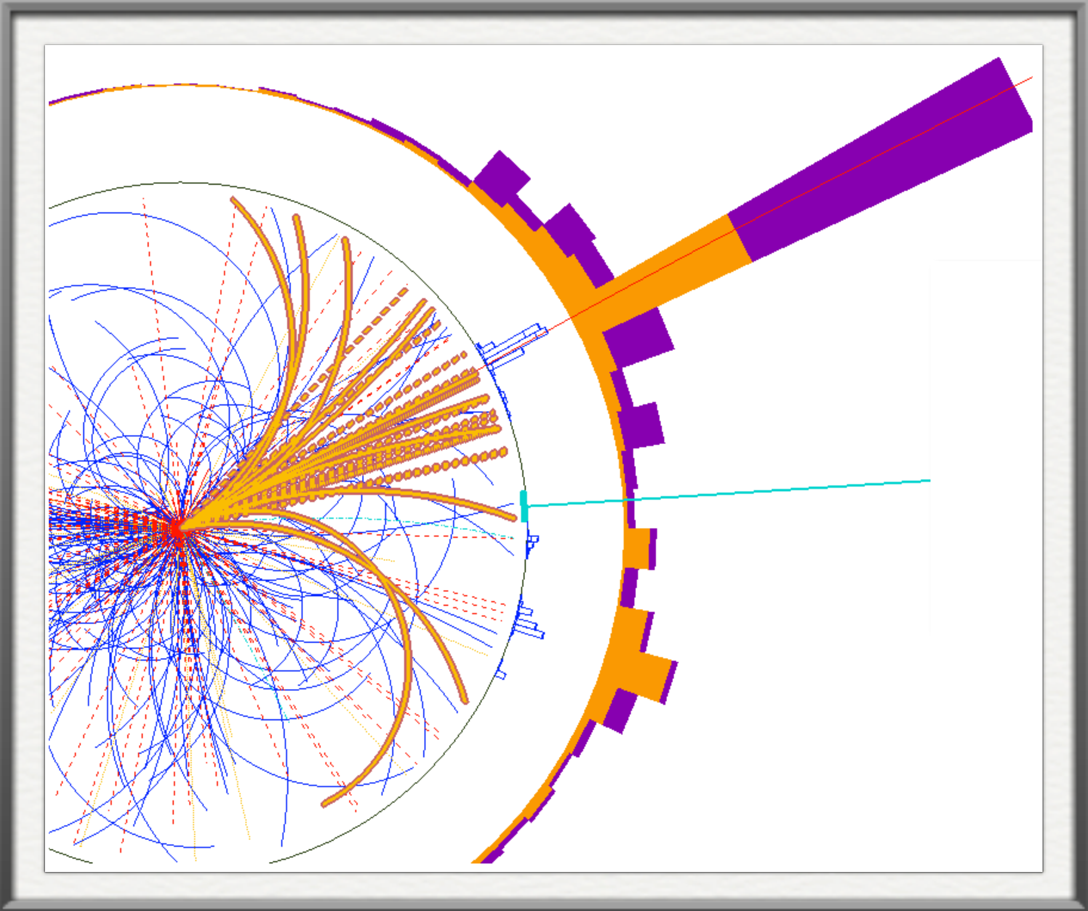
Particle ID: Lecture #3

Fermilab

UIC University of Illinois at Chicago



Richard Cavanaugh, Fermilab & University of Illinois Chicago
LHC Physics Center co-Coordinator

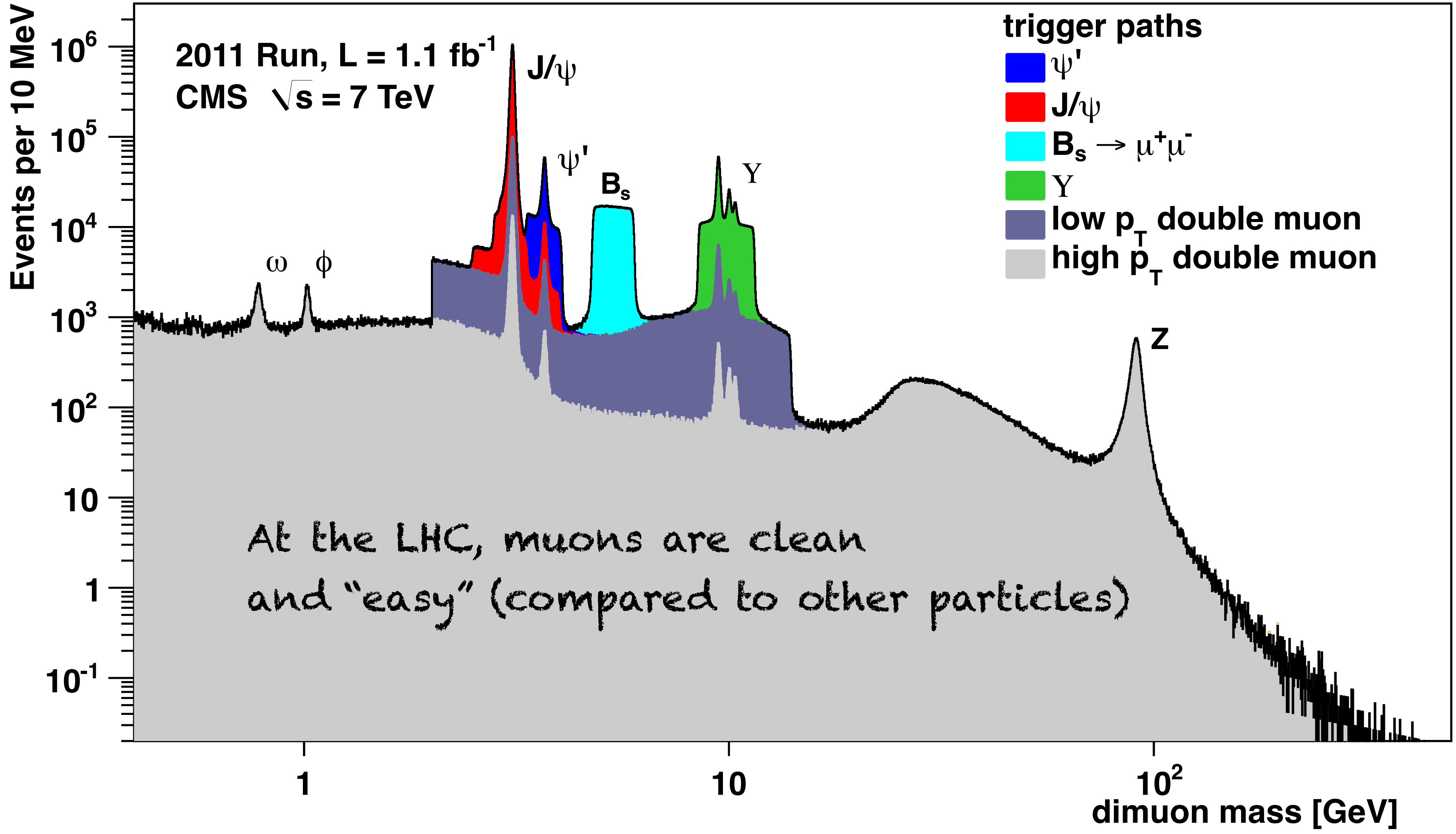
Hadron Collider Physics Summer School
Fermilab, 14 August, 2012

LPC
LHC Physics

- Let's pick where we left off yesterday...
  - Muons!

A spectroscopist's delight!

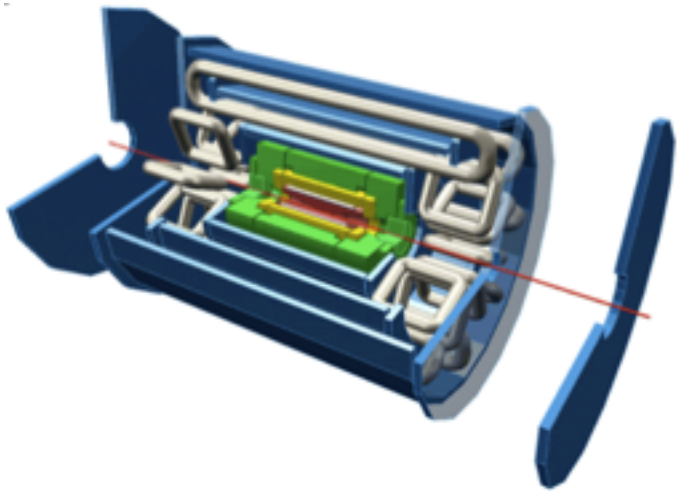
The power of muon identification!



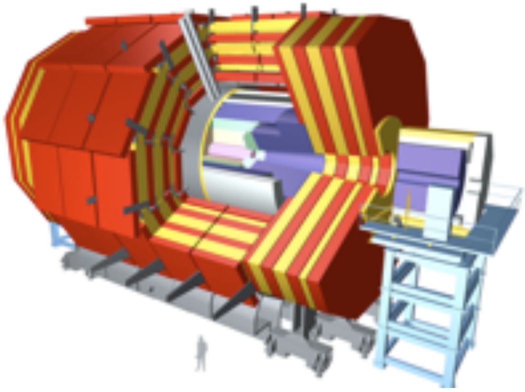
At the LHC, muons are clean and "easy" (compared to other particles)

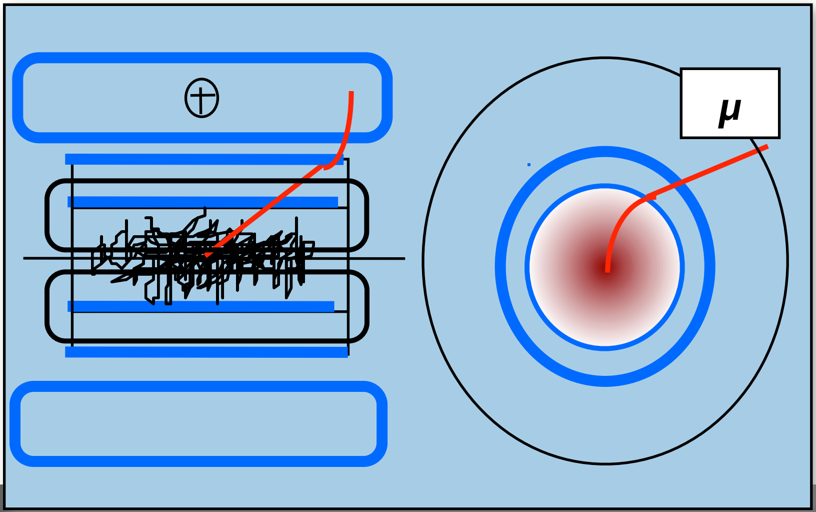
LHC pp experiments

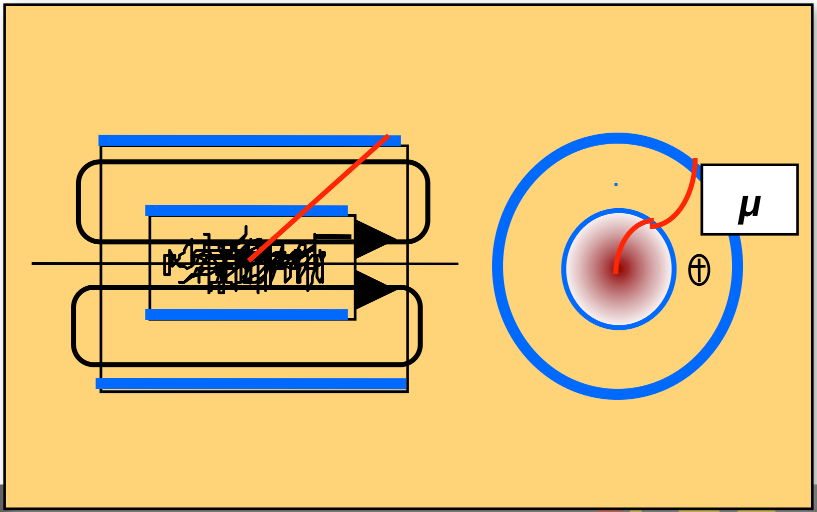
ATLAS



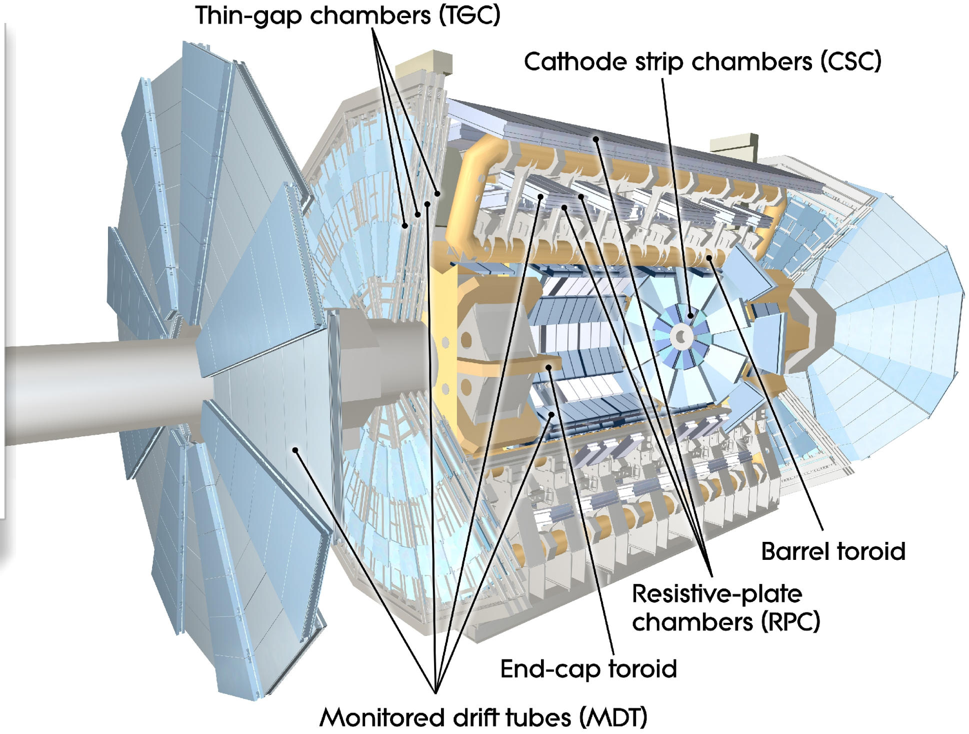
CMS

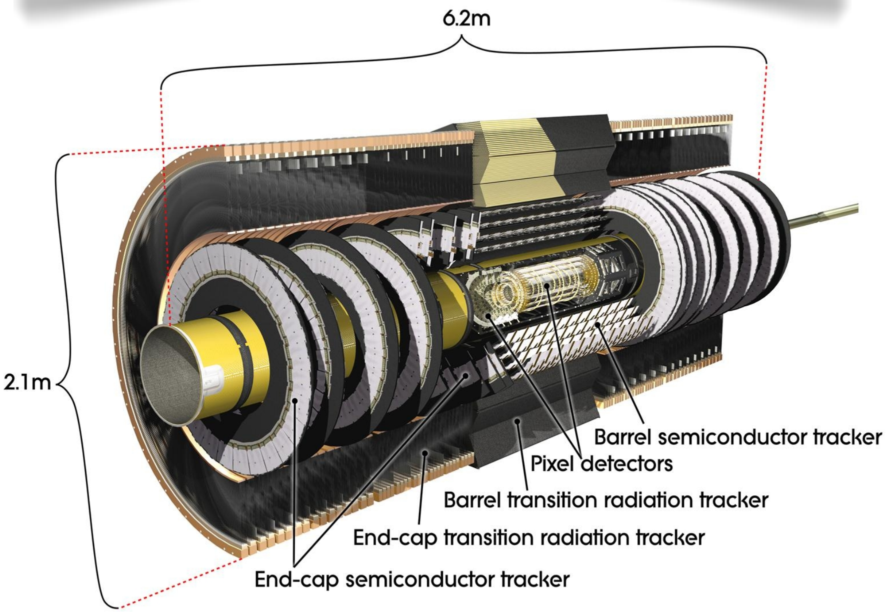






- Use a toroidal field (about 0.5T)
- **Precision chambers**
  - Monitored Drift Tubes in barrel and endcaps
    3 layers for |η|<2.0, 2 layers for 2.0 < |η| < 2.7,
    resolution of 35 μm per chamber
  - Cathode Strip Chambers :
    1 layer (inner) for 2.0 < |η| < 2.7,
    resolution in precise coordinate of 40 μm per station
- **Trigger chambers**
  - Resistive Plate Chambers in barrel (|η| < 1.05),
    1.5 ns of time resolution
  - Thin Gap Chambers in endcaps (1.05 < |η| < 2.7)

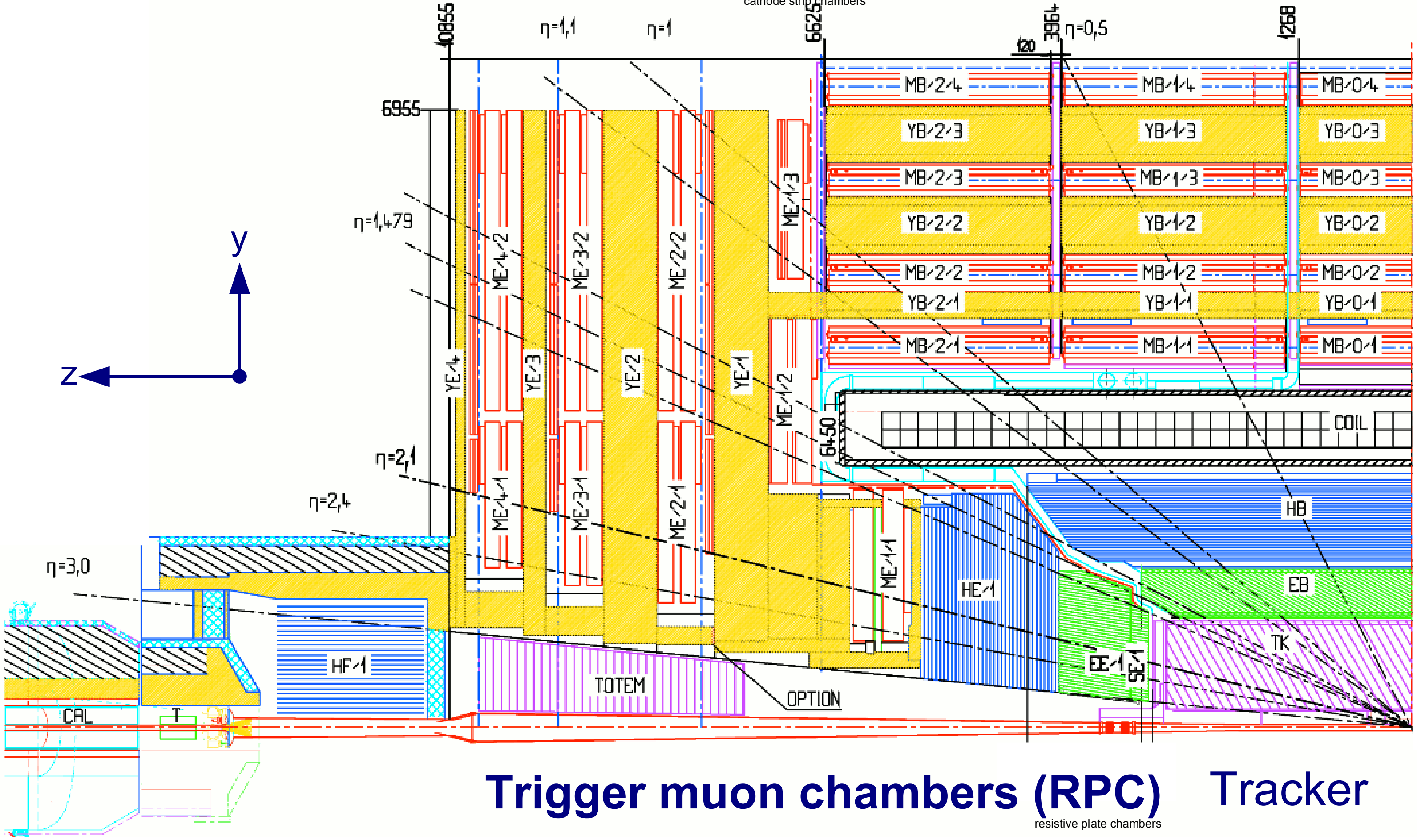




- Inside solenoid (2T)
- Pixels, SemiConductor Tracker,
  Transition Tradiation Tracker
- Cover |η| ≤ 2.5 region, except TRT (|η| ≤ 2)

Forward muon chambers (CSC)
cathode strip chambers

Central muon chambers (DT)
drift tubes



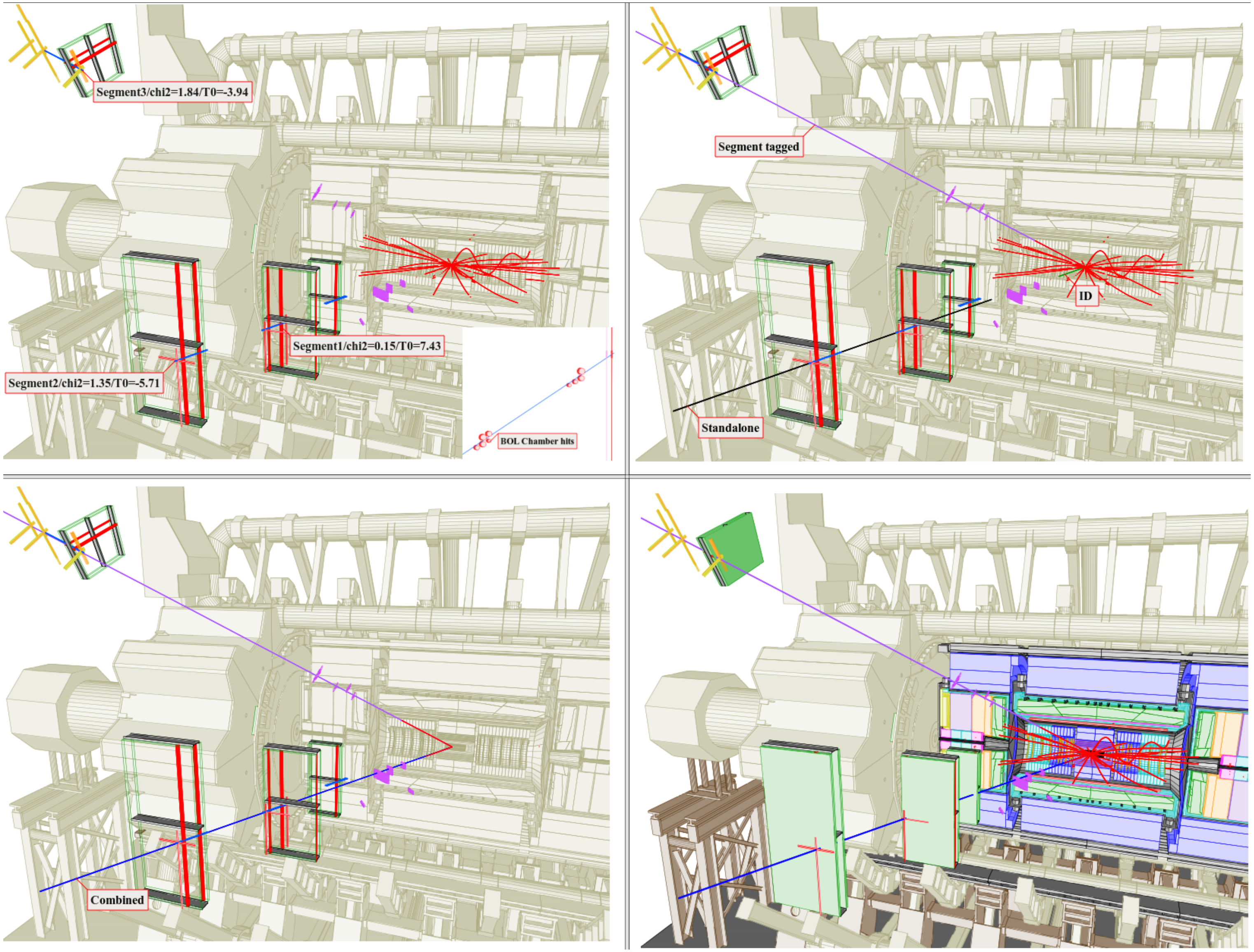
HO
hadron outer

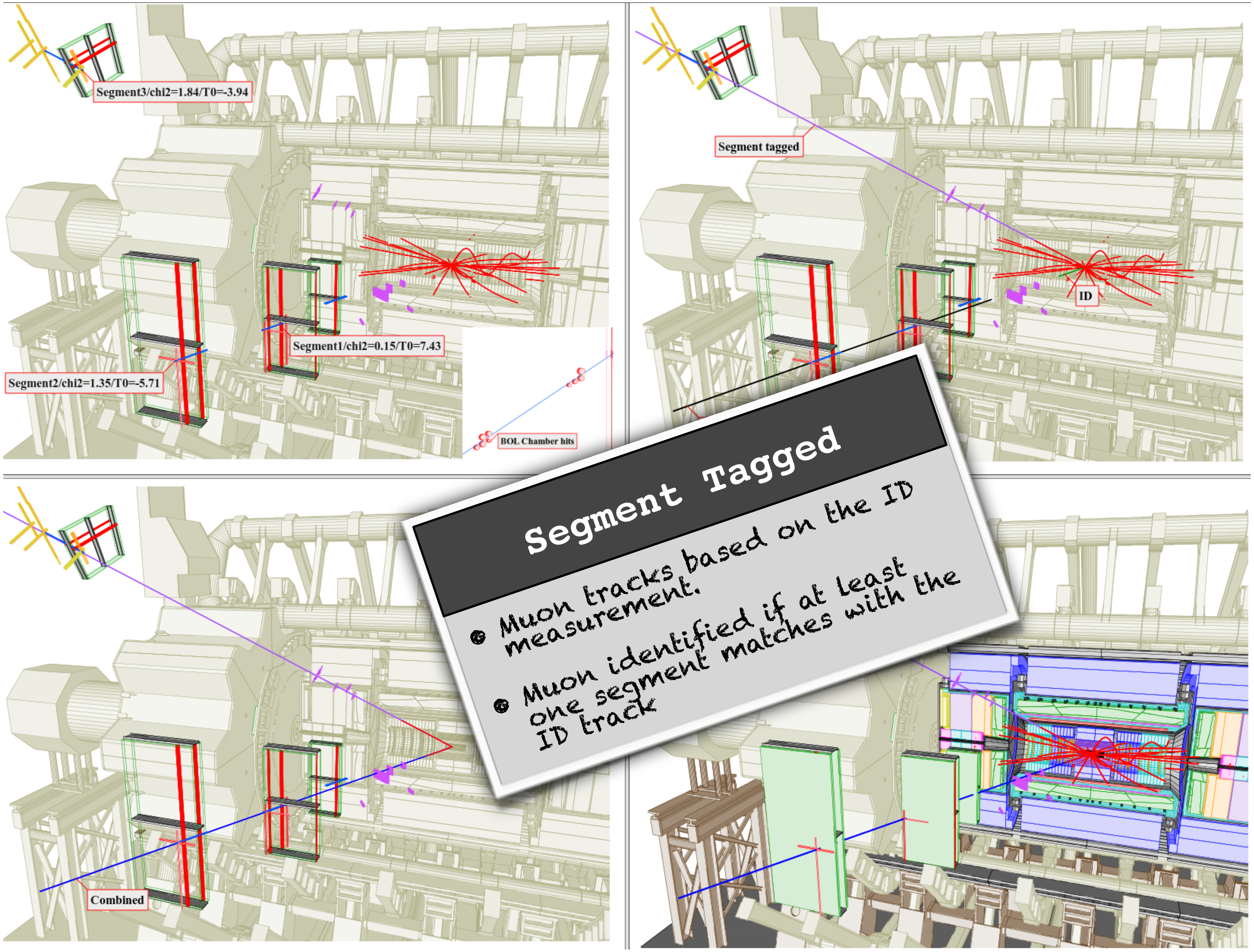
HCAL
hadron calorimeter

ECAL
electron calorimeter

Trigger muon chambers (RPC)
resistive plate chambers

Tracker


Segment3/chi2=1.84/T0=-3.94
Segment1/chi2=0.15/T0=7.43
Segment2/chi2=1.35/T0=-5.71
BOL Chamber hits
Segment tagged
ID
Standalone
Combined

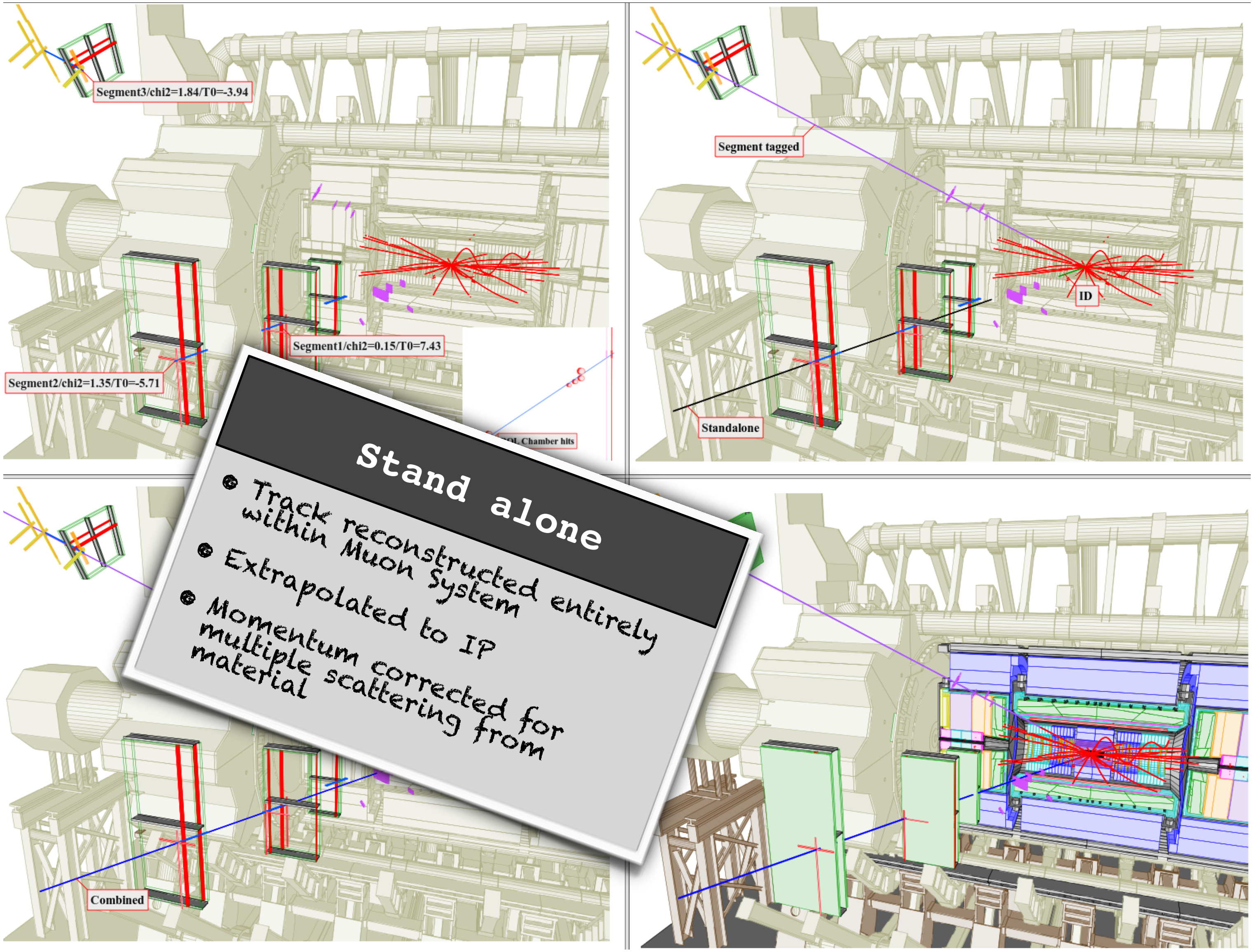


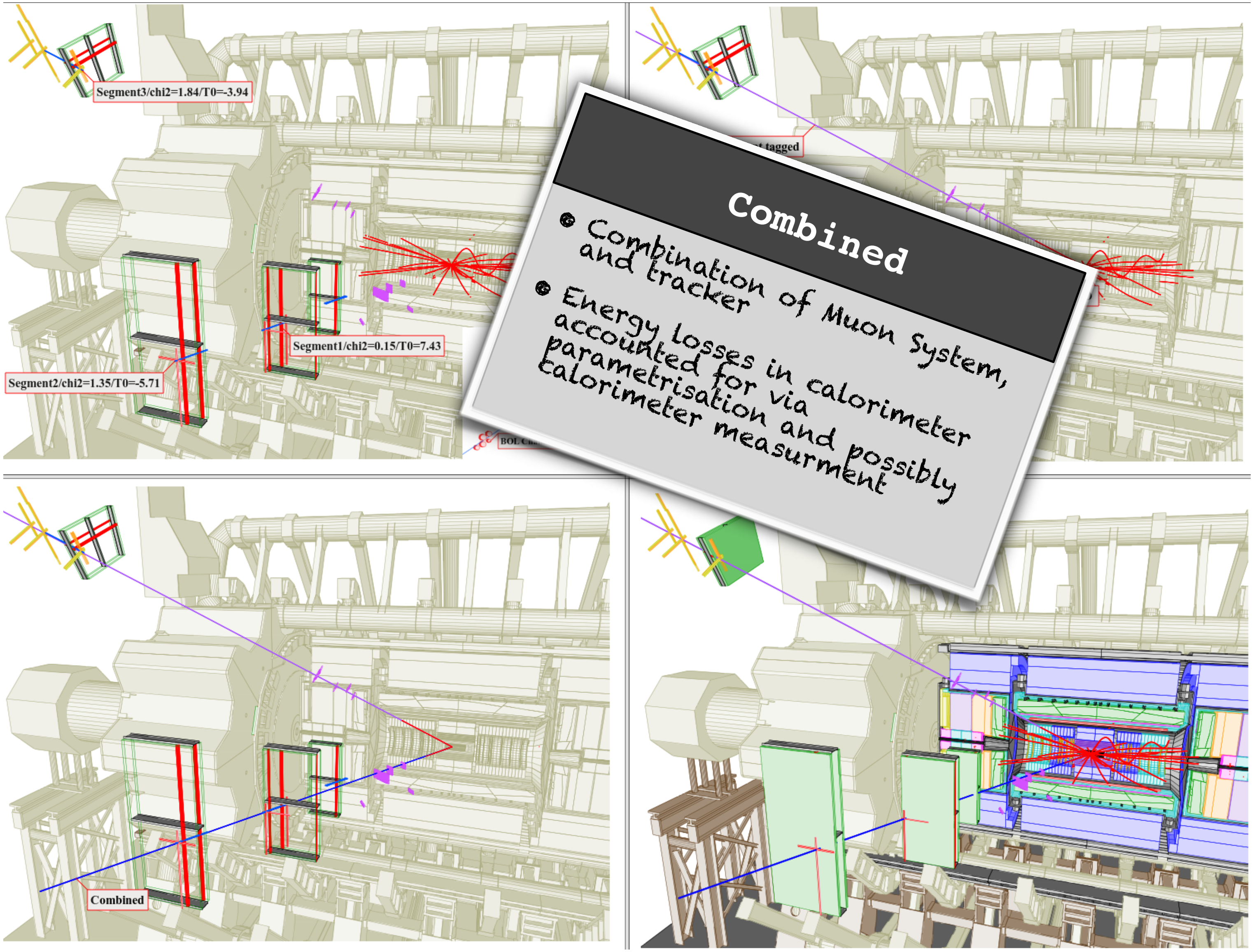
Segment Tagged

- Muon tracks based on the ID measurement.
- Muon identified if at least one segment matches with the ID track

Stand alone

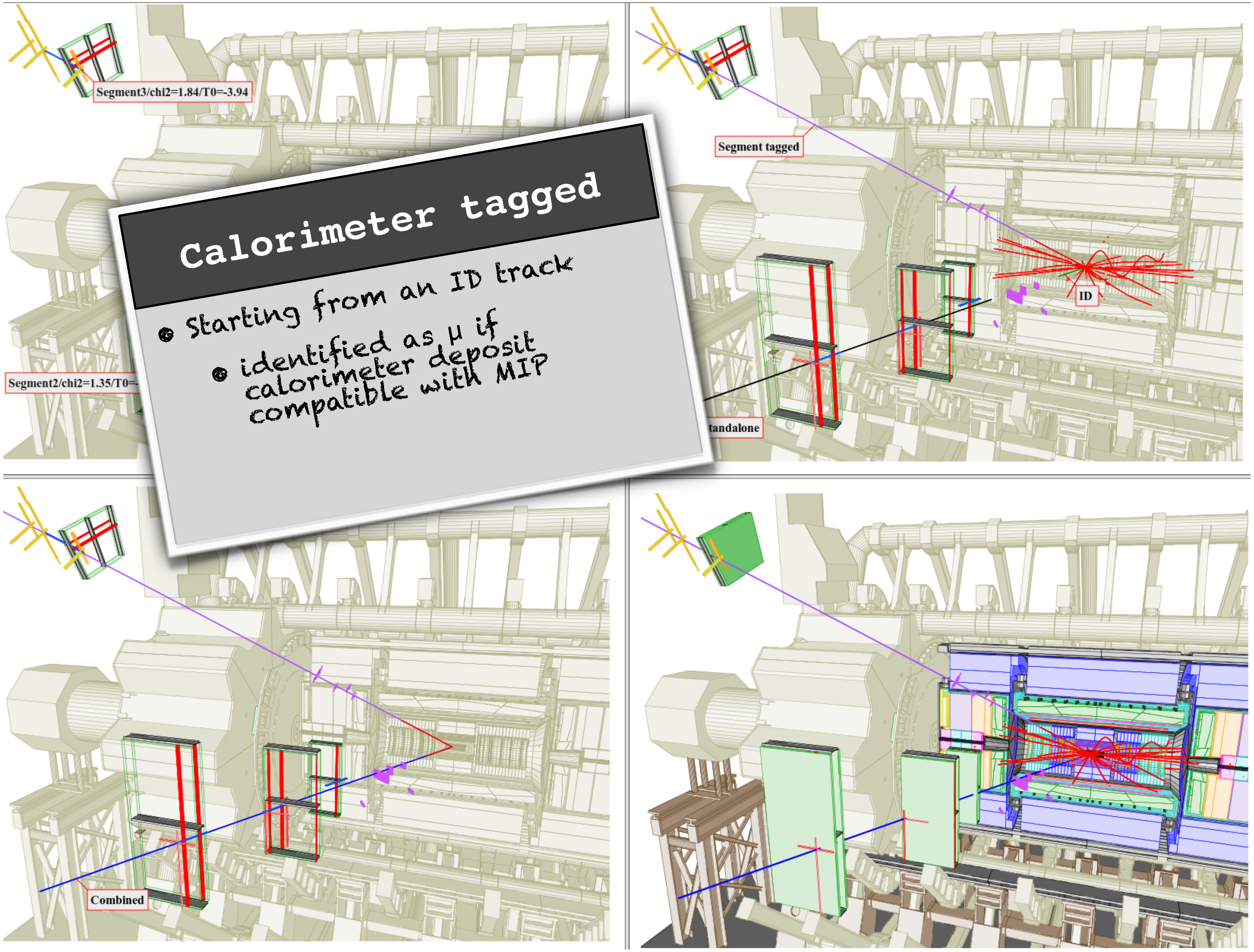
- Track reconstructed entirely within Muon System
- Extrapolated to IP
- Momentum corrected for multiple scattering from material





Combined

- Combination of Muon System, and tracker
- Energy losses in calorimeter accounted for via parametrisation and possibly calorimeter measurment

