Introduction to ~~Particle~~ Fundamental Physics

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May 31 2022

Outline

I) What are we doing & why?

II) What do we know & not know?

III) How do we find out?

Part I

What are we doing?

What is Fundamental Physics?

Study the "building blocks" of our Universe

So what does that even mean?

Our world is made of quantum fields

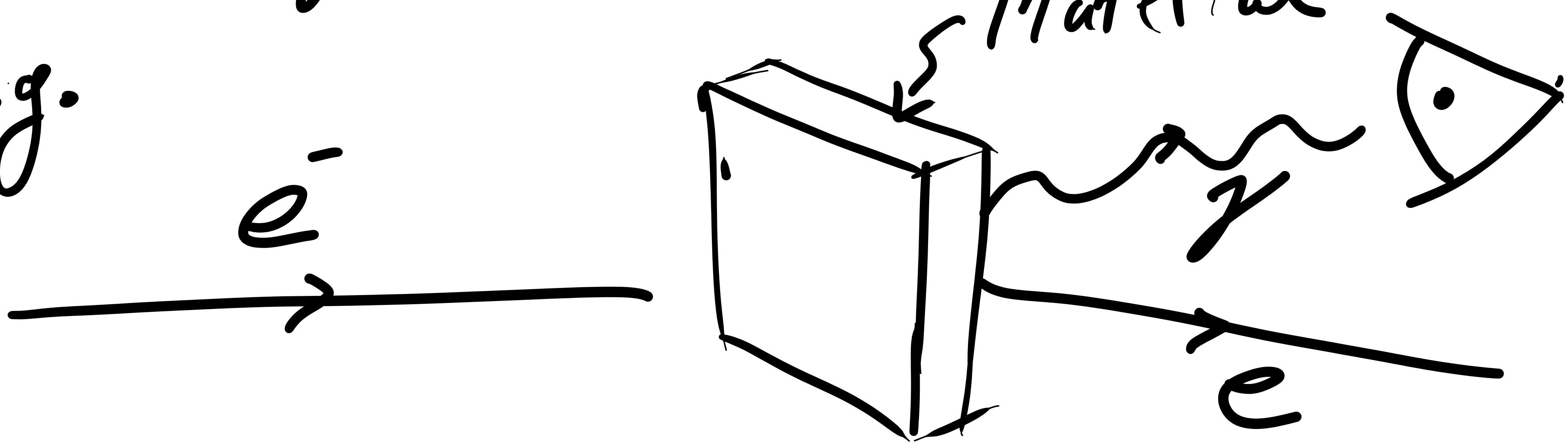
Quantum fields are described by a

Lagrangian = $\mathcal{L}$

Lagrangian ≡ Rule book

- If I know $\mathcal{L}_{\text{Theory}}$ I can compute predictions

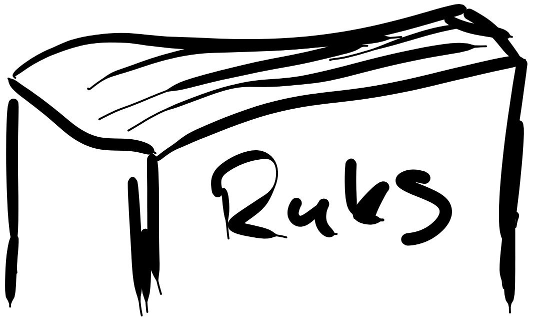
E.g.



Fundamental Physics is about studying Universe!

What are the rules?

- ↳ Lorentz Invariance (sp. rel.)
- ↳ Unitarity (Qu. Mech.)
- ↳ Symmetries (Cons. Laws)



≡ Lagrangian

Beyond Particles

$\mathcal{L}$ Universe

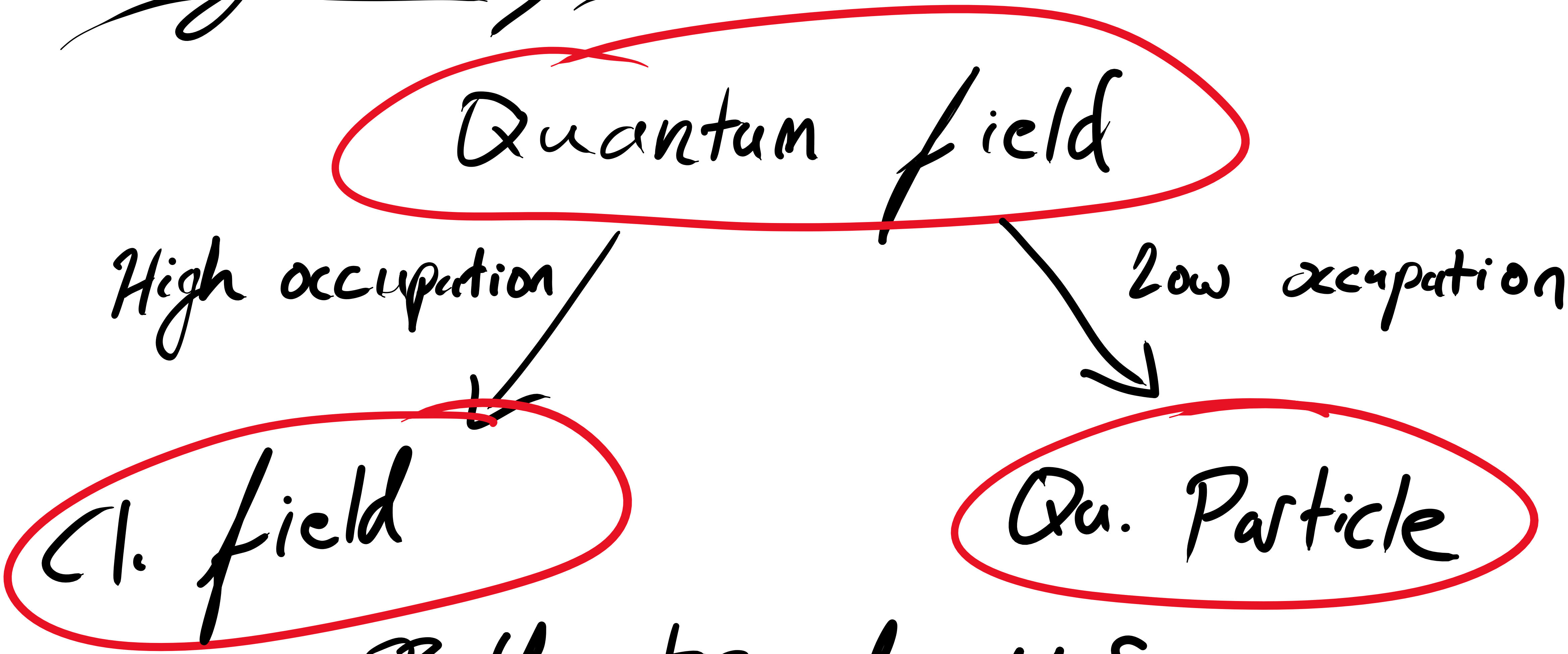
- Governs physics
  - ↳ everywhere
  - ↳ all the time

Every physical system is fair game

Beyond Particles

- ↳ Dense astrophysical objects
- ↳ Early universe cosmology
- ↳ Lab experiments with lasers / B-fields

Beyond Particles



⇒ Both teach us about fundamental physics

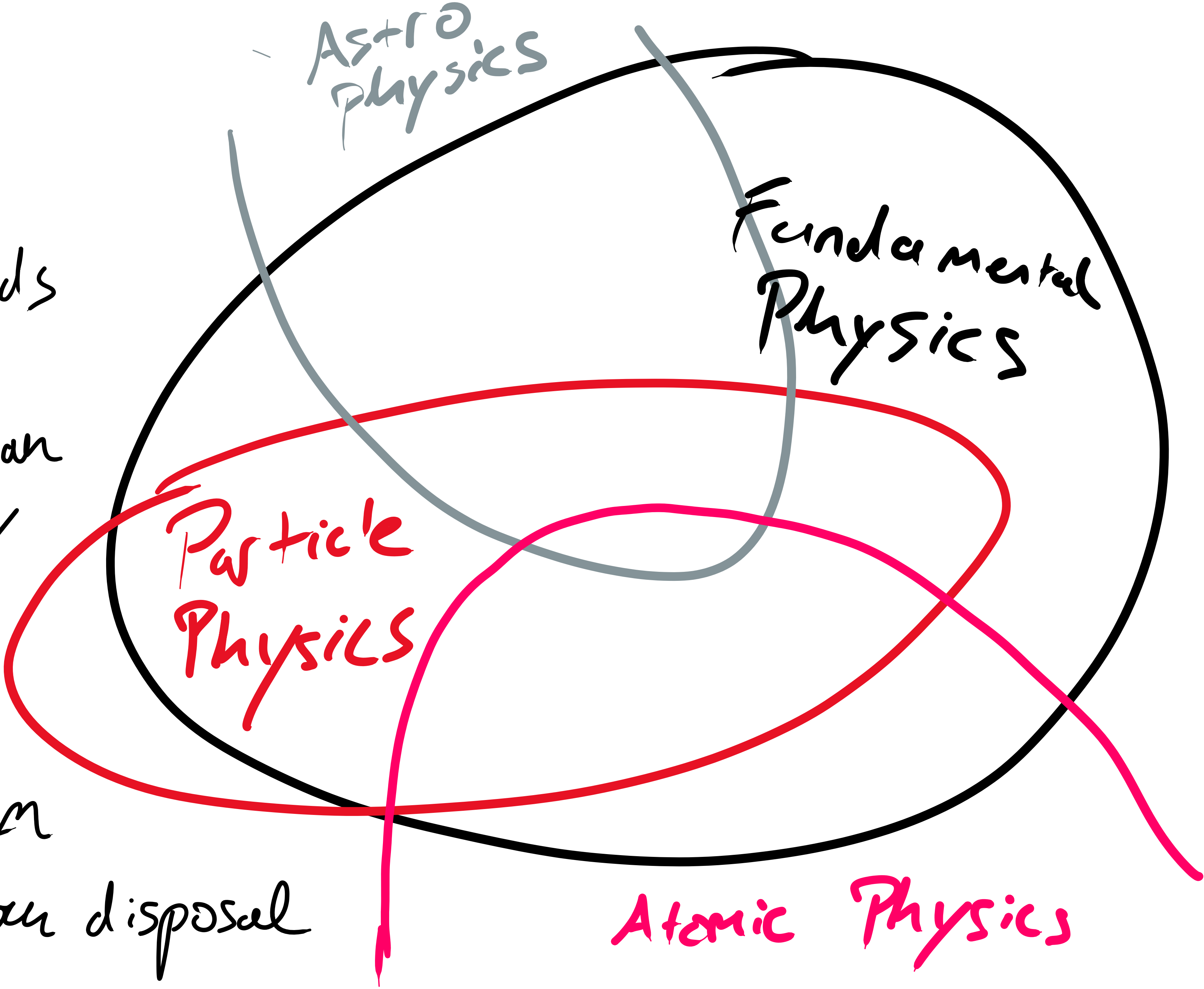
Beyond Particles

Example: New field/particle
ultra light scalar

Axion Star ≡ Star made of cl. fields

Summary

- Our world is made of qu. fields
- Their physics can be summarized w/ $\mathcal{L}$ = Lagrangian
- We study them w/ all tools @ our disposal



Part II

What do we know

& not know?

