



PbPb collisions in CMS

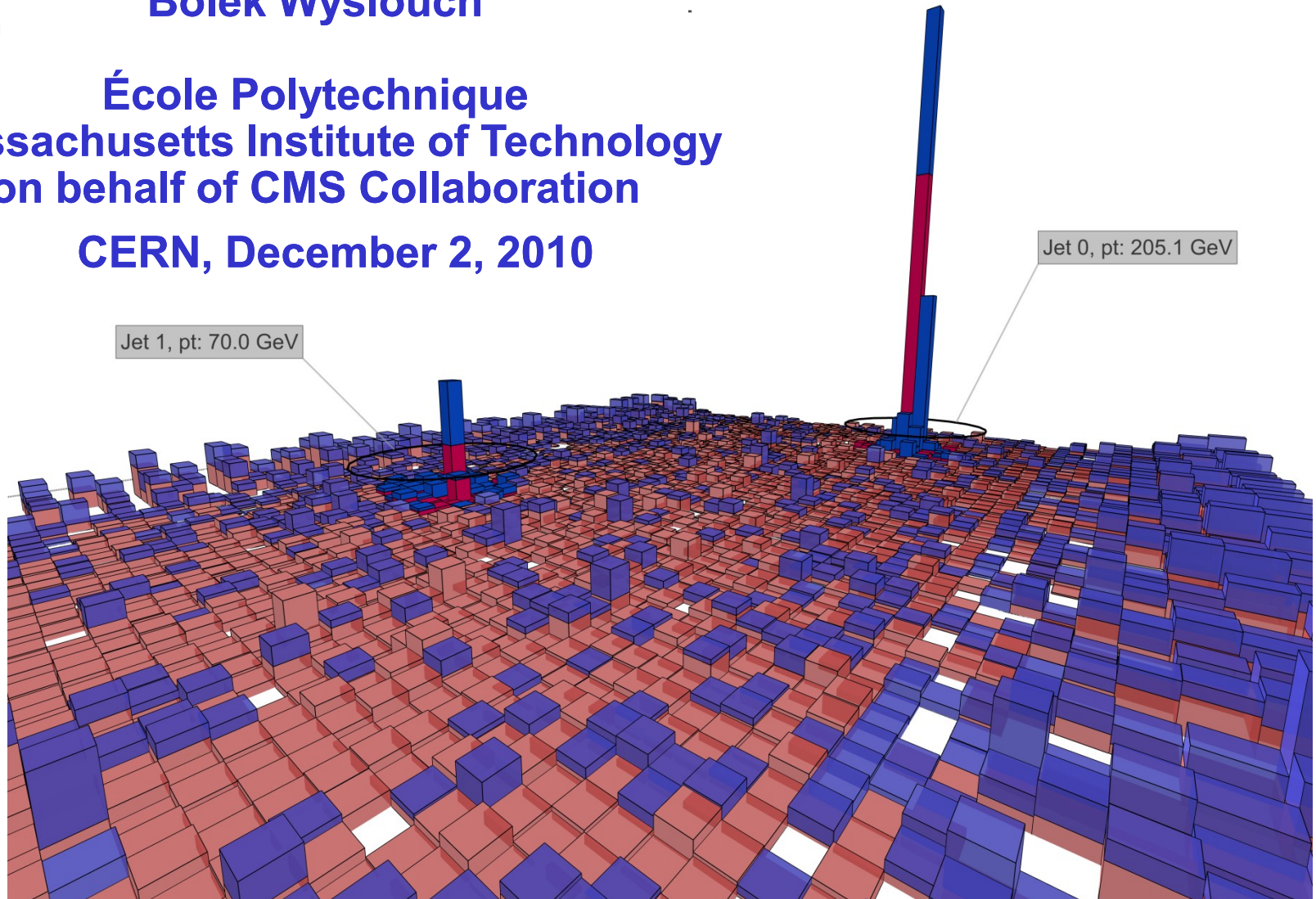


Bolek Wyslouch



École Polytechnique
Massachusetts Institute of Technology
on behalf of CMS Collaboration

CERN, December 2, 2010





Heavy Ions at the LHC

- **Huge energy jump from RHIC: factor 14!**
- **Hottest nuclear matter ever created in the laboratory**
- **New probes or processes**
- **Excellent detectors**
- **Today from CMS:**
 - **Di-muons and the detection of J/psi, Upsilon and Z⁰**
 - **Jets and the phenomenon of jet quenching**



CMS detector at the LHC

EM Calorimeter (ECAL)

Hadron Calorimeter (HCAL)

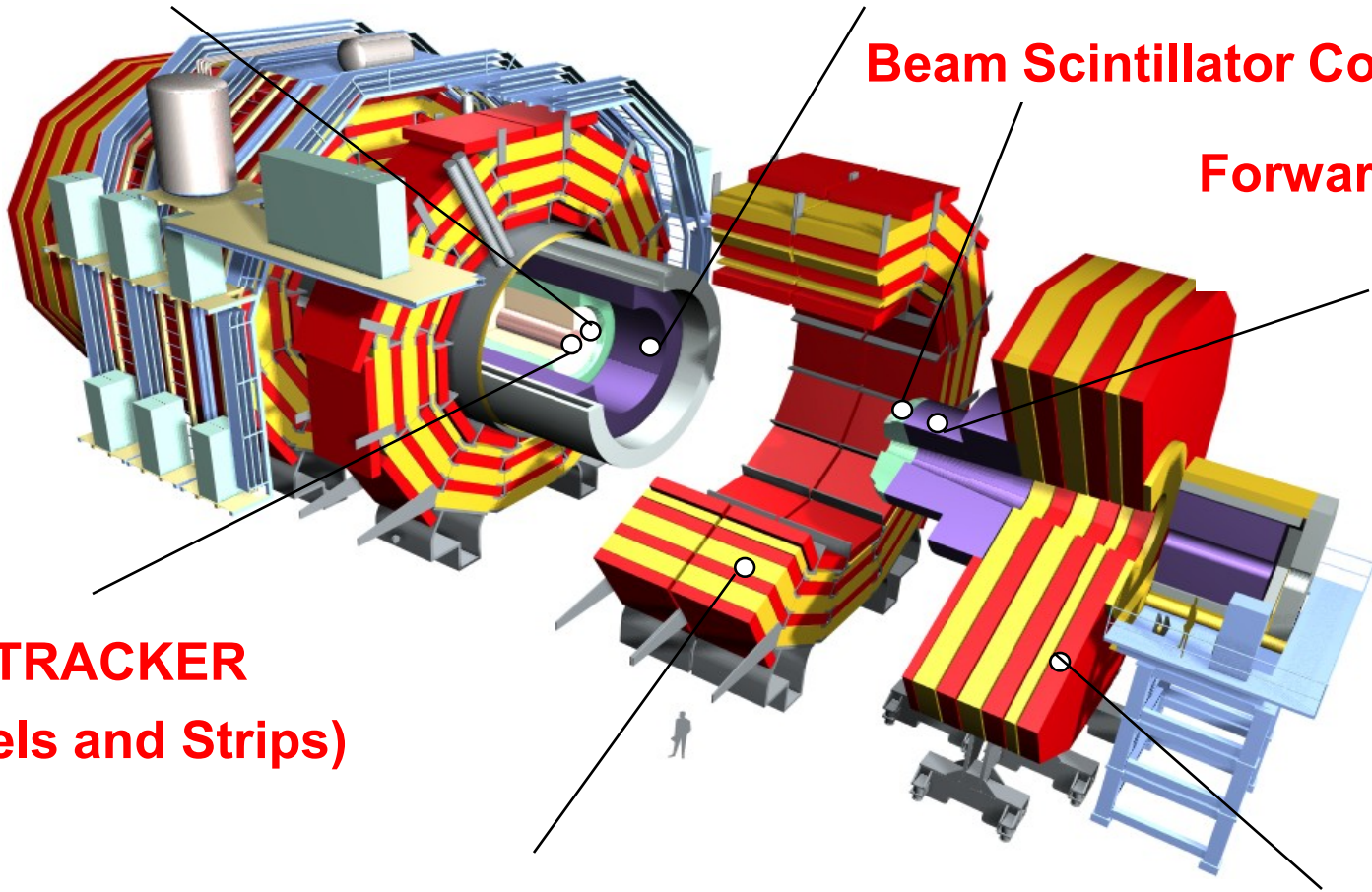
Beam Scintillator Counters (BSC)

Forward Calorimeter (HF)

**TRACKER
(Pixels and Strips)**

**MUON
(Barrel)**

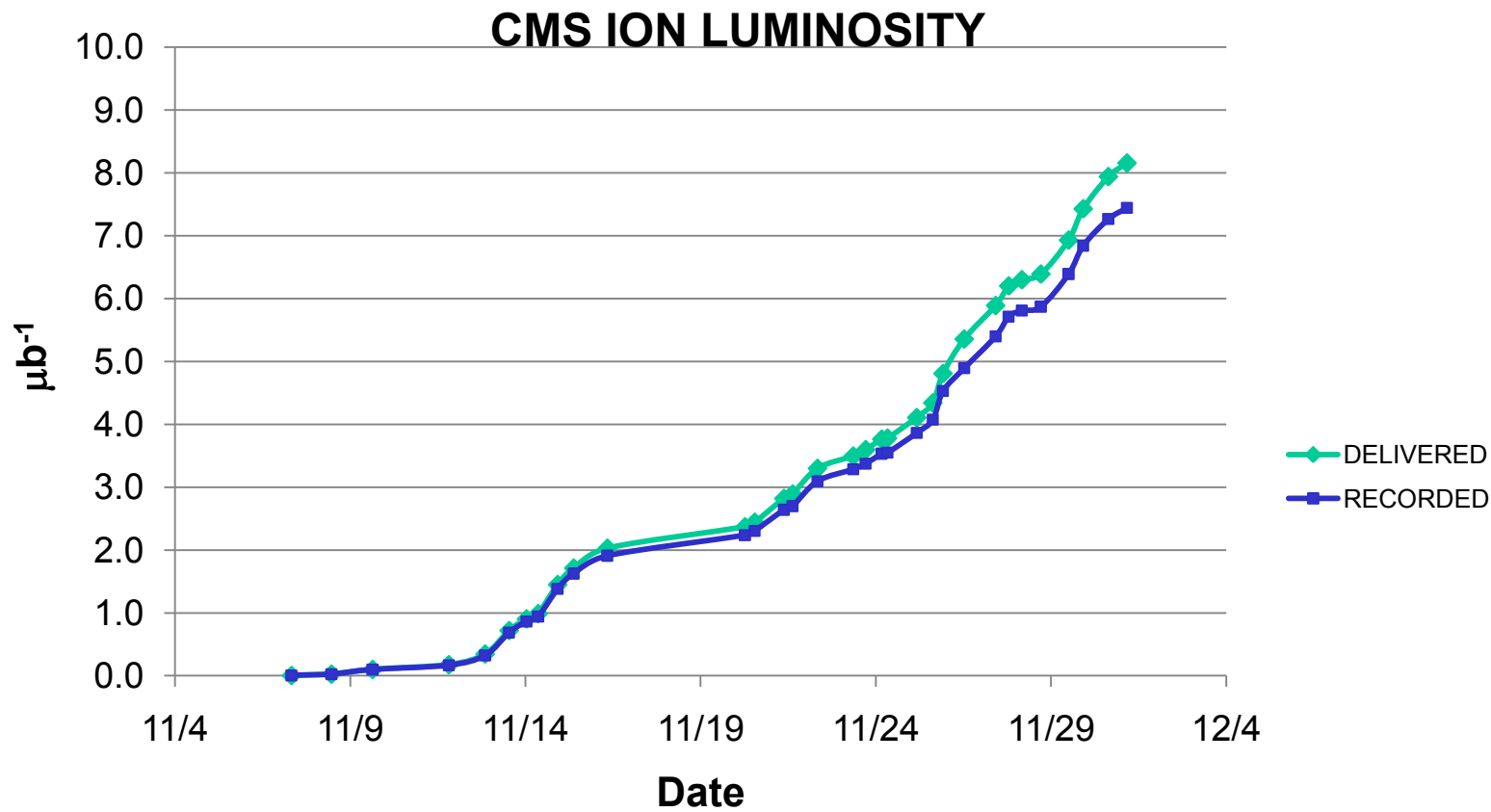
**MUON
(Endcaps)**





Data taking with CMS

- As of this morning $8.2 \mu\text{b}^{-1}$ delivered, $7.4 \mu\text{b}^{-1}$ recorded



GREAT thanks to LHC Team



Triggering on collisions

- **Maximize efficiency for high p_T probes**
 - **Muons**
 - **Jets**
 - **Photons/Electrons**
- **Record large Minimum Bias sample**
- **Additional triggers**
 - **Ultra Peripheral Collisions**
 - **Background monitoring**
- **Minimize backgrounds**

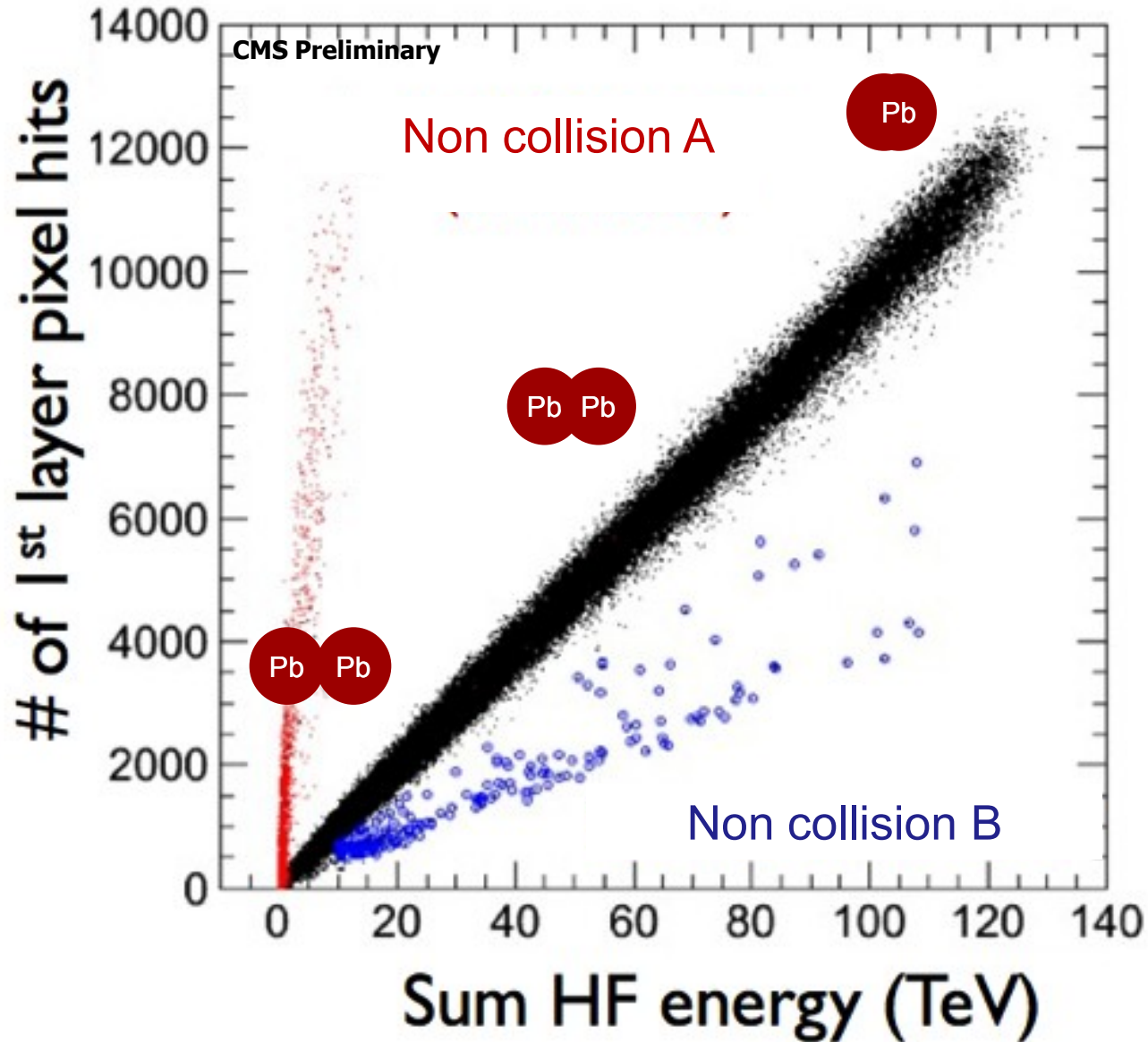


Event Selection

- **Level 1 trigger**
 - **Coincidence of two scintillator counters OR**
 - **Coincidence of two HF towers**
 - **Muons**
- **High Level Trigger**
 - **Jets**
 - **Muons**
 - **Photons**
- **Offline**
 - **Veto on scintillator beam halo**
 - **At least 3 HF towers on each side above threshold ($E > 3$ GeV)**
 - **Reconstructed pixel vertex with two or more tracks**
 - **Beam-scraping removal with pixel cluster vertex compatibility**