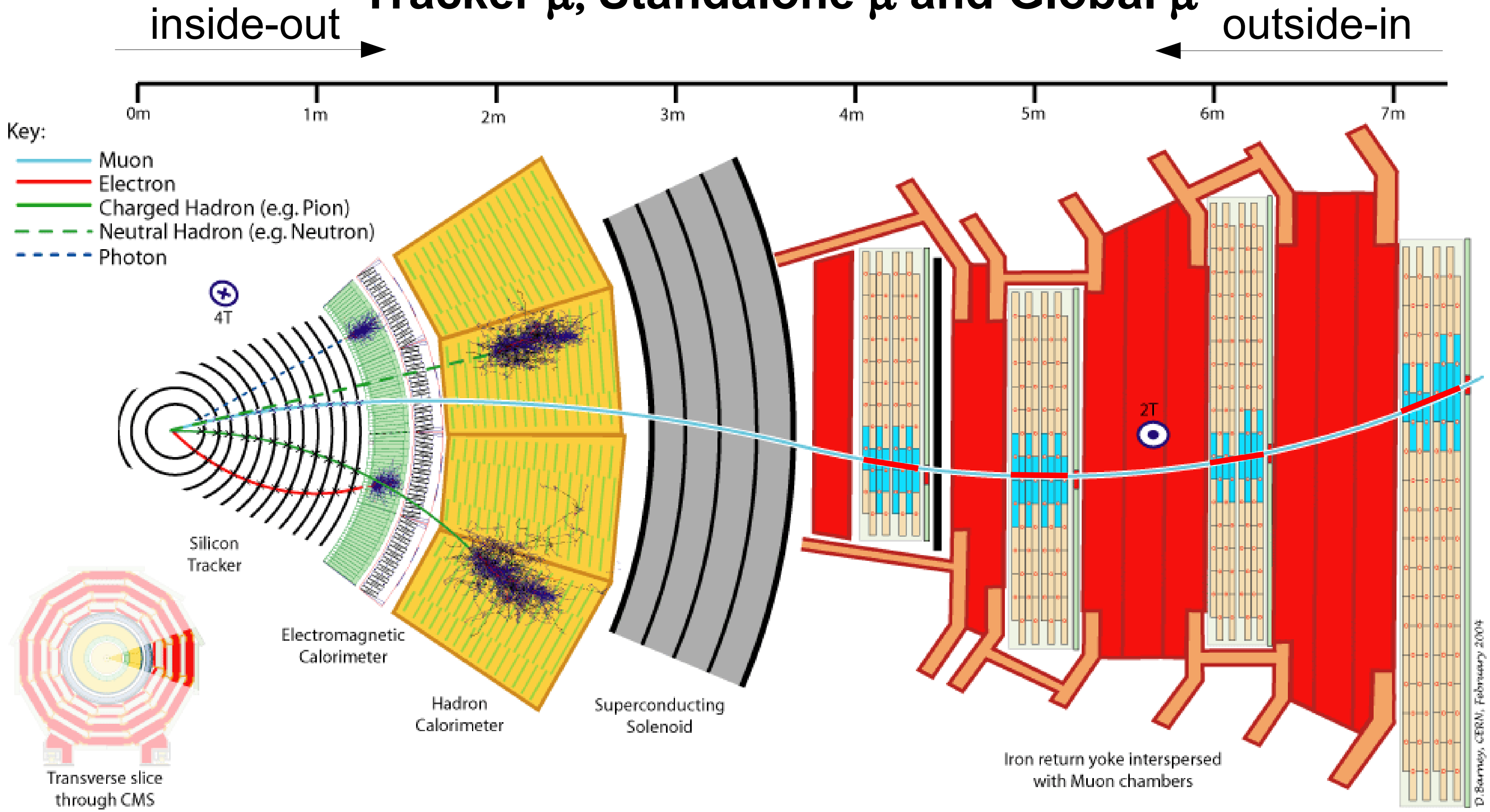


Calorimeter tagged

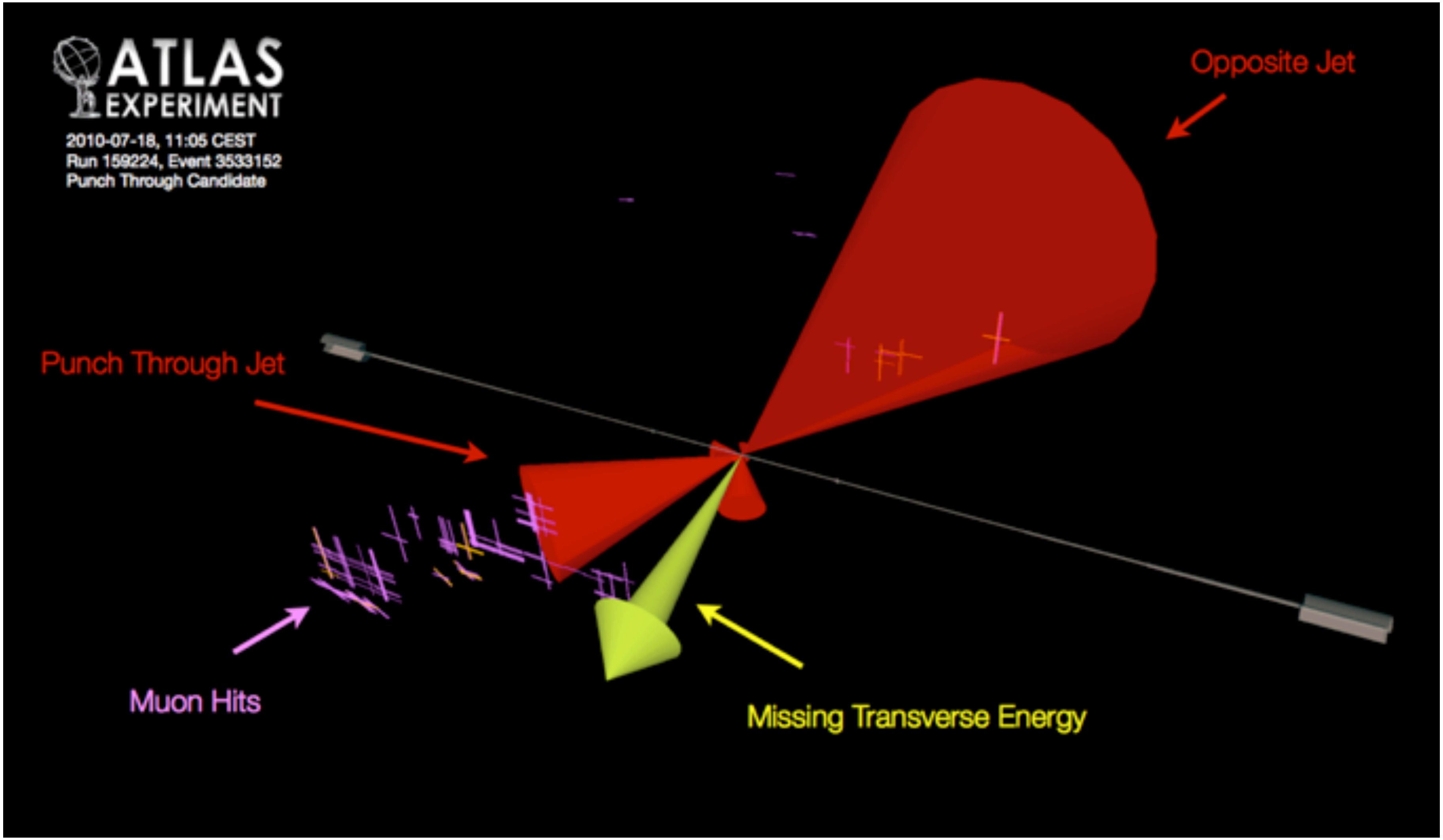
- Starting from an ID track
  - identified as μ if calorimeter deposit compatible with MIP

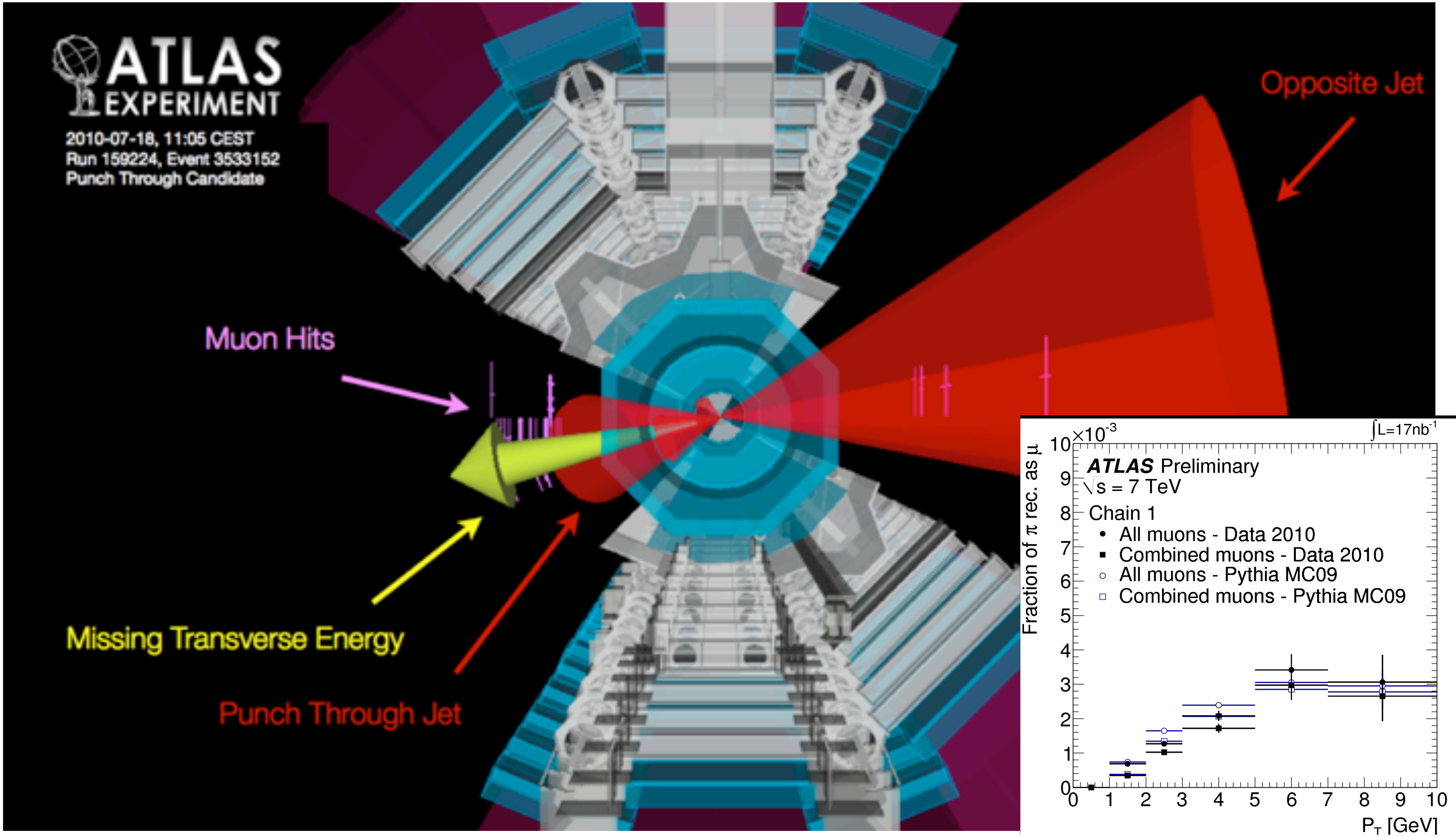
Muon Identification

Tracker μ, Standalone μ and Global μ



Muons


ATLAS EXPERIMENT
2010-07-18, 11:05 CEST
Run 159224, Event 3533152
Punch Through Candidate
Opposite Jet
Punch Through Jet
Muon Hits
Missing Transverse Energy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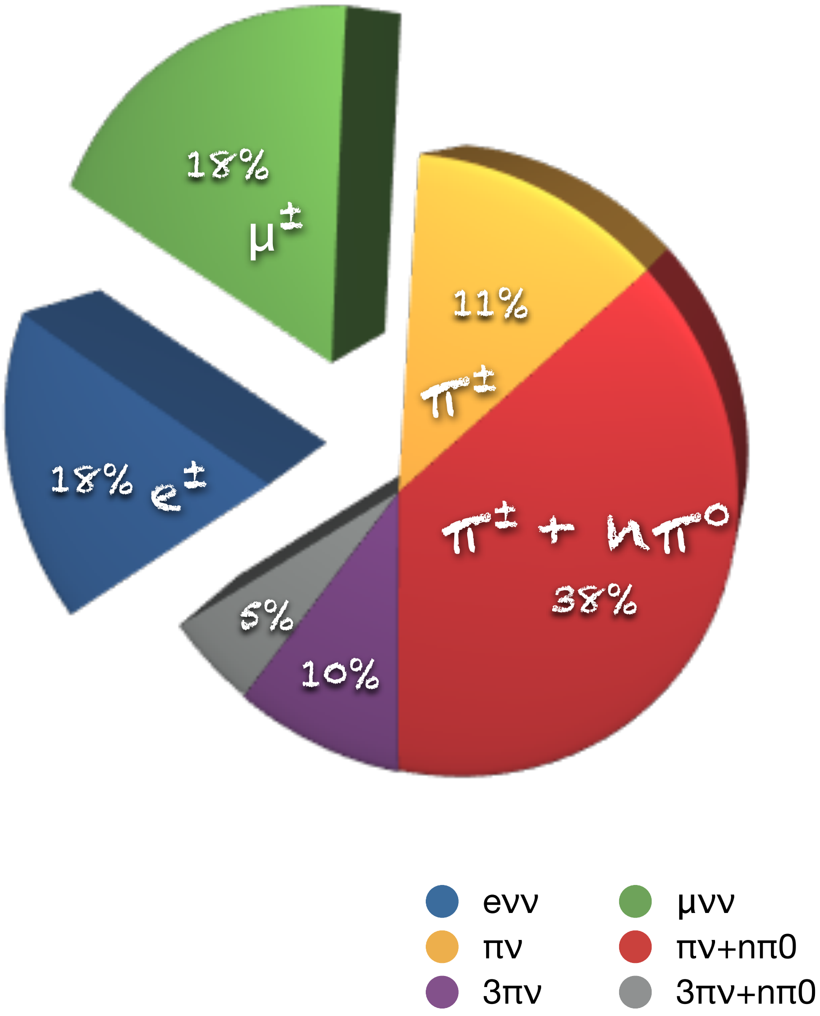
$\int L = 17 nb^{-1}$
ATLAS Preliminary
$\sqrt{s}$ = 7 TeV
Chain 1
• All muons - Data 2010
▪ Combined muons - Data 2010
○ All muons - Pythia MC09
□ Combined muons - Pythia MC09
Fraction of π rec. as μ
$\times 10^{-3}$
0
1
2
3
4
5
6
7
8
9
10
P_T [GeV]

Summary & Outlook

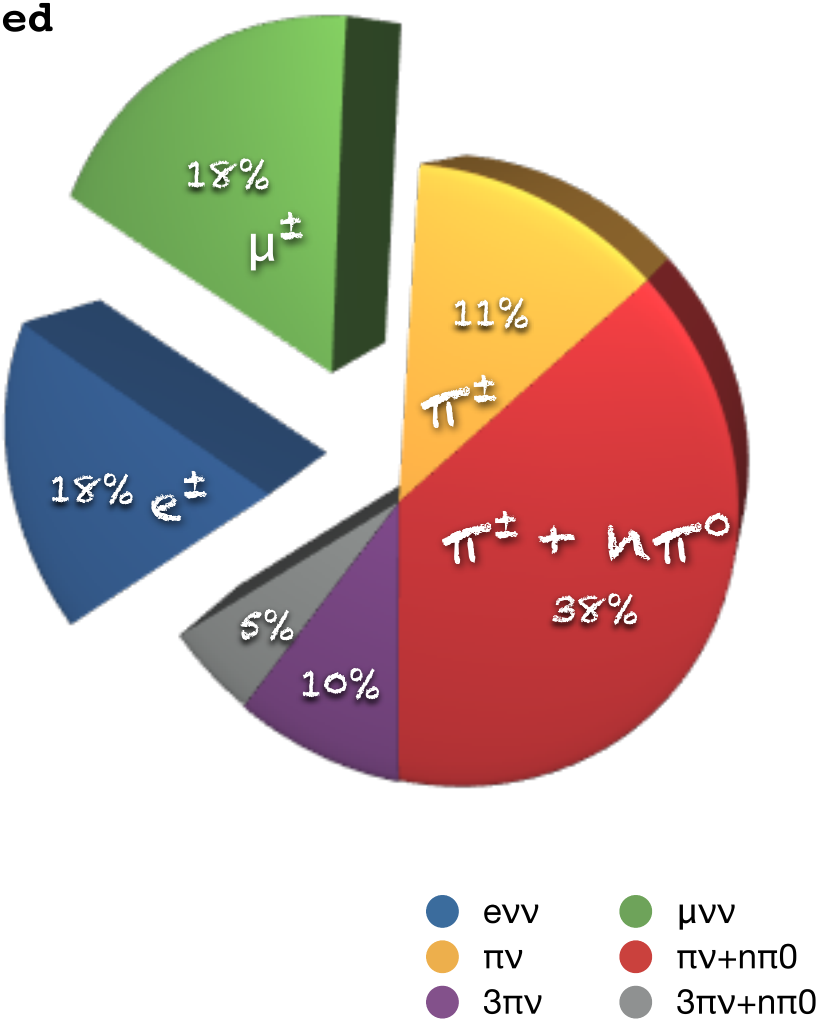
- **We now have a complete list of identified individual particles**
    - e, γ, μ, π, K_L^0, PU-π
    - This list of particles describes the entire event
        - all detector hits are used; redundancy exploited;
        - unused energy avoided; double counting of energy avoided
    - Some of these particles can be identified as prompt
        - we discussed electrons, photons, muons
    - pile-up can be removed from isolation consideration
- **Next, we will use the above list of particles to identify composite or unstable particles**
    - hadronic decays of τ-lepton, quark/gluon jets, b-jets, t-jets, and ν's
- **More tomorrow!**

Basic tau-decay signatures



Basic tau-decay signatures

- Massive, (relatively) long lived



Basic tau-decay signatures

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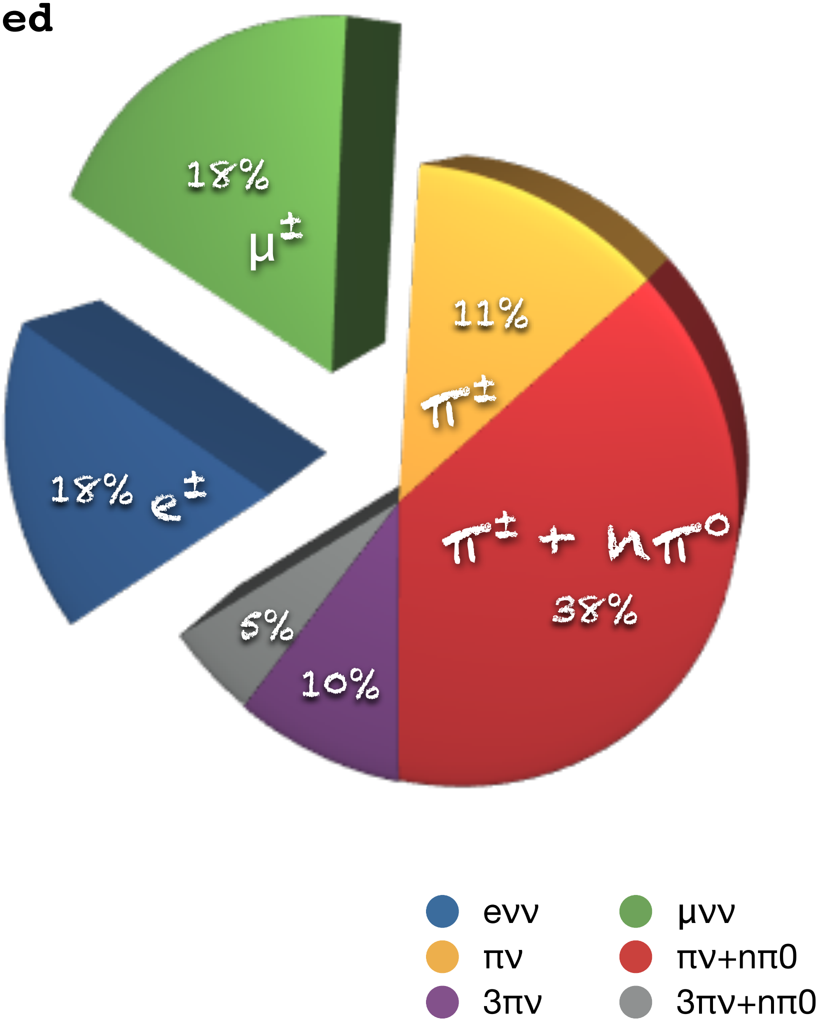

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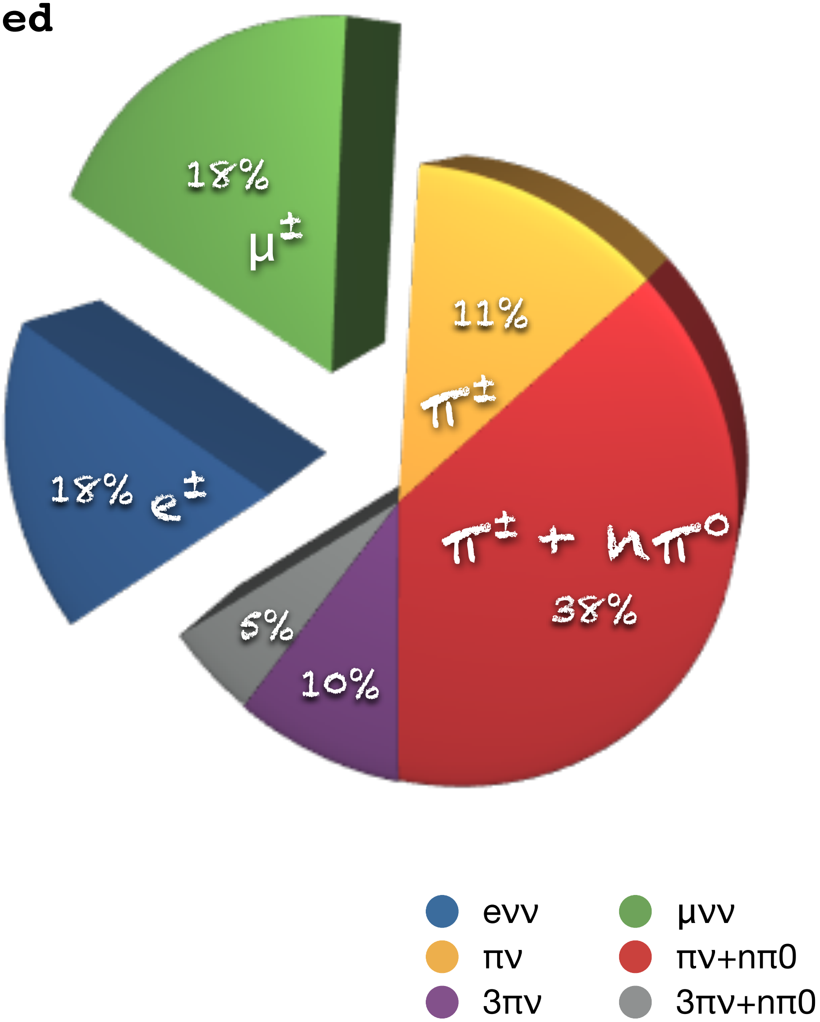

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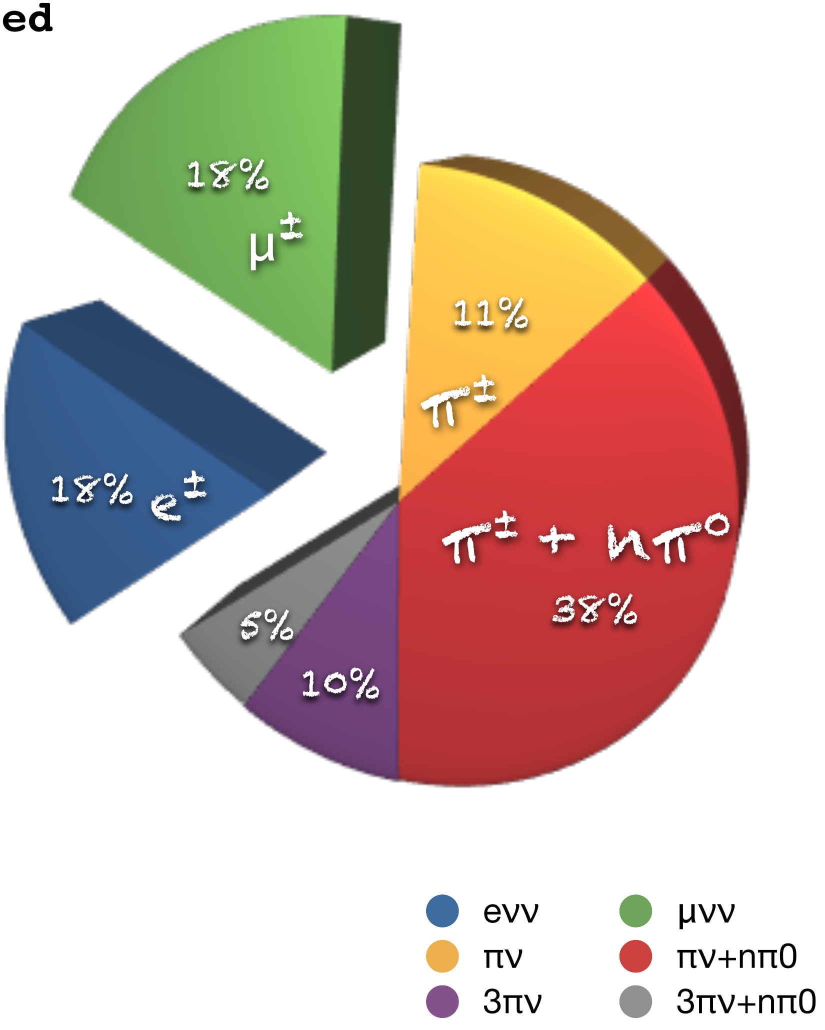

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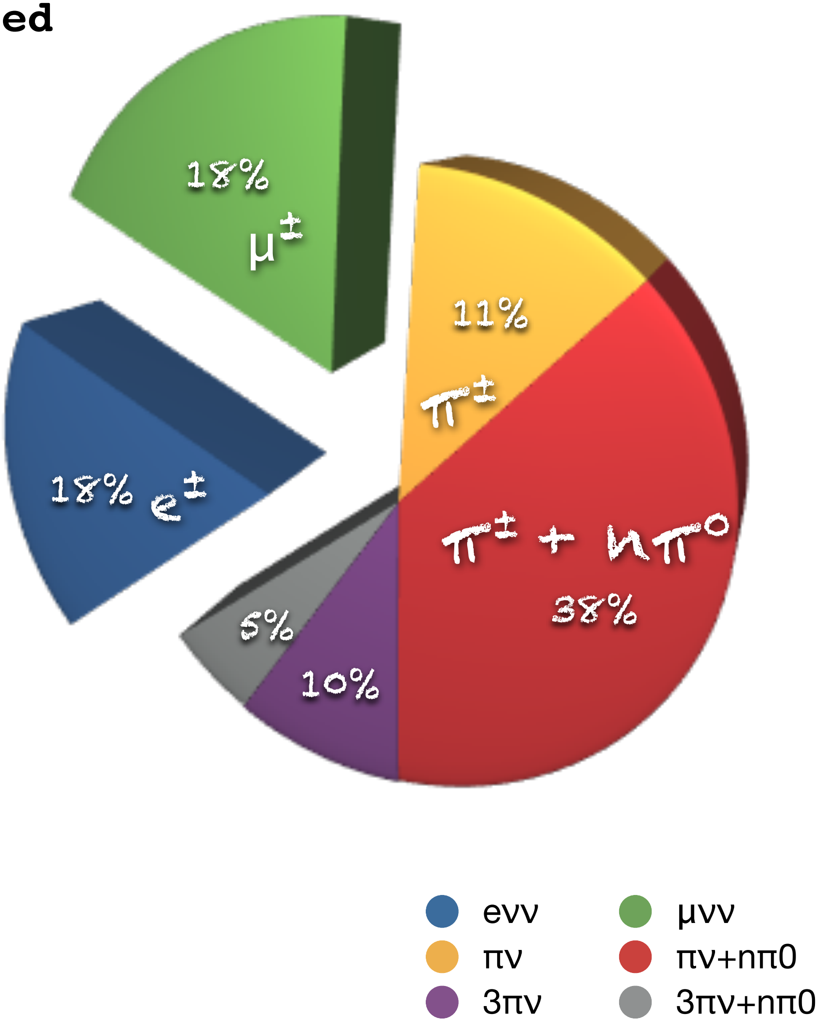

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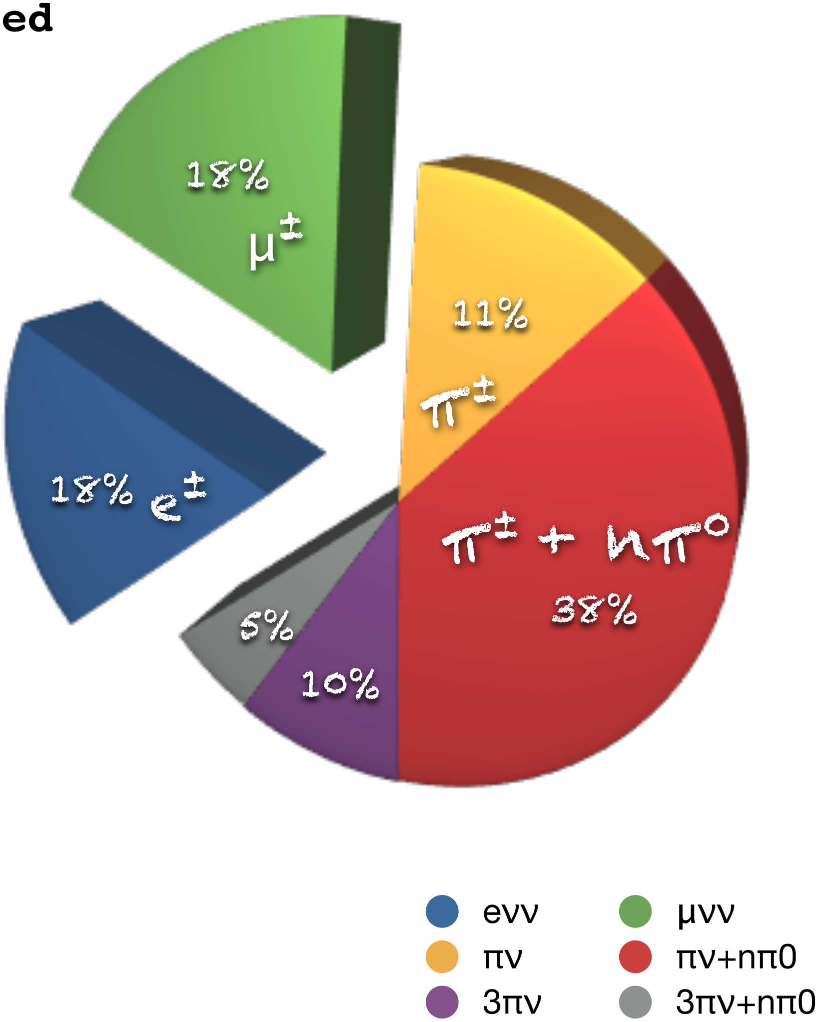

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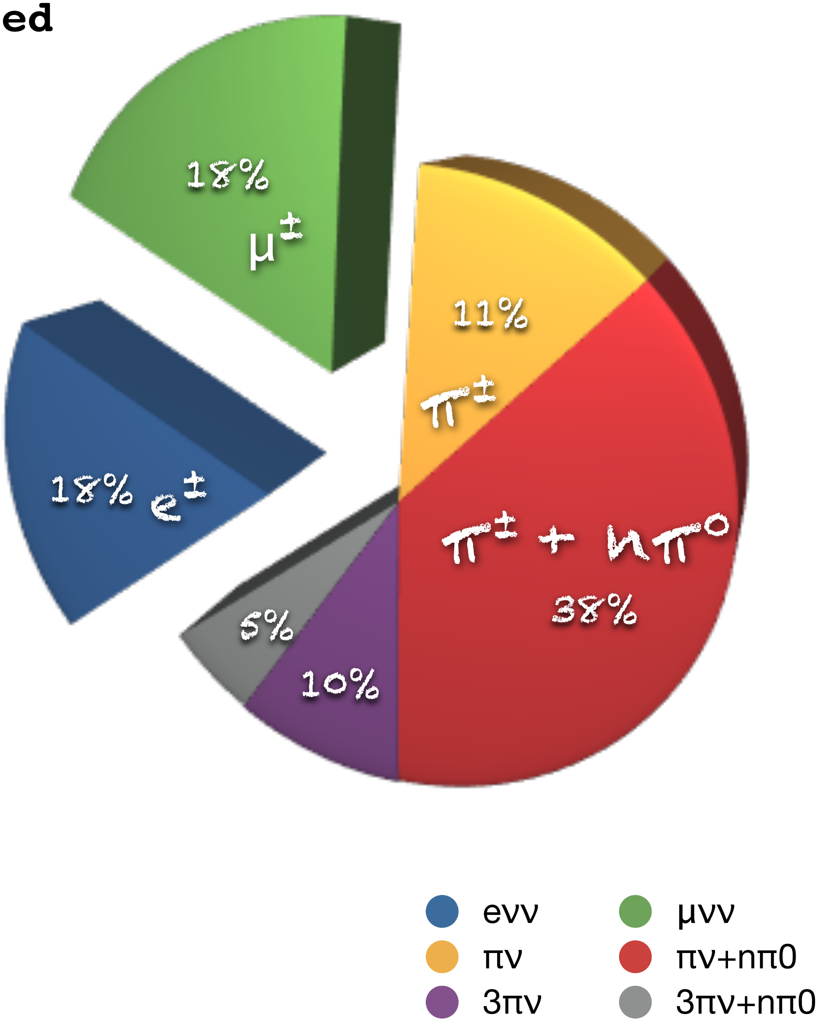

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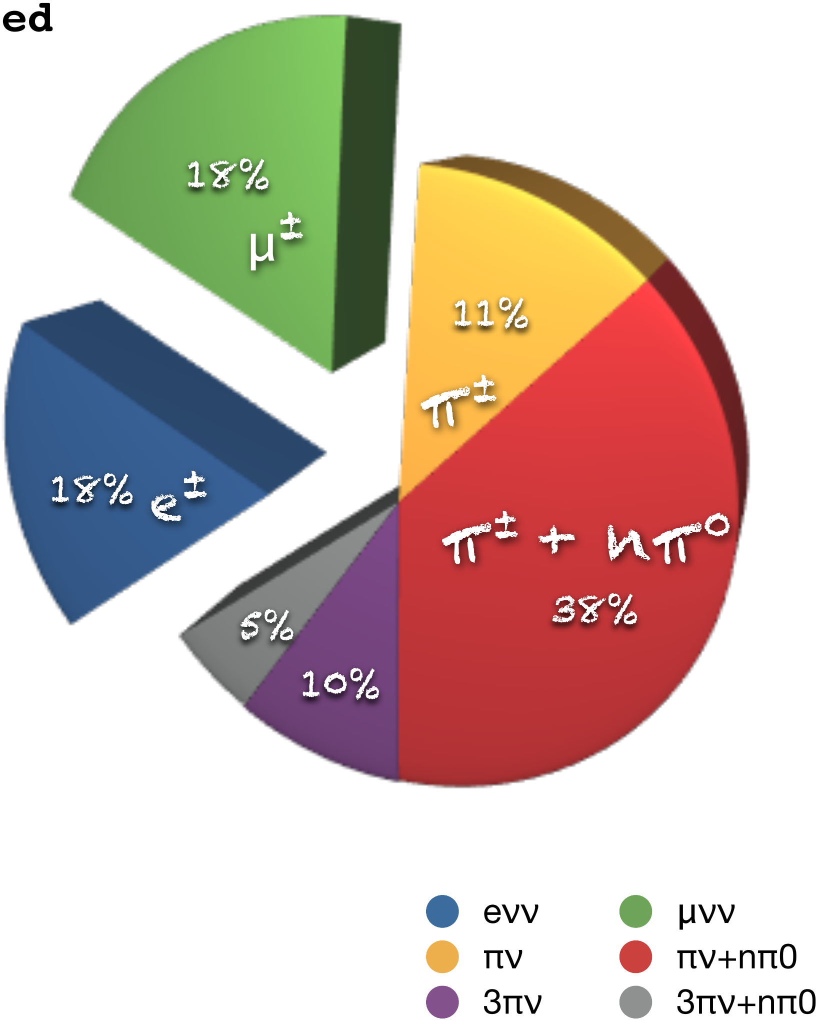

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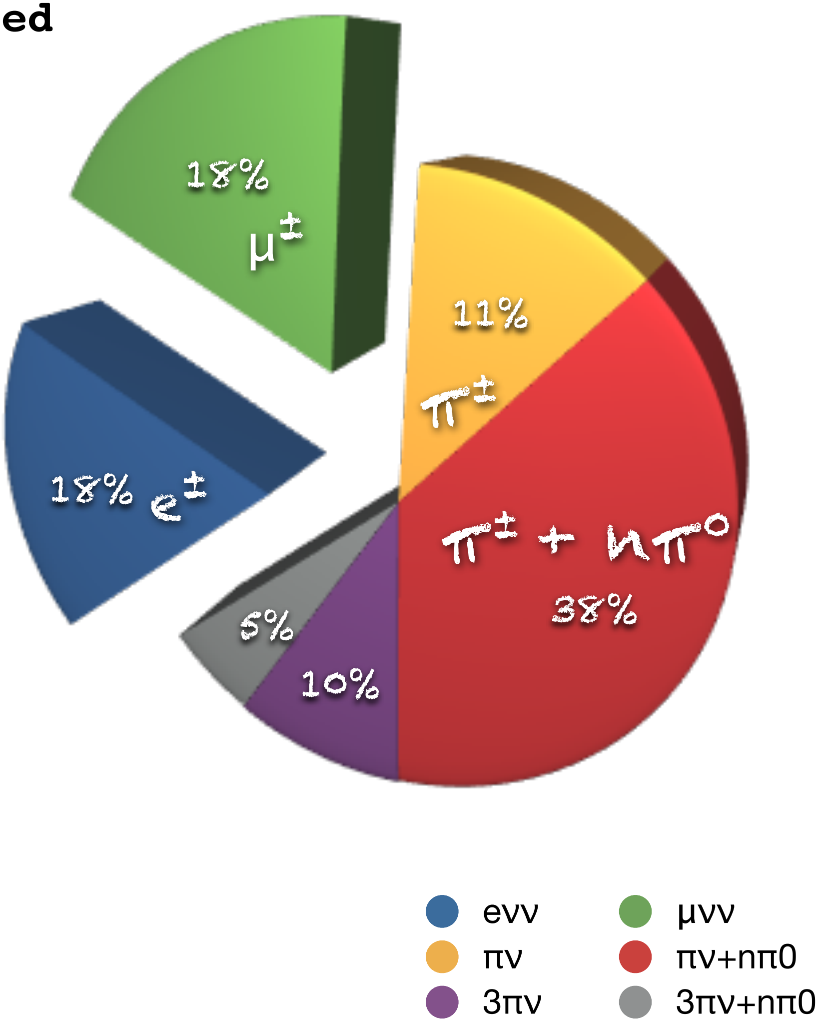
    - 11% $\pi^{\pm}$



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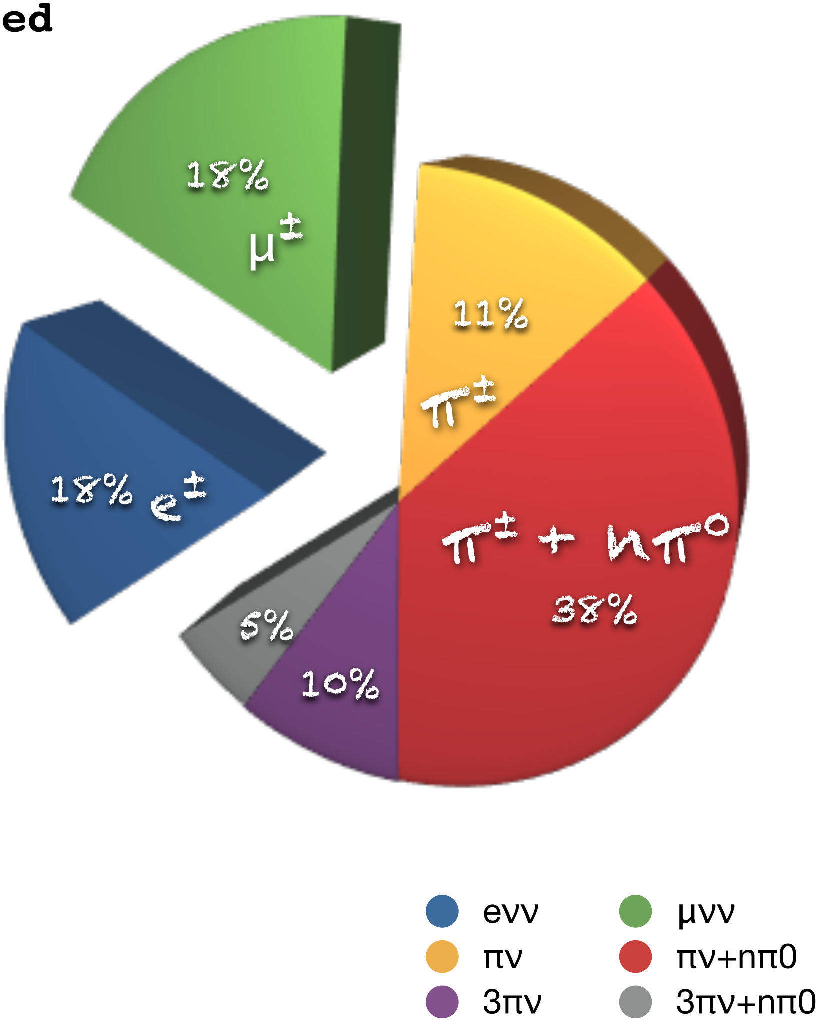

