First PbPb Collisions at the LHC with the CMS Detector

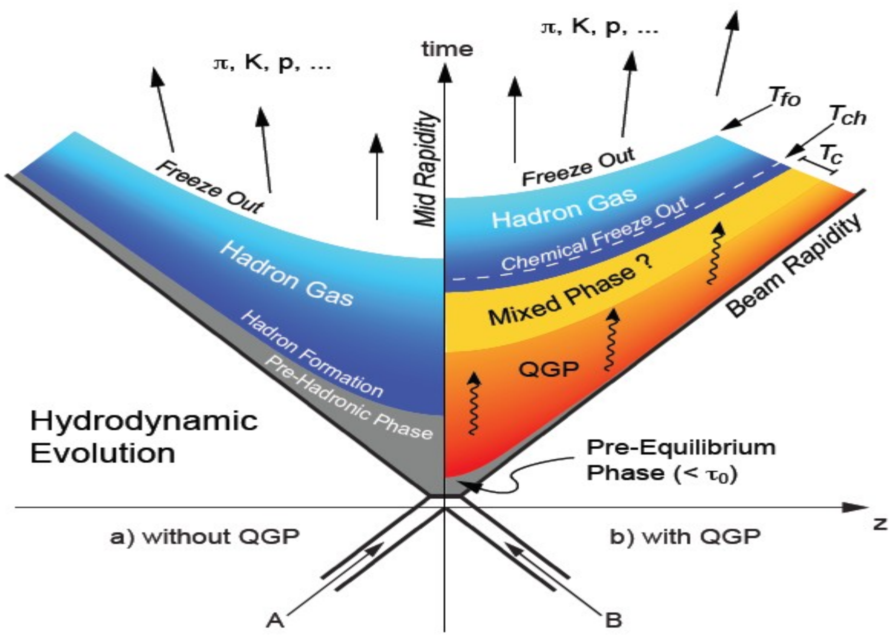
Camelia Mironov

- **Introduction**
  - Heavy-ion collisions
  - The CMS detector
  - 1st PbPb run data
- **Physics analyses** (1st year)
  - Jets
  - Quarkonia
  - Z0

Introduction: Heavy-Ion Collisions

- Goal:
  - study the primordial matter of the Universe, a 'high-density' QCD matter where the relevant degrees of freedom are quarks and gluons - the **Quark-Gluon Plasma (QGP)**
    - Search/recreate the QGP
    - Measure its properties
    - Discovery new features

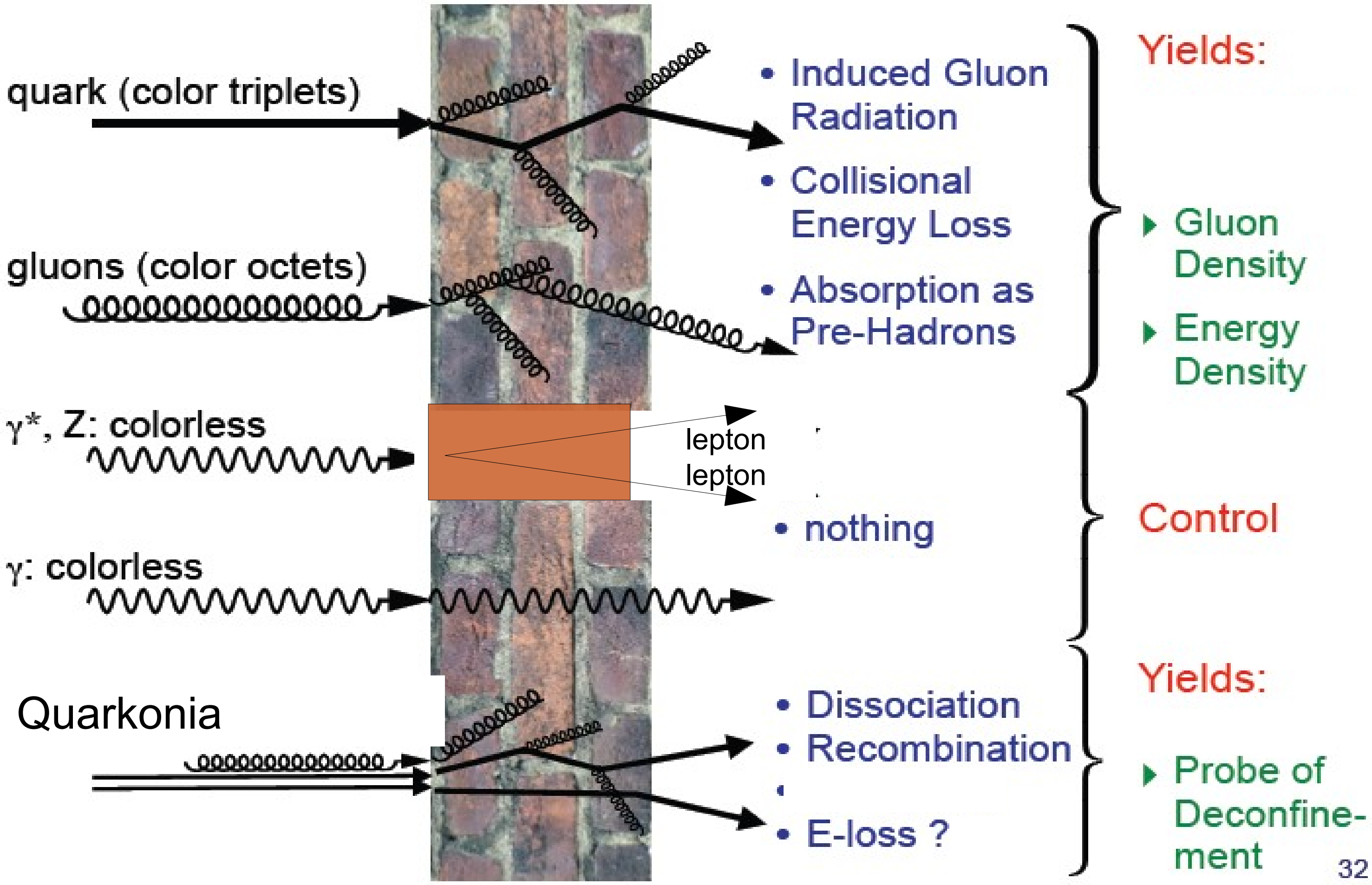
MACHINE	AGS	SPS	RHIC	LHC
Sqrt(s_{NN}) (GeV/A)	4	17	200	2760 5500



Chemical freezeout ($T_{ch} \leq T_c$): inelastic scattering ceases
Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering ceases

Introduction: Heavy-Ion Collisions

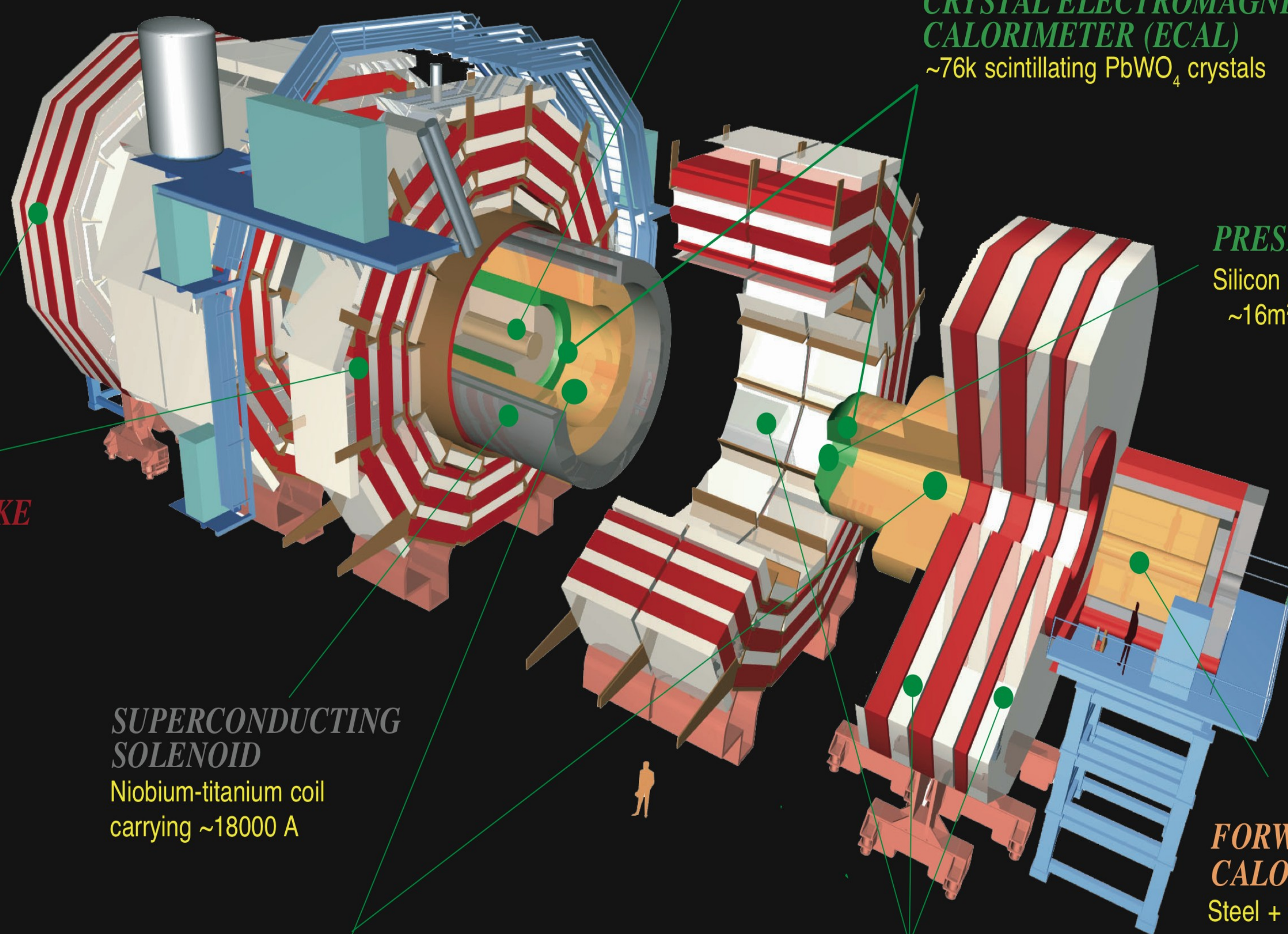
- How:
  - One way: hard-probes (high pt/ET, or mass)



Essential

- Baseline comparison
  - Non-interactig probes (Z,prompt photons)
  - Vacuum/pp and pA reference for cold nuclear matter effects
- LHC
  - Higher energies → higher rates for all probes
  - Better (than previous HI exp) detection capabilities

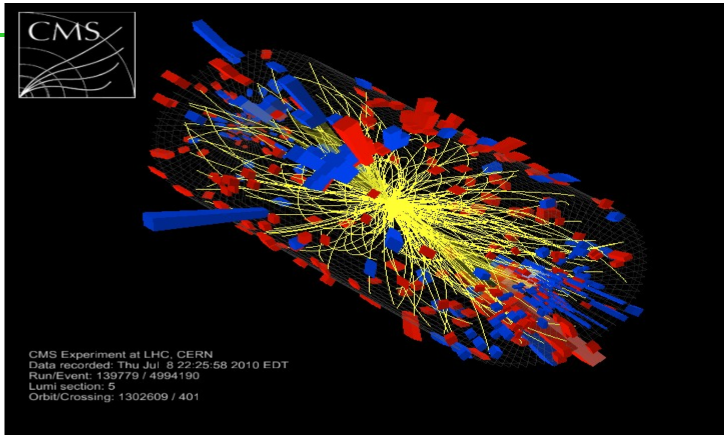
CMS Detector



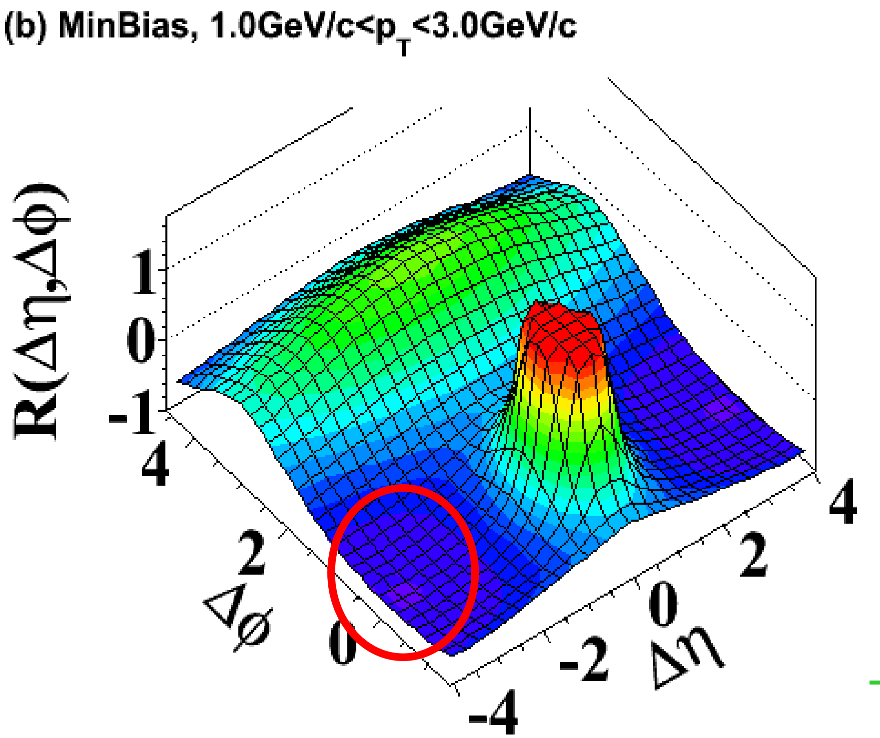
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

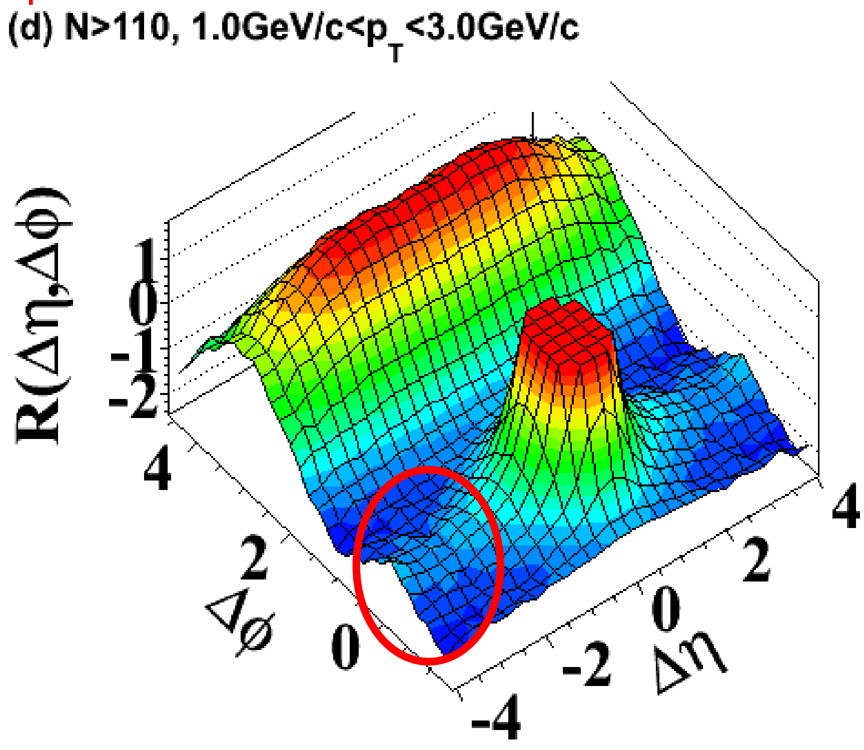
HI Preview? ... pp@7TeV high-multiplicity events

