Experimental overview on small colliding systems at LHC

(Special session on “QGP in small systems?”)

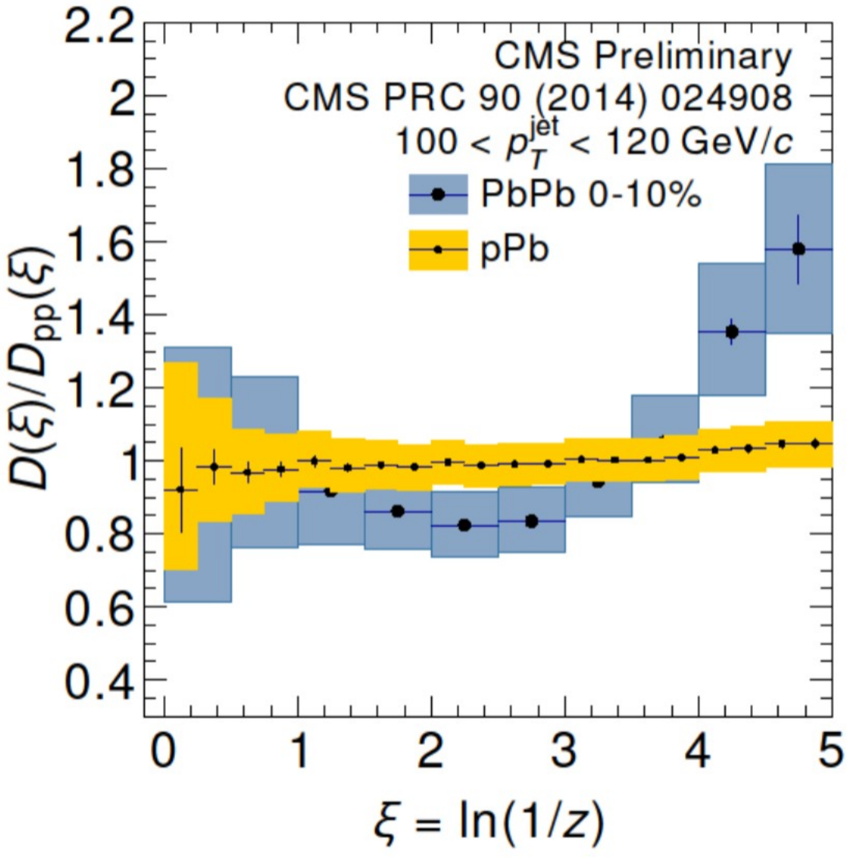
Constantin Loizides
(LBNL)

02 October 2015

Outline

Empirically, hot QGP ≡ P_{QCD} AND pQCD AND NOT pA
(cf.Gyulassy, arXiv:nucl-th/0403032)

- Key results related to bulk properties in pPb and pp at high N_{ch}
- Discussion



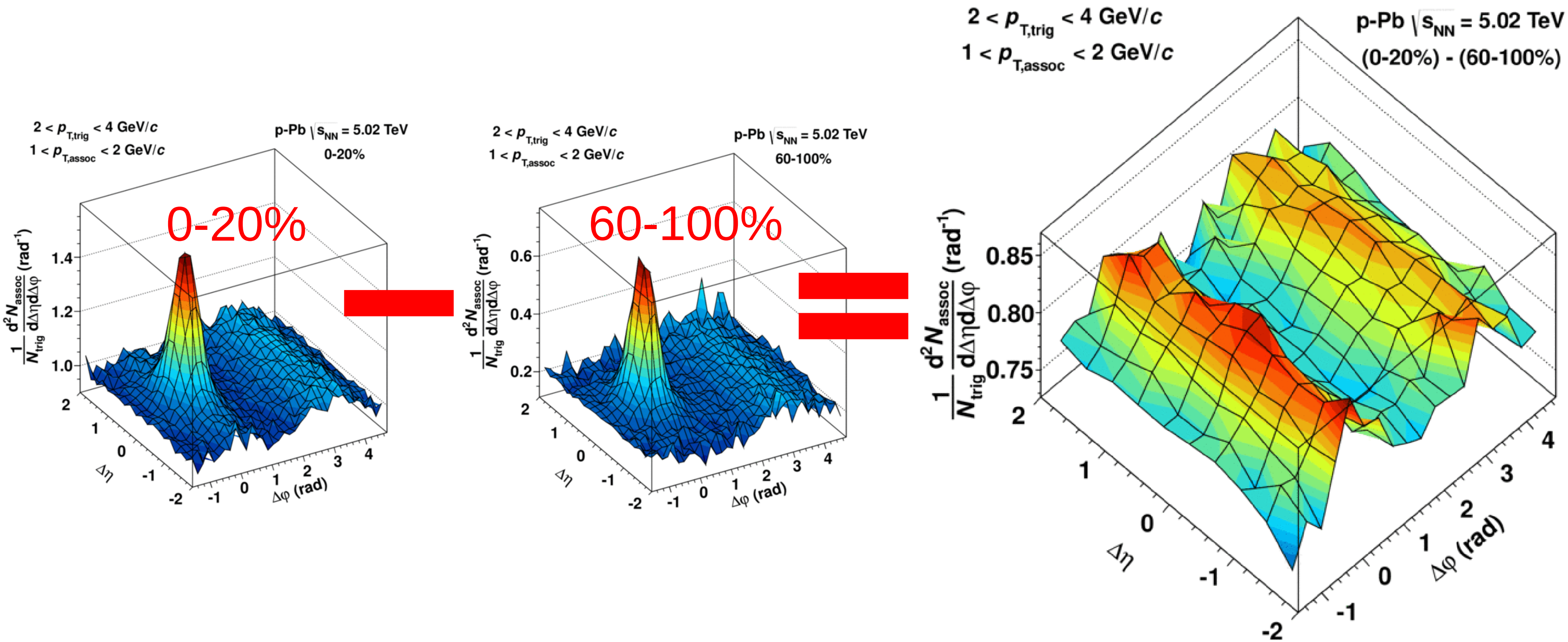
Only a selection of all available results shown, find them all here:

ALICE results: http://aliceinfo.cern.ch/ArtSubmission/publications

ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

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

Observation of double ridge in p-Pb



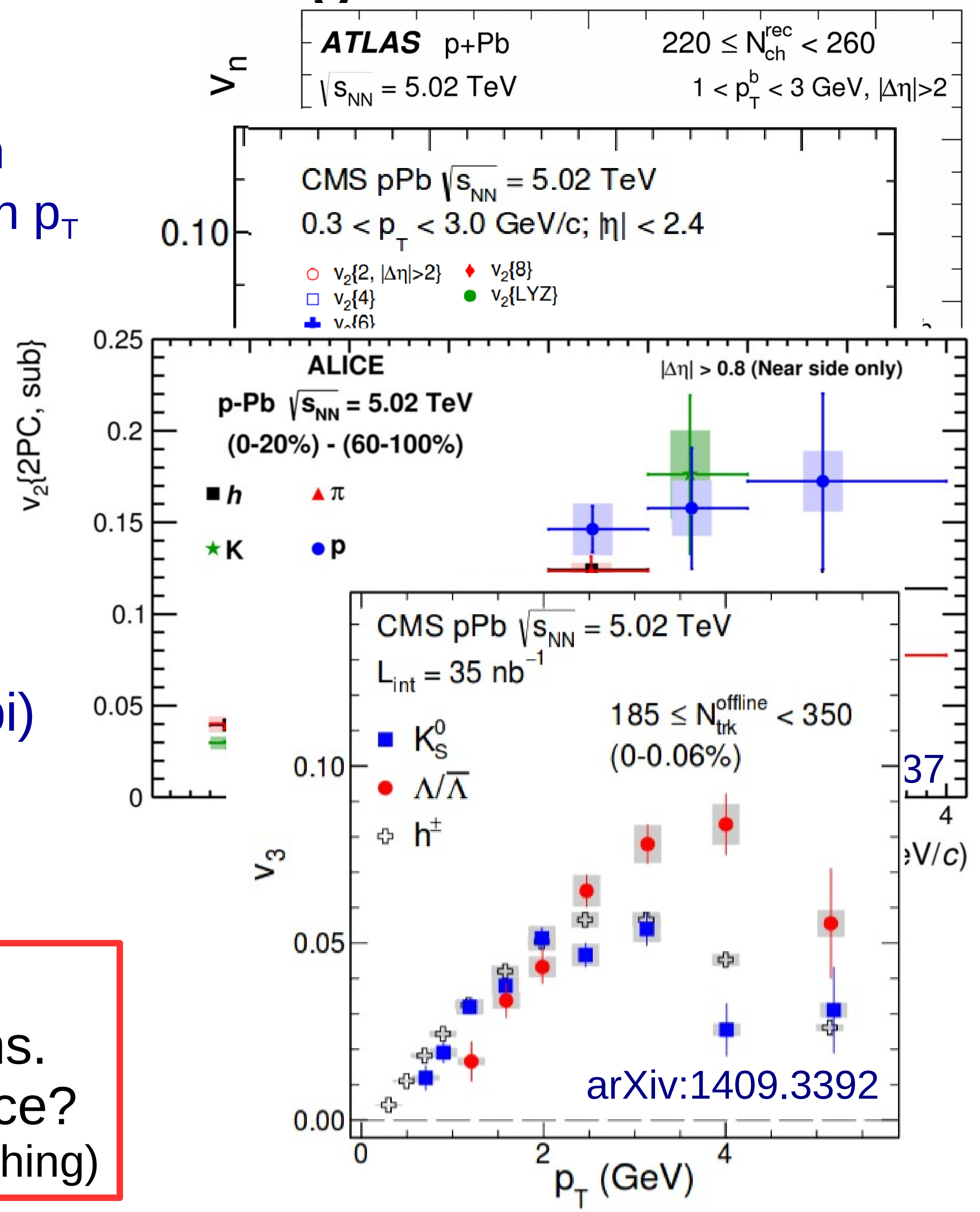
- Suppress non-flow by subtracting per-trigger yields from low mult.
  - Checked that per-trigger yields in 60-100% are similar to pp
  - For large N_{ch}, can use η-gap method instead

ALICE, PLB 719 (2013) 29
ATLAS, PRL 110 (2013) 182302

4 Key features of double ridge

arXiv:1409.1792

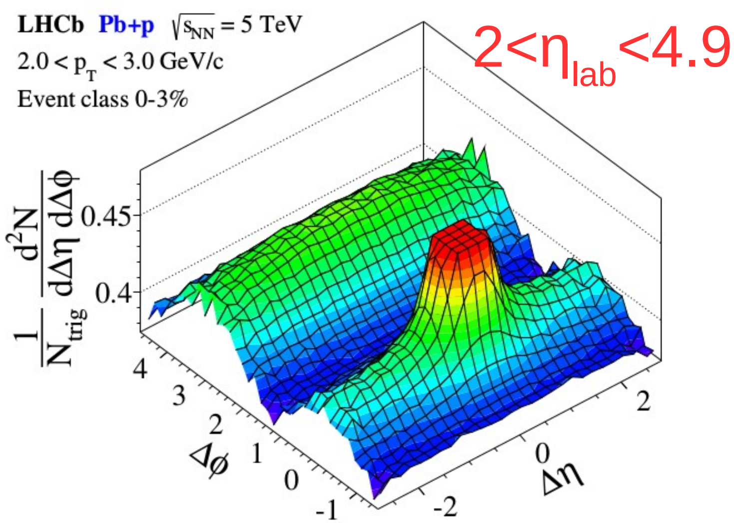
- v_n coefficients
  - Significant v_N (n=2 to 5) with "familiar" ordering + shape in p_T
  - Substantial to even high p_T
- Multi-particle correlations
  - All particles correlated ($v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{LYZ\}$)
- Particle species dependence
  - Crossing of v_2(p) with v_2(pi) at p_T about 2 GeV/c
  - Similar for $v_3(\Lambda)$ vs v_3(K)



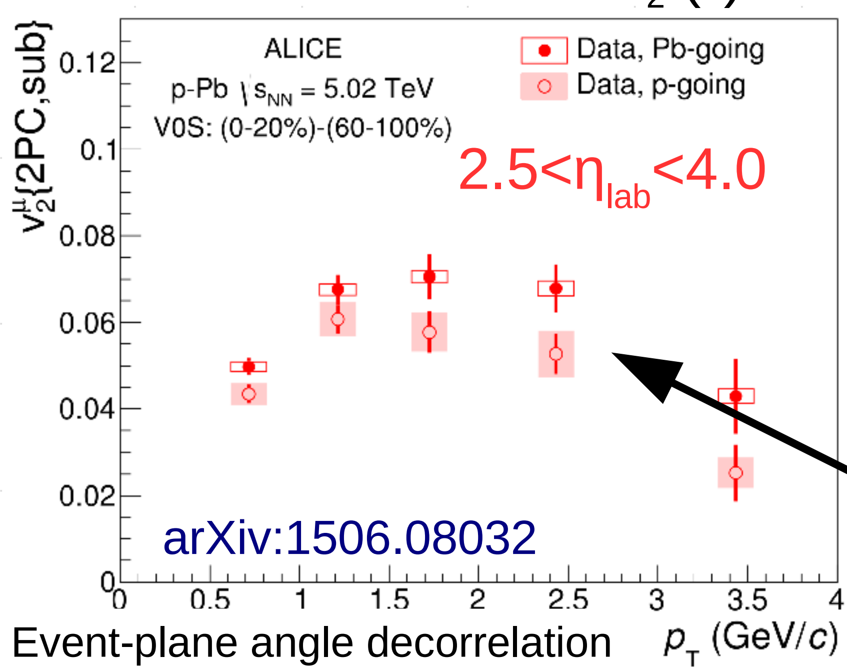
Features qualitatively similar
to those seen in Pb-Pb collisions.
Suggests similar physics at place?
(Note: no direct evidence of jet quenching)

Pseudo-rapidity dependence

LHCb-CONF-2015-004

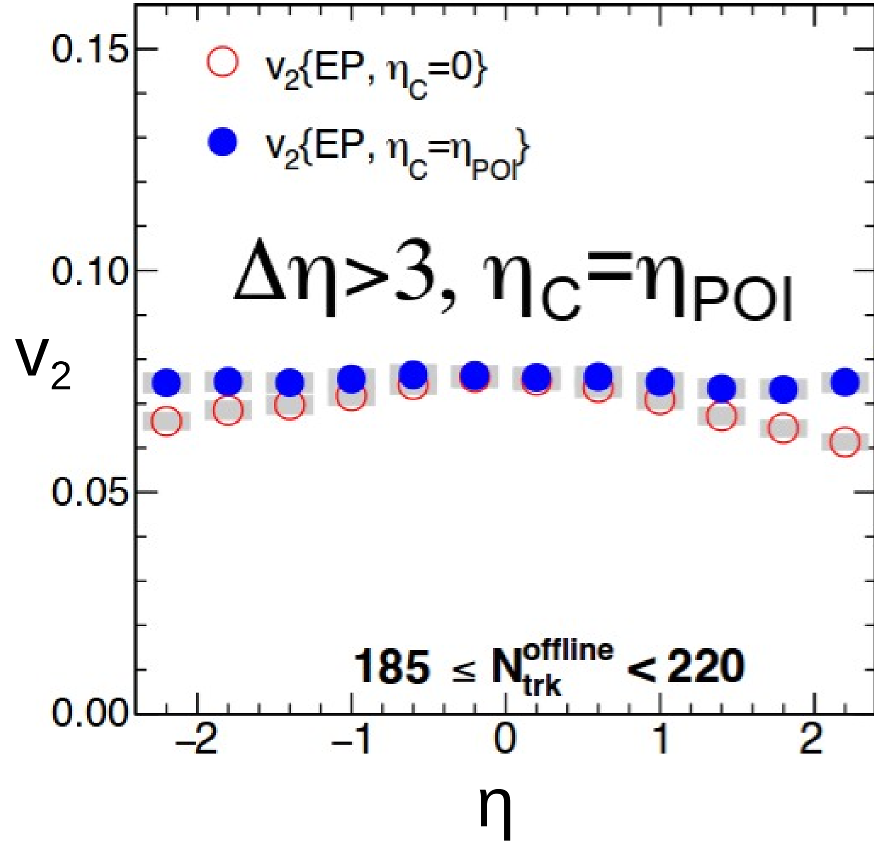


Inclusive muon v_2 (*)



