Results from PbPb Collisions Measured by the CMS Detector

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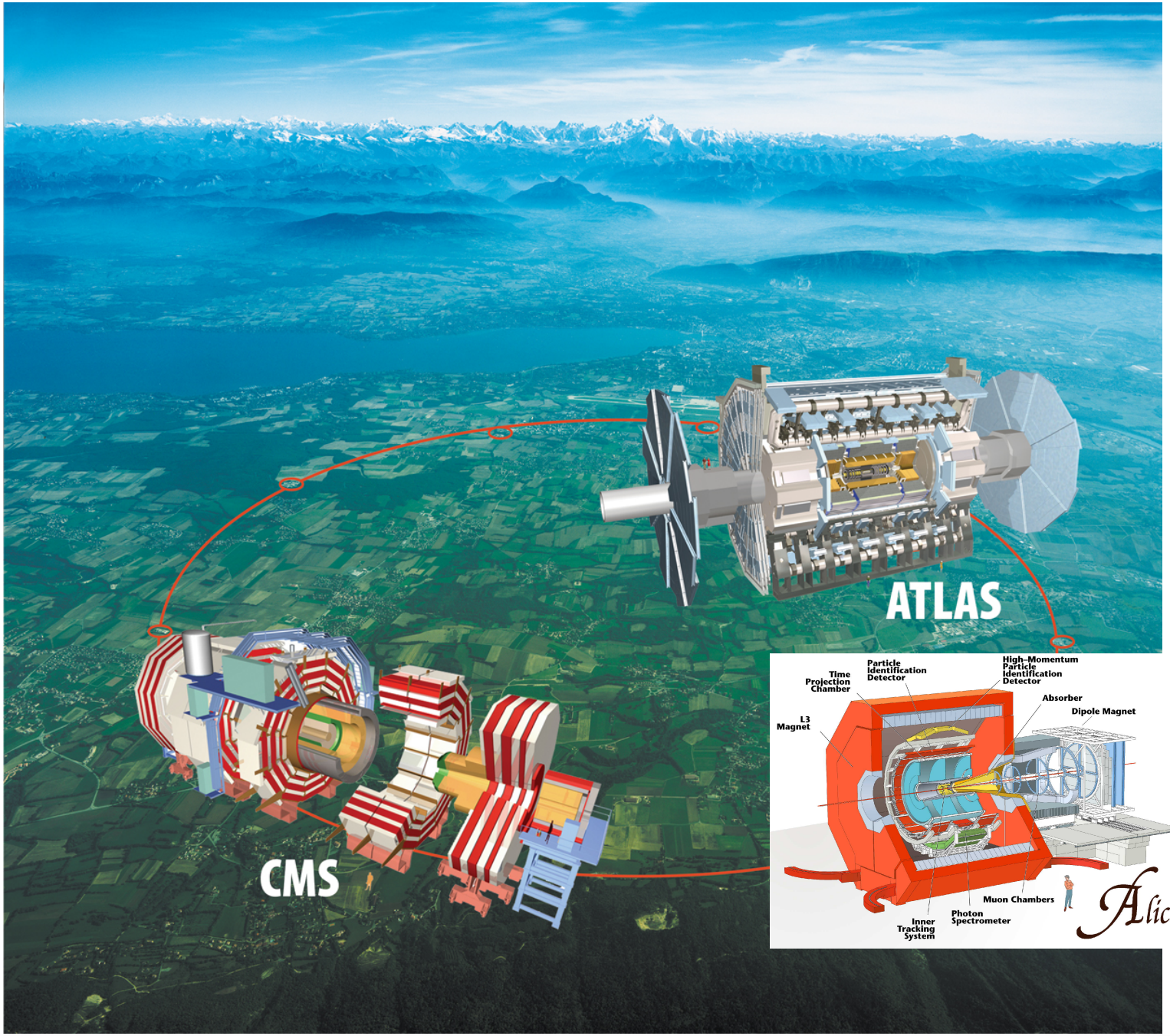
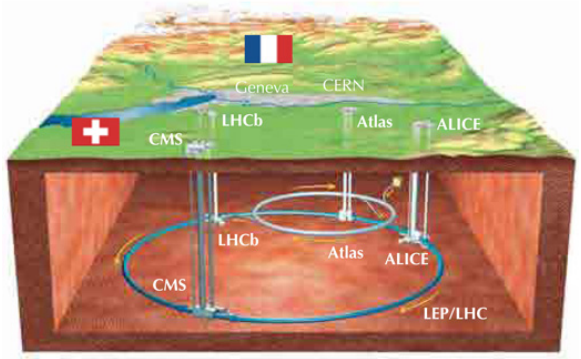
for the CMS Collaboration

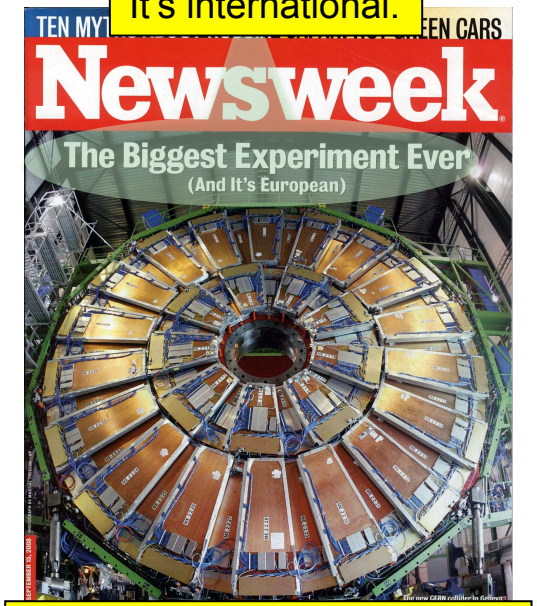
The Large Hadron Collider at CERN

The Heavy Ion Experiments at the LHC at CERN





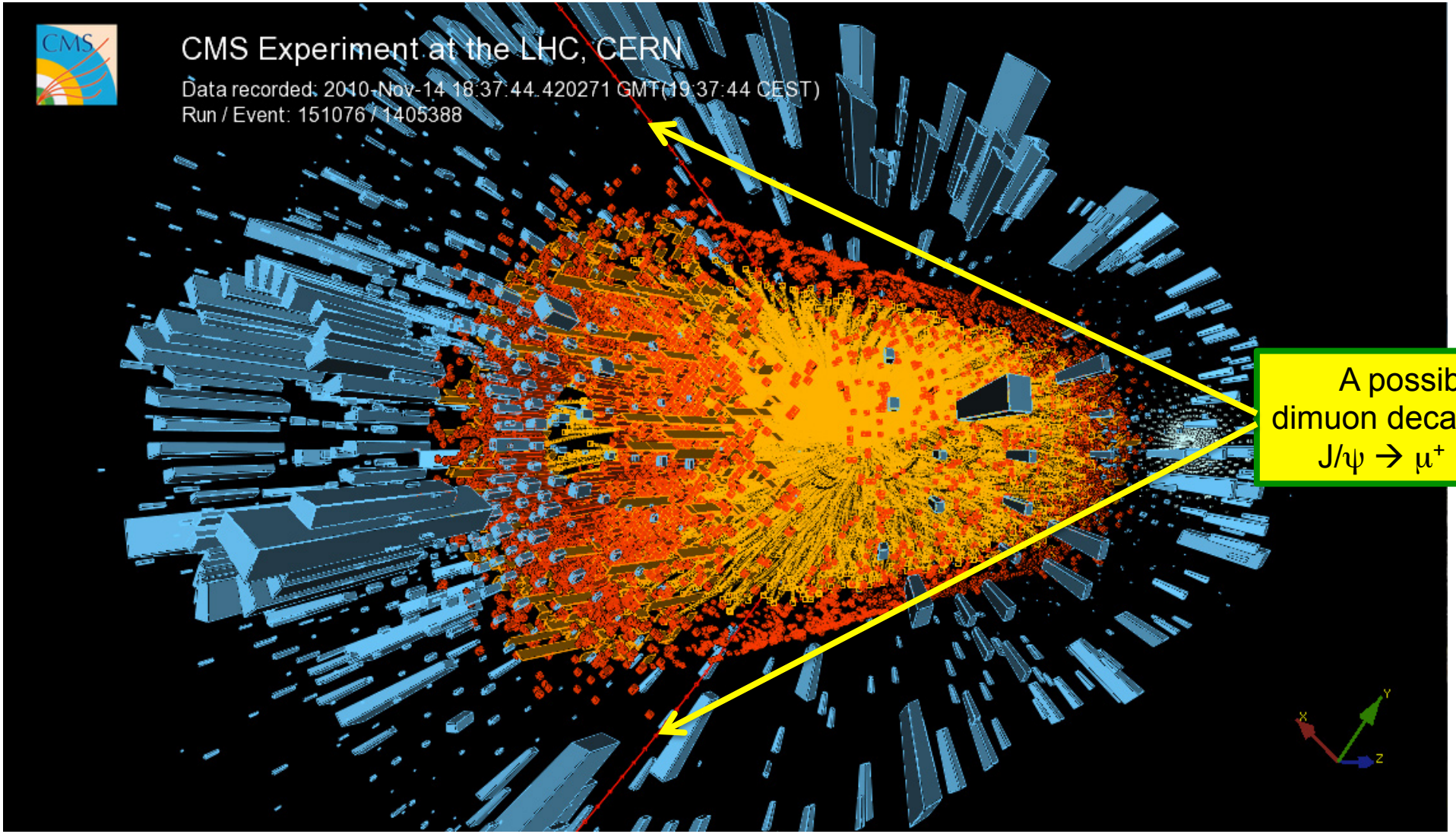
Yes. And no.
It's international.



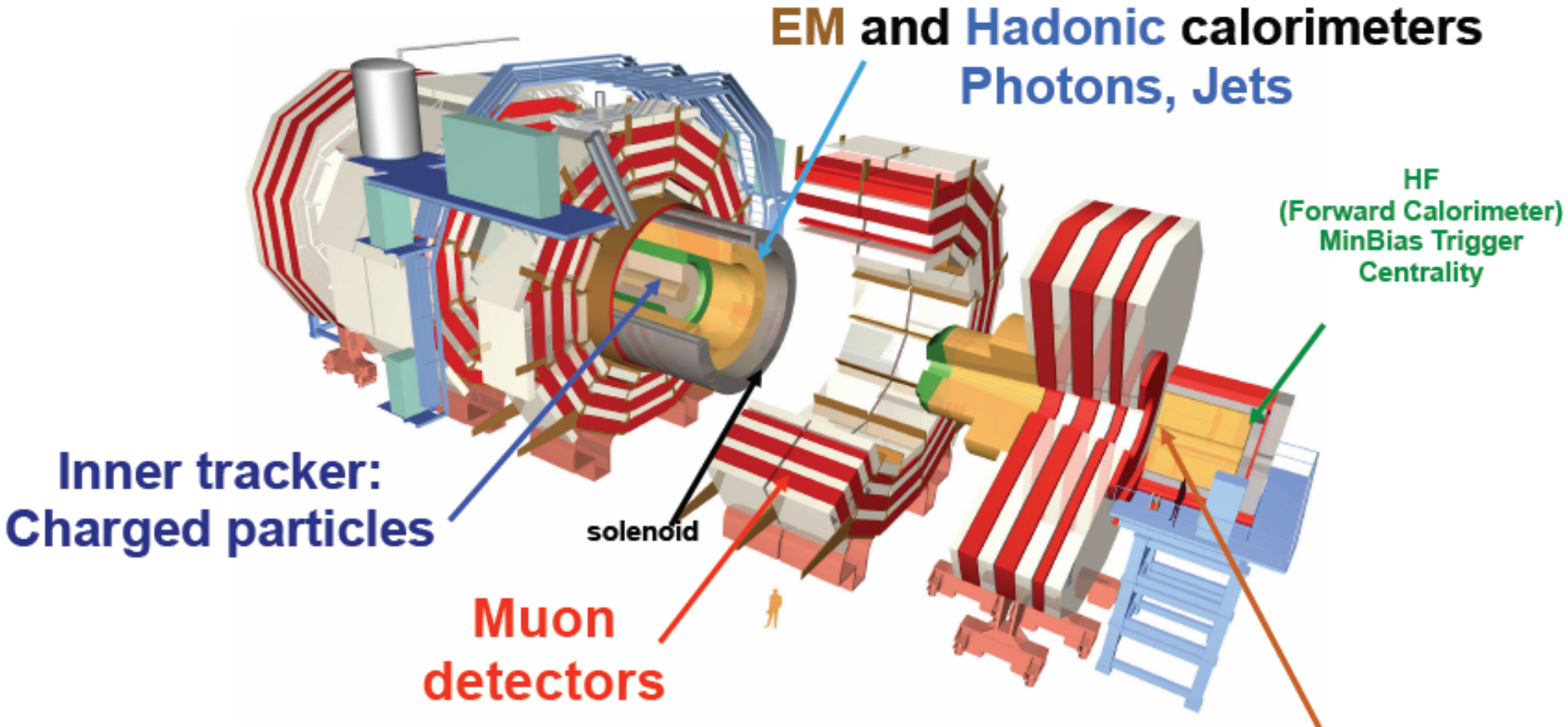
Cover story, Aug. 15, 2008

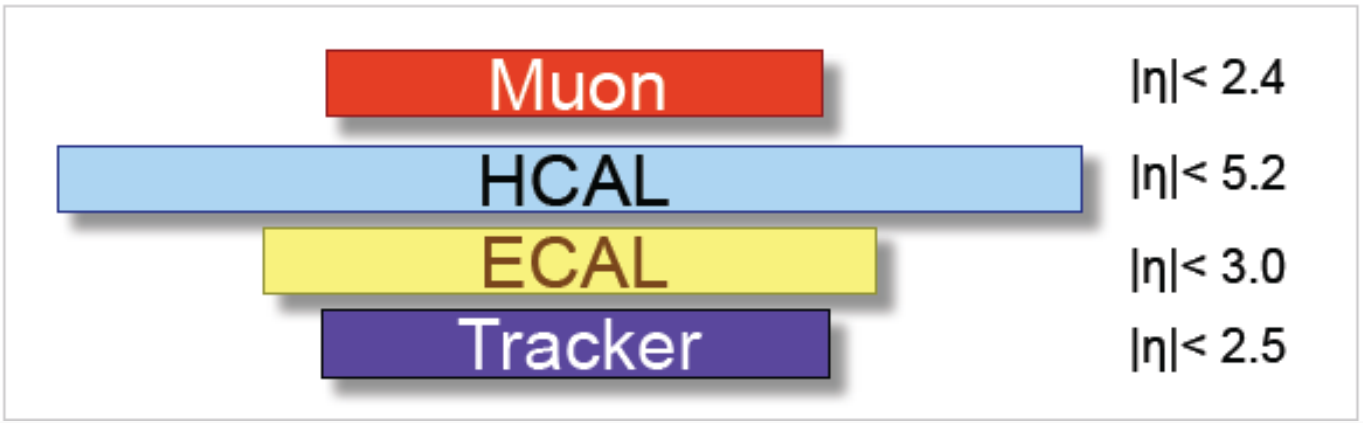
The First Day of HI Collisions by the LHC into CMS

Event Display Taken on November 14, 2010 at 6:37 PM (Geneva)
A central collision of Pb+Pb at 2.76 TeV/nucleon-pair lights up the CMS detector



The CMS Detector





The Goals (as at RHIC) and the Tools (RHIC++)

To produce QGP and characterize its properties

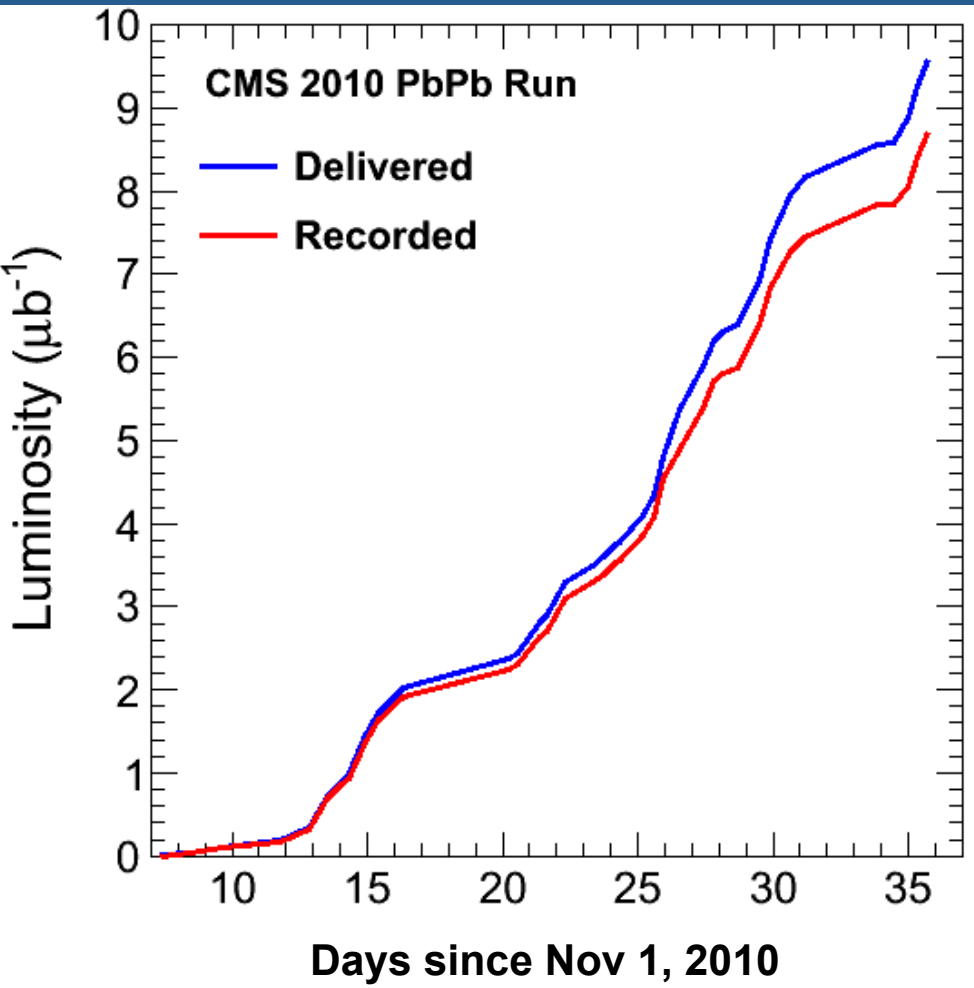
- Energy density and T: location on the phase diagram ?
  - $dN_{ch}/d\eta$, $dE_T/d\eta$, quarkonimum melting (J/ψ , Υ measurements)
- Viscosity, speed of sound: Transport of momentum and energy
  - collective flow and di-hadron correlations
- Opacity, diffusion: Transport of particles
  - Charged hadron R_{AA}
  - Di-jets
  - Heavy flavor

