ADVANCED!

Reconstruction

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Hadron Collider Physics Summer School 2018

Table of Contents

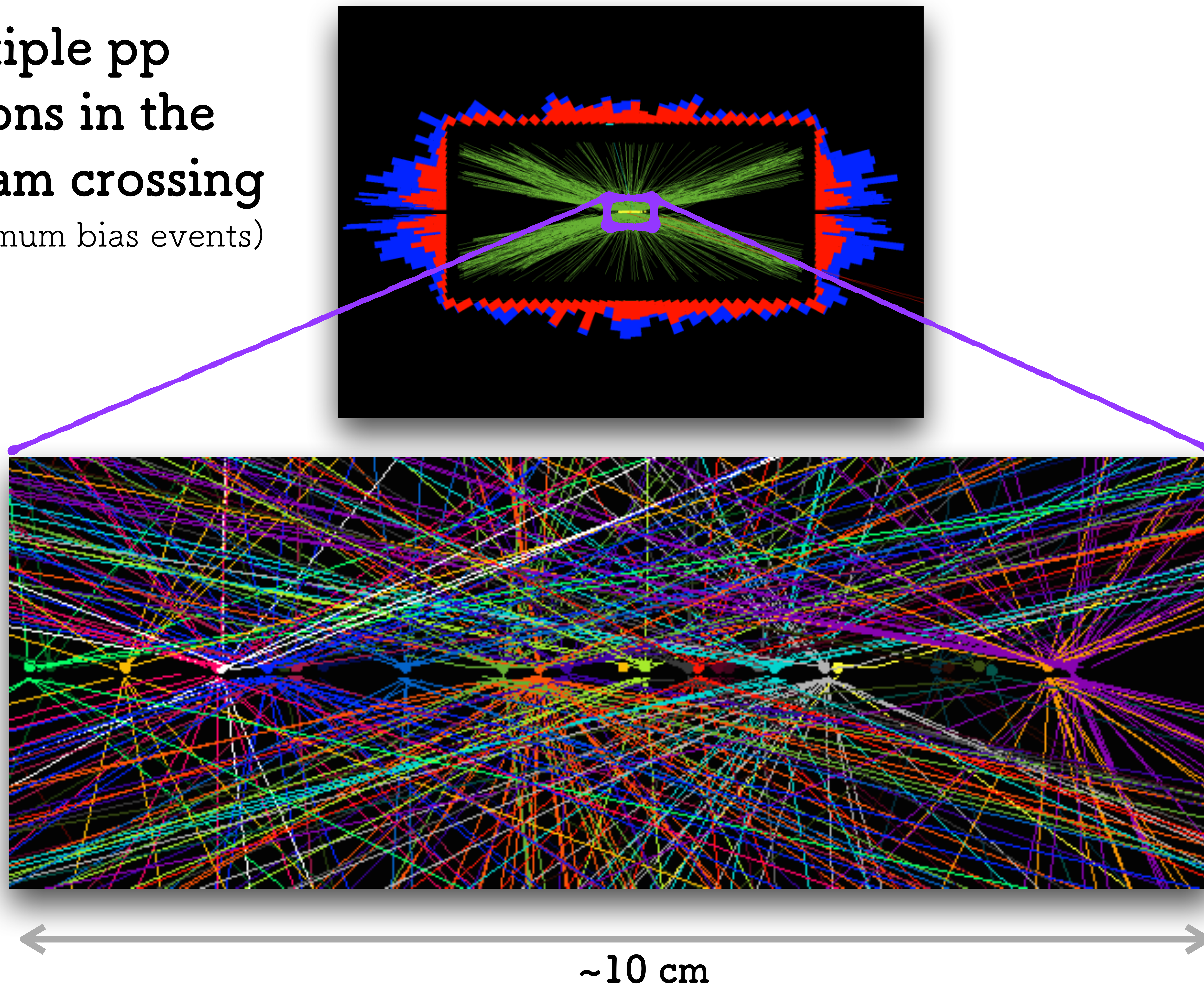
A lot of ground to cover!
My strategy: give you an idea of many things rather than focus on a few

PILEUP: THE ELEPHANT IN THE ROOM

WHAT IS PILEUP?

Multiple pp collisions in the same beam crossing

(mostly minimum bias events)



WHAT IS PILEUP?

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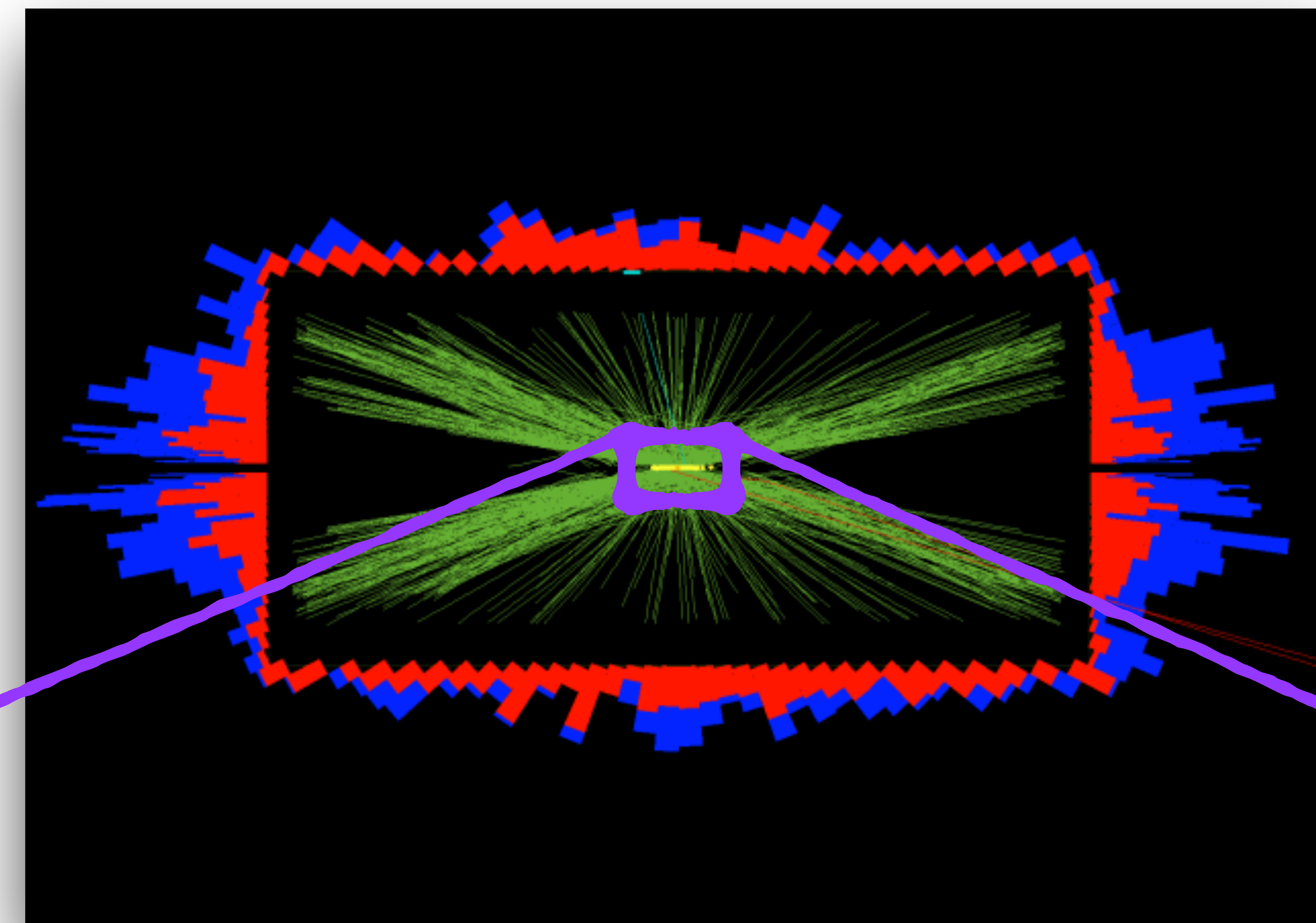


2012: <PU> ~ 20

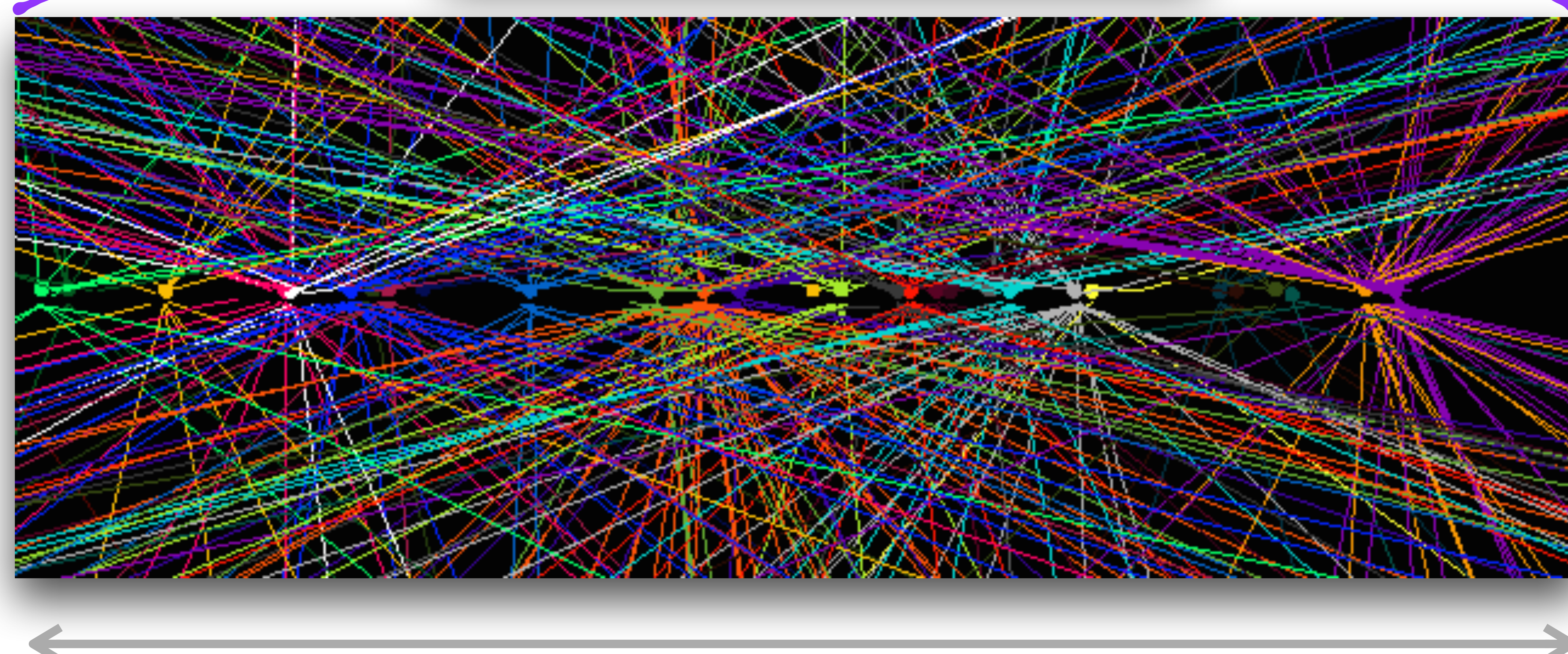
2016: <PU> ~ 20-40

2017: <PU> ~ 50

Run 3: > 50

HL-LHC: 140-200

to give a sense of scale:
1 PU vertex ~ 0.7 GeV of energy per unit area



~10 cm

Particle flow concept

Also was sometimes referred to as "global event description"

Combine the sub-detector information in a complementary way in a single algorithm

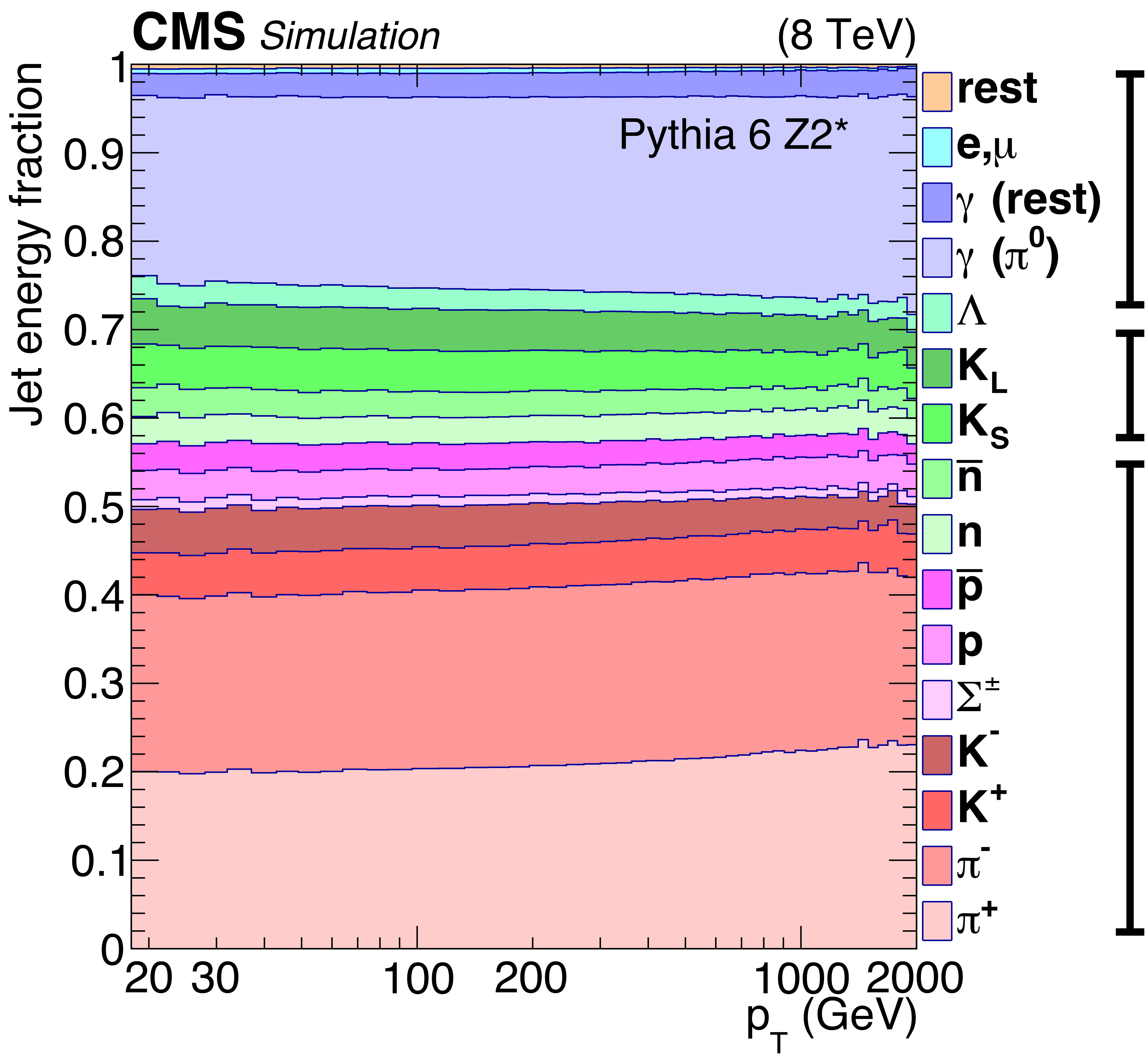
Outputs a list of particles:

- muons, electrons, photons, neutral hadrons, charged hadrons

Avoids double-counting of the energy to create a self-consistent view of the event

Breaking down the event at the particle level can aid in things like jet substructure and pileup mitigation (more later)

Setting the stage, jet composition

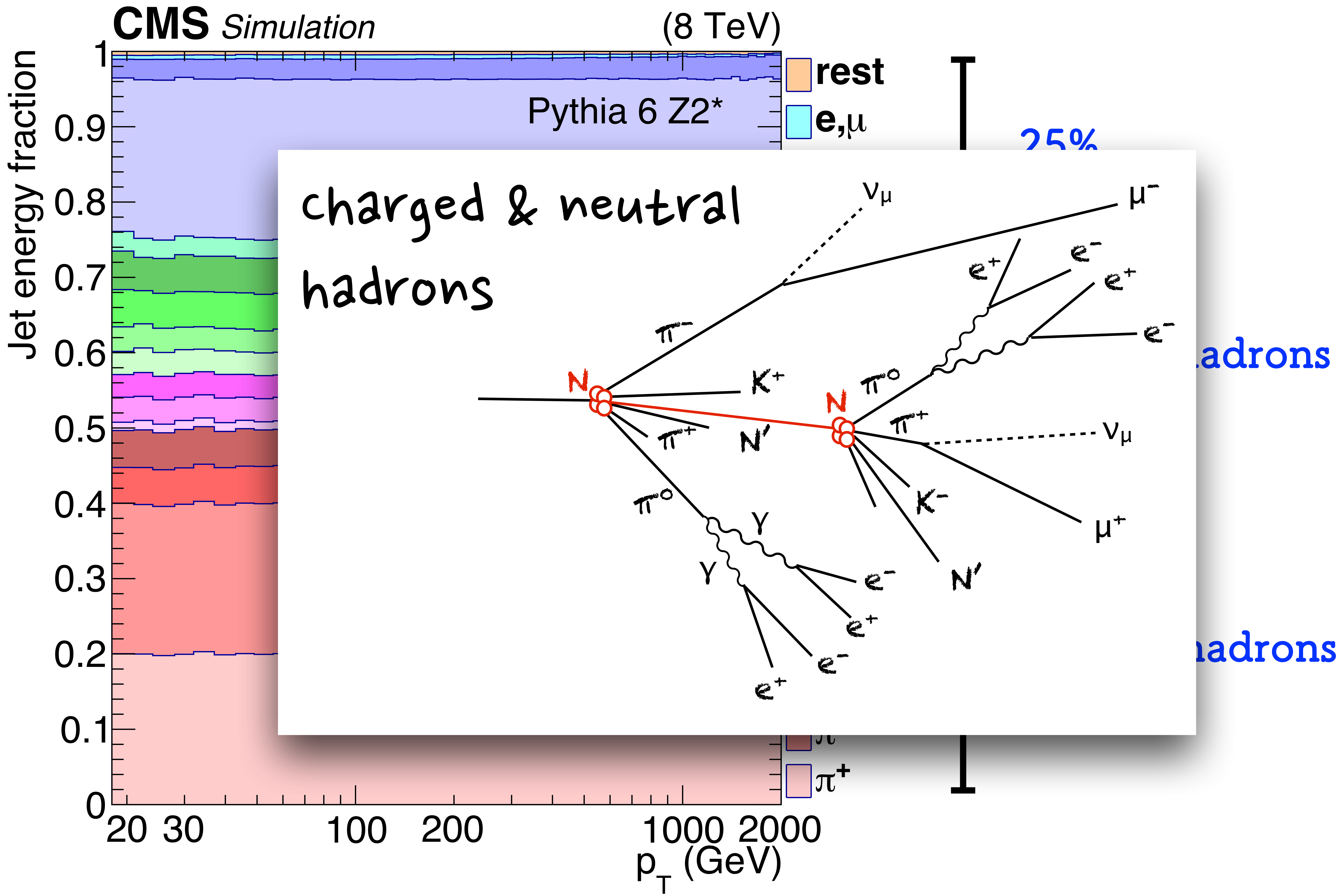


25%
photons

15%
Neutral hadrons

60%
charged hadrons

Setting the stage, jet composition

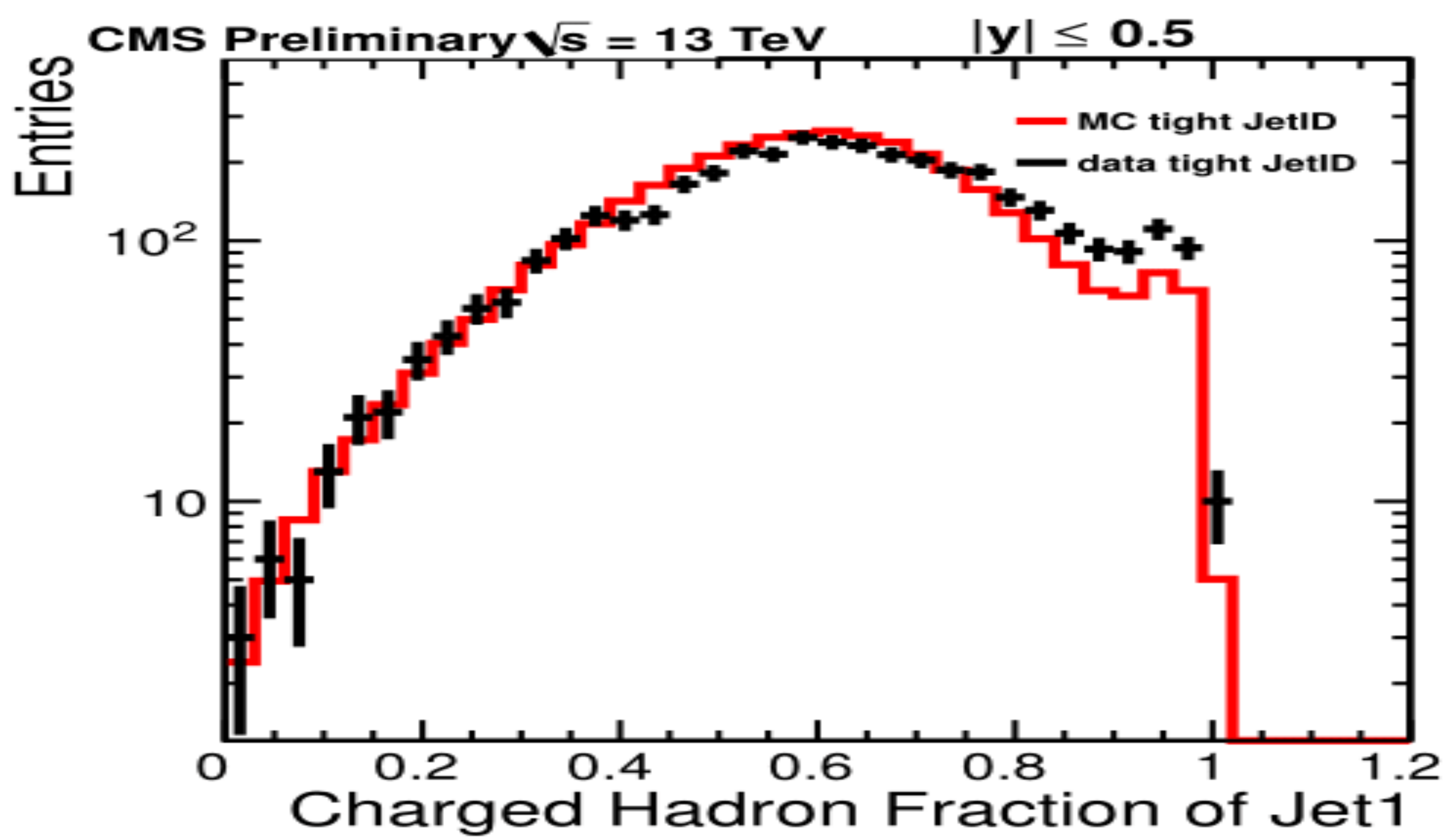


But…fluctuations

The fraction of the jet energy that is charged/neutral hadron and photon fluctuates quite a bit

- Flucutations on the order of 20-30% of the jet energy

Therefore, you still have to measure all the energy in the event!

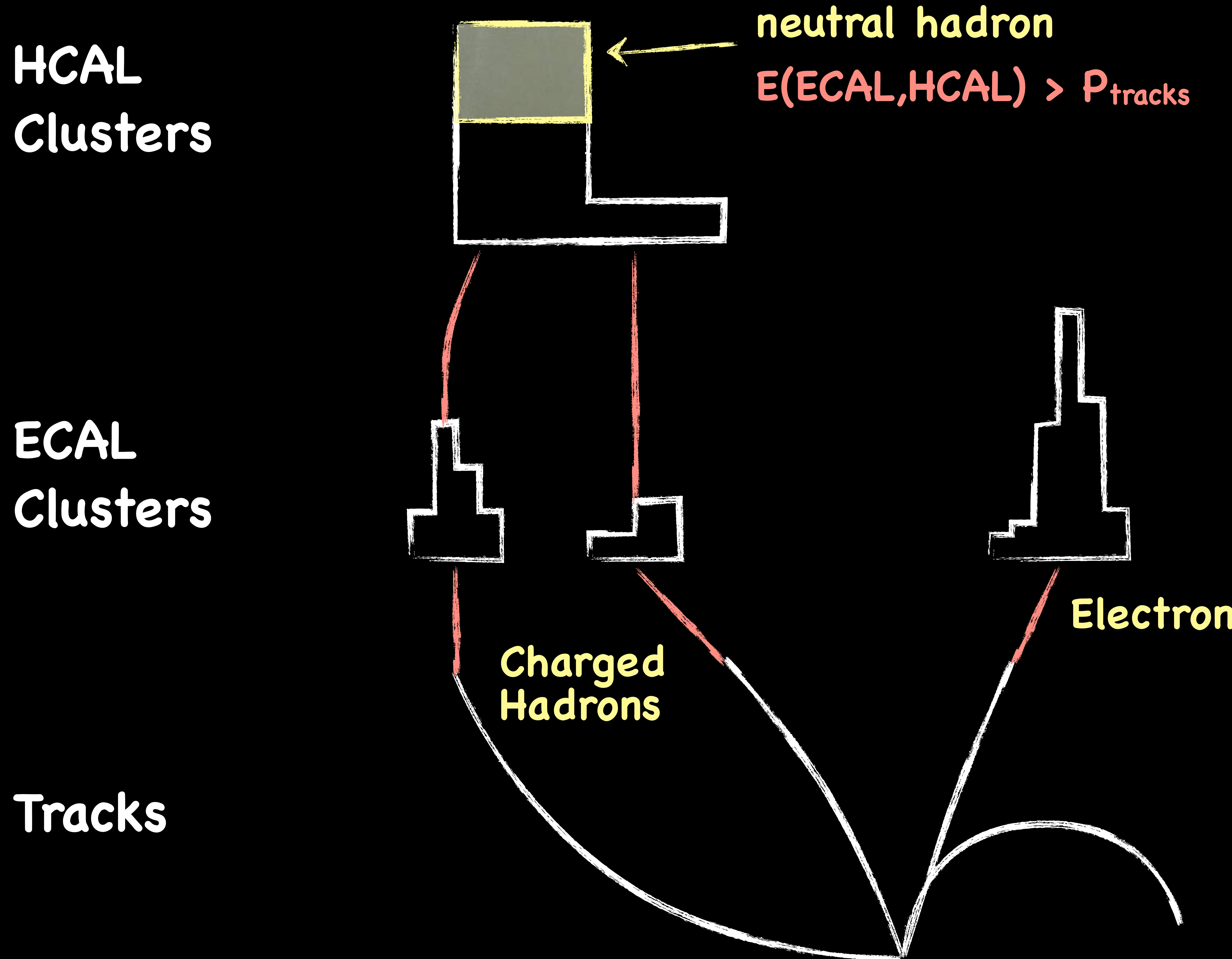


How to reconstruct individual particles?

First Associate Hits within Each Detector

Then Link Across Detectors

Finally Apply Particle ID & Separation



Courtesy: Rick Cavanaugh

Very basic view of the Particle Flow Algorithm

Clean the event during reconstruction

Find and "remove" muons (σ_{track})

Find and "remove" electrons (min[σ_{track}, σ_{ECAL}])

Find and "remove" converted photons (min[σ_{track}, σ_{ECAL}])

Find and "remove" charged hadrons (σ_{track})

Find and "remove" V0's (σ_{track})

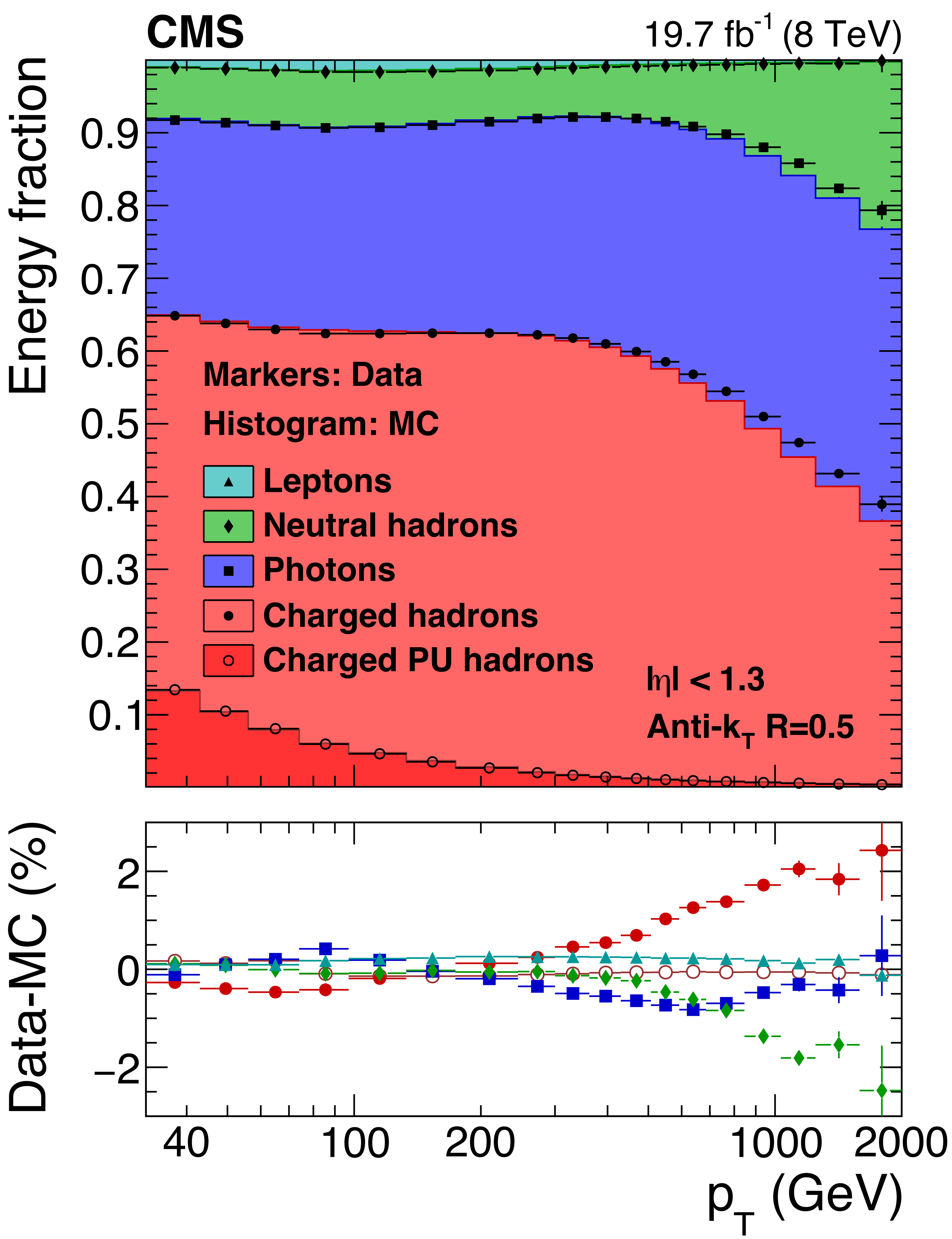
Find and "remove" photons (σ_{ECAL})

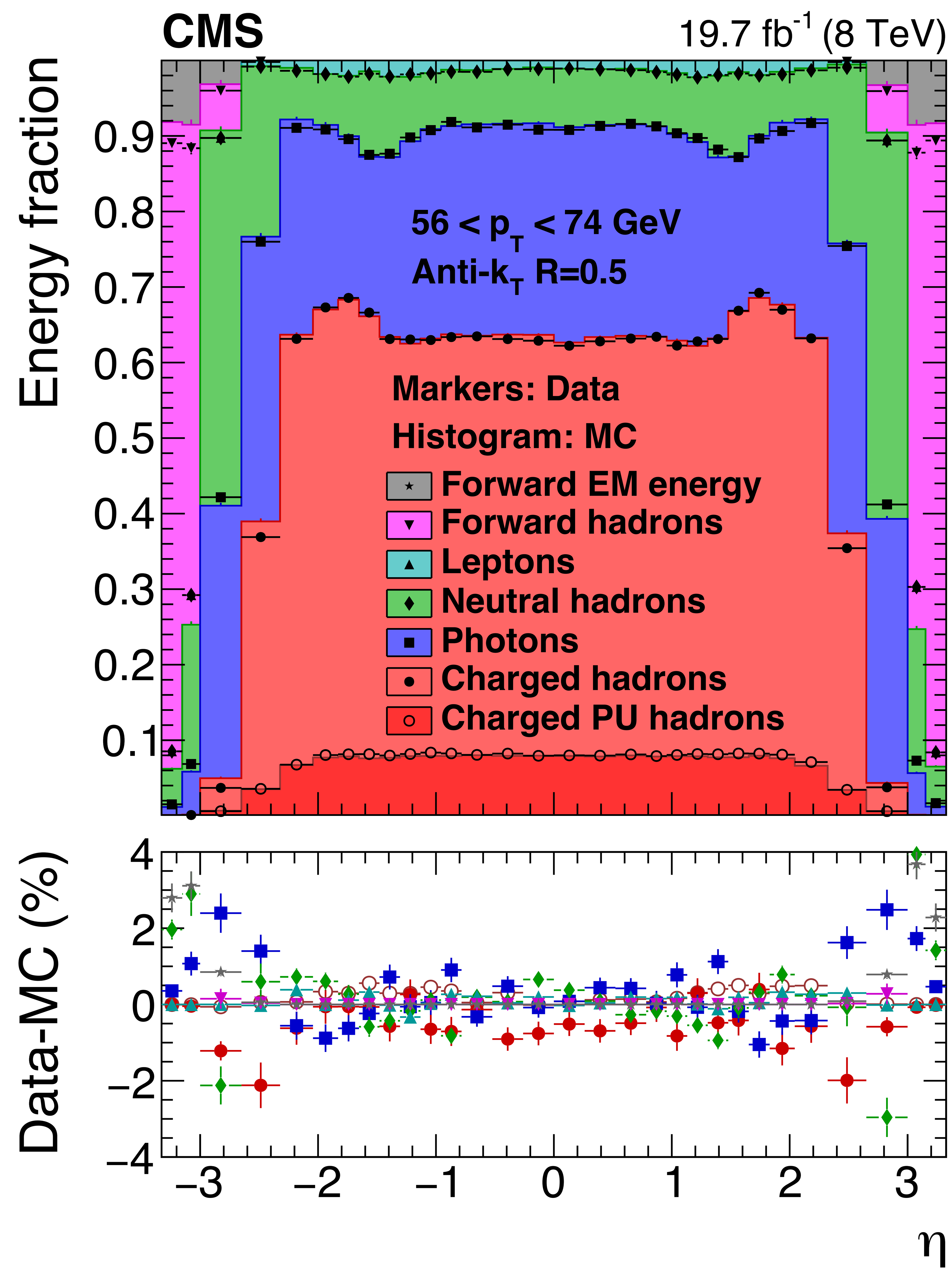
Left with neutral hadrons (10%) (σ_{HCAL} + fake)

Use above list of Reconstructed Particles to describe the entire event!

Courtesy: Rick Cavanaugh

SETTING THE STAGE, JET COMPOSITION



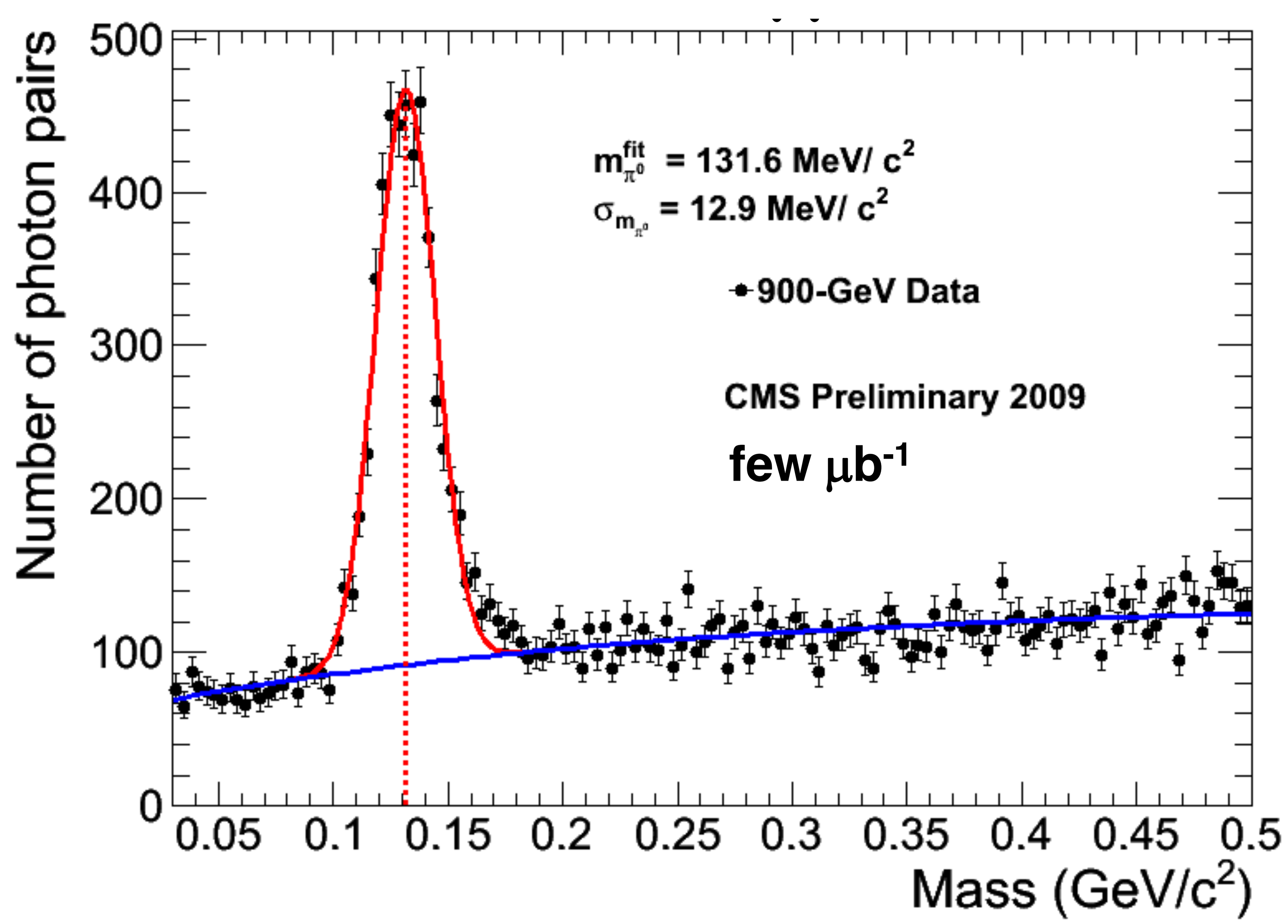


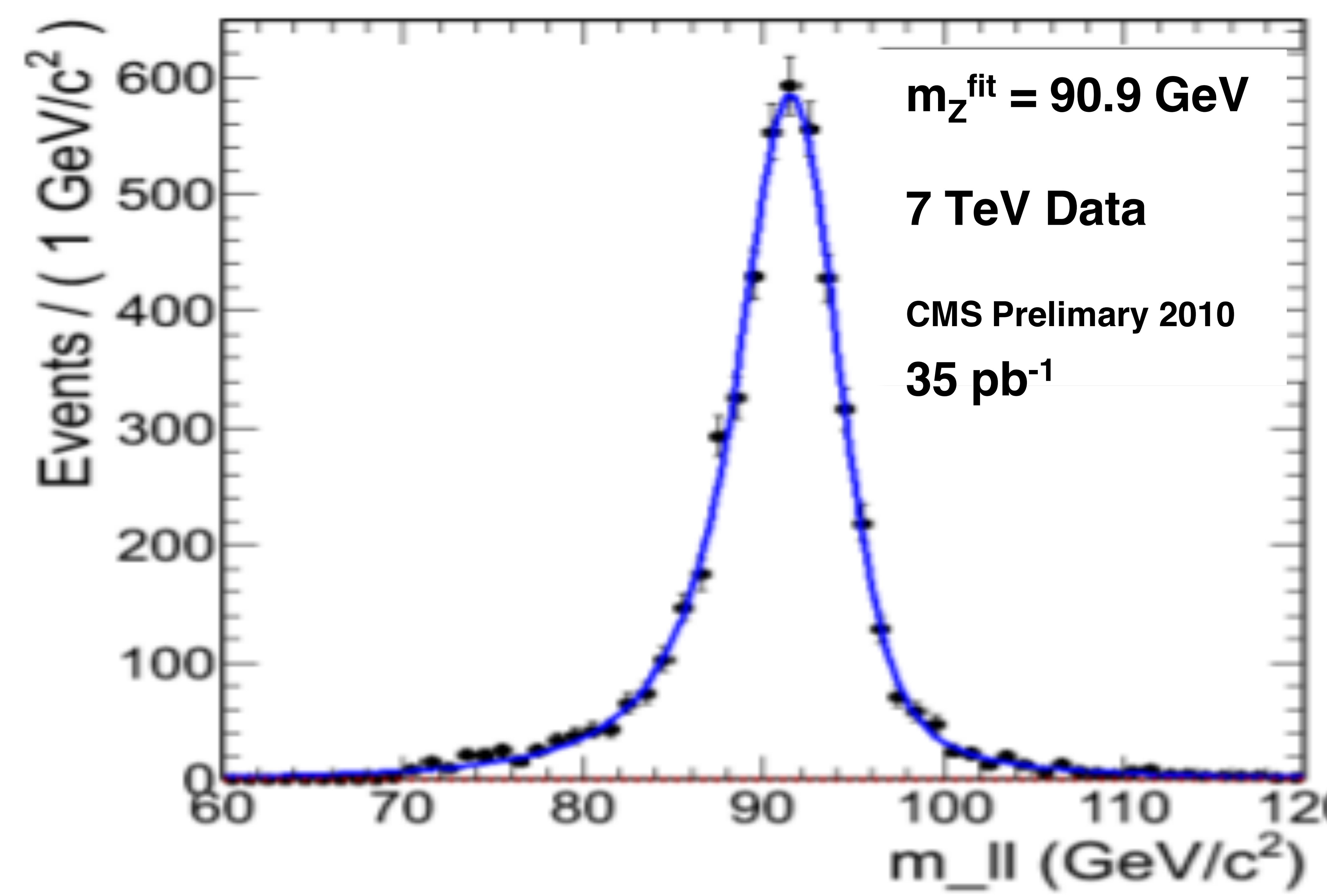
WHY THE CHANGE AT HIGH PT?

PF CALIBRATION

In-situ calibration of particle flow candidates:

Electrons/photons/muons use the Z and π^0



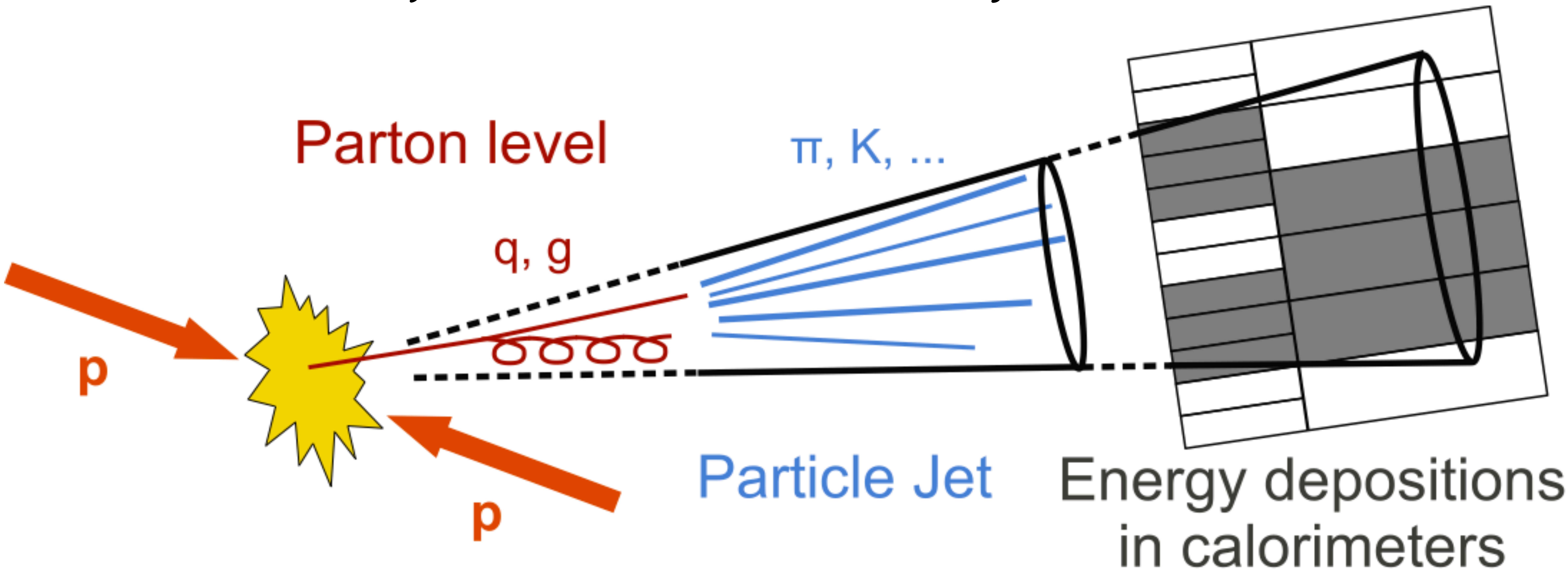


Calibration of the charged/neutral pions use isolated tracking to fit for the energy of charged hadrons calorimeter energy

$E = a + b(p,\eta)\ Eecal + c(p,\eta)\ E_{hcal}$

3. Composite objects and beyond

Now that we have multiple particles,
let's talk about jets a little more formally now



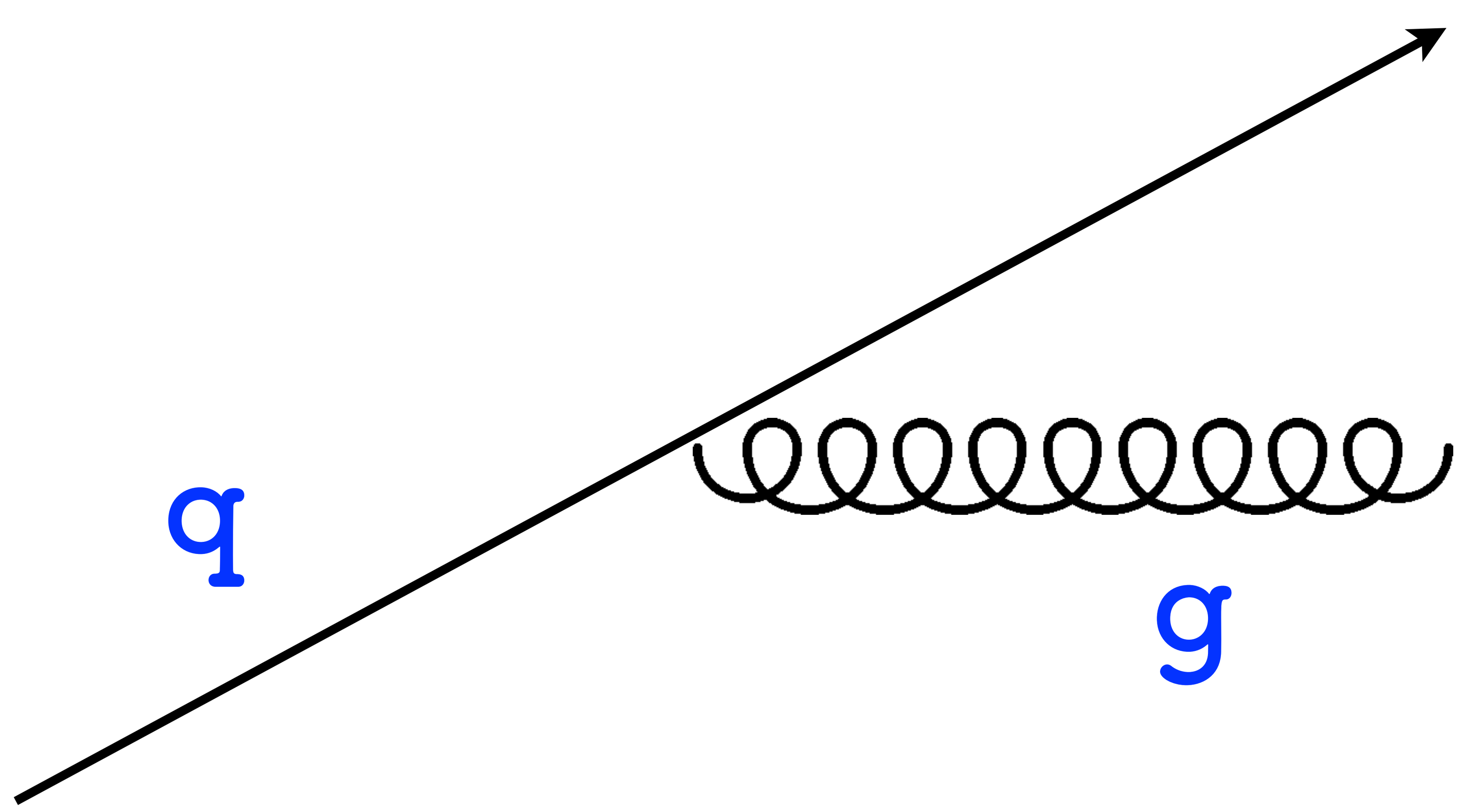
Jet = a spray of stuff (typically from q/g)
reconstructed as a single object

JET CLUSTERING

How to group particles/deposits/etc. together to make a jet?

Jet clustering algorithms have a looong history, but to keep it short — for precise predictions, it is important to have a formal connection between theory and experiment

Often referred to as "IRC safe"



The result of the jet algorithm stable against infinitely soft and collinear emissions

Infrared, IR: As $E \to 0$

Collinear, C: As $\Delta R \to 0$

Sequential recombination algorithms

Hierarchical jet clustering algorithms

- Compute a "distance" between each particle
- Recombine particles pairwise based on smallest "distance" until some condition is met

Distance measure: $d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta R_{ij}}{R^2}$ **Condition:** $d_{ij} < d_{iB} = k_{ti}^{2p}$

Jet distance parameter, R

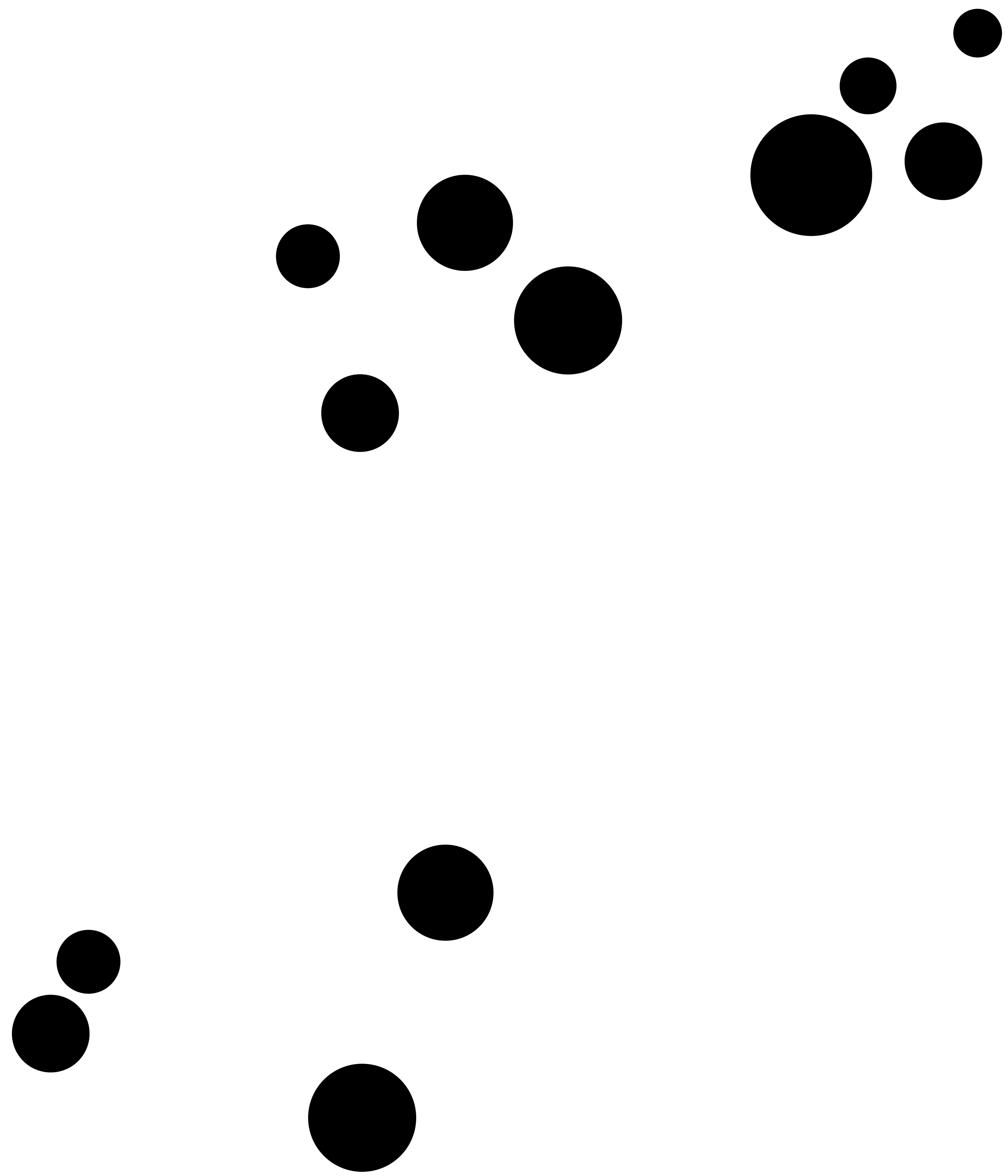
When:

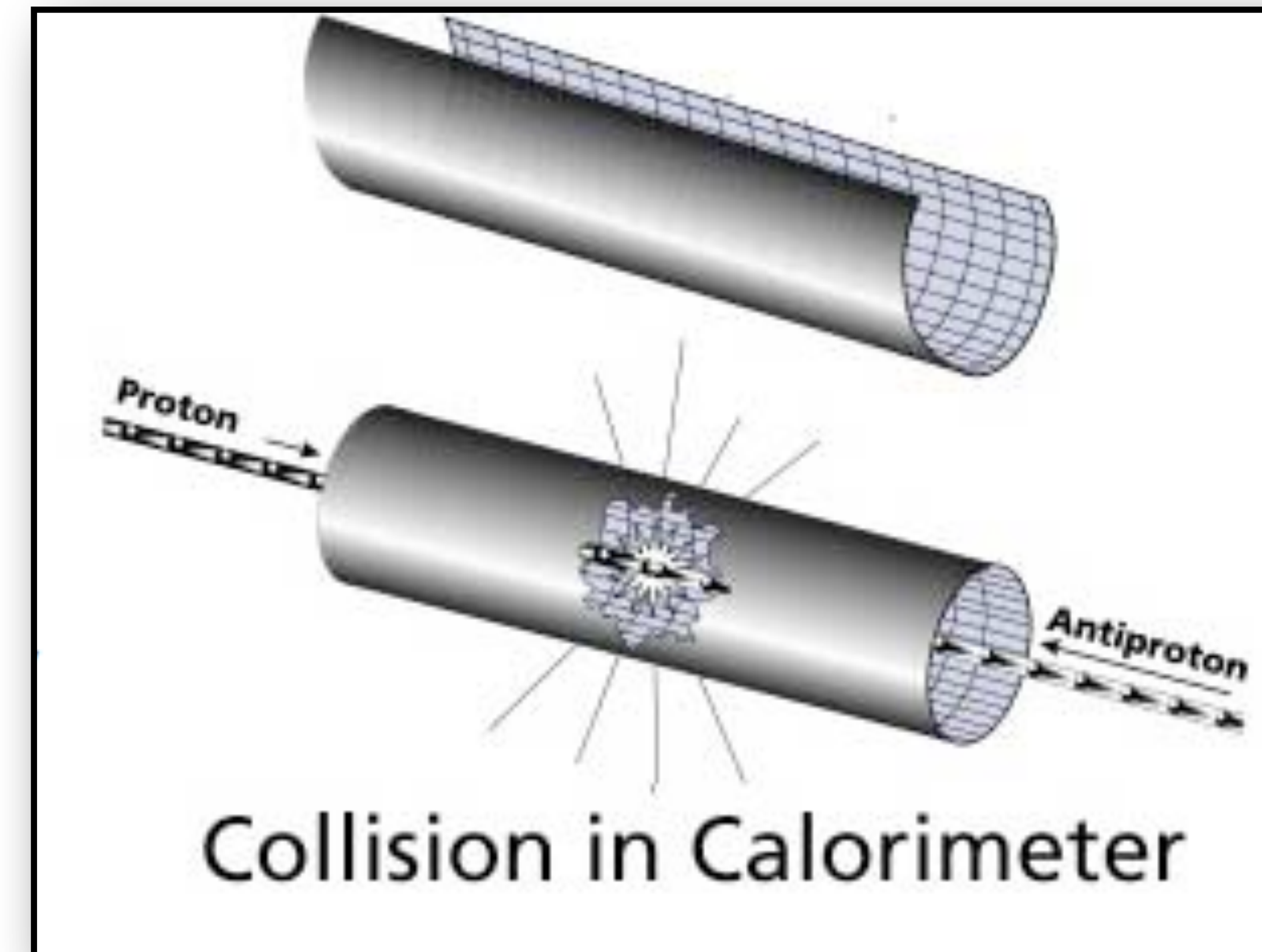
p = 1, kT algorithm - start with softest particles

p = 0, CA algorithm - start with closest particles

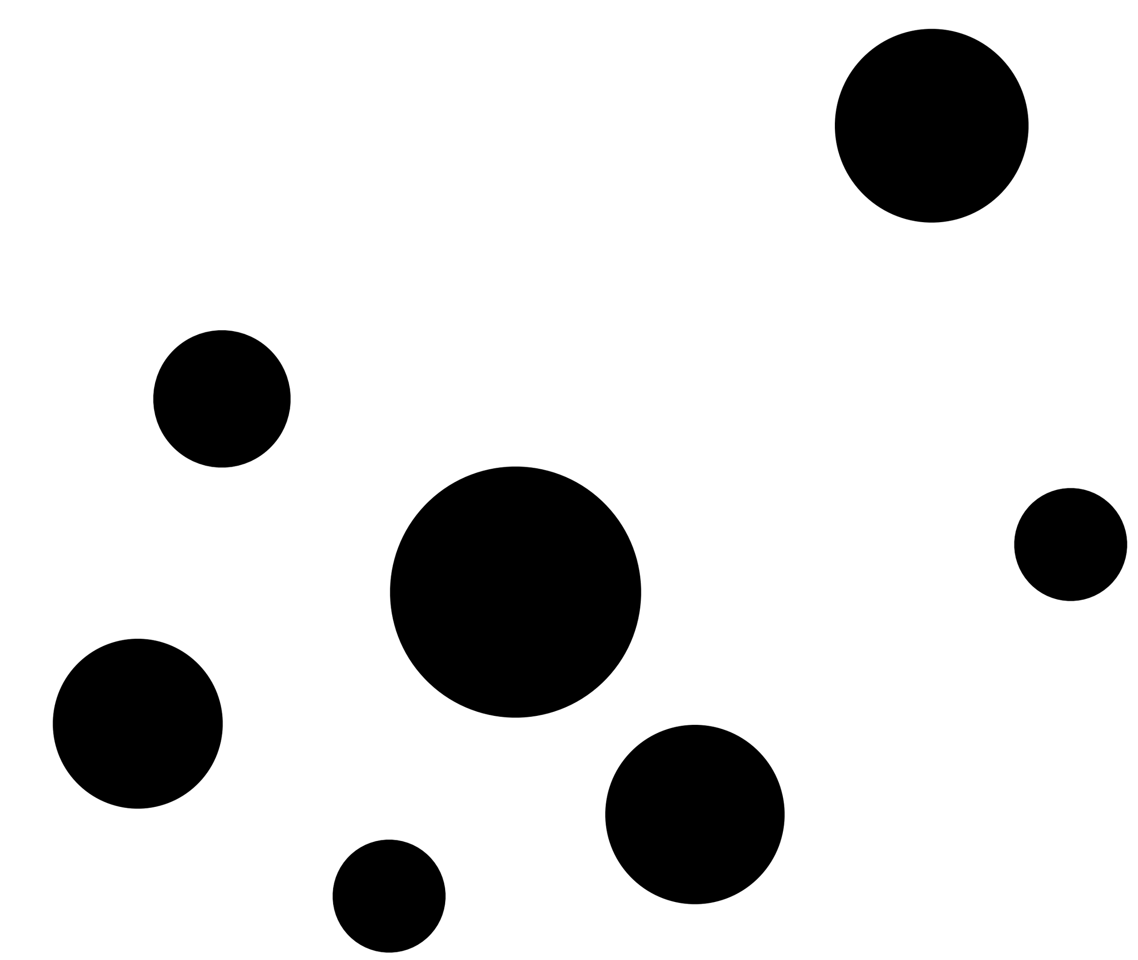
p = -1, anti-kT algorithm - start with hardest particles

Cartoon event display - PF particles





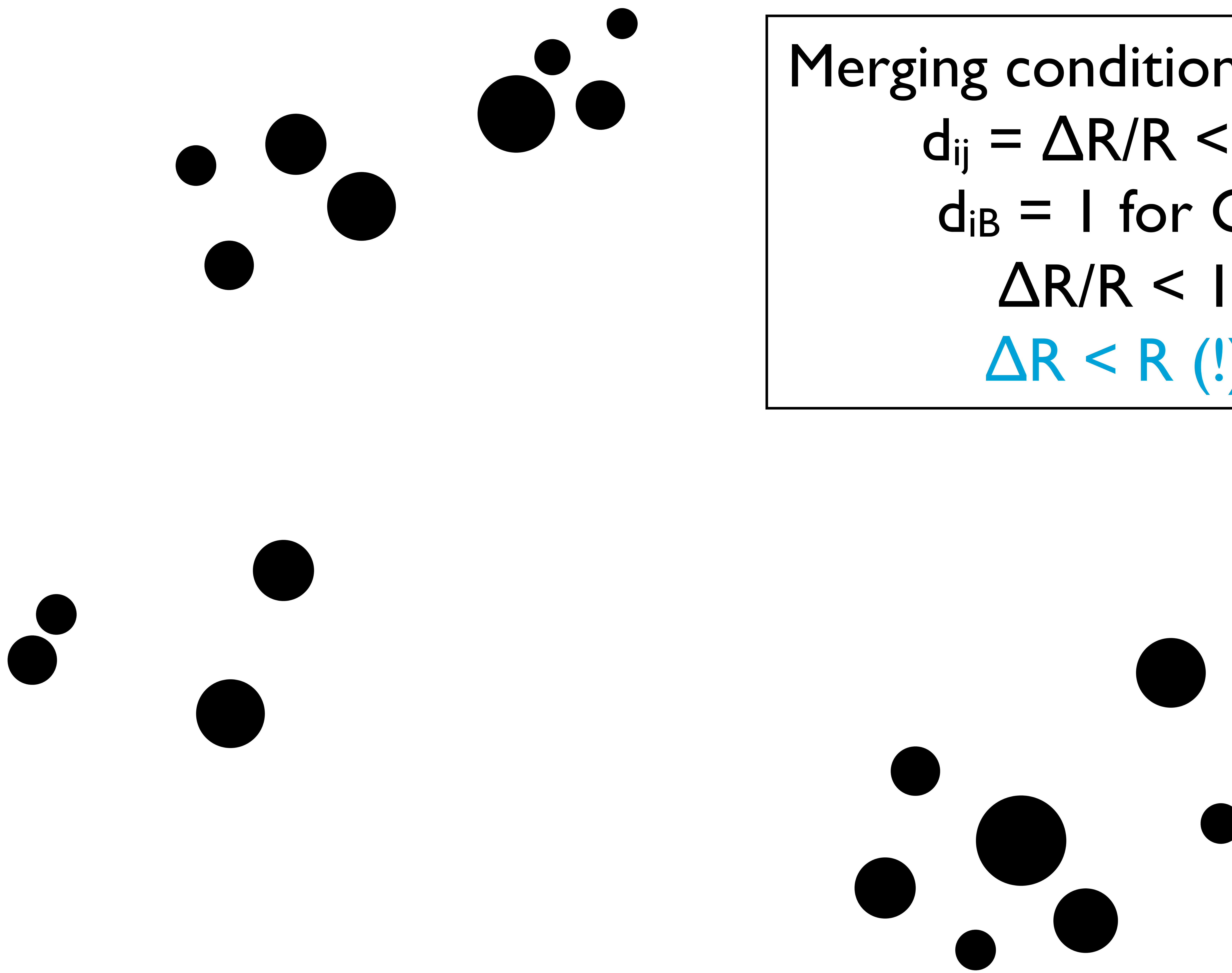
Collision in Calorimeter



Circle = position of particle within the detector
Area ~ energy of particle

Credit: Jim Dolen

Example: Cambridge Aachen Jet Clustering



Merging conditions in CA:

$d_{ij} = \Delta R/R < d_{iB}$

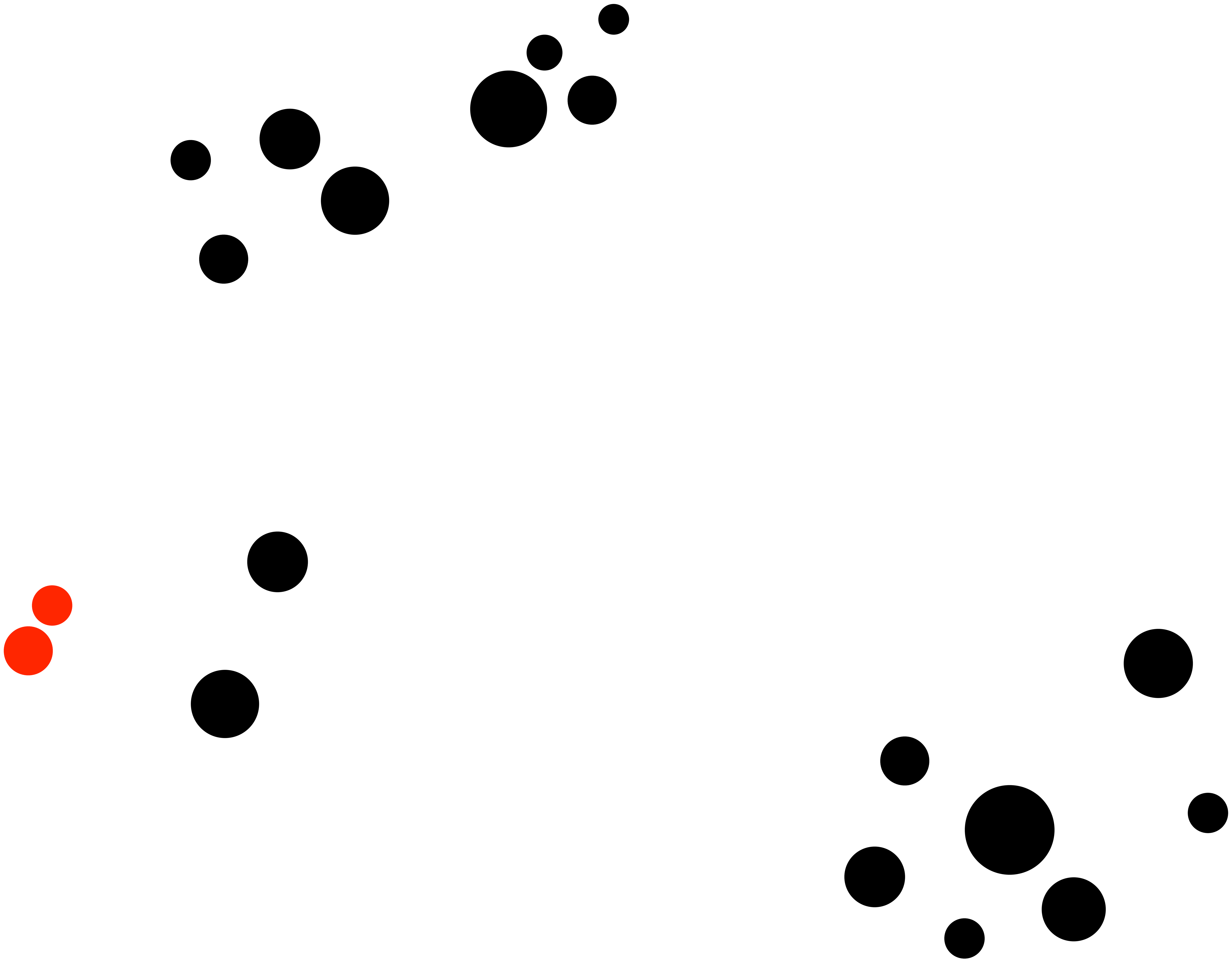
$d_{iB} = 1$ for CA

$\Delta R/R < 1$

$\Delta R < R$ (!)