- Long range,
  near side
  angular correlations

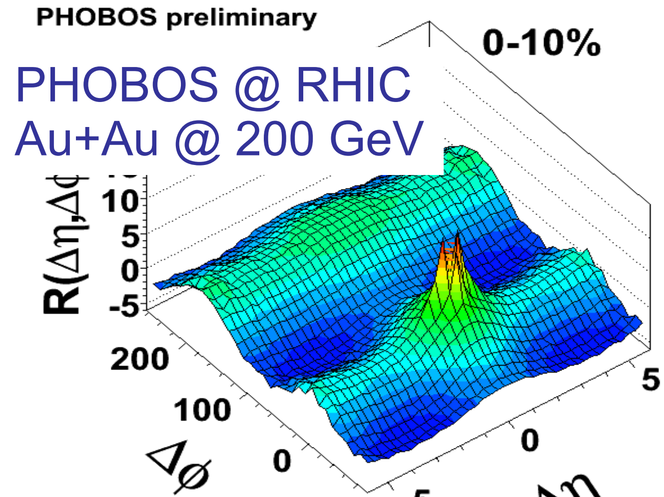


Intermediate p_T: 1-3 GeV/c



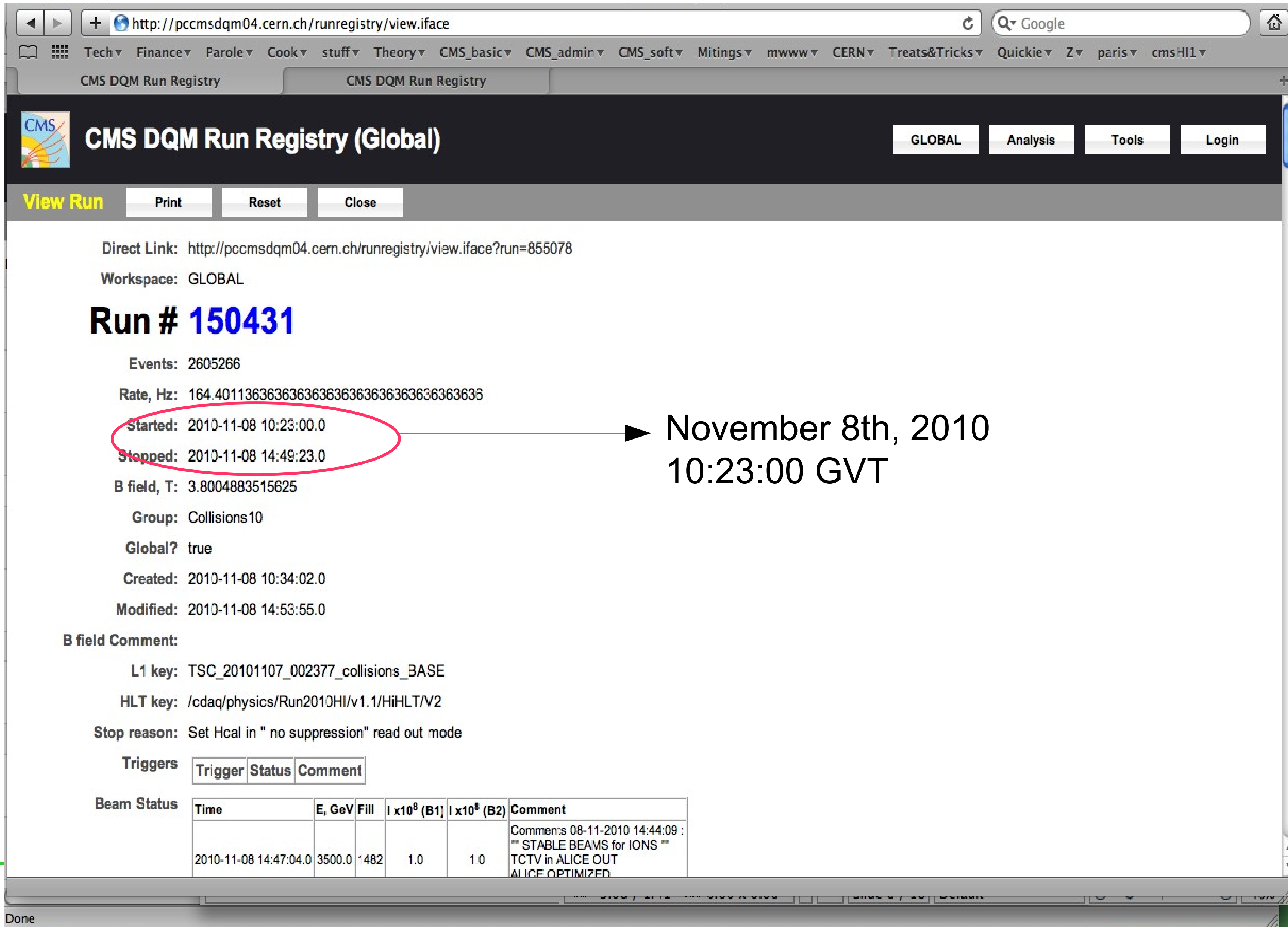


HI Preview? ... pp@7TeV high-multiplicity events



- Hell broke loose!
- Effect similar to the observed in AuAu@200GeV at RHIC
- The result resisted any possible experimental/technical x-checks
- PYTHIA8 (D6T), Madgraph, HERWIG do not include the effect
- The theorists joined the party
  - Initial state correlaitons (“glasma flux tubes”)
  - Hydrodynamic flow of the medium
  - Jet physics with a medium
  - Plain jet physics (angular momentum conservation not accounted for)
- The experimentalist kept saying 'We don not claim QGP formation in pp'

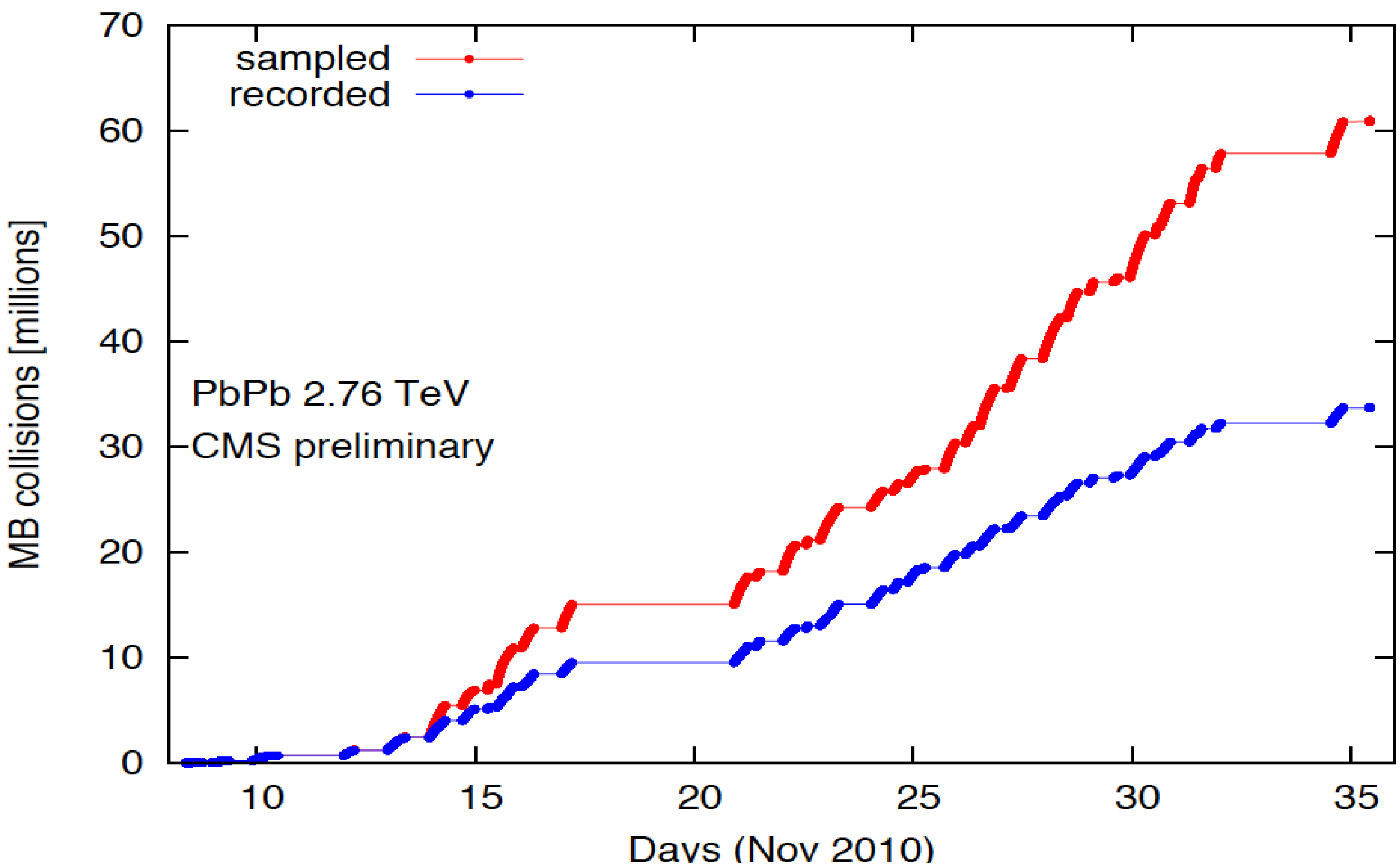
And the real deal started with Pb beams on ...



November 8th, 2010
10:23:00 GVT

And by the end, in December 8th 2010

- Integrated luminosity for HI run, in units of minimum bias collisions (hadronic inelastic collisions)



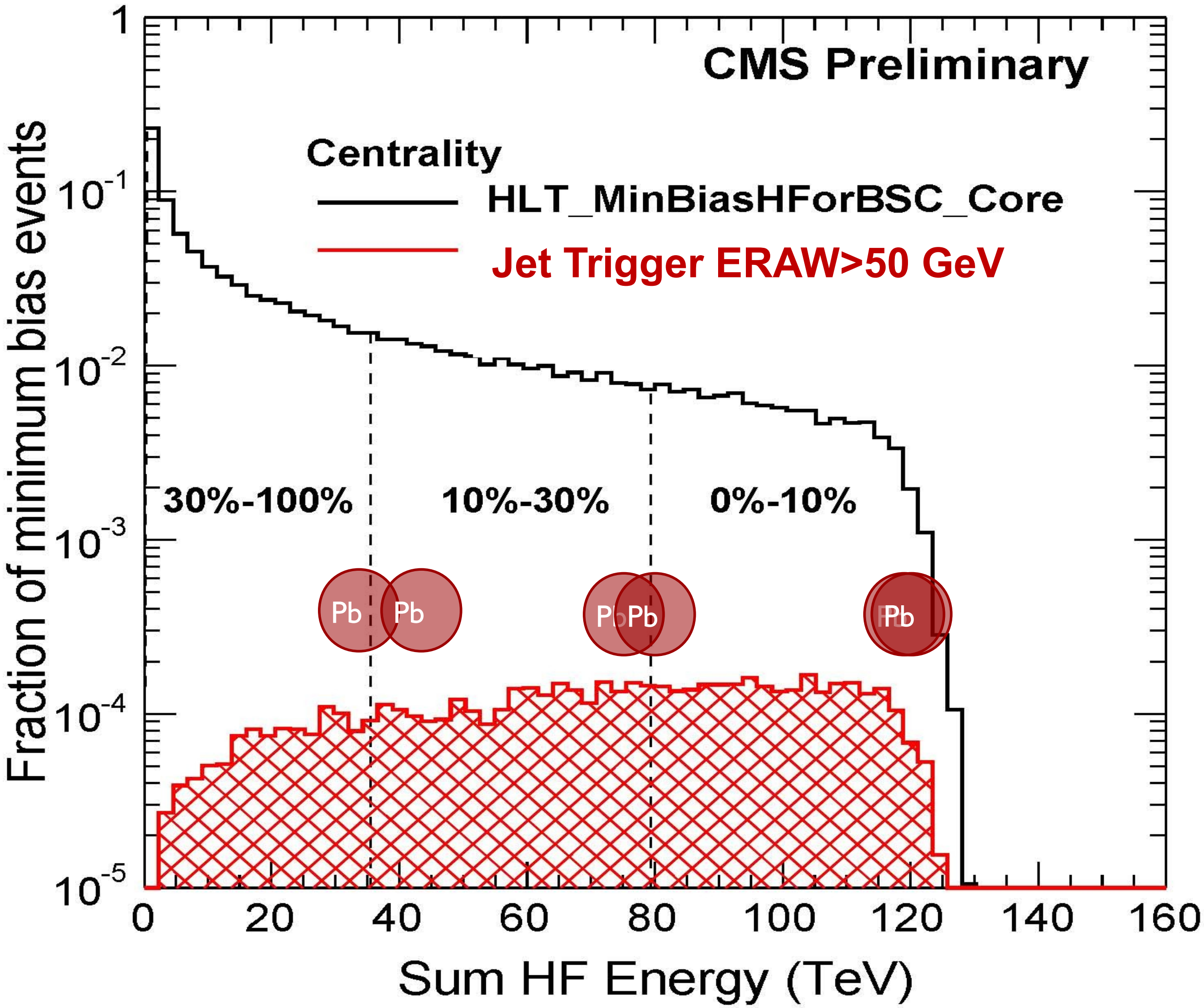
Events selection

- Maximize efficiency for hard-probes:
  - Level 1 Trigger:
    - Coincidence of 2 scintillator counters OR
    - Coincidence of two HF (Hadron Forward calorimeter) towers
    - Jets and (di)muons
  - High Level Trigger :
    - Jets
    - Muons
    - Photons
- Minimize backgrounds:
  - Veto on scintillator beam halo
  - At least 3 HF towers on each side above threshold
  - Reconstructed pixel vertex with two or more tracks
  - Beam-scraping removal with pixel cluster vertex compatibility

N_mb: 55mil events ---> Lumi=7.2 (mub)-1 (assuming Sigma_pbpb=7.65b)

Events classification

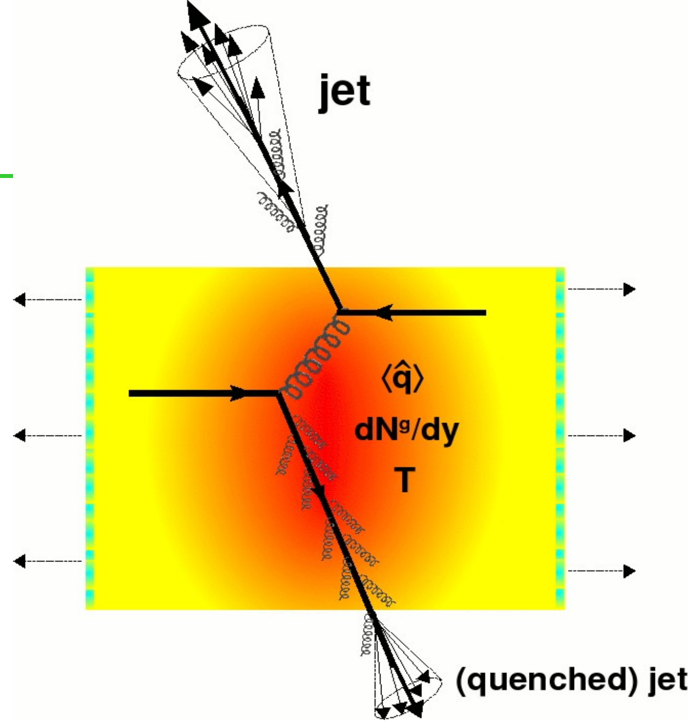
- Centrality – based on energy deposition in forward calorimeters (HF)

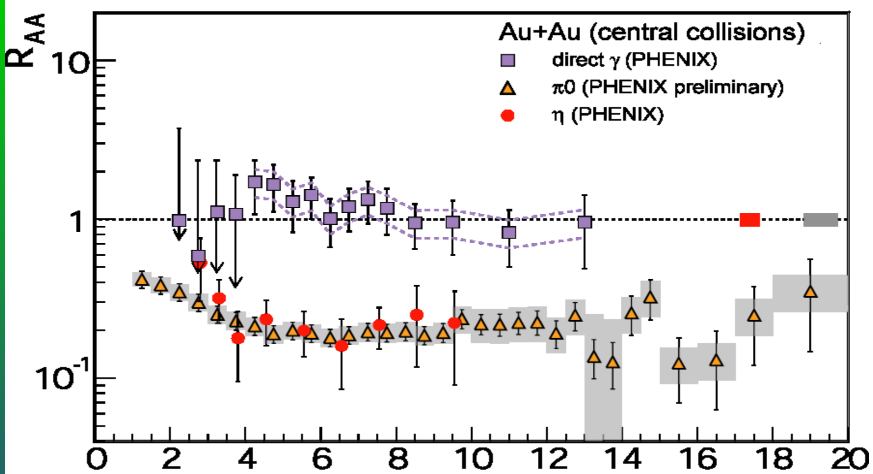


- Jets

Jets in HI: RHIC (~10 years)

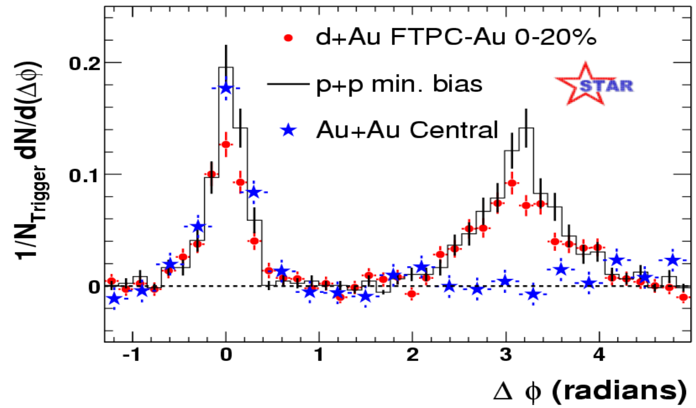
- RHIC: sqrt(s_NN) = 200GeV/A
- indirectly (until recently)
  - via single particle spectra
  - and angular correlations





$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

Average number of NN collision in an AA collision

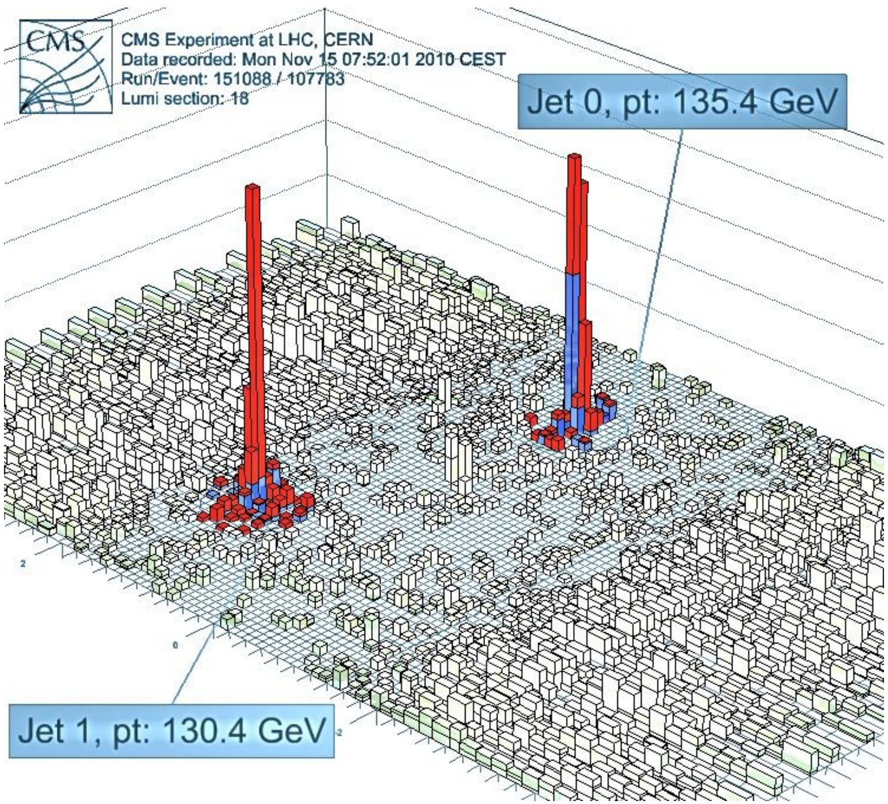


- Azimuthal distribution of particles with 2<pT<pT trigger
- Trigger particle with 4<pT trigger <6 GeV/cc

