Jet Physics
- Experimental Aspects -

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NEW TRENDS IN HEP AND QCD SCHOOL

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This lecture is an attempt to cover the experimental challenges of jet physics at LHC

How to go from detector hits to theory comparison?

What are the new ideas for jet tools?

Notes:

1) jet algorithms⊕theory are not covered in this lectures

2) nice lectures already given (overlap is expected)

Grégory Soyez, Albert de Roeck, Bruno Lenzi, Rikkert Frederix, Marc Besançon

3) some experimental aspects are not covered (ex: efficiencies, trigger)

Dictionary of Hadron Collider Terminology

Reminder

EVENT

HADRON-HADRON COLLISION

Primary (Hard) Parton-Parton Scattering

Initial-State Radiation (ISR) = Spacelike Showers associated with Hard Scattering

Underlying Event

Multiple Parton-Parton Interactions: Additional parton-parton collisions (in principle with showers etc) in the same hadron-hadron collision.

= Multiple Perturbative Interactions (MPI)

= Spectator Interactions

Fragmentation

Perturbative:

Final-State Radiation (FSR)

= Timelike Showers

= Jet Broadening and Hard Final-State Bremsstrahlung

Non-perturbative:

String / Cluster Hadronisation

(Colour Reconnections?)

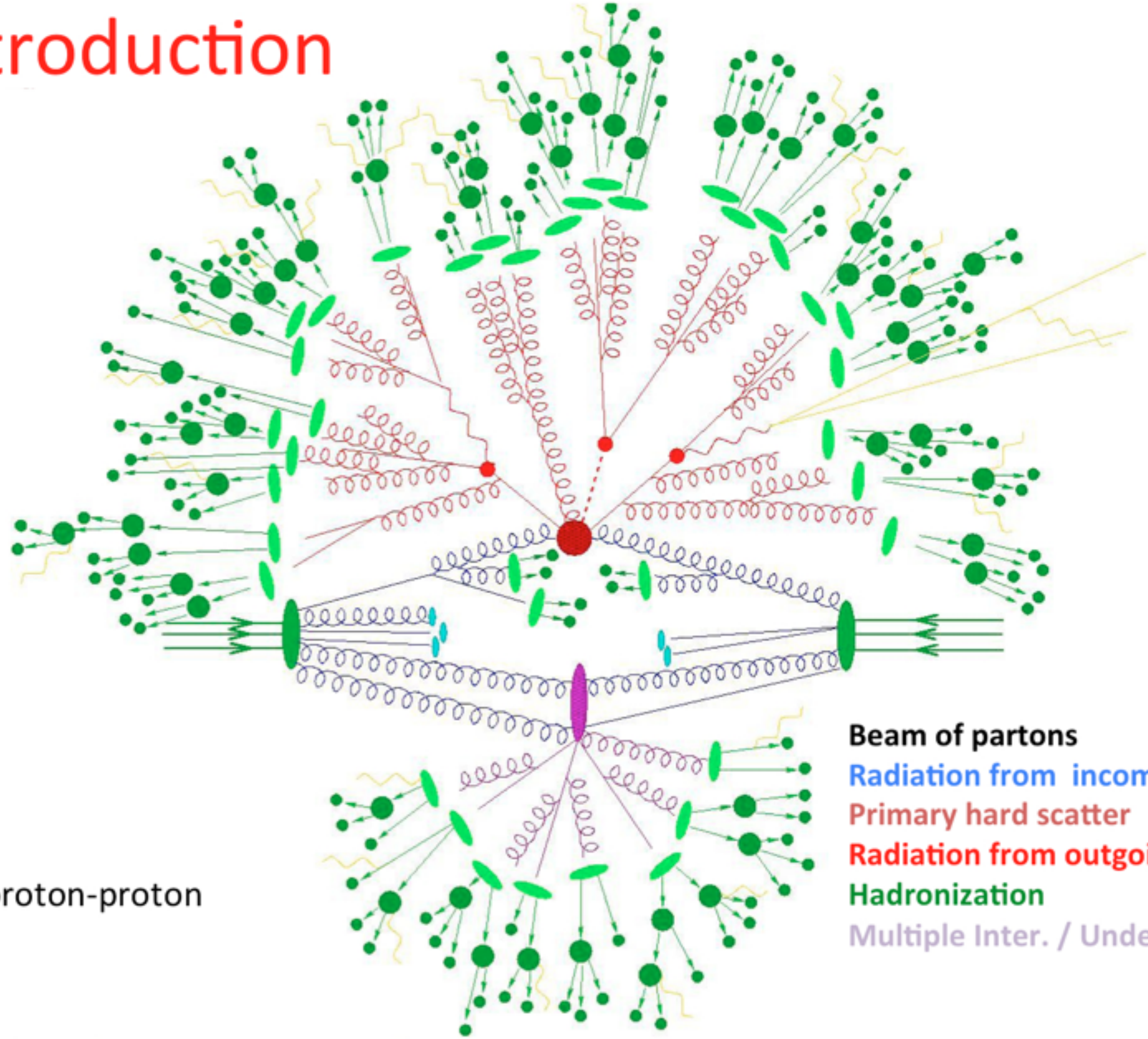
Beam Remnants: Left over hadron remnants from the incoming beams. Coloured and hence correllated with the rest of the event

PILE-UP: Additional hadron-hadron collisions recorded as part of the same event.

TeV4LHC QCD WG - hep-ph/0610012

Is this really what is happening?

Introduction



Typical proton-proton collision

Beam of partons
Radiation from incoming partons
Primary hard scatter
Radiation from outgoing partons
Hadronization
Multiple Inter. / Underlying event

8/30/11 PIC 2011, R. Teuscher IPP/Toronto 2

Truth is a place we can not go

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But, we can take pictures of it

Truth is a place we can not go

Truth is a place we can not go

And, we can paint how we think it is

Truth is a place we can not go

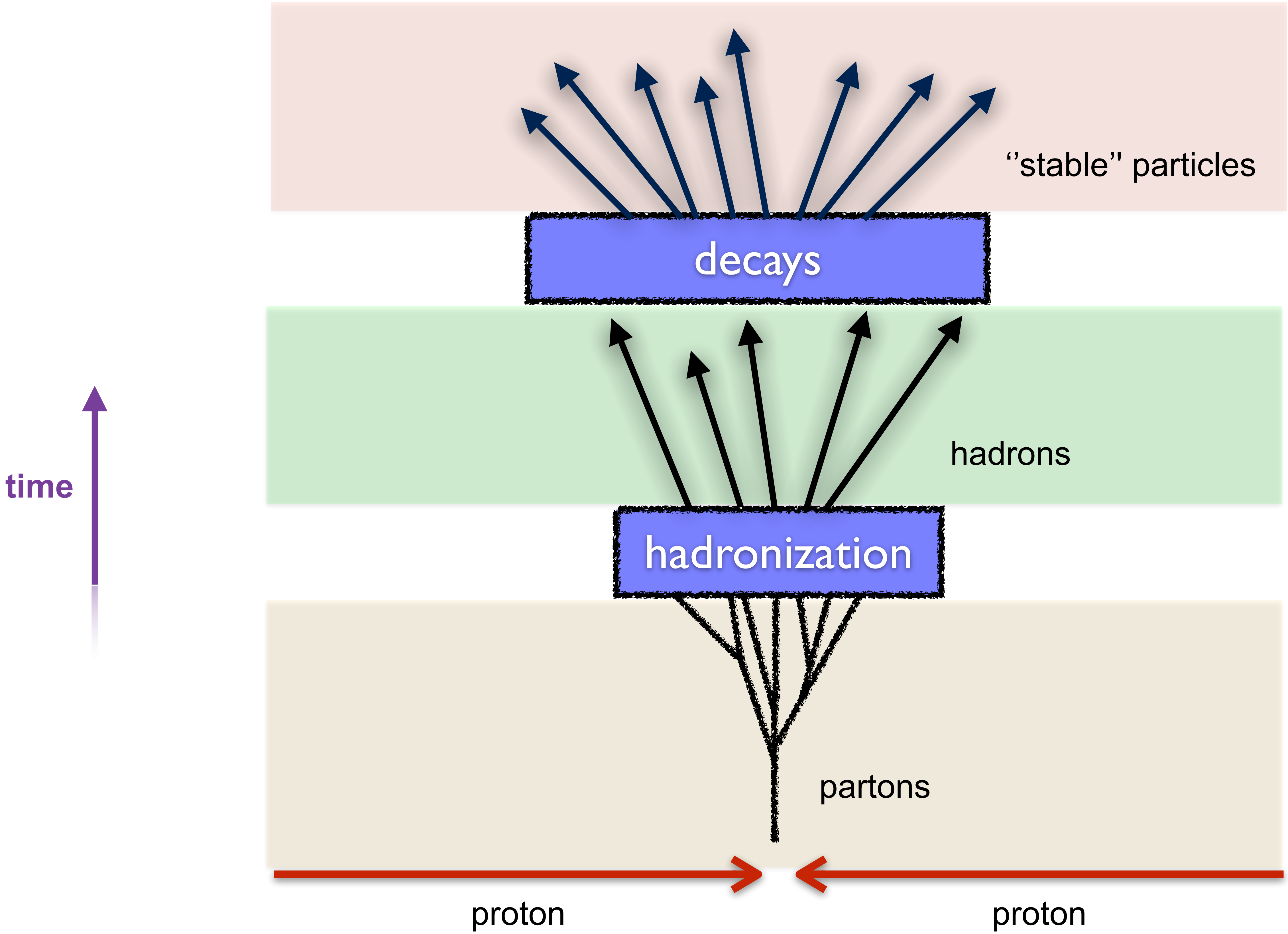
Epistemological Realism - Personal View

Truth is a place we can not go

Our job is to compare photographies with paintings

Both photographers and painters are doing a great job

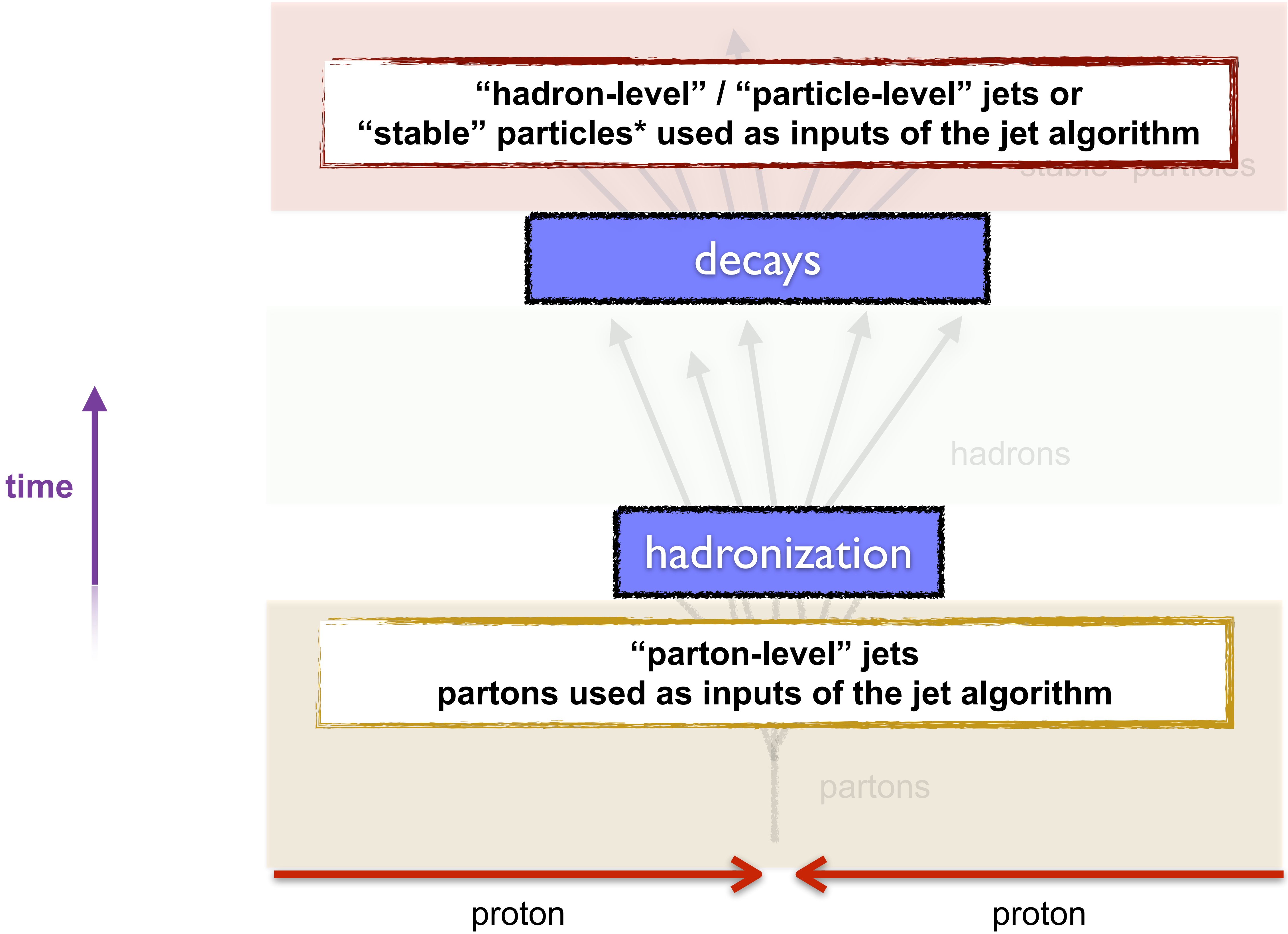
Jet evolution



- Algorithms that combine nearest particles
  - Cambridge/Aachen algorithm: combine particles nearest each other
  - "kT" algorithm: preference for combining lower-momentum particle pairs first, then moving on to higher-momentum pairs
  - "anti-kt" algorithm collects particles around the hardest particle first. It guarantees "cone-like geometry" with well-defined borders around the highest-k_T particles and it maintains the infrared safety and collinear safety of sequential recombination family
- These algorithms correspond to *p*=0, *p*=1 and *p*=-1.

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

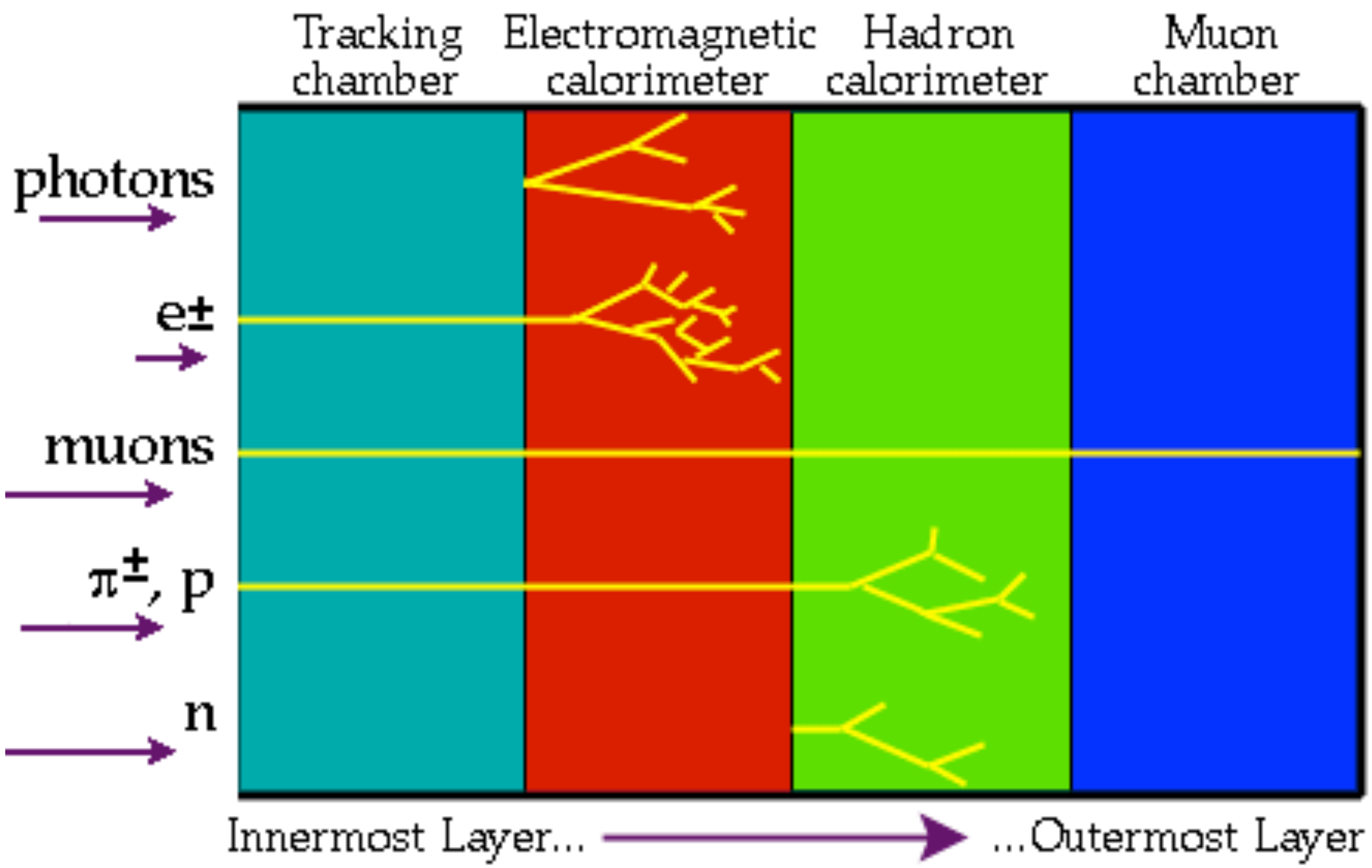
Jet evolution



*Neutrinos are excluded

Experimental Challenge

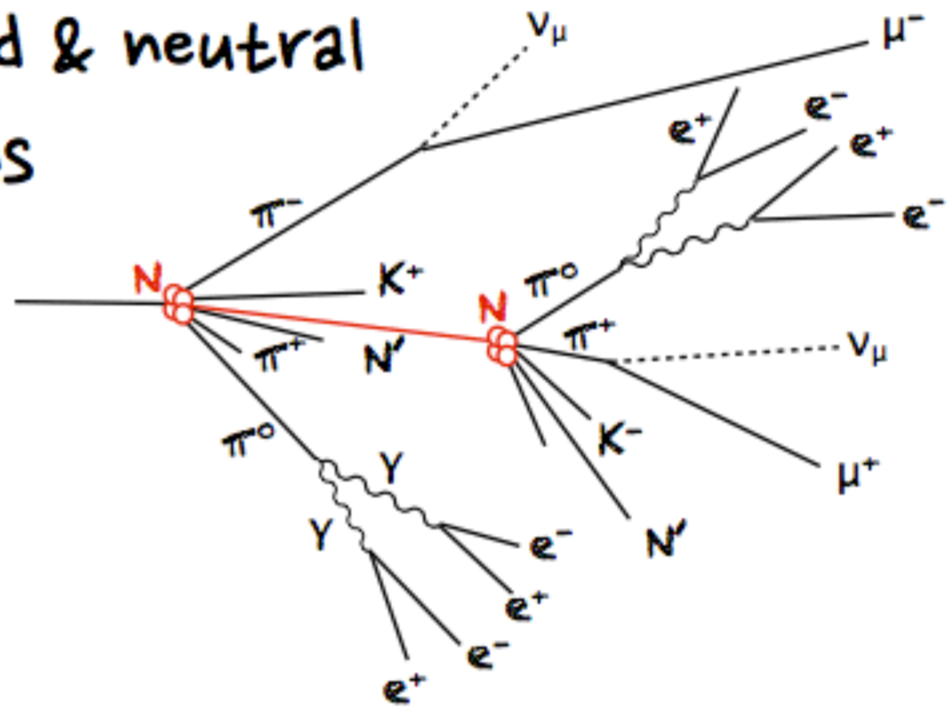
- **Only "stable" particles are detected (τ >10^{-8} s)***
- **Prior knowledge of their interactions are needed**

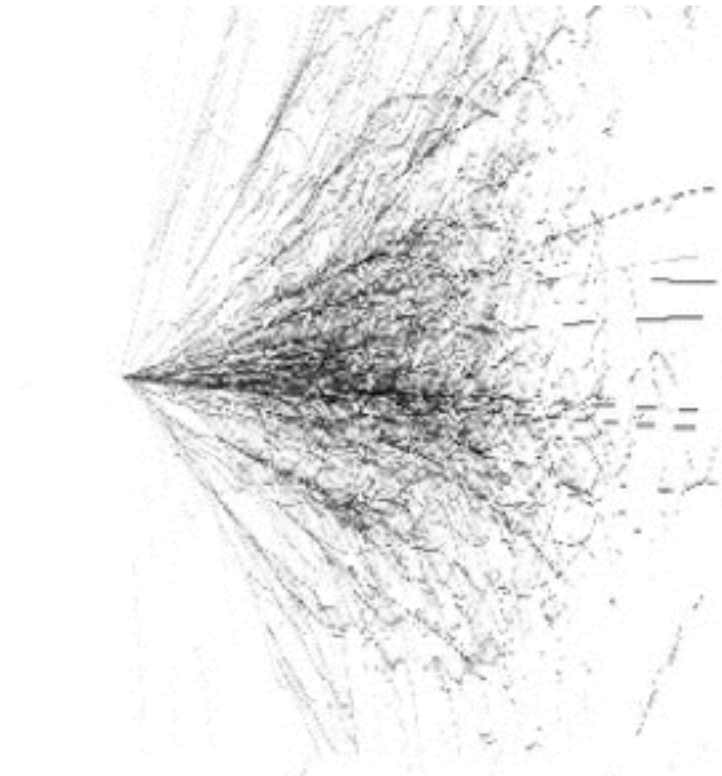


http://www.particleadventure.org/

*These include π, K, p, n, e, μ, γ and K_L^0.
Neutrinos are invisible

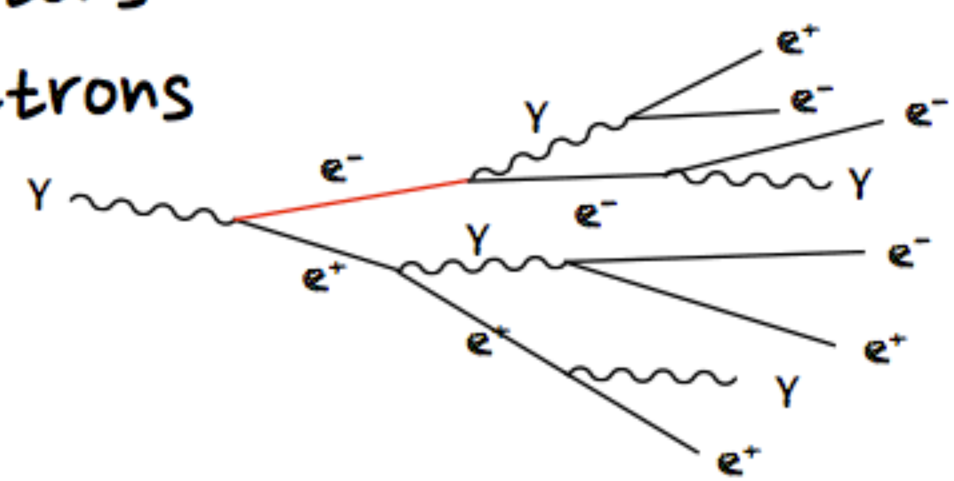
charged & neutral hadrons

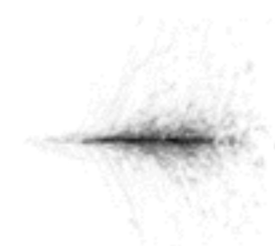




Photons

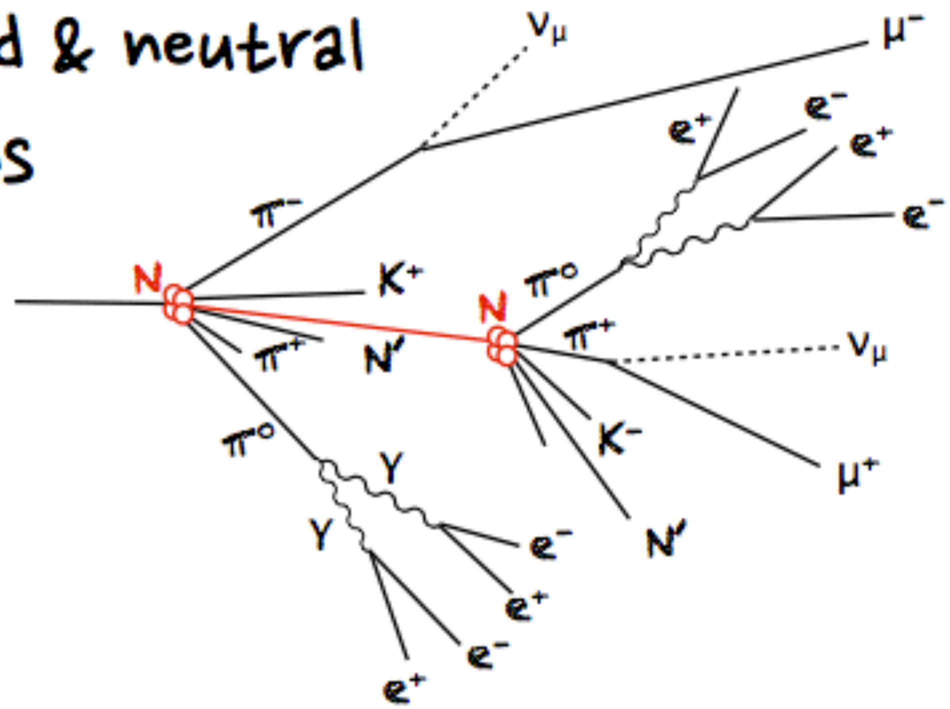
Electrons





R. Cavanaugh, HCPSS 2012

charged & neutral hadrons



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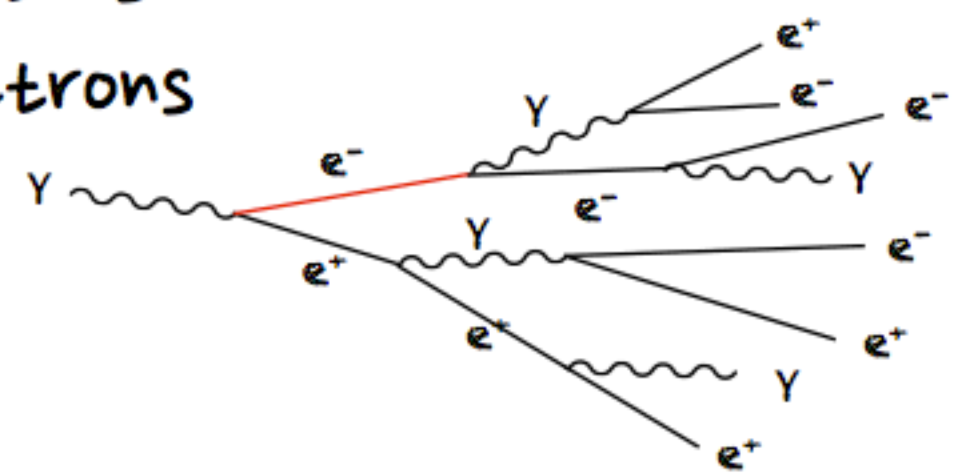
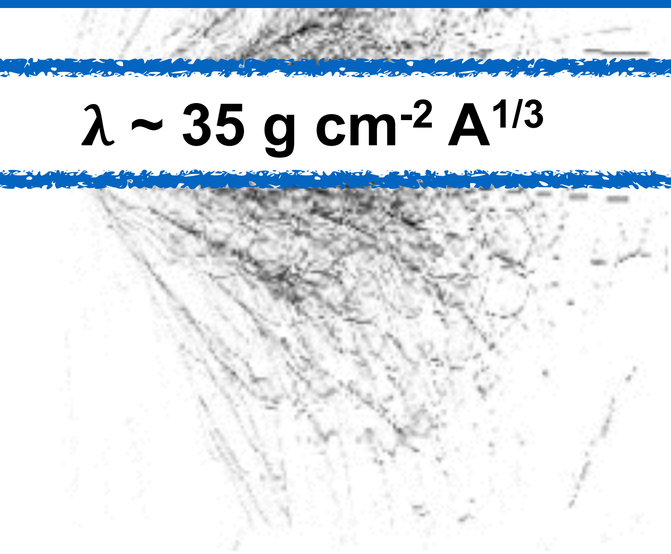
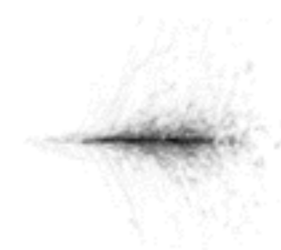


Nuclear Interaction Length

Mean distance over which a hadron collides with a nuclei



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



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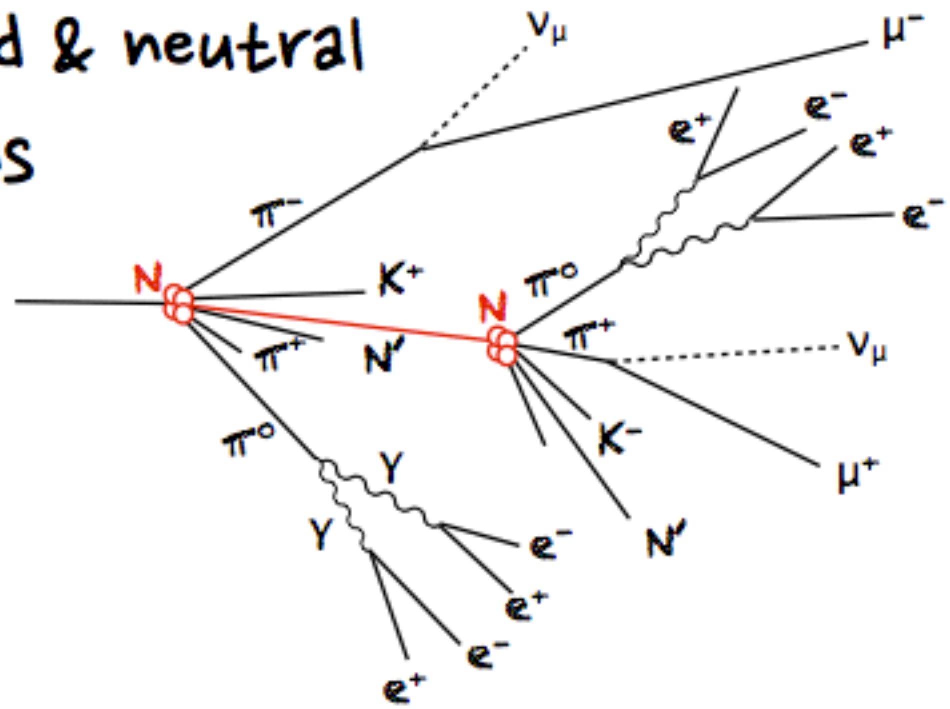

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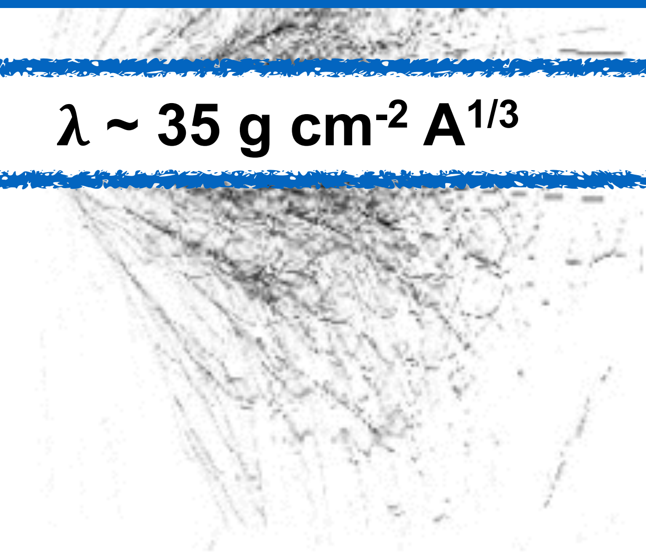

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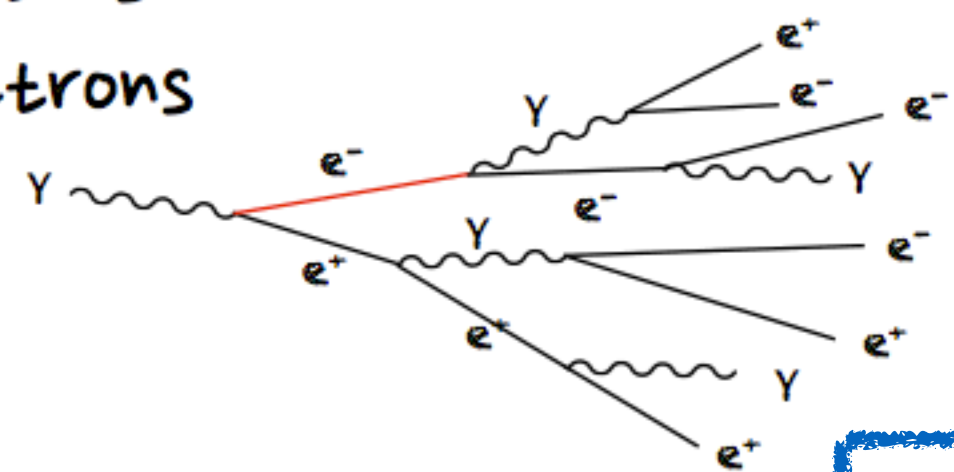


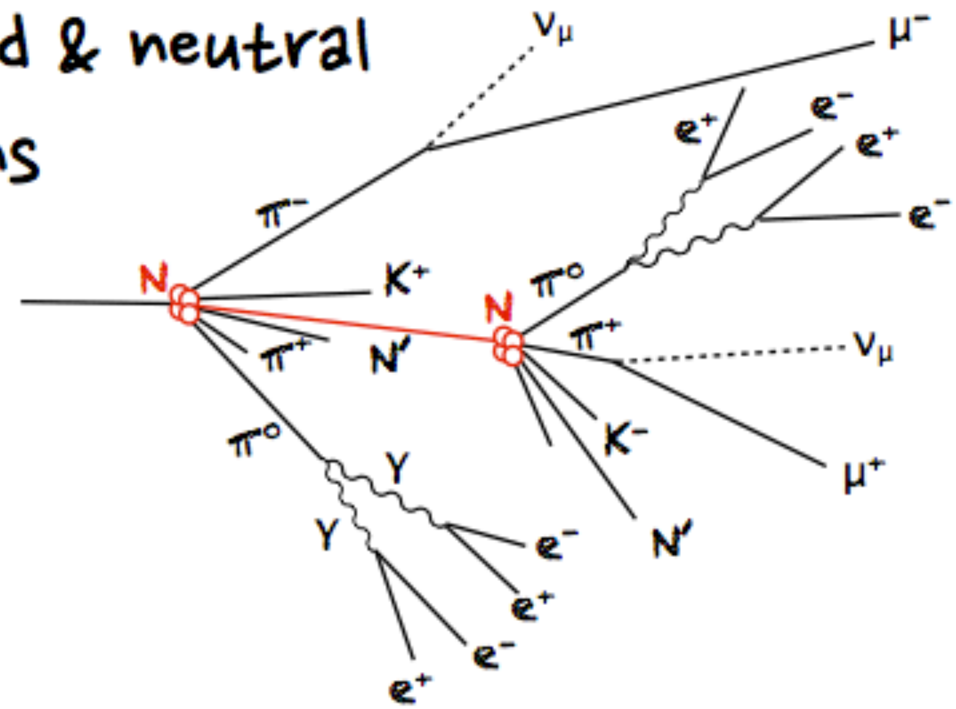
Radiation length

Mean distance over which the electron energy is reduced by a factor of **1/e** due to radiation losses

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}} \text{ g} \cdot \text{cm}^{-2} = \frac{1432.8 \cdot A}{Z(Z+1)(11.319 - \ln Z)} \text{ g} \cdot \text{cm}^{-2}$$

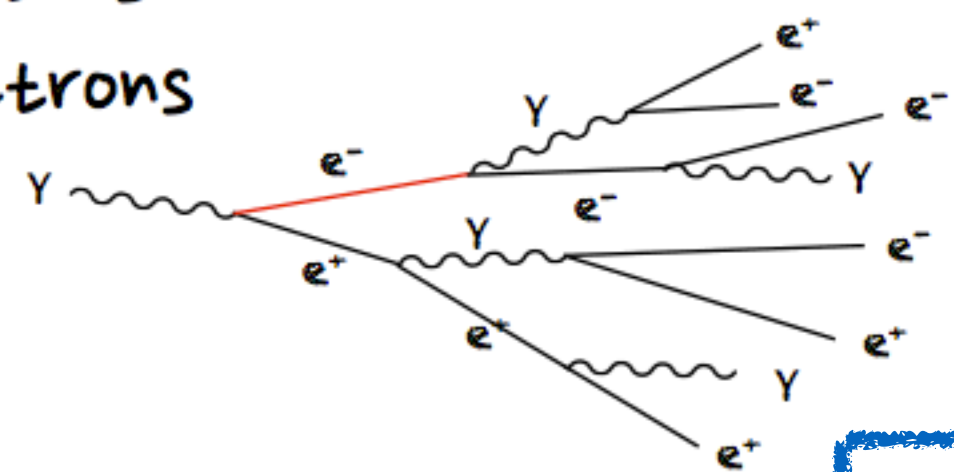
R. Cavanaugh, HCPSS 2012

charged & neutral hadrons



Photons

Electrons



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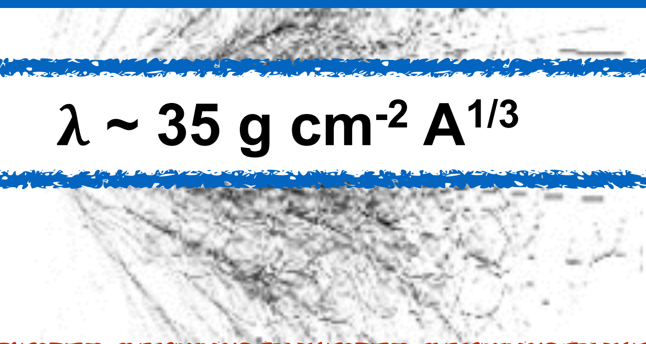

$\lambda \sim 35 \text{ g cm}^{-2} A^{1/3}$

Typical values for lead

$\lambda \sim 17$ cm

$X_0 \sim 5.5$ mm

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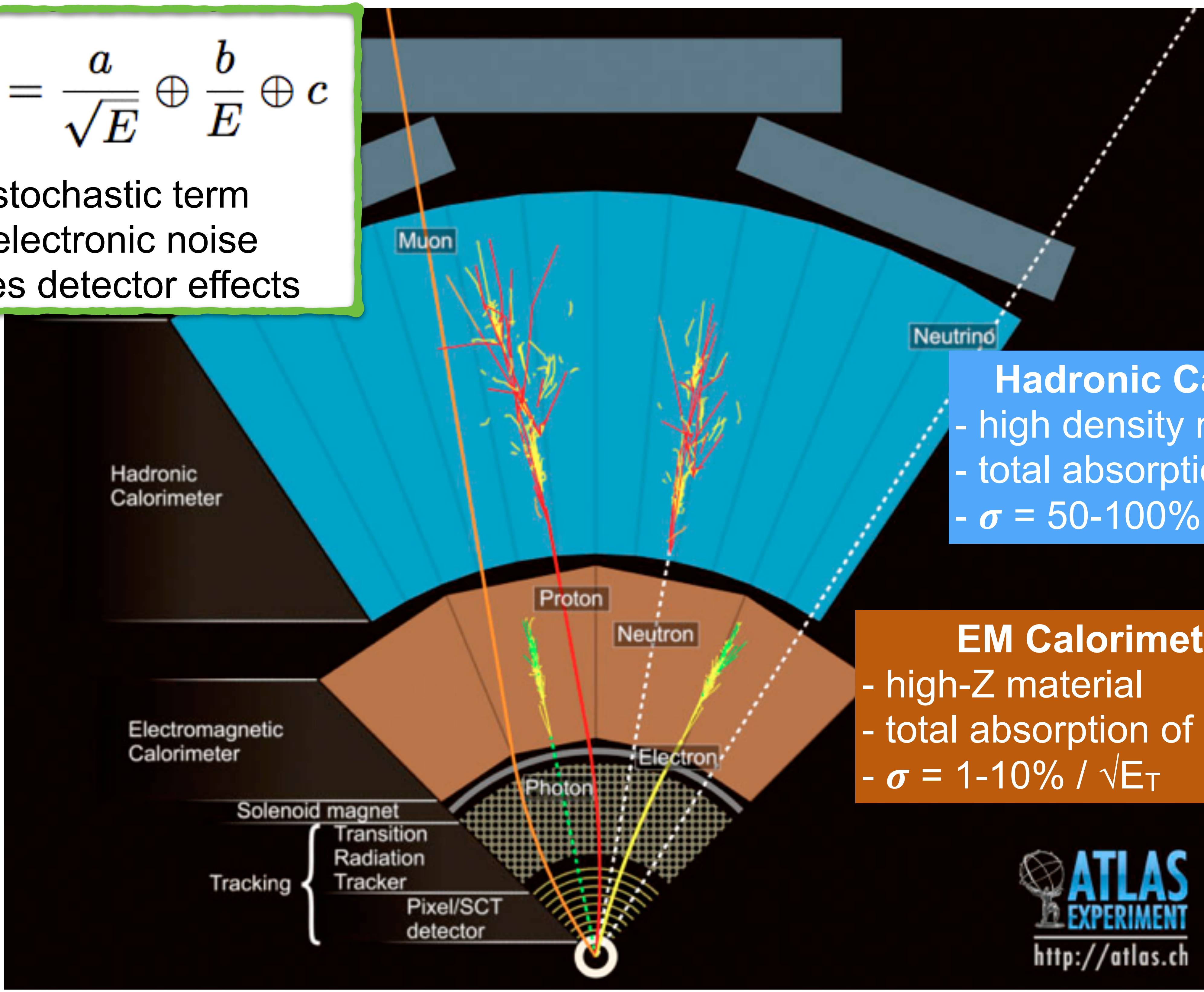
Calorimeters

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

a is the stochastic term
b is the electronic noise
c includes detector effects



Hadronic Calorimeter
- high density material
- total absorption of energy
- σ = 50-100% / $\sqrt{E_T}$

EM Calorimeter
- high-Z material
- total absorption of energy
- σ = 1-10% / $\sqrt{E_T}$

Calorimeters vs Tracker

calorimeter transverse energy uncertainty for charged hadrons:

$$\sigma(E_T) \approx 100\% \sqrt{E_T}$$

Tracker transverse momentum uncertainty for charged hadrons:

$$\sigma(p_T) \approx 0.01\% \ (p_T)^2$$

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

$$\frac{\sigma(p_T)}{p_T} \approx \frac{\sigma(E_T)}{E_T} \quad \rightarrow \quad p_T \approx 10^{\frac{8}{3}} \approx 464 \text{ GeV}$$