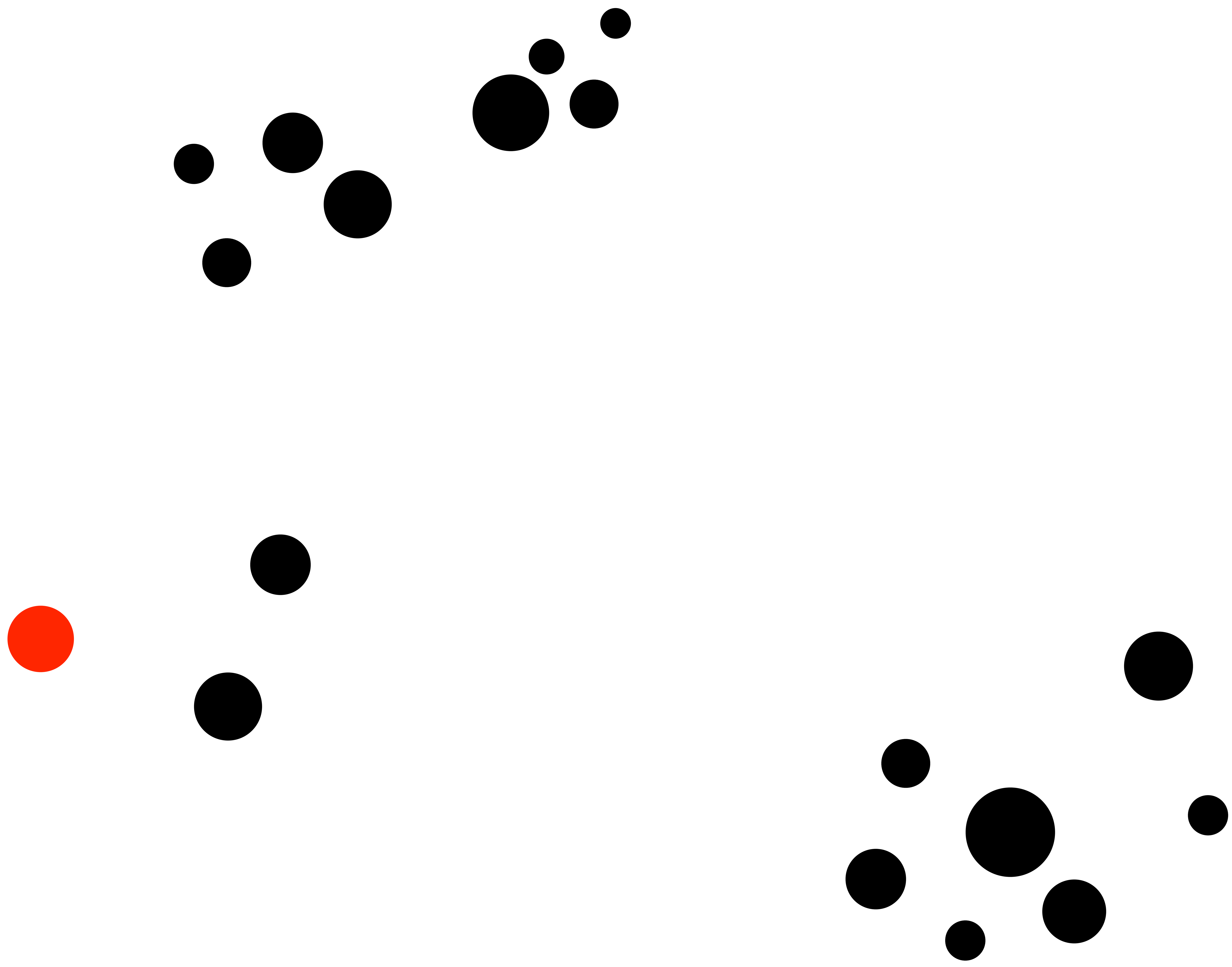
Credit: Jim Dolen

Find the closest pair



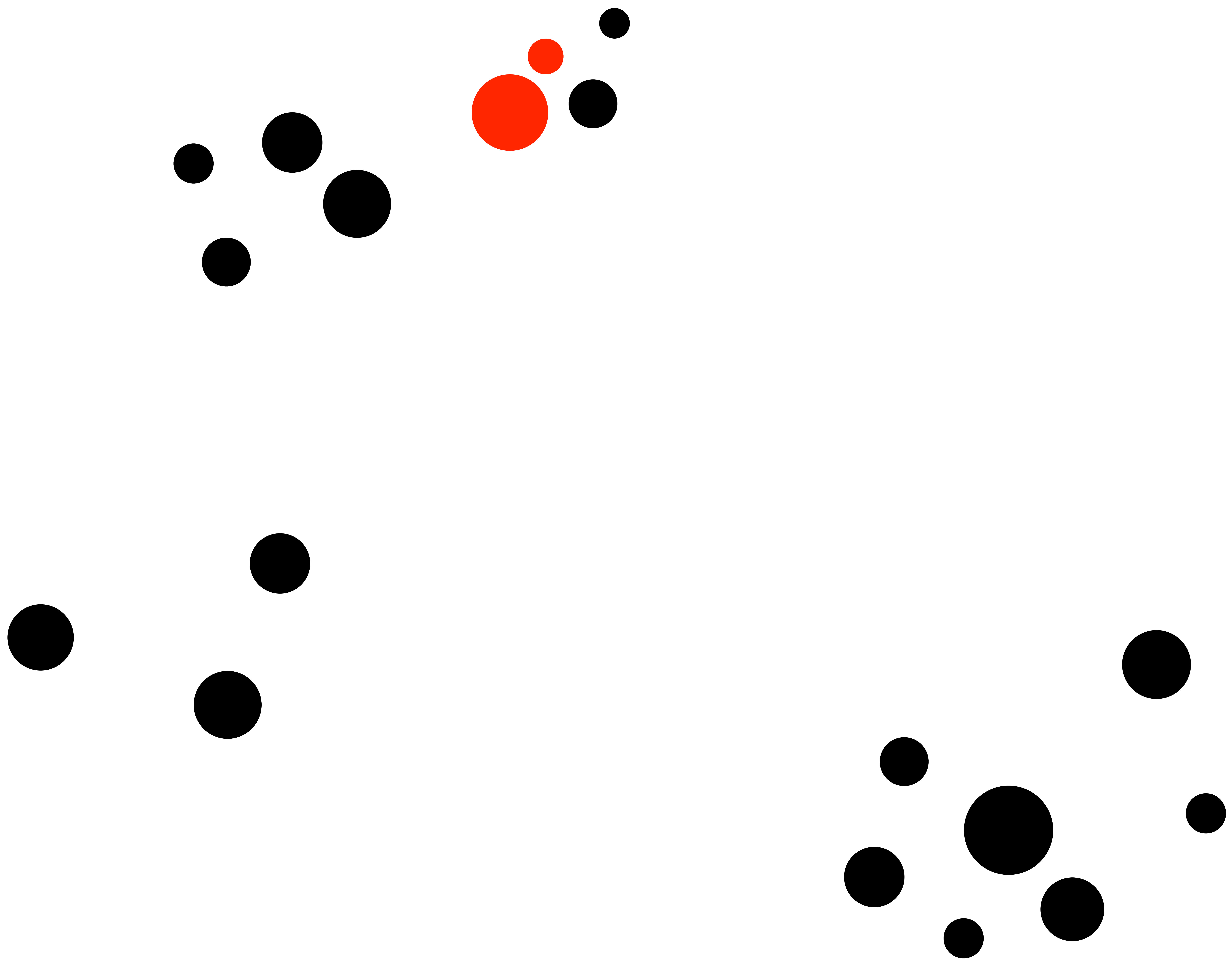
Credit: Jim Dolen

If they are closer than d_{ij}, combine their 4 vectors

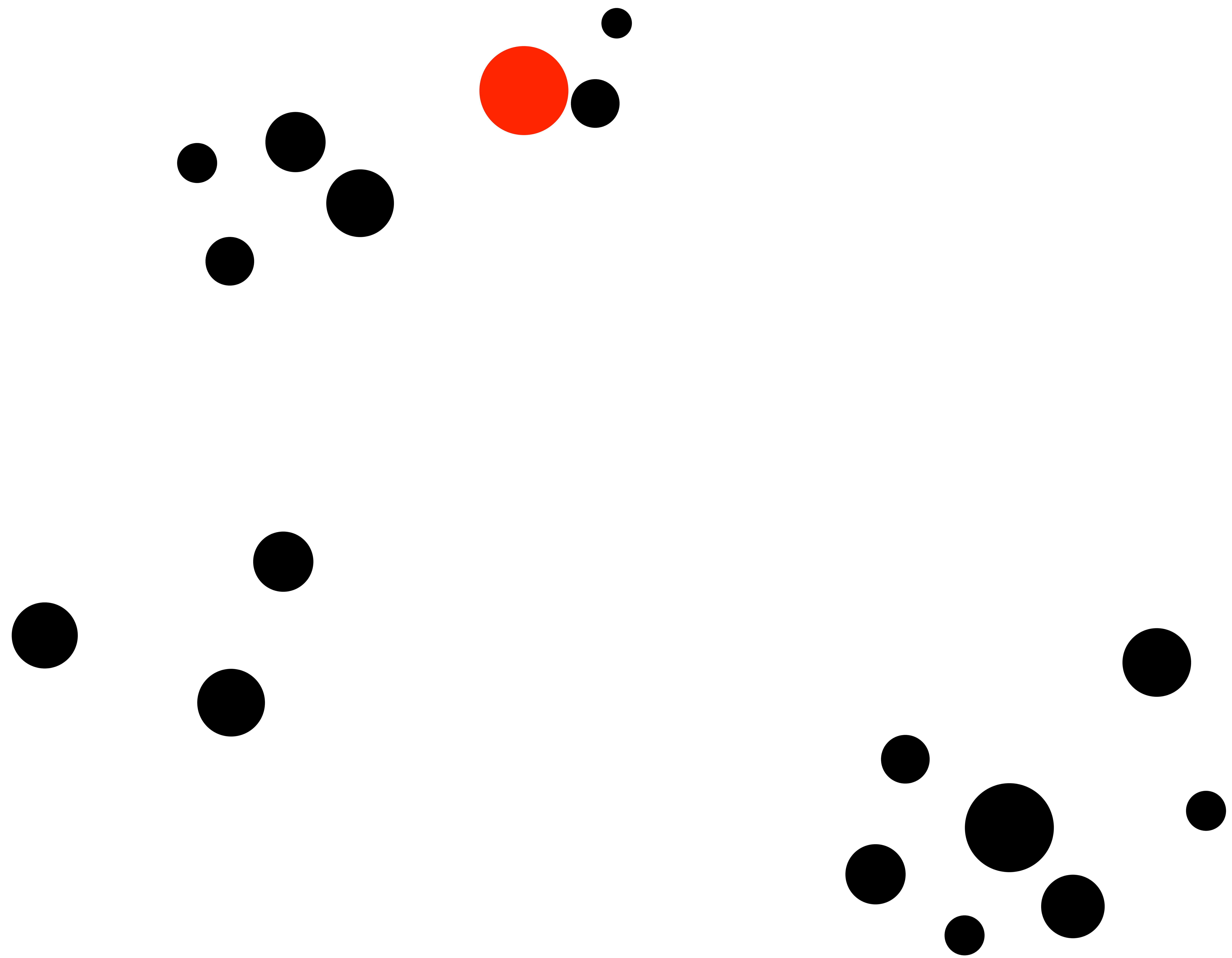


Credit: Jim Dolen

Repeat on the new closest pair



Jim Dolen *Credit: Jim Dolen*



Jim Dolen

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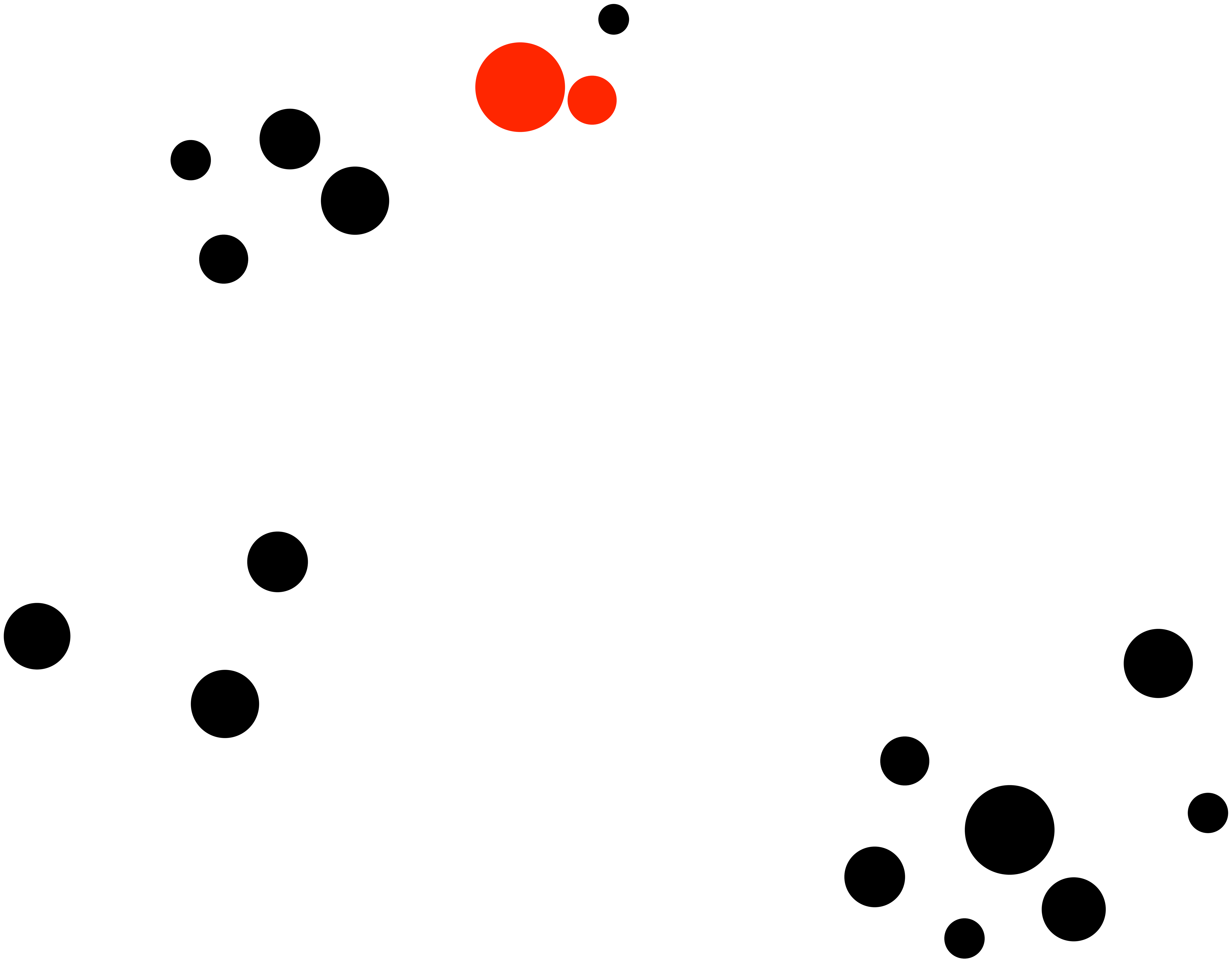

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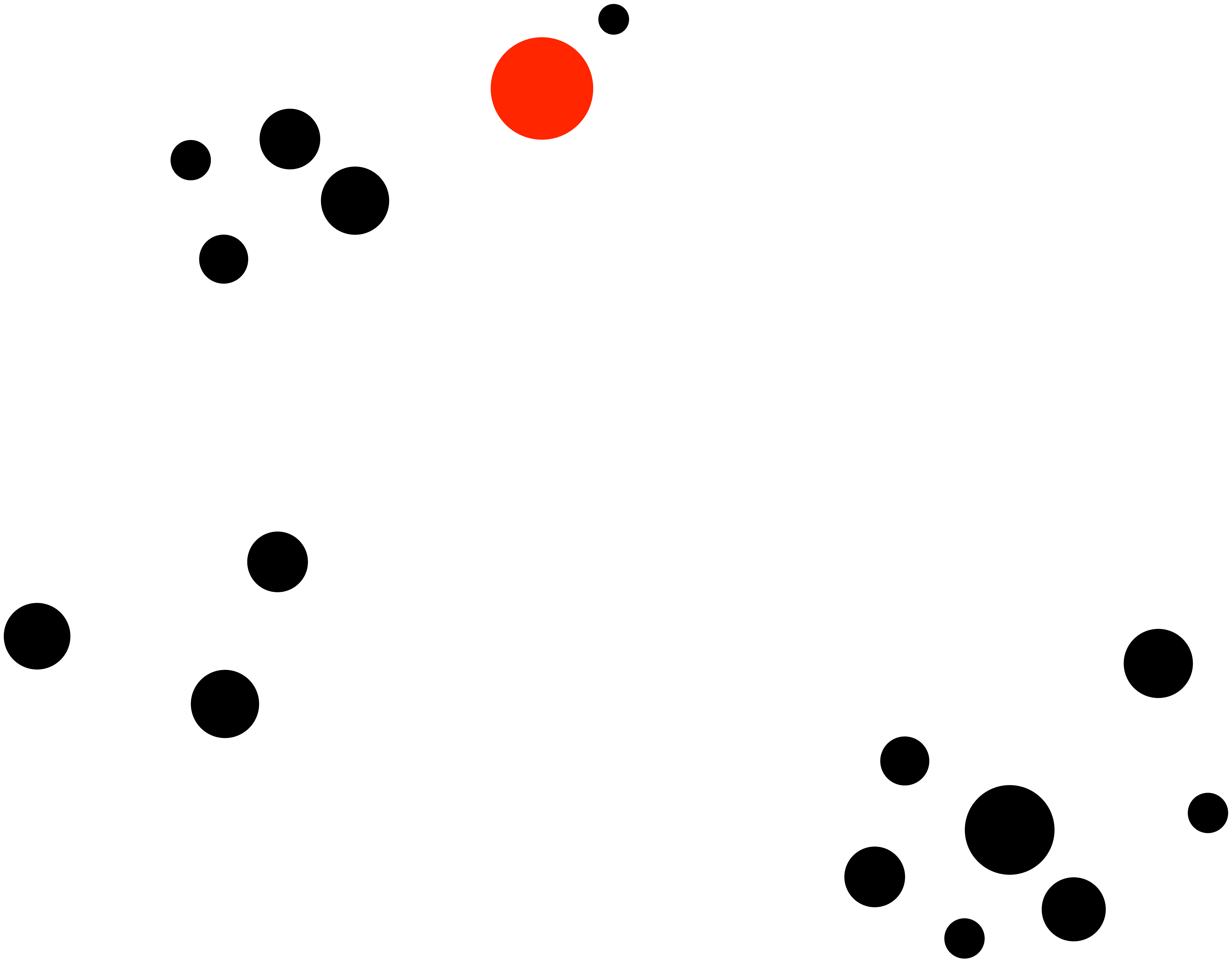

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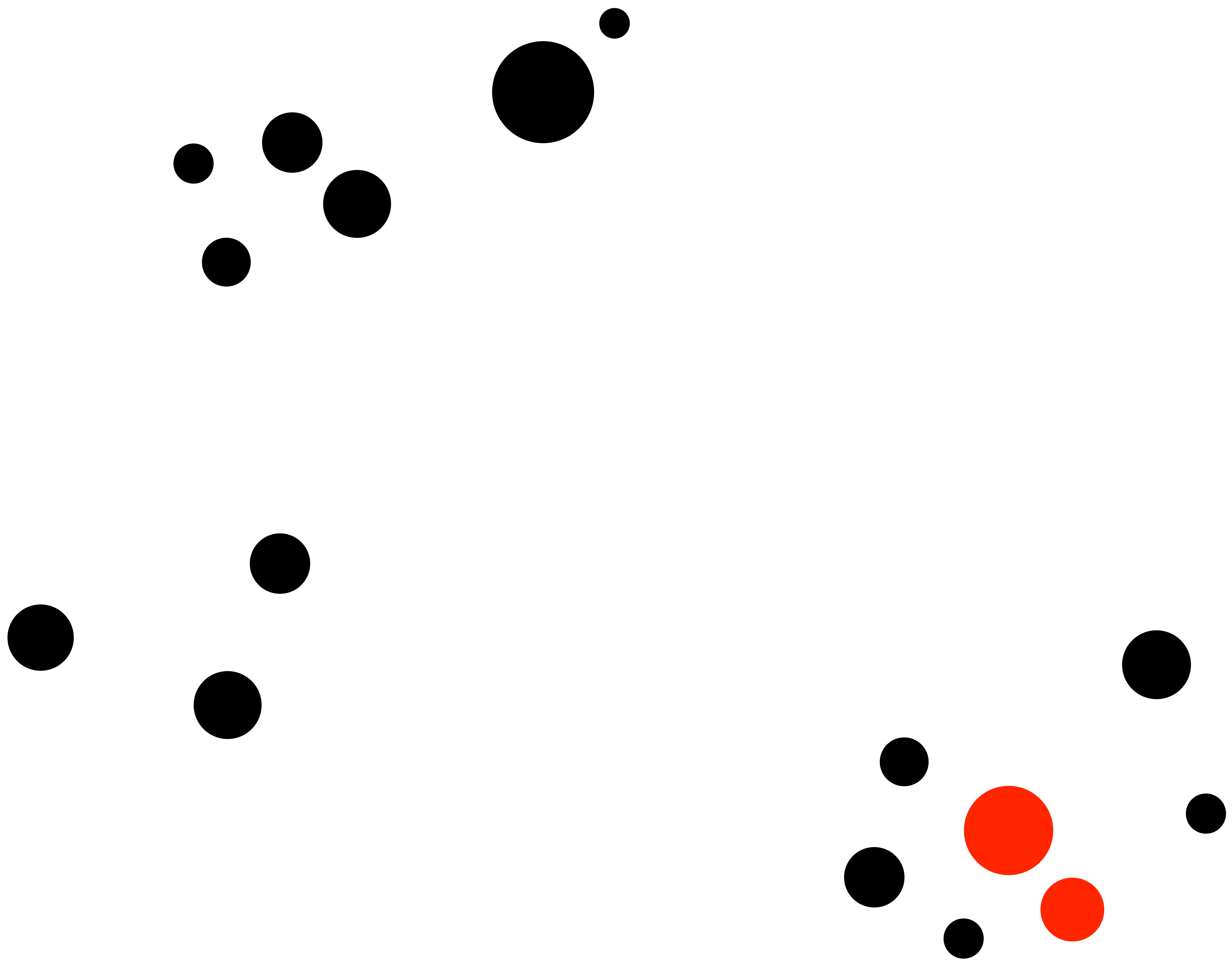

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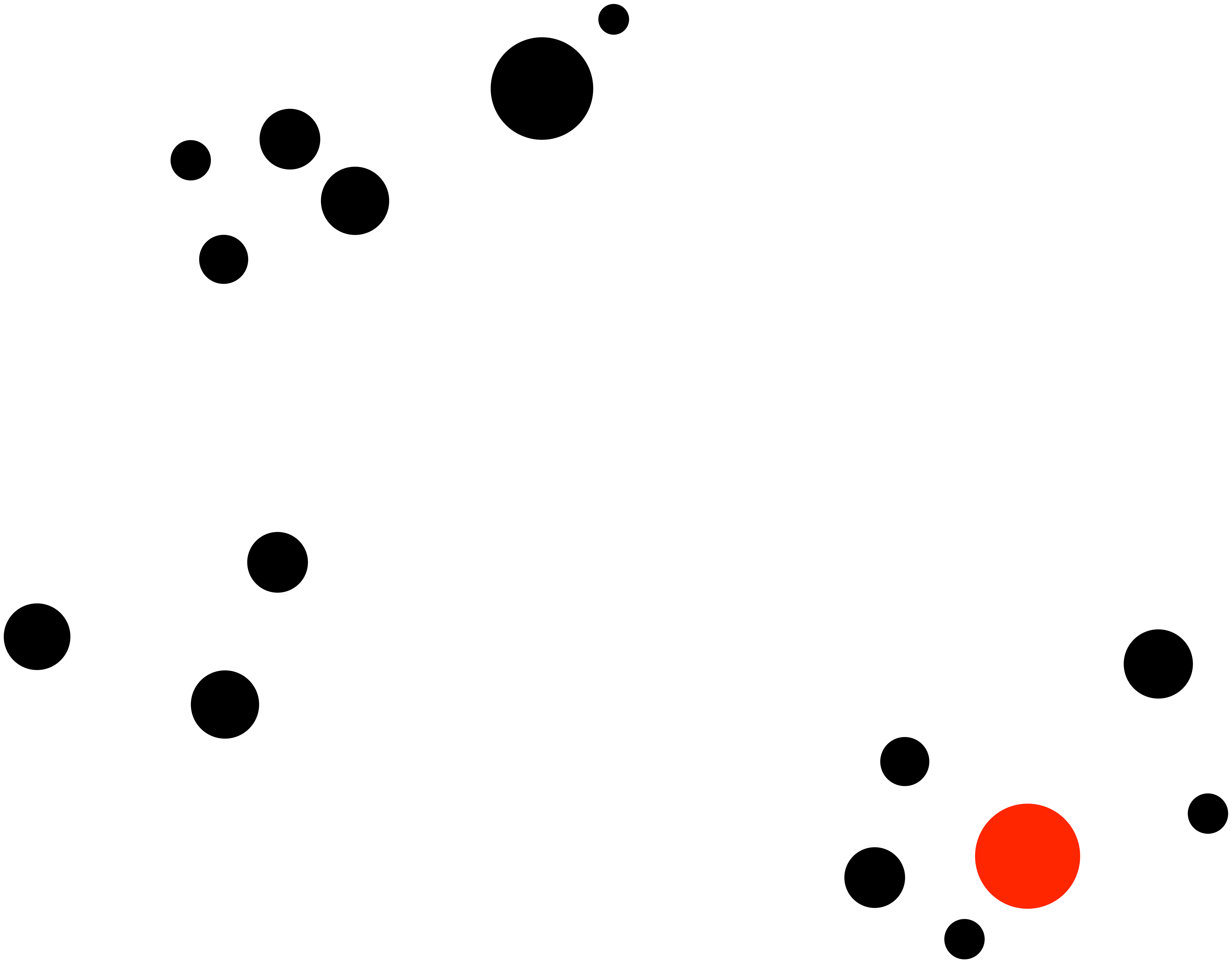

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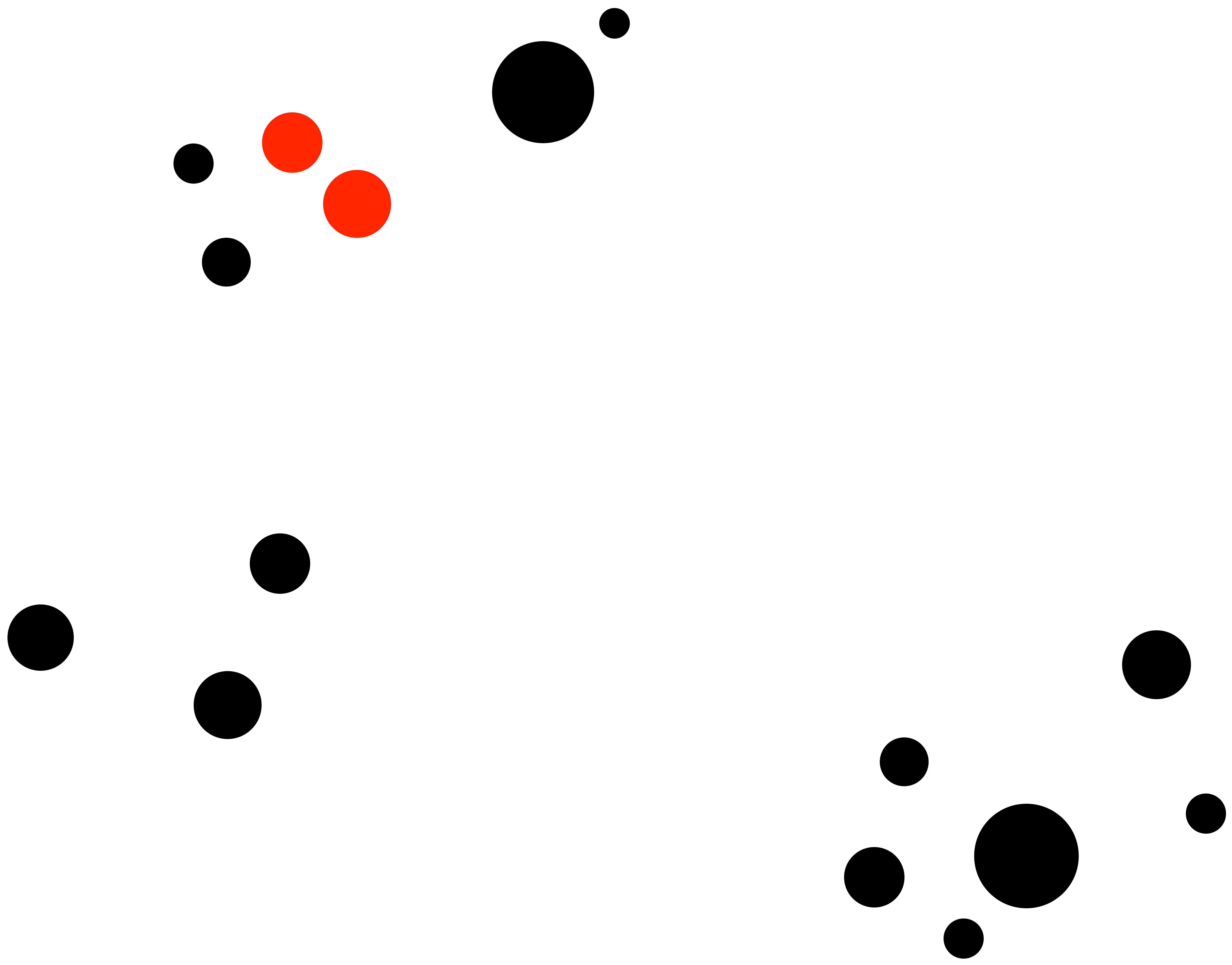

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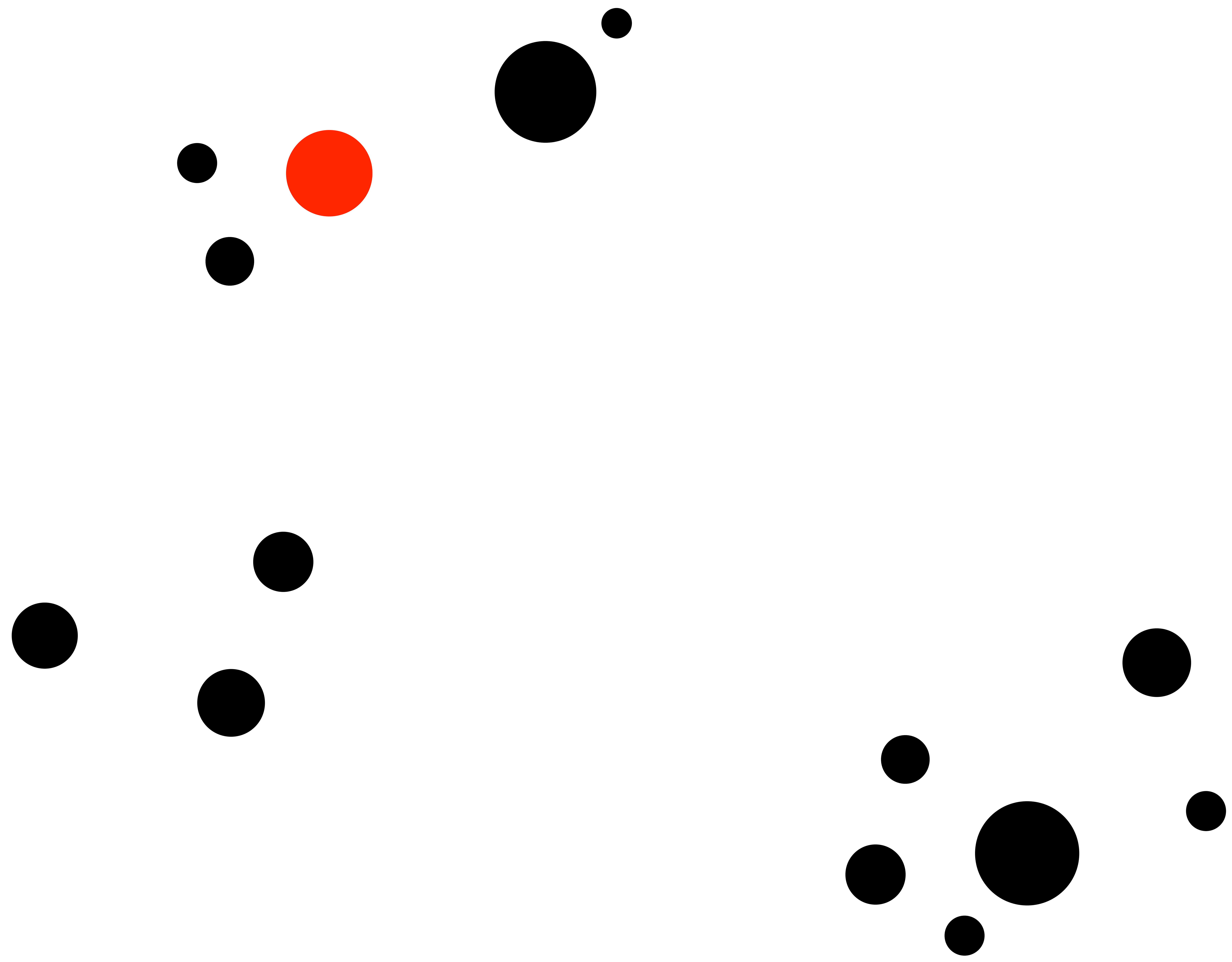

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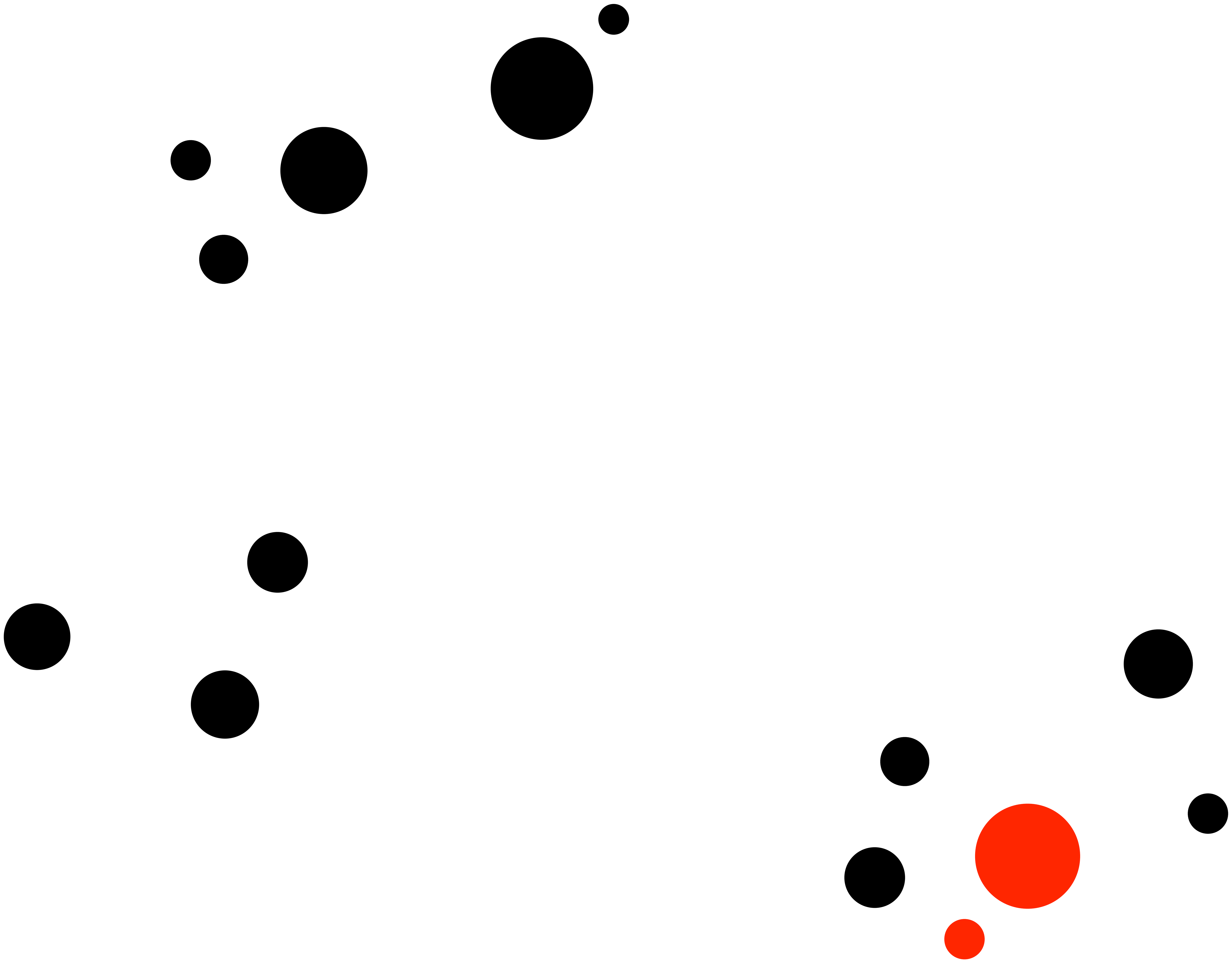

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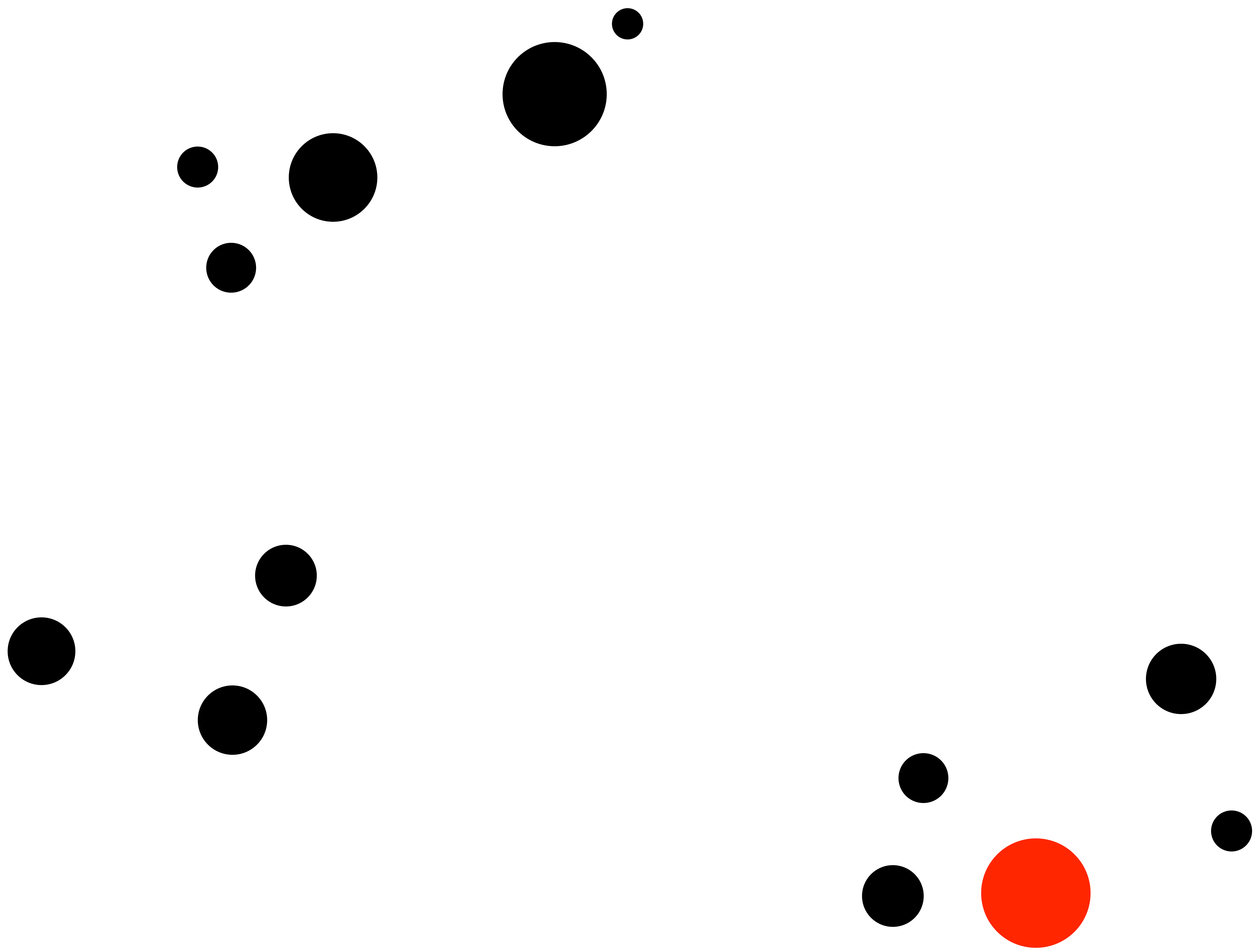

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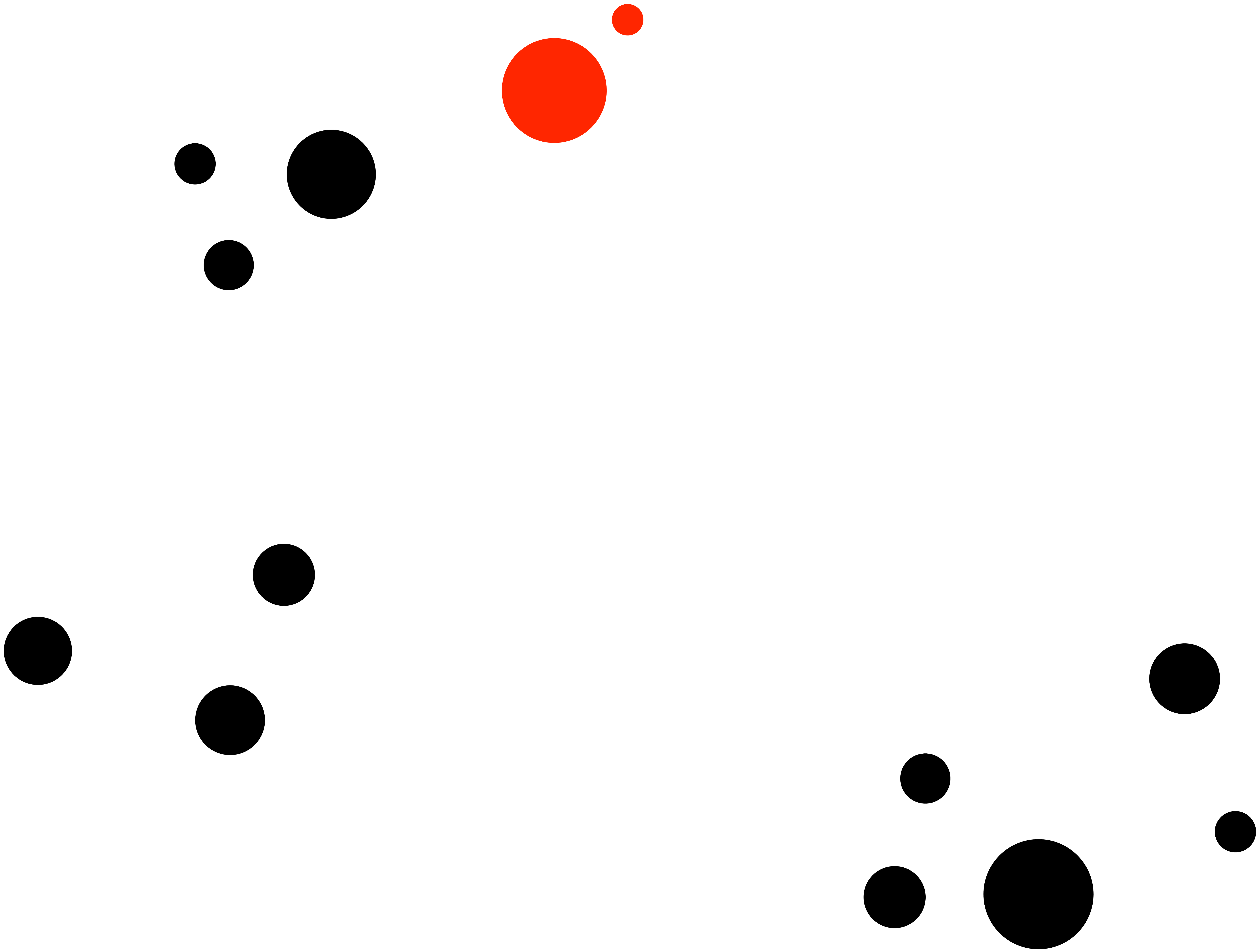

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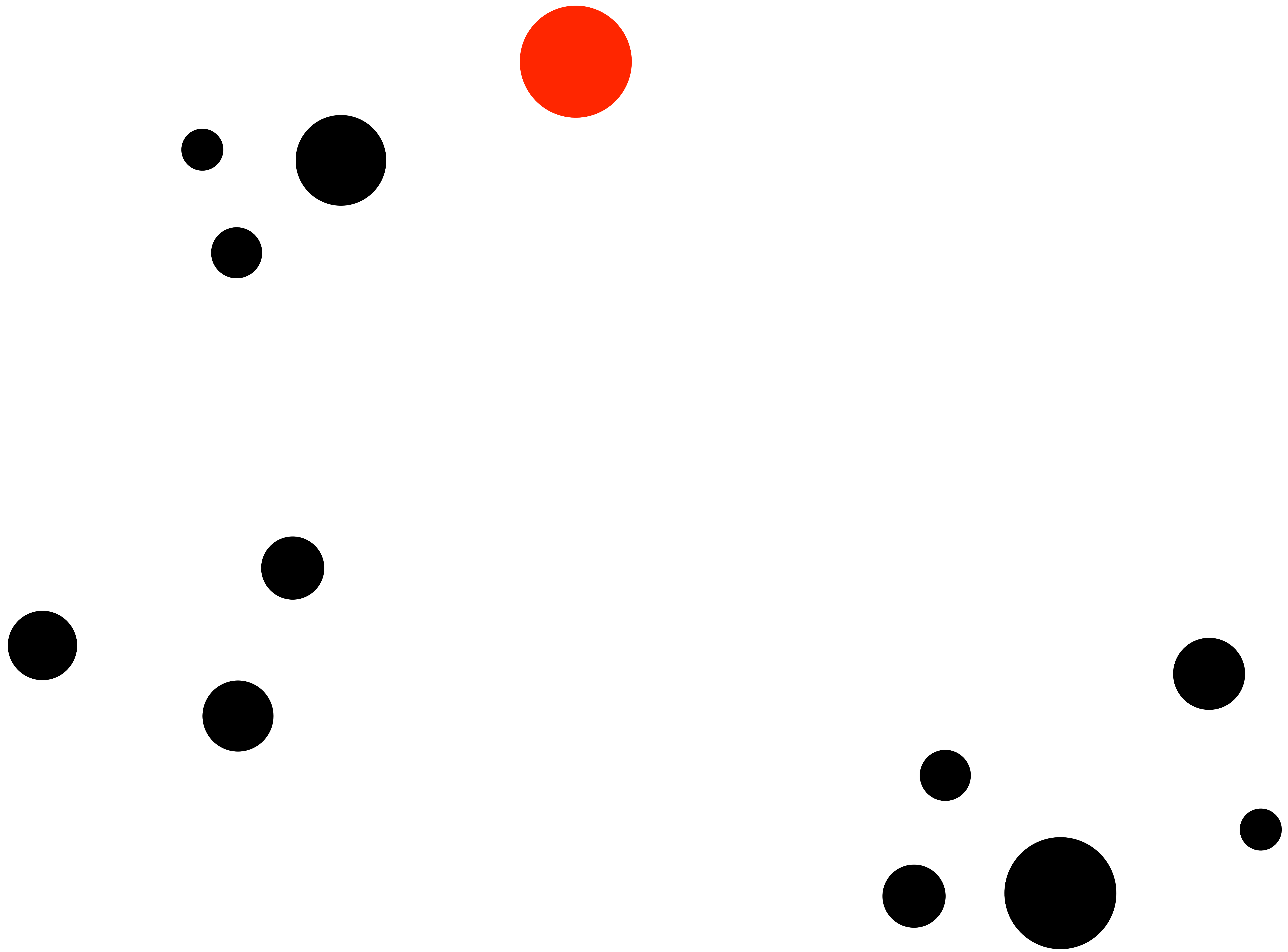

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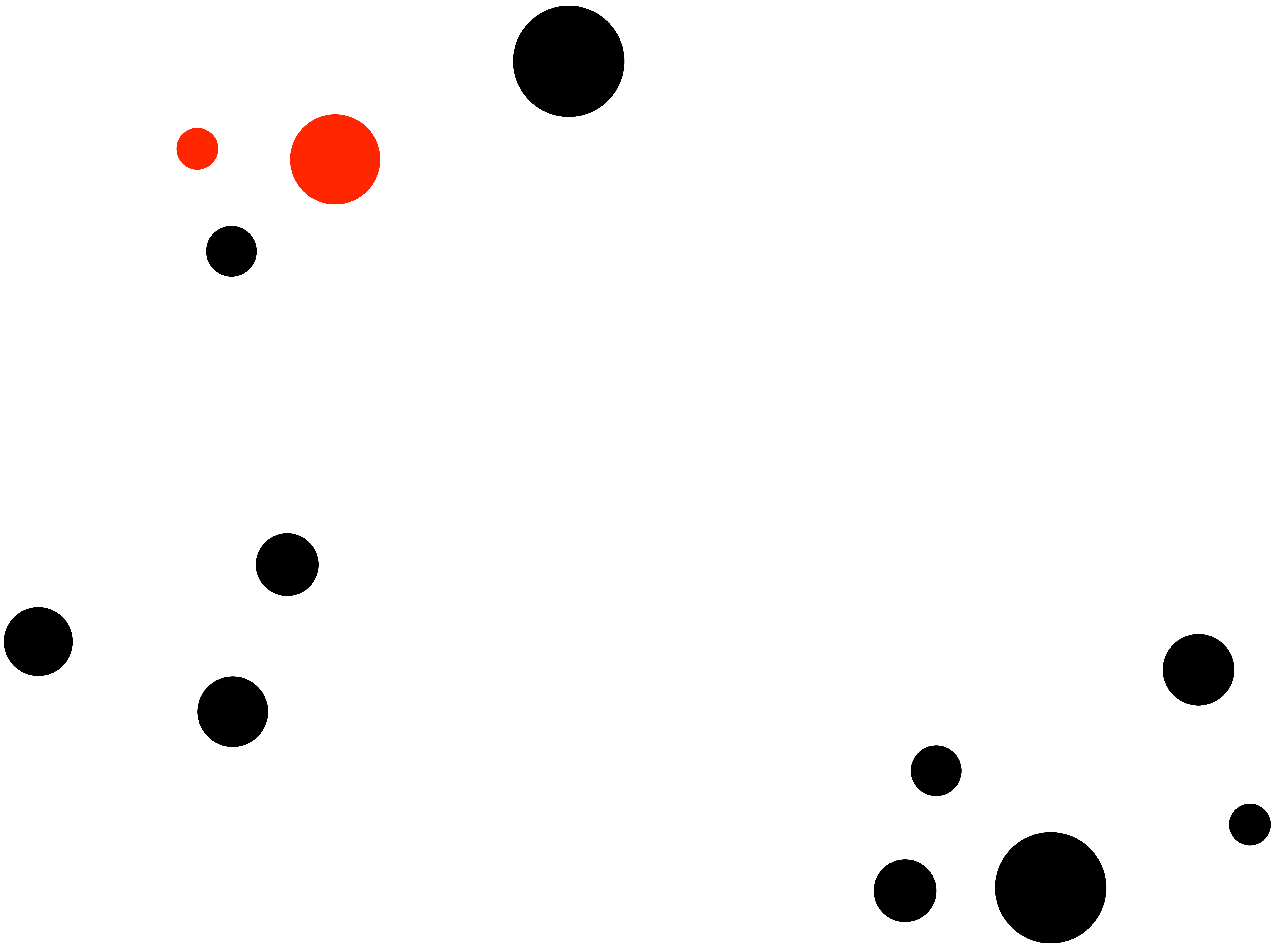

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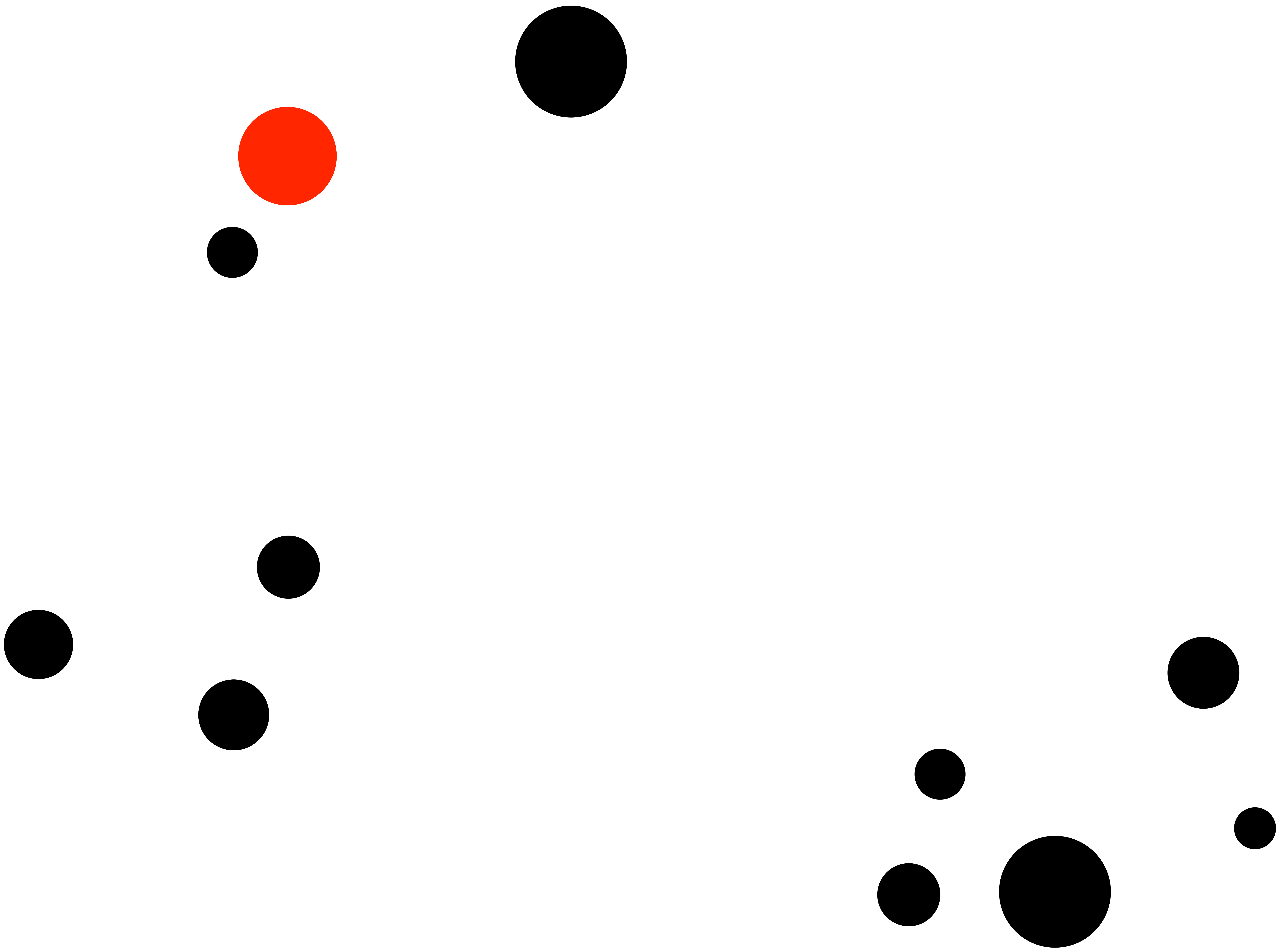

