Heavy Ions in the CMS experiment

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for the CMS Collaboration

Primordial QCD Matter in LHC Conference

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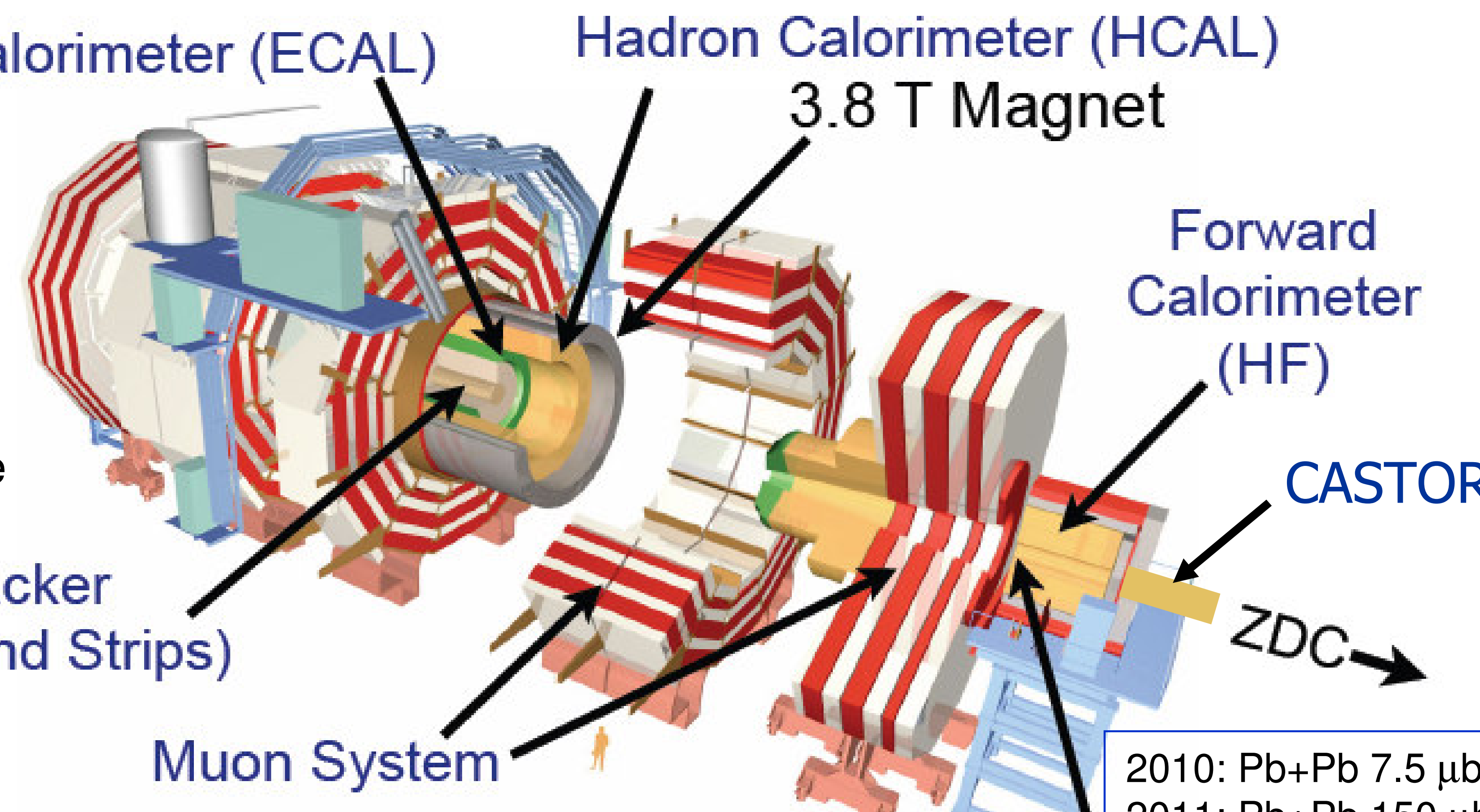
Outline

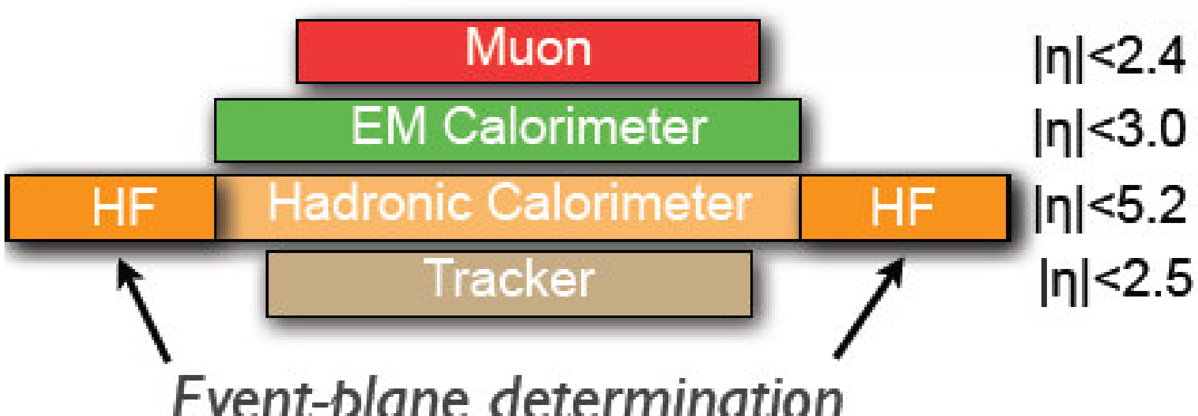
- The CMS experiment and heavy ions
- Global picture of heavy ion collisions
- Hard probes
  - jets
  - quarkonia
  - electroweak gauge bosons
- p+Pb collisions: new results and outlook
- Summary

The CMS Experiment

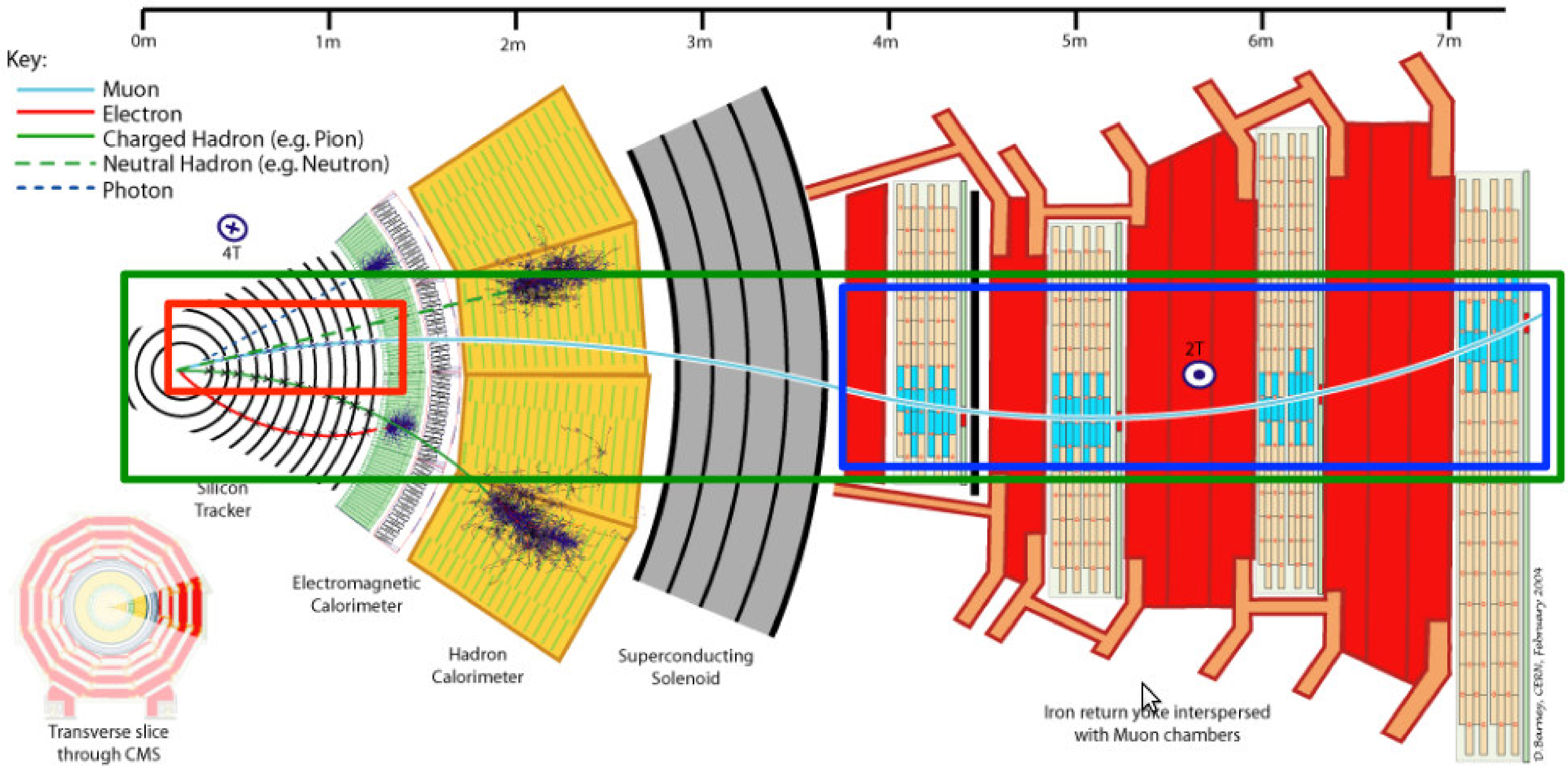
Excellent resolution of tracking and calorimetry; trigger selectivity over a large range in rapidity and full azimuth



2010: Pb+Pb 7.5 μb^{-1}
2011: Pb+Pb 150 μb^{-1}
2013: p+Pb 30 nb^{-1}

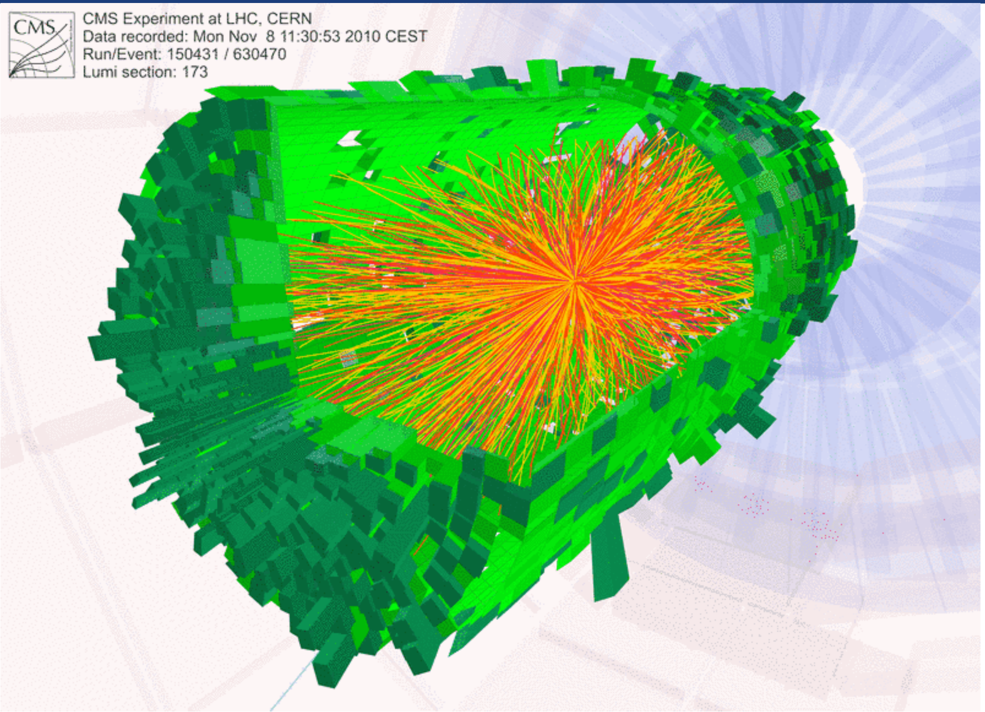


Muon reconstruction

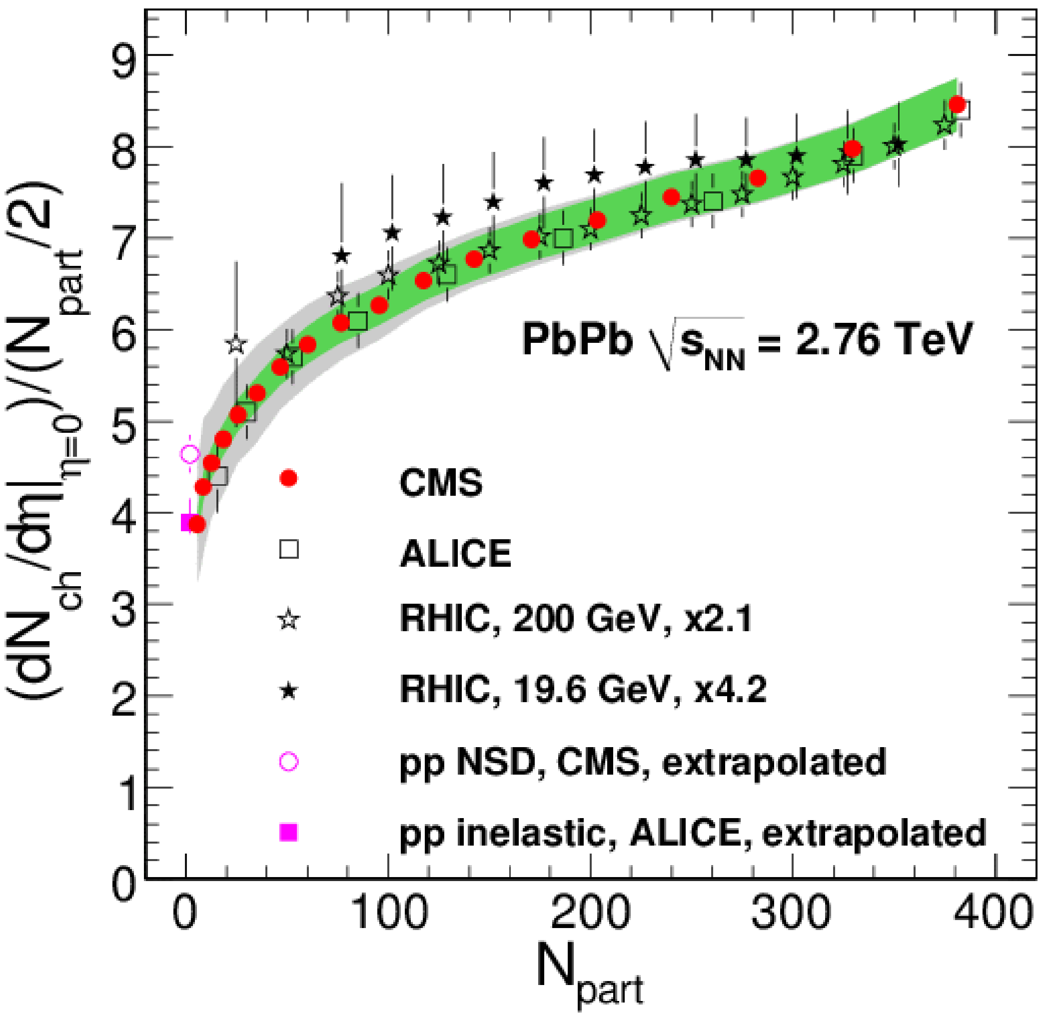


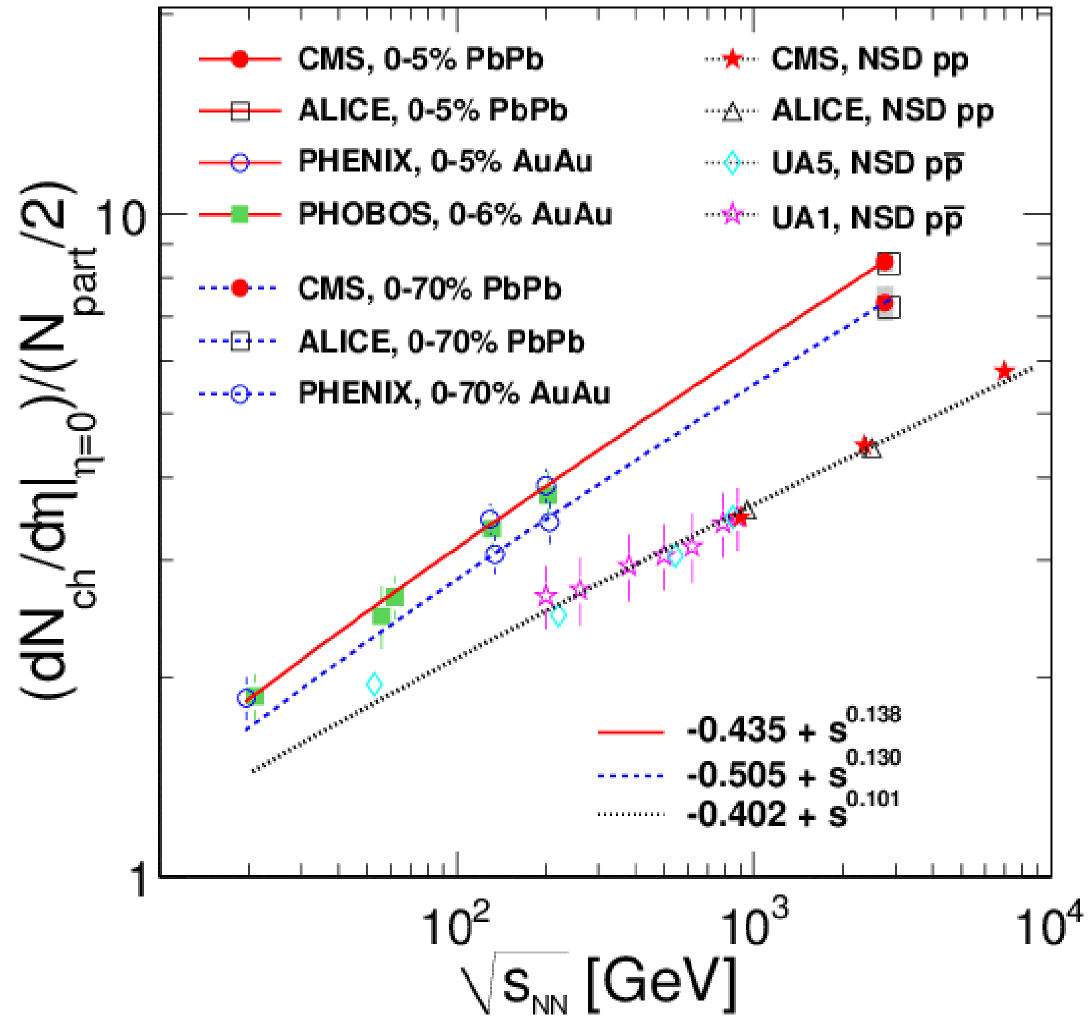
- Muons: silicon tracker + muon subdetectors
  - Tracker p_T resolution: 1-2% up to p_T ~ 100 GeV/c
    - Separation of quarkonium states
    - Displaced tracks for heavy-flavor measurements

Global picture of heavy ion collisions



Charged particle multiplicity



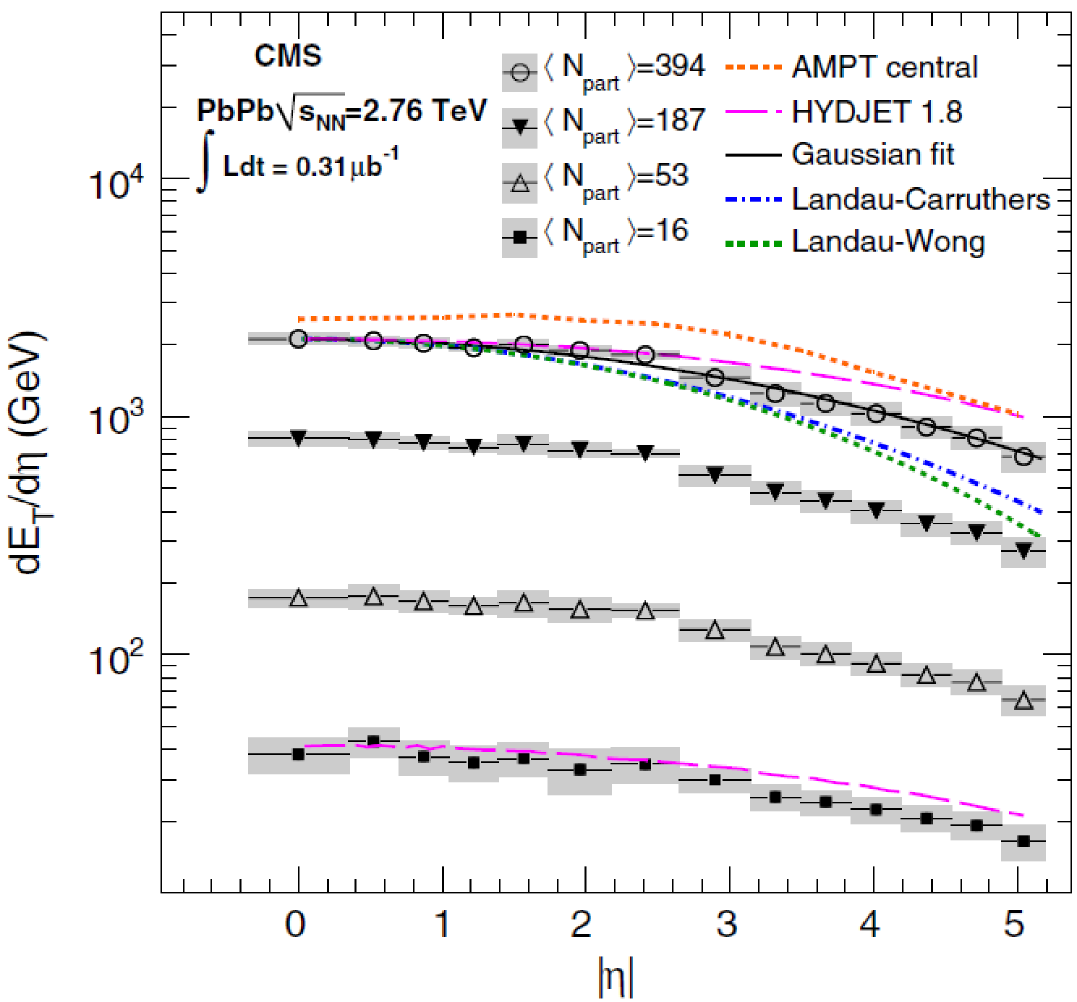


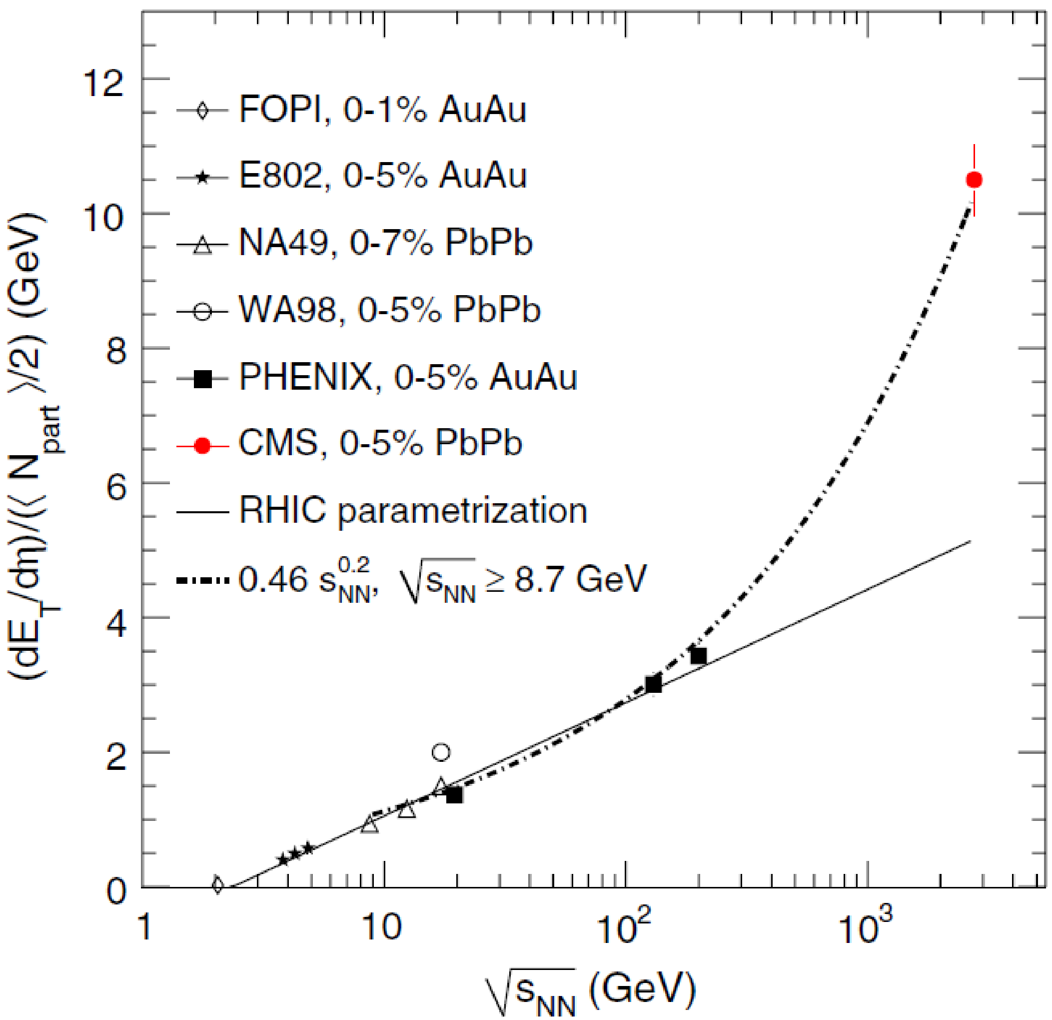
- Centrality dependence:
  - Quite similar to RHIC results
  - Good agreement with ALICE

- √s dependence:
  - p+p, Pb+Pb follow power law

JHEP 08 (2011) 141

Transverse energy density





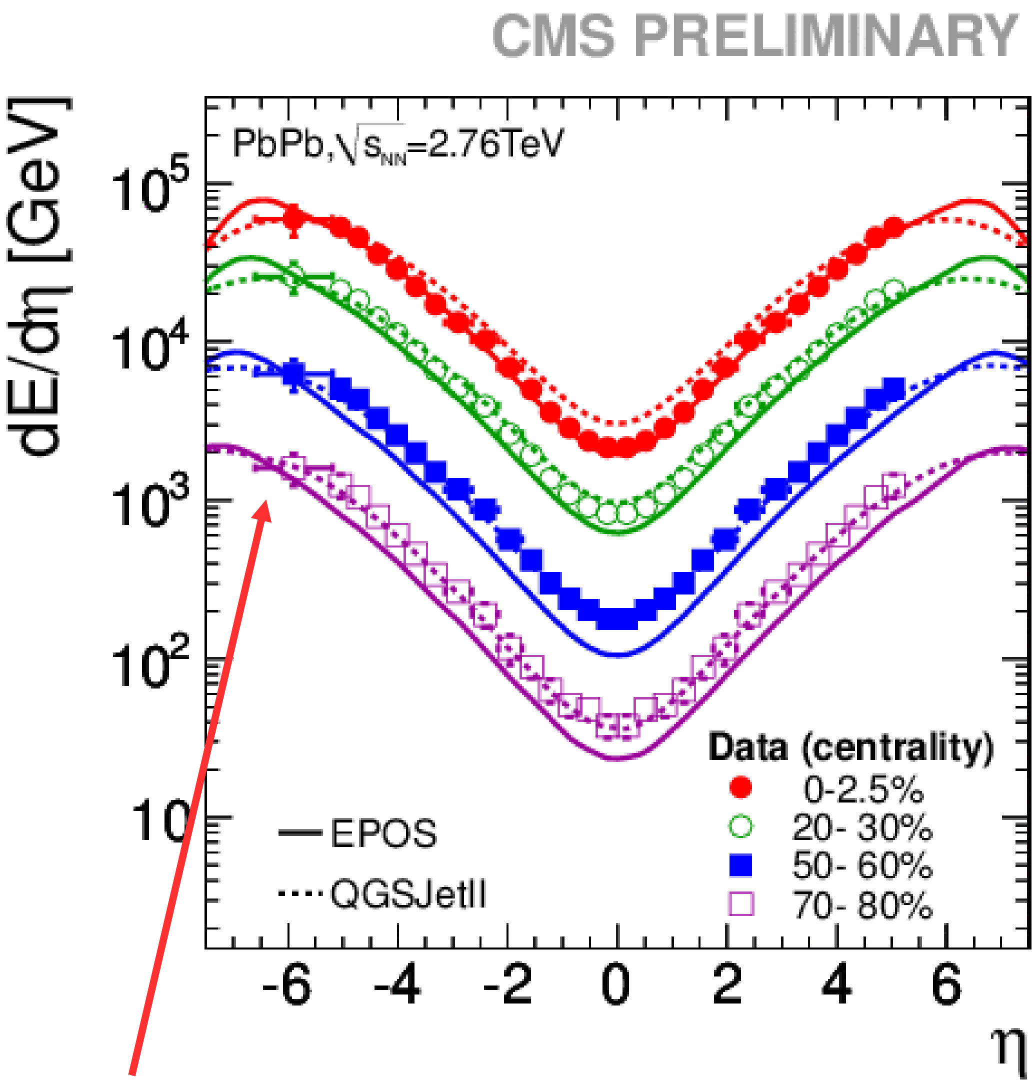
PRL 109 (2012) 152303

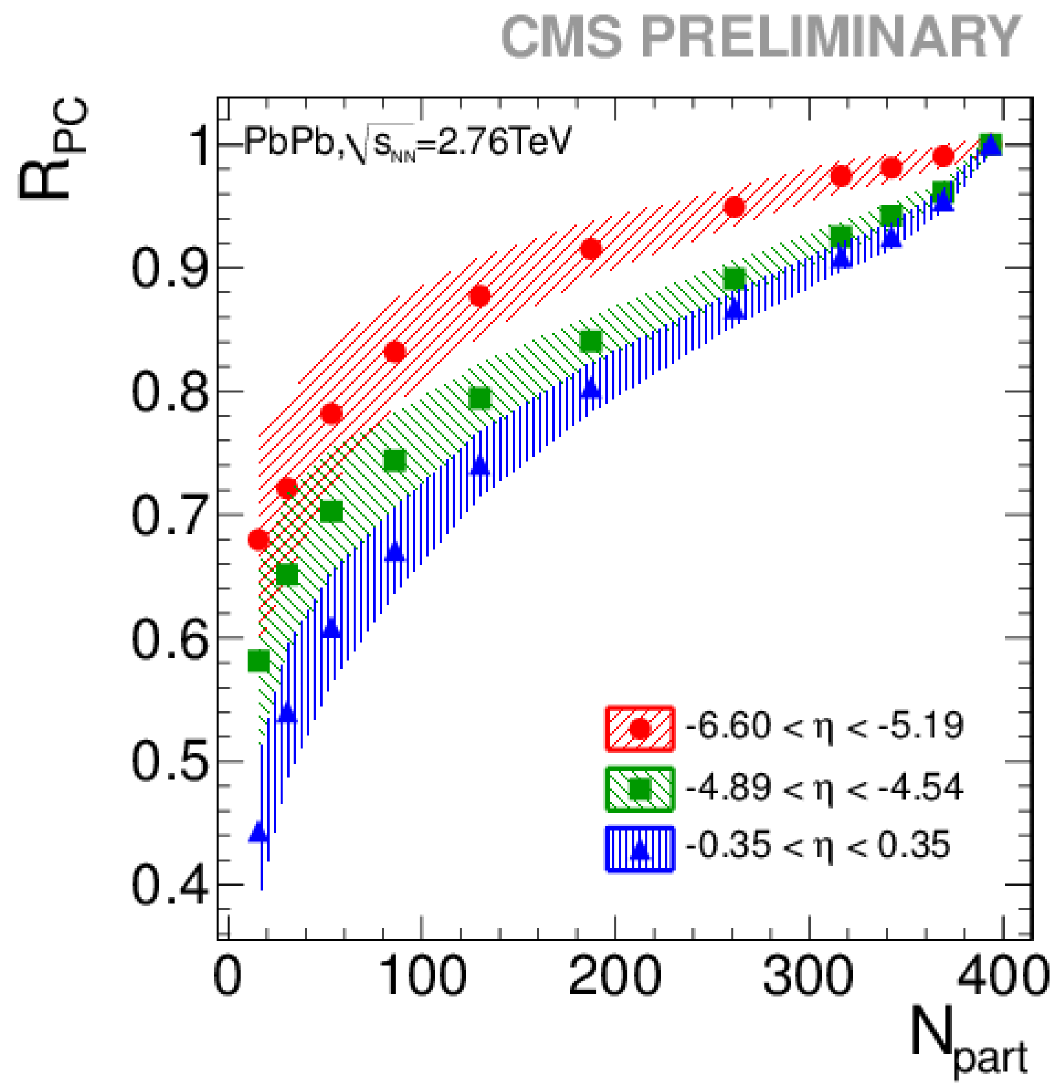
η-coverage: includes the HF calorimeter

Related to the energy released in the collision

Huge increase compared to lower √s (RHIC)

Energy released – measured up to high |η|



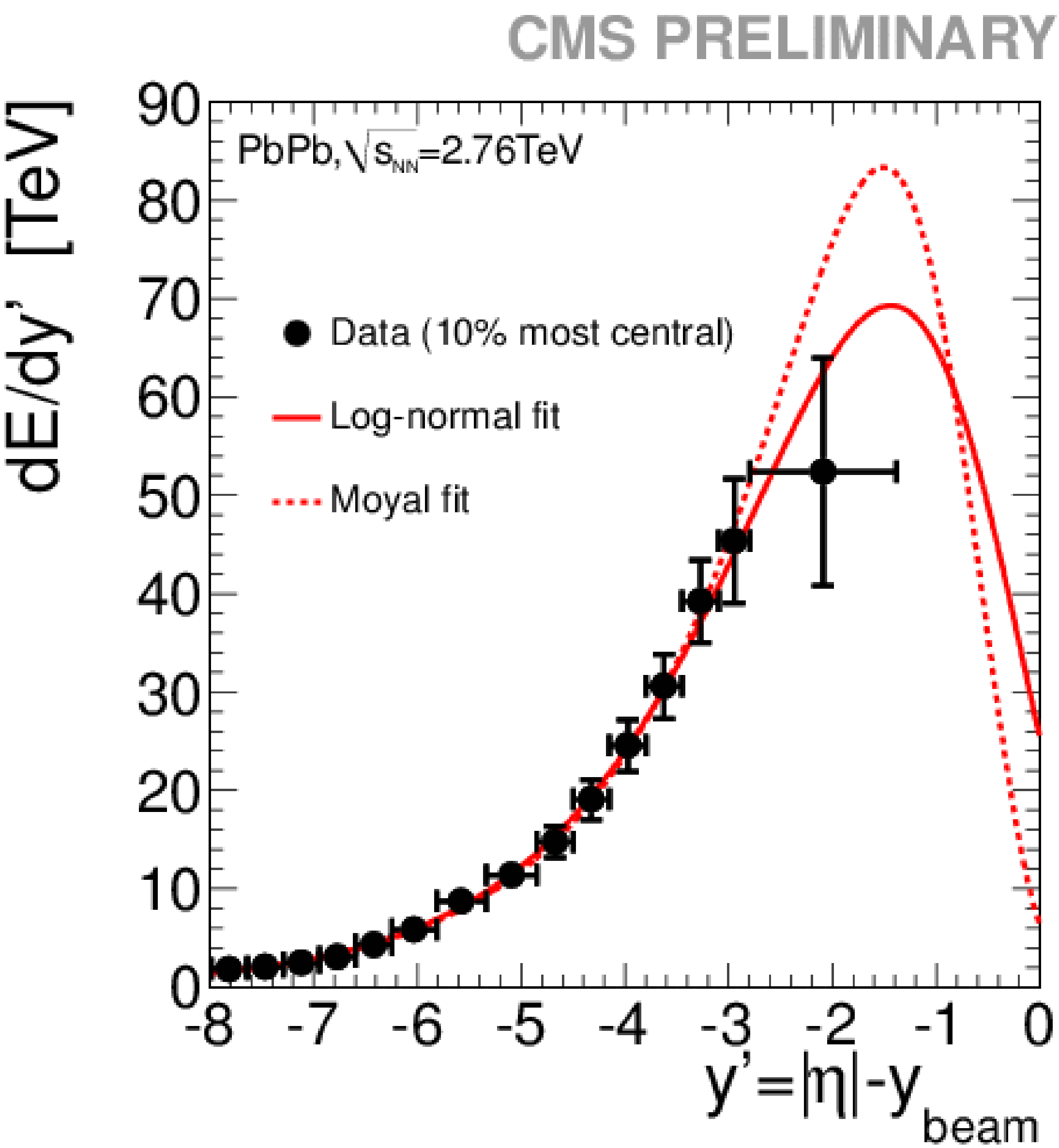


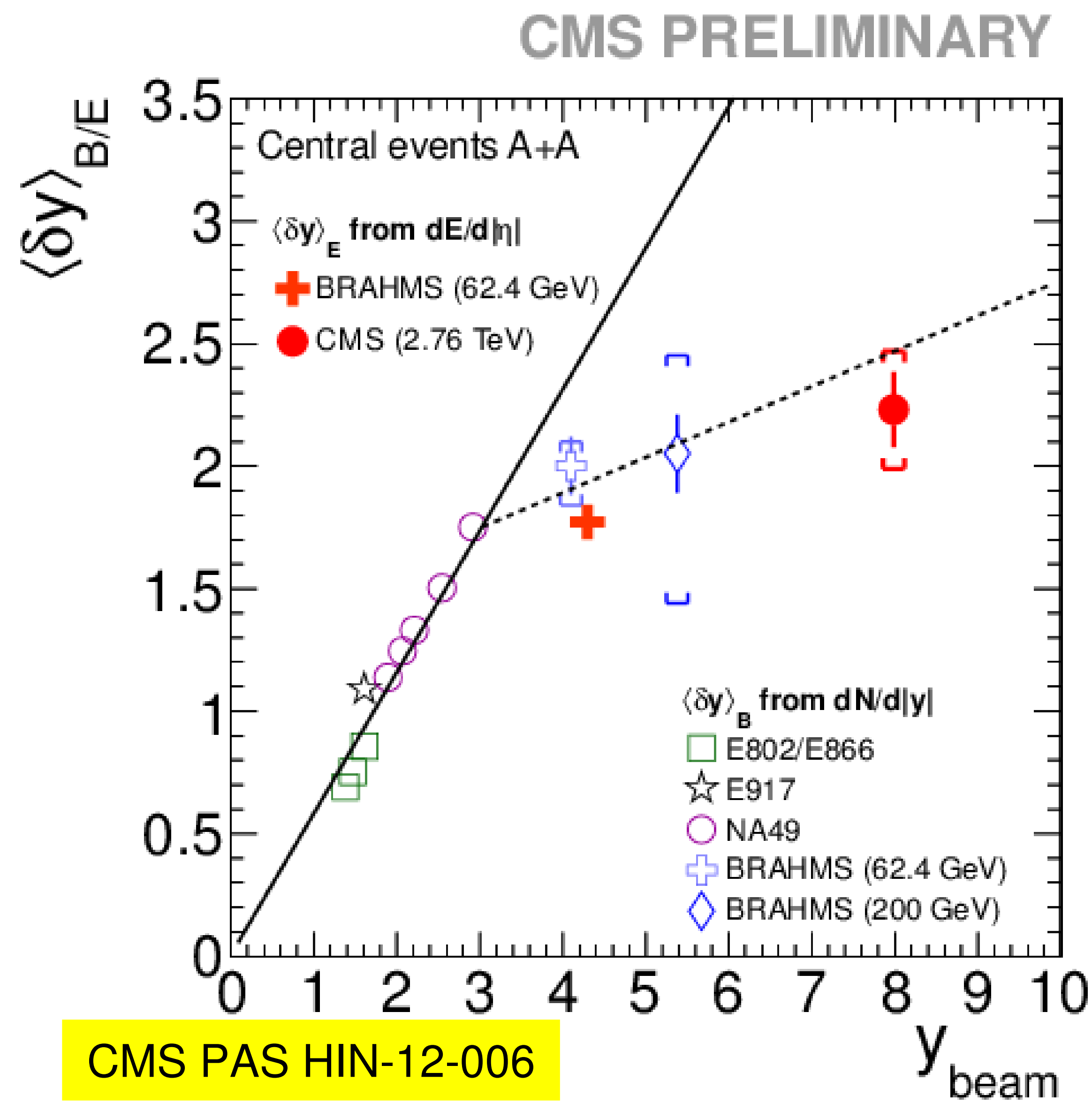
First result using the CASTOR calorimeter

CMS PAS HIN-12-006

At high |η|, the ratio between the energy production in *central* and *peripheral* events is closer to 1 than at midrapidity

Average ‘rapidity loss’





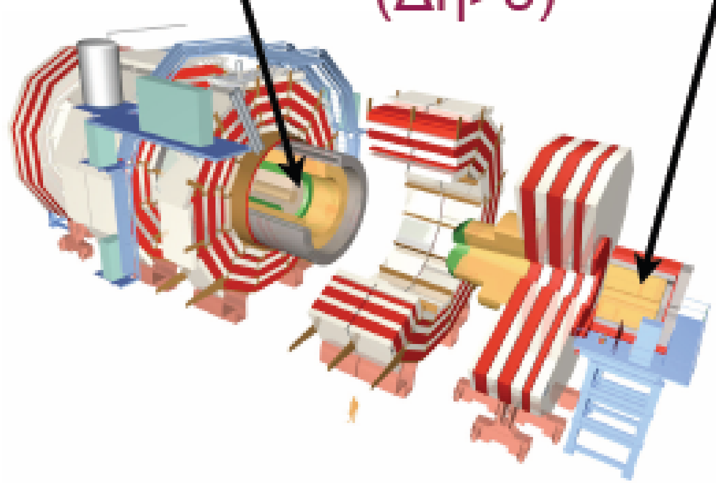
CMS PAS HIN-12-006

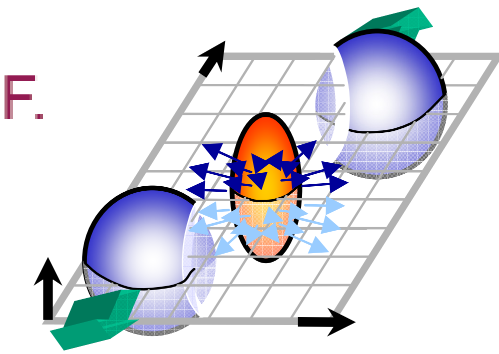
Integration can be done based on various simple assumptions at high |η| → Average rapidity loss compared to earlier experiments

Azimuthal asymmetry: methods

Event Plane

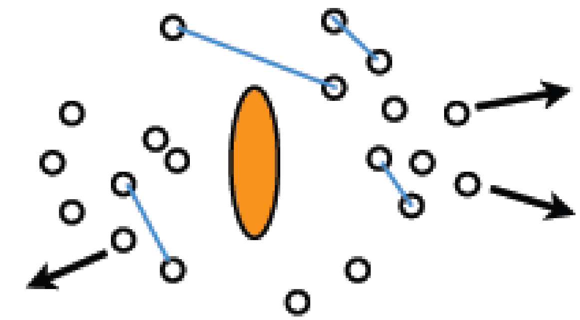
Correlate particles in tracker with those in HF. ($\Delta\eta>3$)





Two-particle Cumulant

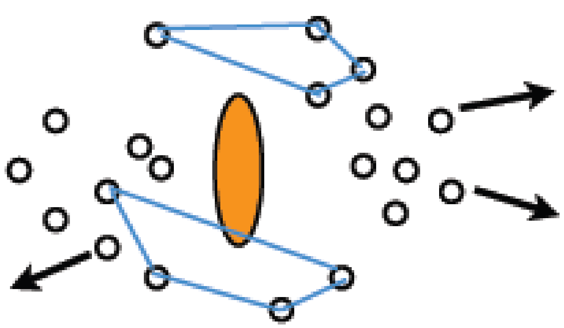
Consider all two-particle correlations.