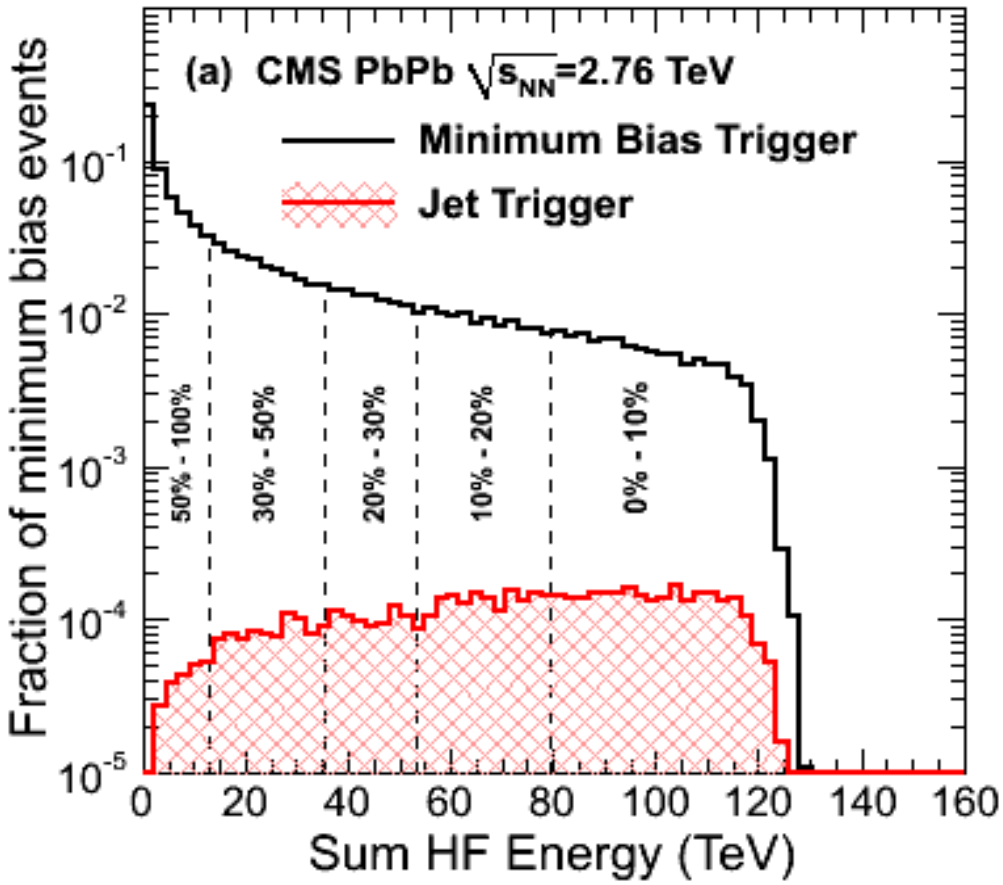
  } colored probes: *sensitive* to the strong interaction

  - Isolated photons R_{AA}
  - Z-boson R_{AA}

  } colorless probes: *insensitive* to the strong interaction
- Color screening

Data Taking During the PbPb Run





Recorded luminosity PbPb 8.7 μb^{-1}

Recorded luminosity pp@2.76 TeV 241 nb^{-1}

Total PbPb data volume ~0.89 PetaByte

RHIC runs HI for months, LHC runs HI for weeks

Triggering on minimum bias, jets, muons and photons

- ALL rare probes written to tape
- ~half of minimum bias written

Note: luminosities will be rescaled by few% after complete analysis of Van der Meer scans

The CMS Results from the First PbPb Run (3 weeks of data!)

13 CMS HI papers from LHC PbPb run 2010

* HIN-10-001: Multiplicity	→ arXiv1107.4800, JHEP, accepted
* HIN-10-002: Elliptic flow	→ PAS (CDS record 1347788)
* HIN-10-003: Z bosons	→ PRL 106 (2011) 212301
* HIN-10-004: Dijets	→ PRC 84 (2011) 024906
* HIN-10-005: Charged spectra	→ PAS (CDS record 1352777)
* HIN-10-006: Quarkonia	→ PAS (CDS record 1353586)
* HIN-11-001: Correlations ("ridge")	→ JHEP 1107 (2011) 076
* HIN-11-002: Photons	→ PAS (CDS record 1352779)
* HIN-11-003: Energy flow	→ PAS (CDS record 1354215)
* HIN-11-004: Fragmentation functions	→ PAS (CDS record 1354531)
* HIN-11-005: Flow (higher harmonics)	→ PAS (CDS record 1361385)
* HIN-11-006: "Ridge" vs. centrality	→ PAS (CDS record 1353583)
* HIN-11-007: Upsilon	→ PRL 107 (2011) 052302

+ a couple more not yet preliminary results

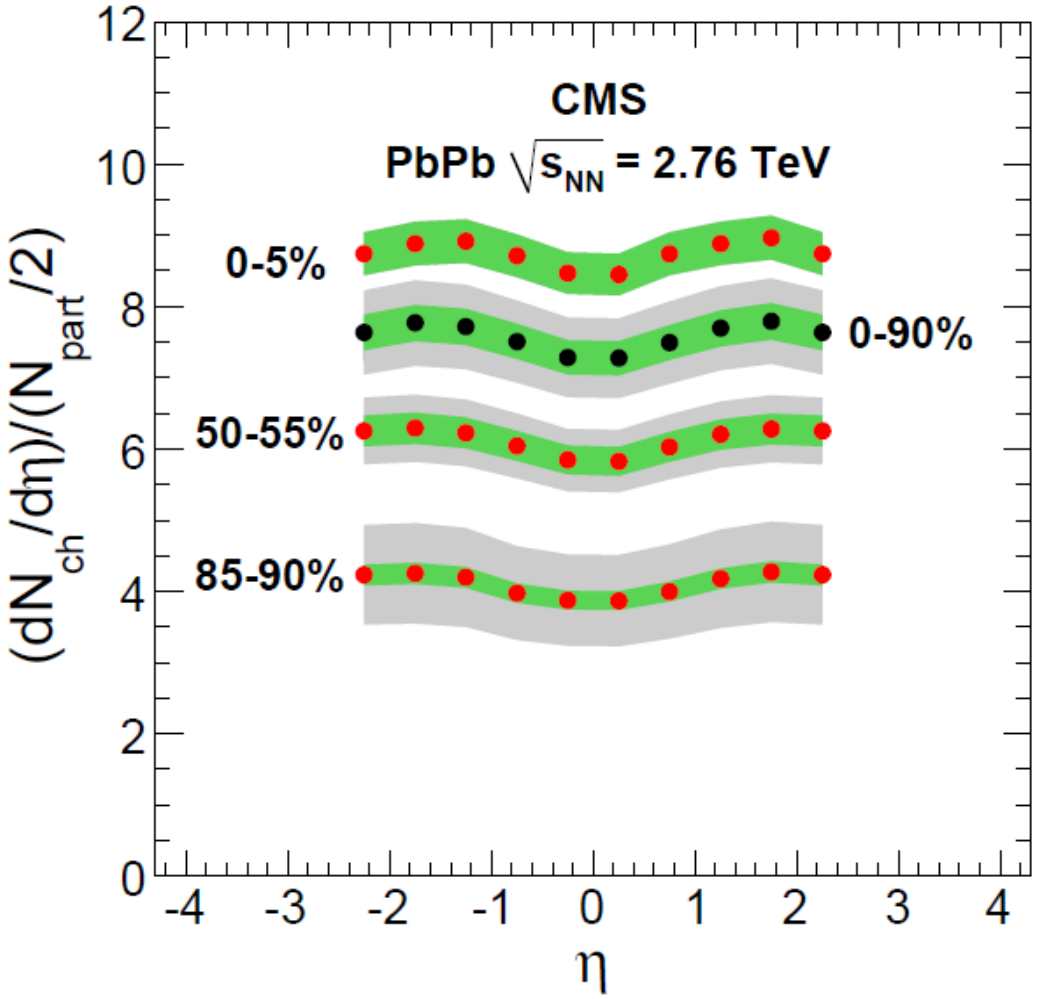
PAS: Physics Analysis Summary
CDS: CERN Document Server

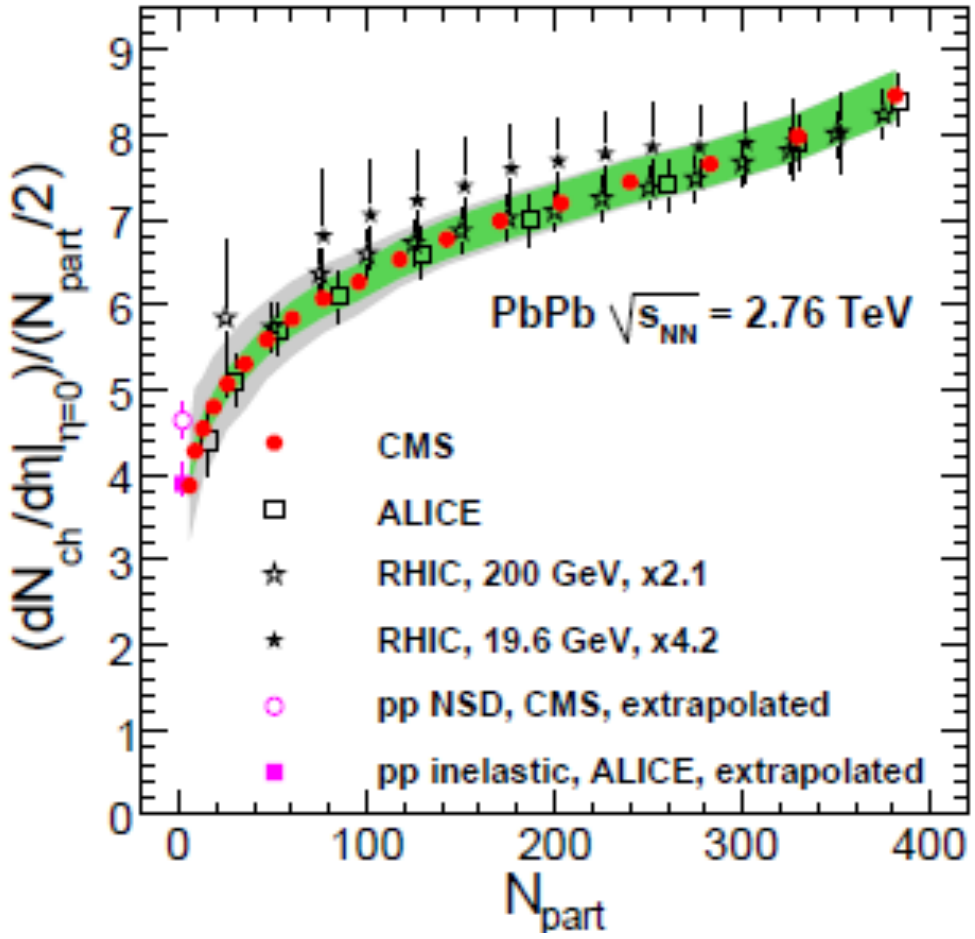
GLOBAL OBSERVABLES

Charged Particle Multiplicity

- Uses pixel tracker and two methods
- Data : B=0T ; Trigger with 99% efficiency, 1% UPC contamination

arXiv1107.4800, accepted JHEP

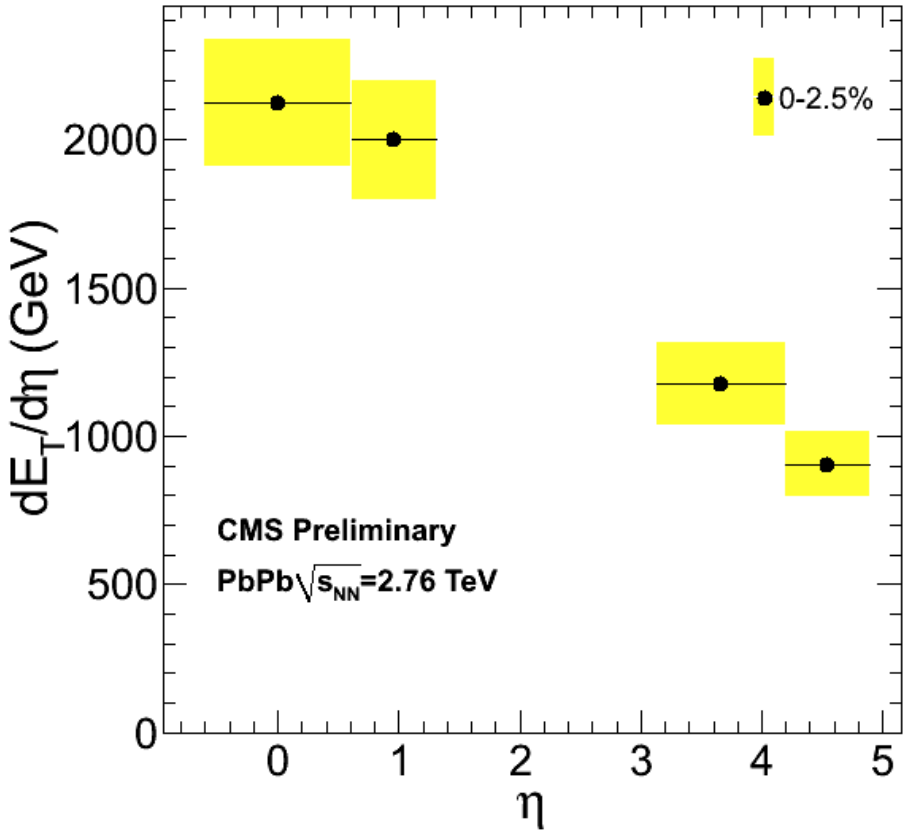


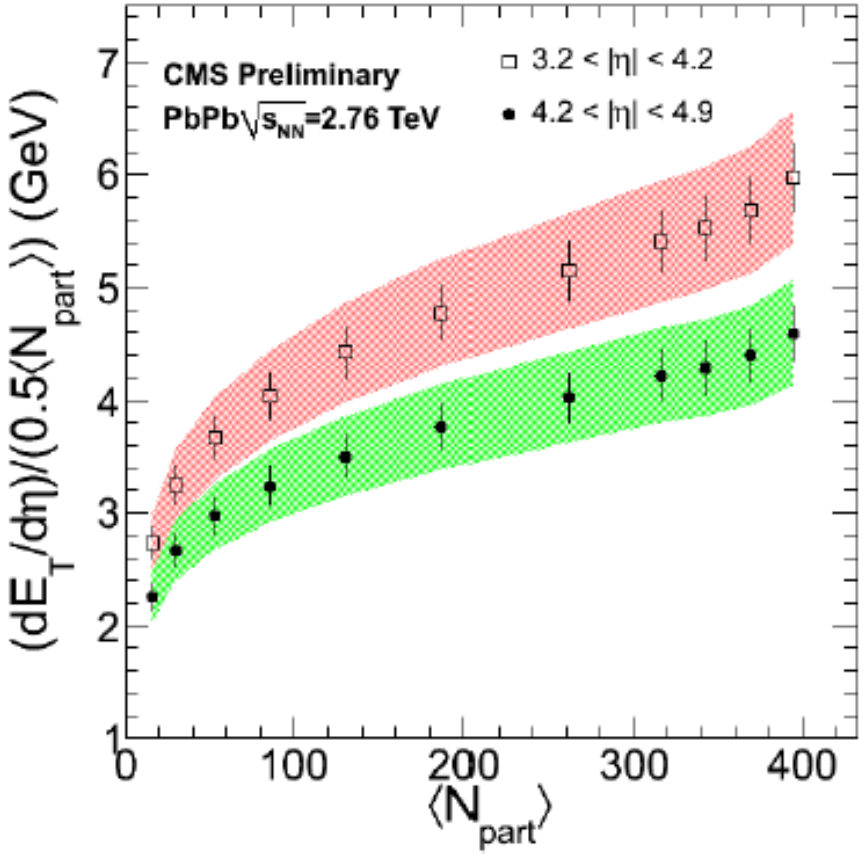


- Central multiplicity $dN_{ch}/d\eta$=1610 ± 55 for 0-5% centrality
- $dN_{ch}/d\eta/ (0.5\ N_{part})$ a factor 2.1 > RHIC ; similar centrality dependence

$dE_T/d\eta$: Rapidity and Centrality Dependence

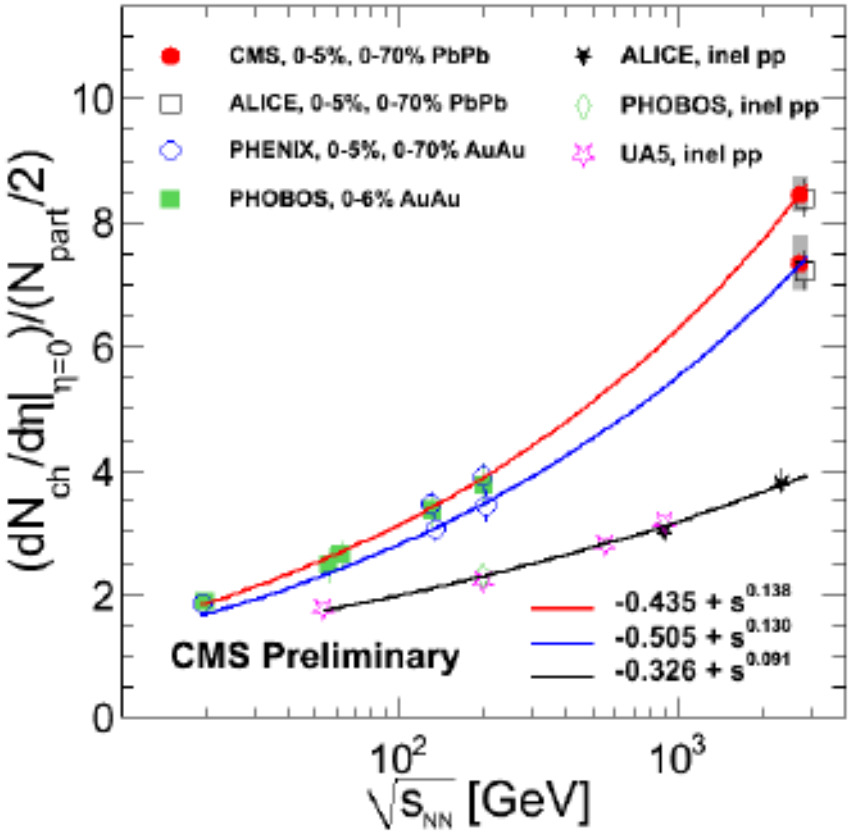
- $dE_T/d\eta$ ($\eta = 0$) ≈ 2 TeV - by a factor of 3.4±0.4 higher than RHIC
- $dE_T/d\eta/ (0.5\ N_{part})$: Monotonic increase with N_{part}