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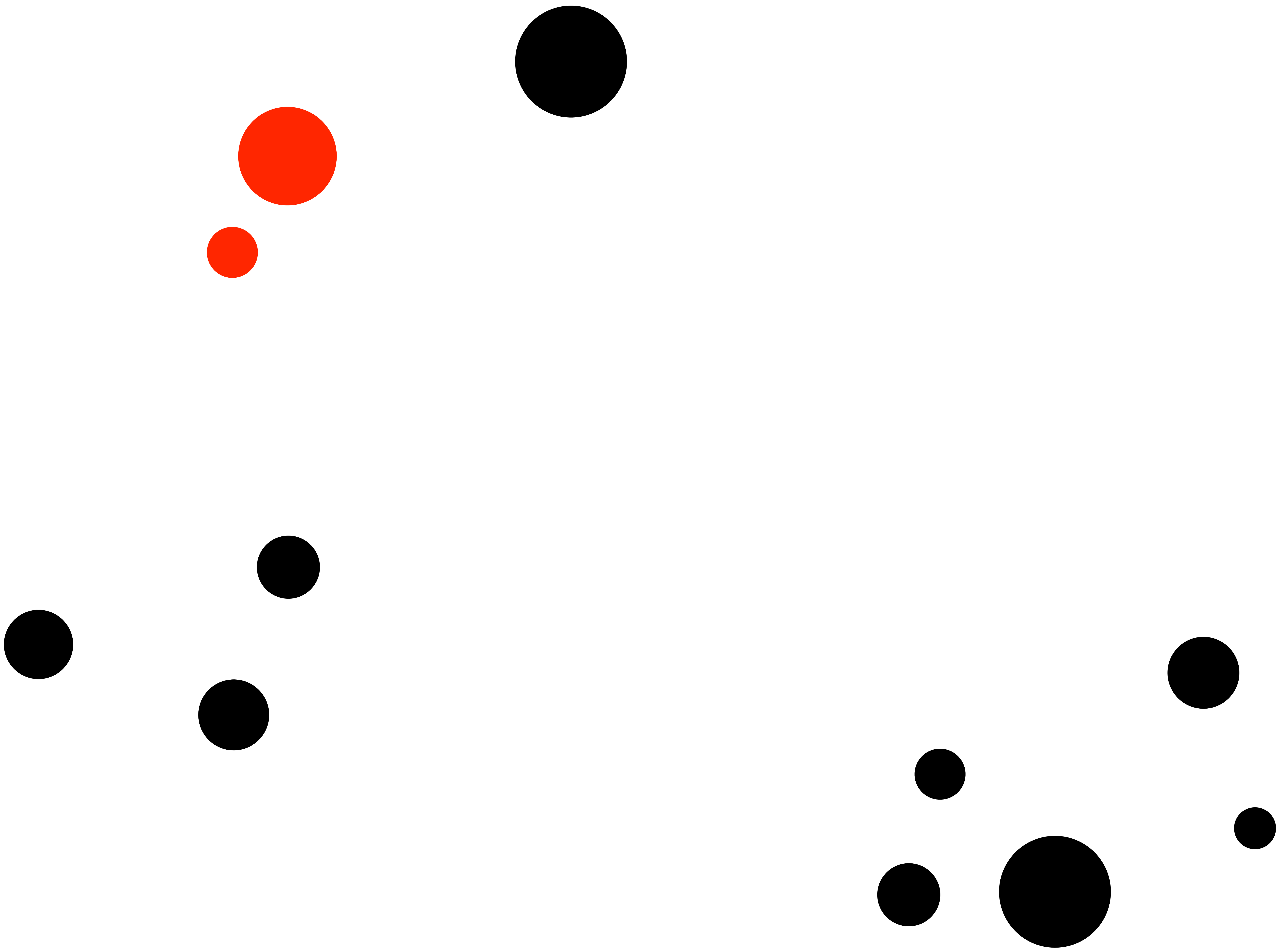

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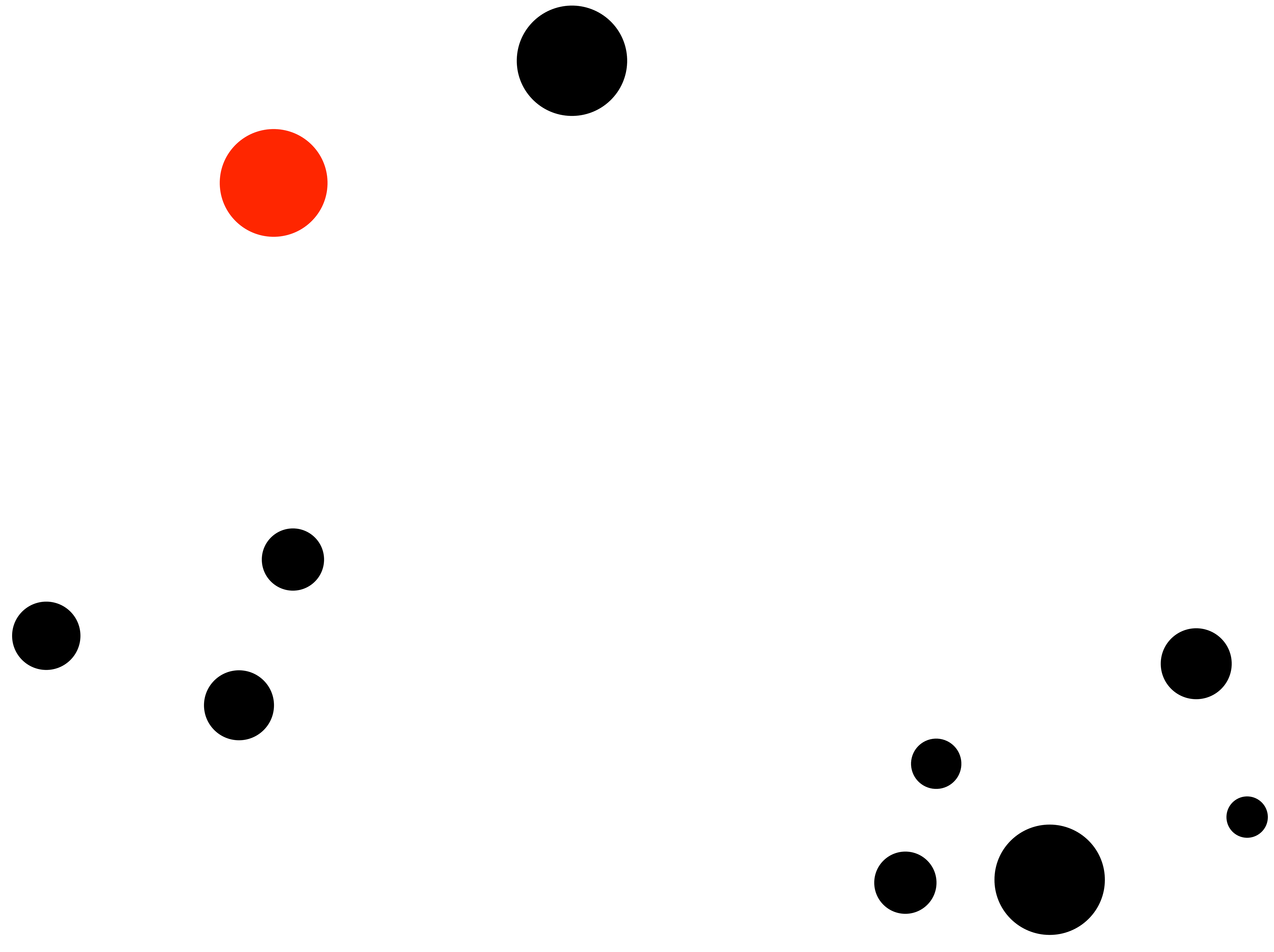

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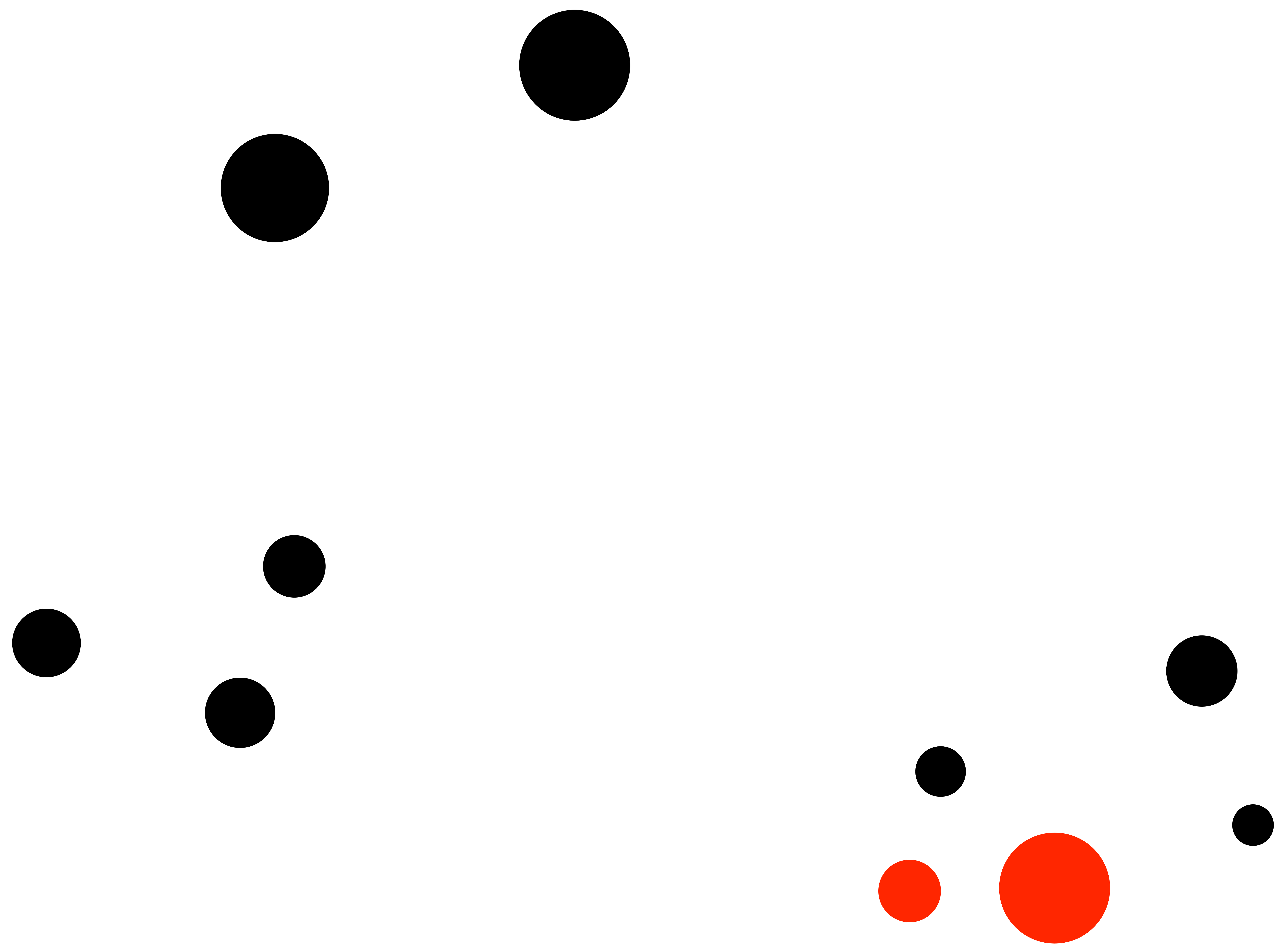

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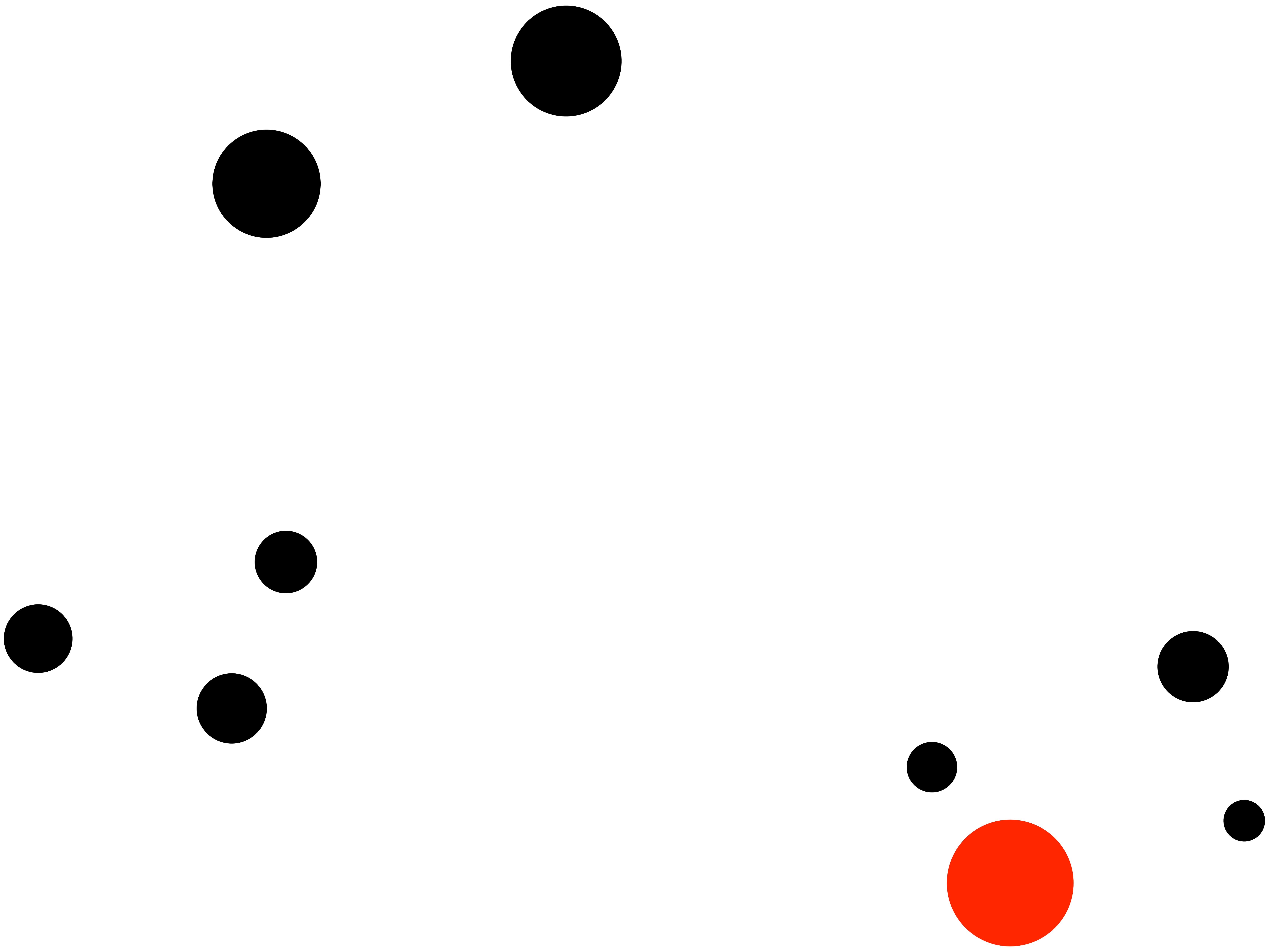

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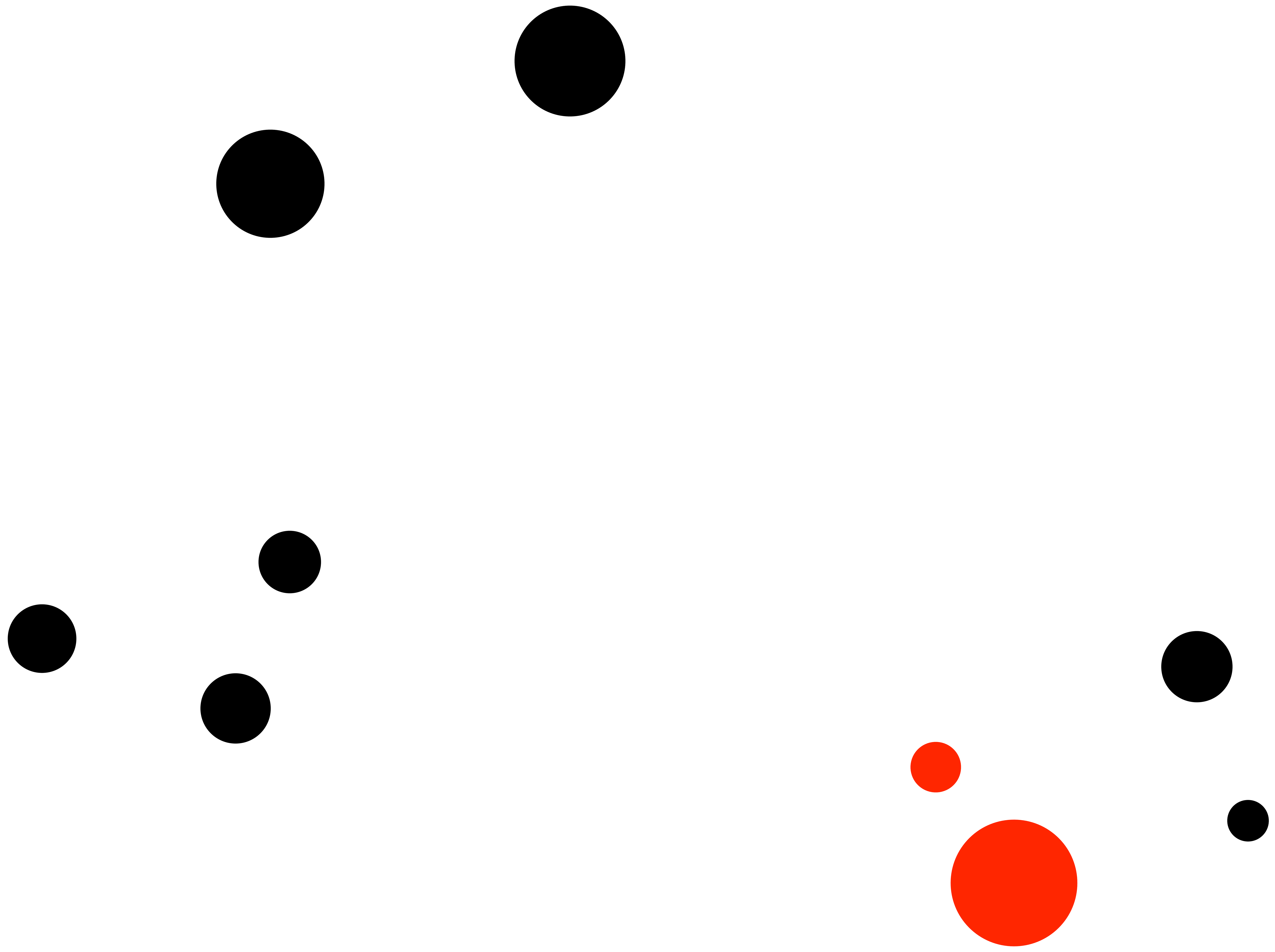

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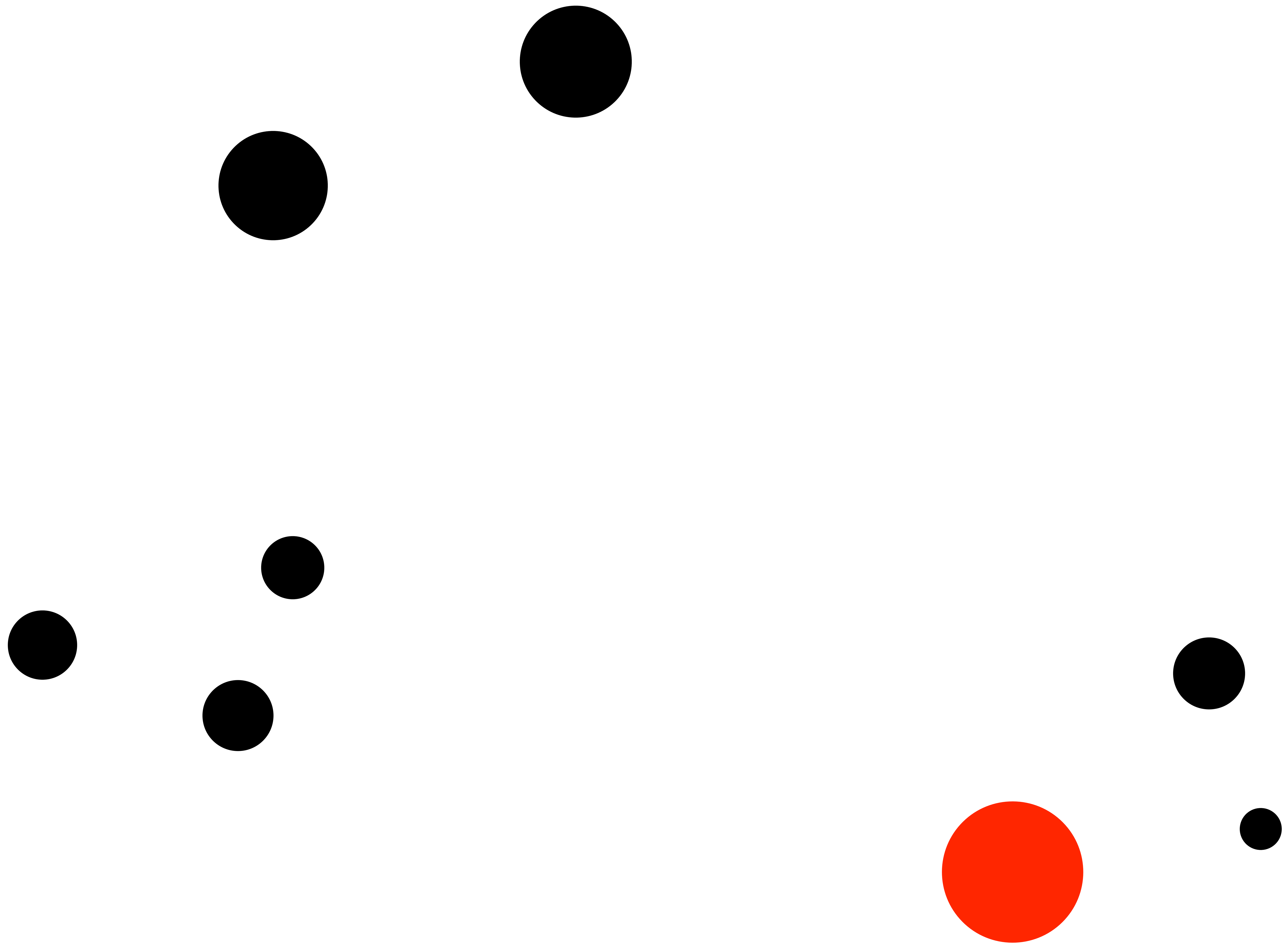

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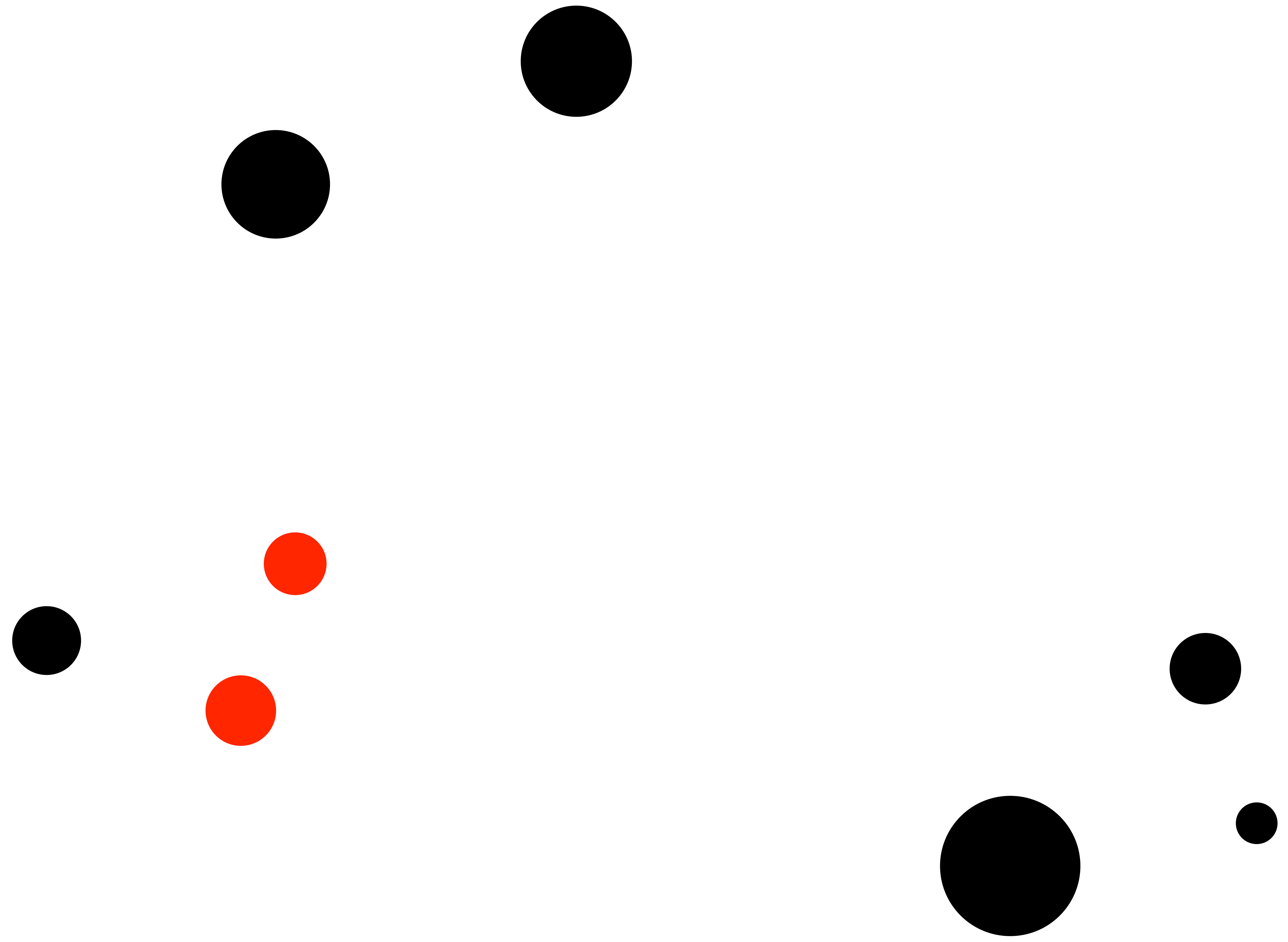

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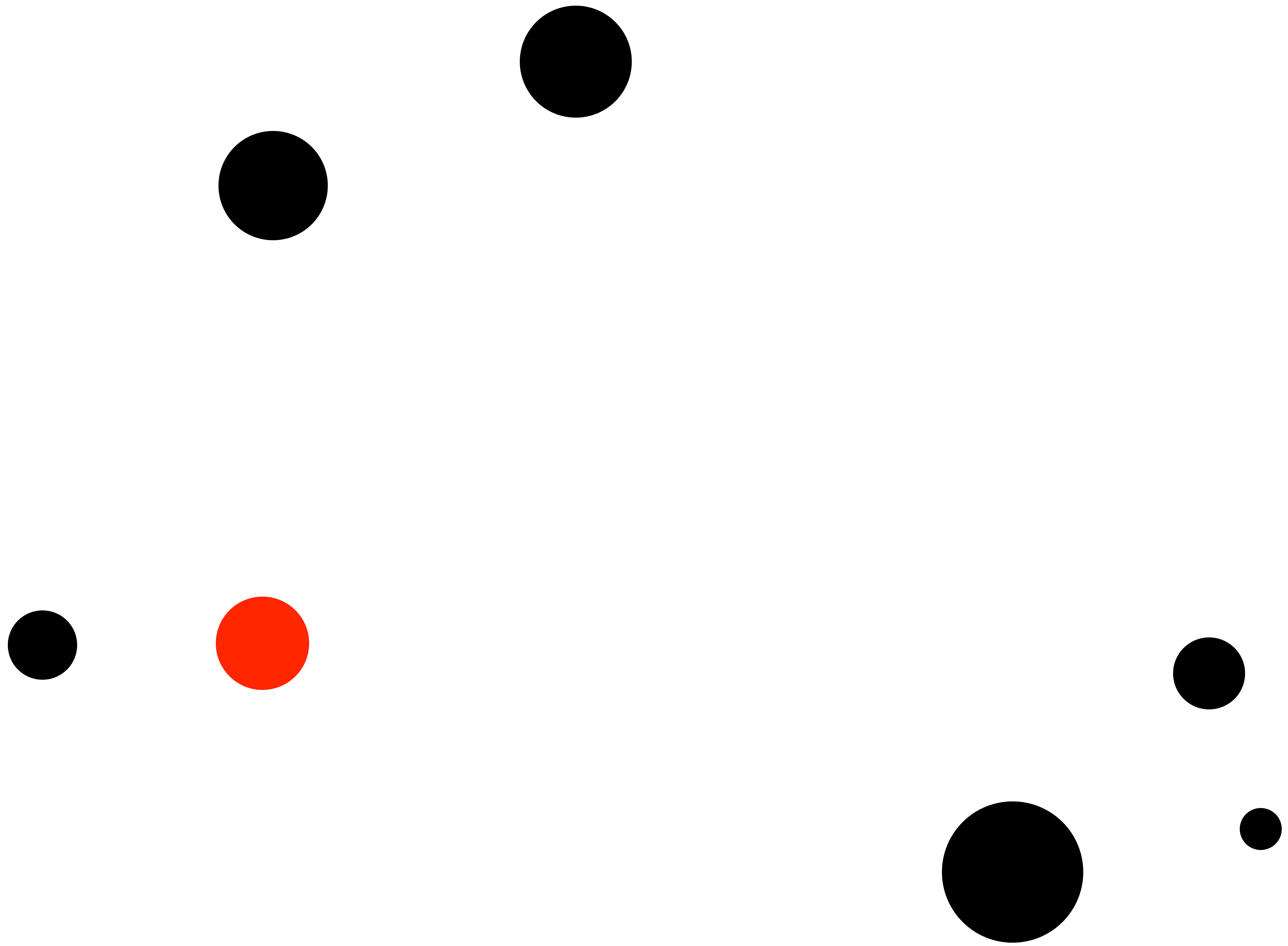

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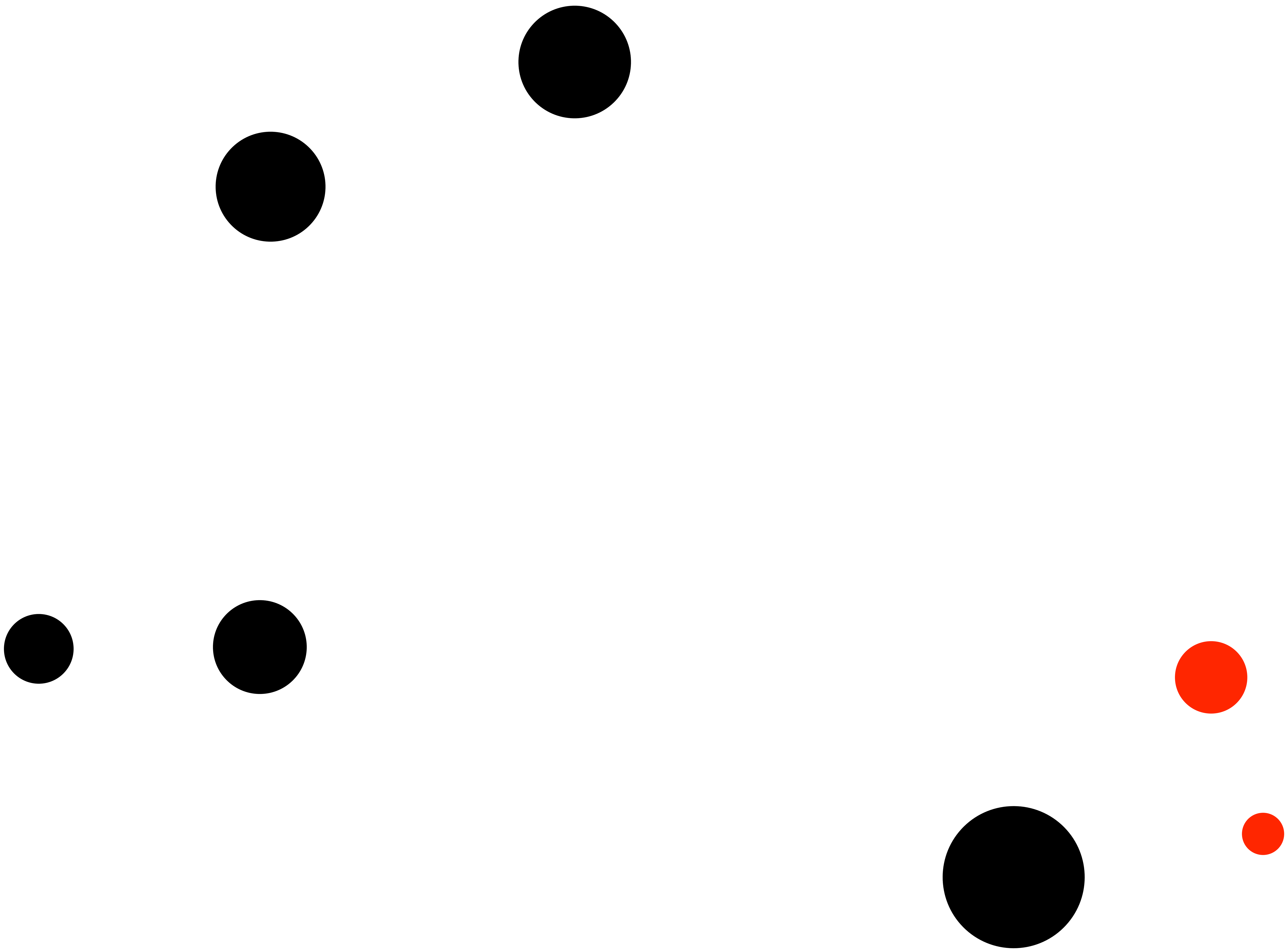

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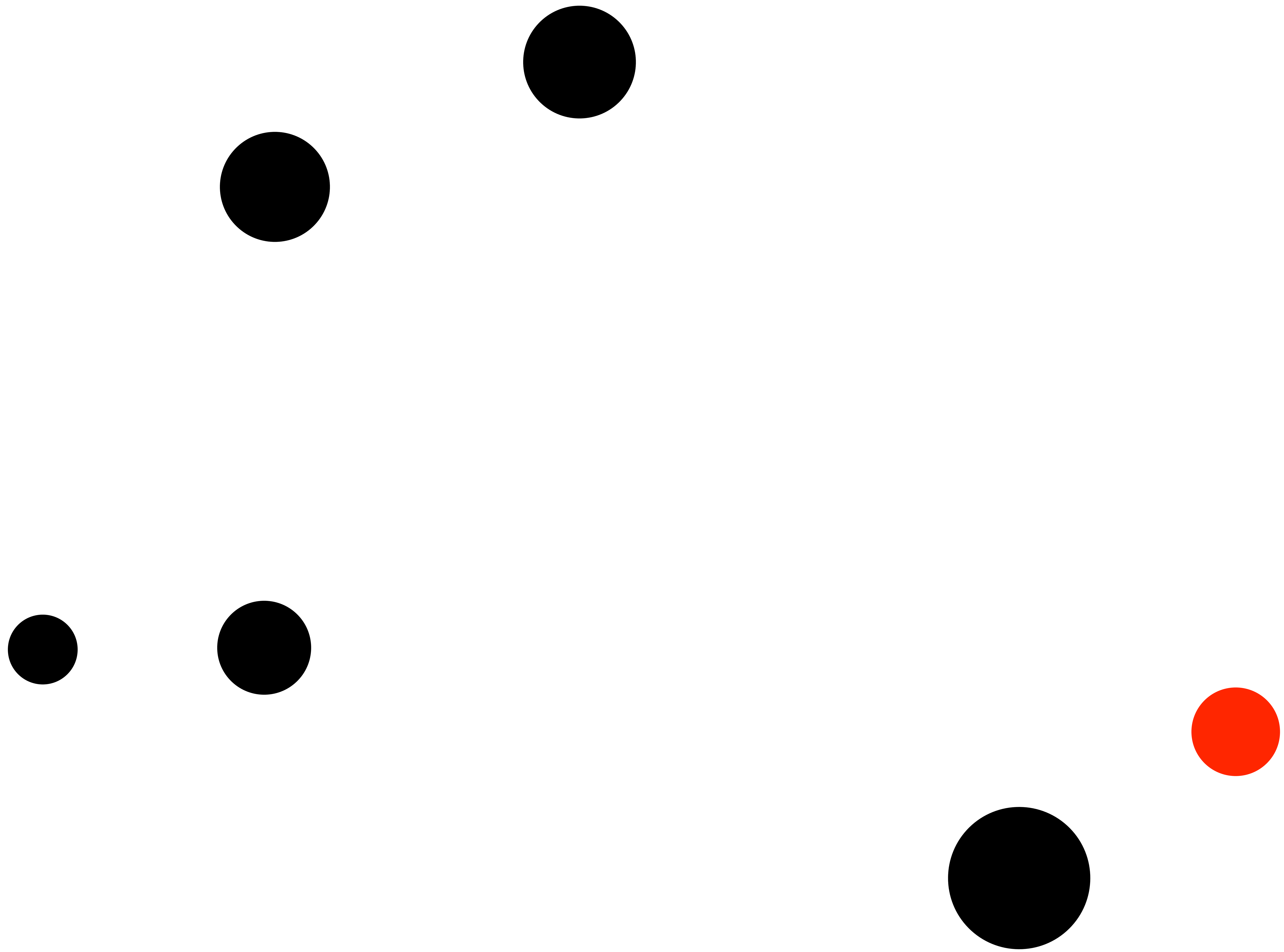

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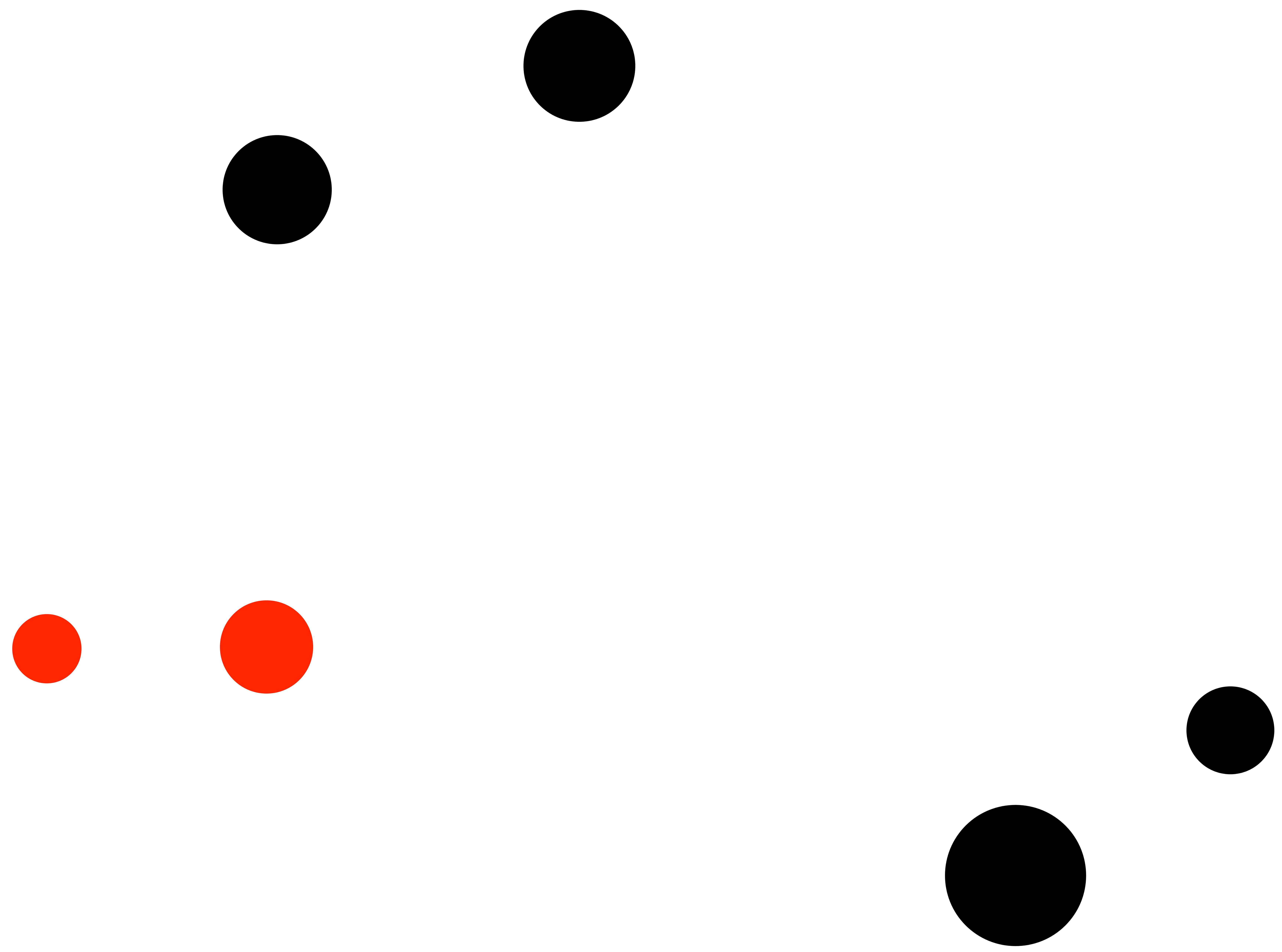

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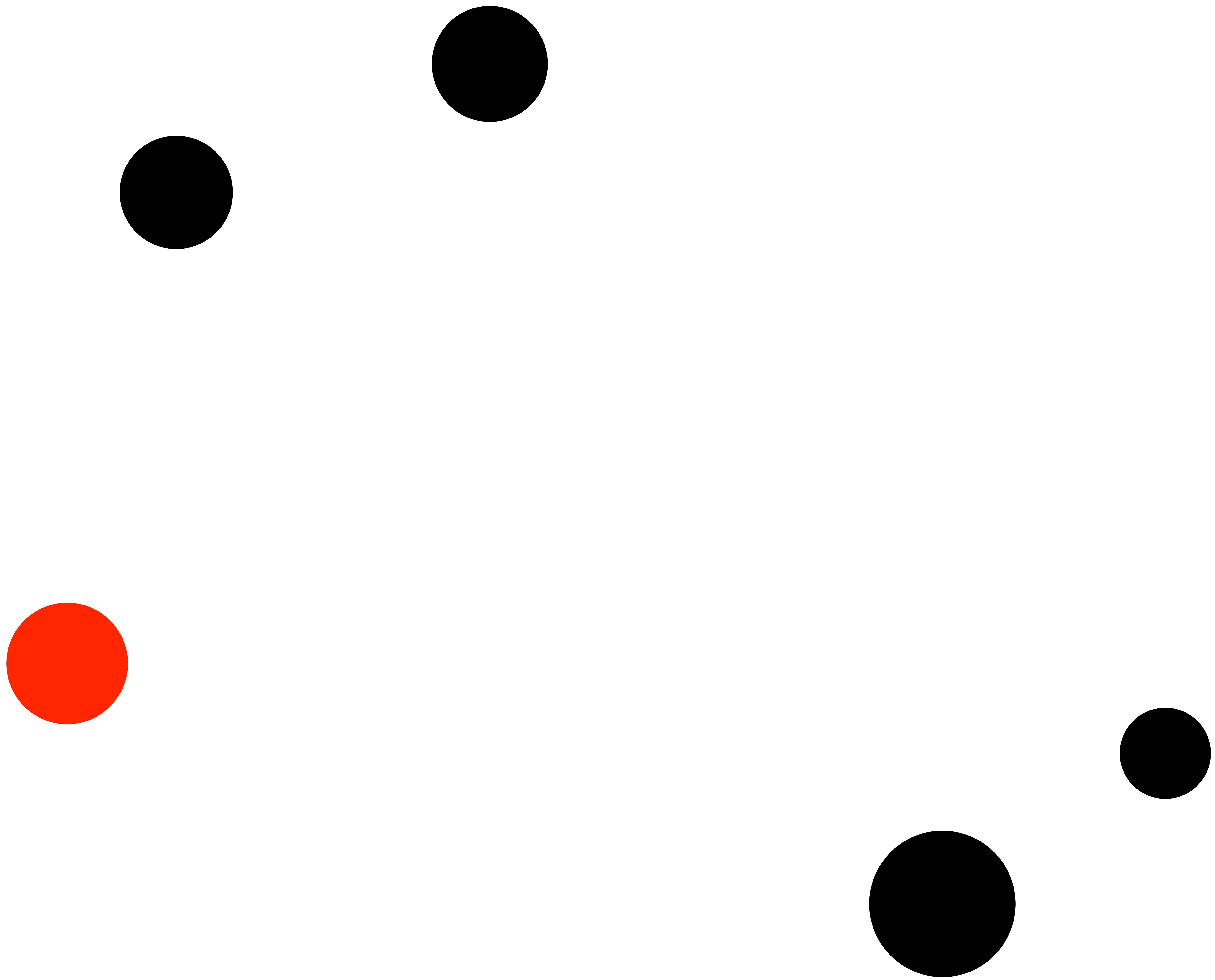

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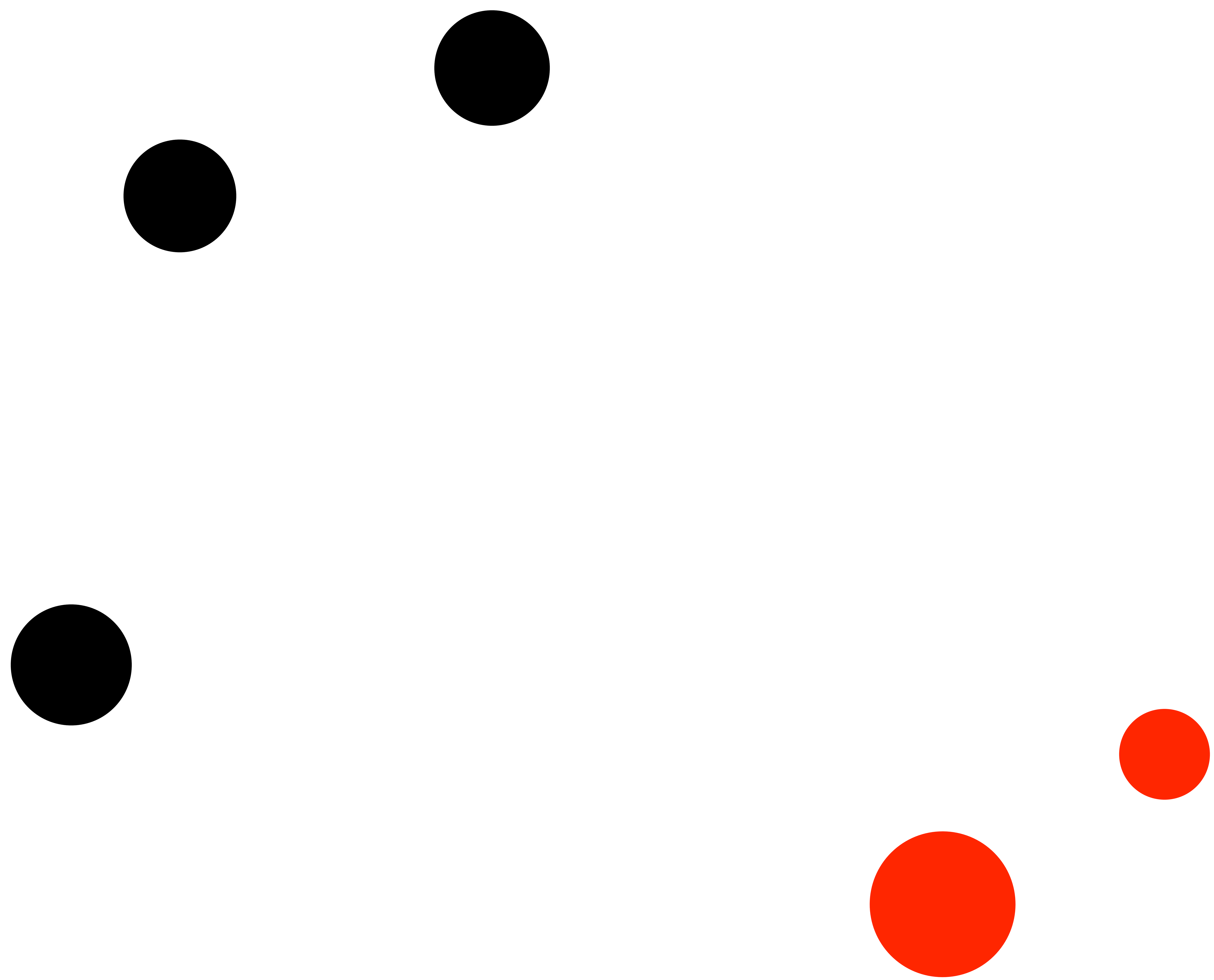

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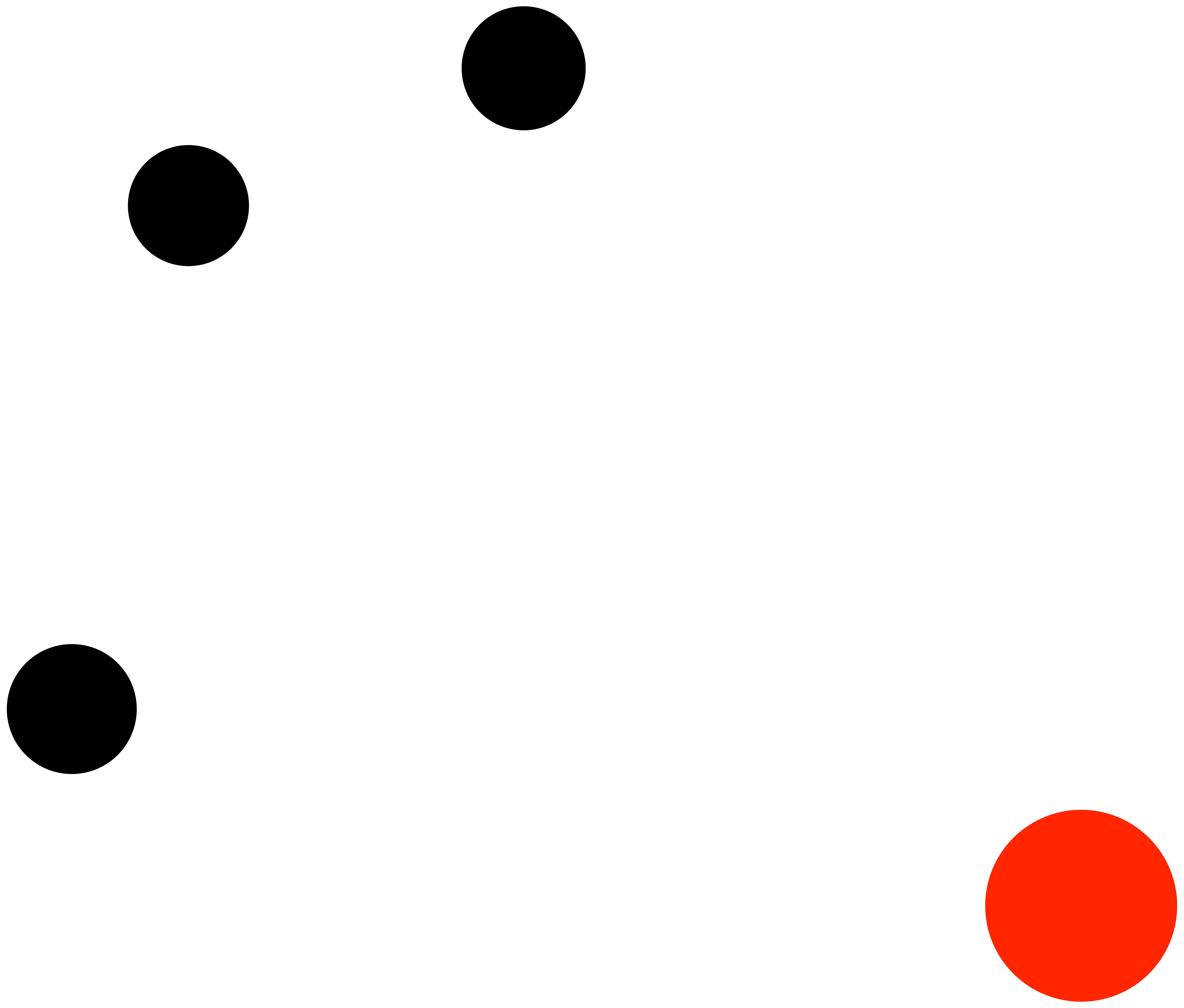

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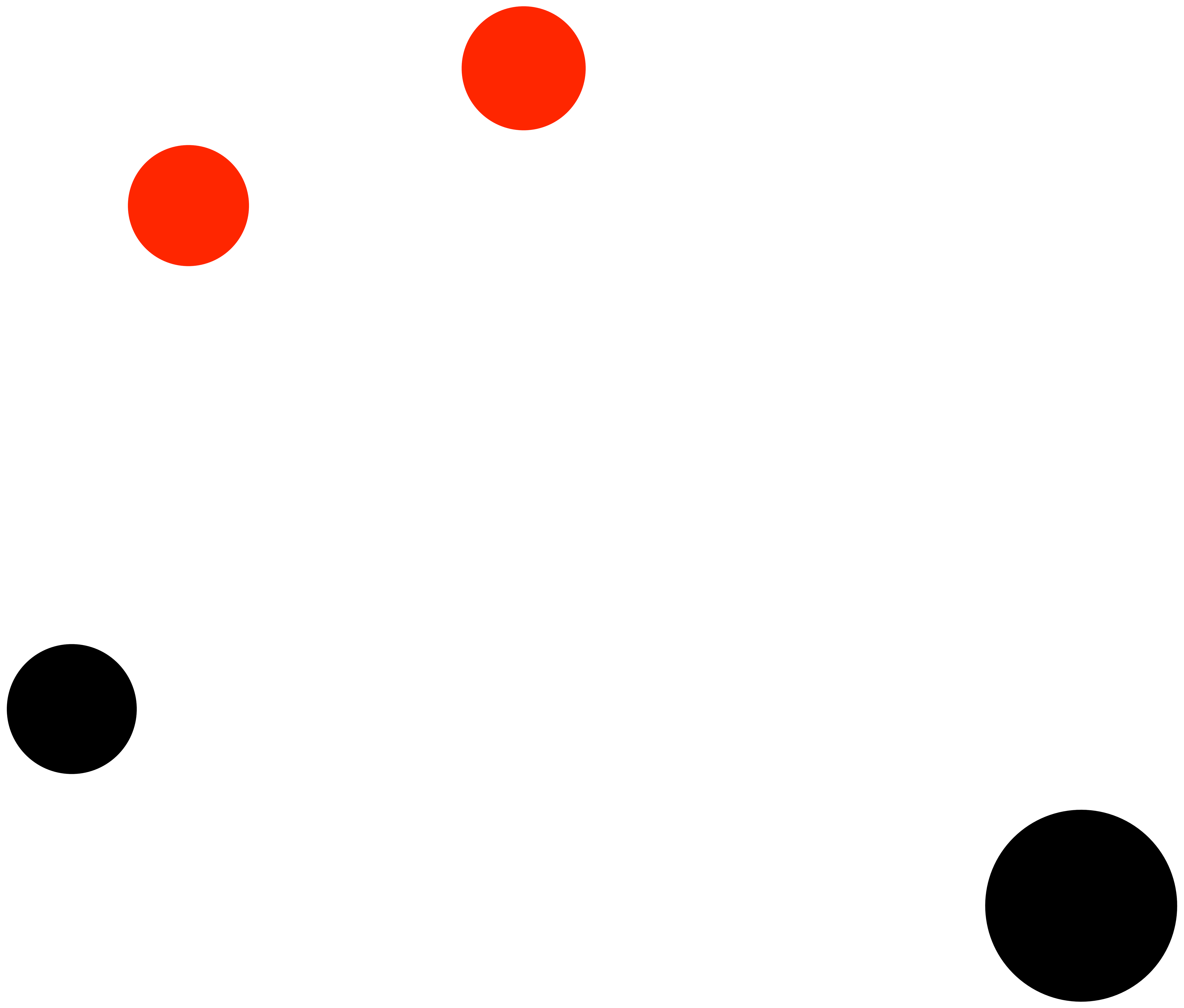

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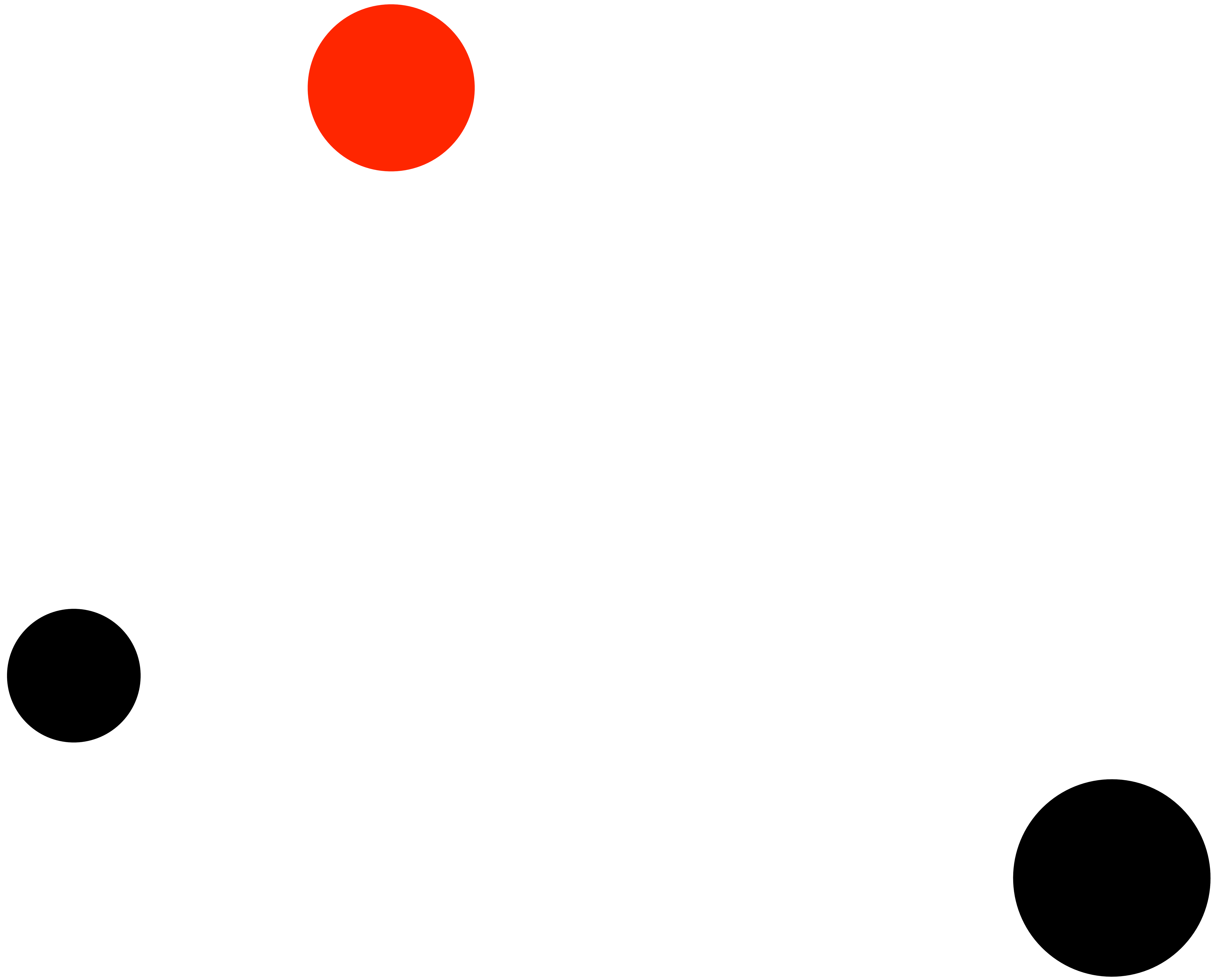
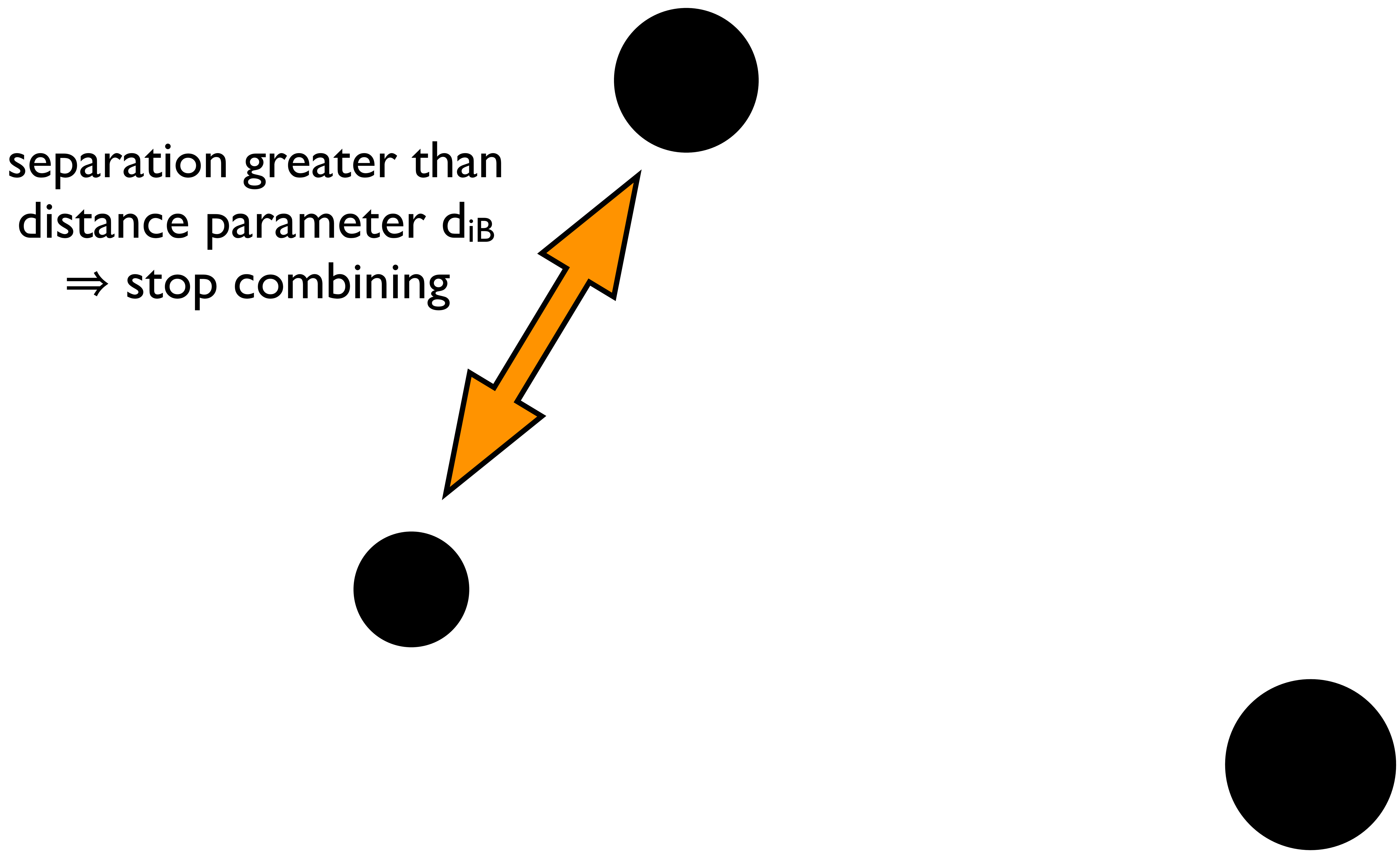