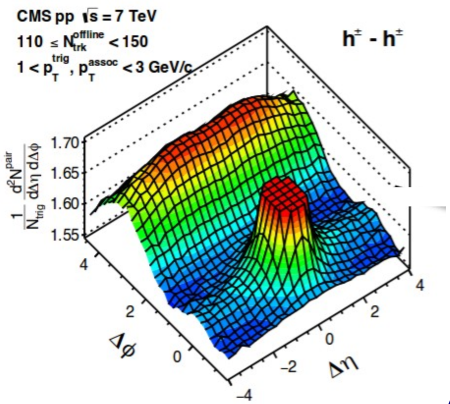
(*) Event-plane angle decorrelation in η not taken into account

CMS-PAS-HIN-15-008

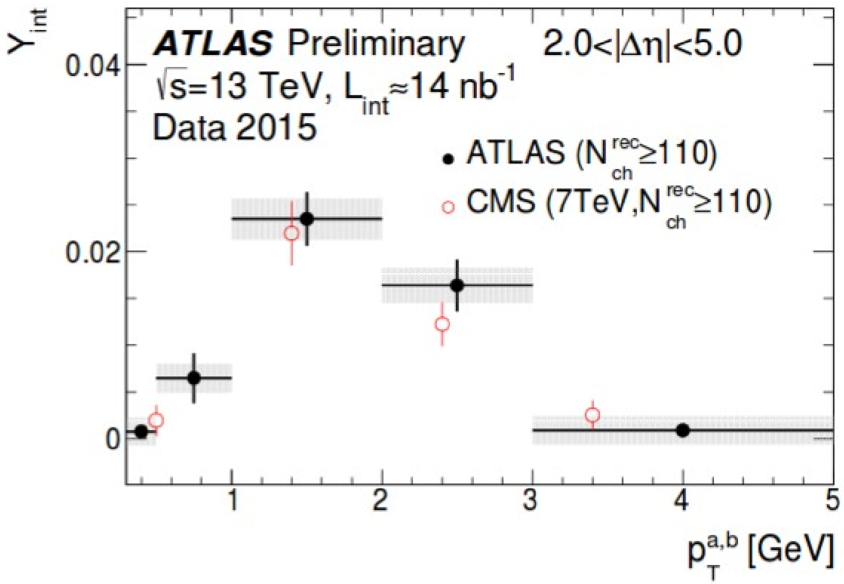


- Ridge extends to $2<\eta_{lab}<4.9$
- Flat η-dependence
- Inclusive muon v_2 measured
  - Above 2 GeV/c sensitive to muons from HF decays