Minimum Bias Event Sample



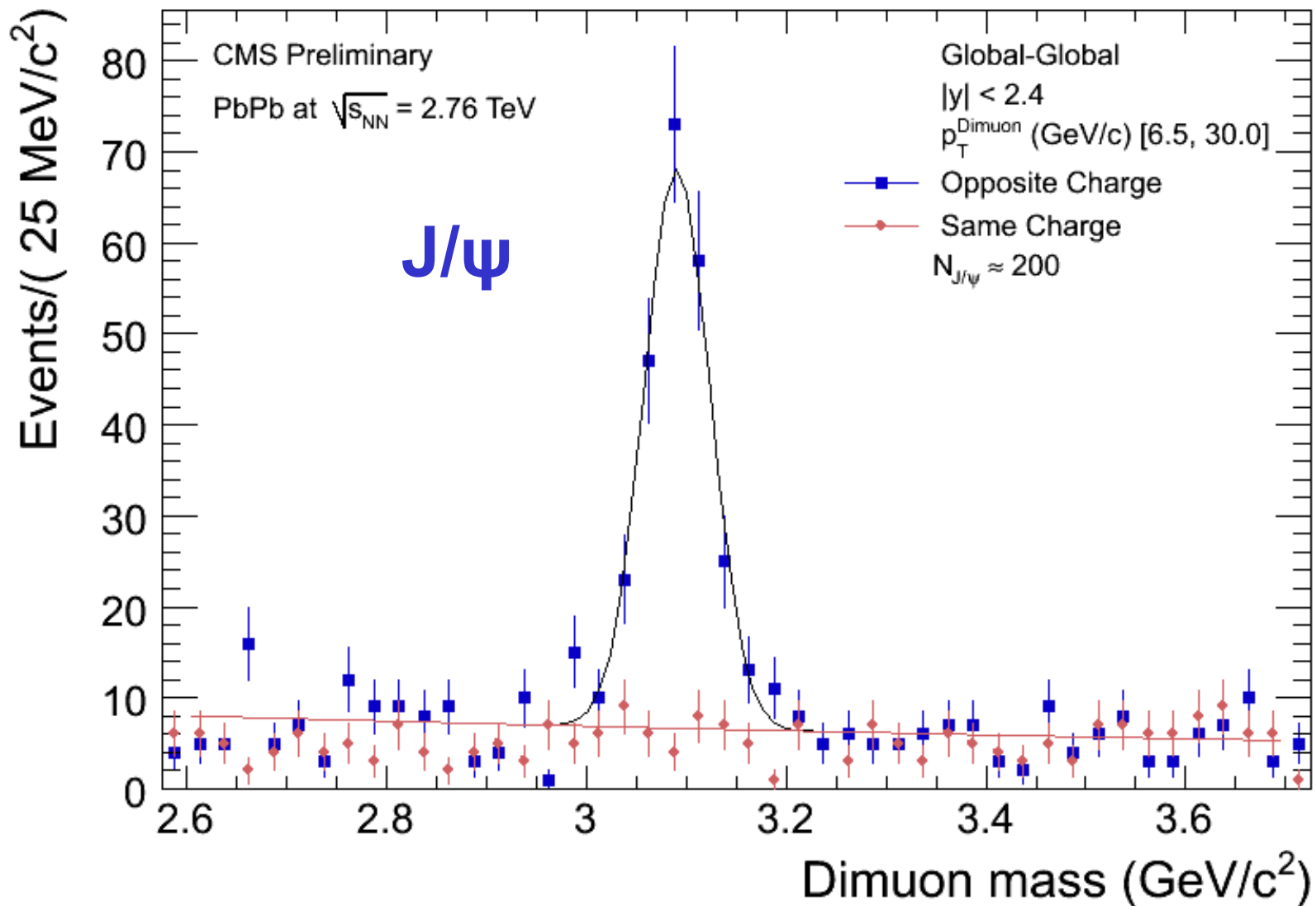


Dileptons: past and future

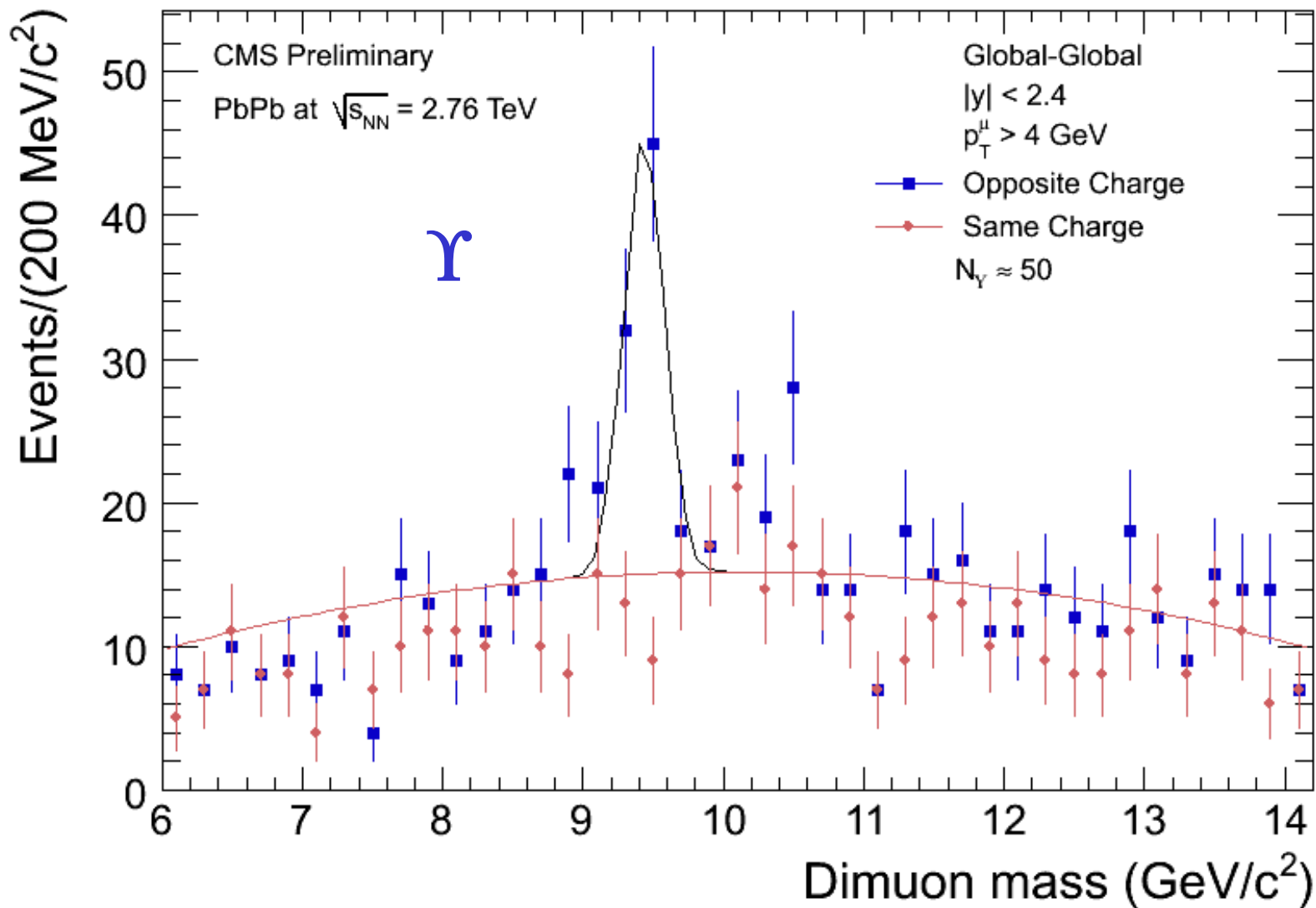
Quarkonia should melt in the Quark Gluon Plasma...

- **J/ψ suppression has been seen at SPS and RHIC**
 - **Details are poorly understood , interplay of cold and hot effects**
 - **Regeneration of J/ψ from the (large) number of uncorrelated cc pairs would be a golden probe of reconfinement (thus deconfinement) at LHC**
- **Only ~100 Upsilon's seen at RHIC**
 - **Successive melting of the three bound states could act as a thermometer**
- **Weak bosons have not been observed at RHIC**
 - **Test of nuclear PDFs**
 - **Standard candle for other processes**
- **CMS will be able to study all of the above in detail**

High p_T $J/\psi \rightarrow \mu^+ \mu^-$

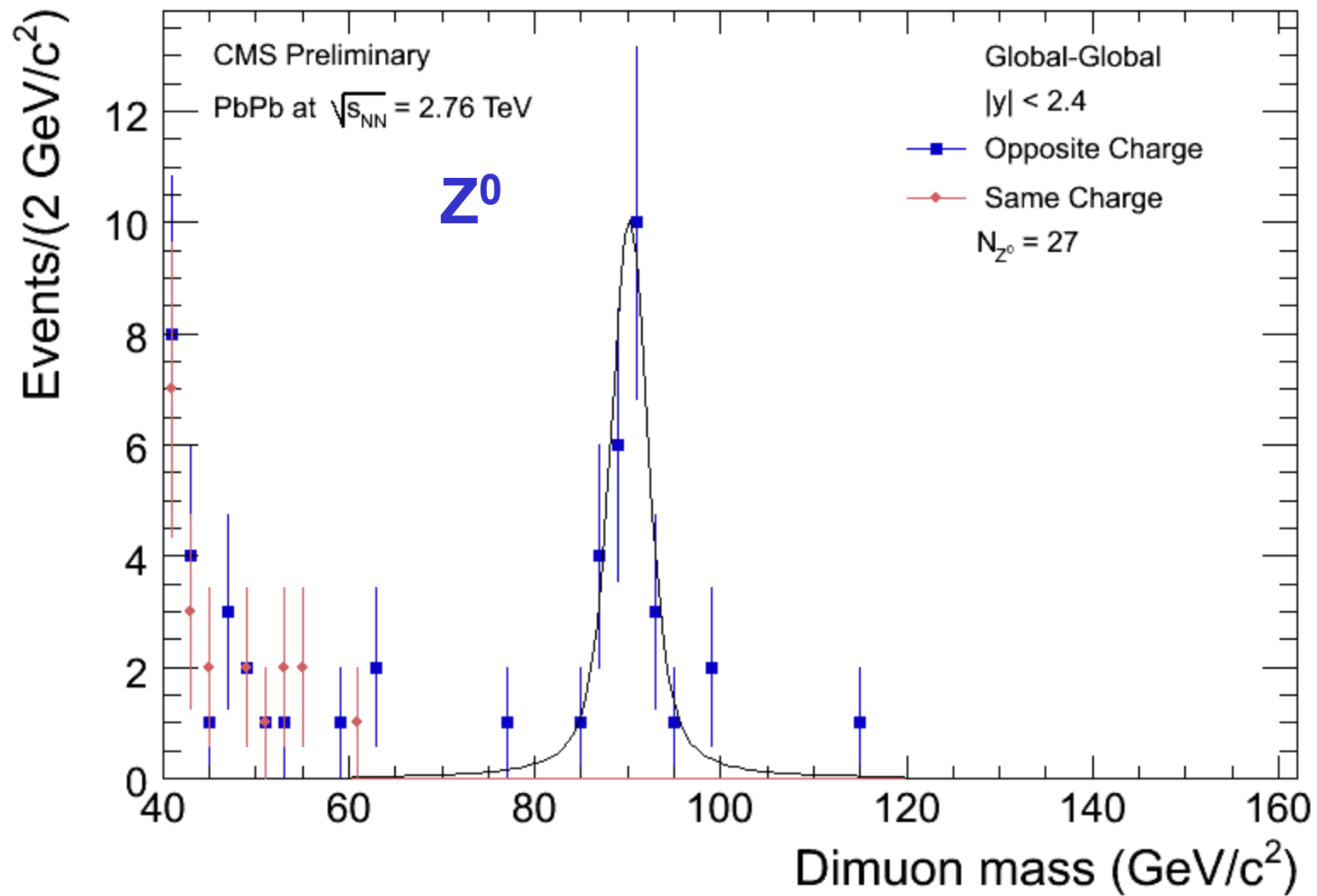


High p_T $\Upsilon \rightarrow \mu^+ \mu^-$



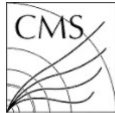


$Z^0 \rightarrow \mu^+ \mu^-$

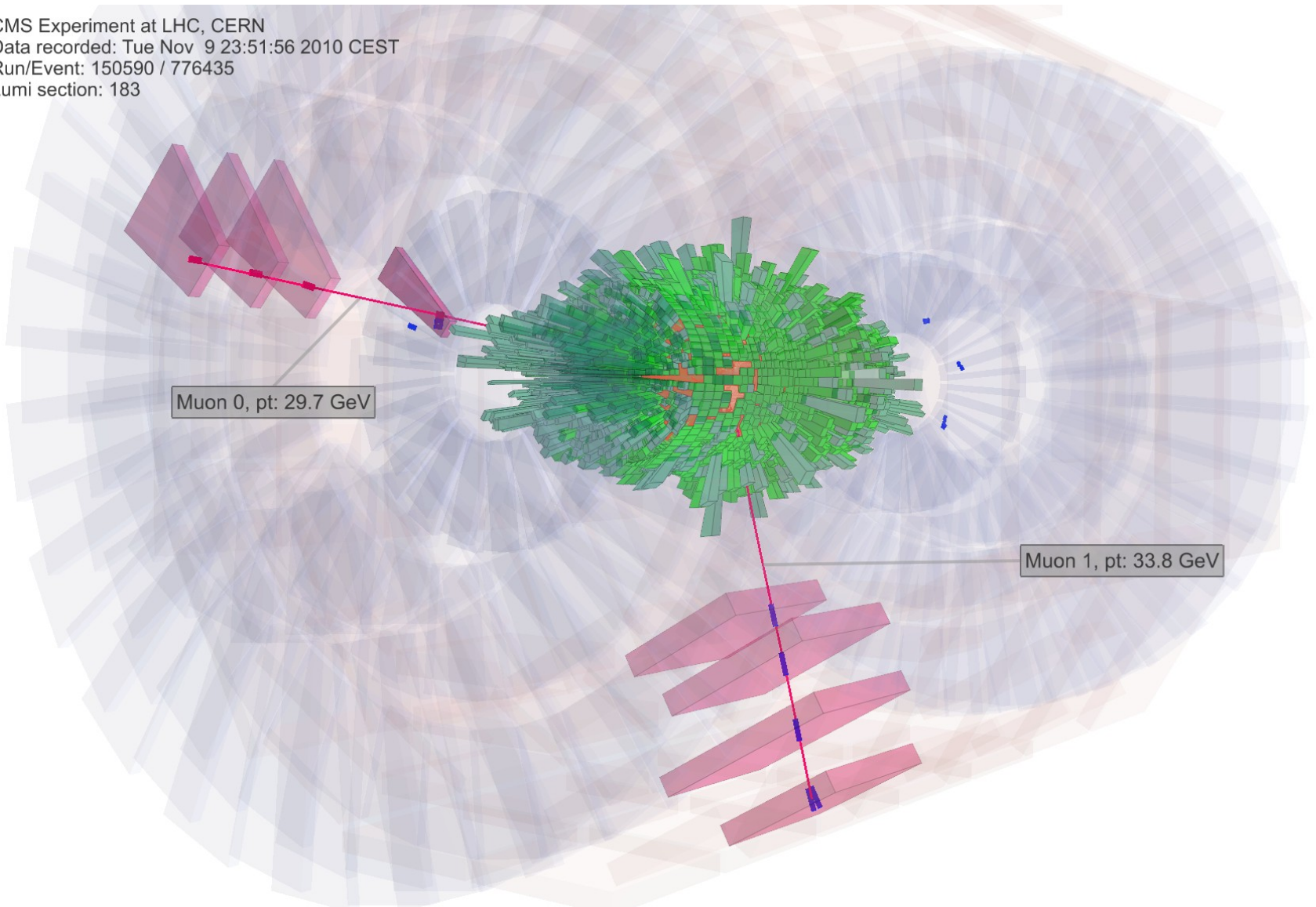




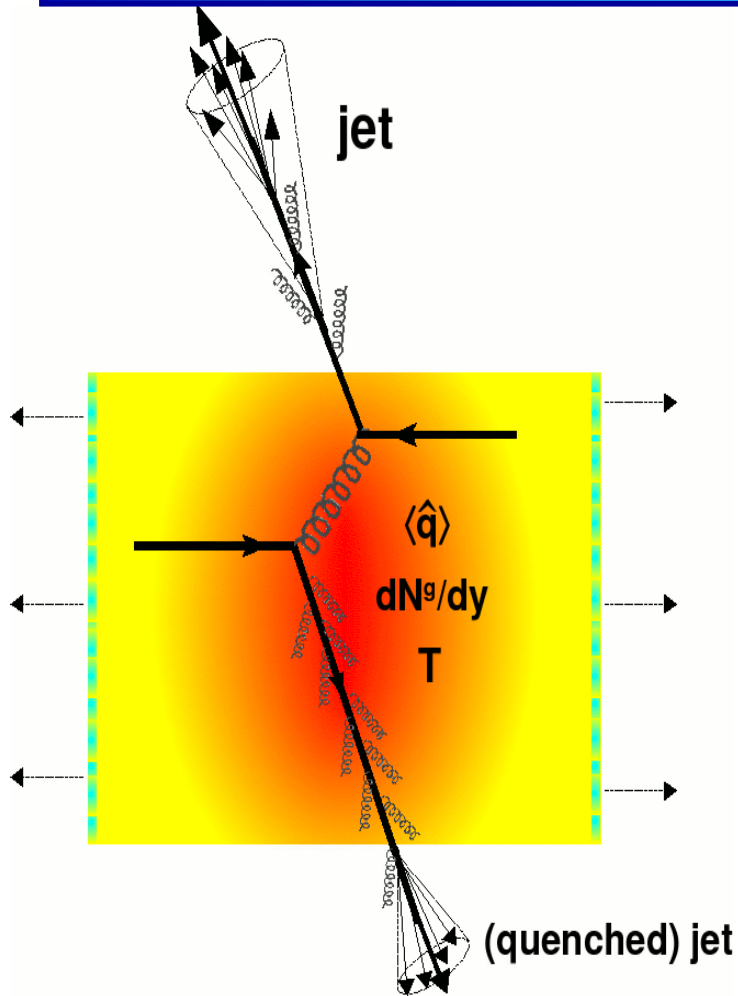
Our first $Z^0 \rightarrow \mu^+ \mu^-$ candidate