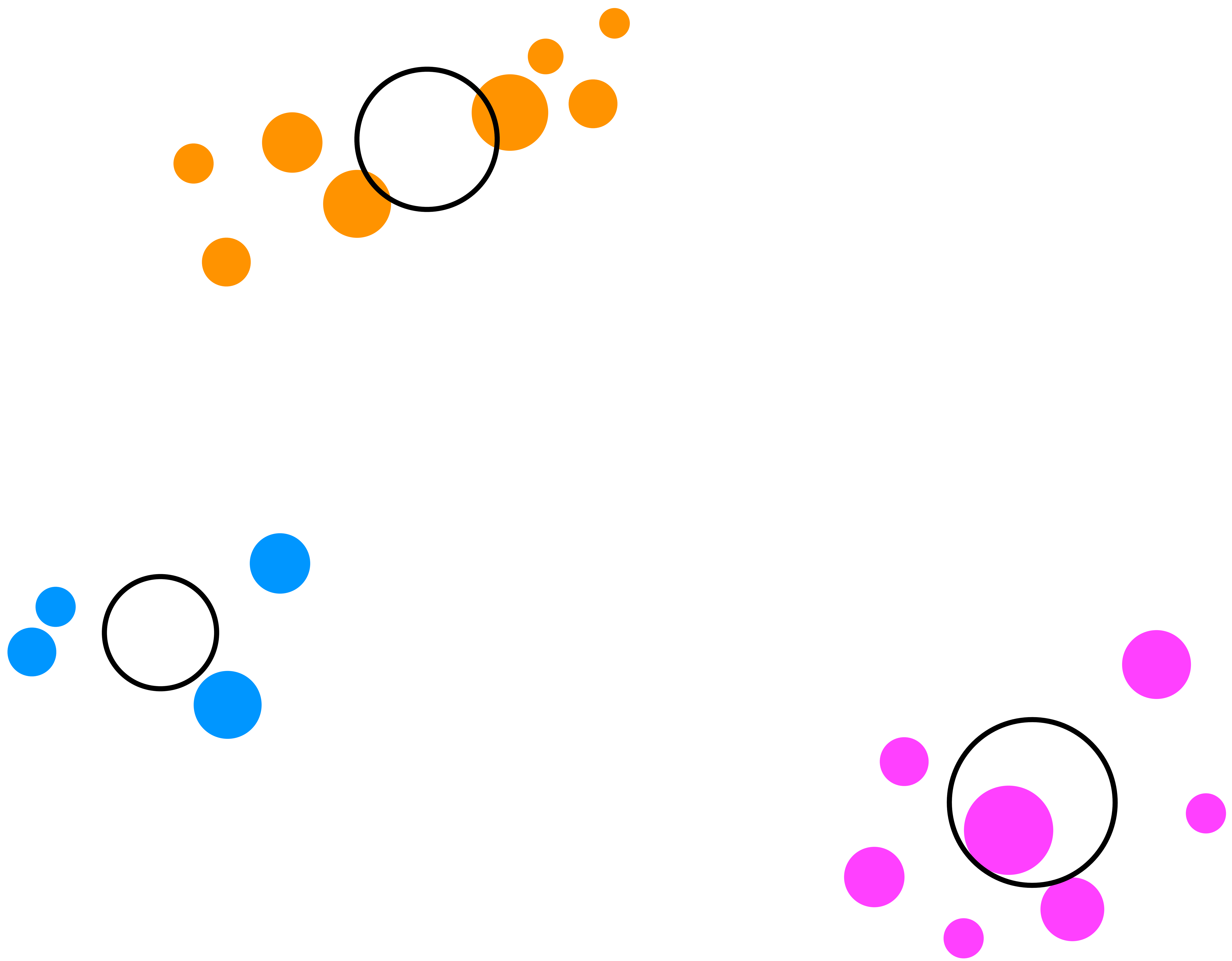
Credit: Jim Dolen

Stop when the closest pair is separated by $\Delta R > R$



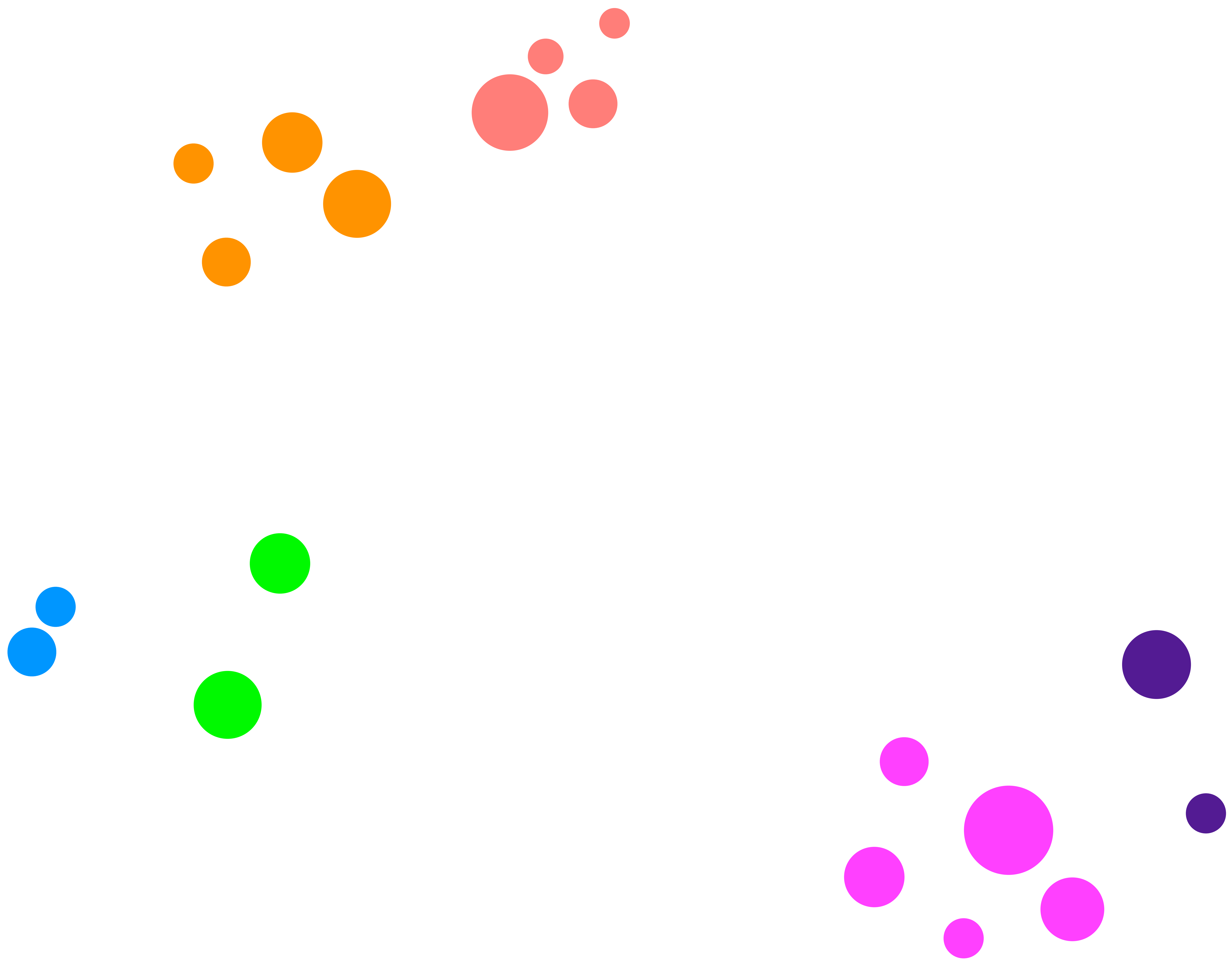
Credit: Jim Dolen

The algorithm found 3 jets, each with 4-vector equal to the sum of its components



Credit: Jim Dolen

If we had used a different distance parameter, the answer would have been much different (6 jets instead of 3)



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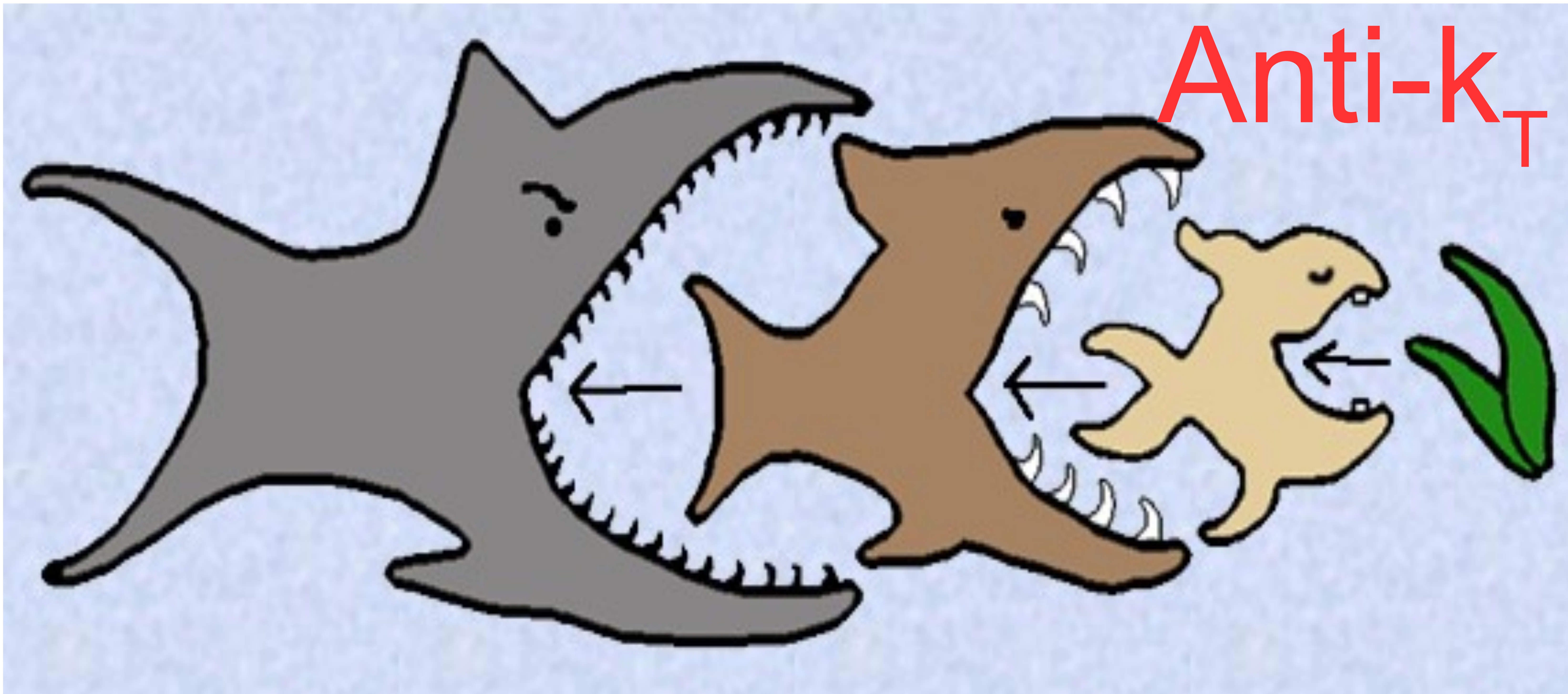
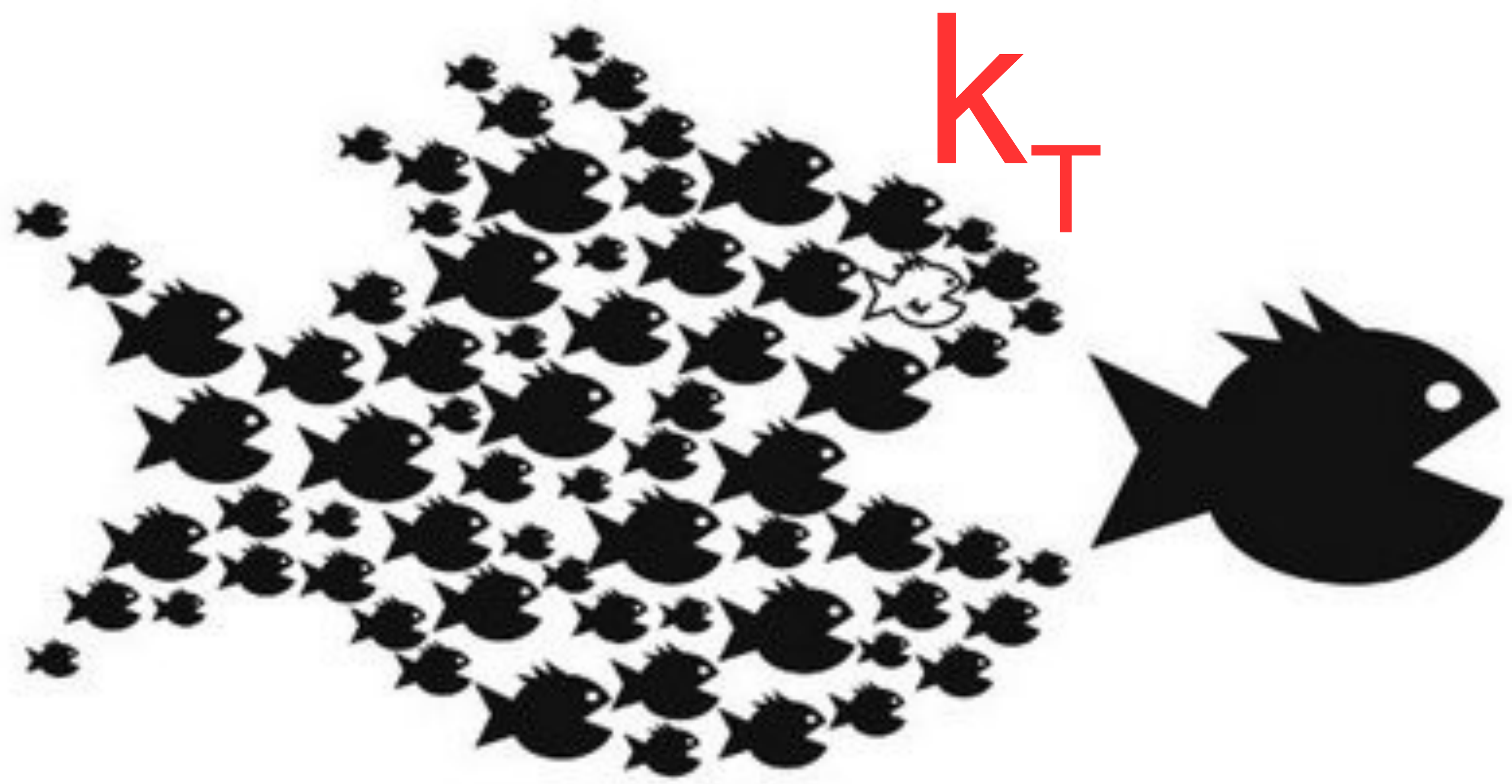
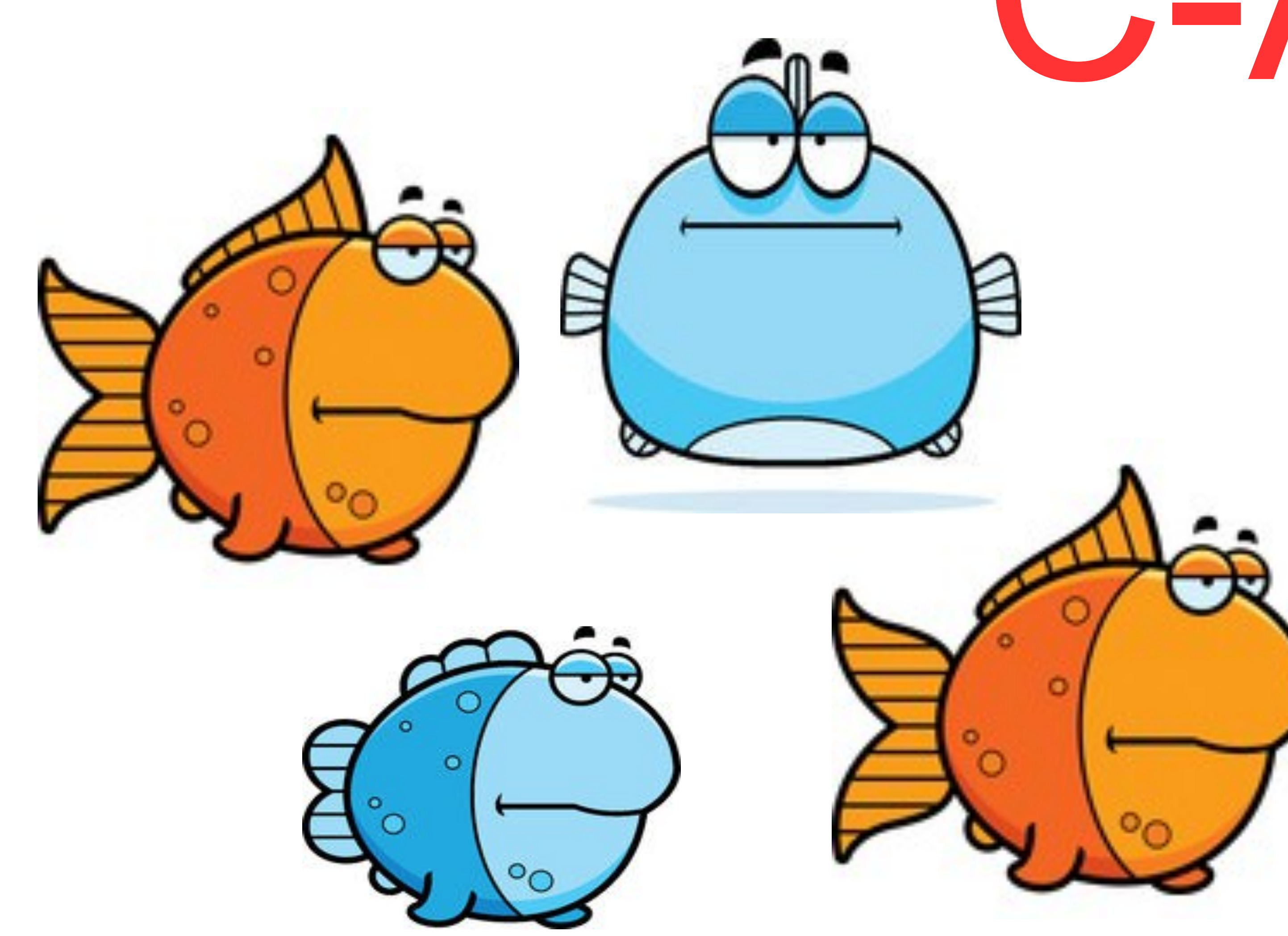
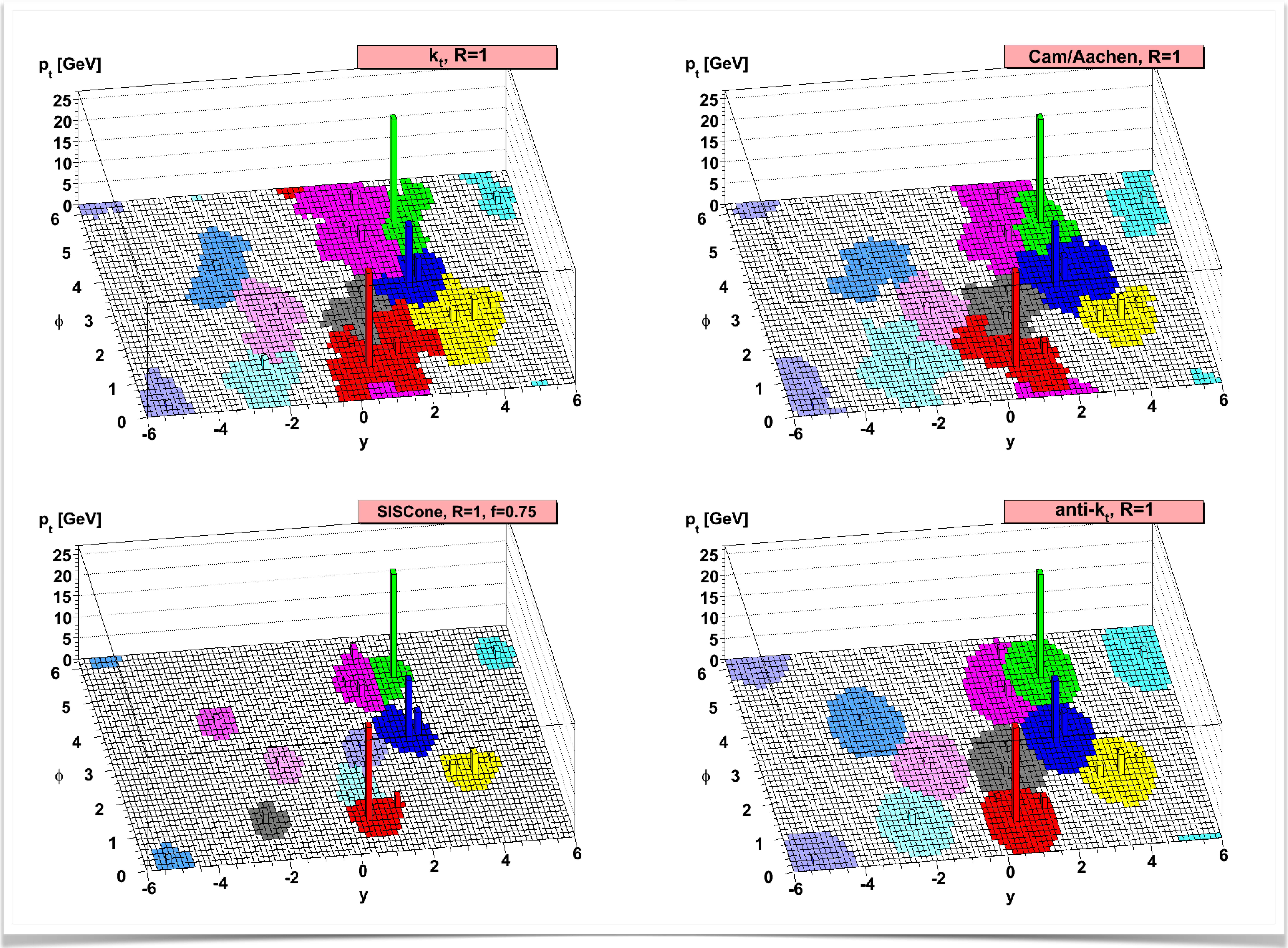

Anti-k_T

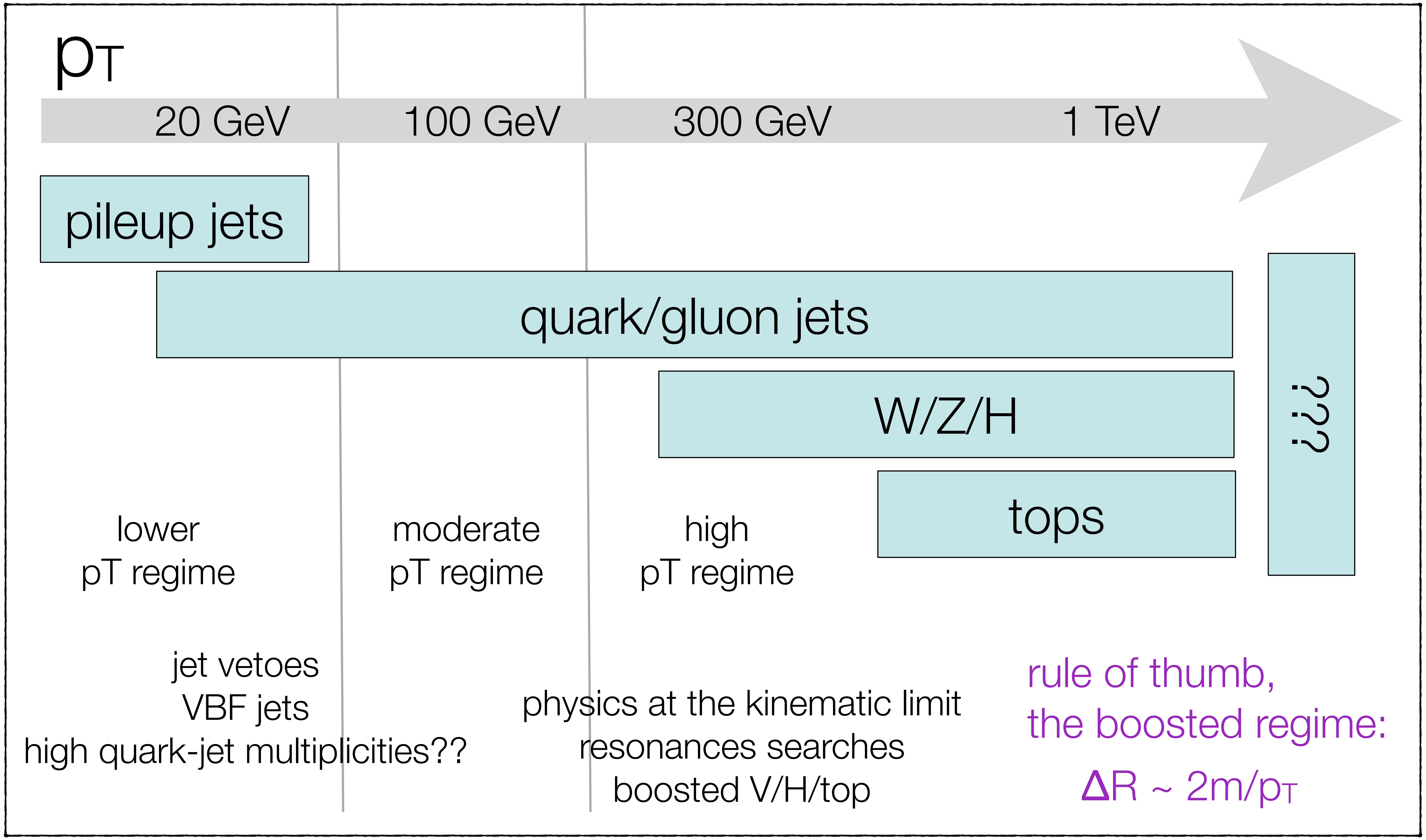

k_T


C-A

Jet algorithms



Which R?...Which Jet?



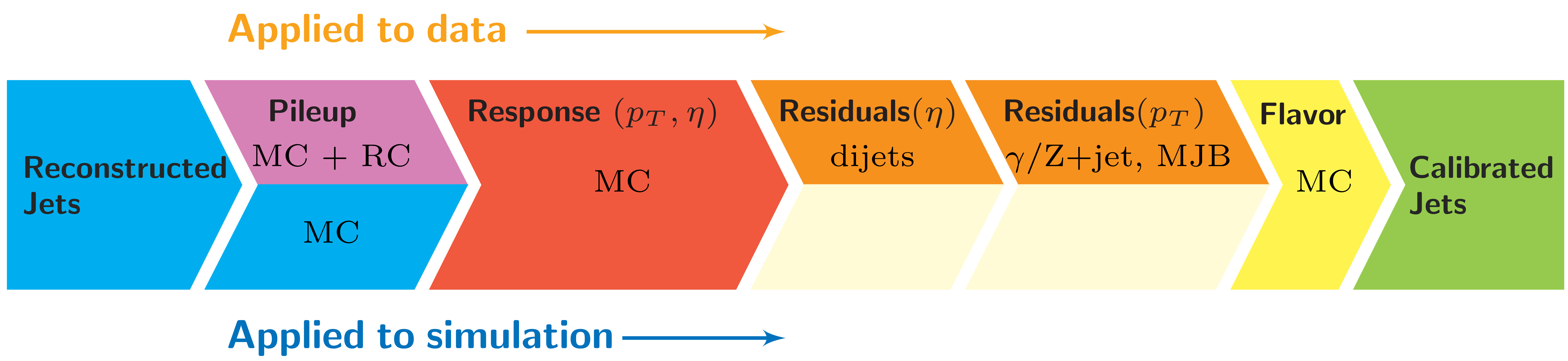
In the end, you pick the R that is appropriate for your analysis.

Discuss this more when talking about jet substructure

Most popular jet algorithm is AK4

A good choice for q/g jets with pT > 25 GeV

Jet energy corrections

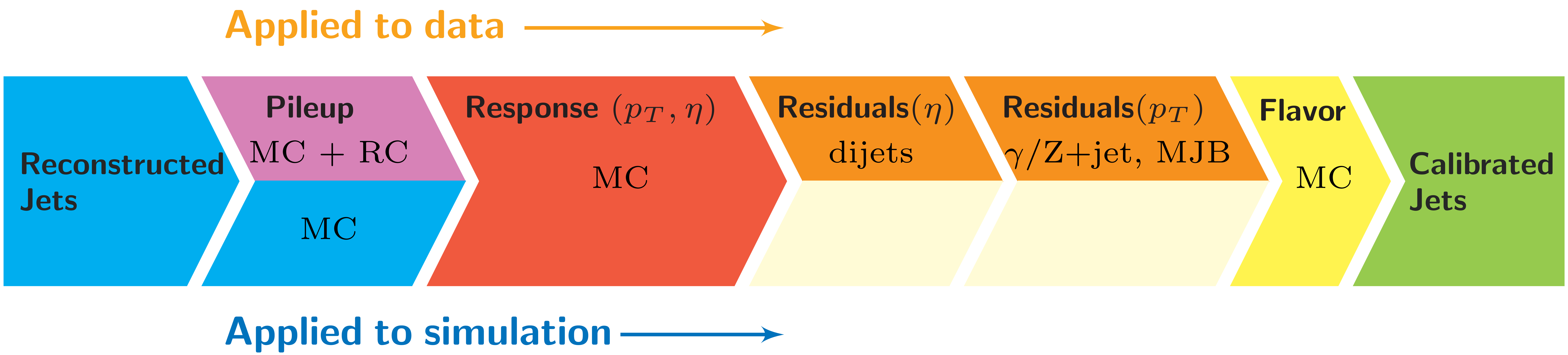


This is an example of the CMS chain of jet energy corrections

Basic chain:

- Correct for pileup (on average)
- Correct for detector effects
  - Can be many things depending on detector: out-of-cone effects, detector response, material loss, etc.
- Correct for data/MC
- Correct for flavor of jet (q,g,b,etc.)

Jet energy corrections



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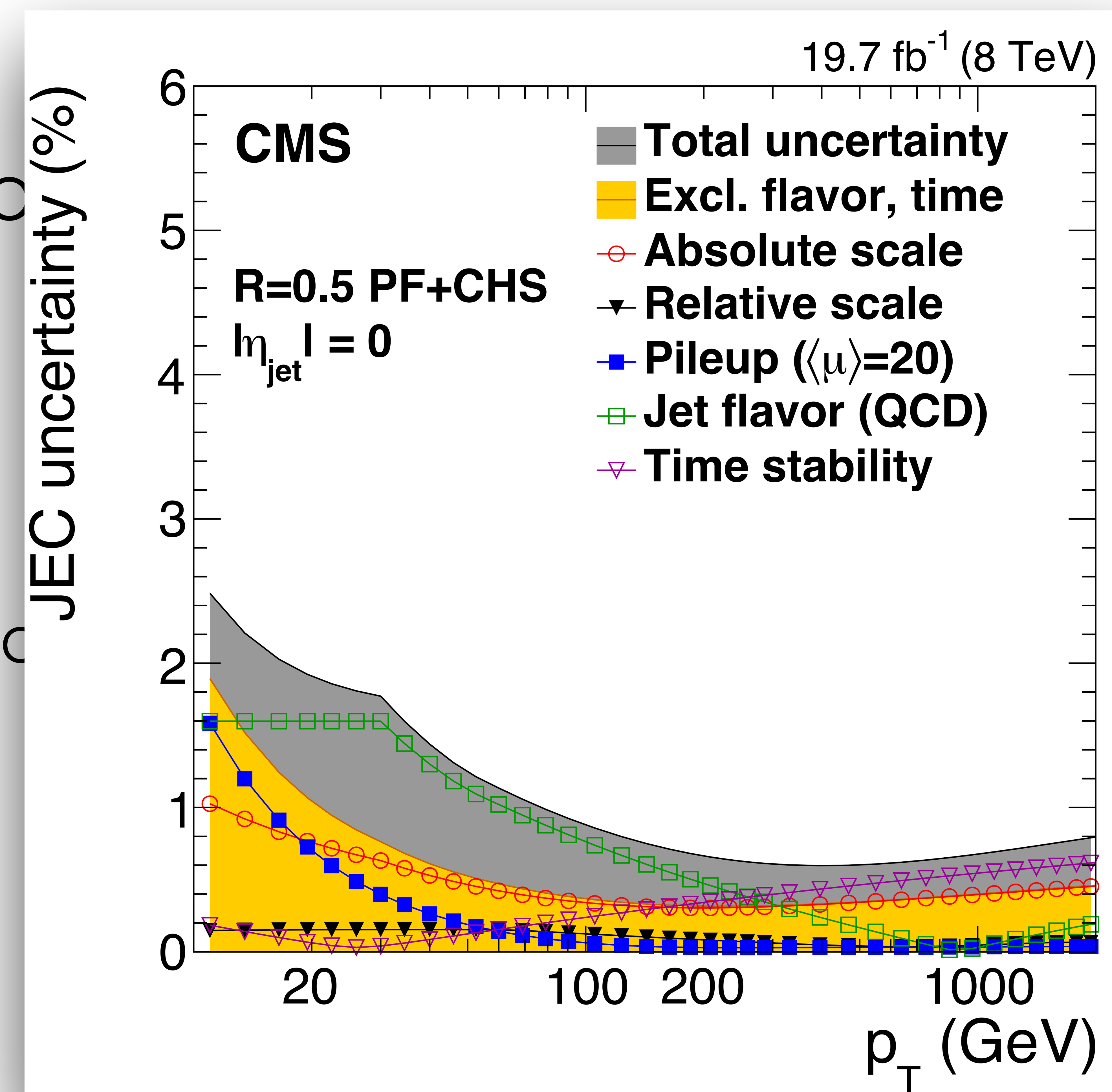
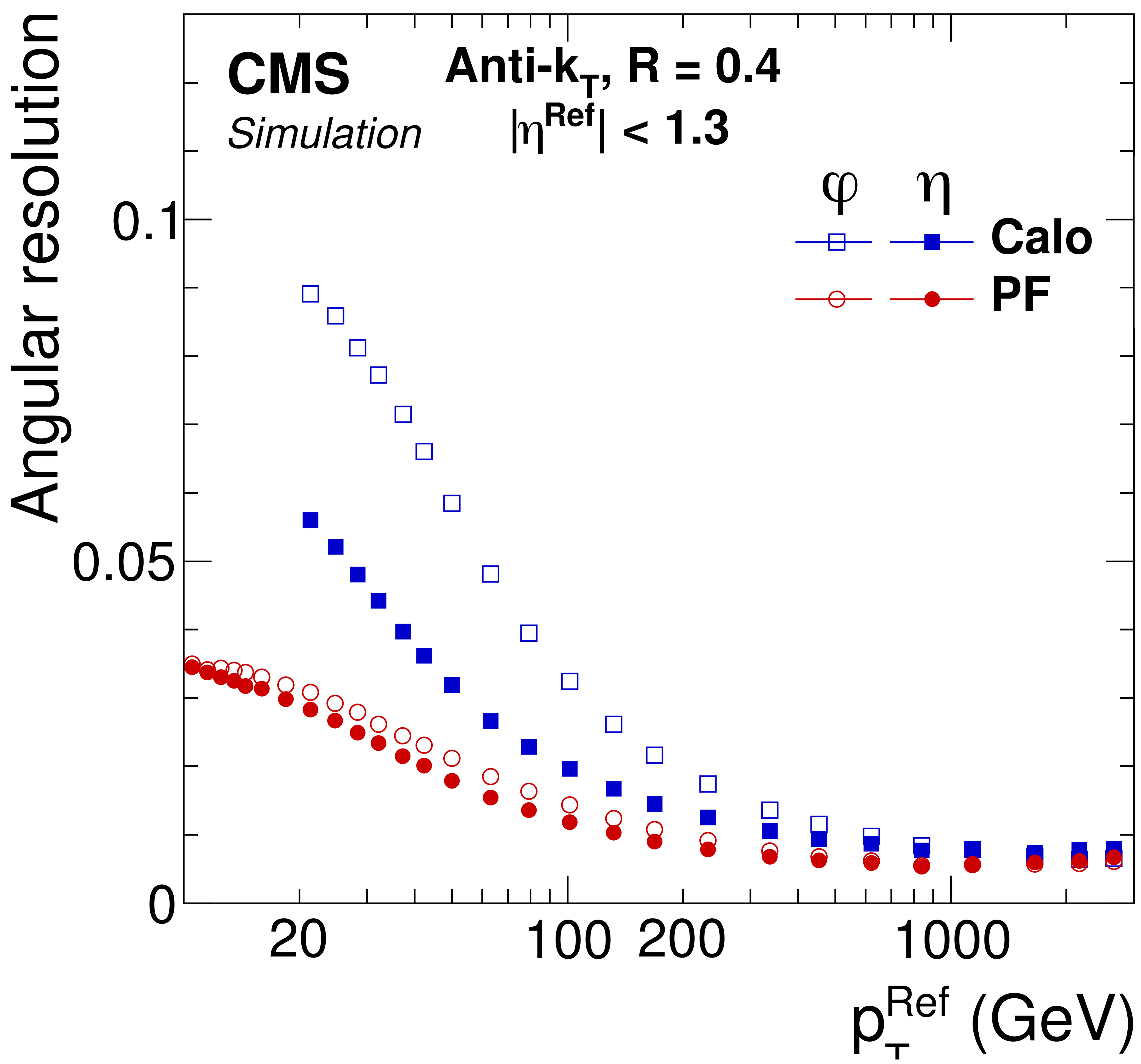
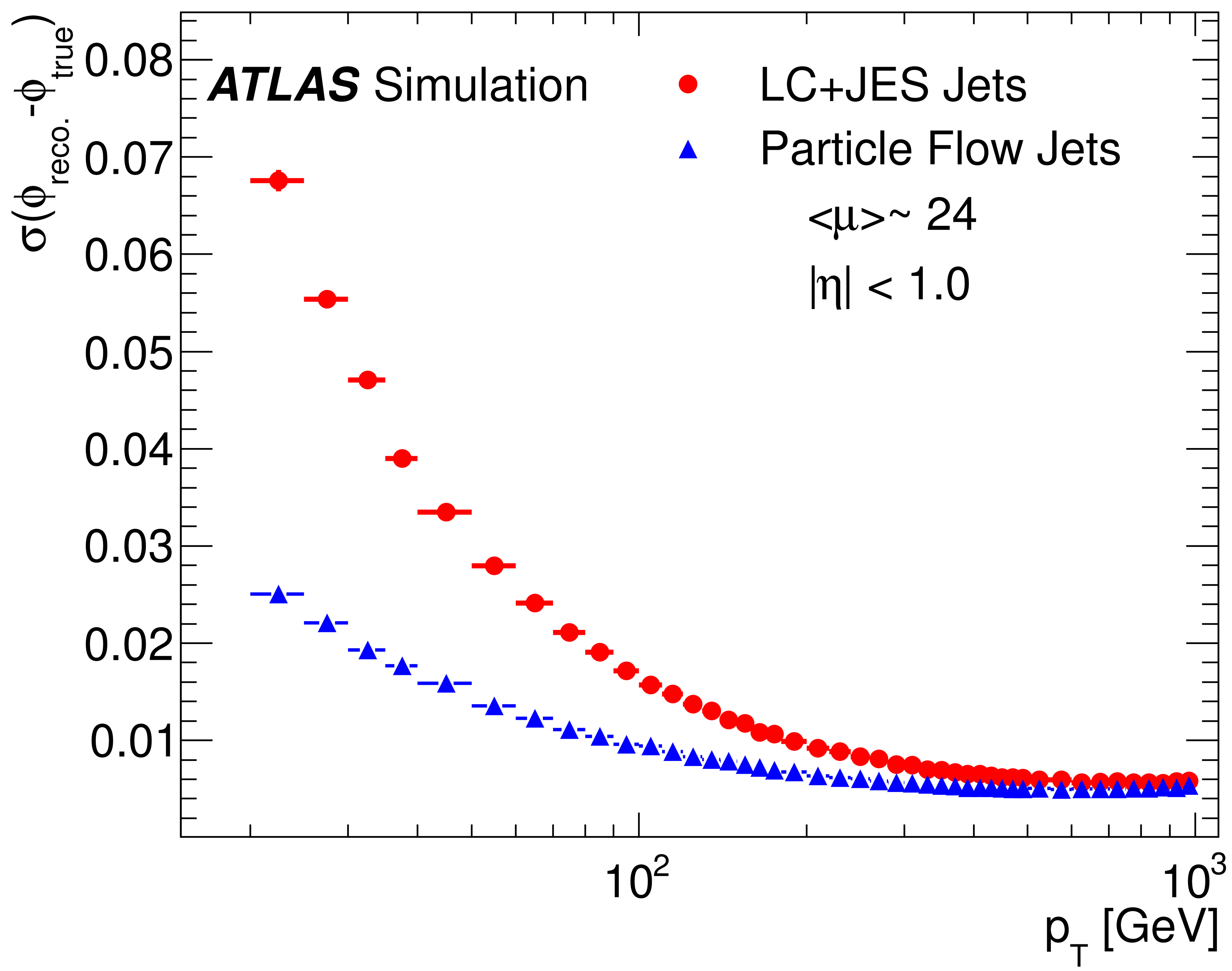


Particle flow jet angular resolution

CMS

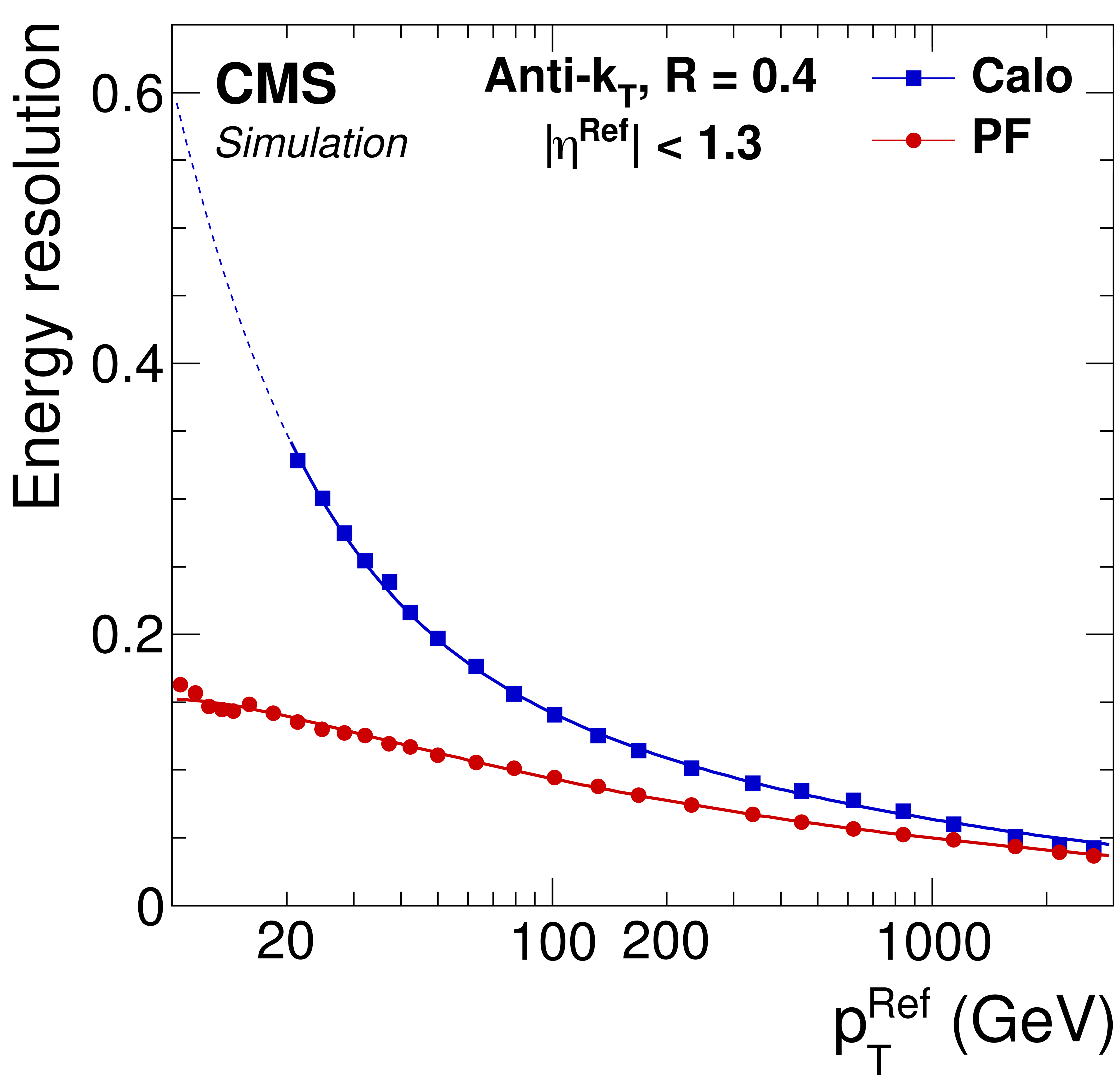


ATLAS

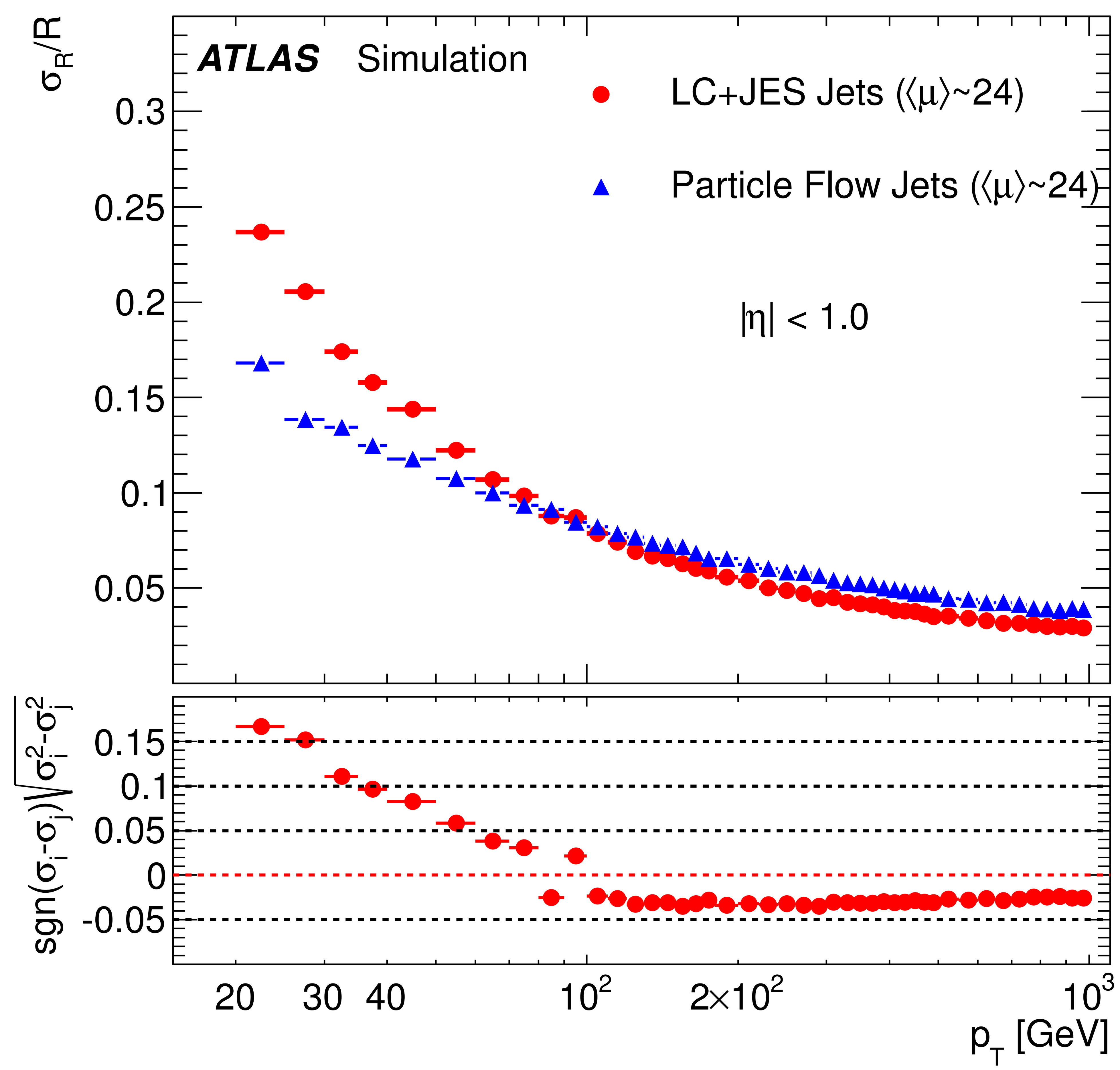


Particle flow jet energy resolution

CMS



ATLAS



Comparing ATLAS & CMS

	ATLAS	CMS
Ecal+Hcal pion resolution	$\frac{\sigma}{E_T} \approx \frac{40\%}{\sqrt{E_T}}$	$\frac{\sigma}{E_T} \approx \frac{100\%}{\sqrt{E_T}} \oplus 7\%$
Missing momentum resolution (TDR)	$\frac{\sigma(\not{E}_T)}{\Sigma E_T} \approx \frac{50\%}{\sqrt{\Sigma E_T}}$	$\frac{\sigma(\not{E}_T)}{\Sigma E_T} \approx \frac{120\%}{\sqrt{\Sigma E_T}} \oplus 2\%$
Inner tracker resolution (TDR)	$\frac{\sigma(p_T)}{p_T} \approx 1.8\% \oplus 60\% \, p_T$ (p_T in TeV)	$\frac{\sigma(p_T)}{p_T} \approx 0.5\% \oplus 15\% \, p_T$ (p_T in TeV)
B field inner region	2 Tesla : pT swept < 350 MeV	4 Tesla : pT swept < 700 MeV

ATLAS has better calorimetry; CMS has better tracking

Good jet & MET resolution important!

Improve CMS Jet & MET resolution using full detector

Courtesy: Rick Cavanaugh

Missing transverse energy

MET: the garbage collector

- You need to understand EVERYTHING in your detector before you can understand missing energy!

MET is the absence of energy in your detector

- Important for signals with neutrinos, e.g. τ ,W, Z, t
- Important for beyond the SM signals like dark matter!

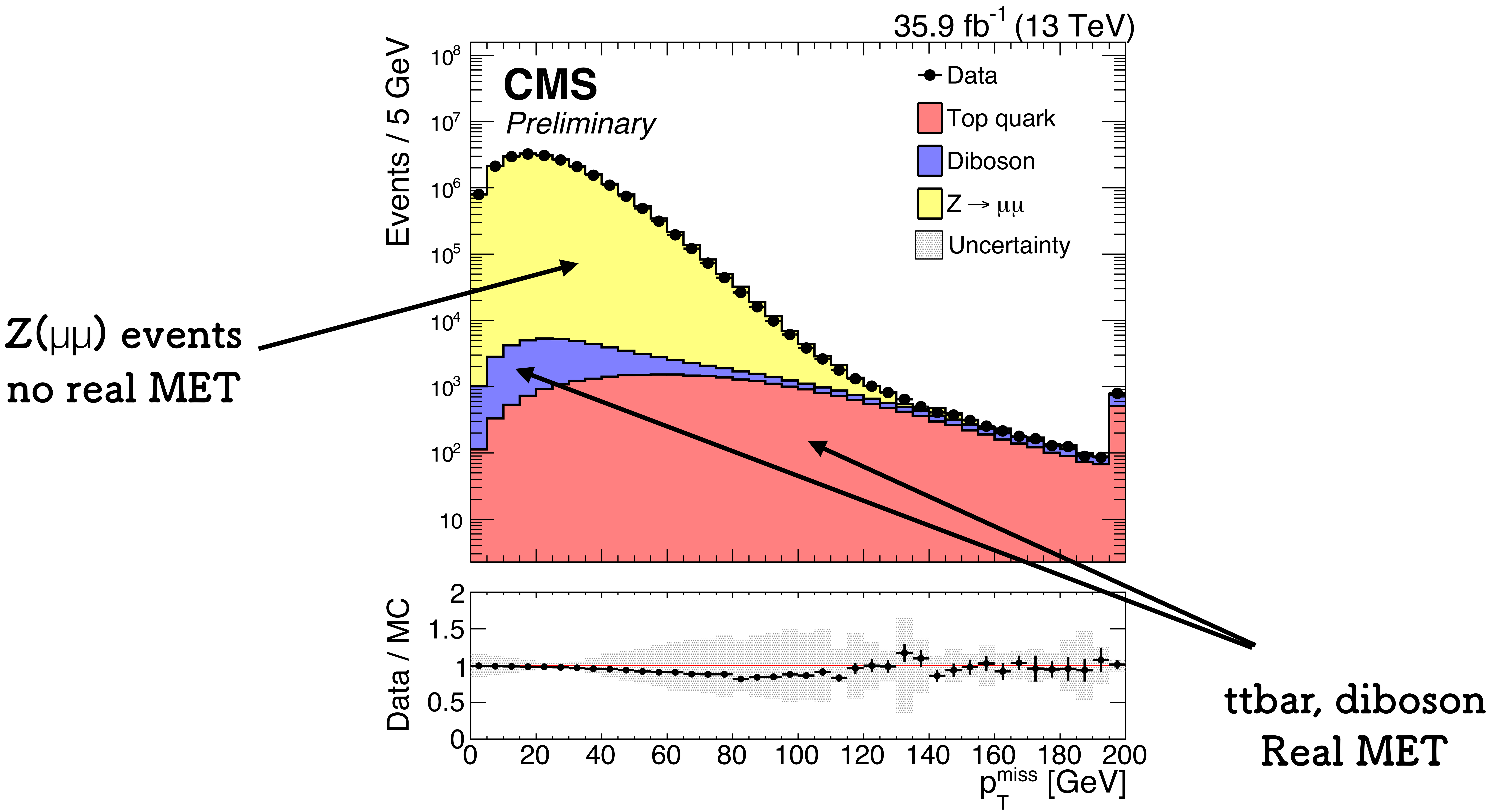
Important:

- **MET resolution** - how well can you measure the energy of everything else without creating imbalances?
  - Physics: missing energy coming from resonances like ttbar

- **MET tails** - how well can you understand the rare/pathological things in your reconstruction
  - Physics: non-resonant, high invisible energy like mono-jet

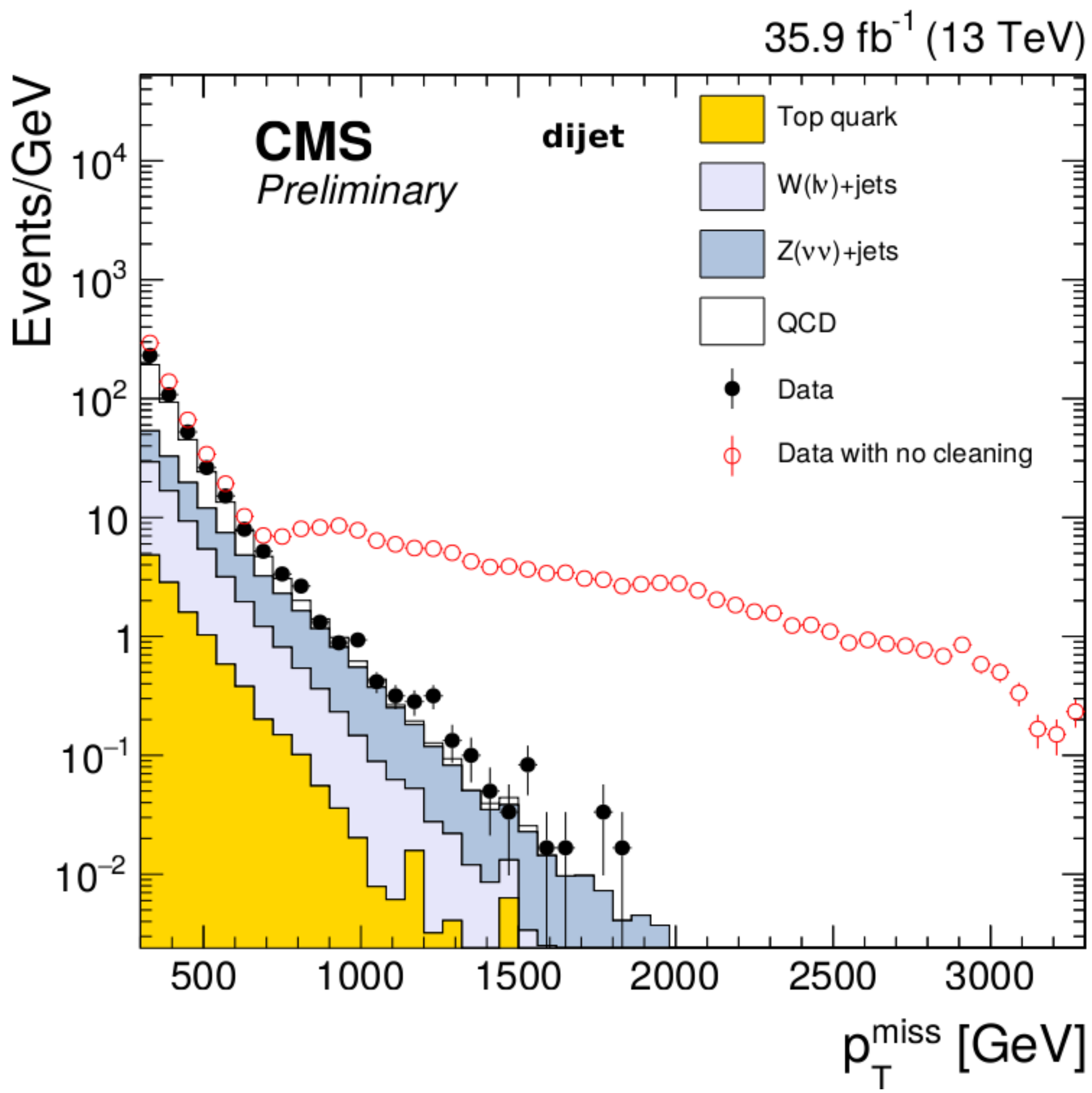
MET Resolution

Core MET resolution vs. real MET tails



The better the MET resolution, the better you can identify real MET

Driven by jet resolution and how you hand soft unclustered deposits



Noise cleaning and filtering

cleaning - remove anomalous spikes before doing reconstruction

filtering - remove anomalous events from the dataset

Sources:

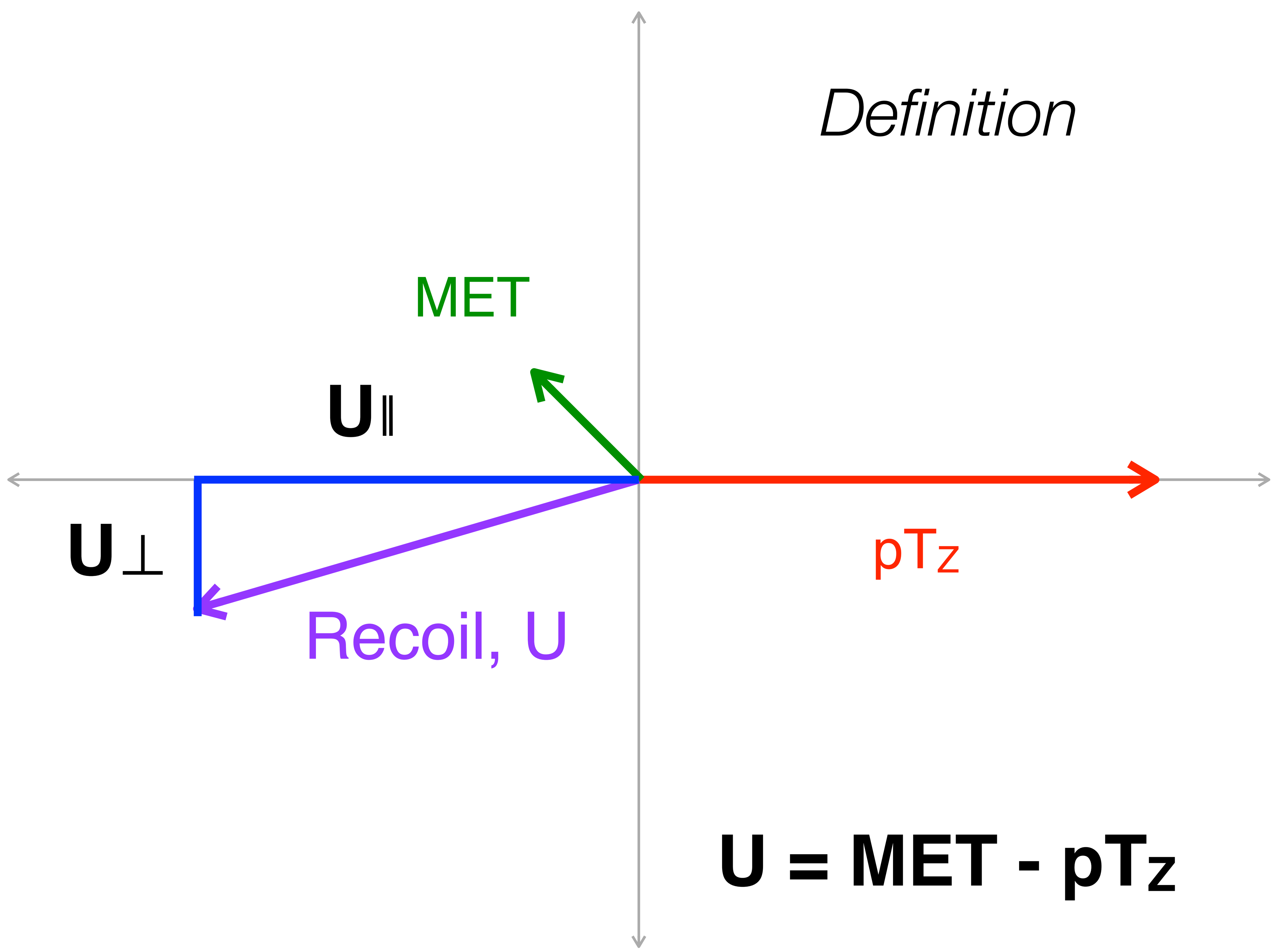
Electronics/detector noise, e.g. spurious interactions with photodectors