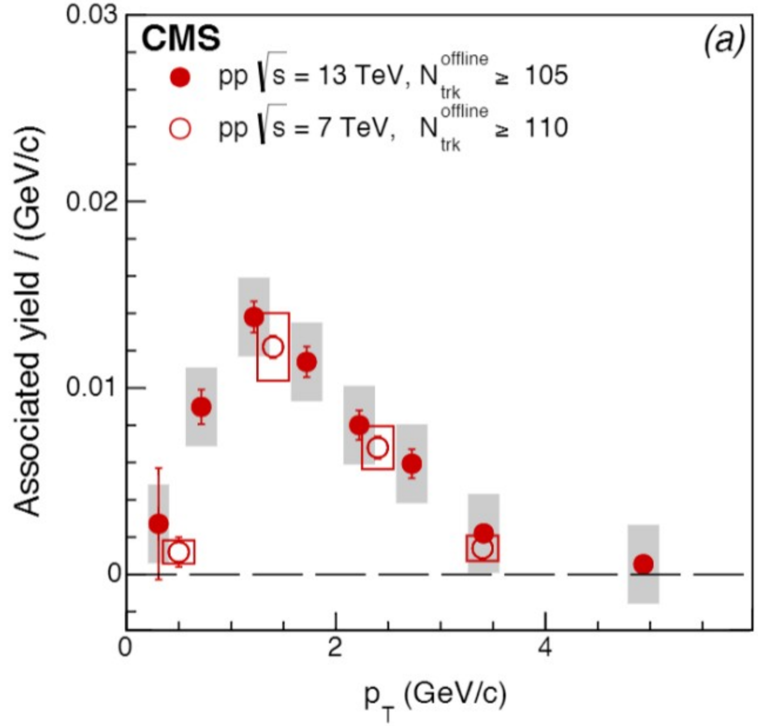
NS ridge in pp



ATLAS-CONF-2015-027



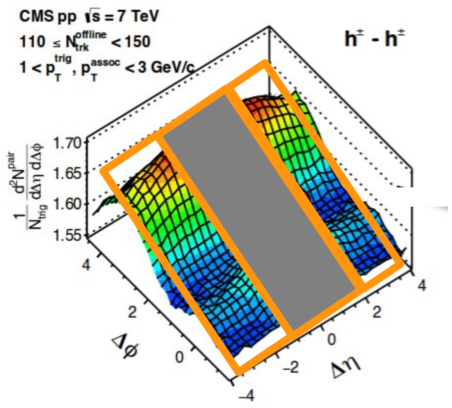
CMS-FSQ-PAS-15-002

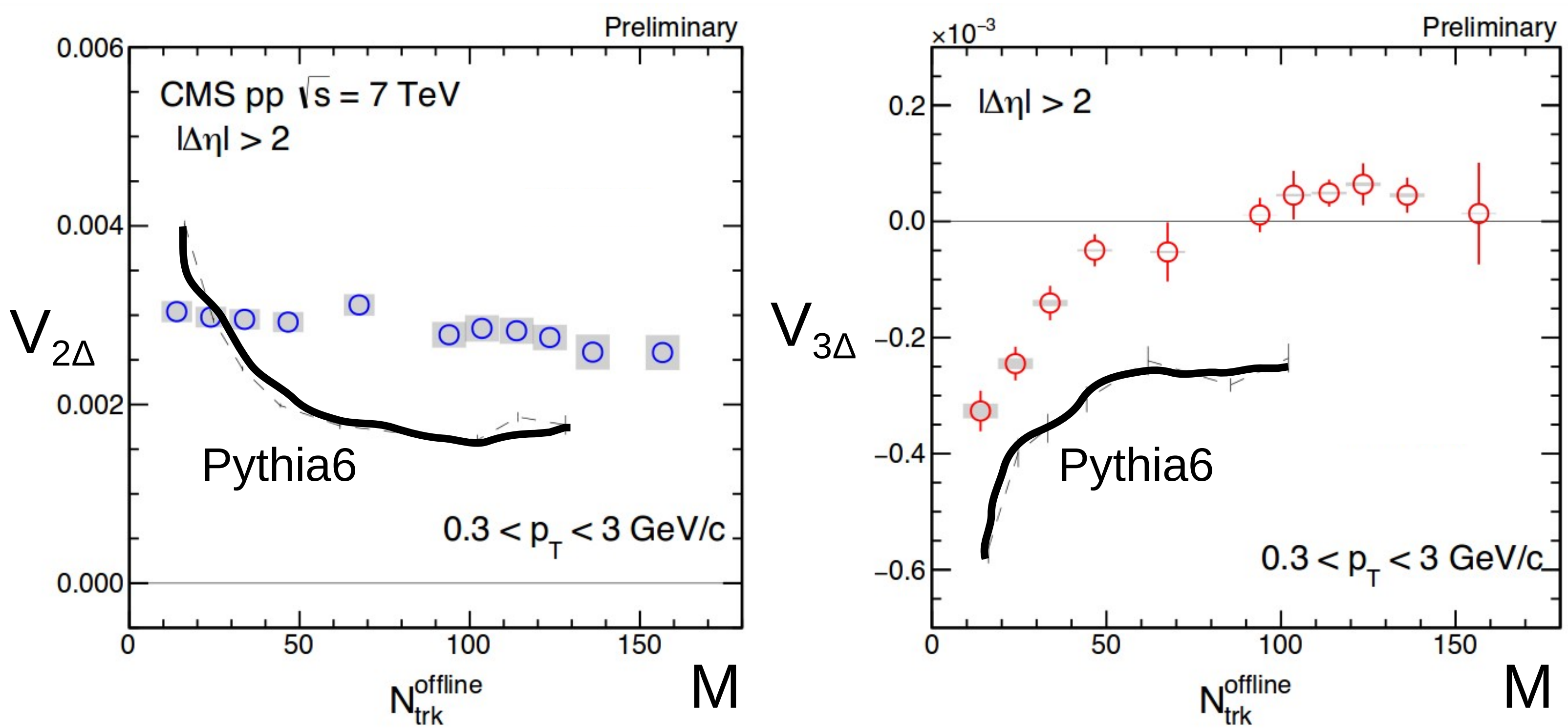


The ridge yield does not significantly change with collision energy
(Confirmation by two experiments!)

The double ridge in pp – before subtraction

CMS-FSQ-PAS-15-002

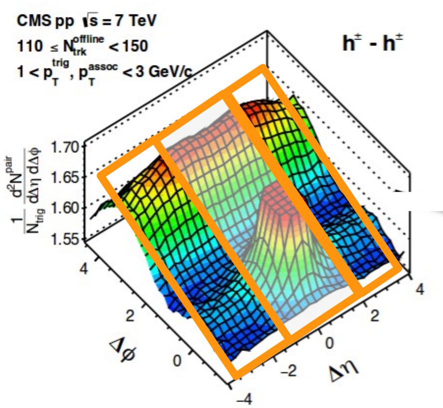




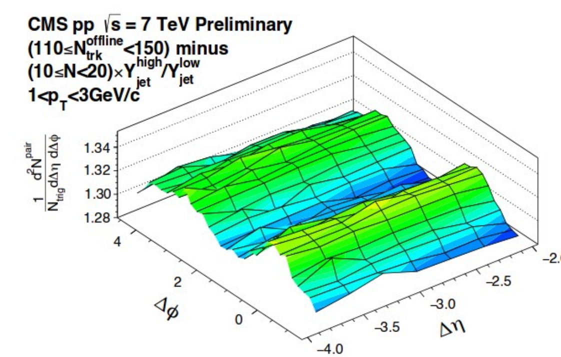
Two-particle long-range coefficients

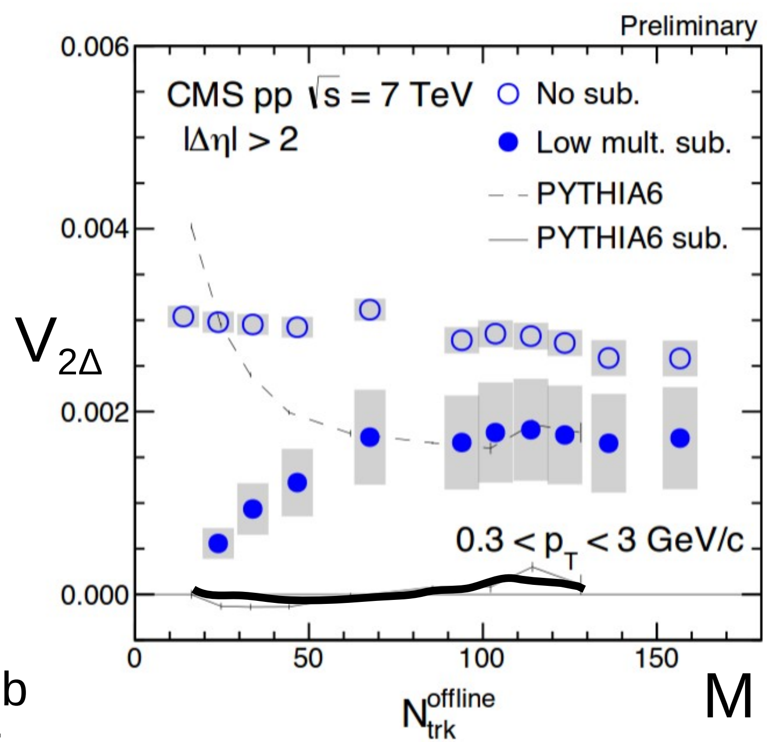
The double ridge in pp – after subtraction

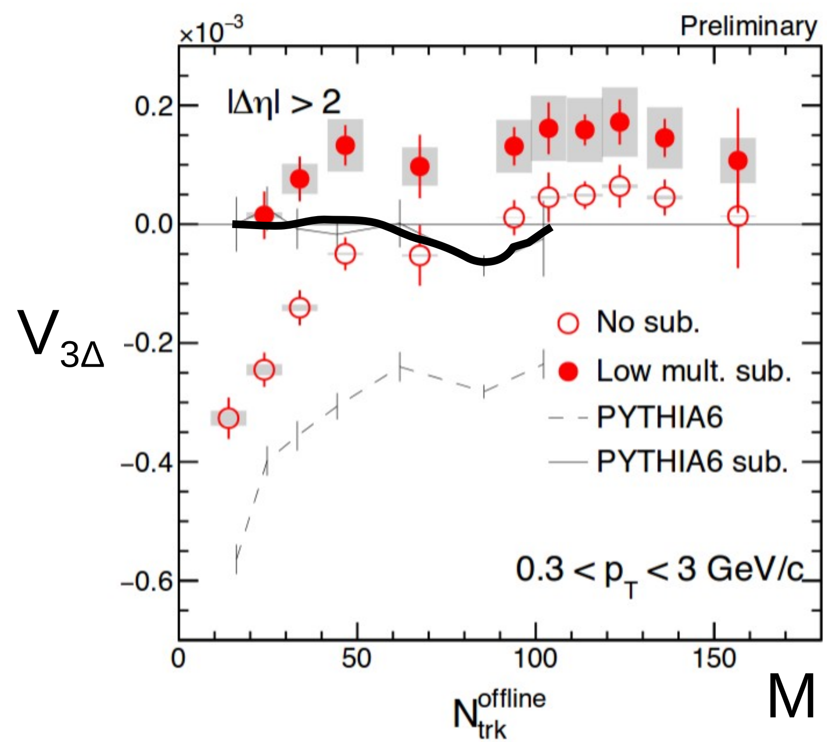
CMS-FSQ-PAS-15-002



- Scale low multiplicity yield by ratio of NS jet yield in high over low (after subtracting the long range correlation in both)





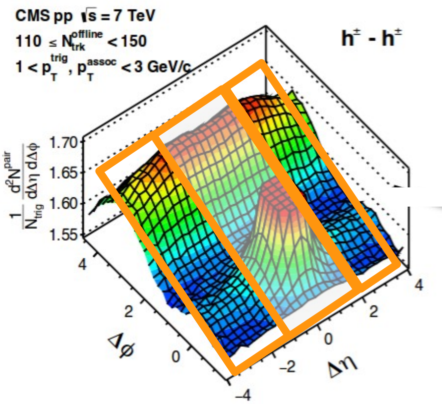


(Method used in p-Pb by ALICE usually for systematics, see eg. arXiv:1212.2001)

