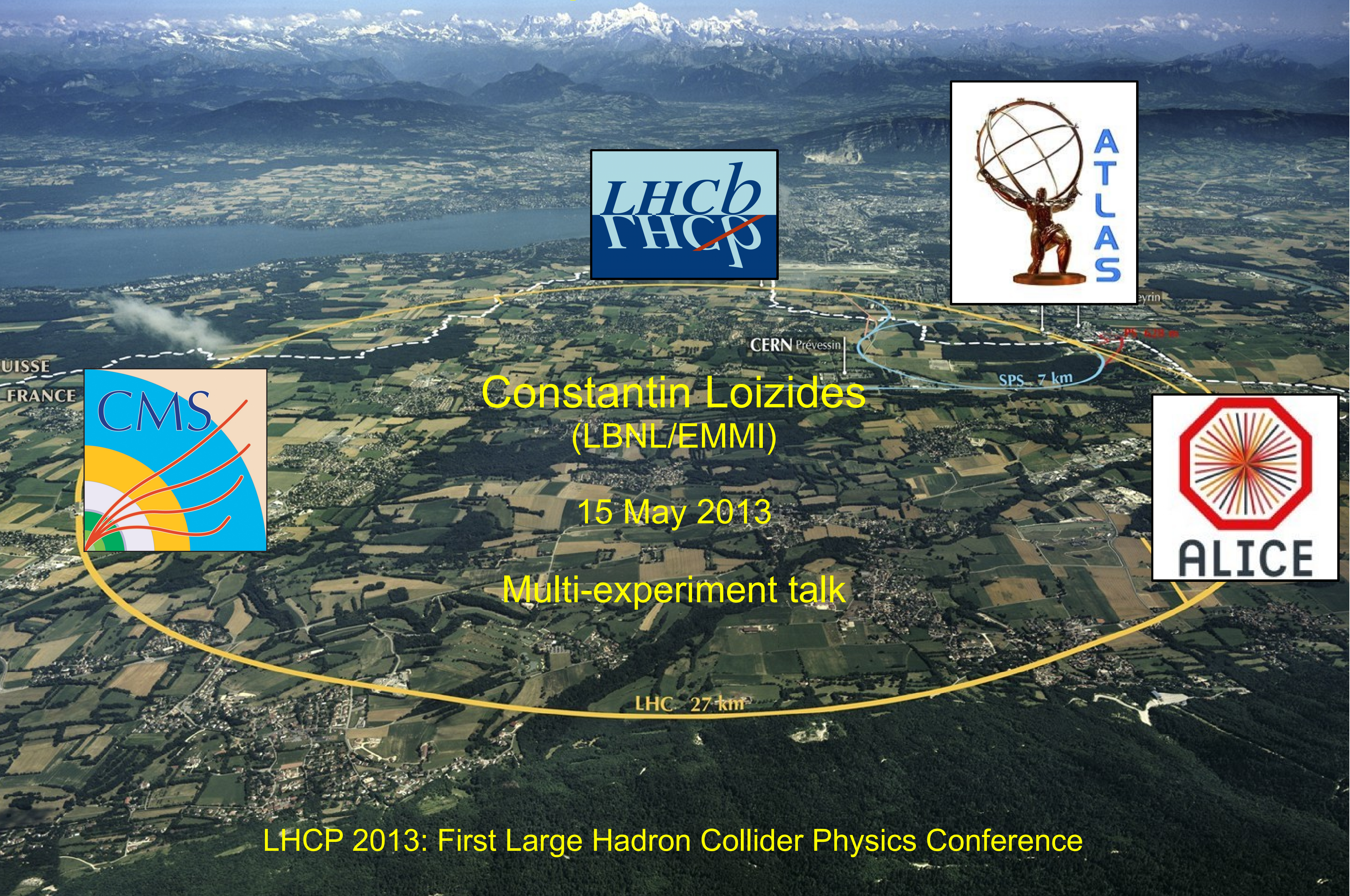
First results from pPb collisions at the LHC



Constantin Loizides
(LBNL/EMMI)

15 May 2013

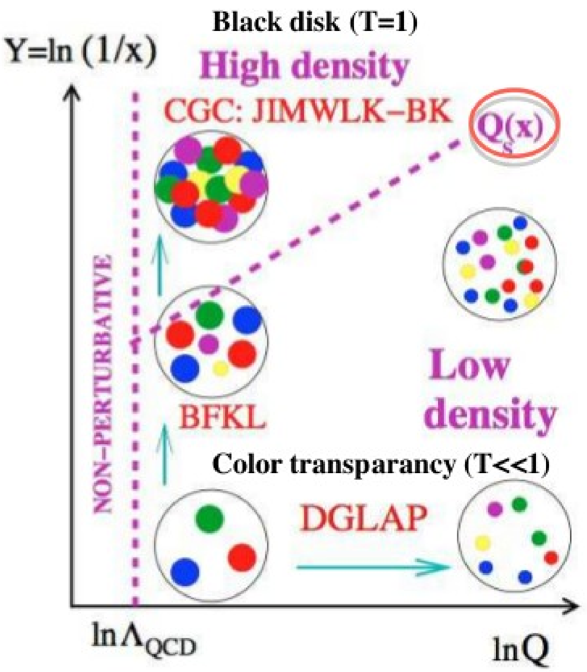
Multi-experiment talk

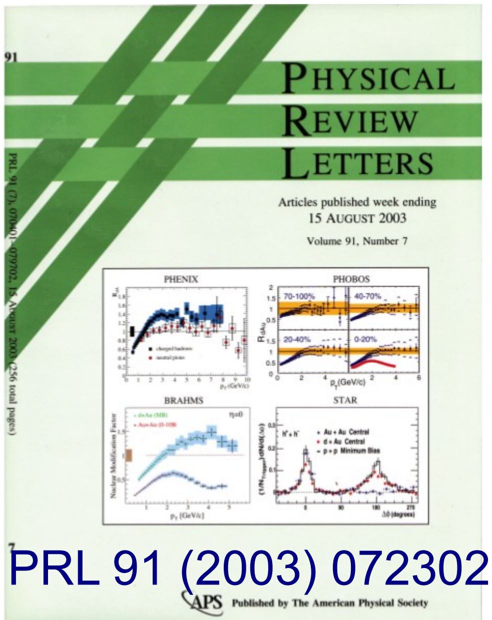
LHCP 2013: First Large Hadron Collider Physics Conference

Motivation for pPb at the LHC

- Study high-density QCD in saturation region
  - Saturation scale (Q_s) enhanced in nucleus ($\sim A^{1/3\lambda}$)
  - In perturbative regime at the LHC: $Q_s \sim 2\text{-}3$ GeV/c
  - Qualitatively expect $x \sim 10^{-4}$ at $\eta=0$ (vs 0.01 at RHIC)
- Study pA as a benchmark for AA
  - Benchmark hard processes to disentangle initial from final state effects
  - Characterize nuclear PDFs at small-x
- Expect surprises
  - History of pA collisions (eg. see talk by W.Busza)
  - pA contains elements of both: pp and AA
- Other physics opportunities
  - Diffraction
  - Photo-nuclear excitation

Motivations summarized in JPG 39 (2012) 015010

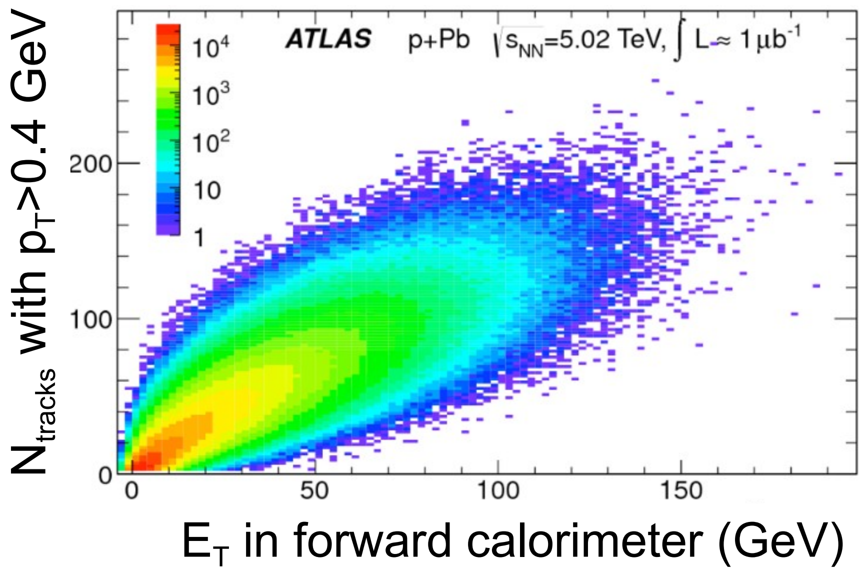


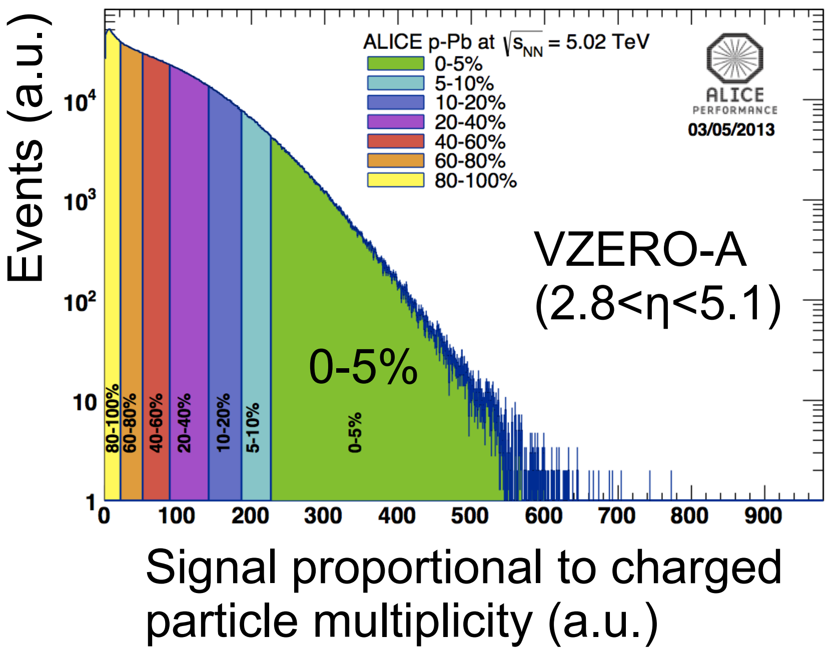


PRL 91 (2003) 072302

Event multiplicity classes in pPb

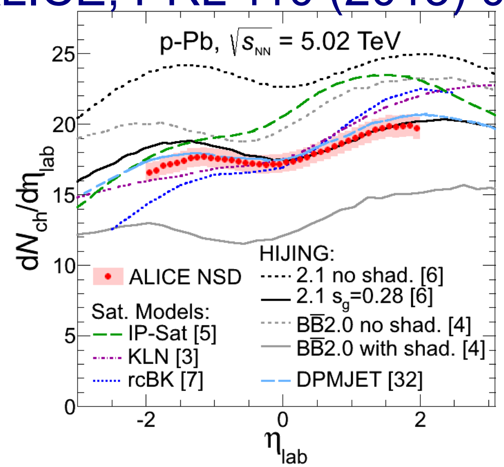
- Correlation between collision geometry and multiplicity not as strong as in AA
- System also exhibits features of biased pp (NN) collisions in the multiplicity tails
- Complicates precise extraction of Glauber related quantities
  - Use minbias values instead ($\sigma_{pA} = A\ \sigma_{pp}$)
- Define event classes by slicing various multiplicity related distributions
  - Every experiment uses its own selection and usually provides (corrected) multiplicity at mid-rapidity
  - Event class definition may matter for particular measurements
  - Systematic checks using different selections

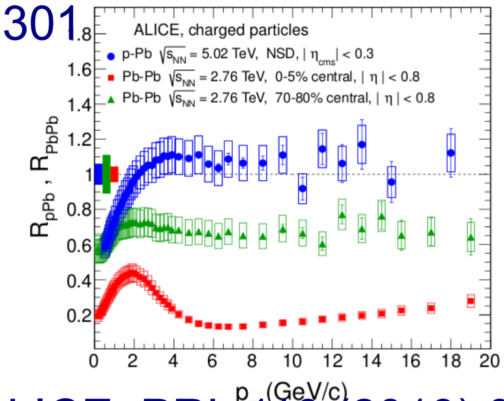




Physics results from 2012 and 2013 runs

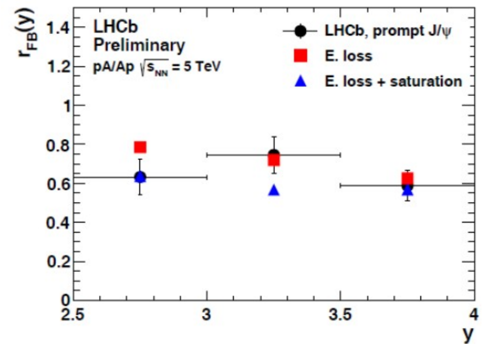
ALICE, PRL 110 (2013) 032301



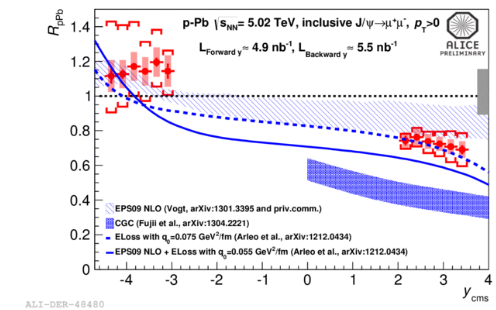


ALICE, PRL 110 (2013) 082302

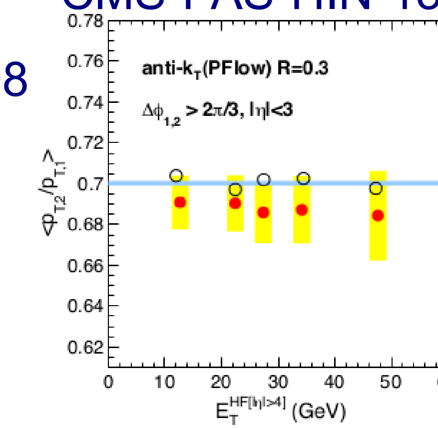
LHCb-CONF-2013-008



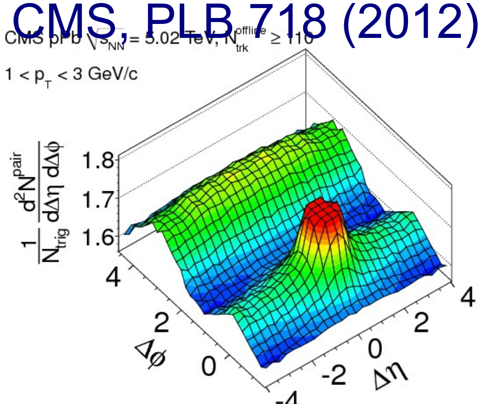
ALICE prel. (Trento)

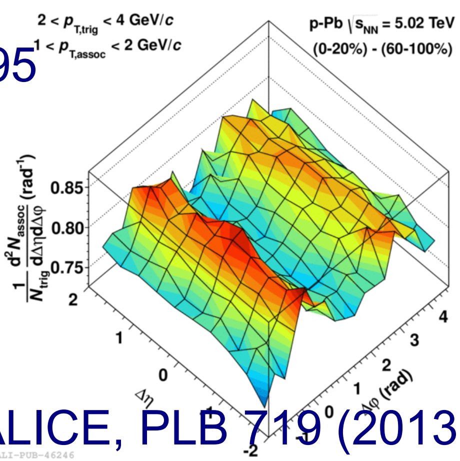


CMS-PAS-HIN-13-001



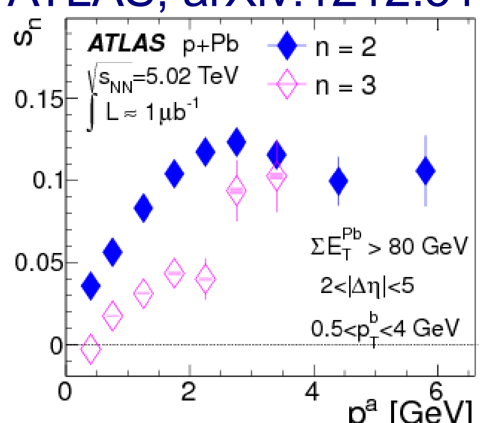
CMS, PLB 718 (2012) 795





ALICE, PLB 719 (2013) 29

ATLAS, arXiv:1212.5198



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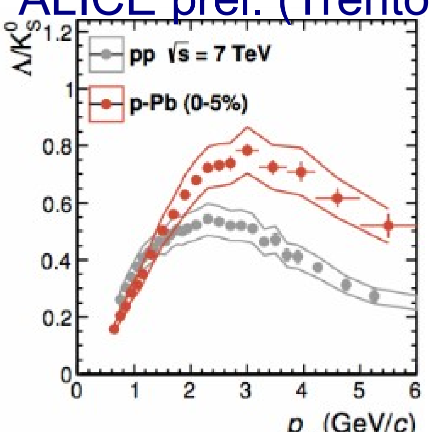
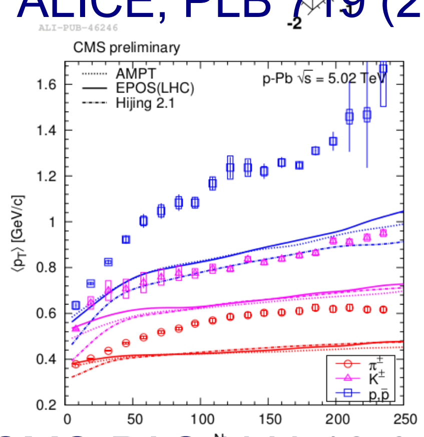
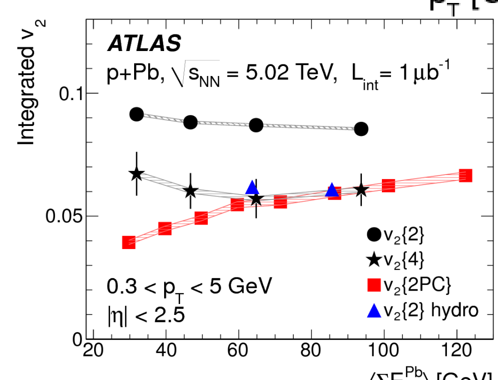


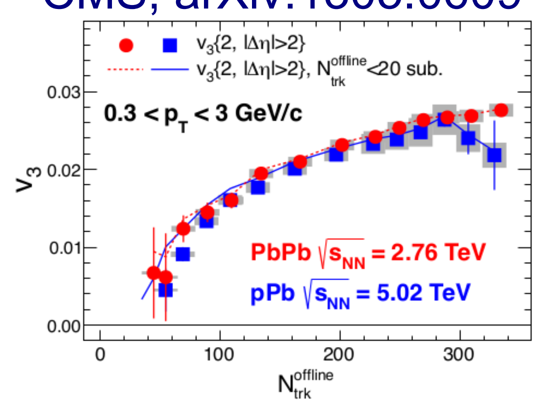


CMS-PAS-HIN-12-016



ATLAS, arXiv:1303.2084

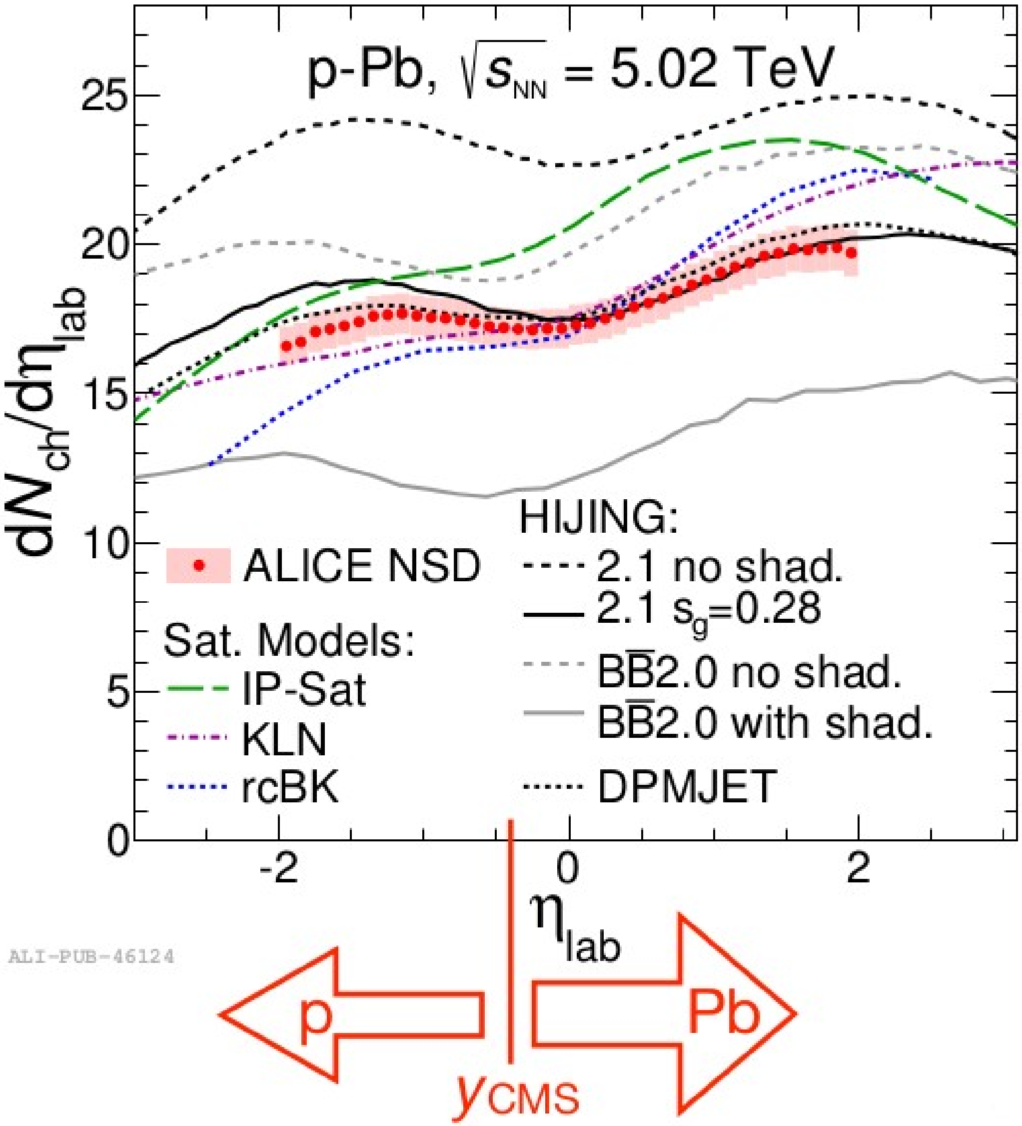
CMS, arXiv:1305.0609



Charged particle pseudorapidity density

ALICE, PRL 110 (2013) 032301

- Tracklet based analysis
  - Dominant systematic uncertainty from NSD normalization of 3.1%
- Reach of SPD extended to |η|<2 by extending the z-vertex range
- Results in ALICE laboratory system
  - y_{cms} = - 0.465
- Comparison with models
  - Most models within 20%
  - Saturation models have too steep rise between p and Pb region
  - See for further comparisons Albacete et al., arXiv:1301.3395

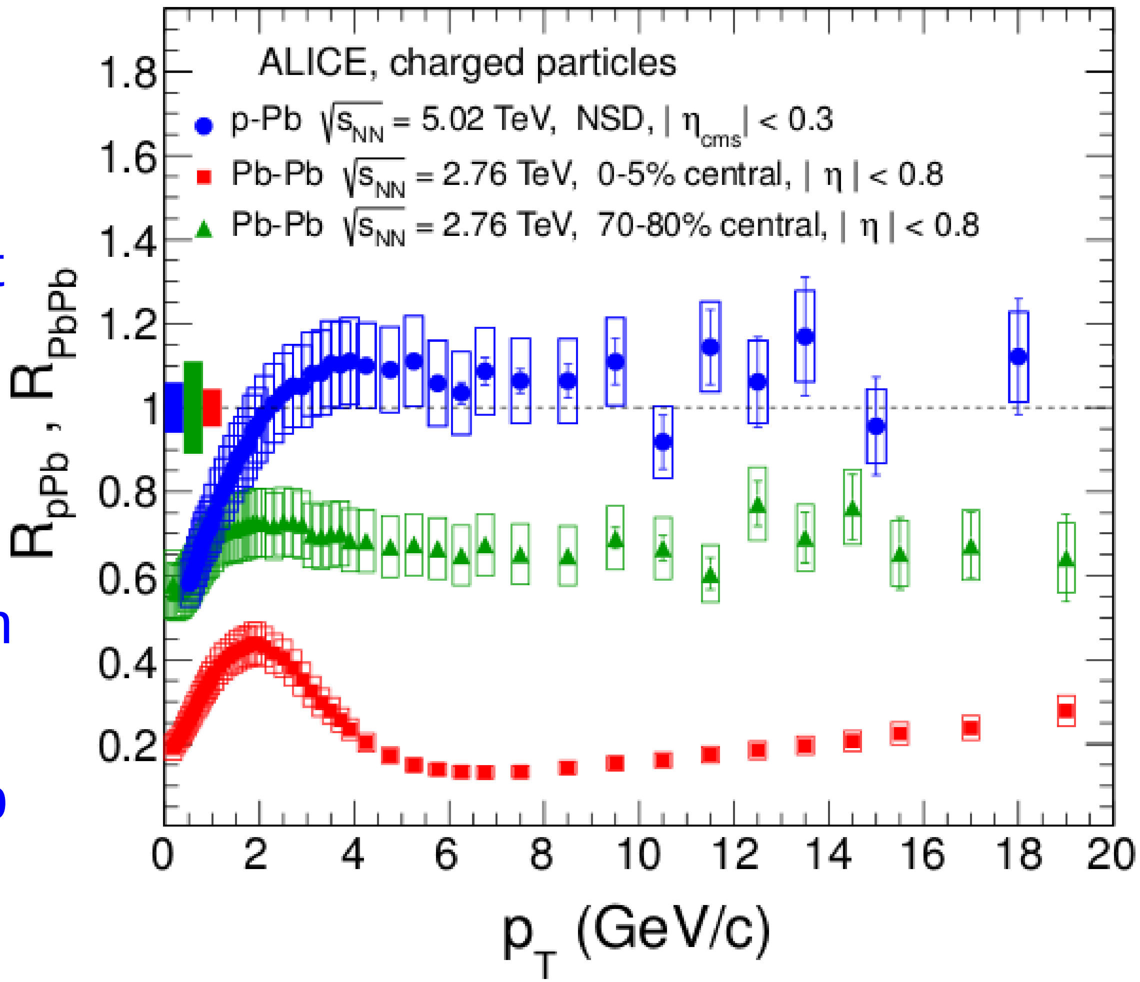


NB: HIJING calculations are expected to increase by ~4% from INEL to NSD

Nuclear modification factor in pPb vs PbPb

$$R_{AB} = \frac{\mathrm{d}N_{AB}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

ALICE, PRL 110 (2013) 082302

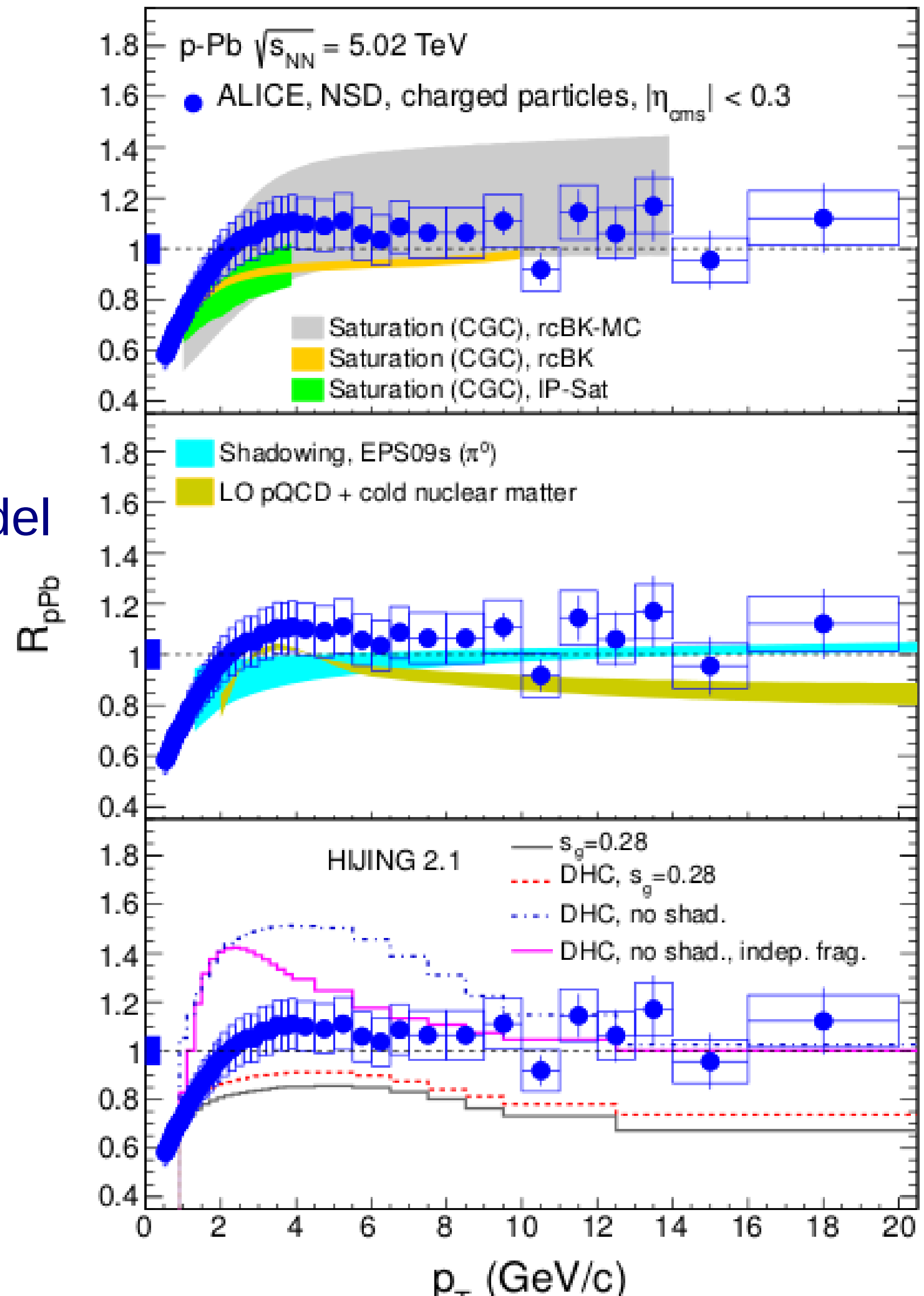


- R_{pPb} (at mid-rapidity) consistent with unity for p_T > 2 GeV/c
- High-p_T charged particles exhibit binary scaling
- Unlike in PbPb, no suppression at high p_T is observed
- Suppression at high p_T in PbPb is not an initial state effect

Nuclear modification factor vs models

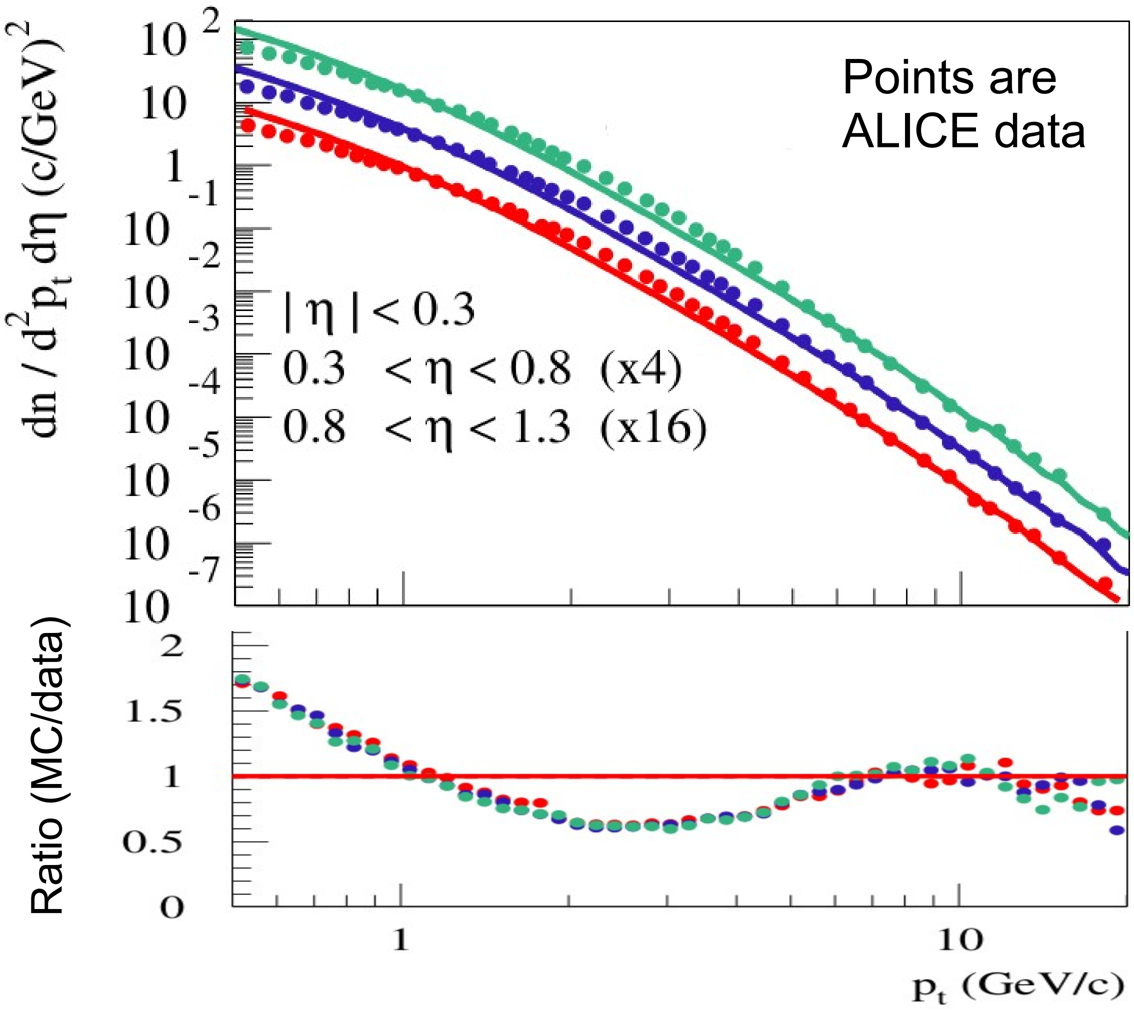
- Saturation (CGC) models:
  - Consistent with the data
  - Large uncertainties
- pQCD models with shadowing
  - Consistent with data
  - Tension at high p_T for LO+CNM model
- HIJING 2.1
  - With shadowing only matches at low p_T (see also dN/dη)
  - No shadowing better at high p_T
- Spectrum itself interesting
  - Neither HIJING nor DPMJET do describe the p-Pb p_T spectrum itself

NB: HJING calculations are expected to increase by ~4% from INEL to NSD

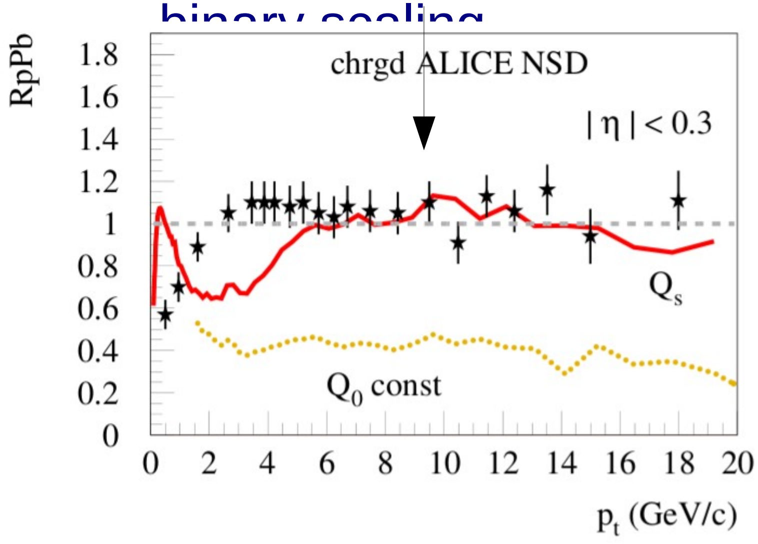


p_T spectrum in bins of η

Werner et al., EPOS3 (Trento)



- EPOS version 3
  - Gribov-Regge multiple scattering ansatz plus energy-momentum conservation with fixed scale breaks binary scaling
  - Introduction of ladder-by-ladder dependent saturation scale restores binary scaling