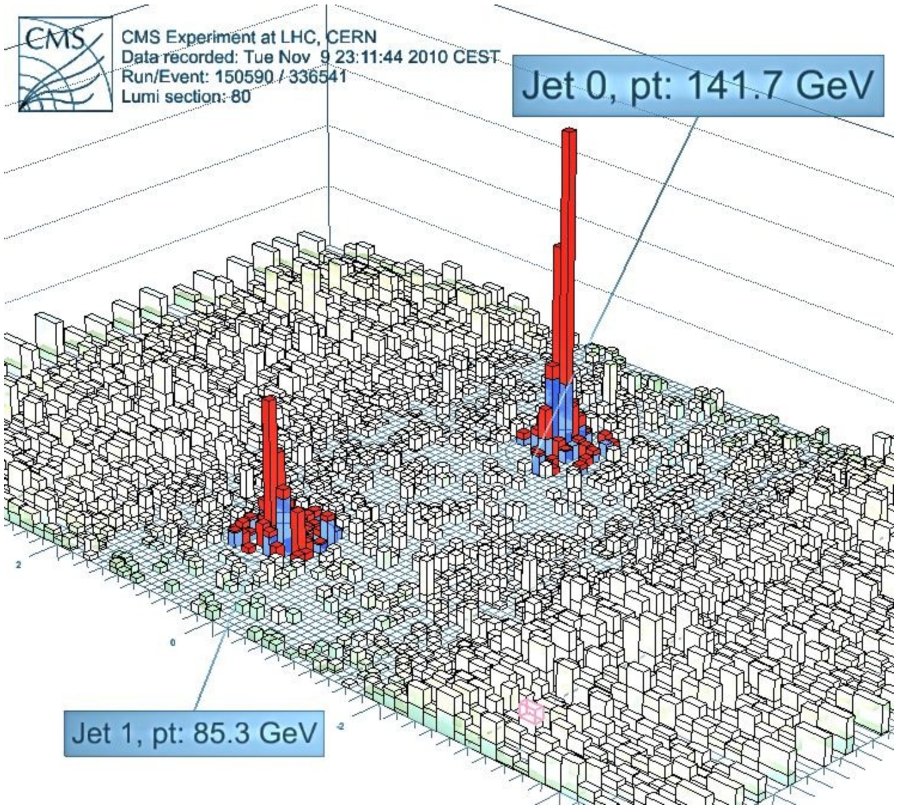
STAR collaboration, Phys. Rev. Lett. 91 (2003) 072304

Jets in HI: LHC (first hours)

- DIJETS



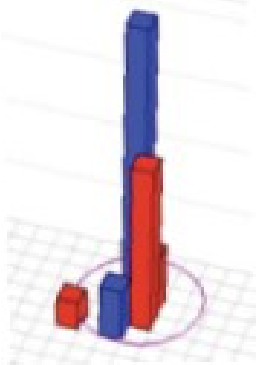
- ... and DIJETS.

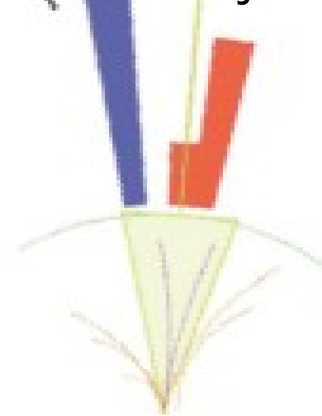
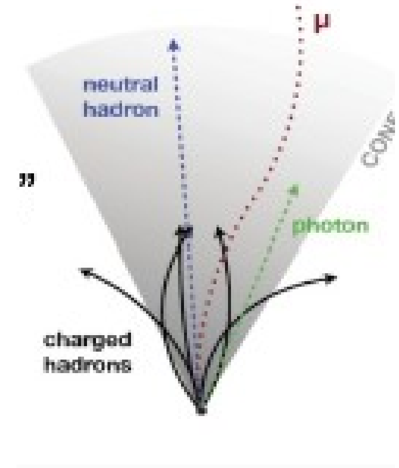


What is going on ?!

CMS Jet reconstruction

- Type
  - Calorimetric Jets (CaloJetS): ECAL and HCAL deposits
  - Track Jets: charged tracks
  - Jet-Plus-Track Jets(JPT): calo jets + tracks
  - Particle-Flow Jets(PFJet): cluster particle flow objects



- Algorithms
  - Iterative cone & anti-kT with background subtraction
  - FastJet (kT, anti-kT, etc) with internal bkg subtraction

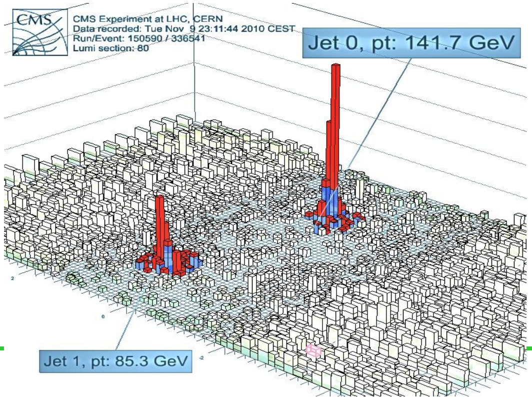
- Special care in HI: Background subtraction
  - Large 'underlying event' activity, that depends on the multiplicity/centrality → specific bkg subtraction procedures

Dijets: selection

- Jets
  - Reconstructed
    - IC5 CaloJet with iterative bkg subtraction with R=0.5
  - |eta|<2 (avoid edges)
  - |phi1-phi2|>2.5 (back-to-back)
- Leading jet: ET>120GeV (trigger is fully efficient)
- Sub-leading jet: ET>50GeV ((believe) above bkg fluctuations)

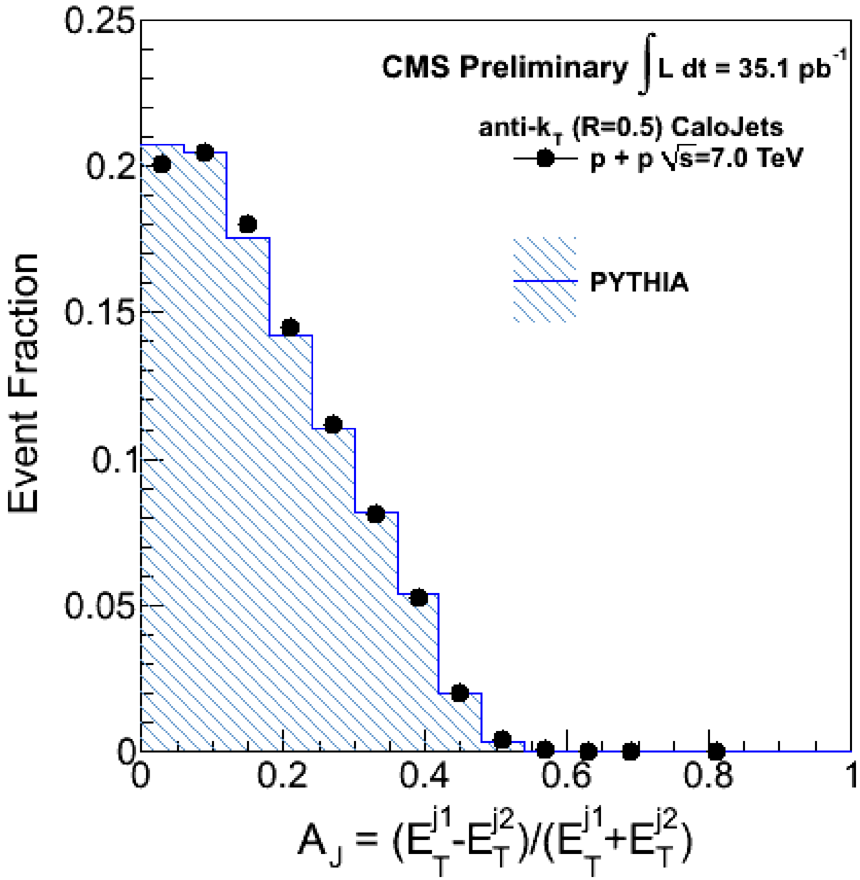
- Look at jet energy asymmetry distributions over many events:

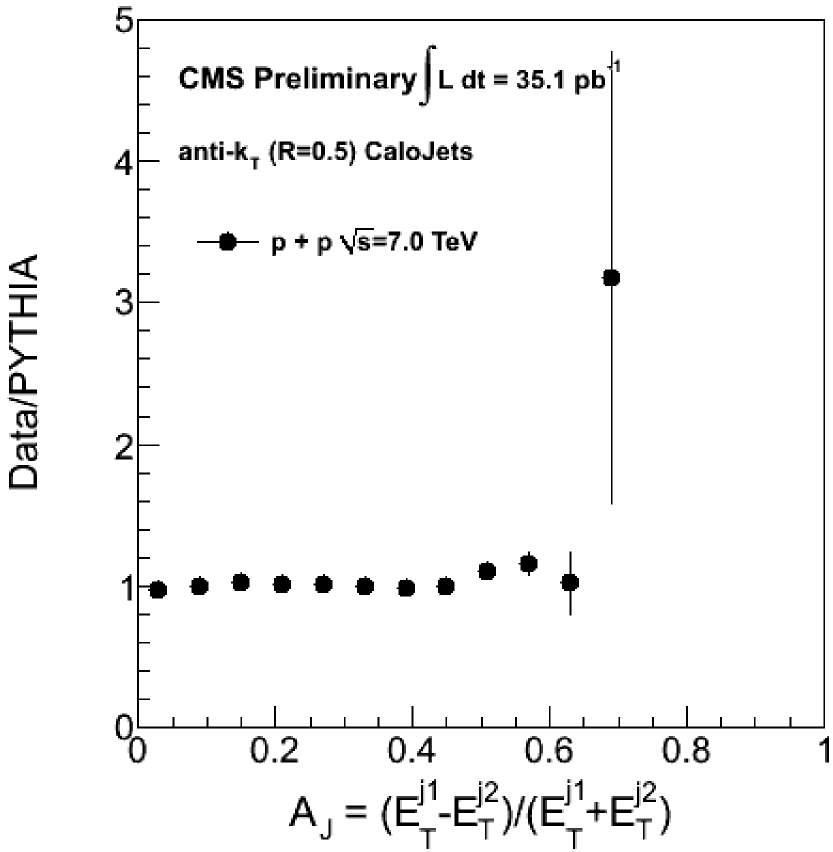
$$A_J = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$$



Dijets: vacuum/pp reference

- CMS pp@7TeV





→ Excellent agreement between PYTHIA and CMS pp@7TeV data

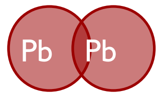
→ Use PYTHIA as a reference at 2.76 TeV

Dijets: HI reference

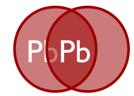
- Reproduce the 'HI underlying event'
  - Embed MC PYTHIA dijets events into REAL DATA events
  - Add simulated response of individual detectors to data events

- Reconstruct the embedded jets and compare to
  - Real data dijets
  - PYTHIA dijets without any background (the vacuum reference)

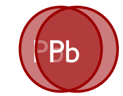
Leading jet ET distributions



Semi-Peripheral



Semi-Central

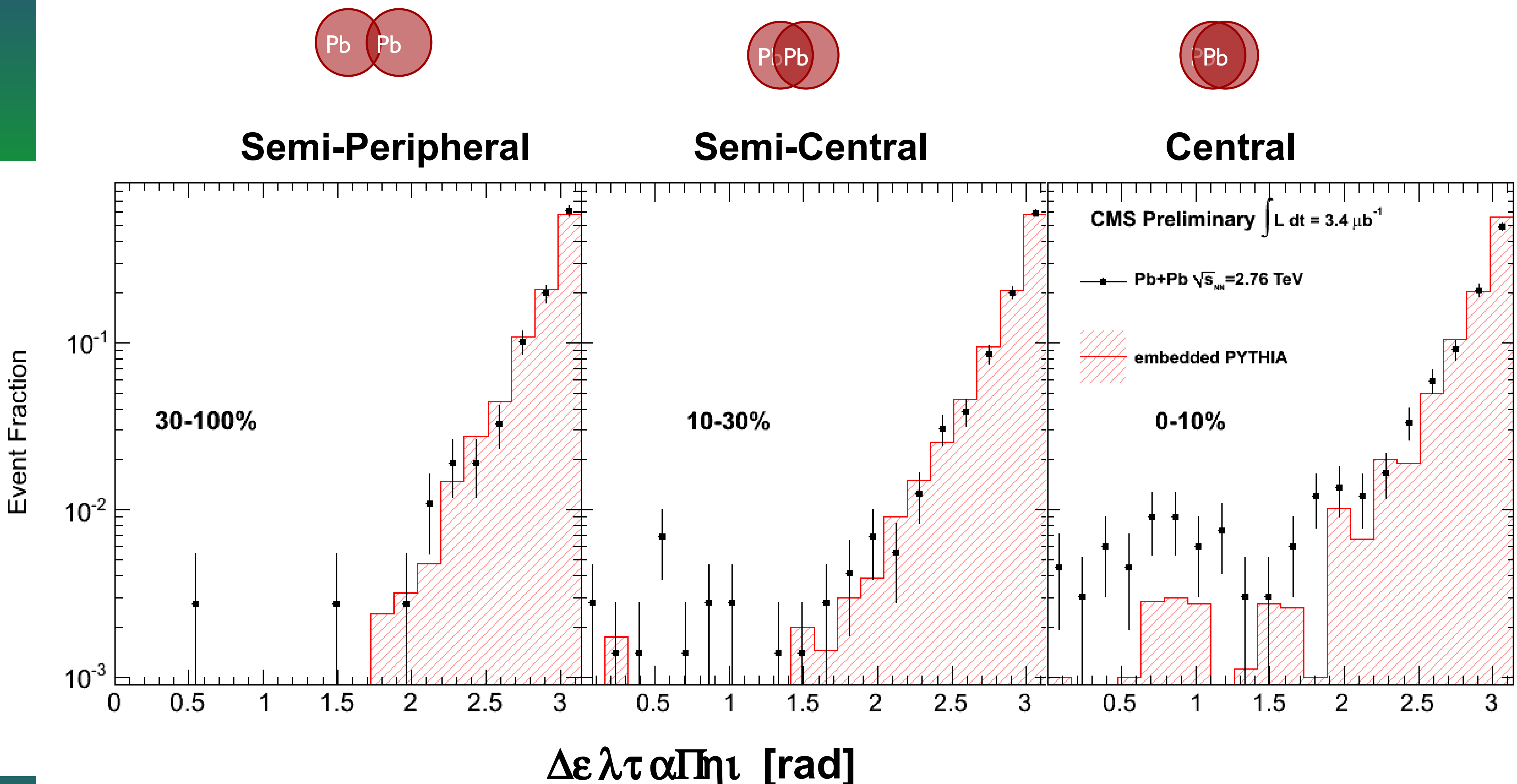


Central

Leading Jet ET (GeV)

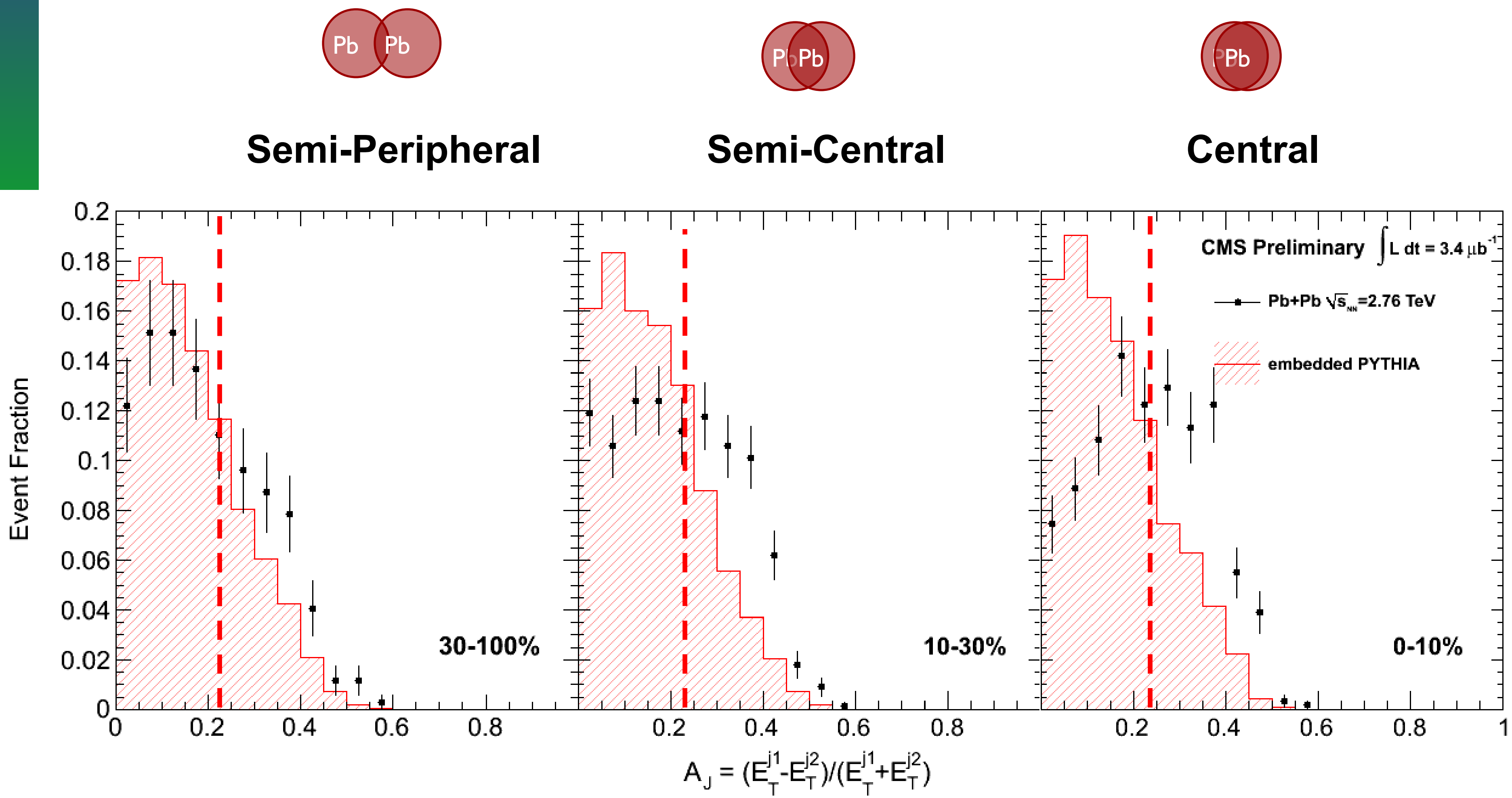
Leading jet ET distribution shape well reproduced by simulations