Methods have different sensitivity to event-by-event fluctuations and non-flow effects.

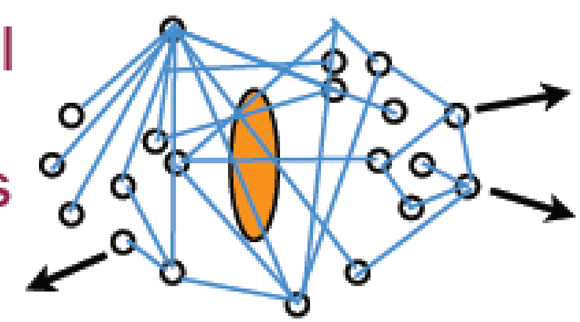
Four-particle Cumulant

Consider all four-particle correlations.

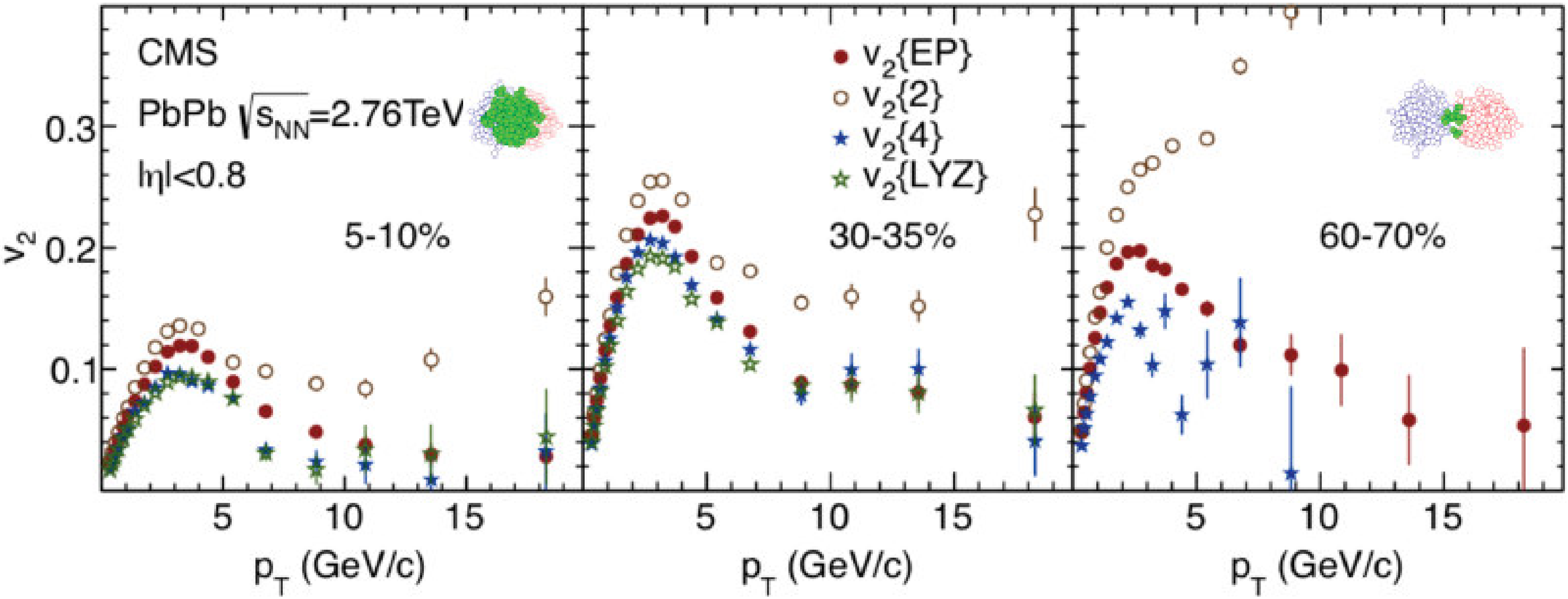


Lee-Yang Zeros

Consider all particle correlations -(Not all shown!).



Azimuthal asymmetry: results



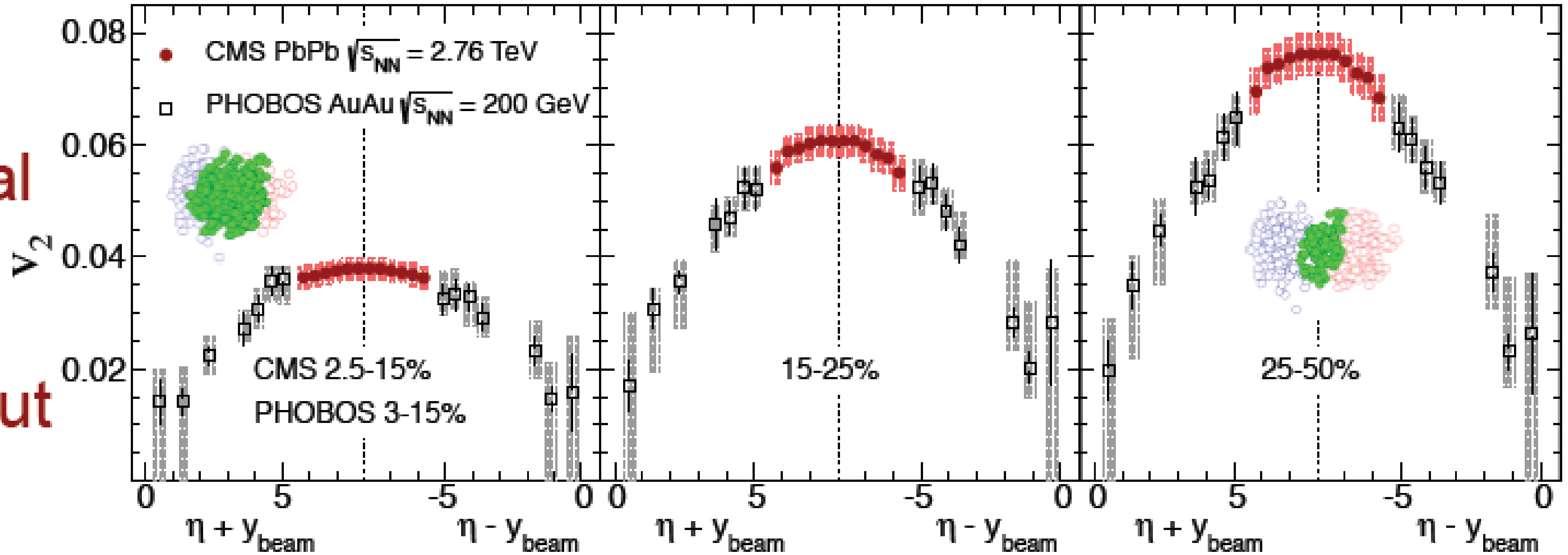
•v_2{EP} determined with 3-unit η-gap between EP and v_2 tracks to suppress non-flow effects.

•v_2{4} and v_2{LYZ} inherently suppress non-flow effects.

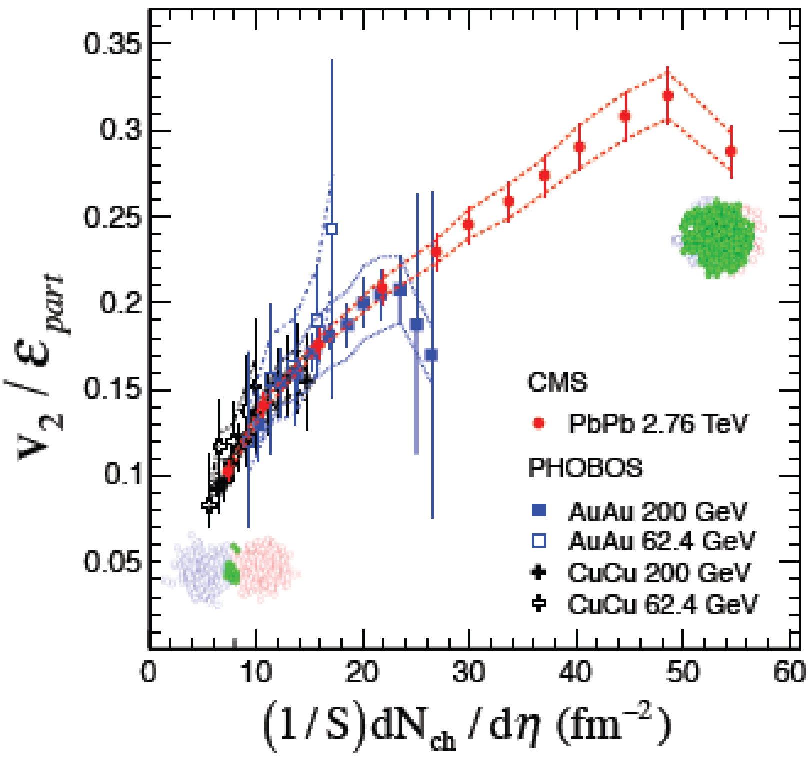
PRC 87(2013) 014902

Scaling properties of elliptic flow (v_2)

- ***Extended longitudinal scaling.*** Integral v_2 connects smoothly with RHIC results, but flattens.



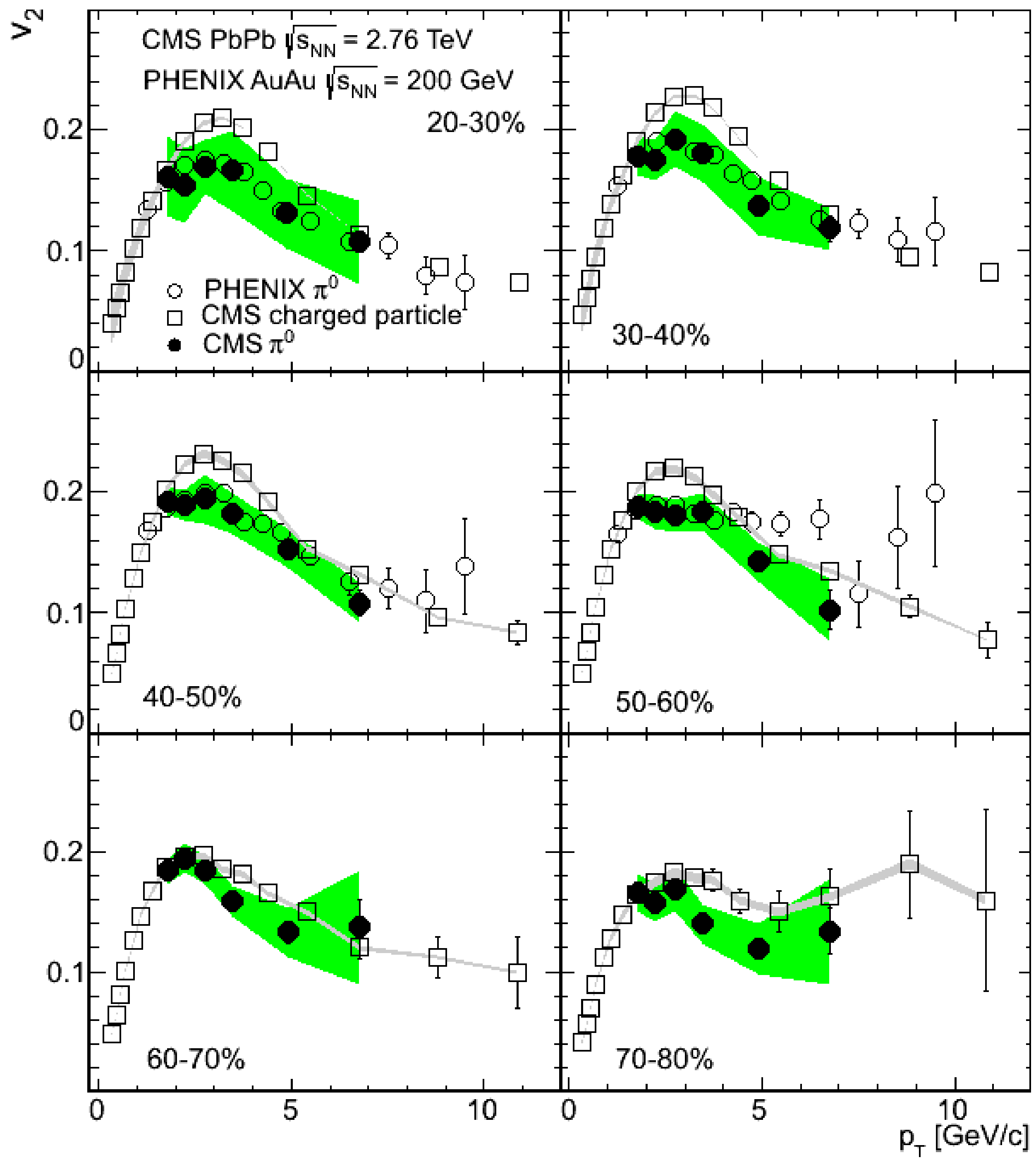
- ***Transverse particle density scaling.*** $v_2\{EP\} / \varepsilon_{part}$ scales with transverse particle density over very large beam energy range.



PRC 87(2013) 014902

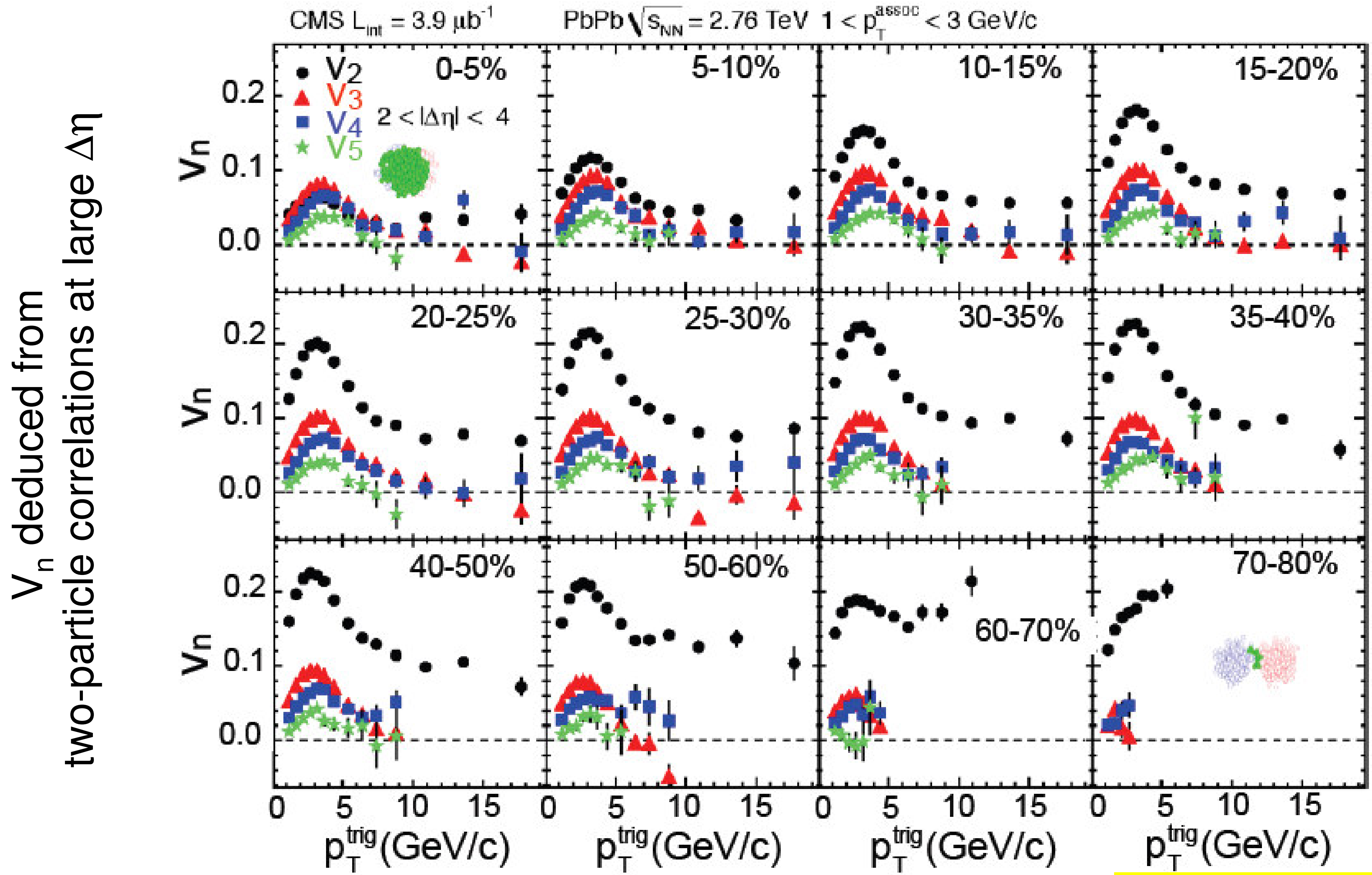
Neutral pions: elliptic flow

- Detected through $\gamma\gamma$ coincidences
- Correlated with HF event plane
- With x14 increase in energy, no significant change from RHIC (for pions)



PRL 110 (2013) 042301

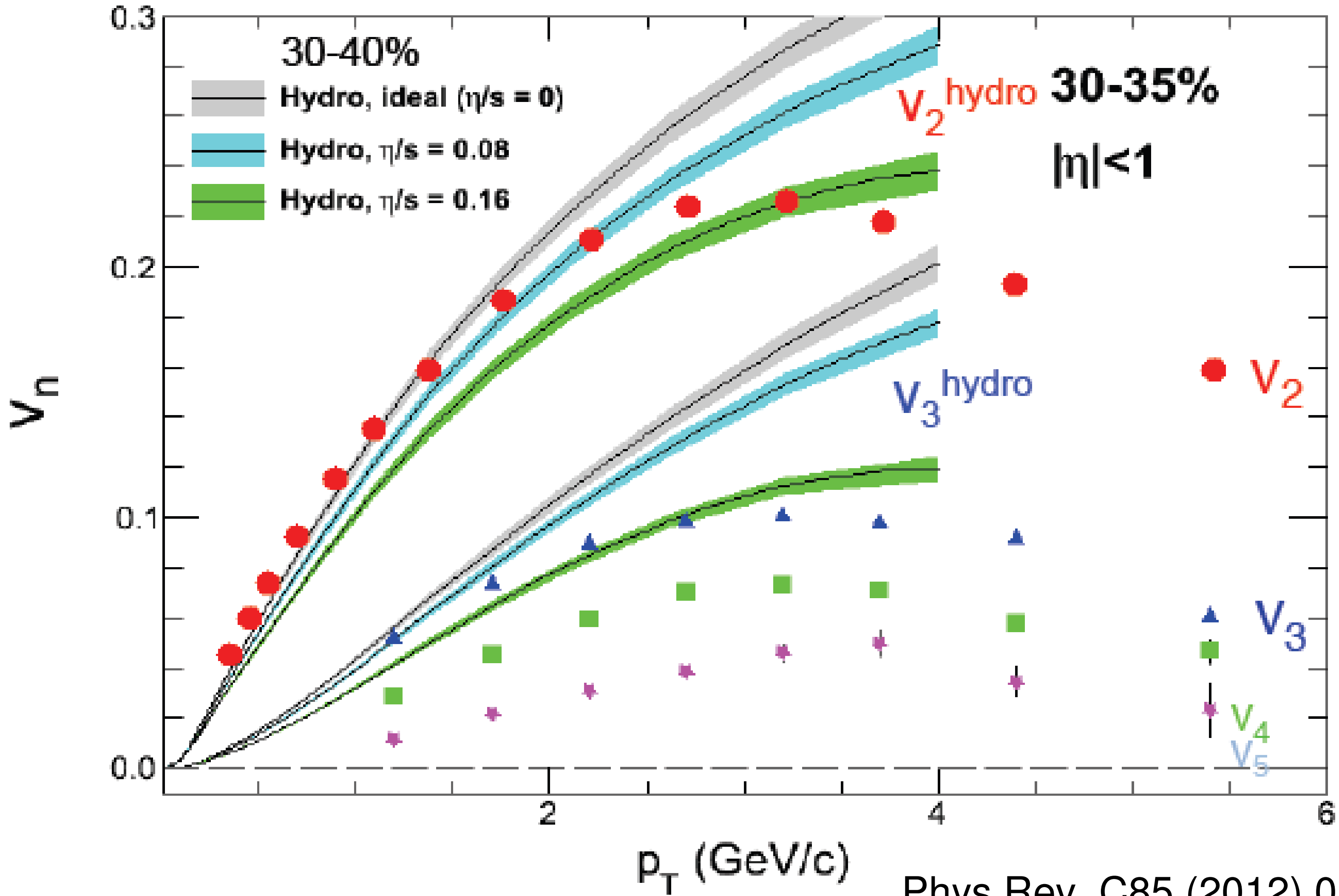
Higher-order Fourier harmonics



V_n (n>2) is changing only a little vs. centrality

EPJC 72 (2012) 2012
PRC 87(2013) 014902

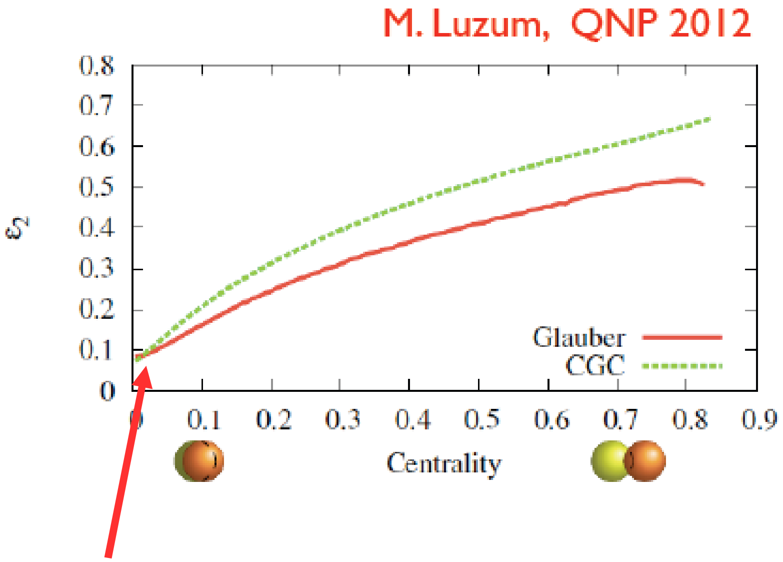
Higher order harmonics



Phys.Rev. C85 (2012) 024901

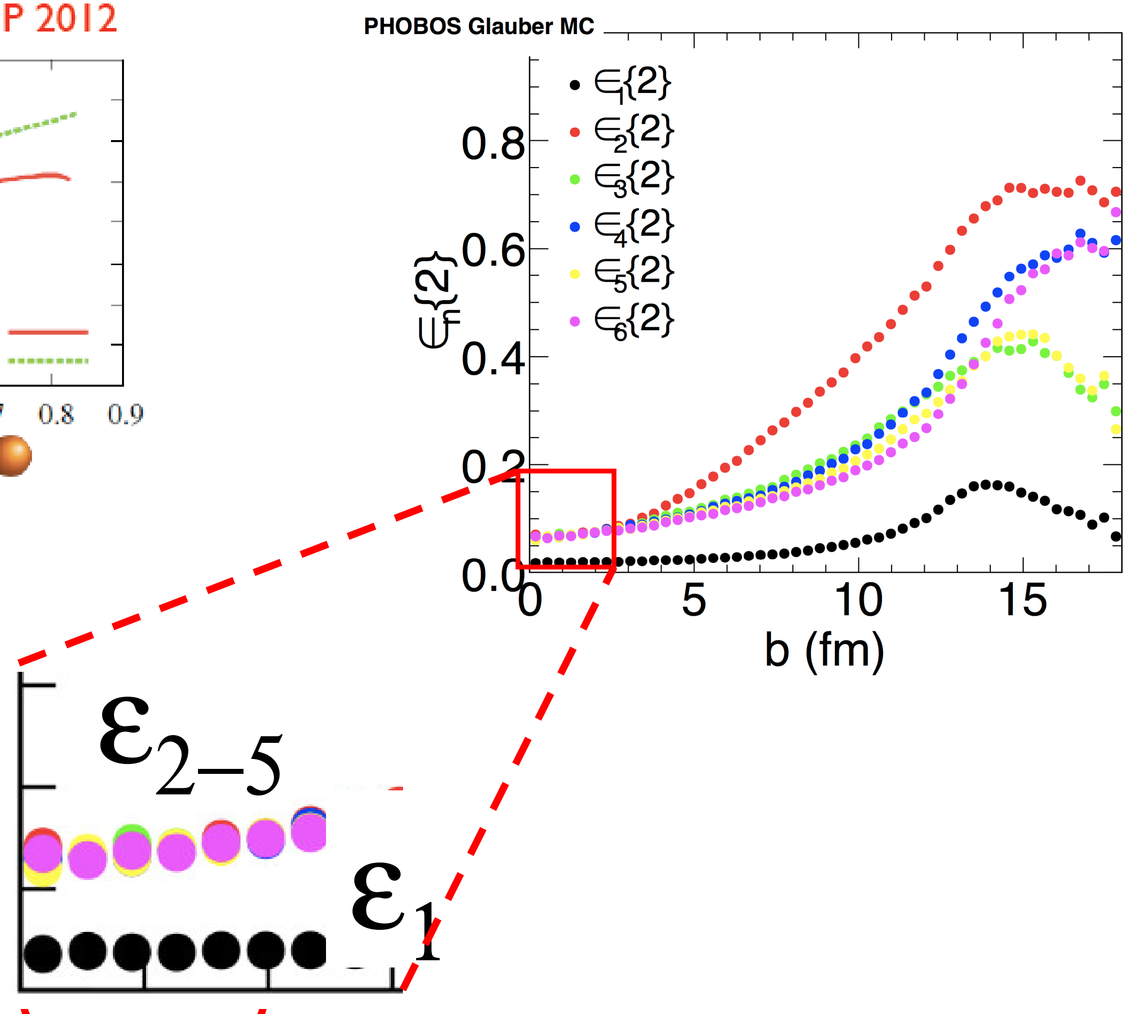
- Hydrodynamical model reproduces the trends well
- η/s close to quantum limit ($1/4\pi$)

Ultra-central collisions



insensitive to initial conditions

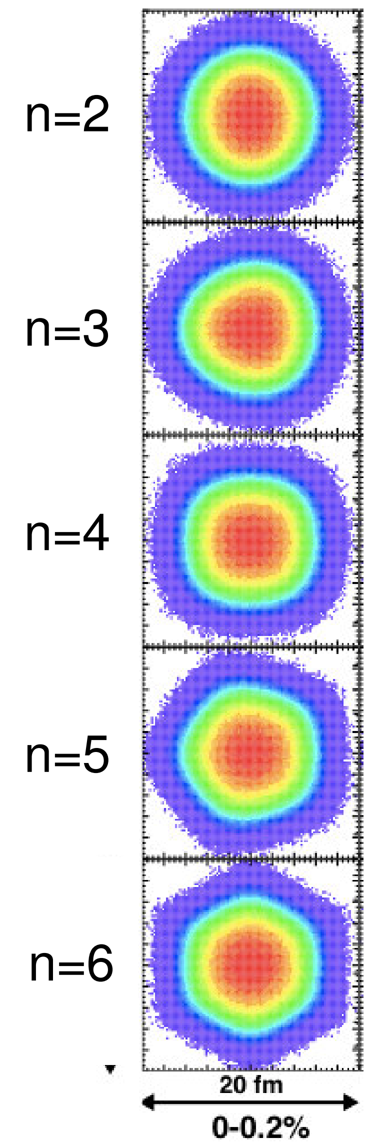
n^{th} order eccentricities vs b



b<2fm

ε_2-ε_5 converge in ultra-central collisions

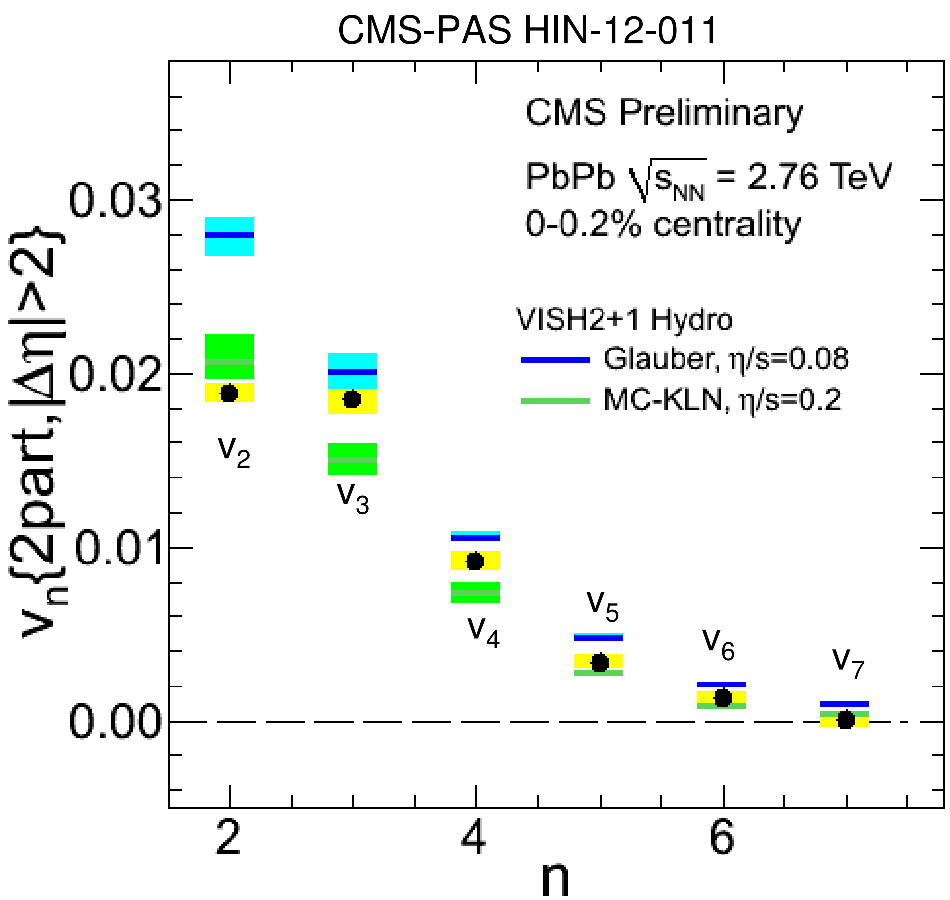
0.2% most central



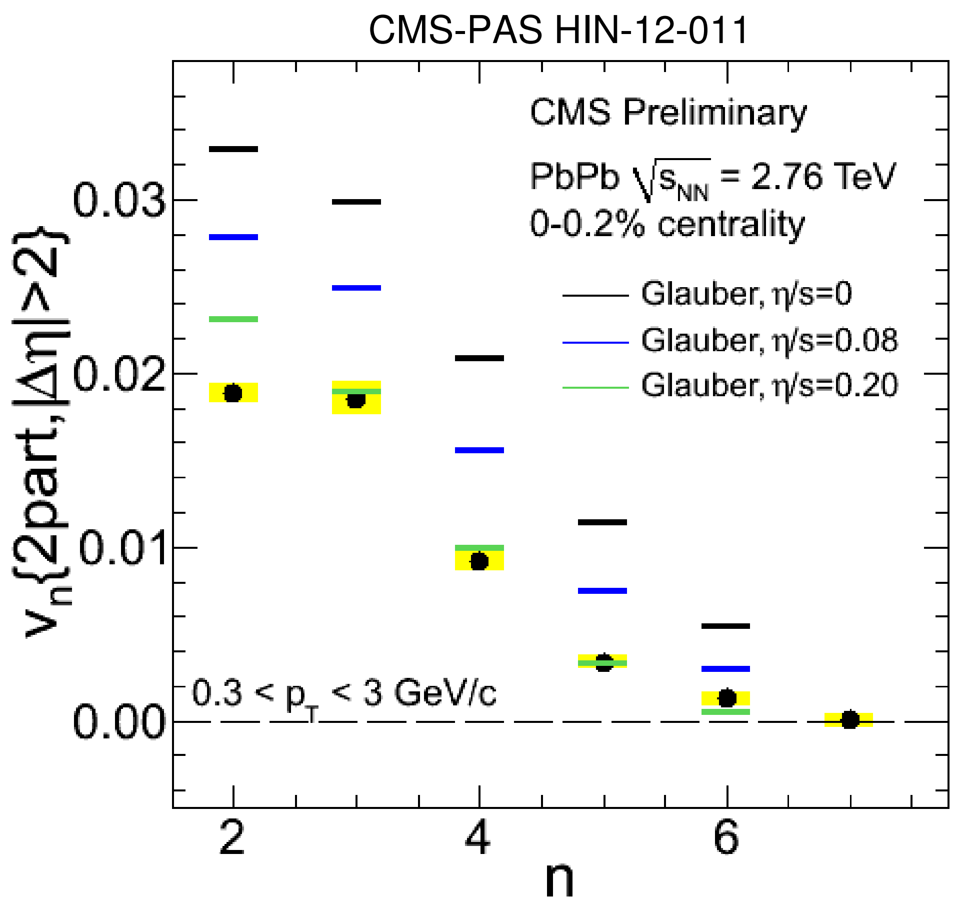
Participant distribution relative to the n^{th} order participant plane

Ultra-central collisions

Calculation by Heinz et al.



Calculation by Luzum et al.