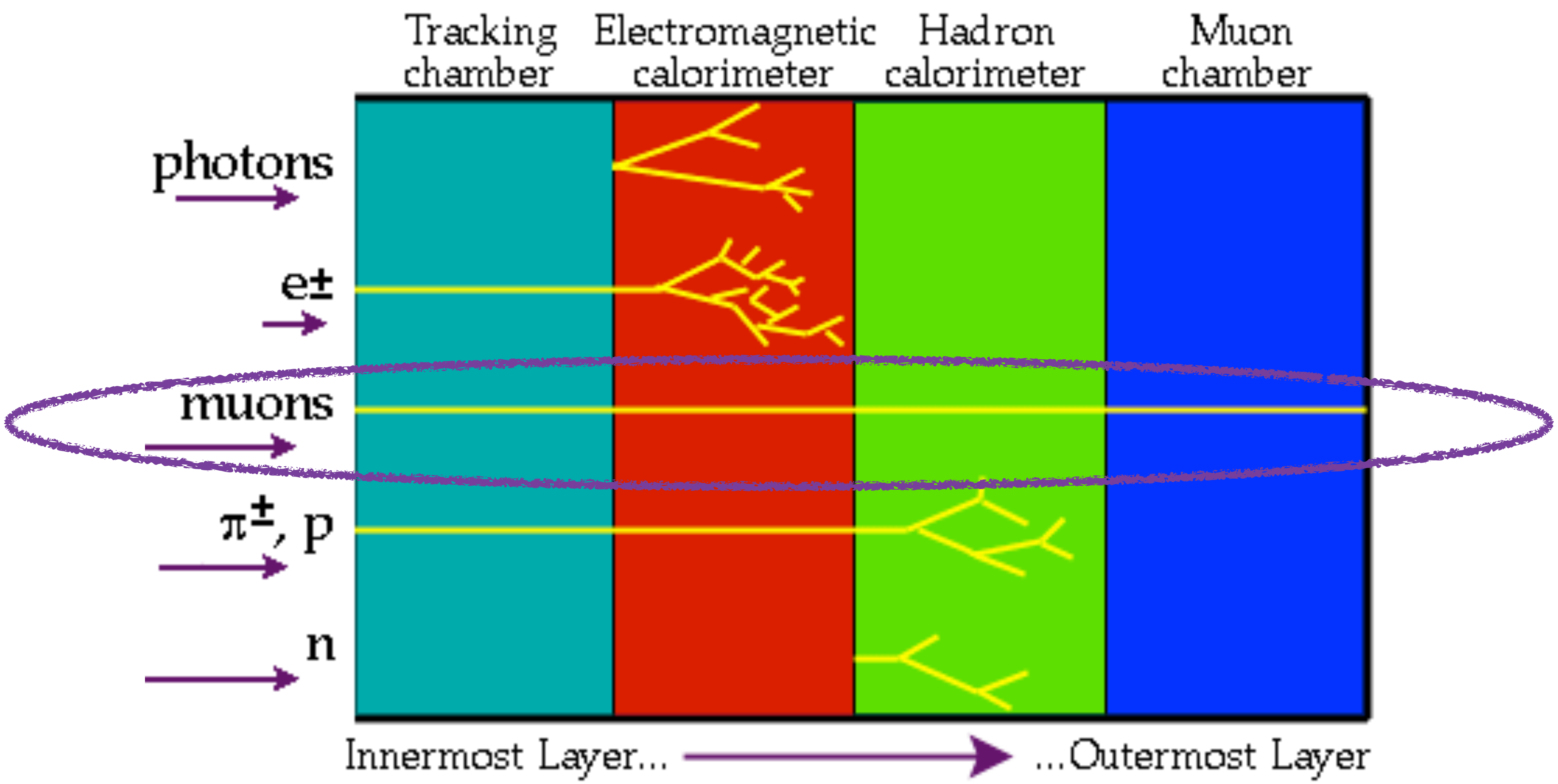
R. Cavanaugh, HCPSS 2012

Strategy to get most of detector is to match tracks with calorimeter clusters

Track momentum is preferred over calorimeter energy

Steps are ordered motivated by momentum resolution and particle identification purity

Muons



http://www.particleadventure.org/

Particle Flow

Strategy to get most of detector is to match tracks with calorimeter clusters

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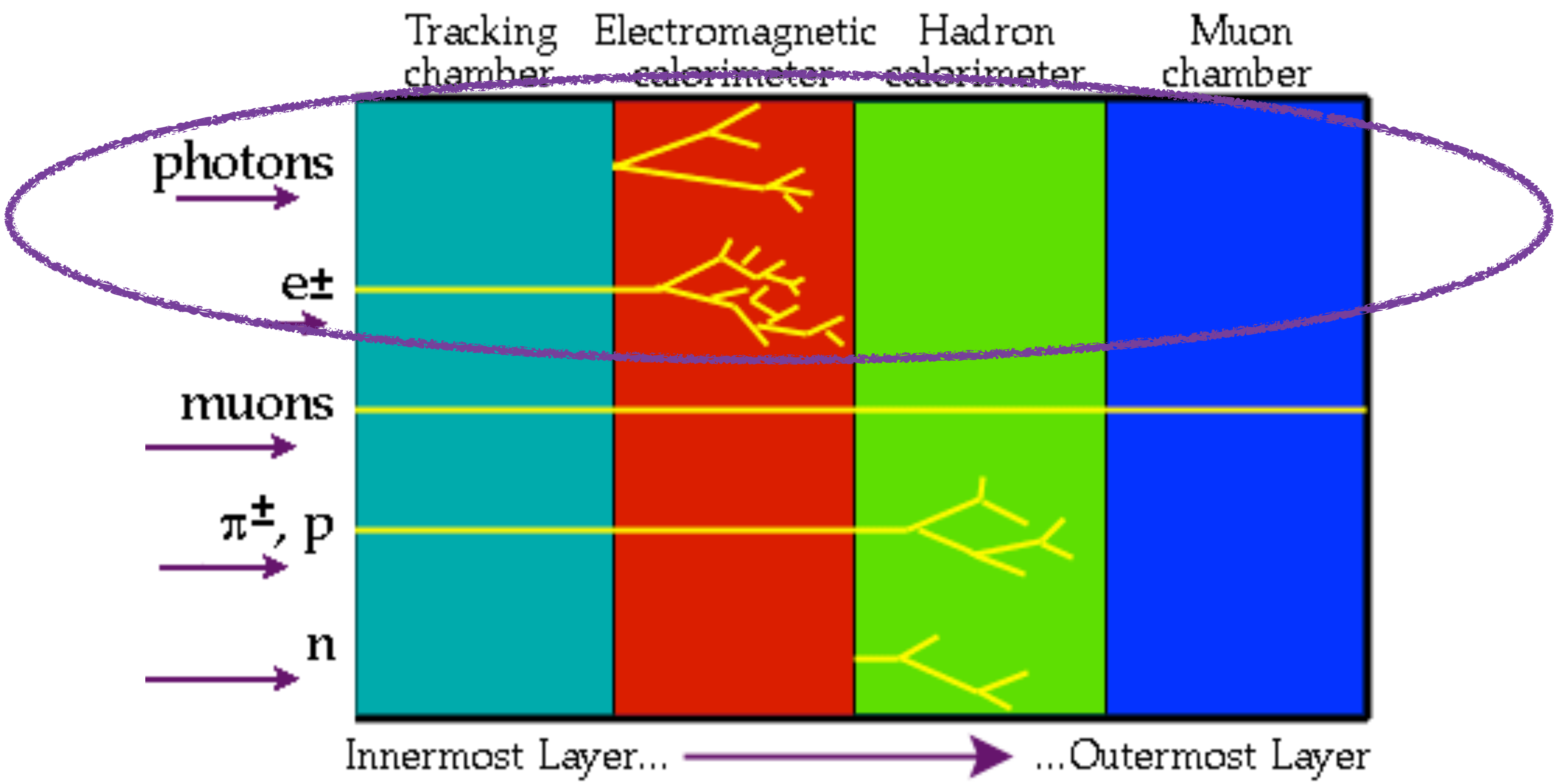
Electrons / Photons



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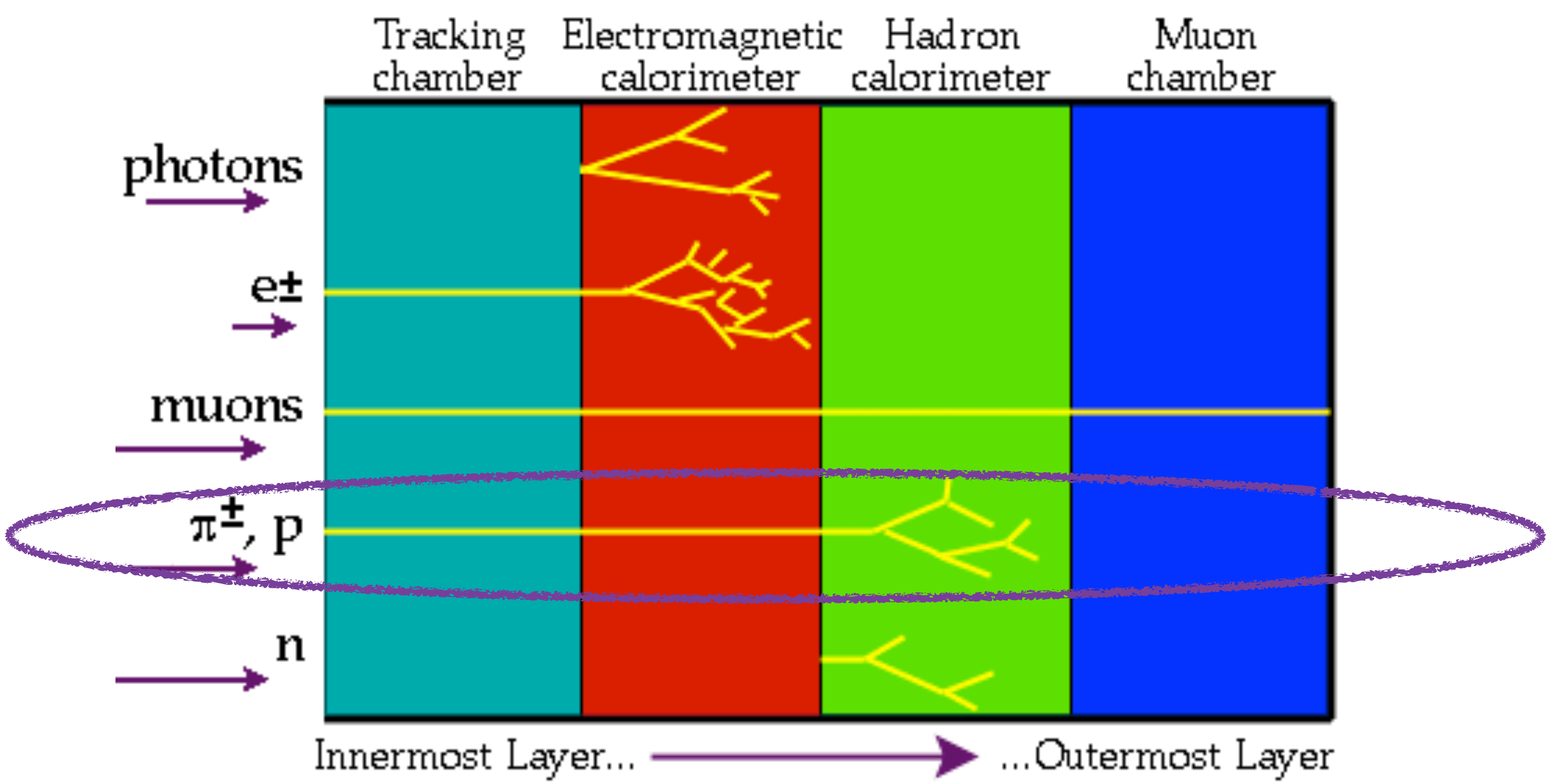
Hadrons



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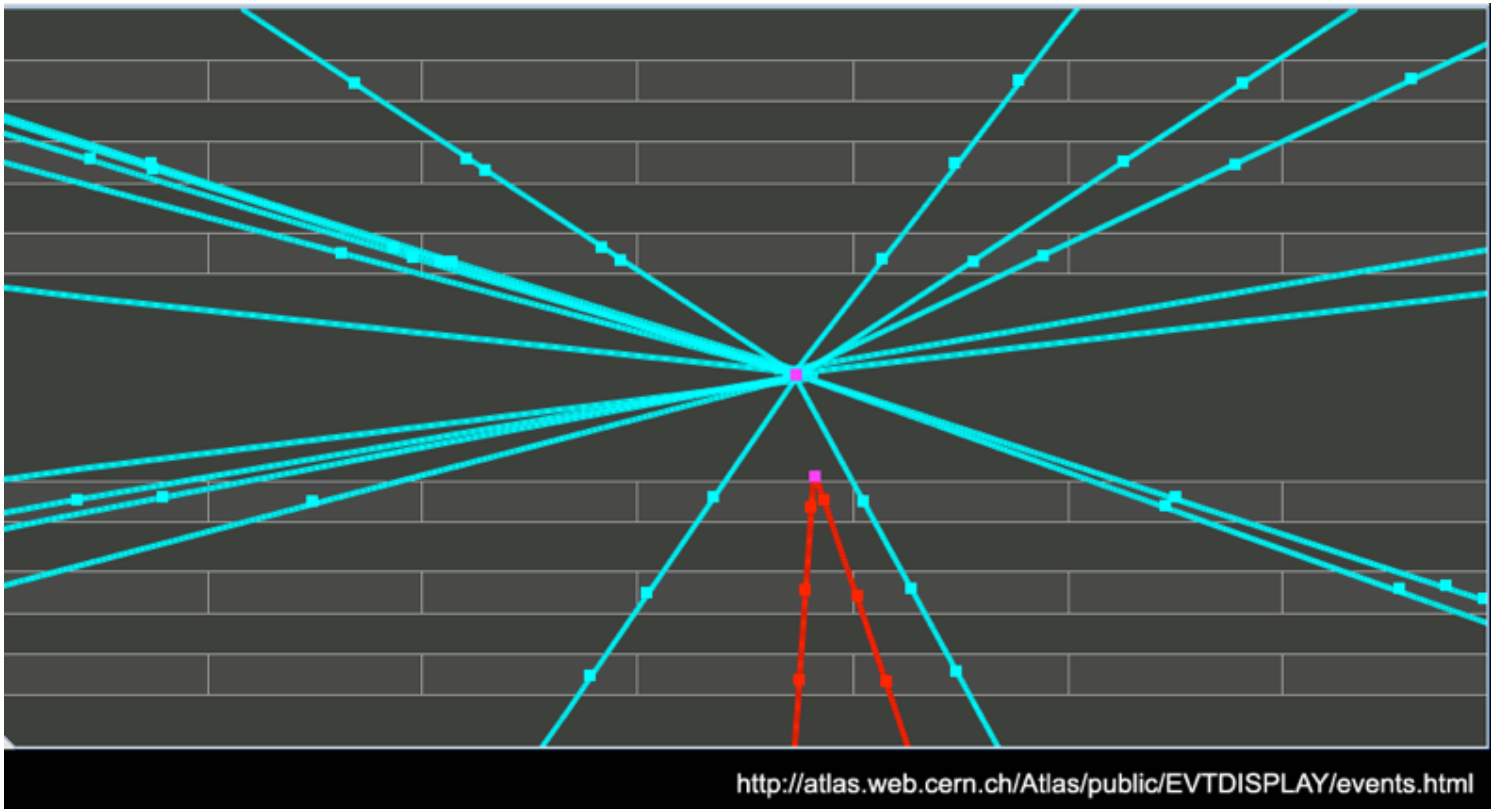
Converted photons



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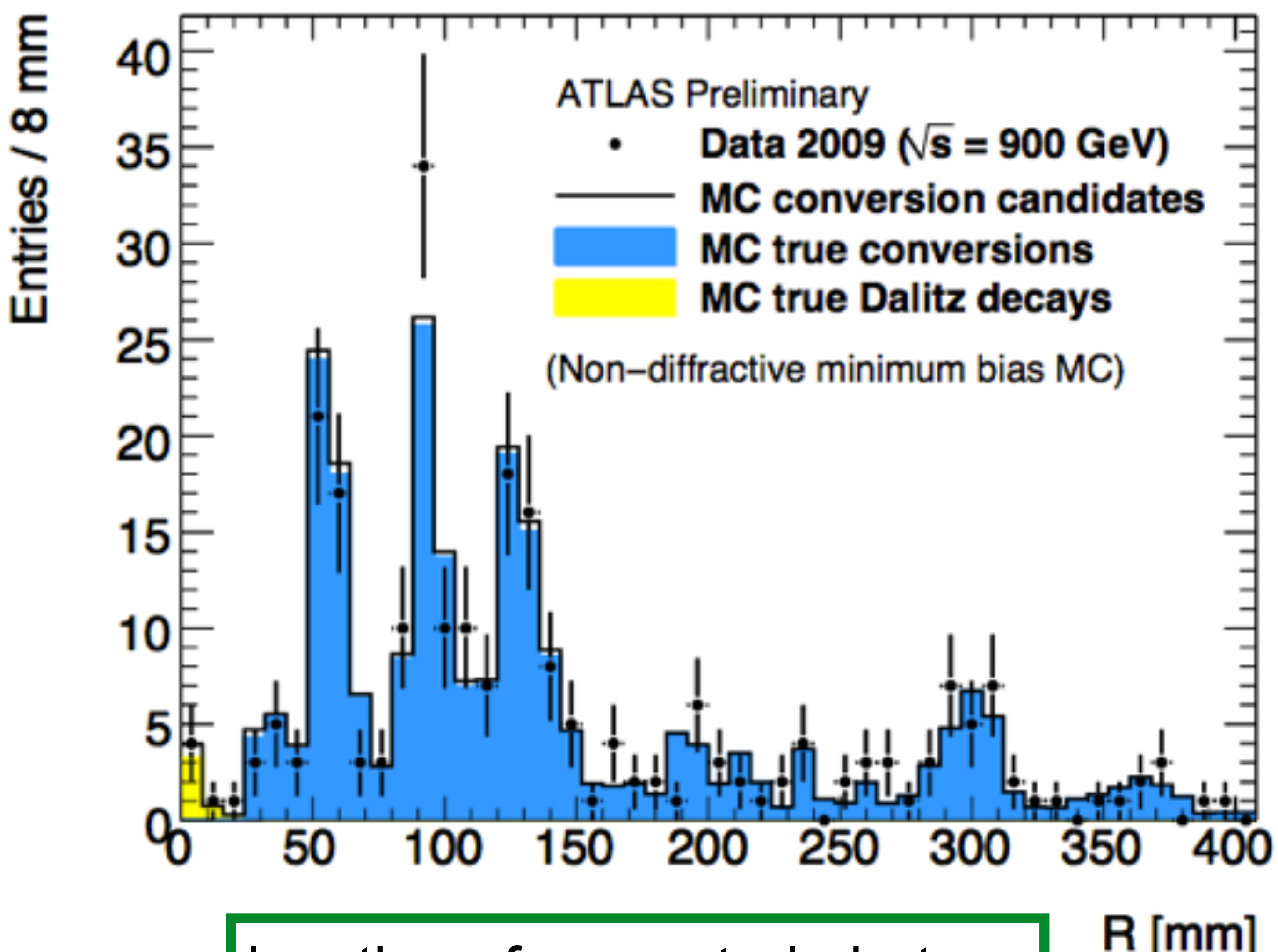

location of converted photons

Particle Flow

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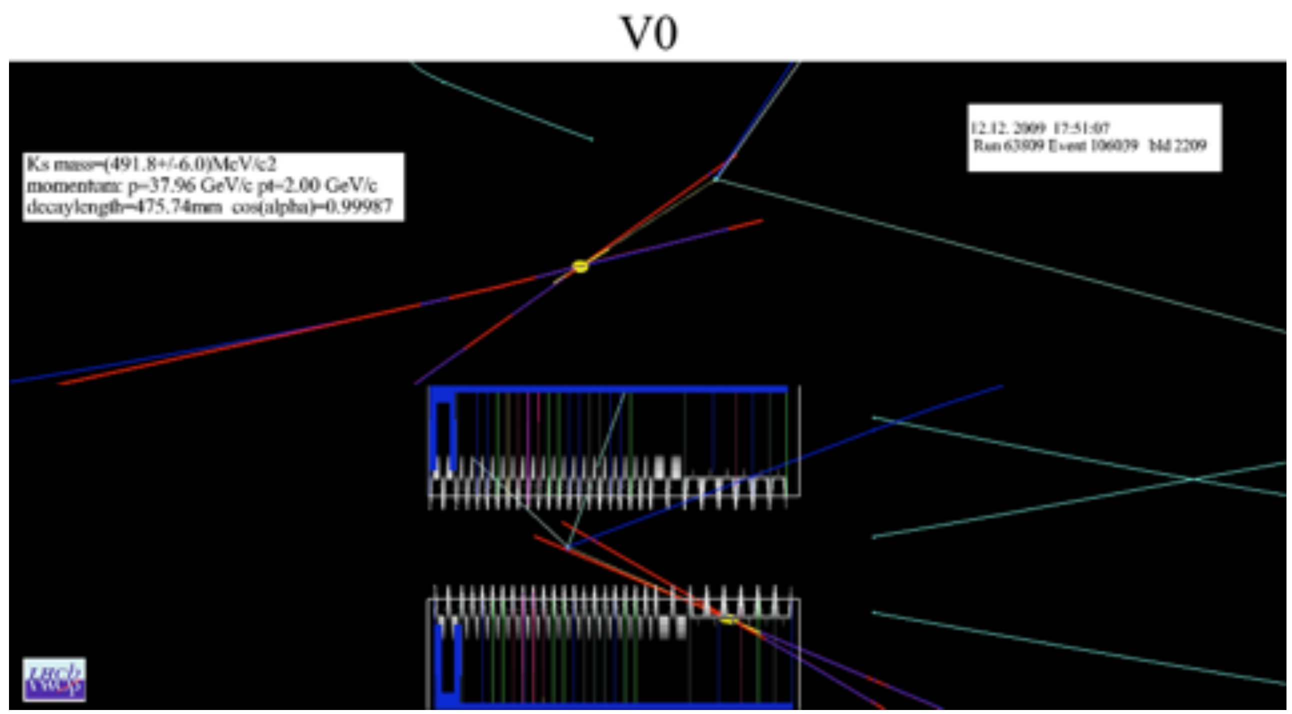
V^0s ($\tau \sim 10^{-10}$ s)



V^0s live long enough to reconstruct its vertex

Particle Flow

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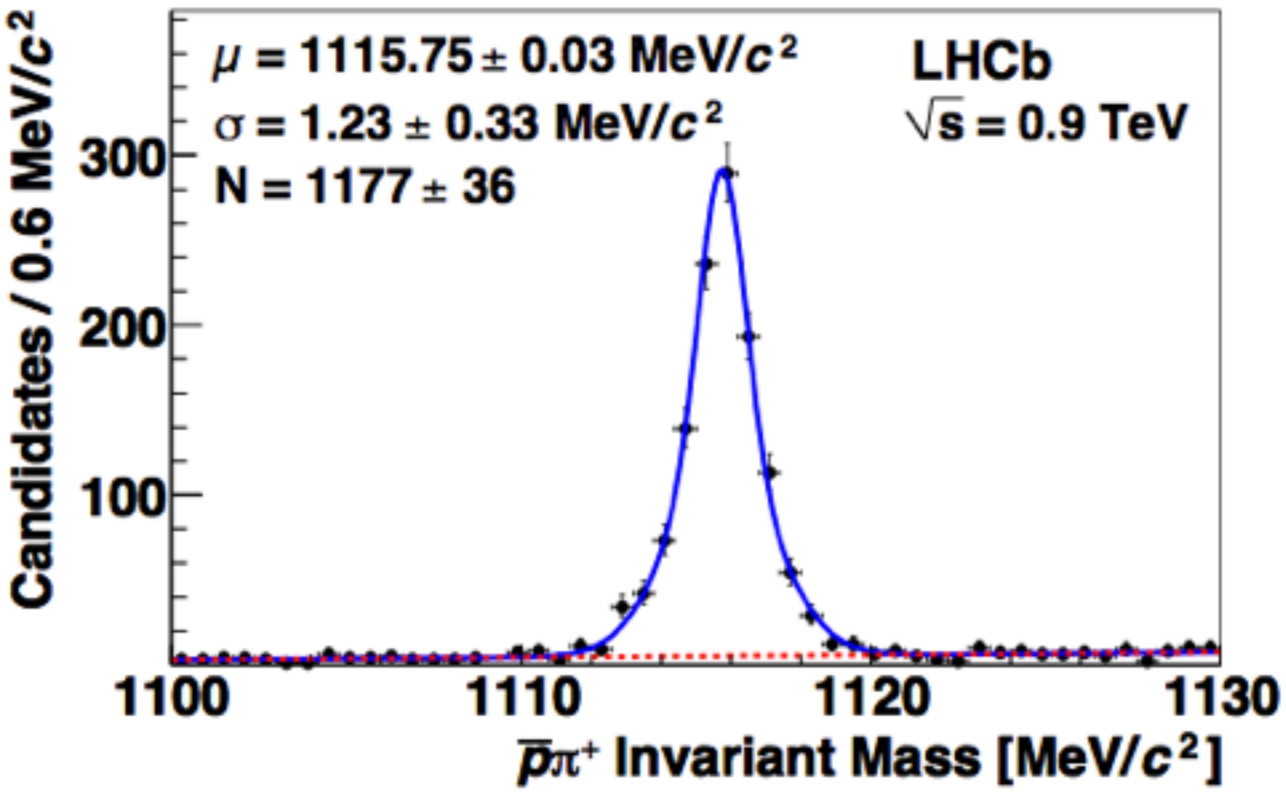
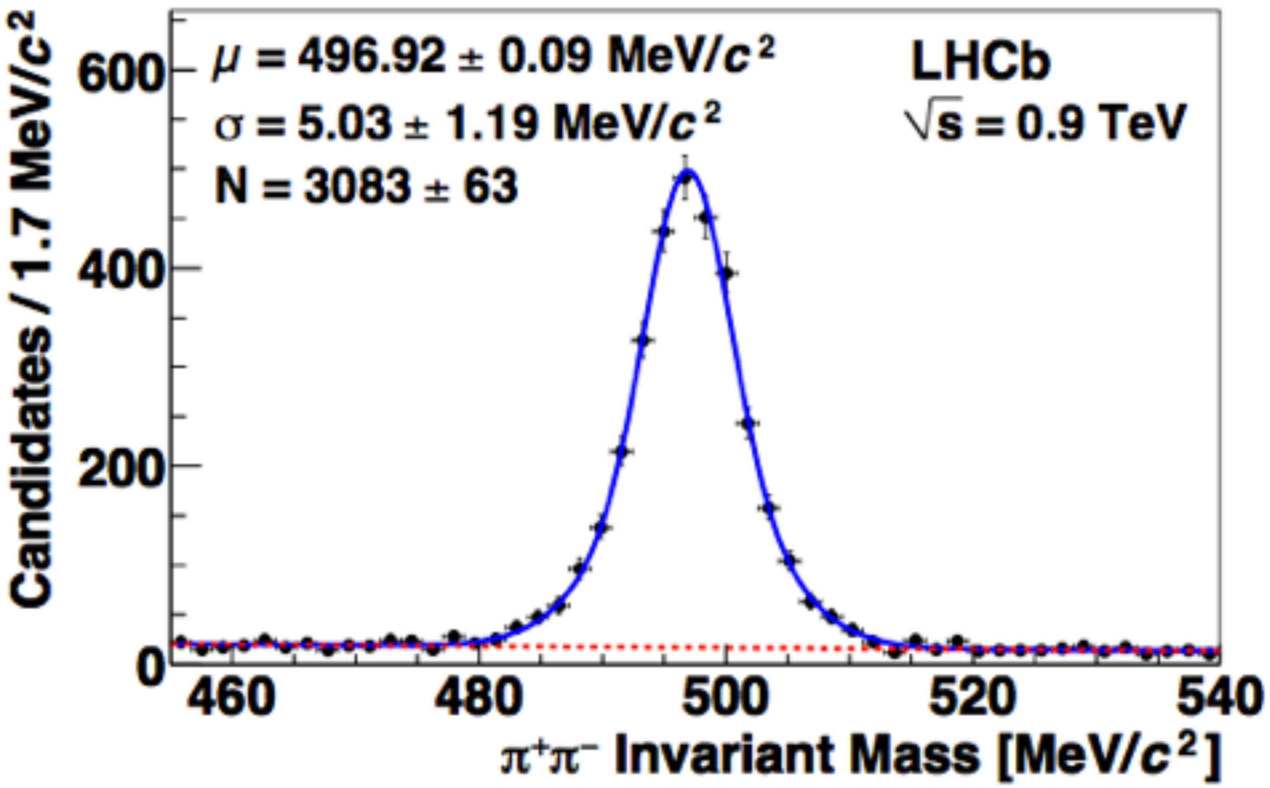
V^0s (τ ~ 10^{-10} s)





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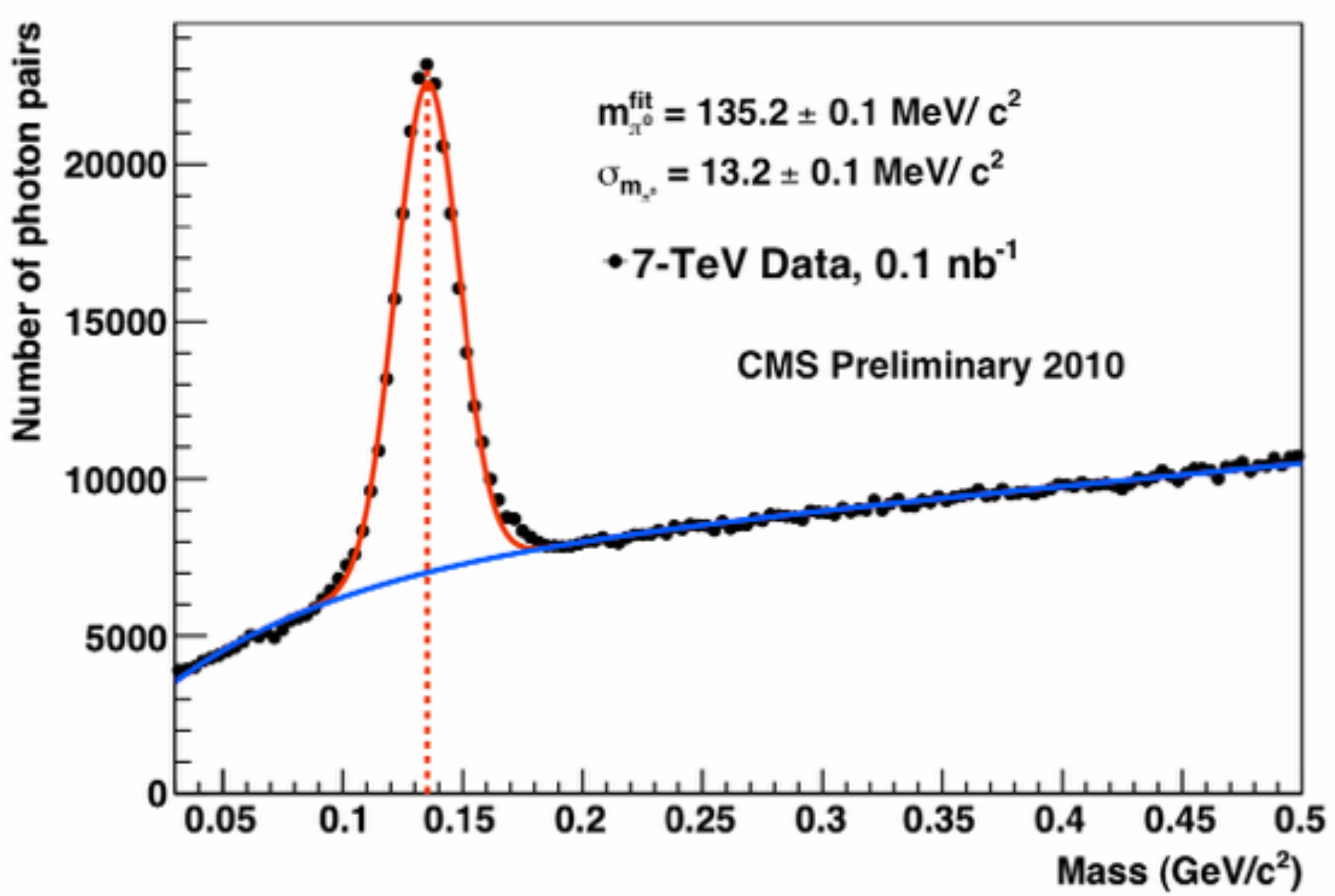
$\pi^0 \rightarrow \gamma\gamma$



Particle Flow

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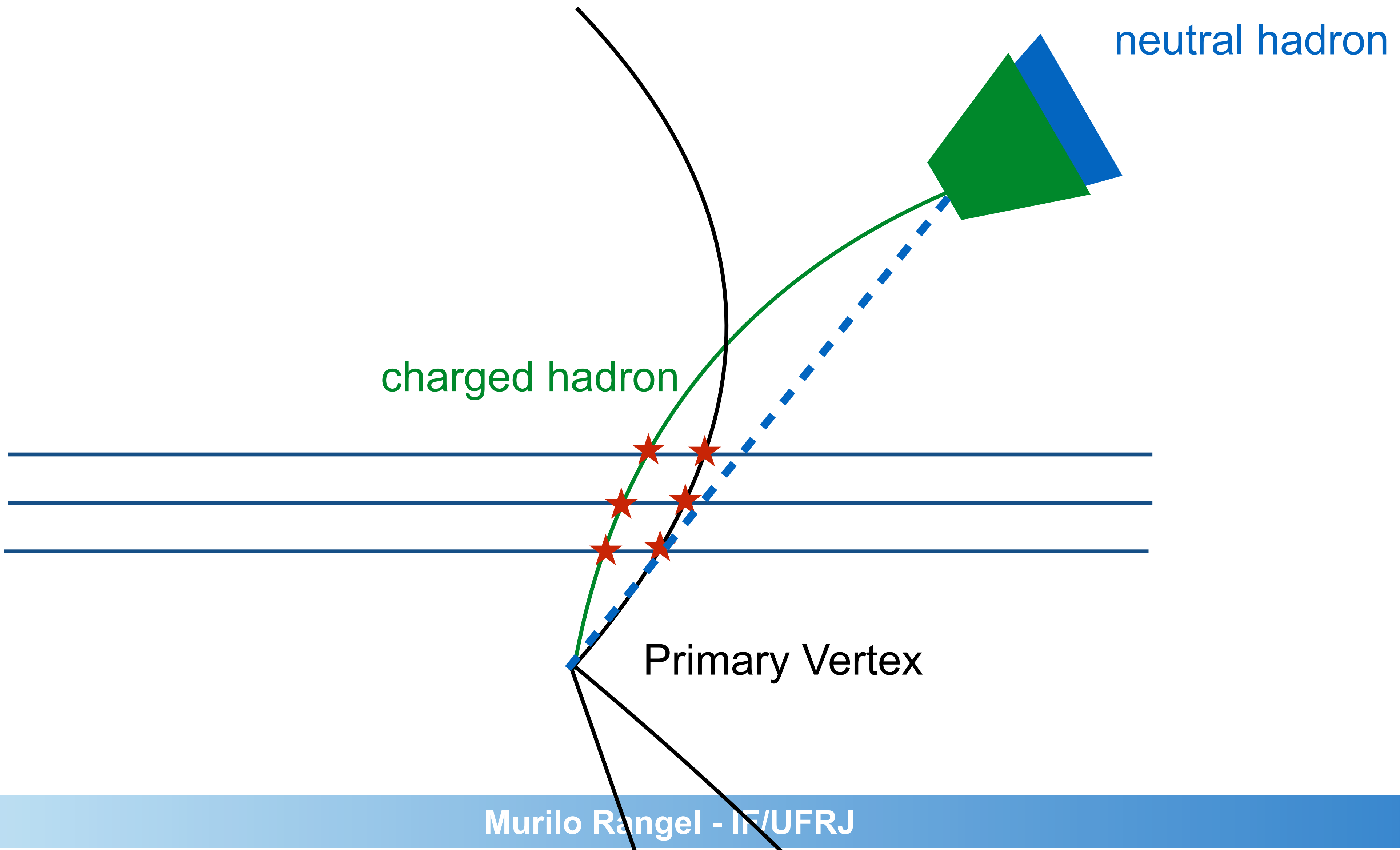
Neutral Hadrons



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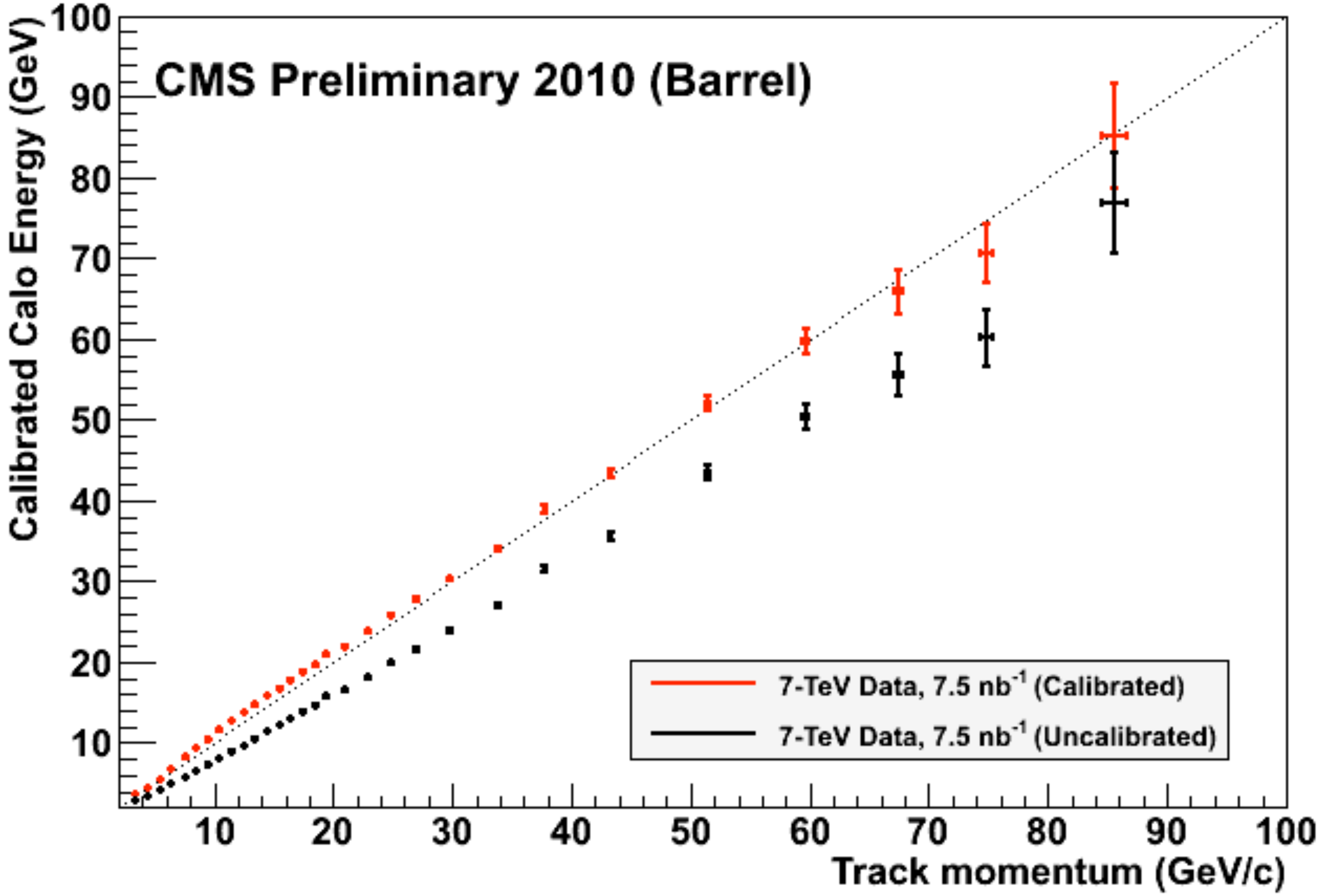

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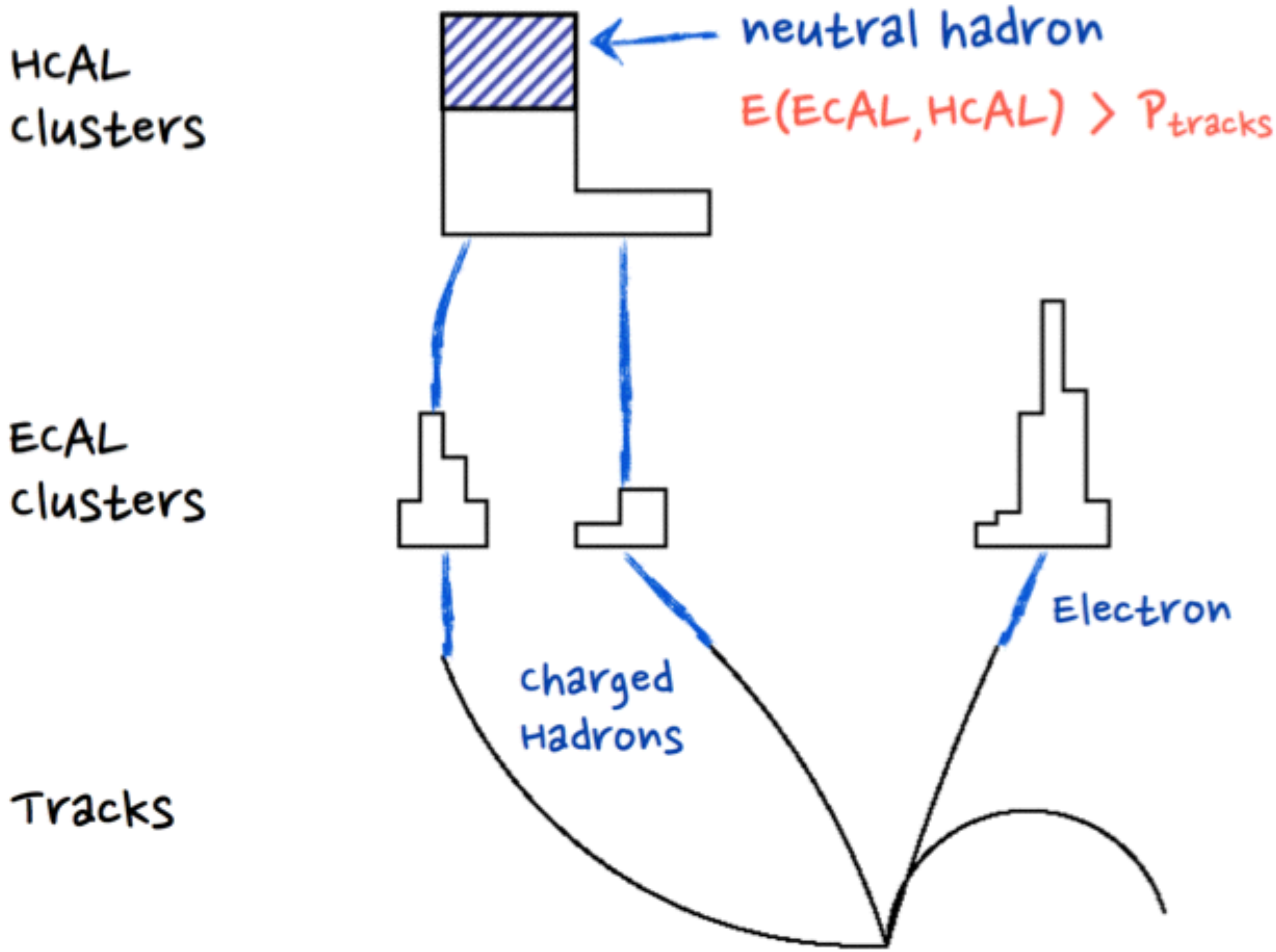