CMS Experiment at LHC, CERN
Data recorded: Tue Nov 9 23:51:56 2010 CEST
Run/Event: 150590 / 776435
Lumi section: 183



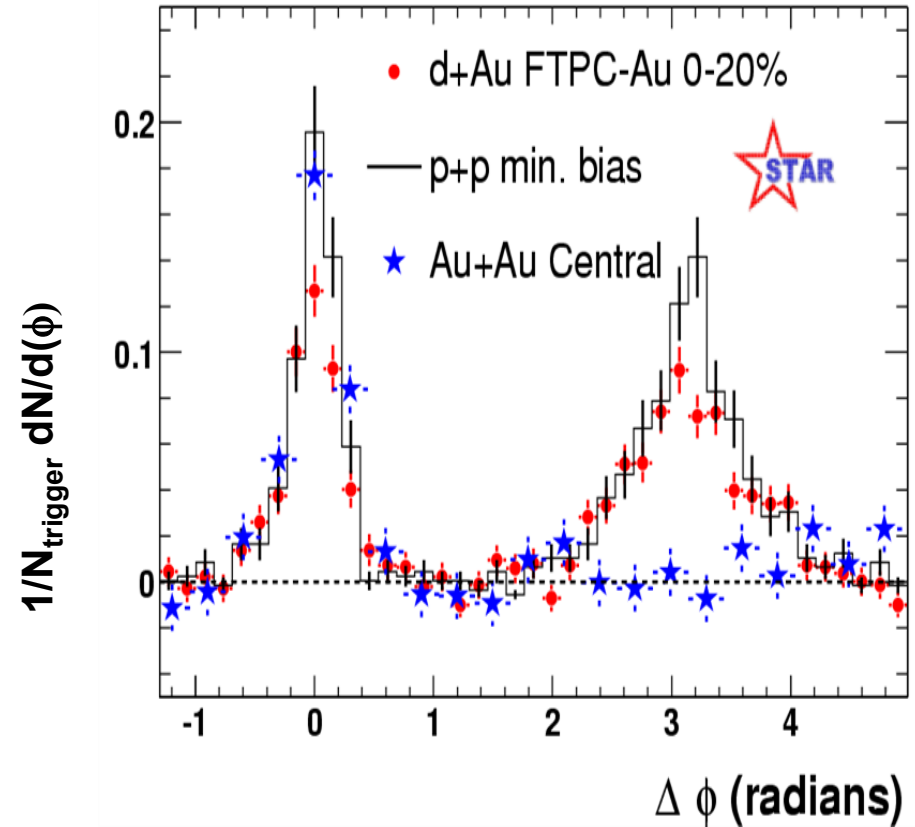
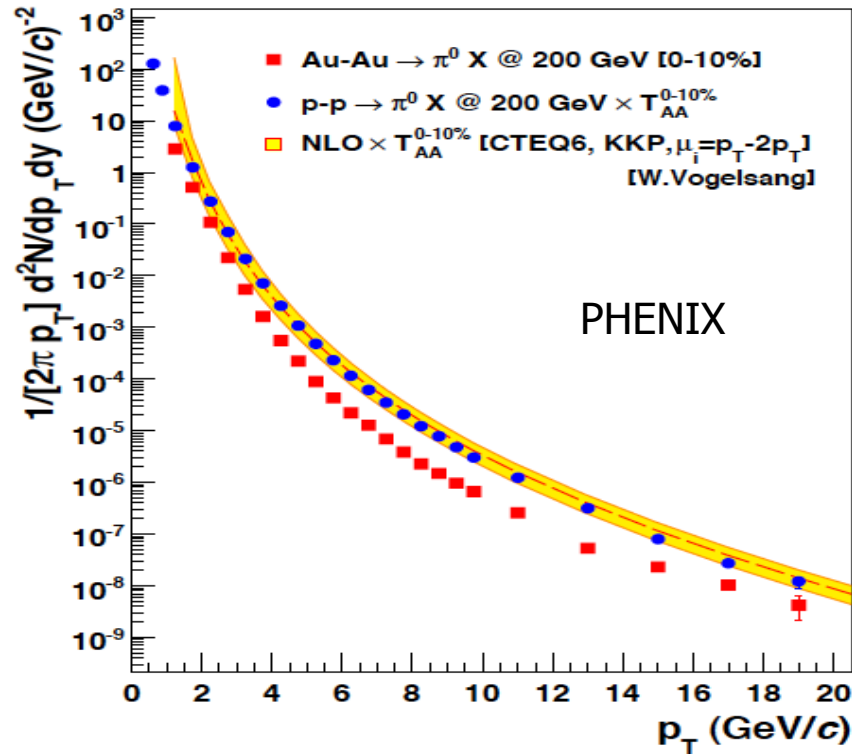
Jet quenching at RHIC at $\sqrt{s_{NN}}=200$ GeV



- Strong quenching effects were observed in single particle spectra and particle correlations
- Direct jet reconstruction possible but very difficult



Very clear effect: spectra and correlations



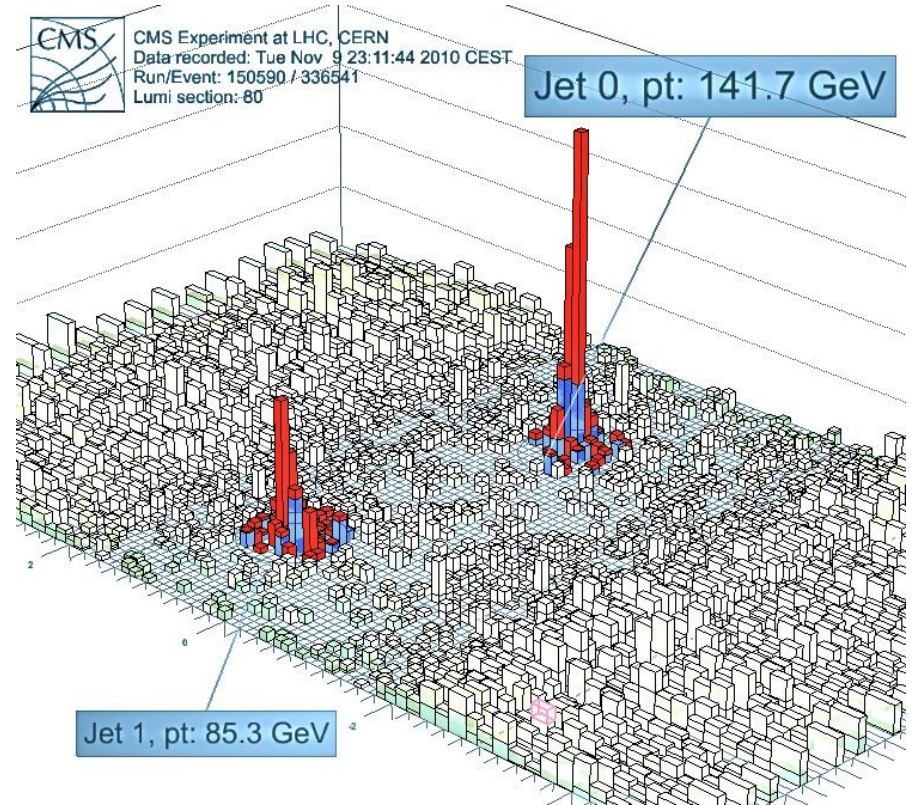
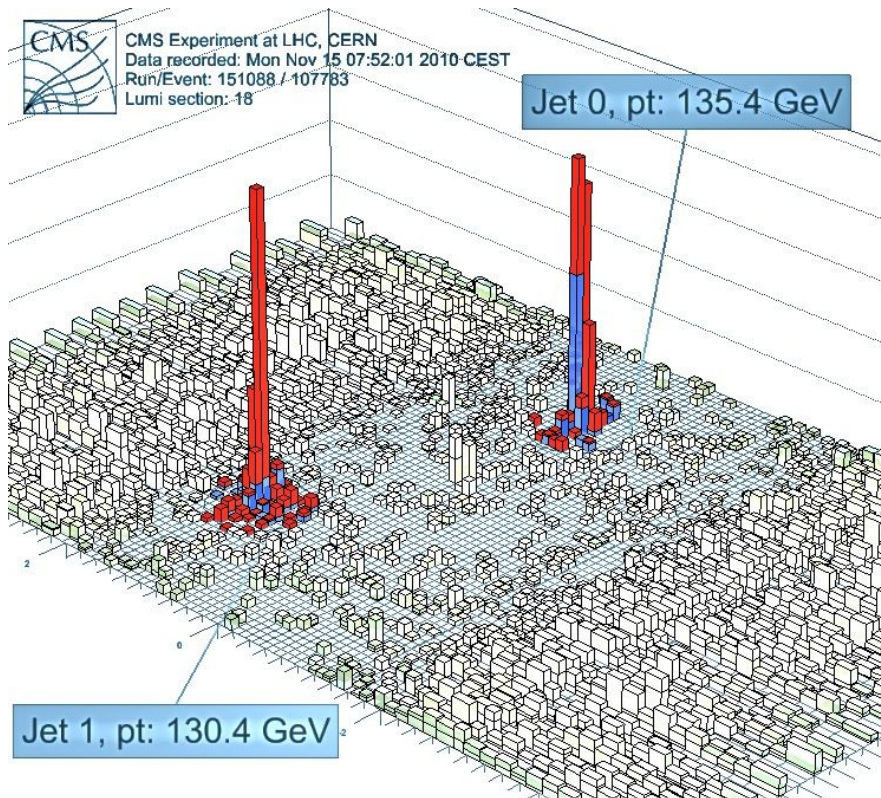
- π^0 p_T AuAu and scaled pp

- Azimuthal distribution of particles with $2 < p_T < p_T$ trigger
- Trigger particle with $4 < p_T$ trigger < 6 GeV/c



Dijet event candidates in CMS

- **First hours of LHC running**
 - **We see dijet events**
 - **We see dijets with unbalanced energy: is this real?**





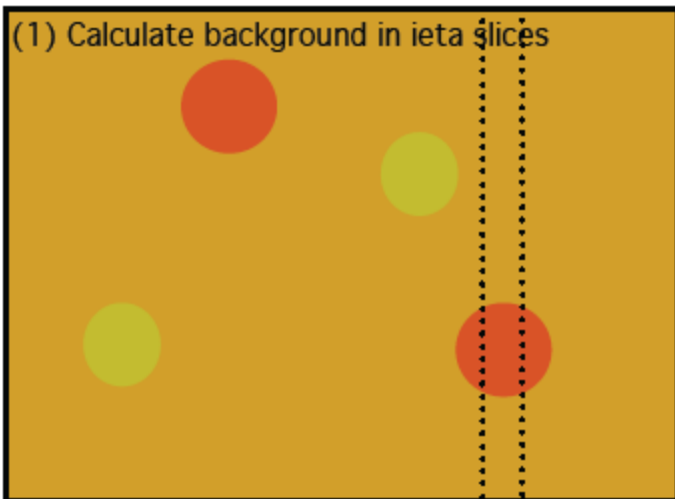
Reconstruction of Jets in HI collisions

- **Jets are accompanied by the large “thermal background” or “underlying event” that depends on the overall event multiplicity**
 - **Use background subtraction procedures**
- **CMS uses several jet finding algorithms**
 - **Iterative Cone**
 - **Anti- k_T (M. Cacciari, G. P. Salam, G. Soyez, JHEP 0804:063,2008.)**
- **Jets are found using different sets of detectors**
 - **Calorimetric Jets: use ECAL and HCAL**
 - **Particle Flow Jets: use Tracker and Calorimeters**
- **Jet cone size can vary**
 - **We use $R=0.5$**
- **CMS HI “workhorse”**
 - **IC5 CaloJets with iterative background subtraction (O. Kodolova et al., EPJC (2007))**

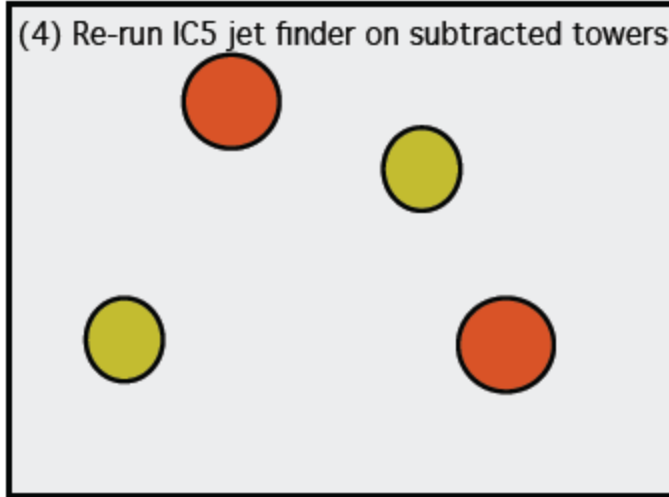
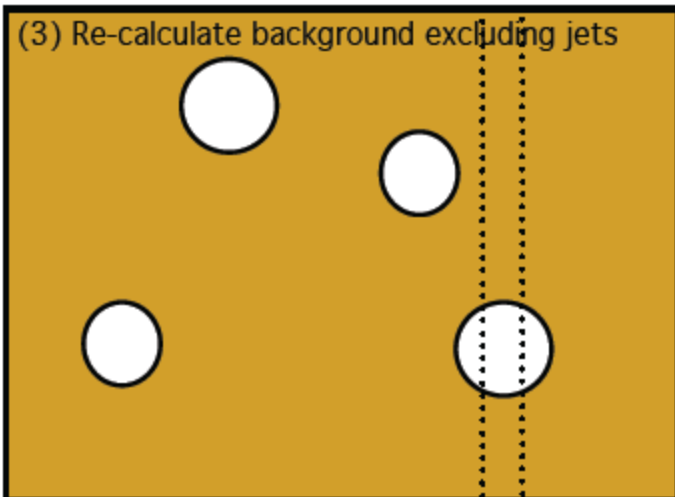
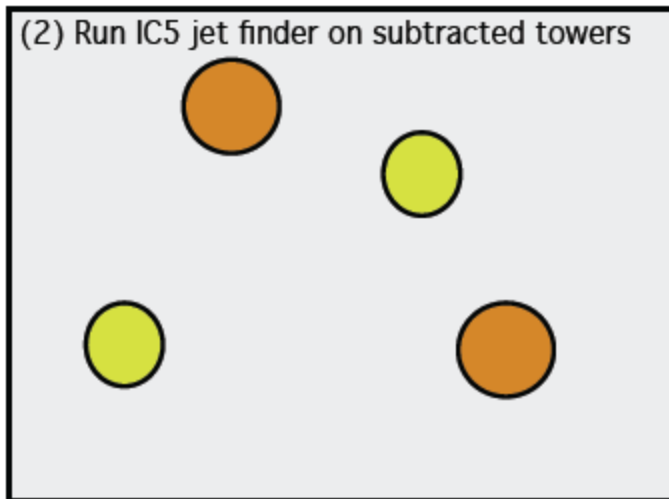


Background subtraction

$i\phi$



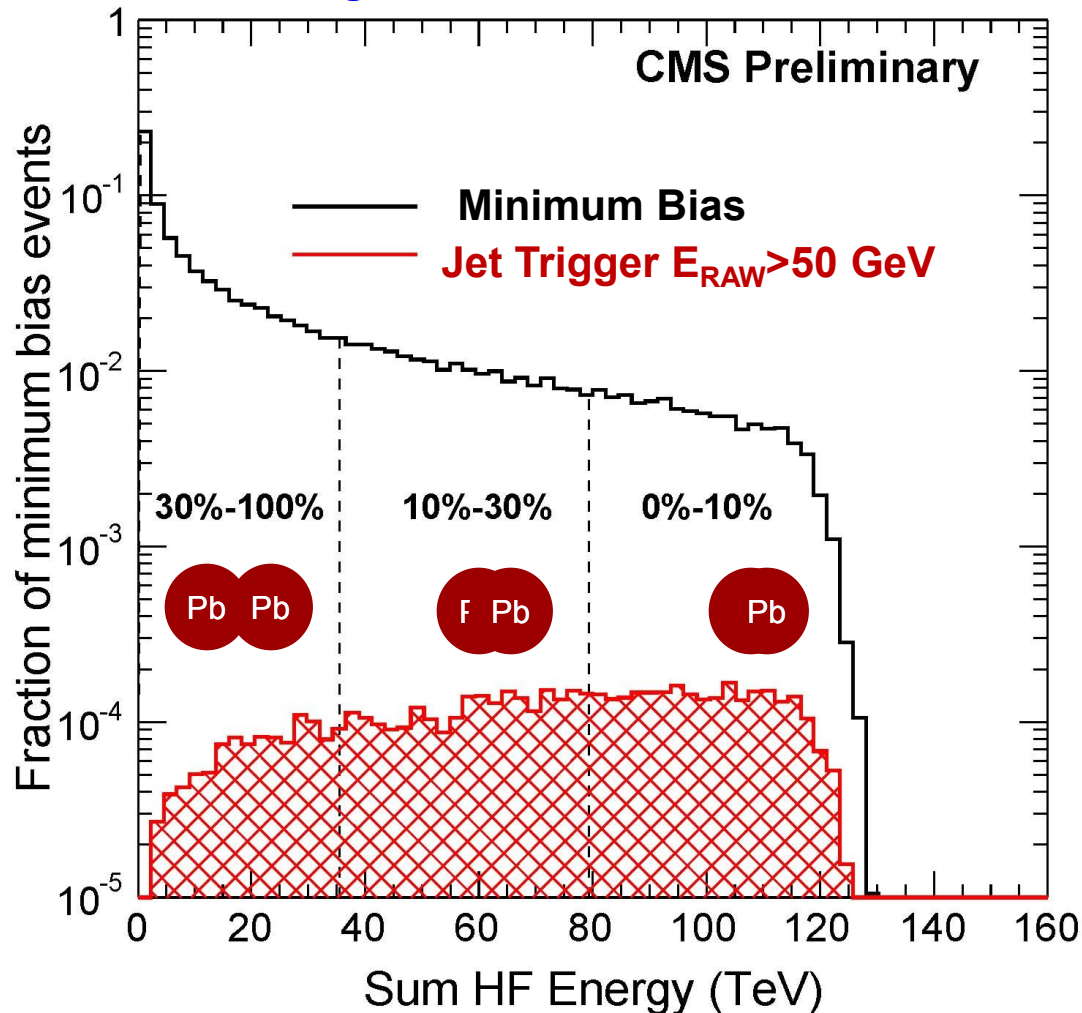
$i\eta$





Centrality Determination

- Use total energy in Forward Calorimeter (HF) to estimate centrality





Dijet selection

- **Leading jet is required to have at least 120 GeV**
 - **Trigger fully efficient**
- **Sub-leading jet is required to have at least 50 GeV**
 - **Above background fluctuations**
- **Leading and sub-leading jets with $|\eta| < 2$**
- **Select back-to-back jets $\Delta\phi > 2.5$**
- **To study jet quenching effects use jet energy asymmetry**