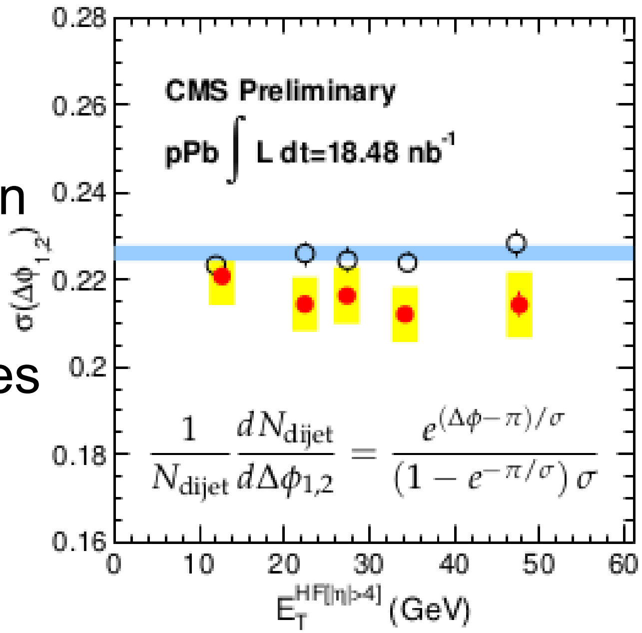


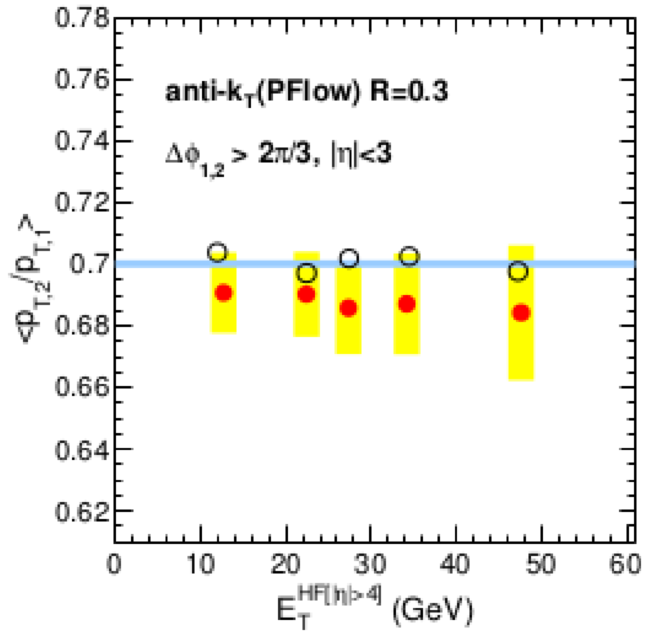
Measured spectra not described in low p_T region

Measurements of dijet properties

CMS-PAS-HIN-13-001

Δφ distribution the same for all forward energy classes





p_T imbalance the same for all forward energy classes

P_{T1}>120 GeV/c
P_{T2}>30 GeV/c
R=0.3
η<|3|

Large imbalance measured in AA is final state effect

(See B. de la Cruz, Tuesday)

Measurements of dijet properties

CMS-PAS-HIN-13-001

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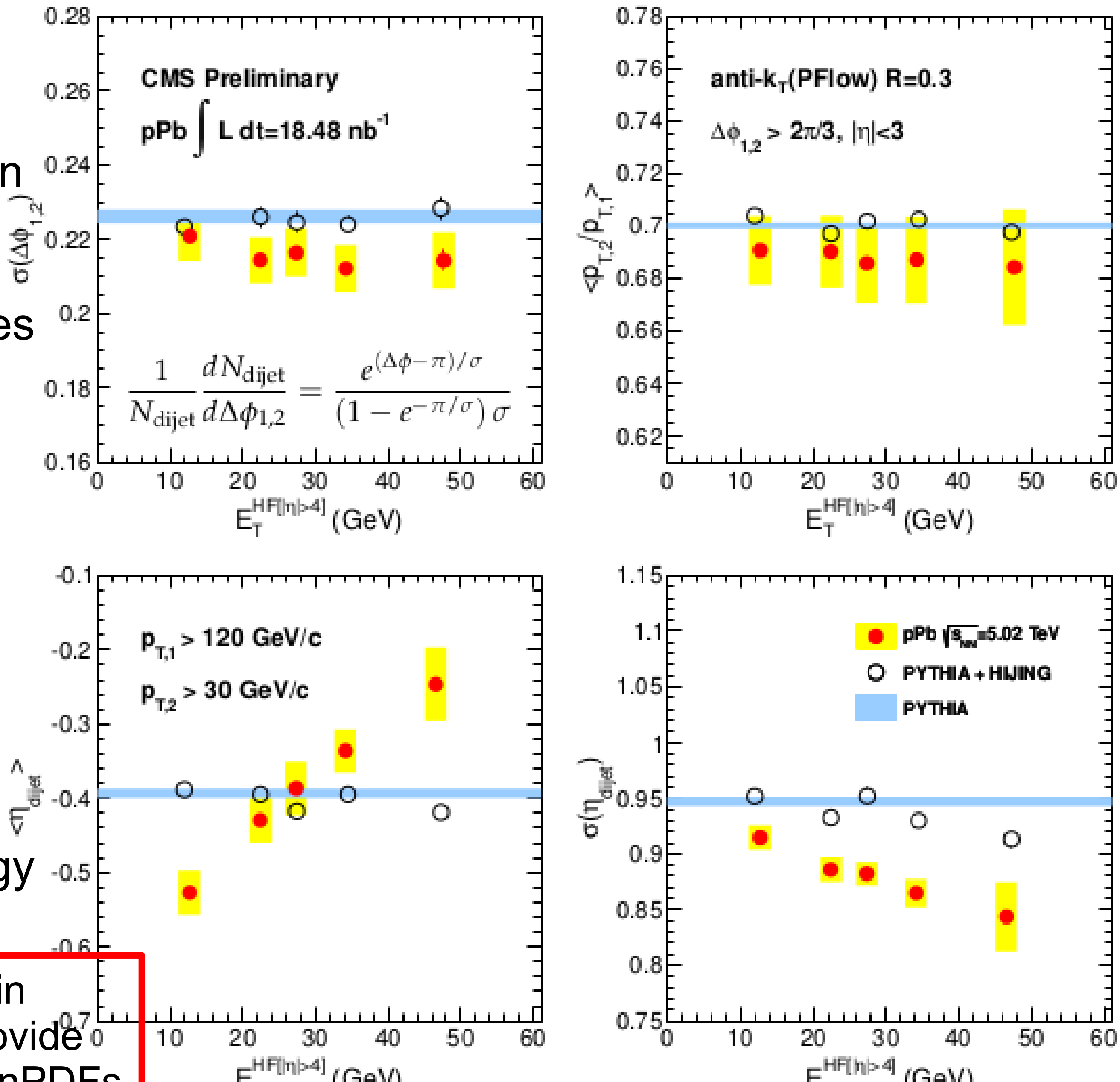


p_T imbalance the same for all forward energy classes

Large imbalance measured in AA is final state effect

Dijet η shifts forward for increasing forward energy

Dijet η width decreases for increasing forward energy

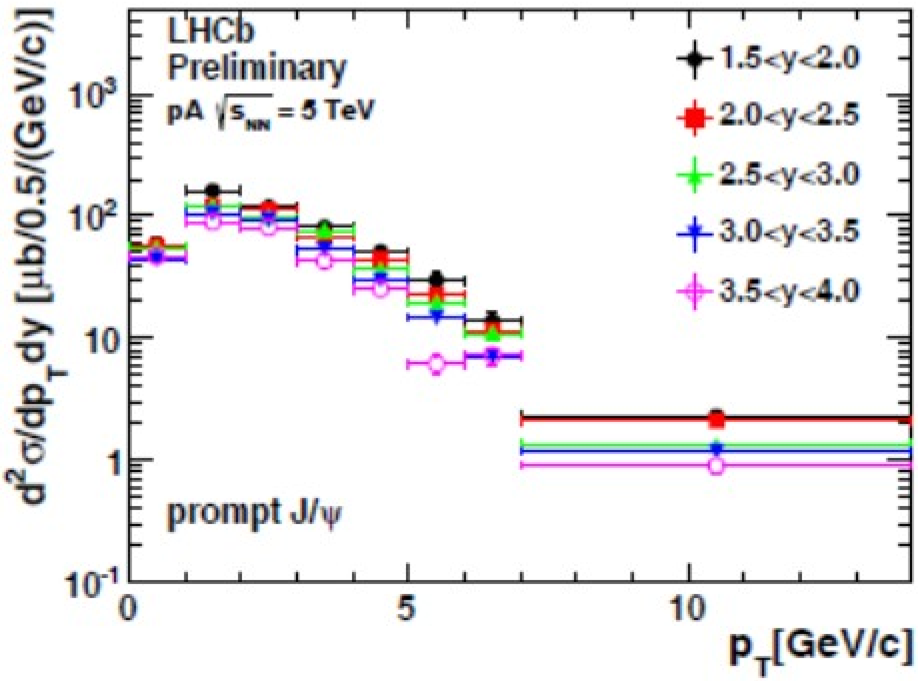
Change seen in dijet η may provide constrains for nPDFs

(See B. de la Cruz, Tuesday)

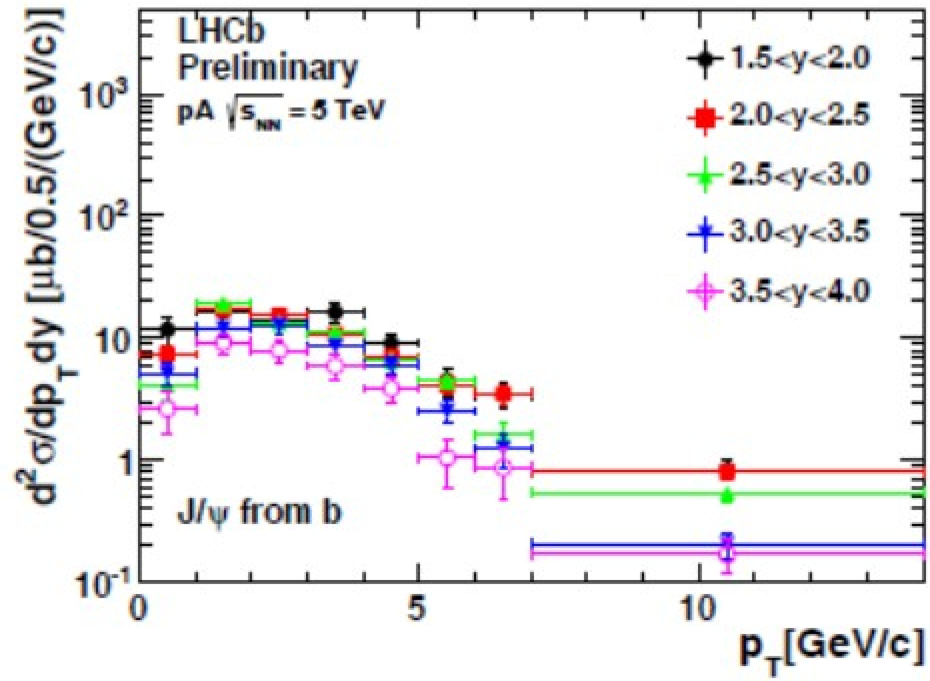
J/ψ double differential cross section

LHCb-CONF-2013-008

Prompt J/ψ



J/ψ from b



Total cross-sections:

Forward: $p_T < 14$ GeV/c , $\mathbf{1.5 < y < 4.0}$

$$\sigma_{pA}(prompt\ J/\psi) = \mathbf{1028.2 \pm 13.6\ (stat.) \pm 88.6 (syst.)}\ \mu b$$

$$\sigma_{pA}(J/\psi\ from\ b) = \mathbf{150.1 \pm 4.2\ (stat.) \pm 12.6 (syst.)}\ \mu b$$

Backward: $p_T < 14$ GeV/c , $\mathbf{-5 < y < -2.5}$

$$\sigma_{Ap}(prompt\ J/\psi) = \mathbf{1141.9 \pm 49.8\ (stat.) \pm 98.4 (syst.)}\ \mu b$$

$$\sigma_{Ap}(J/\psi\ from\ b) = \mathbf{119.7 \pm 8.3\ (stat.) \pm 10.0 (syst.)}\ \mu b$$

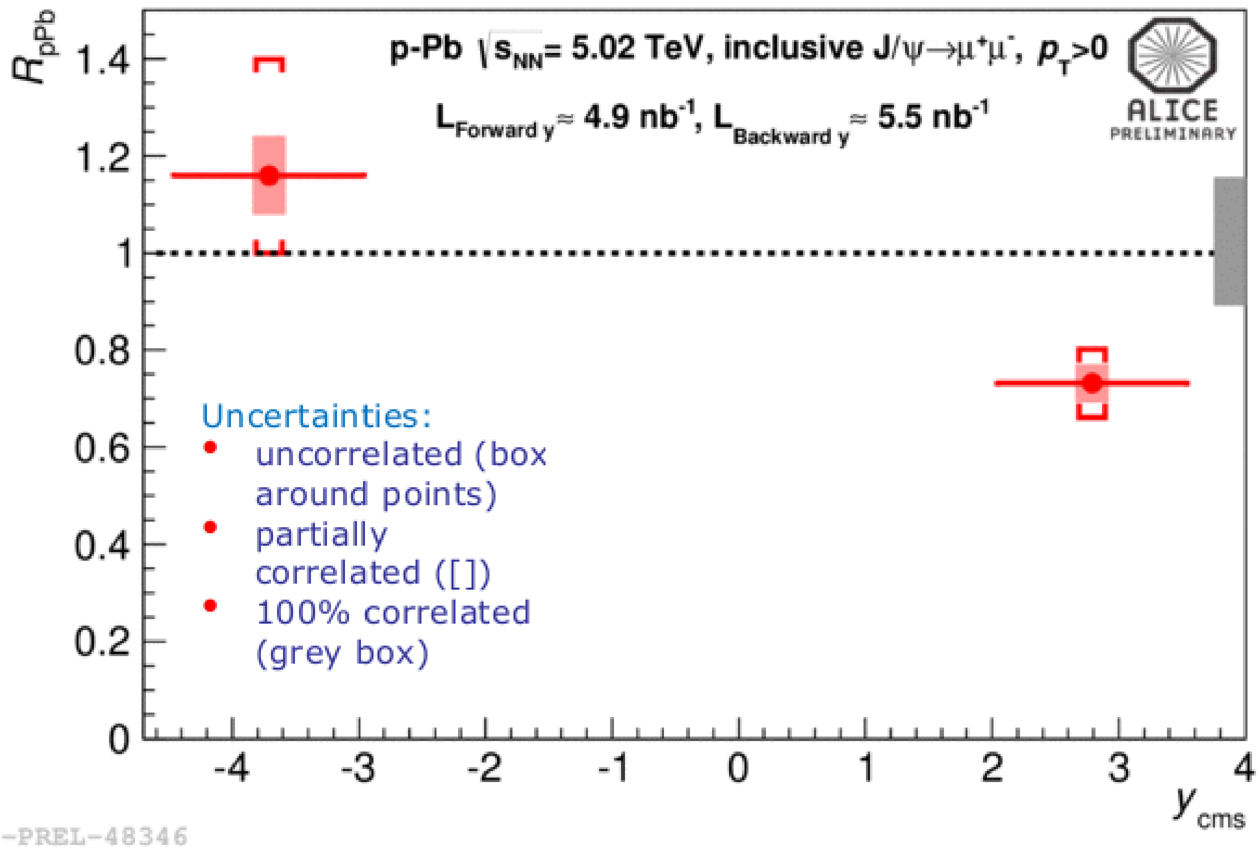
Systematic uncertainties dominated by luminosity, fit model and data-mc consistency

(See A. Rossi, Tuesday)

J/ψ nuclear modification factor

- R_{pPb} decreases towards forward y
- Uncertainty dominated by uncertainty of pp reference

Inclusive J/psi, ALICE preliminary (Trento)



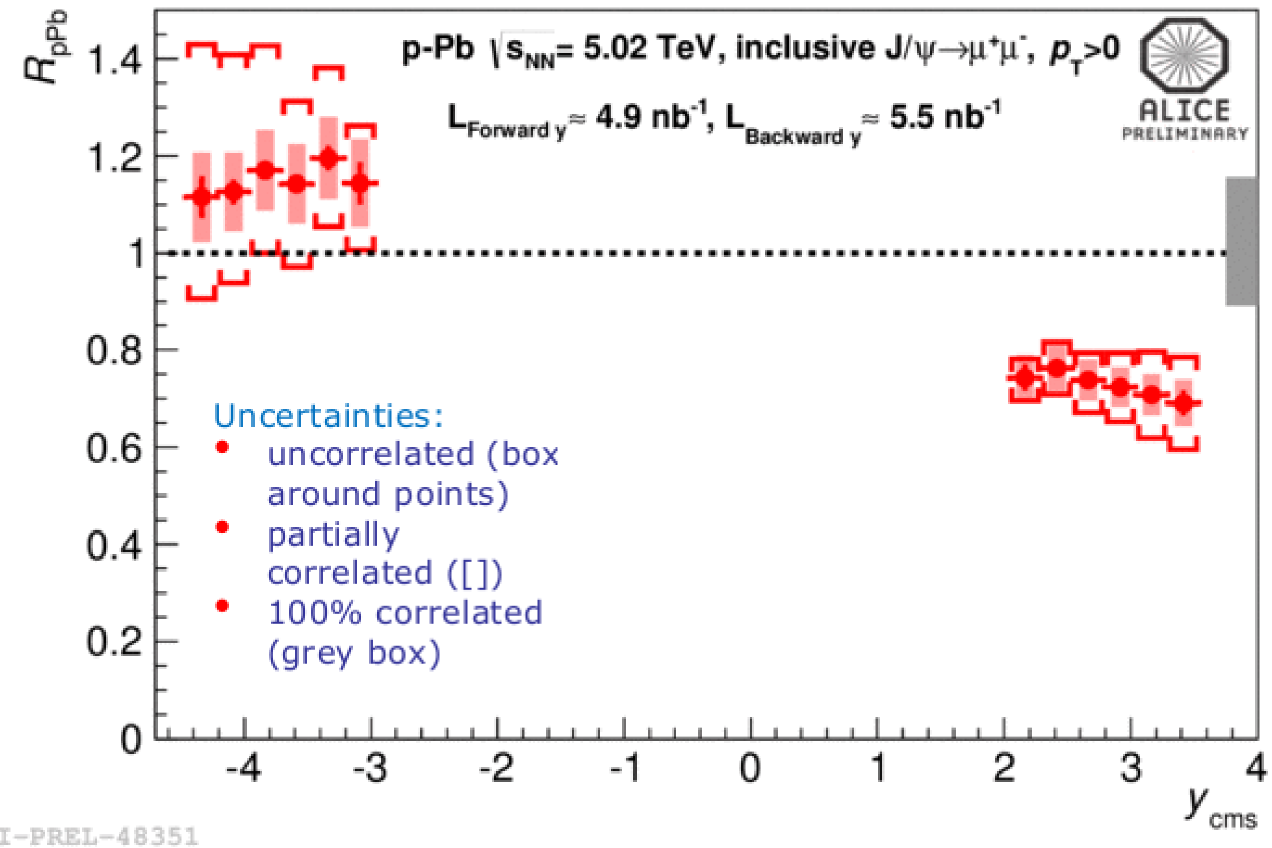
R_{pA} $(2.03<y_{CMS}<3.53)$=
0.732 ± 0.005(stat) ± 0.059(syst) + 0.131(syst. ref) – 0.101(syst.ref)

R_{pA} $(-4.46<y_{CMS}<-2.96)$=
1.160 ± 0.010 (stat) ± 0.096(syst) + 0.296(syst. ref) – 0.198(syst.ref)

J/ψ nuclear modification factor

- R_{pPb} decreases towards forward y
- Uncertainty dominated by uncertainty of pp reference
- No apparent rapidity dependence in backward region

Inclusive J/psi, ALICE preliminary (Trento)



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J/ψ nuclear modification factor vs models

Inclusive J/psi, ALICE preliminary (Trento)

- R_{pPb} decreases towards forward y
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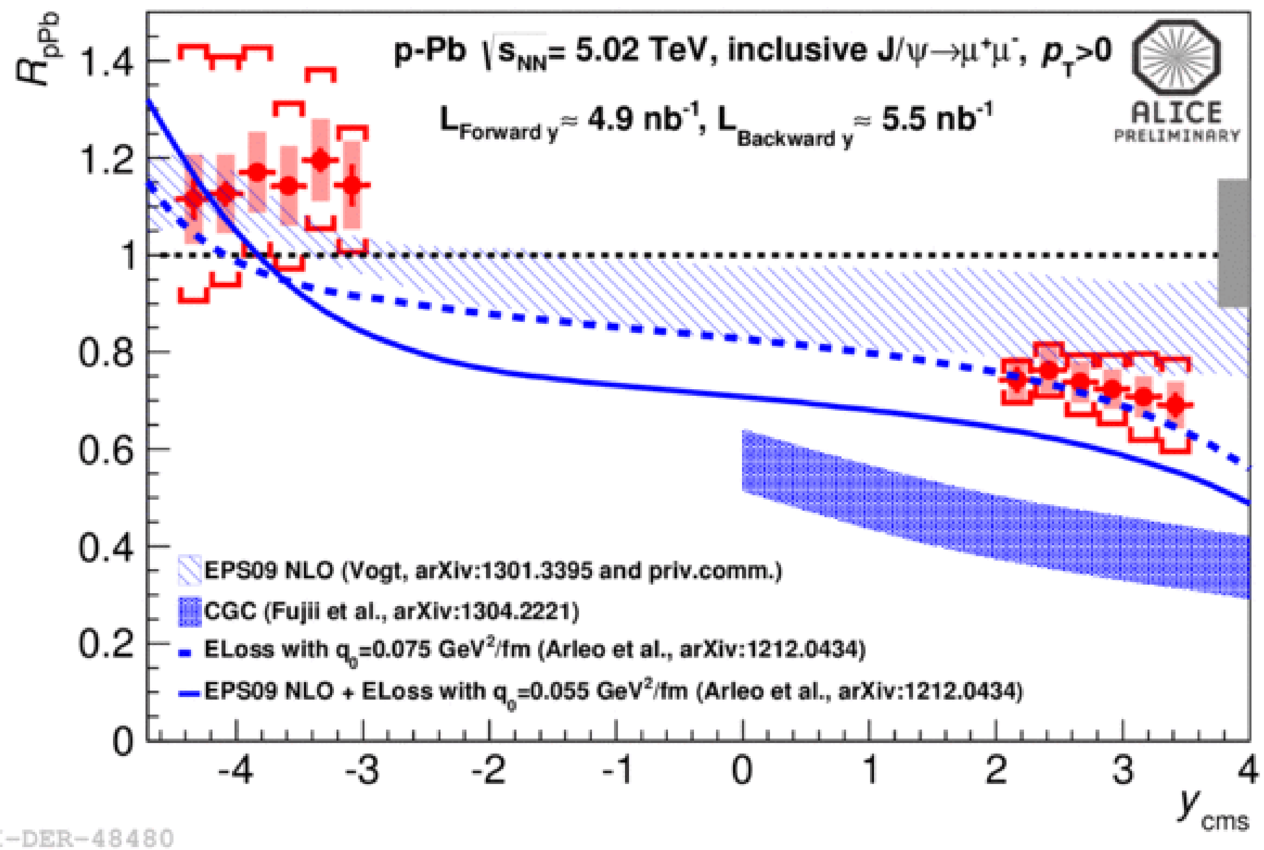
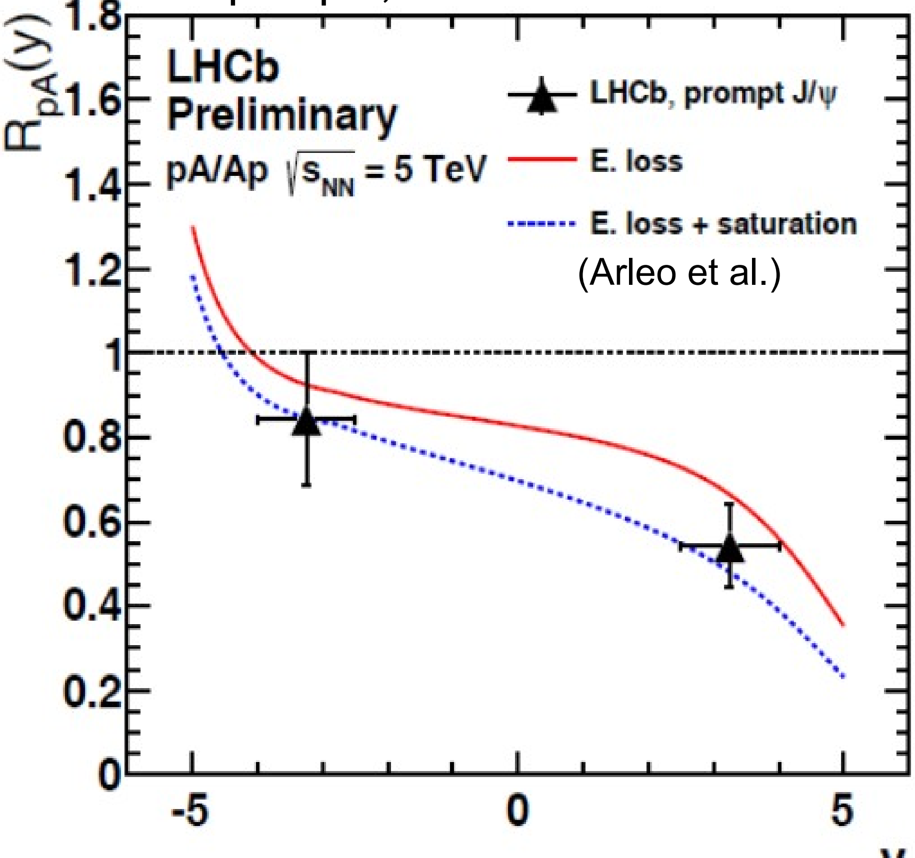
- No apparent rapidity dependence in backward region



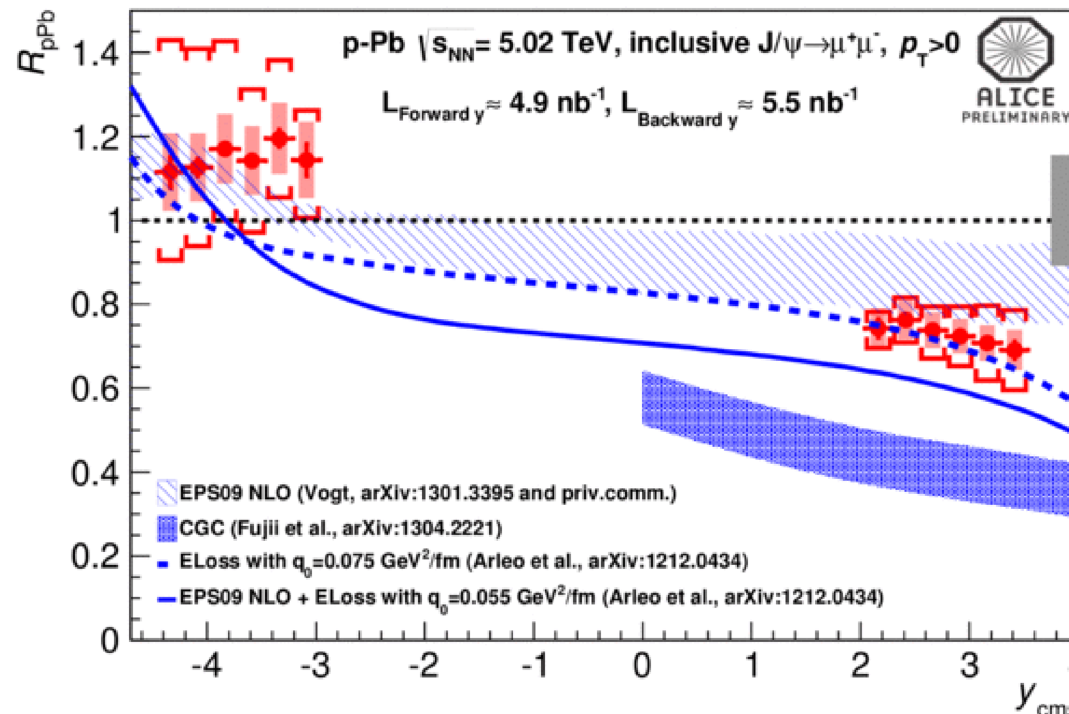
- Comparison with models
  - Good agreement with models incorporating shadowing (EPS09 NLO) and/or a contribution of coherent parton energy loss
  - CGC model (Fujii et al.) disfavored by the data
  - Rapidity dependence in backward region may provide additional constraints

Prompt vs inclusive J/ψ R_{pPb}

Prompt J/psi, LHCb-CONF-2013-008



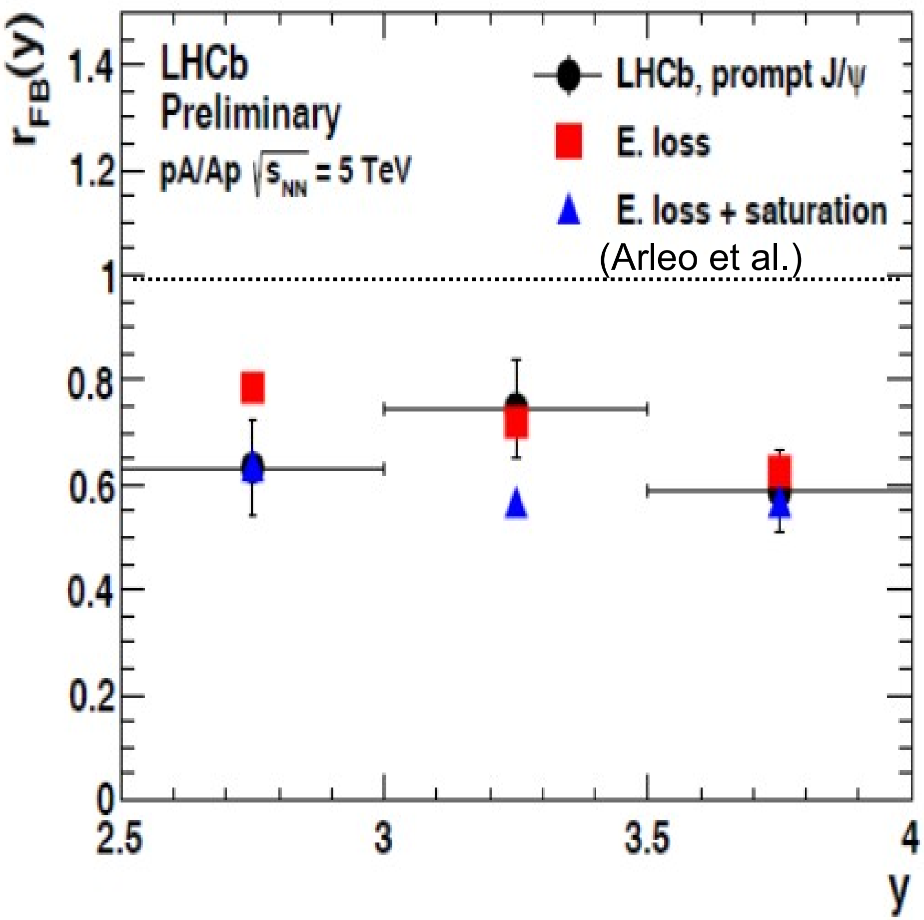
Inclusive J/psi, ALICE preliminary (Trento)



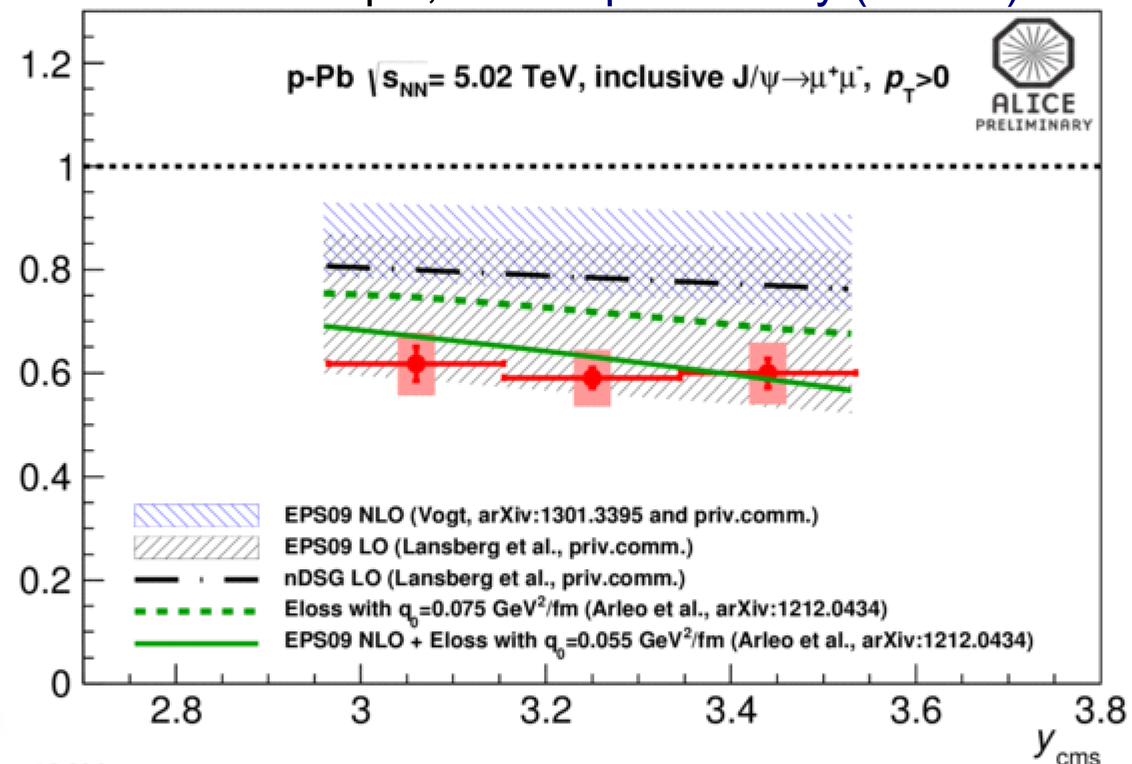
- Comparison between prompt and inclusive measurement
  - Central values for LHCb about 30% lower
    - Both measurements on-the-edge of being compatible within uncertainties
    - Understanding the difference is ongoing
  - Similar conclusions wrt the comparison with models

Forward-backward asymmetry

Prompt J/psi, LHCb-CONF-2013-008

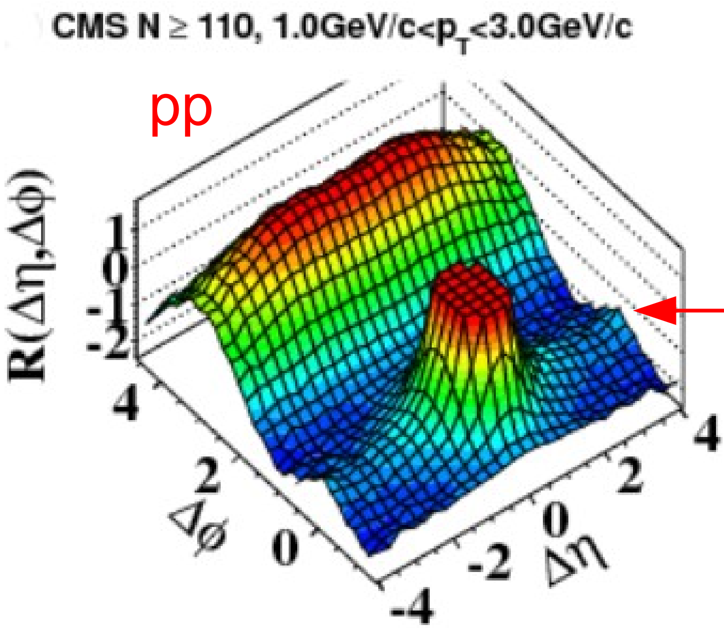


Inclusive J/psi, ALICE preliminary (Trento)



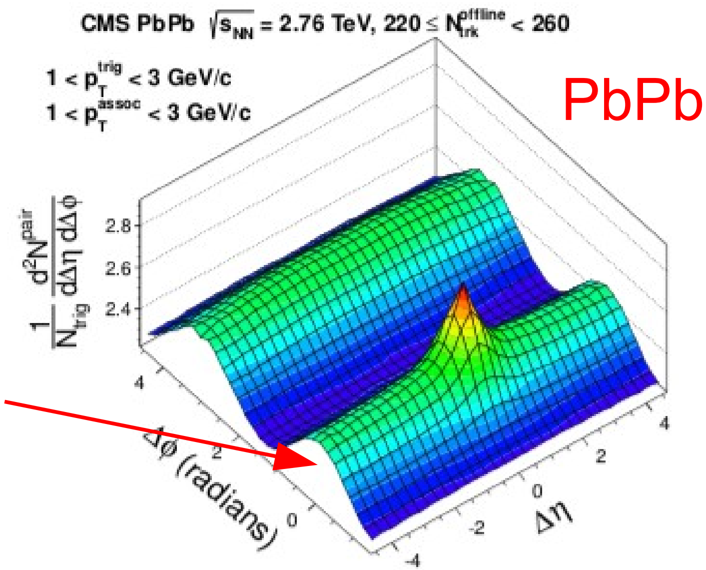
- Forward-to-backward ratio in common |y| ranges
  - Free of uncertainty from pp reference
  - Good agreement between prompt and inclusive measurement
- Models incorporating shadowing and energy loss consistent with data

