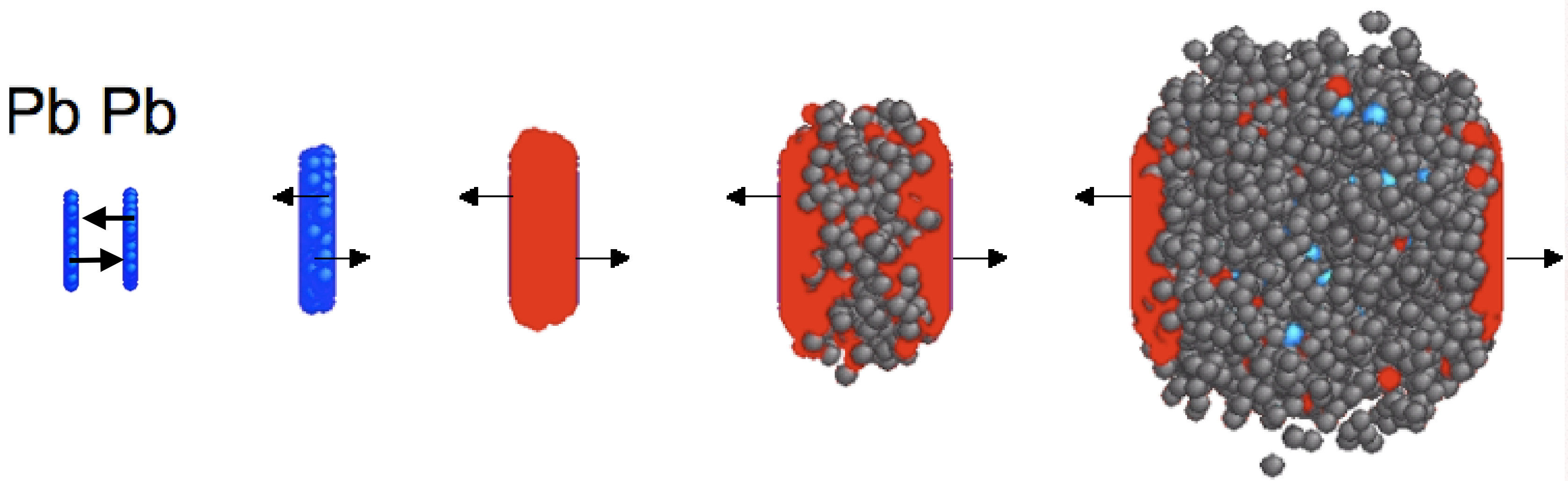
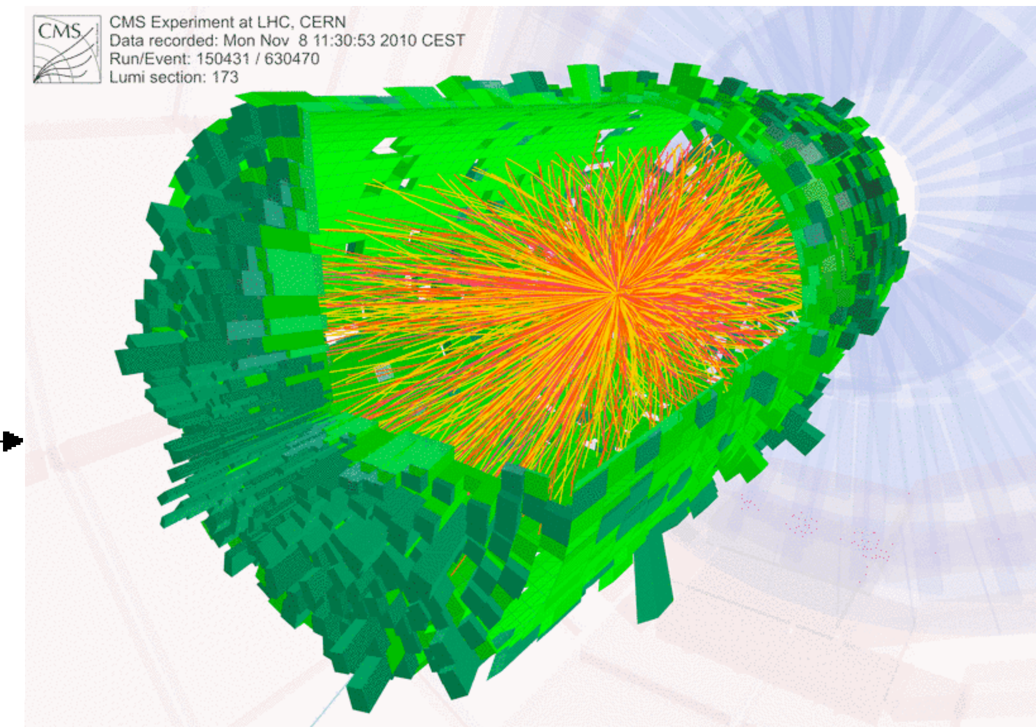
Heavy Ion Results from the CMS Experiment



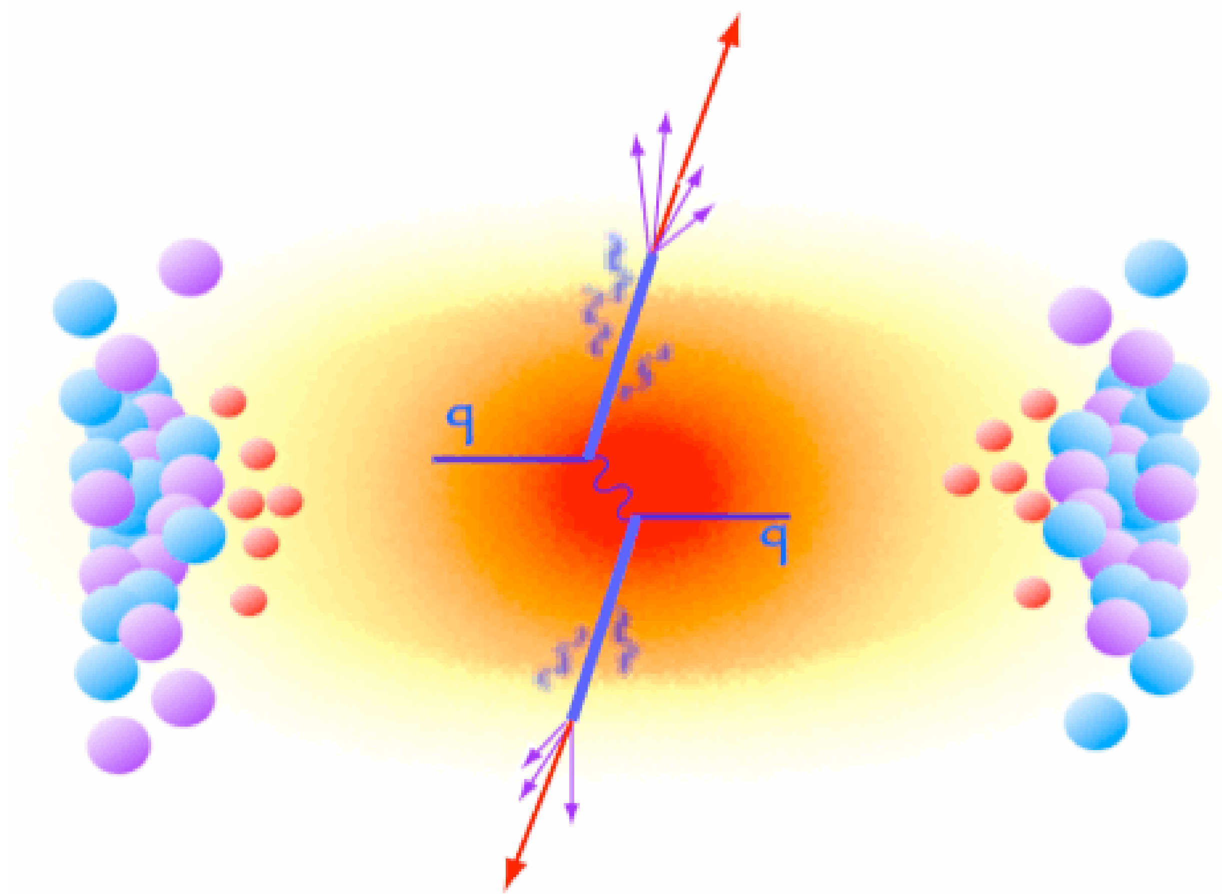


Pelin Kurt Garberson
Vanderbilt University
for the CMS Collaboration

2nd International Conference on Particle Physics
in Memoriam Engin Arık and Her Colleagues, 20-25 June 2011, İstanbul

Motivation for Heavy Ions

By colliding heavy ion nuclei at LHC energies, one expect to form a hot and dense deconfined matter at energy densities never explored before.

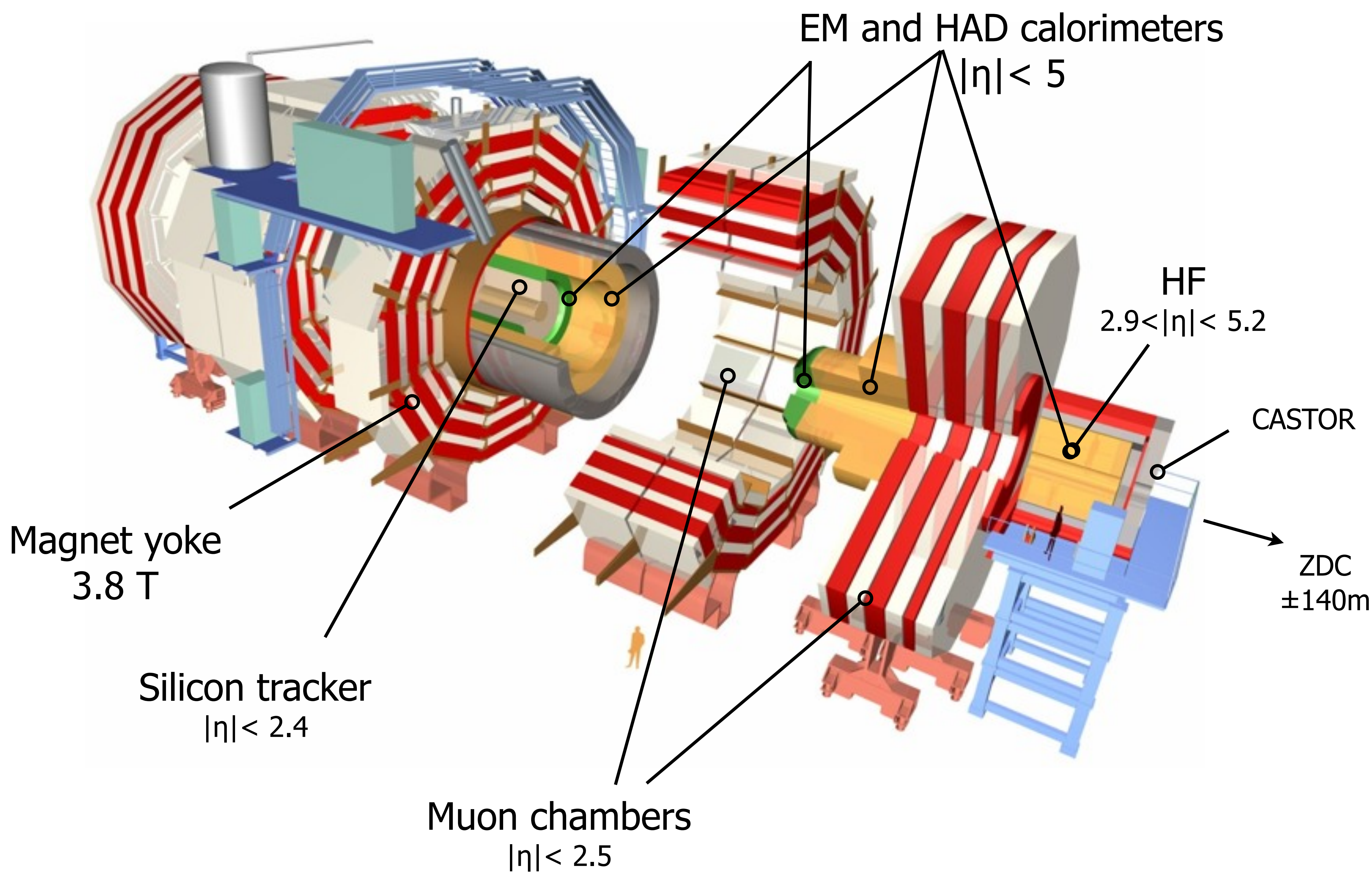


- Study QCD at extreme temperatures and densities
- Discover new form of nuclear matter (Quark-Gluon Plasma, QGP) at high energy densities (above 1GeV/fm ^{3})
- Already at RHIC, conservative estimates of energy density in the early system are well above predicted crossover

QGP Probes

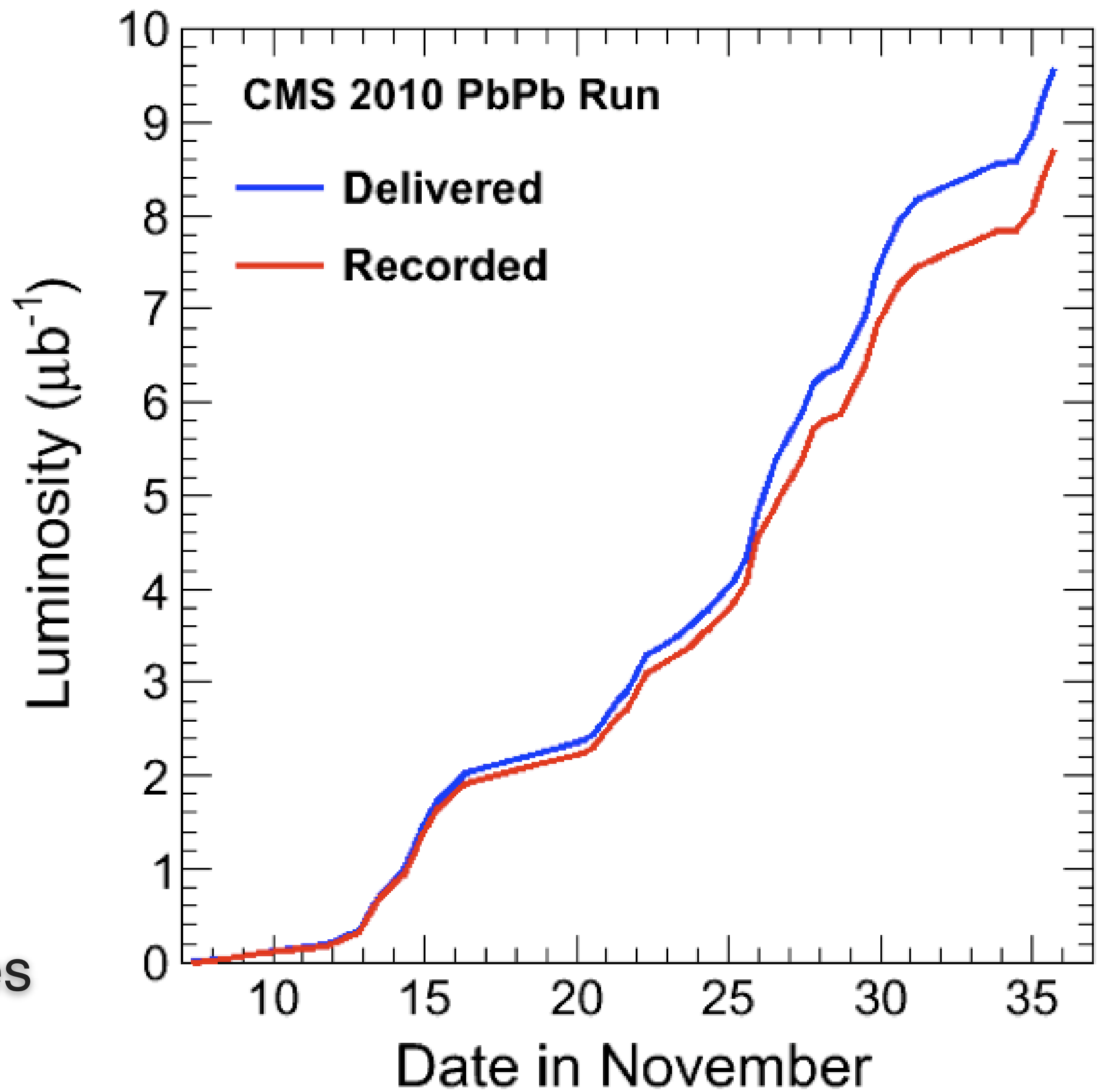
- **Soft Probes**
  - Charged Particle Multiplicity
  - Elliptic Flow
  - Two Particle Correlations
  - Charged Particle Spectra
- **Hard Probes**
  - High E_T jets and "Jet Quenching"
  - Electroweak bosons (γ, Z)
  - Quarkonia (J/ψ, Υ)

Compact Muon Solenoid (CMS)



Data taking during PbPb run

- **November - December 2010**
  - PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
- **CMS detector configured for lead ion collisions**
  - Non Zero Suppressed Mode
  - Data taking up to 220Hz
  - 12MB Event Size
- **Triggering on Minimum Bias events**
  - HF or BSC firing in coincidence on both sides
  - 97% efficient
- **Triggering on Jets, Muons and Photons**



Recorded luminosity PbPb 8.7 μb-1

Recorded luminosity pp@2.76 TeV 241 nb-1

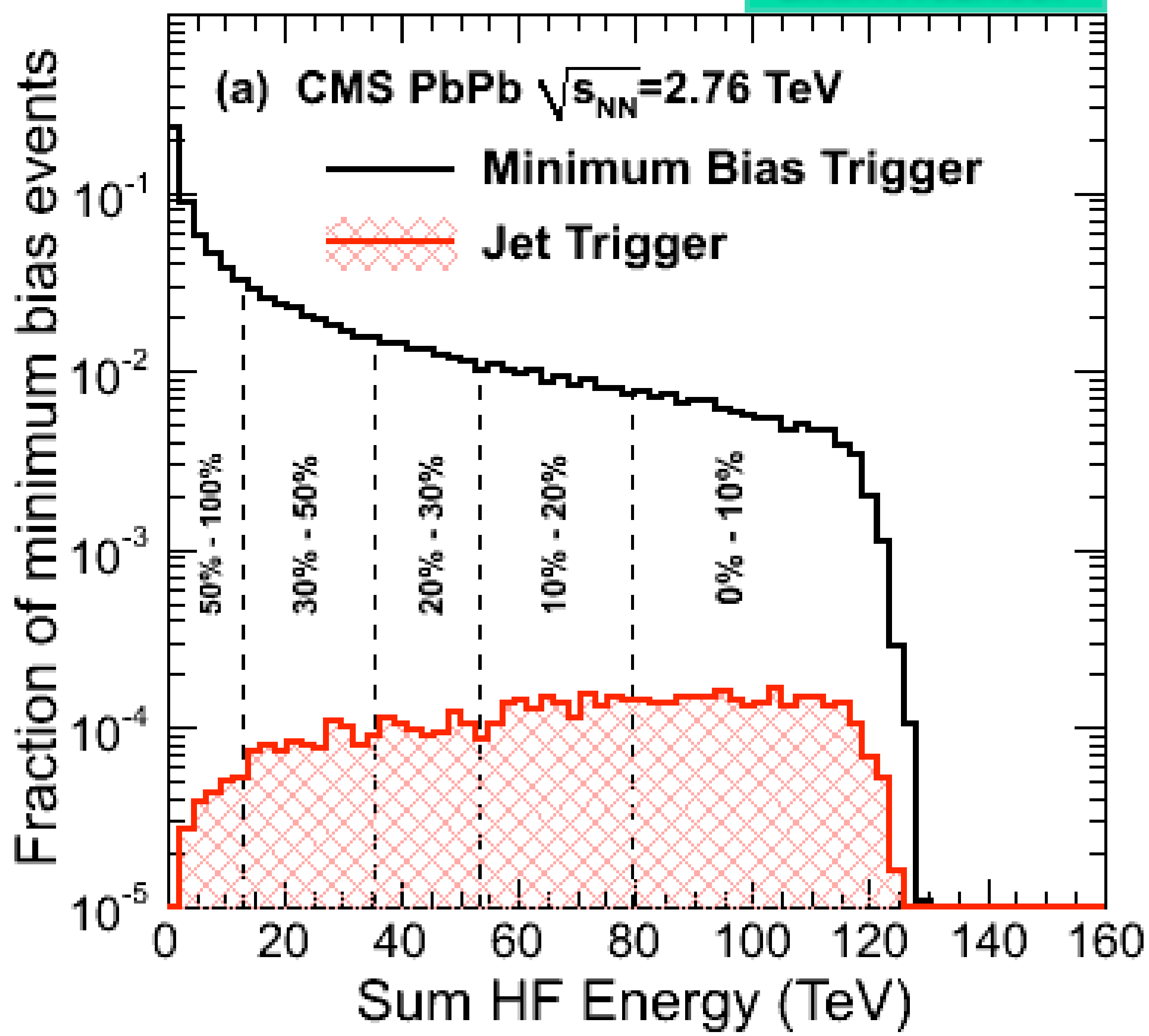
Total PbPb data volume ~0.89 PetaByte

Centrality

Centrality of a collision is defined as the degree of overlap of two colliding nuclei.

In our analyses, the observable used to determine the centrality is the total energy from both Hadronic Forward (HF) calorimeters.

arXiv:1102.1957

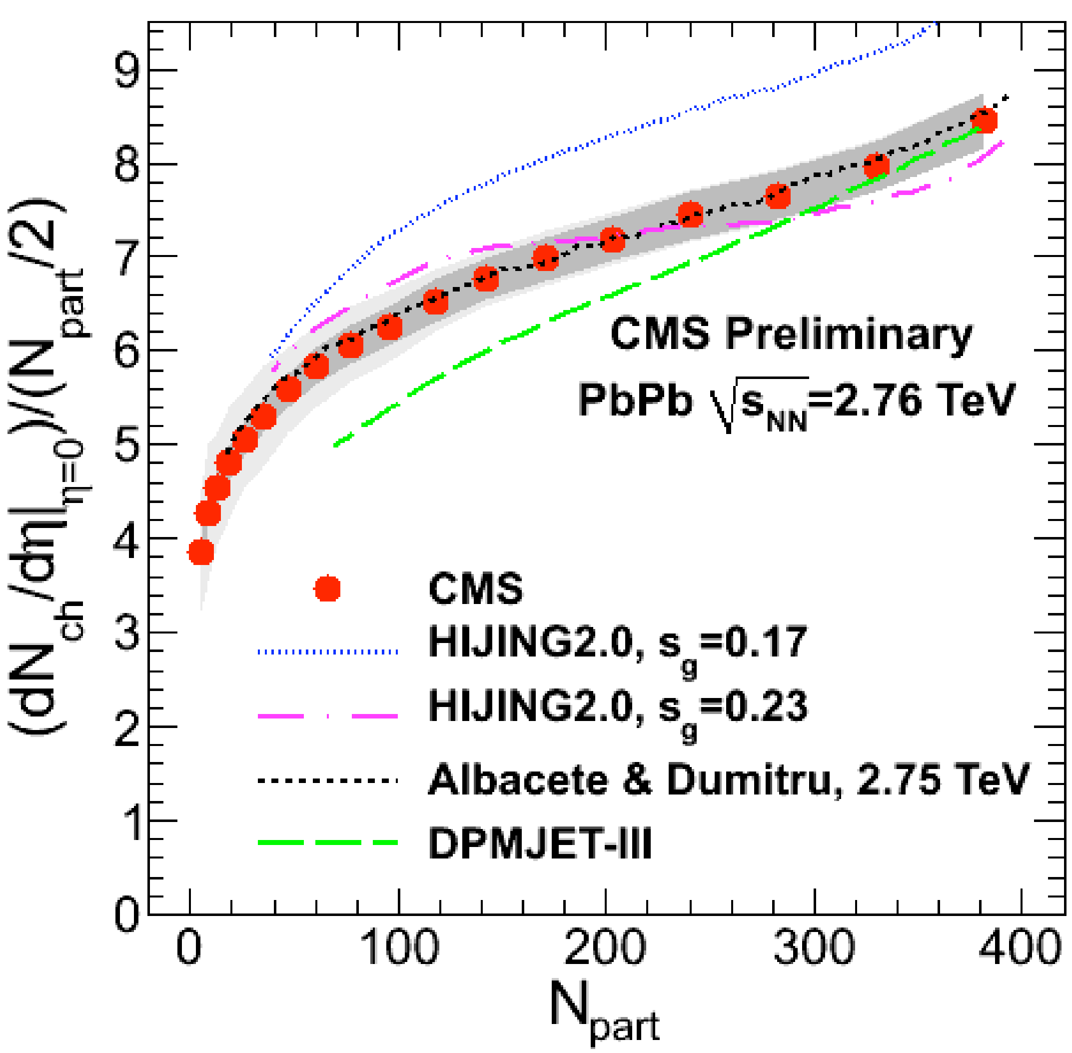


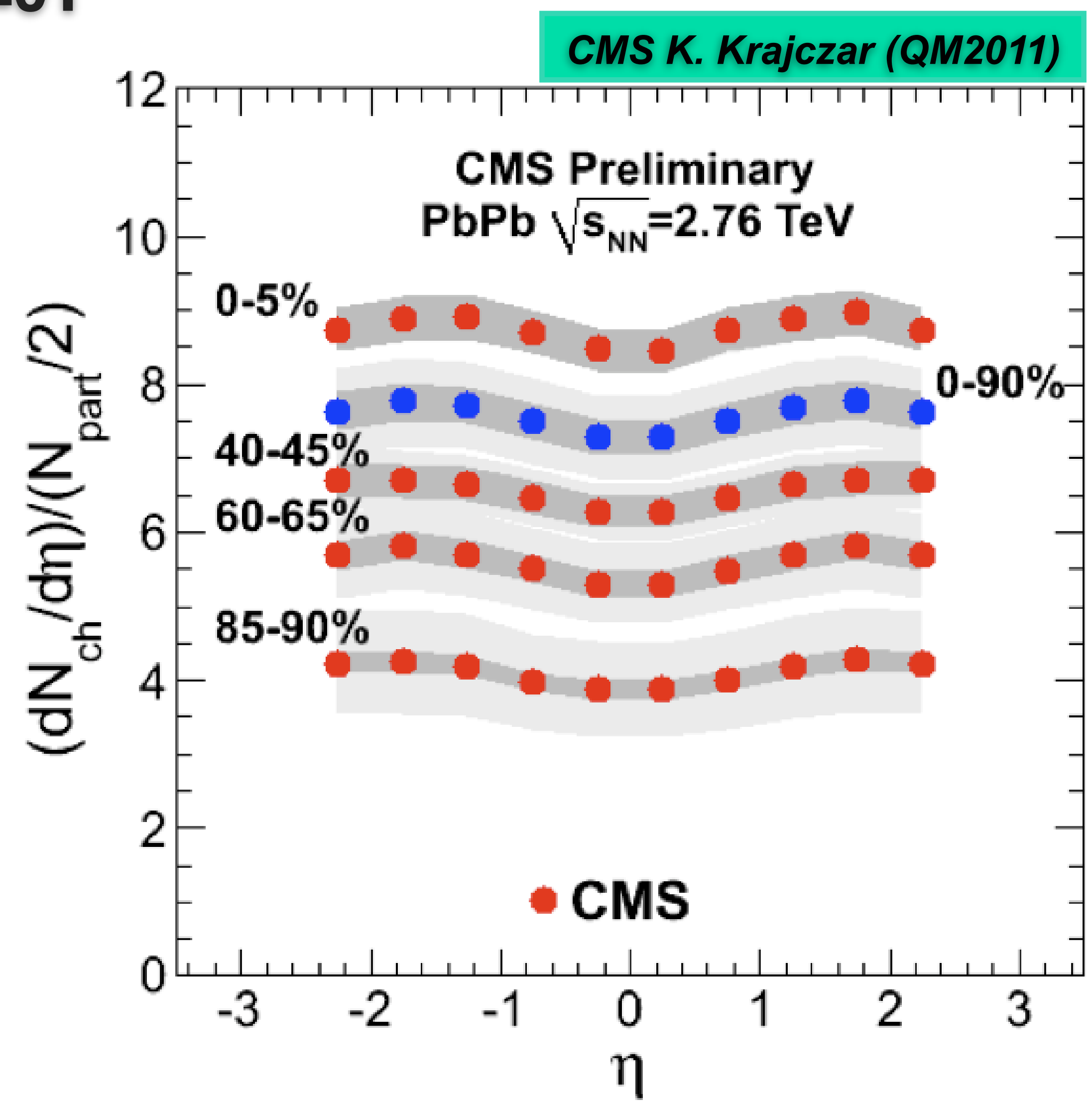
Peripheral (pp like)

Central

Charged Particle Multiplicity ($dN_{ch}/d\eta$)

- **The measurement uses pixel tracker and two methods:**
  - Cluster counting : Determines multiplicity via single layer occupancy
  - Tracklets : Uses all pairs of layers to create cluster pairs
- **Data taken with no magnetic field, B=0T**