Diagrams from R. Cavanaugh and P. Janot

Reconstructed "particles" are used as inputs of the jet algorithm - "detector-level" jets

"Detector-level" jets must be corrected/calibrated to compare with theory/models
Calibration of jets to "particle-level" is necessary

Calibrated jets

- little dependence with detector effects (segmentation, response and resolution)
- good resolution and no angle biases
- good efficiency and low fake rate (Jet Identification)
- stable with beam luminosity (pile-up)
- computer time efficient

Inputs

- calorimeter cells/towers/clusters
- tracks
- tracks+calorimeter (particle flow)

Jet Identification

At “detector-level”, the jet algorithm can reconstruct fake jet candidates:

- Hadronic tau decays (electrons and photons too)
- Cosmic ray
- Detector noise
- Pile-Up contribution

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Jet characteristics can be used to reduce these background rate to $O(1\%)$

- o Charged Fraction (from PV)
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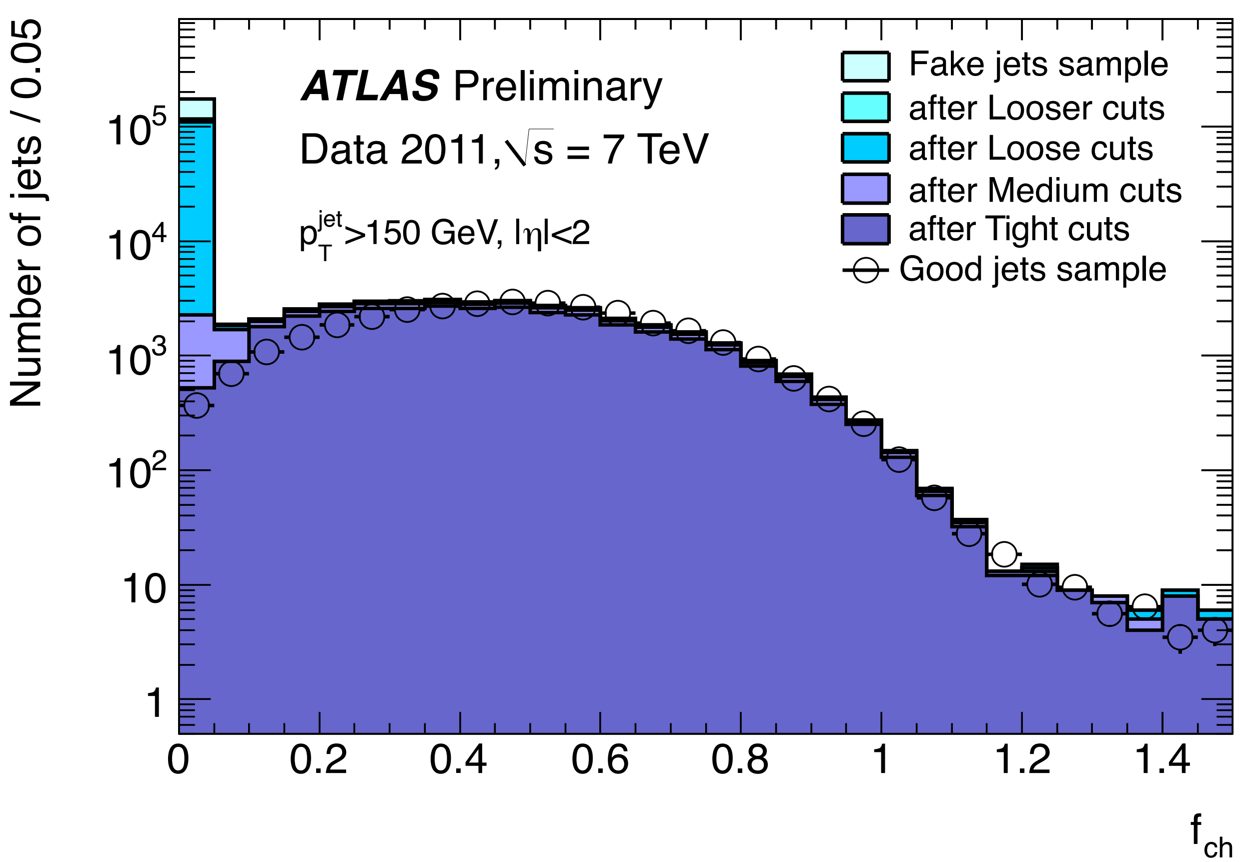

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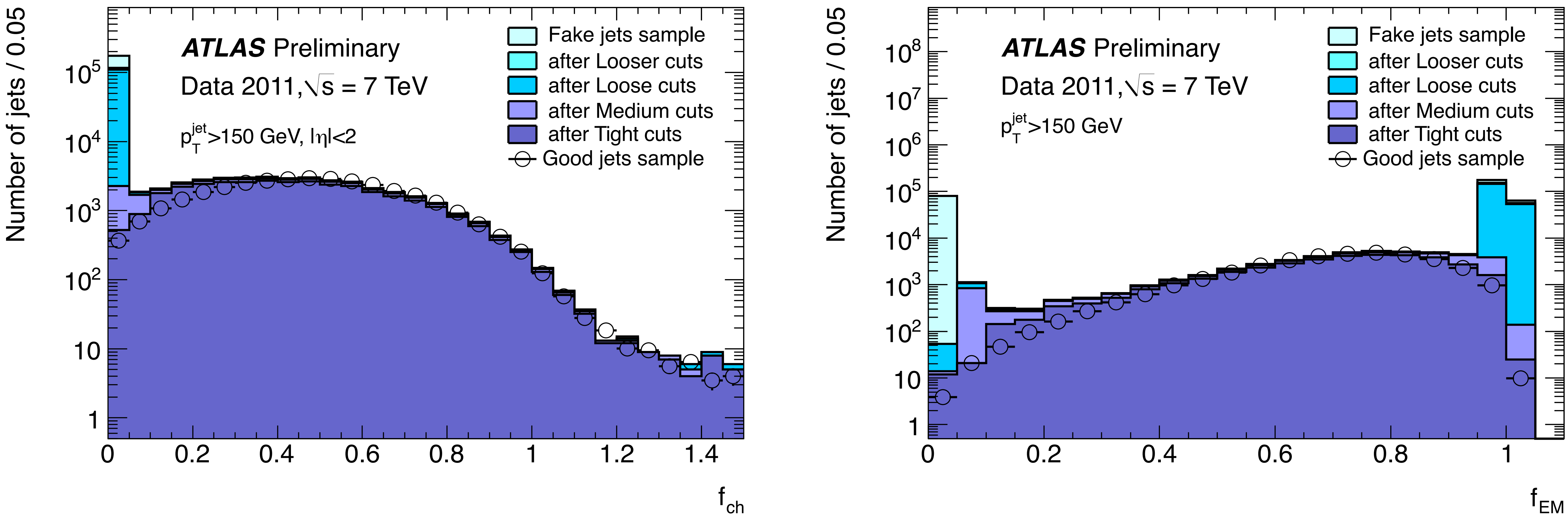

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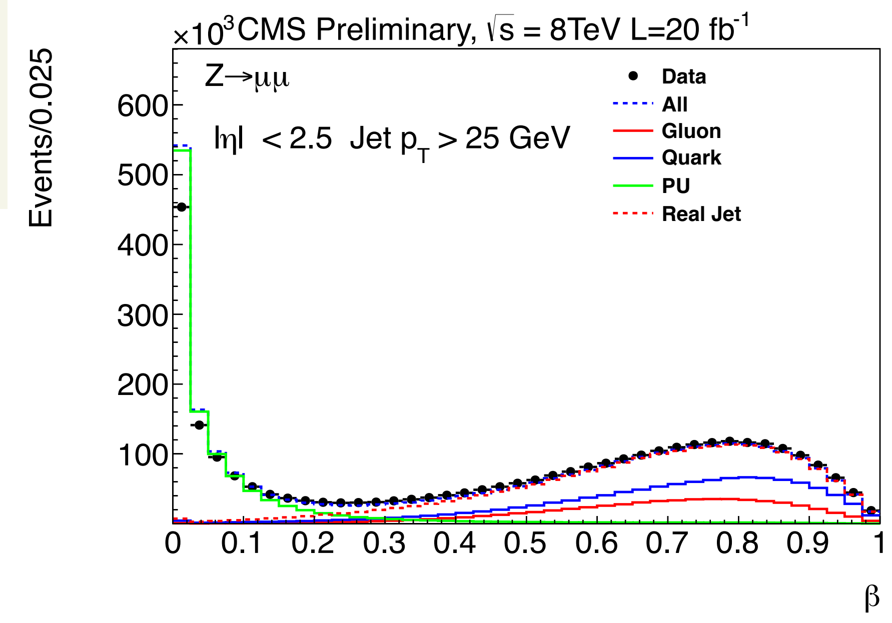

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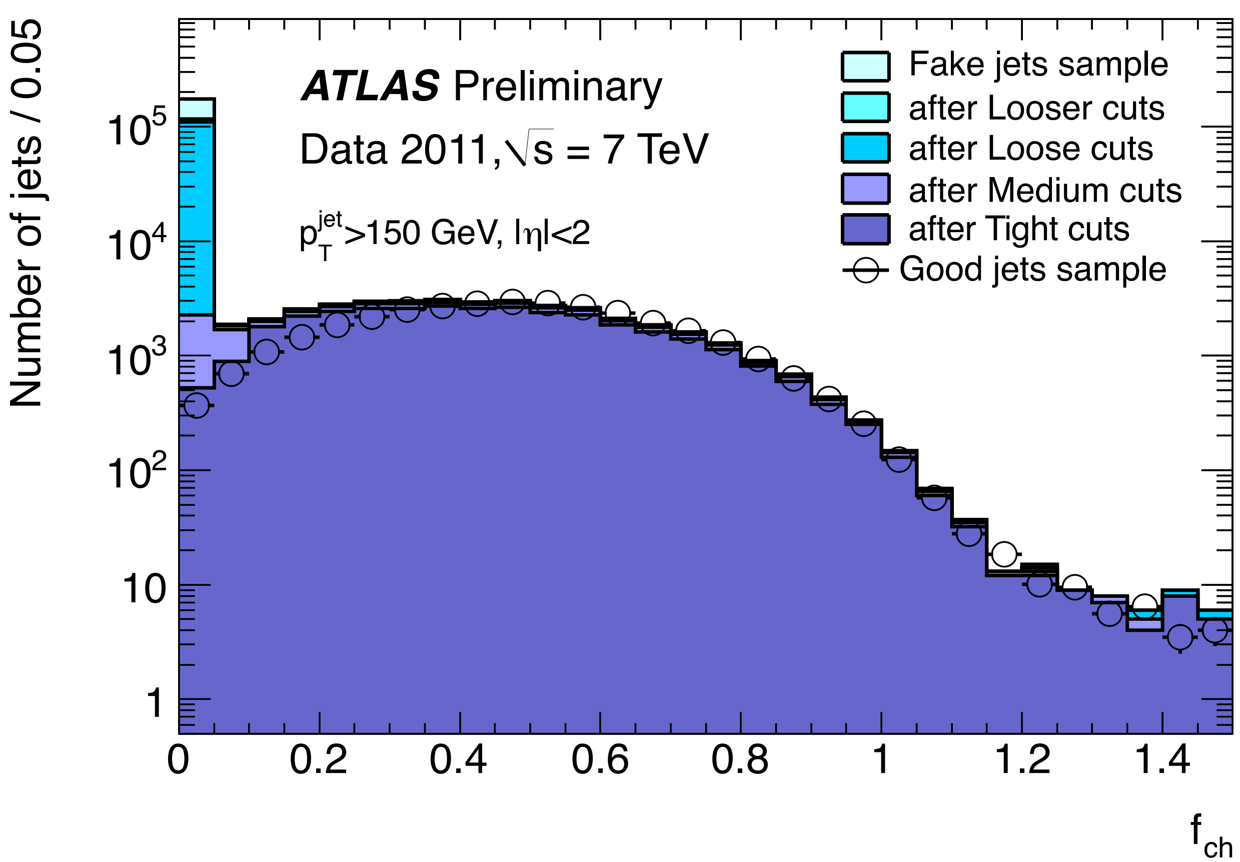
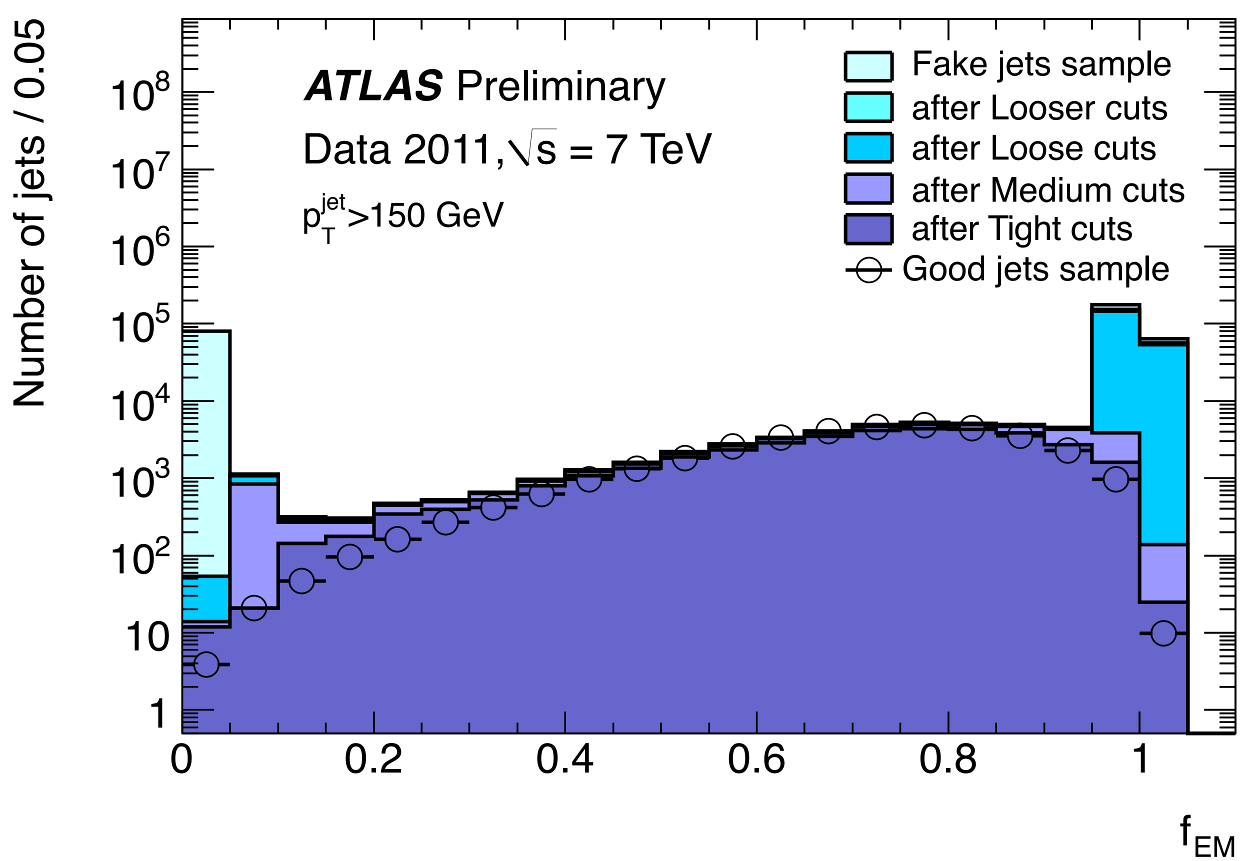
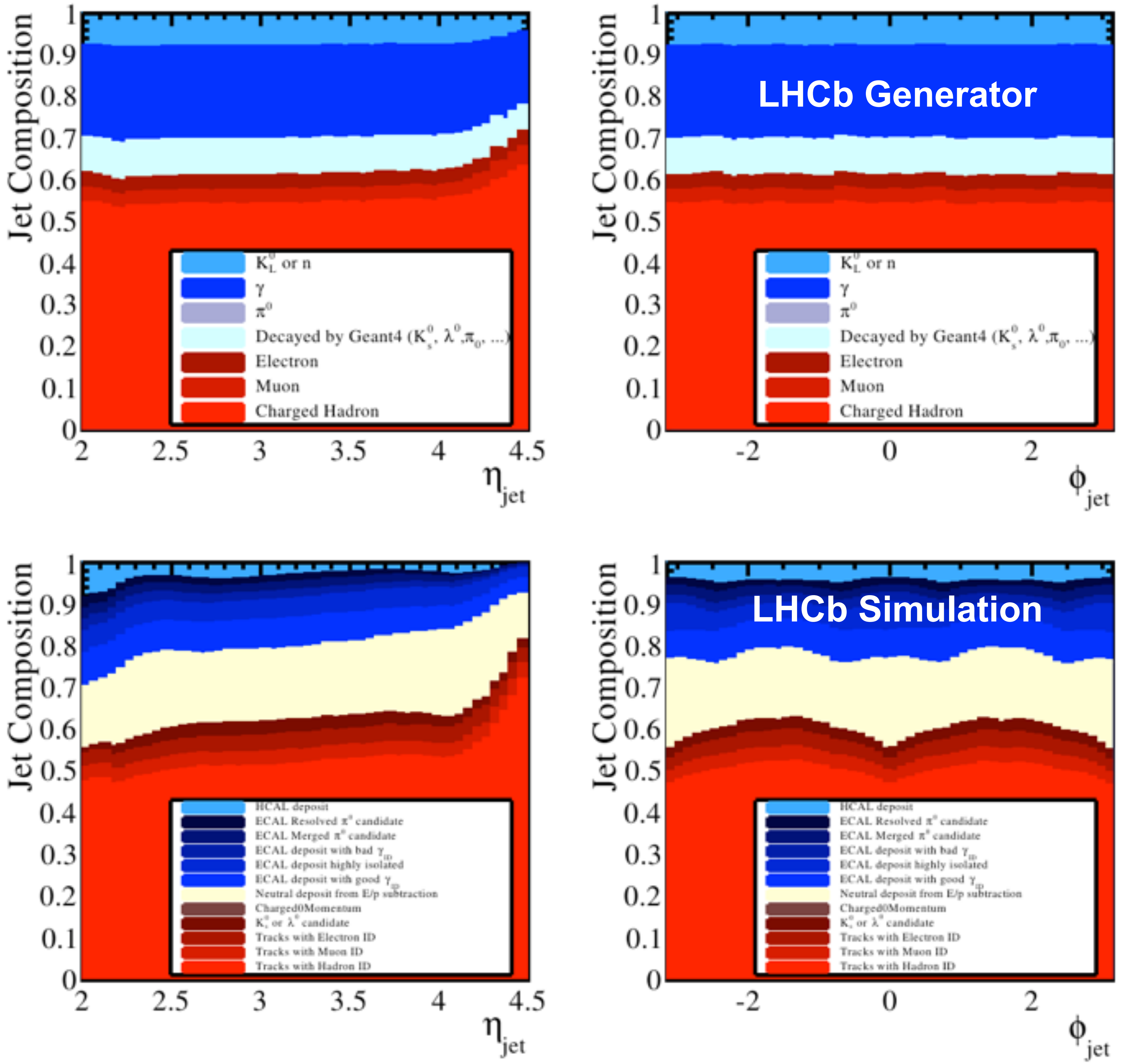




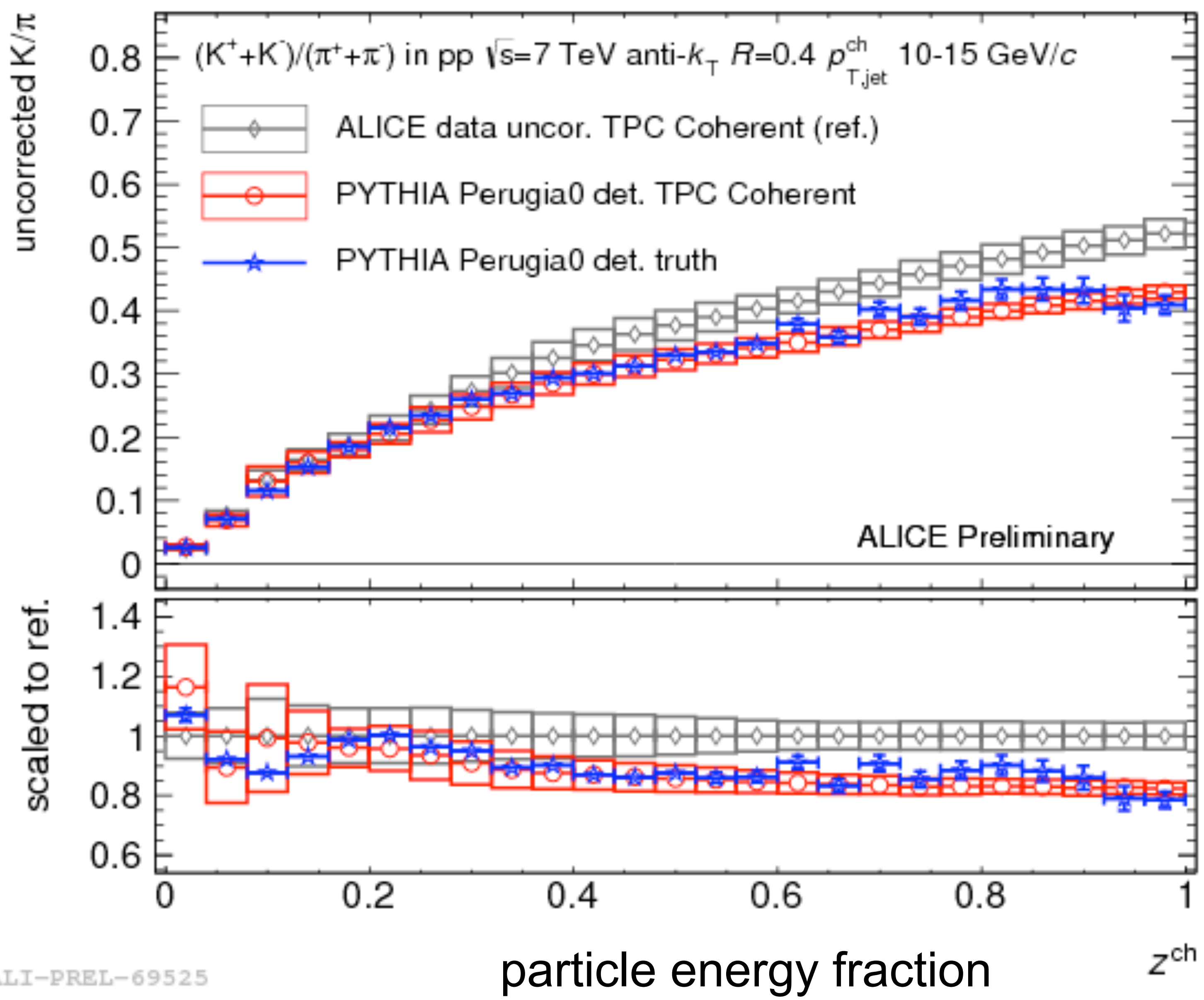
Jet Composition



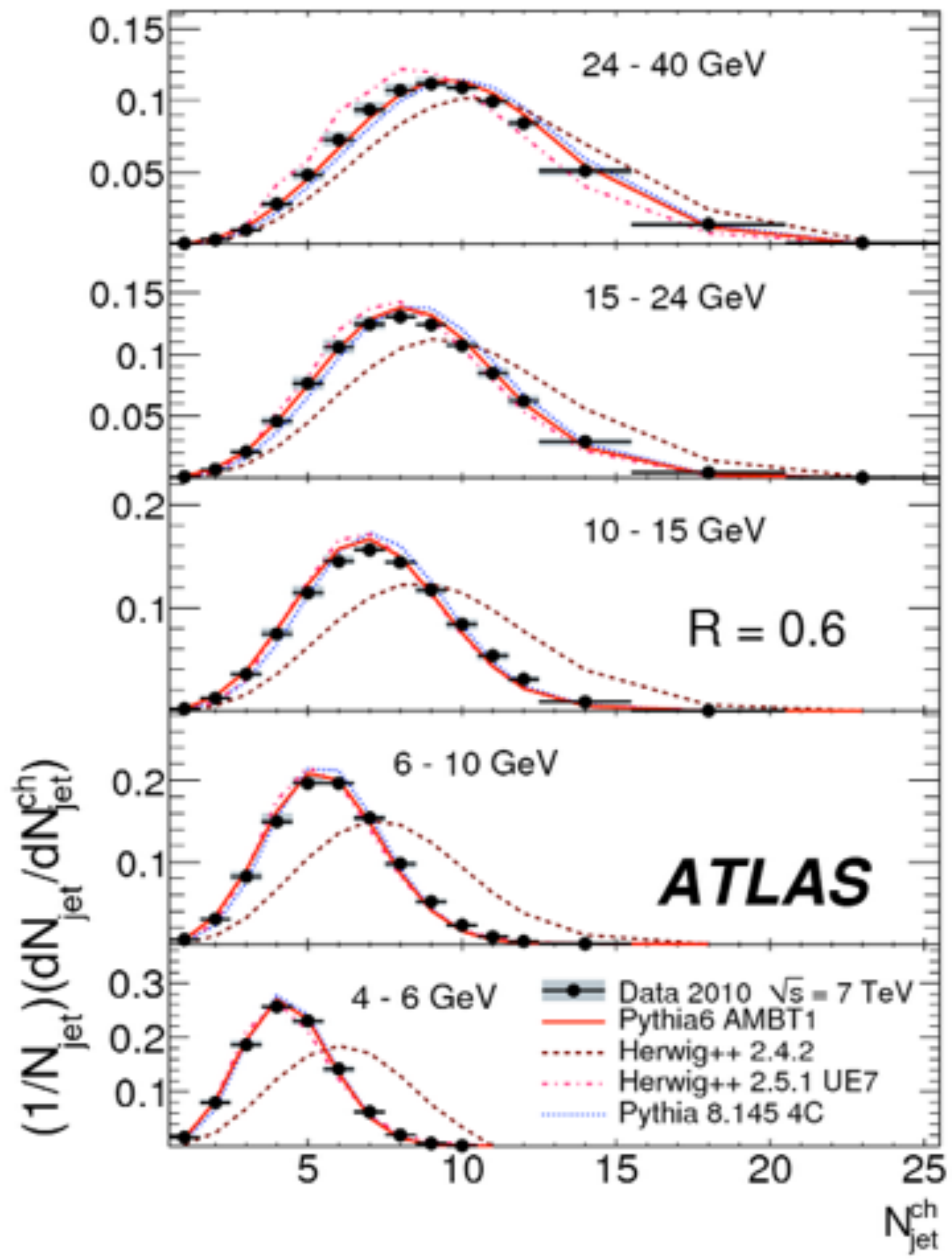
Jet at “particle level”

Jet at "detector level” (uncorrected)

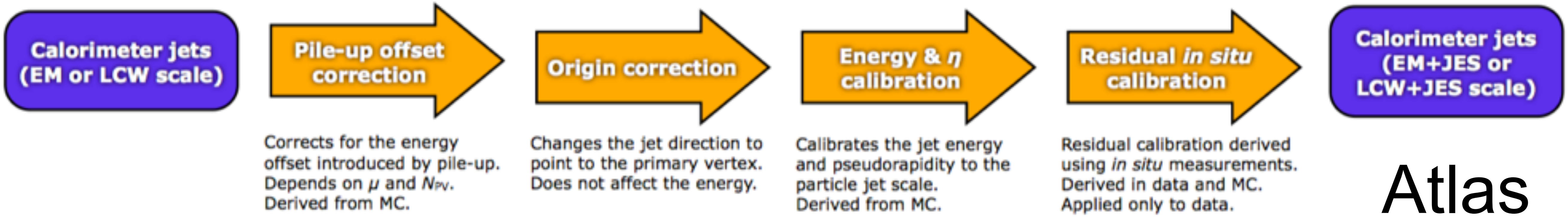
Tests of parton-shower⊕hadronization models are necessary



particle energy fraction

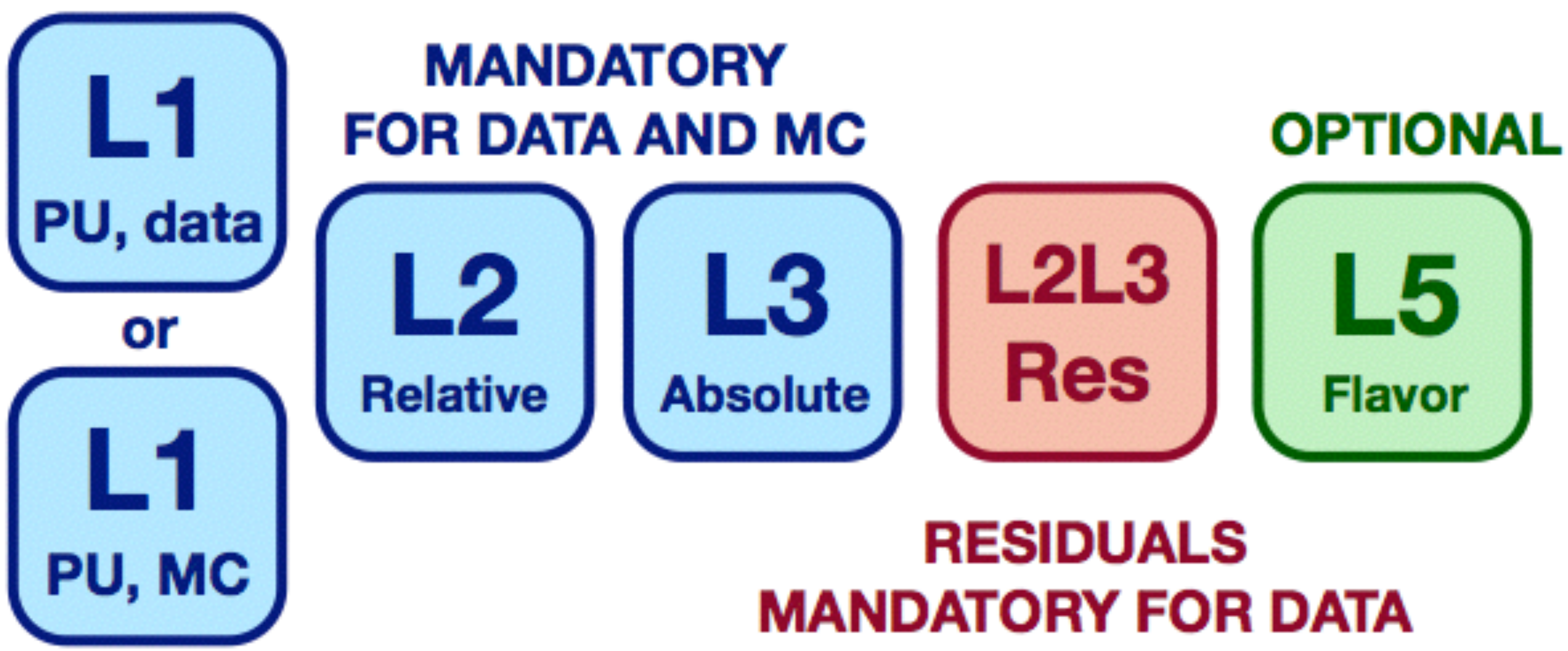


Calibration Factorization



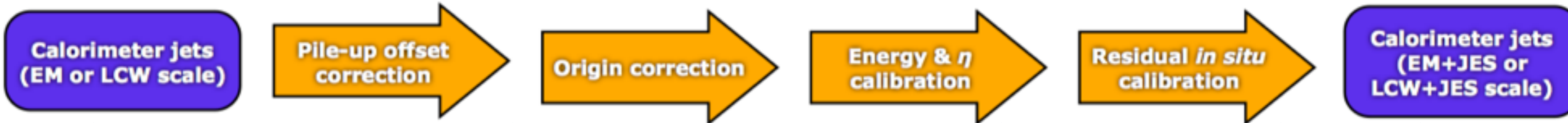
Atlas

CORRECTIONS (FACTORIZED APPROACH):



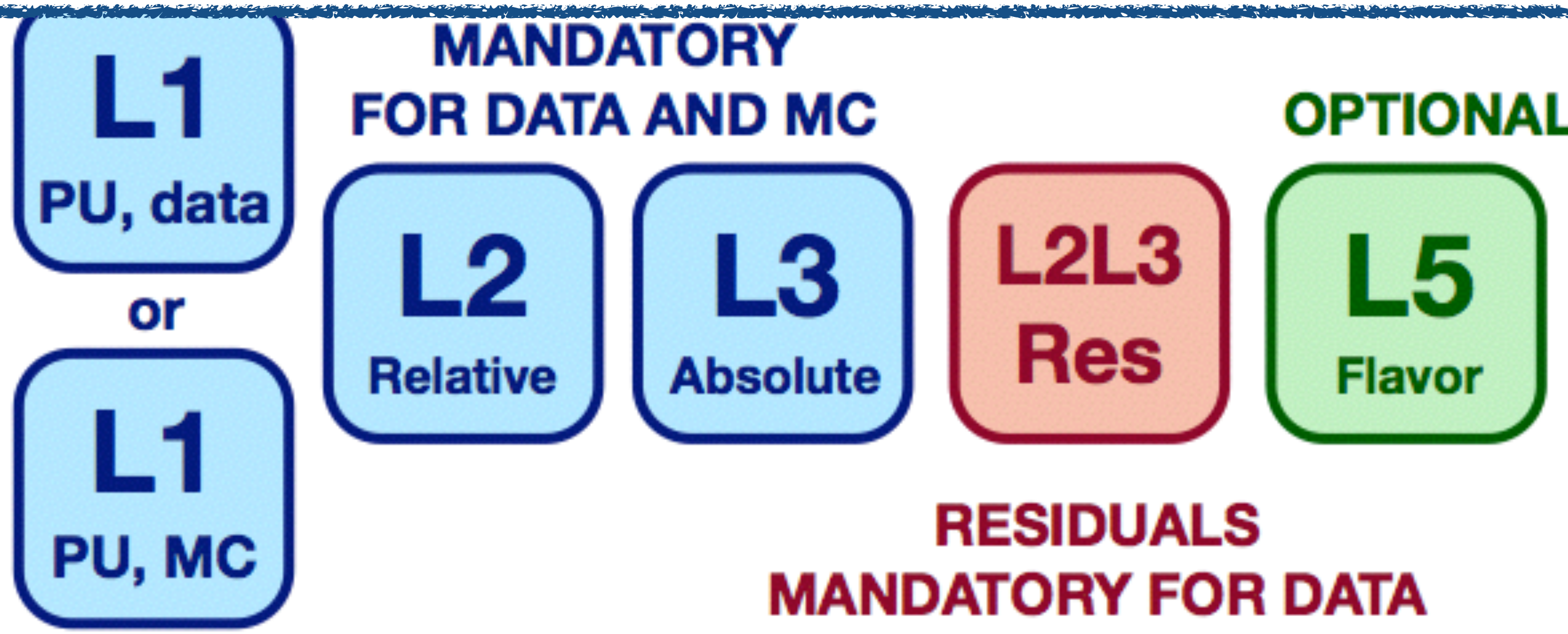
CMS

Calibration Factorization



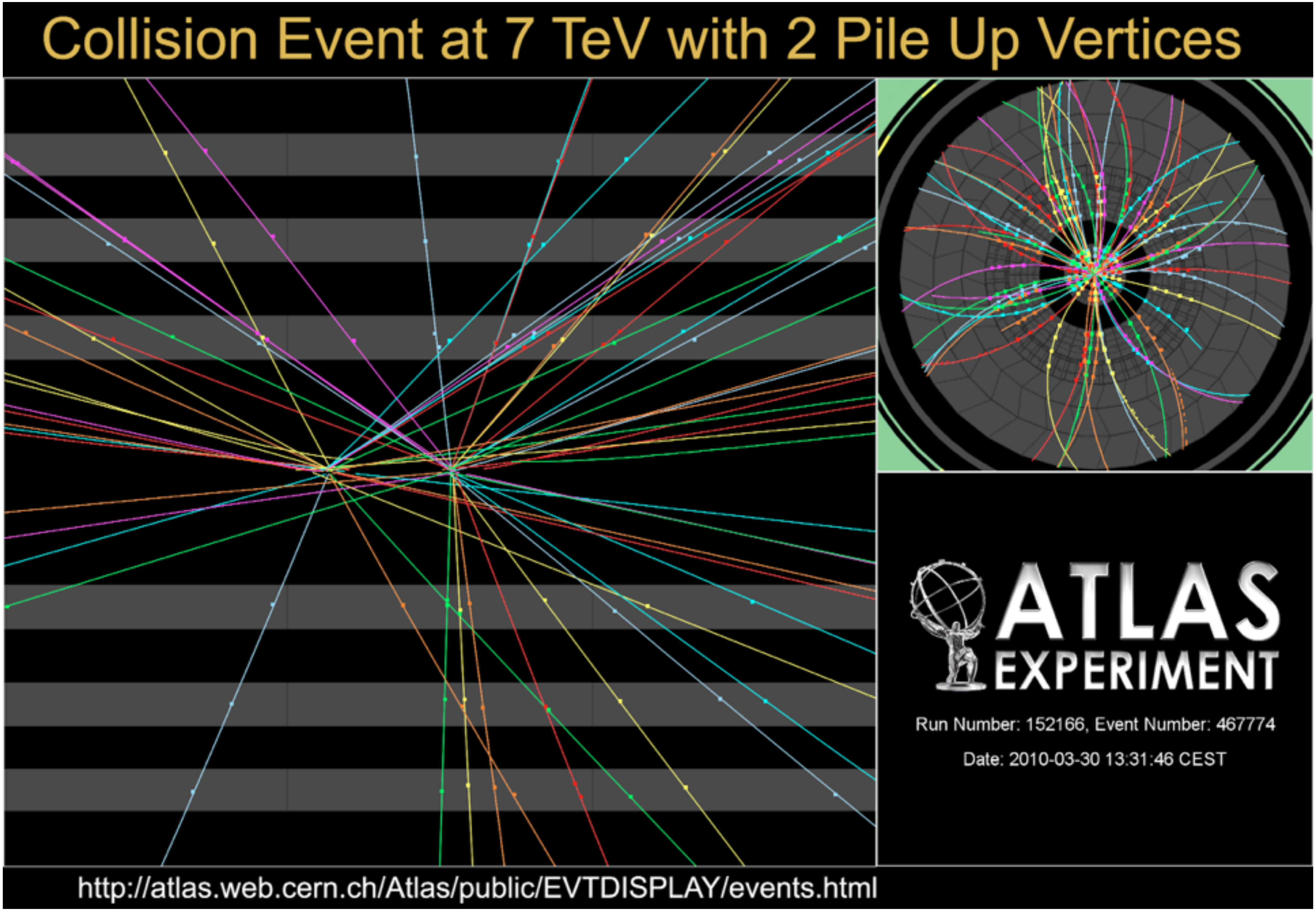
$$p_\mu^{\text{cor}} = \mathscr{C} \cdot p_\mu^{\text{raw}}$$

$$\mathscr{C} = C_{\text{offset}}(p_T^{\text{raw}}) \cdot C_{\text{MC}}(p'_T, \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}(p''_T)$$



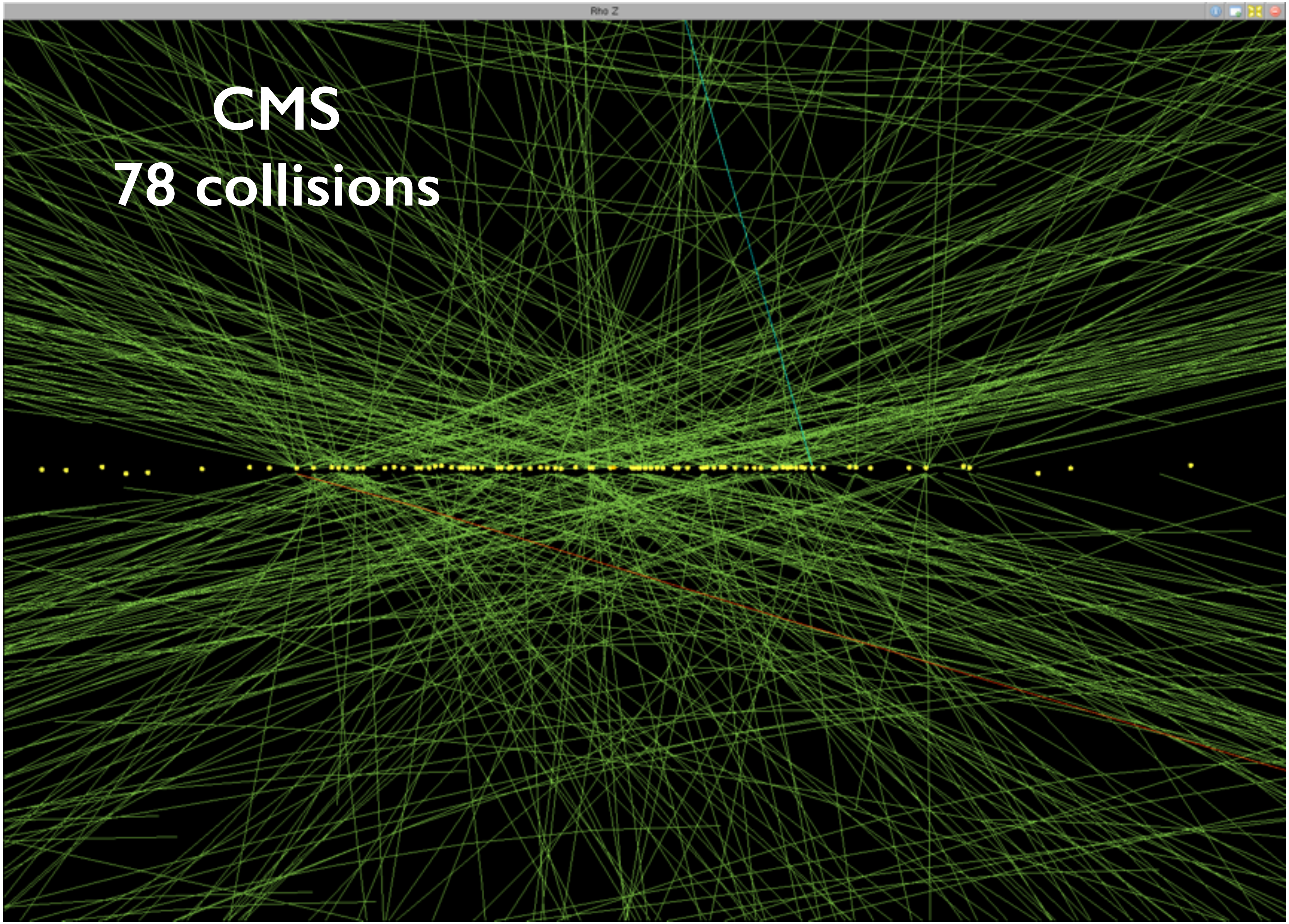
CMS

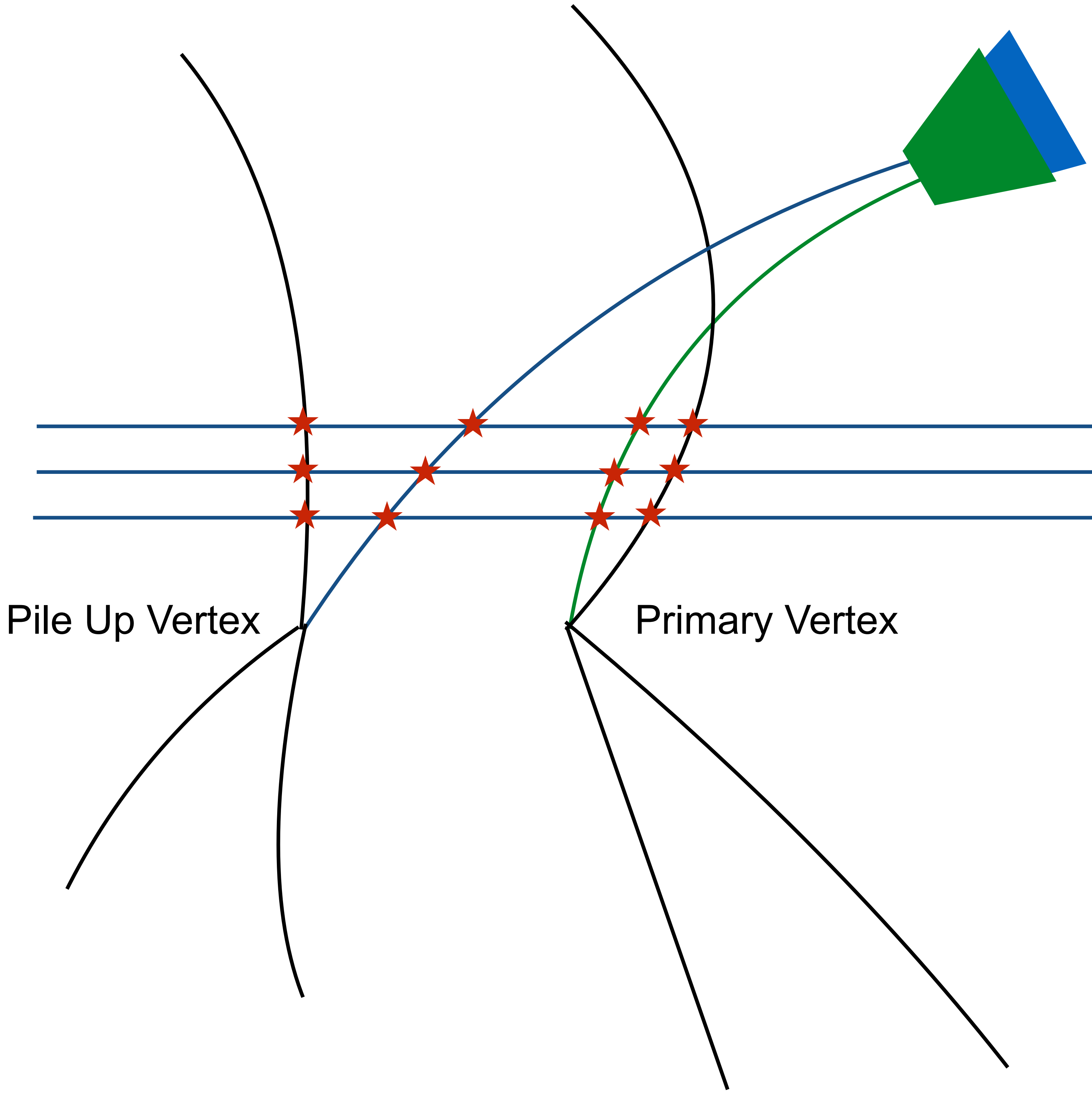
Pile Up



Collision Event at 7 TeV with 2 Pile Up Vertices
ATLAS
EXPERIMENT
Run Number: 152166, Event Number: 467774
Date: 2010-03-30 13:31:46 CEST
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Pile Up