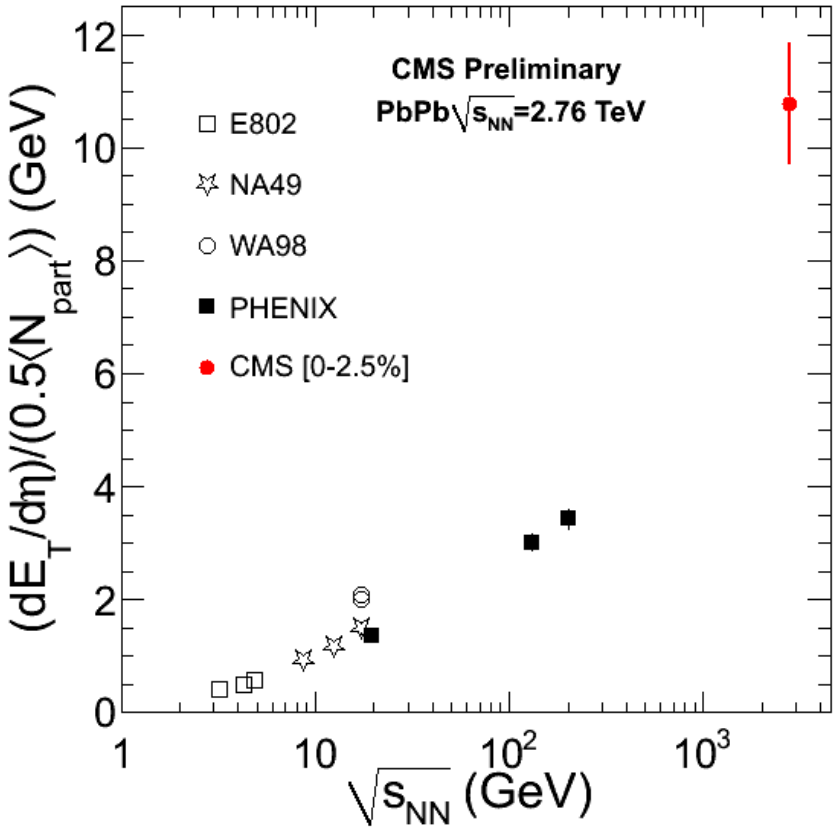




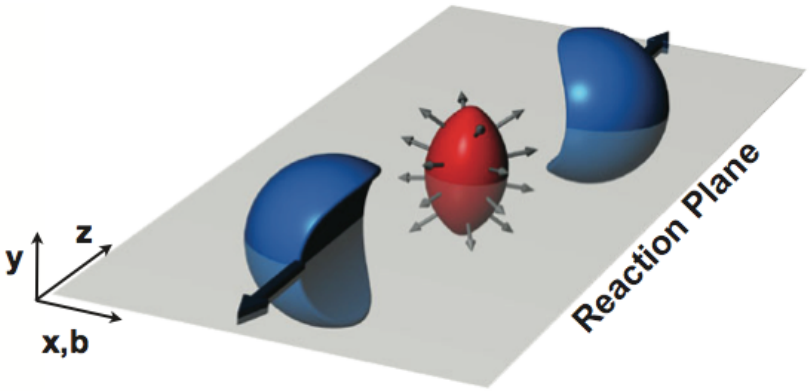
$dN_{ch}/d\eta$ and $dE_T/d\eta$: $\sqrt{s_{NN}}$ Dependence

- $dN_{ch}/d\eta/\ (0.5\ N_{part})$ and $dE_T/d\eta/\ (0.5\ N_{part})$ – power law increase with $\sqrt{s_{NN}}$
- $dE_T/d\eta/\ (0.5\ N_{part})$ rises faster => More energy per particle than at RHIC





Anisotropic Flow in HI Collisions



$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{\mathrm{RP}})]\right)$$

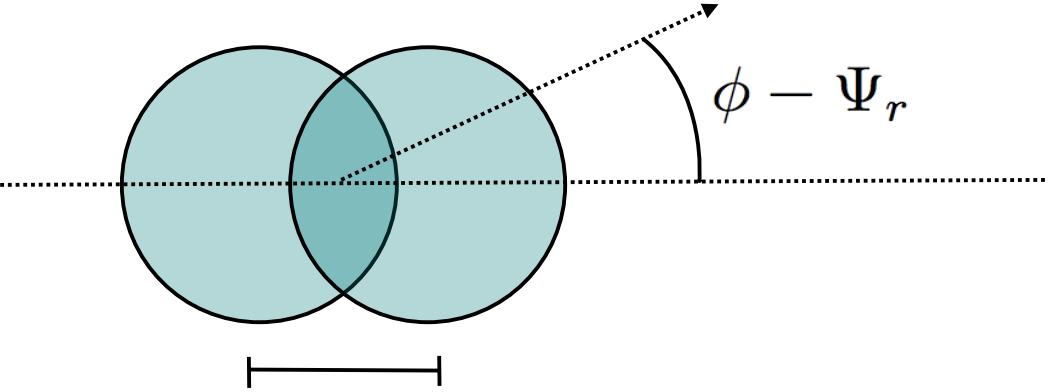
$$v_n = \left\langle \cos[n(\varphi - \Psi_{\mathrm{RP}})] \right\rangle$$

anisotropic flow coefficients

- v_2 has been extensively studied, and to a lesser extent v_4 and v_6
- v_3 and v_5 were surprisingly found to be non-negligible
- An understanding of all the harmonics will provide new insights on the properties of the quark-gluon-plasma “near-perfect” liquid
- CMS has measured v_n , with n = 2 - 6, in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV using two-particle and multi-particle techniques
- Non-flow effects such as resonance decays and jets will complicate the hydrodynamic analysis of the particle correlations

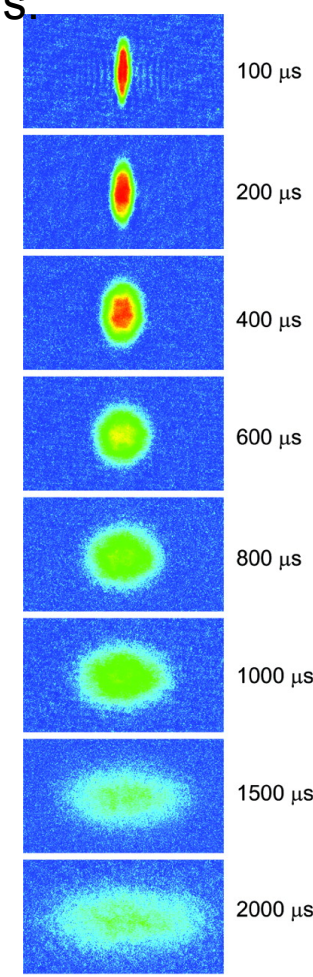
A Closer Look at Anisotropic Flow

Schematic of a heavy ion collision:



Analogous system: A strongly-interacting degenerate fermi-gas of atoms.

Initial State Position Anisotropy



Final State Momentum Anisotropy

K. M. O'Hara et.al, *Science*, **298**, 2179 (2002)

Fourier decompose the azimuthal angle of the particle emission spectrum with respect to the reaction plane:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_r)))$$

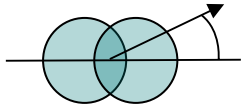
$$v_n = \langle \cos(n(\phi - \Psi_r)) \rangle$$

Second Fourier coefficient n=2 quantifies the particle emission "in-plane" versus "out-of plane"

Measuring the v_2 coefficient can constrain hydrodynamic and transport properties of the hot and dense medium produced in the collision.

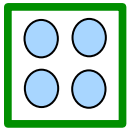
Four Methods Used for Extracting v_2 Signal

Event Plane



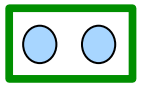
- based on particle correlations with the event plane
- gives an estimate of the reaction plane
- requires corrections for the detector acceptance

4th Order Cumulant



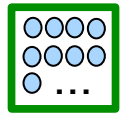
- based on 4-particle correlations
- removes lower order non-flow effects

2nd Order Cumulant



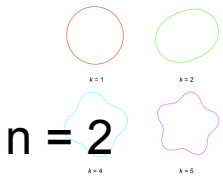
- based on 2-particle correlations

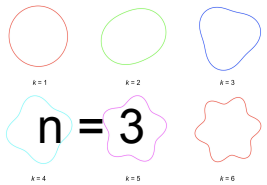
Lee-Yang Zeros

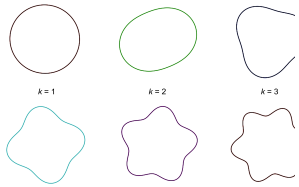


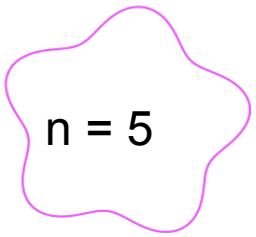
- based on all particle correlations in each event
- removes non-flow effects

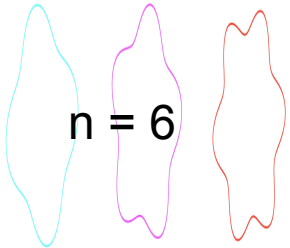
Higher order harmonics up to v_6 were measured using select methods:



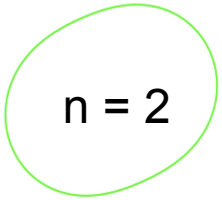


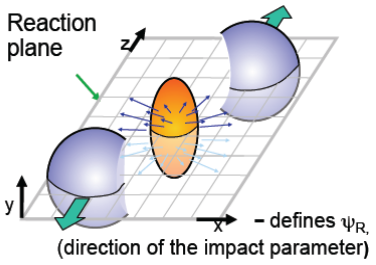


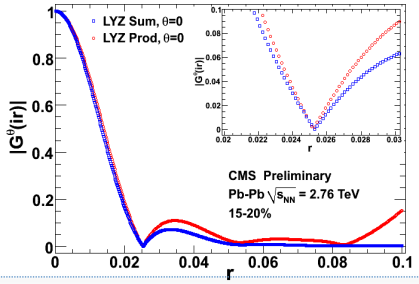


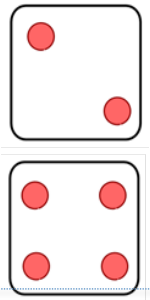


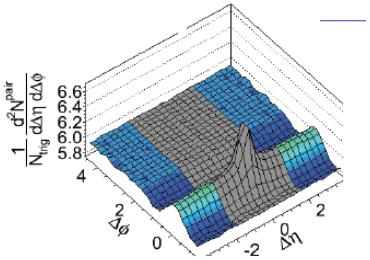
v_n Measurements from CMS

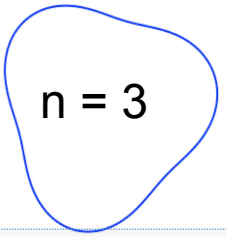


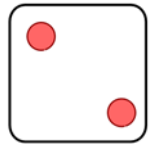


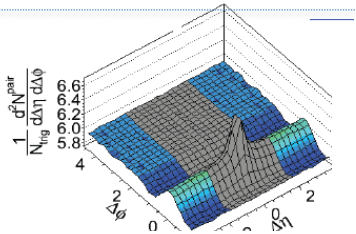


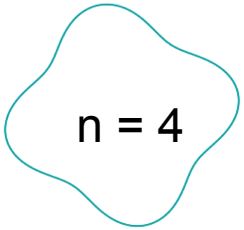


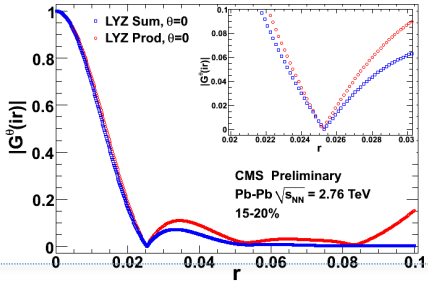


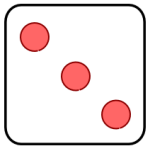


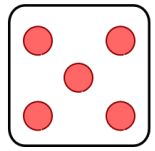


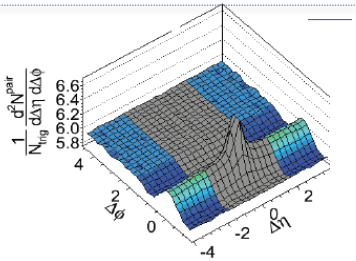


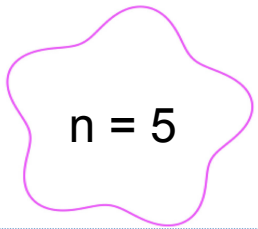


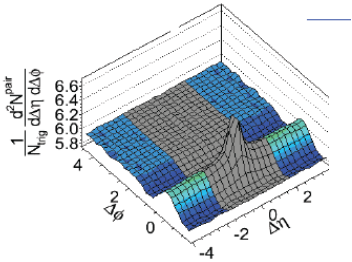


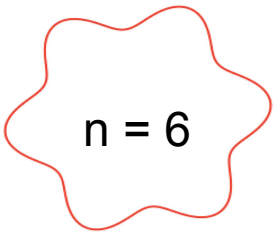


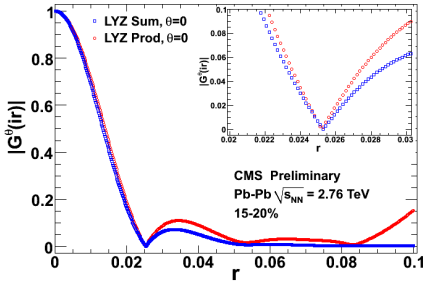




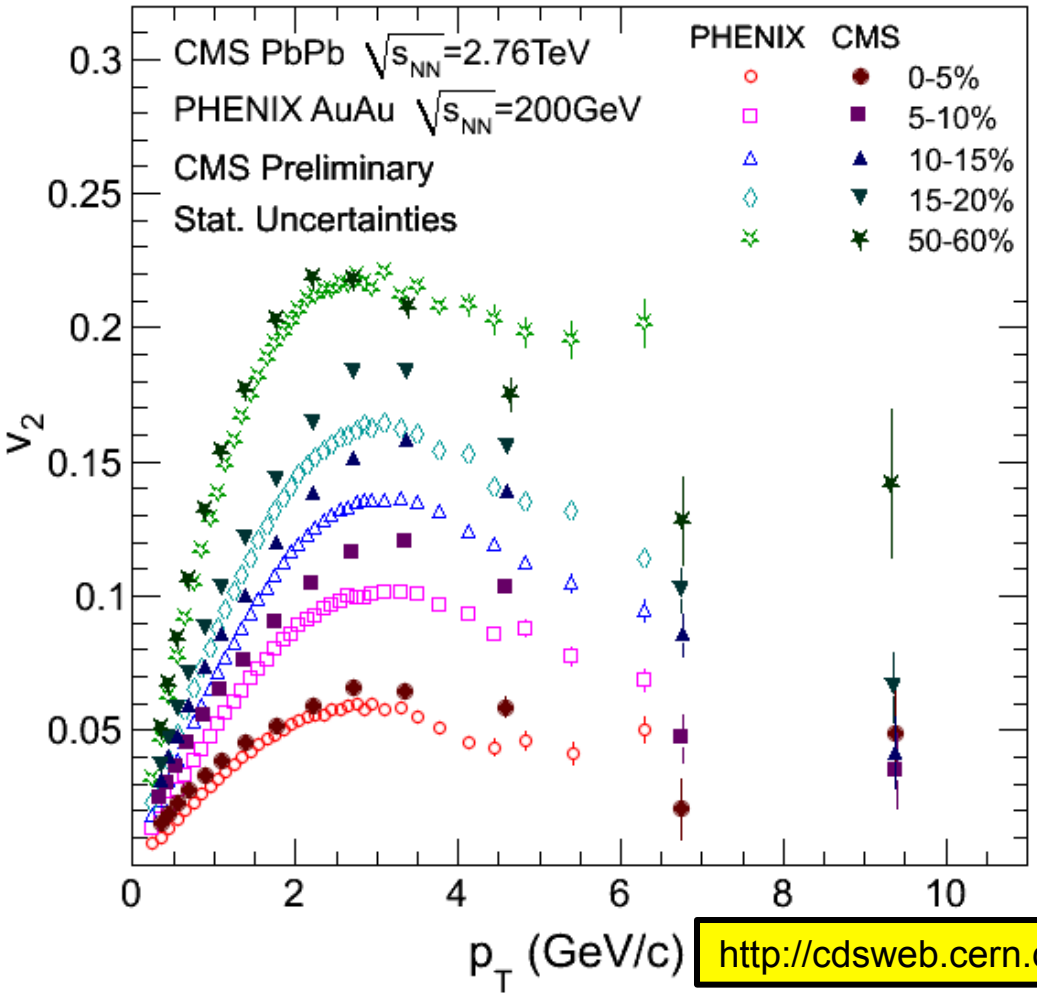


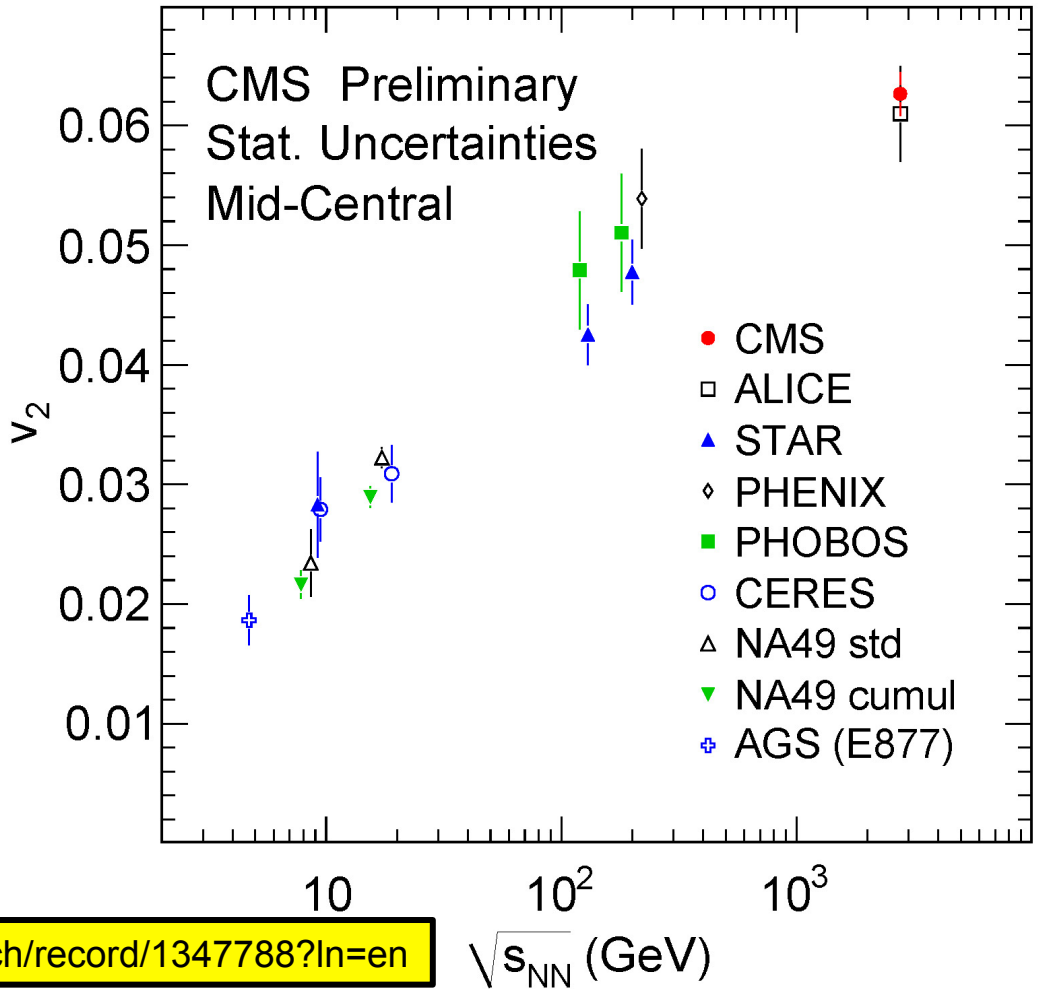






Elliptic flow at Mid-Rapidity: LHC and RHIC





http://cdsweb.cern.ch/record/1347788?ln=en

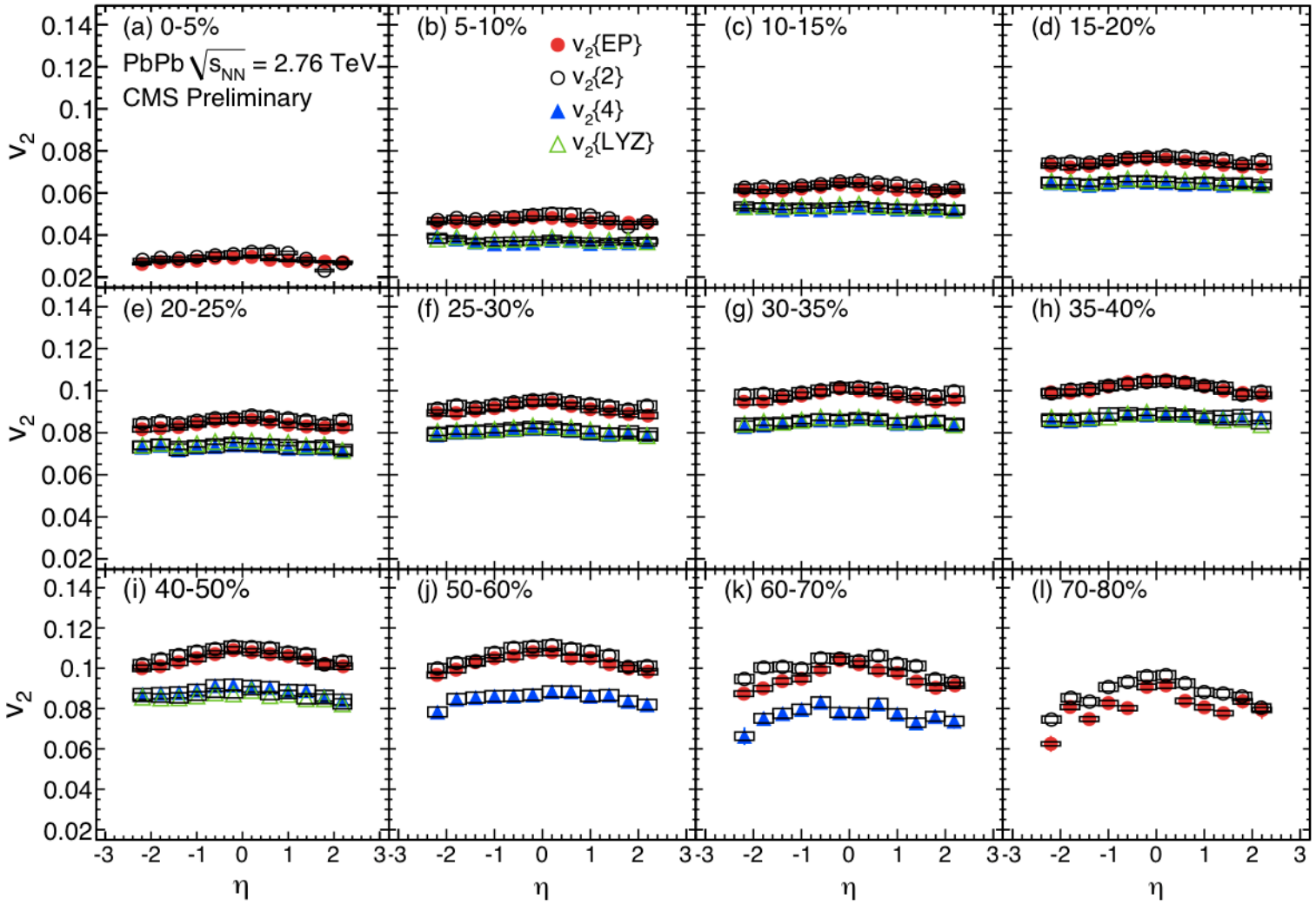
Similar p_T dependence

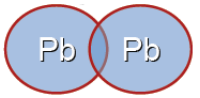
- CMS: EP , $\Delta\eta > 1$
- PHENIX: EP

15-30% increase in integral v_2

- CMS: 20-30%, v_2{LYZ}
- Extrapolated to p_T=0

$v_2(\eta)$: Centrality Dependence

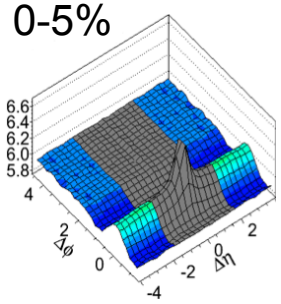


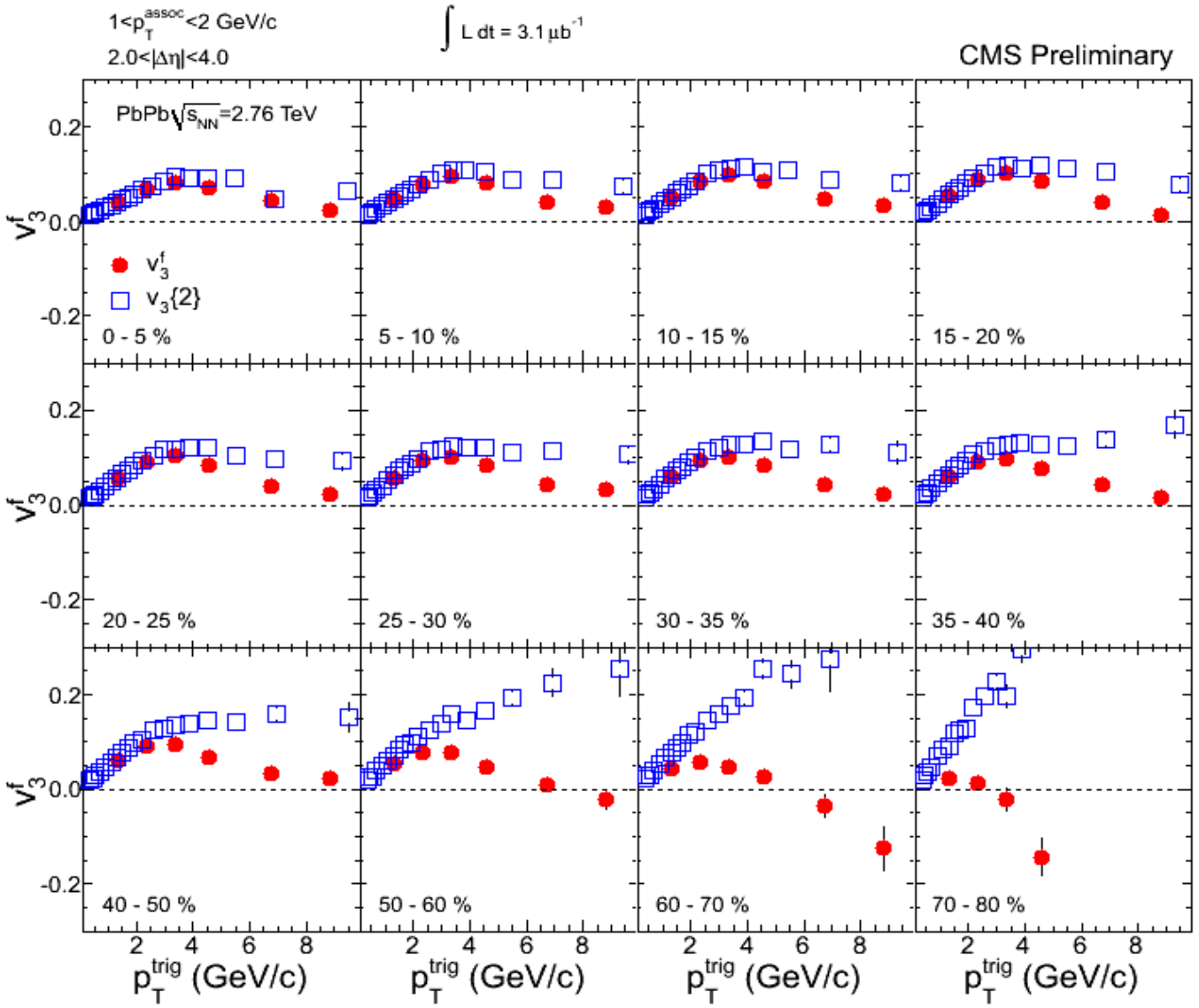


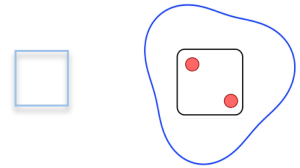
- Multiple methods – give a handle on non-flow and fuctuations
- Weak η- dependence, except for most peripheral (EP and v2{2})
- may constrain descriptions of the longitudinal dynamics

v_3 (p_T): Comparison of Methods

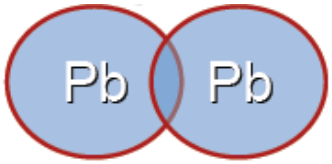
0-5%



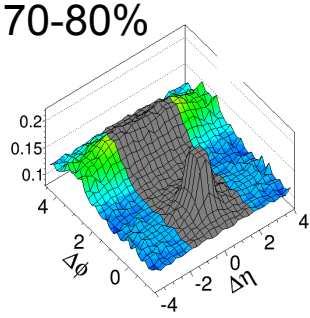




v_3^f

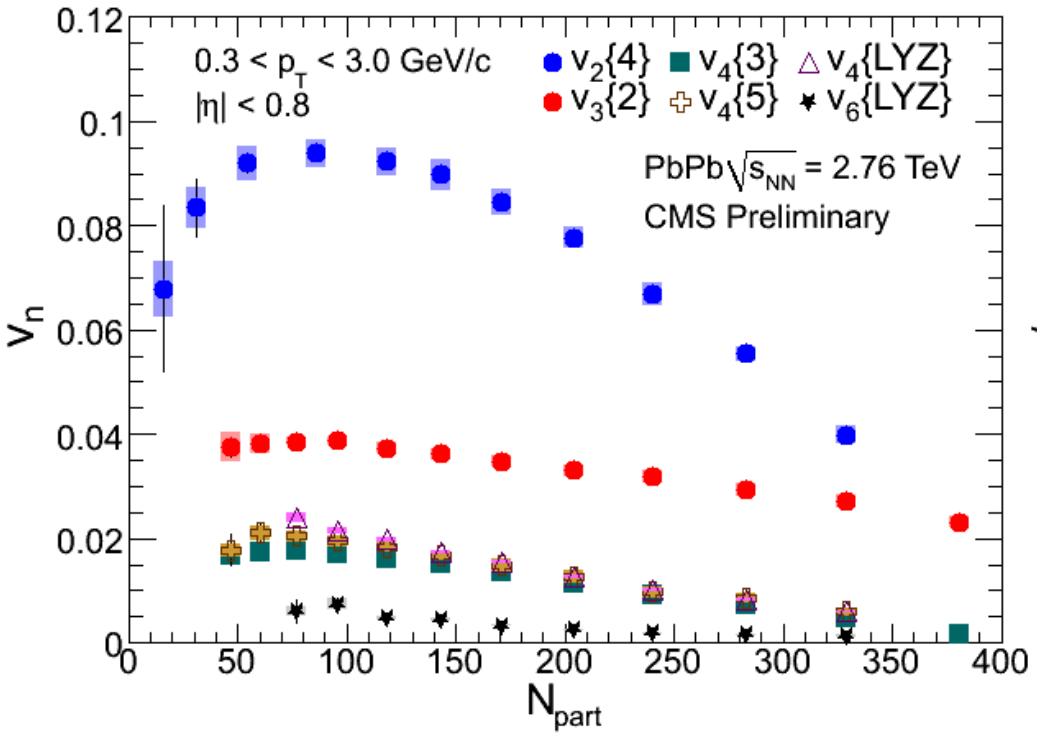


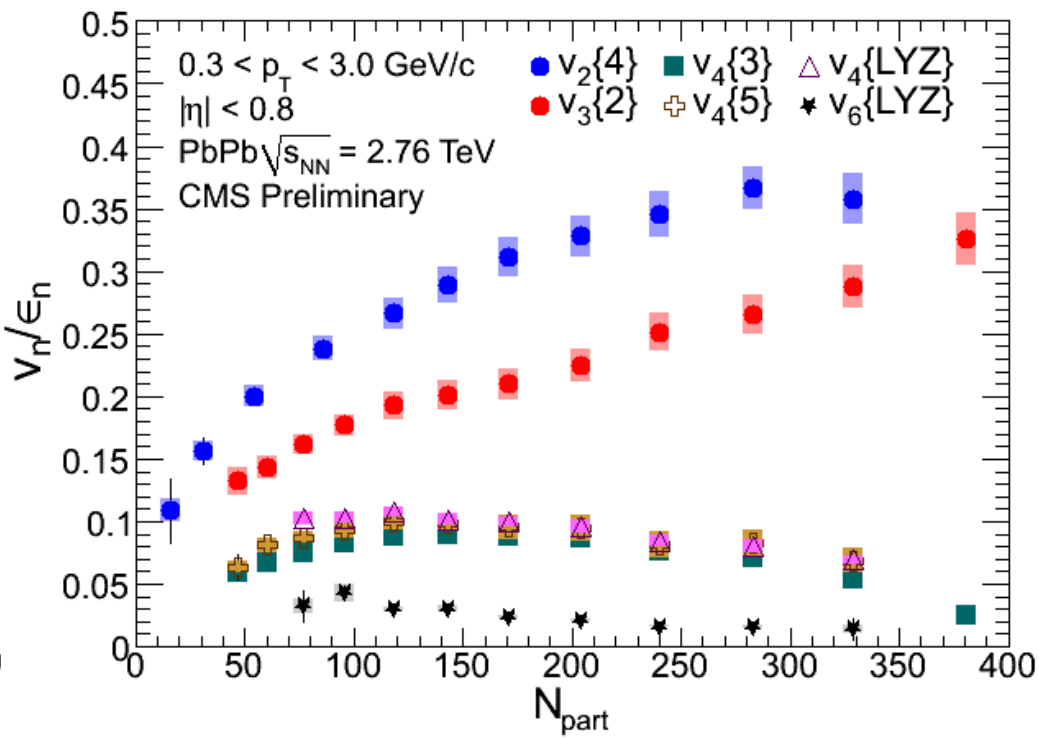
70-80%



- $v_3\{2\}$ and v_3^f comparable at low trigger p_T
- Non-flow dominate $v_3\{2\}$ at high p_T and in peripheral collisions