Azimuthal jet correlation



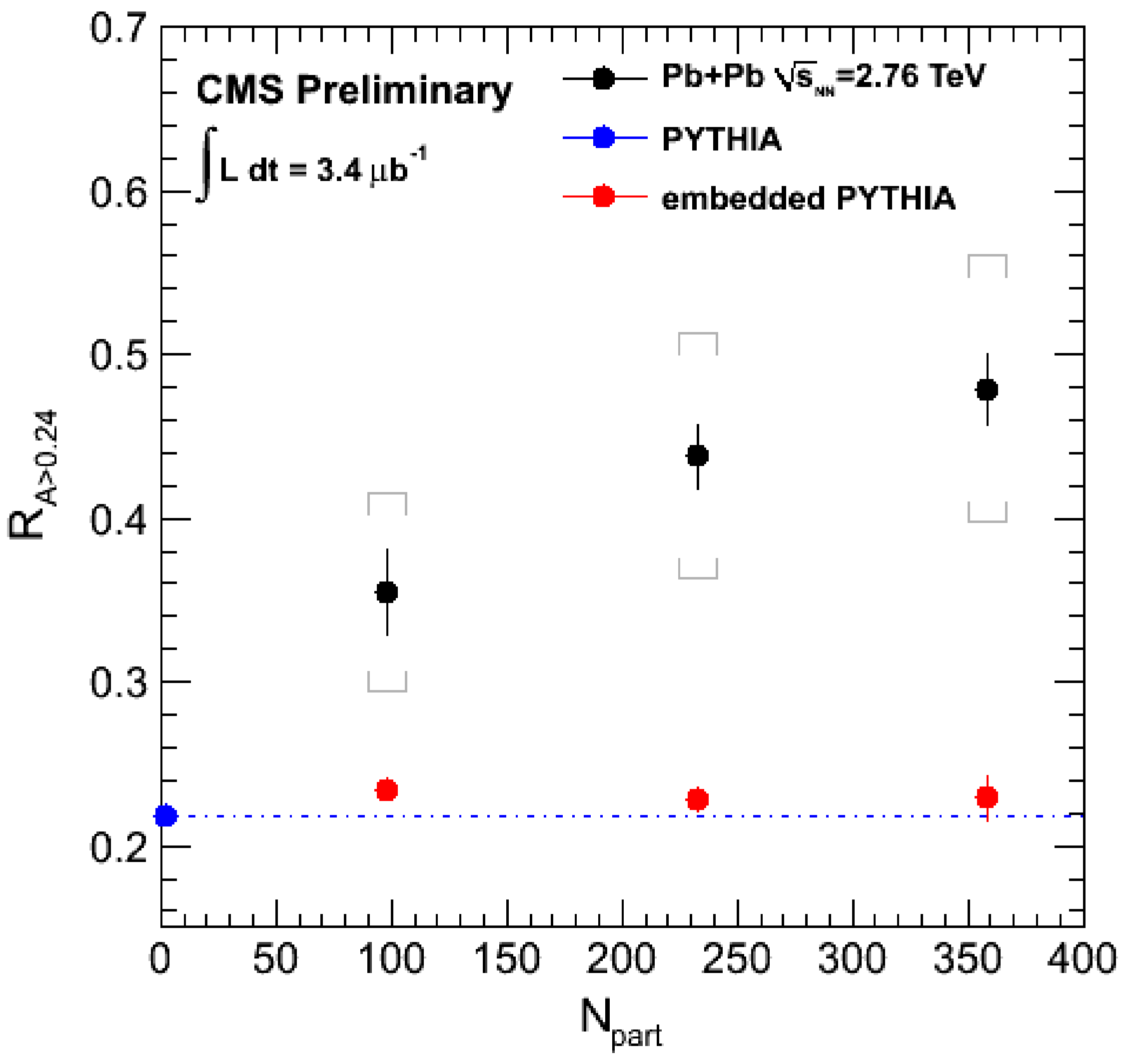
Select back-to-back dijets with Δελταφηι >2.5 for further study

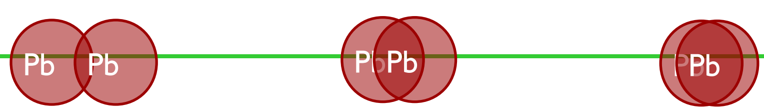
Dijet imbalance



Significant dijet imbalance, well beyond that expected from MC, appears with increasing collision centrality

Dijet imbalance: quantify the effect



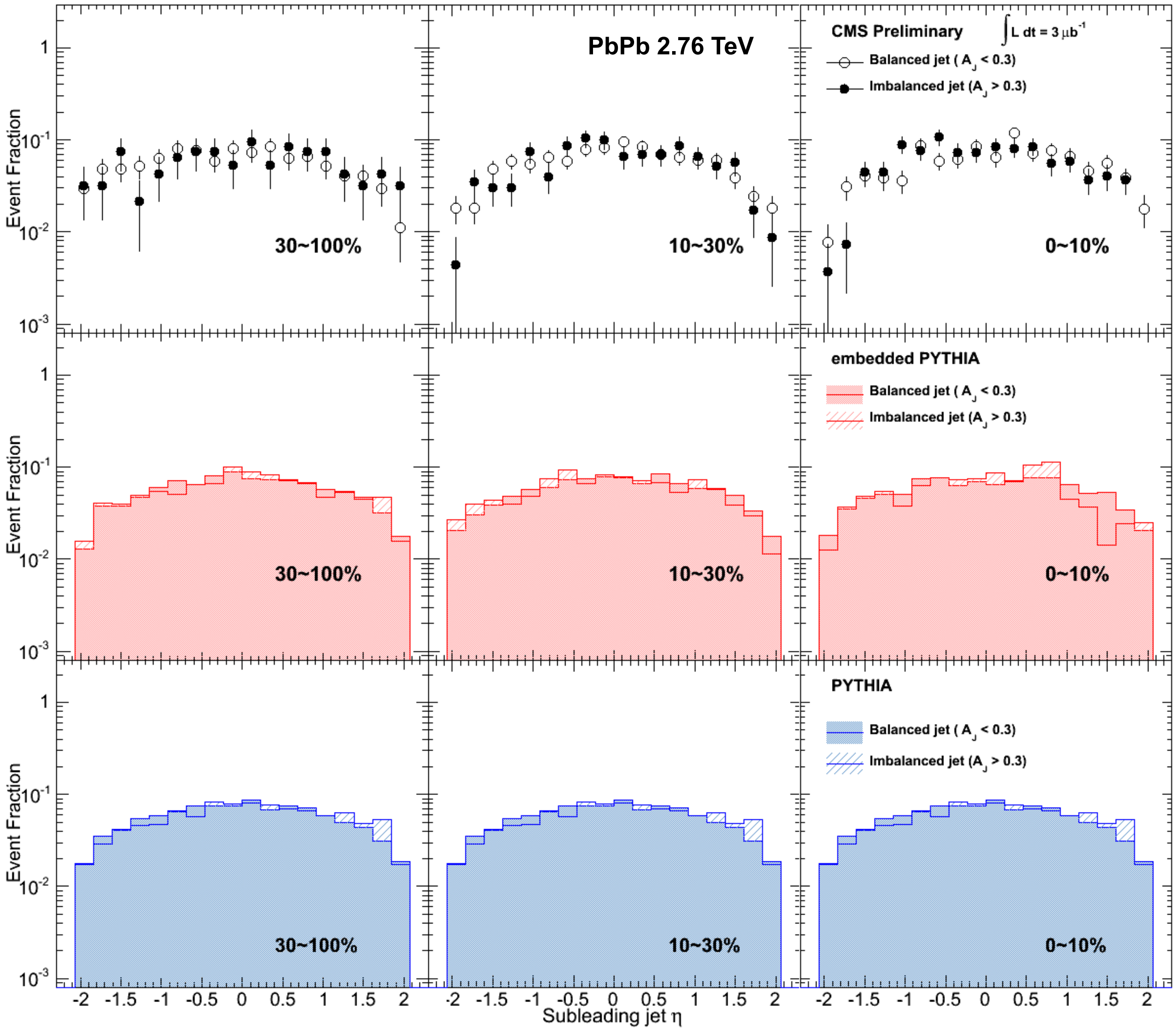


Fraction of jets with imbalance larger than 0.24, as a function of number of participating nucleons averaged over centrality bin.

Dijet imbalance

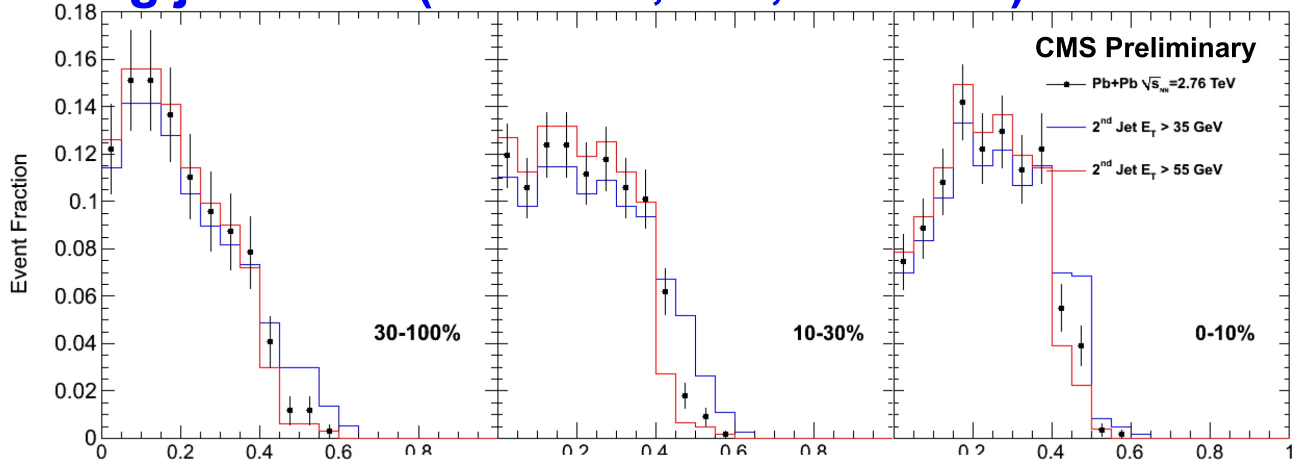
- There is an effect.
- Is it Physics (jet quenching) or … not?
- Robustness checks:
  - Uniformity (eta, phi)
  - Selection biases (different ET)
  - Underlying event subtraction
  - Jet resolution
  - Jet energy corrections
  - Different detector measurement with different reconstruction algo

Imbalance uniformity: pseudorapidity



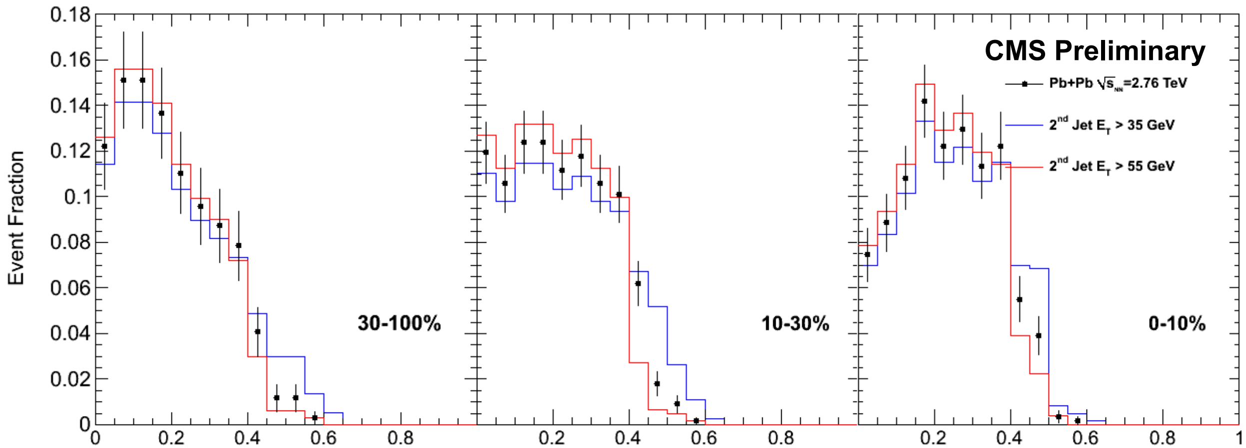
Dijet Imbalance: ET selection bias

Vary the leading jet cutoff (ET = 120, 130, 140 GeV)



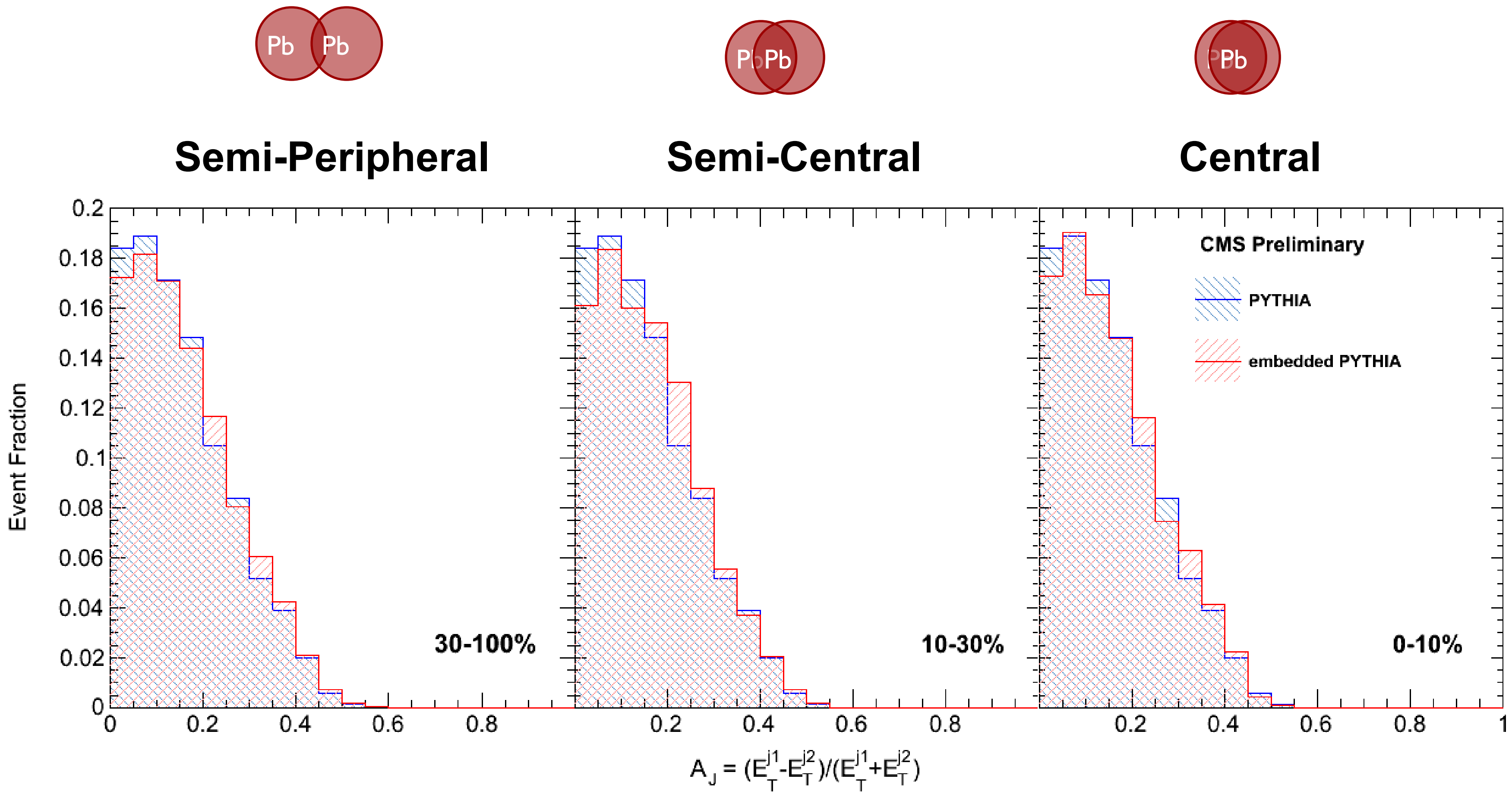
(ET1-ET2)/(ET1+ET2)

Vary the sub-leading jet cutoff (ET = 35, 50, 55 GeV)