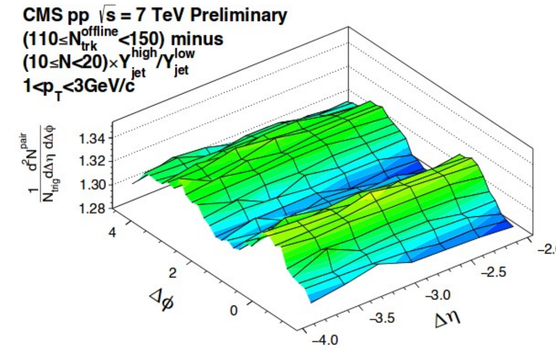
Two-particle long-range coefficients

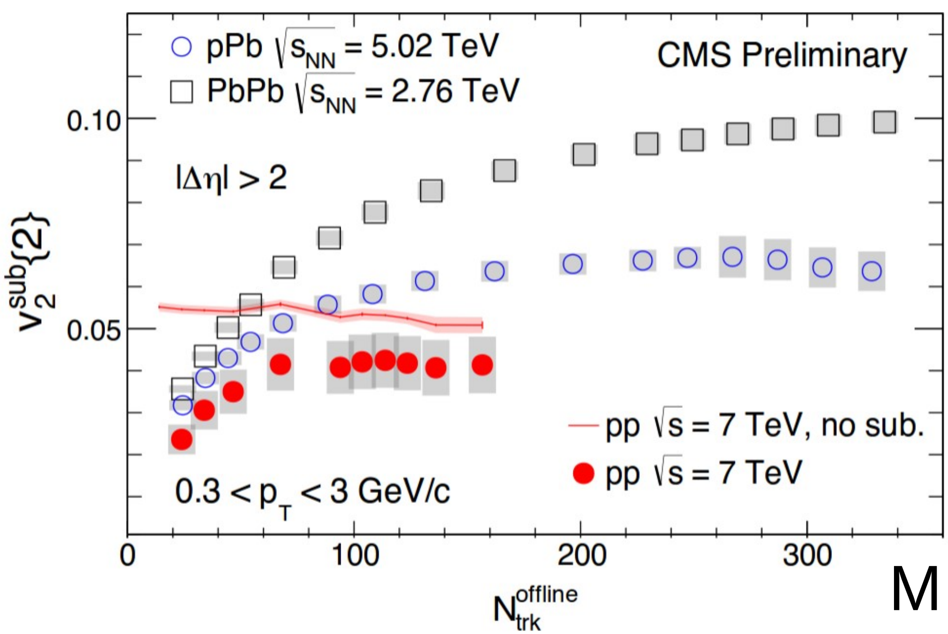
v_2 in pp (at 7 TeV)

CMS-FSQ-PAS-15-002

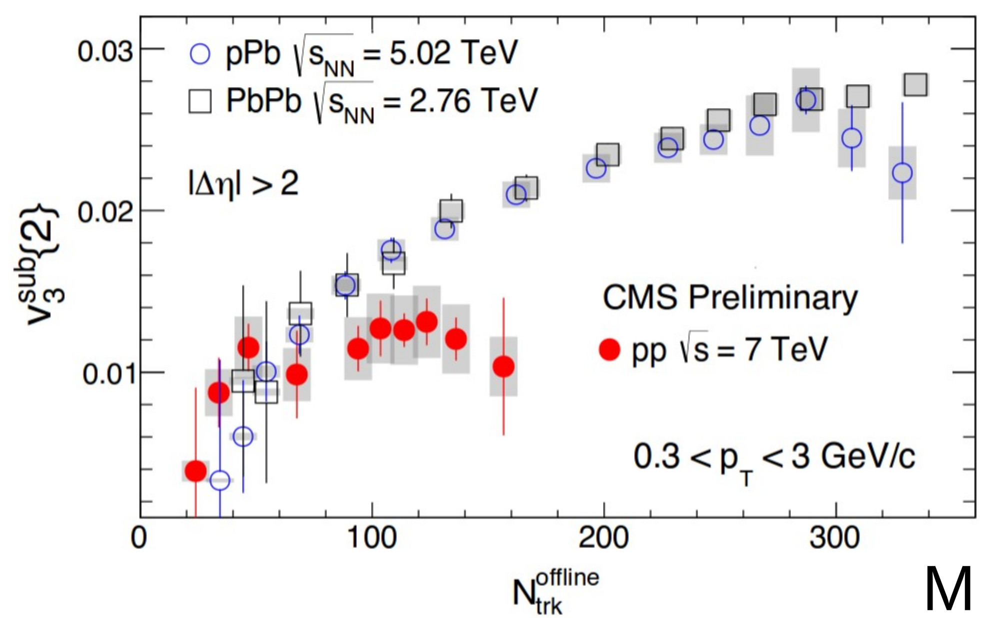


- Scale low multiplicity yield by ratio of NS jet yield in high over low (after subtracting the long range correlation in both)