The Full Harmonic Spectrum



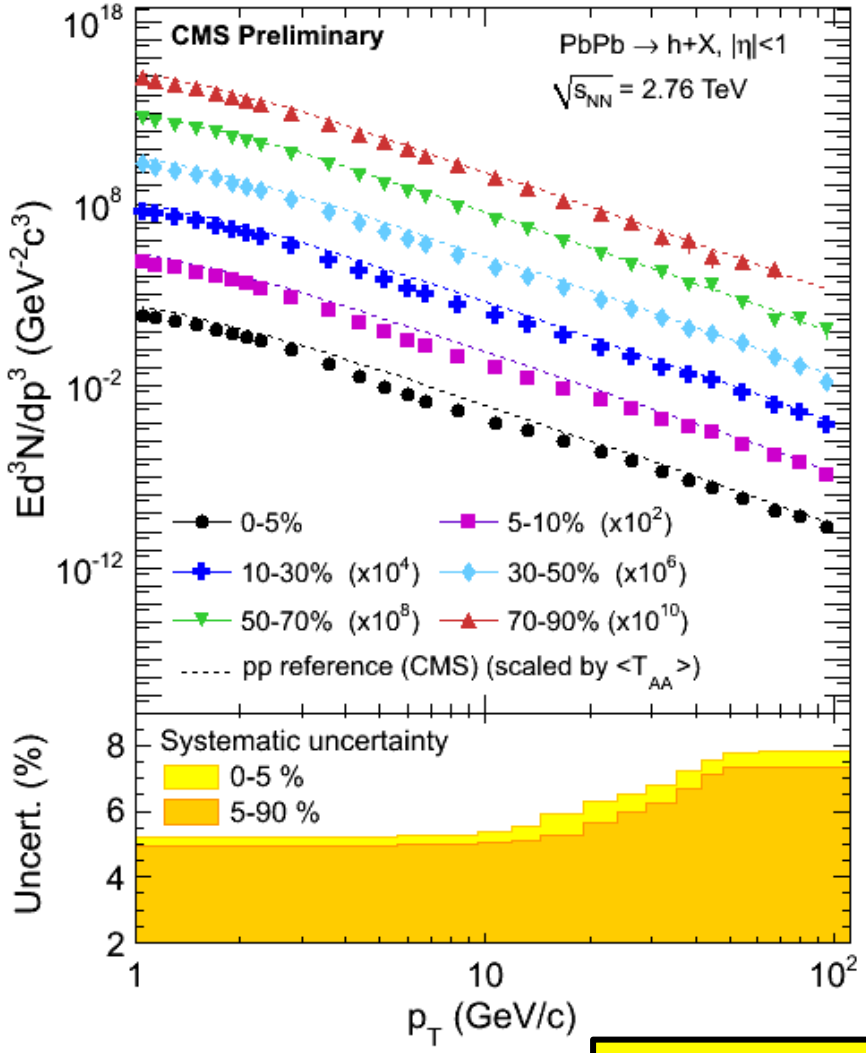


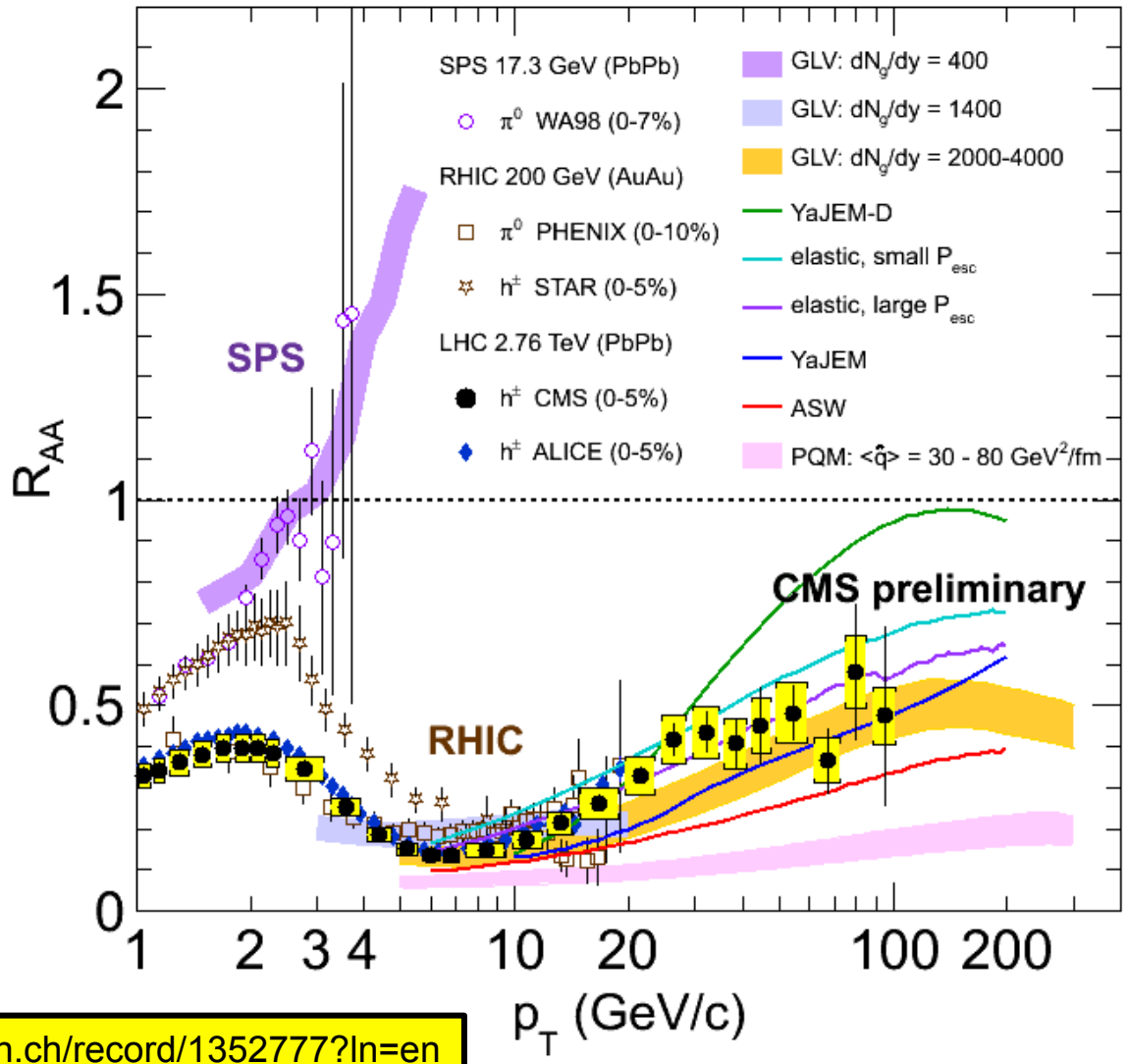
- v_n vs N_{part} shows different trends:
  - even harmonics have similar centrality dependence:
    - decreasing → 0 with increasing N_{part}
  - v_3 has weak centrality dependence, finite for central collisions

HARD PROBES

High p_T Charged Hadrons: Spectra and R_{AA}

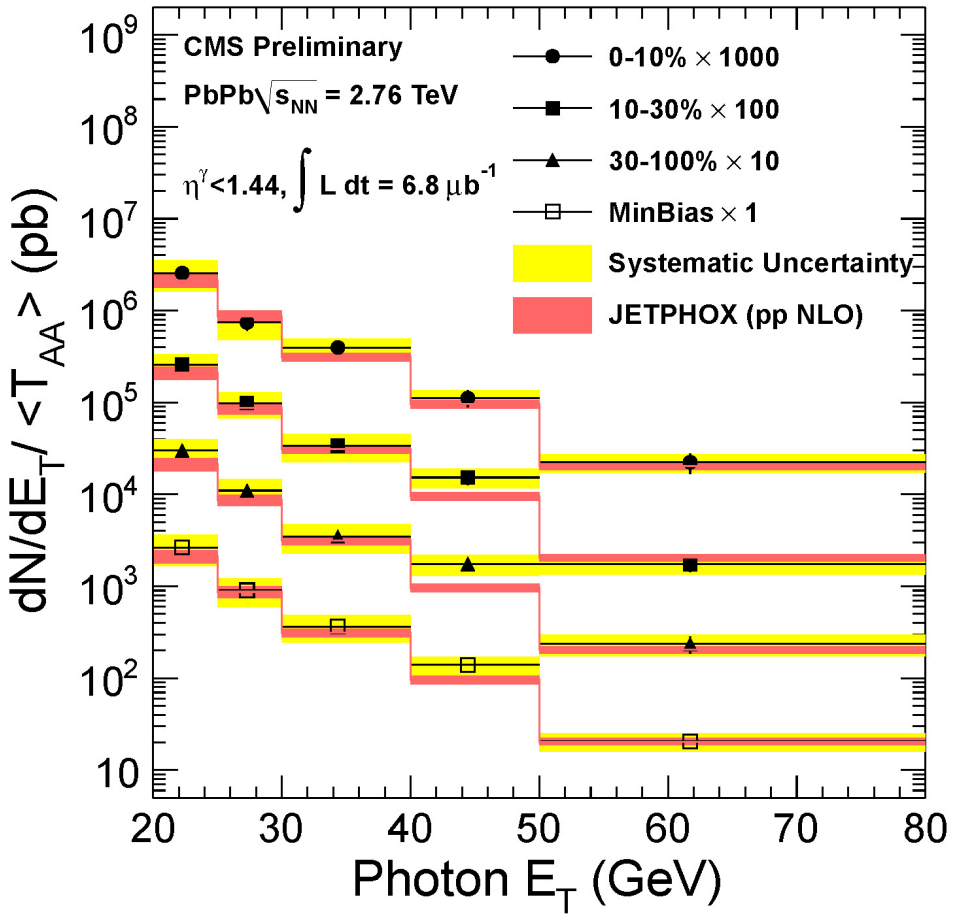
- Measuring charged tracks up to p_T~100 GeV/c (jet triggers)
- Strong constraints to energy loss models

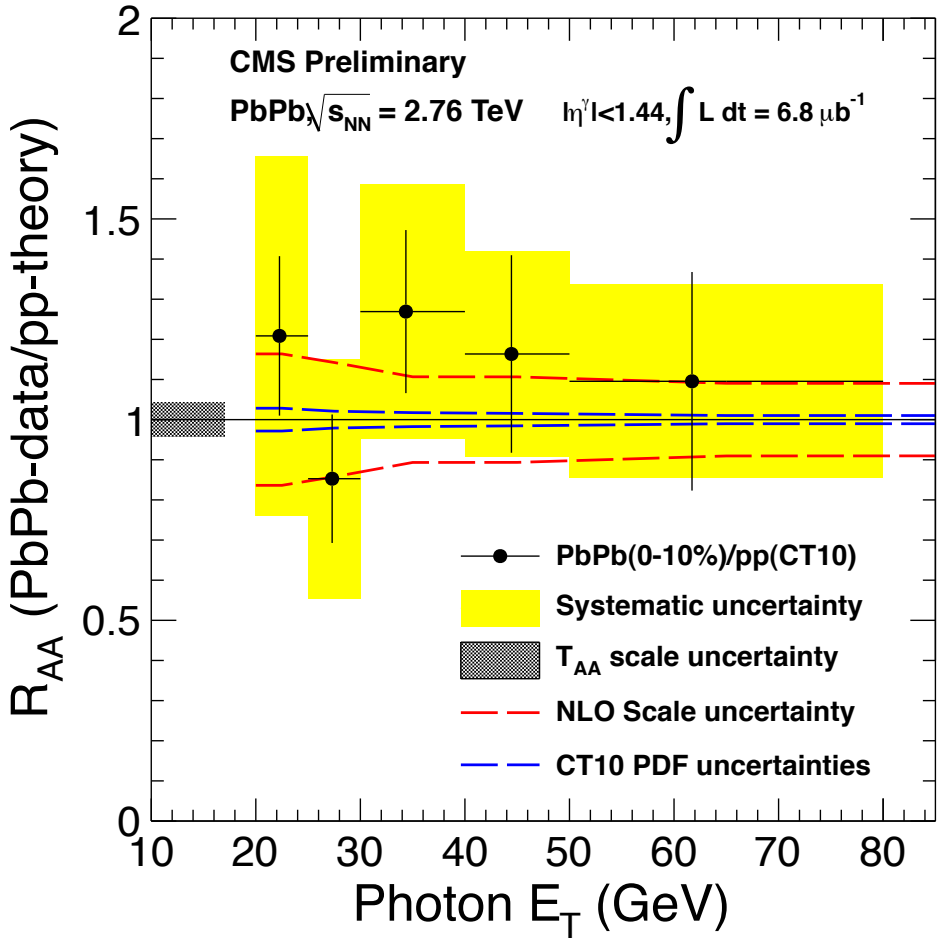




http://cdsweb.cern.ch/record/1352777?ln=en

A Colorless Probe: Isolated High p_T Photons



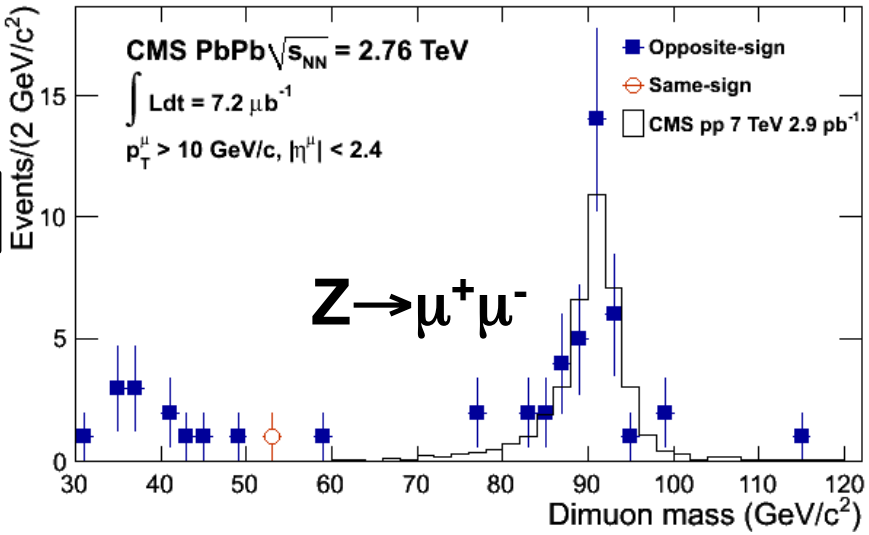


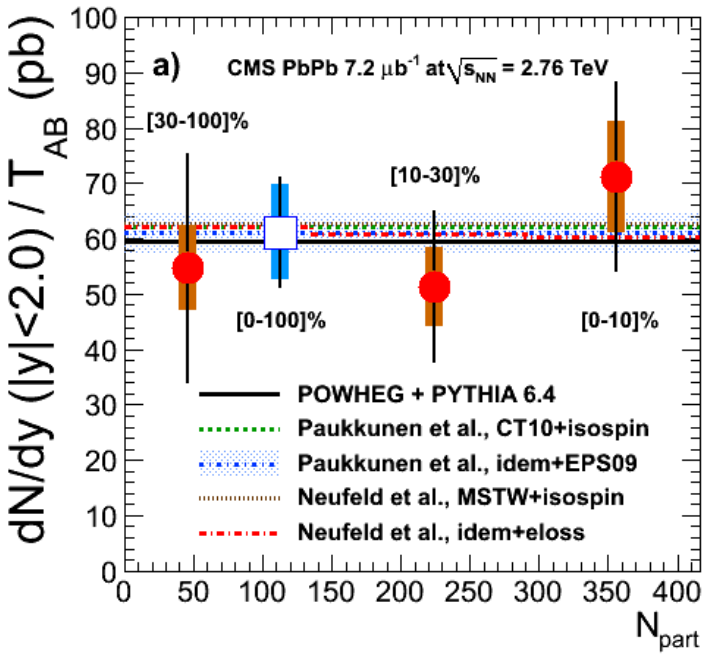
As expected: no nuclear modifications seen

http://cdsweb.cern.ch/record/1352779?ln=en

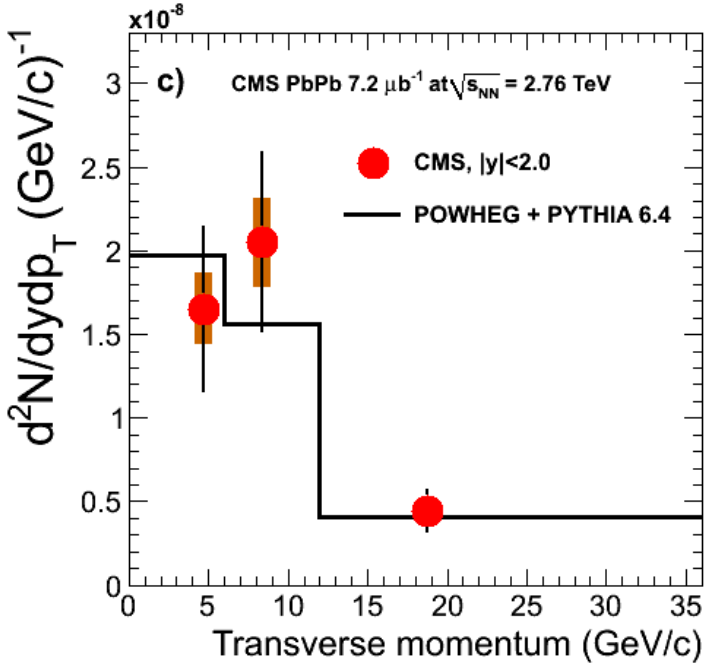
A New Colorless Probe for the QGP: Z Bosons

PRL106 (2011) 212301





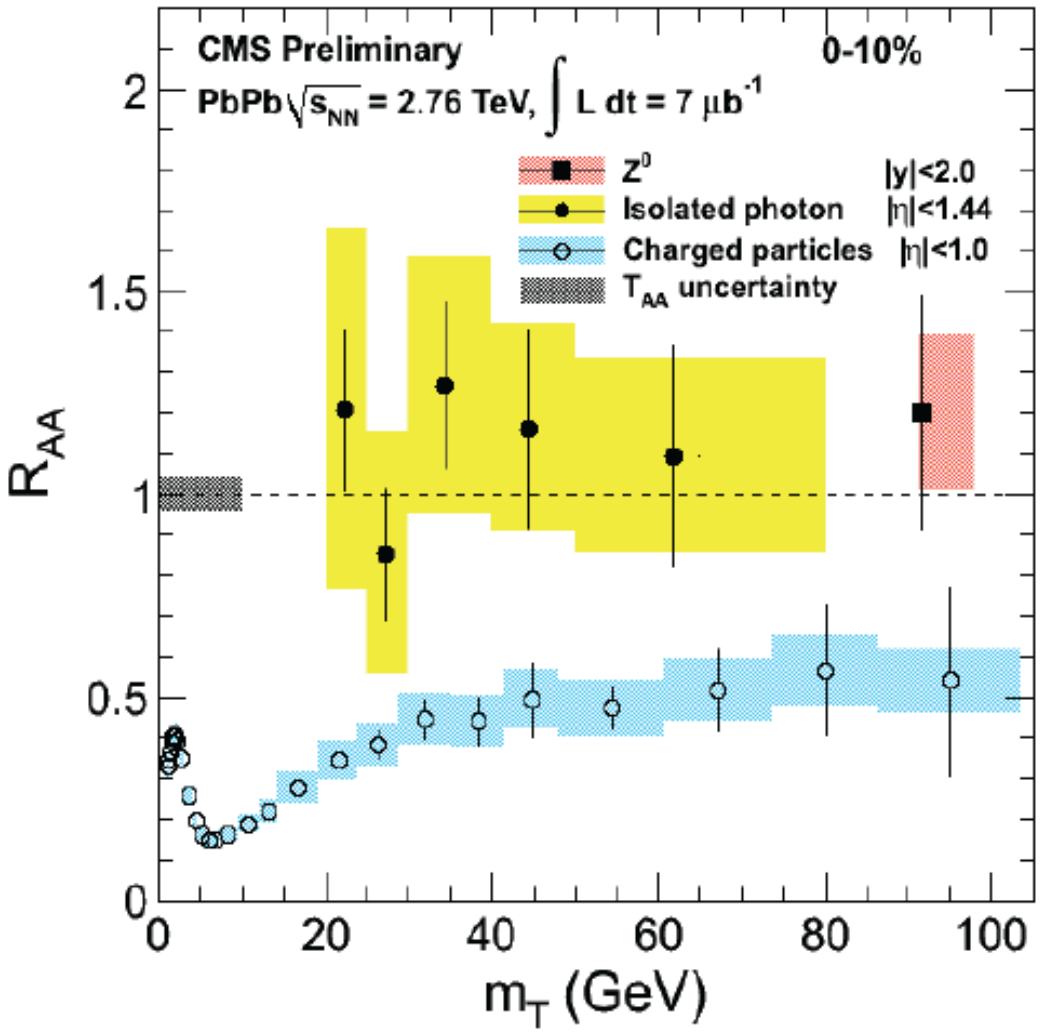
No significant dependence on centrality



p_T dependence consistent with pp

arXiv:1102.5435

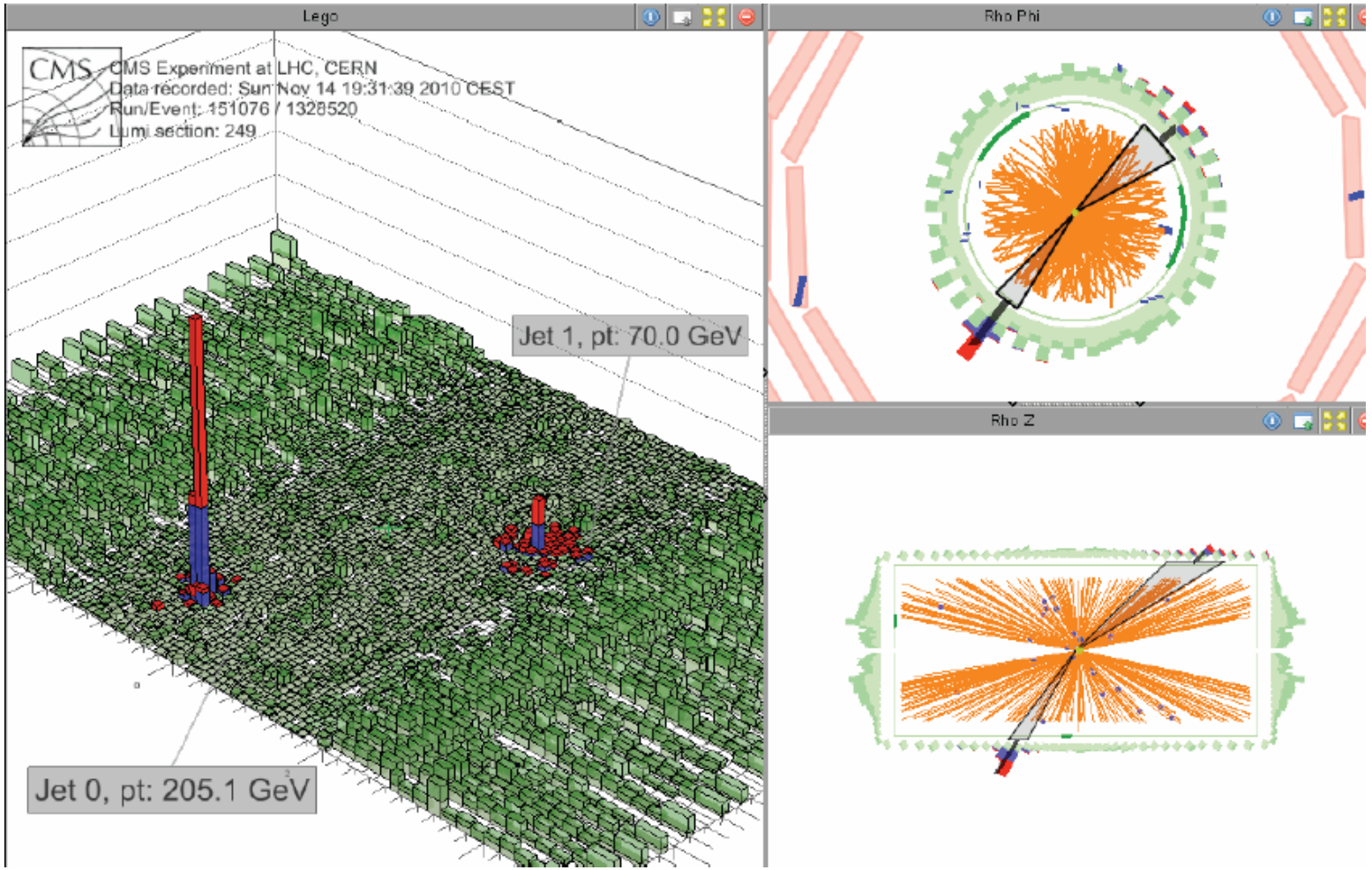
R_{AA} Summary



QGP is transparent to photons and Z^0s

QGP is opaque to charged hadrons (jets?)