Two-particle angular correlations

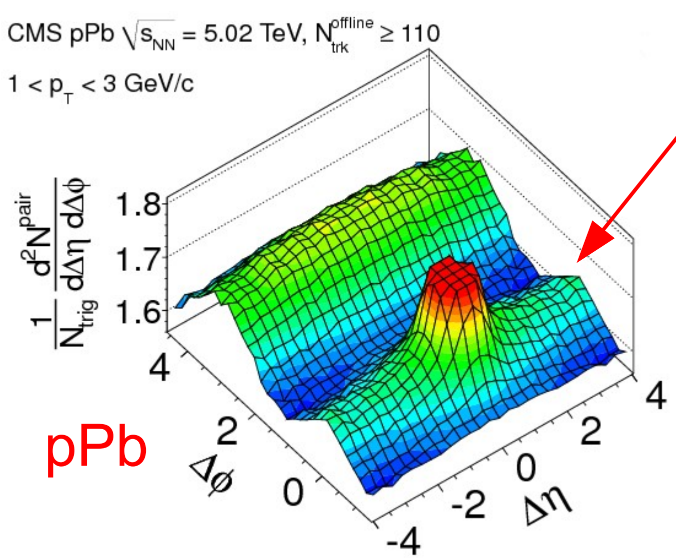


CMS, JHEP 1009 (2010) 91

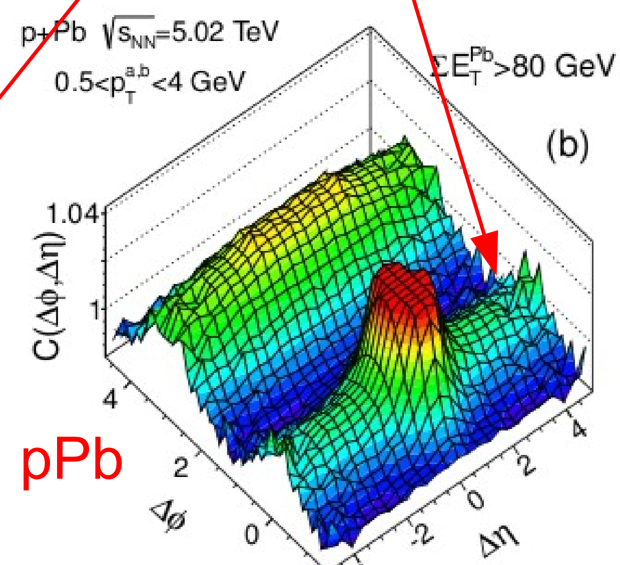
Near-side ridges apparent in high multiplicity events at LHC energies



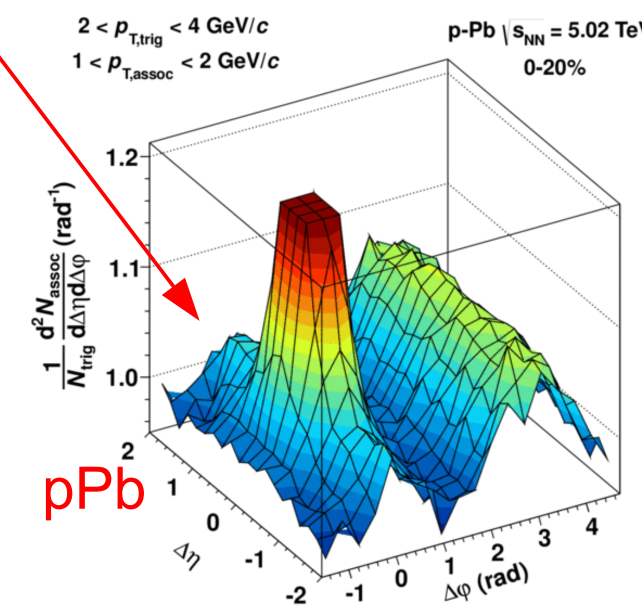
CMS, arXiv:1305.0609



CMS, PLB 718 (2012) 795



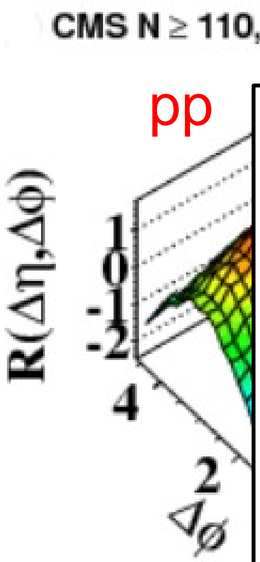
ATLAS, arXiv:1212.5198



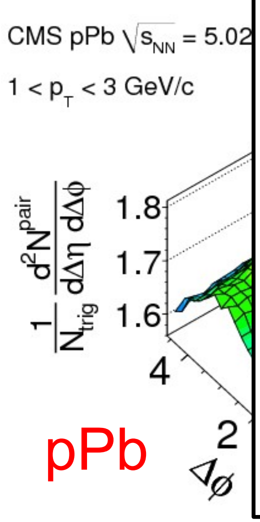
ALICE, PLB 719 (2013) 29

Two-particle angular correlations

pp

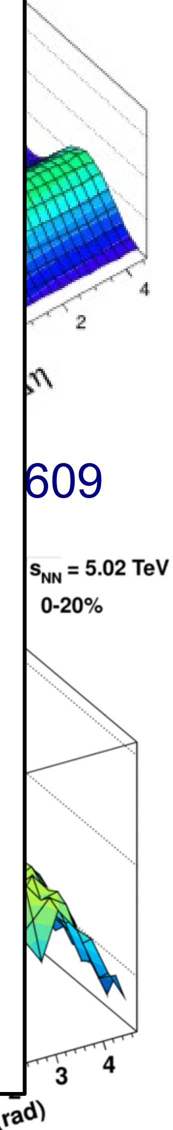


CMS, JH...



pPb

PbPb



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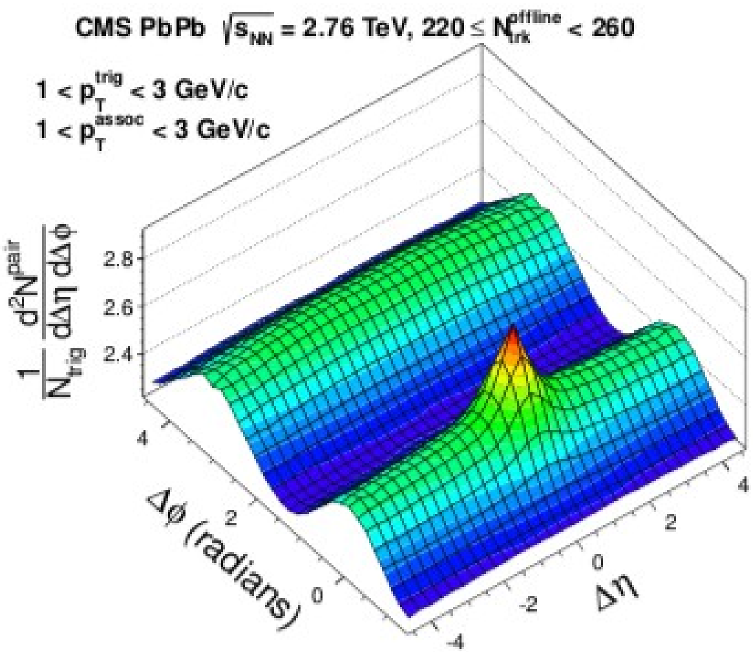
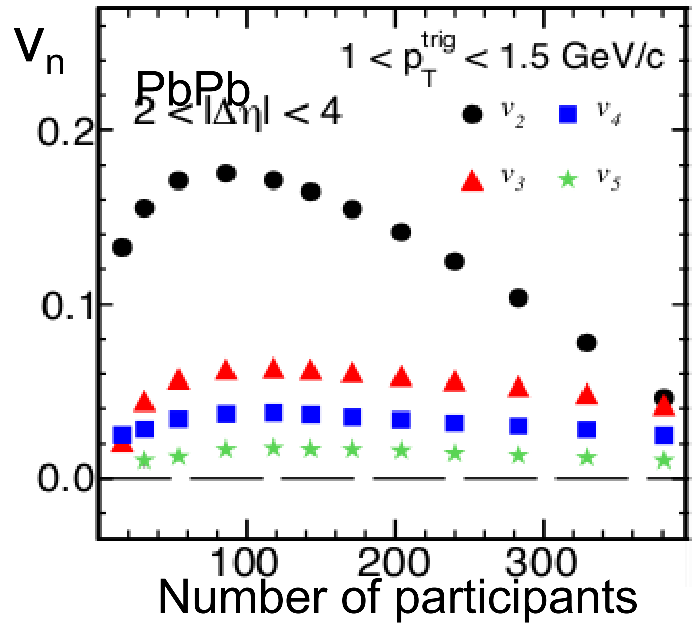
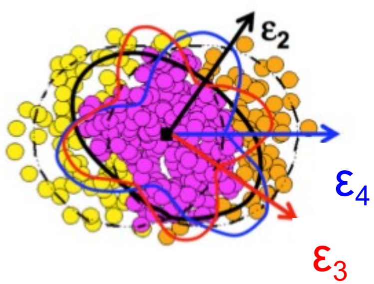


CMS, EPJC 72 (2012) 10052





$$\frac{dN}{d\varphi} \sim 1 + 2v_2\cos[2(\varphi-\psi_2)] + 2v_3\cos[3(\varphi-\psi_3)] + 2v_4\cos[4(\varphi-\psi_4)] + 2v_5\cos[5(\varphi-\psi_5)] + \ldots$$

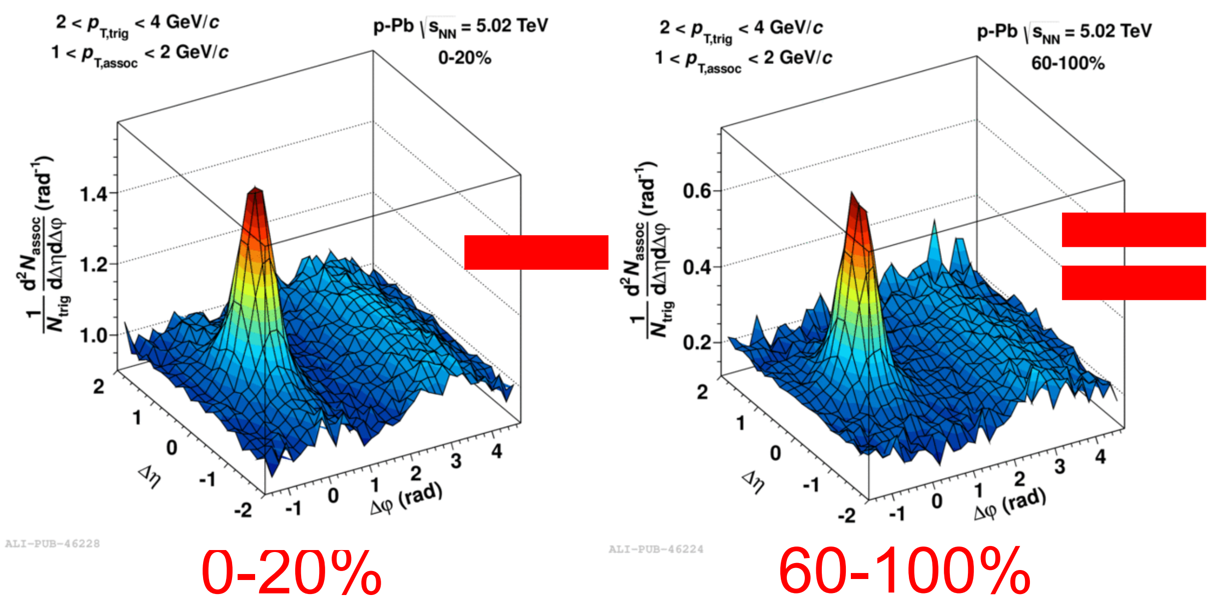
In PbPb, long-range correlations can be explained by flow harmonics (v_n)

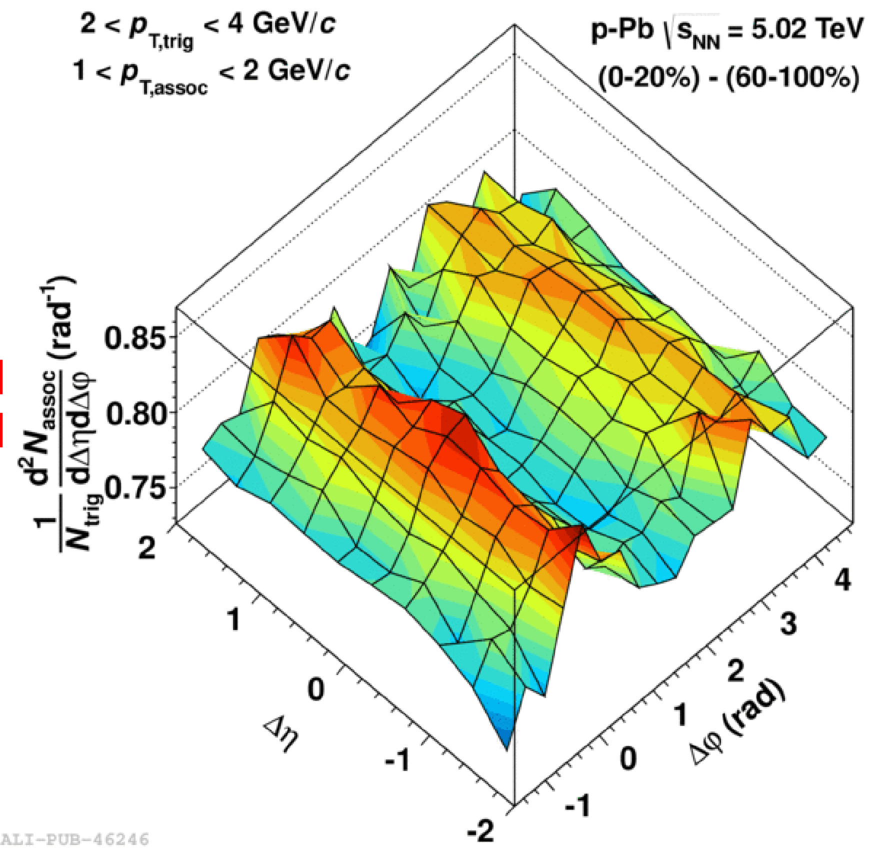
(see M. Floris, Tuesday)

CMS, PLB 718 (2012) 795 ATLAS, arXiv:1212.5198 ALICE, PLB 719 (2013) 29

Extraction of double ridge structure

ALICE, PLB 719 (2013) 29

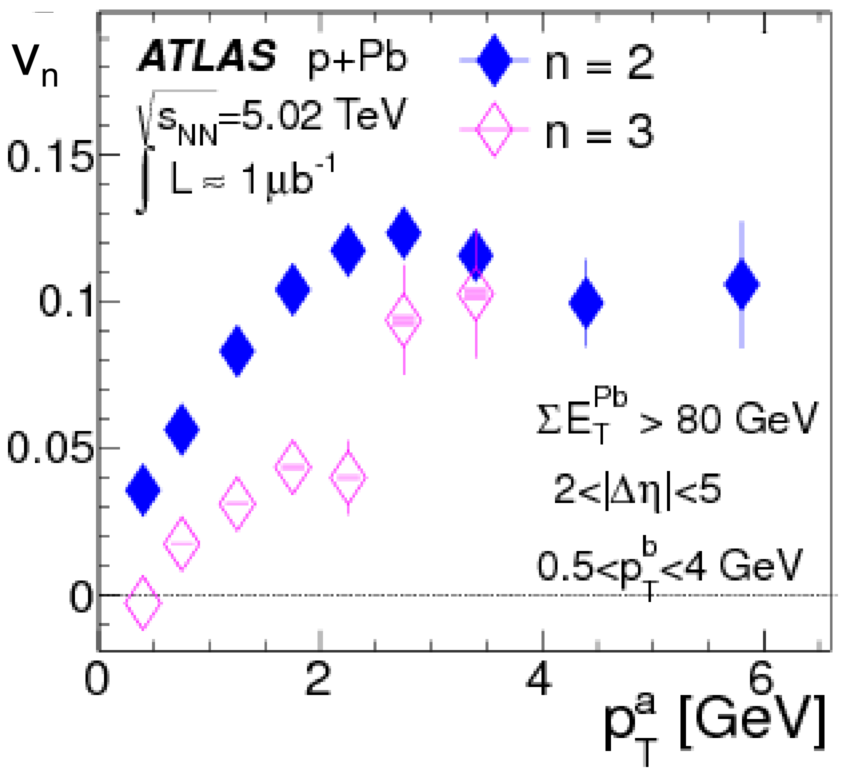




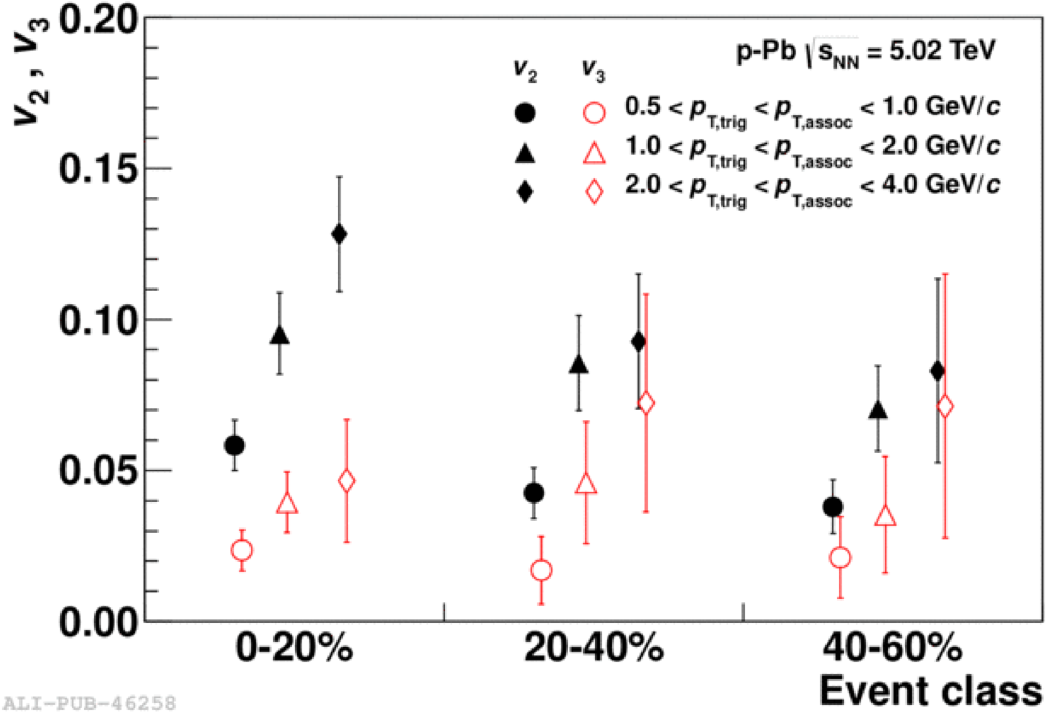
- Extract double ridge structure using a standard technique in AA collisions, namely by subtracting the jet-like correlations
  - It has been verified that the 60-100% class is similar to pp
  - The near-side ridge is accompanied by an almost identical ridge structure on the away-side
  - Similar analysis strategy by ATLAS (arXiv:1212.5198)

Ridge v_2 and v_3

ATLAS, arXiv:1212.5198



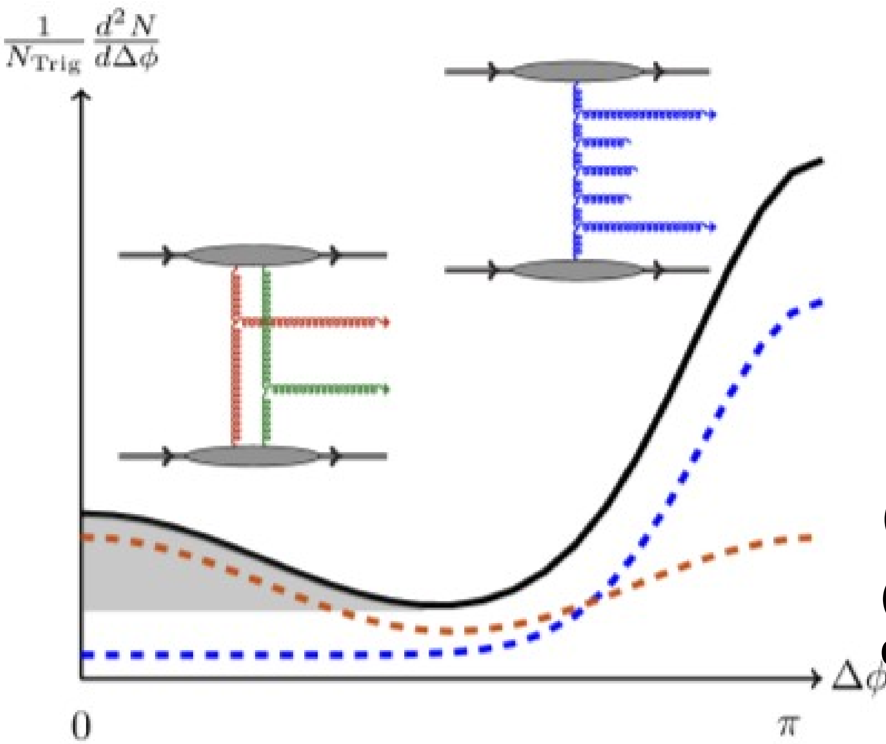
ALICE, PLB 719 (2013) 29



- Large values for v_2 and v_3 reached for high-multiplicity events

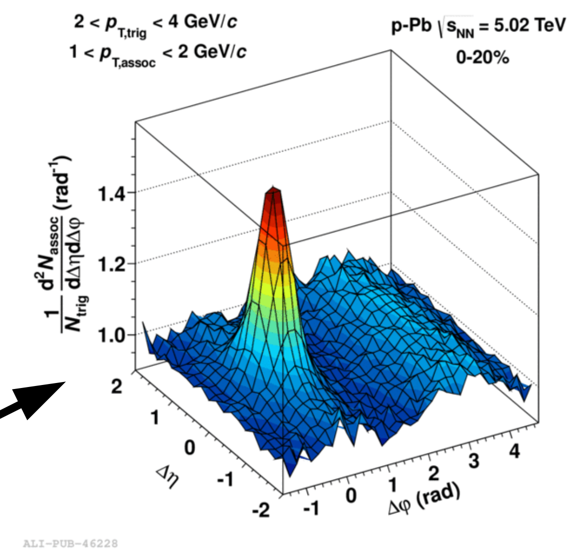
Ridge modulation v_2 and v_3 and CGC

- Two symmetric ridges are predicted by CGC glasma graphs

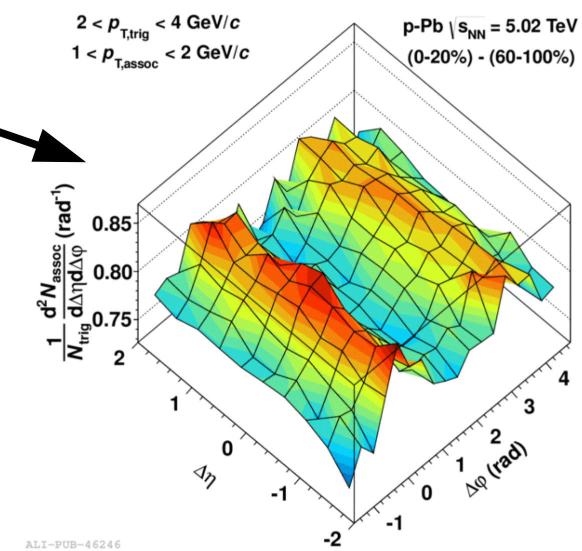


Dusling and Venugopalan, arXiv:1302.7018

BFKL-Minijets

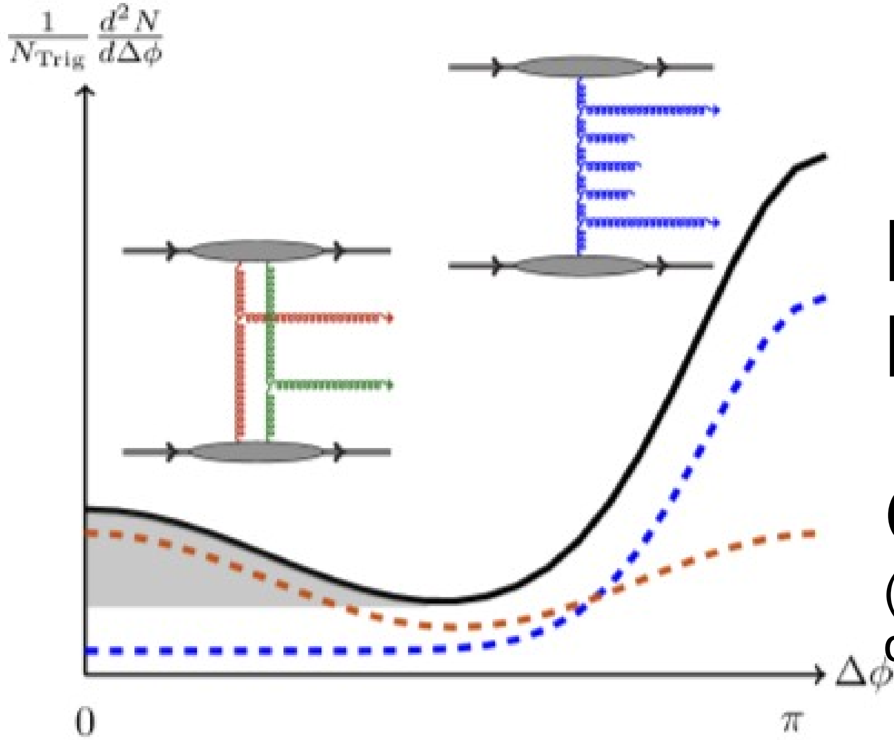


Glasma
(enhanced by α_s^{-8} for $k_T < Q_s$)



Ridge modulation v_2 and v_3 and CGC

- Two symmetric ridges predicted by CGC glasma graphs found to describe the ridge yields and shape



Dusling and Venugopalan, arXiv:1302.7018

BFKL-Minijets

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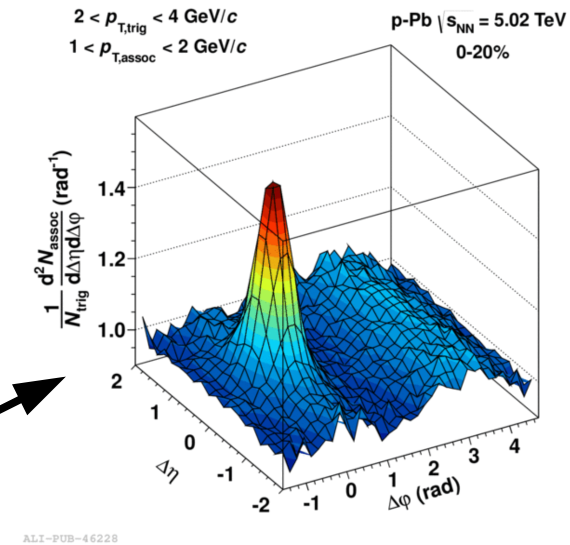
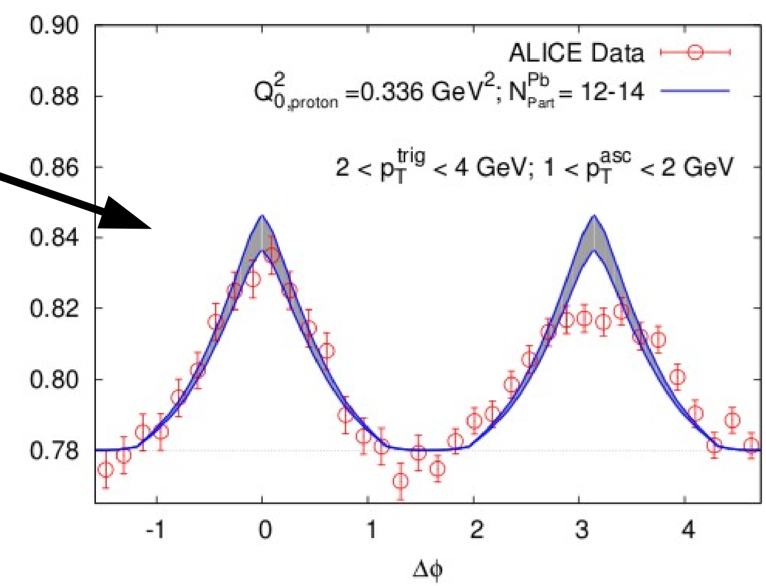
(enhanced by α_s^{-8} for $k_T < Q_s$)

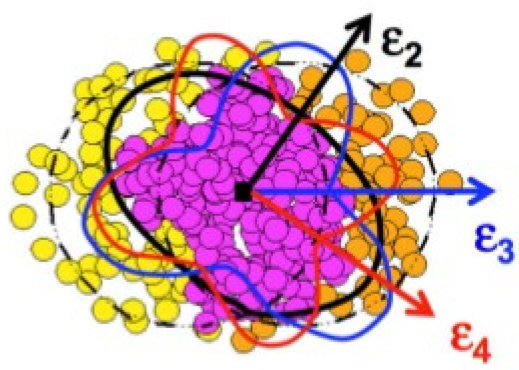




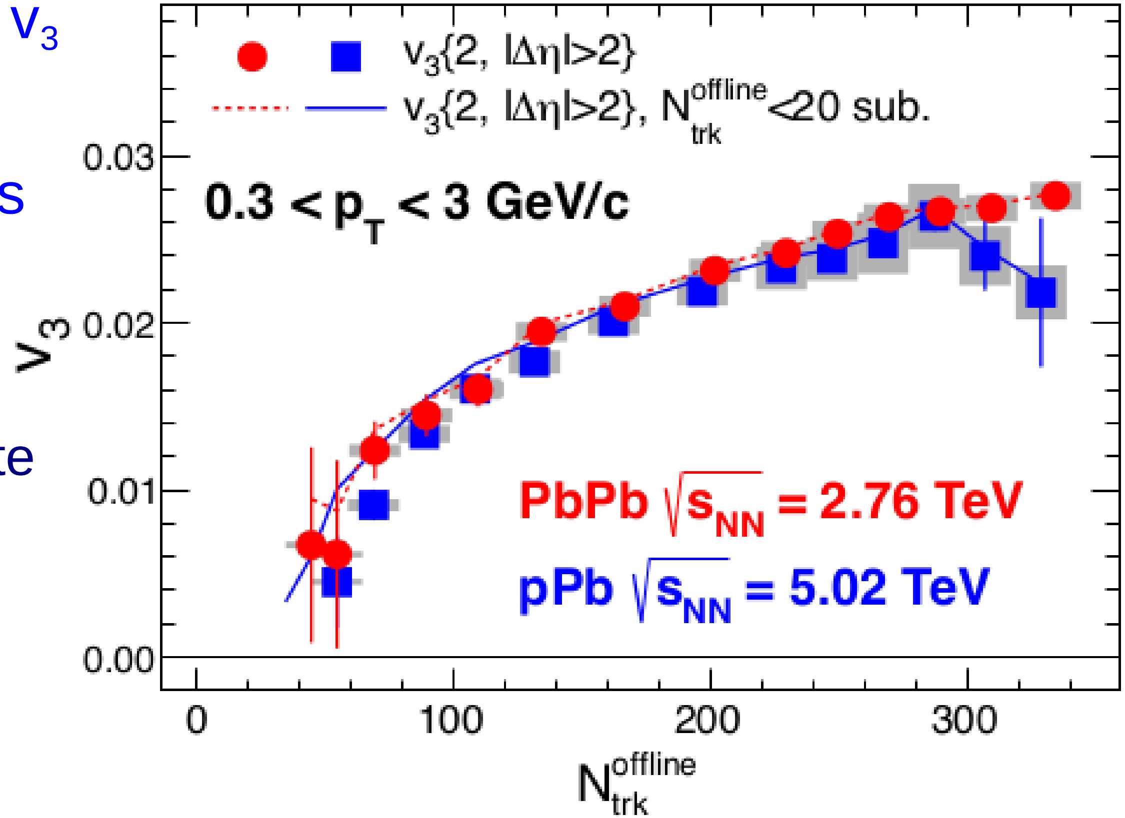
- However, a large v_3 component would be a challenge for the model

v_3 in PbPb and pPb

- Observe essentially the same v_3 in pPb as in PbPb
- Turn on at around M=50 tracks
- Established picture in PbPb
  - Fluctuations of initial state are transformed into final state through interactions



CMS, arXiv:1305.0609



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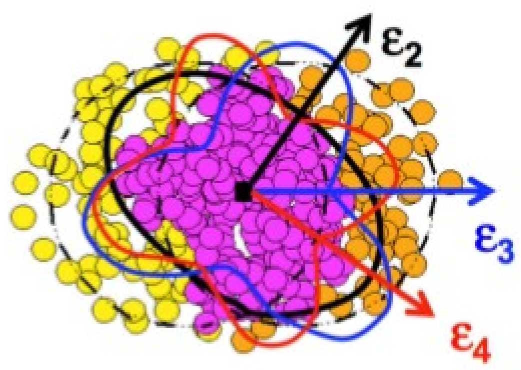
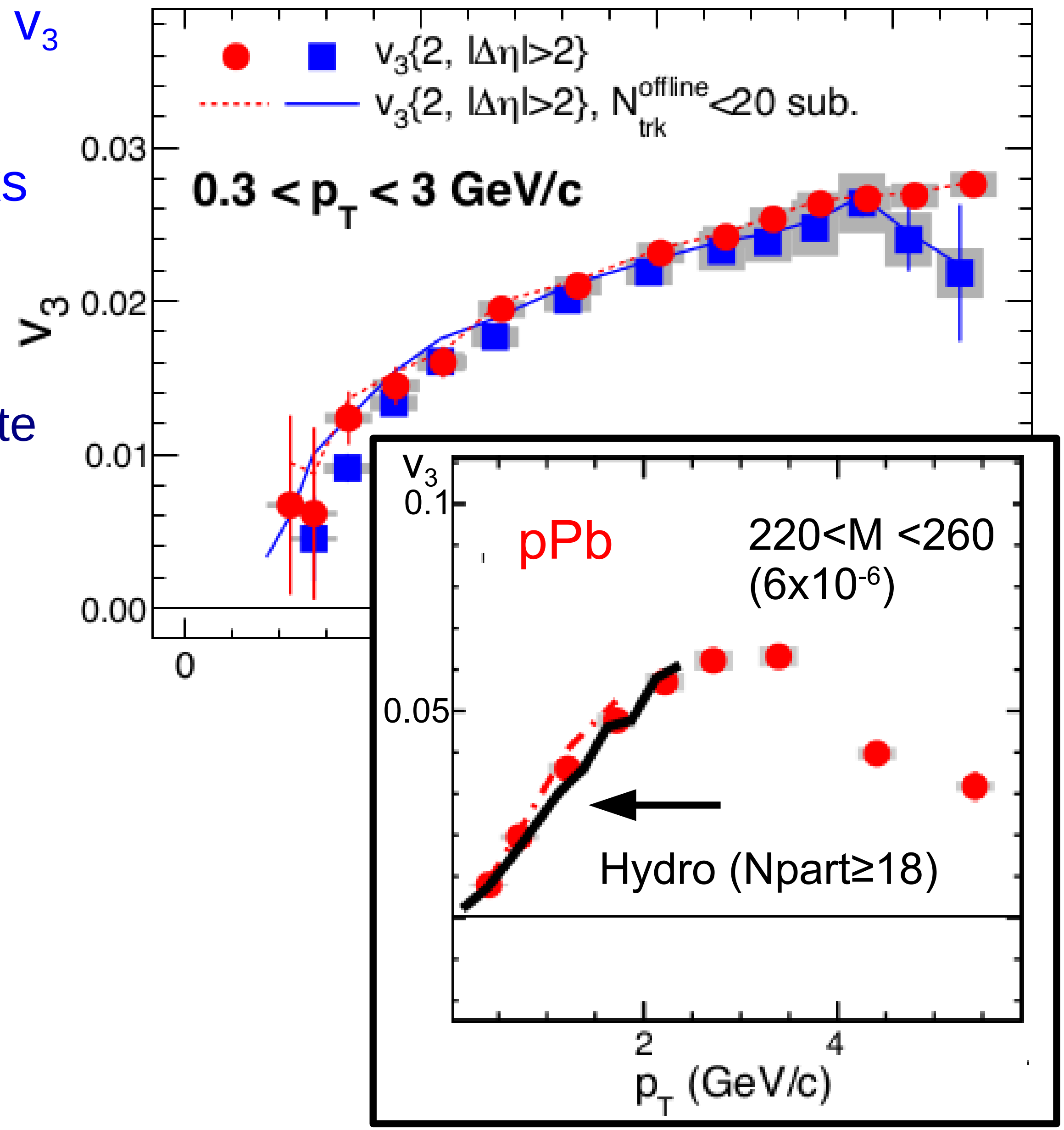