Unique perspective on hydrodynamic flow

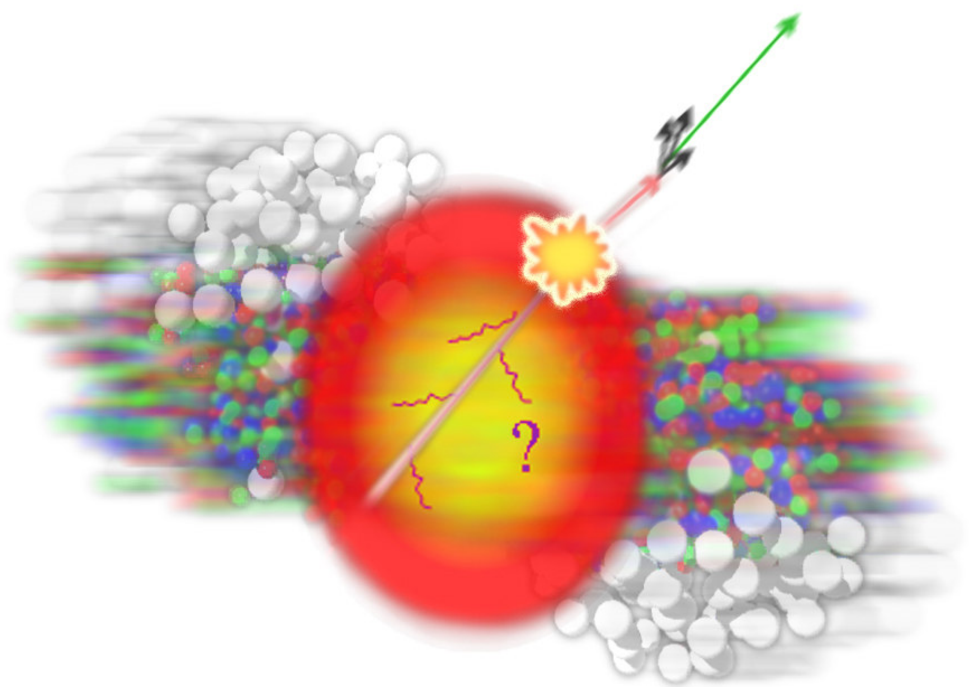
- Hierarchy of coefficients reproduced by hydro
- Some tension between v_2 and $v_{3..7}$

Note, AMPT 0-0.2%: <b> = 1.6fm, RMS(b) = 0.6fm

Summary: global observables

- Charged particle multiplicity reaches 1600 particles per η unit
- Steeply increasing $dE_T/d\eta$ vs. $\sqrt{s}$
- E_T at very high η changes less with centrality (than at $\eta=0$)
- Average rapidity loss only slightly higher than at RHIC
- Azimuthal asymmetry: LHC similar to RHIC
- v_2/eccentricity scales with transverse particle density
- Extended longitudinal scaling in line with RHIC data

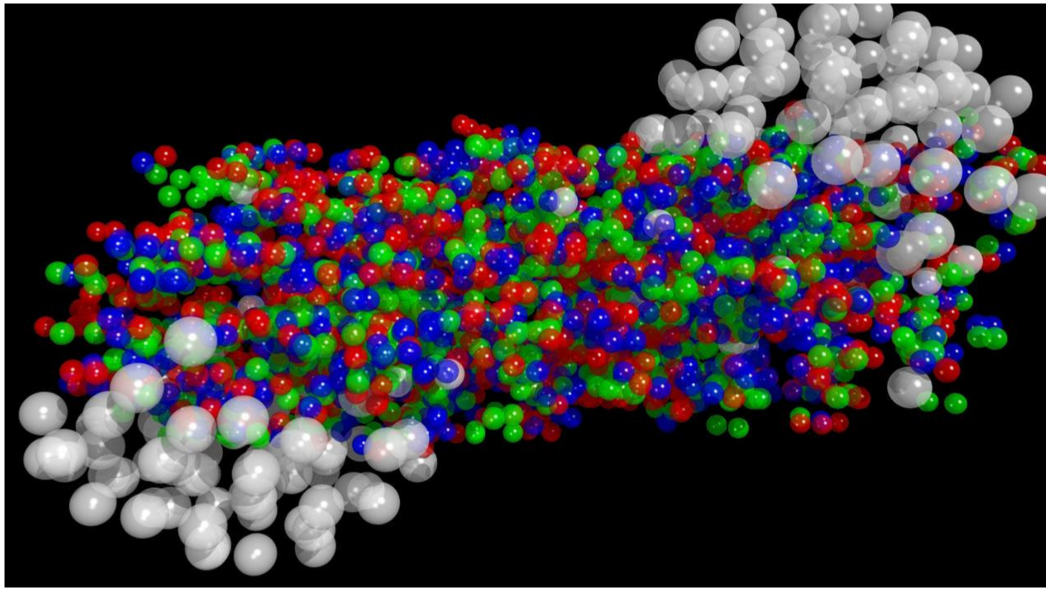
Hard probes



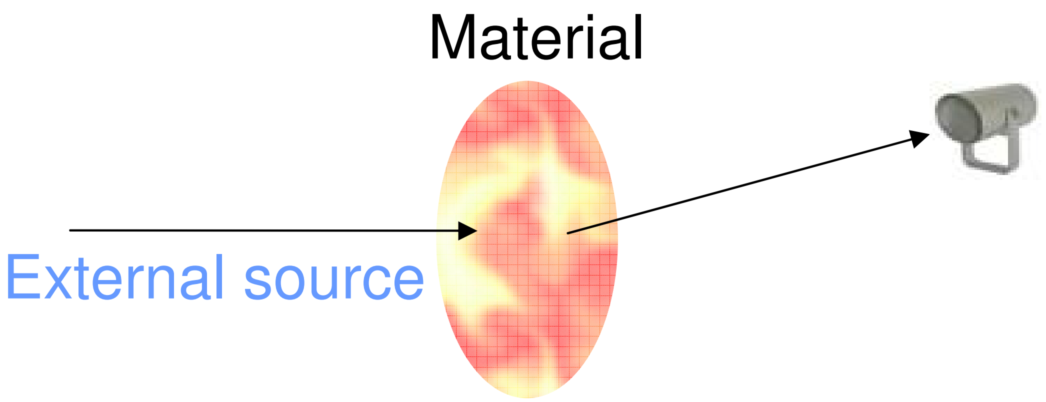
Hard probes of heavy ion physics

- Goal: Understand the properties of QGP

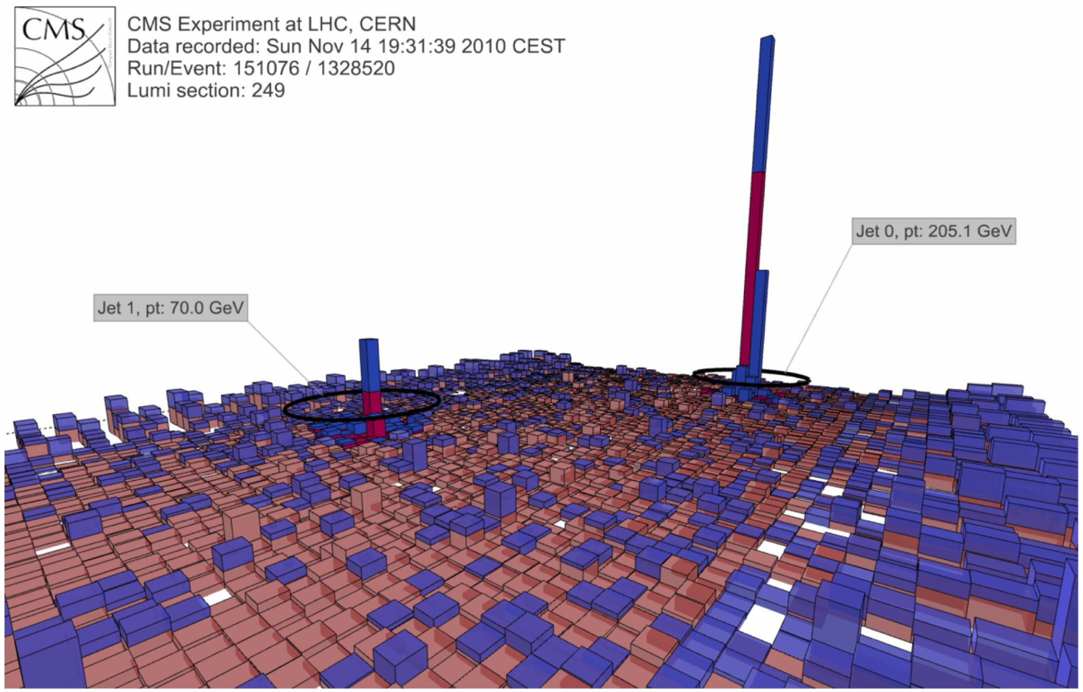
- Problem: the lifetime of QGP is so short (O(fm/c)) such that it is not feasible to probe it with an external source.



- Solution: take advantage of the large cross-sections of high p_T jets, γ/W/Z, quarkonia at the LHC energy, use these hard probes produced in the collision itself.

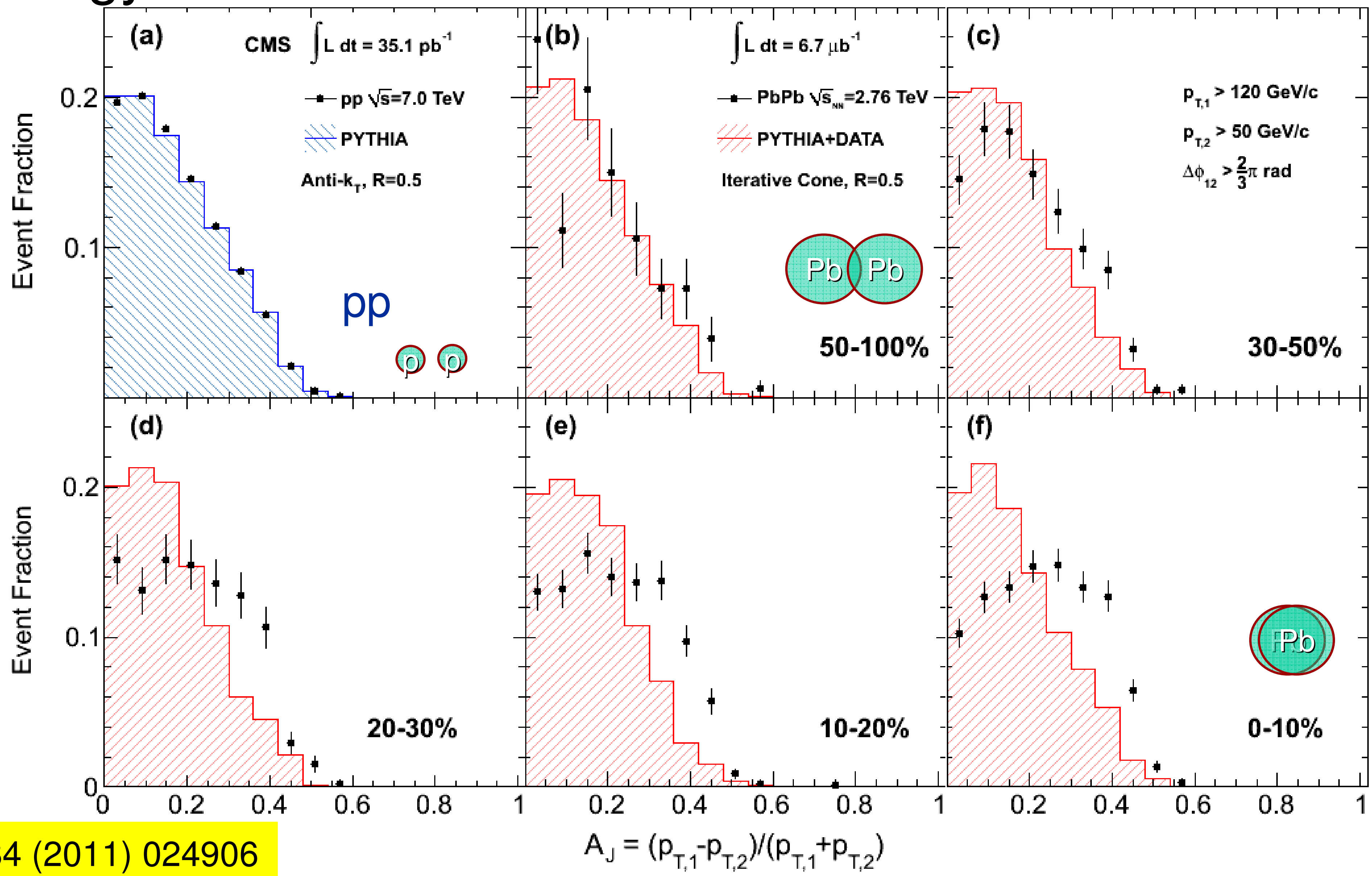


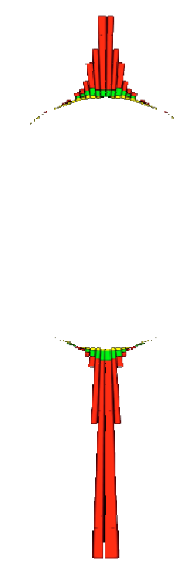
Jets: how strongly interacting is the medium?



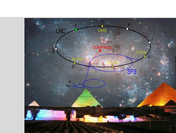
Jet energy imbalance

- Parton energy loss is observed as a pronounced dijet energy imbalance in central PbPb collisions



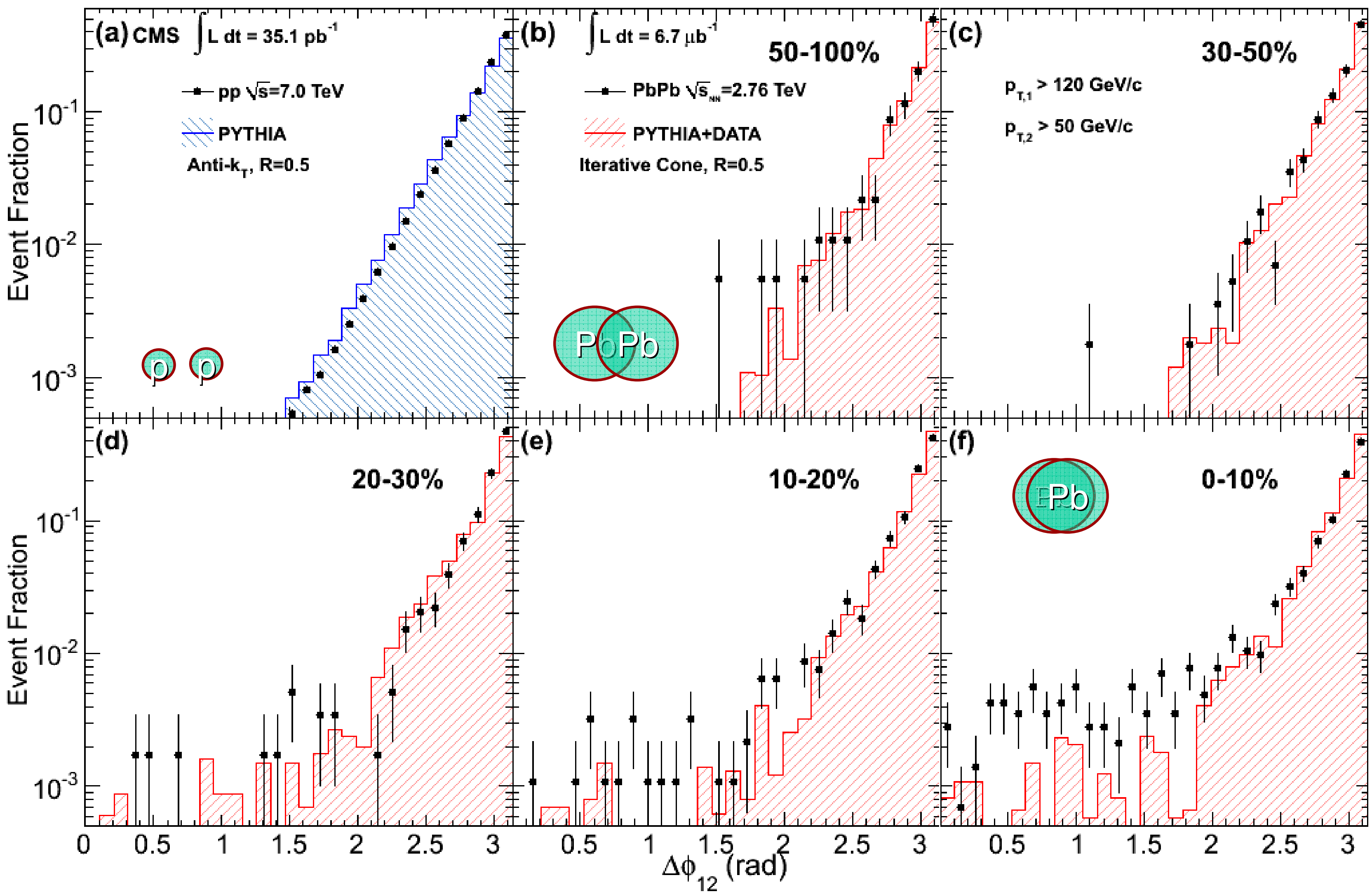


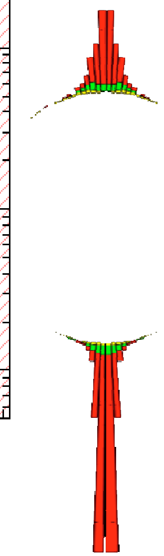
PRC 84 (2011) 024906



Dijets in PbPb – no φ-decorrelation

- The propagation of high-p_T partons in a dense nuclear medium does **not** lead to a visible angular decorrelation



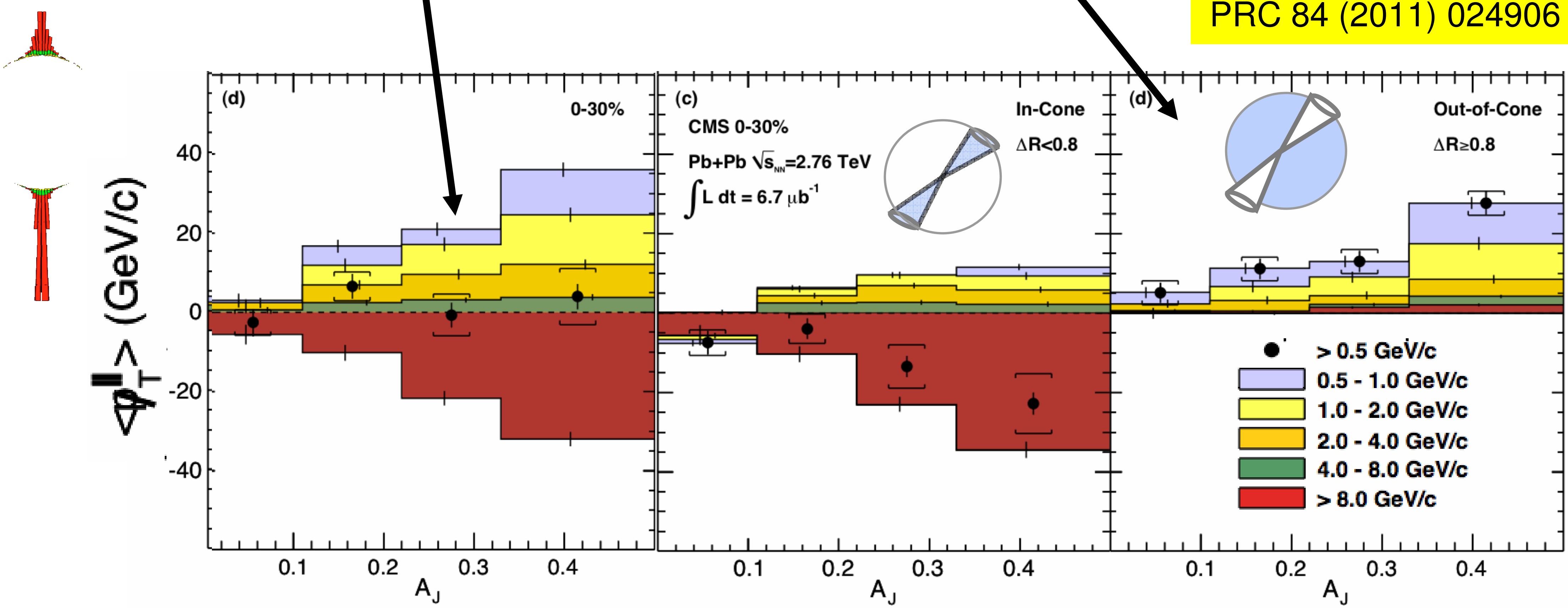


PRC 84 (2011) 024906

Dijets – energy redistribution

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

PRC 84 (2011) 024906

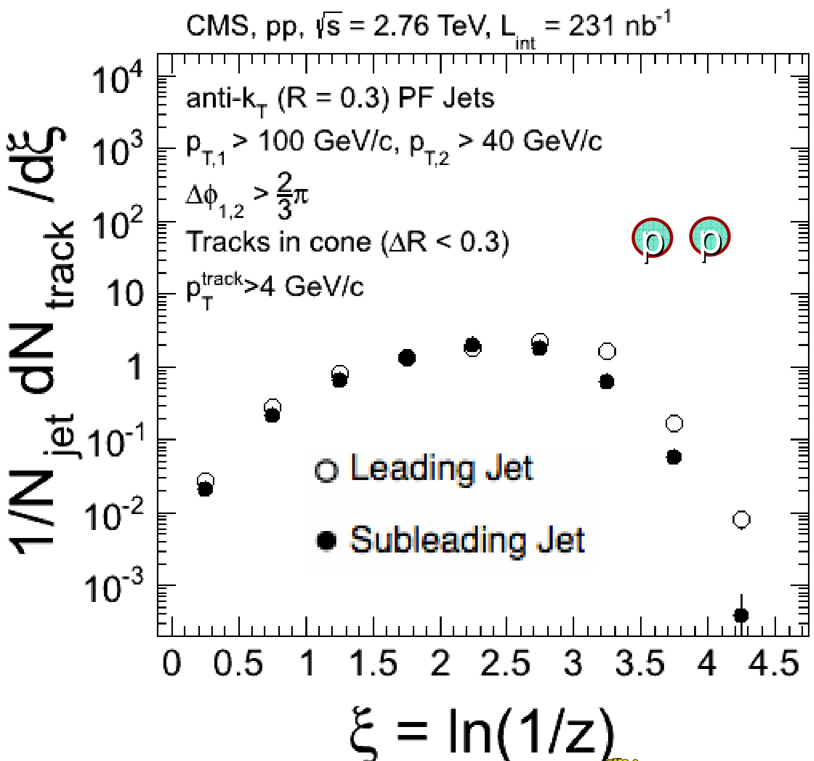


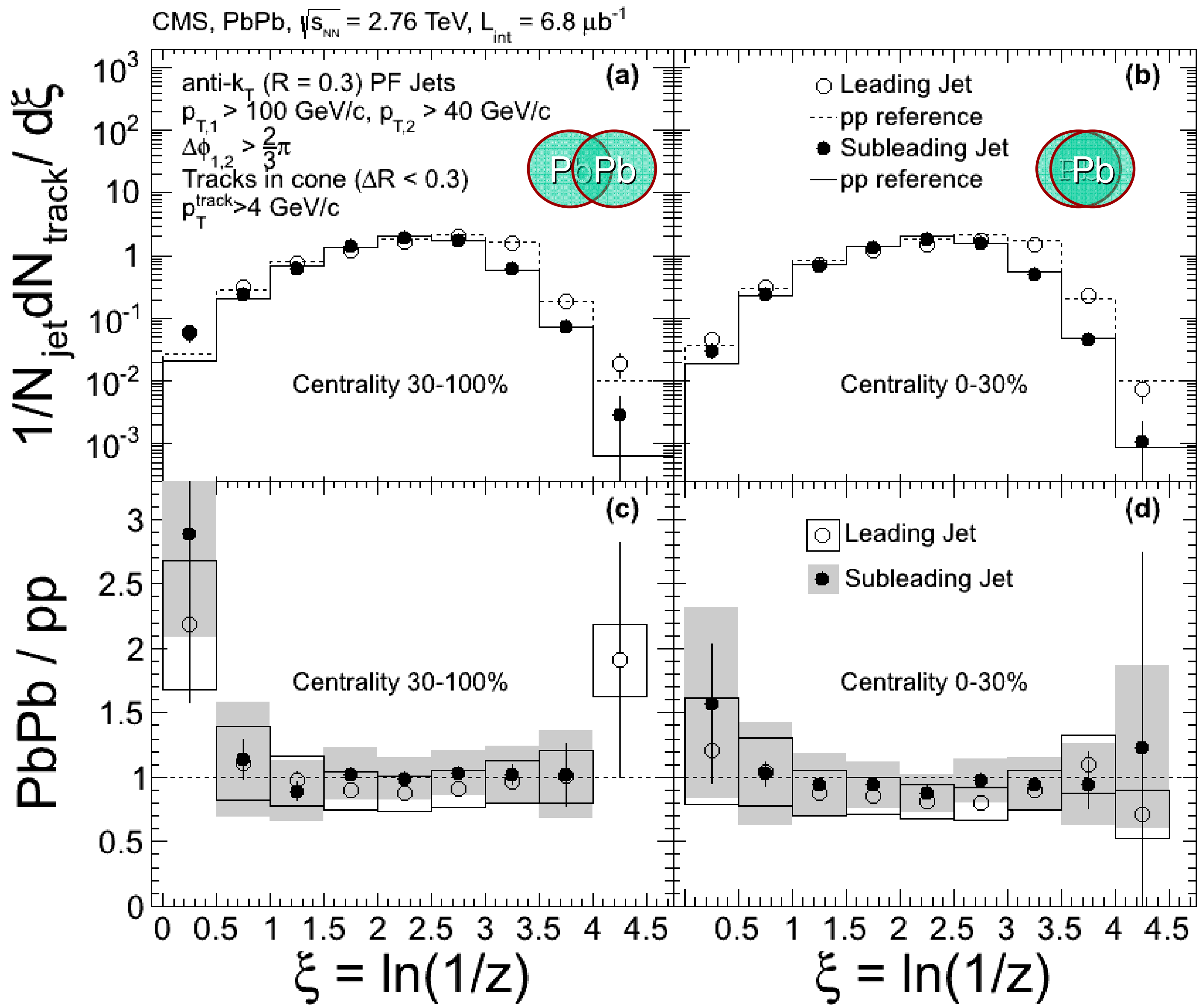
$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

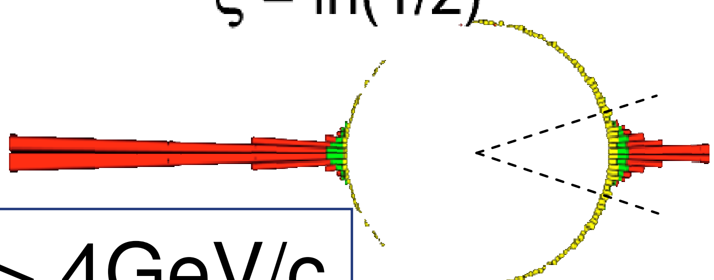
$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

Dijets – jet fragmentation

- Hard part of the fragmentation is independent of energy lost in medium, ~consistent with pp





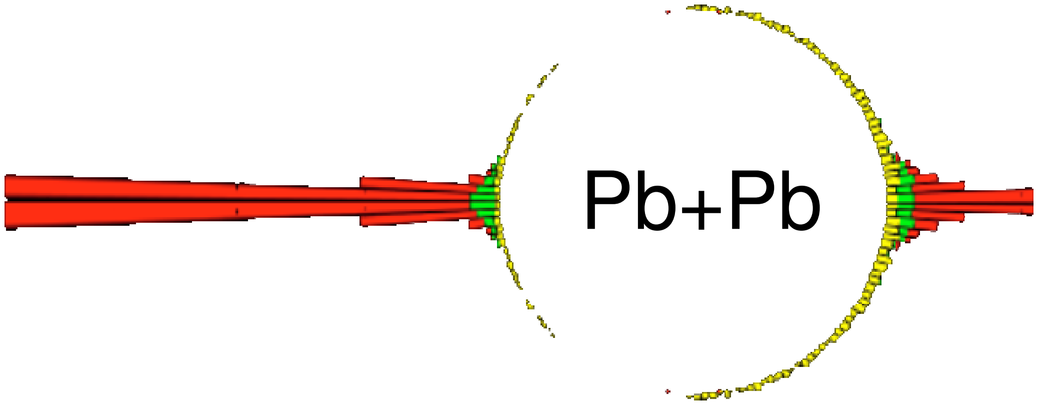


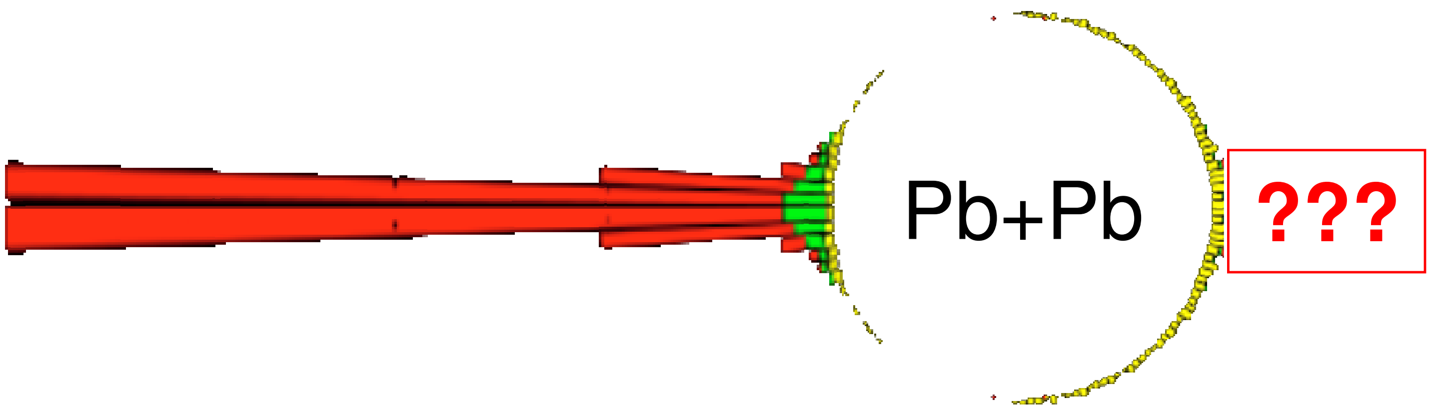
$p_T > 4 GeV/c$

JHEP 10 (2012) 087

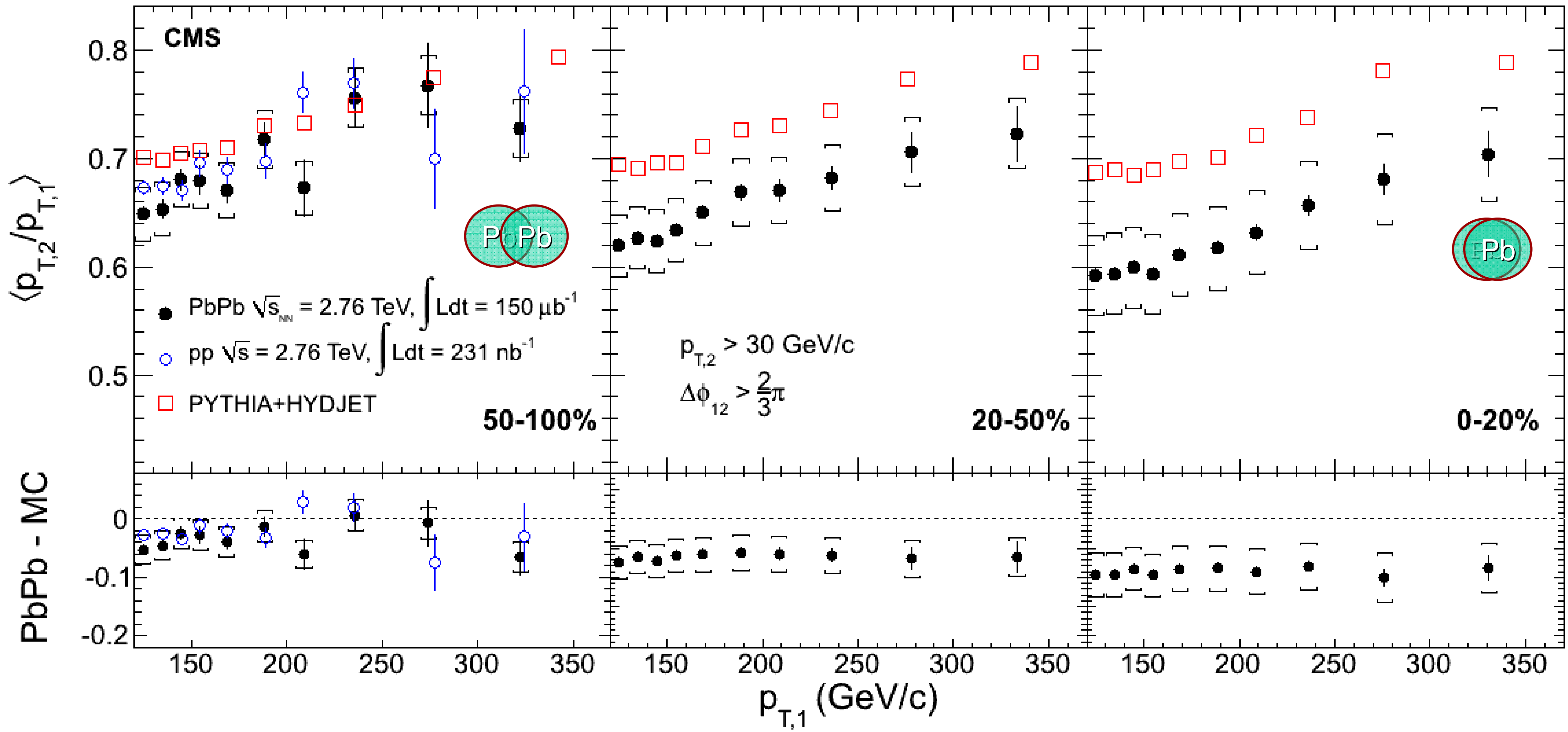
$\Delta R = 0.3$

How does the dijet imbalance depend on the leading jet energy?





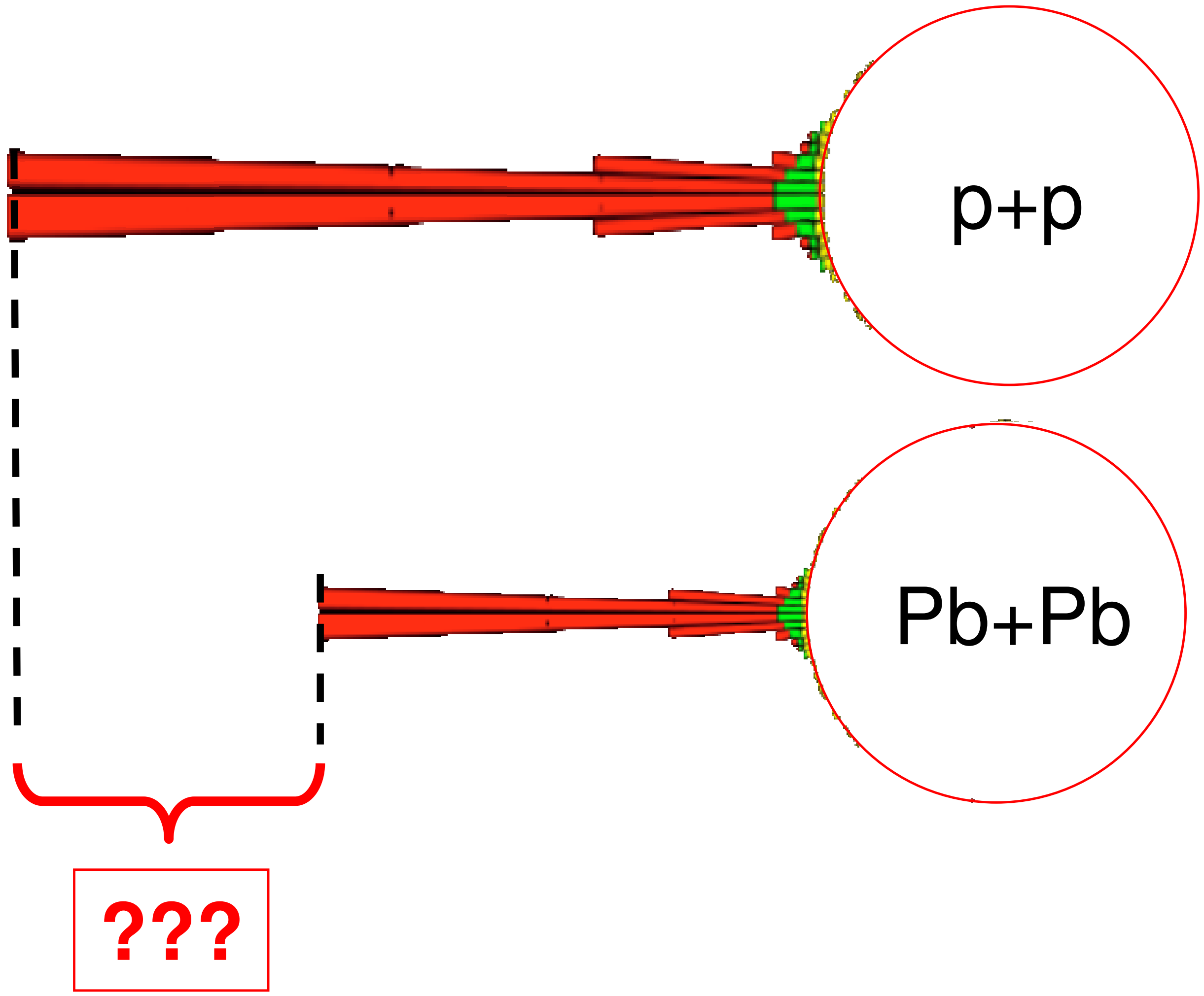
Dijet energy ratio (imbalance)



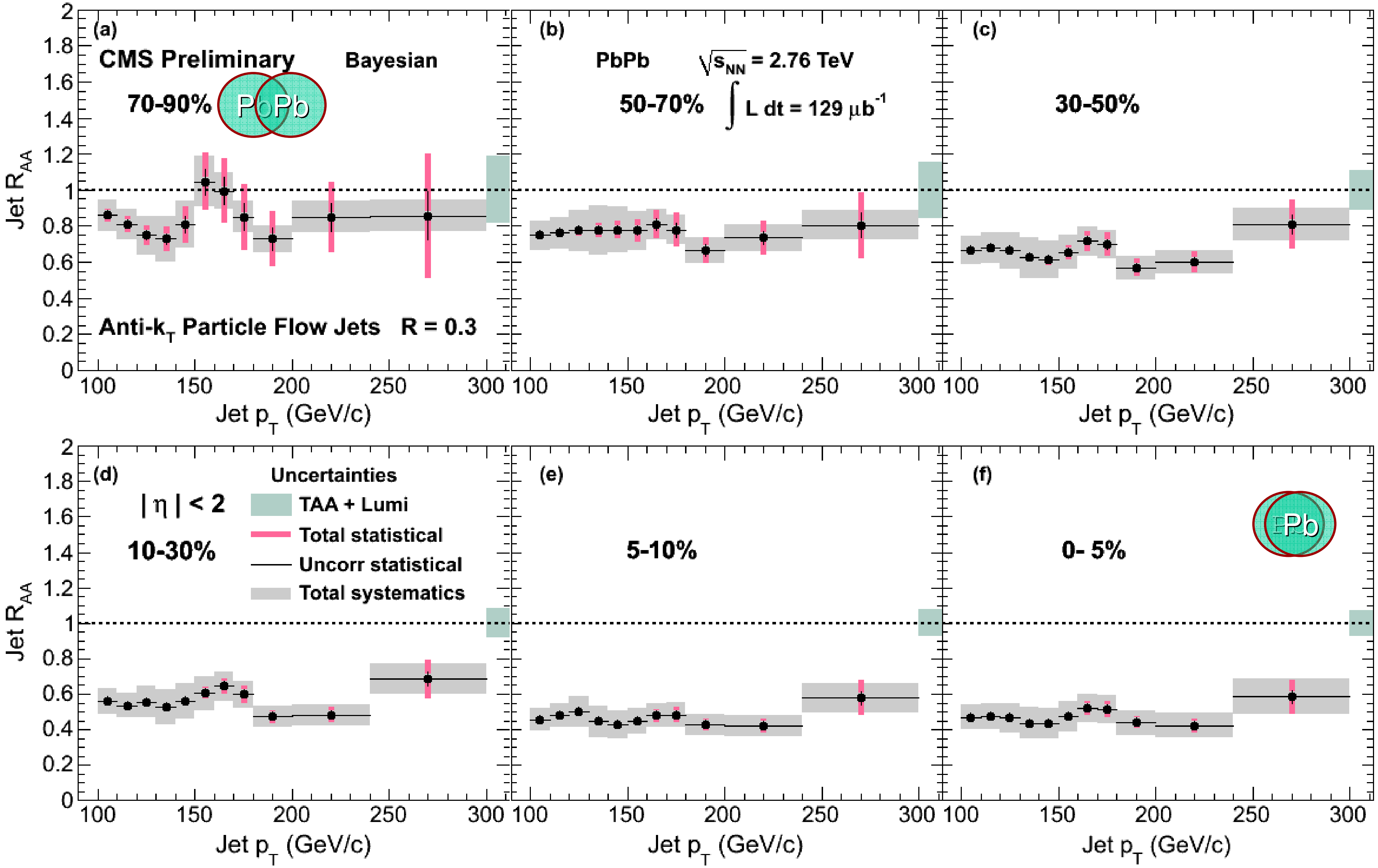
- Energy imbalance increases with centrality
- p_T-ratio deviates from the unquenched reference in a p_T-independent way

PLB 712 (2012) 176

How much energy do single jets lose?



