CMS heavy-ion overview

Raphael Granier de Cassagnac
Laboratoire Leprince-Ringuet
ERC grant “QuarkGluonPlasmaCMS”
for the CMS Collaboration

Quark Matter conference, Darmstadt
May 22nd, 2014

Overview of 13 talks & 15 posters

- [List of talks]
  - Kim, B mesons
  - Zsigmond, electroweak
  - Moon, charmonia
  - Appelt, jet R_{pA} & R_{AA}
  - Devetak, factorization breakdown
  - Wang, multiparticle
  - Xu, η-dependence of correlations in pPb
  - Sharma, K_S & Λ flow
  - Gulhan, jet-track
  - Abdulsalam, bottomonia
  - Barbieri, dijets & photons
  - Jung, b-jets
  - Dogra, BEC

- [List of posters]
  - Akbiyik, γγ in pPb
  - Chudasama, Y in UPC
  - Chen, K_S & Λ flow
  - Edwards-Bruner, $dE_T/d\eta$
  - Elayavalli, jet performances
  - Innocenti, B mesons
  - Kim, shapes and FF
  - Krajczar, F/B
  - Lai, jet reconstruction
  - Lee, J/ψ in pPb
  - Lisniak, Hough transform
  - Siklér, BEC
  - Varma, φ mesons
  - Veres, pPb cross section
  - Yu, b-jet performances

Overview of 27 papers & 10+11 PAS

- All available at:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
- The quark matter 2014 release:
  - HIN-12-007: ψ' in PbPb
  - HIN-13-007: W in pPb
  - HIN-14-001: R_{pPb}(jet)
  - HIN-14-002: $v_{2,3}(K_S,\Lambda)$ in pPb
  - HIN-14-003: Z in pPb
  - HIN-14-004: B in pPb
  - HIN-14-006: $v_{2,3}$(2…8) in pPb
  - HIN-14-007: R_{pPb}(b-jet)
  - HIN-14-008: $v_{2,3}(\eta)$ in pPb
  - HIN-14-010: jet+track in PbPb
  - HIN-14-012: factorization break.
  - HIN-14-013: Bose-Einstein corr.

Overview of a plethora of probes

- Already at QM'12
  - Jets, b-jets
  - W, Z, photons
  - 5 quarkonia
  - Charged particles

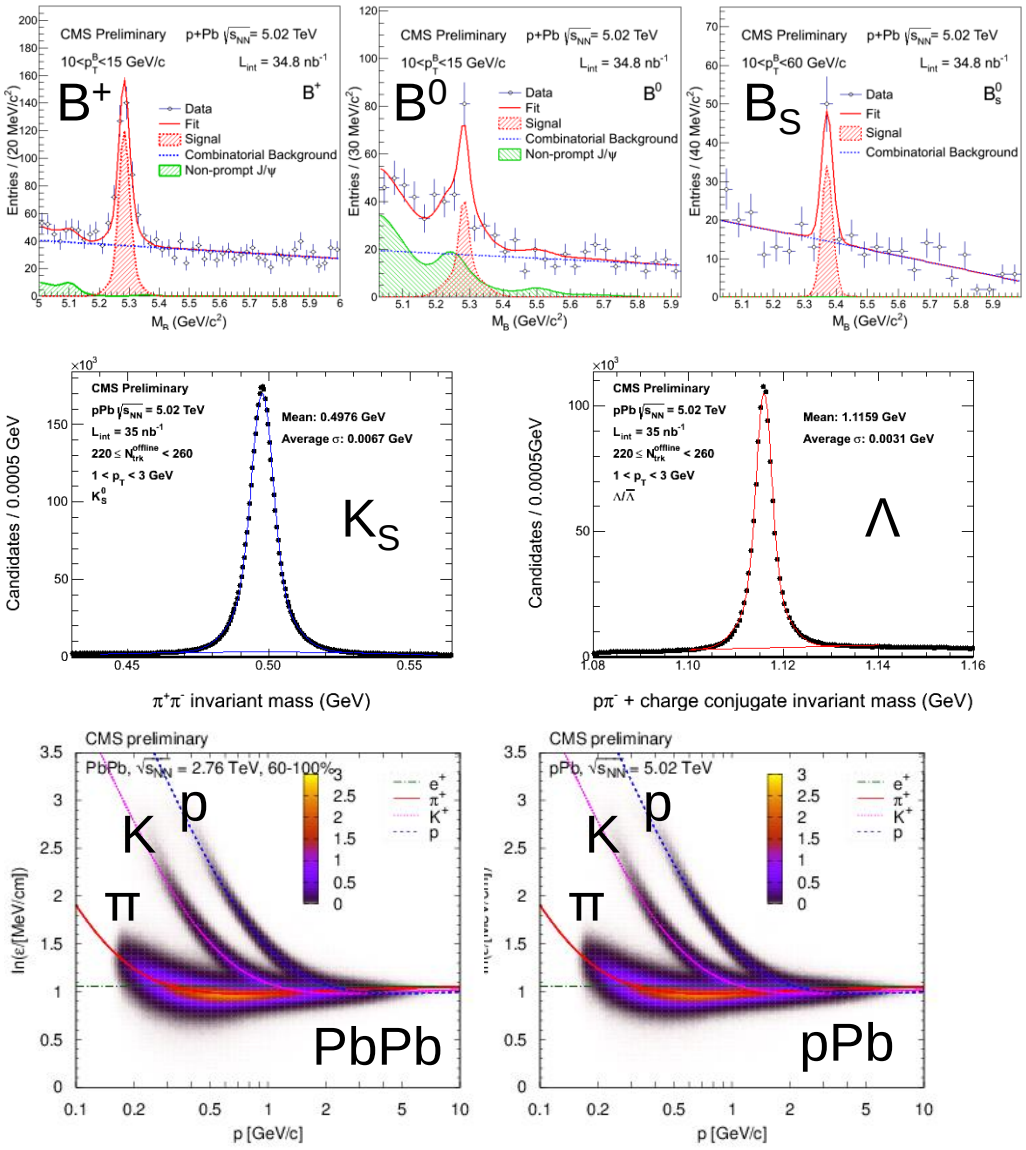
  & their correlations…

Overview of a plethora of probes

- Already at QM'12
  - Jets, b-jets
  - W, Z, photons
  - 5 quarkonia
  - Charged particles

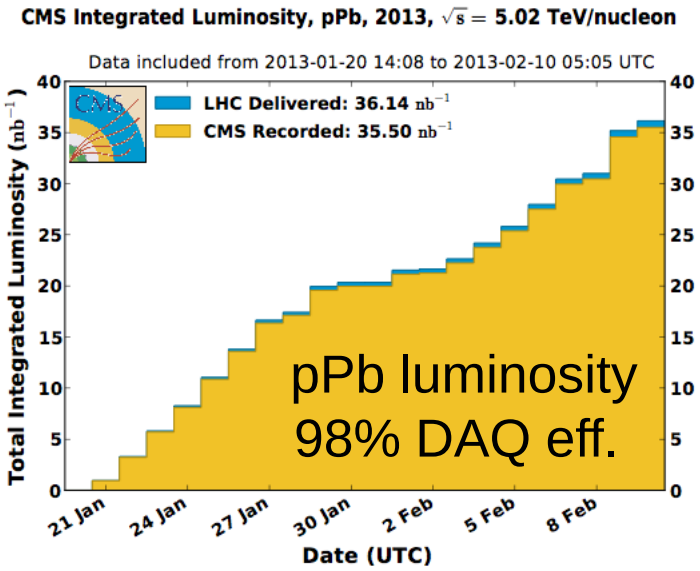
  & their correlations…

- New (in pPb, also in 50-100% PbPb)
  - B^+, B^0, B_S mesons
  - K_S, Λ
  - $\pi^{\pm}$, $K^{\pm}$, $p\bar{p}$



Overview of five HI-oriented runs

Period	Species	Energy	Lumi
Dec. 2010	Pb+Pb	2.76 TeV	7 μb^{-1}
Dec. 2011	Pb+Pb	2.76 TeV	150 μb^{-1}
Mar. 2011	p+p	2.76 TeV	230 nb^{-1}
Jan. 2013	p+Pb	5.02 TeV	35 nb^{-1}
Fev. 2013	p+p	2.76 TeV	5.4 pb^{-1}

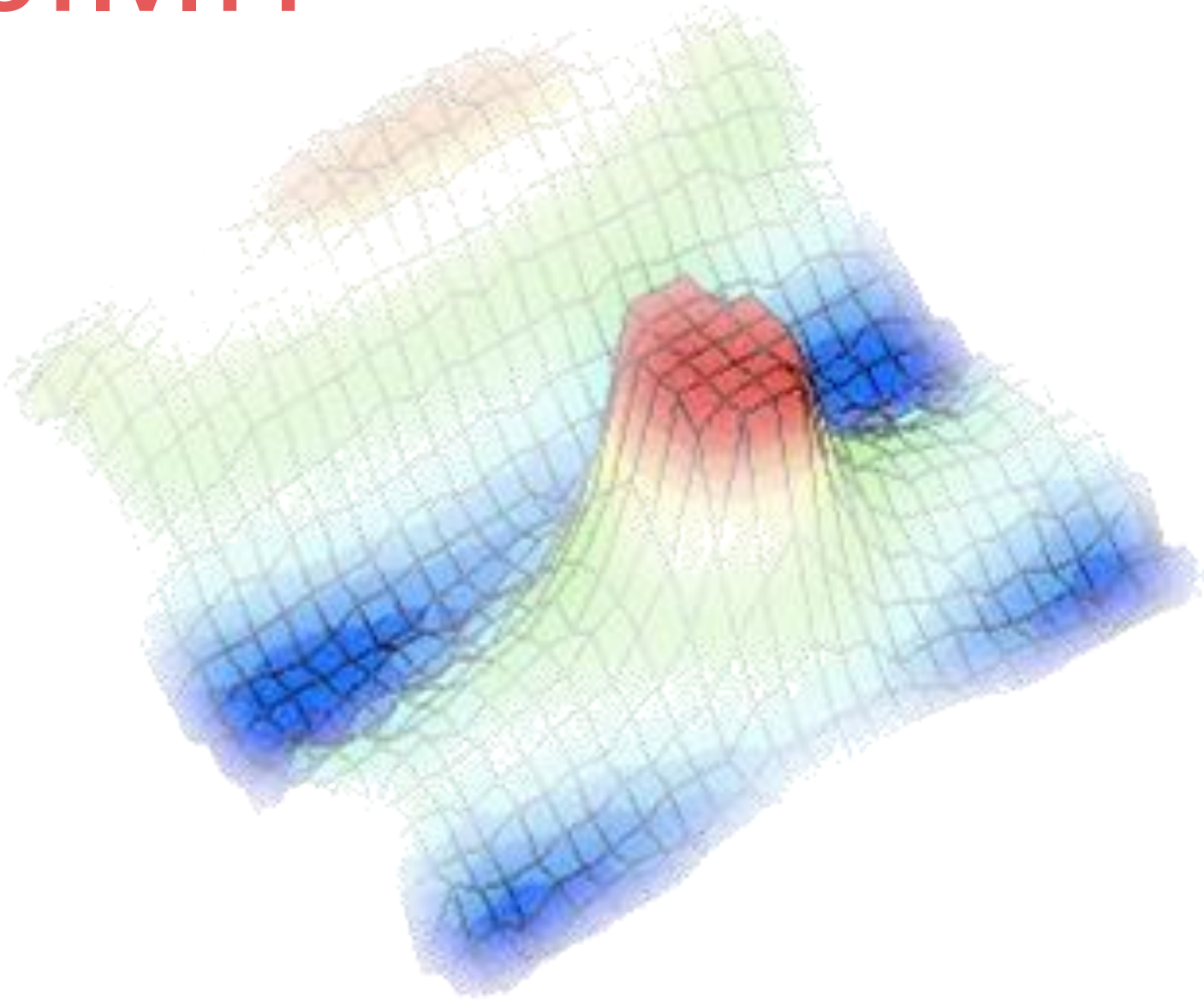


- Same N_{coll} scaled luminosities for pp, pPb, PbPb
  - (as many Z's and W's, modulo the √s dependence)
- New since QM12
  - PbPb results updated with 20 x more pp reference data
  - pPb results, awaiting 5.02 TeV pp reference data

Brief outline

- Collectivity
  - Ridge, elliptic flow, triangular flow, HBT radii, spectra…
- Energy loss
  - Jet fragmentation & shape, b-jets & mesons, high p_T…
- Nuclear PDF
  - From jets, Z and W…
- Melting
  - J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S)

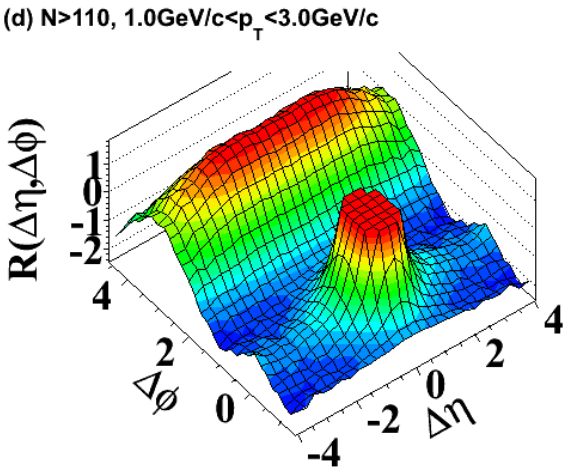
COLLECTIVITY

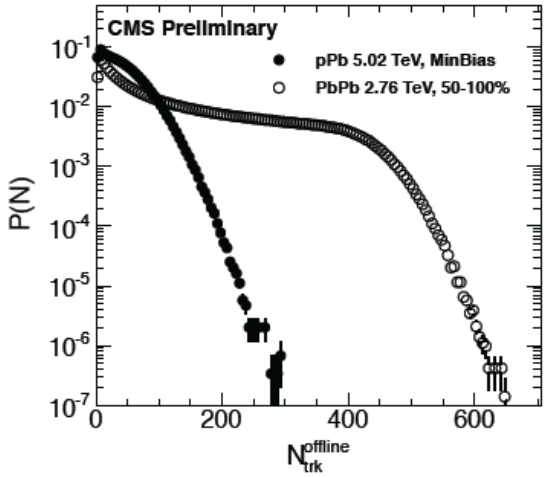


The “ridge” at LHC

- Early observation in high multiplicity 7 TeV pp collisions
  - Origin still unclear
- Then seen in PbPb collisions, reminiscent of RHIC
  - Believed to arise from collective flow
- Now confirmed in pPb collisions
  - Is it collective flow? CGC?
  - Tool: highest pPb multiplicity (<0.0003%) ≈ 55-60% PbPb centrality

pp: JHEP 09 (2010) 091



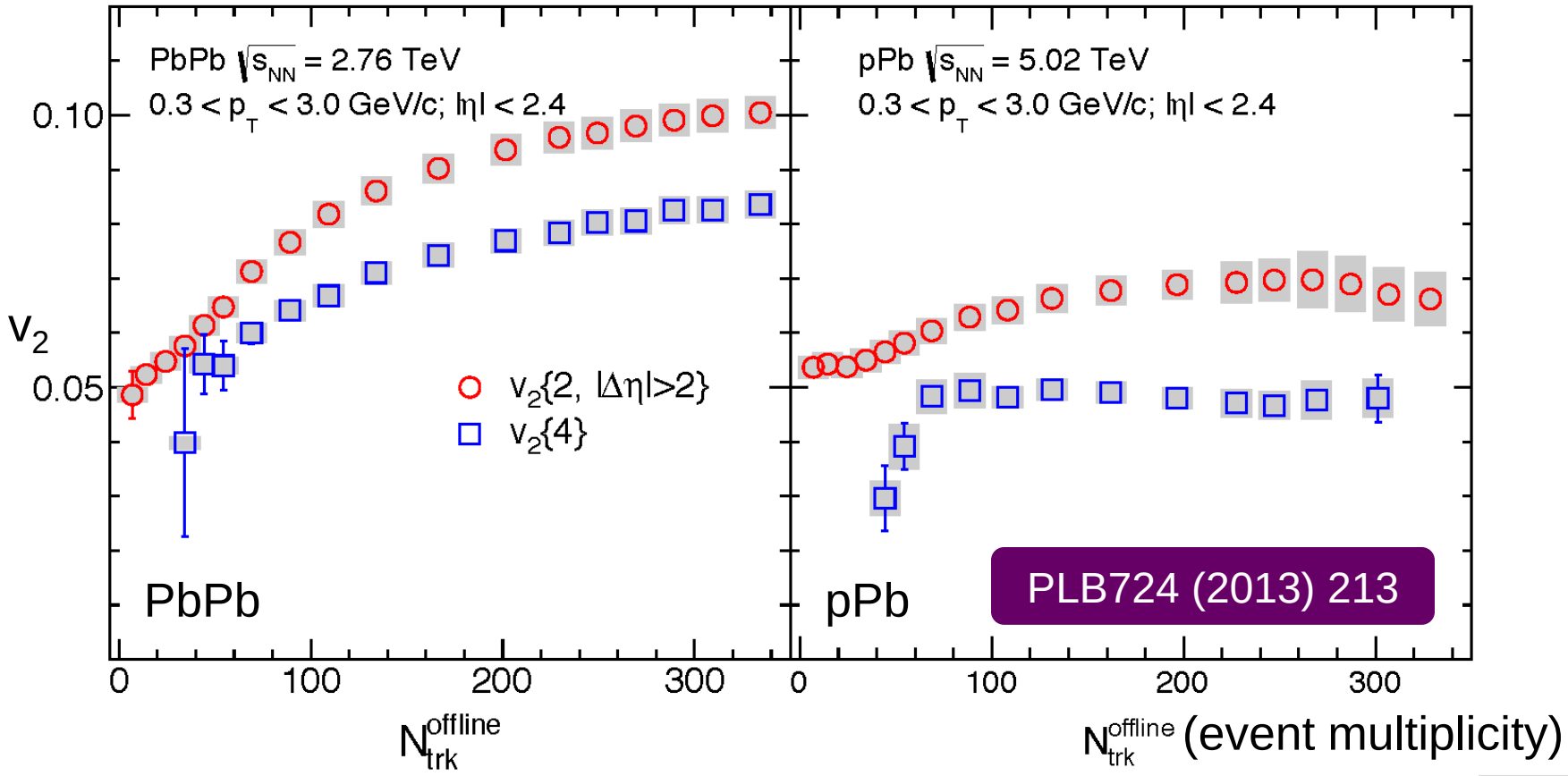


pPb: PLB718 (2013) 795
pPb: PLB724 (2013) 213

Multiparticle correlations

- v_2 stays large when calculated with multi-particles
  - $v_2(4) \neq v_2(2)$
  - (non-flow, fluctuations…)