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



Event statistics in this analysis

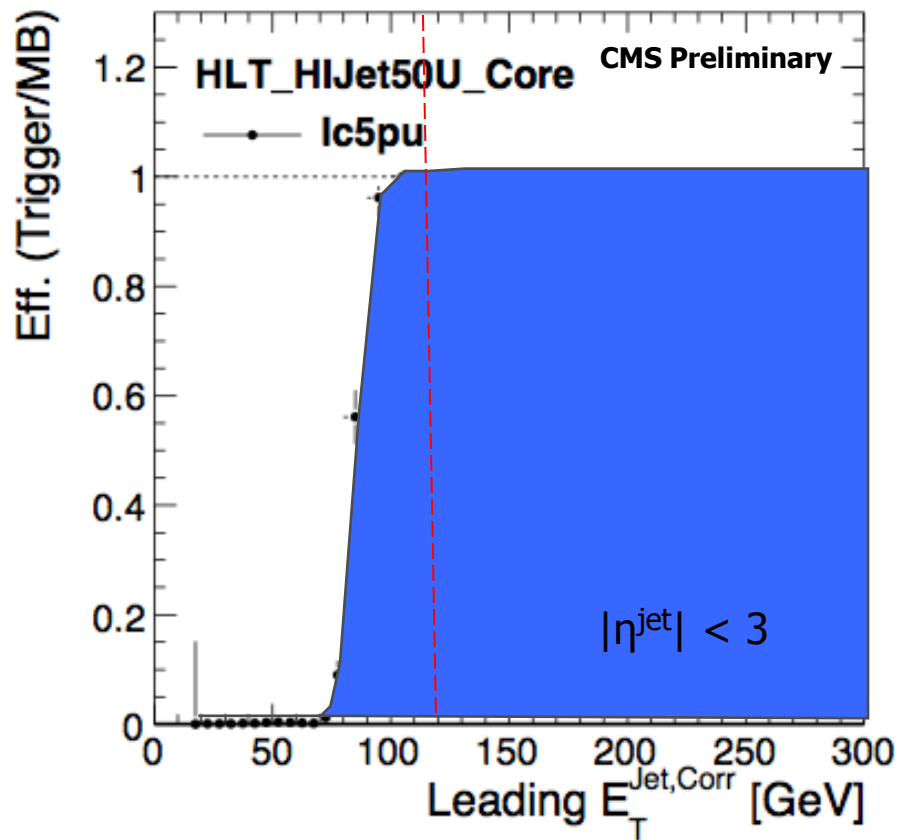
Table 2: Various selections on the data set. % values are always with respect to to the line above (the cuts are applied in sequence).

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

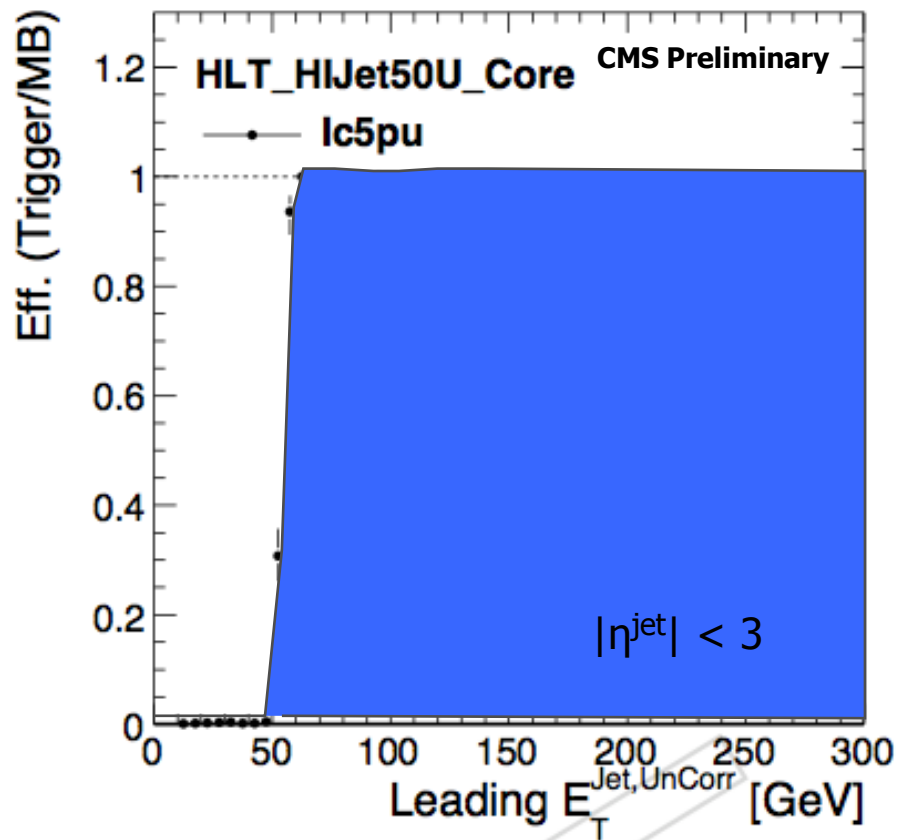
1562 dijets within our cuts



Jet Trigger Efficiency



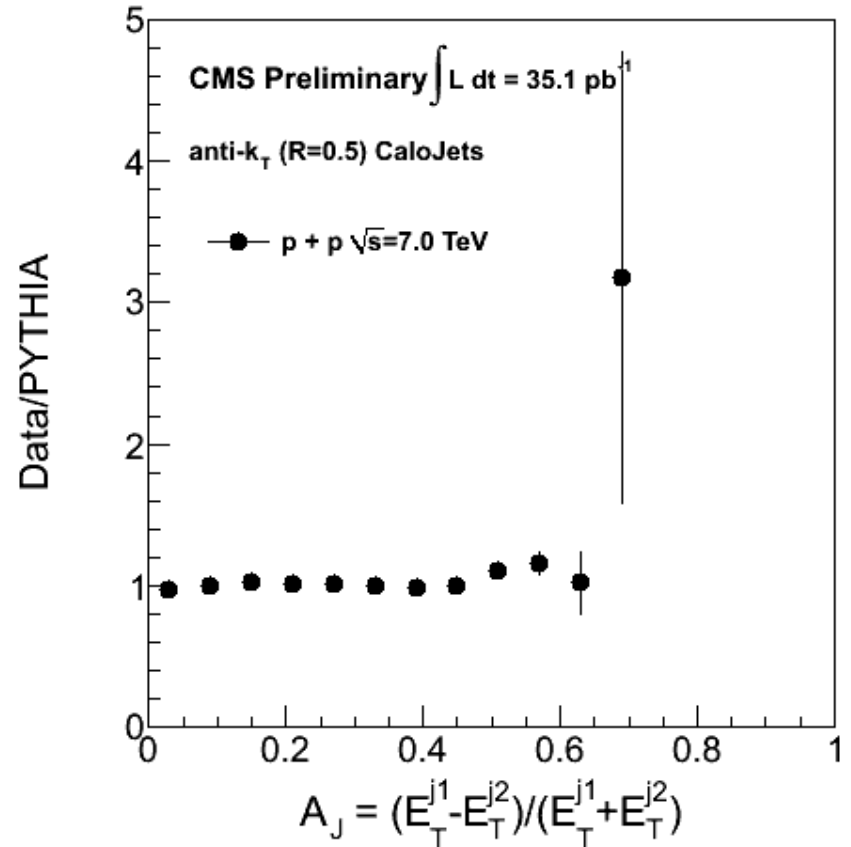
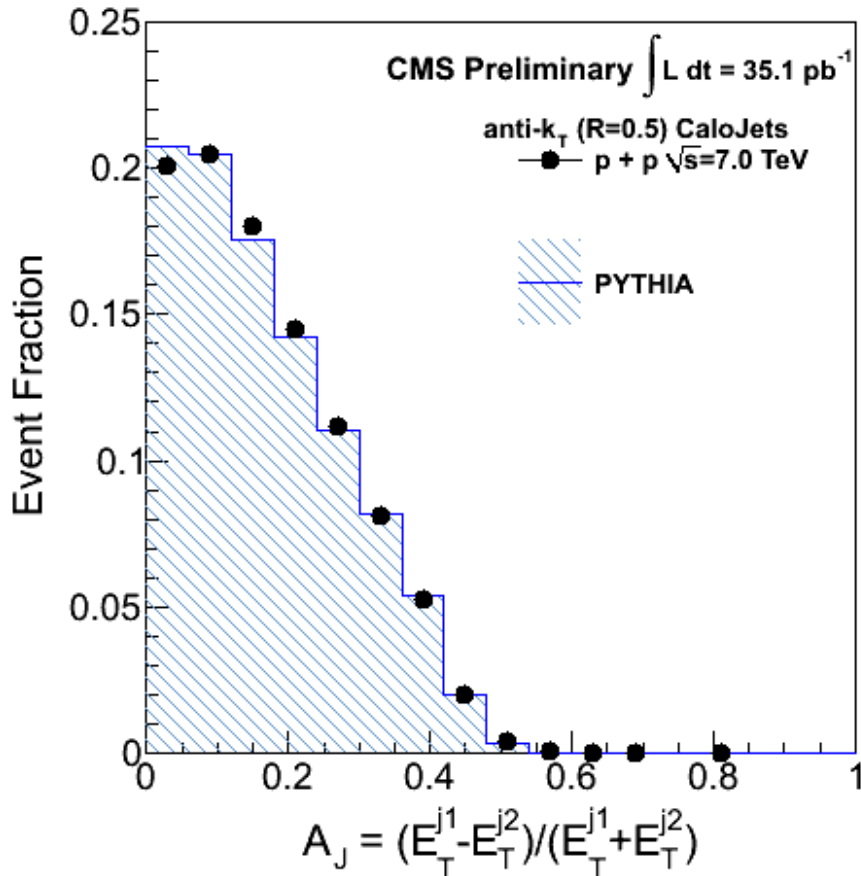
Corrected Jet Energy



Raw Jet Energy



A_j in proton-proton collisions at 7 TeV



Excellent agreement with PYTHIA+CMS simulation

We will use PYTHIA as a reference at 2.76 TeV



Estimation of underlying event effects

- **Embed PYTHIA dijets into minimum bias REAL data events**
 - **Add simulated response of individual detector elements (pixels, strips, crystals etc) to data events**
- **Reconstruct jets and compare with**
 - **Dijets in data**
 - **PYTHIA jets without background**
- **Advantages compared to full HI simulation:**
 - **Well understood pp jet response**
 - **Realistic background**