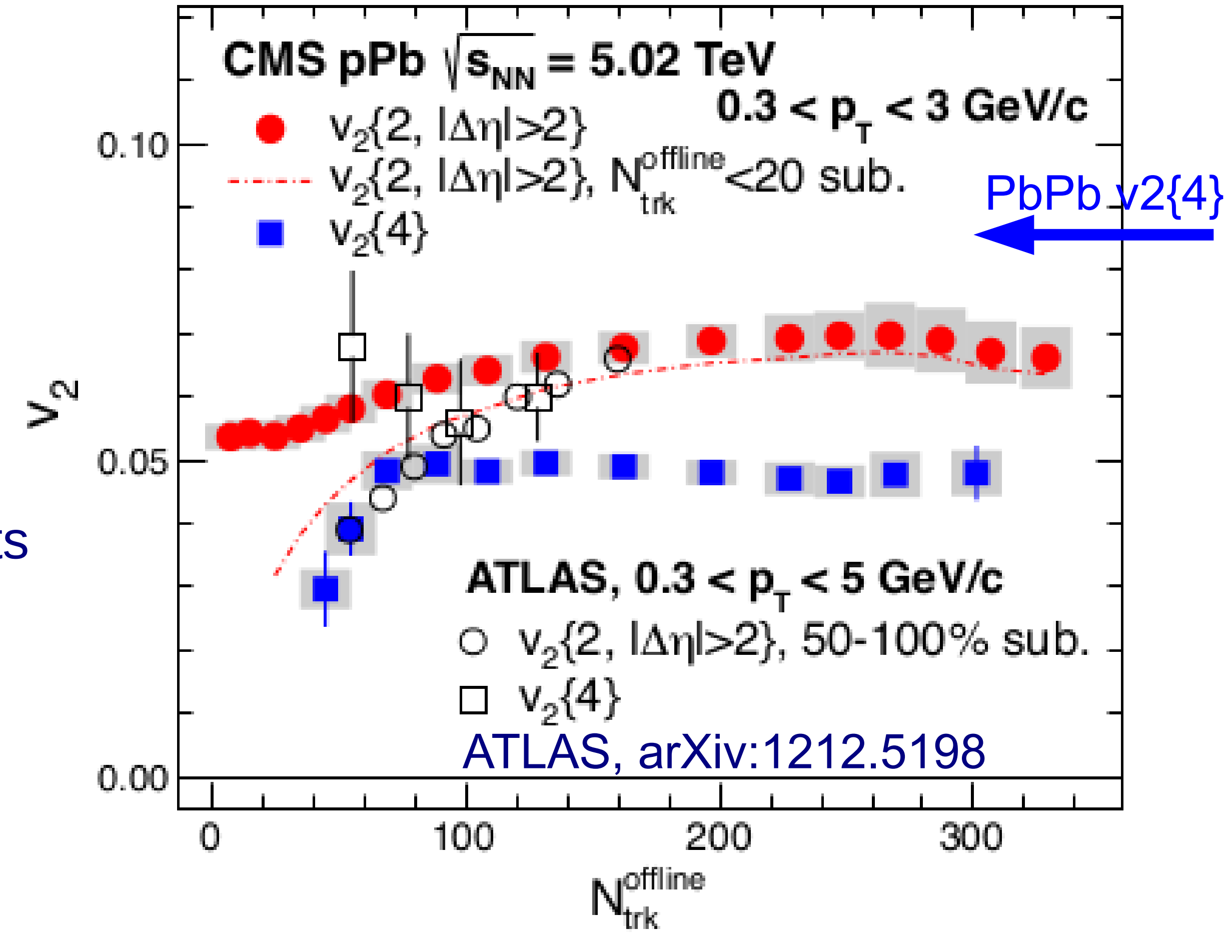


- Hydrodynamical predictions (4.4 TeV, arXiv:1112.0915) consistent with pPb data

Multi-particle correlations in pPb: $v_2\{4\}$

- Using four particle angular correlations subtracting those from two particles
- Genuine four particle correlations present in pPb
  - Turn-on at around M=50 offline tracks
  - Difference to ATLAS points at low M probably due to multiplicity fluctuations
  - Magnitude smaller than in PbPb

CMS, arXiv:1305.0609



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  - Magnitude smaller than in PbPb
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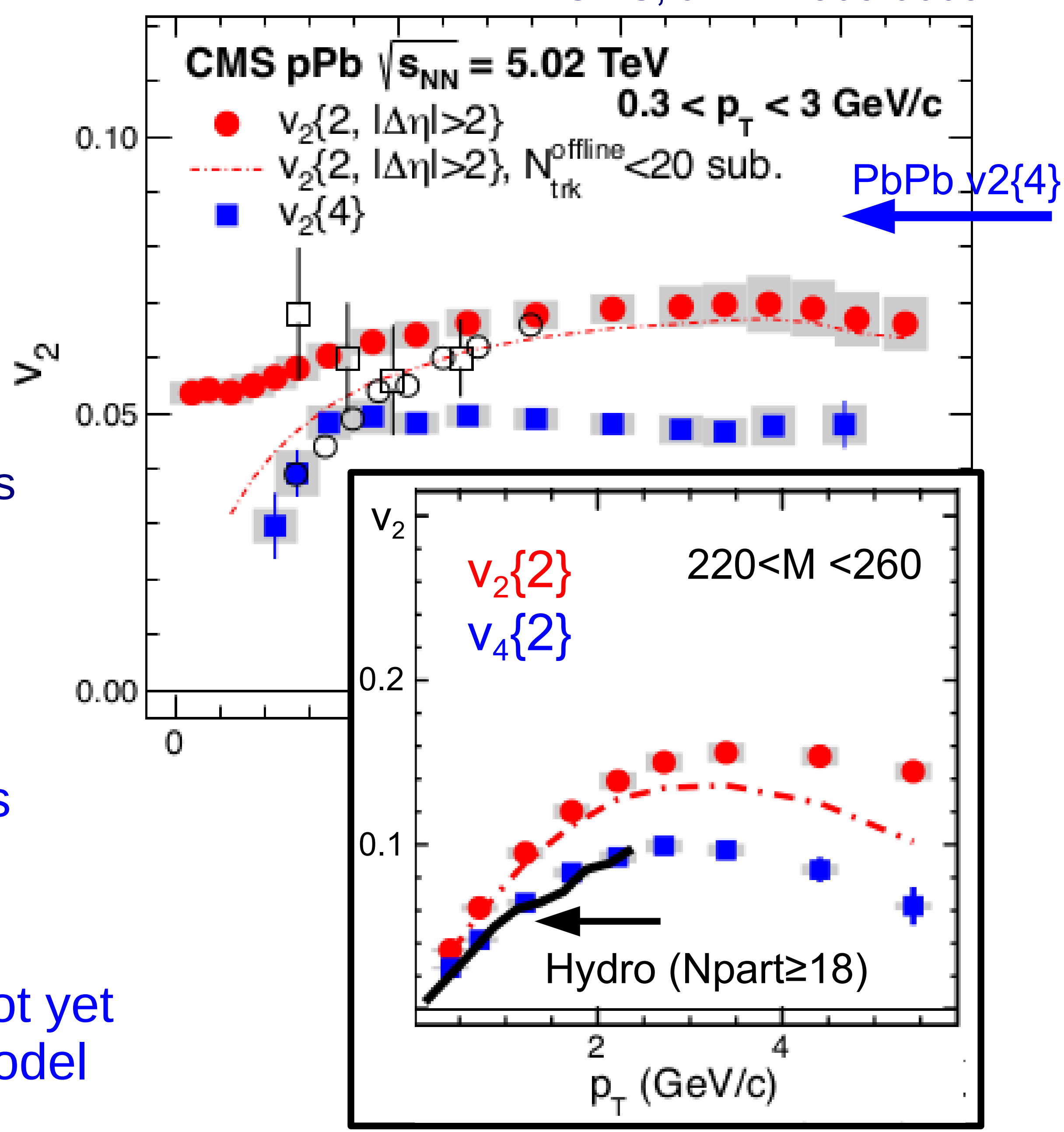
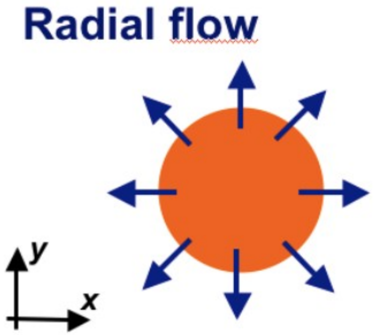
- Higher order correlations not yet included in CGC glasma model

CMS, arXiv:1305.0609



Identified particle spectra



$$p_T^{flow} = p_T + m\beta_T^{flow}\gamma_T^{flow}$$

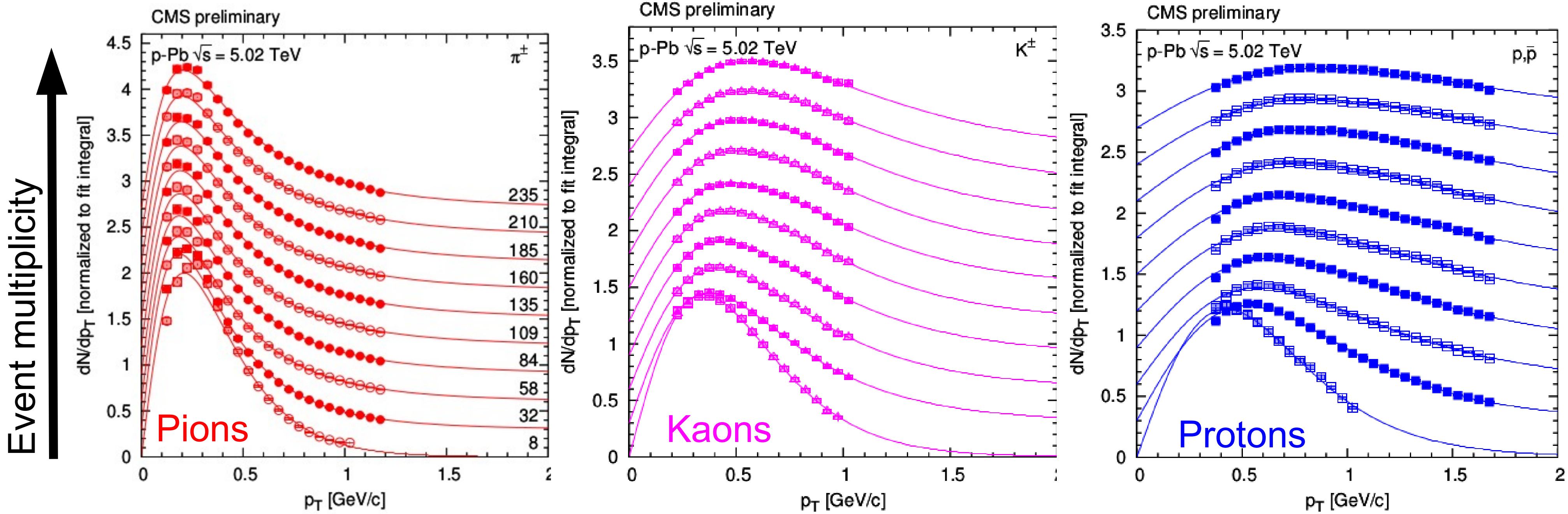
Radial flow expected to be built up and reflected in spectra, in particular in p/π ratio

Shuryak and Zahed, arXiv:1301.4470

(see M. Floris, Tuesday)

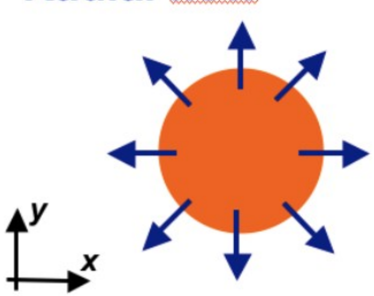
Identified particle spectra

CMS-PAS-HIN-12-016



- Spectra measured in bins of multiplicity
  - For kaons and more for protons shape changes with increasing multiplicity

Radial flow



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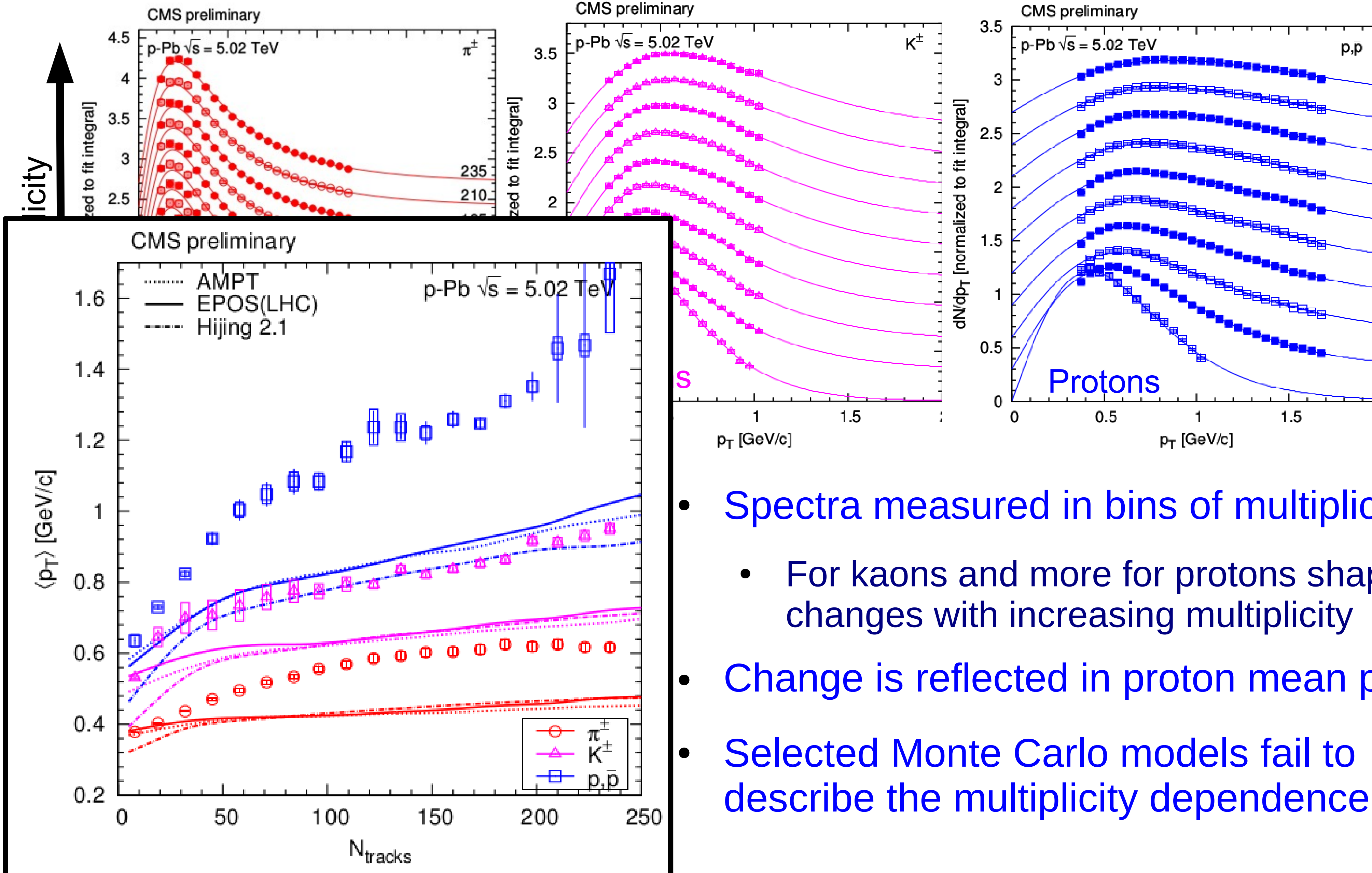
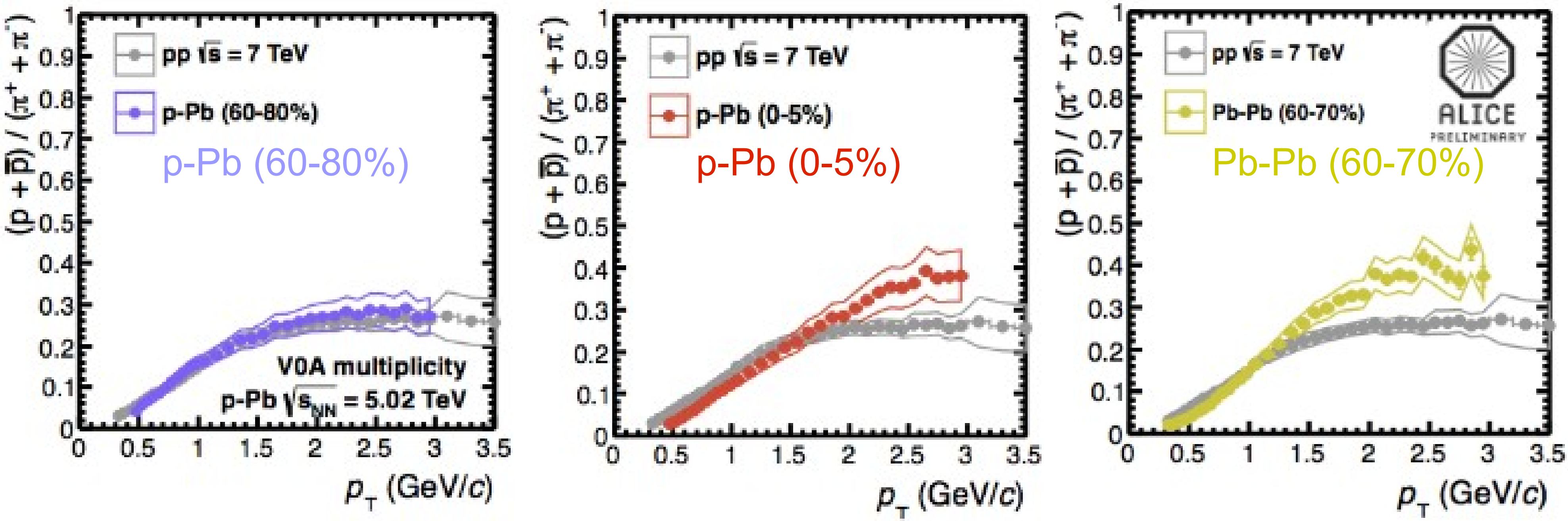


- Spectra measured in bins of multiplicity
  - For kaons and more for protons shape changes with increasing multiplicity
- Change is reflected in proton mean p_T
- Selected Monte Carlo models fail to describe the multiplicity dependence

Proton-to-pion ratio

Systematic errors are largely correlated across multiplicity

ALICE preliminary (Trento)



- Ratio shows similar p_T dependence as observed in PbPb
  - Significant increase at intermediate with increasing V0A multiplicity
  - Corresponding significant depletion in the low-p_T region
- Dependence in Pb-Pb usually explained by radial flow
  - Dependence in pPb qualitatively as expected by eg. Shuryak and Zahed, arXiv:1301.4470

Λ/K^0_s ratio versus p_T

- Clear evolution of Λ/K^0_s ratio with increasing V0A multiplicity
- Also this is reminiscent of a similar trend observed in AA

ALICE preliminary (Trento)

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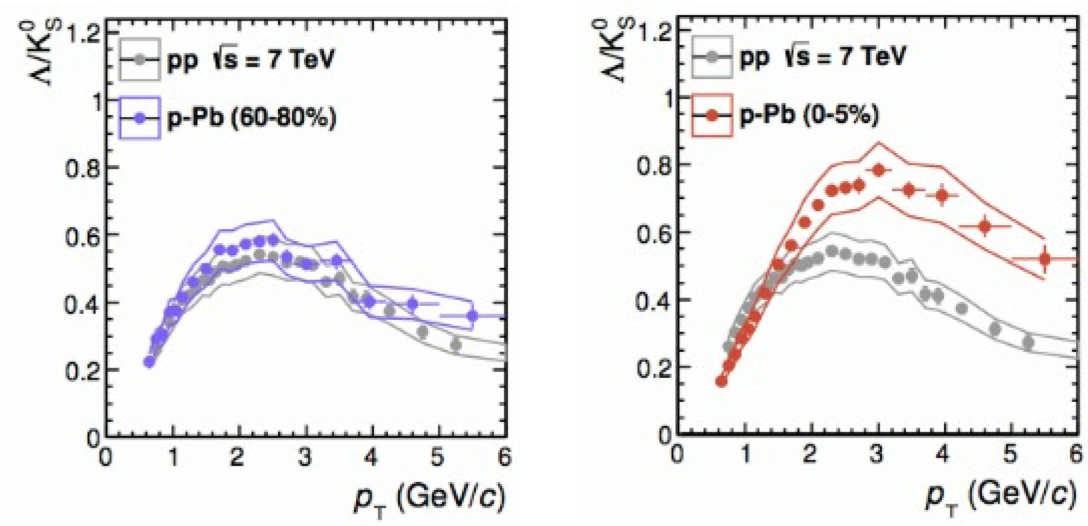
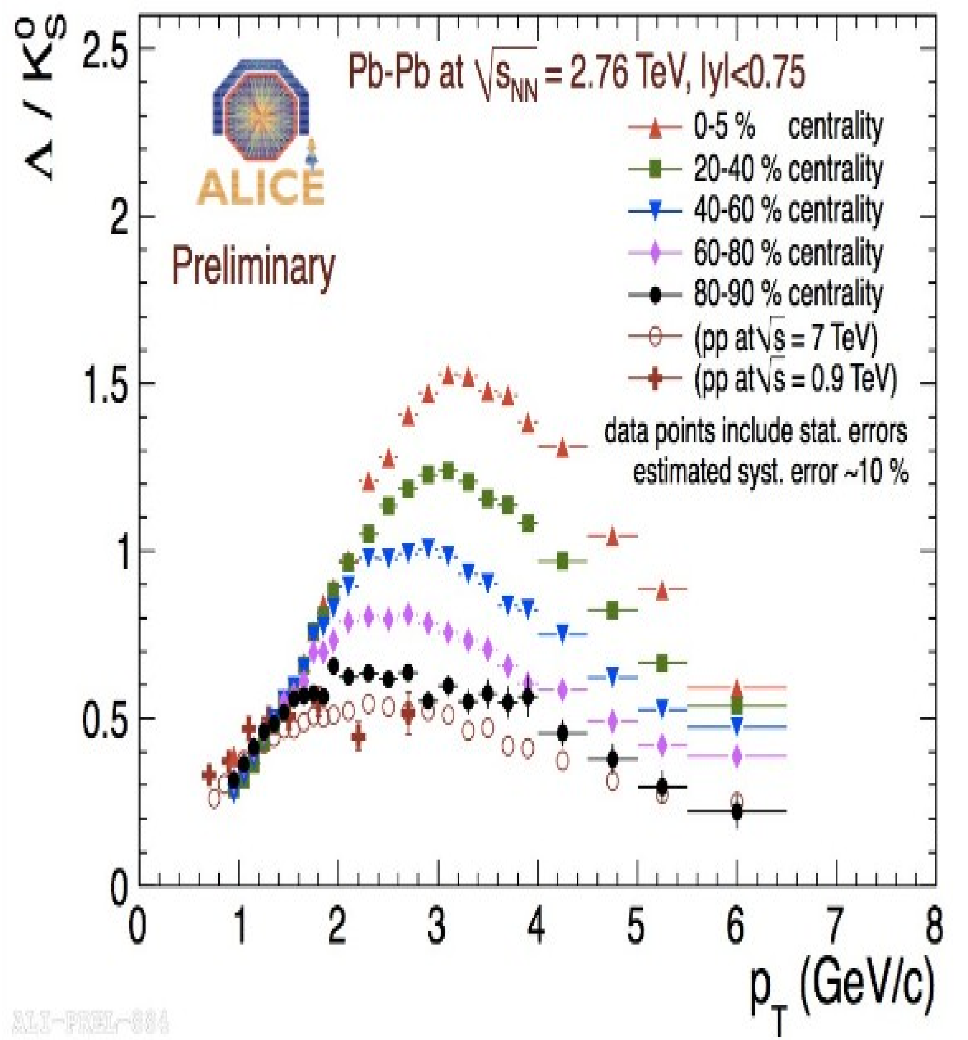
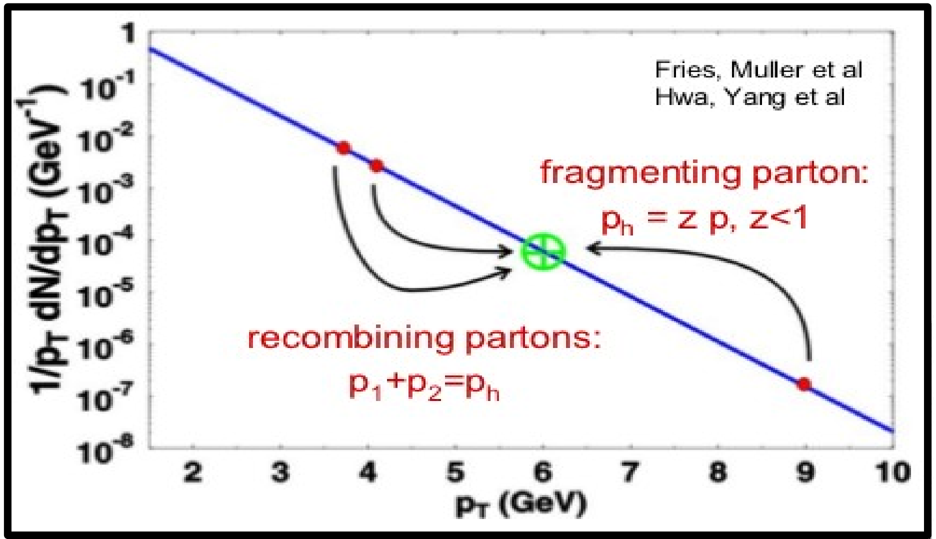
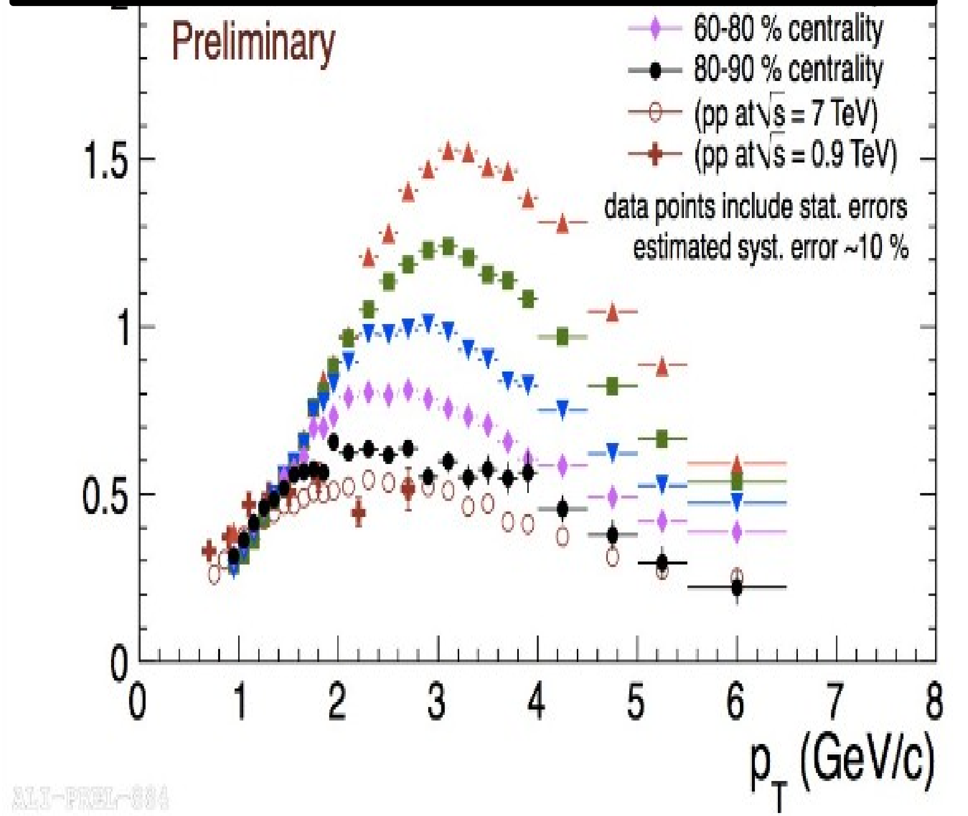




Λ/K^0_s ratio versus p_T

- Clear evolution of Λ/K^0_s ratio with increasing V0A multiplicity
- Also this is reminiscent of a similar trend observed in AA
- In AA this is generally explained by collective flow and parton recombination





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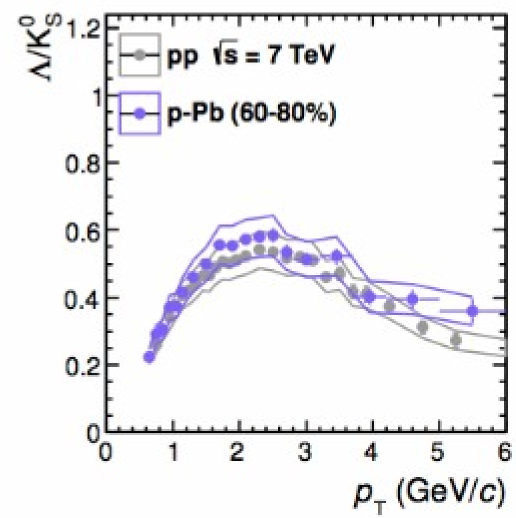
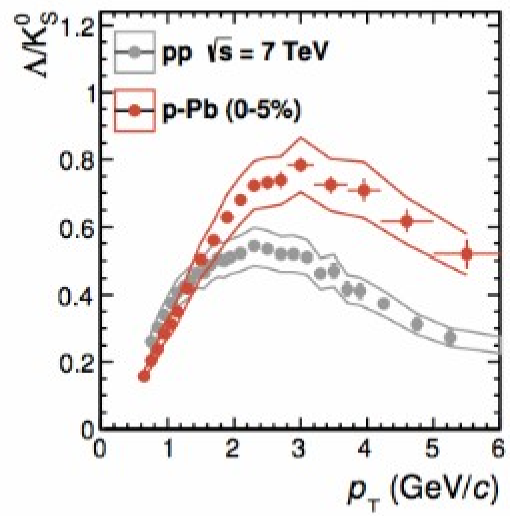
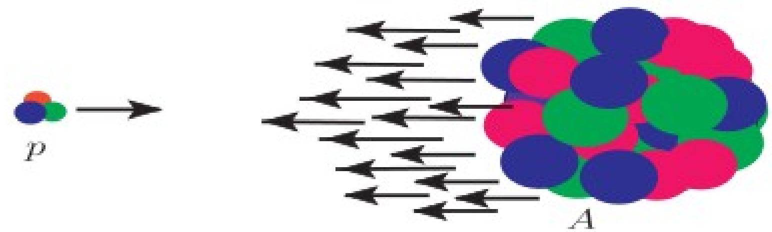




Which one have we seen?

Proton on lead collisions is like shooting a bullet through a glass



Color–Glass–Condensate in pPb

Saturation

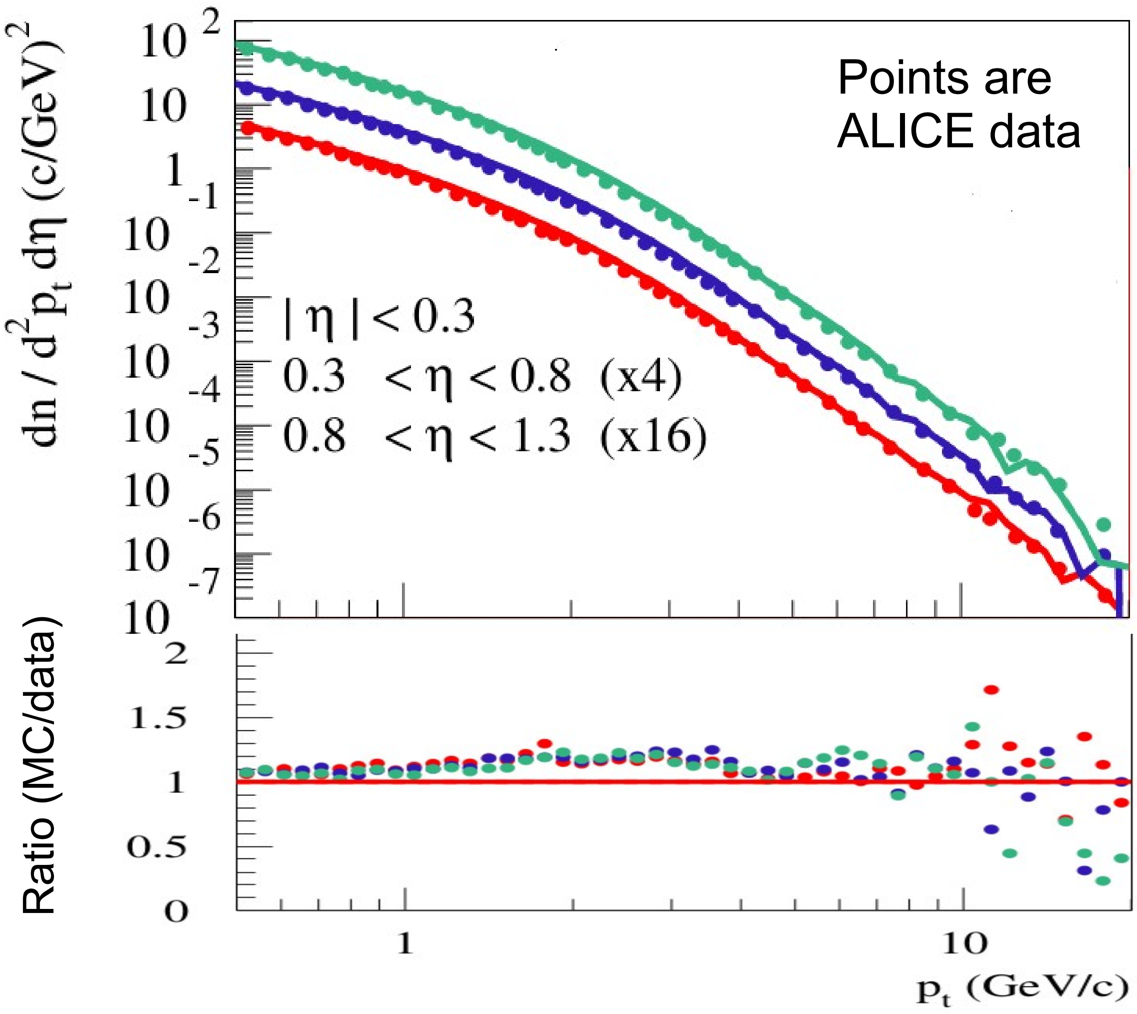
Collective flow in pPb collisions

Collectivity

(adapted from A. Rezaeian)

Which one have we seen?

Werner et al., EPOS3 (Trento)

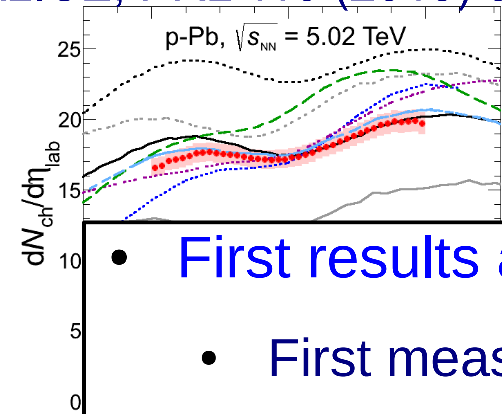


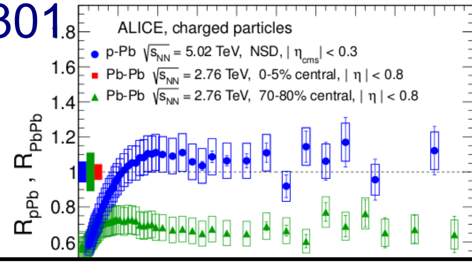
- EPOS version 3
  - Gribov-Regge multiple scattering ansatz plus energy-momentum conservation with fixed scale breaks binary scaling
  - Introduction of ladder-by-ladder dependent saturation scale restores binary scaling
  - Integration of 3D viscous hydrodynamics allows to also describe low-p_T region

Probably aspects of both!