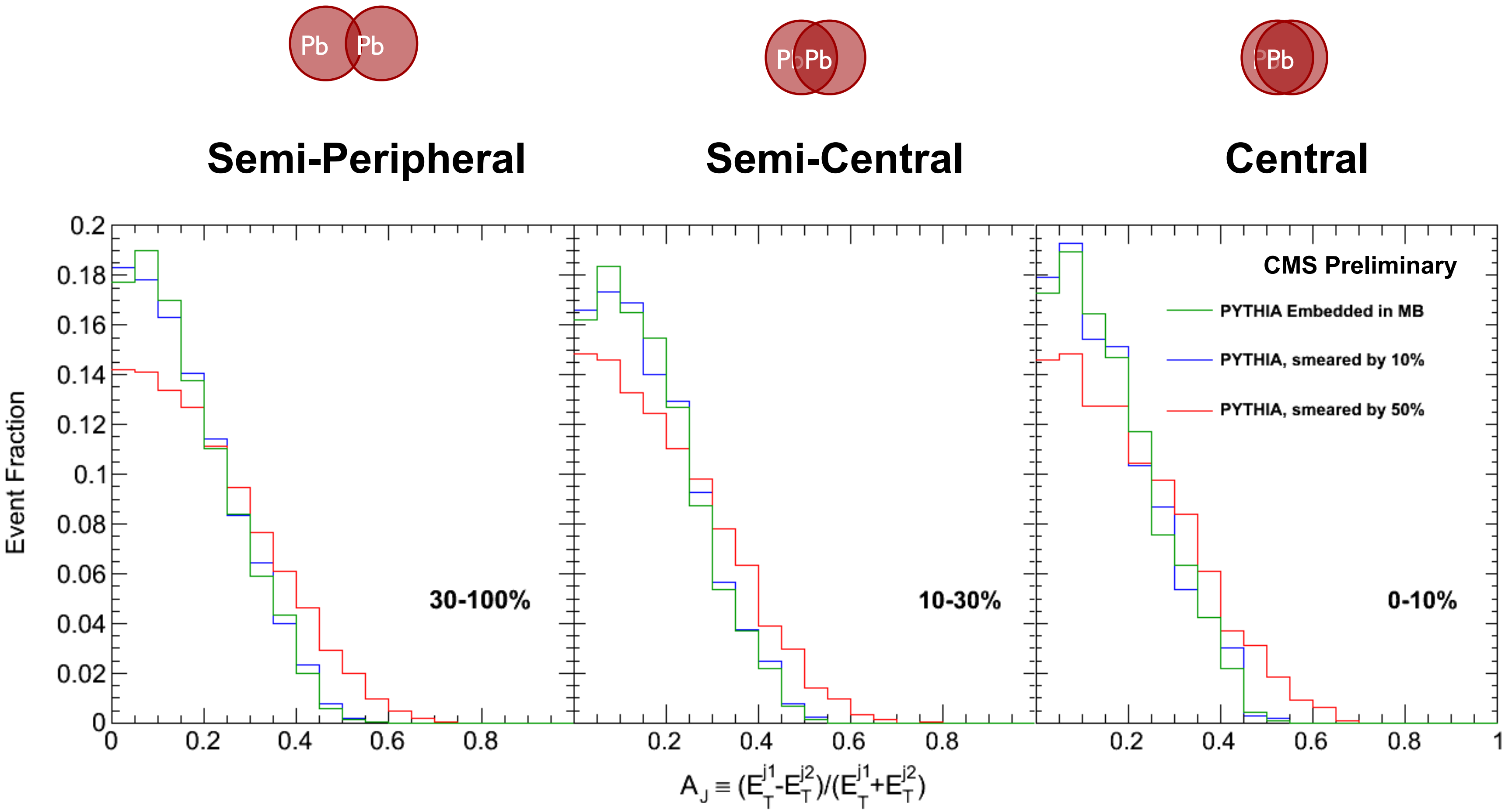
(ET1-ET2)/(ET1+ET2)

Dijet imbalance: underlying event



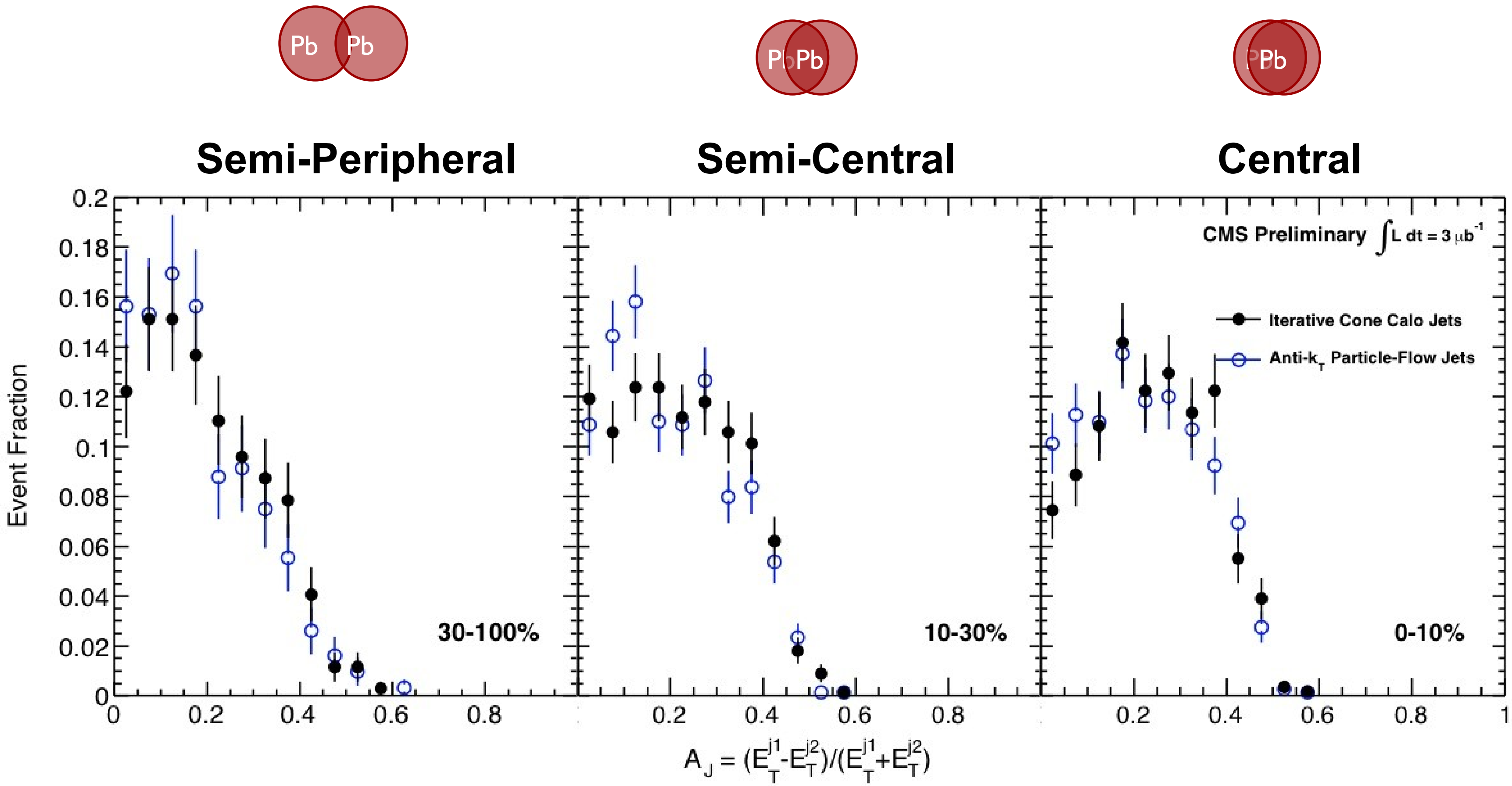
From comparison of simulation with and without embedding: Background subtraction works really well

Dijet imbalance: jet resolution



- **The jet resolution was smeared by 10 and 50% in simulation**

Dijet imbalance: different reconstructed jets



Particle Flow: Extensive use of tracker information, different background subtraction, different jet finder algorithm

Excellent agreement between two very different methods

Jets in HI: CMS

- January 16th:
  - Confident that the dijet imbalanced observed is not an artifact of the way the data was analyzed and events reconstructed (ATLAS arXiv:1011.6182)
  - **Main question: where is the 'missing energy'?**

- January 17th and 5 hypernews messages later:
  - Are you sure you are sure?
  - Matteo Cacciari, Gavin Salam, Gregory Soyez: http://arxiv.org/abs/1101.2878
    - The devil is in the details: fluctuations in the background, in the detector response, etc

- http://arxiv.org/abs/1101.2878

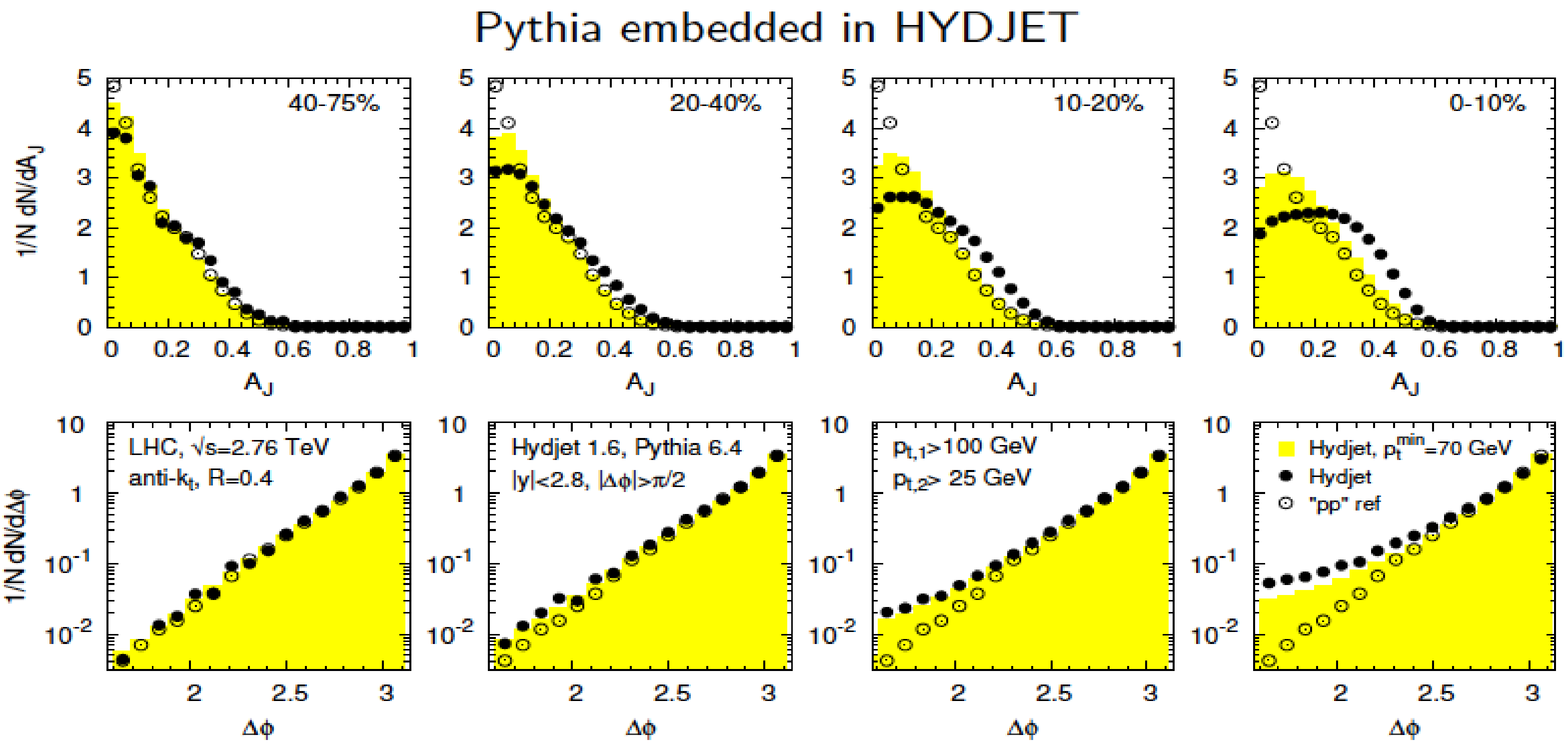
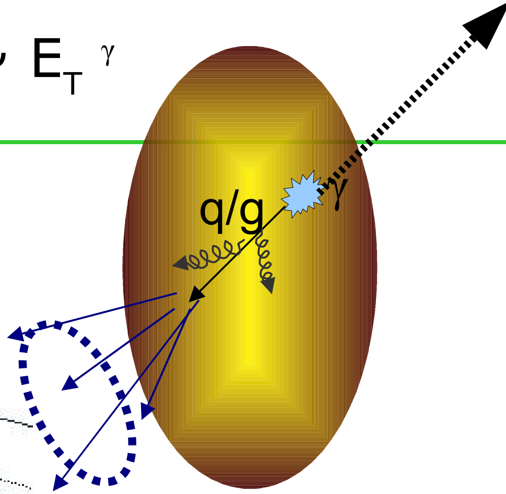
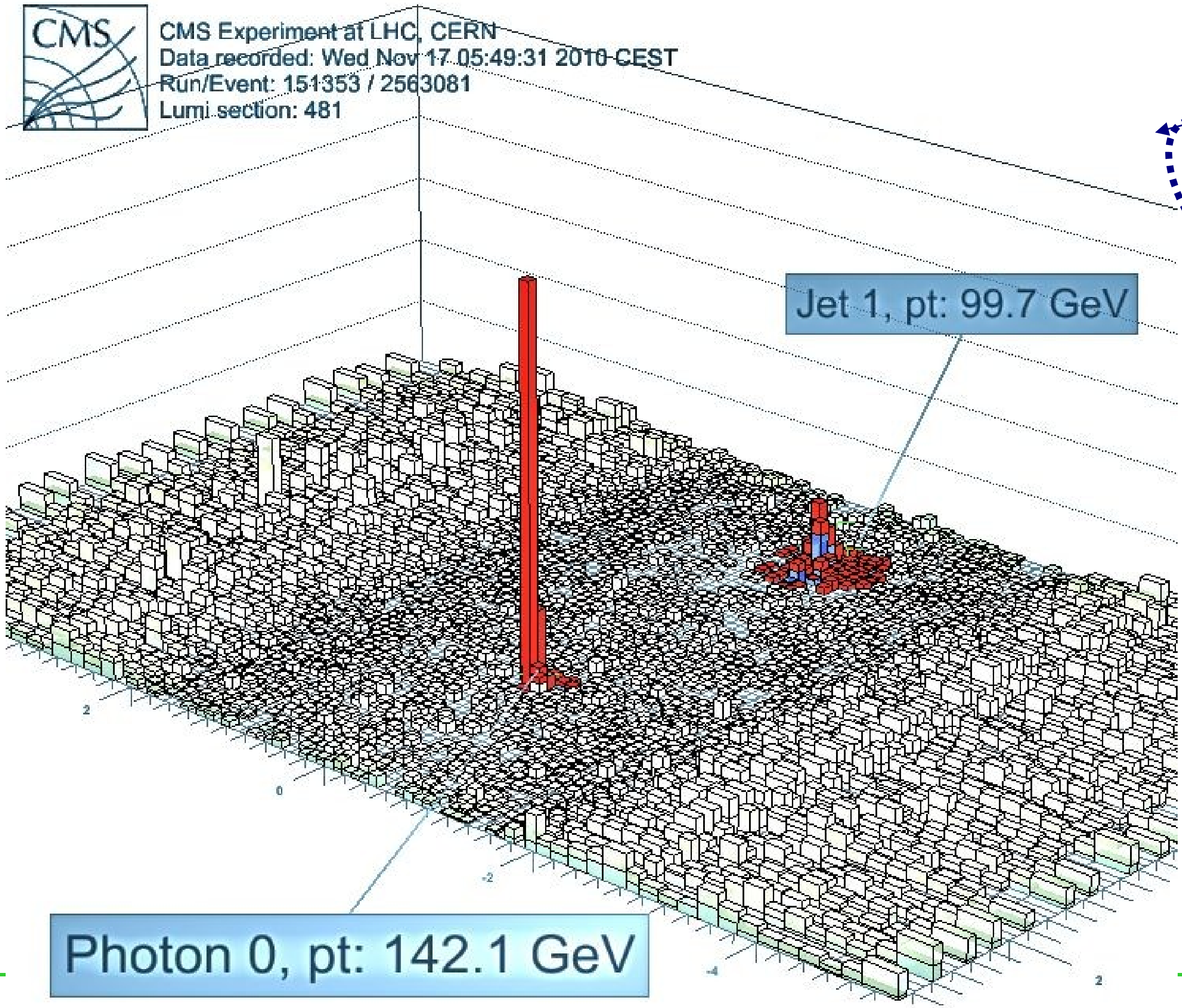


Figure 3: Simulated distribution of A_J and $\Delta\phi$, as obtained when embedding Pythia events in a PbPb background described by HYDJET 1.6. None of the results in this figure involved jet quenching and the results obtained with HYDJET include a simple calorimeter simulation. Four different centrality regions are shown as indicated in the plots on the top row. For each plot there are results from Pythia simulations with two different generation cutoffs on the $2 \to 2$ scattering, $p_t^{\min} = 10\,\text{GeV}$ and $p_t^{\min} = 70\,\text{GeV}$, so as to illustrate its impact. The results labelled "pp" reference always correspond to those of Fig. 2. Jet clustering has been performed with the anti-k_t algorithm [15] with $R = 0.4$, as implemented in FastJet [16] and the heavy-ion background subtraction has been performed as described in [9] with the background density estimated using a StripRange of half-width 0.8 centred on the jet being subtracted.

Control probe: photon+jet

$E_T^{parton} \sim E_T^{\gamma}$



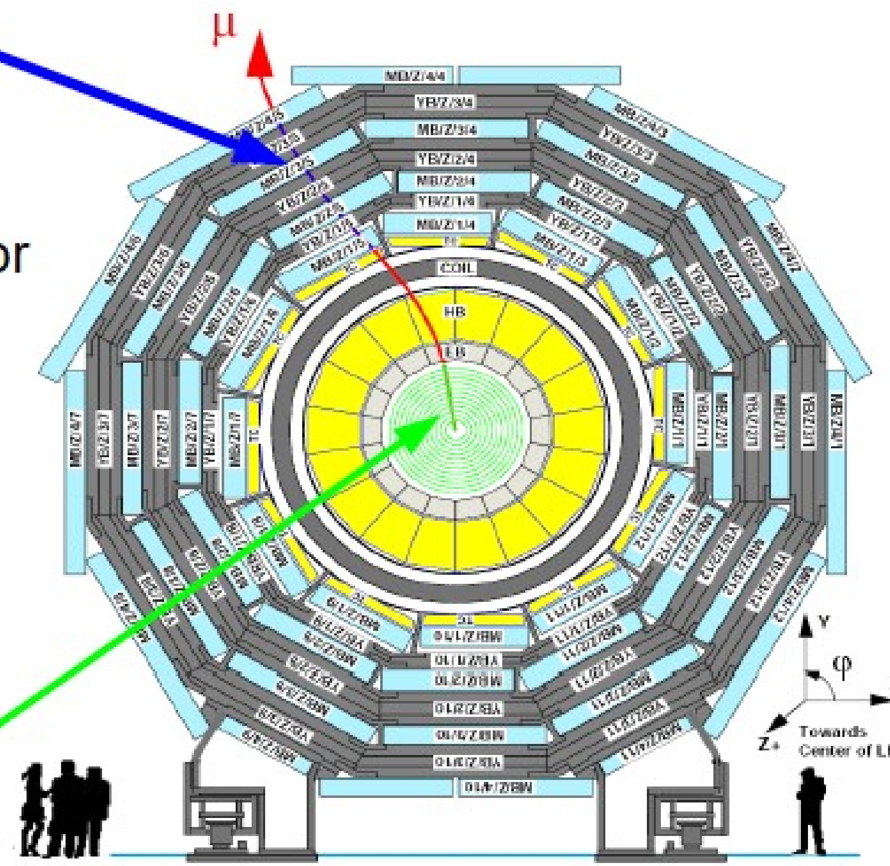


More on this, next year...