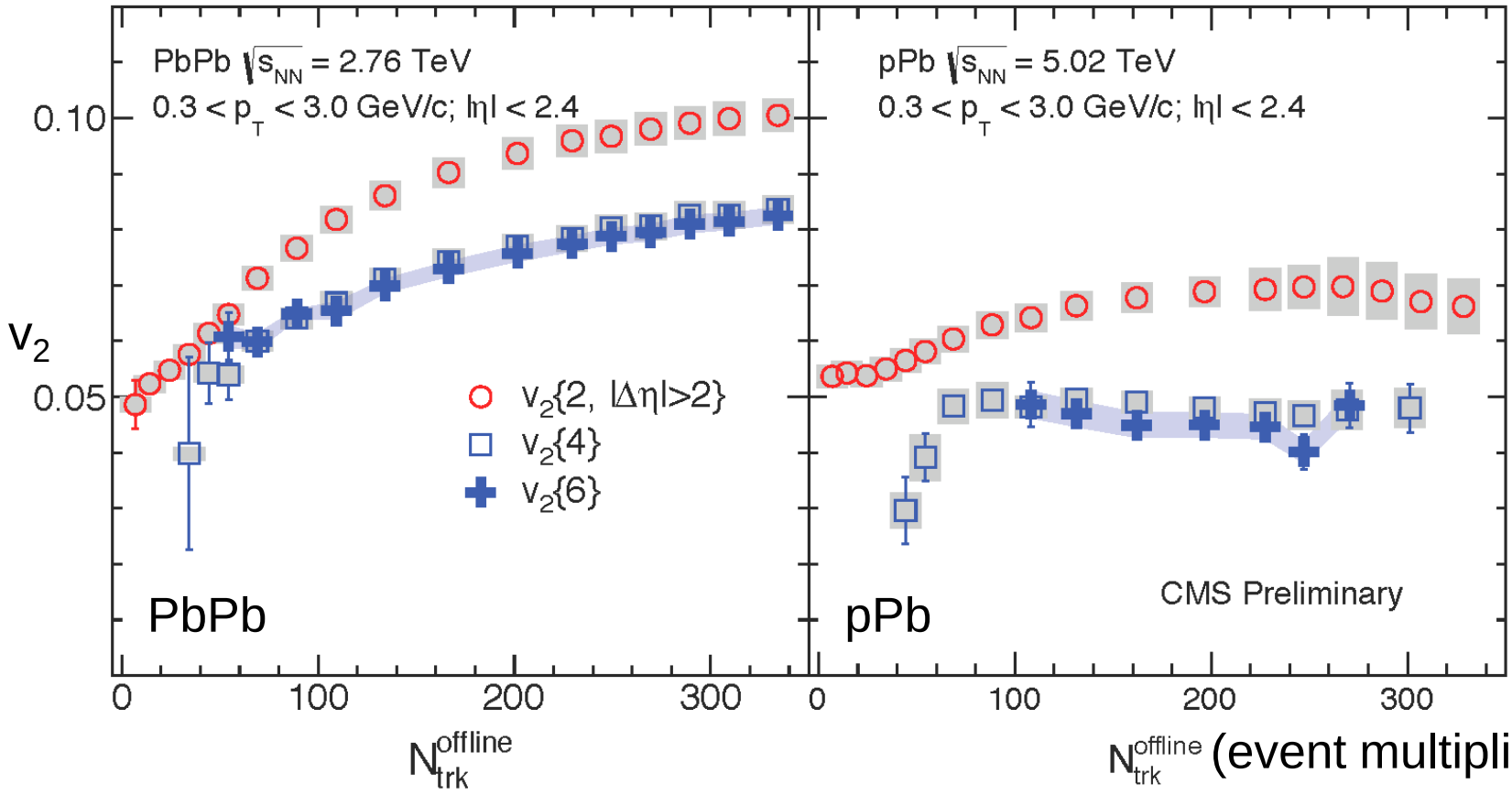
Talk by Wang
PAS-HIN-14-006



Multiparticle correlations

- v_2 stays large when calculated with multi-particles
  - $v_2(4)=v_2(6)$

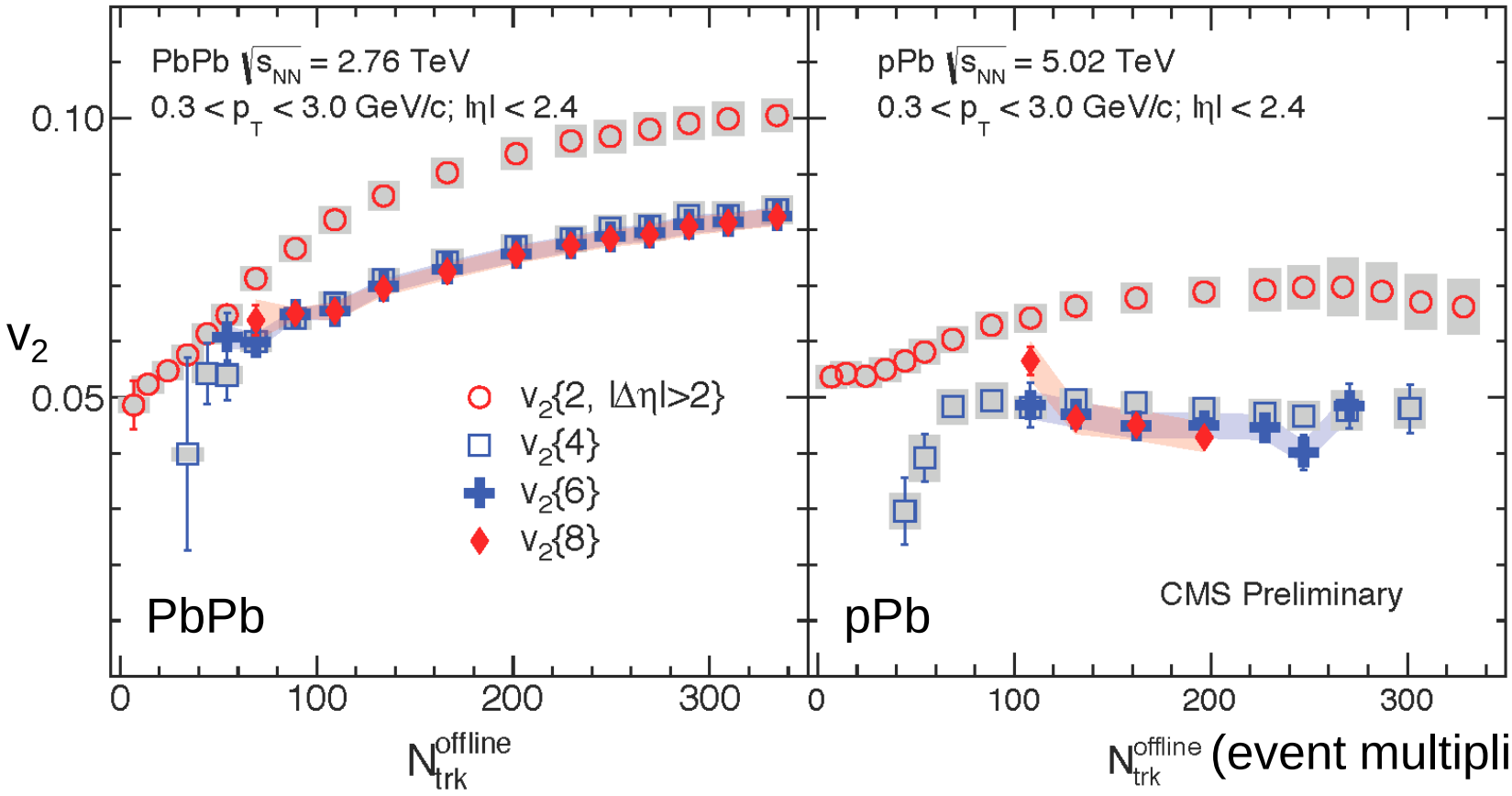
Talk by Wang
PAS-HIN-14-006



Multiparticle correlations

- v_2 stays large when calculated with multi-particles
  - $v_2(4)=v_2(6)=v_2(8)$

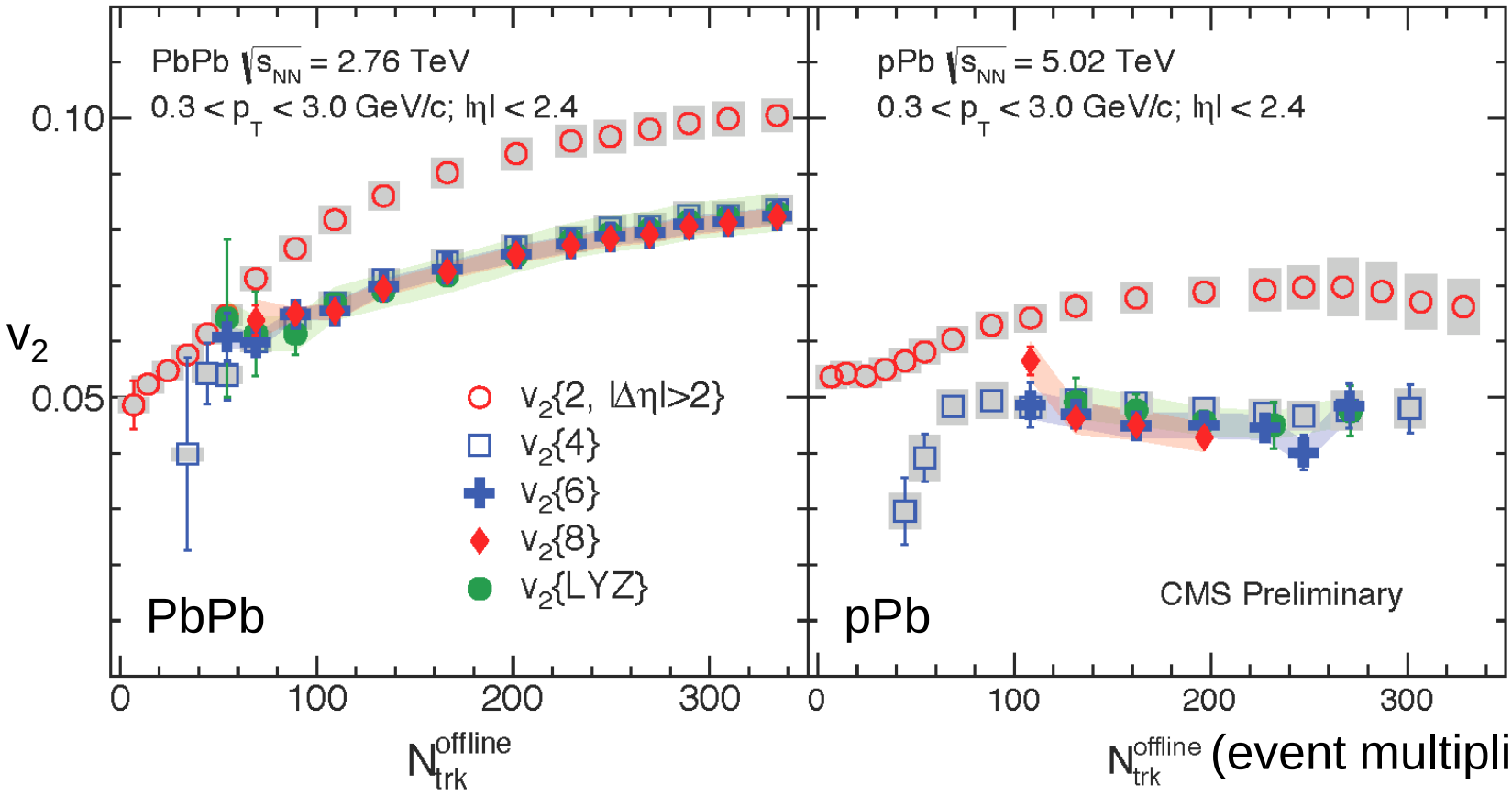
Talk by Wang
PAS-HIN-14-006



Multiparticle correlations

- v_2 stays large when calculated with multi-particles
  - $v_2(4)=v_2(6)=v_2(8)=v_2(LYZ)$ within 10%
  - True collectivity in pPb collisions!

Talk by Wang
PAS-HIN-14-006

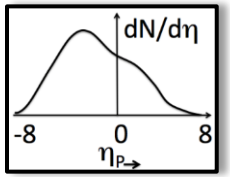


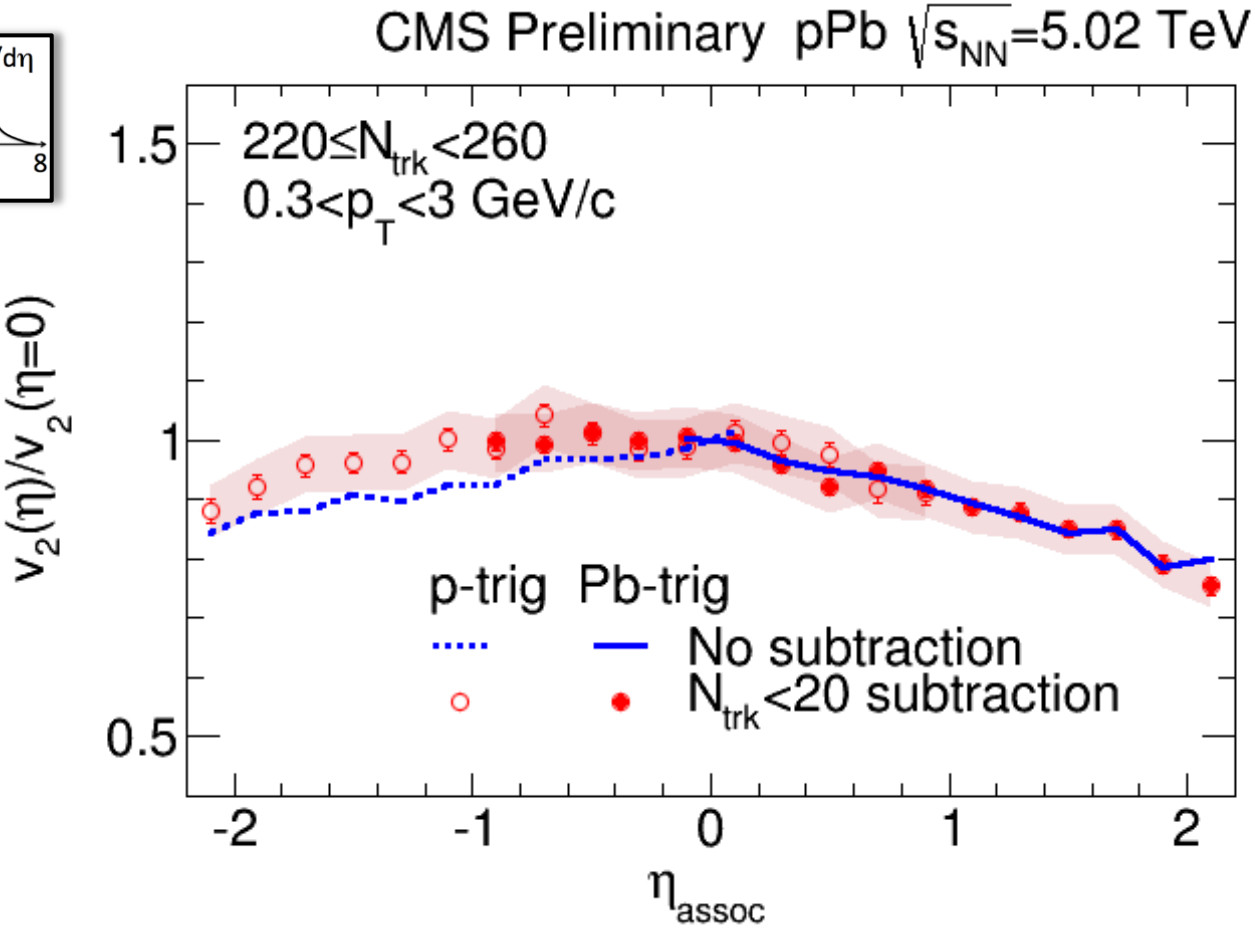
In pPb, η-dependence of v_2

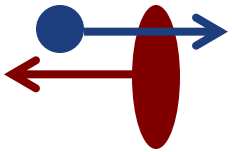
- In pPb collisions, v_2 depends on η

→ More v_2 with higher particle densities

Talk by Xu
PAS-HIN-14-008





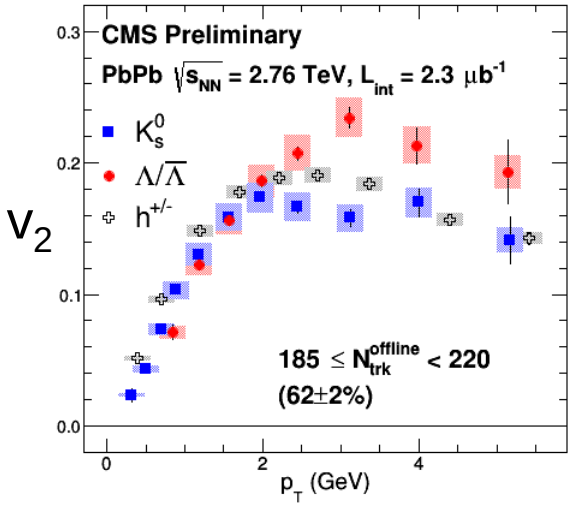


Elliptic flow of identified particles

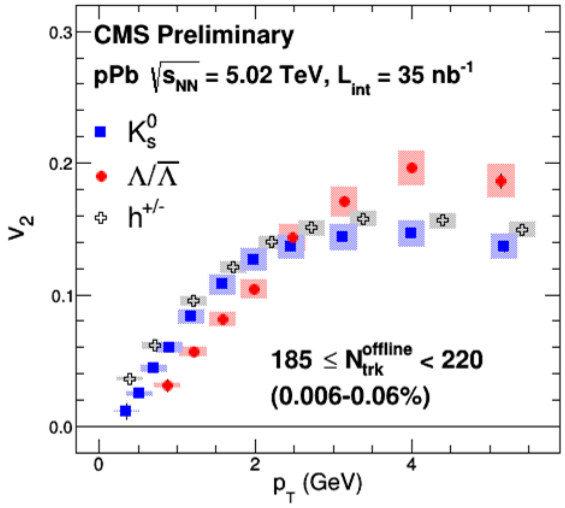
Identified K_S and Λ & charged hadrons

v_2 (and v_3) from 2-particle correlations

show mass ordering in pPb and PbPb (stronger in pPb)



PbPb



pPb

Talk by Sharma
Poster by Chen
PAS-HIN-14-002

Elliptic flow of identified particles

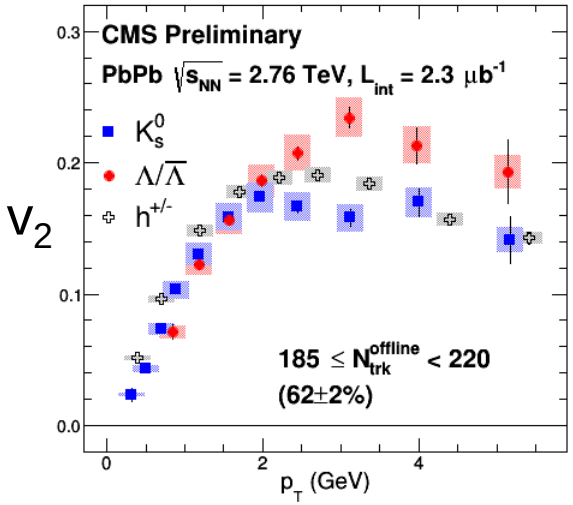
Identified K_S and Λ & charged hadrons

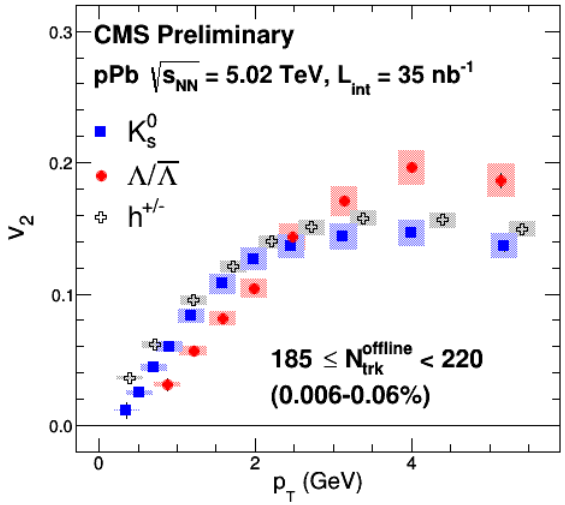
v_2 (and v_3) from 2-particle correlations

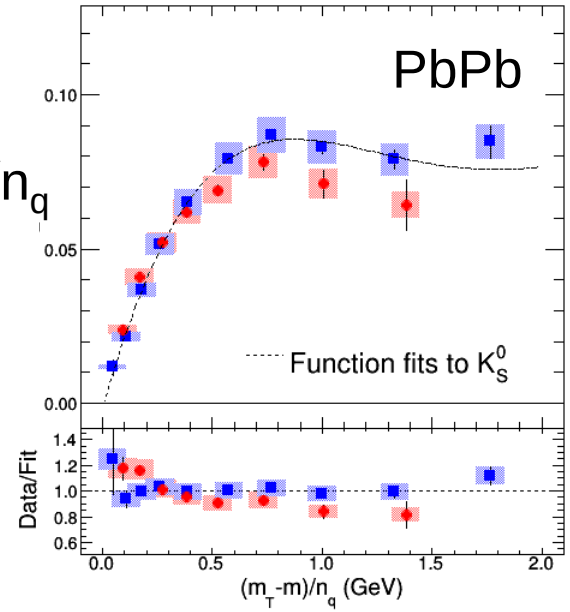
show mass ordering In pPb and PbPb (stronger in pPb)