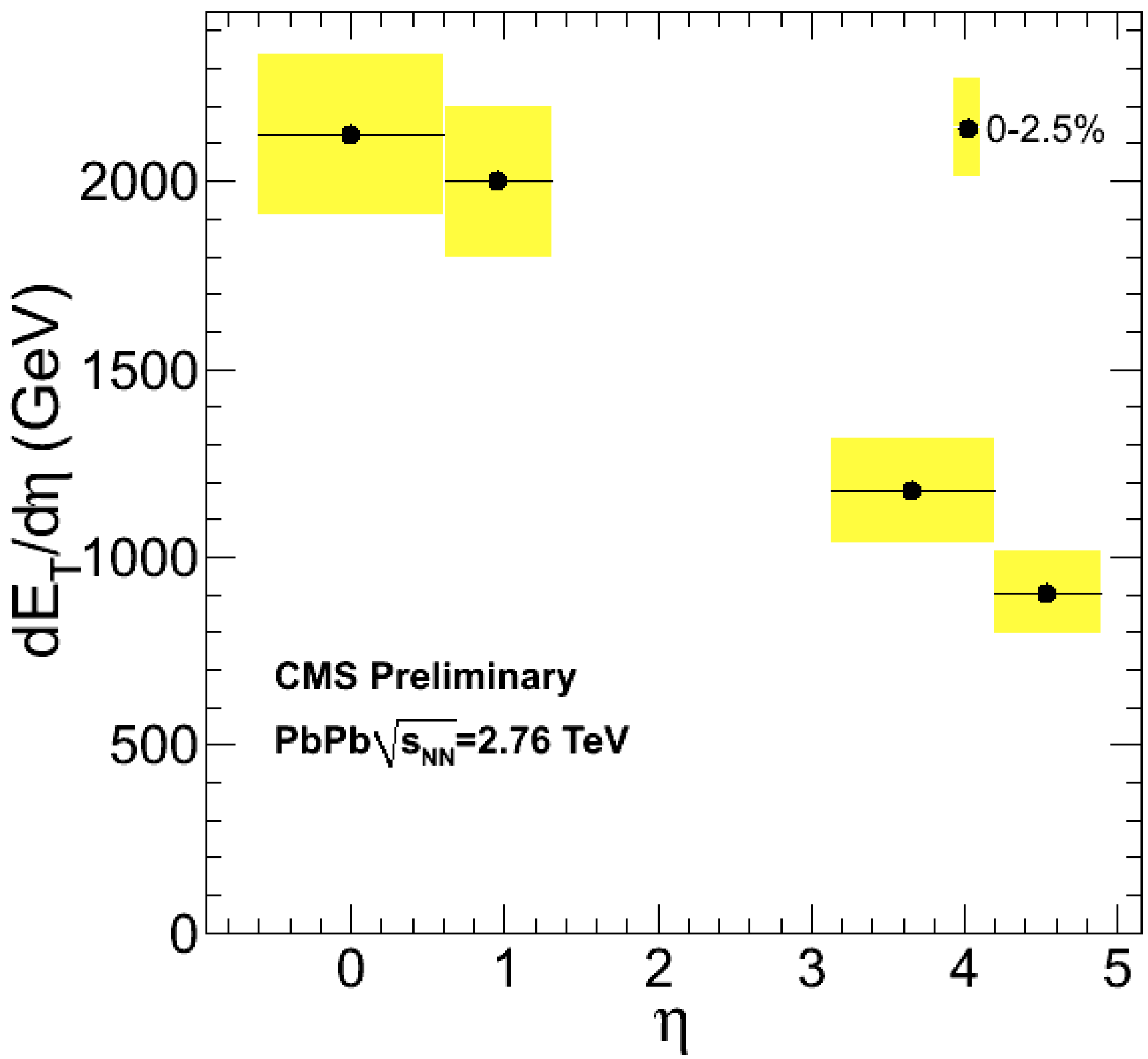




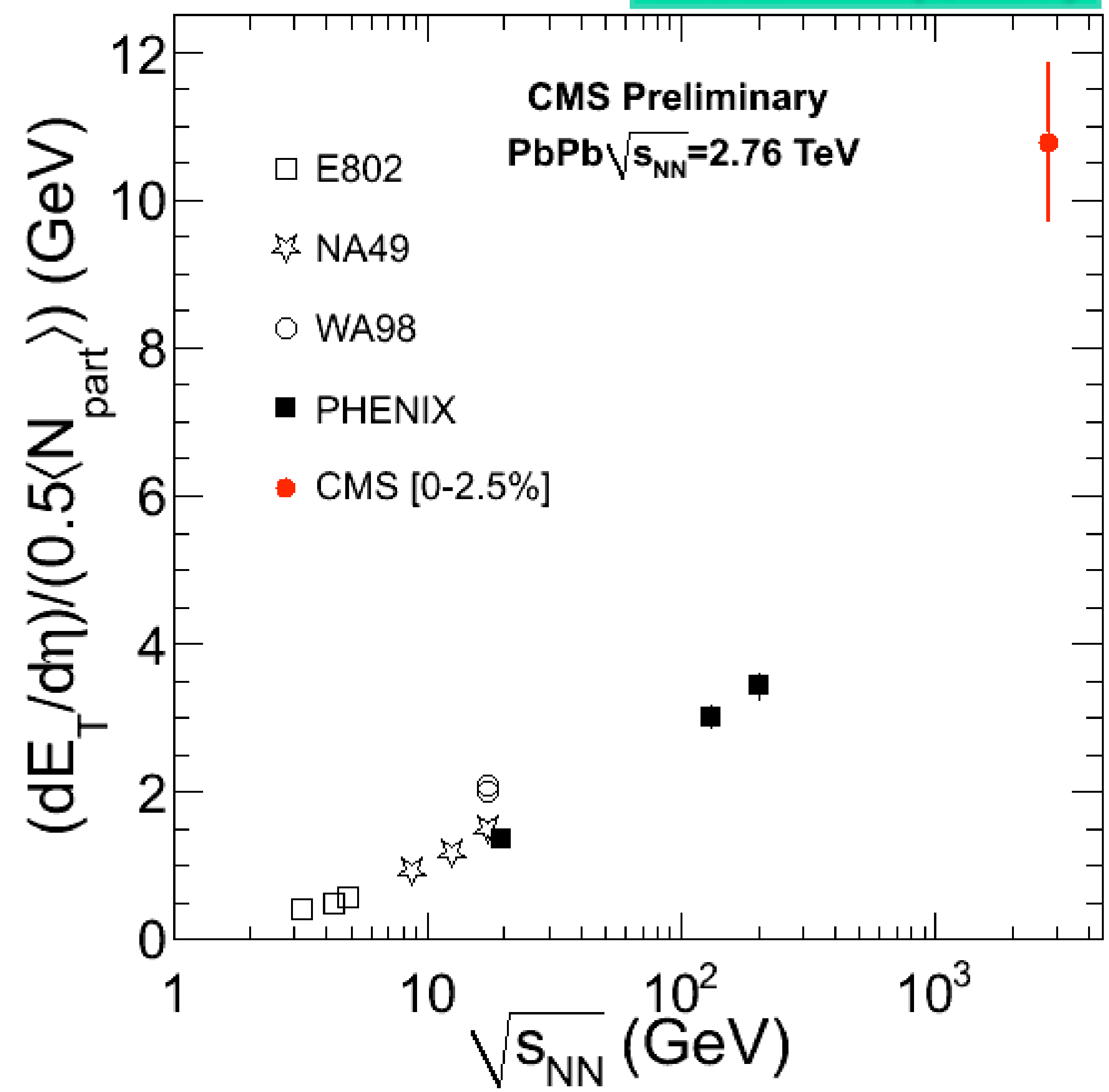
- $dN_{ch}/d\eta$ increases from peripheral to central collisions.
- $dN_{ch}/d\eta$ is ~flat over $|\eta|<2.5$ (<10% variation).

Measured $dE_T/d\eta$

- Three times larger than at RHIC energies
- Measured over wide range of pseudorapidity

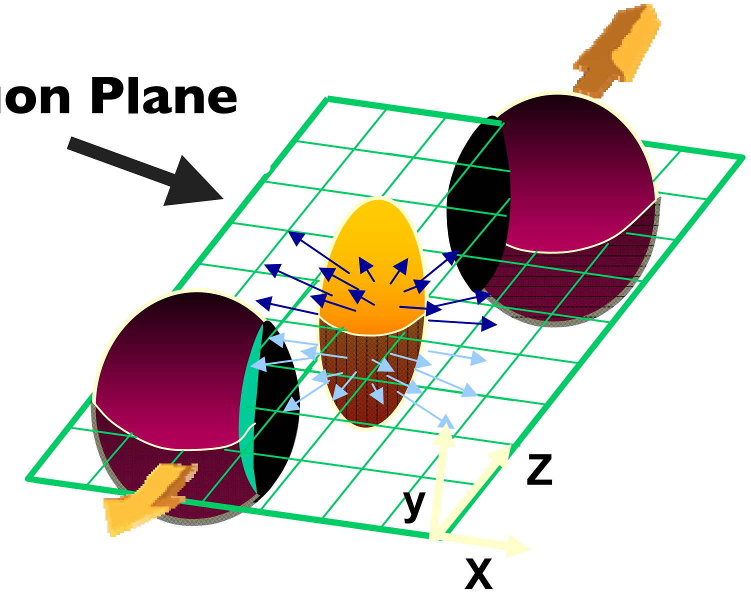


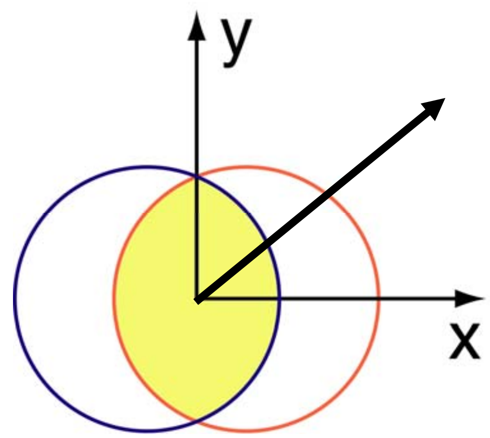
CMS M. Malek (QM2011)

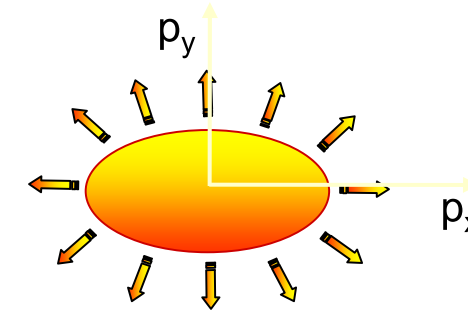


dE_T /dη reaches ~2.1 TeV at η=0; falls with pseudorapidity

Charged Hadron Azimuthal Anisotropy







initial spatial anisotropy “almond like shape”

anisotropy in momentum space

- **In non-central nucleus-nucleus collisions, a reaction plane is defined by**
  - Beam direction
  - Impact parameter
- **Strong re-scattering of the partons in the initial state may lead to local thermal equilibrium and the build up collective anisotropic expansion.**
  - This results in an anisotropic azimuthal distribution of the final state hadrons
  - The anisotropy is quantified in terms of a Fourier expansion of the observed yields
  - The second coefficient of the expansion, v_2, referred to as “elliptic flow”.

CMS has measured up to 6th order harmonic coefficients in a broad centrality, p_T and pseudo-rapidity range employing a variety of methods !!!

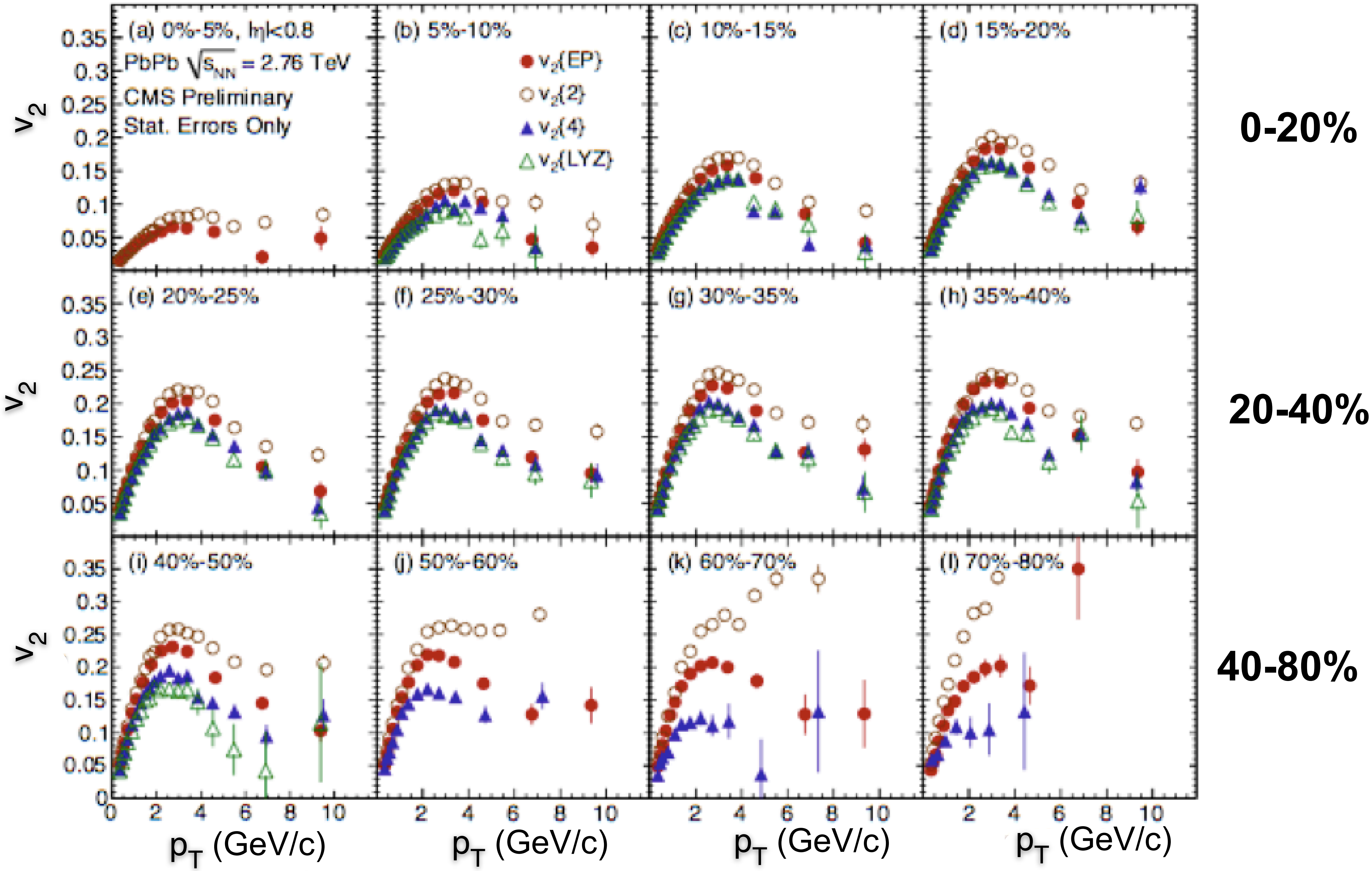
Elliptic Flow

- **It is used to explore hydrodynamic flow at the LHC energy by measuring azimuthal anisotropy as a function of transverse momentum, pseudorapidity, and centrality in a broad kinematic range :**
  - $0.3 < p_T < 12.0$ GeV
  - $|\eta| < 2.4$
  - 12 centrality classes in the range 0-80%

- **Four methods:**
  - Event plane
  - Cumulant 2nd order
  - Cumulant 4th order
  - Lee-Yang Zeros

Each method has different sensitivity to non-flow!

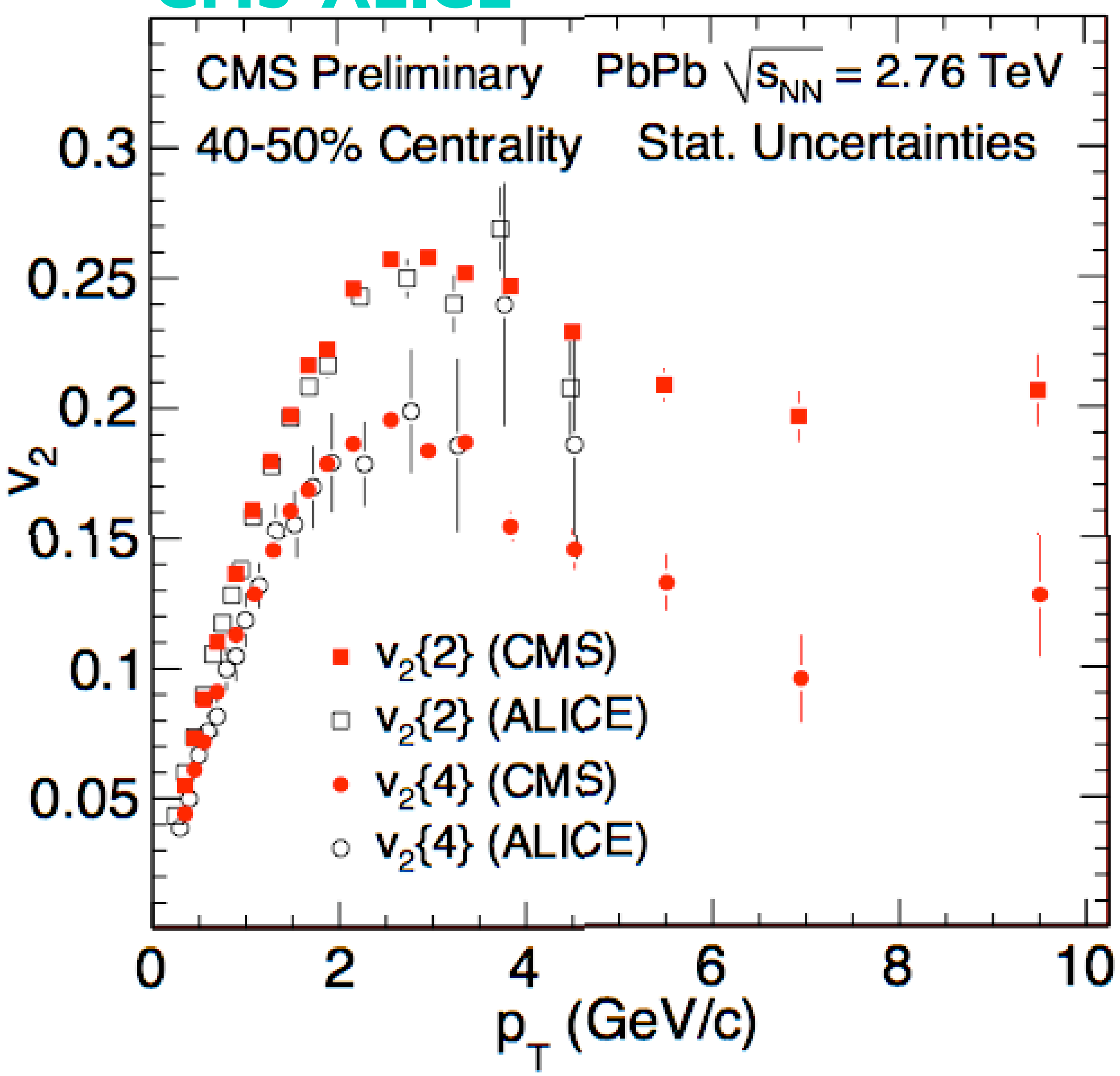
$v_2(p_T)$ vs Centrality



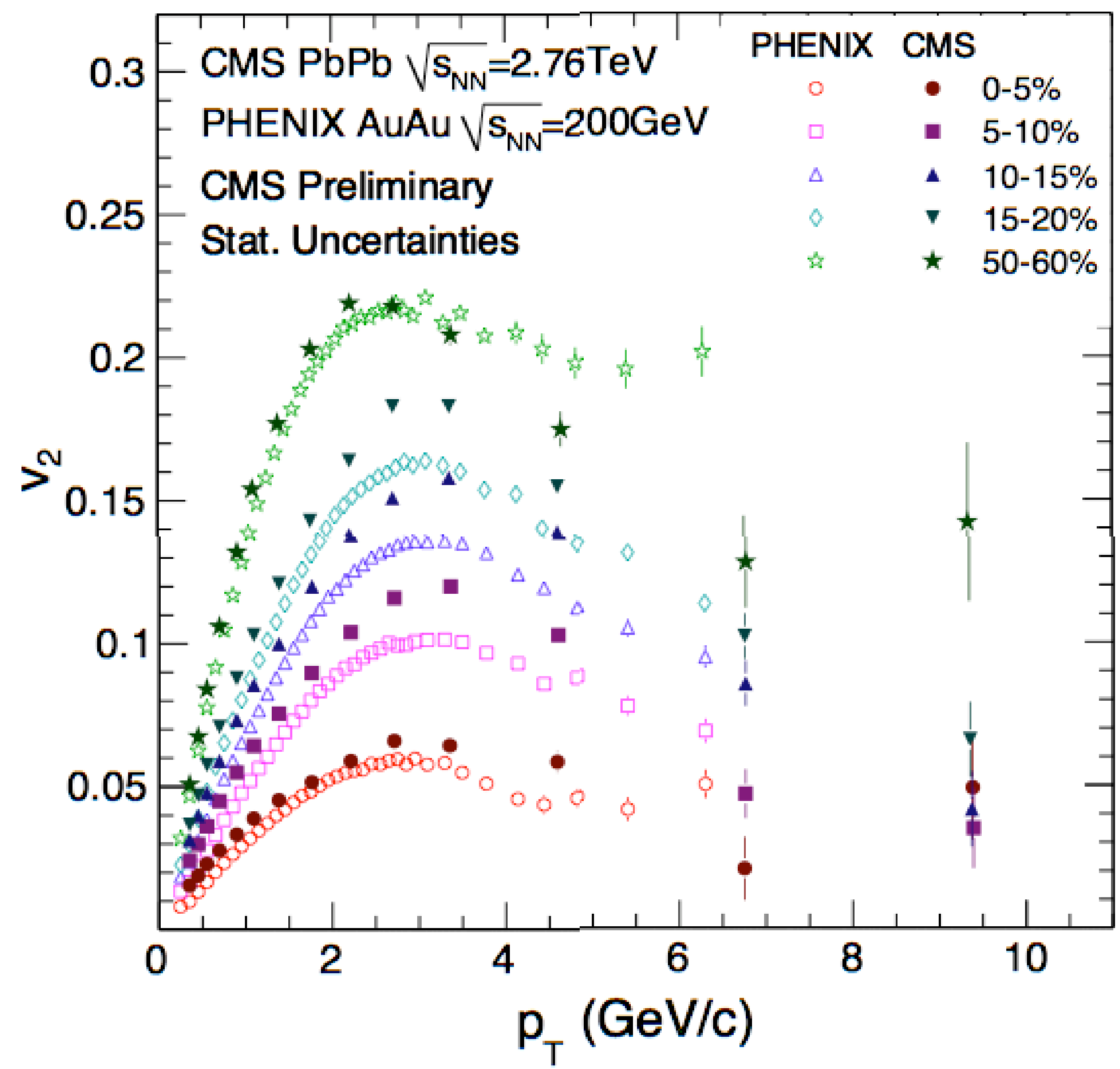
- v_2 increases from central to peripheral collisions up to 50% centrality
- v_2 peaks at around 3 GeV
- The different methods show differences consistent with the expected sensitivity to non-flow effects

$v_2(p_T)$ Comparison with ALICE and PHENIX

CMS-ALICE



CMS -PHENIX

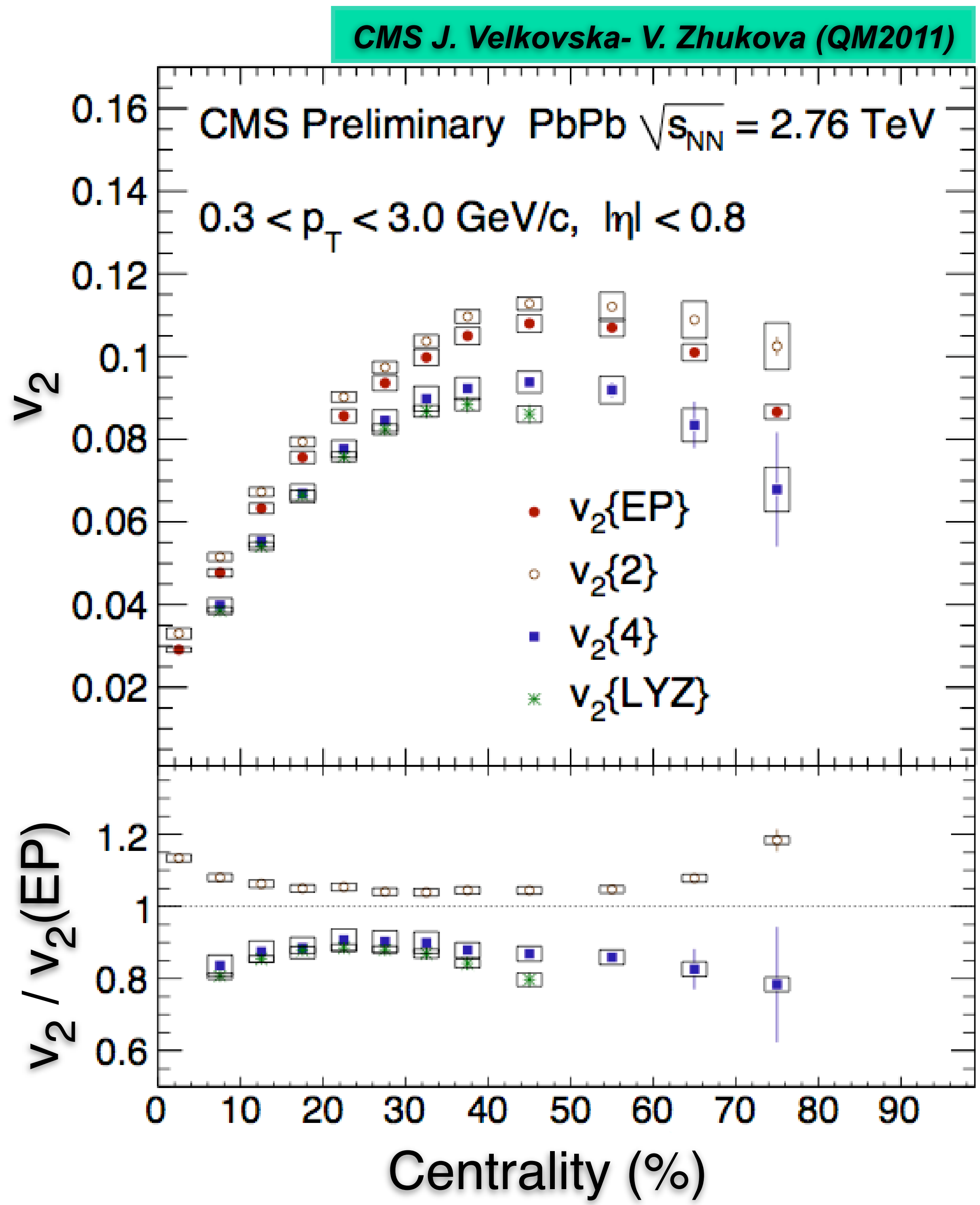


- Good agreement between CMS and ALICE.
- The p_T dependence in each centrality bin shows a similar trend in both CMS and PHENIX

PHENIX Collaboration Phys. Rev. Lett., 105, 062301 (2010)

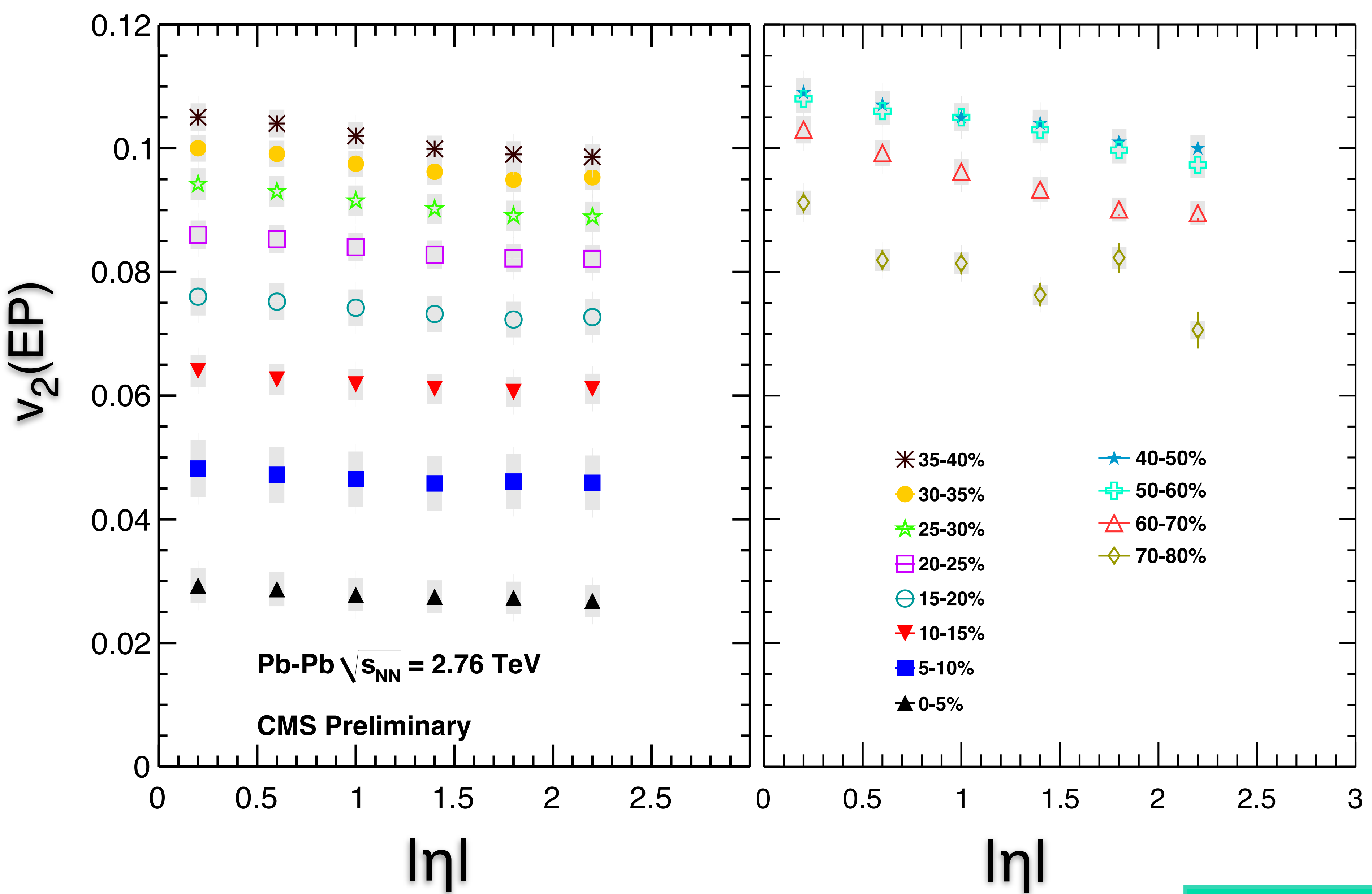
CMS J. Velkovska- V. Zhukova (QM2011)

Integrated v_2 vs Centrality



Flow is maximum around 40-50% centrality, consistent with RHIC results.