- Dimuons

CMS Muon reconstruction

Stand Alone Muon: a reconstructed track in the muon detector only



Global Muon: a reconstructed track through the tracker and the muon detector

- Combined (global) fit to hits in both the tracker and muon spectrometer
- Seeded by a Stand Alone Muon and a tracker-track

Tracker Muon: a reconstructed track in the tracker that is loosely matched to segments in the muon detector

- No combined (global) fit needs to be performed. No Stand Alone Muon needs to be reconstructed.

CMS: JPsi->$\mu^+\mu^-$

- From SPS->RHIC->LHC: no clear/unique understanding of J/Ψ production
  - make as many differential measurements in as broad as possible kinematical regions
- Things not clear in pp either (the baseline):
  - **CMS: arXiv:1011.4193**

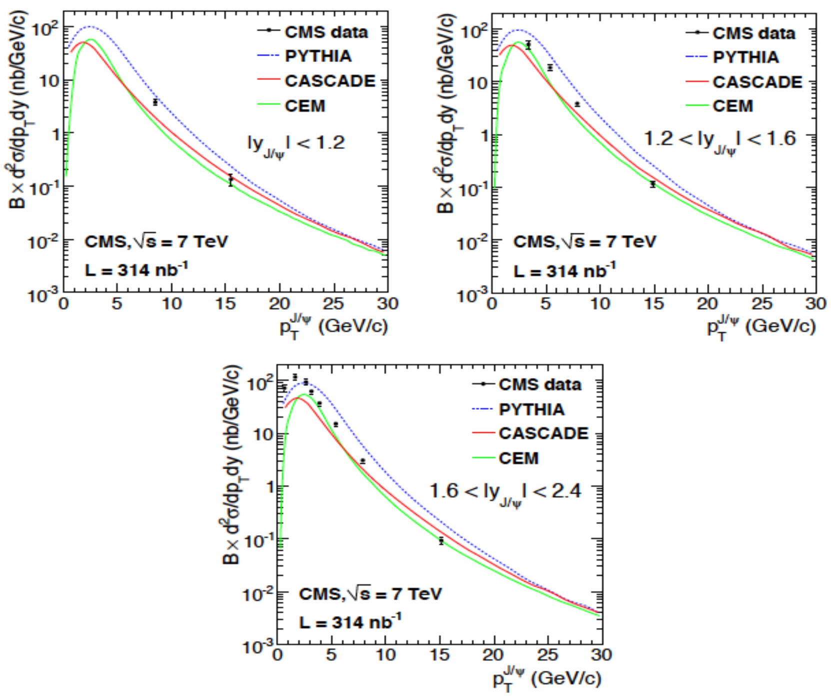


Figure 6: Differential prompt J/ψ production cross section, as a function of p_T for the three different rapidity intervals. The data points are compared with three different models, using the PYTHIA curve to calculate the abscissa where they are plotted [48].

CMS pp: JPsi->$\mu^+\mu^-$

CMS: arXiv:1011.4193

- Different production sources:
  - Prompt: direct production, from χ_C and ψ' decays
    - $$\sigma(pp \to J/\psi + X)\cdot BR(J/\psi \to \mu^+\mu^-) = 70.9 \pm 2.1(\text{stat}) \pm 3.0(\text{syst}) \pm 7.8(\text{luminosity})\ \text{nb}$$
  - Secondary: from B decays
    - $$\sigma(pp \to bX \to J/\psi X)\cdot BR(J/\psi \to \mu^+\mu^-) = 26.0 \pm 1.4\ (\text{stat}) \pm 1.6\ (\text{syst}) \pm 2.9\ (\text{luminosity})\ \text{nb}$$

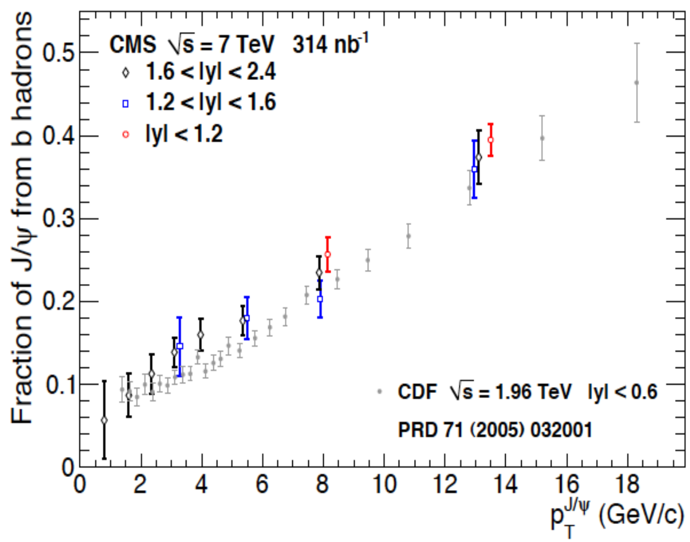


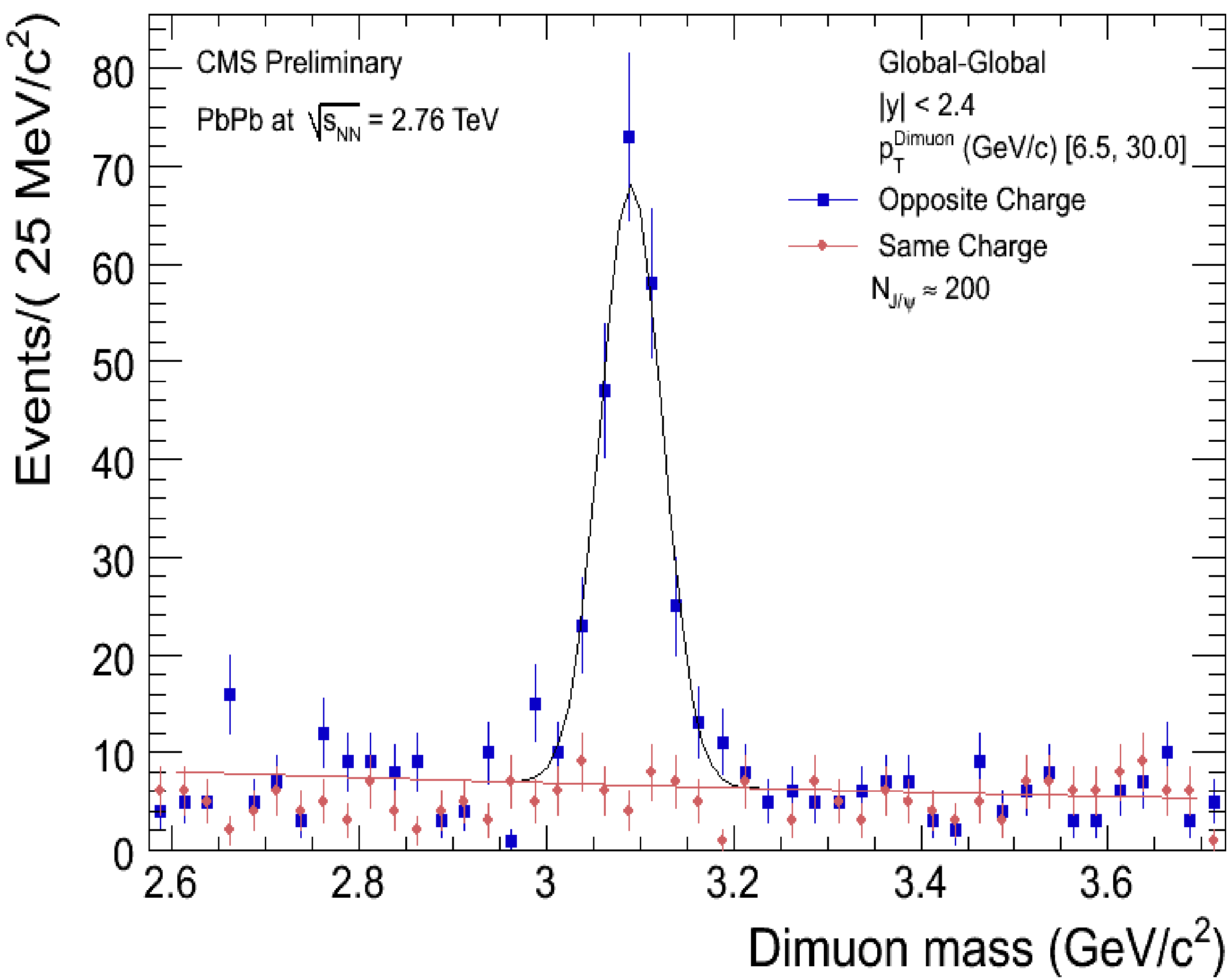
Figure 5: Fraction of the J/ψ production cross section originating from b-hadron decays, as a function of the J/ψ p_T, as measured by CMS in three rapidity bins and by CDF, at a lower collision energy.

|y|<2.4

pT [6.5,30]GeV/c

- Additional complications in HI: energy loss (both B and c)
- Not trivial.

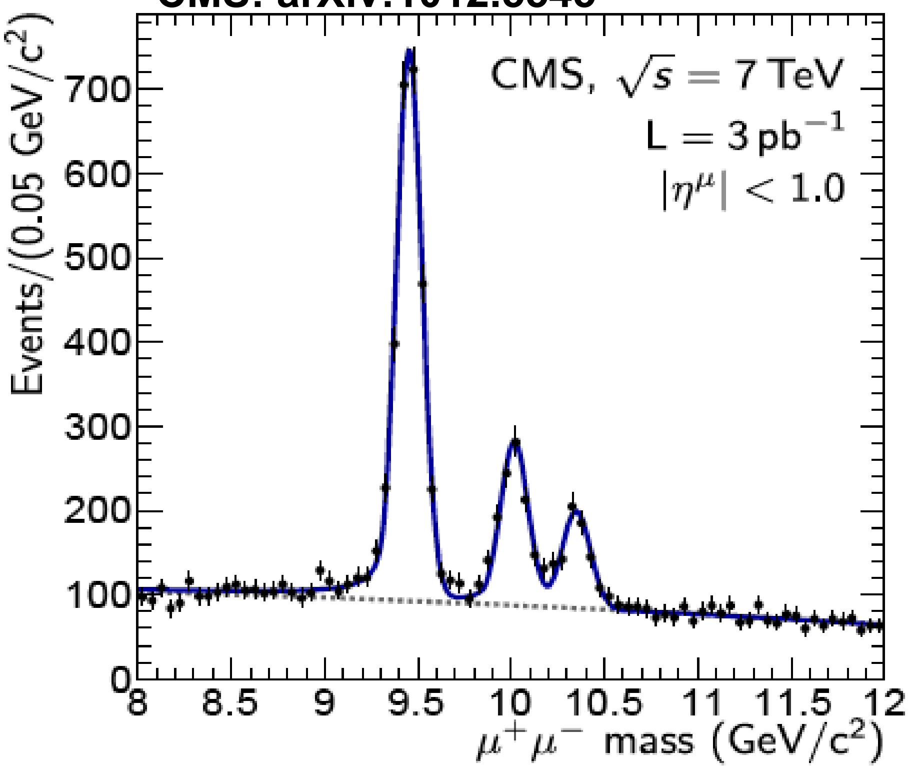
CMS HI Teaser:
first look at Jpsi->$\mu^+\mu^-$ (prompt+non-prompt)

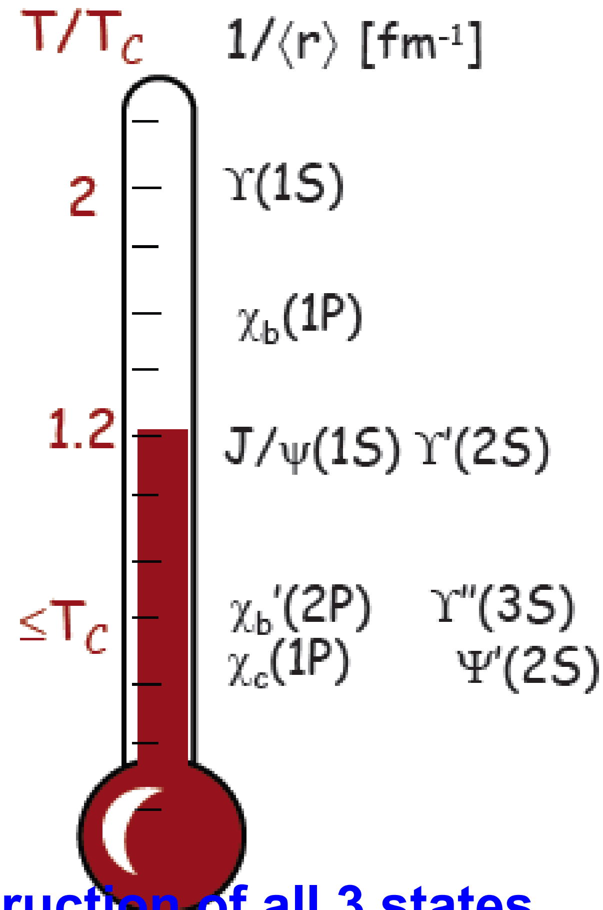


CMS: Upsilon->$\mu^+\mu^-$

- Successive melting of the 3 bound states, can act as a thermometer of the QGP
- At RHIC, just a handful (<100 in AuAu@200GeV, in ee channel)