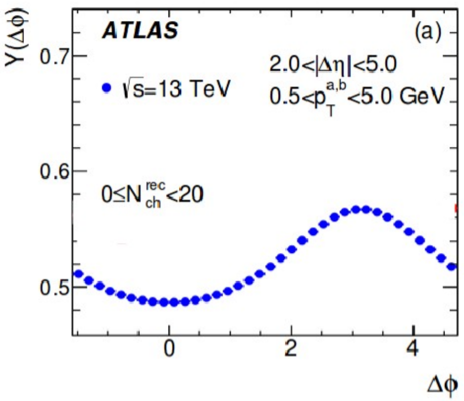
$v_2(pp) \approx 4\%$ at high M

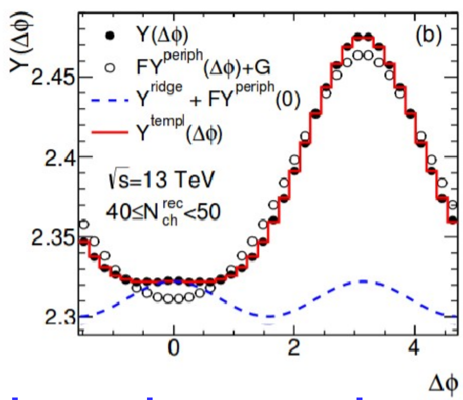


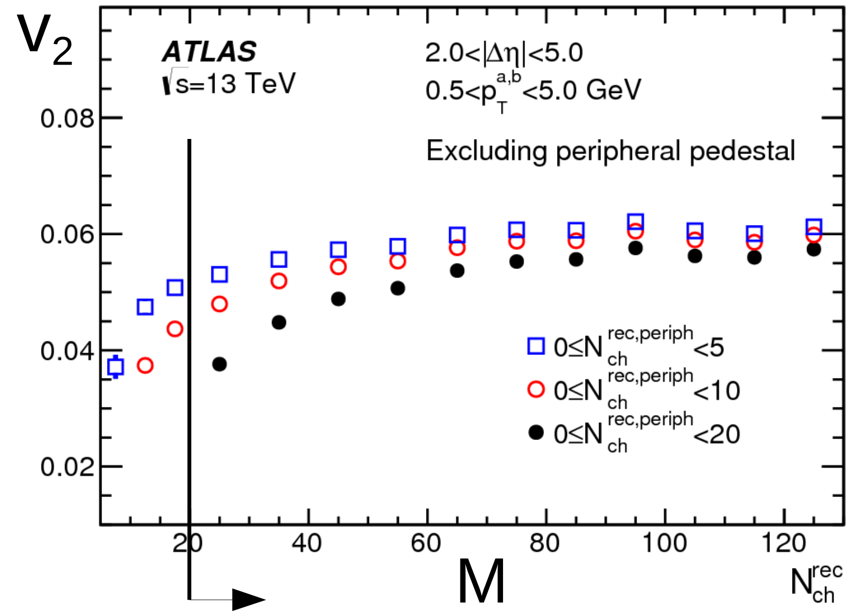
$v_3(pp) \approx 1.2\%$ at high M

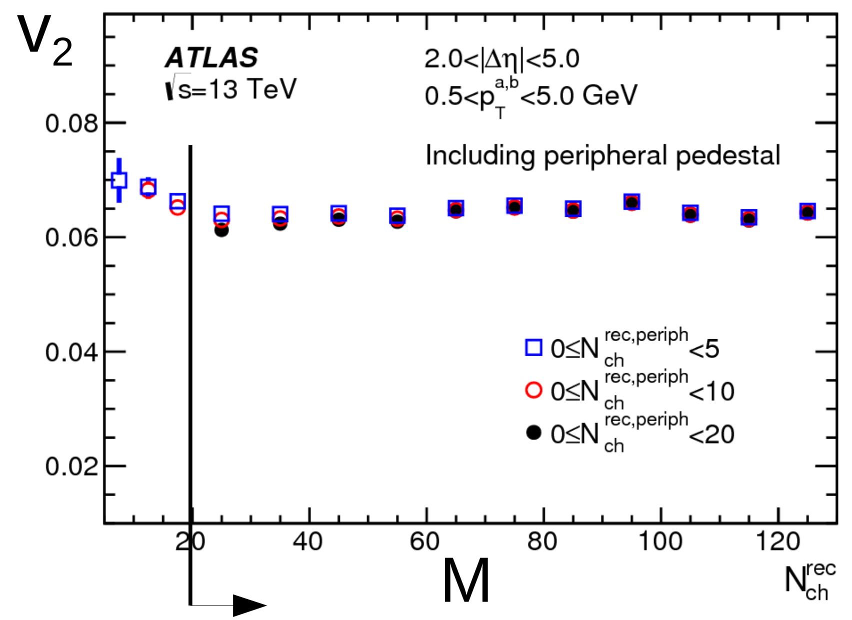
10 Double ridge in pp (at 13 TeV)

ATLAS, arXiv:1509.04776









Result reported above 20

- Peripheral subtraction via template fit to determine F and $v_{2,2}$

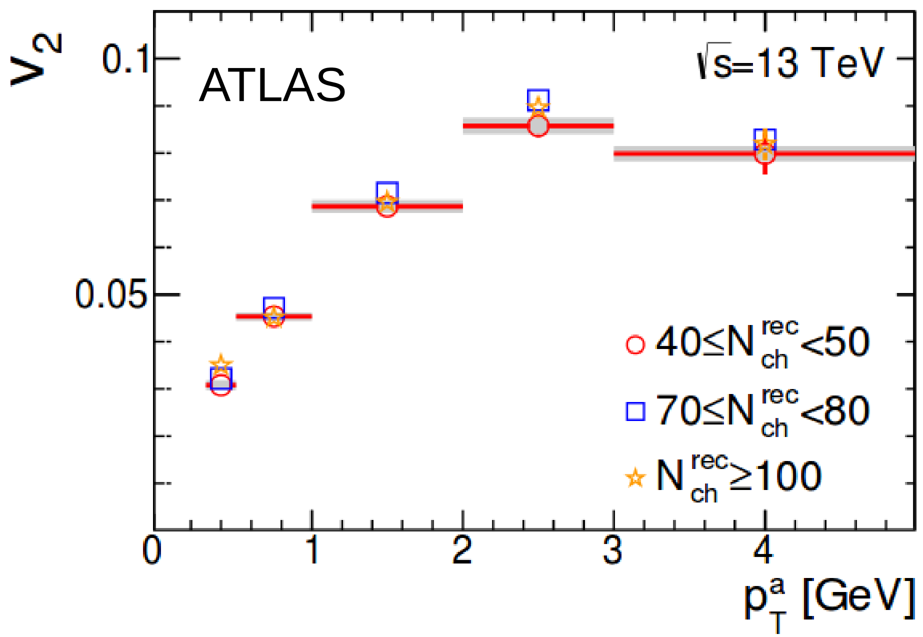
$$Y^{\text{temp}}(\Delta\Phi) = F\,Y^{\text{periph}} + Y^{\text{ridge}}$$

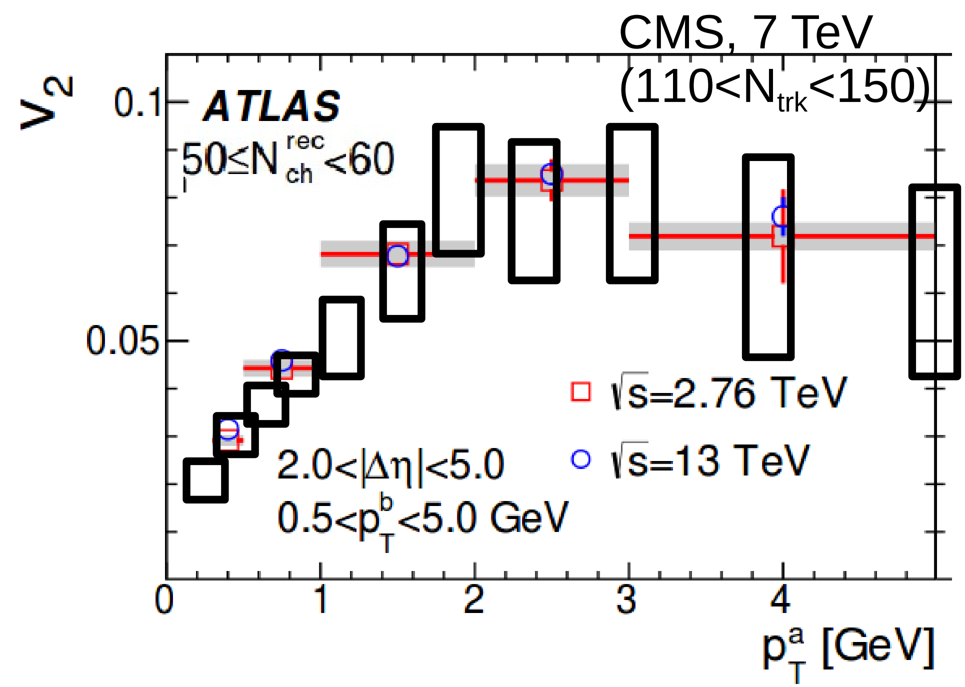
$$Y^{\text{ridge}}(\Delta\Phi) = G(1 + v_{2,2}\cos(2\Delta\Phi))$$

- Two particle coefficients found to factorize into single particle ones
- At low N_{ch} ambiguity whether to allow or not a $v_{2,2}$ component in peripheral
  - Role of different event types (diffraction) in low M events?
  - Needs more study: for now take it as method uncertainty on v_2 at low M