Particles

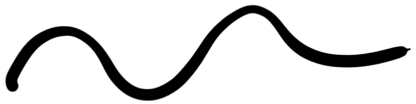
$\mathcal{L}$ = function({fields})

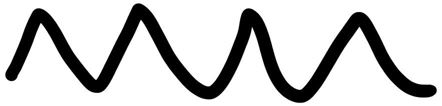
Excitation of field ⟶ Particle

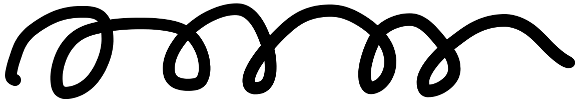
We learn $\mathcal{L}$ by studying particles

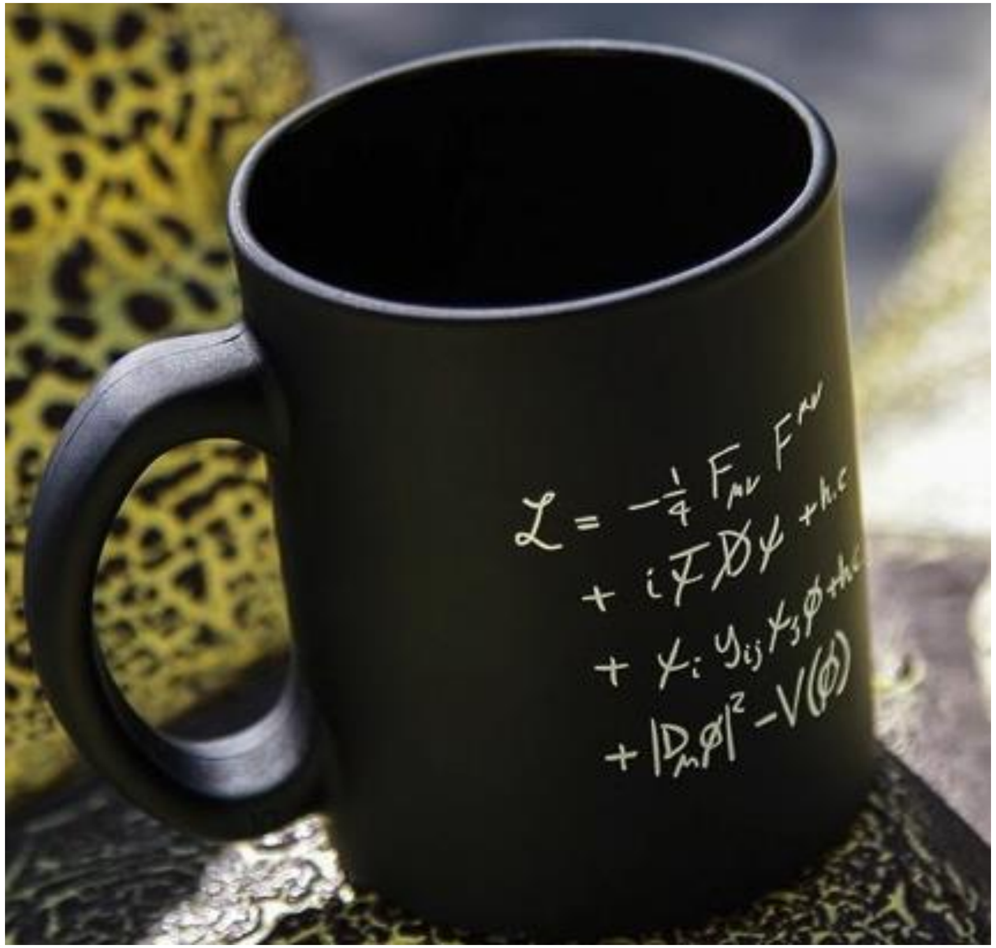
What do we know now?

- 3 Forces

γ :  : photon

W/Z :  : weak Boson

g :  : gluon

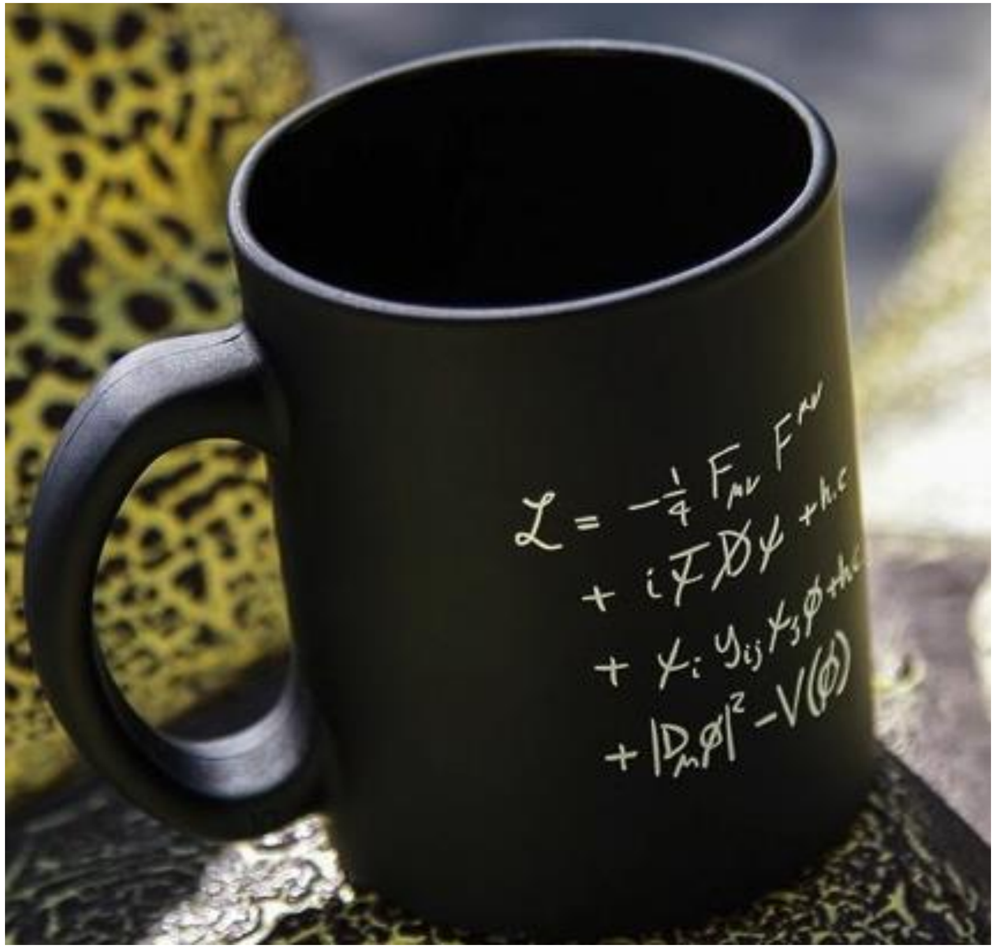


What do we know now?