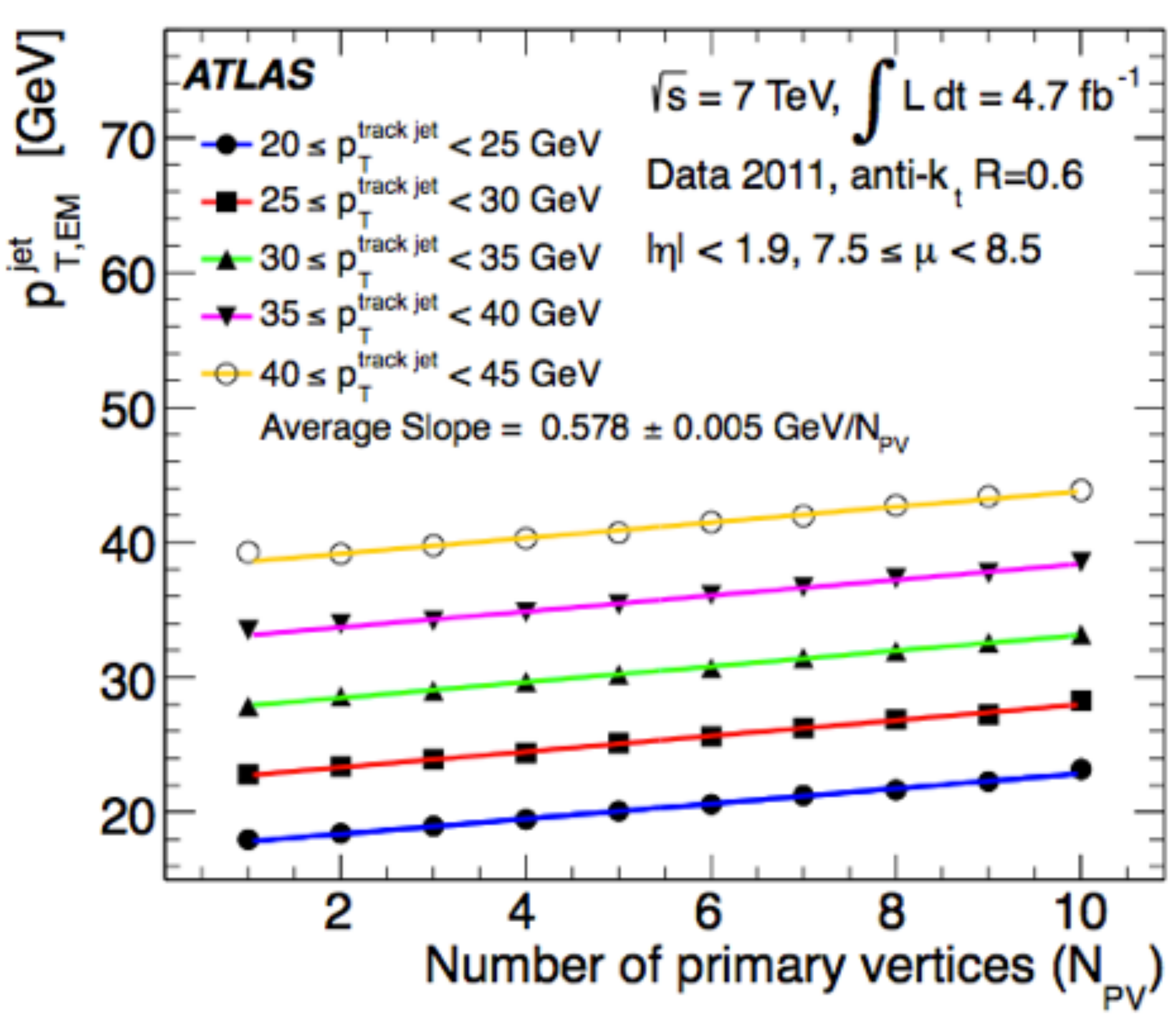


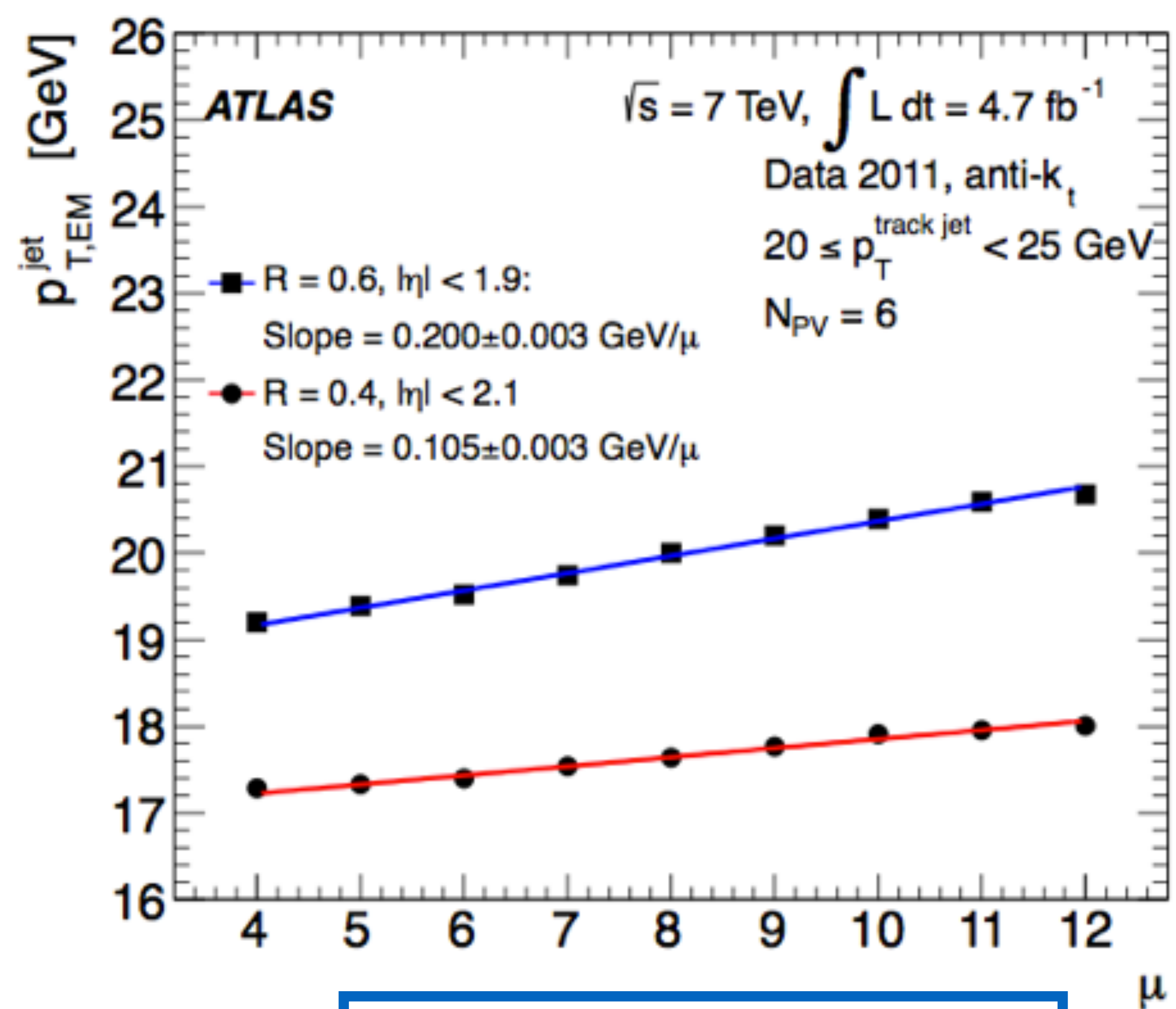

Pile Up Vertex
Primary Vertex

Pile up Correction

In-time pile up activity depends on the number of Primary Vertices (**PVs**)
Out-of-time pile up activity depends on the average number of **PVs**

$$\mu = \frac{L \times \sigma_{\text{inel}}}{N_{\text{bunch}} \times f_{\text{LHC}}}$$





larger R, larger PU

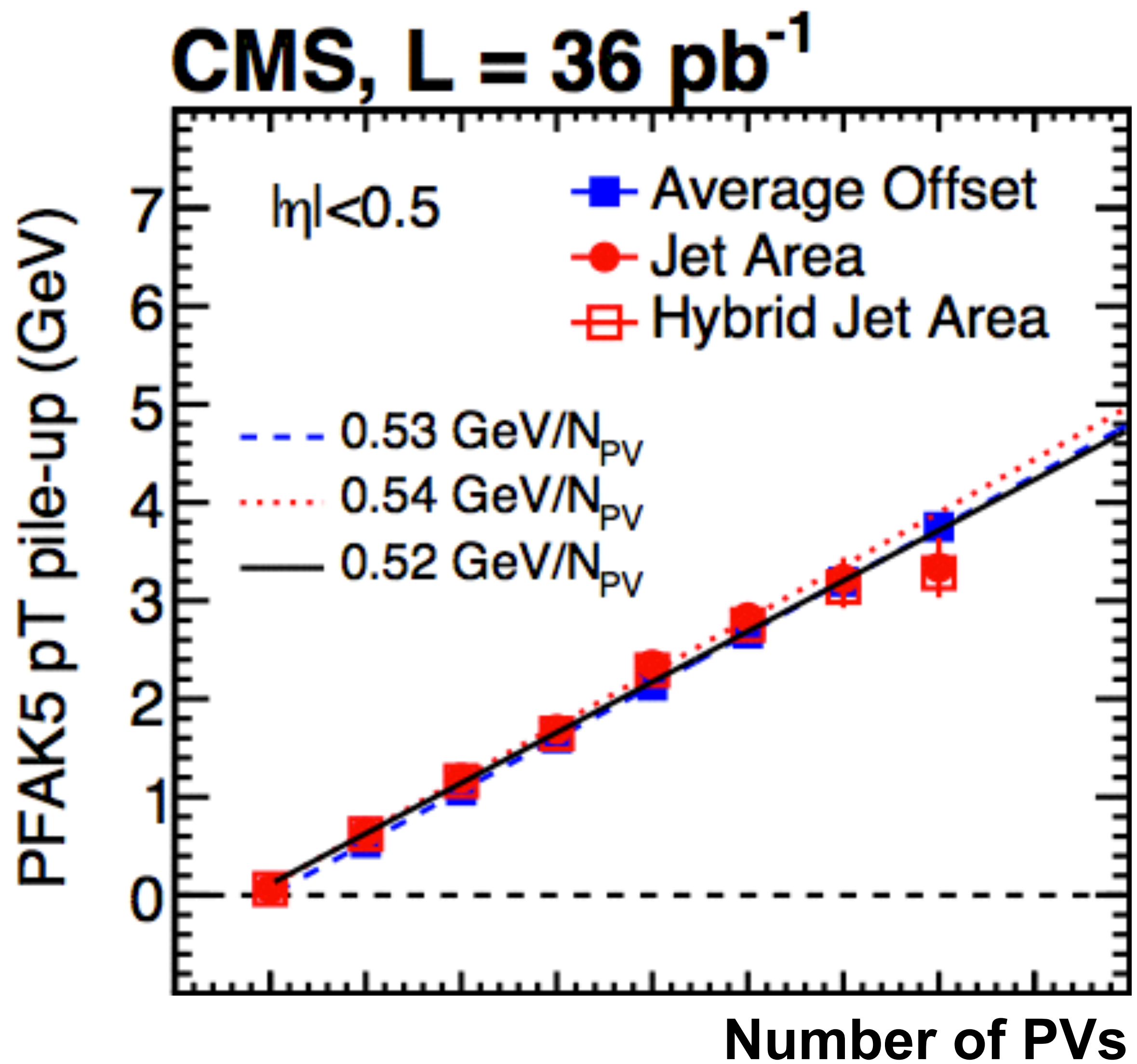
Pile up Correction

Jet "independent" PU correction is also possible, e.g., jet area method.

- ➡ adding "infinite" number of very soft 4-momentum vectors to cluster jets
  jet area is defined (A^j) as the space occupied by the very soft particles
- ➡ distribution of p_T^j/A^j is related to the PU activity

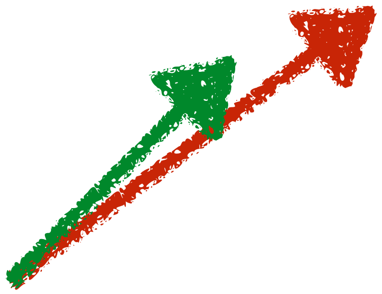
$$C_{\text{area}}(p_T^{\text{raw}}, A_j, \rho) = 1 - \frac{(\rho - \langle \rho_{\text{UE}} \rangle) \cdot A_j}{p_T^{\text{raw}}}$$

NPVs=1



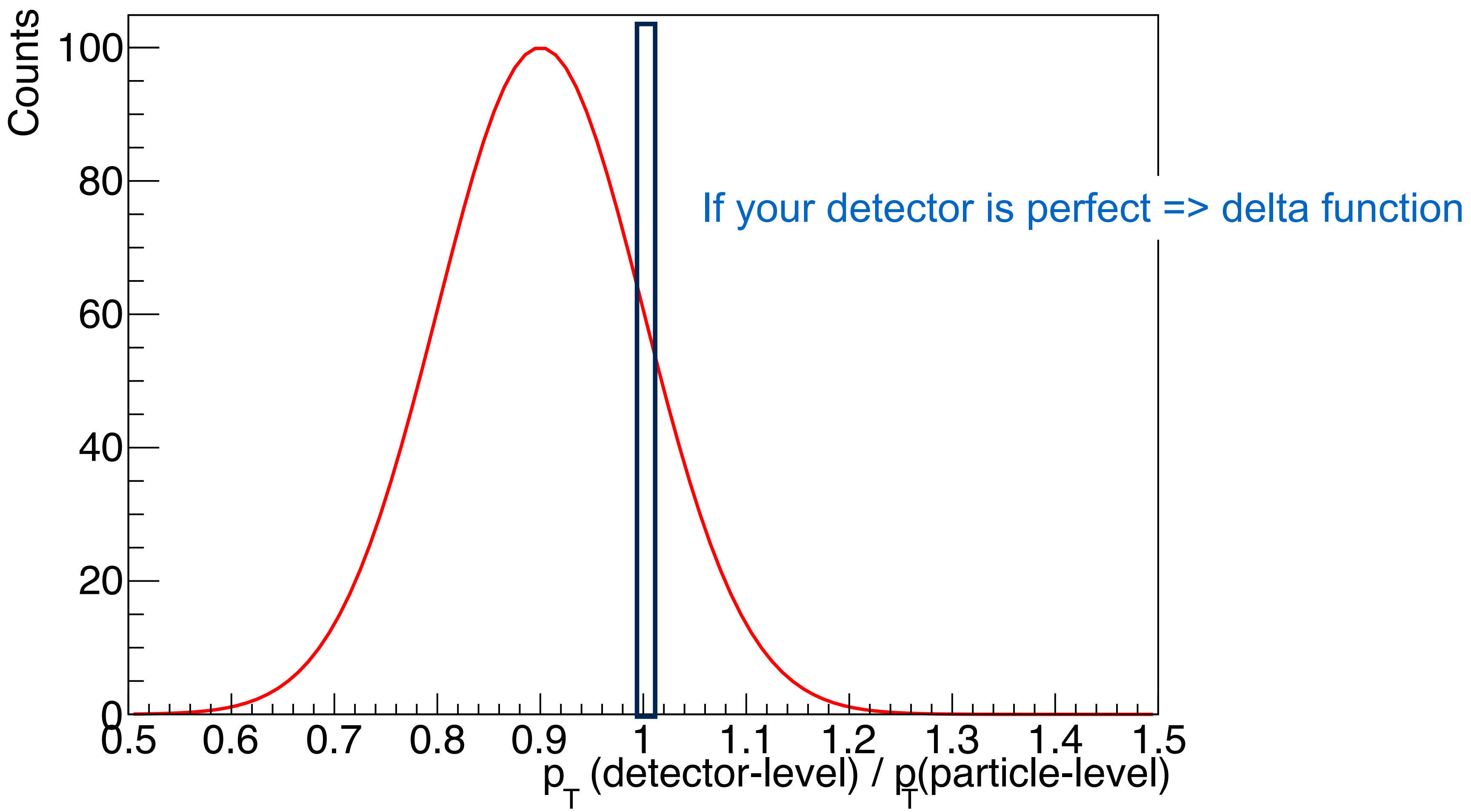
Jet Energy Calibration - Simple view

Using simulation, we can match jets at "particle-level" and at "detector-level"



Calibration factor is taken from the ratio p_T(detector-level)/p_T(particle-level)

+ factor is applied to 4-momentum: angle biases needed to be checked

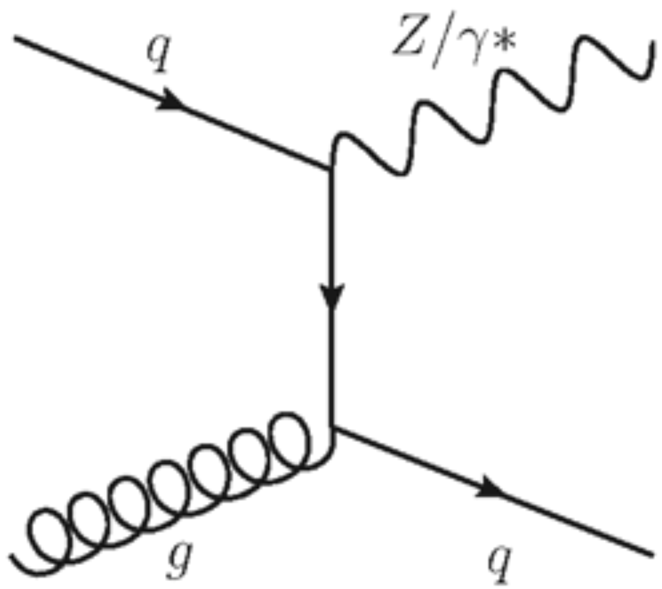


Jet Energy Calibration - Samples

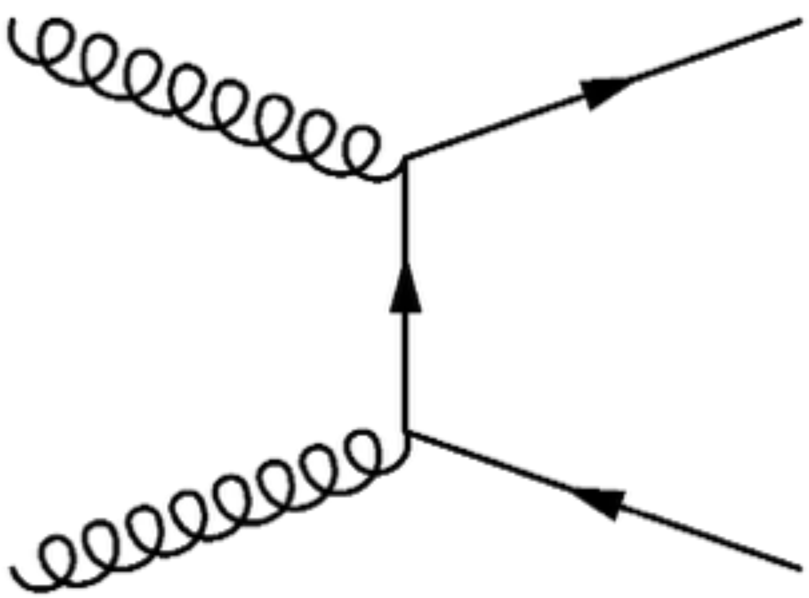
We do not want to be simulation dependent.

Data-driven methods are developed using production of well calibrated object with a jet

photon+jet or Z(→$\mu^+\mu^-$/e^+e^-)+jet



Two jet production are also very useful for relative jet energy calibration



Jet Energy Calibration - Dijet

Dijet sample

➡ Both objects are the subject for calibration - this sample can be used to calibrate one region of the detector relative to another one.

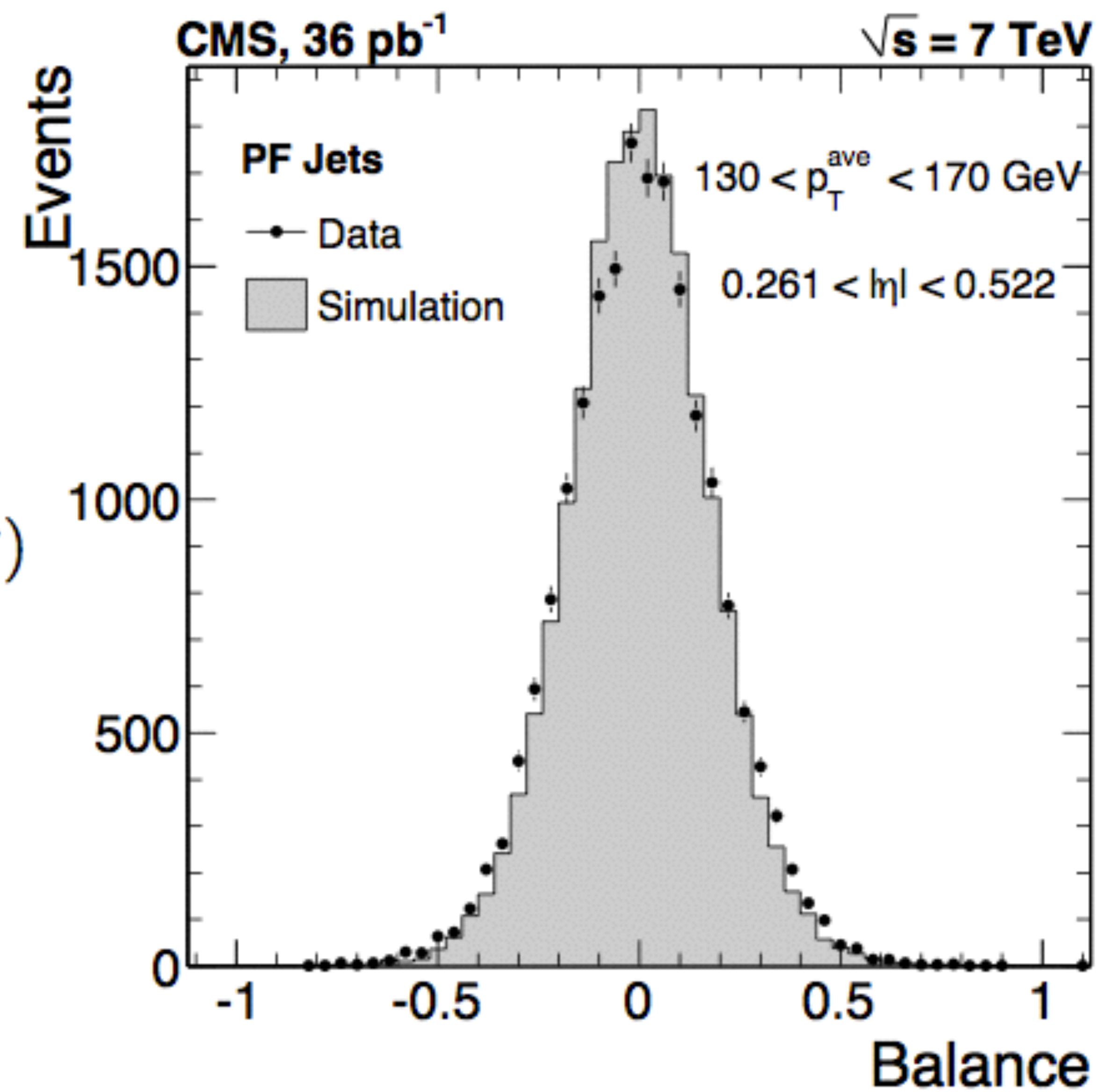
➡ Jet energy (p_T) resolution can be measured

$$\mathscr{A} = \frac{p_T^{\mathrm{Jet1}} - p_T^{\mathrm{Jet2}}}{p_T^{\mathrm{Jet1}} + p_T^{\mathrm{Jet2}}}$$

$$\sigma_{\mathscr{A}}^2 = \left|\frac{\partial \mathscr{A}}{\partial p_T^{\mathrm{Jet1}}}\right|^2 \cdot \sigma^2(p_T^{\mathrm{Jet1}}) + \left|\frac{\partial \mathscr{A}}{\partial p_T^{\mathrm{Jet2}}}\right|^2 \cdot \sigma^2(p_T^{\mathrm{Jet2}})$$

$$\sigma(p_T) \equiv \sigma(p_T^{\mathrm{Jet1}}) = \sigma(p_T^{\mathrm{Jet2}})$$

$$\frac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_{\mathscr{A}}$$

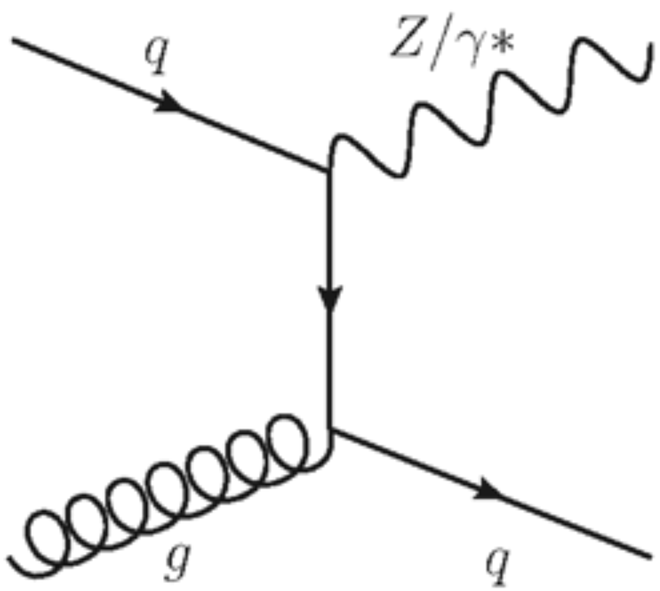


γ/Z+jet

The reference object energy resolution is much better than the jet energy resolution.

➡ At LO, the γ/Z is balanced with the parton that originates the jet.

➡ Missing transverse energy projection fraction (MPF) is used to include effects like:
- additional parton radiation
- underlying-event (UE) contribution
- out-of-cone contribution



Jet Energy Calibration - V+jet

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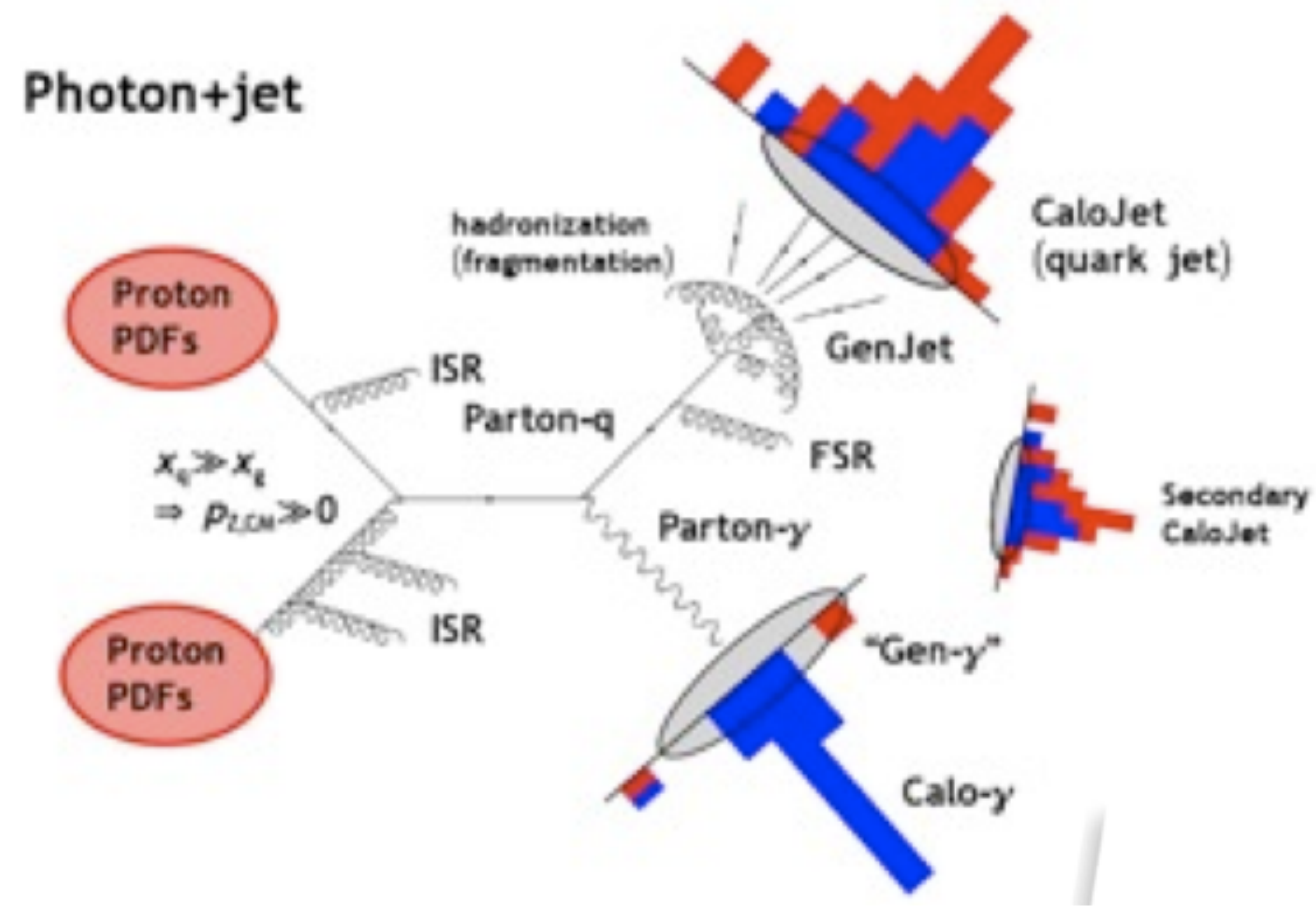

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$$\vec{p_T}^{\gamma,Z} + \vec{p_T}^{\text{recoil}} = 0.$$

$$R_{\gamma,Z}\vec{p_T}^{\gamma,Z} + R_{\text{recoil}}\vec{p_T}^{\text{recoil}} = -\vec{\not{E}}_T,$$

$$R_{\text{recoil}} = R_{\gamma,Z} + \frac{\vec{\not{E}}_T \cdot \vec{p_T}^{\gamma,Z}}{(p_T^{\gamma,Z})^2} \equiv R_{MPF}.$$

γ/Z+jet
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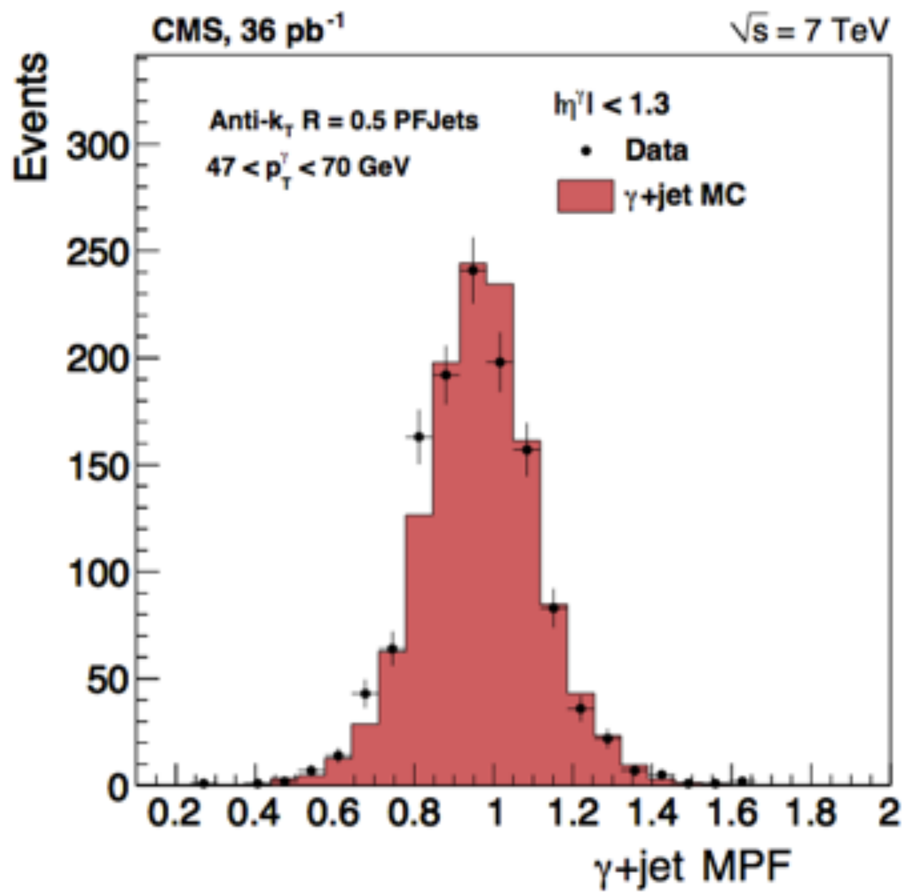
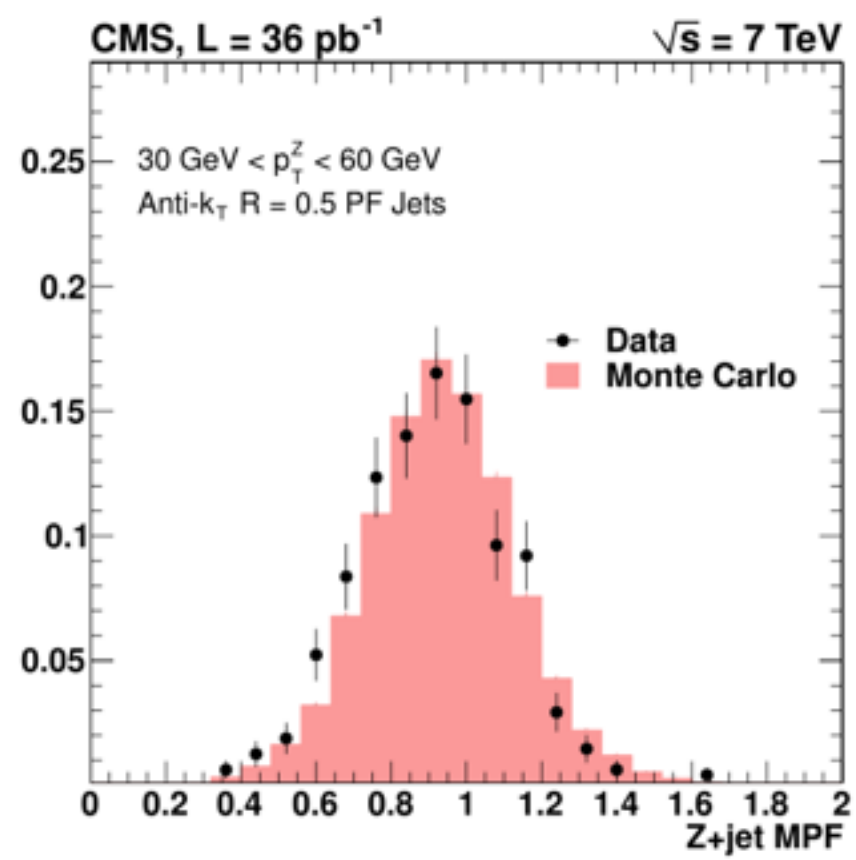
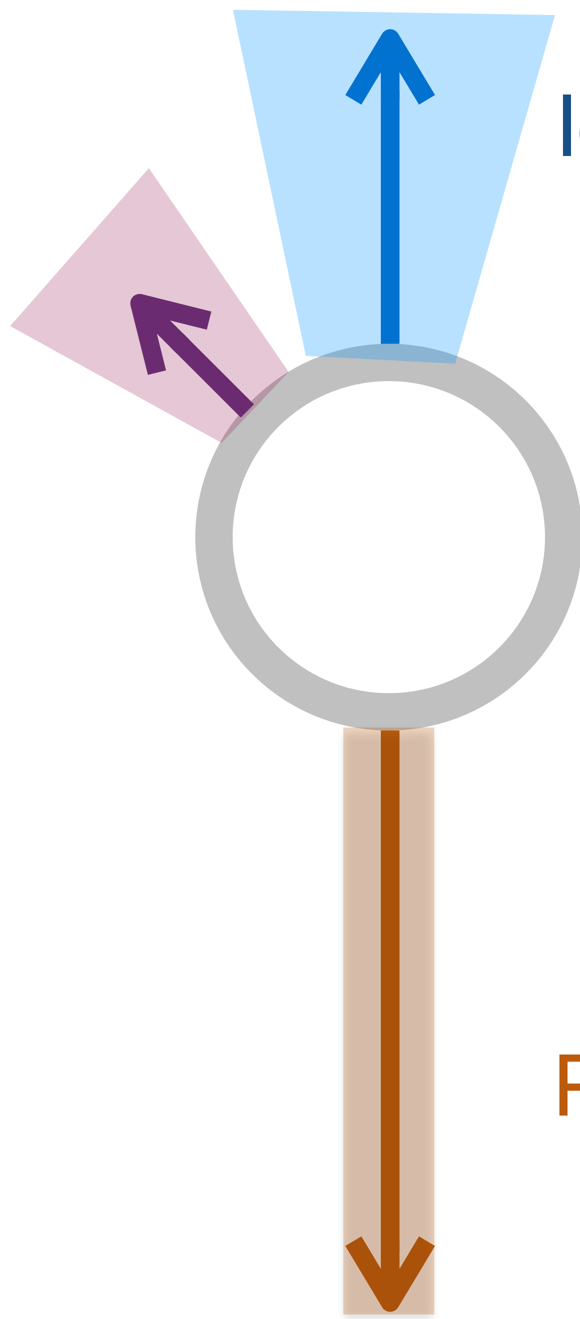




Jet Energy Calibration - ISR/FSR

By vetoing additional jets in the sample ($p_T^{Jet2} > \alpha\, p_T^{\gamma}$), the effect of initial and final parton radiation can be studied