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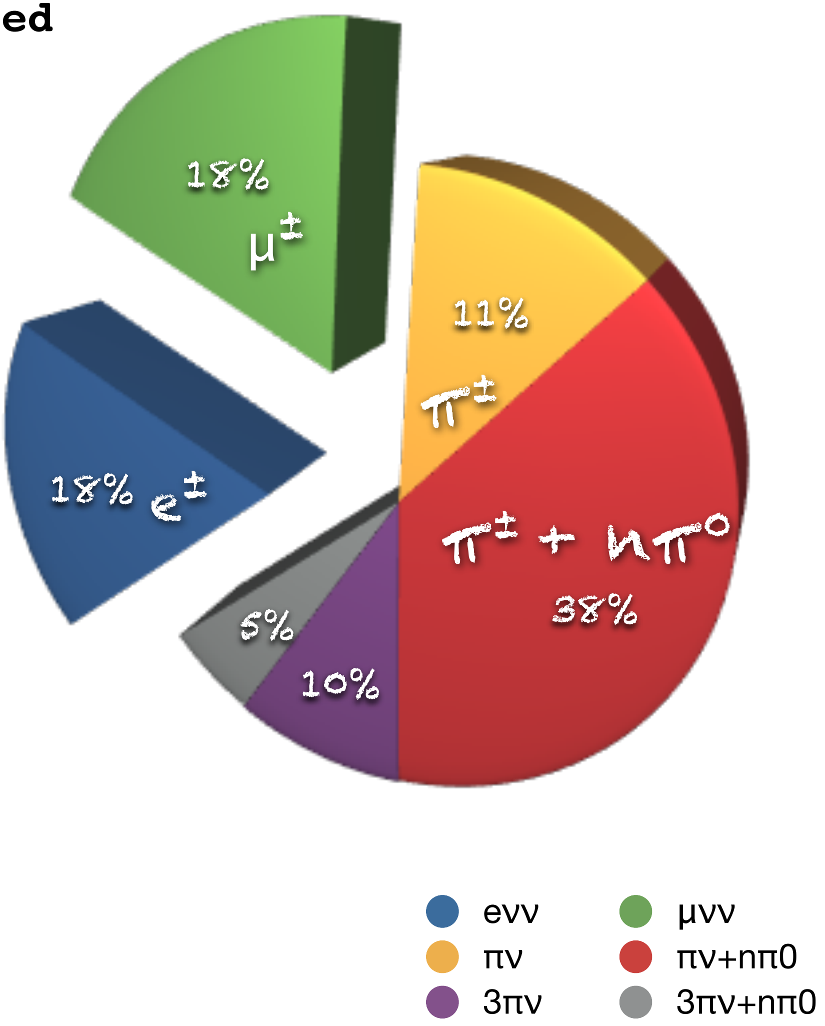

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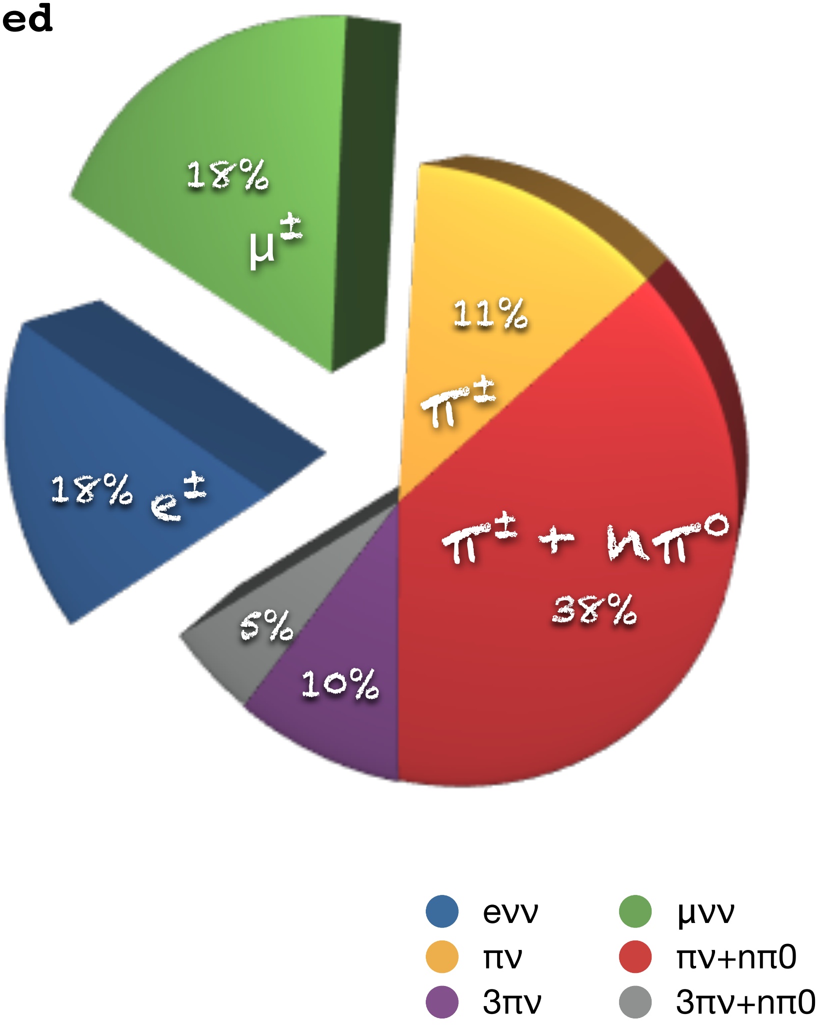

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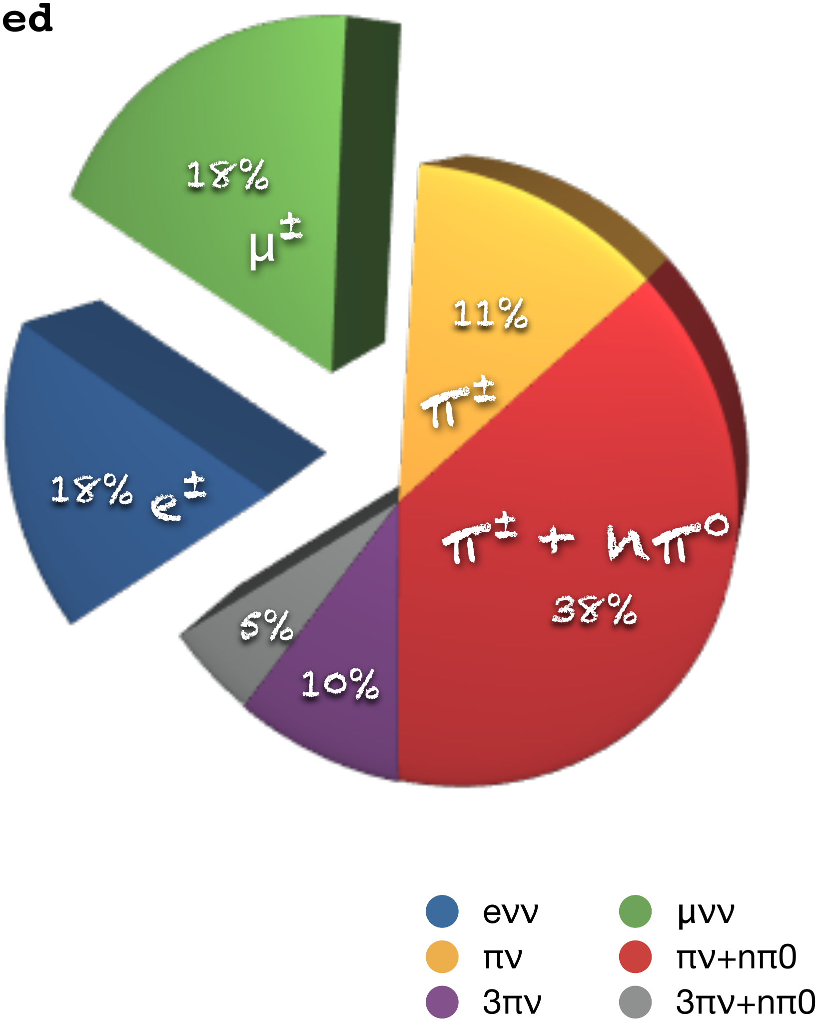

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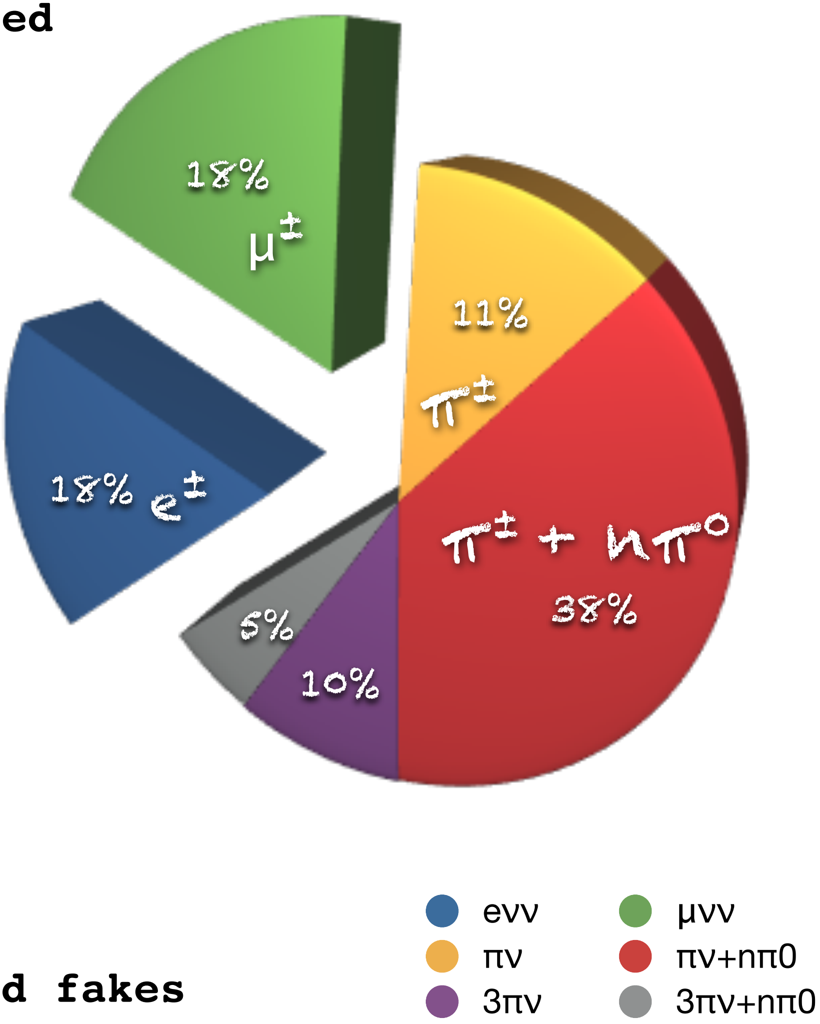
- **Experimental inefficiencies and fakes**



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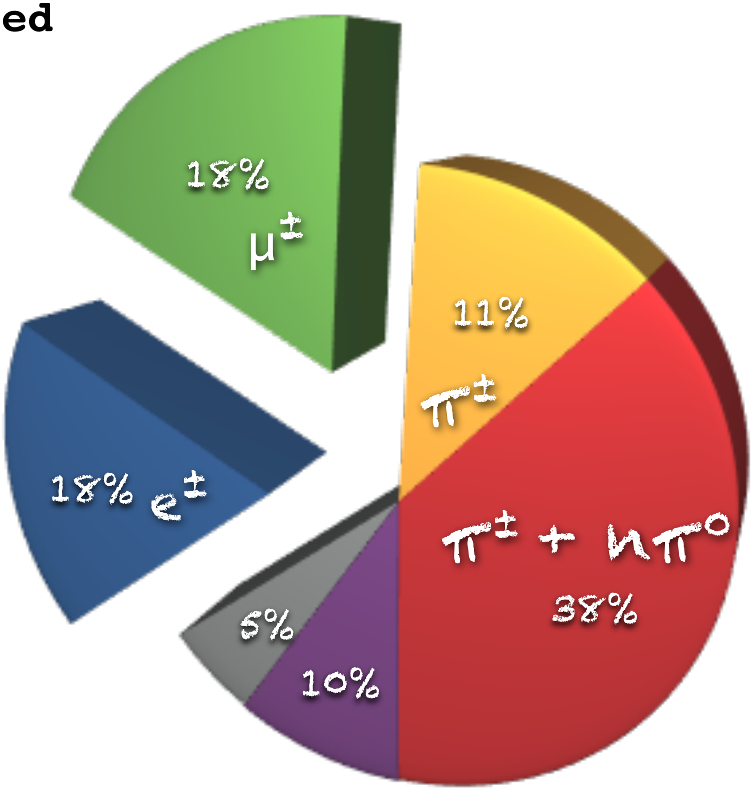
  - reality: 0,1,2,3,4 pions + 0,1,2,3,4+ photons



● eνν ● μνν
● πν ● πν+nπ0
● 3πν ● 3πν+nπ0

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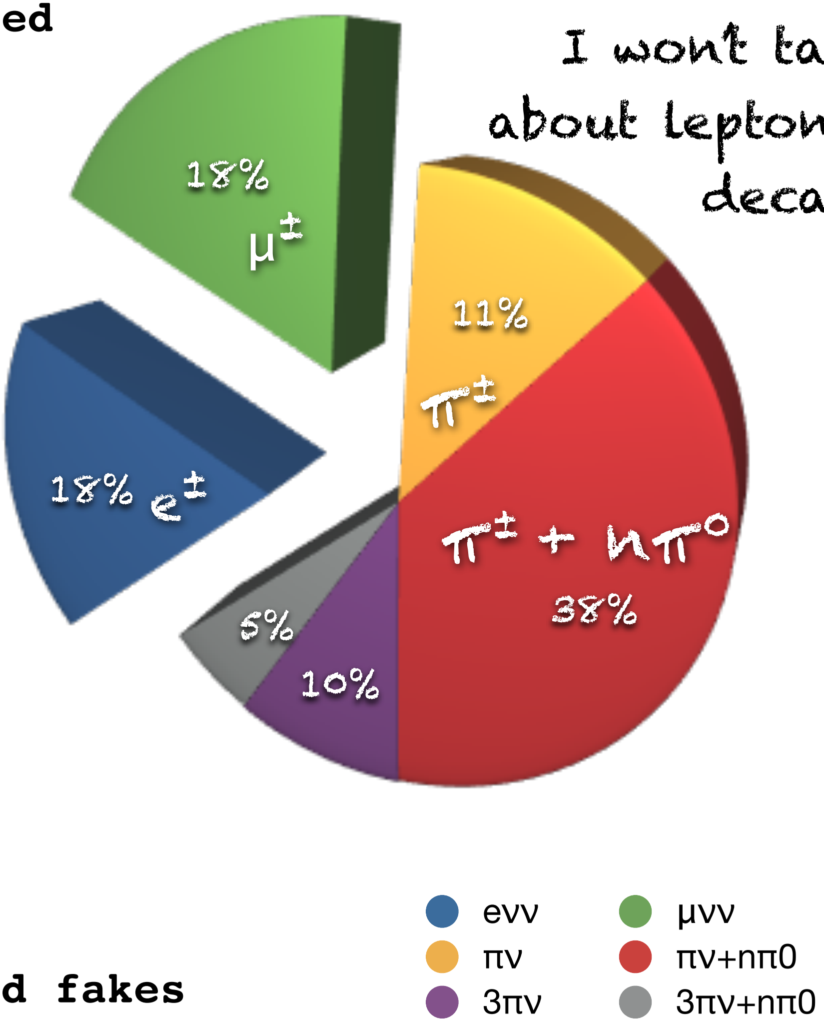
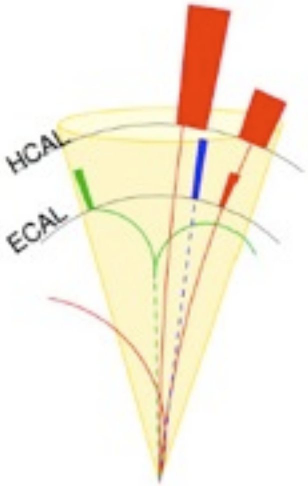
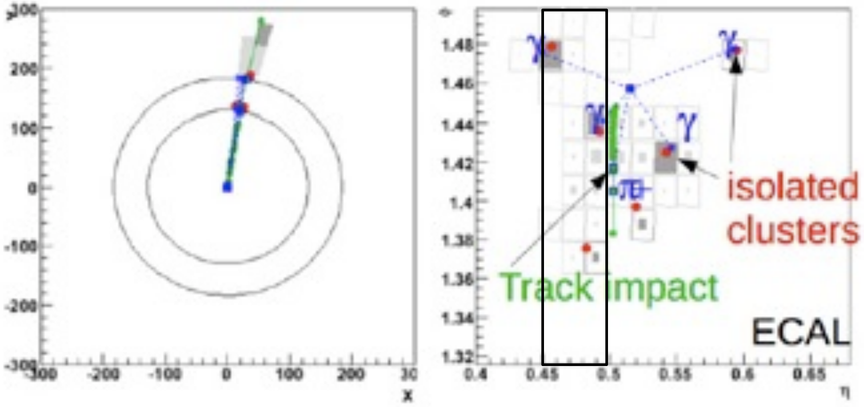


I wont talk about leptonic decays

Tau Identification

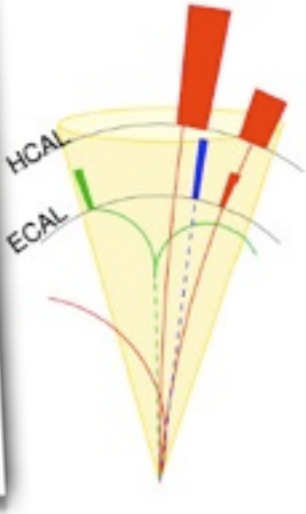


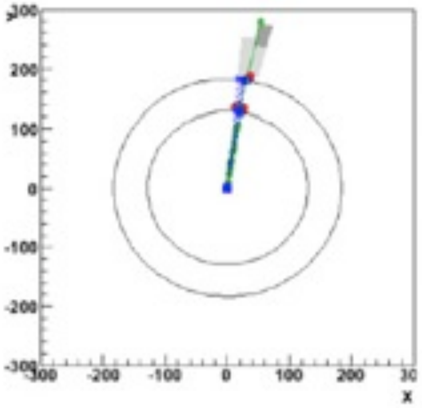


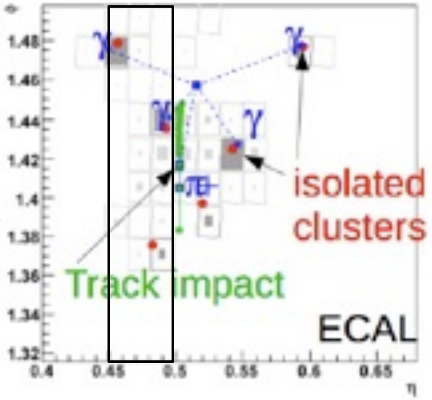
Tau Identification

Basic Idea

- Start with highest p_T γ or $e^{\pm}$ in jet
- Cluster all γ's or e's into strips
  - $\Delta\eta\times\Delta\varphi = 0.05\times0.2$
  - to capture all conversions
- Combine with $\pi^{\pm}$'s to form tau-candidates







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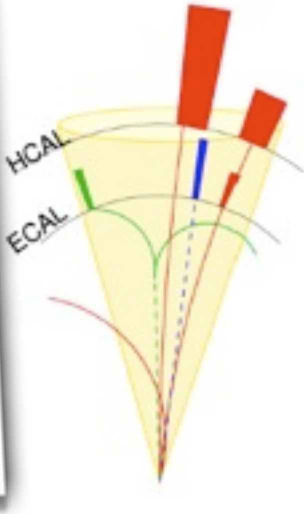

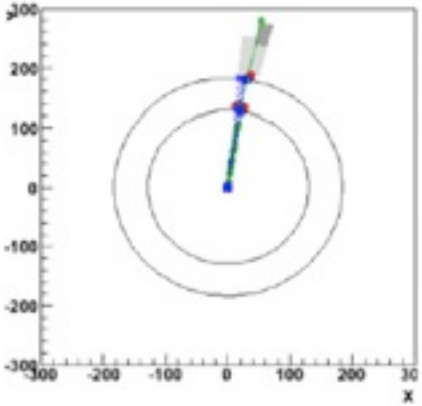

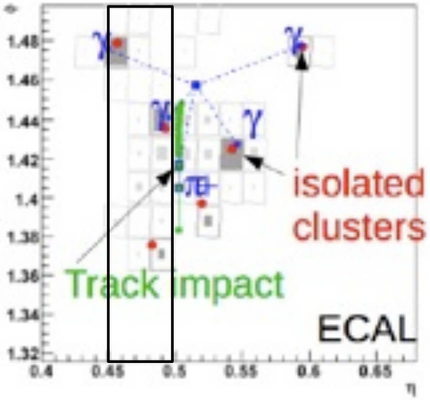

1 $\pi^\pm$, 0 π^0

- Branching Fraction: 11.6%
- Single isolated $\pi^\pm$

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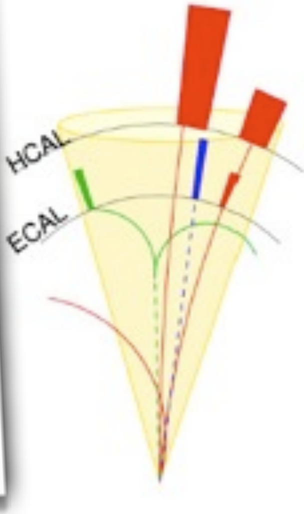

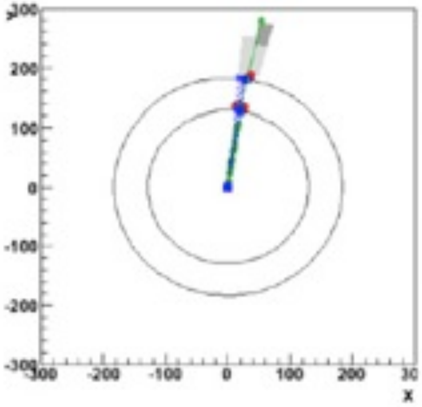

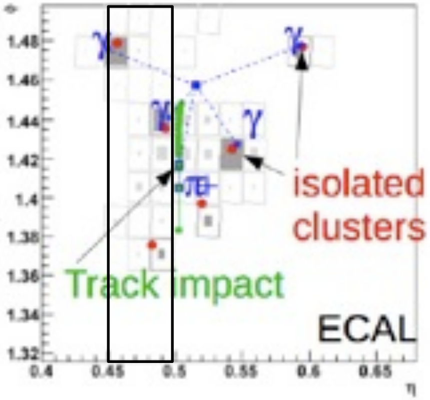

1 $\pi^\pm$, 0 π^0

- Branching Fraction: 11.6%
- Single isolated $\pi^\pm$

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- Branching Fraction: 9.8%
- three $\pi^\pm \approx a_1$ mass

Tau Identification

Basic Idea

- Start with highest p_T γ or $e^{\pm}$ in jet
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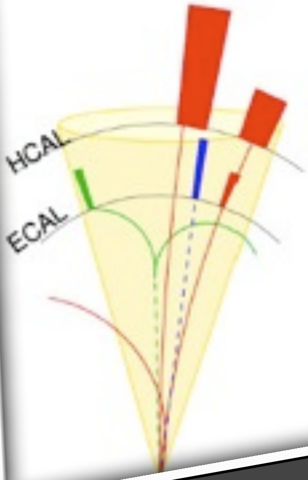

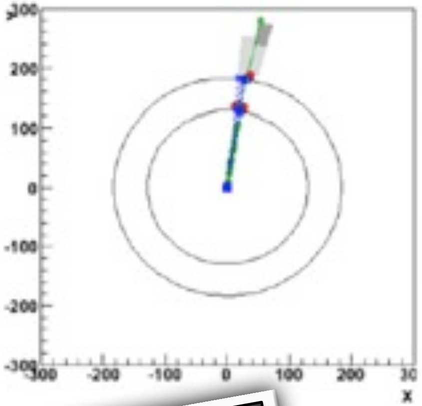

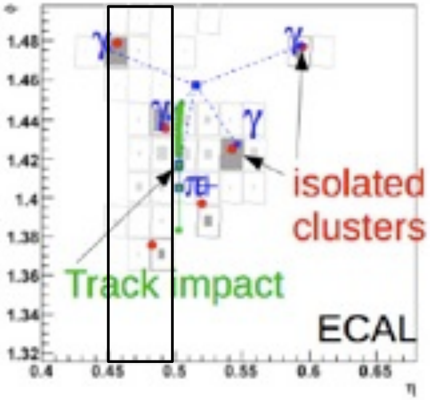

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- single strip ≳ 1 GeV
- single $\pi^{\pm}$
- strip ≈ π^0 mass
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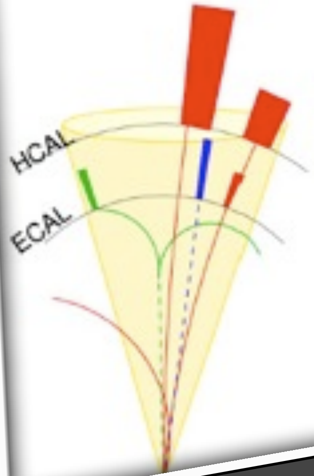

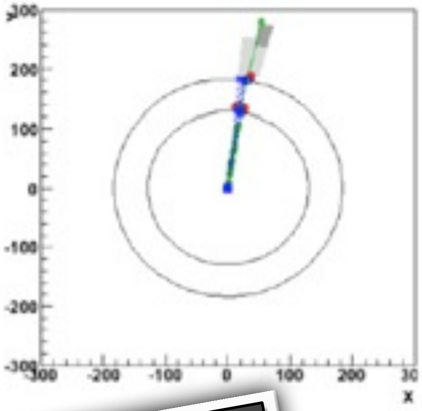

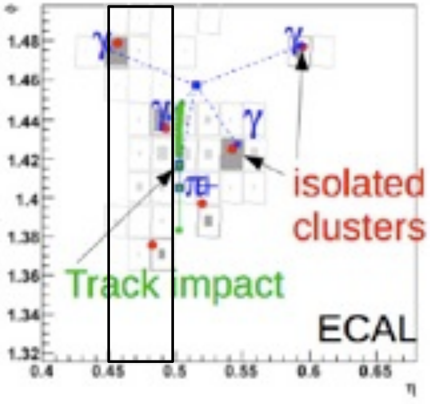

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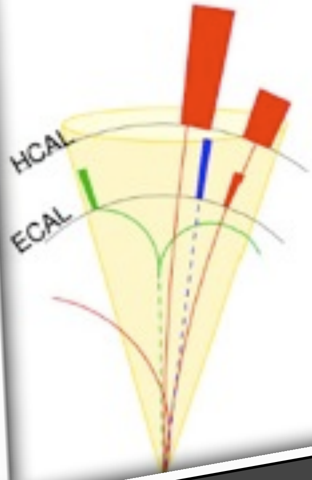

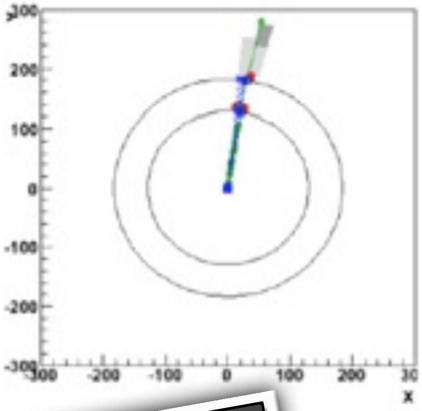

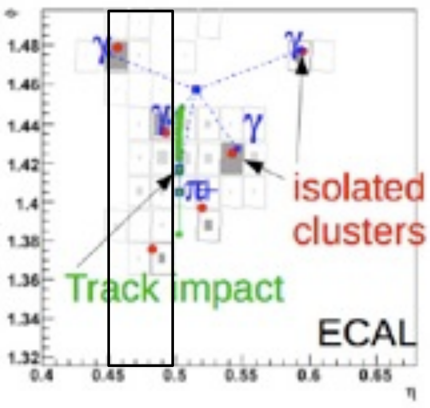

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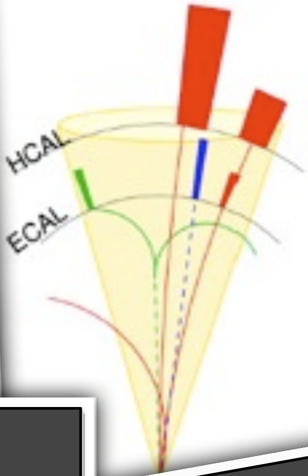
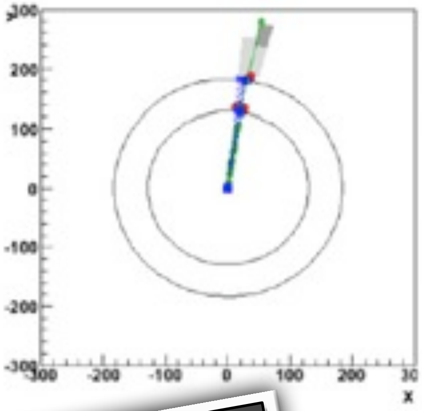
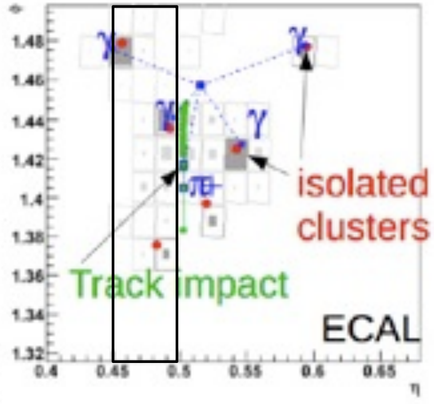
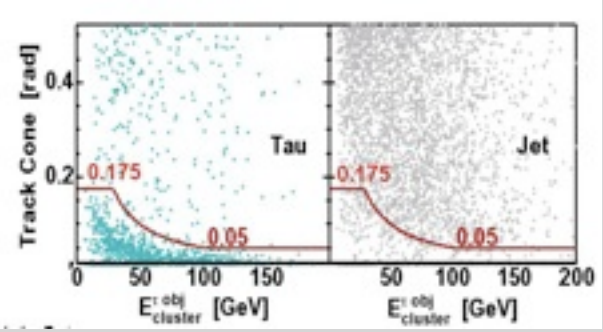






Shrinking Cone

- Tau constituents must lie within a shrinking $\Delta R \lesssim 2.8 / pT(\tau)$



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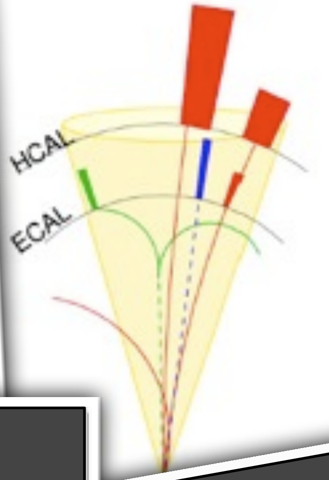

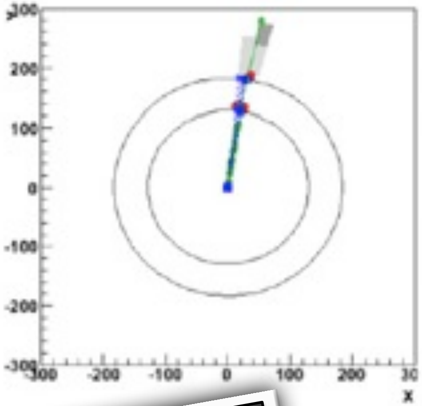

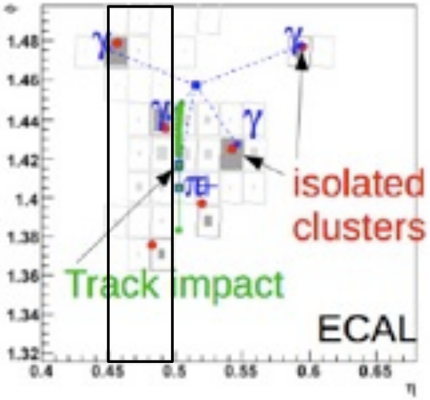

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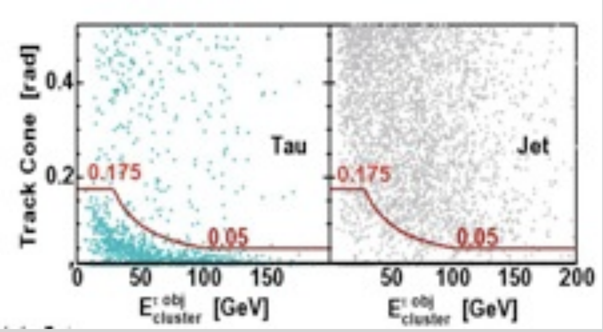

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Cou

1

Isolation

- Isolation cone of ΔR = 0.5
- summed pT of all particles, except constituents of tau-candidate
- *loose*: no π± with pT > 1.0 GeV; no γ with pT > 1.5 GeV
- *medium*: no π± with pT > 0.8 GeV; no γ with pT > 0.8 GeV
- *tight*: no π± with pT > 0.5 GeV; no γ with pT > 0.5 GeV

Contamination due to e's, μ's

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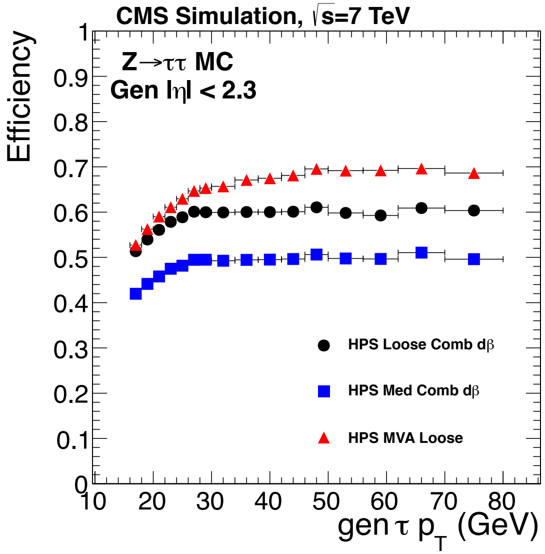

Contamination due to e's, μ's

Discriminate against μ's

- loose: $\pi^{\pm}$ not matched with segments in muon chamber
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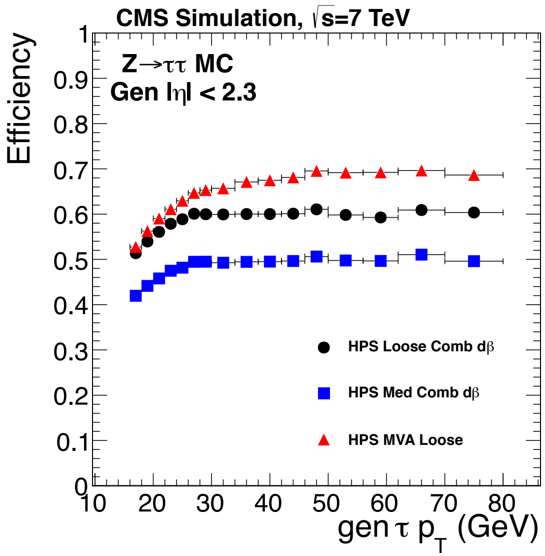

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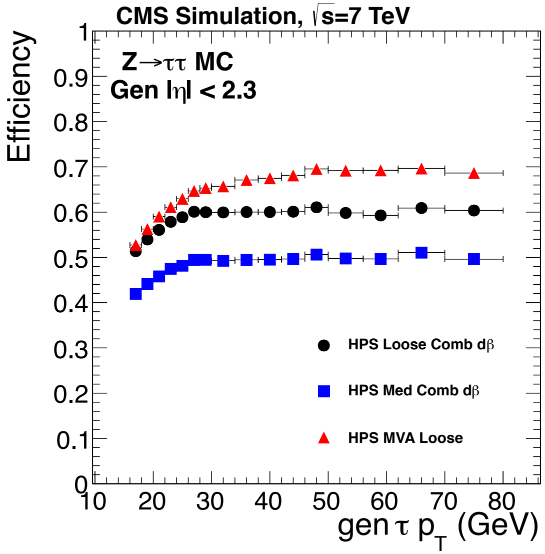
Discriminate against e's

- use BDT with
  - mean of Δη and Δφ of neutral candidates weighted by their pT
  - output of pf electron discriminator, ξ
  - EM energy fraction of leading $\pi^{\pm}$ or γ candidate
  - ratio between HAD energy of leading charged $\pi^{\pm}$
  - number of neutral signal candidates. Visible mass of the tau candidate
  - fraction of visible E of tau candidate carried by the neutral candidates
- 91% eff for e^- 16%



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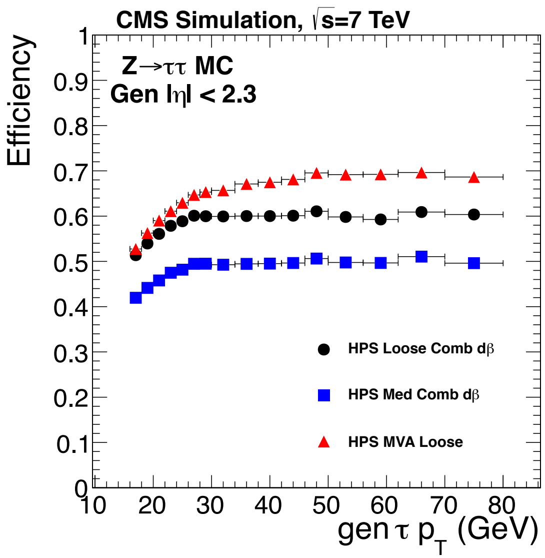