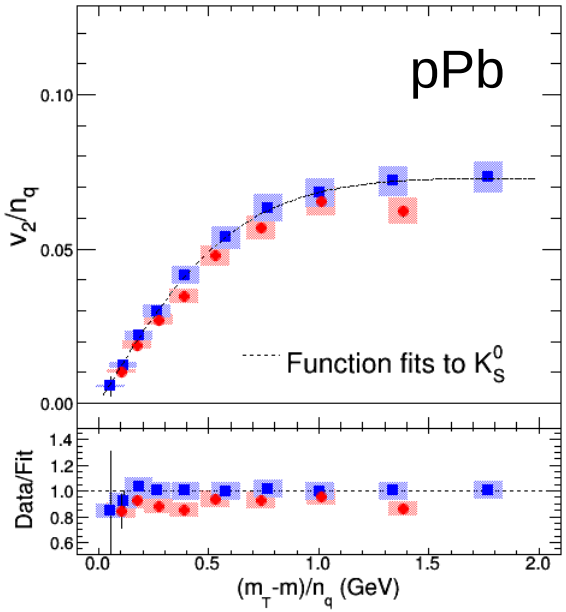
and ≈ quark scaling (better in pPb)

Talk by Sharma
Poster by Chen
PAS-HIN-14-002





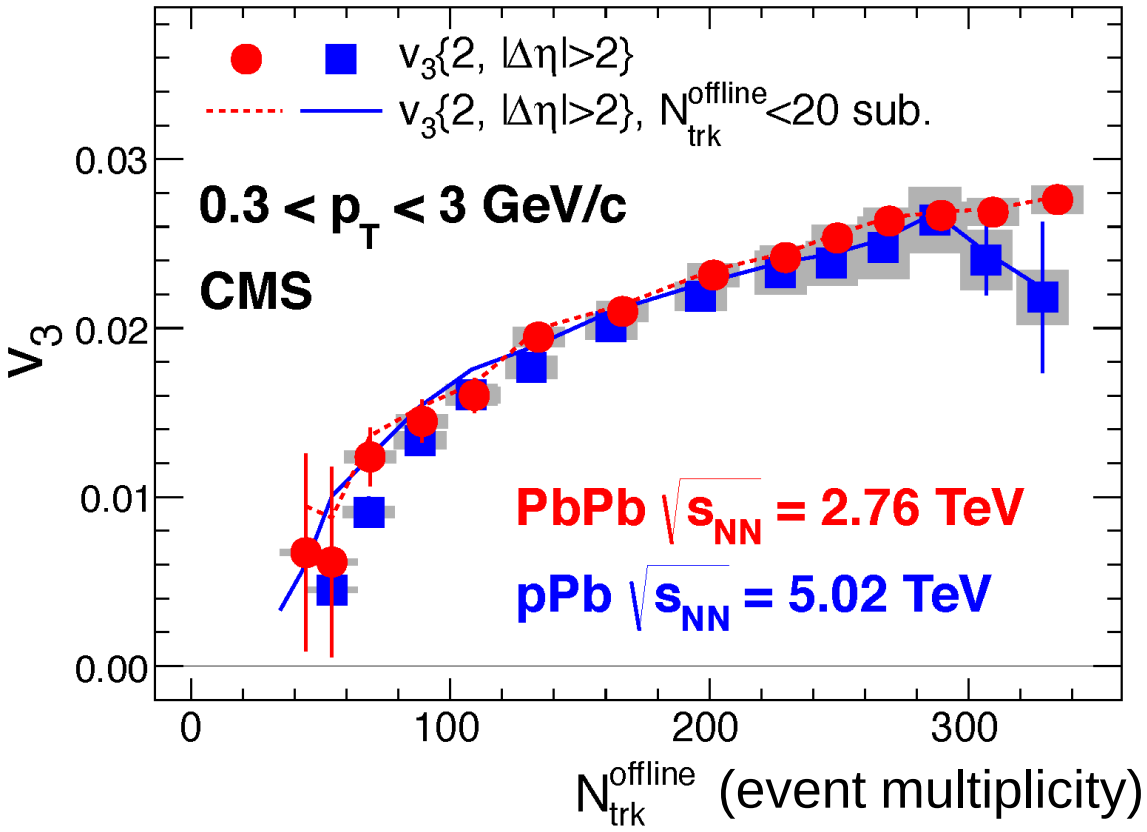


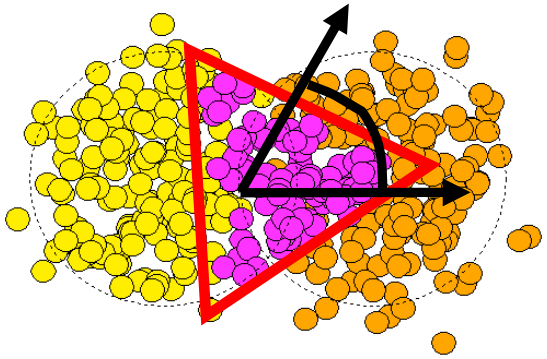


Triangular flow

- Remarkable similarity in the v_3 signal as a function of multiplicity in pPb and PbPb

PLB724 (2013) 213



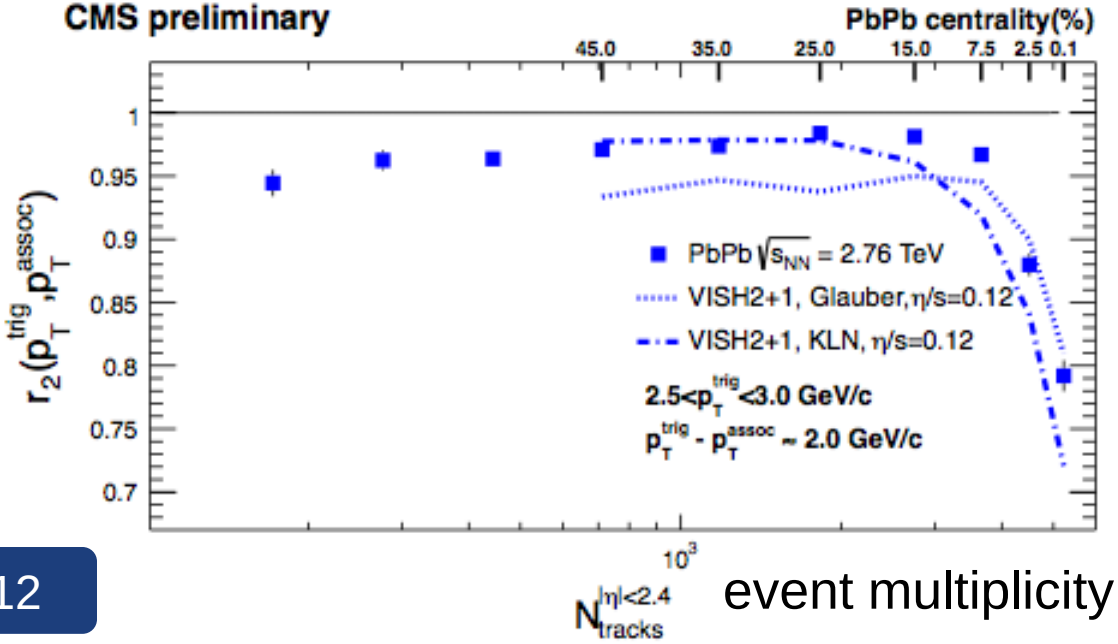


Checking factorization

- From two particle correlations
  - $V_{n\Delta}(p_{T1},p_{T2}) = v_n(p_{T1}) \times v_n(p_{T2})$ factorization is assumed
- Breaking down, in hydro, due to fluctuations
  - $r_n = V_{n\Delta}(p_{T1},p_{T2}) / \sqrt{V_{n\Delta}(p_{T1},p_{T1}) \times V_{n\Delta}(p_{T2},p_{T2})}$

(also available in p_{T1}, p_{T2} bins)

Large breaking in very central PbPb collisions, qualitatively reproduced



Talk by Devetak, PAS-HIN-14-012

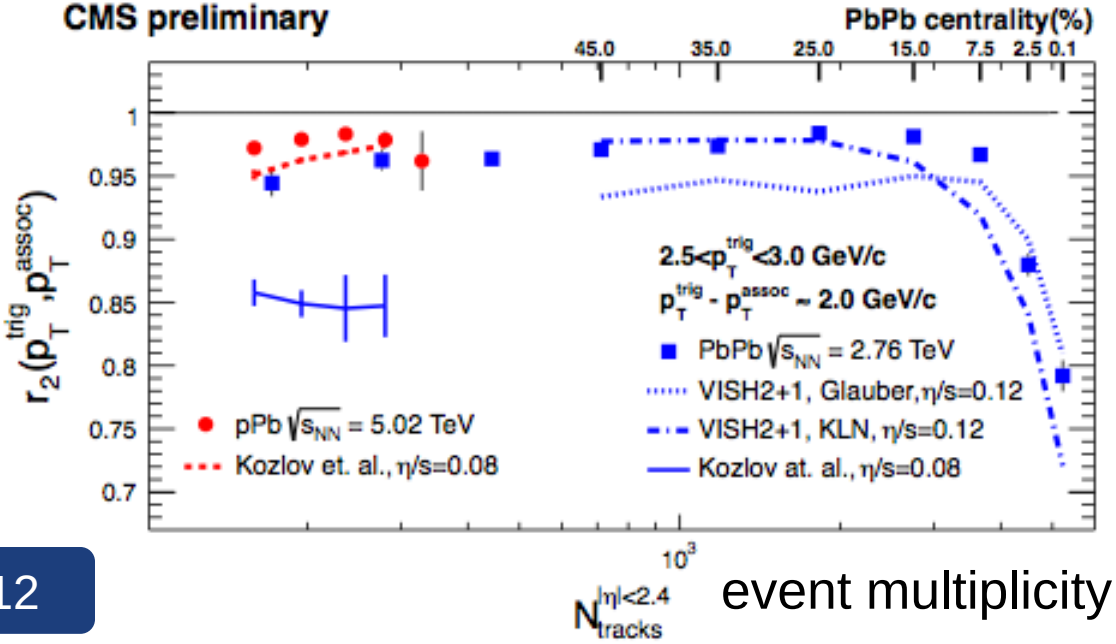
Checking factorization

- From two particle correlations
  - $V_{n\Delta}(p_{T1},p_{T2}) = v_n(p_{T1}) \times v_n(p_{T2})$ factorization is assumed
- Breaking down, in hydro, due to fluctuations
  - $r_n = V_{n\Delta}(p_{T1},p_{T2}) / \sqrt{V_{n\Delta}(p_{T1},p_{T1}) \times V_{n\Delta}(p_{T2},p_{T2})}$

(also available in p_{T1}, p_{T2} bins)

Large breaking in very central PbPb collisions, qualitatively reproduced

Similar/smaller breaking in pPb vs PbPb

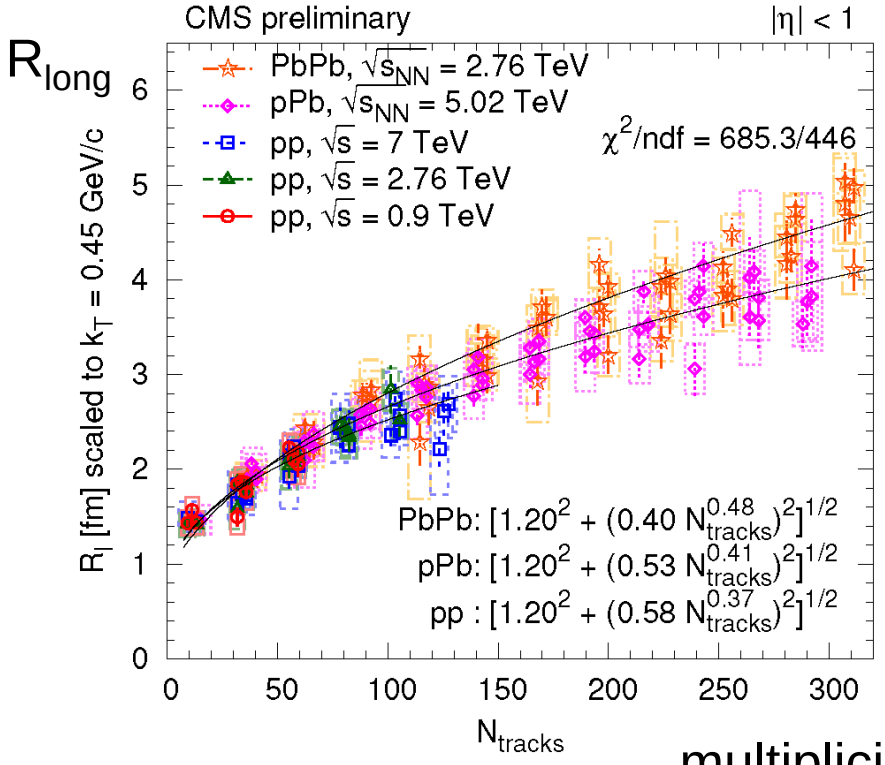


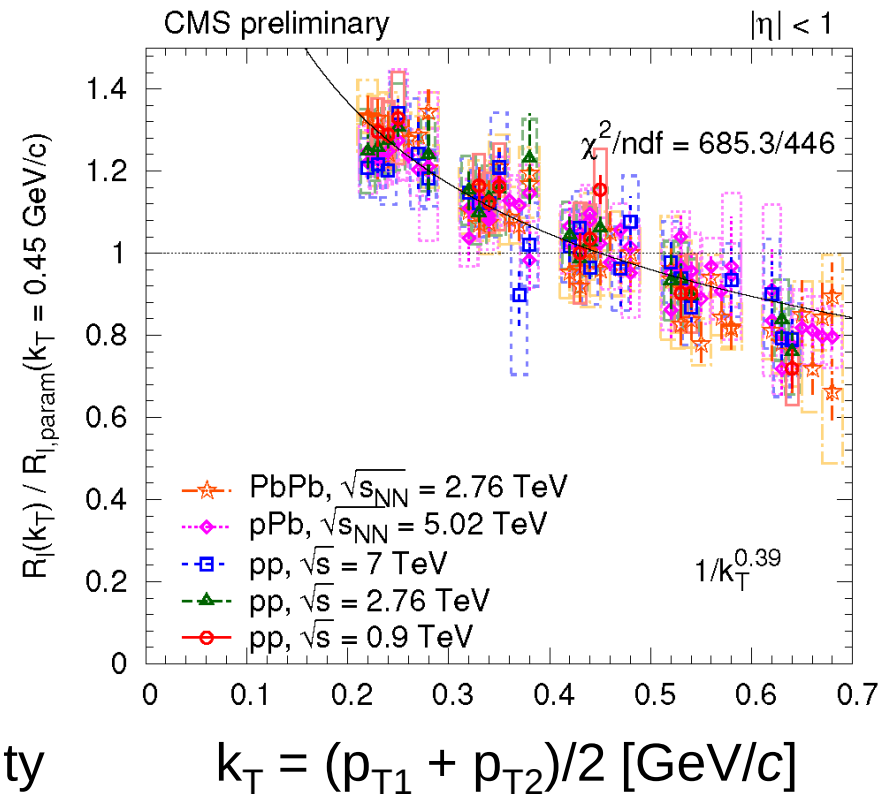
Talk by Devetak, PAS-HIN-14-012

Bose-Einstein correlations

- Similar large radii (R_{long} up to 5 fm) in pPb & PbPb
  - Thanks to π/K/p separation
- Scaling with multiplicity and k_T

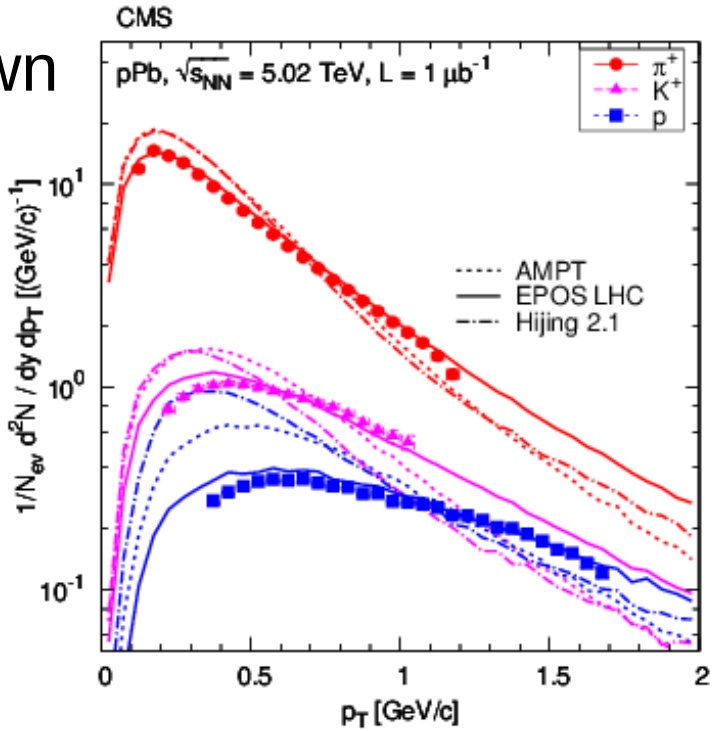
Talk by Dogra
Poster by Sikler
PAS-HIN-14-013





Summary (1/4) collectivity

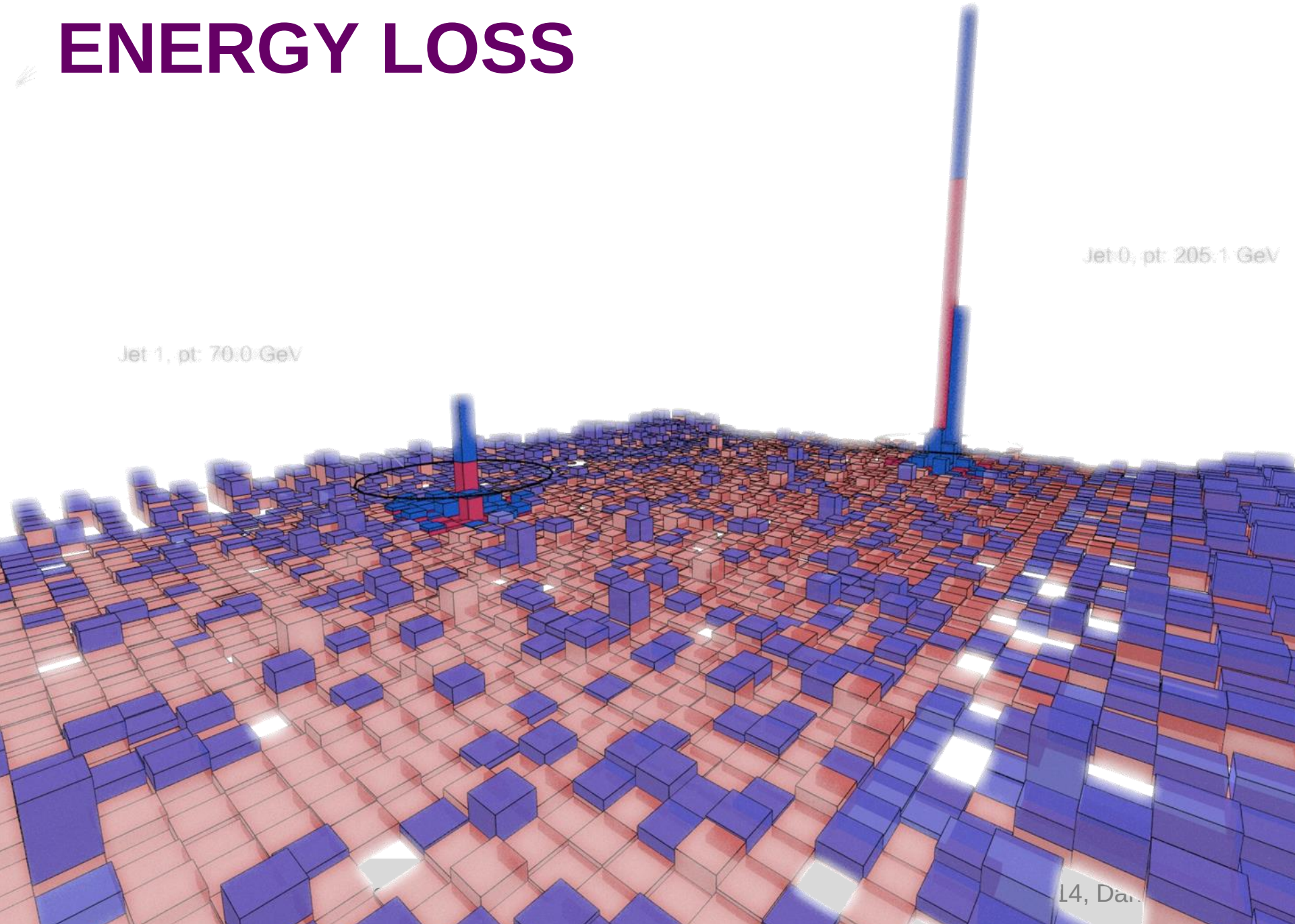
- pPb looks a lot like PbPb, and as hydro predicts!
  1. Strong v_2 from multiparticle correlations
  2. Similar mass ordering
  3. v_2 depending on η in pPb
  4. Same v_3 versus multiplicities
  5. Same factorization breakdown
  6. Similar HBT radii (5 fm)
  7. and the spectra are better reproduced by generators incl. hydro (EPOS) →