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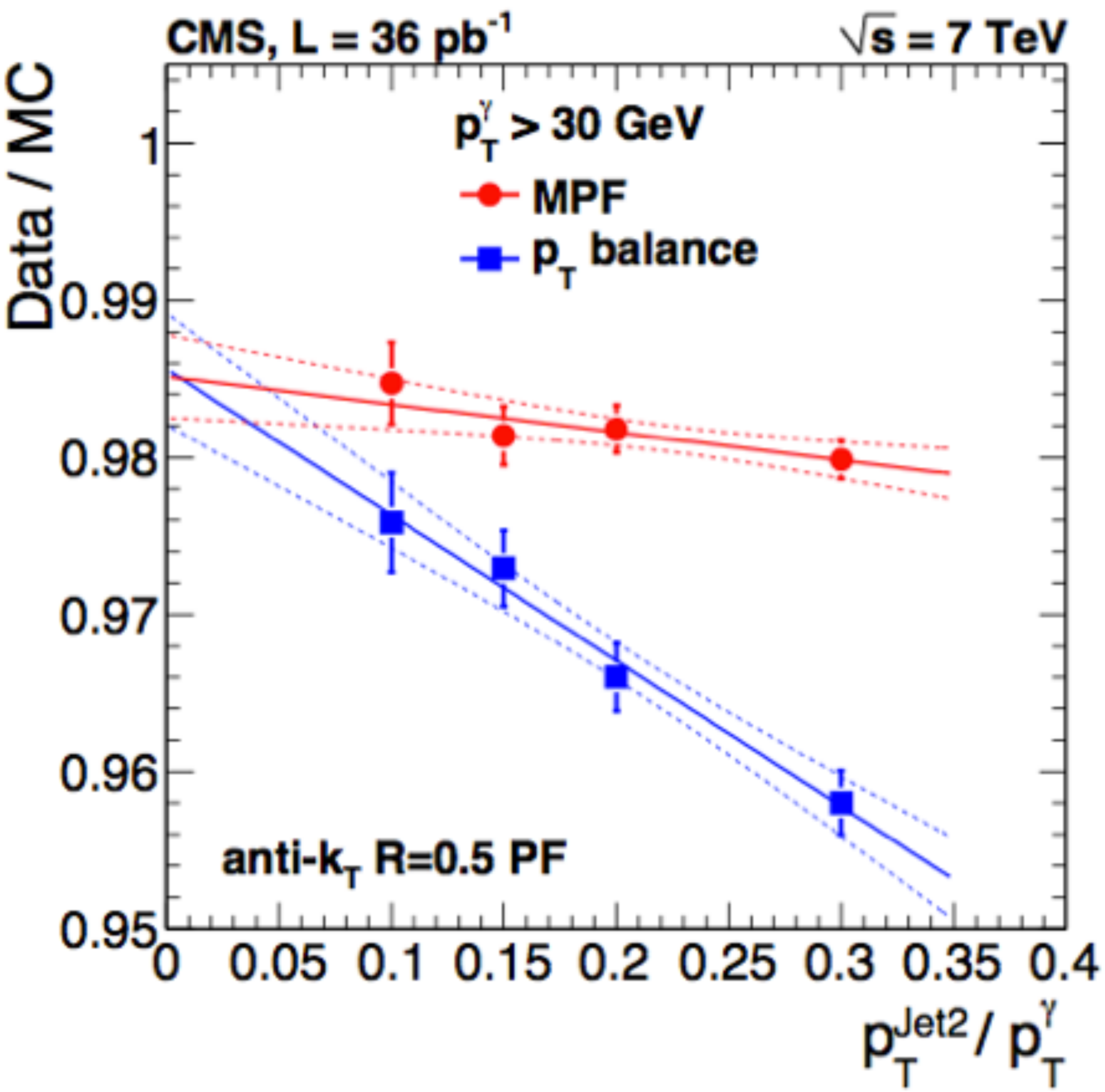
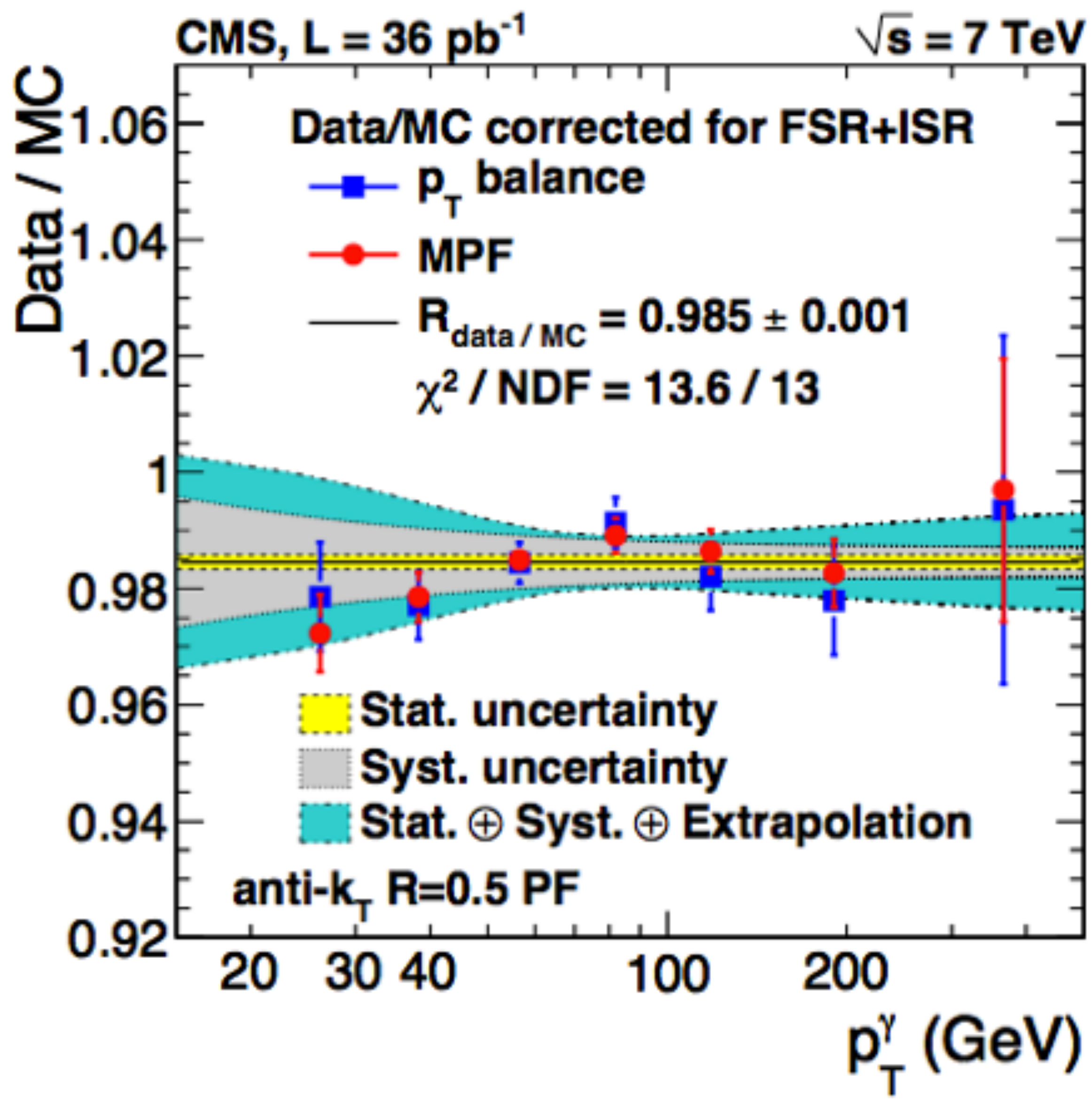
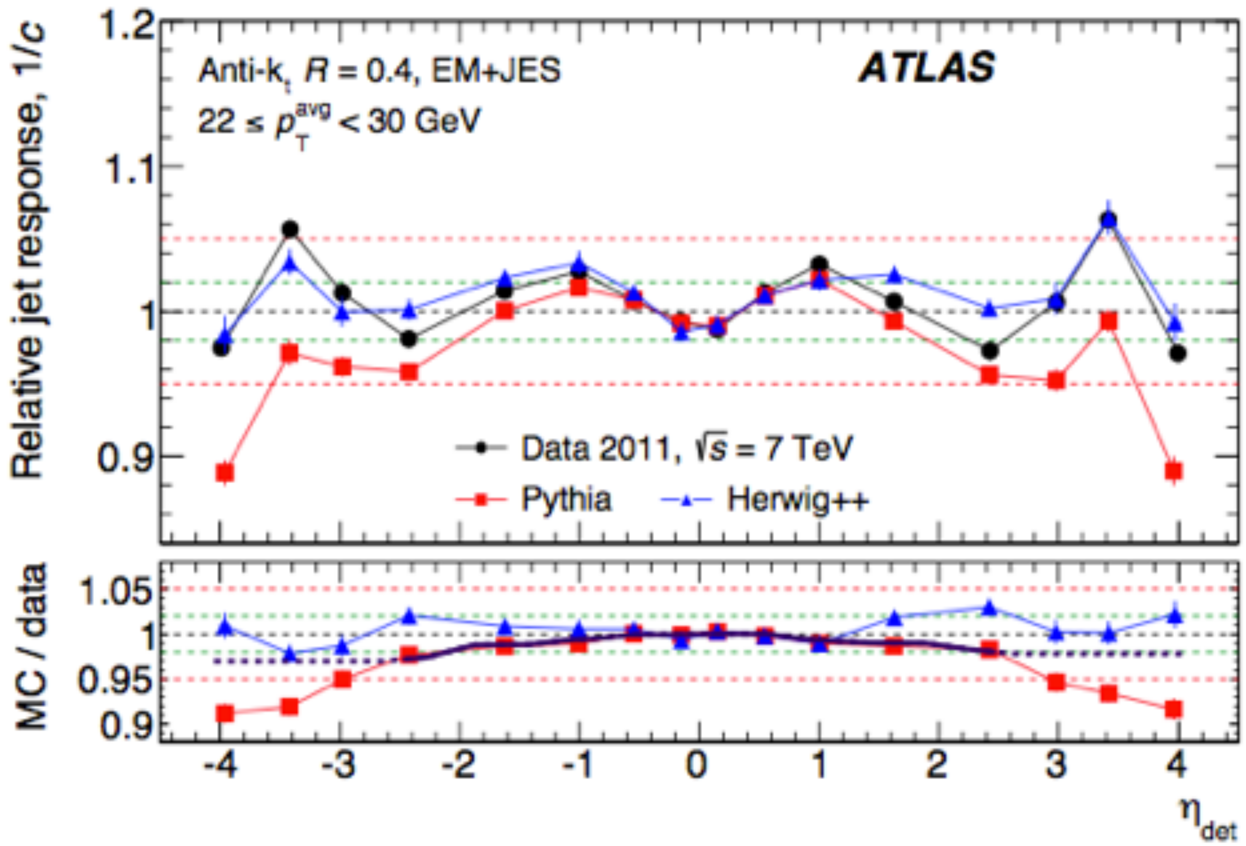


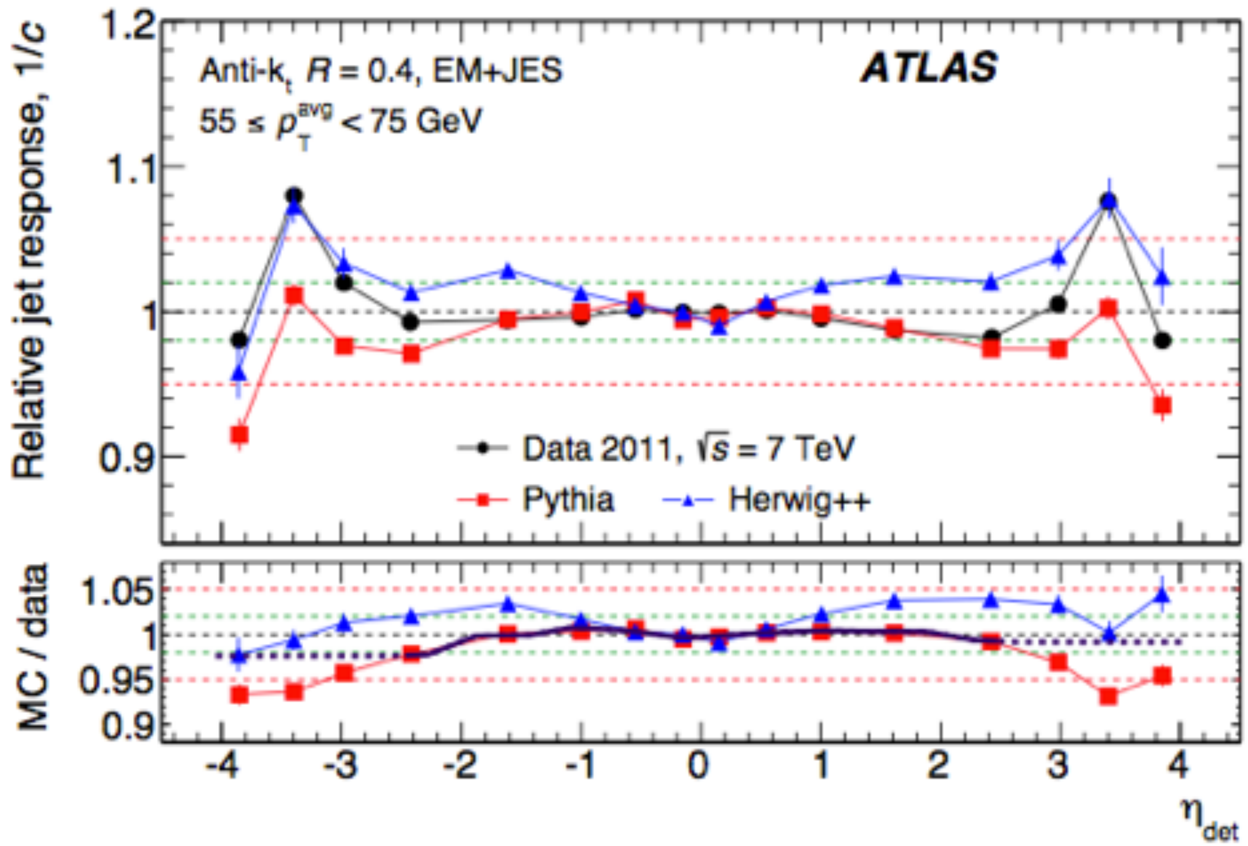


Calibration derived in data may need to be corrected by residual effects

⇛ data-to-MC differences

⇛ different MC can provide different corrections



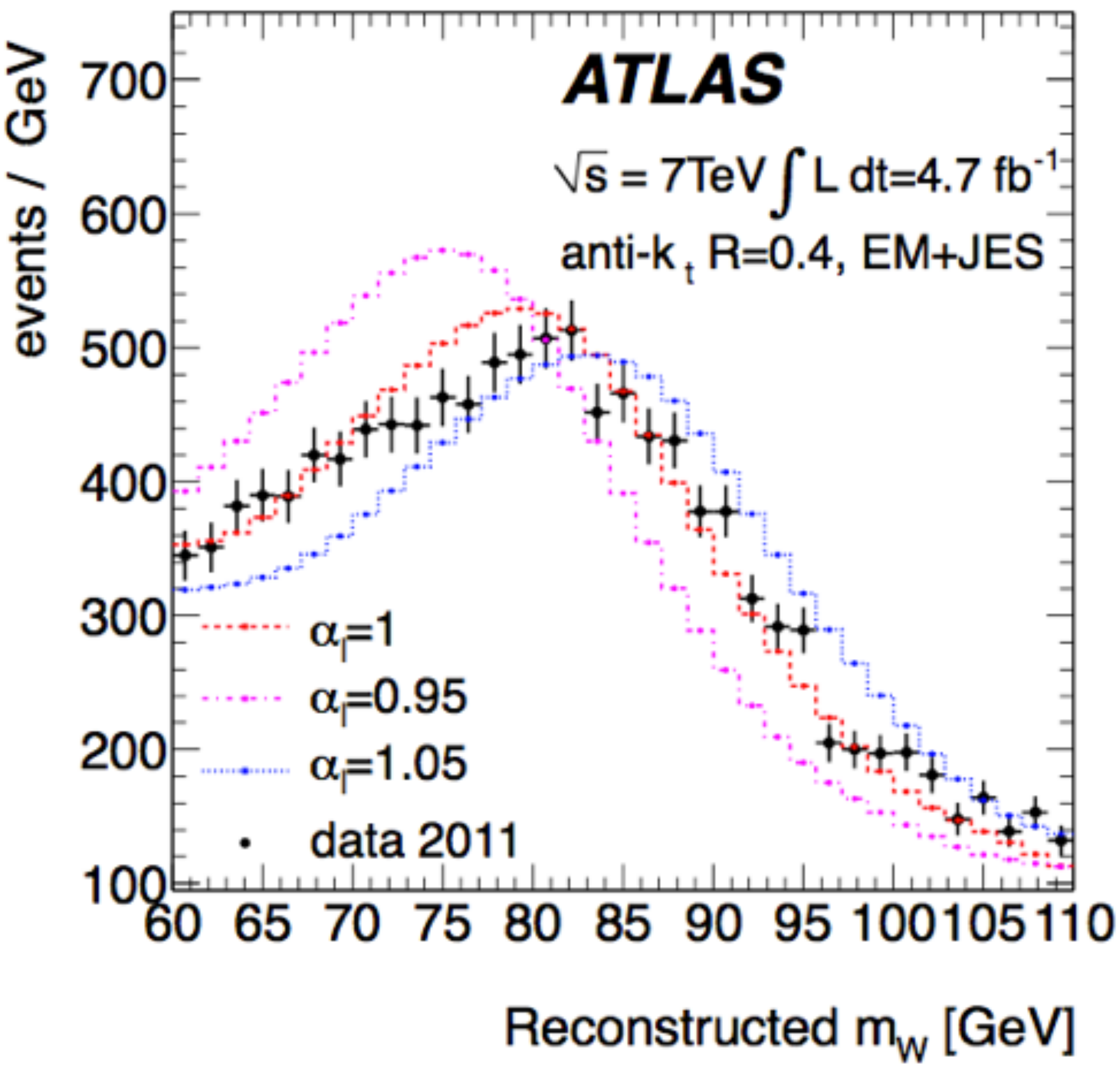


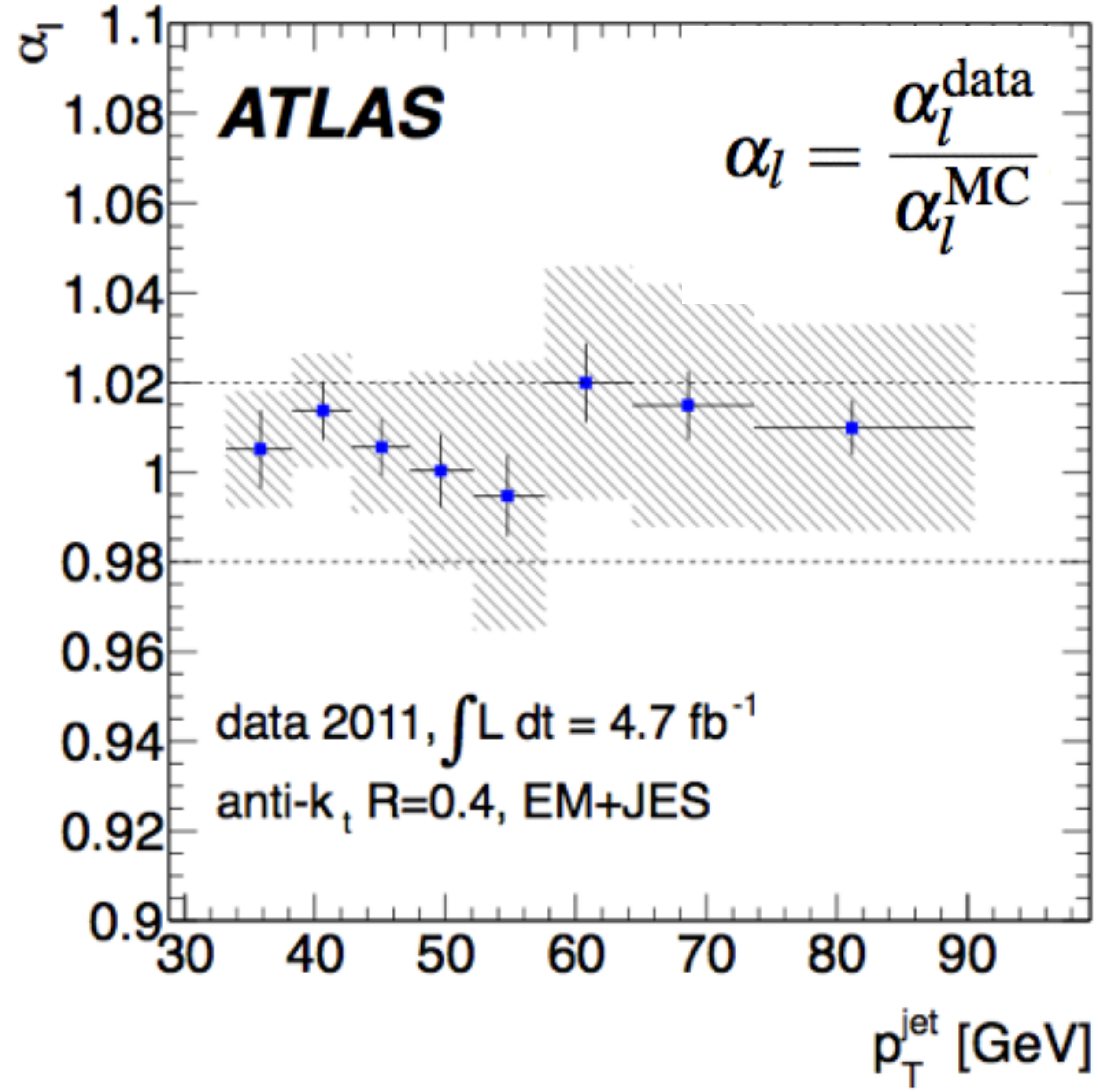
Sanity check using W→jets

Good knowledge of the W boson mass can be used to test the jet energy calibration

⇛ W from top quark decay

⇛ sensitive to jets originating from quarks



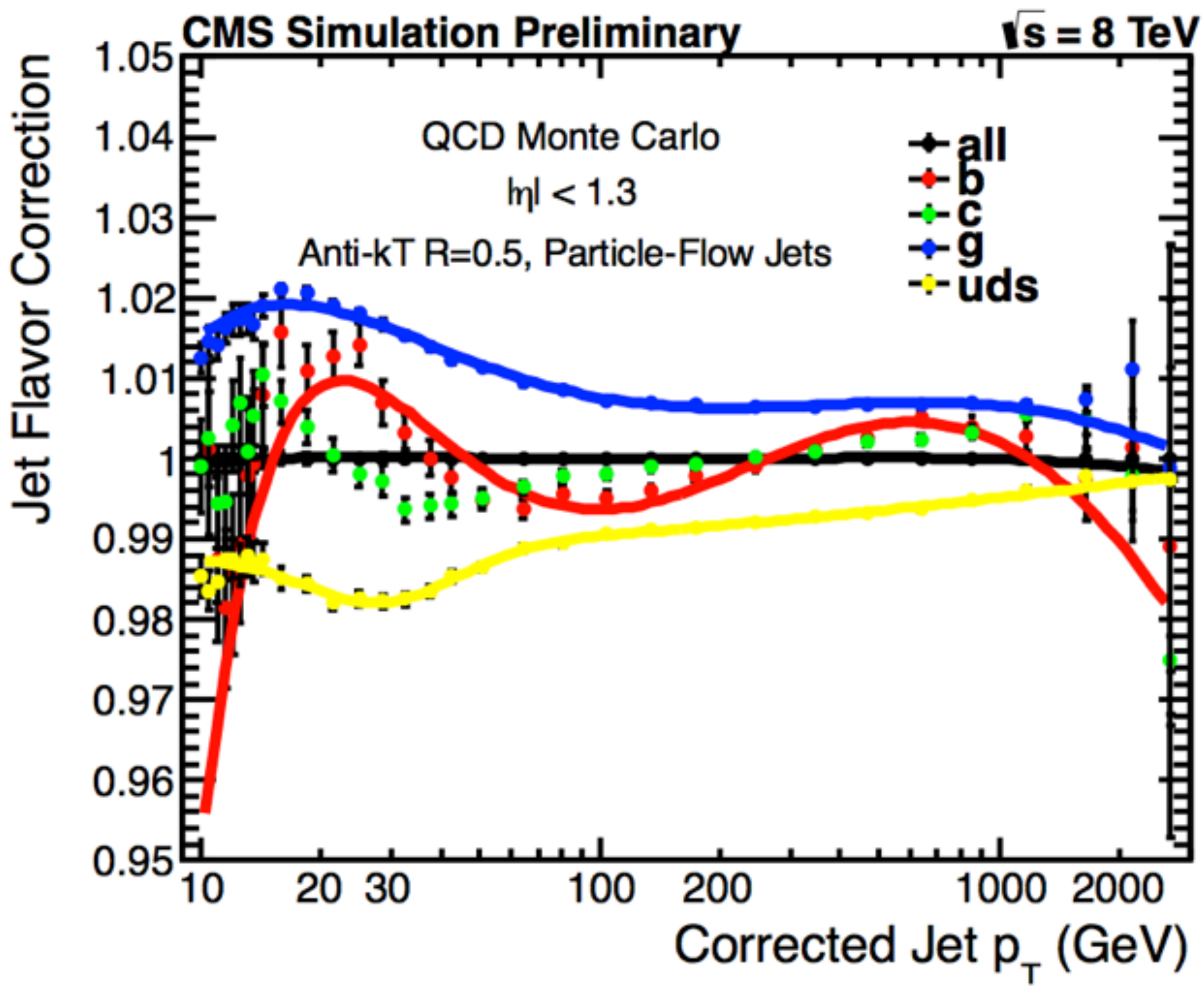


Jet Calibration - Flavour dependence

How can the calibration vary by changing the initial parton **flavour** (gluon)?

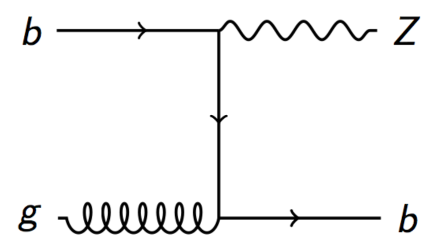
➪ Usually no extra correction is applied

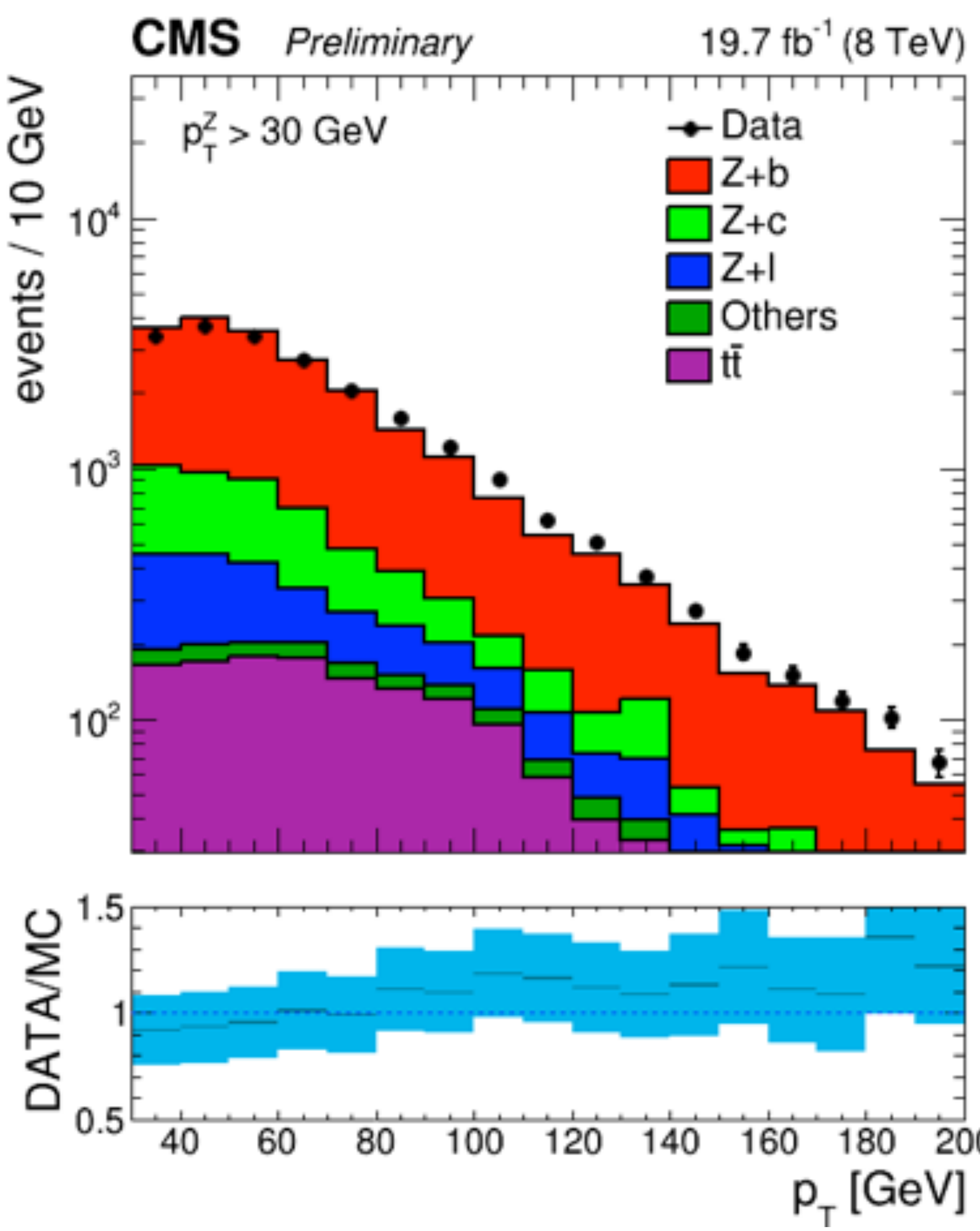
➪ Differences go to the systematic error of the calibration

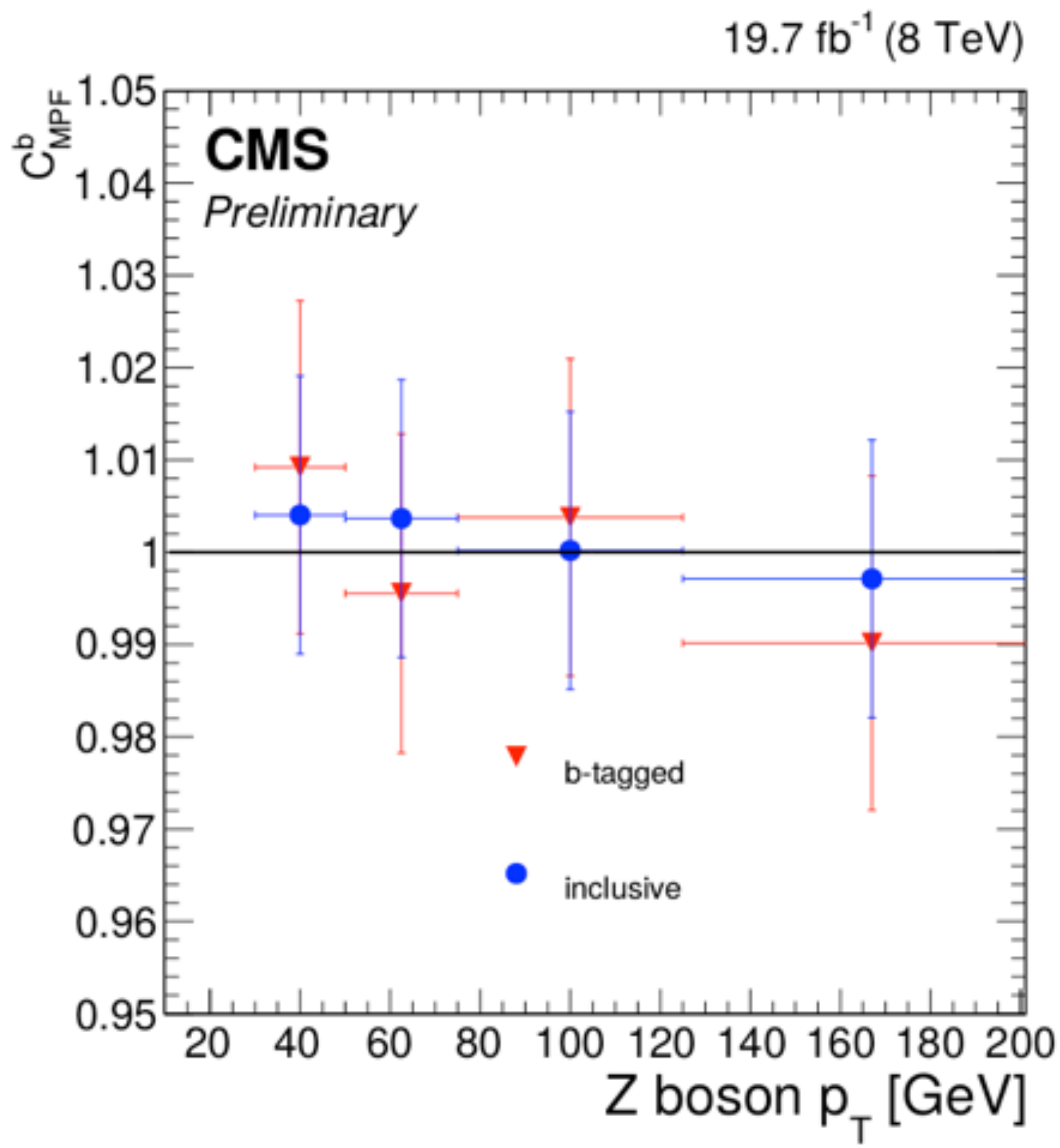


Jet Calibration for b-jets

➪ Using a data sample enriched in b-jets, one can check possible additional corrections



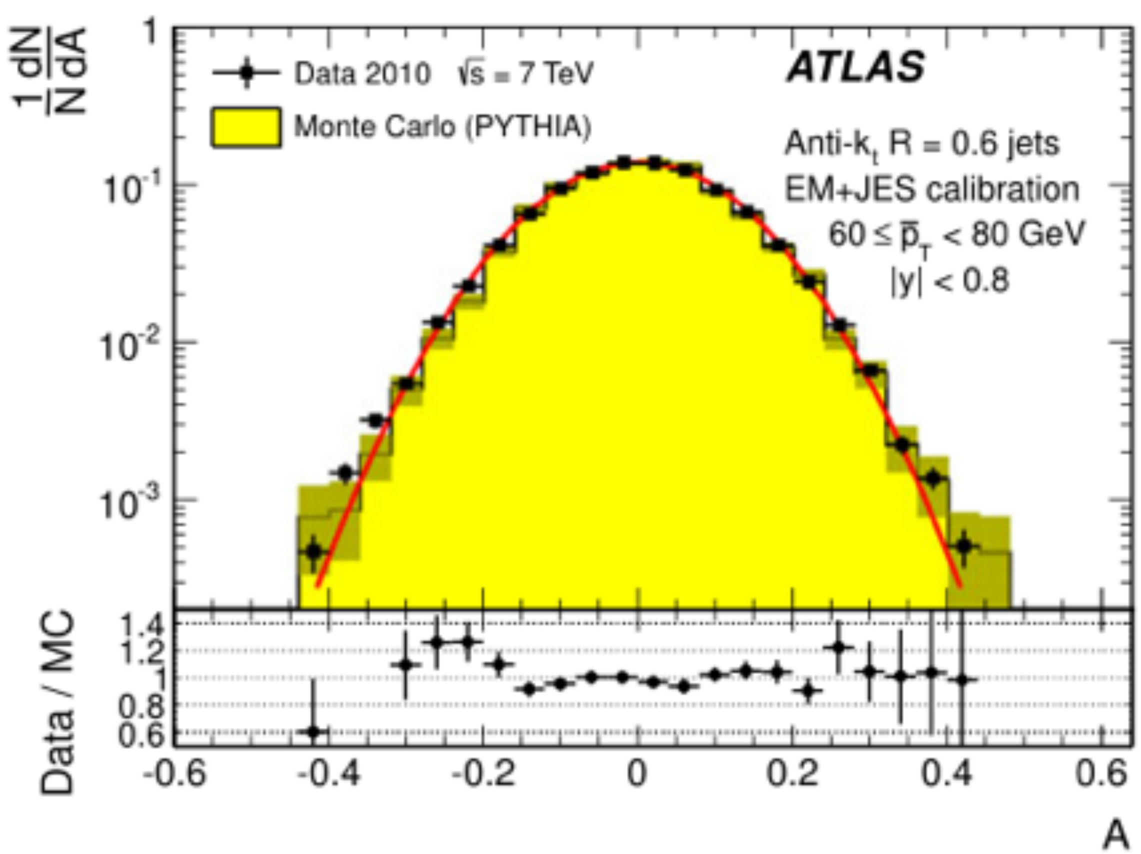


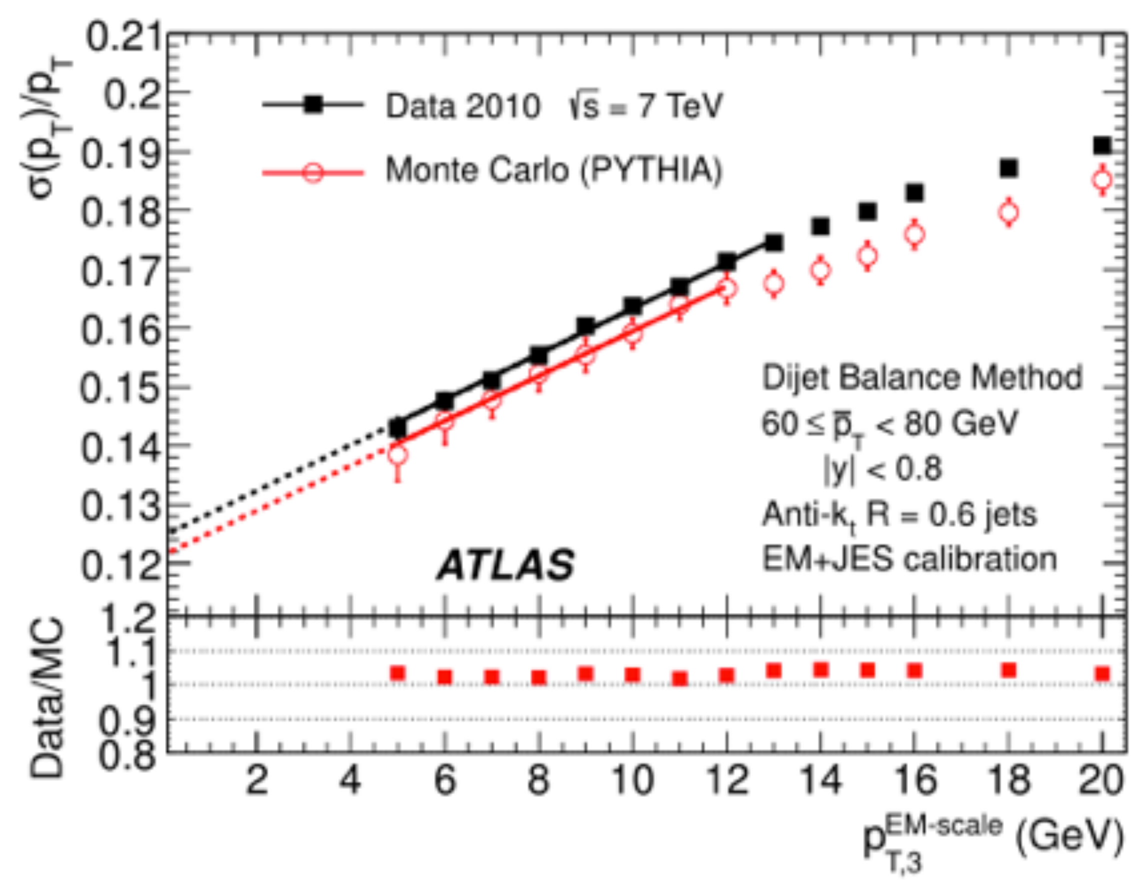


Jet p_T resolution

In dijet events, asymmetry distribution provides information about the jet energy resolution

- Extra activity affects the resolution
  - ⇒ resolution is evaluated with different veto thresholds of a third jet in the event
- Contribution from balance between "particle-jets" need to be considered





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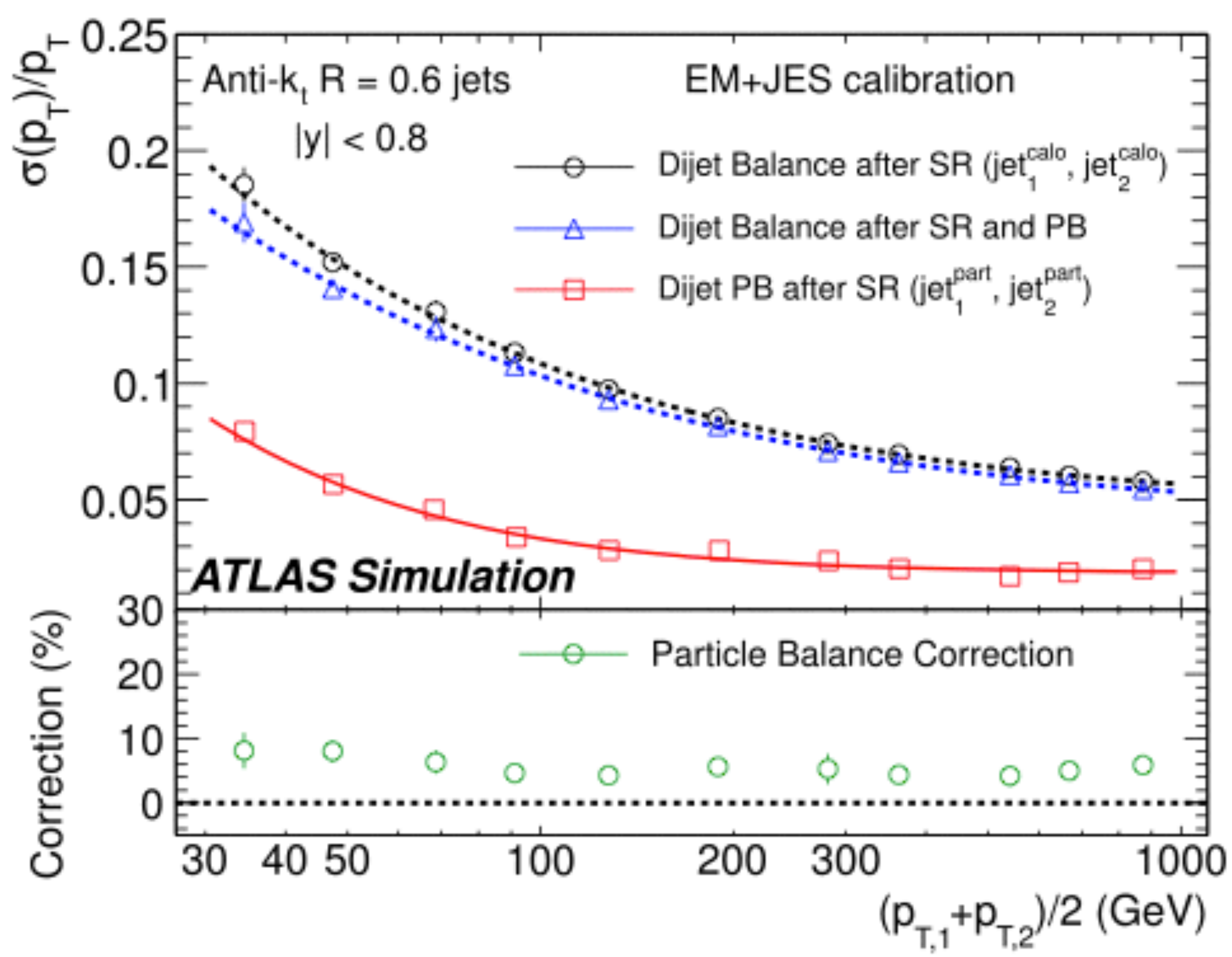


