Event Reconstruction at the LHC I

FERMILAB-CERN
HADRON COLLIDER PHYSICS
SUMMER SCHOOL
2024

Richard Cavanaugh, Fermilab/UIC, HCPSS 31 July 2024


The goal of event reconstruction...
s-Benz EQA 300 4MATIC | WLTP: Stromverbrauch kombiniert: 18,7–17,4 kWh/100 km | CO_2-Emissionen kombiniert:
Benz EQS 450 4MATIC SUV | WLTP: Stromverbrauch kombiniert: 24,3–19,9 kWh/100 km | CO_2-Emissionen kombiniert


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The goal of event reconstruction...
...put the pieces back together!

History of Event Reconstruction

Cloud Chamber

Invented 1911

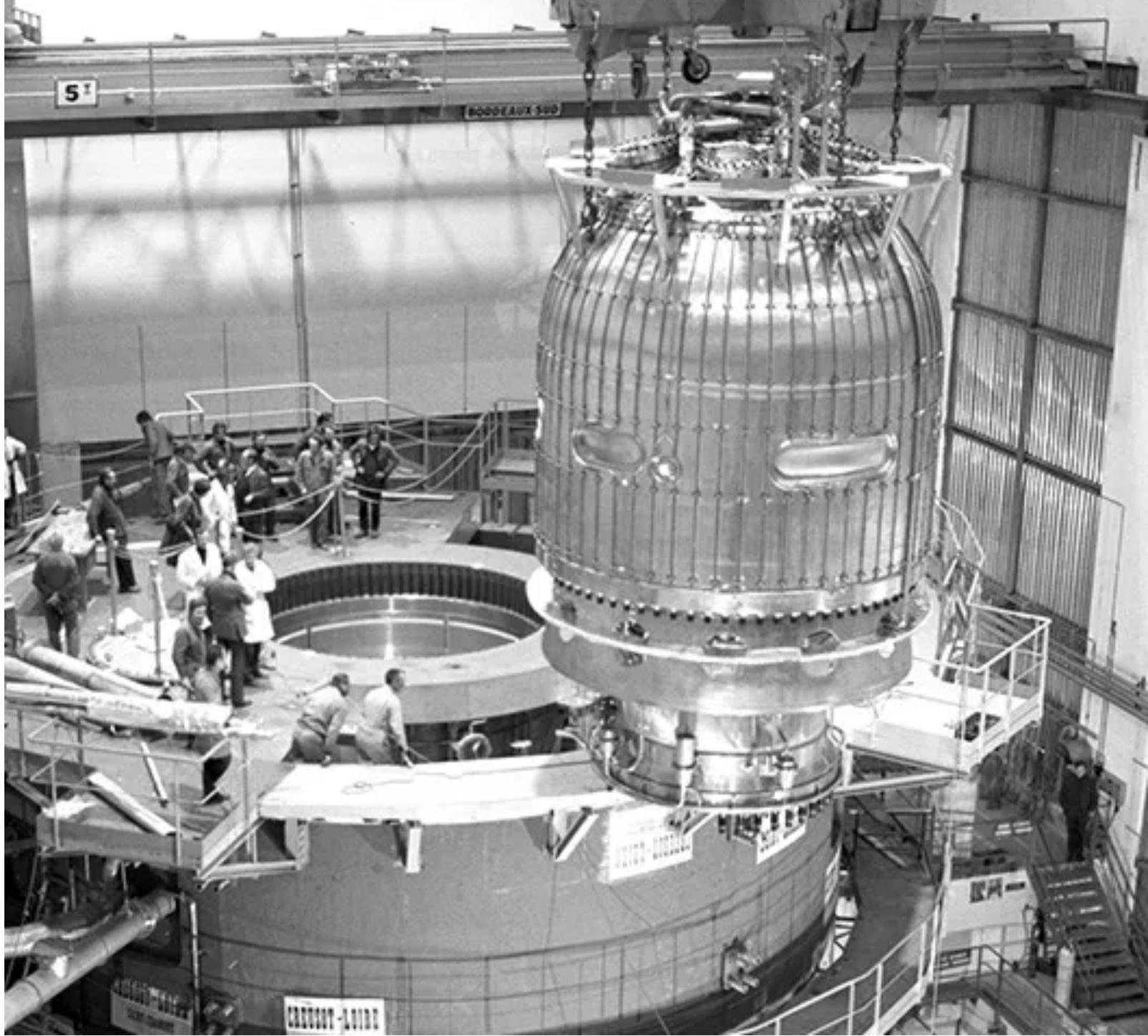
Nobel 1927

History of Event Reconstruction

Bubble Chamber

Invented 1952

Nobel 1960



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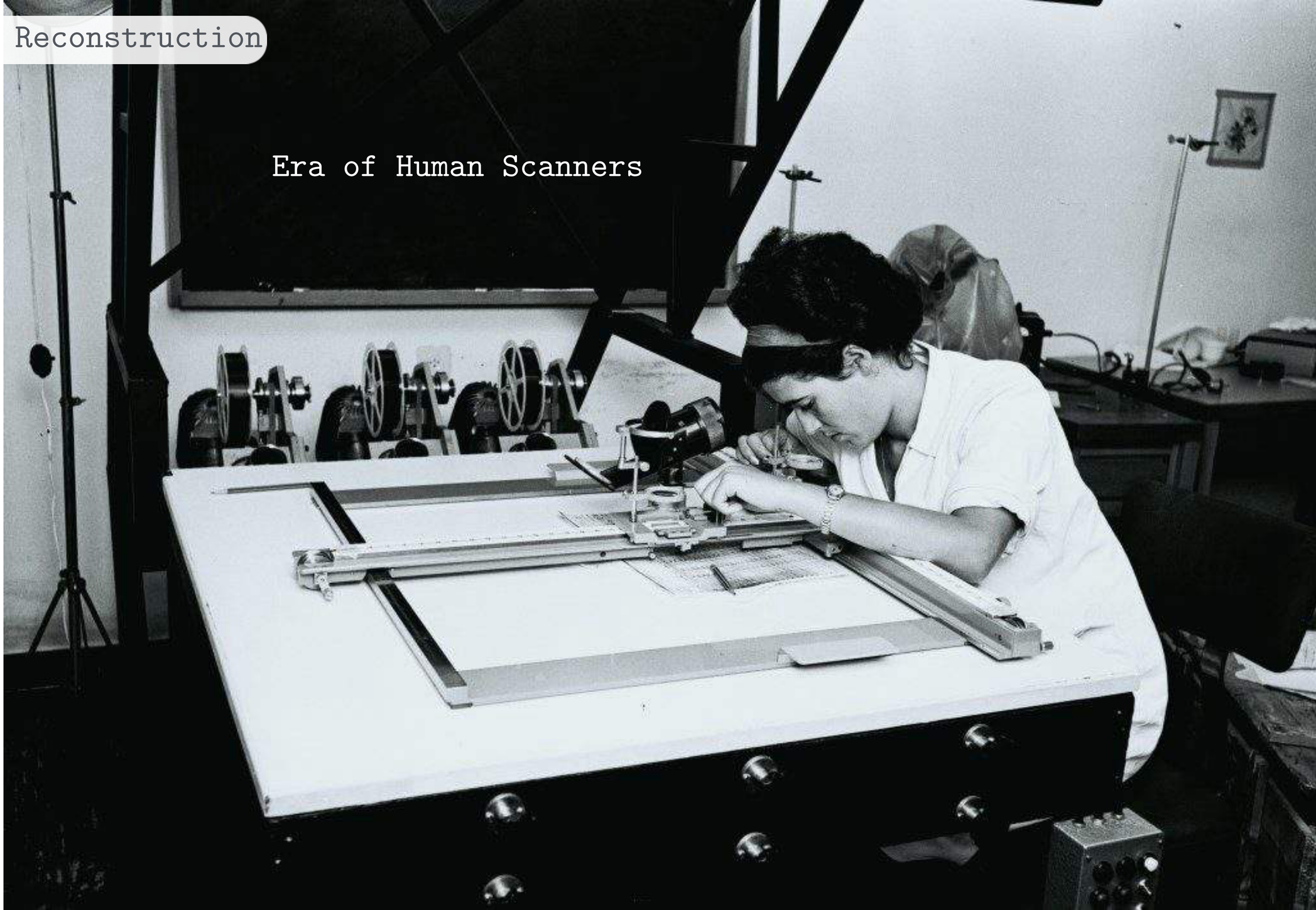
Era of Human Scanners



History of Event Reconstruction

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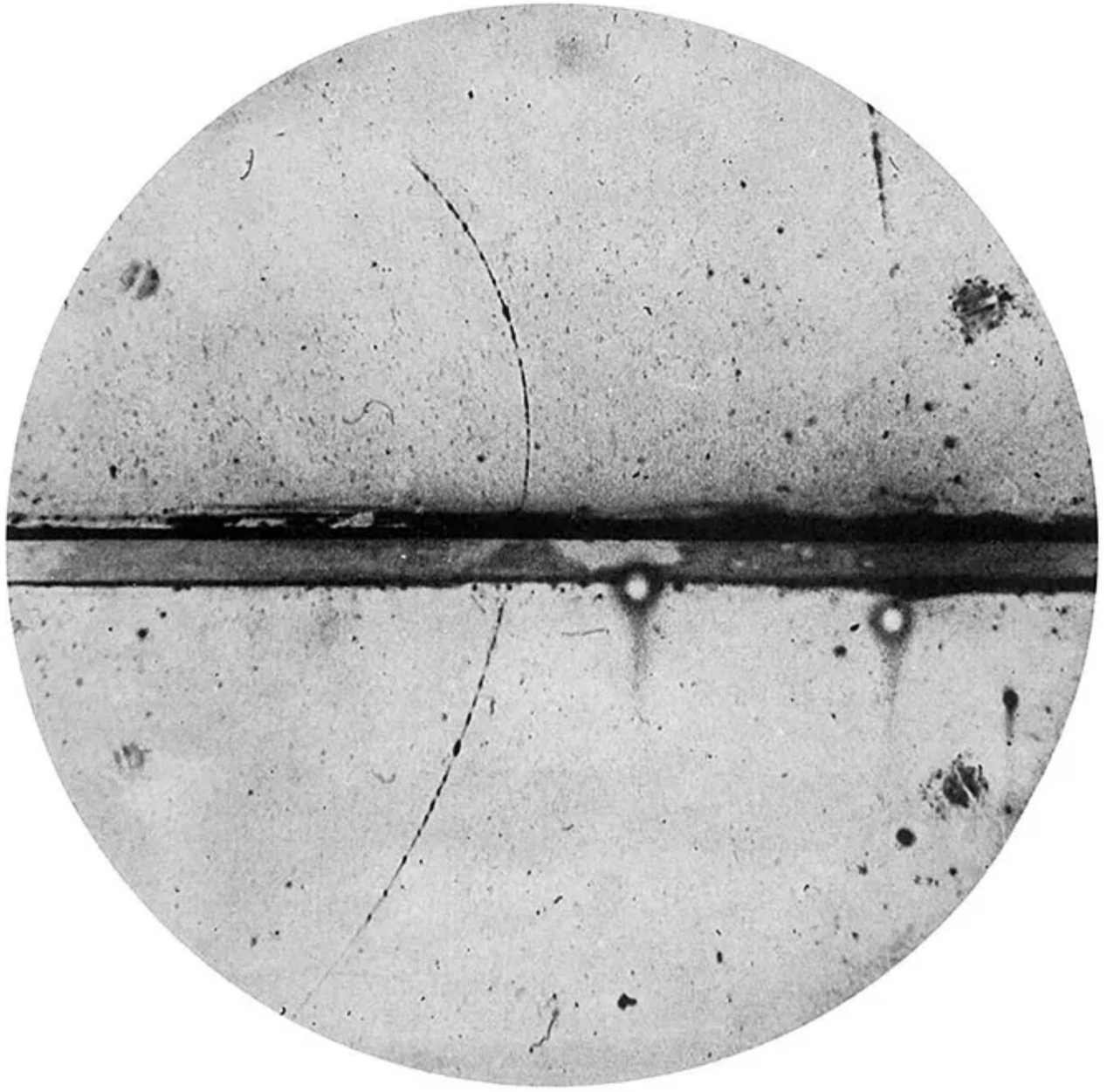
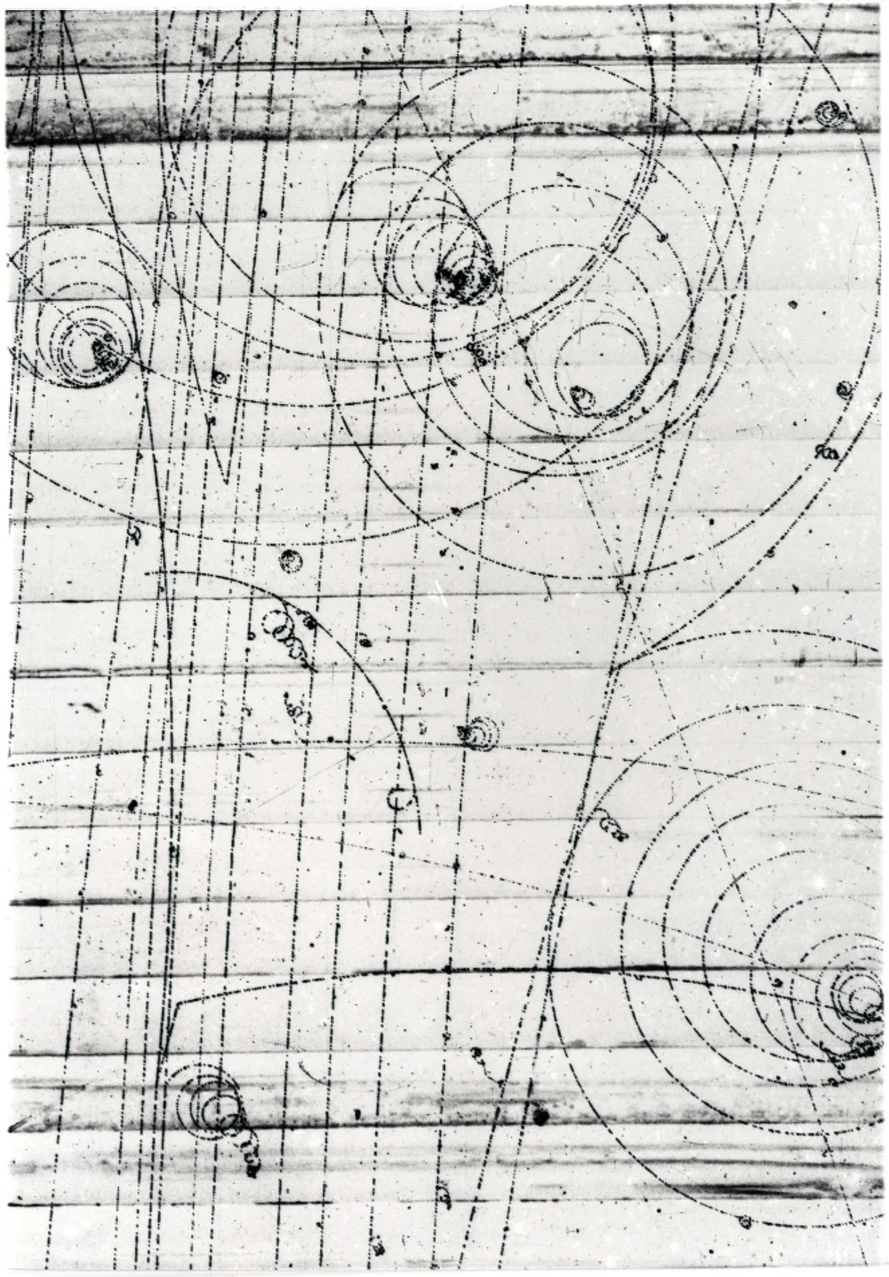
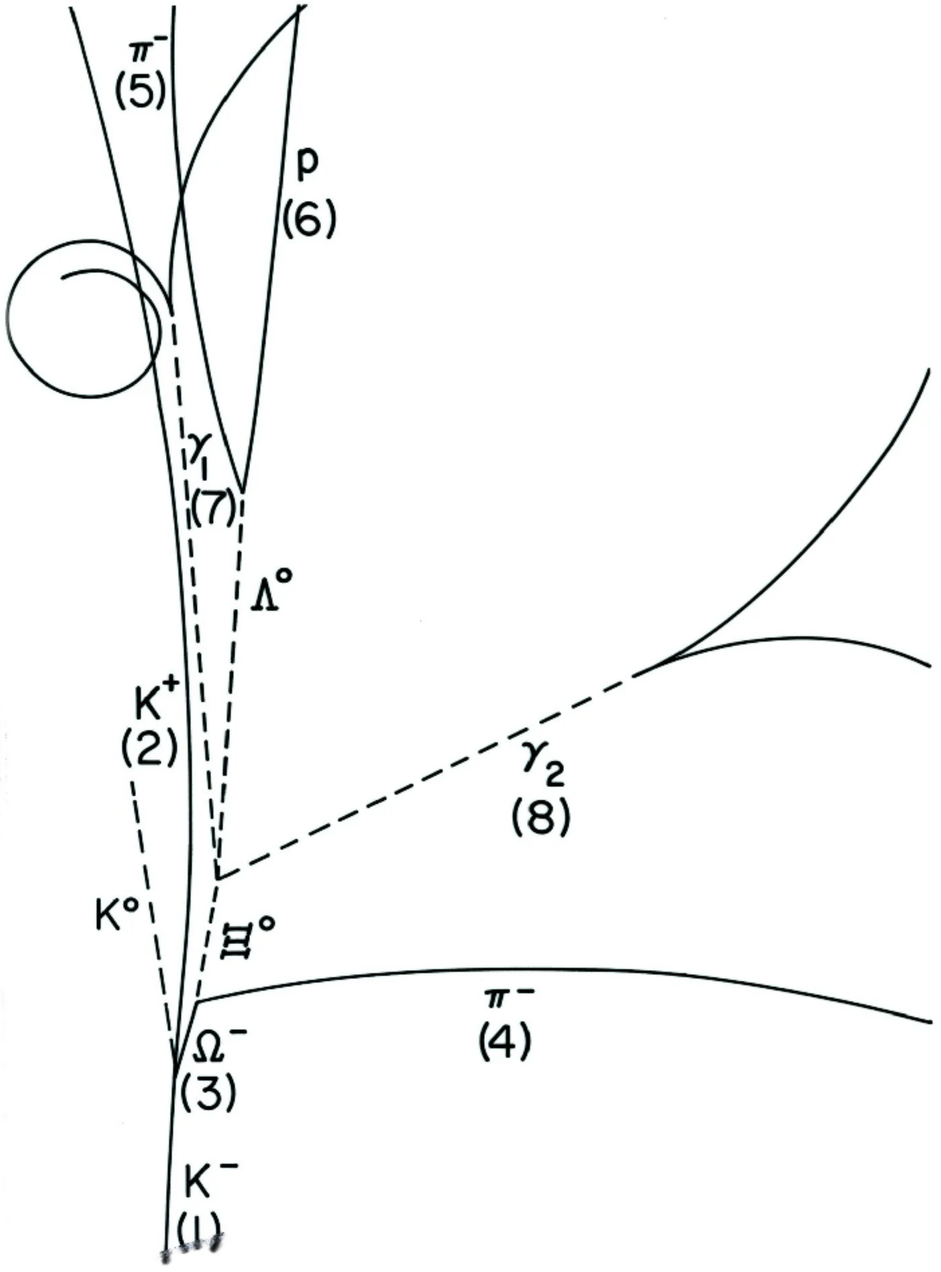


Discovery of the positron (1932 - Nobel 1936)





But, data collection and analysis rates just too low!

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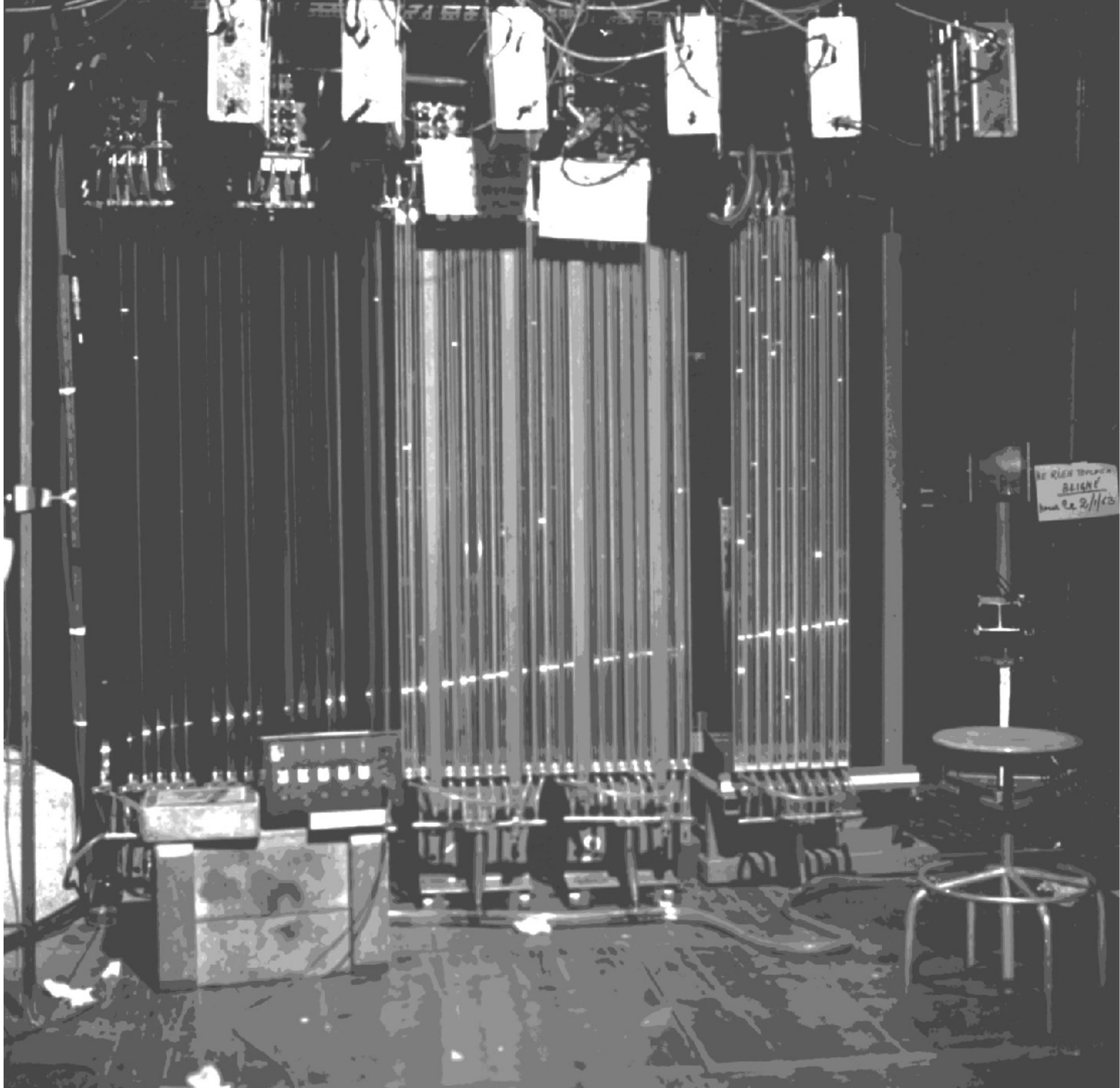
Electronic Detectors:

Spark Chamber (1963)



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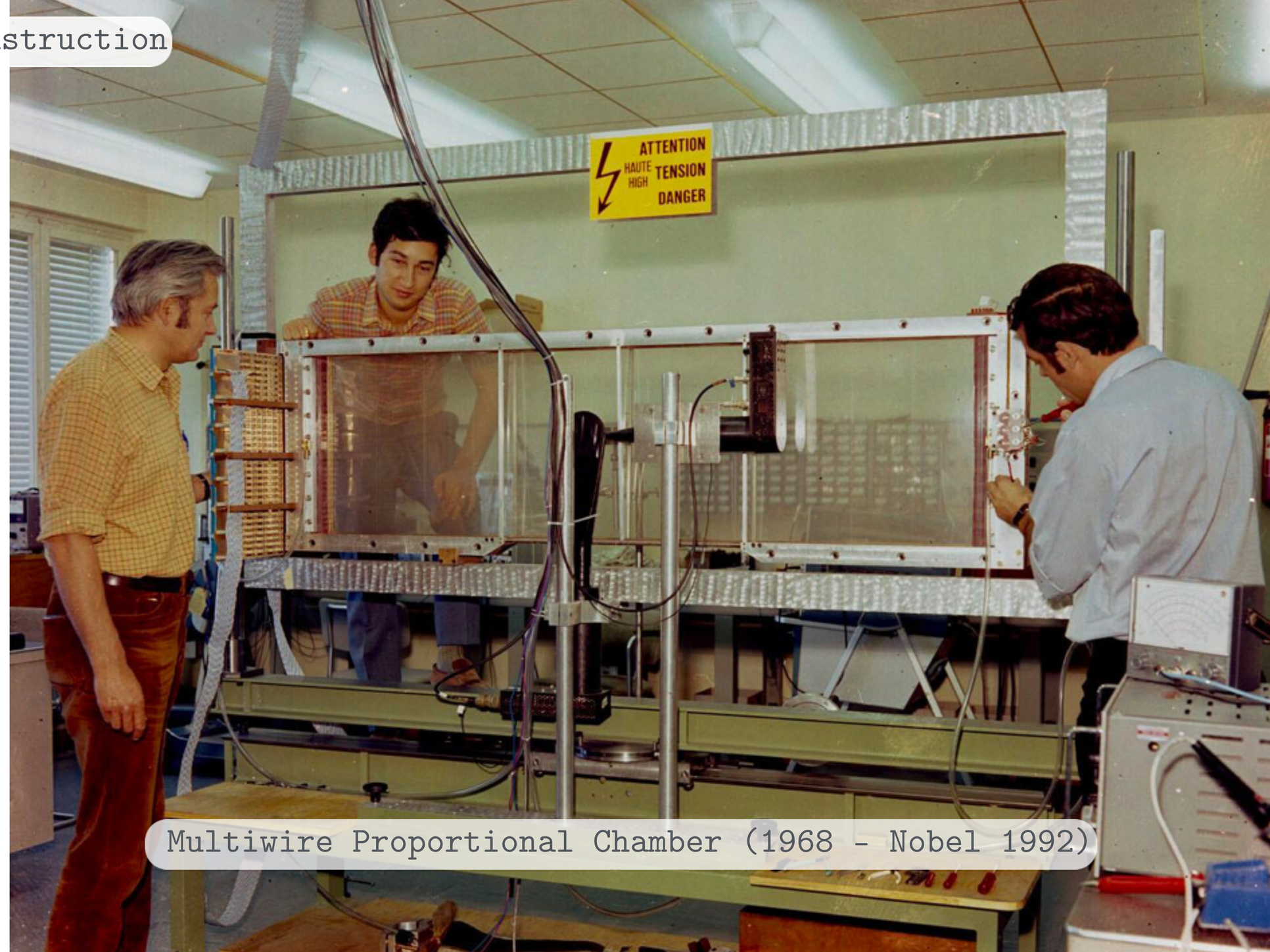
Electronic

Detectors:

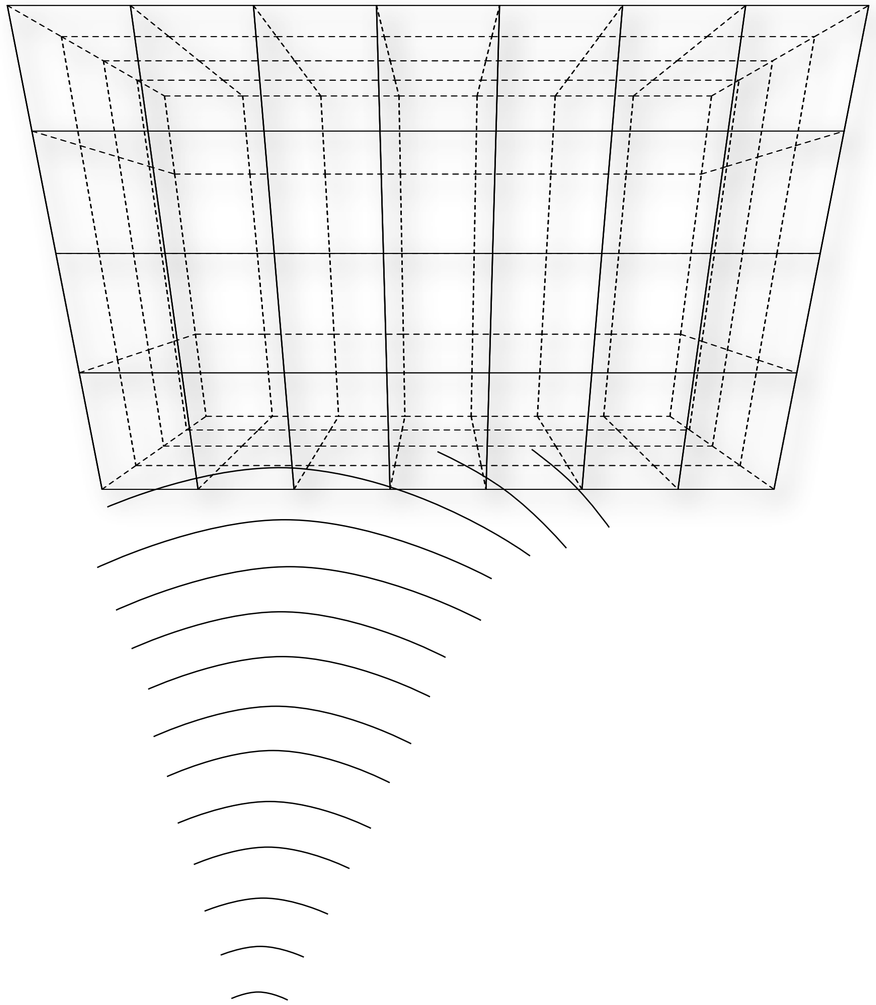


Multiwire Proportional Chamber (1968 - Nobel 1992)

Electronic Detectors:

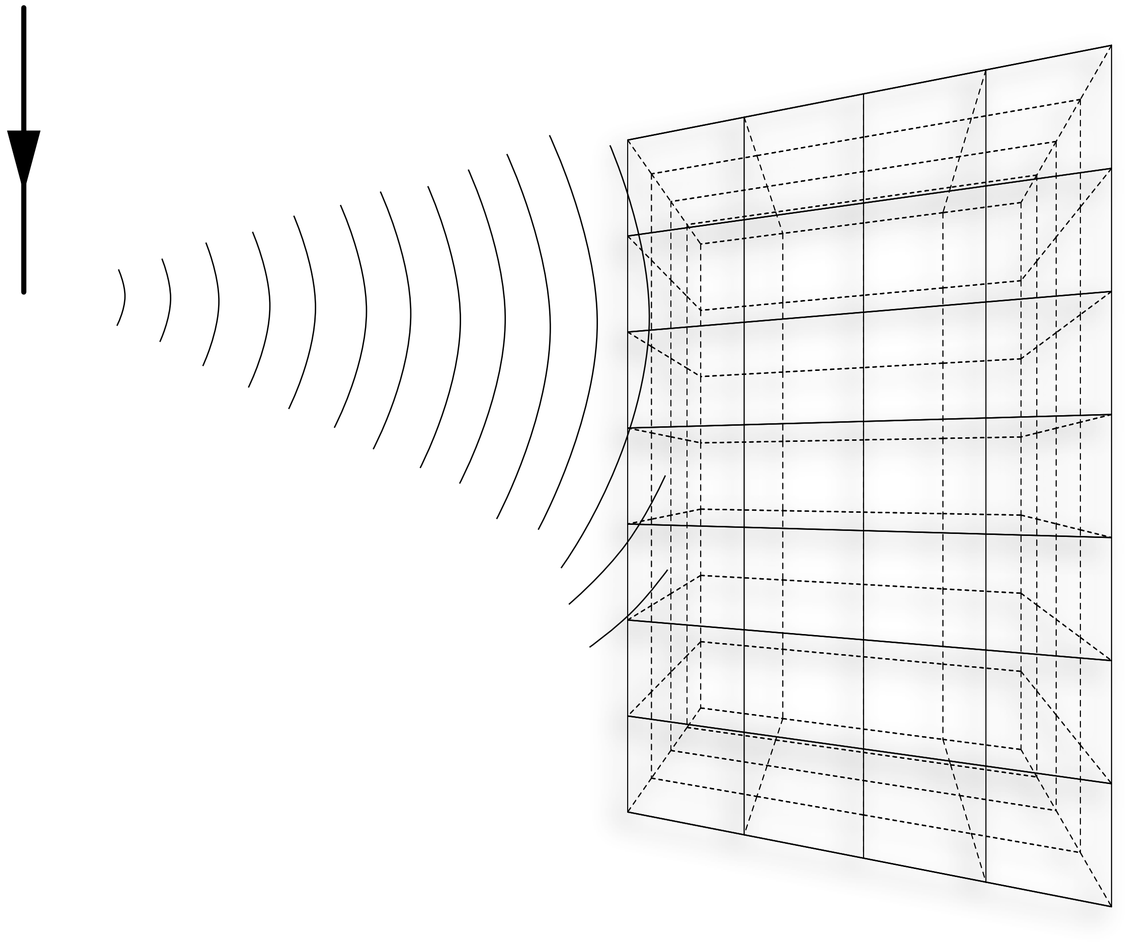
History of Event Reconstruction

The Big Picture!



Particle Physics Detector

The Big Picture!



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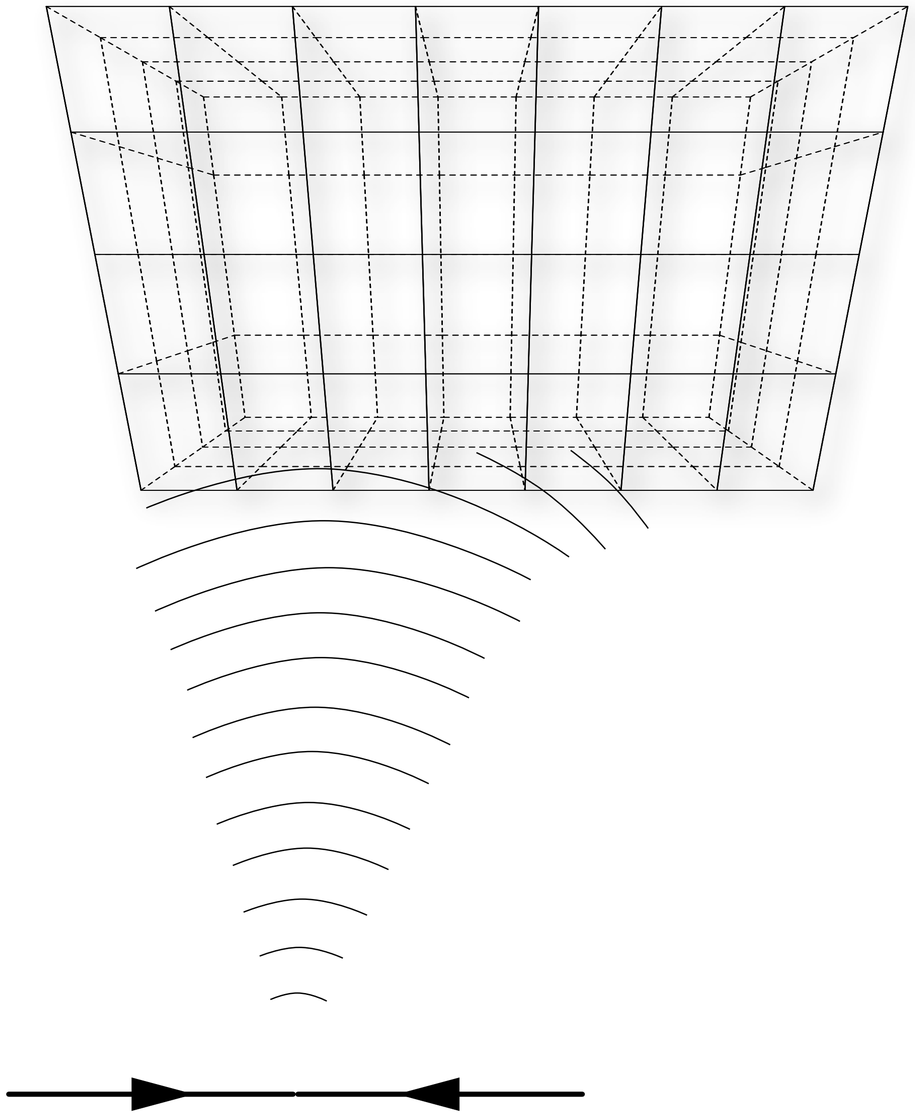
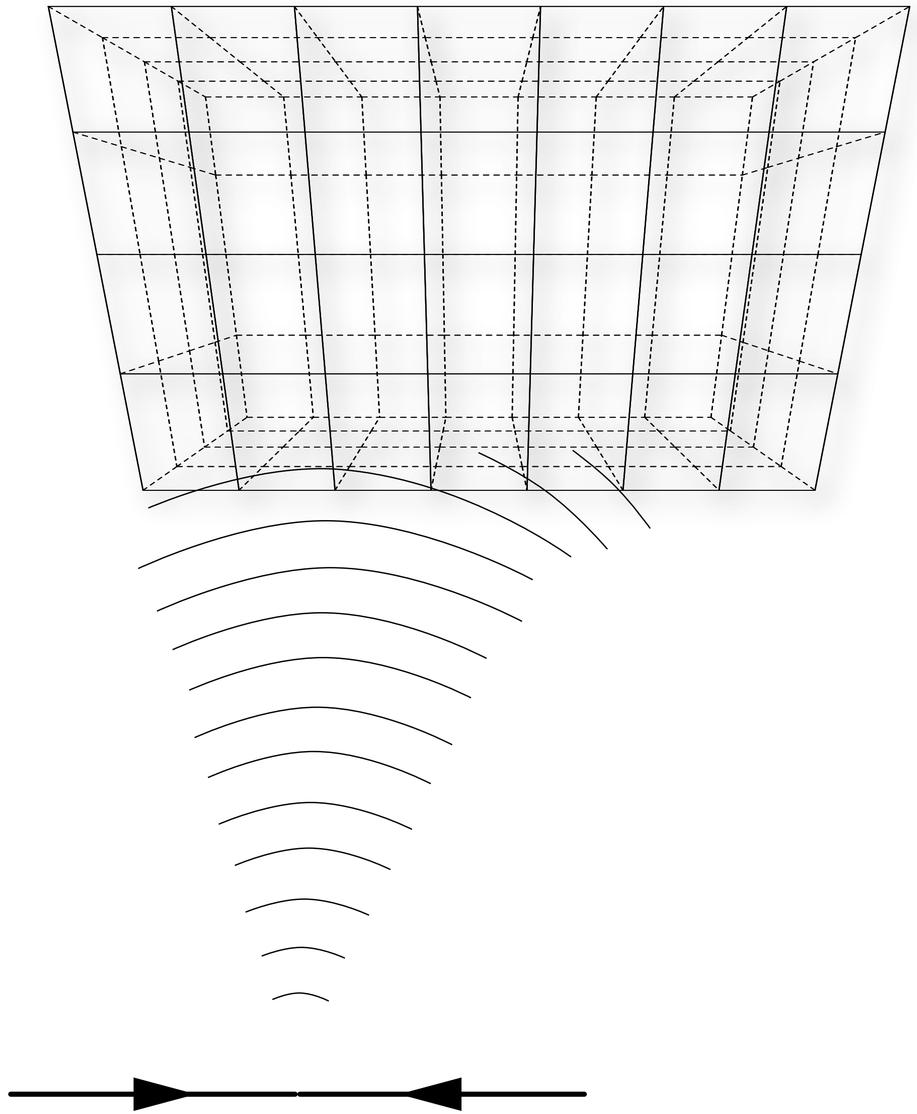


Particle Physics Detector

The Big Picture!

- Physics process => Partons



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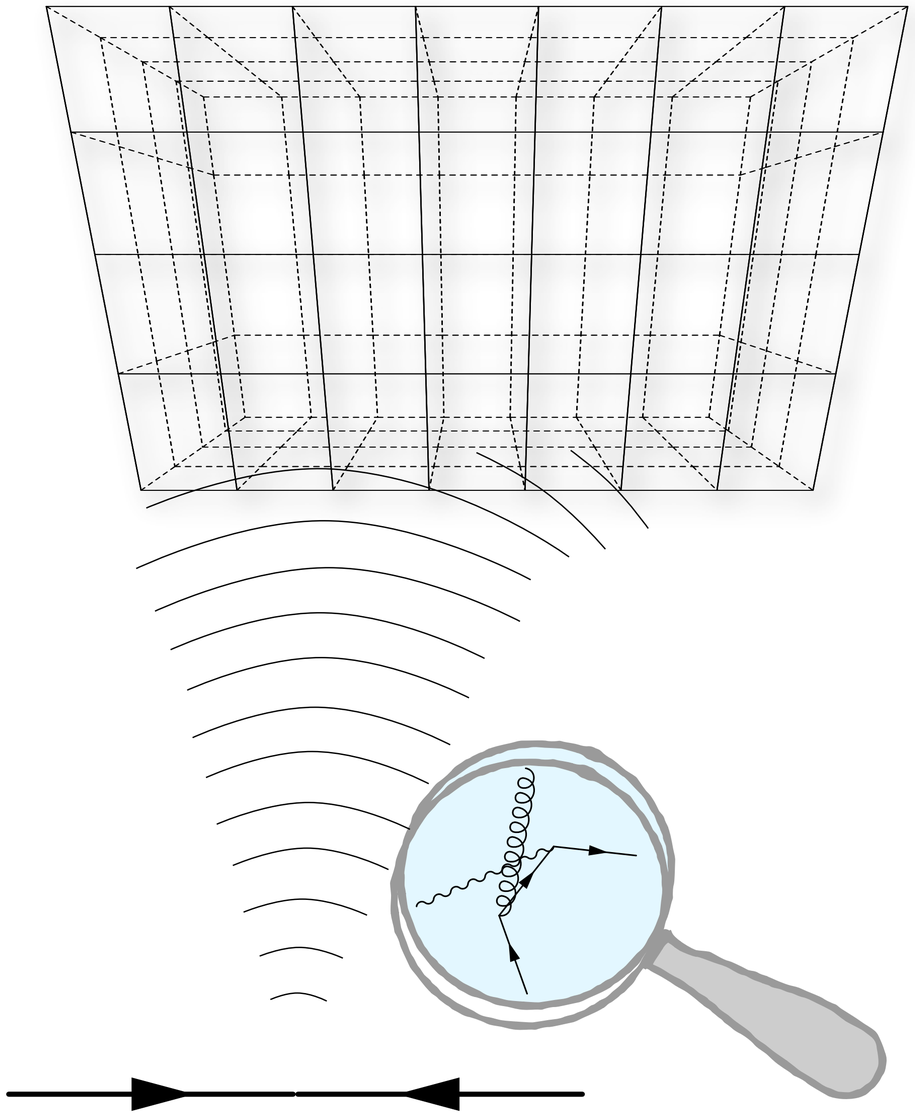

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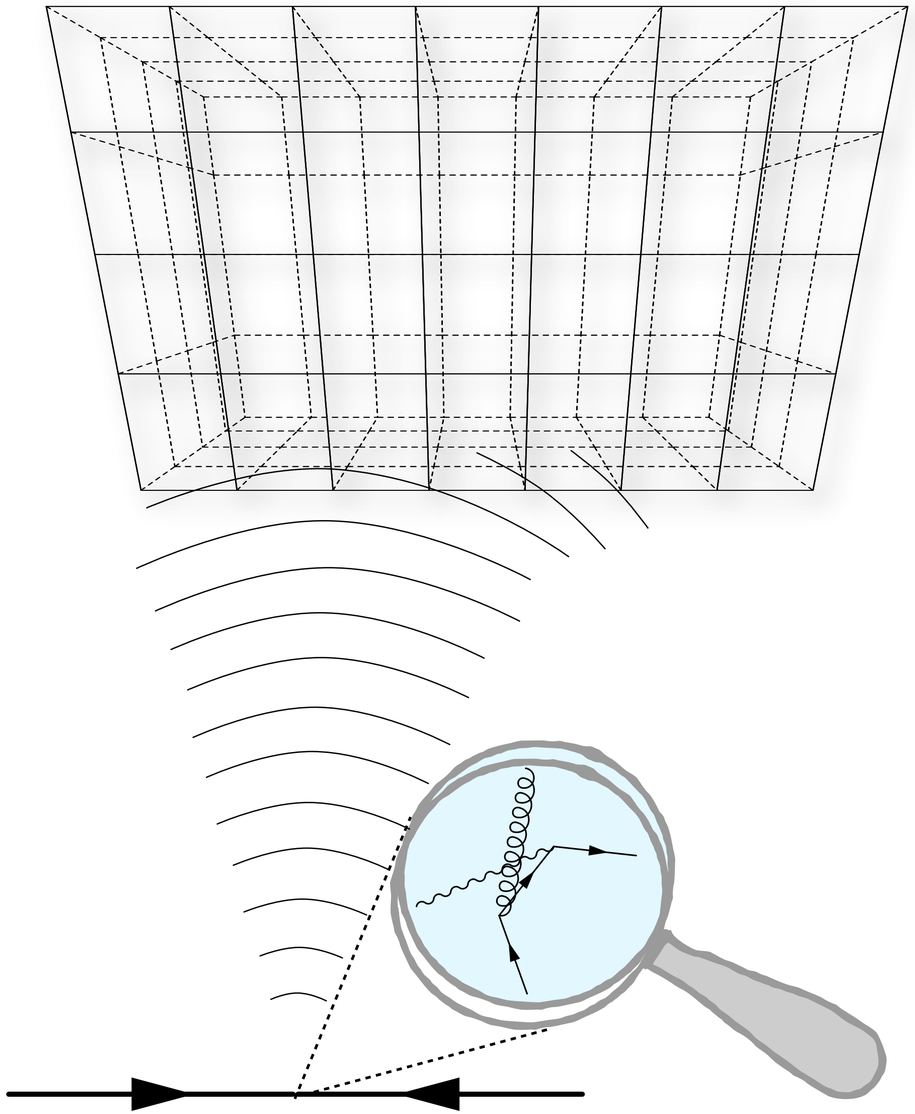

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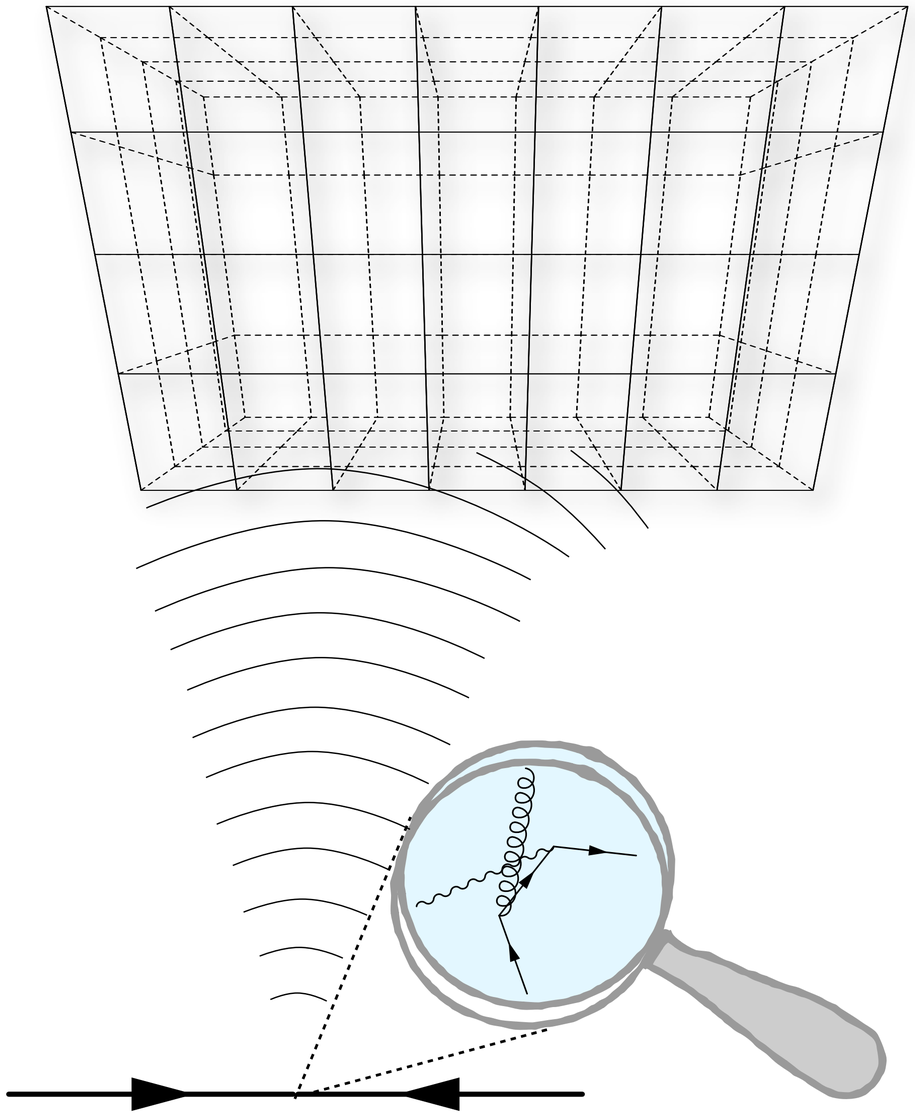

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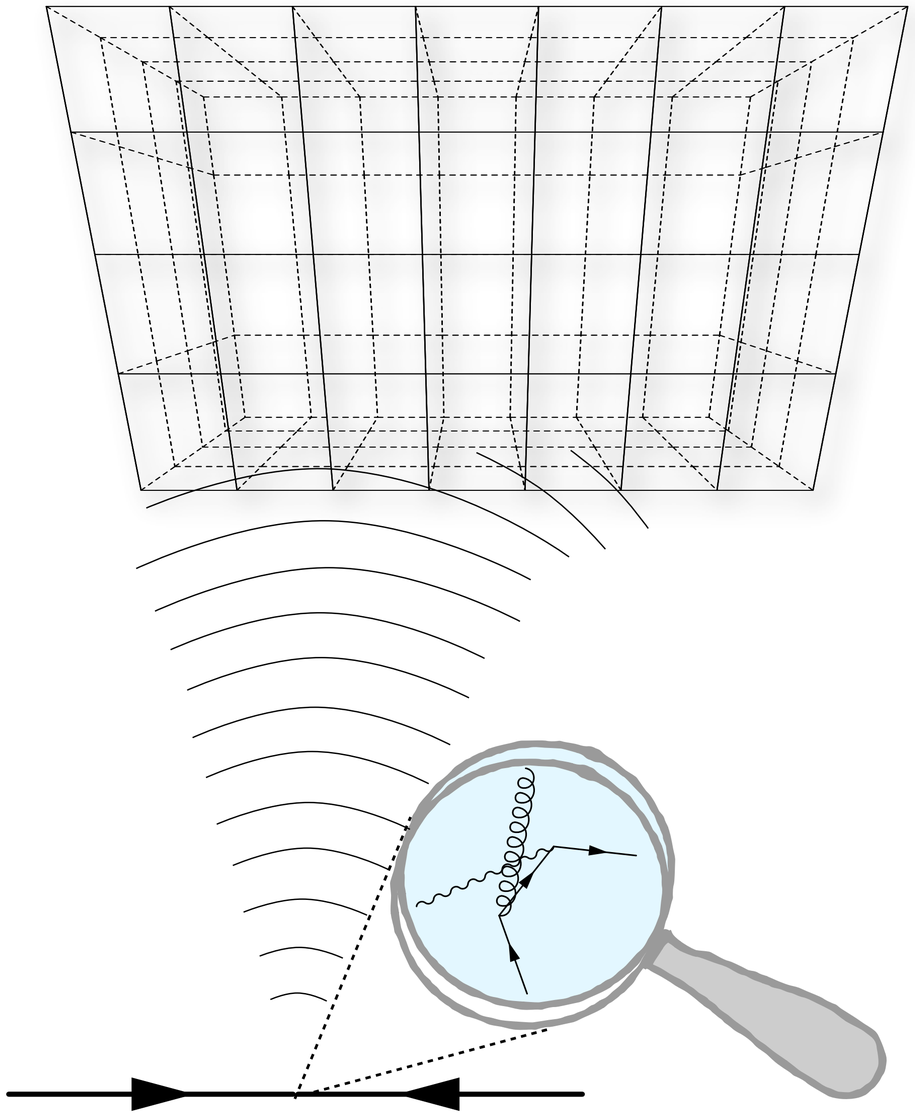
- Partons =>
  - (decay or not to) visible particles



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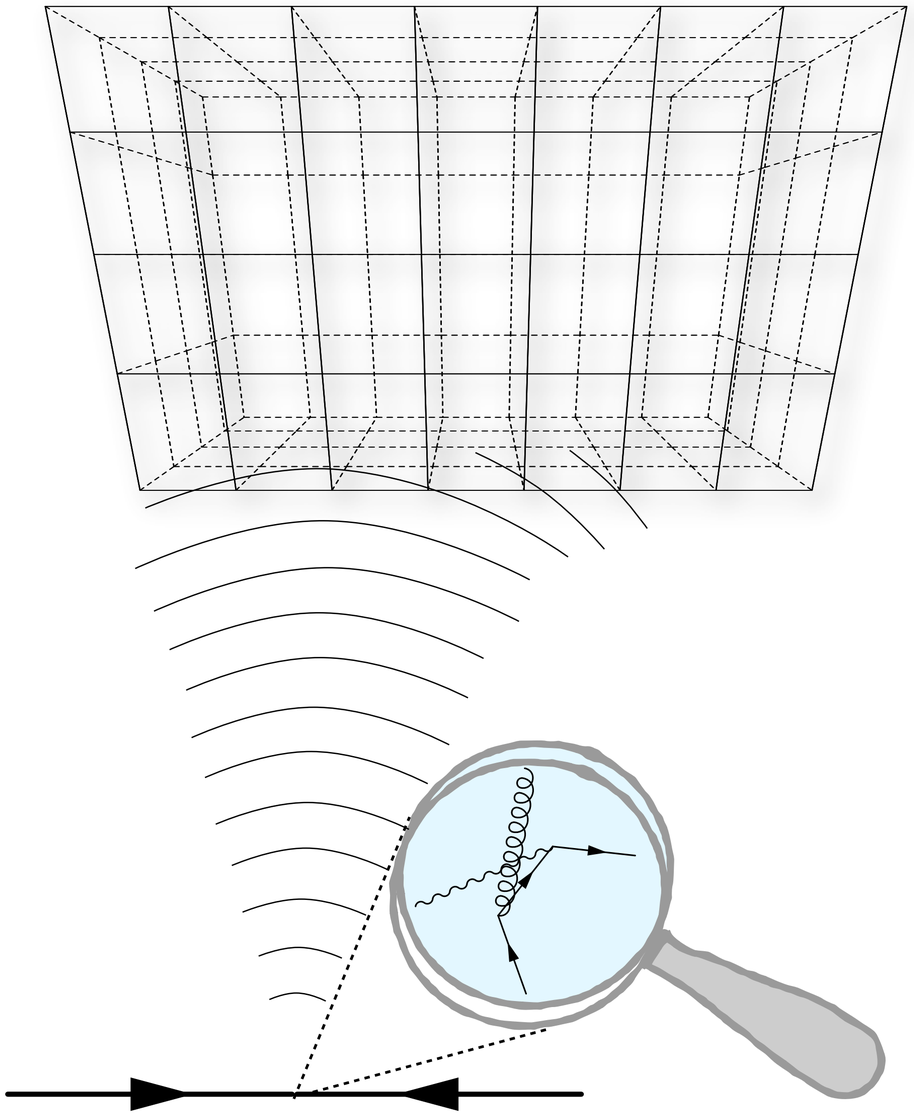

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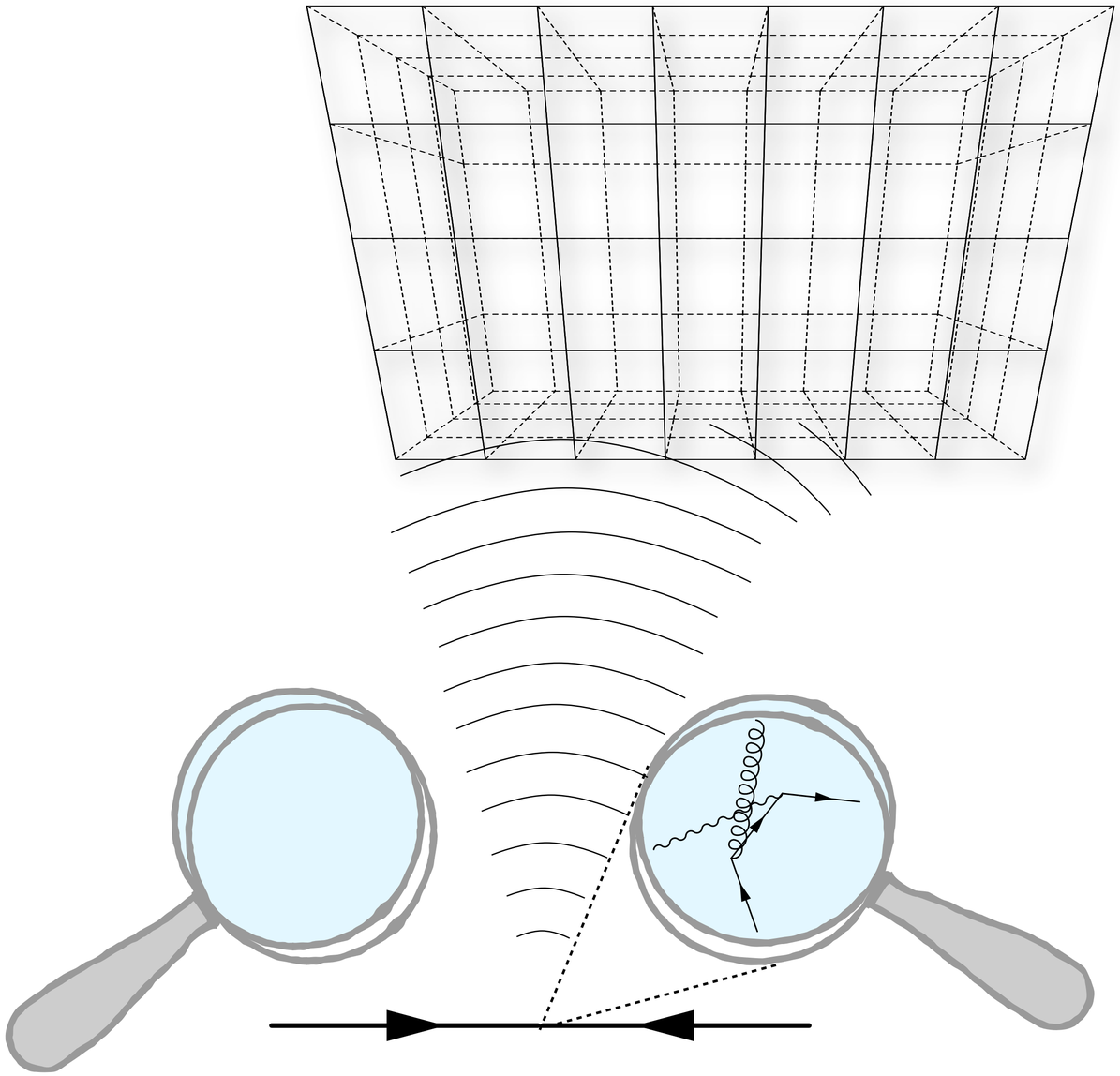

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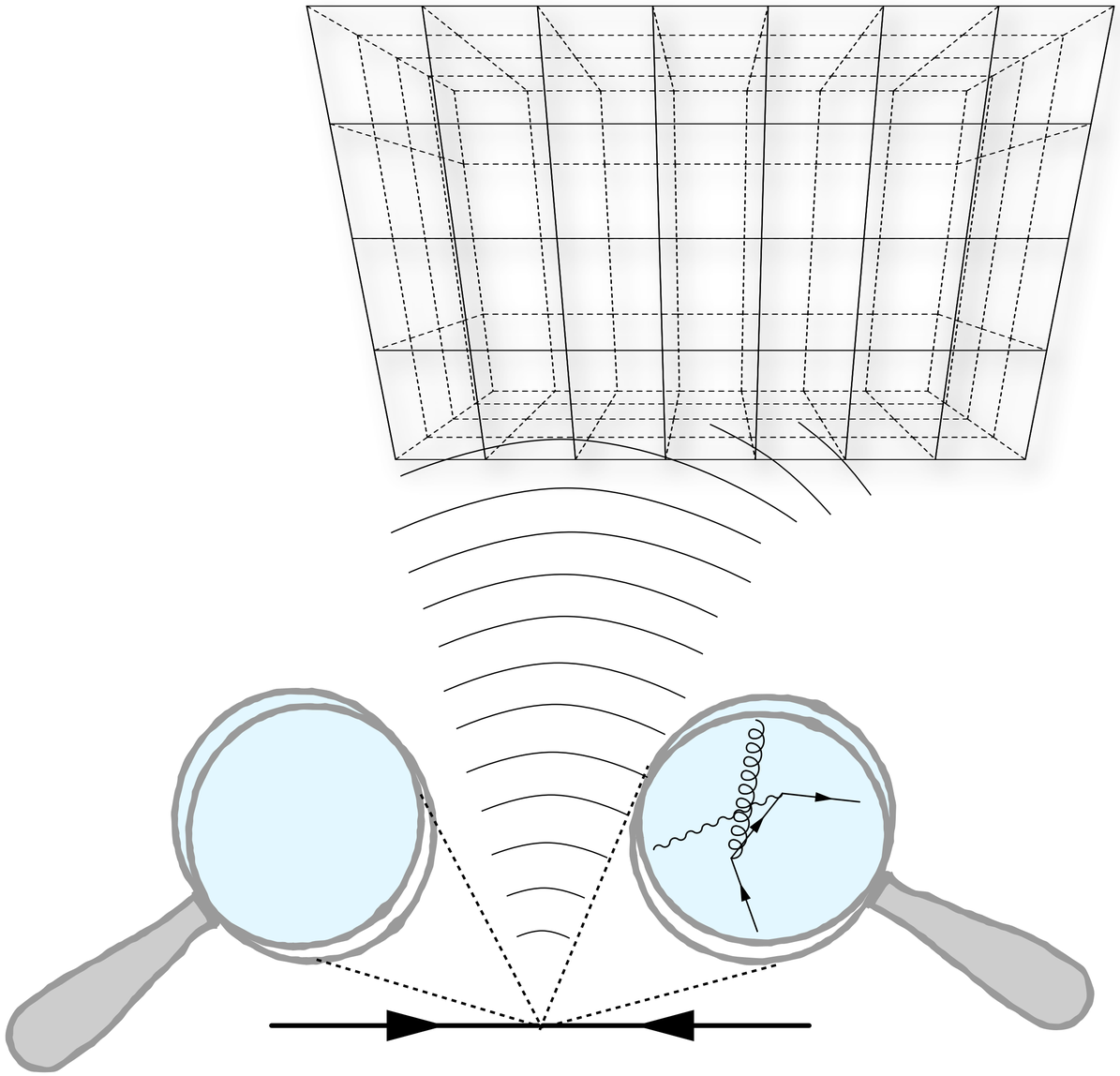

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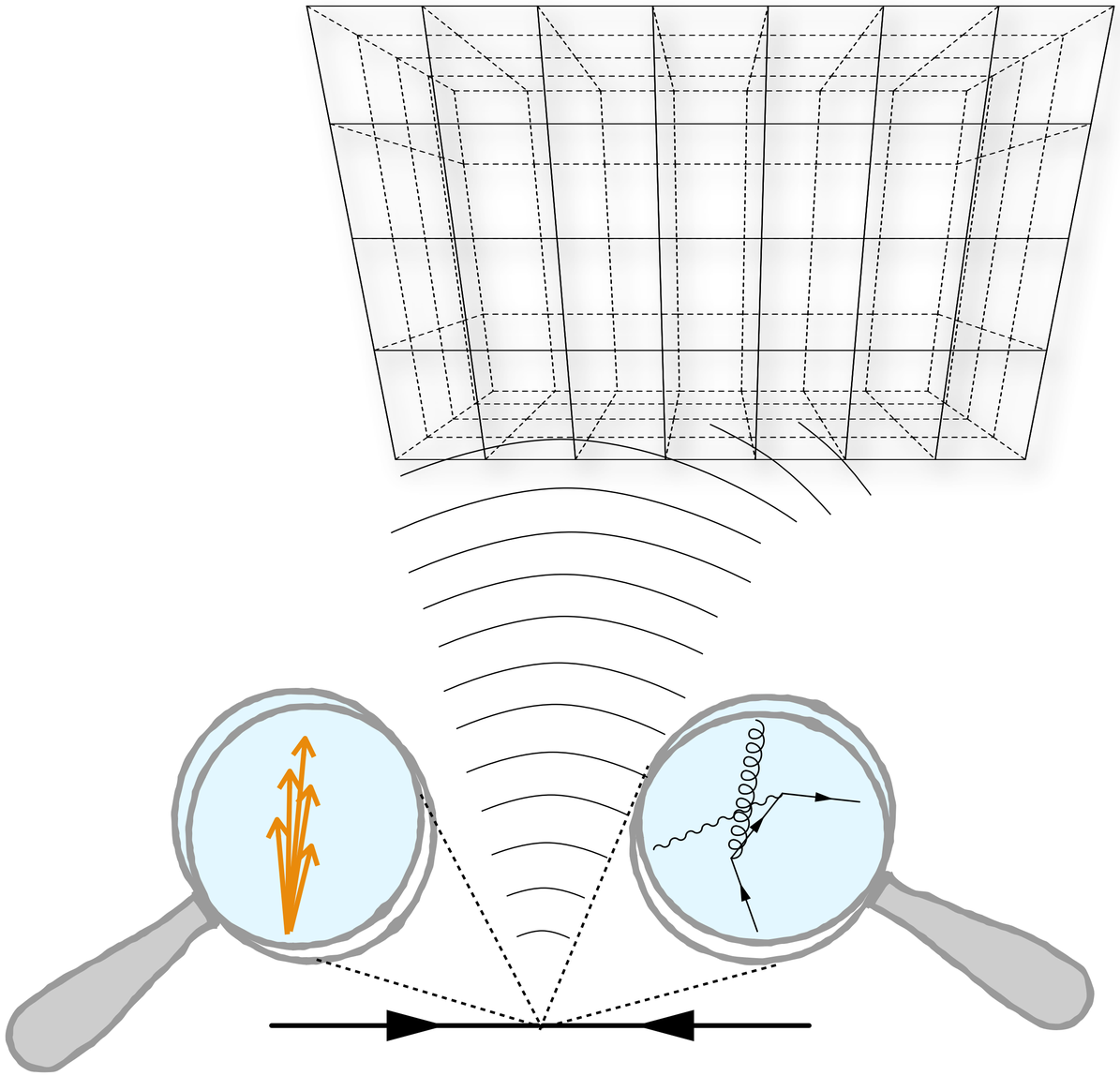

Particle Physics Detector

The Big Picture!

- Physics process => Partons
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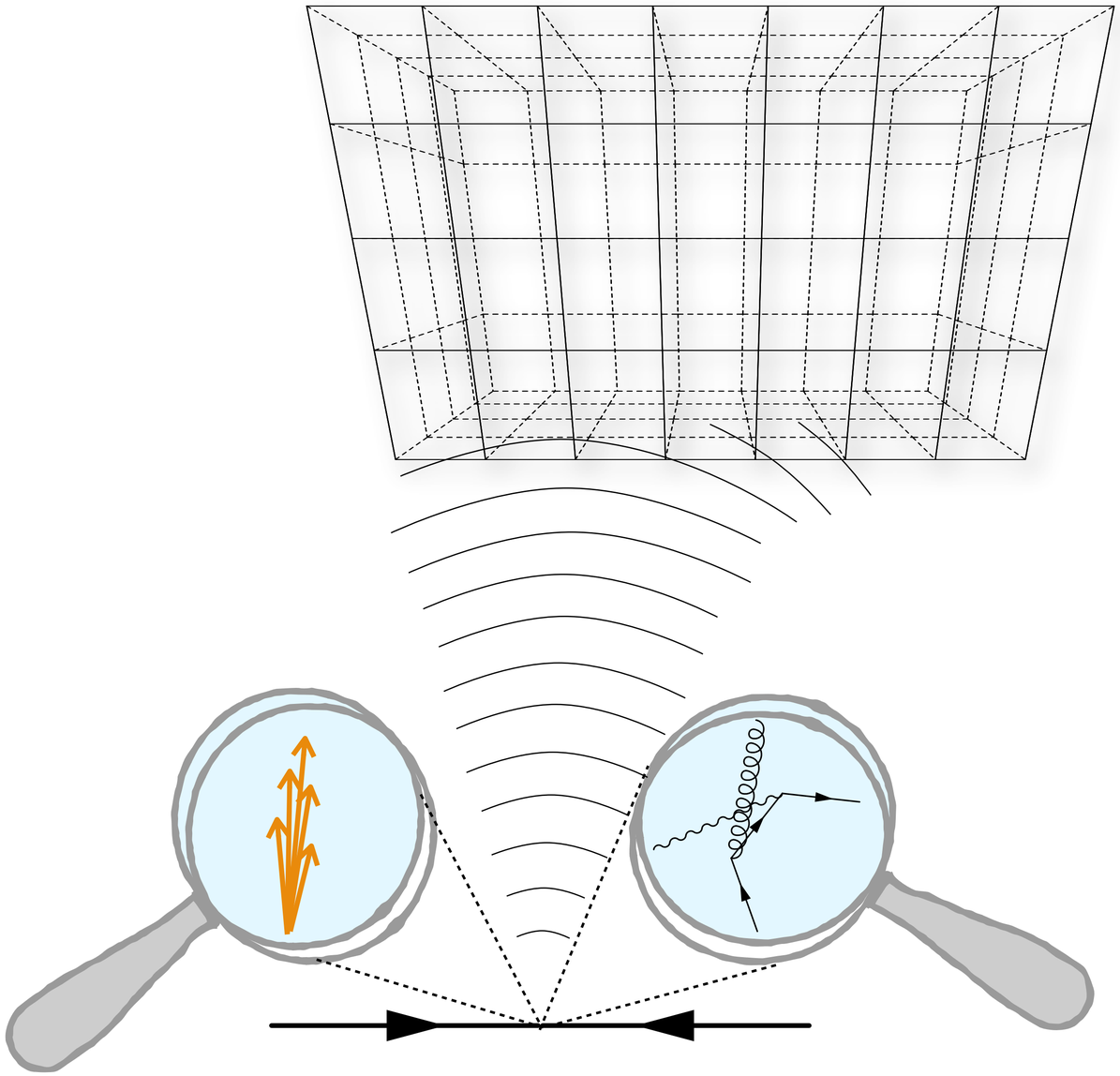

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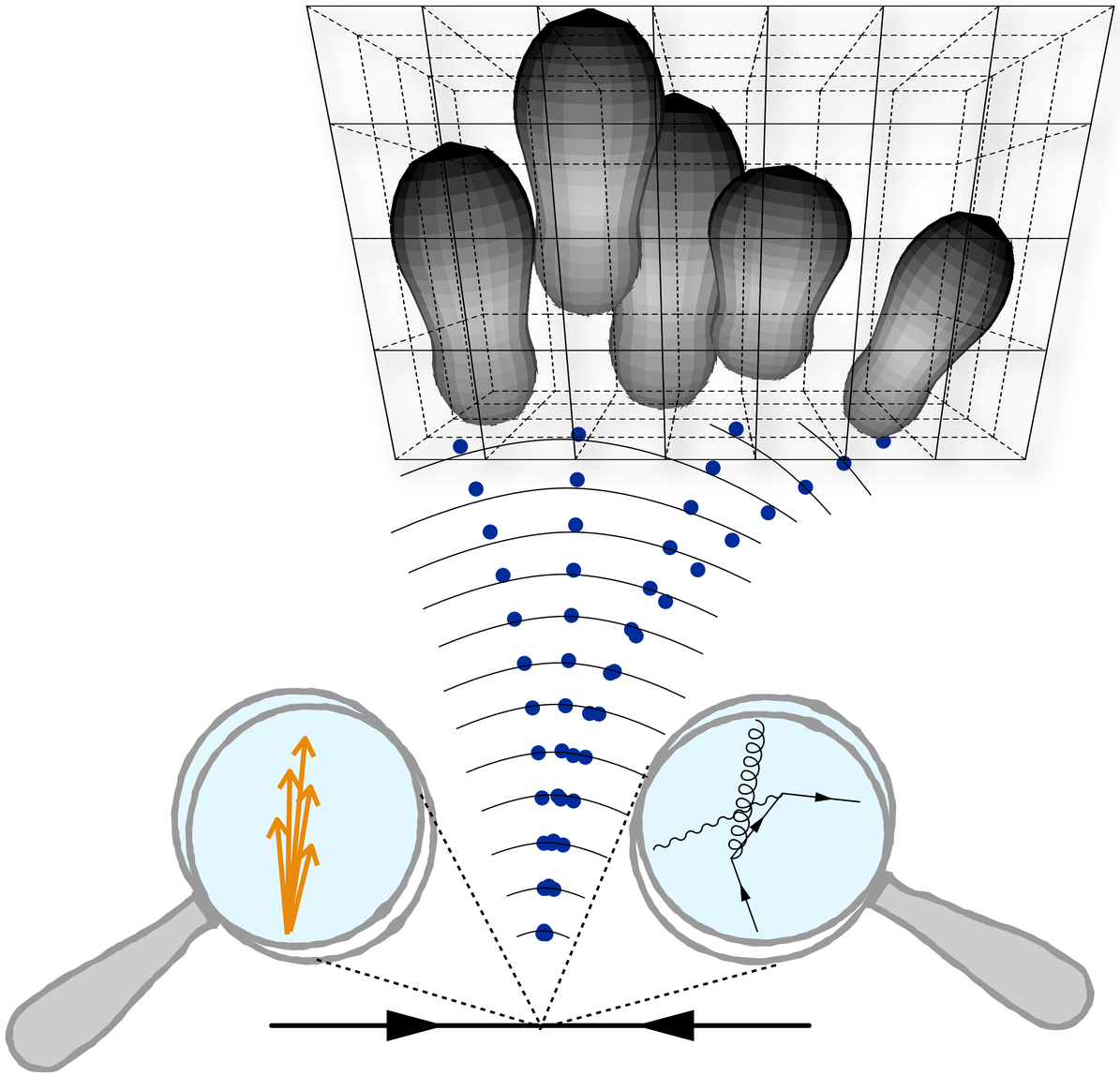

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- Physics process => Partons
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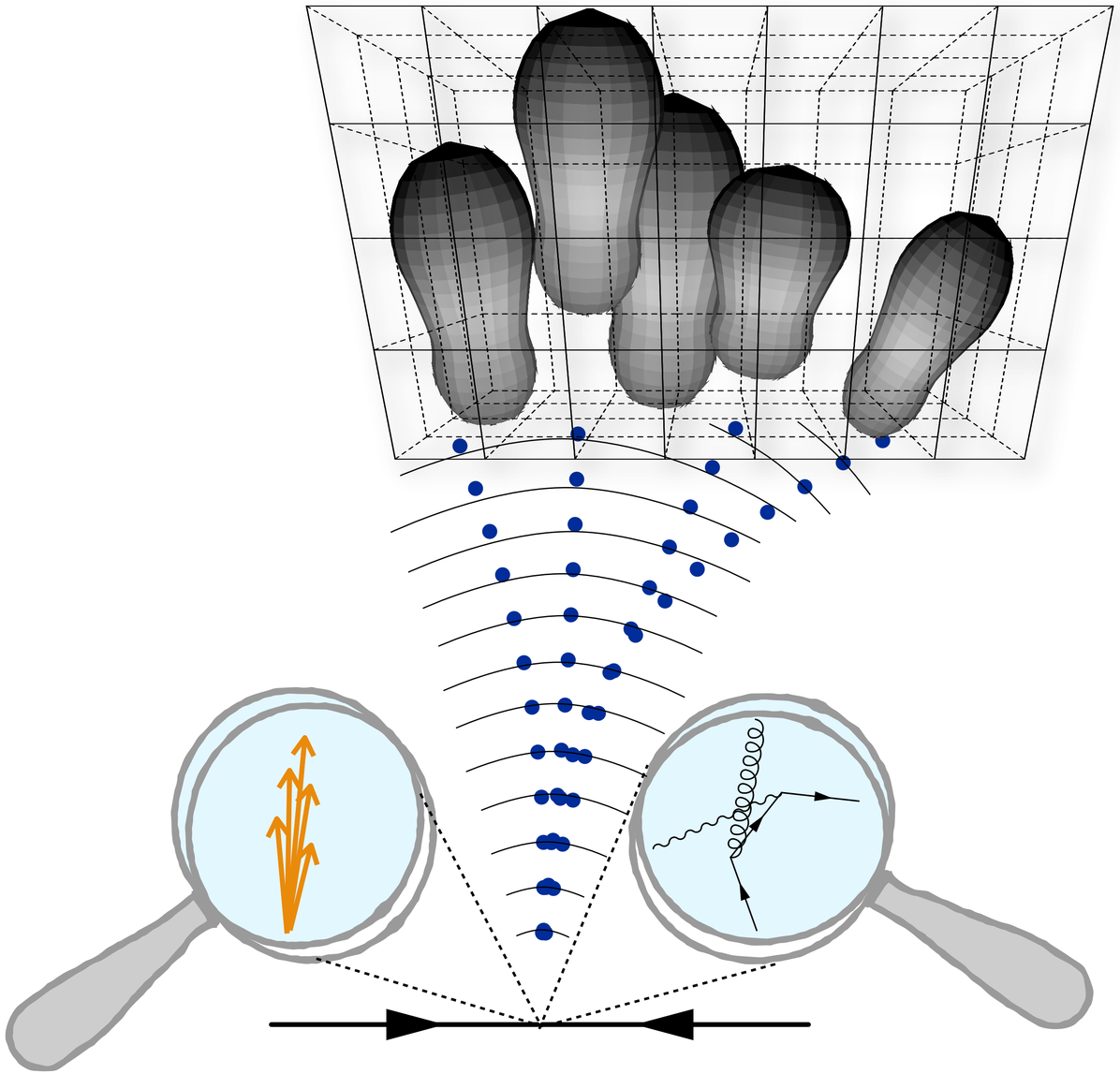
  - Reconstructed quantities
    (momenta, charge, energies, angles)



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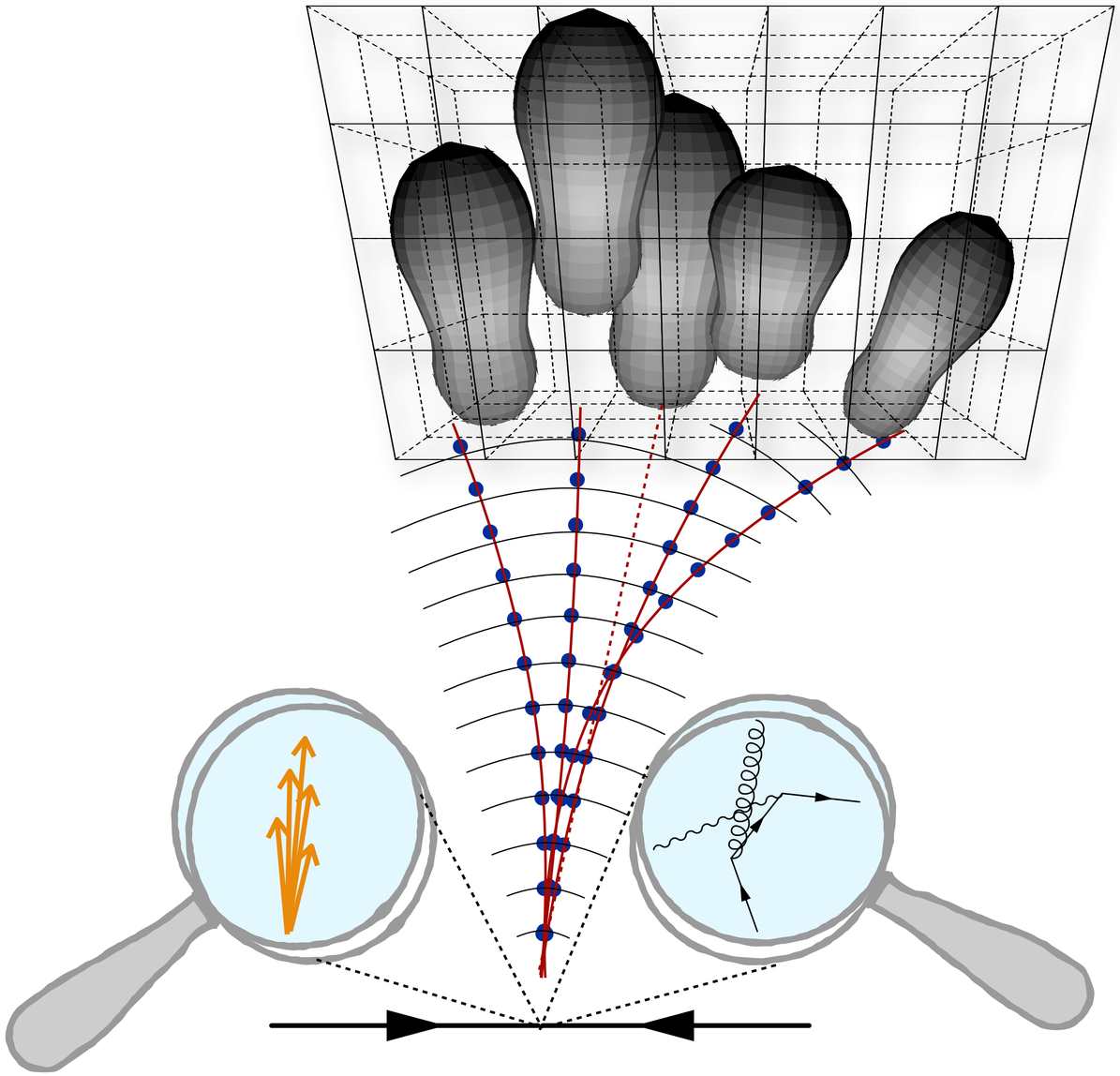

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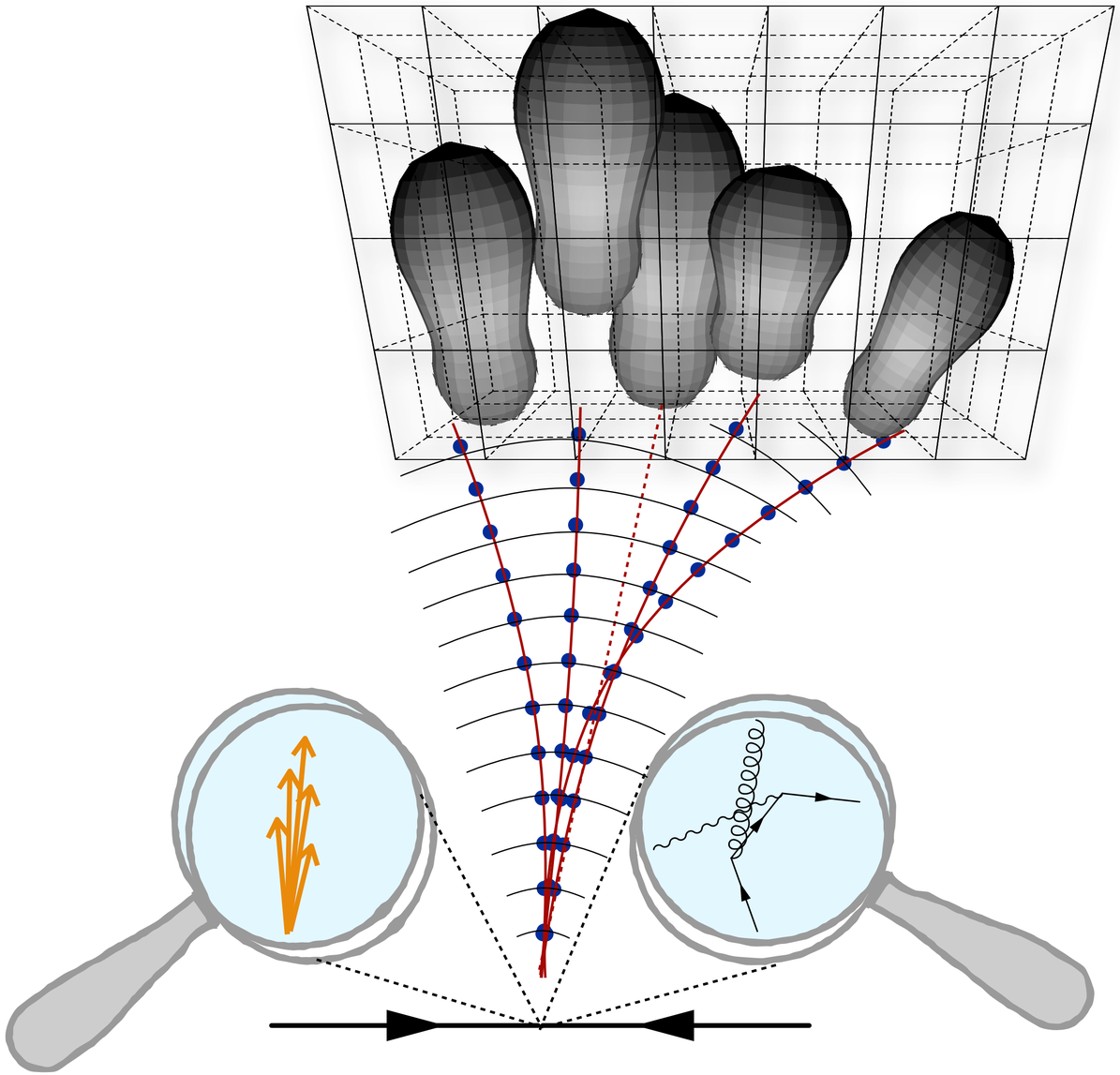
  - List of identified (candidate) particles $\{\mu, \gamma,$ charged/neutral hadrons$\}$



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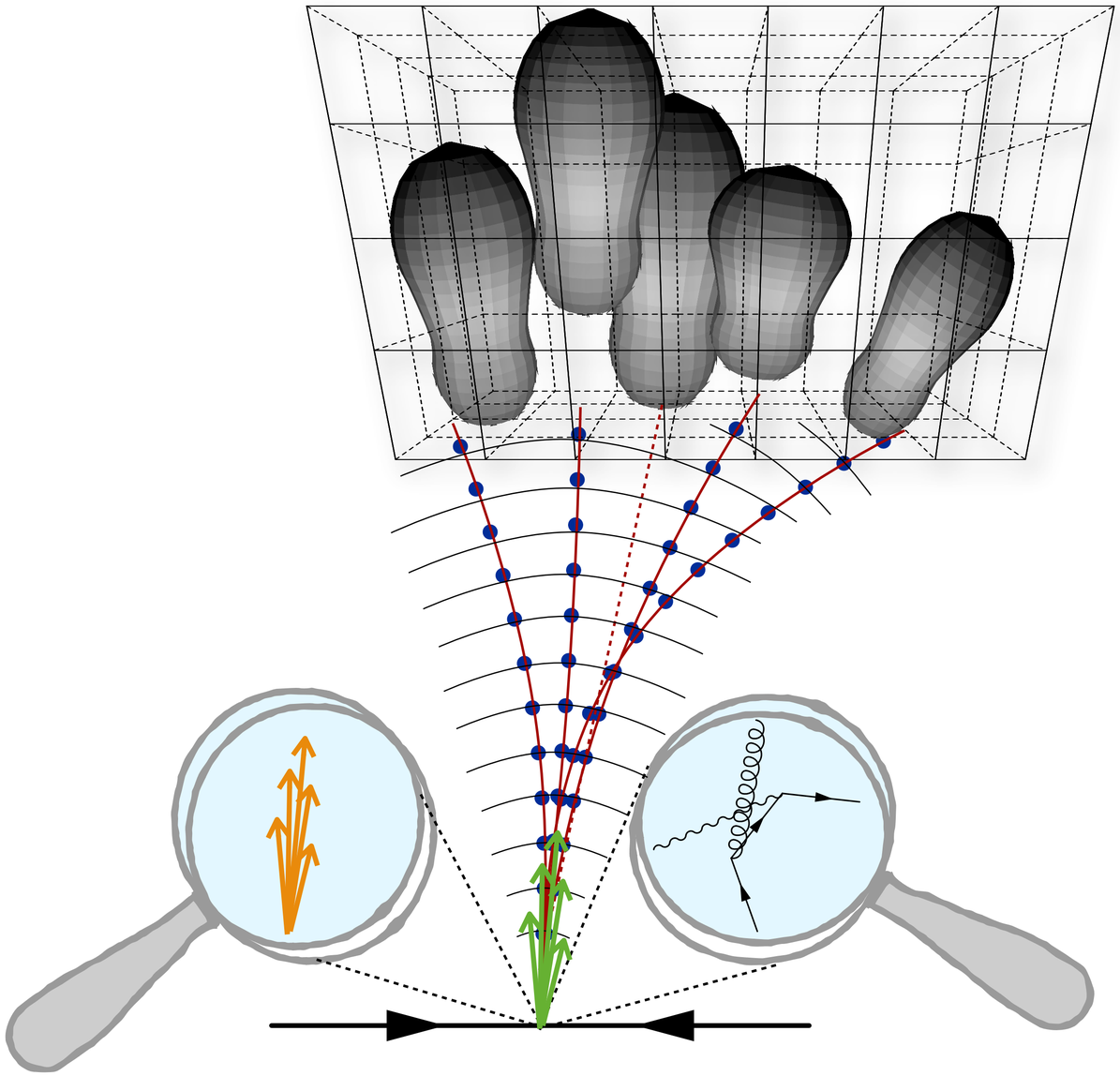

Particle Physics Detector

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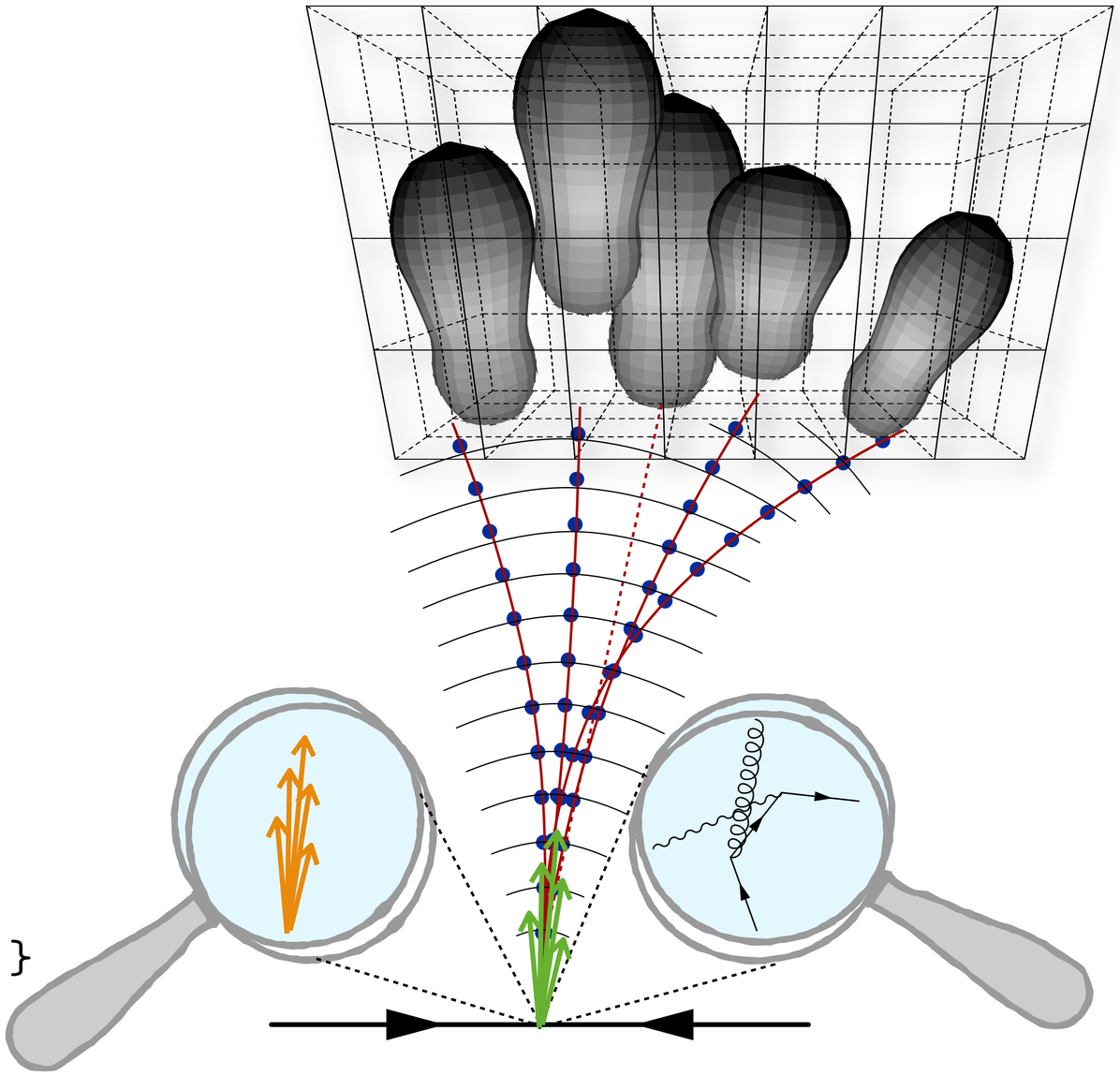
- List of identified particles =>
  - Reconstructed (candidate) partons
    {q/g (jets), W/Z, t, μ, e, γ, ν (MET),...}



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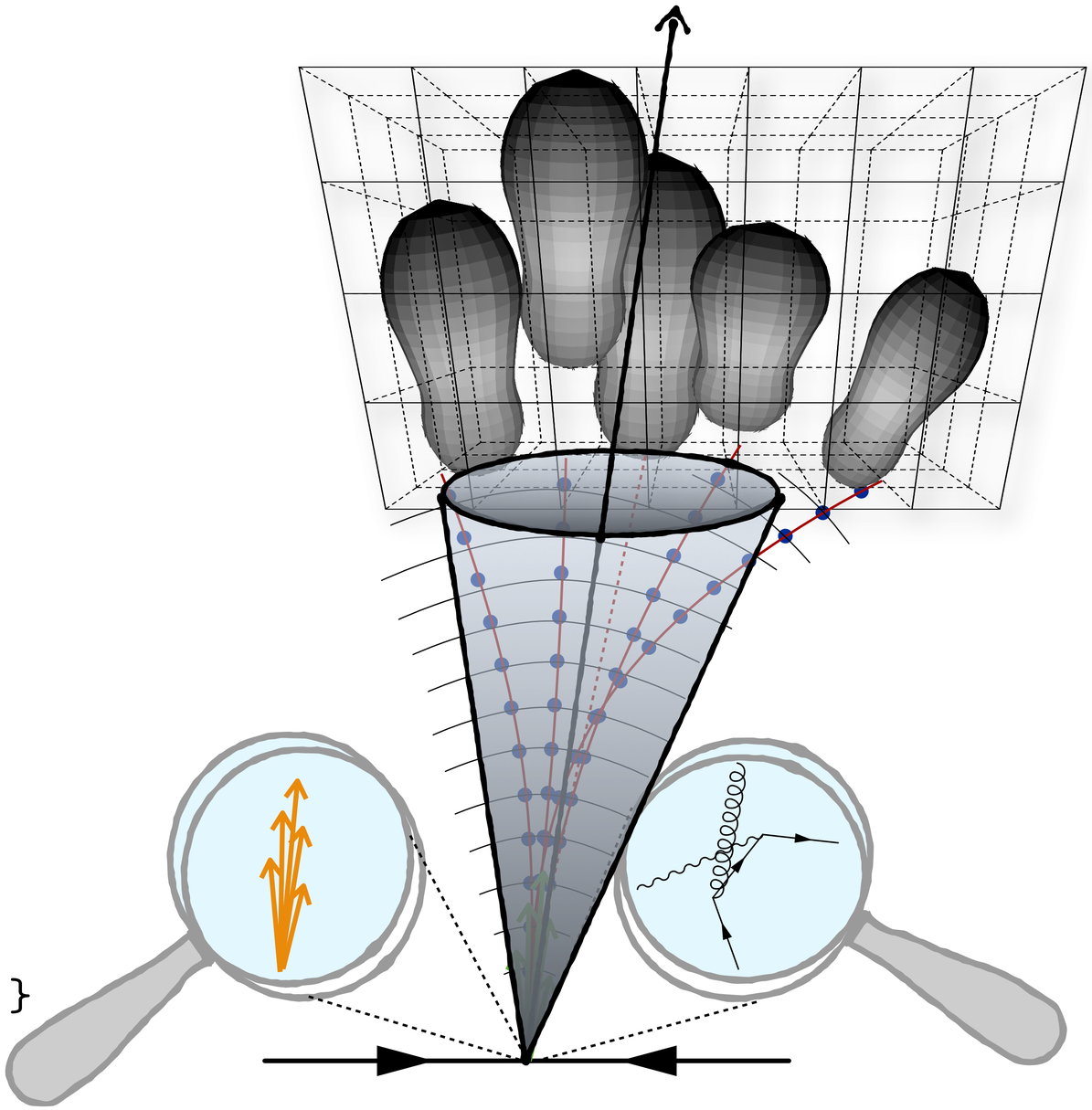