11 $v_2(p_T)$ in pp

ATLAS, arXiv:1509.04776

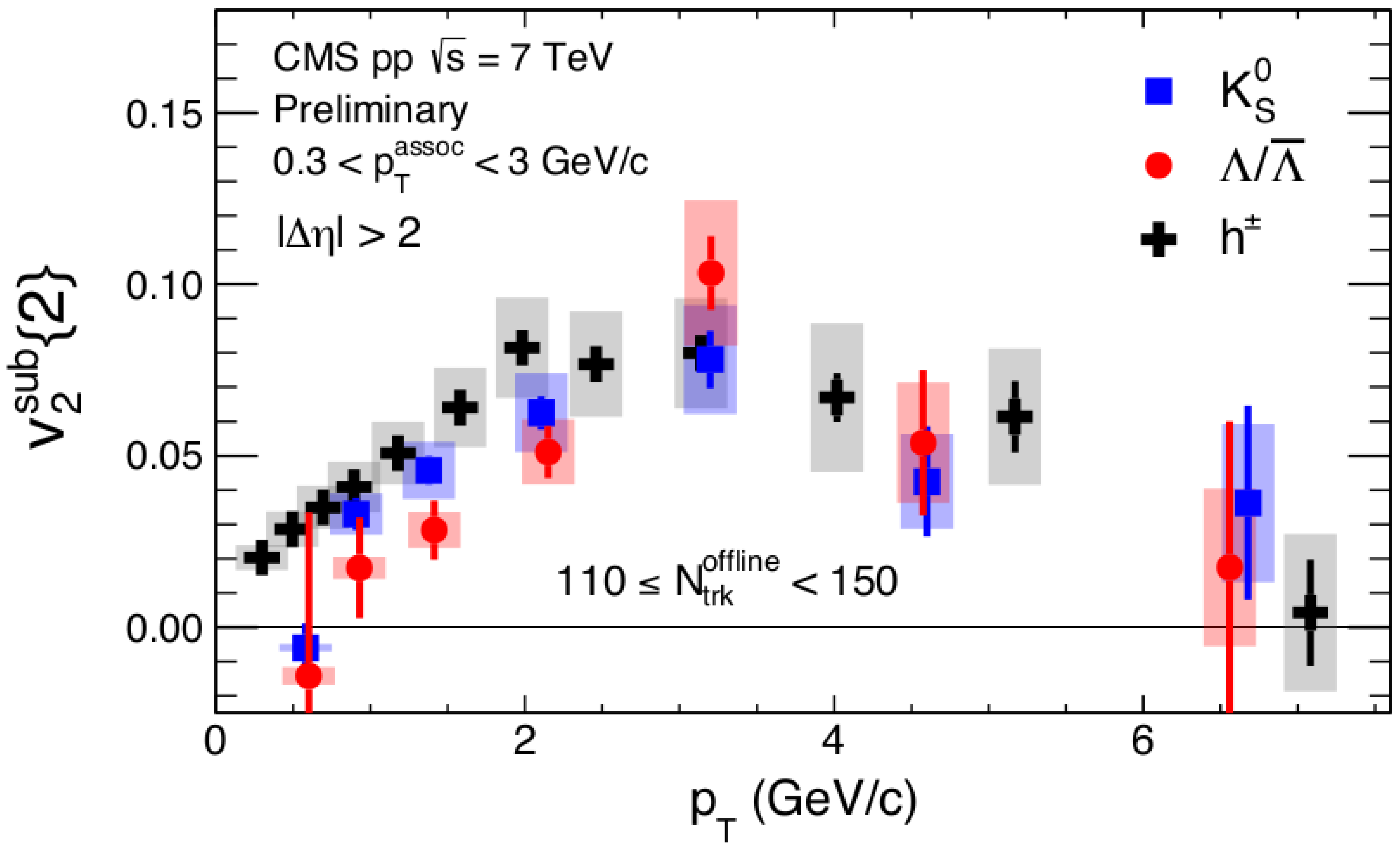




- Multiplicity independence (unambiguous for M>~70)
- Collision energy independence
  - Also consistent with the CMS data at 7 TeV

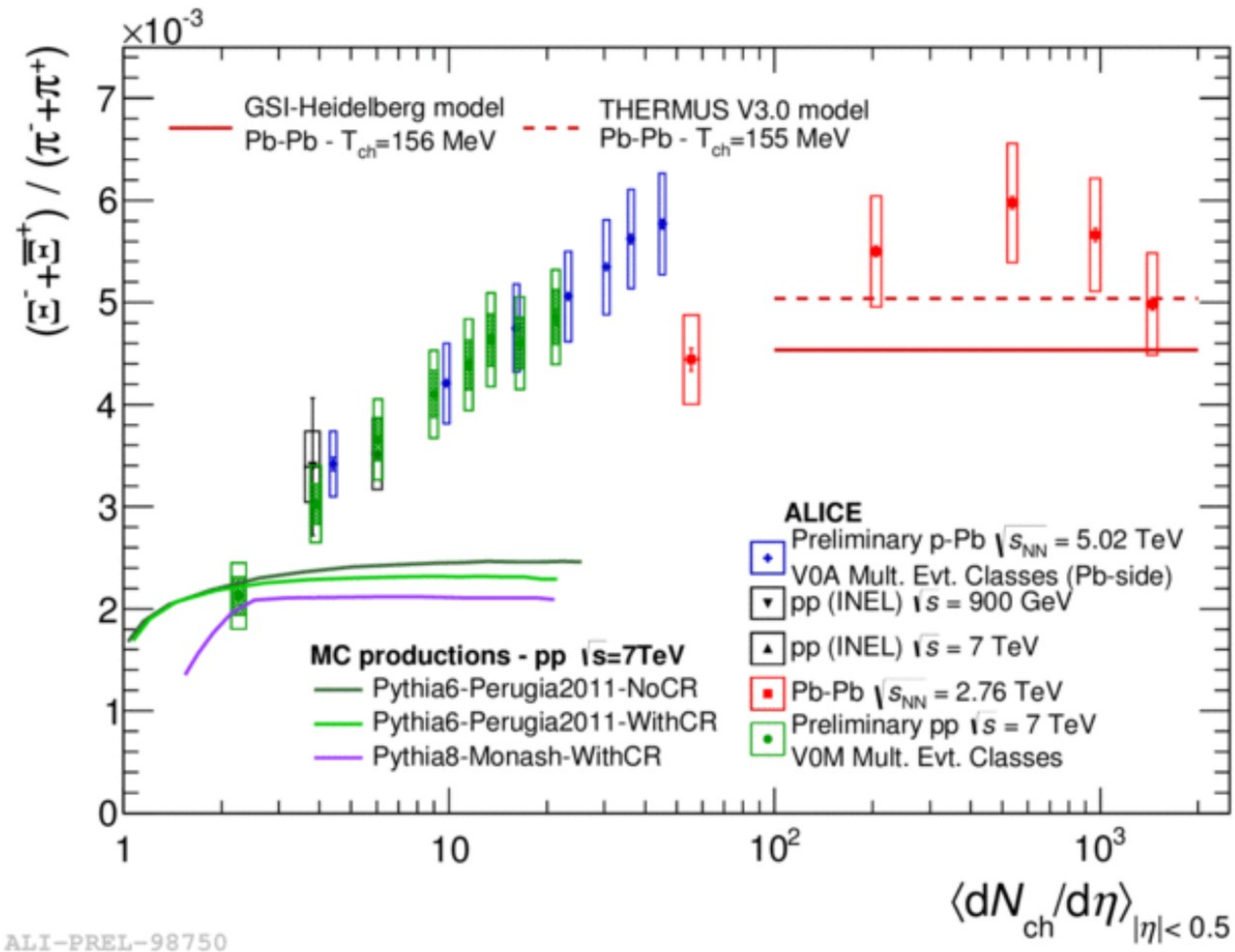
12 PID dependence of v_2 in pp

CMS-FSQ-PAS-15-002



Mass ordering and crossing (?) in low p_T region for high multiplicity

Particle ratios vs multiplicity



Steady release of canonical suppression with increasing M

(same for Λ, less so for Ω, and Φ≈flat)

14 Summary (observables) Pb-Pb, p-Pb, pp (at high M)

- Low p_T spectra (radial flow): yes, yes↑, yes↑
- Particle ratios: GC level, except Ω ≈ at high N_{ch}, similar trend
- Statistical model: GC (to 10-30%), $\gamma_s \approx 1$ (larger deviations), $\gamma_s < 1$ (MB)
- Azimuthal anisotropy (v_n): n=1-6, n=1-5, n=2,3
  - Higher order cumulants: $v_2\{4\}=...=v_2\{LYZ\}$, $v_2\{4\}=...=v_2\{LYZ\}$, subtr. only
  - Characteristic p_T shape: yes, yes, yes (subtr. only)
  - Characteristic multiplicity dep.: yes, yes, ?
  - Weak η dependence: yes, yes, -
- Mass dependence: v_2,v_3, v_2,v_3 (only sub
- Factorization breaking: yes, yes, ?
- v_n distributions: yes, -, -
- Event angle and v_N correlations: yes, -,
- HBT radii (k_T, R_{out}/R_{side}): yes,1, yes,≈1,
- Suppression (energy loss): yes, ?, -