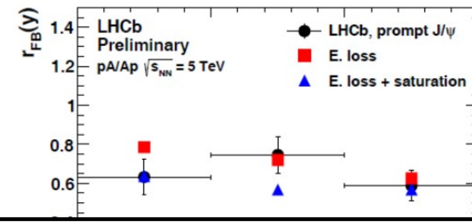
Summary

ALICE, PRL 110 (2013) 032301

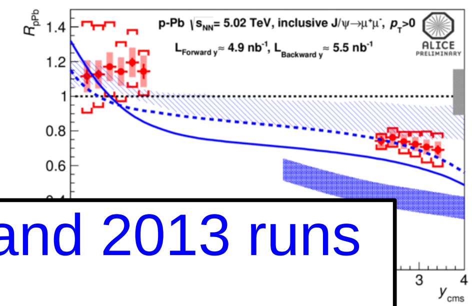




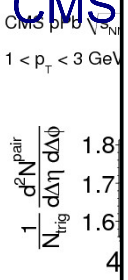
LHCb-CONF-2013-008



ALICE prel. (Trento)

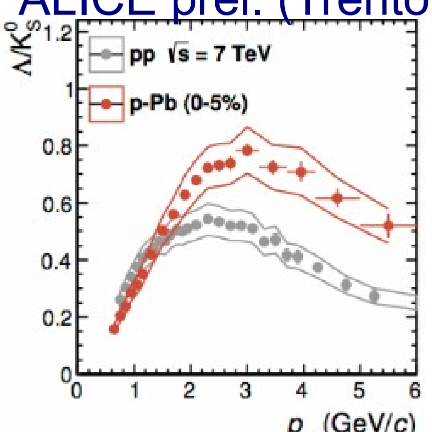


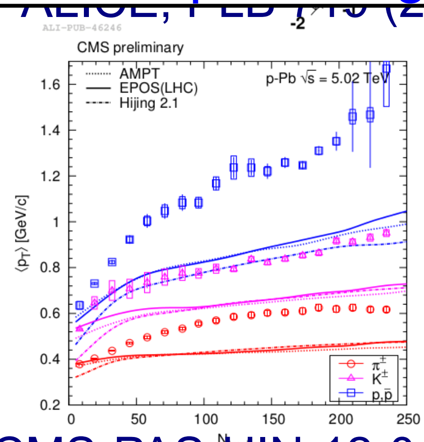
CMS



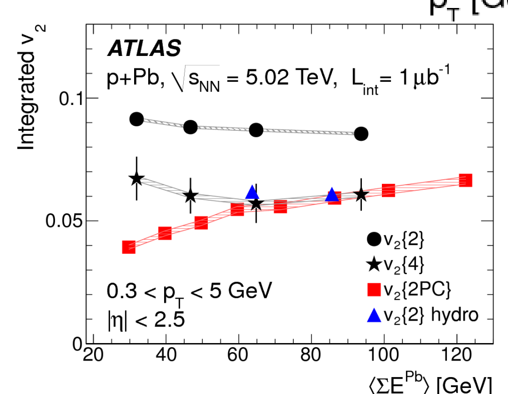
- First results and surprises already from the pPb 2012 and 2013 runs
  - First measurements (Unidentified and identified spectra, J/psi, Dijet)
    - More work needed (eg. diffraction, fluctuations and centrality)
  - Two-particle correlation and PID results imply interesting debate of the role of initial and final state effects in pPb
    - More experimental results needed (eg. identified v_2, HBT, R_{pPb} vs cent.)
- Thanks to LHC for a very successful 2013 pPb run, and to the collaborations for providing beautiful results so quickly

ALICE prel. (Trento)



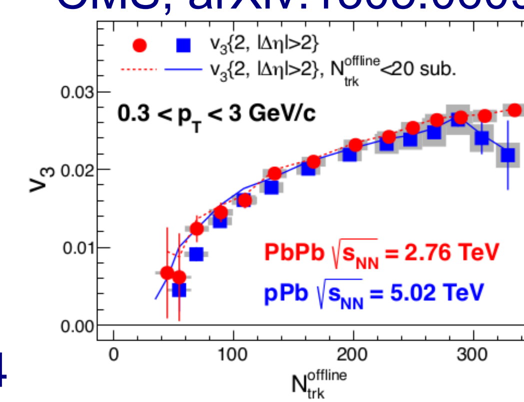


CMS-PAS-HIN-12-016



ATLAS, arXiv:1303.2084

CMS, arXiv:1305.0609



Extra

LHC pPb runs at 5.02 TeV

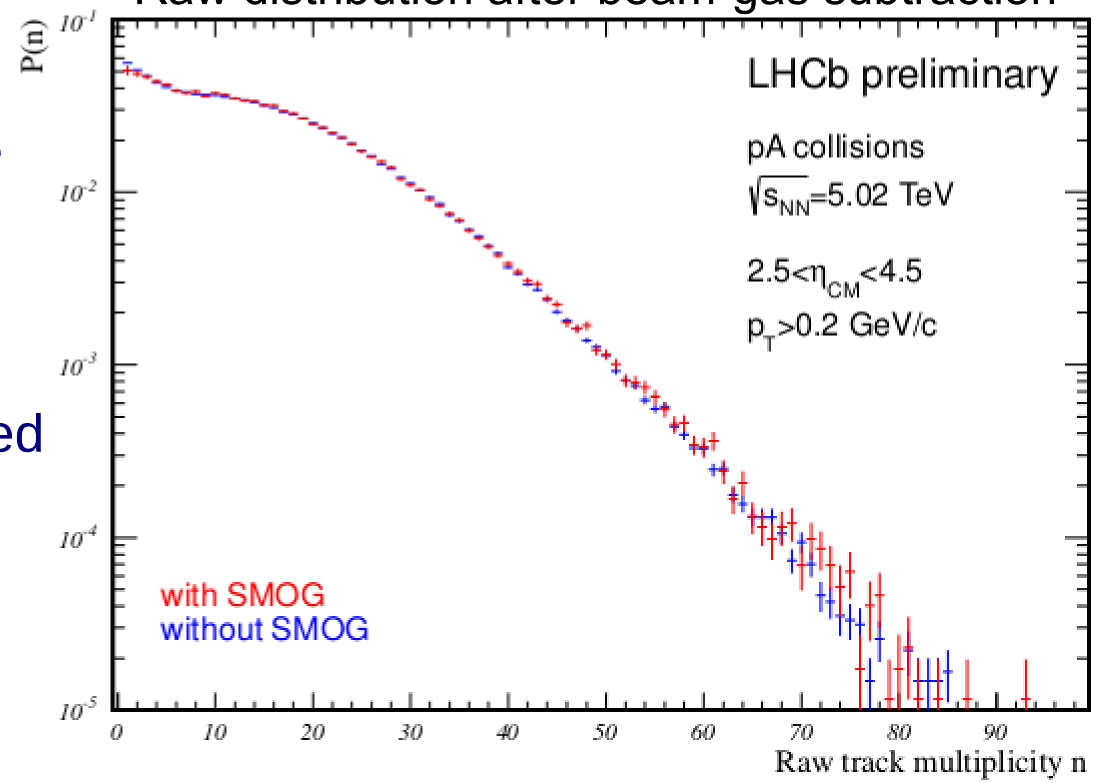
- LHC operated with
  - 4 TeV proton beam and 1.57 TeV / nucleon Pb beam
    - Center of mass energy 5.02 TeV per nucleon pair
    - Center of mass per nucleon pair rapidity shift dY = 0.465 in direction of proton
- 2012 pilot run (4 hours of data taking)
  - About 1/µb per experiment with very low pileup
- 2013 long run (3 weeks of data taking)
  - Delivered about 30/nb to ATLAS, CMS and ALICE
    - ALICE recorded also about 50/µb with $\mu<0.003$ (for the rest $\mu<0.05$) (check numbers)
    - Few 1/nb for LHCb (new to heavy-ion operation)
  - Beam reversal (relevant for ALICE and LHCb) for about half of statistics
  - Van der Meer scans in both beam configuations
- No pp reference data available at 5.02 TeV
  - Use scaled results pp collisions at 2.76, 7 and 8 TeV and/or models

Inelastic pPb cross section

- Count collisions which produce at least one track in 2.5<η<4.5 (proton side) with p_T>0.2 GeV/c
  - In HIJING/DPMJET only 1-2% events without a charged particle
- Analysis steps
  - Beam gas subtraction
  - Pileup below permille level ignored
  - Trigger efficiency 100% ±1%
  - Correction for finite single track finding efficiency: 98% ± 2%
  - Convert using integrated luminosity measured with SMOG
  - Systematic uncertainty dominated by 5.2% error on luminosity

LHCb, CERN-LHCb-CONF-2012-034

Raw distribution after beam-gas subtraction



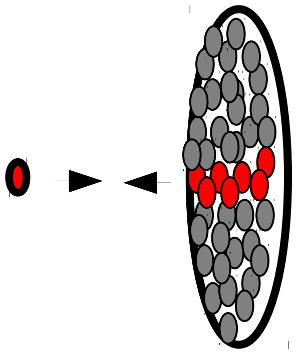
$$\sigma_{inel}(2.5 < \eta_{cm} < 4.5,\ p_T > 0.2\,\mathrm{GeV}/c) = 2.09 \pm 0.12\,\mathrm{b}$$

(consistent with HIJING, DPMJET and Glauber with σ_{NN}=70mb)

NSD pPb normalization

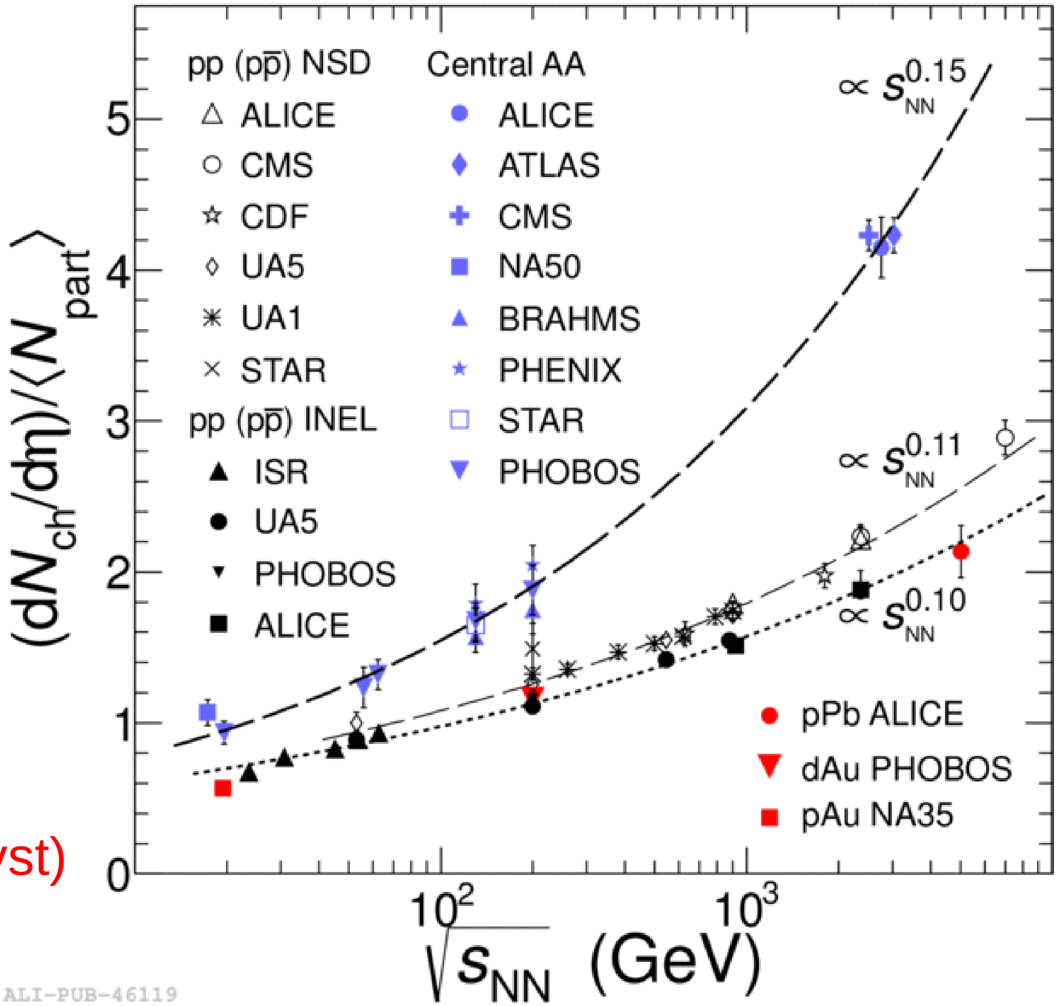
ALICE, PRL 110 (2013) 032301

- Event selection
  - VZERO-A (2.8<η<5.1) and VZERO-C (-3.7<η<-1.7) incl. time cuts
  - Systematic variation using ZDC on nucleus side (ZNA)



- Resulting event sample
  - Non single-diffractive (NSD)
    - At least one binary N+N interaction is NSD (Glauber picture)
    - Inspired from DPMJET, which includes incoherent SD of the projectile with target nucleons that are mainly concentrated on the surface of the nucleus
    - SD about 4% from HIJING, DPMJET or standalone Glauber
  - Negligible contamination from SD and EM processes
- Validated with a cocktail of generators
  - DPMJET for NSD (2b)
  - PHOJET + Glauber for incoherent SD part (0.1b)
    - SD/INEL = 0.2 in pp at 7 TeV (arXiv:1208.4968)
  - EM with STARLIGHT (0.1-0.2b)

ALICE, PRL 110 (2013) 032301



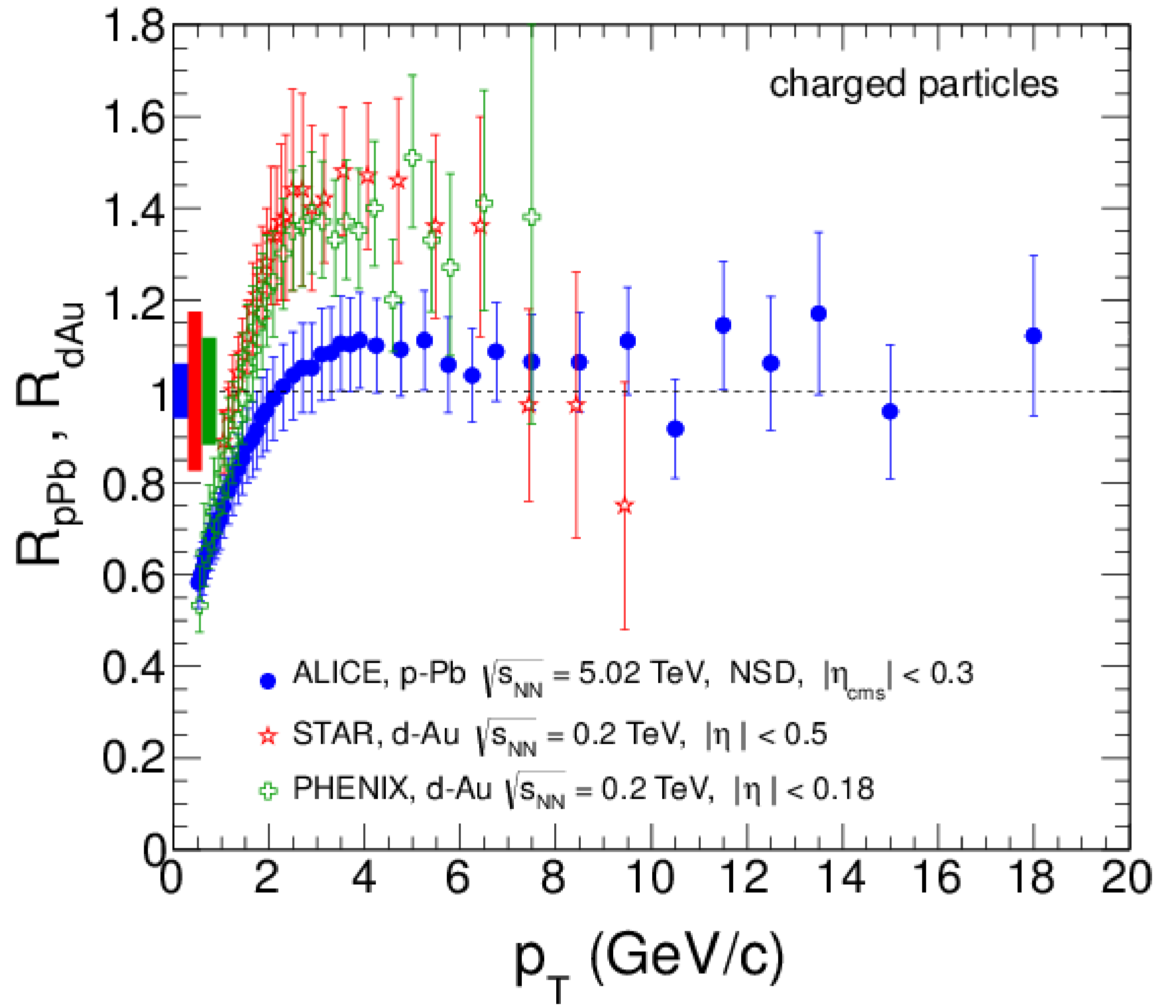
- Measurement (tracklet based)
  - dN/dη = 16.81 ± 0.71 (syst)
  - Converted into centre-of-mass system using HIJING
  - Dominant uncertainty from NSD normalization of 3.1%
- Glauber model for pPb
  - With σ_{INEL}= 70 ± 5 mb
  - <Npart> = 7.9 ± 0.6 (syst)
- Participant scaled value
  - (dN/dη)/<Npart> = 2.14 ± 0.17 (syst)
  - About 15% below NSD pp
  - Similar to pp INEL
- Inelastic pPb would be 4% lower (estimate from models)

Cronin effect at RHIC and LHC

ALICE, PRL 110 (2013) 082302
STAR, PRL 91 (2003) 072304
PHENIX, PRL 91 (2003) 072030

$$R_{AB} = \frac{\mathrm{d}N_{AB}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

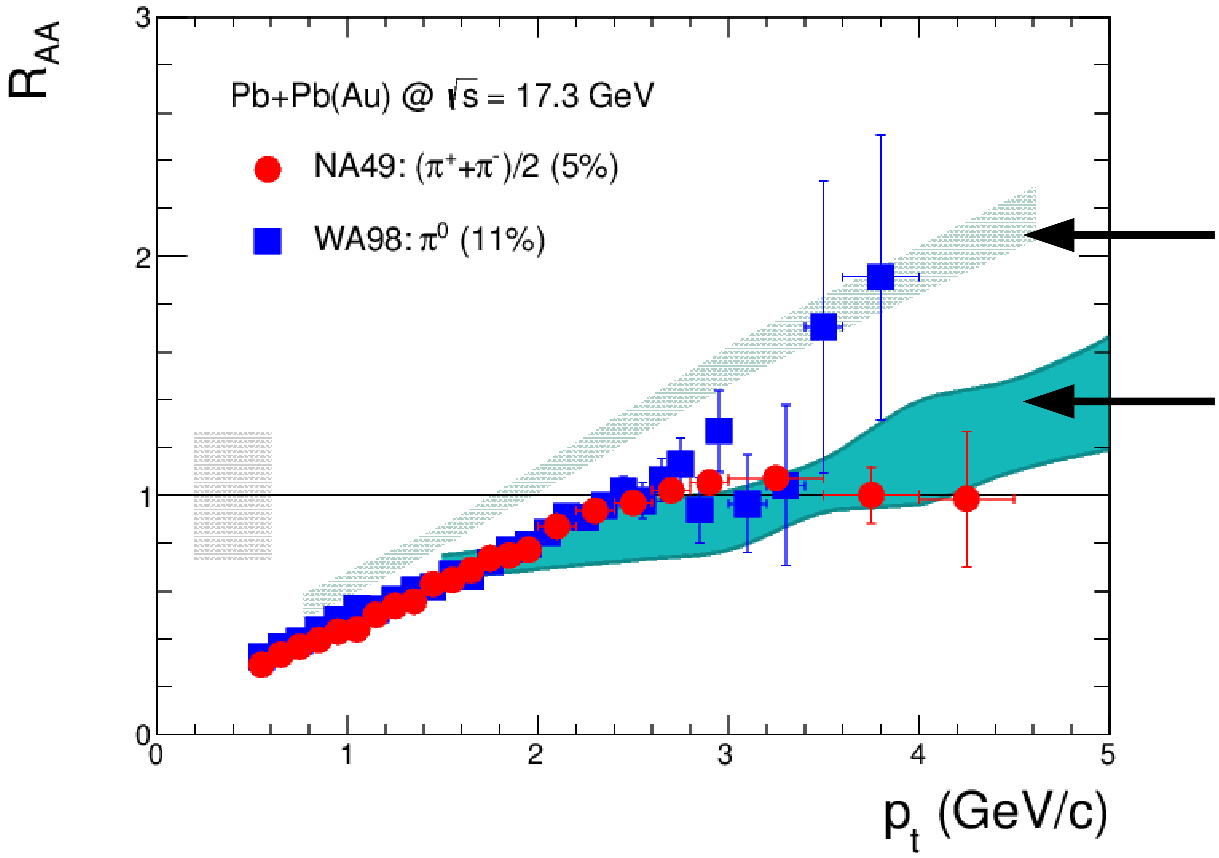
- $R_{AB} > 1$ at intermediate p_T observed in dAu collisions at RHIC typically attributed to Cronin effect
- No enhancement seen in pPb at the LHC
- No Cronin effect?



Cronin effect at SPS

- Reminder from SPS energies: RAB ≈ 1 does not necessarily imply absence of effects

NA49, NPA 783 (2007) 65
WA98, PRL 89 (2002) 252301



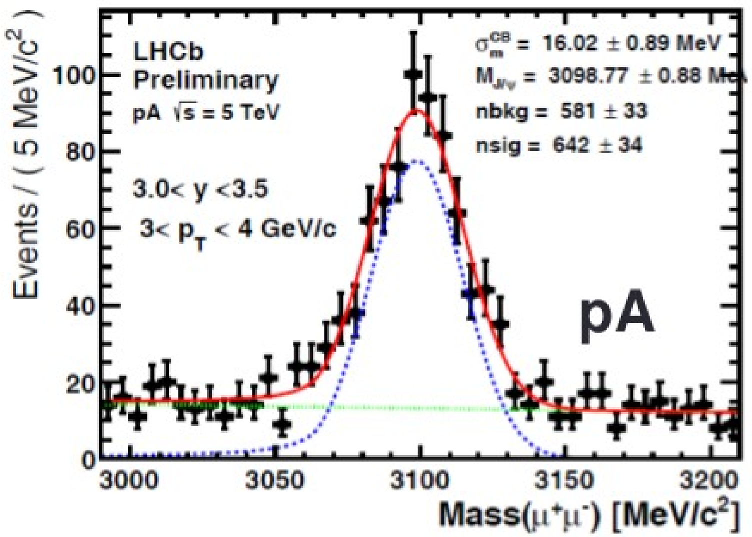
Calculation taking into account:

Cronin effect + shadowing

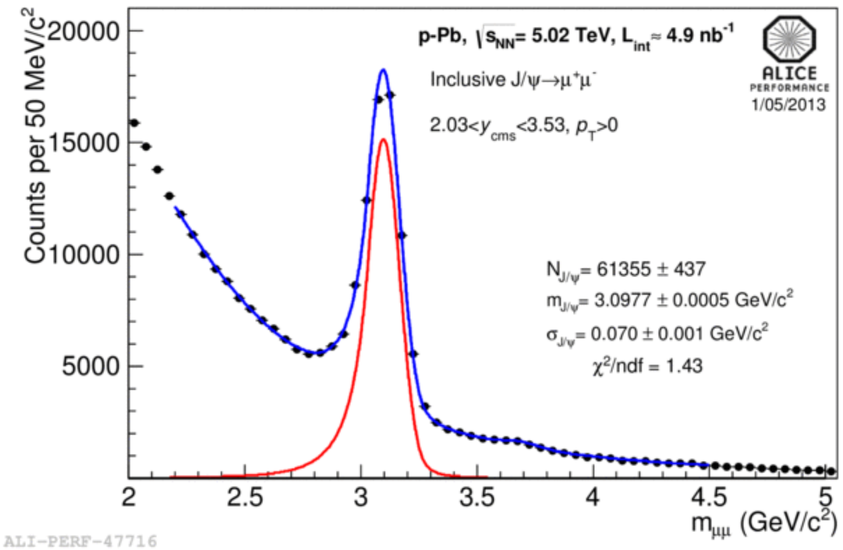
Cronin effect, shadowing plus partonic energy loss

- Model comparisons are required to understand R_{pPb} at the LHC

LHCb-CONF-2013-008



ALICE (Trento)

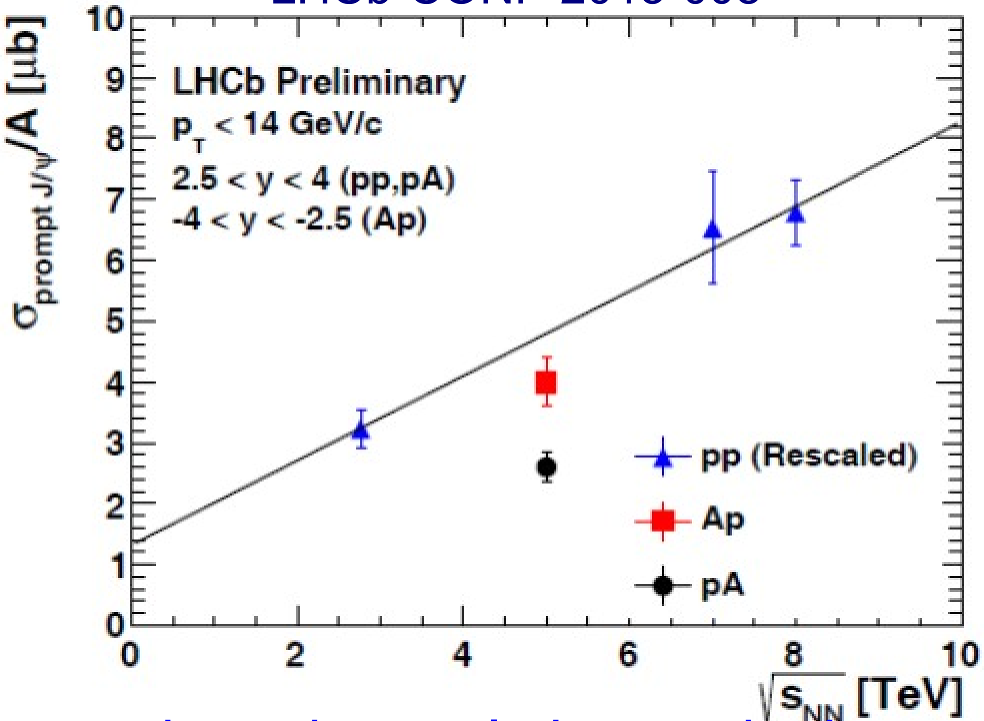


- Extraction of prompt J/psi and J/psi from b decays using simultaneous fit of mass and pseudo-proper time
- Obtain (total) cross sections
  - Forward: 1.5<y<4.0 (0.75/nb)
  - Backward: -5.0<y<-2.5 (0.3/nb)
  - p_T<14 GeV/c

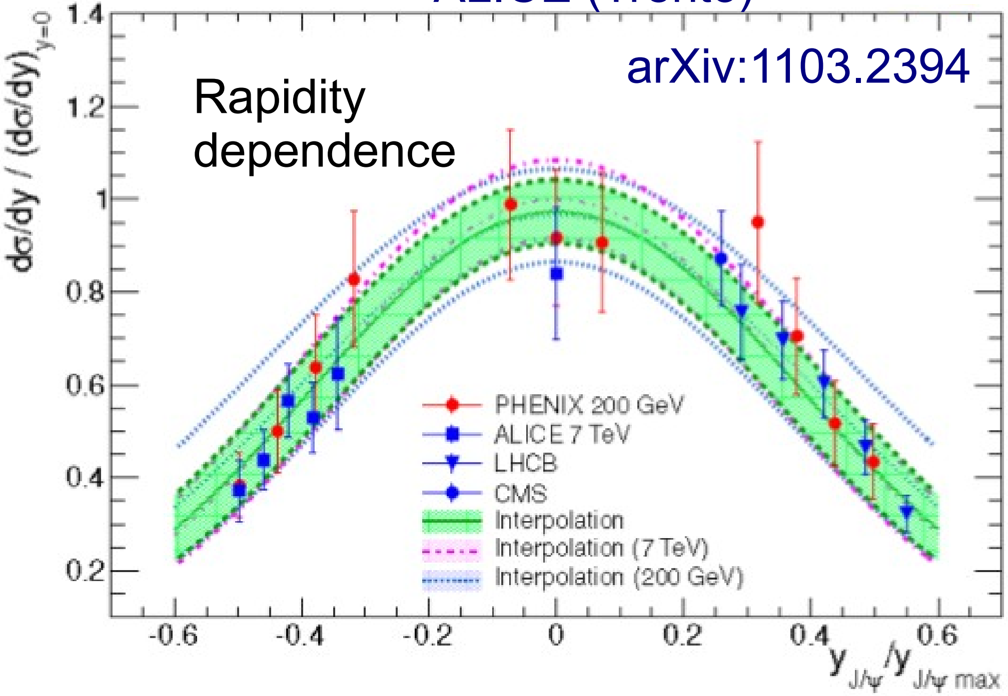
- Extraction of inclusive J/psi using Crystal Ball as signal and exponential plus polynomial as background
- Obtain invariant yields
  - Forward: 2.03<y<3.53 (~4.9/nb)
  - Backward: -4.46<y<-2.96 (~5.5/nb)
  - p_T<15 GeV/c

J/ψ interpolated pp reference

LHCb-CONF-2013-008



ALICE (Trento)



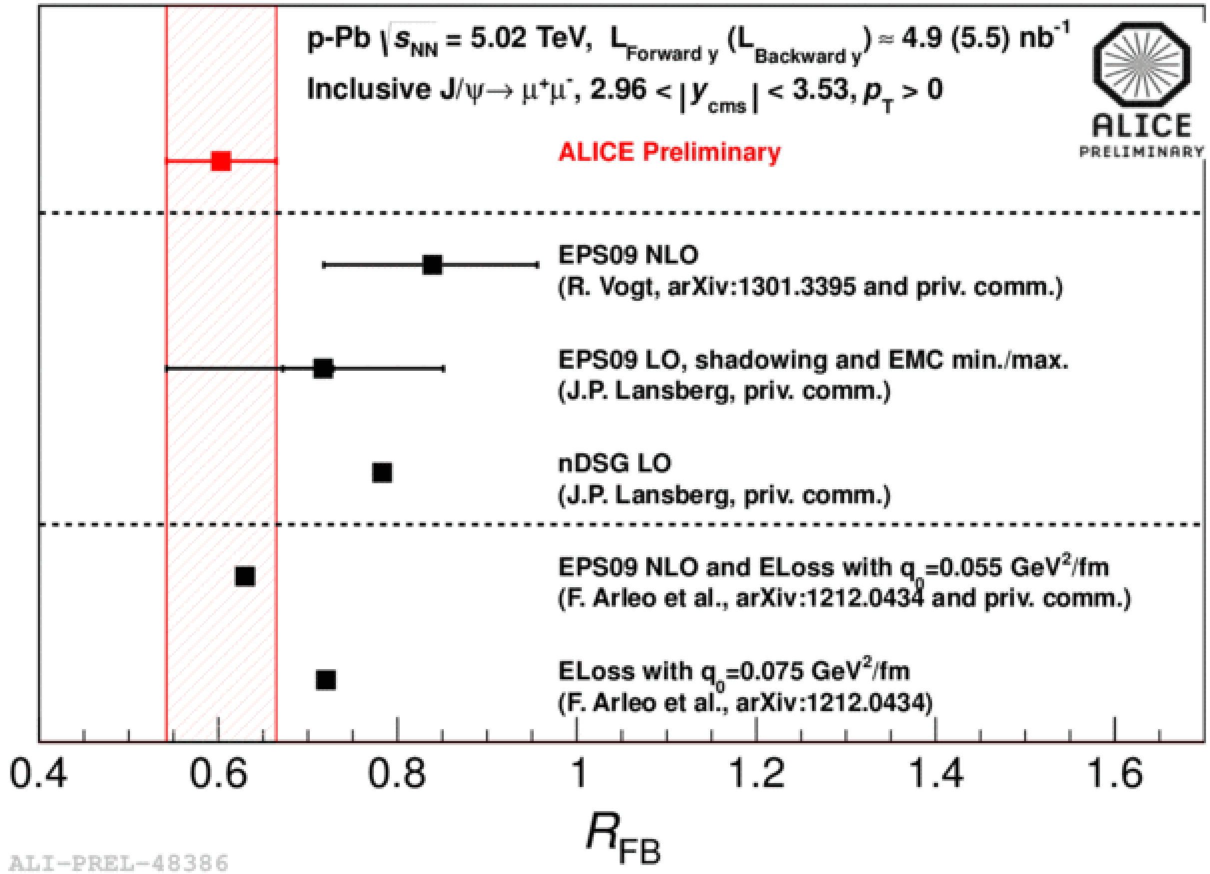
- Linear interpolation to obtain prompt J/psi cross section in pp at 5.02 TeV
- Clear suppression in pPb, while moderate in Pbp

LHCb and ALICE interpolations are consistent within large uncertainties. Need pp reference run at 5.02 TeV!

- Interpolation between RHIC, CDF and LHC data based on phenomenological shape for the inclusive J/psi cross section
  - $d\sigma/dy=3.85\pm0.68\ \mu b^{-1}$ (2.03<y<3.53)
  - $d\sigma/dy=2.65\pm0.66\ \mu b^{-1}$ (-4.46<y<-2.96)
- Consistent with FONLL and CEM

Forward-backward asymmetry

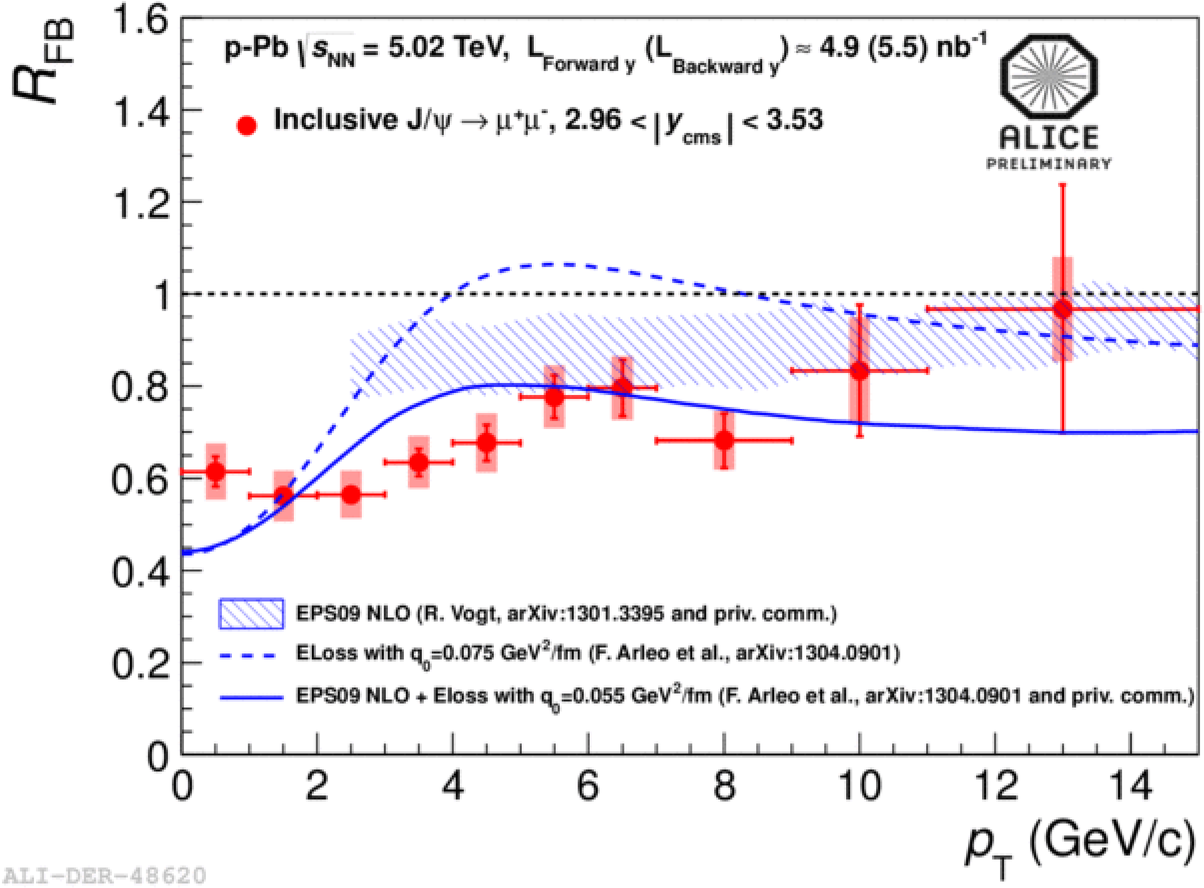
Inclusive J/psi, ALICE preliminary (Trento)



- Forward-to-backward ratio in the range 2.96<|y|<3.53
  - R_{FB} = 0.60 ± 0.01 (stat) ± 0.06 (syst)
  - Free of uncertainty from pp reference
- Pure saturation models seem to overestimate the ratio

Forward-backward asymmetry

Inclusive J/psi, ALICE preliminary (Trento)



- p_T dependence of forward-to-backward ratio in common 2.96<|y|<3.53
  - Ratio increases with increasing p_T
  - Provides additional constraints for models

DHC: Correlation measure

ALICE, PLB 719 (2013) 29

- Associated yield per trigger particle (with $p_T^{trig} > p_T^{assoc}$)

$$\frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm assoc}}{{\rm d}\Delta\eta\, {\rm d}\Delta\varphi} = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}$$