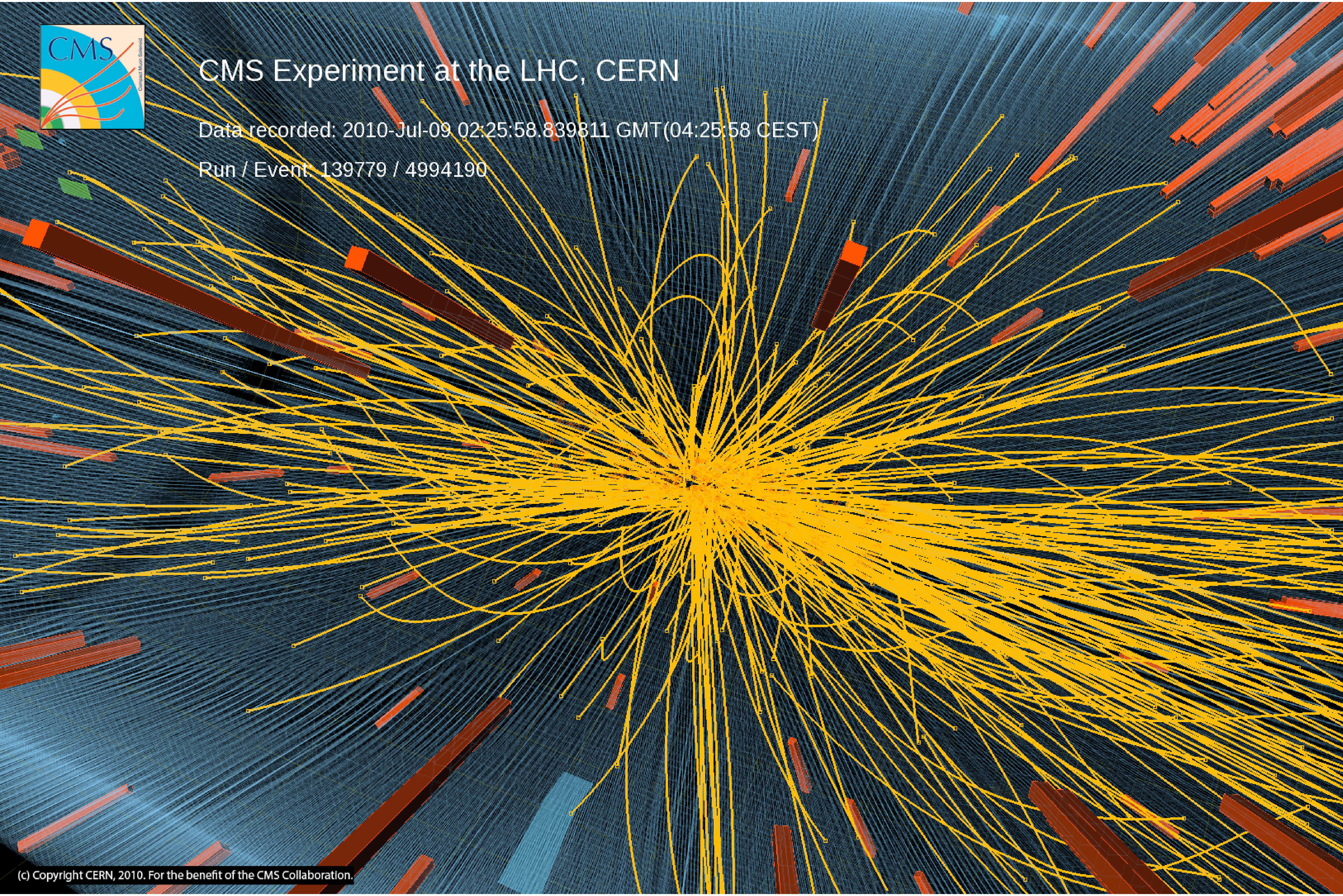
Integrated v_2 (EP) vs Pseudorapidity



CMS V. Zhukova (QM2011)

Stronger pseudorapidity dependence is observed for the most peripheral collisions.

High Multiplicity pp Collisions

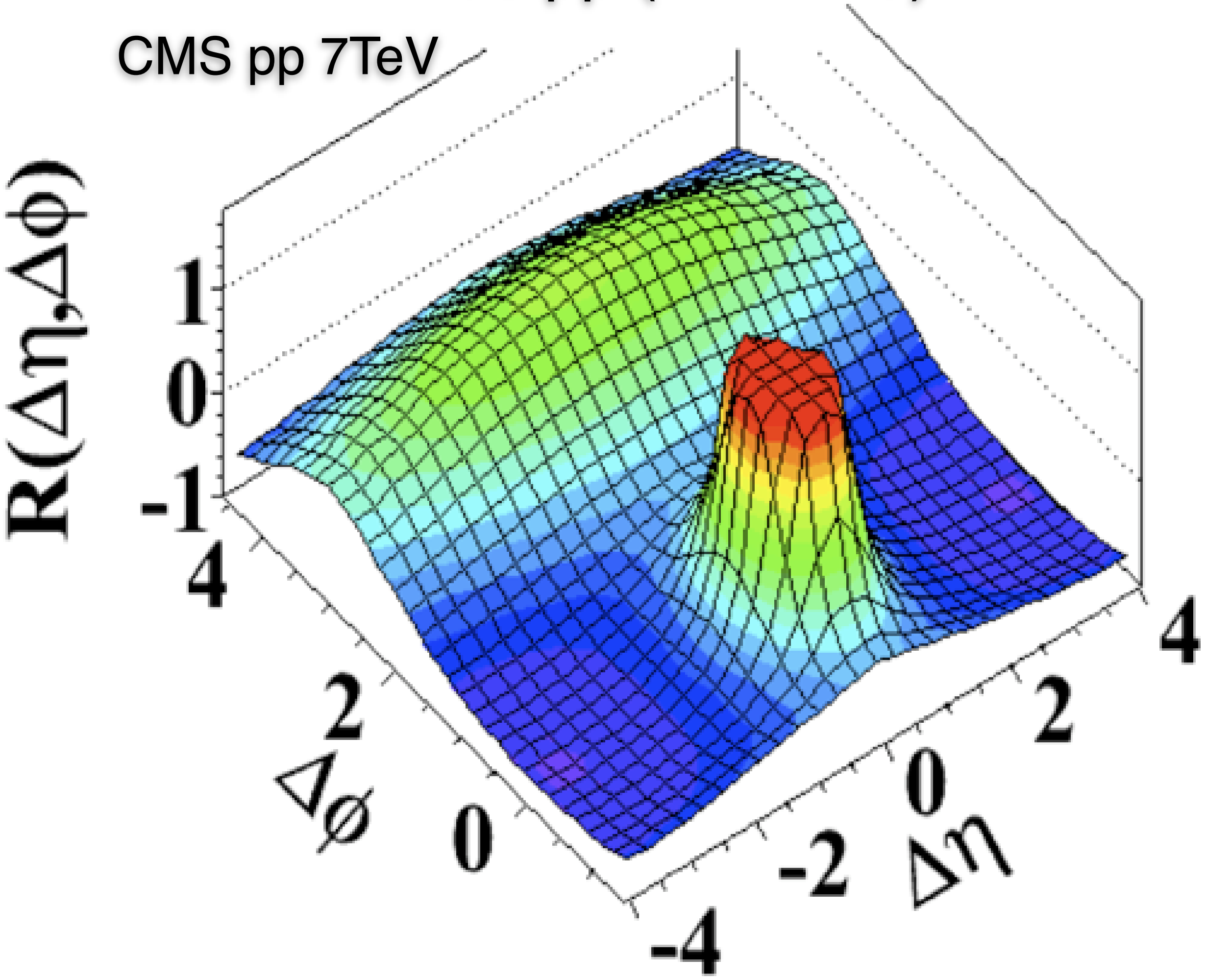


Ridge in High Multiplicity

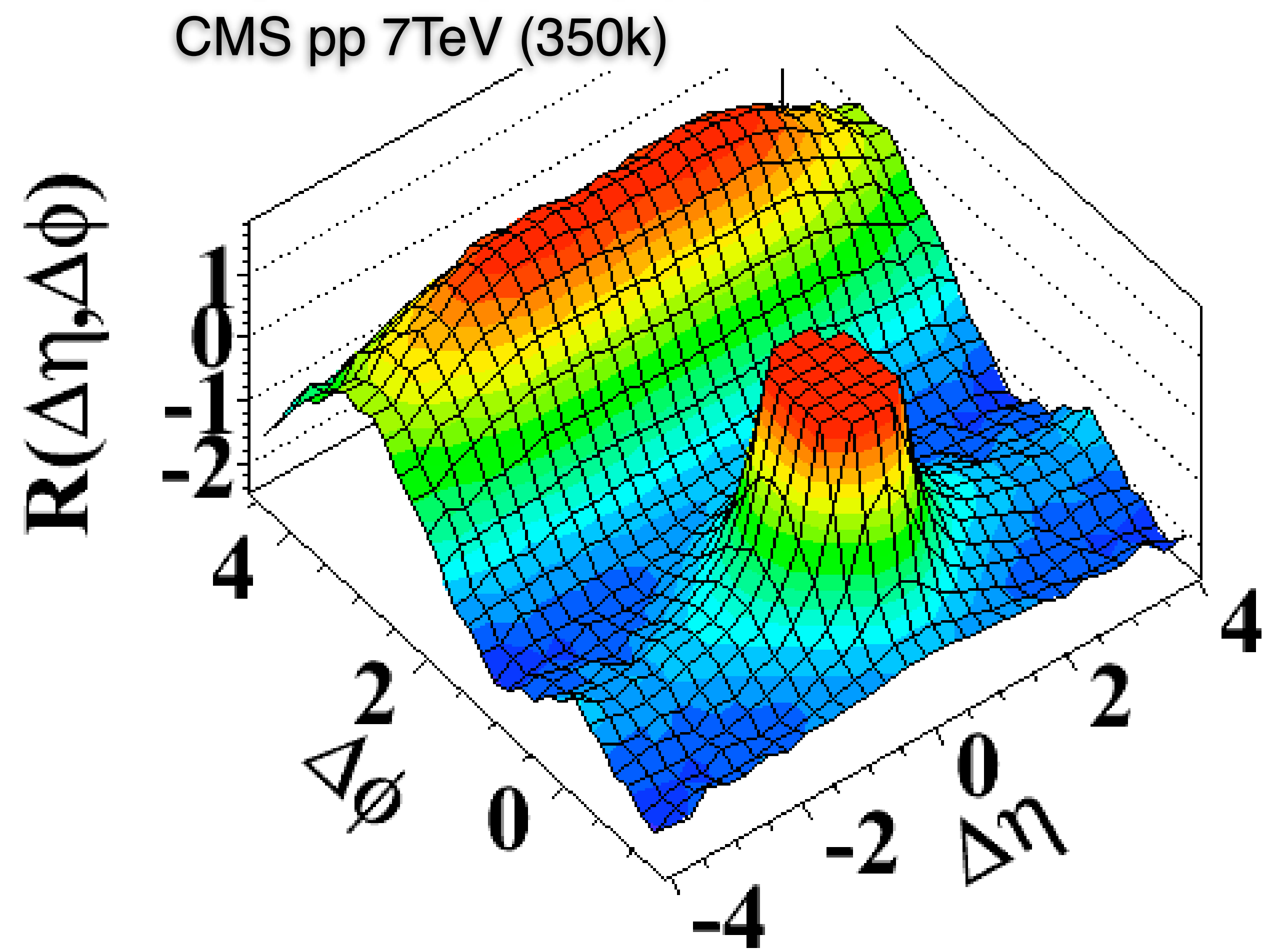
Ridge in pp at LHC

Intermediate p_T range : 1-3GeV

Minimum Bias pp (<N> ~15)



High Multiplicity pp (<N> ~110)



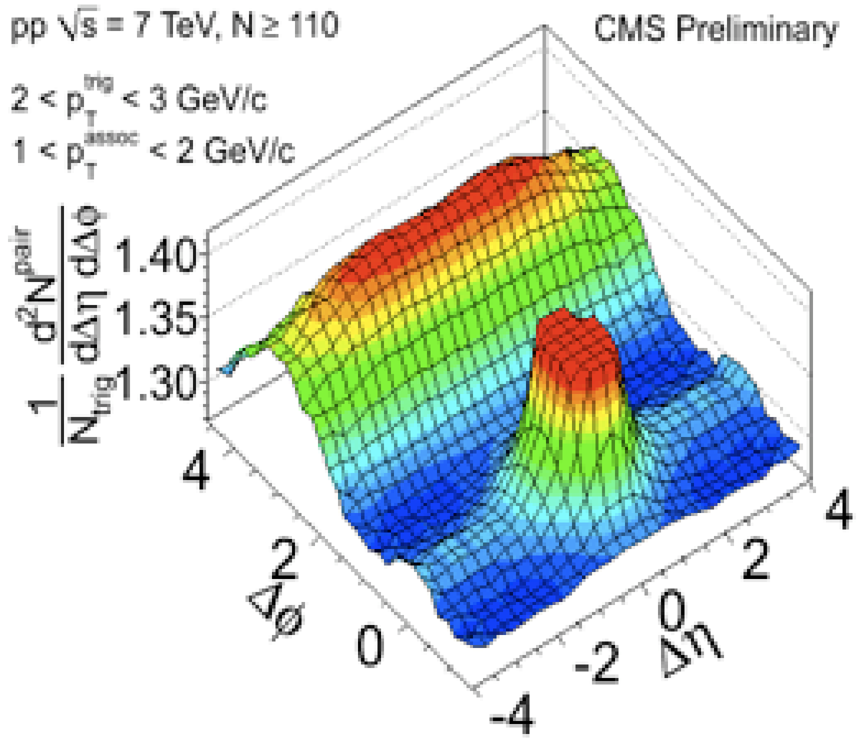
JHEP 09 (2010) 091

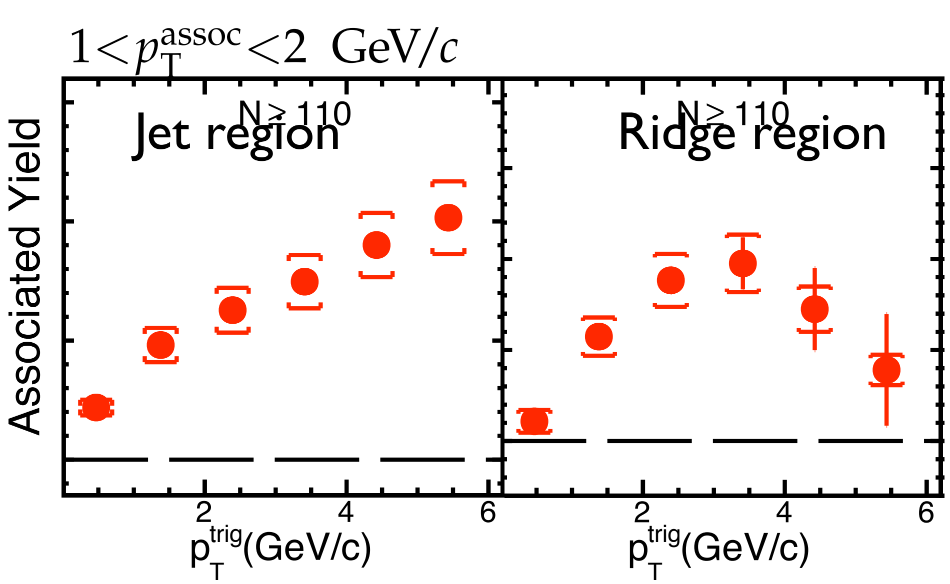
CMS W. Li (QM2011)

Striking "**ridge-like**" structure extending over $\Delta\eta$ at $\Delta\phi \sim 0$.
(not observed before in hadron collisions or MC models)

Ridge in pp and PbPb

CMS pp 7TeV N ≥110





CMS PbPb 2.76 TeV, 0-5%

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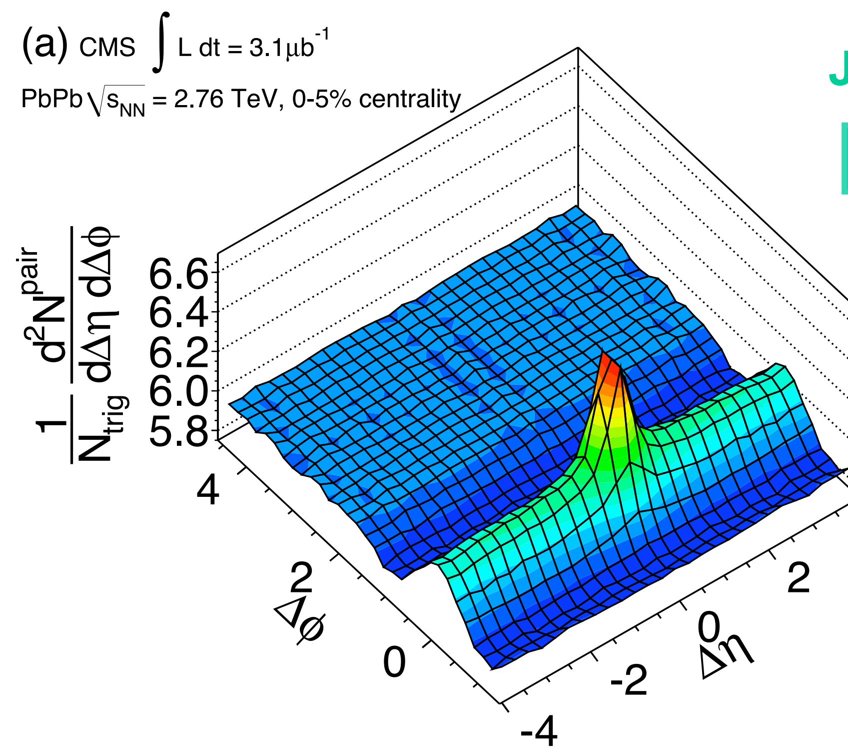
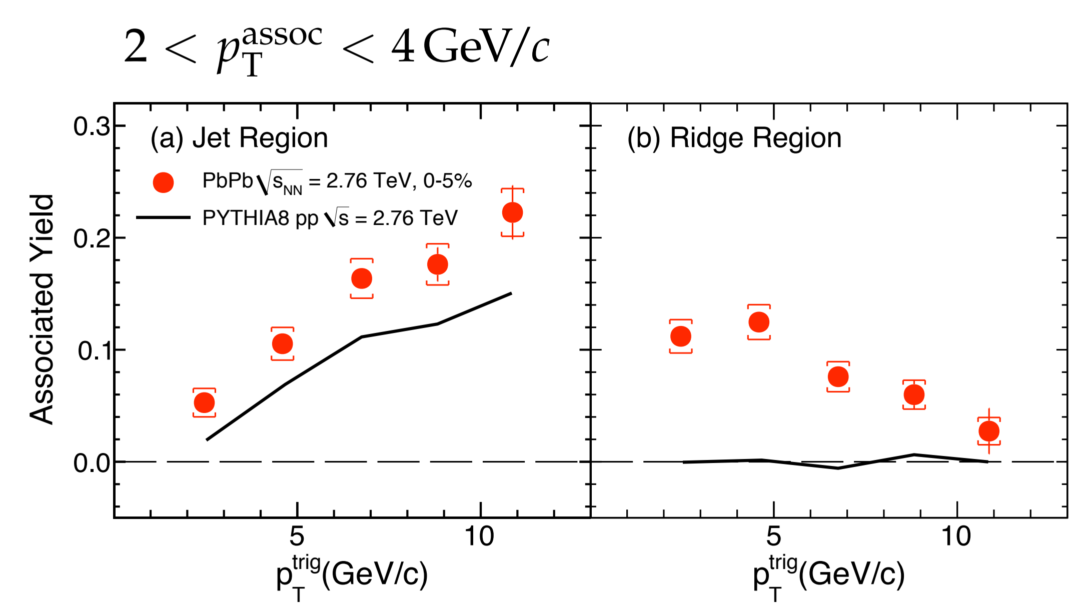
CMS W. Li (QM2011)





short range Jet region (|η|<1)

long range Ridge region (2<|η|<4)

Centrality Dependence in PbPb

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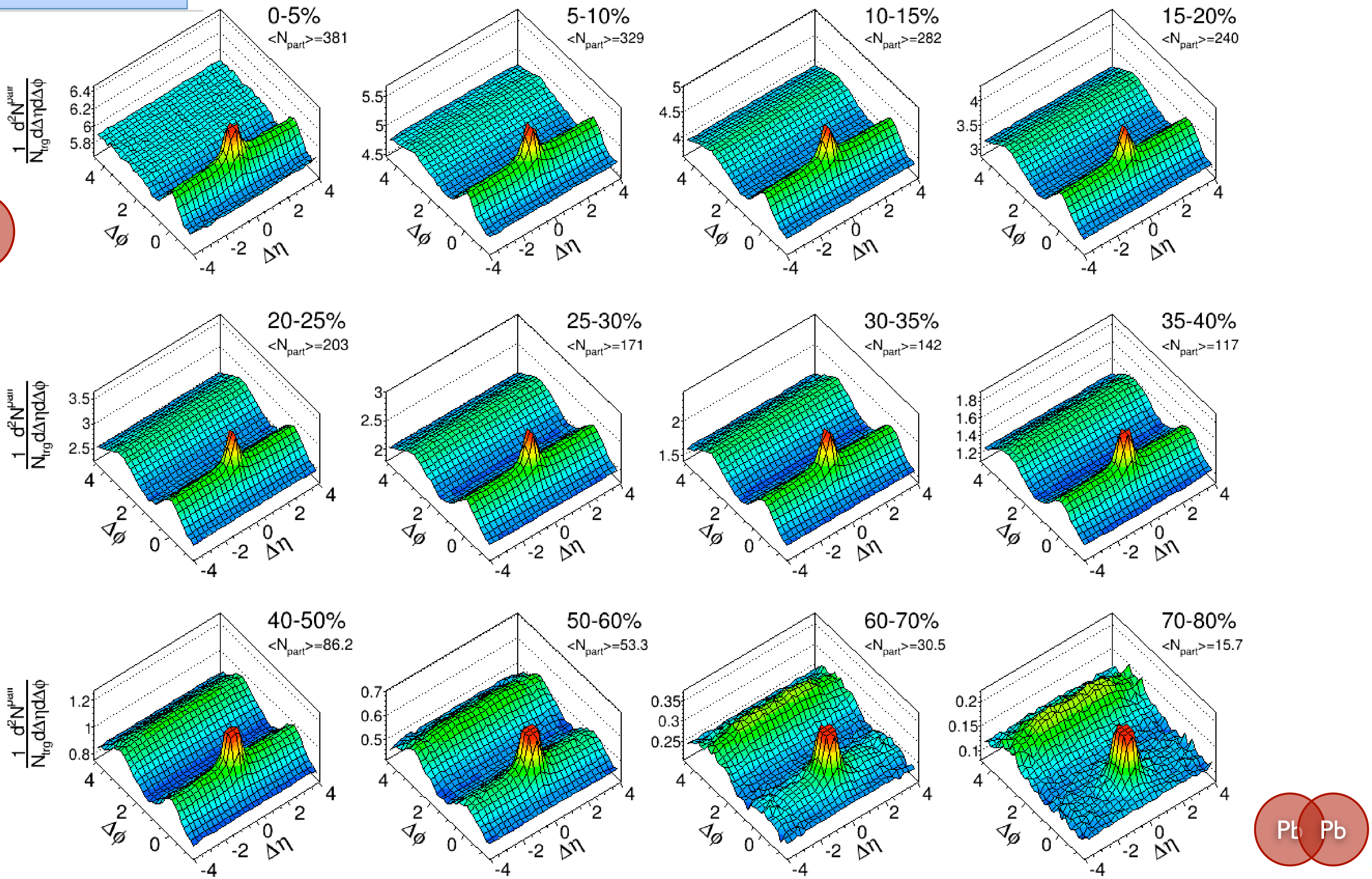
CMS W. Li (QM2011)

p_T^{trig} : 4 - 6 GeV/c
p_T^{assoc} : 2 - 4 GeV/c

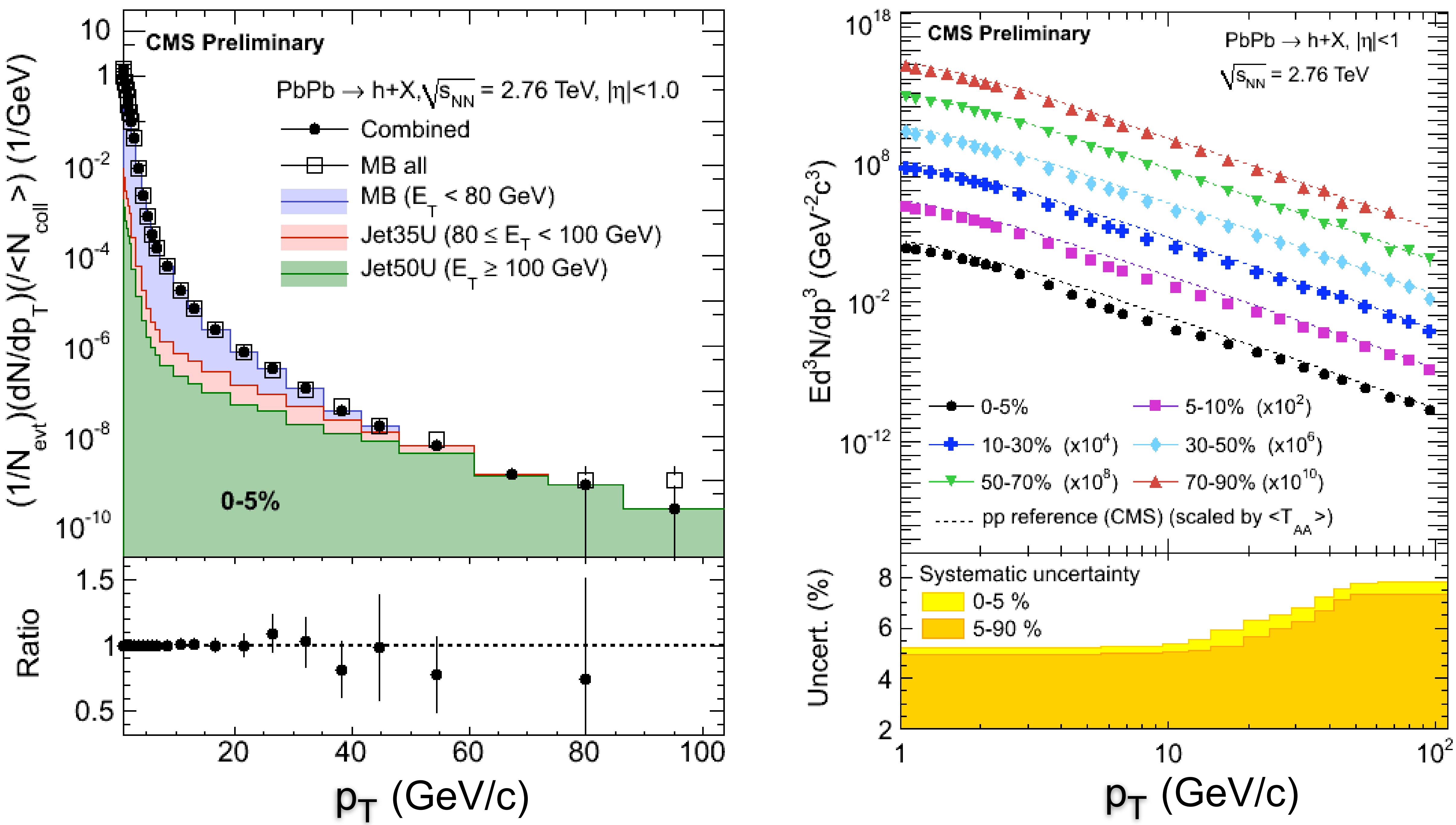
$\int L\,dt = 3.1\,\mu b^{-1}$

PbPb 2.76 TeV

CMS Preliminary



Charged Hadron Spectra in PbPb

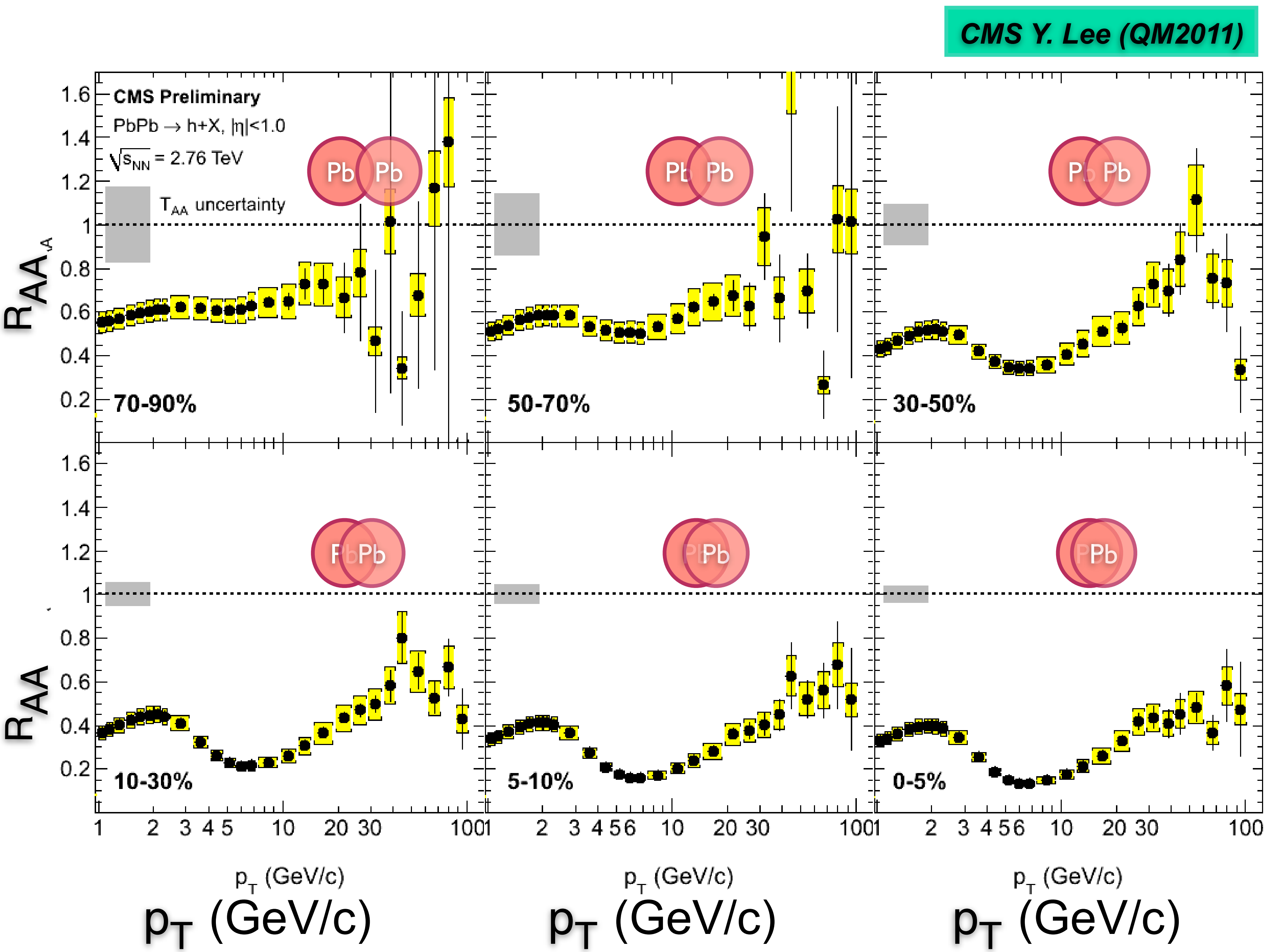


- Measuring charged tracks up to p_T ~ 100GeV
- Using jet triggers to enhance statistics at high p_T