High-multiplicity pPb collisions show collectivity!

arXiv:1307.3442, EPJC-accepted

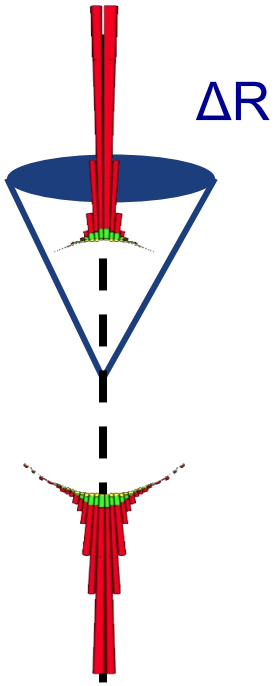
ENERGY LOSS

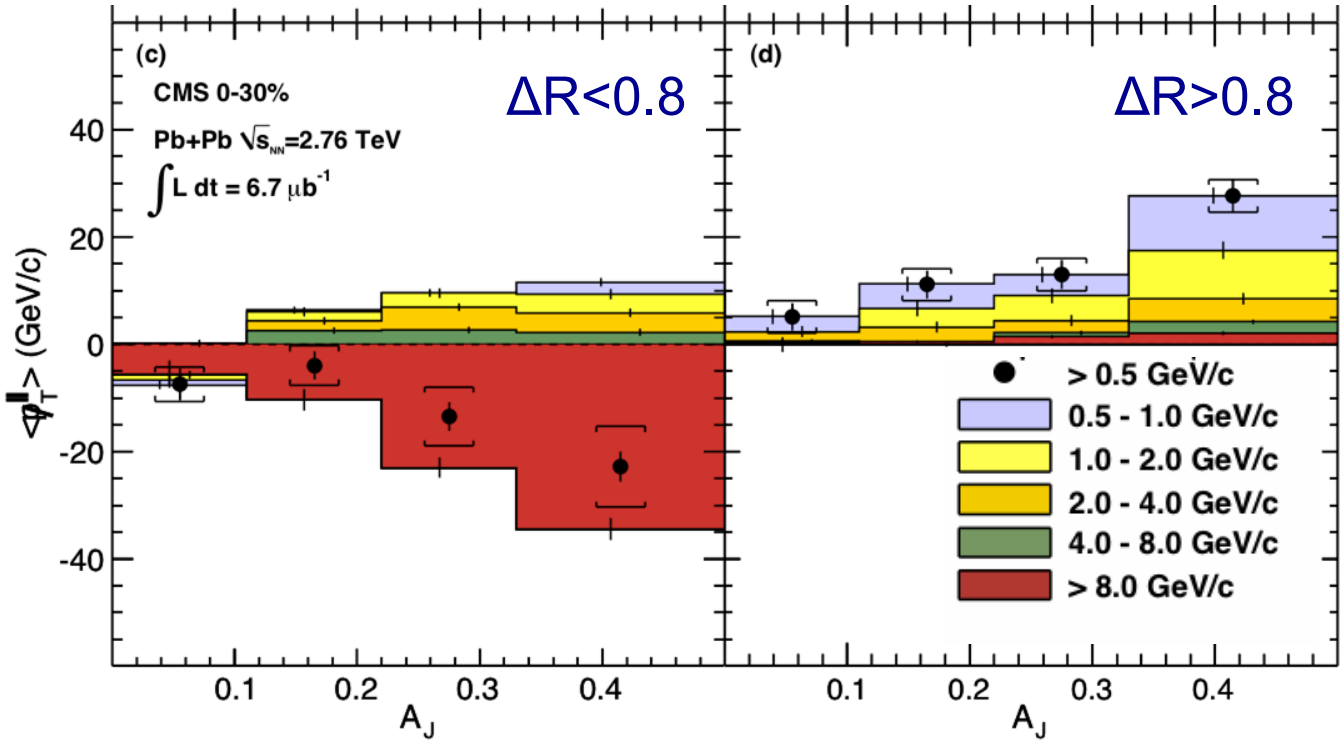


Tracing back the lost energy…

- Since early 2011 we know the (subleading) jet energy is moved from high p_T to lower p_T and from small to large angles

PRC 84 (2011) 024906



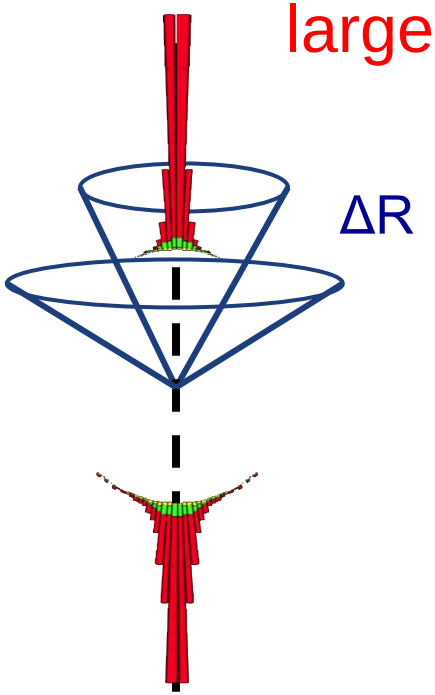


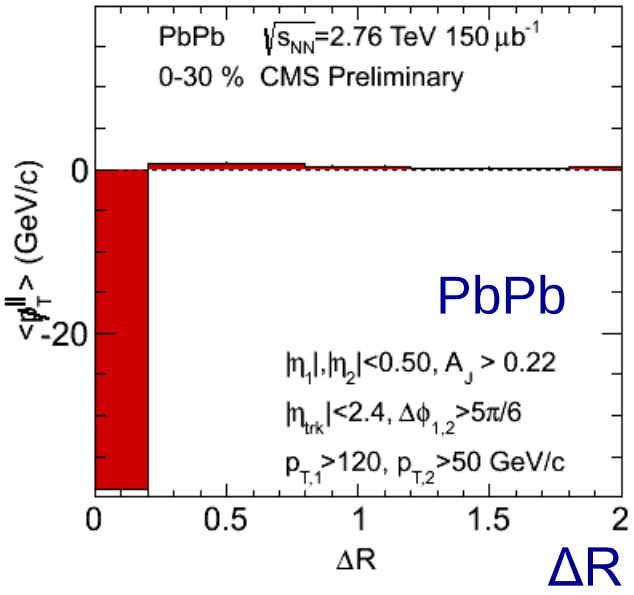
dijet asymmetry = $(p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$

Tracing back the lost energy…

- Detailed ($\Delta R, p_T$) distributions
  - Summing charged particles for unbalanced (A_J>0.22) dijets in central (0–30%) collisions…
  - 35 GeV missing at ΔR<0.2, large p_T particles (>8GeV)

Talk by Gulhan, PAS-HIN-14-010

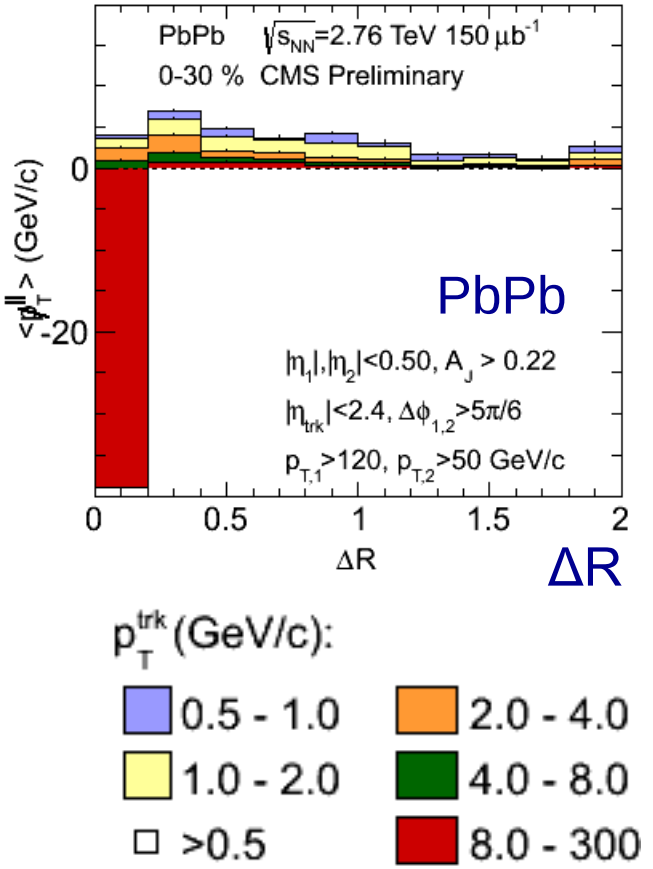




Tracing back the lost energy…

- Detailed ($\Delta R, p_T$) distributions
  - Summing charged particles for unbalanced (A_J>0.22) dijets in central (0–30%) collisions…
  - 35 GeV missing at ΔR<0.2, large p_T particles
  - Balanced by low p_T particle up to very large ΔR

Talk by Gulhan, PAS-HIN-14-010

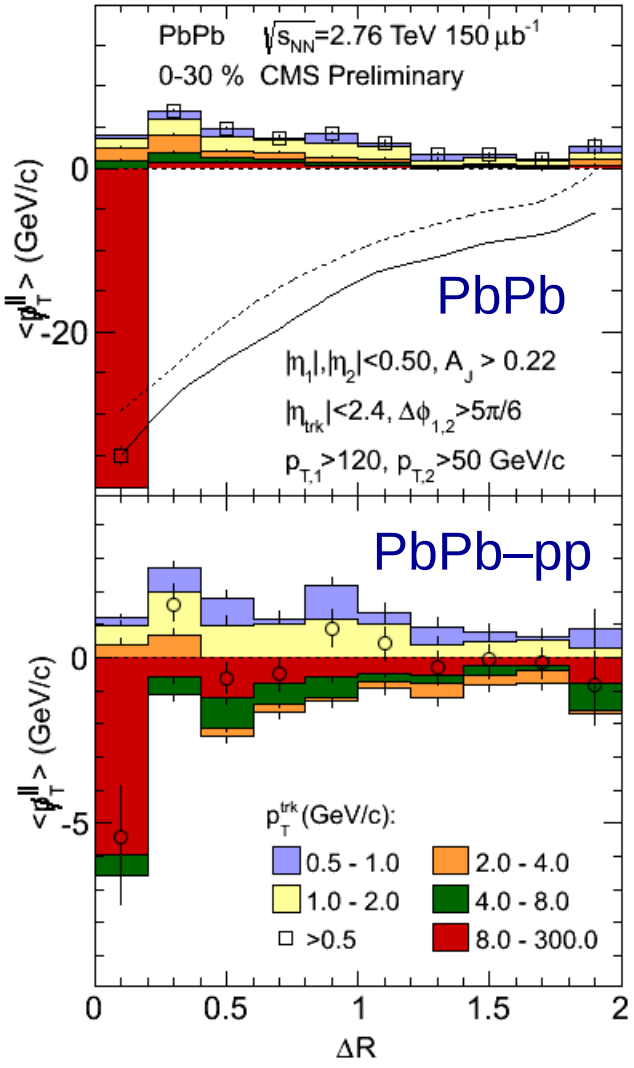


Tracing back the lost energy…

- Detailed ($\Delta R, p_T$) distributions

  Talk by Gulhan, PAS-HIN-14-010

  - Summing charged particles for unbalanced (A_J>0.22) dijets in central (0–30%) collisions…
  - 35 GeV missing at ΔR<0.2, large p_T particles
  - Balanced by low p_T particle up to very large ΔR
  - Subtracting the same from pp shows a different p_T mix

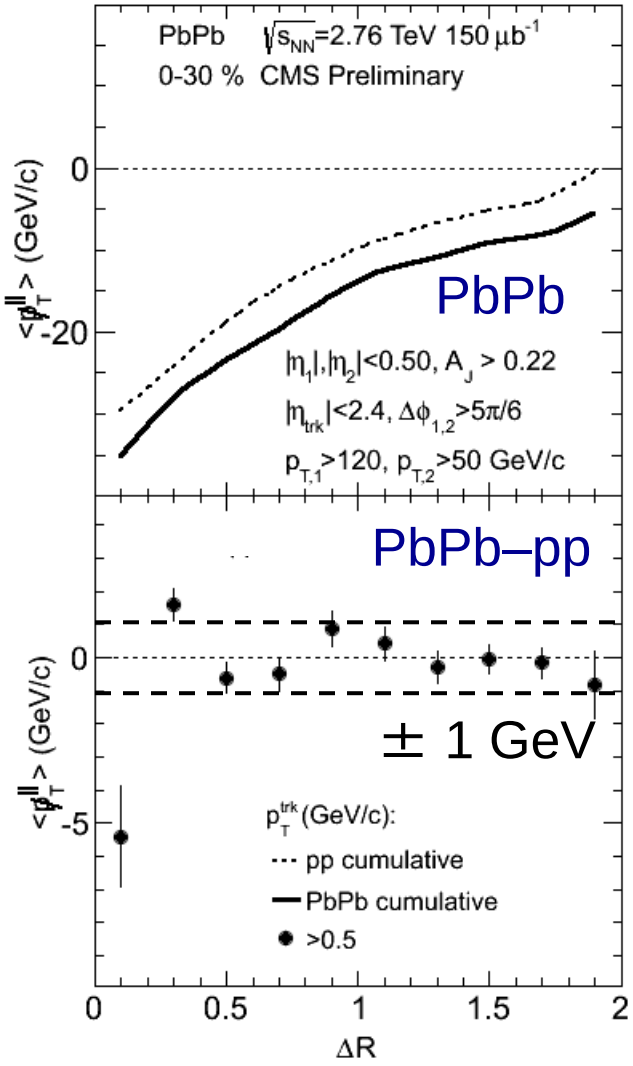


Tracing back the lost energy…

- Detailed ($\Delta R, p_T$) distributions

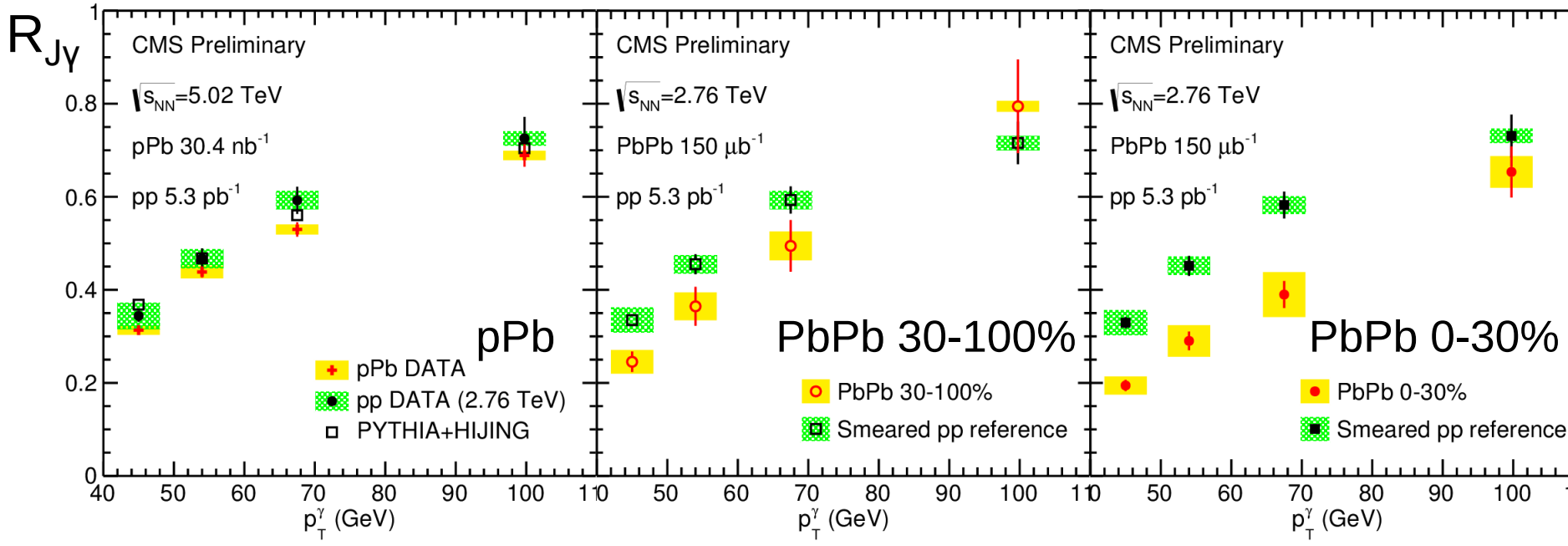
Talk by Gulhan, PAS-HIN-14-010

  - Summing charged particles for unbalanced (A_J>0.22) dijets in central (0–30%) collisions…
  - 35 GeV missing at ΔR<0.2, large p_T particles
  - Balanced by low p_T particle up to very large ΔR
  - Subtracting the same from pp shows a different p_T mix
  - But a similar p_T-integrated ΔR distribution