Leading Jet E_T Distributions

Pb Pb

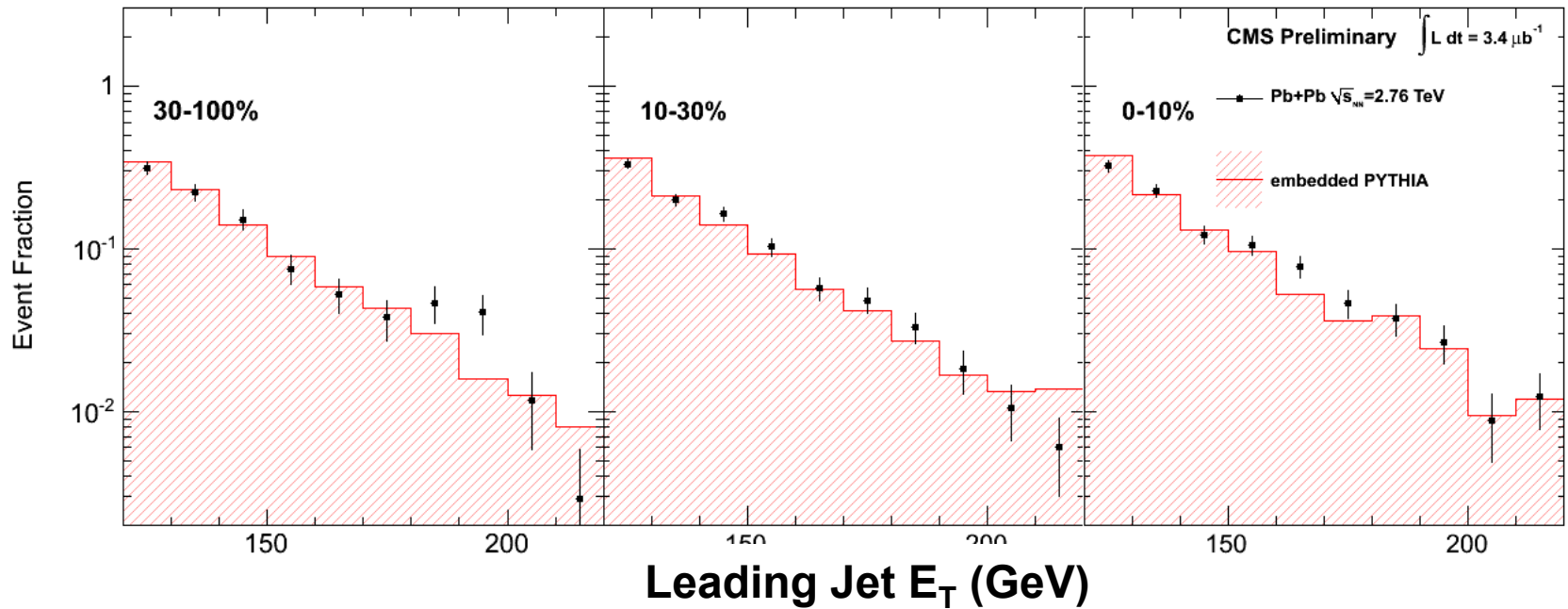
Semi-Peripheral

F Pb

Semi-Central

Pb

Central



Leading jet E_T distribution shape well reproduced by simulations



Azimuthal dijet correlation

Pb Pb

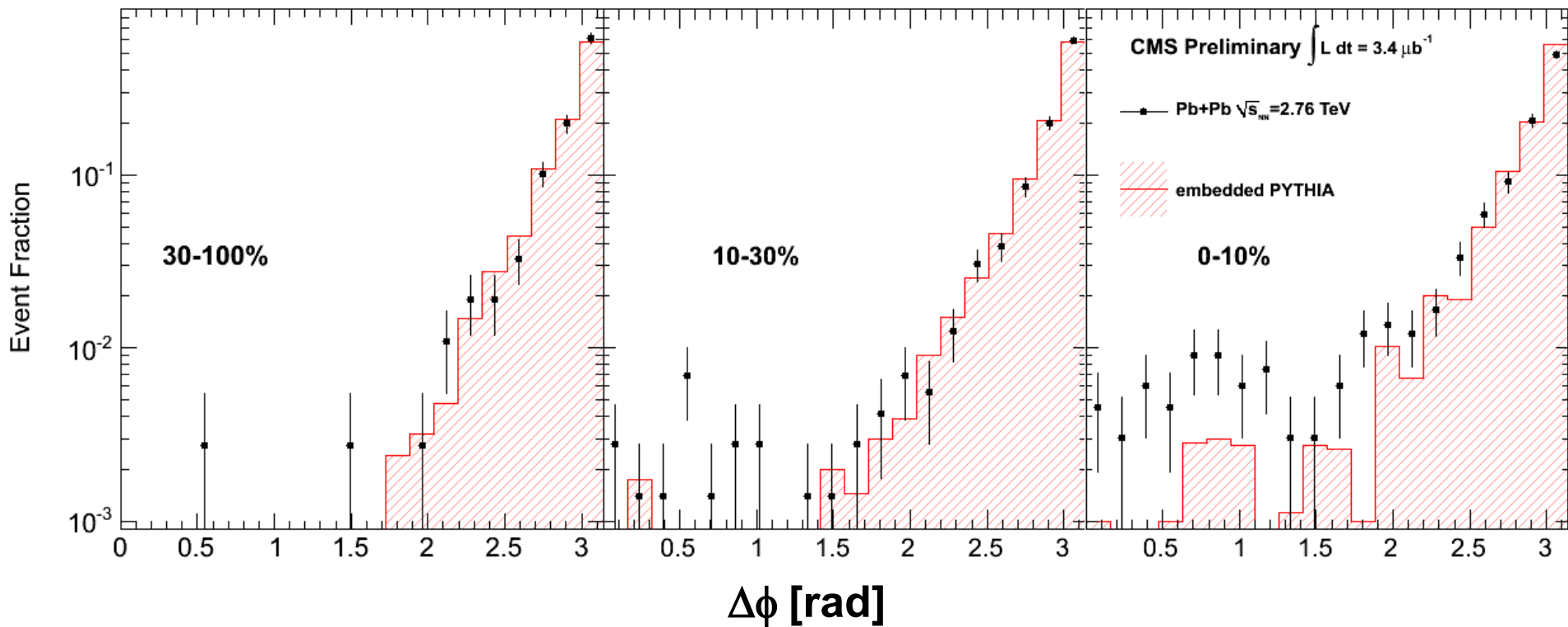
Semi-Peripheral

F Pb

Semi-Central

Pb

Central



Select back-to-back dijets with $\Delta\phi > 2.5$ for further study



Dijet energy imbalance

Pb Pb

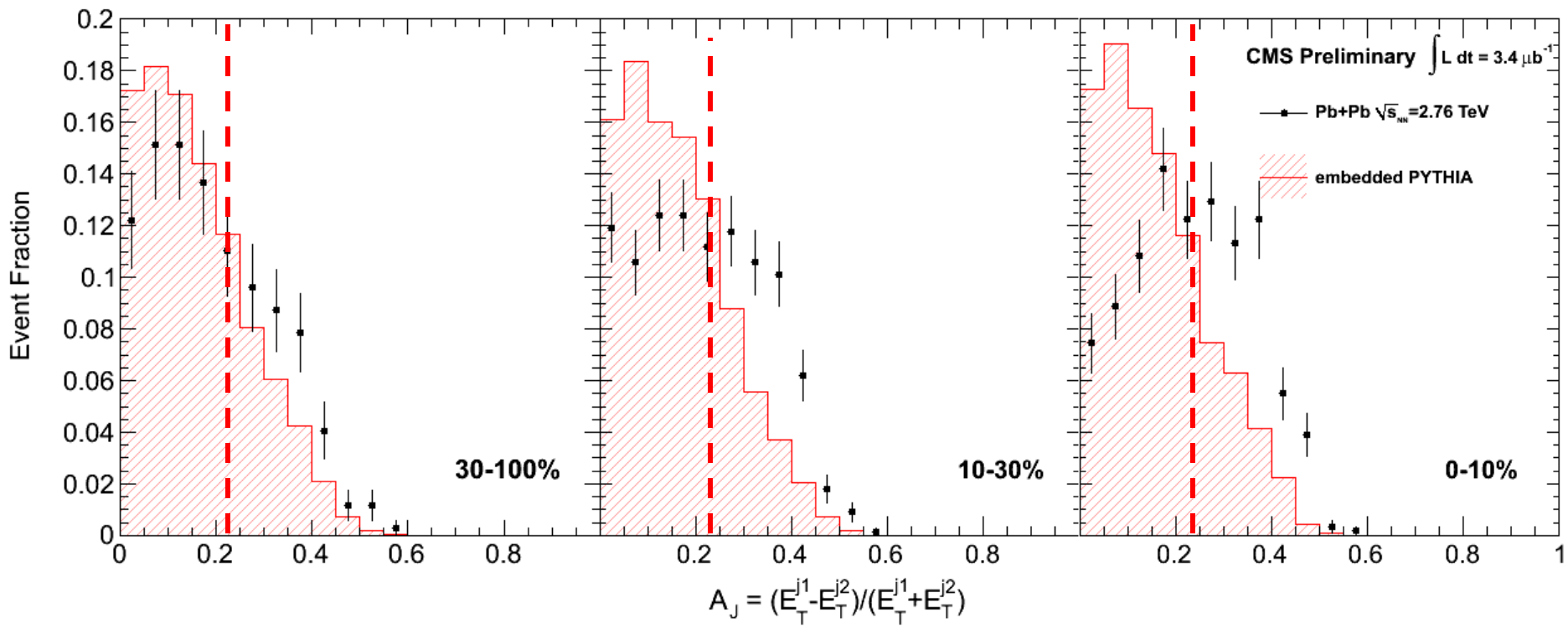
Semi-Peripheral

Pb

Semi-Central

Pb

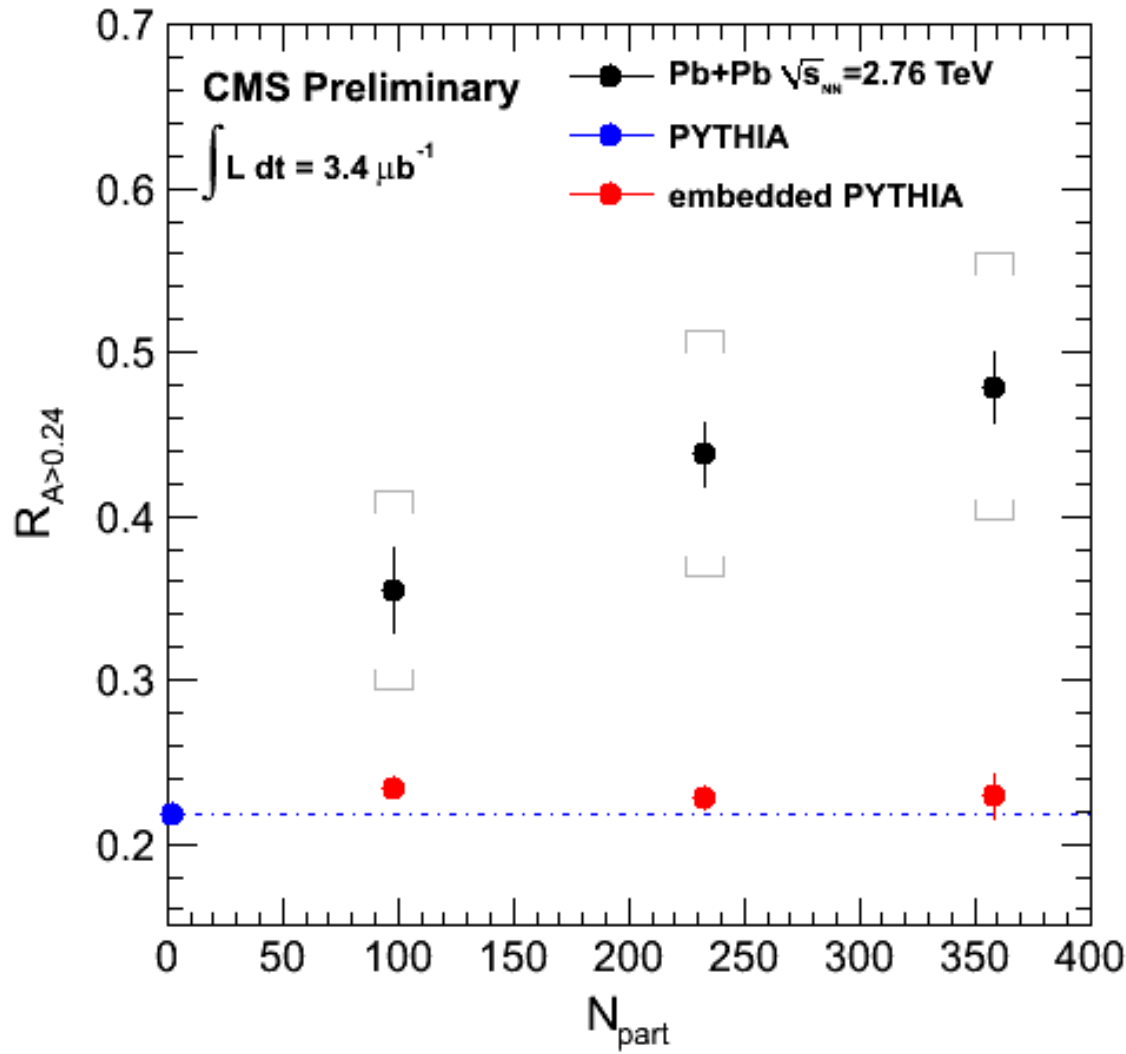
Central



A significant dijet imbalance, well beyond that expected from unquenched MC, appears with increasing collision centrality



Quantifying the imbalance: fraction of unbalanced dijets



- Fraction of jets with imbalance larger than 0.24
- Plot as a function of number of participating nucleons (volume) averaged over centrality bin



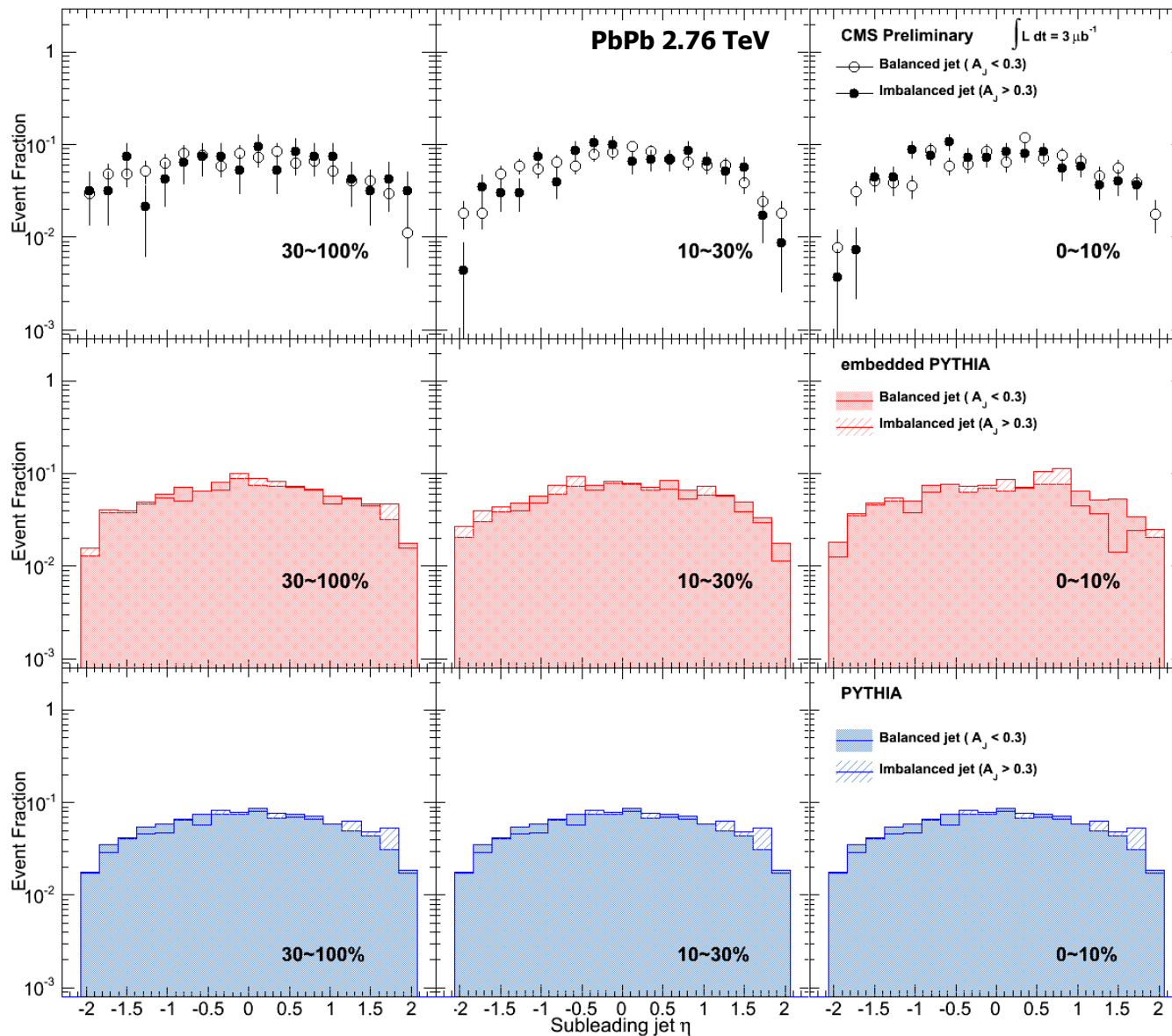


Systematic studies

- **We conducted extensive studies to convince ourselves that the effect is real...**

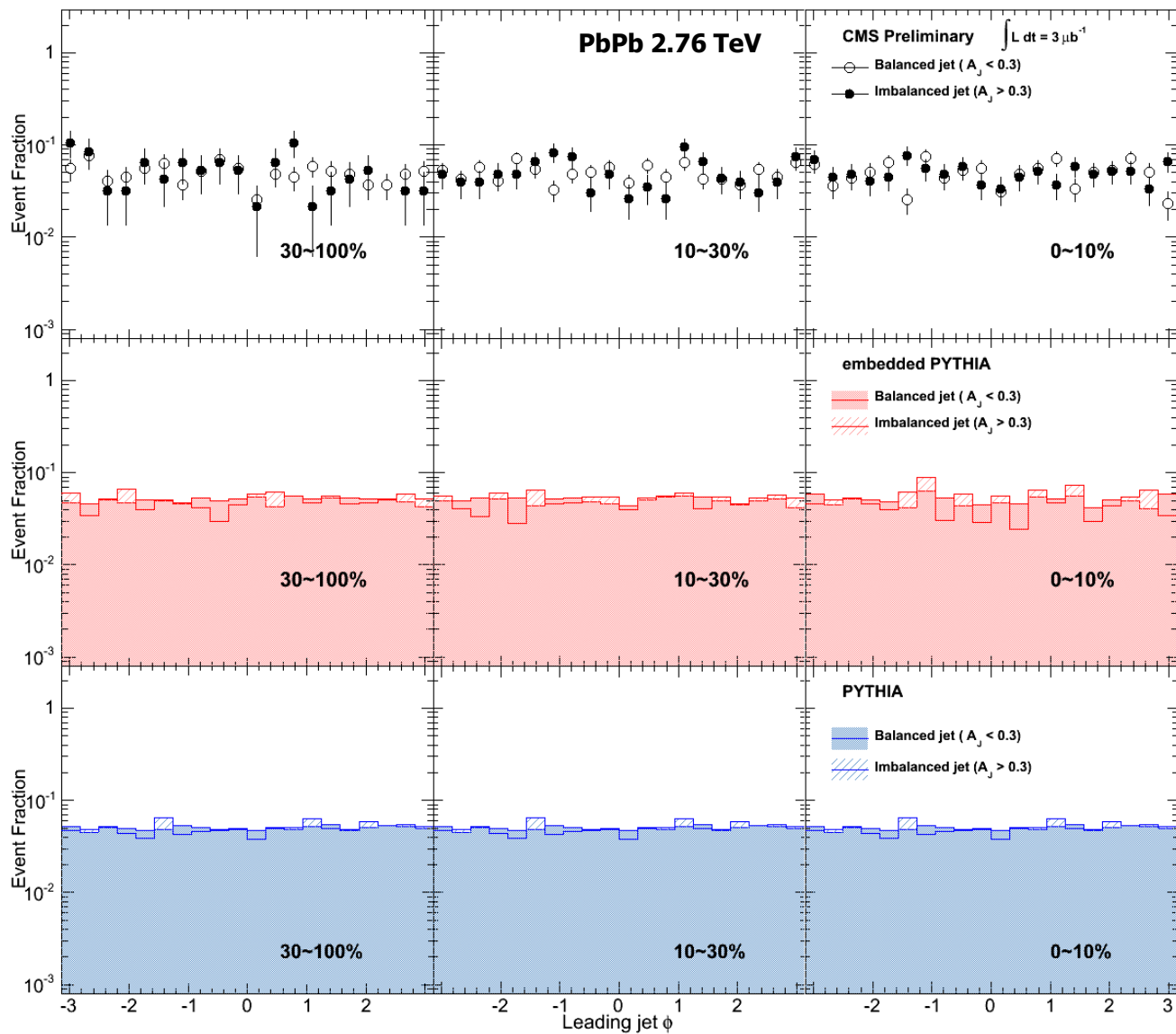


Imbalance uniformity: pseudorapidity





Imbalance uniformity: azimuth





Influence of HI underlying event

Pb Pb

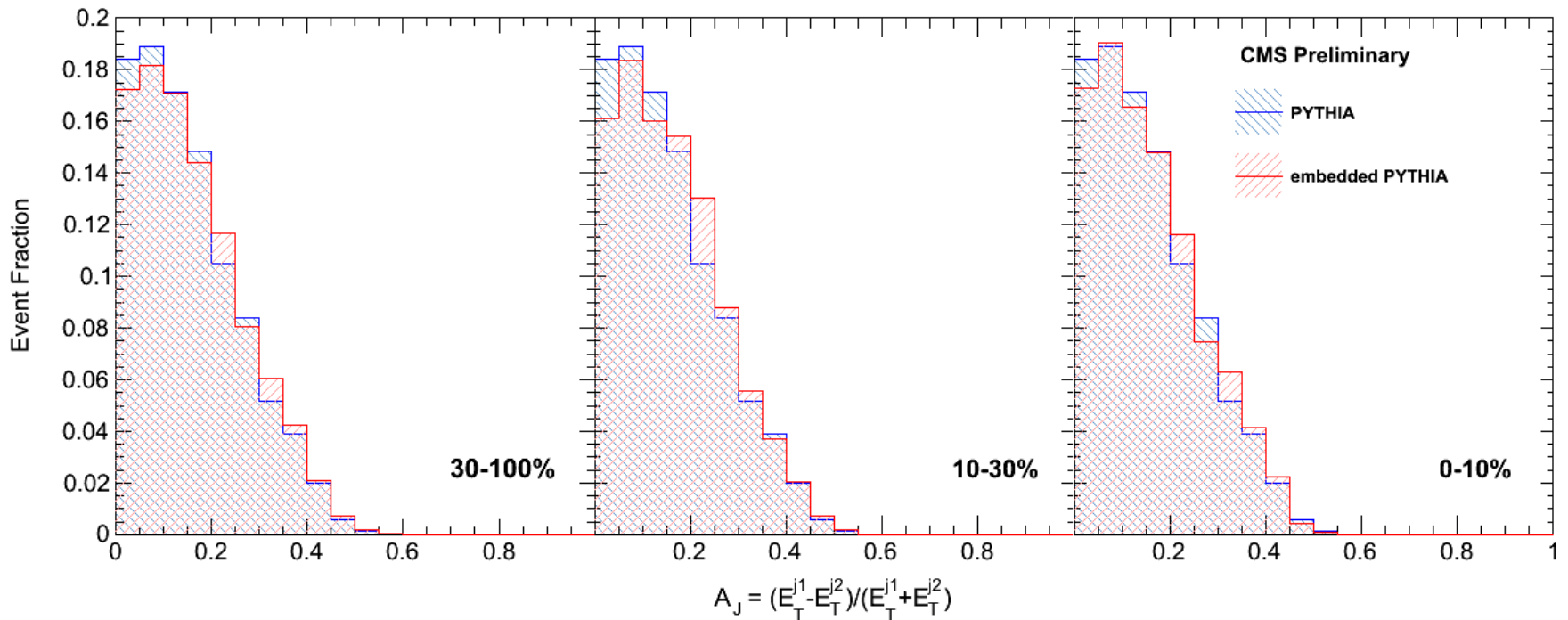
F Pb

Pb

Semi-Peripheral

Semi-Central

Central



Comparison of energy imbalance in simulation with and without embedding in data for central events
Background subtraction works really well!