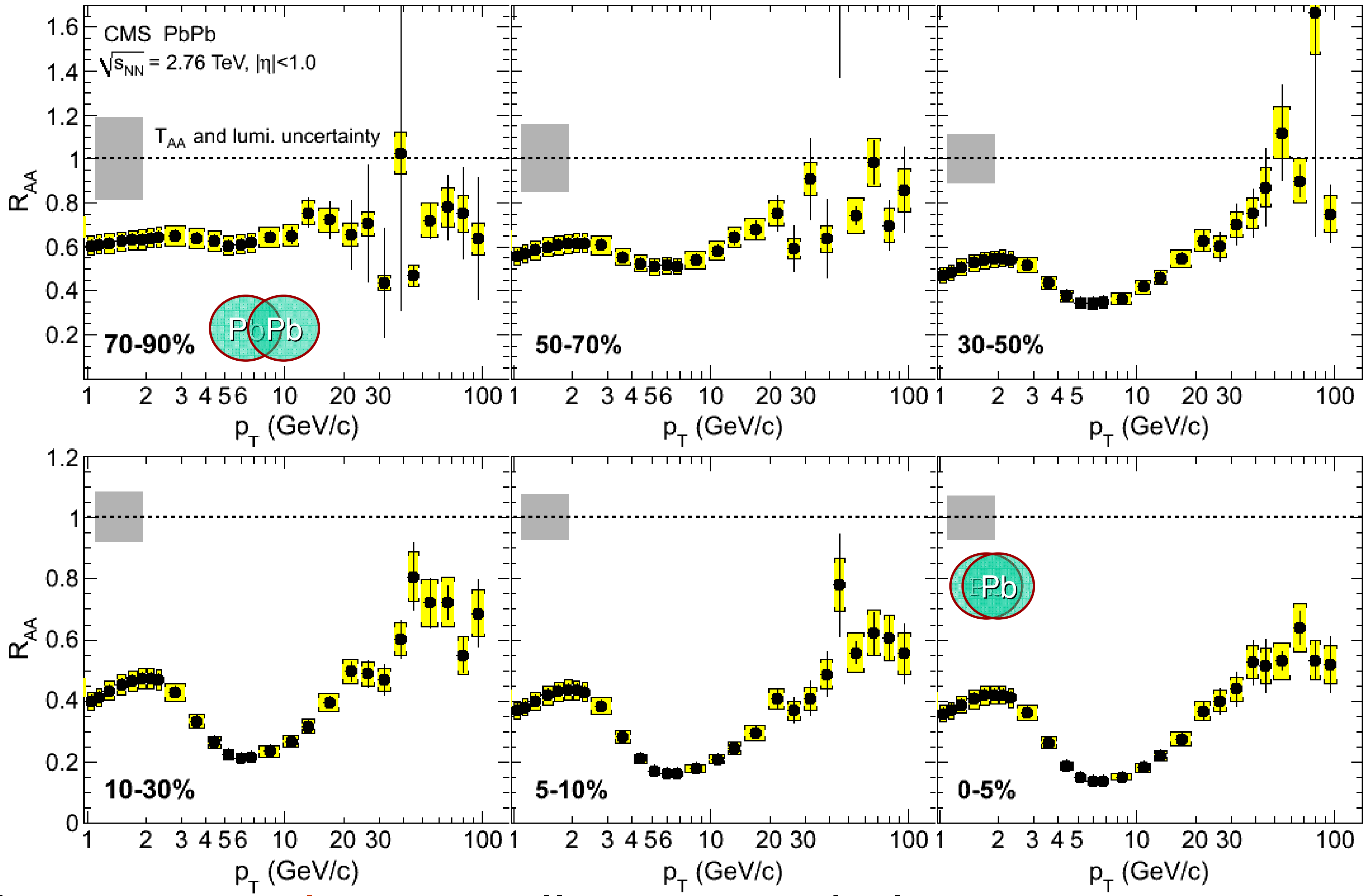
Nuclear modification factors of jets



Suppression: no significant p_T–dependence

CMS PAS HIN-12-004

Charged hadron R_{AA}: update with 2011 data

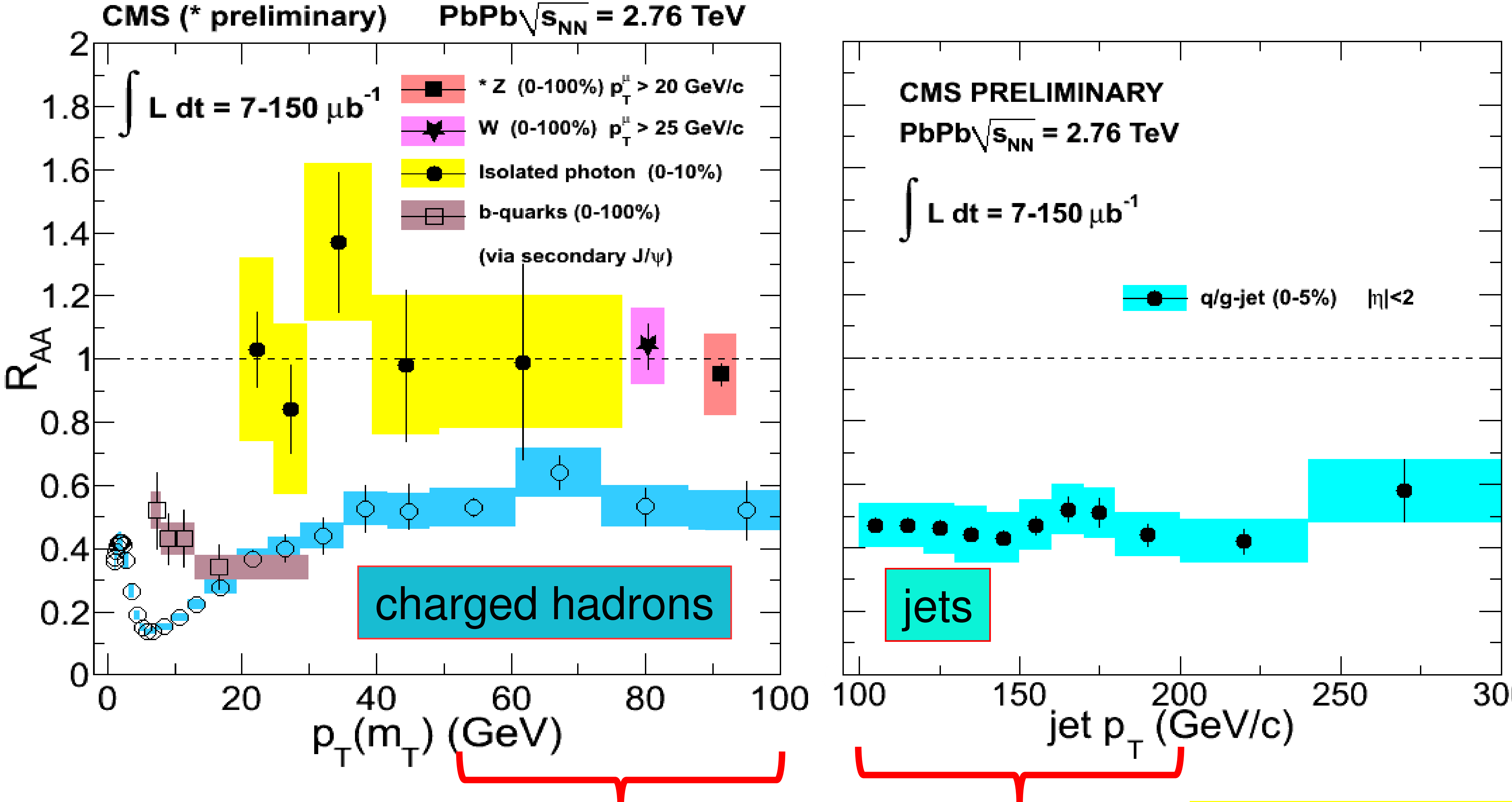


20 times more data, smaller uncertainties

→ what is the connection to jet R_{AA}?

EPJC 72 (2012) 1945

Nuclear modification factors

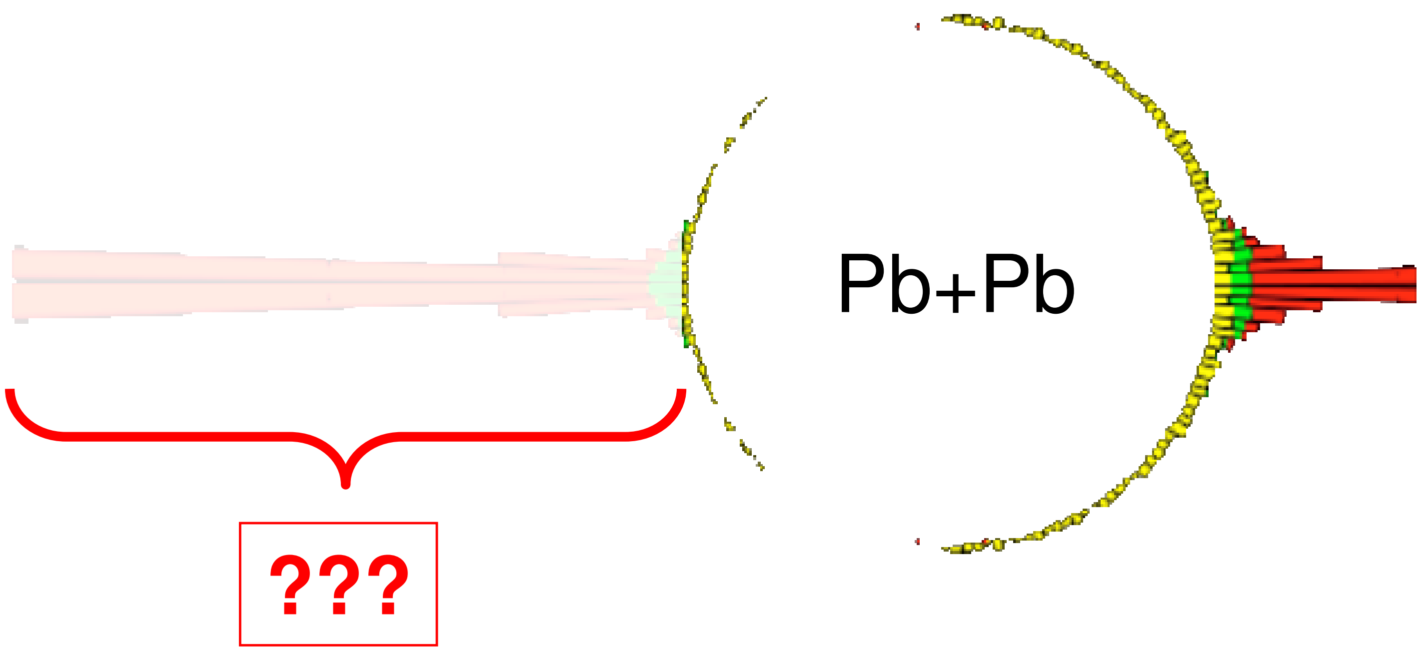


Sampling the ~same parton p_T range

CMS PAS HIN-12-004

Note: jets fragment into high-p_T particles in pp and PbPb the same way – *see later…*

How can we quantify the jet energy loss with a ‘calibrated’ measurement?



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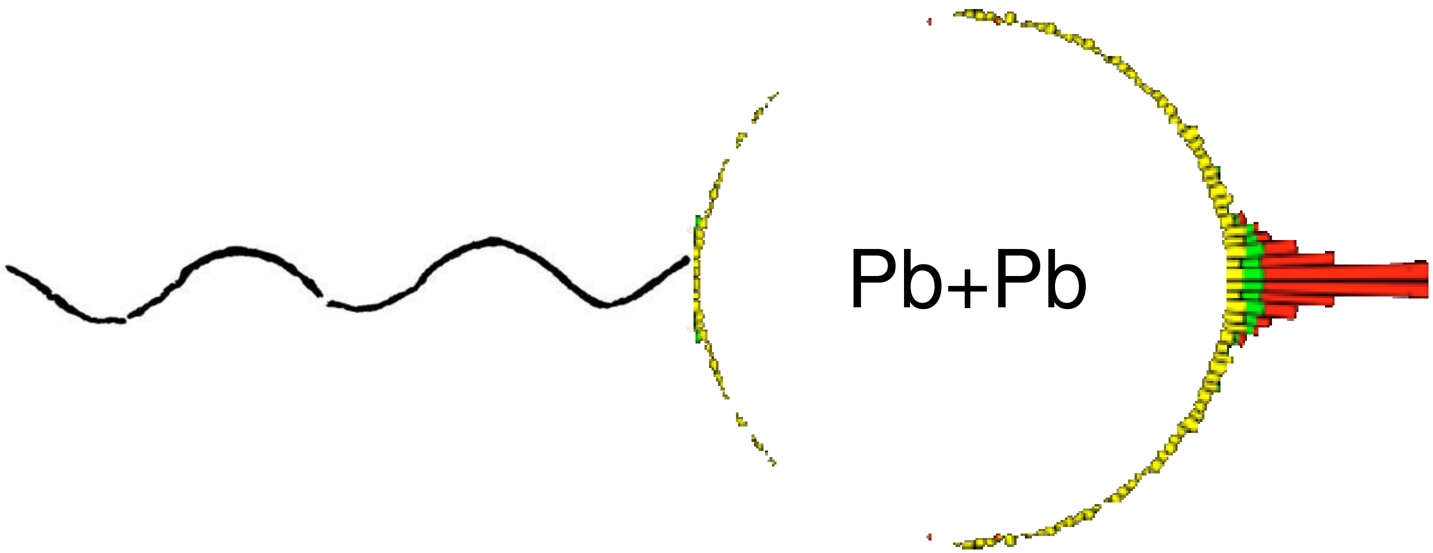
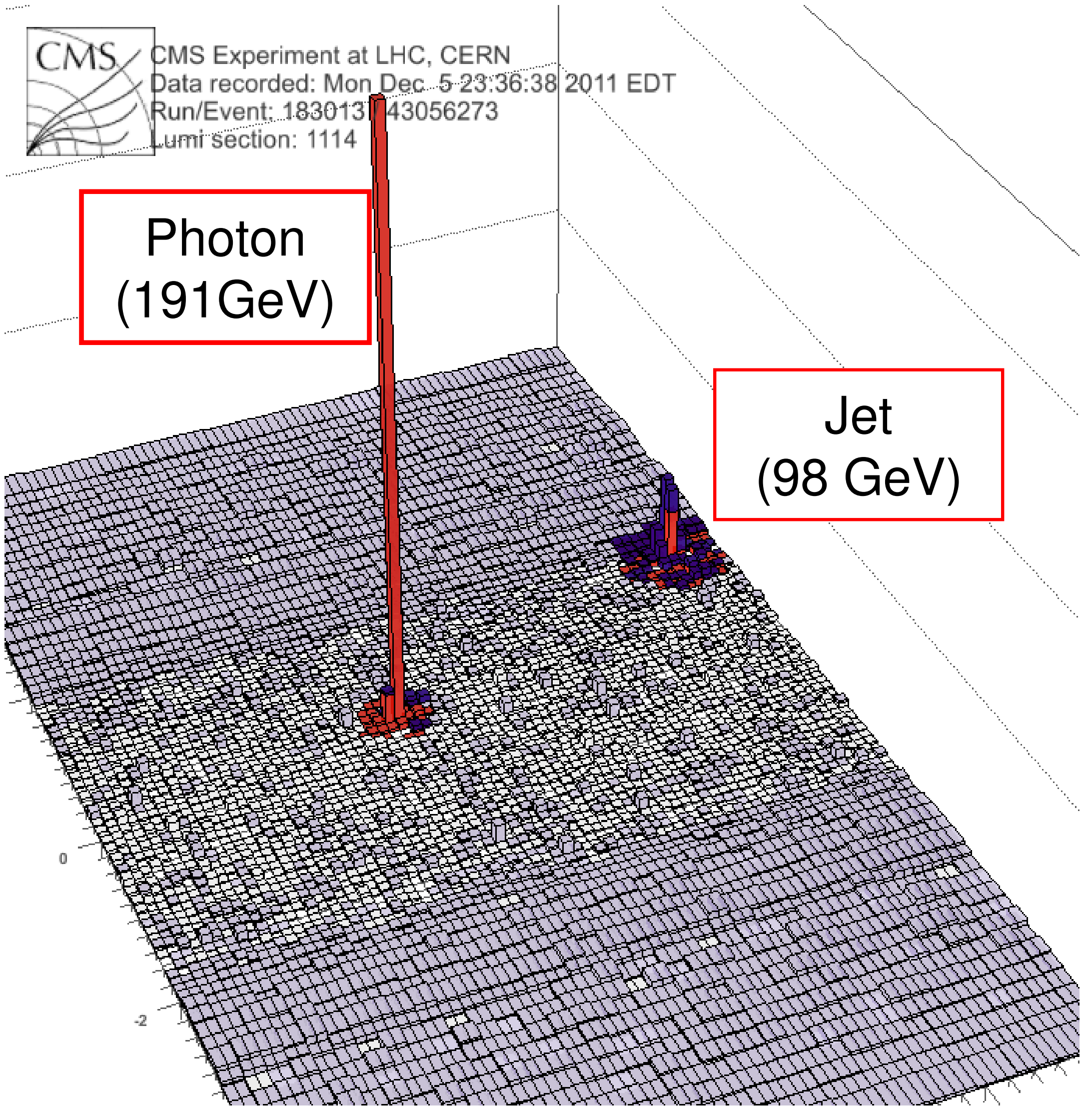
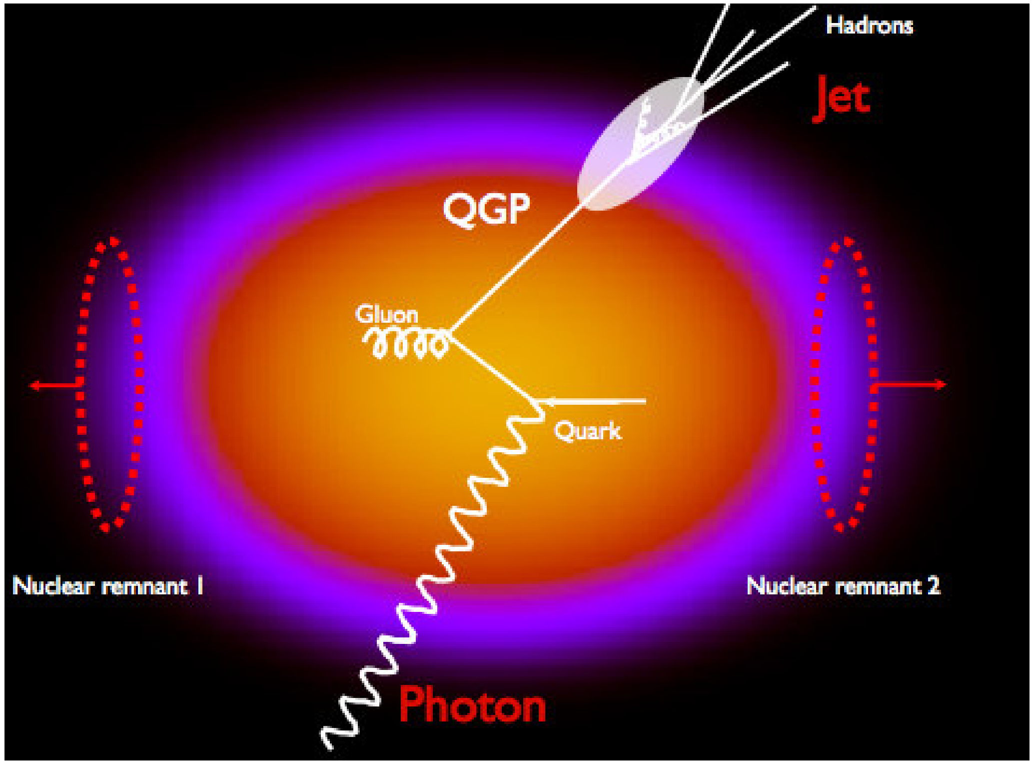


γ+jet: u, d quark energy loss



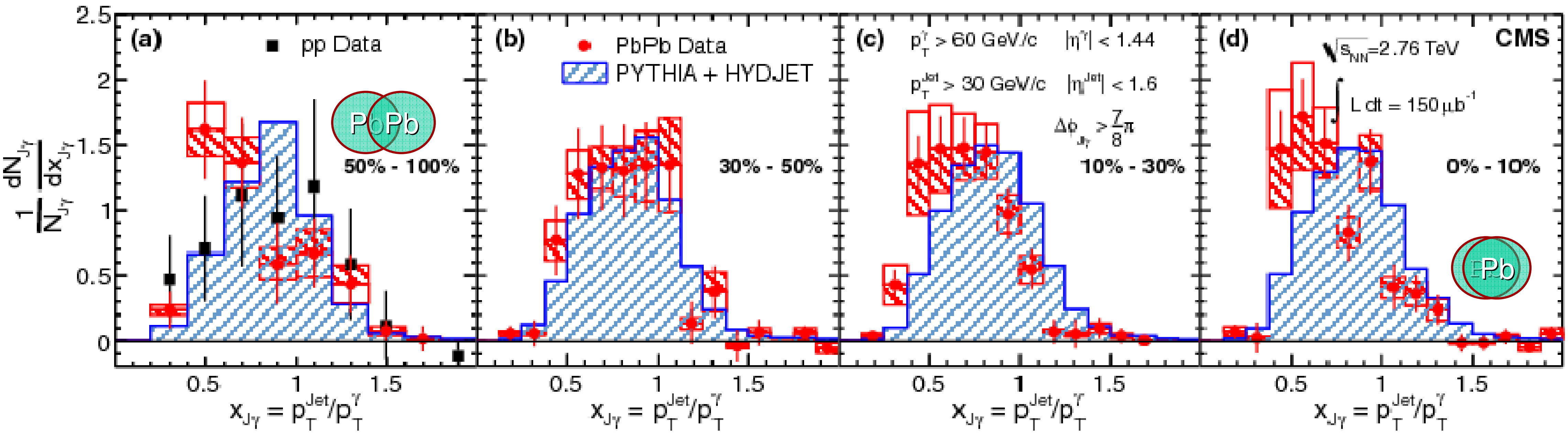


Photon tag:

- Identifies jet as u,d quark jet
- Provides initial quark direction
- Provides initial quark p_T

γ-jet correlations

- Photons serve as an unmodified energy tag for the jet partner
- Ratio of the p_T of jets to photons ($x_{J\gamma}=p_T^{jet}/p_T^{\gamma}$) is a direct measure of the jet energy loss
- Gradual centrality-dependence of the $x_{J\gamma}$ distribution

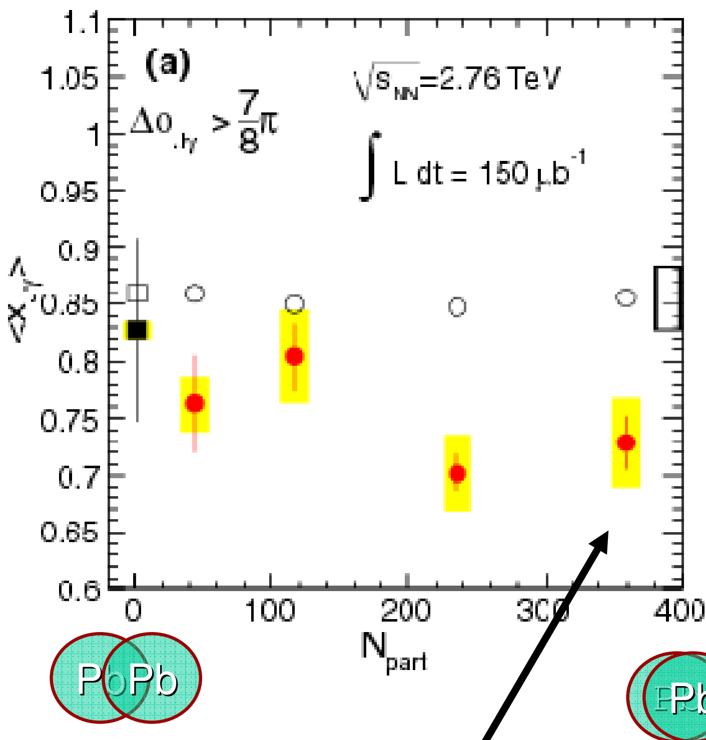


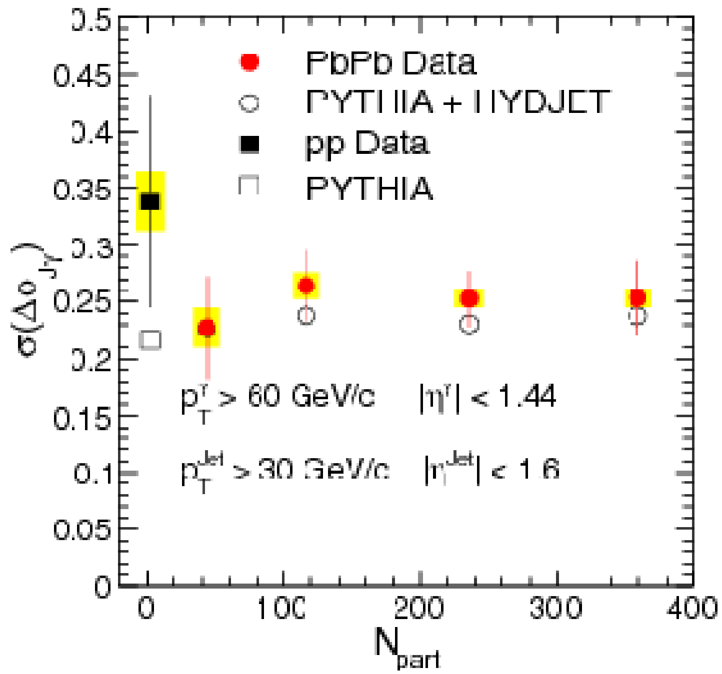
PLB 718 (2013) 773

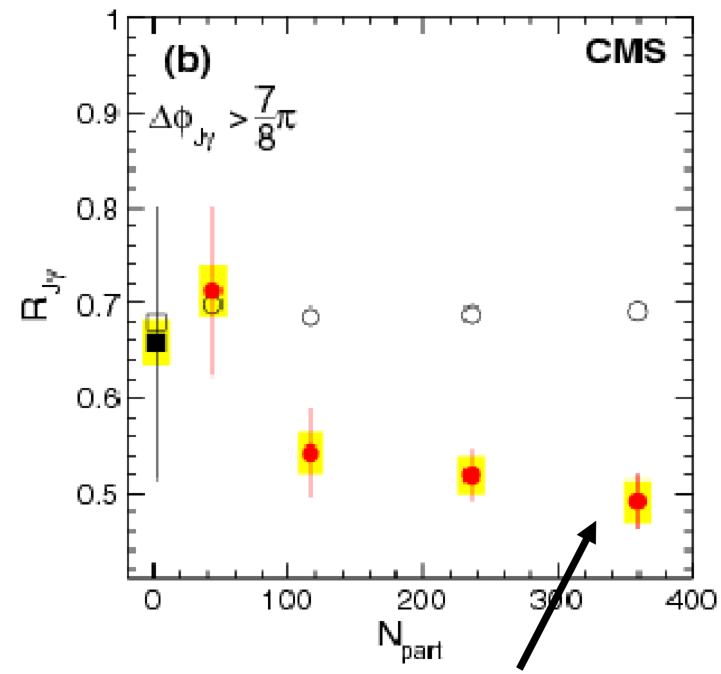
γ-jet correlations

$x_{J\gamma} = p_T^{jet}/p_T^{\gamma}$

$R_{J\gamma}$ = fraction of photons with jet partner >30 GeV/c







Increasing p_T-imbalance

Jets lose ~14% of their initial energy

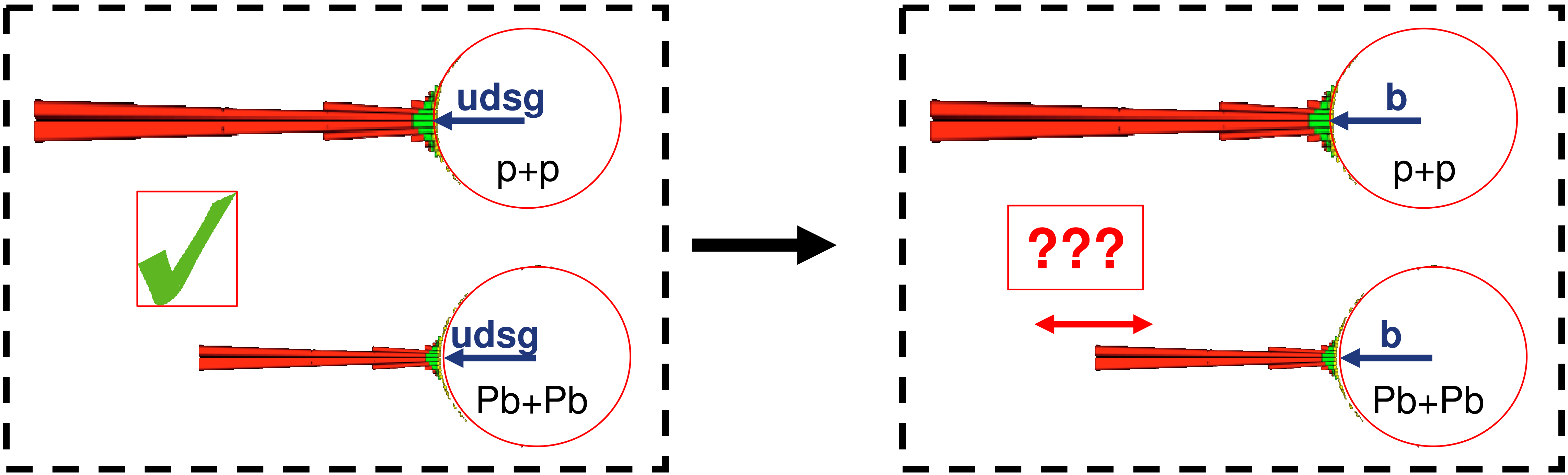
No φ-decorrelation

Less jet partners above threshold

~20% of photons lose their jet partner

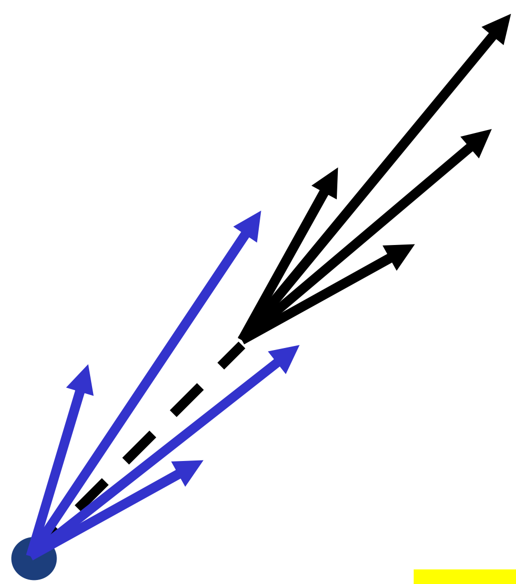
PLB 718 (2013) 773

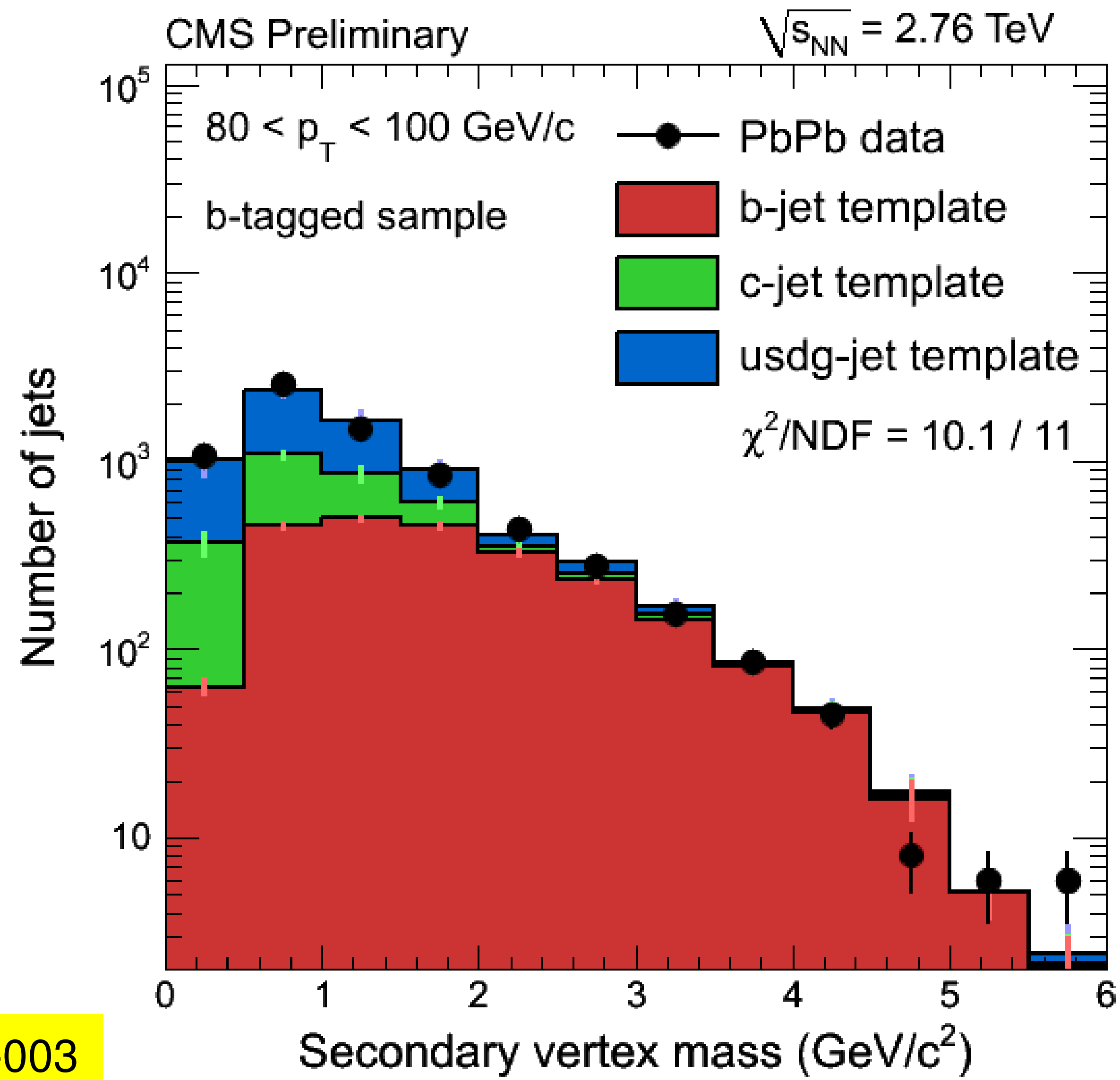
Are heavy-quark jets quenched, too?



Tagging and counting b-quark jets

- Secondary vertex tagged using flight distance significance
- Tagging efficiency estimated in a data-driven way
- Purity from template fits to (tagged) secondary vtx mass distributions

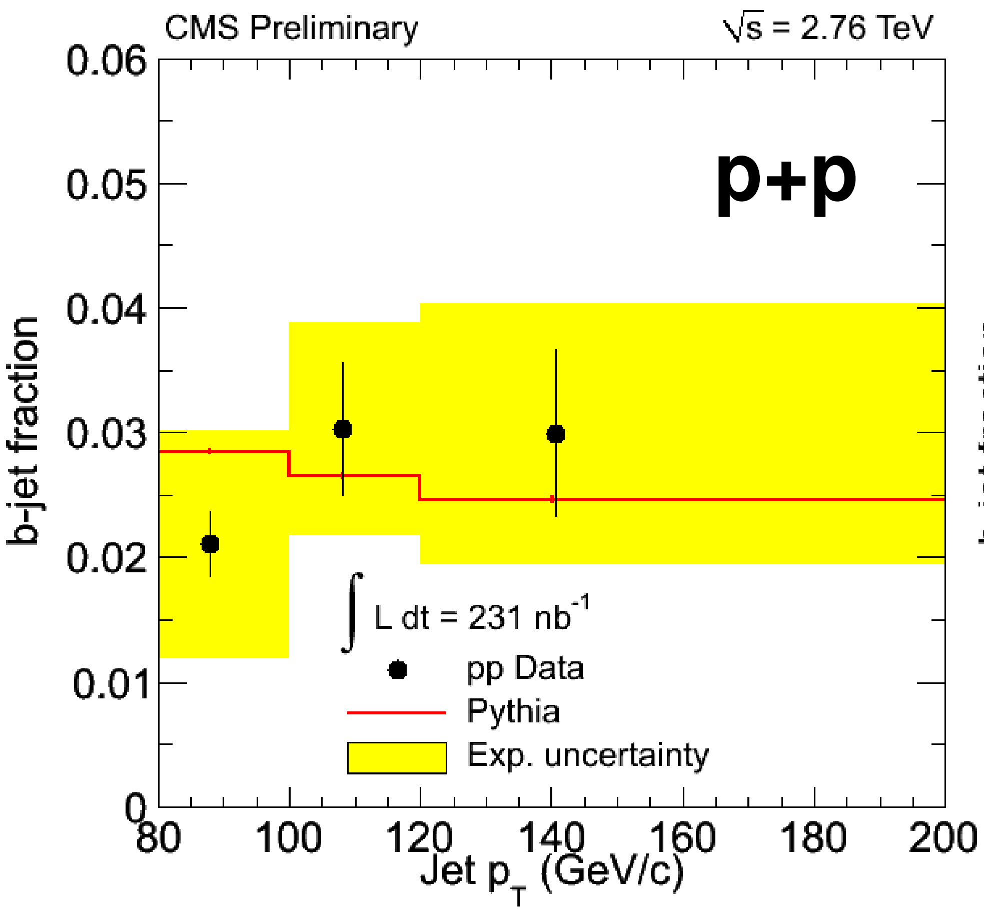


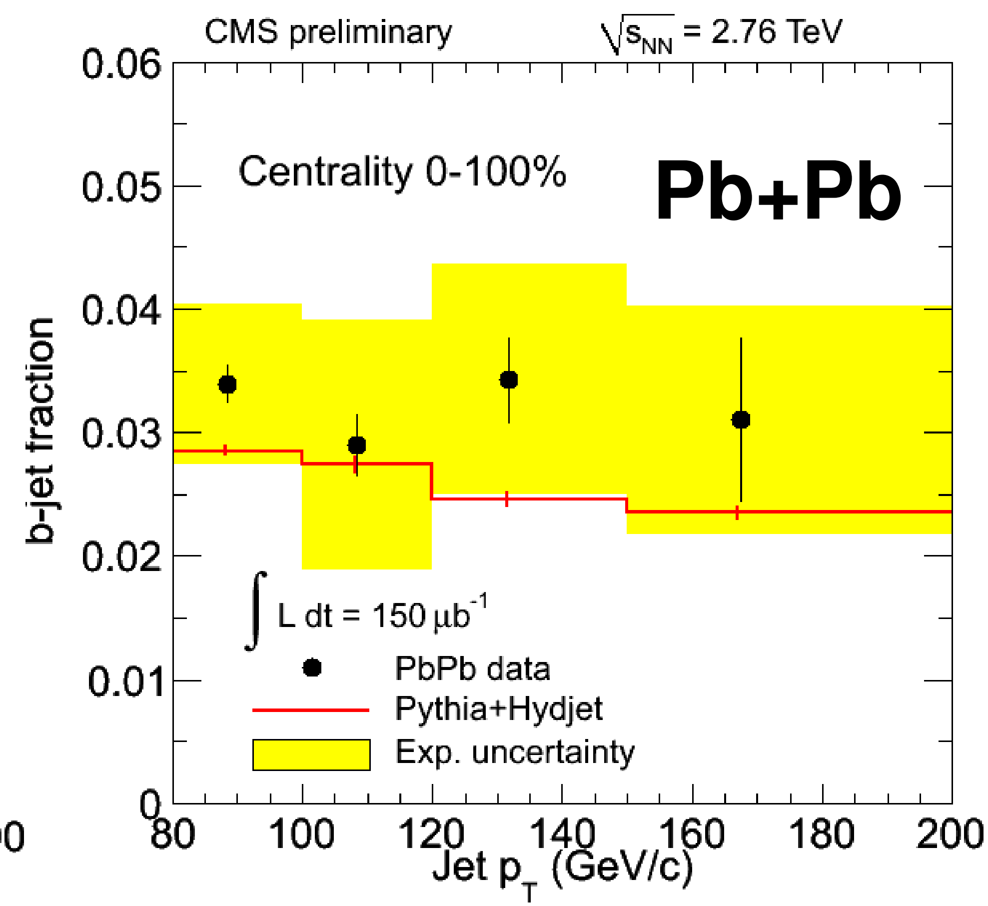


CMS PAS HIN-12-003

Fraction of b-jets among all jets

b-jet fraction: similar in pp and PbPb
→ b-jet quenching is comparable to light-jet quenching (R_{AA}≈0.5), within present systematics

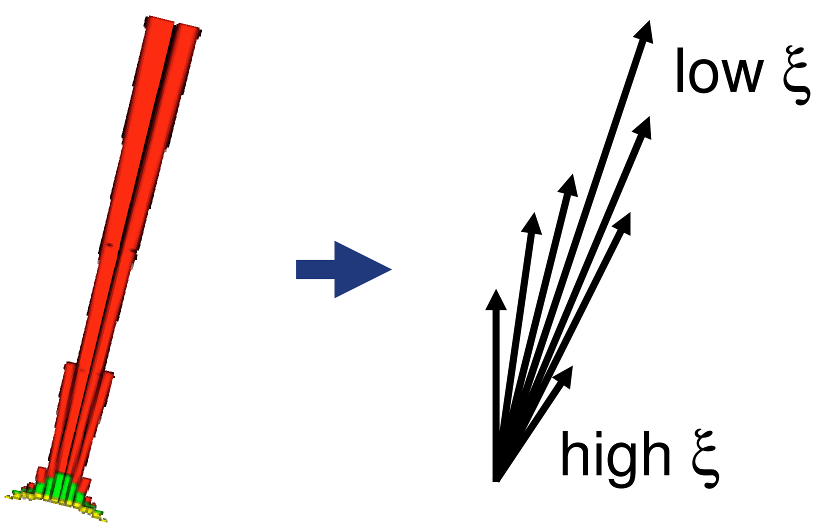


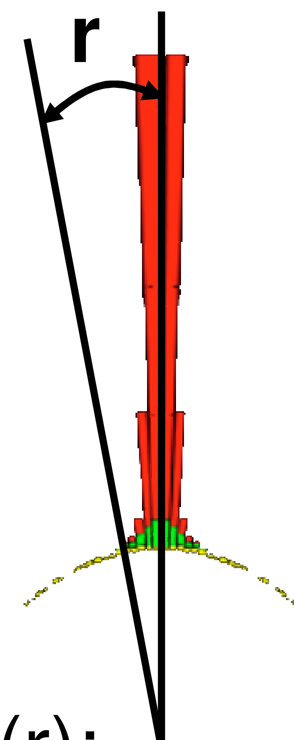


CMS PAS HIN-12-003

How do jets get modified?
Do their shape, or fragmentation change?