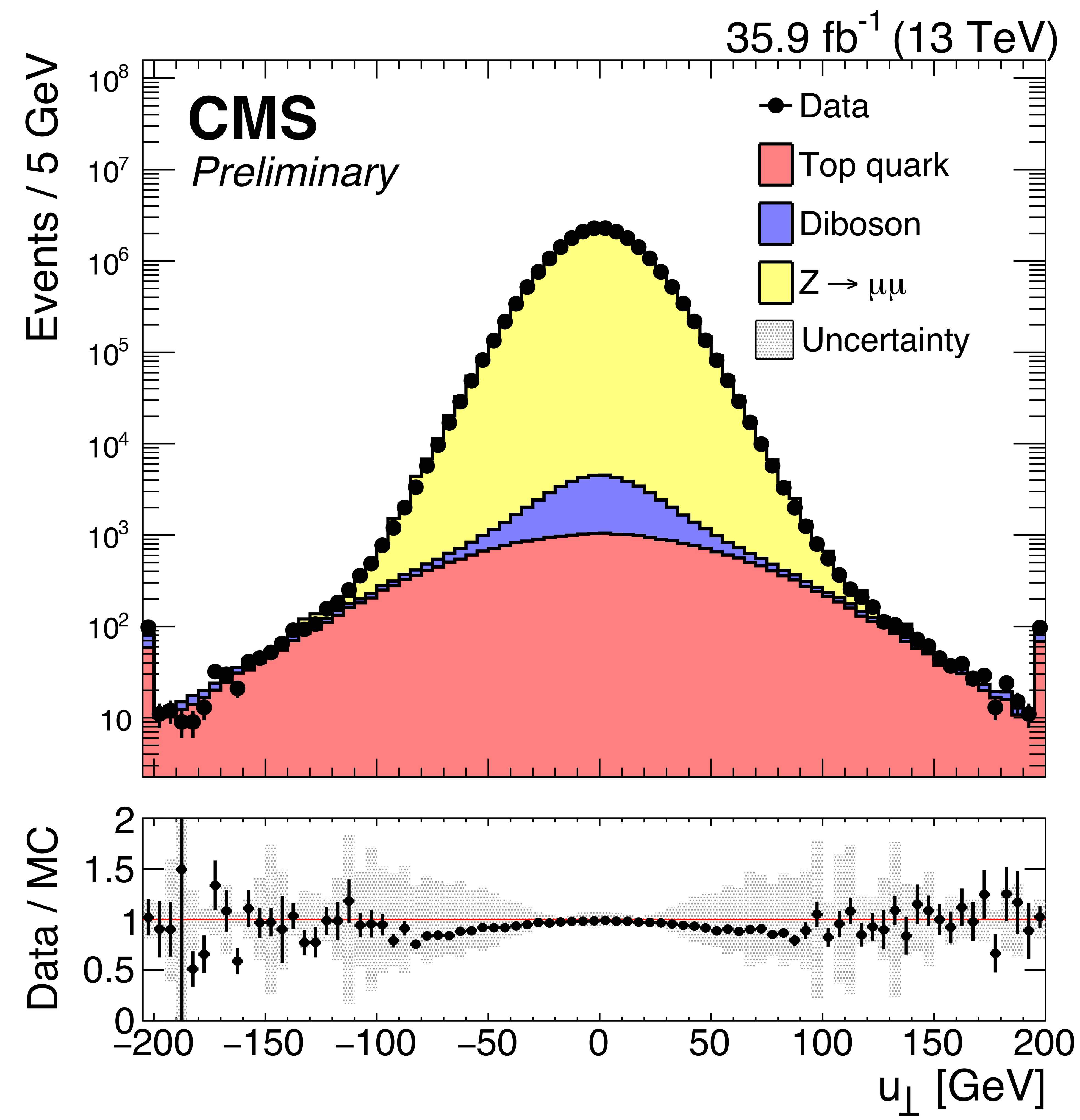
Physics signals like beam halo muons

Reconstruction effects, poorly id'ed low pT muons

MET VALIDATION IN DATA

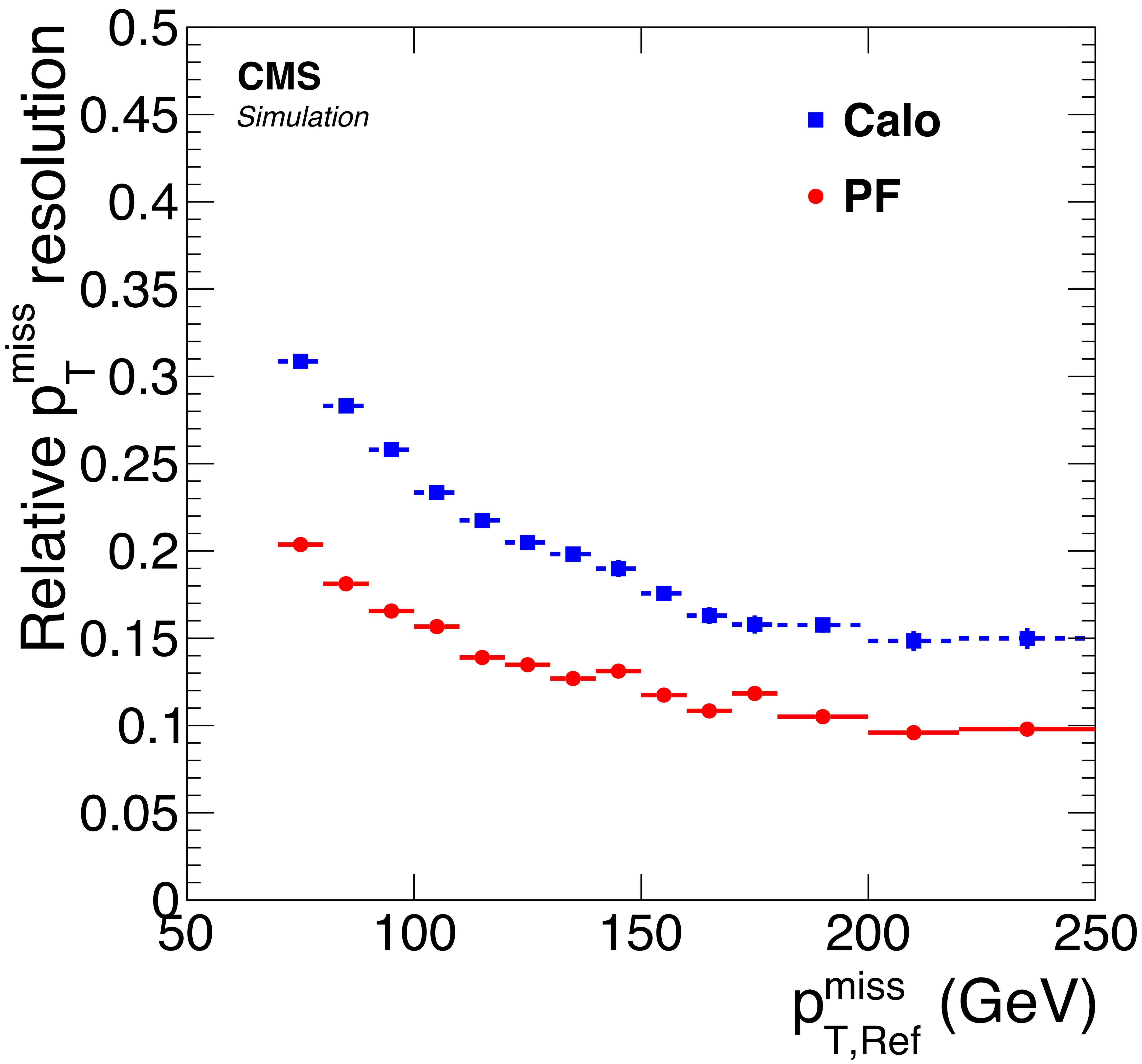
Use Drell-Yan events where a well-measured Z boson can be treated as MET to understand the recoil



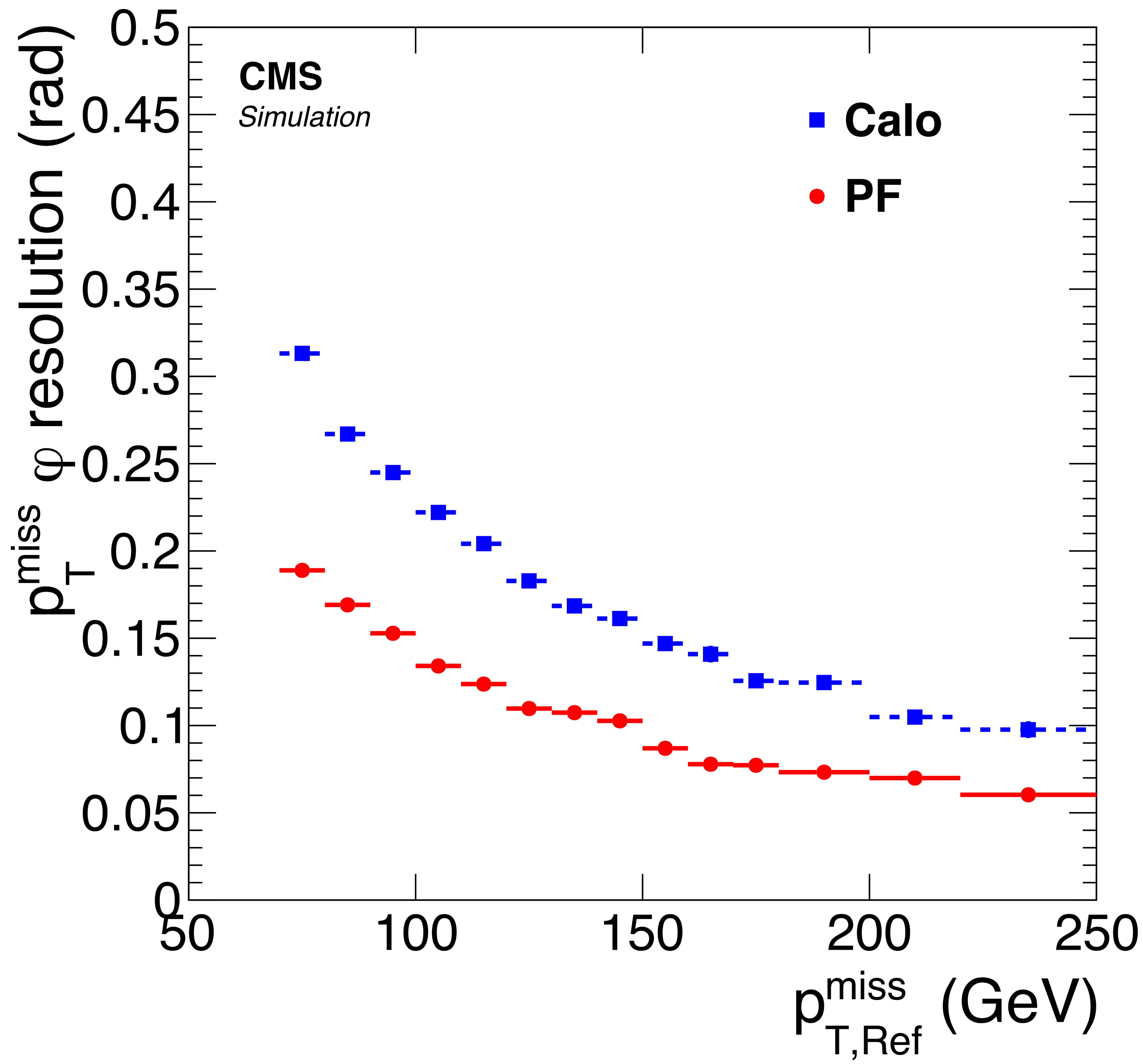


Particle Flow MET

scale resolution



angular resolution



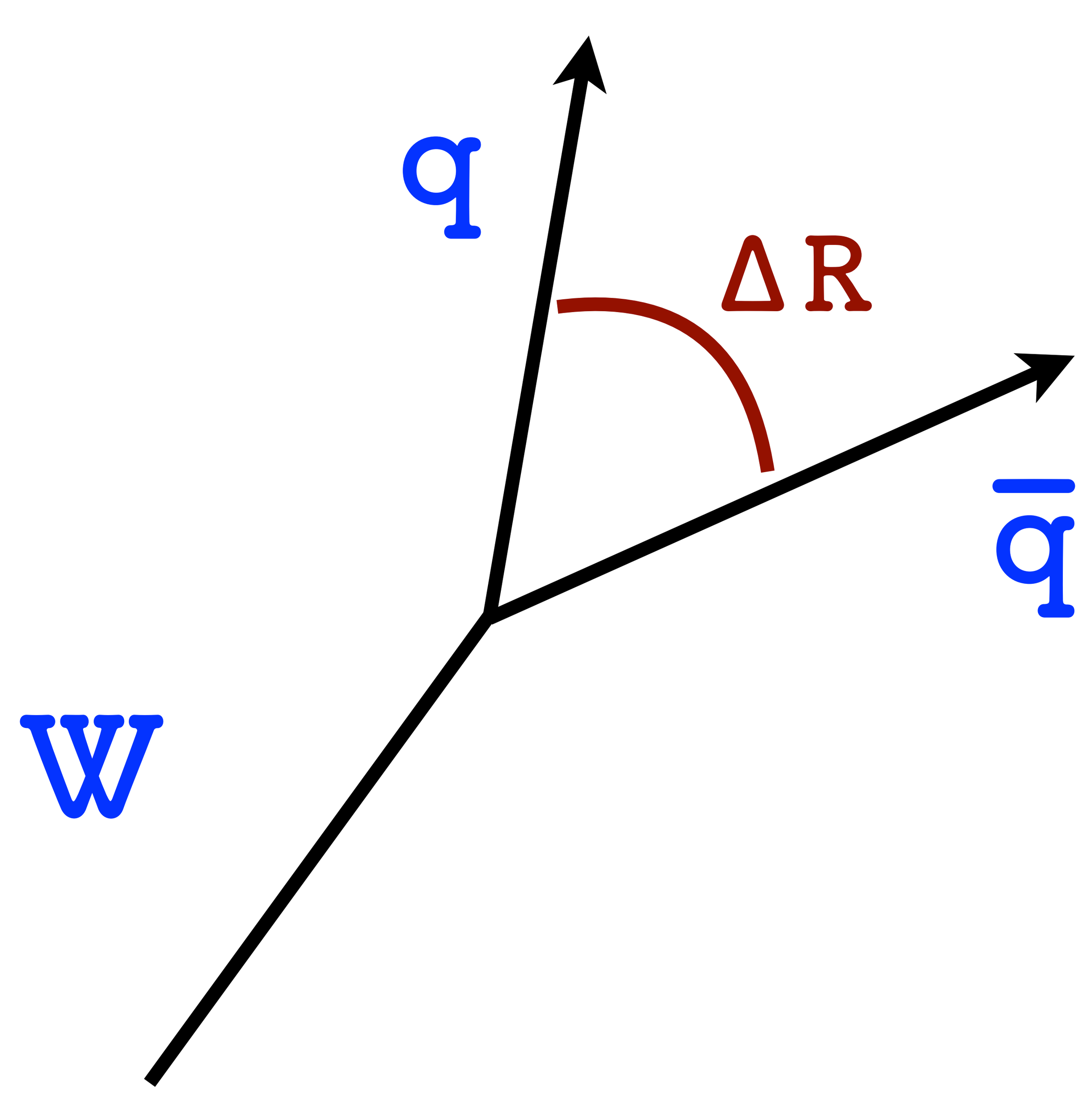
Jet substructure

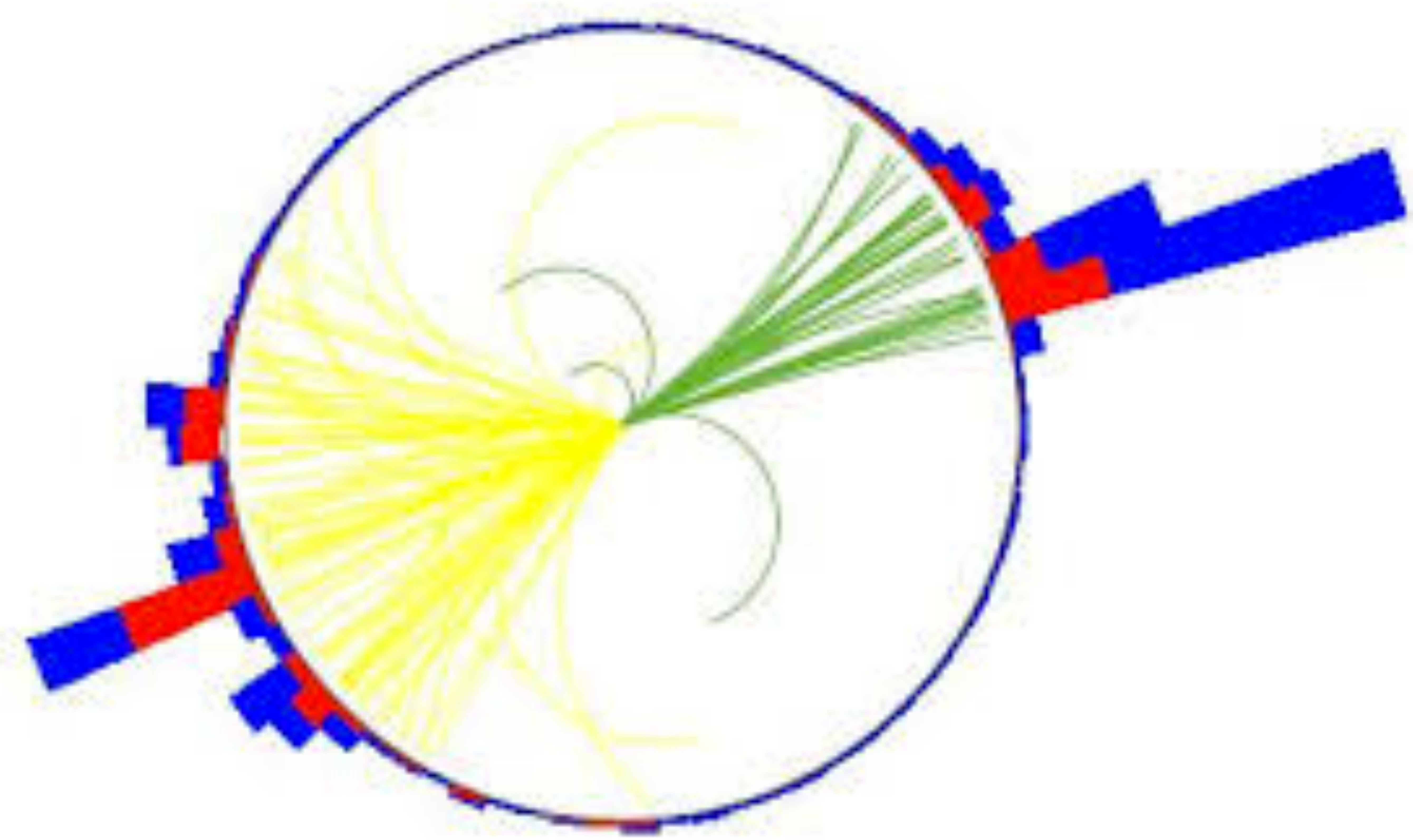
Finding structure in QCD radiation

At LHC energies, interesting heavy objects can be produced with a lot of boost.

Characteristic angular separation

$\Delta R_{dau} = 2\ m_{mother} / p_{T,mother}$





HIGH MASS RESONANCES

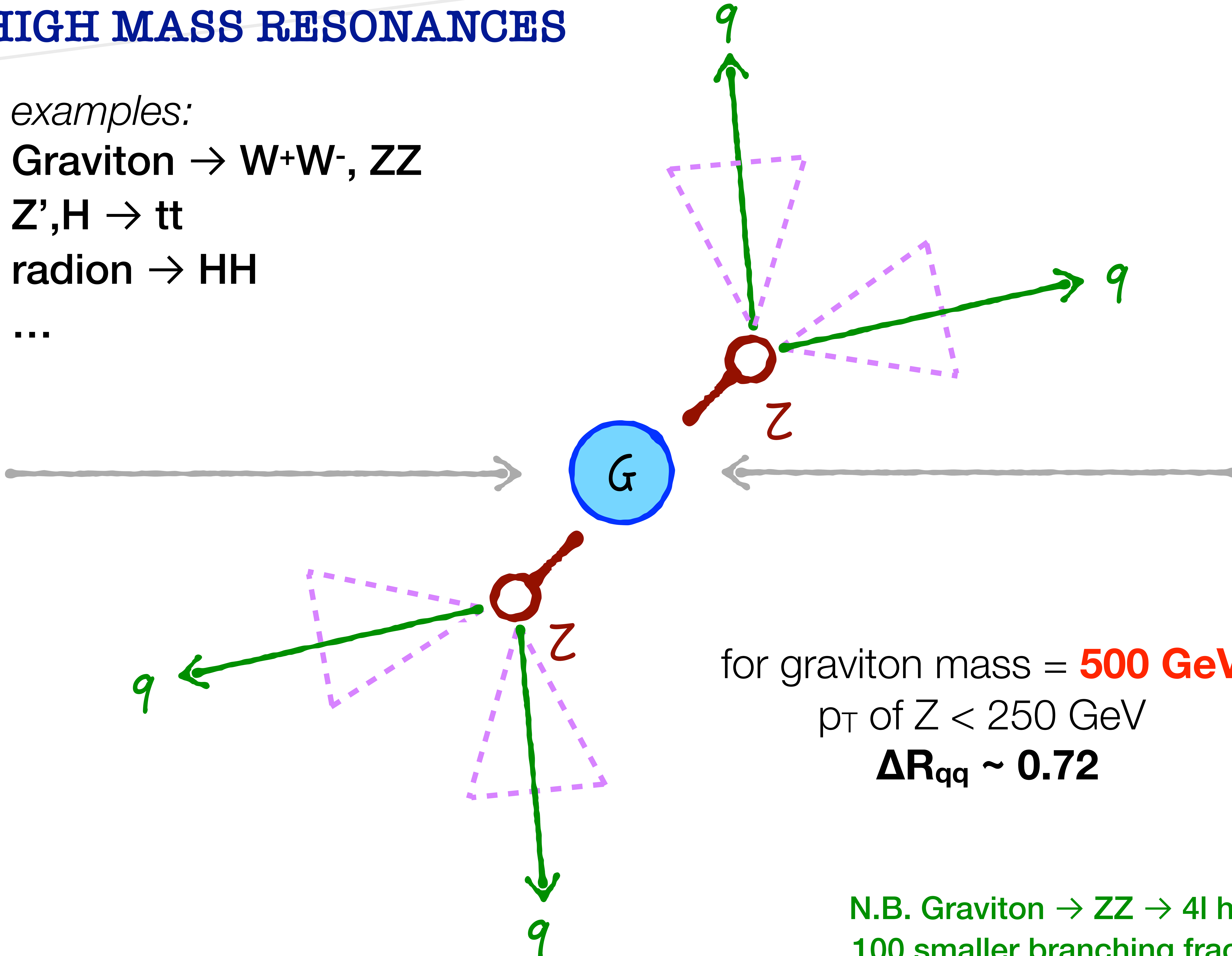
examples:

Graviton → W^+W^-, ZZ

Z',H → tt

radion → HH

...



for graviton mass = **500 GeV**

p_T of Z < 250 GeV

ΔR_{qq} ~ 0.72

N.B. Graviton → ZZ → 4l has a 100 smaller branching fraction

HIGH MASS RESONANCES

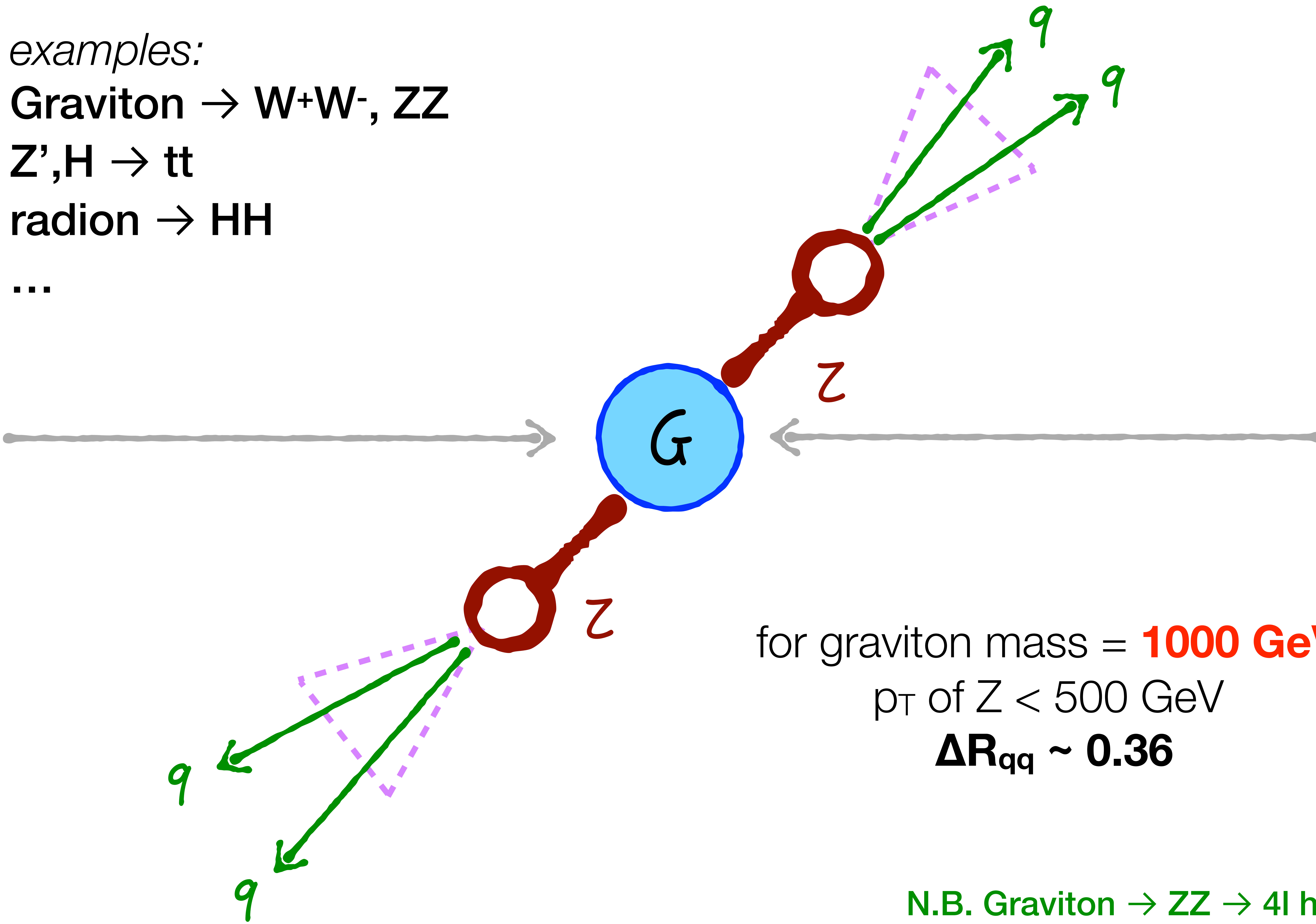
examples:

Graviton → W^+W^-, ZZ

Z',H → tt

radion → HH

…

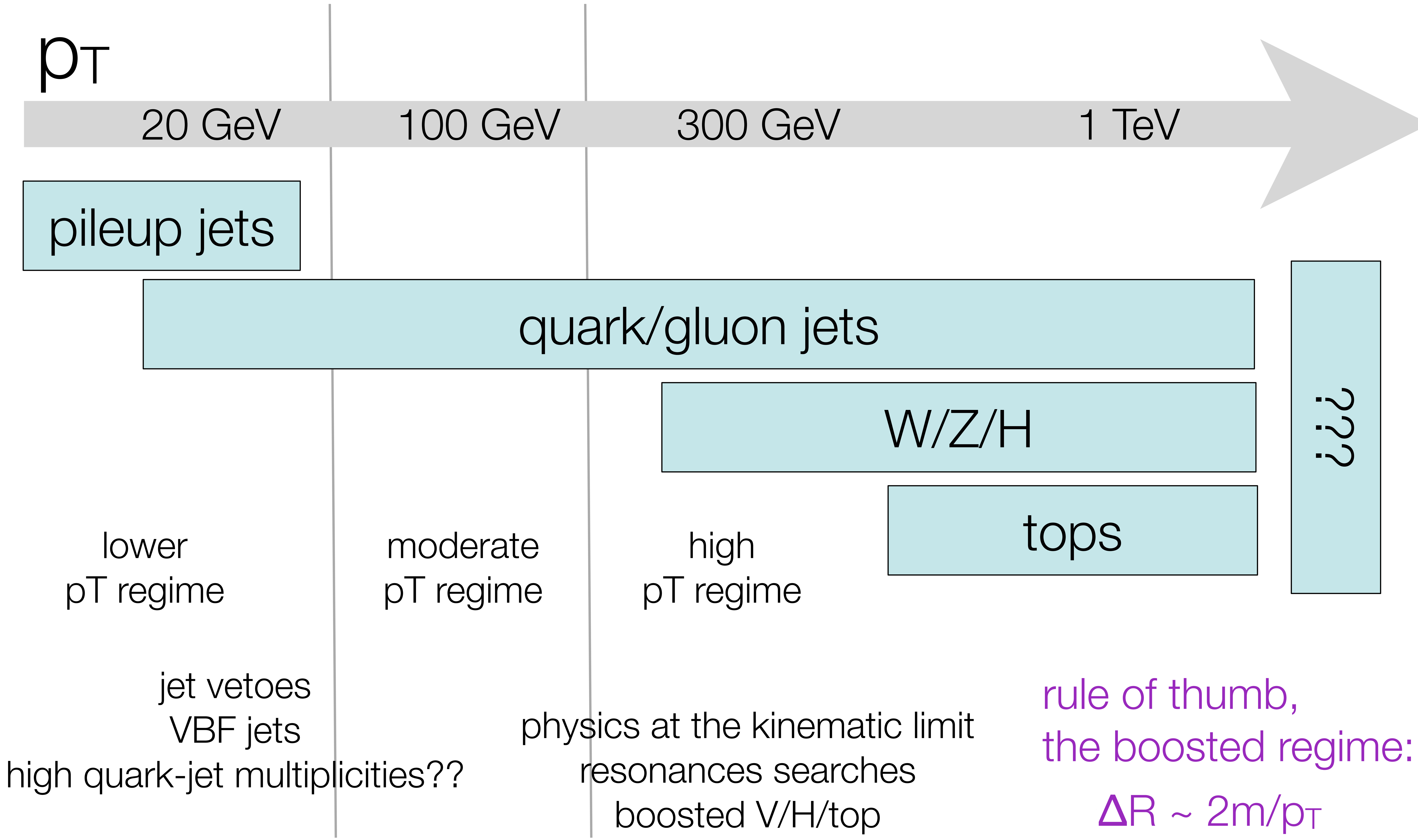


for graviton mass = **1000 GeV**

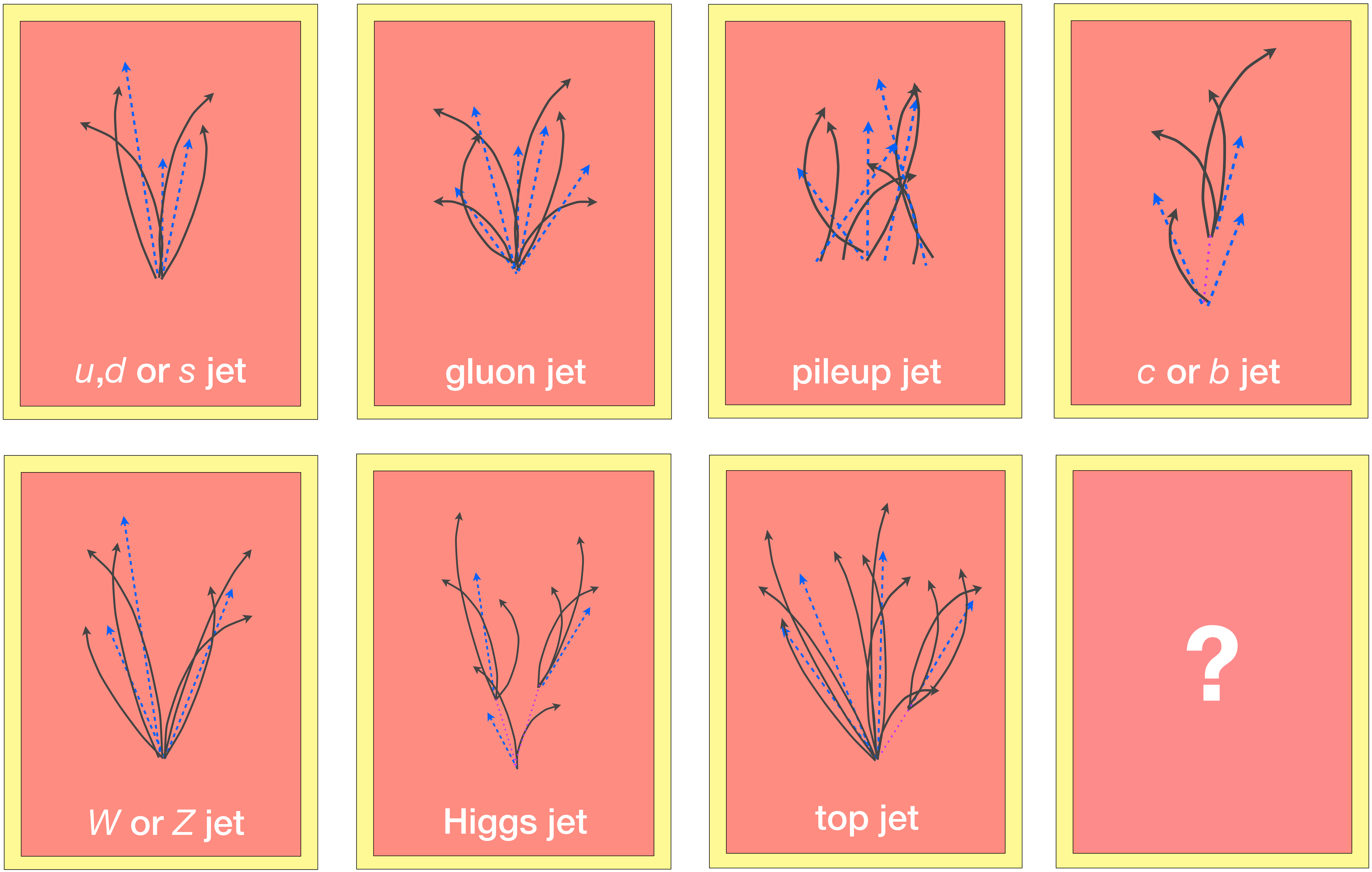
p_T of Z < 500 GeV

ΔR_{qq} ~ 0.36

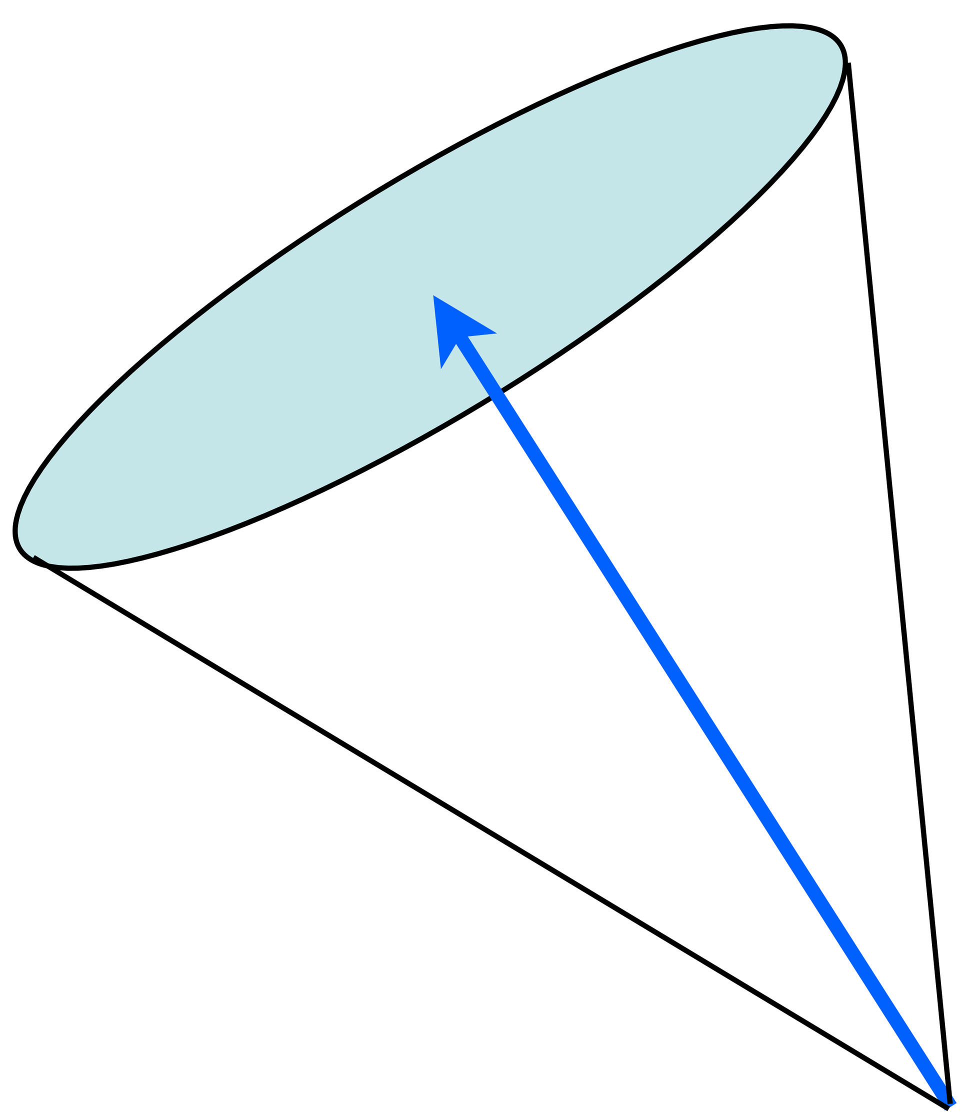
N.B. Graviton → ZZ → 4l has a 100 smaller branching fraction


pT
20 GeV
100 GeV
300 GeV
1 TeV
pileup jets
quark/gluon jets
W/Z/H
tops
???
lower
pT regime
moderate
pT regime
high
pT regime
jet vetoes
VBF jets
high quark-jet multiplicities??
physics at the kinematic limit
resonances searches
boosted V/H/top
rule of thumb,
the boosted regime:
ΔR ~ 2m/pT

Jet substructure



A JET REVOLUTION



udsg/c/b

$\{\eta, \phi, p_T\}$

+

{tracking}

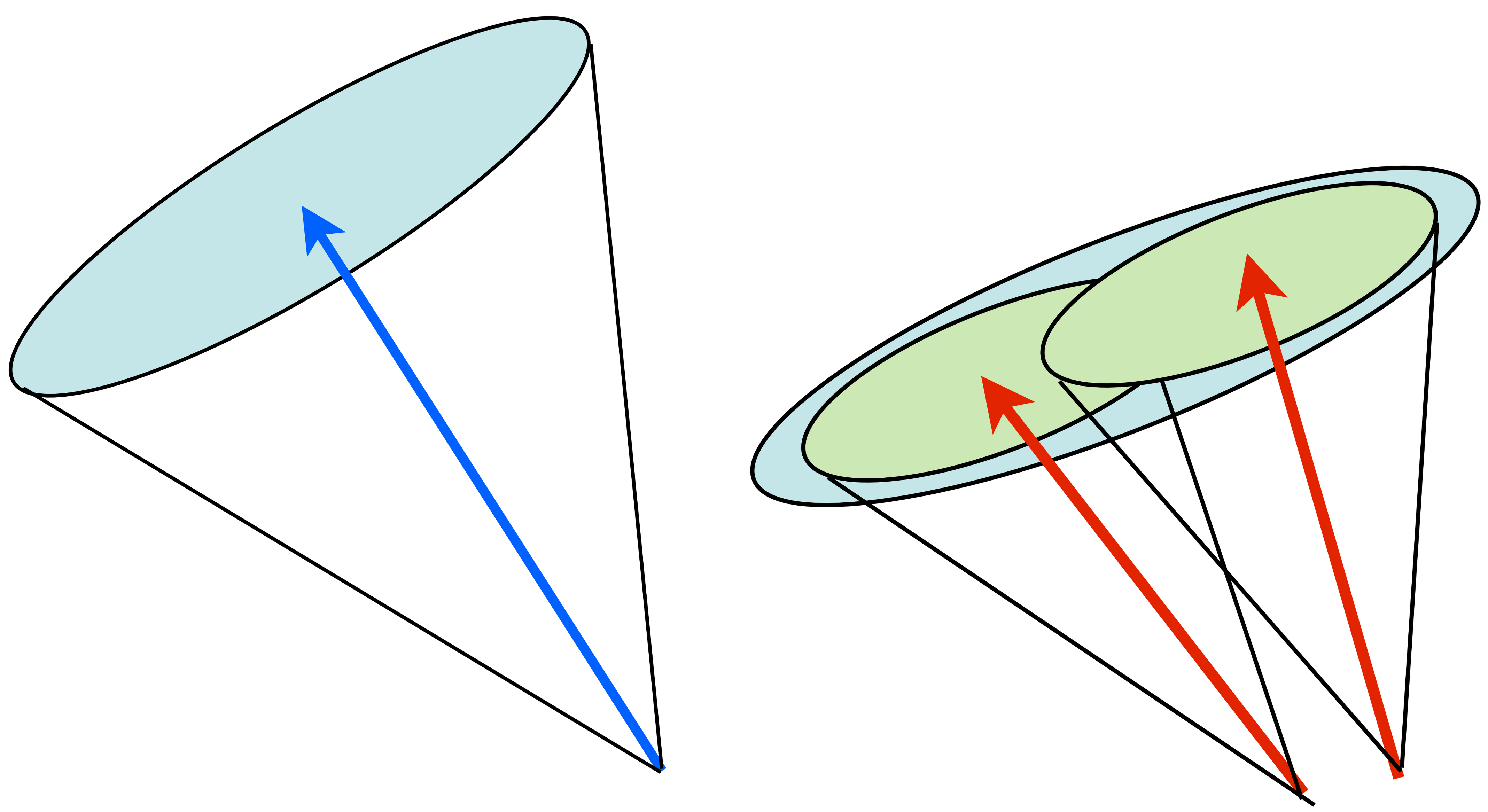
"flavor"-tagging:

b-tagging

c-tagging

uds-tagging

A JET REVOLUTION



u/ds/g/c/b/W/Z/H/t/pu

quantum numbers:
color charge (quarks vs. gluons)
electric charge
spin

An explosion in the field of jet substructure and properties!

$\{\eta, \phi, p_T\}$
+
{tracking}
+
{m,shapes,subjets}

"flavor"-tagging:
b-tagging
c-tagging
u/ds-tagging
top-tagging
W/Z/H-tagging
pileup-tagging

Jets with displaced vertices

Displacement ~ > O(mm) scale

OBSERVABLES

pT, η , ϕ + tracking

mass

4-vector sum of jet constituents

highly sensitive to soft QCD and pileup; grooming can be used to mitigate these dependencies

substructure

several classes: declustering/reclustering, generalized jet shapes and energy flow, statistical interpretation, jet charge

algorithms

some combination of cuts on mass, shapes, tracking

most typical in top tagging

And nowadays ... machine learning too!

OBSERVABLES

pT, η , ϕ + tracking

mass

4-vector sum of jet constituents

highly sensitive to soft QCD and pileup; grooming can be used to mitigate these dependencies

substructure

several classes: declustering/reclustering, generalized jet shapes and energy flow, statistical interpretation, jet charge

algorithms

some combination of cuts on mass, shapes, tracking

most typical in top tagging

And nowadays ... machine learning too!

challenge: modeling the QCD backgrounds is hard!

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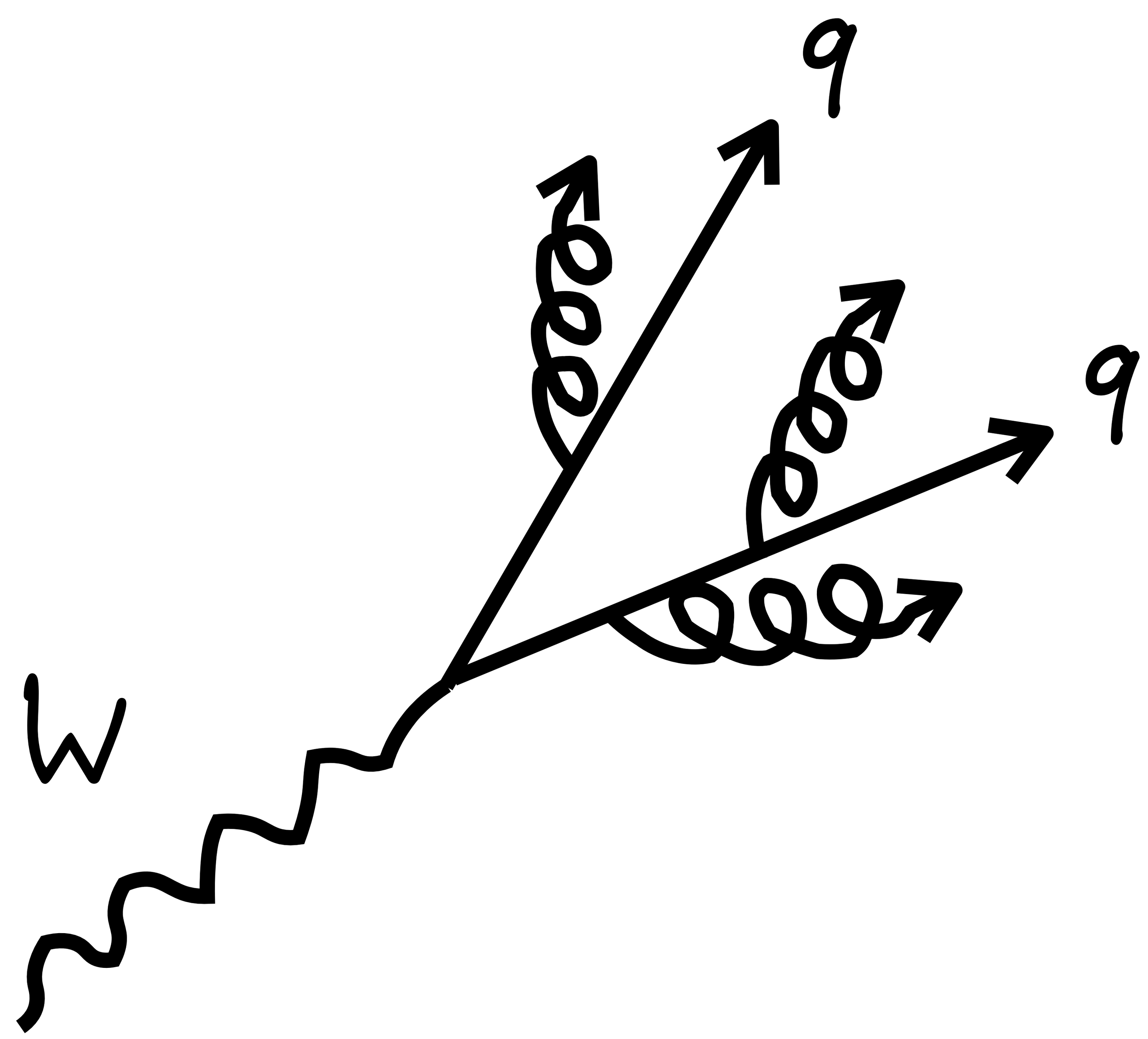
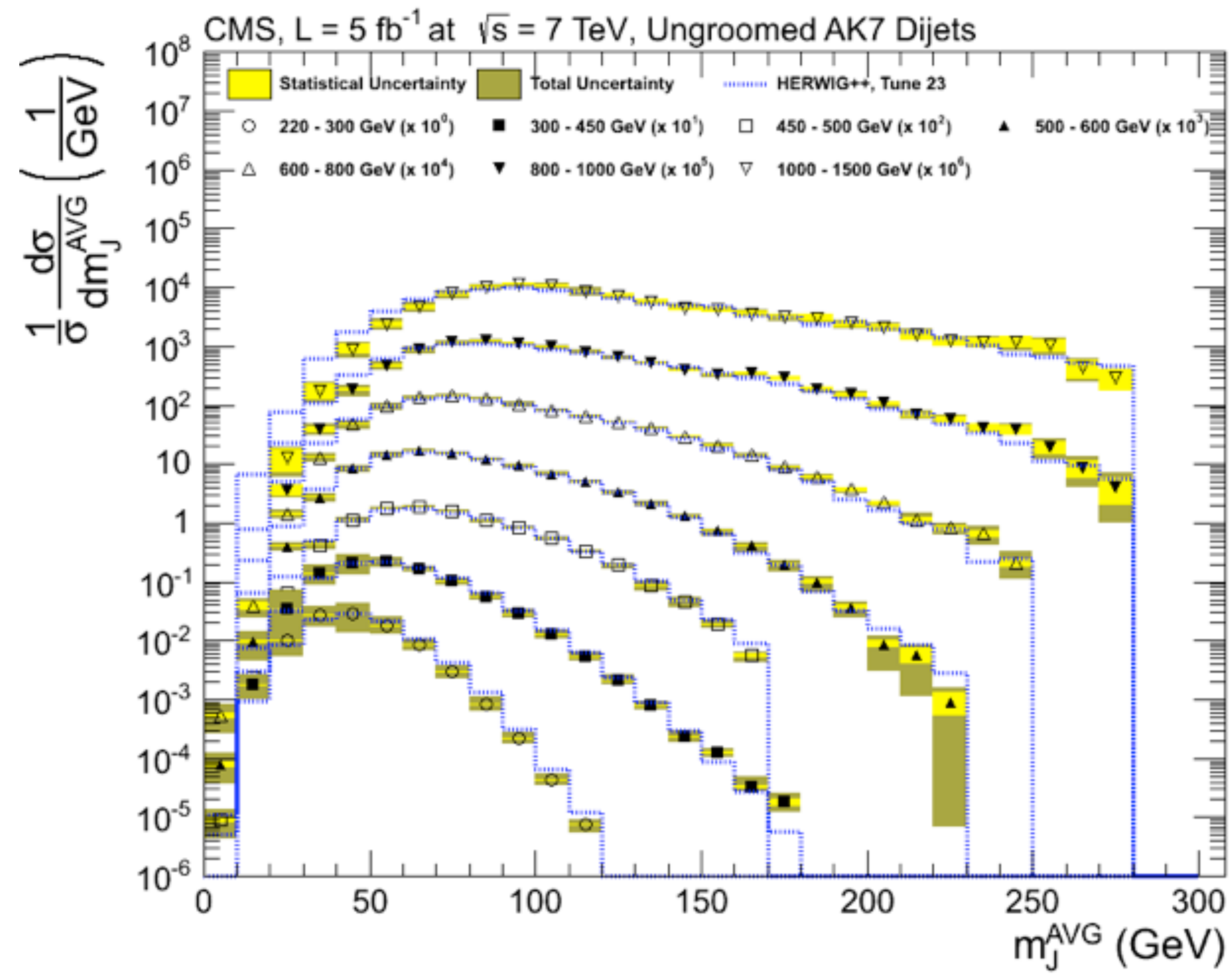
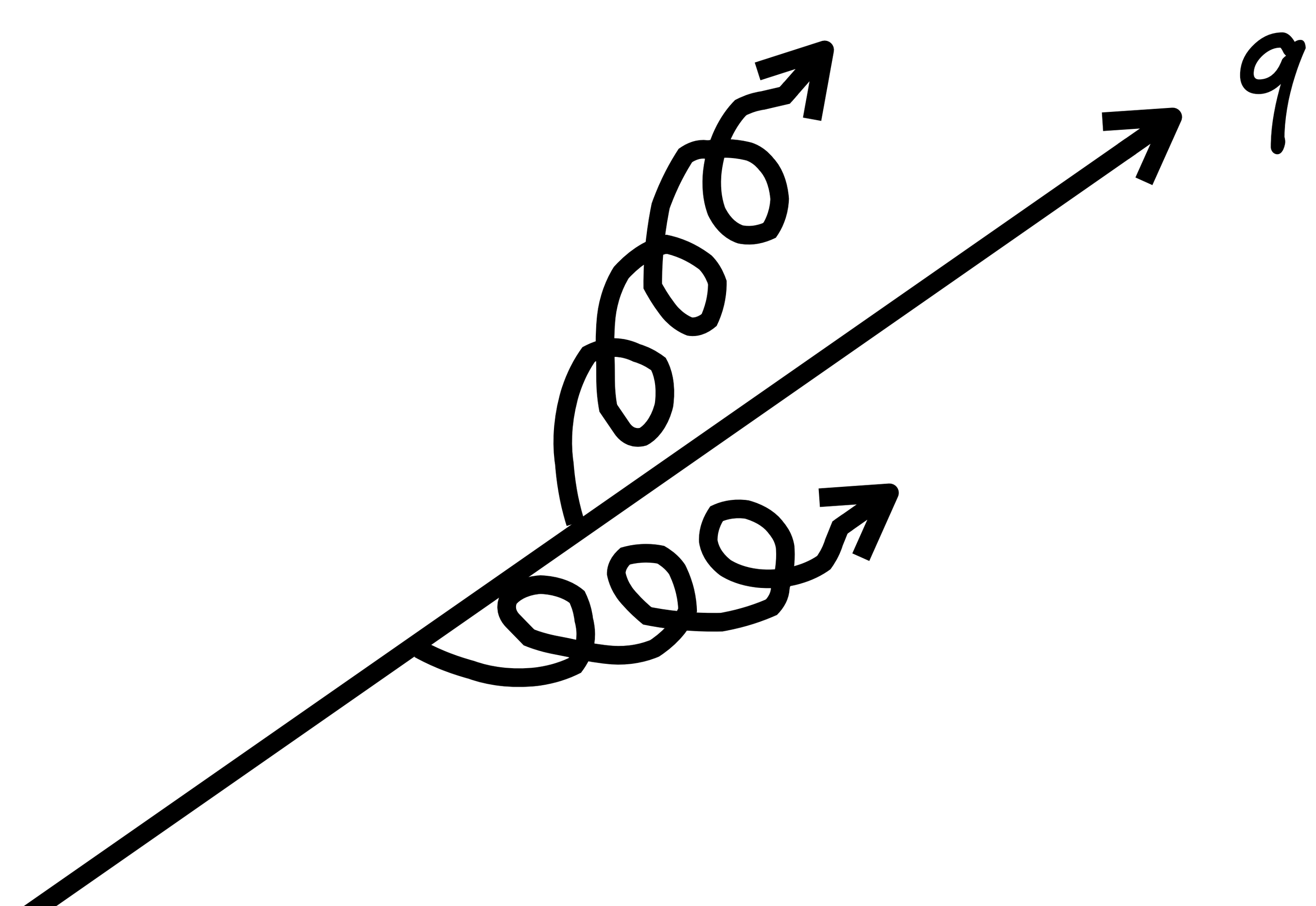
but jet mass is a perturbative quantity



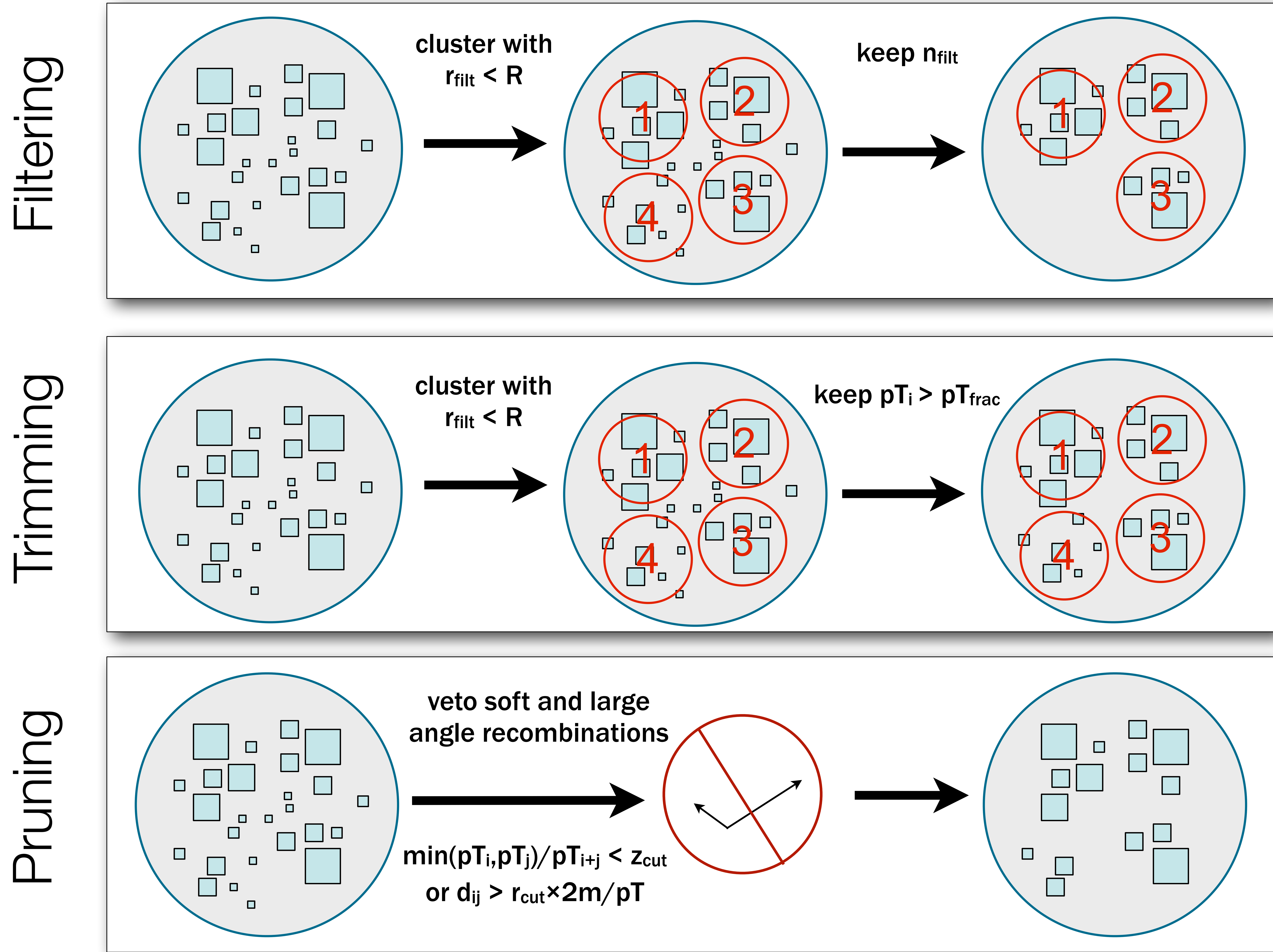




$$\langle M^2 \rangle \simeq \left.\begin{array}{ll} \text{quarks:} & 0.16 \\ \text{gluons:} & 0.37 \end{array}\right\} \times \alpha_s p_t^2 R^2$$

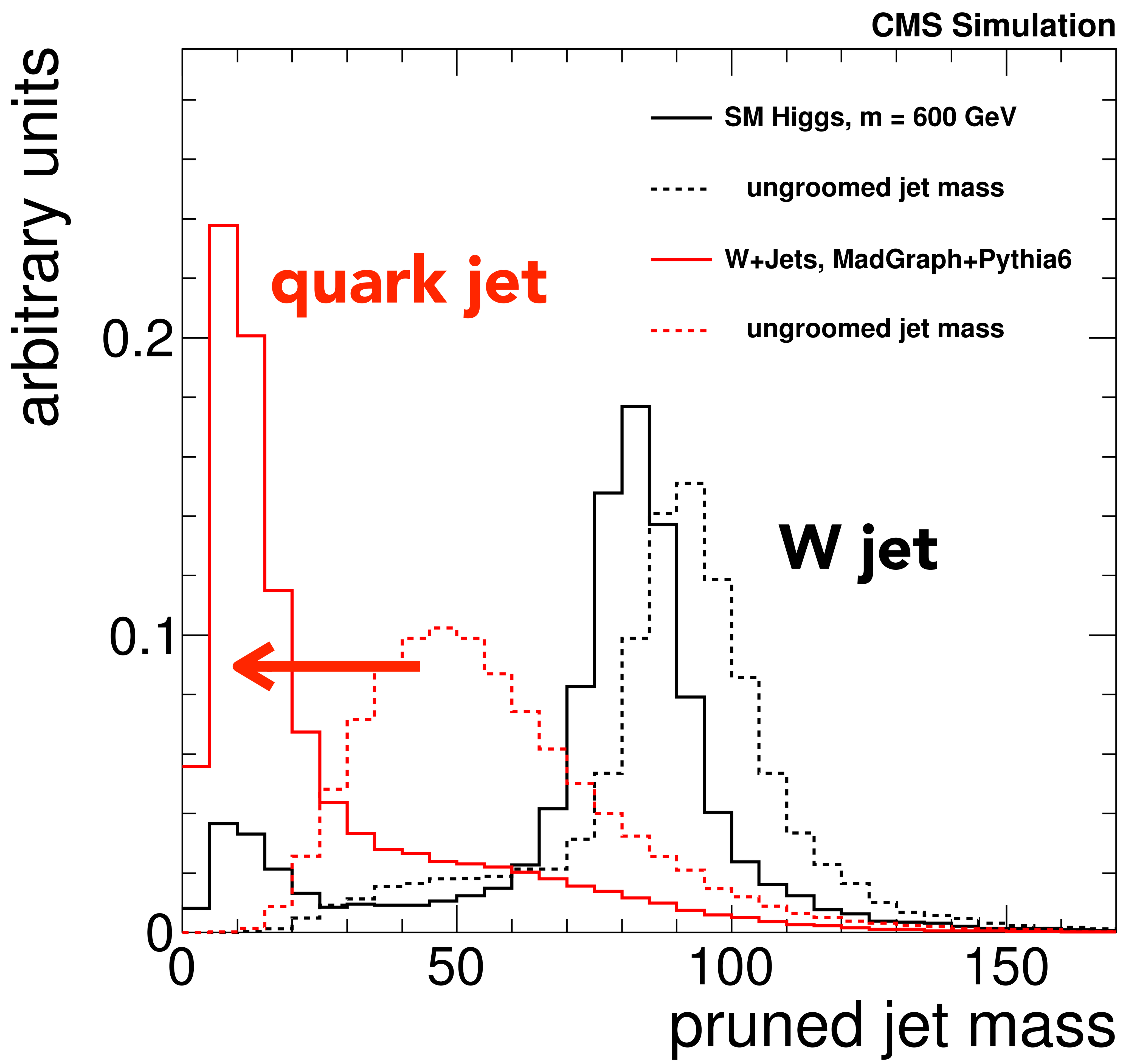
(GROOMED) MASS

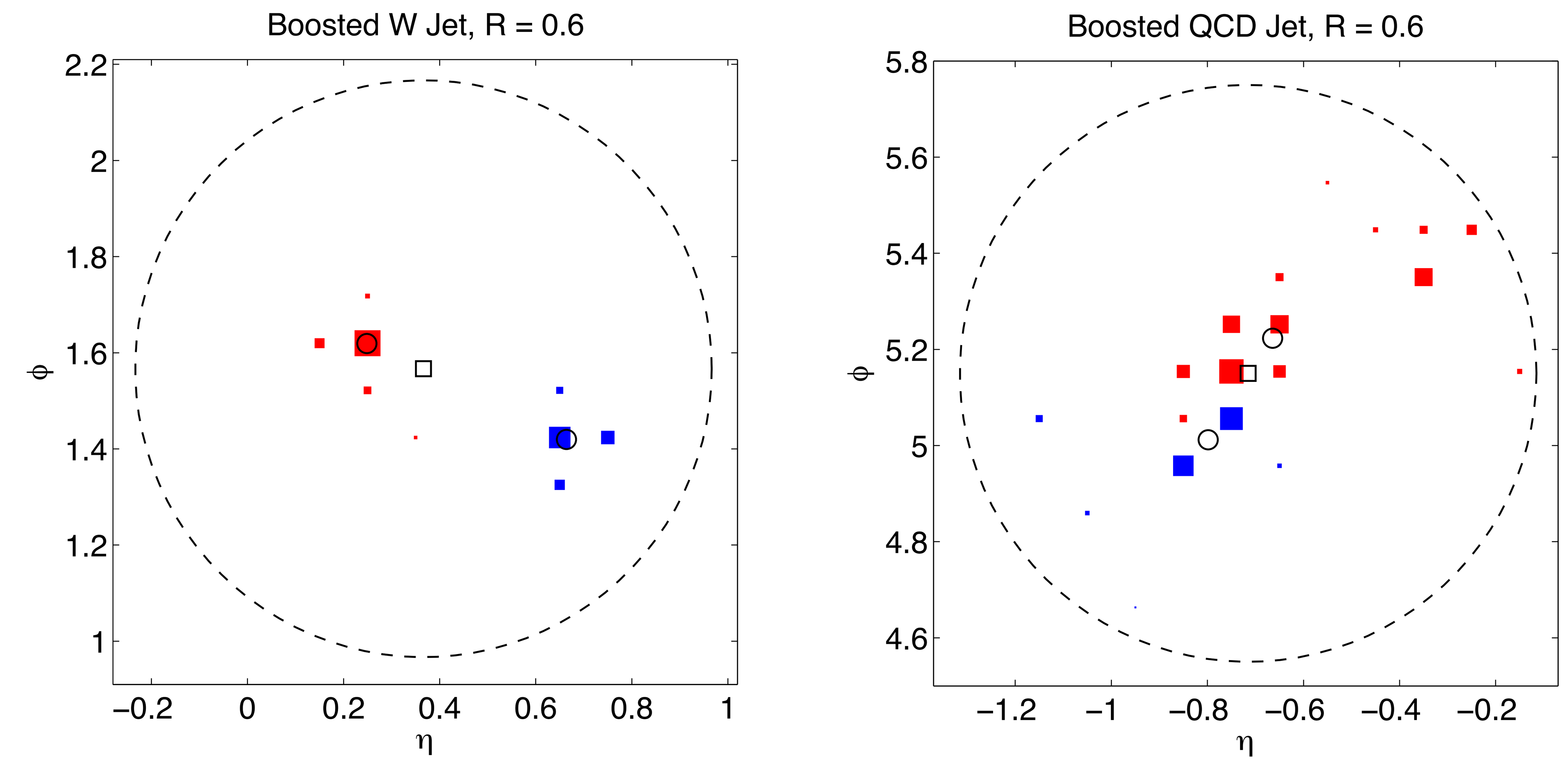
arXiv:0802.2470
arXiv:0912.1342
arXiv:0903.5081



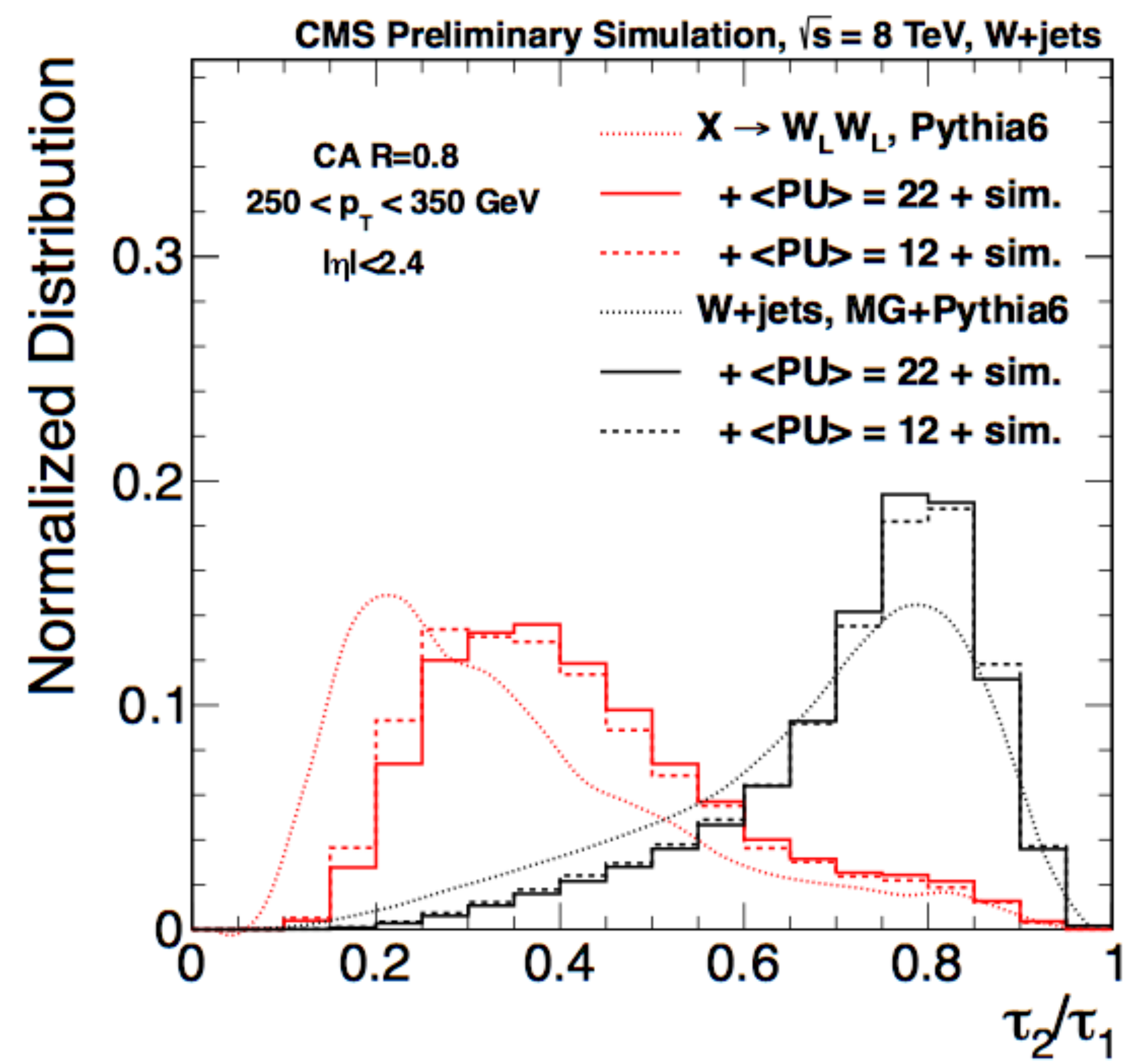
Jet substructure examples

jet (groomed) mass:
a very powerful discriminator





how prong-y are these jets?