Particle Physics Detector

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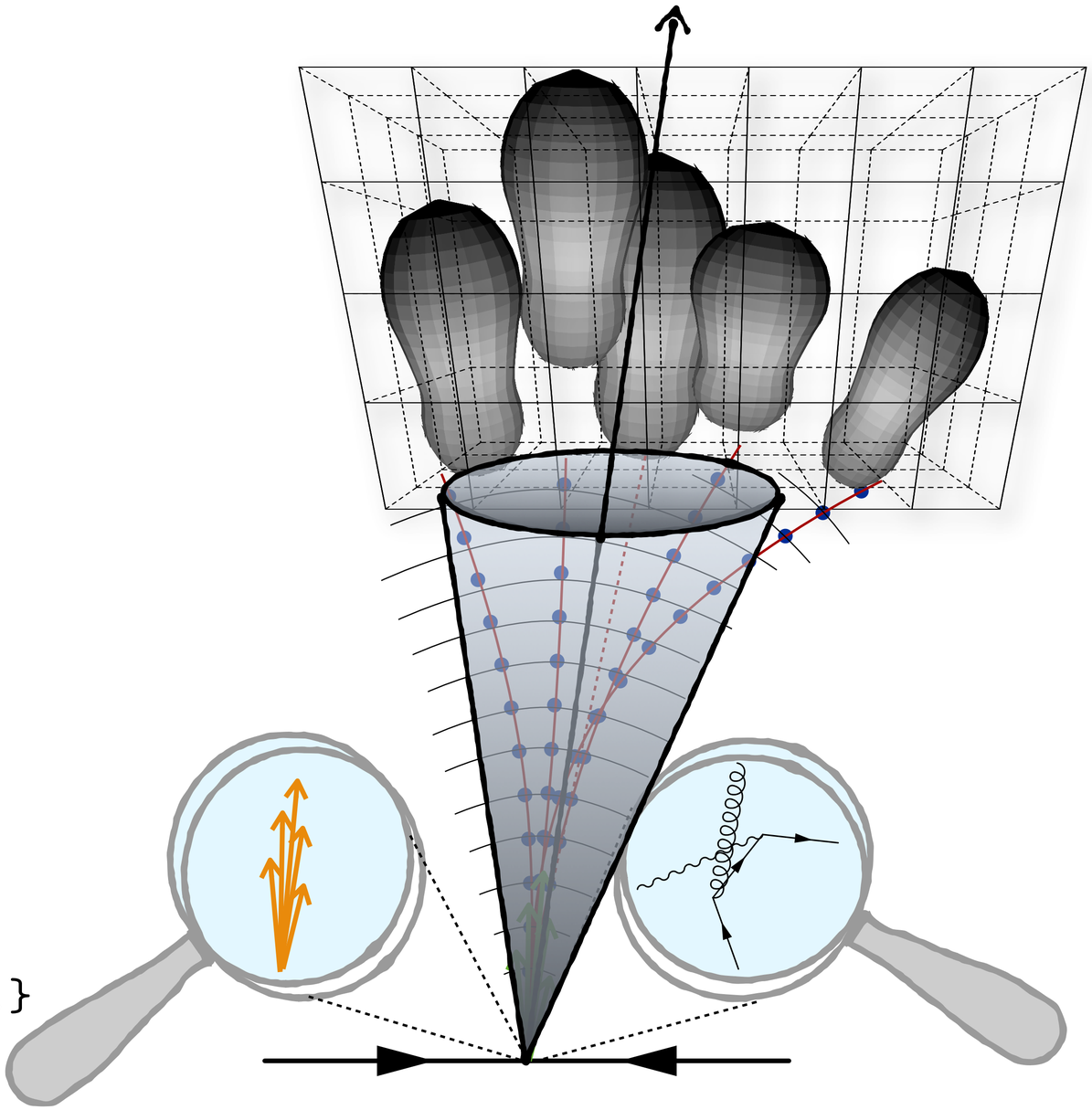
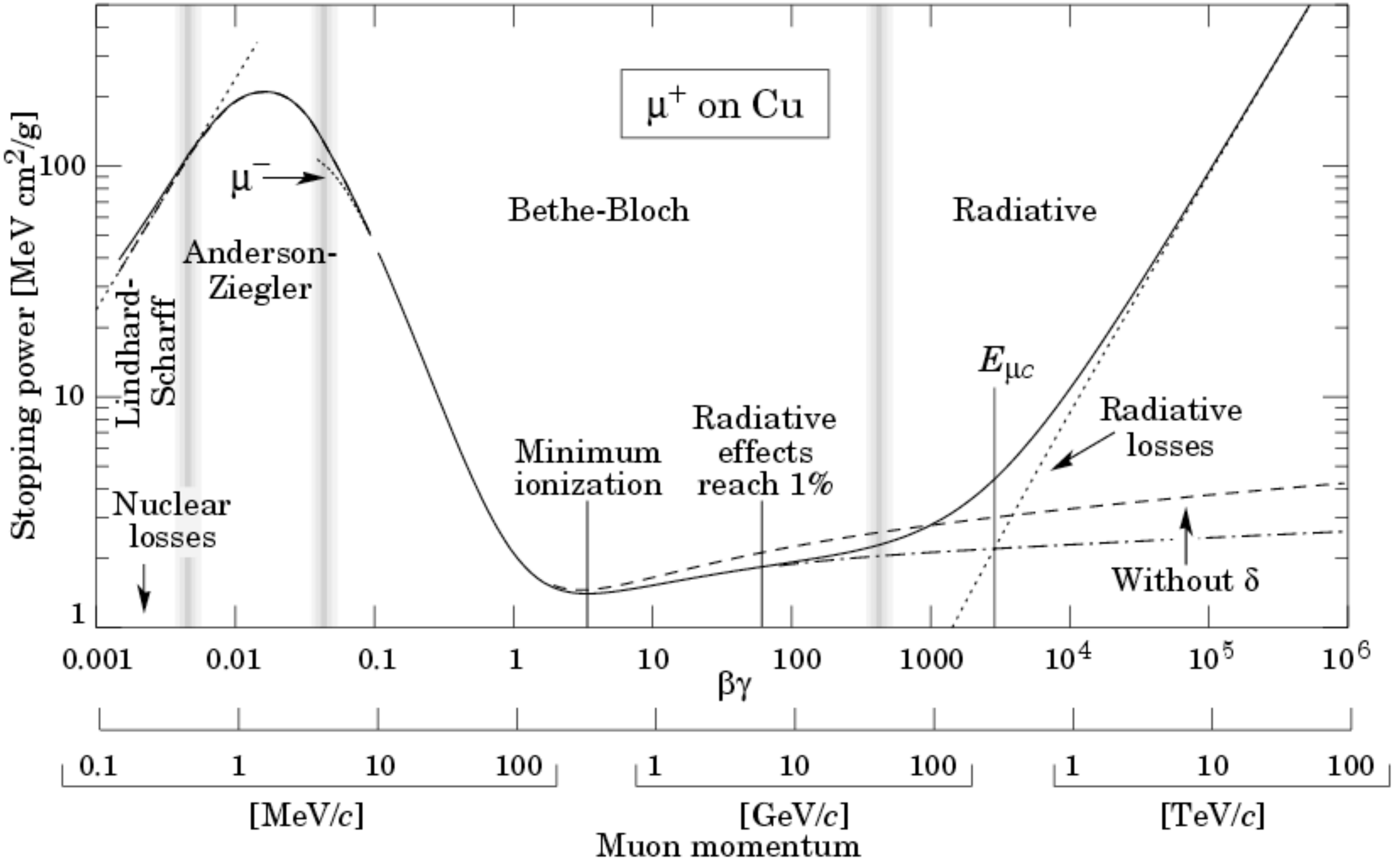
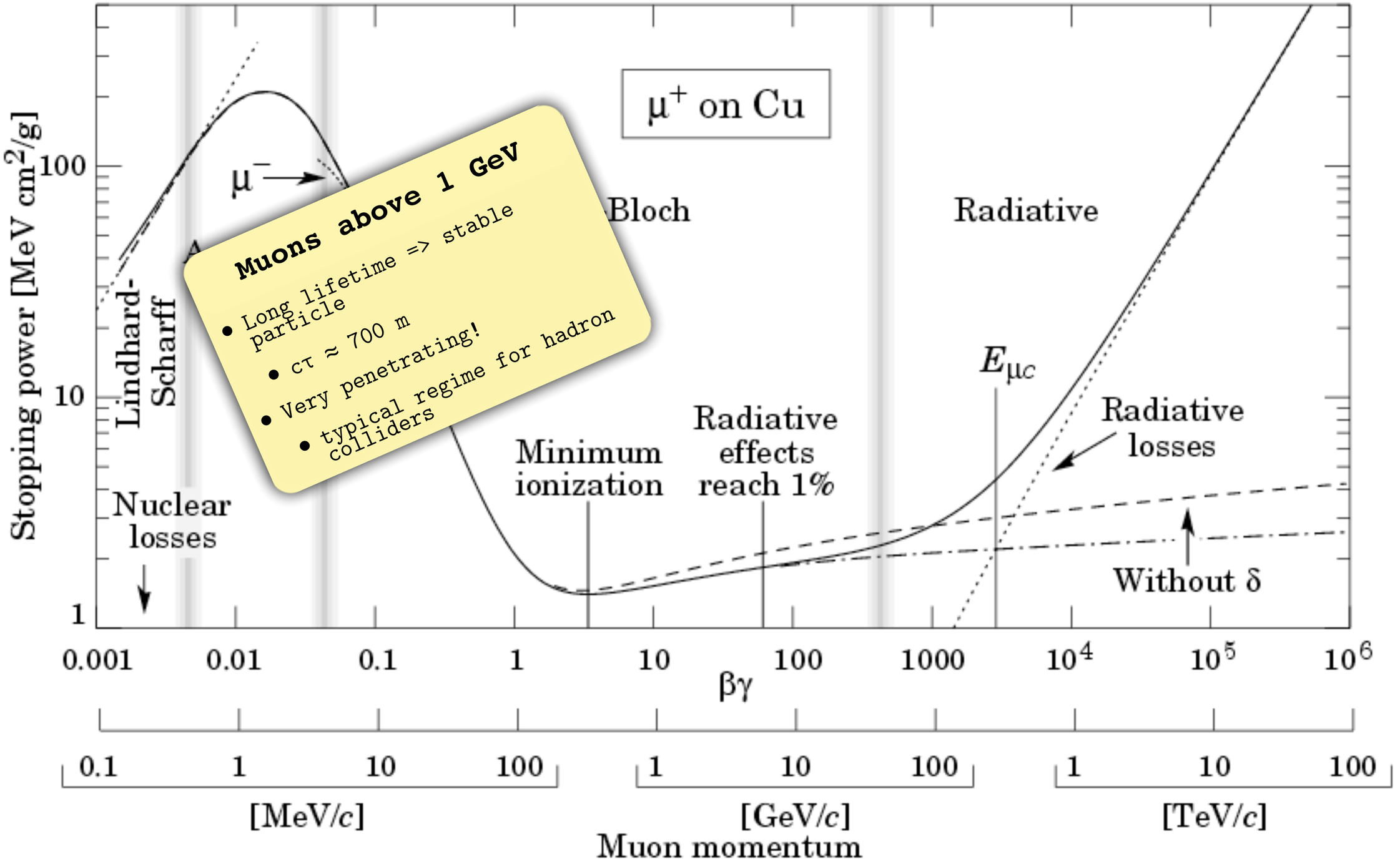
- Reconstructed partons =>
  - Physics process (hypothesis)



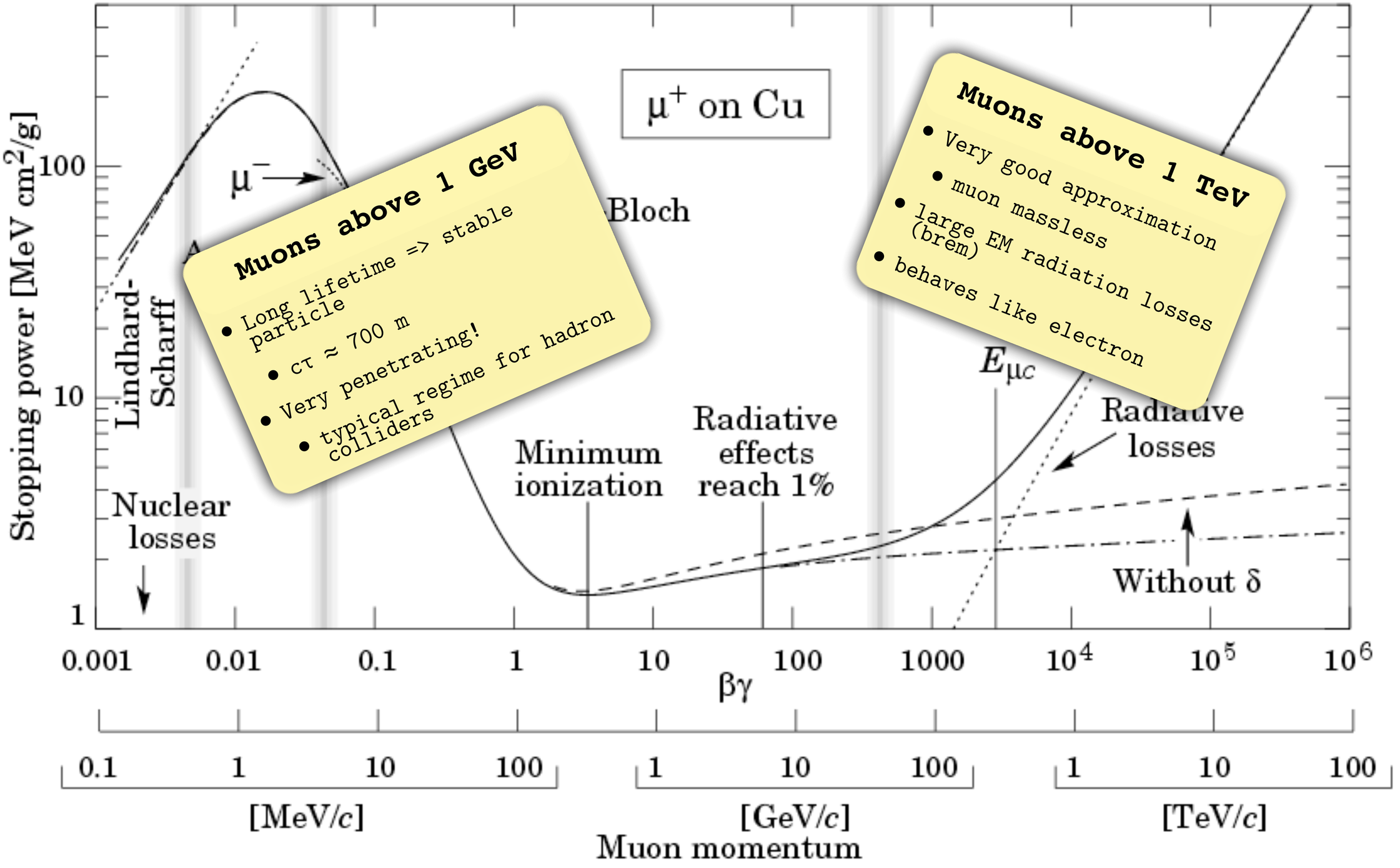
Particle Physics Detector

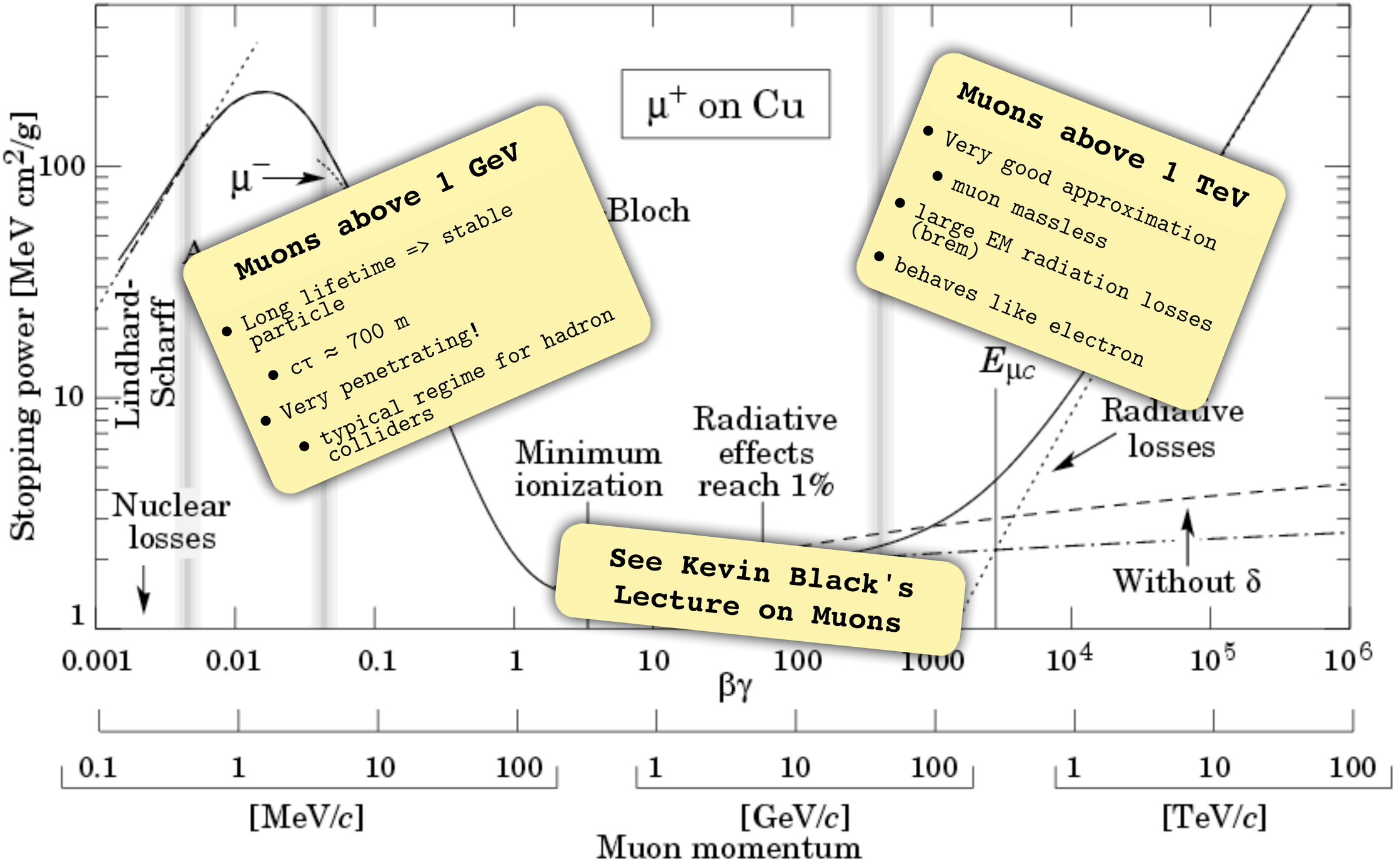

μ+ on Cu
Stopping power [MeV cm²/g]
100
10
1
μ−
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Bethe-Bloch
Minimum
ionization
Radiative
effects
reach 1%
Eμc
Radiative
losses
Without δ
Radiative
0.001
0.01
0.1
1
10
100
1000
10⁴
10⁵
10⁶
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum



Muons above 1 GeV

- Long lifetime => stable particle
  - cτ ≈ 700 m
- Very penetrating!
  - typical regime for hadron colliders


μ+ on Cu
Muons above 1 GeV
• Long lifetime => stable particle
• cτ ≈ 700 m
• Very penetrating!
• typical regime for hadron colliders
Muons above 1 TeV
• Very good approximation
• muon massless
• large EM radiation losses (brem)
• behaves like electron
Stopping power [MeV cm²/g]
μ⁻
Bloch
Lindhard-Scharff
Nuclear losses
Minimum ionization
Radiative effects reach 1%
Eμc
Radiative losses
Without δ
βγ
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum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Eμc
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Without δ
0.001
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βγ
0.1
1
10
100
1
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10
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[MeV/c]
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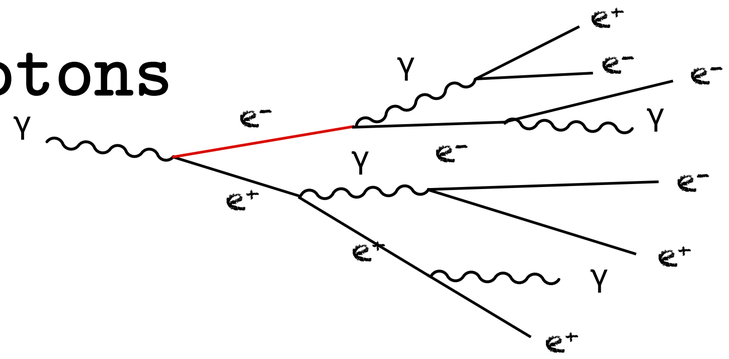
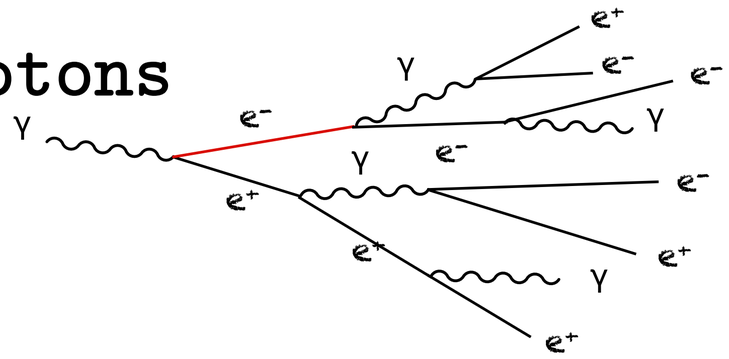
See Kevin Black's Lecture on Muons

Electrons & Photons



Electrons & Photons



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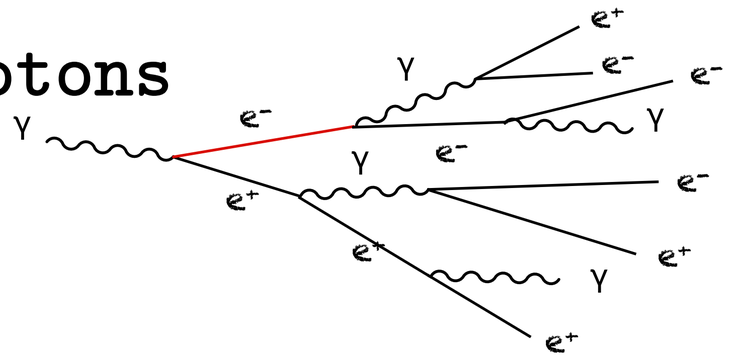


Radiation Length

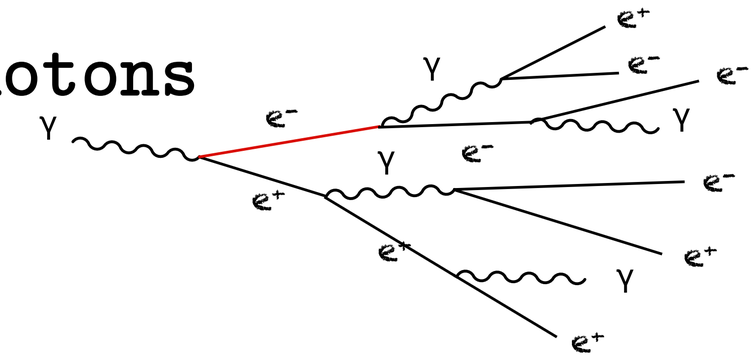
- Characteristic distance over which the electron energy is reduced by a factor of 1/e due to radiation losses only

$$X_0 = \frac{716.4\ \mathrm{g\ cm^{-2}}\, A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Higher Z materials have short length
  - want high-Z material for EM calorimeter

Example: Lead
ρ = 11.4 g/cm^3 ; X_0 = 5.5 mm

Electrons & Photons



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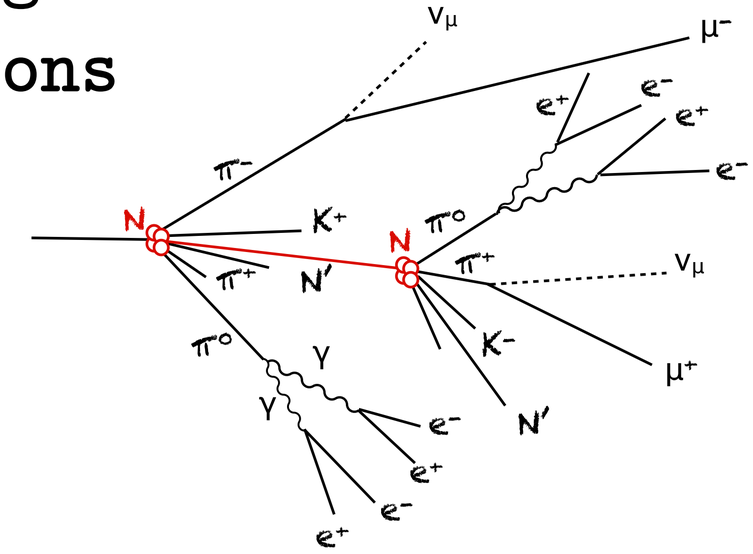
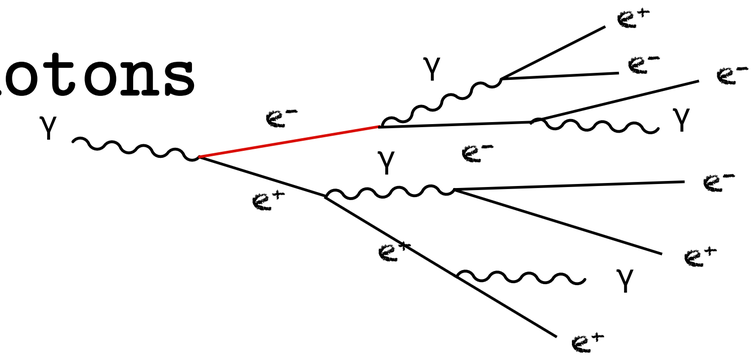
Charged & Neutral Hadrons



Electrons & Photons



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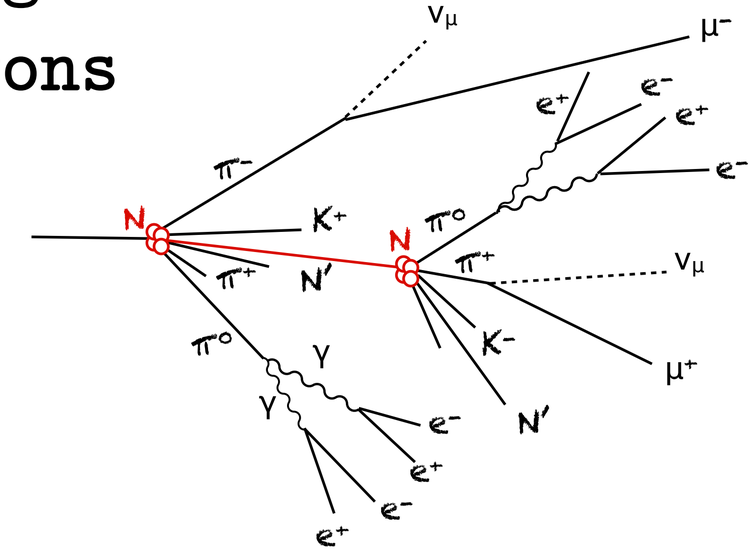
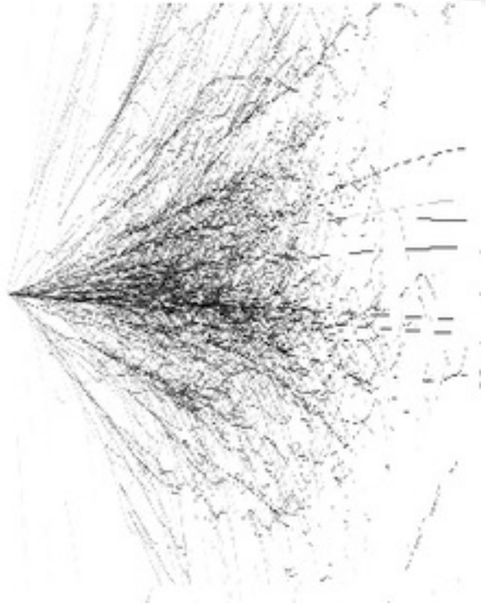
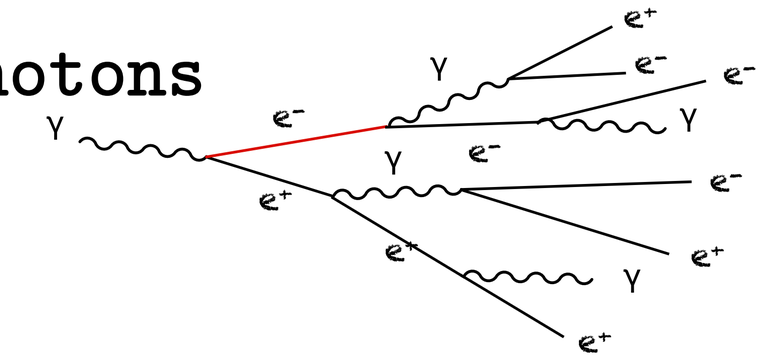
Charged & Neutral Hadrons





Electrons & Photons



Radiation Length

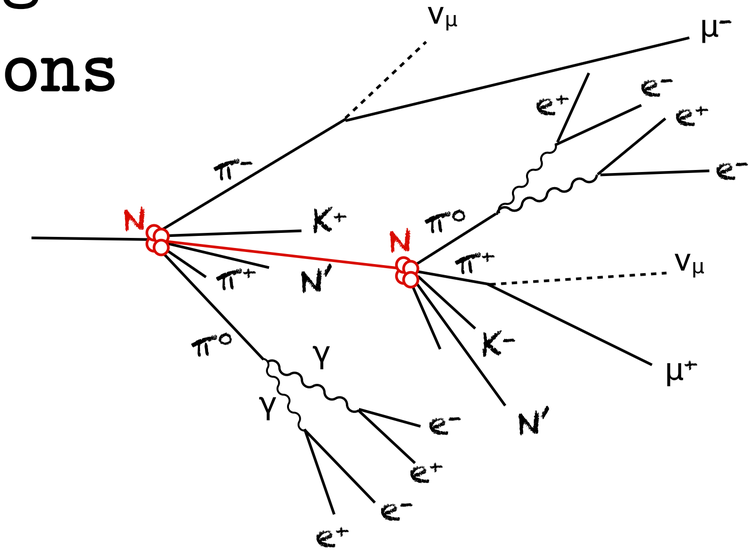
- Characteristic distance over which the electron energy is reduced by a factor of 1/e due to radiation losses only

$$X_0 = \frac{716.4\ \mathrm{g\ cm^{-2}}\, A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Higher Z materials have short length
- want high-Z material for EM calorimeter

Example: Lead
ρ = 11.4 g/cm^3 ; X_0 = 5.5 mm

Charged & Neutral Hadrons



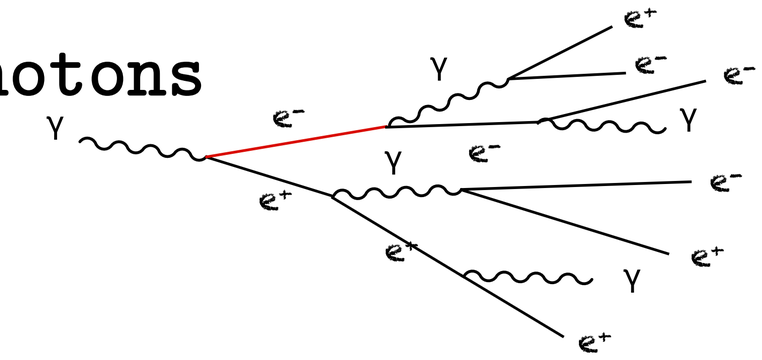
Nuclear Interaction Length

- Collisions of hadrons with nuclei produce hadronic showers

$$\lambda \approx 35\ \mathrm{g\ cm^{-2}}\, A^{1/3}$$

- Nuclear interaction length much longer in high-Z materials than EM radiation length $\lambda > X_0$
- Hadronic showers develop later than EM showers; more diffuse
- Example: Lead λ = 17 cm

Electrons & Photons



See Jim Hirschauer's Lectures on Calorimetry

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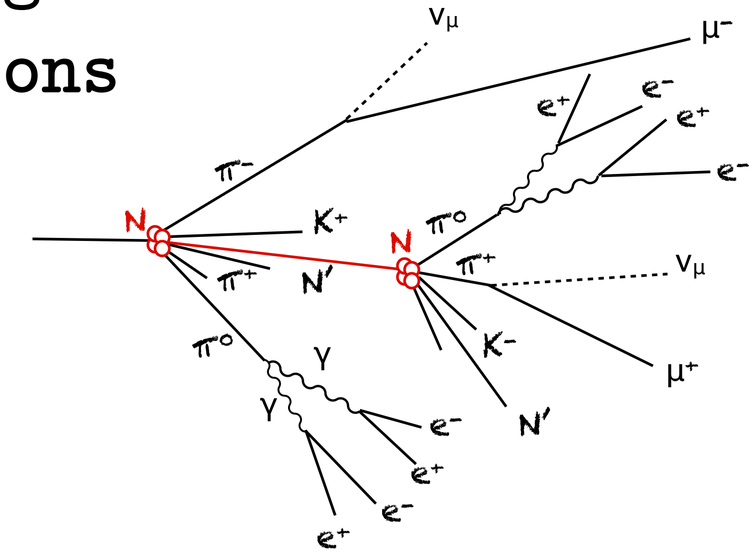

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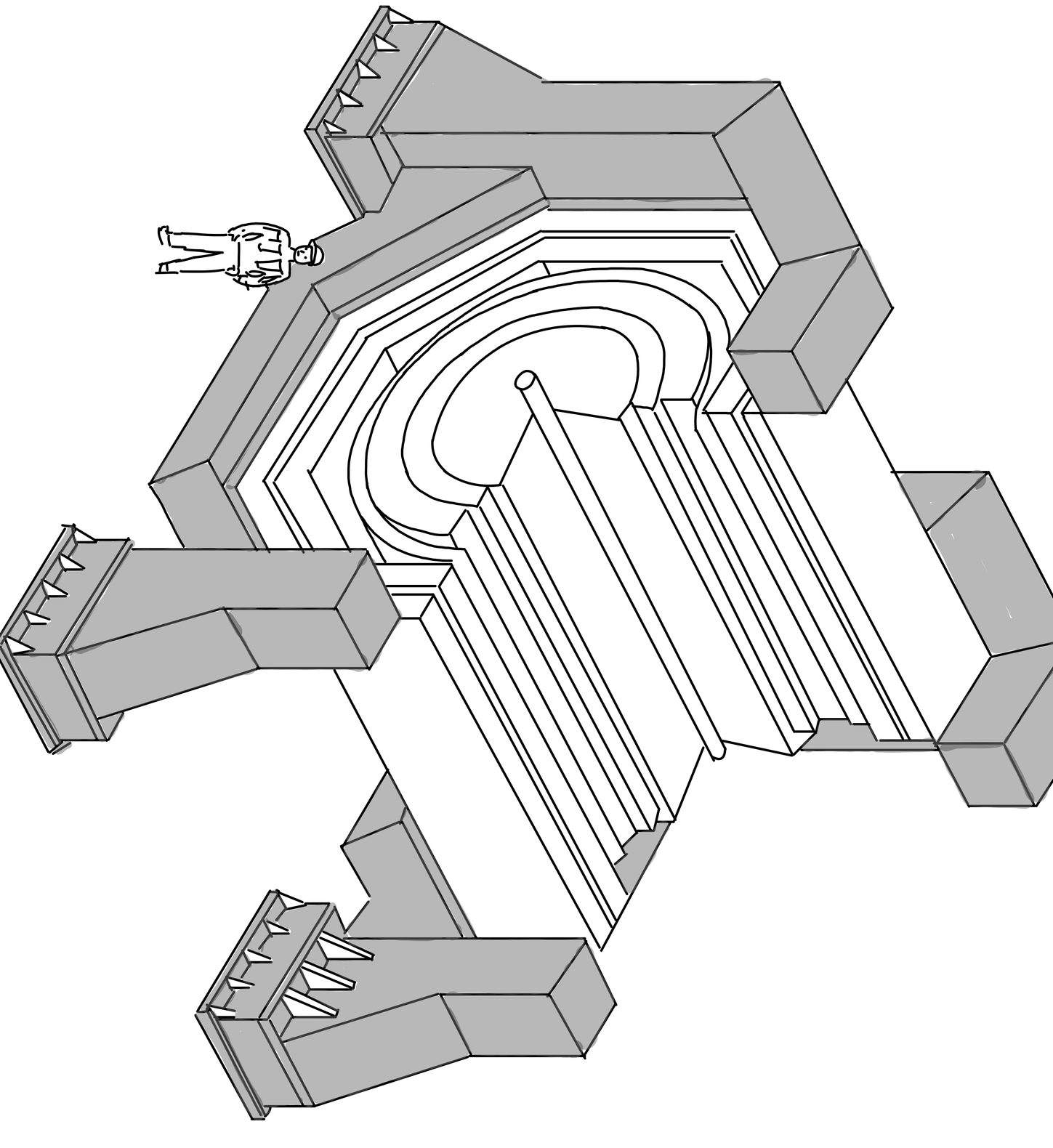

Particle Detector

- Goal: completely surround collision by layering different types of instruments
- We know how particles interact with matter
- Identify particles by exploiting differences
  - in showering
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- Energy (particles are absorbed)
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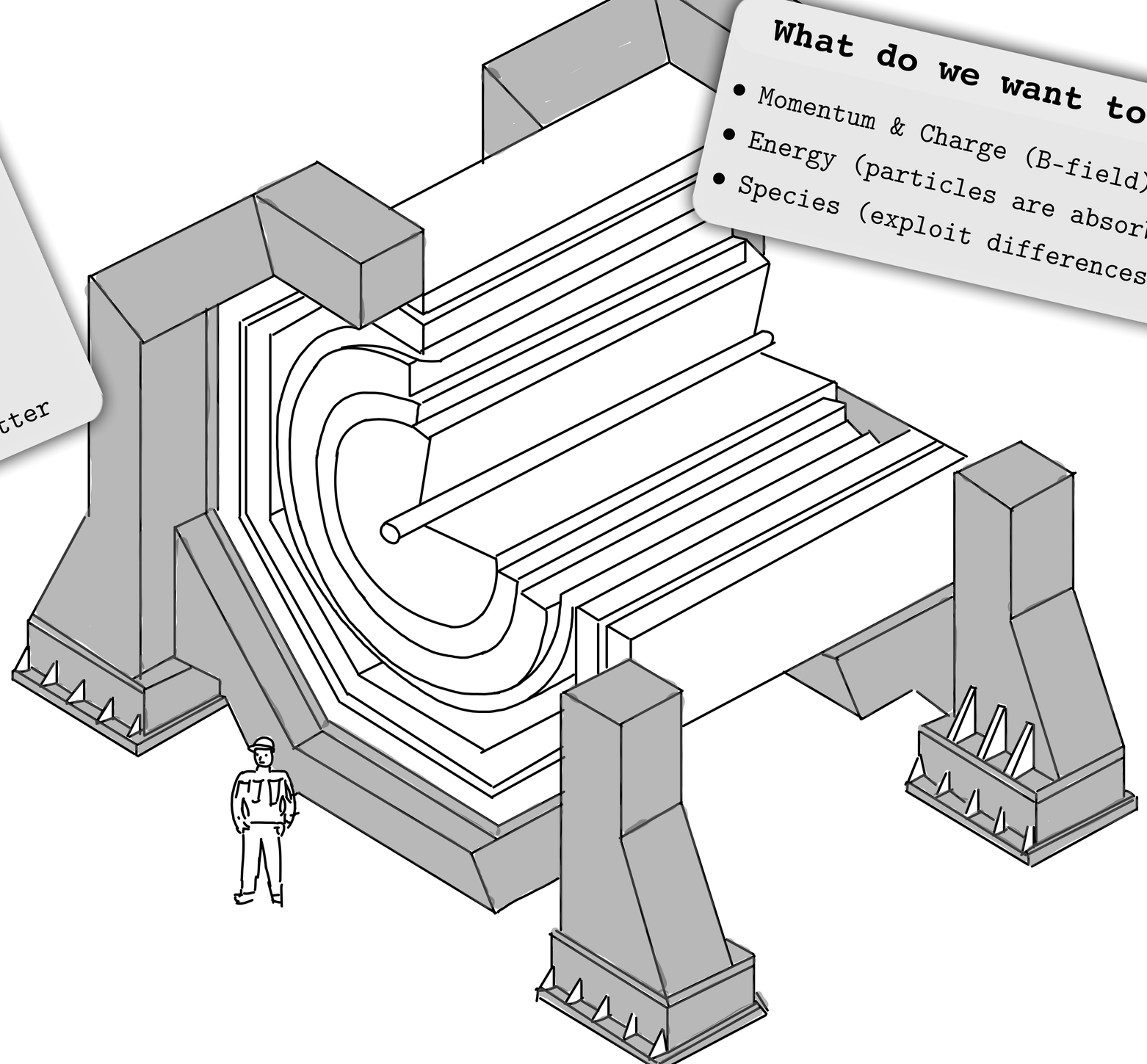

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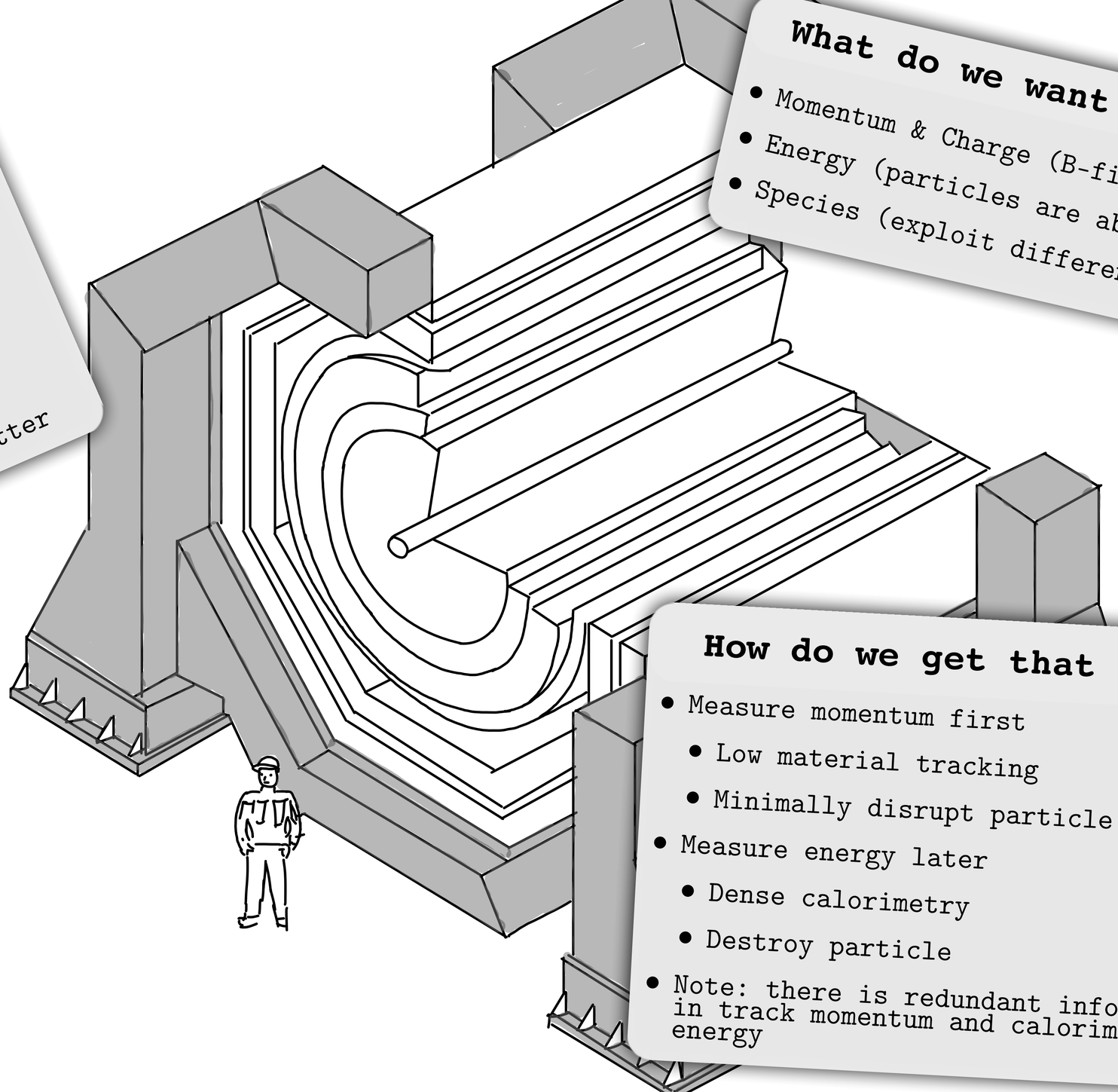
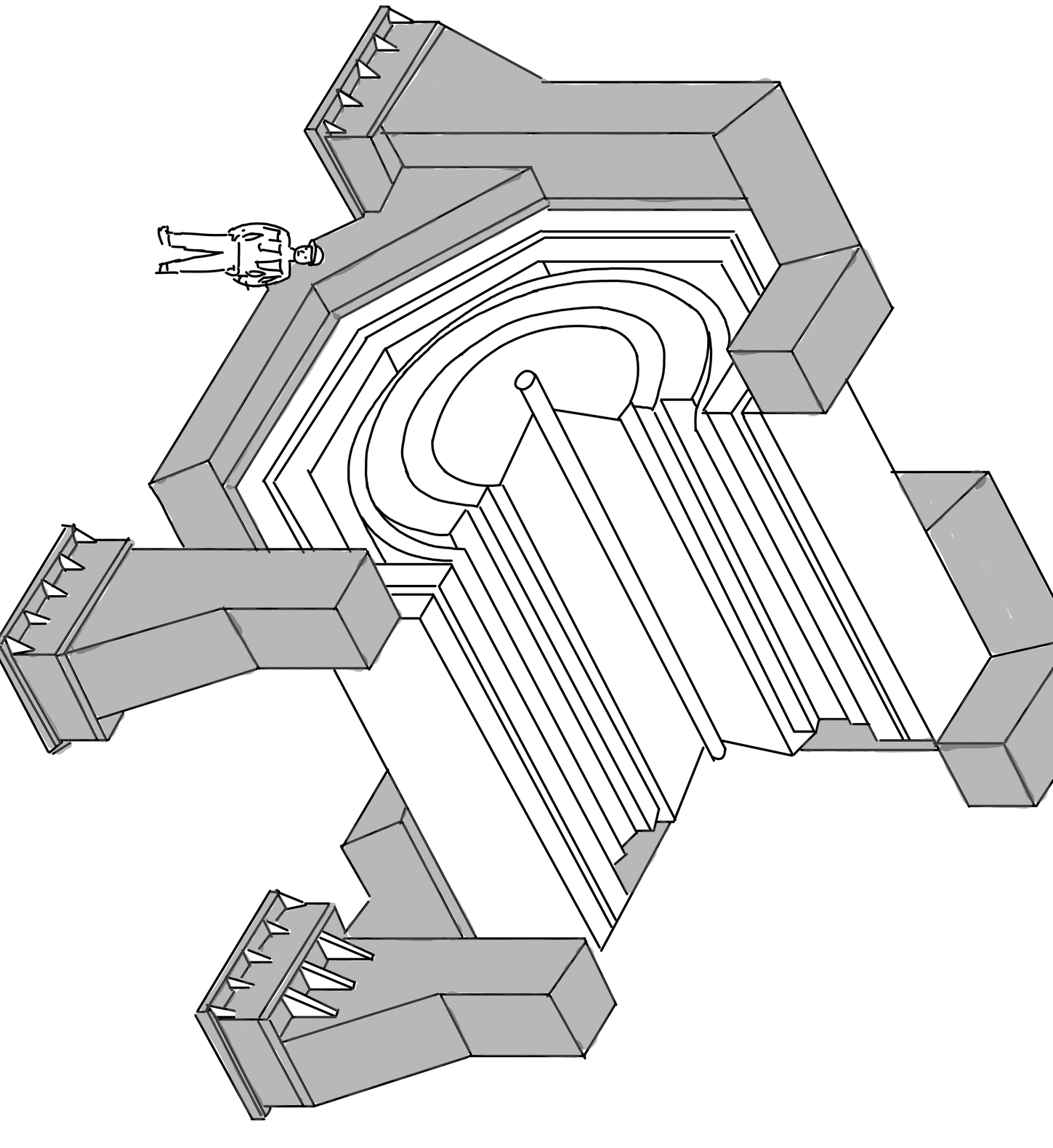


What do we want to know

- Momentum & Charge (B-field)
- Energy (particles are absorbed)
- Species (exploit differences)

How do we get that info?

- Measure momentum first
  - Low material tracking
  - Minimally disrupt particle
- Measure energy later
  - Dense calorimetry
  - Destroy particle
- Note: there is redundant information in track momentum and calorimeter energy



Inner Tracking Detectors

- Purpose: measure momentum and charge of charged particles
- Minimise multiple scattering
  - Use as little material as possible
- Two main technologies:
  - Gas/wire drift chambers
    - Low material budget
      worse momentum resolution
      slower
  - Solid-state (silicon)
    - more material
      better momentum resolution
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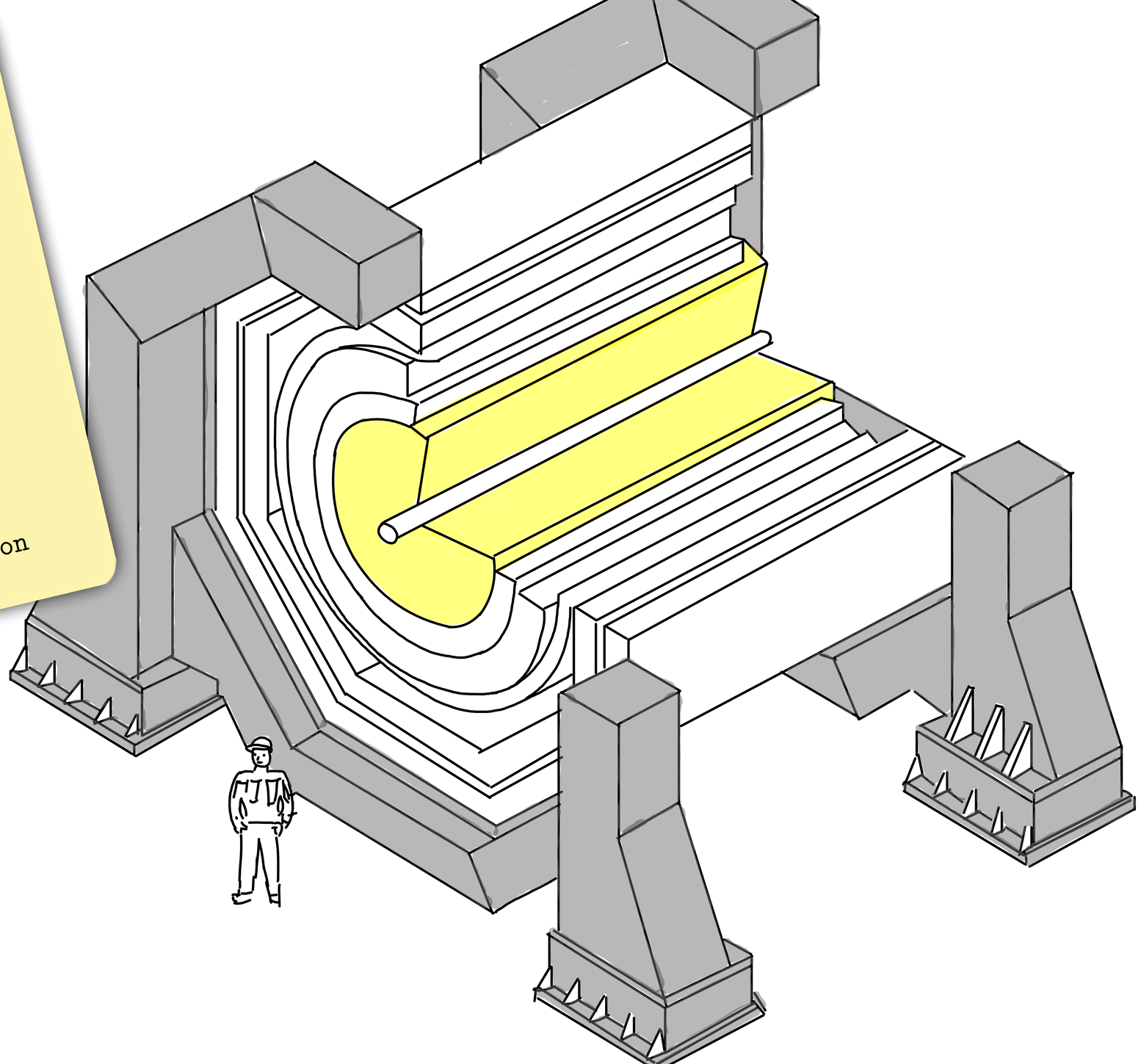

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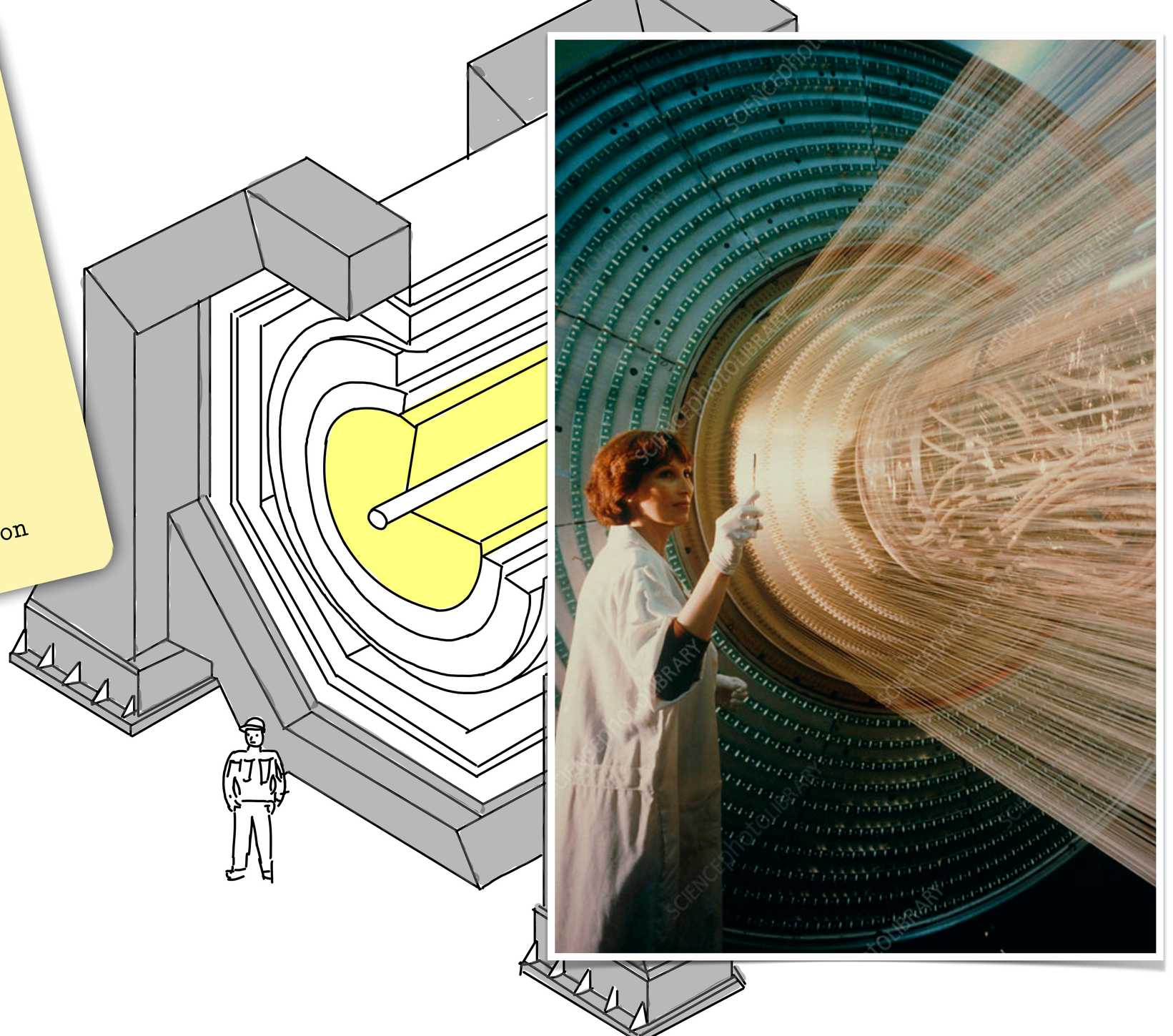

Richard Cavanaugh, Fermilab/UIC, HCP Summer School 31 July 2024

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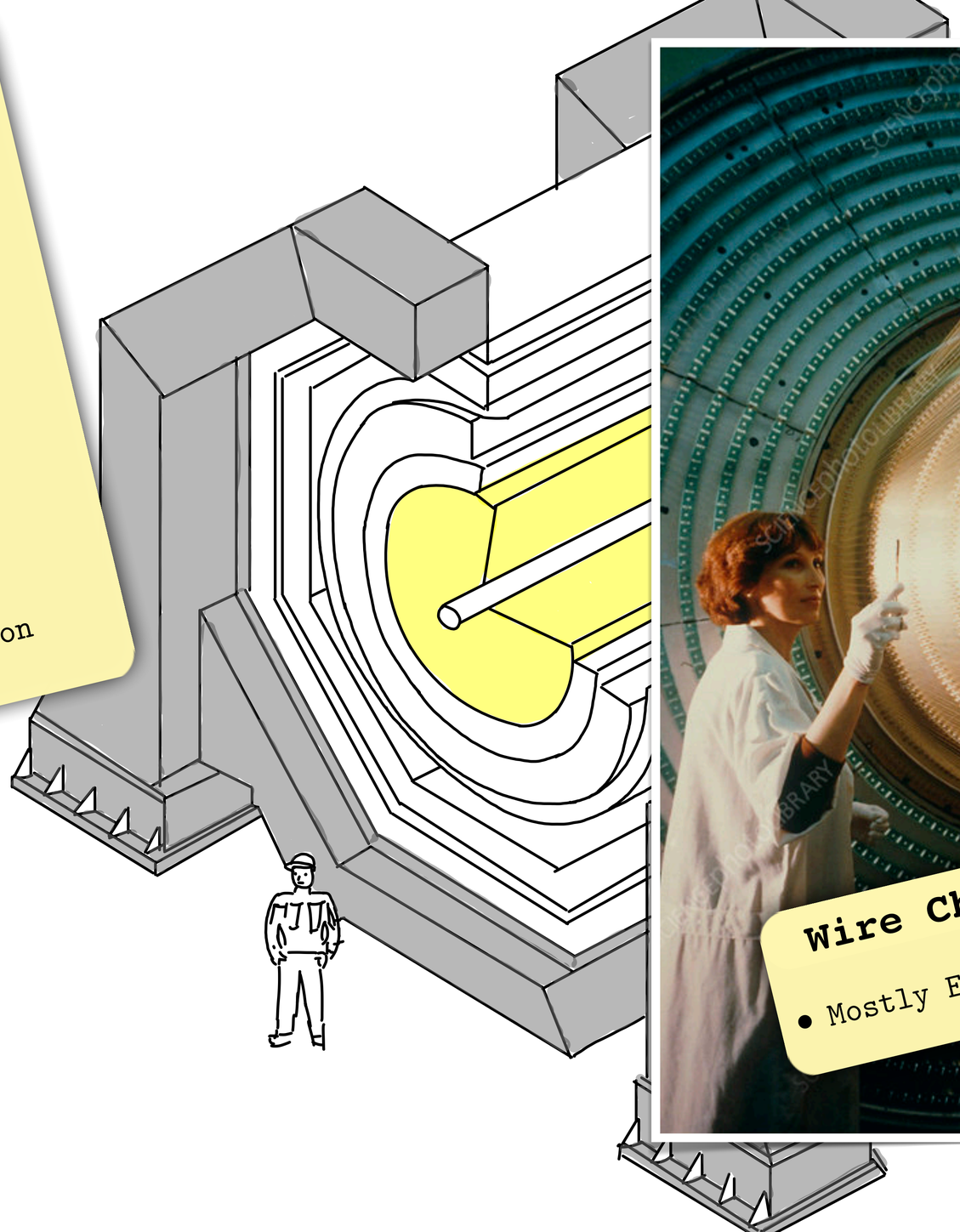

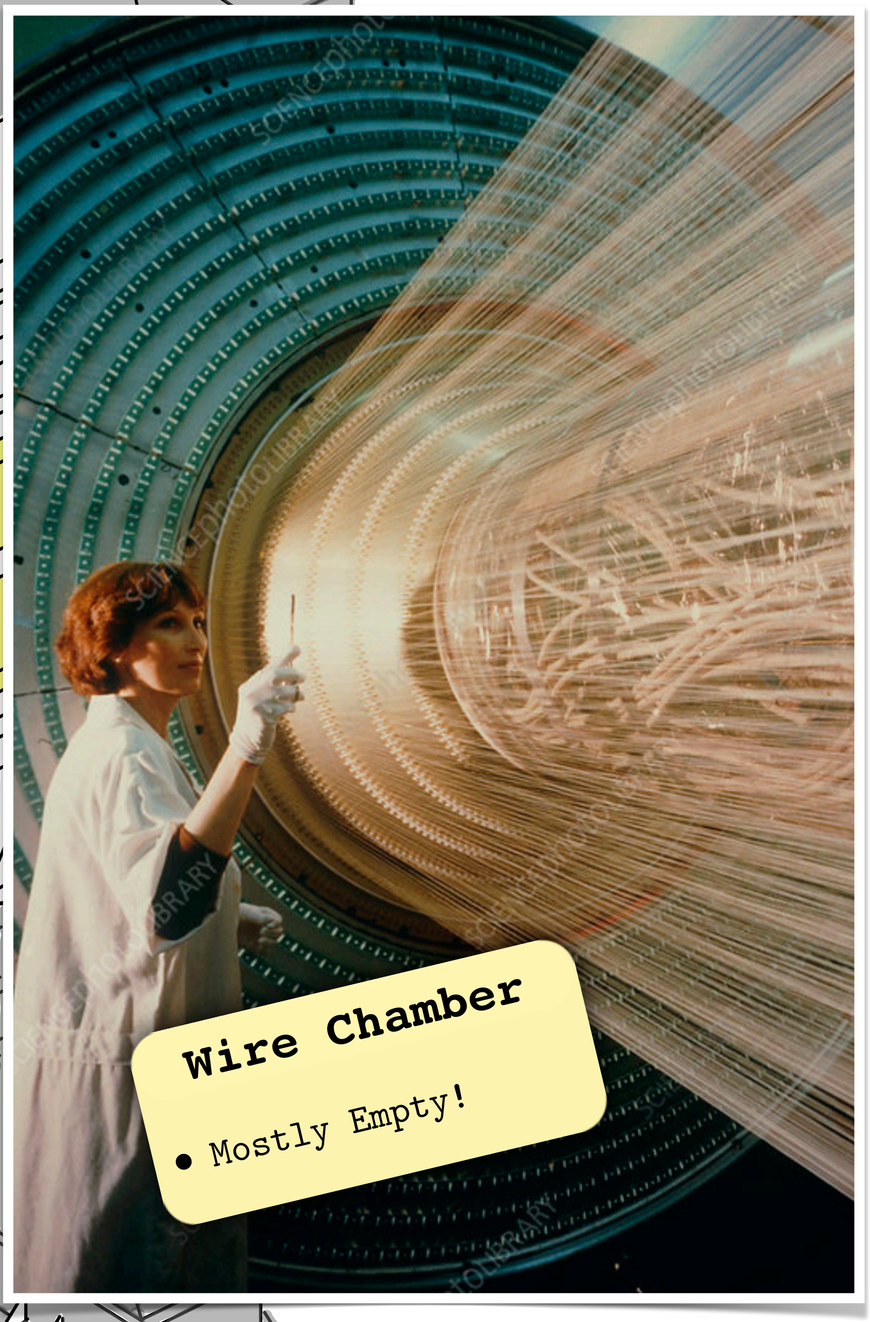

Wire Chamber

- Mostly Empty!

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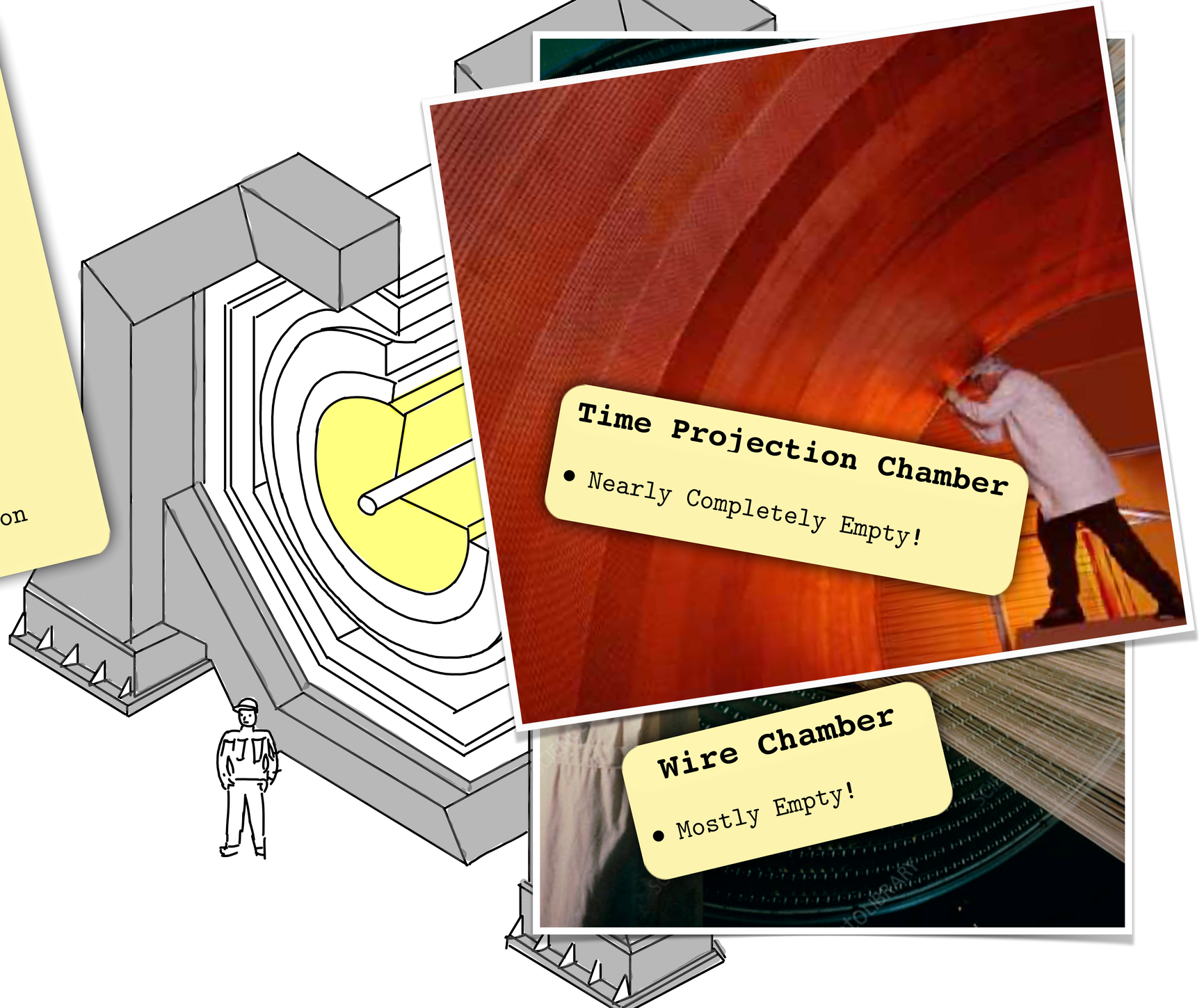

Time Projection Chamber

- Nearly Completely Empty!

Wire Chamber

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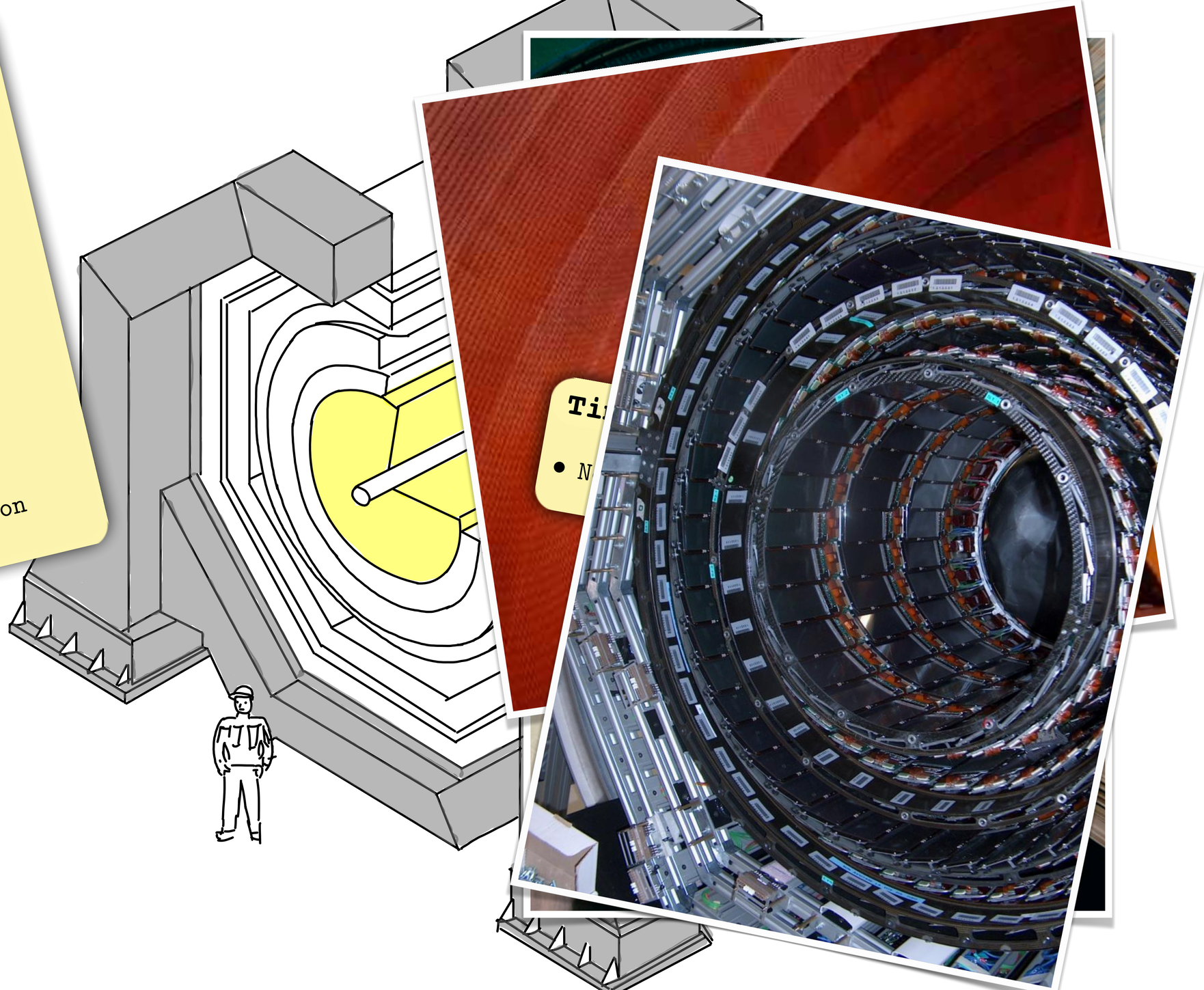

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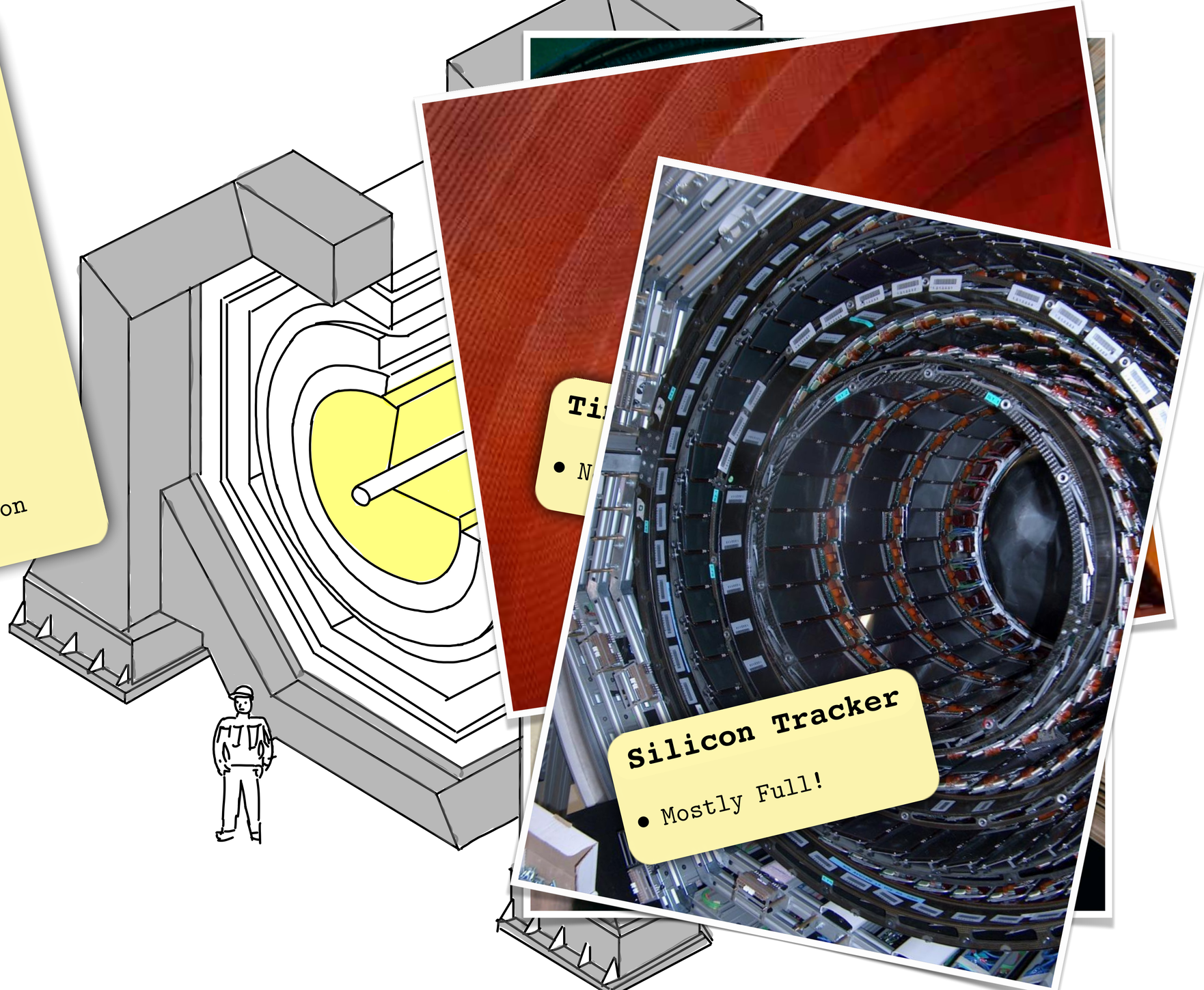

Silicon Tracker

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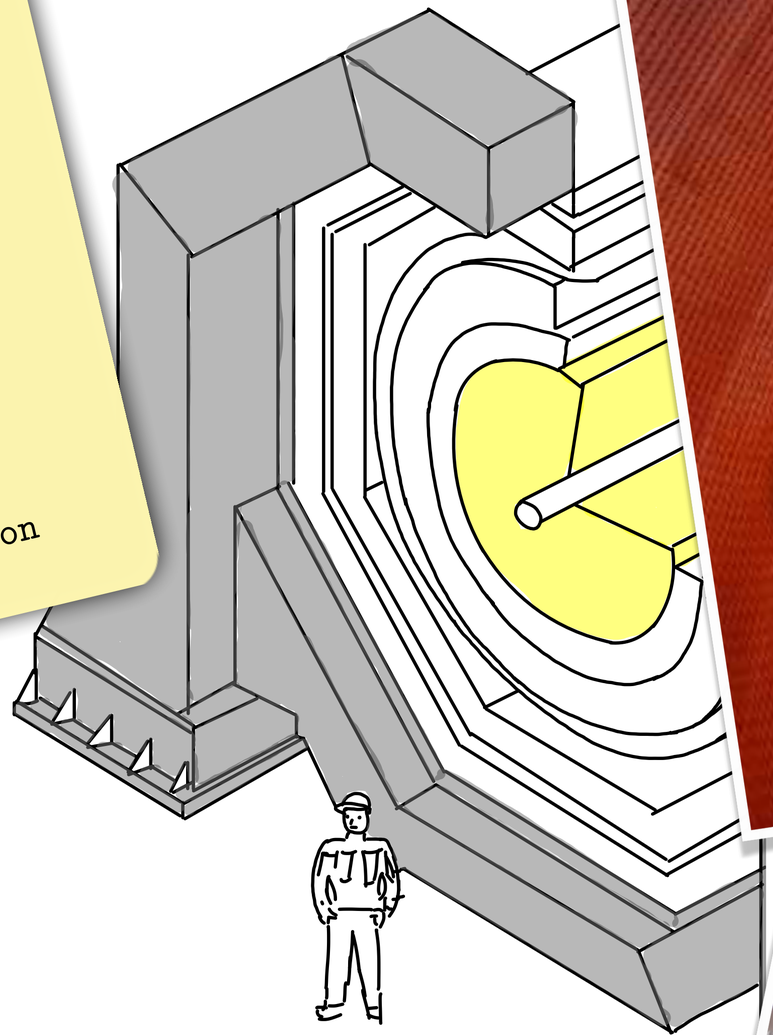

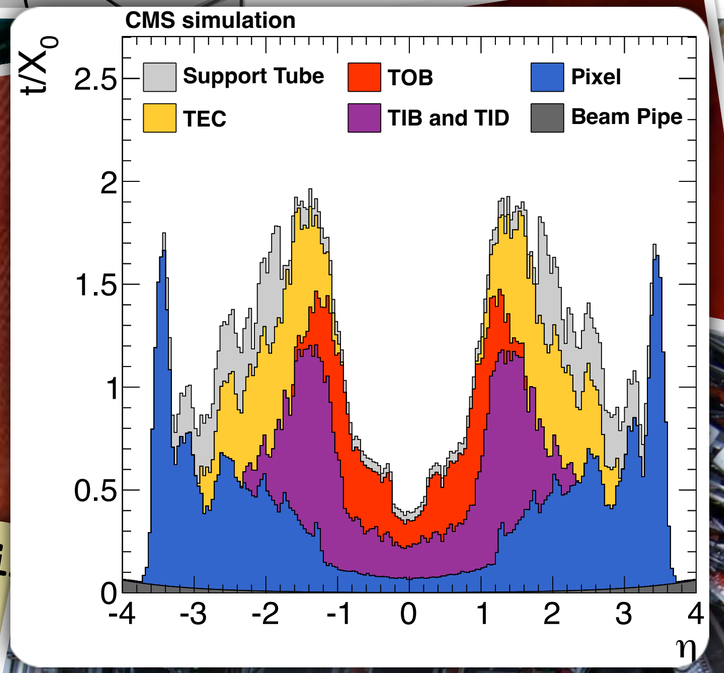

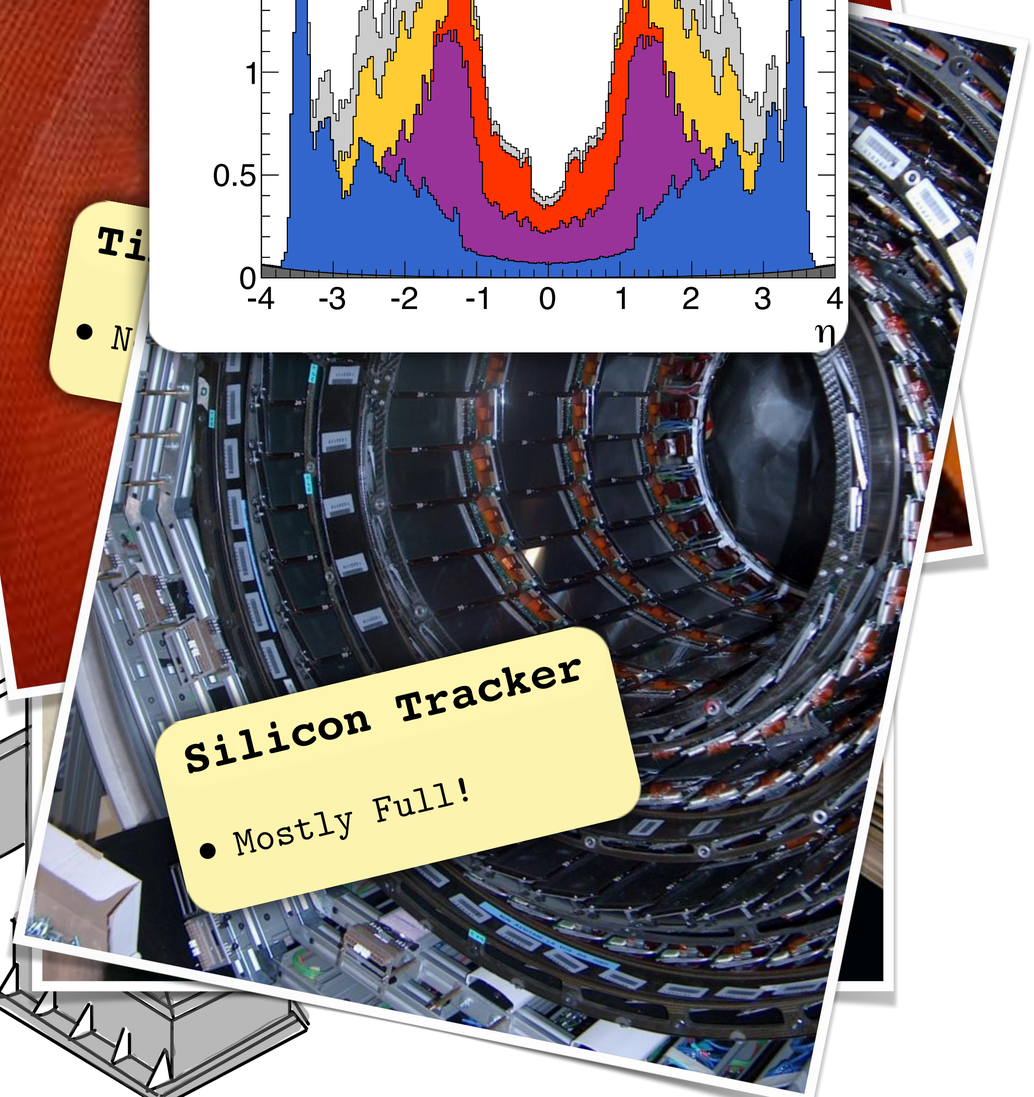

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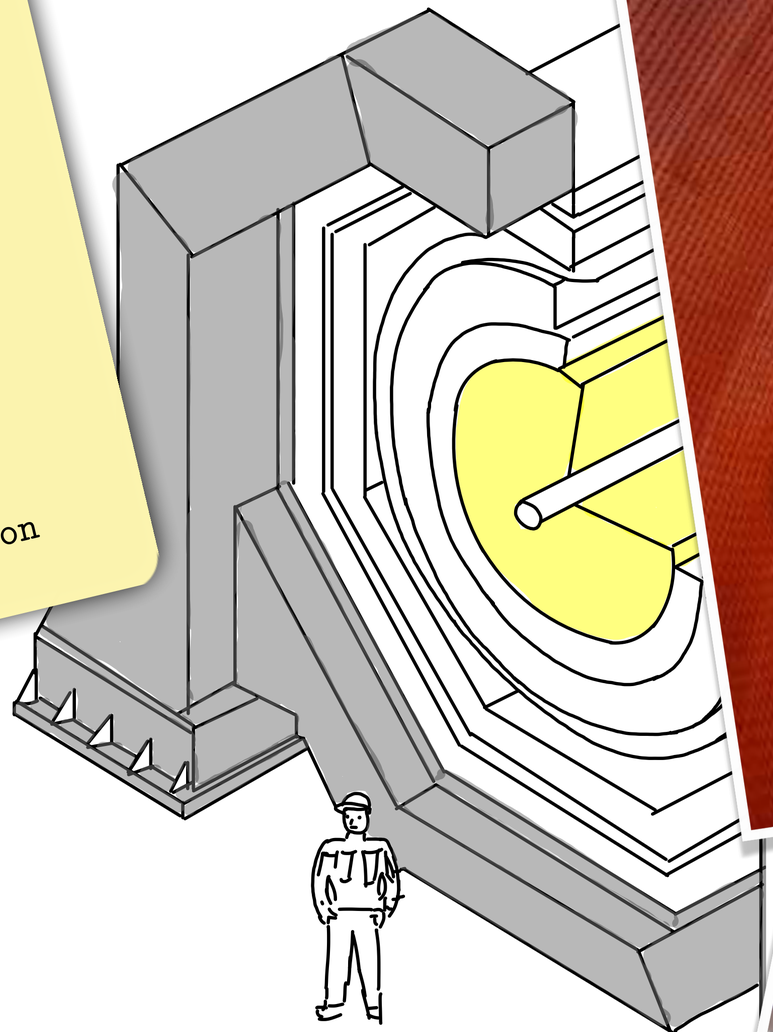

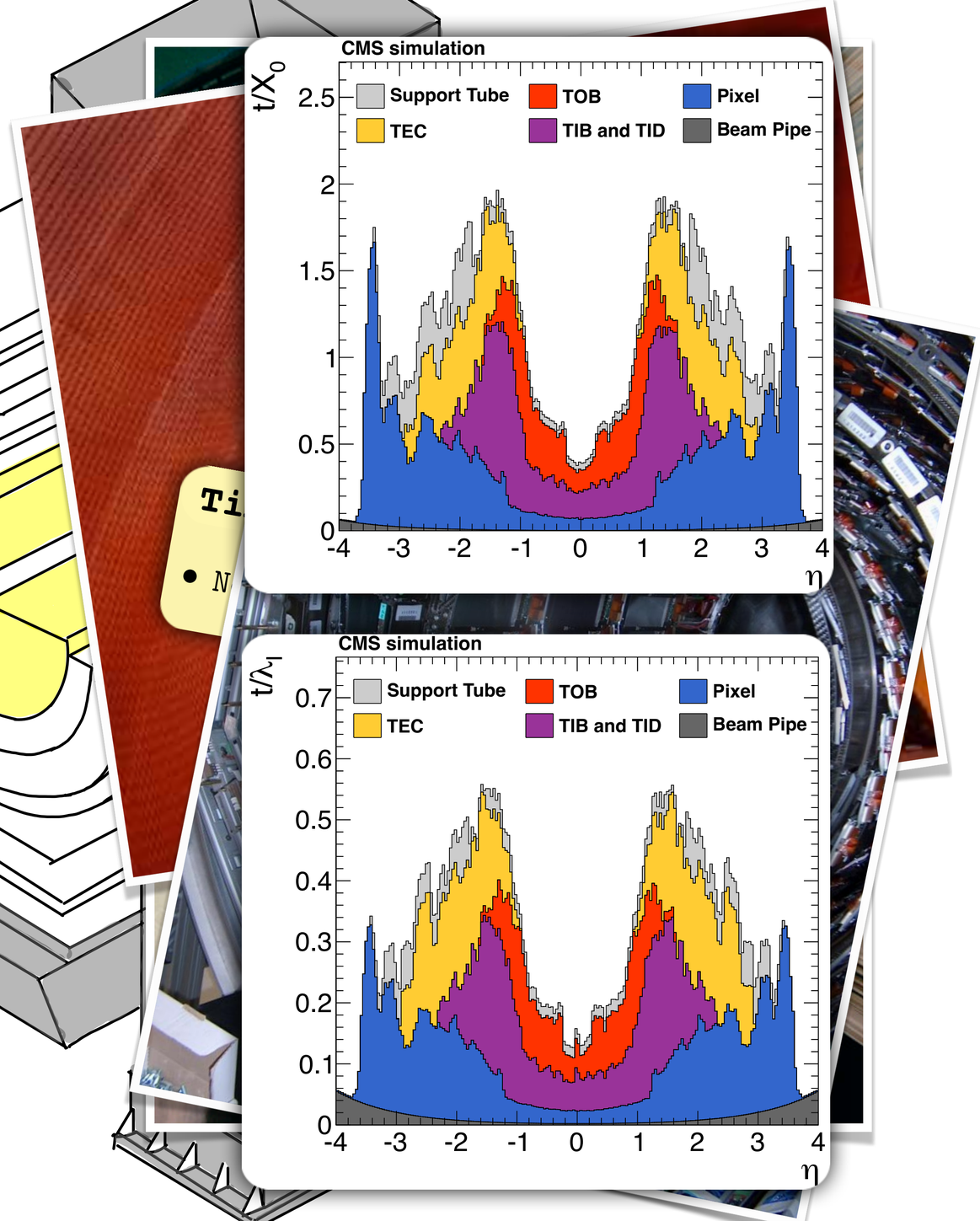

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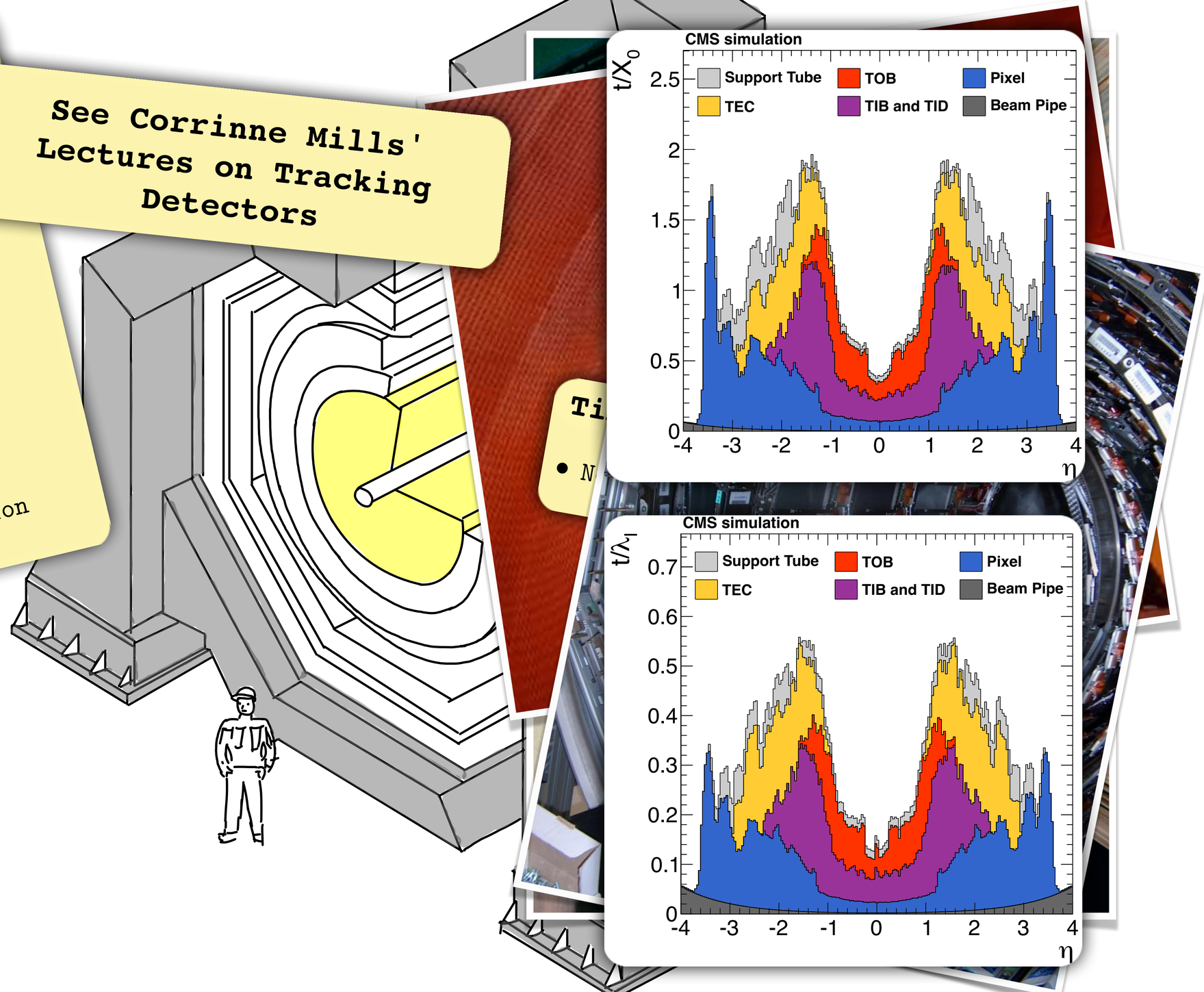

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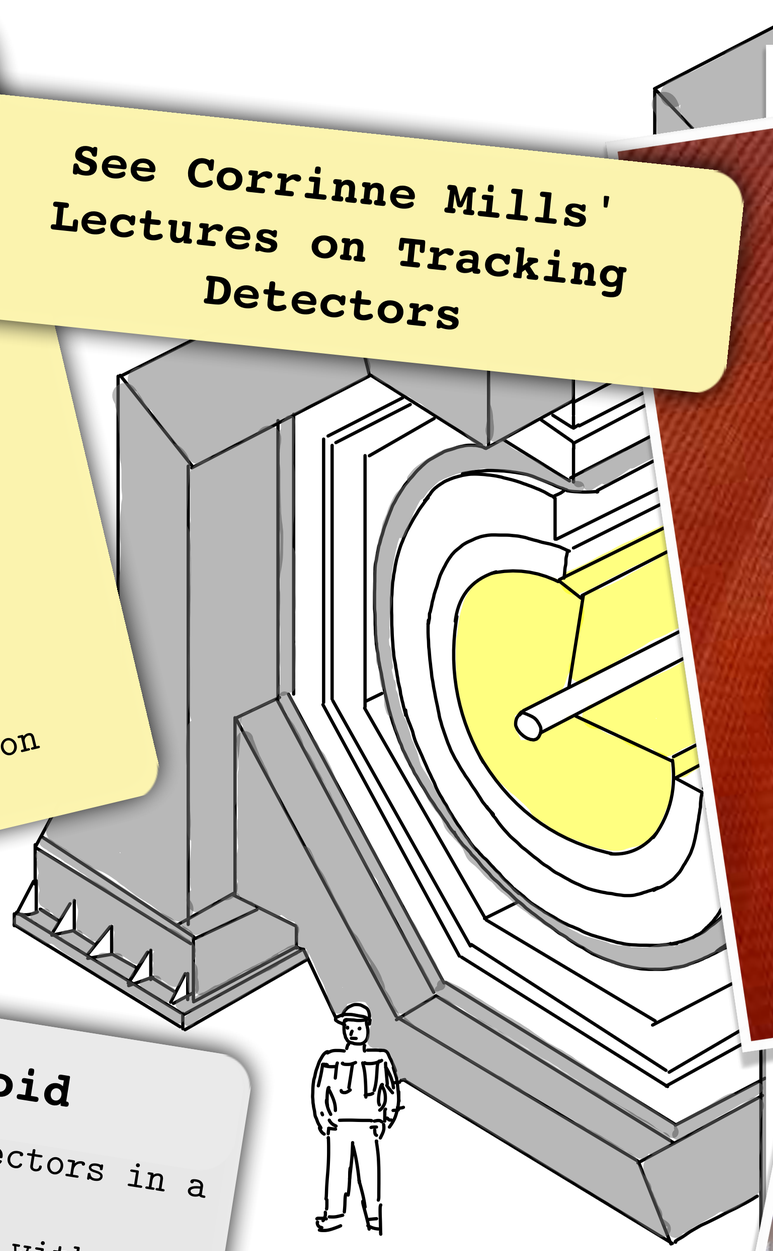
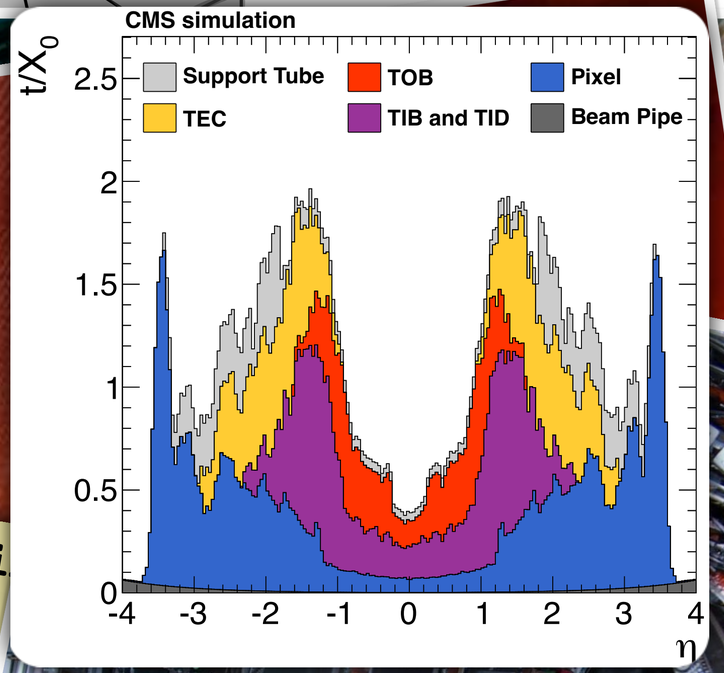
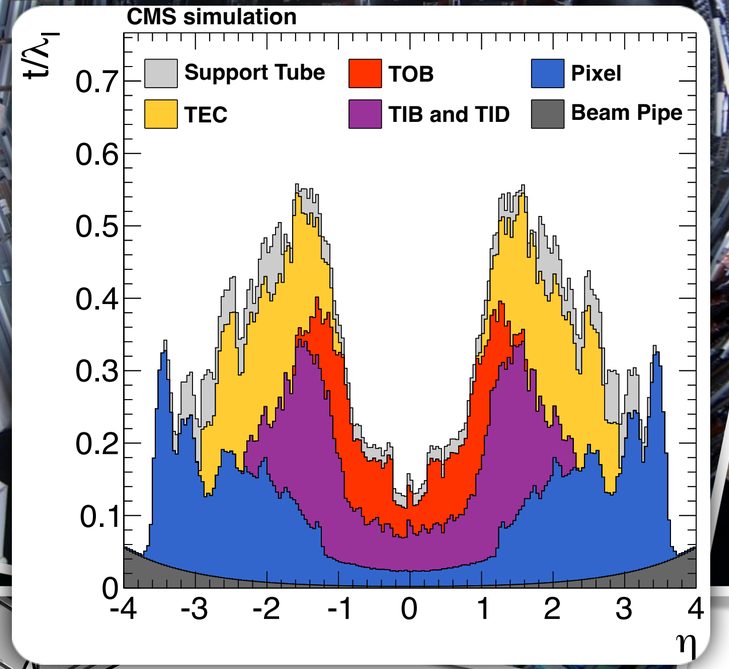


Magnetic Solenoid

- Immerse inner tracking detectors in a uniform magnetic field
- Charged particle will curve with a radius inversely proportional to its momentum





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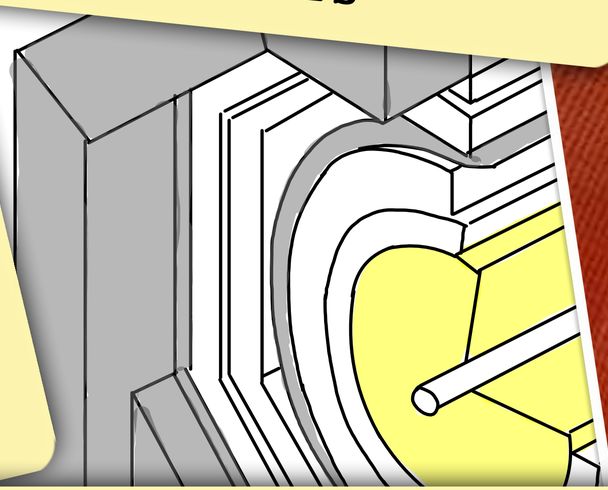

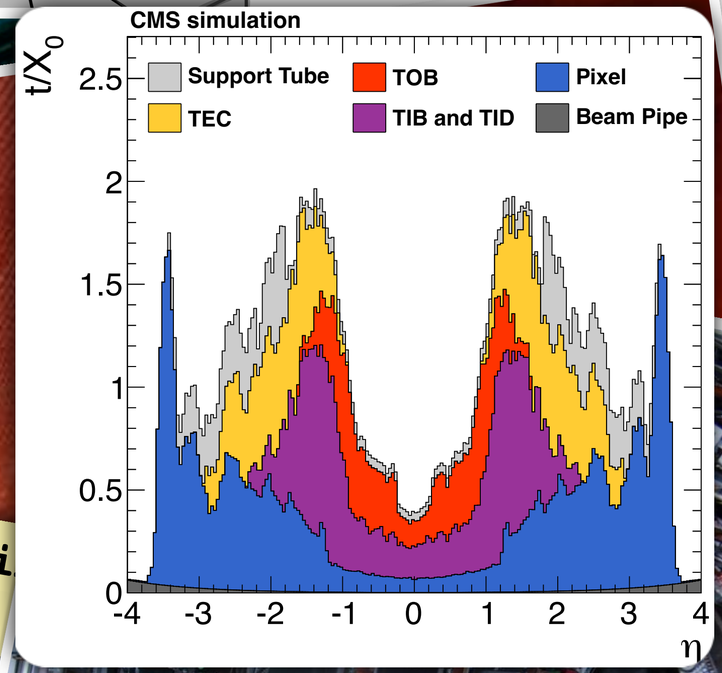

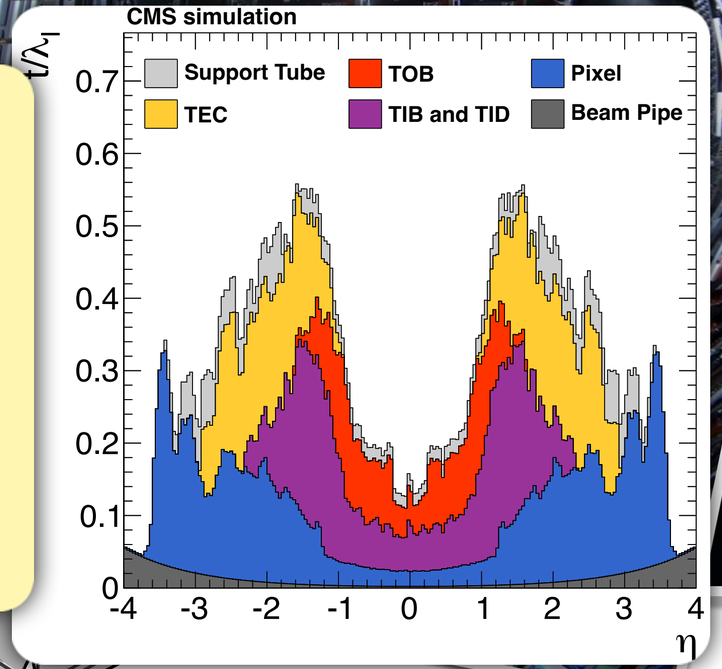

Momentum & Charge Measurement

- You already studied this in Kevin Black's lectures!
- Quick reminder:
  - $p_T \propto$ radius of curvature
- Momentum resolution $\propto p_T^2$
  - Gets better at low p_T
  - Gets worse at high p_T