Unmodified jet energy in pPb

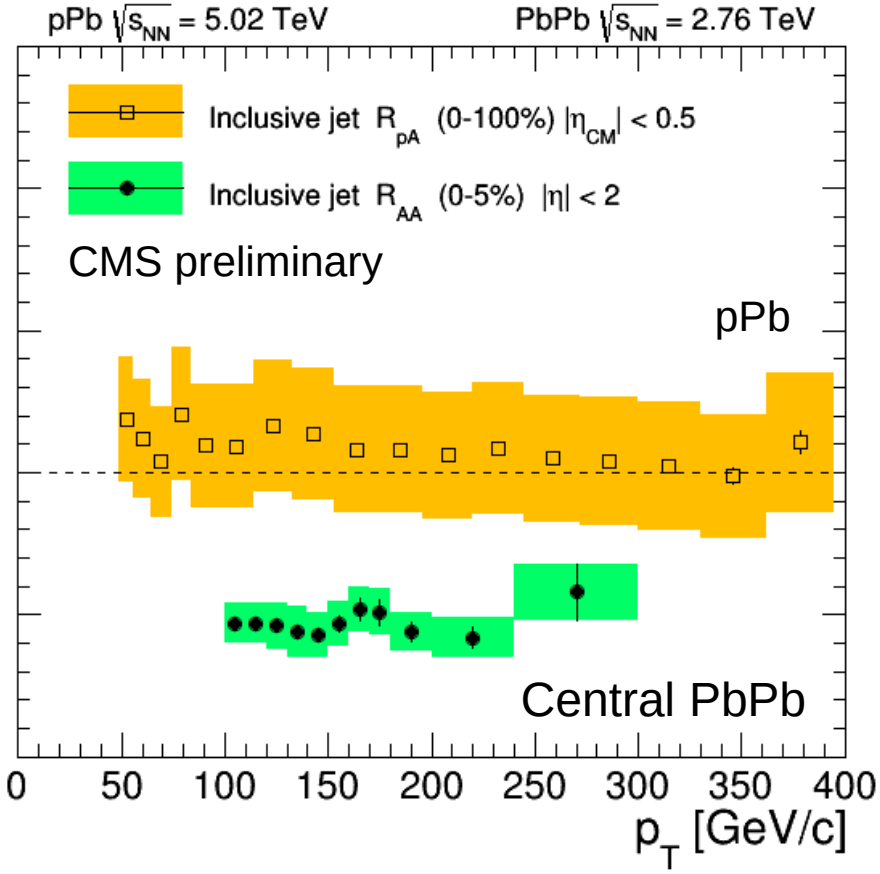
- Jet energy is essentially unmodified in pPb
  - As seen for instance in gamma-jet correlations
  - $R_{J\gamma}$ = fraction of photons with a jet of $p_{Tjet} > 30$ GeV



(Complementary p_T imbalance available)
(PbPb results updated with new pp reference)

Talk by Barbieri
PAS-HIN-13-006

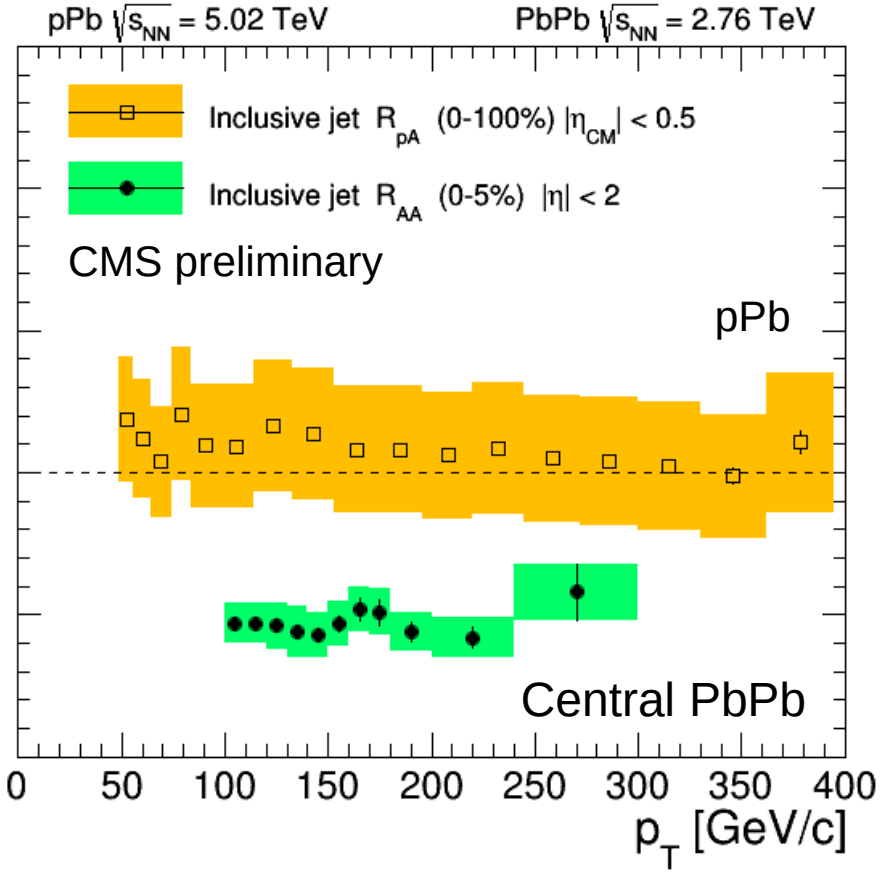
R_{pA} & R_{AA} for jets

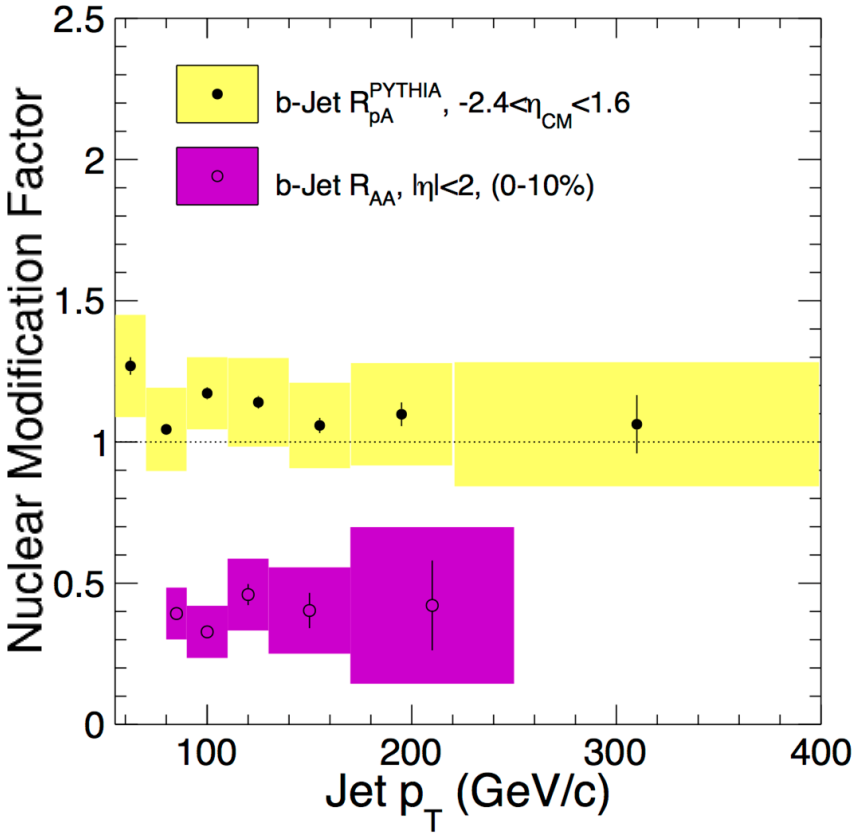


(Jet = anti-k_T with R = 0.3,
BG subtracted, p_T unfolded)

Talk by Appelt, HIN-12-004, HIN-14-001

R_{pA} & R_{AA} for jets and b jets

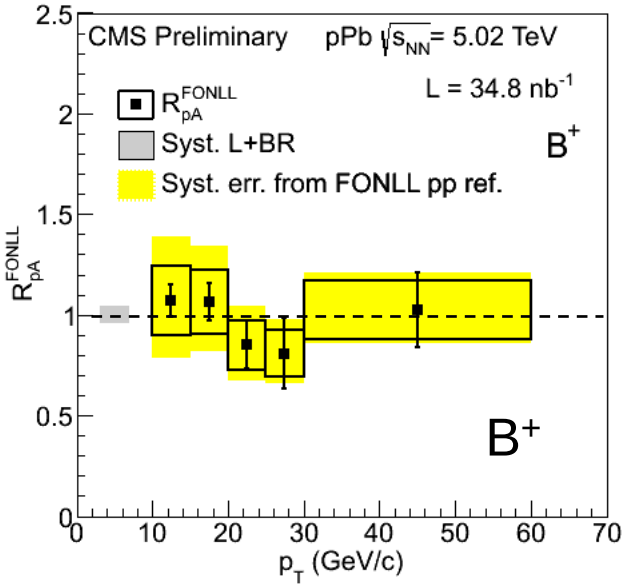


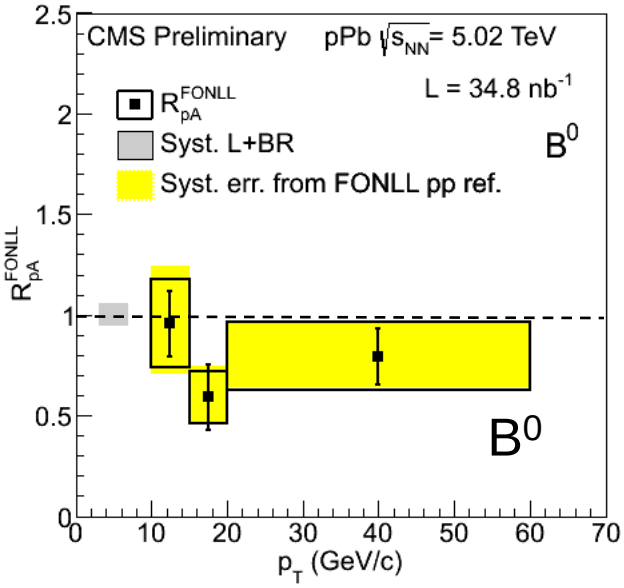


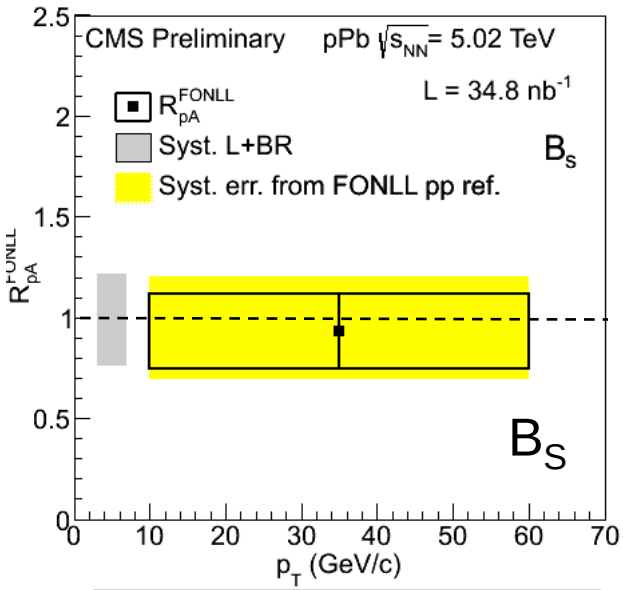
- Jets coming from b (second vertex)
  - as suppressed as incl. jets ($R_{AA} \approx 0.5$)
  - not suppressed in pPb ($R_{pA} \approx 1$)

Talk by Jung, PAS-HIN-14-007, PbPb:1312.4198

R_{pA} & R_{AA} for B mesons

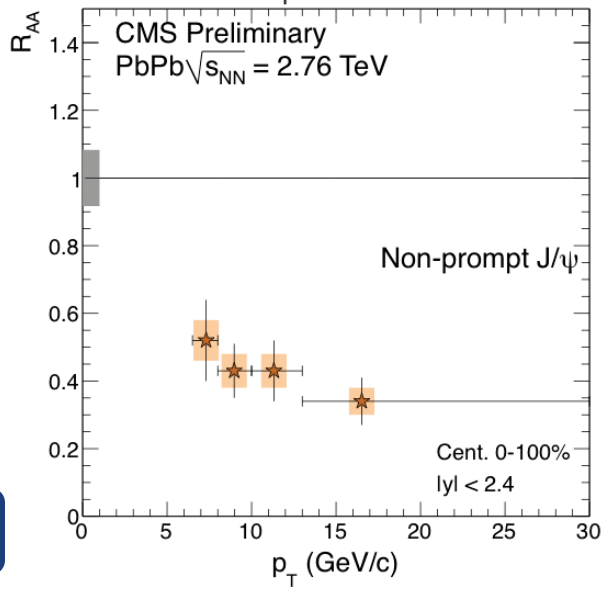






pPb exclusive B decays (p_T(B) > 10 GeV)
($B^+ \rightarrow J/\psi\ K^+$, $B^0 \rightarrow J/\psi\ K^*$, $B_S \rightarrow J/\psi\ \varphi$)
Showing no modification
(large uncertainty, incl. the FONLL ref)

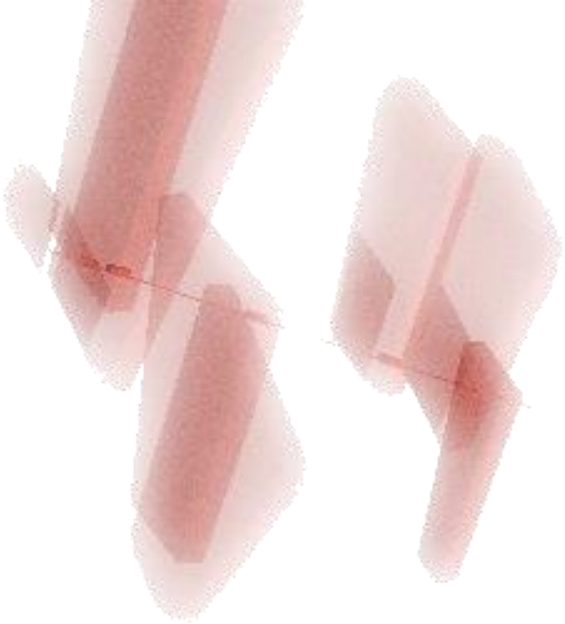
PbPb, inclusive B → J/ψ X ($p_T(\psi)$ > 6.5 GeV)
Showing strong suppression

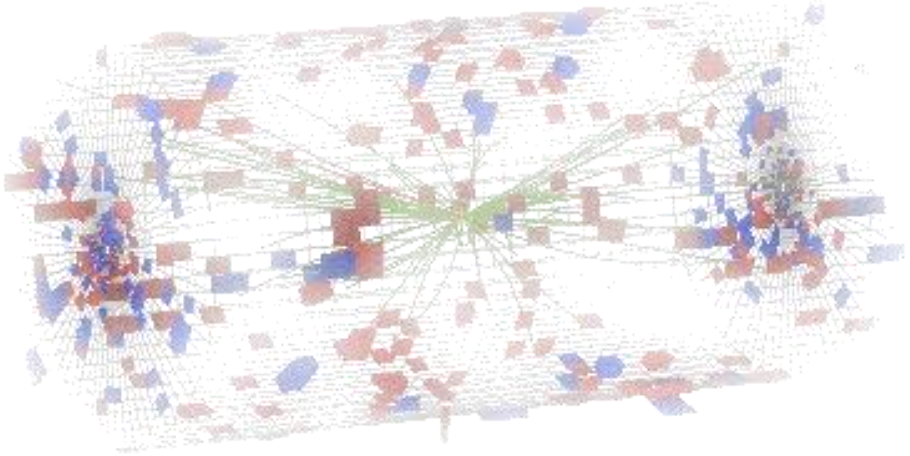


Talk by Kim, pPb: PAS-HIN-14-004, PbPb:1312.4198

Summary (2/4) Energy loss

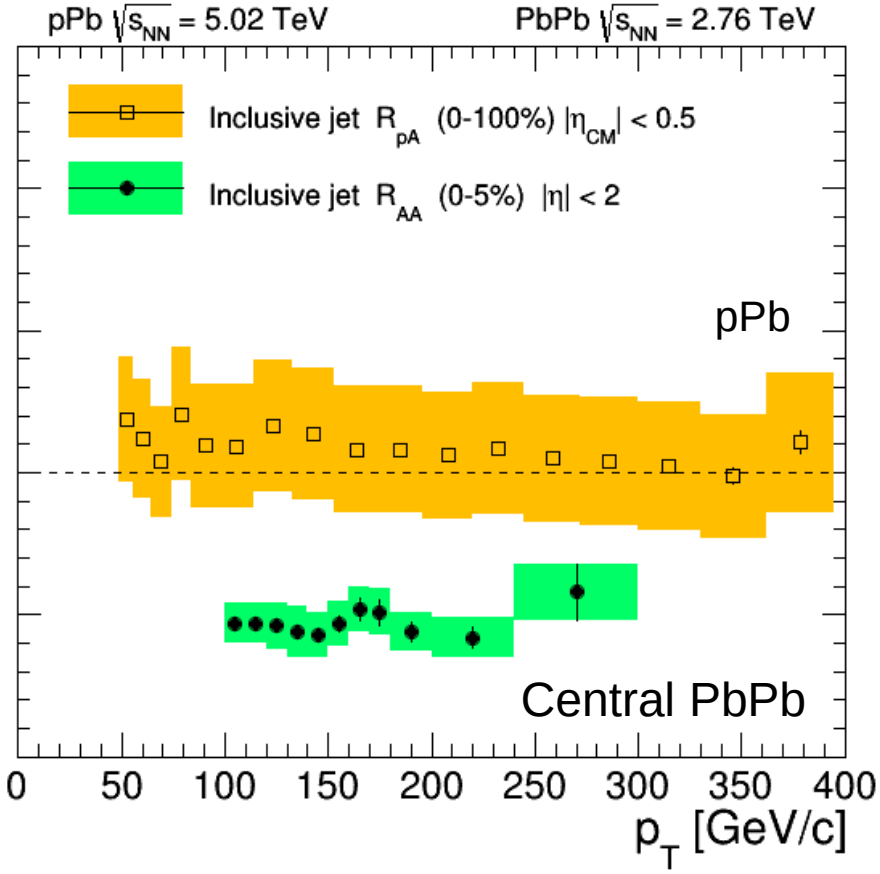
- Jets are heavily quenched in PbPb
  - Extensive studies on where the energy goes, to large angles and lower p_T
- Jets are not strongly quenched in pPb
  - $R_{pA} \approx 1$
- No strong flavour dependence at high p_T
  - $R_{AA} \approx 0.5$ for b-jet and inclusive jet