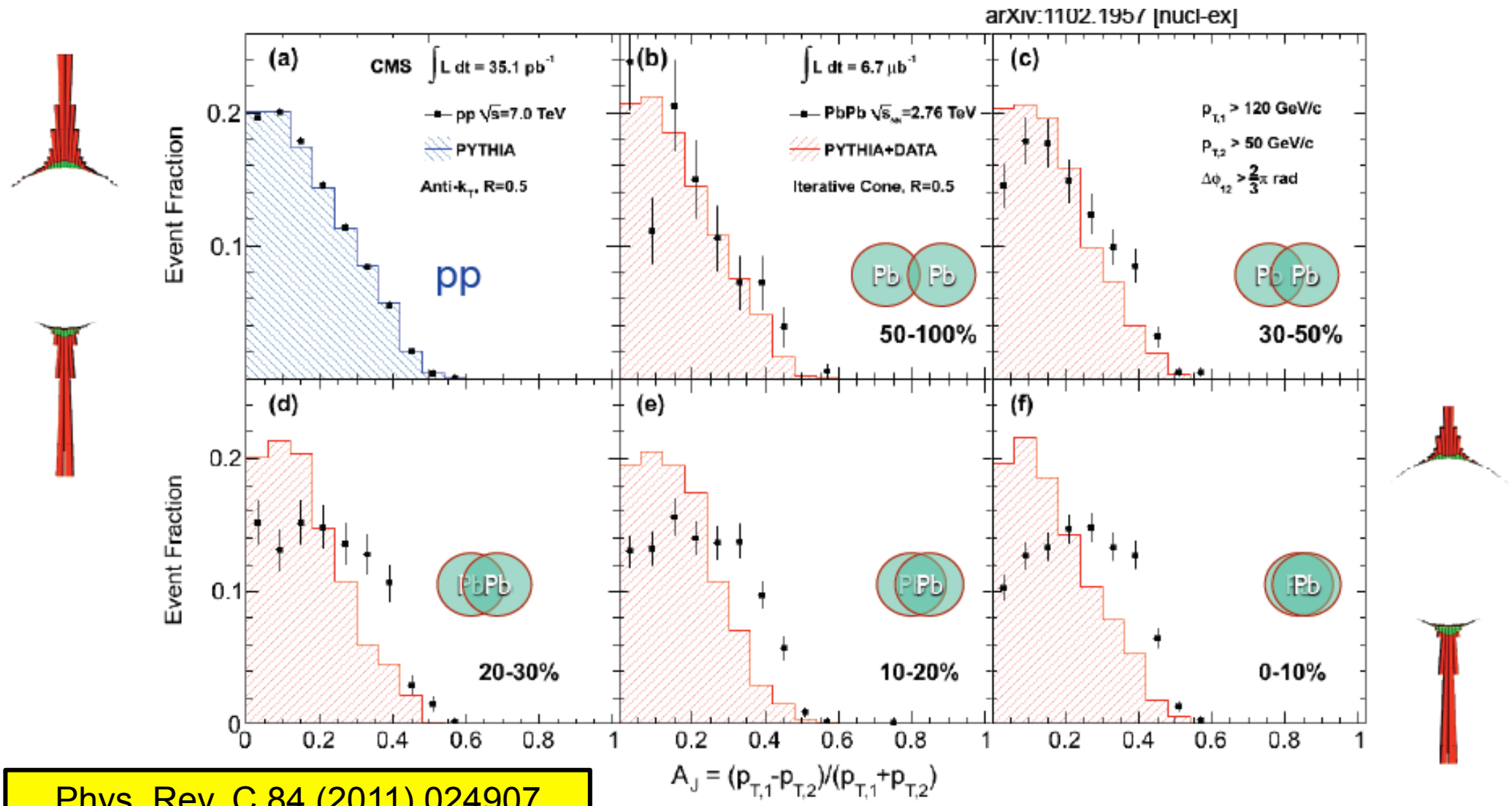
Jet Quenching:The Opposite of Transparency



Quantify the di-jet energy imbalance by asymmetry ratio

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

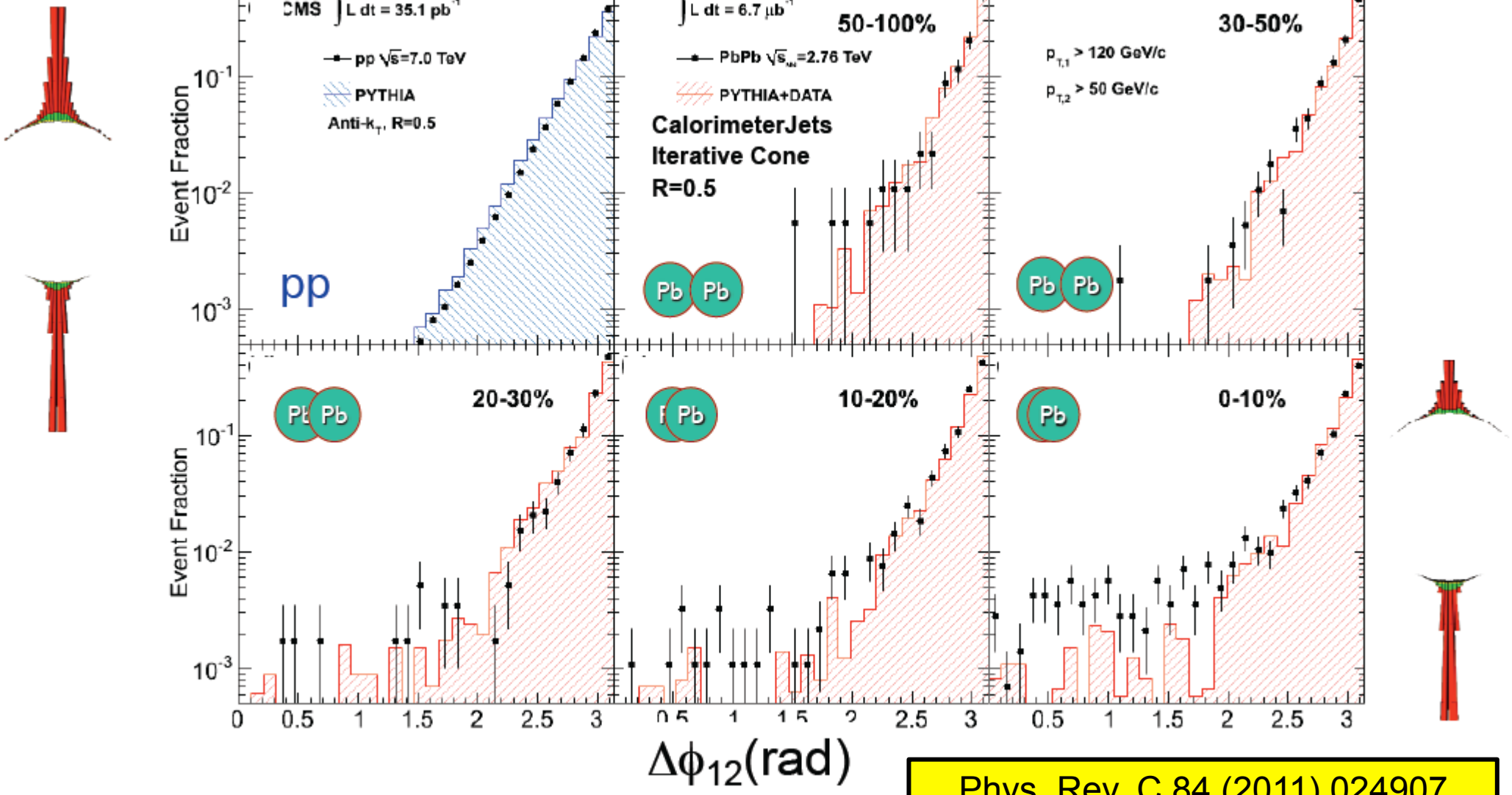
Di-jet Imbalance



Phys. Rev. C 84 (2011) 024907

- Di-jet imbalance increases with centrality
- Not reproduced by MC (PHYTHIA + PbPb data)

Jet Angular Correlations

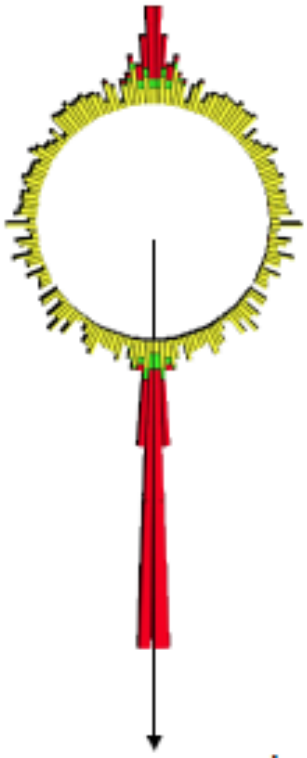


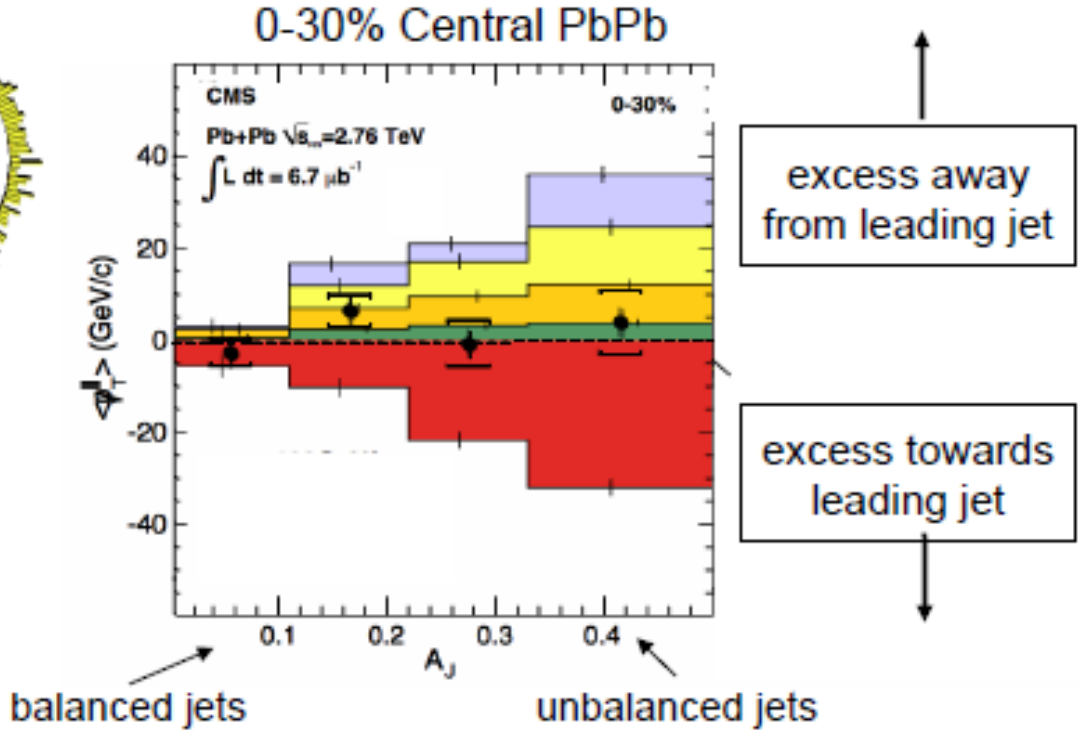
Phys. Rev. C 84 (2011) 024907

- Back-to-back even in central collisions

Where Does the "Lost" Energy Go ?

Missing $p_T^{\parallel}$: $\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$





Calculate missing p_T in ranges of track p_T:

- > 0.5 GeV/c
- 0.5 - 1.0 GeV/c
- 1.0 - 2.0 GeV/c
- 2.0 - 4.0 GeV/c
- 4.0 - 8.0 GeV/c
- > 8.0 GeV/c

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

CMS PAS HIN-10-004

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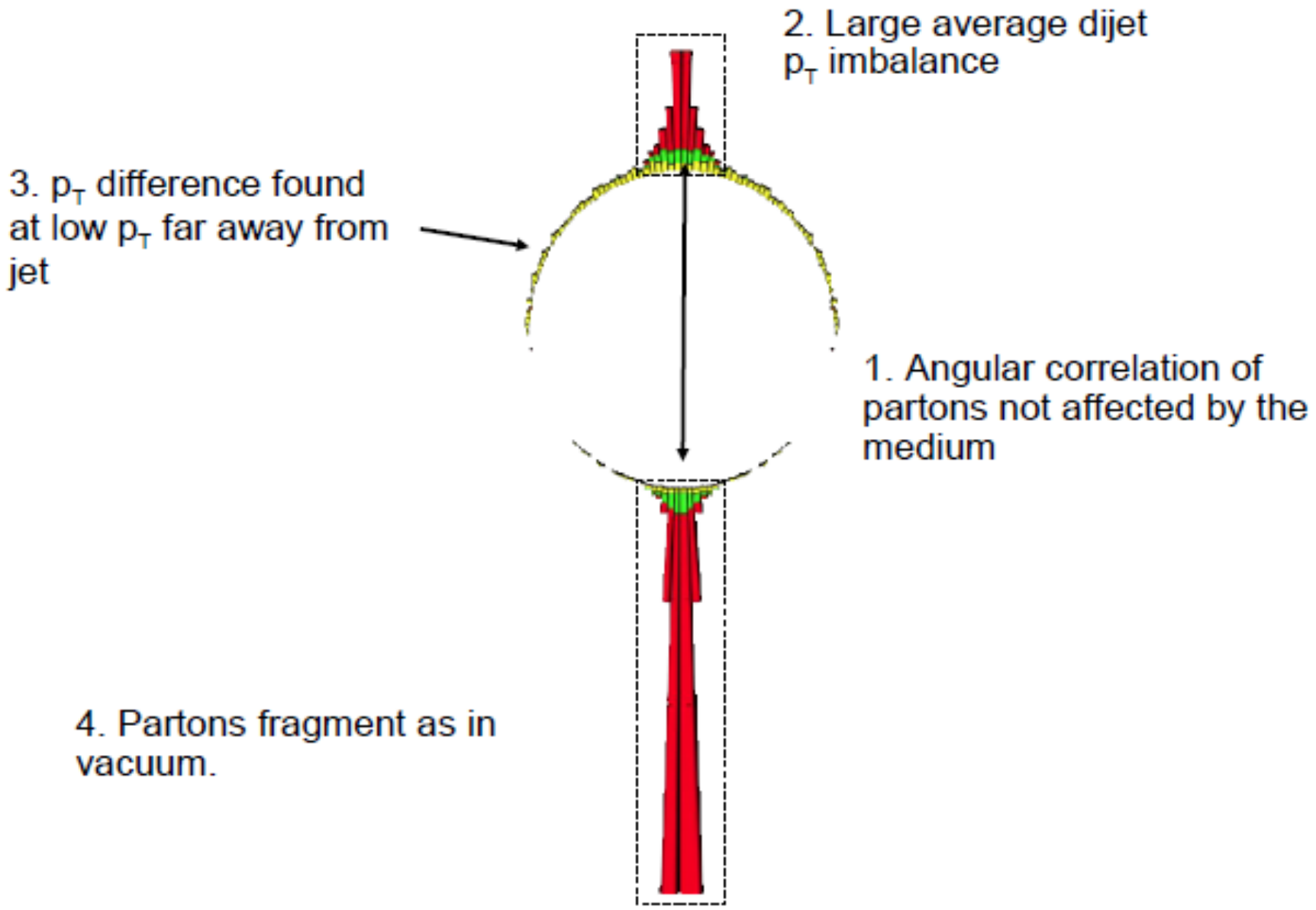
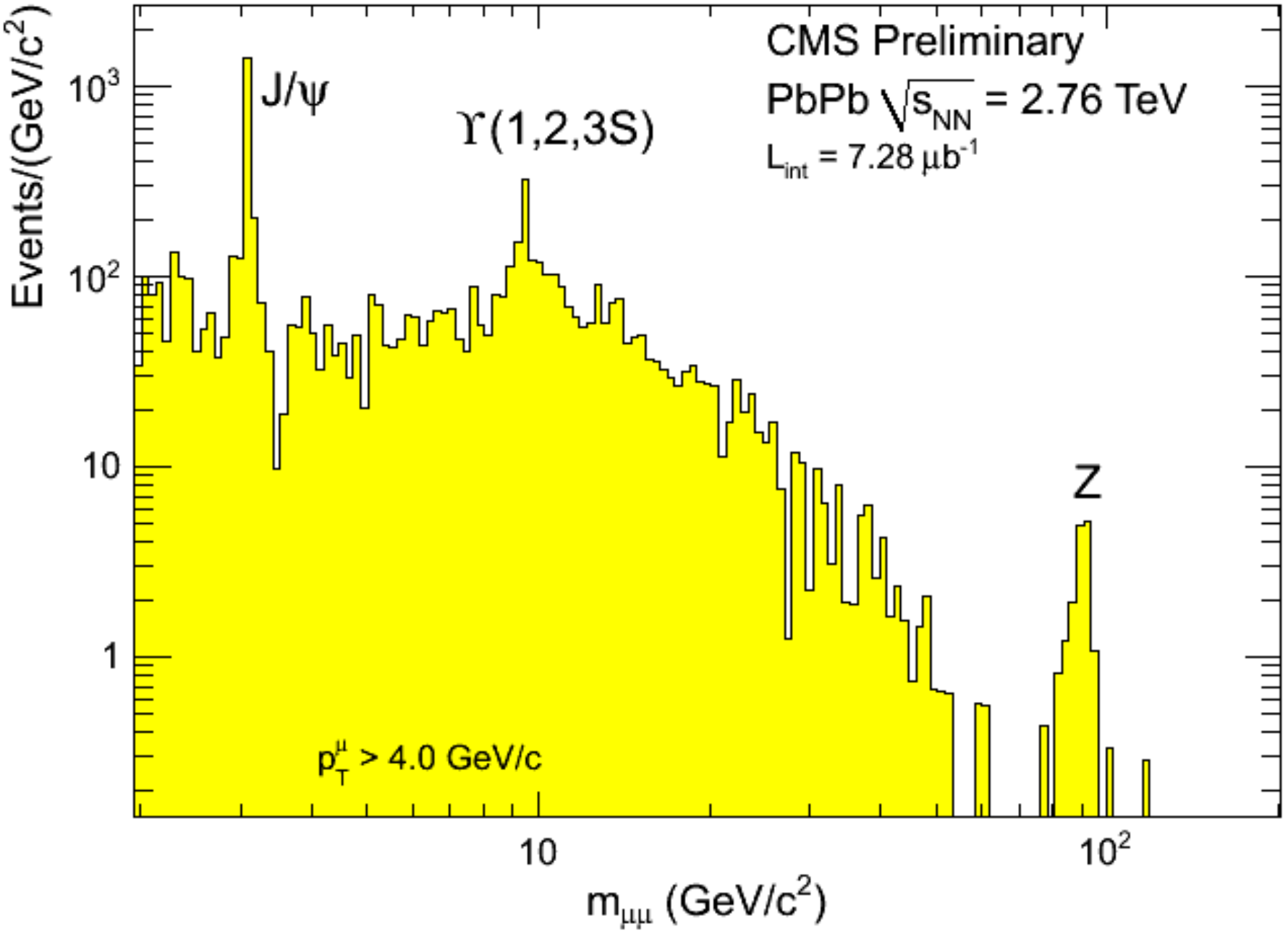
Jet Results Summary