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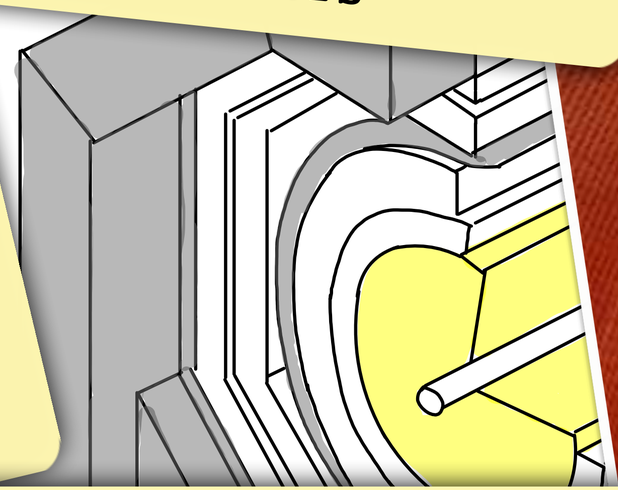

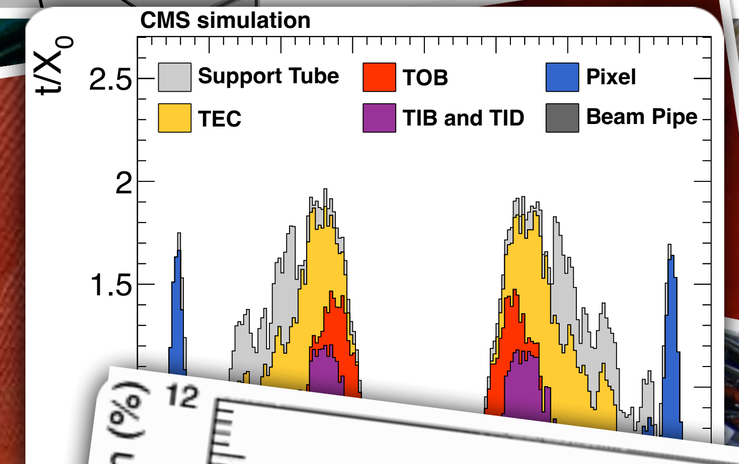

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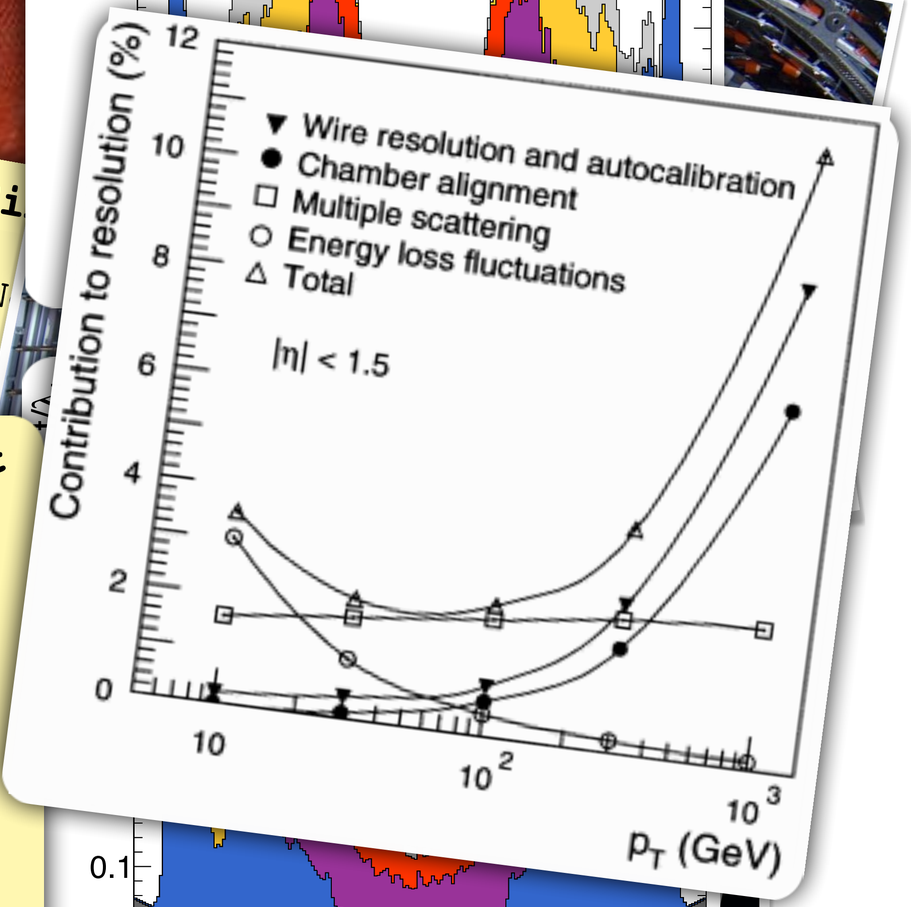
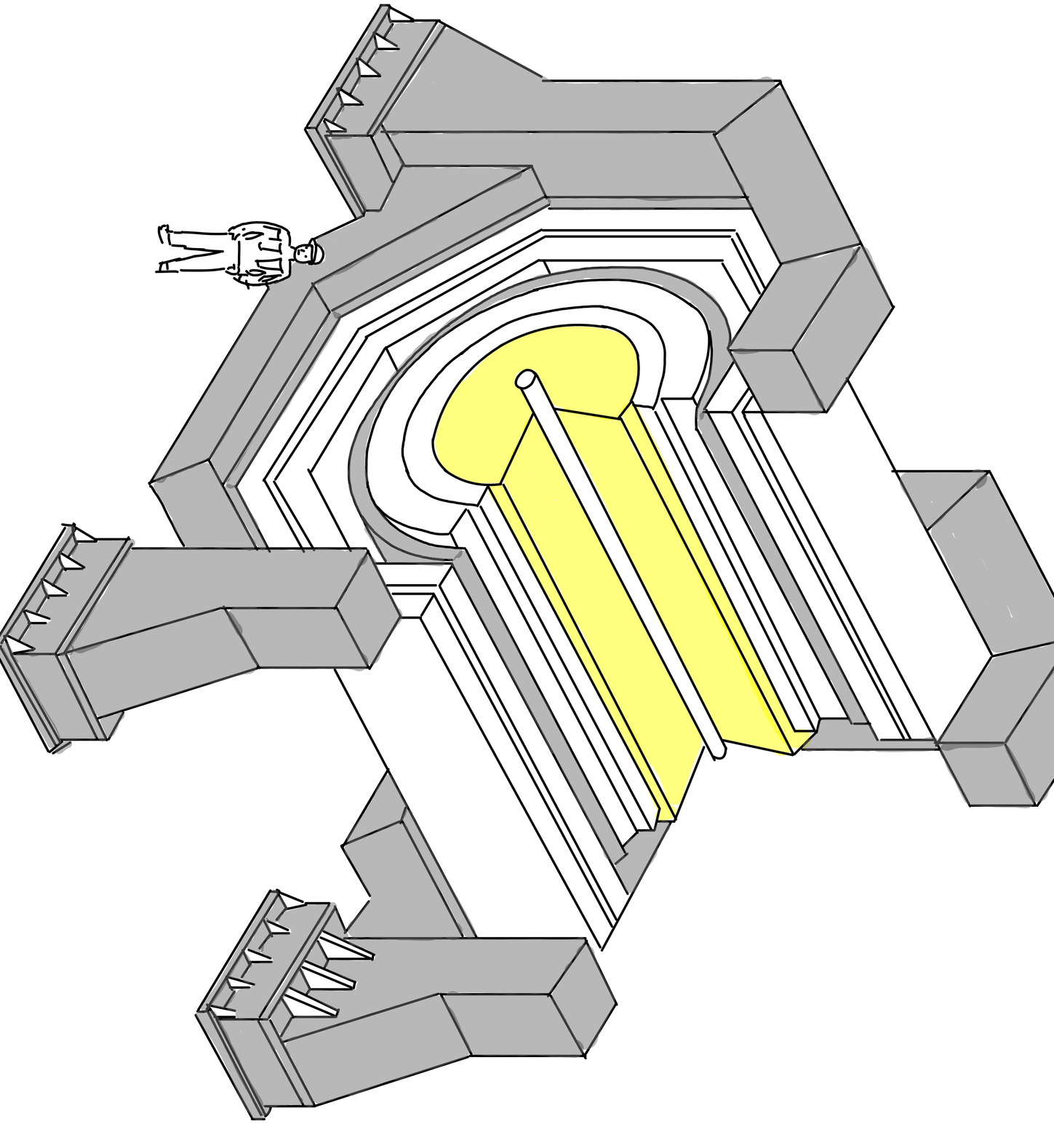
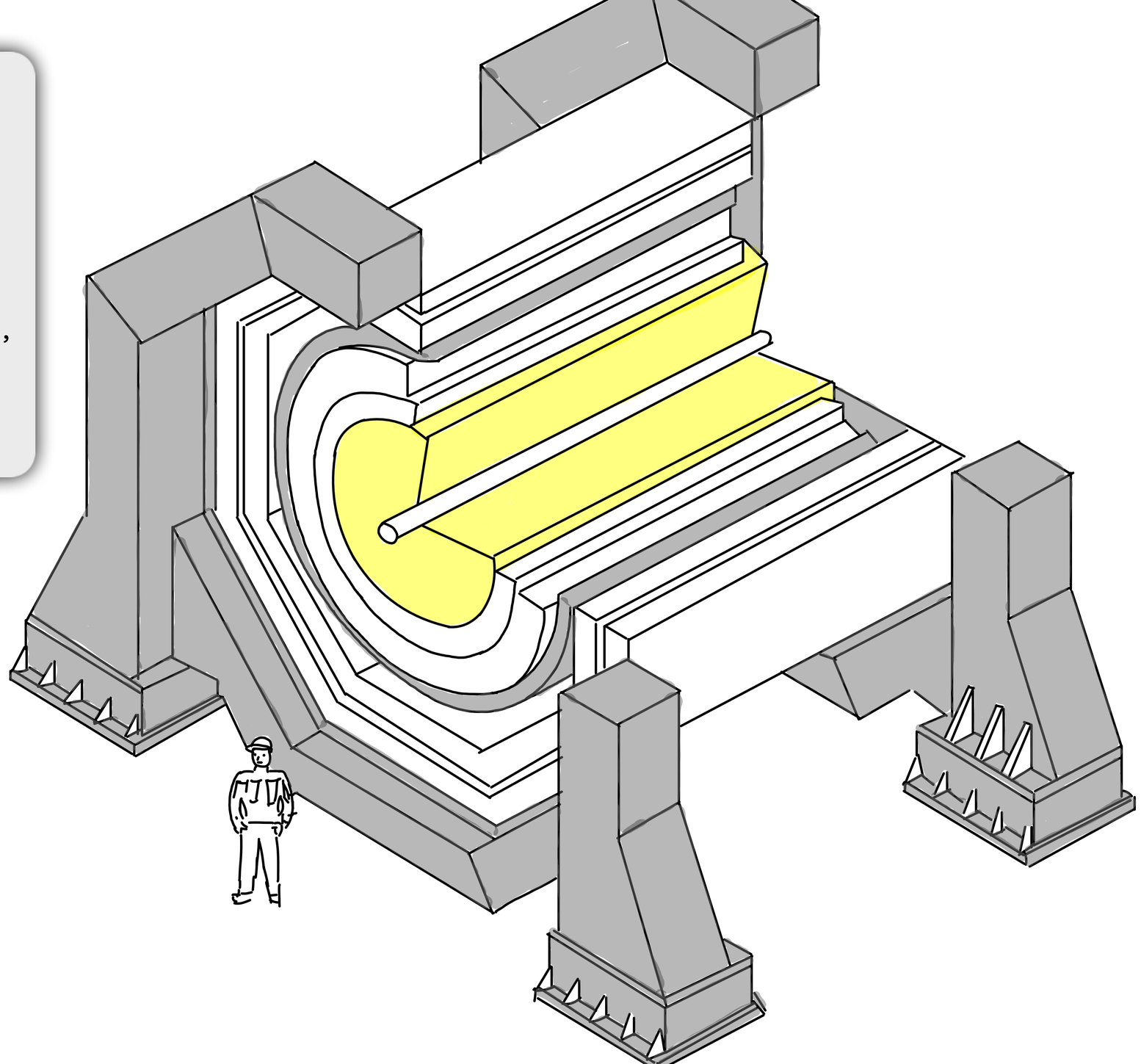




Sampling Calorimeters

- Active Medium: provides signal
  - Scintillator, ionising noble liquid, etc
- Passive Medium: functions as absorber
  - High density material like lead, iron copper, depleted uranium
- Lower resolution; depth segmentation (longitudinal shower profile)



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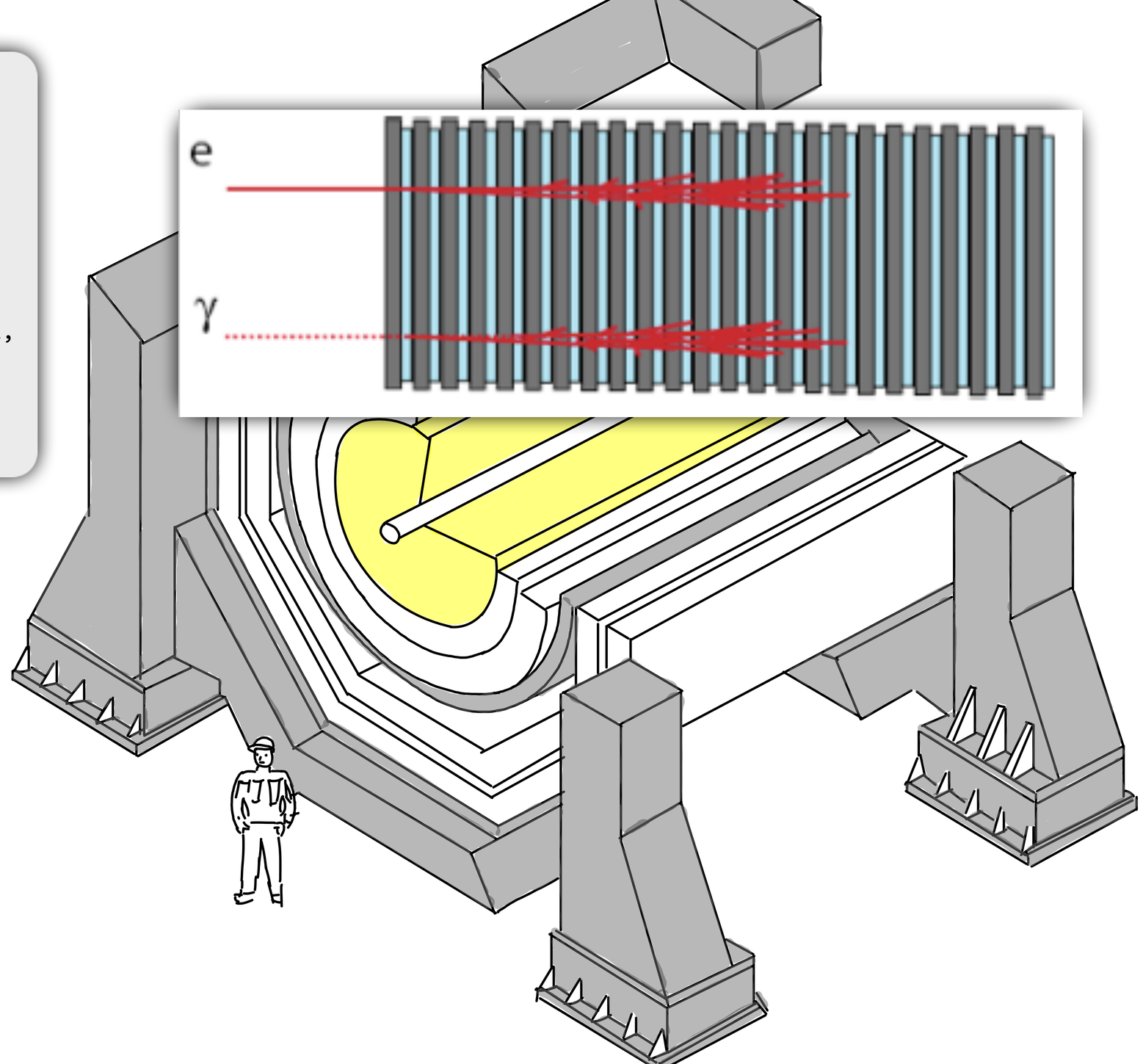

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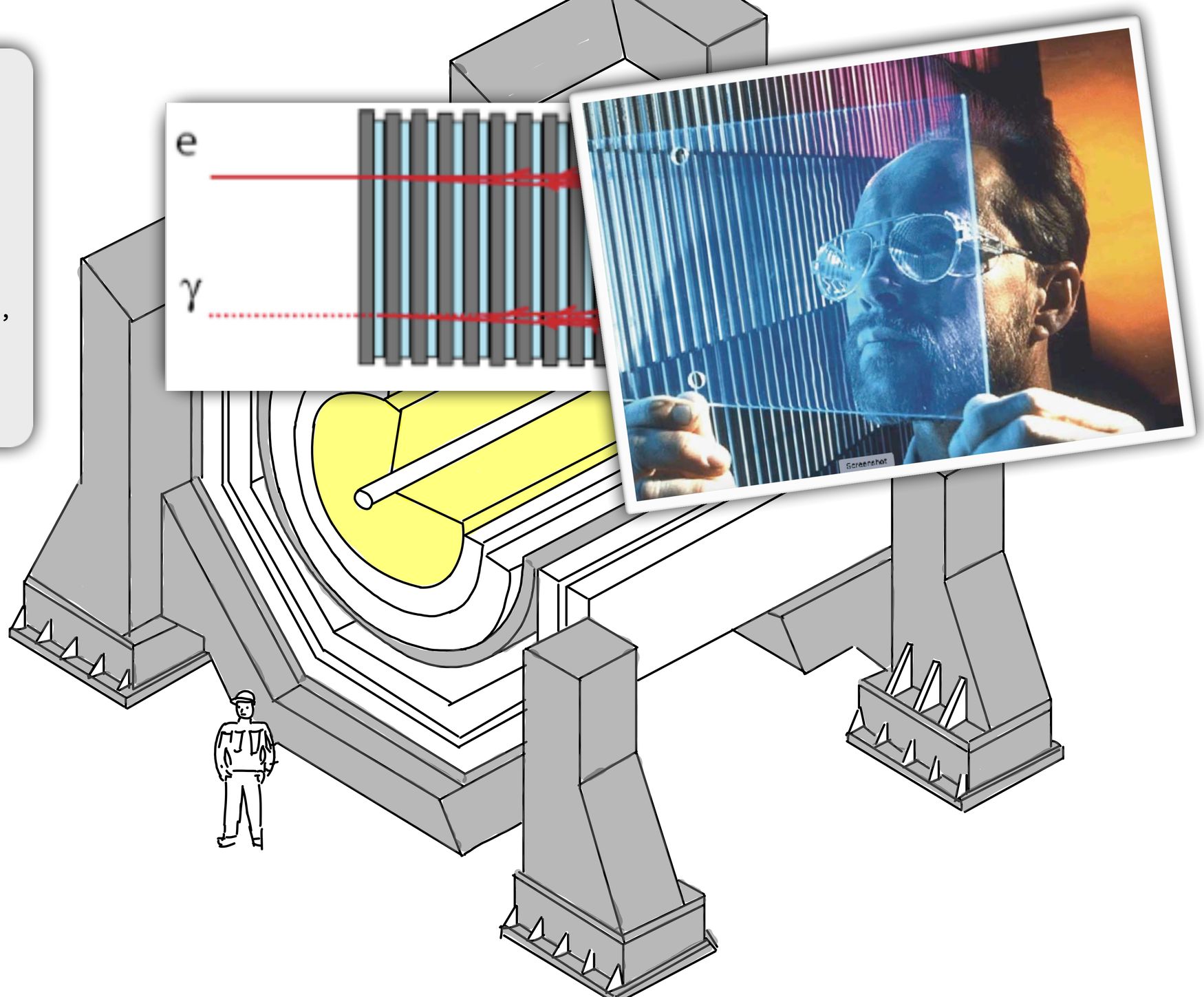

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- Entire volume provides signal
- Inorganic heavy scintillating crystals
  - CsI, NaI, PbWO, etc
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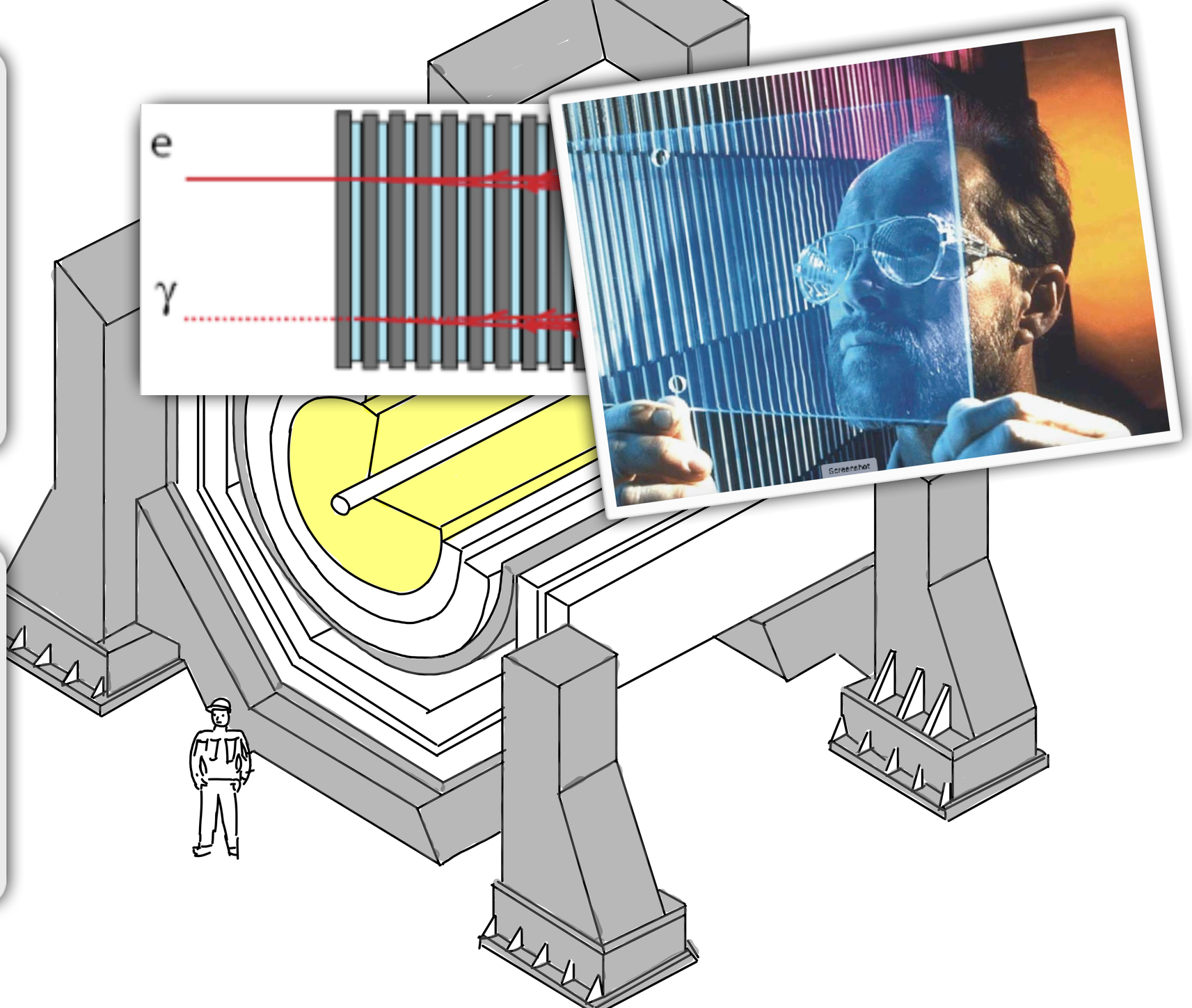

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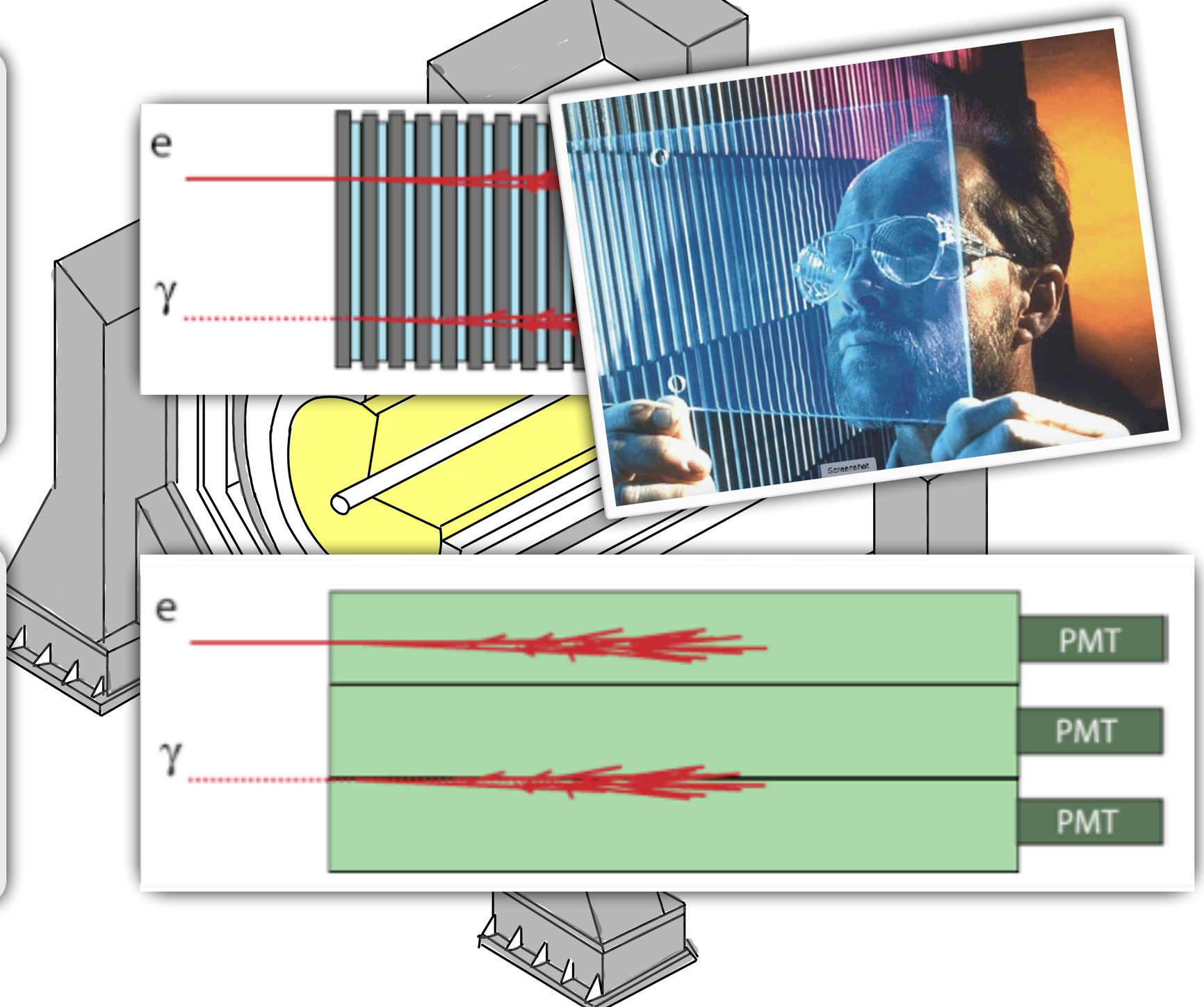

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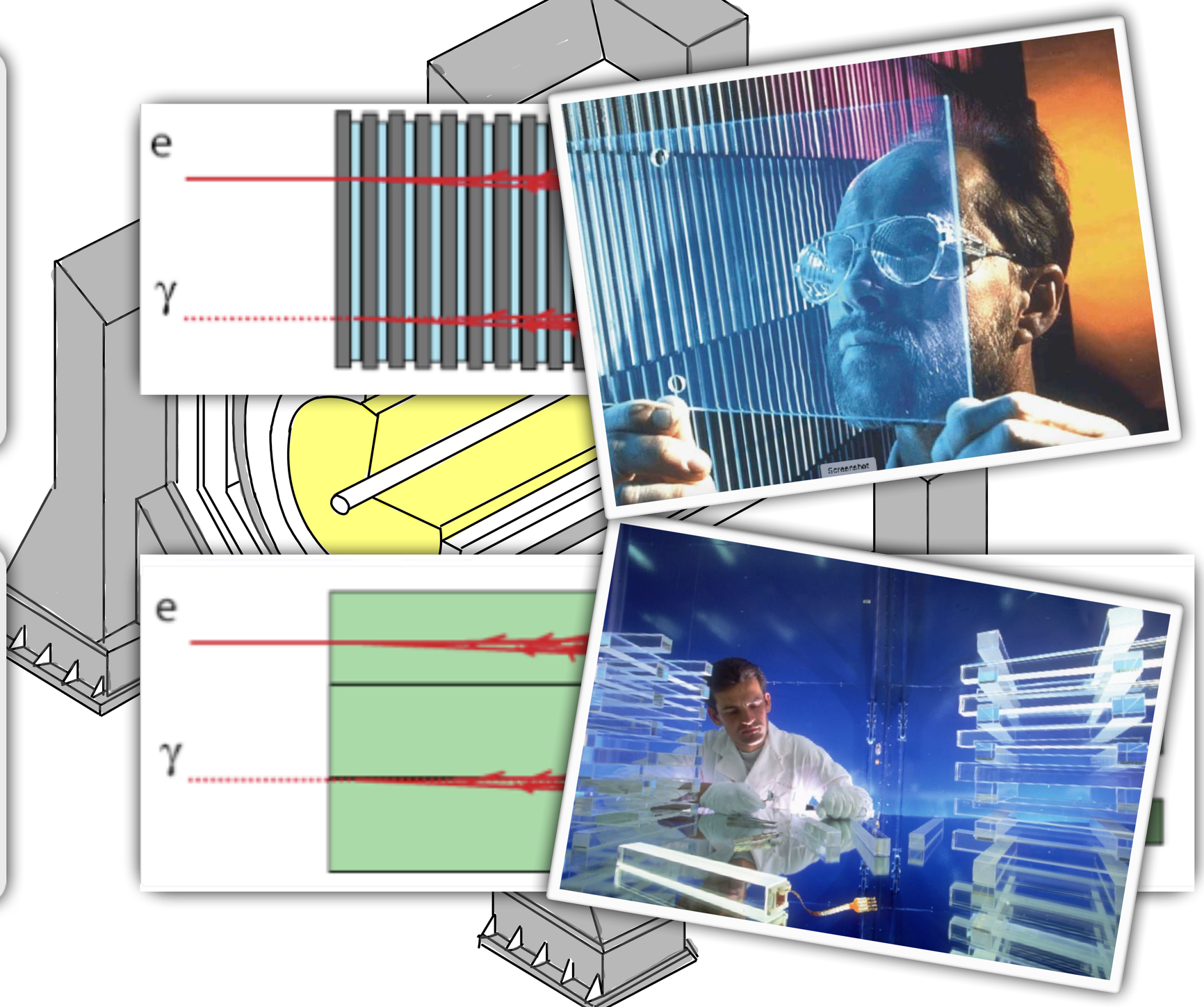
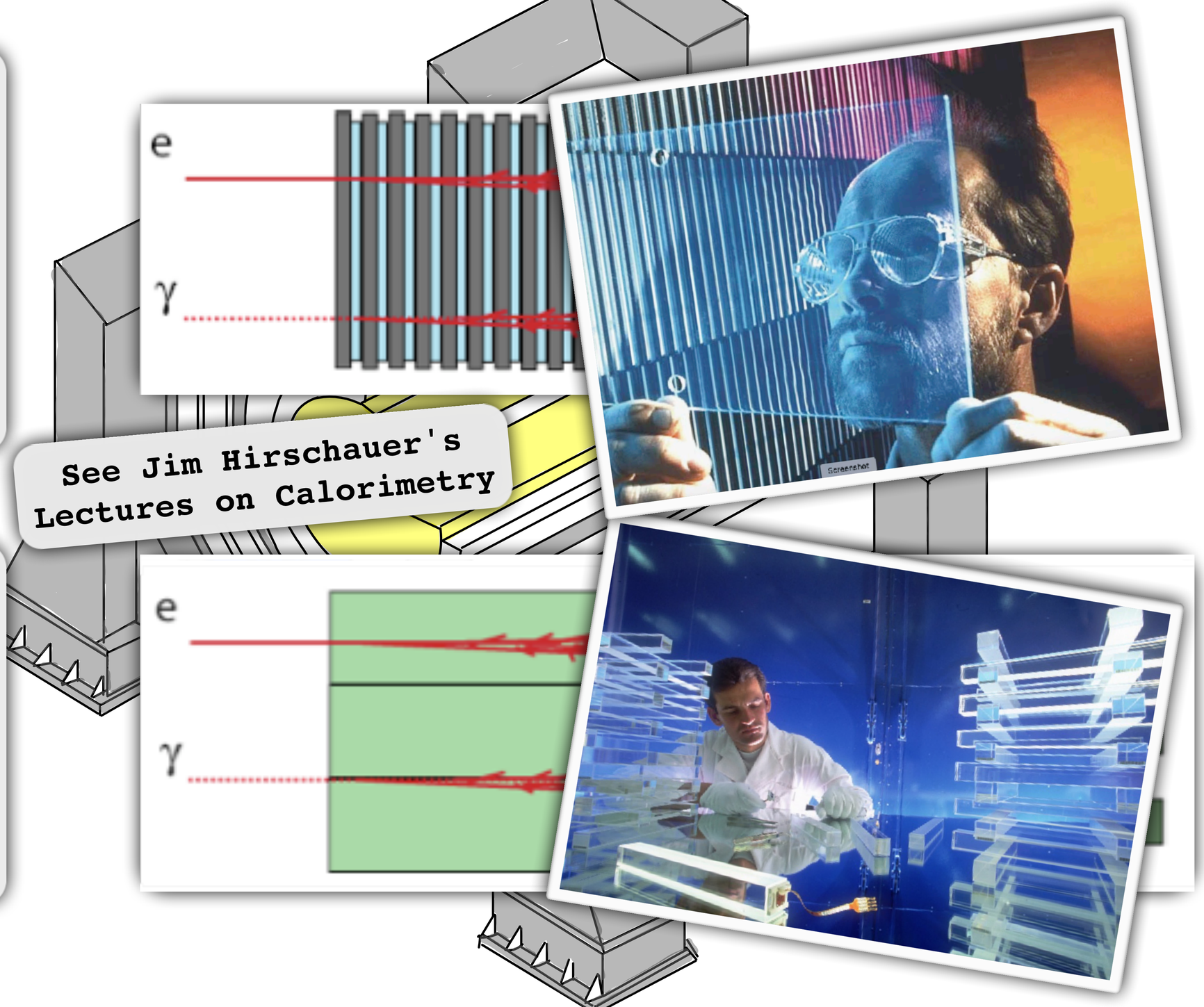


Sampling Calorimeters

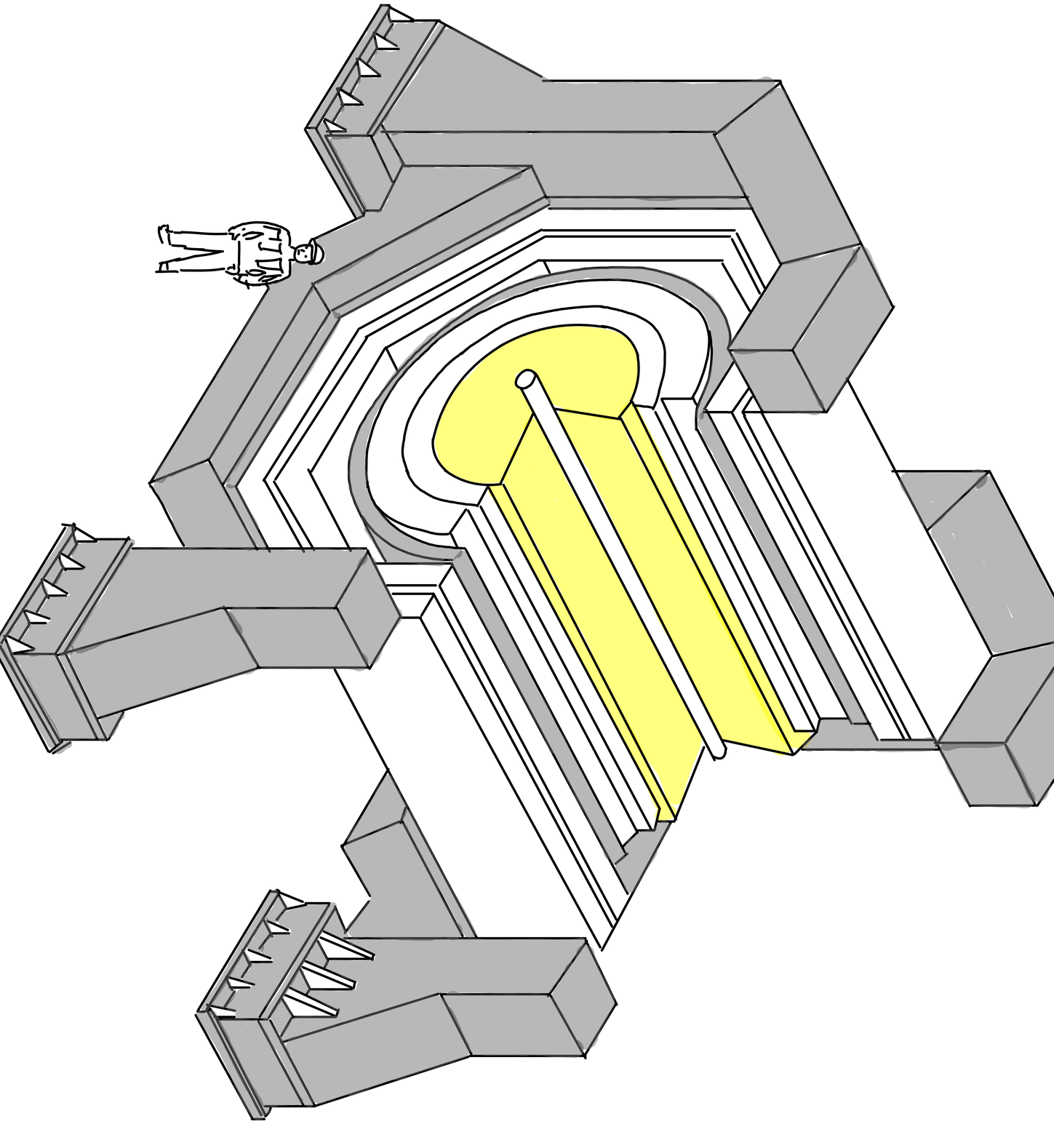
- Active Medium: provides signal
  - Scintillator, ionising noble liquid, etc
- Passive Medium: functions as absorber
  - High density material like lead, iron copper, depleted uranium
- Lower resolution;
  depth segmentation
  (longitudinal shower profile)

Homogeneous Calorimeters

- Entire volume provides signal
- Inorganic heavy scintillating crystals
  - CsI, NaI, PbWO, etc
  - Ionising noble liquids
- Better resolution;
  no depth segmentation
  (no longitudinal shower profile)

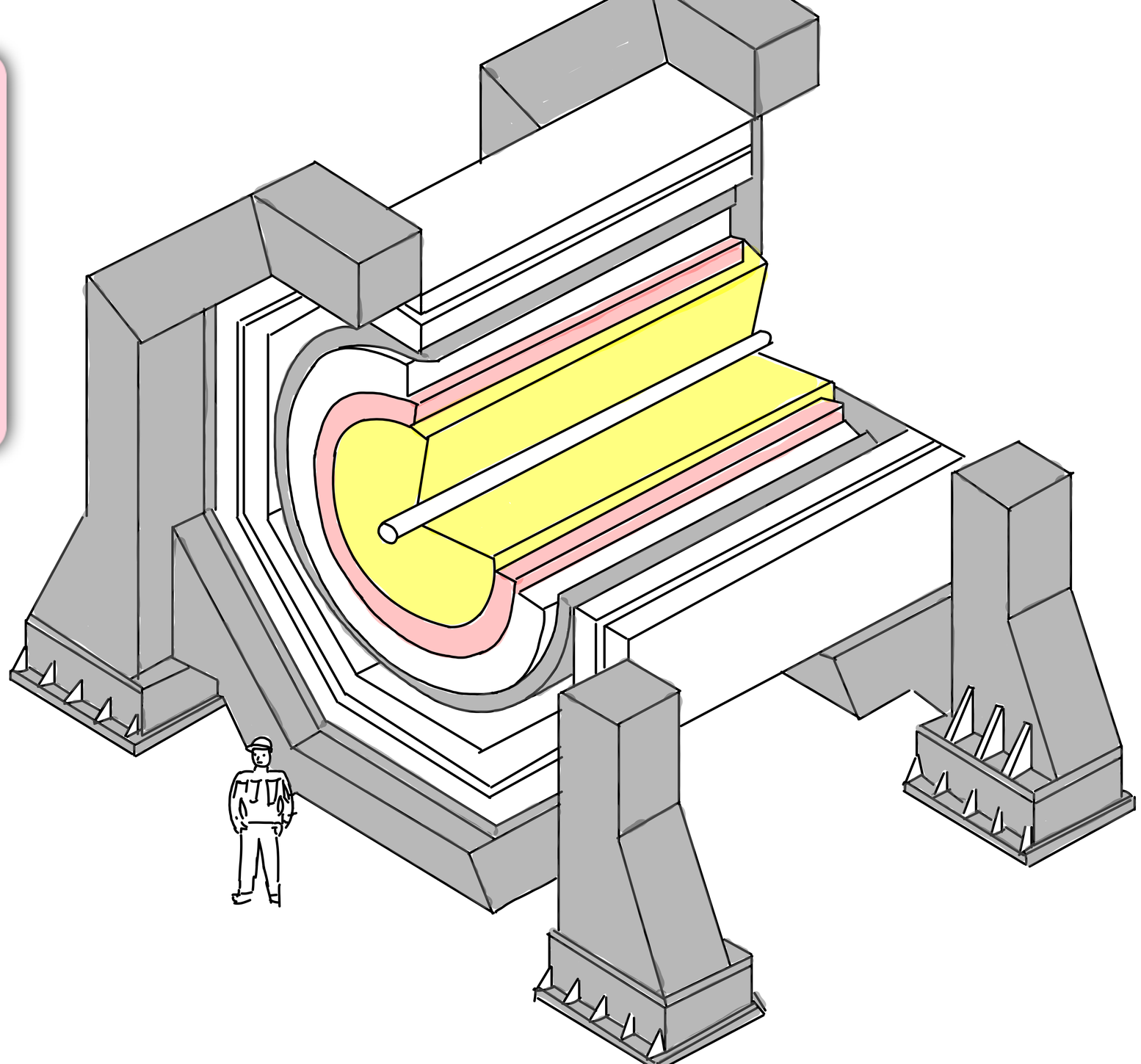


See Jim Hirschauer's Lectures on Calorimetry



EM Calorimeters

- Purpose: measure energy of EM particles
- How?
  - High Z material causes EM shower
  - Total absorption / stops particle
  - Important parameter is X_0 (usually X_0 = 15-30 mm)



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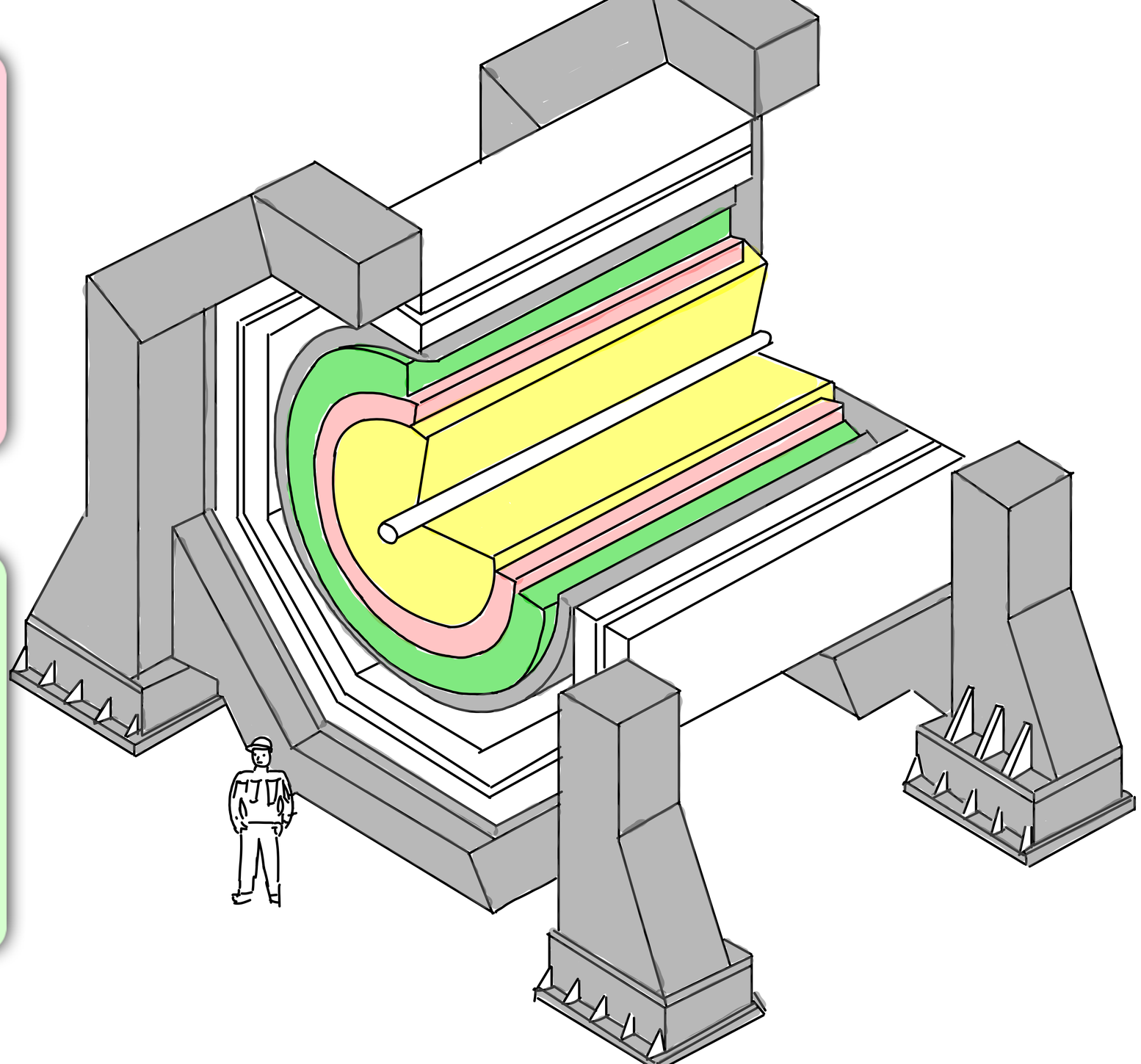

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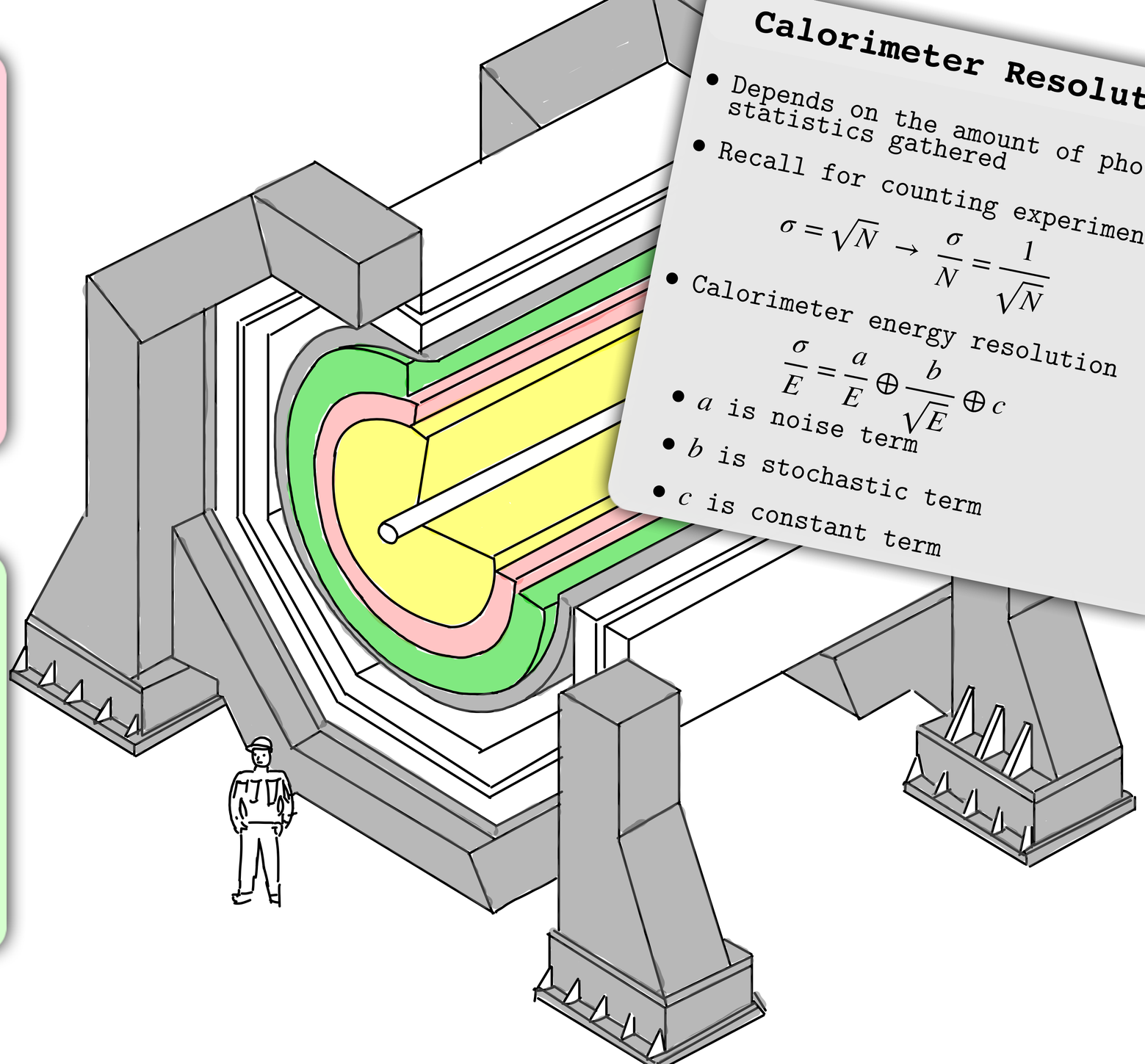

Calorimeter Resolution

- Depends on the amount of photo-statistics gathered
- Recall for counting experiment

$$\sigma = \sqrt{N} \rightarrow \frac{\sigma}{N} = \frac{1}{\sqrt{N}}$$

- Calorimeter energy resolution

$$\frac{\sigma}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c$$

- a is noise term
- b is stochastic term
- c is constant term

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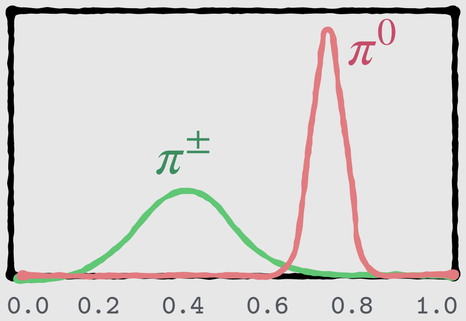
Non-Compensation

- EM vs HAD response different



- Large fluctuations in HAD shower composition (EM vs HAD)
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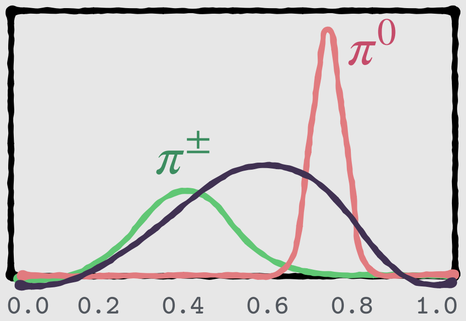

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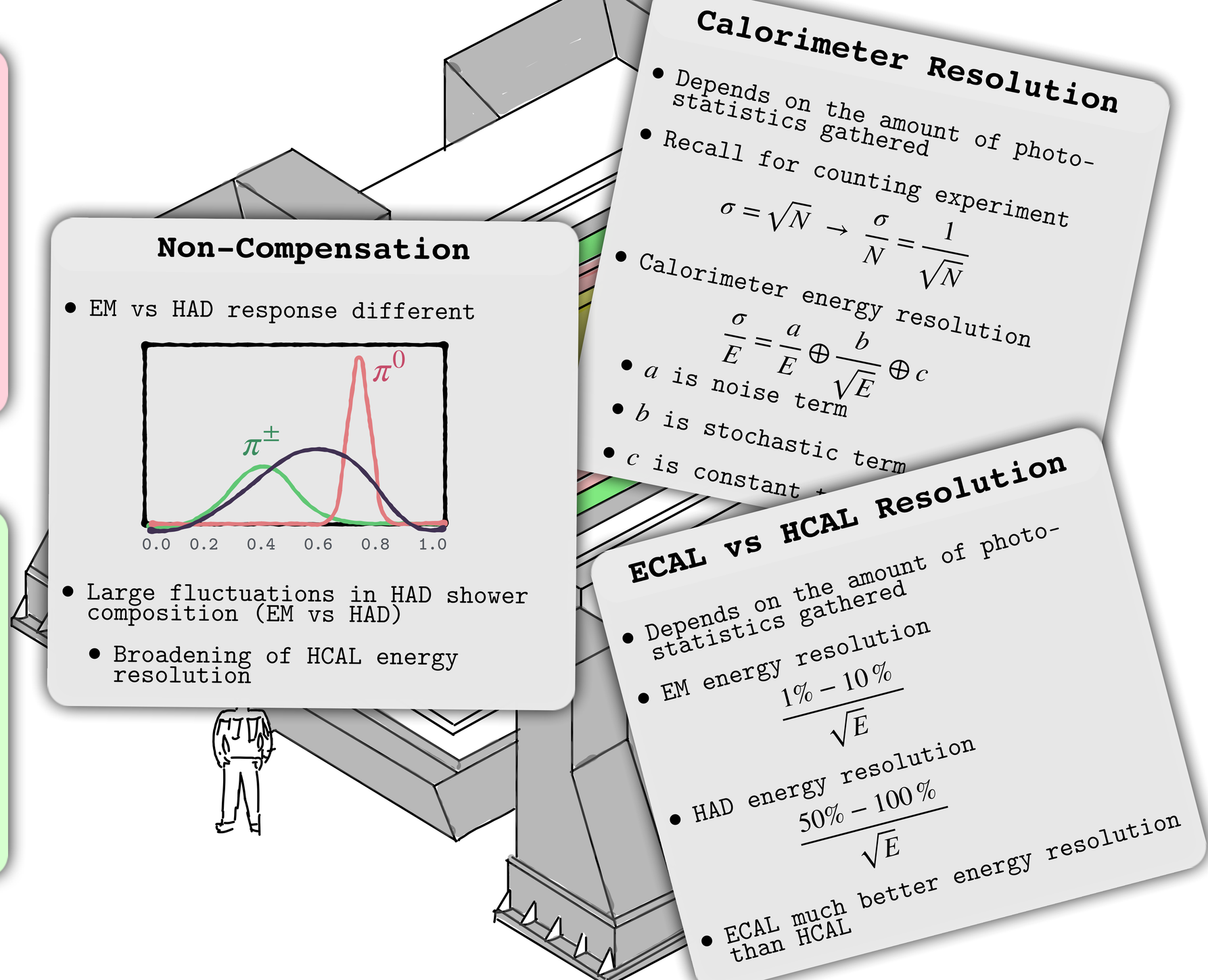

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ECAL vs HCAL Resolution

- Depends on the amount of photo-statistics gathered
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$$\frac{1\% - 10\%}{\sqrt{E}}$$

- HAD energy resolution

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- ECAL much better energy resolution than HCAL

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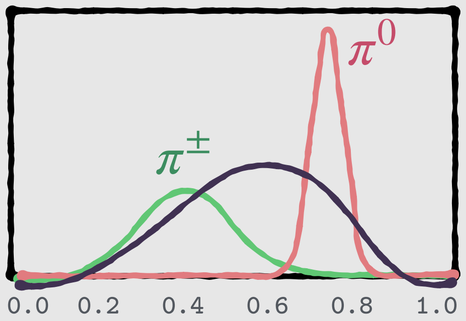

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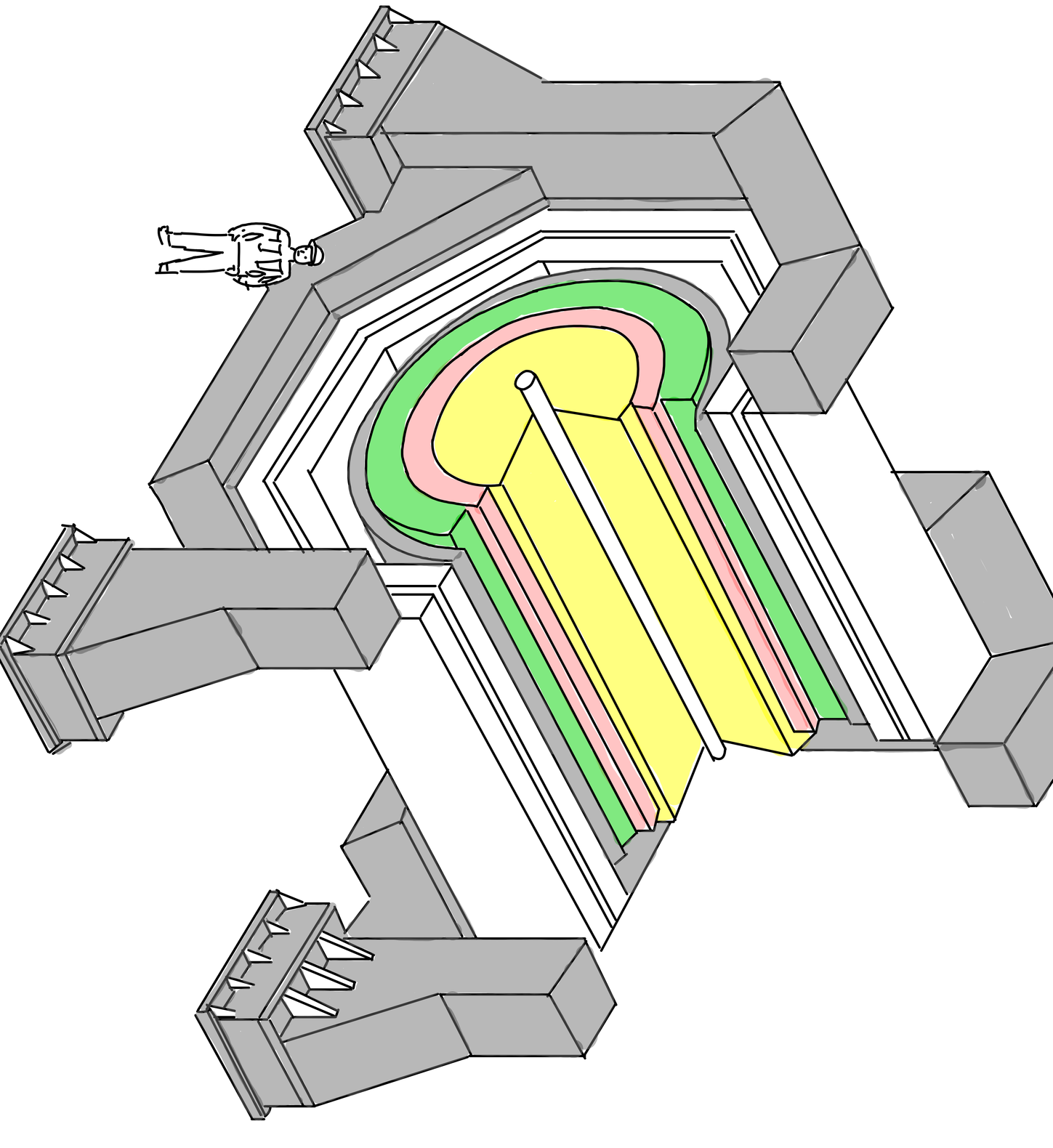
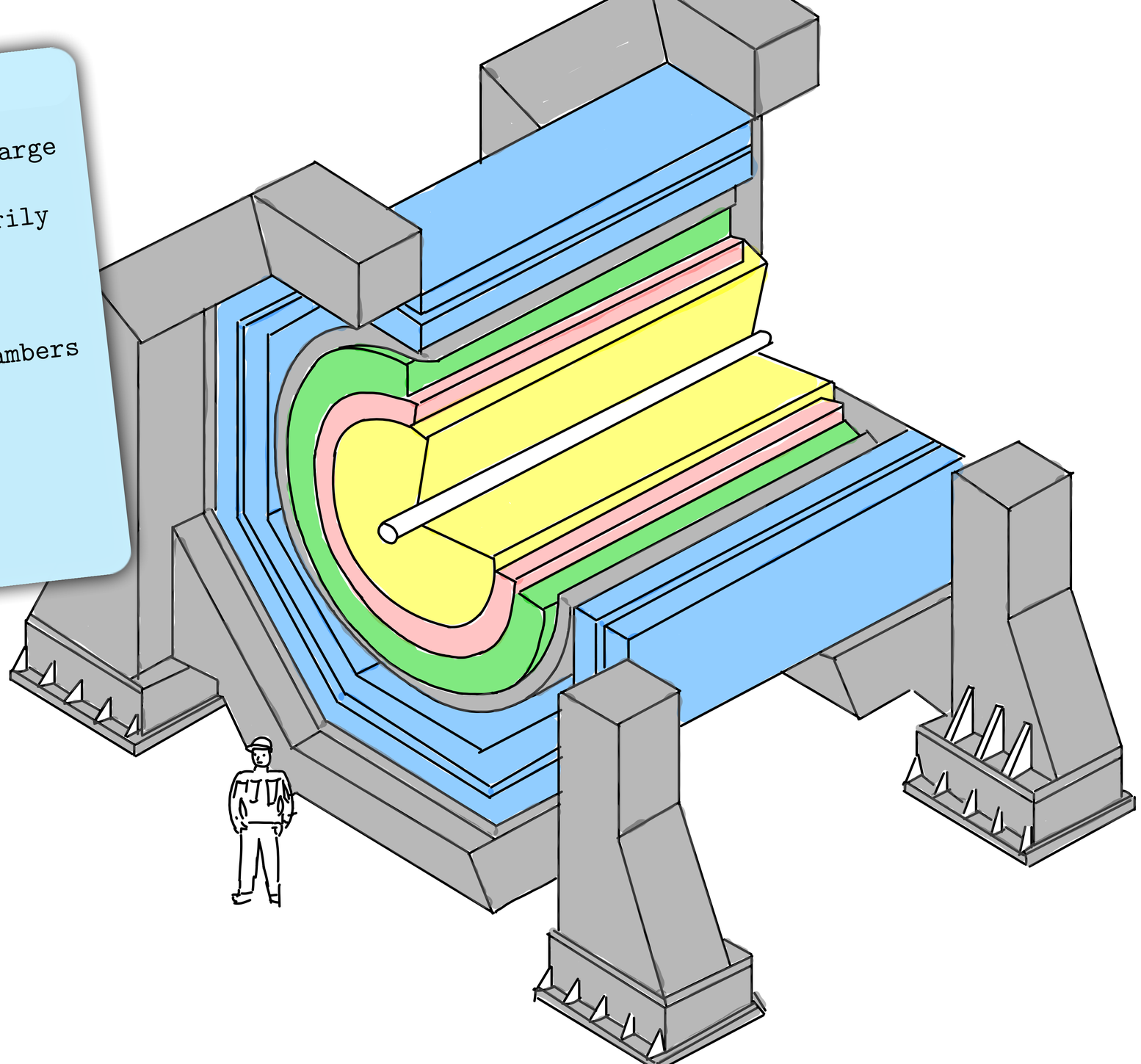


Muon Chambers

- Purpose: measure momentum + charge of muons (tracking)
- Muon signature is extraordinarily penetrating
  - Place chambers at outermost layers
- LHC Experiments: gas wire chambers
  - Resistive Plate Chambers
  - Drift Tubes
  - Cathode Strip Chambers
  - Thin Gap Chambers



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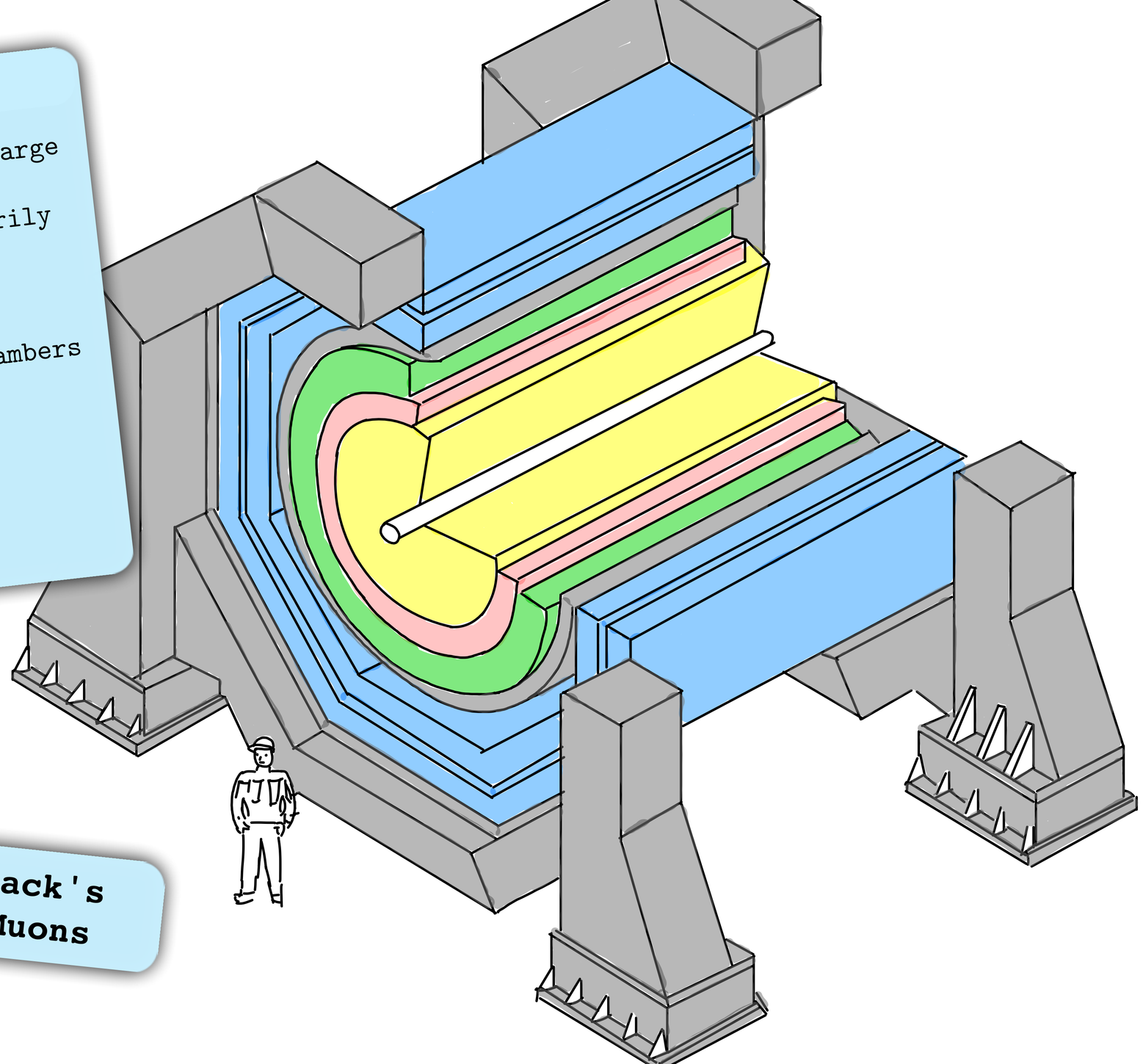
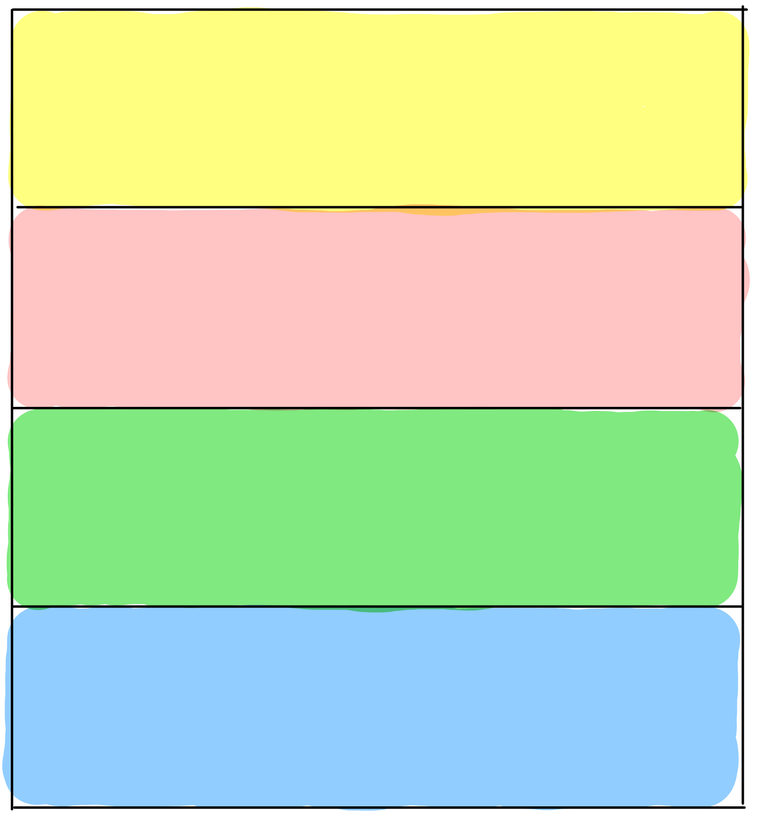
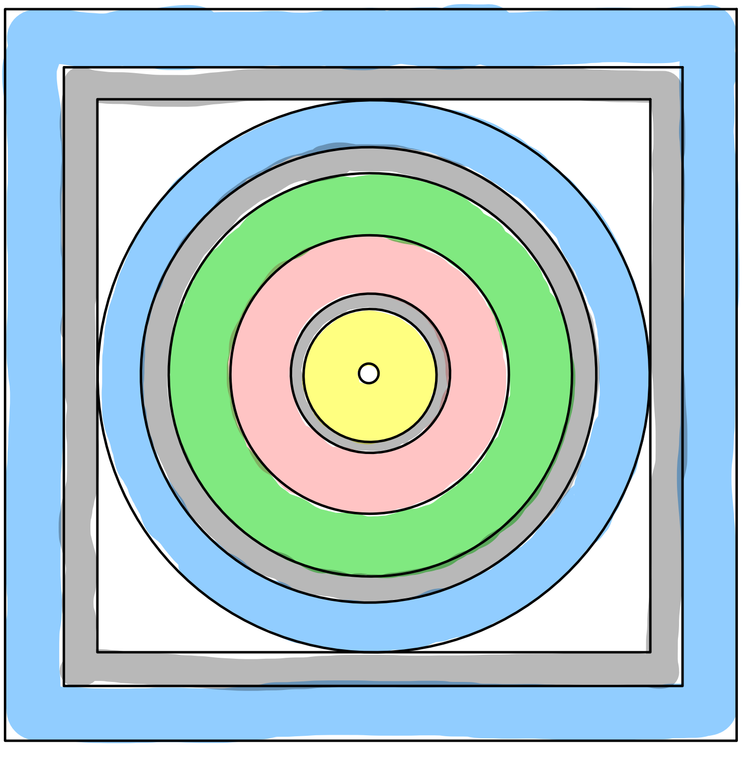
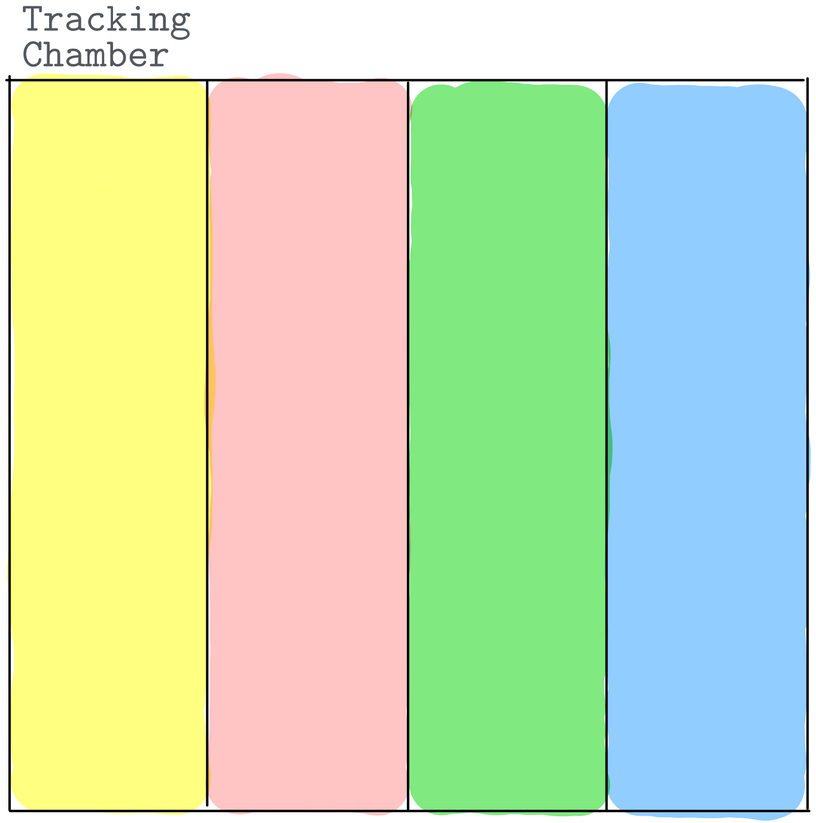


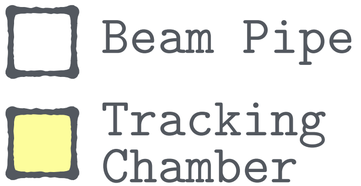
See Kevin Black's Lecture on Muons





Beam Pipe


Tracking
Chamber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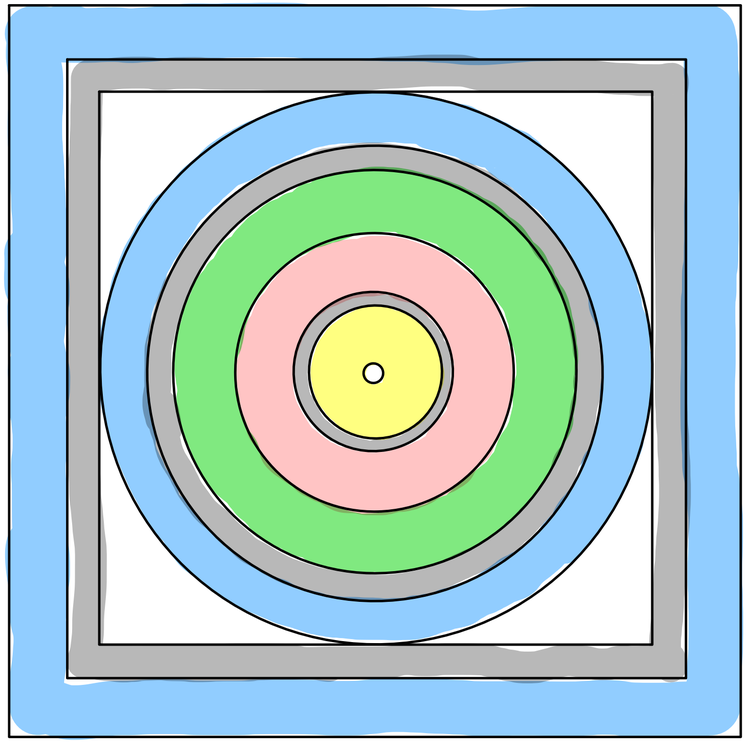

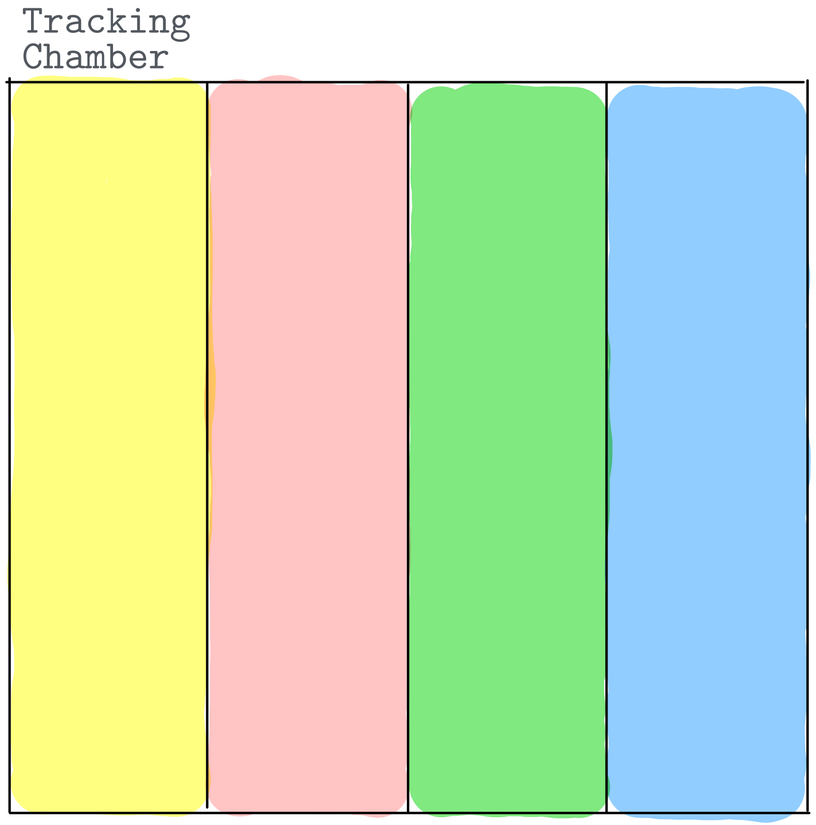
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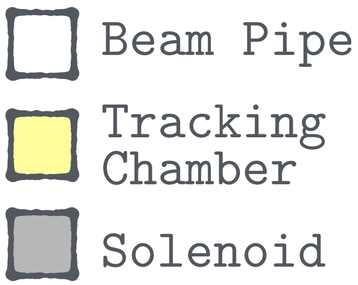
Beam Pipe
Tracking
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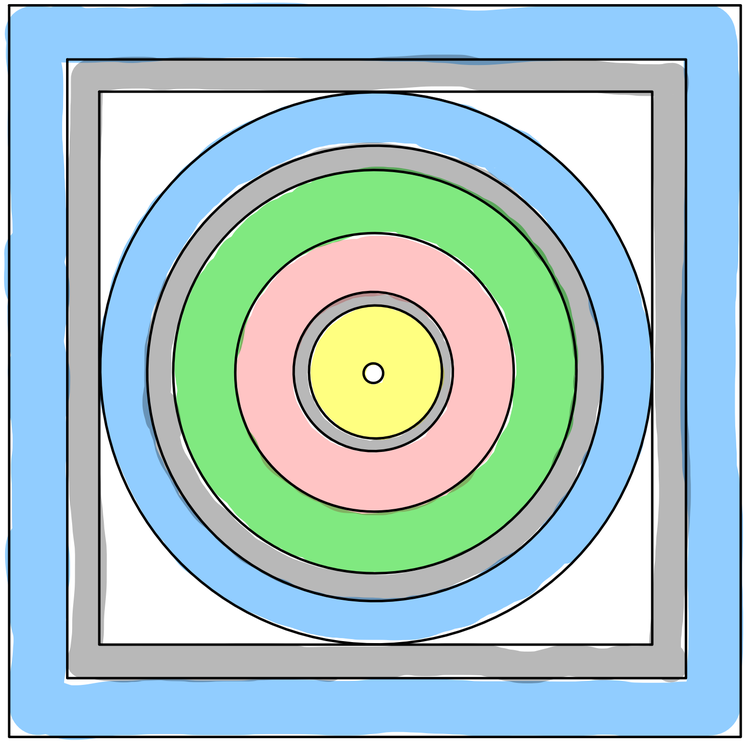
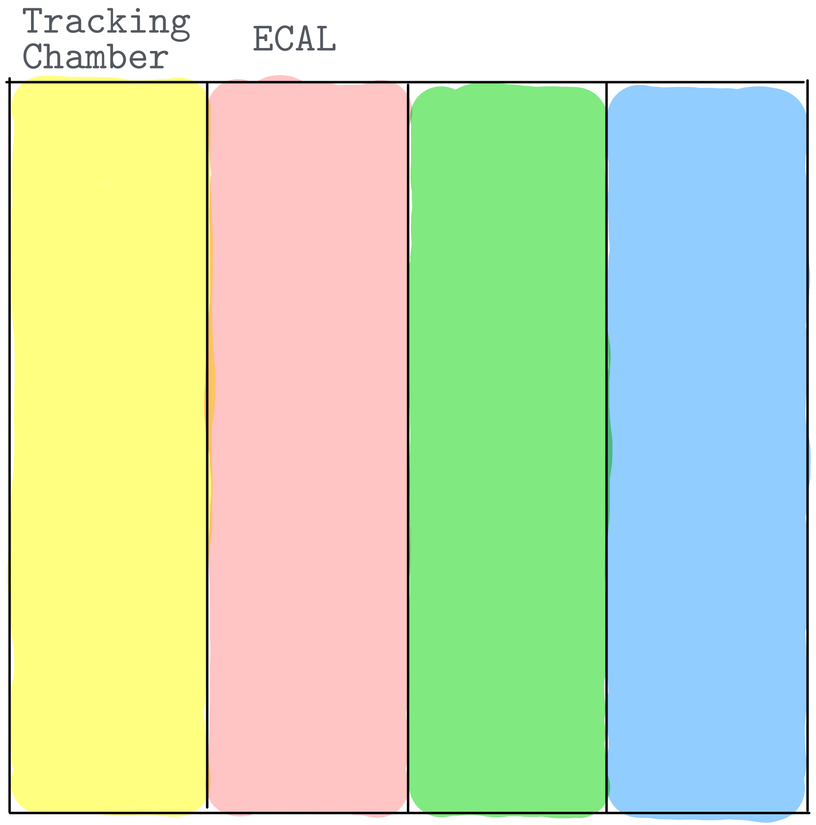
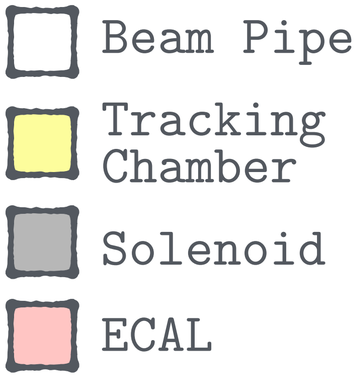
Solenoid




Tracking Chamber
ECAL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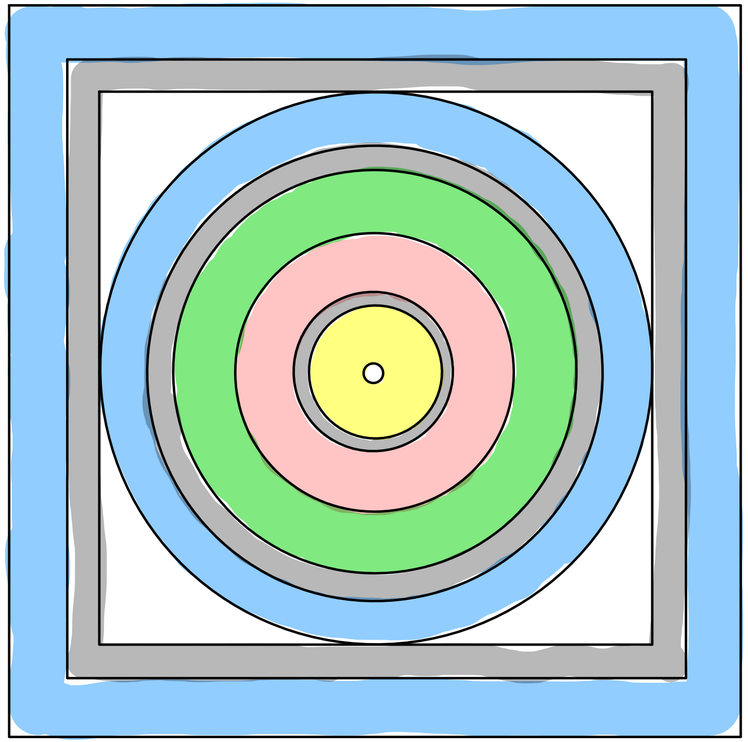

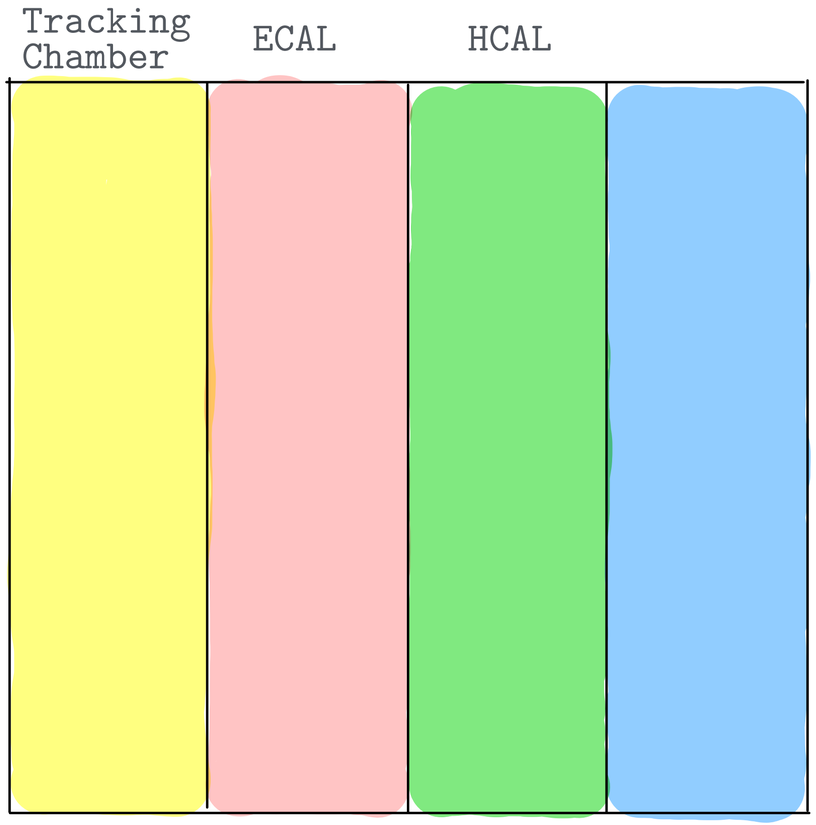
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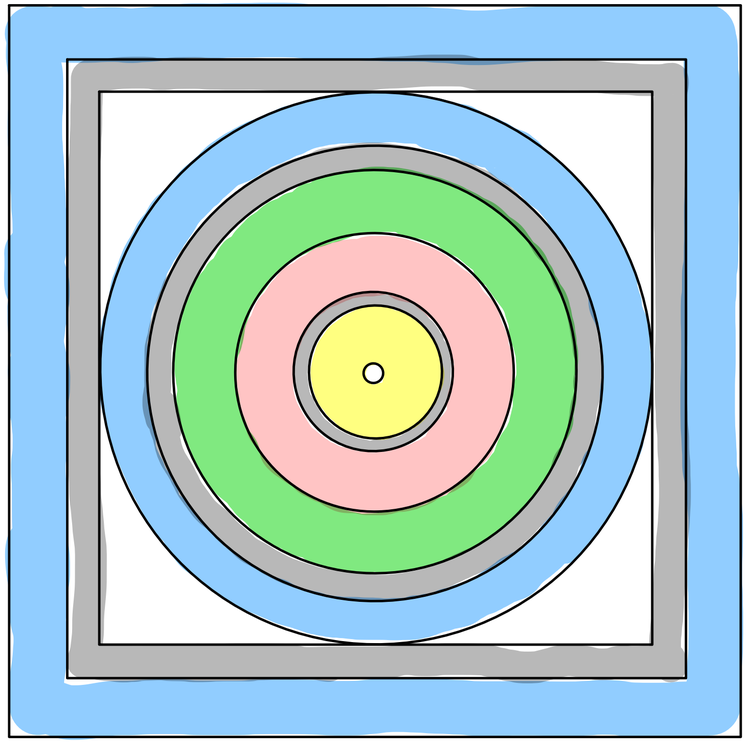

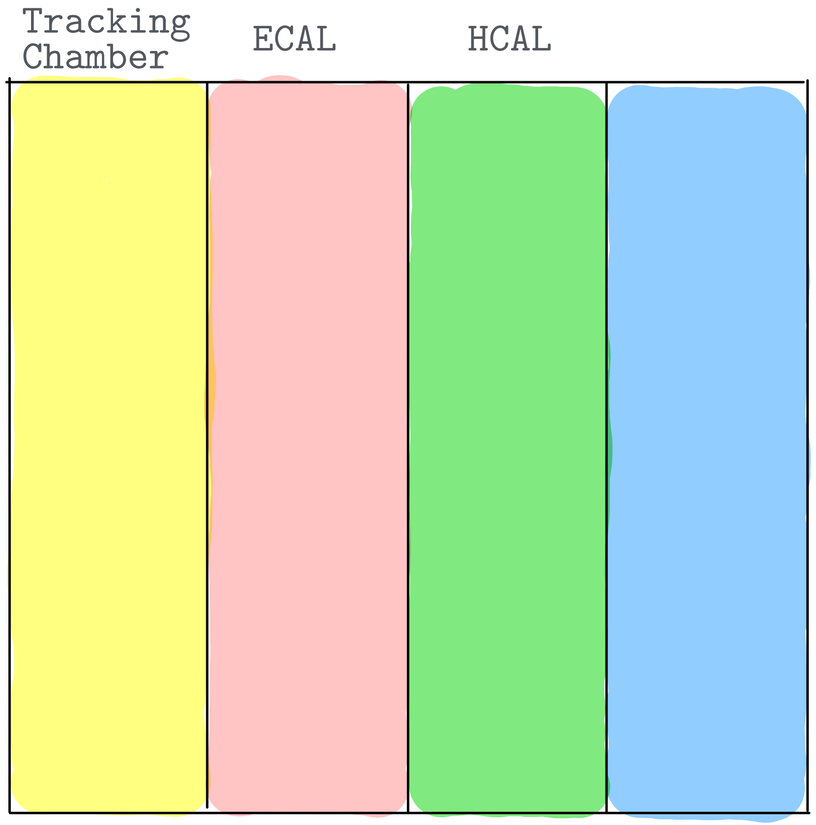
Tracking Chamber
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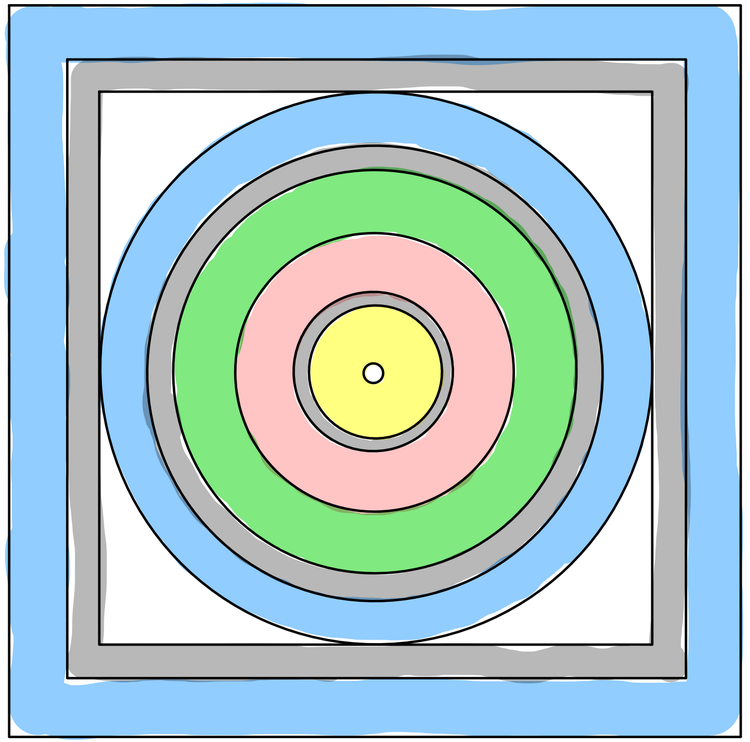

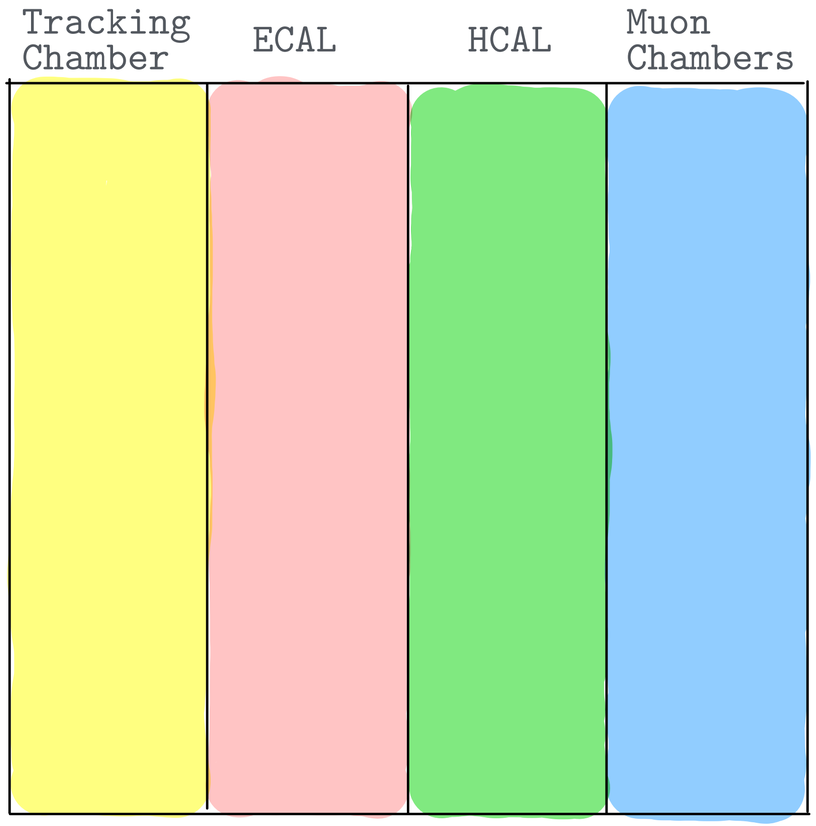
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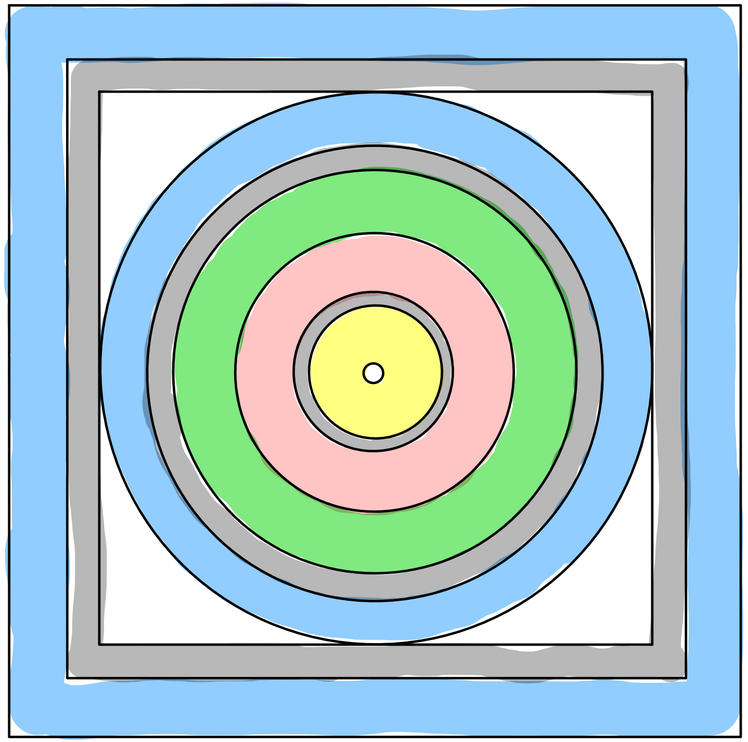
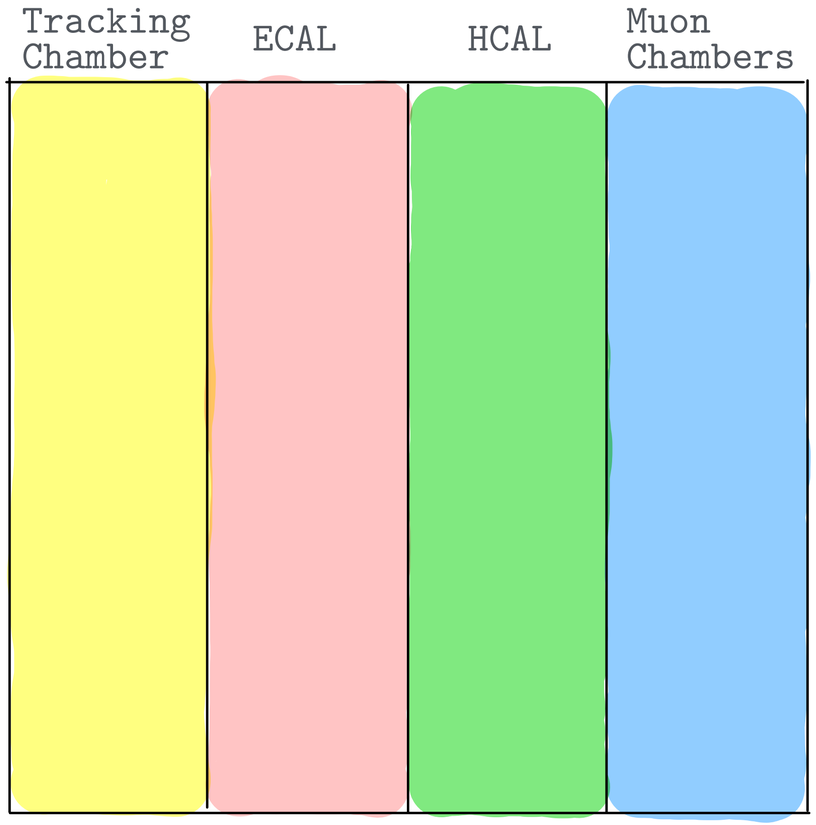
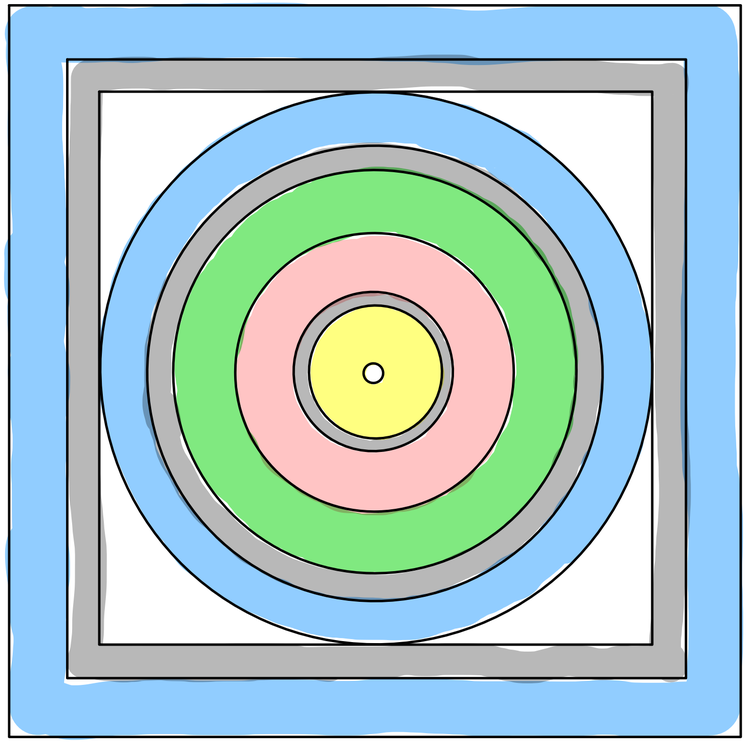