Jet Resolution

Pb Pb

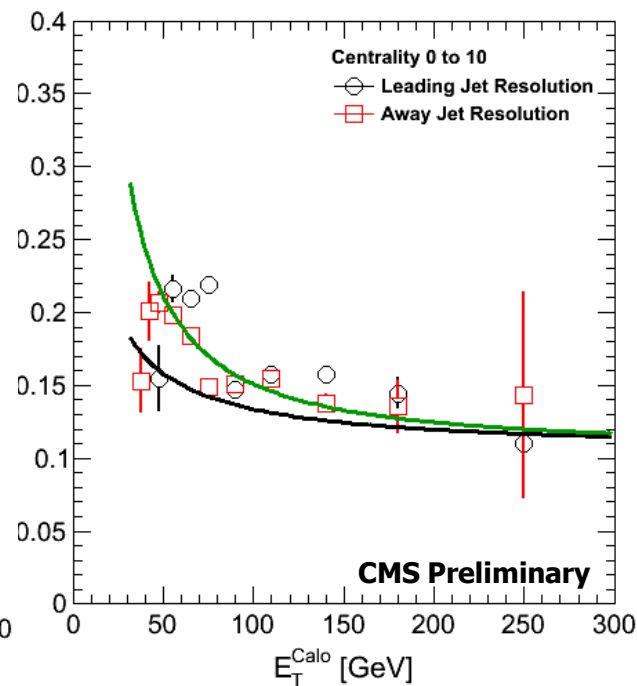
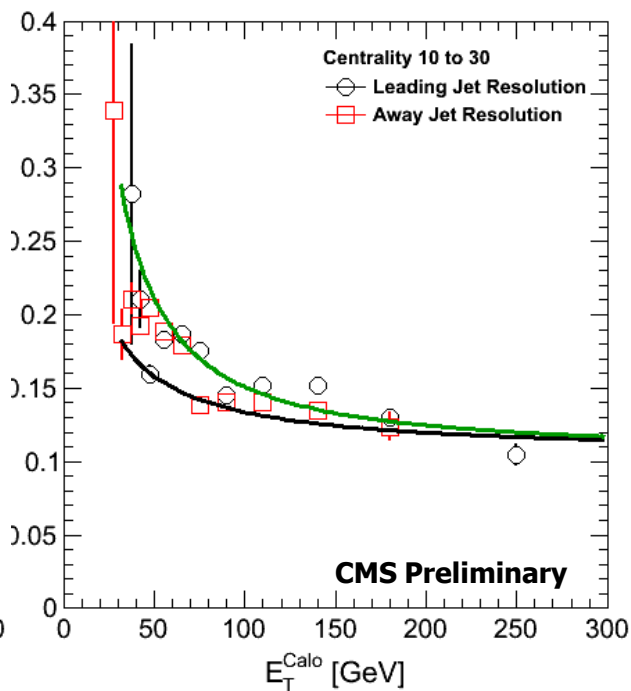
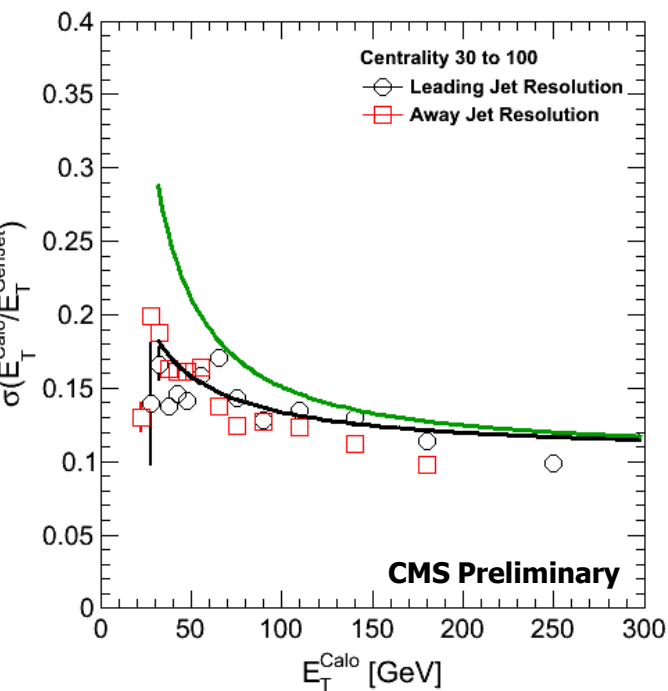
Semi-Peripheral

Pb Pb

Semi-Central

Pb

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



Jet Response

Pb Pb

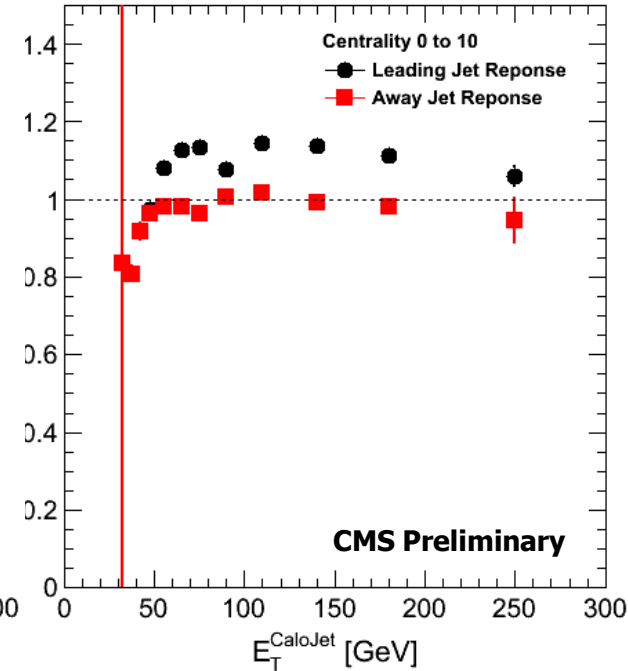
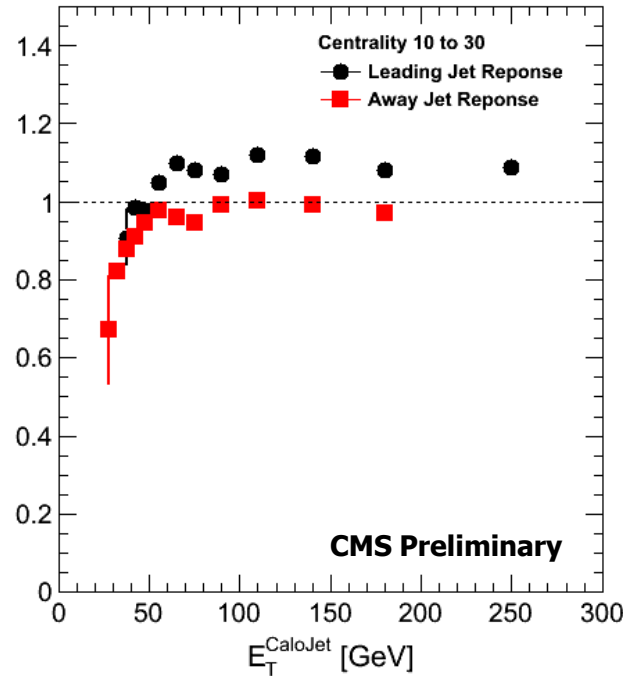
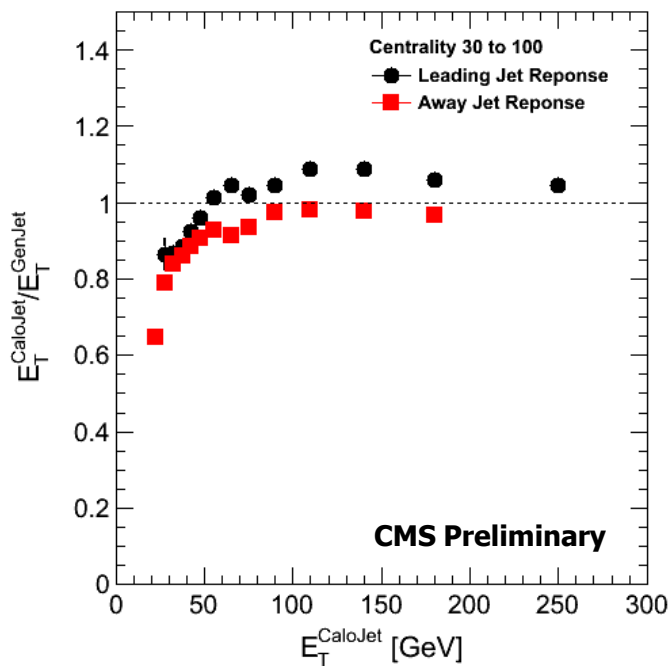
Semi-Peripheral

Pb Pb

Semi-Central

Pb

Central



- Response of jets is influenced by the dijet selection
- Poorer resolution, due to the heavy-ion background, as compared to pp



Dijet imbalance and jet energy resolution

Pb Pb

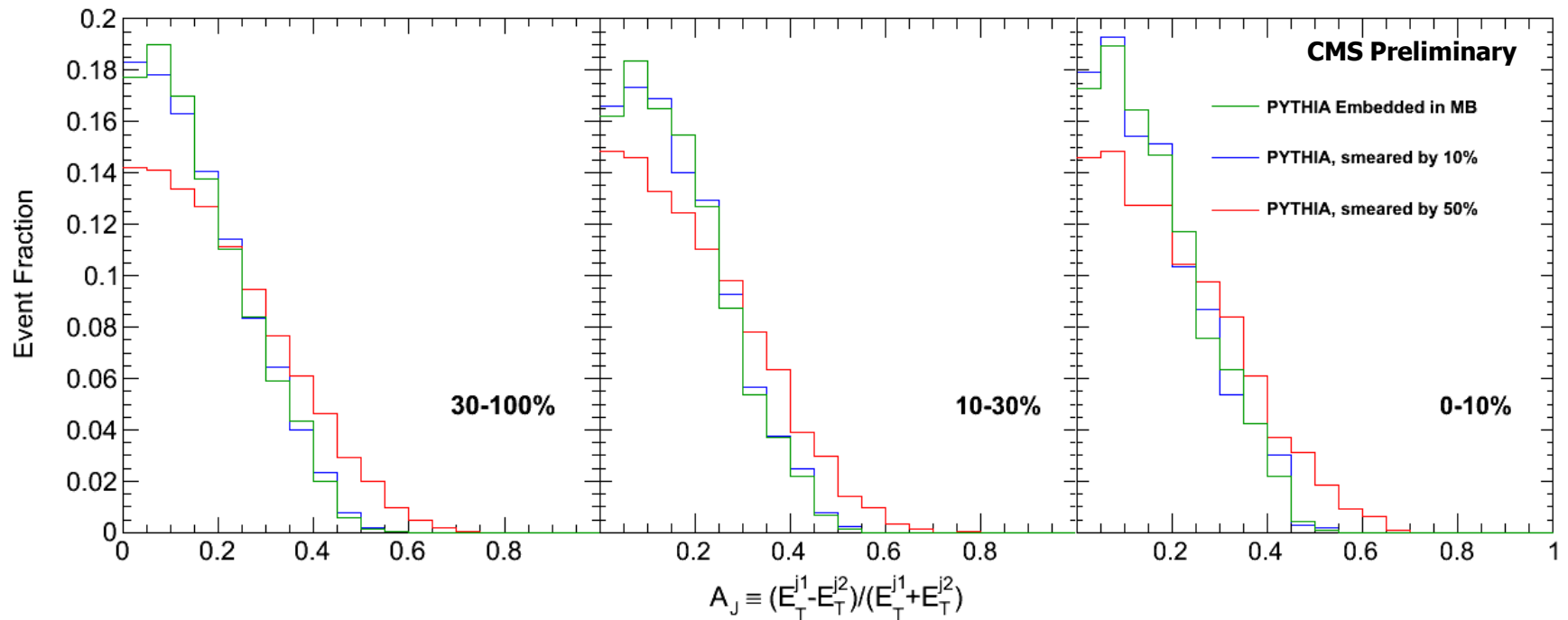
Semi-Peripheral

F Pb

Semi-Central

Pb

Central



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



Dijet imbalance and Jet Energy Scale

Pb Pb

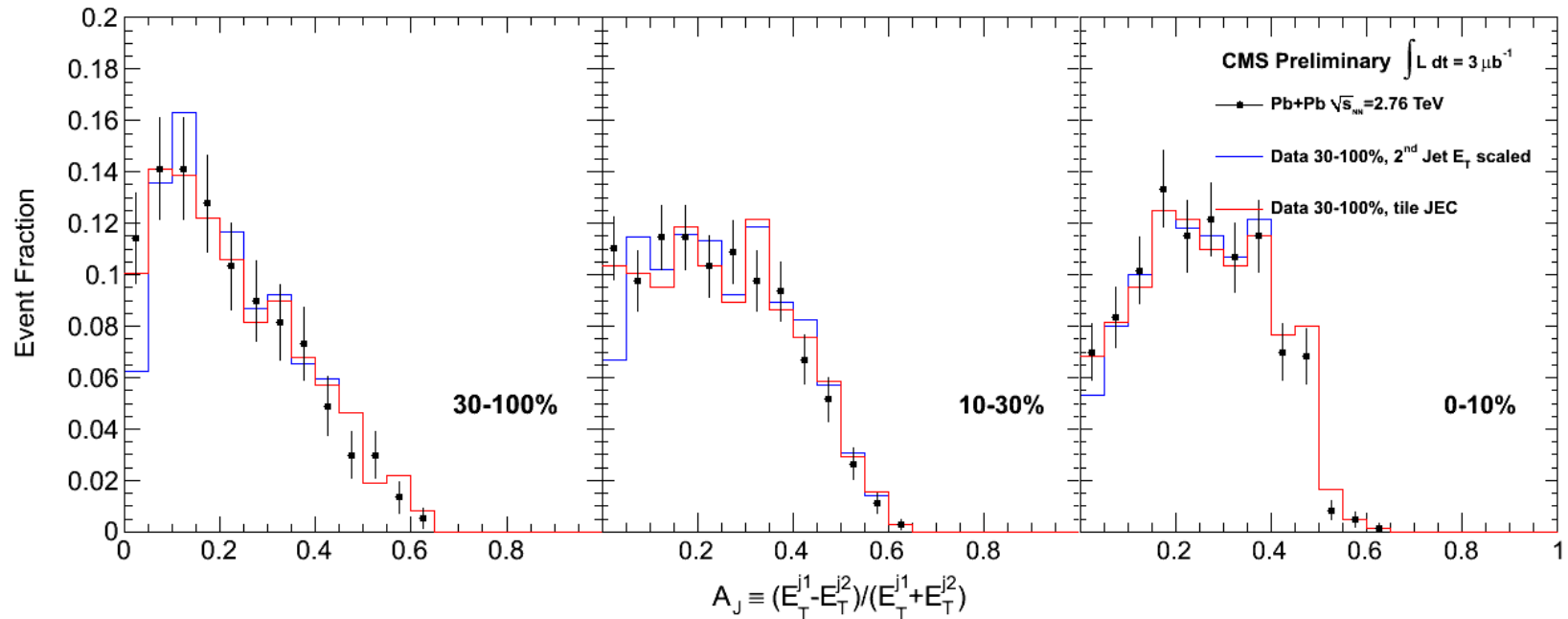
Pb Pb

Pb

Semi-Peripheral

Semi-Central

Central



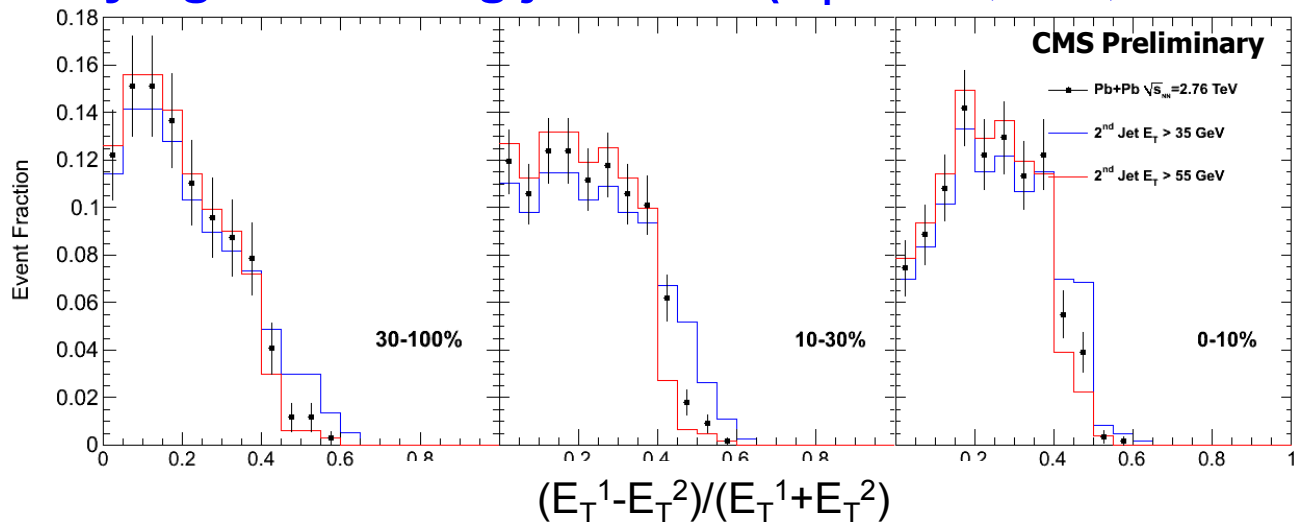
The energies of sub-leading jets were shifted up by 1σ of the uncertainty in the correction.