Compact Muon Solenoid: $\mu^+\mu^-$ Invariant Mass

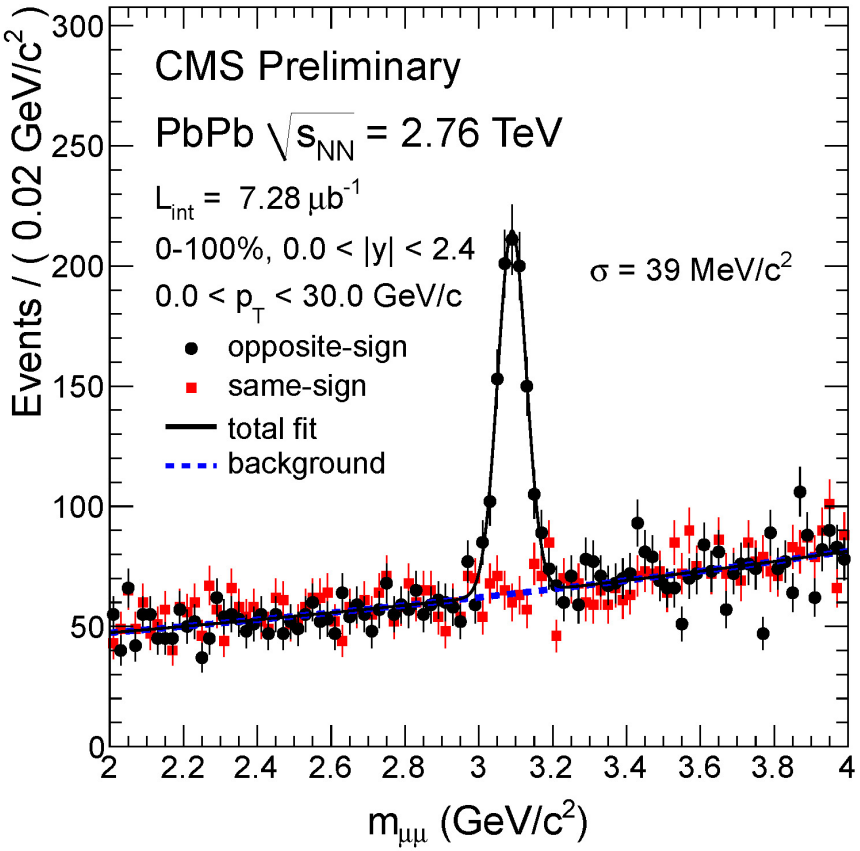


J/ψ and ϒ

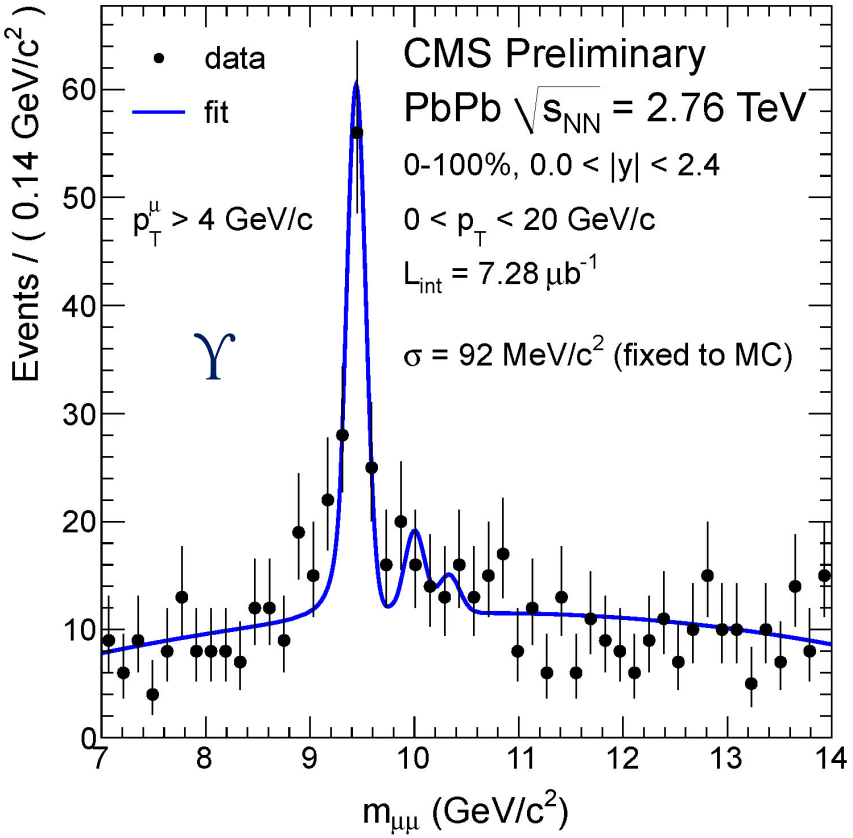
- J/ψ and ϒ observed in $\mu^+\mu^-$ channel
- CMS muon acceptance $|\eta|<2.4$, $p_{T\mu}>2$-4 GeV/c
- Excellent mass resolution ~1%, comparable to pp
- Use displaced vertices to separate prompt J/ψ and B-decays

http://cdsweb.cern.ch/record/1353586?ln=en

$N_{J/\psi}$ =734±54

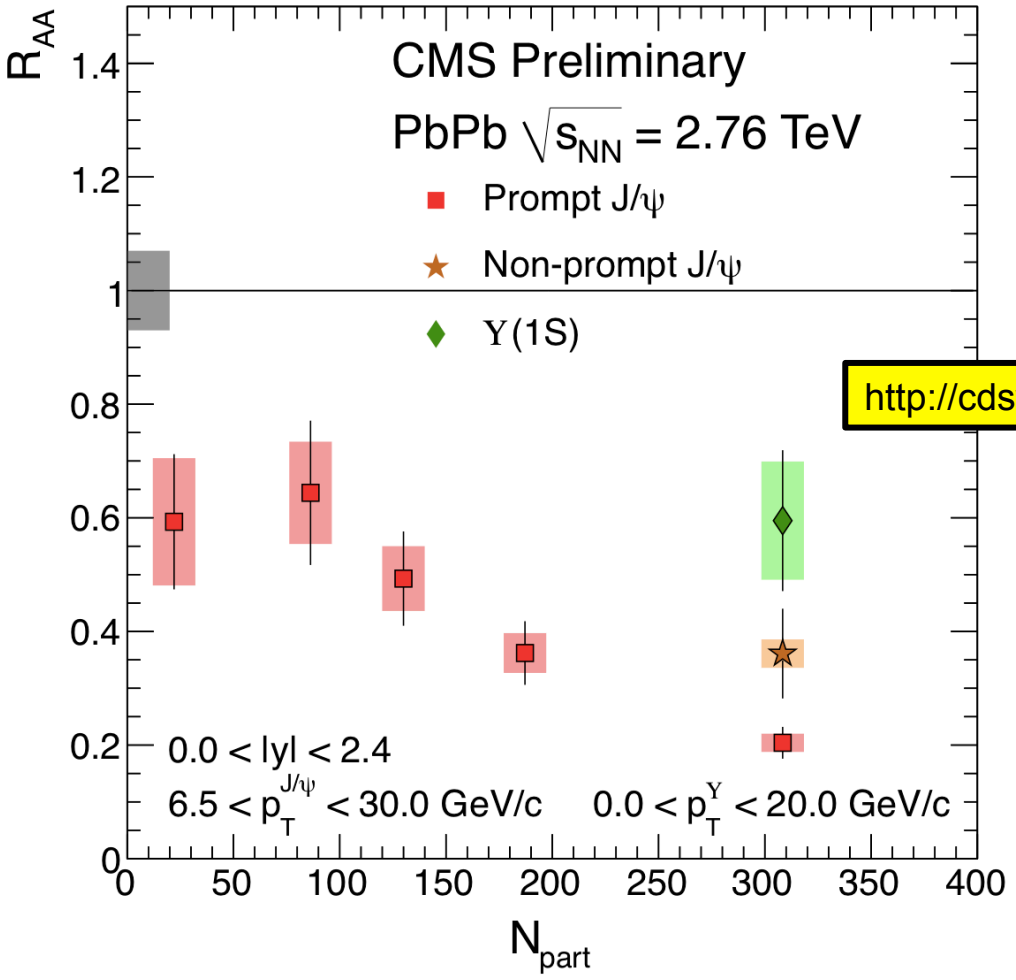


N_{Υ} =86±12



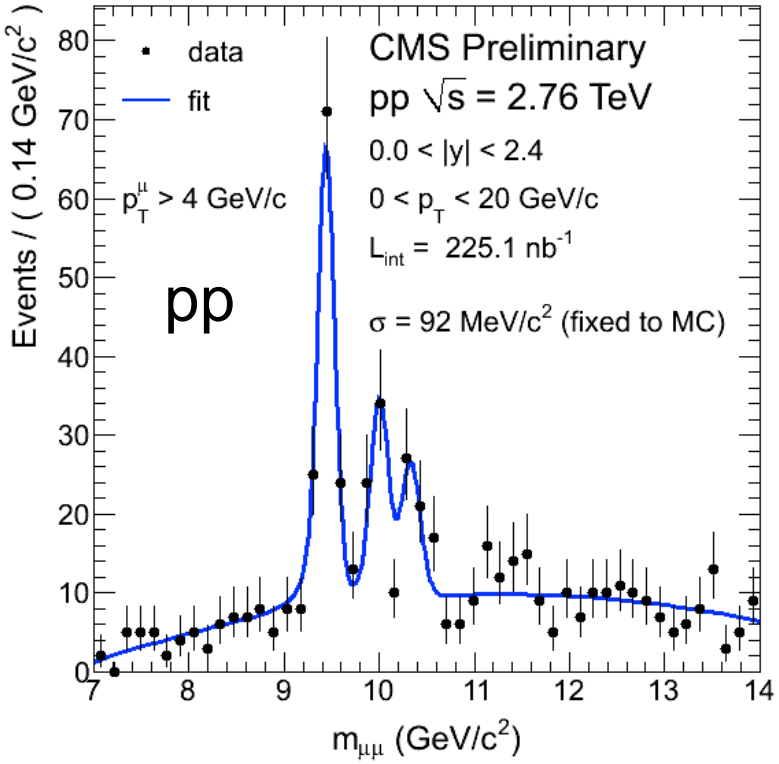
All quarkonia suppressed: R_{AA} vs. centrality

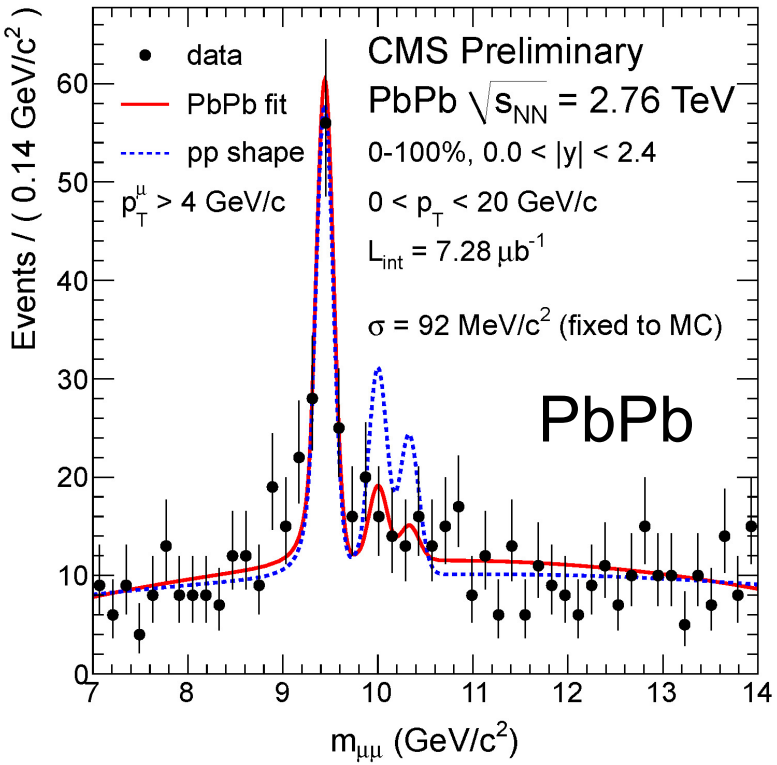
- Non-prompt J/ψ suppression is a measure of b-quark quenching
- High p_T J/ψ is strongly suppressed at the LHC
- Inclusive ϒ(1S) is suppressed



http://cdsweb.cern.ch/record/1353586?ln=en

Suppression of excited Υ states





$$\Upsilon(2S+3S)/\Upsilon(1S)\Big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$

$$\Upsilon(2S+3S)/\Upsilon(1S)\Big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

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

PRL107 (2011) 052302

- Excited states Υ(2S,3S) relative to Υ(1S) are suppressed
- Probability to obtain measured value, or lower, if the real double ratio is unity, has been calculated to be less than 1%

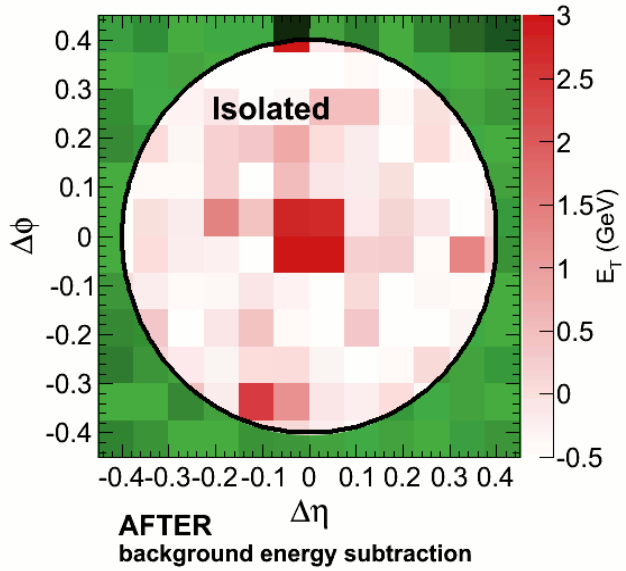
Summary

- Broad experimental program and excellent detector performance
- CMS has obtained significant statistics of hard probes
- CMS conducted detailed measurements of global properties of medium in PbPb and pp collisions
- Our measurements 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

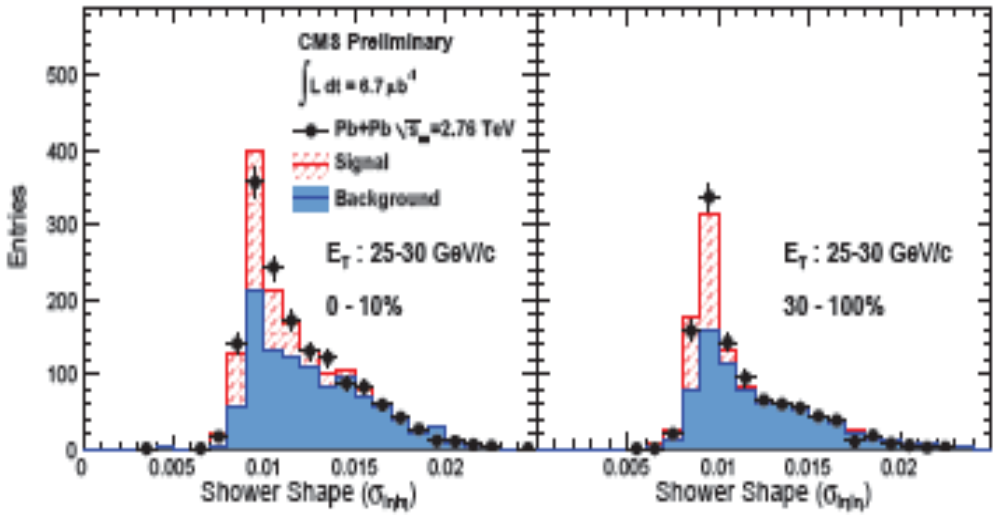
BACK-UP

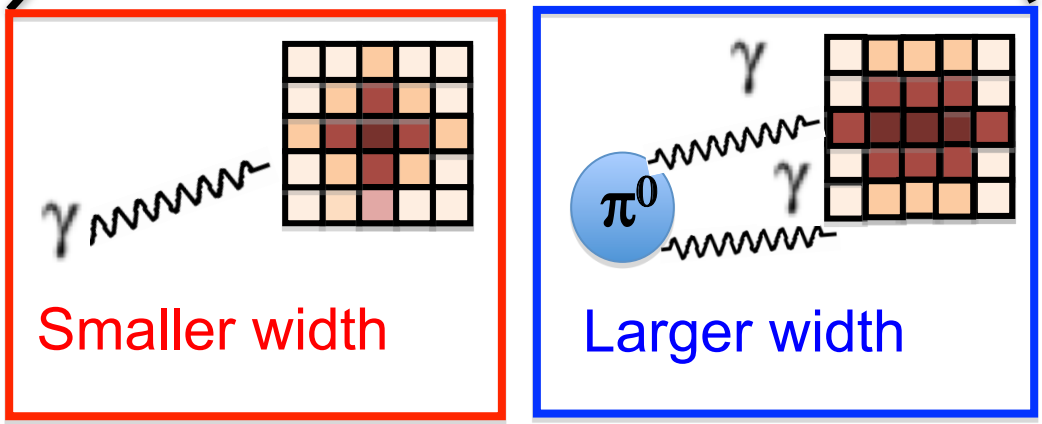
Isolated photons

- Colorless probes
  - Check suppression
  - Nuclear parton distribution function
  - Initial state
- Photon selection
  - Identify isolated electromagnetic clusters
    - E_{HCAL}/E_{ECAL} <0.2
    - Energy in cone (R<0.4) less than 5 GeV
  - Transverse shower shape