- Signal (same event) pair yield

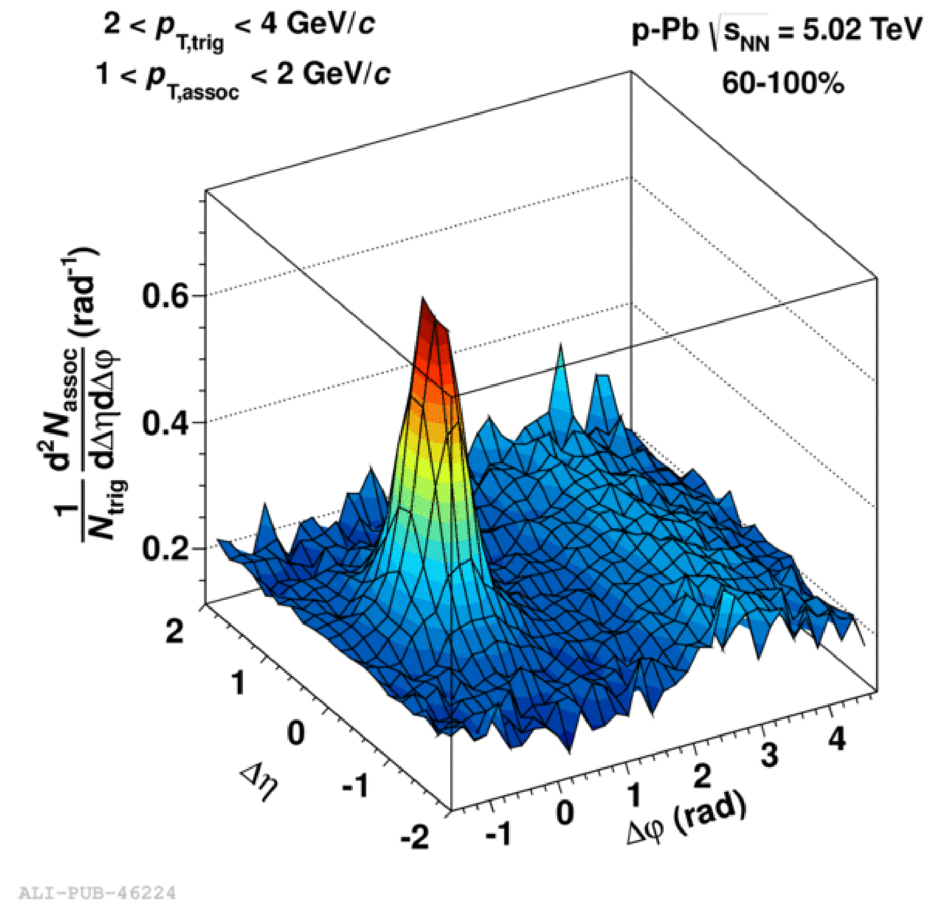
$$S(\Delta\eta, \Delta\varphi) = \frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm same}}{{\rm d}\Delta\eta\, {\rm d}\Delta\varphi}$$

  - Definition as ratio of sums is multiplicity independent

$$\frac{N_{pair}}{N_{trig}} = \frac{\sum_{i=1}^{N_{evt}} \sum_{j=1}^{N^i_{source}} \frac{1}{2} n_{ij}(n_{ij}-1)}{\sum_{i=1}^{N_{evt}} \sum_{j=1}^{N^i_{source}} n_{ij}} = \frac{N_{evt}\langle N_{source}\rangle \frac{1}{2}\langle n(n-1)\rangle}{N_{evt}\langle N_{source}\rangle\langle n\rangle} = \frac{1}{2}\frac{\langle n(n-1)\rangle}{\langle n\rangle}$$

- Background (mixed event) pair yield

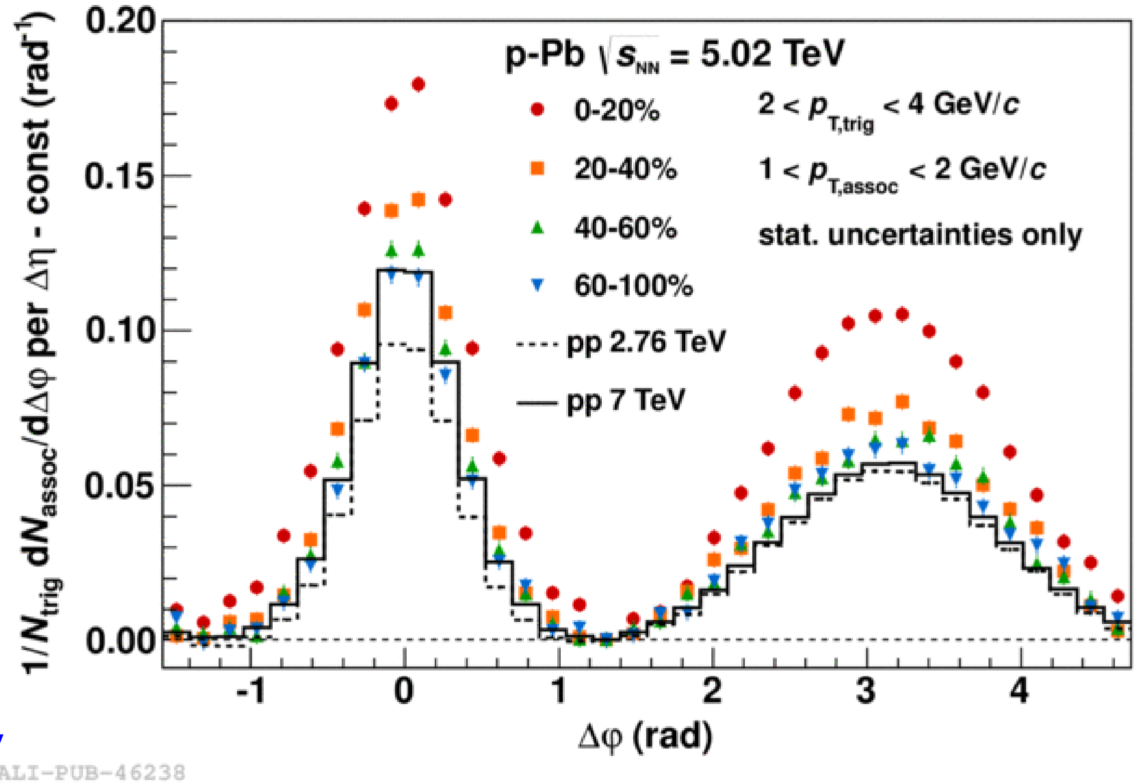
$$B(\Delta\eta, \Delta\varphi) = \frac{1}{B(0,0)} \frac{{\rm d}^2 N_{\rm mixed}}{{\rm d}\Delta\eta\, {\rm d}\Delta\varphi}$$



DHC: Multiplicity dependence

ALICE, PLB 719 (2013) 29

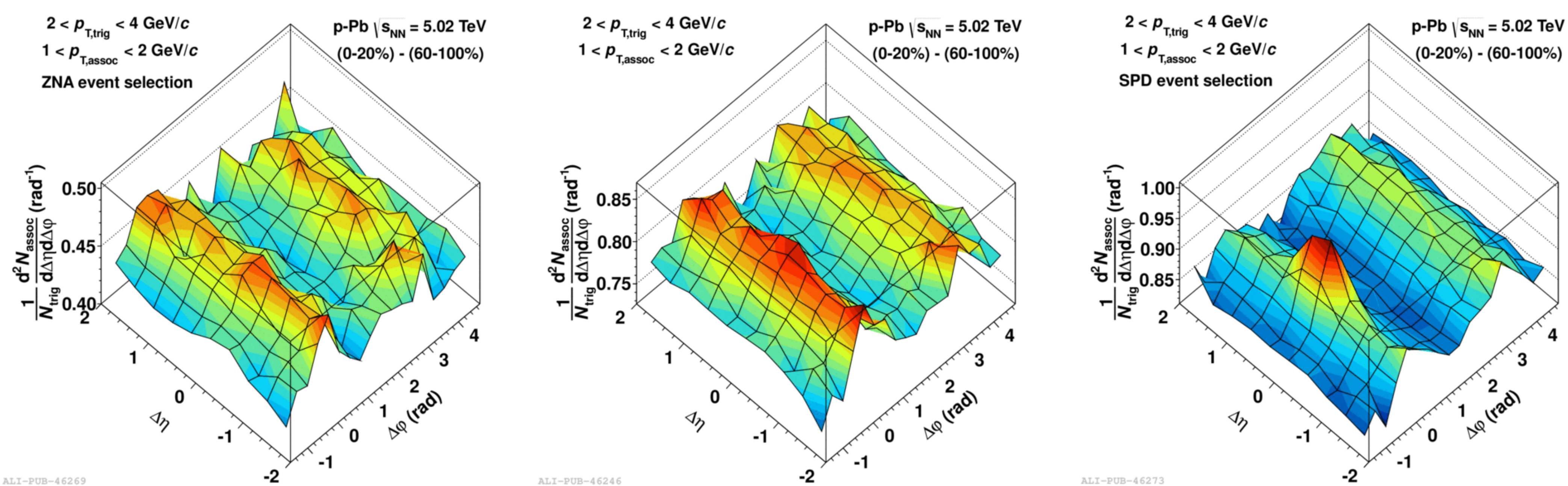
- Compare associated yield in pPb multiplicity classes and pp
  - Project to Δφ over |Δη|<1.8
  - Subtract baseline at Δφ~1.3
- Low multiplicity pPb is similar to pp (at 7 TeV)
- Yield rises on near and away side with increasing multiplicity
- In contrast with away-side suppression observed in dAu at RHIC at forward η (similar x)



DHC: Two ridges

ALICE, PLB 719 (2013) 29

- A residual jet peak at (0,0) remains even after subtraction of 60-100% from the 0-20% multiplicity class
- Compare effects using different event class definition

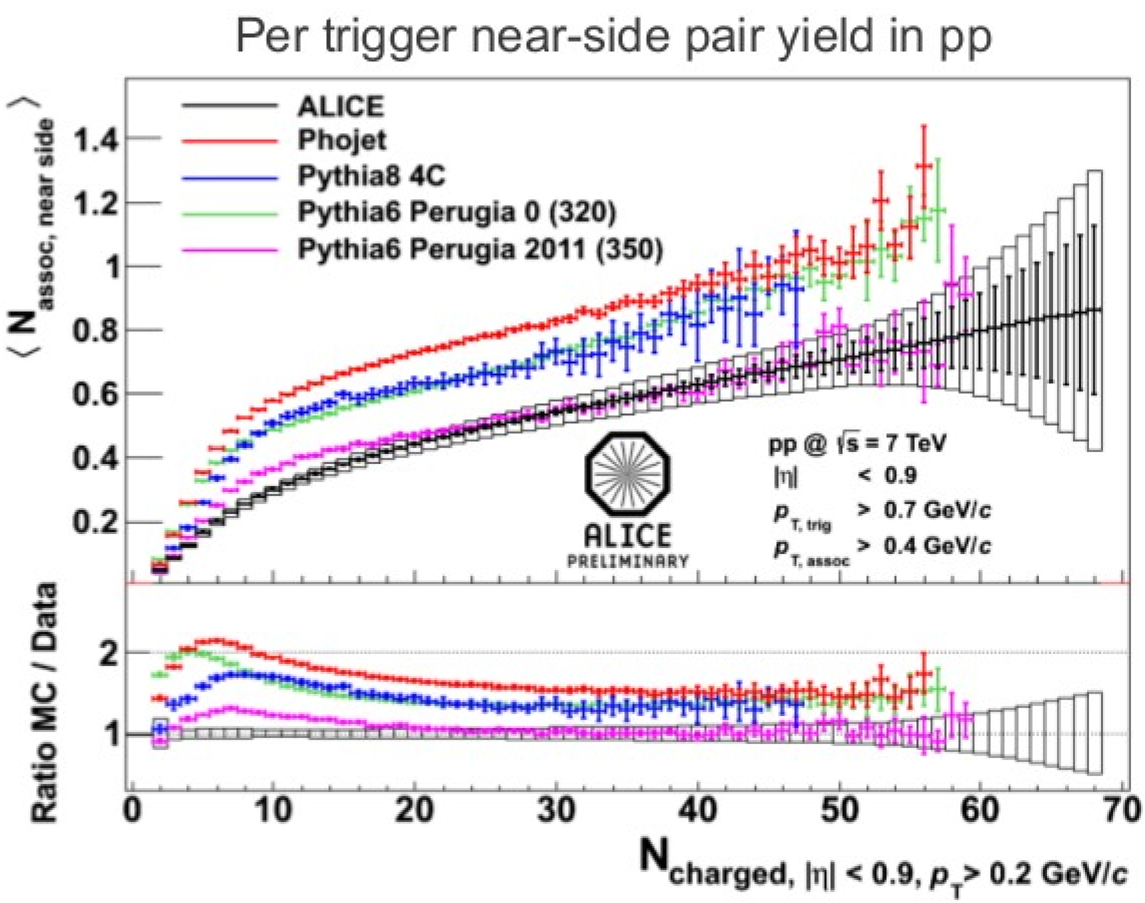


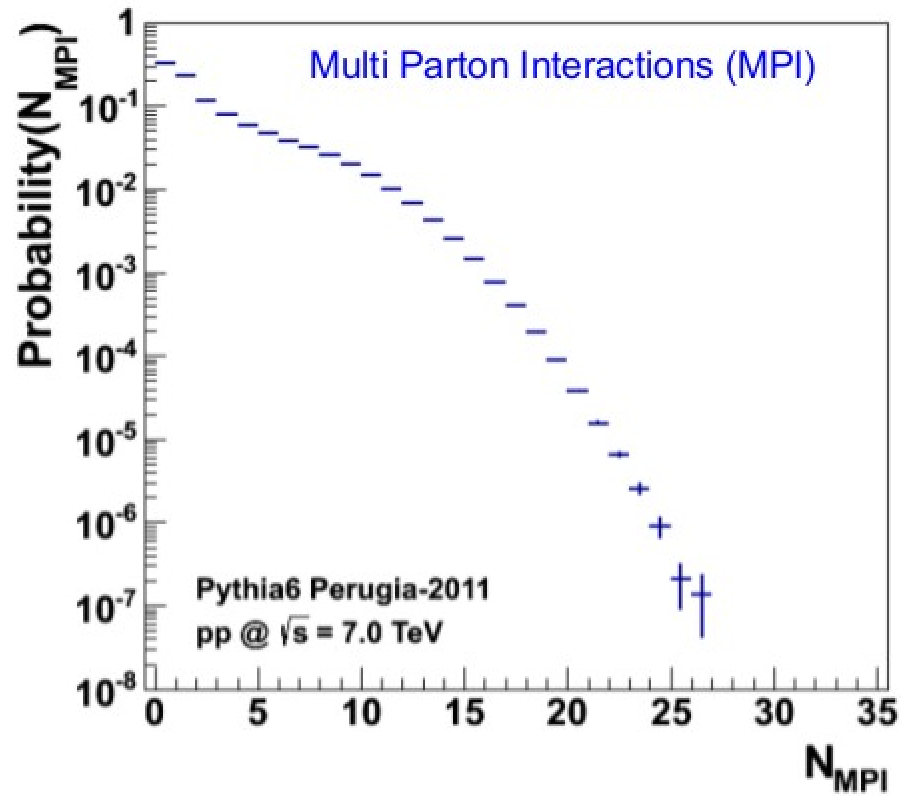
ZNA VZERO SPD

auto-correlation →

← η separation

DHC: Selection bias on fragmentation (pp) 58



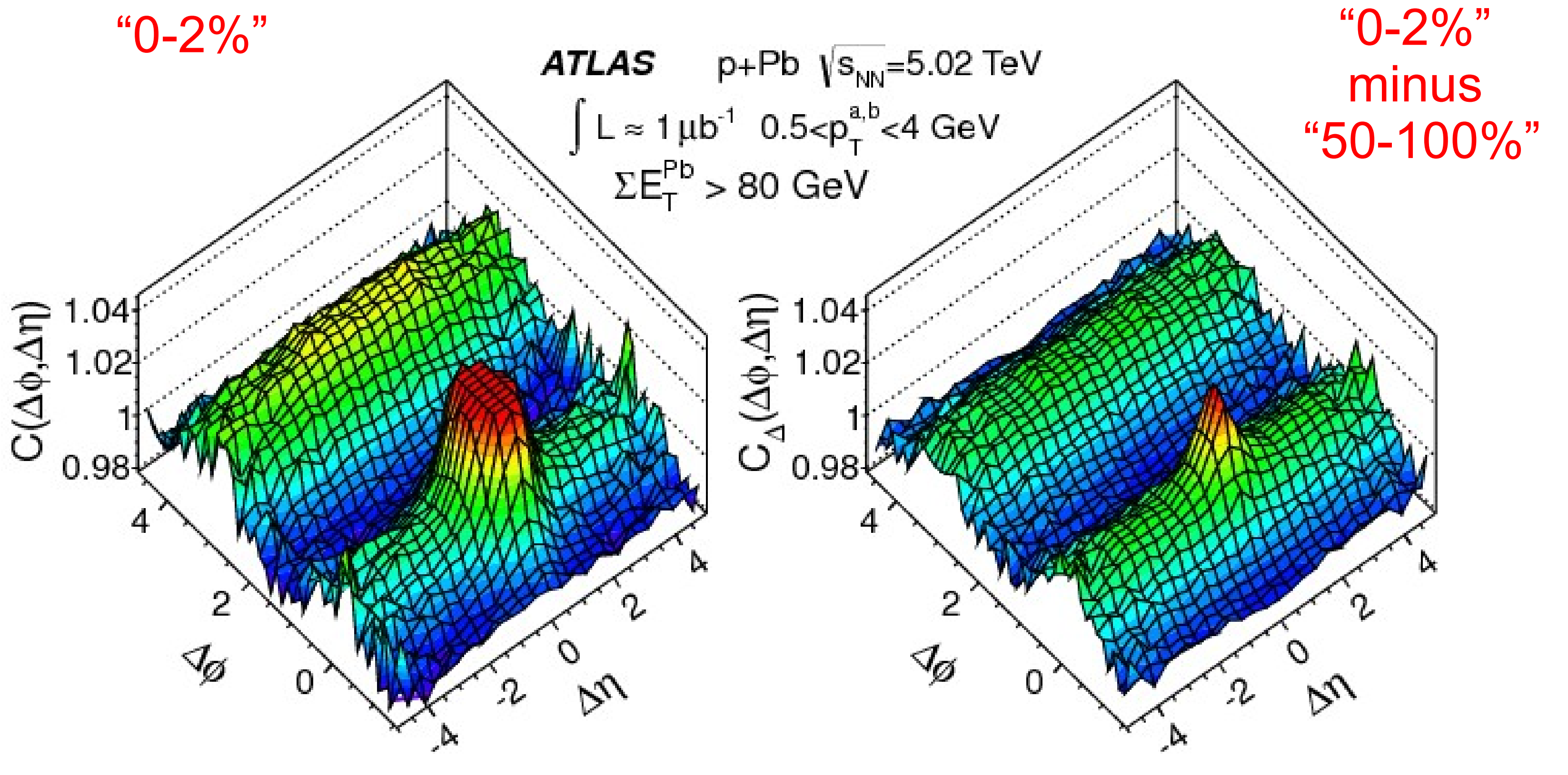


- By selecting on multiplicity, jet fragmentation is biased towards higher number of fragmenting products
- Competition between higher number of MPI and fragmentation

Extraction of double ridge structure

ATLAS, arXiv:1212.5198

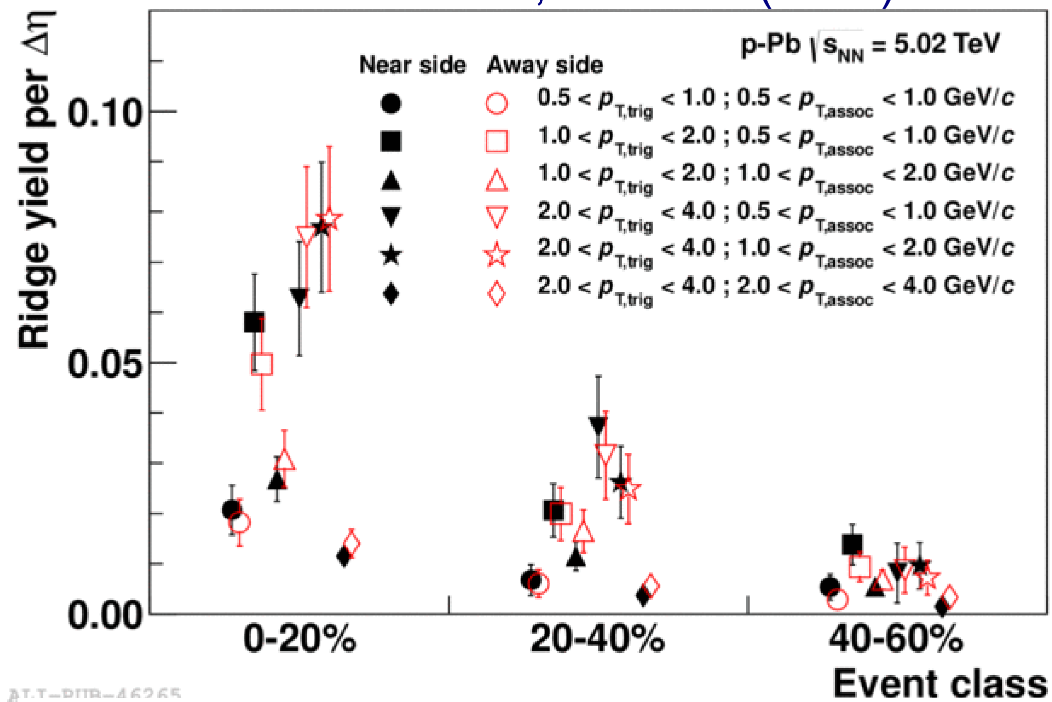
- Similar two ridge structures also observed by ATLAS
  - Event multiplicity classes defined by sum of transverse energy (3.1<η<4.9) on the Pb nucleus side
  - Here, the jet peak at (0,0) remains even after subtraction of 50-100% from the 0-2% multiplicity class

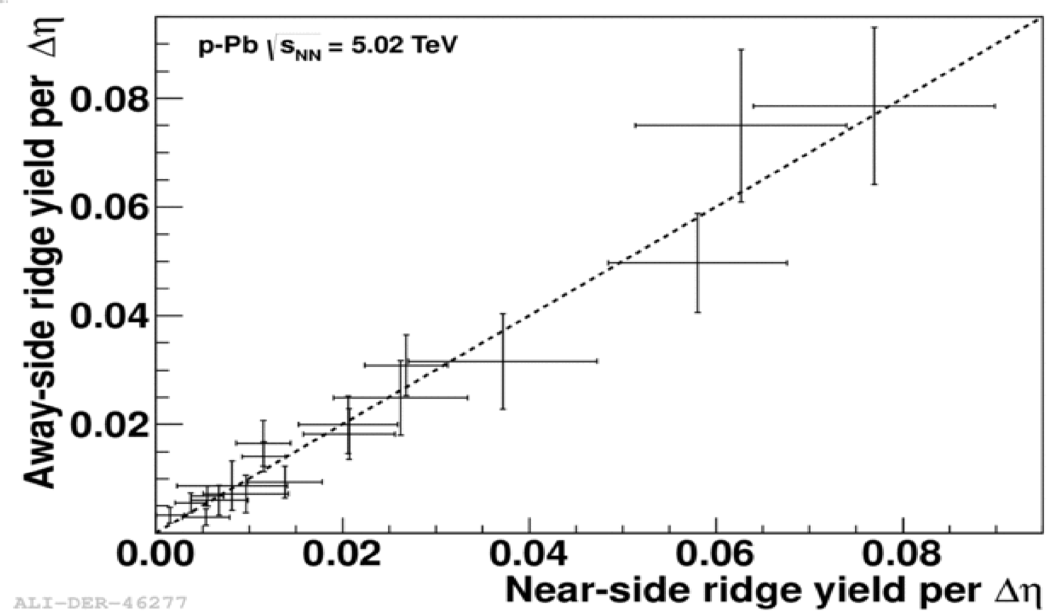


DHC: Ridge yields

- Integrate two ridges above baseline on the
  - Near side (|Δ|<π/2)
  - Away side (π/2<|Δ|<3π/2)
- Near and away-side ridge yields
  - Change significantly
  - Agree for all p_T and multiplicity ranges
  - Increase with trigger p_T and multiplicity
  - Widths are approximately the same (not shown)
- The correlation between near- and away-side yields suggests a common underlying origin

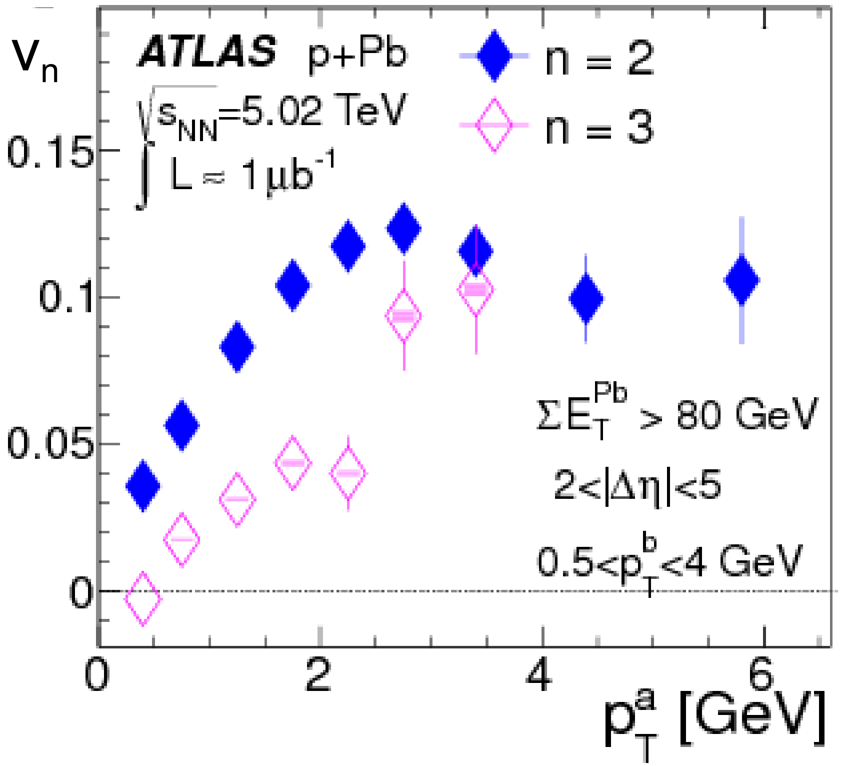
ALICE, PLB 719 (2013) 29



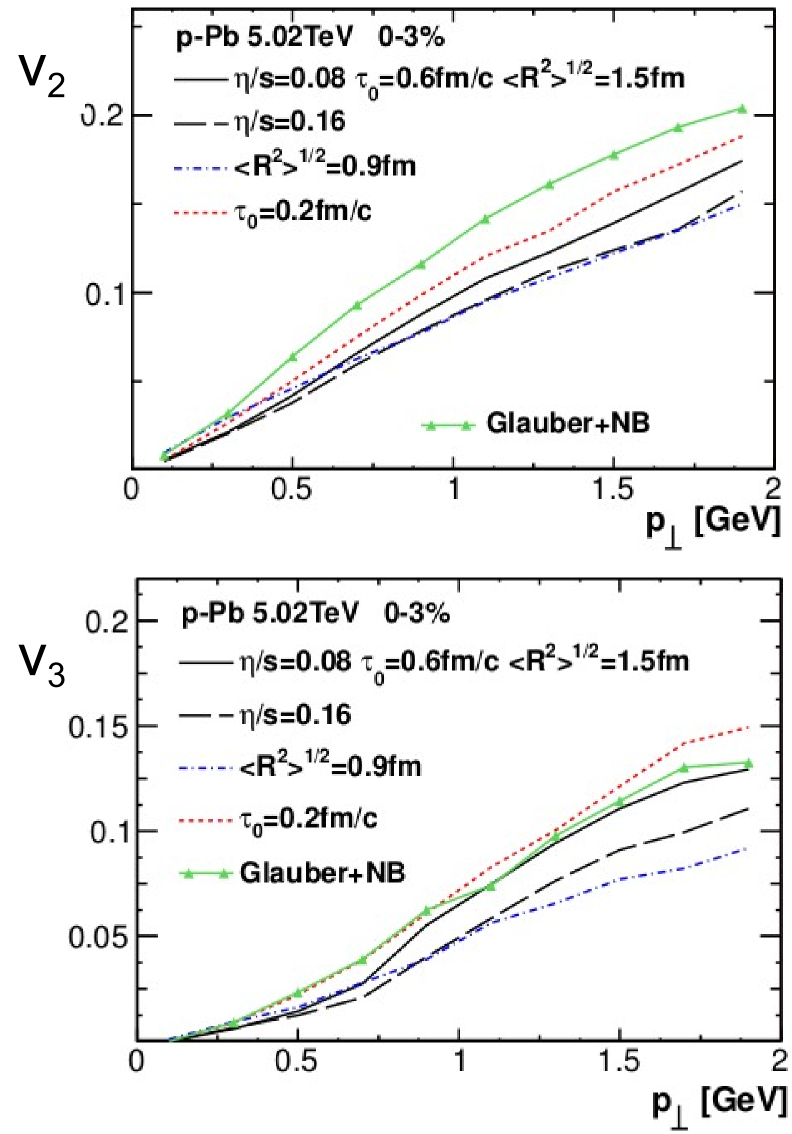


Ridge v_2 and v_3 and hydrodynamics

ATLAS, arXiv:1212.5198



Bozek and Broniowski, arXiv:1304.3044

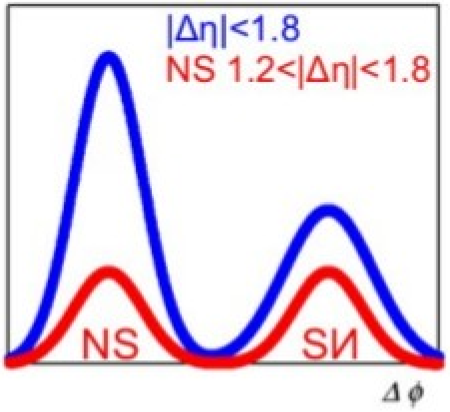


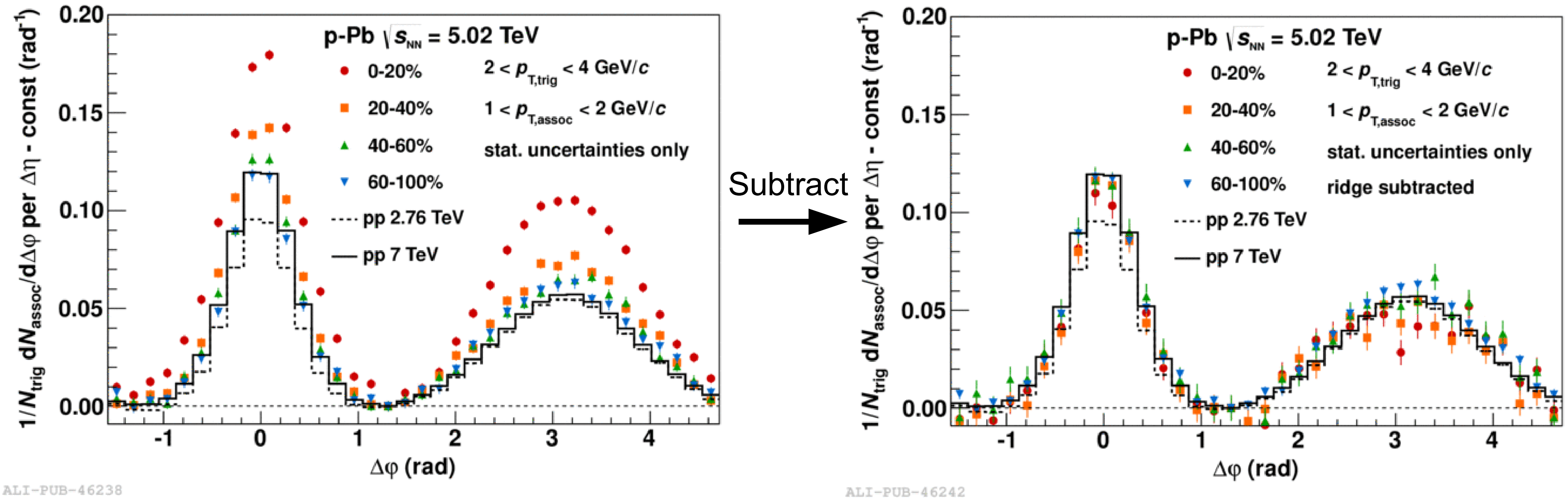
- Large values for v_2 and v_3 reached for high-multiplicity events
- Results are roughly consistent with viscous hydrodynamic calculations
  - Calculations in pPb less robust wrt changes of assumptions than in AA

DHC: Symmetric ridge

ALICE, PLB 719 (2013) 29

- What would the assumption of a symmetric ridge give?
  - Determine the near-side ridge in $1.2 < |\Delta\eta| < 1.8$
  - Mirror to away-side and subtract





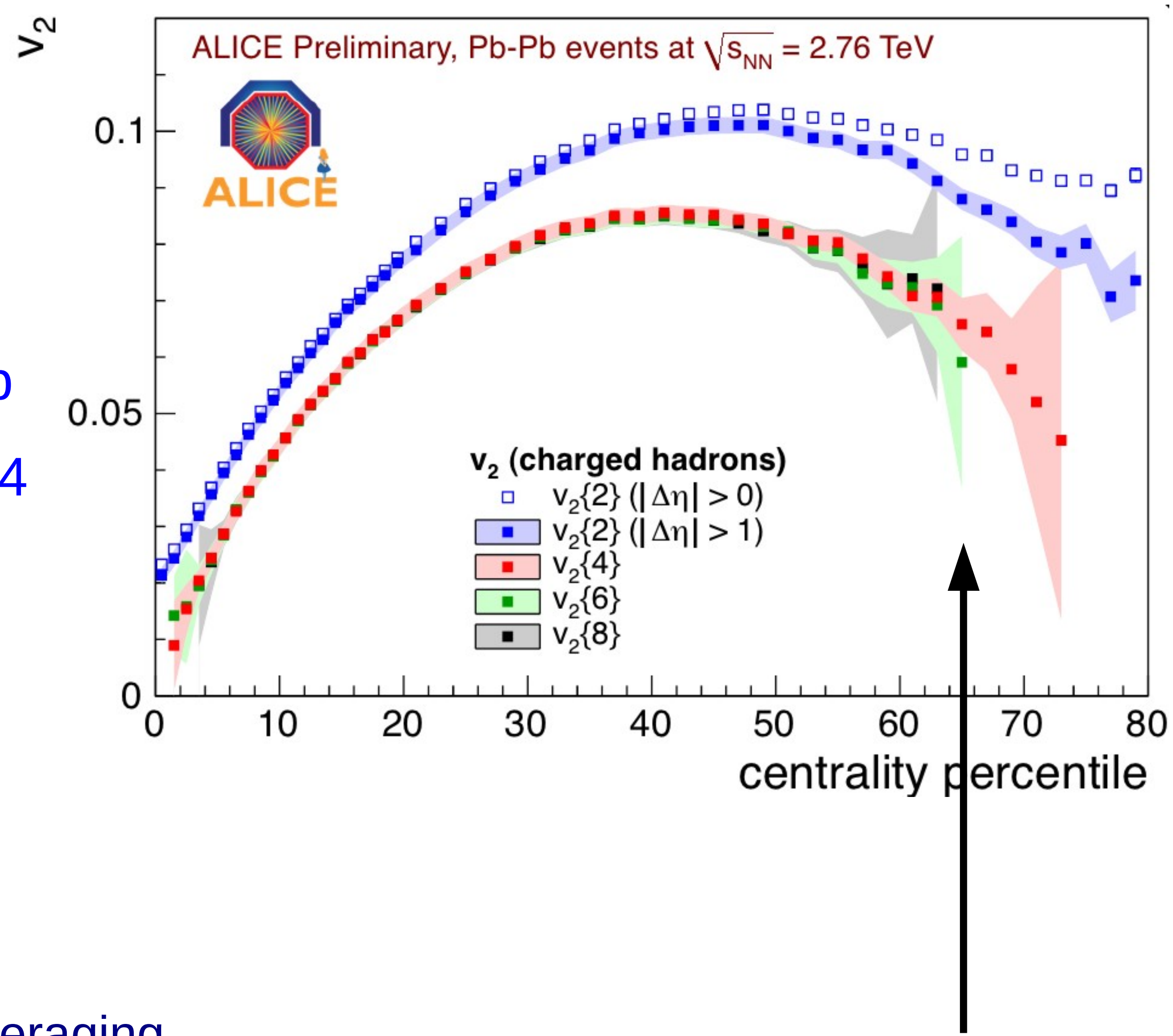
- No significant other multiplicity dependent structures left over

Multi-particle correlations in PbPb: $v_2\{4\}$

- Cumulants to extract genuine k-particle correlations excluding those from k-1 particles
- Higher order cumulants successfully used in PbPb
- Definitions for k=2 and k=4
  - $v_2\{2\}^2 = \langle v_2 \rangle^2 + \sigma_{v_2}^2 + \delta_2$