12 fermions

6 quarks
↳ ud, cs, tb

6 leptons
↳ e, μ, τ $Q = e$
↳ ν_e, ν_μ, ν_τ **Neutrinos**

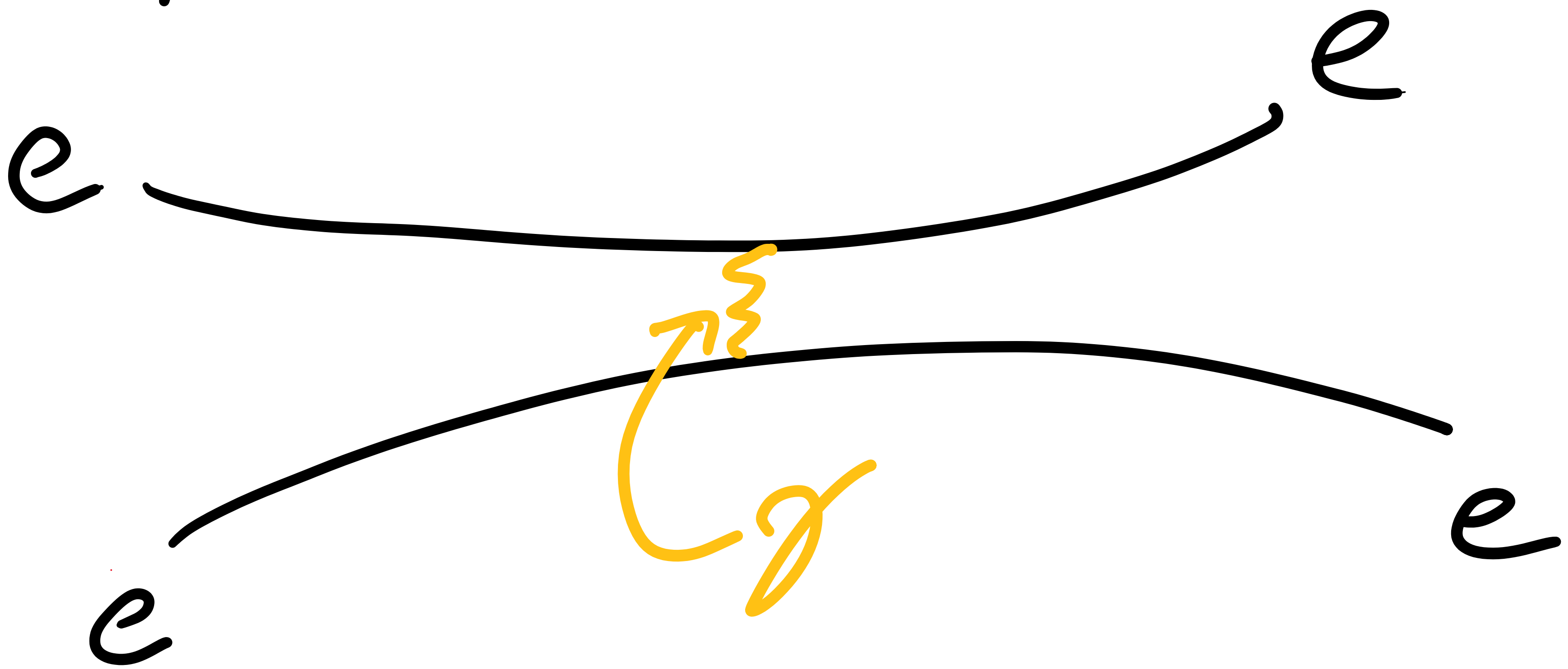


Generations

(e, ν_e)	(μ, ν_μ)	(τ, ν_τ)
(u, d)	(c, s)	(t, b)
light	**Medium**	**Heavy**

Interactions : 1 generation

Electrons talk to Photons

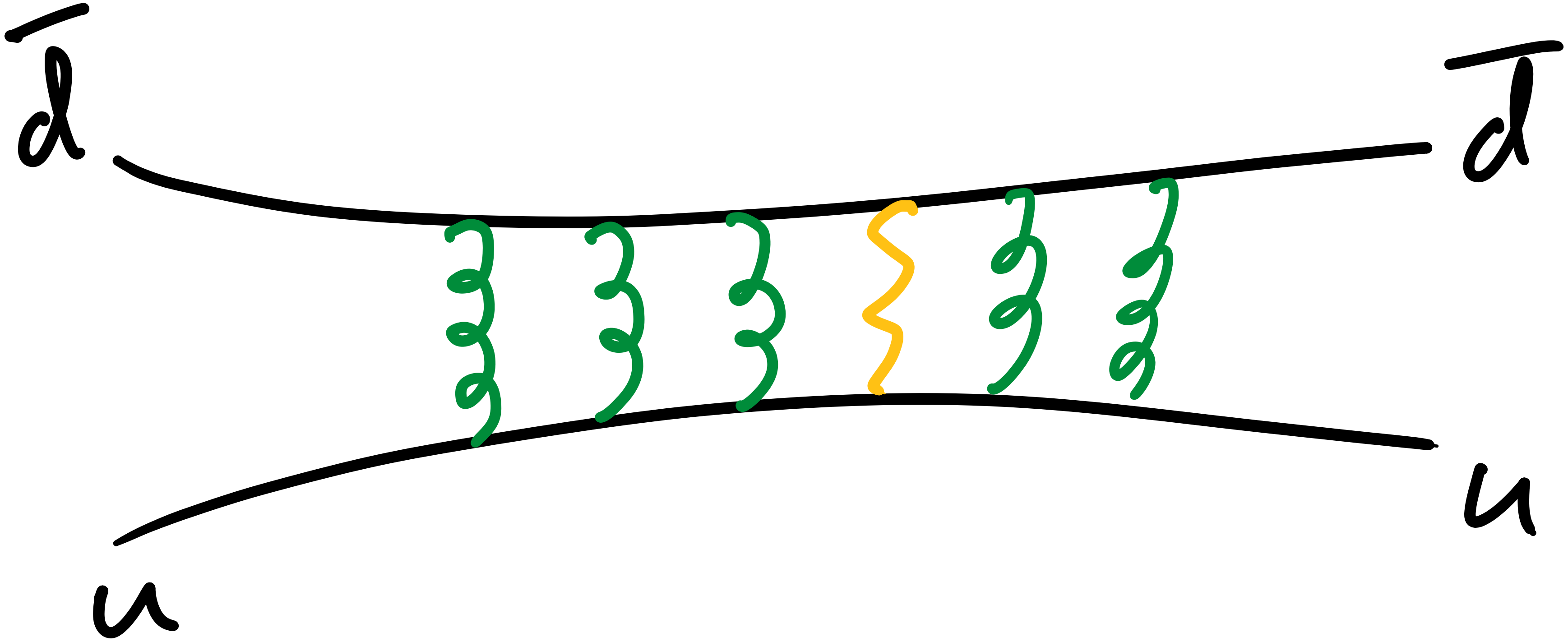


ee → ee

Interactions :

Quarks talk to gluons & photons



$$u\bar{d} \to u\bar{d}$$

Weak Interaction

W, Z } very very heavy { $m_e = 511$ keV, $m_W = 80$ GeV, $m_Z = 91$ GeV

Heavy ⟶ short distance ⟶ weak Interaction

Higgs Mechanism

Mass: $\mathcal{L} = m \bar{\psi} \psi$

Higgs: $\mathcal{L} = g \phi \bar{\psi} \psi$

$\hookrightarrow \phi = v + \delta\phi$

$= g v \bar{\psi} \psi + g \delta\phi \bar{\psi} \psi$

Background field creates mass

Neutrino Masses

- Neutrinos are special
- Higgs mechanism does not work
- Predicted to be massless*

Reality

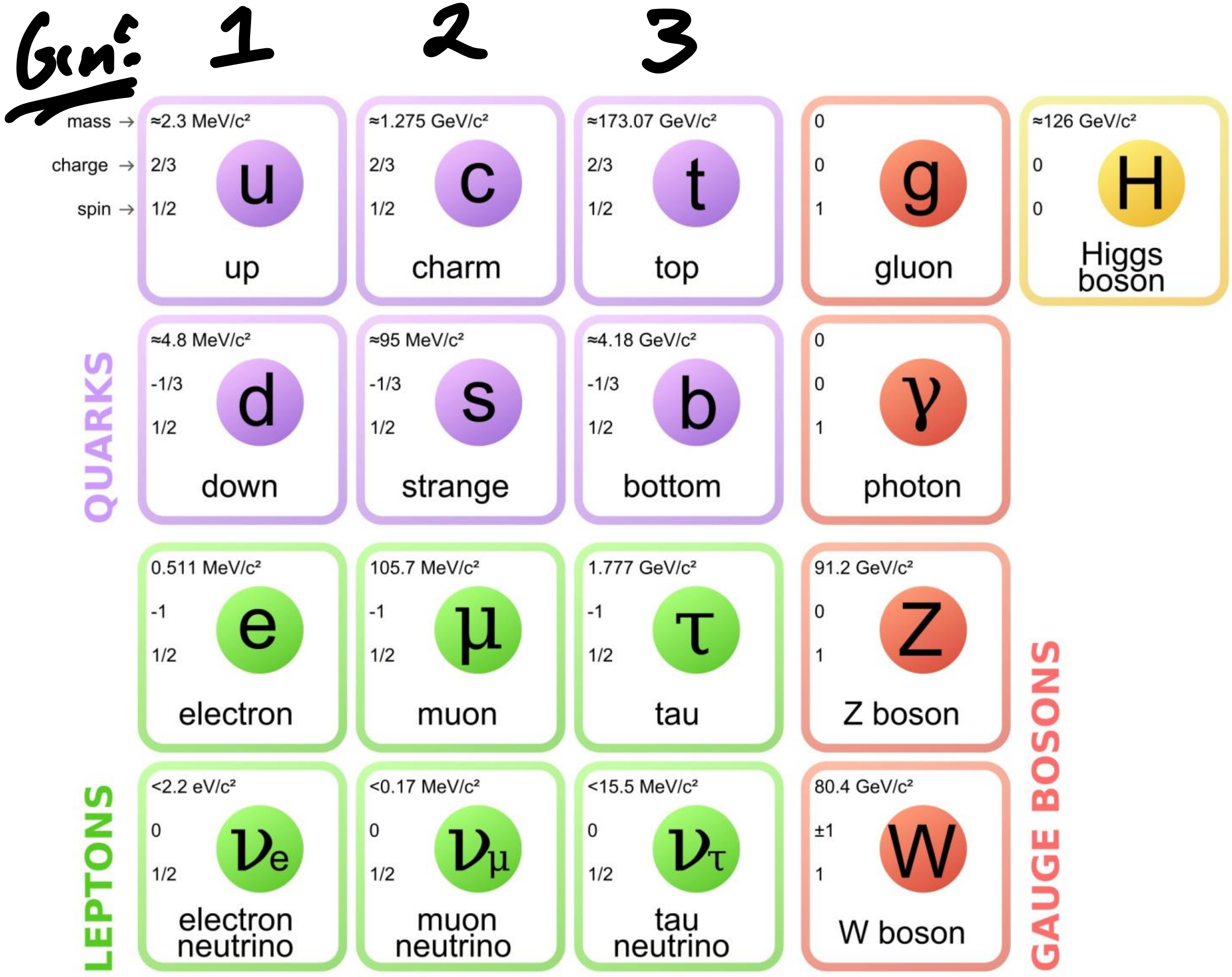
- Neutrinos have mass
- They "oscillate"!

} ← 2015 Nobel Prize

* A bit of a lie here

The Standard Model

- All masses
- Most couplings
- A lot of data
- Works very well



Our composite world

↳ Protons & Neutrons — QCD

Bound quarks & gluons

↳ Atomic Nuclei — QCD

Bound protons & neutrons

↳ Atoms — QED

Bound electrons & nuclei

Beyond the Standard Model

- What is dark matter?
- Why are proton's stable?
- How did matter dominate over anti-matter?
- Why do neutrinos have mass?

ARE WE MISSING ANYTHING?

Part III

How do we find out?

Beyond Particles

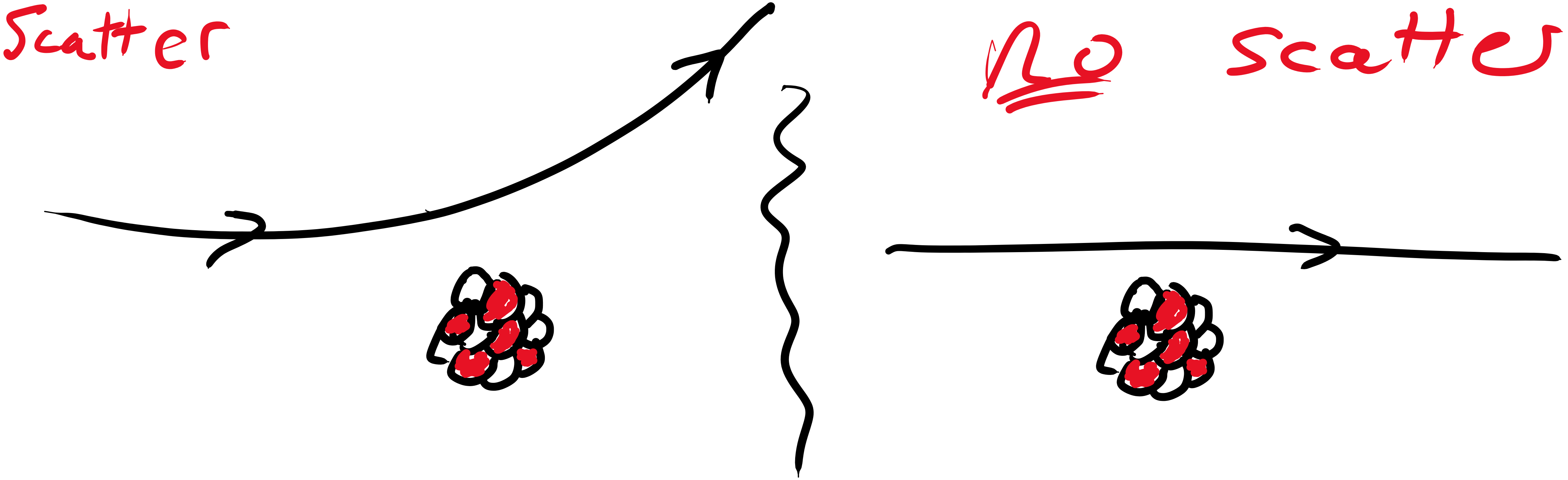
$\mathcal{L}$ Universe

- Governs physics
  - ↳ everywhere
  - ↳ all the time

Every physical system is fair game

What can we compute?

↳ Probability of scattering

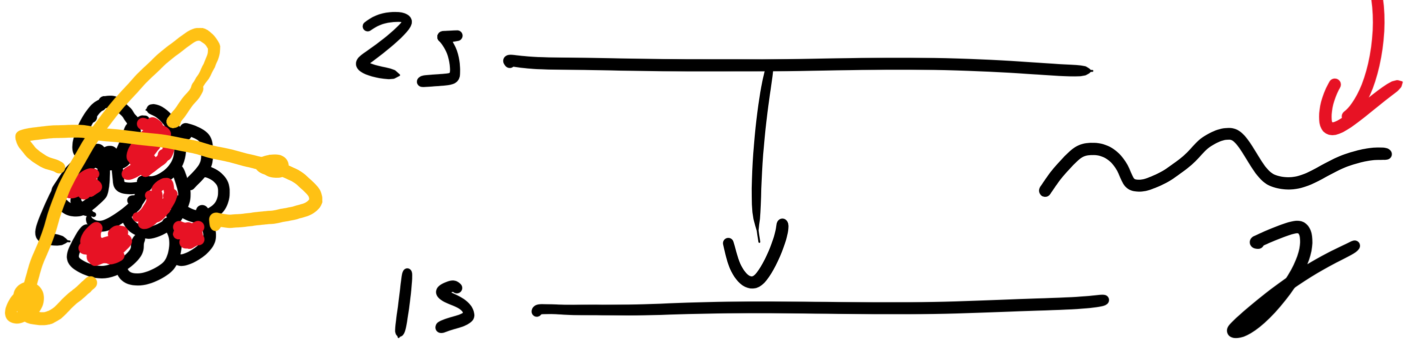


What can we compute?