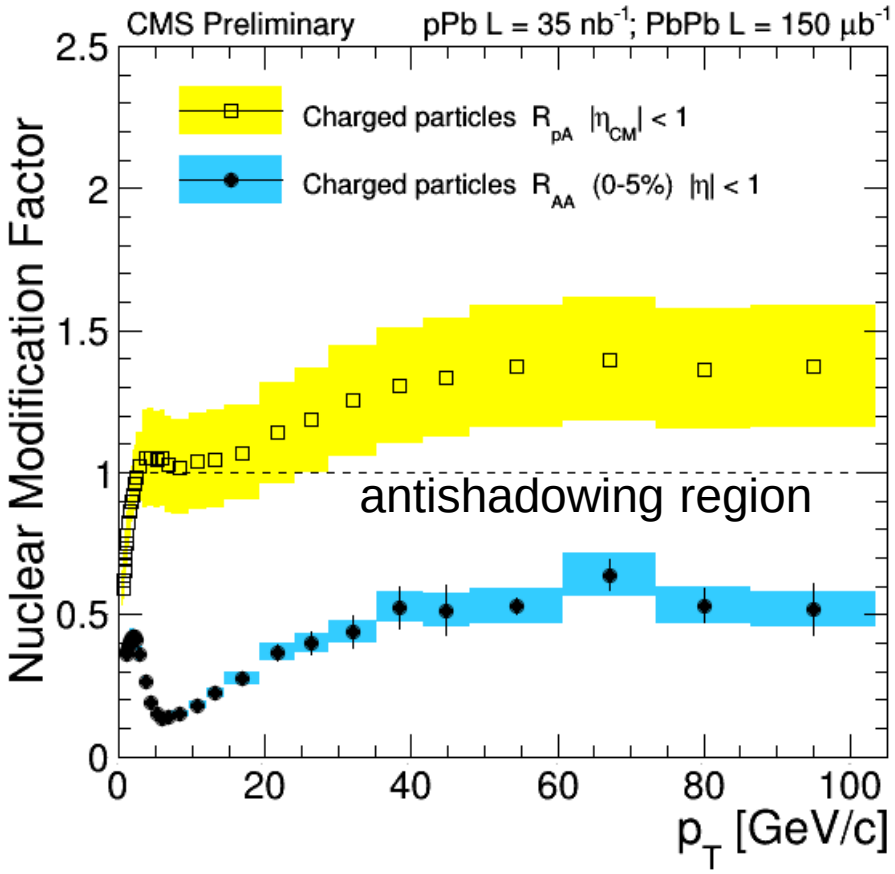




NUCLEAR PDF

R_{pA} & R_{AA} for jets and tracks

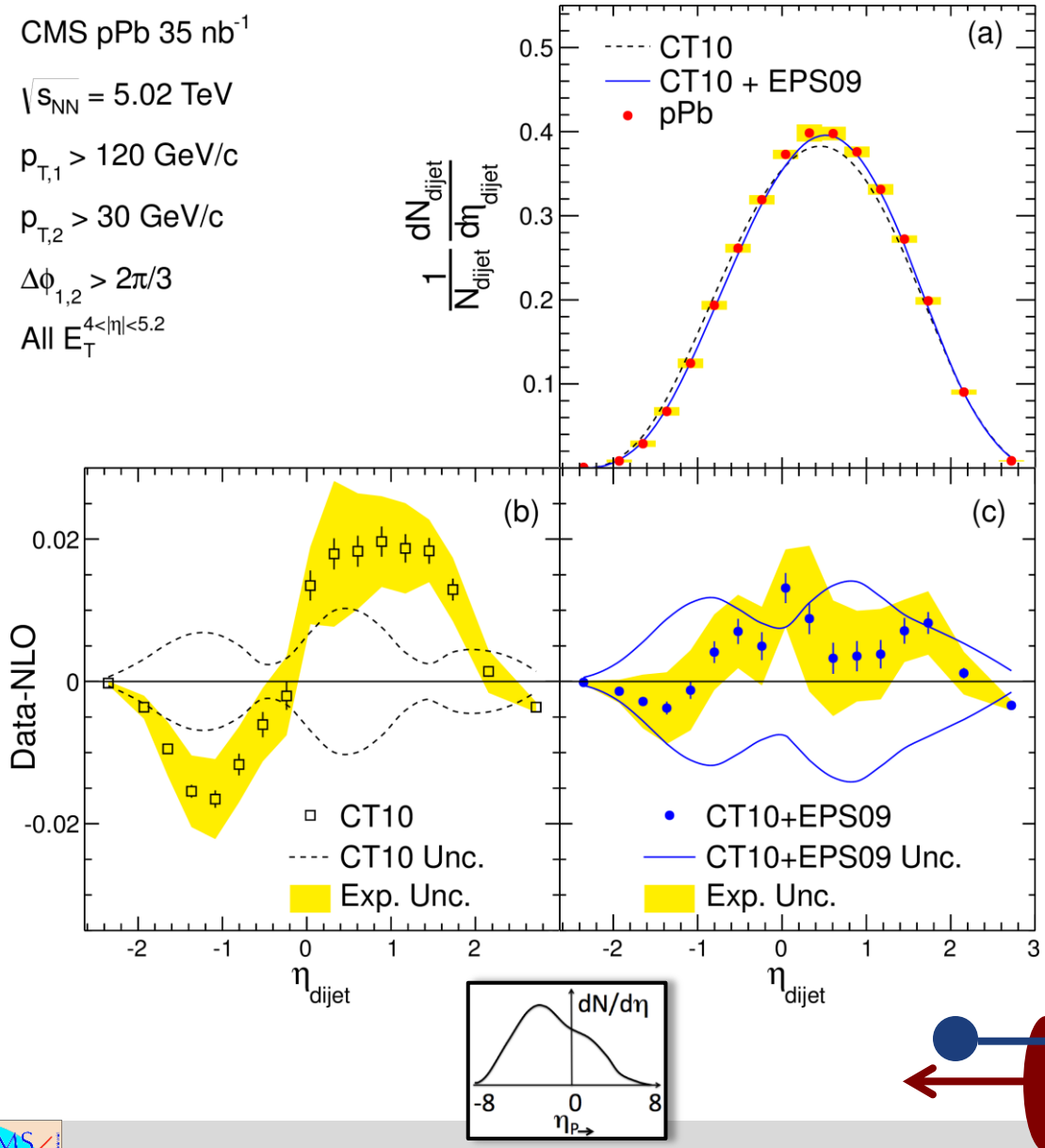




Talk by Appelt, HIN-12-004,
HIN-14-001, HIN-12-017
EPJC 72 (2012) 1945,

Enhancement observed at high p_T
Too large to be due to antishadowing?
Other nuclear effect?
But urgent need for pp reference

Modified dijet rapidity in pPb

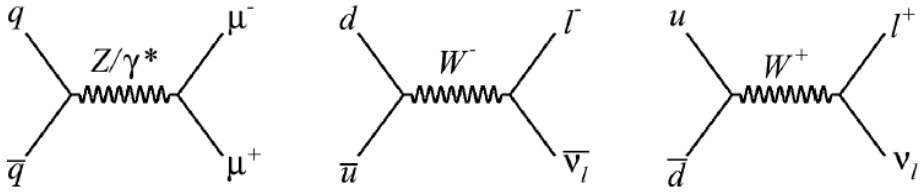


- $\eta_{dijet} = (\eta_1+\eta_2)/2$ has sensitivity to (gluon) PDF modifications
- Shifted by an amount comparable to (EPS09) nPDF predictions
- (large multiplicity dependence of the effect)

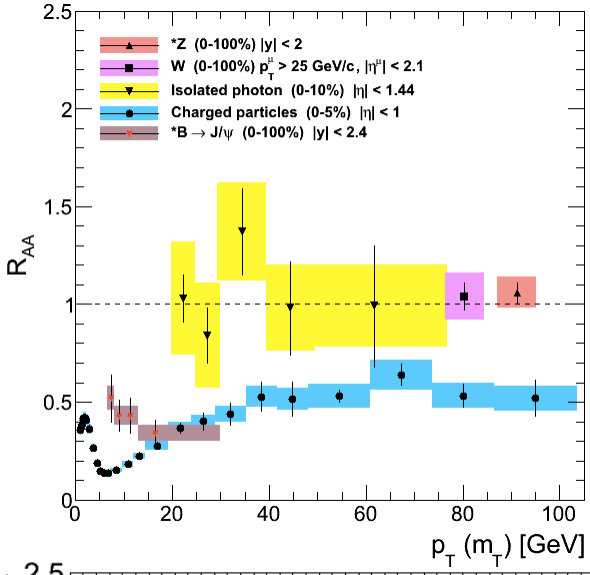
Talk by Barbieri
arXiv: 1401.4433

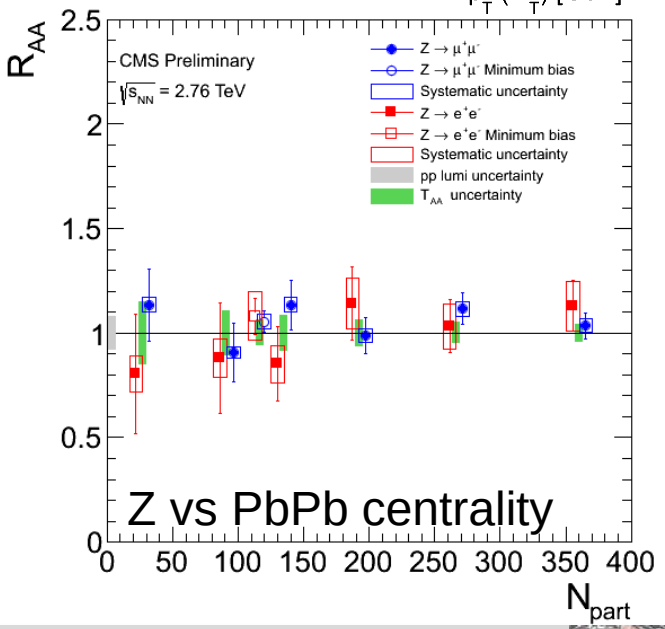
Electroweak bosons from PbPb to pPb

- Standard candles: Z^0 and $W^{\pm}$ unmodified in PbPb →
- pPb providing the best opportunity to probe (valence) q and (sea) $\overline{q}$ nPDF
  - Higher statistics
  - Collision asymmetry
  - Well controlled pp reference



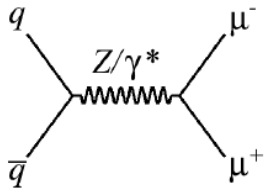
Talk by Zsigmond, PbPb:PAS-HIN-13-004

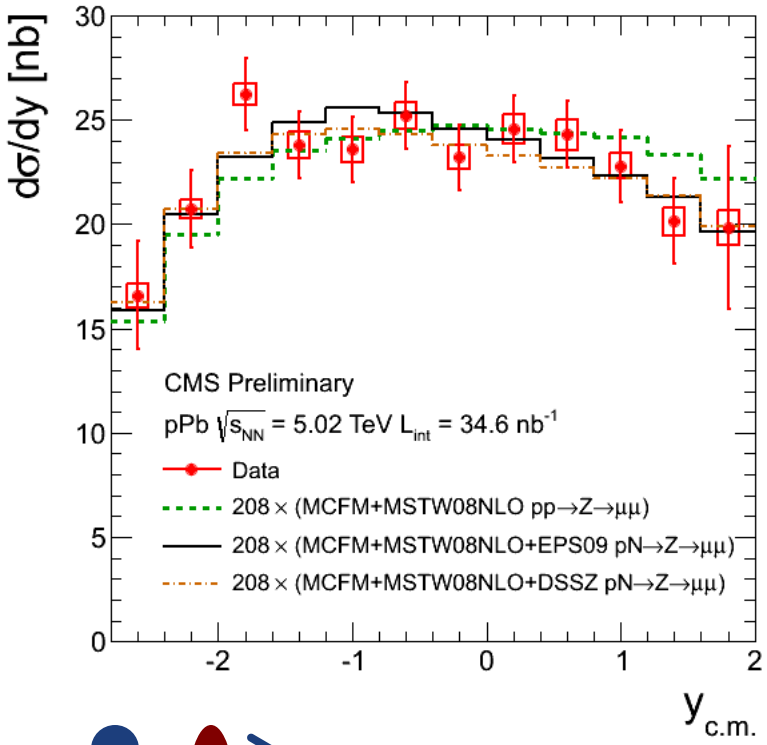


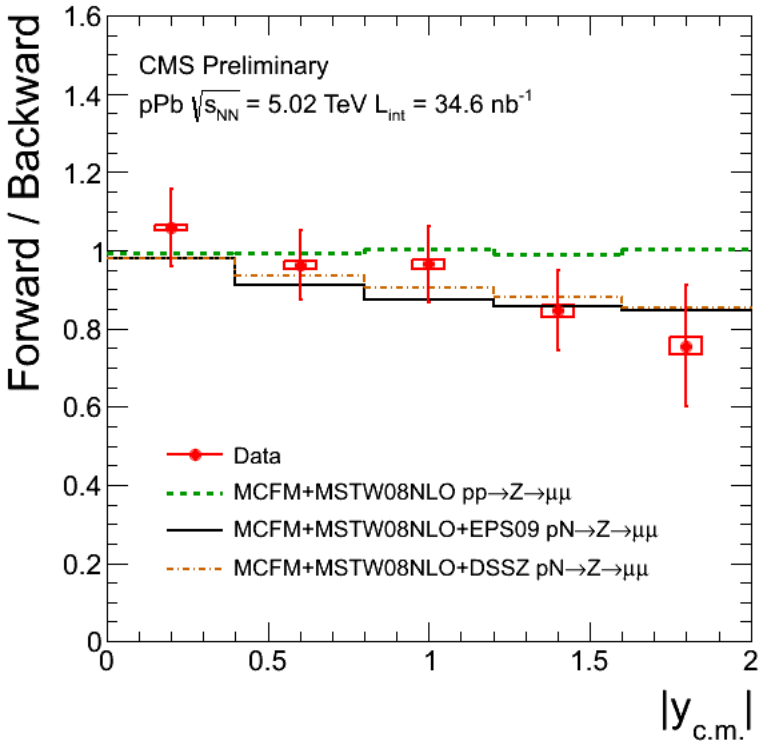


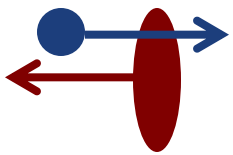
Z^0 in pPb

- ≈ 2200 Z → μμ showing little nuclear effect
  - maybe a hint of forward/backward asymmetry





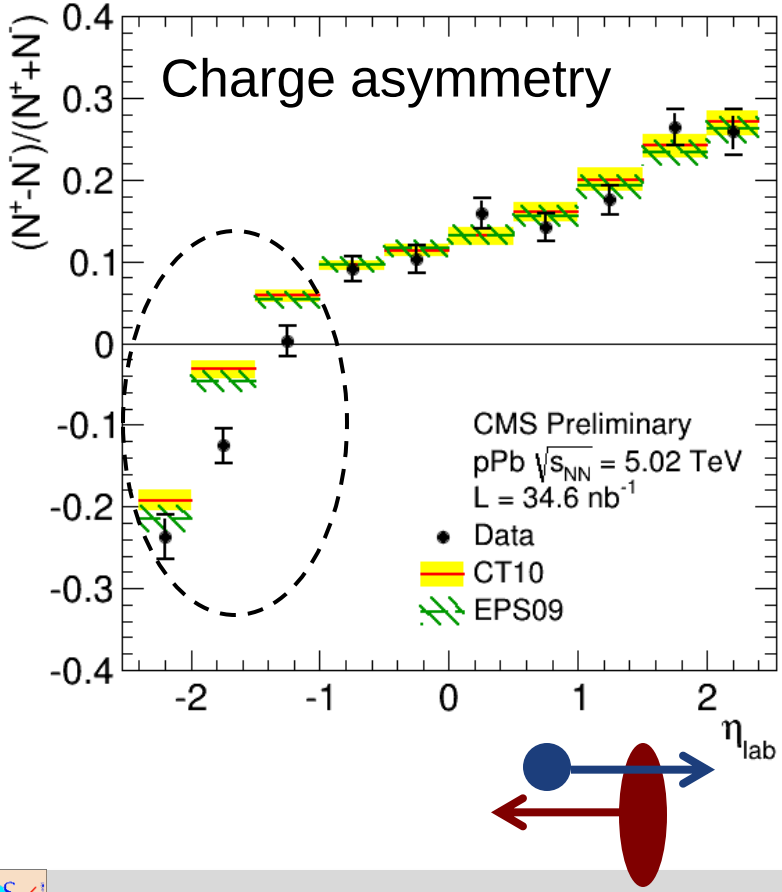


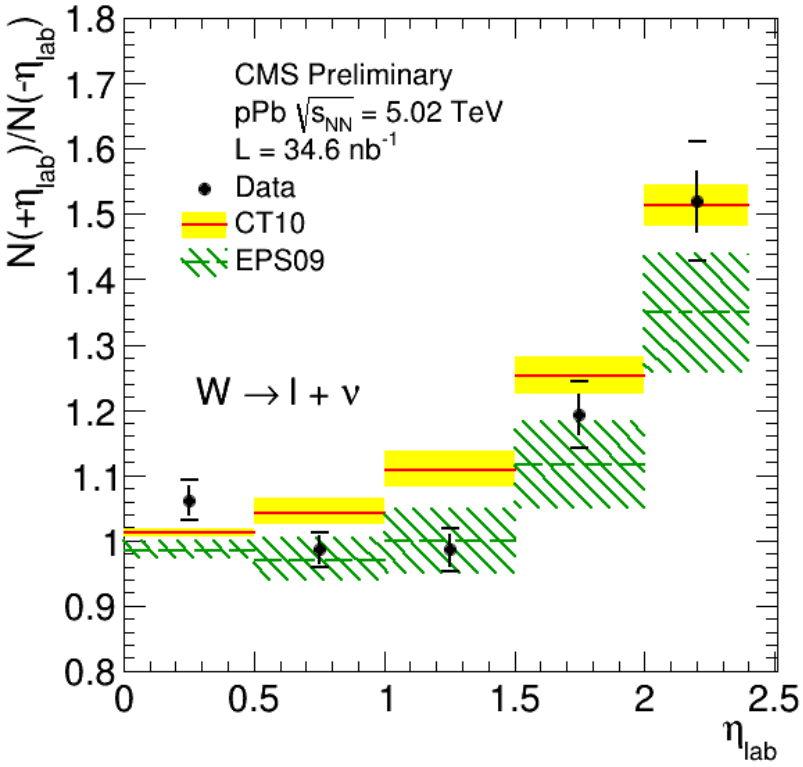


Talk by Zsigmond, PAS-HIN-14-003

W^+ and W^- in pPb

- ≈ 21000 W → μ & 16000 W → e
  - Showing small deviations from unmodified PDFs
  - A hint of a different u/d modification? (not in EPS09)





Forward/ Backward (in lab)

Talk by Zsigmond, PAS-HIN-13-007

Summary (3/4) nPDF

- Precision data start constraining nPDF in the high Q^2 regime
  - Dijet pseudorapidity shift → mostly gluons
  - Electroweak bosons → quarks / antiquarks, distinguishing ups and downs

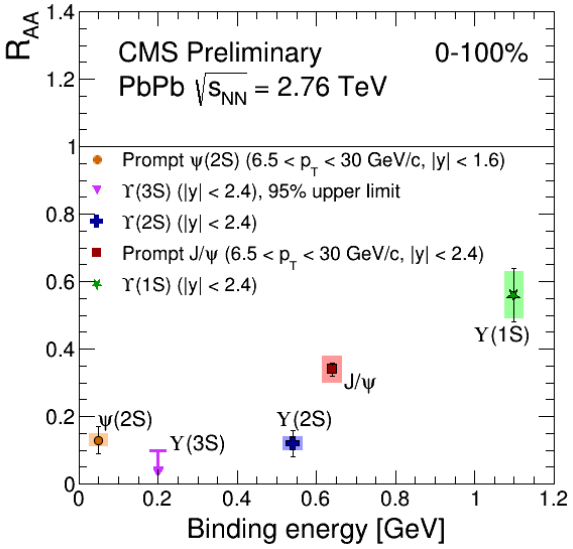
MELTING

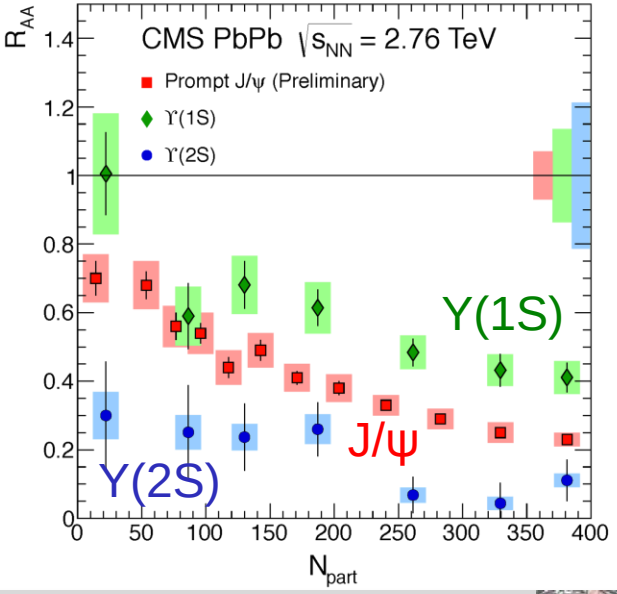

J/ψ
ρ, ω ϕ
η
ψ(2S)
Υ(1,2,3S)
Z
CMS Preliminary 2013
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
L_{int} = 35 nb^{-1}

Five quarkonia

- The suppression of 5 quarkonia was observed in PbPb
  - Well-ordered with binding energy
  - Inclusive bottomonia
  - Charmonia p_T > 6.5 GeV

  + p_T-inclusive J/ψ from ALICE less suppressed than at RHIC, calling for recombination
- Quarkonia melt in quark matter