Jet fragmentation function:
Distribution of track momenta projected onto the jet axis, presented as a function of $\xi=\ln(p^{jet}/p_{||}^{track})$:

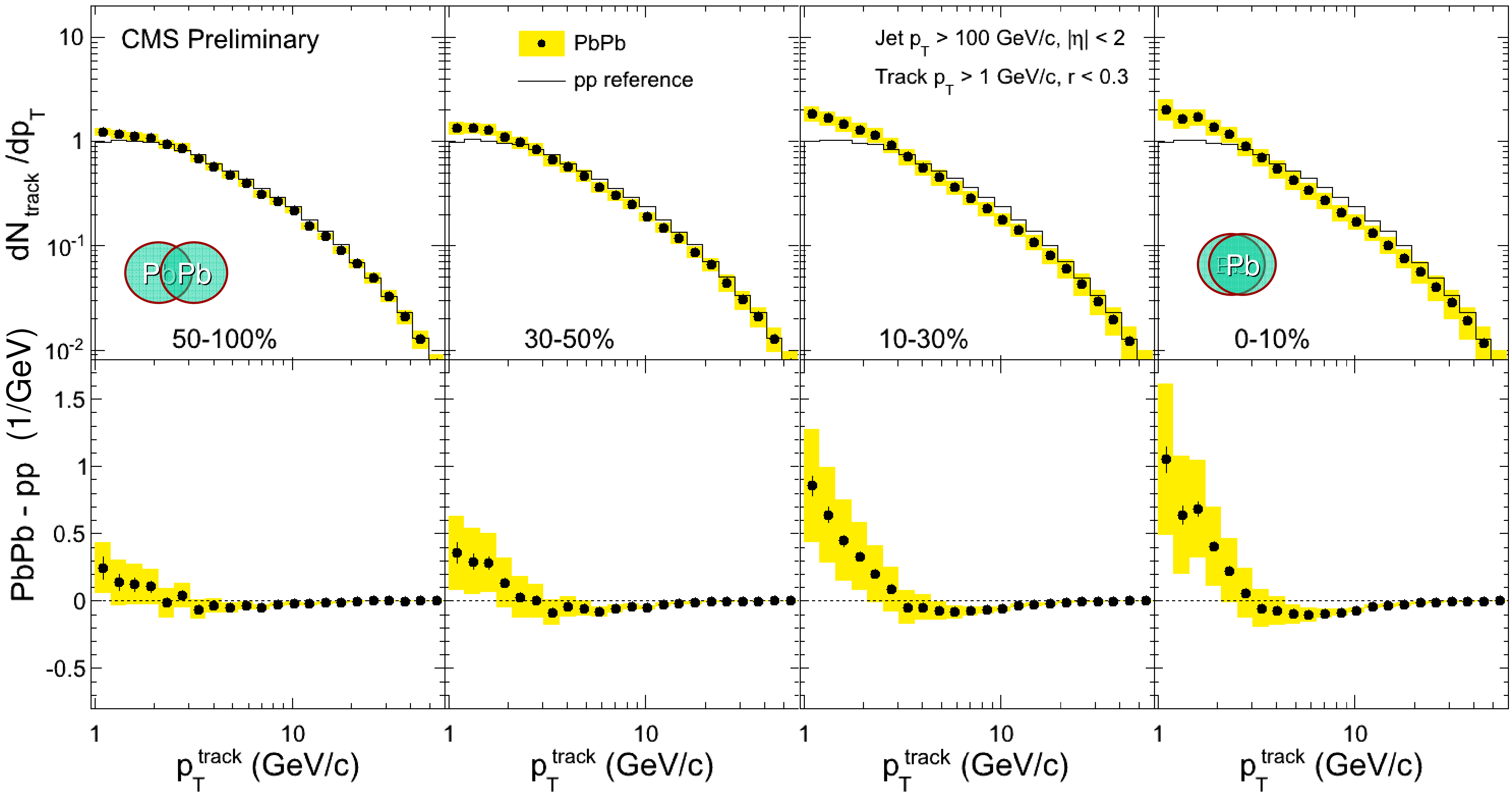




Jet shape:
p_T-flow vs. η-φ distance from the jet axis (r):

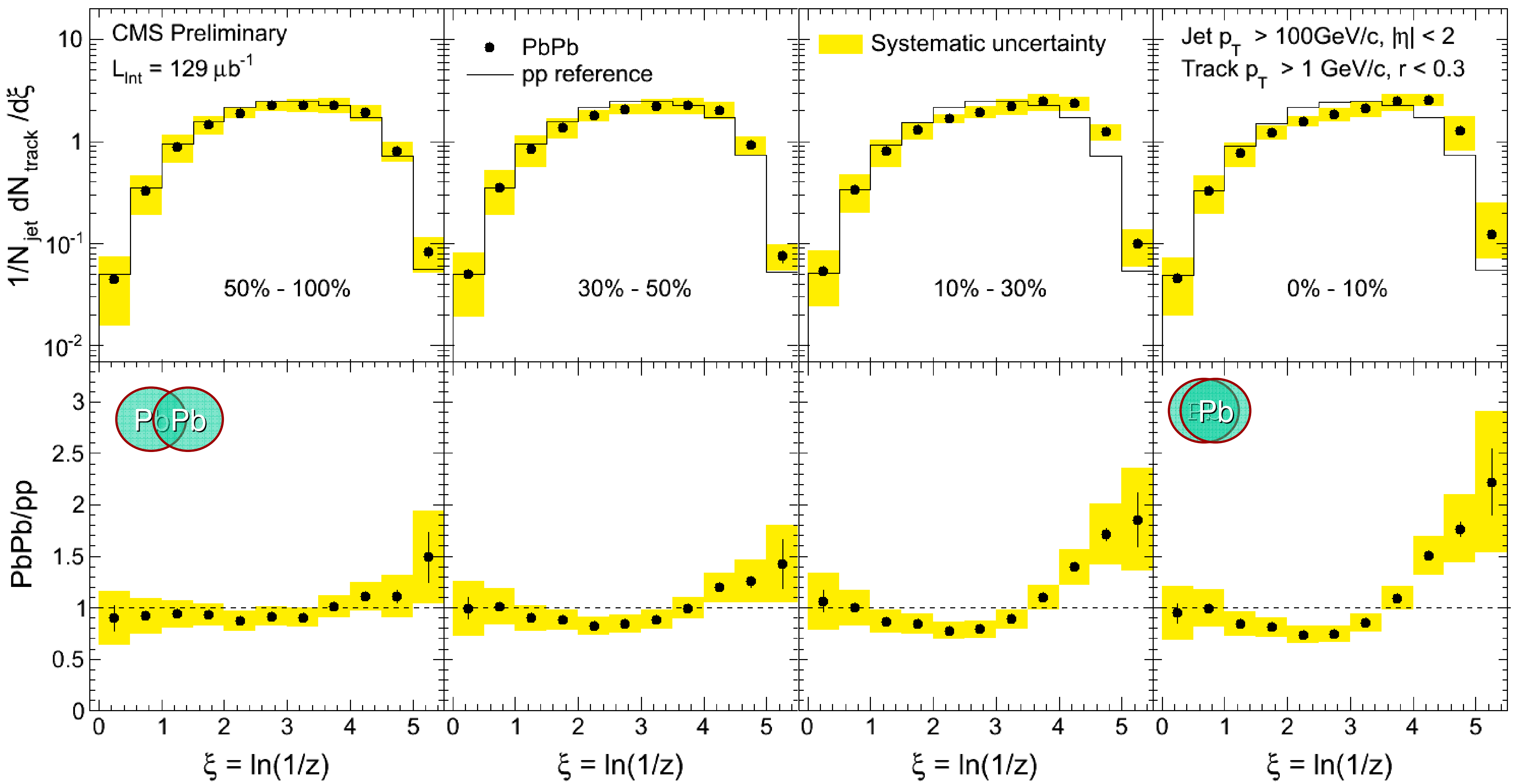
$$\rho(r) \sim \frac{1}{\delta r}\frac{1}{N_{\mathrm{jet}}}\sum_{\mathrm{jets}}\frac{p_{\mathrm{T}}(r-\delta r/2, r+\delta r/2)}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

Track p_T distributions in jet cones (R=0.3)



High p_T (low ξ): **no change** compared to jets in pp collisions
In (central) PbPb: **excess** of tracks compared to pp at low p_T (high ξ)

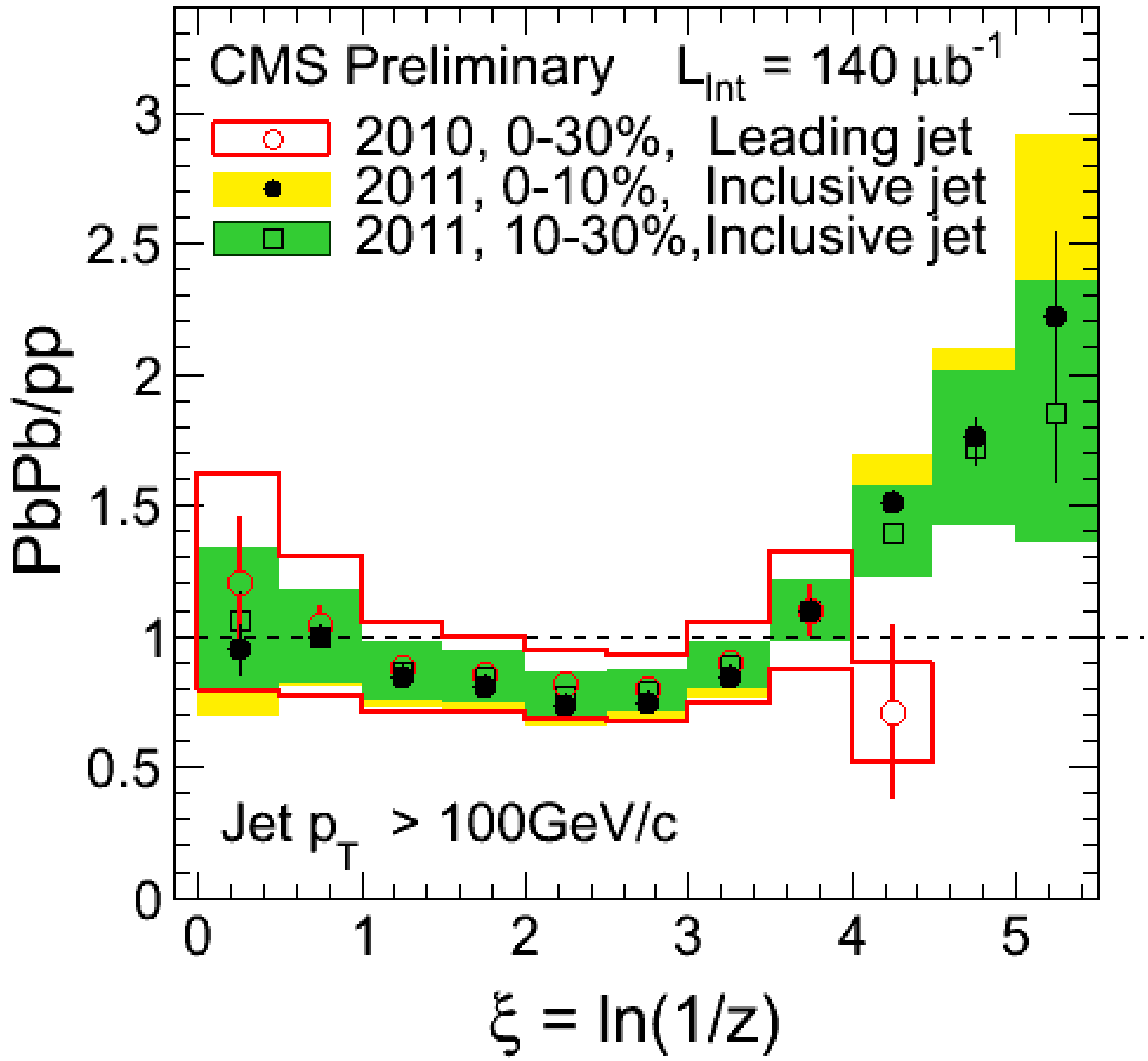
Jet fragmentation functions



20 times more data in 2011: decreased uncertainties down to much lower track p_T (starting from 1 GeV/c) reveals an excess at high ξ compared to pp

CMS PAS HIN-12-013

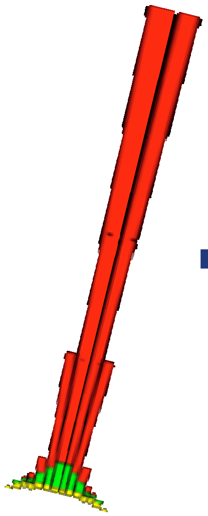
Jet fragmentation functions: 2010 → 2011

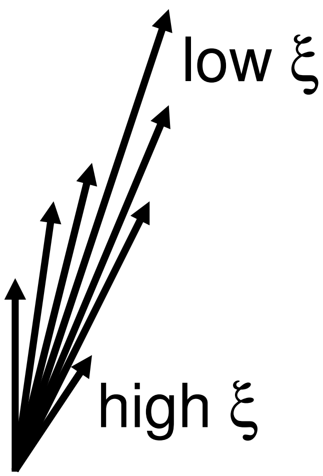


Results are consistent

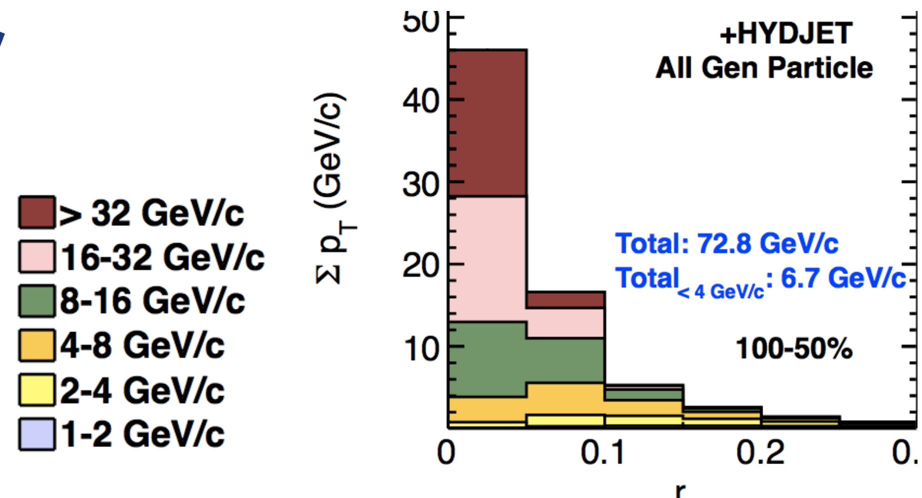
Collecting high statistics helps extend the range

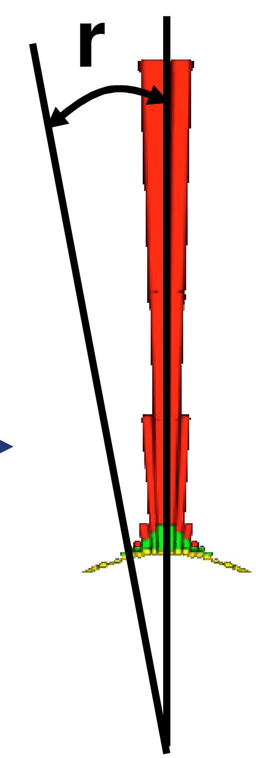
What do we expect for the jet shapes?





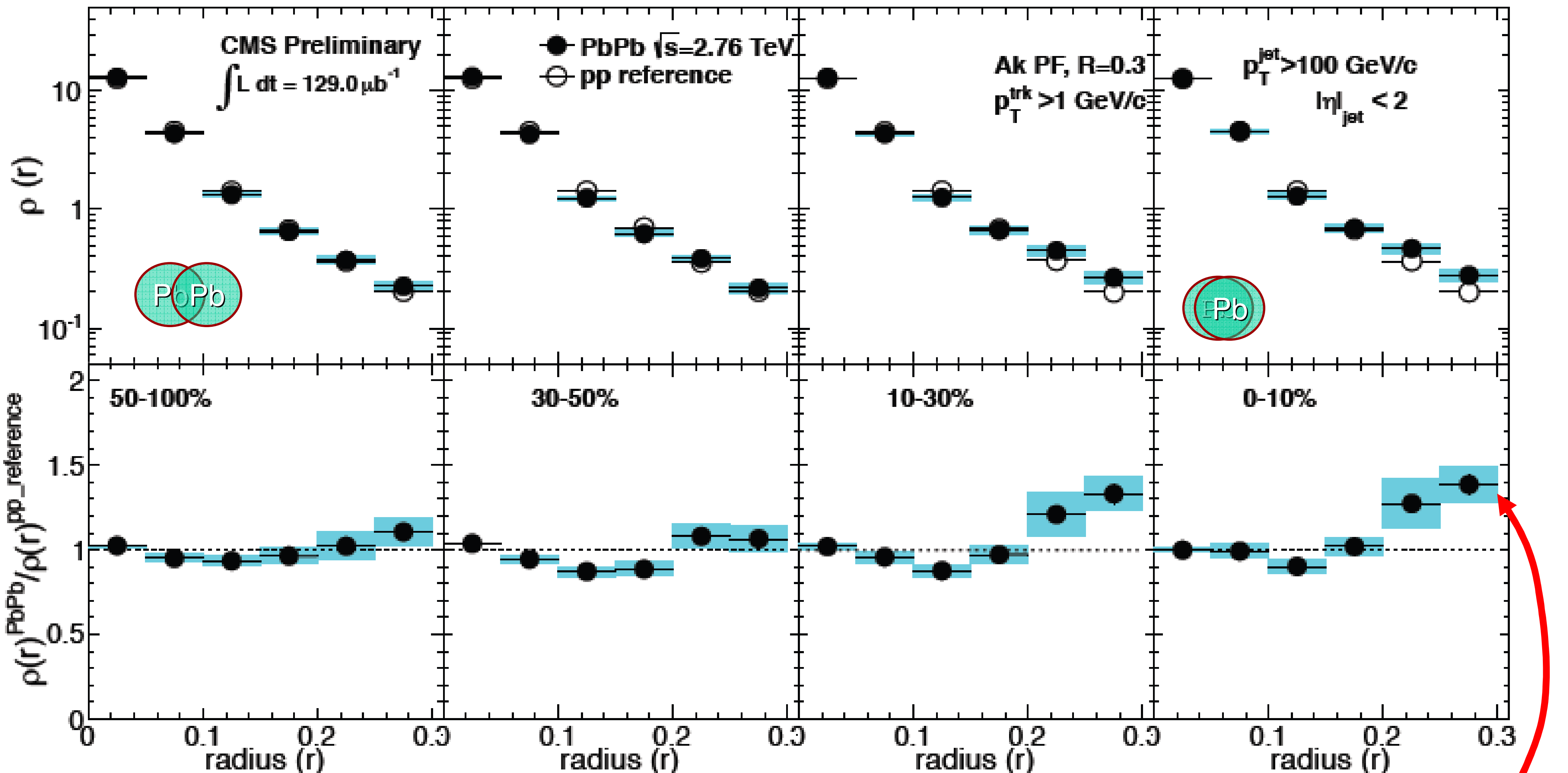
Low-ξ particles tend to be closer to the jet axis; high-ξ particles extend to large distances (radii).





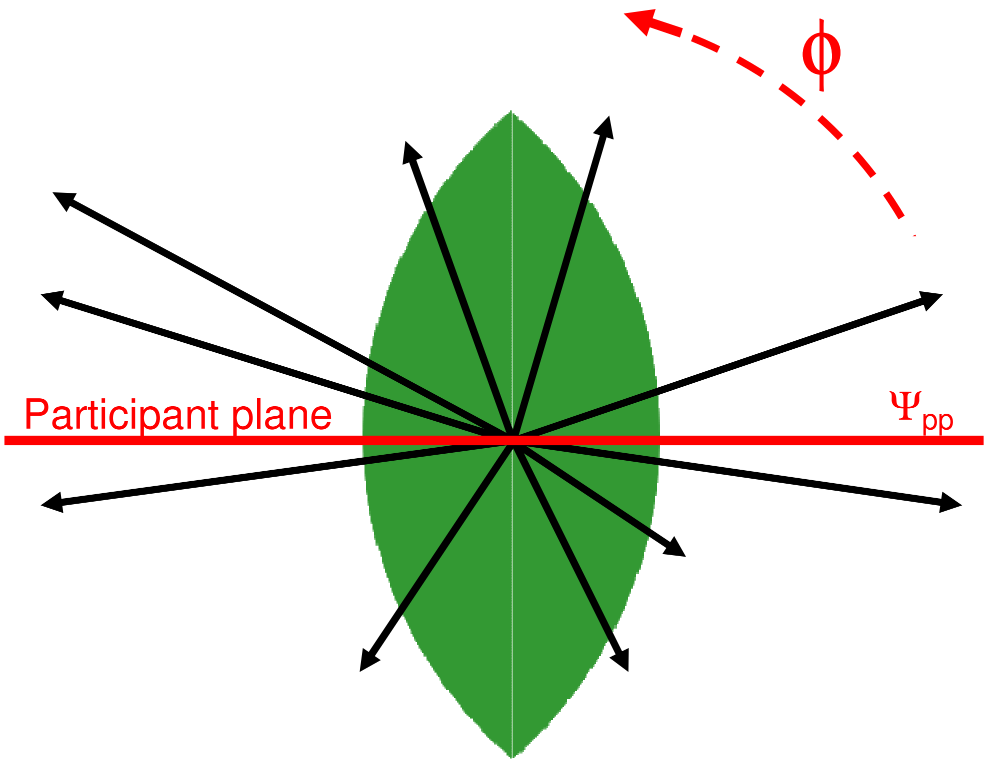
Excess p_T-flow is expected at large radii, and no change at r≈0 (compared to pp collisions).

Changing jet shapes vs. centrality



Compared to pp: same p_T-flow close to the jet axis;
more p_T-flow at large radii;
and a bit less in between.

Testing energy loss with high-p_T tracks, as a function of azimuthal angle (v_2)



Overlap zone is almond-shaped

→ Parton energy loss is smaller along the short axis

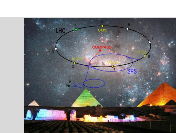
→ More high-p_T tracks expected closer to the event plane

→ Azimuthal asymmetry (v_2):

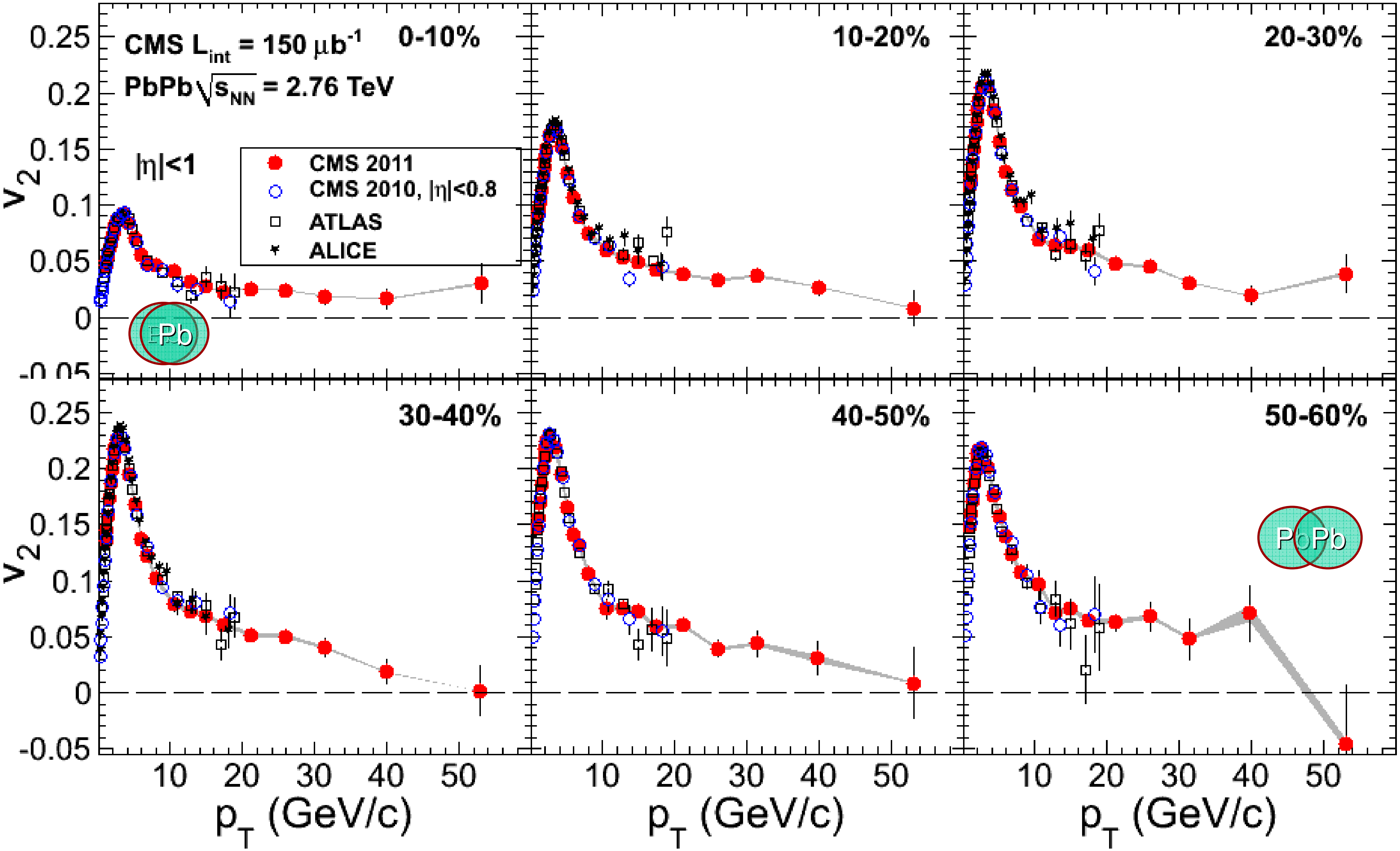
$$dN/d\phi \propto 1 + 2v_2\cos(2(\phi - \Psi_{EP}))$$

$$\Delta E \propto \begin{cases} L & \text{pQCD, collisional} \\ L^2 & \text{pQCD, radiative} \\ L^3 & \text{AdS/CFT} \end{cases}$$

→ v_2 is sensitive to the path-length dependence of the energy loss



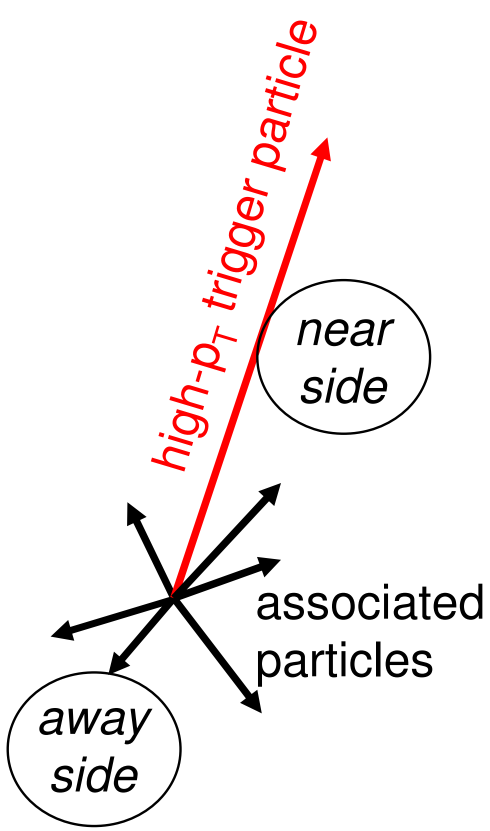
Charged hadron v_2 at very high p_T



- v_2 is non-zero up to very high p_T
- Sensitive to the path length dependence of energy loss

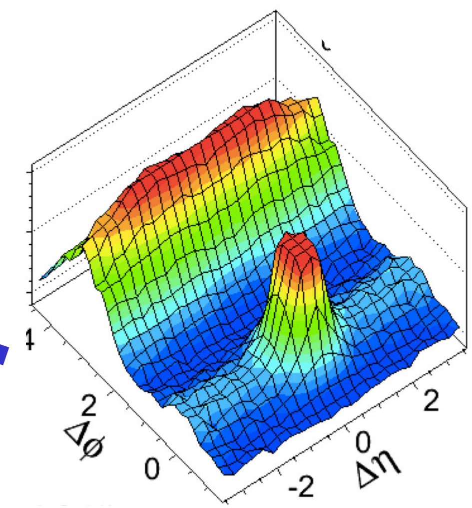
PRL 109 (2012) 022301

Studying jet modification: particles associated to a high-p_T trigger particle



High-p_T trigger particle from jet fragmentation.

Let us subtract all v_n harmonics! ($n \geq 2$)



Expectation on the "near side":

- some excess at low p_T (as seen in the jet FF)

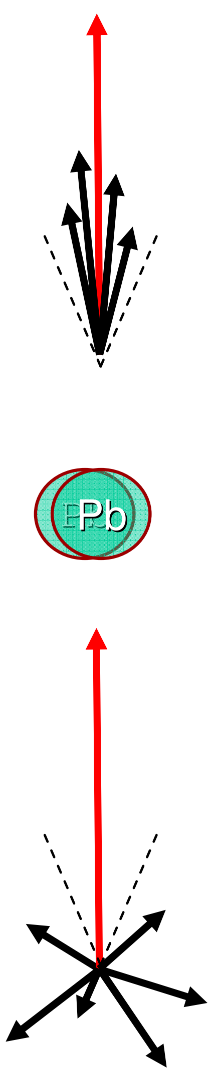
Expectation on the "away side":

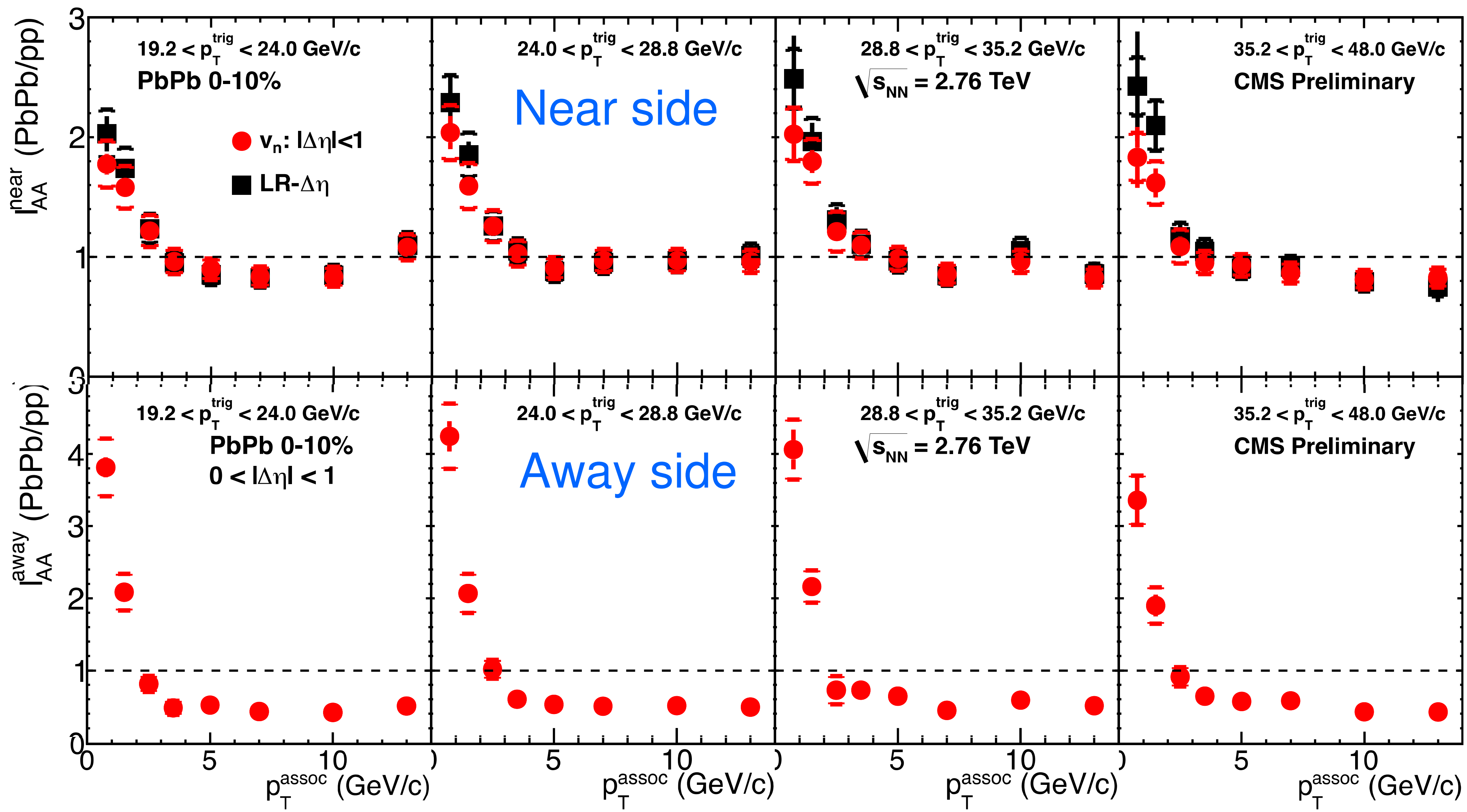
- high p_T: deficit compared to pp (quenching)
- low p_T: excess, due to redistribution of momentum

$$I_{AA}^{near} = \frac{Y_{PbPb}^{near}}{Y_{pp}^{near}}$$

$$I_{AA}^{away} = \frac{Y_{PbPb}^{away}}{Y_{pp}^{away}}$$

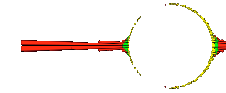
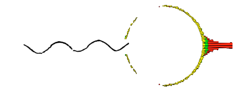
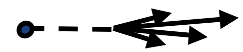
High-p_T triggered two-particle correlations

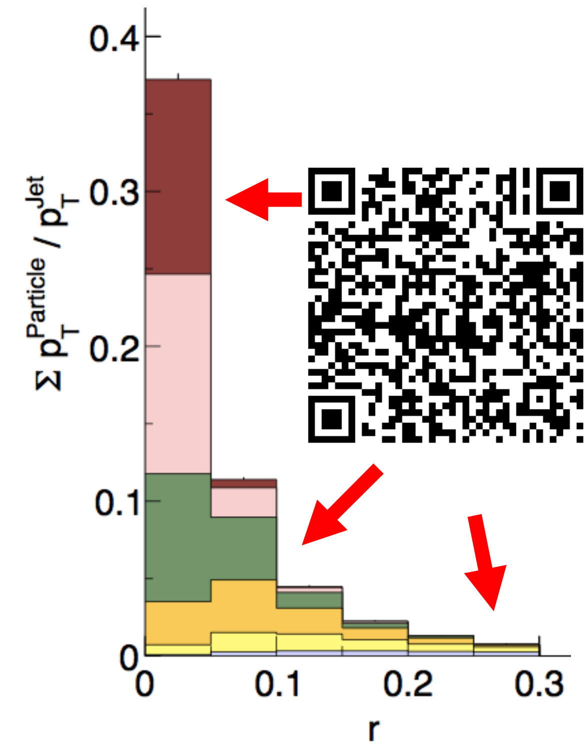


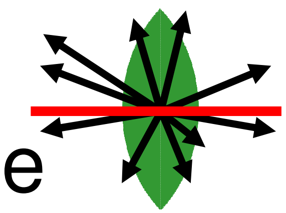
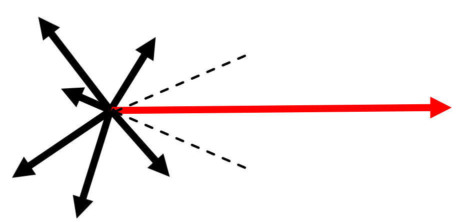


Away-side: large enhancement below ~3 GeV/c and deficit at higher p_T.
Near-side: consistent with jet FF's.
All v_n harmonics subtracted! ($n \geq 2$)

Summary of jets in CMS (PbPb)

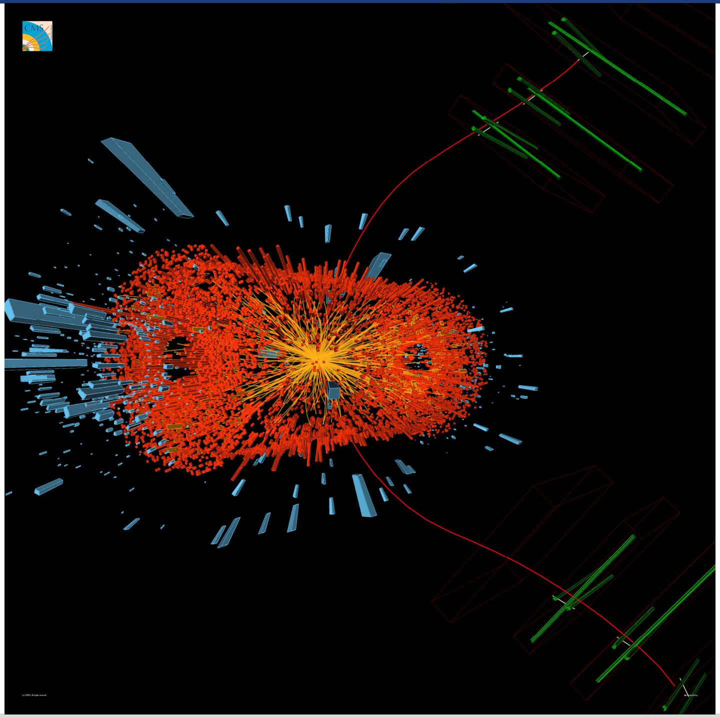
- Energy imbalance and jet R_{AA} independent of jet p_T 
- First γ-jet measurement shows consistent energy loss 
- b-quark jets are also quenched 
- Jet shapes and fragmentation functions show excess at low p_T (large radii) but high p_T (core) is unchanged



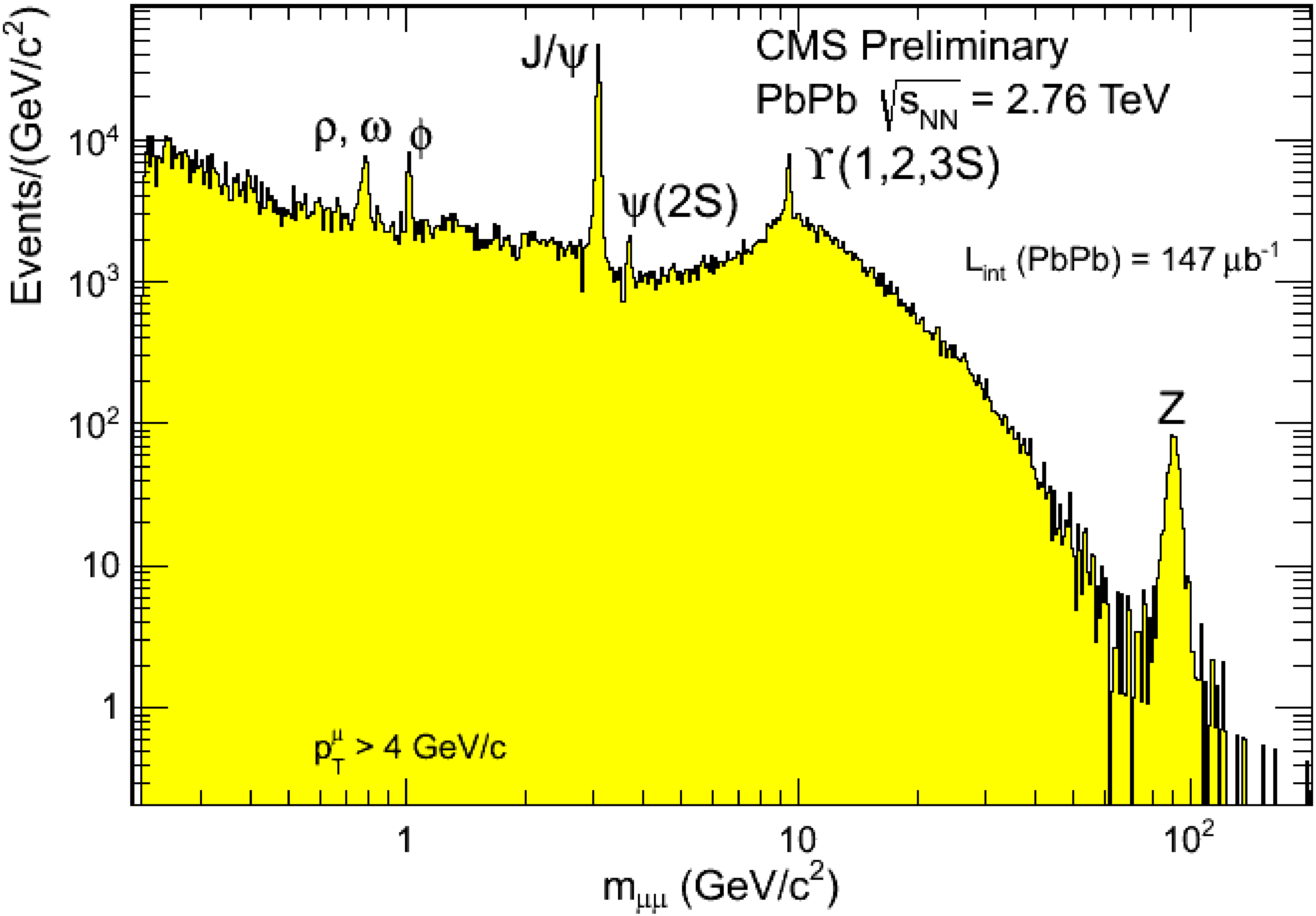
- v_2 persists to very high p_T, reflects path length dependence 
- Two-particle correlations: low-p_T enhancement and high-p_T suppression on the away side (compared to pp) 

Jet-quenching picture is made more precise and quantitative!