↳ Energy levels!

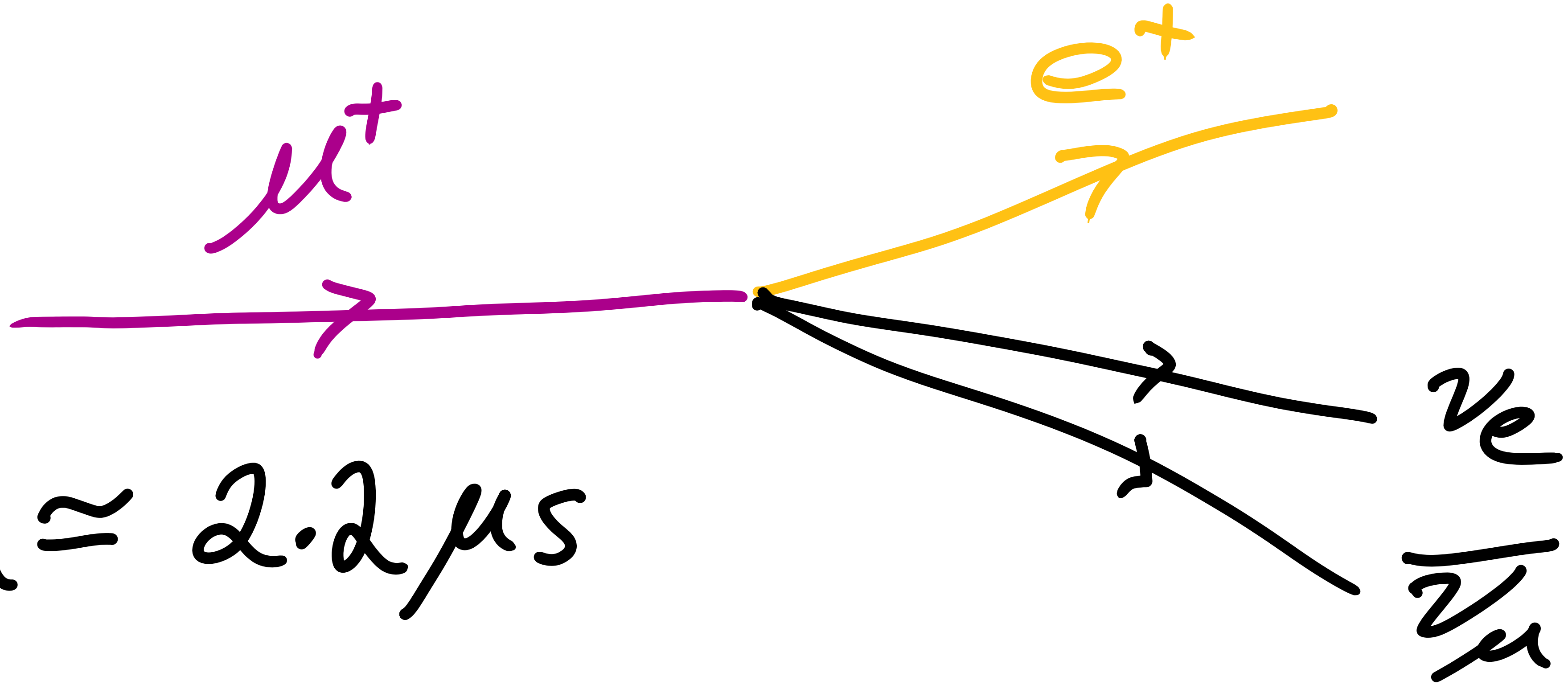
Atomic Transitions

Measure E_γ



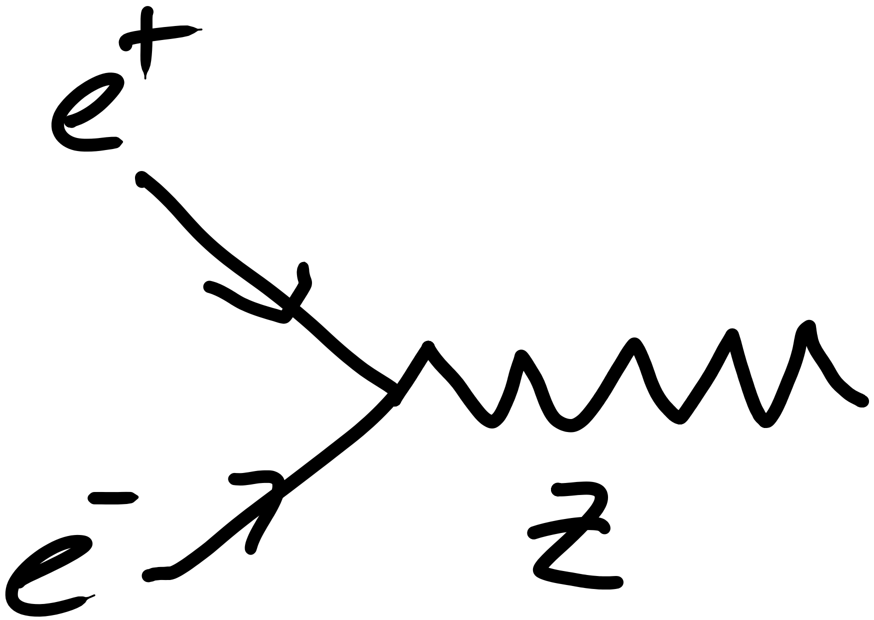
What can we compute?

↳ Lifetime of unstable particle



$\tau_\mu \simeq 2.2\,\mu s$

Example I: LEP



Challenge

Need ~50 GeV beam

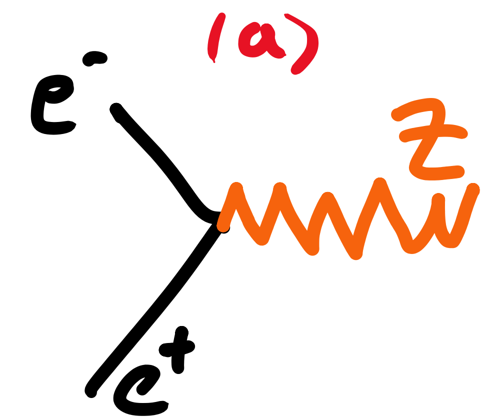
1) Smash high energy beams
2) Make heavy particles
3) Count them!

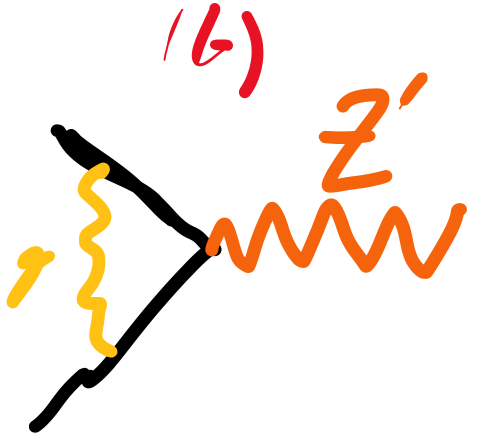
Example I: LEP

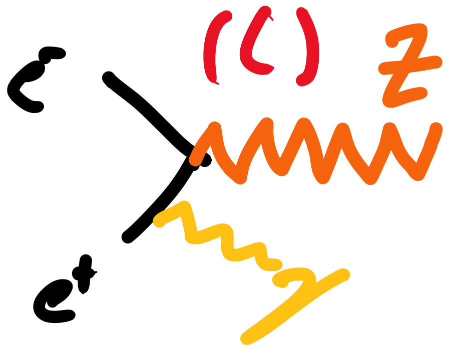
Theory	Experiment
1) Rate of $e^+e^- \to Z$	1) How many e^+ & e^-?
2) Branching ratio $Z \to \mu^+\mu^-$	2) How many $\mu^+\mu^-$
	3) Do the $\mu^+\mu^-$ "look" right?