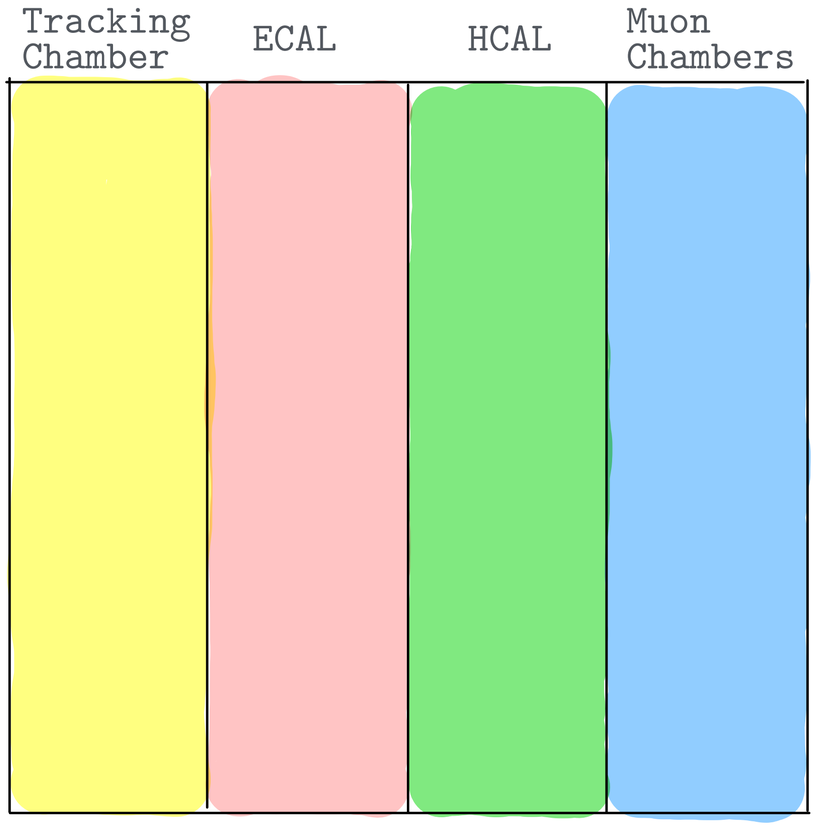
γ

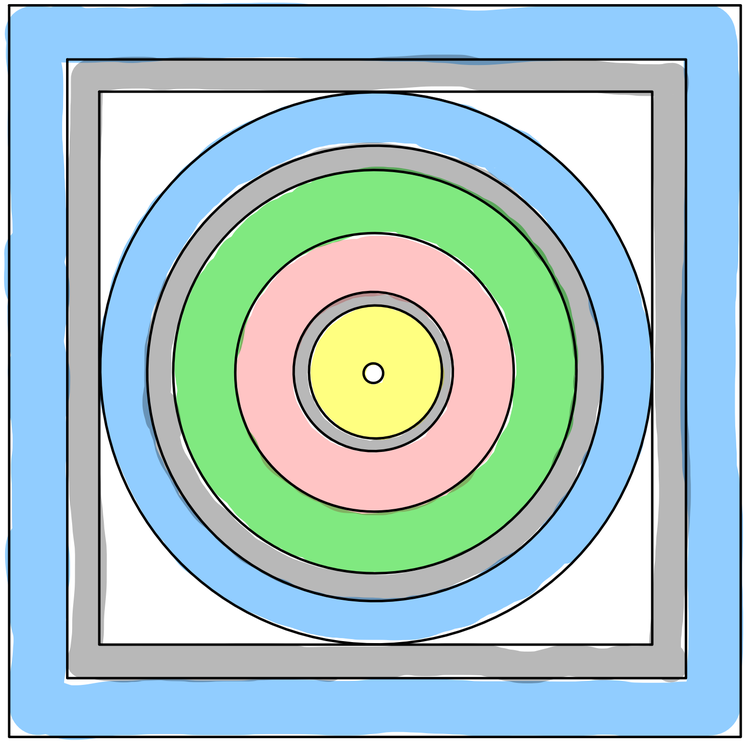




- Photons

γ





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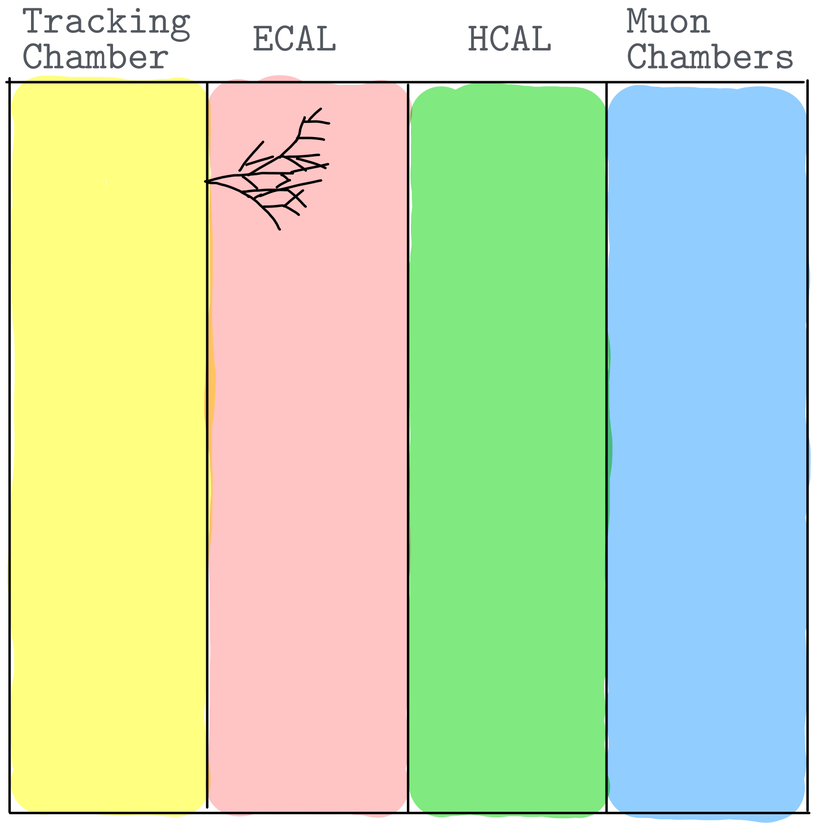
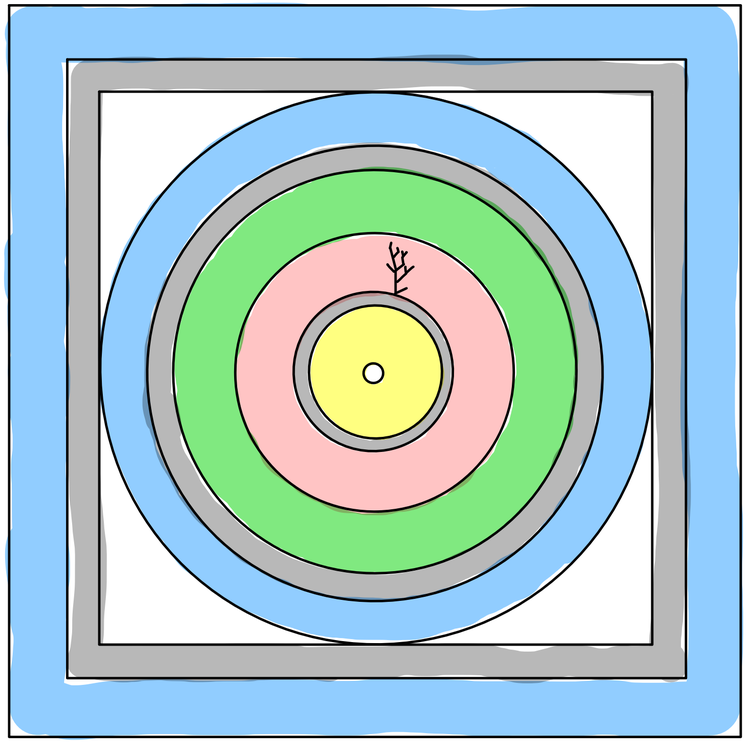
  - Deposit all energy in EM; no track

γ





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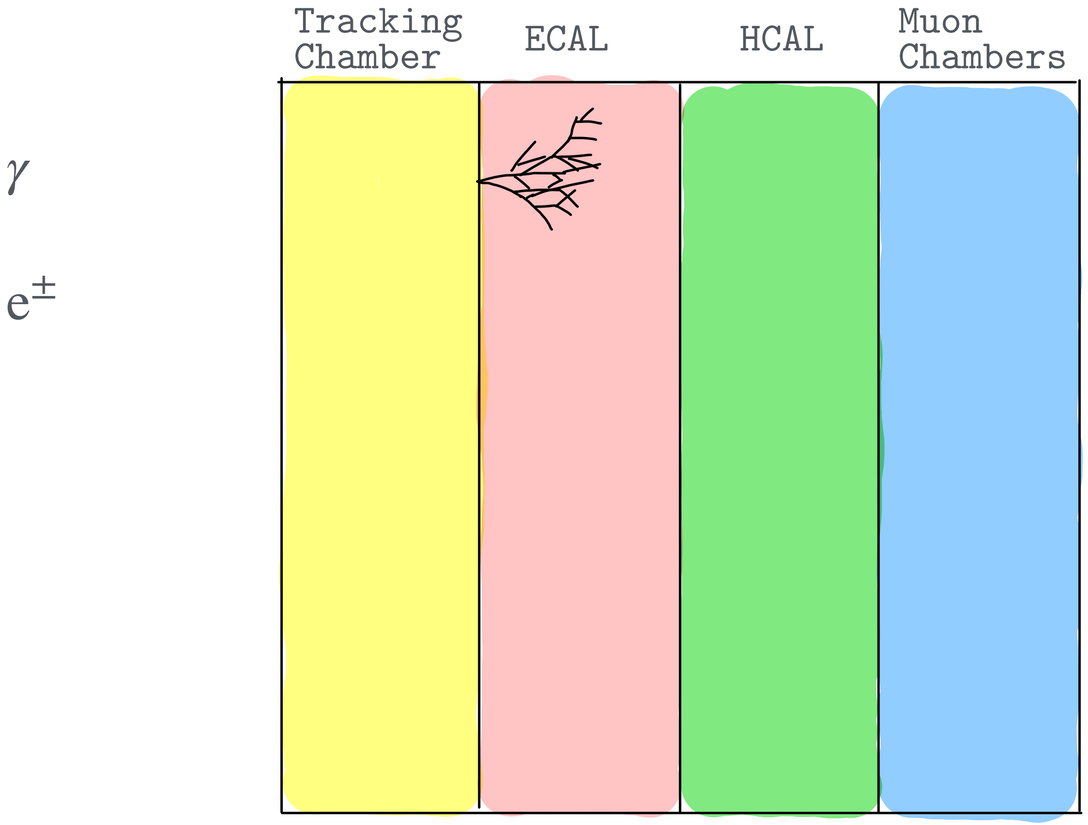

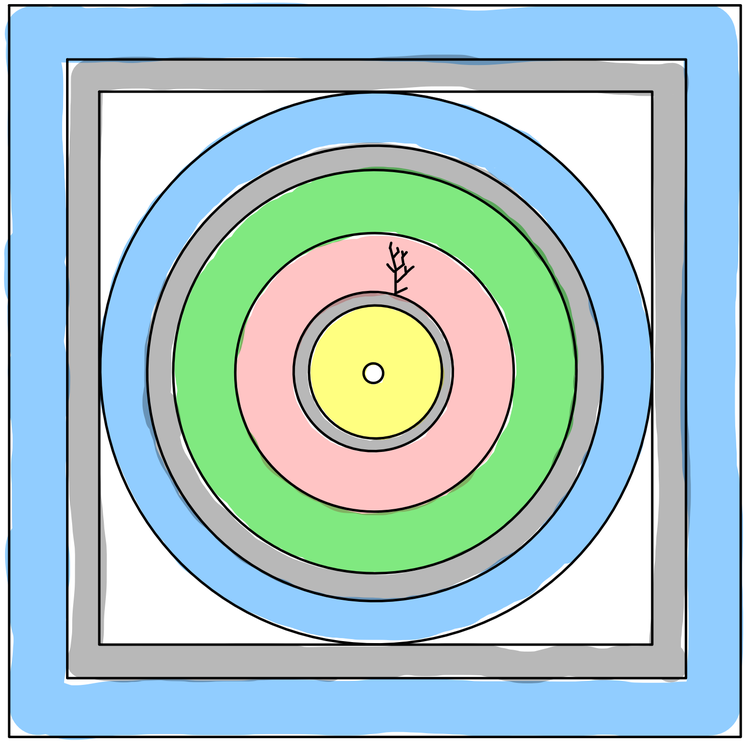

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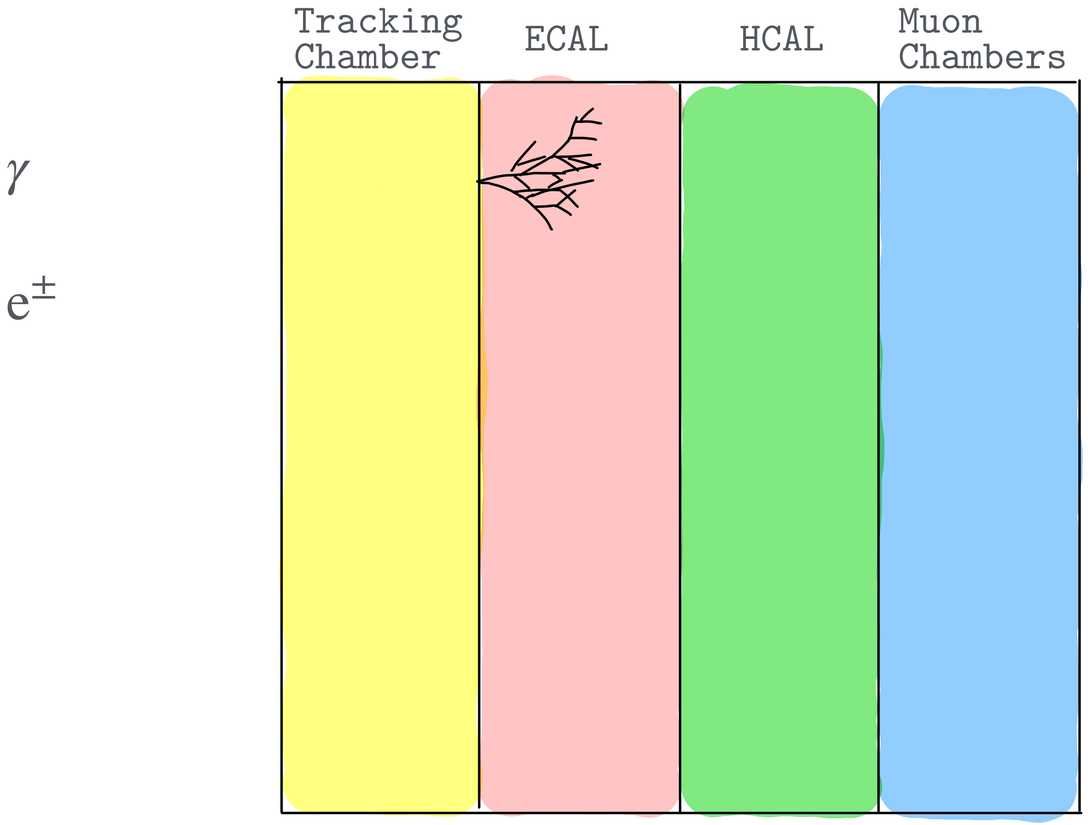

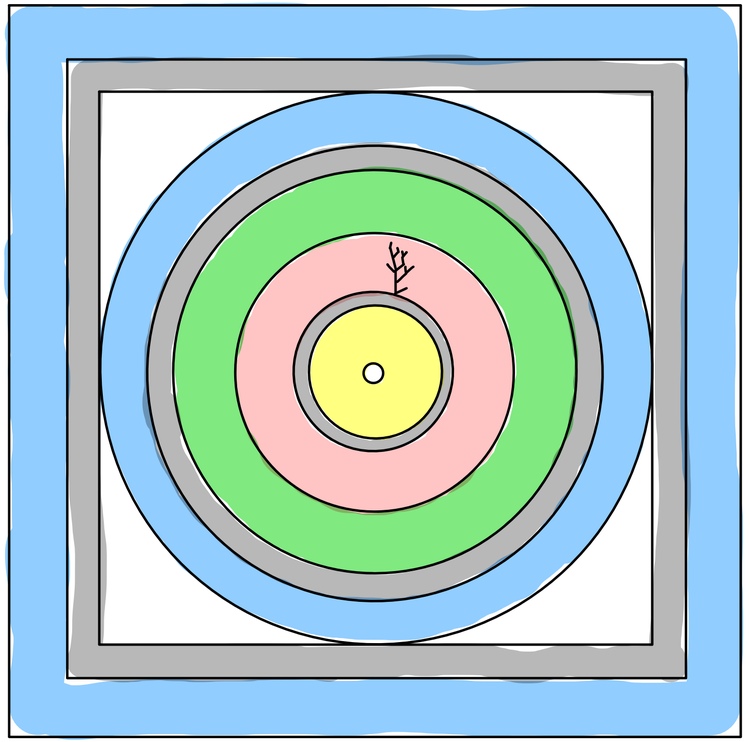

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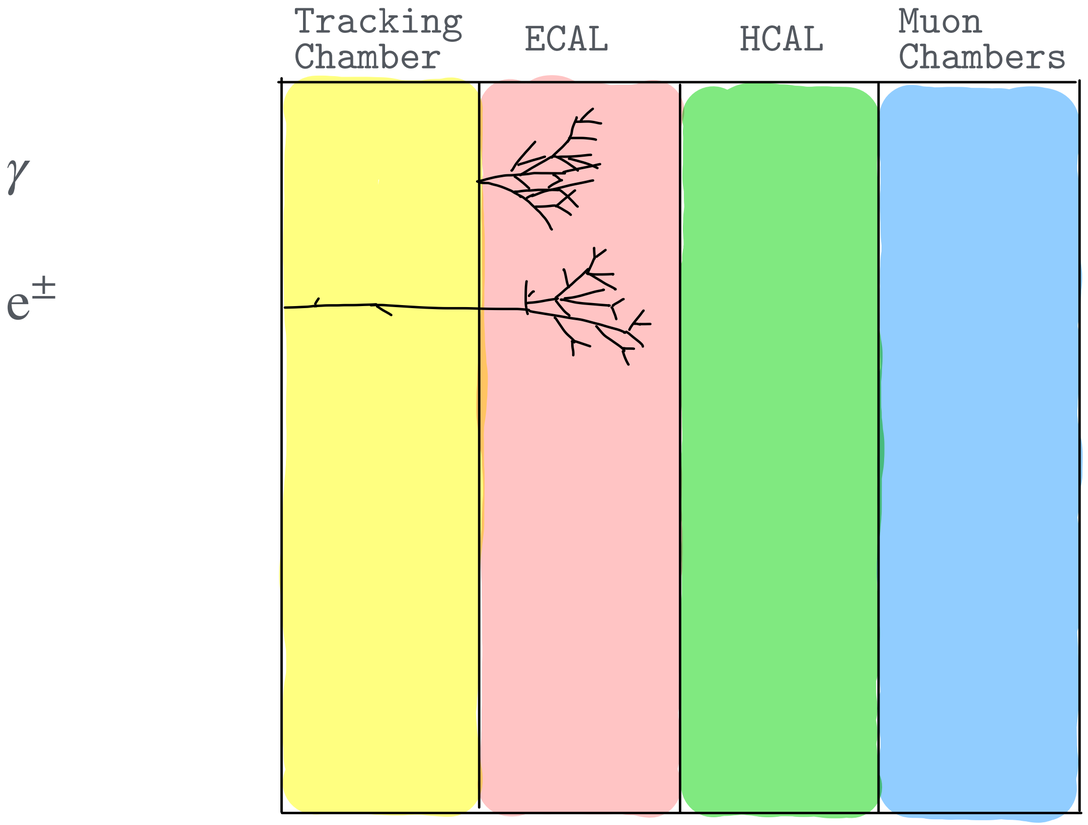

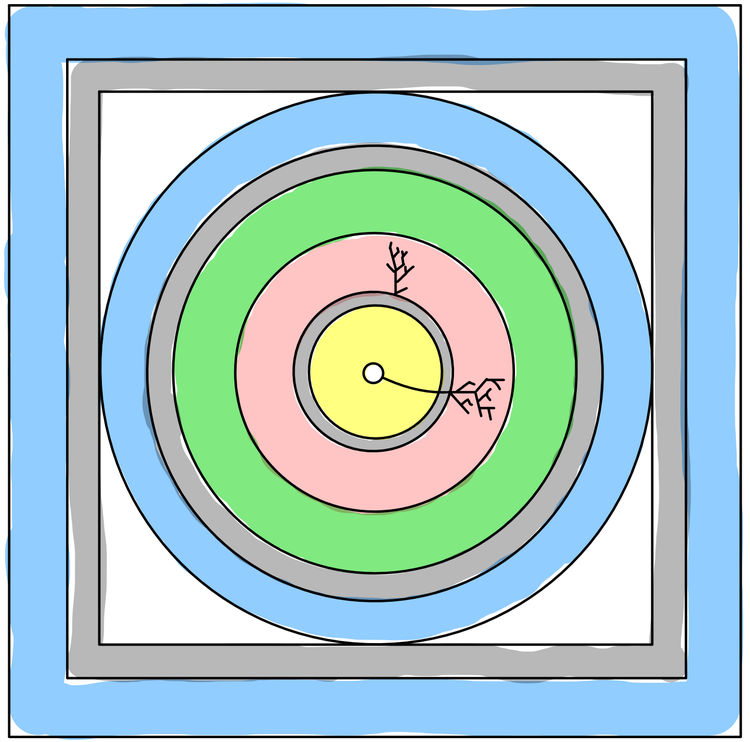

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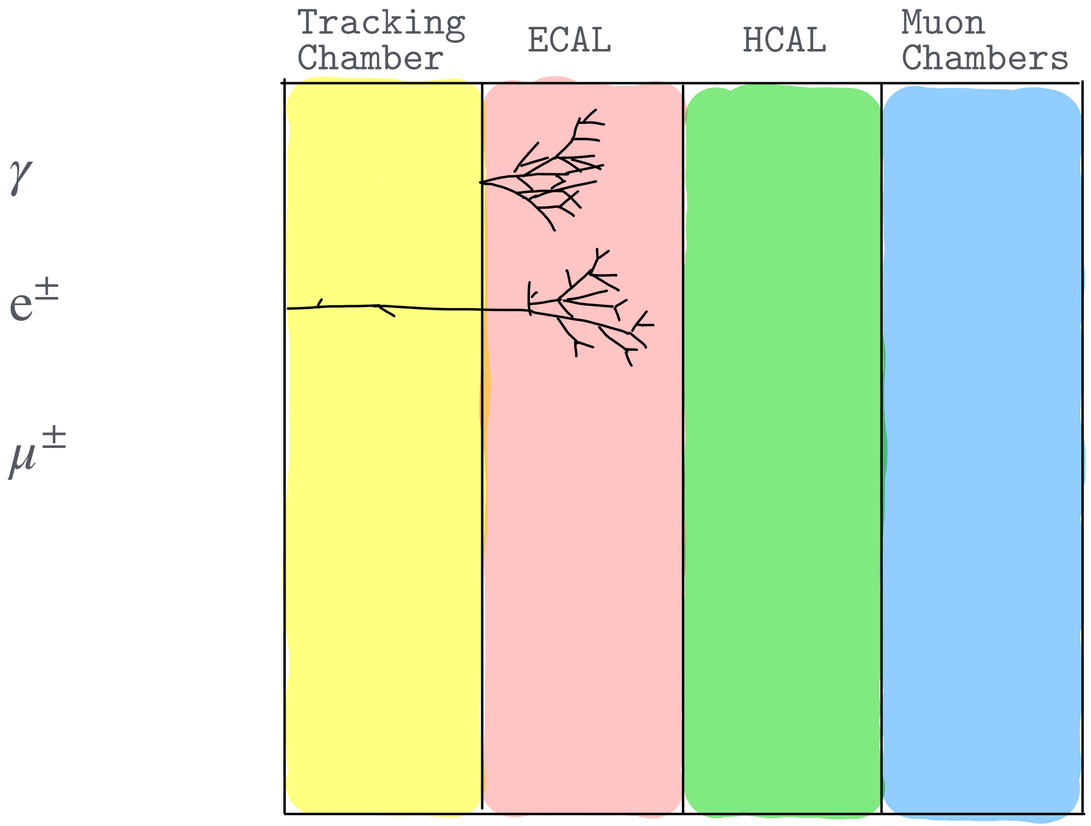

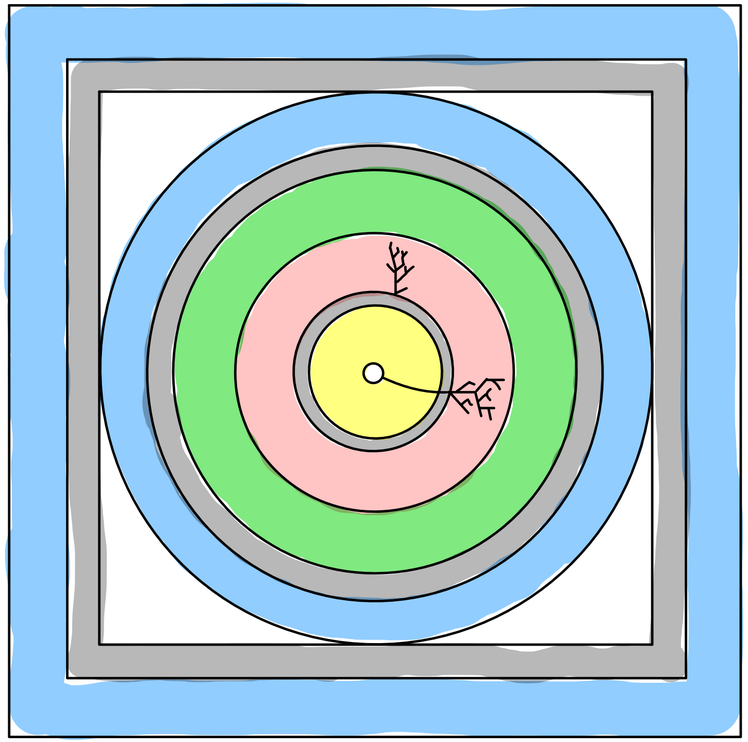

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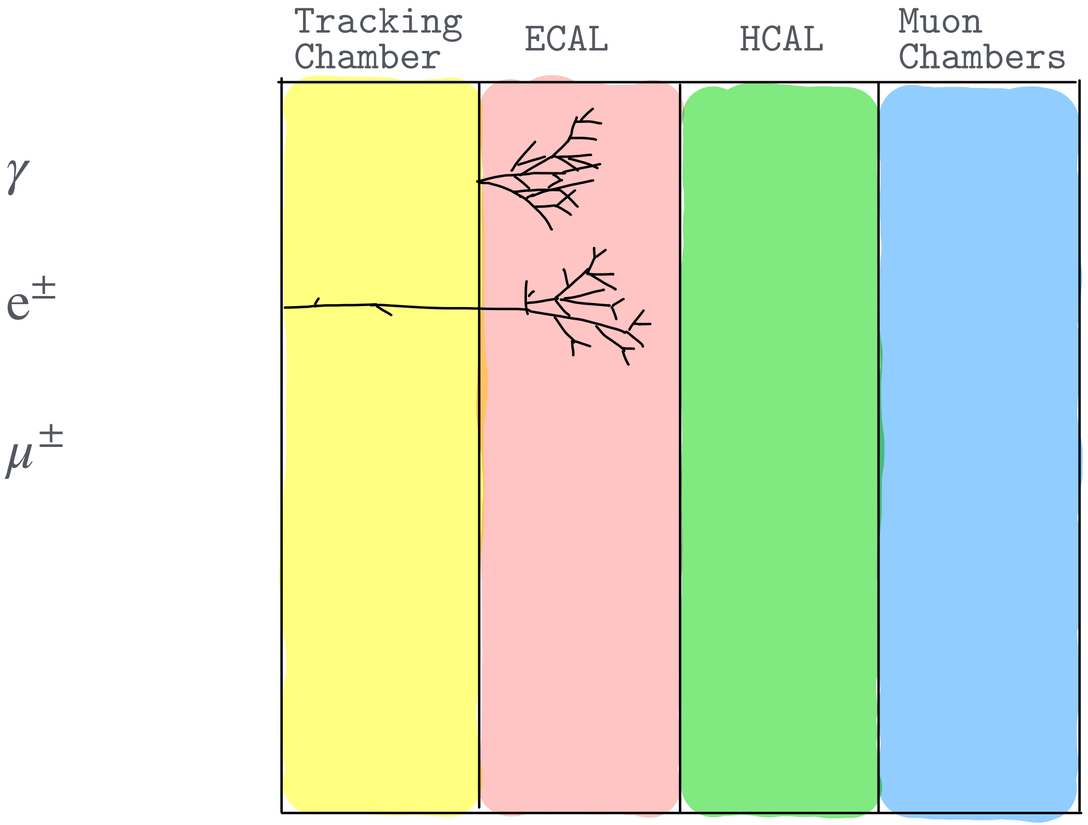

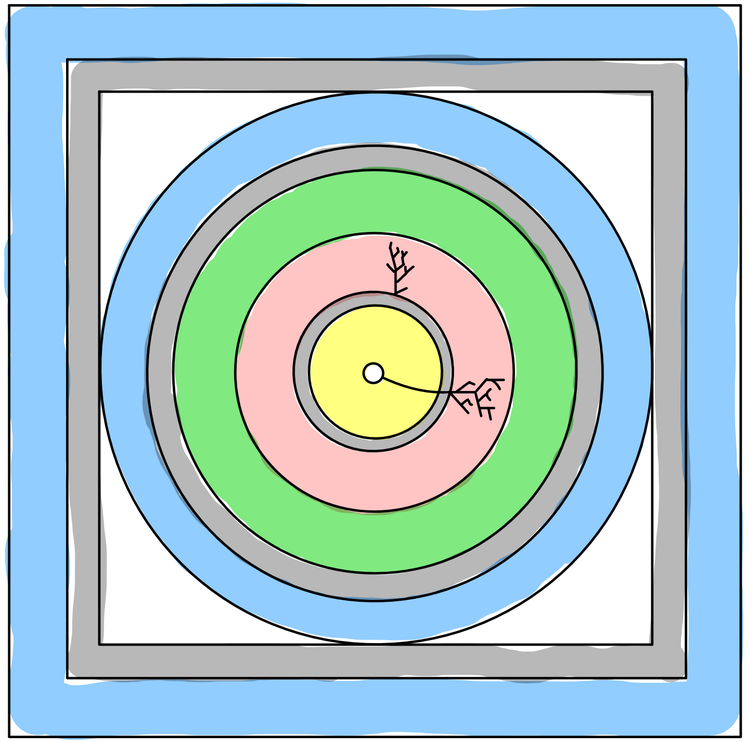

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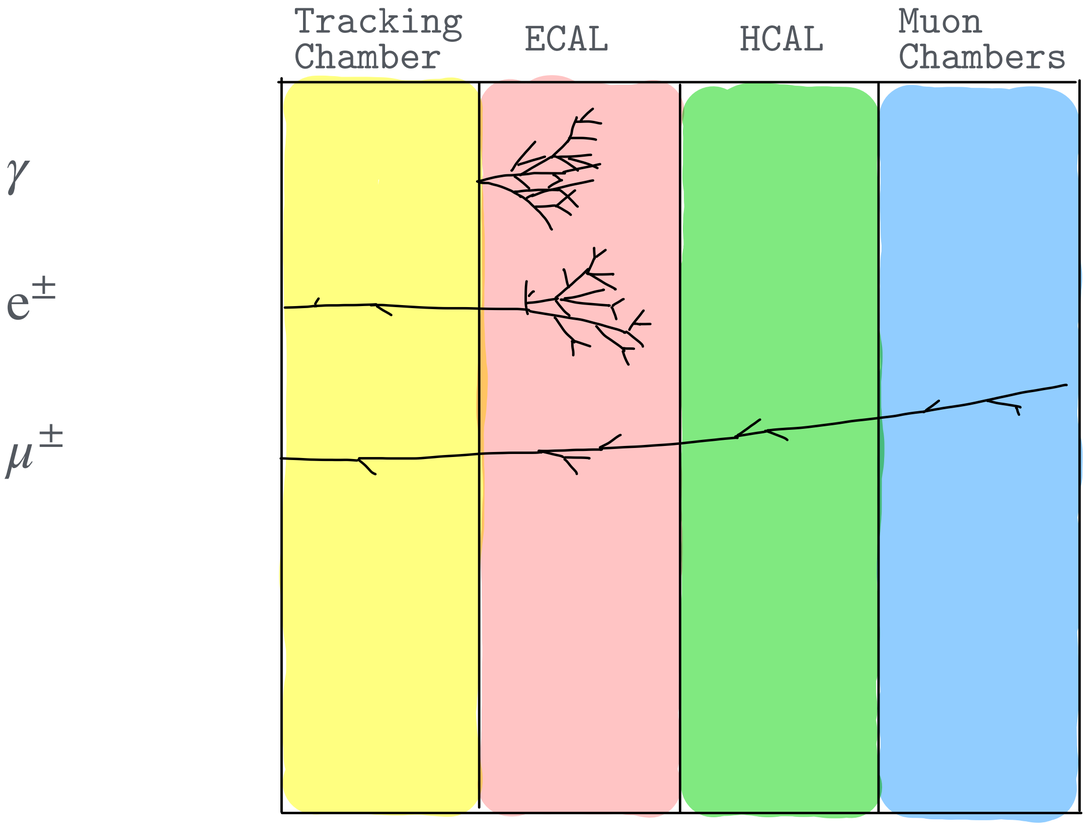

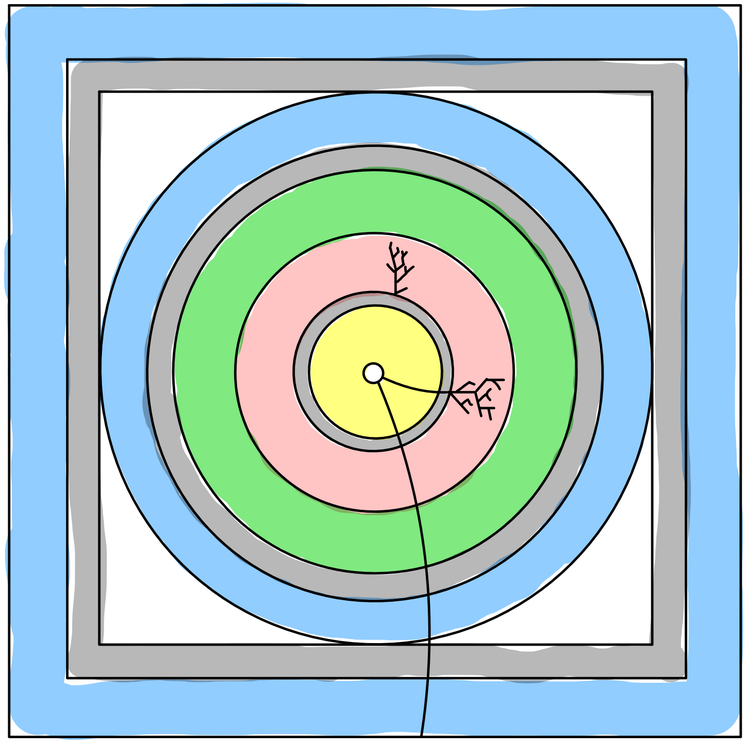

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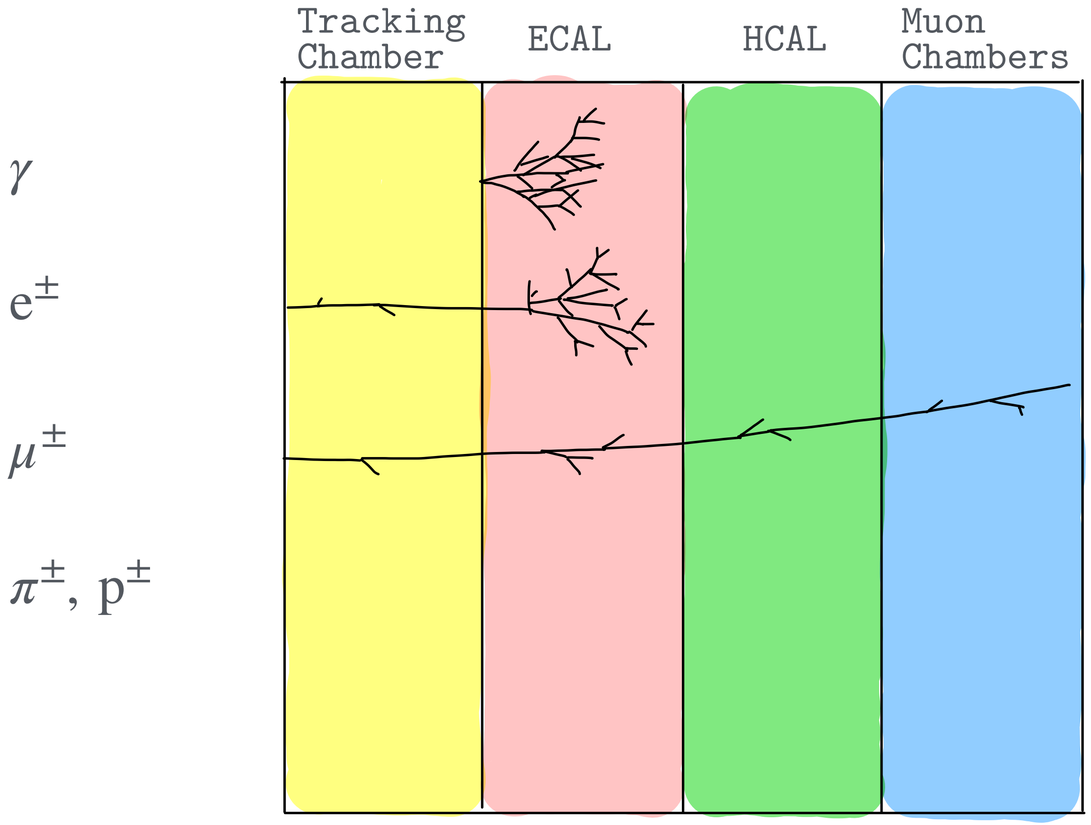

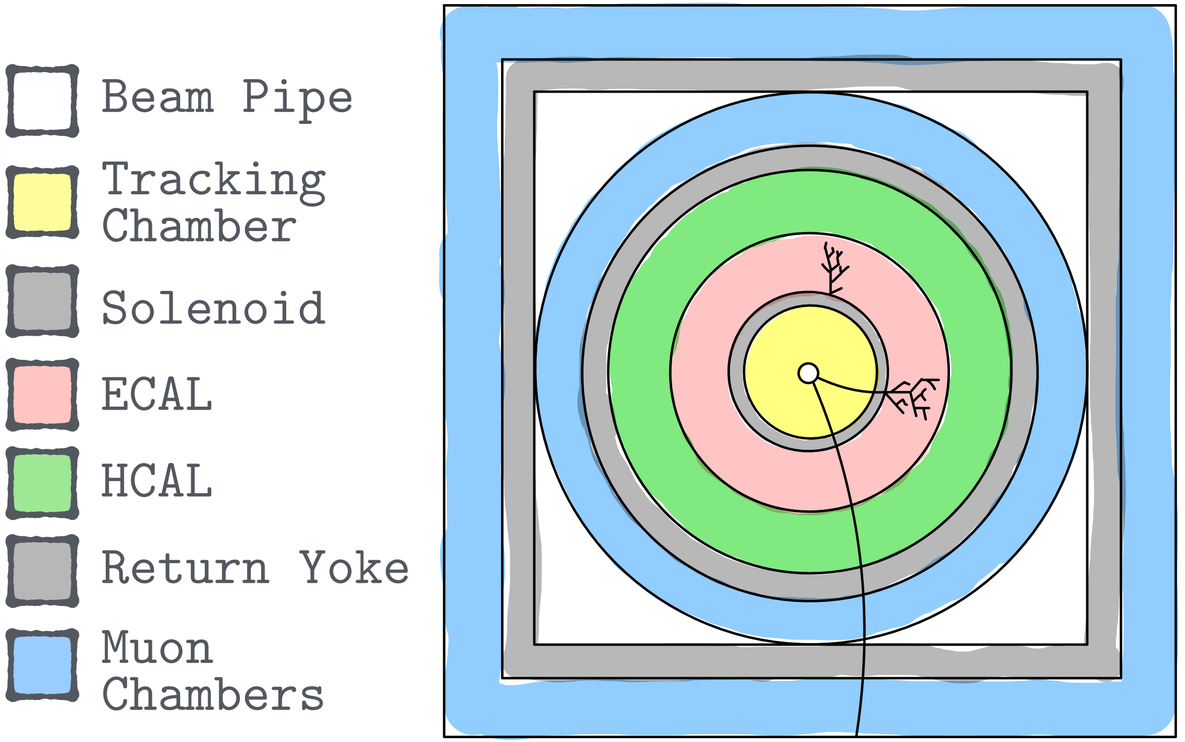

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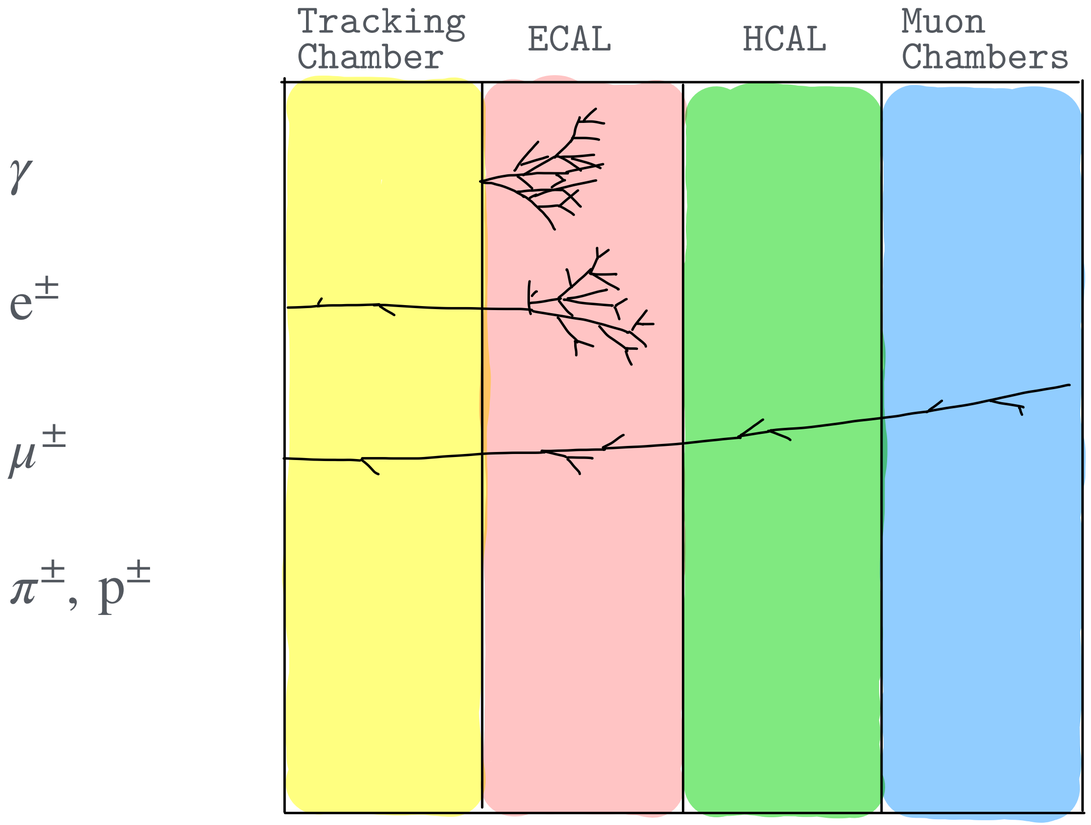
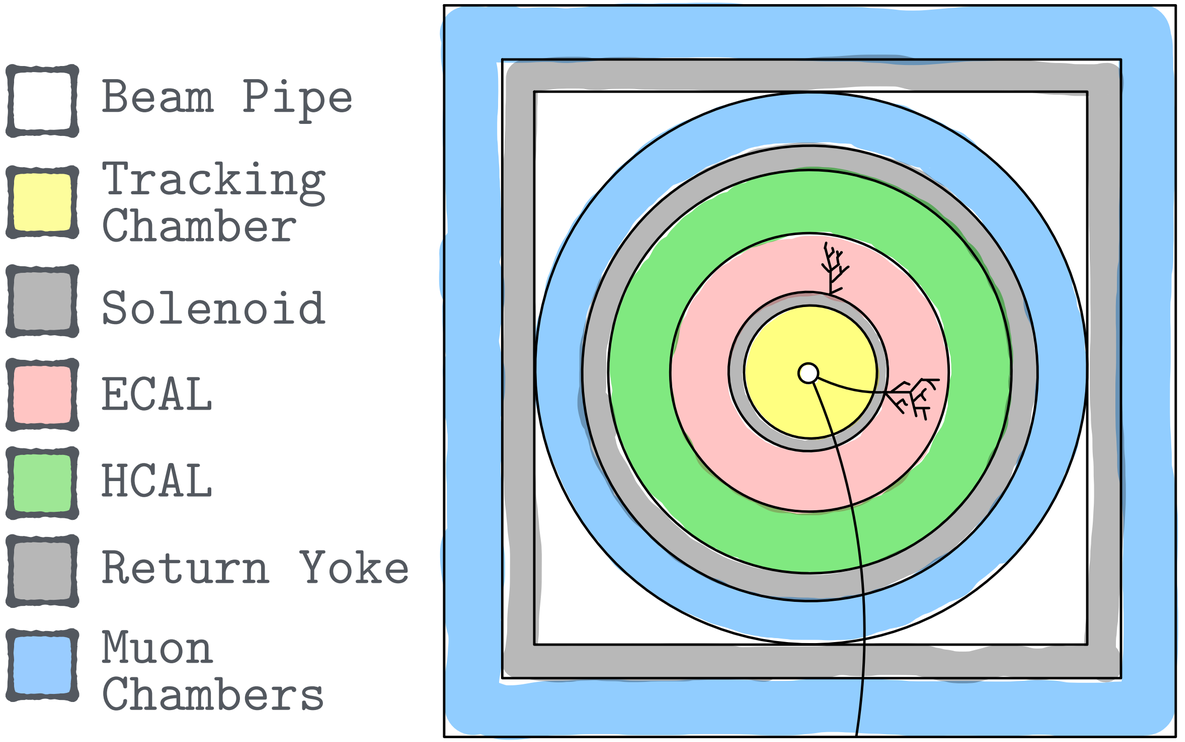
- Charged Hadrons





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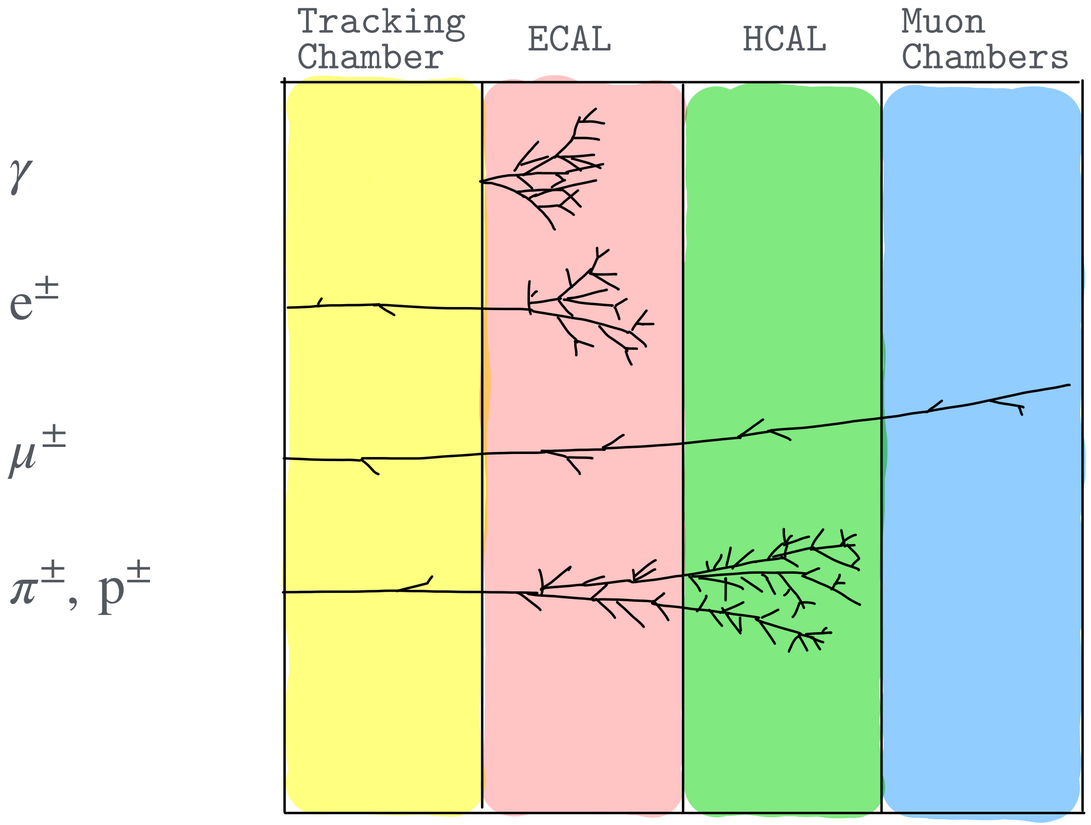
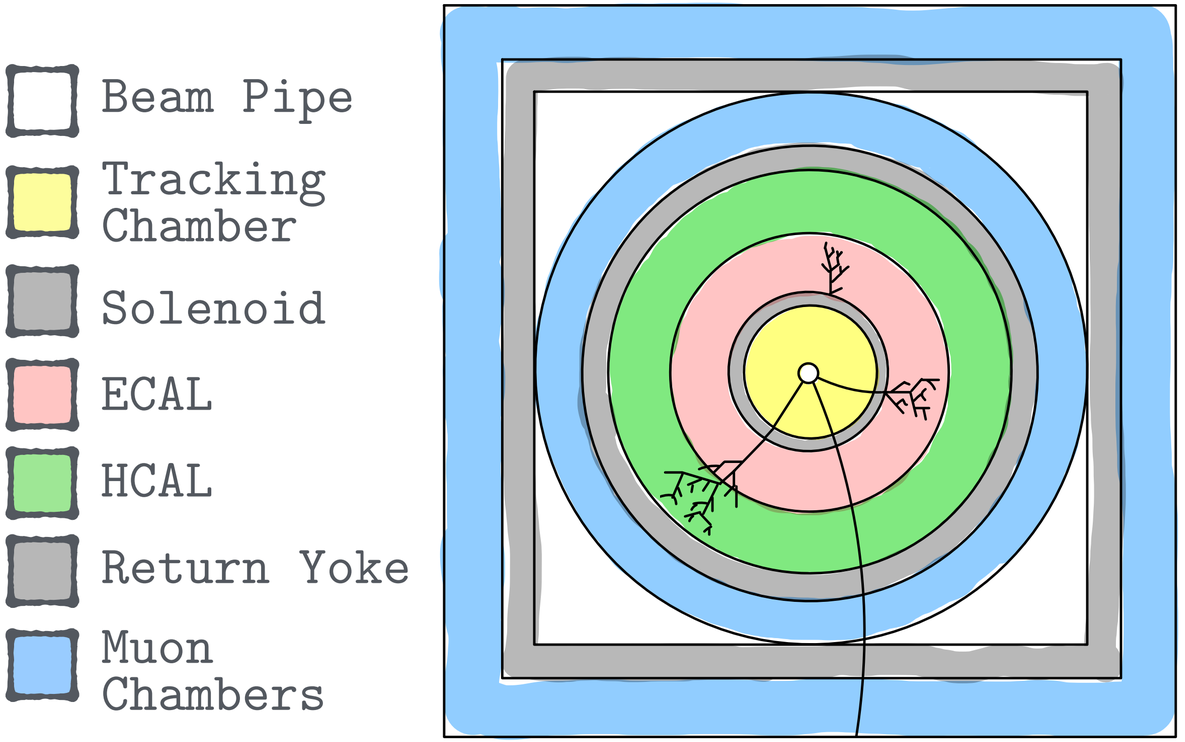
- Charged Hadrons
  - Deposit all energy in ECAL+HCAL; matched to track





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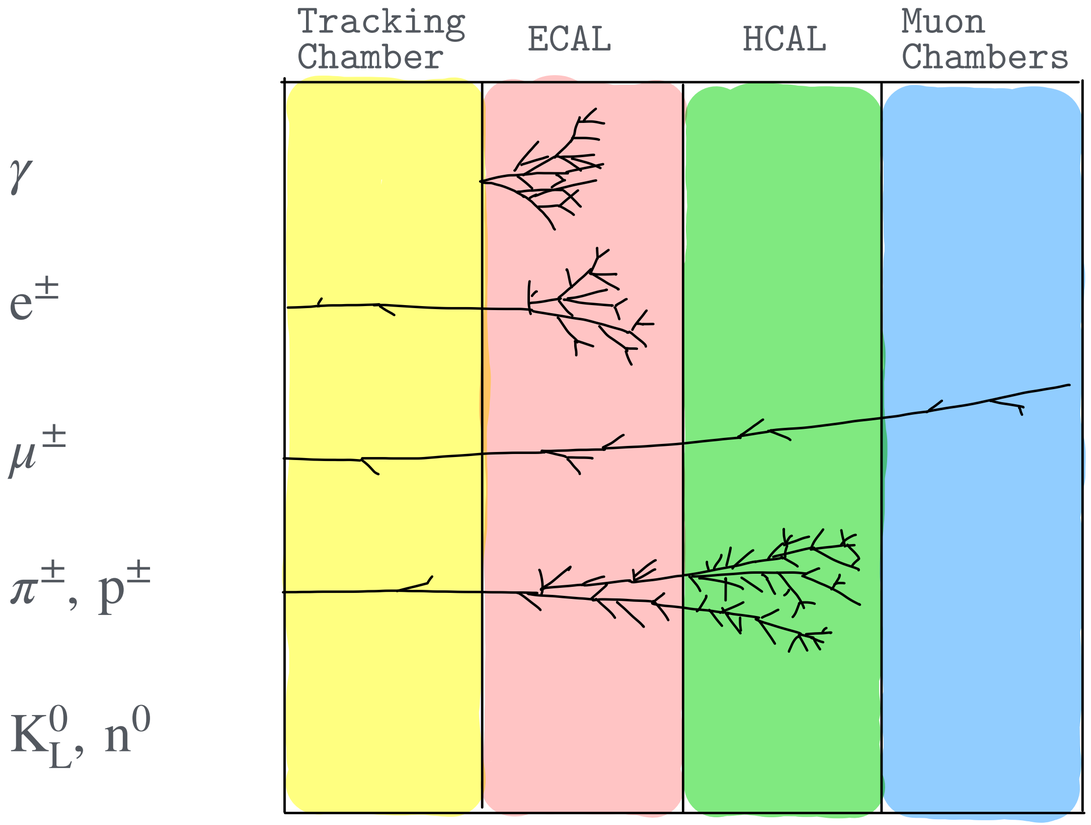

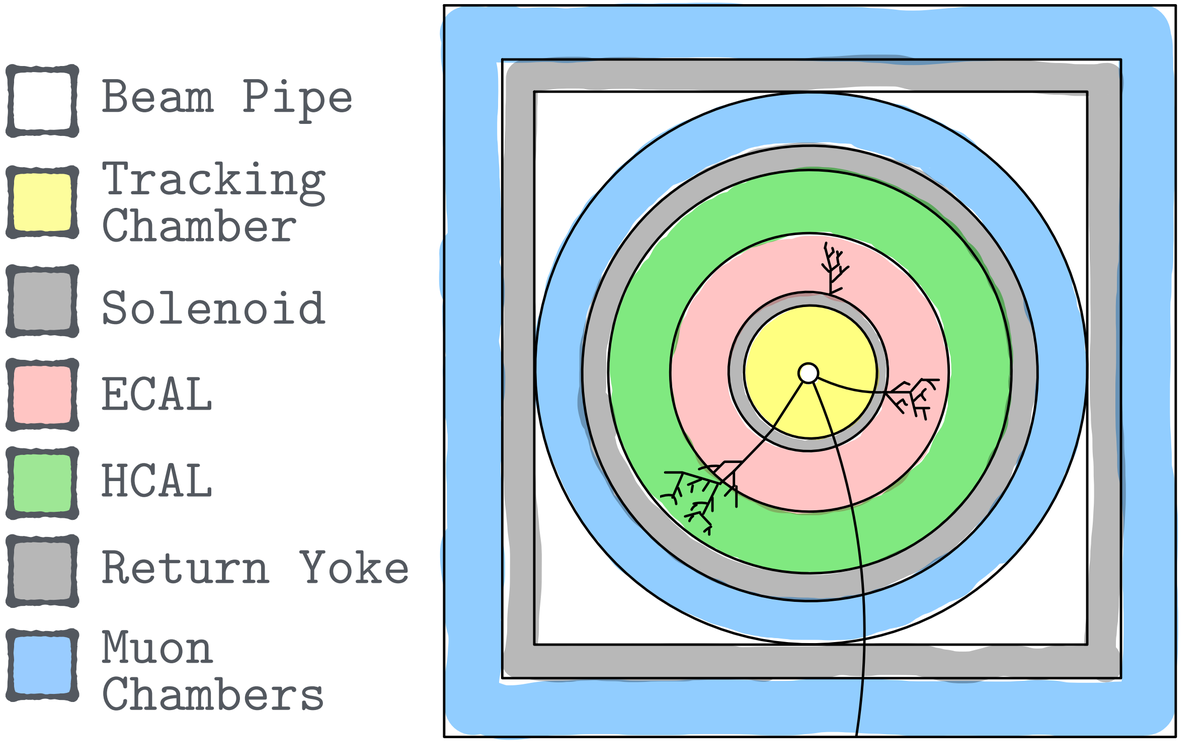

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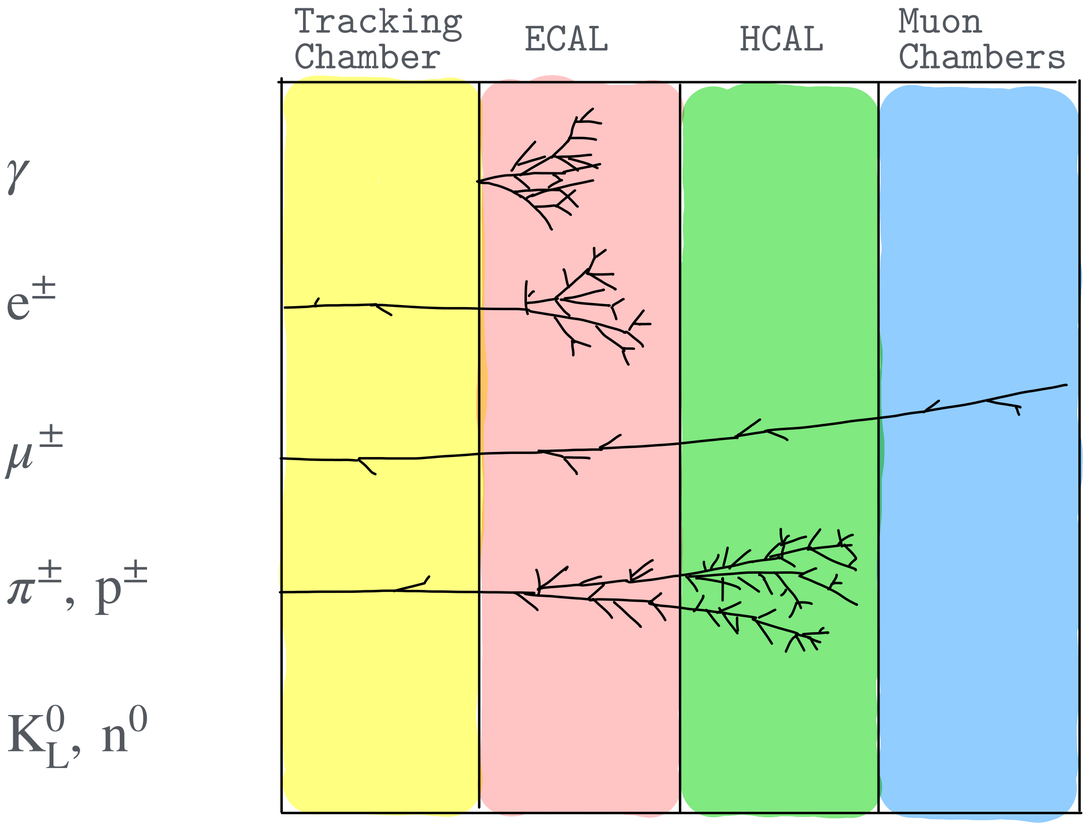
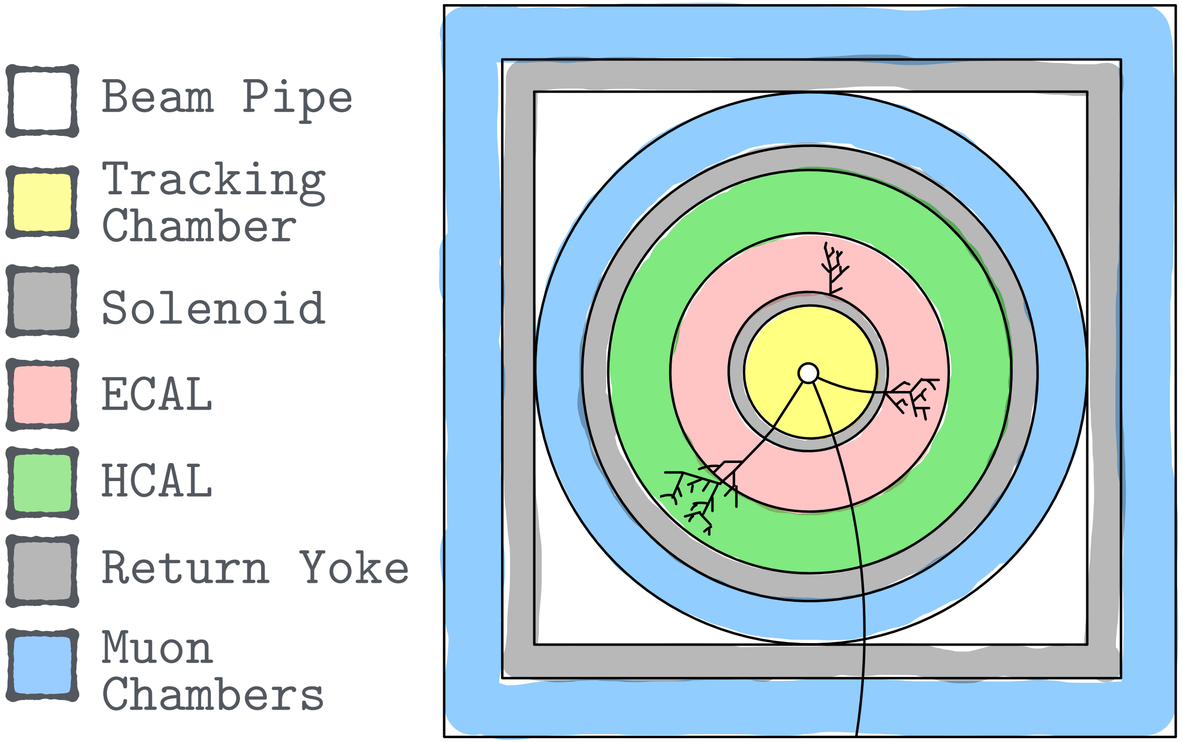
- Charged Hadrons
  - Deposit all energy in ECAL+HCAL; matched to track
- Neutral Hadrons





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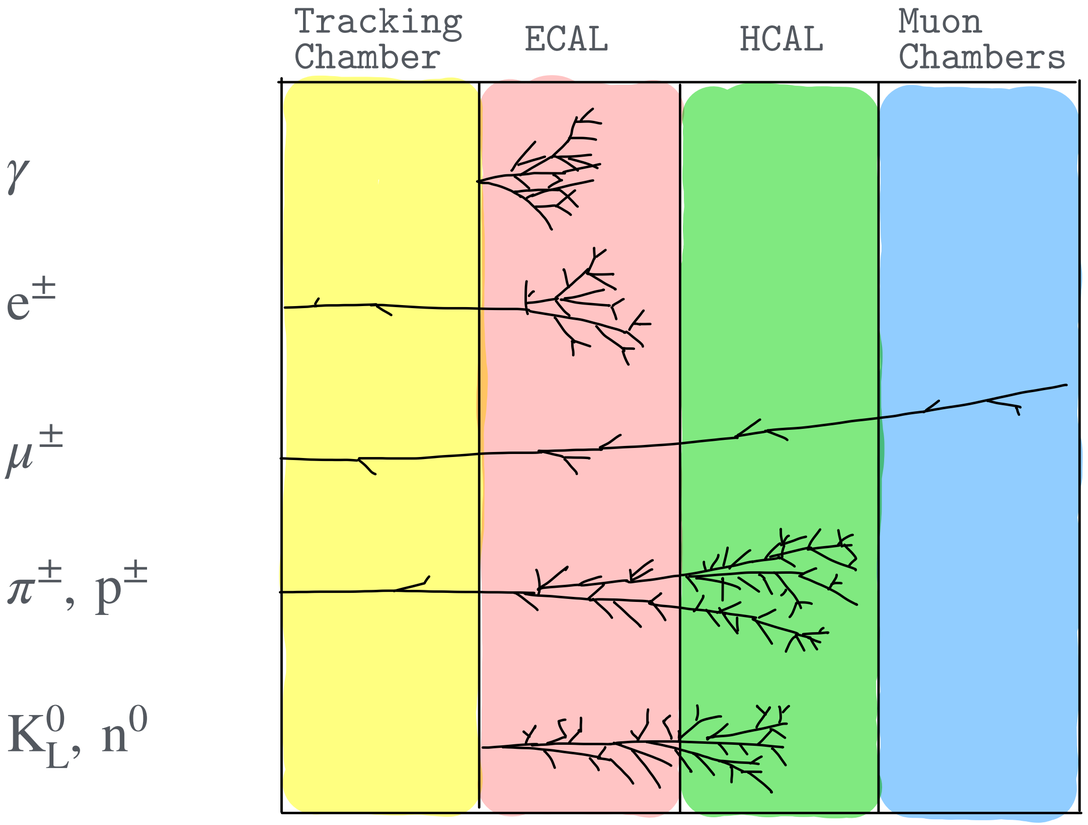

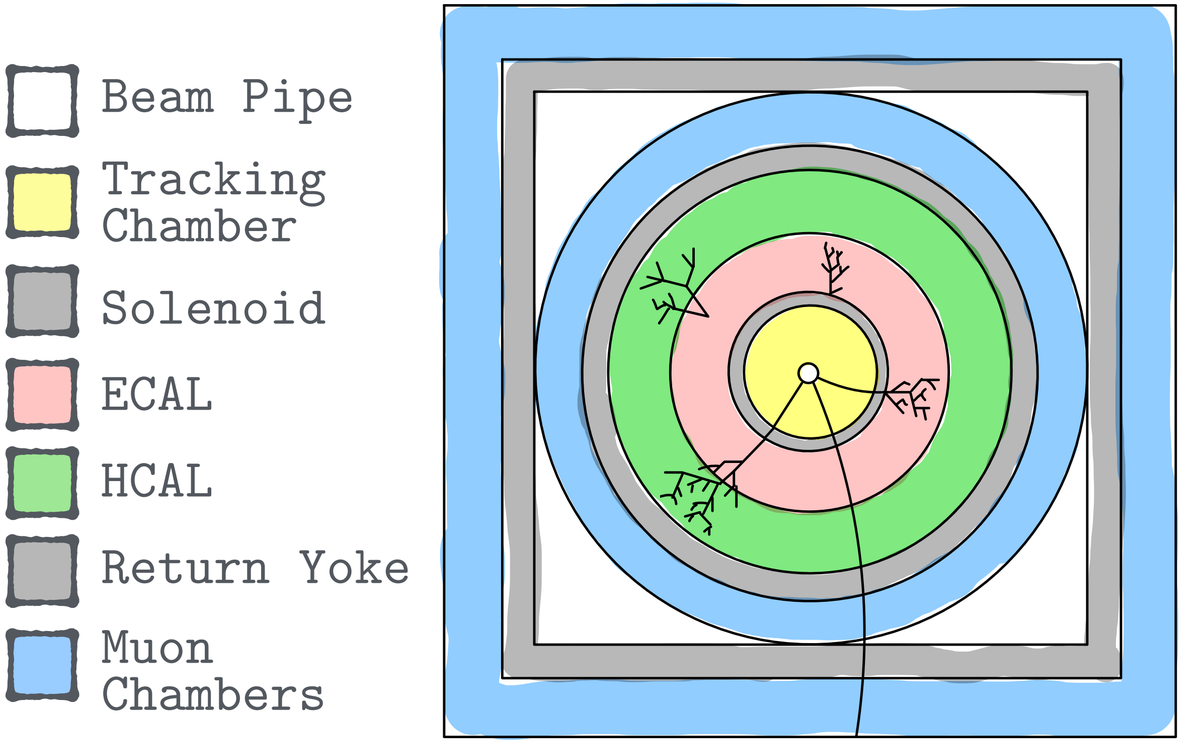

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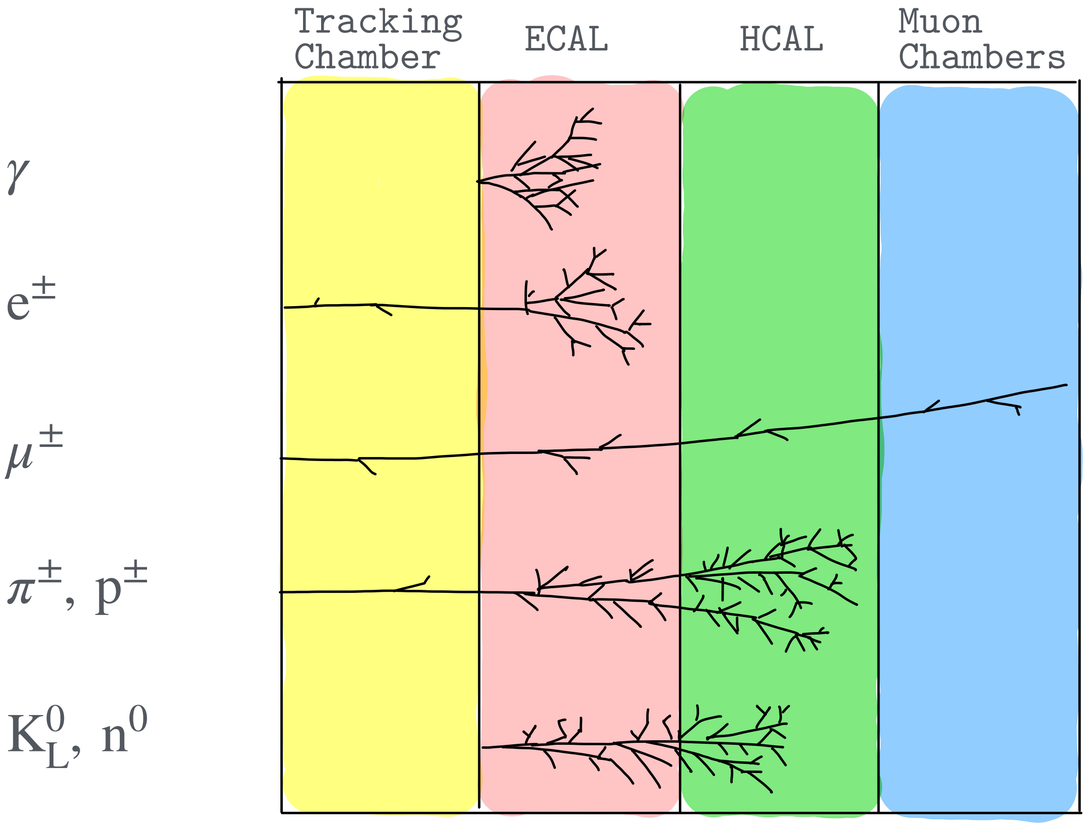

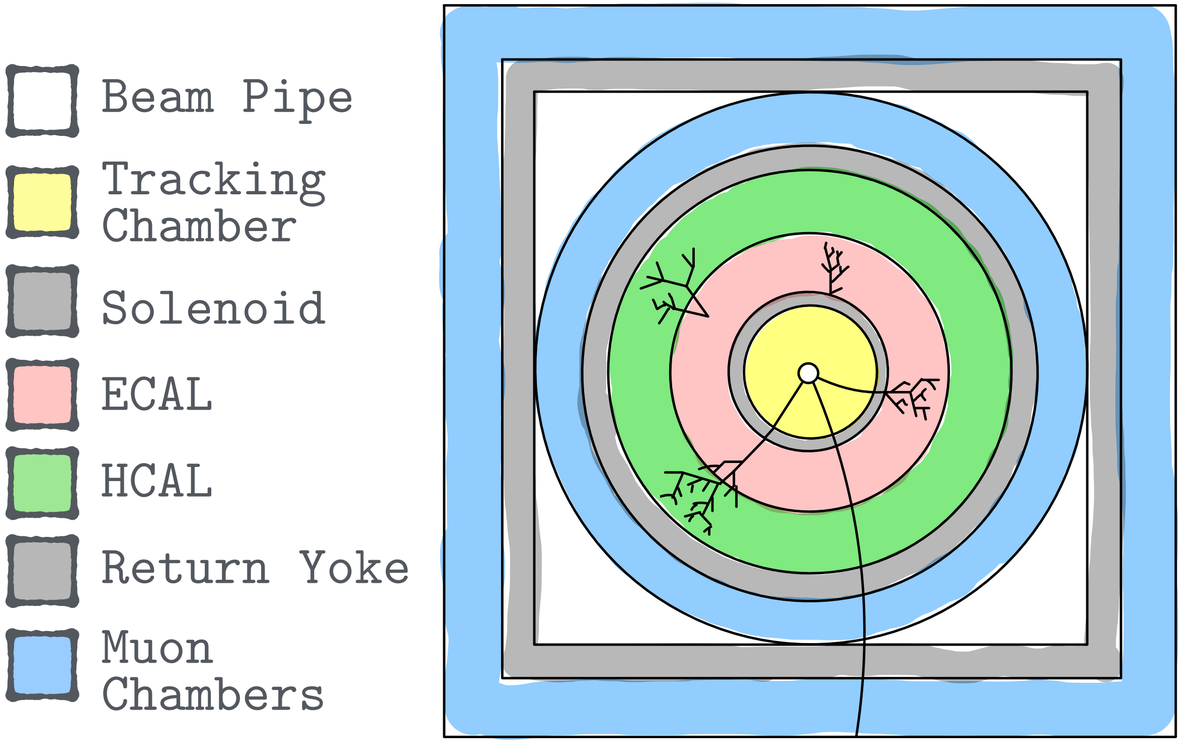

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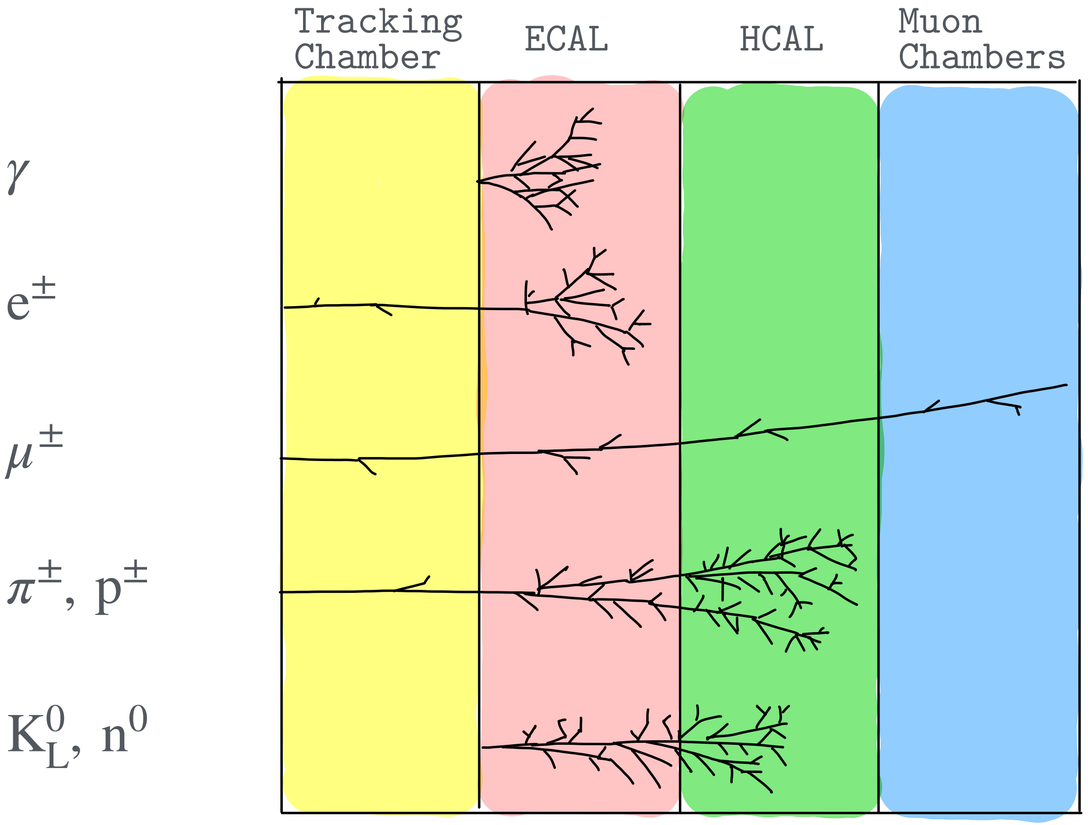
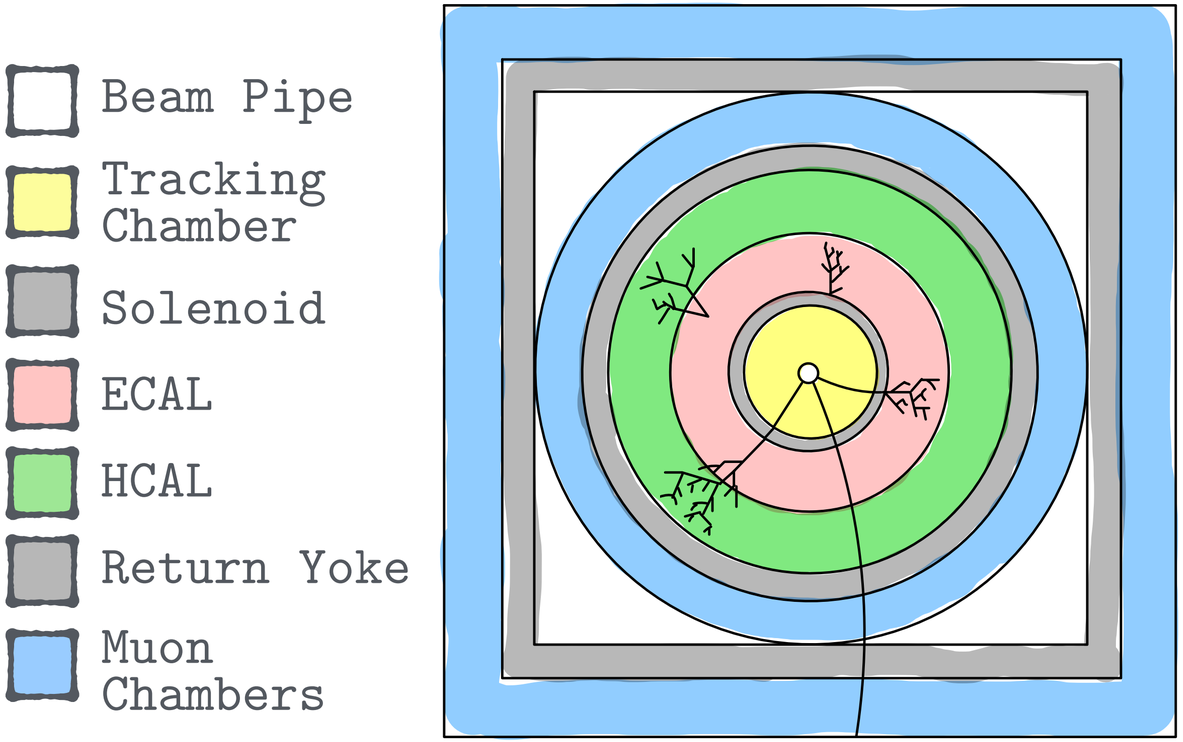
- Charged Hadrons
  - Deposit all energy in ECAL+HCAL; matched to track
- Neutral Hadrons
  - Similar to Charged Hadrons; but no track
- Neutrinos





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- Charged Hadrons
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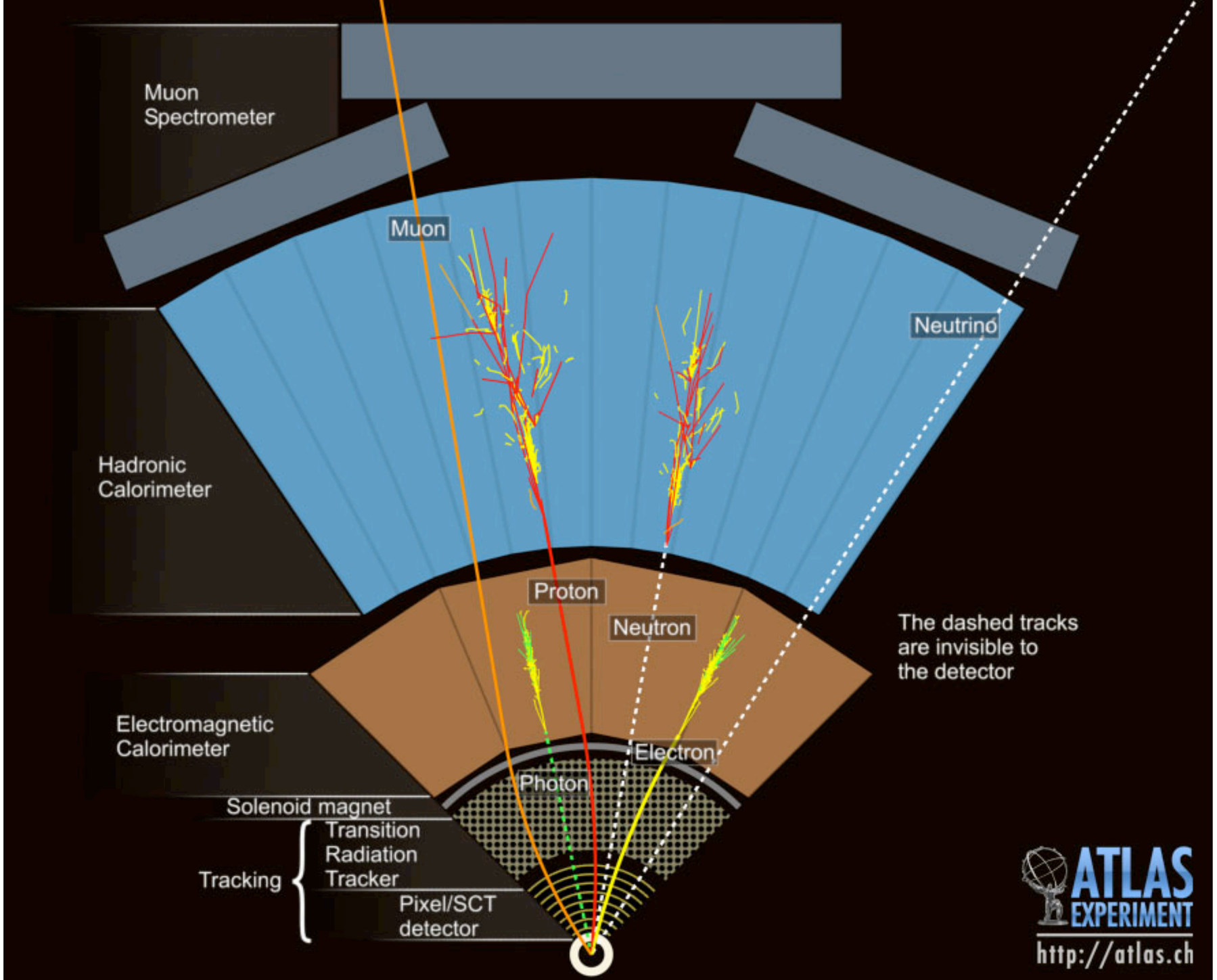
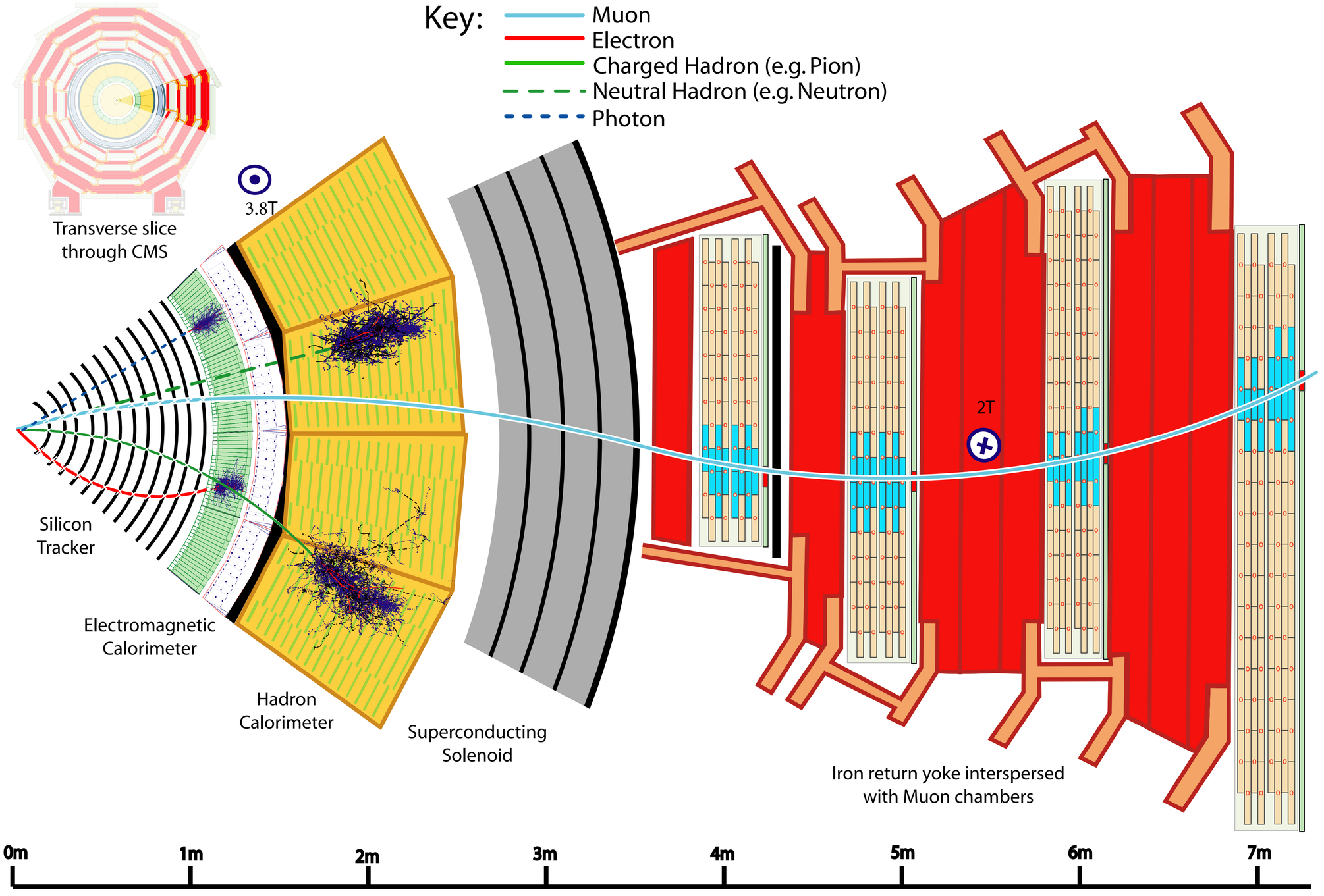
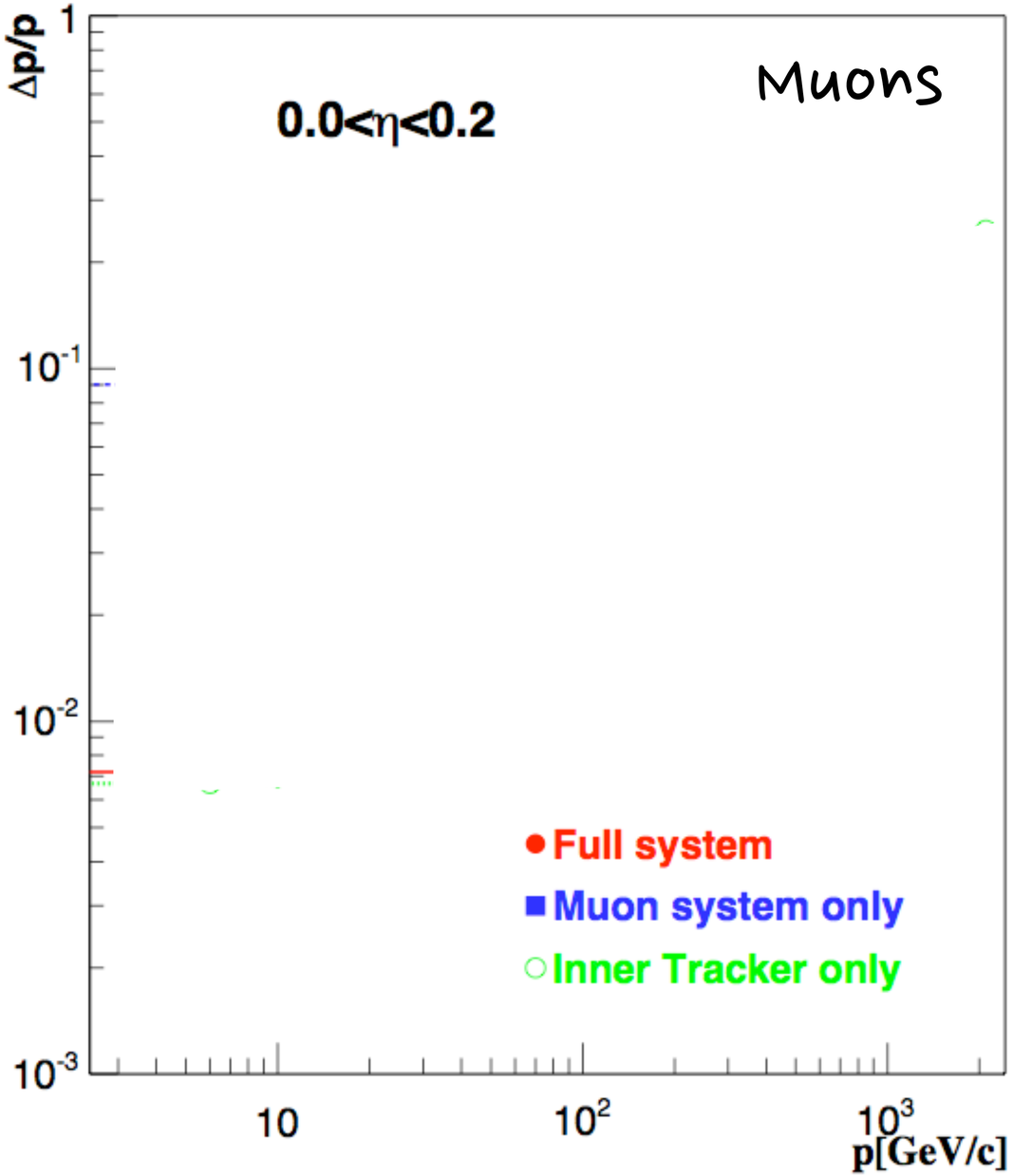
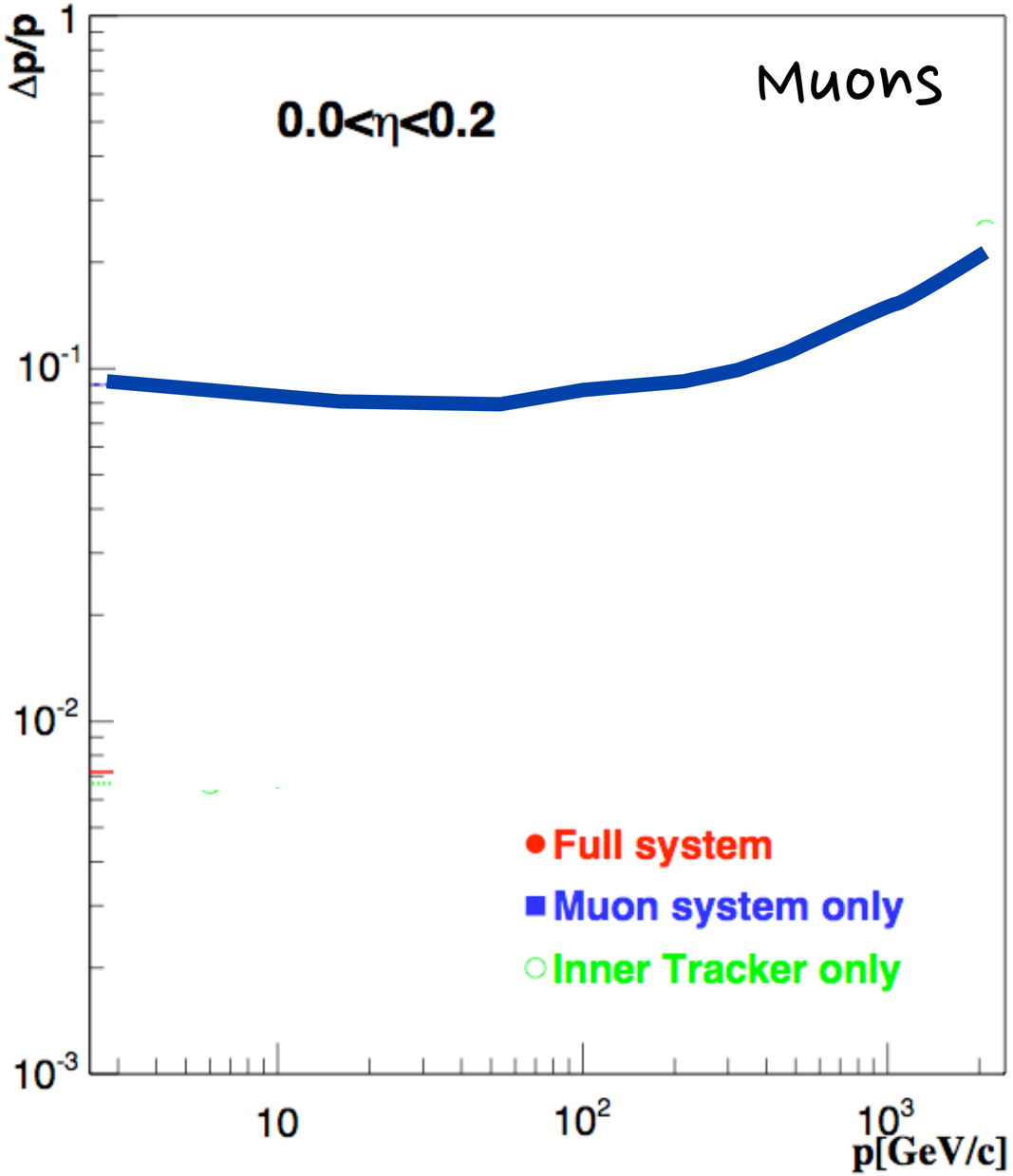
- Neutral Hadrons
  - Similar to Charged Hadrons; but no track
- Neutrinos
  - Pass through all material; measured indirectly by momentum imbalance


Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch




Muons
0.0<η<0.2
Δp/p
1
10^{-1}
10^{-2}
10^{-3}
10
10^{2}
10^{3}
p[GeV/c]
Full system
Muon system only
Inner Tracker only