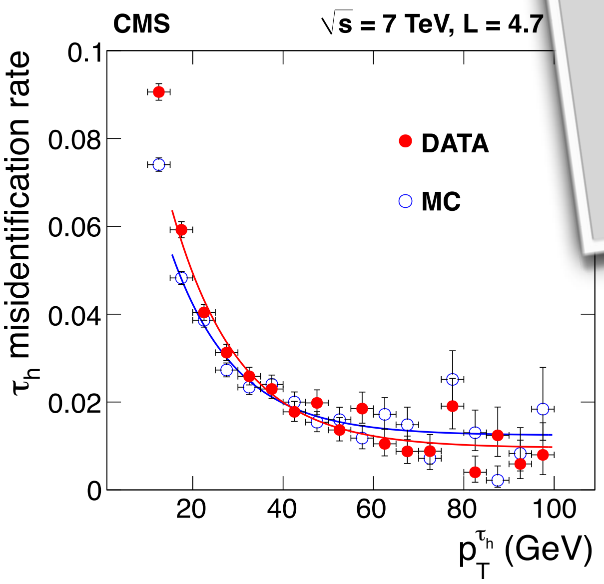

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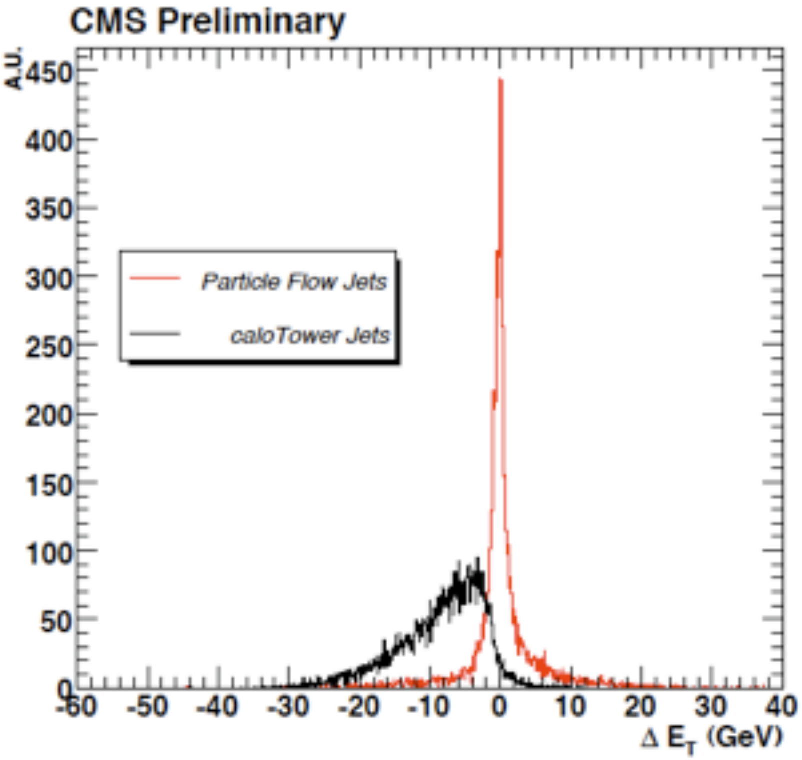

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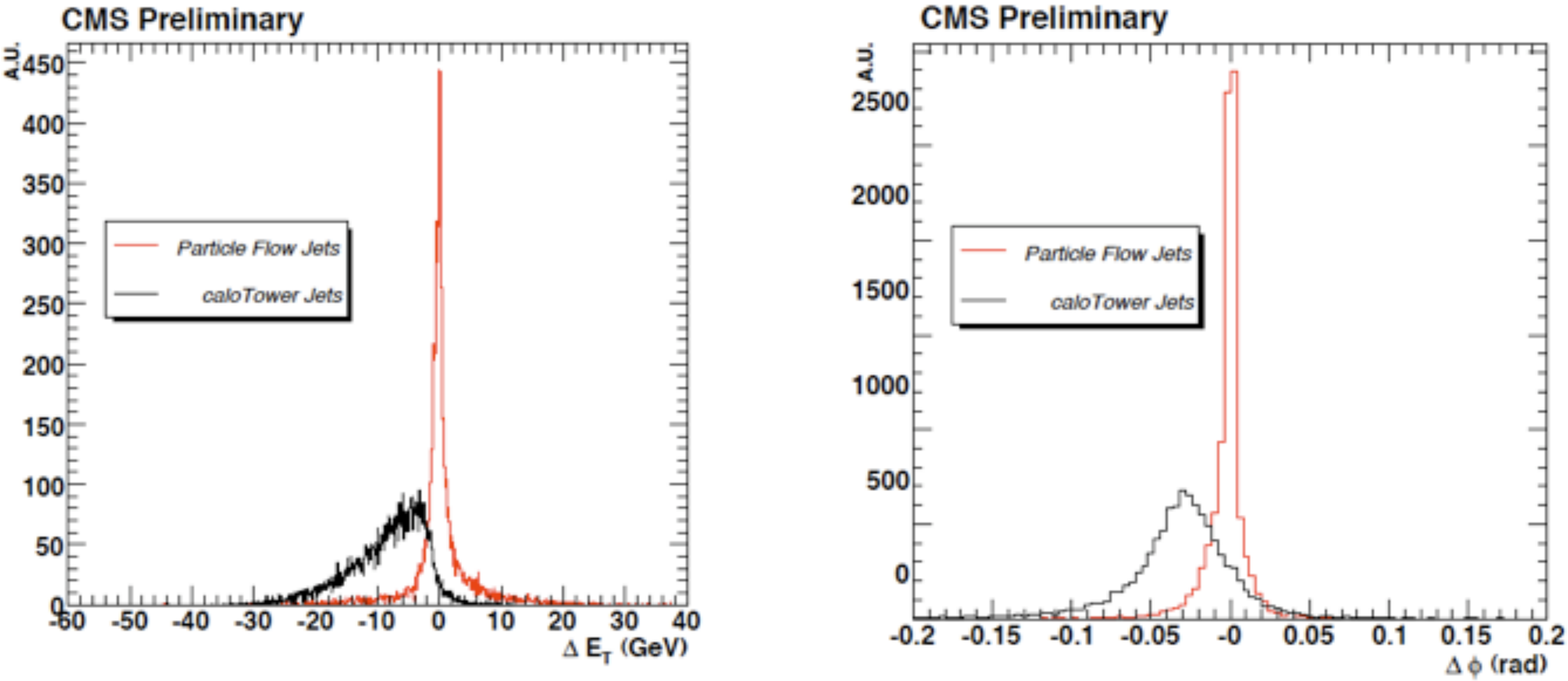

b-jet Identification

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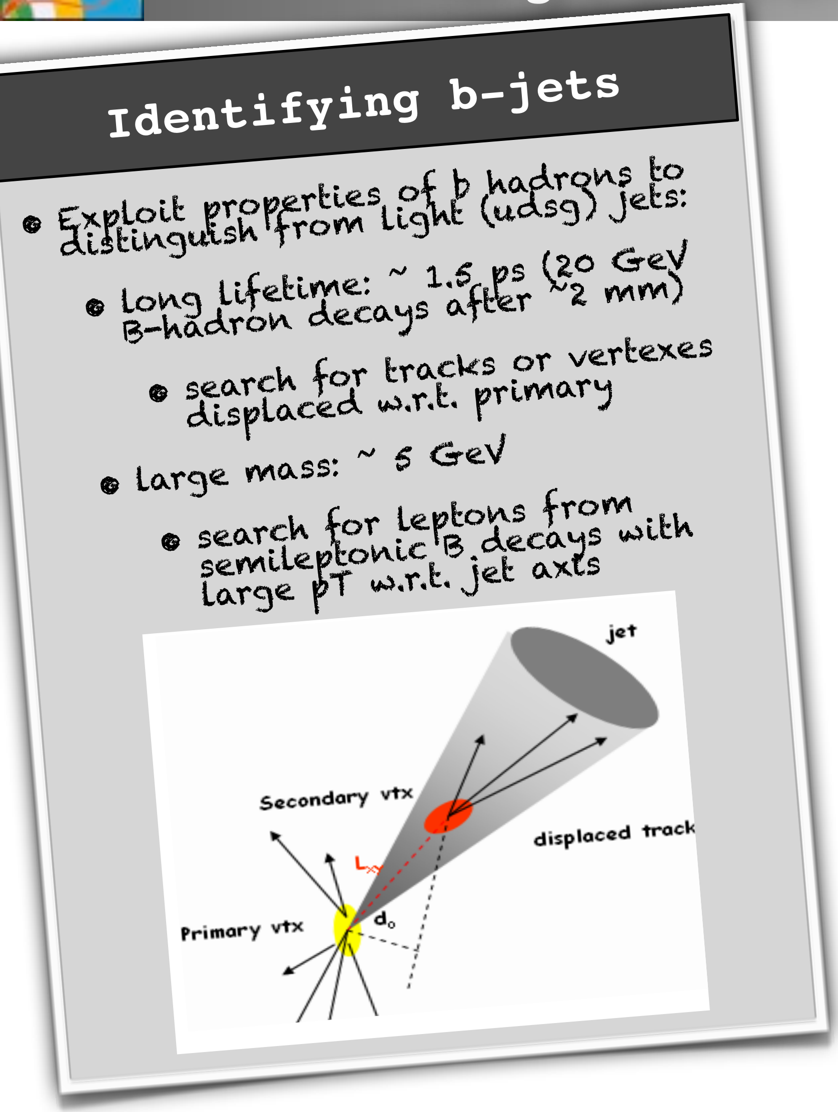

Identifying b-jets

- Exploit properties of b hadrons to distinguish from light (udsg) jets:
  - long lifetime: ~ 1.5 ps (20 GeV B-hadron decays after ~2 mm)
    - search for tracks or vertexes displaced w.r.t. primary
  - large mass: ~ 5 GeV
    - search for leptons from semileptonic B decays with large pT w.r.t. jet axis

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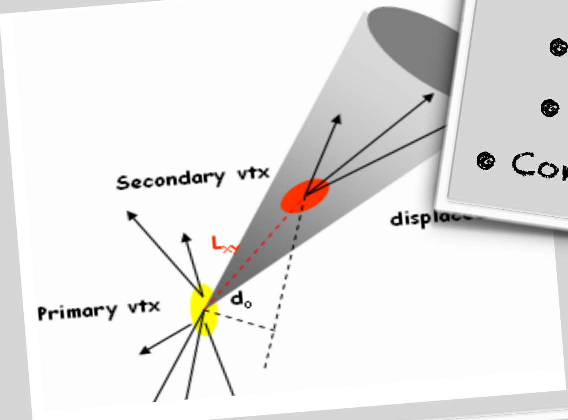

b-tagging Algorithms

- Impact parameter
  - Track counting
  - Jet (B)Probability
- Secondary Vertex based
  - Simple
  - Combined
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  - Soft muons by 3D IP
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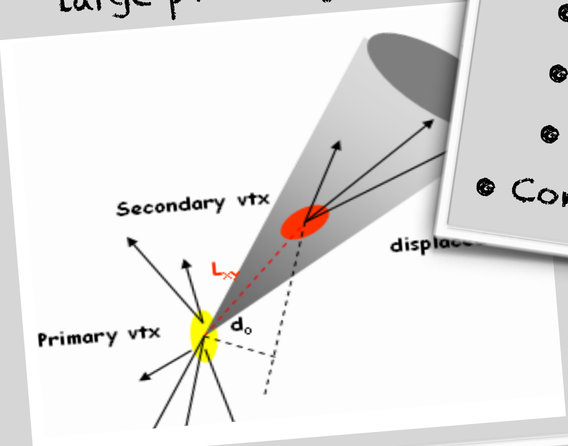

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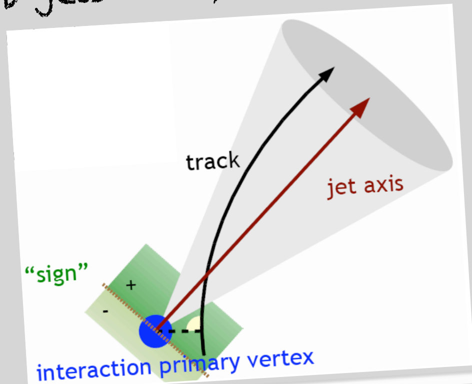

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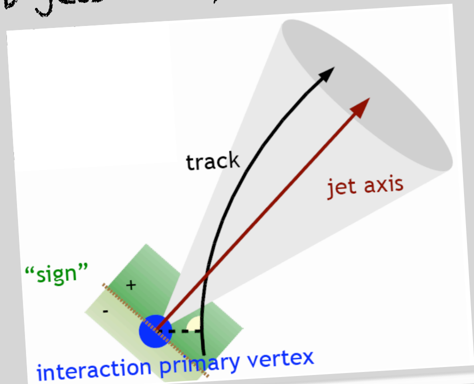
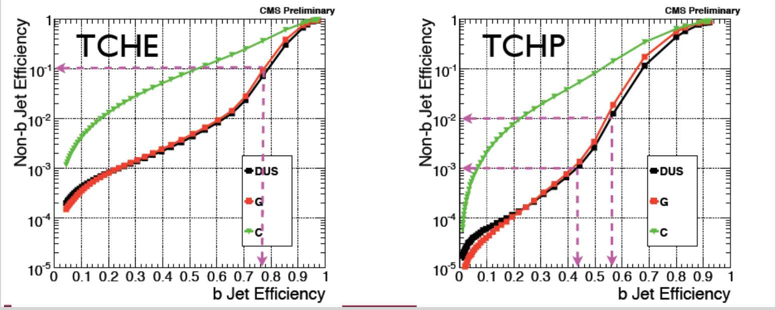


Track Counting

- Identify a jet as a "b-jet" if at least N tracks each with a 3D impact parameter significance exceeding some value S
  - for High efficiency, require only 2 such tracks
  - for High purity, require 3 such tracks



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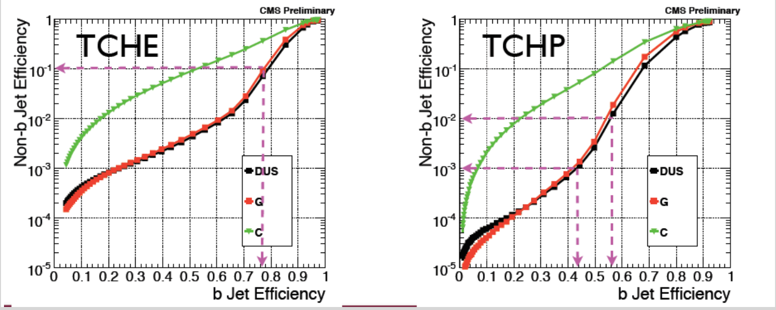
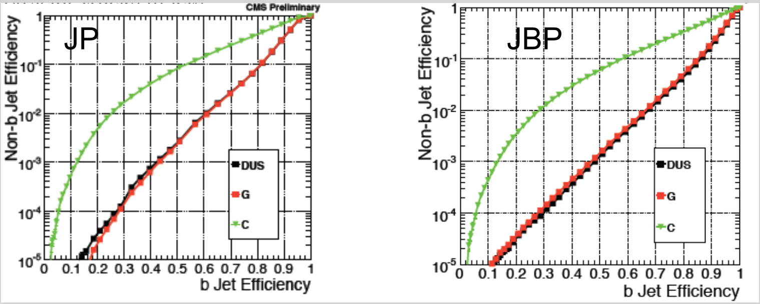


Jet [B] Probability

- Jet Probability
  - Determine the prob that each track in jet comes from PV
  - estimate combined prob that all tracks in jet come from PV
- Jet B Probability
  - Estimate how likely it is that the 4 most displaced tracks are compatible with the PV
  - Use "4" since the average track multiplicy in weak B hadron decays is 5 and average track



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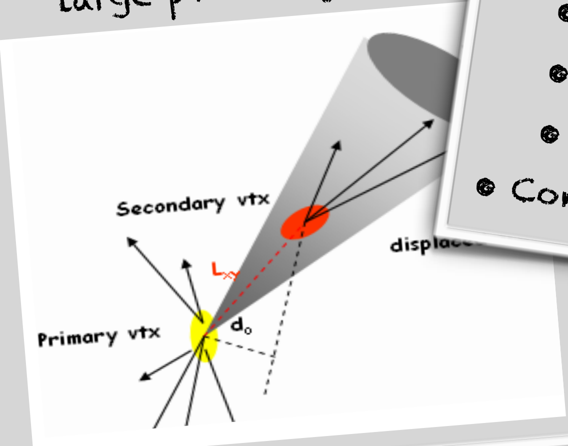

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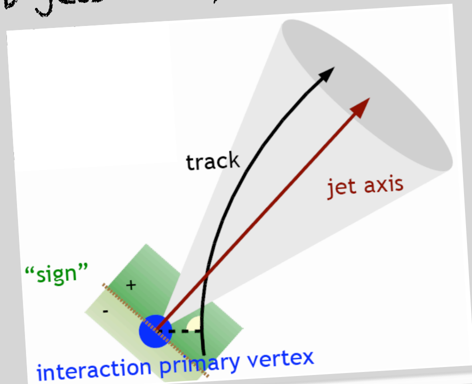

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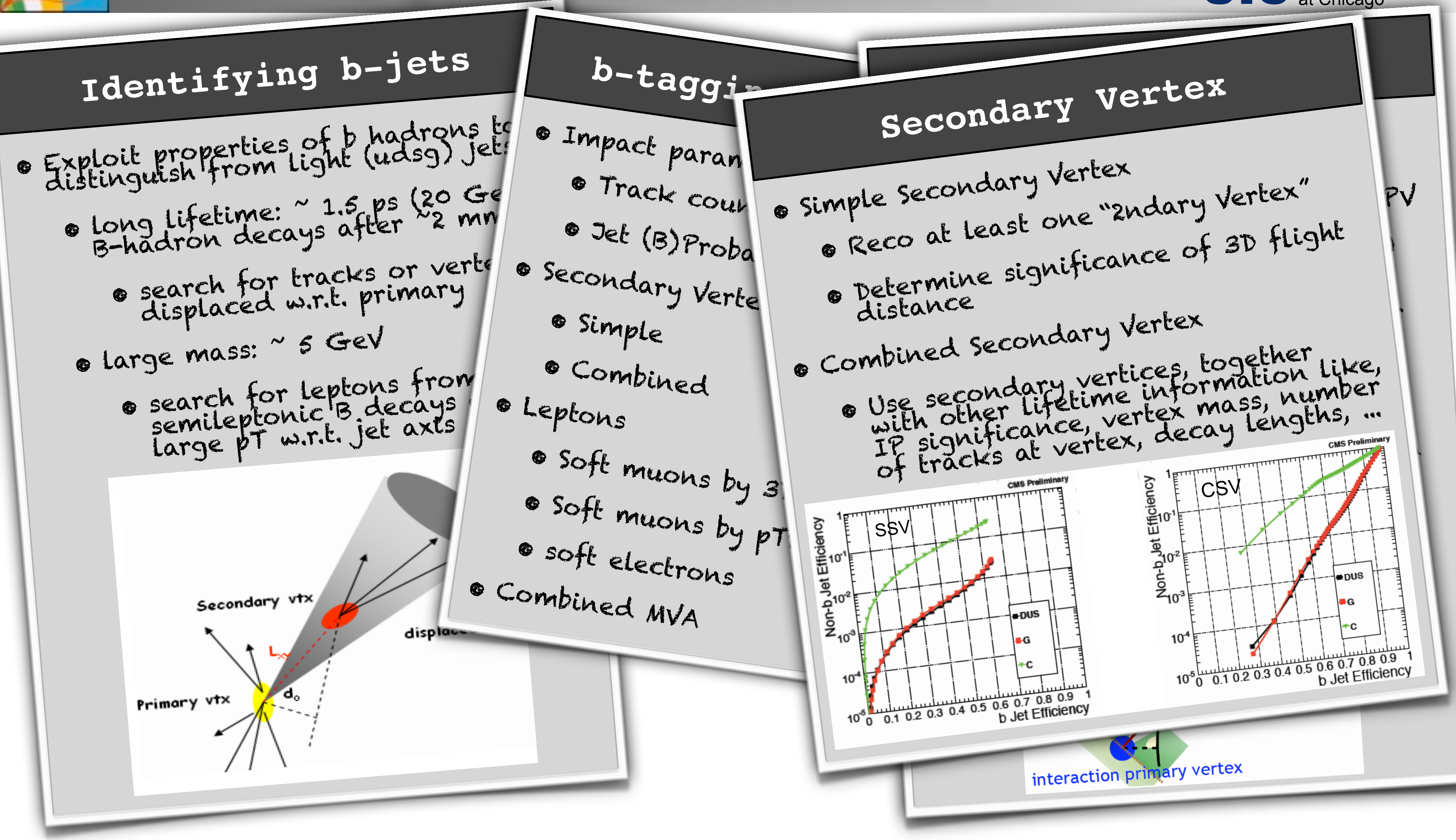

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Secondary Vertex

- Simple Secondary Vertex
  - Reco at least one “2ndary Vertex”
  - Determine significance of 3D flight distance
- Combined Secondary Vertex
  - Use secondary vertices, together with other lifetime information like, IP significance, vertex mass, number of tracks at vertex, decay lengths, ...

Date: 14.08.2012

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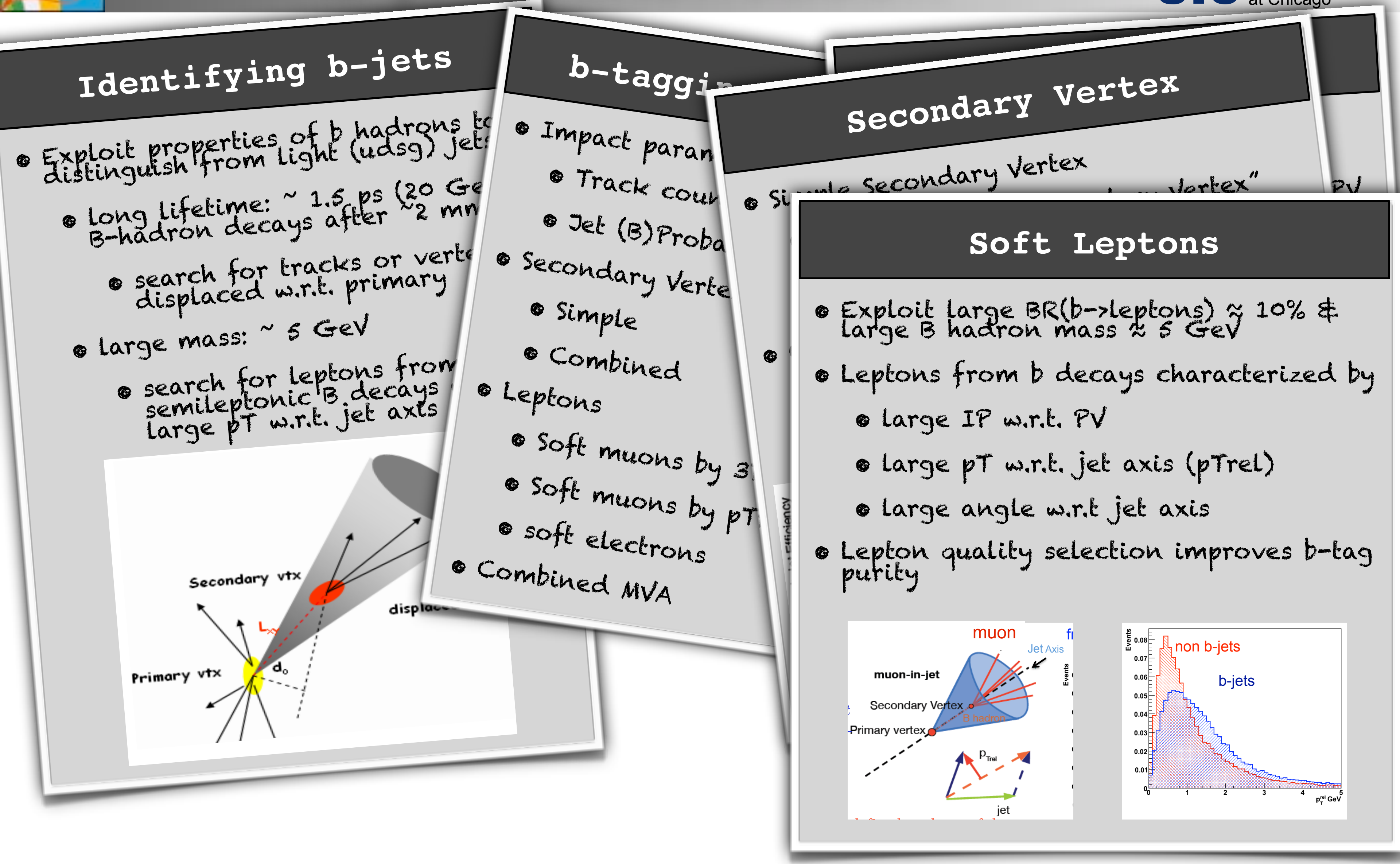

Identifying b-jets

- Exploit properties of b hadrons to distinguish from light (udsg) jets
  - long lifetime: ~ 1.5 ps (20 Ge B-hadron decays after ~2 mm
    - search for tracks or verte displaced w.r.t. primary
  - large mass: ~ 5 GeV
    - search for leptons from semileptonic B decays large pT w.r.t. jet axis

b-taggi

- Impact paran
  - Track cou
  - Jet (B)Proba
- Secondary Verte
  - Simple
  - Combined
- Leptons
  - Soft muons by 3
  - Soft muons by pT
  - soft electrons
- Combined MVA

Secondary Vertex

Simple Secondary Vertex

- Si Vertex" PV

Soft Leptons

- Exploit large BR(b->leptons) ≈ 10% & large B hadron mass ≈ 5 GeV
- Leptons from b decays characterized by
  - large IP w.r.t. PV
  - large pT w.r.t. jet axis (pTrel)
  - large angle w.r.t jet axis
- Lepton quality selection improves b-tag purity

R. Cavanaugh, HCPSS 2012

b-tag Efficiency & Fake Rates

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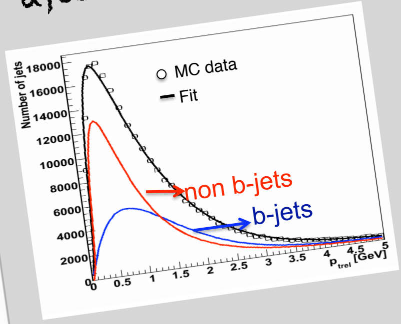
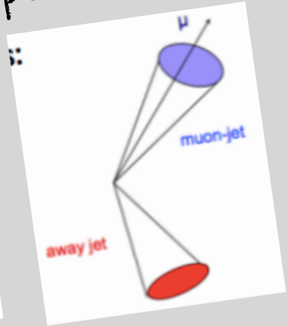
pTrel Method

- Based data samples with ≥ 2 jets + non-isolated muon close by
- Determine b-content by fitting the pTrel distribution of muon+jet to a linear combination of pTrel templates for b and non-b before and after tagging the muon+jet.
- b-tag efficiency calculates as ratio between the # of b-jets before and after tagging by the pTrel fits





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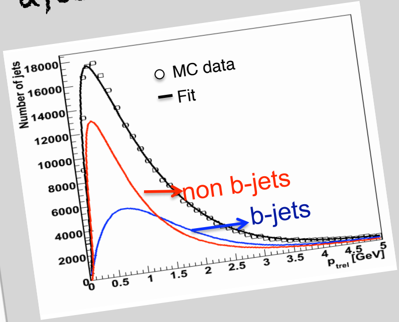
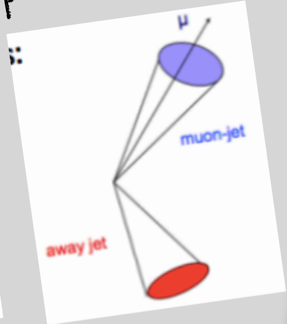
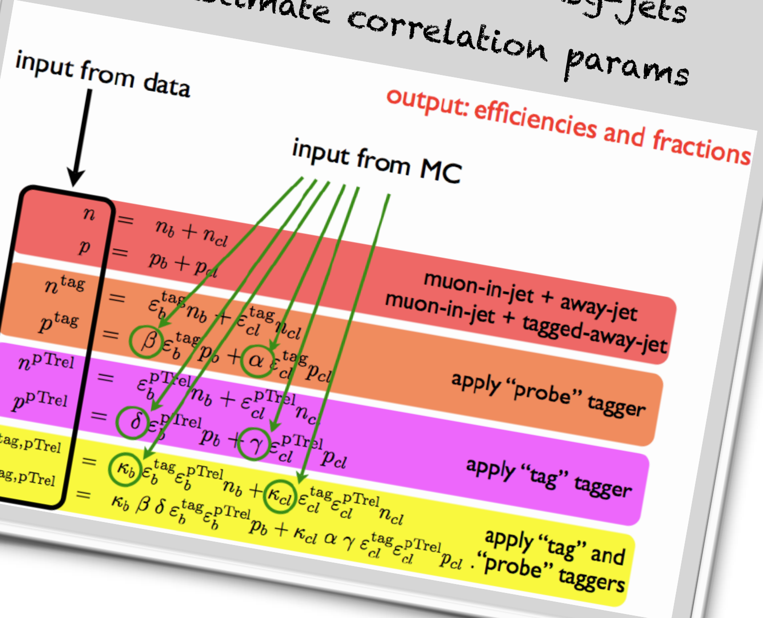




System8 Method

- Based on 2 independent b-taggers and 2 samples
  - muon-in-jet with away-jet
  - muon-in-jet with tagged-away-jet
- 2 categories: b-jets and udsg-jets
- MC to estimate correlation params



$$
\begin{aligned}
n &= n_b + n_{cl}\\
p &= p_b + p_{cl}\\
n^{\rm tag} &= \varepsilon_b^{\rm tag} n_b + \varepsilon_{cl}^{\rm tag} n_{cl}\\
p^{\rm tag} &= \boxed{\beta}\, \varepsilon_b^{\rm tag} p_b + \boxed{\alpha}\, \varepsilon_{cl}^{\rm tag} p_{cl}\\
n^{\rm pTrel} &= \varepsilon_b^{\rm pTrel} n_b + \varepsilon_{cl}^{\rm pTrel} n_{cl}\\
p^{\rm pTrel} &= \boxed{\delta}\, \varepsilon_b^{\rm pTrel} p_b + \boxed{\gamma}\, \varepsilon_{cl}^{\rm pTrel} p_{cl}\\
n^{\rm tag,pTrel} &= \boxed{\kappa_b}\, \varepsilon_b^{\rm tag} \varepsilon_b^{\rm pTrel} n_b + \boxed{\kappa_{cl}}\, \varepsilon_{cl}^{\rm tag} \varepsilon_{cl}^{\rm pTrel} n_{cl}\\
p^{\rm tag,pTrel} &= \kappa_b\, \beta\, \delta\, \varepsilon_b^{\rm tag} \varepsilon_b^{\rm pTrel} p_b + \kappa_{cl}\, \alpha\, \gamma\, \varepsilon_{cl}^{\rm tag} \varepsilon_{cl}^{\rm pTrel} p_{cl}\,.
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b-tag Efficiency & Fake Rates

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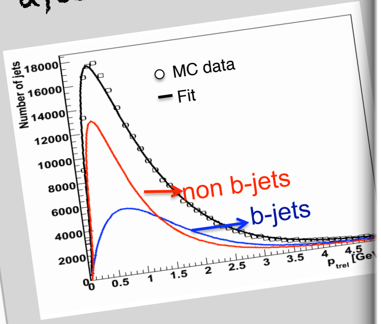

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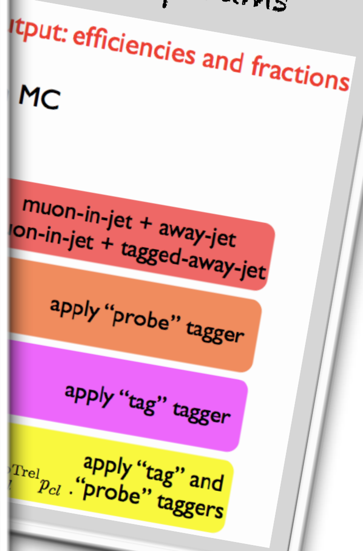


utput: efficiencies and fractions

MC

muon-in-jet + away-jet
on-in-jet + tagged-away-jet

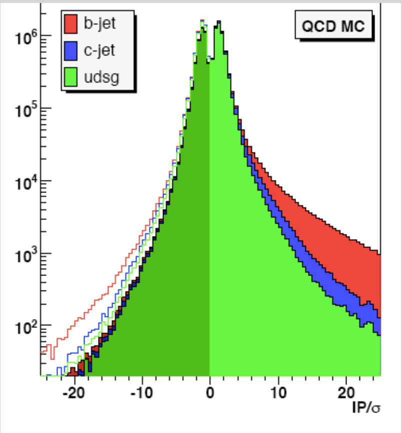
apply "probe" tagger

apply "tag" tagger

apply "tag" and "probe" taggers

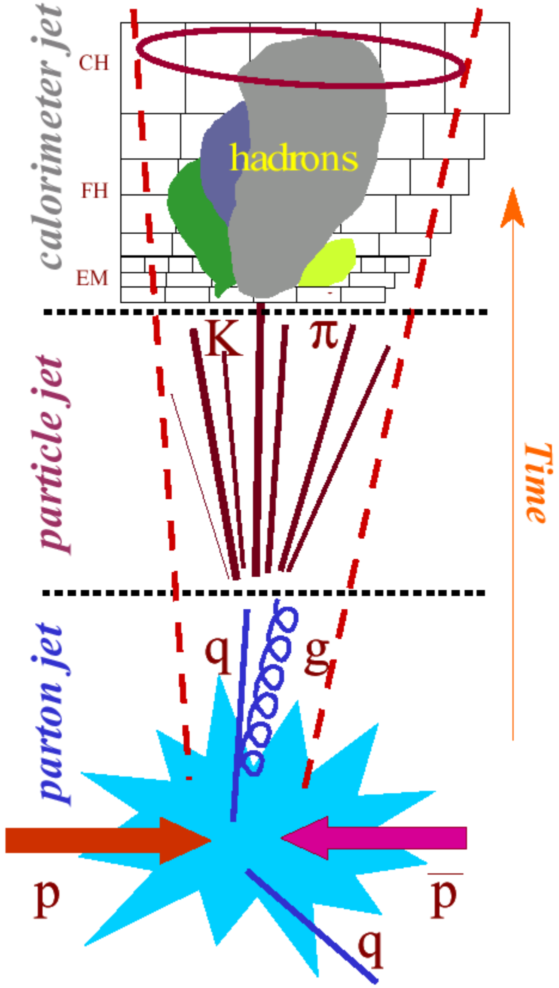
Mistag rates

- Look at tracks with negative IP
  - model mistag rate due to detector effects (resolutions, bad tracks, etc)
- Distribution of negative and positive discriminators should be approx. symmetric for udsg jets
  - small positive assymmetry due to K_S^0, Λ^0's, etc and displaced tracks from bad reconstruction

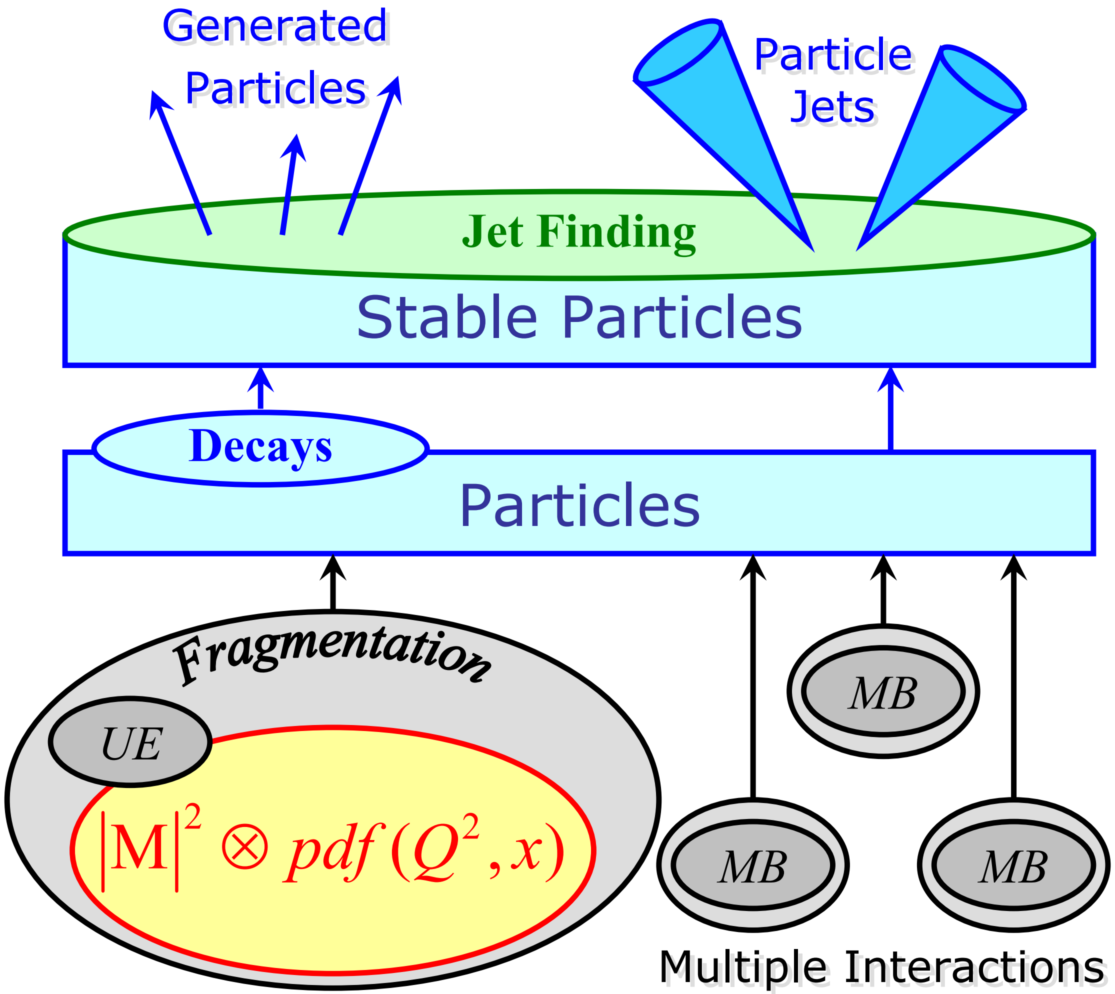


Jets

Experiment ("Nature")



Modeling Particle Jets



Clustering particles to Jets

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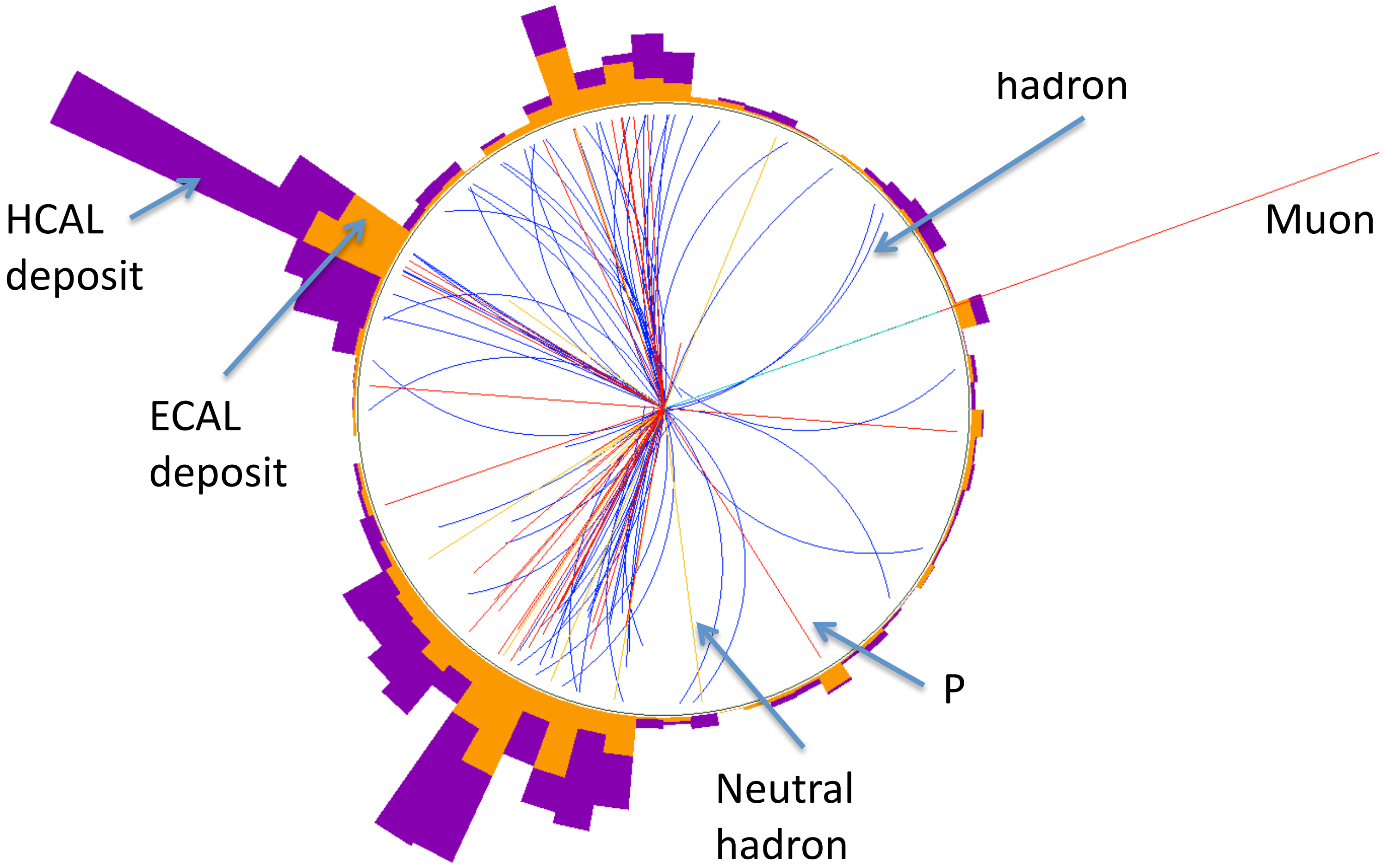

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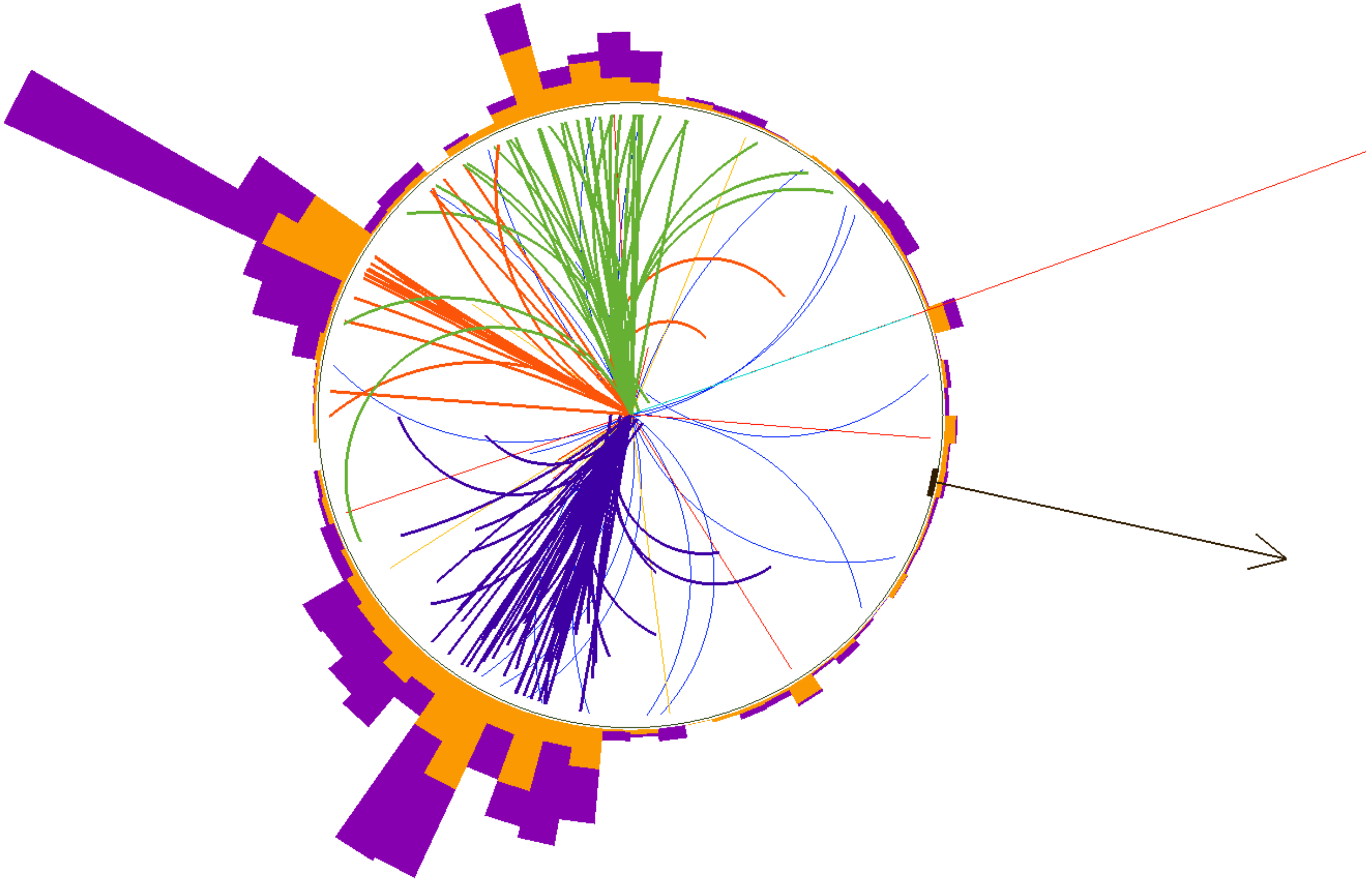
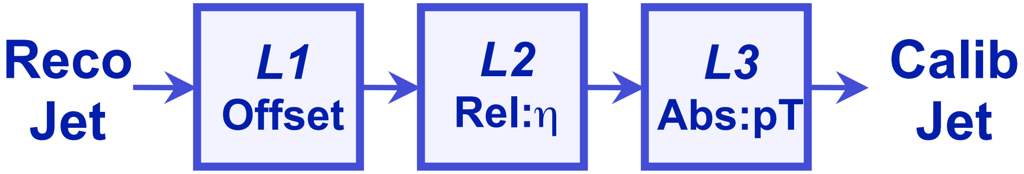


Jet Energy Corrections

Reco Jet → ***L1* Offset** → ***L2* Rel:η** → ***L3* Abs:pT** → **Calib Jet**

Jet Energy Corrections

1. **Offset:** removal of pile-up.