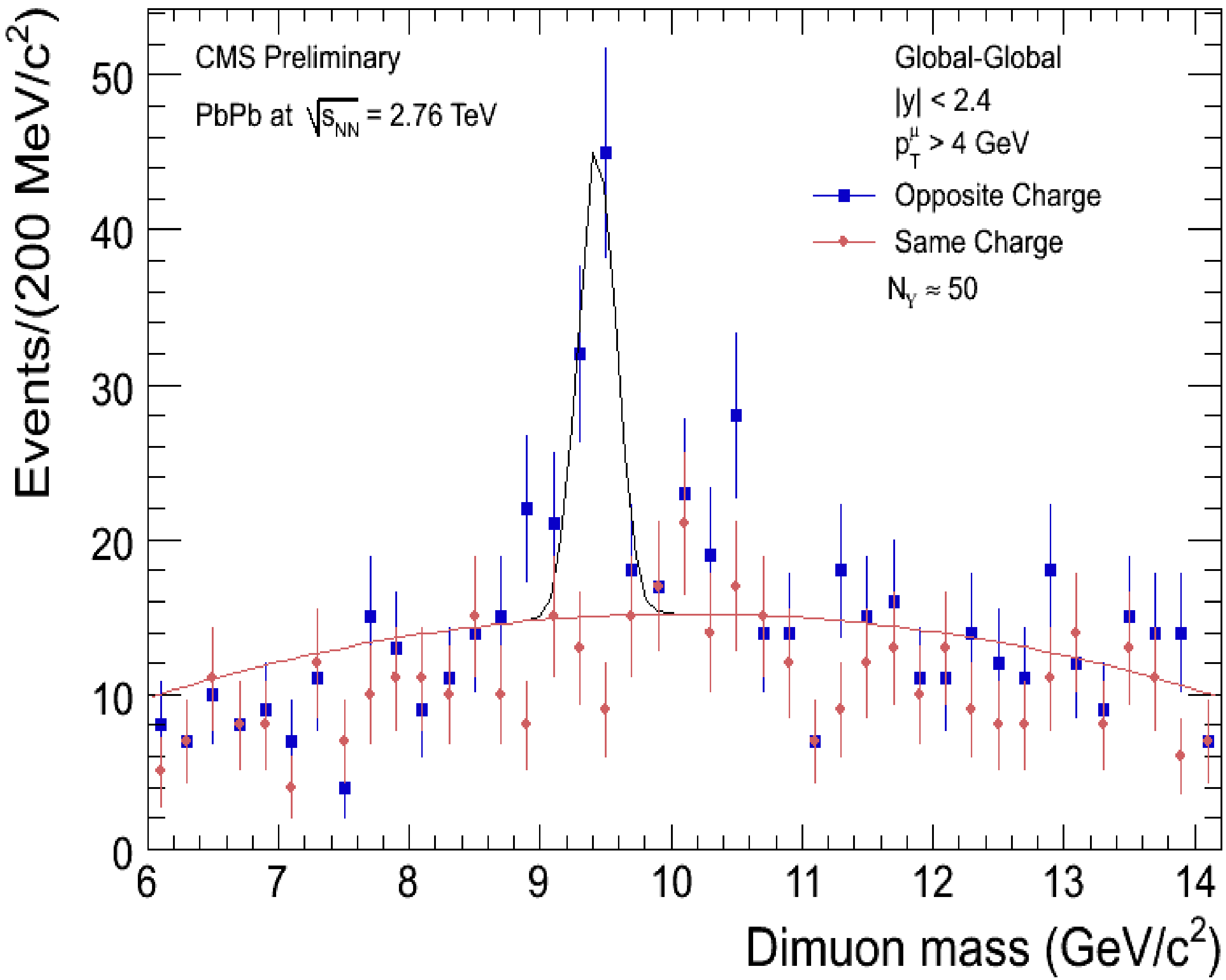
CMS: arXiv:1012.5545





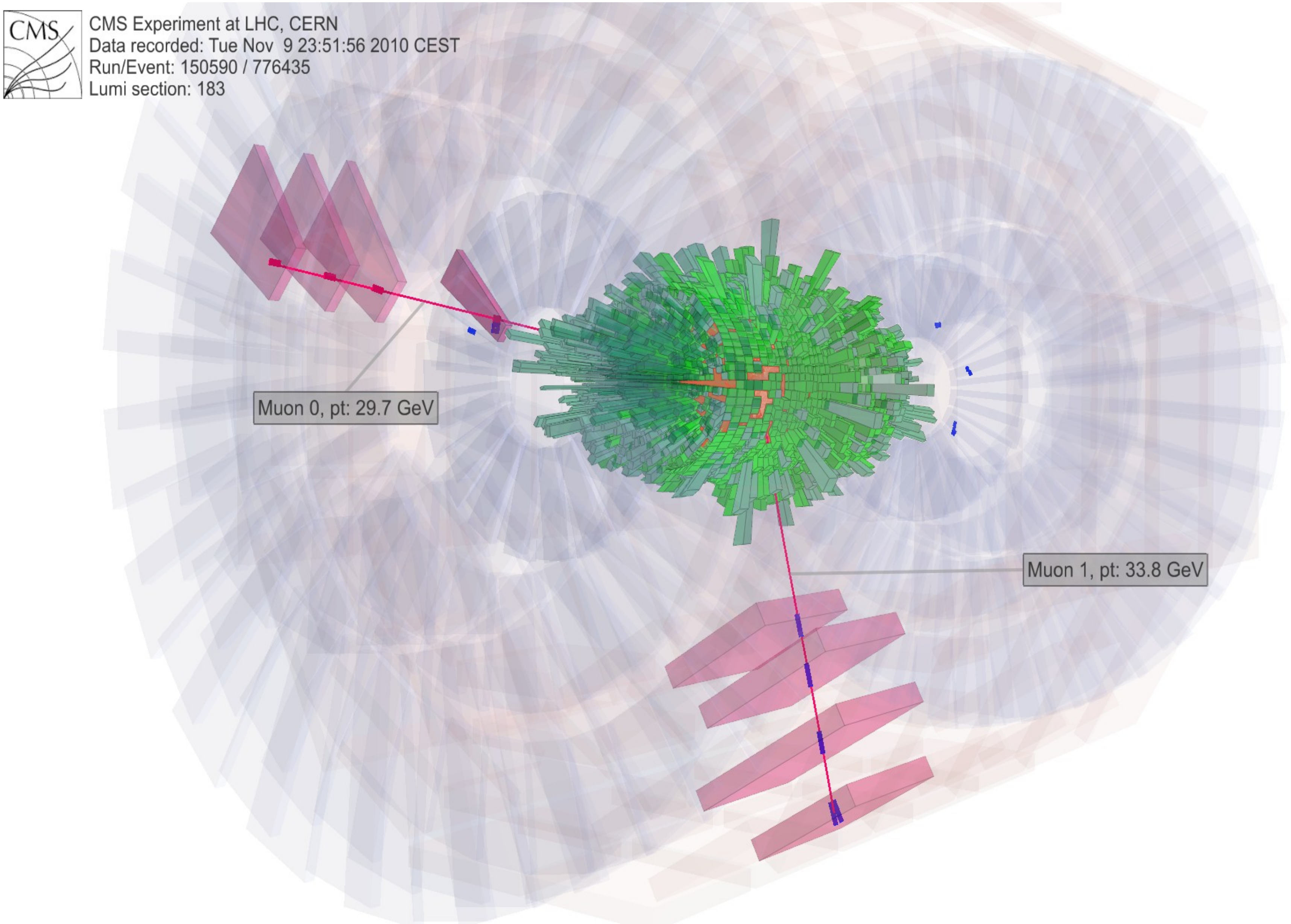
The CMS detector resolution allowes the reconstruction of all 3 states

CMS HI Teaser:
first look at Upsilon->$\mu^+\mu^-$



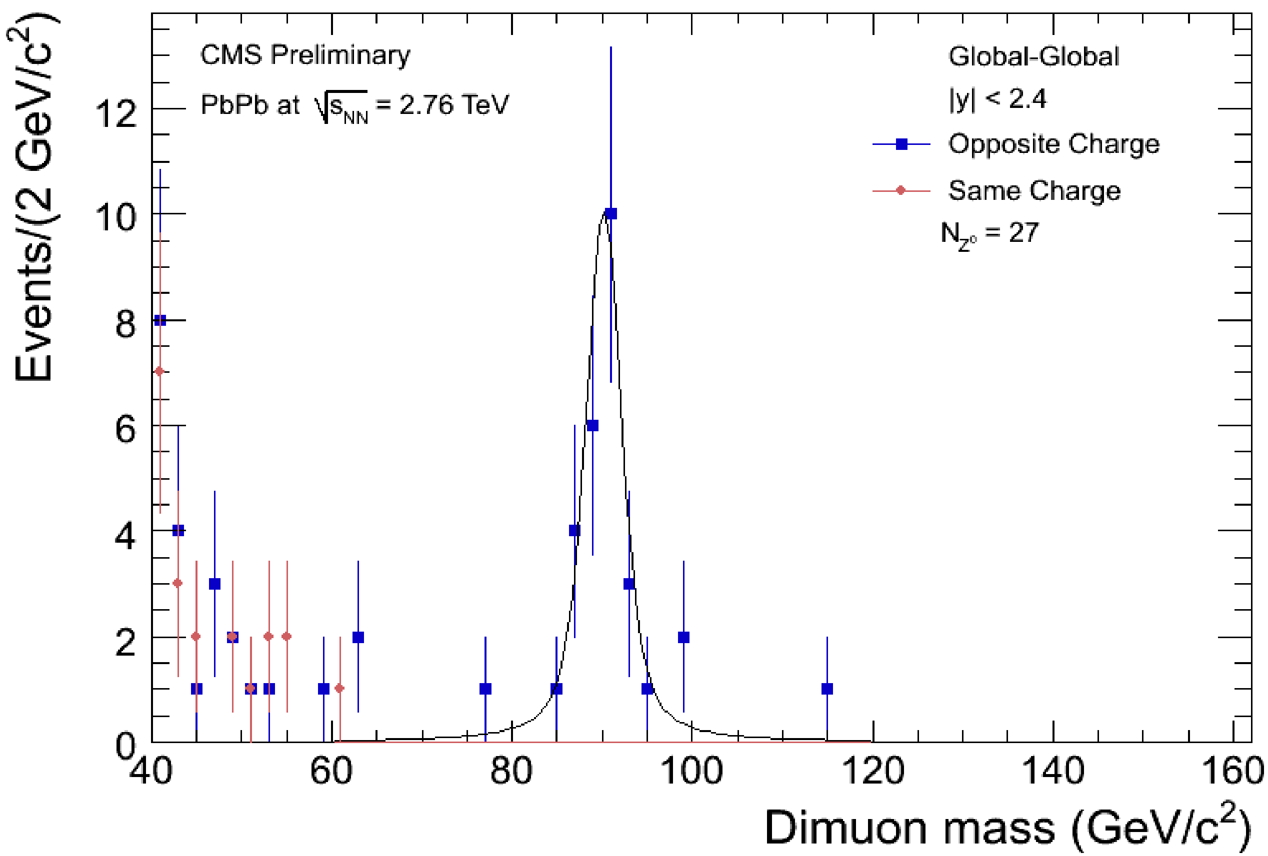
Might need to wait for next year to get more data though ;)

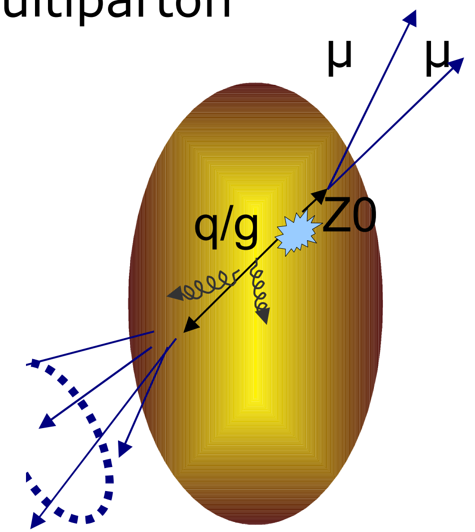
CMS HI: Z->mumu


CMS
CMS Experiment at LHC, CERN
Data recorded: Tue Nov 9 23:51:56 2010 CEST
Run/Event: 150590 / 776435
Lumi section: 183
Muon 0, pt: 29.7 GeV
Muon 1, pt: 33.8 GeV

CMS HI: $Z^0(\mu^+\mu^-)$

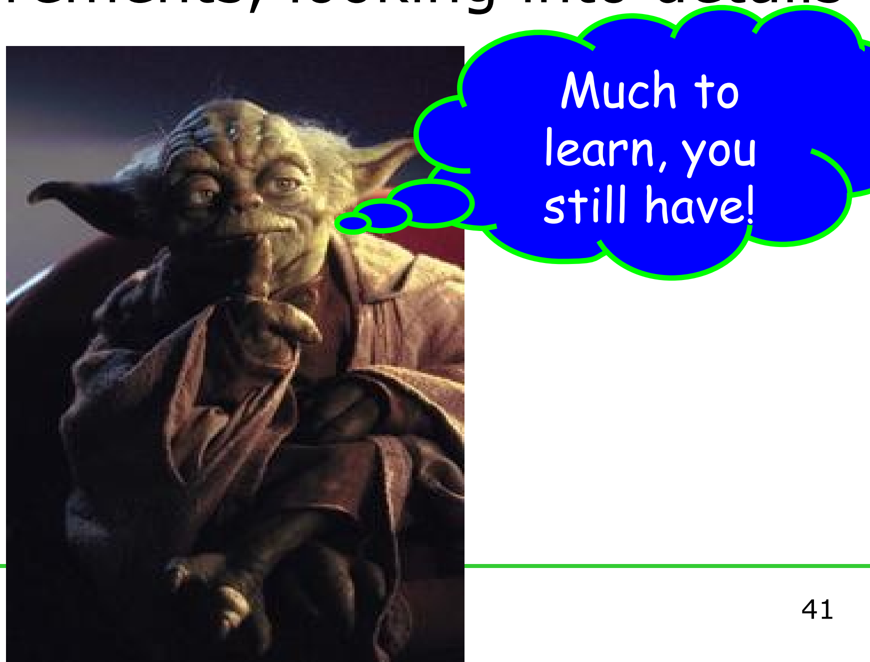
- Control probe of the medium (like photons, just much easier to reconstruct): for jets, or other processes
- Probe of initial state effects: modification of PDFs, multiparton scattering, energy loss …
- It was never measured before in HI





Summary

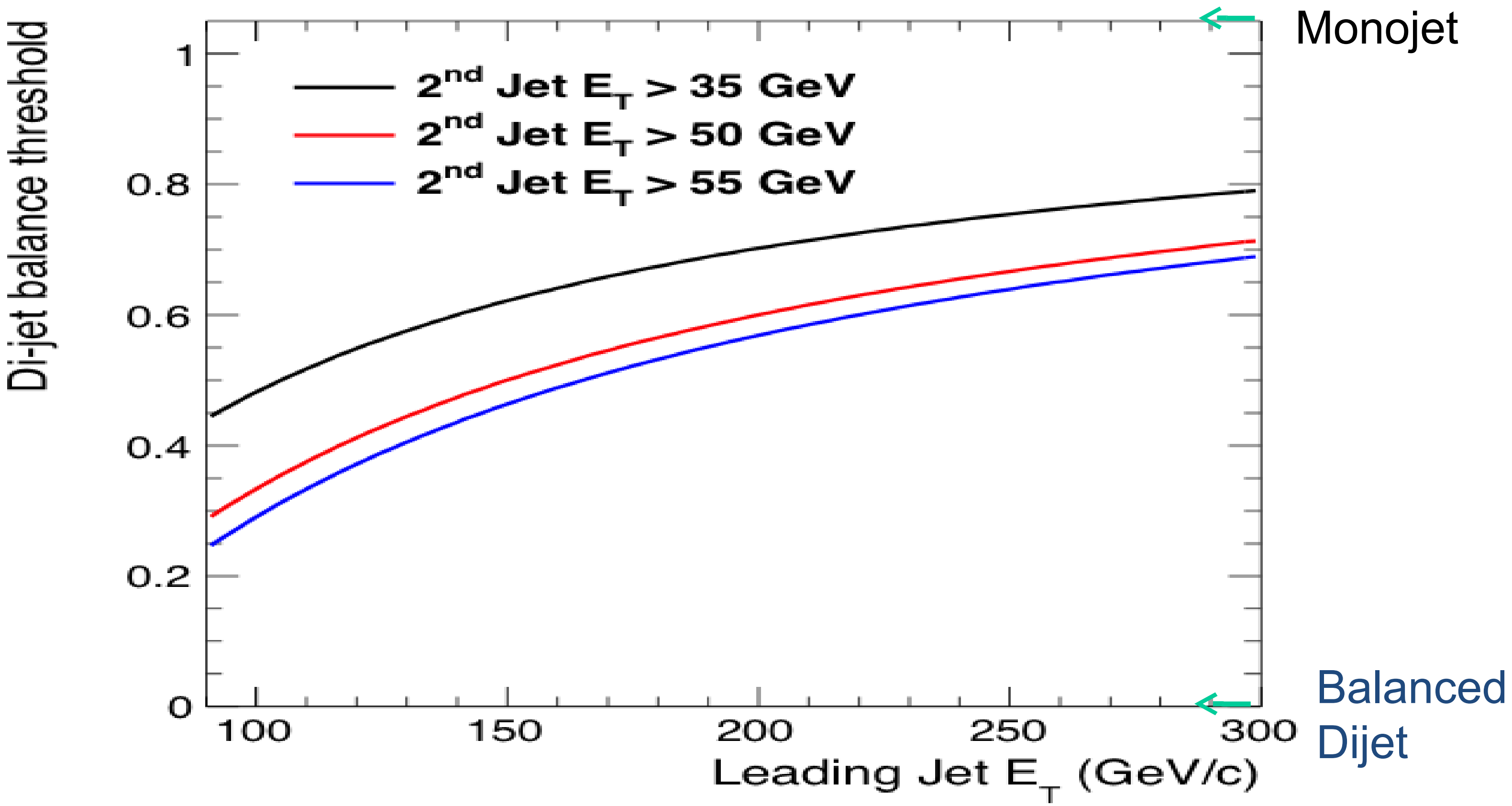
- First LHC PbPb collisions marked the opening of Pandora's Box for HI physics.
- The detector allows for precision and differential measurements of many observables in a wide kinematic range, which are mandatory for study of the properties of QGP.
- The abundance of information/possible measurements also oblige for precision measurements, looking into details and quantifying the effects.