Δp/p
1
Muons
0.0<η<0.2
10^-1
10^-2
10^-3
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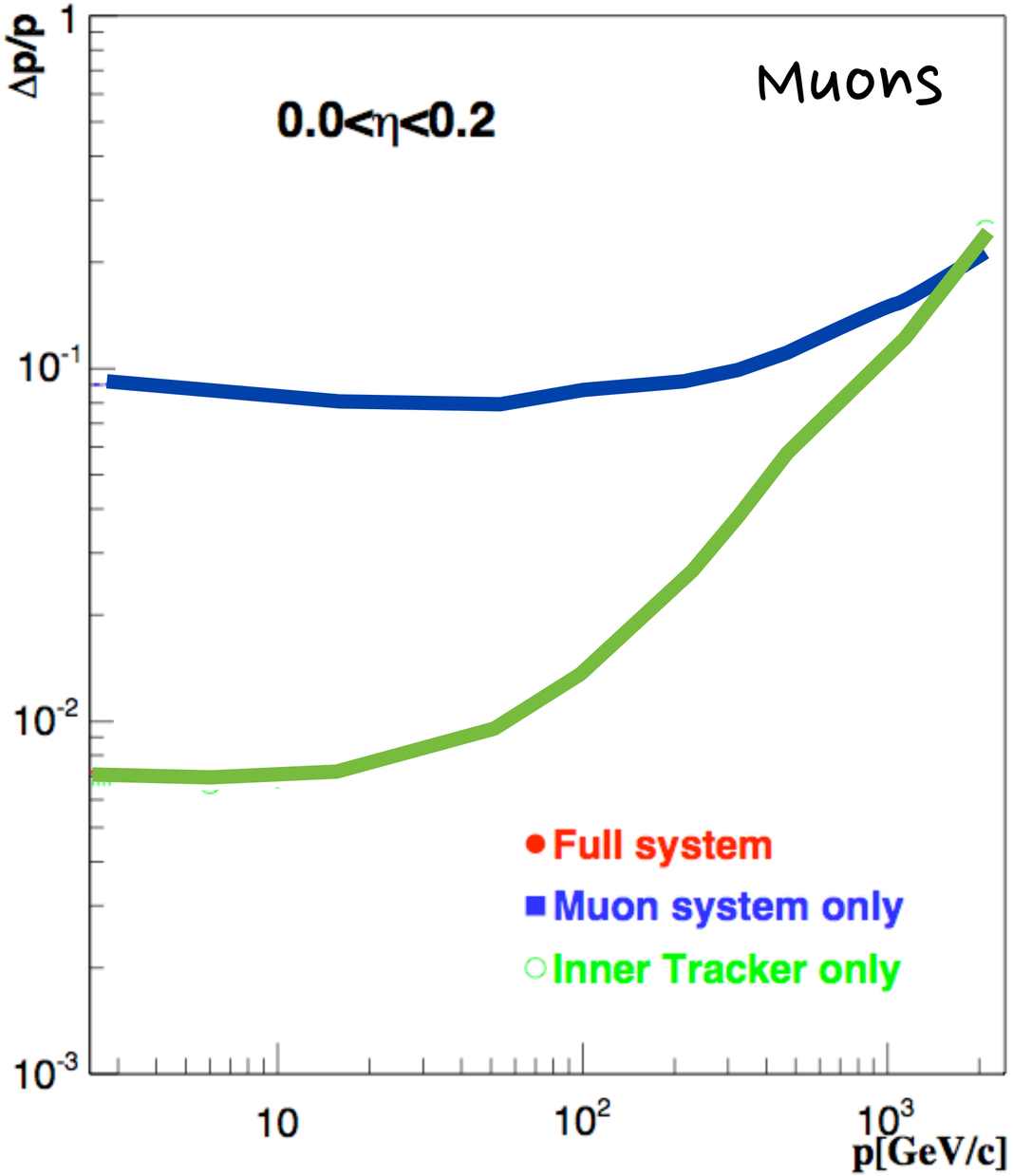
10
10^2
10^3
p[GeV/c]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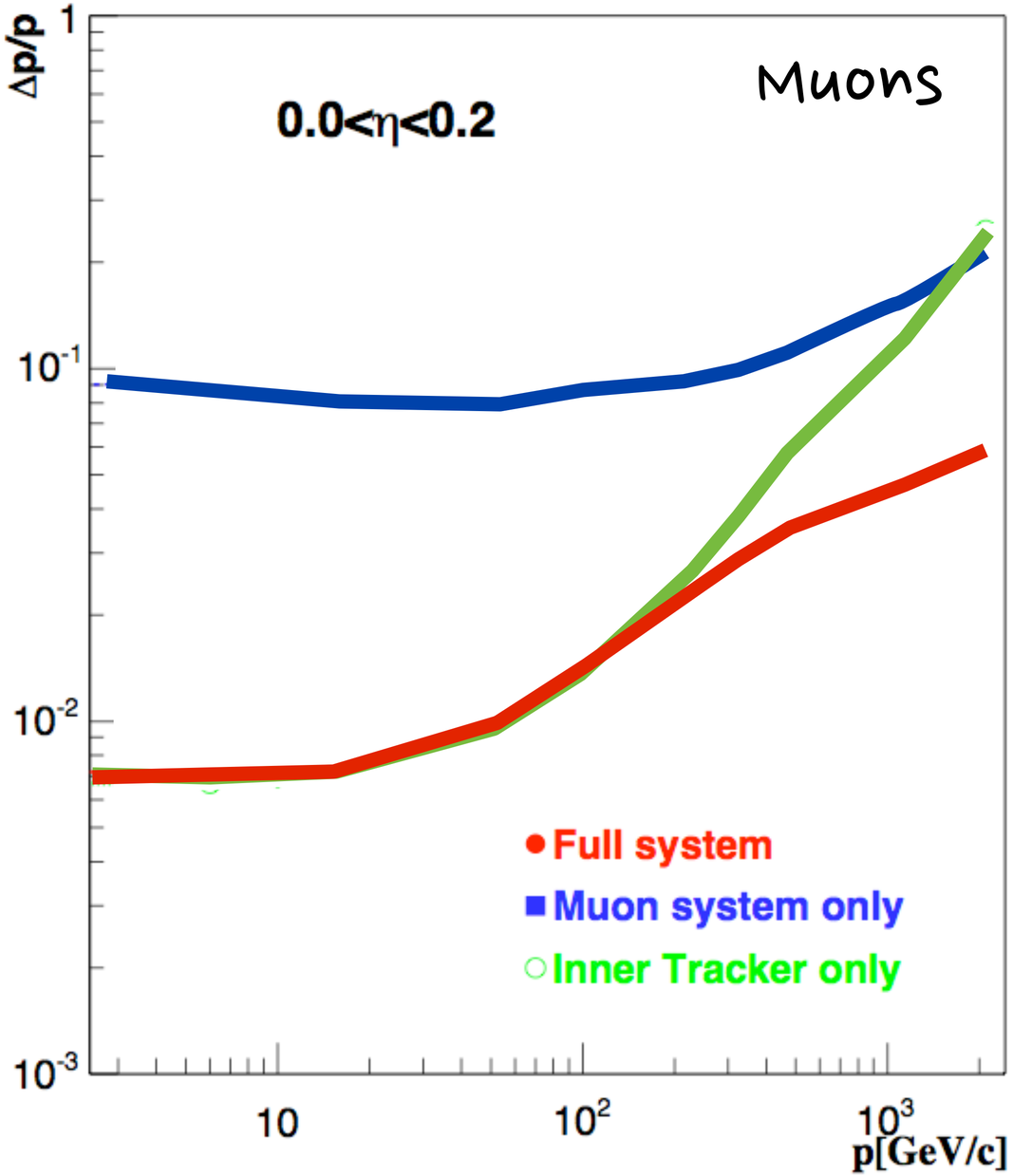
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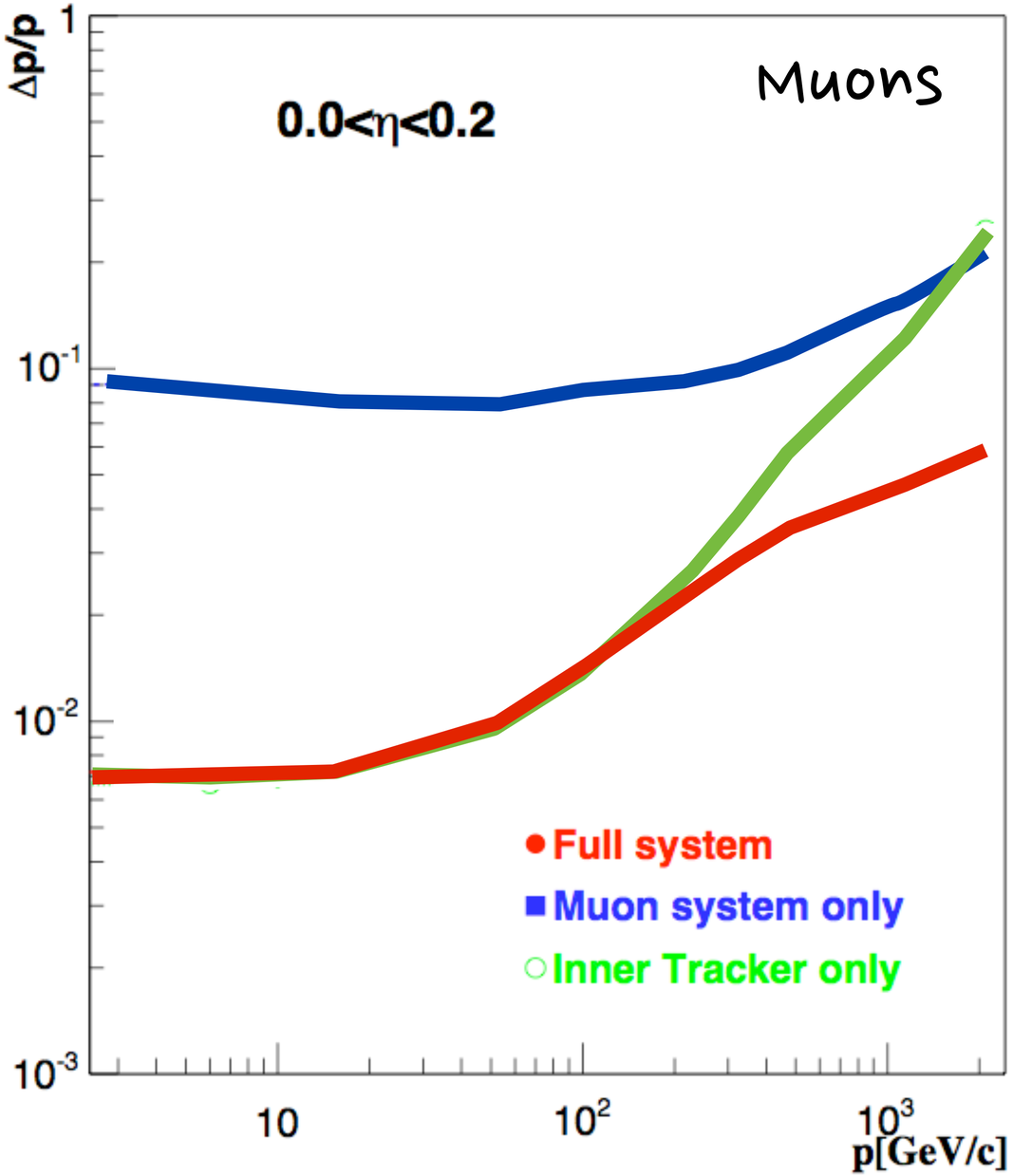
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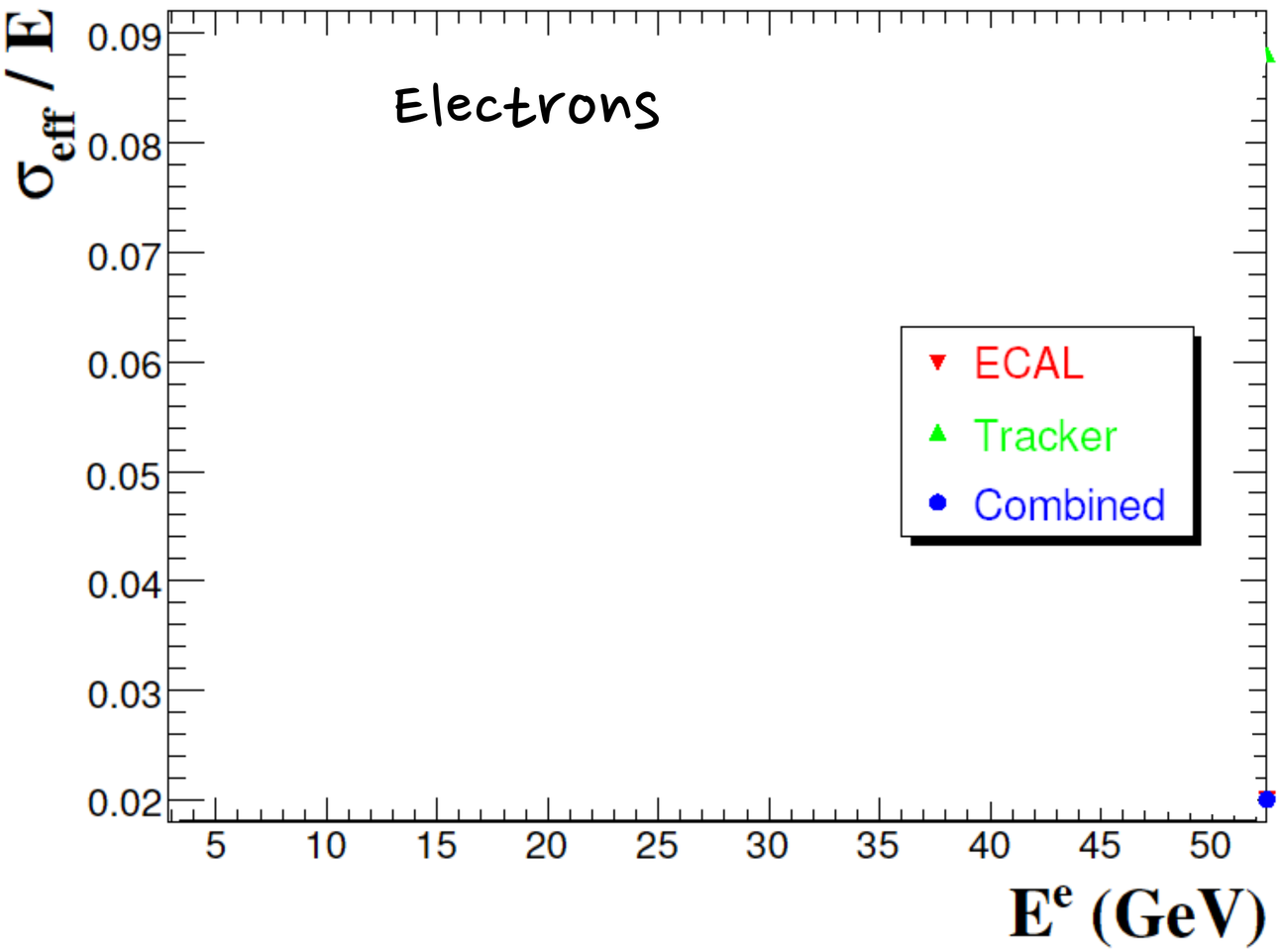
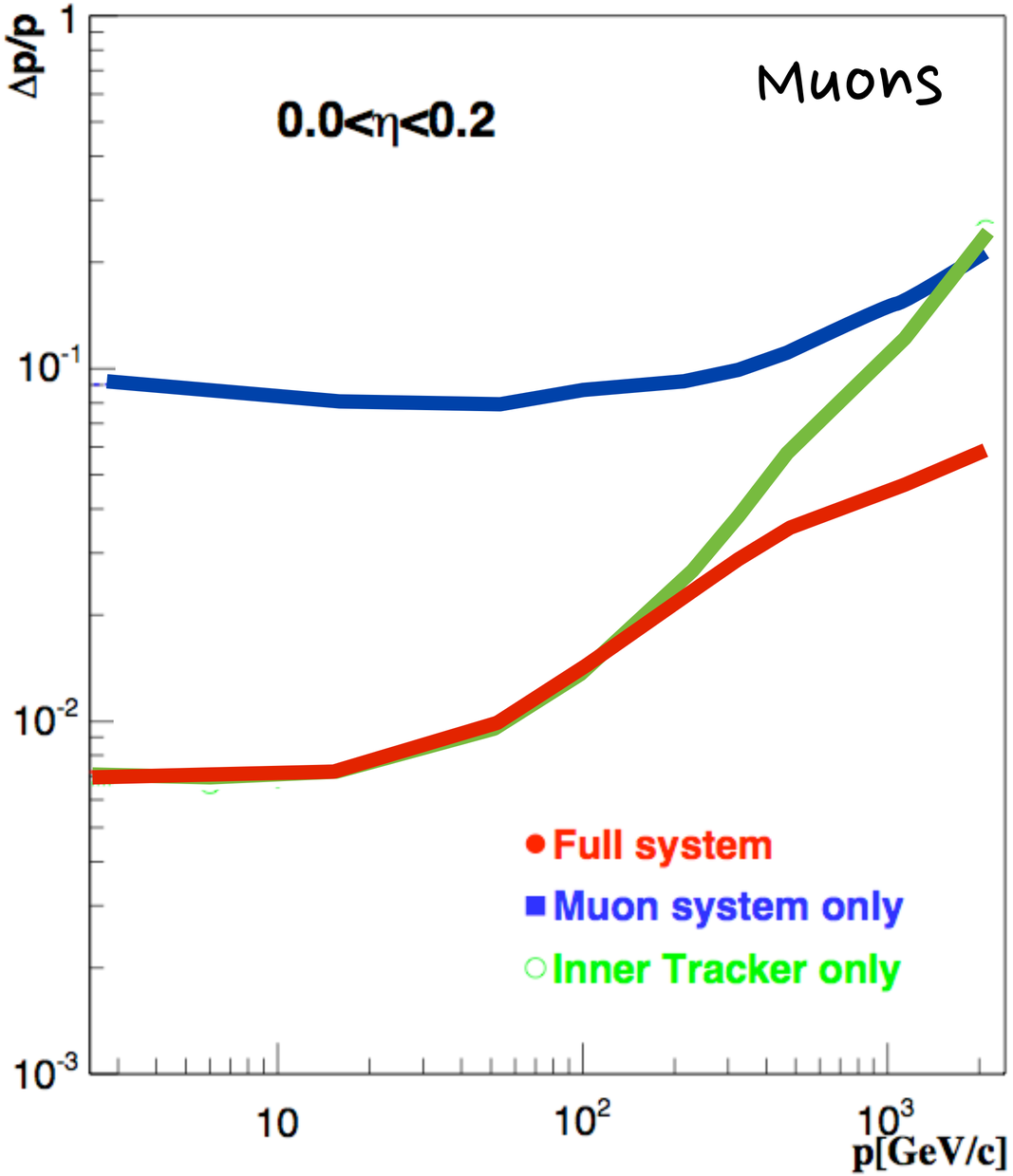

Electrons
σ_{eff} / E
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
5
10
15
20
25
30
35
40
45
50
E^e (GeV)
ECAL
Tracker
Combined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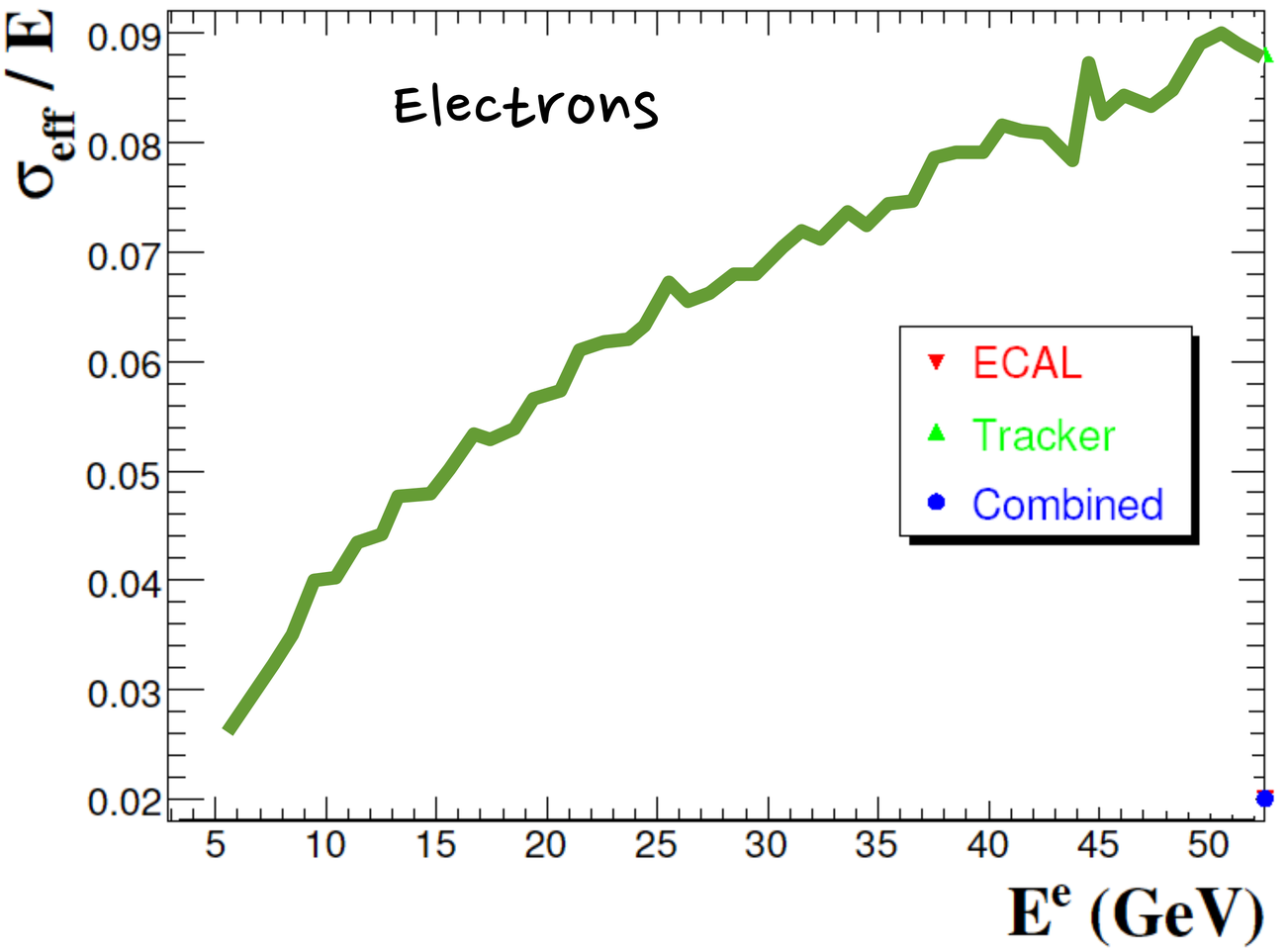
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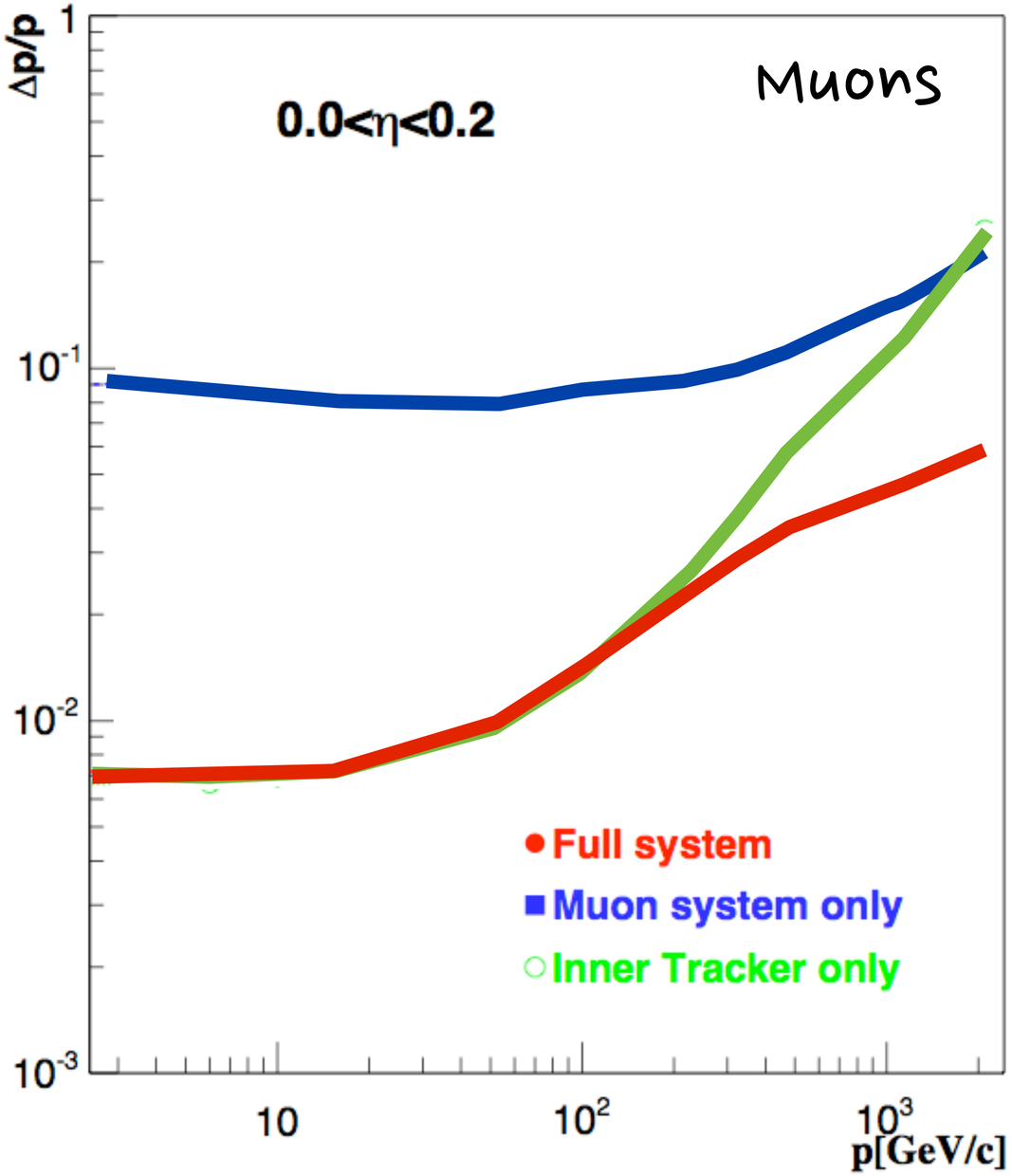
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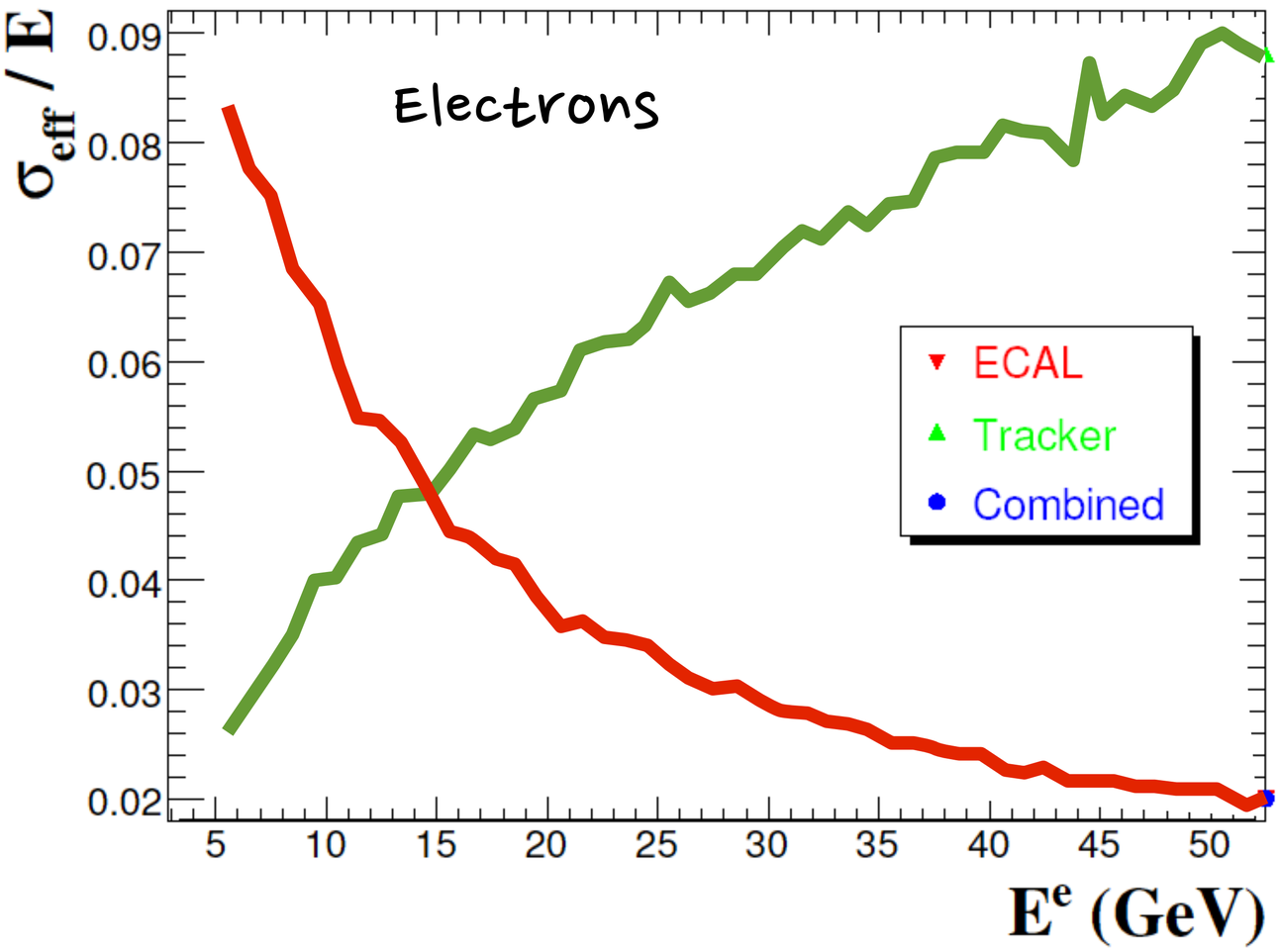
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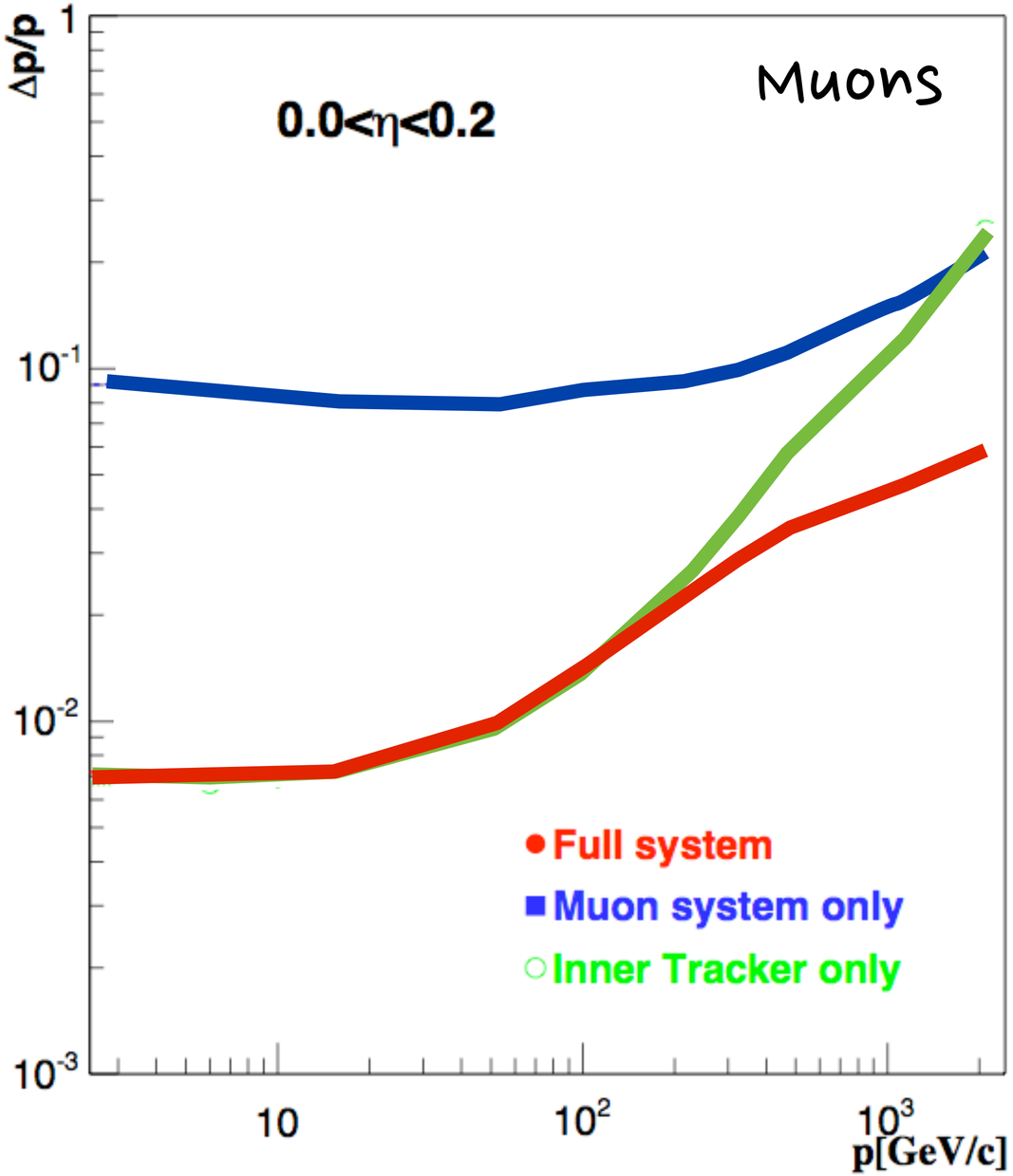
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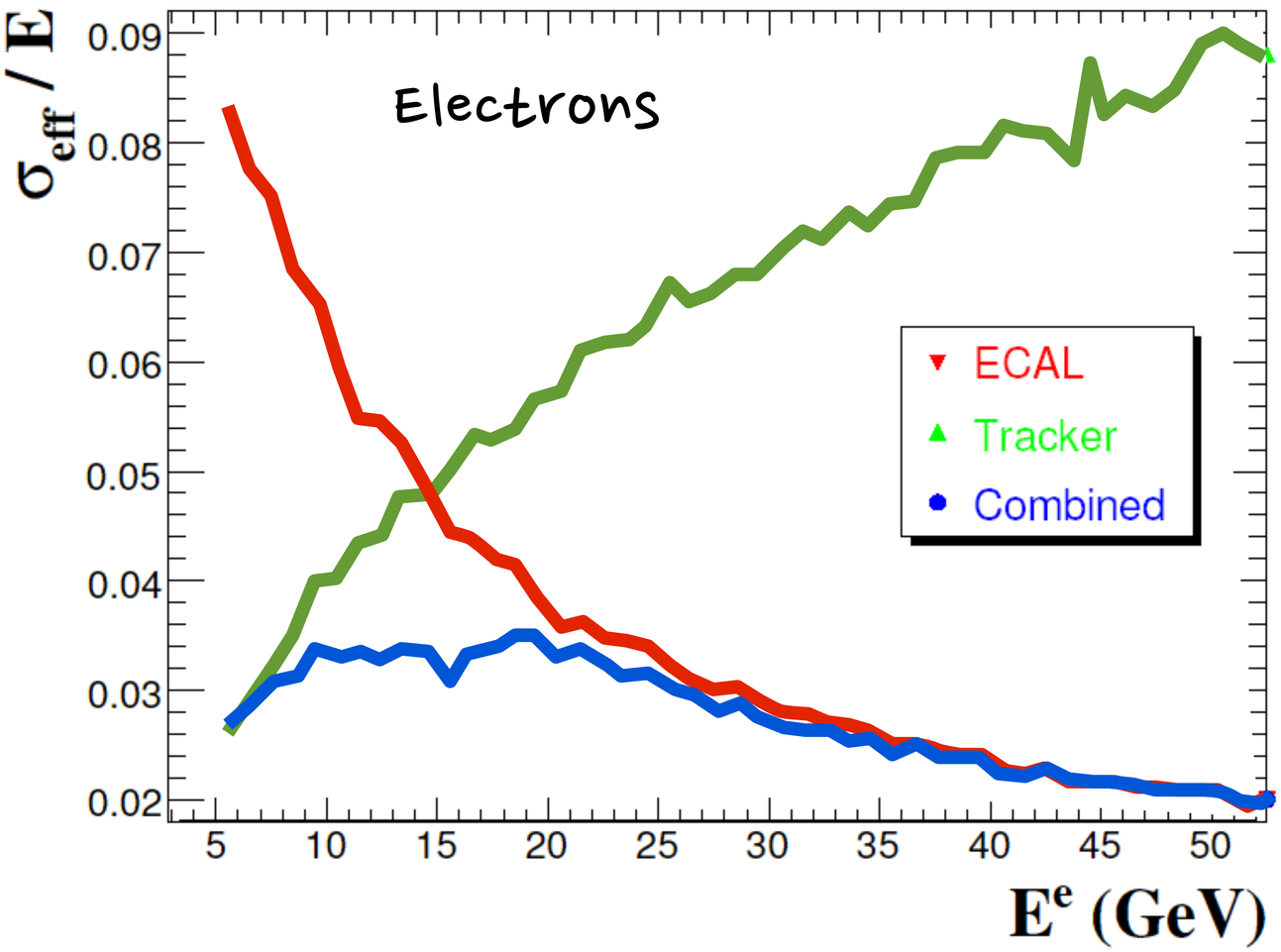
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E^e (GeV)
ECAL
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Combined

Back of envelope estimation for pions

Back of envelope estimation for pions

Calorimeter transverse energy uncertainty for charged hadrons

Back of envelope estimation for pions

Calorimeter transverse energy uncertainty for charged hadrons

$$\sigma(E_{\mathrm{T}}) \approx 100\% \sqrt{E_{\mathrm{T}}}$$

Back of envelope estimation for pions

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Tracker transverse momentum uncertainty for charged hadrons

Back of envelope estimation for pions

Calorimeter transverse energy uncertainty for charged hadrons

$$\sigma(E_{\mathrm{T}}) \approx 100\% \sqrt{E_{\mathrm{T}}}$$

Tracker transverse momentum uncertainty for charged hadrons

$$\sigma(p_{\mathrm{T}}) \approx 0.01\% (p_{\mathrm{T}})^2$$

Back of envelope estimation for pions

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The point at which the calorimeter resolution overcomes the tracker resolution is very roughly

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$$\frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}} \approx \frac{\sigma(E_{\mathrm{T}})}{E_{\mathrm{T}}} \rightarrow p_{\mathrm{T}} \approx 10^{\frac{8}{3}} \approx 460 \ \mathrm{G}eV$$

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Almost always pays to use the tracker p_T, rather than calorimeter E_T

Set the stage: Jet Composition

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- Charged Particles: ~60%

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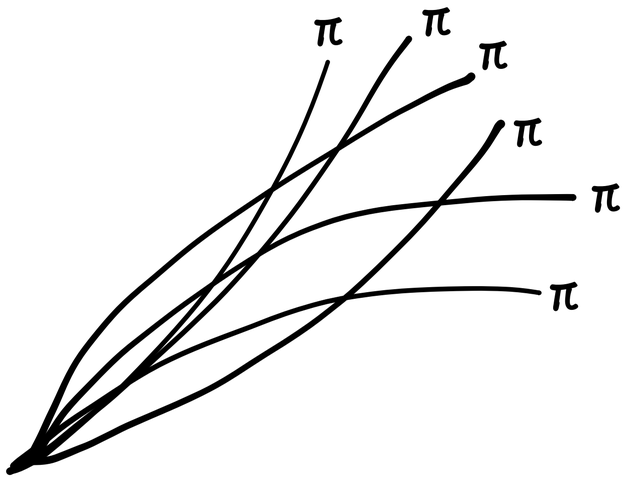
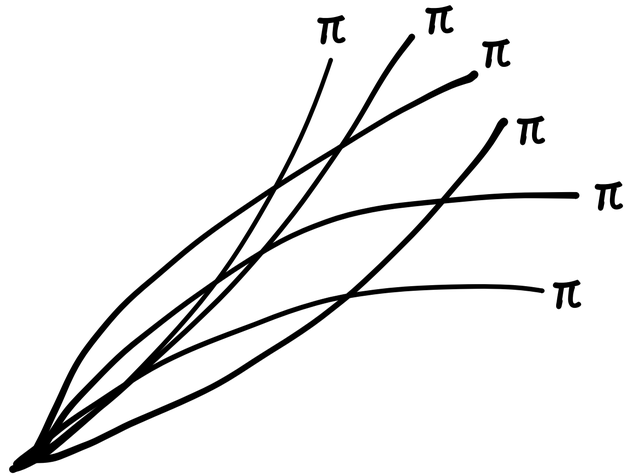


Set the stage: Jet Composition

- Charged Particles: ~60%
  - Mostly charged pions, kaons and protons, but also some electrons and muons (decays in flight, semileptonic B decays, etc)



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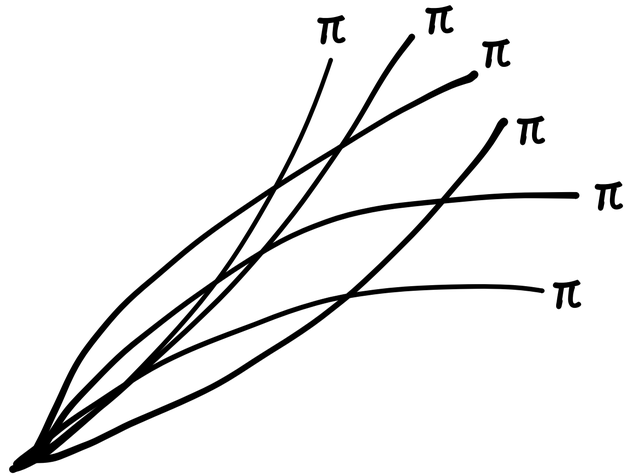

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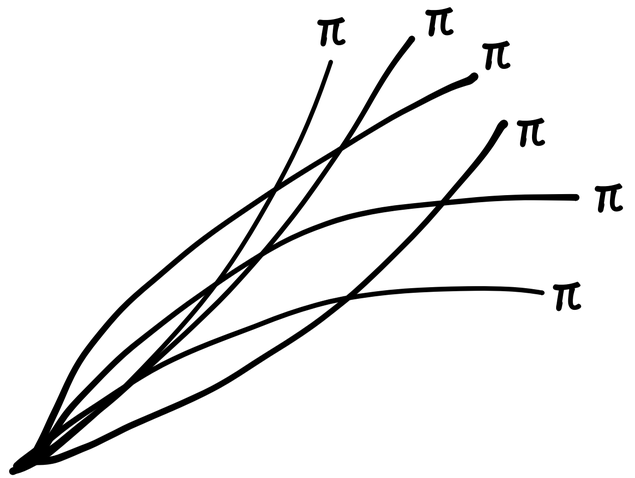
- Photons: ~25%



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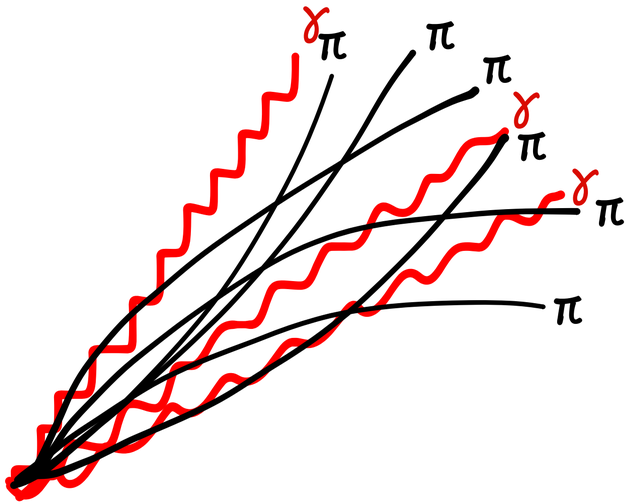

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- Charged Particles: ~60%

Tracking Detectors

  - Mostly charged pions, kaons and protons, but also some electrons and muons (decays in flight, semileptonic B decays, etc)

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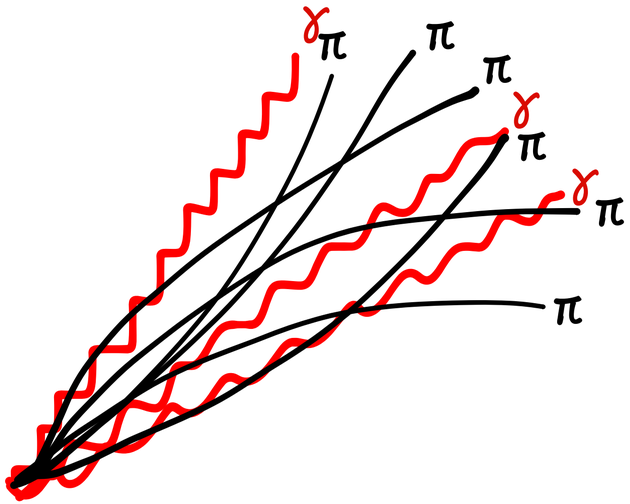

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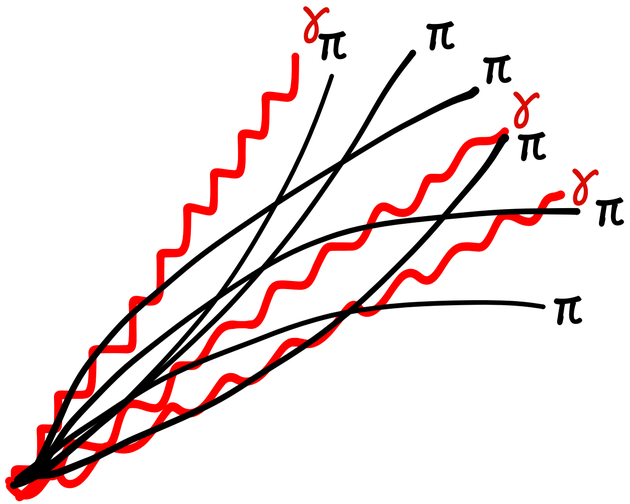

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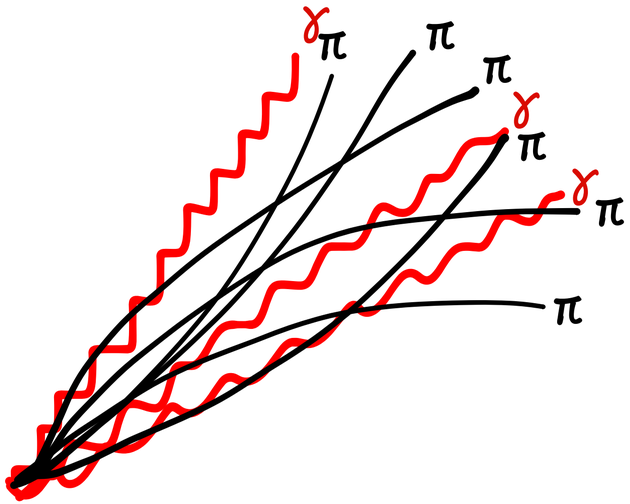

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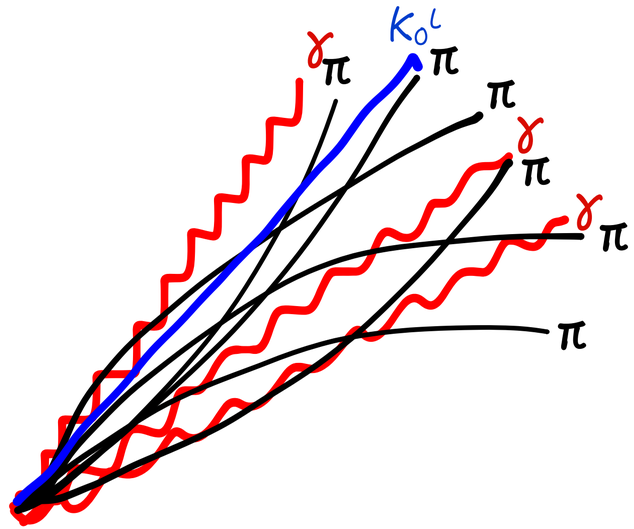

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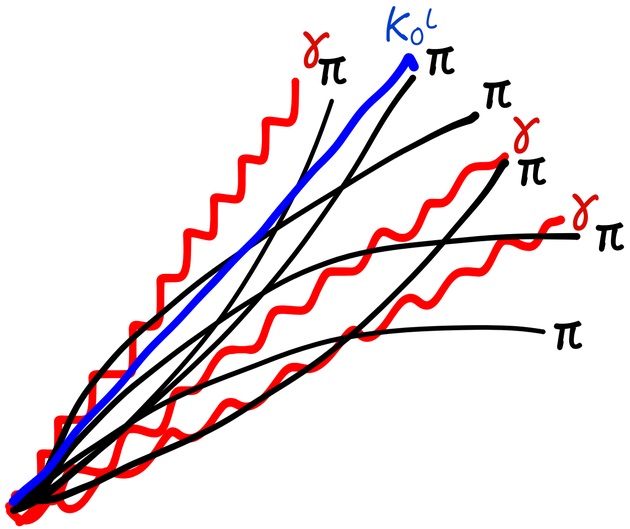

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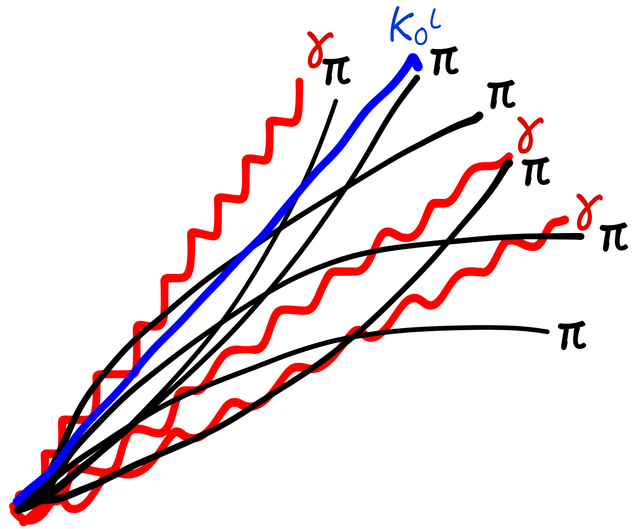

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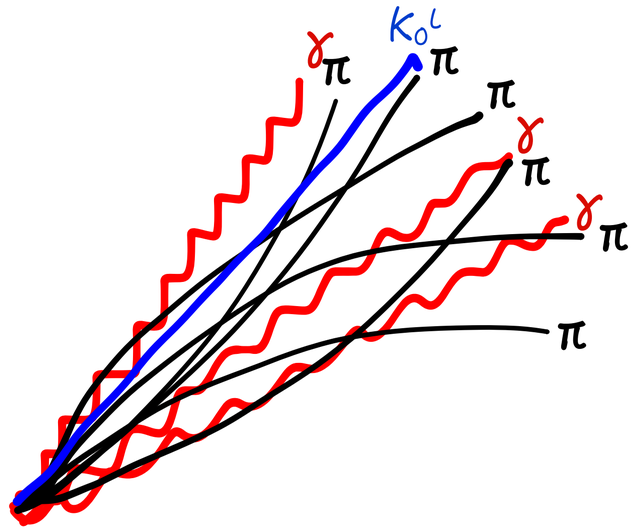

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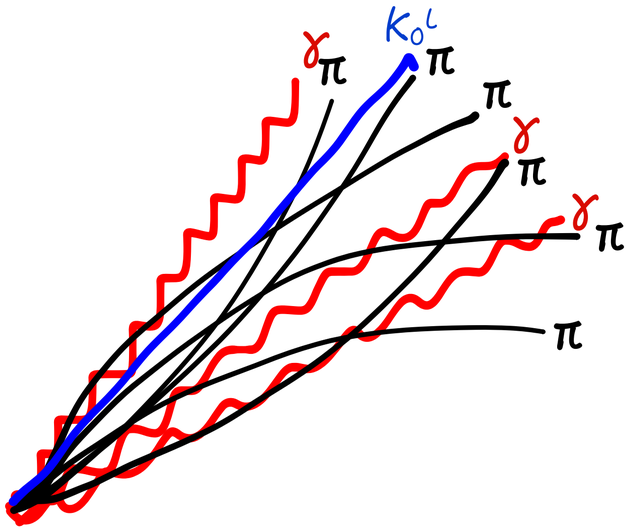

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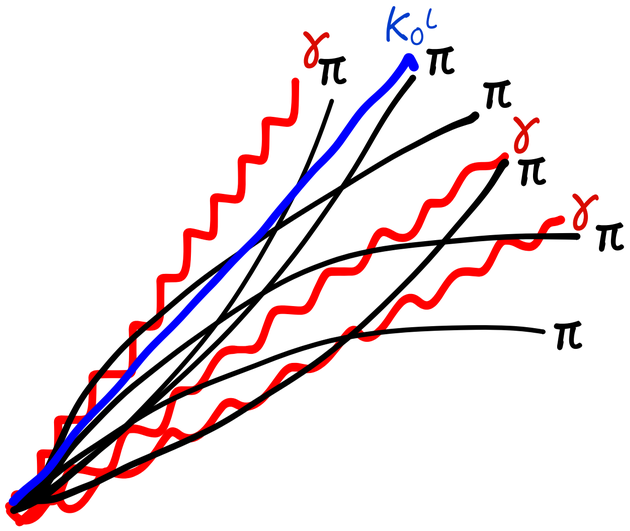

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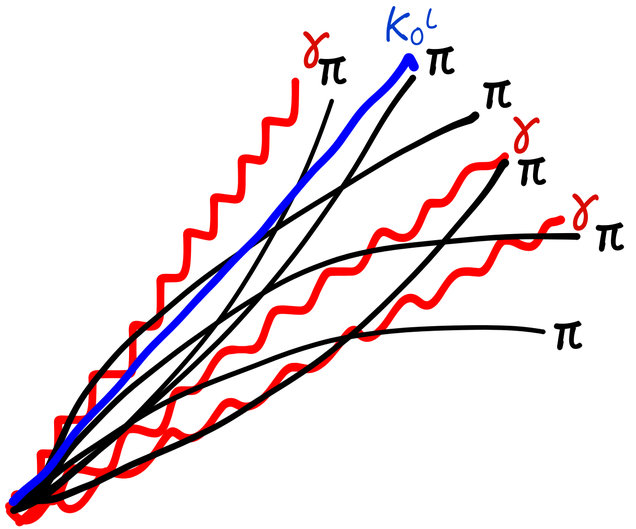

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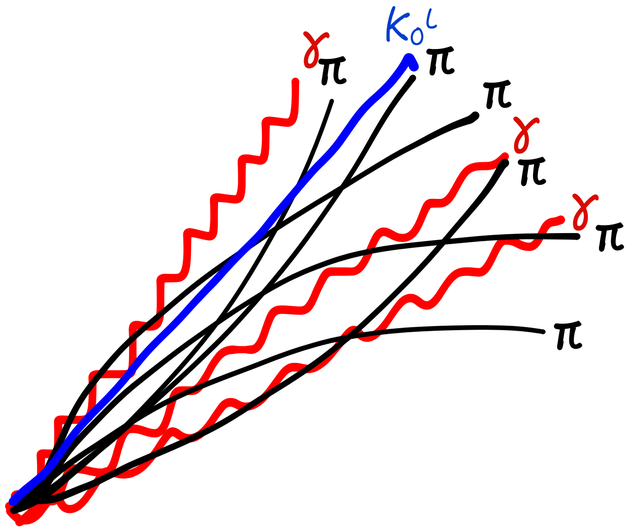
- Jets are columnated
  - particles belonging to a jet not isolated (important later)



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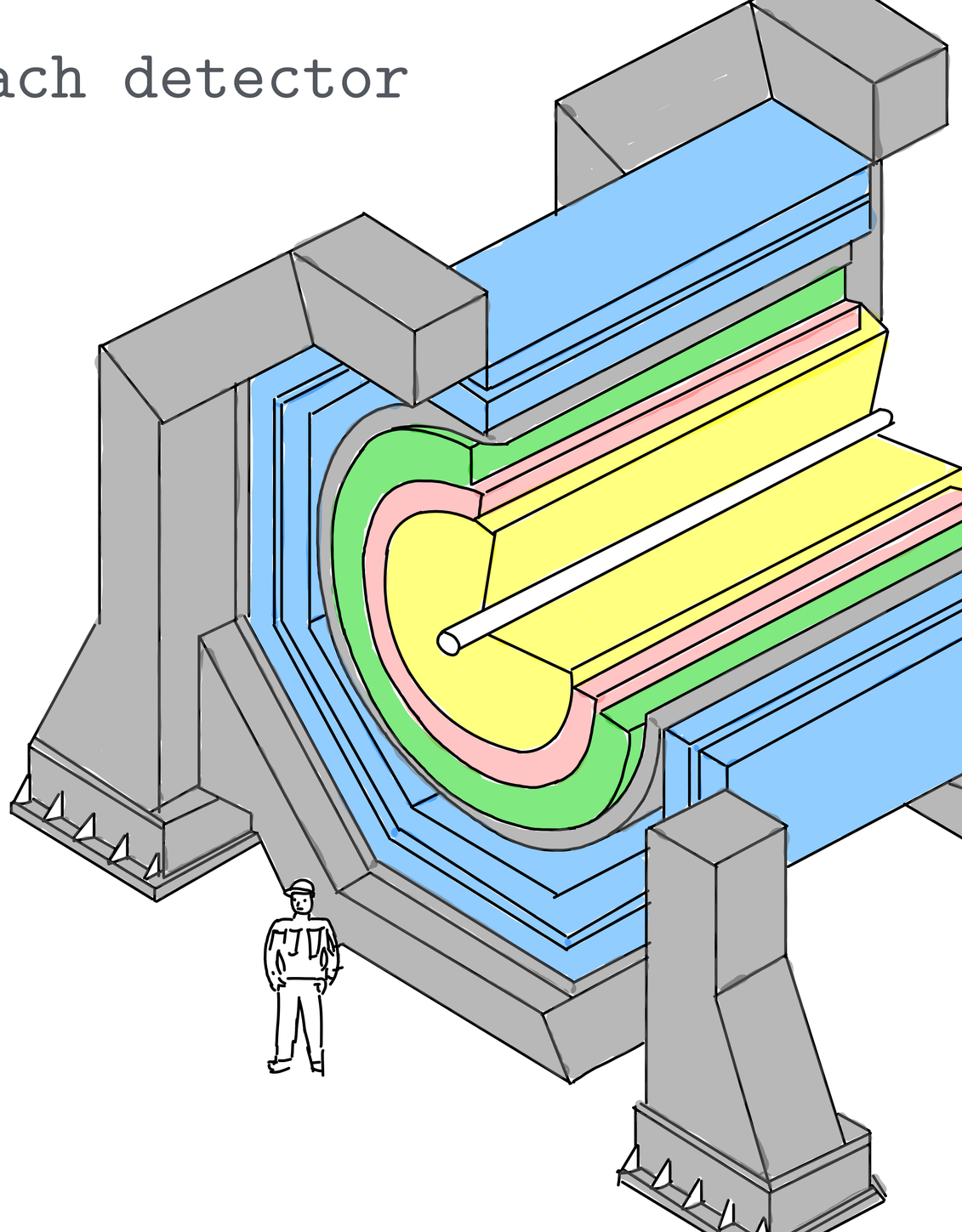

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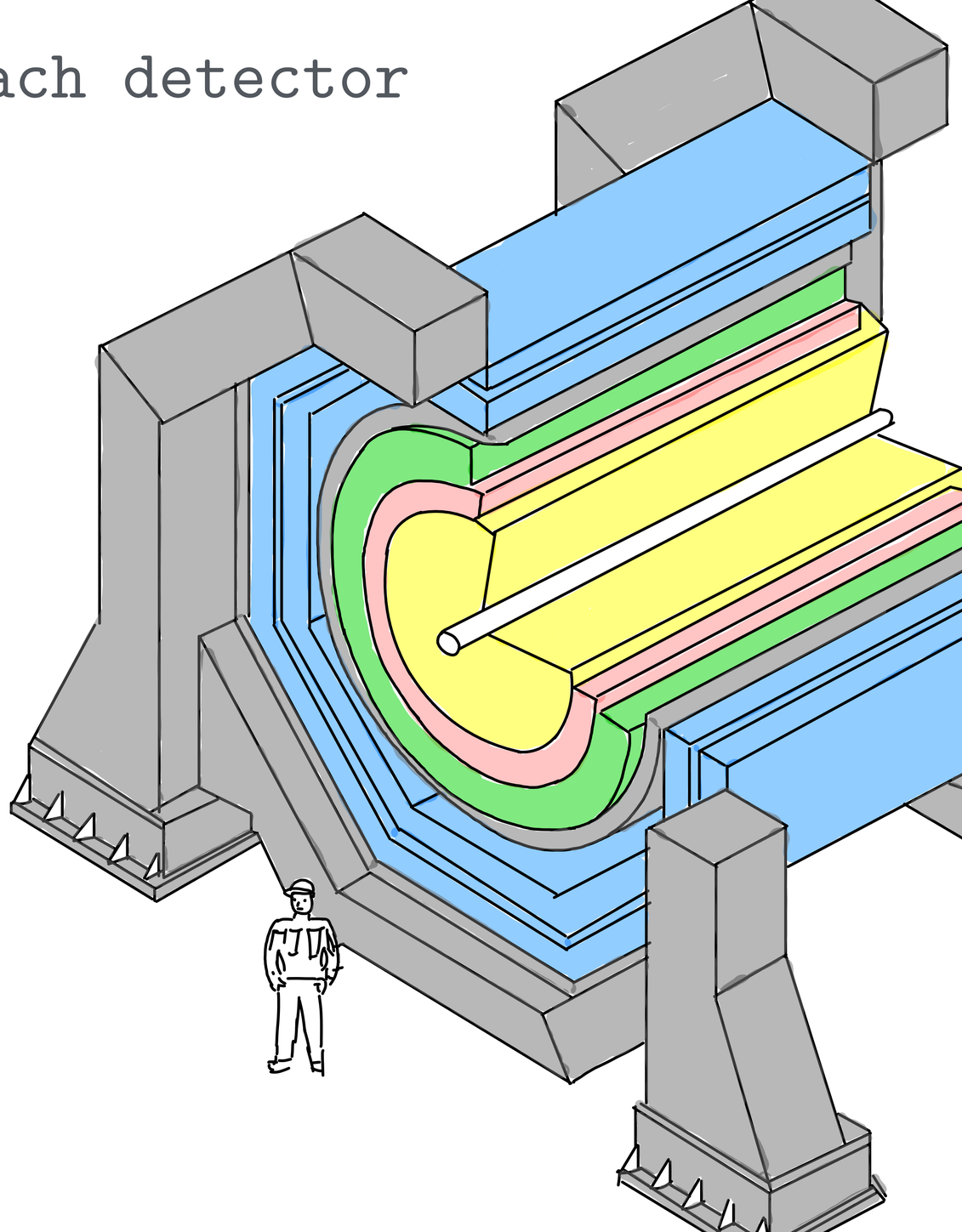

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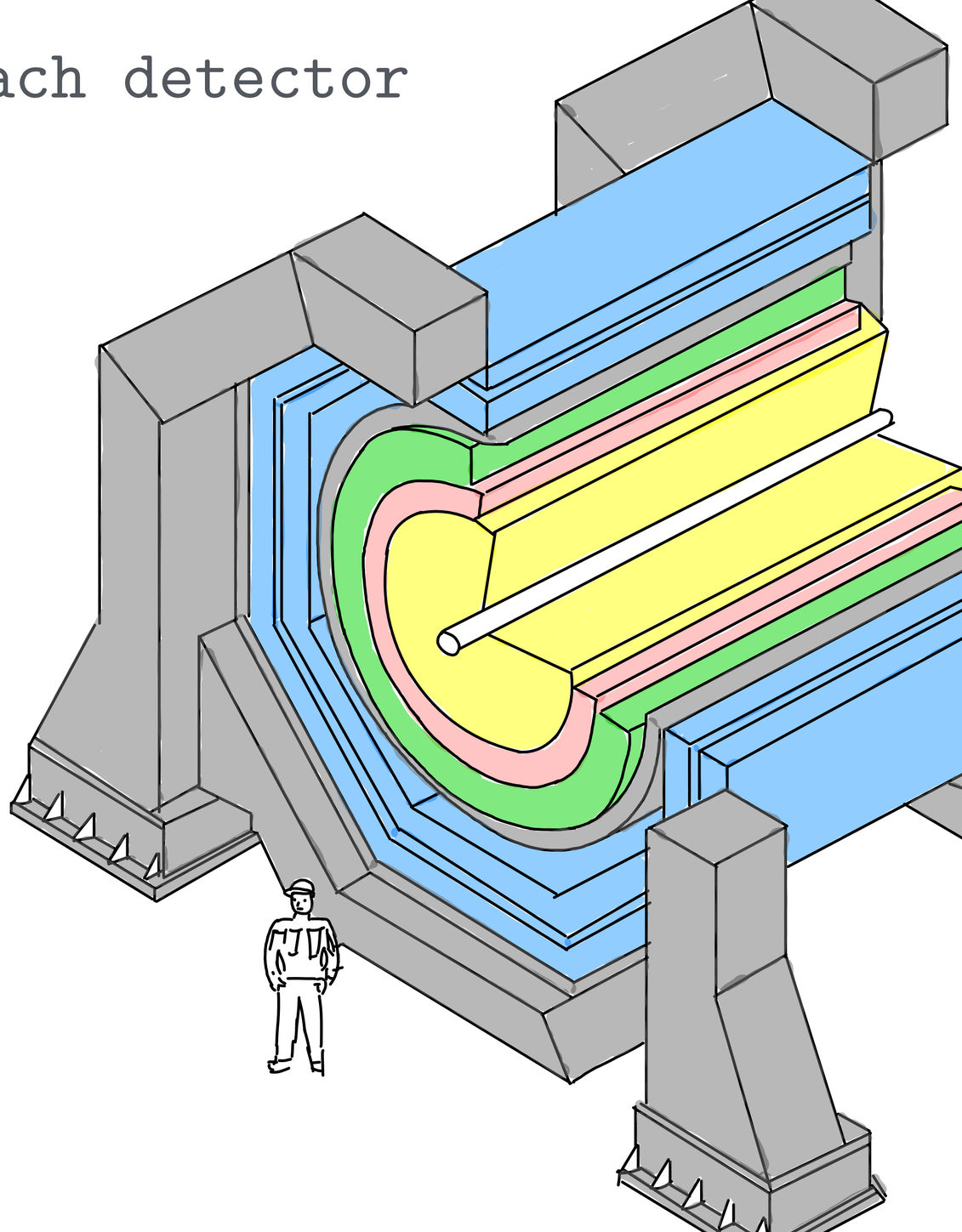

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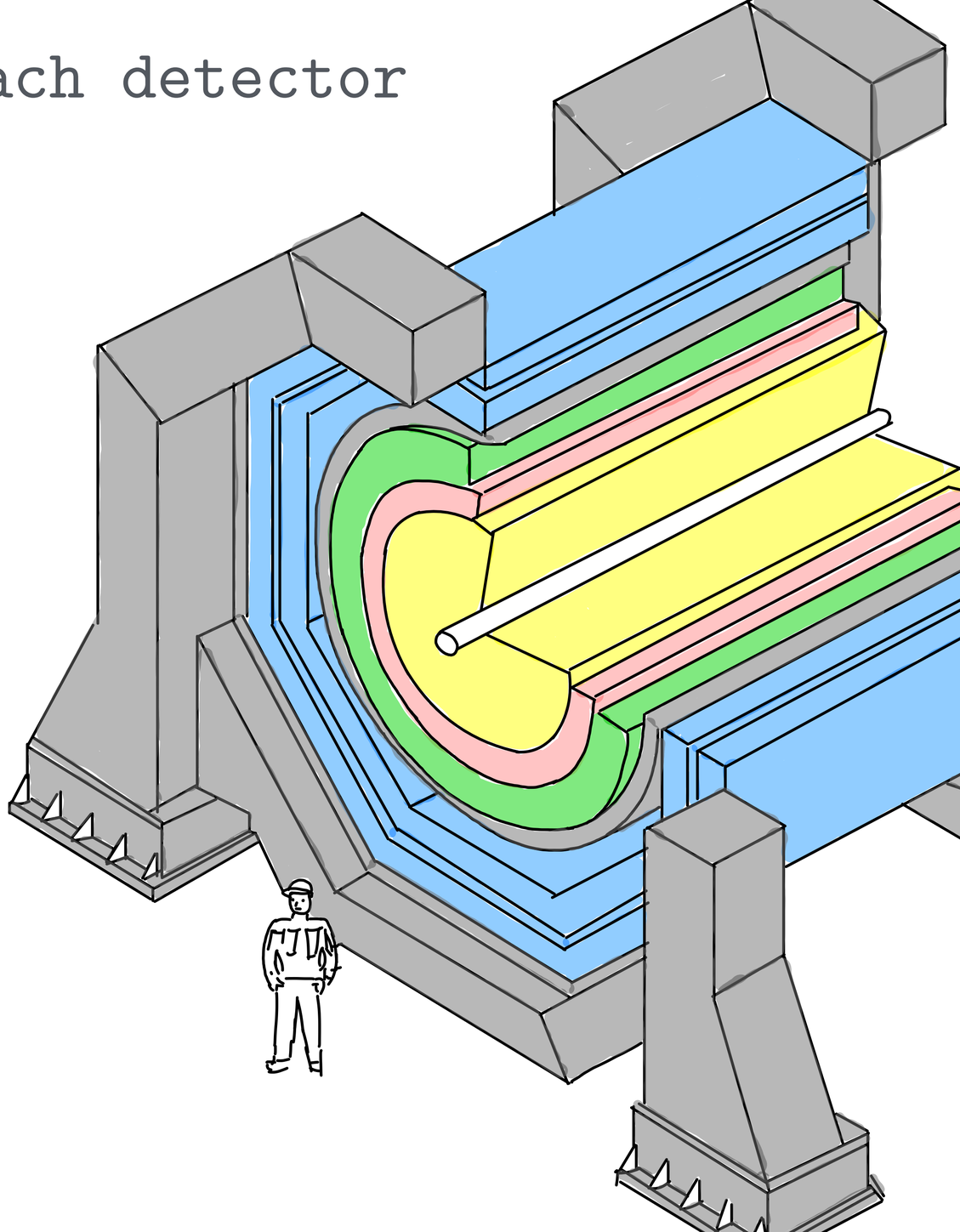

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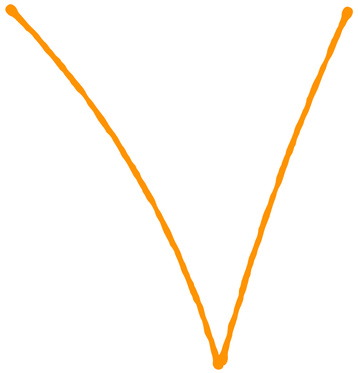

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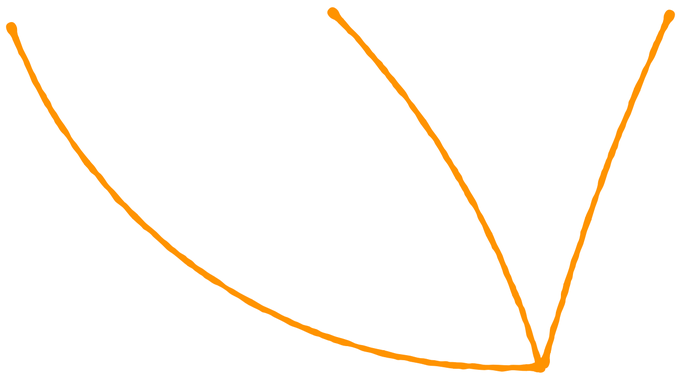

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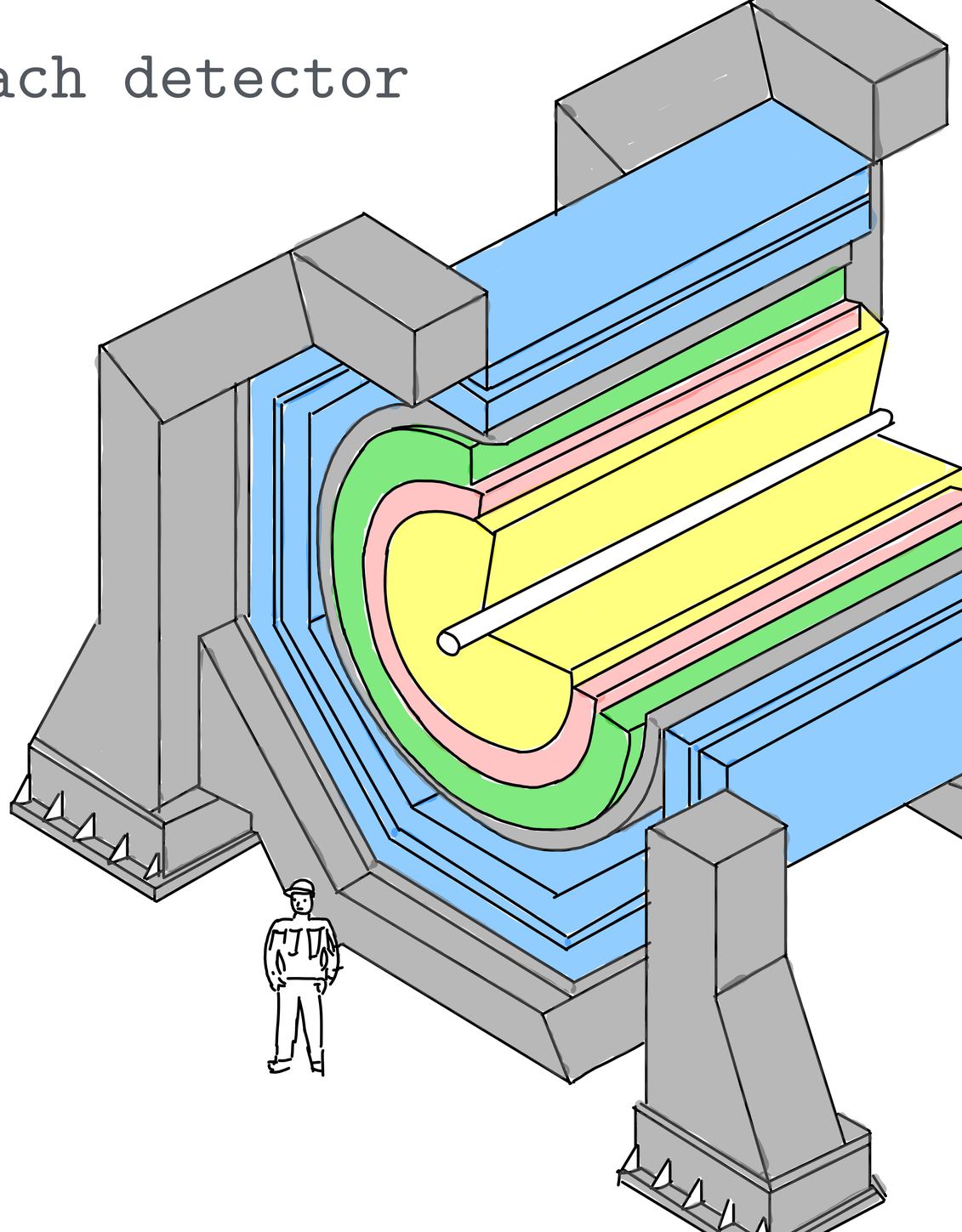

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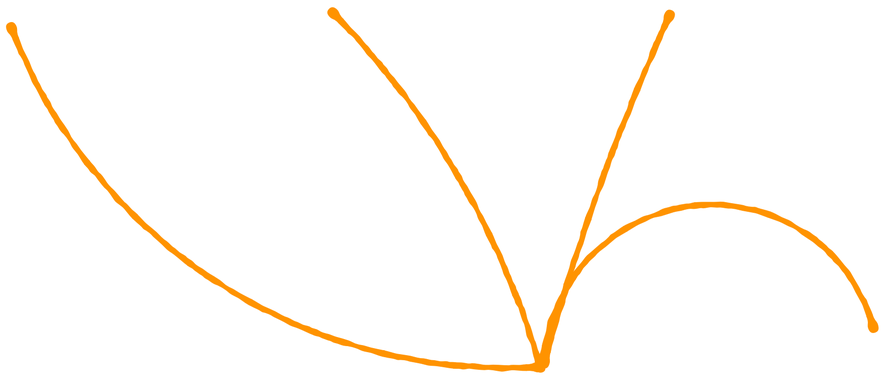

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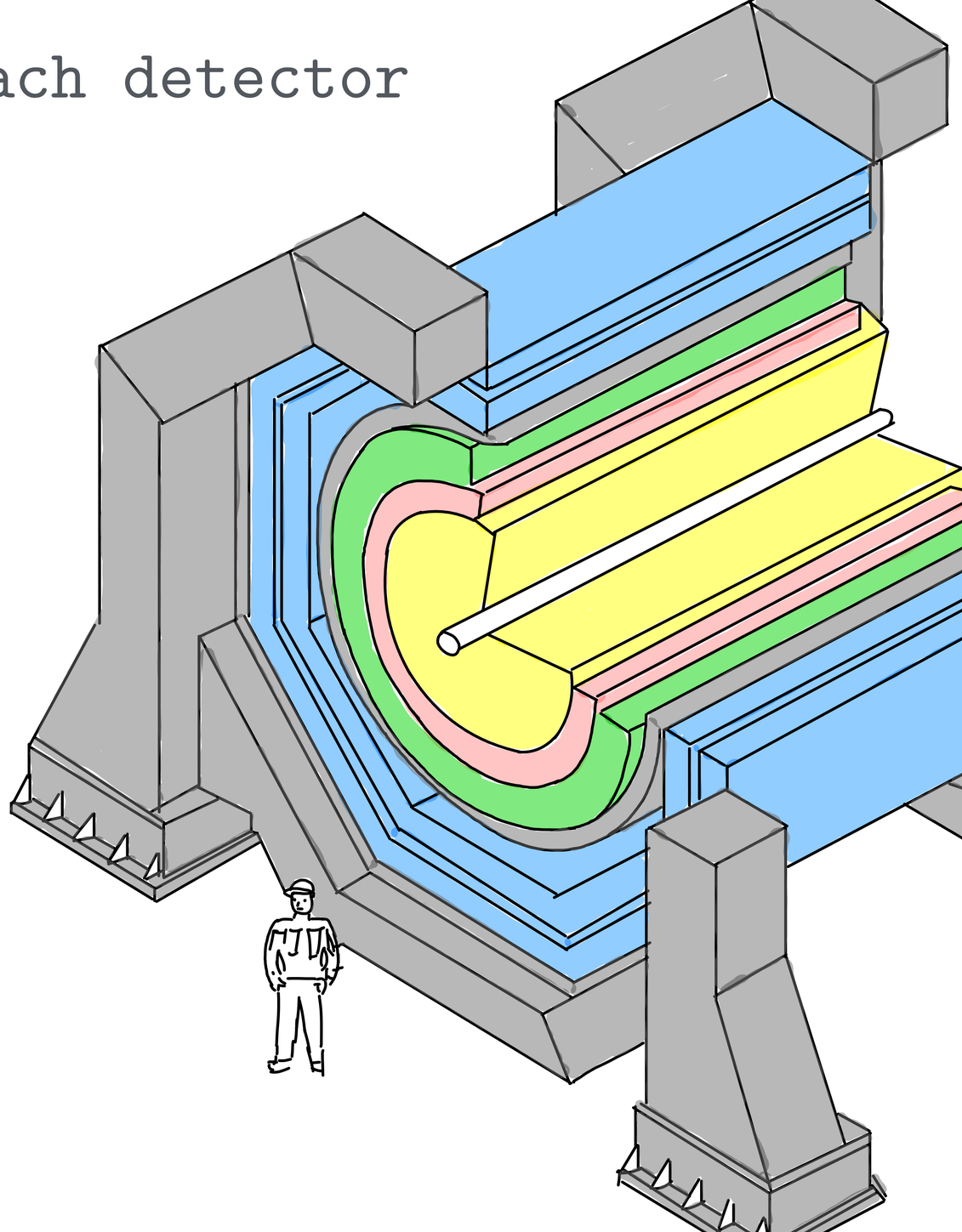

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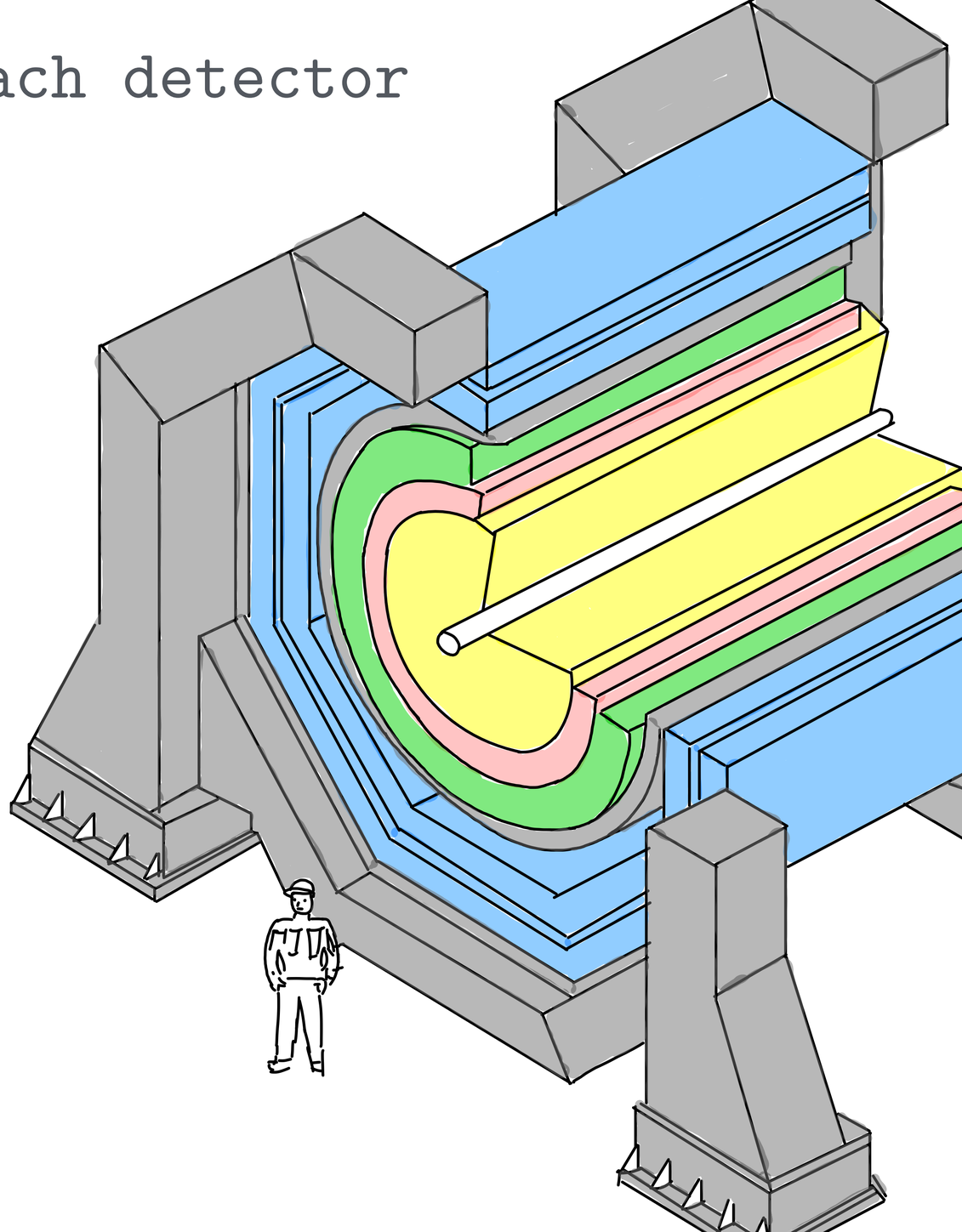

ECAL Clusters

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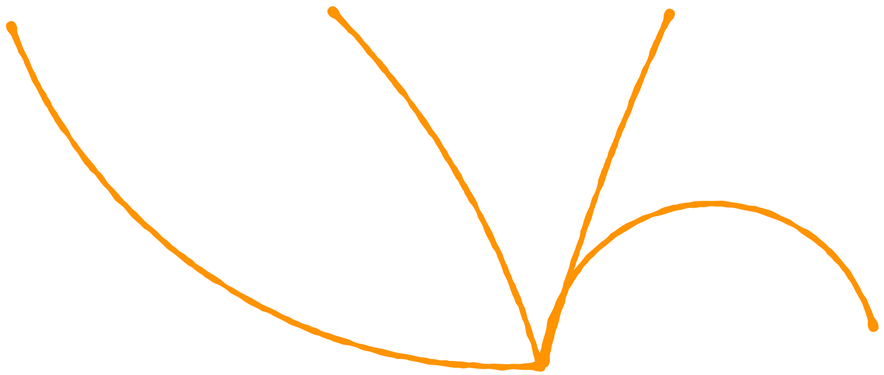

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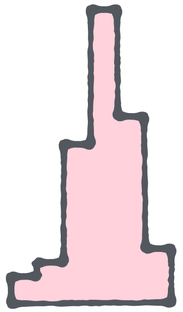

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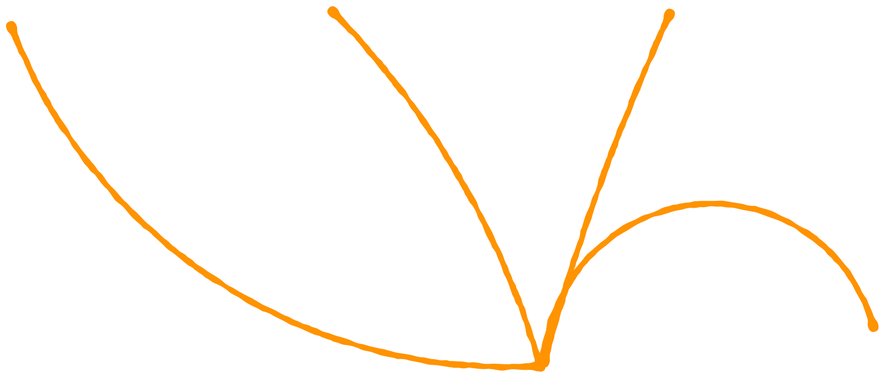

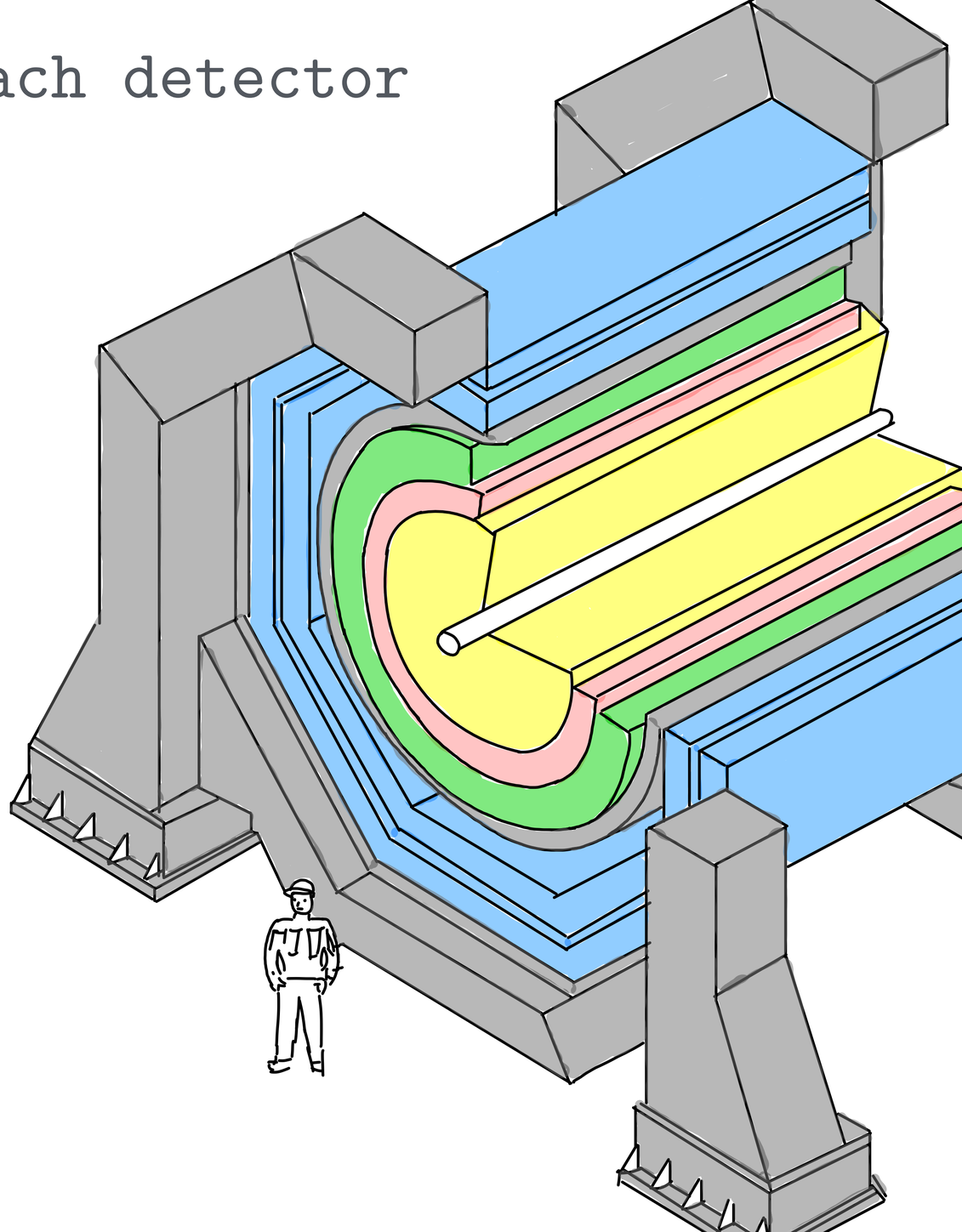

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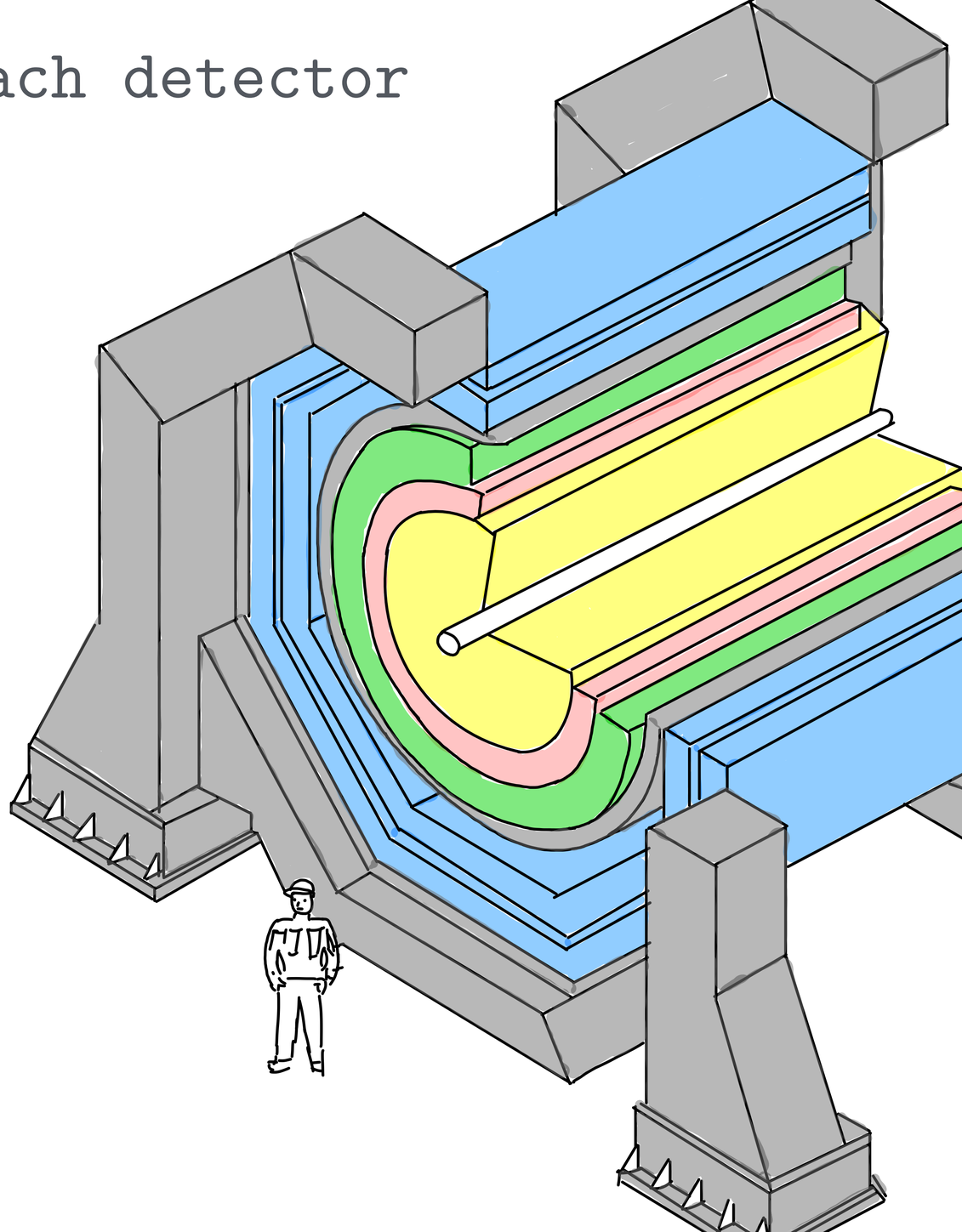

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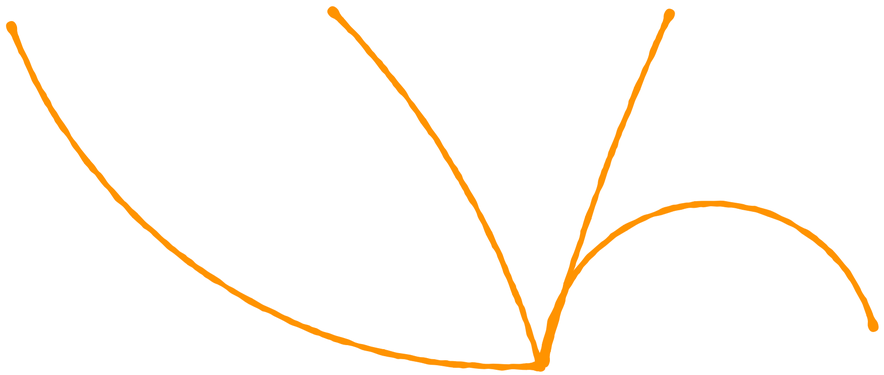

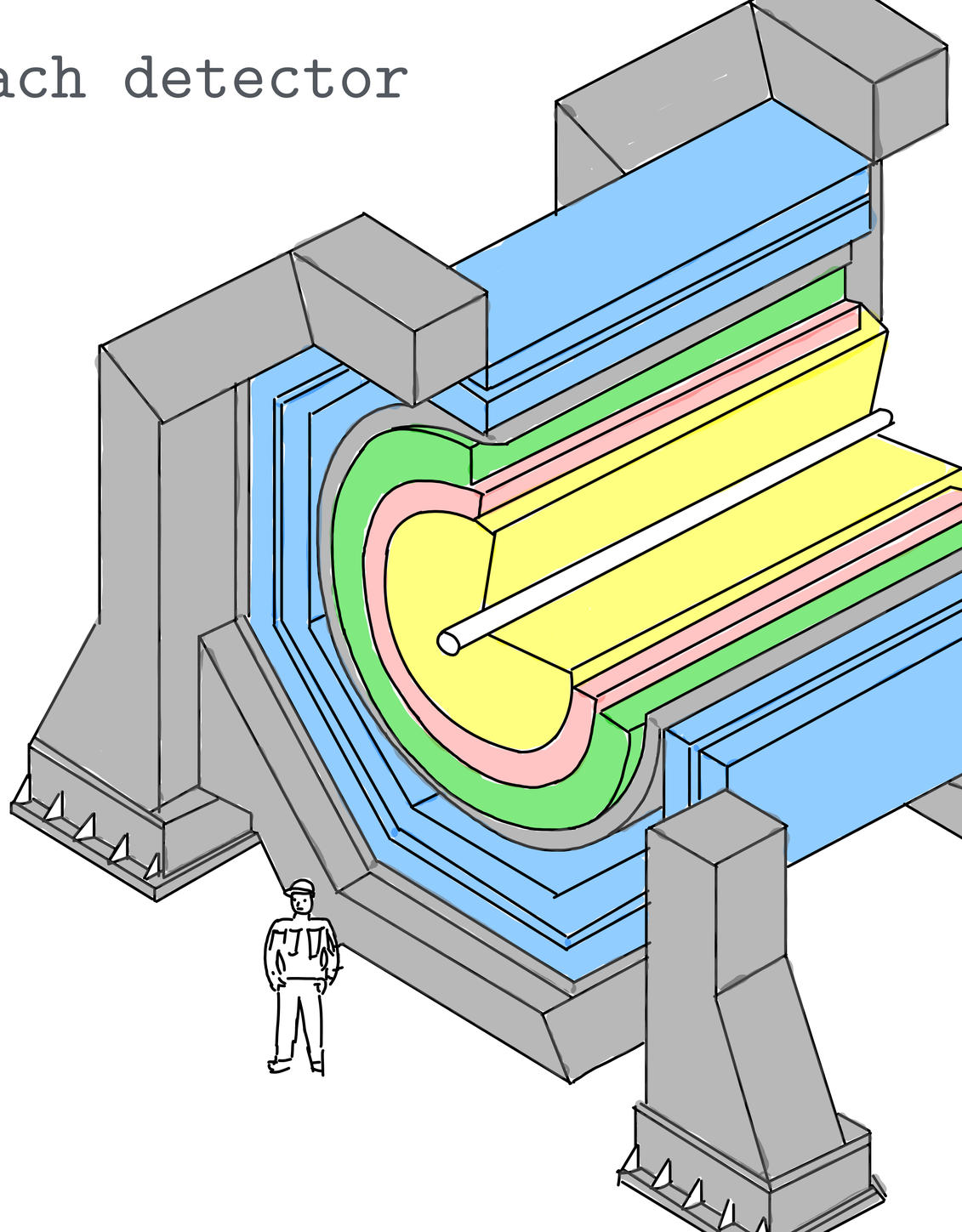

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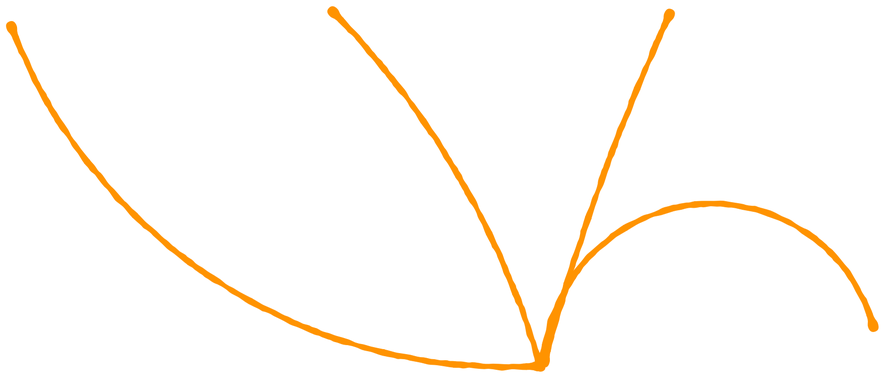
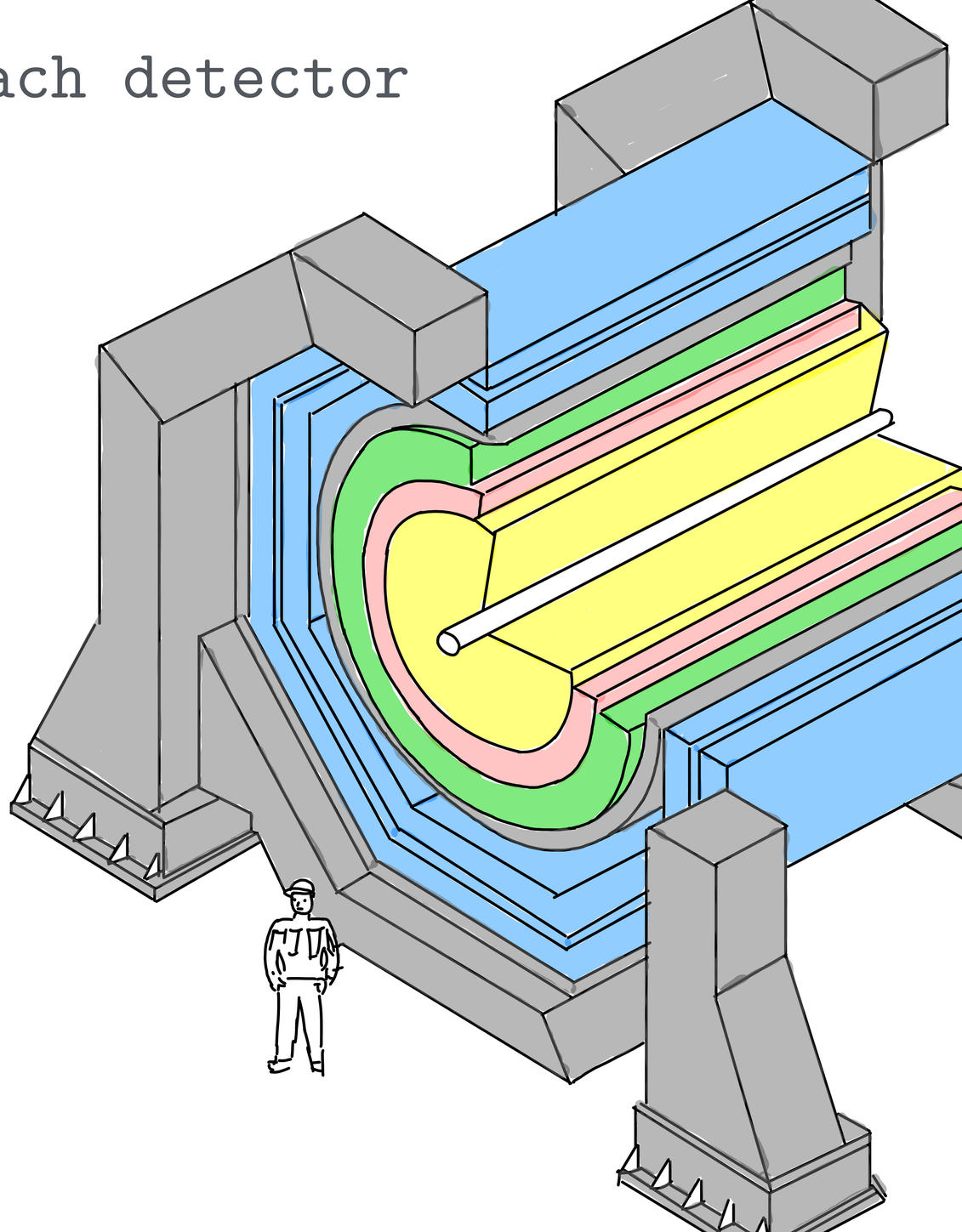
ECAL Clusters

Tracks





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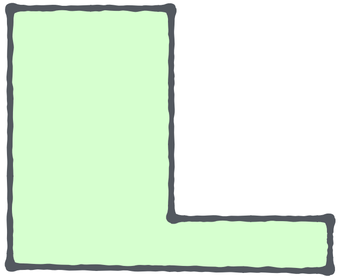

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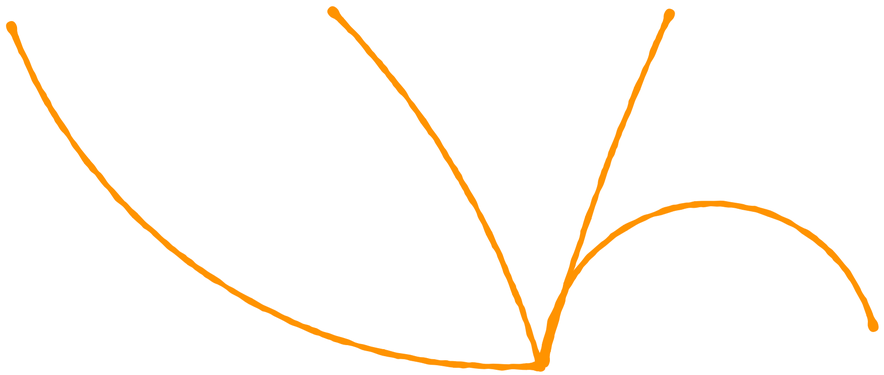