Transverse shower shape using high ECAL granularity

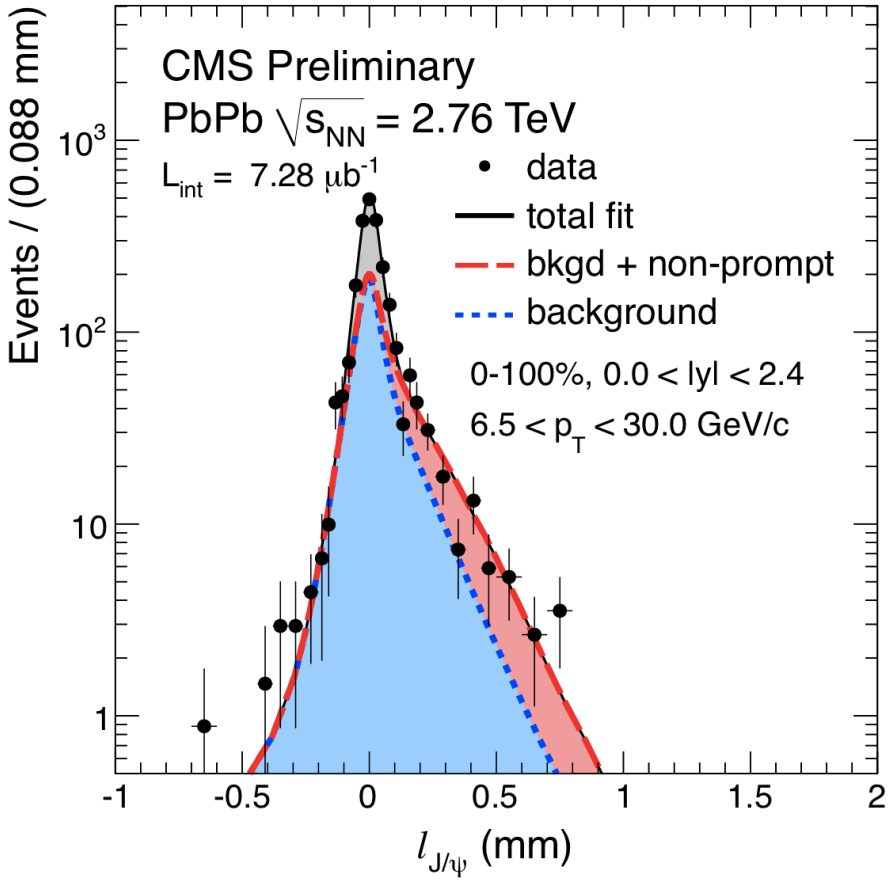


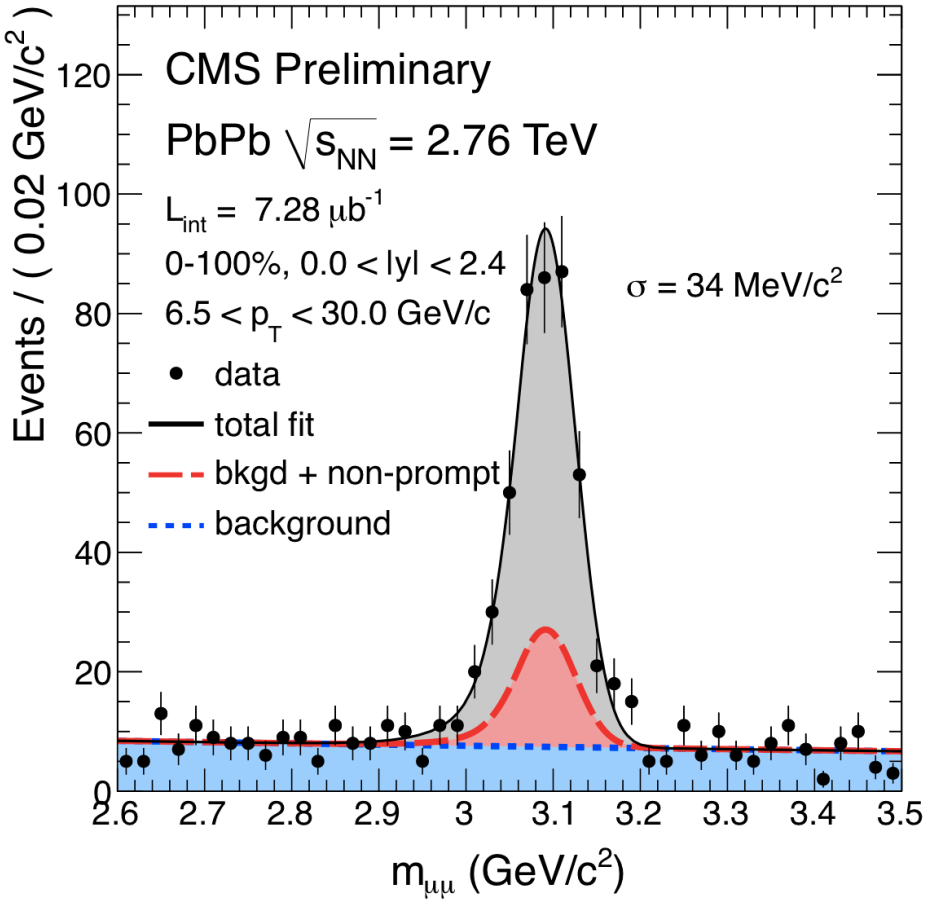


J/ψ: prompt and from B decays

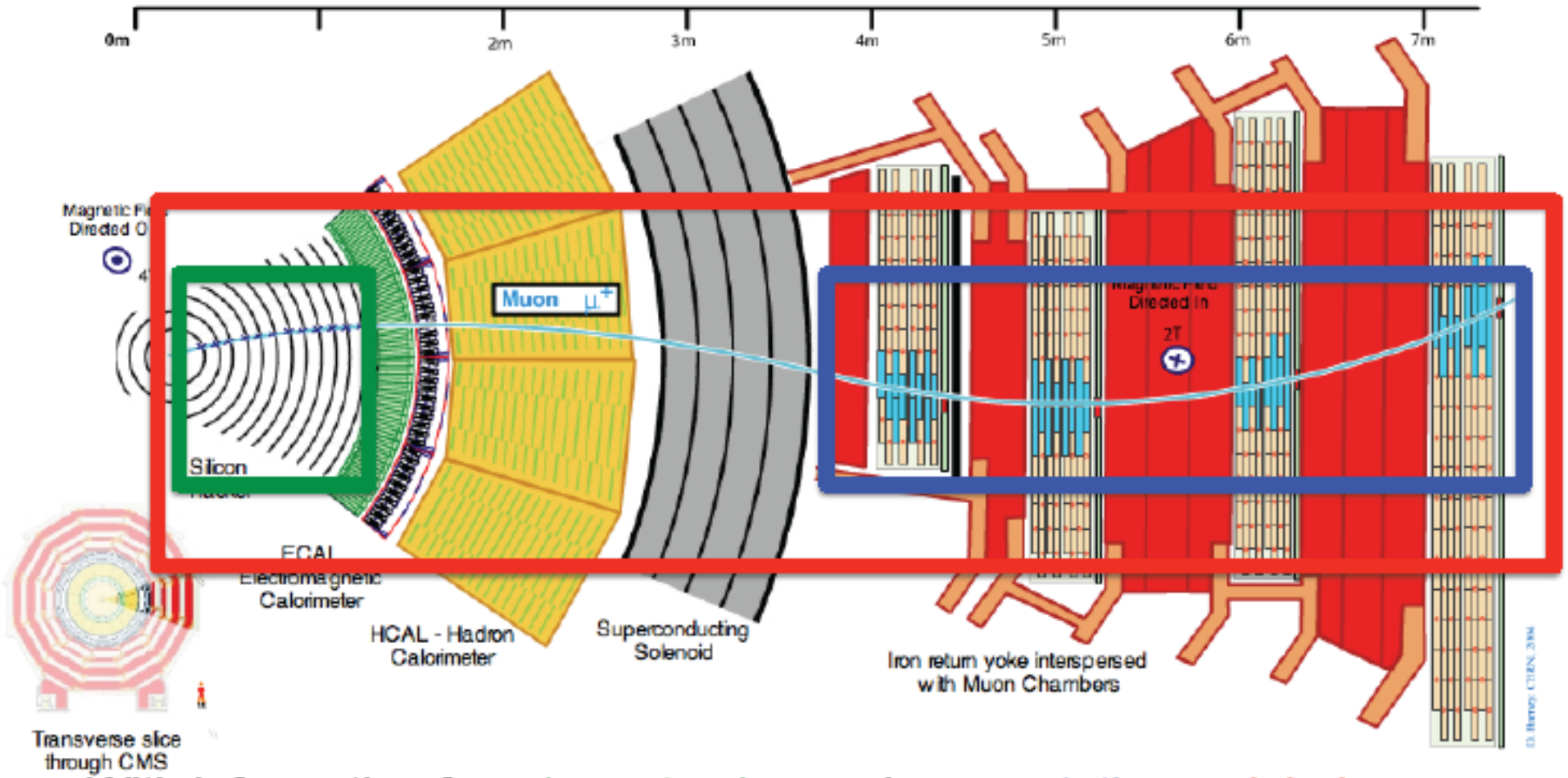
- Use separation of primary and $\mu^+\mu^-$ vertices in plane transverse to beam
- Long B decay times lead to displaced vertices

- Separate:
  - Prompt J/ψ production
  - Non-prompt J/ψ from B decays



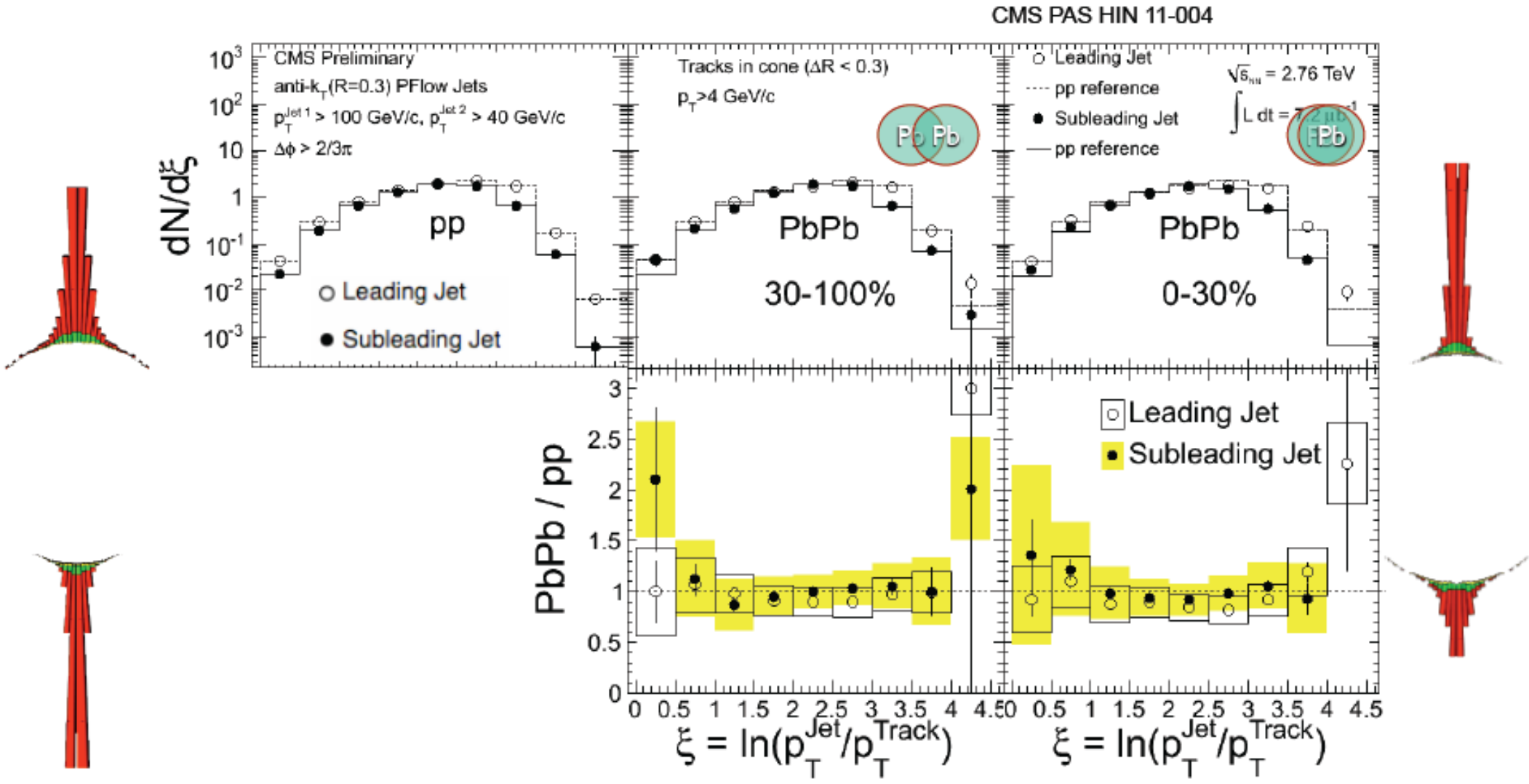


Muon reconstruction mechanism



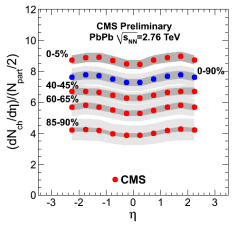
- With information from inner tracker and muon stations, global muons reconstructed
- Global muons need p ≥ 3 GeV to reach the muon station, but loose 2~3 GeV energy in the absorber(iron yoke) so total momentum of the muon that reach the muon stations is ≈ 5 GeV (depending on eta)

Fragmentation Functions

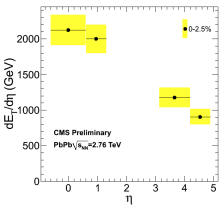


Leading and sub-leading jets in PbPb fragment like the corresponding energy jet in pp

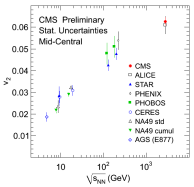
Take home messages from CMS

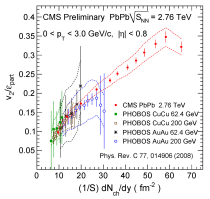


Charged hadron multiplicity

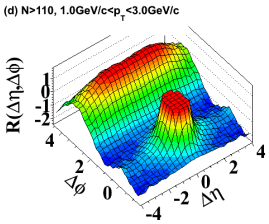


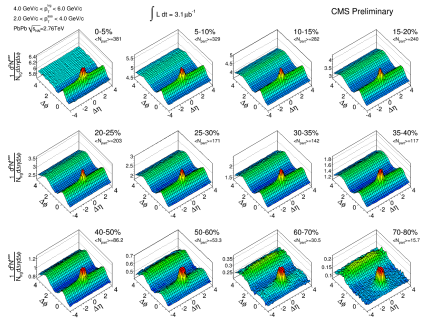
First: E_T



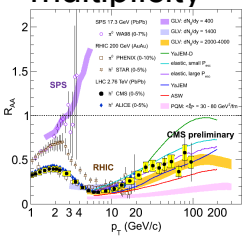


v_2 in wide acceptance

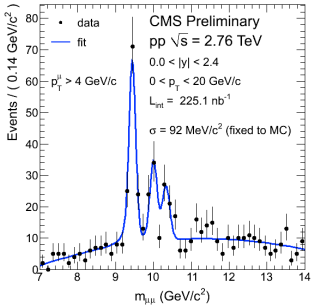


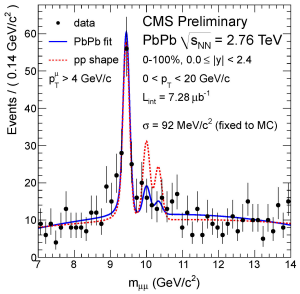


First dihadron correlations pp and PbPb in wide acceptance

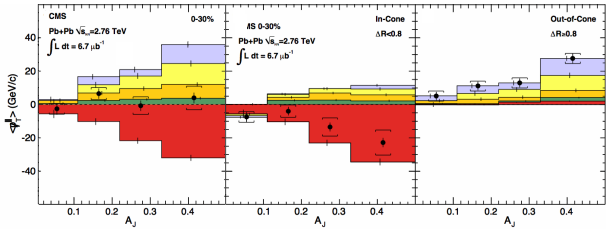


First: h+- R_{AA} p_T up to100 GeV/c

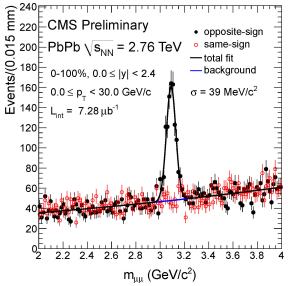


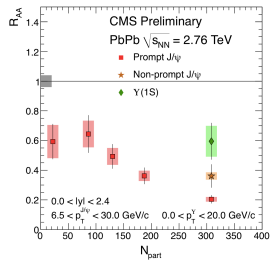


A First: Suppression of excited ϒ

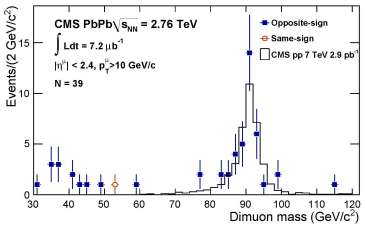


First: Jet imbalance and jet fragmentation function





First: Prompt J/ψ and B-hadrons through non-prompt J/ψ



First: Gauge bosons: Z, W, isolated-γ