Example I: LEP

Production

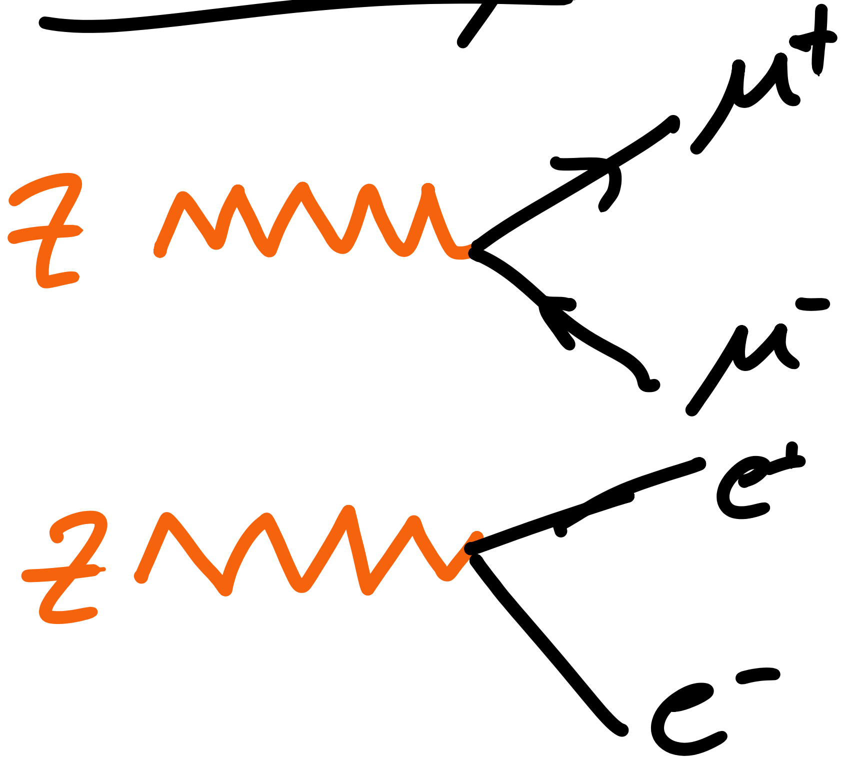




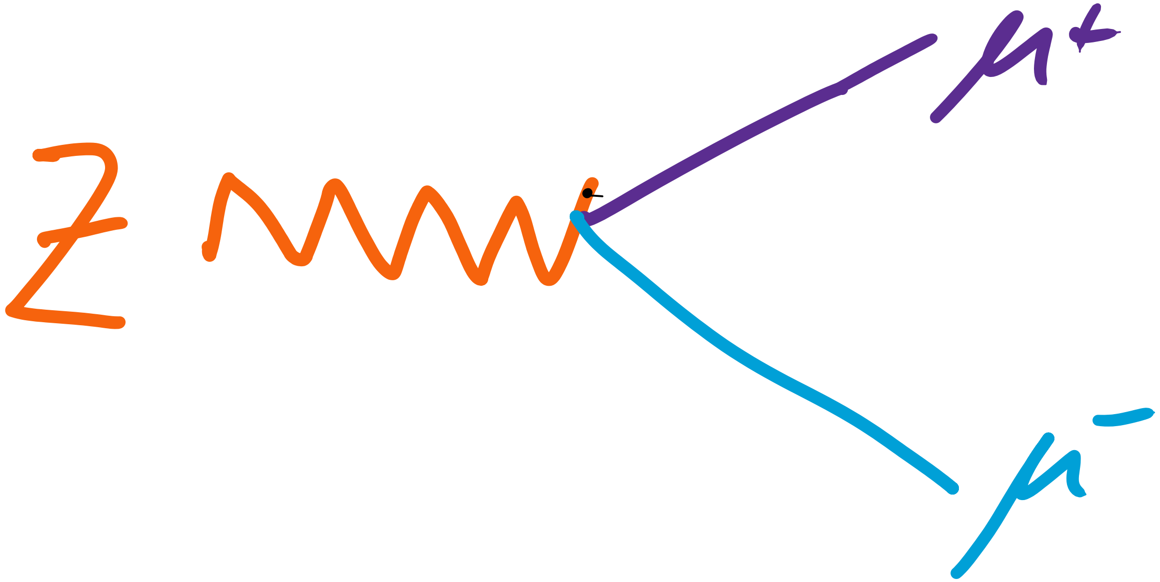


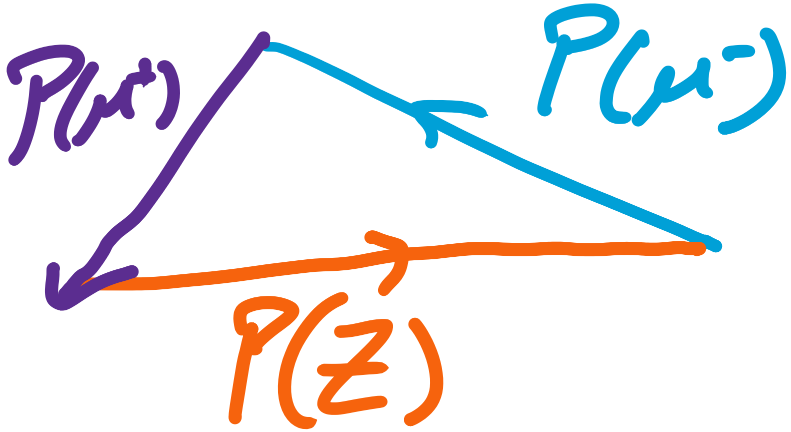
(a) $\gg$ (b),(c)

Decay



Example I: LEP



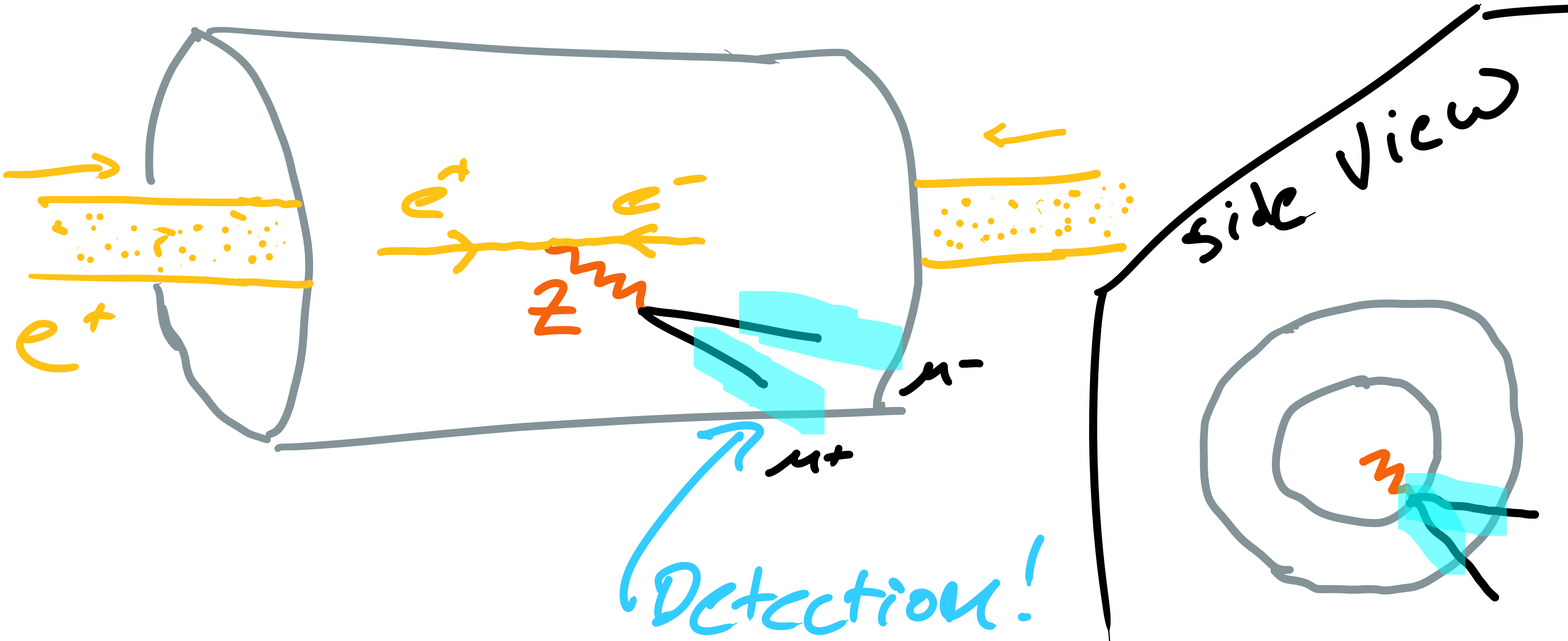


- Energy & Momentum Cons.

$$m_{\mu\mu}^2 = (E_{\mu^-} + E_{\mu^+})^2 - (\vec{p}_{\mu^-} + \vec{p}_{\mu^+})^2$$