    $v_2 \gg 1/\sqrt{M}$
  - $v_2\{4\}^2 = \langle v_2 \rangle^2 - \sigma_{v_2}^2$

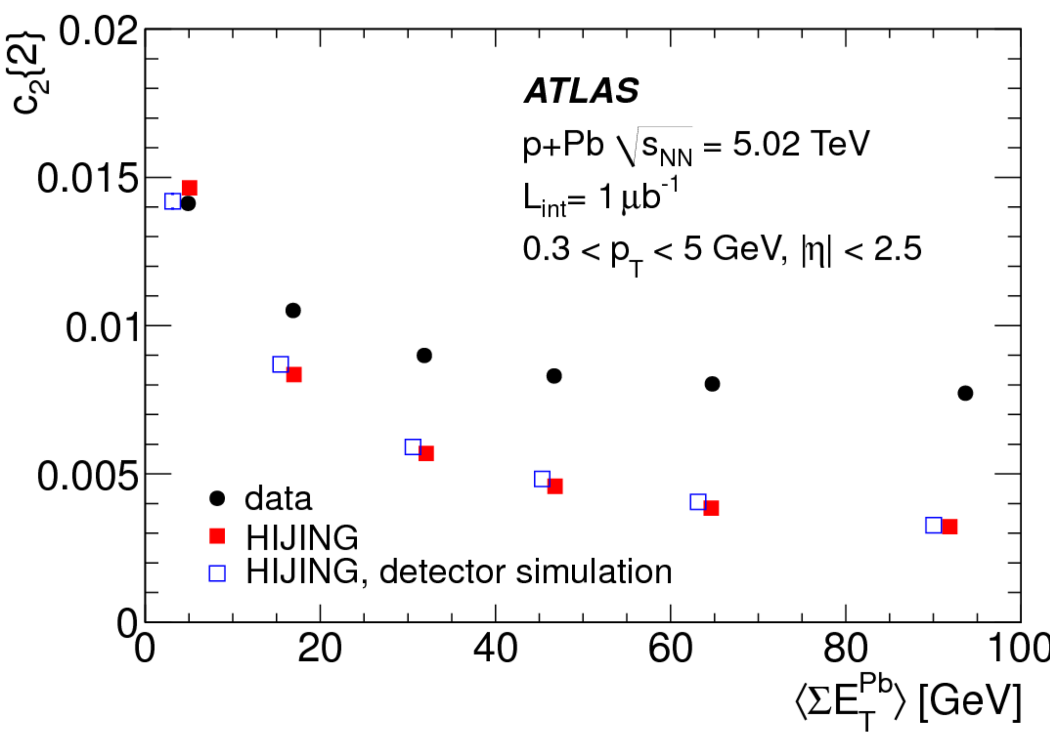
    $v_2 \gg 1/M^{3/4}$
    - eg. M=100, v_2>>0.03
  - Care is needed when averaging over M, as cumulants are also sensitive to multiplicity fluctuations

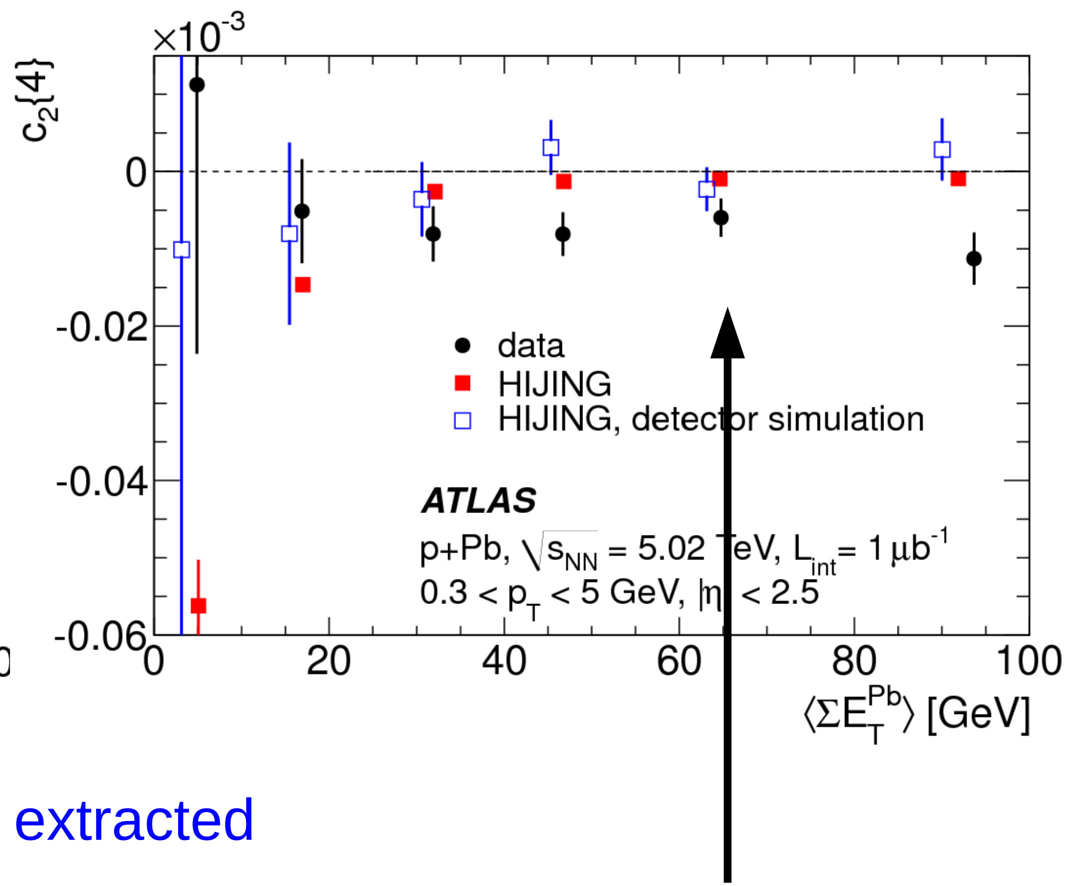


M=<N_{ch}>≈100 in |η|<1

Multi-particle correlations in pPb

ATLAS, arXiv:1303.2084





<N_{ch}>≈100

- Second and fourth order cumulant extracted
  - Second order above HIJING as expected if additional correlations present
  - Fourth order has different trend than HIJING
    - In high-multiplicity region there are four or higher particle correlations not present in HIJING

Correlation function p_T dependence

|Δη|>2

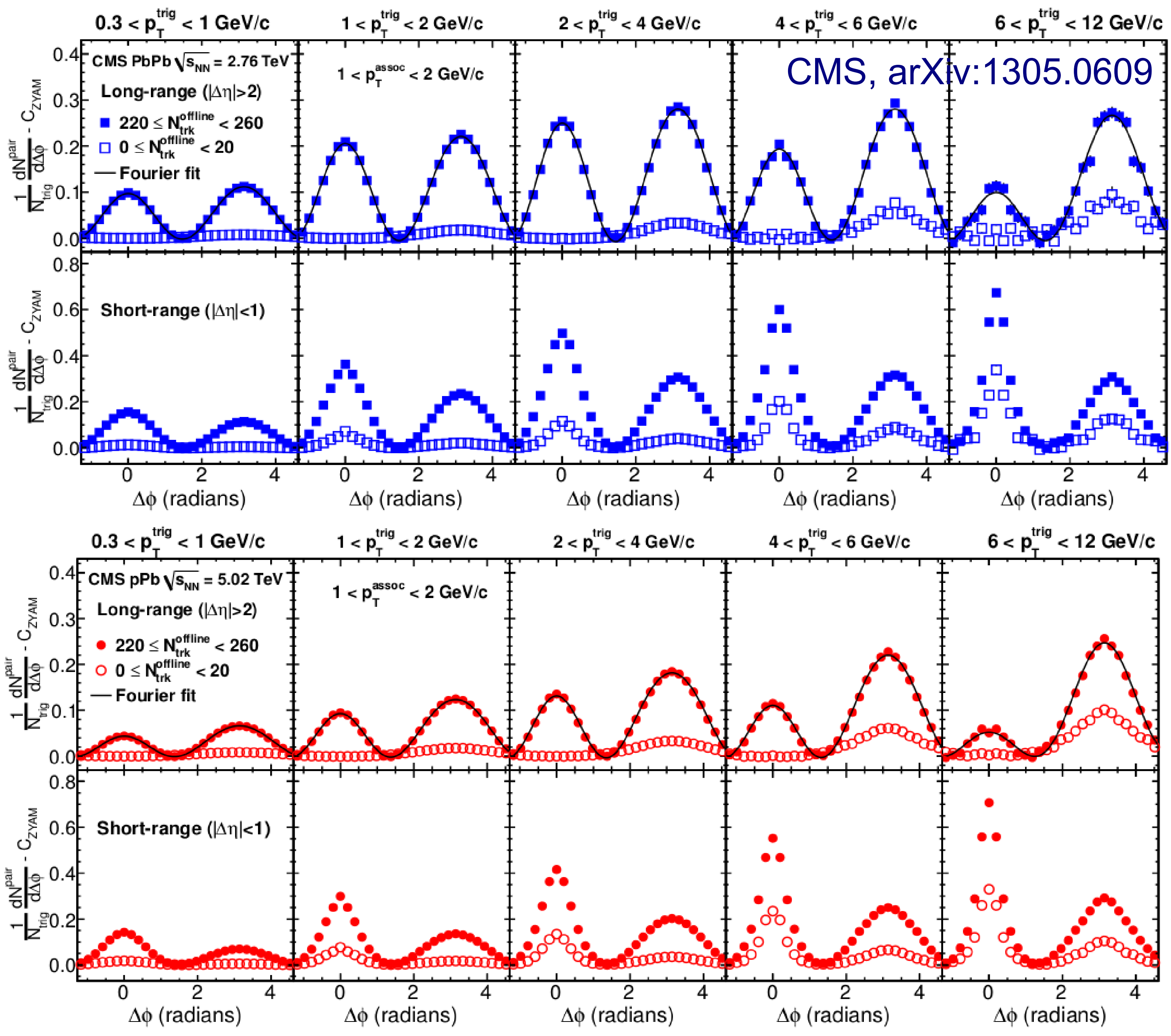
PbPb

|Δη|<1

|Δη|>2

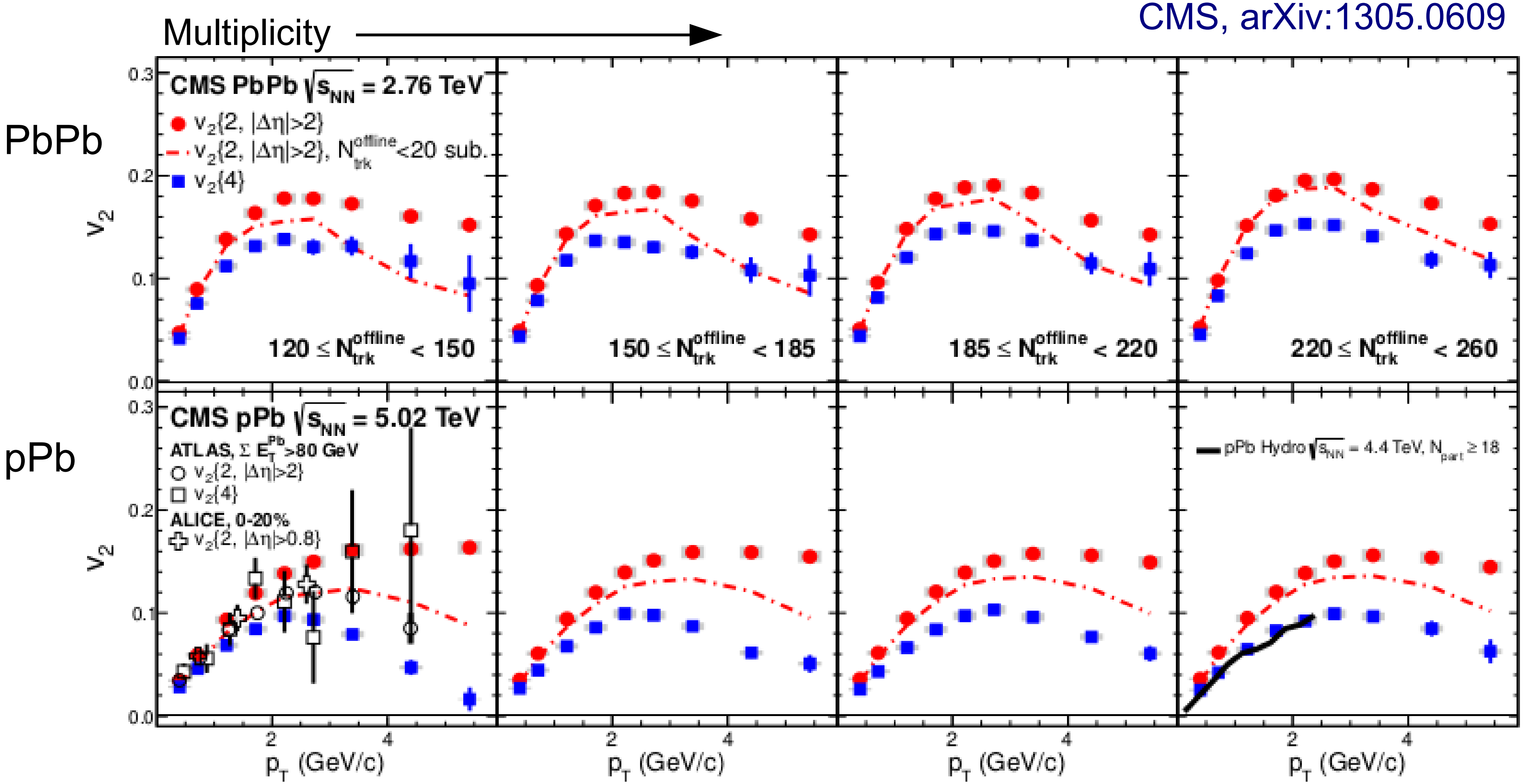
pPb

|Δη|<1



v_2 in PbPb and pPb

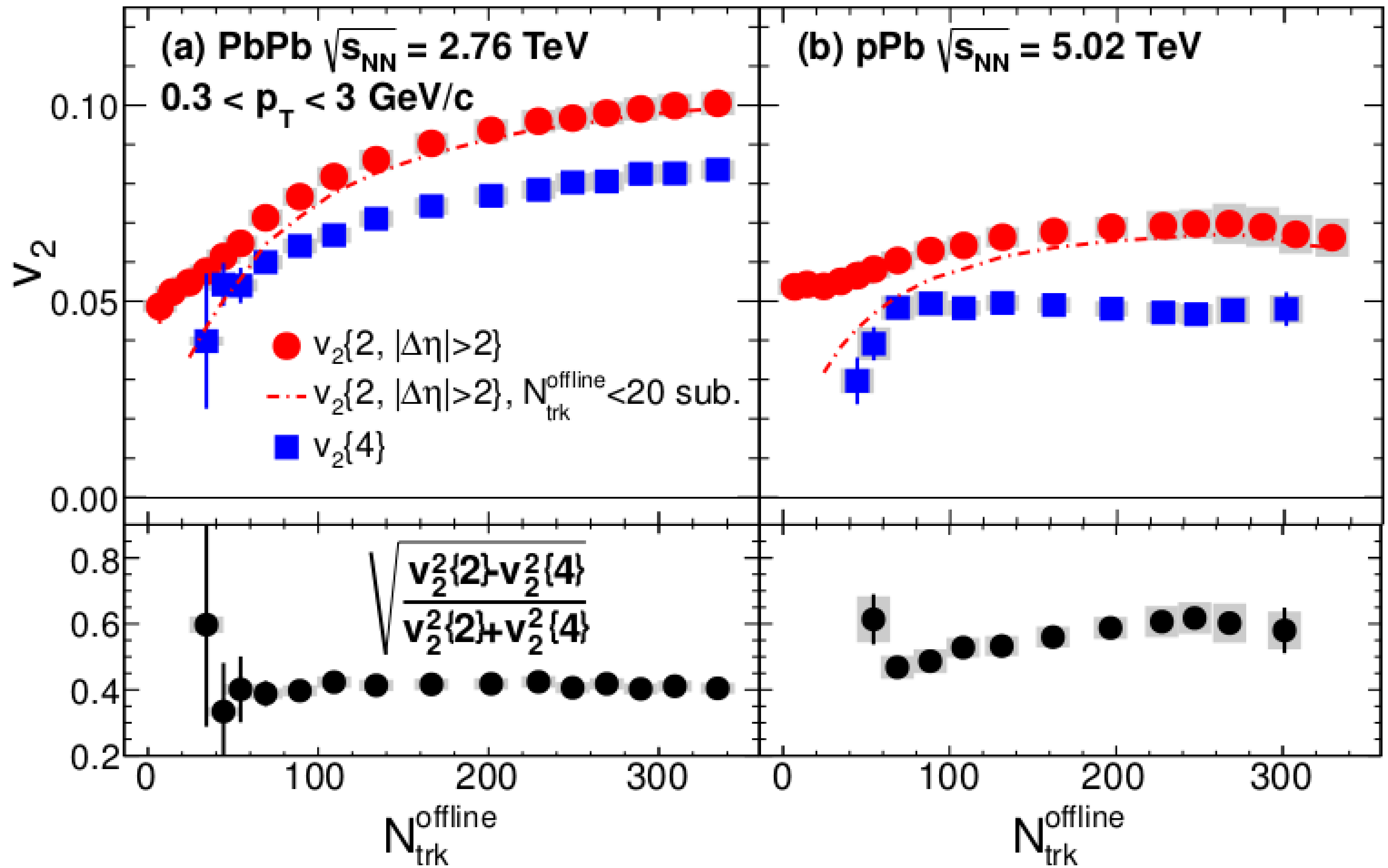
CMS, arXiv:1305.0609



Similar shape of v_2 in pPb and PbPb but with smaller magnitude

Integrated v_2 in PbPb and pPb

CMS, arXiv:1305.0609

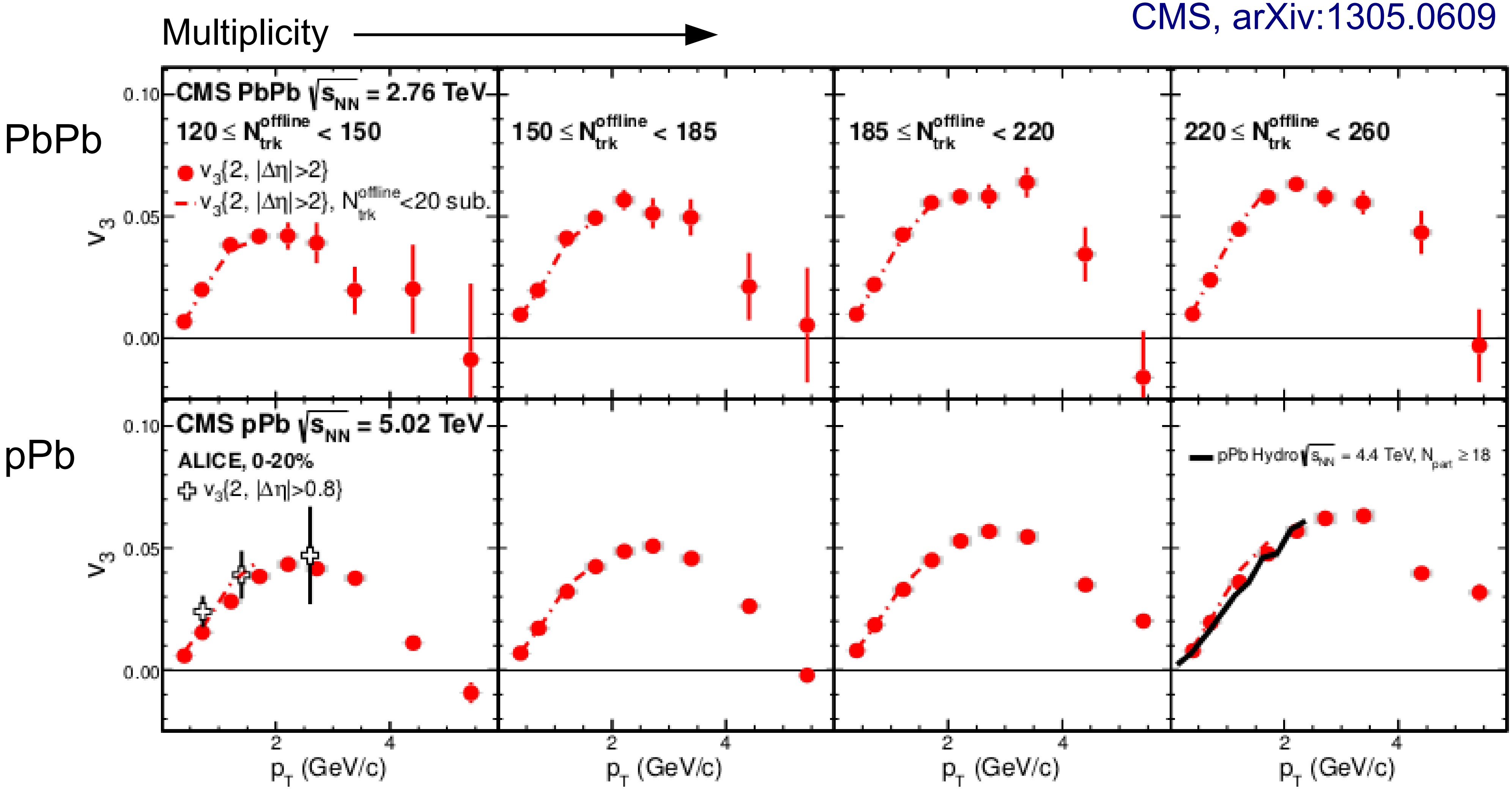


v_2 in pPb is smaller than in PbPb

v_3 in PbPb and pPb

CMS, arXiv:1305.0609

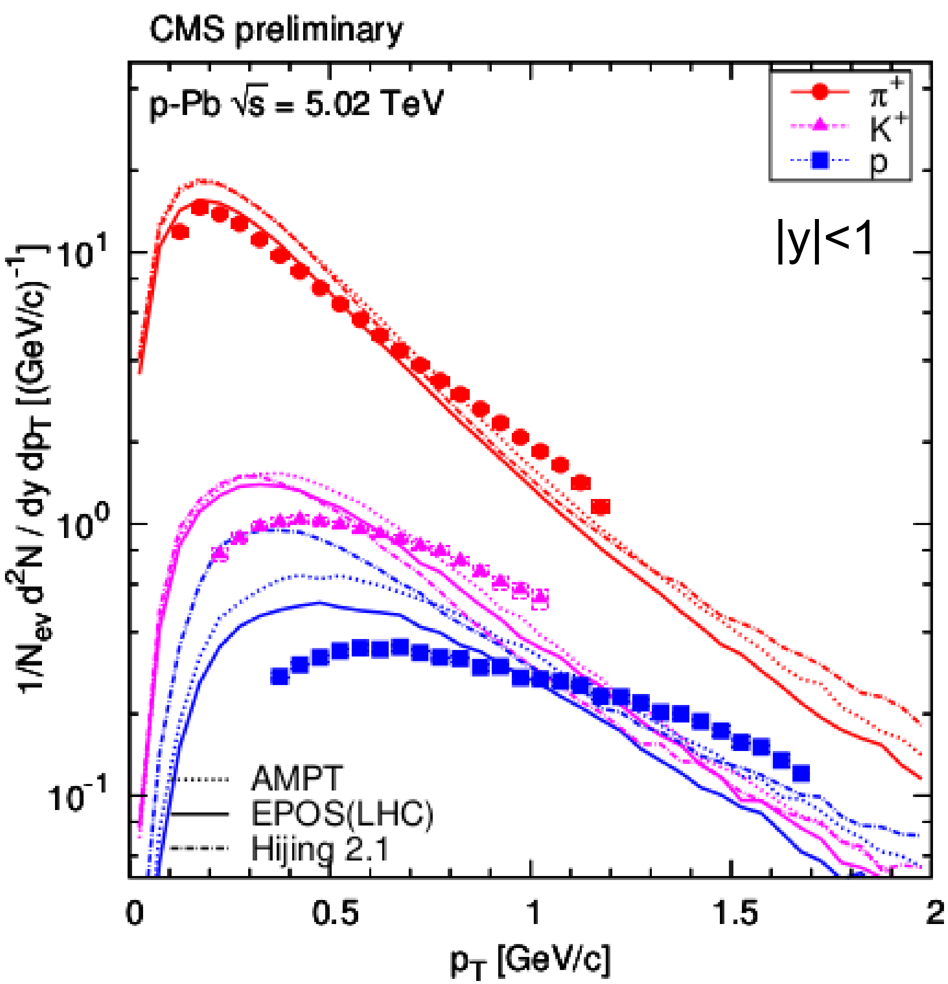
Multiplicity →

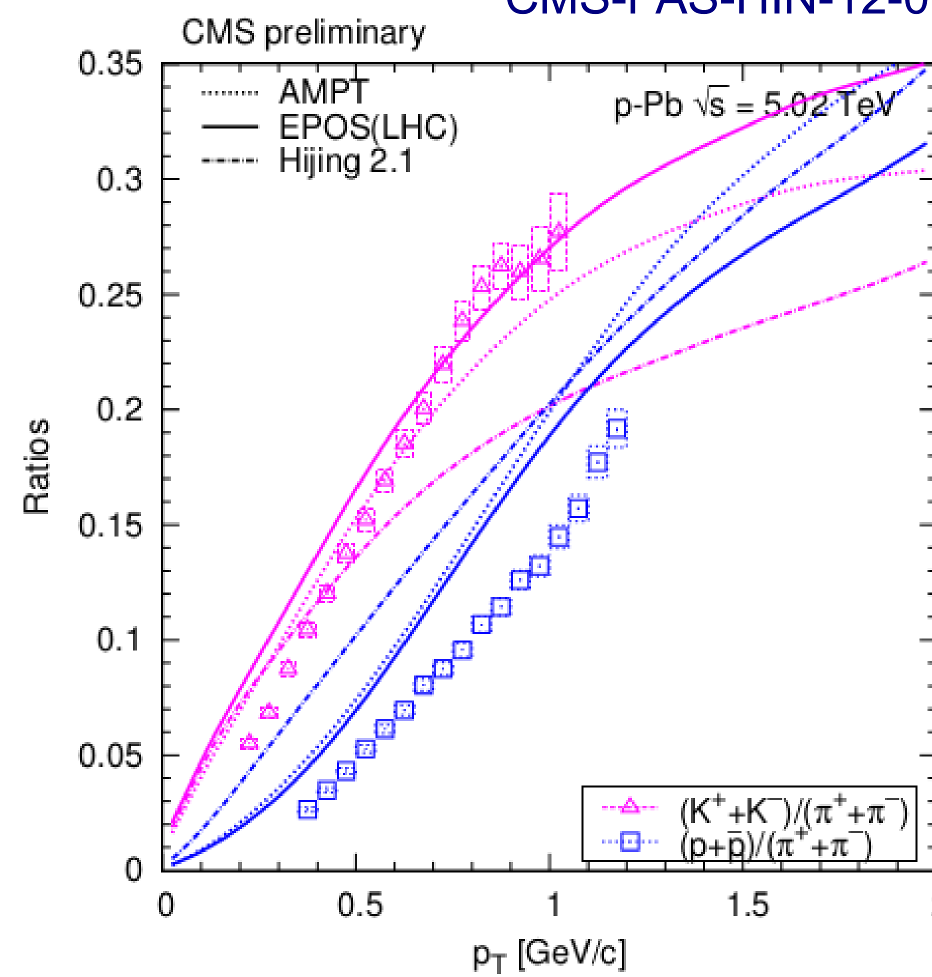


Similar shape and magnitude of v_3 in pPb and PbPb

Identified particle spectra and ratios

CMS-PAS-HIN-12-016

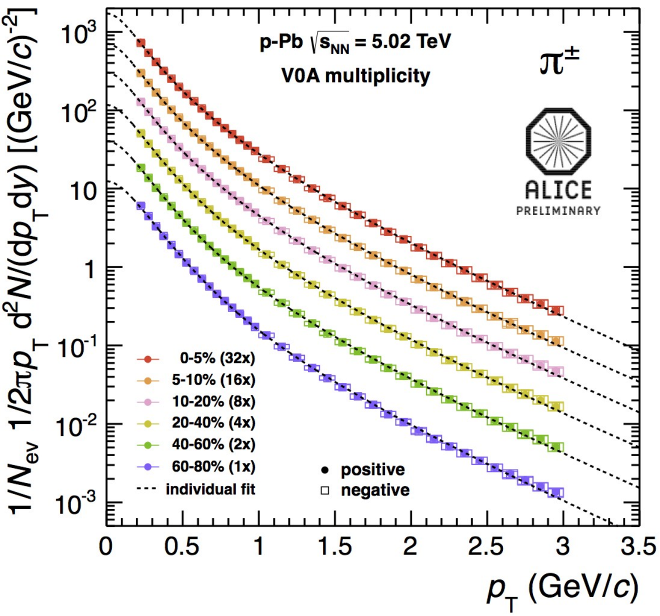


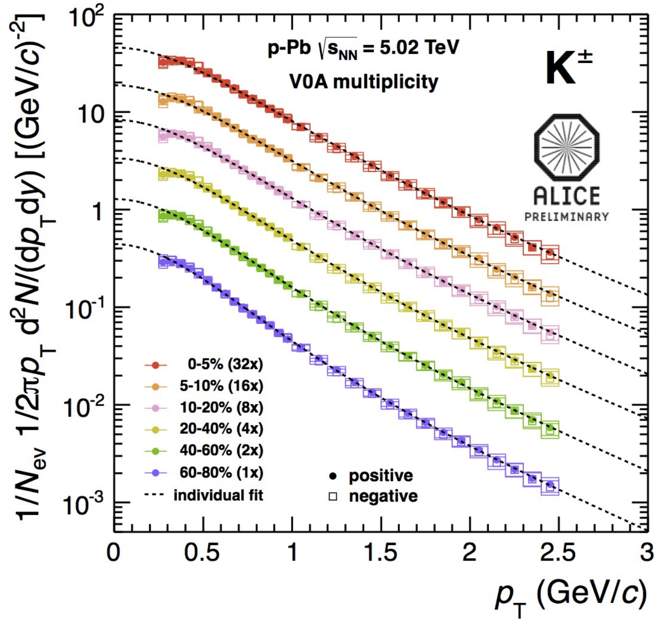


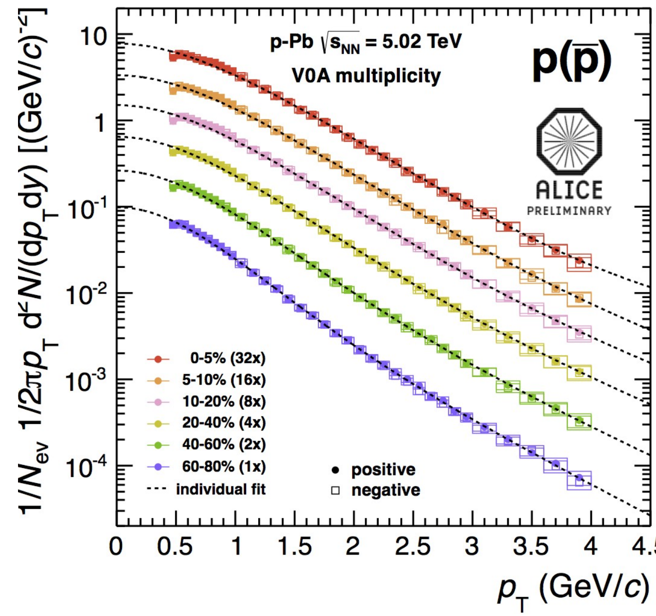
- Use template fits to energy loss at |y|<1
  - Pions (0.1 GeV/c < p <1.2 GeV/c)
  - Kaons (0.2 GeV/c < p < 1.05 GeV/c)
  - Protons (0.4 GeV/c < p < 1.7 GeV/c)
- Generators exhibit too steep p_T dependence
- Significant deviations in particular for the p/π ratio.

Identified particle p_T spectra

ALICE preliminary (Trento)

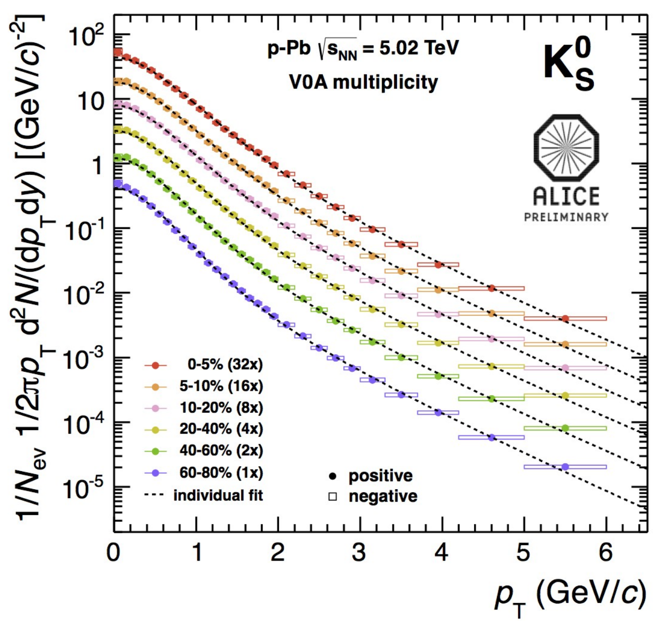


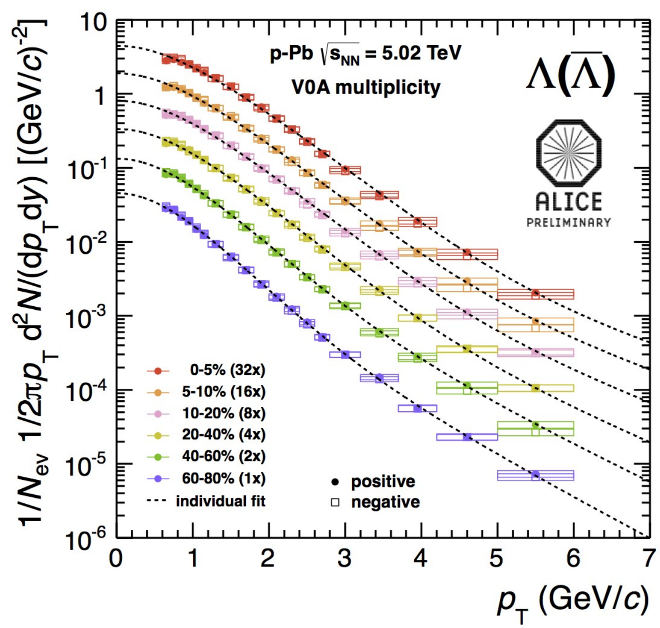




p_T spectra in several V0A multiplicity classes

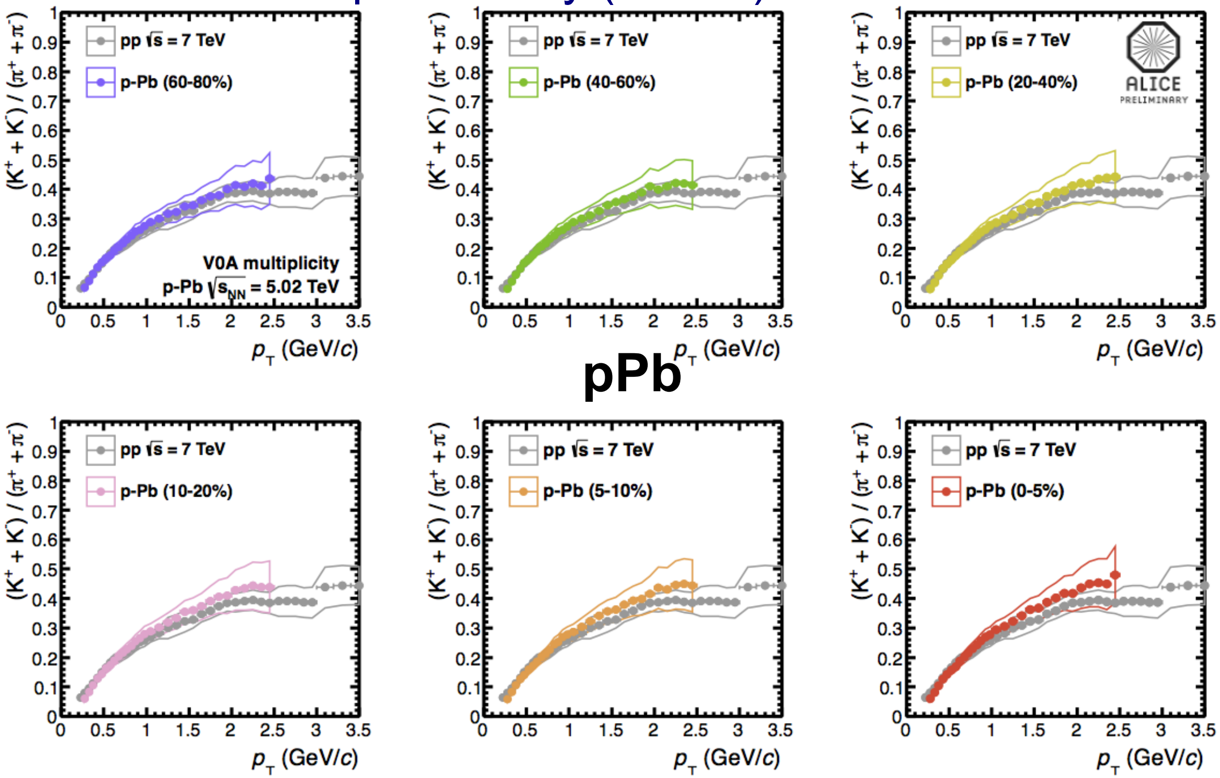
$\pi^{\pm}$	0.2 – 3.0 GeV/c
$K^{\pm}$	0.25 – 2.5 GeV/c
$p(\bar{p})$	0.45 – 4.0 GeV/c
K^0_S	0 – 6.0 GeV/c
$\Lambda(\bar{\Lambda})$	0.6 – 6.0 GeV/c