CMS Y. Lee (QM2011)

Charged Particle R_{AA} in Different Centralities

Nuclear modification factor R_{AA} is ratio of measured particle yields to what would have been measured if a Heavy-Ion collision was just a superposition of independent p-p collisions.



$$R_{AA} = \frac{1/N_{evnts} d^2N_{PbPb}/dydp_T}{< T_{AB} > d^2\sigma_{pp}/dydp_T}$$

$$T_{AB} = < N_{coll} > / \sigma_{pp}$$

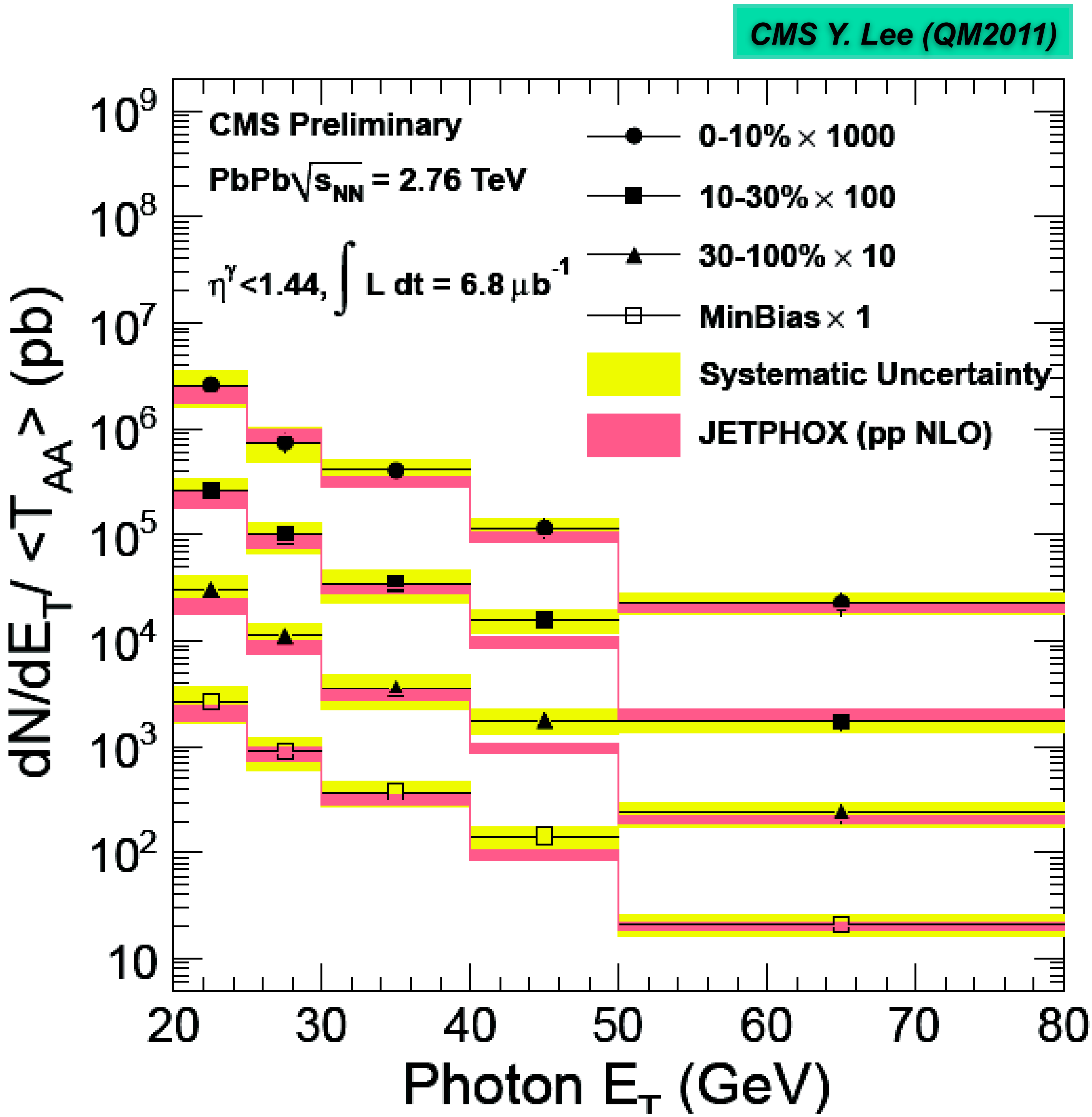
T_{AB} : nuclear overlapping function

N_{coll} : number of binary collisions

σ_{pp} : NN cross-section

- Dip structure developing as a function of centrality
- R_{AA} increases as a function of p_T where p_T >10GeV (flattening of the unquenched NN spectrum at high p_T

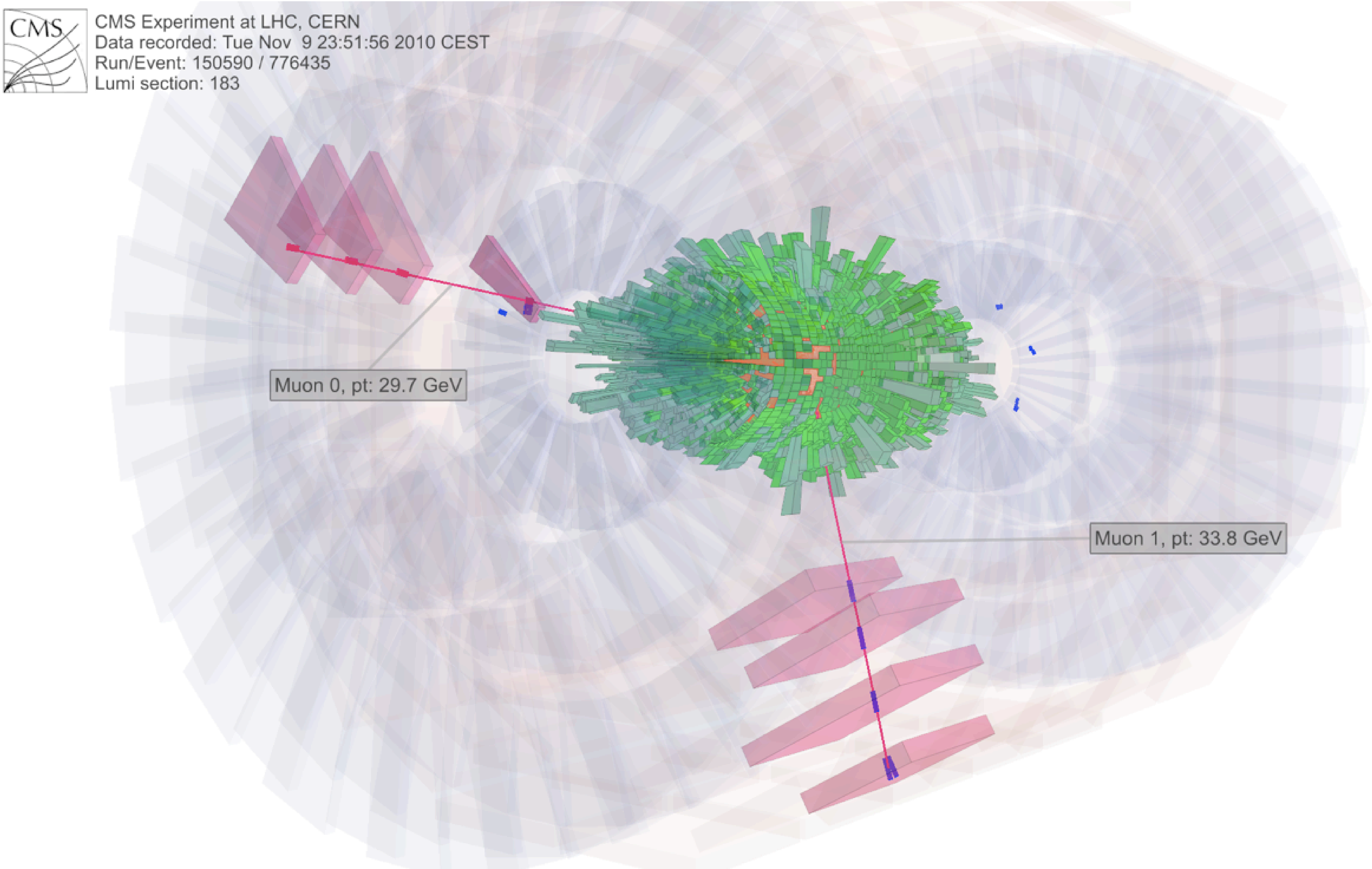
Photon E_T Spectra in PbPb Collisions



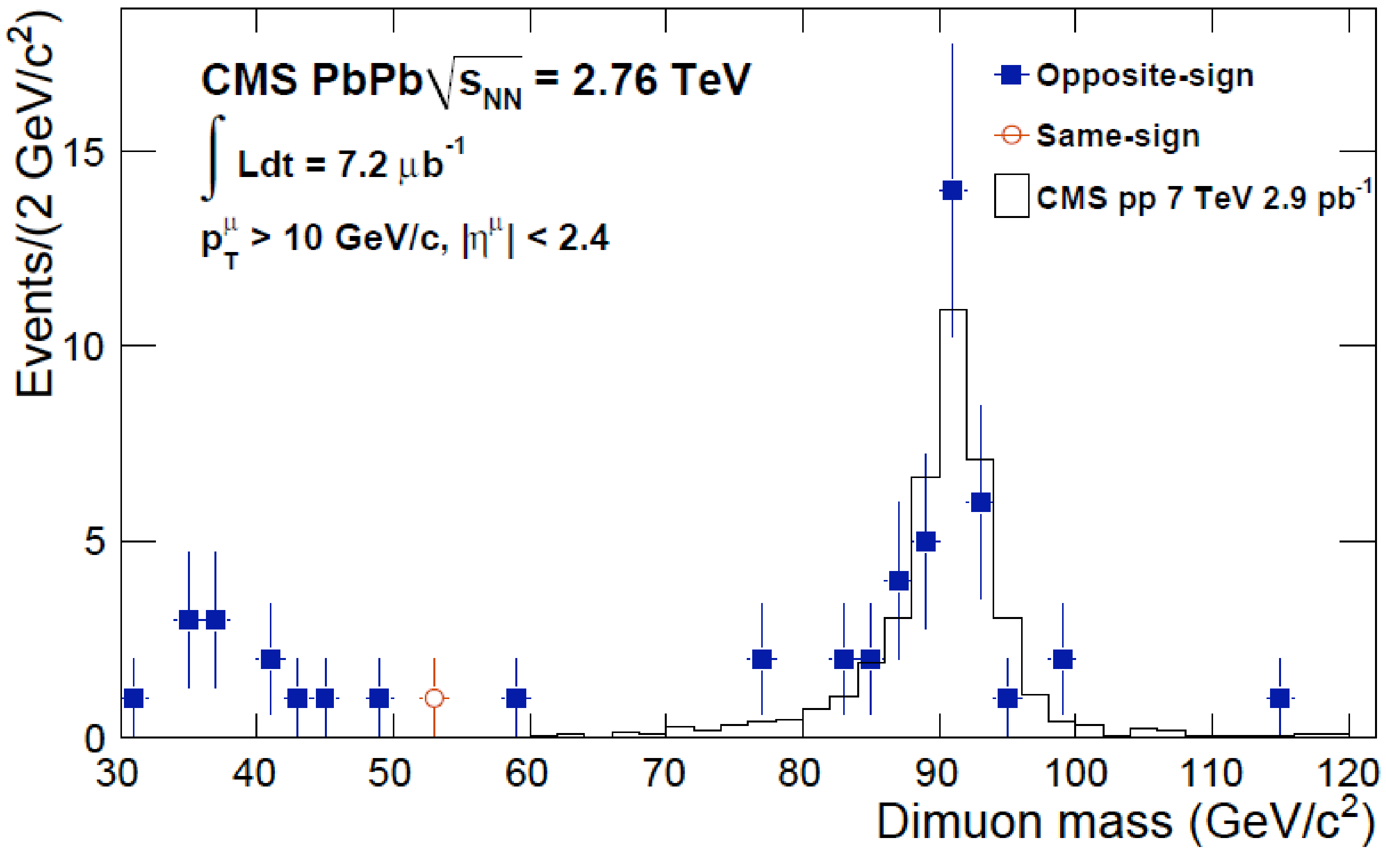
The photons provide a direct test of pQCD and the nuclear parton densities when they pass trough the hot and dense medium without interacting strongly.

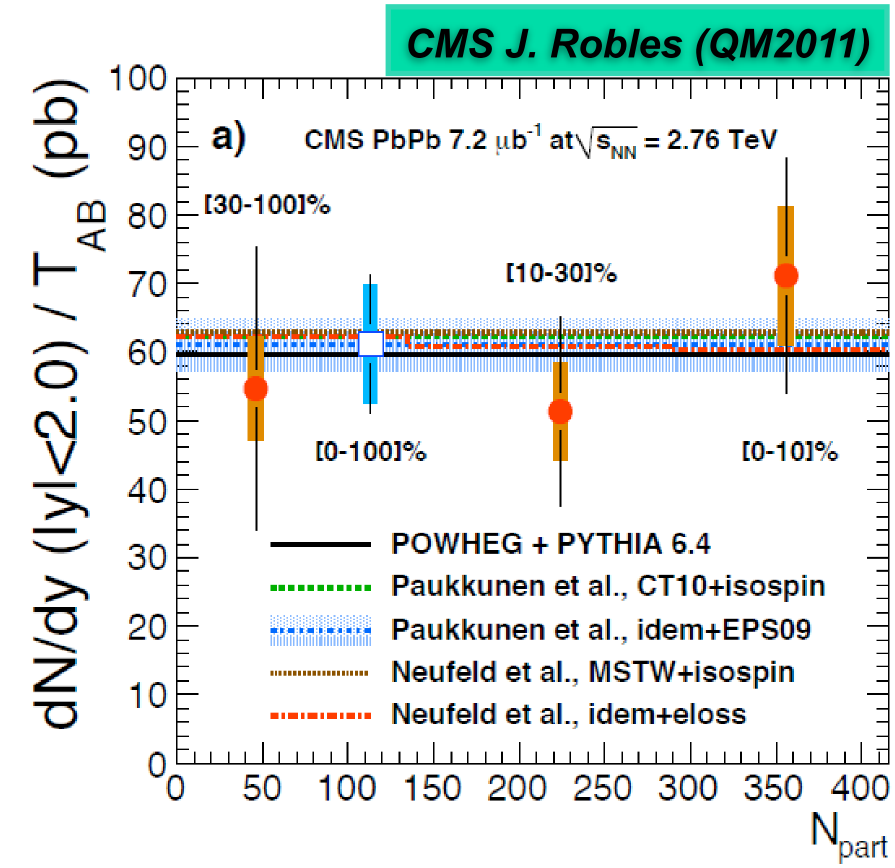
- $|\eta| < 1.44$
- E_T range : 2 - 80 GeV
- Three centrality bins :
  - 0-10%, 10-30% and 30-100%
- The reconstructed photon spectra in each centrality bin is scaled by T_{AA}.

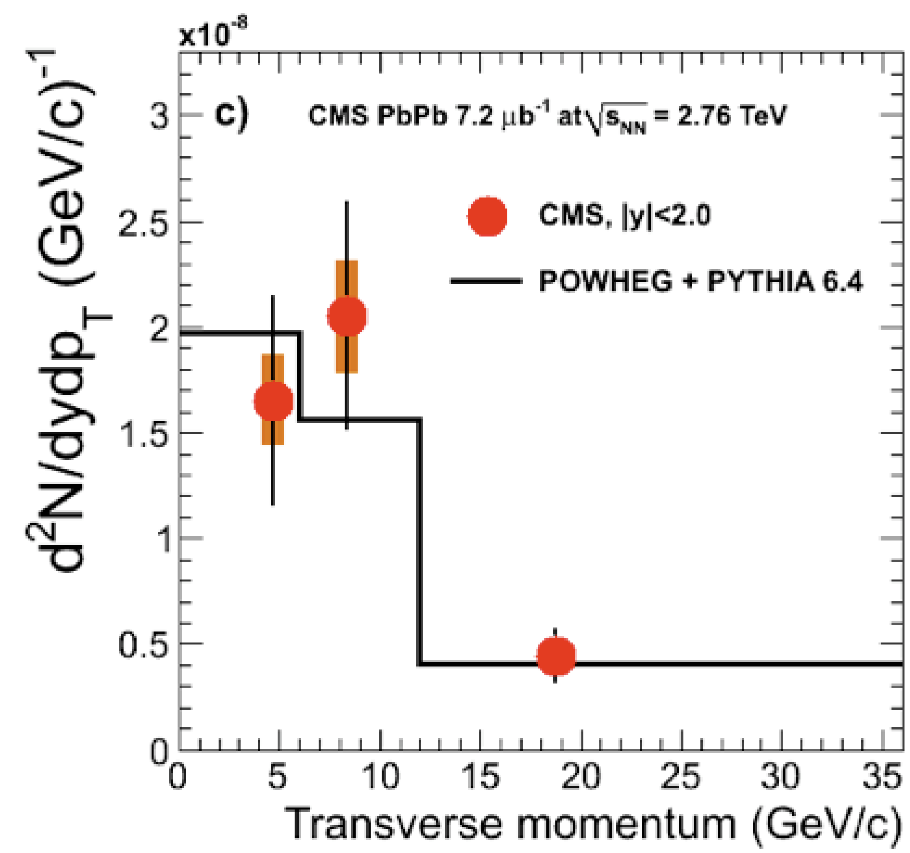
Our First Z → $\mu^+\mu^-$ Candidate in PbPb



Study of Z → $\mu^+\mu^-$ in PbPb Collisions

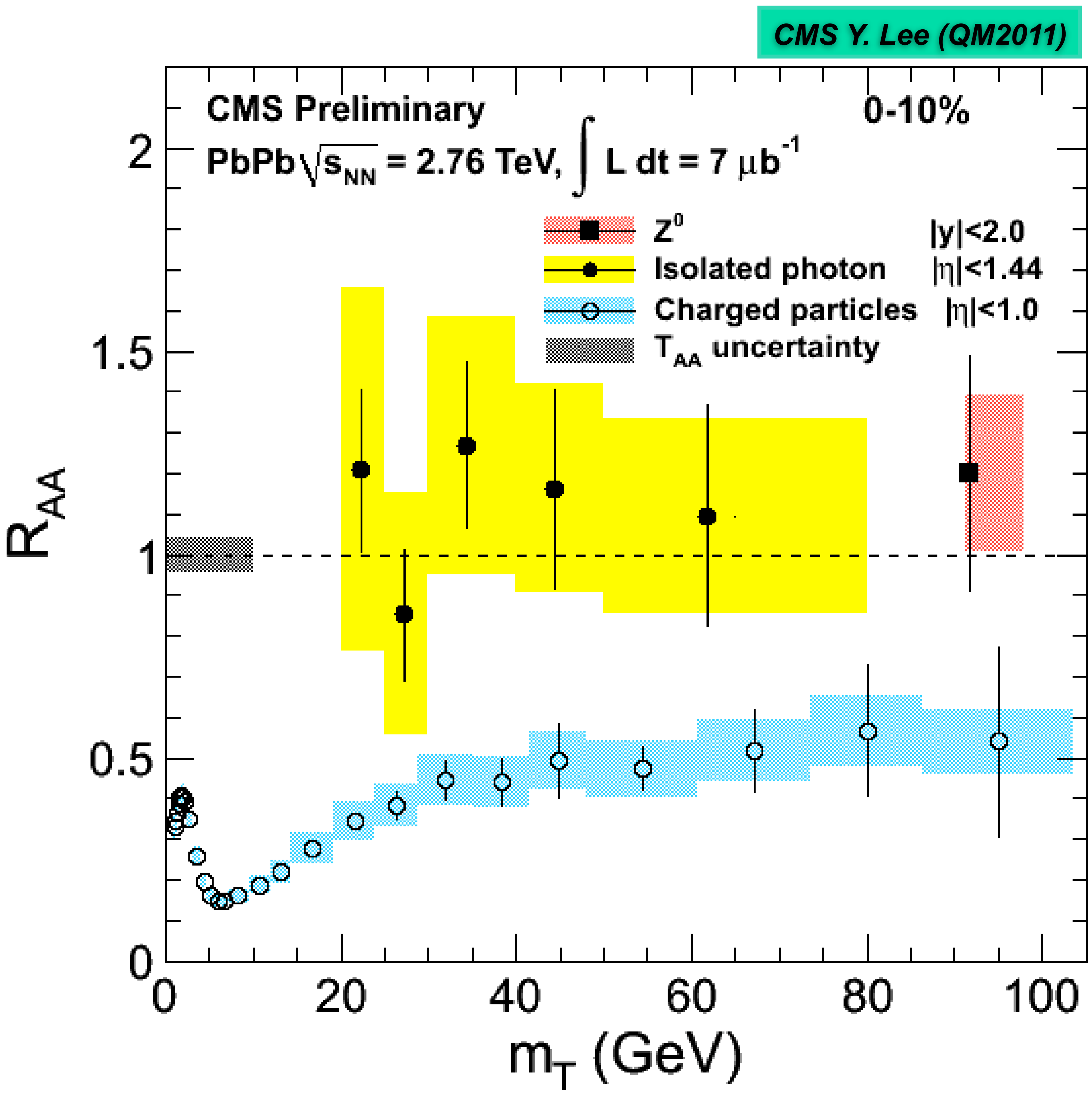






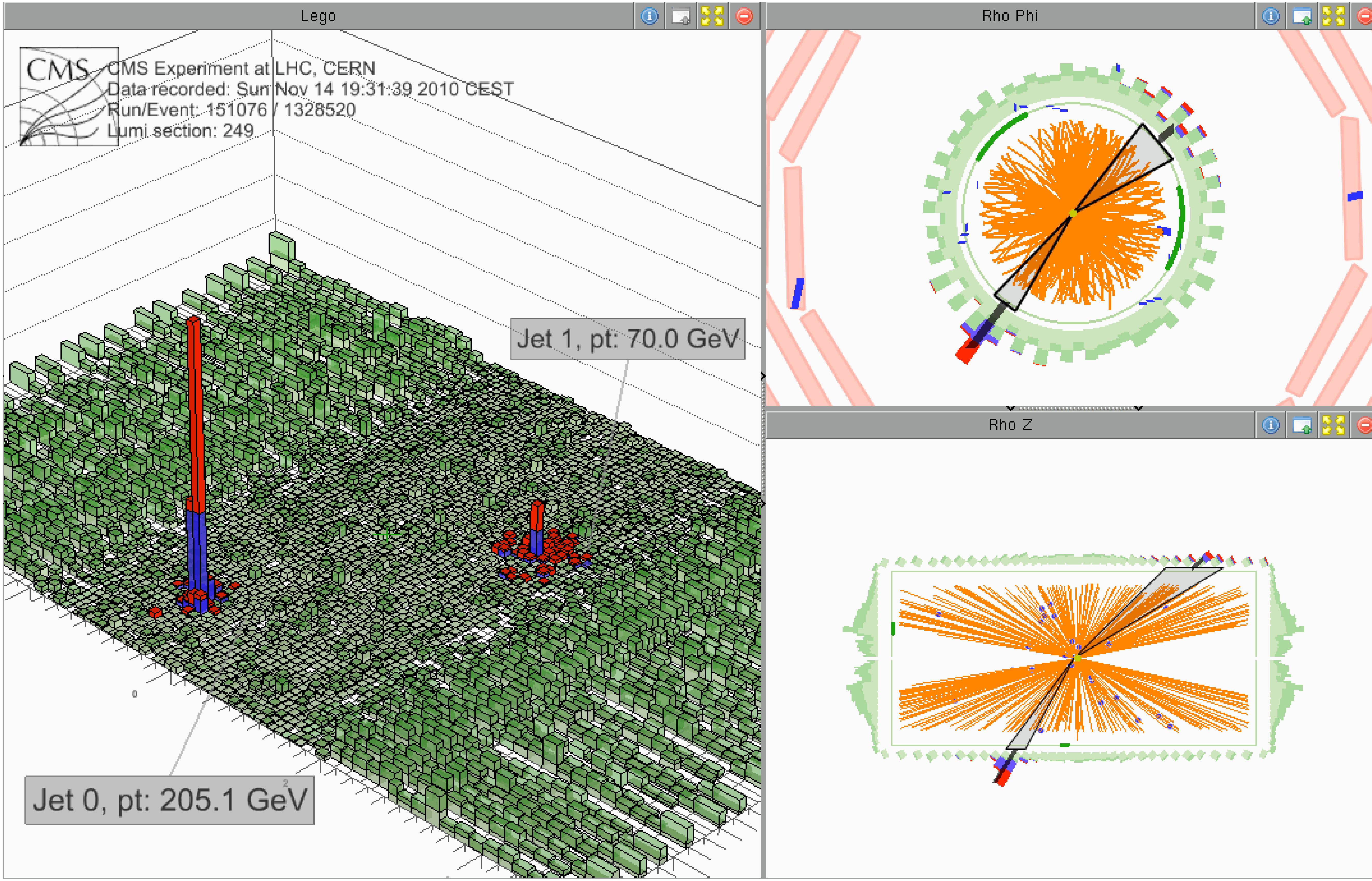
- Clean Z signal from opposite-sign di-muon
- No significant dependence on centrality
- p_T dependence is consistent with pp

R_{AA} for Z Bosons, Isolated Photons and Charged Particles



- CMS has measured the R_{AA} of Z bosons, isolated photons and charged particles.
- No modification is observed in Z and isolated photon production.
- Large suppression is observed for charged hadron particles.