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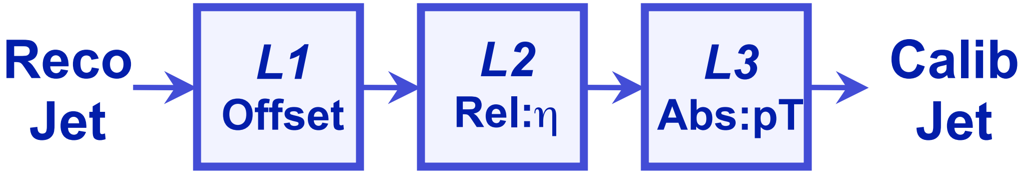

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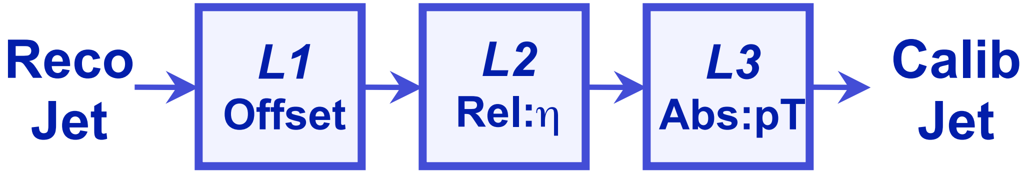

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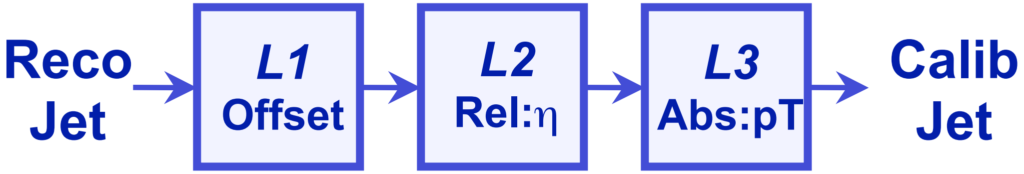

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$$\boxed{E^{\mathrm{corrected}} = (E^{\mathrm{raw}} - E_{\mathrm{offset}}) \times C(\mathrm{Rel}{:}\eta) \times C(\mathrm{Abs}{:}p_T)}$$

Offset Corrections: Pile-up

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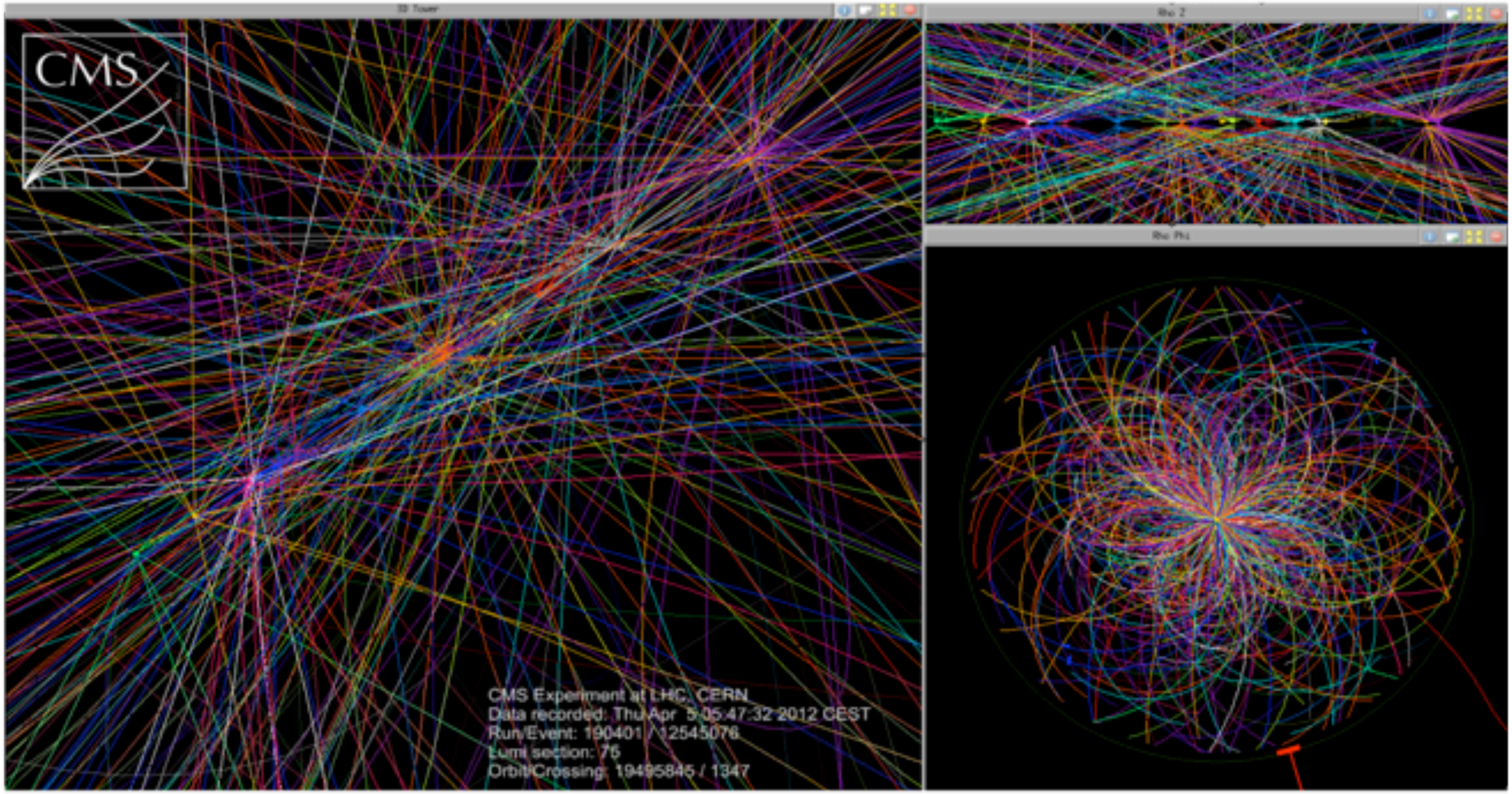

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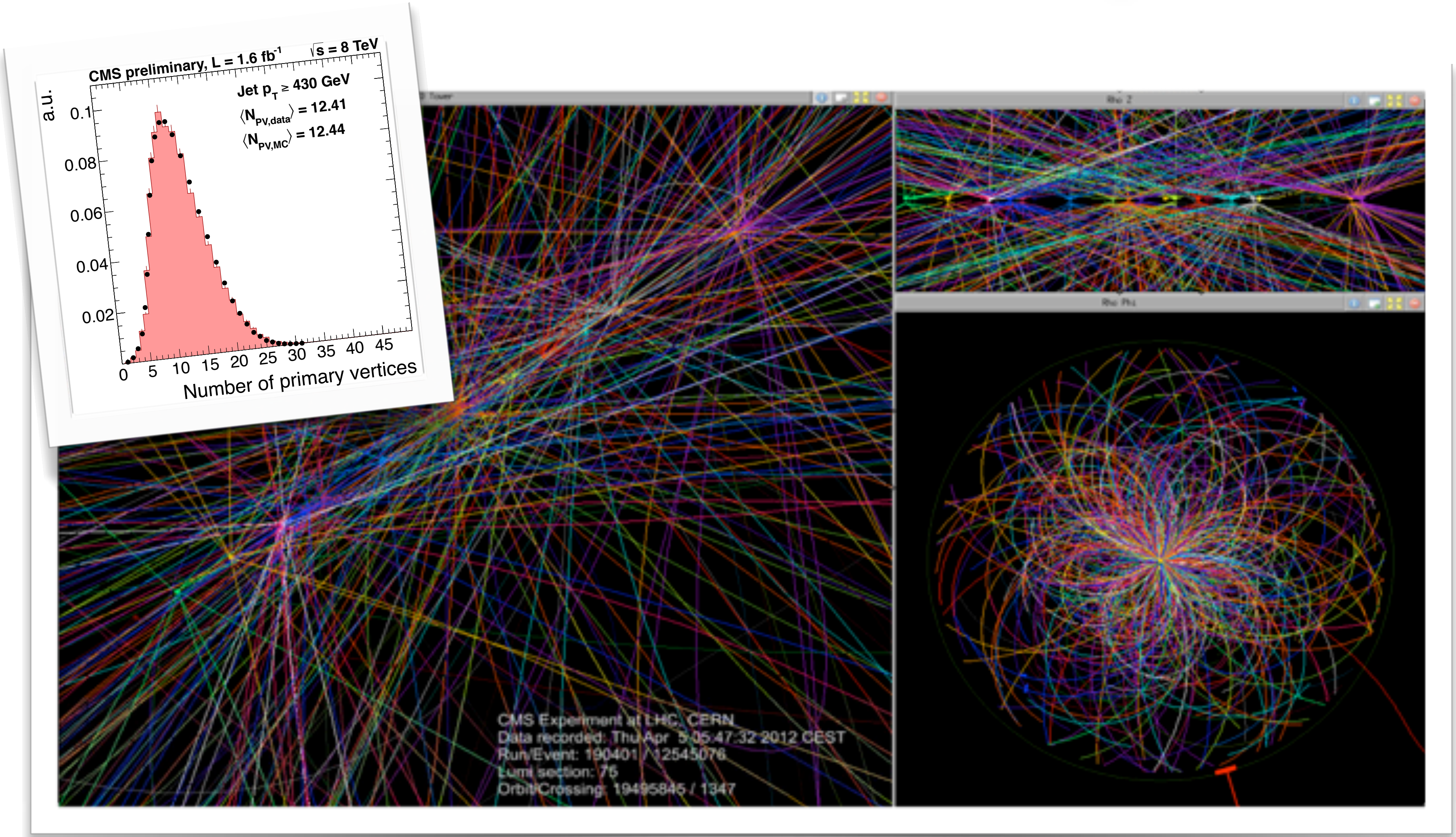

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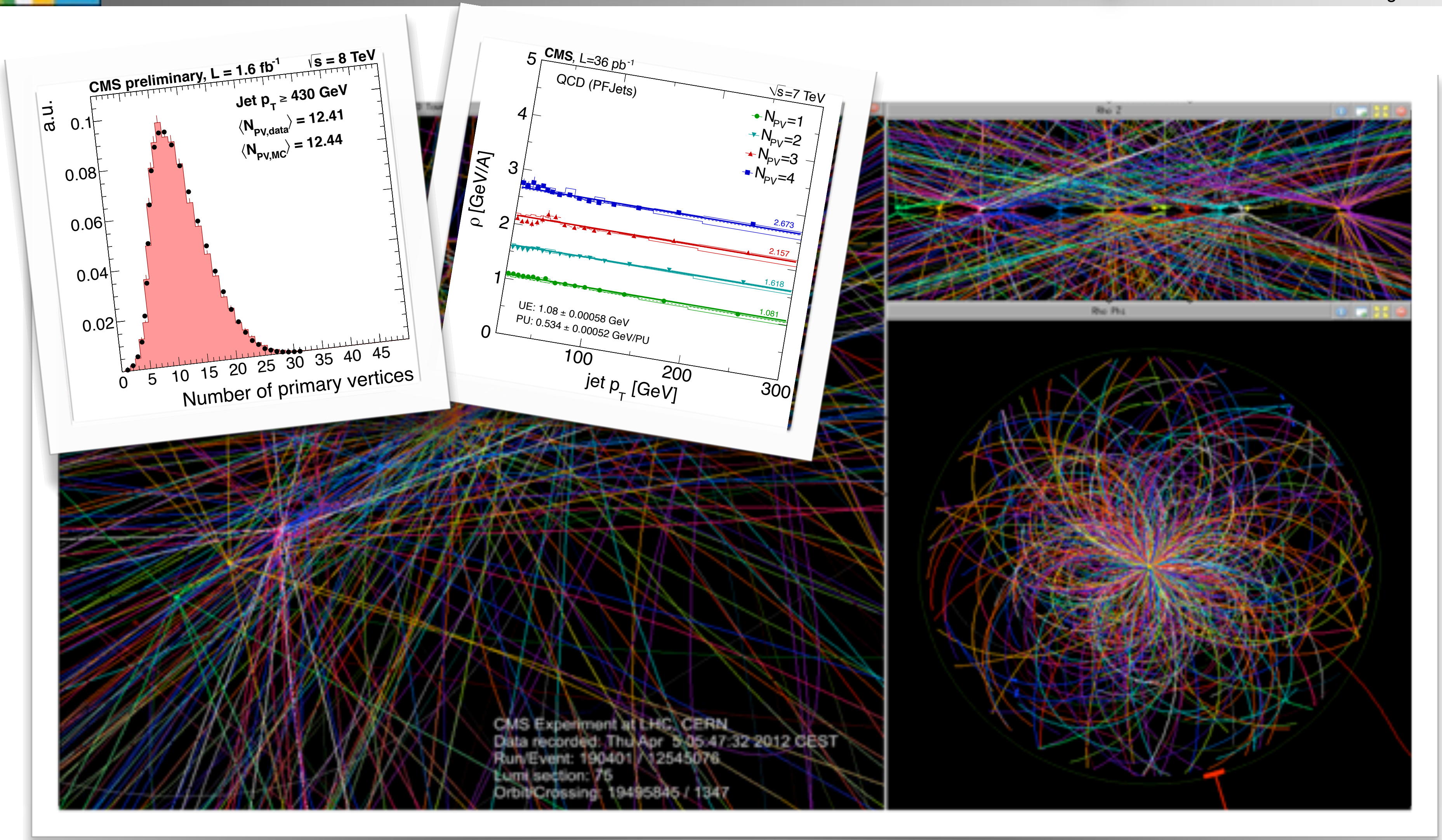

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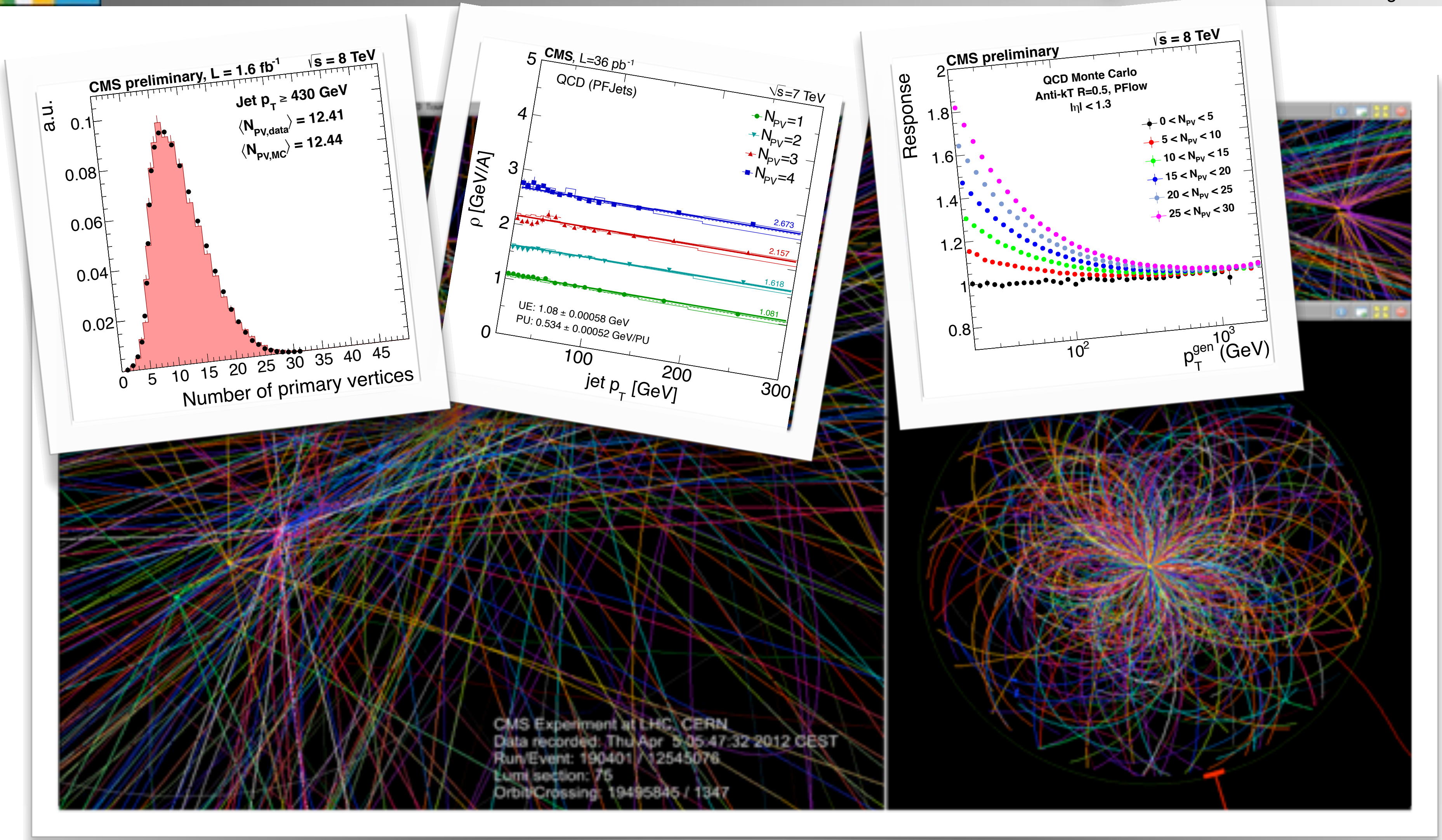

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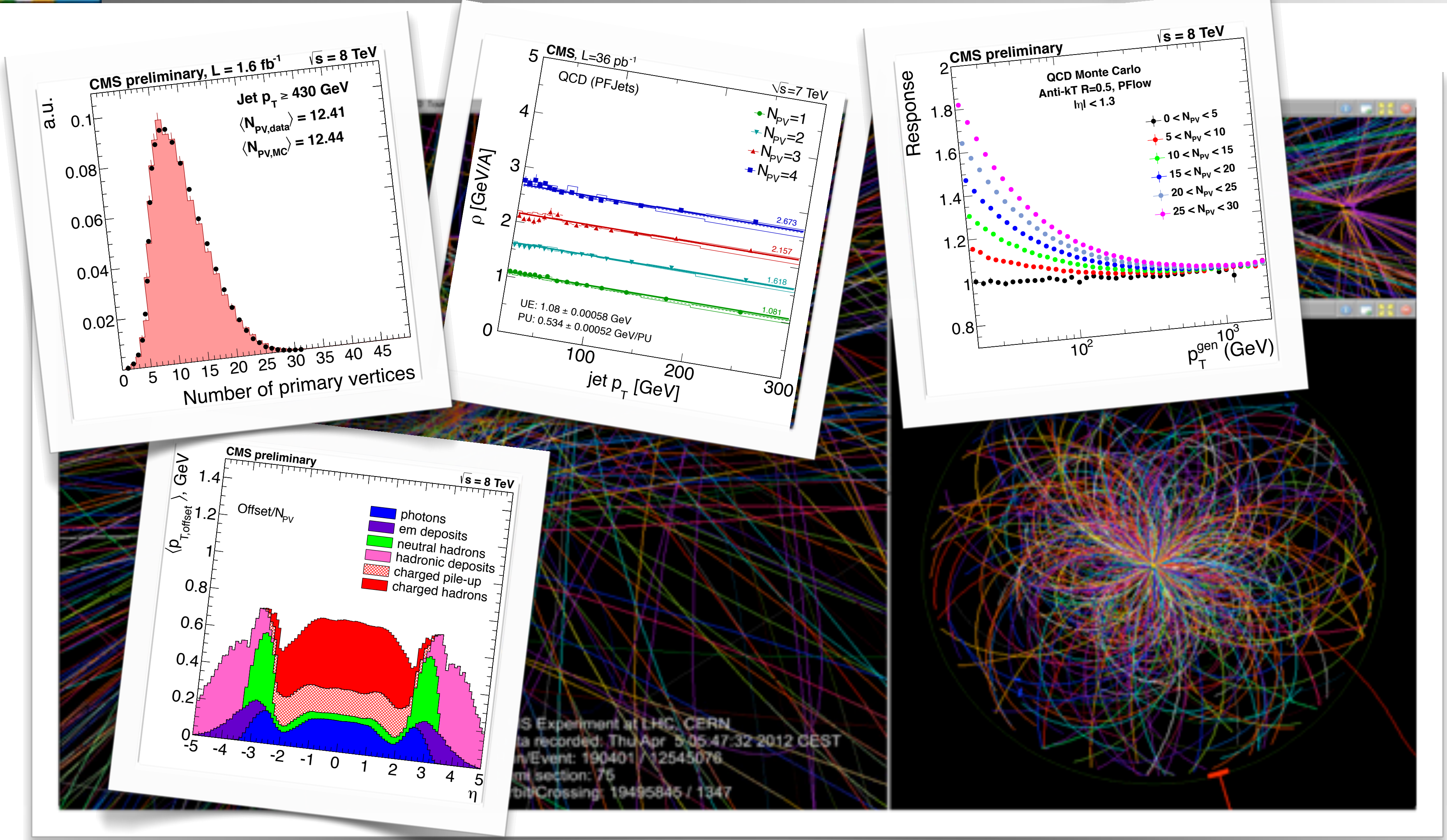

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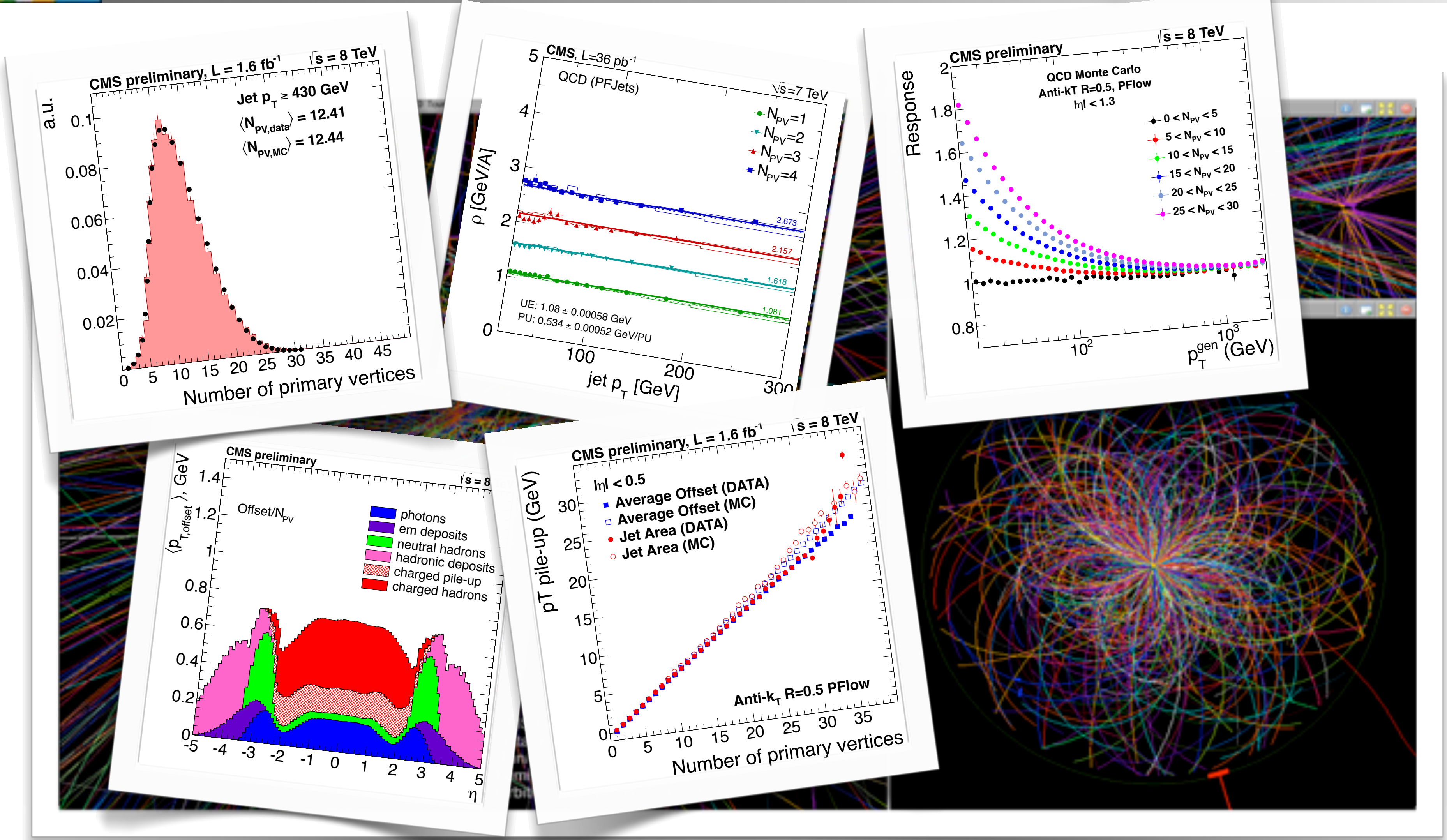

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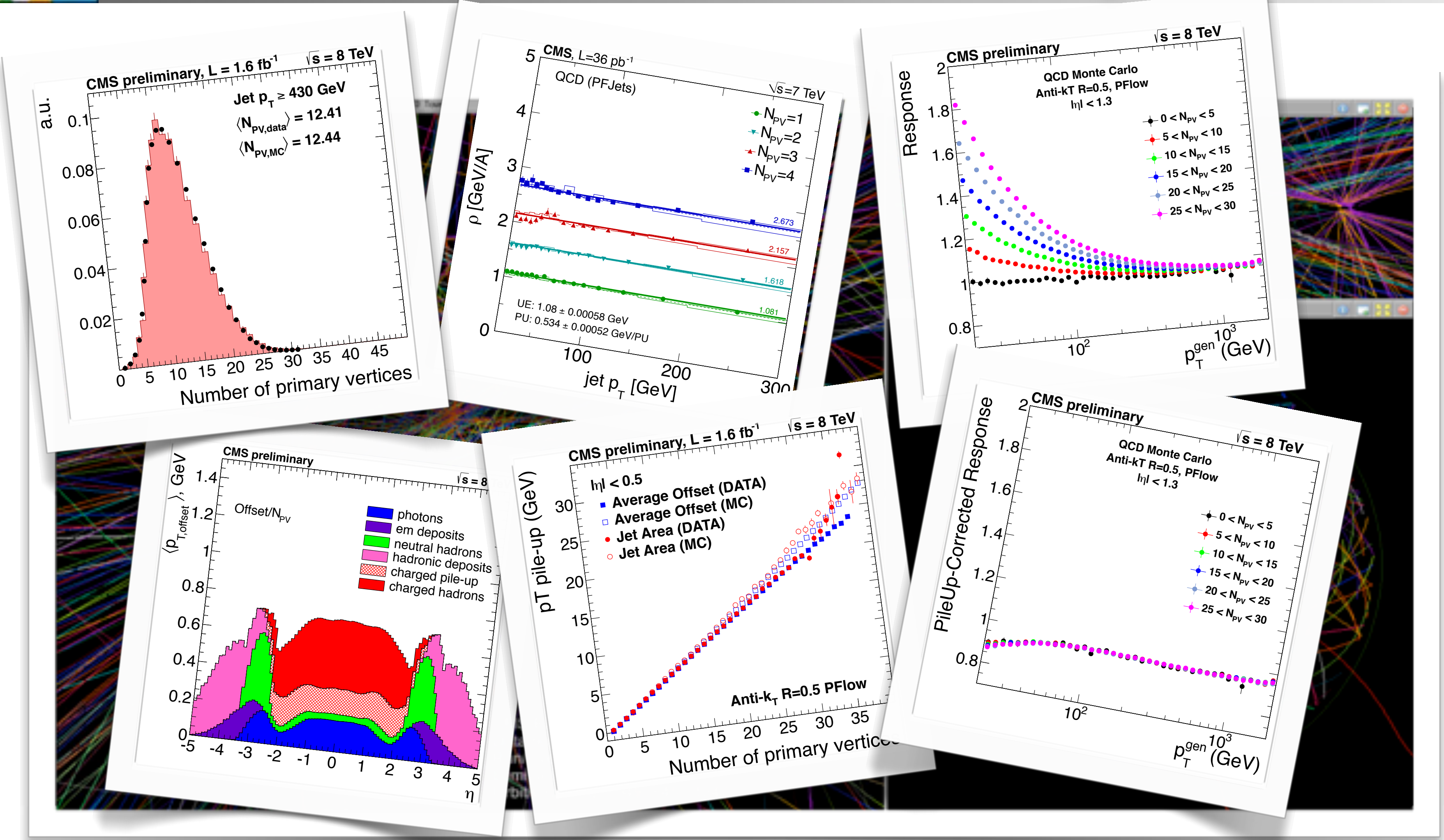

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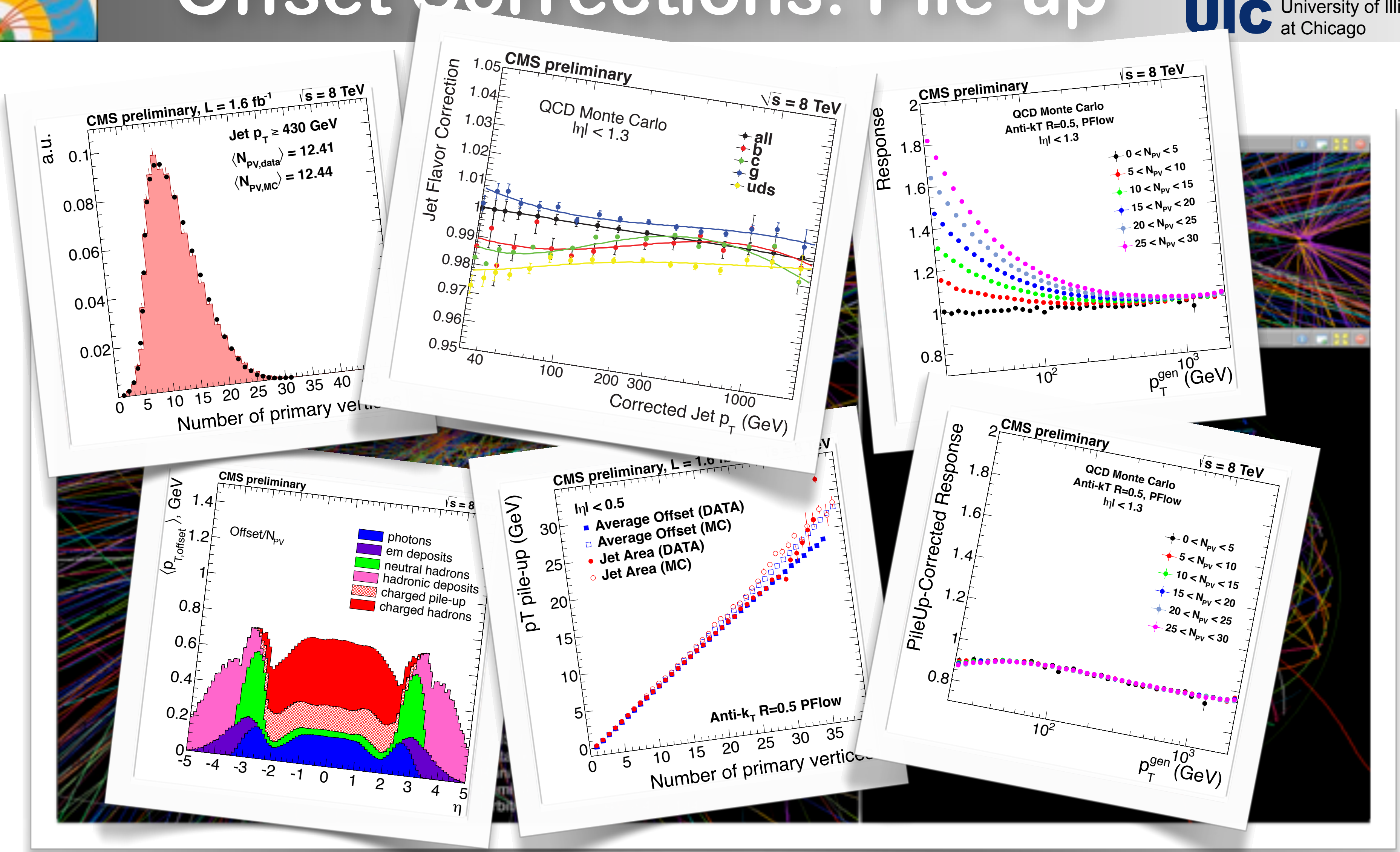

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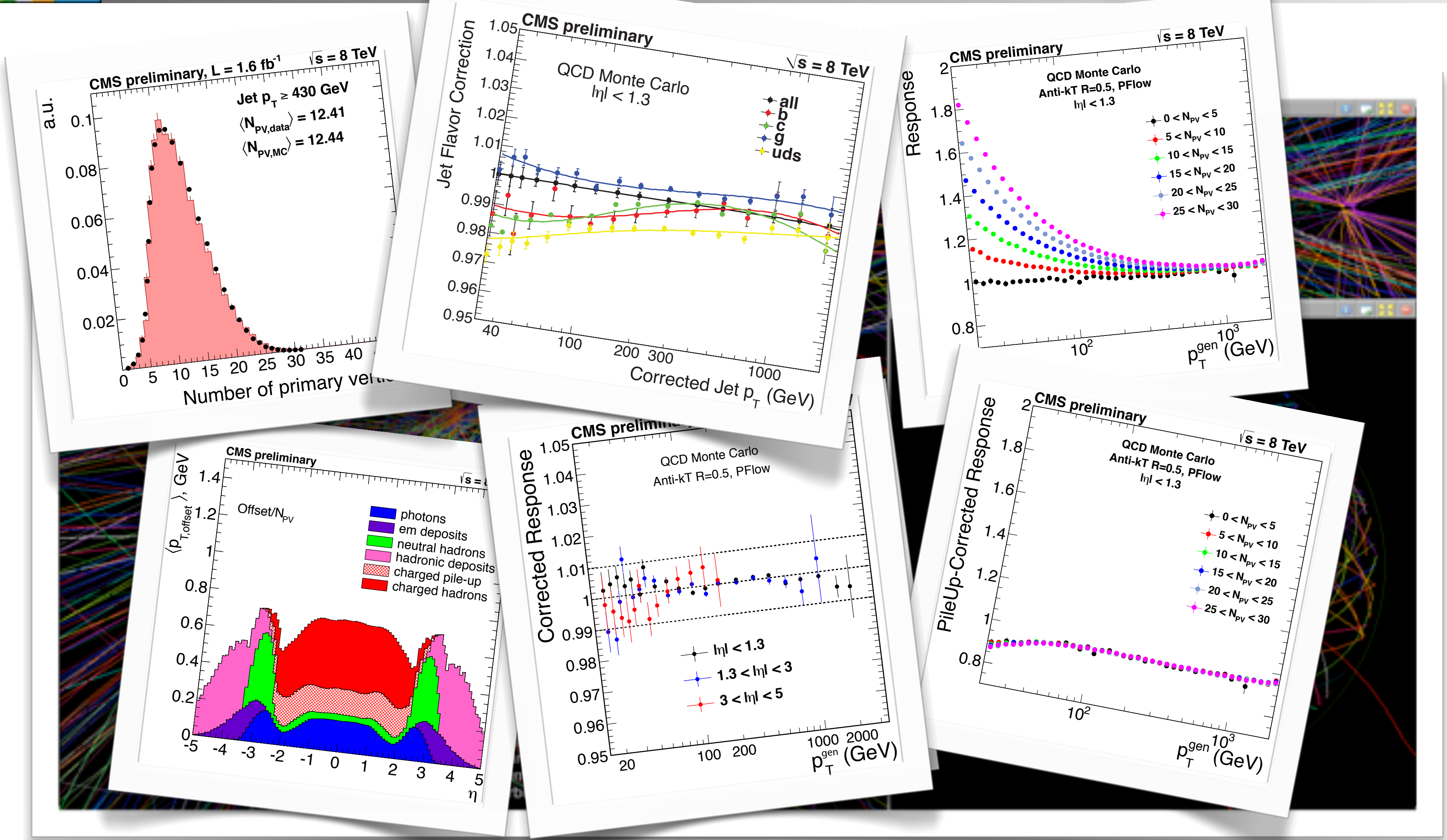