To compare with theory, one needs to unfold measured distribution

➡ correction for bin migration effects due to detector resolution

➡ non-trivial mathematical operation

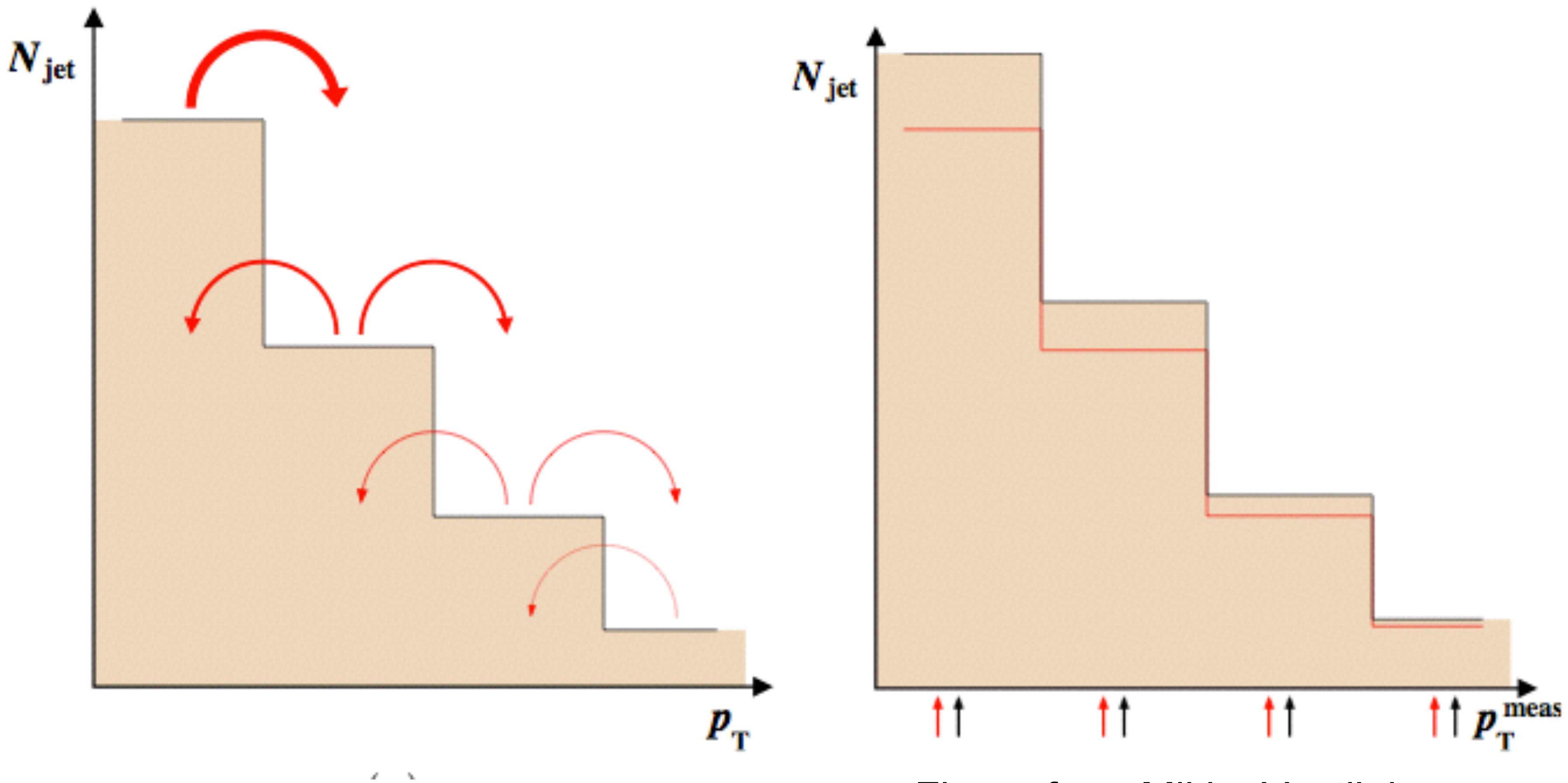
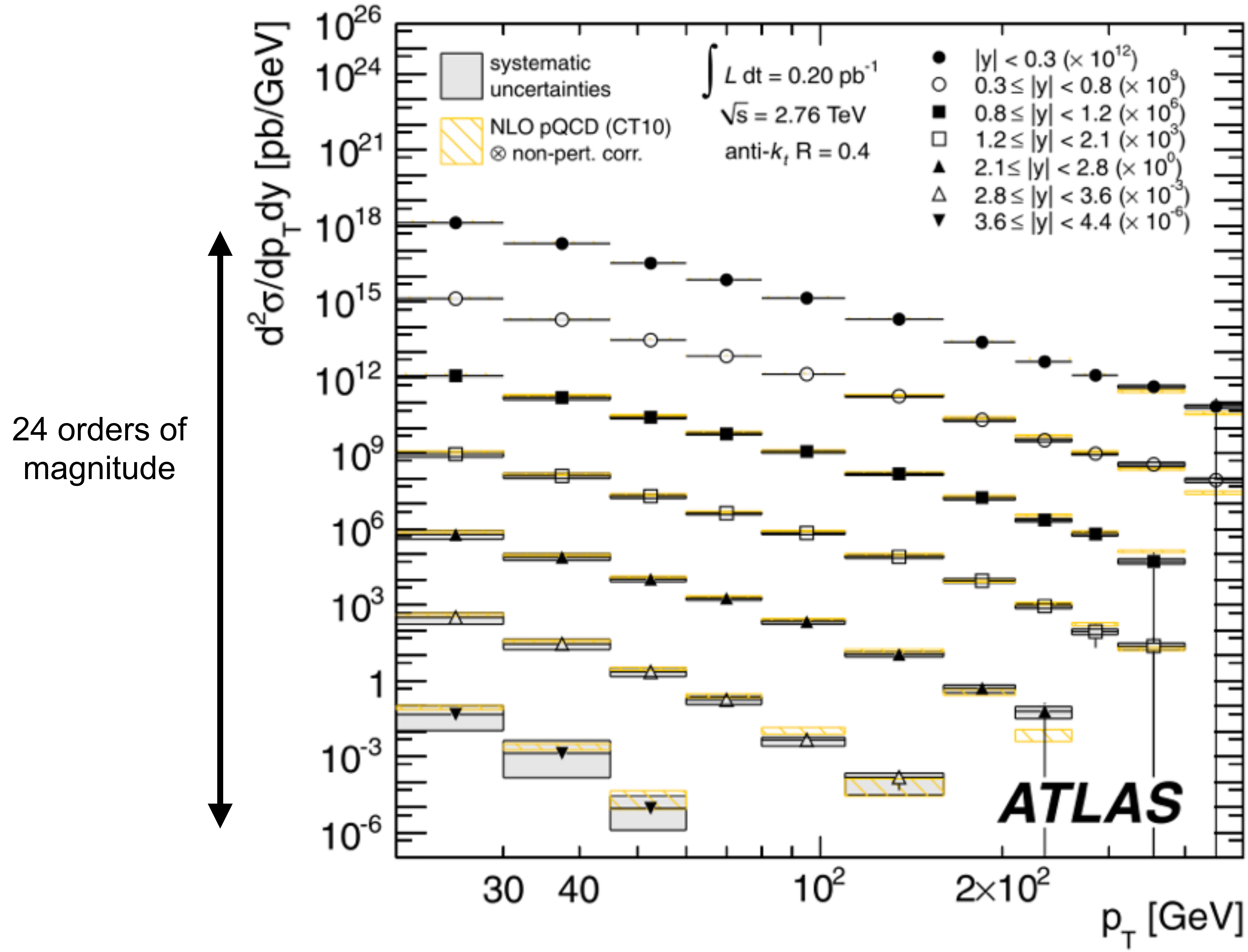


Figure from Mikko Voutilainen

Measurement

Calibration
Correction
Unfolding

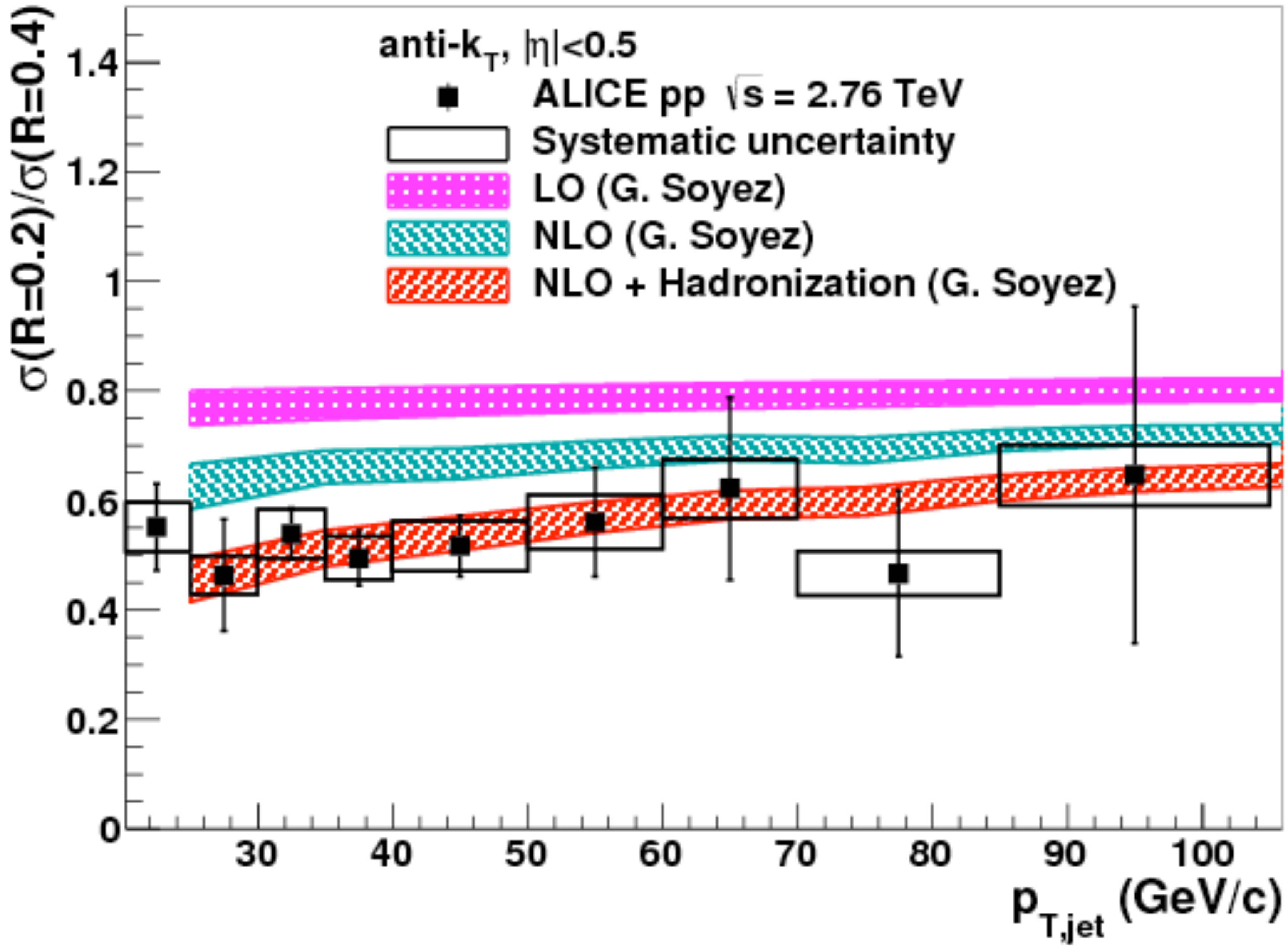
Calibration
Correction
Unfolding



systematic uncertainties
NLO pQCD (CT10) ⊗ non-pert. corr.
∫L dt = 0.20 pb^-1
√s = 2.76 TeV
anti-k_t R = 0.4
|y| < 0.3 (× 10^12)
0.3 ≤ |y| < 0.8 (× 10^9)
0.8 ≤ |y| < 1.2 (× 10^6)
1.2 ≤ |y| < 2.1 (× 10^3)
2.1 ≤ |y| < 2.8 (× 10^0)
2.8 ≤ |y| < 3.6 (× 10^-3)
3.6 ≤ |y| < 4.4 (× 10^-6)
ATLAS
d²σ/dp_T dy [pb/GeV]
p_T [GeV]
30
40
10^2
2×10^2
10^26
10^24
10^21
10^18
10^15
10^12
10^9
10^6
10^3
1
10^-3
10^-6
24 orders of magnitude

How the jet reconstruction parameter (R) affects cross section?

$$\mathcal{R}(p_t; R_1, R_2) = \frac{\frac{d\sigma}{dp_t}(R = R_1)}{\frac{d\sigma}{dp_t}(R = R_2)}$$

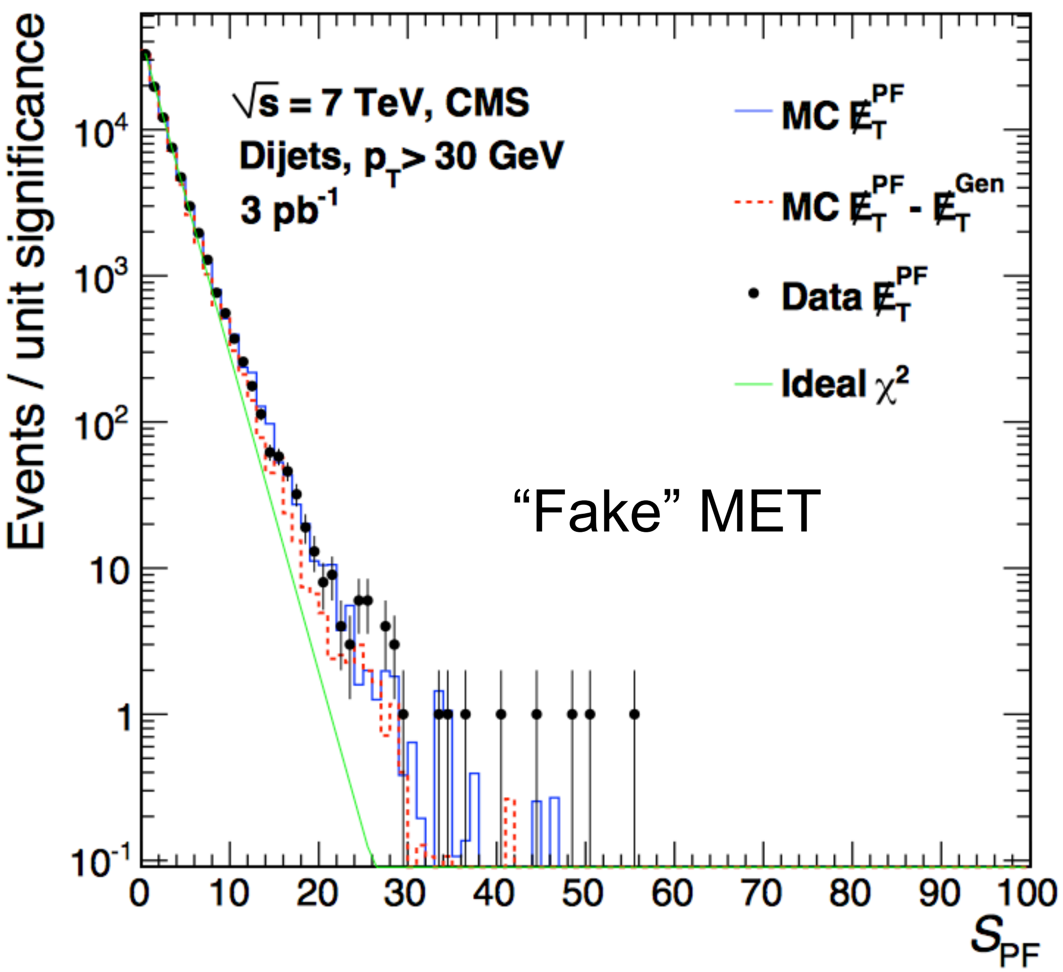


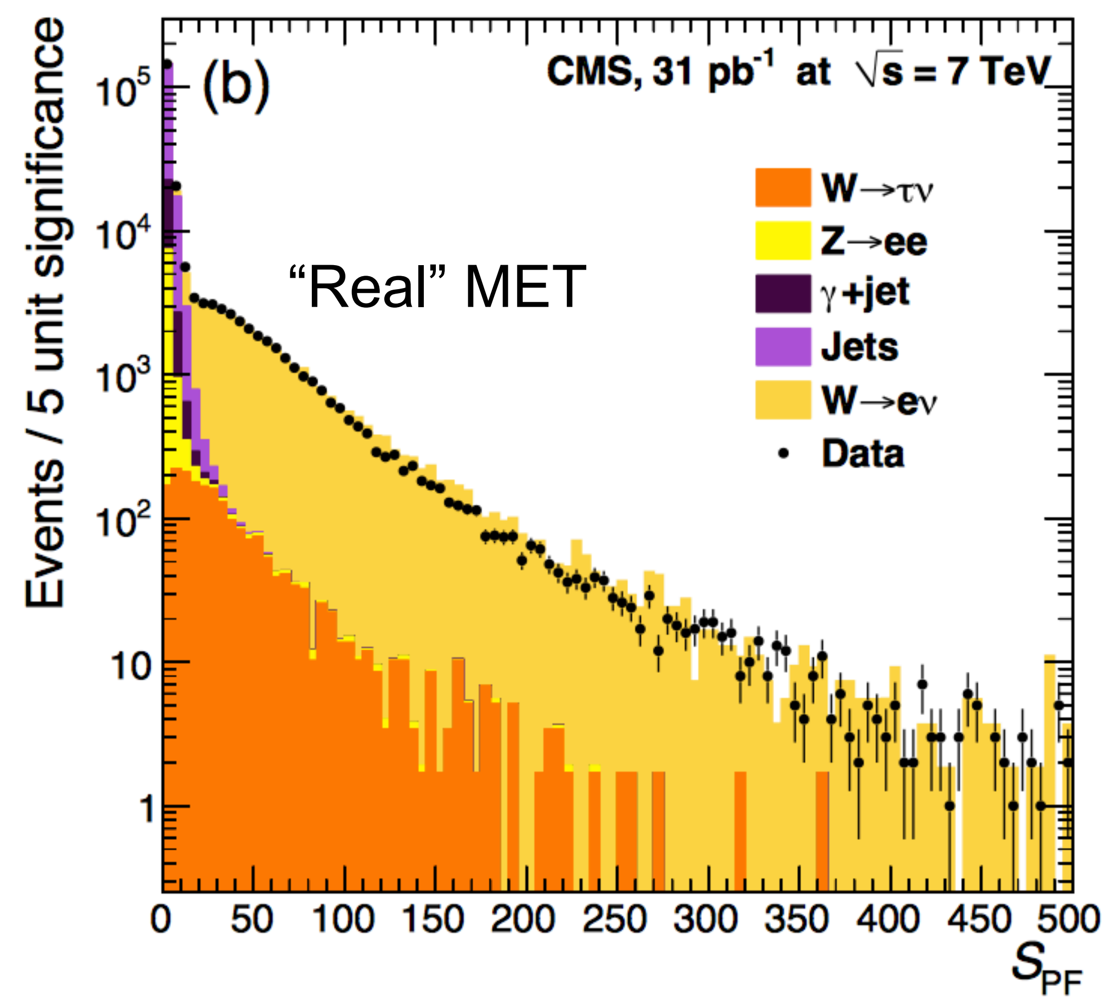
⊙ pQCD calculation considers the ratio directly, rather than each distribution separately, making the calculated ratio effectively one perturbative order higher than the individual cross sections

Missing Transverse Energy

Neutrinos and dark matter particles are identified with MET

- ➡ Use of calibrated objects: muons, photons, electrons, jets
- ➡ Pileup robust strategy
- ➡ Resolution can be used to quantify MET consistency





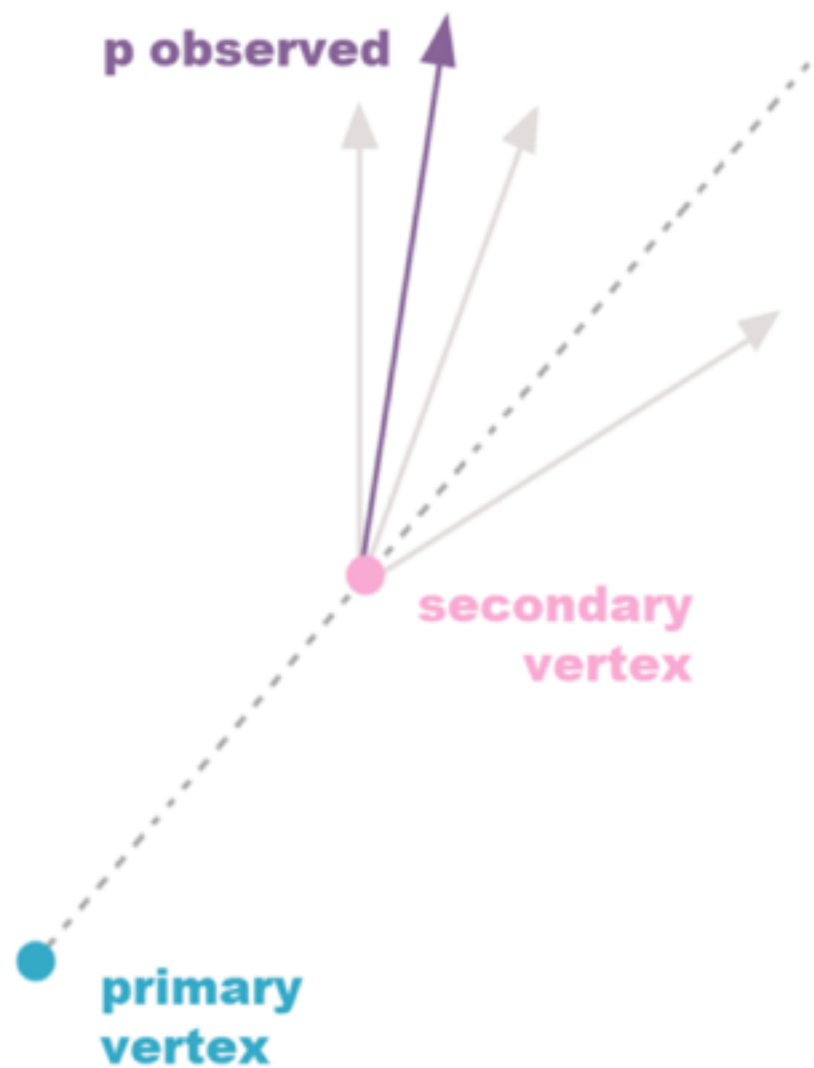
$$\mathcal{S} \equiv 2\ln\left(\frac{\mathcal{L}(\vec{\varepsilon} = \sum \vec{\varepsilon}_i)}{\mathcal{L}(\vec{\varepsilon} = 0)}\right)$$

b-tagging

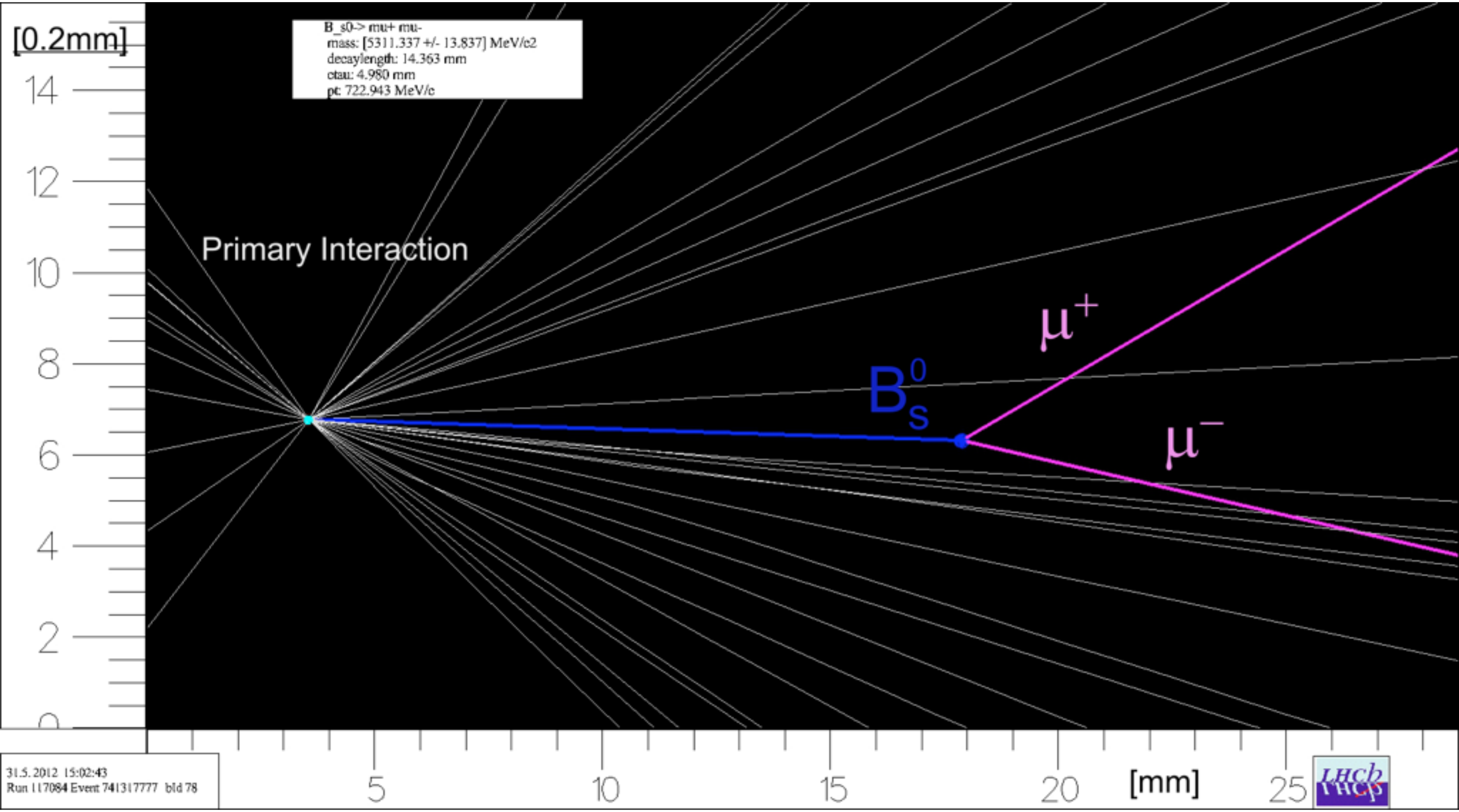
- b-hadrons can decay >~ 1 mm away from the PV.
  - Need secondary vertex resolution of *O*(30 μm)

- c-hadrons have similar behaviour

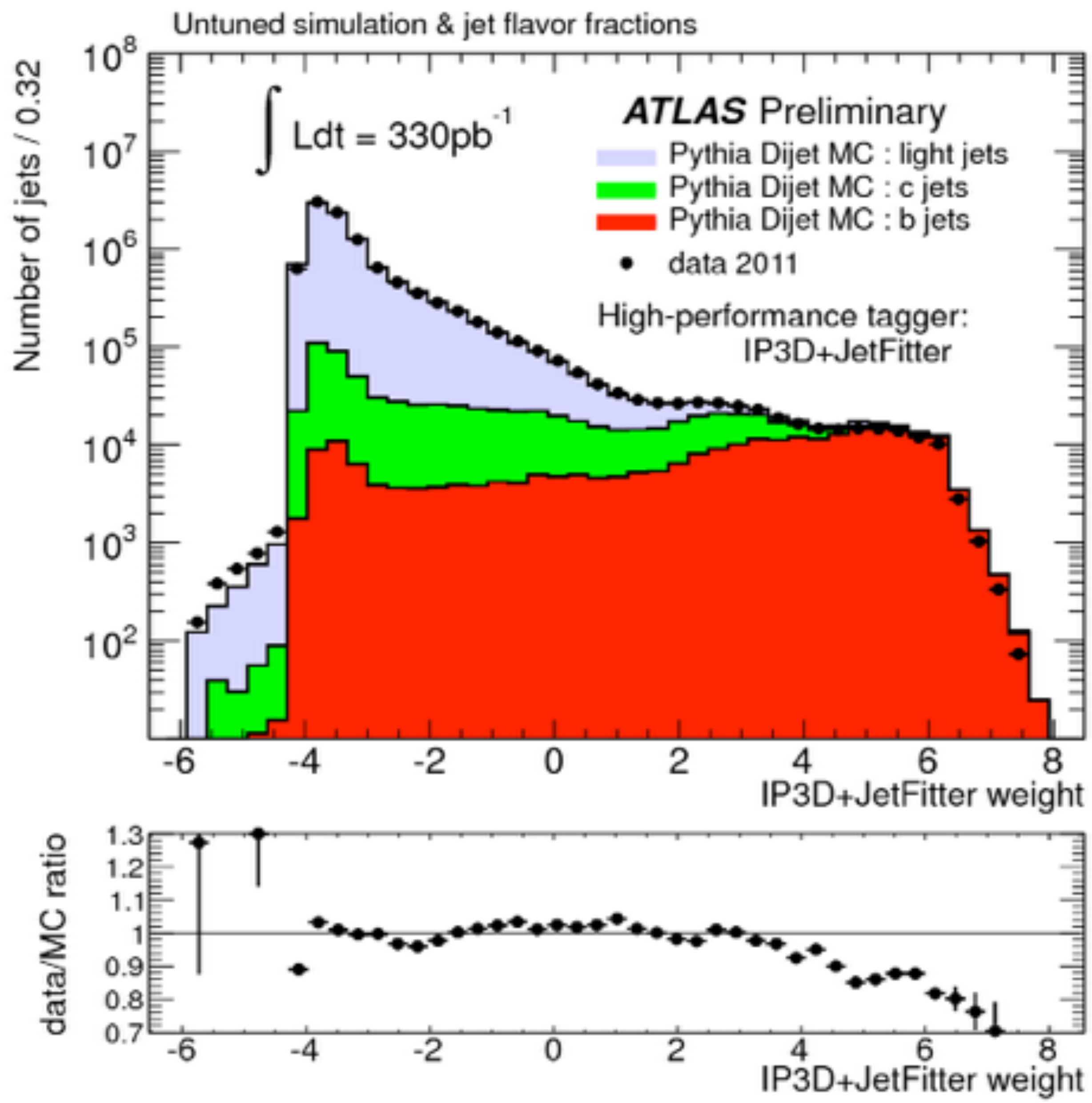
$$d_0 \sim \theta L_B \sim \left(\frac{p_\perp}{p_{||}}\right) L_B \sim \left(\frac{p_\perp}{p_{||}}\right) (c\tau_B)\gamma_B \sim \left(\frac{m_B}{p_B}\right) (c\tau_B)\gamma_B \sim (c\tau_B)$$

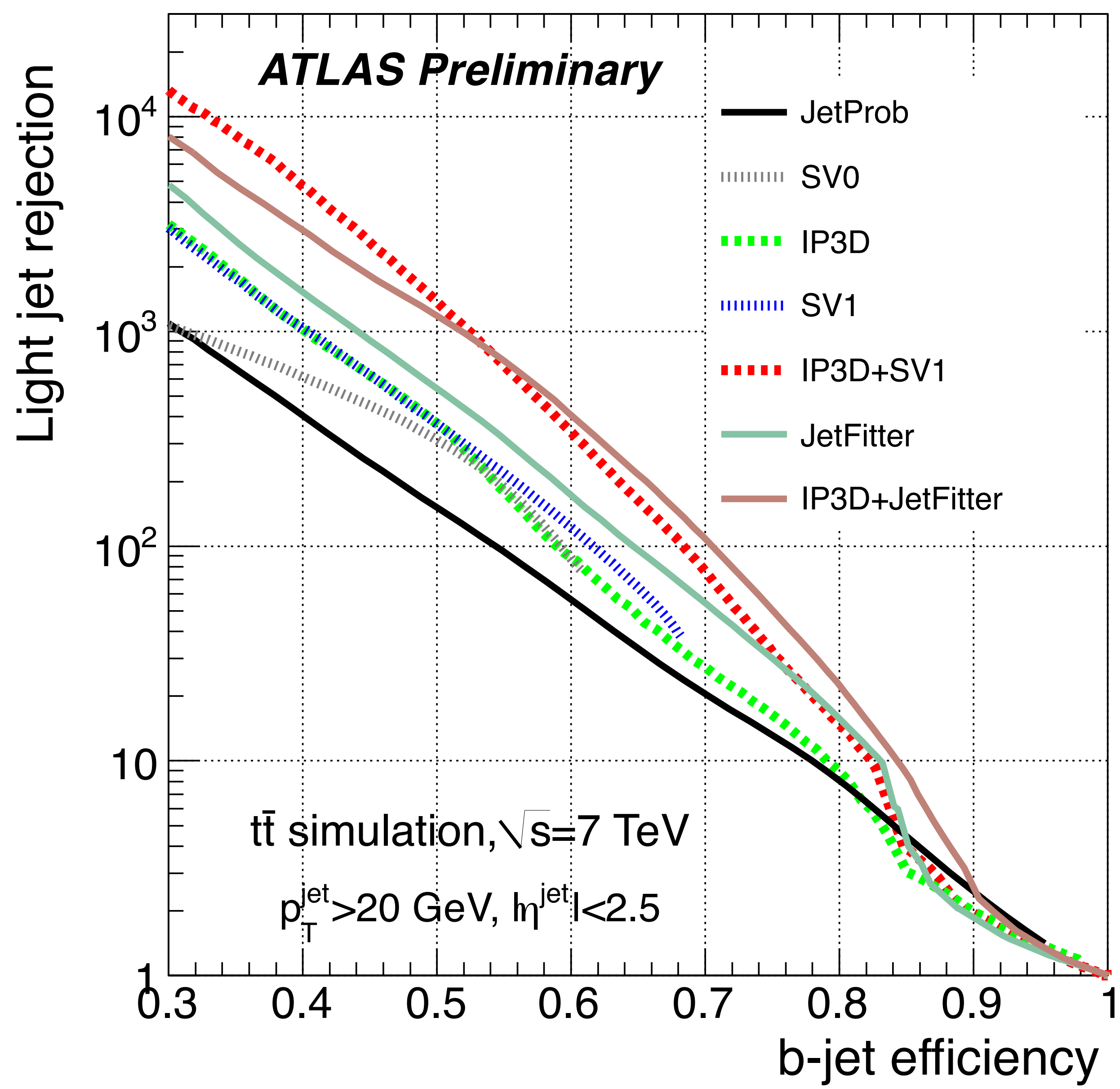


Secondary Vertex



- Use of **tracks** is mandatory
- Several variables can be used for discrimination between b-jets and l-jets
  Multivariate techniques are often used





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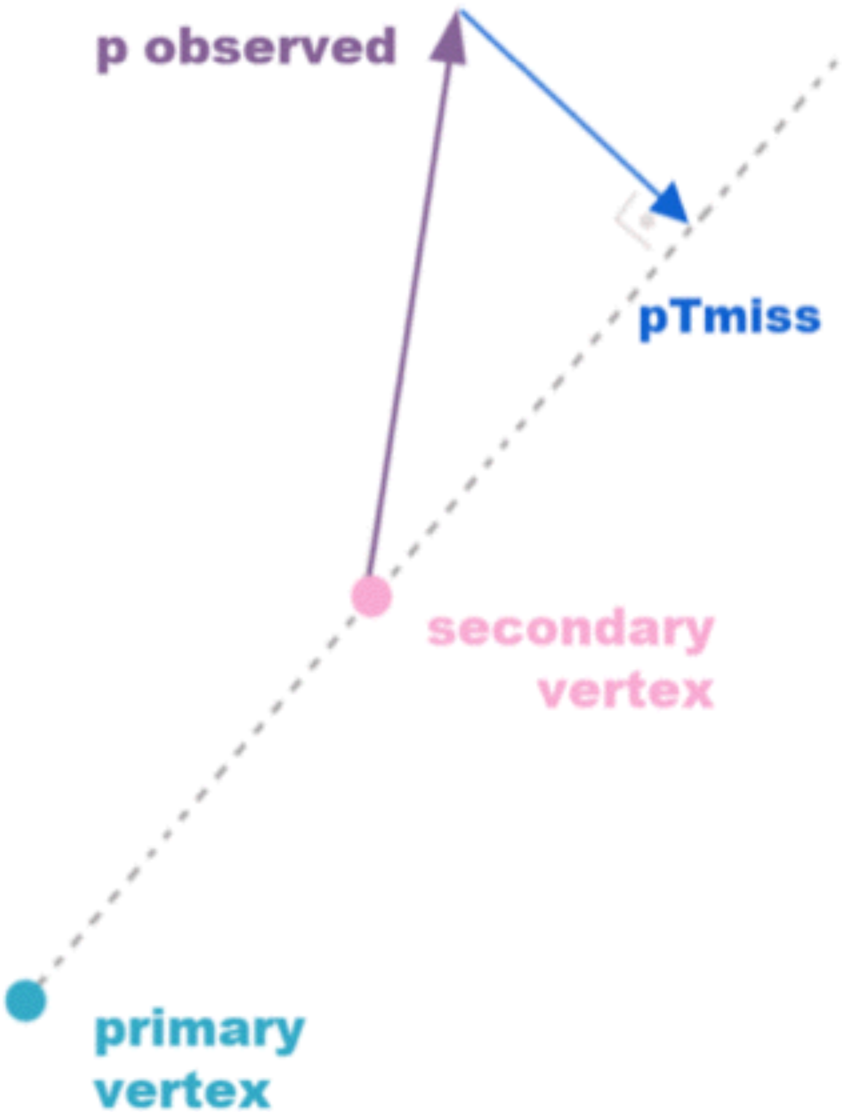
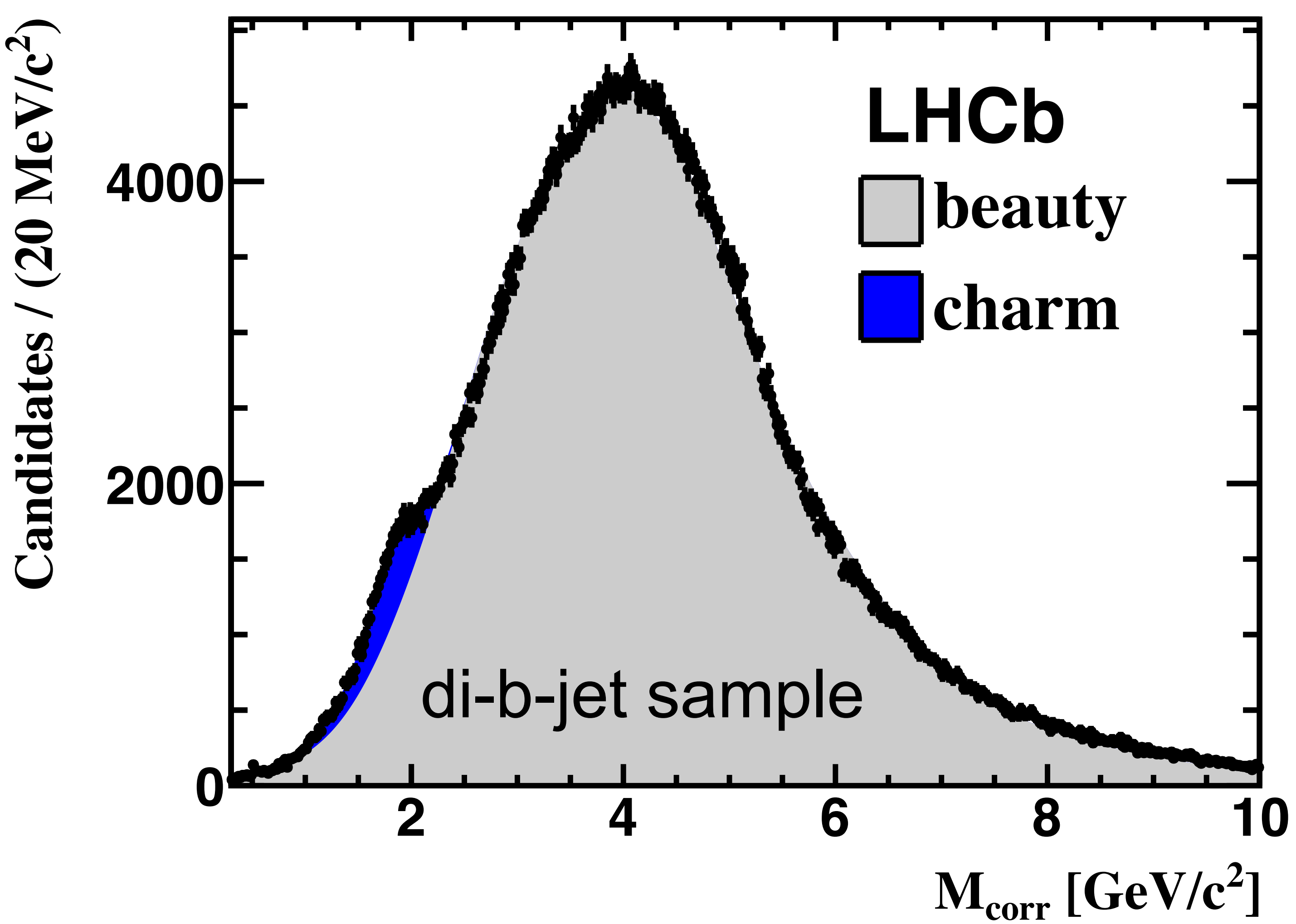
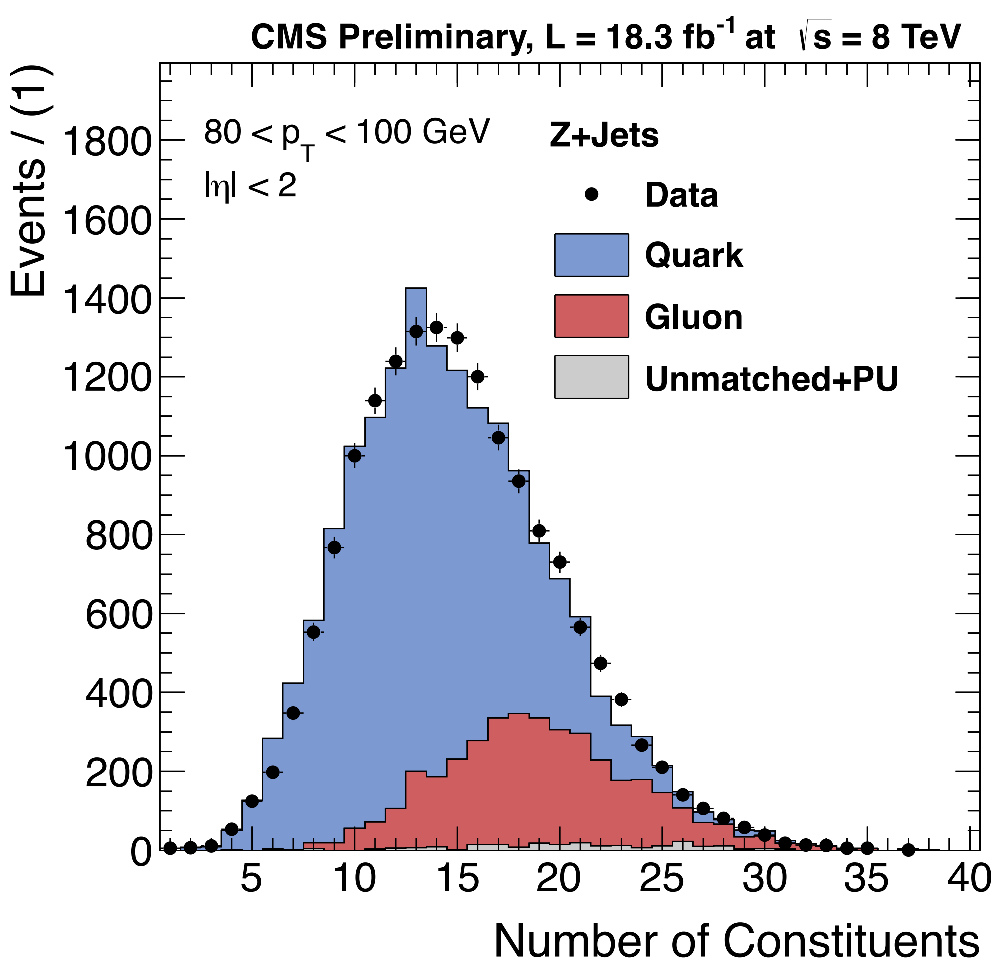


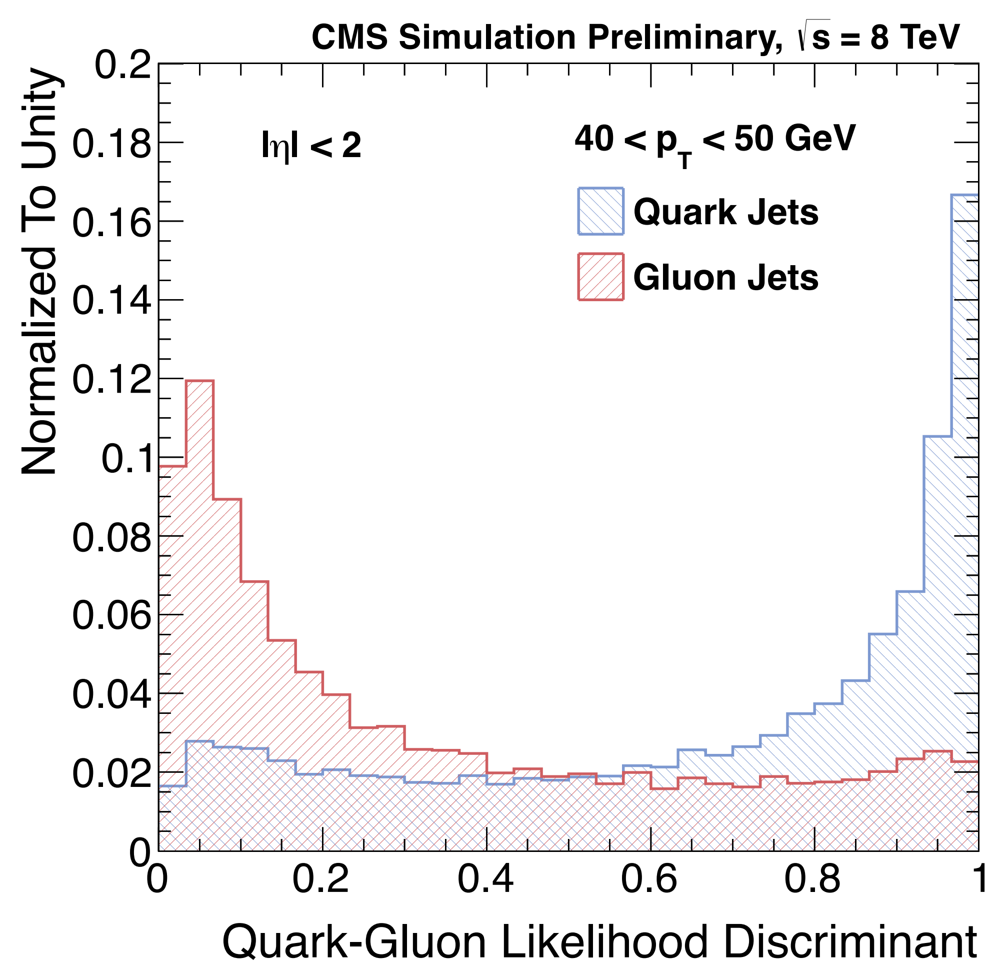


$$m_{corr} = \sqrt{m^2 + |pT_{miss}|^2} + |pT_{miss}|$$

Quark-Gluon Tagging

- Many measurements and searches can benefit from identifying jets parton origin
  - ⇨ Models that predict production of many quarks vs multi-jet QCD production
- Colour factor ∝ radiation ∝ particle multiplicity
  - ⇨ $C_A/C_F = 9/4$
- Other variables can be used: width, number of subjets, etc.