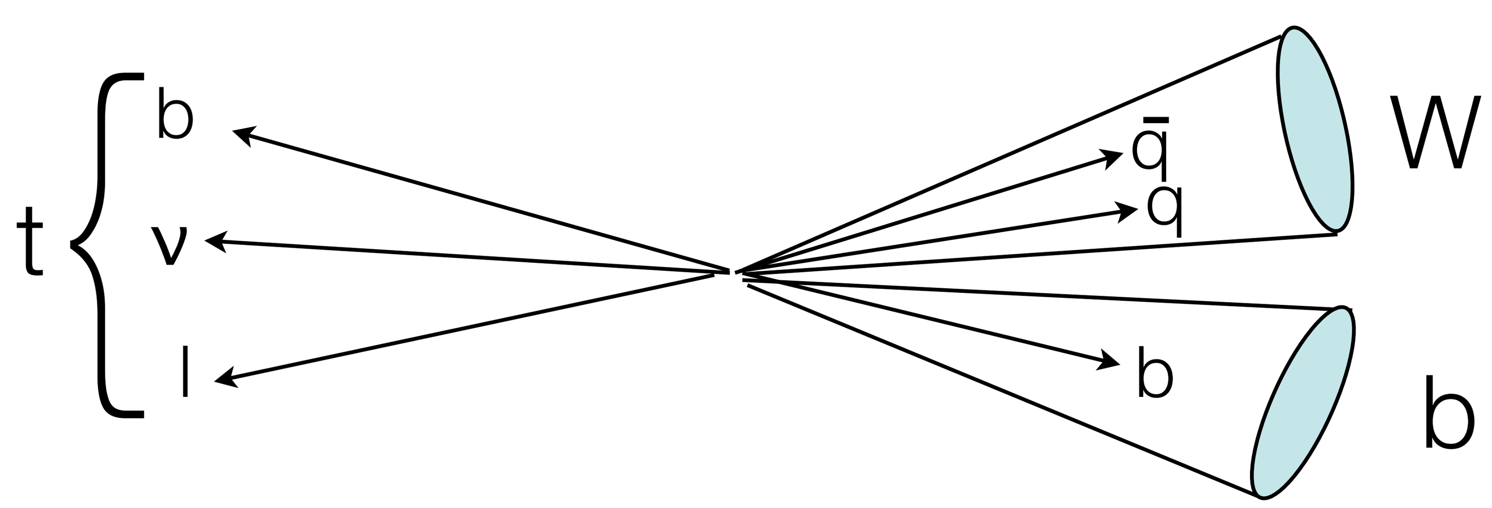


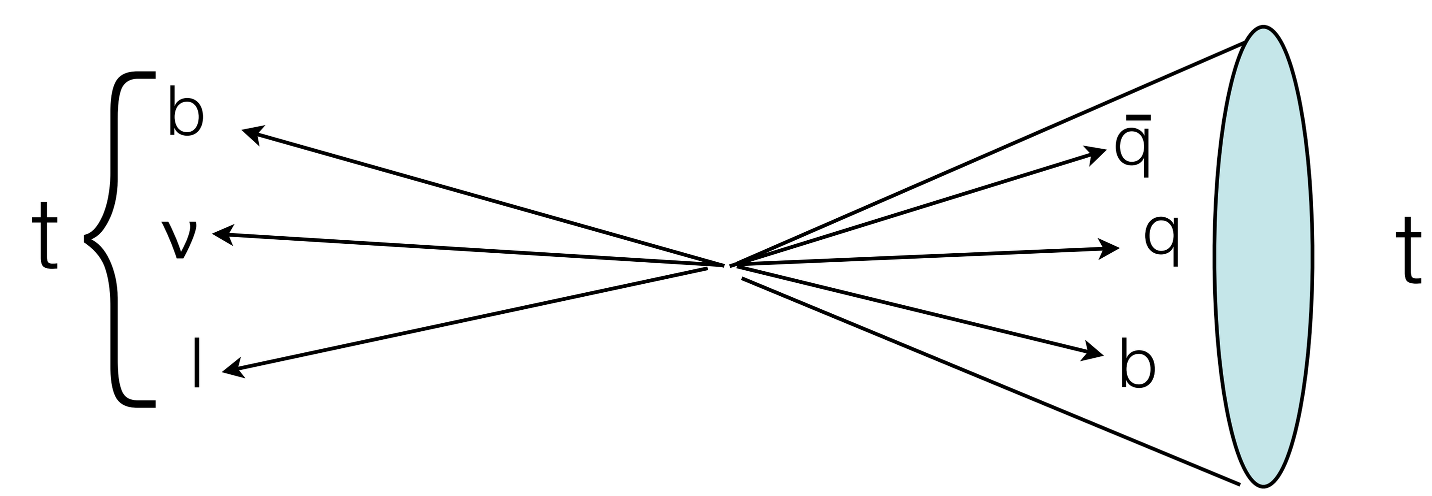
example: N-subjettiness

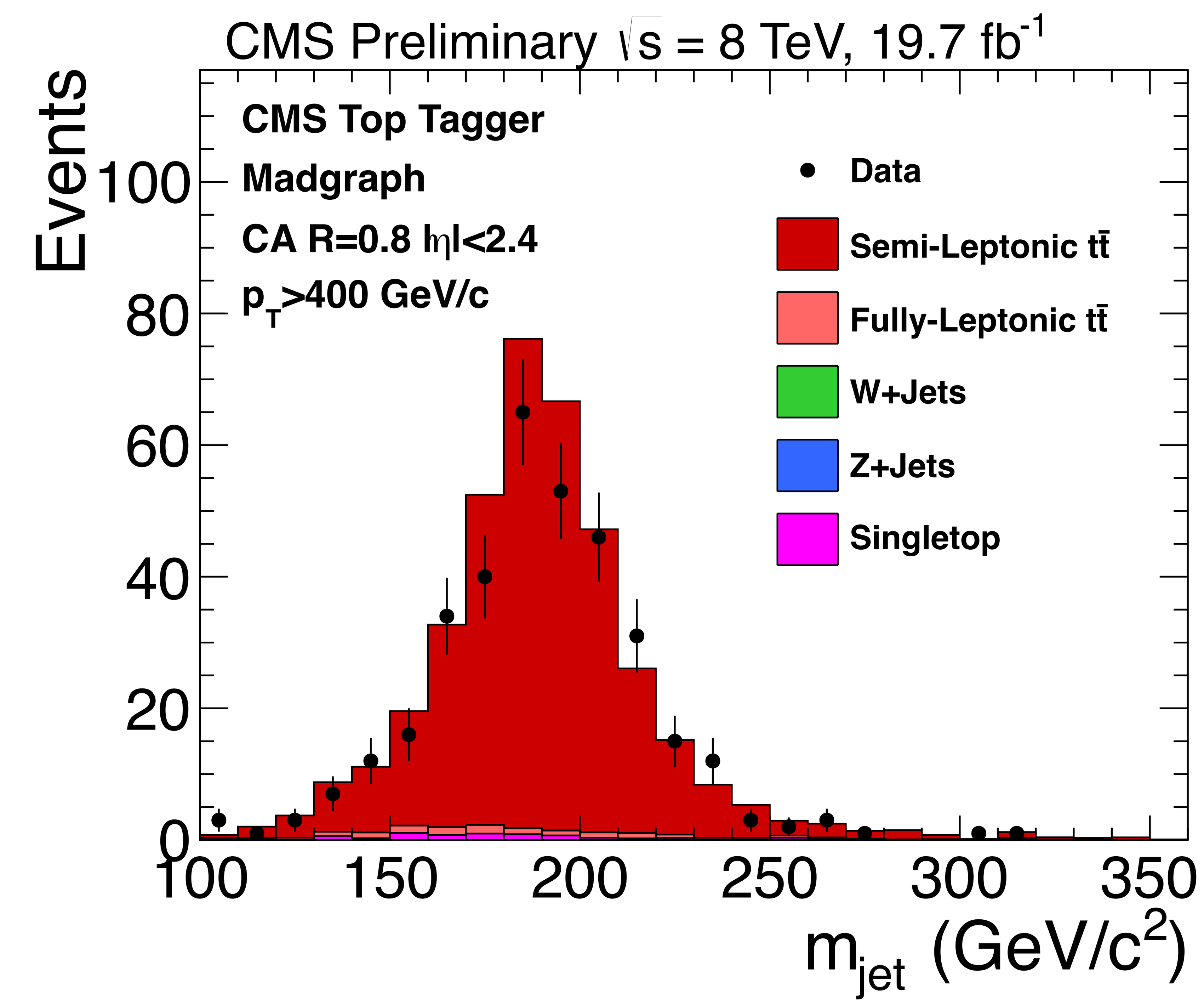
STANDARD CANDLES

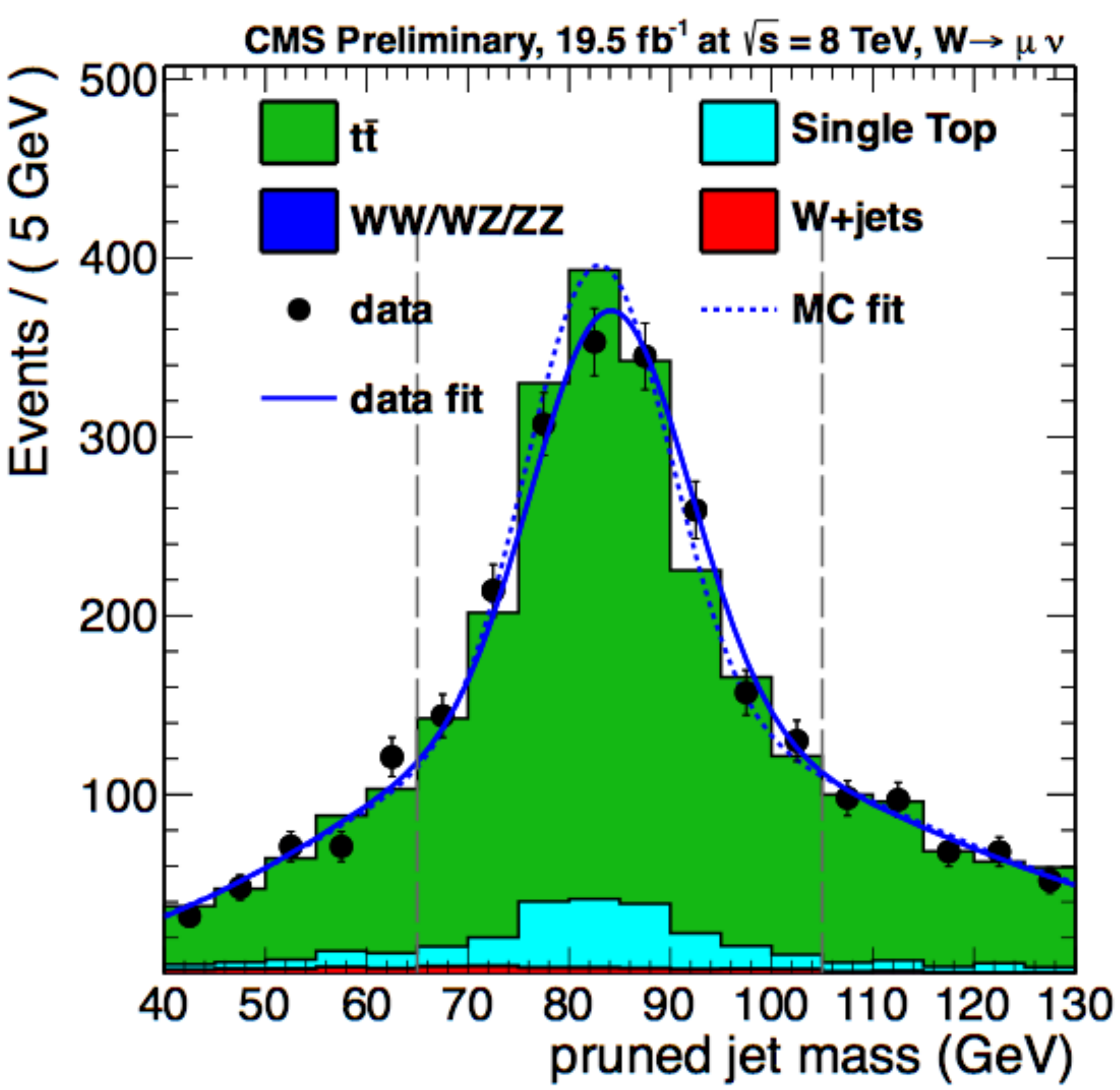
Example:

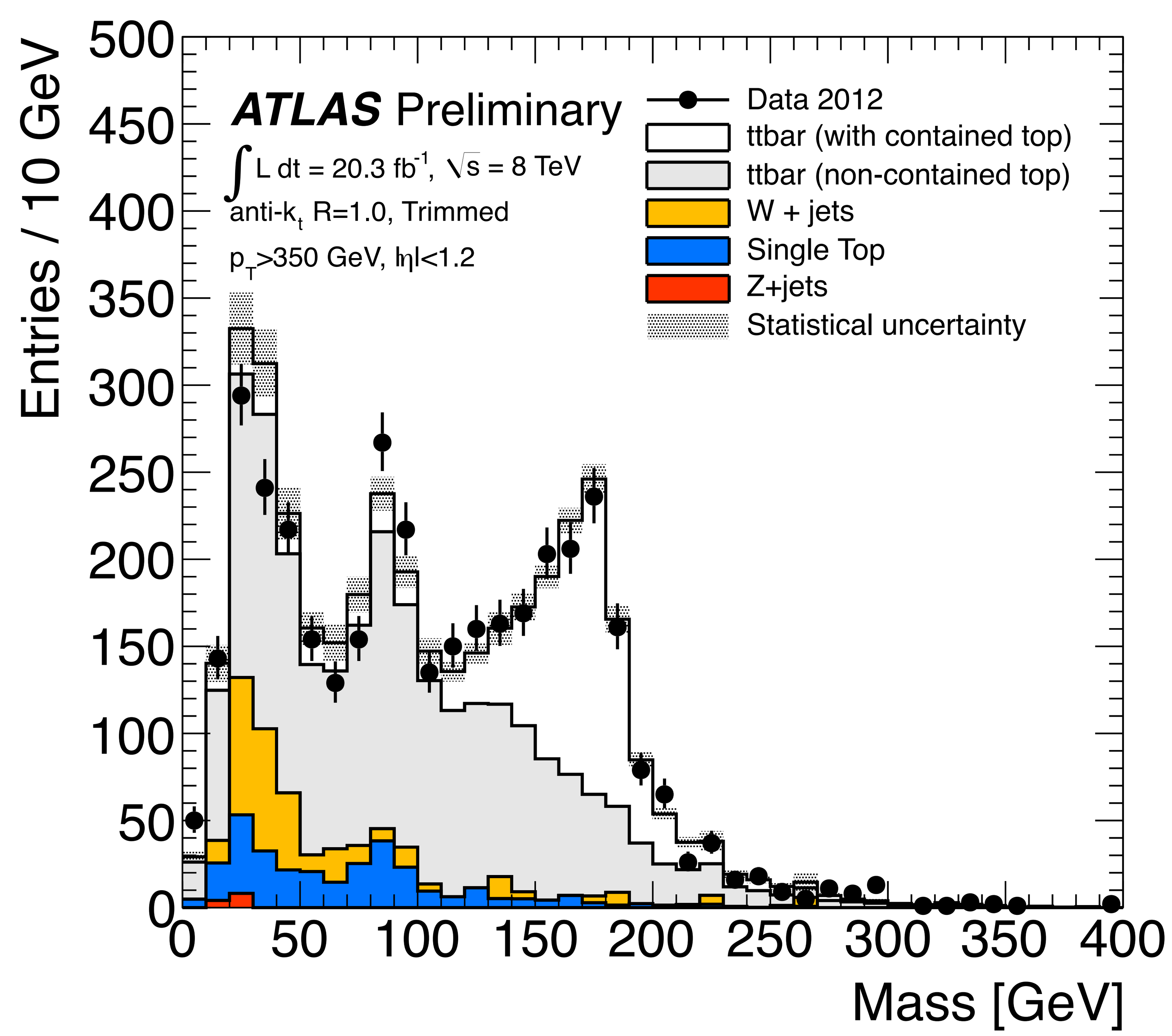
Semi-leptonic tt events are important for validating tagging techniques of heavy objects











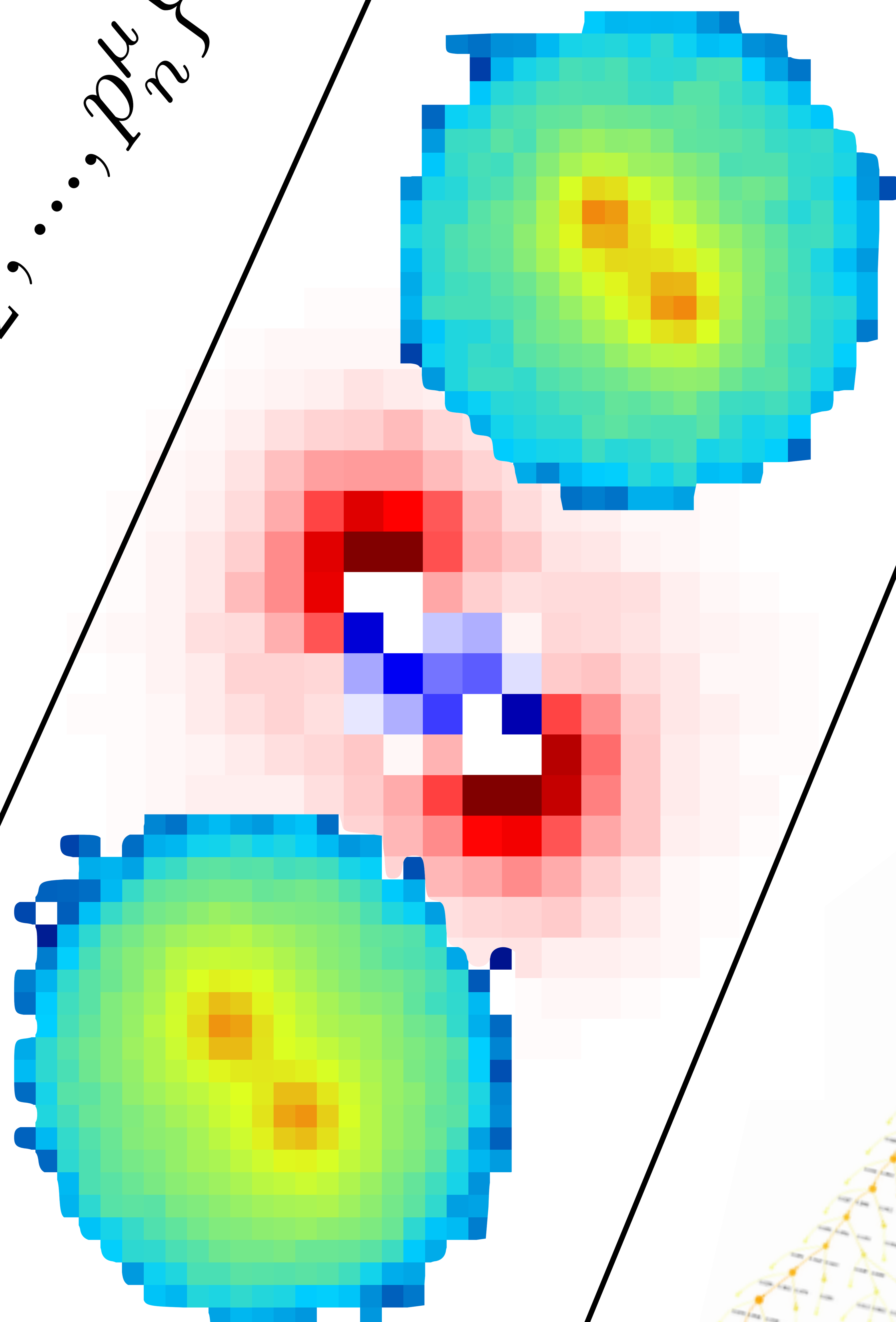
Using events to do evaluate tag-and-probe efficiency **scale factors** and **mass scale/resolution** measurements

Machine learning boom!

Fixed sets

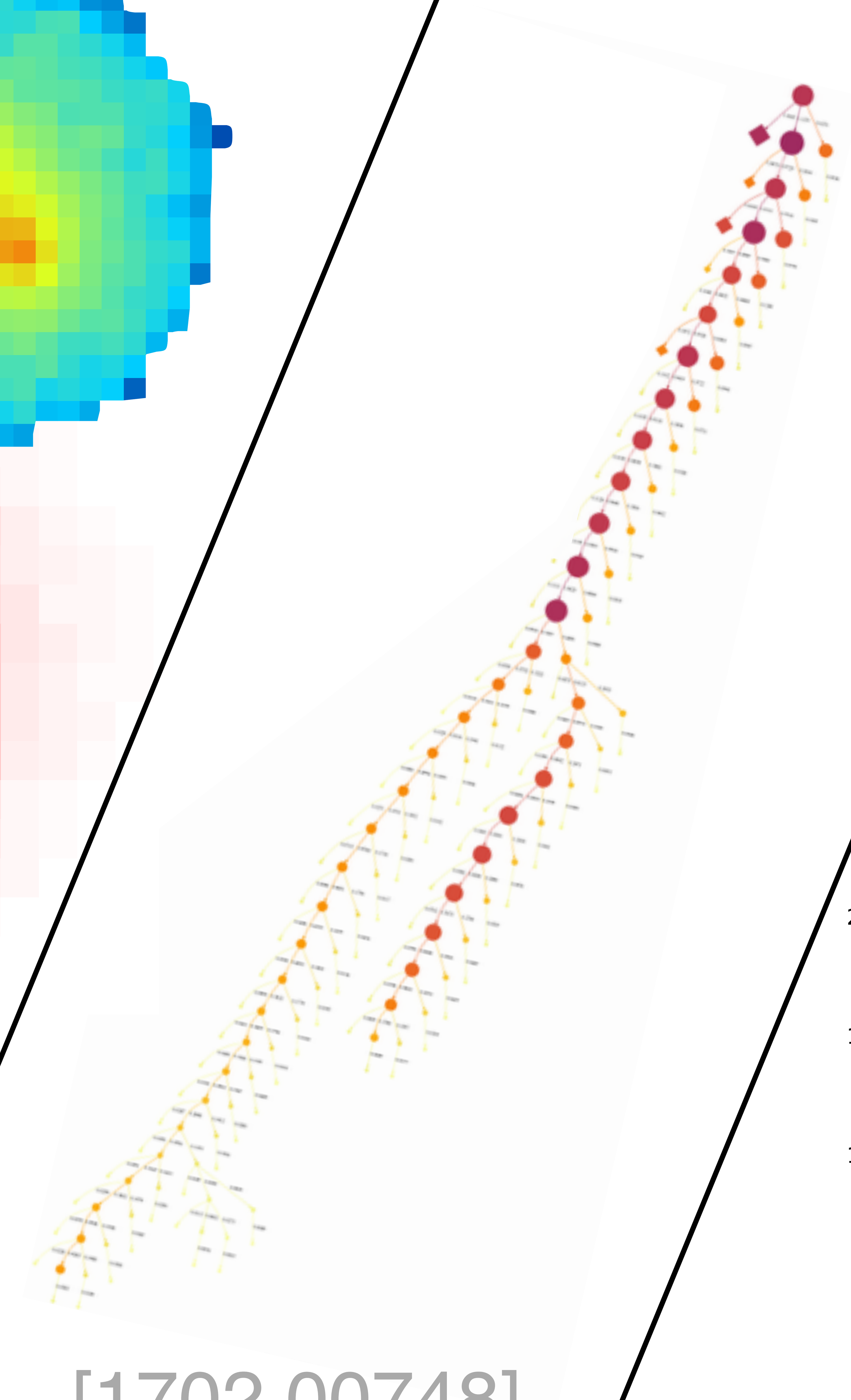
$$J = \{p_1^\mu, p_2^\mu, \ldots, p_n^\mu\}$$

Images



Jet Images: [1407.5675]

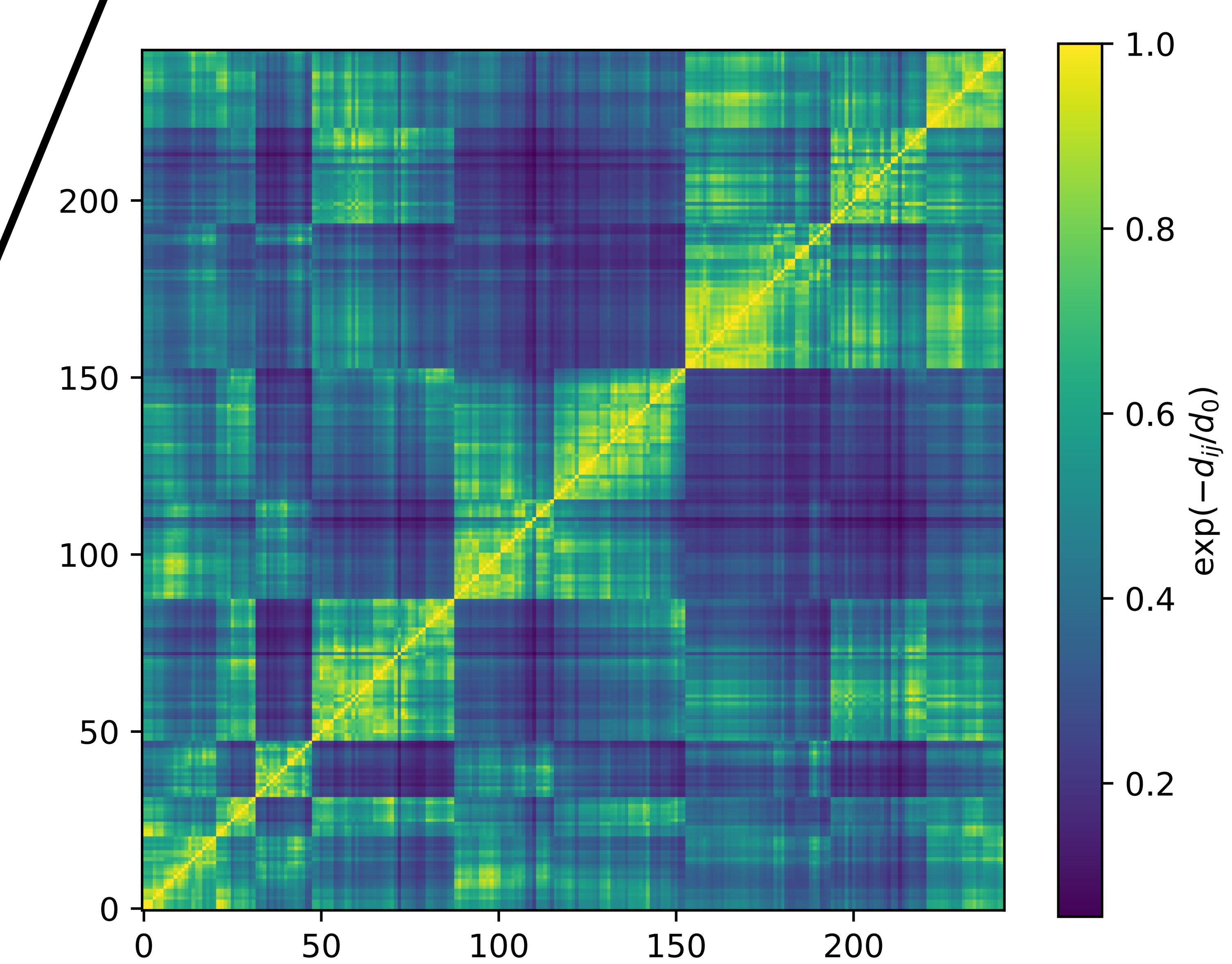
Sequences/ Trees



[1702.00748]

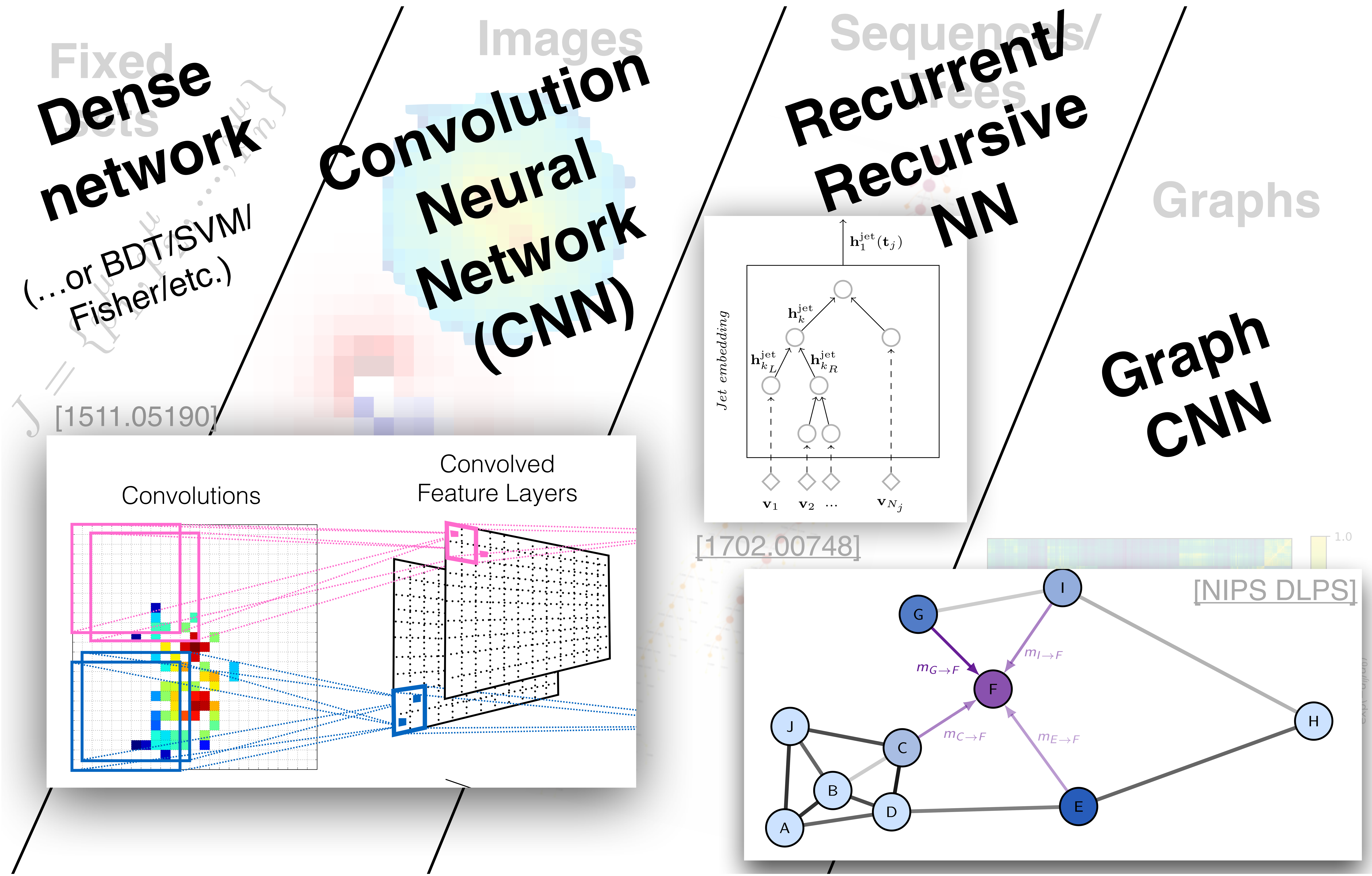
Graphs

[NIPS DLPS]



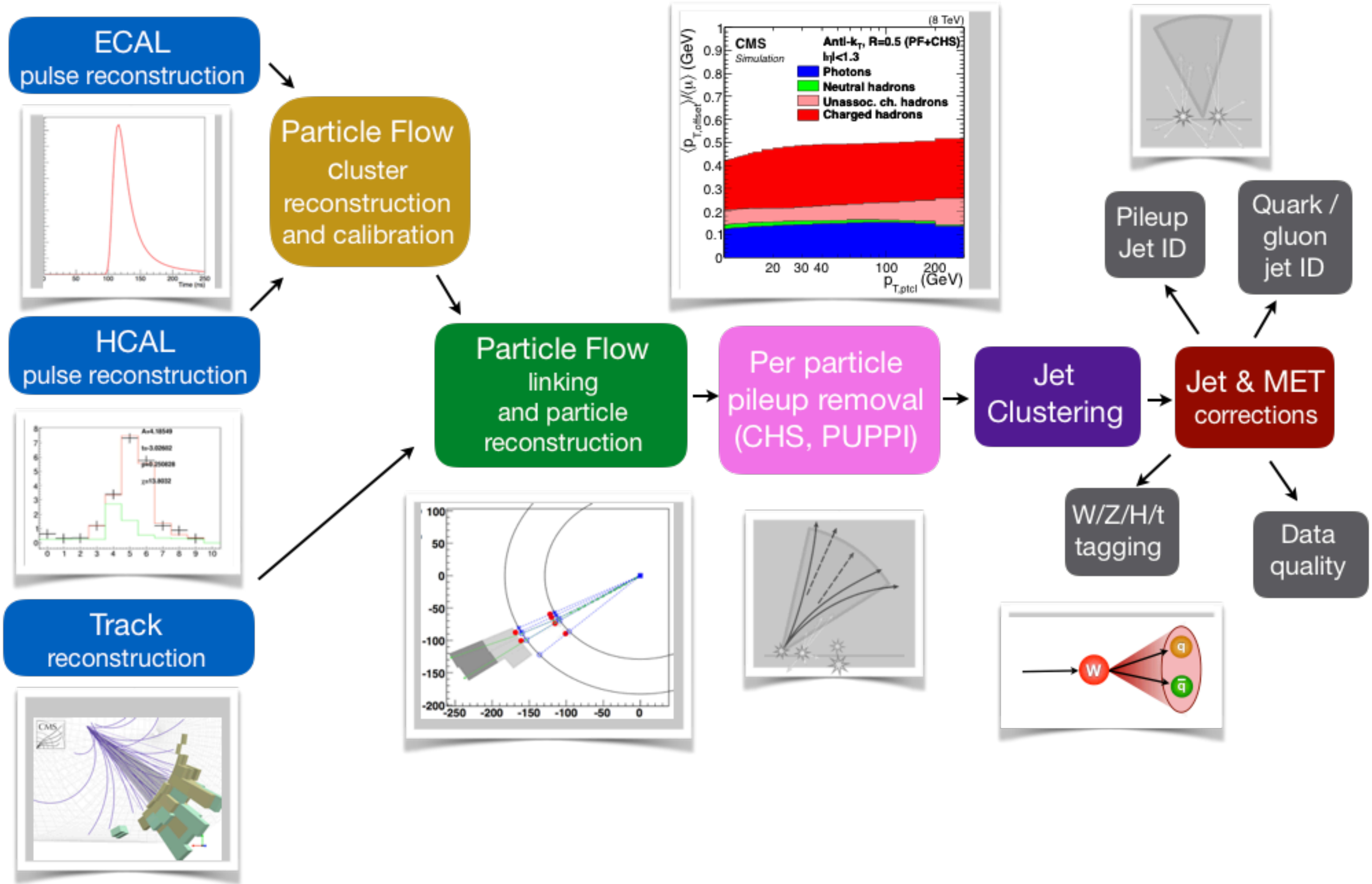
Courtesy: Ben Nachman

Machine learning boom!



Courtesy: Ben Nachman

JETS AND MET


ECAL
pulse reconstruction
HCAL
pulse reconstruction
Track
reconstruction
Particle Flow
cluster
reconstruction
and calibration
Particle Flow
linking
and particle
reconstruction
Per particle
pileup removal
(CHS, PUPPI)
Jet
Clustering
Jet & MET
corrections
Pileup
Jet ID
Quark /
gluon
jet ID
W/Z/H/t
tagging
Data
quality
CMS
Simulation
(8 TeV)
Anti-k_T, R=0.5 (PF+CHS)
$|\eta|$<1.3
Photons
Neutral hadrons
Unassoc. ch. hadrons
Charged hadrons
$\langle p_{T,offset} \rangle / \langle \mu \rangle$ (GeV)
$p_{T,ptcl}$ (GeV)
W

Jet substructure and Pileup

searches for new physics at the kinematic limit **require** jet substructure techniques

jet substructure is ***characterizing radiation***

[jets are just an organizing principle]

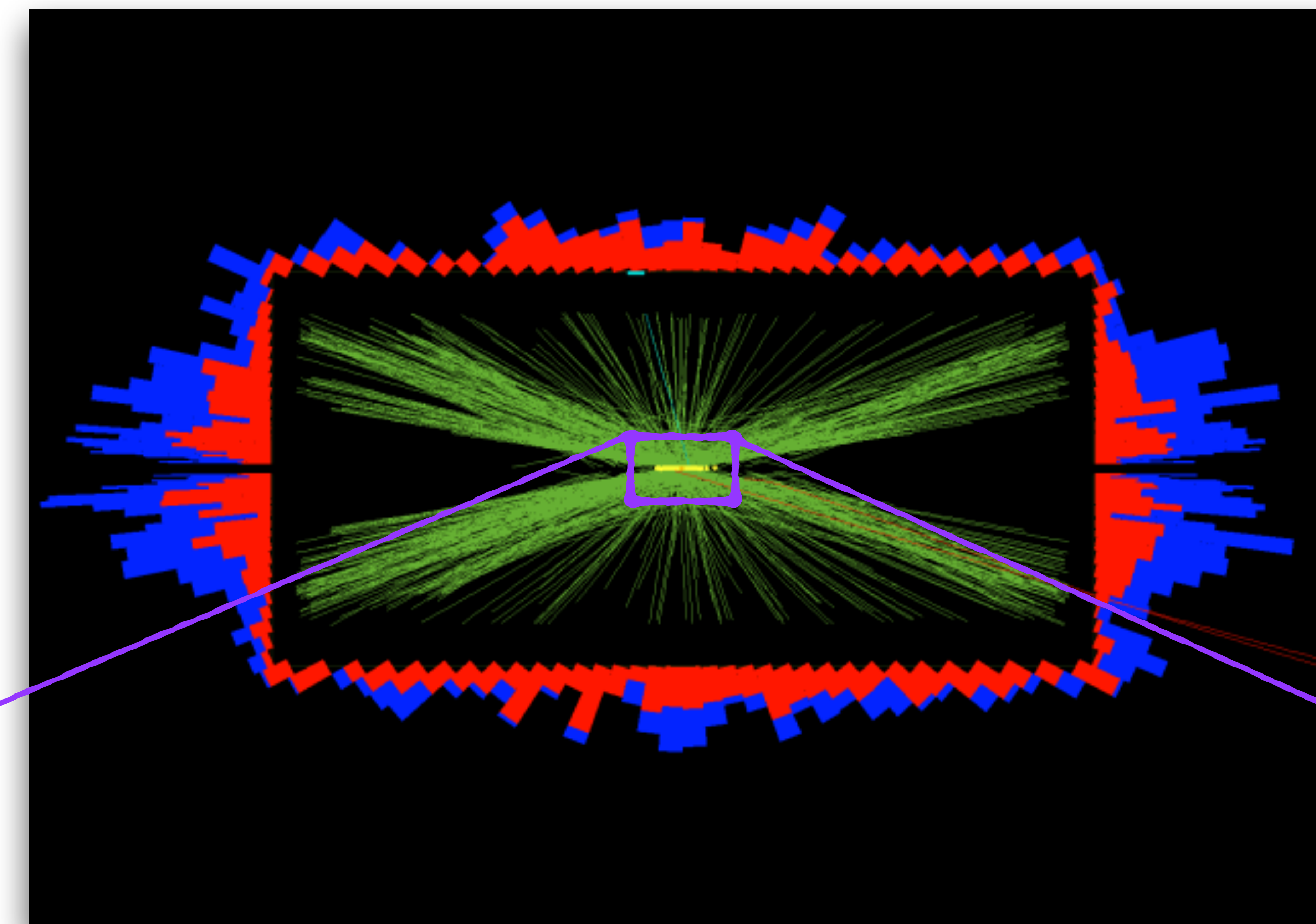
understanding radiation affects everything

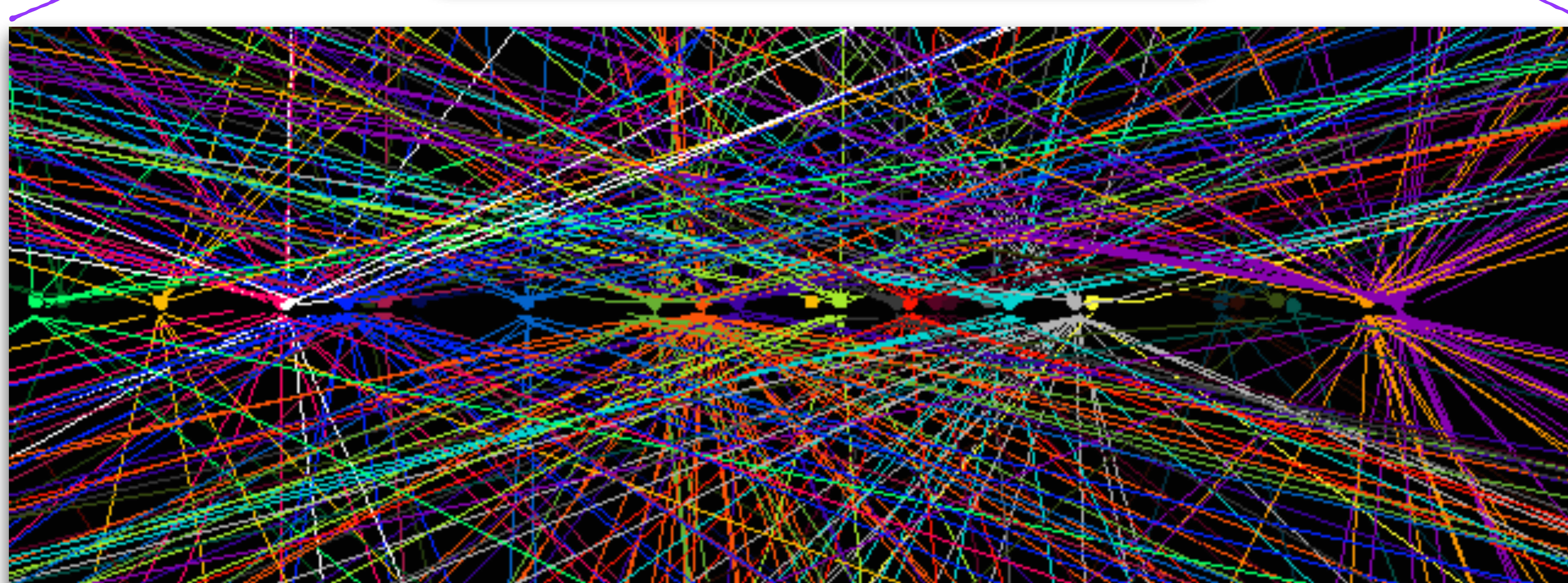
e.g. jet substructure ↔ pileup mitigation

physics at intermediate (Higgs scale) energies are **more affected by pileup**

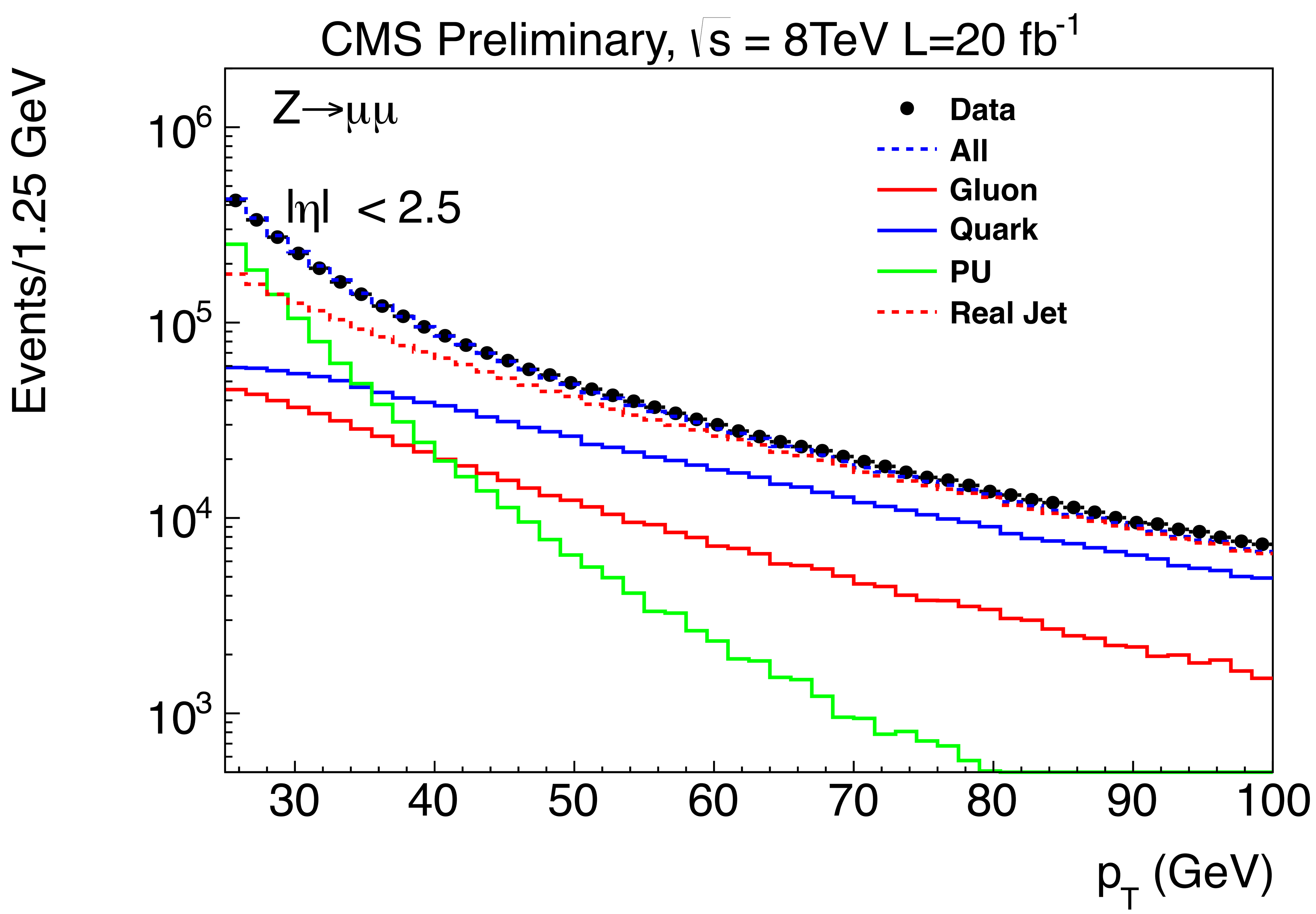
What Is Pileup?

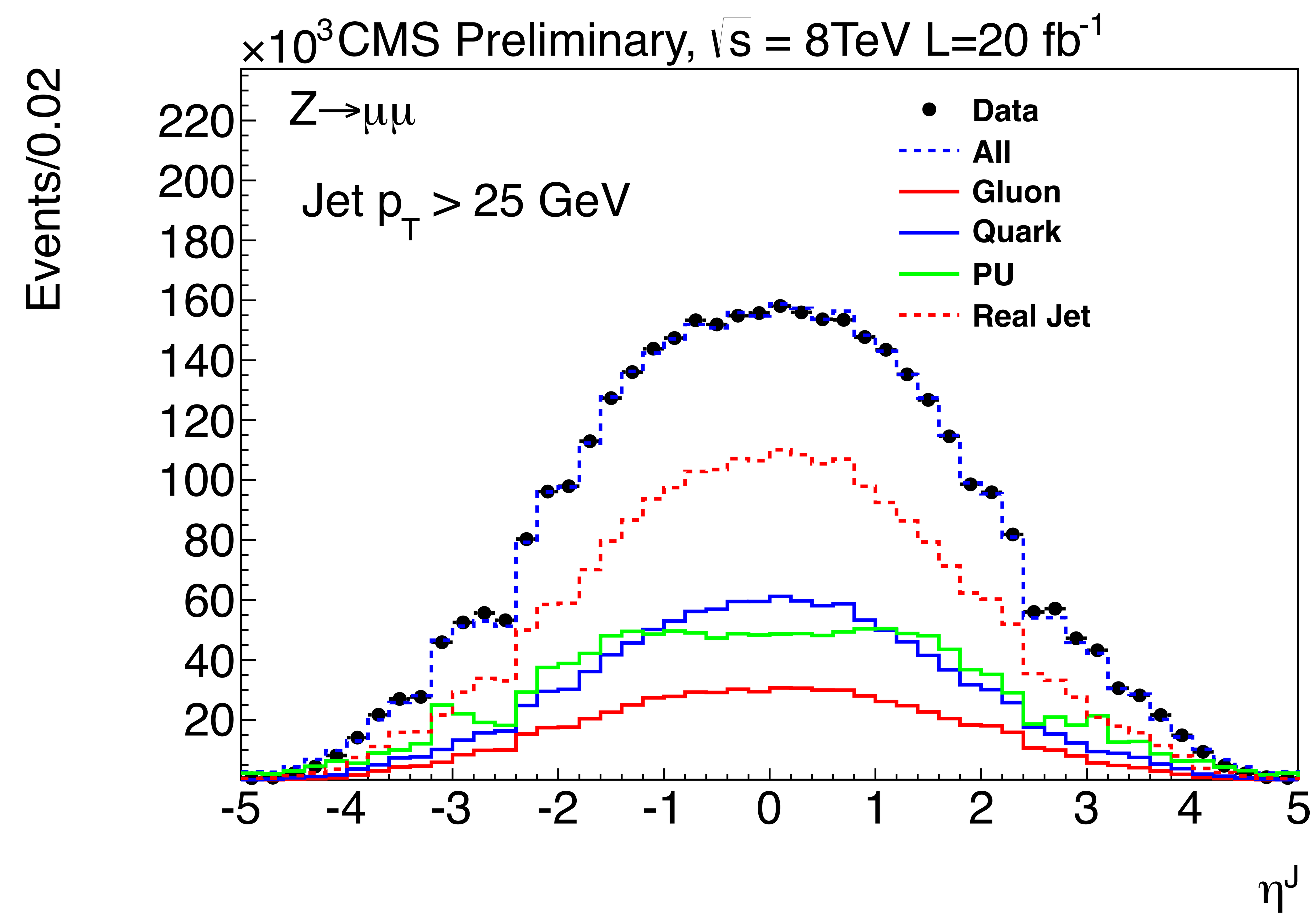
additional pp interactions that occur in each beam crossing because the instantaneous bunch-by-bunch collision luminosity is very high



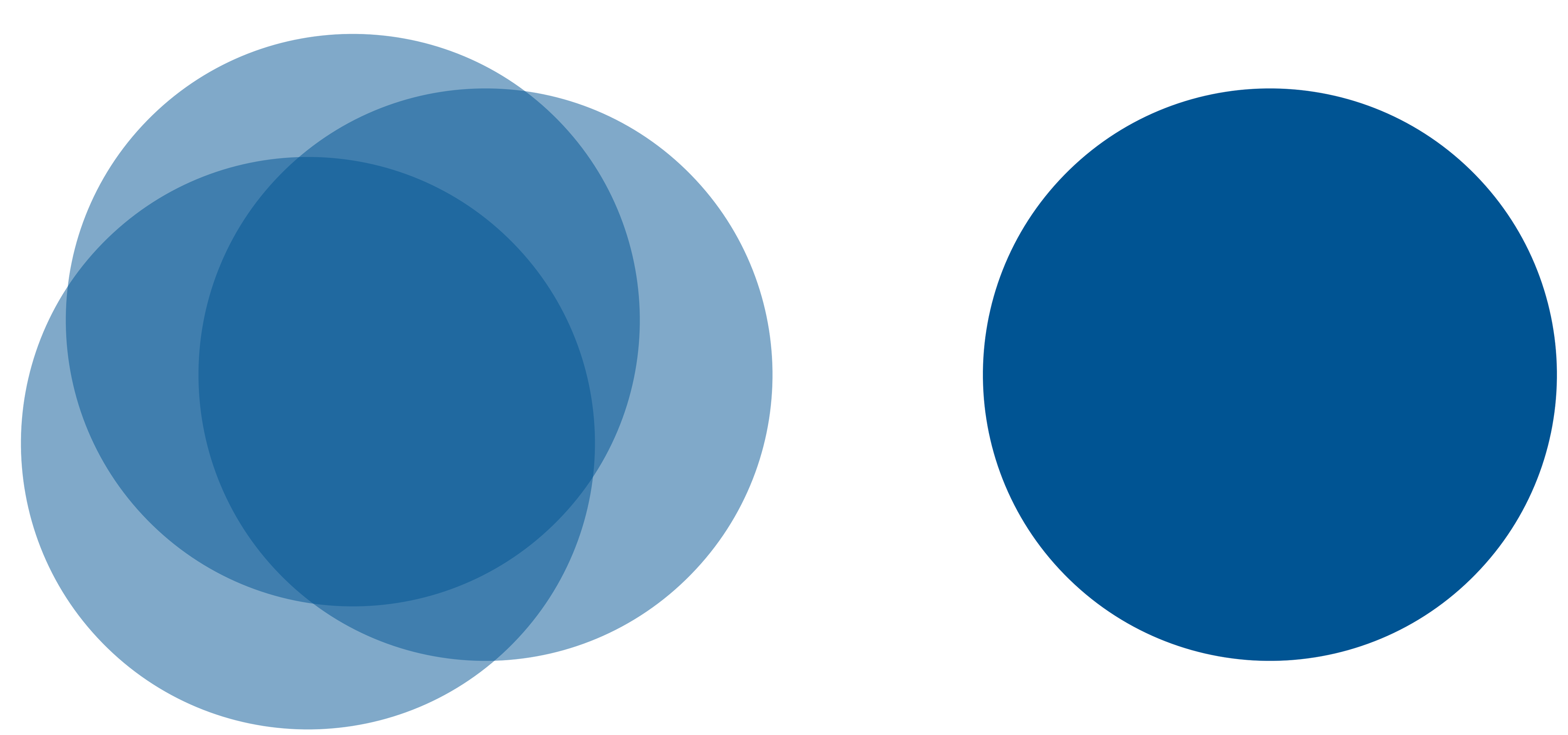


WHAT IS PILEUP?