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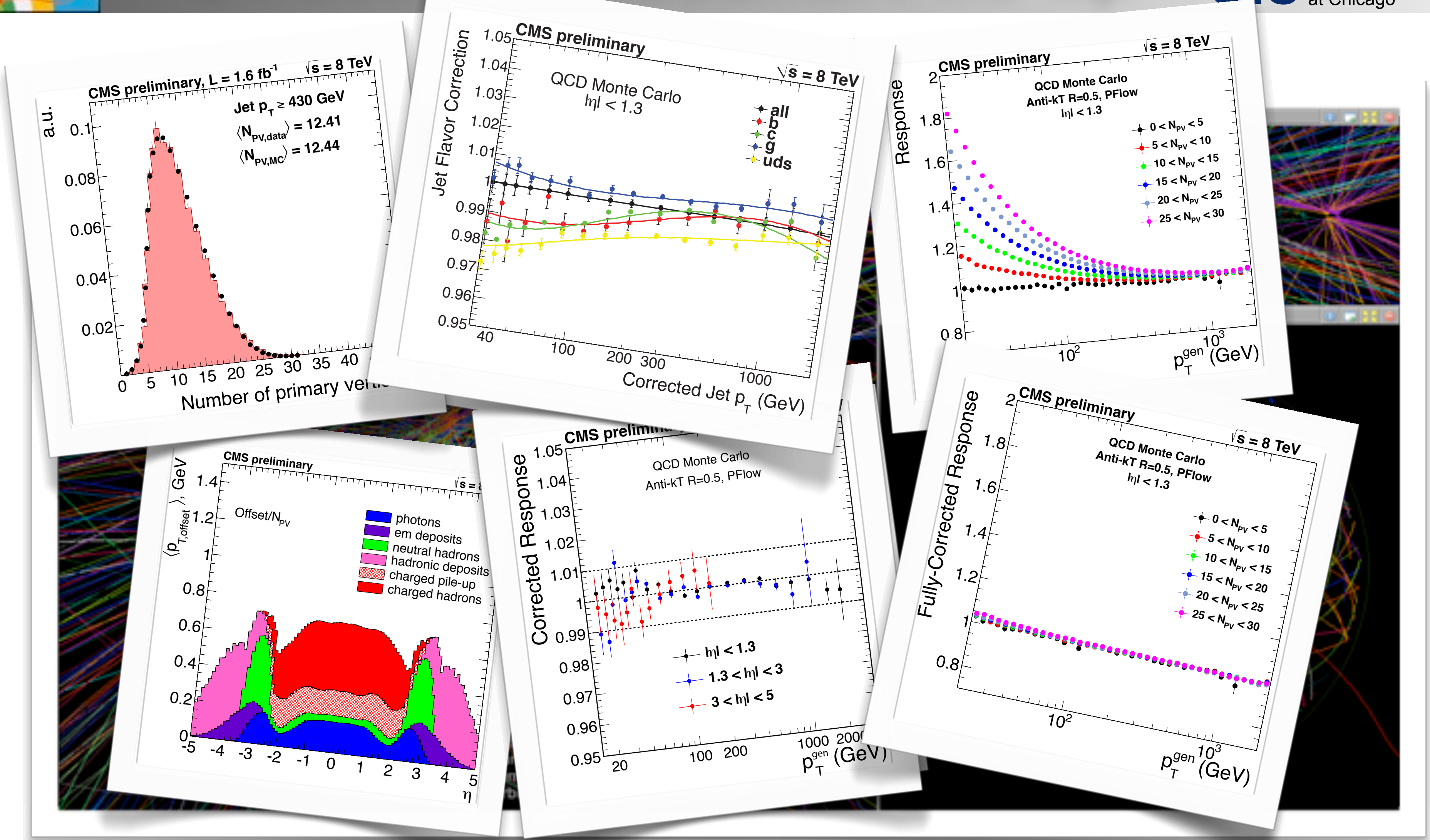

Relative Jet Energy Scale

Relative Jet Energy Scale

Dijet balancing

- Relative correction (vs η): flatten relative response vs η
- Extract relative jet response with respect to barrel
- Use of 2→2 di-jet process

$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle}$$

$$c(\eta, \langle p_T^{probe} \rangle) = \frac{1}{r(\eta, \langle p_T^{probe} \rangle)}$$

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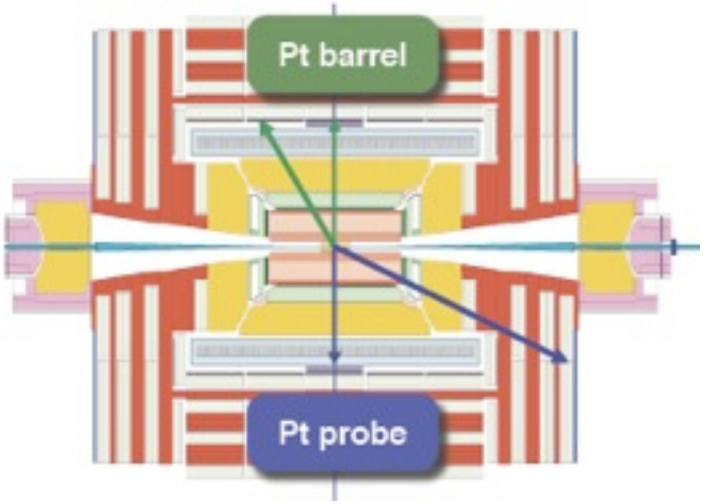

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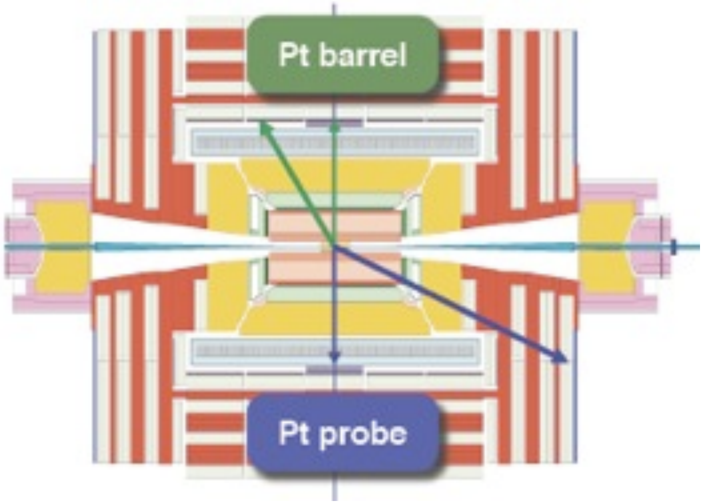

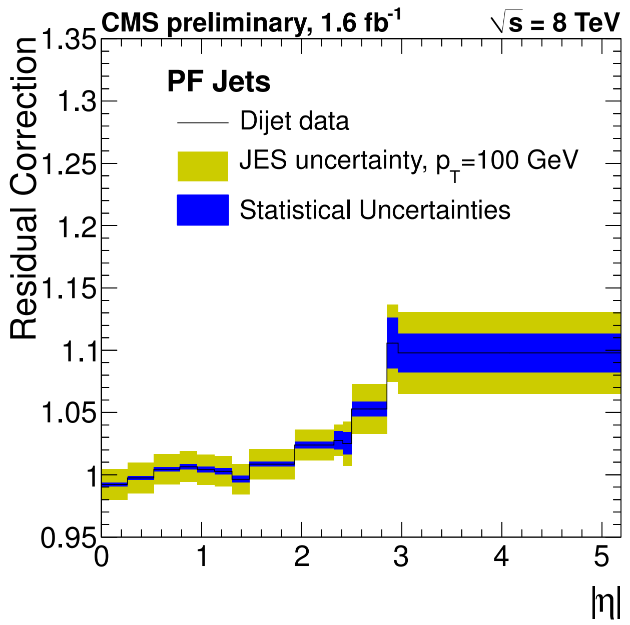

Absolute Jet Energy Scale

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Photon-jet balancing

- Absolute (pT) correction: flatten absolute response variation vs pT
  - Balance in transverse plane
- γ + jet
  - Isolation + topological selection
  - High σ, needed for large pT corrections
- Z→ee + jet, Z→$\mu\mu$ + jet
  - Z reco + topological selection
  - Clean, smaller systematics at low pT
- Problems with back-to-back balancing:
  - "Out of cone" parton showering
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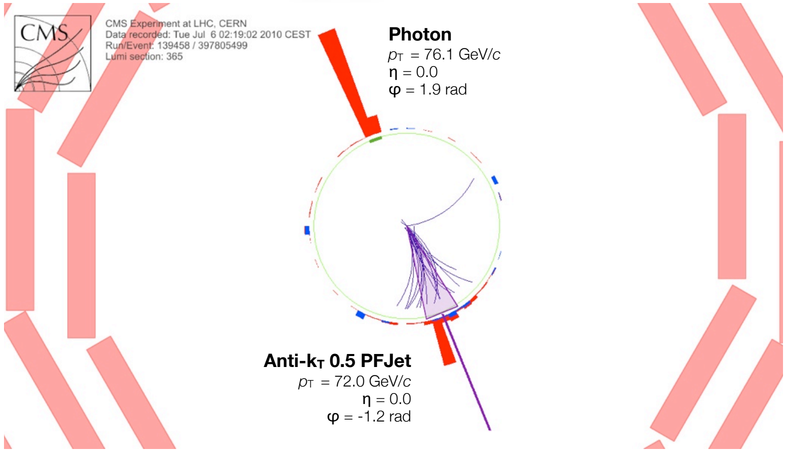

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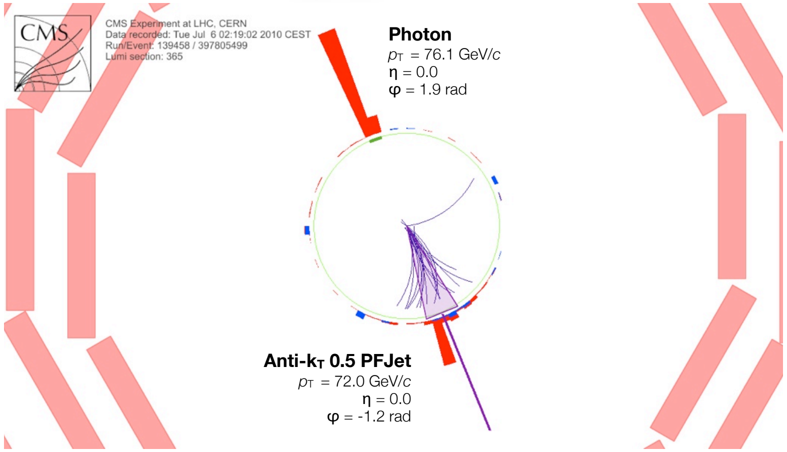

Missing ET Projection Fraction

- Idea: hadronic recoil and true photon pT perfectly balanced → interpret response of hadronic recoil as response of leading jet

$$\begin{aligned} \vec{p}_T^{\,\mathrm{recoil}} + \vec{p}_T^{\,\gamma} &= 0 \\ R_{\mathrm{recoil}}\, \vec{p}_T^{\,\mathrm{recoil}} + \vec{p}_T^{\,\gamma} &= -\vec{\not{E}} \\ R_{\mathrm{recoil}} &= 1 + \frac{\vec{\not{E}} \cdot \vec{p}_T^{\,\gamma}}{|\vec{p}_T^{\,\gamma}|^2} \end{aligned}$$

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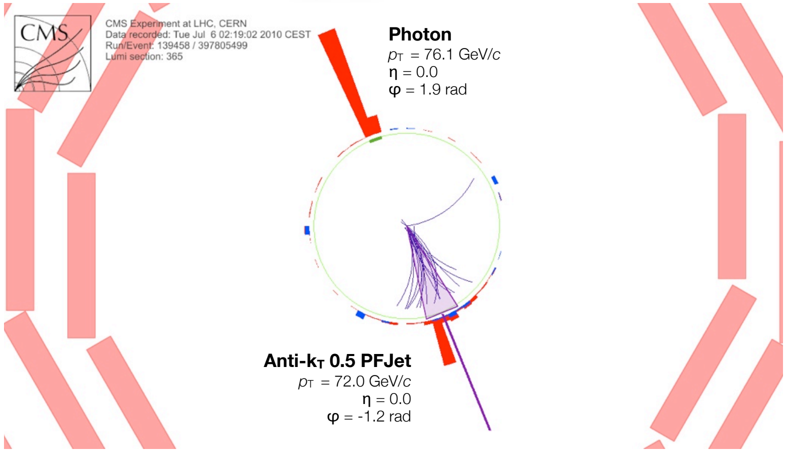

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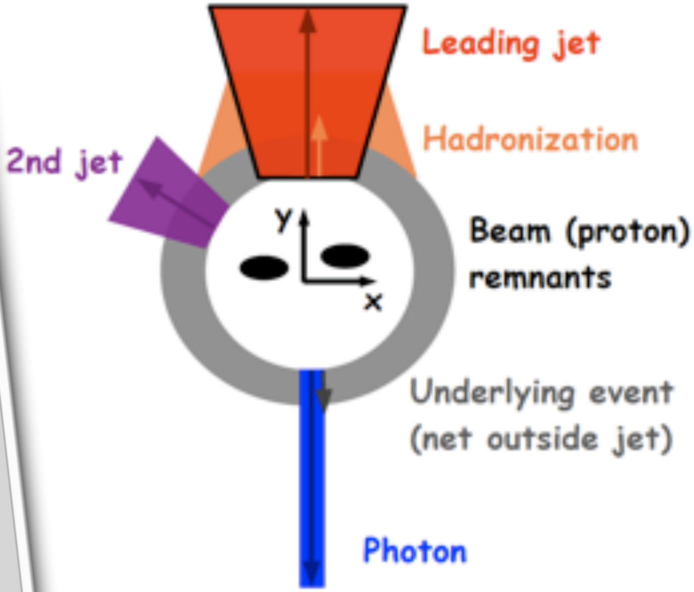

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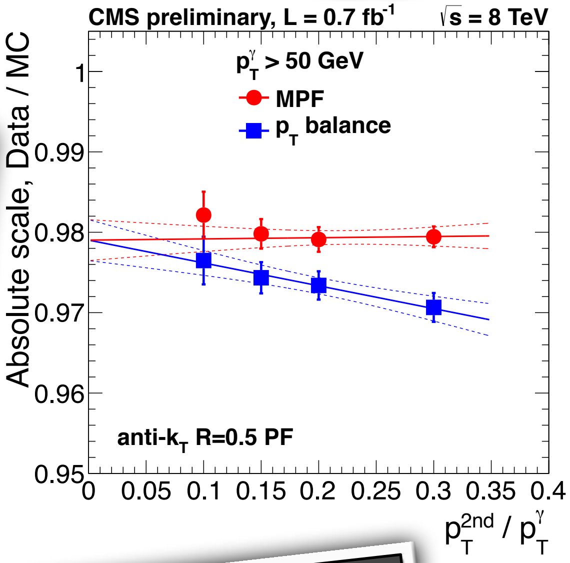

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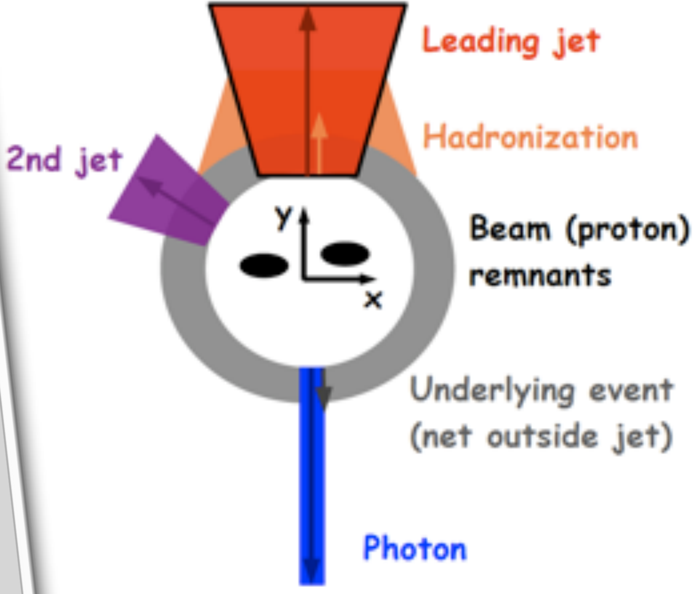

Absolute Jet Energy Scale

Fermilab
UIC University of Illinois at Chicago

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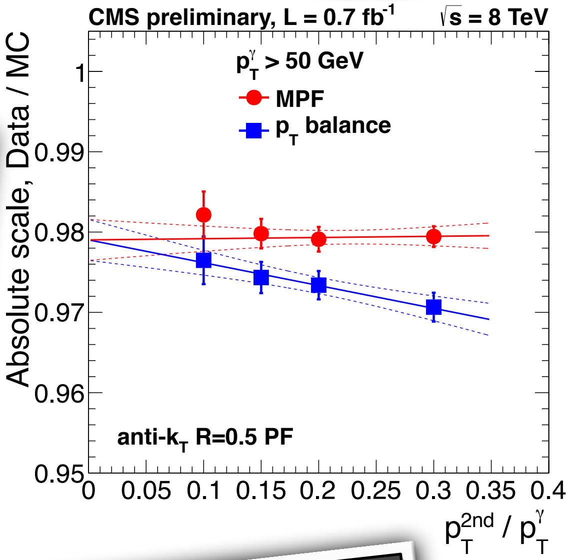
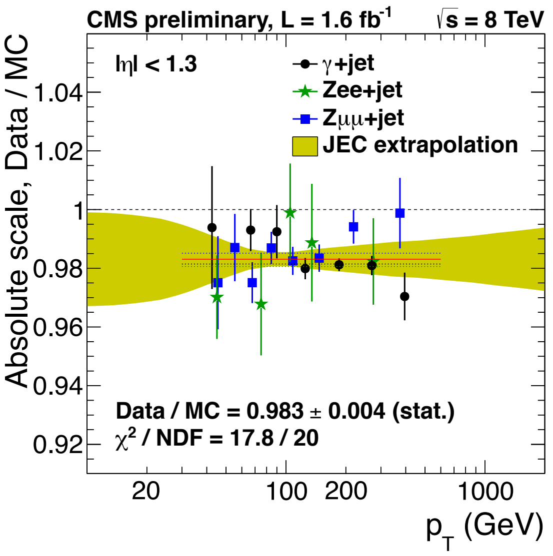
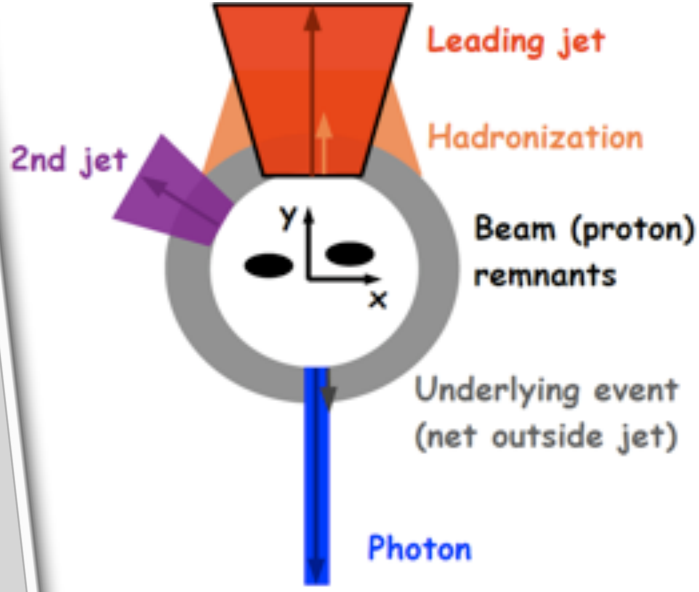
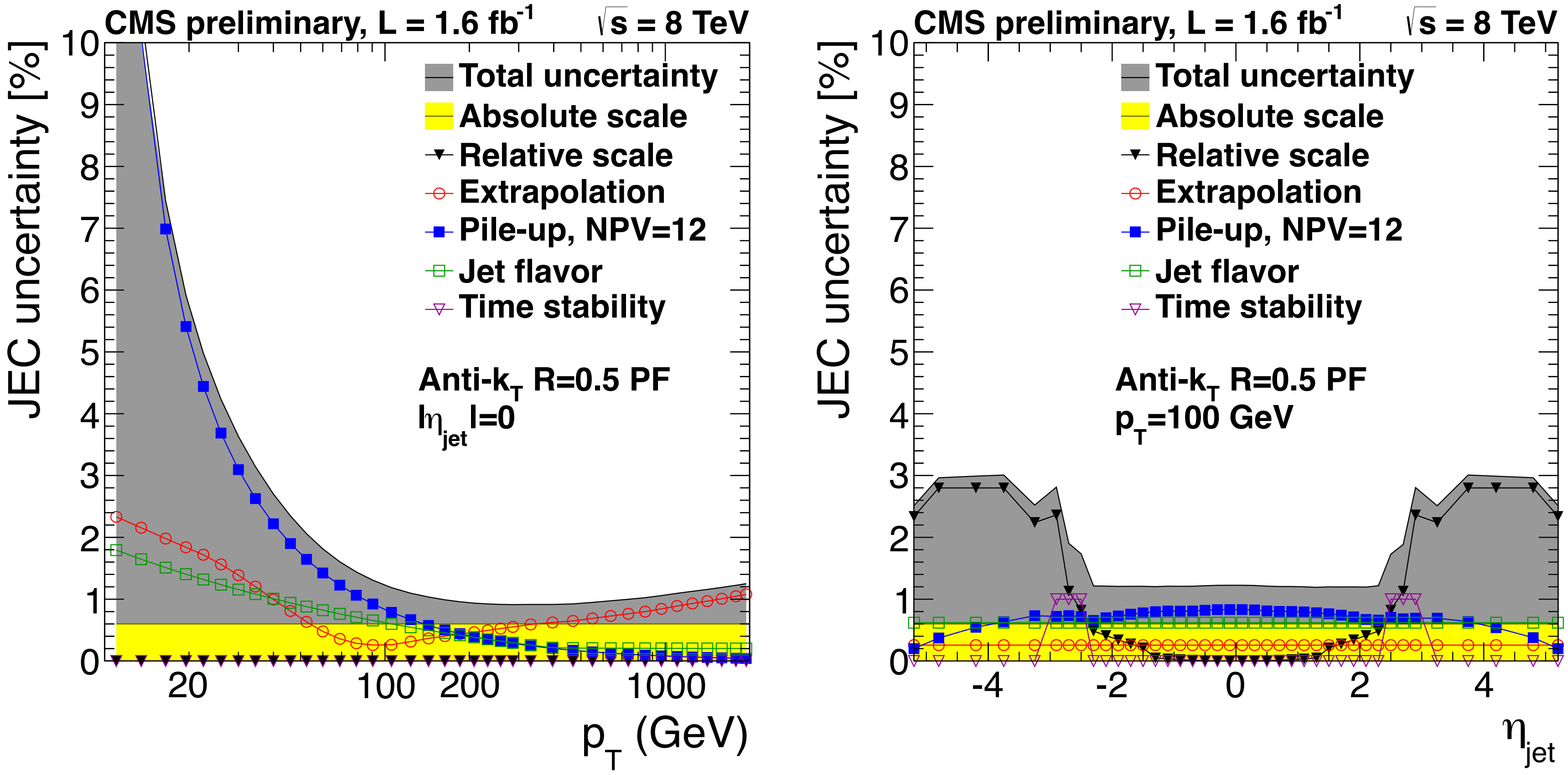




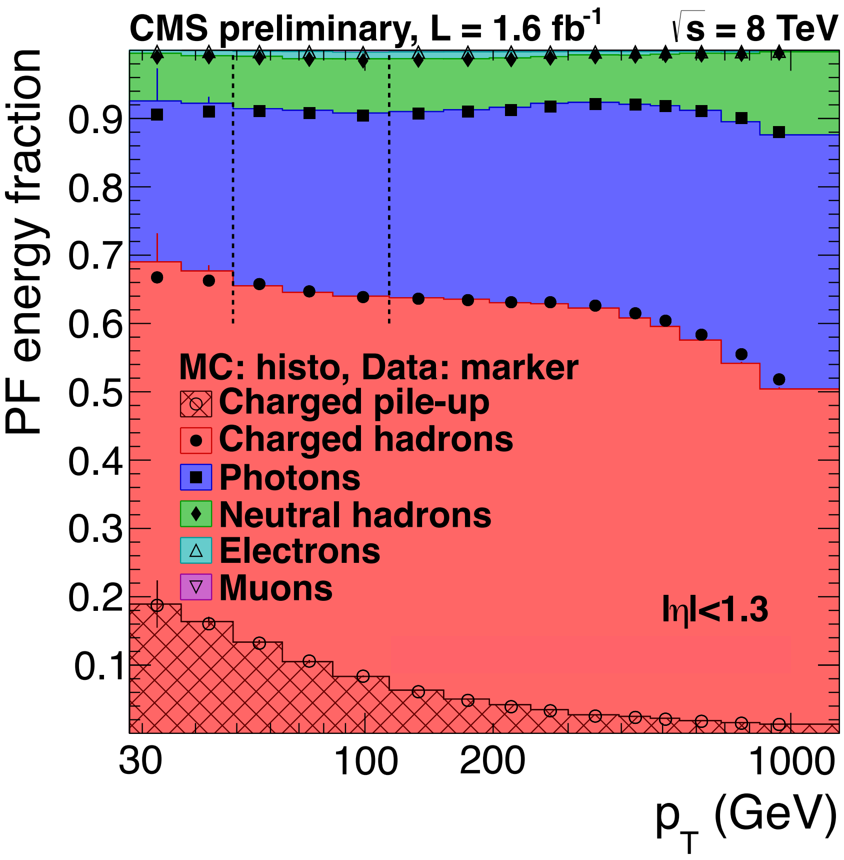


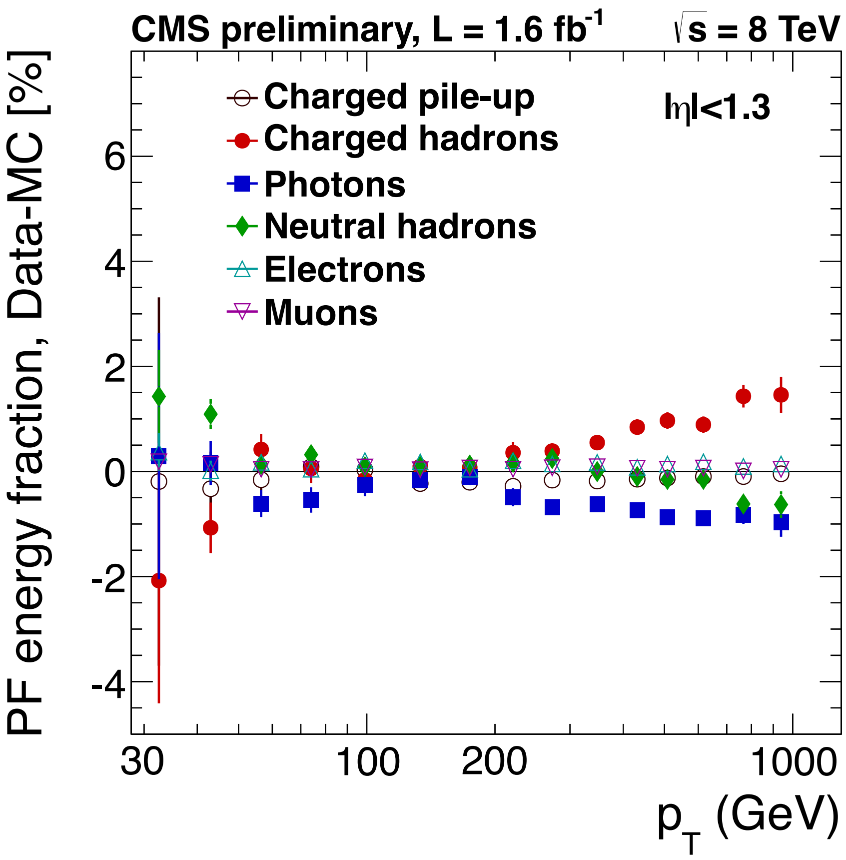
LPC LHC Physics Center

JES Systematic Uncertainties



Jet Composition





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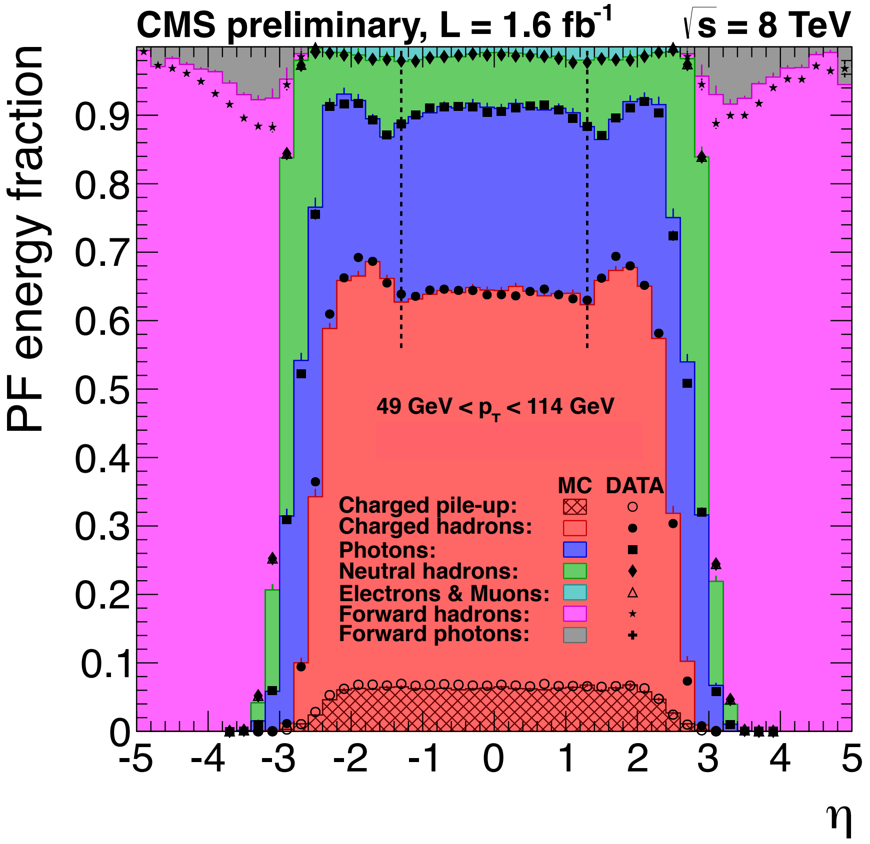
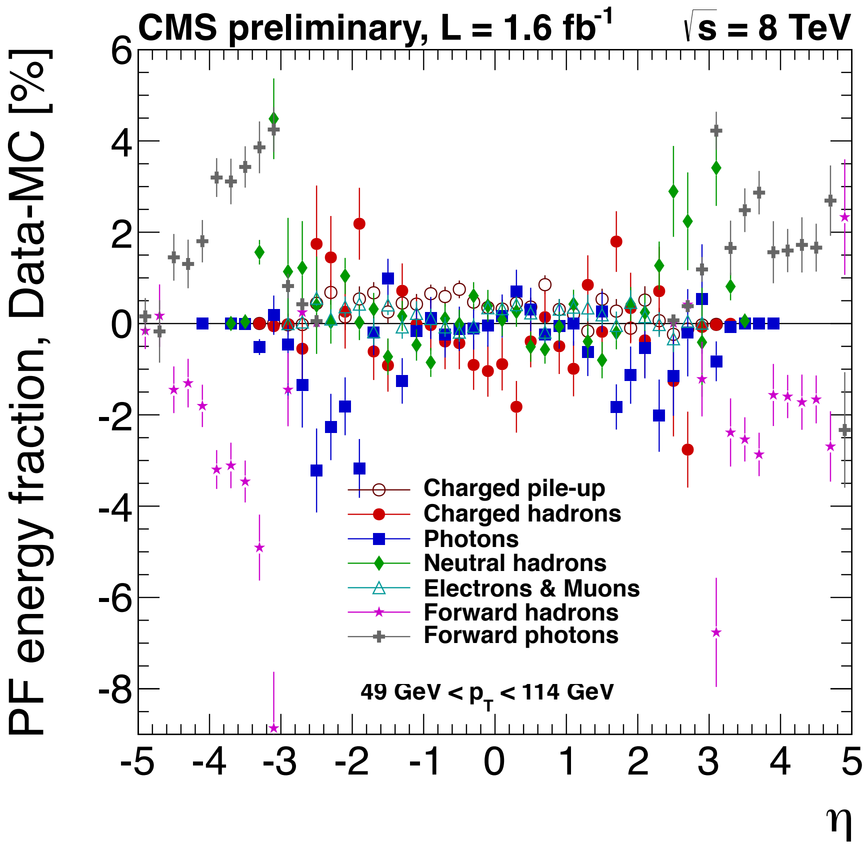
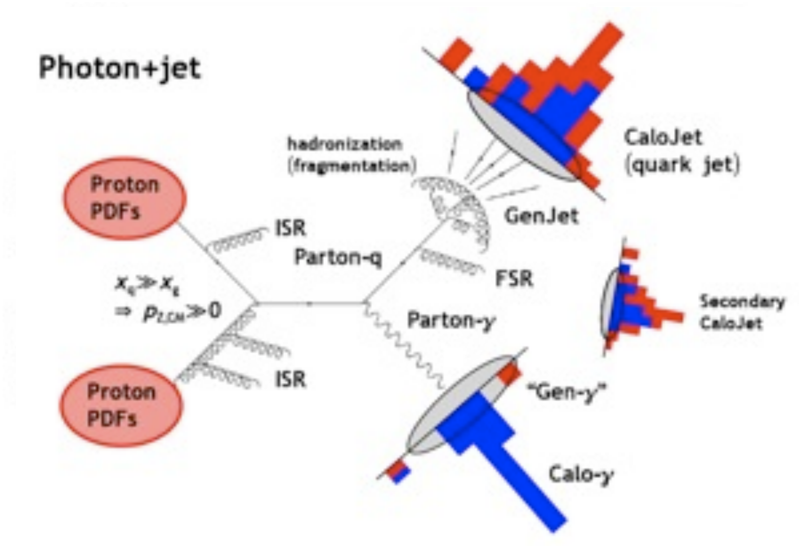
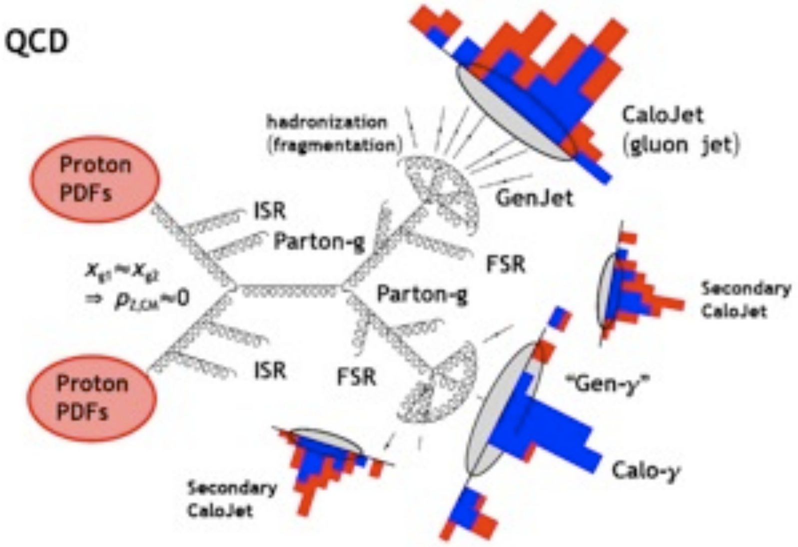




Flavor & Parton





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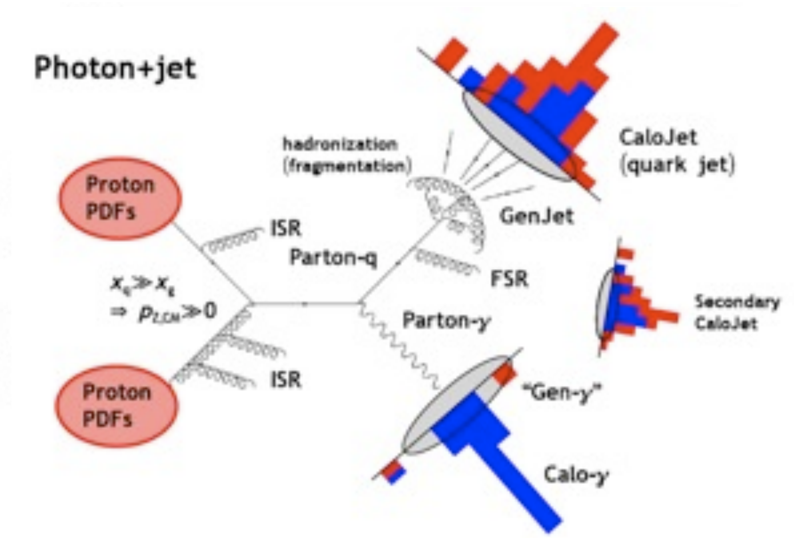

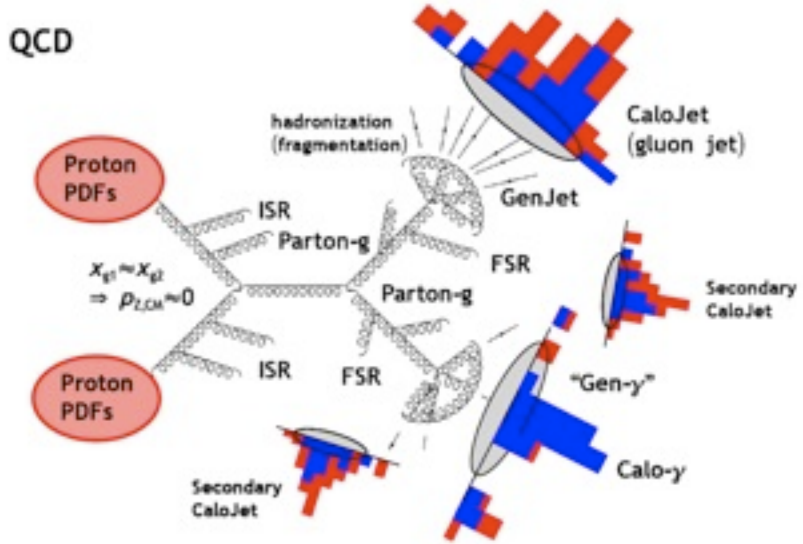

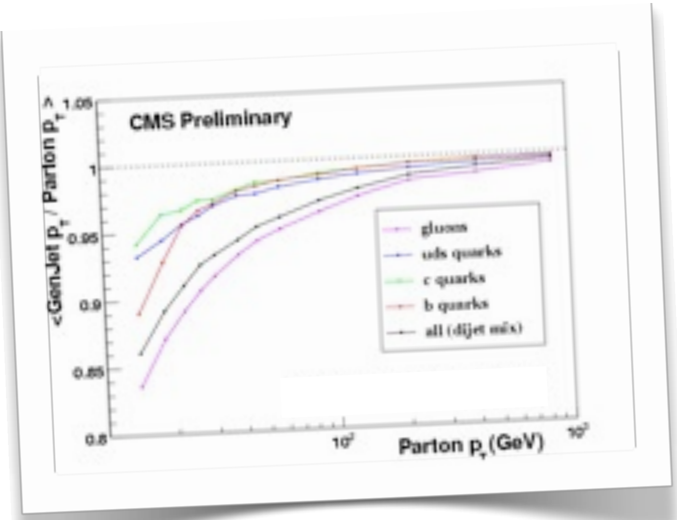

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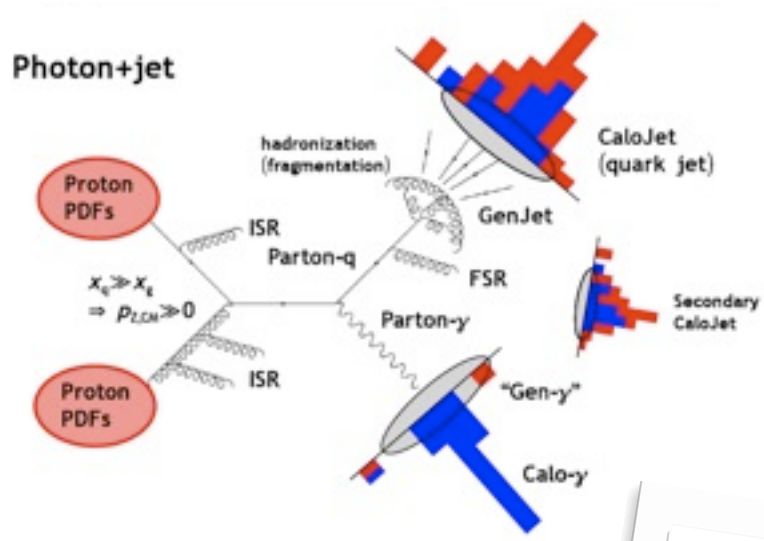