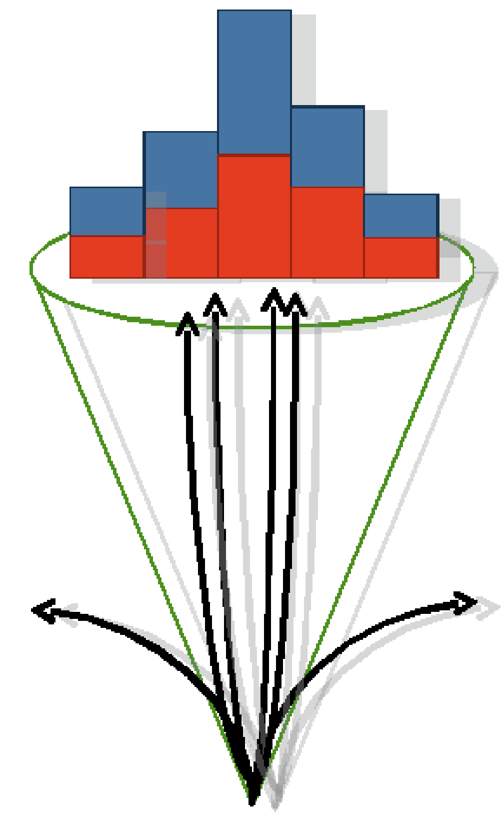
Jets in CMS detector



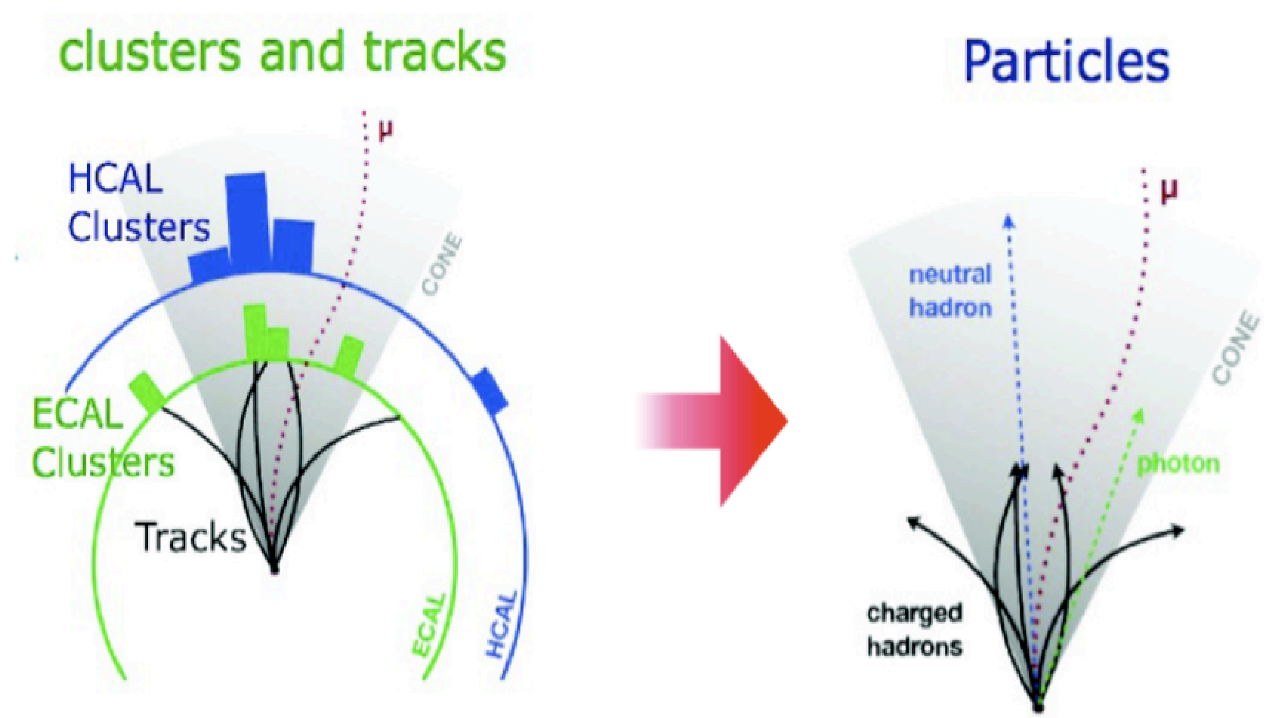
Jet Reconstruction

- **Calorimeter Based Jet Finder**
  Iterative Cone Algorithm in R=0.5
- **Particle Flow Jet Finder**
  Anti-kt Clustering Algorithm in R=0.3
- **Underlying Event Subtraction**
  Iterative pile-up subtraction

O. Kodolova, et. al. Eur. Phys. J. C50(2007) 117



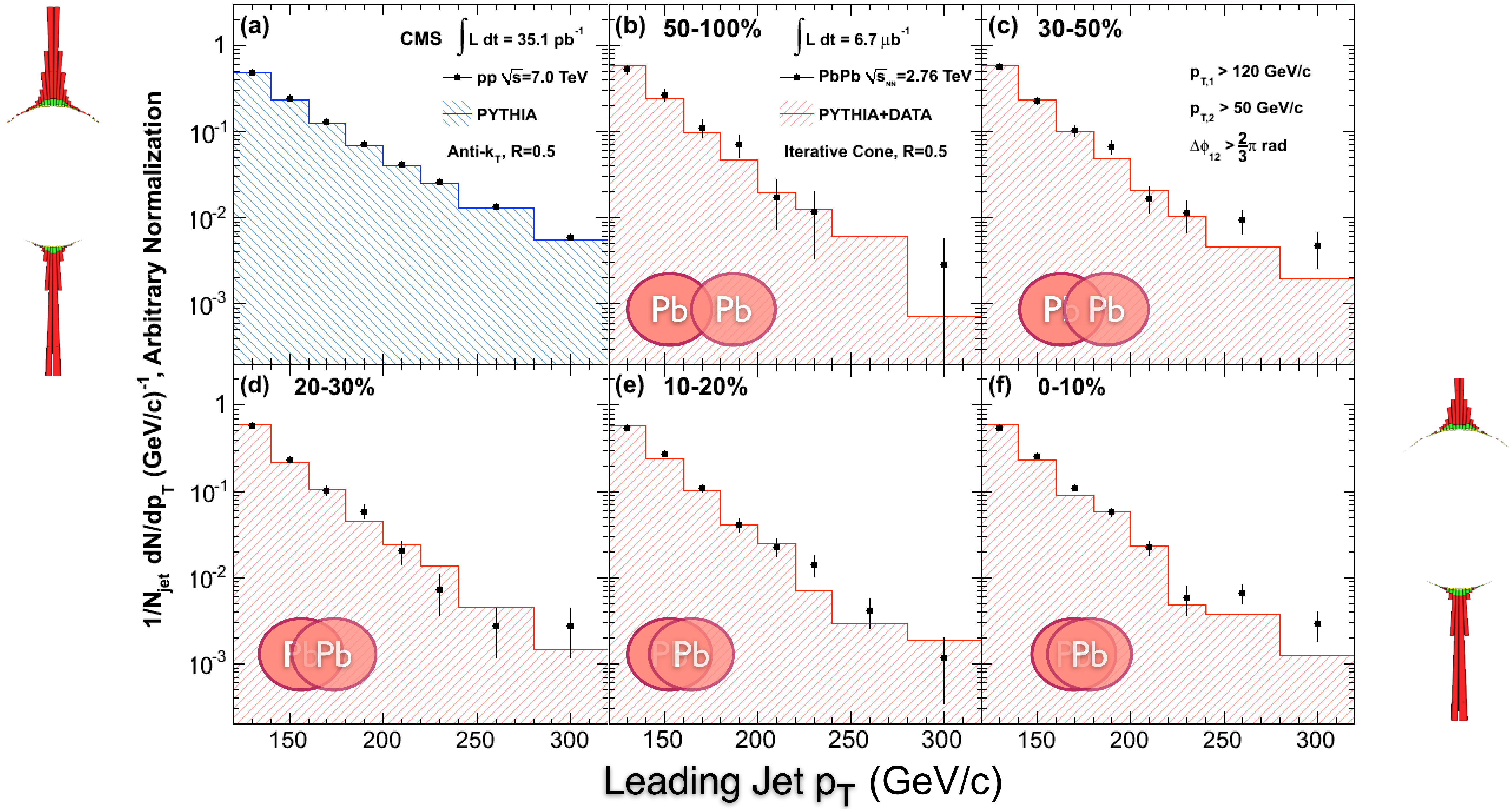
PF candidate combines information from various detectors to make the best combined estimation of particle properties.



Leading Jet Spectra

arXiv:1102.1957

CMS C. Roland (QM2011)



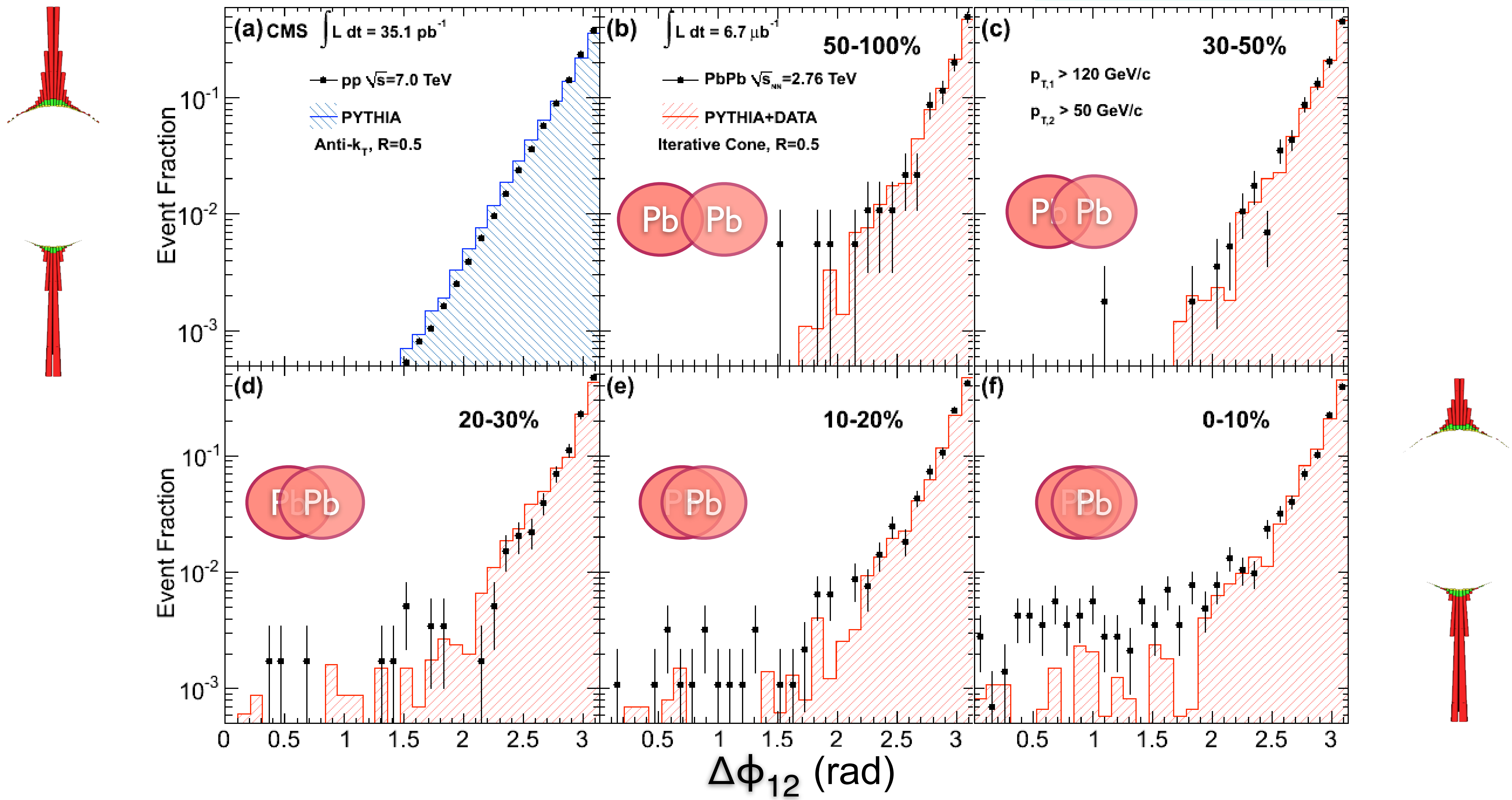
Large data sample reach to very high jet p_T.

Shape of leading jet spectrum not strongly modified.

Jet Angular Correlation

arXiv:1102.1957

CMS C. Roland (QM2011)



No strong angular deflection of reconstructed jets.

Dijet Asymmetry

- **Dijet Selection**
  |η|<2
  Leading Jet $p_T > 120$GeV/c
  Subleading Jet $p_T > 50$GeV/c
  $\Delta\phi > 2\pi/3$

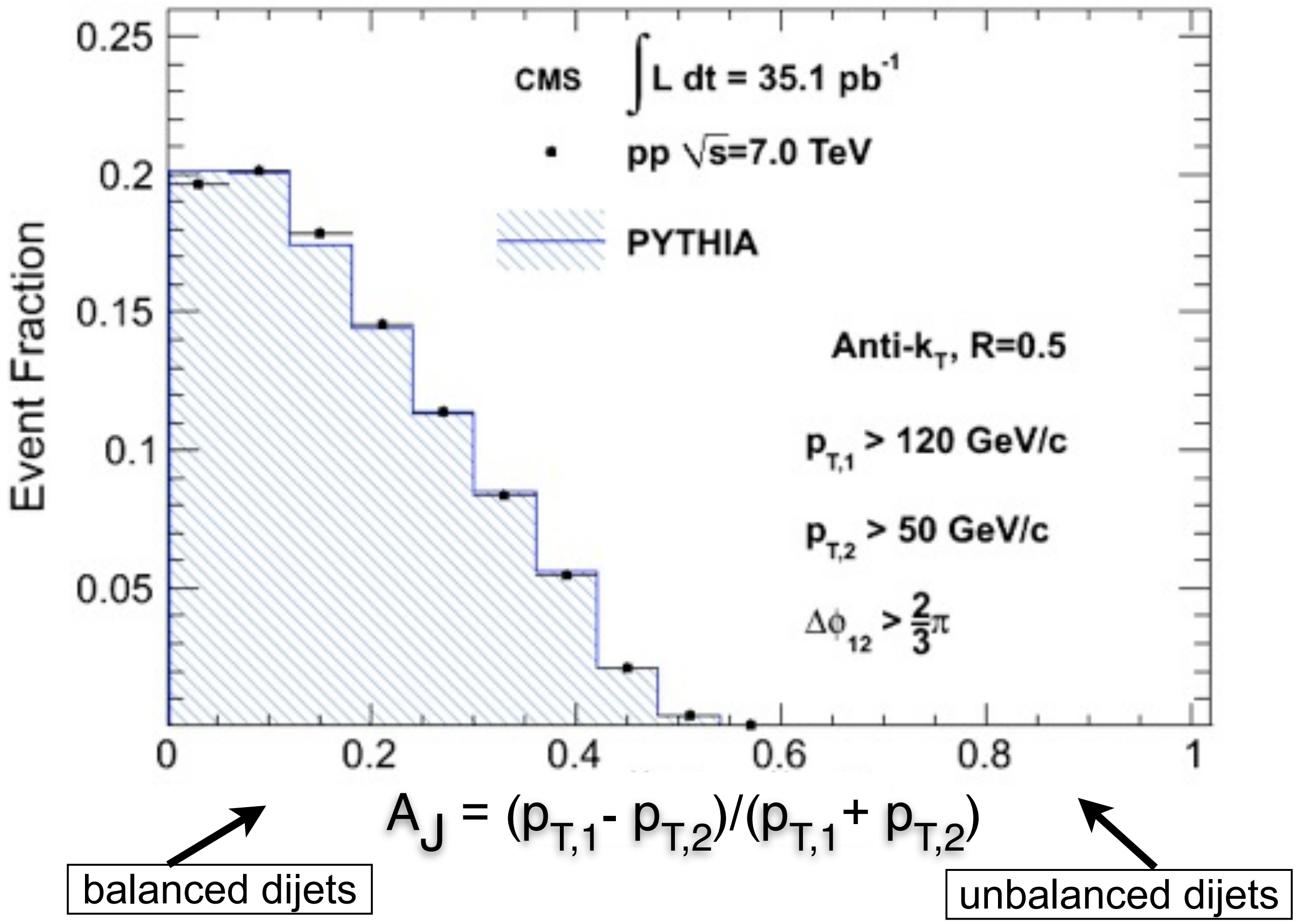
- **Dijet pair momentum balance can be quantified by asymmetry ratio**

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- **Removes uncertainties in overall jet energy scale**

arXiv:1102.1957

CMS M. Tonjes (QM2011)



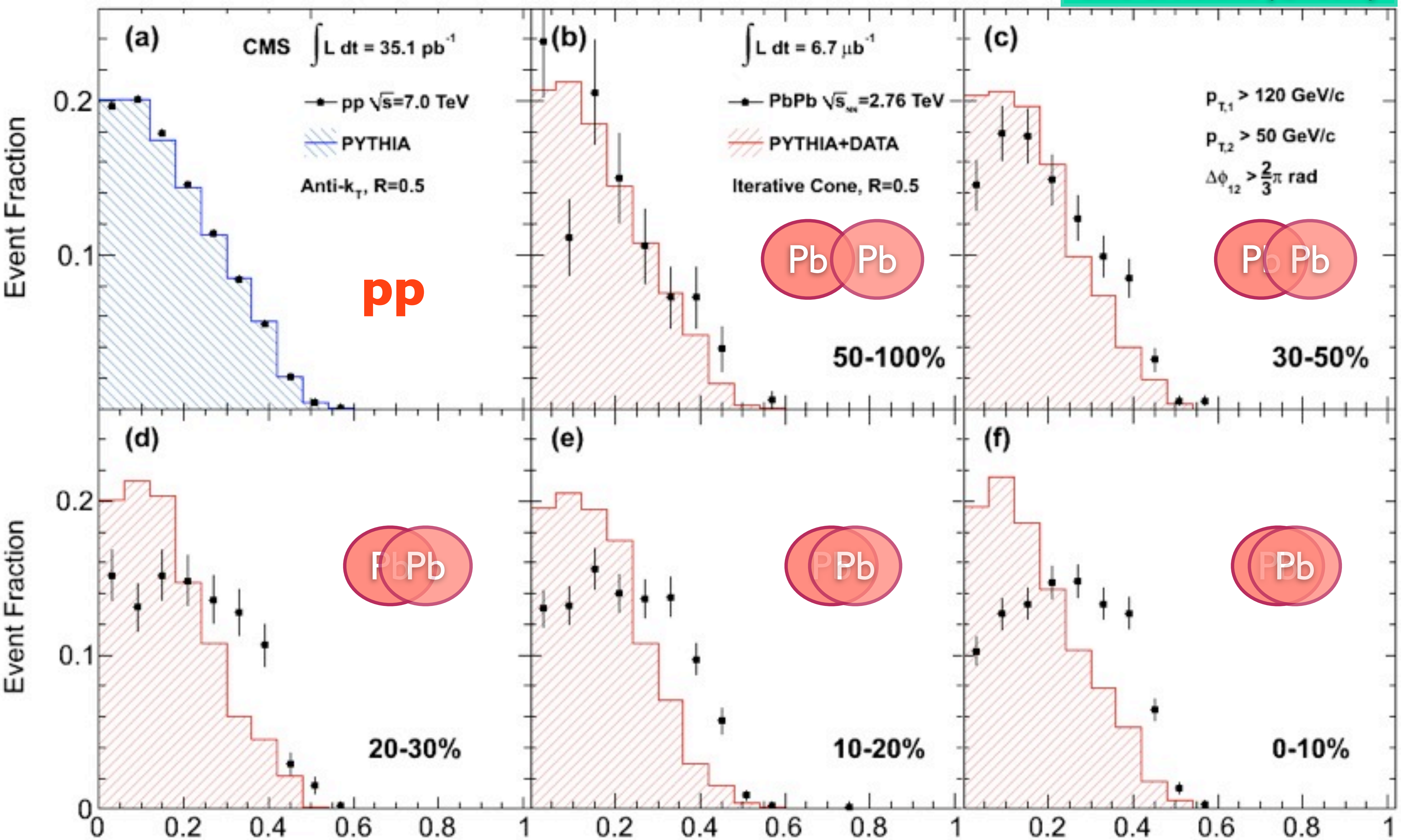
Jet p_T cuts place threshold on A_J

example: $p_{T,1} = 120$ & $p_{T,2} > 50$ GeV/c ⇒ $A_J < 0.41$

Dijet Asymmetry

arXiv:1102.1957

CMS C. Roland (QM2011)



$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$

Parton energy loss is observed as a pronounced energy imbalance in central PbPb.

Where does the Missing Jet Energy Go?

- Large dijet energy imbalance seen in calorimeters
- Verify behavior in tracker and understand where energy goes (low p_T, large angle)
  - Investigate missing momentum using all charged particles.

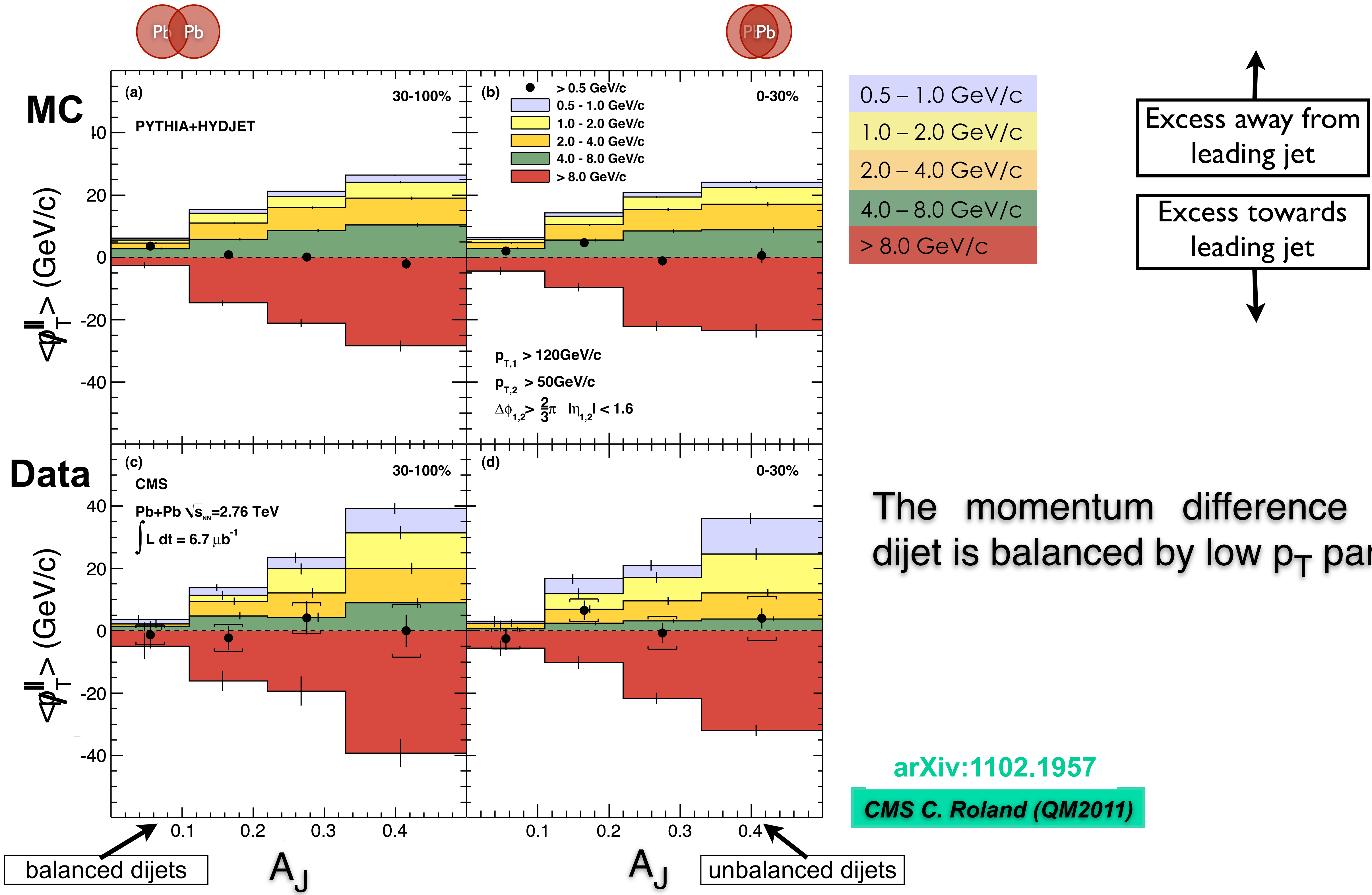
$$\not{p}_{\mathrm{T}}^{\parallel} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

Calculate projection of p_T on leading jet axis and average over selected tracks with $p_T > 0.5$GeV and $|\eta|<2.4$

➔ Allow us to see which p_T range carries the balance of the jet momentum

➔ Explore momentum balance to low p_T over all angles

Missing $p_T^{||}$ Results



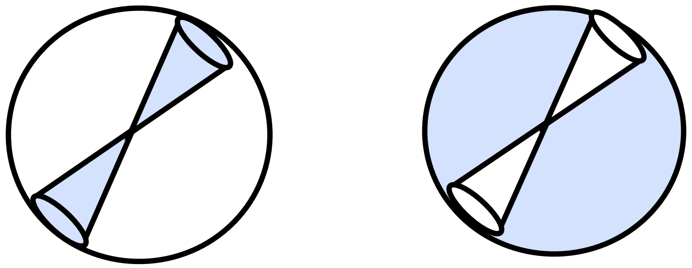
The momentum difference in the dijet is balanced by low p_T particles.

arXiv:1102.1957

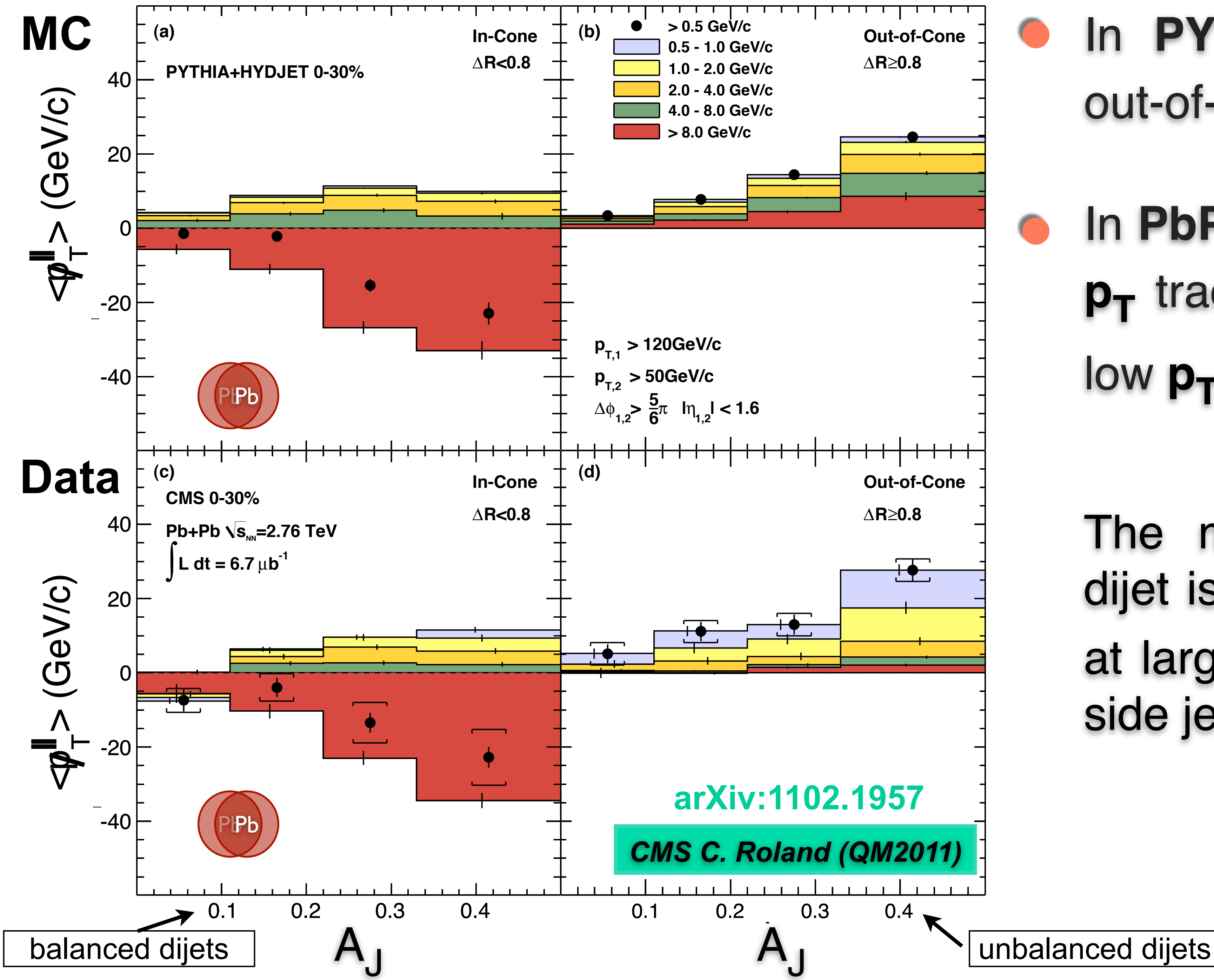
CMS C. Roland (QM2011)

Radial Dependence of Missing $p_T^{||}$

In-Cone
$\Delta R<0.8$



Out-of-Cone
$\Delta R\geq 0.8$



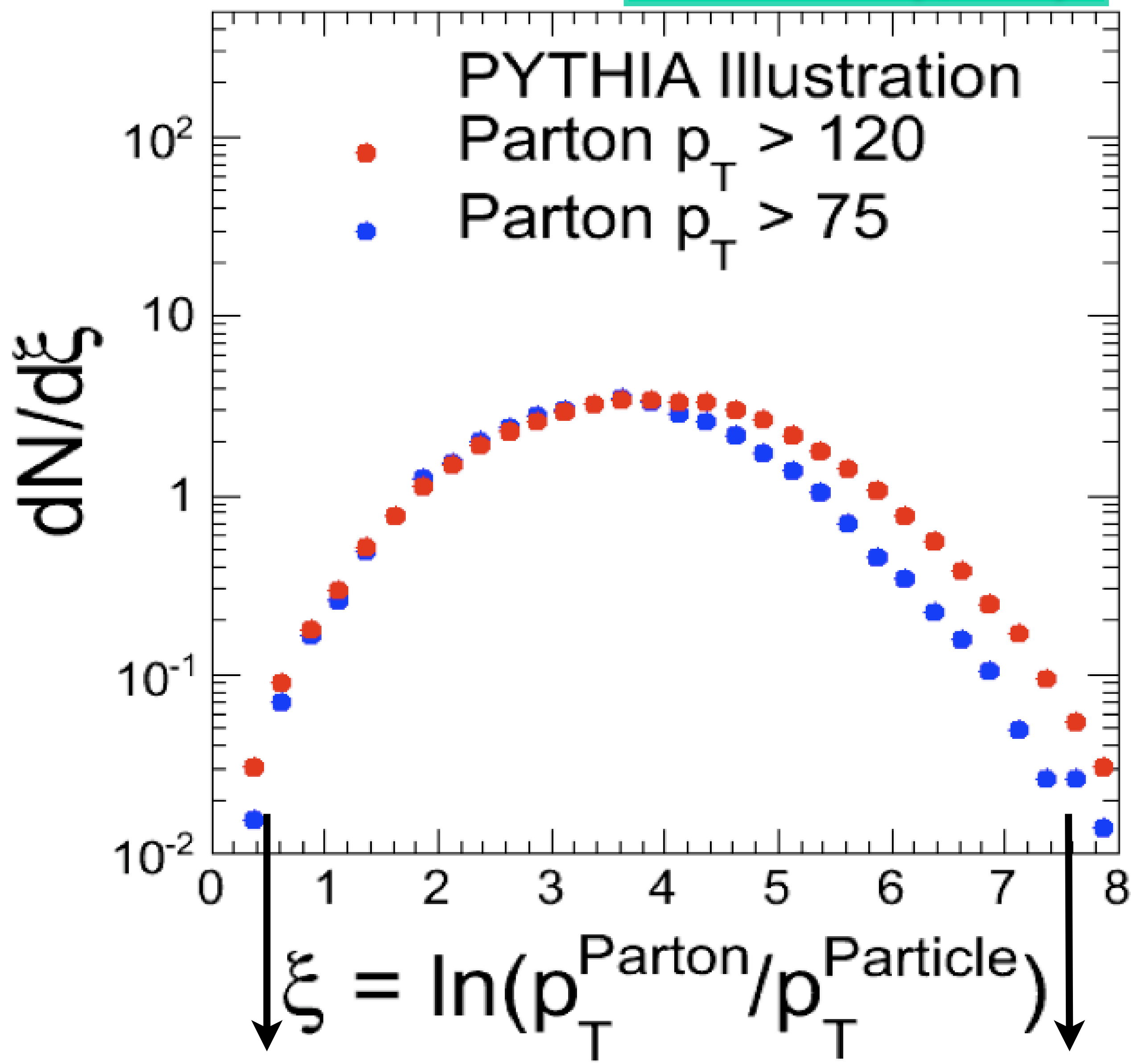
- In **PYTHIA**, the balance is found out-of-cone as well but at higher $\mathbf{p_T}$
- In **PbPb Data**, in-cone excess of high $\mathbf{p_T}$ tracks is balanced by out-of-cone low $\mathbf{p_T}$ tracks.