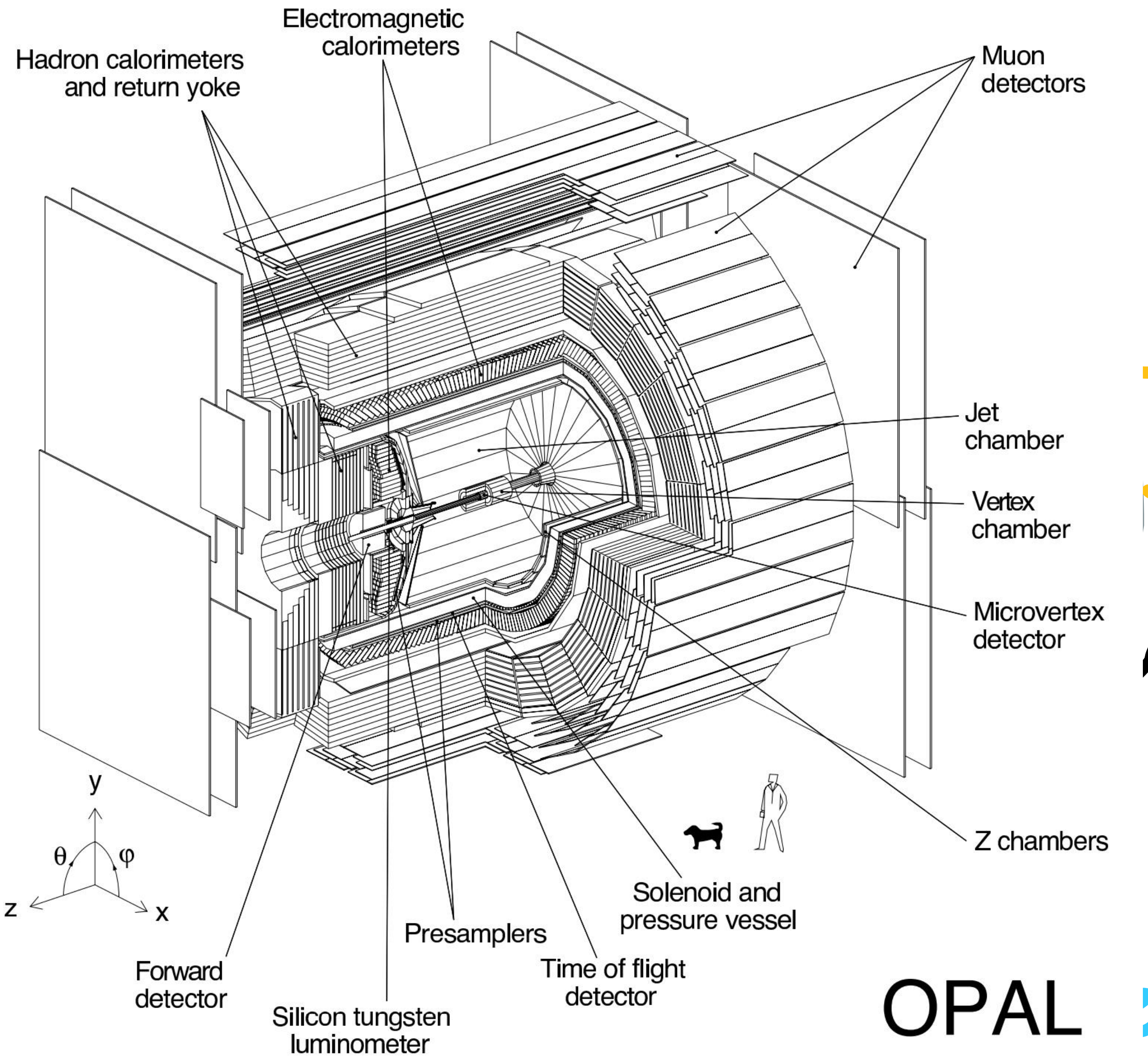
Invariant Mass

Example I: LEP

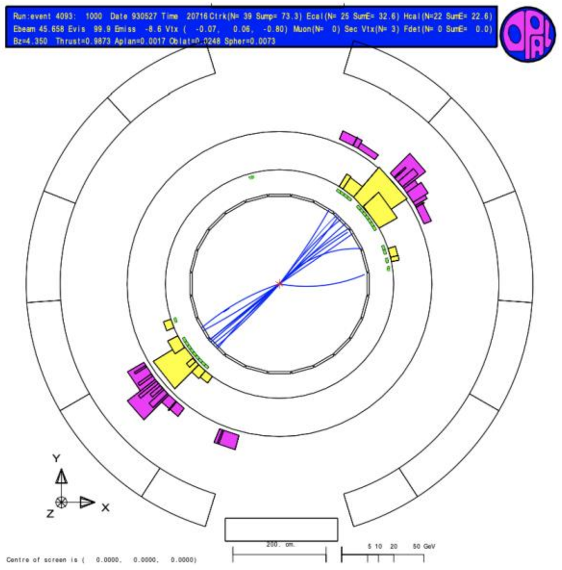


Example I: LEP

hep-ex

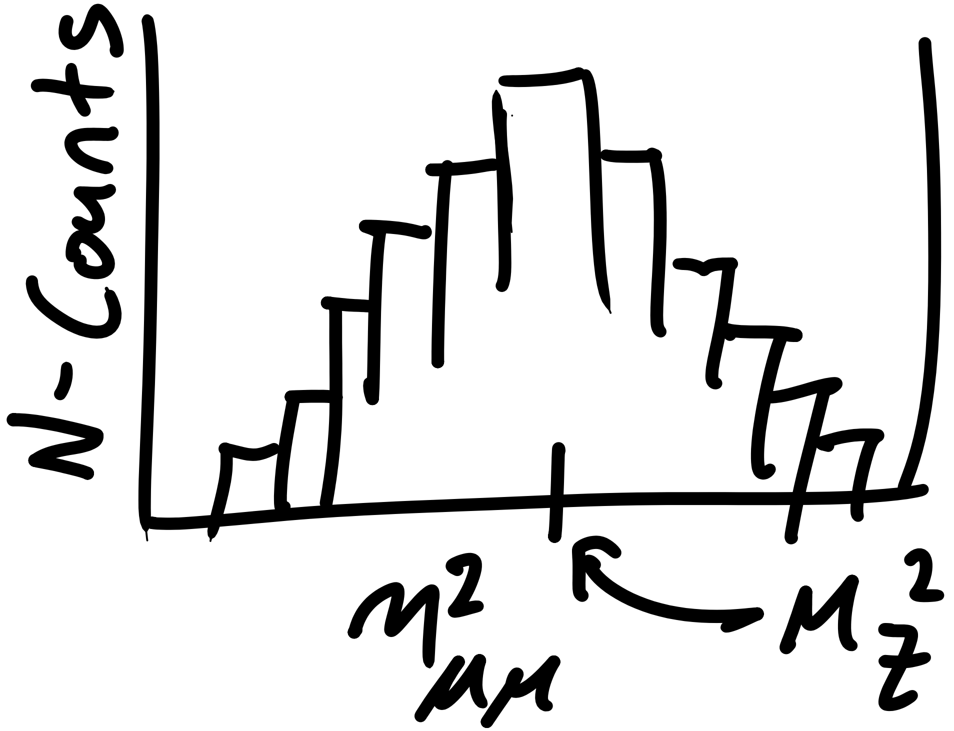


side view

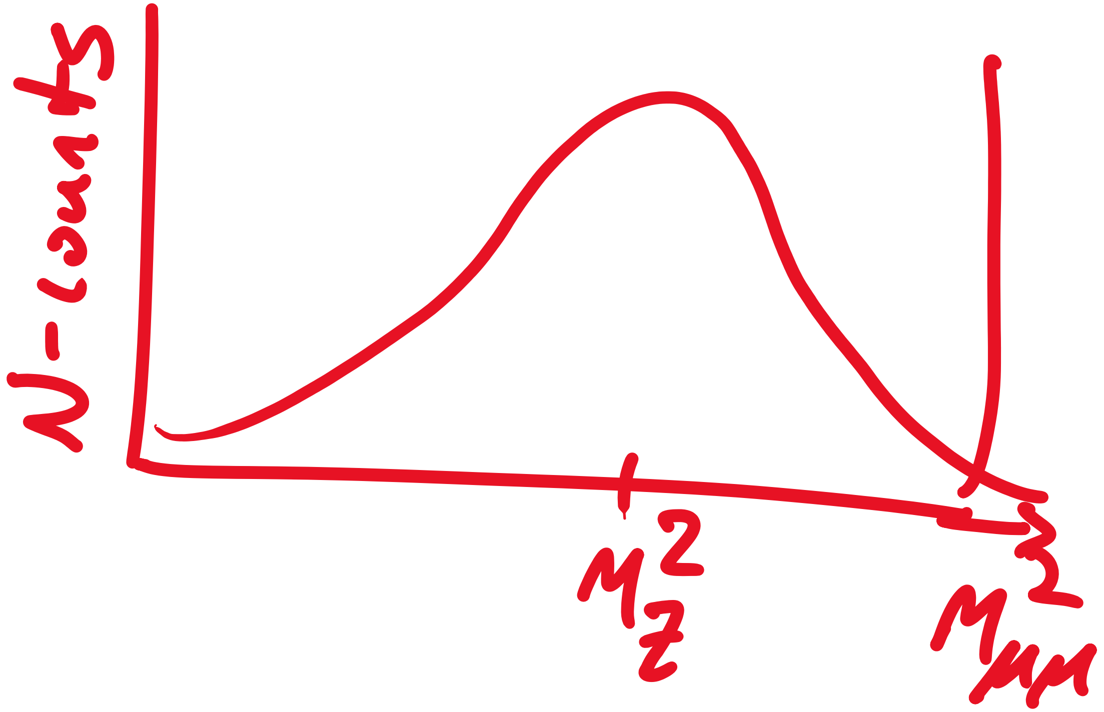


Example I: LEP

Bin using $m_{\mu\mu}^2$

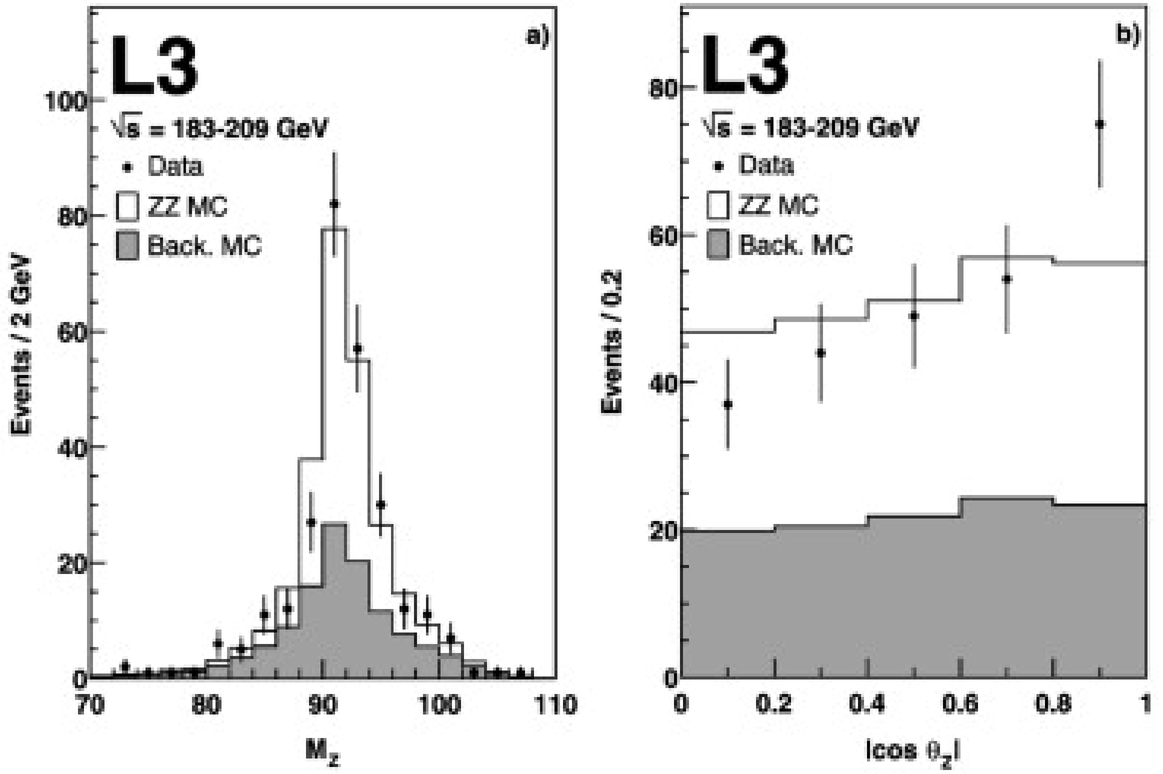


Compare w/ Theory



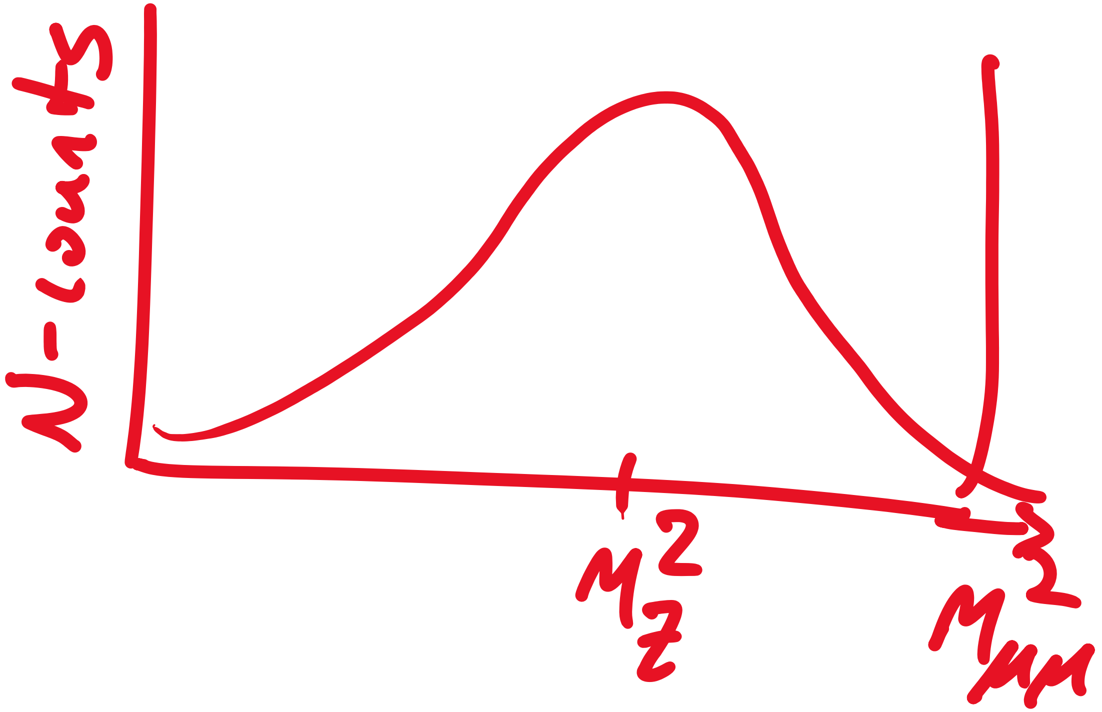
Example I: LEP

Bin using $m^2_{\mu\mu}$



hep-ex/030813

Compare w/ Theory



Example I: LEP

$M_Z(\text{LEP}) = 91.852 \pm 0.0030$ GeV

4.57×10^6 events

Why bother? Ask me!