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

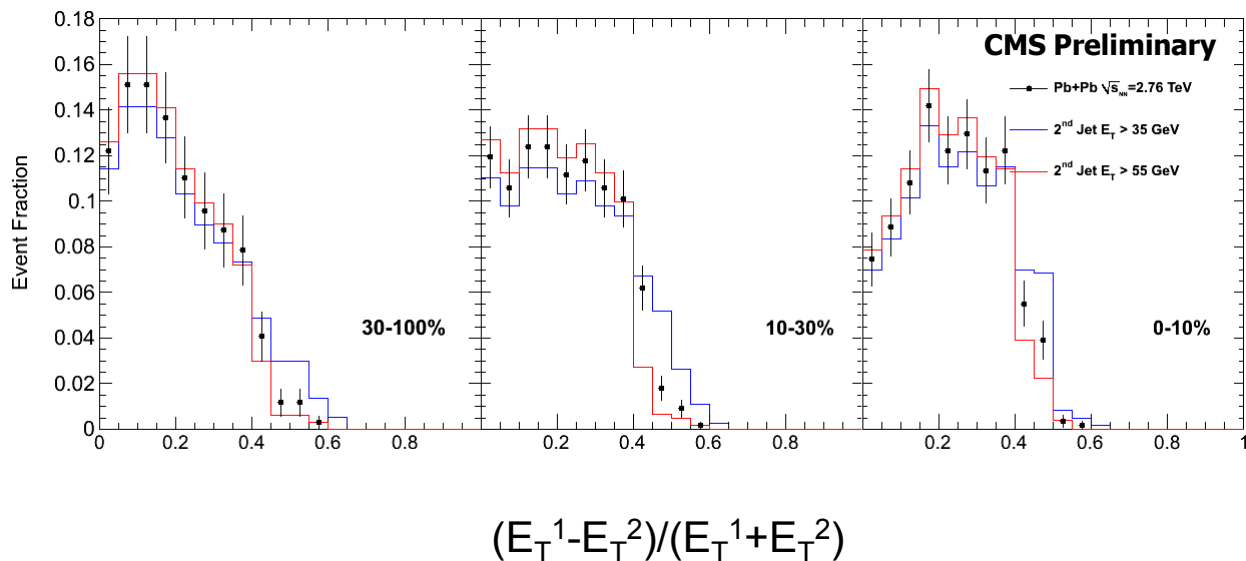


Dijet imbalance and jet energy selection cut

Varying the leading jet cutoff ($E_T = 120, 130, 140$ GeV)



Varying the sub-leading jet cutoff ($E_T = 35, 50, 55$ GeV)





Dijet imbalance with Calo- and Particle Flow- Jets

Pb Pb

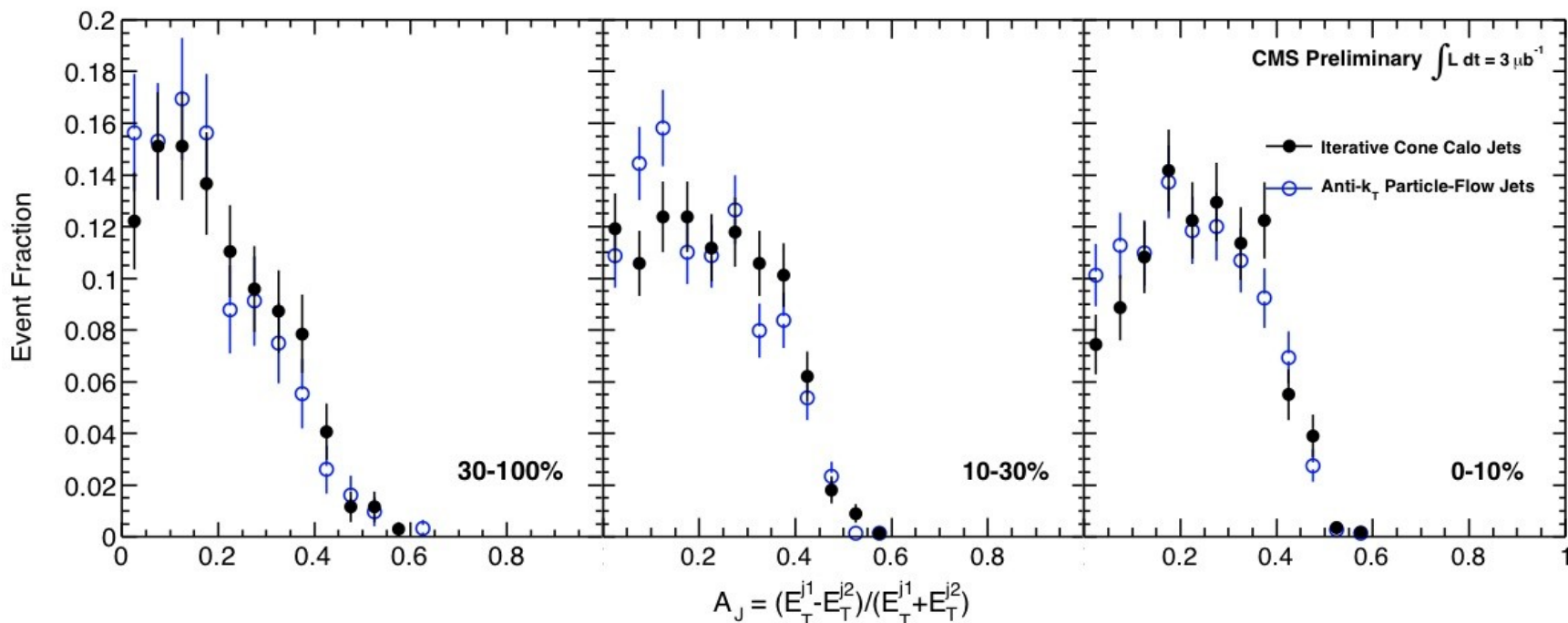
F Pb

Pb

Semi-Peripheral

Semi-Central

Central



**Particle Flow: Extensive use of tracker information, different background subtraction, different jet finder algorithm
Jet energy corrections are smaller than for CaloJets**

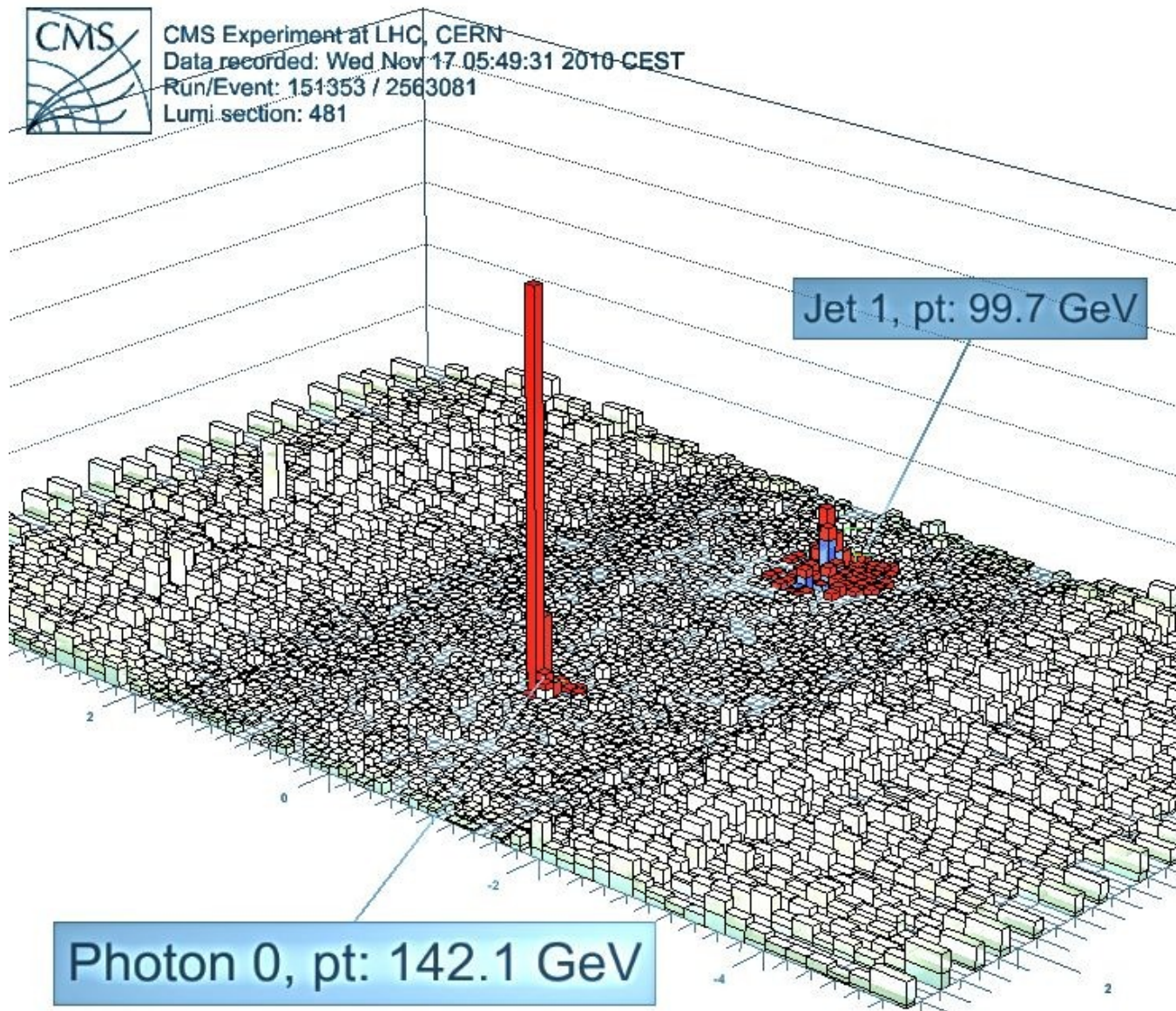
Excellent agreement between two very different methods 37



Future studies: γ -jet ?



CMS Experiment at LHC, CERN
Data recorded: Wed Nov 17 05:49:31 2010-CEST
Run/Event: 151353 / 2563081
Lumi section: 481





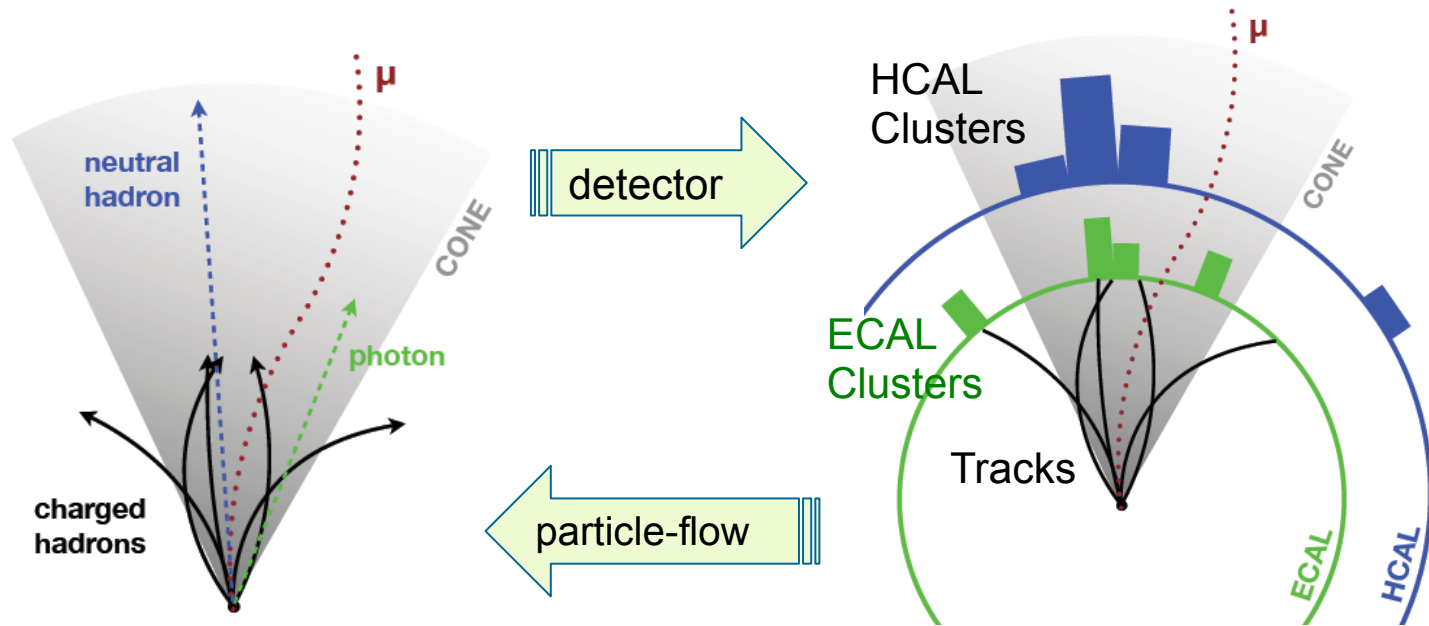
Summary

- **CMS continues to collect good data with heavy ion collisions. The detector is working very well.**
- **First observation of new phenomena in heavy ion collisions**
 - **Z^0 production**
 - **Large number of dijets with unbalanced energies indicative of jet quenching**
- **By the end of the current data taking with the factor of almost 2-3 compared to the present analysis statistics we hope to get a deeper insight into the new phenomena**
- **Special thanks to the LHC accelerator team for fantastic performance during the heavy ion runs**



Backup

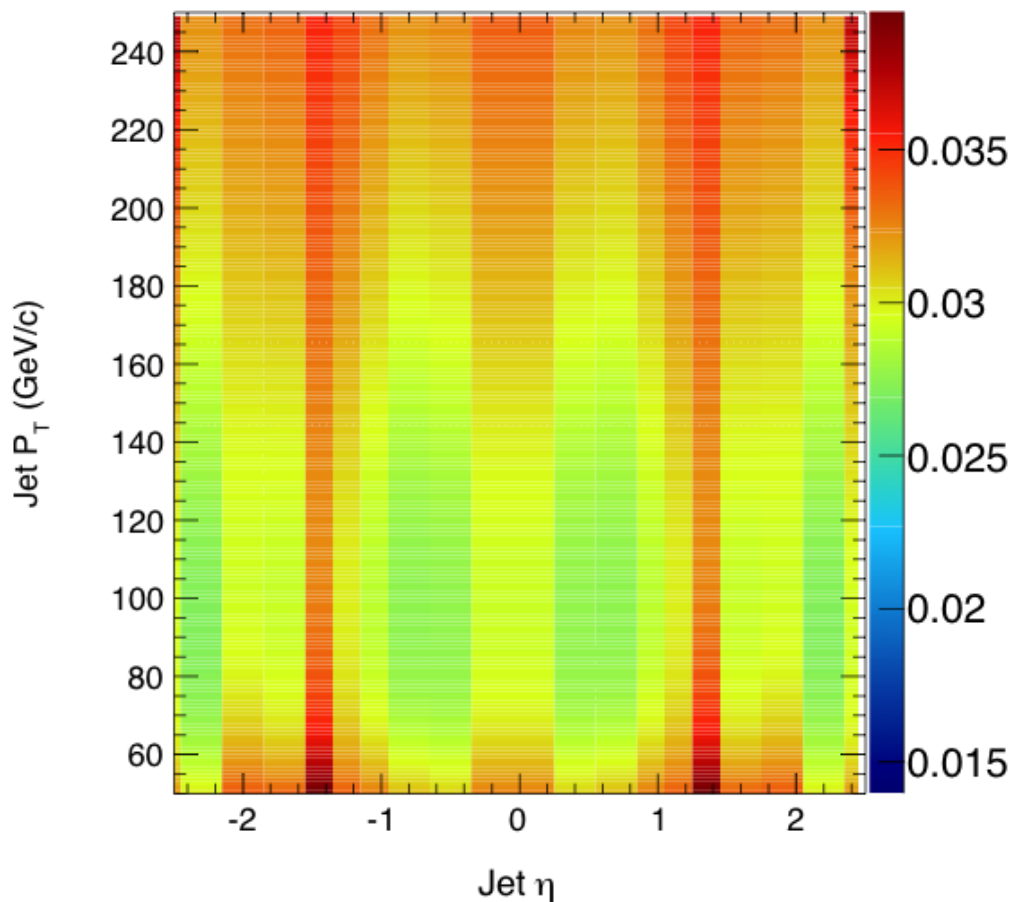
Overview: the Particle Flow algorithm



The list of individual particles is then used to **build jets**, to **determine the missing transverse energy**, to **reconstruct and identify taus from their decay products**, to **tag b jets** ...