Dimuons: how hot is the medium?



Dimuon spectrum – huge mass range

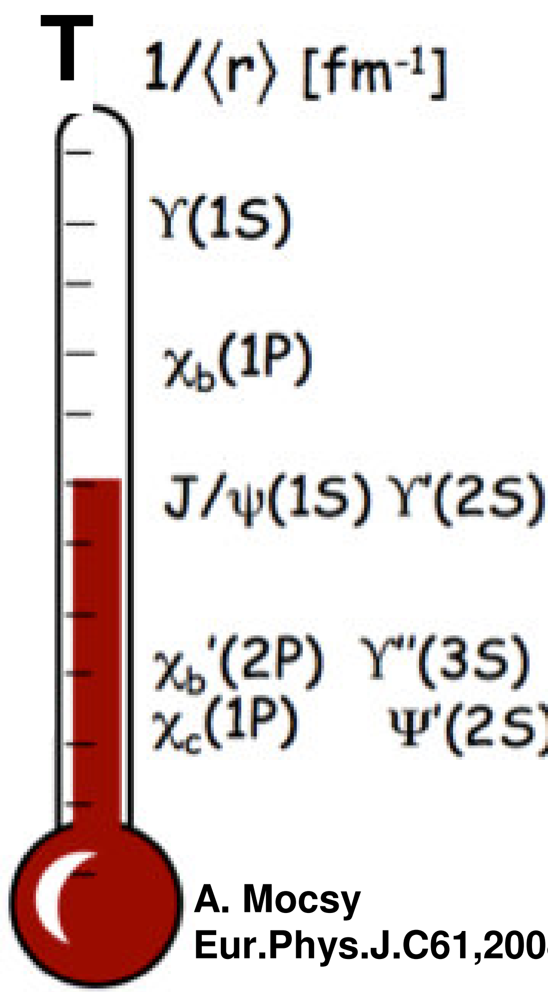


Hidden heavy flavor thermometer

arXiv:0901.3831

	Ψ (2S)	Υ(3S)	Υ(2S)	J/ψ	Υ(1S)
Δ E(GeV)	0.05	0.20	0.54	0.64	1.10

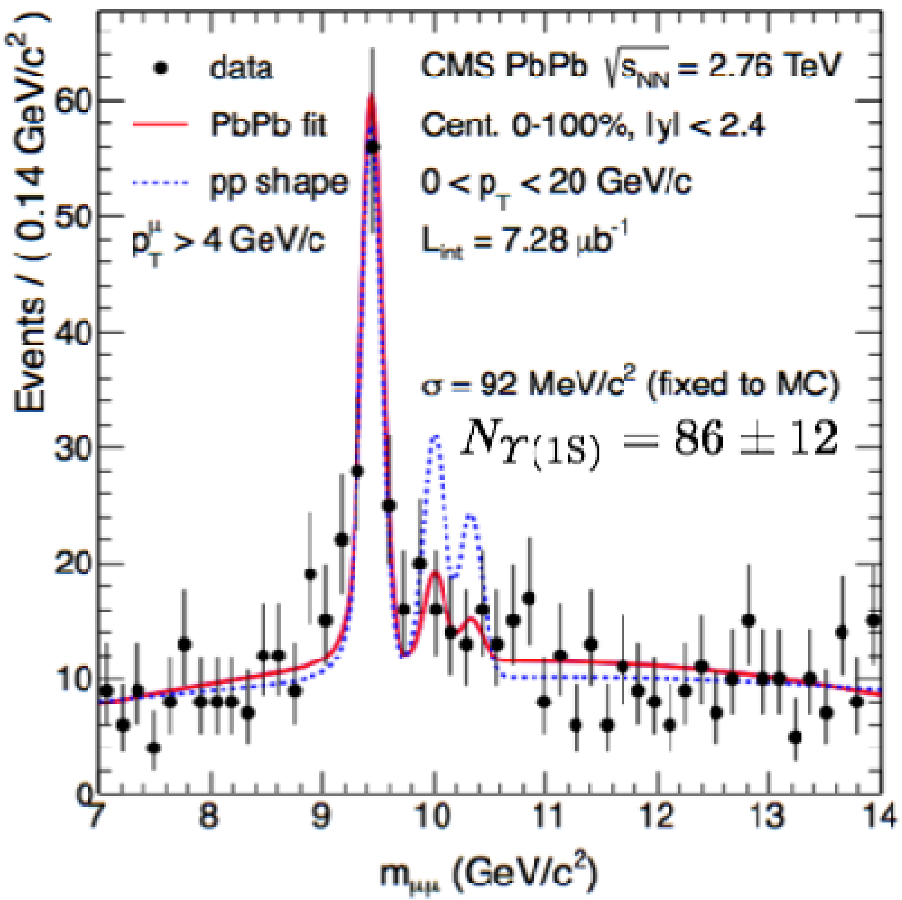
- Onia state in a deconfined, colour charged medium: Debye screening
  - if $\lambda_D(T) < r_0$ → screening → melting of the bound state → yields suppressed
  - Screening at different T for different states → sequential melting
- Onia: thermometer for the QGP



A. Mocsy
Eur.Phys.J.C61,2008

Sequential Upsilon suppression

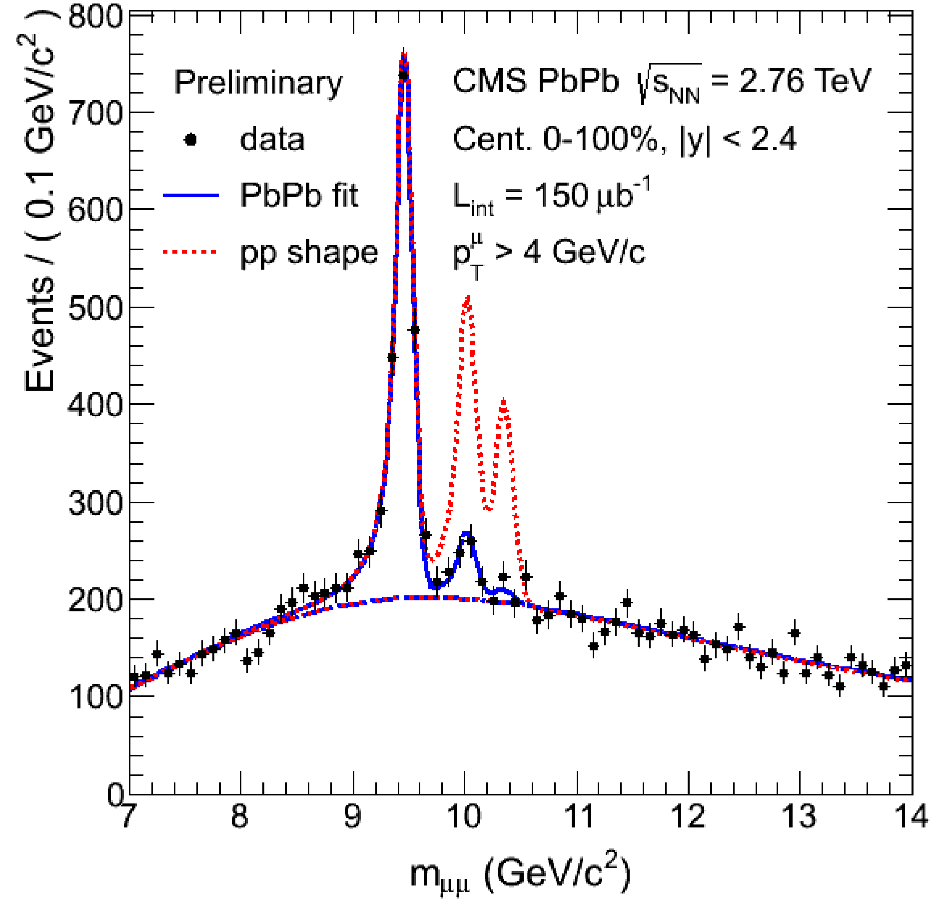
2010 data



Indication of suppression of (Y(2S)+Y(3S)) relative to Y(1S) 2.4σ significance

PRL 107 (2011) 052302

2011 data

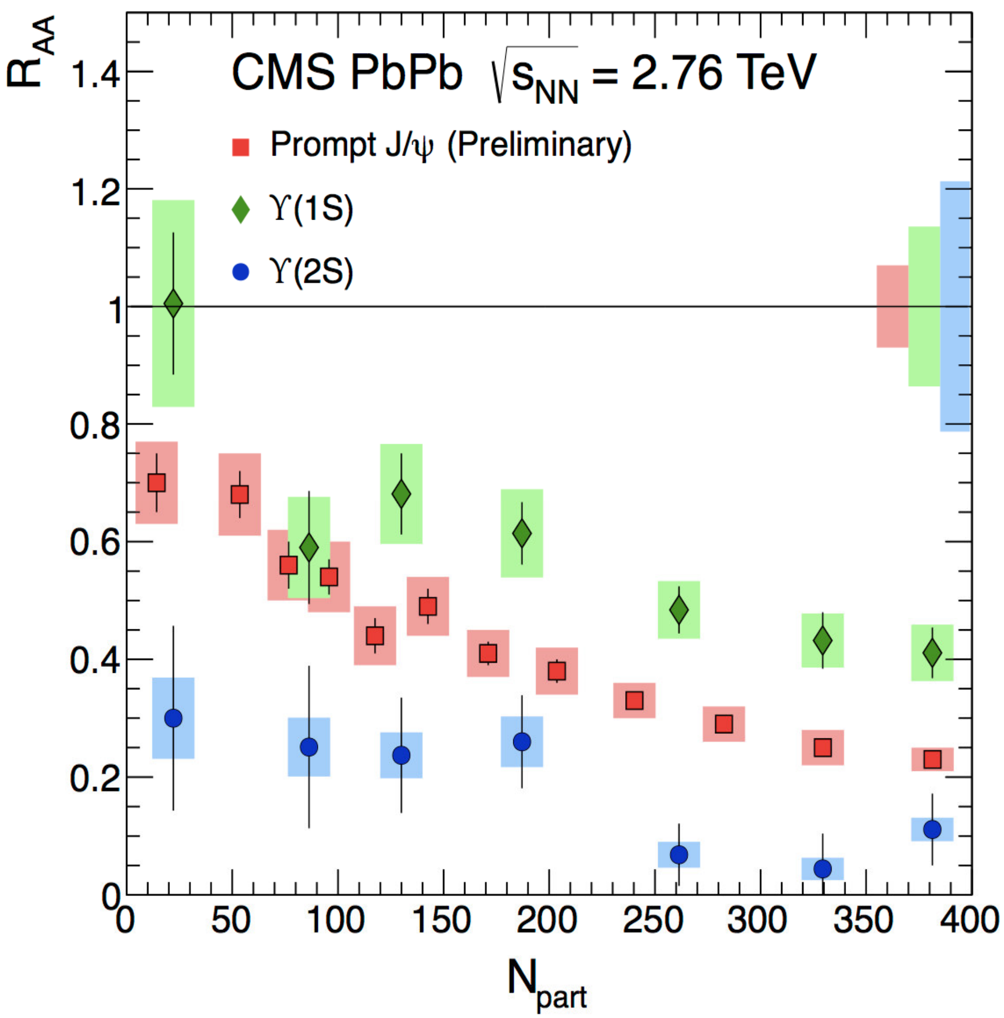


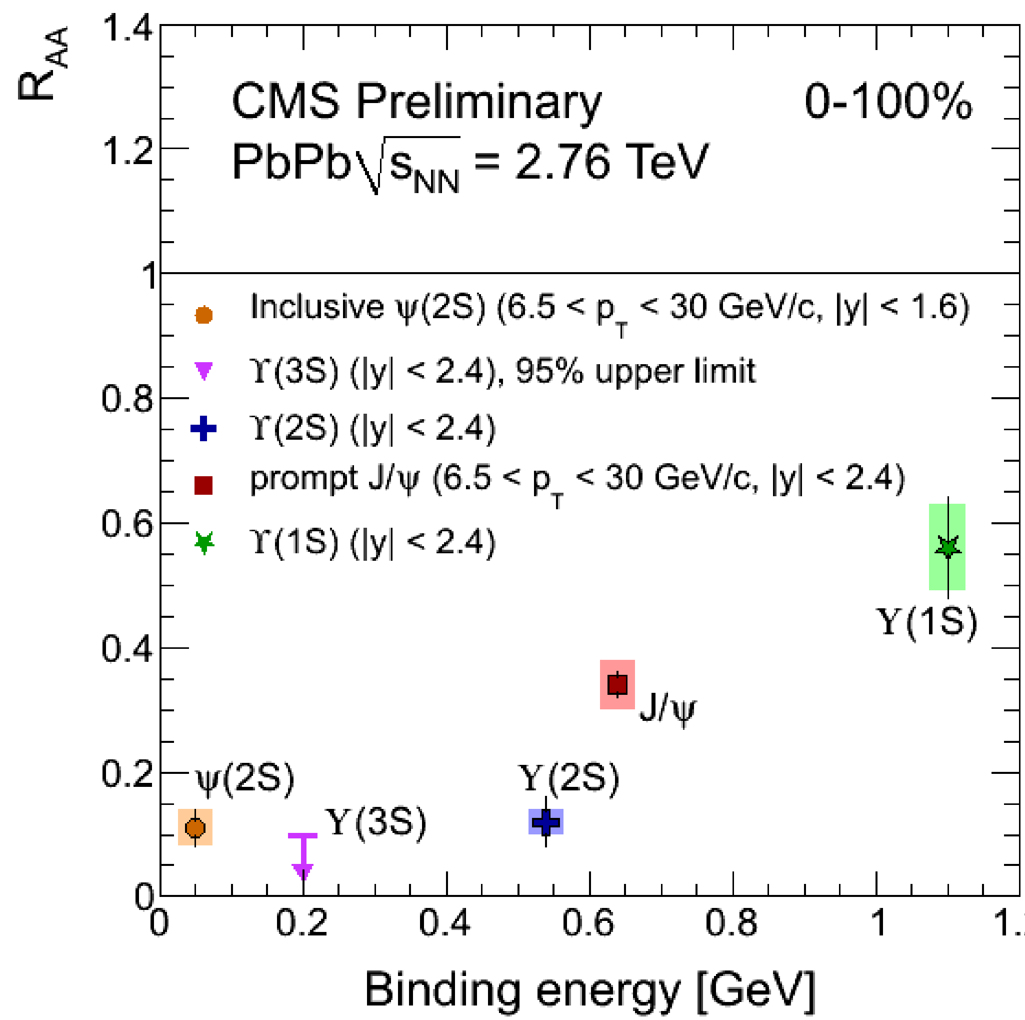
Observation of sequential suppression of Y family
Detailed studies

PRL 109 (2012) 222301

Quarkonium suppression

Note: $6.5<p_T<30$ GeV for J/ψ and $\psi(2s)$





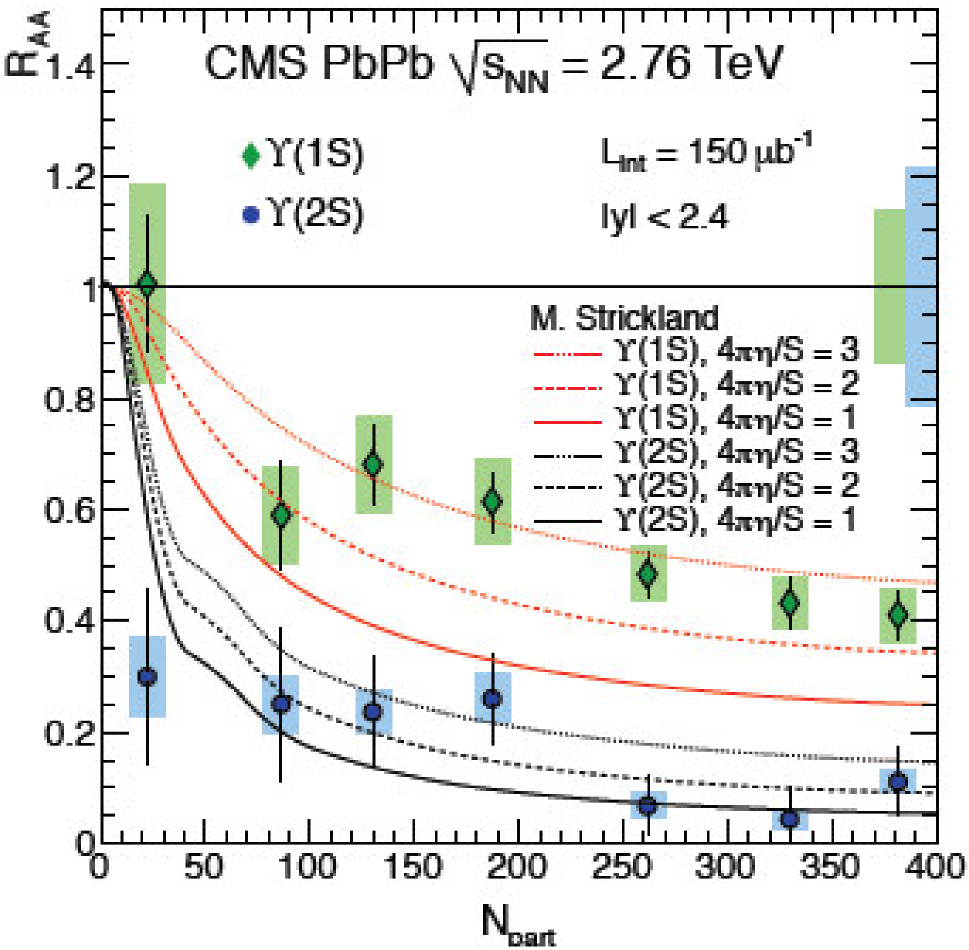
Clear hierarchy in R_{AA} of different quarkonium states

Expected in terms of binding energy

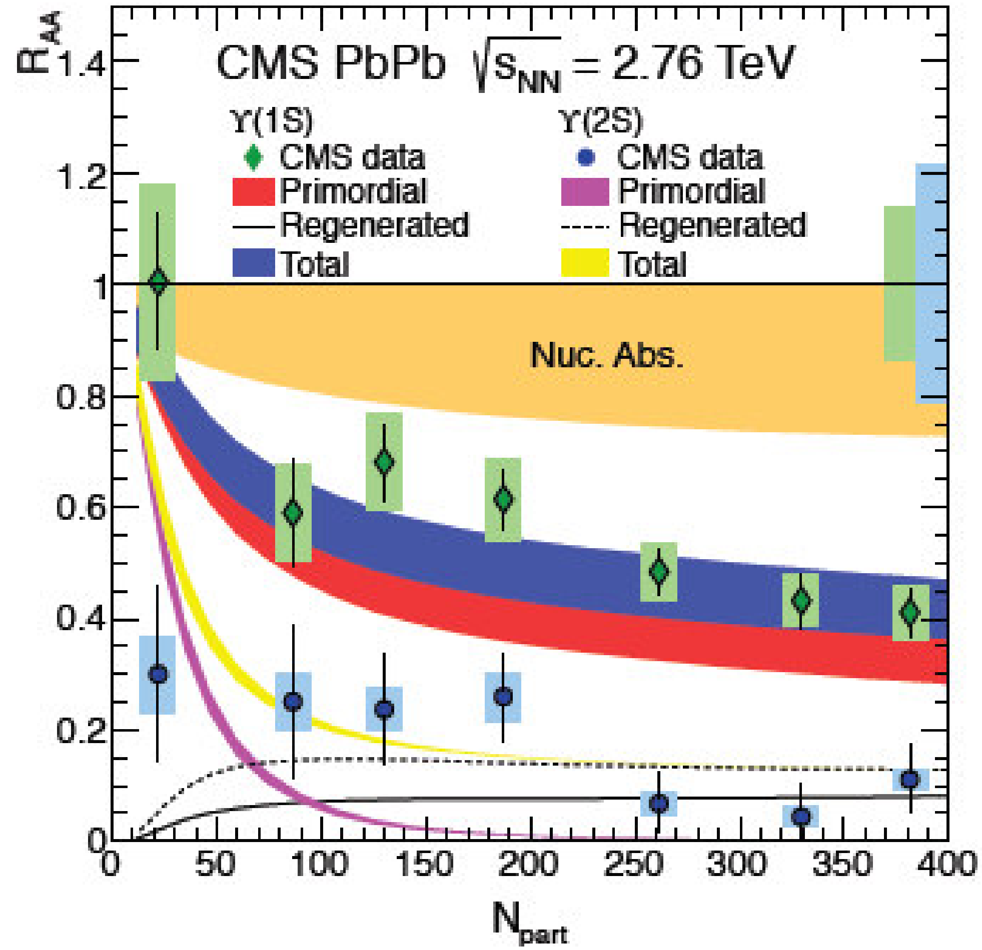
PRL 109 (2012) 222301

CMS PAS HIN-12-014, HIN-12-007

Bottomonium suppression



arXiv:1207.5327

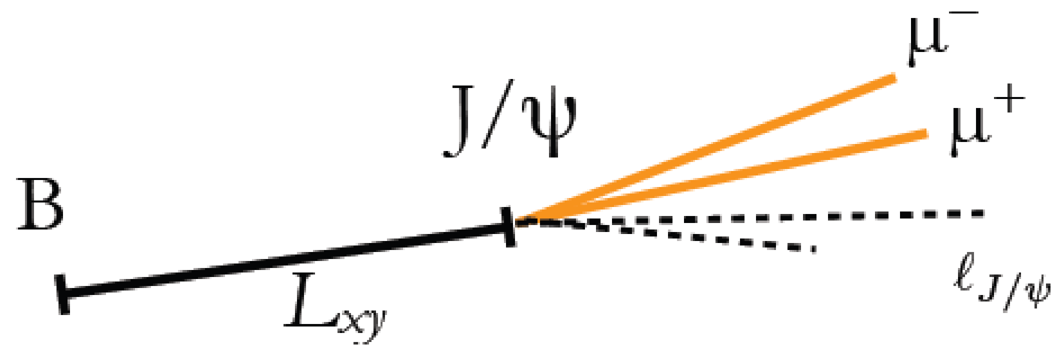


Eur.Phys. J. A48 (2012) 72

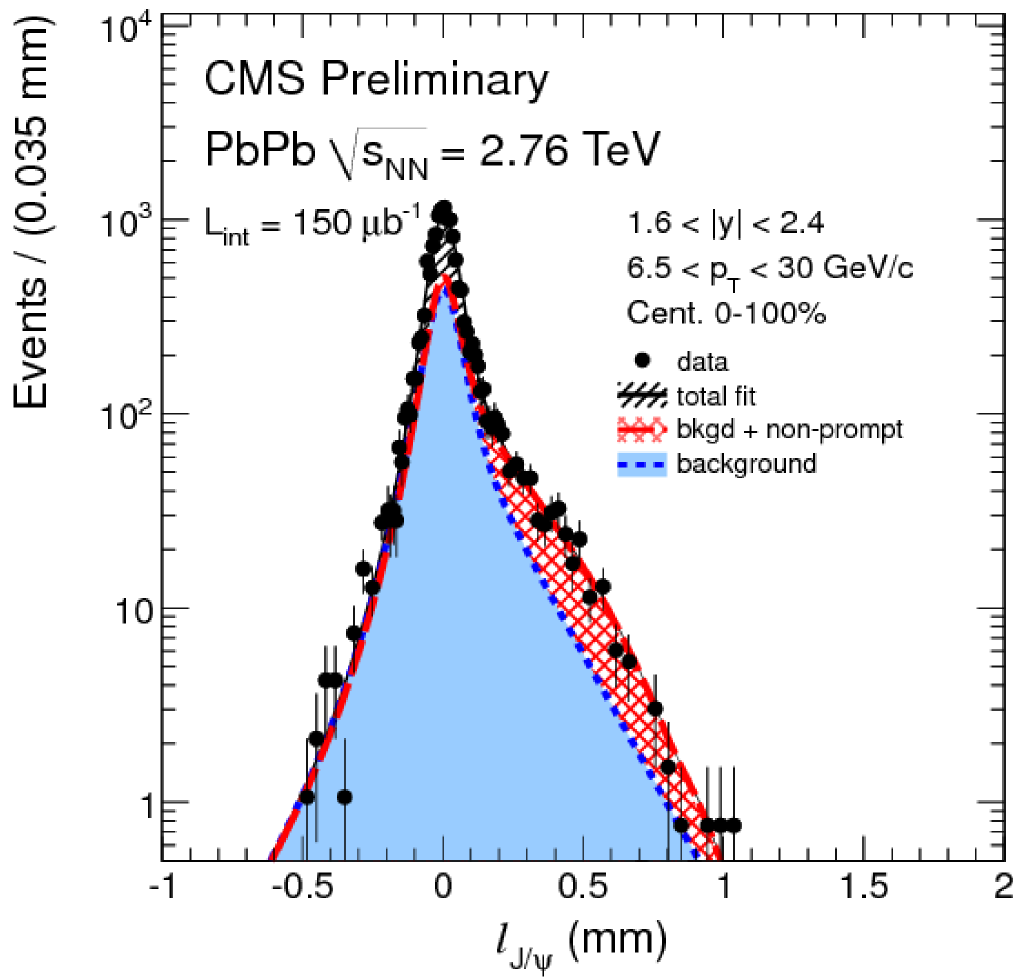
PRL 109 (2012) 222301

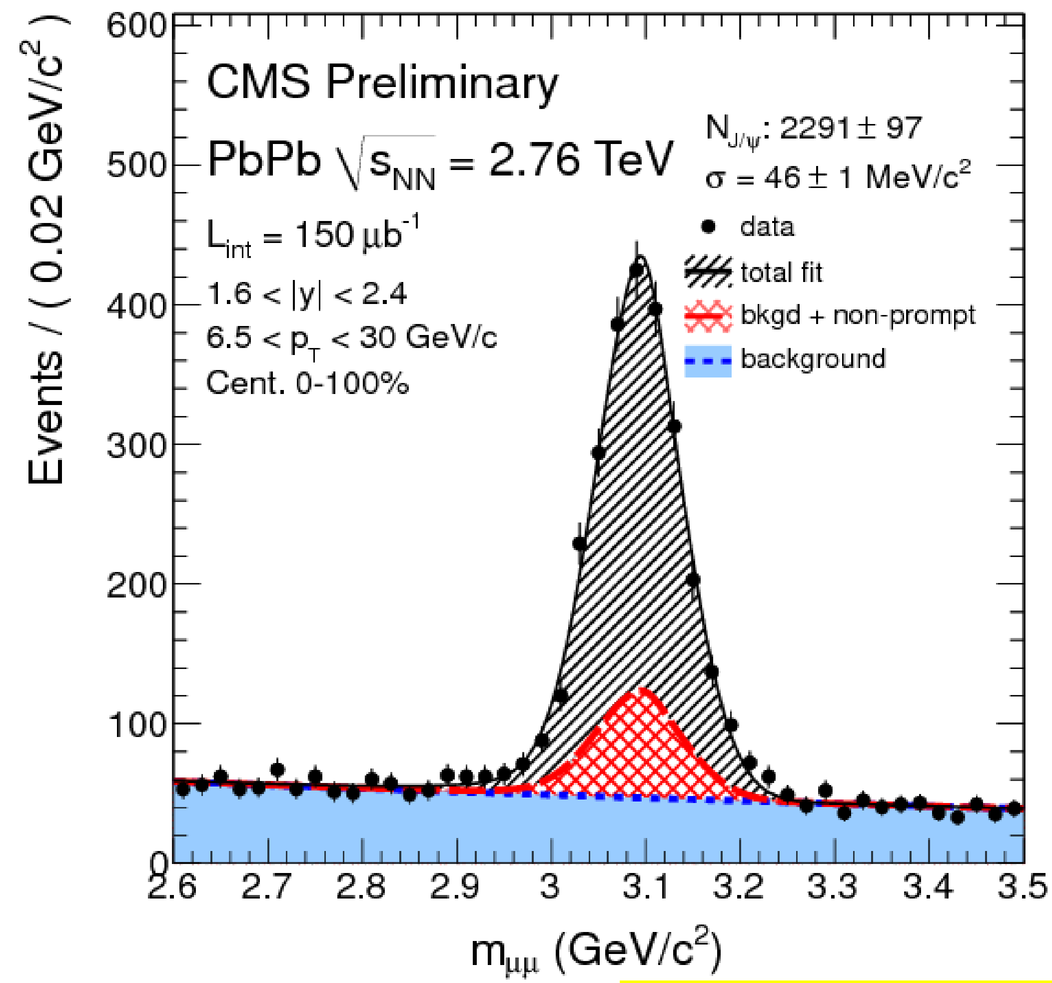
regeneration for the excited state,
absorption/shadowing to be considered

b-quark energy loss: non-prompt J/Ψ



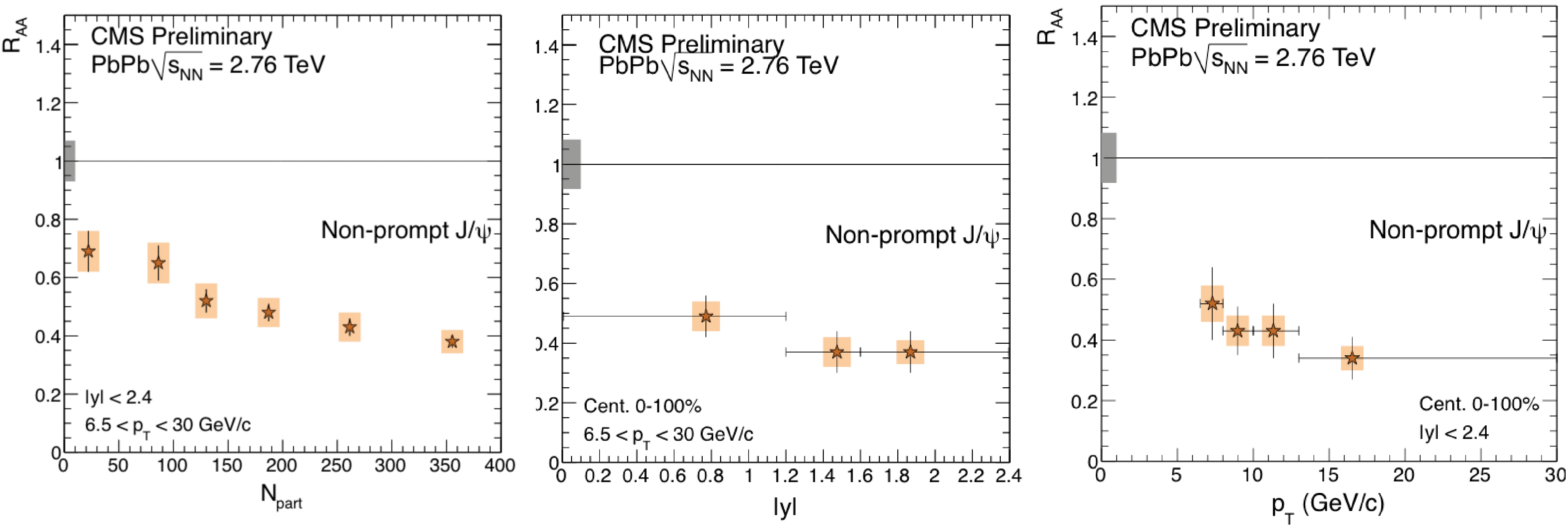
$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$





CMS PAS HIN-12-014

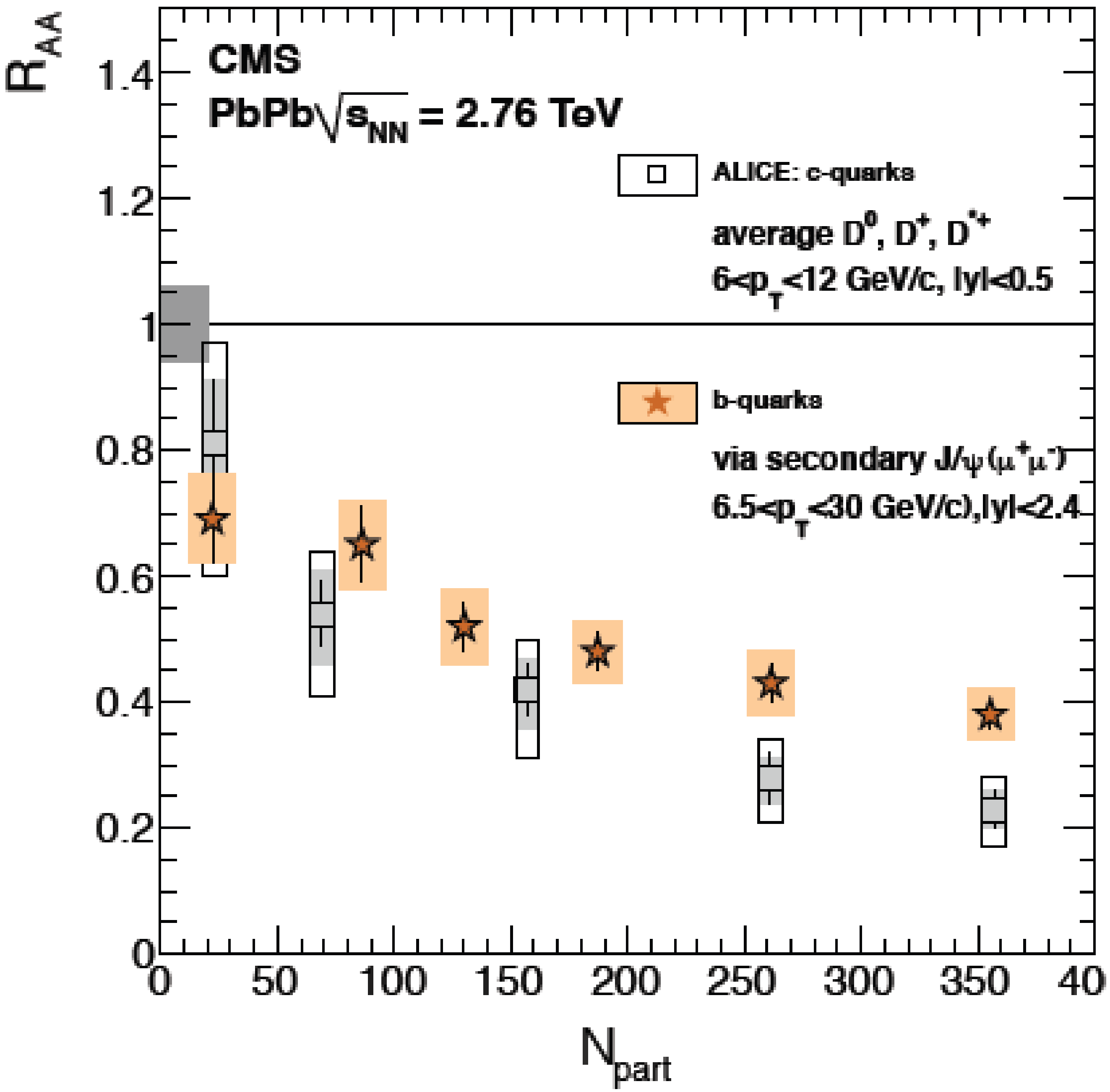
b-quark energy loss: non-prompt J/Ψ



- **Centrality (p_T, y integrated)**: slow decrease of R_{AA}
  - 50-100% (peripheral): factor ~1.4
  - 0-5% (central): factor ~2.5
- **y (p_T, centrality integrated)**:
  - hints of less suppression at mid-rapidity
- **p_T (y, centrality integrated)**:
  - hints of increasing suppression at high-p_T