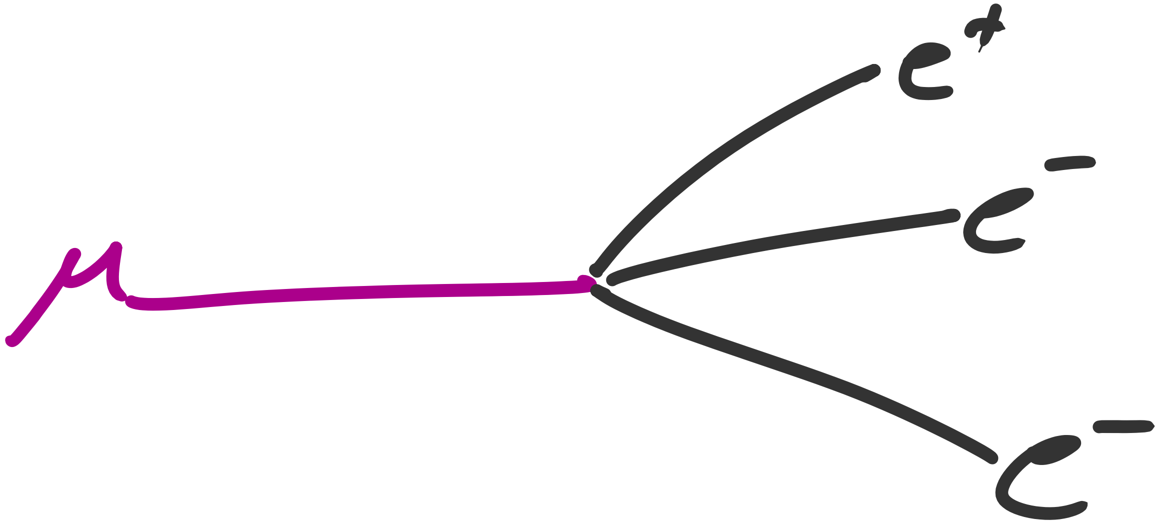
Example II: Mu2e ($\mu \to e$)

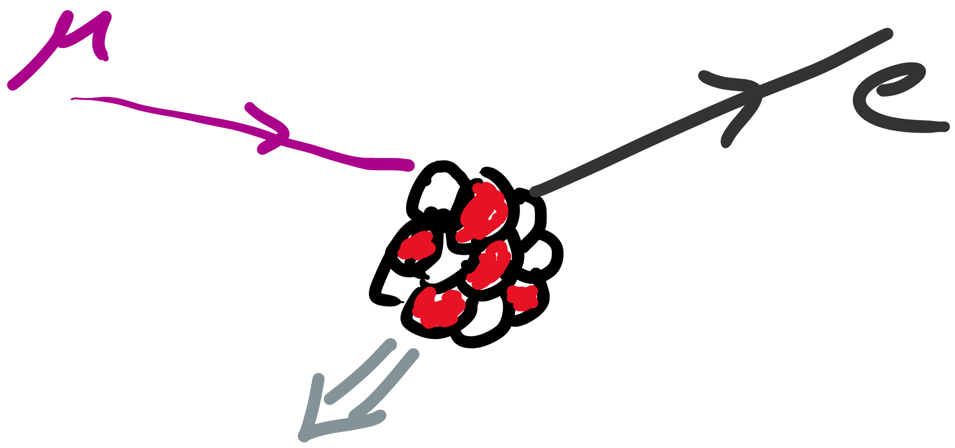
Background:

- Charged leptons (e, μ, τ) have **never** been observed to change flavour
- SM predicts this will never* occur

* This is a bit wrong

Example II: Mu2e ($\mu \to e$)





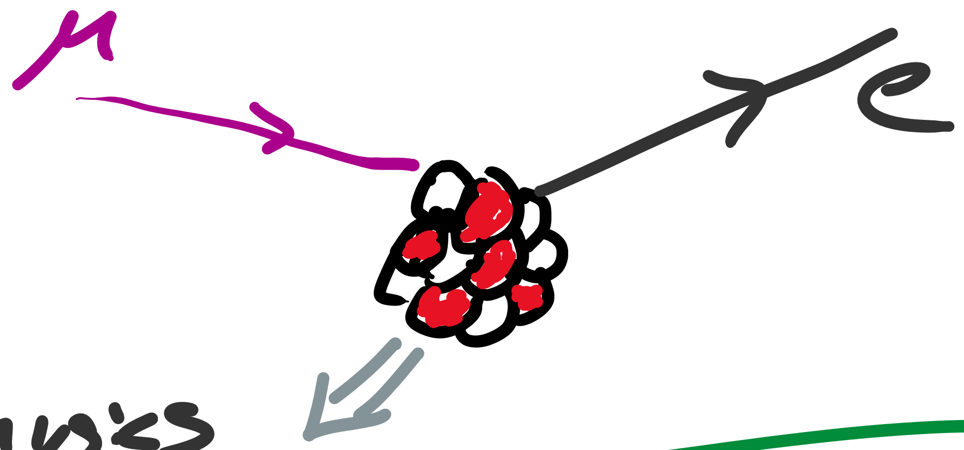
i) $\mu \to e\,\gamma$

ii) $\mu \to 3e$

iii) $\mu \to e$

Example II: Mu2e ($\mu \to e$)

- If we ever observe this we have discovered New Physics



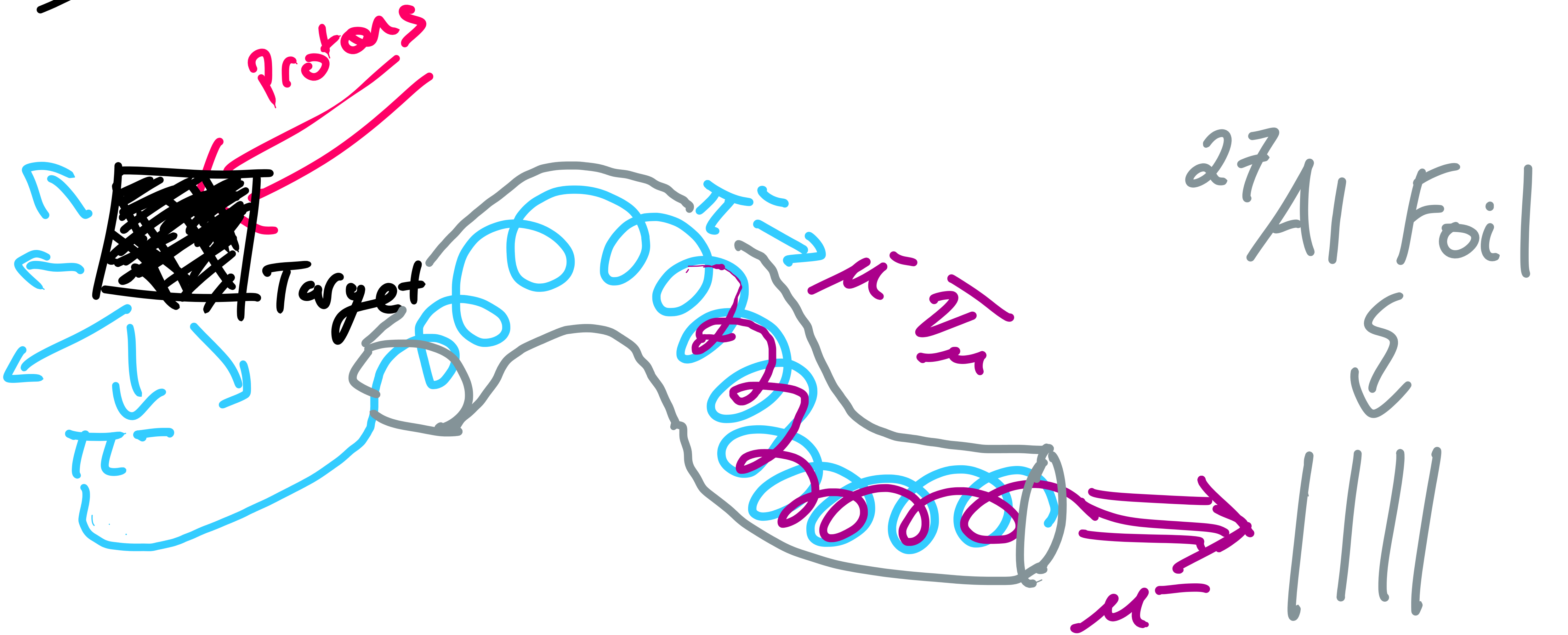
- Need many many .

Muons

Challenge
As many muons as possible

(ii) $\mu \to e$

Example II: Mu2e ($\mu \to e$)



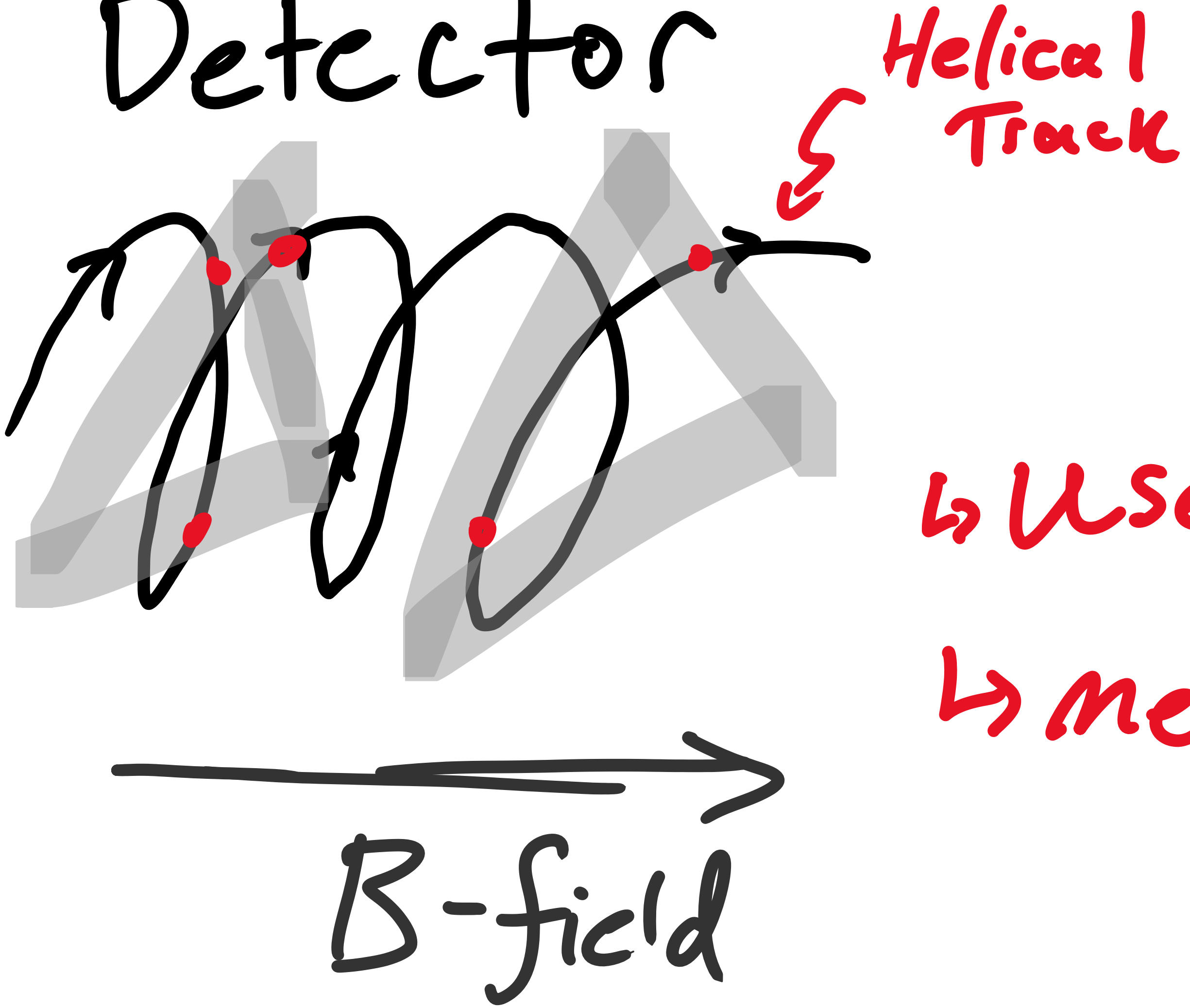
Example II: Mu2e ($\mu \rightarrow e$)

$$E_{e^-} \simeq m_\mu$$

1) Muons stop 2) Form Atoms 3) Capture on ^{27}Al

Example II: Mu2e ($\mu \to e$)

Detector



$$R = \frac{m v_\perp}{|q| B}$$

↳ Use timing

↳ measure velocity!