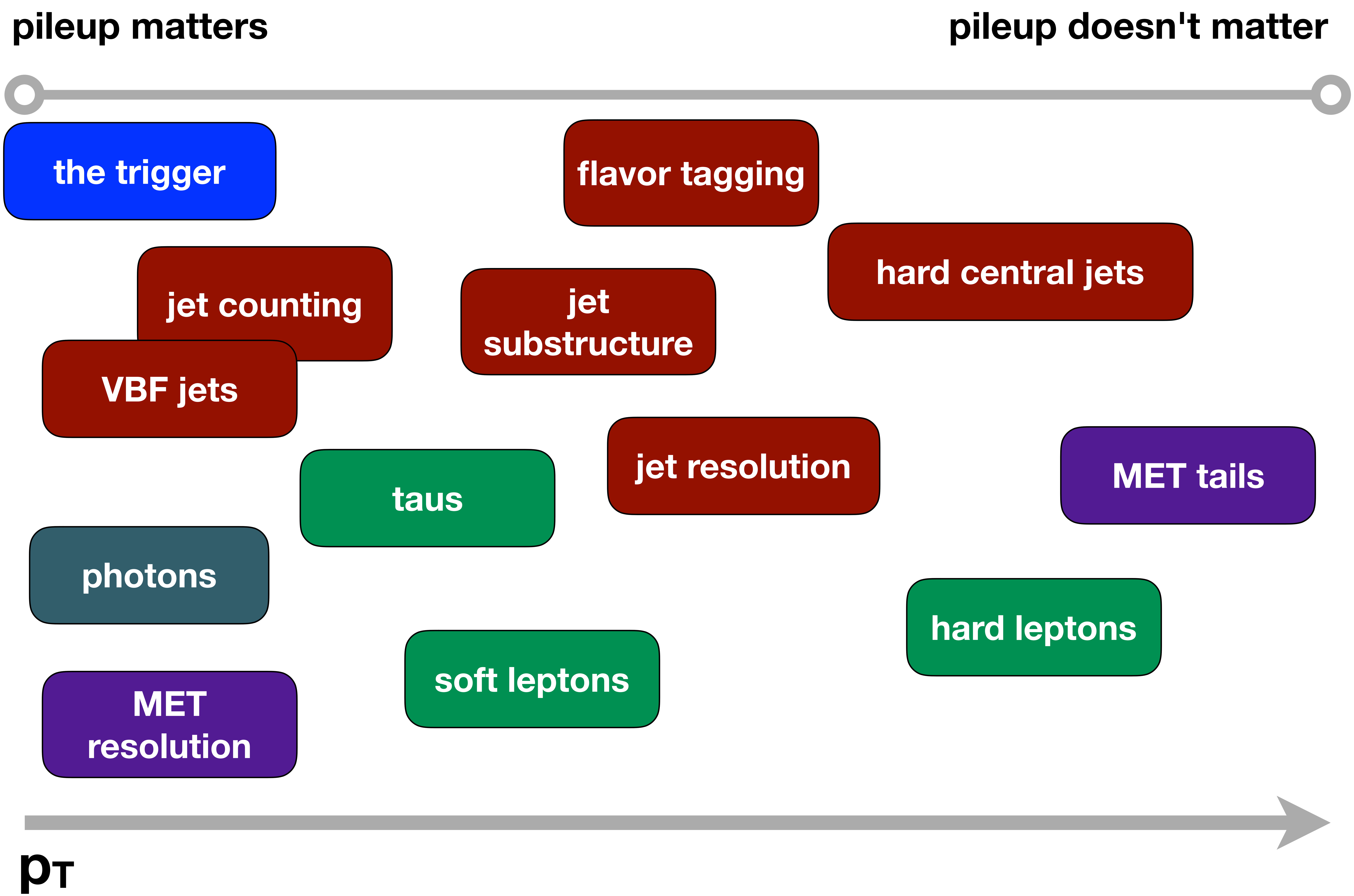


“stochastic” vs. “hard” pileup jets



both contribute to pileup, it’s not necessarily either/or

Who feels pileup?



HANDLES ON PILEUP

properties

asymptotic behavior

local shape

tracking/vertexing

precision timing

depth segmentation

techniques

(apologies, not a complete list!)

ρ correction/subtraction

(area, 4-vector, shape, particle)

grooming

topoclustering

charged hadron subtraction

jet cleansing

pileup jet ID

…

asymptotic behavior

local shape

tracking/vertexing

precision timing

depth segmentation

(apologies, not a complete list!)

ρ correction/subtraction

(area, 4-vector, shape, particle)

grooming

topoclustering

charged hadron subtraction

jet cleansing

pileup jet ID

...

a lot of methods out there!

CERN PU mitigation workshop,
an early exploration of methods
https://indico.cern.ch/event/306155/

asymptotic behavior

local shape

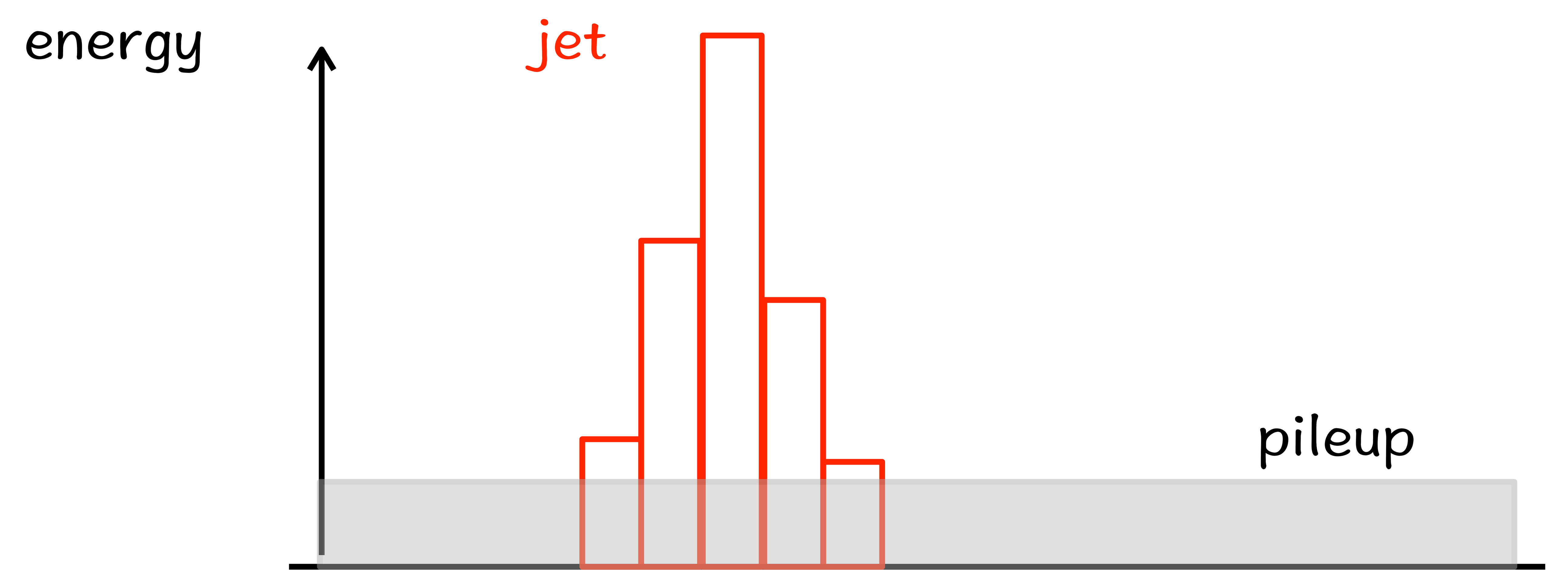
tracking/vertexing

precision timing

depth segmentation

“ρ subtraction”

jet pt correction =
 median energy density x area



many variations of this method, including for jet shapes

Modification of the lepton isolation variable in PU

$$I^{\mu}_{\Delta\beta} = \frac{\sum p_T^{\text{CH-PV}} + \max\left(0\,,\, \sum p_T^{\text{NH}} + \sum p_T^{\gamma} - \frac{1}{2}\sum p_T^{\text{CH-PU}}\right)}{p_T^{\mu}}$$

Using the charged-to-neutral ratio (2/3 vs. 1/3) and vertexing information

HANDLES ON PILEUP

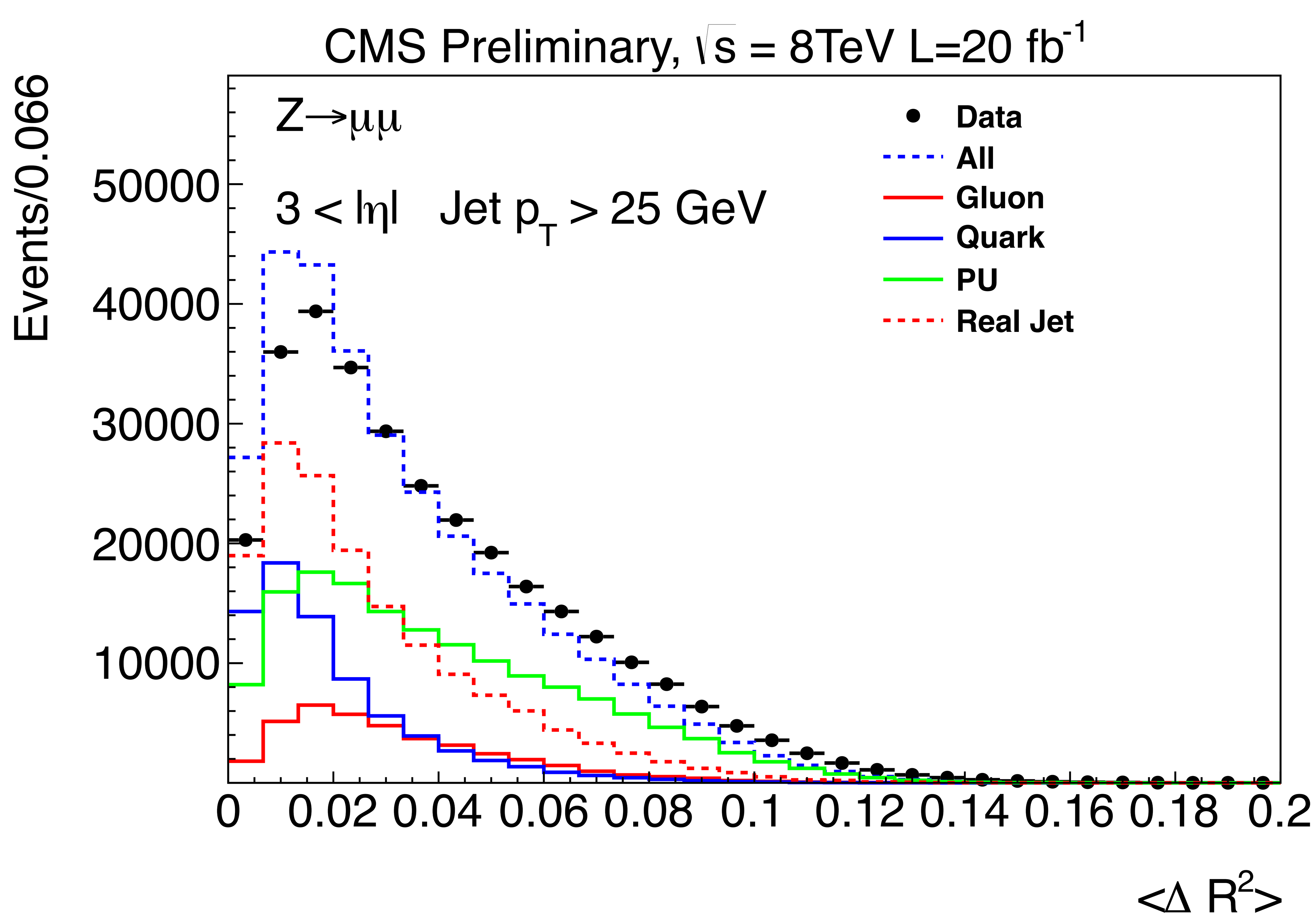
asymptotic behavior

local shape

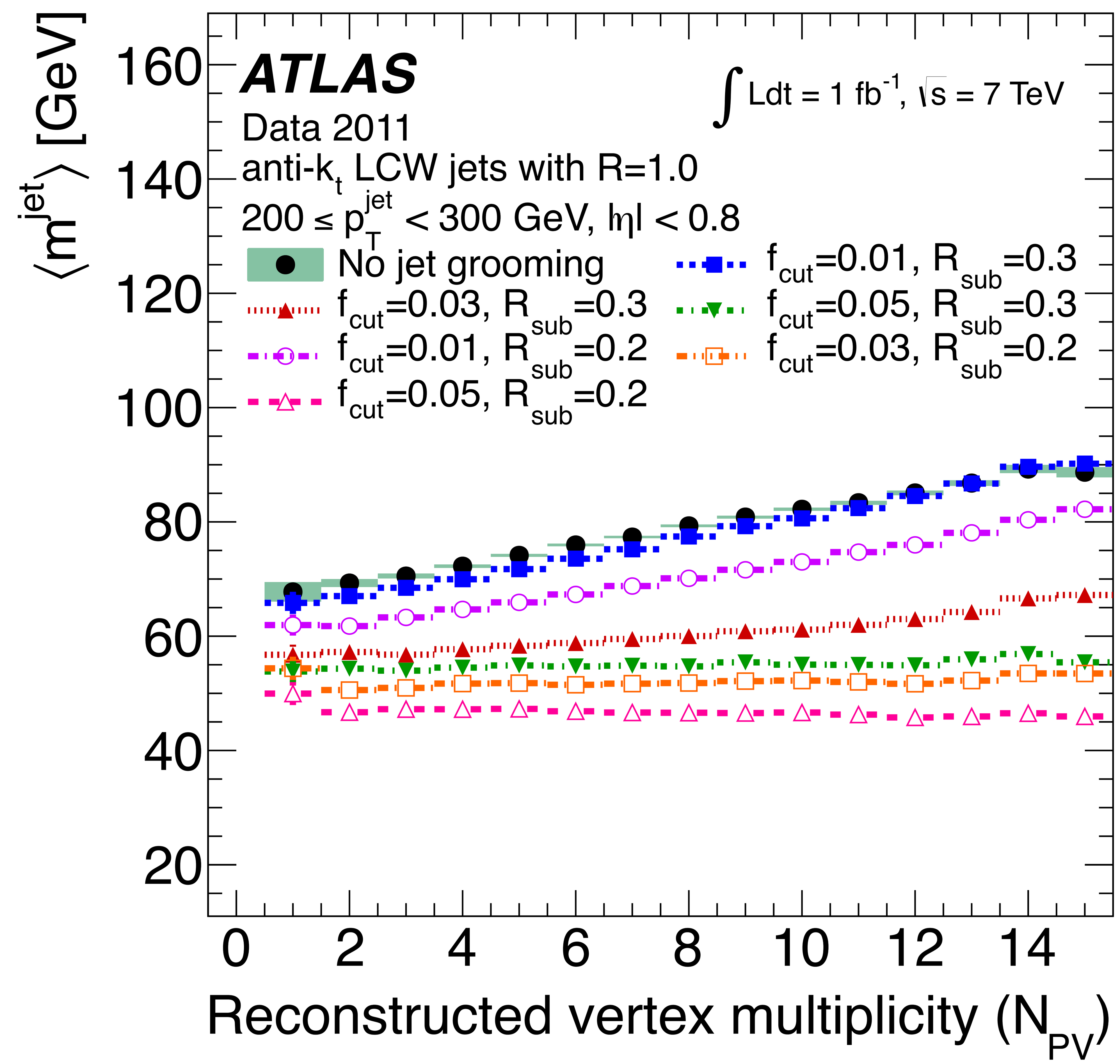
tracking/vertexing

precision timing

depth segmentation



jet grooming, cleans up soft and wide-angle radiation



"jet RMS" of forward pileup jets

HANDLES ON PILEUP

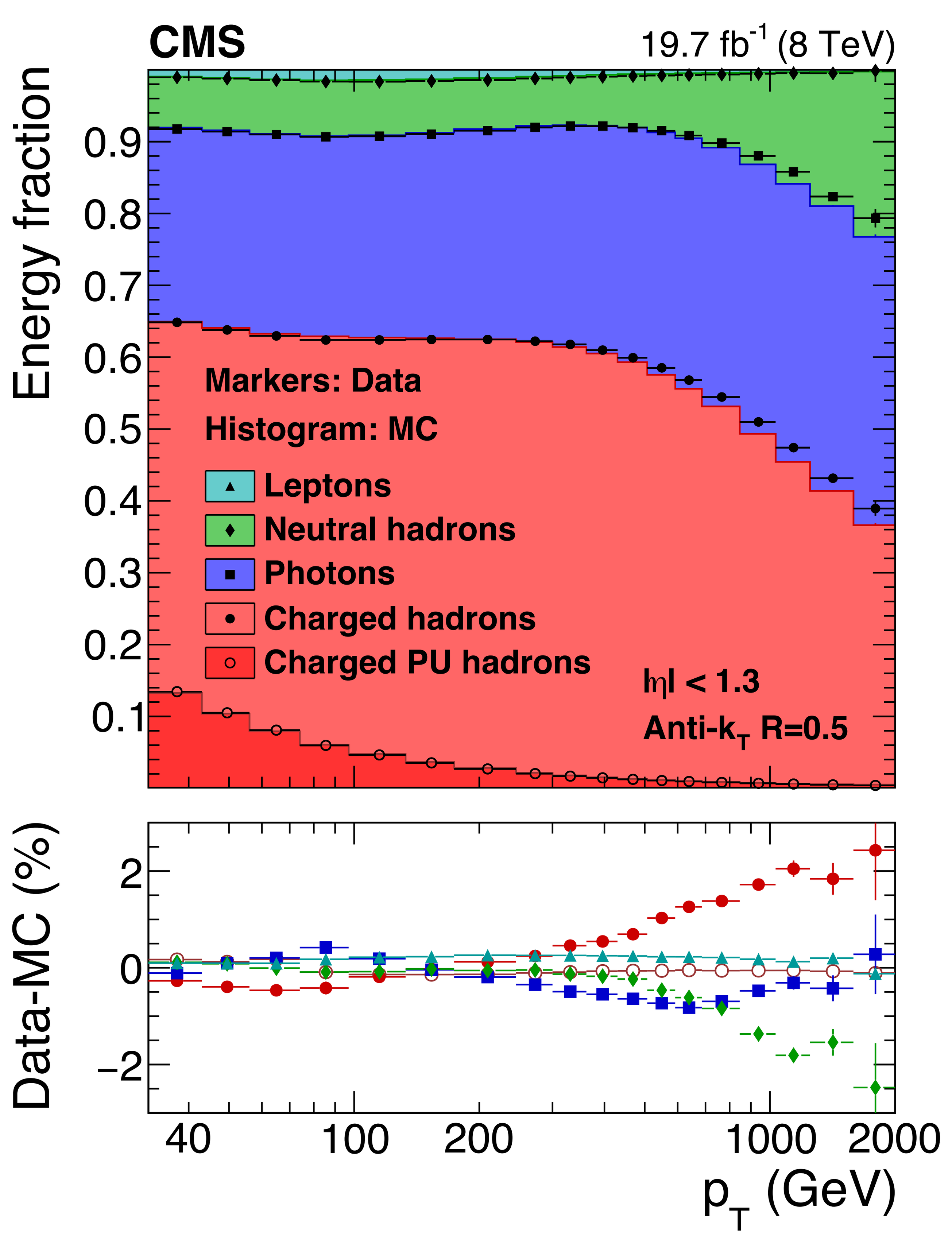
asymptotic behavior

local shape

tracking/vertexing

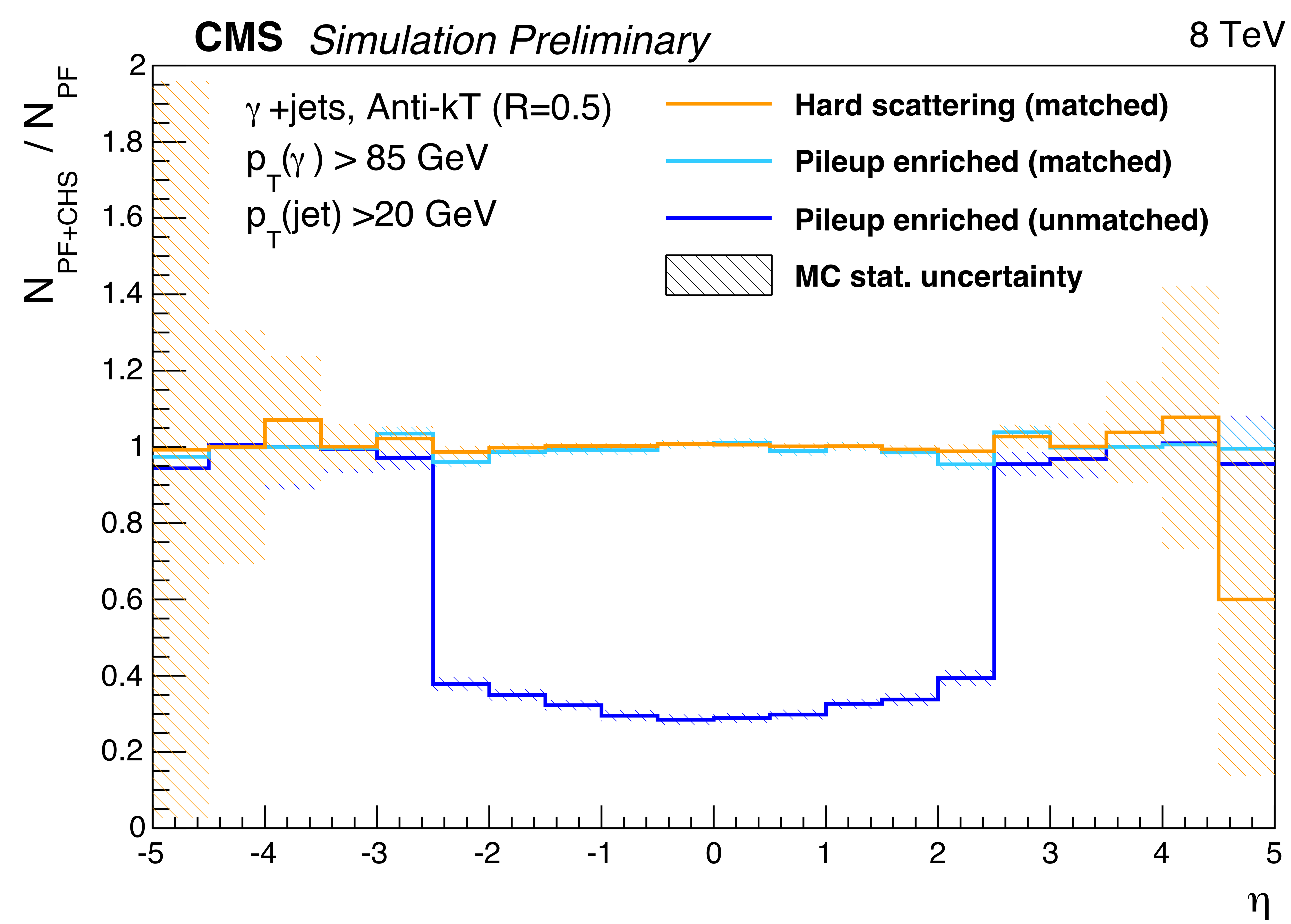
precision timing

depth segmentation



Charged Hadron Subtraction (CHS)

Falls out naturally from Particle Flow!



HANDLES ON PILEUP

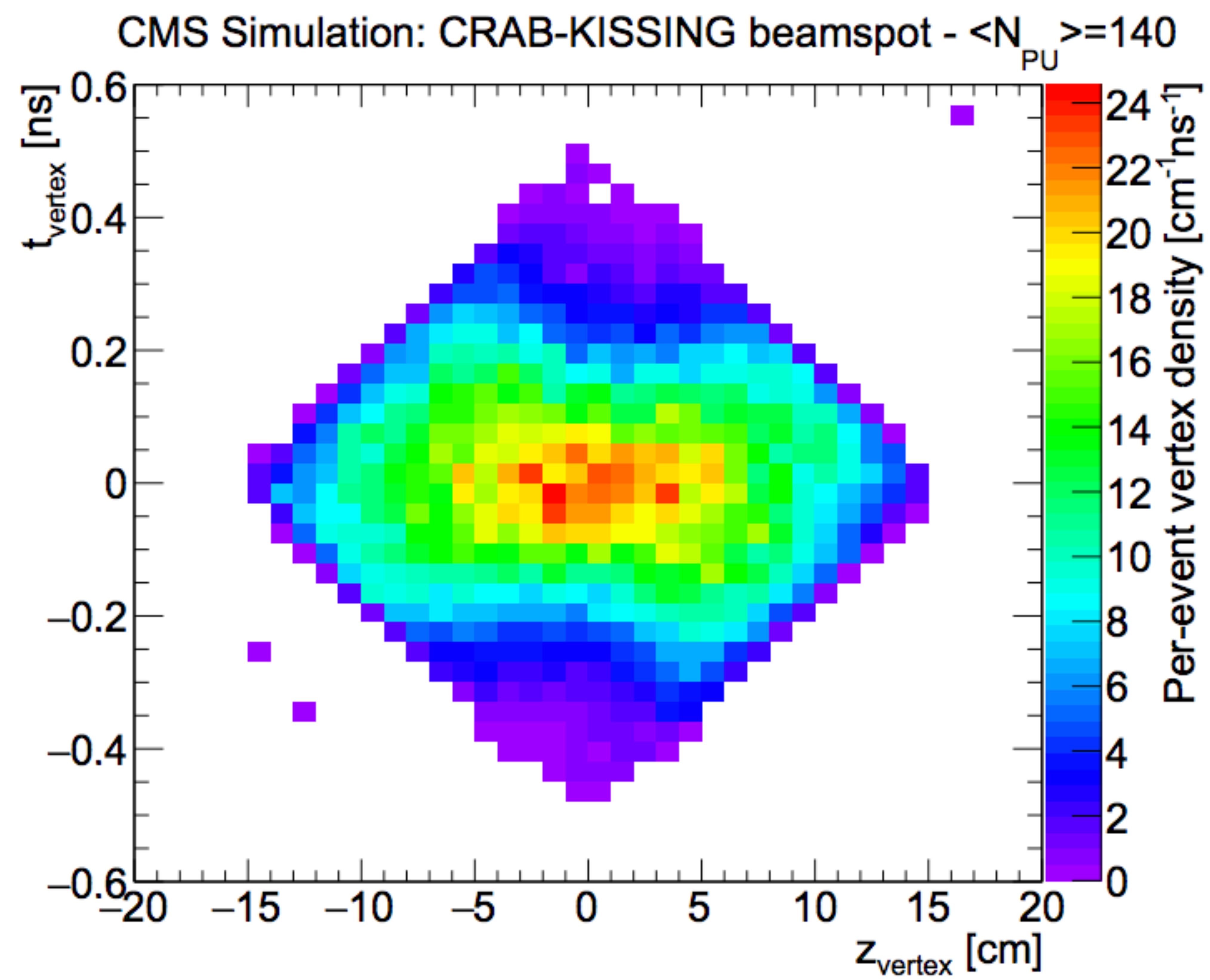
asymptotic behavior

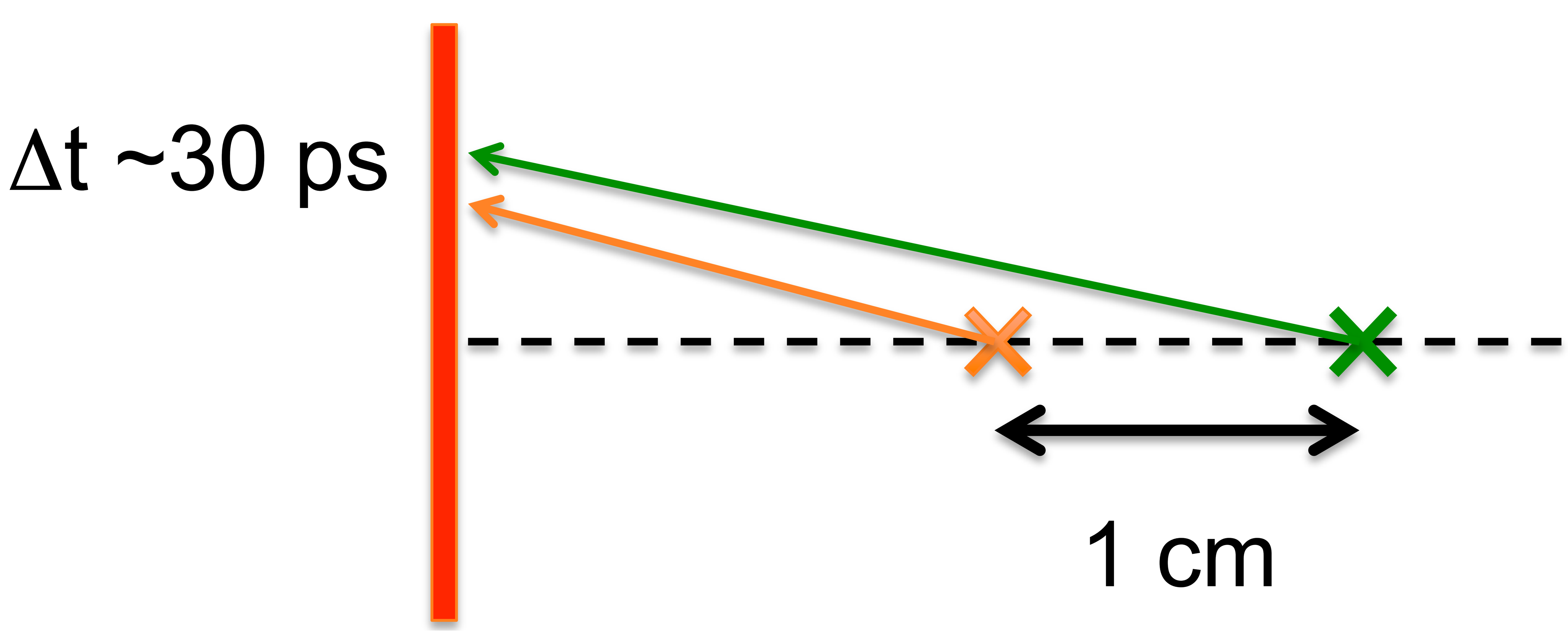
local shape

tracking/vertexing

precision timing

depth segmentation





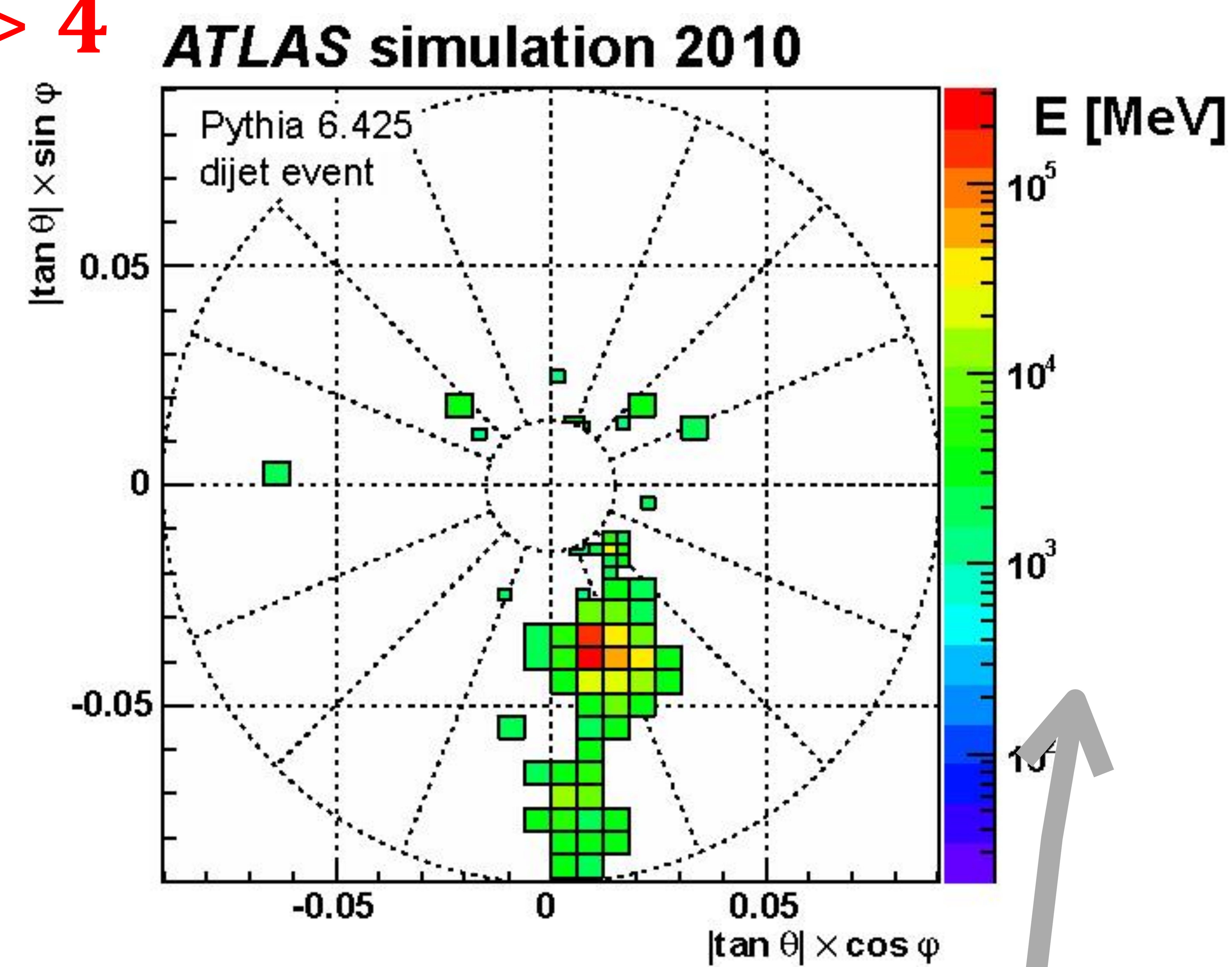
σ_t ~ 30 ps buys a factor of ~10 reduction in effective pileup

but open questions…
e.g. can we achieve that time resolution for ~few GeV photons?

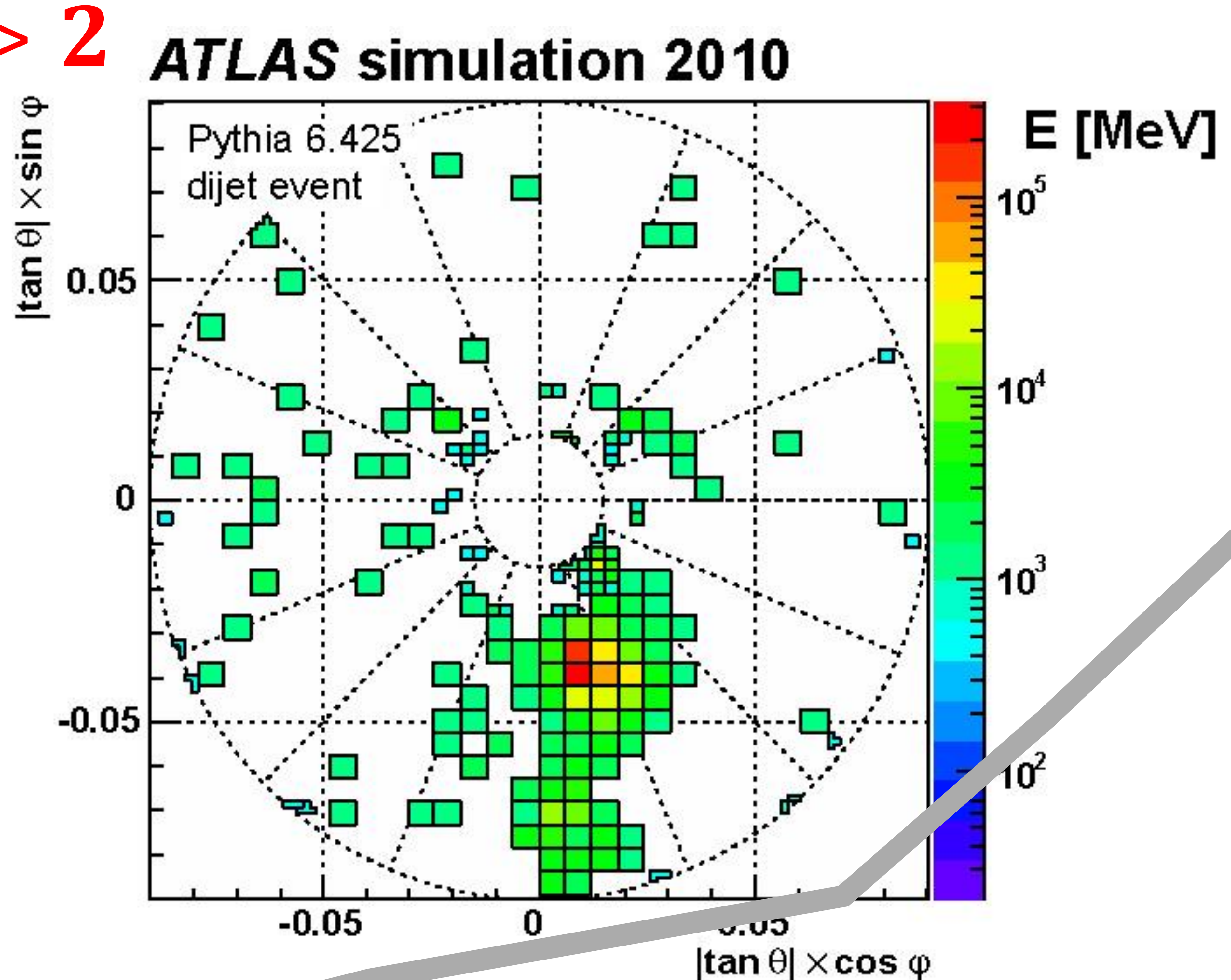
HANDLES ON PILEUP

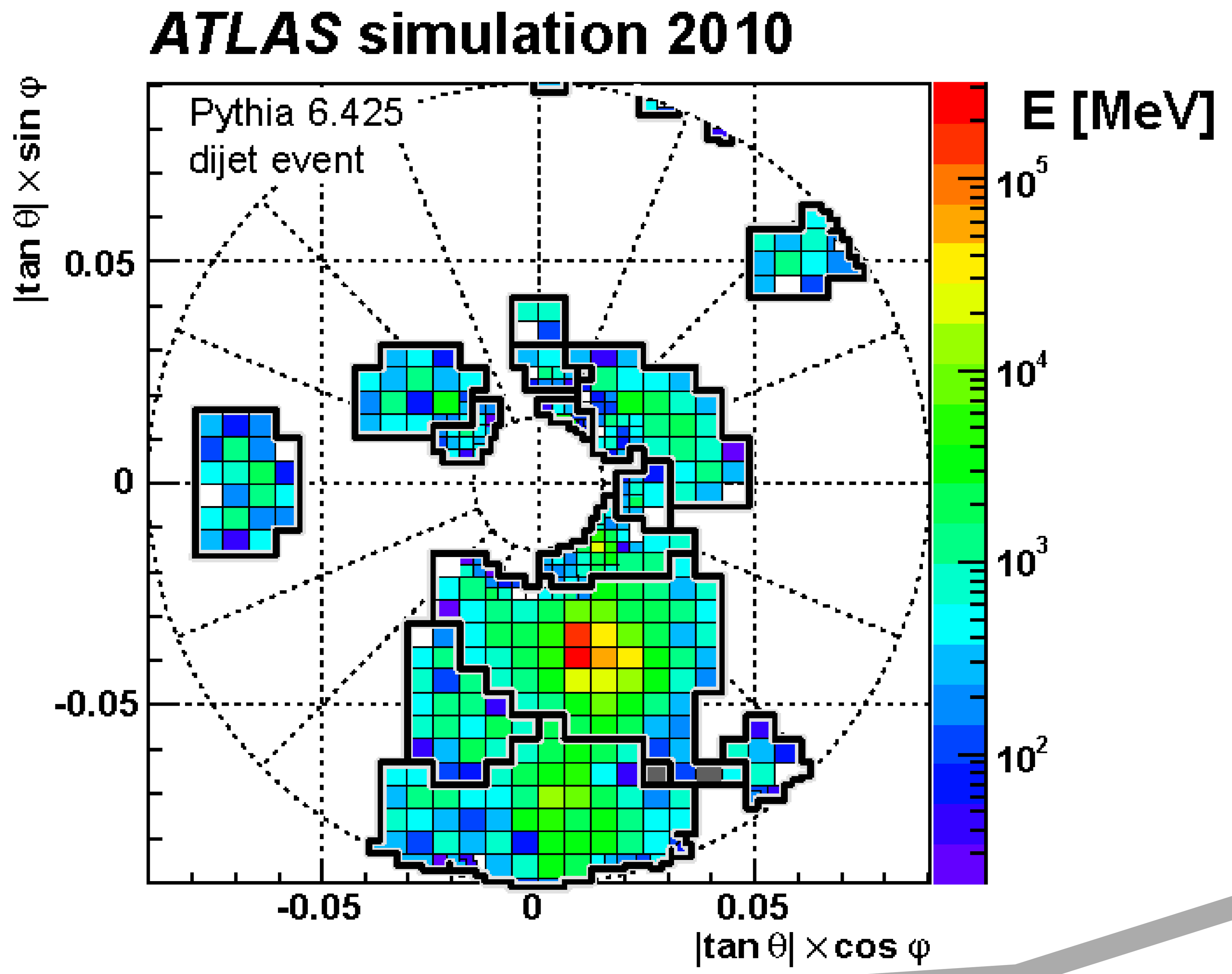
- asymptotic behavior
- local shape
- tracking/vertexing
- precision timing
- **depth segmentation**

$\left|\frac{E}{\sigma}\right| > 4$



$\left|\frac{E}{\sigma}\right| > 2$





clustering uses neighbors in depth too! no longer 2D clustering

HOLISTIC VIEWS ON PILEUP

Notice that each method that we've described works on a given **physics object**···

each method presented so far also has its downfalls

What if we act on the event building blocks?
e.g. constituents/particles

constituent subtraction, softkiller, PUPPI

hep-ph:1403.3108
hep-ph:1407.0408
hep-ph:1407.6013

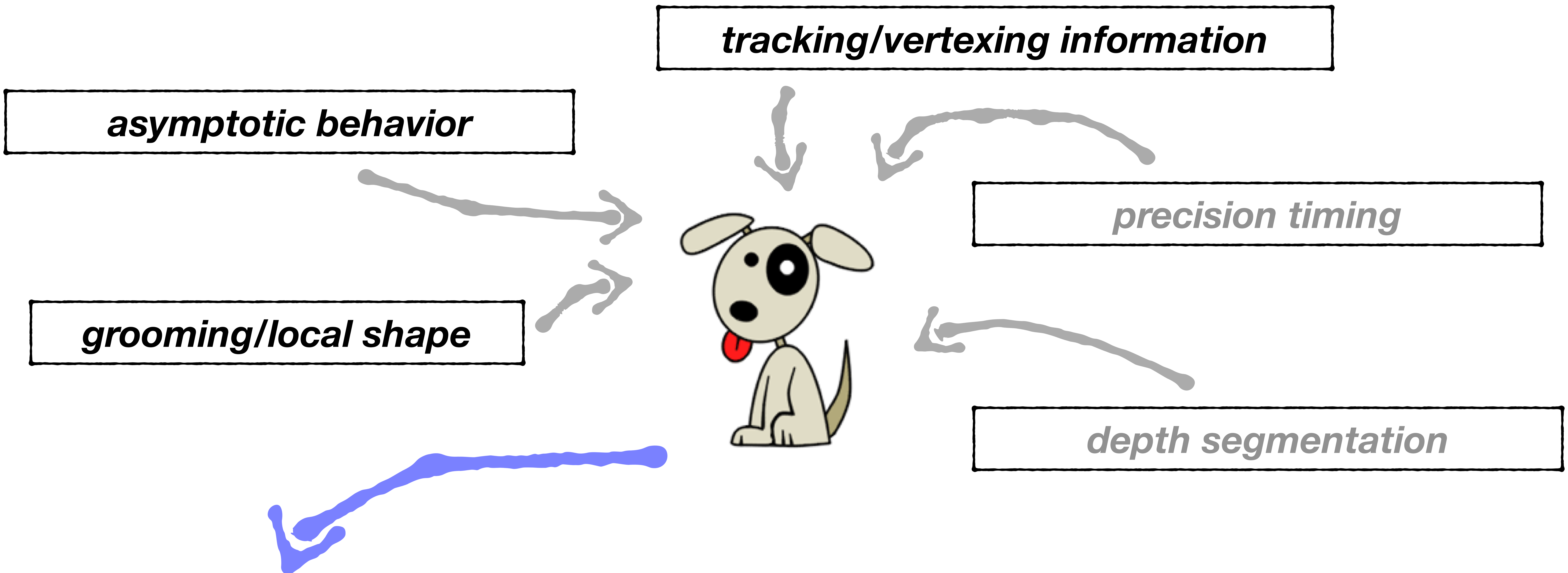
What if we exploit all information possible simultaneously?

asymptotic, local shape, tracking, etc···

What if, you could identify each particle in the event and give the likelihood that it's pileup?

THE PUPPI APPROACH:

PILEUP PER PARTICLE IDENTIFICATION

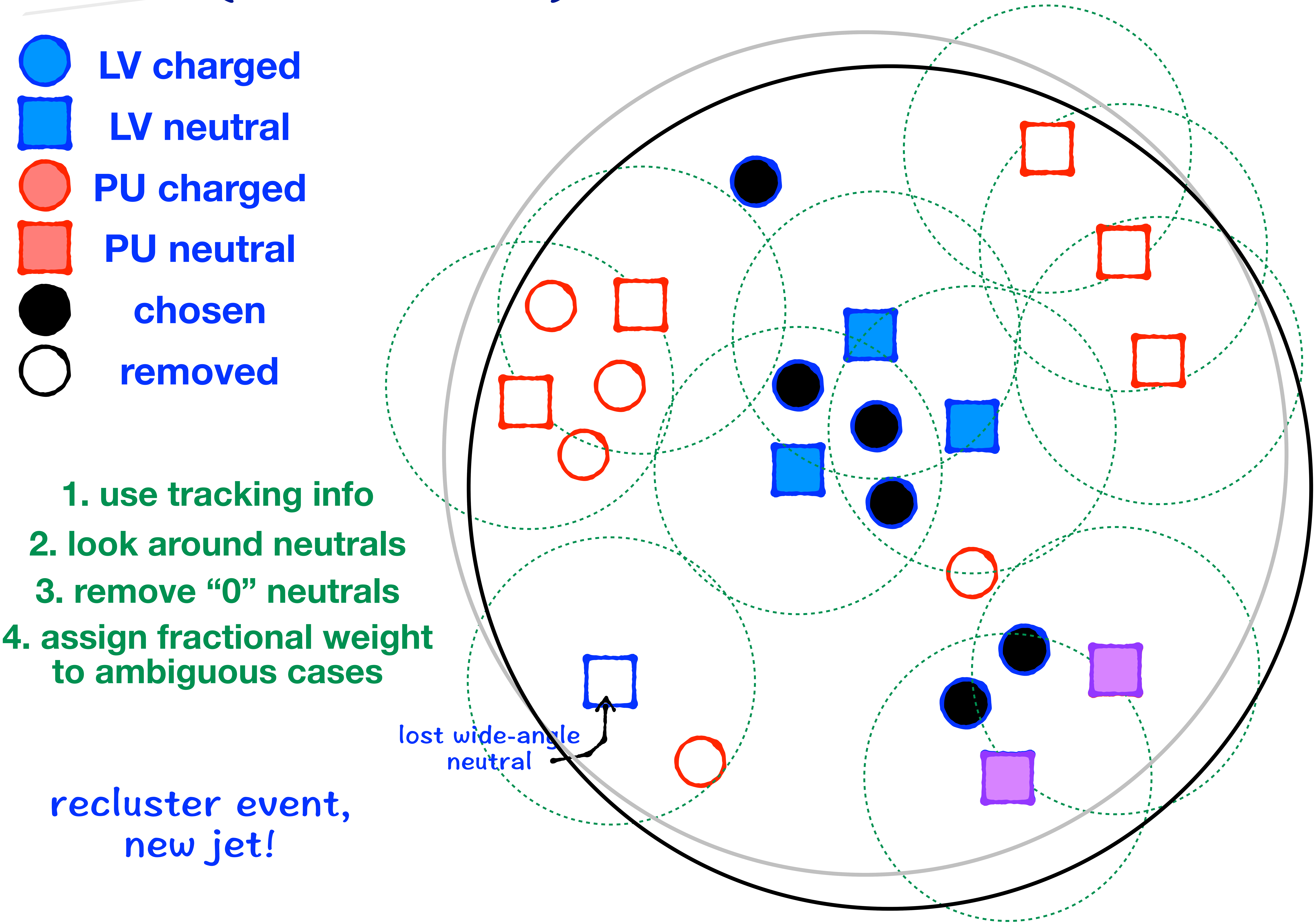


Define on a ***per particle*** basis, ***before jet clustering***, a weight for ***how likely*** a particle (or jet constituent) is to be from pileup or the leading vertex, then rescale each particle four momentum by that weight

$$\alpha_i^C = \log\left[\sum_{j\in \mathrm{Ch,LV}} \frac{p_{T,j}}{\Delta R_{ij}}\Theta(R_0 - \Delta R_{ij})\right]$$

define an α_i per particle; sample the PU α distribution per event; ask how likely particle i is to be pileup

PUPPI (IN CARTOONS)

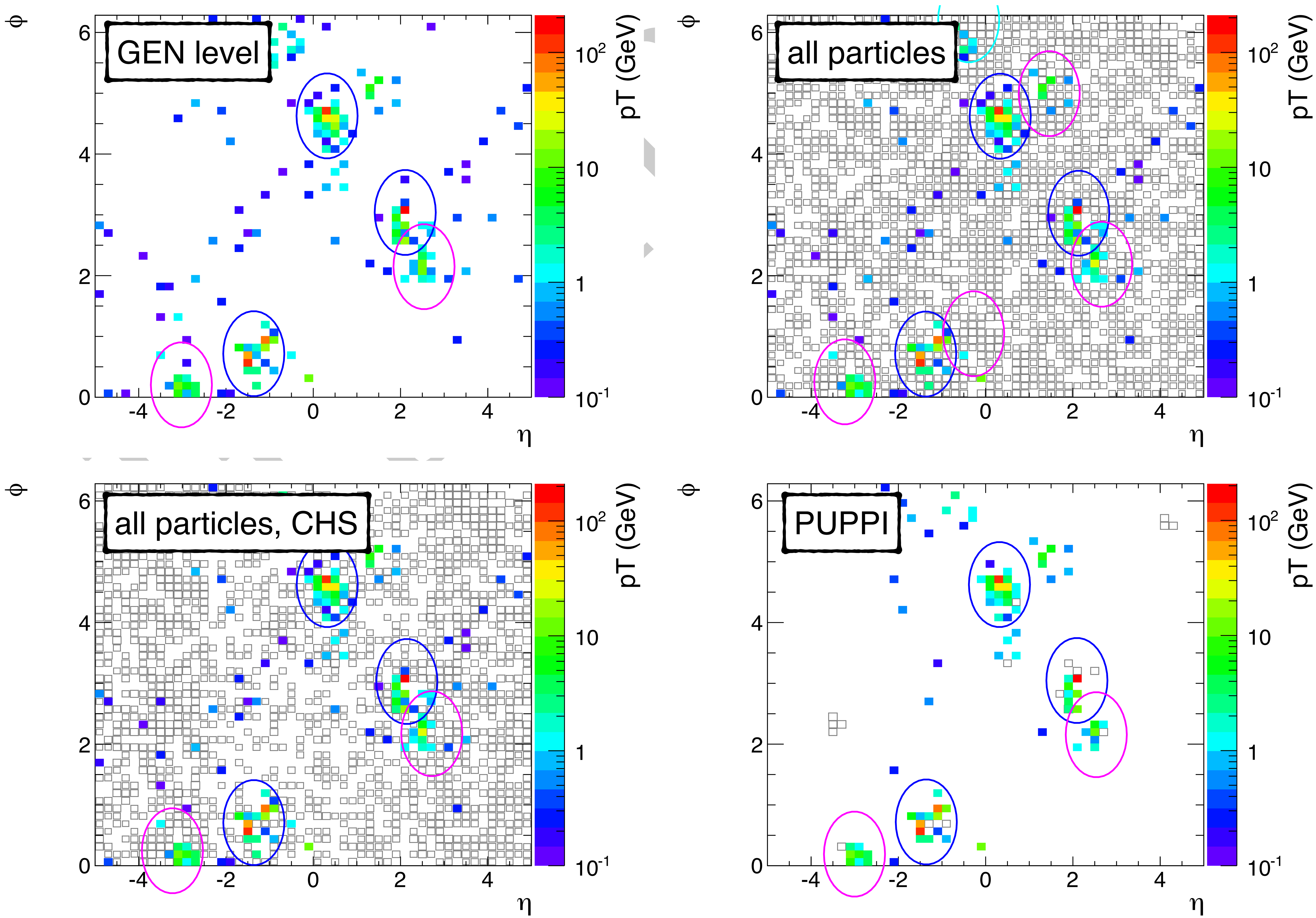


1. use tracking info
2. look around neutrals
3. remove “0” neutrals
4. assign fractional weight to ambiguous cases

recluster event,
new jet!