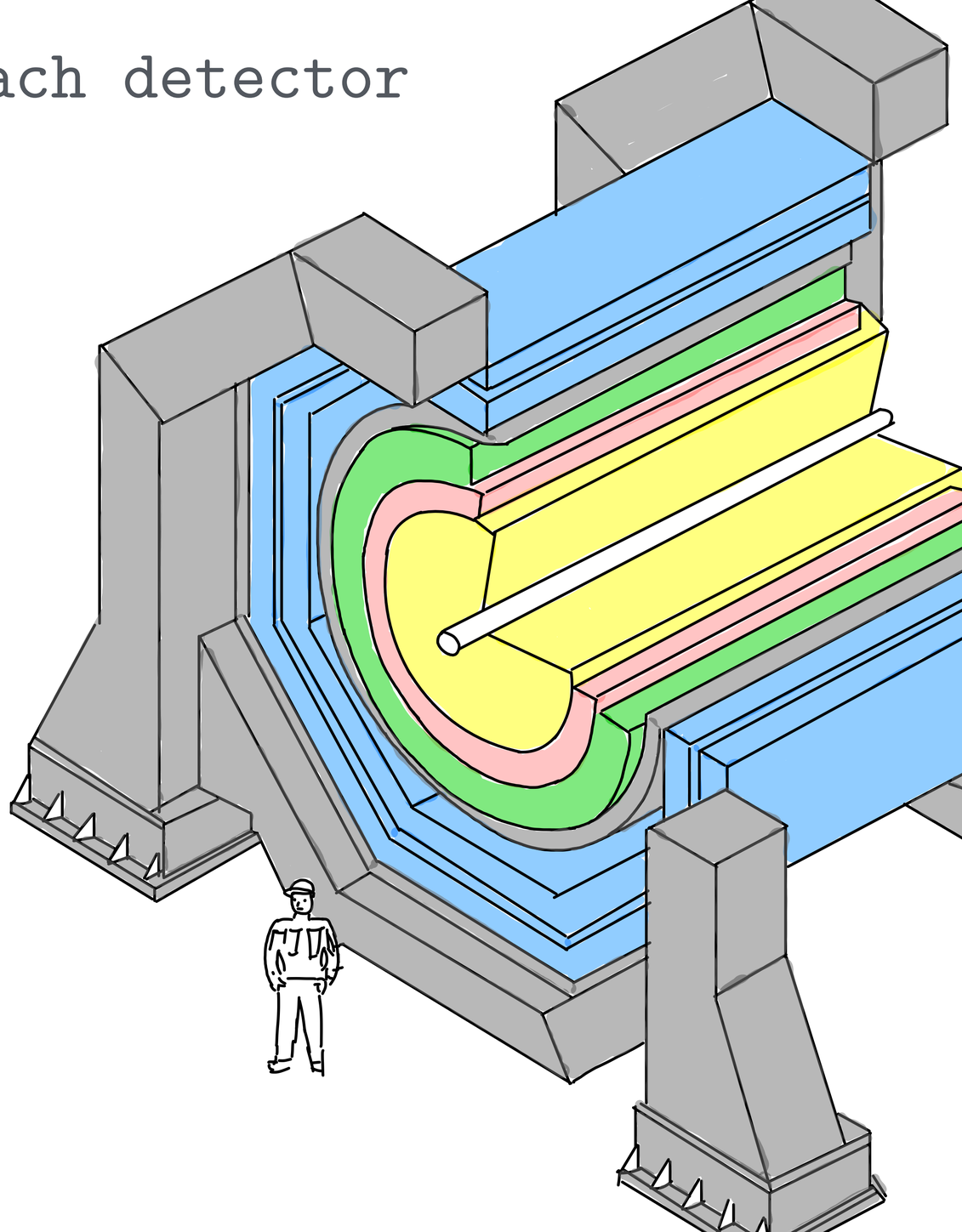

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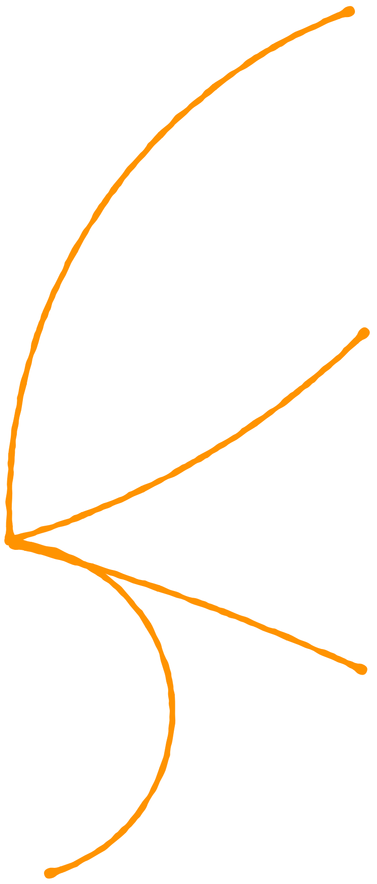
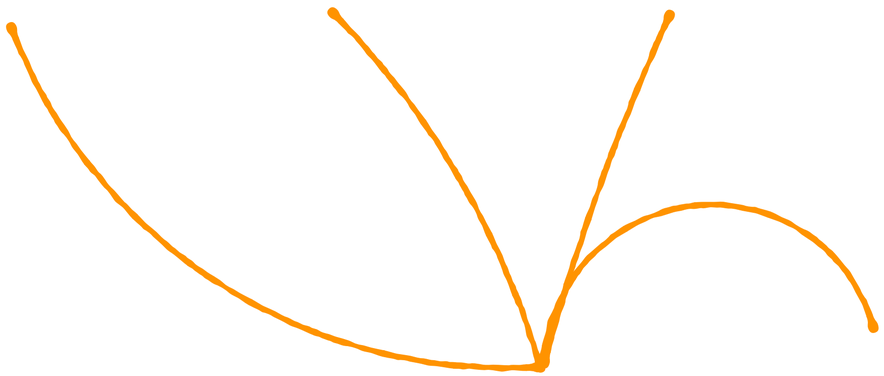


Track finding & reconstruction: Kalman Filter

Tracks



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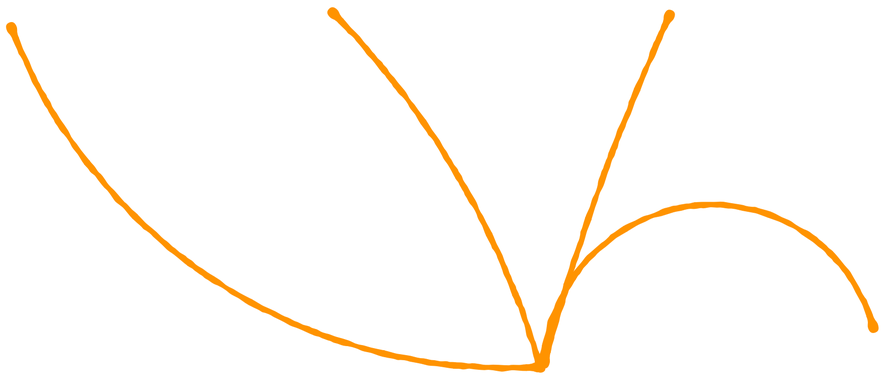

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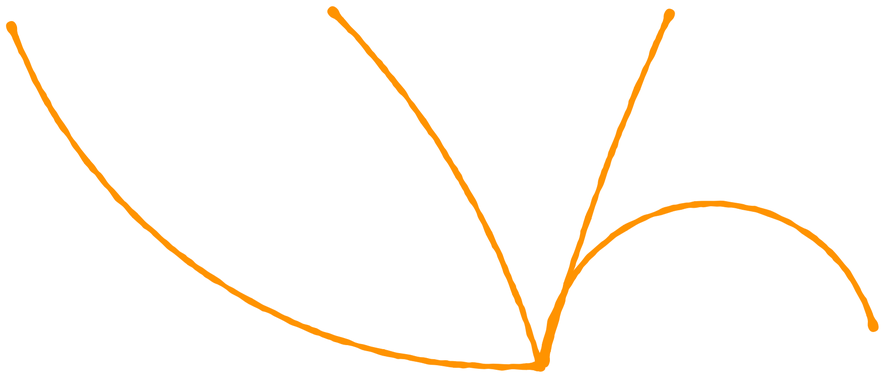

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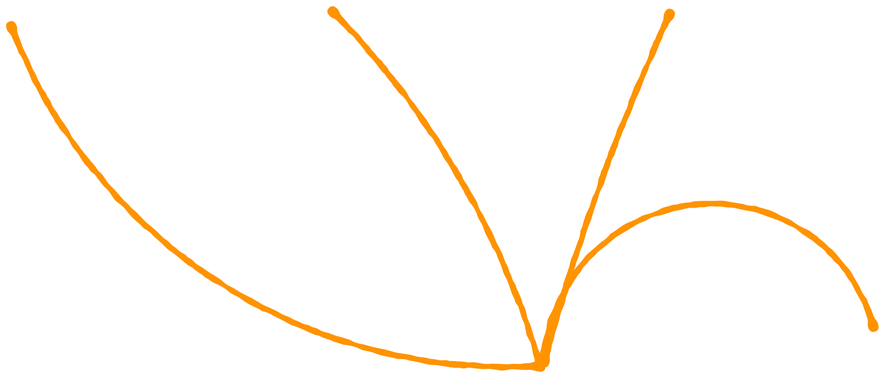

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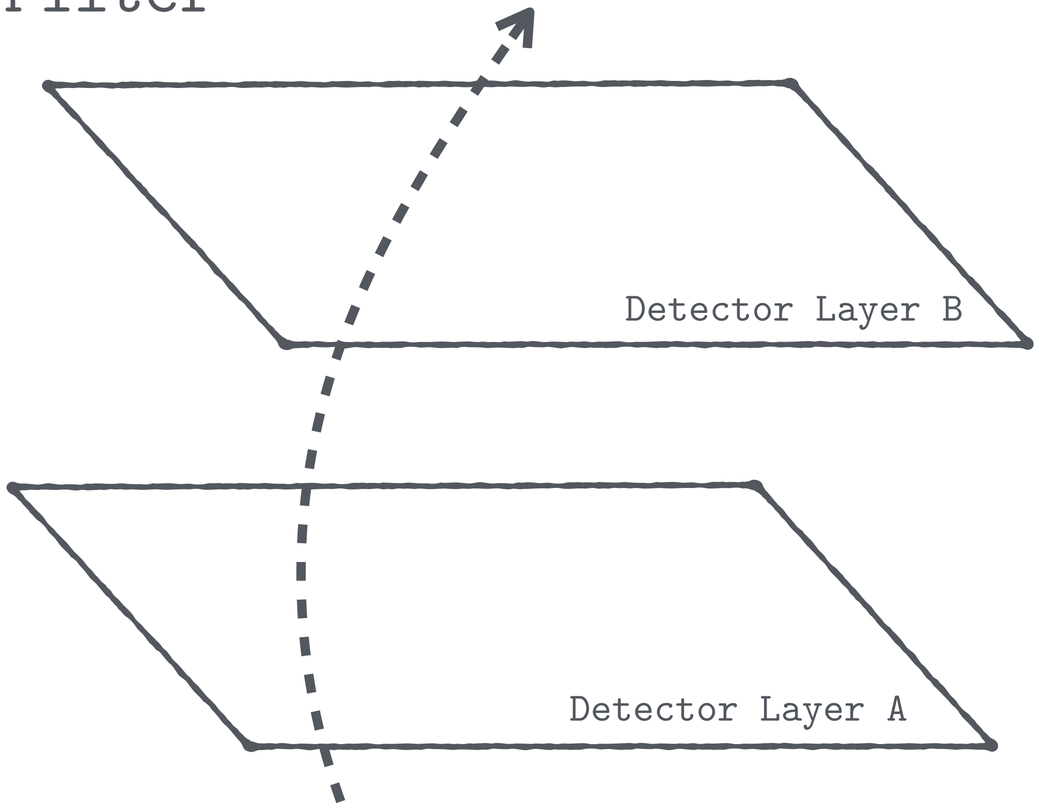

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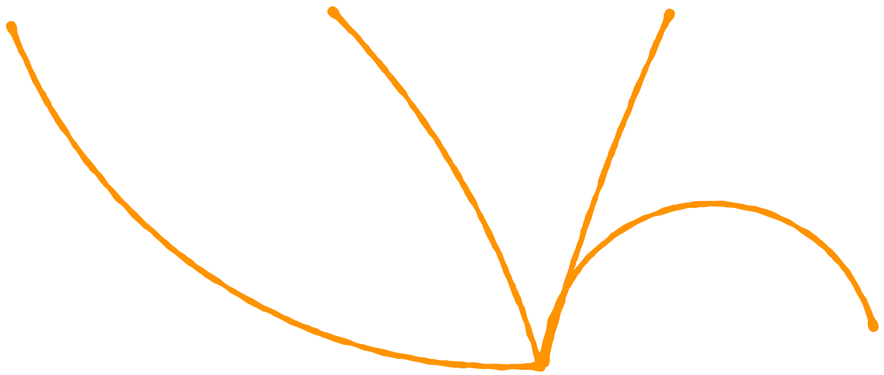


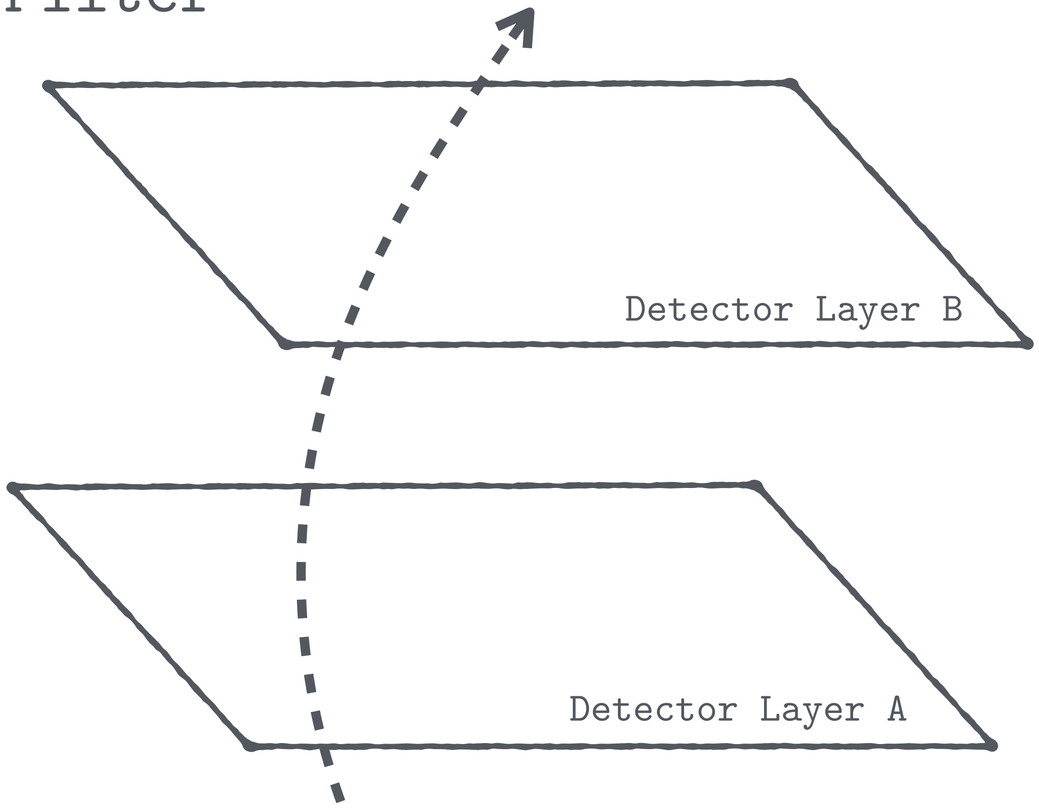
Track finding & reconstruction: Kalman Filter

Measurement and Covariance

- Measurement vector

$$\vec{m} = \begin{pmatrix} x \\ y \end{pmatrix}$$

- And its covariance matrix $\mathbb{V}$



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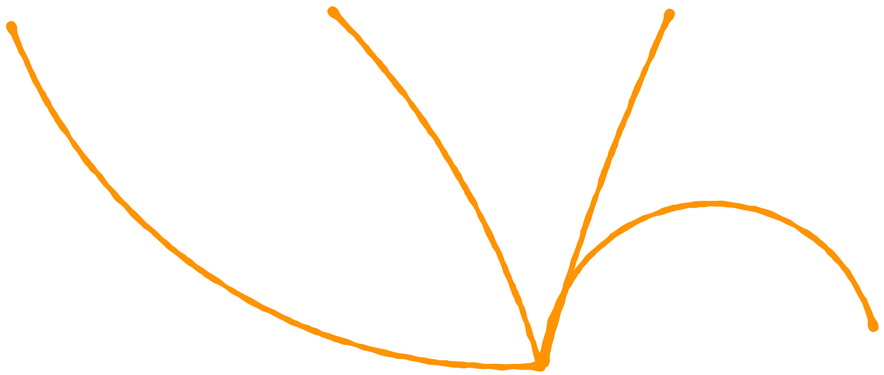

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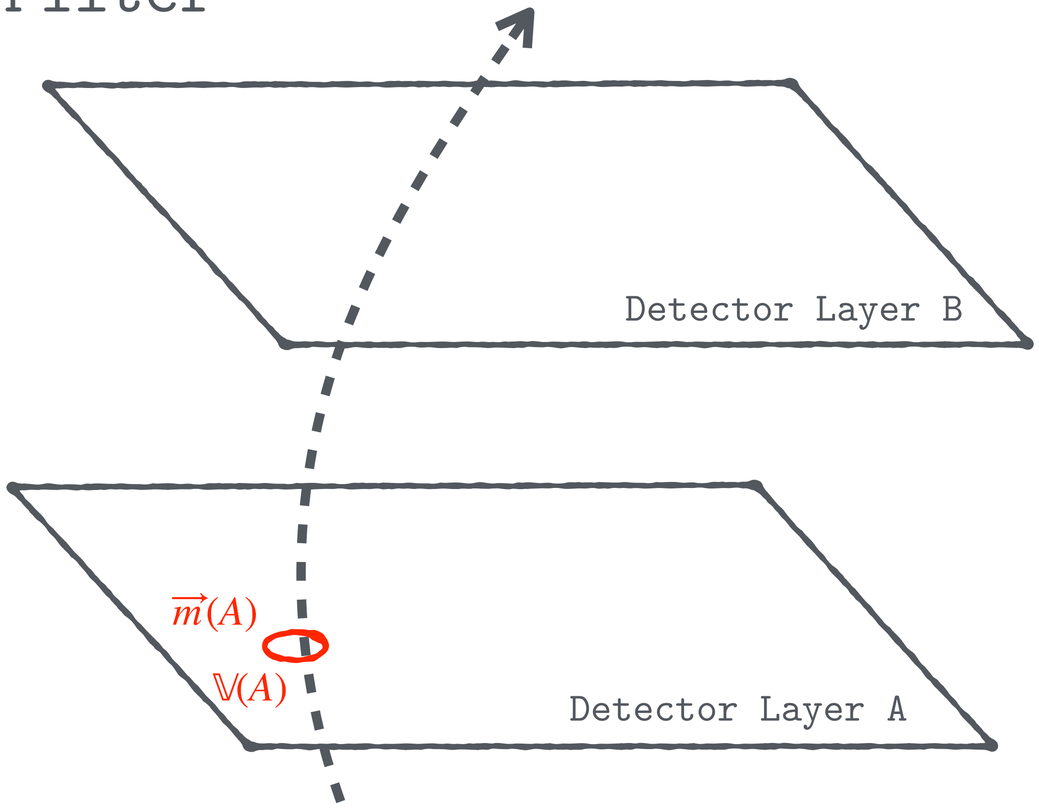

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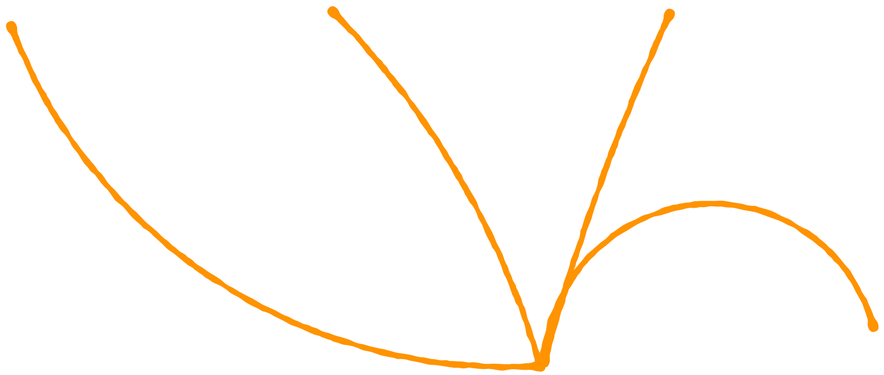

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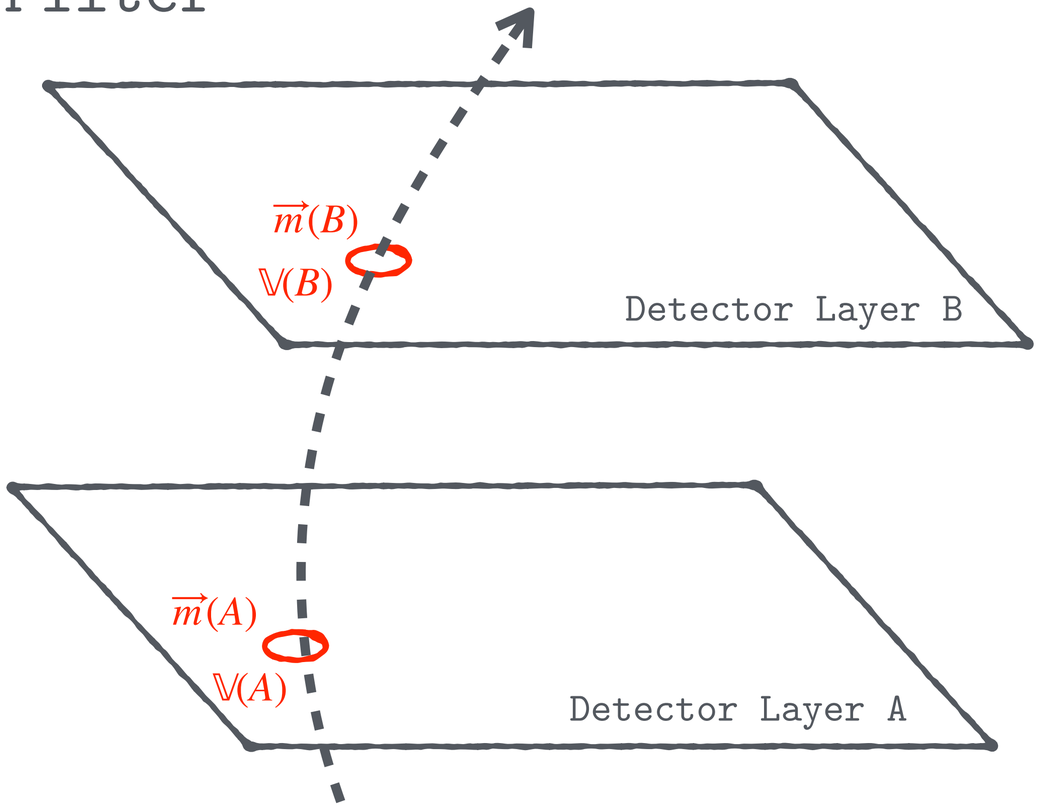
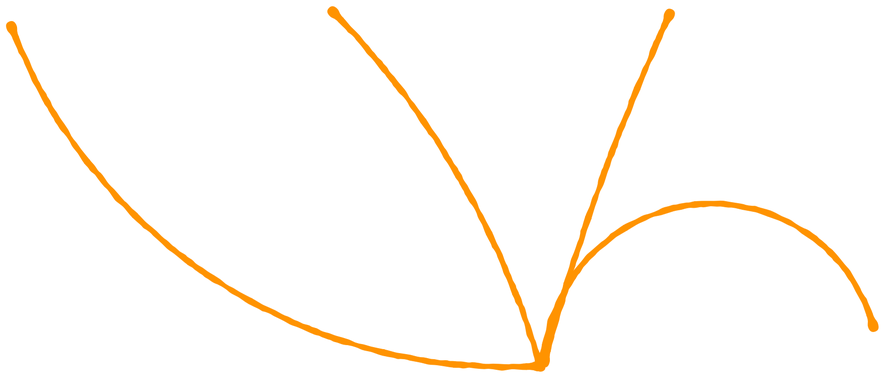


Tracks



Track finding & reconstruction: Kalman Filter

Measurement and Covariance

- Measurement vector

$$\vec{m} = \begin{pmatrix} x \\ y \end{pmatrix}$$

- And its covariance matrix $\mathbb{V}$

State vector and Covariance

- Many ways to parameterise a track

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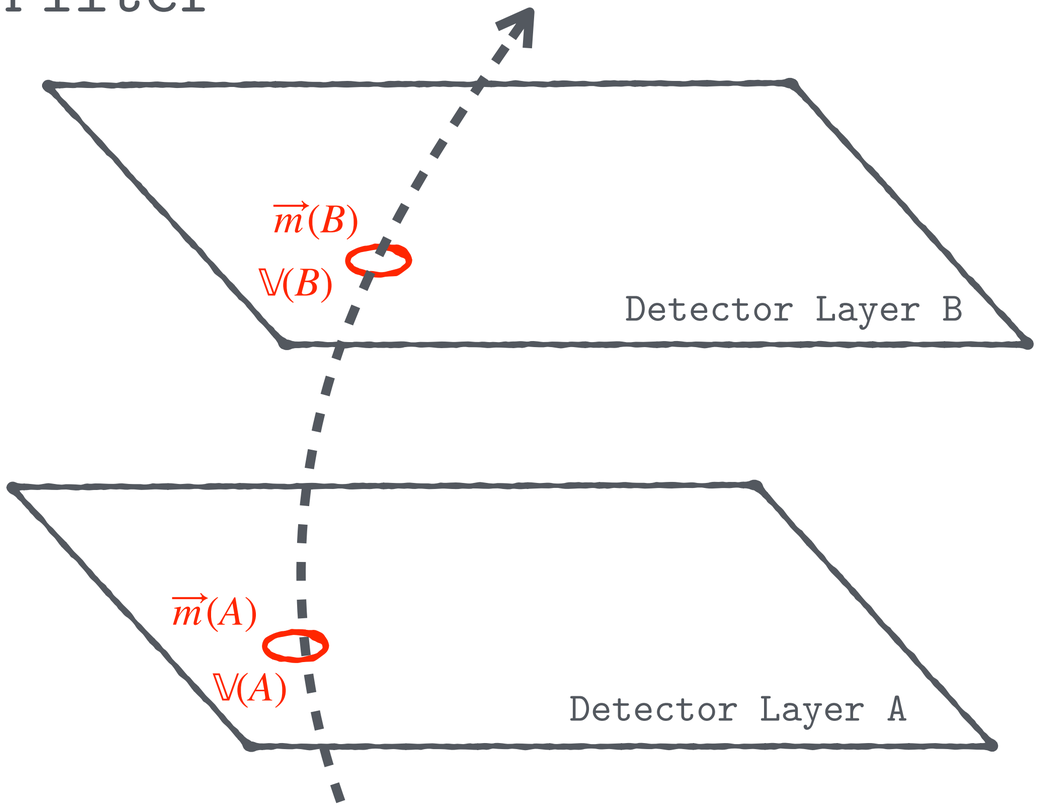

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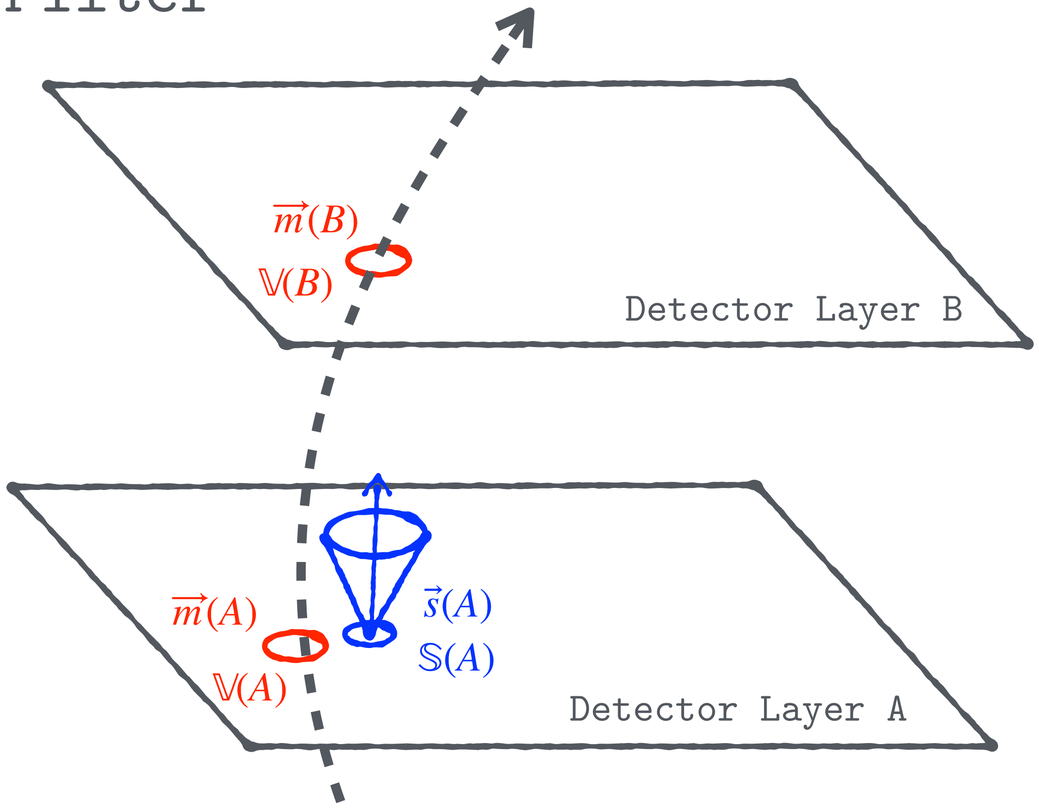

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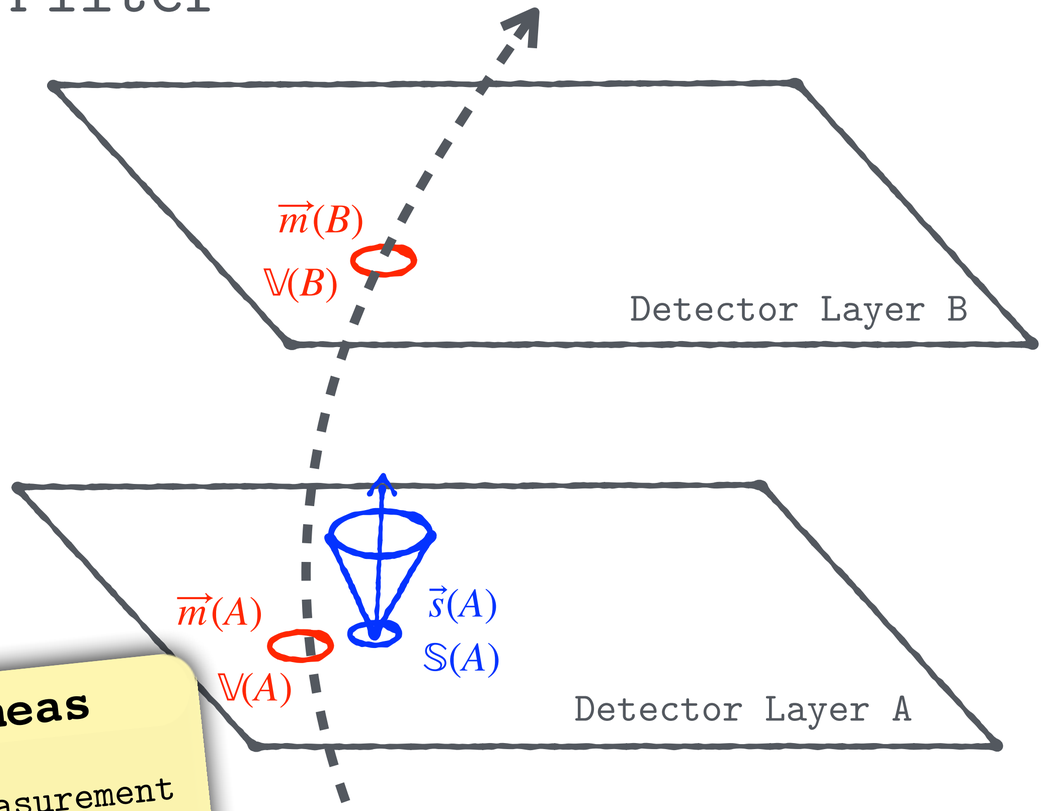
Tracks



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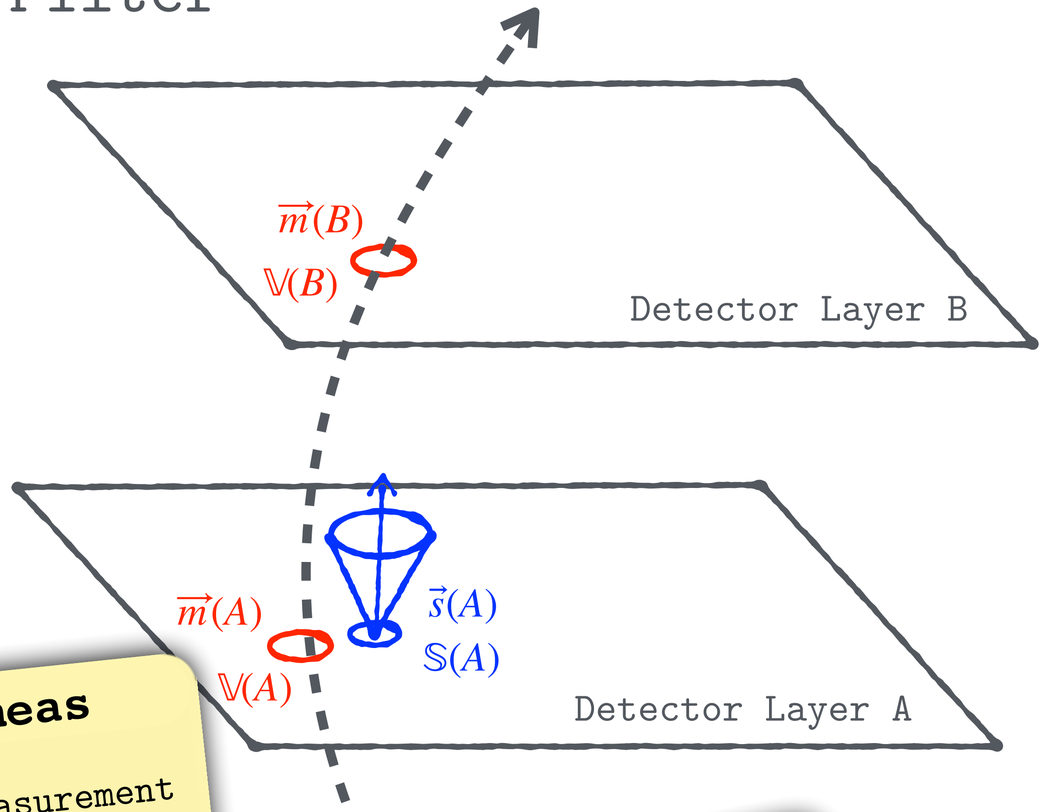

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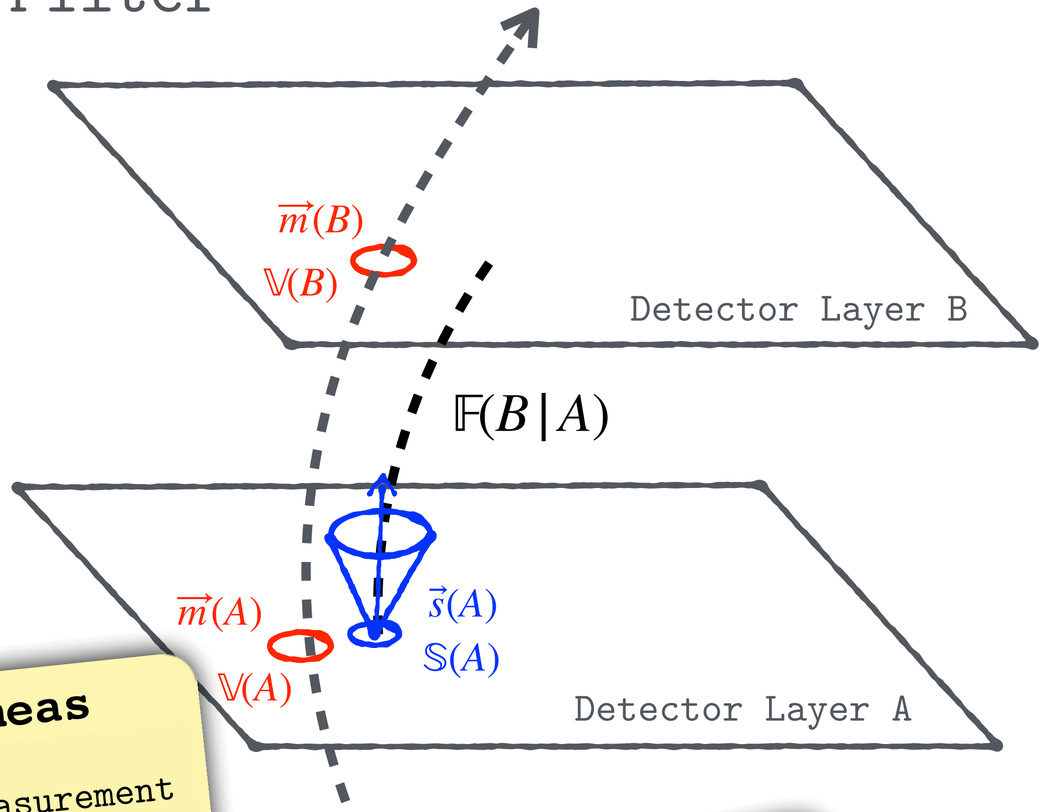

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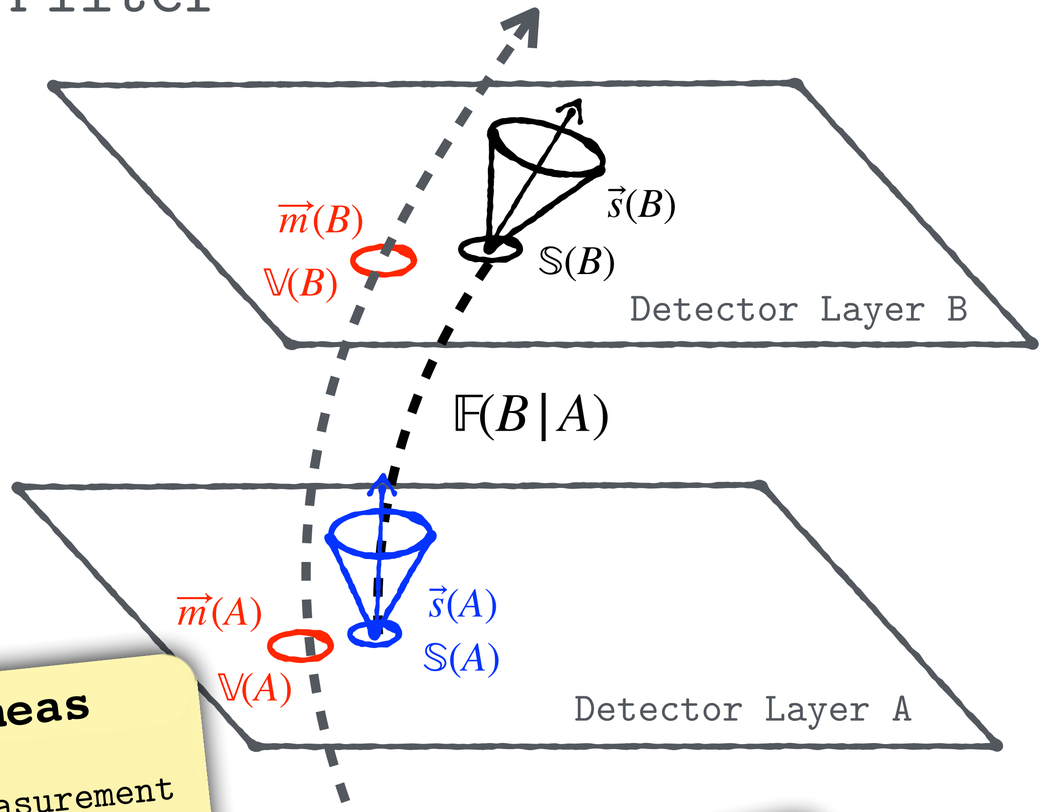

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Noise Model

- Due to Multiple Scattering, etc: $\mathbb{W}$

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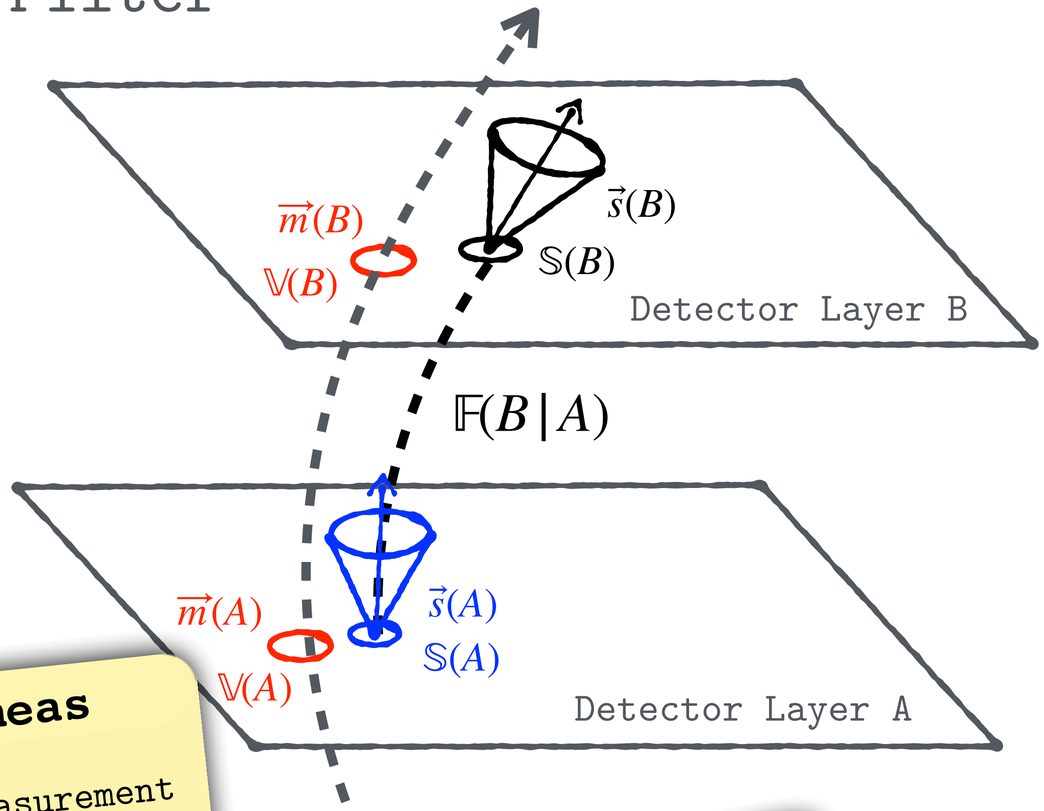

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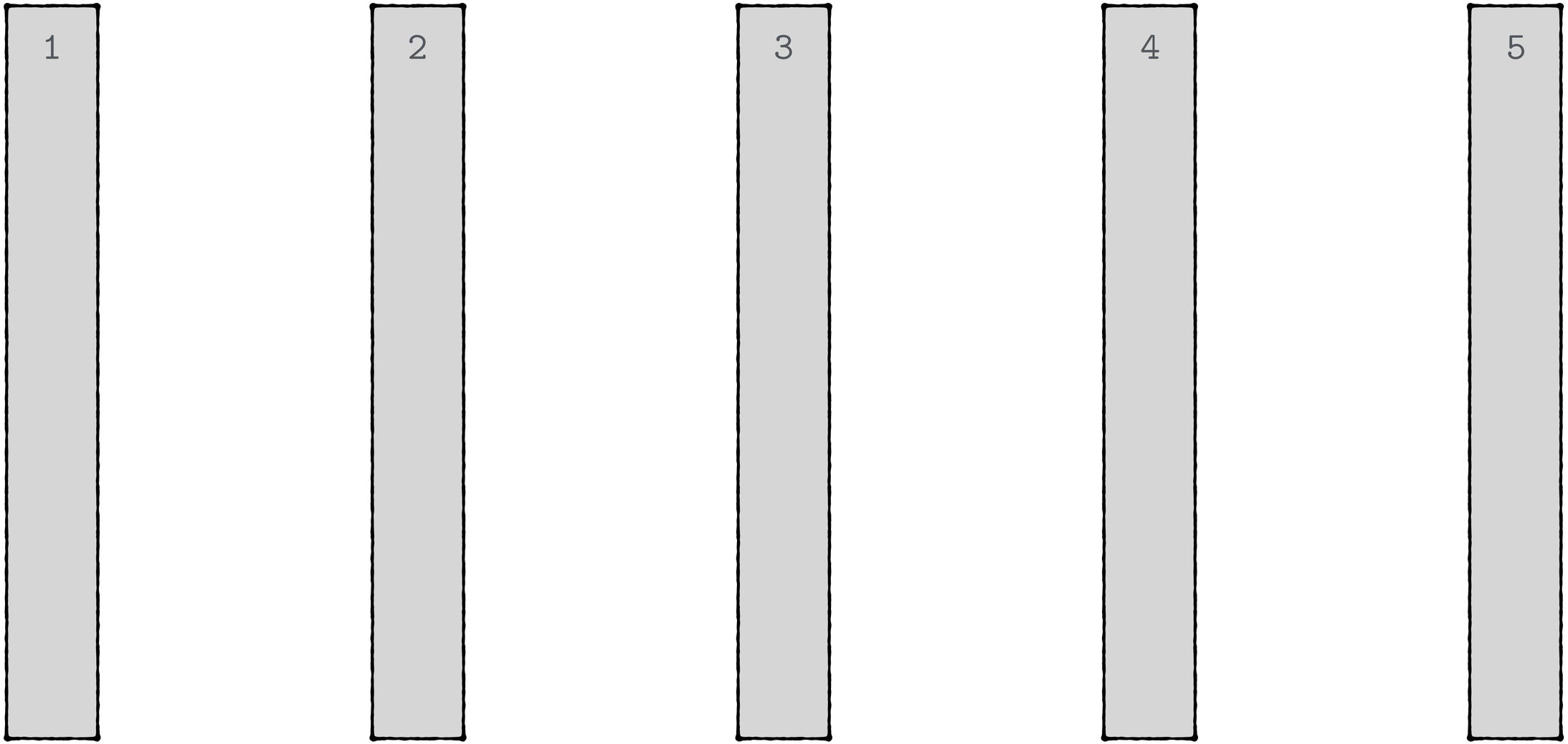

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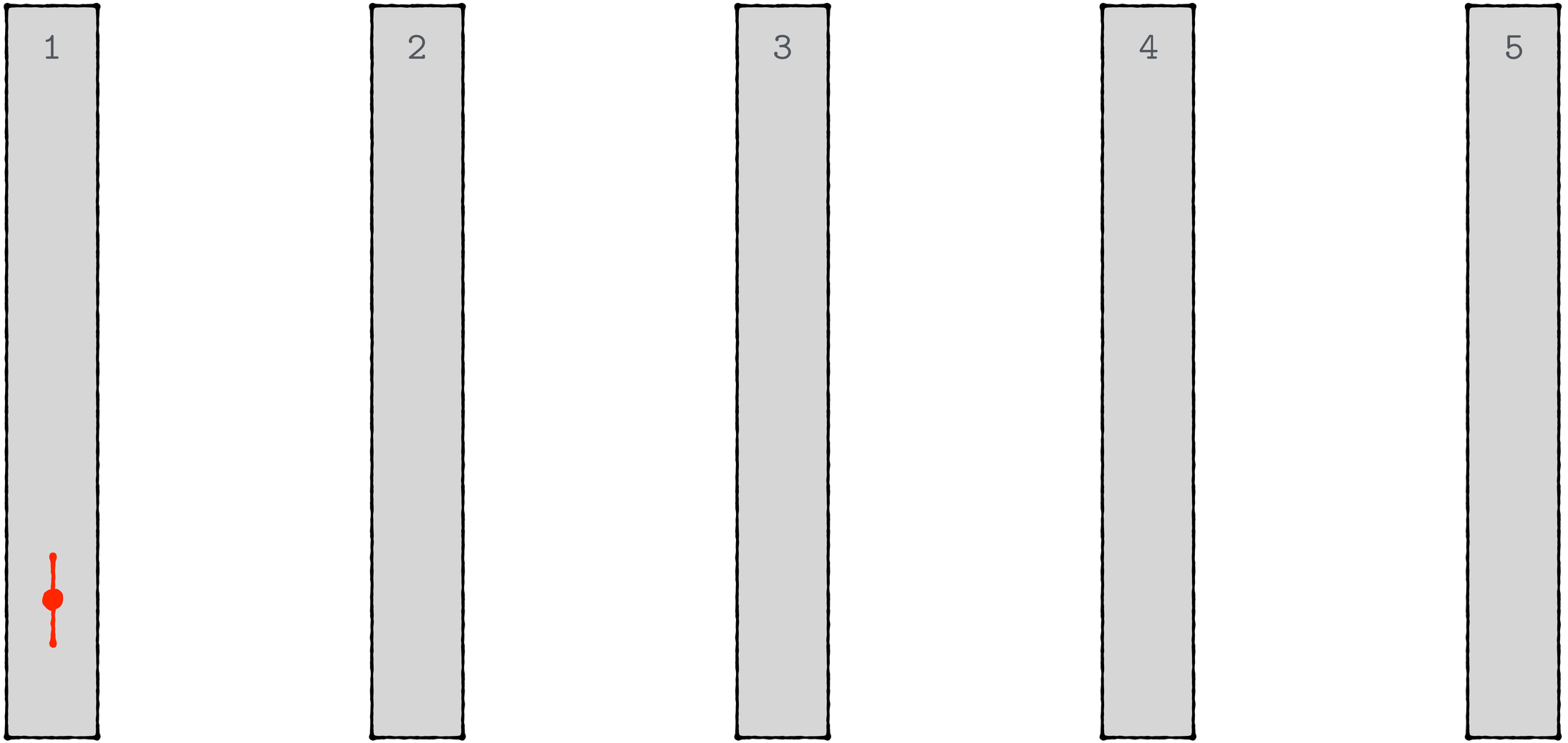

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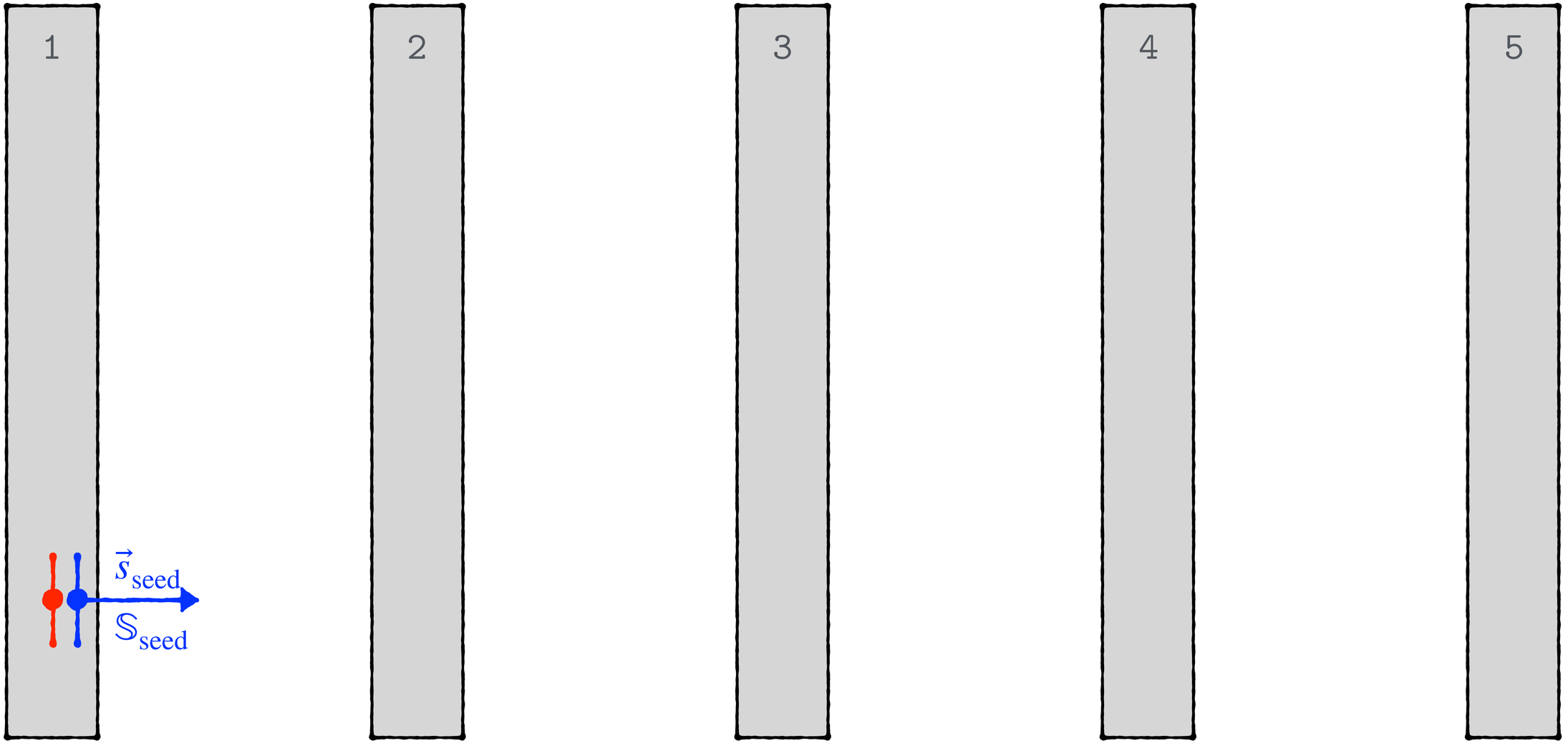
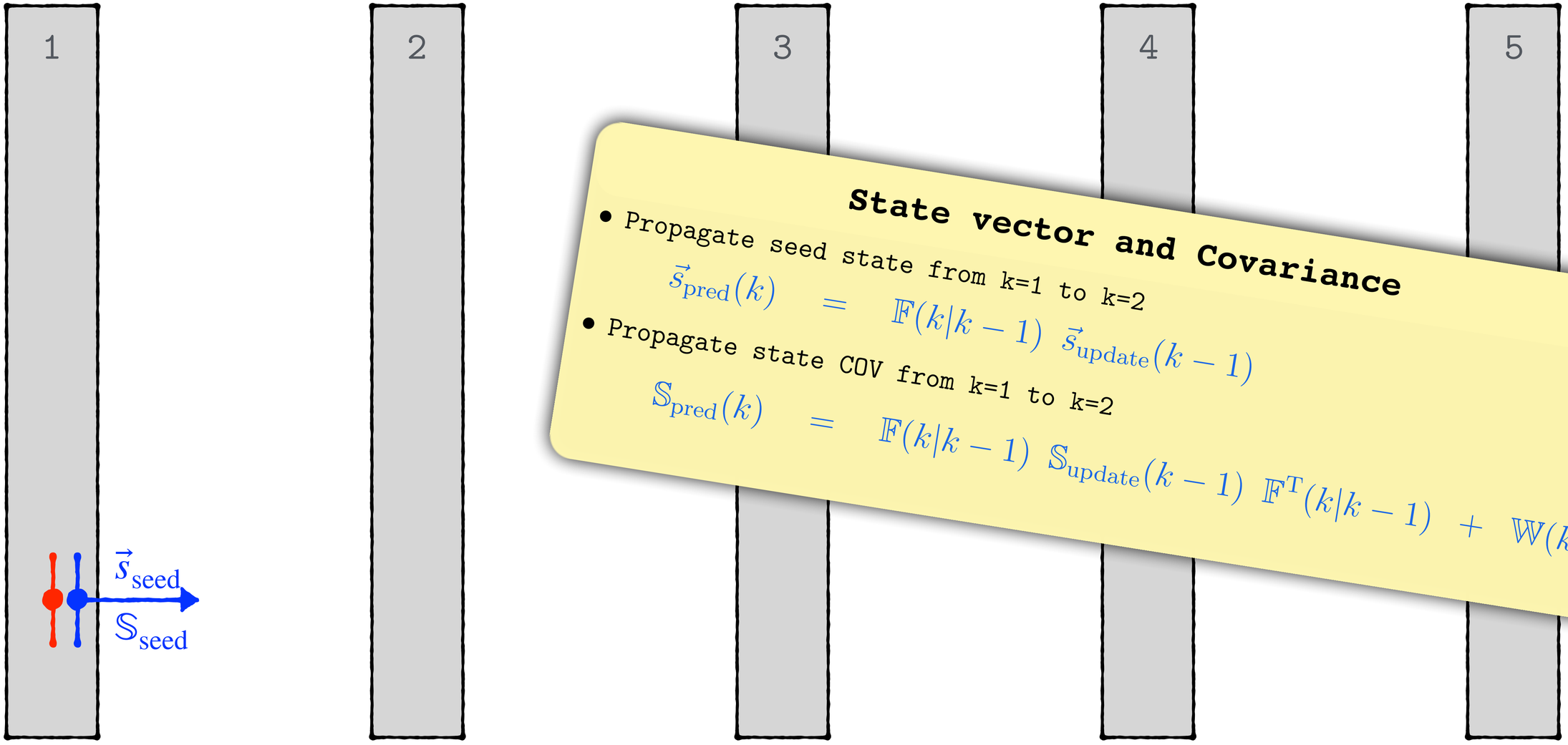


Prediction

Measurement

Filtered

Track finding & reconstruction: Kalman Filter



State vector and Covariance

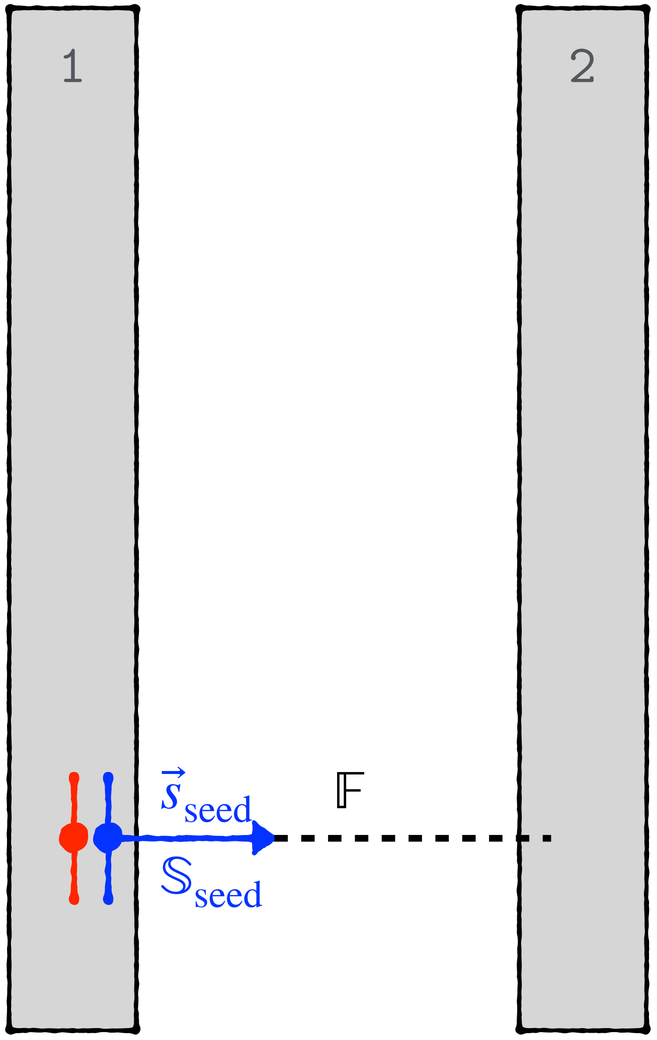
- Propagate seed state from k=1 to k=2

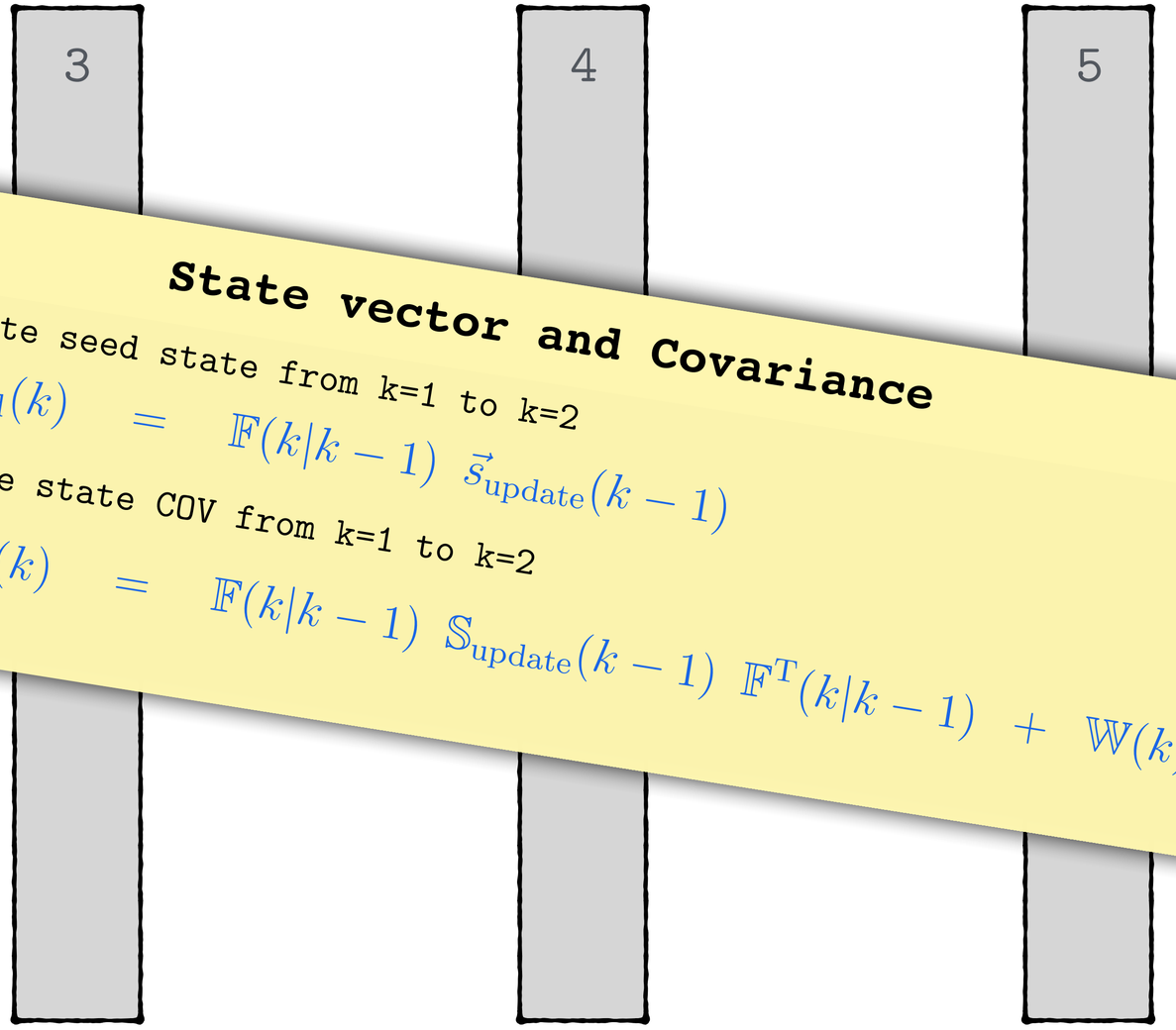
$$\vec{s}_{\text{pred}}(k) = \mathbb{F}(k|k-1)\ \vec{s}_{\text{update}}(k-1)$$

- Propagate state COV from k=1 to k=2

$$\mathbb{S}_{\text{pred}}(k) = \mathbb{F}(k|k-1)\ \mathbb{S}_{\text{update}}(k-1)\ \mathbb{F}^{\text{T}}(k|k-1) + \mathbb{W}(k)$$

Track finding & reconstruction: Kalman Filter





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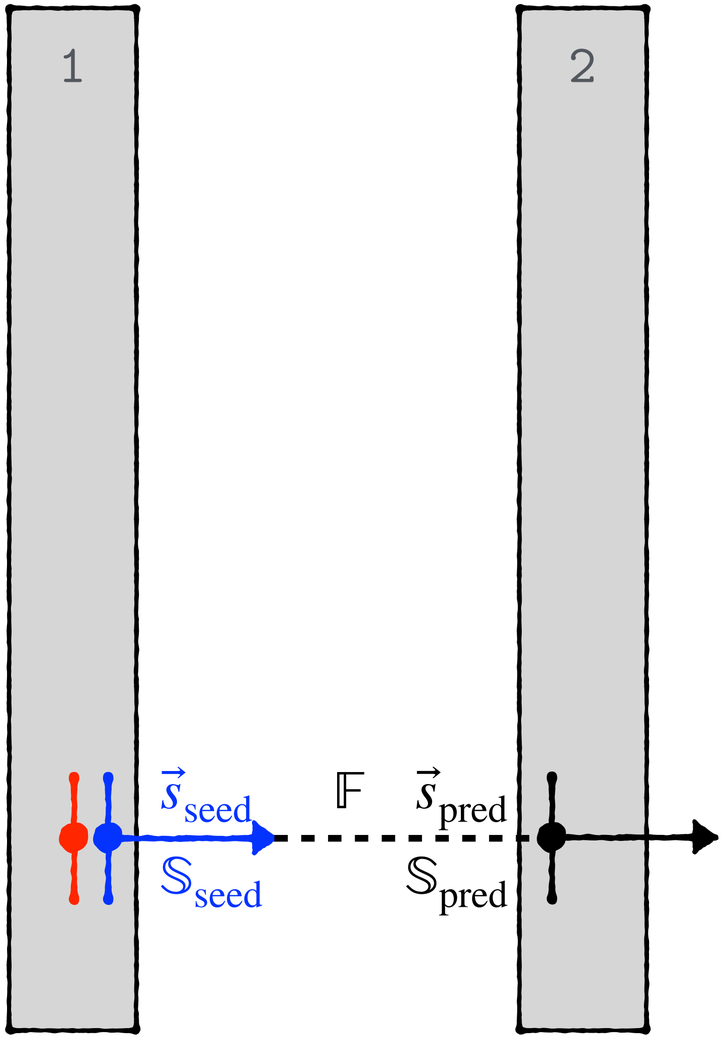
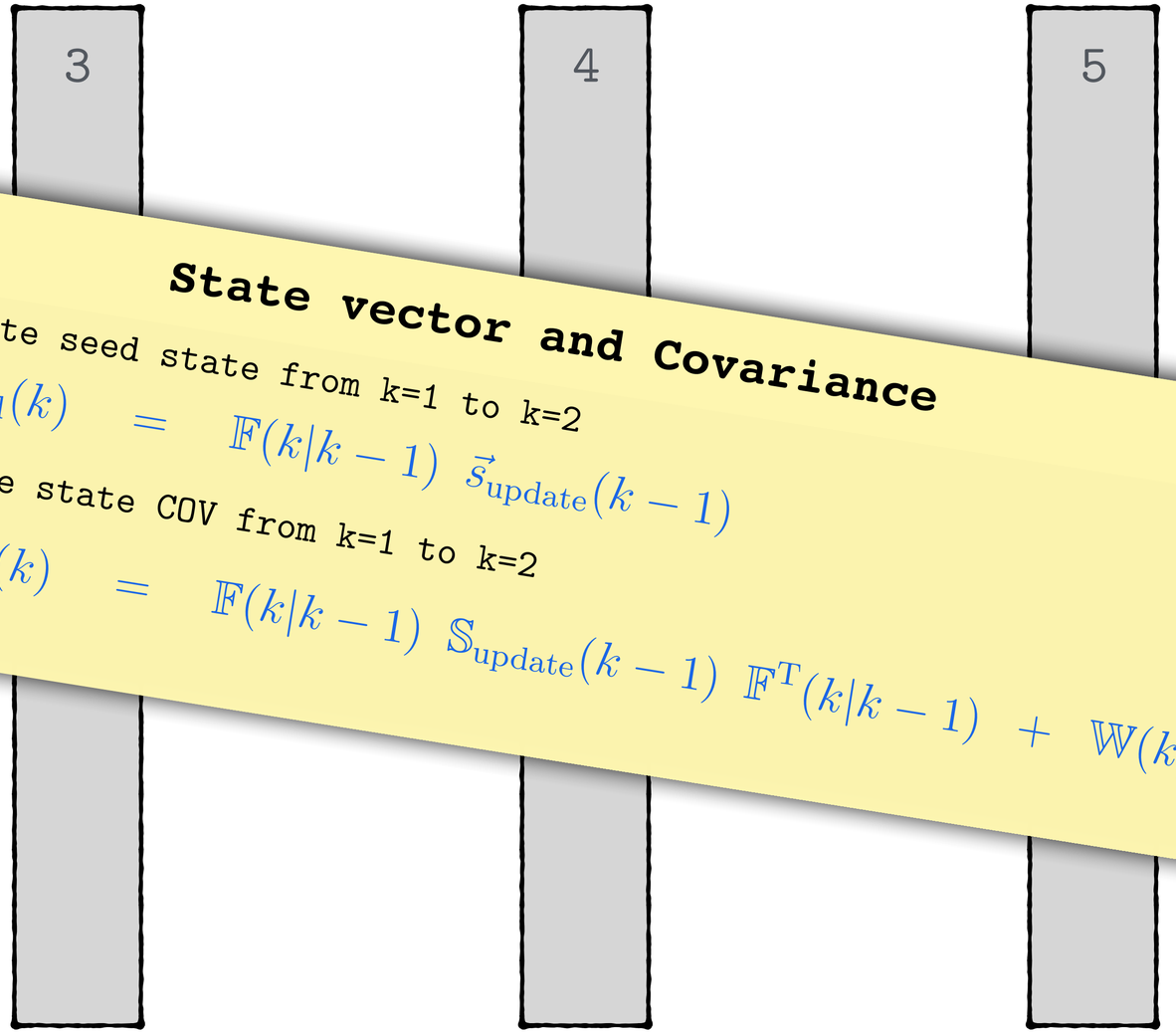
Track finding & reconstruction: Kalman Filter





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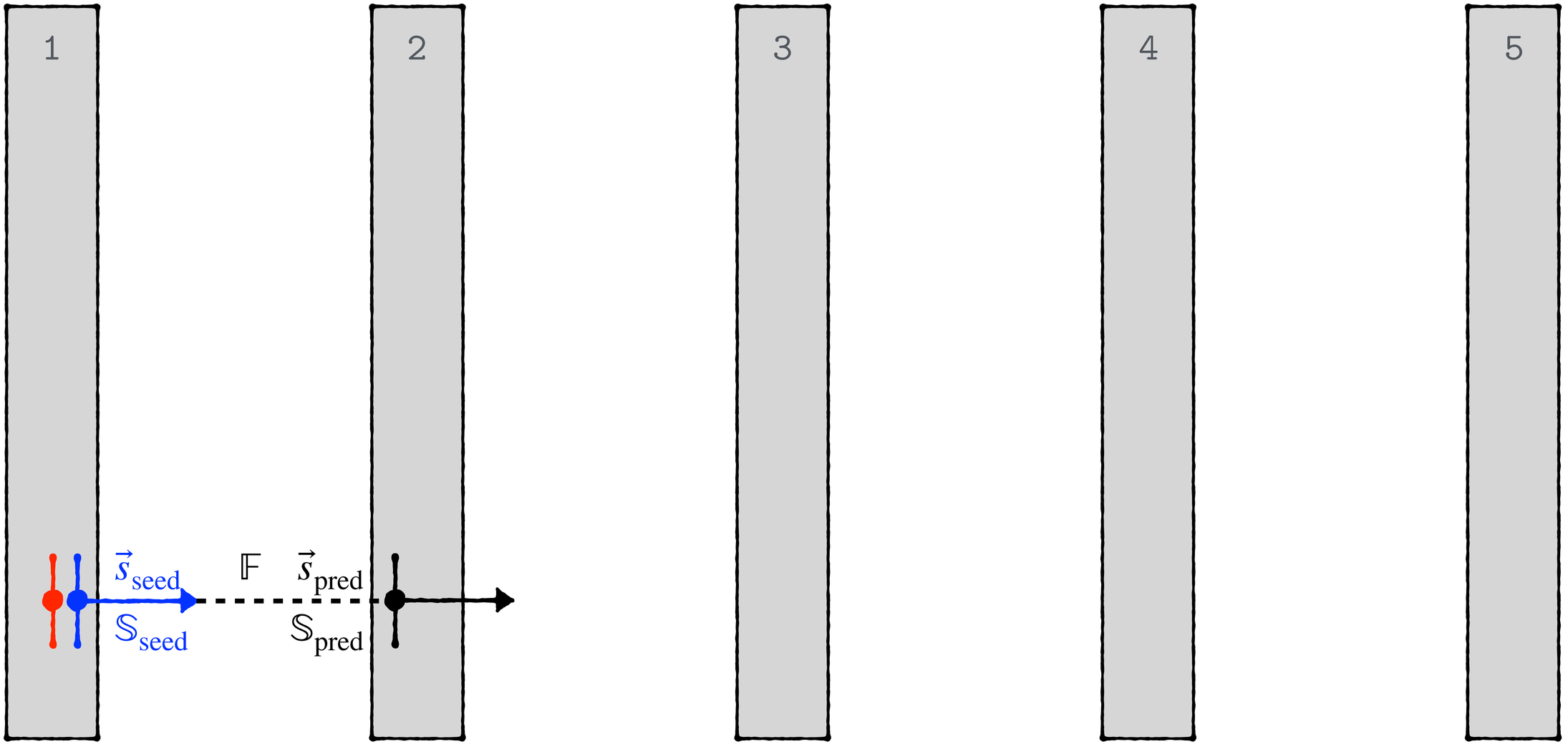

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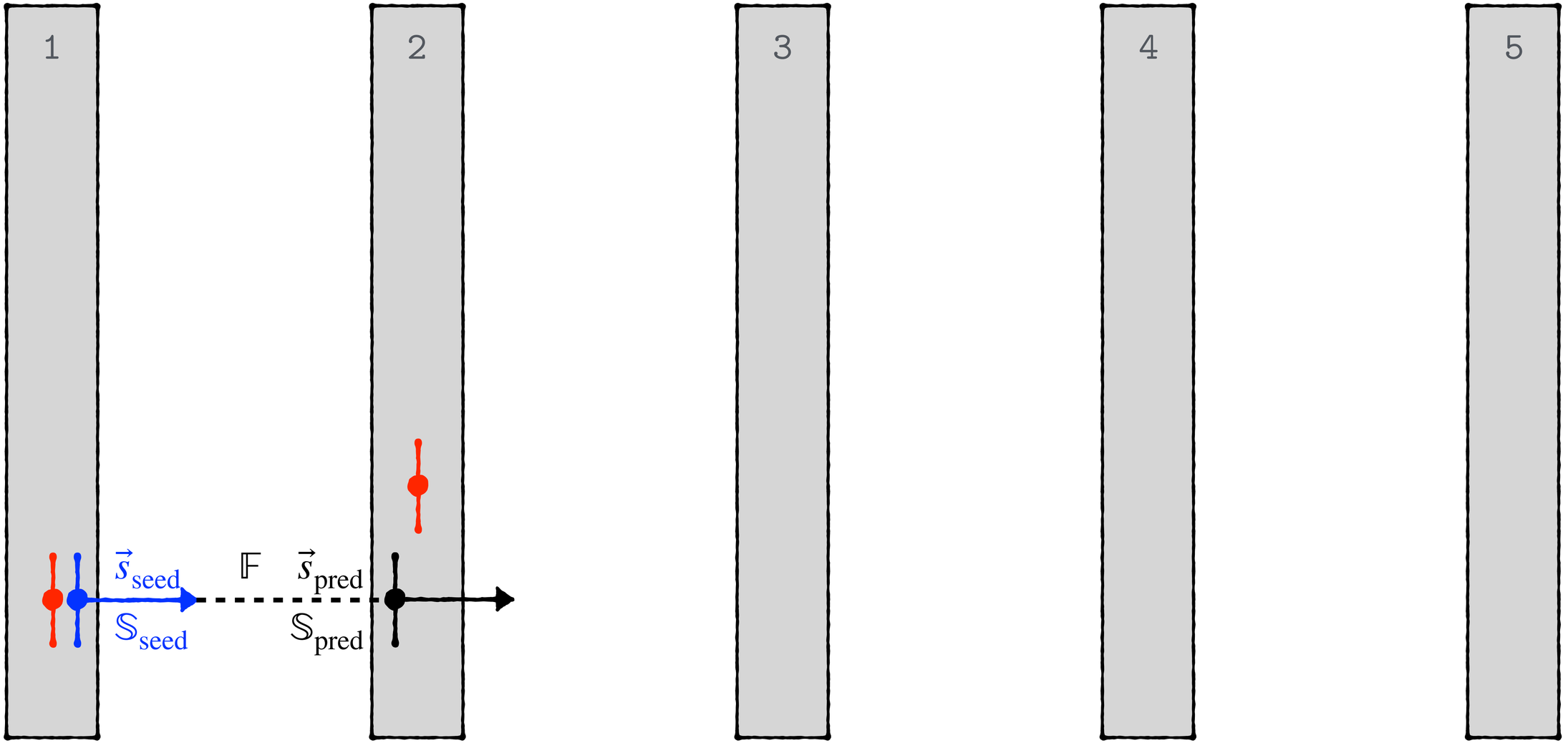

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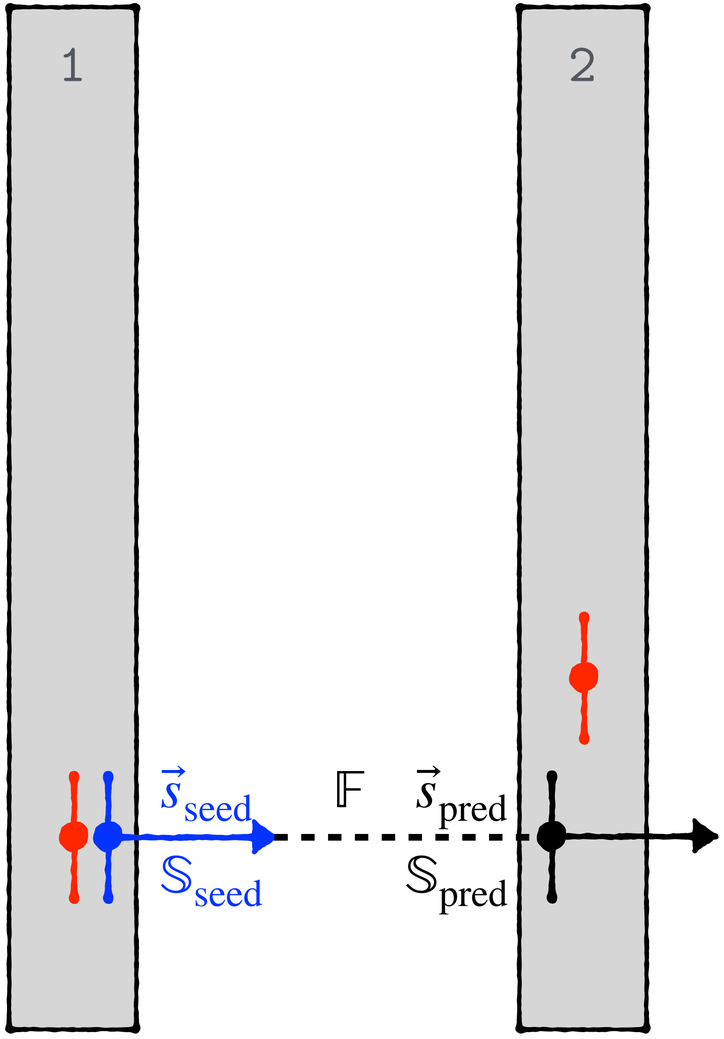

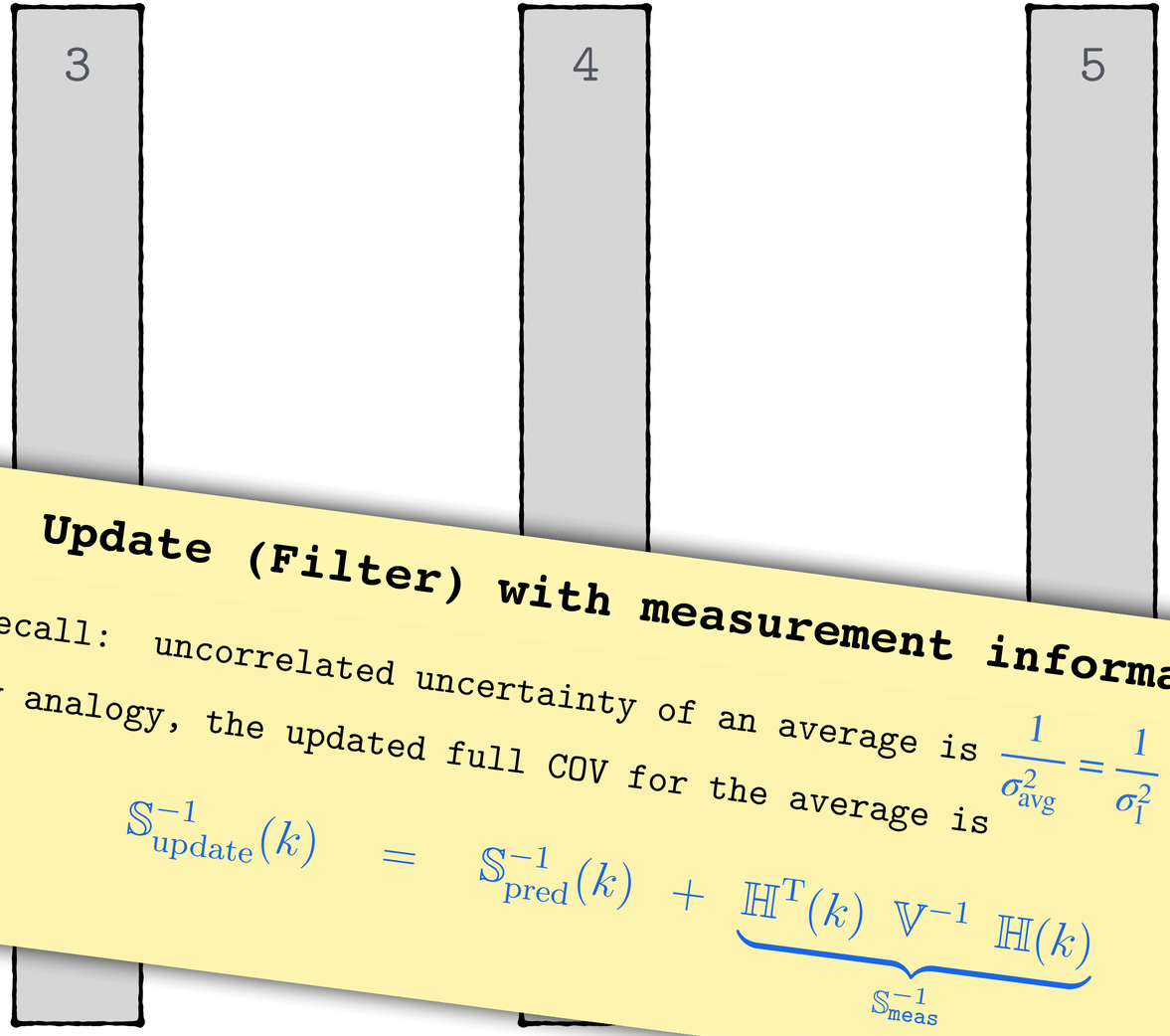

Update (Filter) with measurement information

- Recall: uncorrelated uncertainty of an average is $\frac{1}{\sigma^2_{\text{avg}}} = \frac{1}{\sigma^2_1} + \frac{1}{\sigma^2_2}$
- By analogy, the updated full COV for the average is

$$\mathbb{S}^{-1}_{\text{update}}(k) = \mathbb{S}^{-1}_{\text{pred}}(k) + \underbrace{\mathbb{H}^{\text{T}}(k)\ \mathbb{V}^{-1}\ \mathbb{H}(k)}_{\mathbb{S}^{-1}_{\text{meas}}}$$

Prediction

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Track finding & reconstruction: Kalman Filter

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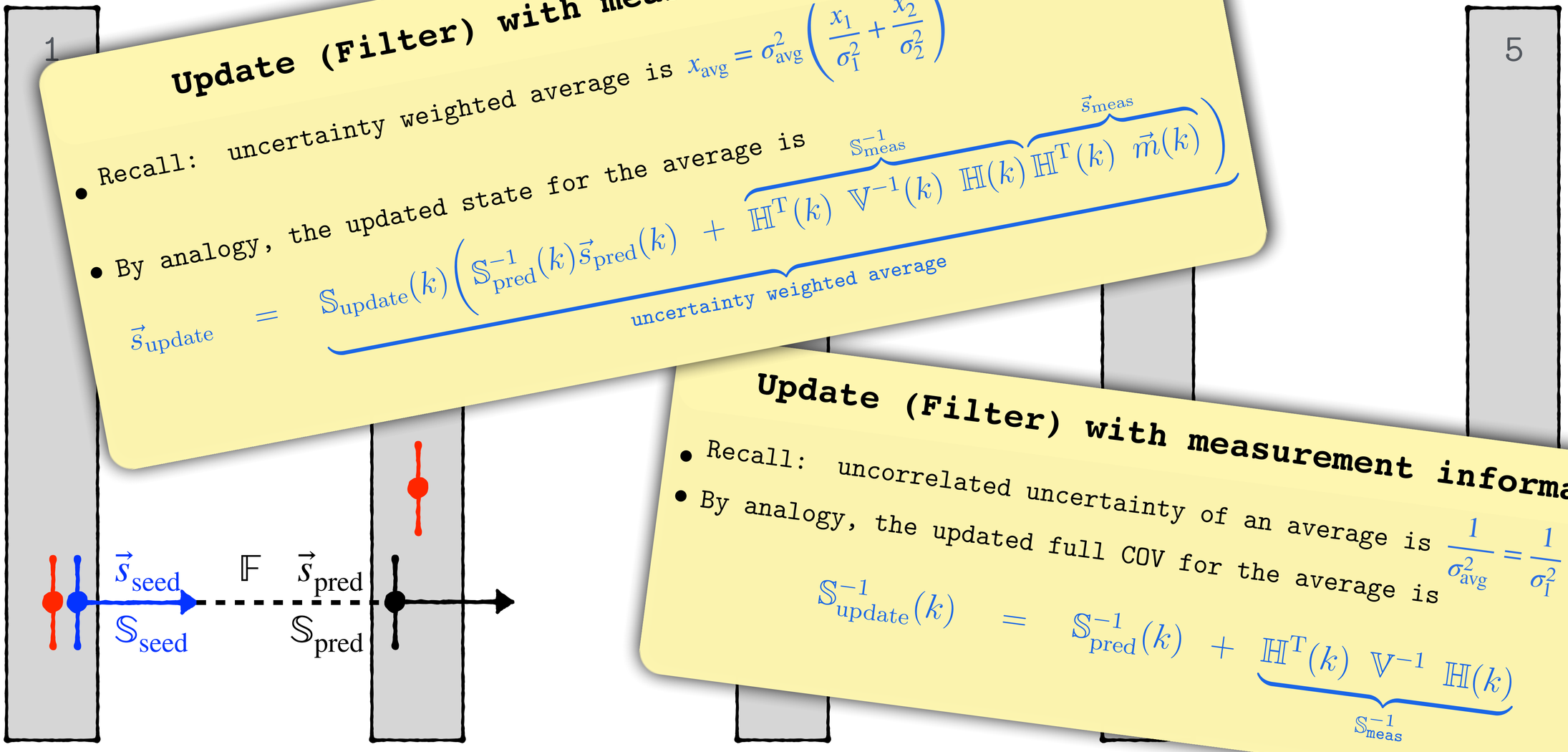

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uncertainty weighted average

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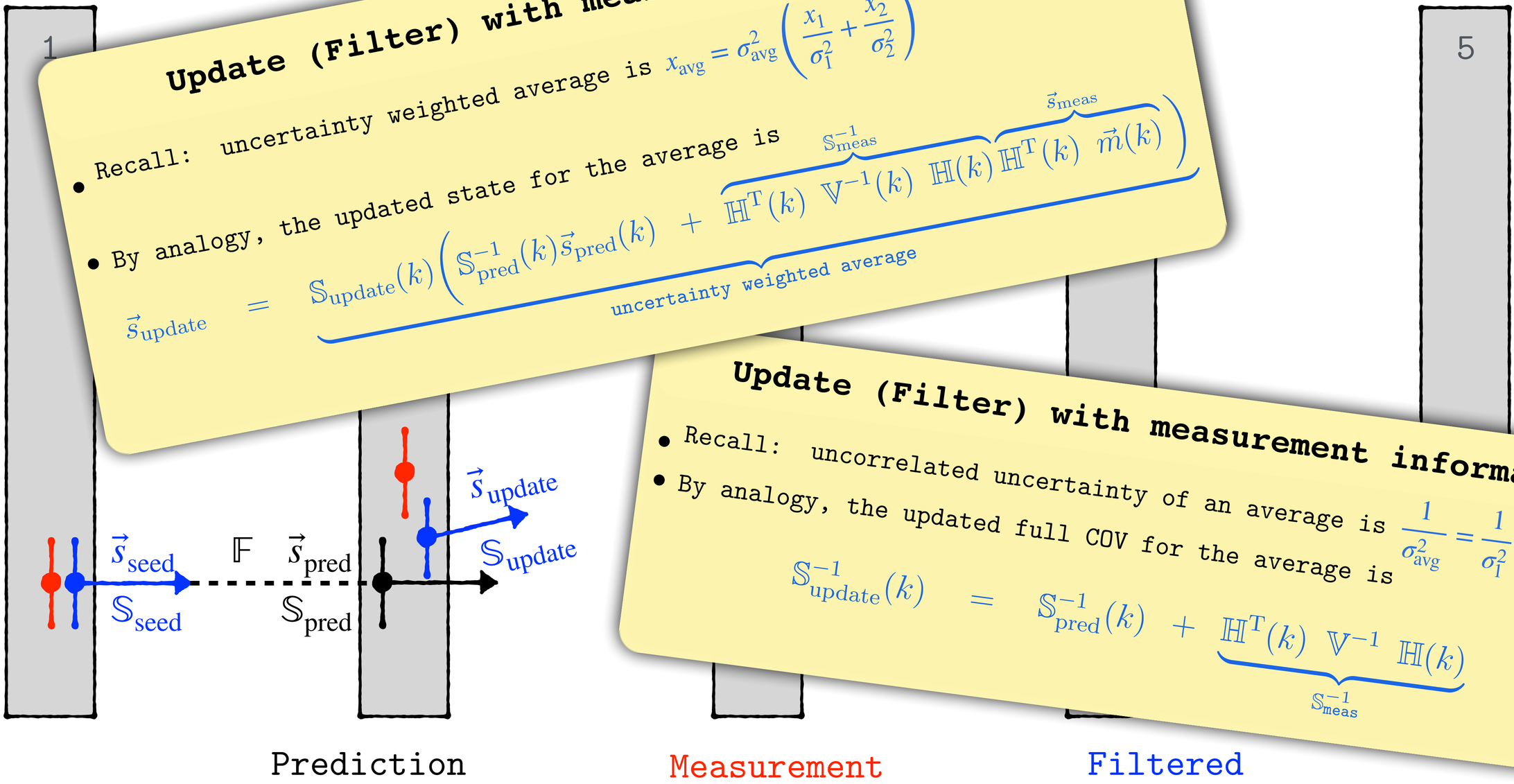

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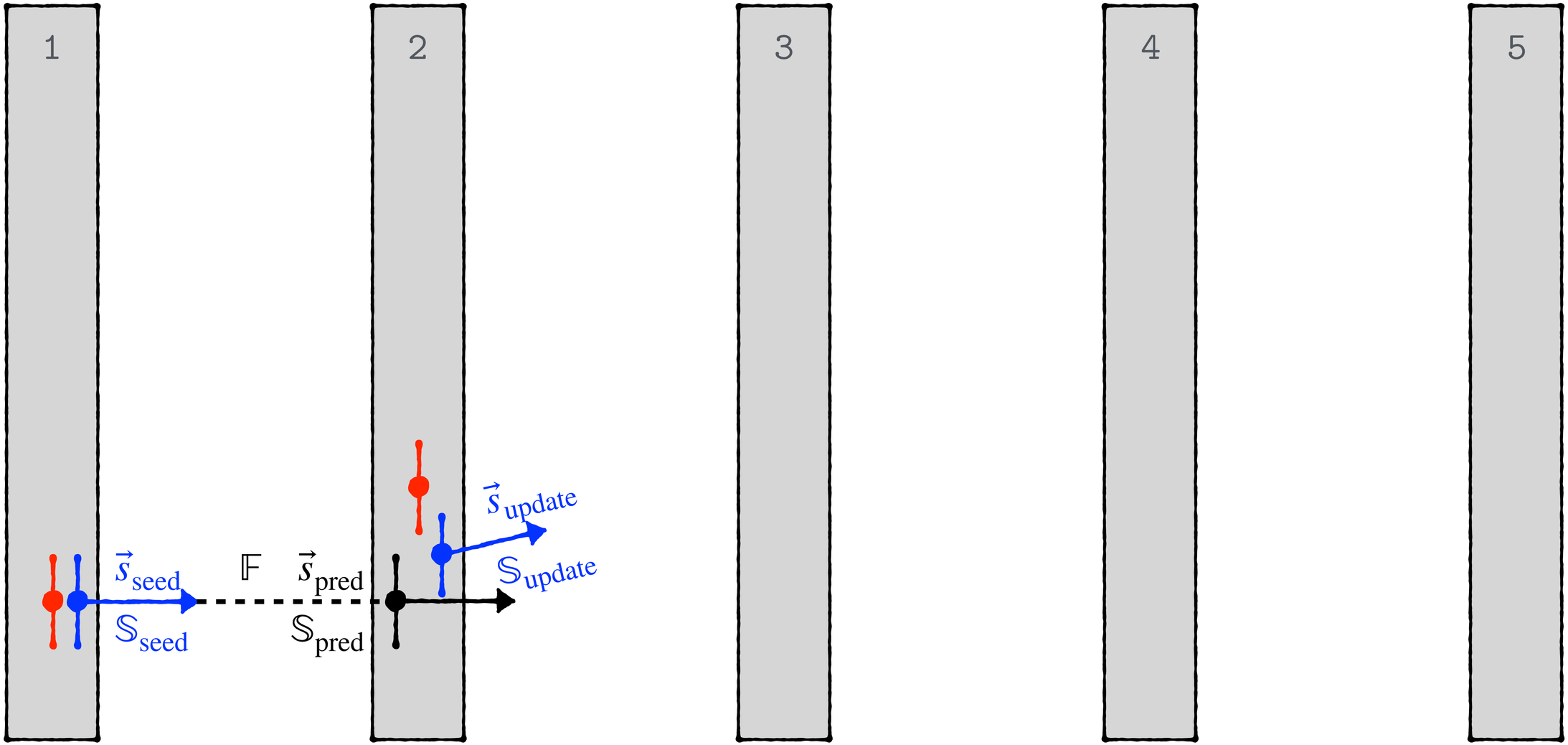

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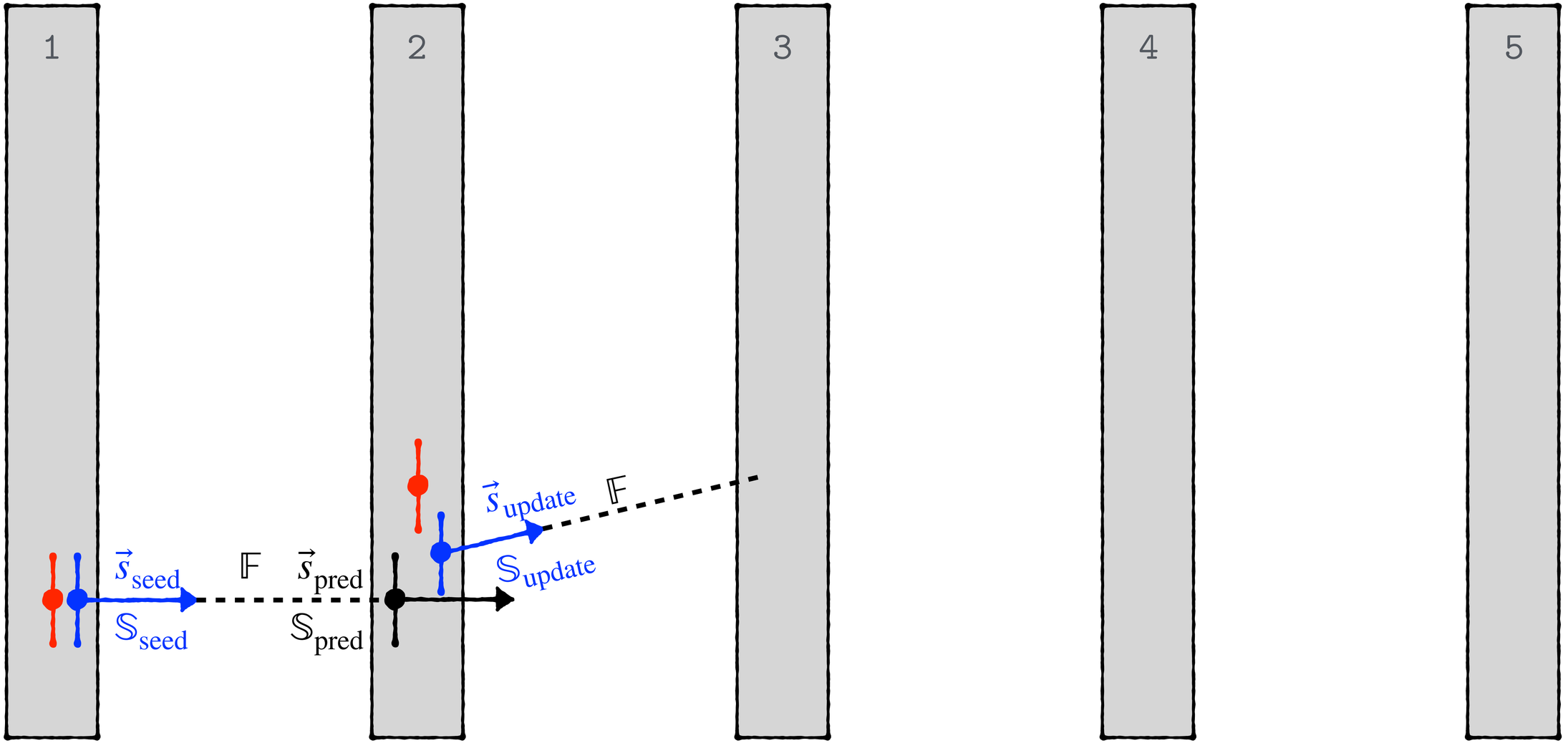