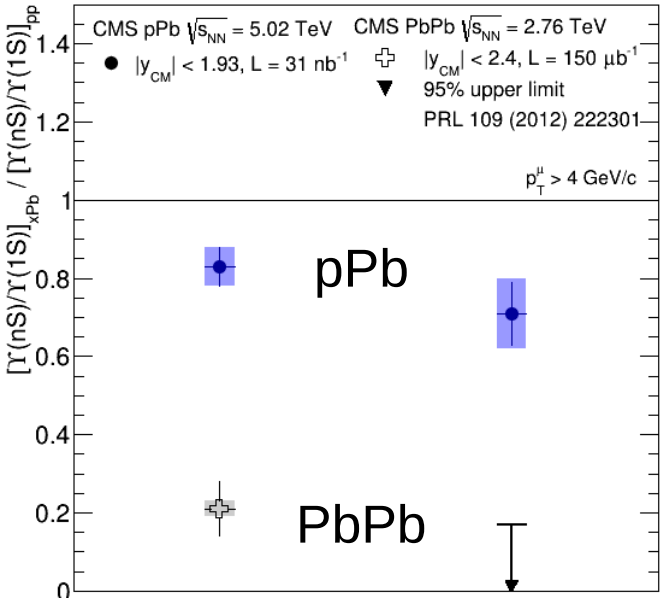


Talks by Moon & Abdulsalam
PRL109 (2012) 2220301,
PAS-HIN-12-014, PAS-HIN-12-007

Upsilon in pPb

- Excited states less suppressed than in PbPb

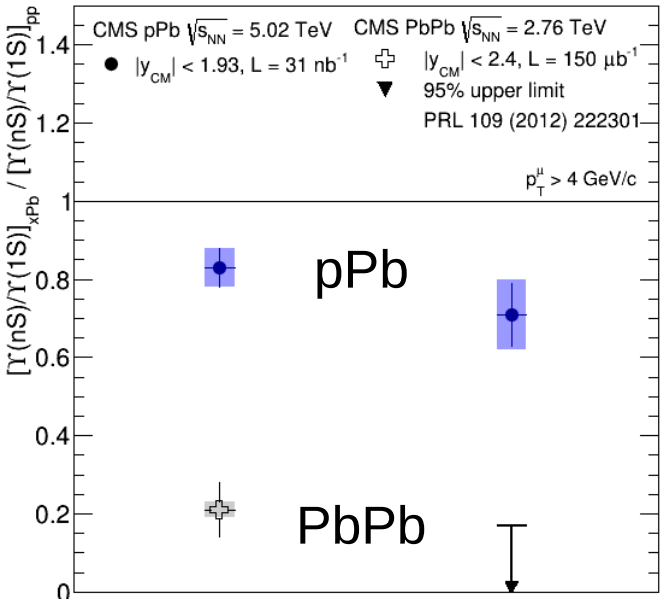
Talk by Abdulsalam
JHEP 04 (2014) 103

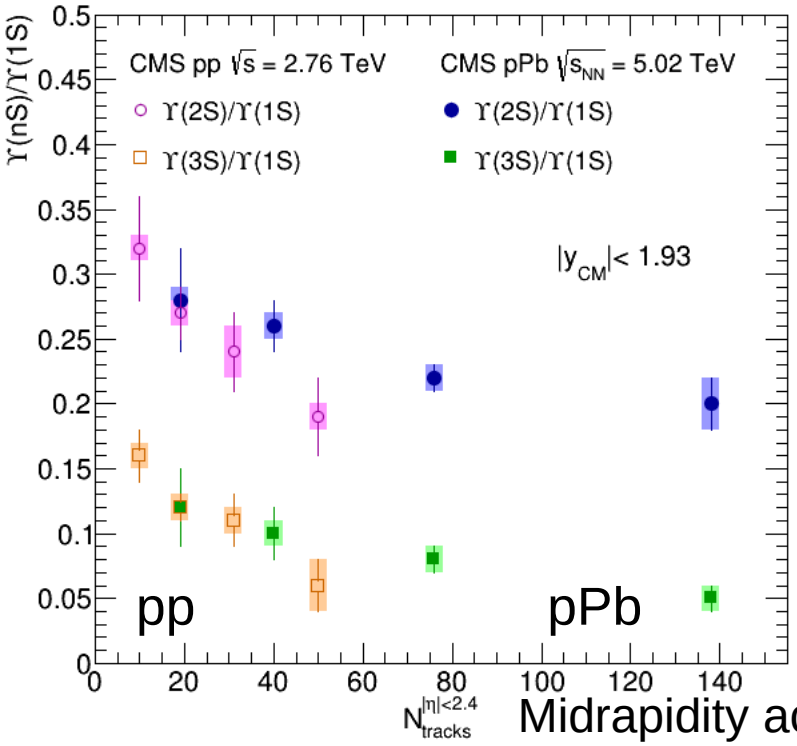


Upsilon in pPb

- Excited states less suppressed than in PbPb
- Excited/ground state ratio appears to vary w.r.t. the pPb and pp(!) event multiplicity (at midrapidity)
  - Excited states adding multiplicity?
  - Activity suppressing the excited states?

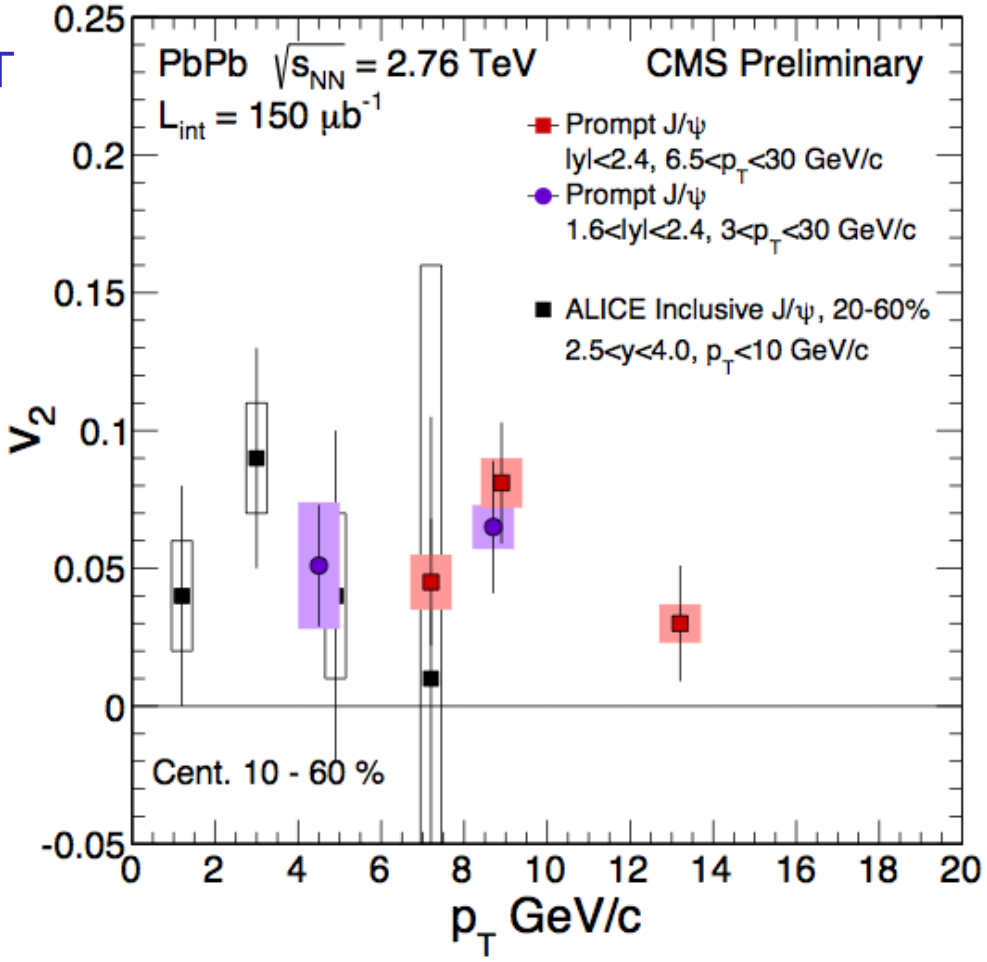
Talk by Abdulsalam
JHEP 04 (2014) 103





J/ψ azimuthal anisotropy

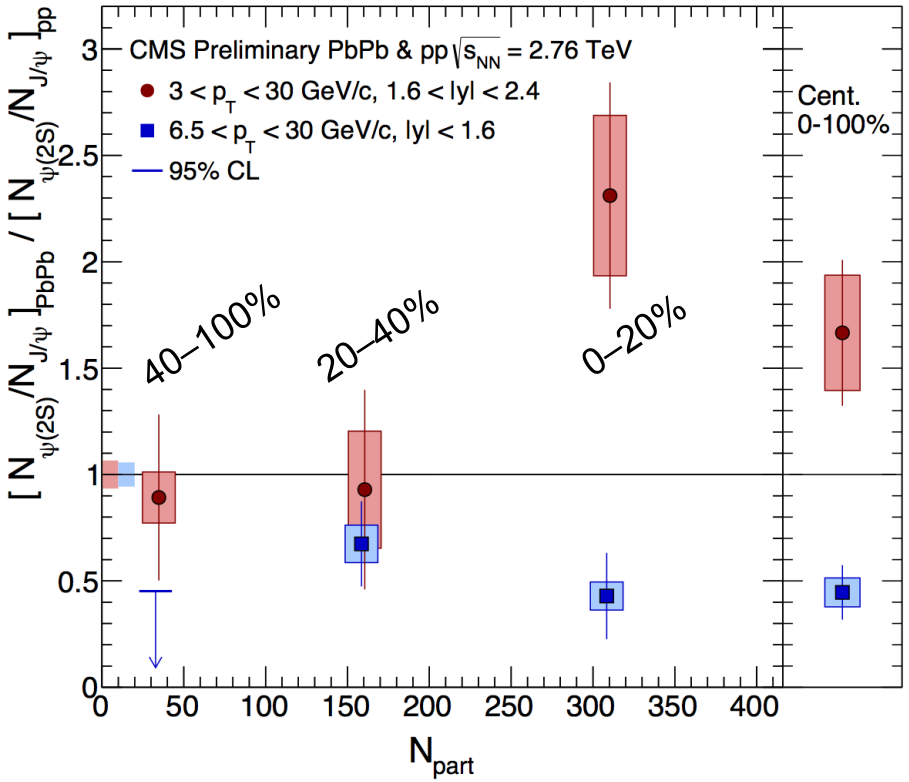
- Significant v_2 at high p_T
  - Need more data to resolve the p_T dependence
  - From regeneration to path-length dependence of J/ψ suppression?



Talk by Moon, PAS-HIN-12-001

ψ’ in PbPb collisions

- Surprisingly large $(\psi'/\psi)_{PbPb} / (\psi'/\psi)_{pp}$ ratio confirmed:
  - new pp reference, 20 times larger, now negligible uncertainty
  - non-prompt component subtracted



- ψ’ very suppressed at high p_T (more than ψ)

  → $R_{AA}(\psi') = 0.13 \pm 0.05$
- Much less at lower p_T

  → $R_{AA}(\psi') = 0.67 \pm 0.19$

(Centrality-integrated R_{AA})

Talk by Moon, HIN-12-007
to be submitted soon

Summary (4/4) Melting

- Sequential suppression from R_{AA}
- Two intriguing observations
  - Y(nS)/Y(1S) depends on event activity (or vice versa) in both pPb & pp
  - Lower p_T ψ' less suppressed… Could some regeneration models favour them?

Conclusions

- Collectivity
  - Many observables indicating that high-multiplicity pPb collisions show collectivity
- Energy loss
  - Detailed study of the structure of energy loss
  - First look at b-jets: behaving as inclusive jets
- Nuclear PDF
  - From jets, Z and W, first constraints on high Q^2 nuclear PDFs, hints of nuclear effects
- Melting
  - Apparent sequential melting of five quarkonia, with excited states showing interesting behaviours…

Conclusions

- Collectivity
  - Many observables indicating that high-multiplicity pPb collisions show collectivity
- Energy loss
  - Detailed study of the st
  - First l
-
  - High Q^2 nuclear
  - effects
- M ng
  - Apparent sequential melting of five quarkonia, with excited states showing interesting behaviours…

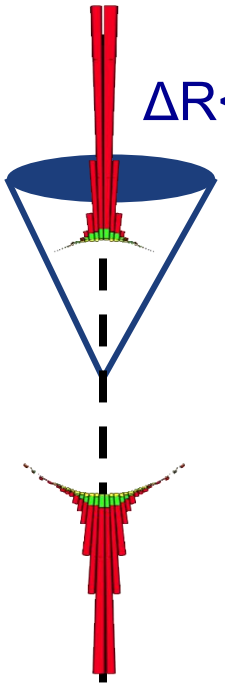
Much more to study on tape…
Ready to take more data & increase the statistics of the rarest QGP probes!

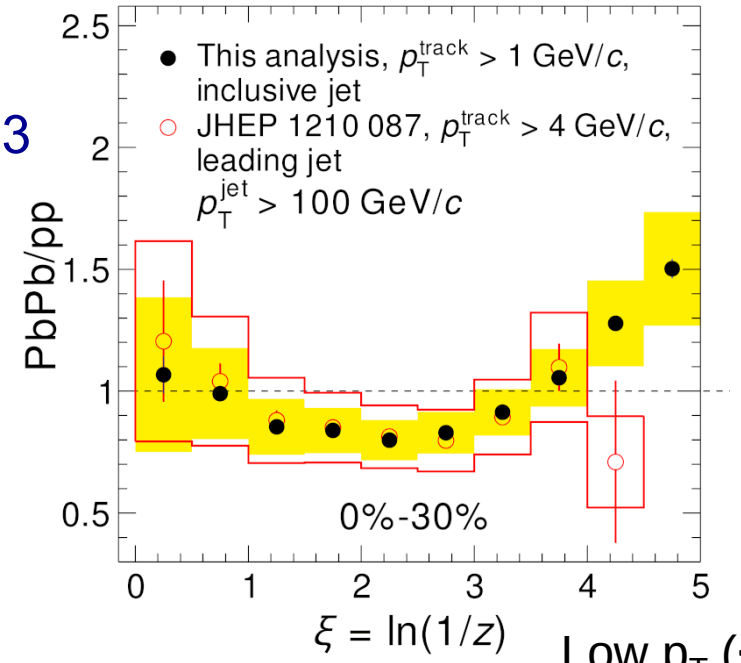
BACK-UP

Fragmentation and shape…

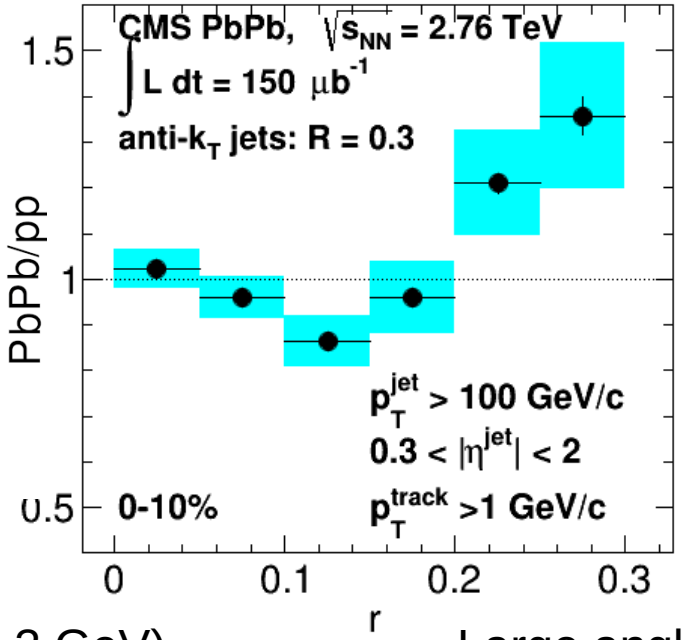
- Jet energy is moved from high p_T to lower p_T and from small to large angles
  - e.g. for jets of $\Delta R = 0.3$

PAS-HIN-12-013
PLB 730 (2014) 243



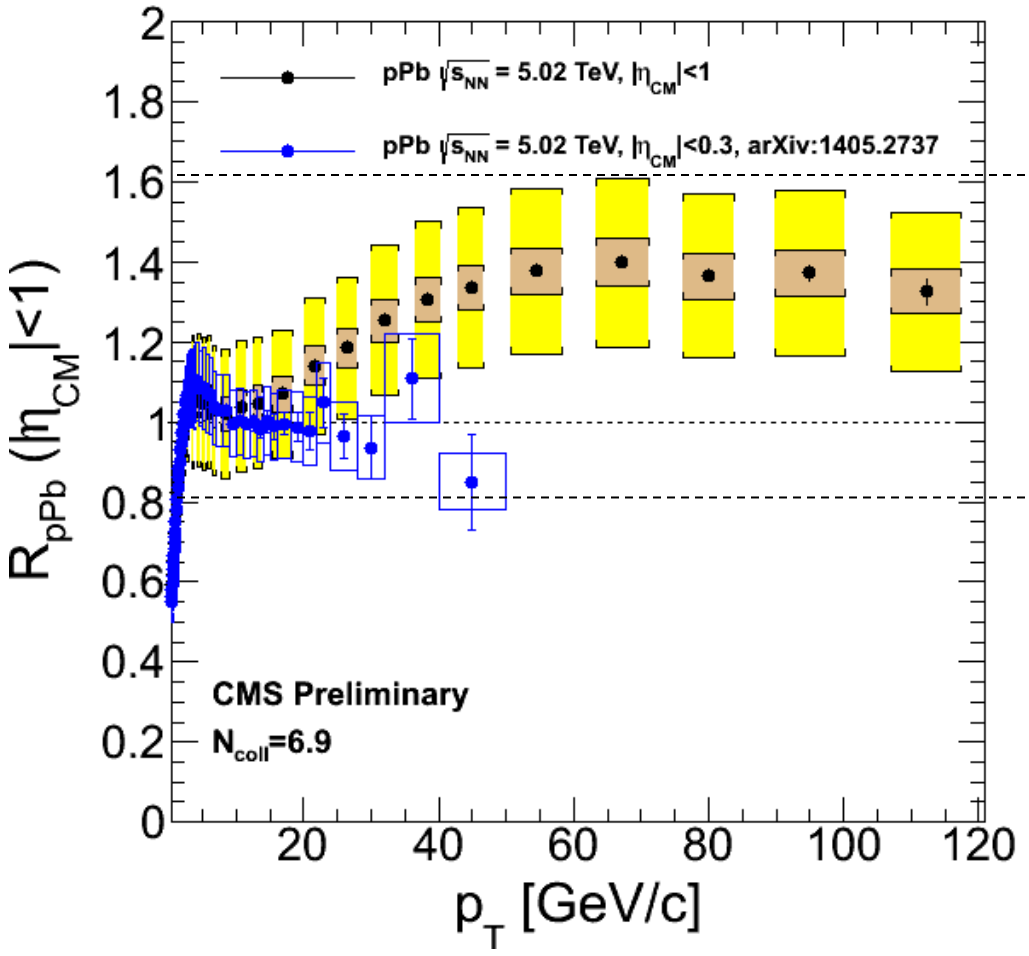


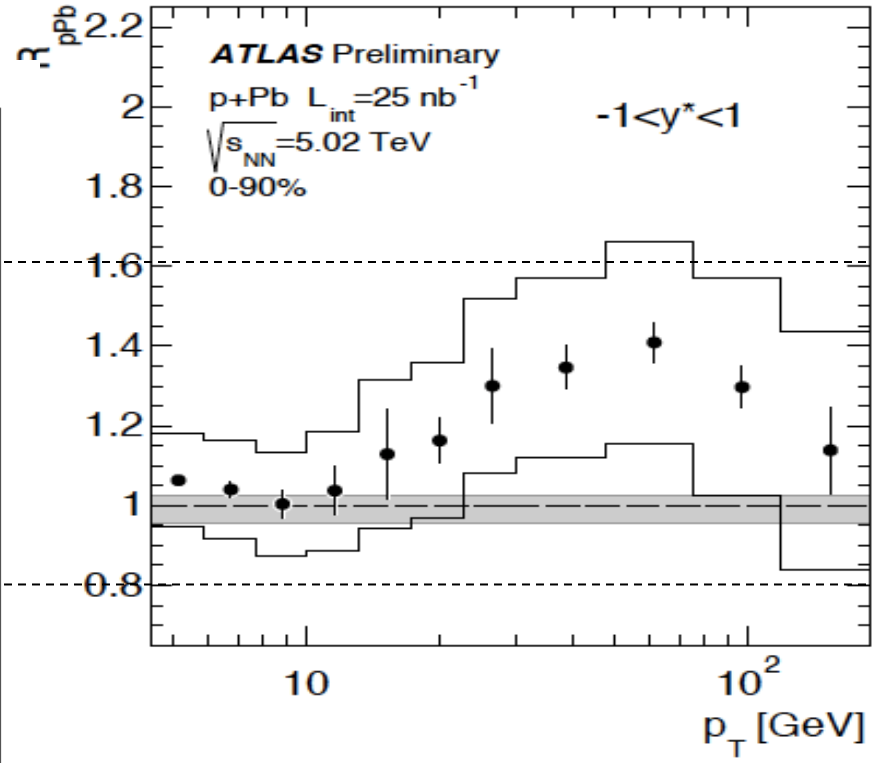
Low p_T (< 3 GeV)