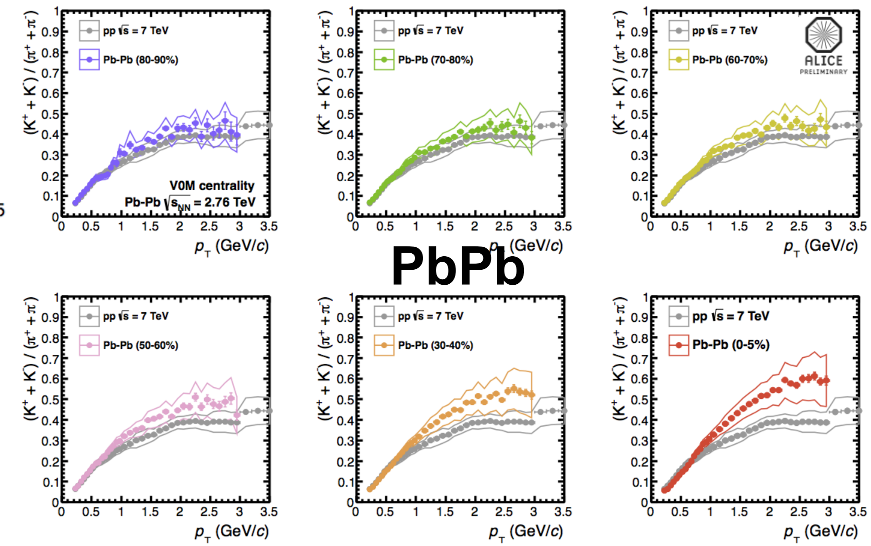


K/π ratio versus p_T

ALICE preliminary (Trento)



ALICE, arxiv:1303.0737



Systematic errors are largely correlated across multiplicity

- <u>weak evolution with multiplicity</u> in p-Pb

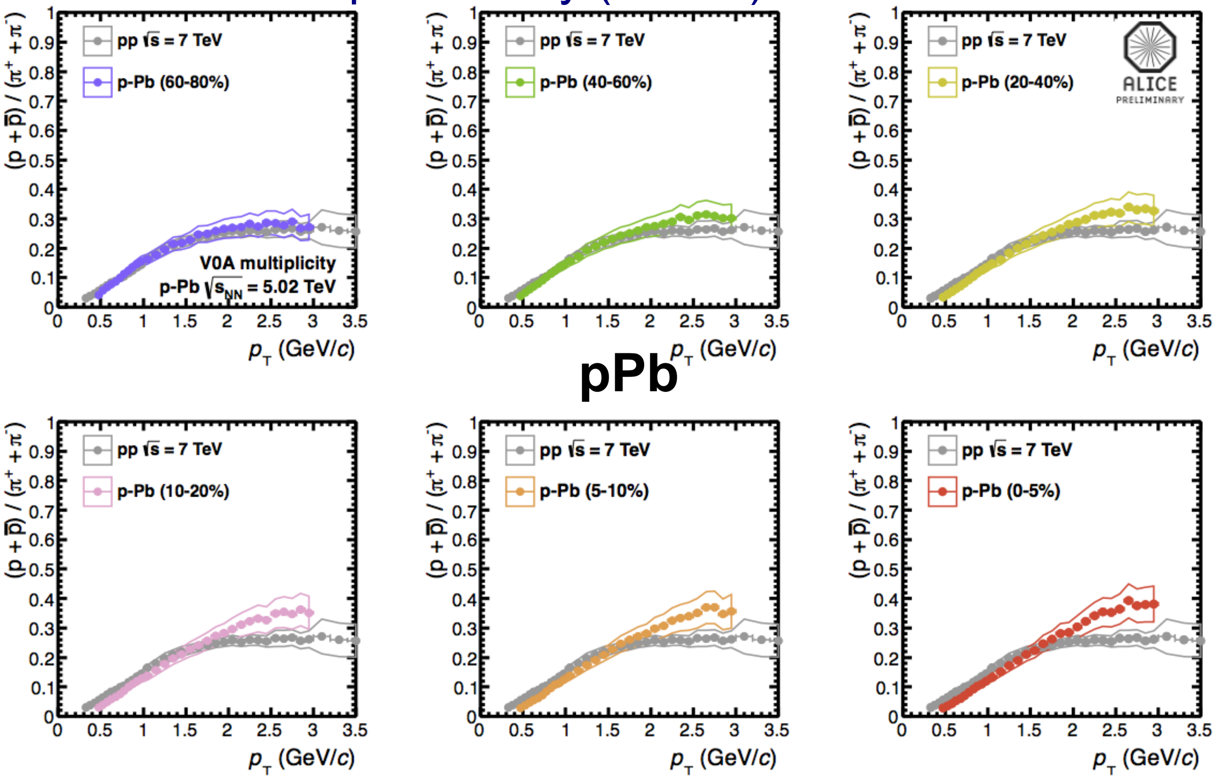
→ small increase at intermediate p_T with increasing V0A multiplicity

→ corresponding small depletion in the low-p_T region

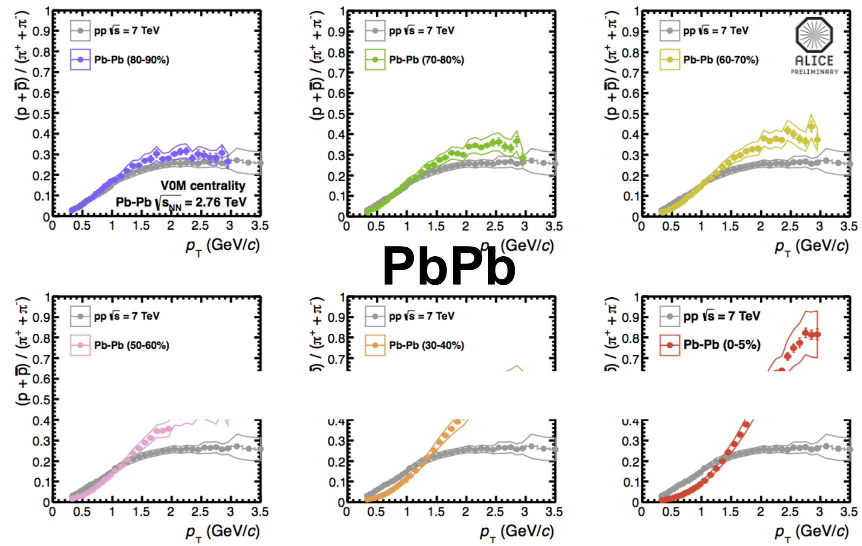
- <u>hints at similar behavior</u> as observed <u>in Pb-Pb</u> collisions

p/π ratio versus p_T

ALICE preliminary (Trento)



ALICE, arxiv:1303.0737



Systematic errors are largely correlated across multiplicity

- <u>shows similar behavior</u> as observed <u>in Pb-Pb</u> collisions

→ significant increase at intermediate p_T with increasing V0A multiplicity

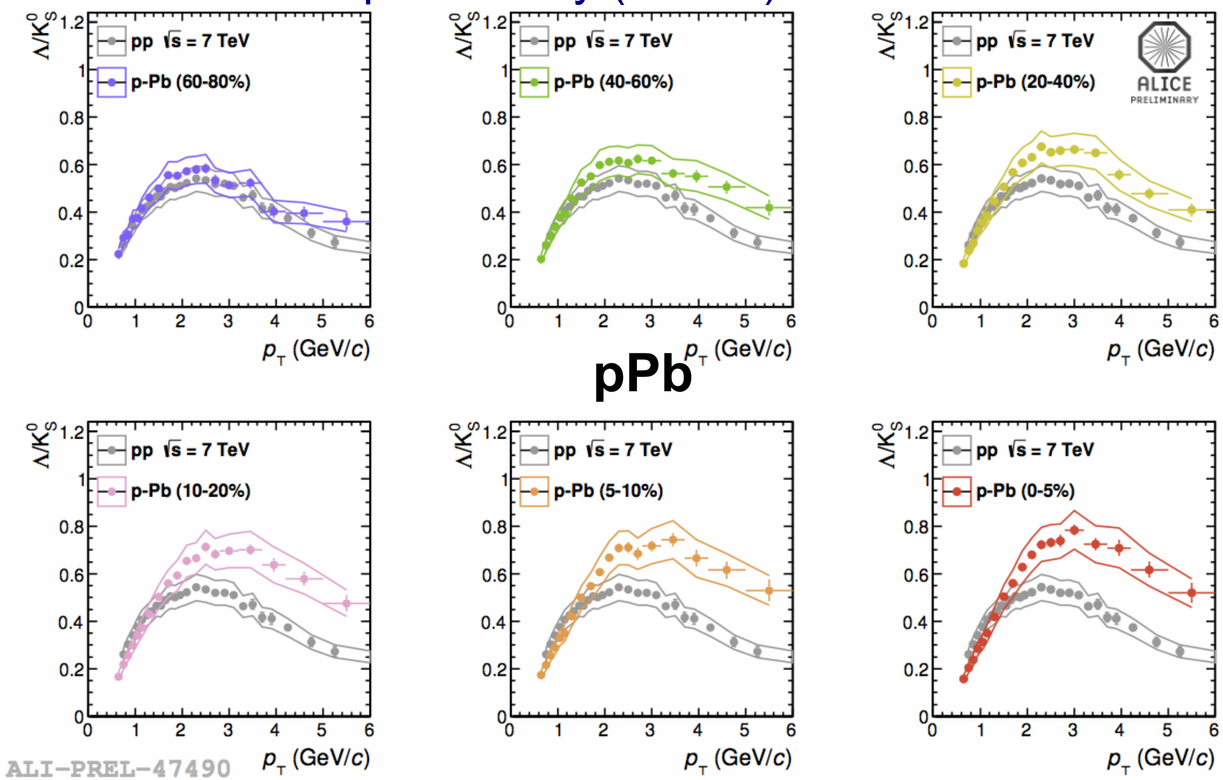
→ corresponding significant depletion in the low-p_T region

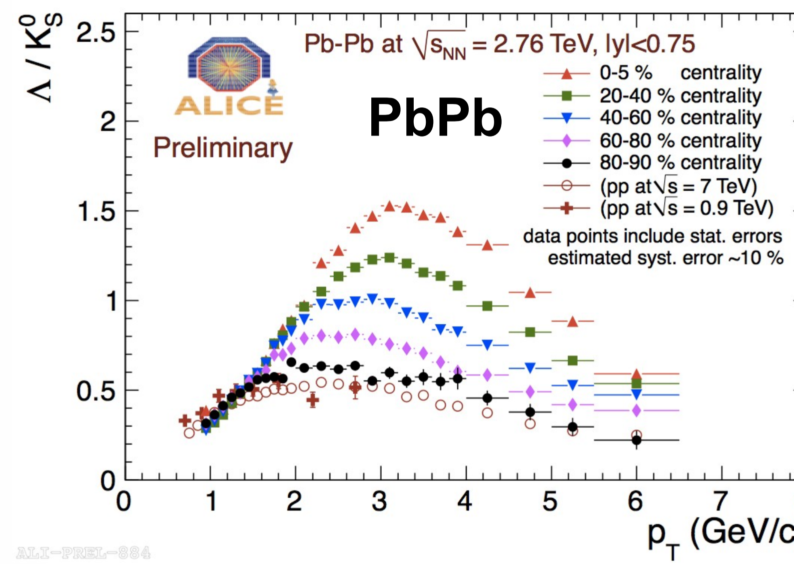
→ stronger enhancement than K/π

- Pb-Pb generally understood in terms of collective flow and/or recombination

Λ/K^0_s ratio versus p_T

ALICE preliminary (Trento)





Systematic errors are largely correlated across multiplicity

- <u>clear evolution with multiplicity</u> in pPb

→ significant increase at intermediate p_T with increasing V0A multiplicity

→ corresponding significant depletion in the low-p_T region

- also this is <u>reminiscent of nucleus-nucleus phenomenology</u>...

...generally understood in terms of collective flow and/or recombination

Spectra shape analysis: pPb

π/K/p spectral-shape analysis:

➢ performed with hydro-motivated Blast-Wave model
Schnedermann, PRC 48, 2462 (1993)

aims at characterizing spectral shapes in V0A multiplicity classes with a small set of parameters

➢ simultaneous fit of all particles with 3 parameters

$\langle\beta_T\rangle$ radial flow
T_{fo} freeze-out temperature
n velocity profile

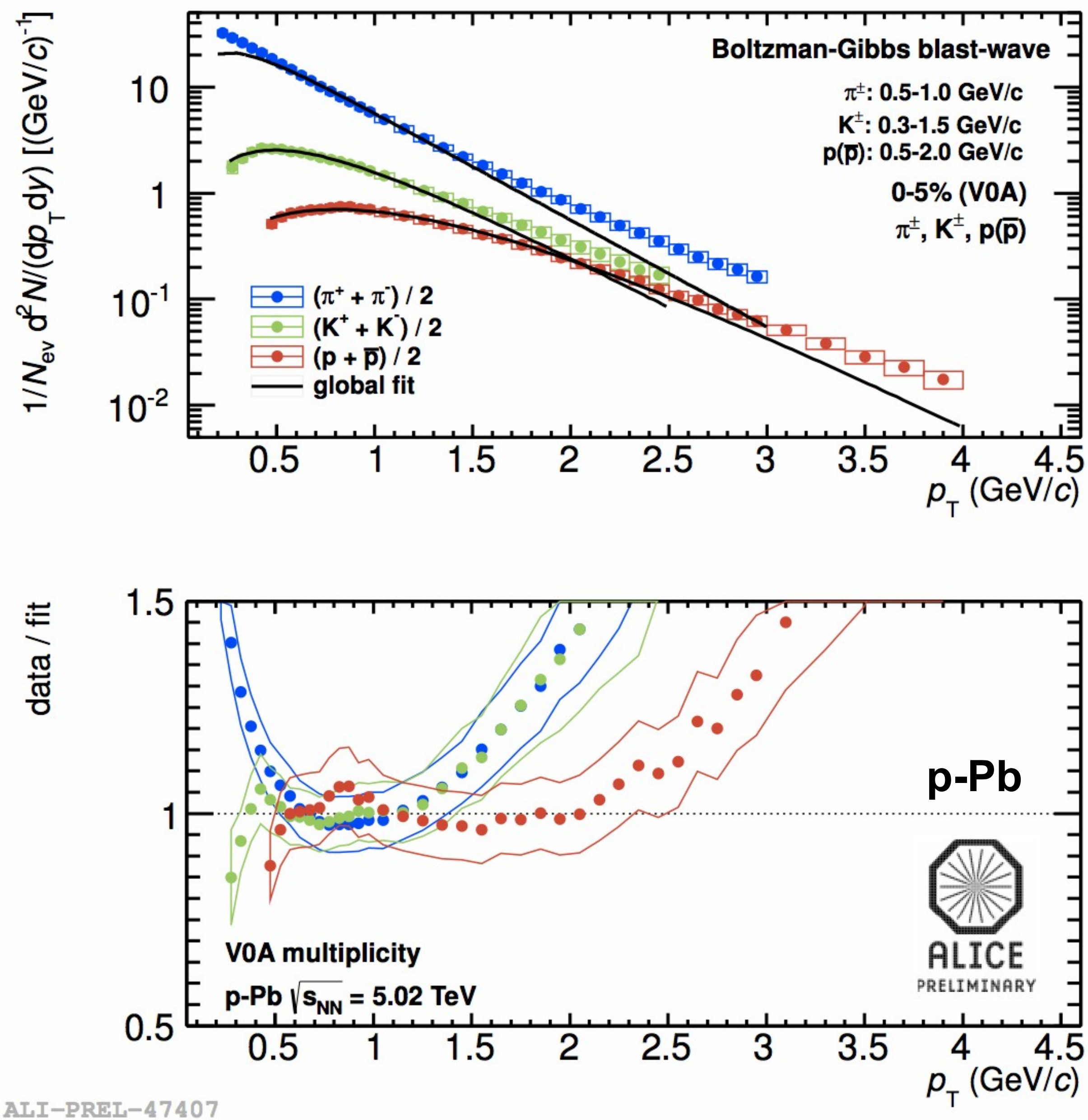
➢ global fit performed in the following p_T ranges:

π 0.5 – 1.0 GeV/*c*
K 0.3 – 1.5 GeV/*c*
p 0.5 – 2.0 GeV/*c*

➢ Blast-Wave fits reasonable, though not very good

worse than central Pb-Pb
better than pp minimum bias

ALICE preliminary (Trento)

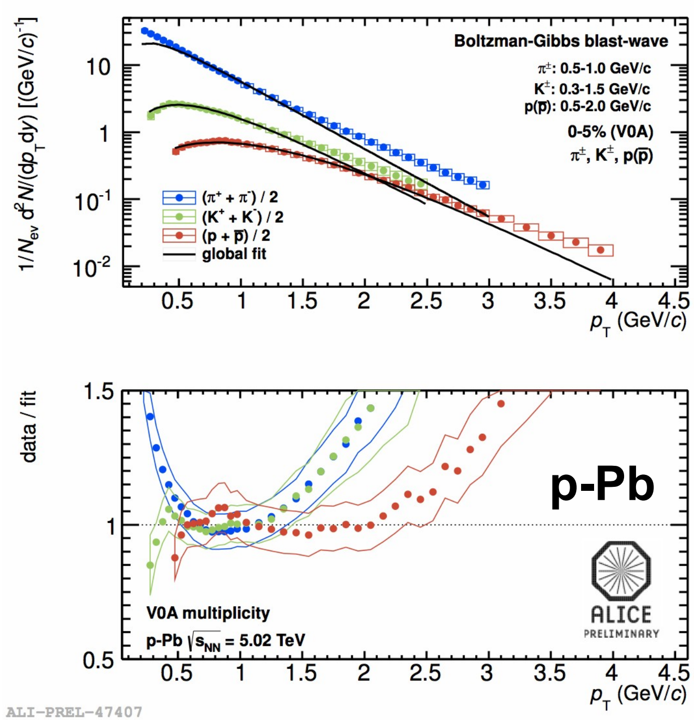


Spectra shape analysis: pp

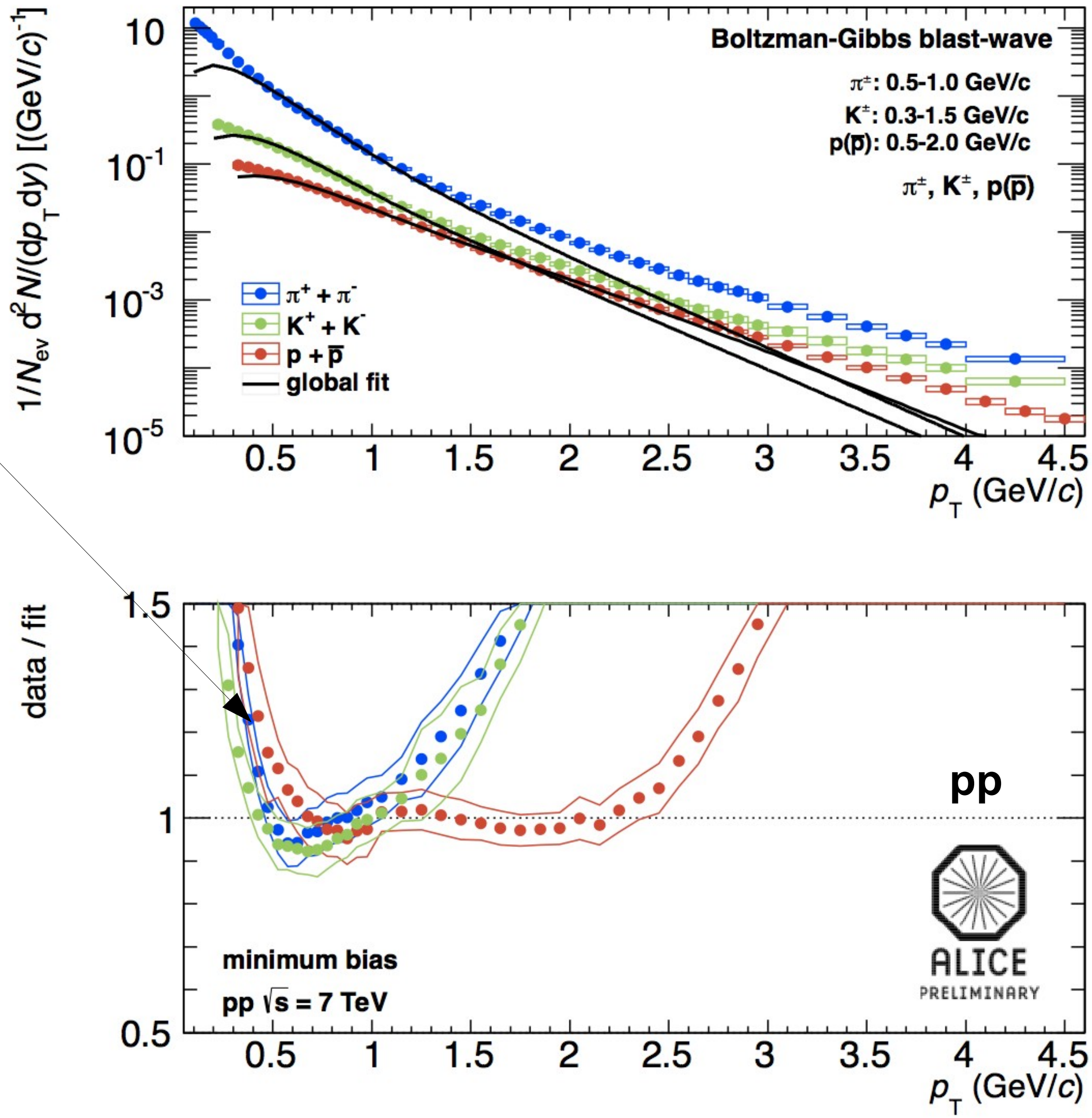
π/K/p spectral-shape analysis:

- performed with hydro-motivated Blast-Wave model
  Schnedermann, PRC 48, 2462 (1993)
- Blast-Wave fits reasonable, though not very good

better than pp minimum bias:
not successful at very low p_T



ALICE preliminary (Trento)



Spectra shape analysis: PbPb

π/K/p spectral-shape analysis:

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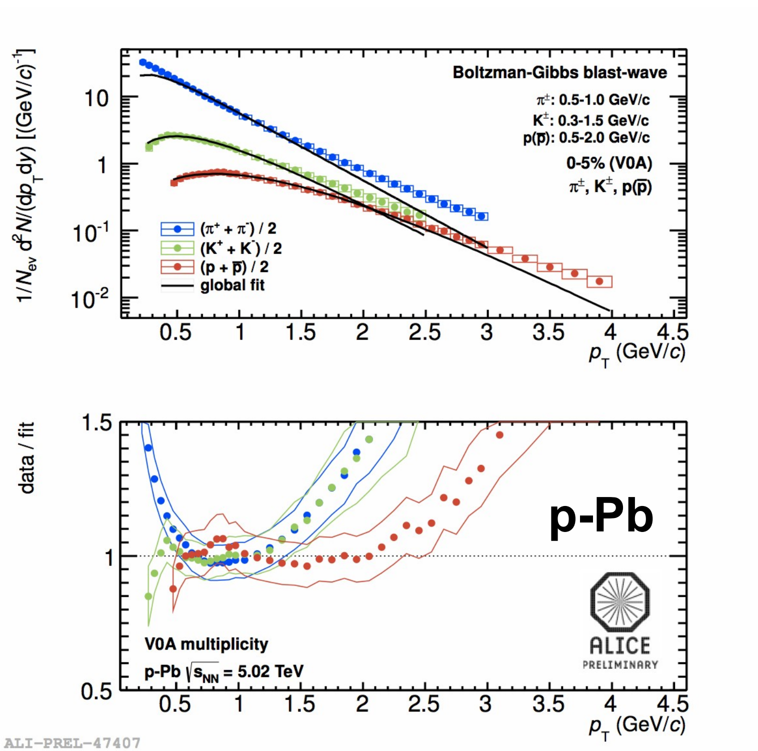
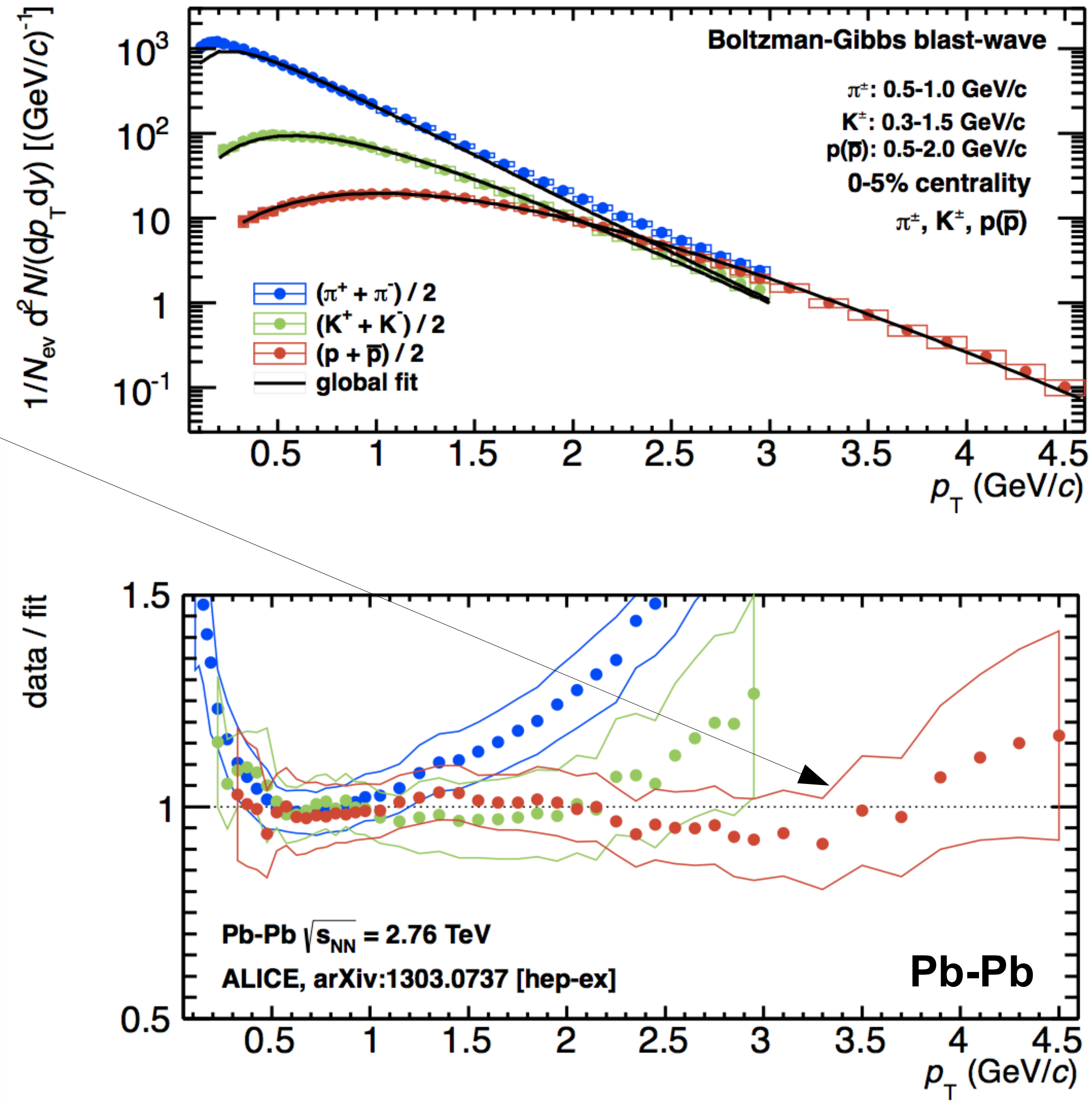
  Schnedermann, PRC 48, 2462 (1993)
- Blast-Wave fits reasonable, though not very good

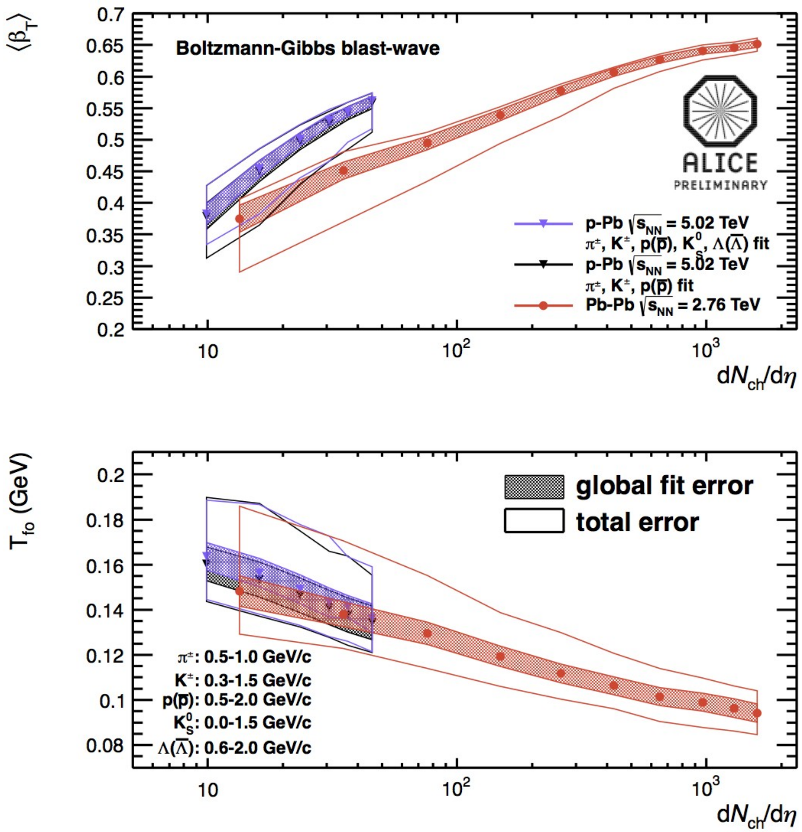
worse than central Pb-Pb: successful up to higher p_T

ALICE, arxiv:1303.0737

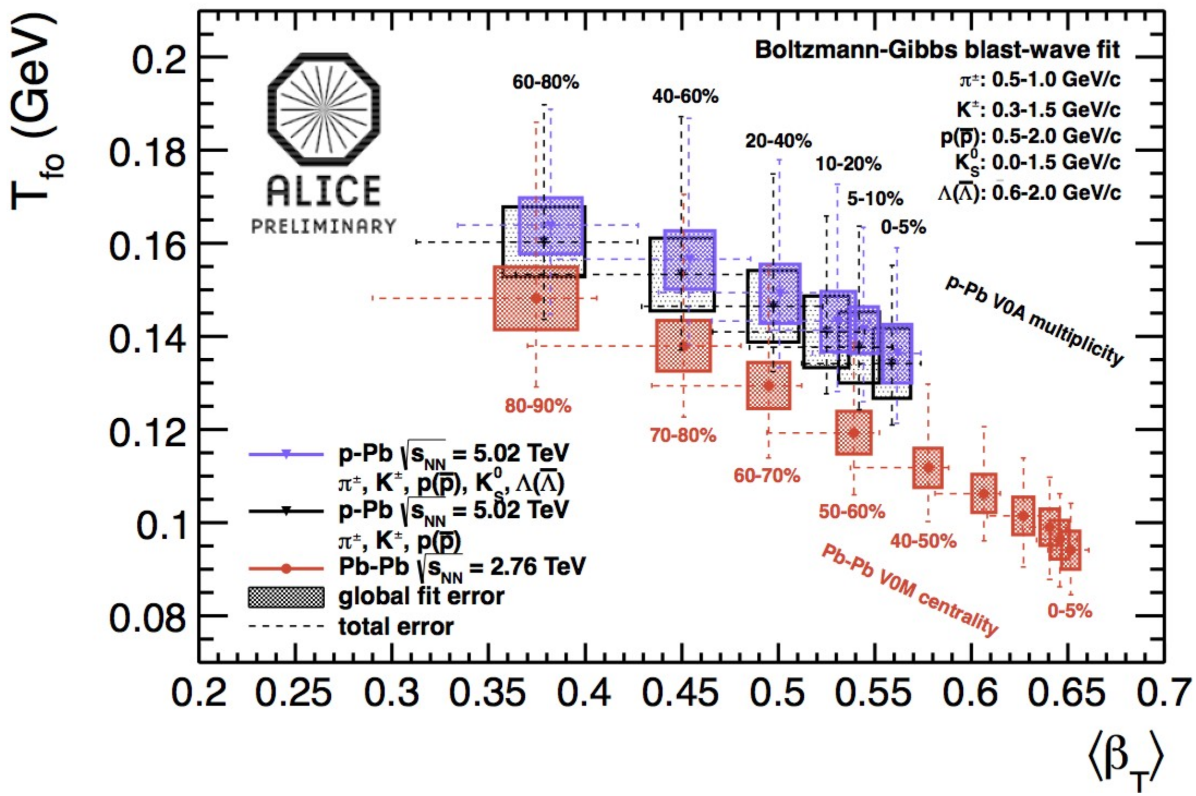




Global Blast-Wave fit parameters



ALICE preliminary (Trento)



- p-Pb presents similar features as observed in Pb-Pb

→ parameters evolve with increasing multiplicity: larger $\langle\beta_T\rangle$, smaller T_{fo}

→ T_{fo} is similar to Pb-Pb for similar multiplicity, $\langle\beta_T\rangle$ is larger in p-Pb

- same results when including also Λ and K^0_S in the p-Pb global fit

Global Blast-Wave fit parameters

π/K/p spectral-shape analysis:

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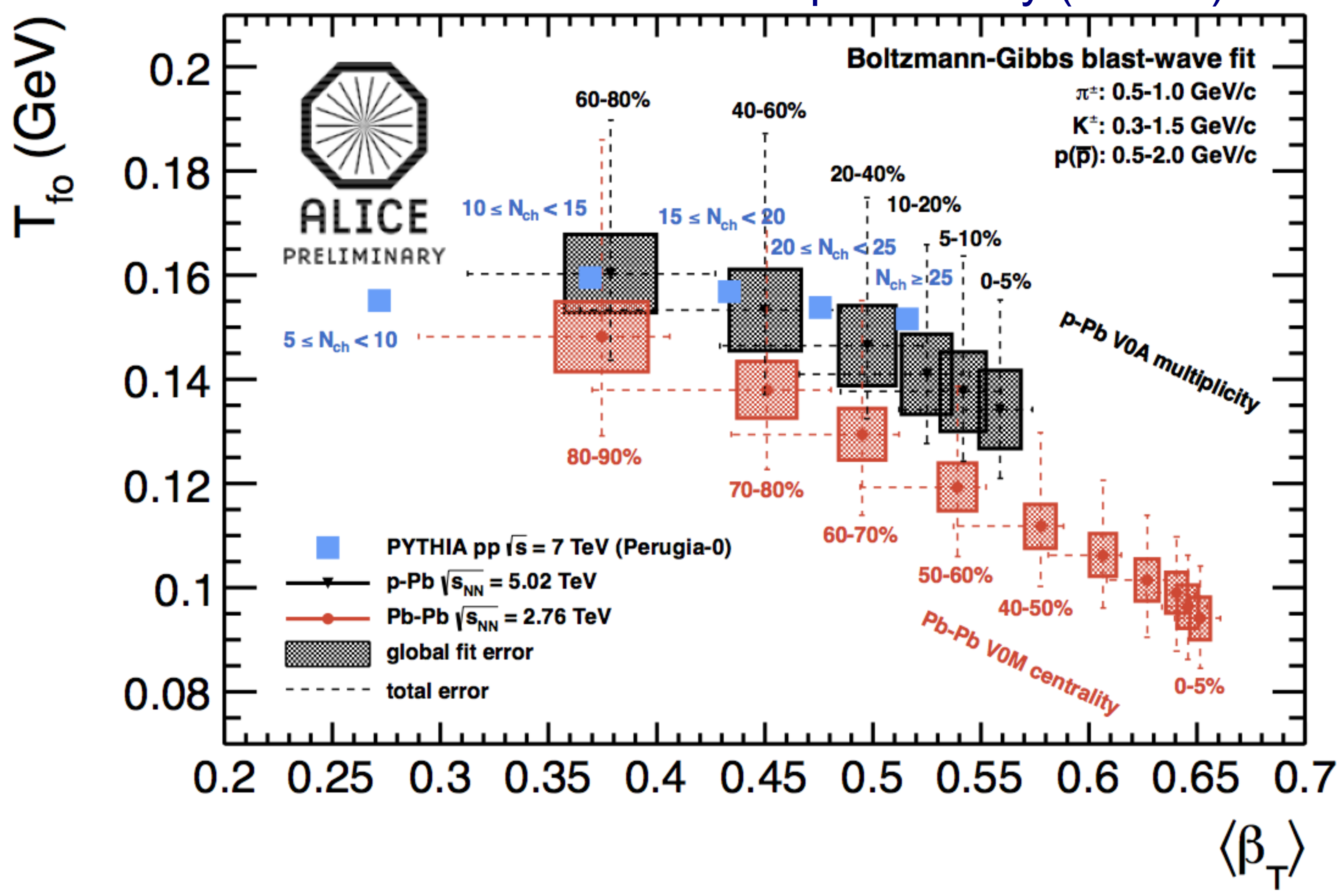
ALICE preliminary (Trento)



Blast-wave spectral analysis consistent with collective features (radial flow) present in pPb as in PbPb.
Not fully conclusive as also exhibited by PYTHIA.

Comparison with hydrodynamical model

Prediction from Bozek model

Bozek, PRC 85, 014911 (2012)

- initial conditions form Glauber Monte Carlo
- E-by-E (3+1)-D viscous hydrodynamic expansion
- statistical hadronization at freeze-out (Cooper-Frye)

Comparison done for similar $dN_{ch}/d\eta$

ALICE (5-10% V0A)

$dN_{ch}/d\eta = 36.4 \pm 0.8$ $|\eta| < 0.5$

Bozek ($11 \le$ Npart ≤ 17)

$dN_{ch}/d\eta = 38.9$ $|\eta| < 1.0$

- reasonable agreement between data and model

data/model ratio rather flat at low p_T (where hydro would dominate)

arbitrary absolute normalization (approximate multiplicity match)

ALICE preliminary (Trento)