CMS PAS HIN-12-014

Open charm and beauty



In central collisions, R_{AA} hierarchy between c and b:

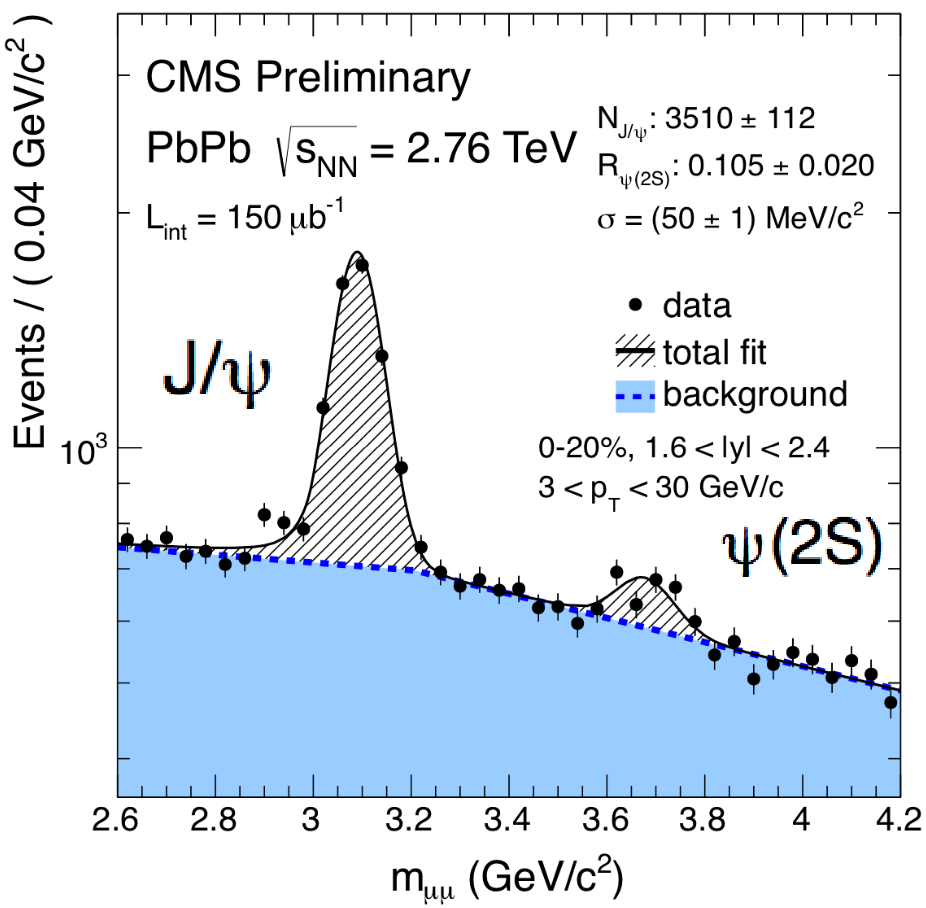
$$\mathbf{R_{AA}^{charm} < R_{AA}^{bottom}}$$

CMS PAS HIN-12-014

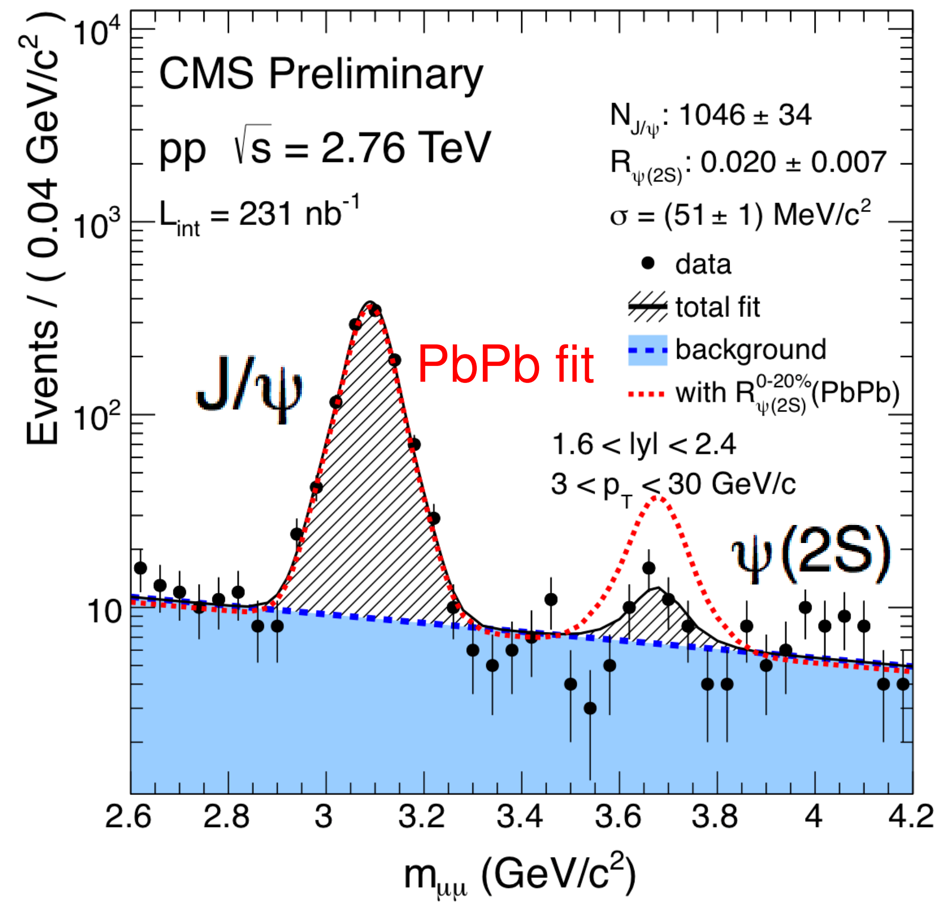
Phys.Rev.Lett. 109 (2012) 112301

J/ψ vs. ψ(2S)

PbPb (p_T > 3GeV)



pp (p_T > 3GeV)



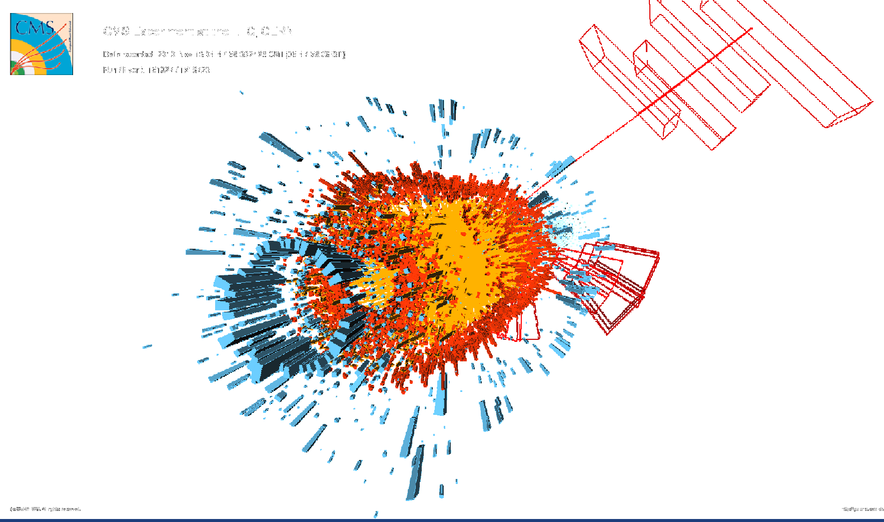
Indication that the loosely bound ψ(2S) is
less suppressed than the more tightly bound J/ψ for p_T > 3GeV

not more than 2σ significance, limited by pp statistics!!

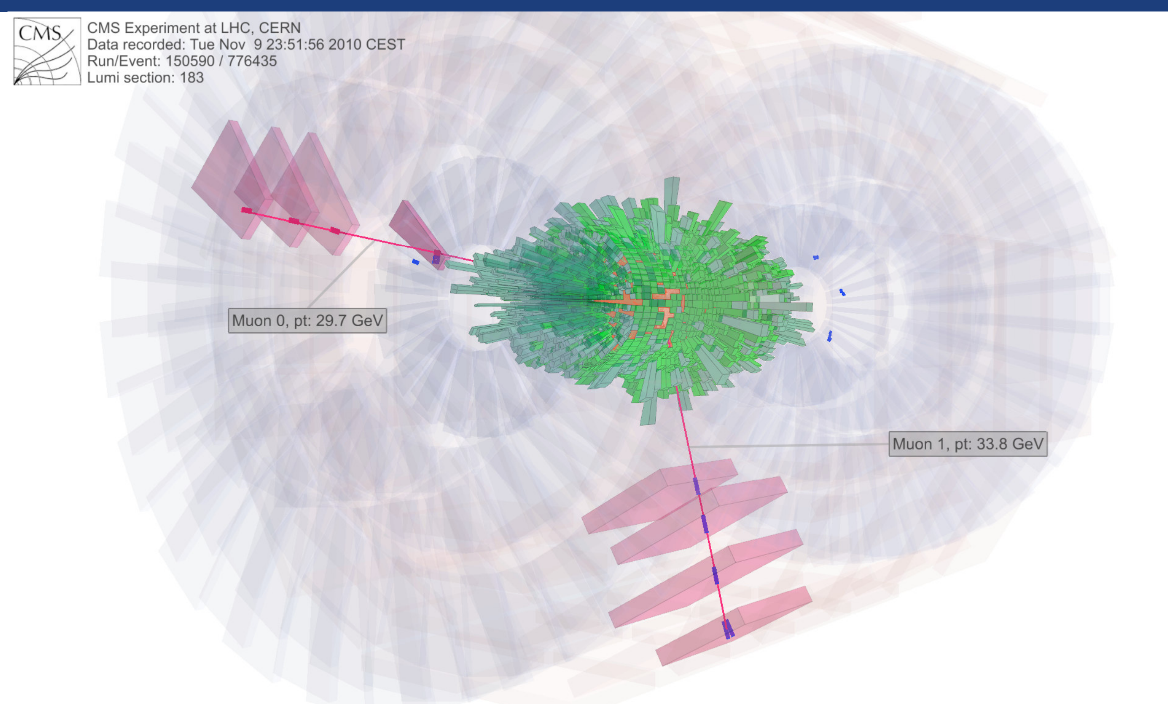
CMS PAS HIN-12-007

Summary: dimuons

- Dimuons are measured in a huge mass range in CMS
- Suppression of quarkonia is sensitive to temperature
- Quarkonia states are (indeed) suppressed according to their binding energy
- These measurements are relevant for questions of regeneration, quantifying viscosity, entropy density
- b-quarks are slightly less suppressed than c-quarks at LHC
- More pp data at 2.76 TeV is needed to clarify the Ψ' vs. J/Ψ suppression

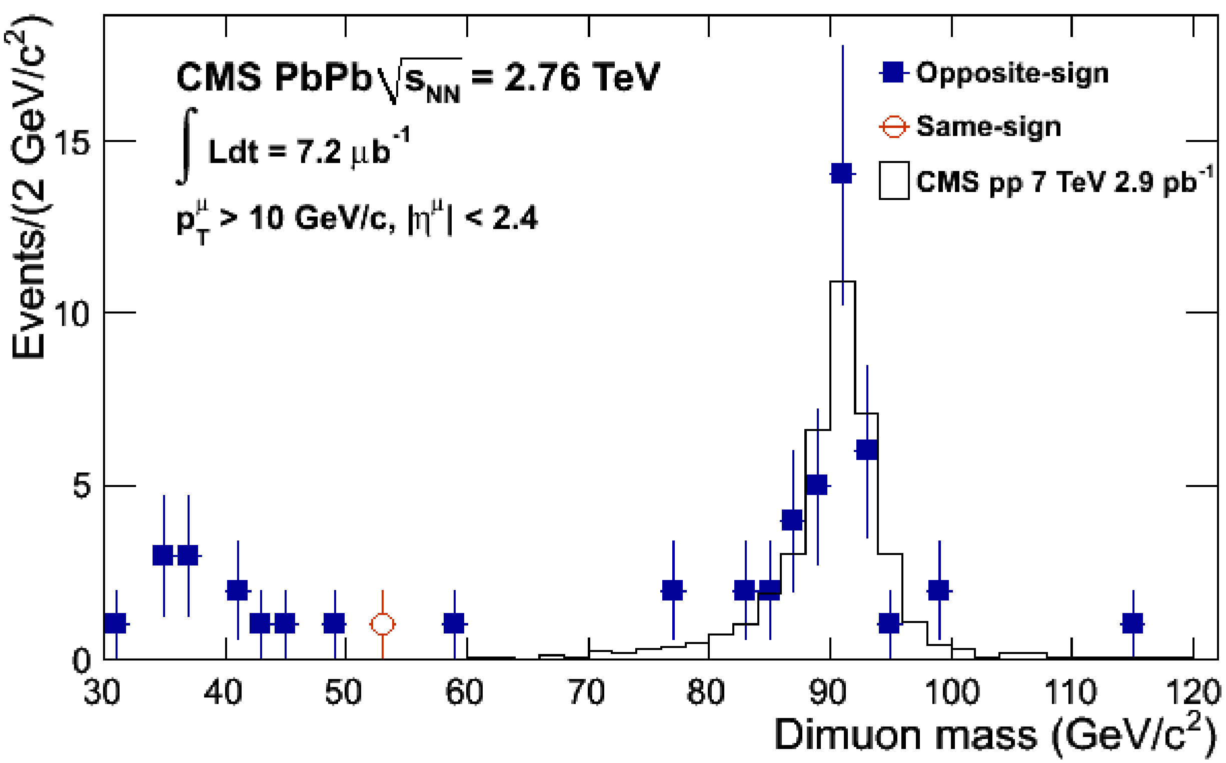


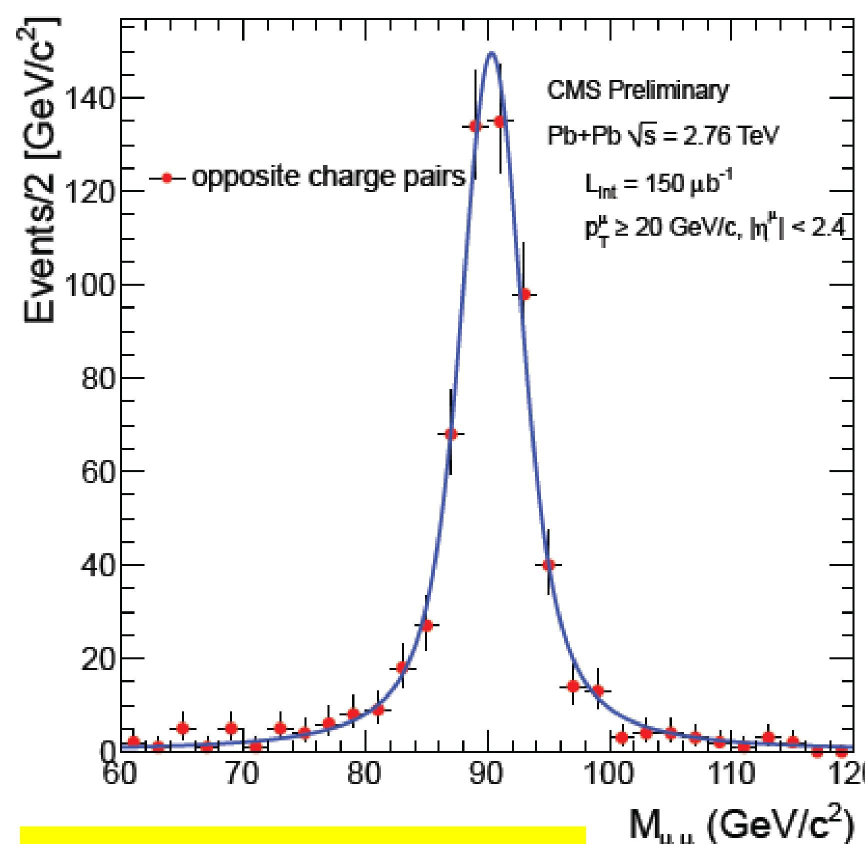
Electroweak bosons: the control experiment



Why measure electroweak bosons?

- Electro+weak bosons are essentially not perturbed by the QCD medium
  - At 1st order, check the binary scaling hypothesis,
  - Serve as a reference to modified processes (jets…),
  - 2nd order modif. ultimately constrain initial state (npdf)





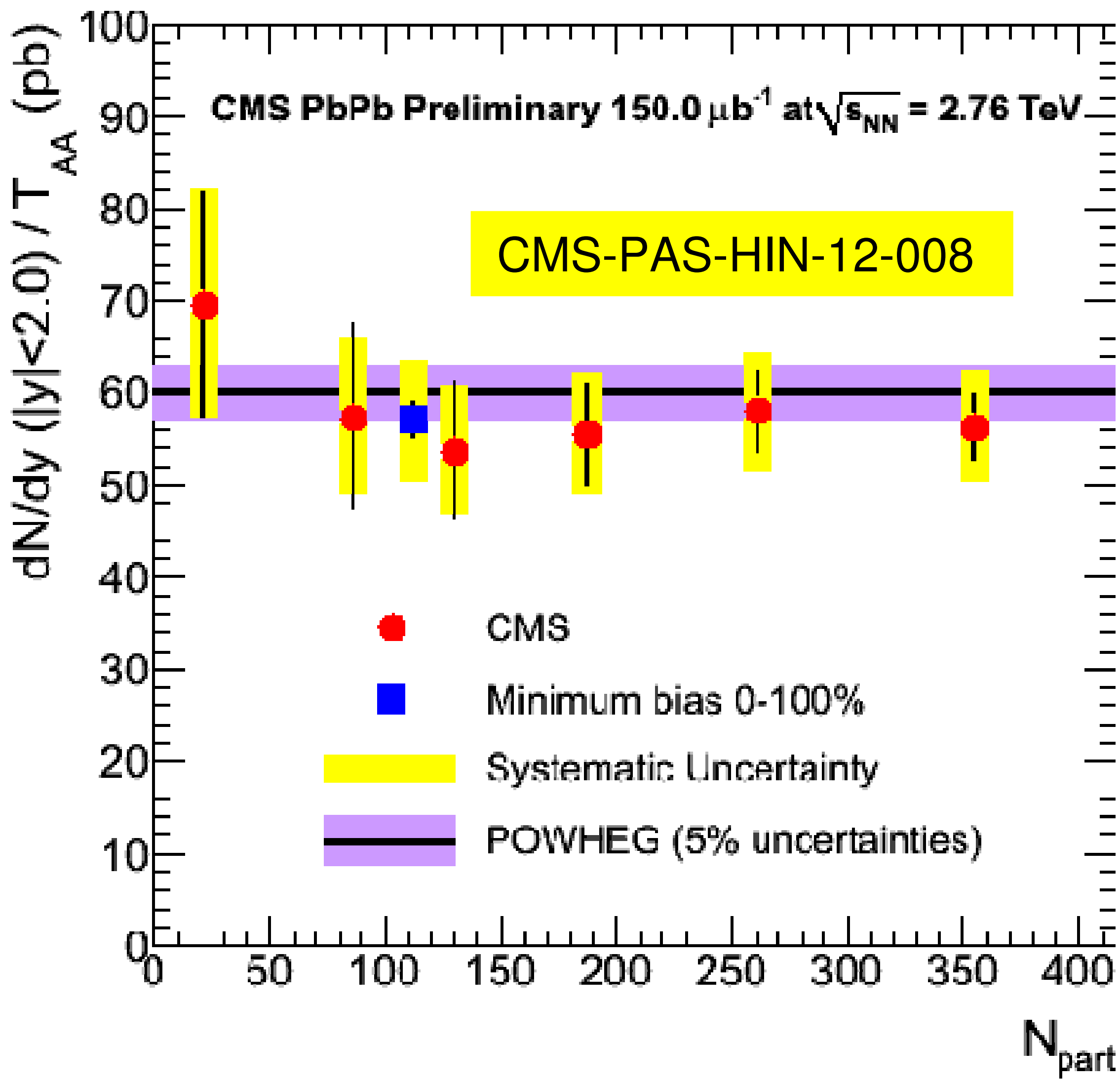
- 39 candidates in 2010, p_T^μ > 10 GeV/*c*
- 616 candidates in 2011, p_T^μ > 20 GeV/*c*

PRL 106 (2011) 212301
CMS-PAS-HIN-12-008

Centrality independence: Z boson

$$dN_{AA} / T_{AA} = d\sigma_{pp} \times R_{AA}$$

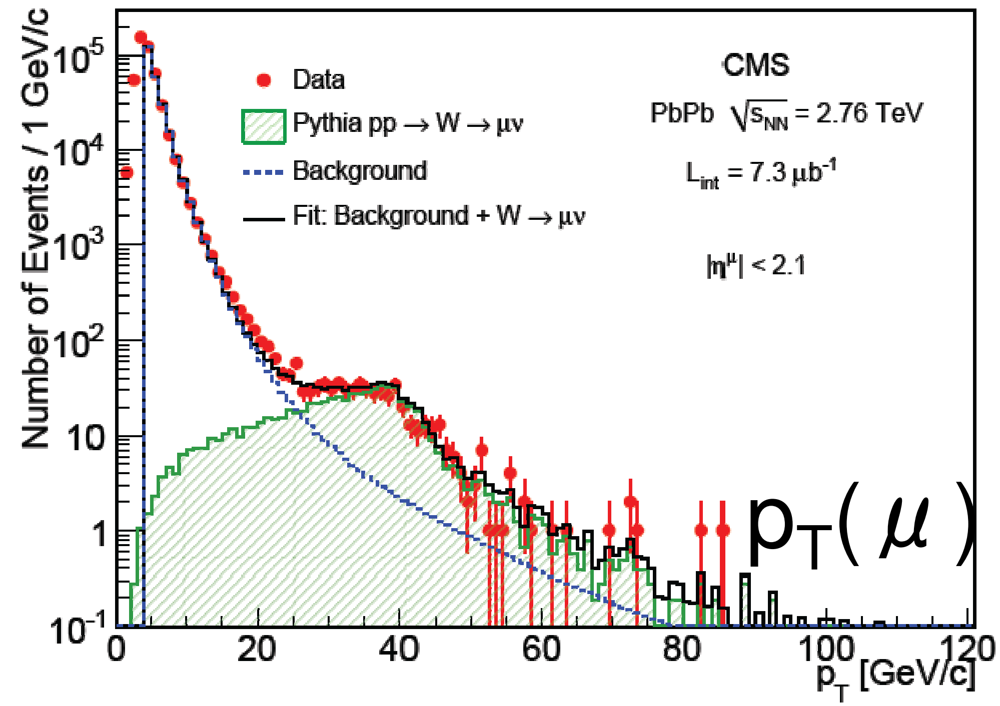
- Very low pp statistics available at 2.76 TeV
  - ≈ 20 times less Z than PbPb
- Compare to POWHEG (NLO generator) instead
  - –Well tested at Tevatron (2 TeV) and LHC (7 TeV)
  - –5% uncertainty from NNLO, pdfs, etc.

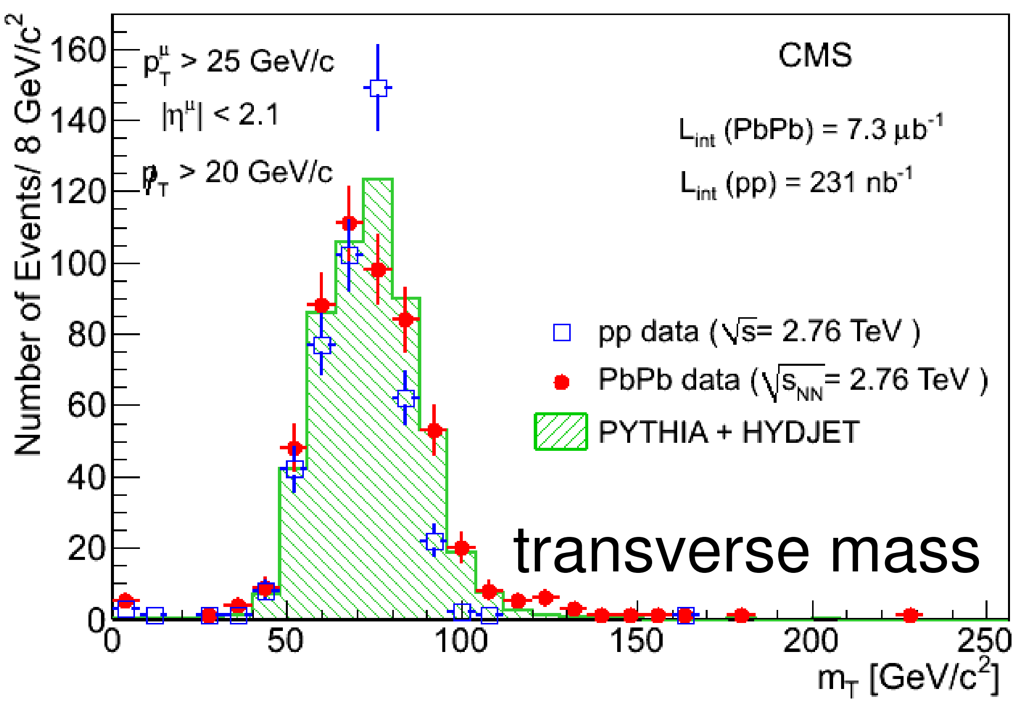


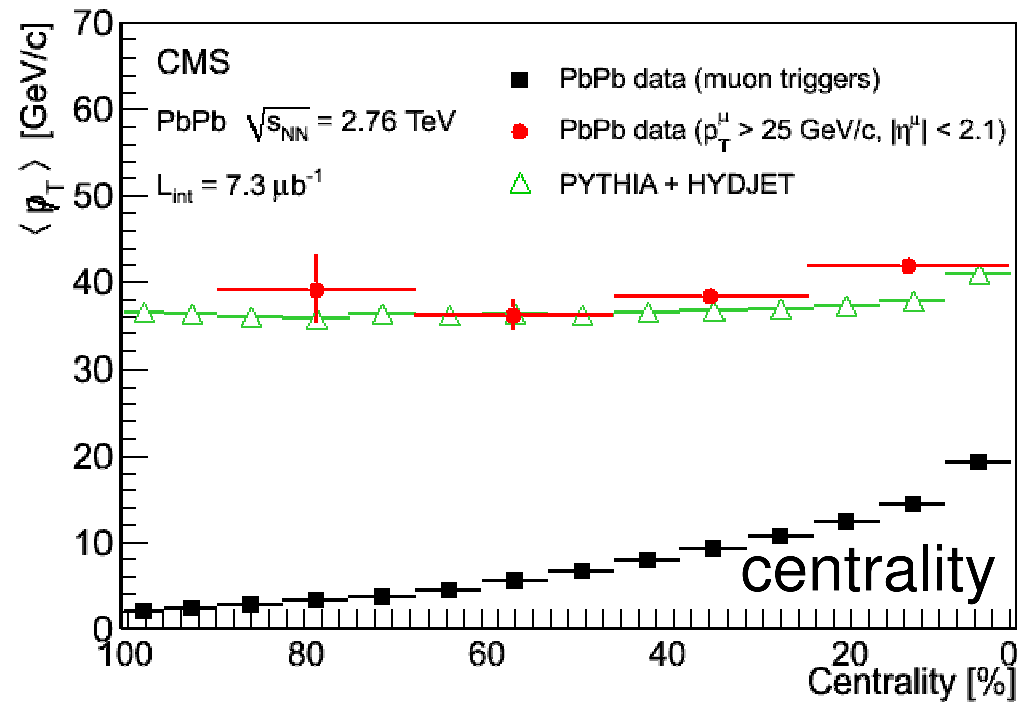
$$R_{AA} = 0.95 \pm 0.03 \pm 0.13$$

W → μν (2010)

- Signal already visible in muon p_T spectrum →
- Simple missing p_T from tracks (p_T > 3 GeV/*c*) ↘
- Then transverse mass ↓







Centrality independence: W bosons

$dN_{AA} / T_{AA} = d\sigma_{pp} \times R_{AA}$

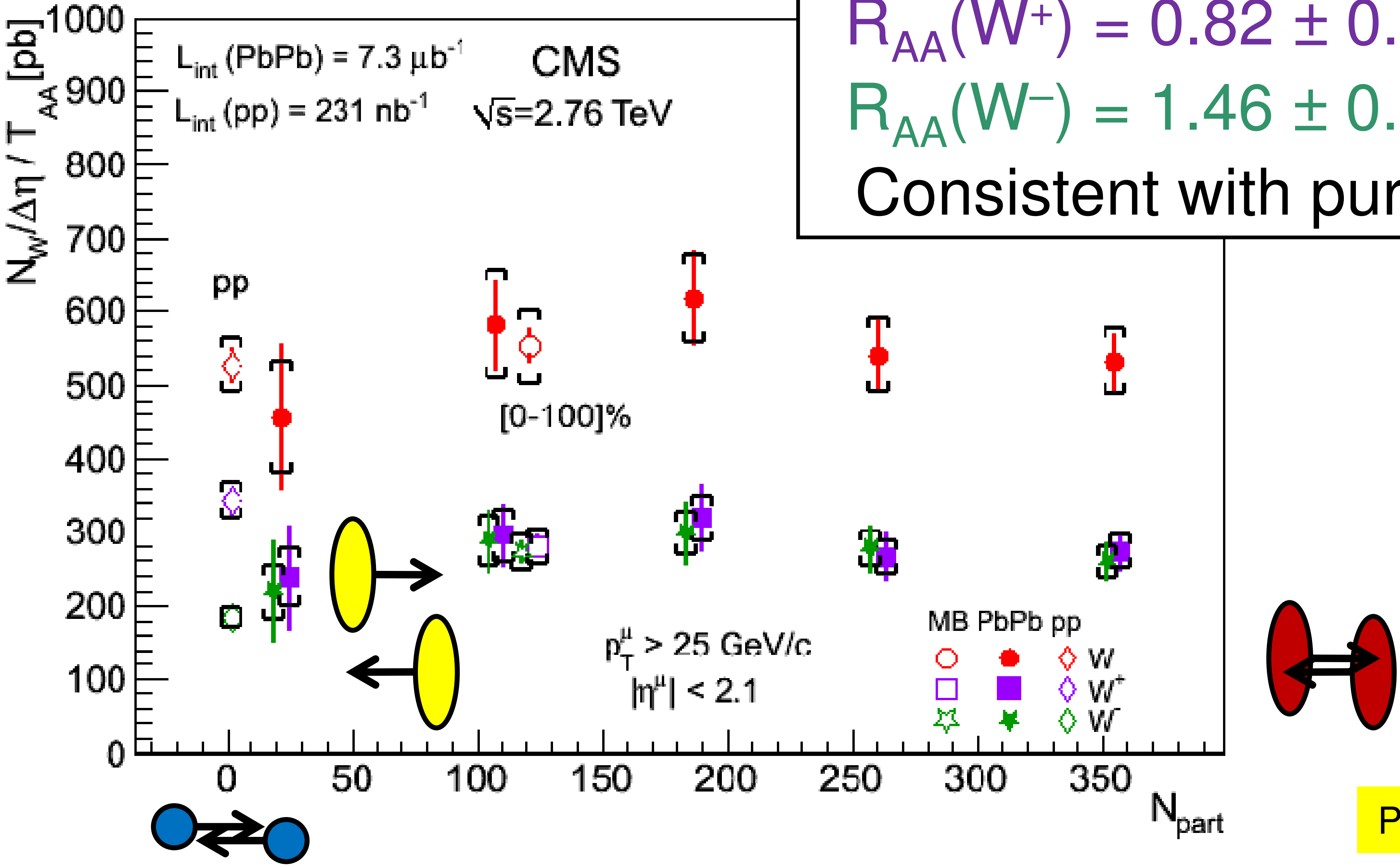
2010 PbPb ≈ pp data

$R_{AA}(W) = 1.04 \pm 0.07 \pm 0.12$

$R_{AA}(W^+) = 0.82 \pm 0.07 \pm 0.09$

$R_{AA}(W^-) = 1.46 \pm 0.14 \pm 0.16$

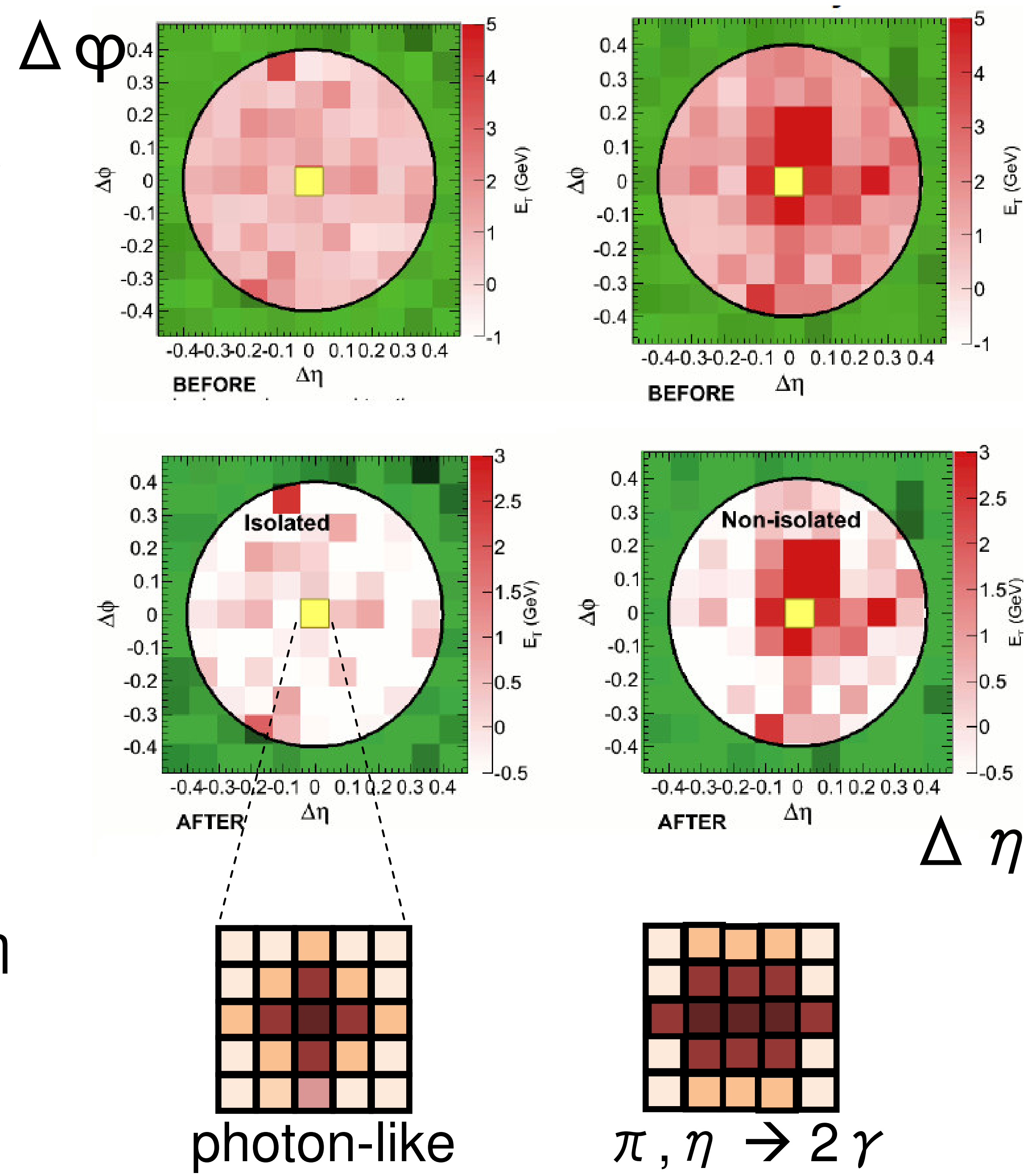
Consistent with pure isospin



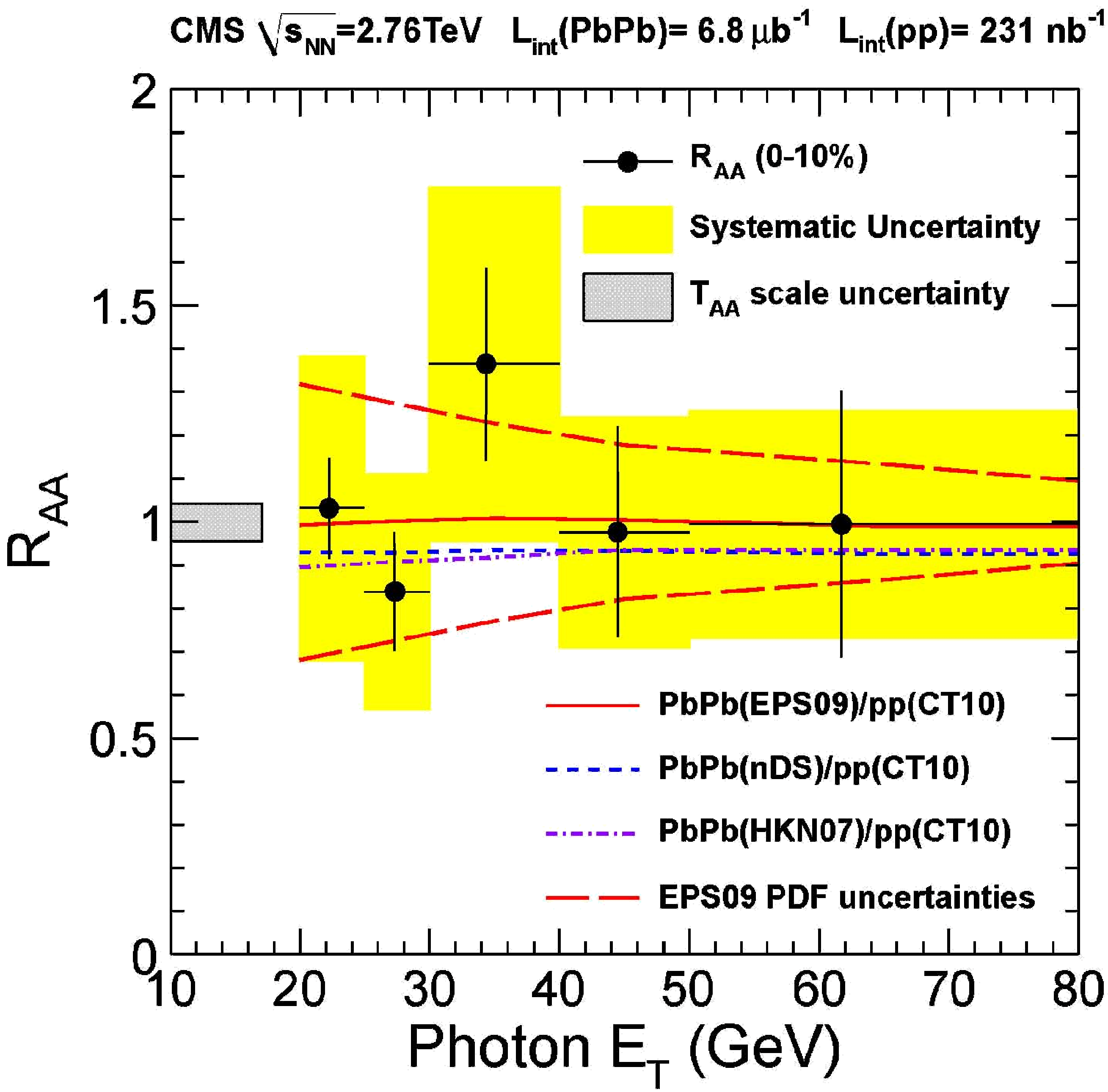
PLB 715 (2012) 66

Isolated photons

- Trigger on ECAL clusters
  - Uncorrected E_T > 15 GeV, fully efficient for E_T > 20 GeV
- Subtract underlying event
  - From same pseudorapidity strip, event by event
- Look for isolated cluster
  - Remove photons from bremsstrahlung and jet fragmentation…
- Look at shower shape in the highly segmented ECAL
  - Further remove isolated π^0, η



Photons are also unmodified



- Normalised by pp
- Consistent with unity
- Uncertainties still larger than modified pdf uncertainties…

PLB 710 (2012) 256

Summary: EWK bosons

- $Z \rightarrow \mu\mu$
  - Proportional to binary collisions
  - Nuclear effects (isospin, shadowing…) small wrt uncertainties
- $W \rightarrow \mu\nu$
  - Proportional to binary collisions
  - Expected strong isospin effect when separating W^+ and W^-
  - Shadowing (4%) small wrt uncertainties
- Isolated photons
  - Proportional to binary collisions
  - Nuclear effects (isospin, shadowing…) small wrt uncertainties
  - Serving as reference to opposite-side suppressed jets…

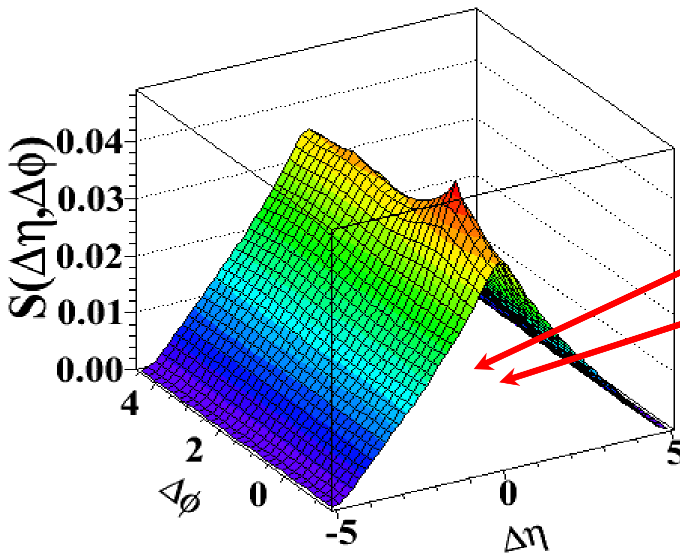
pPb collisions: 2012/13
the reference measurement (?)