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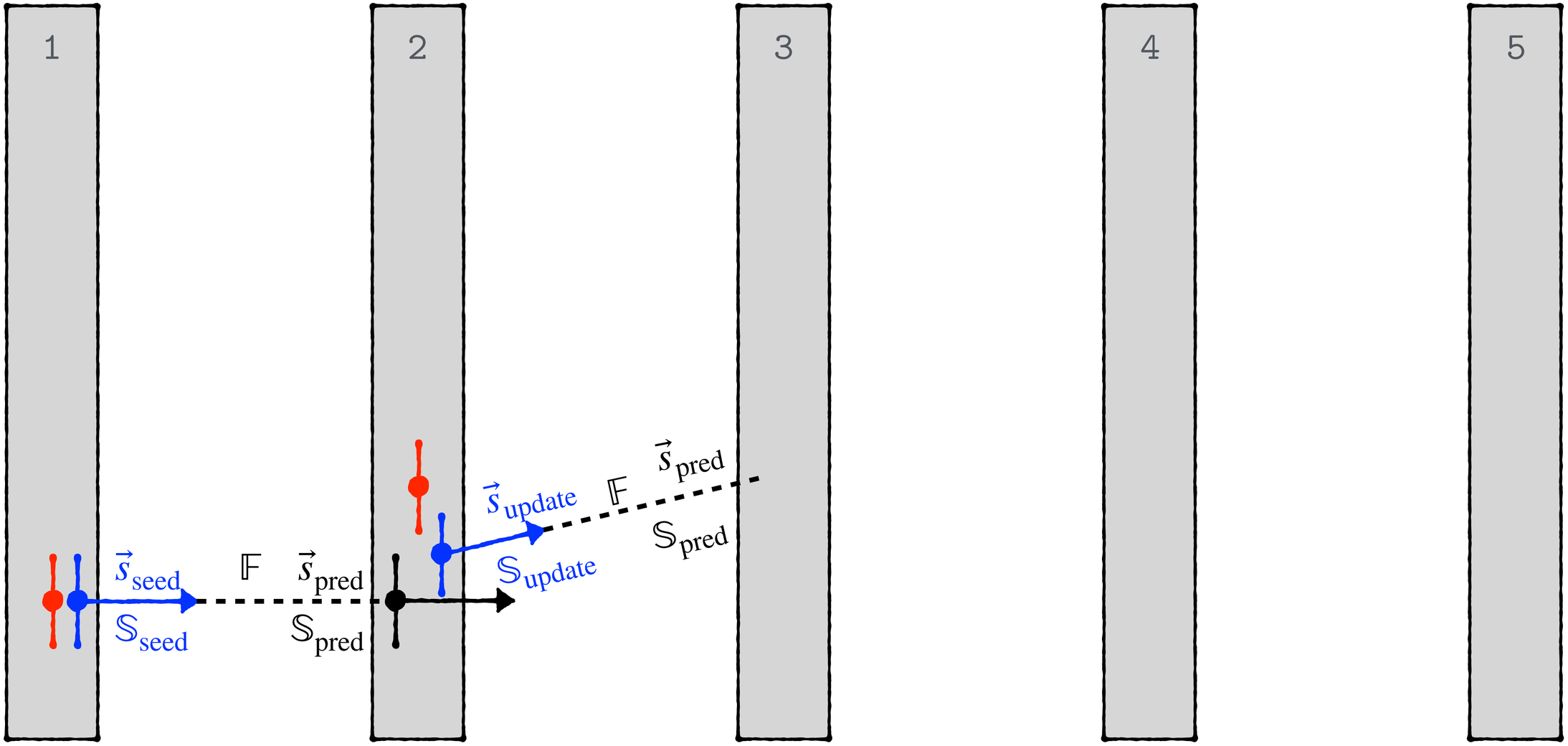

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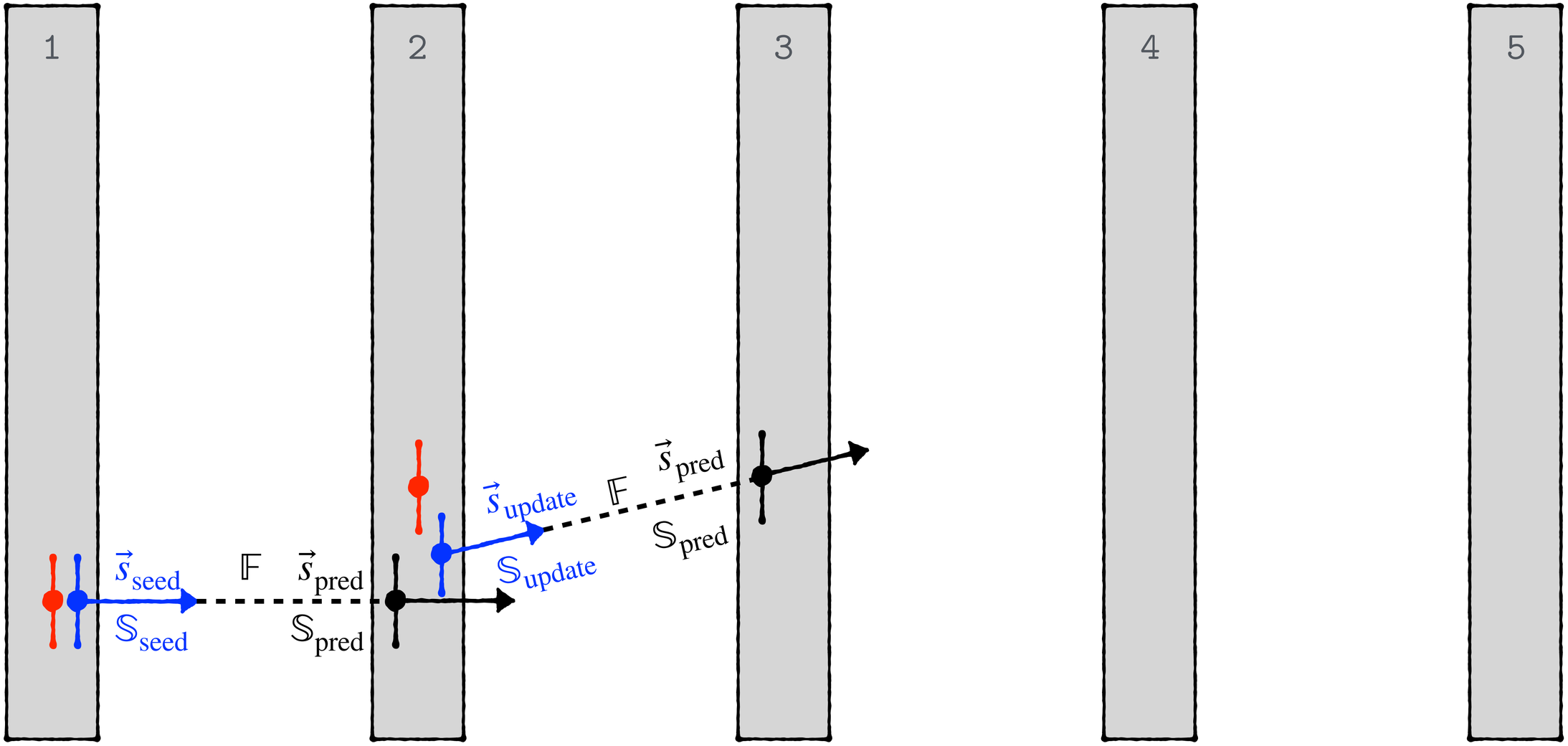

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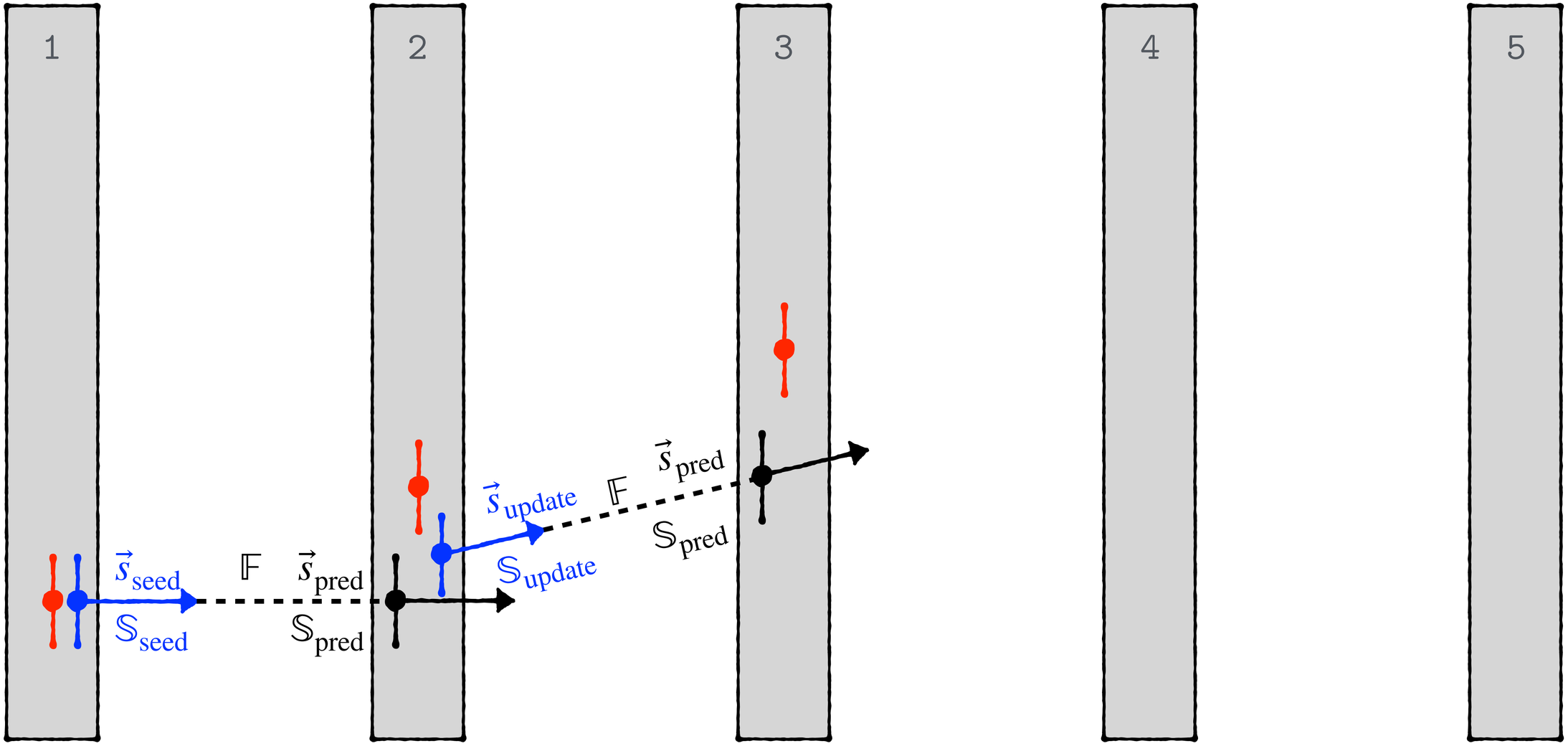

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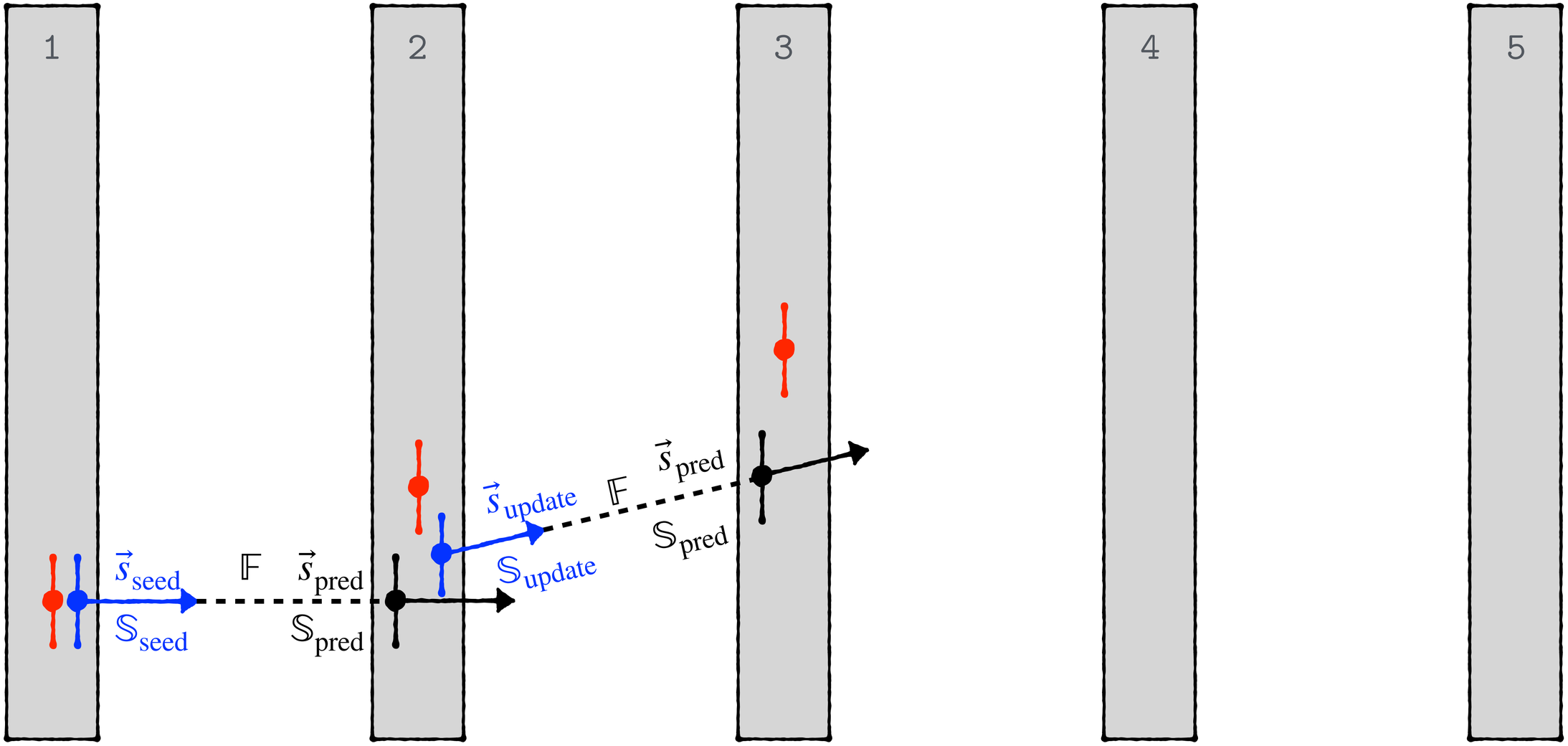

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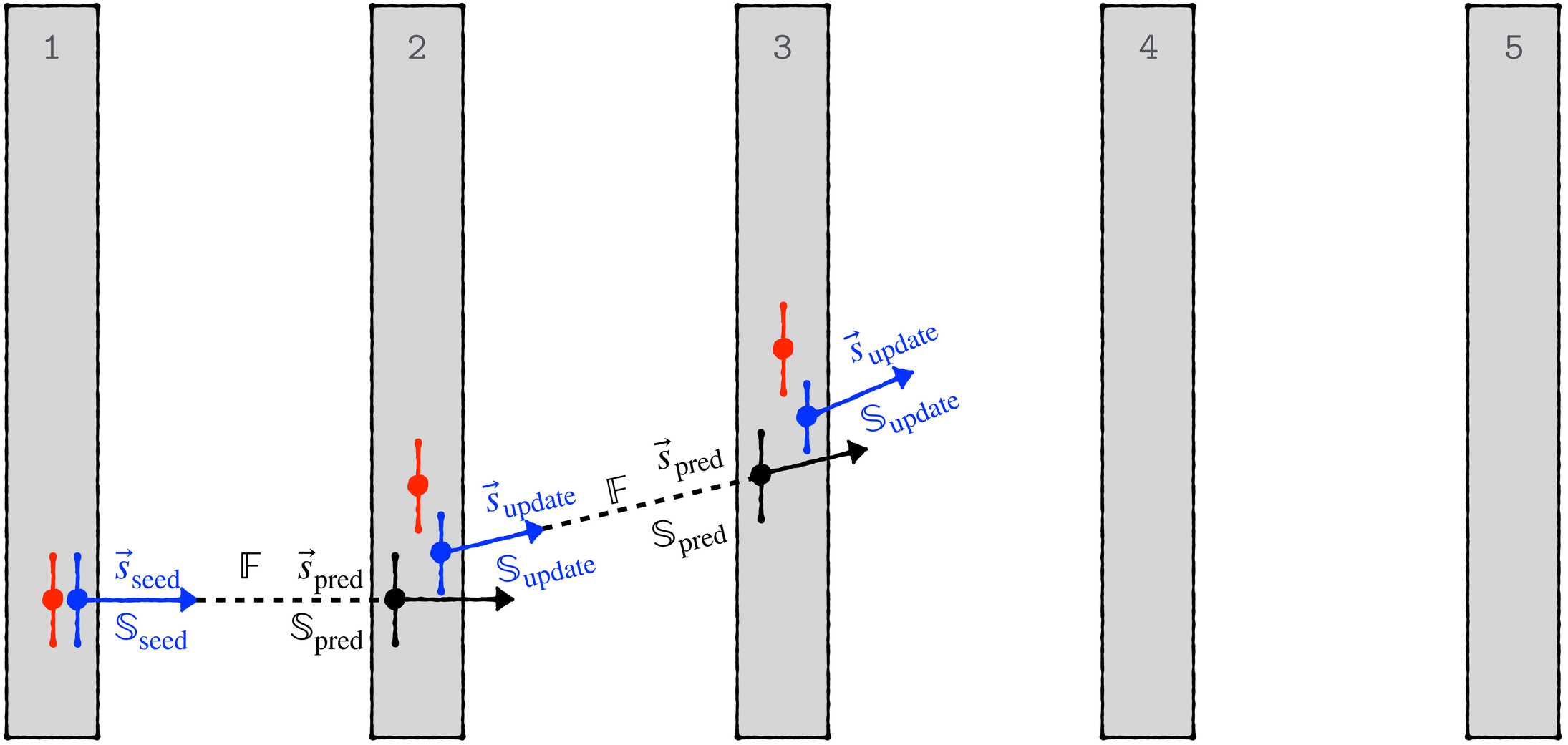

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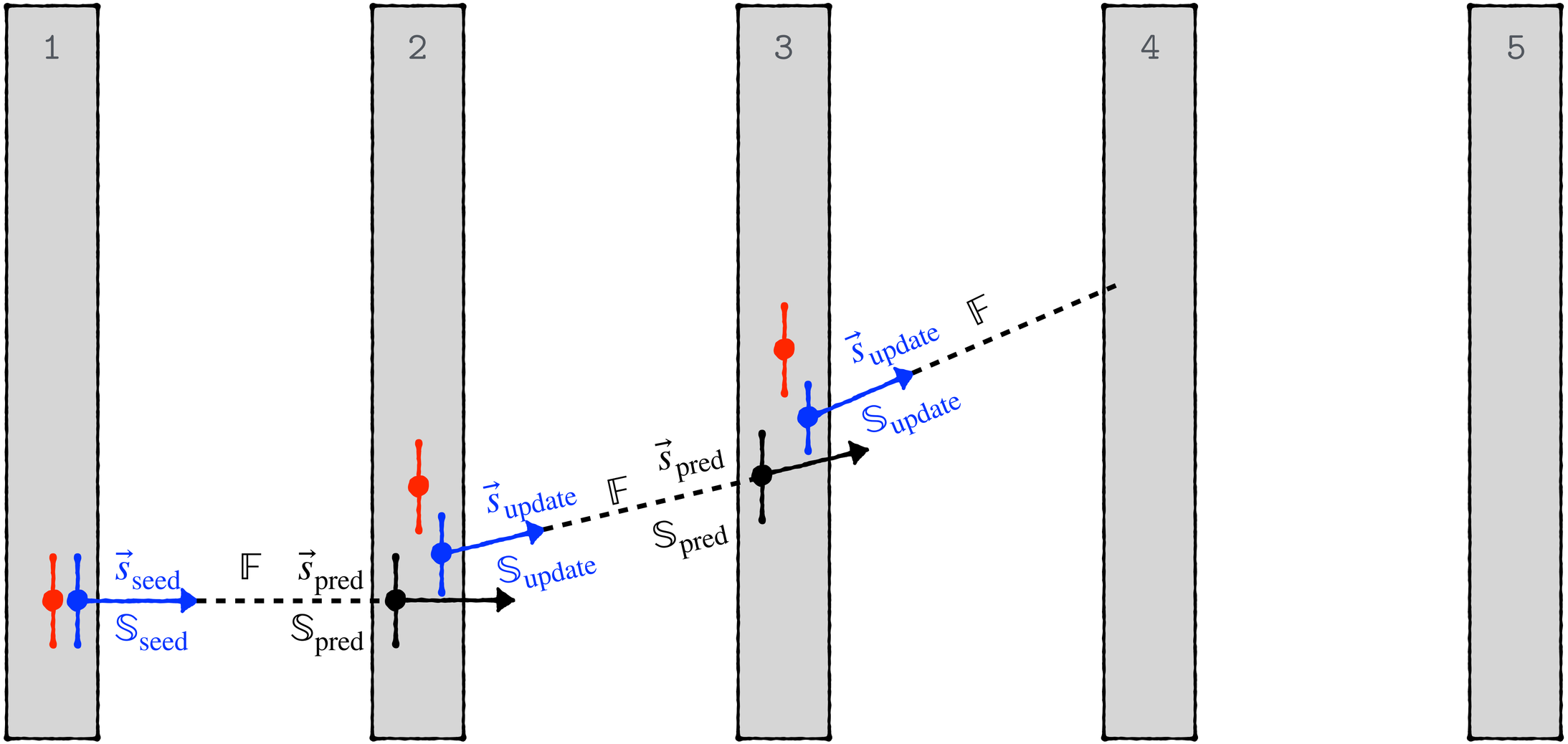

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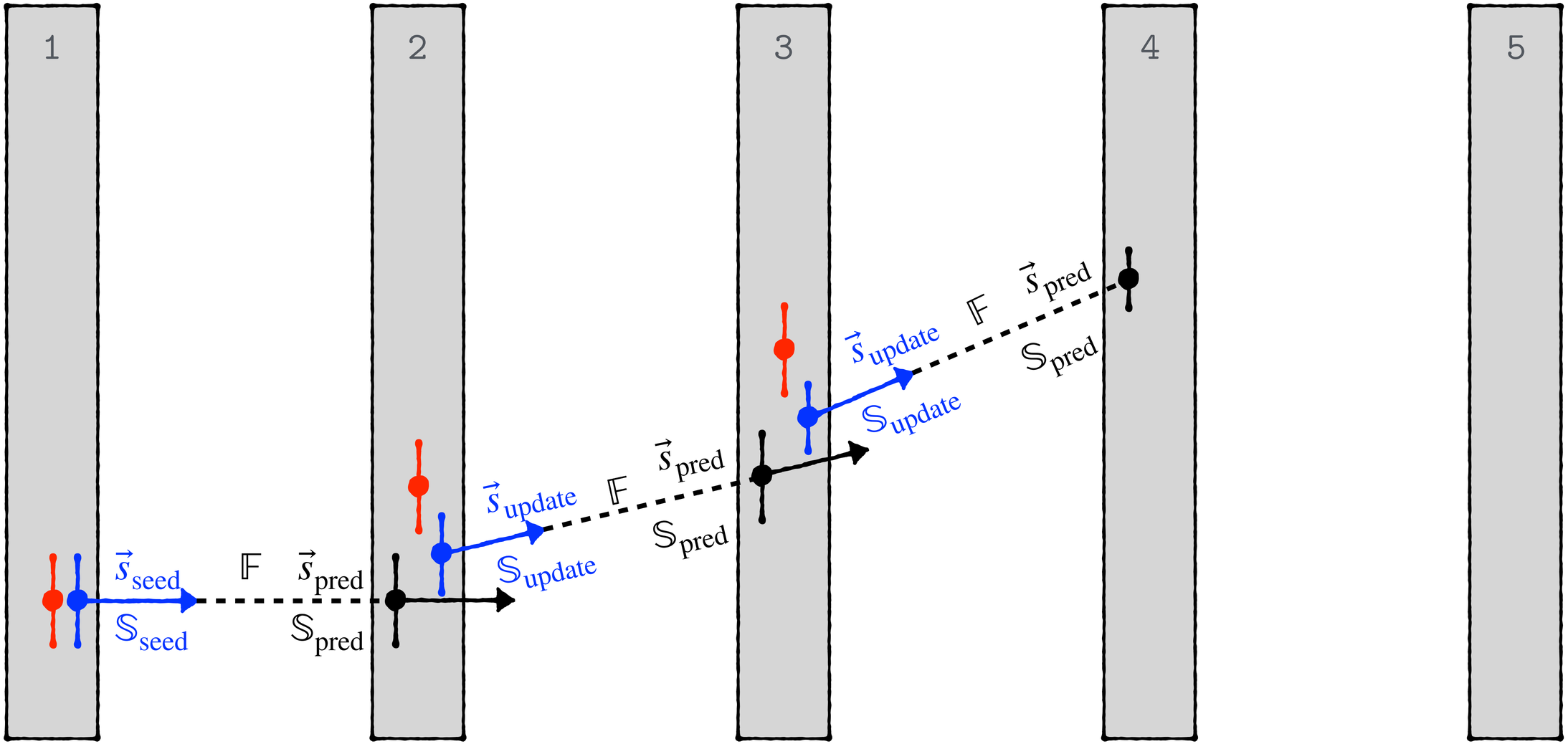

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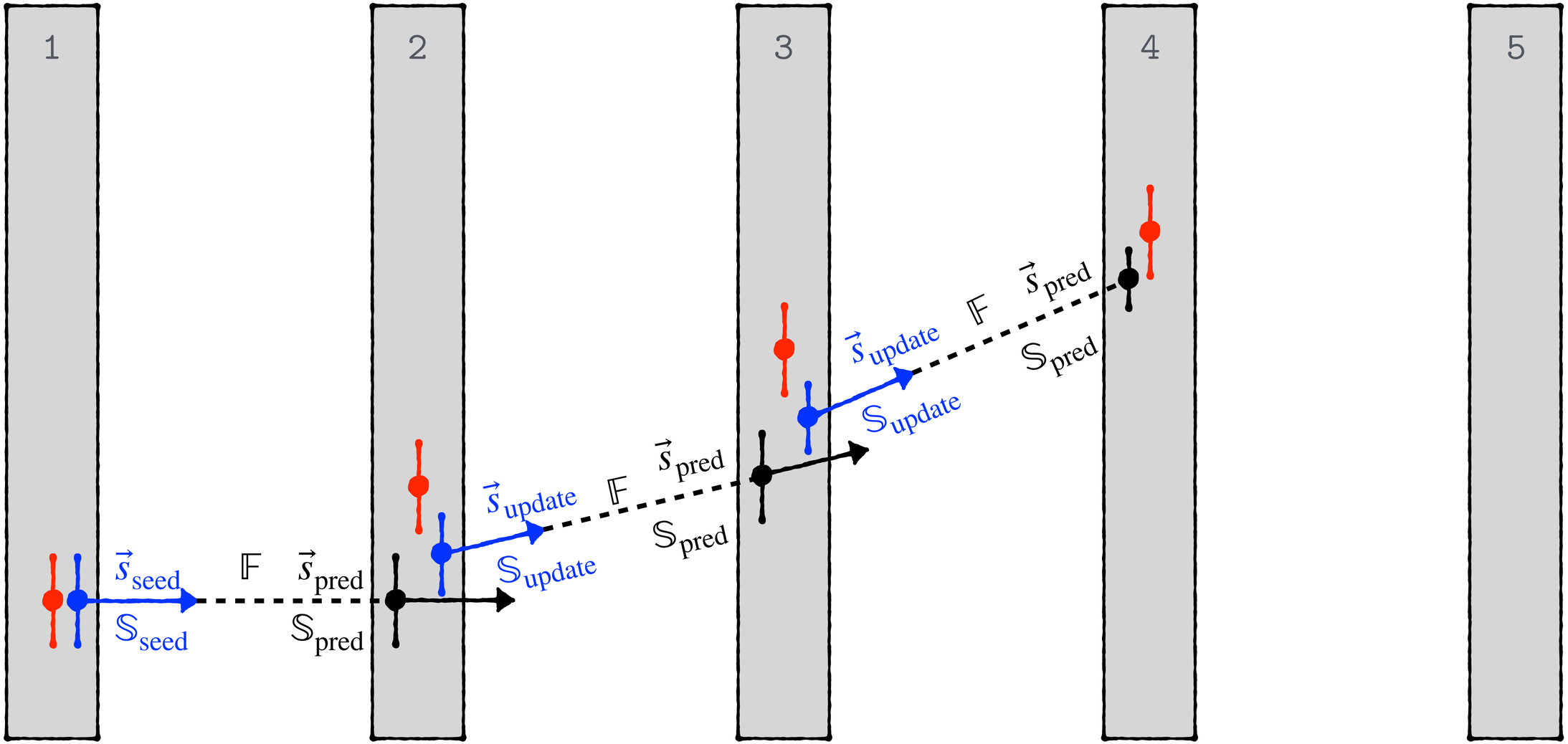

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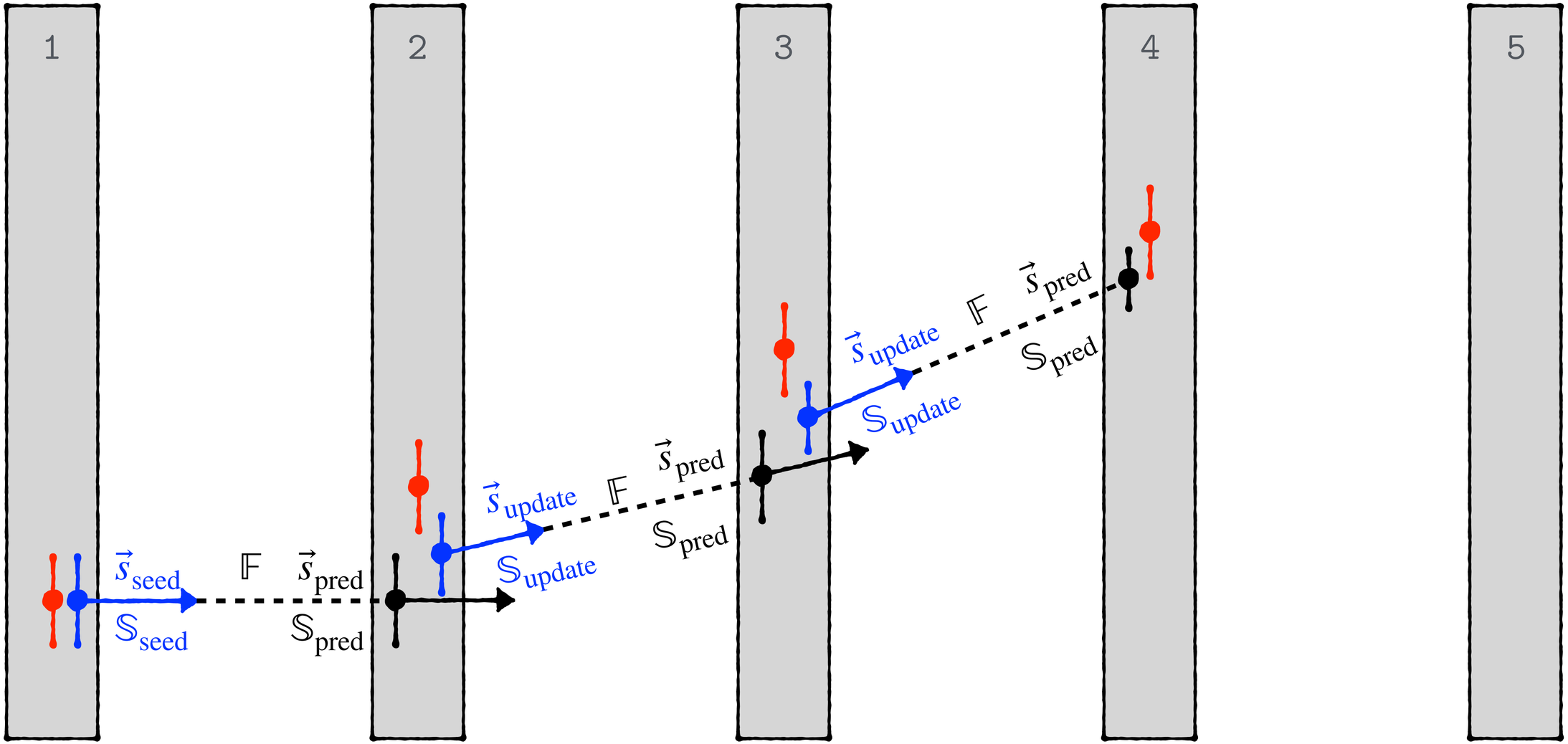

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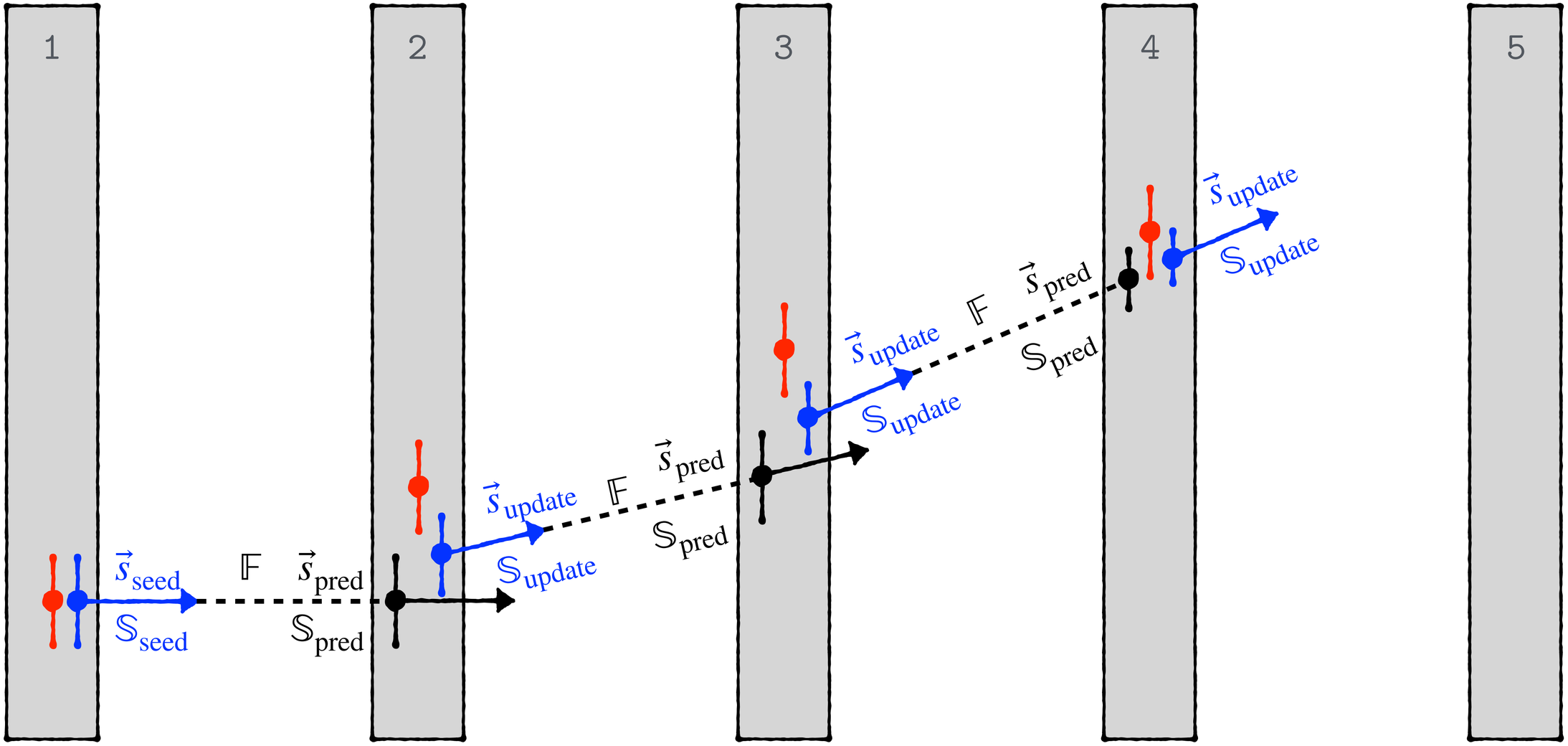

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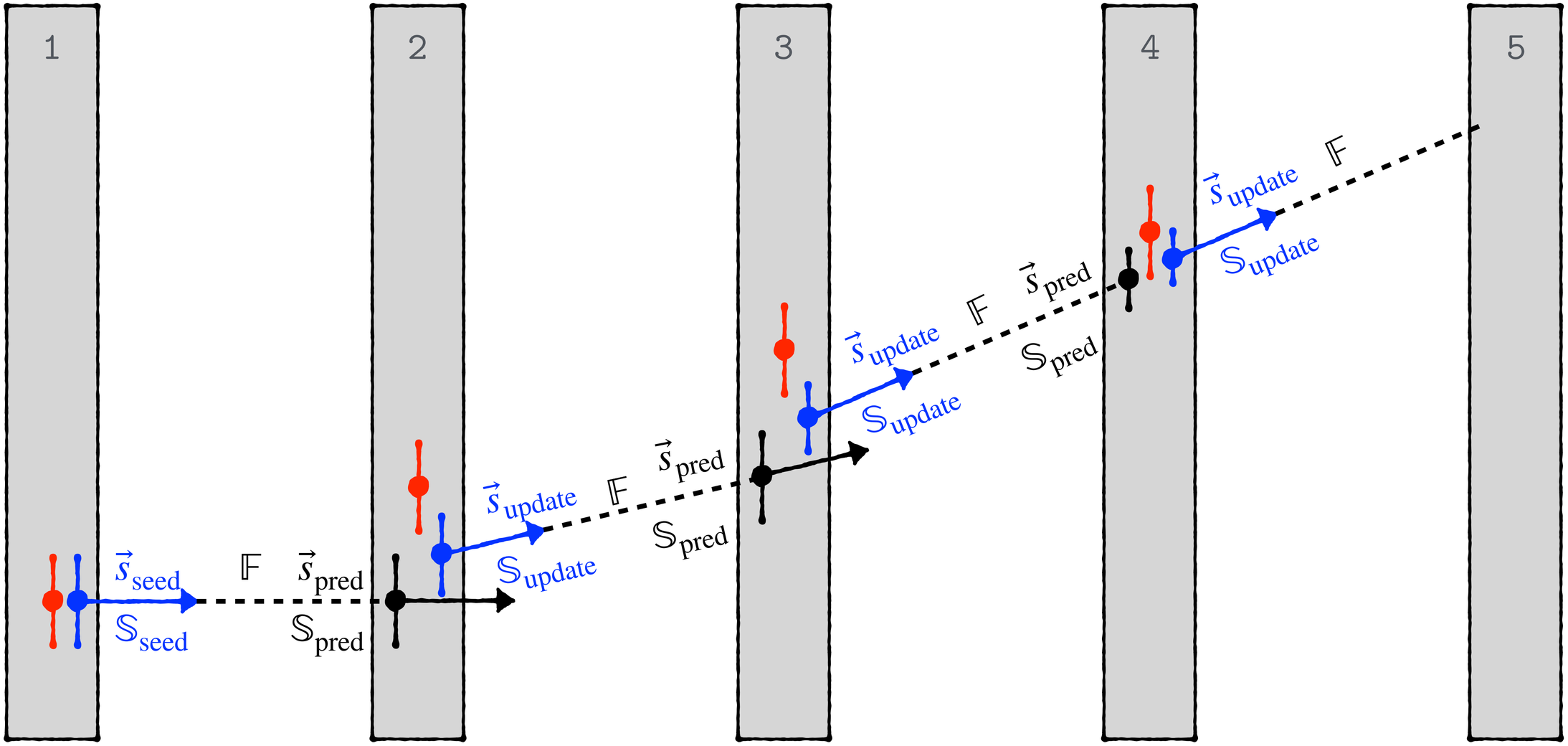

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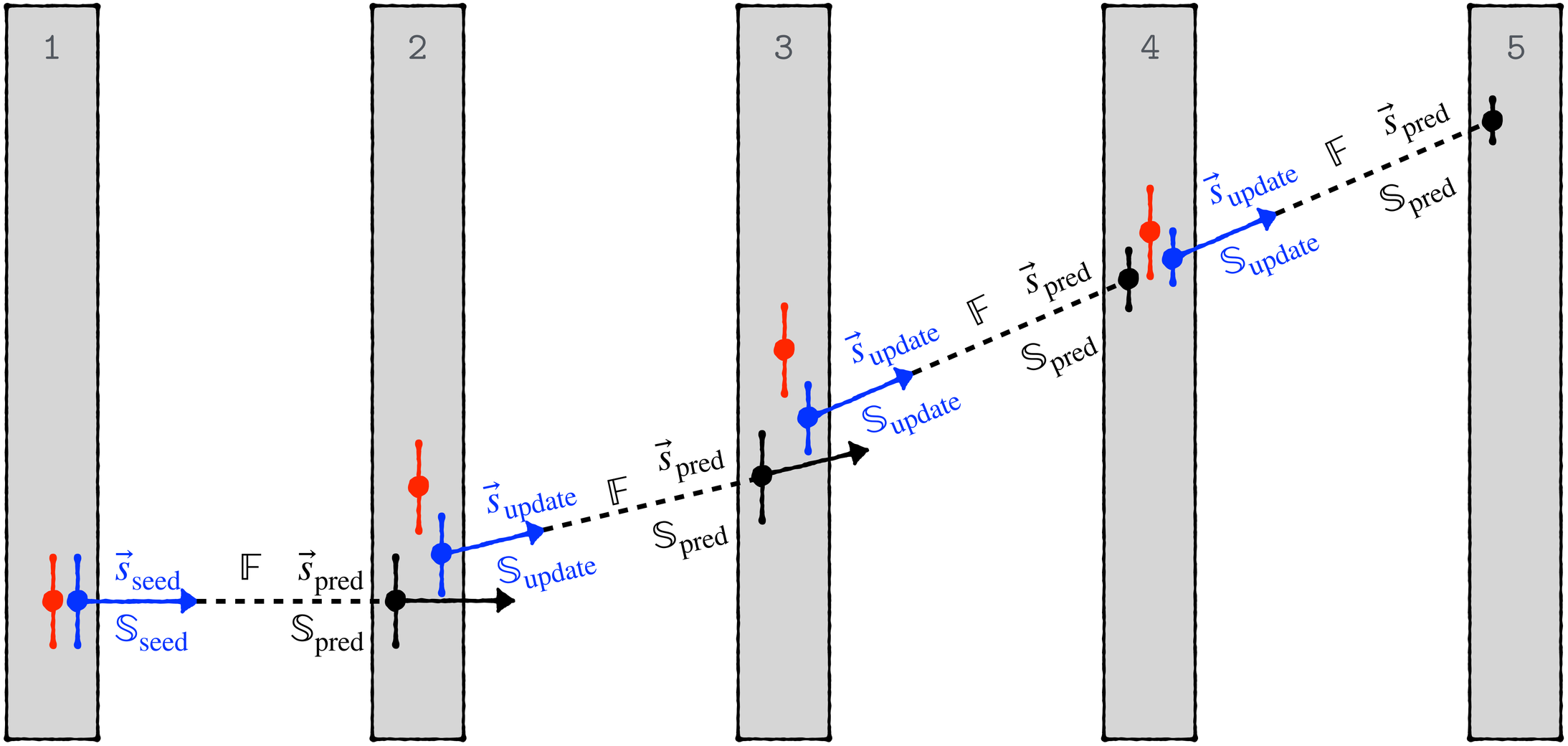

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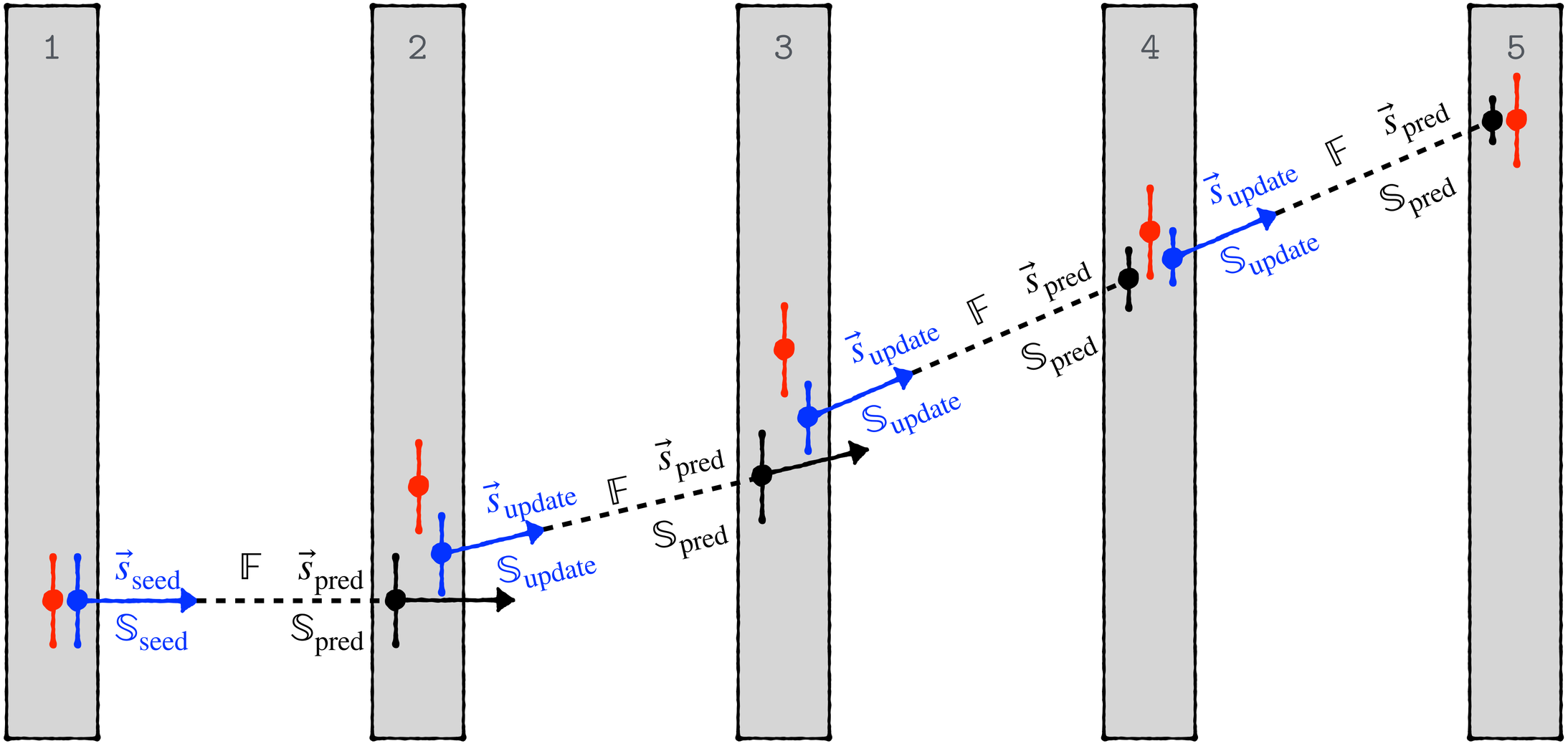
Track finding & reconstruction: Kalman Filter



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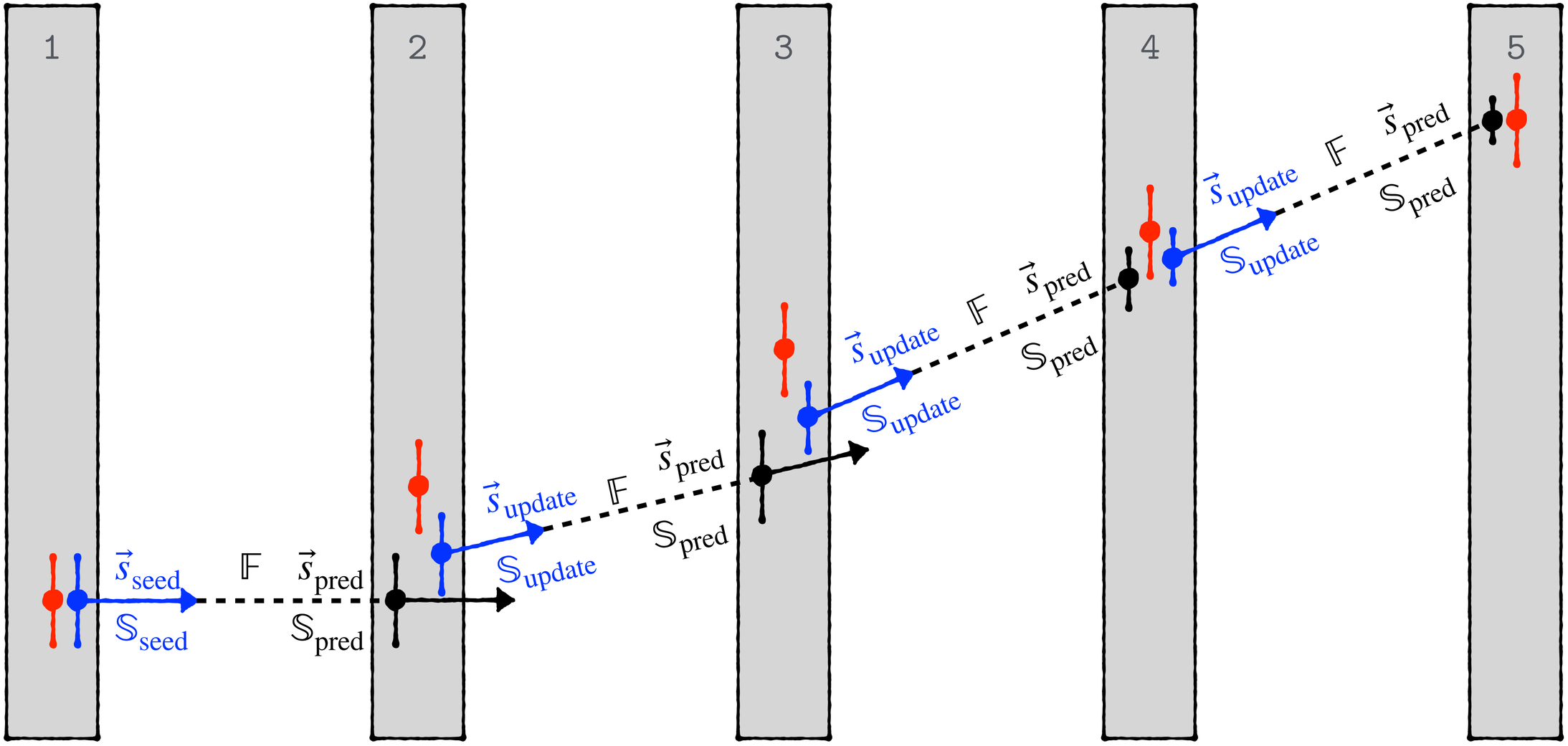

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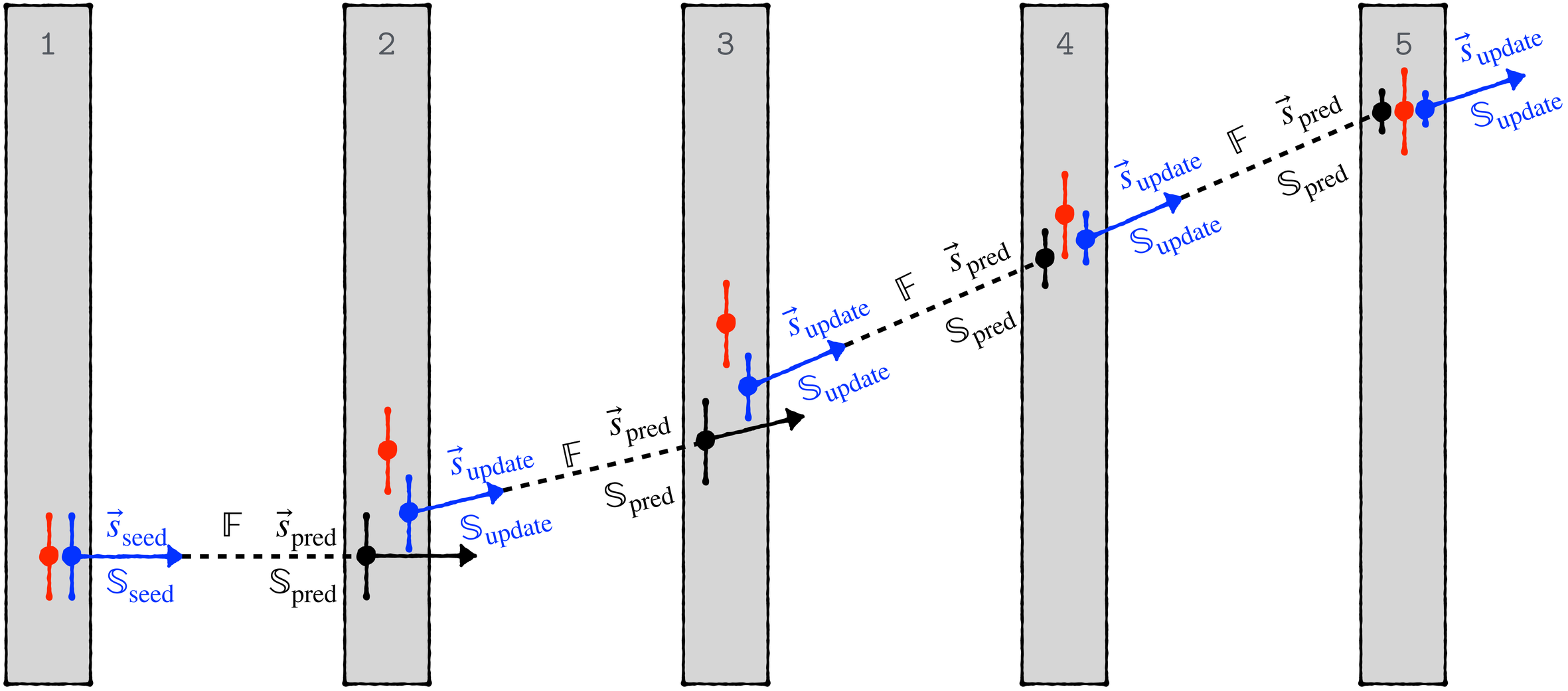

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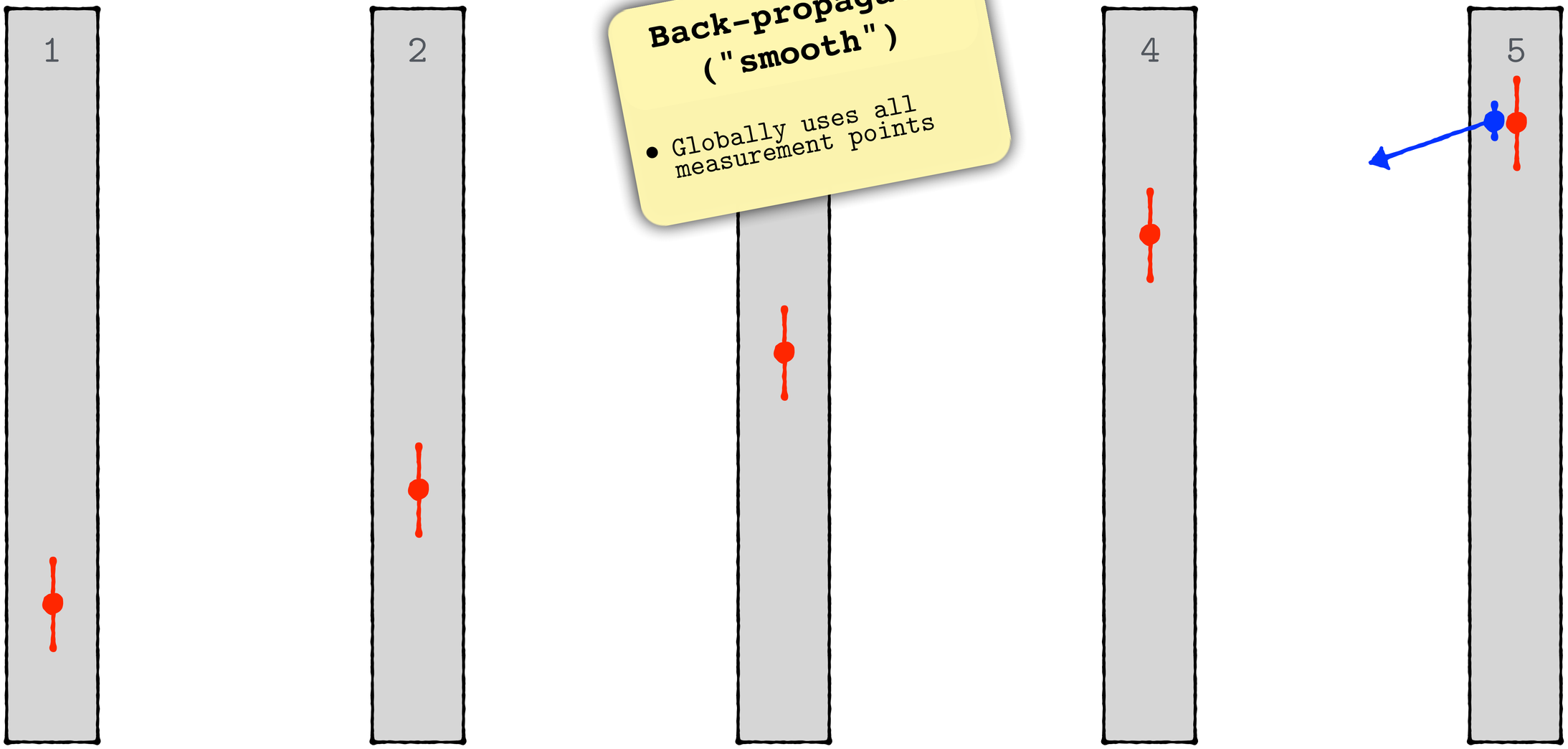

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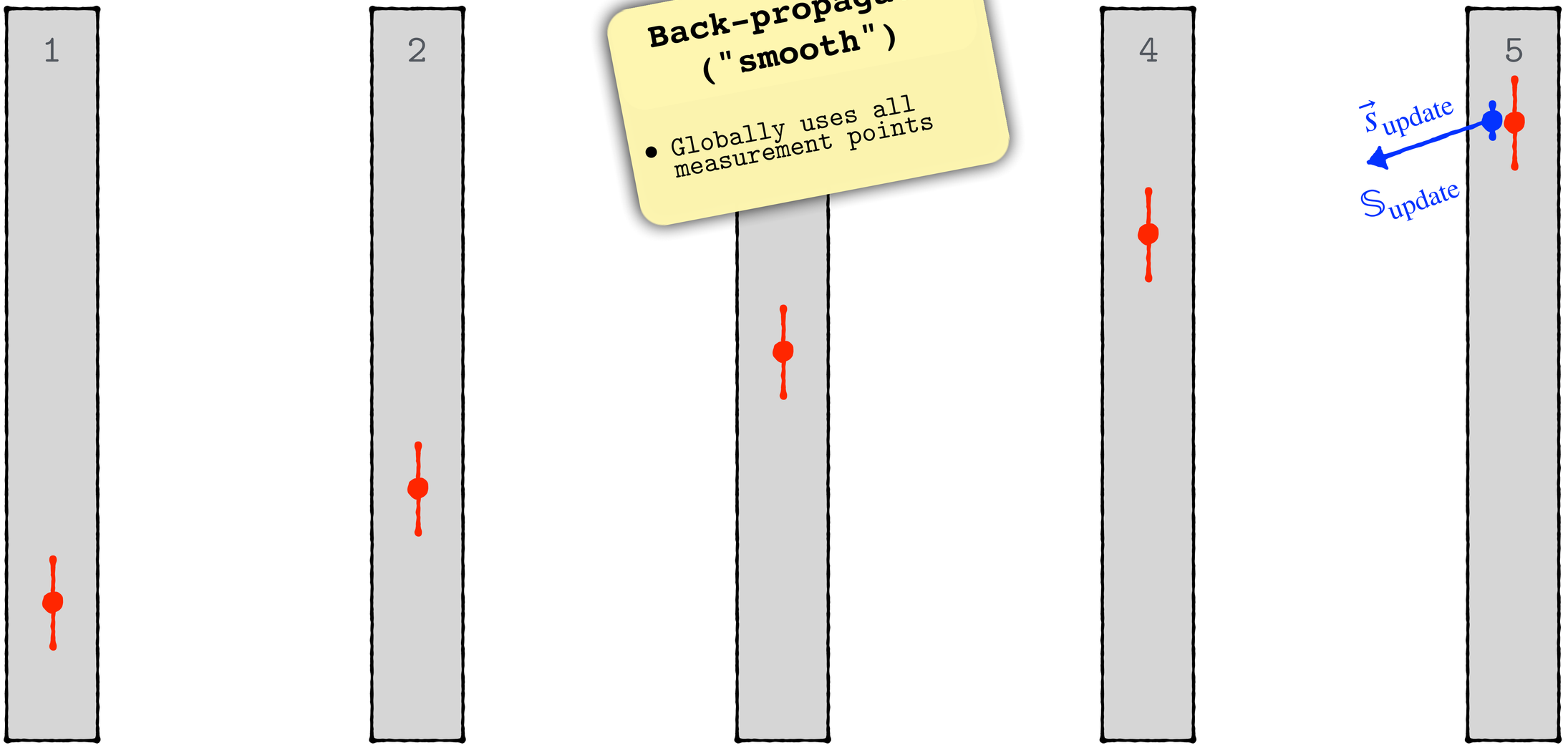

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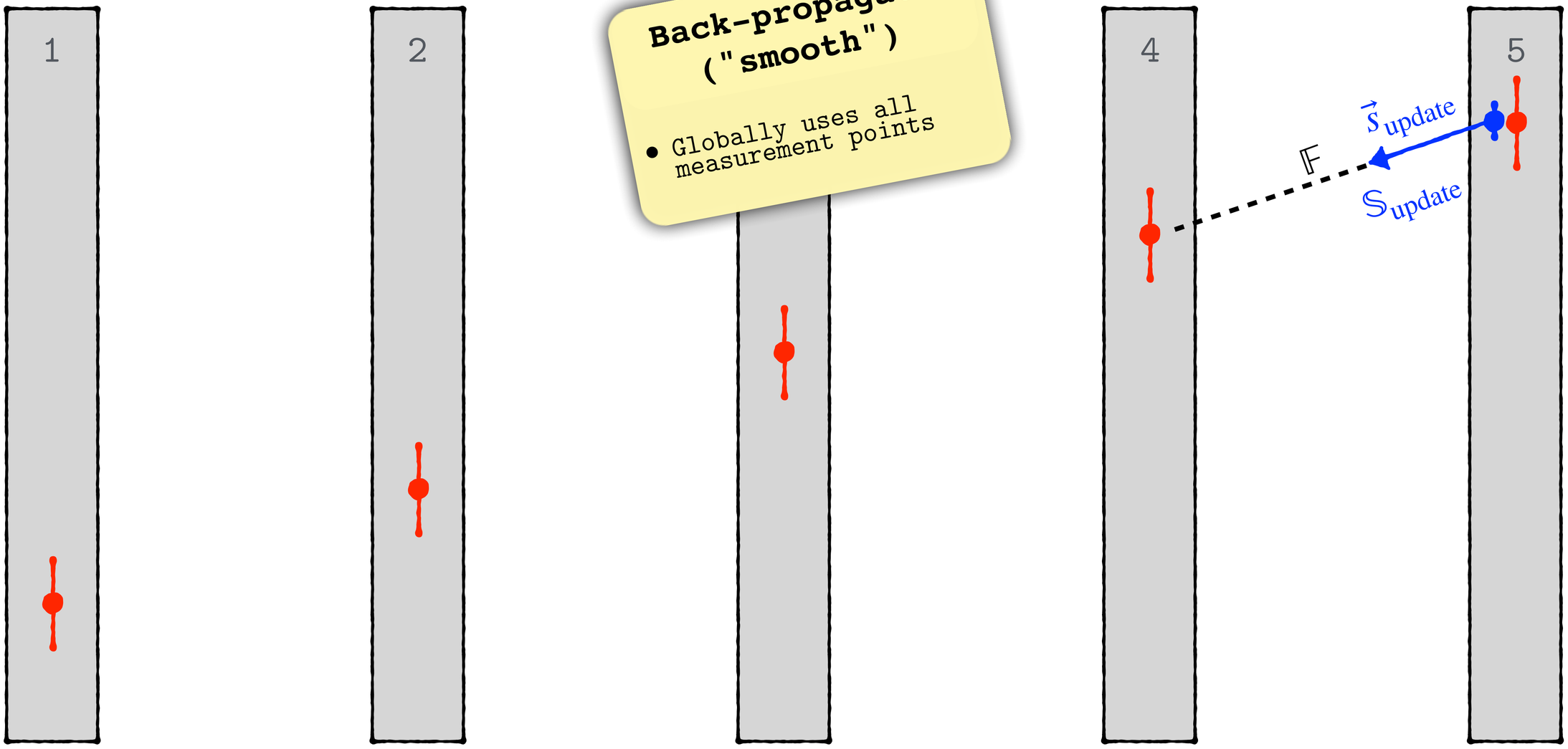

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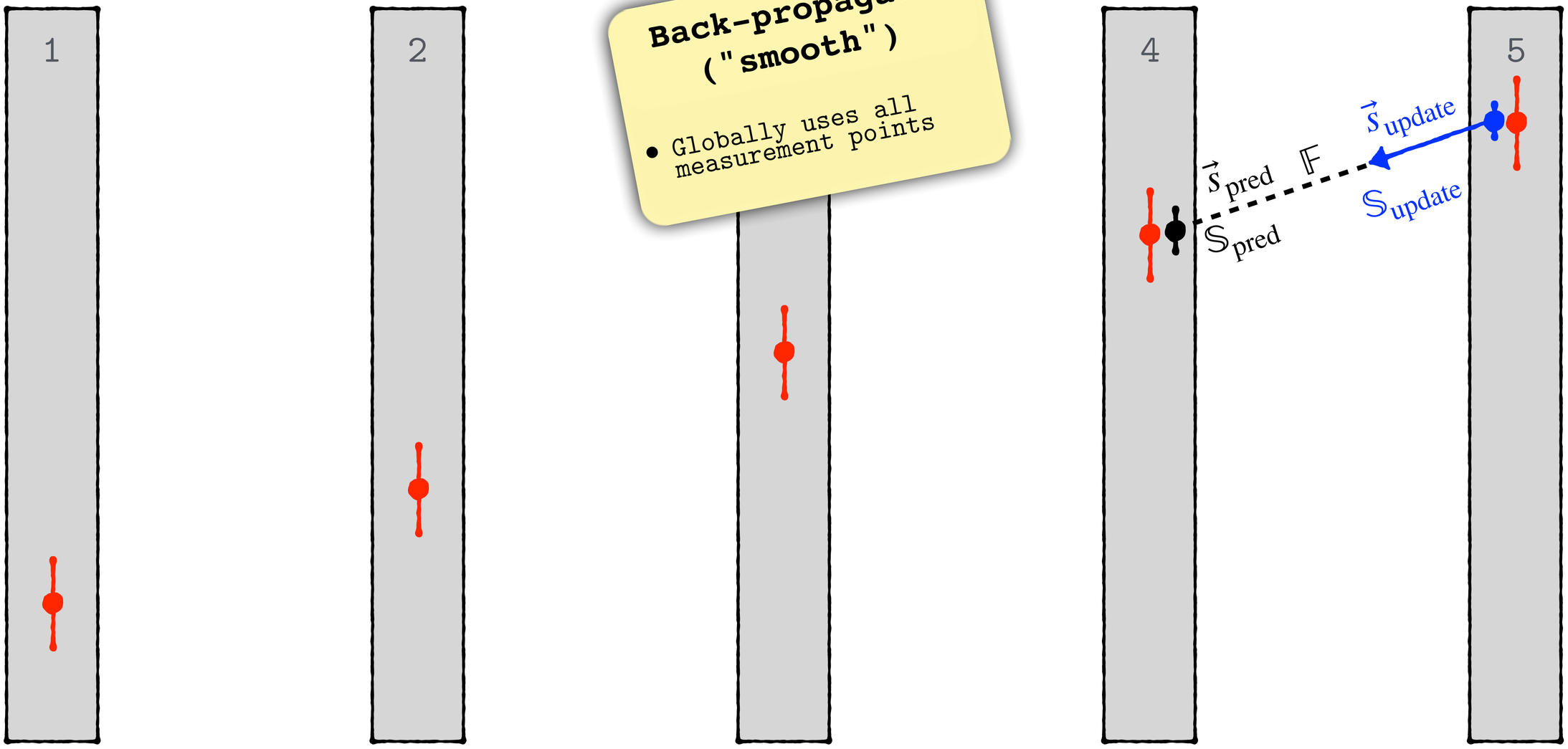

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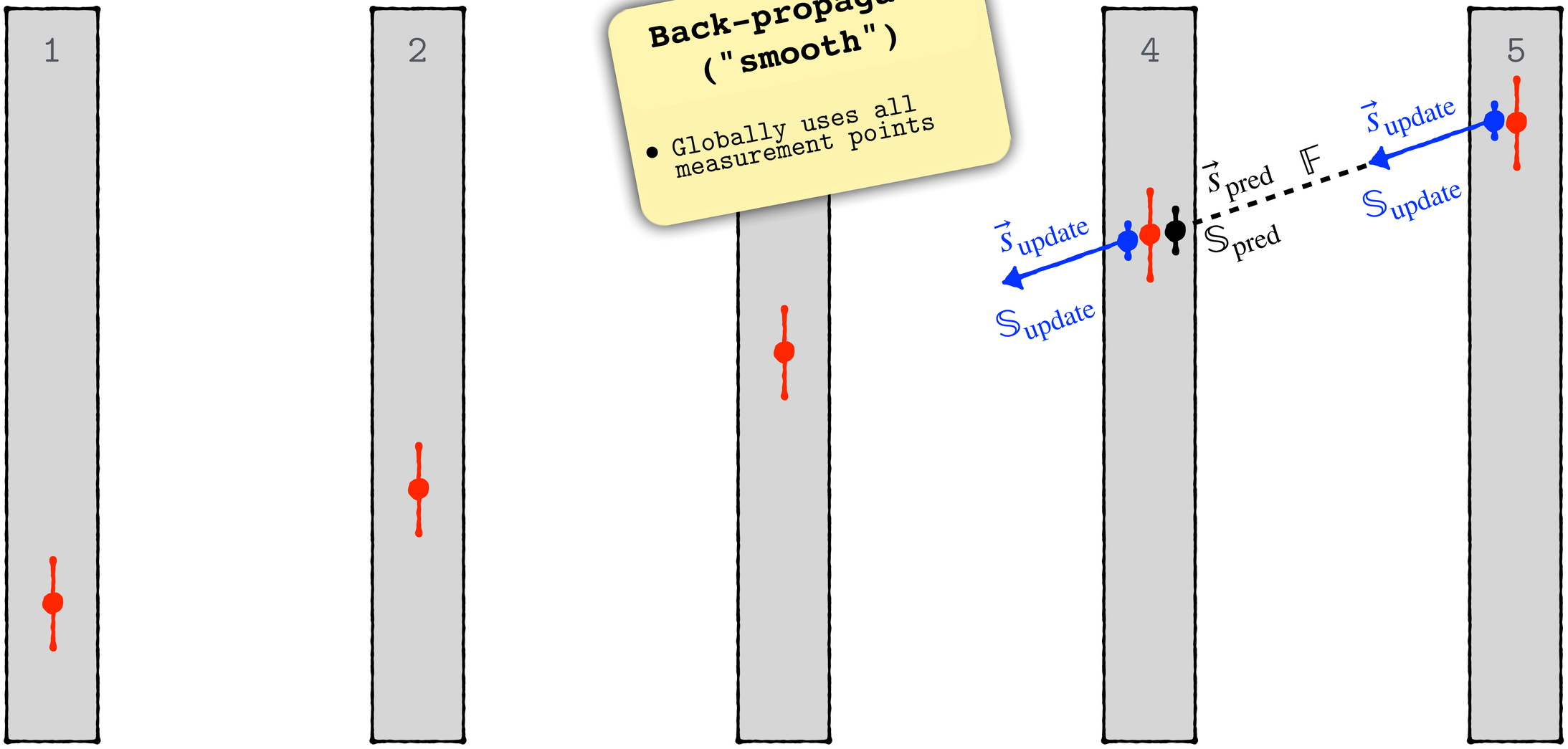

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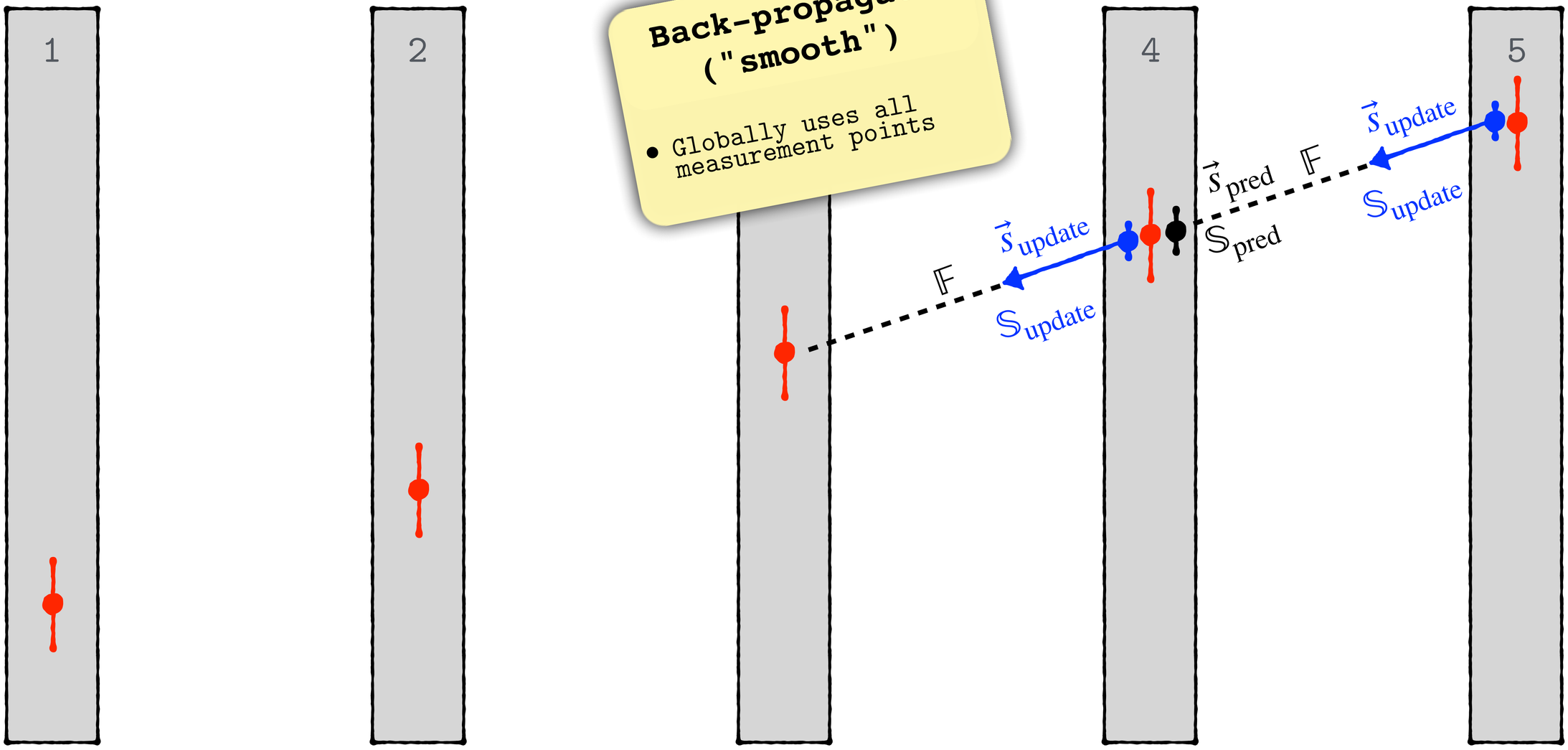

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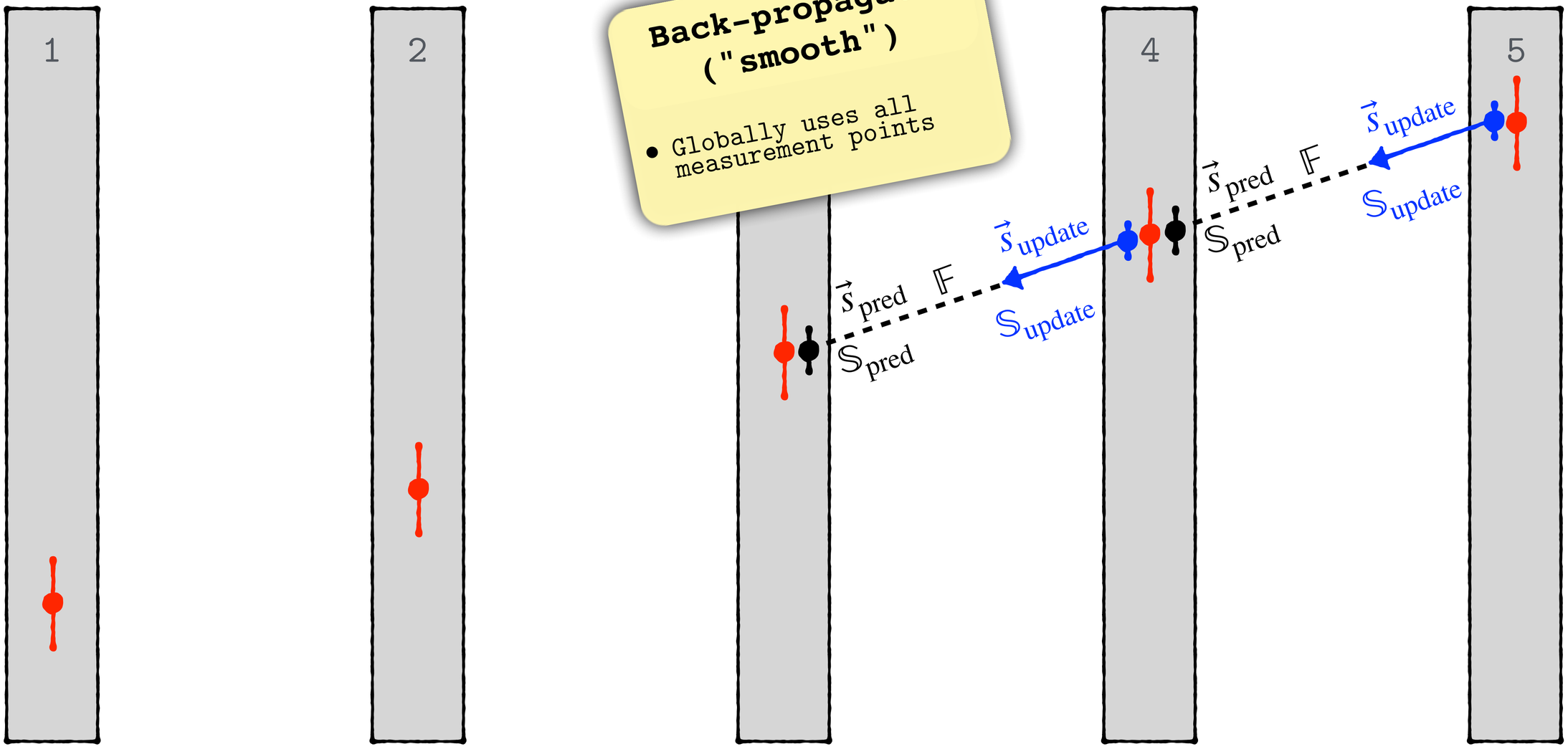

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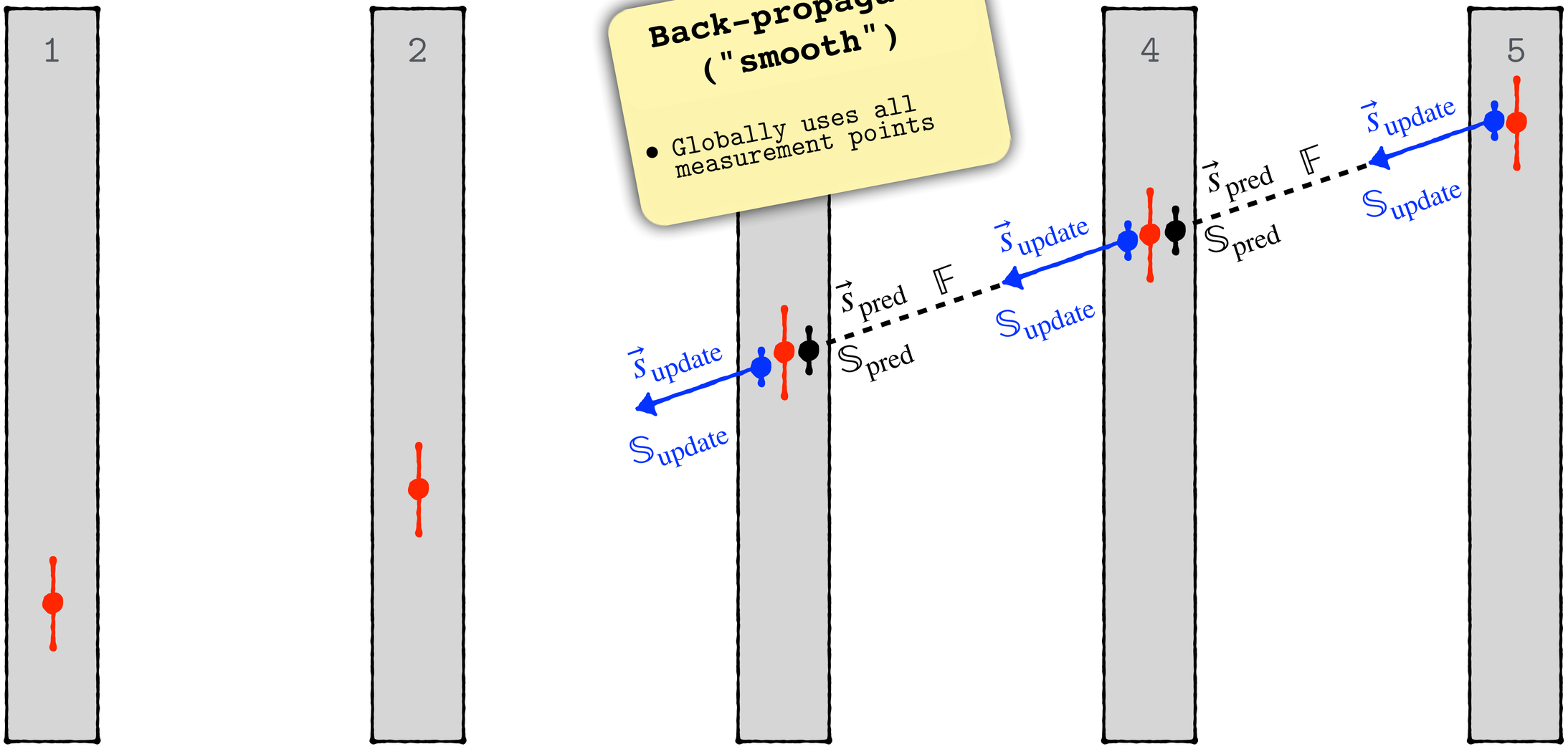

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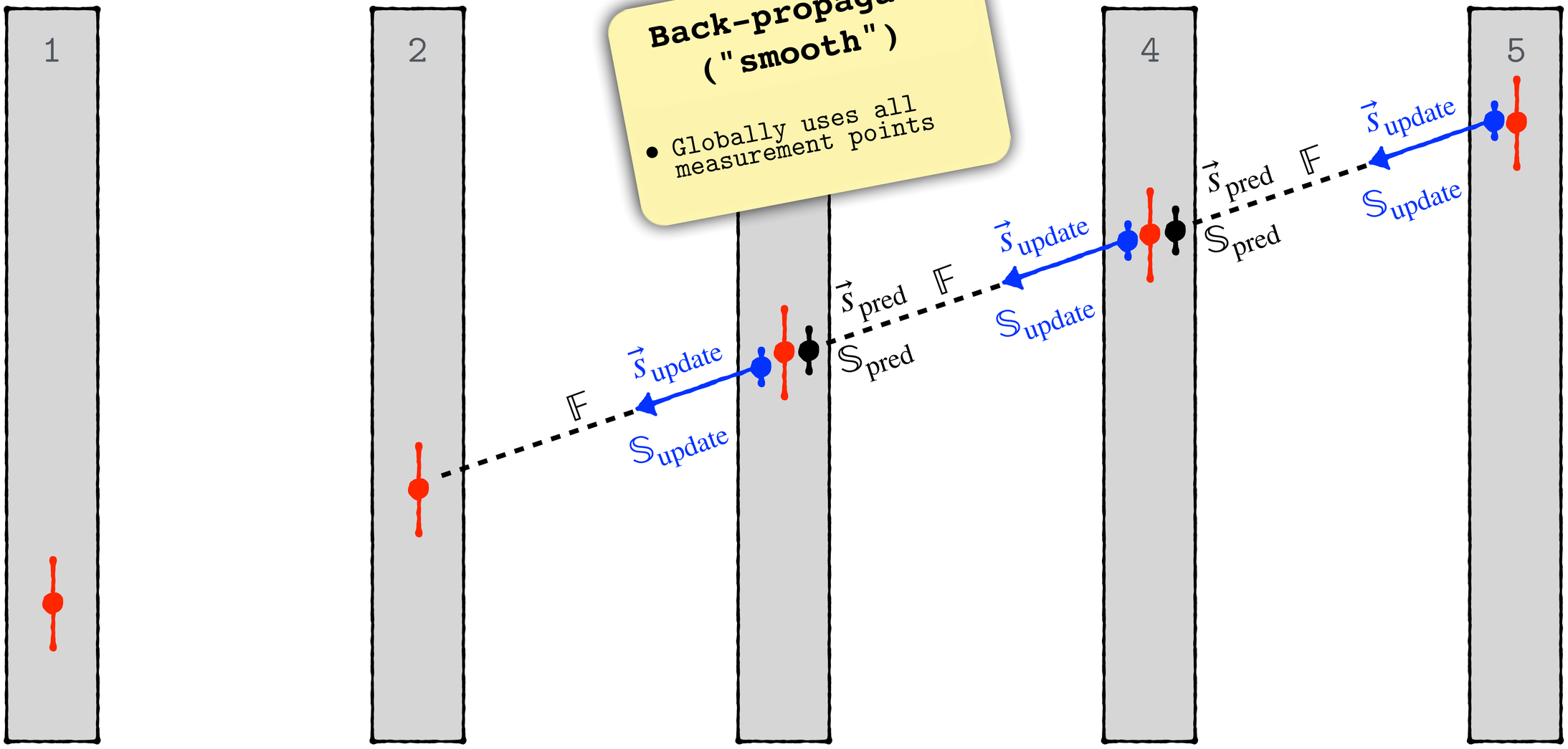

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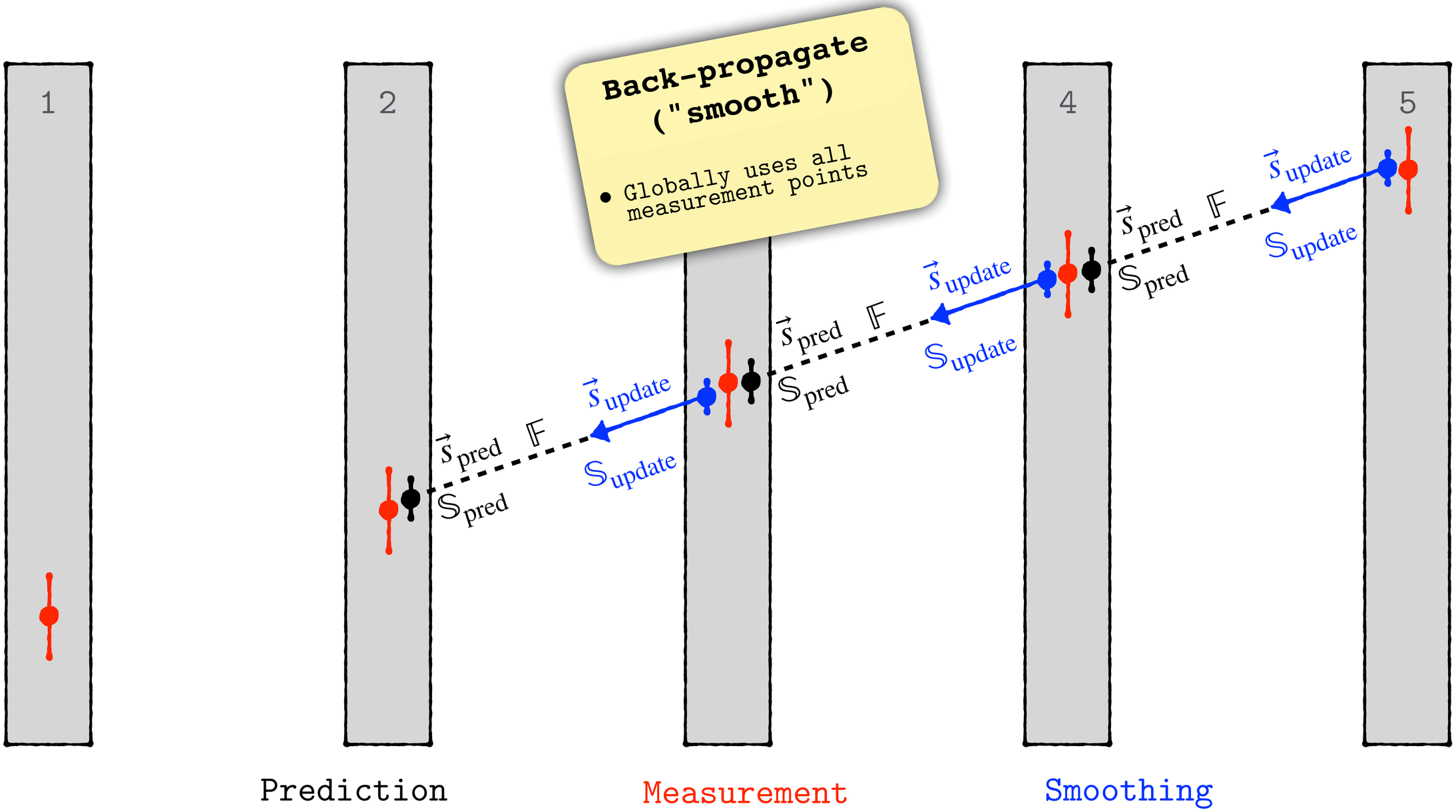

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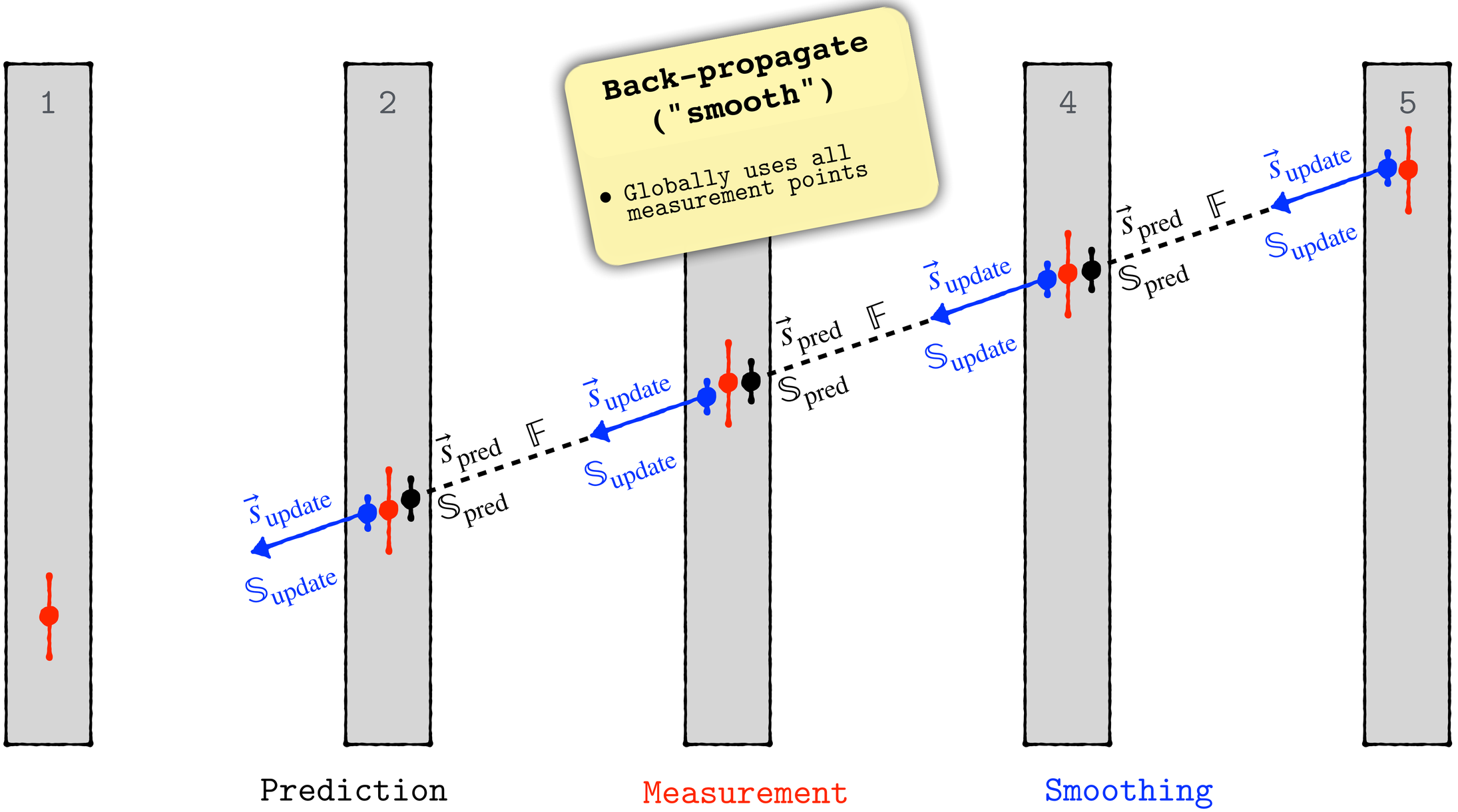

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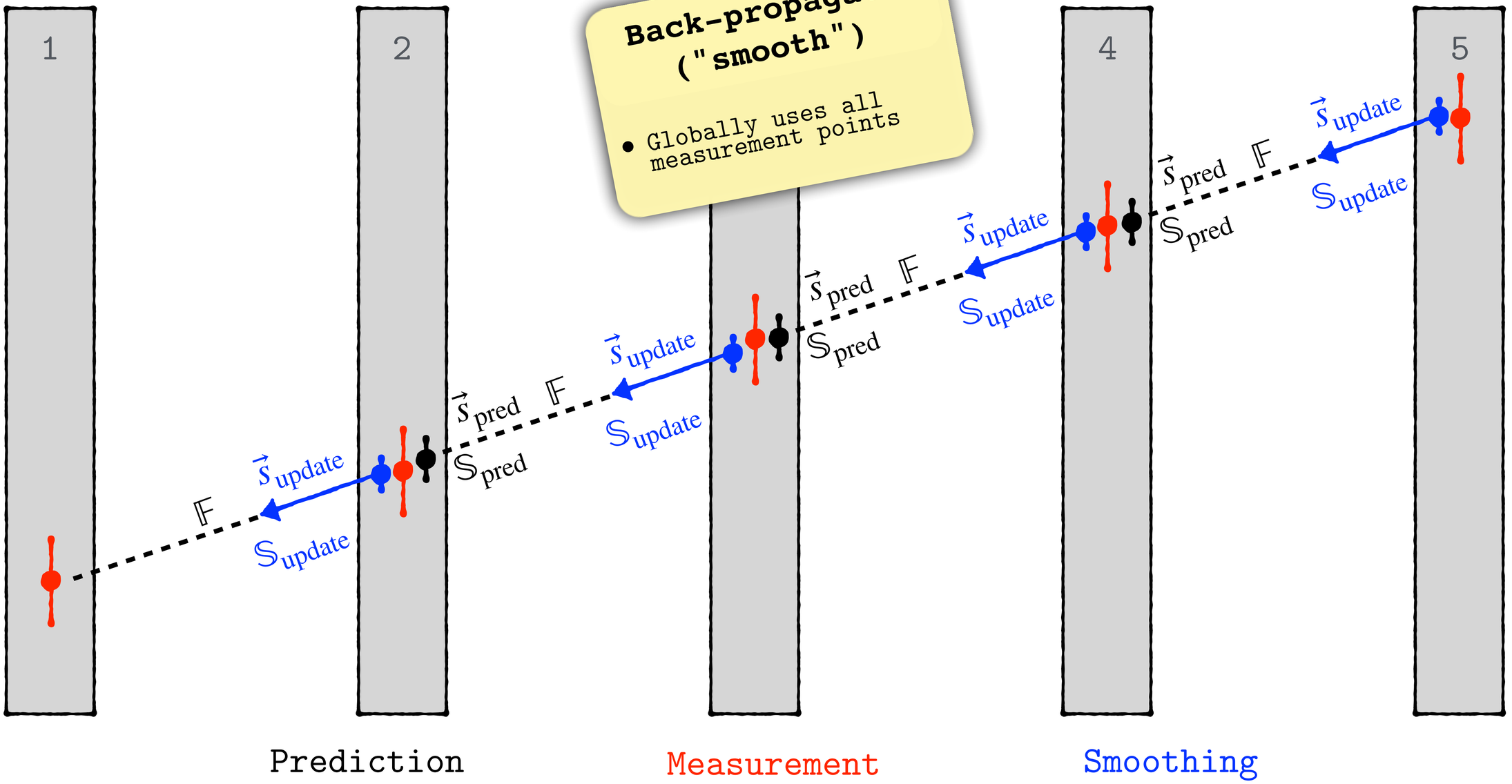

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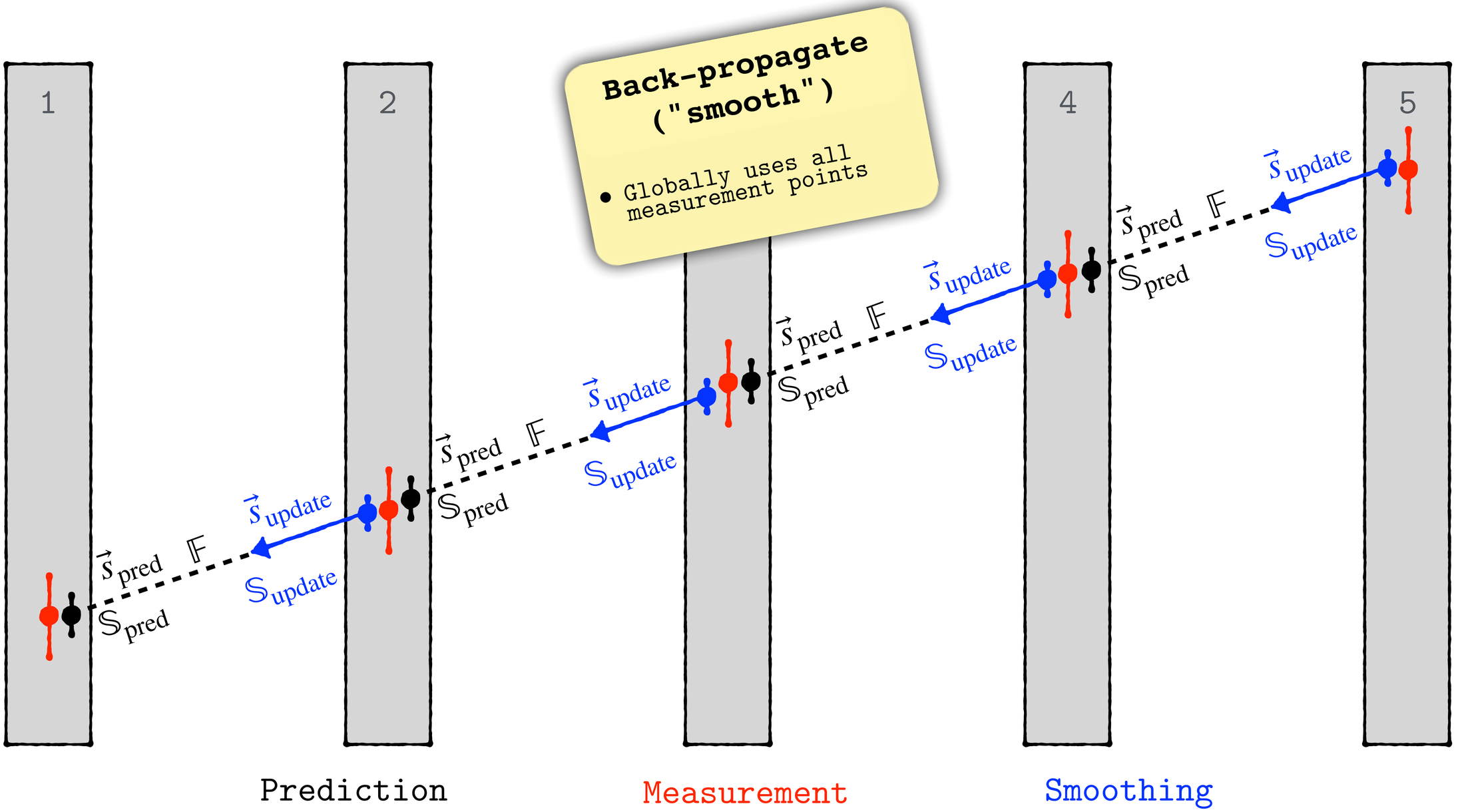