Example II: Mu2e ($\mu \to e$)

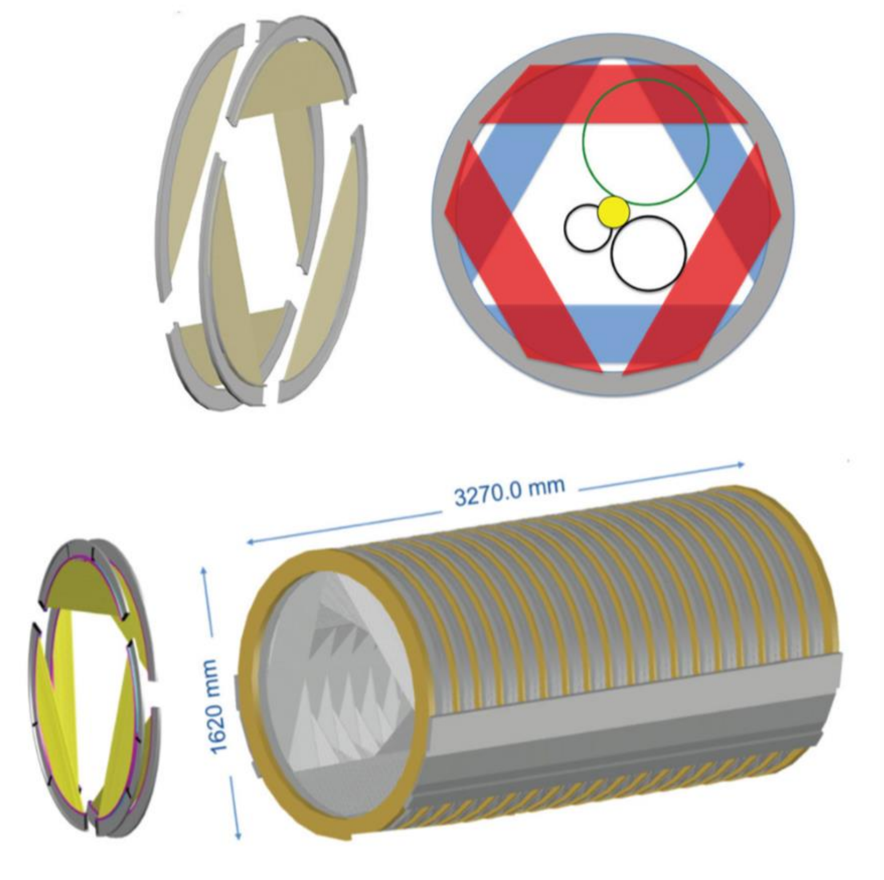
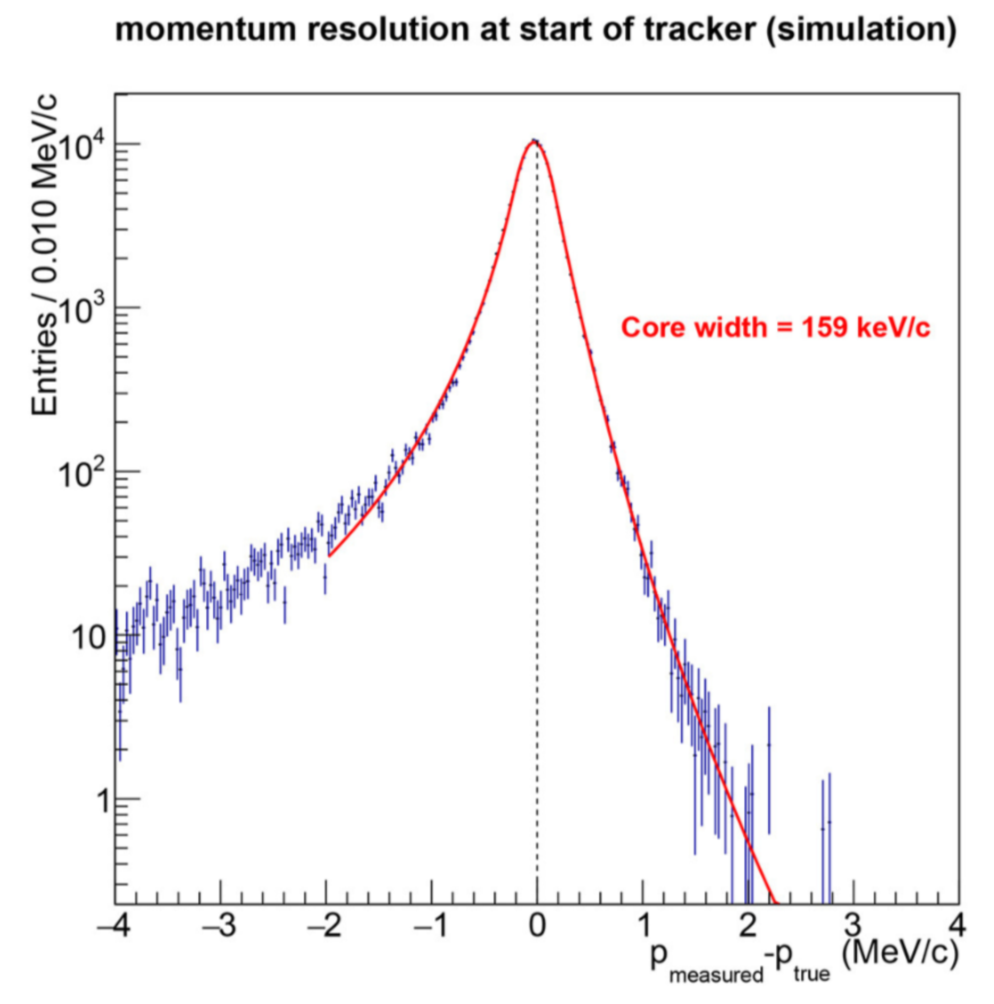
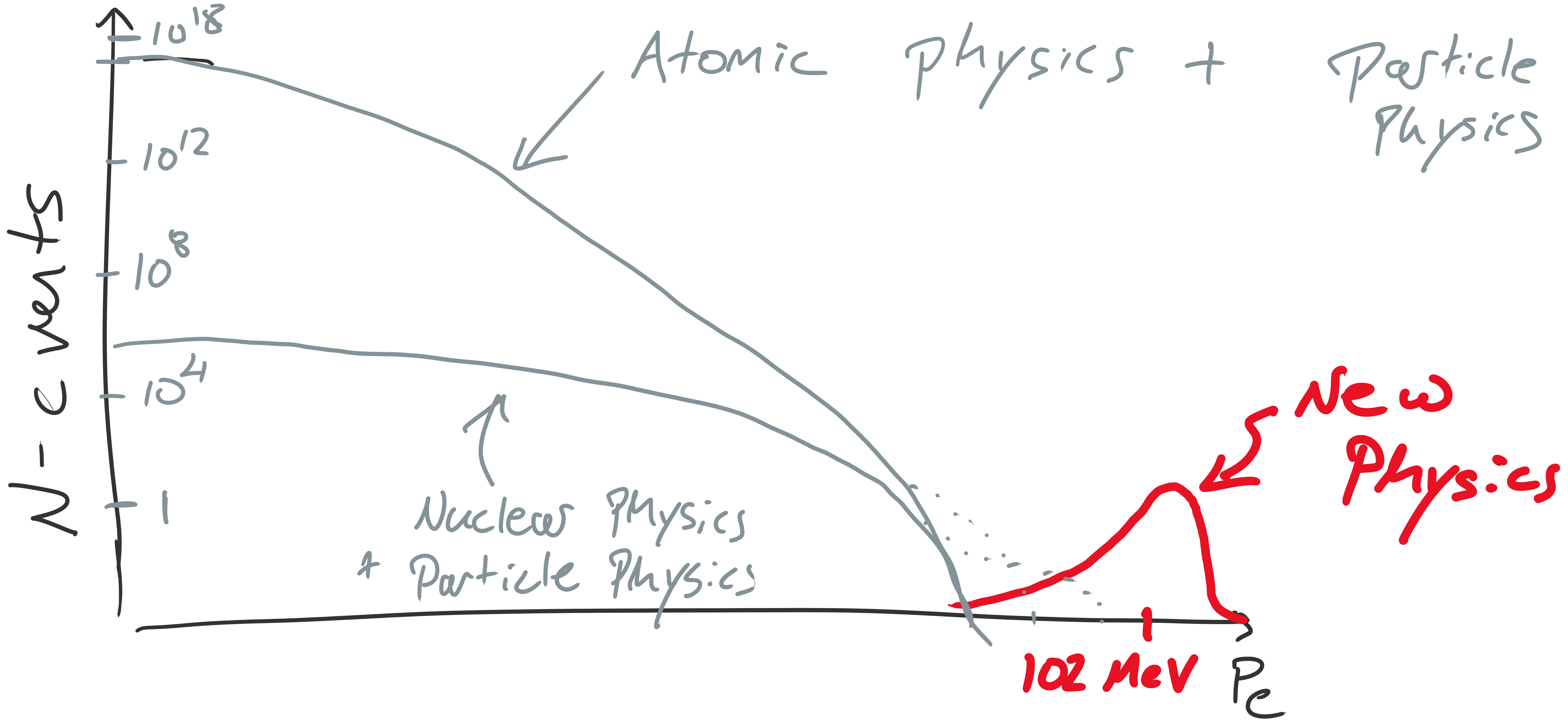


FIGURE 11 | The Mu2e tracker. The upper left picture shows panels assembled into a plane and a station. The assembled tracker is shown in the bottom figure. The upper right shows a beam's-eye view of a station: the three circles are projections of tracks at the Michel peak (small black circle), an intermediate momentum, and the conversion energy (last in green). Figures from Miyashita [35].



From: Bernstein, 2019, Frontiers in Physics

Example II: Mu2e ($\mu \to e$)



What is the Big Picture

- Fundamental physics can be studied **anywhere** **anytime**
- Need : Good **theory** + Good **Experiment**

$\mathcal{L}$ ⟶ Prediction ⋮ Measure ⟵ Exp.

↳ Compare ↙

What would I ask me?

- How do you actually compute
- Why do you draw squigly diagrams
- What is your favourite part of the SM?
- What upcoming experiments are important?
- What do you measure/compute for exp.?