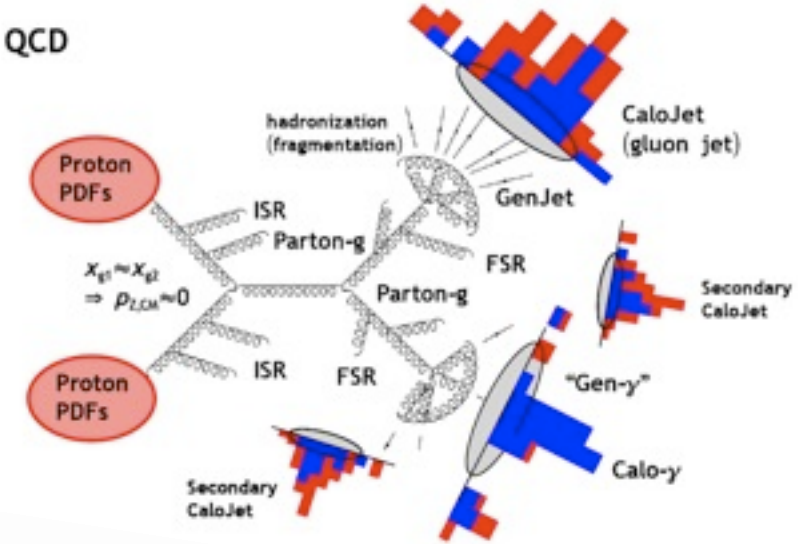

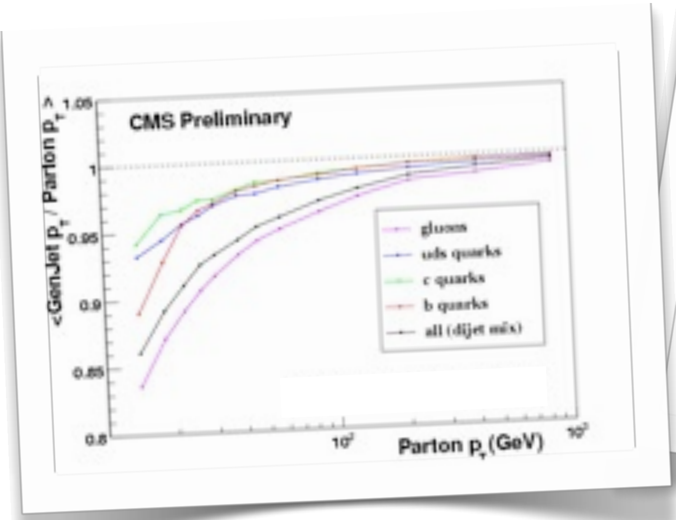

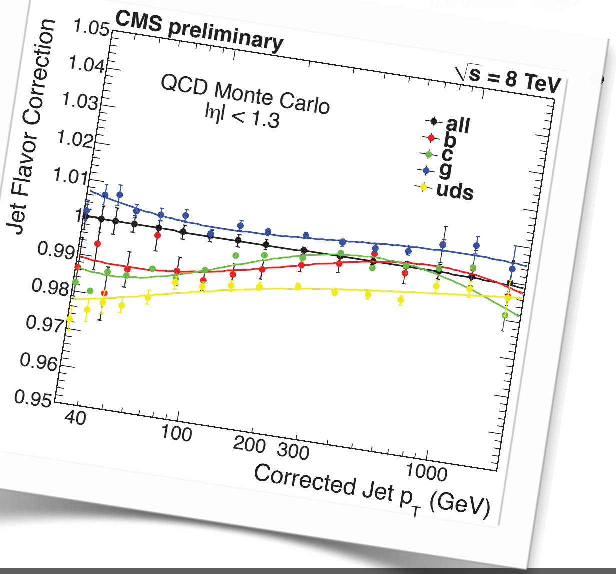

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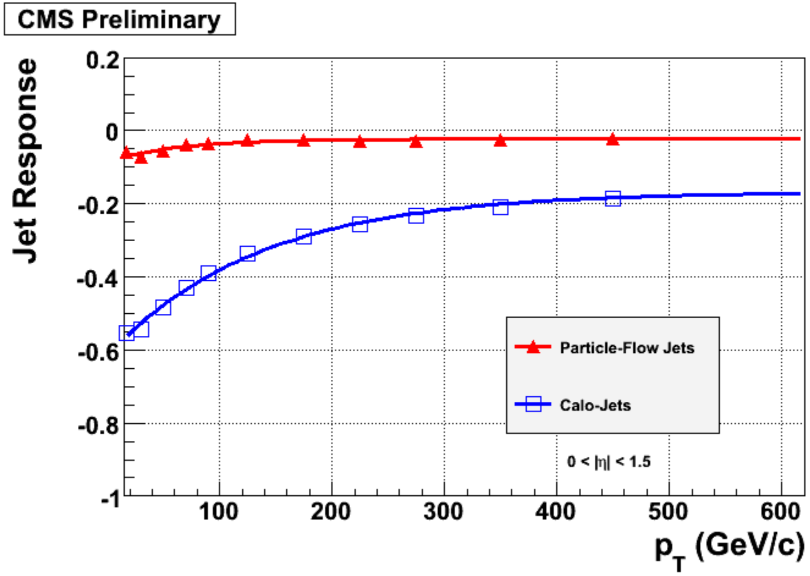

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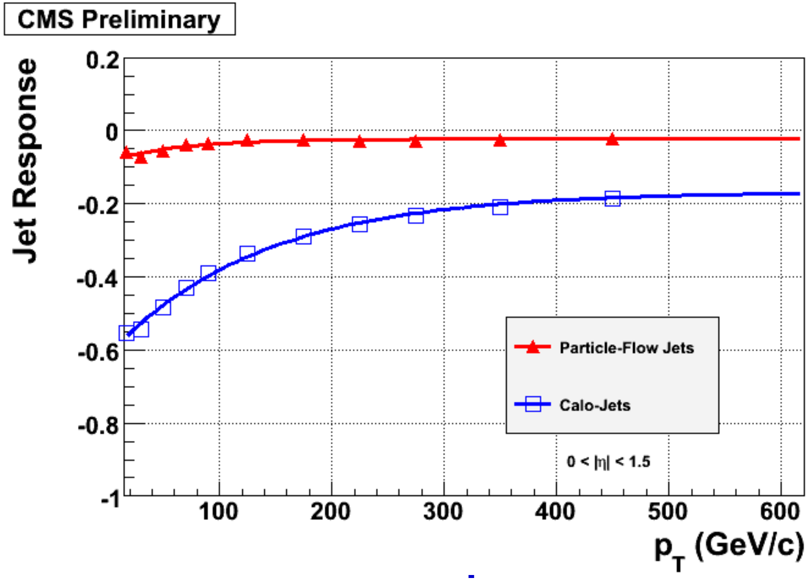

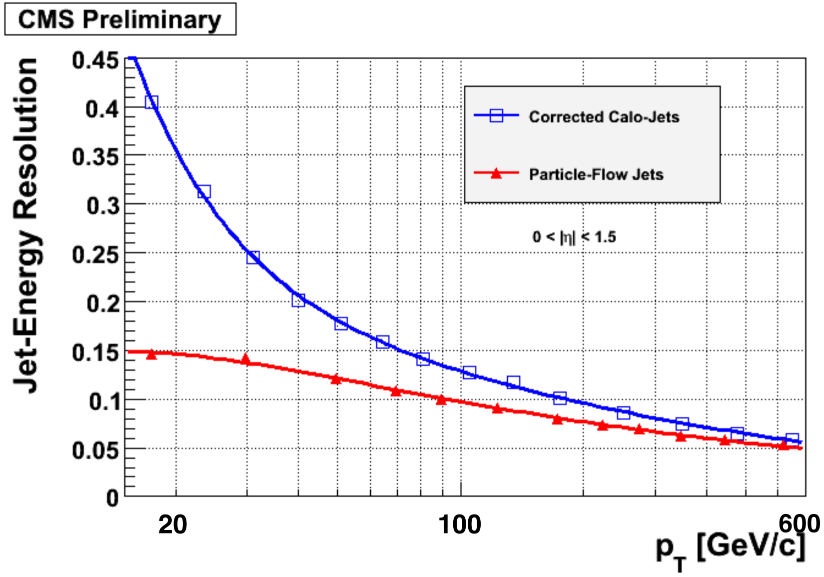

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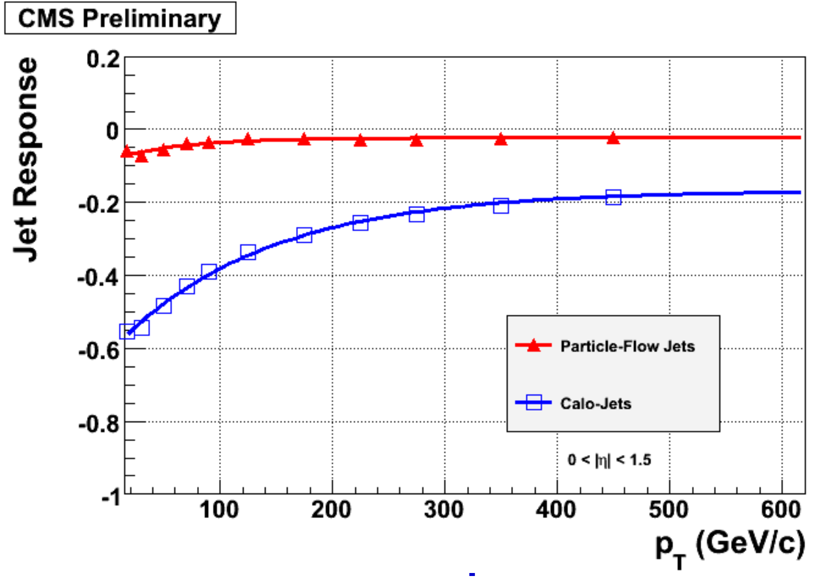

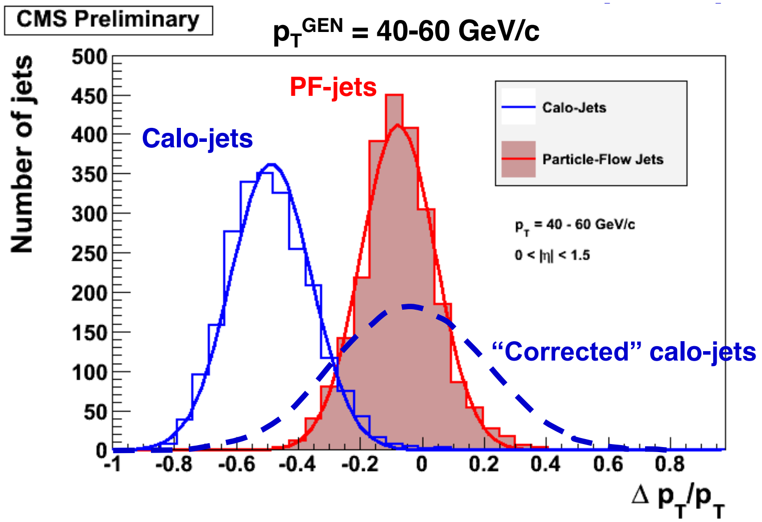

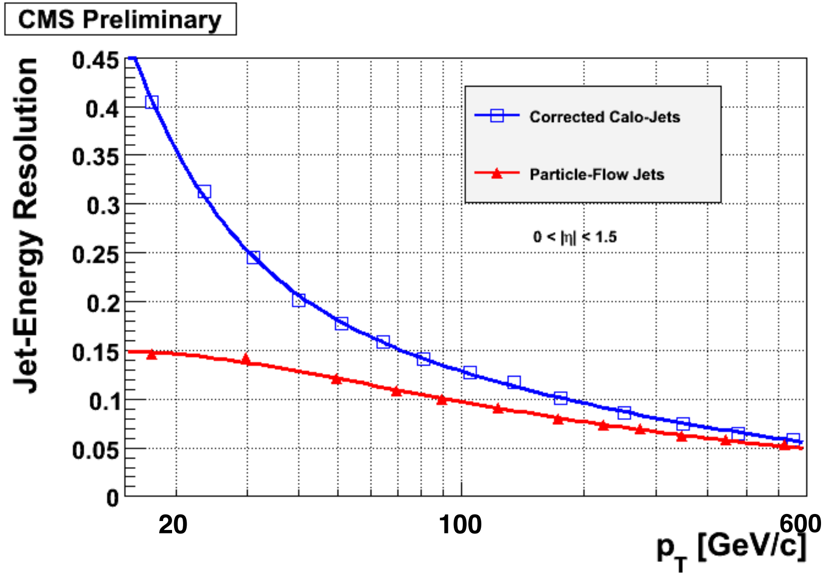

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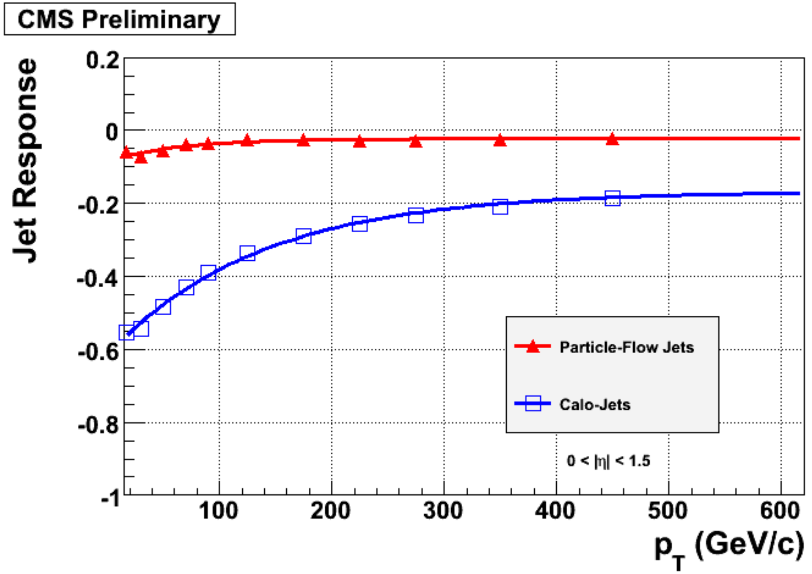

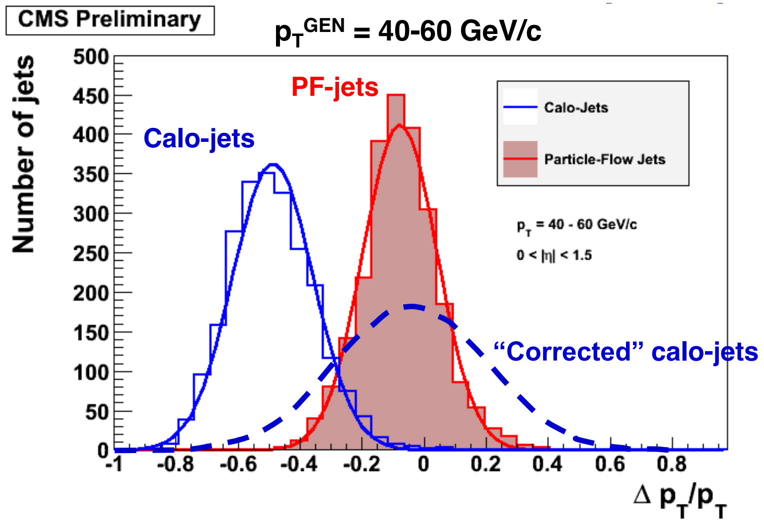

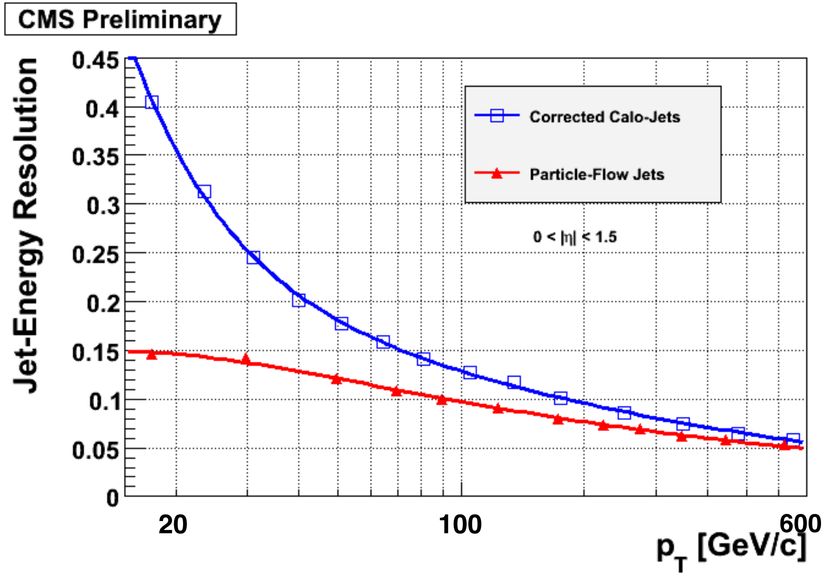

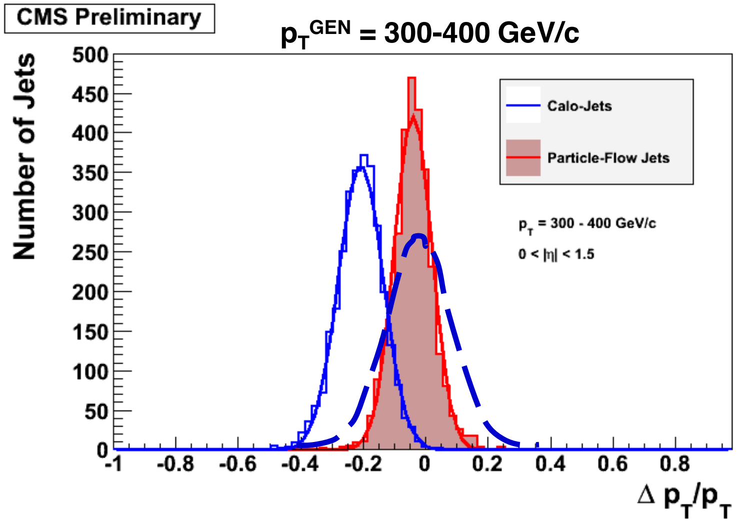

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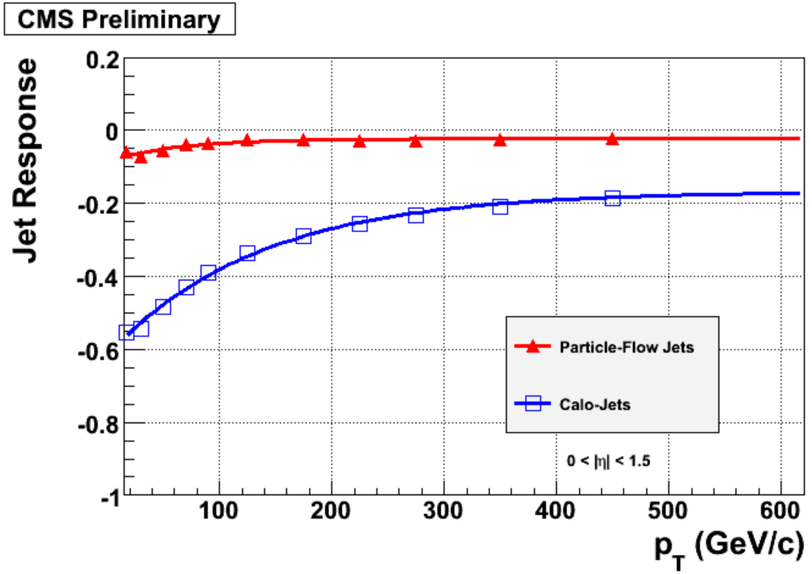

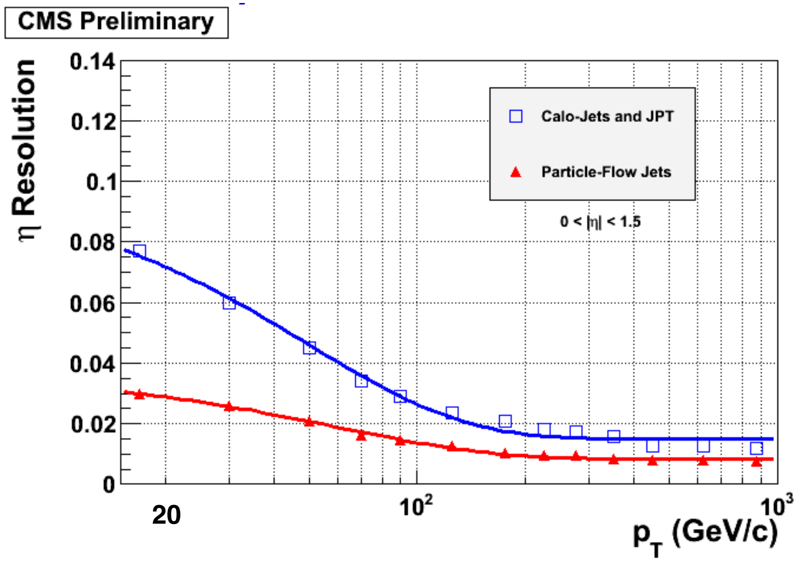

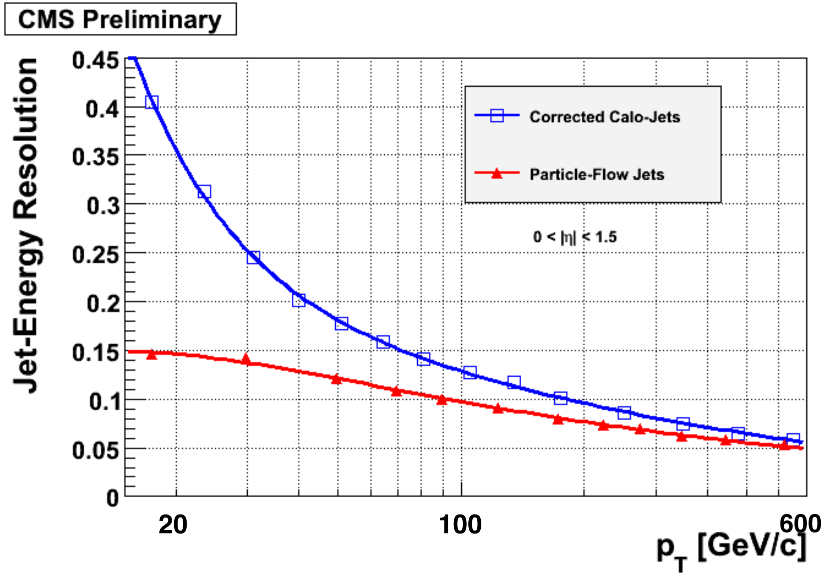

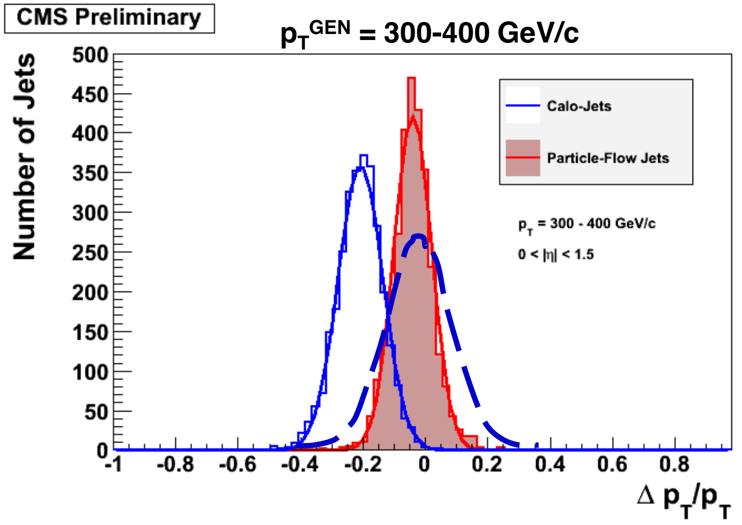

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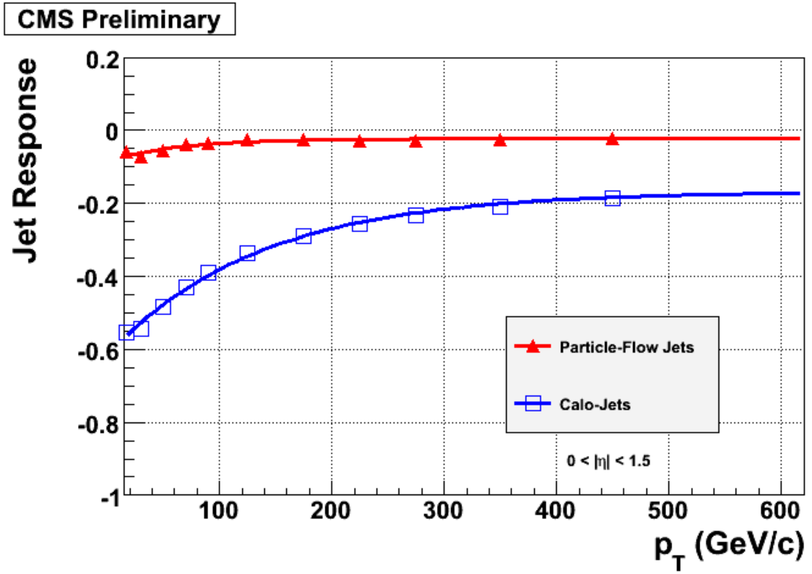

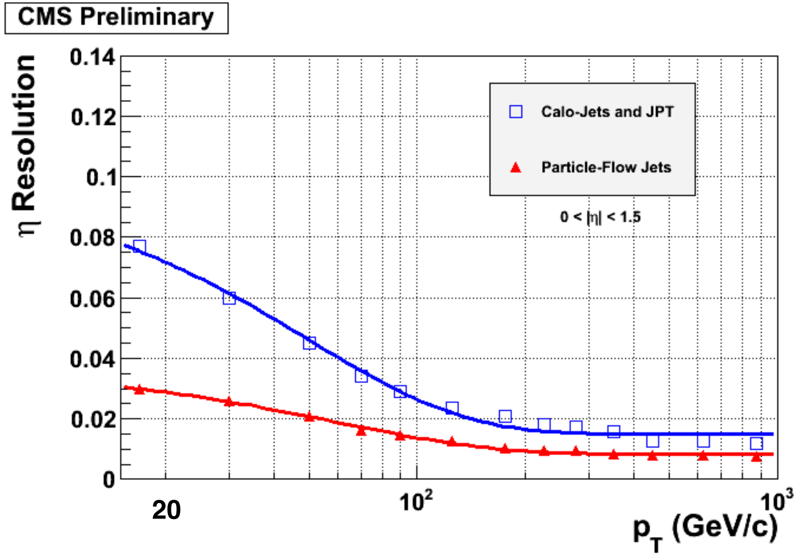

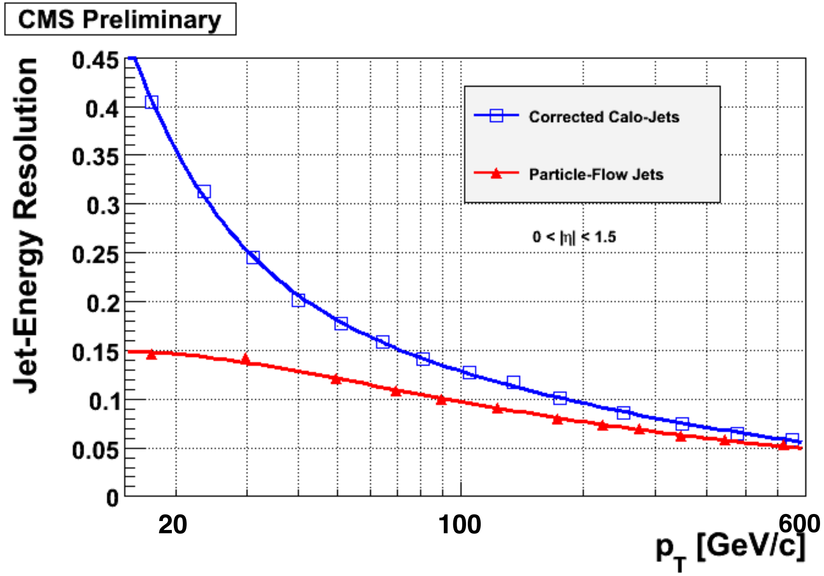

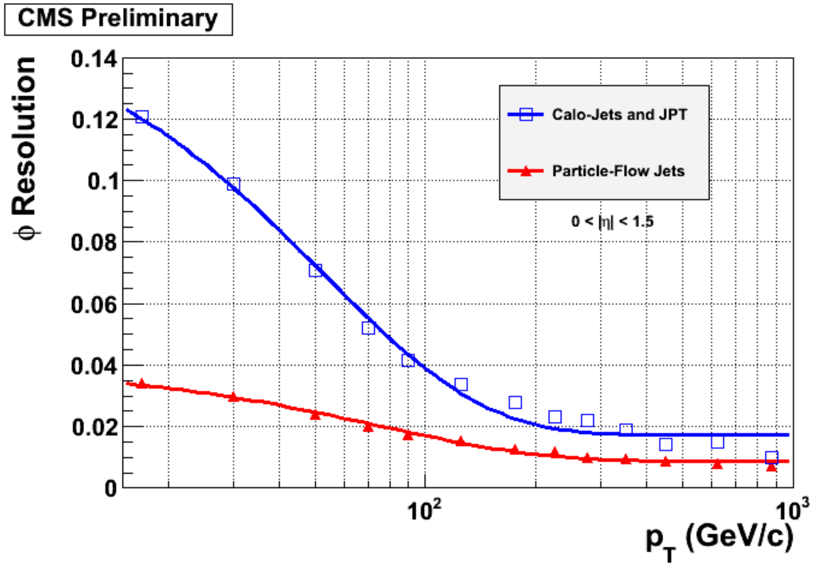

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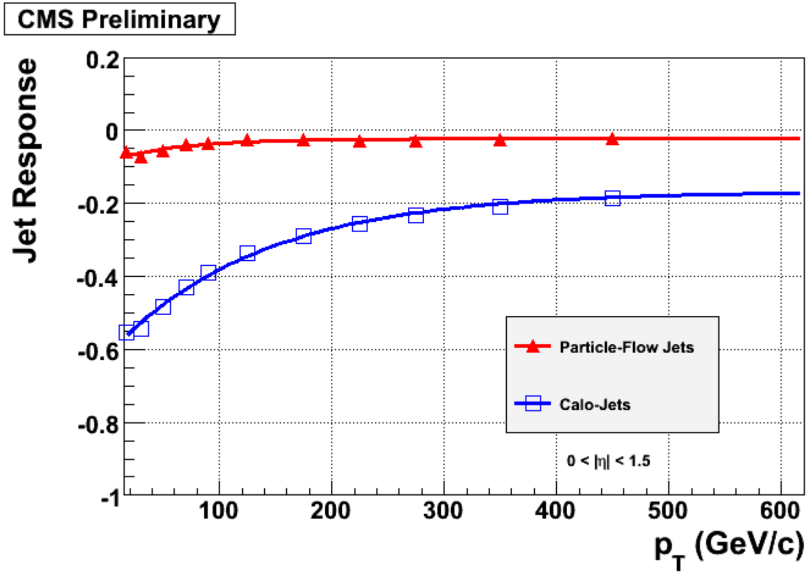

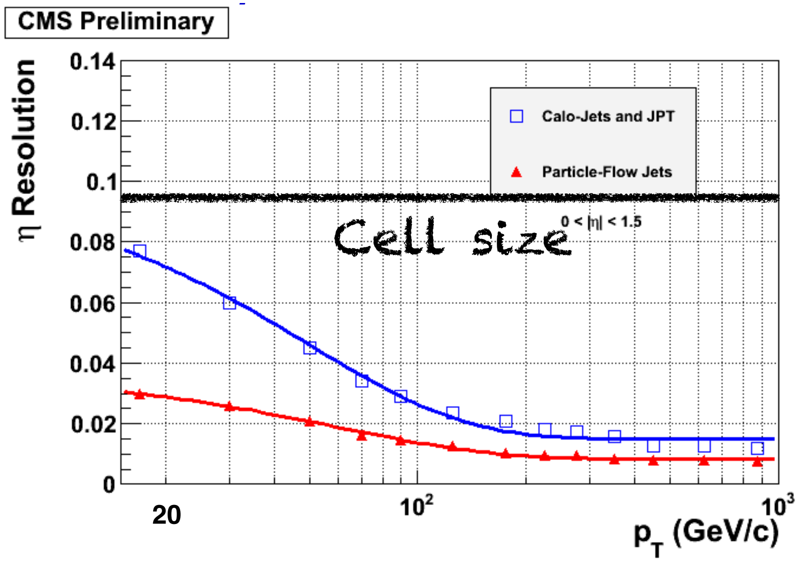

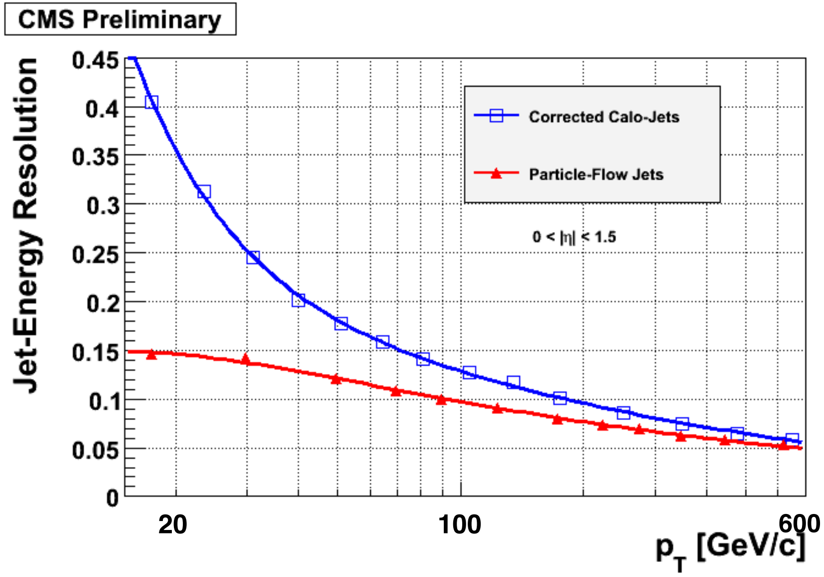

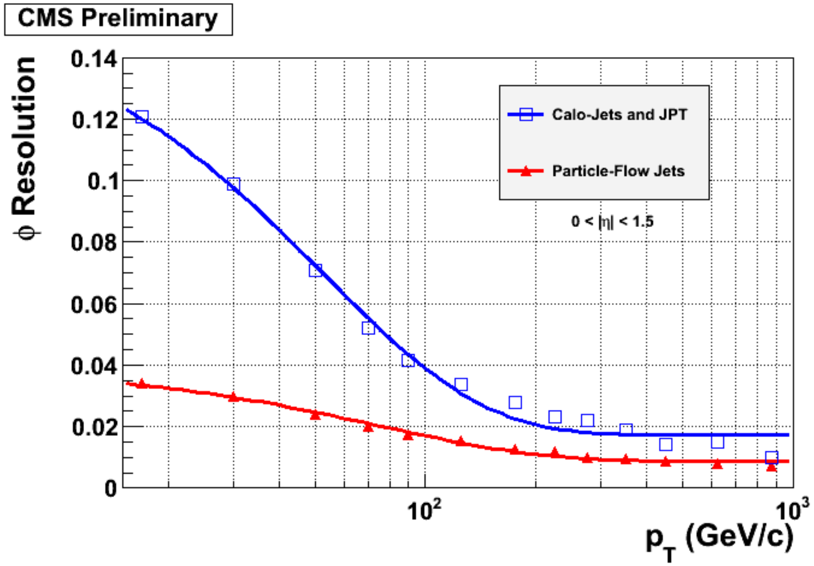

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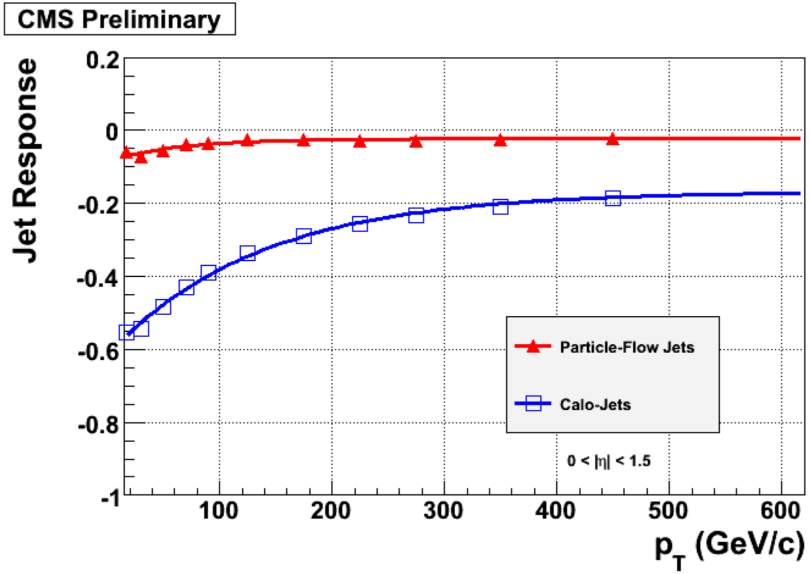