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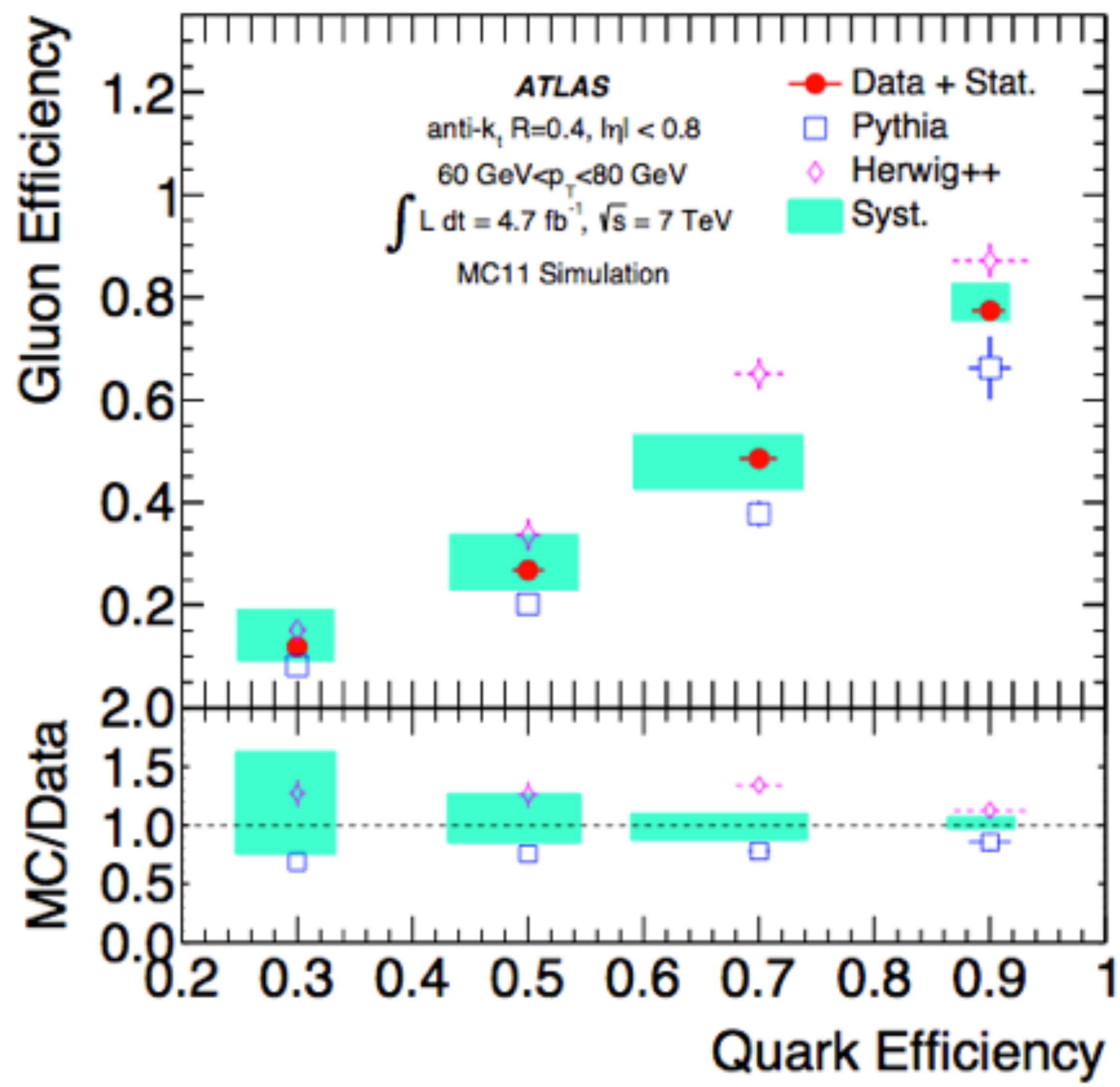
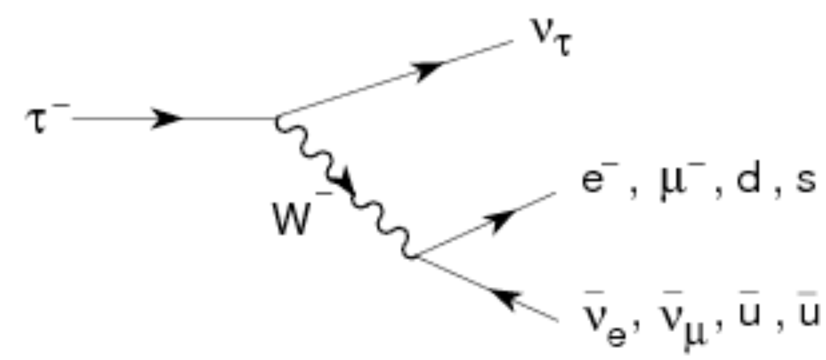
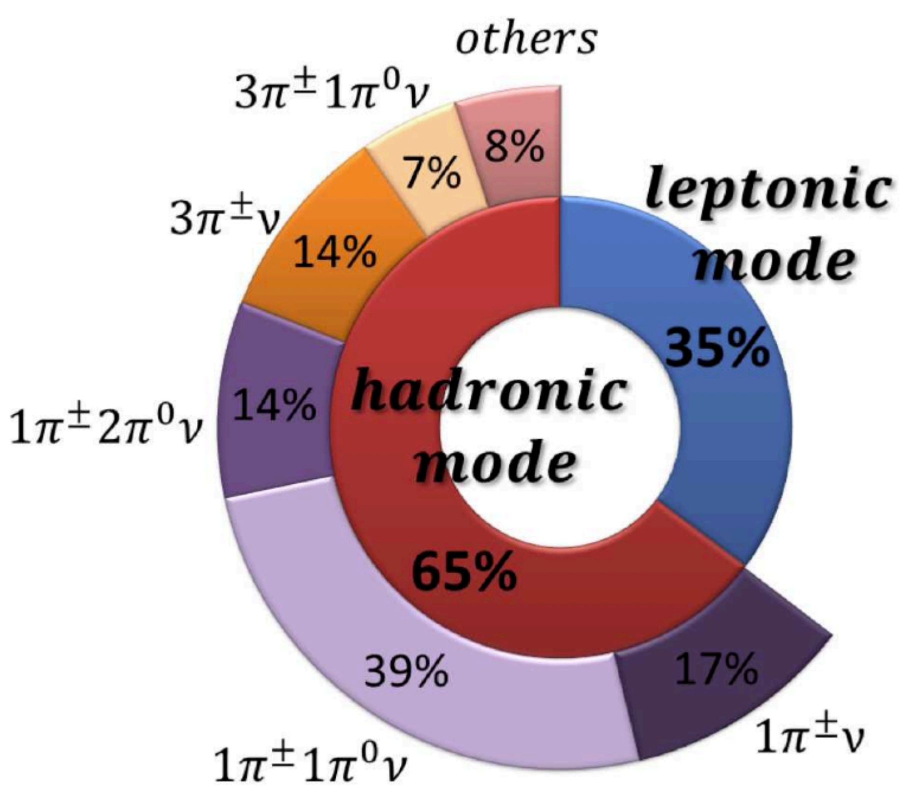
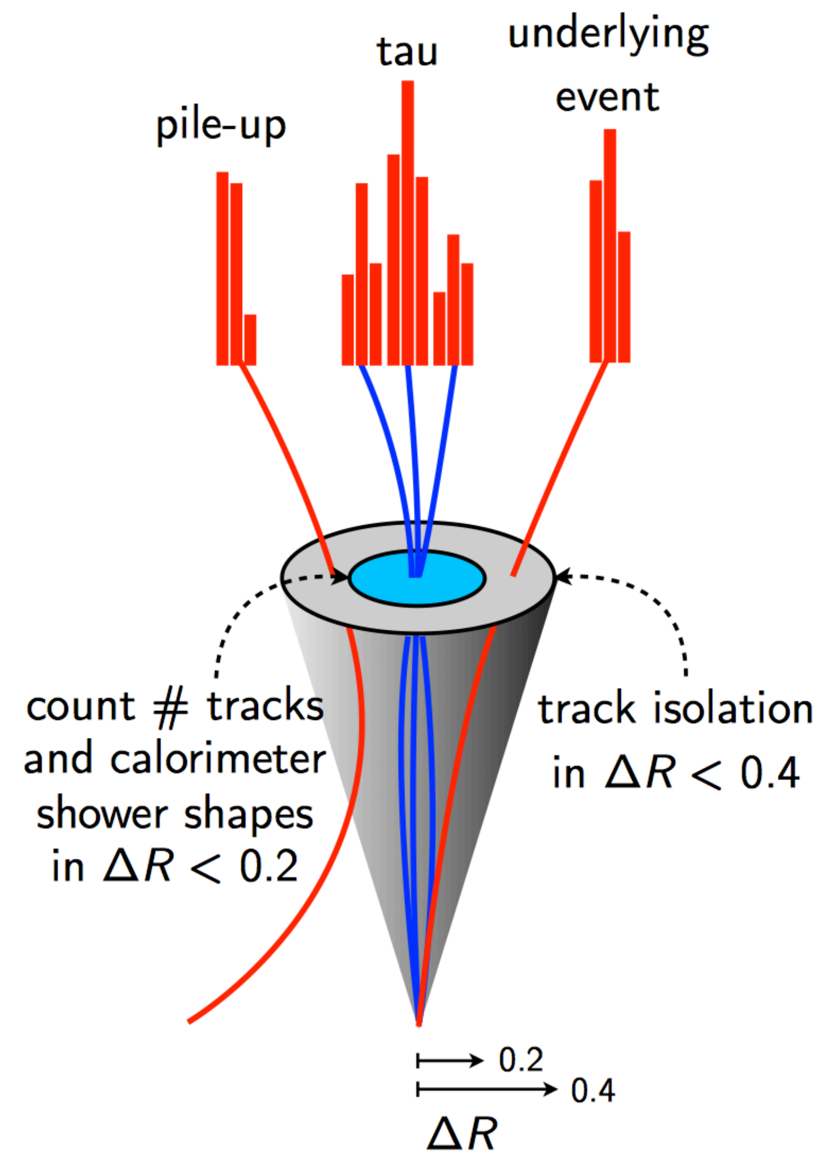


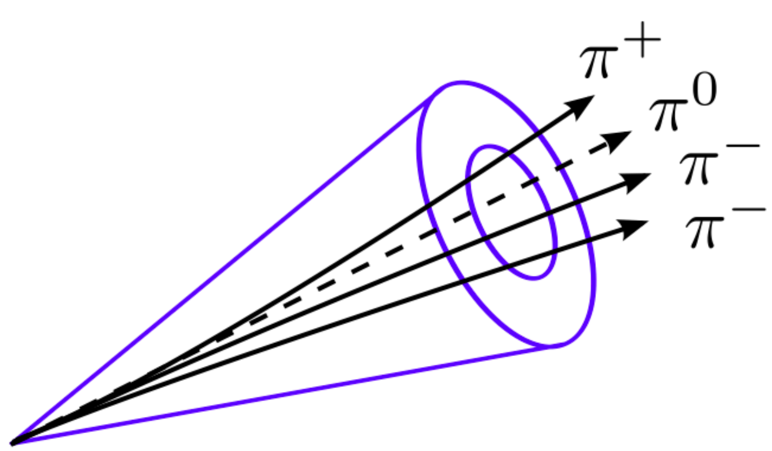
Tau-jet is the first use of jets to tag other particles than quarks/gluons
It is massive enough to decay hadronically (M~1.8 GeV)
Tau-jets are different than quark/gluon jets

- "displaced" tracks: decay in beam pipe cτ=87 μm
- narrow jets with 1 or 3 tracks, possibly with neutrals









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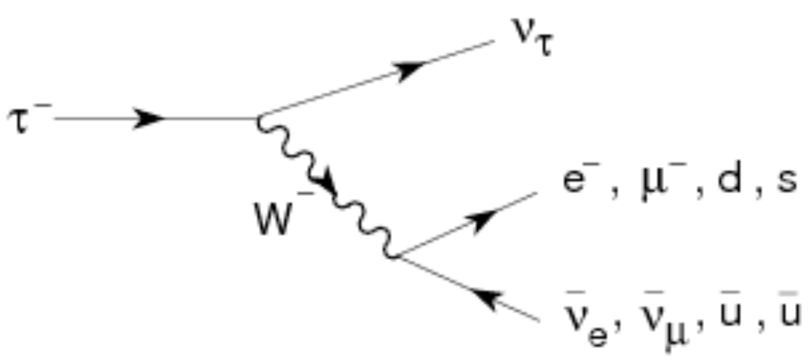

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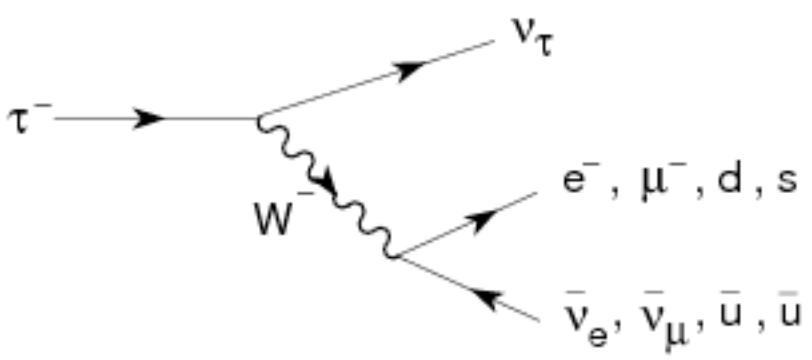

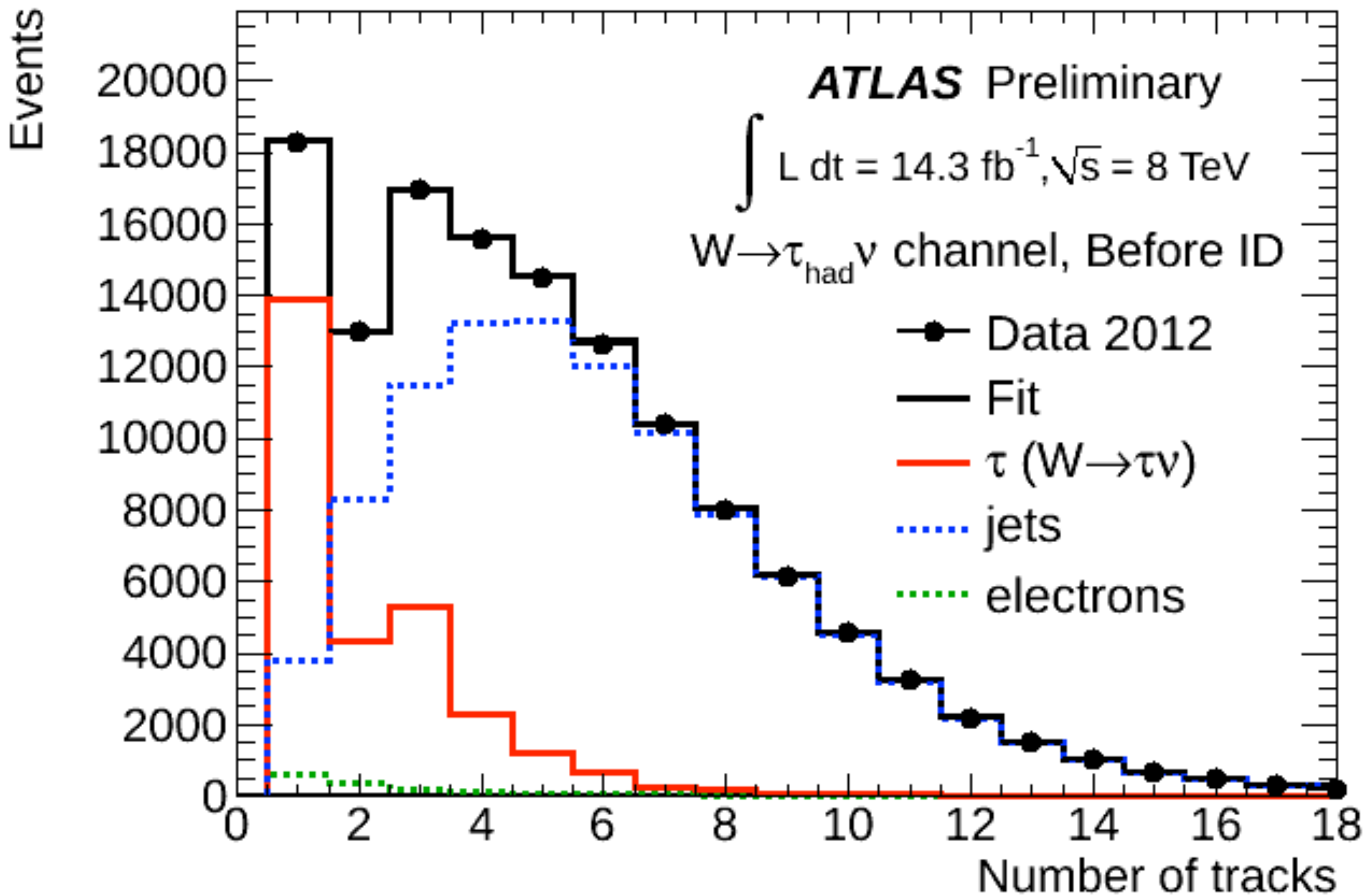

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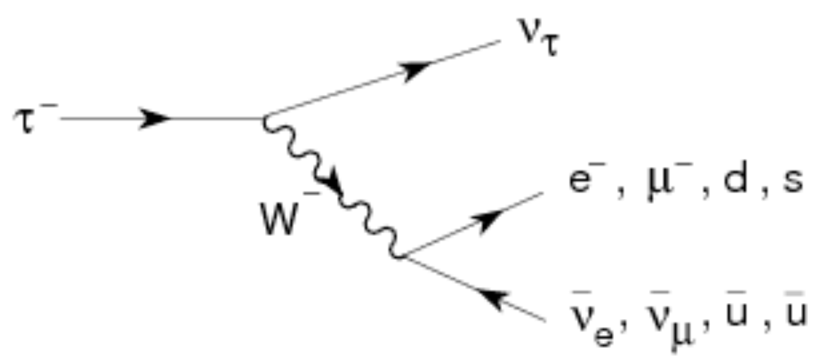
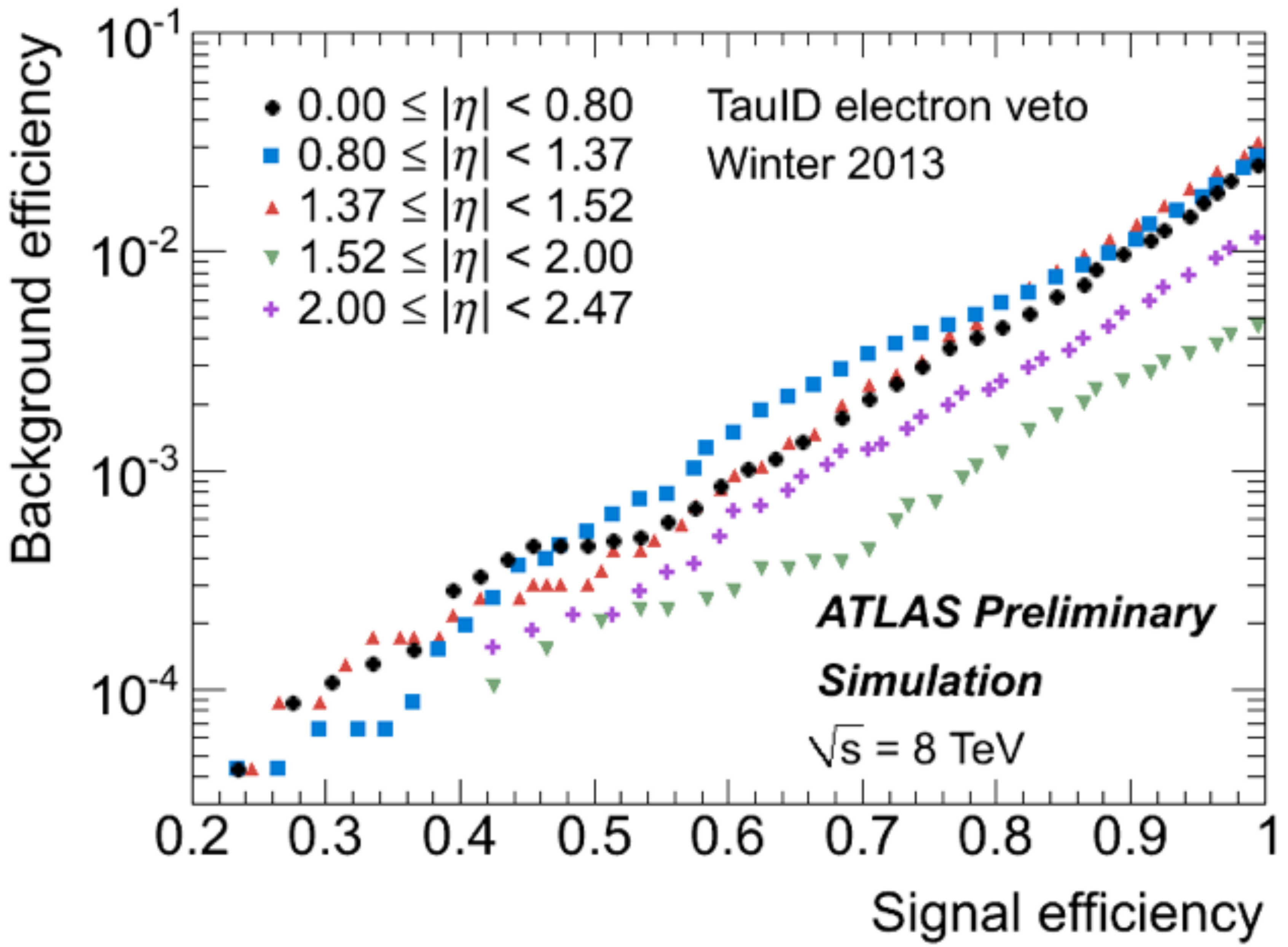
- ”displaced” tracks: decay in beam pipe cτ=87 μm
- narrow jets with 1 or 3 tracks, possibly with neutrals

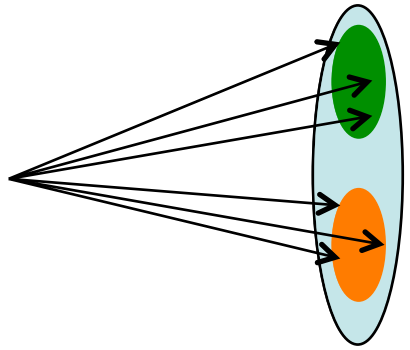




Boosted High Mass Particles

- At higher LHC energies, high mass particles (W,Z,H,top) move boosted regimes

  This can be used to reduce the backgrounds for signals, e.g.,
  - ⇒ WH measurements
  - ⇒ WW measurements and high-mass searches ($p \sim M_X/2$)
  - ⇒ Boosted top quark decays



- Hadronic decays of W bosons may be boosted into a single (fat) jet
  - ⇒ Typical size of this jet is $\Delta R > 2/\gamma$, where γ is boost factor of W
  - ⇒ How can we separate these “W-jets” from light uds jets and b-jets?
- Several well-motivated handles to quantify substructure
  - ⇒ Main observable is the mass of the boosted (fat) jet
  - ⇒ Jet pruning techniques serve to reduce the mass of QCD light jets
  - ⇒ Mass drop observable contrasts fat jet mass with subjet masses
  - ⇒ Jet variables must be intended to be robust against pileup contributions

Jet Pruning

C/A jet (R>0.8)

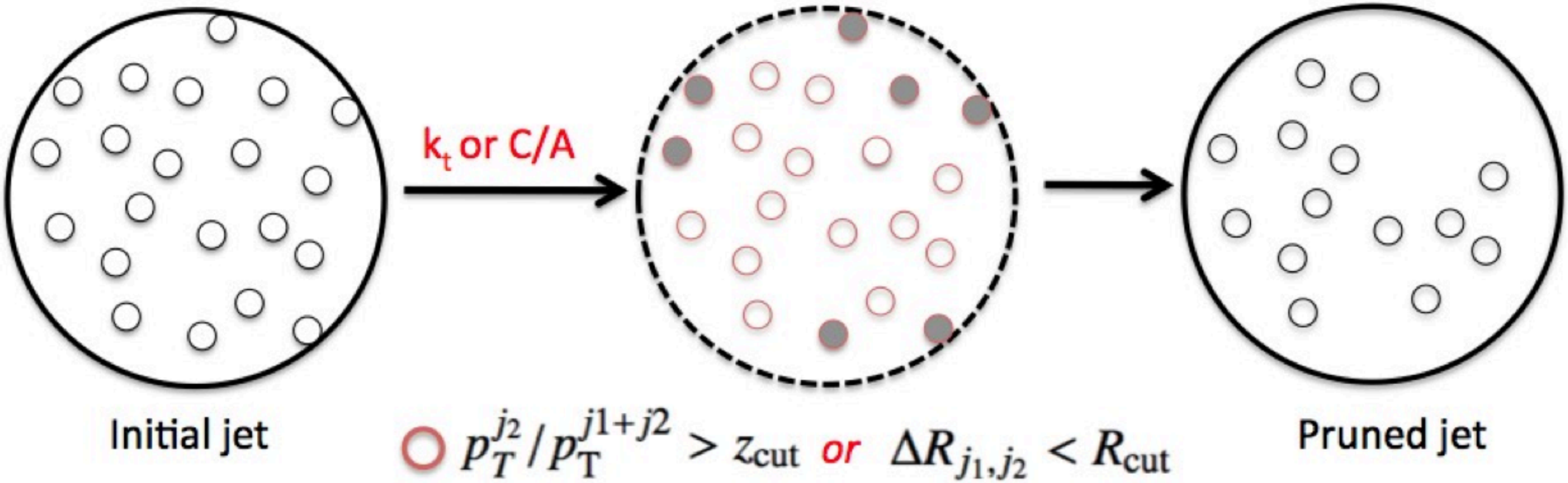
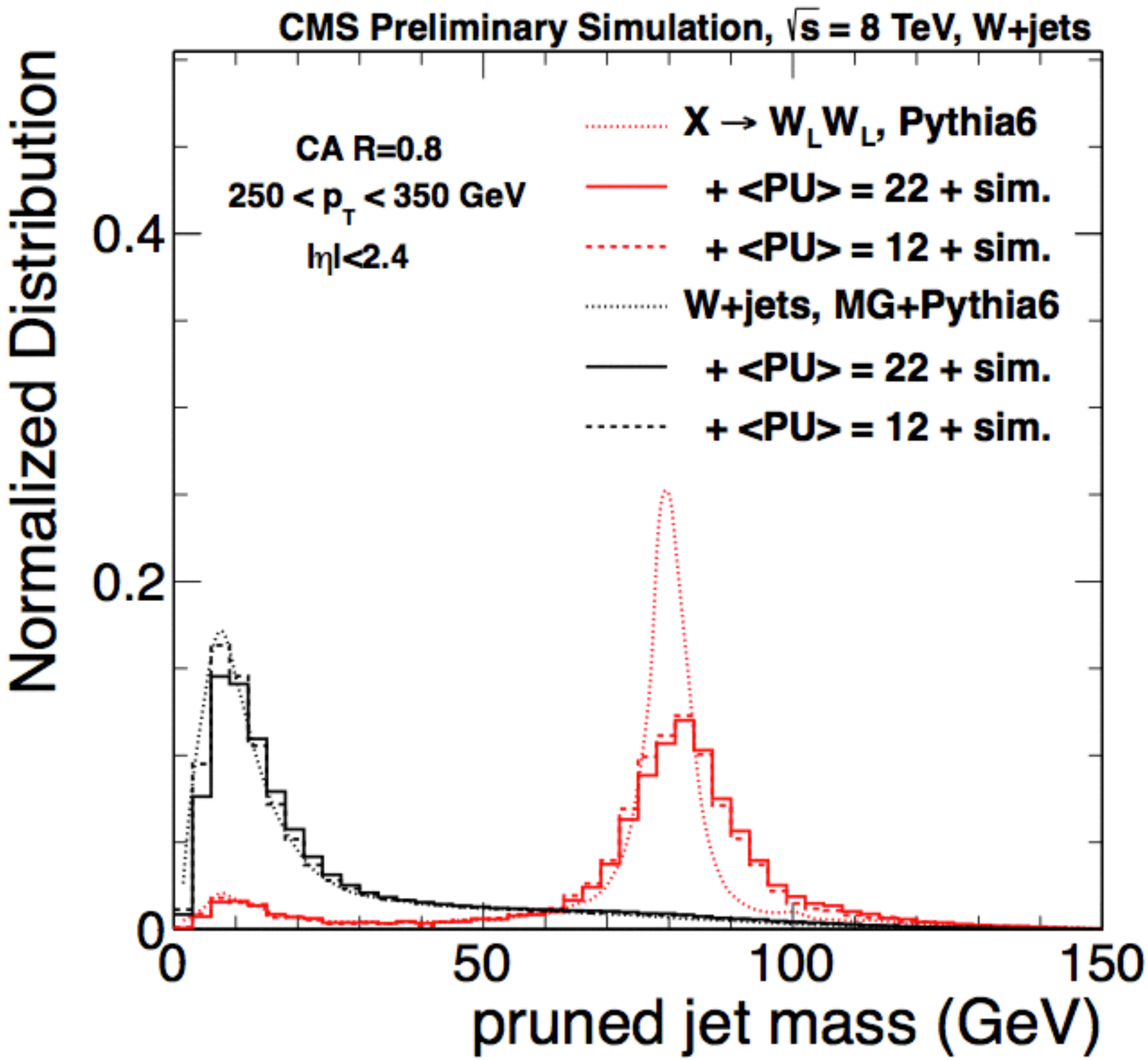


Figure from JHEP09(2013)076

recluster using distance between particles
and ignoring softer "proto-jets" if $z<z_{cut}$
$z=\min(p_T^i,p_T^j)/p_T^p$

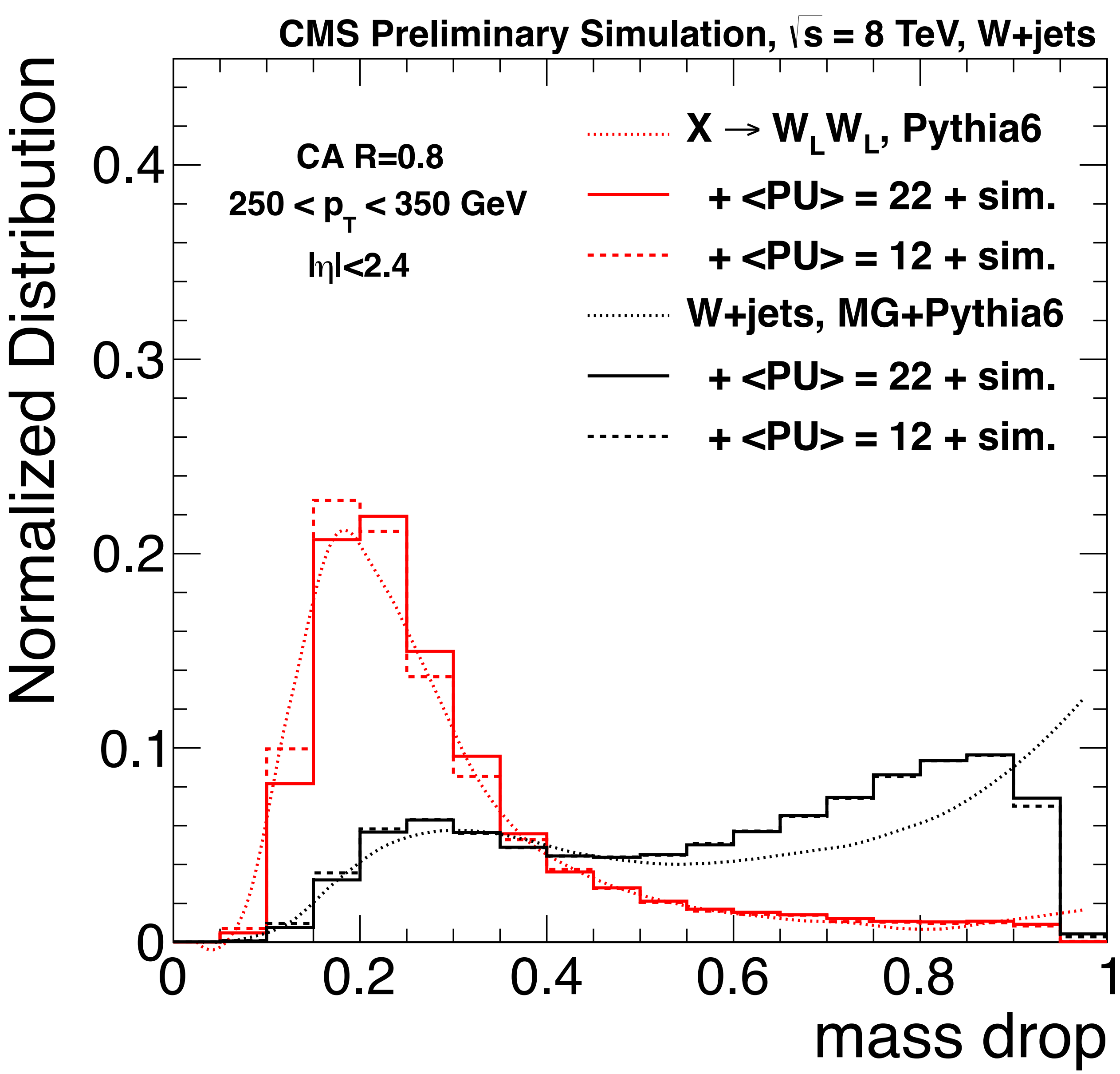
Jet Pruning

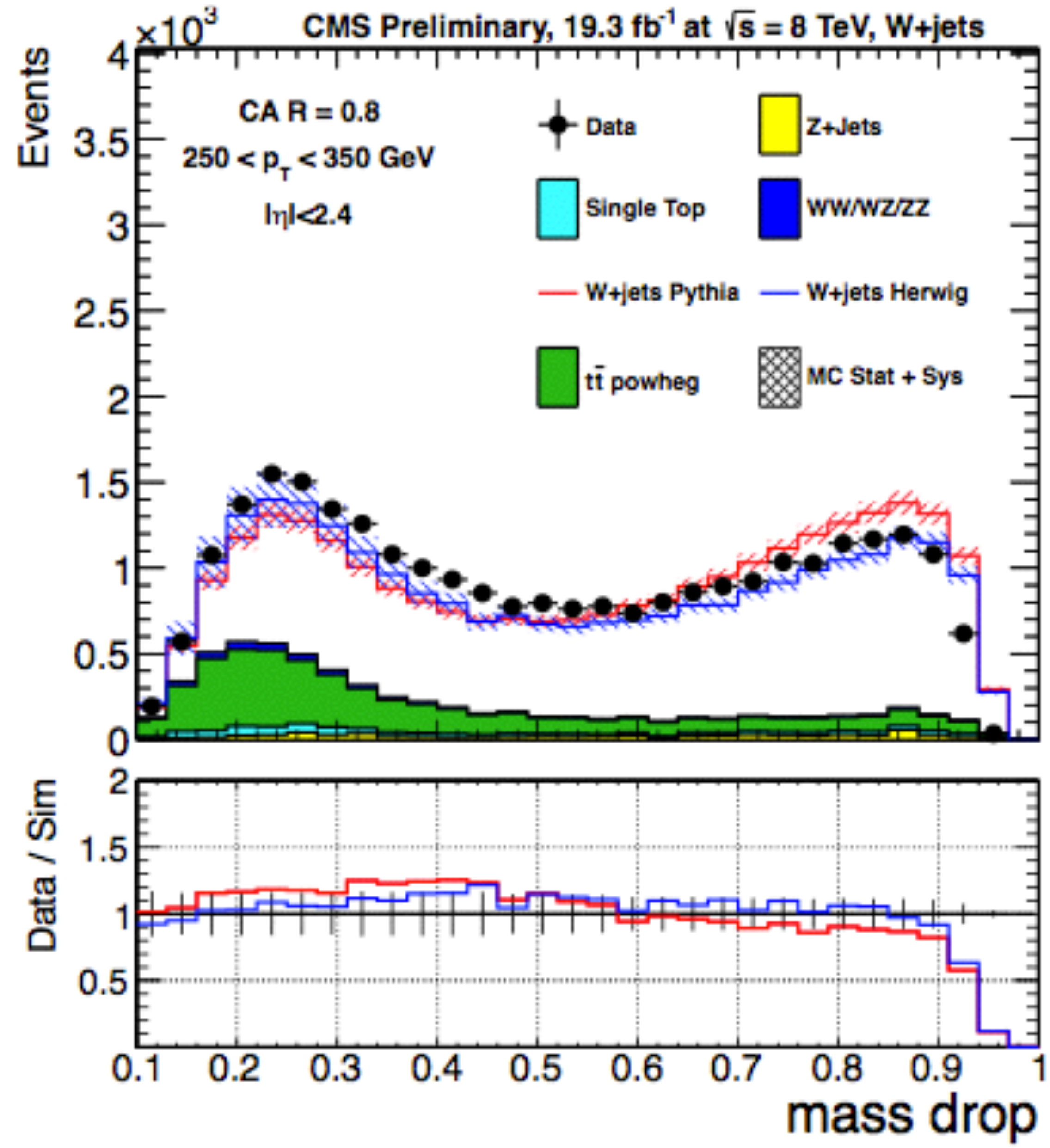

CMS Preliminary Simulation, √s = 8 TeV, W+jets
CA R=0.8
250 < p_T < 350 GeV
|η|<2.4
X → W_L W_L, Pythia6
+ <PU> = 22 + sim.
+ <PU> = 12 + sim.
W+jets, MG+Pythia6
+ <PU> = 22 + sim.
+ <PU> = 12 + sim.
Normalized Distribution
0
0.2
0.4
0
50
100
150
pruned jet mass (GeV)

Jet variables can be used to discriminate between W-jets from parton-jets:

◉ **Mass drop**: Undoing the last clustering step, the highest mass jet should have mass much lower than the W-jet.