The momentum difference in the dijet is balanced by low p_T particles at large angles relative to the away side jet axis.

Fragmentation Functions

Jet fragmentation functions (ξ) defined as *log(1/z)*, where *z* is the momentum fraction of the jet carried by an individual particle.

CMS Y. Yilmaz (QM2011)



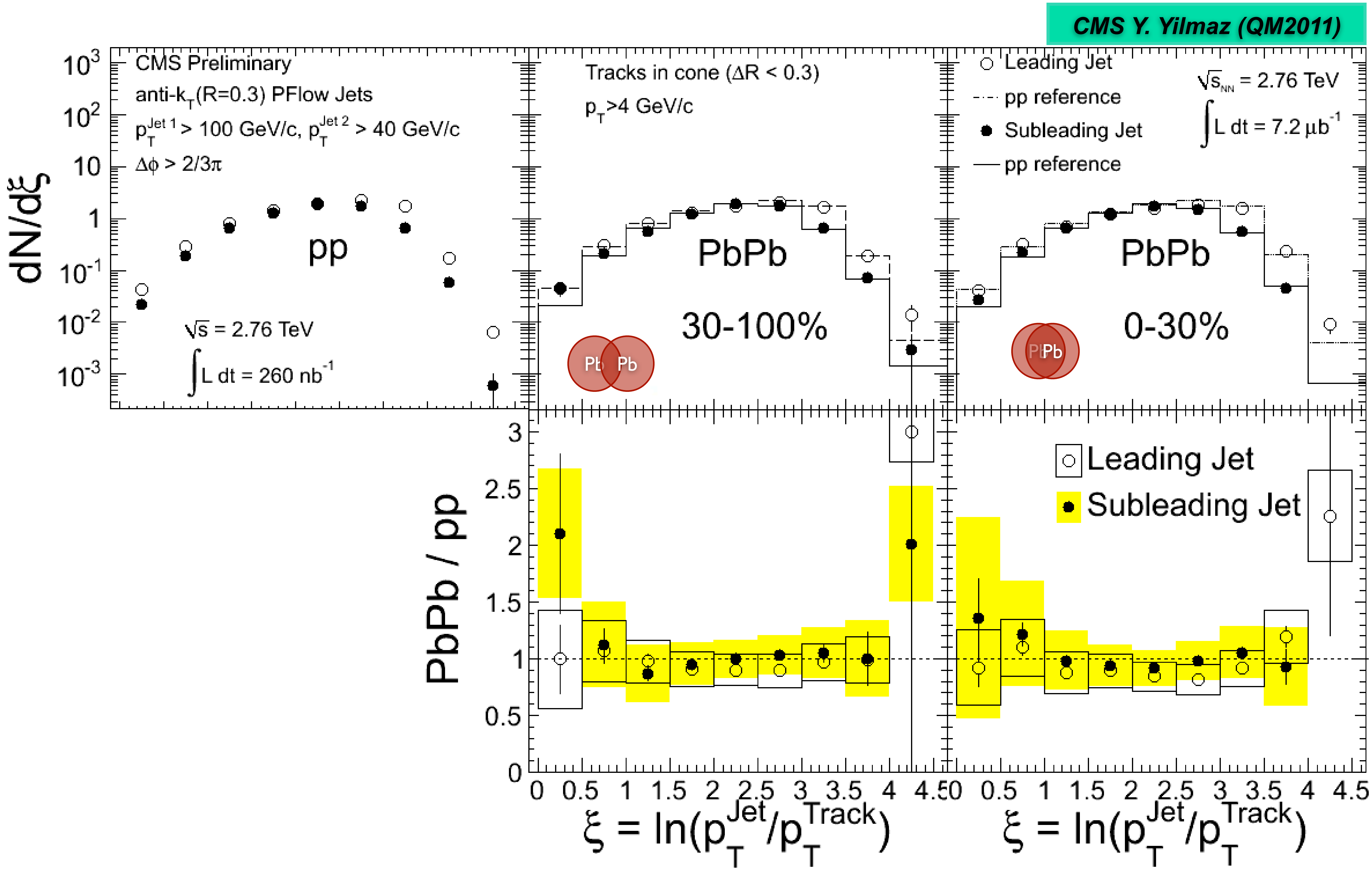
$$\xi = log\frac{1}{z}$$

$$z = \frac{P_T^{particle}}{P_T^{Jet}}$$

Particles carrying **large** fraction of parton momentum

Particles carrying **small** fraction of parton momentum

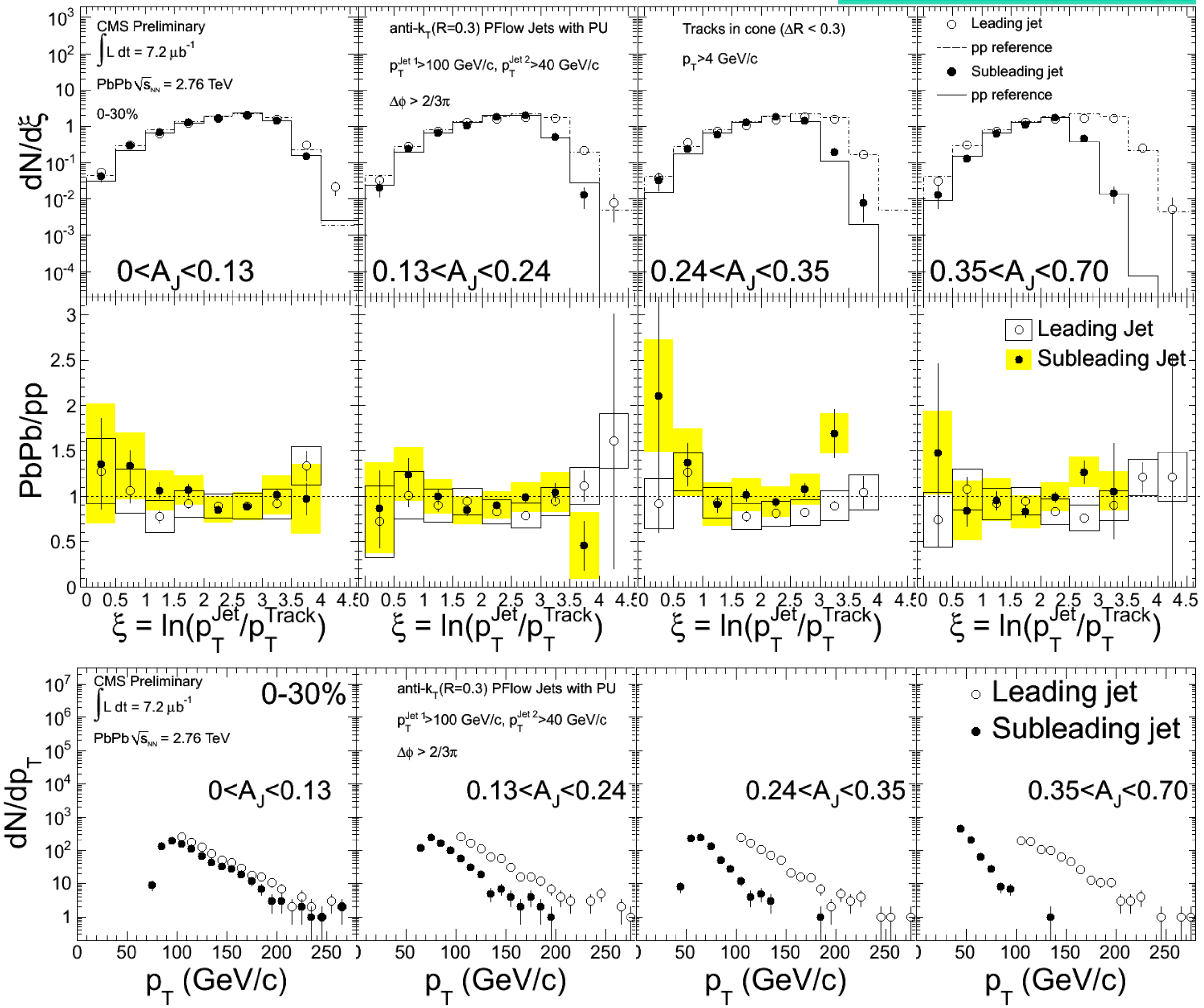
Fragmentation Functions



Both leading and subleading jets in PbPb fragment like jets of corresponding energy in pp collisions.

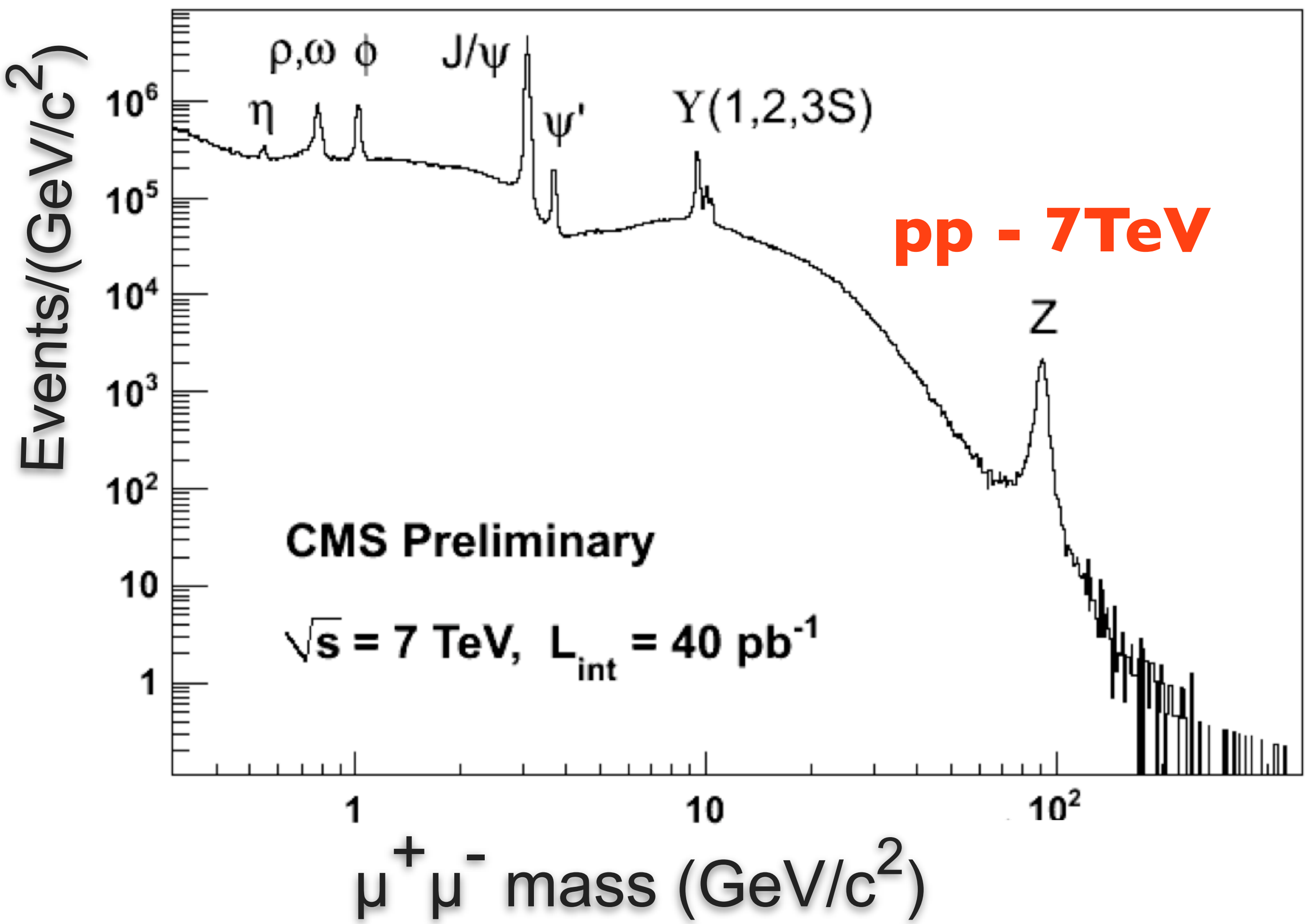
PbPb/pp vs Dijet Imbalance

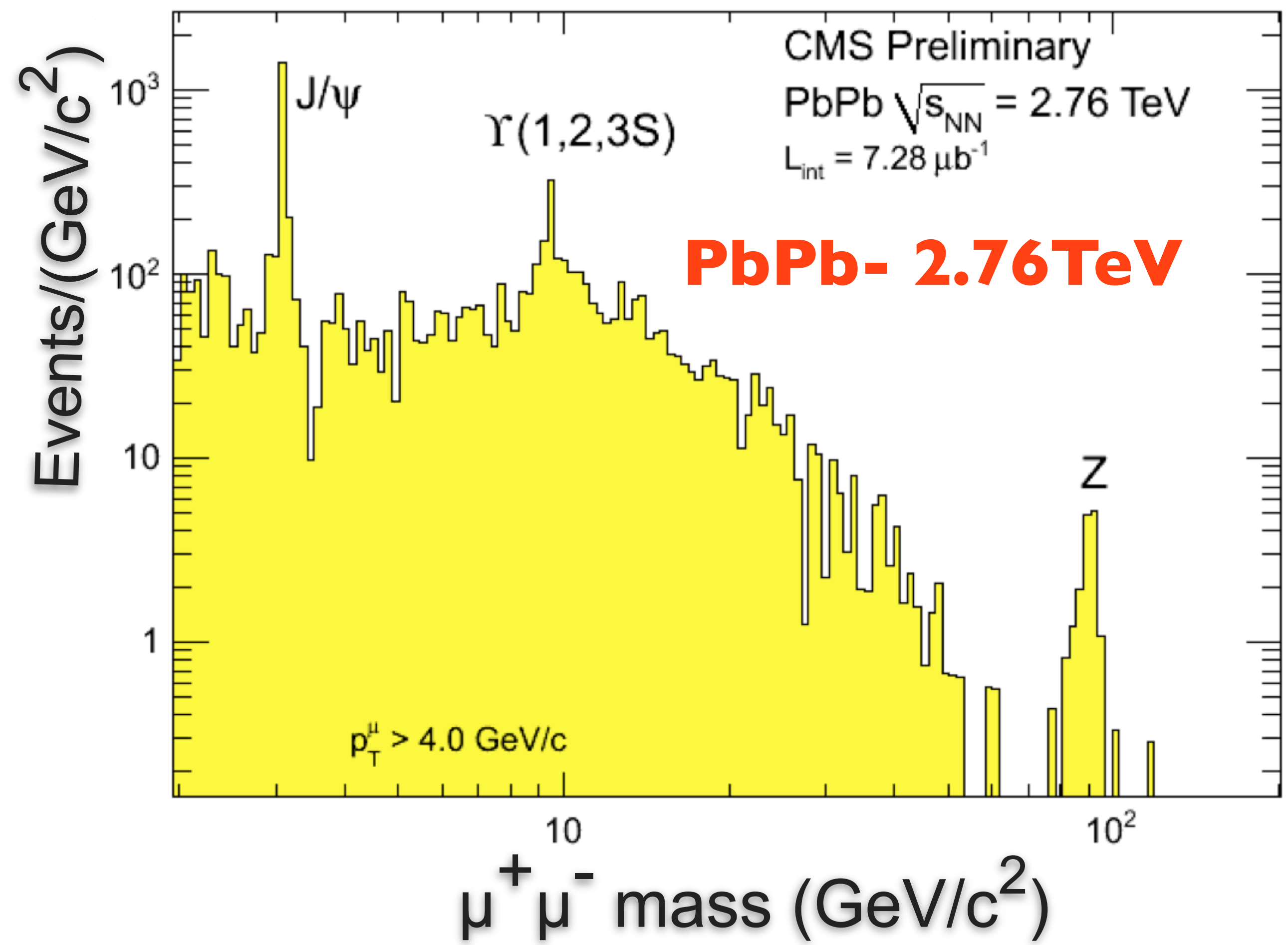
CMS Y. Yilmaz (QM2011)



Fragmentation pattern independent of energy lost in the medium.
Consistent with partons fragmenting in the vacuum.

Quarkonium Production in pp and PbPb





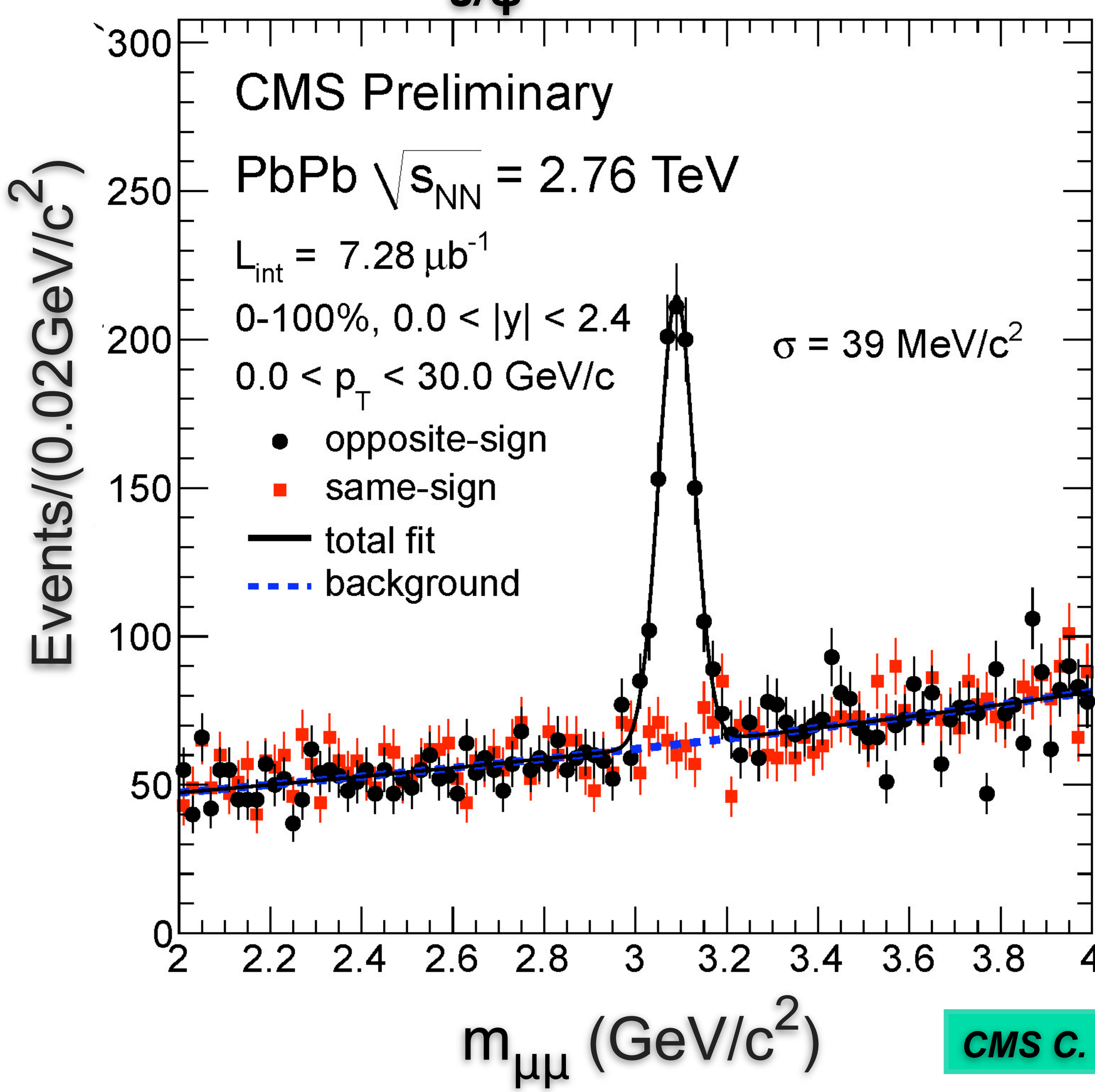
CMS C. Silvestre (QM2011)

Hard probes, J/ψ, ϒ and Z, are observed in $\mu^+\mu^-$ channel in both pp and PbPb collisions...

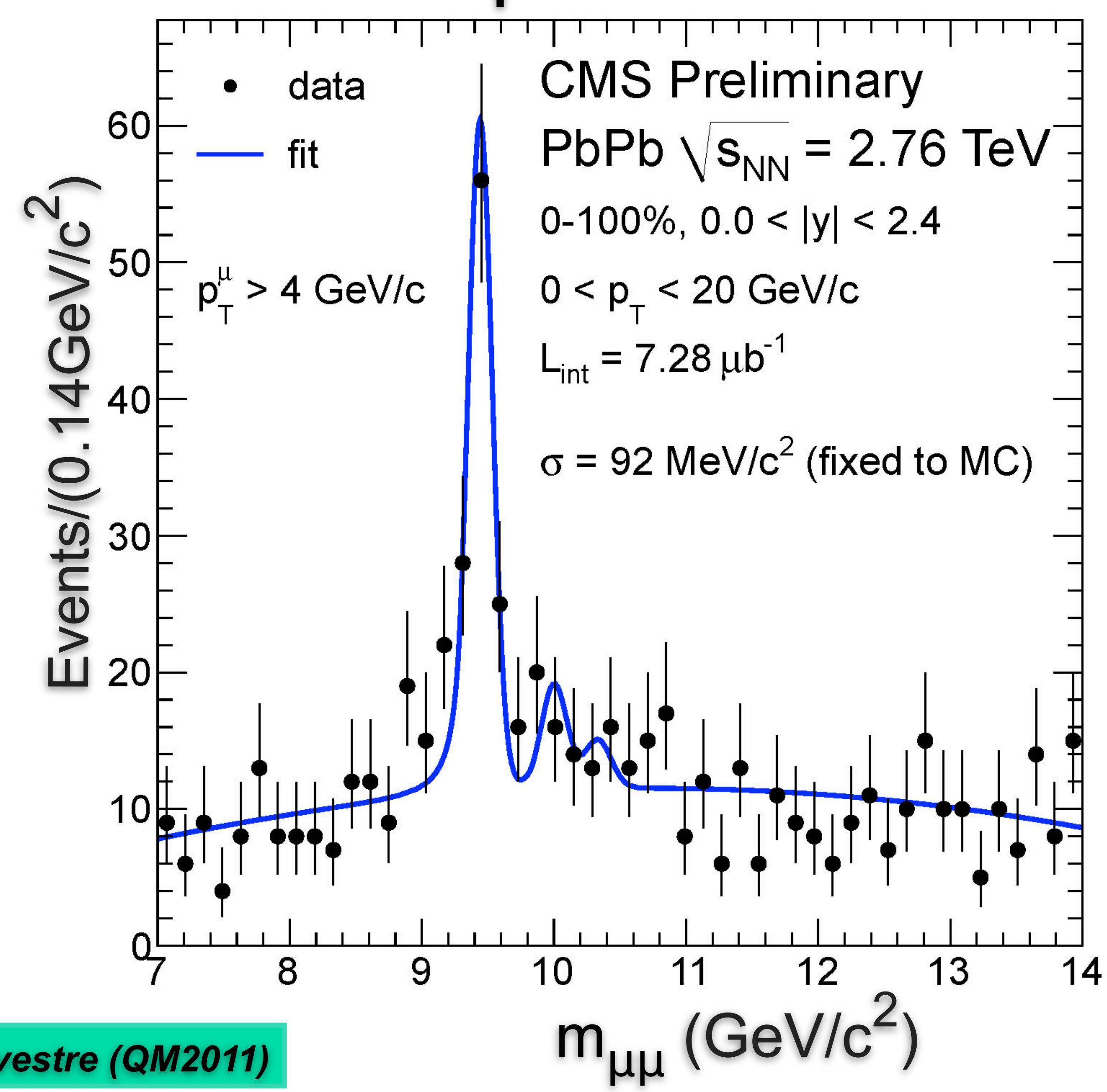
J/ψ and Υ

- J/ψ and Υ are observed in $\mu^+\mu^-$ channel
- CMS muon acceptance $|\eta| < 2.4$ $p_T^{\mu} > 2 - 4$ GeV
- Excellent mass resolution ~1%, comparable to *pp*