PileUp Per Particle ID

colored cells = process of interest
black cells = pileup

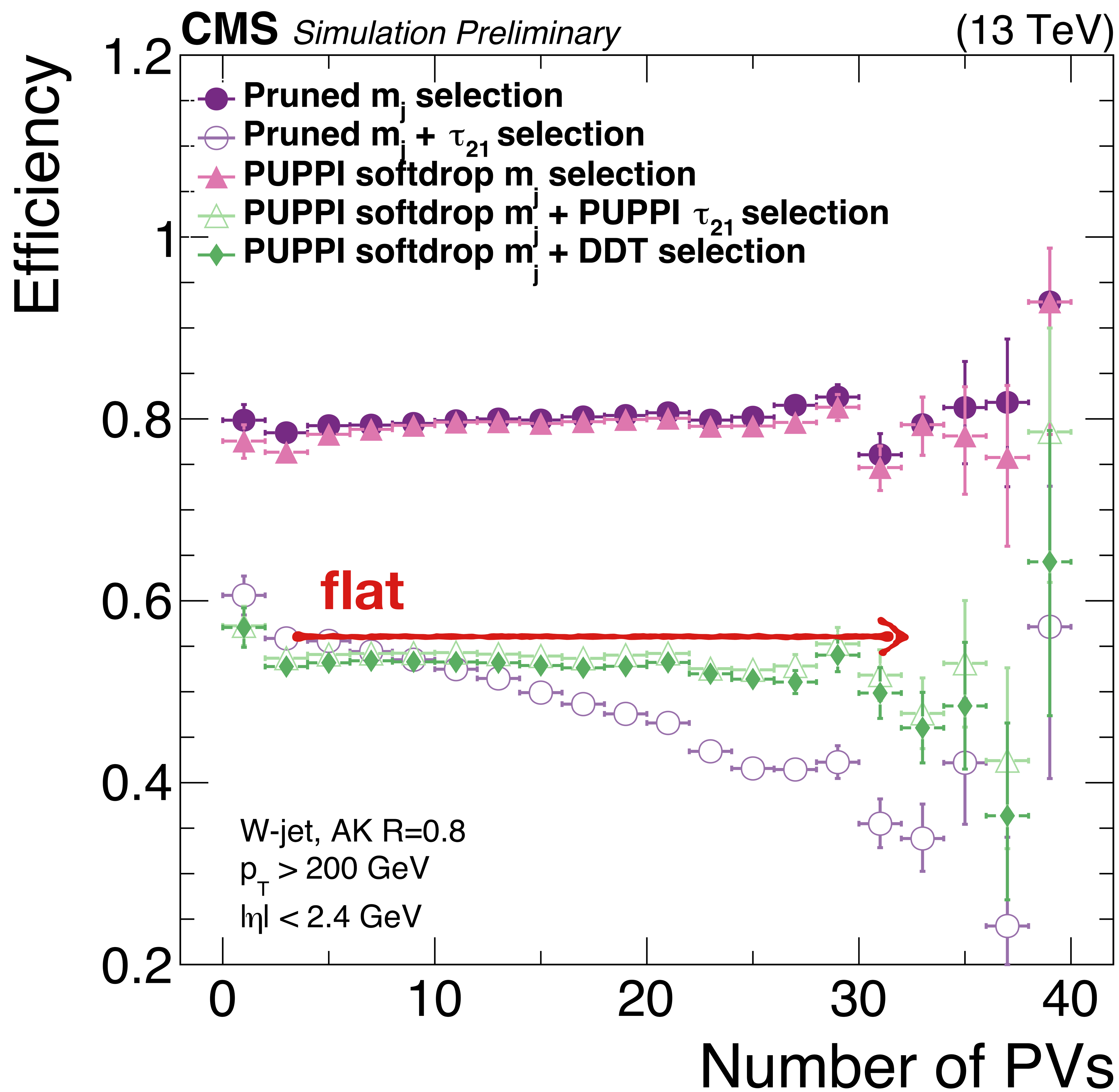


N.B. Particle level studies assuming perfect tracking for |η| < 2.5

PUPPI PERFORMANCE

"Classic" use-case for per particle pileup mitigation, it works for all jet shapes

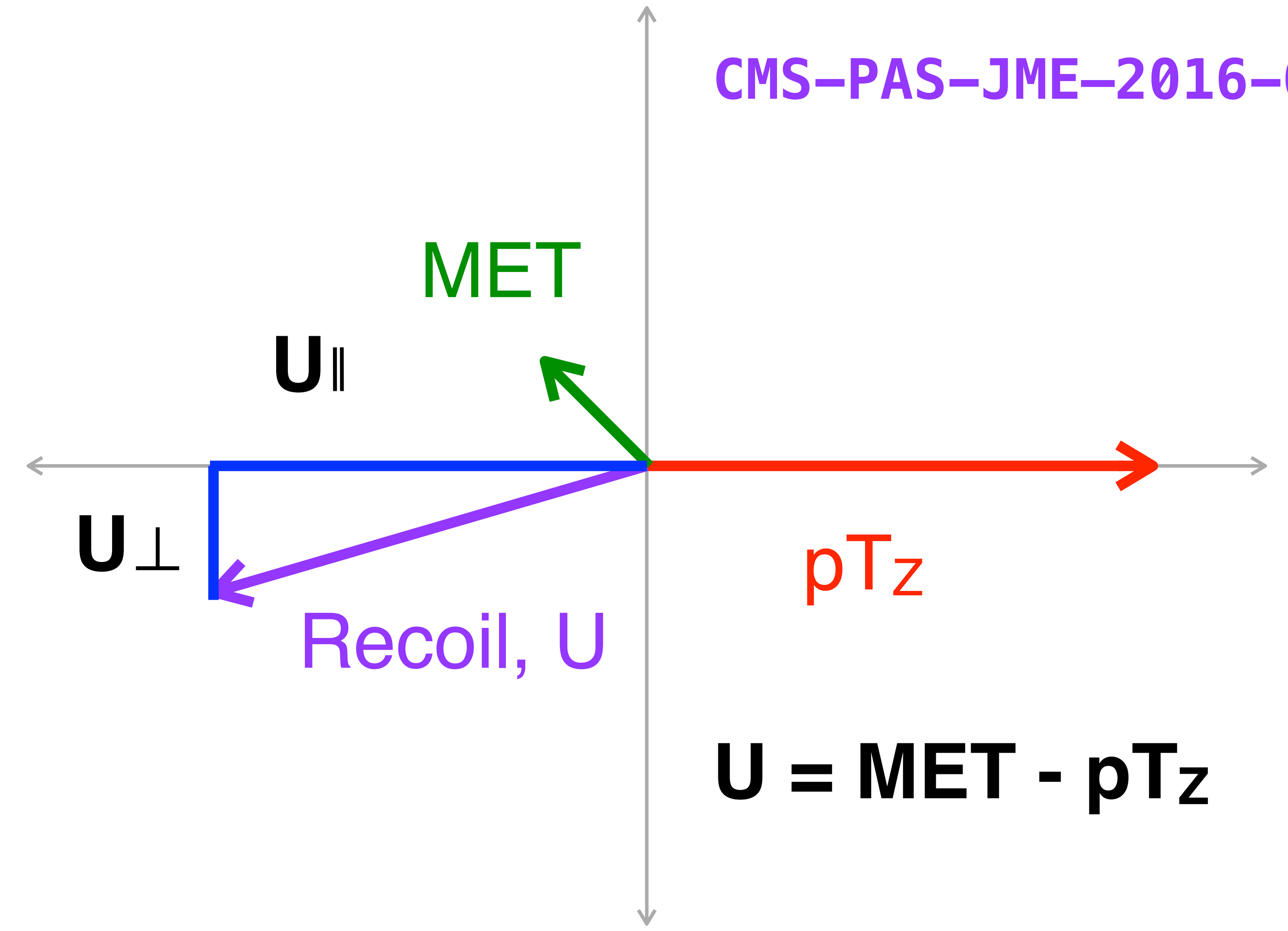
Here, this is the effect of PUPPI on W-tagging shown for PFCHS inputs vs. PUPPI inputs

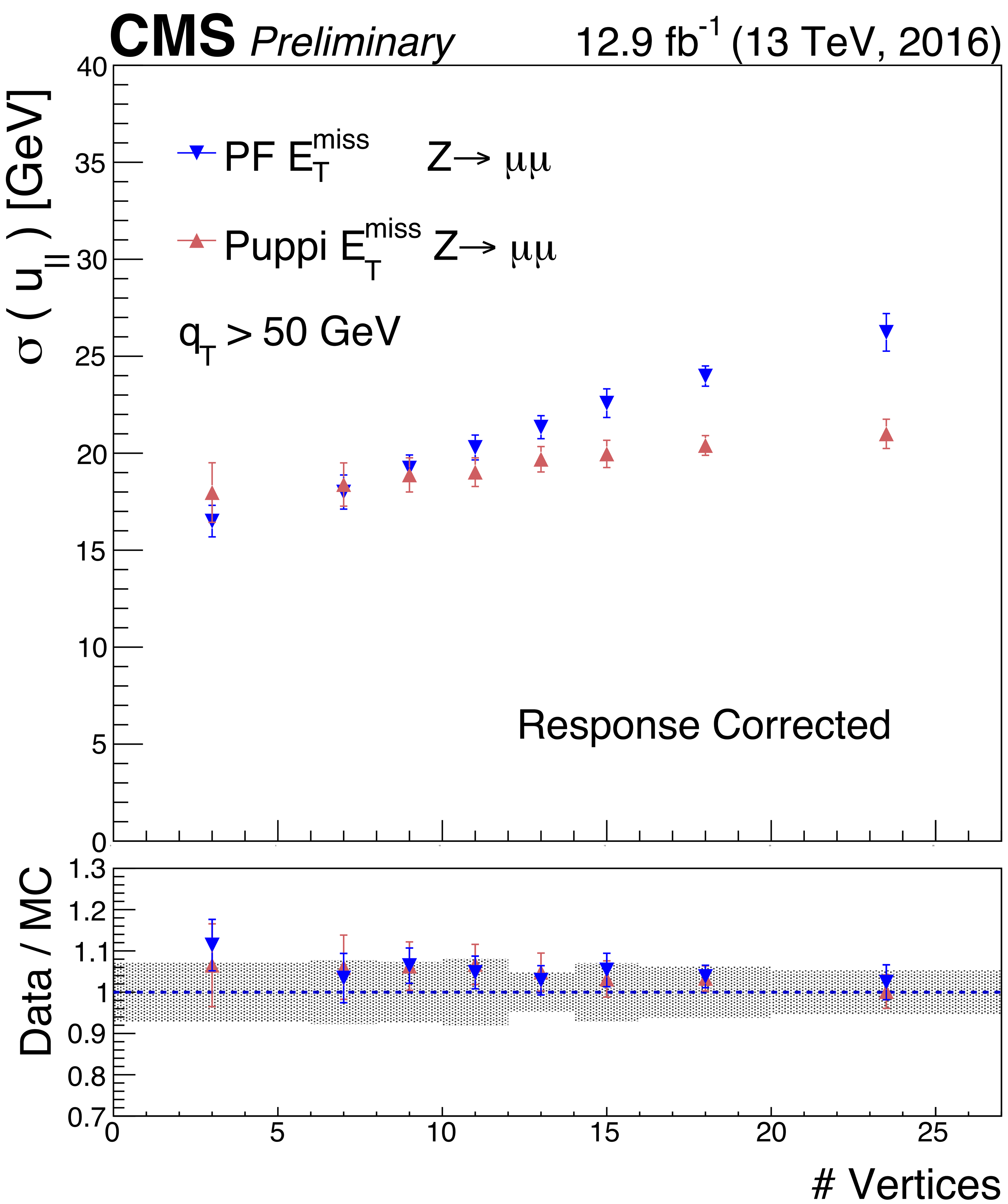


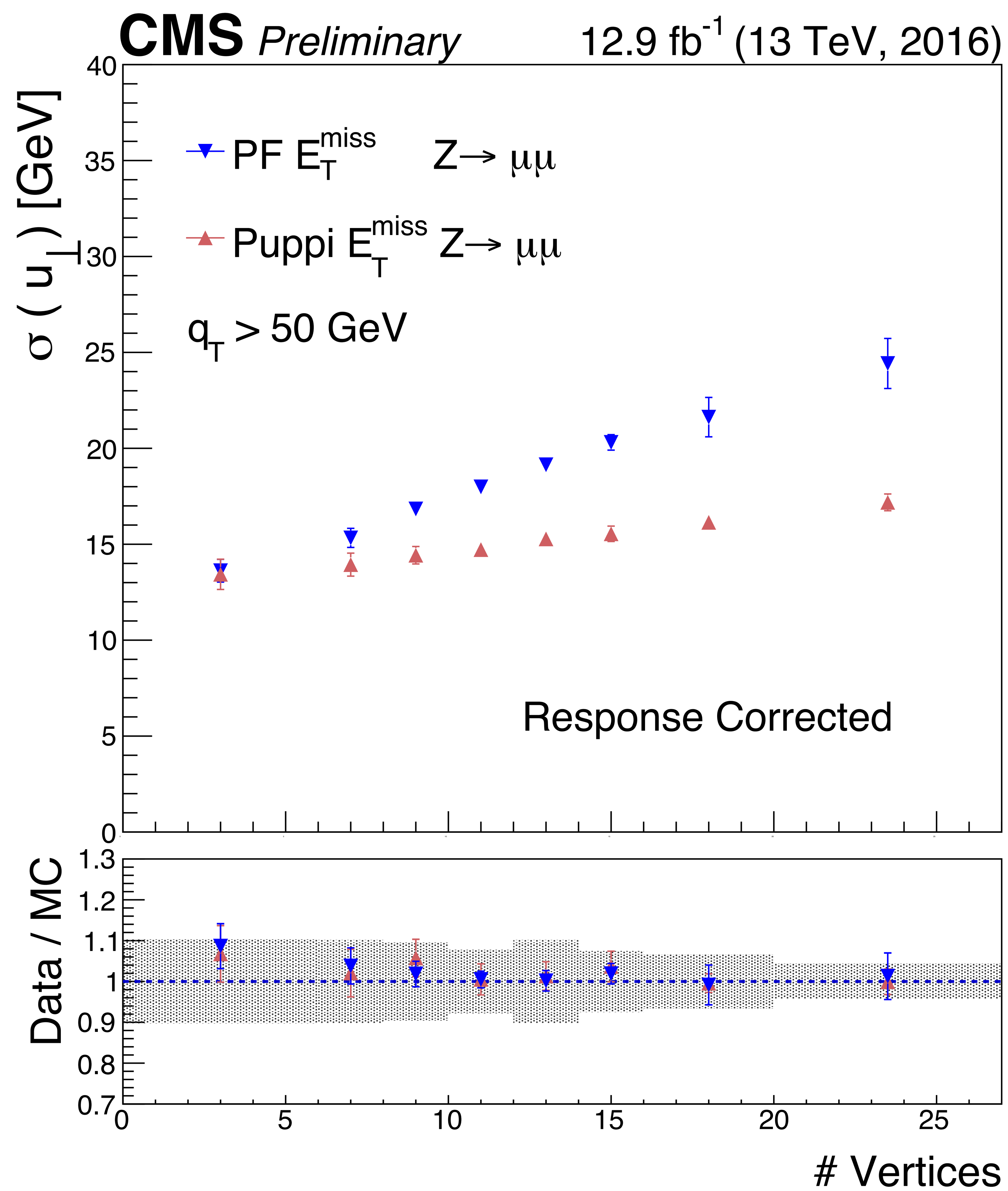
PUPPI PERFORMANCE

CMS-PAS-JME-2016-004

20-30% resolution improvement in the MET resolution @ N_{PV} ~20 over traditional "PU" corrected MET

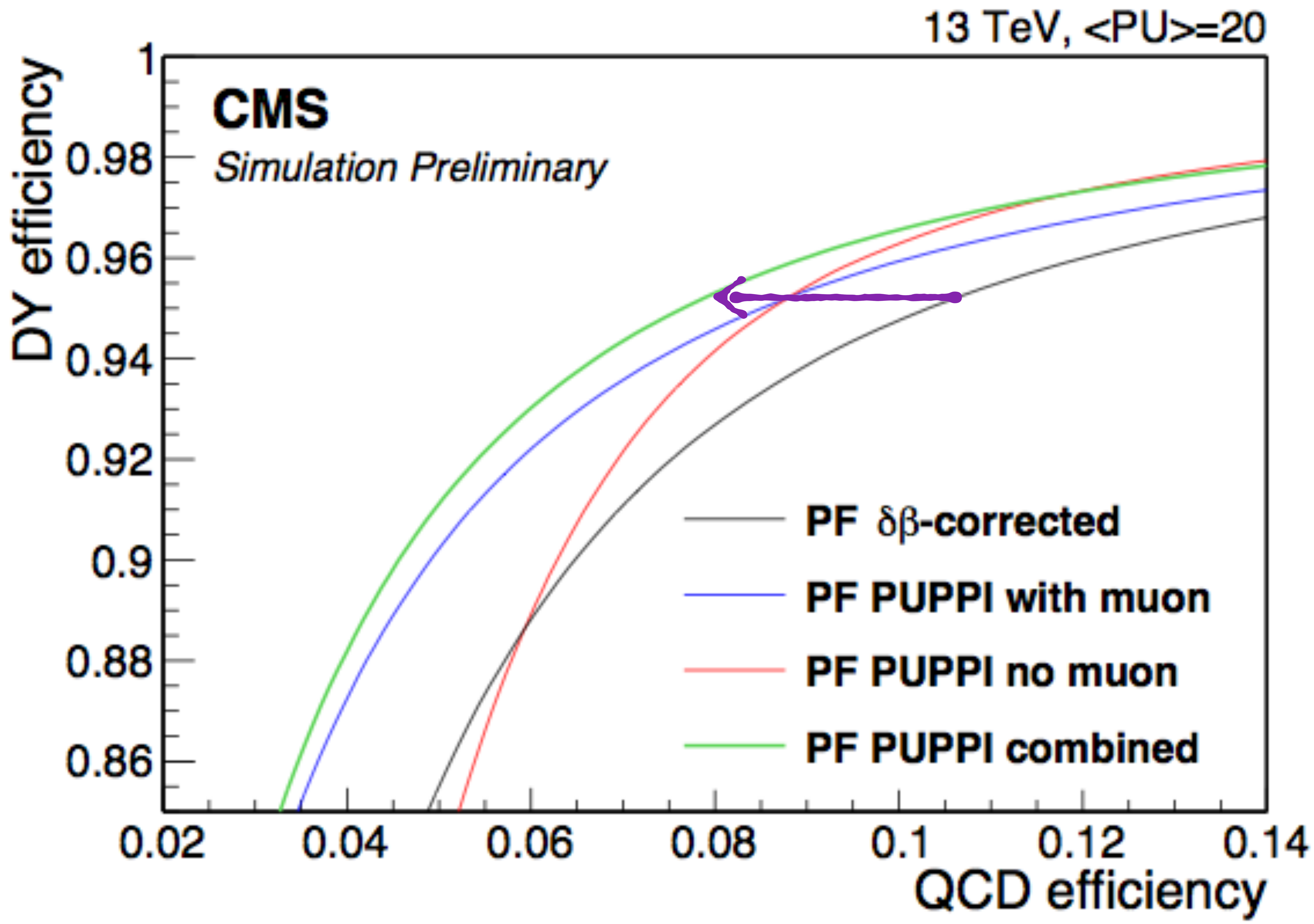






PUPPI PERFORMANCE

CMS-DP-2015-034



25% decrease in backgrounds using per particle uncertainties at 20 PU!

"combined" curve uses both muon hypotheses

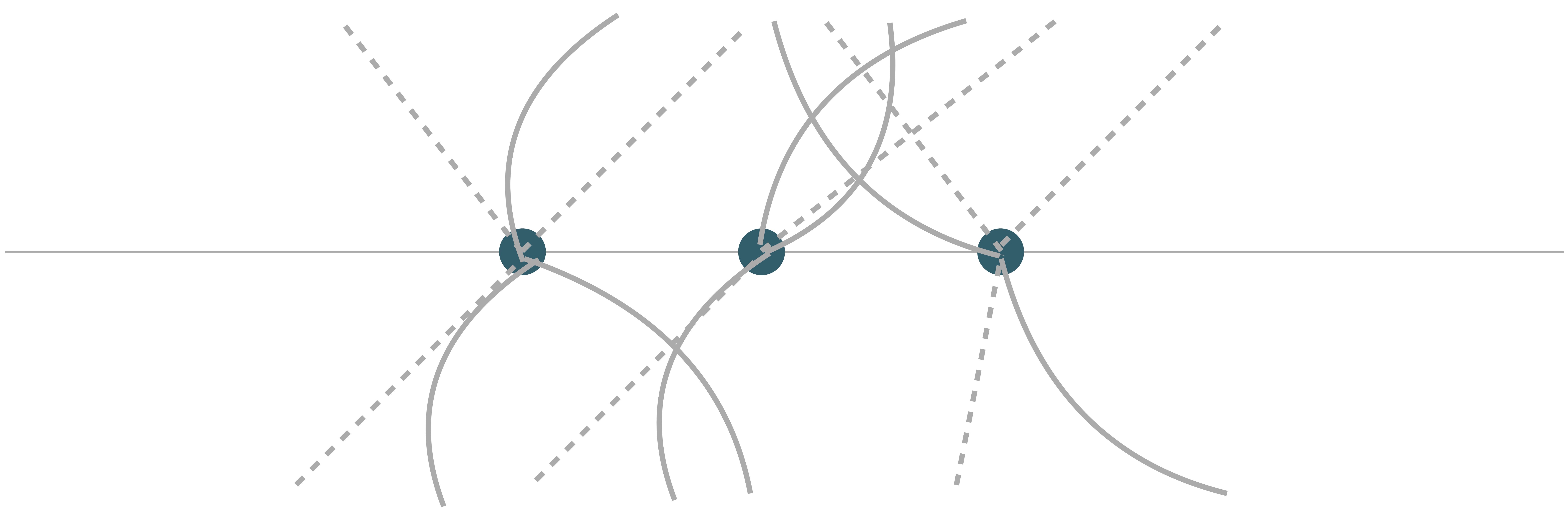
Vs. traditional methods

A REALLY HOLISTIC APPROACH

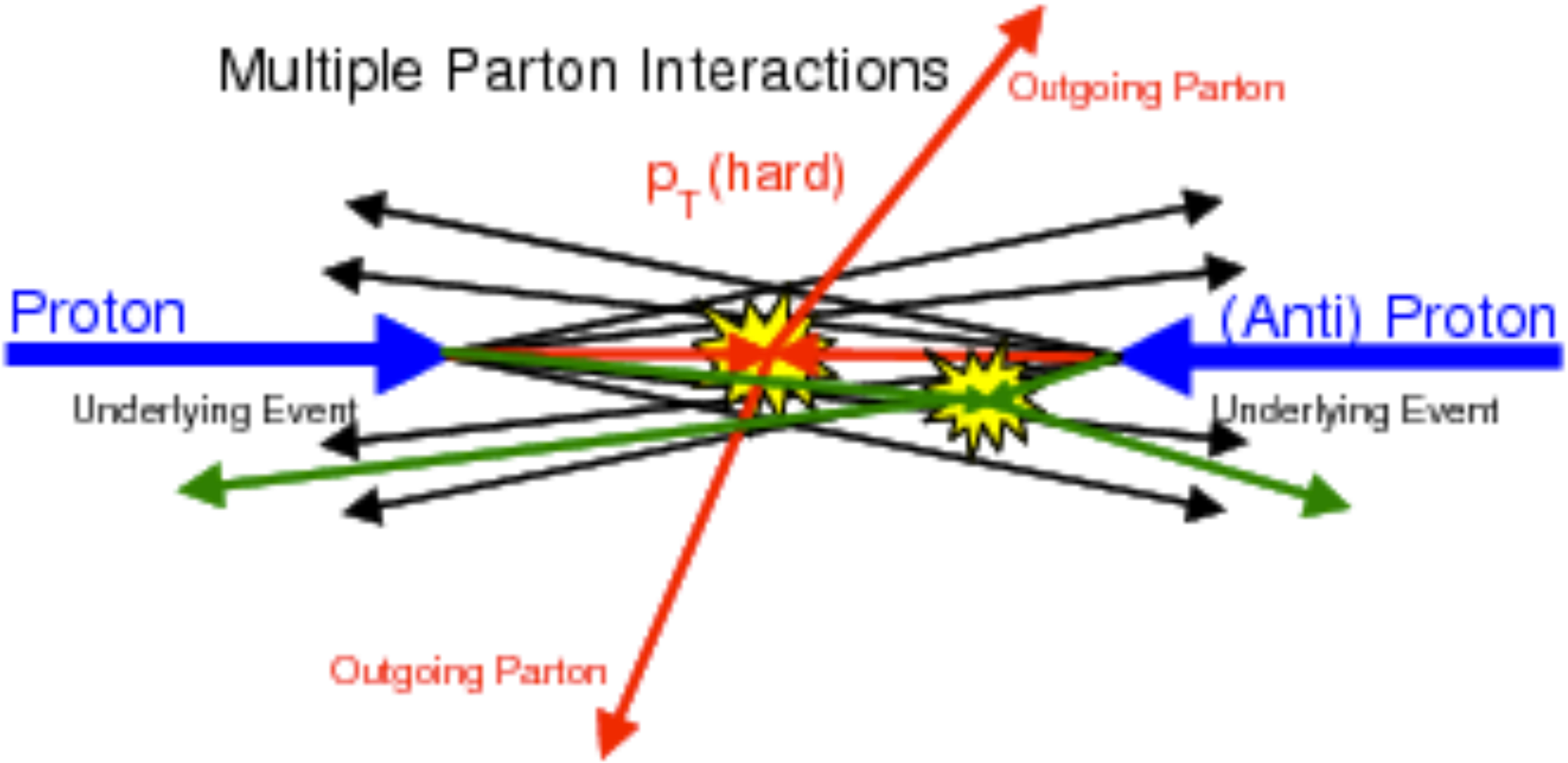
What if, you could identify each particle in the event and give the likelihood that it's pileup?

What if, you could identify each particle in the event and give the likelihood that it belongs to a given vertex i?

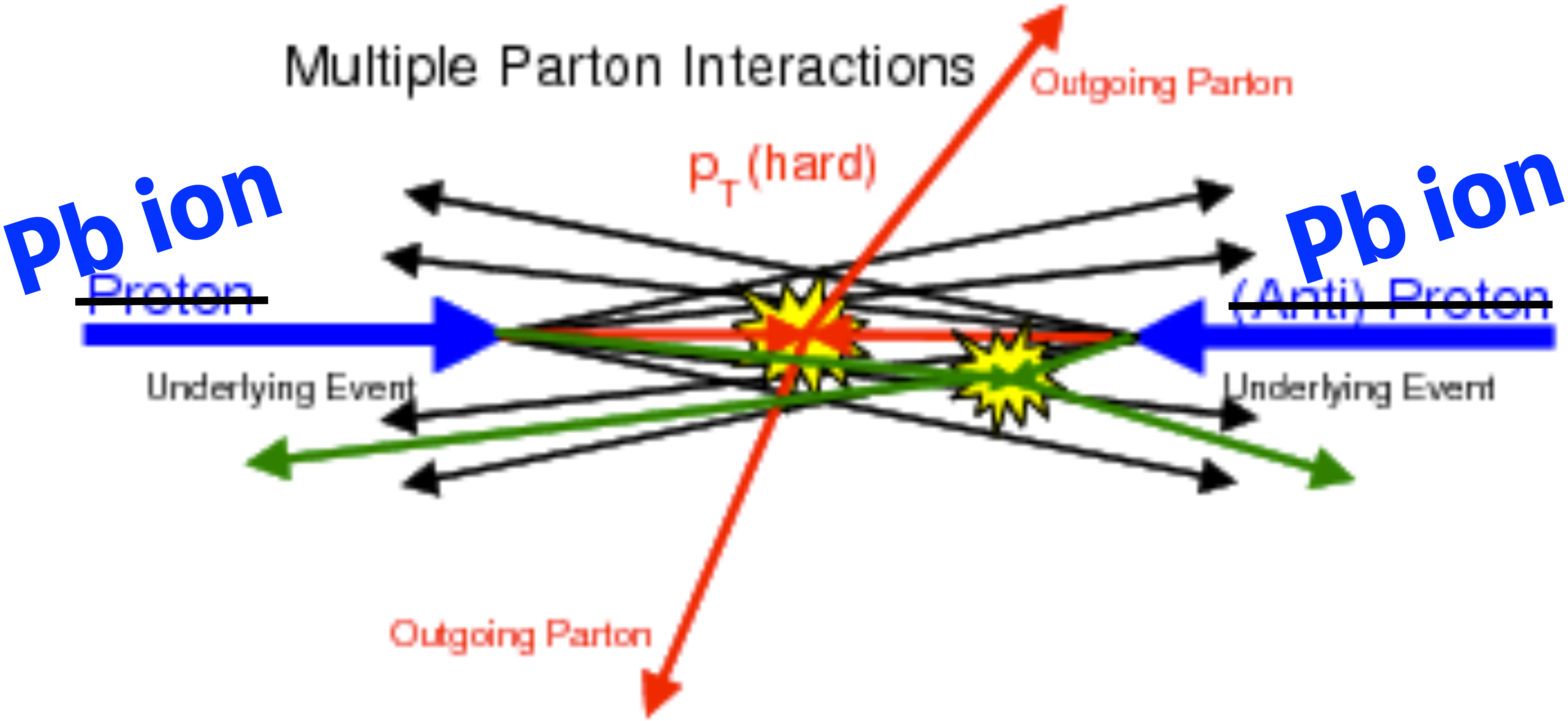
a combination of the PUPPI approach and the ATLAS forward vertex jet tagging ideas….



Contrast against Underlying event



Contrast against Underlying event

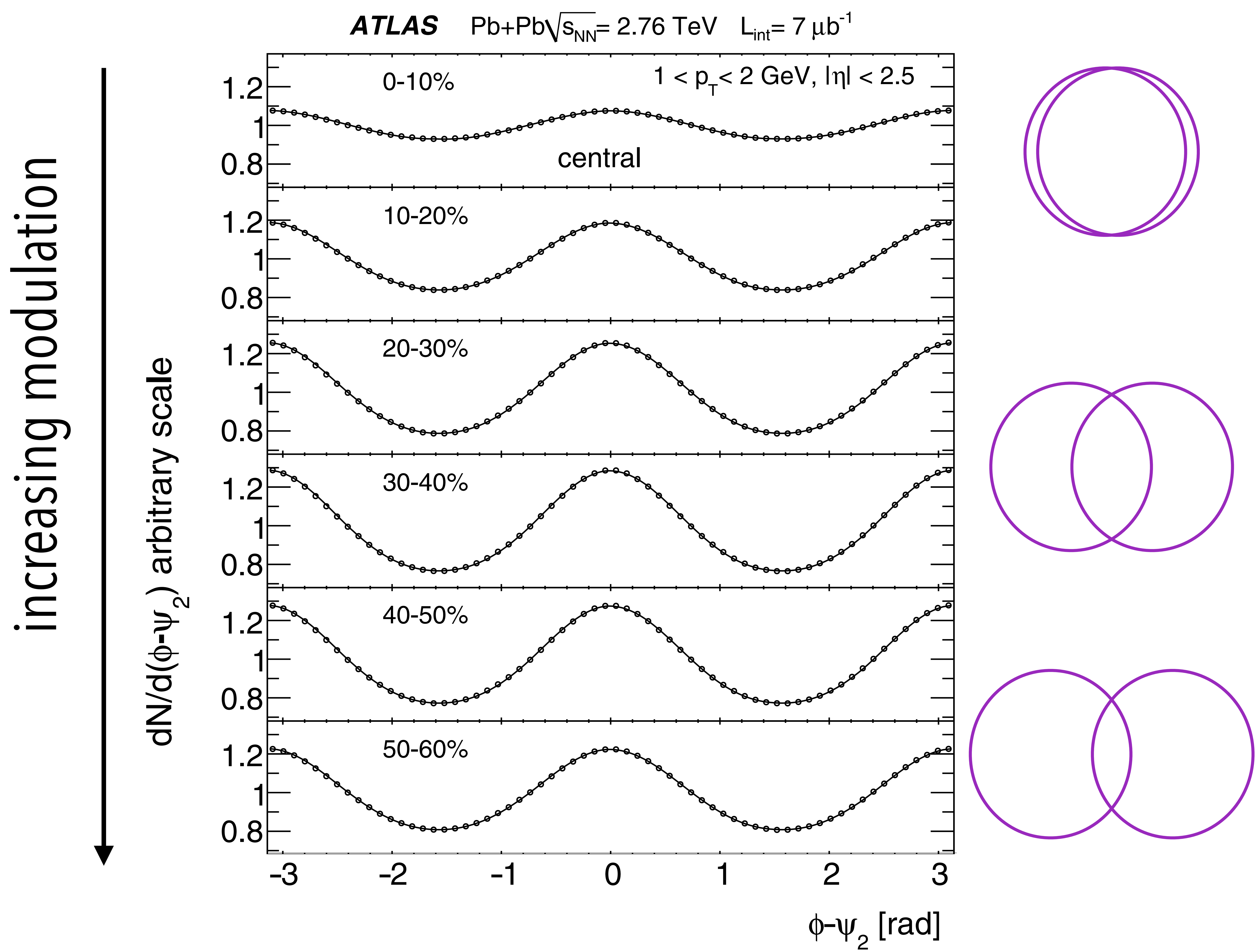


Underlying event in heavy ions

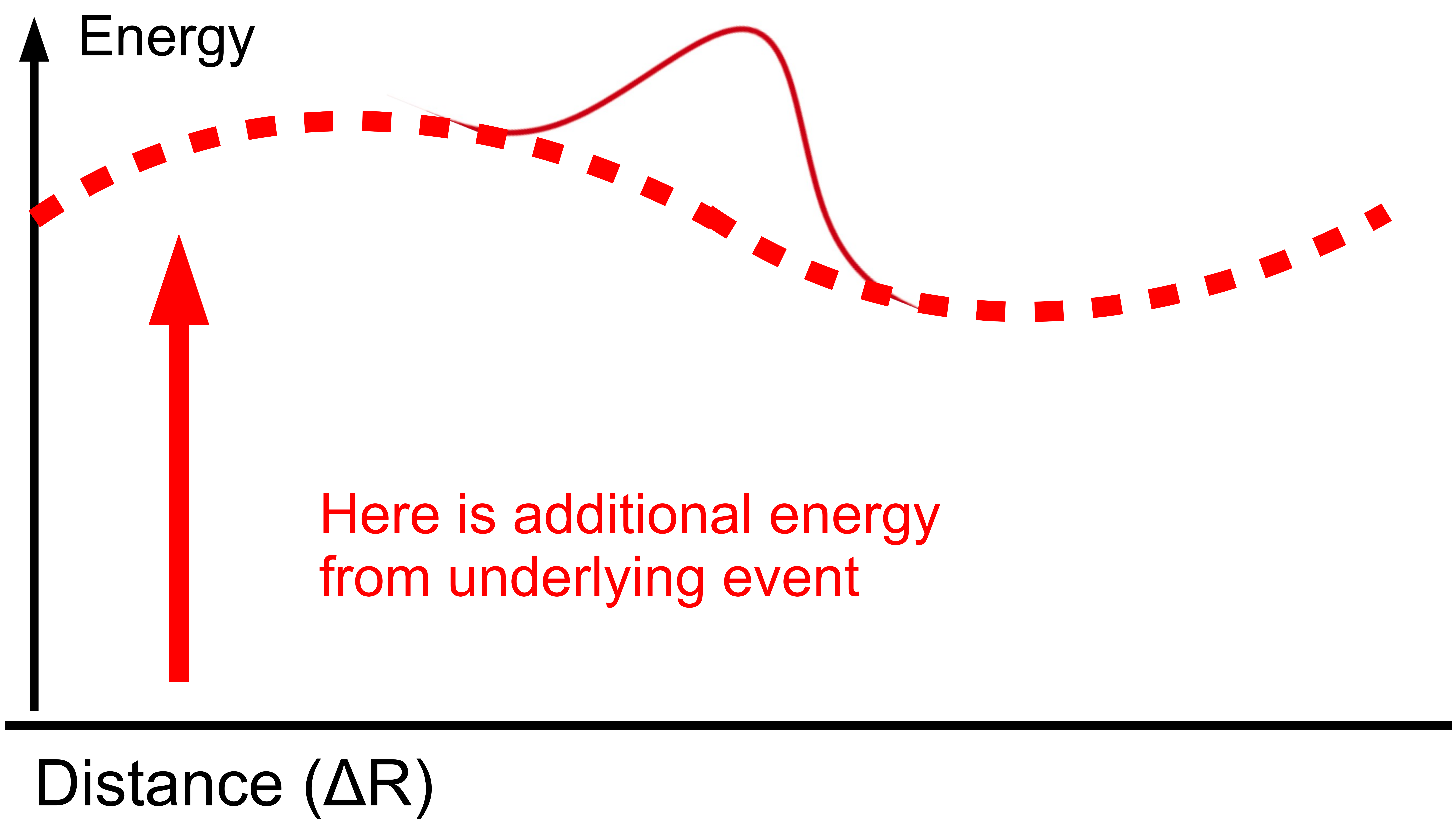
Similar to A LOT of pileup, but without a vertexing handle

…. and it has some correlated structure!

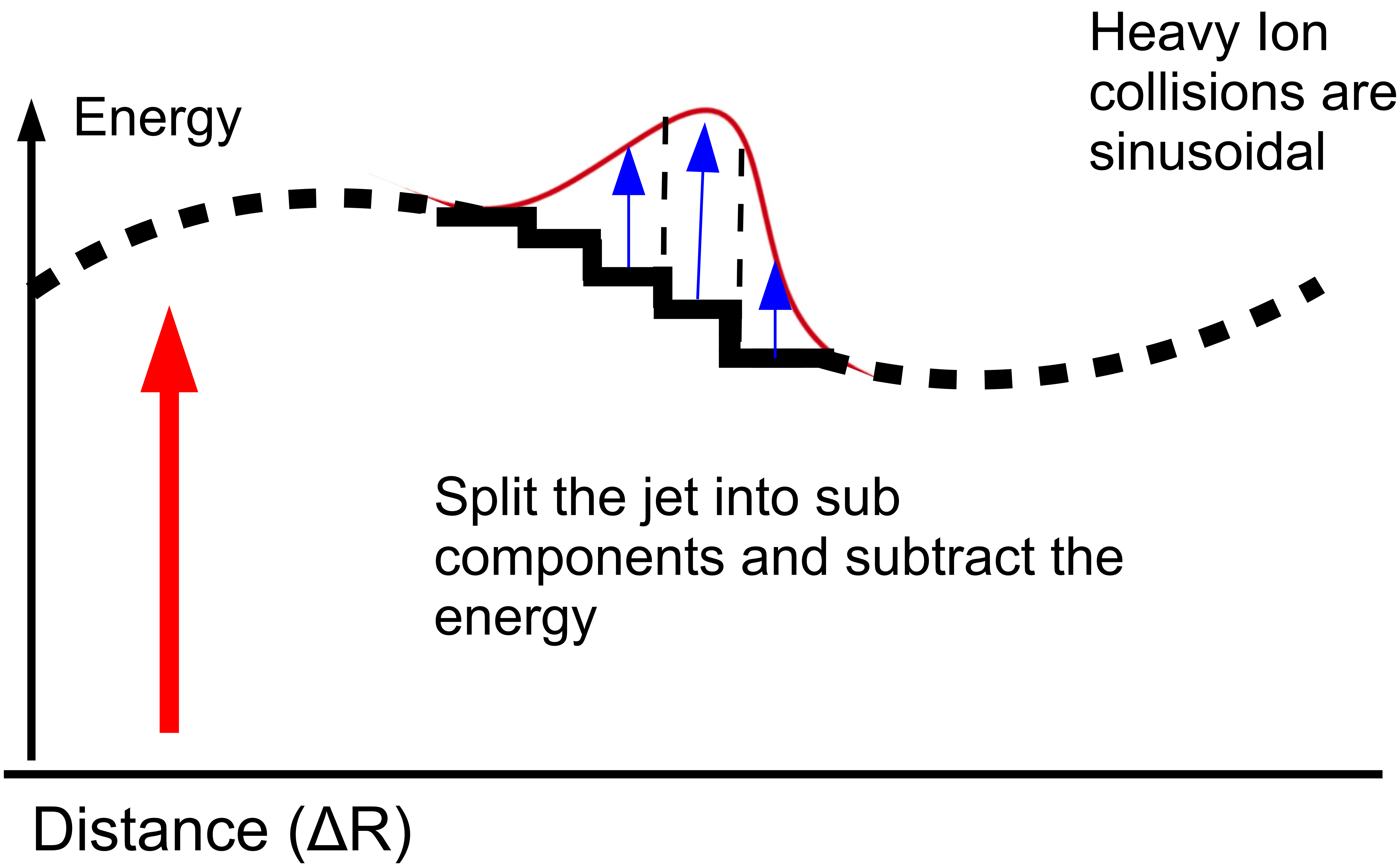
"Underlying event" in Heavy ions



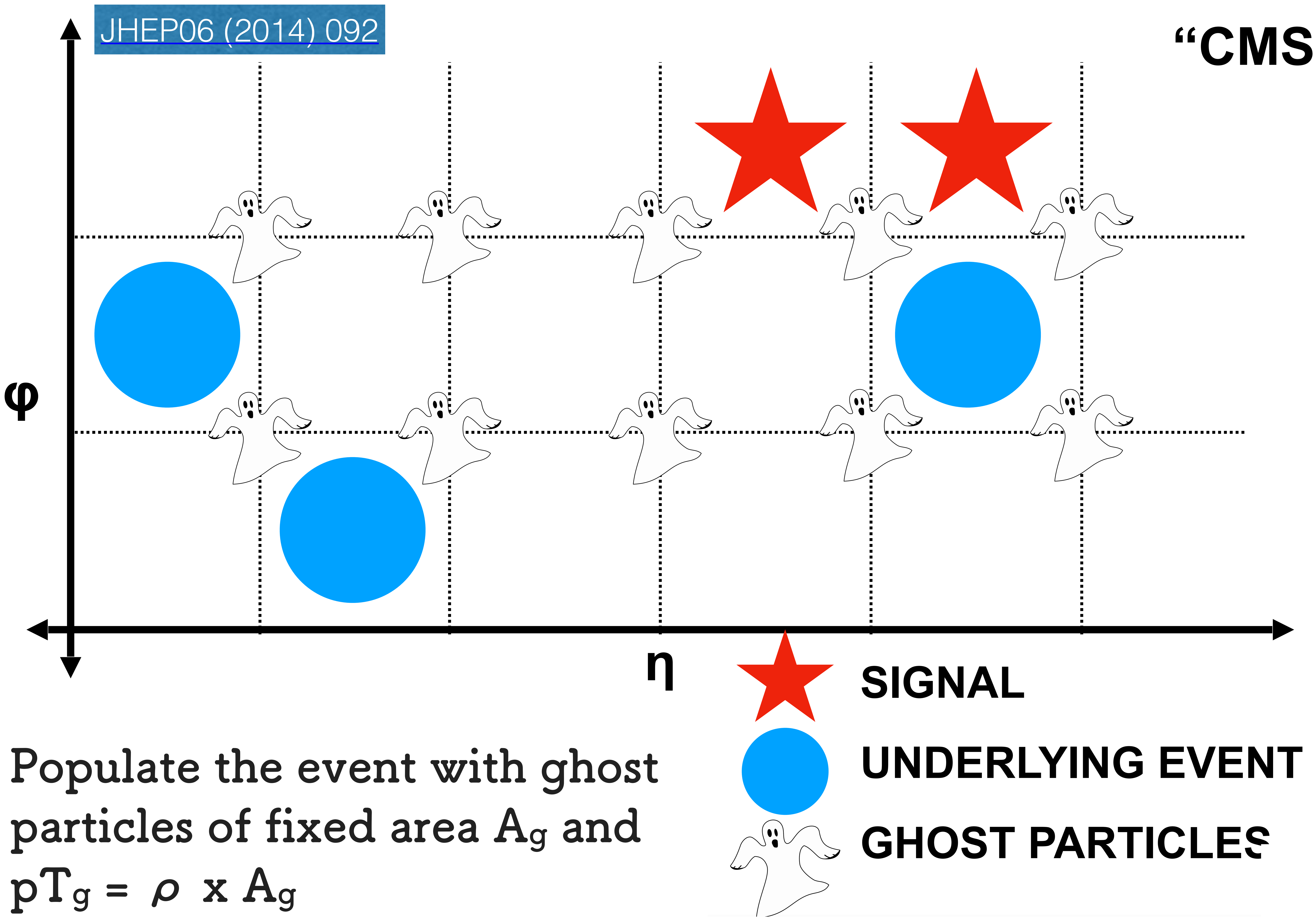
"Underlying event" in Heavy ions



“Underlying event” in Heavy ions



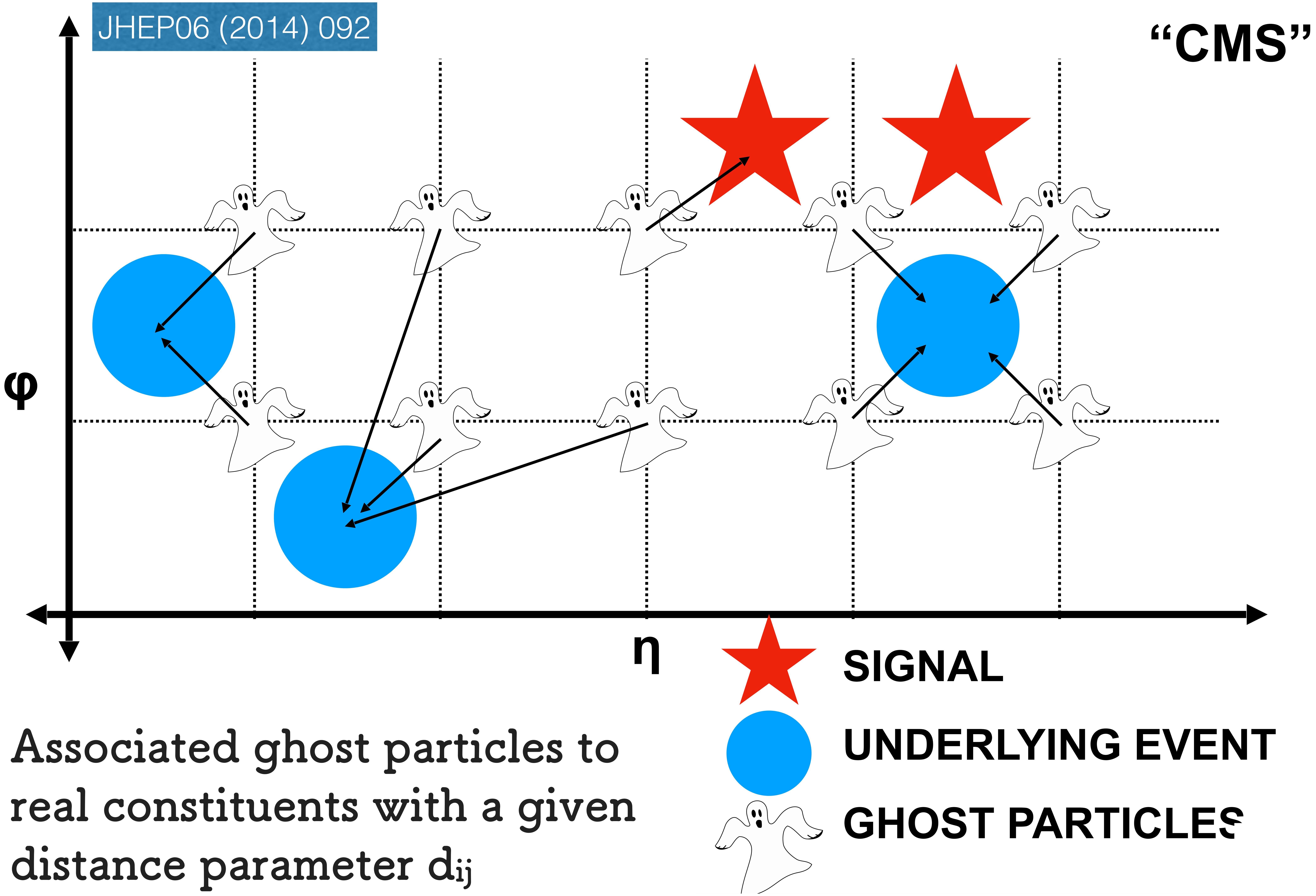
Example: Constituent subtraction



Populate the event with ghost particles of fixed area A_g and $pT_g = \rho \times A_g$

Credit: Chris McGinn

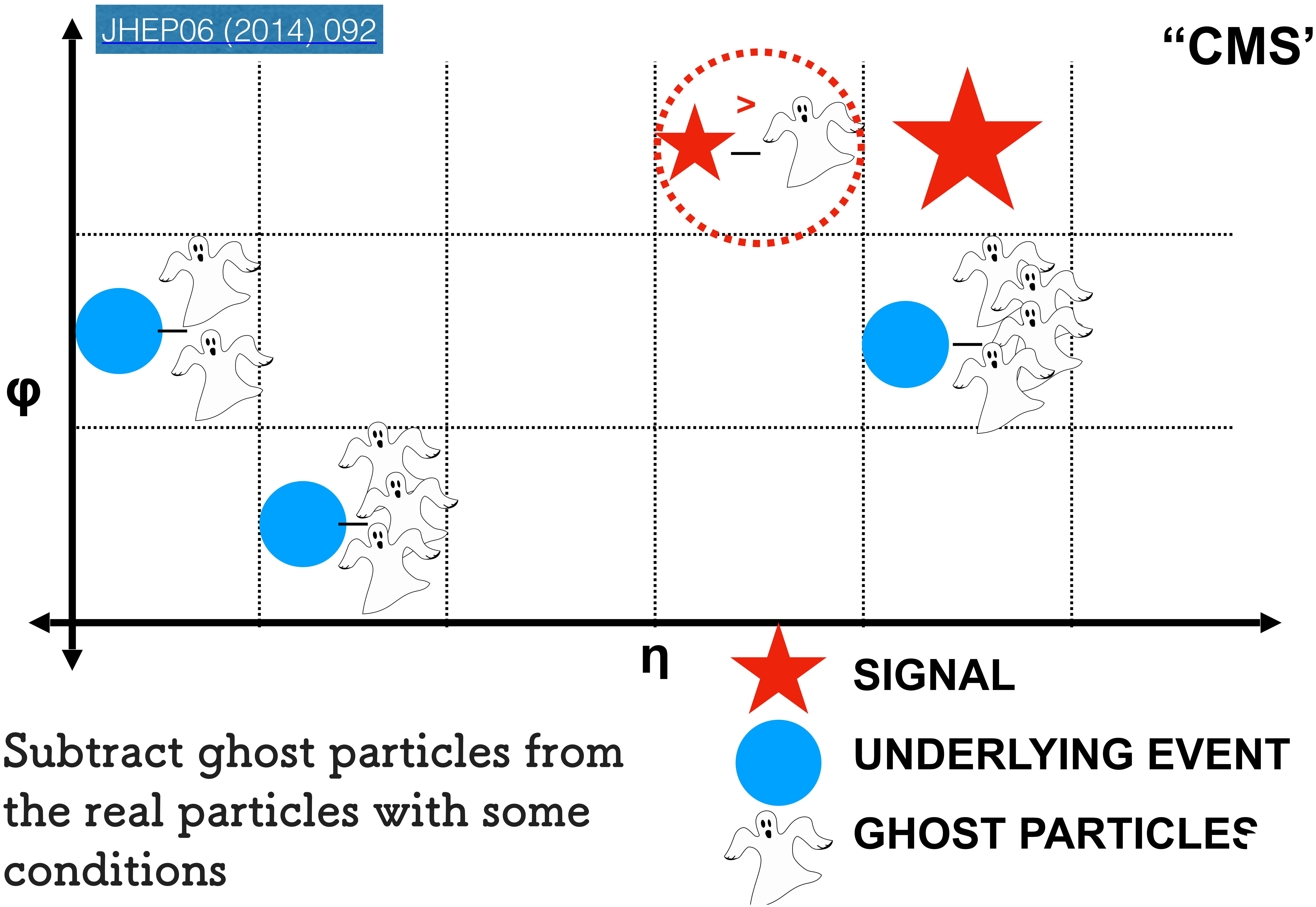
EXAMPLE: CONSTITUENT SUBTRACTION



Associated ghost particles to real constituents with a given distance parameter d_{ij}

Credit: Chris McGinn

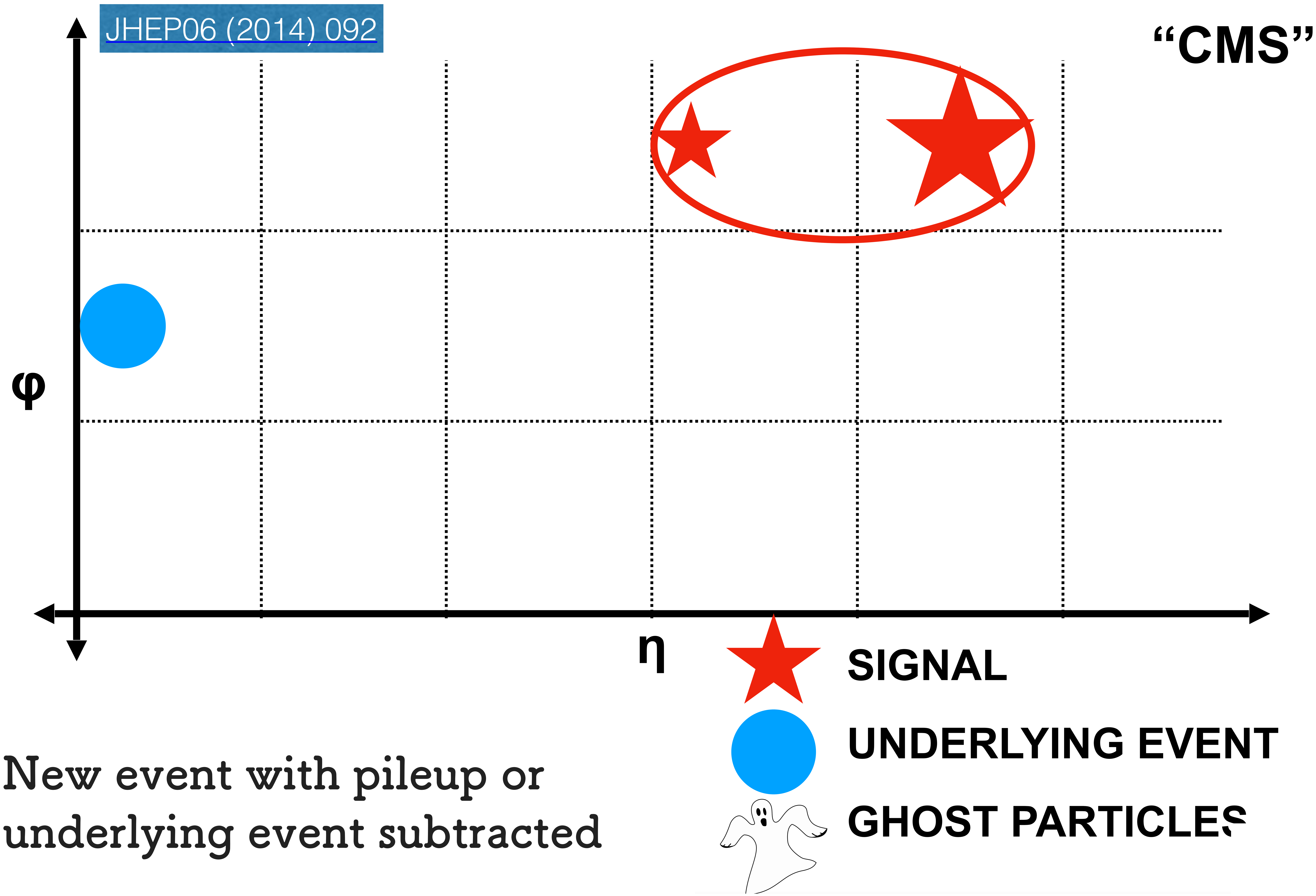
Example: Constituent subtraction



Subtract ghost particles from the real particles with some conditions

Credit: Chris McGinn

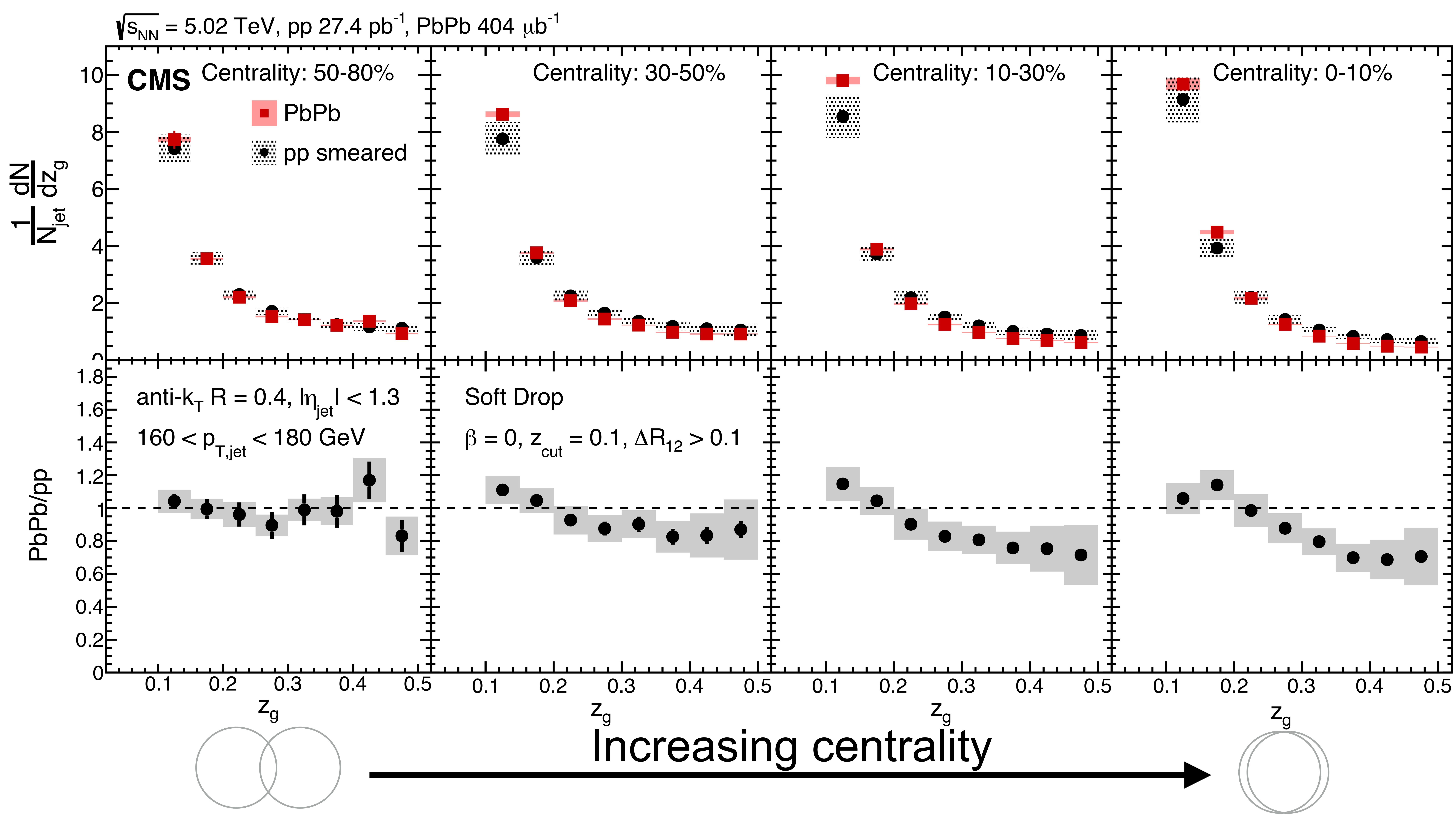
Example: Constituent subtraction



New event with pileup or underlying event subtracted

Credit: Chris McGinn

Example: modification of substructure splitting function in HI!

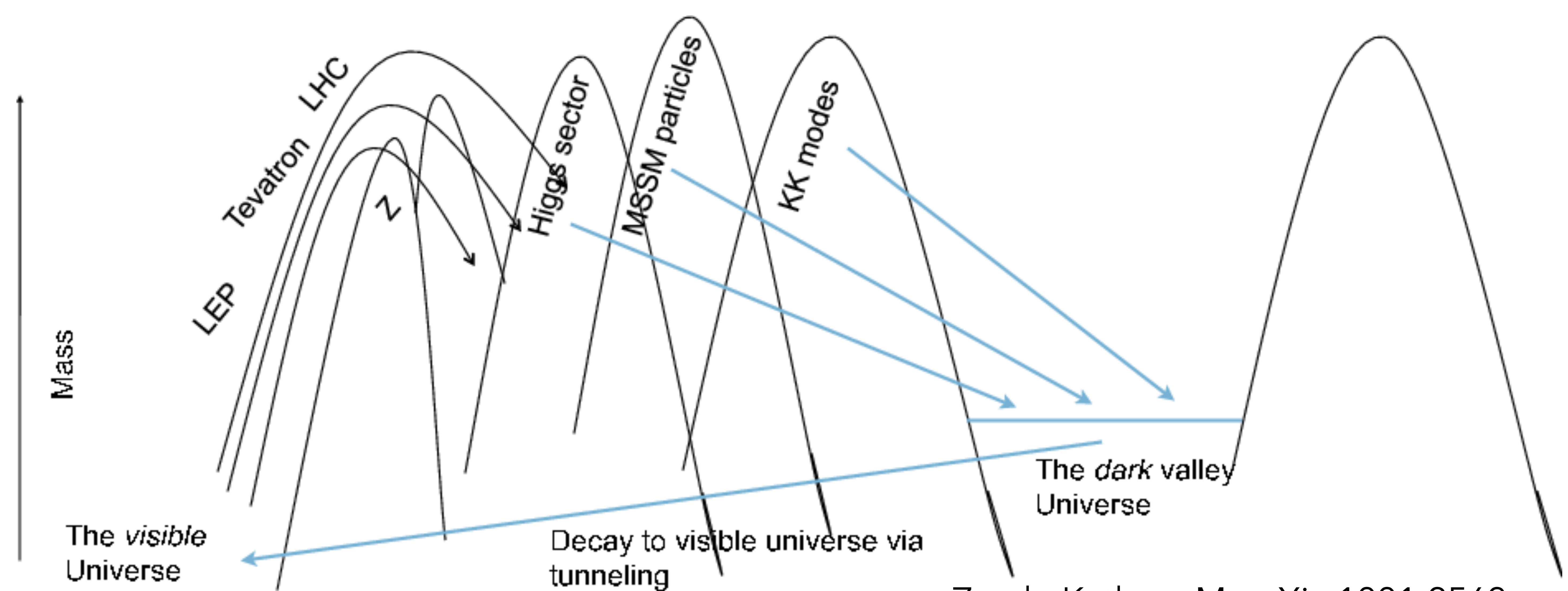


3D. Very Exotic objects

Long-lived Theoretical Motivations

Including but not limited to:

- Split SUSY
- Baryogenesis
- Twin Higgs
- RPV SUSY
- Emerging Jets
- Semi-visible Jets
- Dark Photons
- GMSB
- Hidden Valley Models

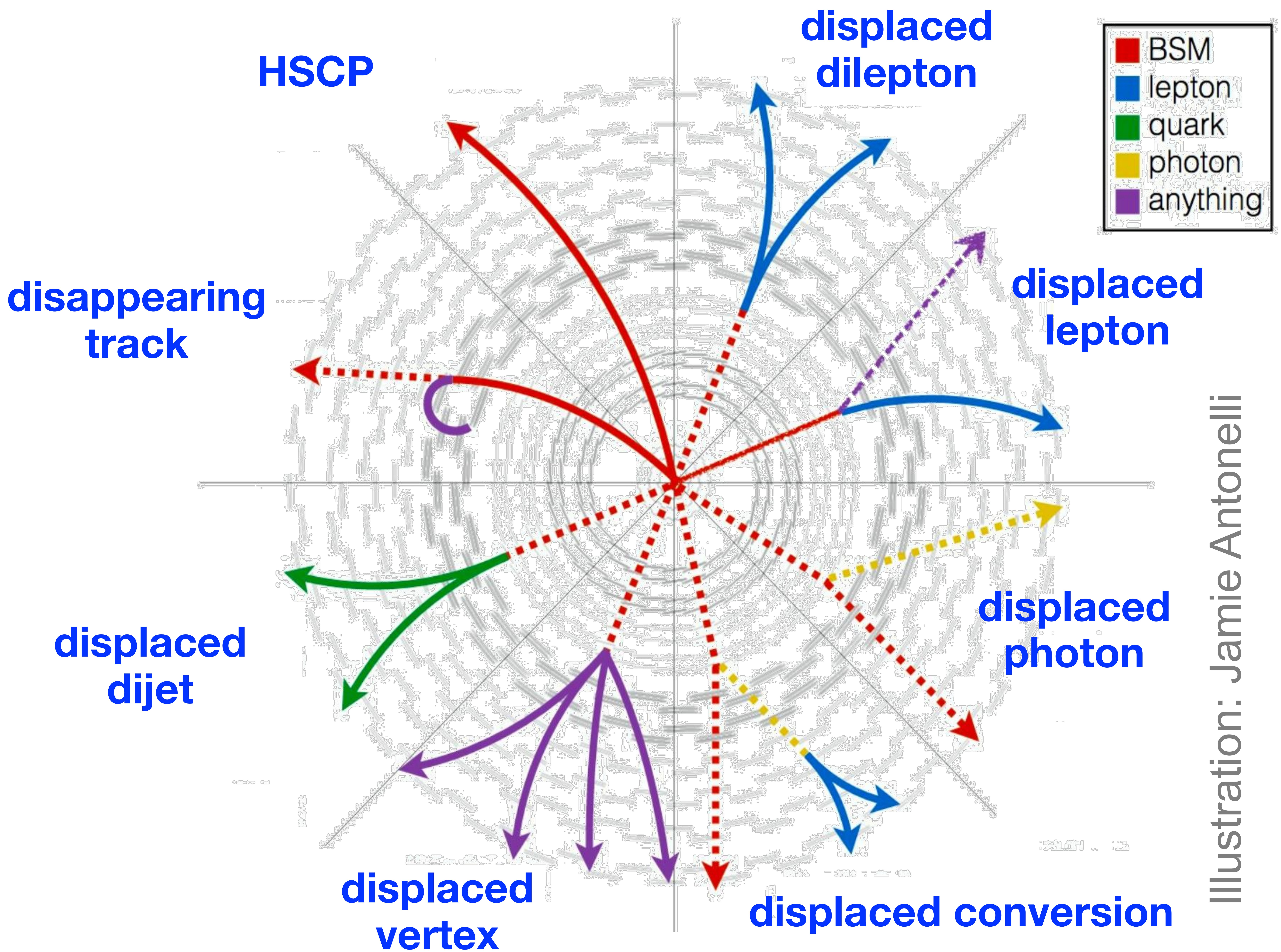


Zurek, Kathryn M. arXiv:1001.2563

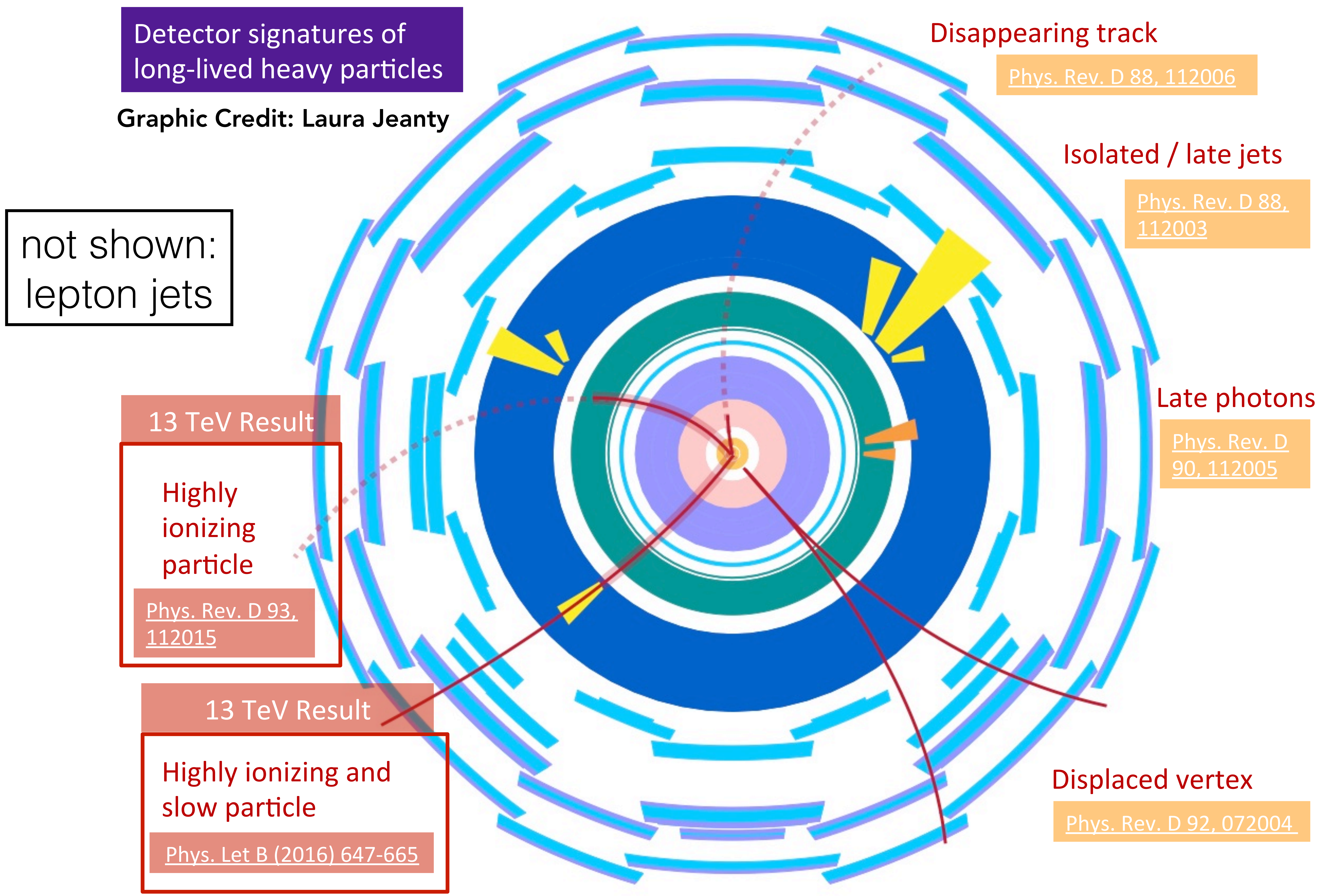
As purely kinematics gains from the LHC diminish exotic decays **continue to indirectly probe higher energy scales**

Credit: Josh Hardenbrook

Very exotic signatures



VERY EXOTIC SIGNATURES



Long-lived, things to keep in mind

A rich variety of signals

- Displaced signals at $c\tau$ > 1mm
  - Reminder: prompt and displaced not exclusive, lifetime distribution ~ $e^{-\tau}$
- Out-of-time signals
- New tracking, kinked tracks, ...

Important to remember that we have to pass the trigger

- Make sure we save such events!
- This can be very non-trivial including new hardware triggers

Use the detector in creative ways!

- dE/dX as a powerful discriminator
- How can we use timing to improve things?
- **Often times, this requires developing completely new types of reconstruction algorithms!**

Wrapping up

My goals for the lectures:

- understand how the design of the detector map into efficient reconstruction of important physics processes
- give basic concept of those reconstruction algorithms
- illustrate examples of how simple reconstruction techniques are built to create composite and complex physics objects

In the landscape of linear luminosity scaling, reconstruction is a great place to improve and extend physics capability

The detectors are more or less fixed; the luminosity is steadily increasing

Room for creativity! Think about novel, interesting, significant physics signals and how you would best detect them.

A fertile area for machine learning applications