$$\mu = m_{\rm sub1}/m_{\rm jet}$$

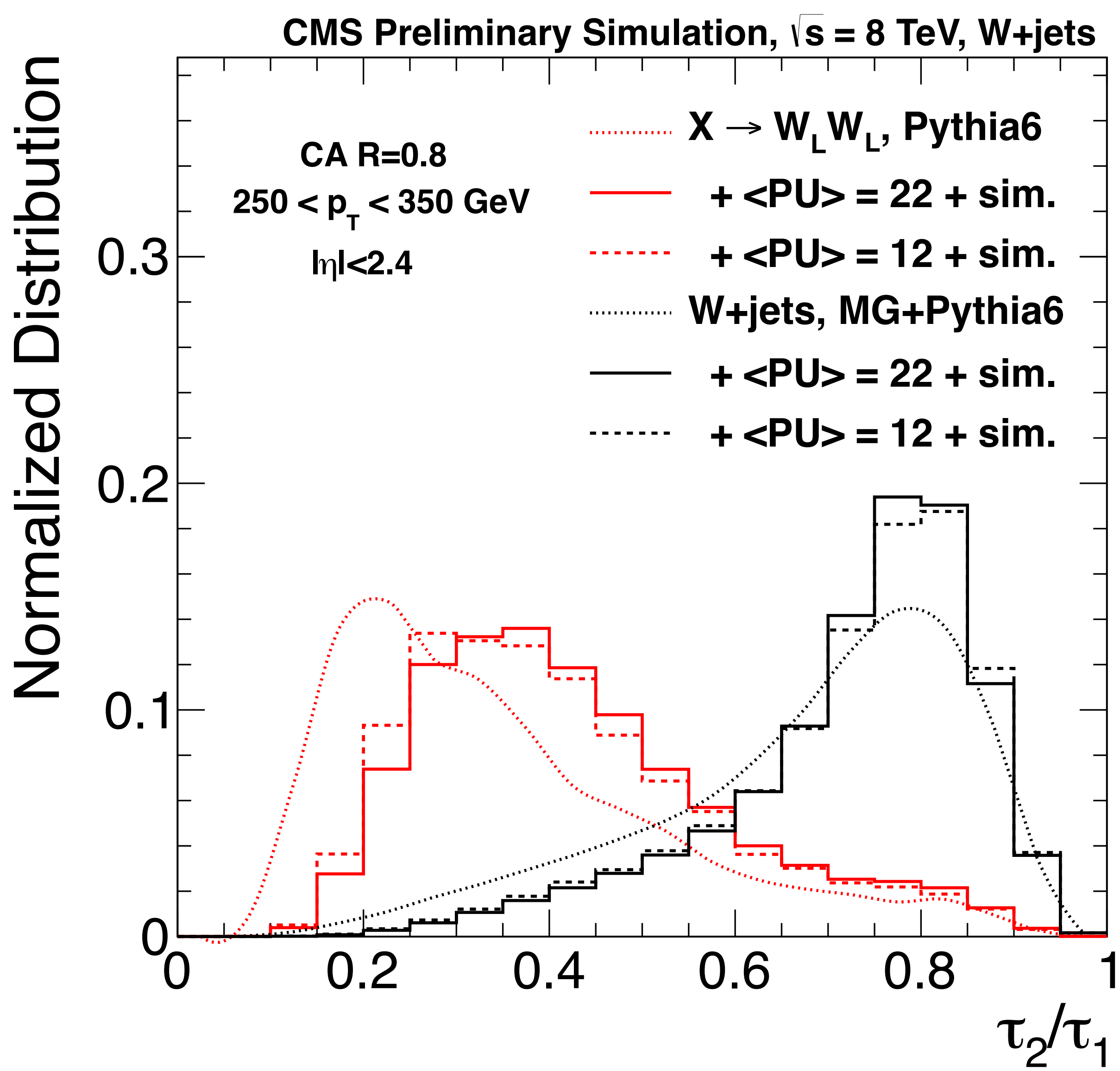


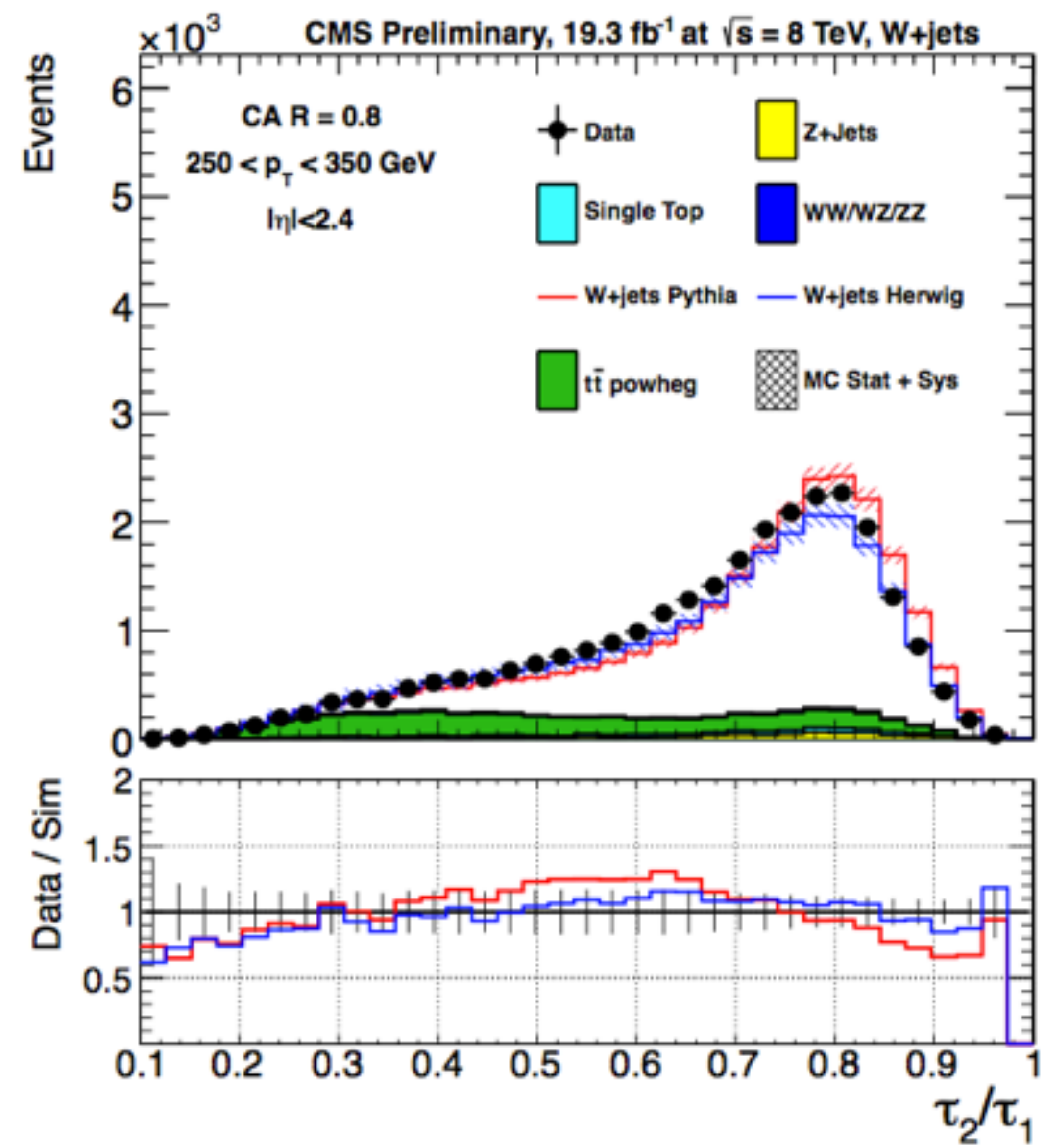


Jet variables can be used to discriminate between W-jets from parton-jets:

- **N-subjettiness**: For W→jets, τ_2/τ_1 is a good discriminant

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$



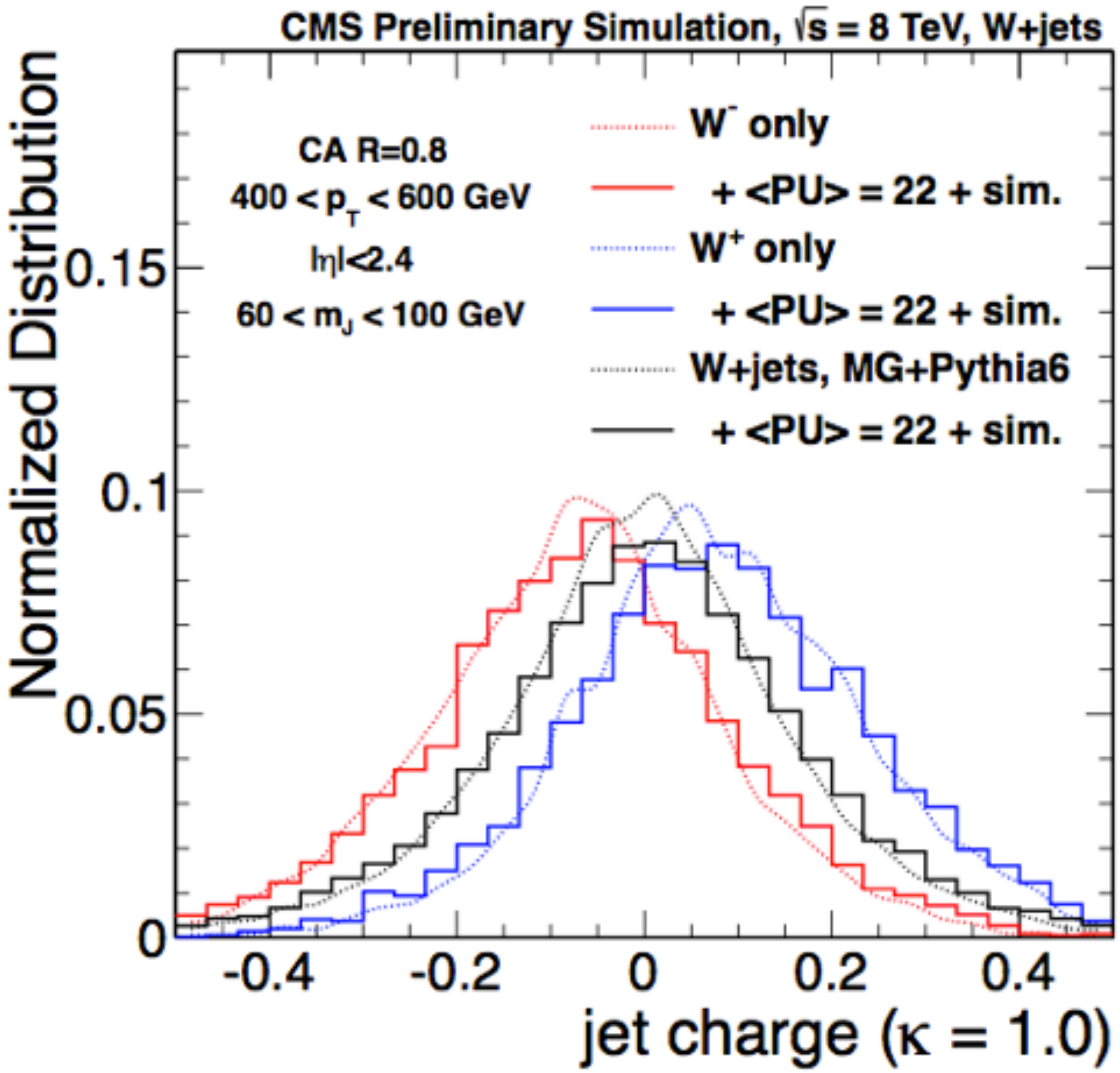


Fat Jet Variables

Jet variables can be used to discriminate between W-jets from parton-jets:

- **Charge**: Neutral jets are background-like vs W-jets

$$Q^{\kappa} = \frac{\sum_i q_i (p_T^i)^{\kappa}}{(p_T^{jet})^{\kappa}}$$



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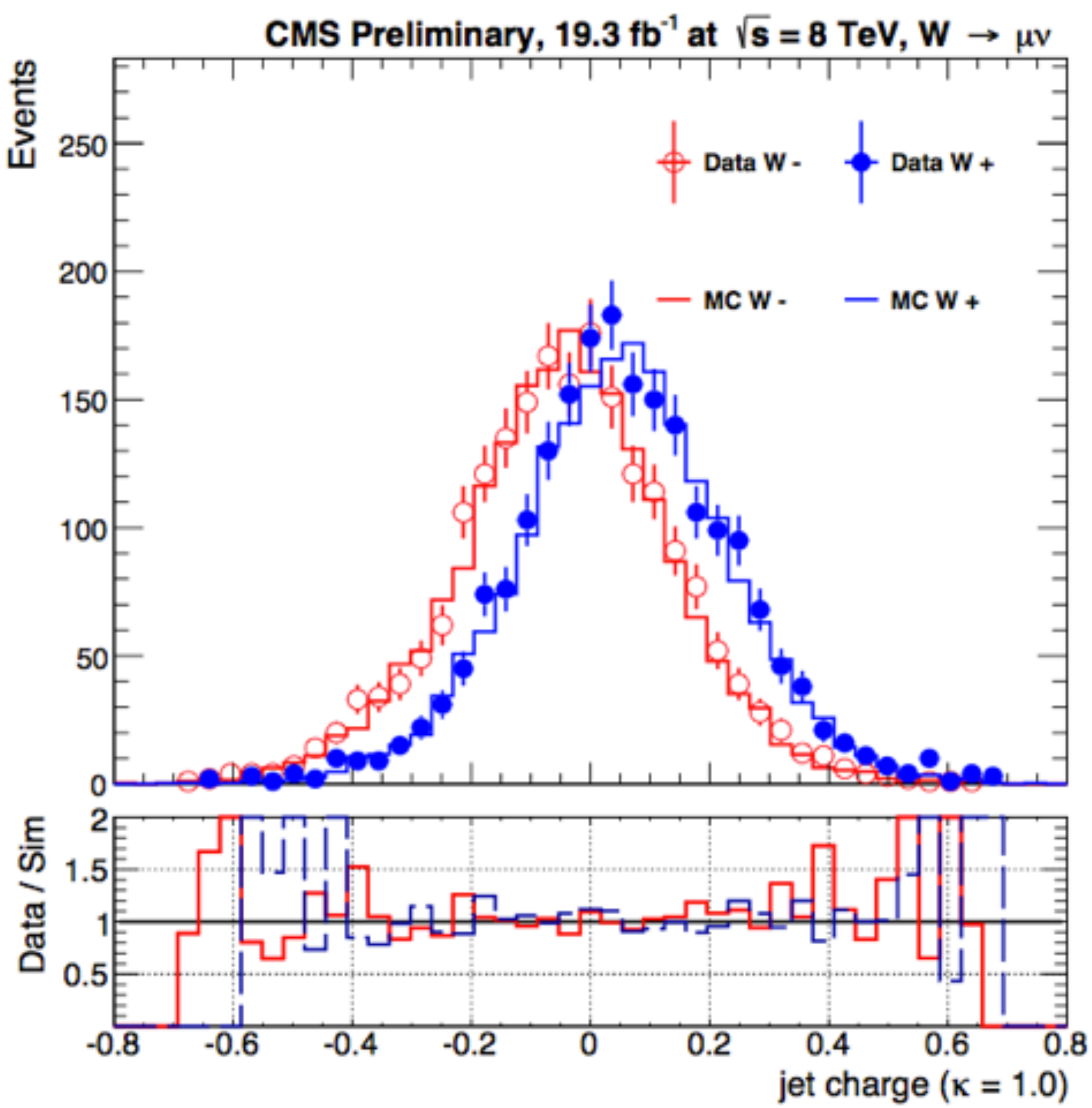
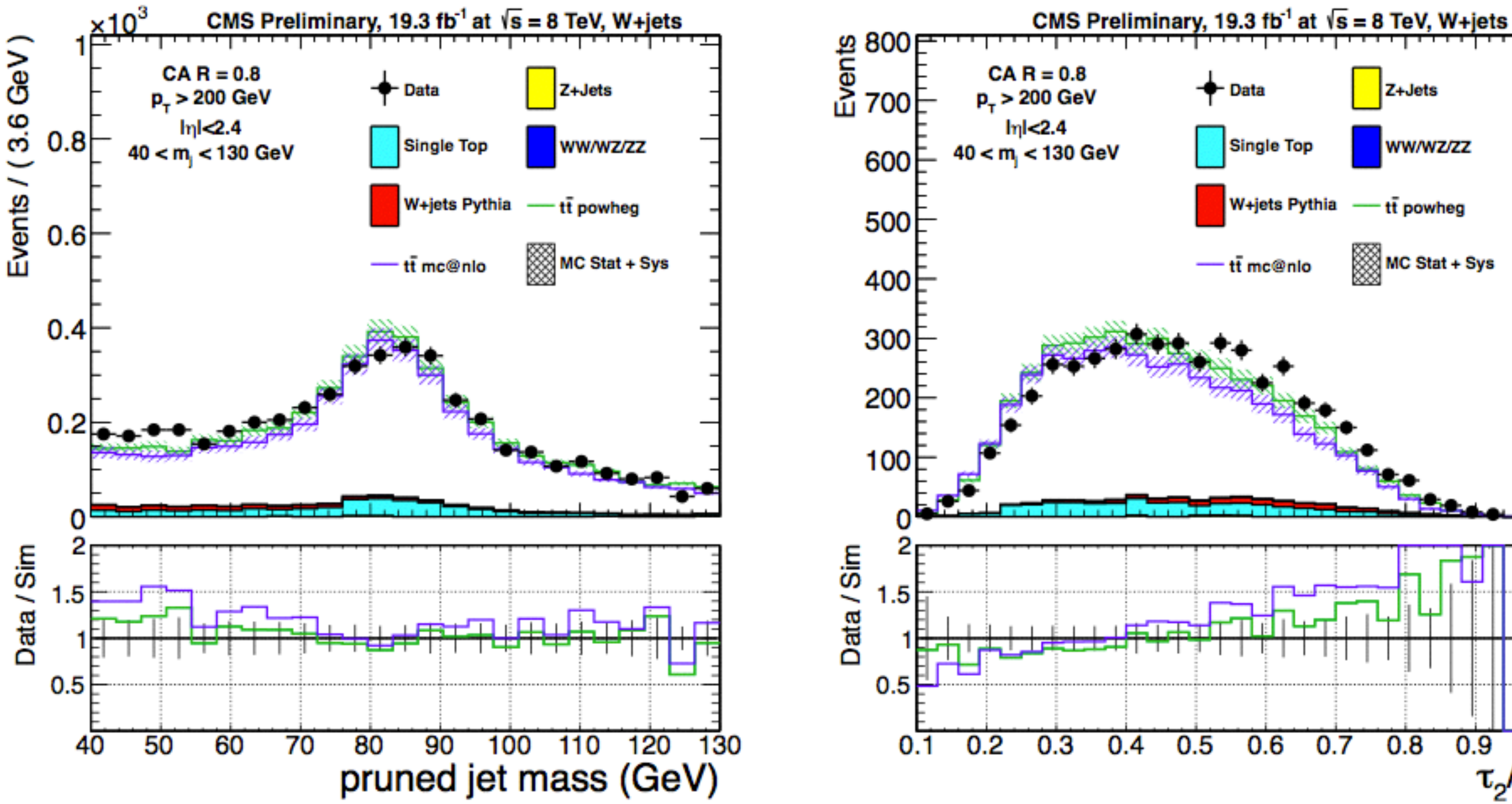
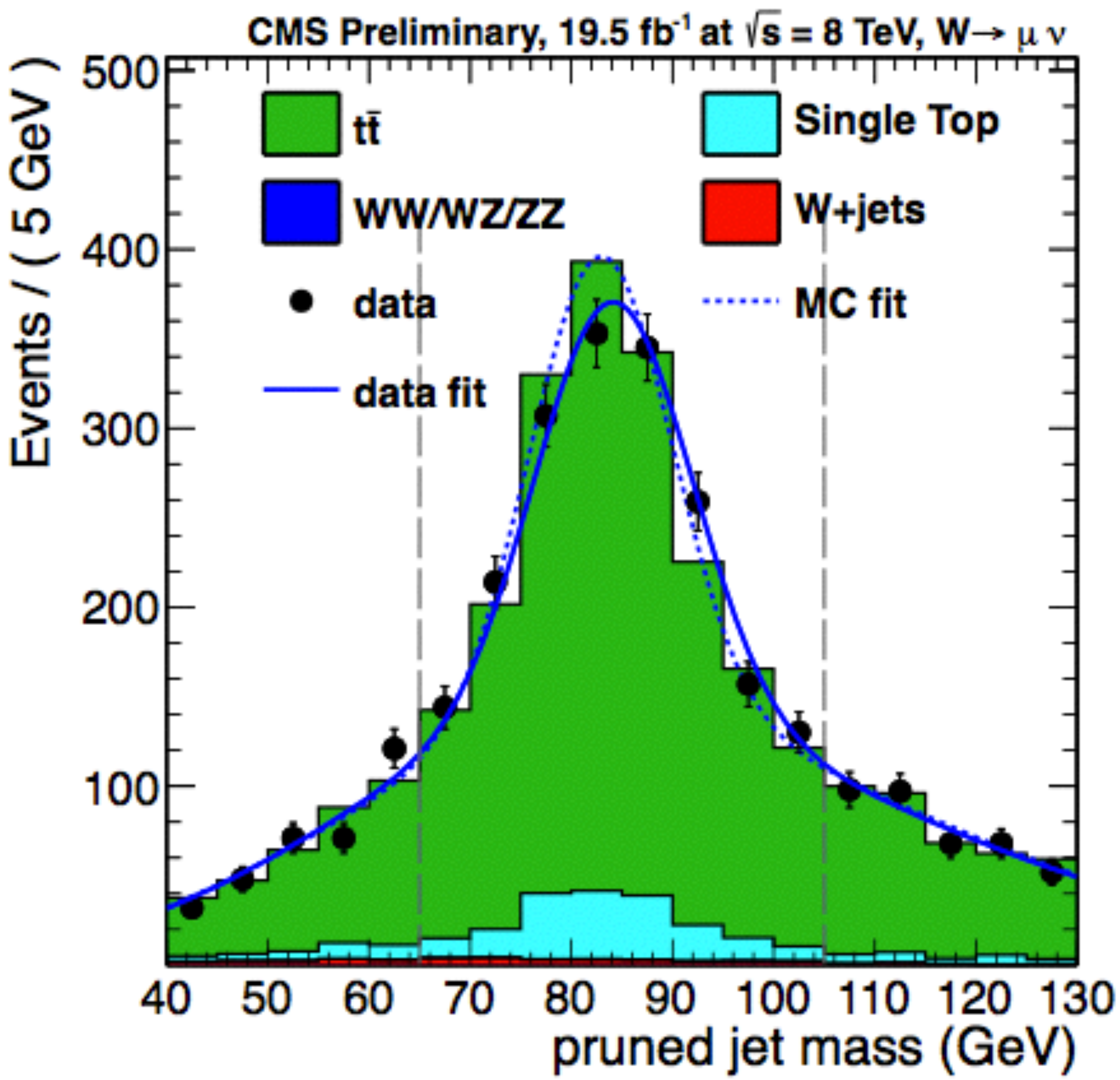


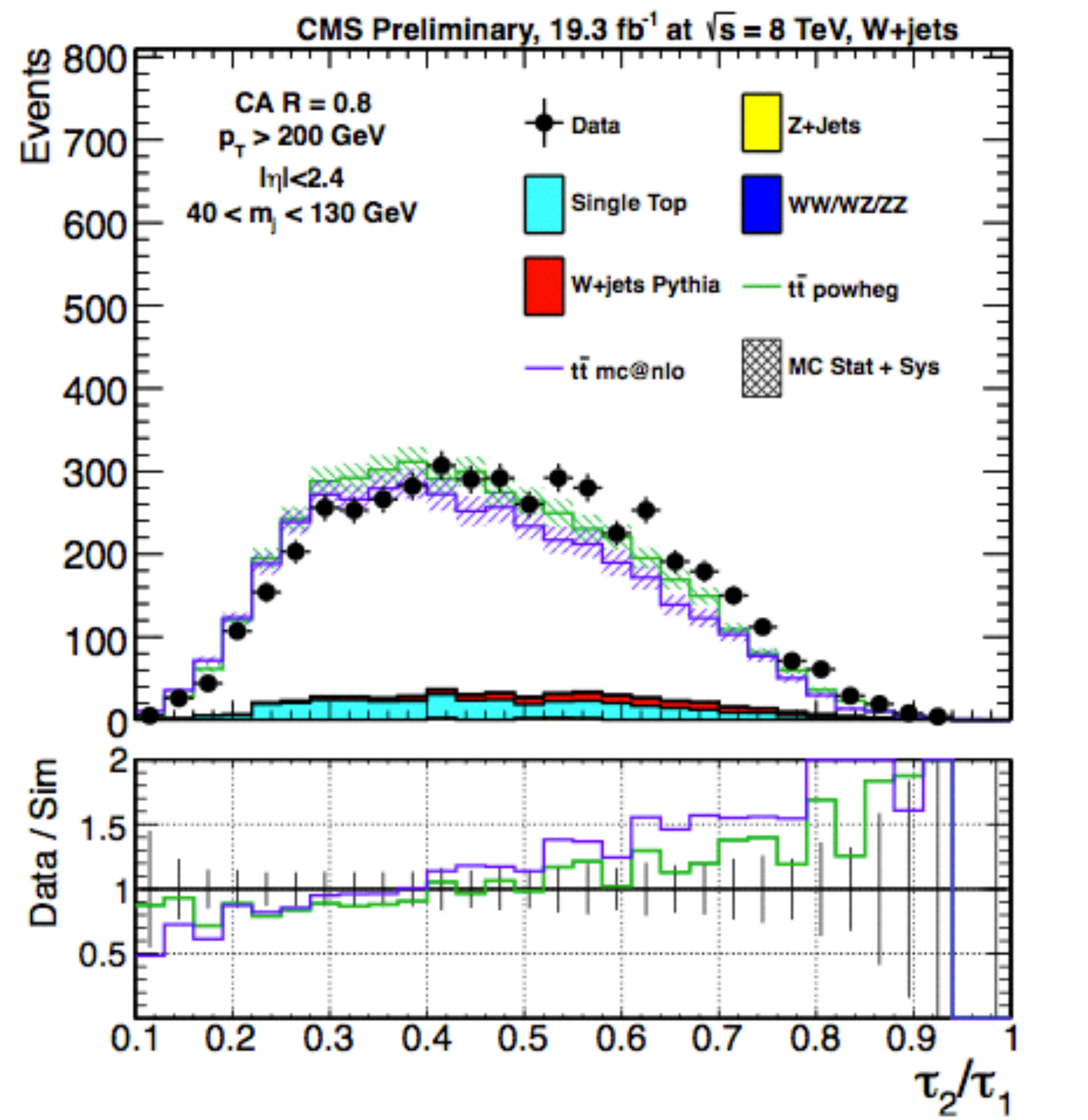
Data studies show promising results.



W-Jet

Data studies show promising results.

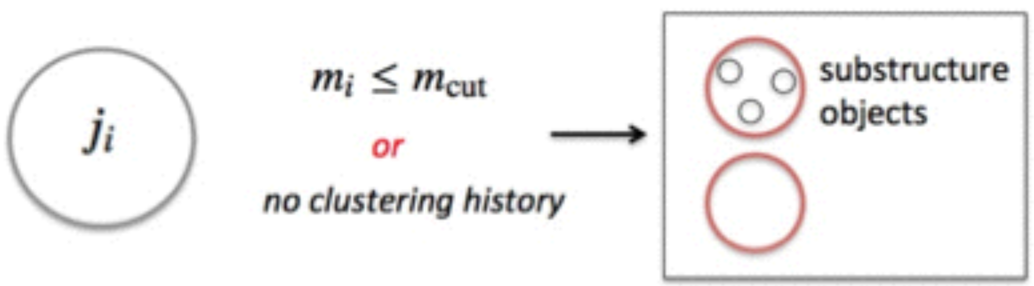




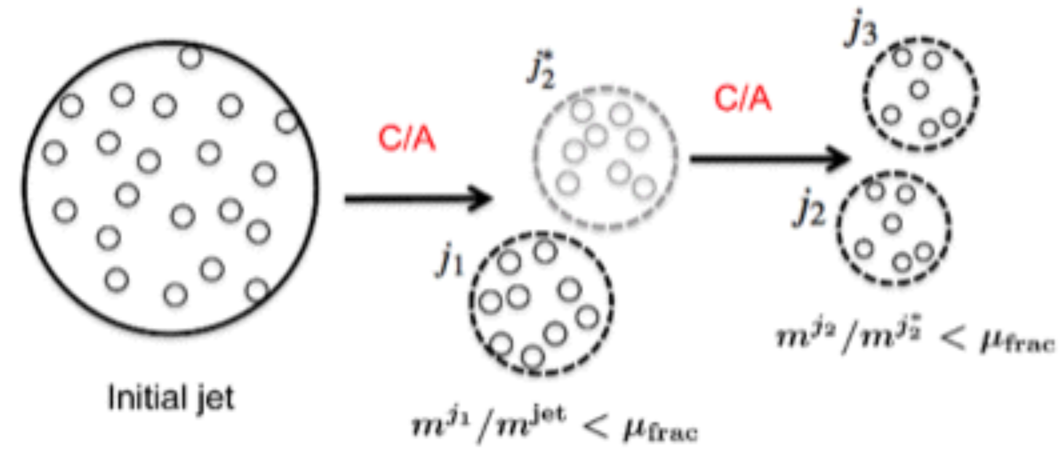
Top Quark Tagging

Boosted top quarks can be produced in decays of ultra-high-mass resonances
⇨ one big fat jet can contain the top quark decays

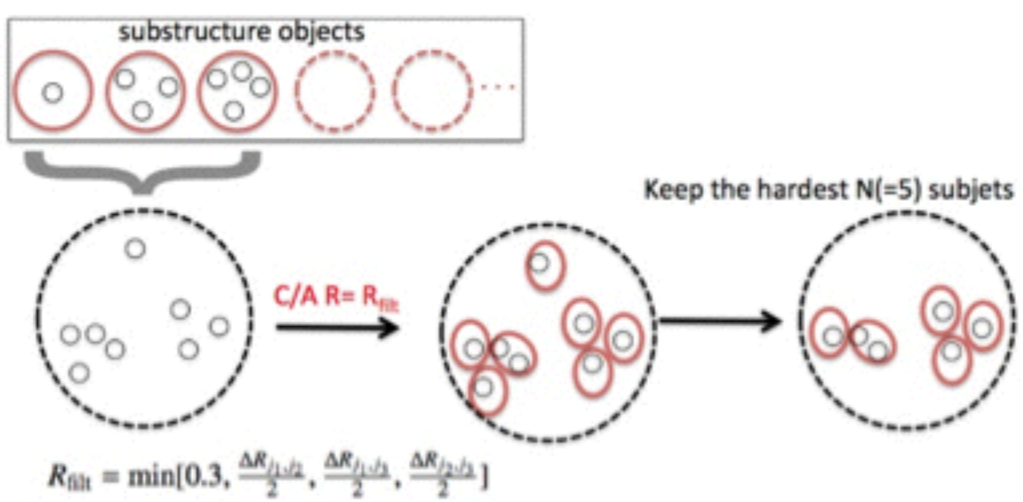
HEPTopTagger has been proposed to tag top quarks with hadronic W boson



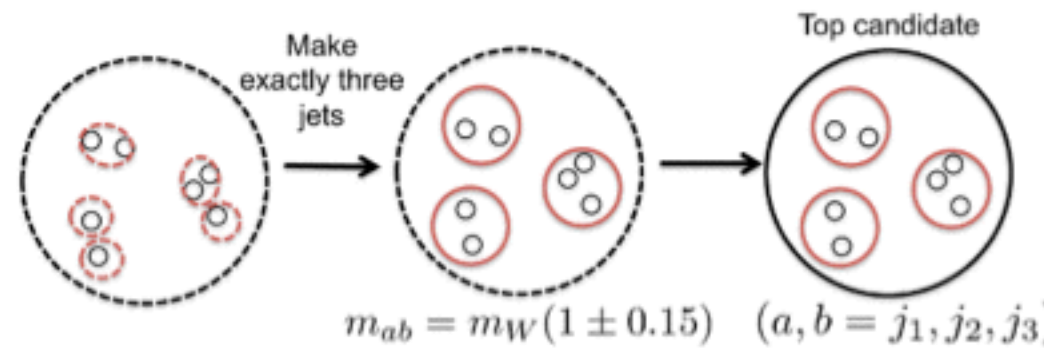
(a) Every object encountered in the declustering process is considered a 'substructure object' if it is of sufficiently low mass or has no clustering history.



(b) The mass-drop criterion is applied iteratively, following the highest subjet-mass line through the clustering history, resulting in N_i substructure objects.



(c) For every triplet-wise combination of the substructure objects found in (b), recluster the constituents into subjets and select the N_{subjet} leading-p_T subjets, with $3 \leq N_{\text{subjet}} \leq N_i$ (here, $N_{\text{subjet}} = 5$).

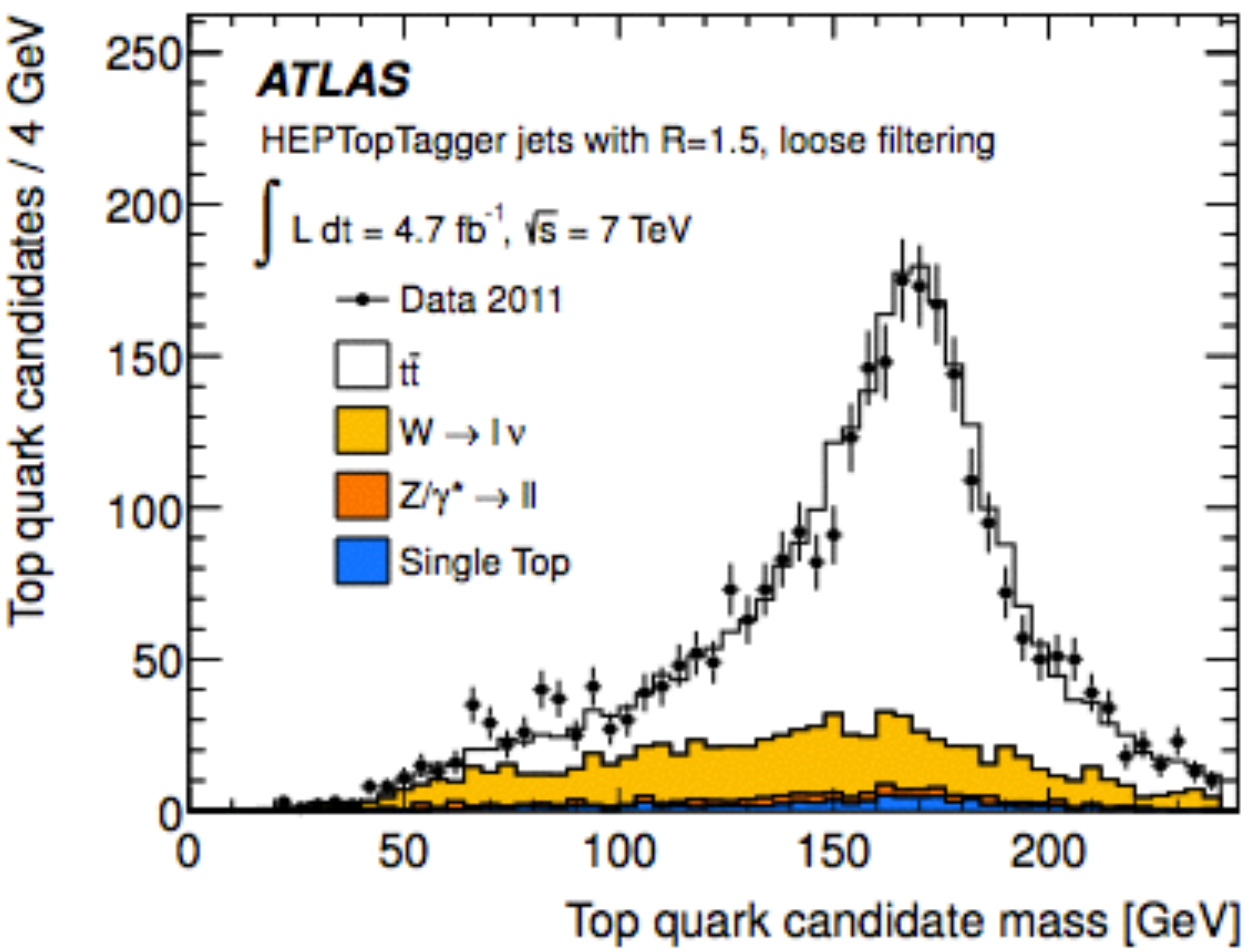


(d) Recluster the constituents of the N_{subjet} subjets into exactly three subjets to make the top candidate for this triplet-wise combination of substructure objects.

Figure from JHEP09(2013)076

Boosted top quarks can be produced in decays of ultra-high-mass resonances
⇨ one big fat jet can contain the top quark decays

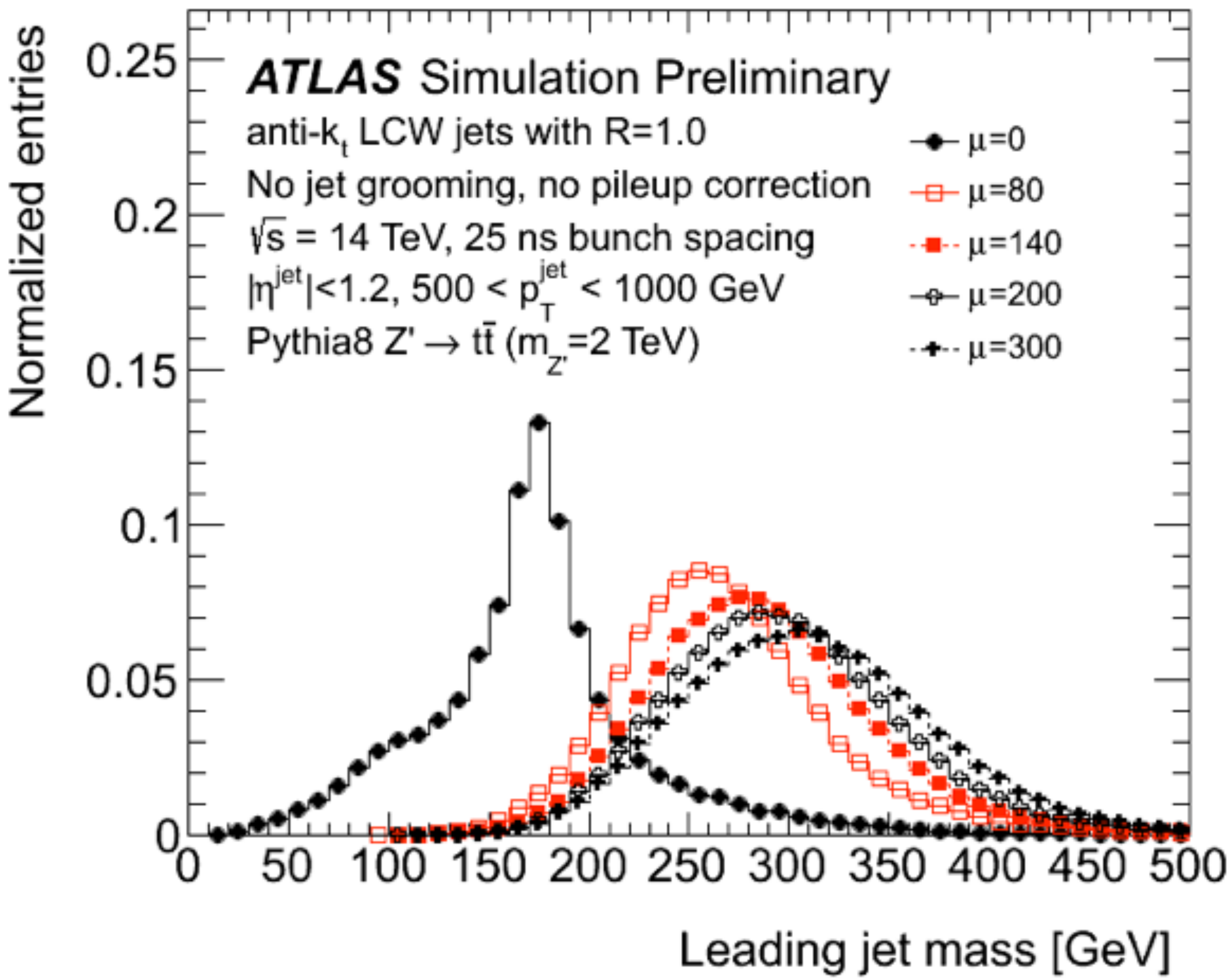
Data studies show promising results.



(d) $R = 1.5$, loose filtering

Future - High Pile Up

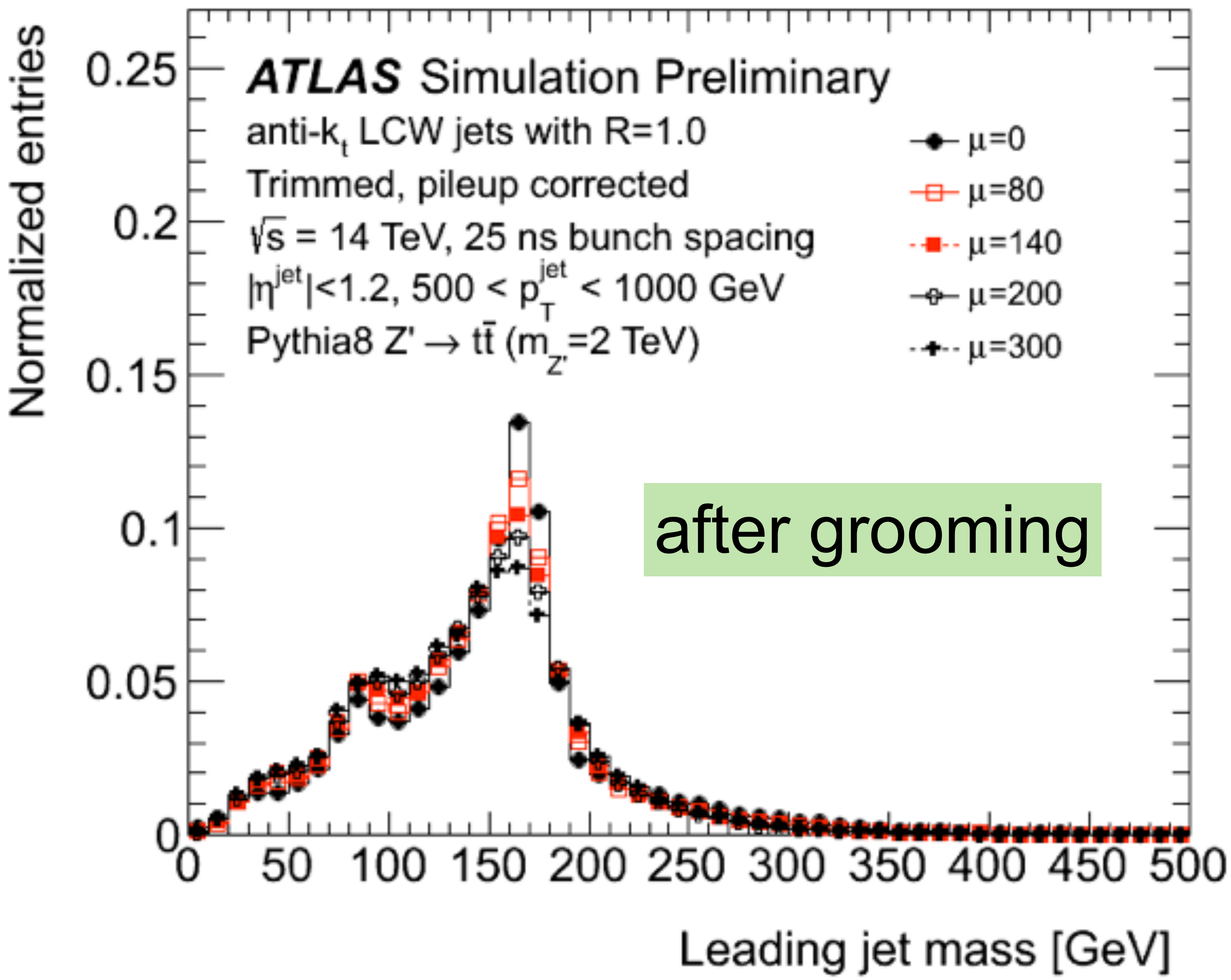
Jet substructure methods must be robust against pile up for the next run.



Future - High Pile Up

Jet substructure methods must be robust against pile up for the next run.

So far, simulation studies are promising!



Summary

Jets are key ingredients of measurements and new physics searches

Understanding jets improves impact of data

Jet algorithms can be used to tag boosted objects