$N_{J/\psi}$=734±54



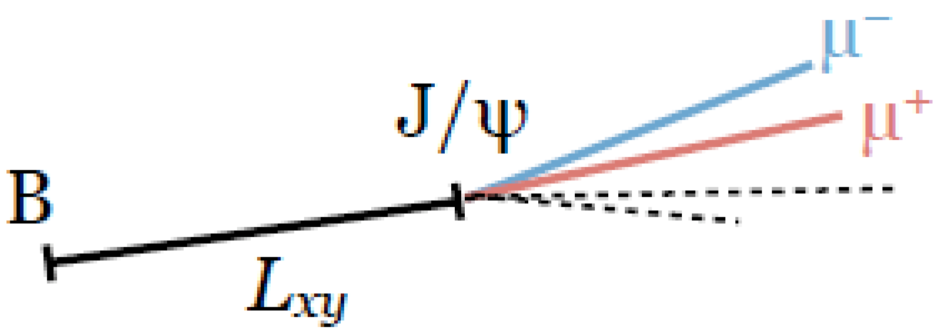
N_{Υ}=86±12



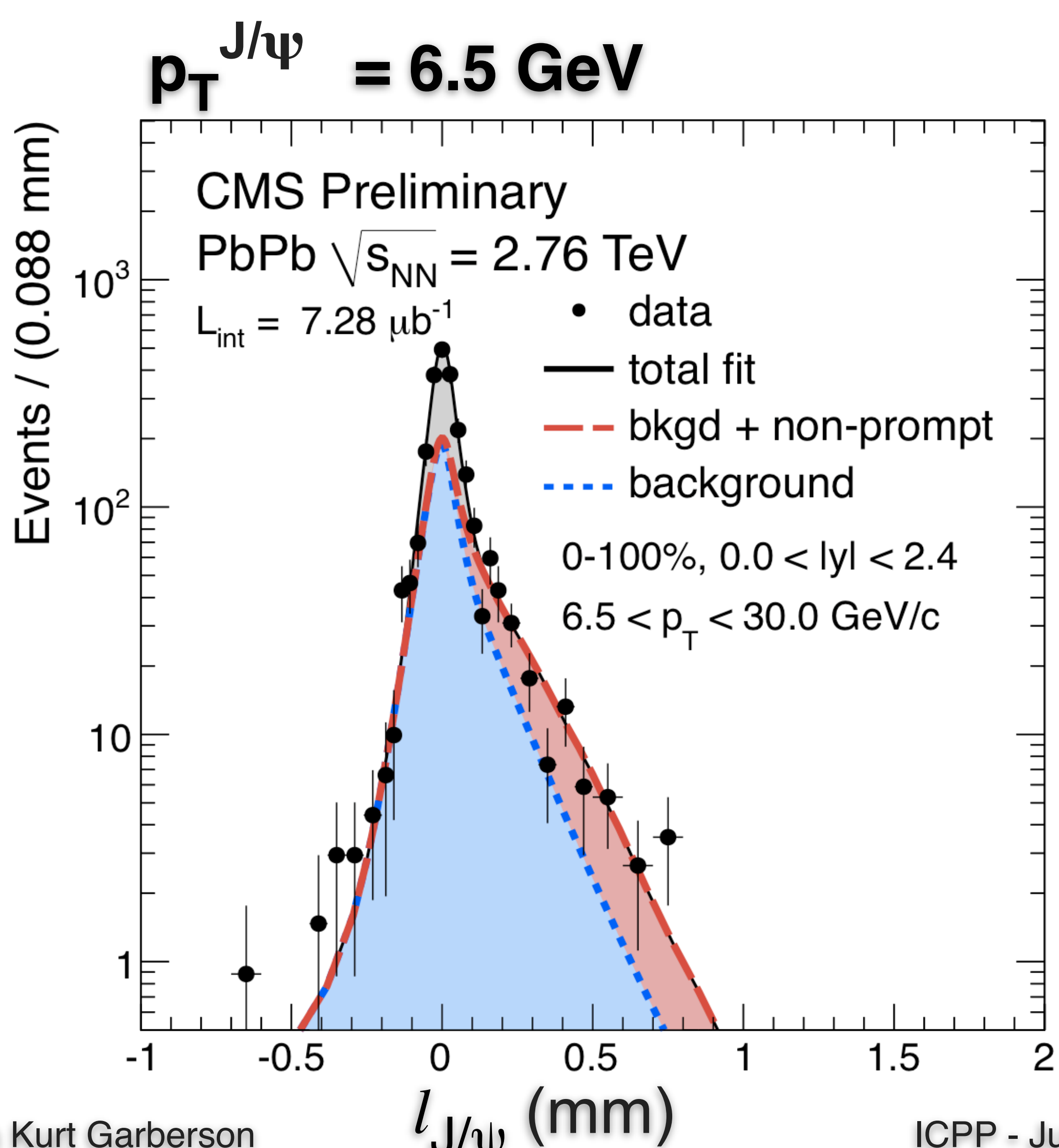
CMS C. Silvestre (QM2011)

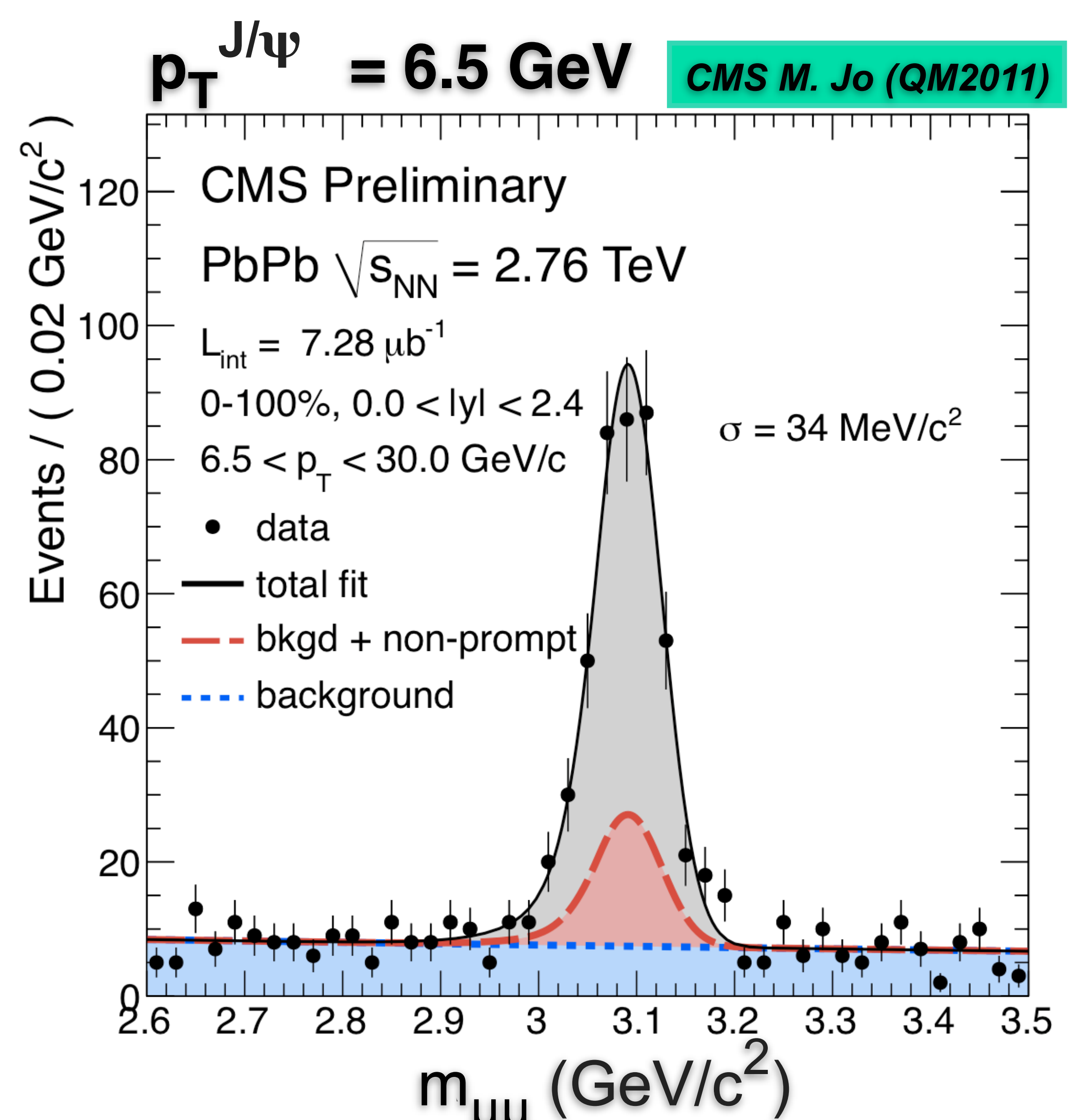
J/ψ : Prompt and Non-Prompt (from B decays)

Promt and non-promt J/ψ have been separated for the first time in HI collisions.



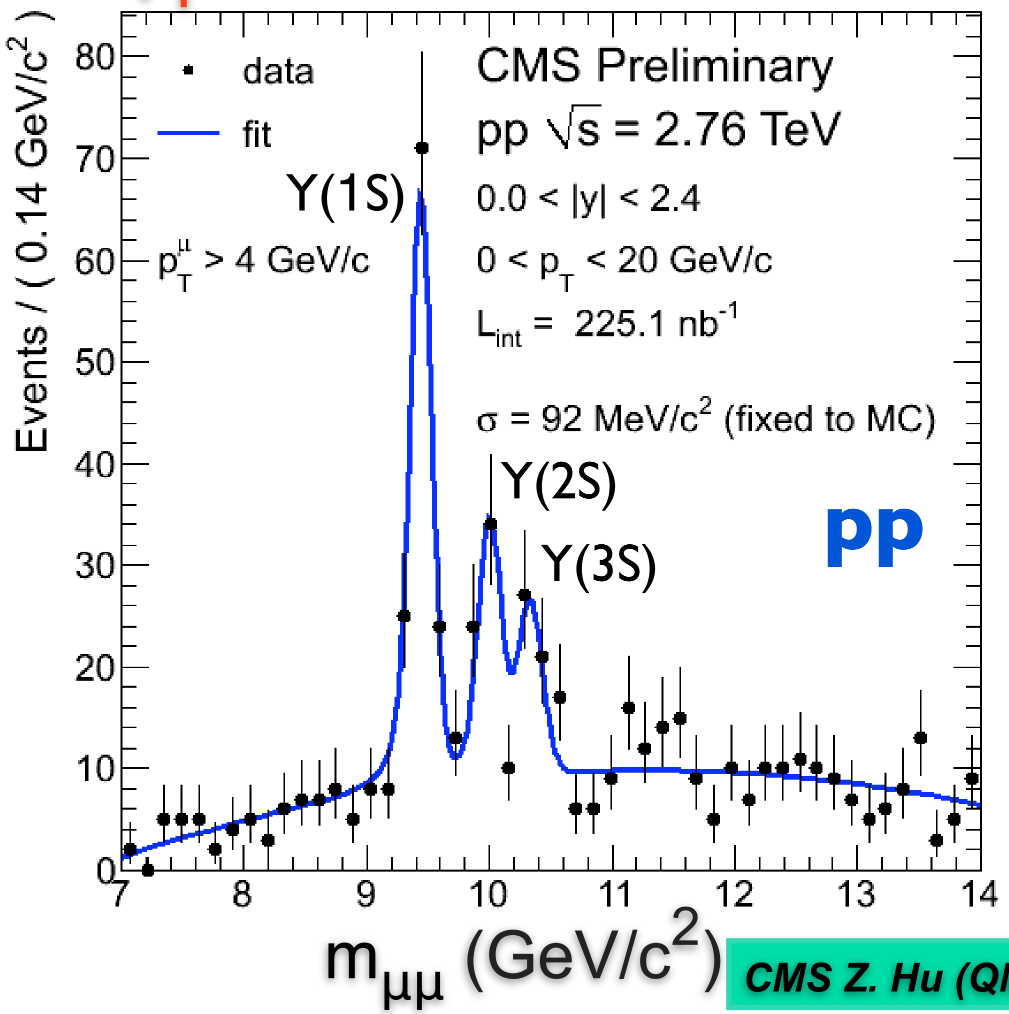
- Use seperation of primary and $\mu^+\mu^-$ vertices in plane transverse to beam
- Long B decay times lead to displaced vertices



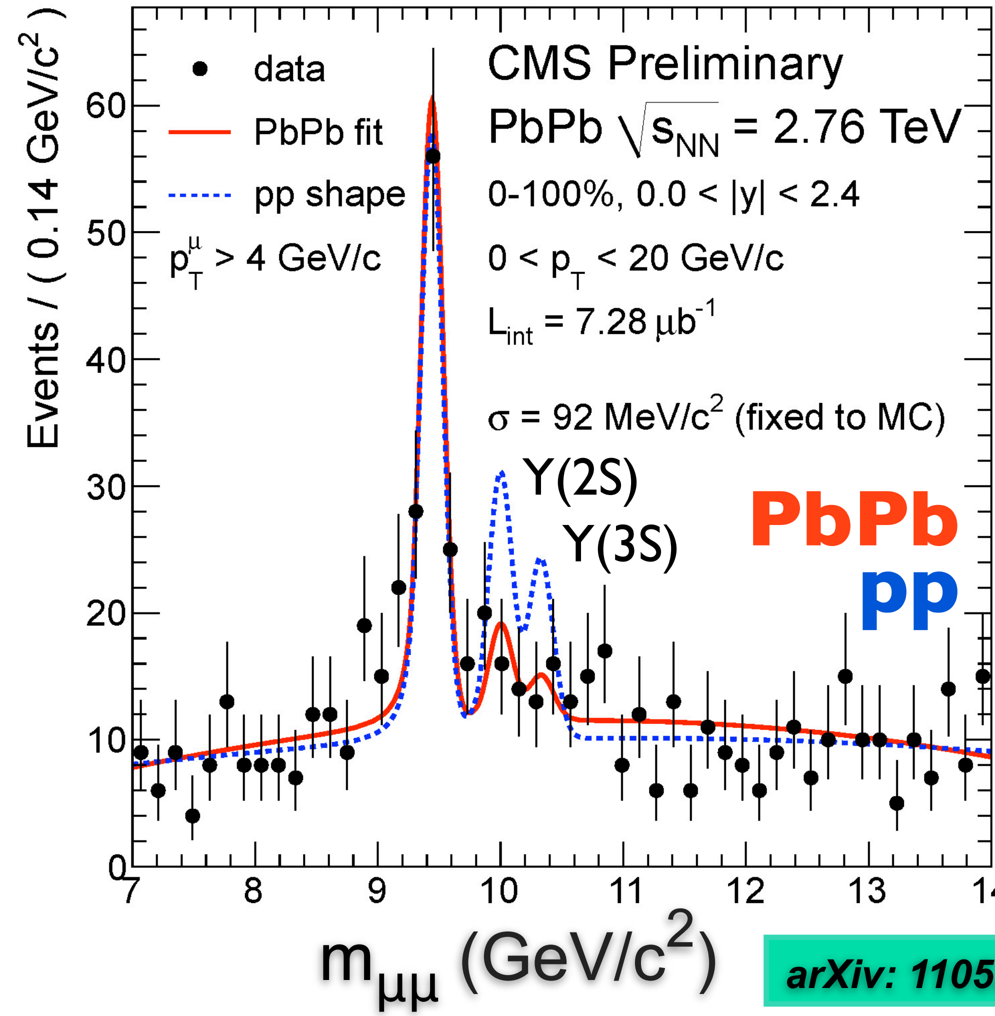


Suppression of Excited Υ states in pp and PbPb

p_T^{μ} = 4 GeV



CMS Z. Hu (QM2011)



arXiv: 1105.4894 Sub. to PRL

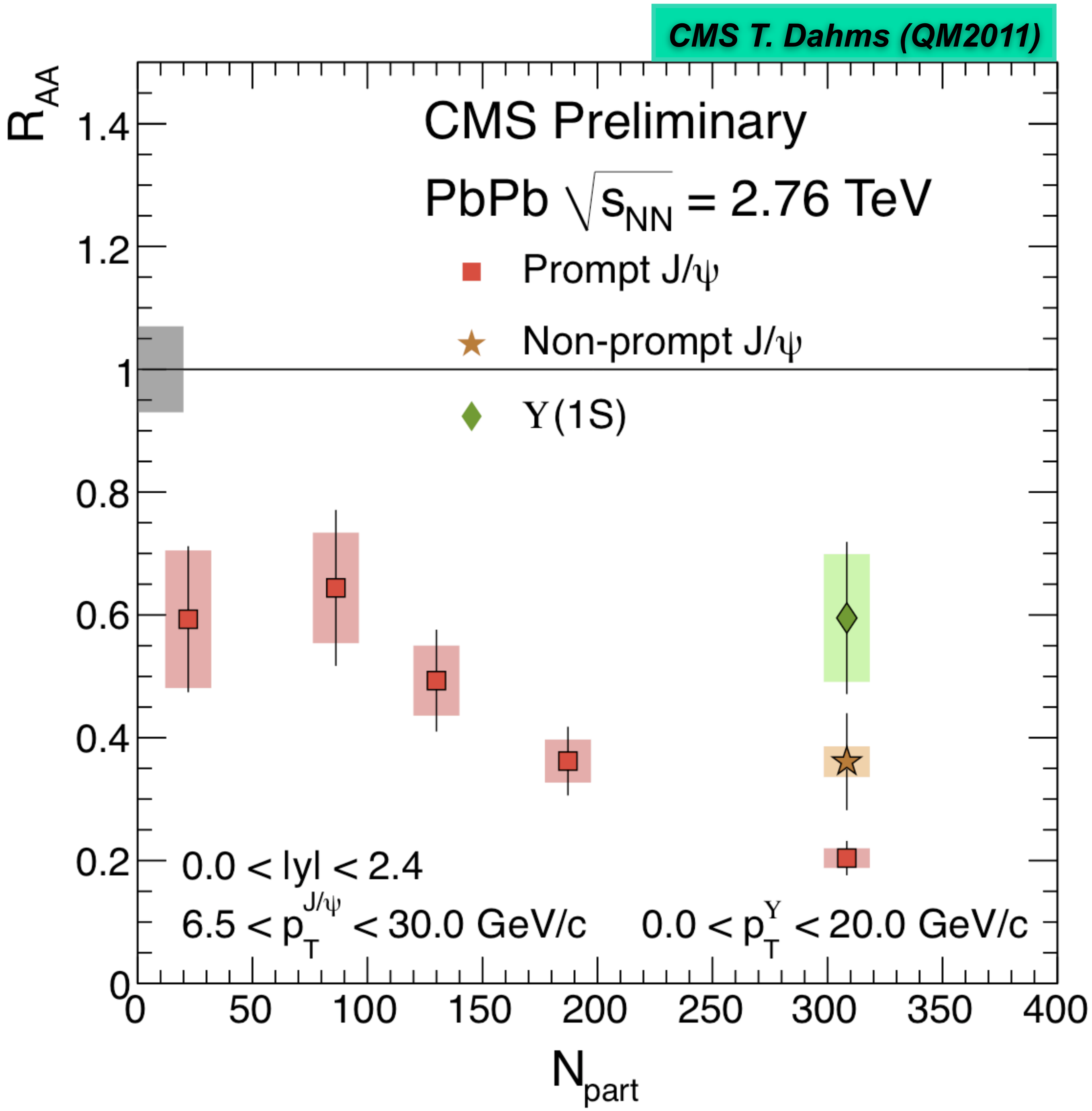
- A Double ratio is performed to estimate the suppression

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

} Υ(2S+3S) relative to Υ(1S) in pp and PbPb

- Υ(2S)+Υ(3S) excited states are suppressed (relative to Υ(1S)) in PbPb collisions.

All Quarkonia Suppressed : R_{AA} vs Centrality



- **High p_T prompt J/ψ is strongly suppressed at LHC**
  - J/ψ production is more suppressed in central compare to peripheral events
- **Non-prompt J/ψ is a measure of b-quark quenching**
  - Non-prompt J/ψ are less suppressed than prompt J/ψ
- **Inclusive Υ(1S) is suppressed**

Summary

- **CMS has collected high quality data with heavy ion collisions in 2010. The detector has shown excellent performance in all major sectors.**
- **CMS has obtained significant statistics of hard probes**
- **CMS conducted detailed measurements of global properties of medium in PbPb and pp collisions**
- **Our measurement indicate consistent view of the hot and dense medium**
  - Strong collective effects in the medium
  - No quenching of weakly and electromagnetically interacting probes
  - Strong quenching of partons, including b-quarks
  - Suppression of quarkonia, including excited states of the Υ

Thanks to CERN for fantastic LHC performance!

References

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

1- Charged Hadron Multiplicity CMS-PAS-HIN-10-001

1- Energy Flow CMS-PAS-HIN-11-003

2- Dihadron Correlation arXiv:1105.2438; CMS-PAS-HIN-11-001;CMS-PAS-HIN-11-006

3- Elliptic Flow CMS-PAS-HIN-10-002

4- Nuclear Modification Factor CMS-PAS-HIN-10-005

5- Electroweak Bosons Z, W arXiv:1102.5435v1

6- Isolated Photons CMS-PAS-HIN-11-002

7- Jet Measurements :

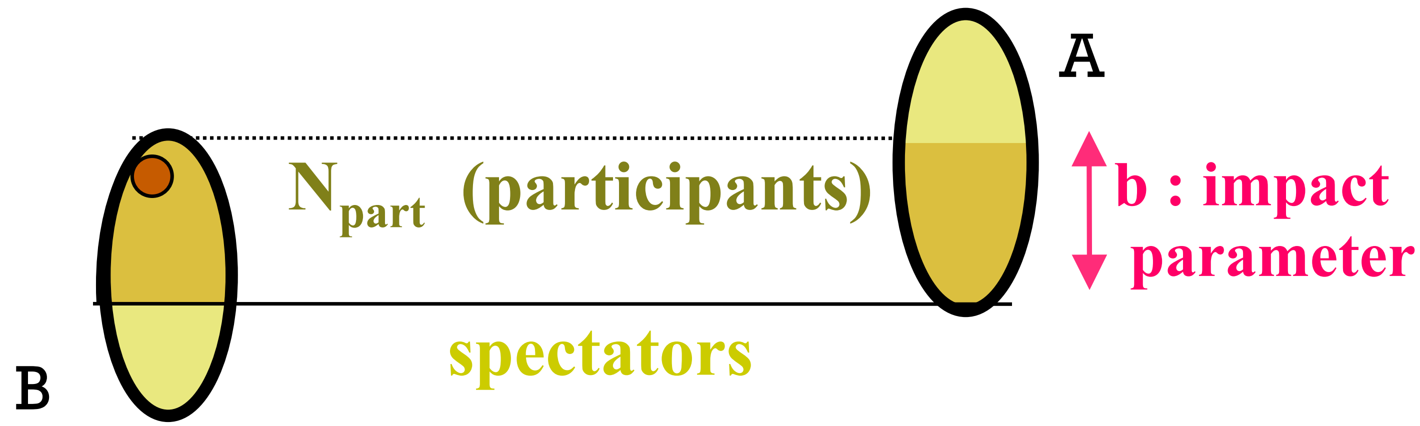
- Dijet Asymmetry arXiv:1102.1957
- Fragmentation Functions CMS-PAS-HIN-11-004

8- Quarkonia:

- J/ψ measurement CMS-PAS-HIN-10-006
- Υ suppression arXiv:1105.4894; CMS-PAS-HIN-11-007

Backup

How do we quantify the medium effects?



- N_{part} : number of nucleons which undergo at least one collision
- N_{coll} : number of n+n collisions taking place in A+B collision
- Modification nuclear factor $R_{AA} = \frac{1/N_{evnts} d^2N^Z/dydp_T}{<T_{AB}> d^2\sigma_{pp}/dydp_T}$

quantifies the effect of the medium on a particle production

- To compare measured PbPb yields to theoretical pp cross sections, we need T_{AB} : nuclear overlap function
  - In absence of medium effects
    - $R_{AA} = 1$ for perturbative probes
  - T_{AB} is proportional to N_{coll}

$$T_{AB} = <N_{coll}>/\sigma_{pp}$$

Elliptic Flow (Methods)

- **Event Plane Method**
  - 3-subevent method is used to calculated resolution corrections based on pseudorapidity
  - $(-2 \leq \eta < -1)$, $(-0.75 < \eta \leq 0.75)$, $(1 \leq \eta < 2)$
  - $\Delta\eta > 1$ pseudorapidity separation between event plane and v_2 tracks
  - Flattening of the event planes (Fourier expansion)
  - high pT limit of 3.0 GeV/c on the tracks to determine event planes
- **Cumulant 2^{nd} and 4^{th} Order Method**
  - auto-correlations are avoided by removing the particles that are used for determining differential flow from the integral flow
  - Fixed multiplicity in each centrality class
- **Lee-Yang Zeros Method**
  - Sum and product generating functions were used

Cumulant Method

- Since all particles are correlated to the reaction plane, they are also indirectly correlated with each other.

$$< v_n >^2 = < cos[n(\phi_i - \phi_j)] >$$

integrated flow

$$v_n(p_T) = \frac{< cos[n(\phi_i - \phi_j)] >}{< v_n >}$$

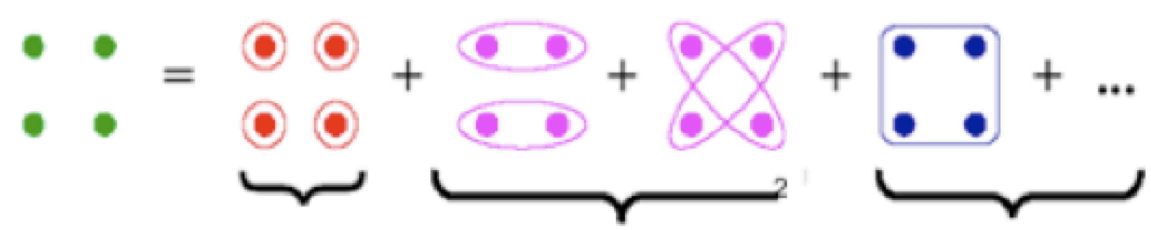
differential flow

- **2-particle correlations** can be expressed in terms of flow and non-flow components:

→ - the few particle correlations (resonance decays, jets, etc.)

$$\left\langle e^{in(\varphi_1 - \varphi_2)} \right\rangle_m = v_n^2 + \left\langle e^{in(\varphi_1 - \varphi_2)} \right\rangle_c$$

- **4-particle correlation** can be decomposed in the similar way:

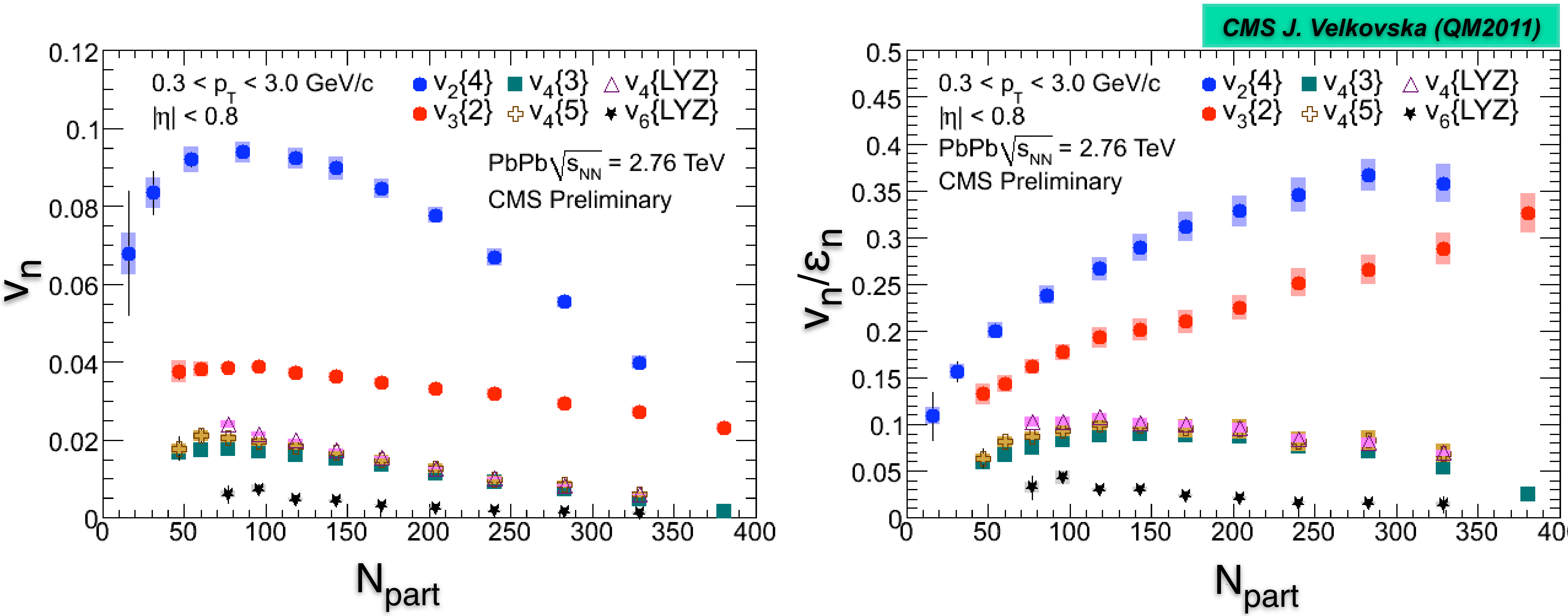


$$v_n^4 \qquad 2 < e^{in(\phi_1 - \phi 2)} >_c^2 \qquad O(\frac{1}{N^3})$$

- Integral and differential flow signals are obtained by using generating functions:

$$G_n = \prod_{i=1}^{M} \left(1 + \frac{2\,x\,\cos(n\varphi_i) + 2\,y\,\sin(n\varphi_i)}{M}\right) \qquad D_{p/n} = \frac{\langle e^{ip\psi} G_n(z) \rangle}{\langle G_n(z) \rangle}$$

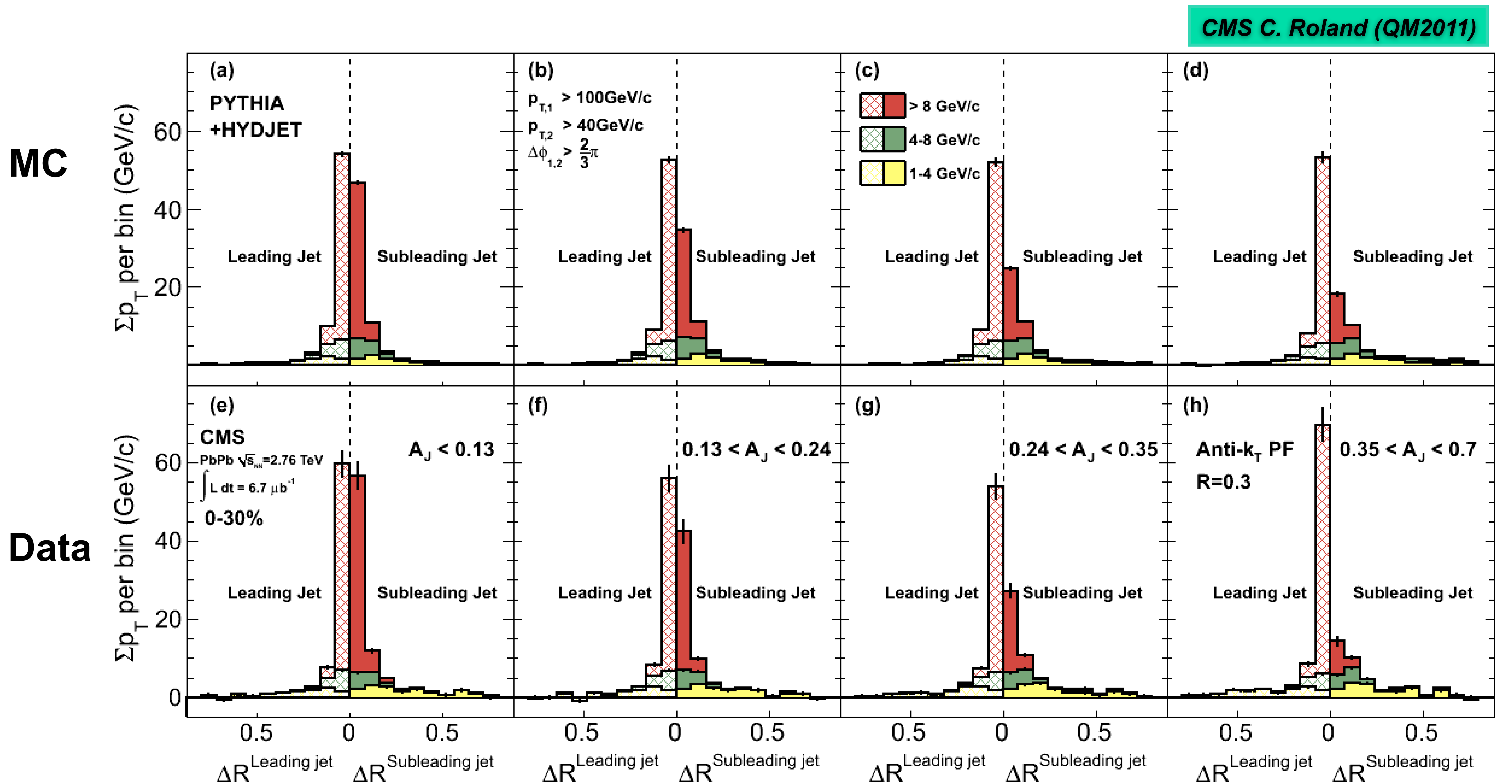
Full Harmonic Spectrum



v_n vs N_{part} show different trends :