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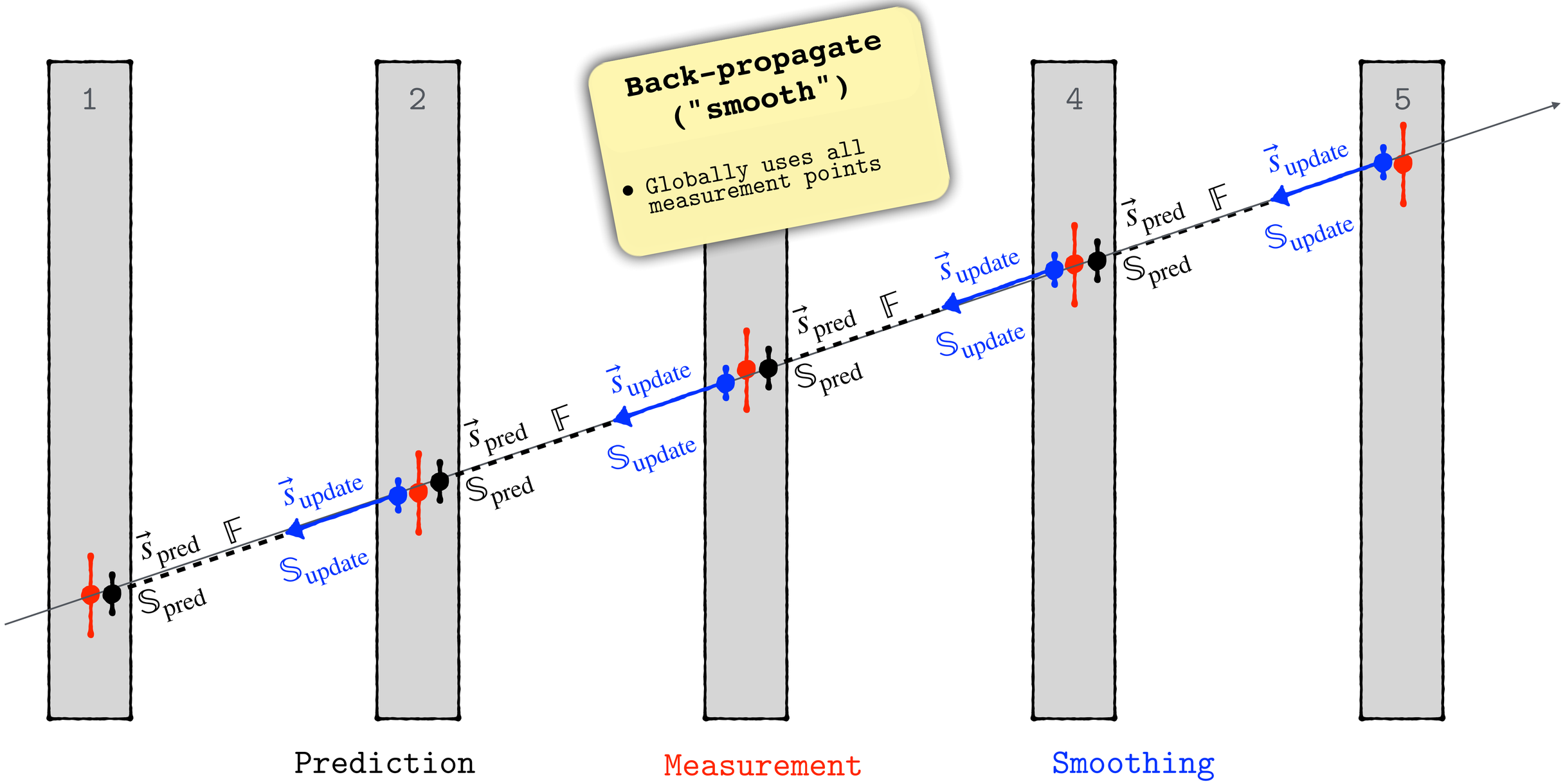

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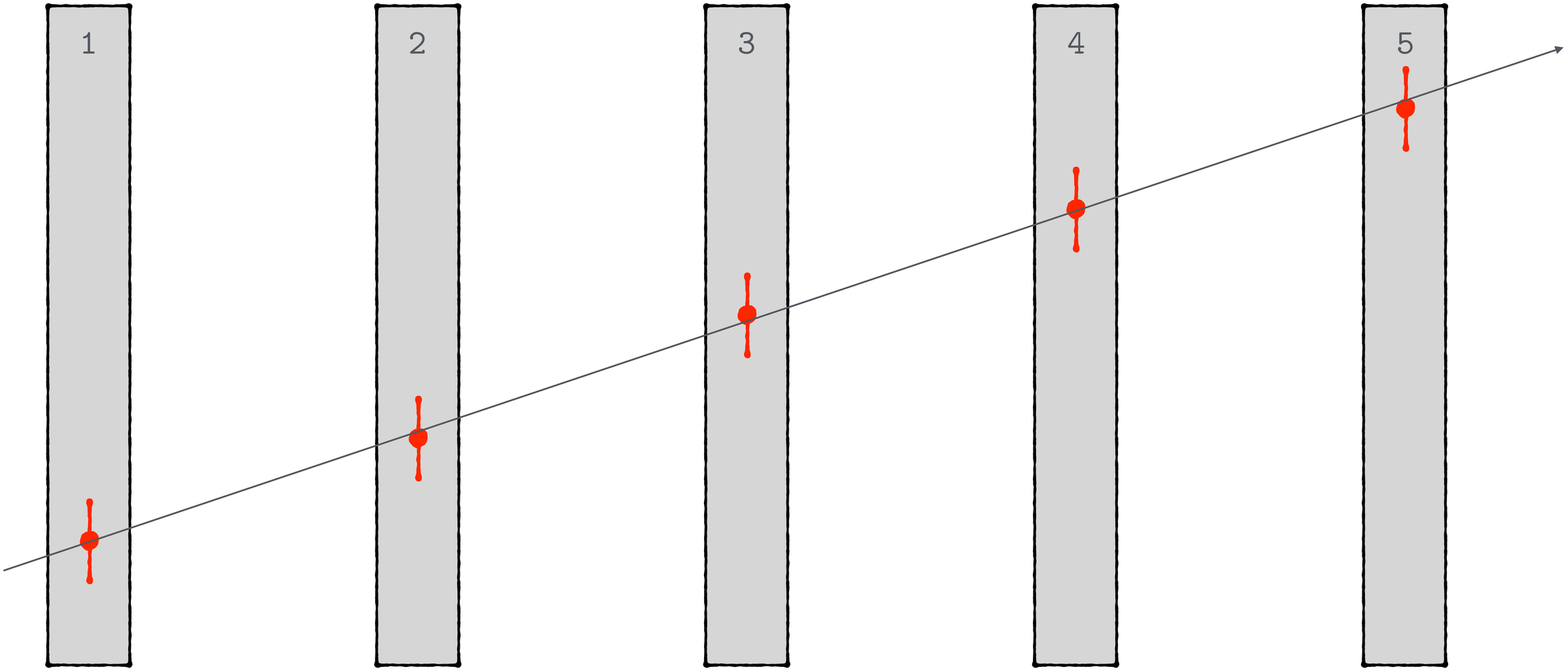


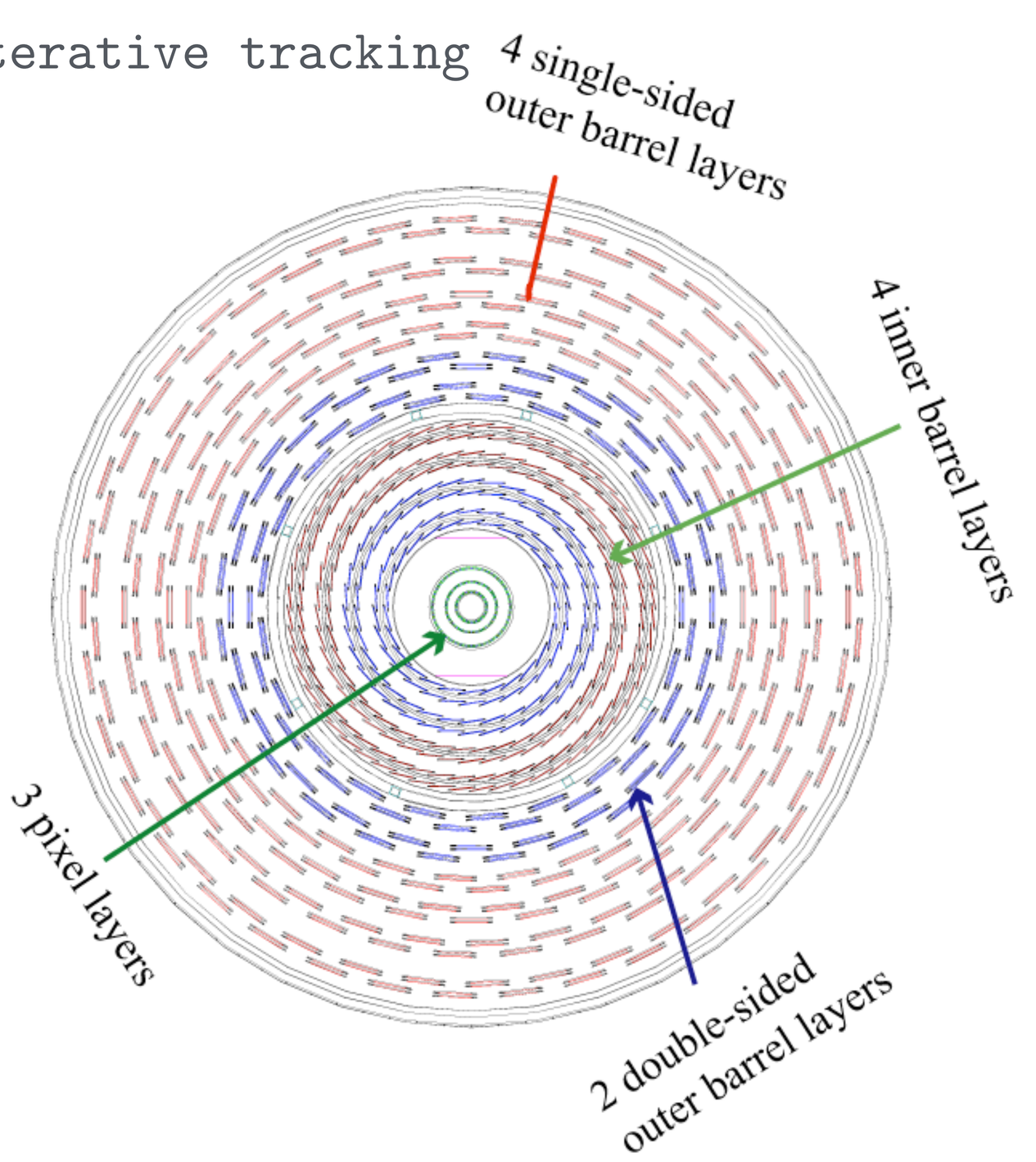
Prediction

Measurement

Smoothing

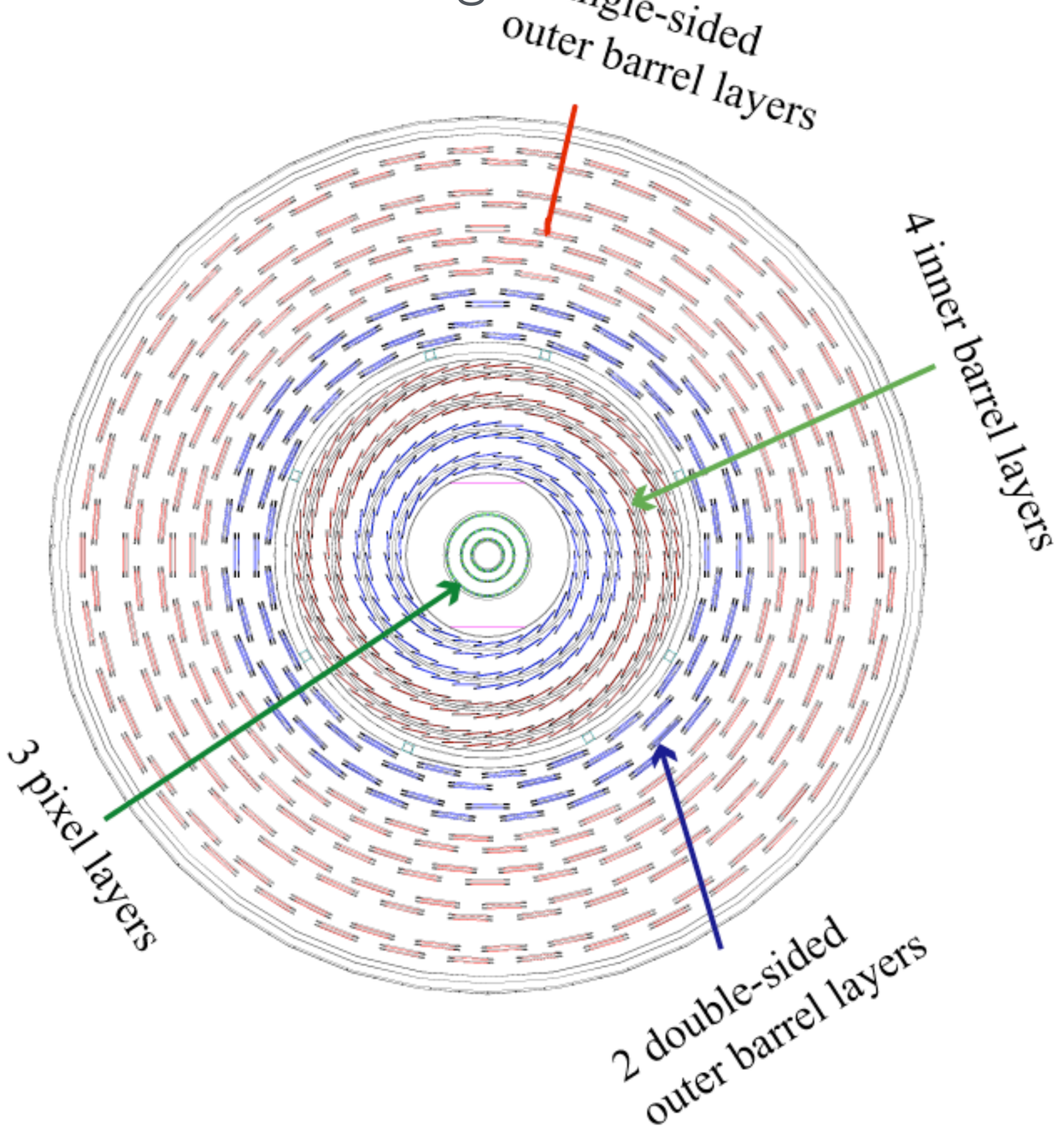
Track finding & reconstruction: Iterative tracking

Track finding & reconstruction: Iterative tracking



Track finding & reconstruction: Iterative tracking

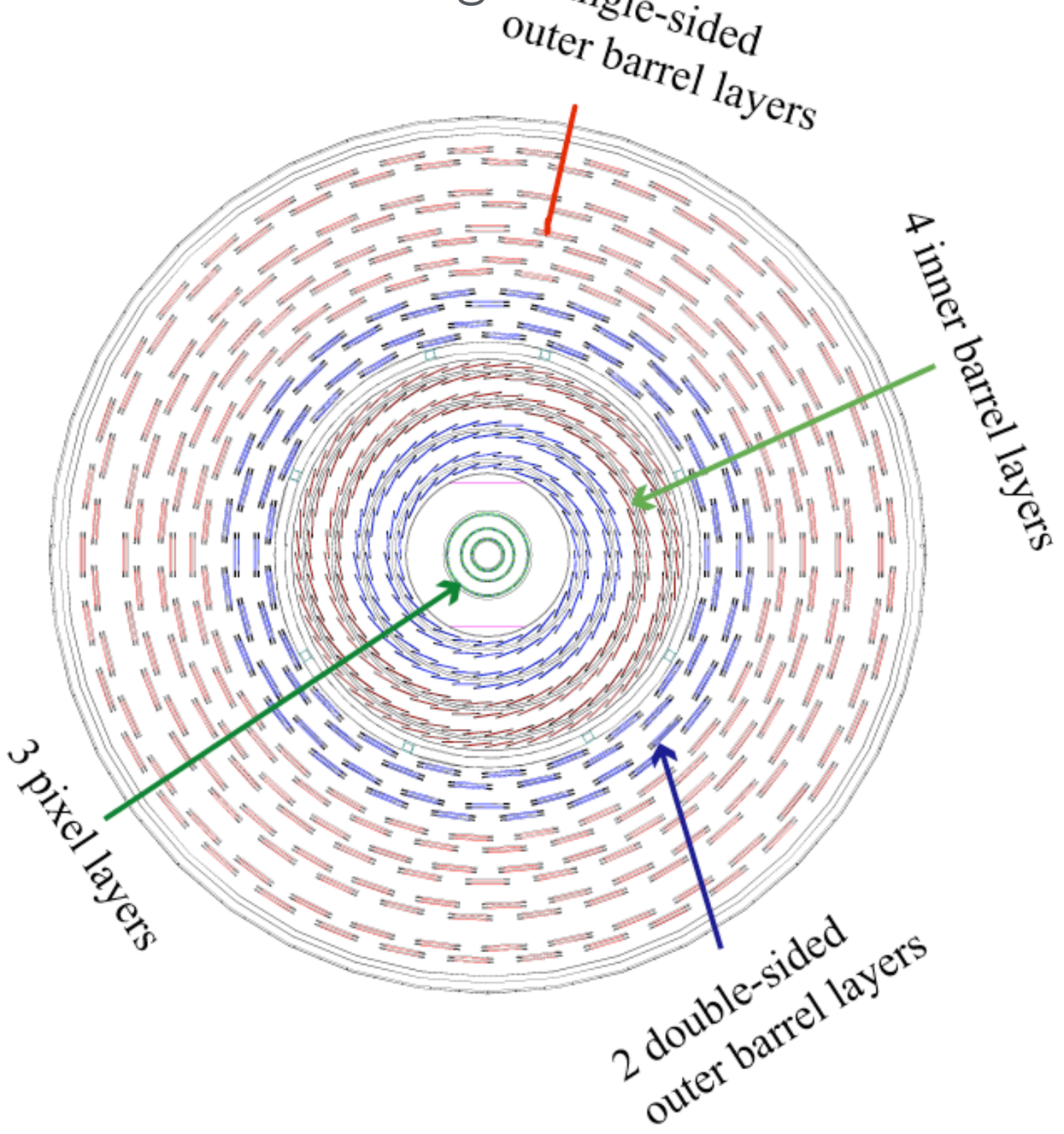
Fake tracks come from wrong combinations of hit associations



Track finding & reconstruction: Iterative tracking

Fake tracks come from wrong combinations of hit associations

So, reduce the number of hits fed to the track finder



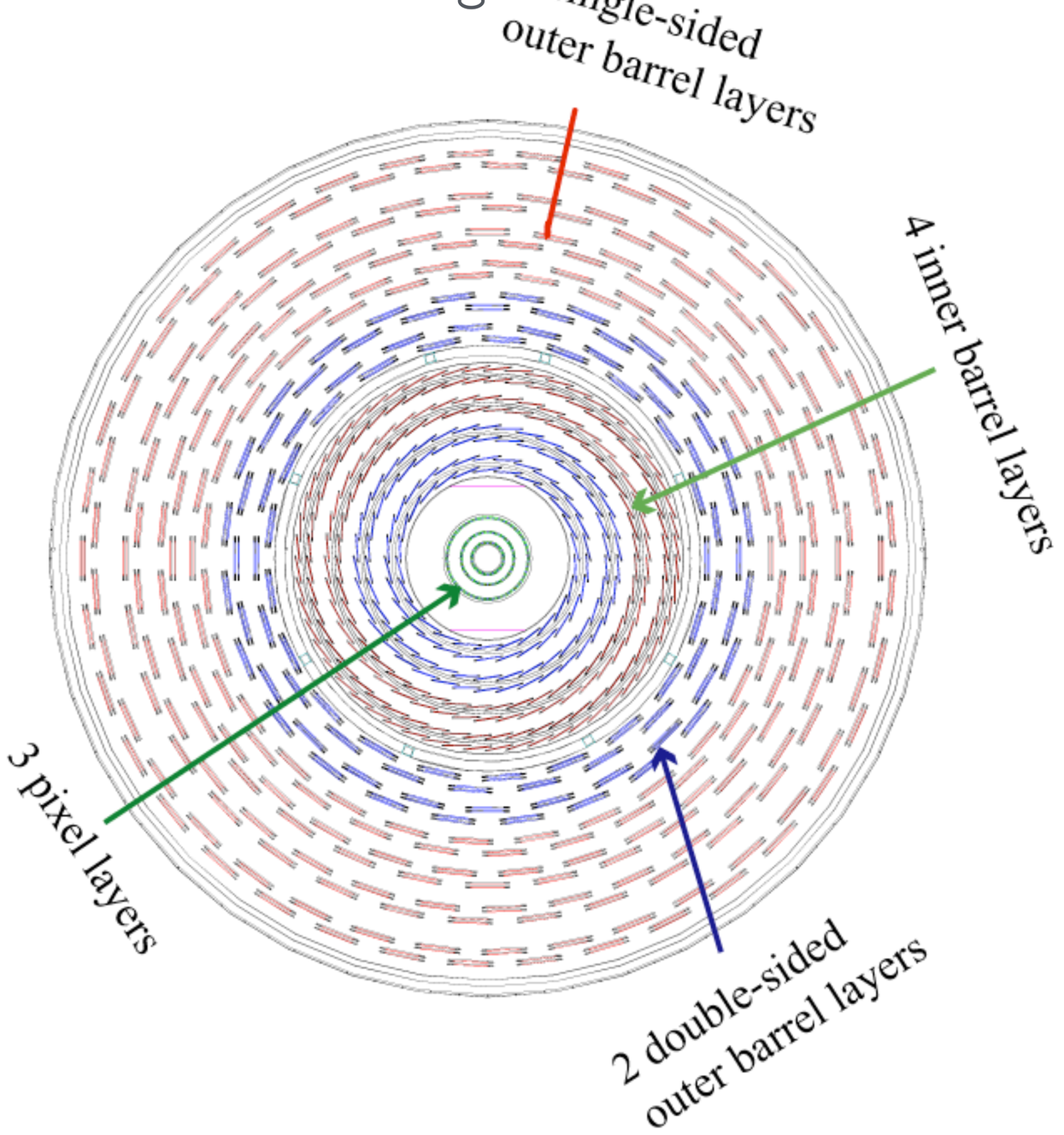
Track finding & reconstruction: Iterative tracking

Start from a very pure track seeding

- Example: 3 pixel hits, very tight origin constraint, $p_T > 0.9$ GeV
  - 75% efficiency, less than 1% fakes
- Reconstruct corresponding tracks (≥ 3 hits) & "remove" the used hits
  - 40% of the hits are removed

Fake tracks come from wrong combinations of hit associations

So, reduce the number of hits fed to the track finder



Track finding & reconstruction: Iterative tracking

Start from a very pure track seeding

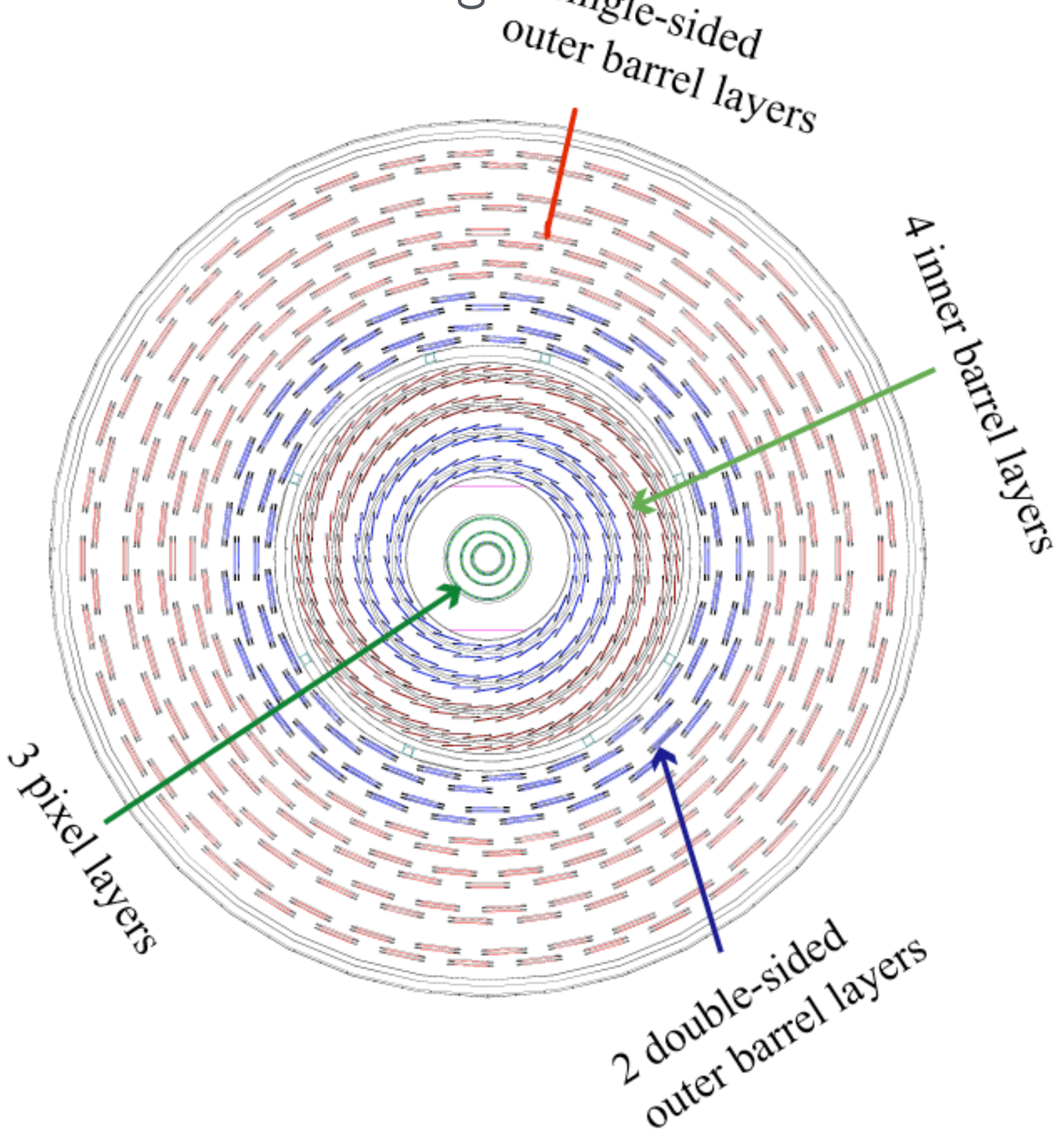
- Example: 3 pixel hits, very tight origin constraint, pT > 0.9 GeV
- less than 1% fakes

Next, try a looser seeding on 60% remaining hits

- Example: 2 pixel hits, very tight origin constraint, pT > 0.9 GeV
  - adds 15% efficiency, still less than 1% fakes
  - Combinatorial possibilities much less
- Reconstruct the corresponding tracks (≥ 3 hits) & remove the used hits
  - 10% of the hits are removed in this 2nd iteration

F mbinations

So, reduce the number of hits fed to the track finder



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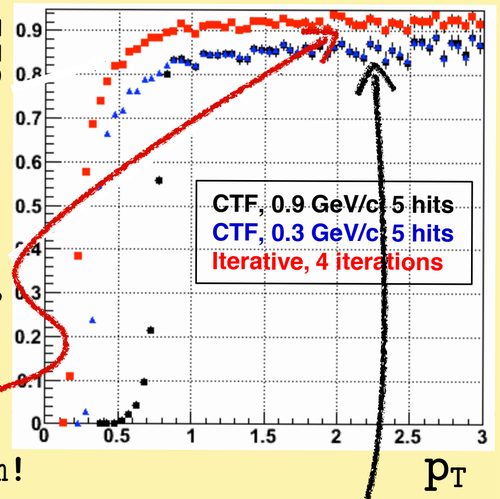
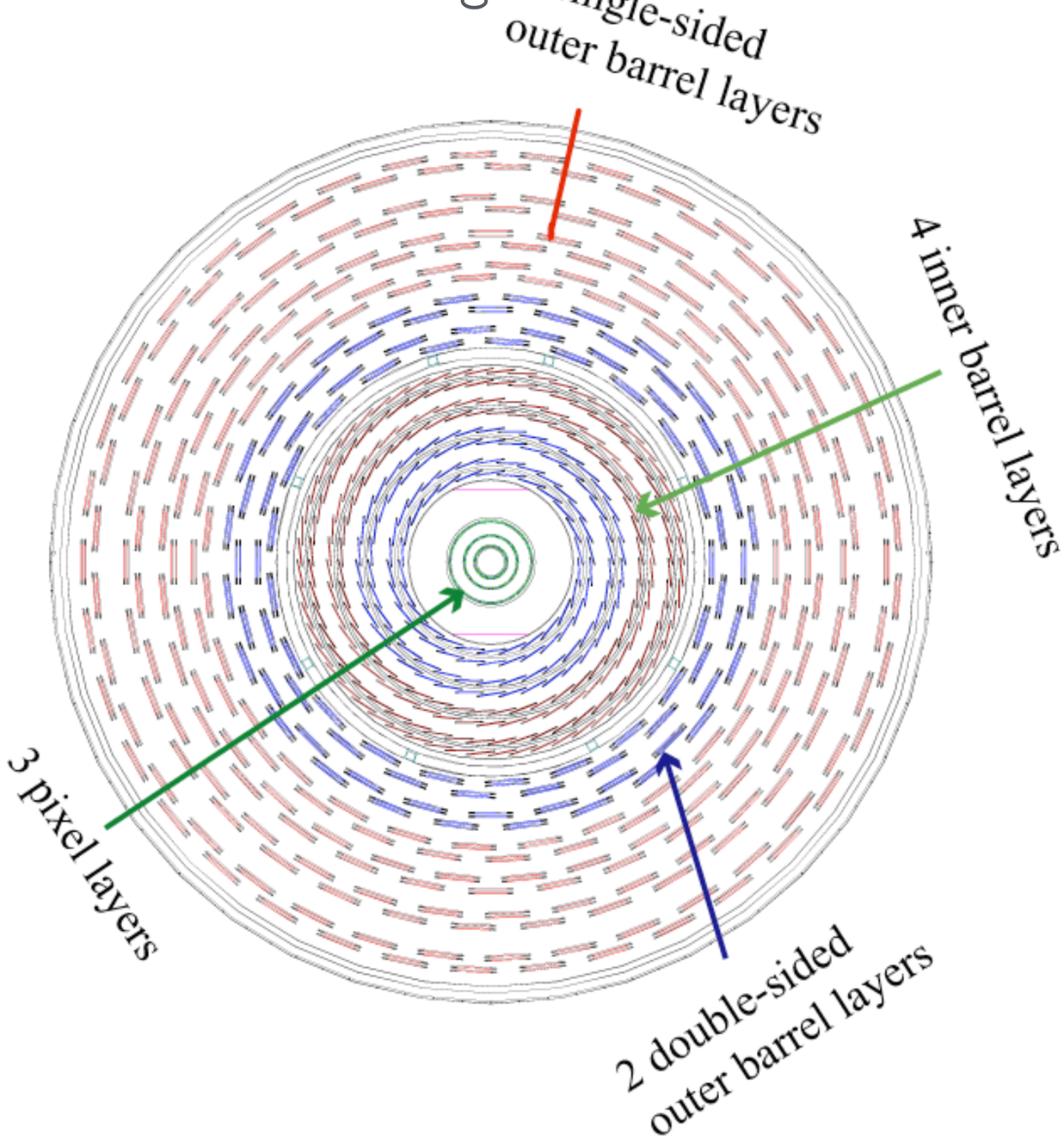
  - adds 15% efficiency, still less than 1% fakes

And so on...with more iterations

- 3rd iteration:
  - 3 pixel hits, tight origin constraint, pT > 0.2 GeV
- 4th iteration:
  - 2 pixel hits, looser origin constraint, pT > 0.3 GeV
  - 93% efficiency, 1-2% fake rate
  - down to very low momentum!
- Recall original situation
  - 85% efficiency, 20% fake rate





Track finding & reconstruction: Iterative tracking

Start from a very pure seeding

- Example: 3 pixel hits, v
  origin constraint, pT >
  less

Next, try a looser
60% remainin

- Example: 2 pixel hit
  origin constraint, p
  - adds 15% efficiency, s
    than 1% fakes
    much

And even try to catch secondary tracks

- Interactions, conversions, decays,...
- 5th iteration:
  - Inner tracker seeding, loose origin constraint, pT > 0.5 GeV
- 6th iteration:
  - Outer tracking seeding, very loose origin constraint, pT > 0.8 GeV

And so on...with more iterations

- 3rd iteration:
  - 3 pixel hits, tight origin constraint, pT > 0.2 GeV
- 4th iteration:
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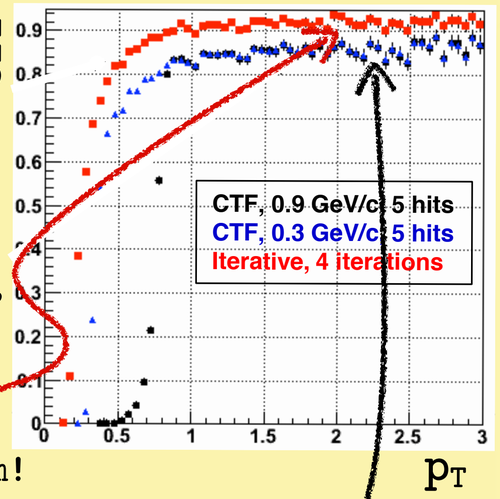

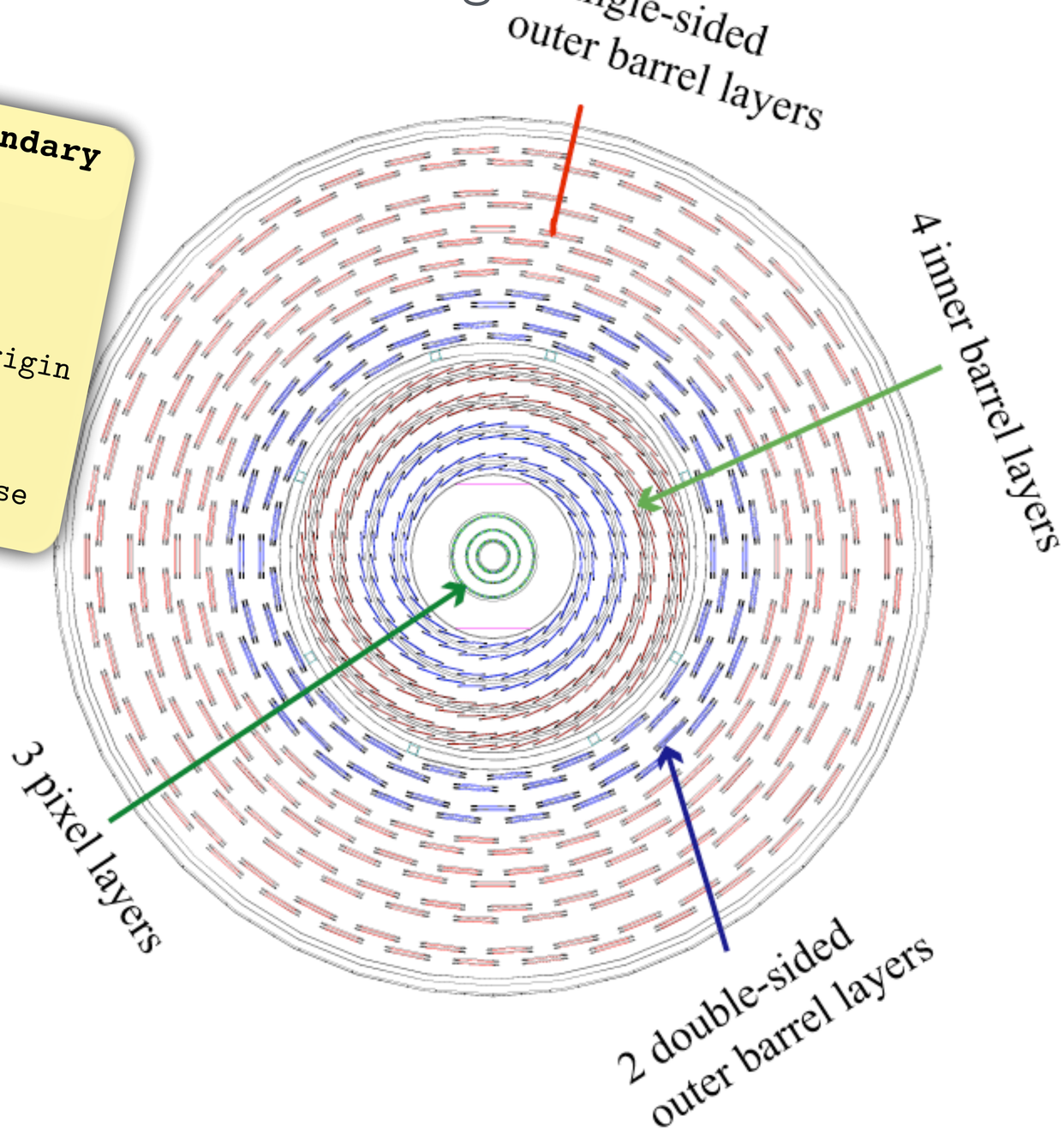

Important details! Tracker Material Budget

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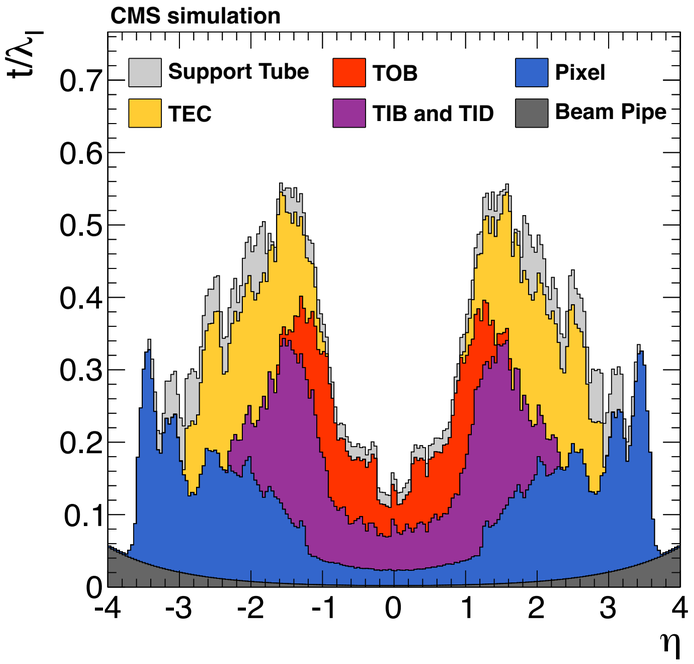

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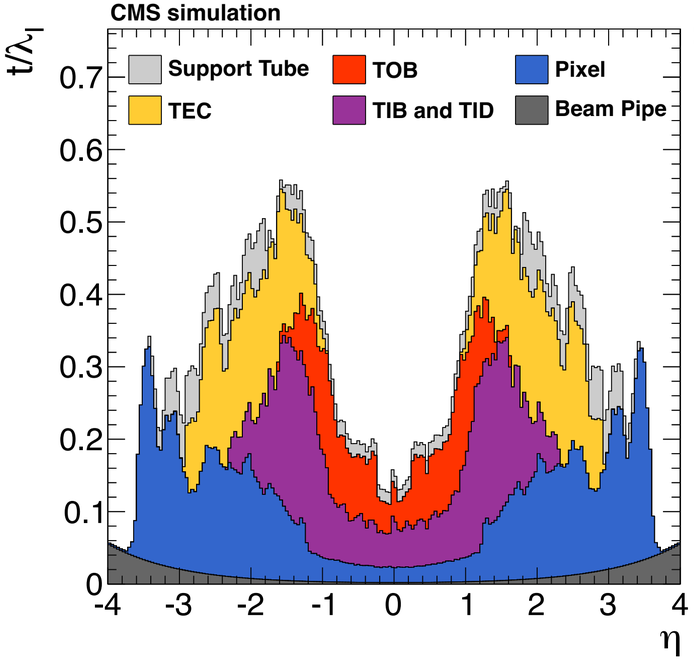

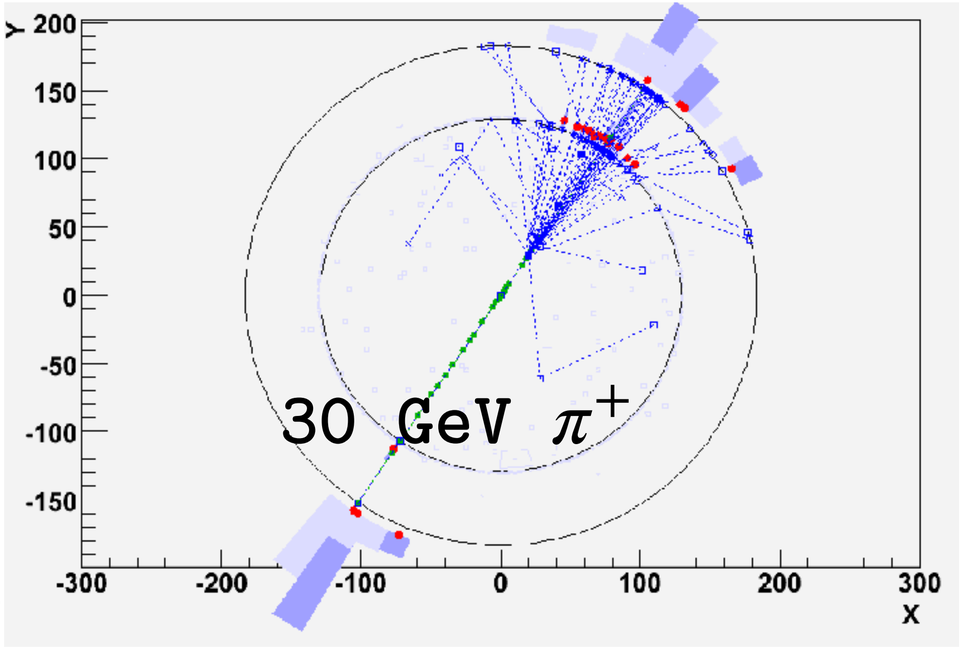

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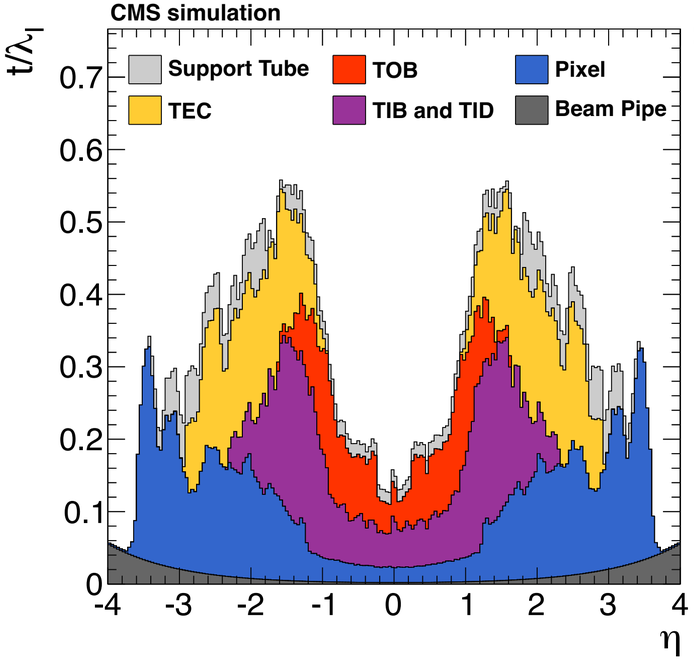

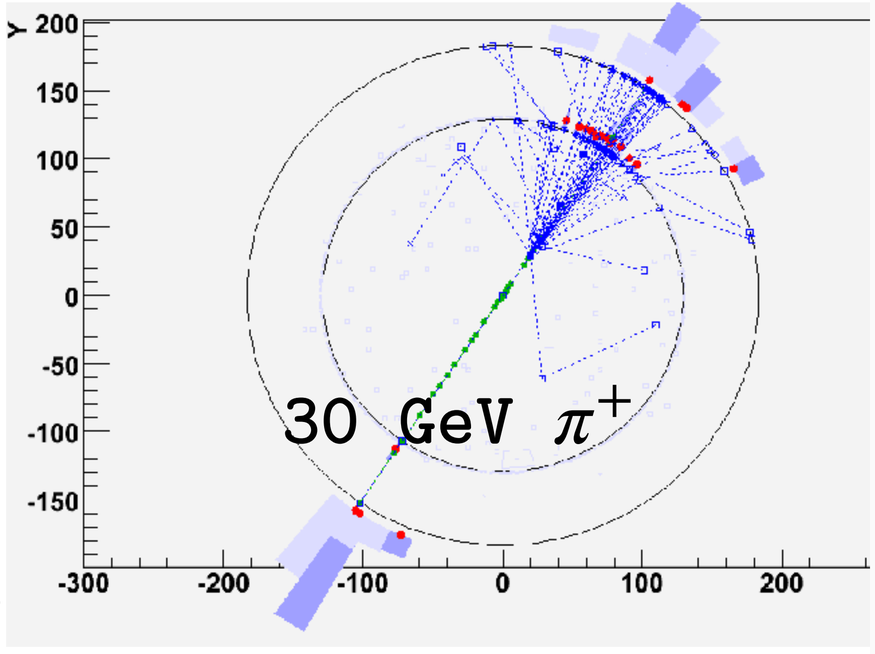

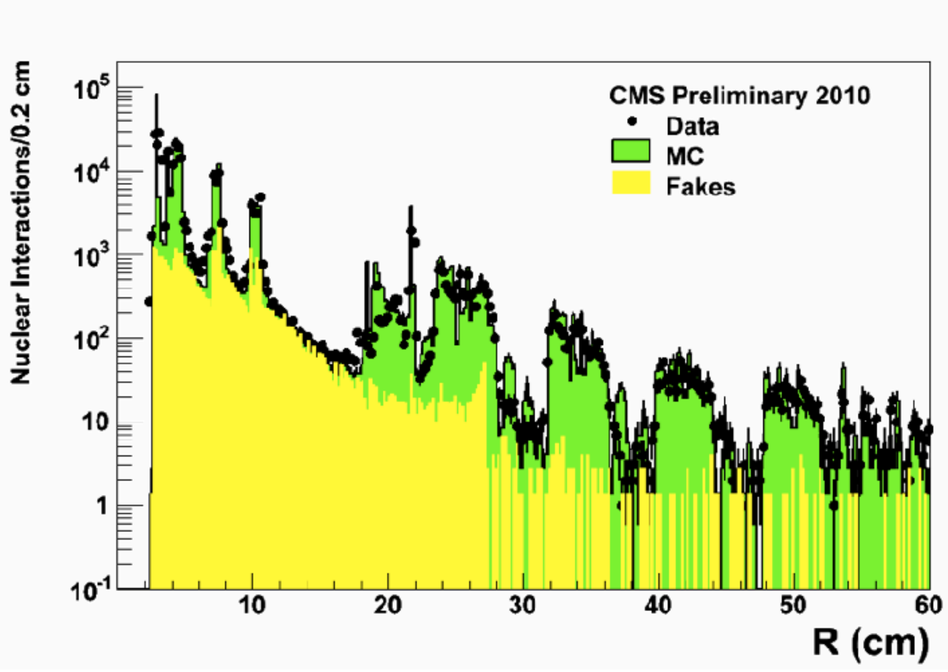

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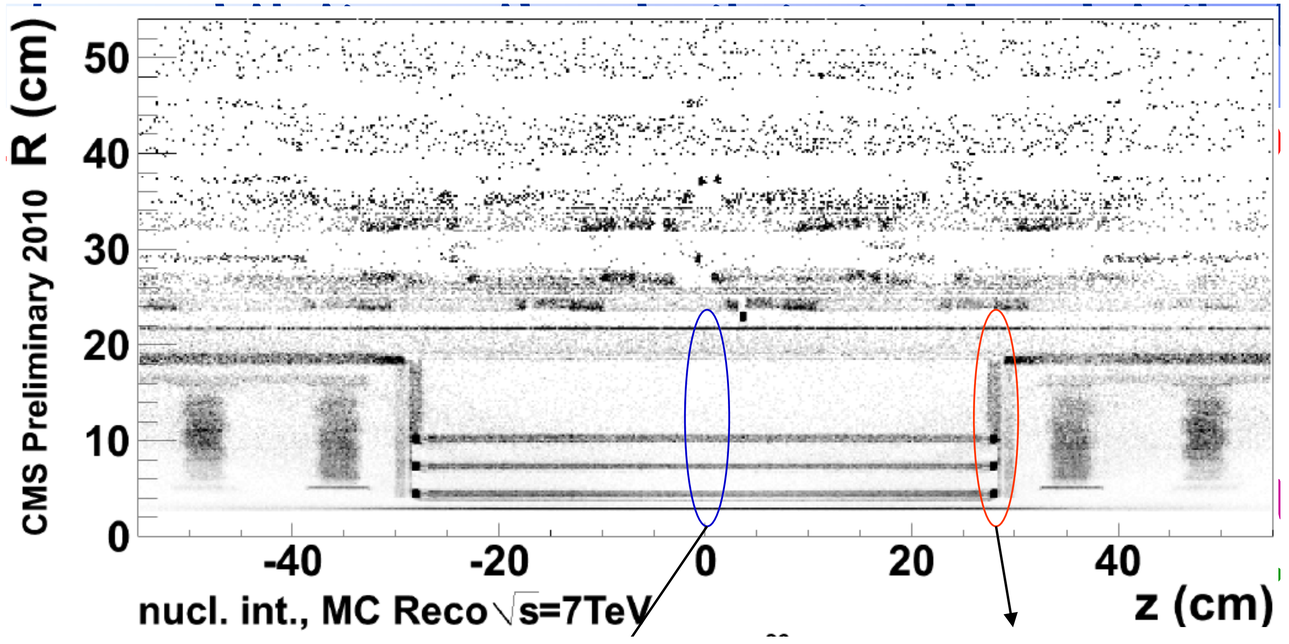

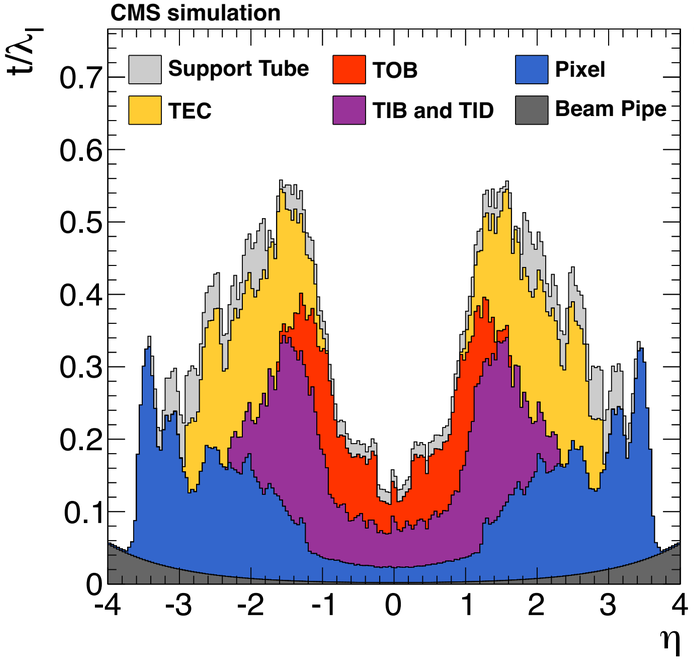

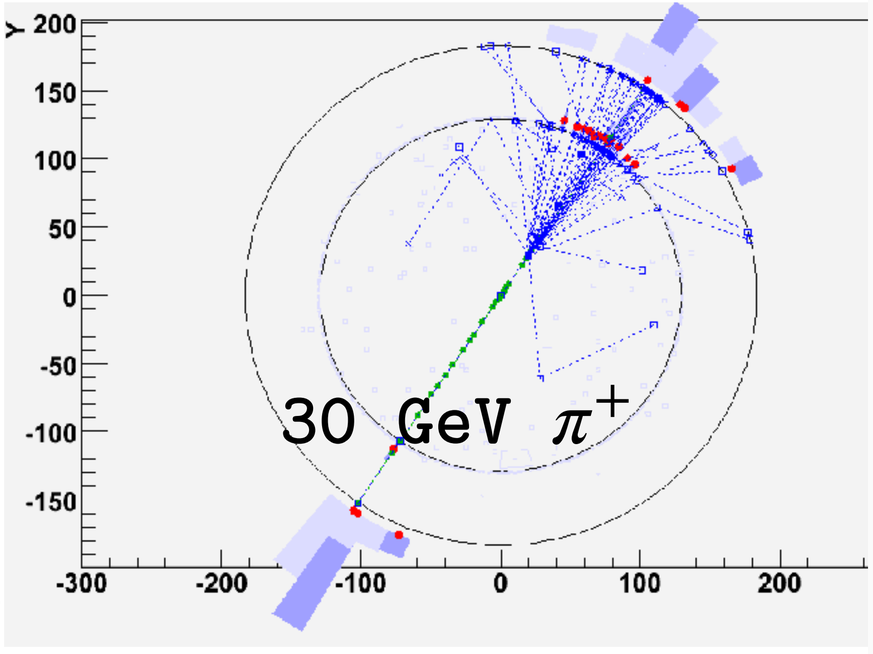

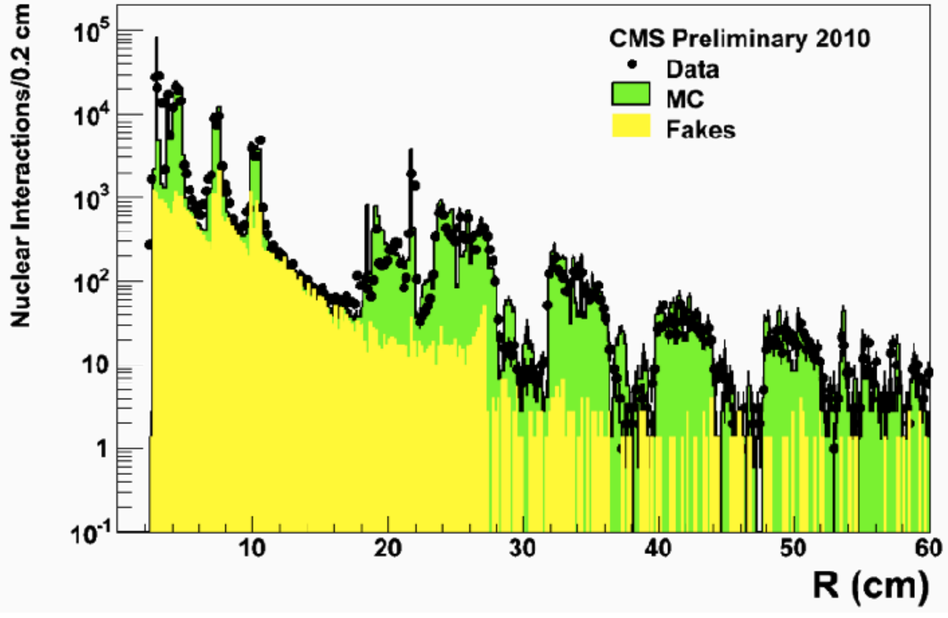

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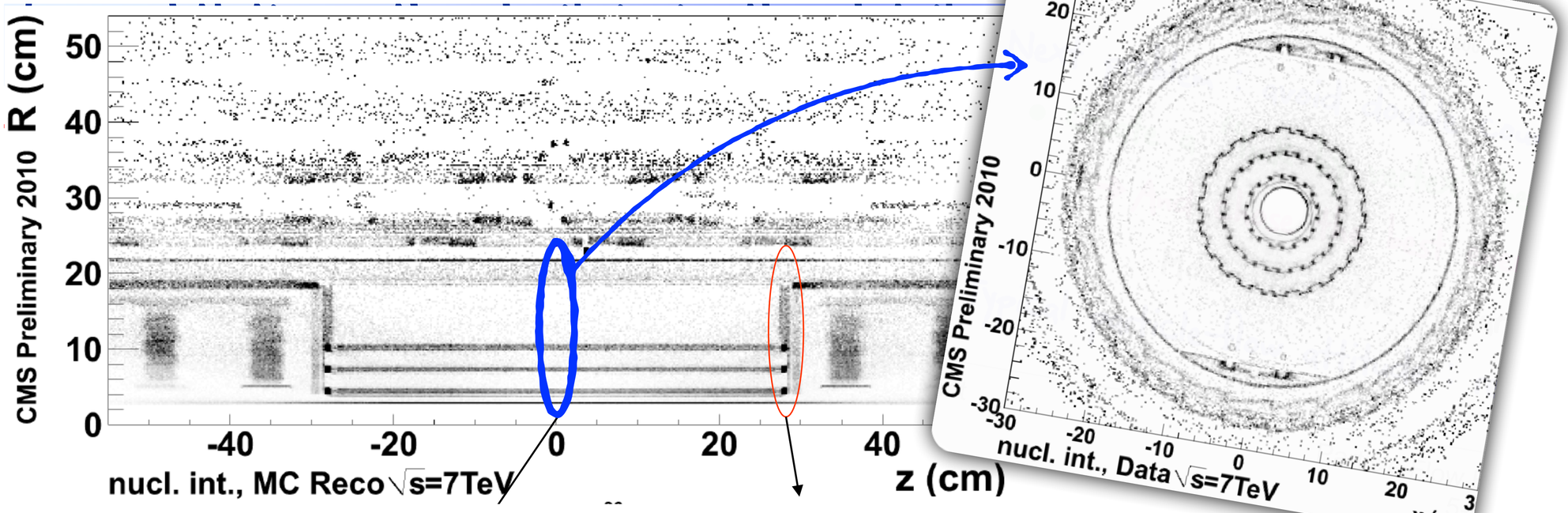

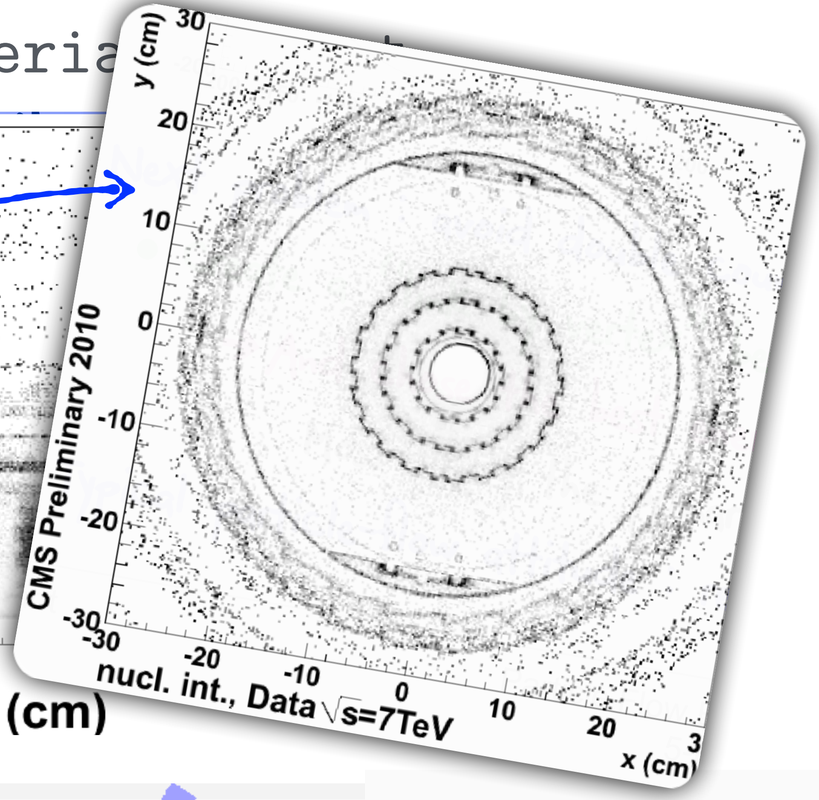

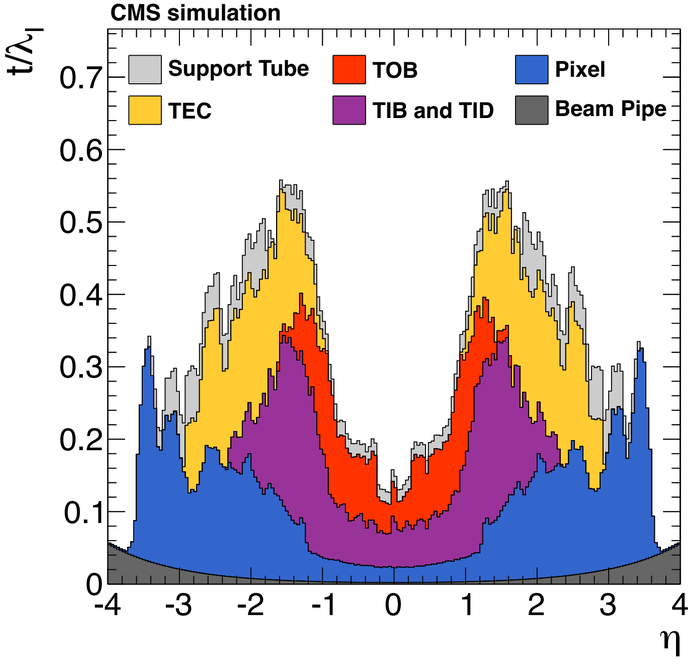

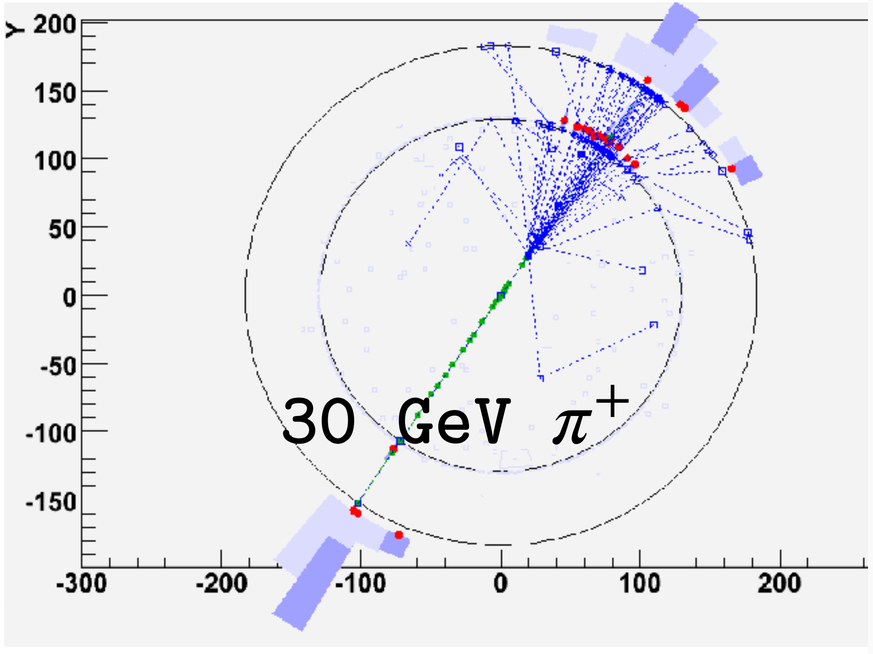

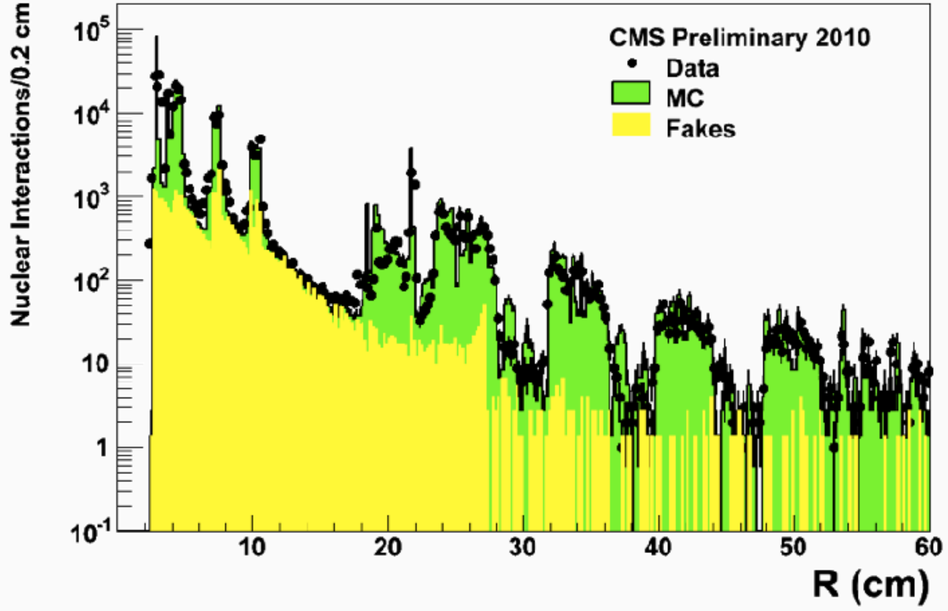

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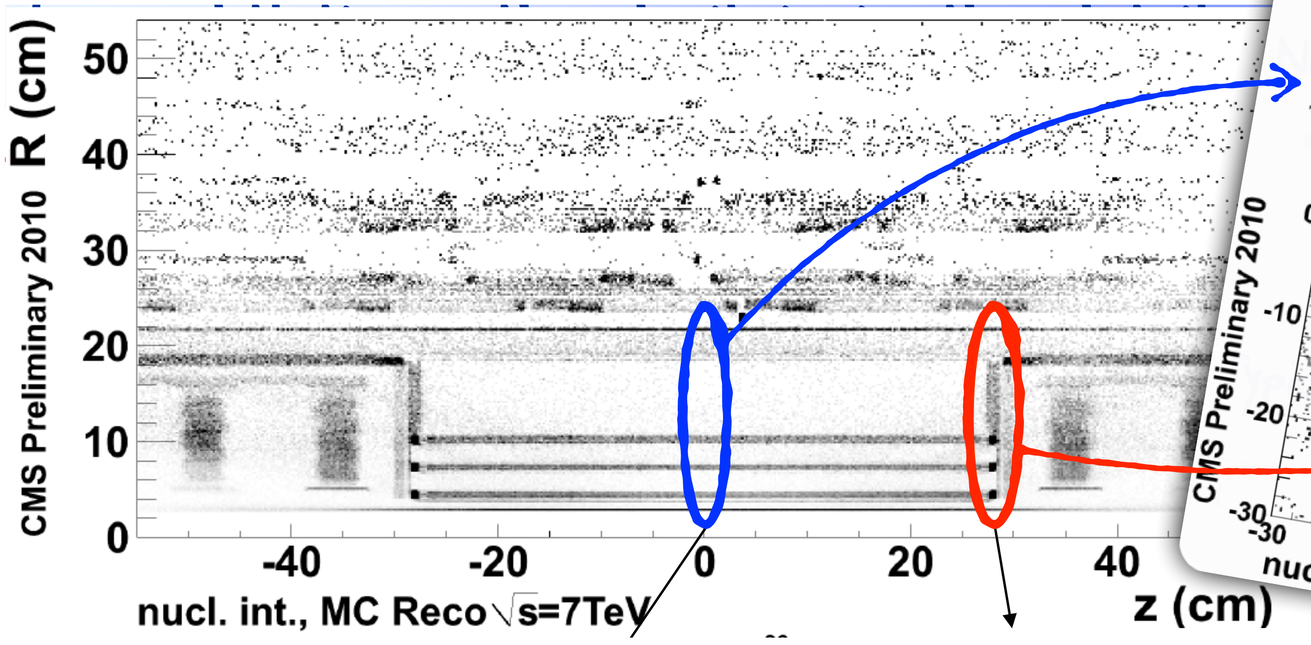

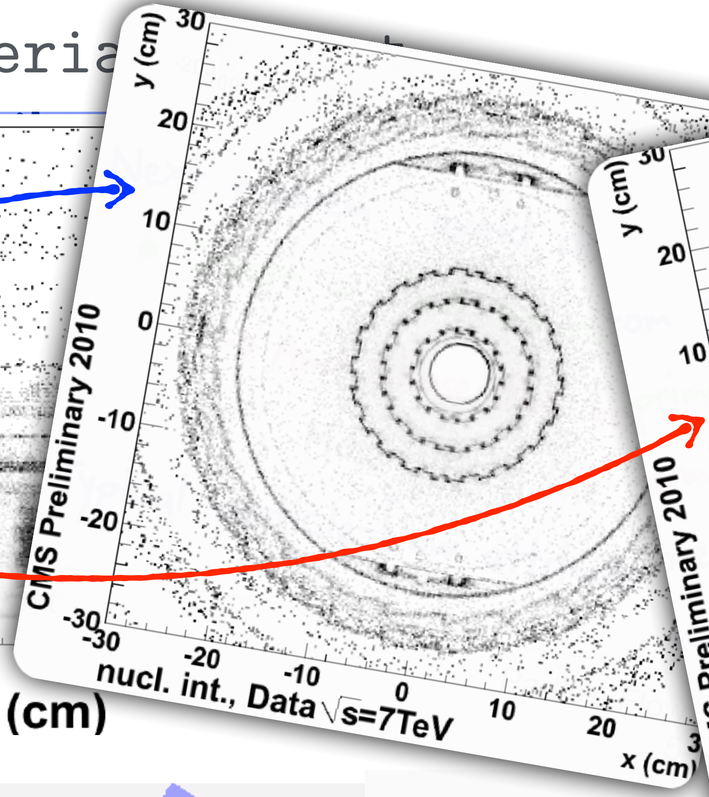

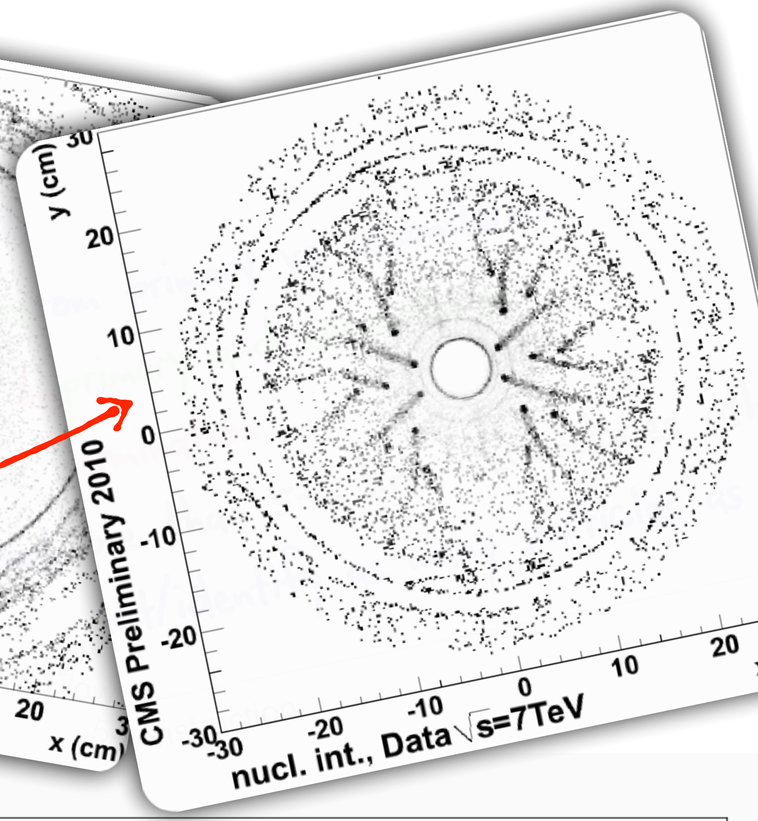

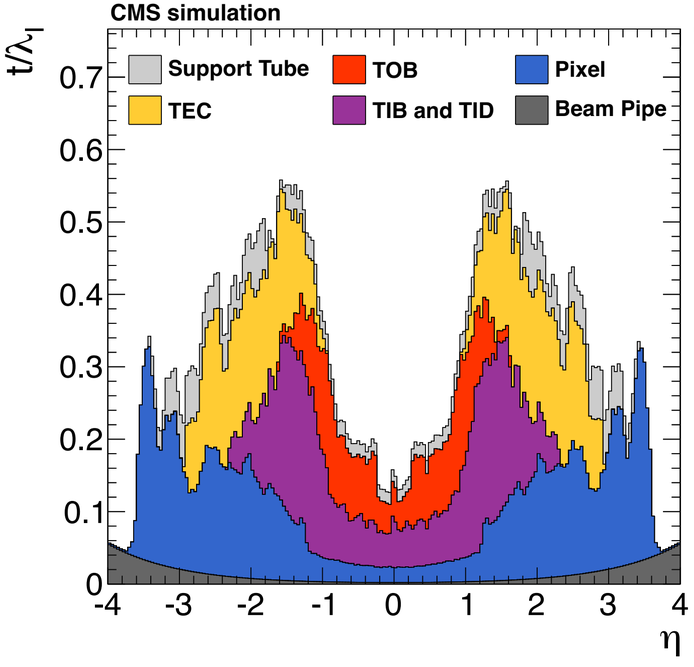

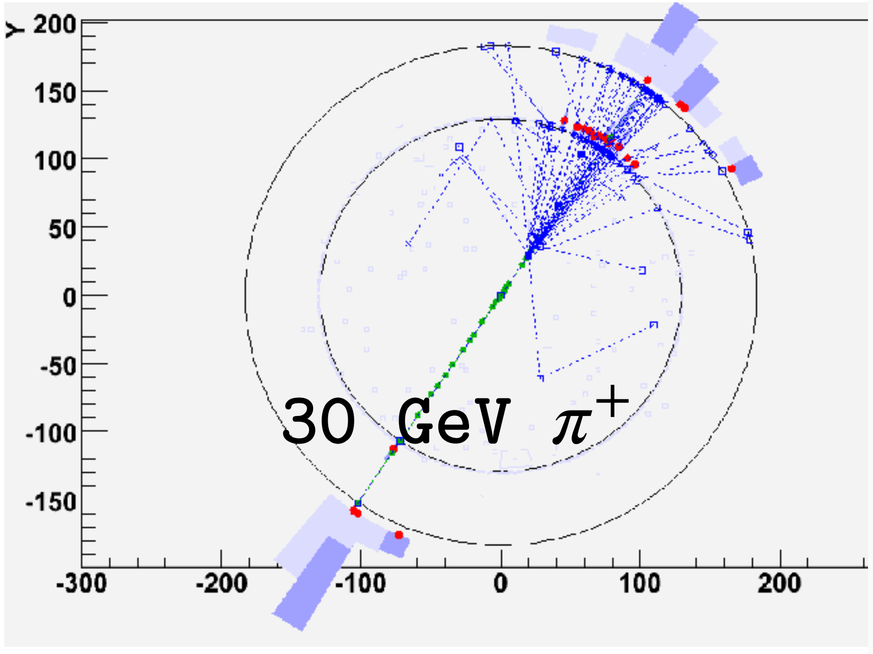

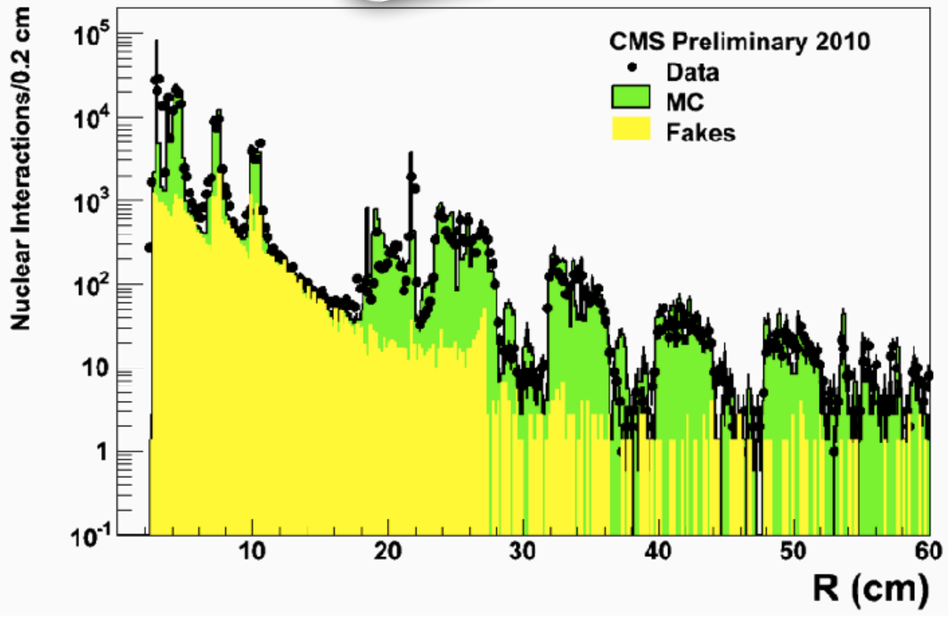

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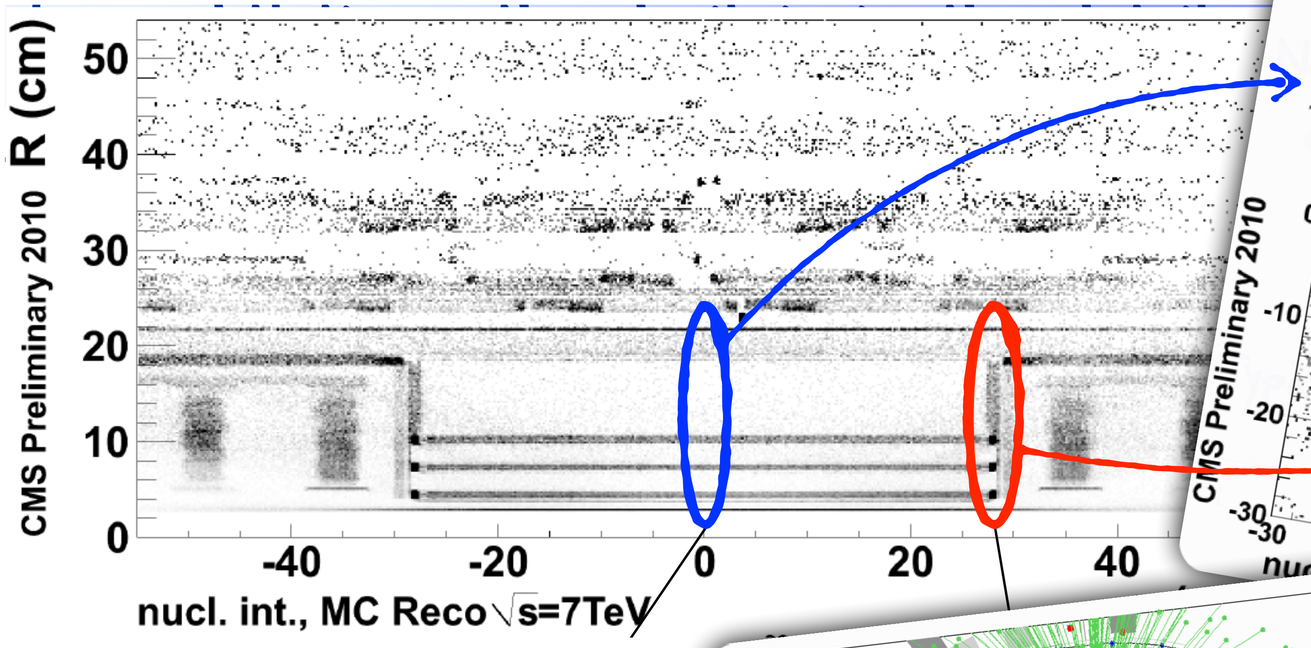
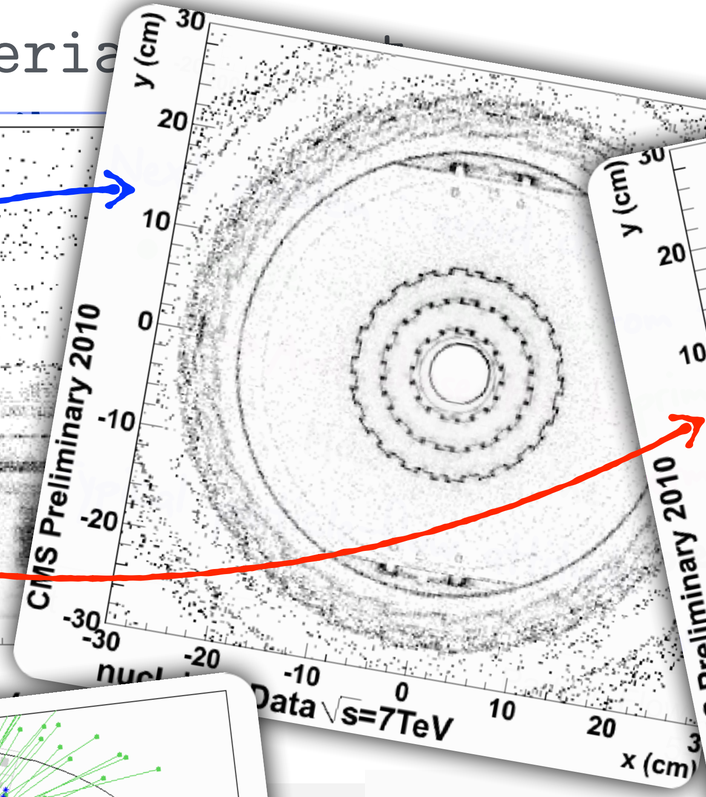
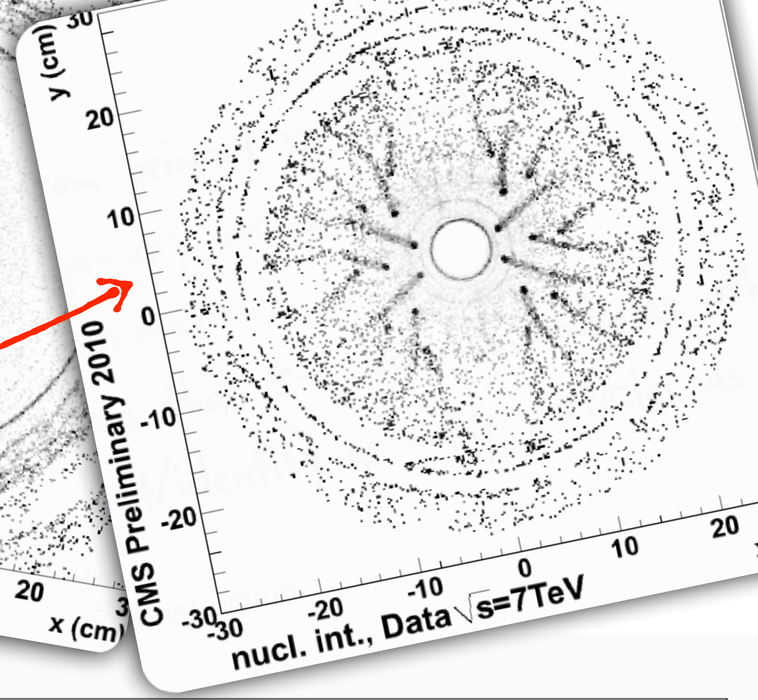
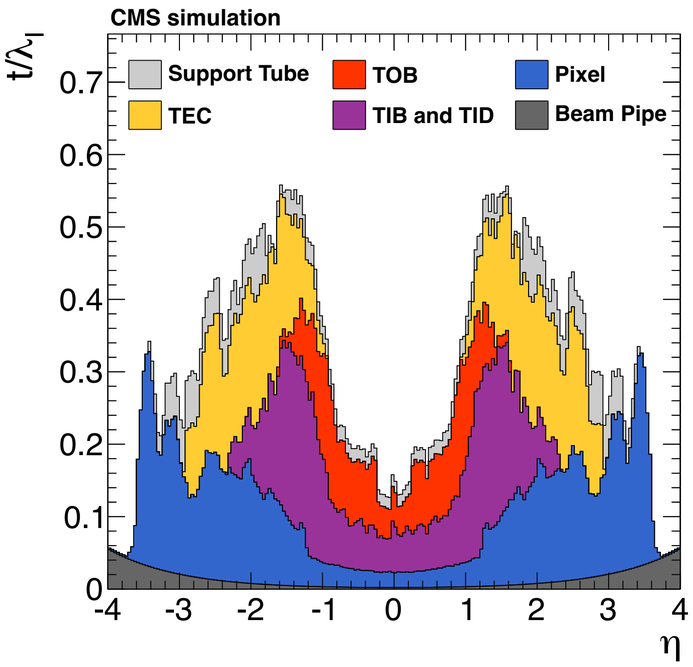
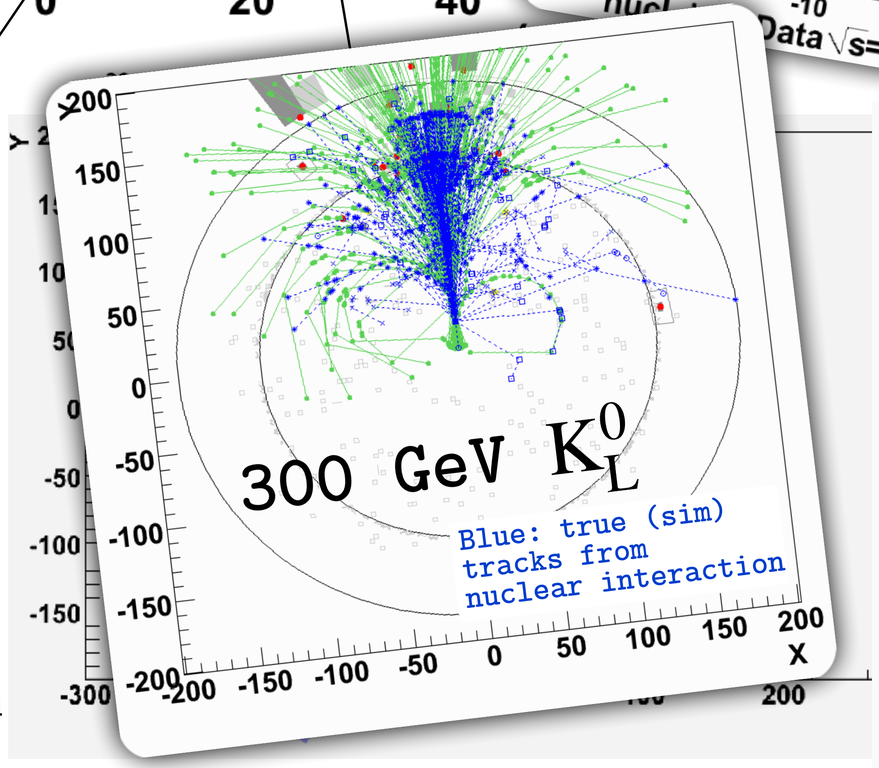
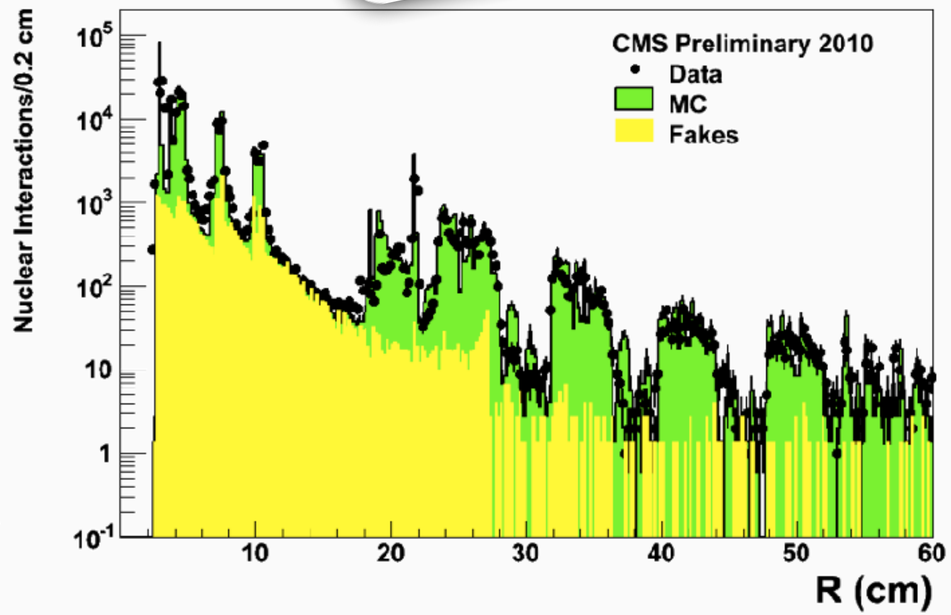




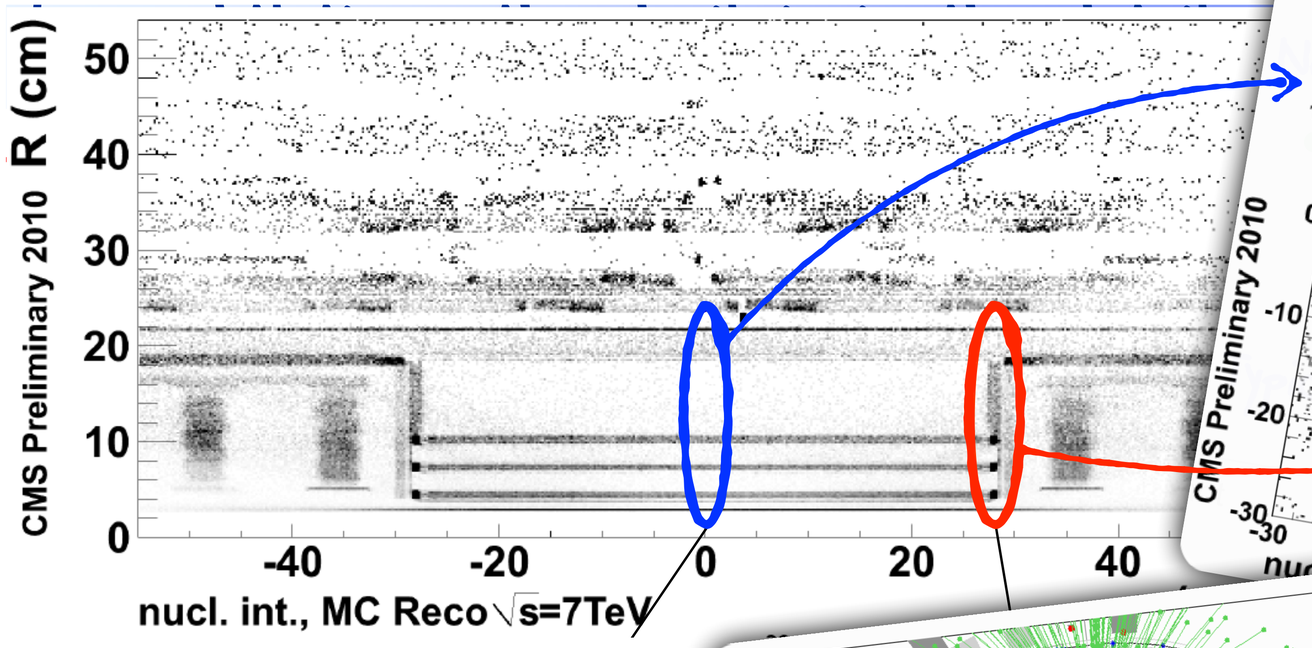


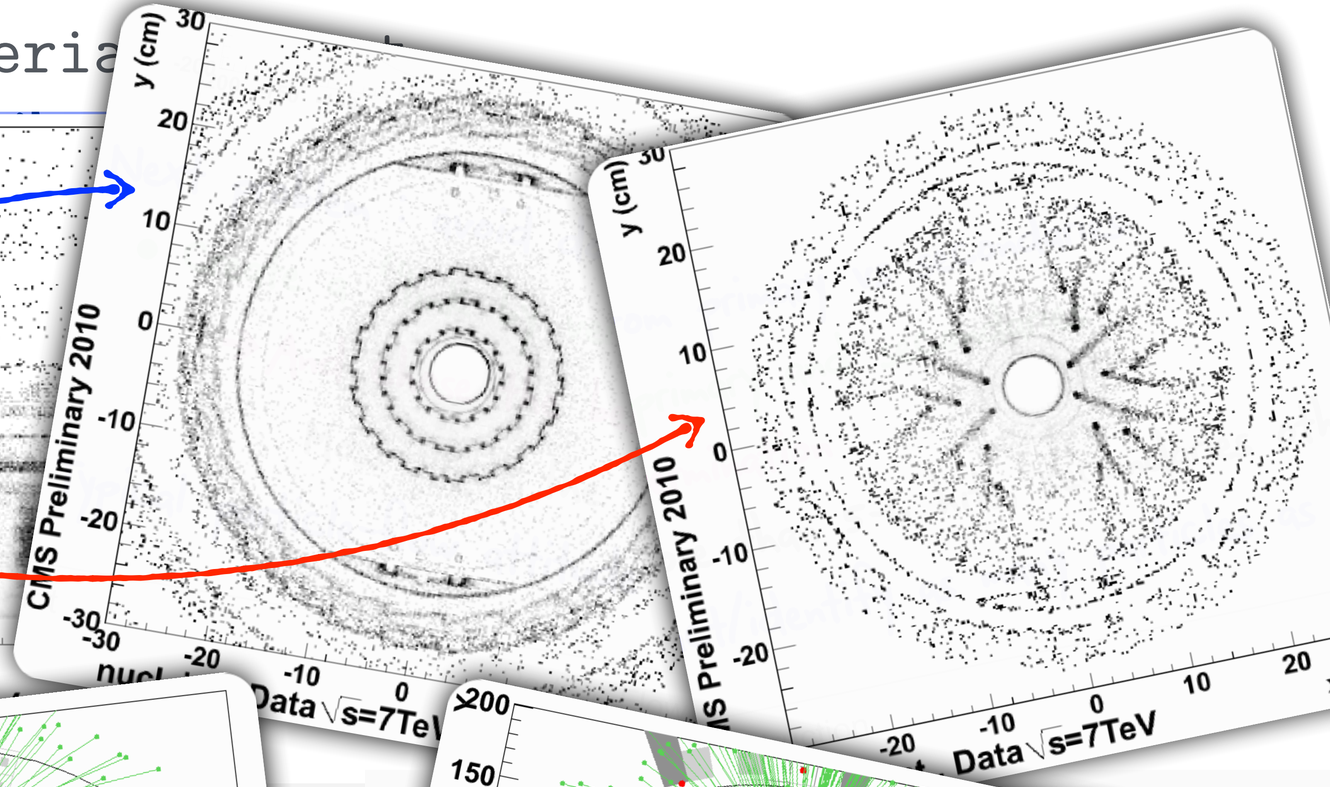


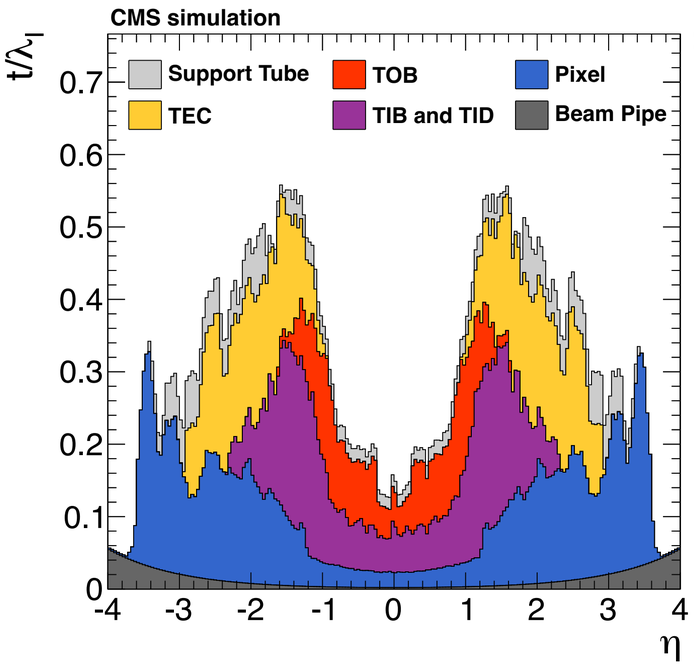


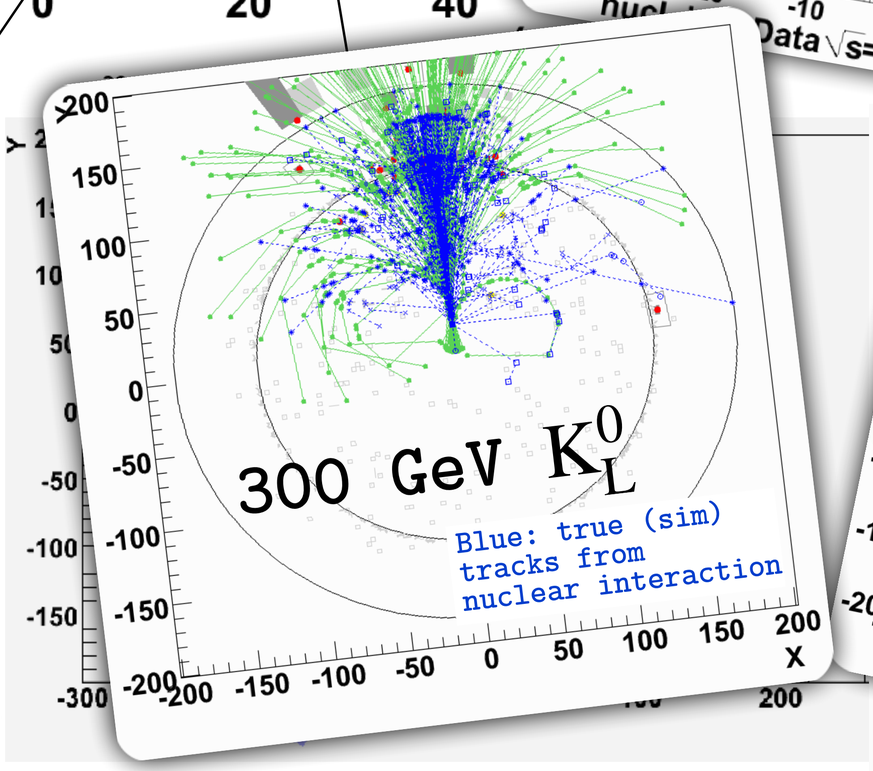


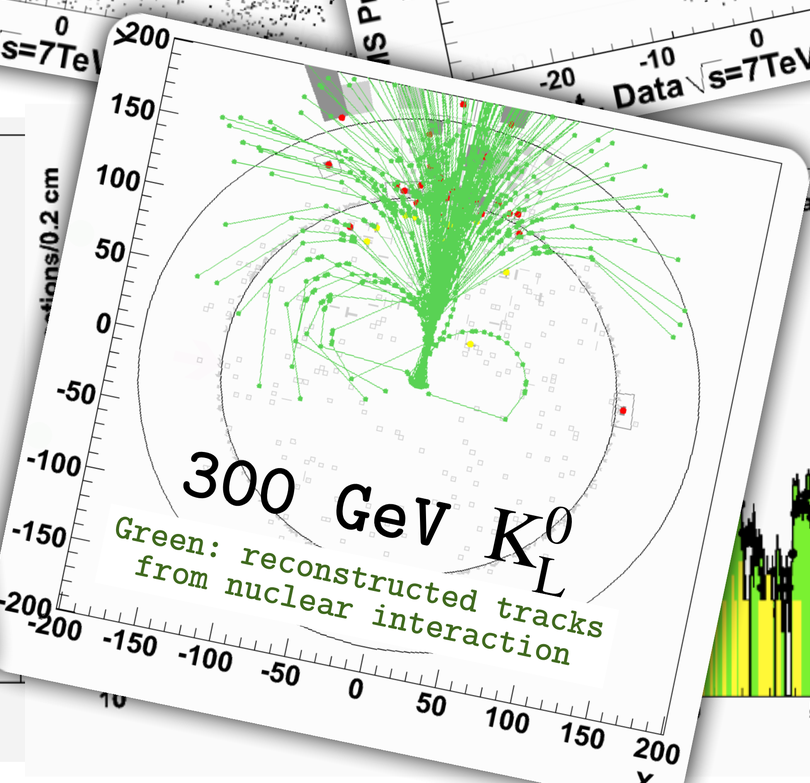
Important details! Tracker Materia

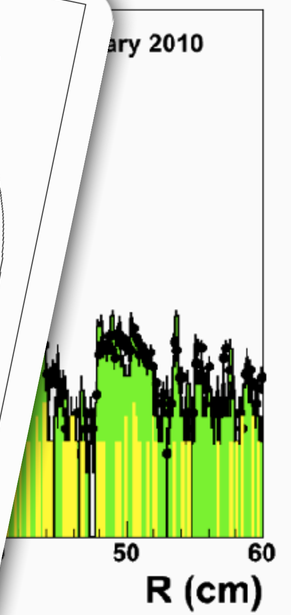












OK...I'll stop here