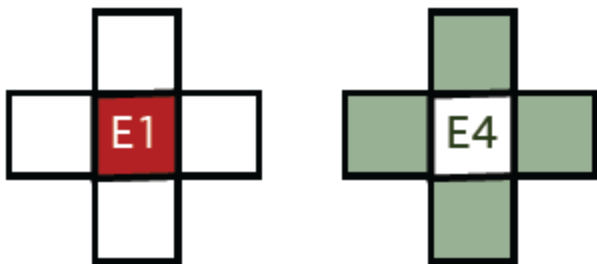
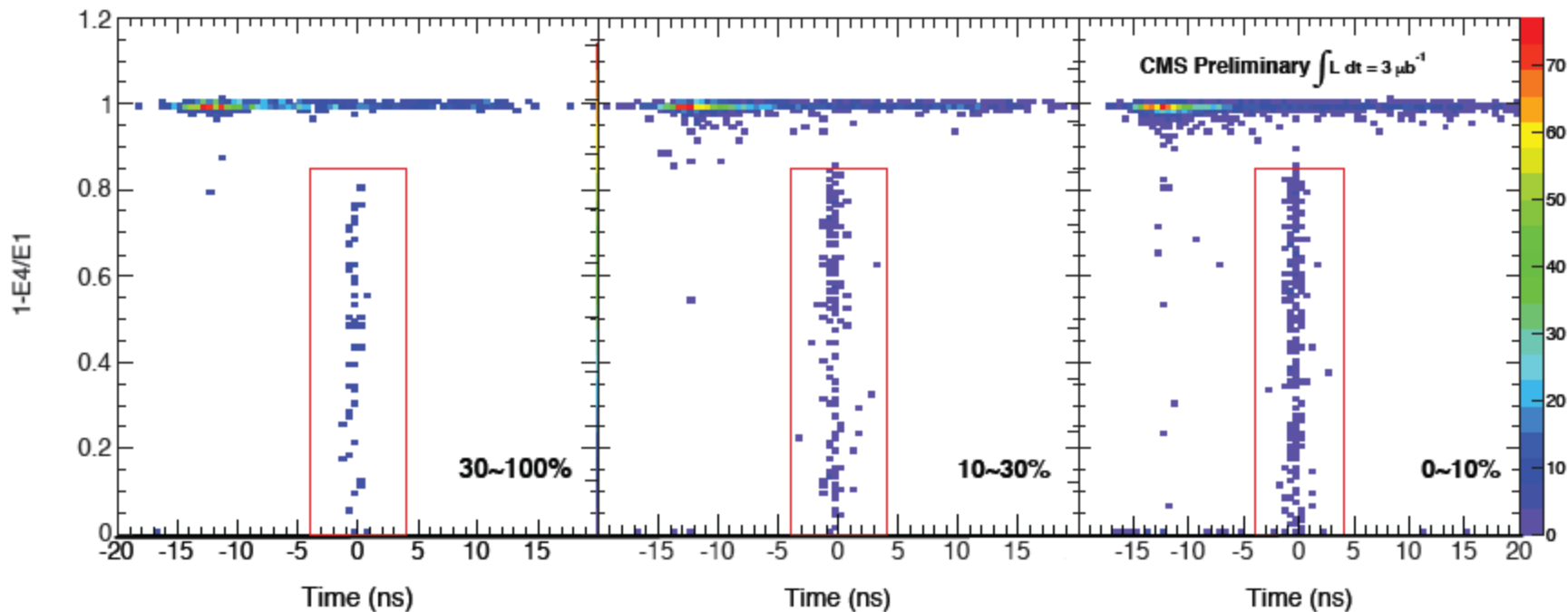


Jet Energy Correction Uncertainties



The uncertainty is estimated to be within 4% for our dijets in pp events

Cleaning of ECAL Spikes



Applied to energetic hits with $E_T > 20$ GeV

$|t_{recol}| < 4$ ns

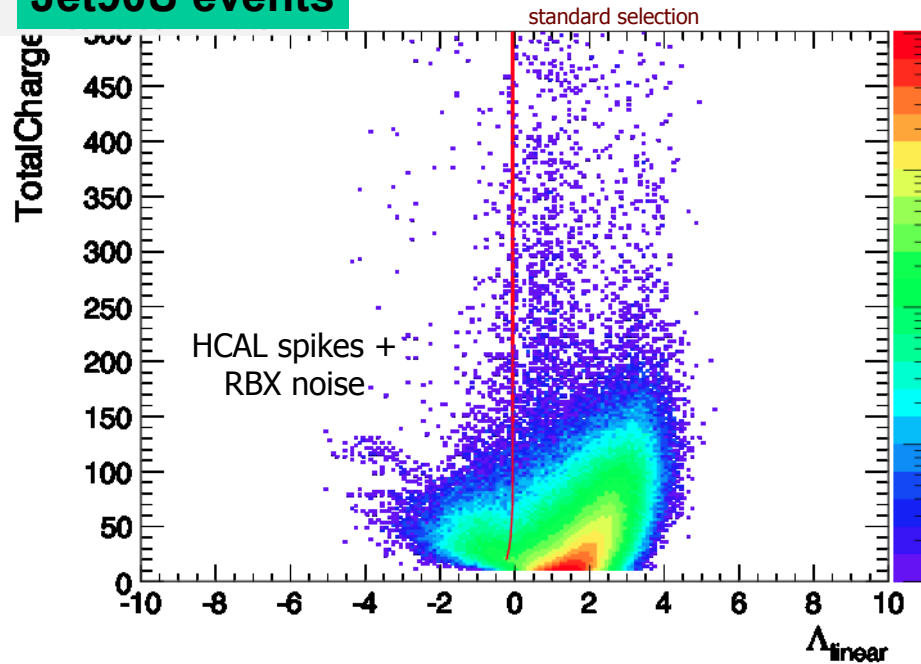
$1 - E_4/E_1 < 0.85$

spikes contain large energy deposit in one rechit

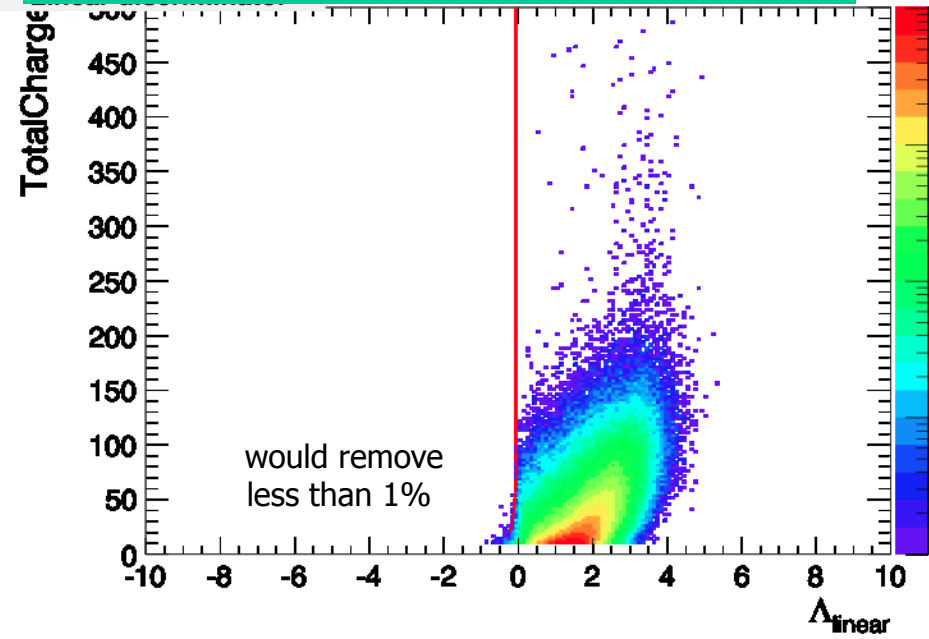


HCAL Noise Cleaning

Jet90U events



Jet90U events + collision selections

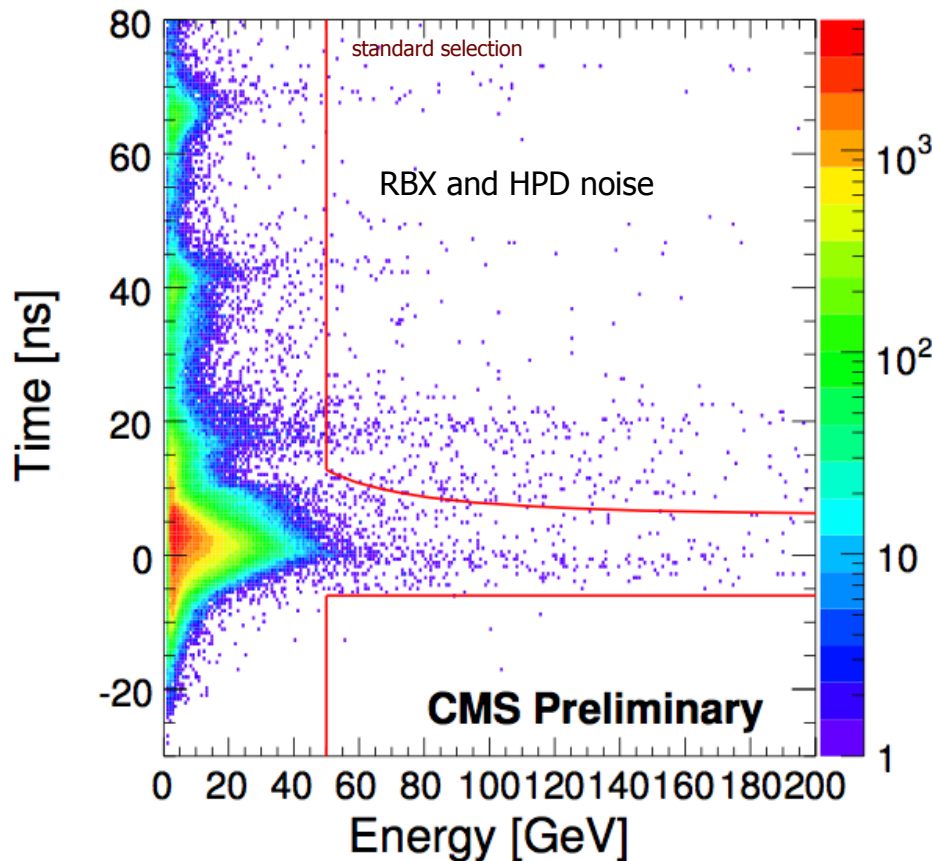


Linear discriminant between signal and noise pulse shape over 10 time slices. Selection not used.

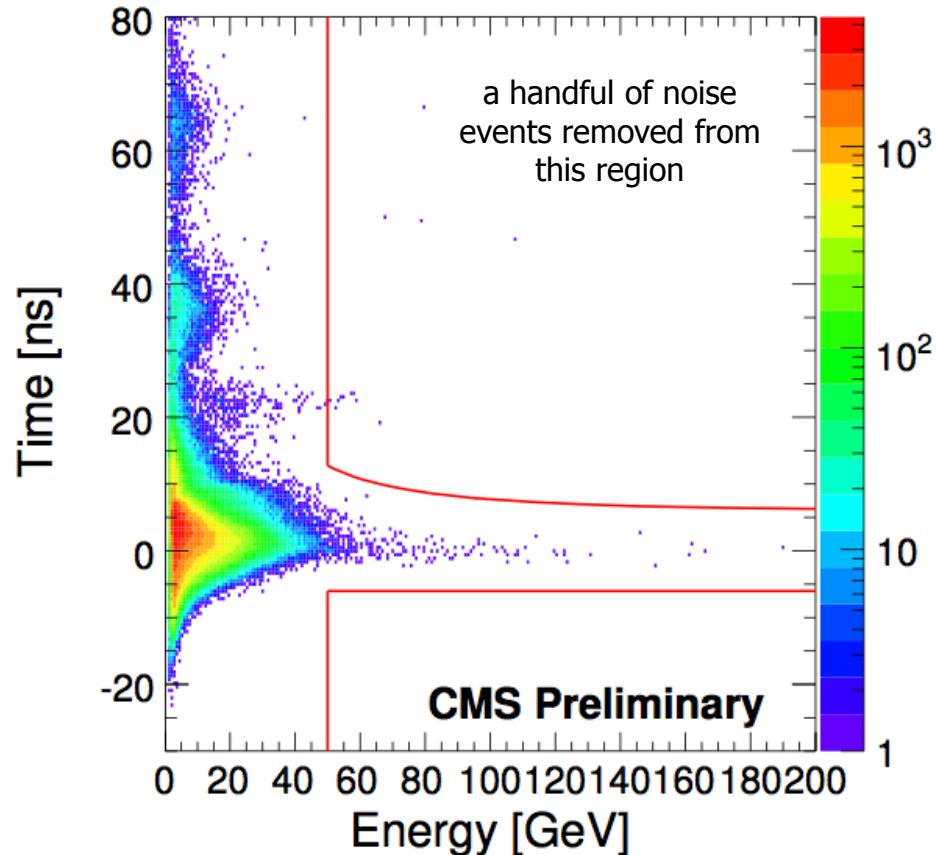


HCAL Noise Cleaning

Jet90U events



Jet90U events + collision selections



Low energy behavior is an artifact of the algorithm poorly resolving time differences



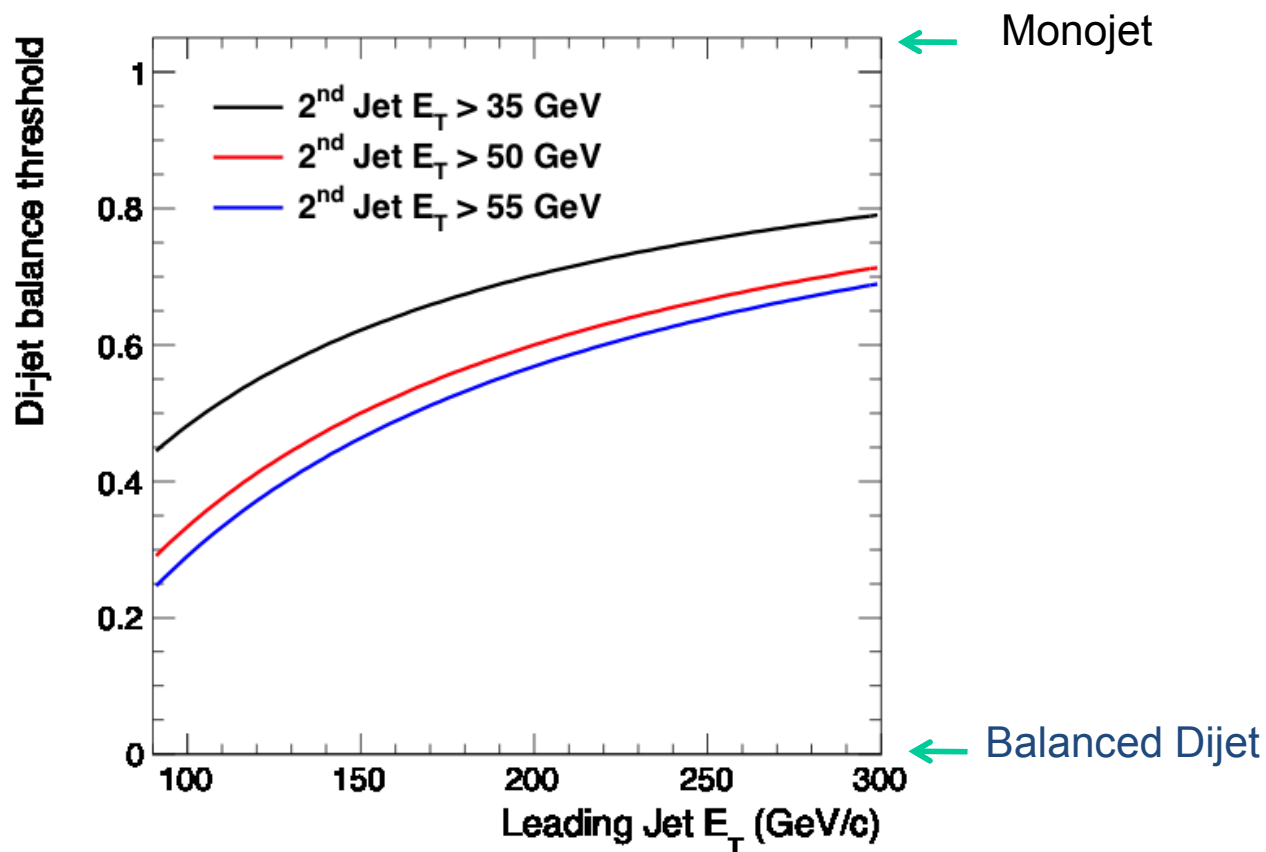
Summary of Selections

Cut	events remaining	% of events remaining
Core Physics	2730344	100.00
HLT_HIJet50U	69383	2.54
no BSC halo	69053	99.52
HF offline coinc	52421	75.91
vertex	51933	99.07
PKAM removal	51816	99.77
ECAL spike veto	48849	94.27
HCAL timing cut	48826	99.95

with respect to previous selection



Dijet Balance Range



Maximum dijet imbalance sampled for various sub-leading jet cutoffs



Typical dijet in PbPb Collisions at CMS



CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249