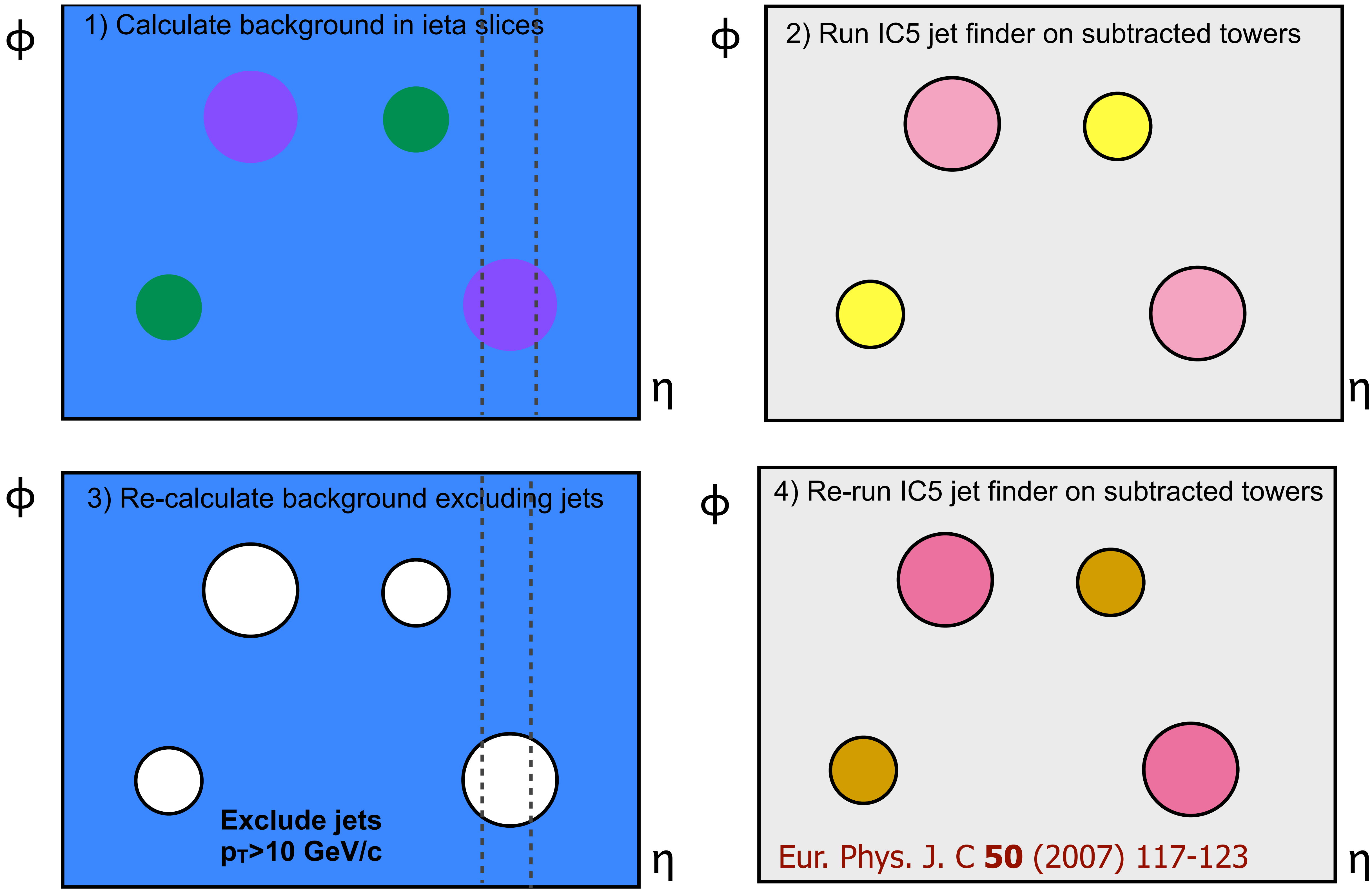
- **Even harmonics have similar centrality dependence**
  Decreasing → 0 with increasing N_{part}
- **v_3 has weak centrality dependence**
  Finite for central collisions

Track-Jet Correlation Result

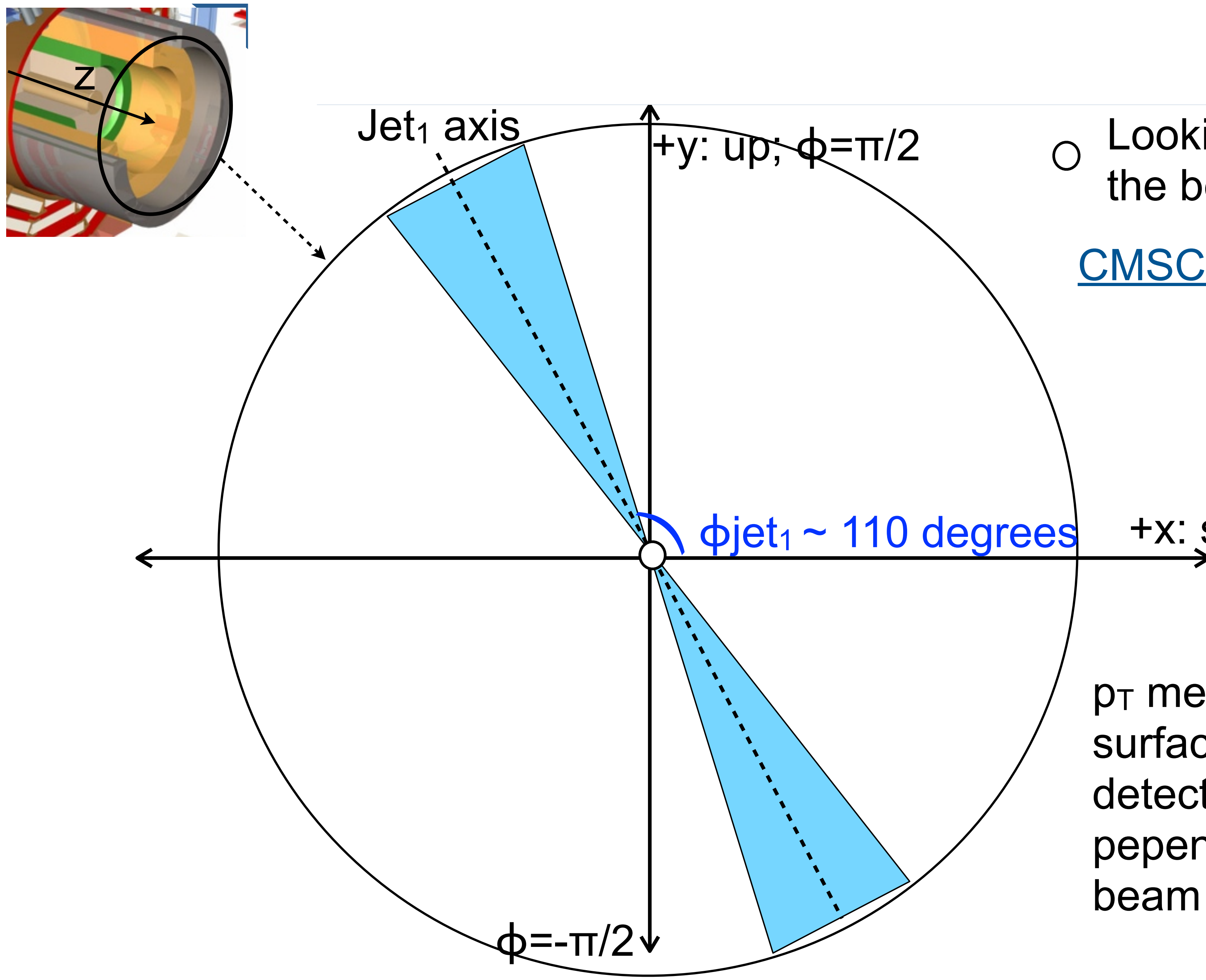


- Underlying event contribution is subtracted for the tracks associated with the jets using jet-by-jet subtraction.
- Imbalance in calorimeter measurement reflected also in charged tracks.

Iterative PileUp Subtraction



ϕ Definition (for $< p_T^{||} >$)



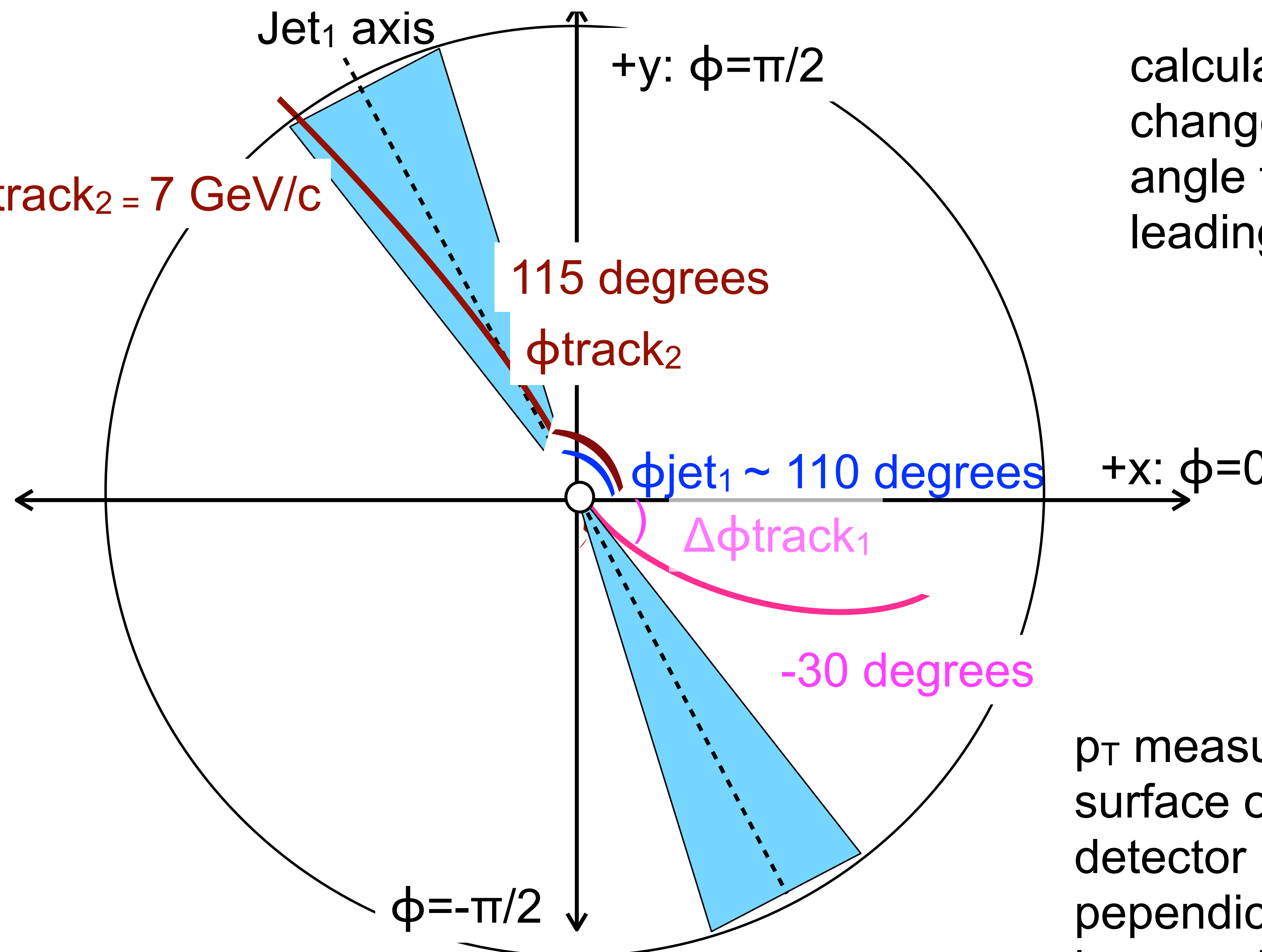
- Looking down the beam axis

CMSConventions

p_T measured at surface of detector pependicular to beam axis

$$p_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

Pictoral < $p_T^{||}$ > Example

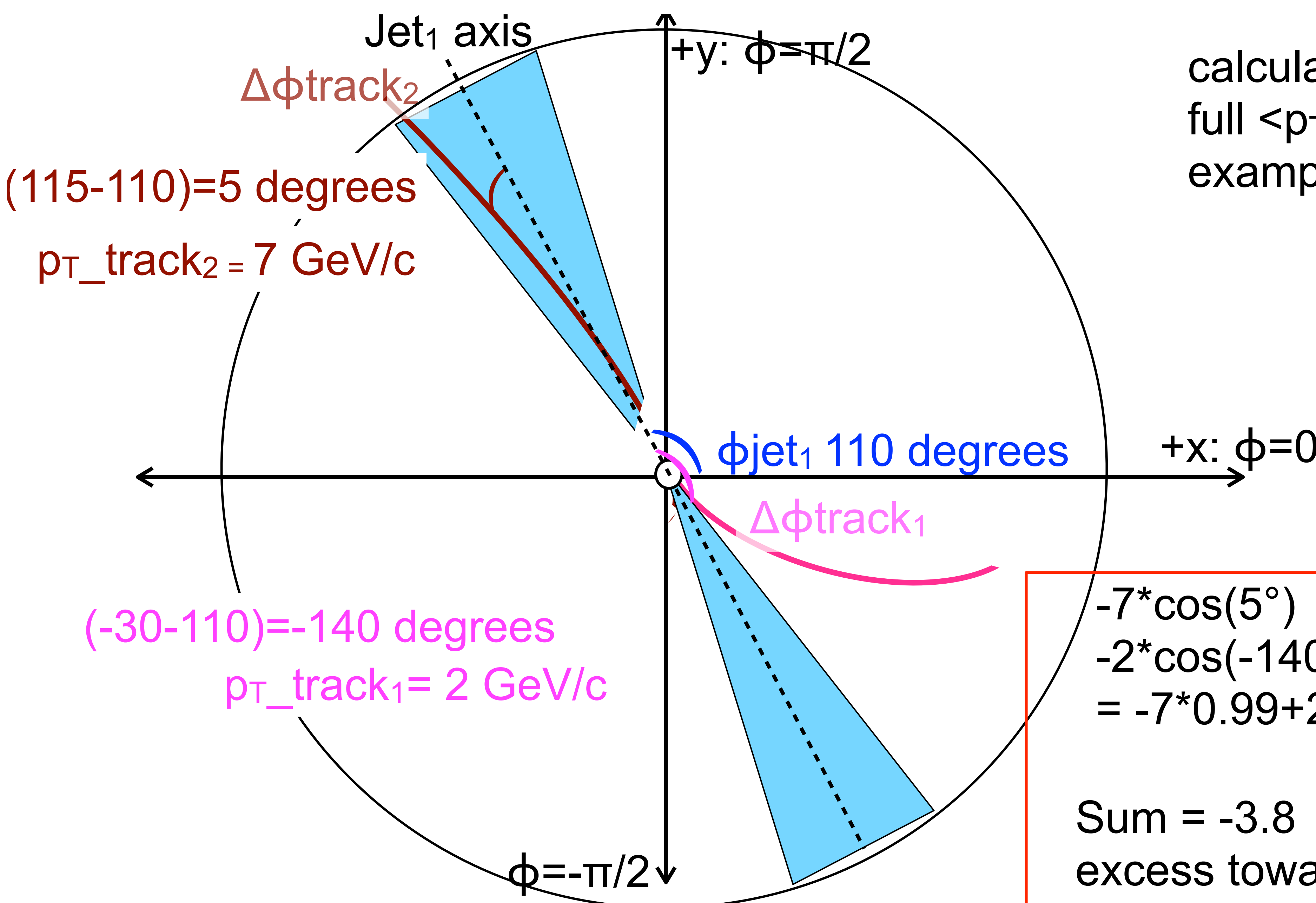


calculate change in angle from leading jet

p_T measured at surface of detector pependicular to beam axis

$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{T,\text{track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

Pictoral < $p_T^{||}$ > Example



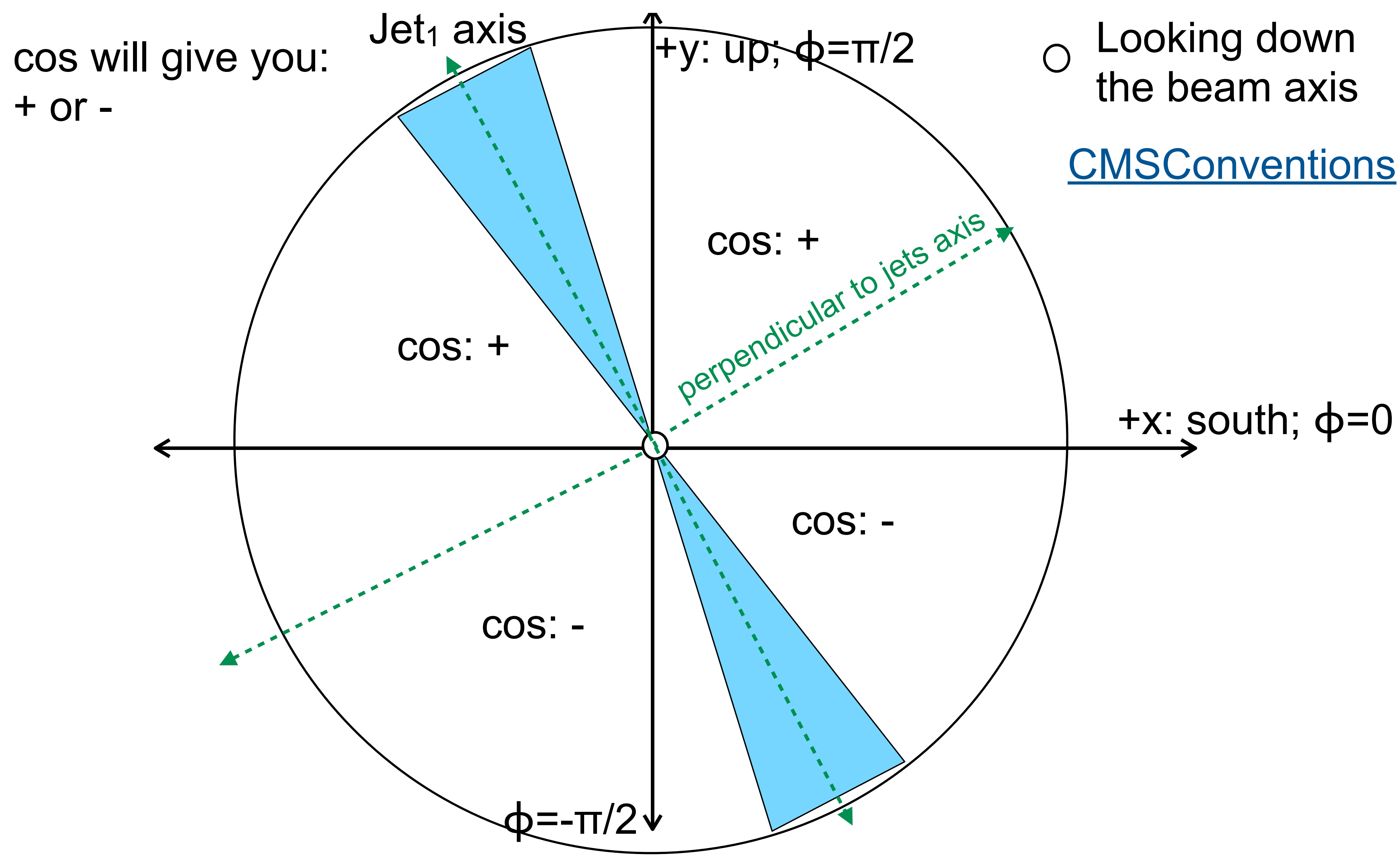
calculate
full <$p_T^{||}$>
example

-7*cos(5°)
-2*cos(-140°)
= -7*0.99+2*0.77

Sum = -3.8
excess towards
leading jet

$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

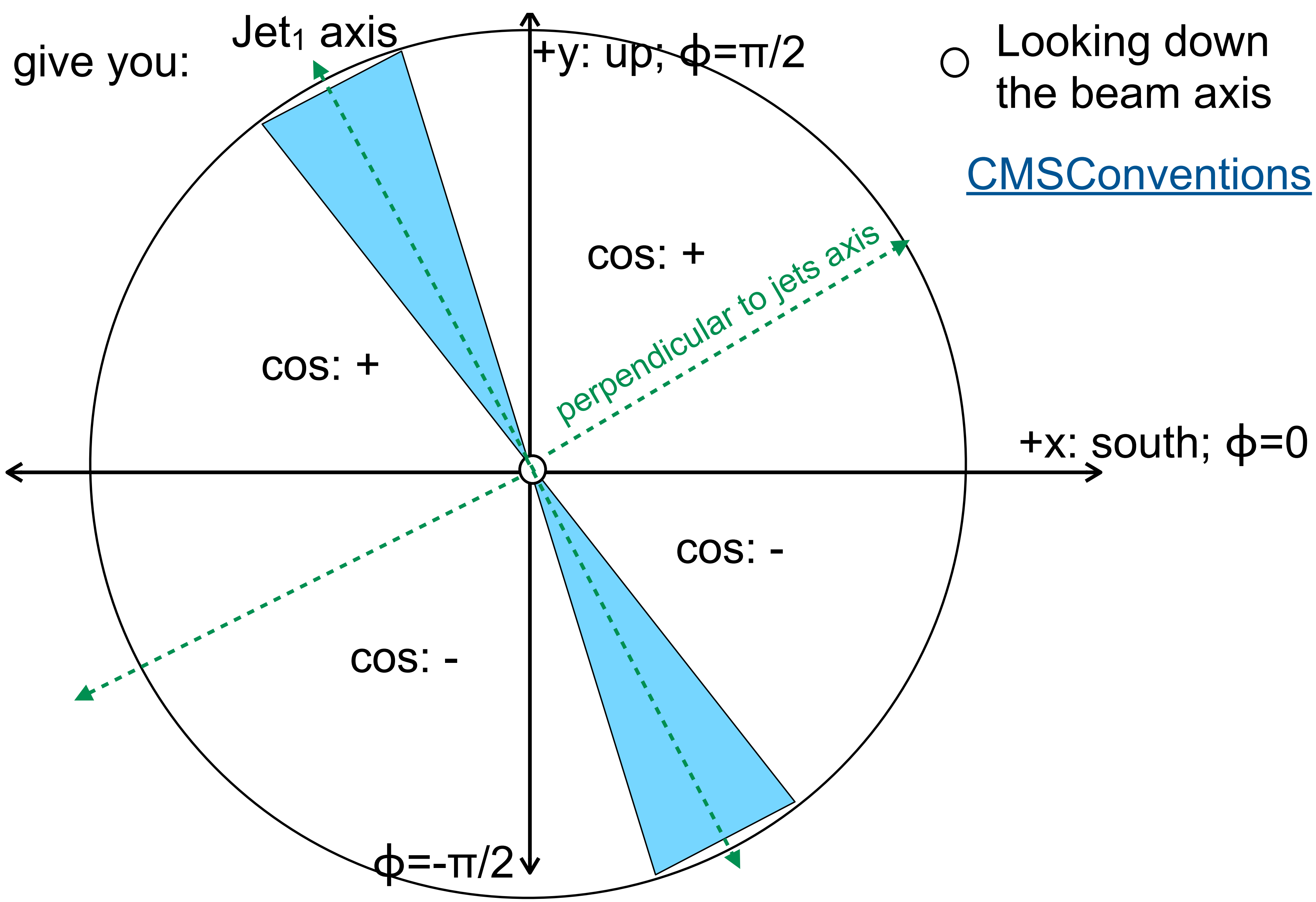
Pictoral < $p_T^{||}$ > Example



$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \boxed{\cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)}$$

Result of the $\cos(\phi_{track}-\phi_{jet1})$

cos will give you:
+ or -



- Looking down the beam axis

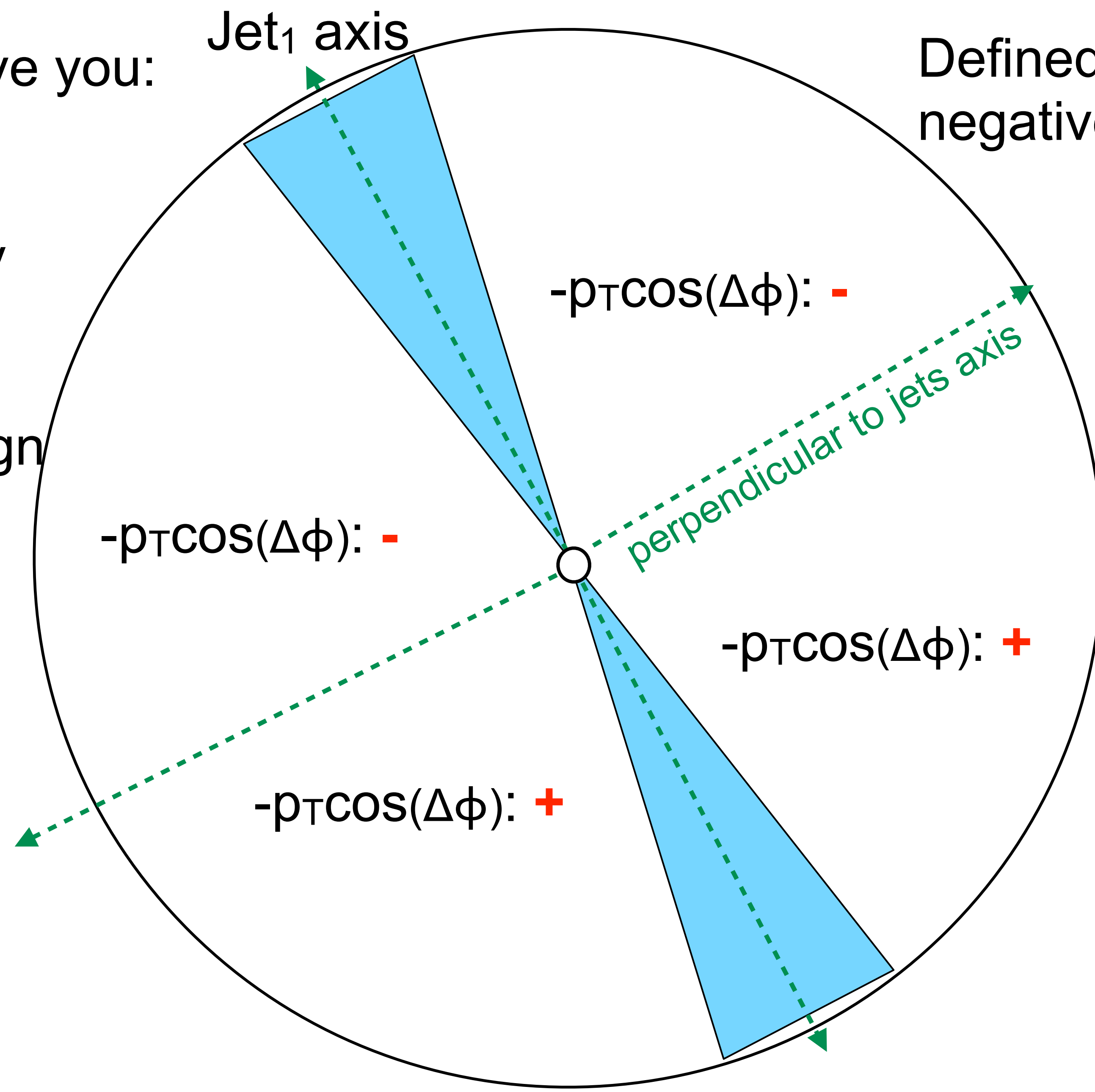
CMSConventions

$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$

$-p_T$, track $\cos(\phi_{track}-\phi_{jet1})$

cos will give you:
+ or -

multiply by
$-p_T$,
quadrants
reverse sign



Defined as
negative towards leading

$$\not{p}_T^{||} \equiv \sum_{\text{tracks}} -p_{\text{T,track}} \cos\left(\phi_{\text{track}} - \phi_{\text{leading jet}}\right)$$