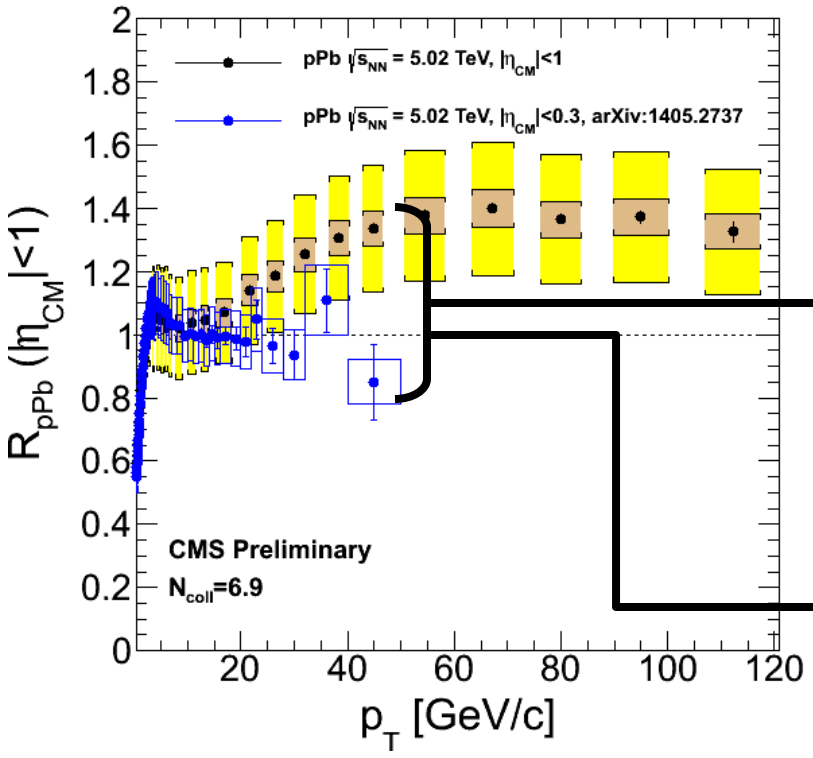
Large angles

R_{pA} comparison ATLAS / CMS

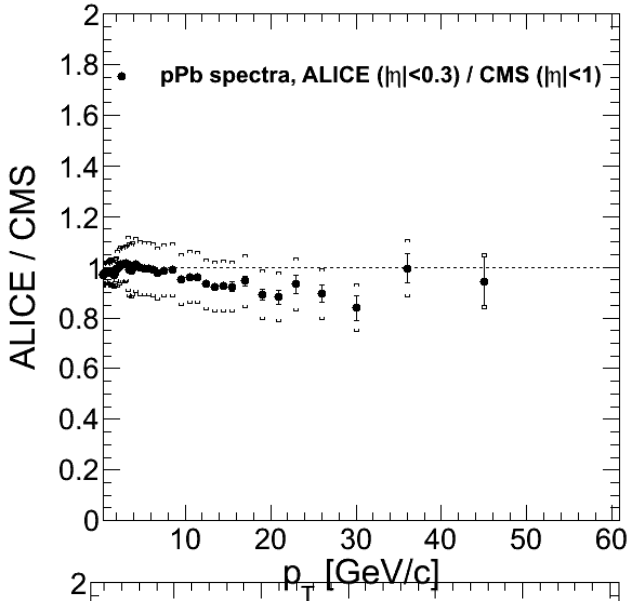




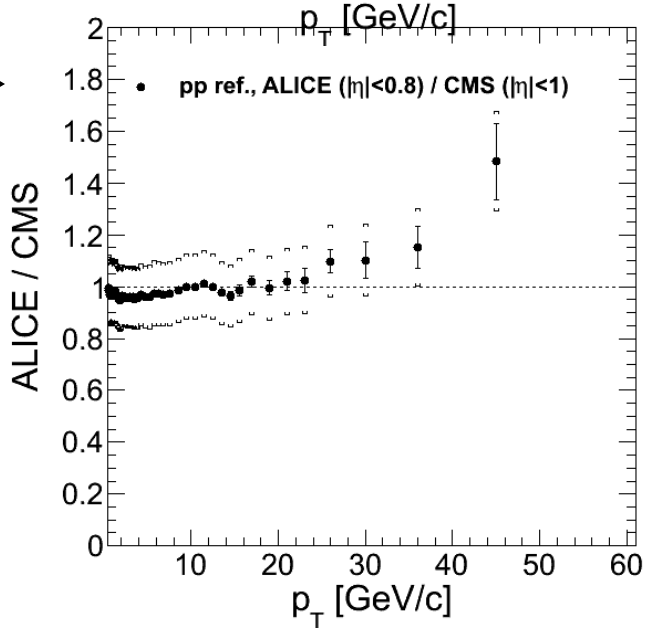
R_{pA} comparison ALICE / CMS



Small tension in pPb data, but compatible within systematics

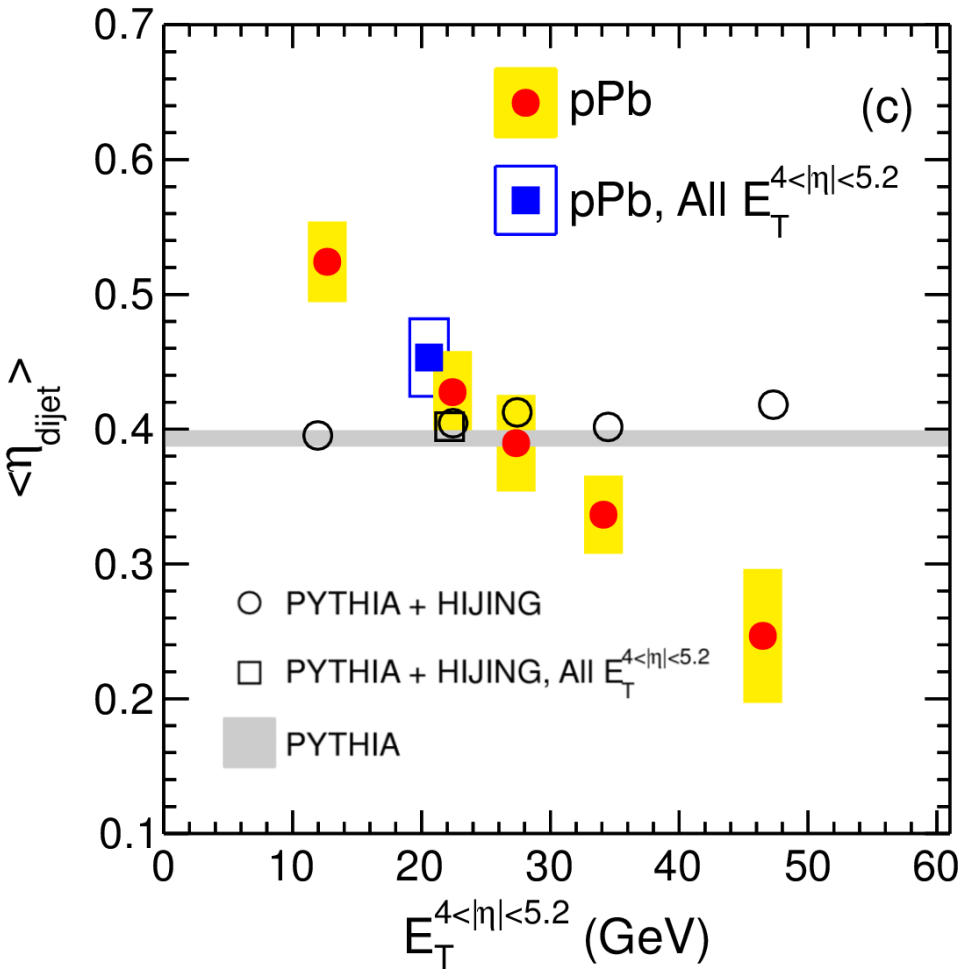


Large tension in pp reference, mostly due to the pp data (not to the method of extrapolation)



→ Would be much simplier with pp data at 5 TeV

Modified dijet rapidity in pPb

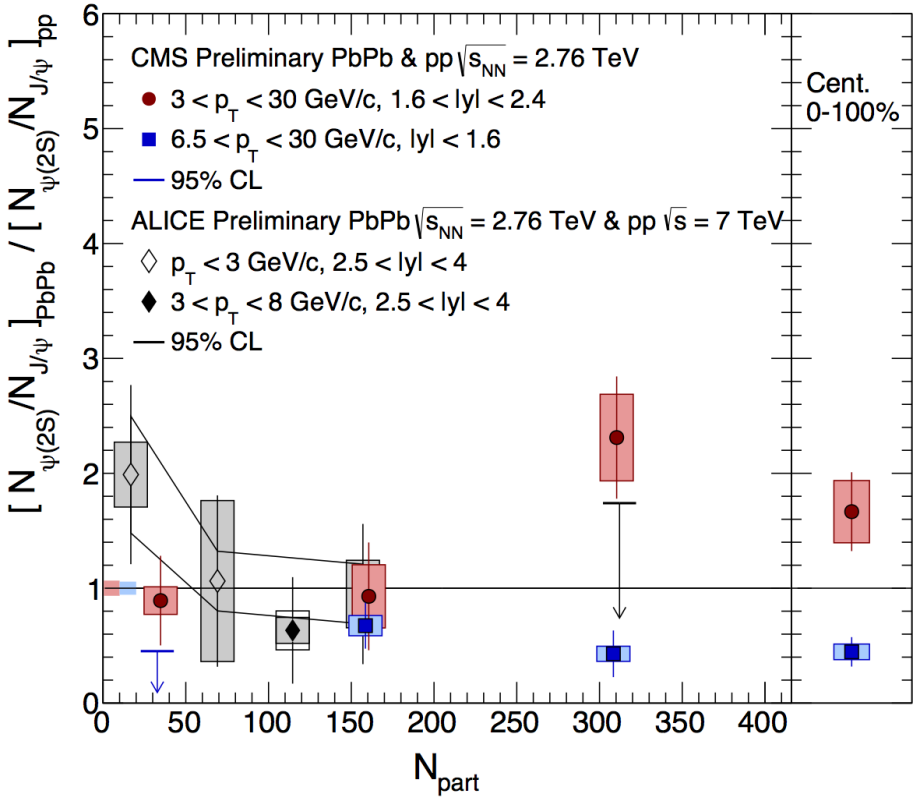


- $\eta_{dijet} = (\eta_1+\eta_2)/2$ is shifted
- By an amount comparable to (EPS09) nPDF predictions
- But its multiplicity dependence is very large

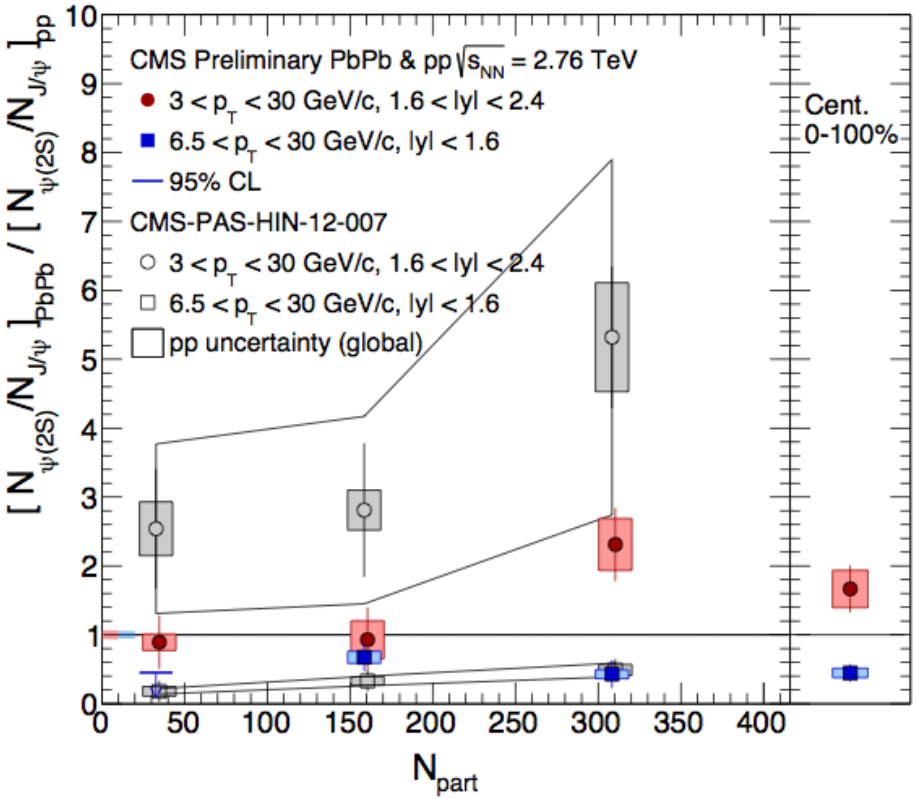
Talk by Barbieri
arXiv: 1401.4433

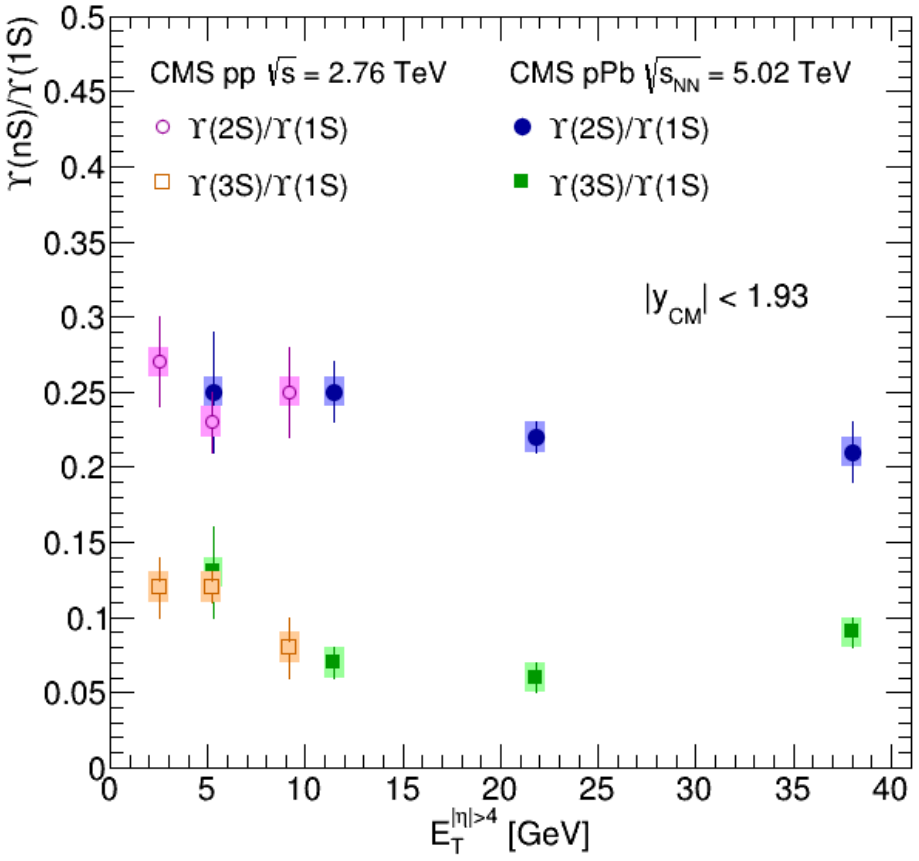
ψ’

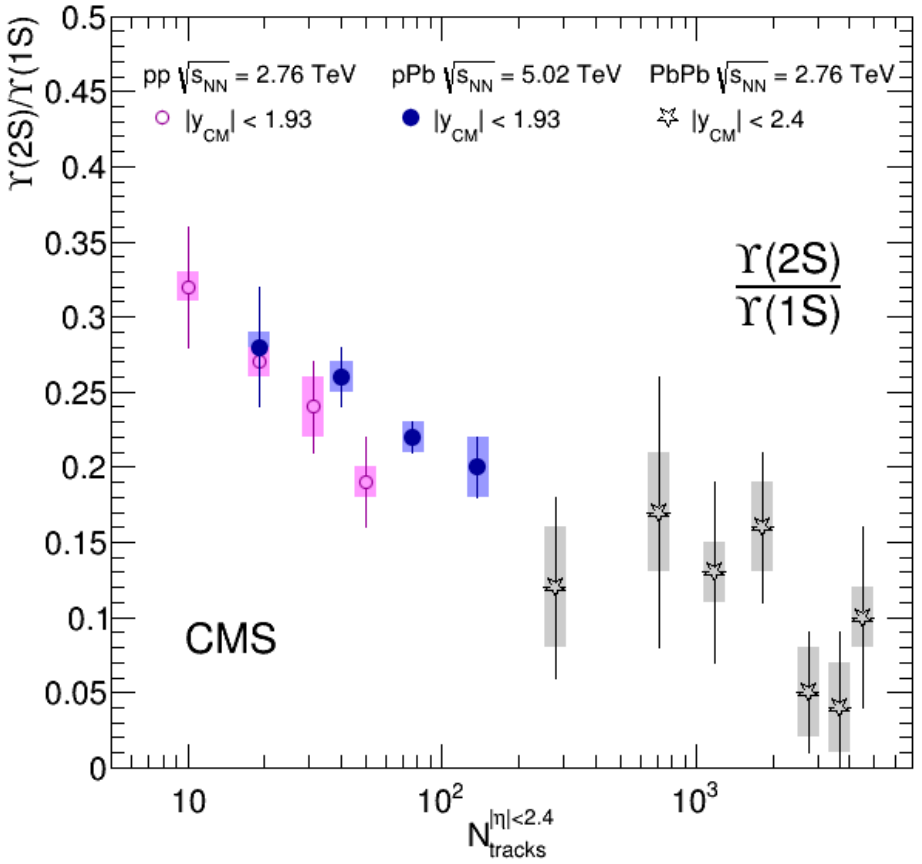
ALICE / CMS



old / new




CMS pp $\sqrt{s}$ = 2.76 TeV
CMS pPb $\sqrt{s_{NN}}$ = 5.02 TeV
Υ(2S)/Υ(1S)
Υ(3S)/Υ(1S)
Υ(2S)/Υ(1S)
Υ(3S)/Υ(1S)
$|y_{CM}| < 1.93$
Υ(nS)/Υ(1S)
$E_T^{|\eta|>4}$ [GeV]


pp $\sqrt{s_{NN}}$ = 2.76 TeV
$|y_{CM}| < 1.93$
pPb $\sqrt{s_{NN}}$ = 5.02 TeV
$|y_{CM}| < 1.93$
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
$|y_{CM}| < 2.4$
$\frac{\Upsilon(2S)}{\Upsilon(1S)}$
CMS
Υ(2S)/Υ(1S)
$N_{tracks}^{|\eta|<2.4}$

Y suppression