Defining two-particle correlation

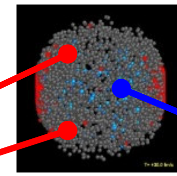
Signal pair distribution:

Background pair distribution:

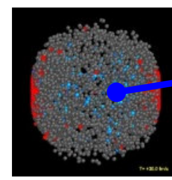
same event pairs

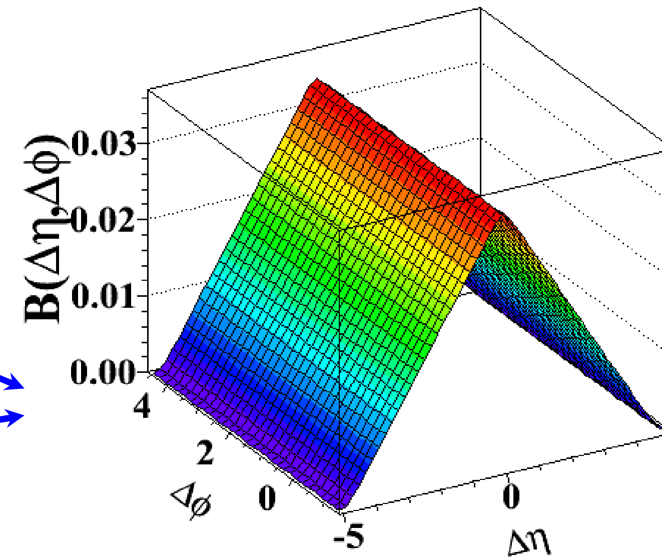


Event 1



Event 2





mixed event pairs

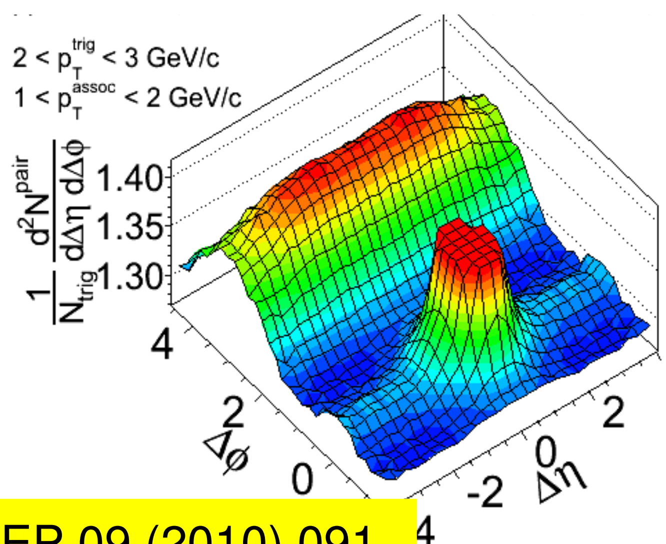
$$S\left(\Delta\eta,\Delta\phi\right)=\frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\phi}$$

$$B\left(\Delta\eta,\Delta\phi\right)=\frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta d\Delta\phi}$$

High multiplicity pp (N>110) $\sqrt{s}=7\,TeV$

$\Delta\eta = \eta_1 - \eta_2$

$\Delta\varphi = \varphi_1 - \varphi_2$

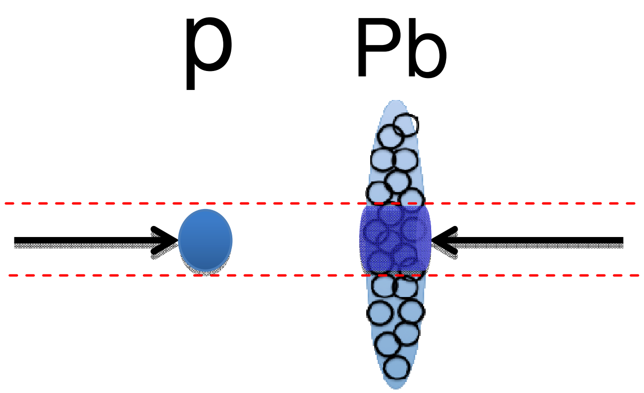


Associated hadron yield per trigger:

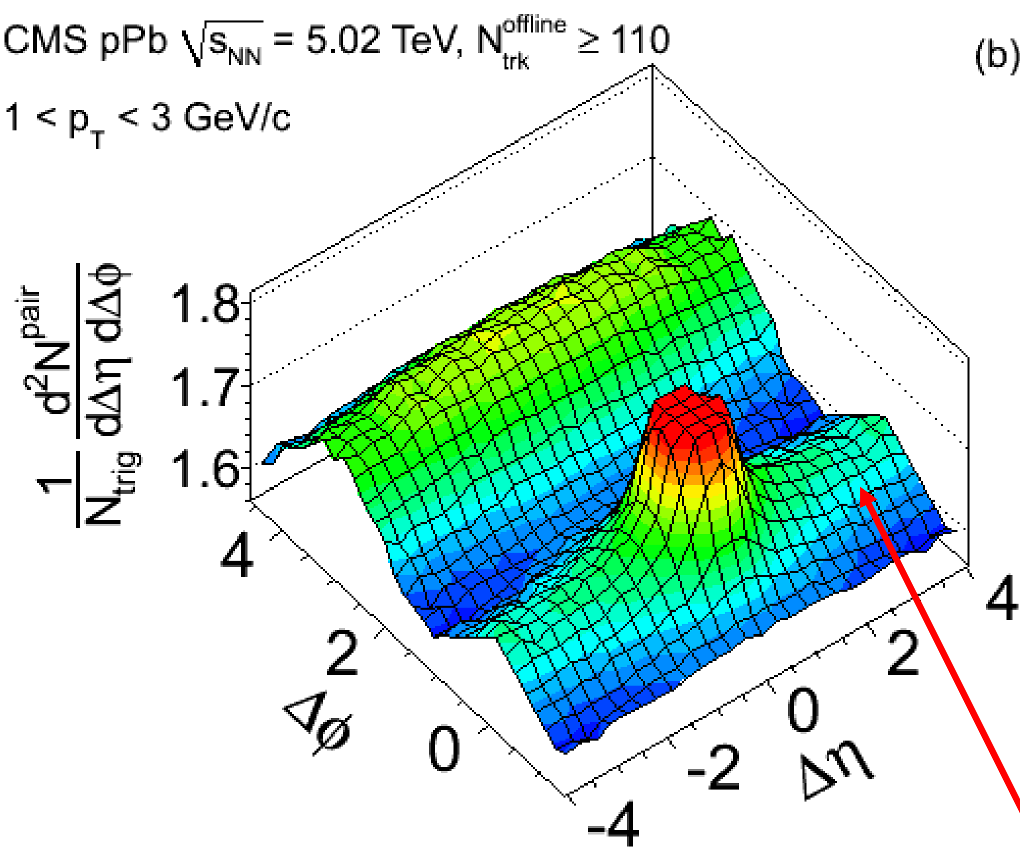
$$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi}=B\left(0,0\right)\times\frac{\boxed{S(\Delta\eta,\Delta\phi)}}{\boxed{B(\Delta\eta,\Delta\phi)}}$$

JHEP 09 (2010) 091

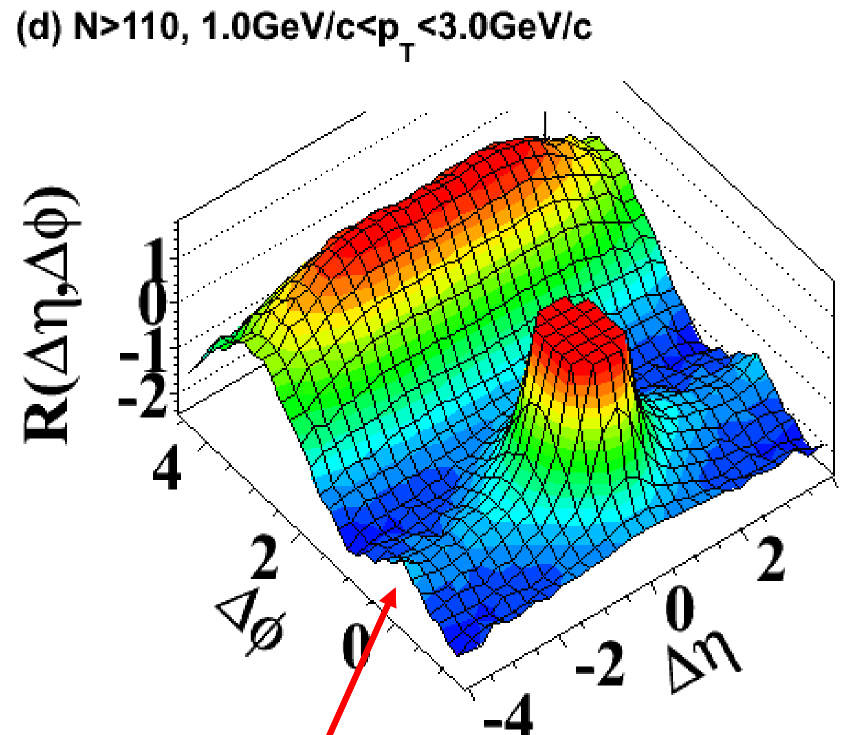
pPb: the “ridge” is observed again!



Physical origin still unclear



p+p 7 TeV



PLB 718 (2013) 795

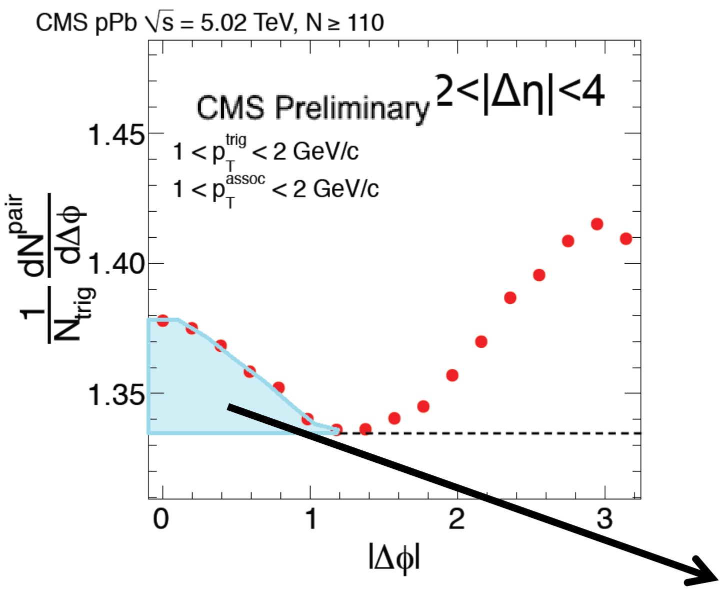
N ≡ number of offline tracks with p_T>0.4 GeV/c

Much bigger than in pp!

JHEP 09 (2010) 091

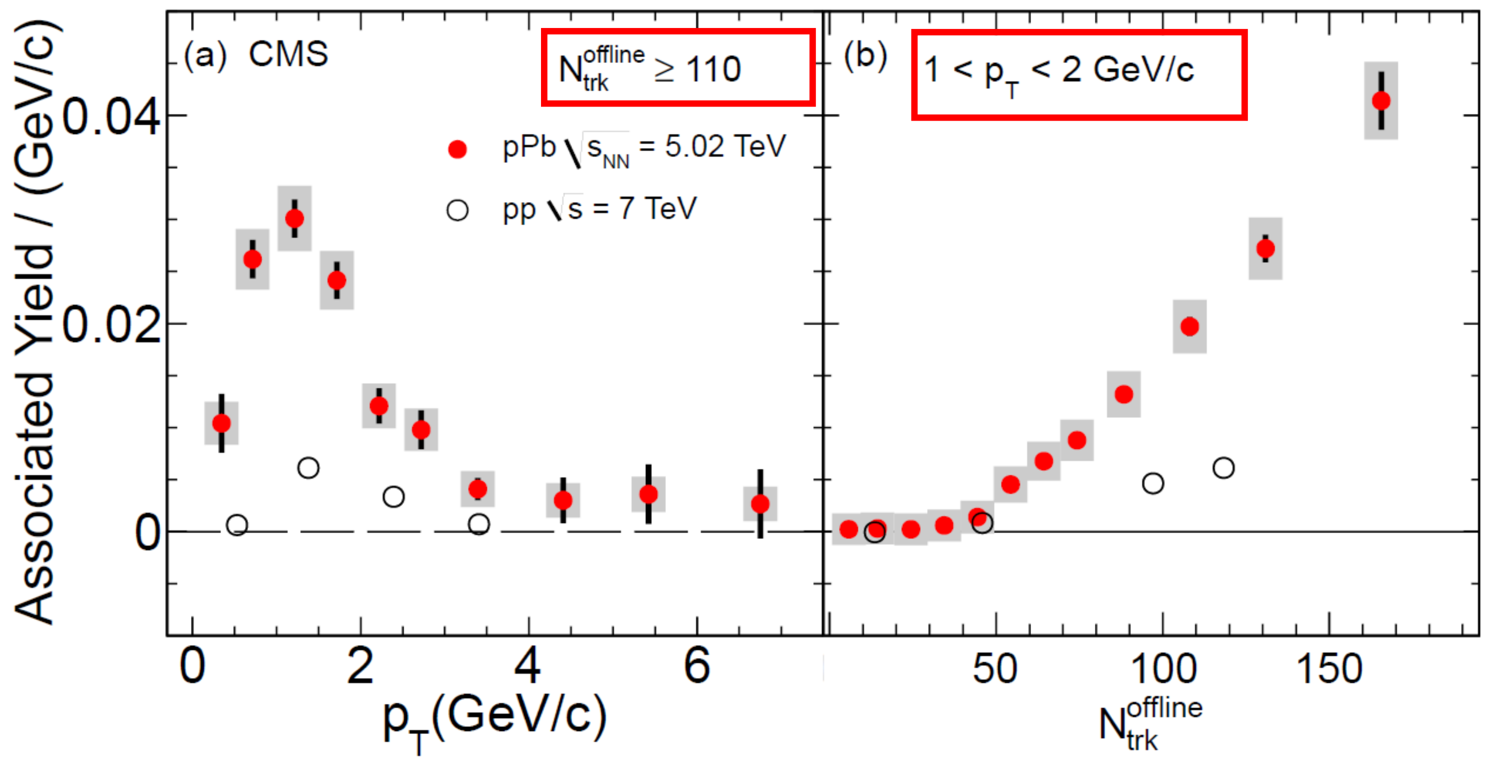
Associated yield vs. p_T and multiplicity

ZYAM example



At high multiplicity, the strength of the effect rises and falls with p_T

In the p_T range where the yield is the strongest, the ridge turns on at N≈50

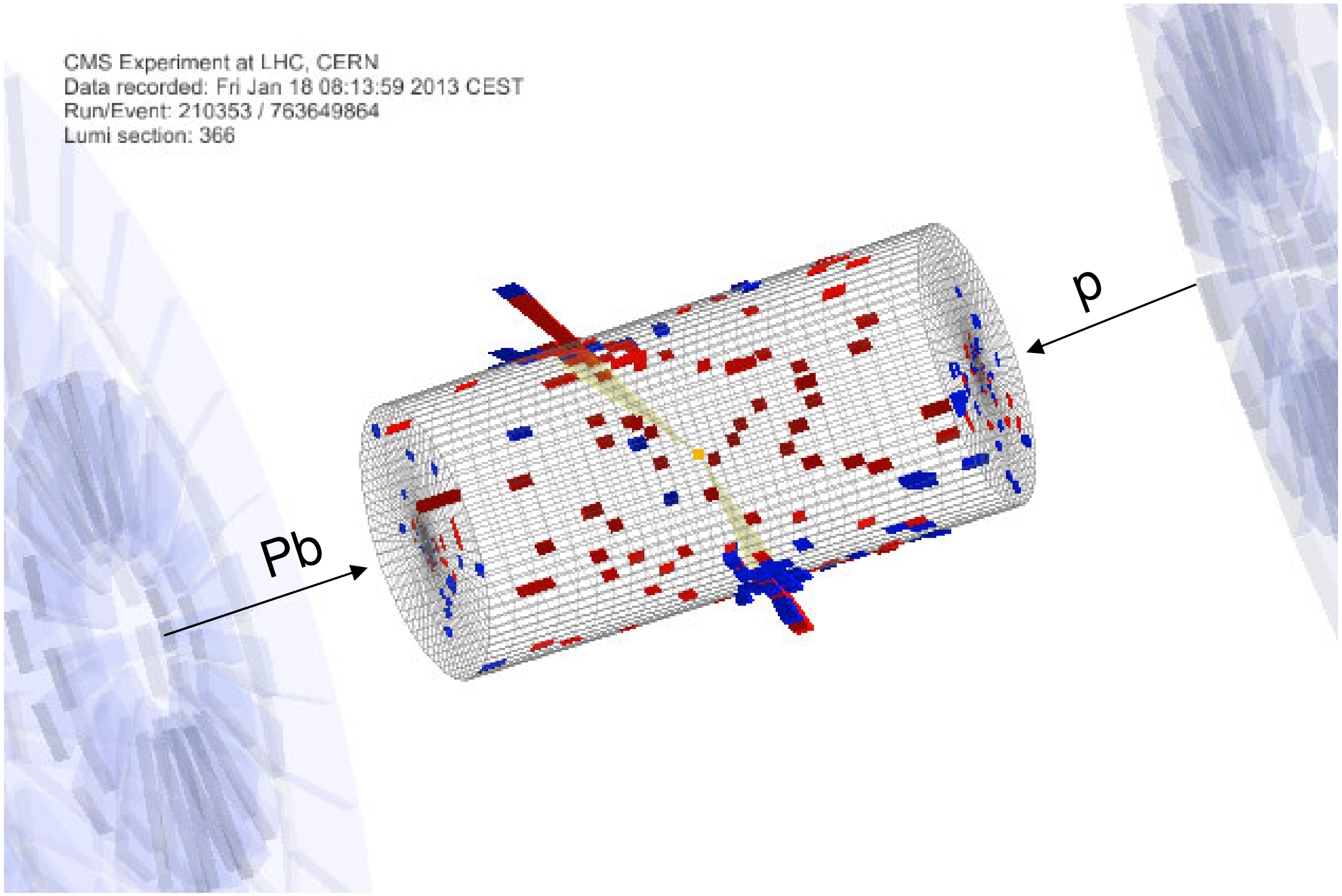


N ≡ number of offline tracks with p_T>0.4 GeV/c

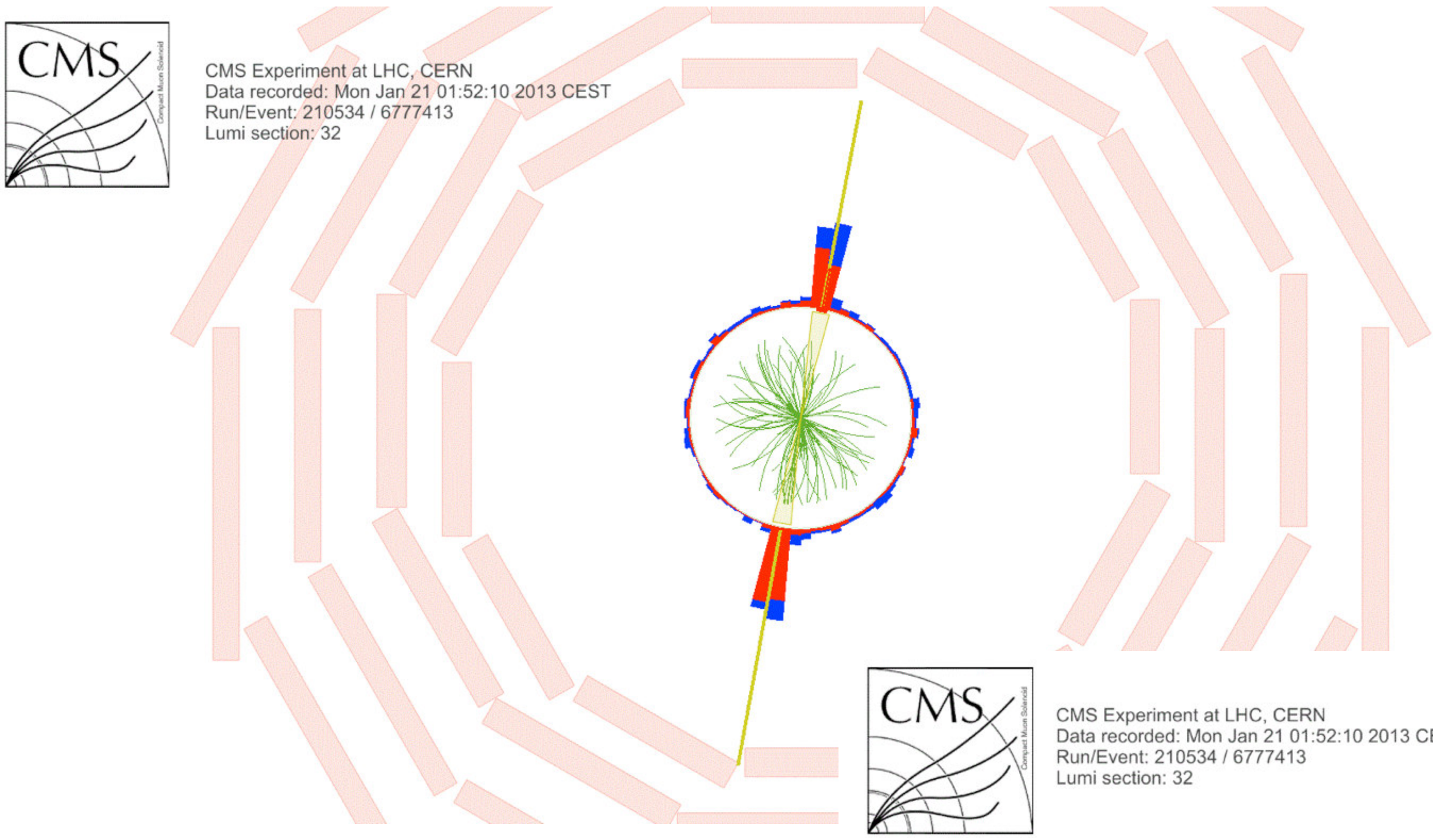
PLB 718 (2013) 795

Dijet event in pPb at $\sqrt{s_{NN}} = 5$ TeV

Much more to come…



Dijet event in pPb at $\sqrt{s_{NN}}$ = 5 TeV

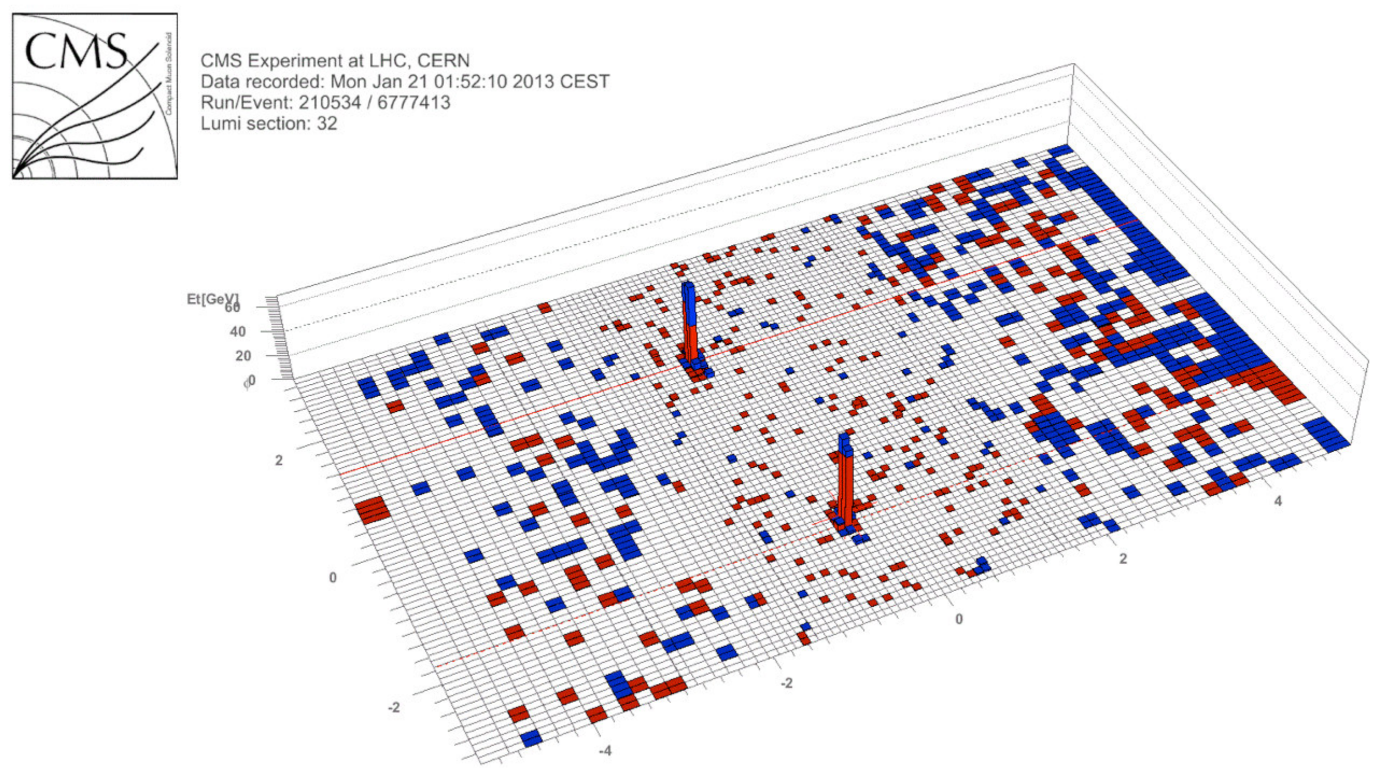


leading jet:

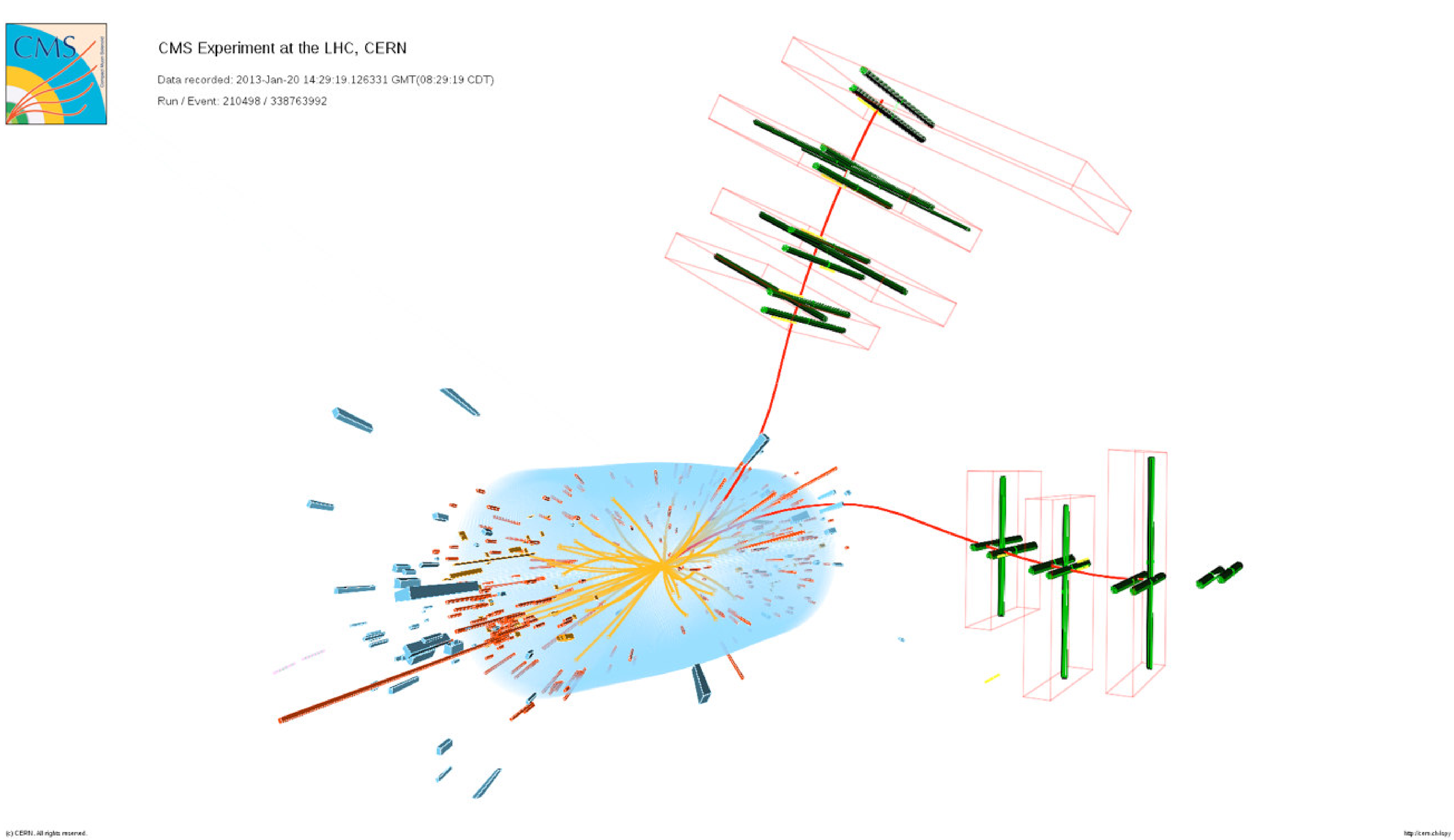
E_T = 170.3 GeV

sub-leading jet:

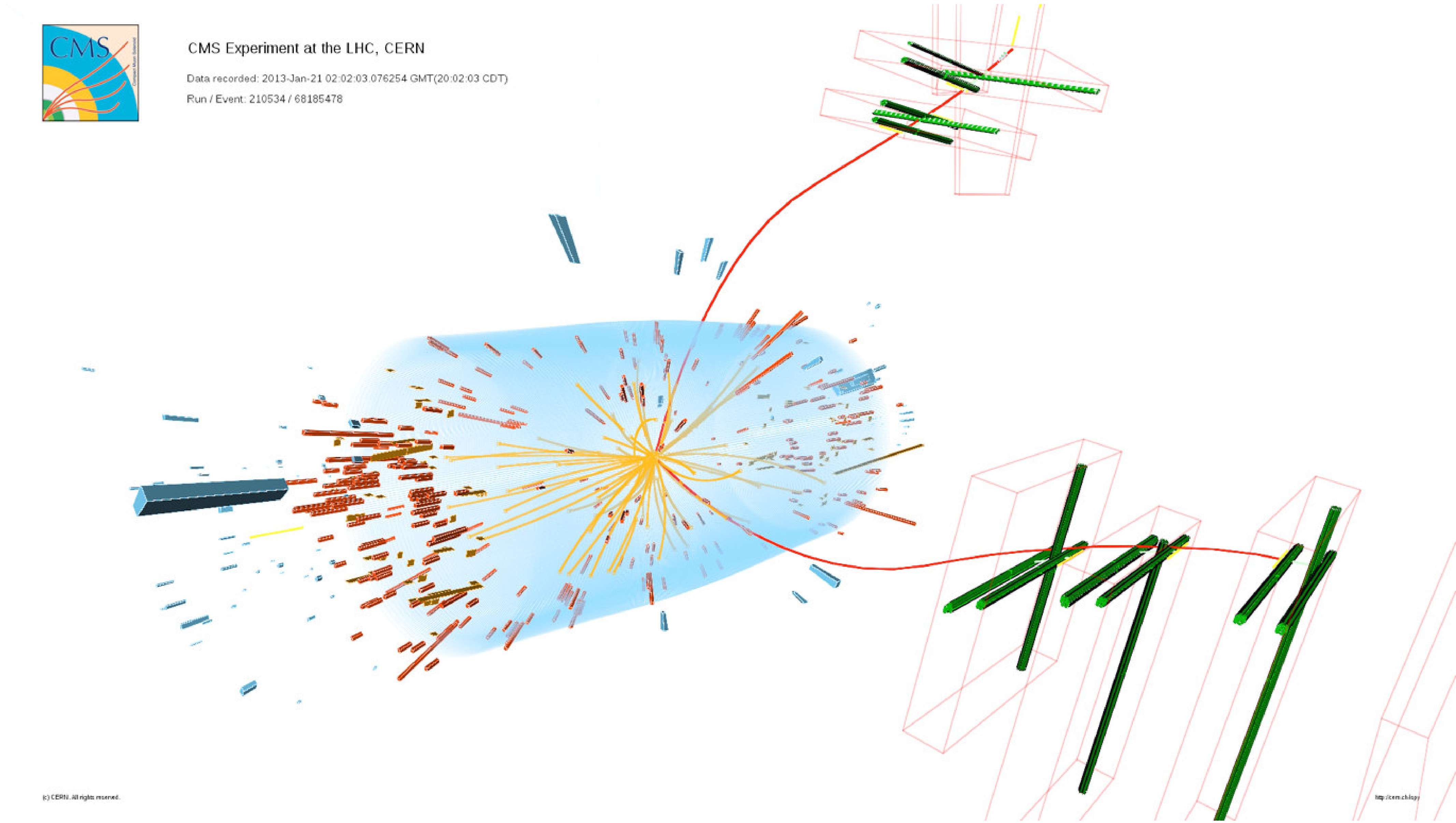
E_T = 166.9 GeV



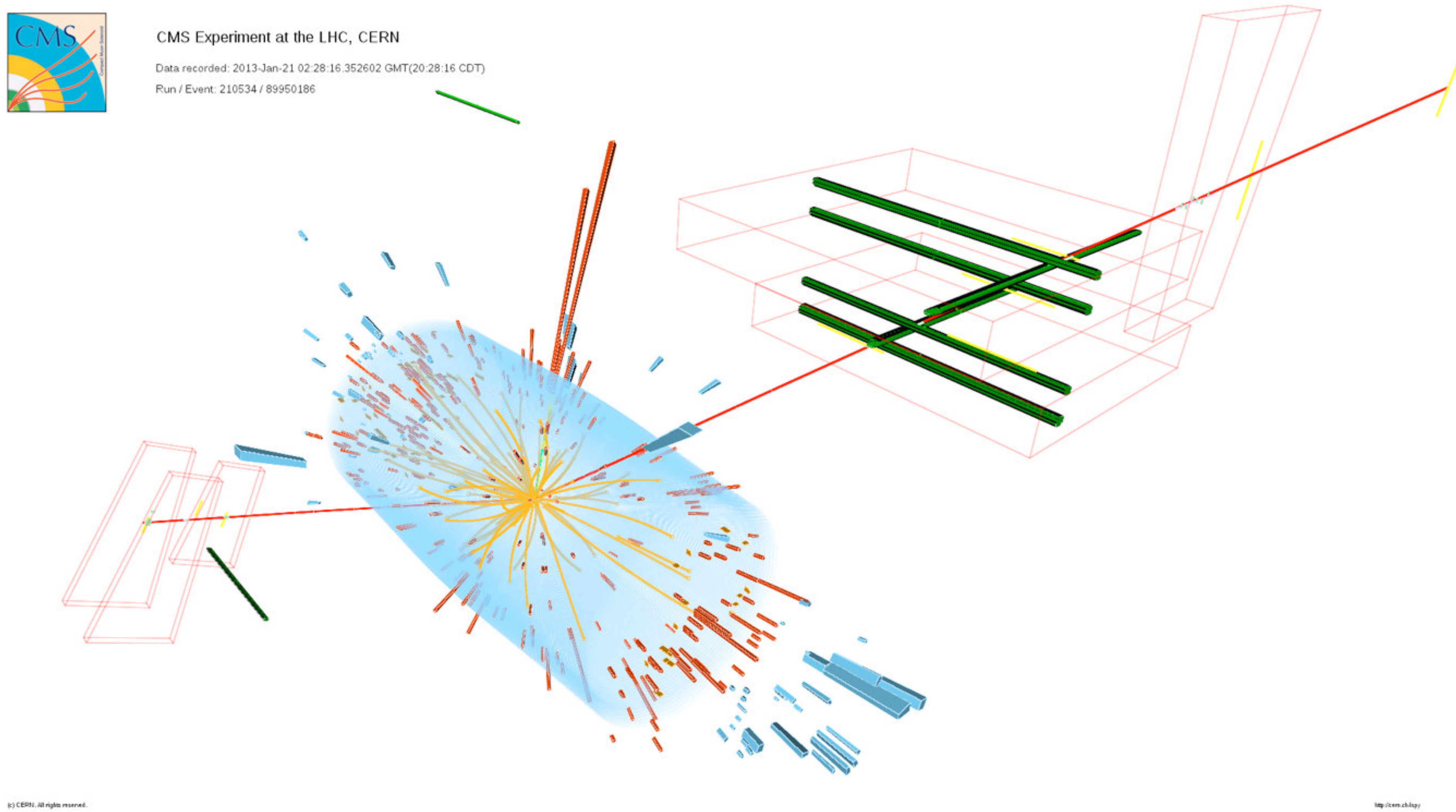
J/ψ candidate in pPb at $\sqrt{s_{NN}}$ = 5 TeV



Υ(1S) candidate in pPb at $\sqrt{s_{NN}}$ = 5 TeV



Z candidate (+jet) in pPb at $\sqrt{s_{NN}} = 5$ TeV



Conclusions

- The CMS experiment has completed two years of successful Heavy Ion program with 19 published papers
- CMS excels in measuring hard probes (jets, EWK bosons, quarkonia) as well as global properties (multiplicities, elliptic flow, energy flow)
- Various properties of the created medium are studied at a quantitative level, with new tools at the LHC energies
- All challenges in data taking, triggering, reconstruction were met so far
- We are at the end of a successful p+Pb data taking (although we hoped for more luminosity and wanted some more pp data @ 2.76 TeV)
- We are looking forward to the high luminosity runs starting in 2015

→ Many more results to come; we are still at the beginning!

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