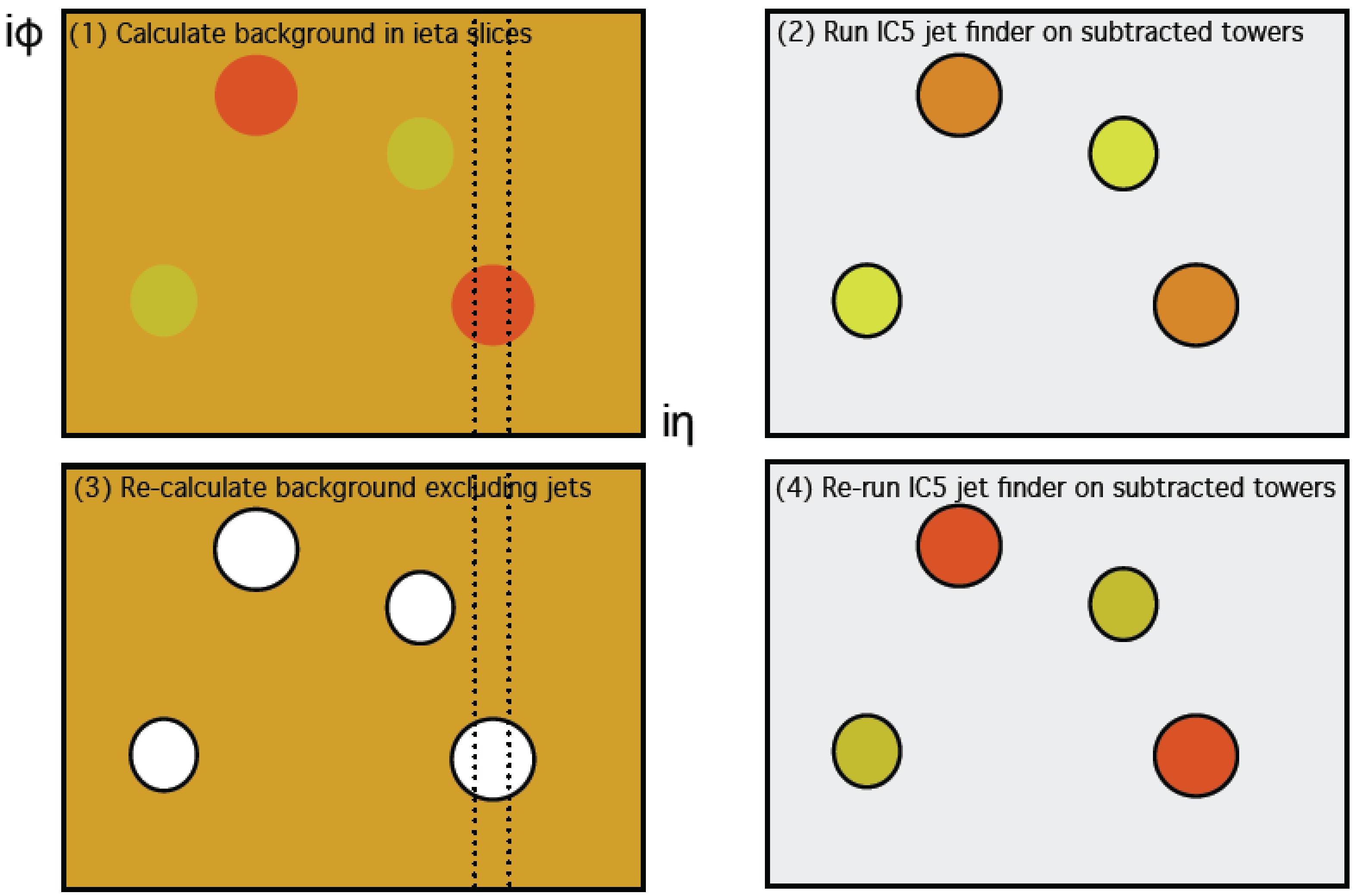
Back me up

Dijet Imbalance range

- Maximum dijet imbalance sampled for various sub-leading jet cut-offs



Background subtraction



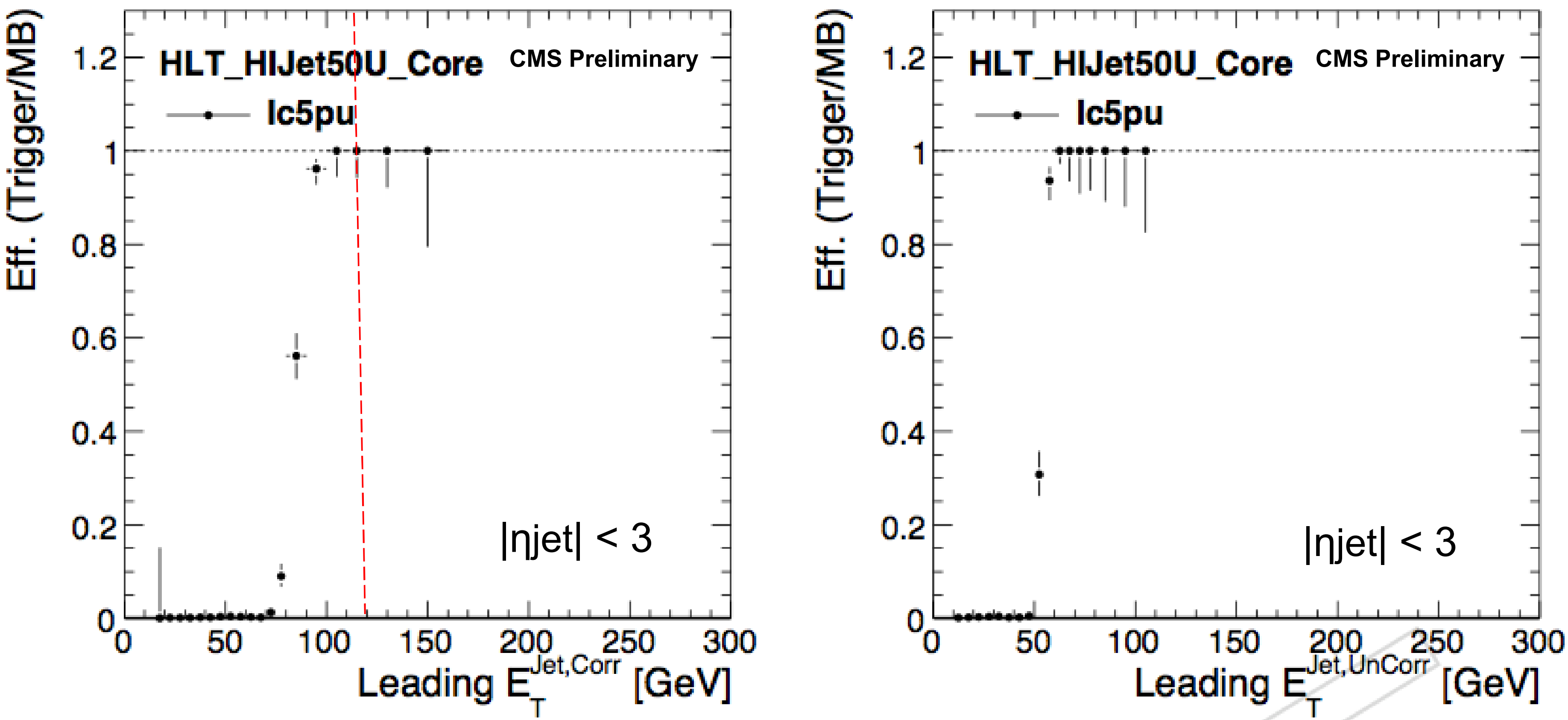
Event statistics in this analysis

Table 2: Various selections on the data set. % values are always with respect to to the line above (the cuts are applied in sequence).

Centrality	0-10%		10-30%		30-100%		0-100%	
Cut	evts	%	evts	%	evts	%	evts	%
tree entries	20023	100.00	19156	100.00	8654	100.00	47833	100.00
L1a36 OR L1a44 (minbias)	20023	100.00	19156	100.00	8654	100.00	47833	100.00
leading jet E_T >120 GeV	976	4.87	991	5.17	419	4.84	2386	5.45
leading jet $\|\eta\|$ <2	748	76.64	841	84.86	404	96.42	1993	83.53
subleading jet $\|\eta\|$ <2	722	96.52	799	95.00	389	96.29	1910	95.84
subleading jet E_T > 50 GeV	649	89.89	721	90.24	363	93.32	1733	90.73
dphi of 2 jets E_T > 2.5	557	85.82	661	91.68	344	94.77	1562	90.13

1562 dijets within our cuts

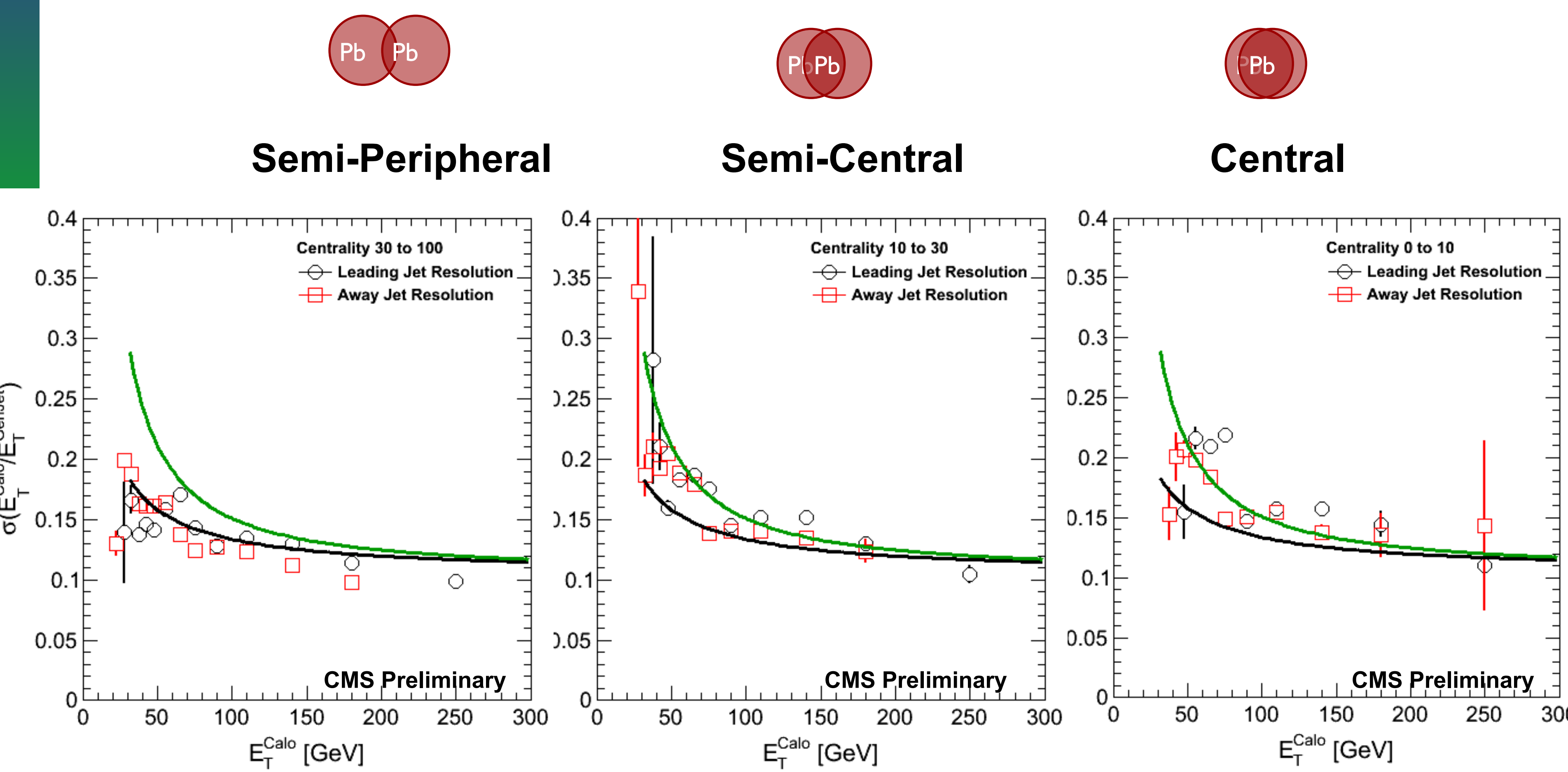
HI CaloJets: trigger efficiency



Corrected Jet Energy **Raw Jet Energy**

Dijet imbalance: jet resolution

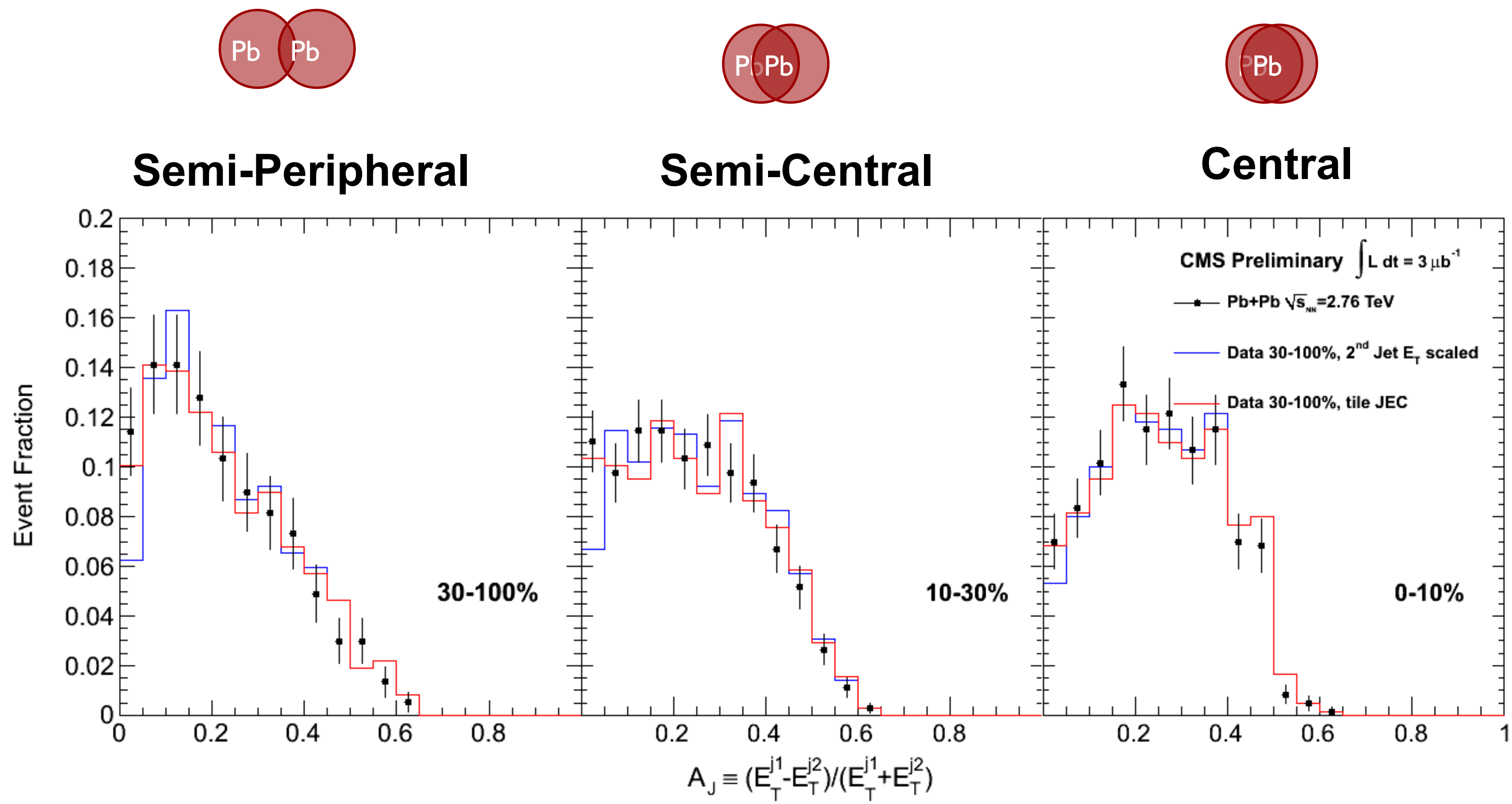
Semi-Peripheral Semi-Central Central



The resolution of jets changes due to the heavy-ion underlying event

Black is the fitted resolution in peripheral events,
Green is with estimated resolution due to background fluctuations

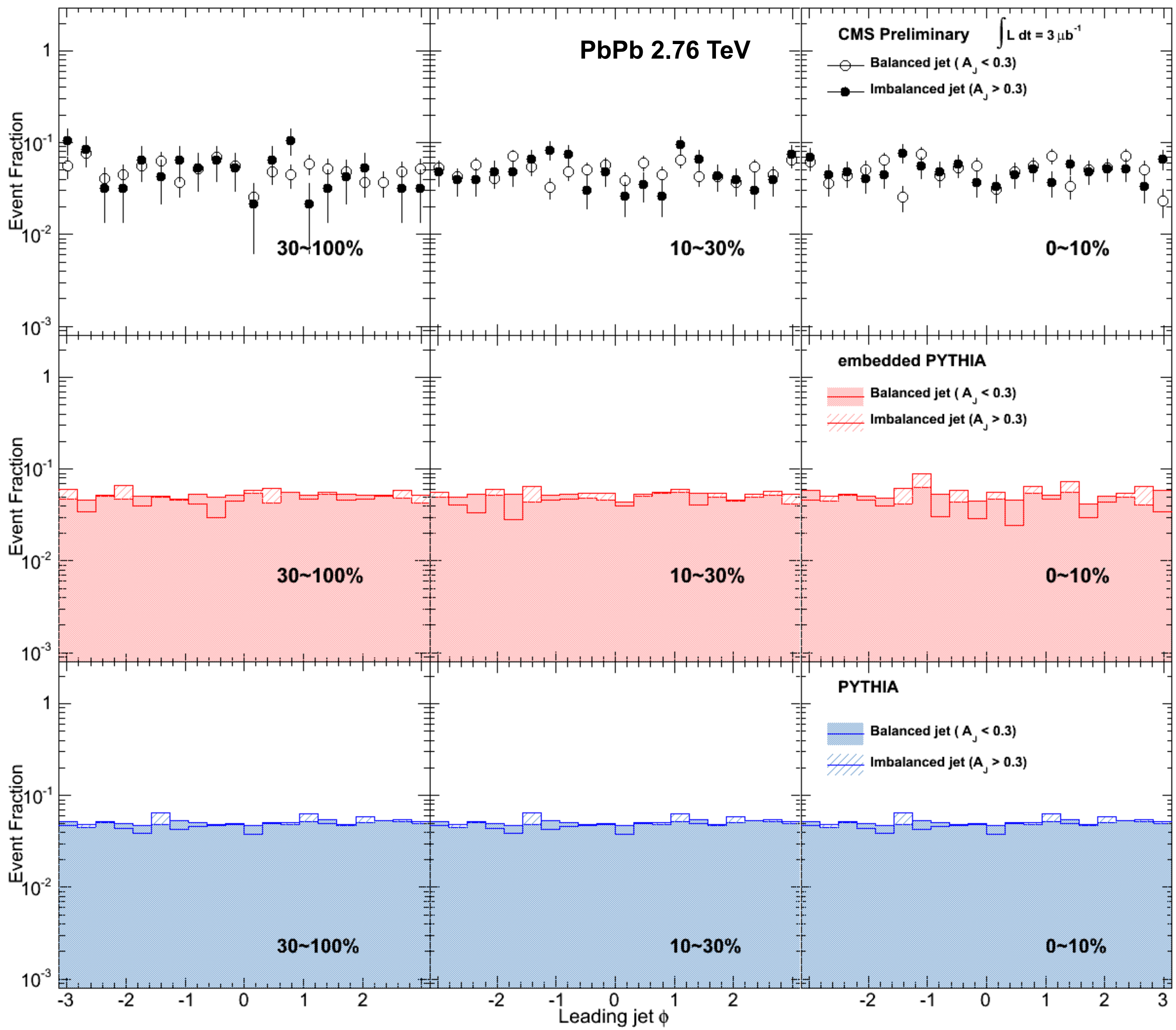
Dijet imbalance: jet energy scale



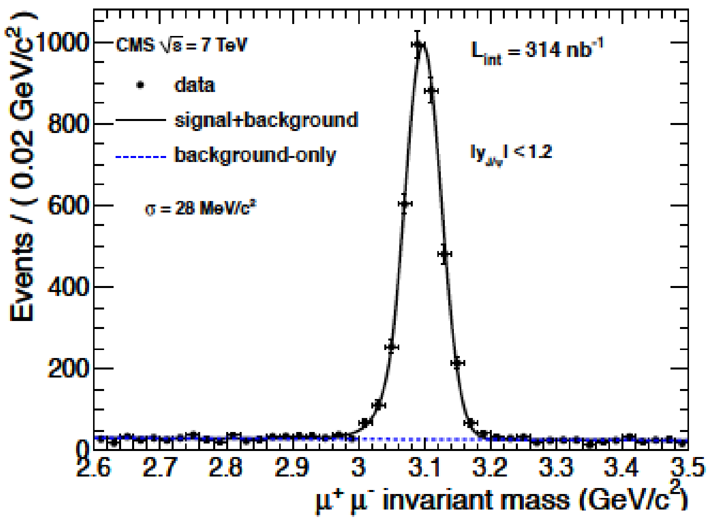
The energies of sub-leading jets were shifted up by 1σ of the uncertainty in the correction.

The slope of the jet correction as a function of pT was shifted by 1σ of its uncertainty

Imbalance uniformity: azimuth



CMS pp@7TeV: Jpsi->mumu(inclusive)



← Barrel

+ better resolu

+ low bkg

Endcap →

+ down to pT