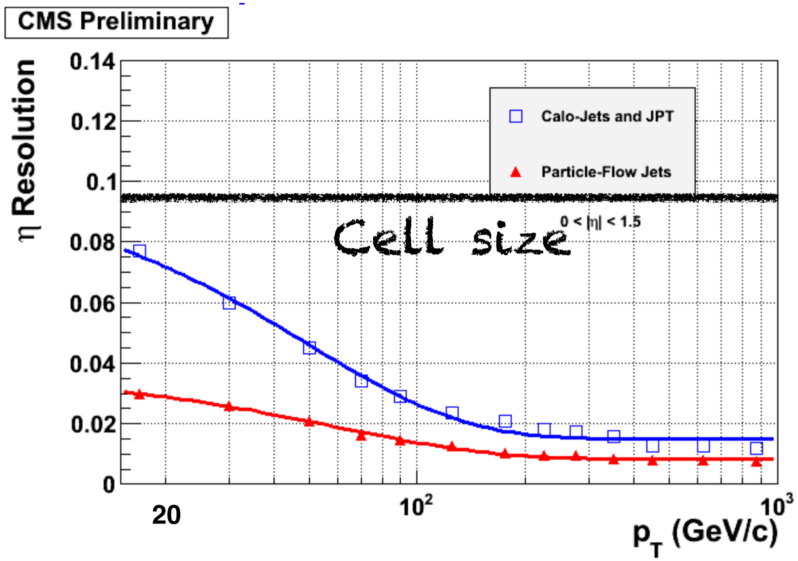

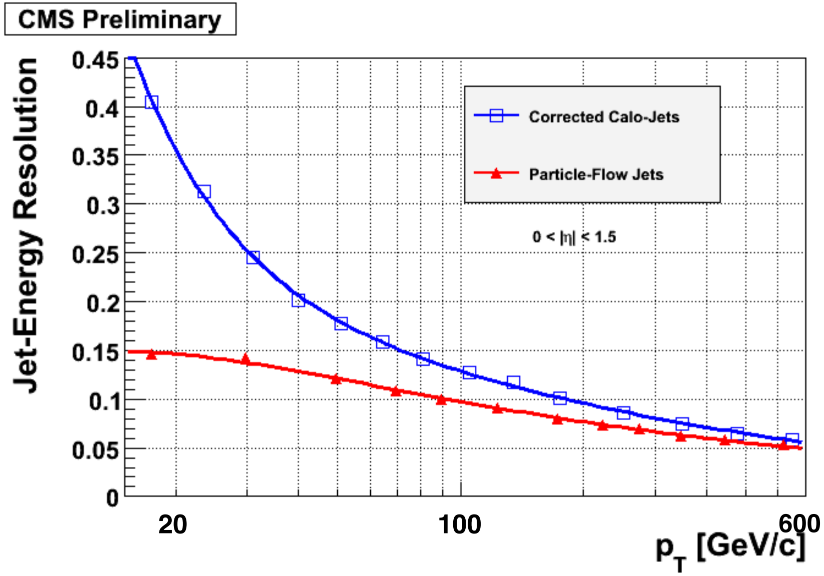

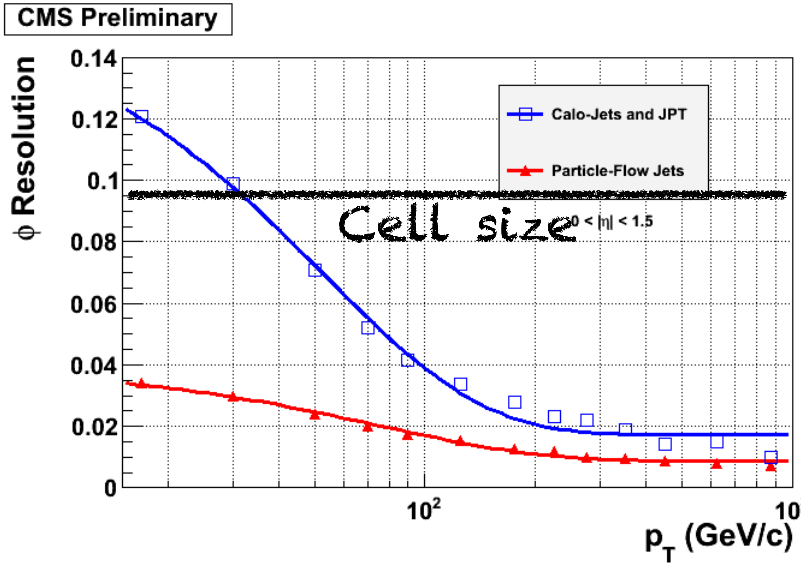

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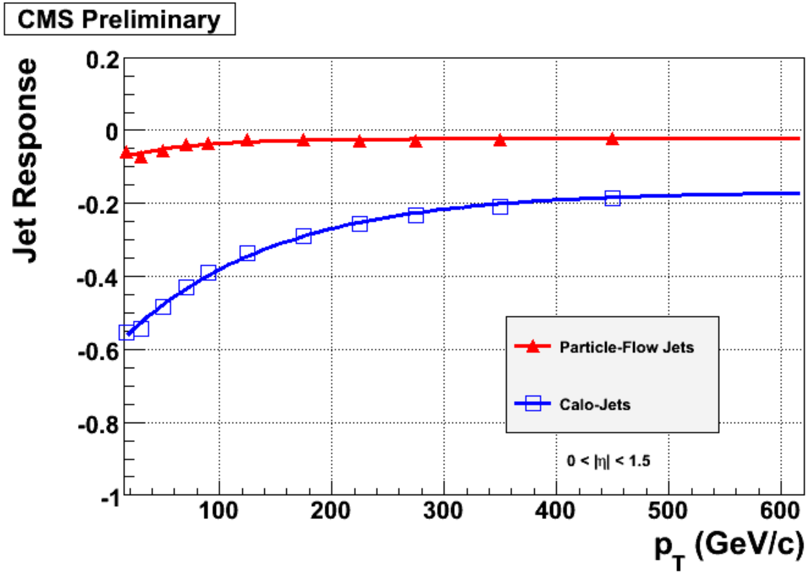

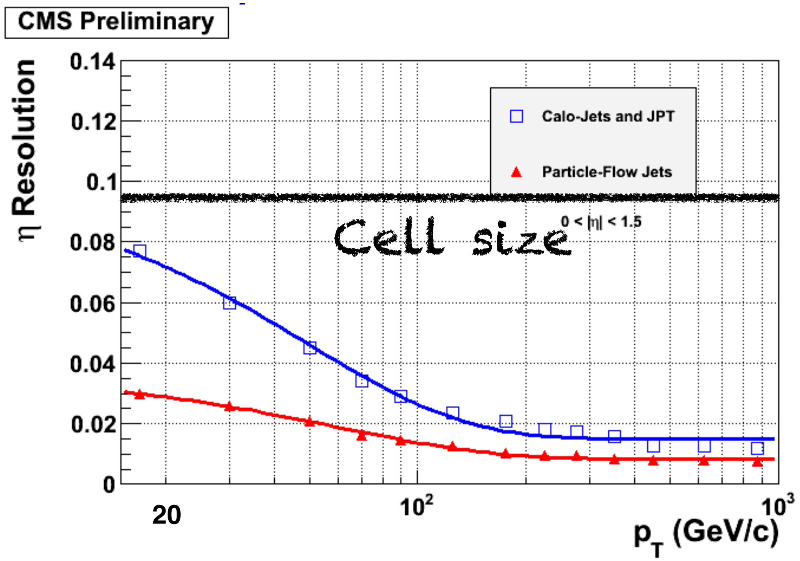

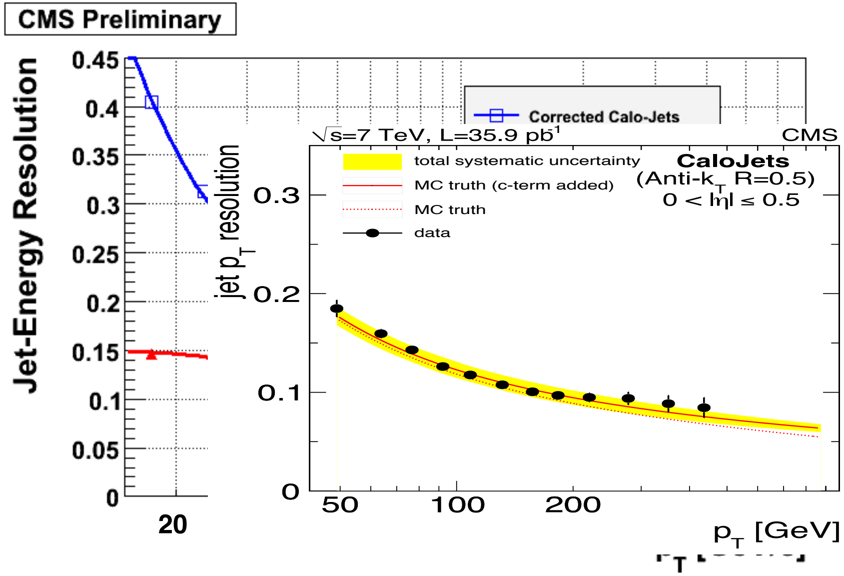

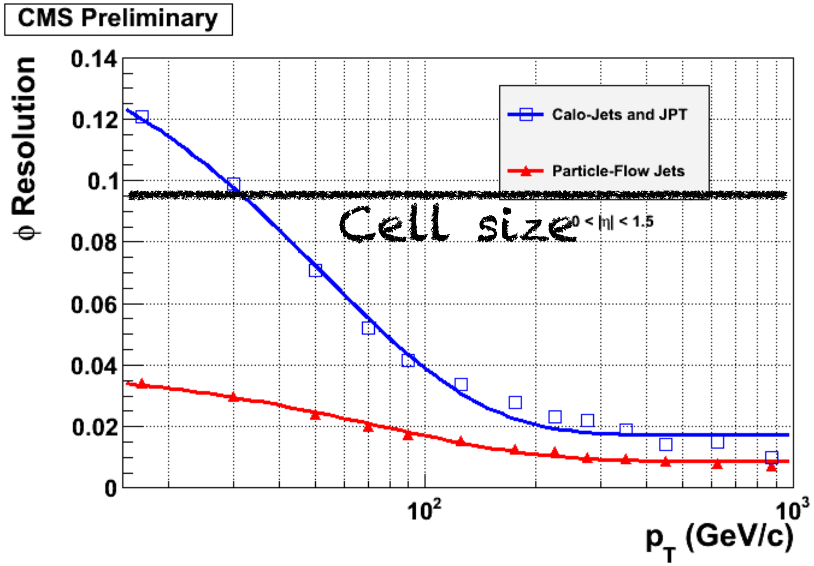

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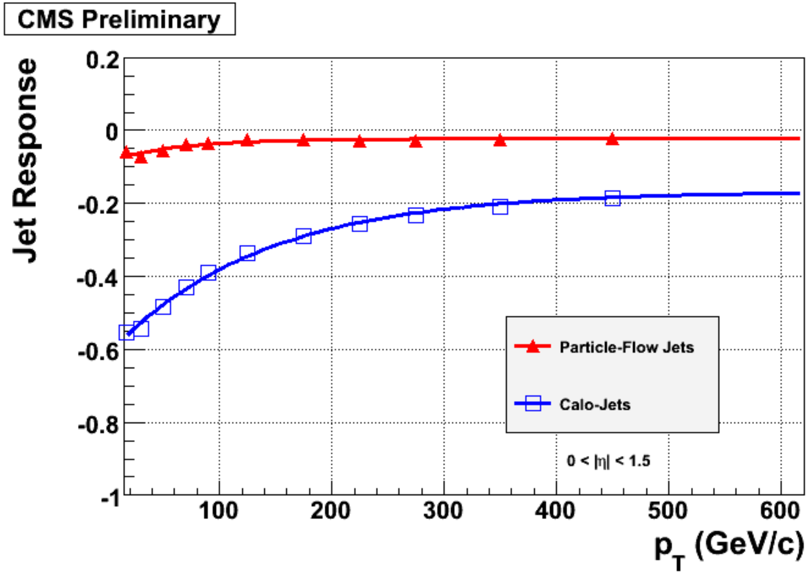

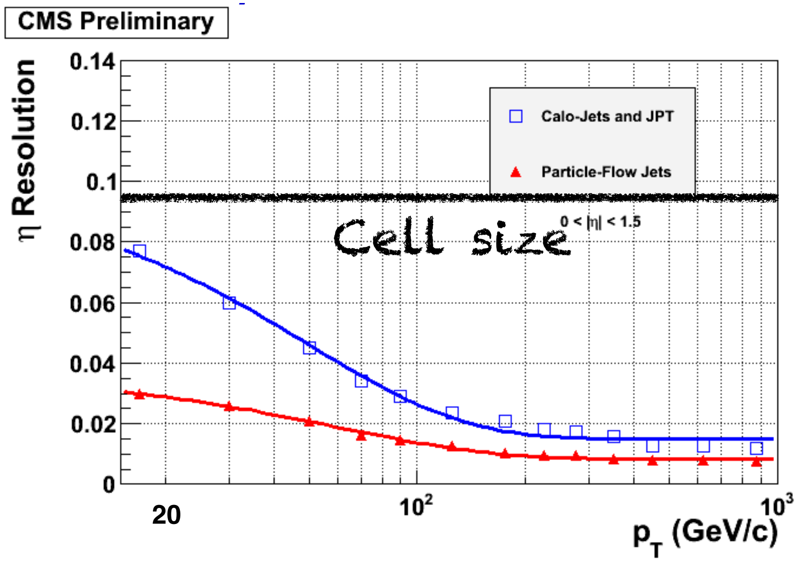

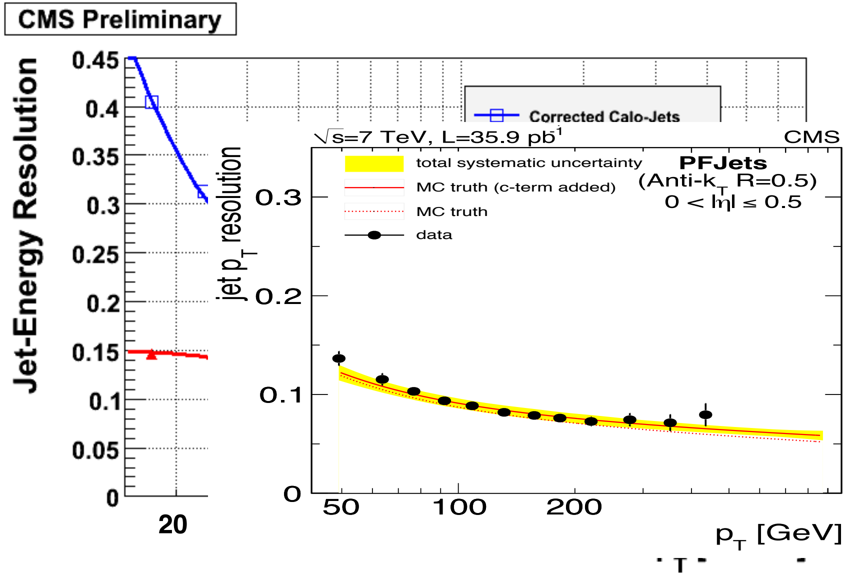

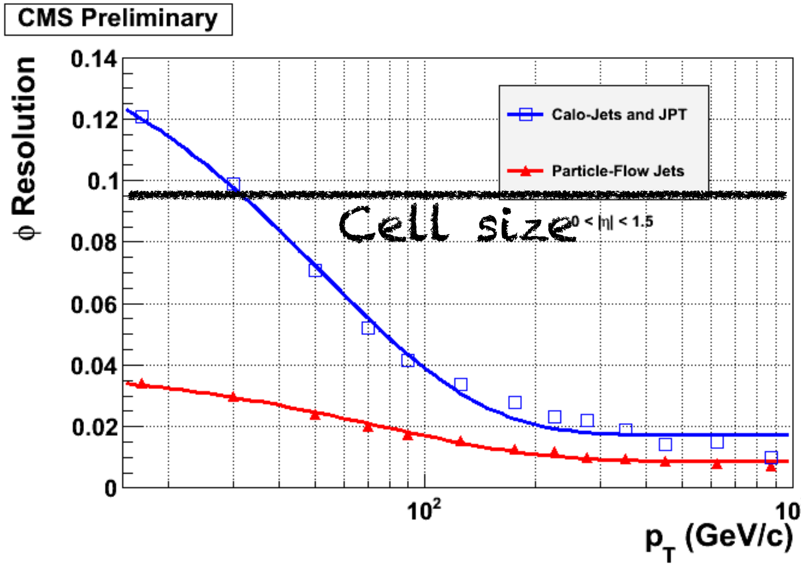

Missing ET using Particle Flow

- MET is the transverse momentum vector sum over all reconstructed particles:

$$\vec{\not{E}}_T = - \sum_{\text{particles}} (p_x \hat{\mathbf{i}} + p_y \hat{\mathbf{j}})$$

- The list of reconstructed particles form a global event description, provided by the **PF Algorithm**:
  - { $\mu^\pm$, $e^\pm$, γ, $\pi^\pm$, K_L^0, pile-up particles, etc }

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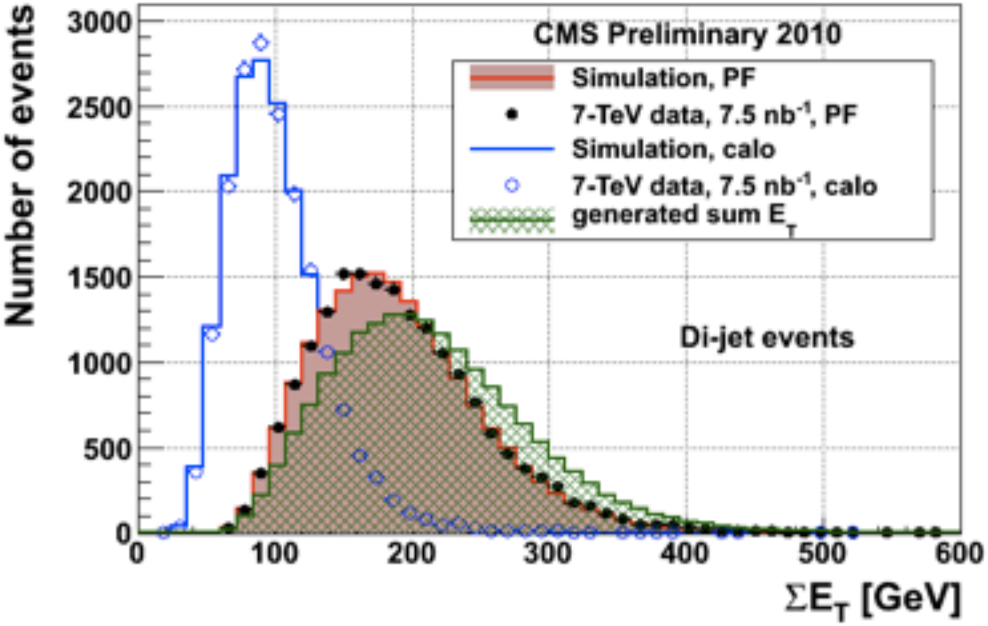
- Study performance of MET vs $\sum E_T$

MET Performance



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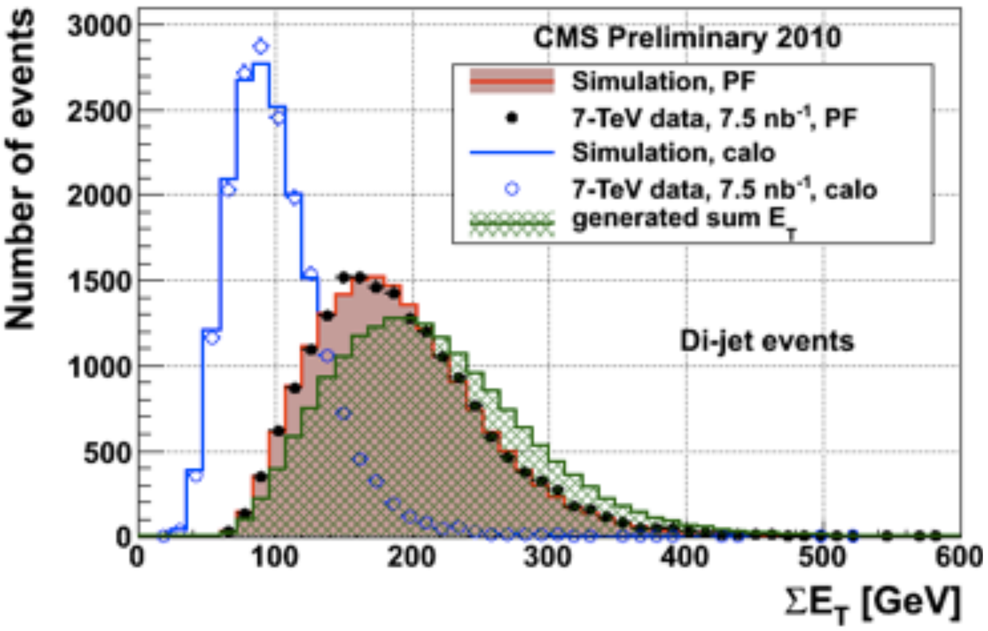

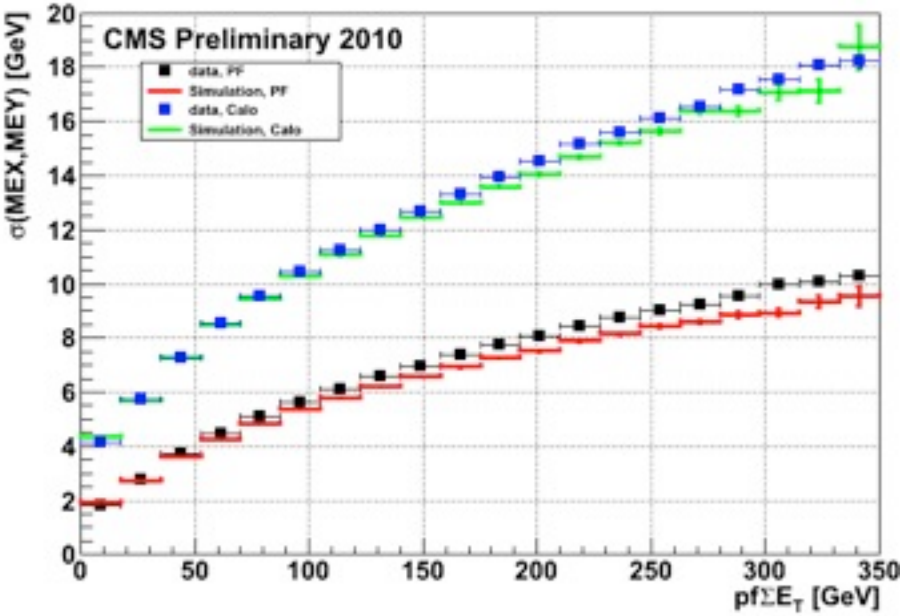

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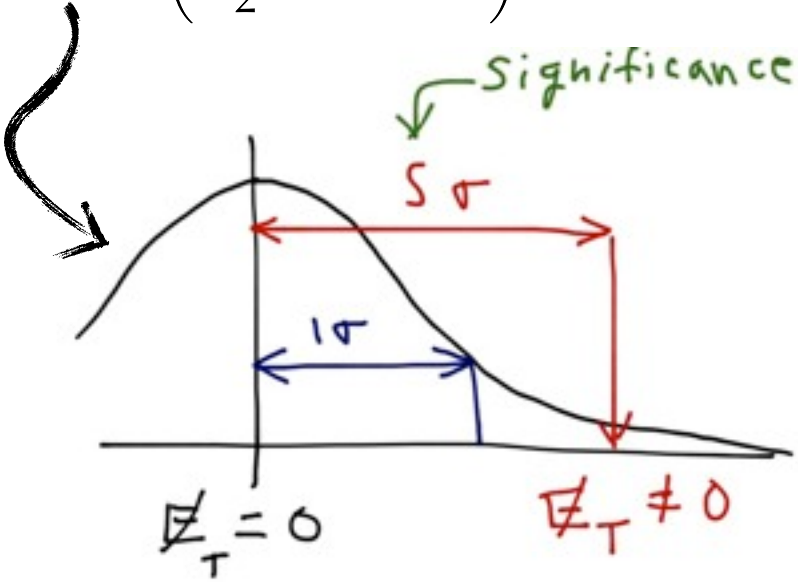

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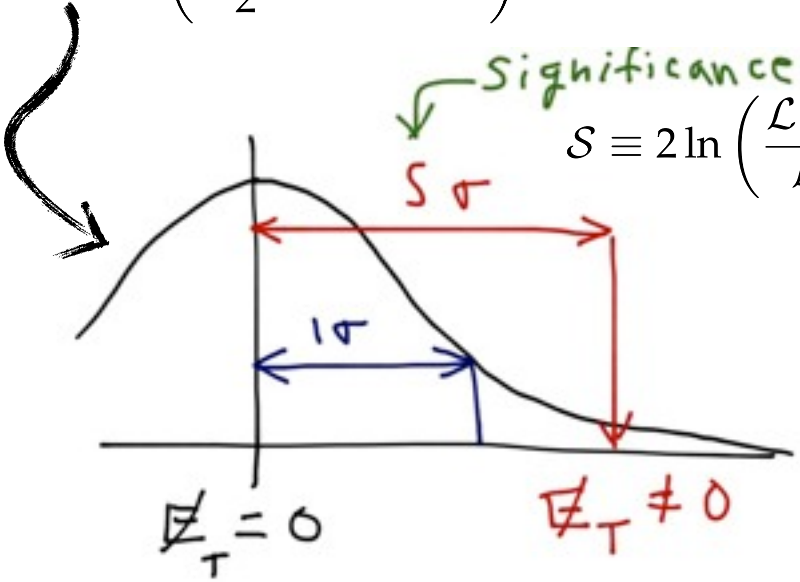

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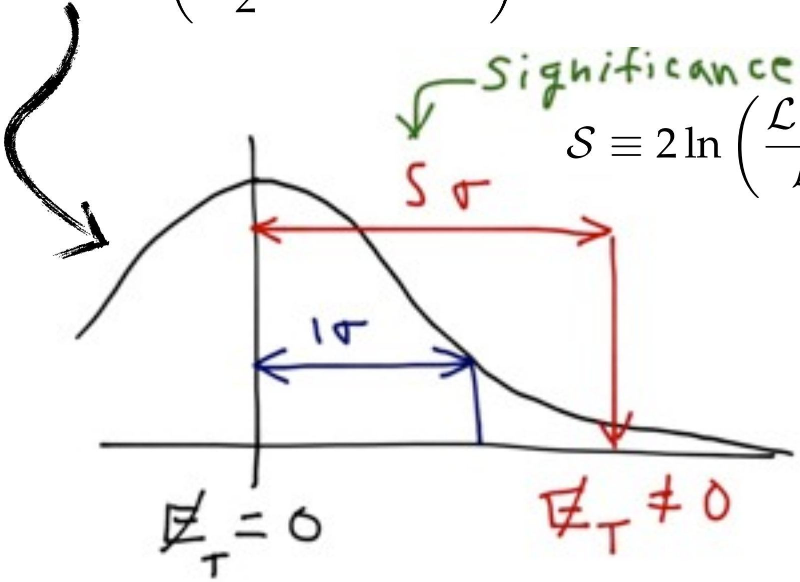

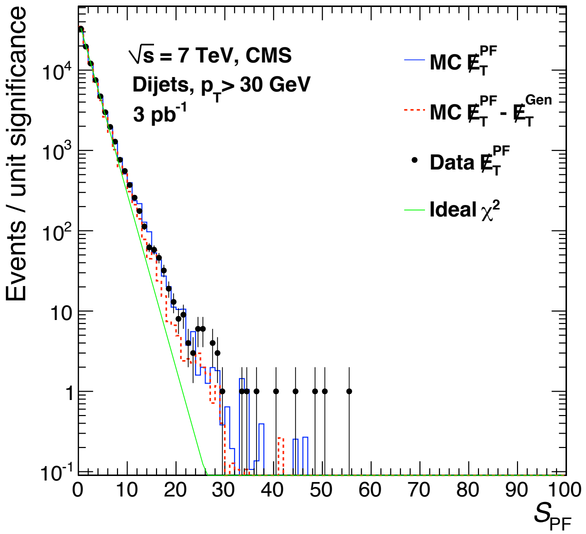

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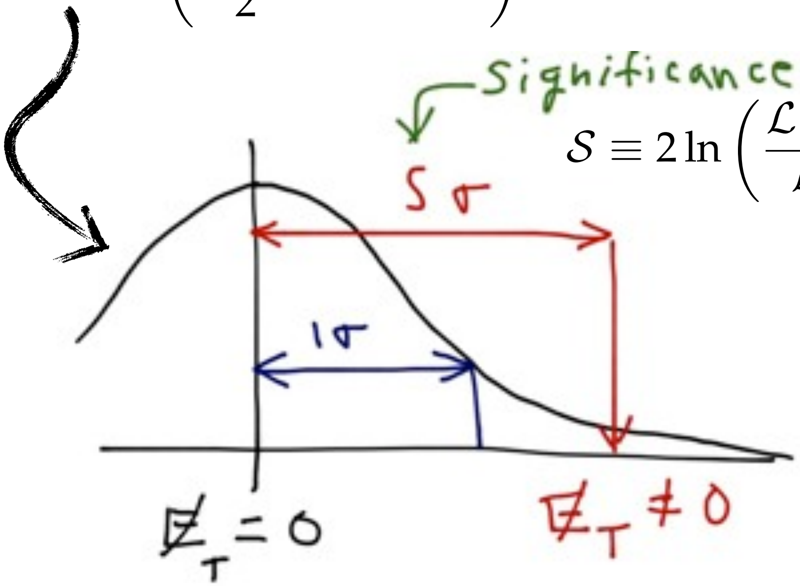

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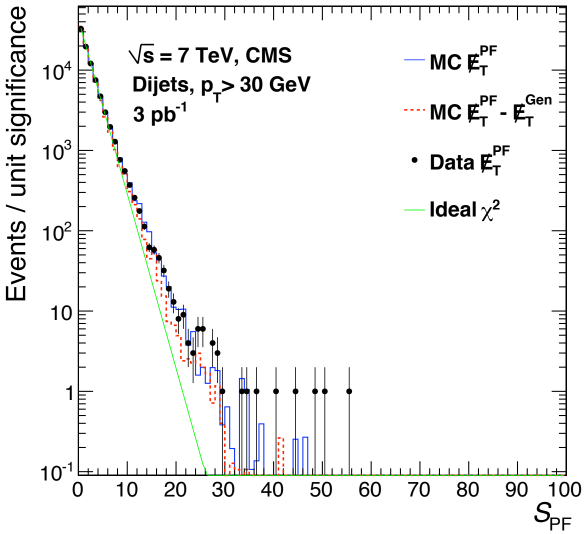

- Zero true MET events should follow a flat $P(\chi^2)$ distribution

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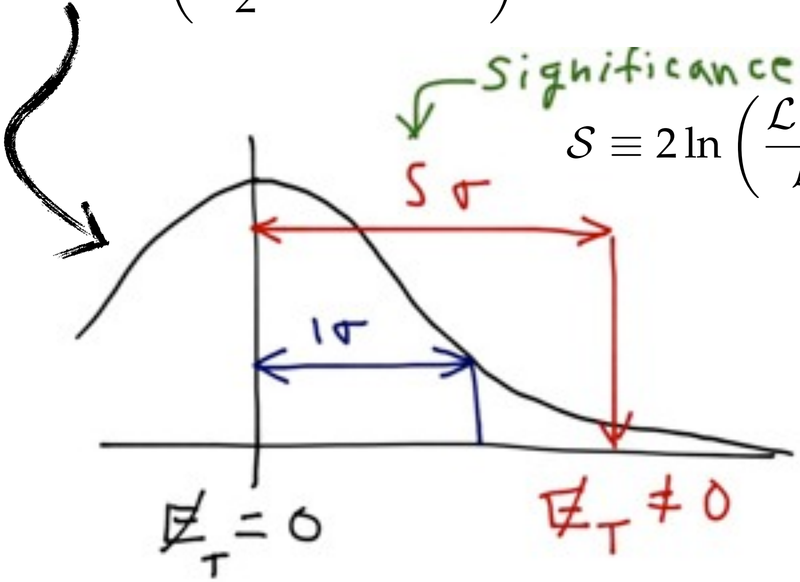
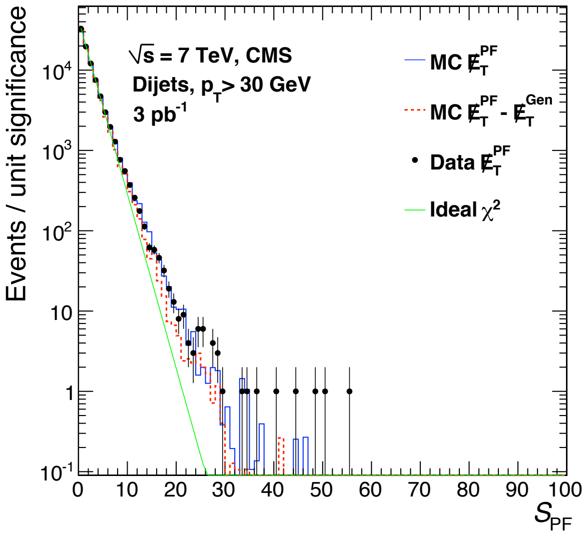
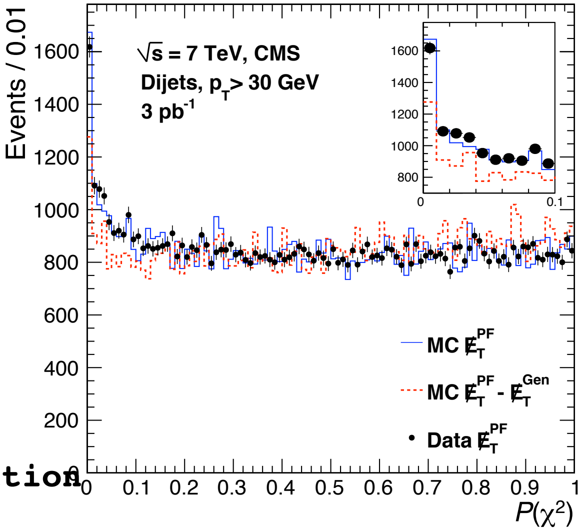
- Use error propagation over all particles to find total significance that observed MET is compatible with zero MET

$$\mathcal{L}(\vec{\varepsilon}) \sim \exp\left(-\frac{1}{2}(\vec{\varepsilon})^{T}\mathbf{V}^{-1}(\vec{\varepsilon})\right)$$



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





- Zero true MET events should follow a flat $P(\chi^2)$ distribution

Missing E_T Significance

- p_T uncertainty measured for each & every particle
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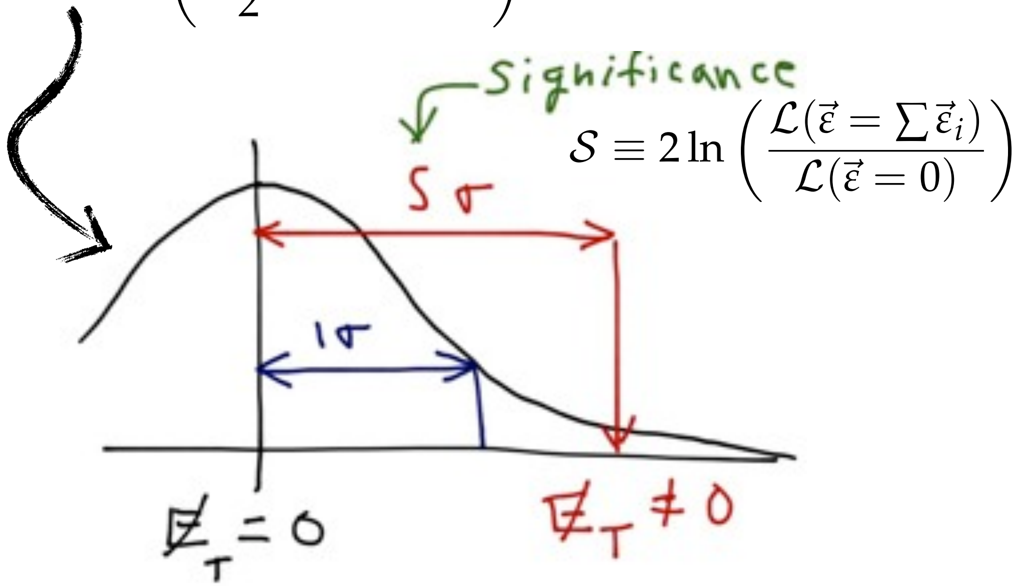

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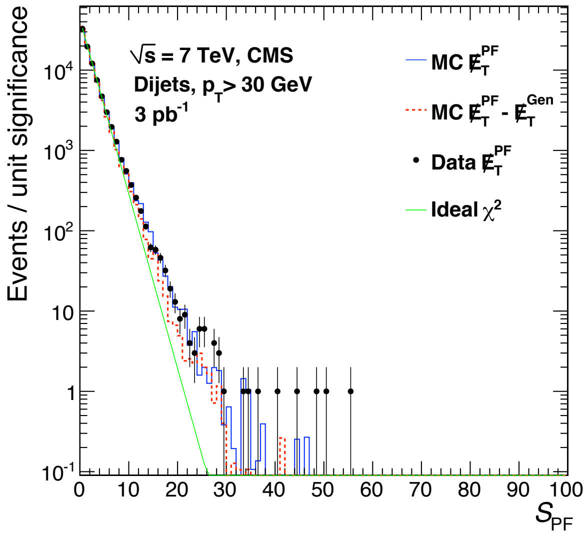

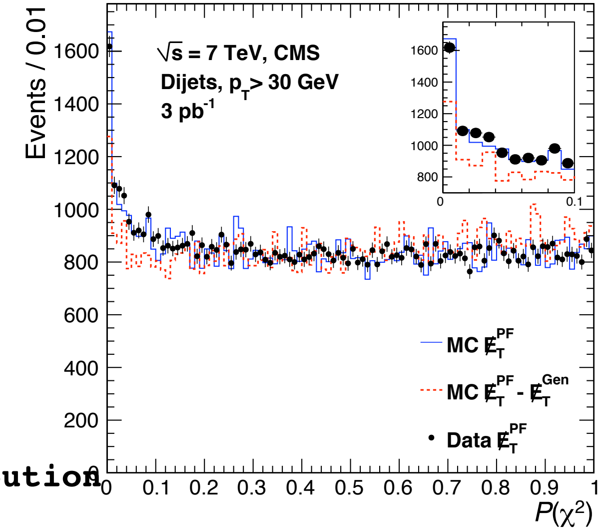

- Zero true MET events should follow a flat $P(\chi^2)$ distribution
- Real true MET events (& badly reconstructed events) peak at zero $P(\chi^2)$

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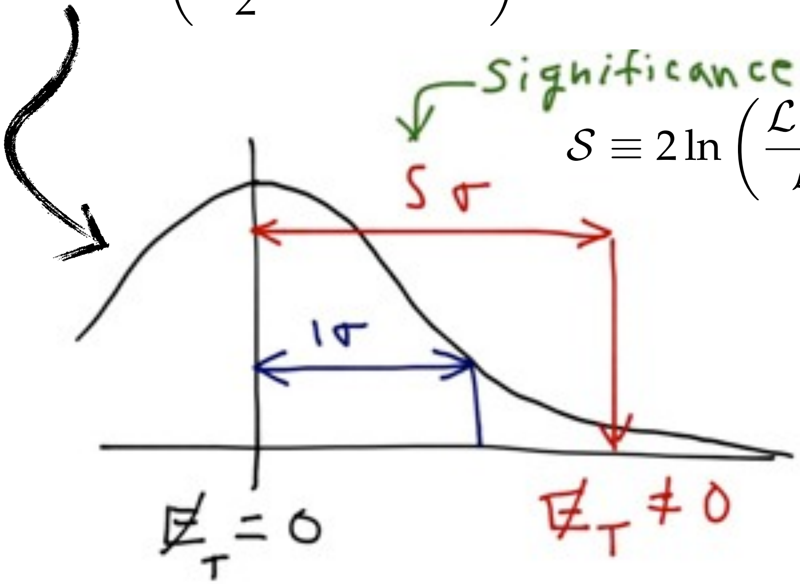

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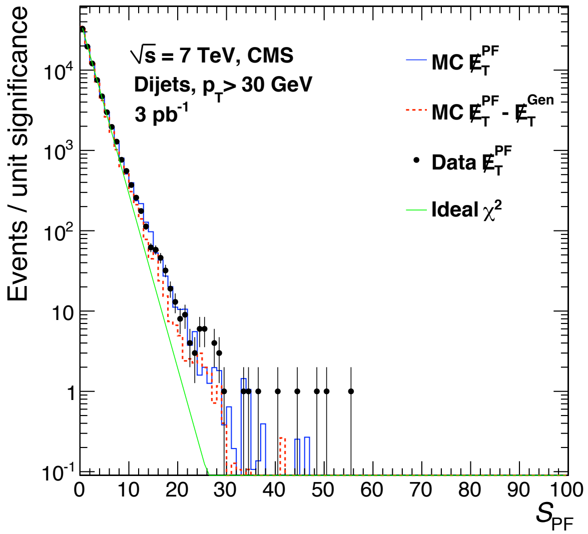

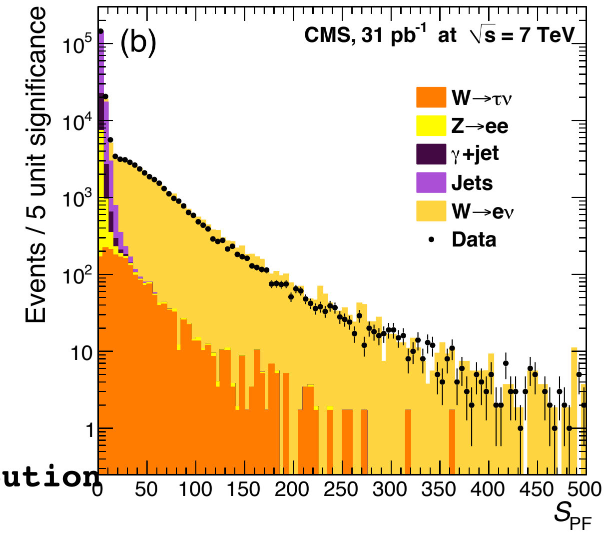

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The Tree of Particles