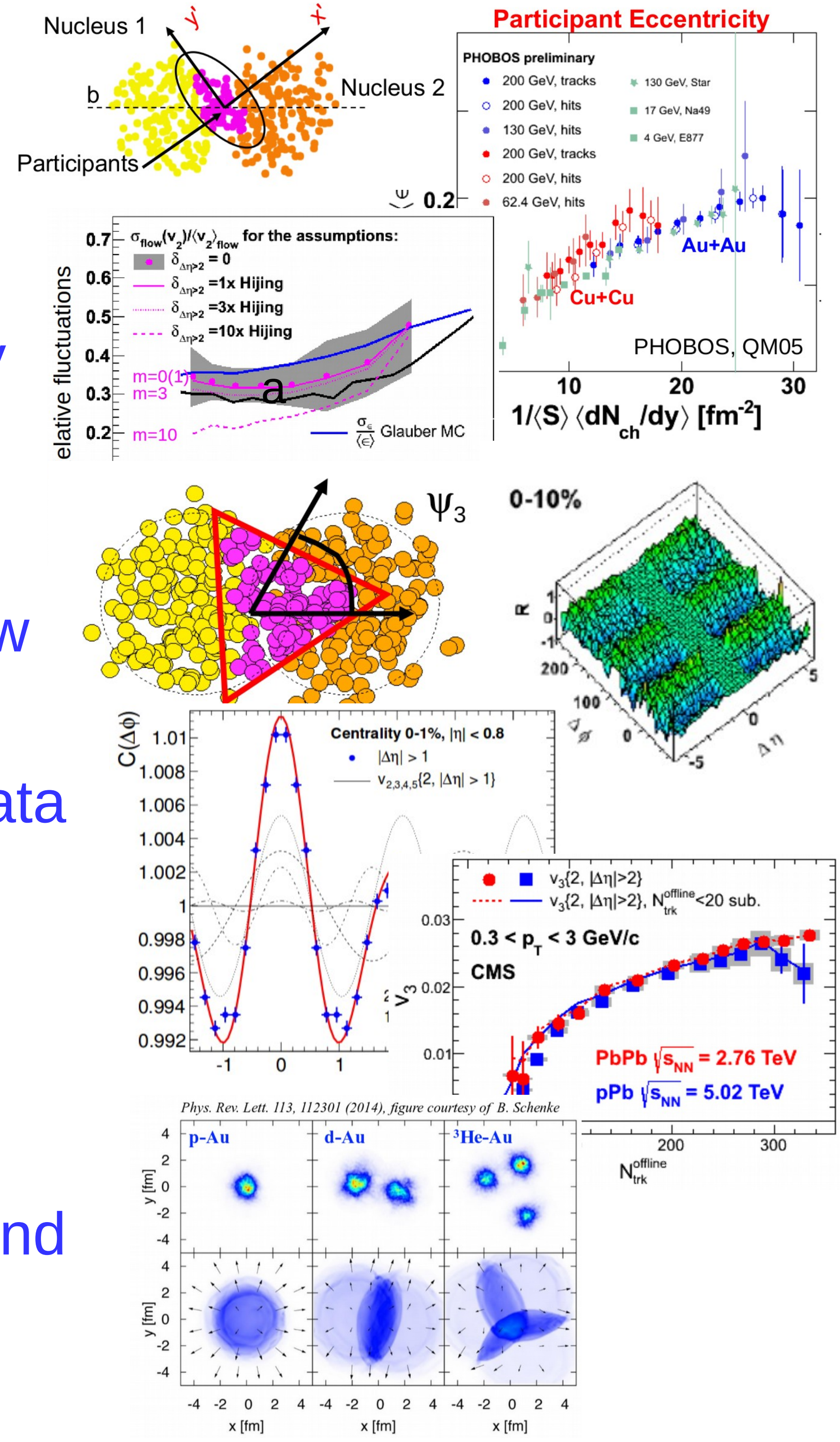
- Weak collectivity <u>proven</u> in Pb-Pb and p-Pb, not known in pp
- Strong collectivity (thermo +hydro dynamics) <u>compatible</u> with most Pb-Pb and p-Pb
- Only limited amount of data in pp at high N_{ch} but <u>compatible</u> with SC
  - Not unreasonable to expect pp≈pPb at high N_{ch}!

15 What is the underlying physics?

- Hypothesis:
  The Physics underlying the strong collectivity is the same
  - sQGP: thermo and hydrodynamics (maybe “at the edge”) (→Piotr)

Taking a look back...

- Larger than expected Cu-Cu v_2 lead to postulation of importance of geometry fluctuations and participant eccentricity
- Geometry fluctuations successfully predicted flow fluctuations
- Resulted in prediction for triangular flow based on “analogy” arguments
- Triangular flow visible in Pb-Pb LHC data
- Geometry fluctuations also allow to understand the p-Pb (pp?) data
  - Sub-nuclear scales become important
- Geometry engineering at RHIC with successful predictions on p-Au, d-Au and ^{3}He-Au



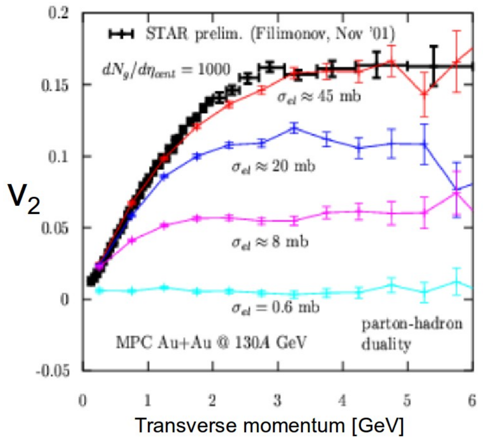
17

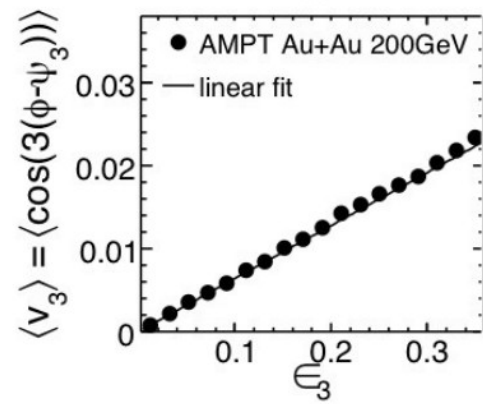
What is the underlying physics?

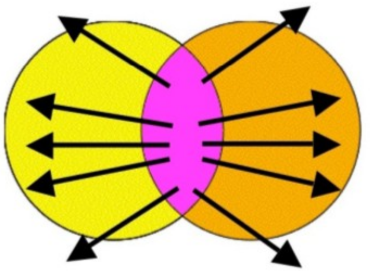
- Hypothesis:
  The Physics underlying the observed collectivity is the same
  - sQGP: thermo and hydrodynamics (maybe "at the edge") (→Piotr)
    - Inconsistent with large v_2 and without direct evidence of jet quenching?

18 On the other hand ...

- Hydro at RHIC established also because parton cascade needed huge cross sections
  - Today, know that 1.5-3mb works for AMPT
- AMPT was used to substantiate postulation of triangularity. It had the right underlying geometry fluctuations all the time!
- Many of us thought that developing v_n via interactions (transport) is in principle the same as via pressure gradients (hydro)
  - But neglects fake flow due to anisotropic escape probability (dominant even in AA?)
- AMPT describes a lot of data but with questionable concepts
  - String melting into quarks, parton formation and spatial coalescence
  - Check if / where current models need corrections







See Guo-Liang Ma, Mon
Zi-Wei Lin, Wed
Jamie Nagle, Tue
arXiv:1502.05572

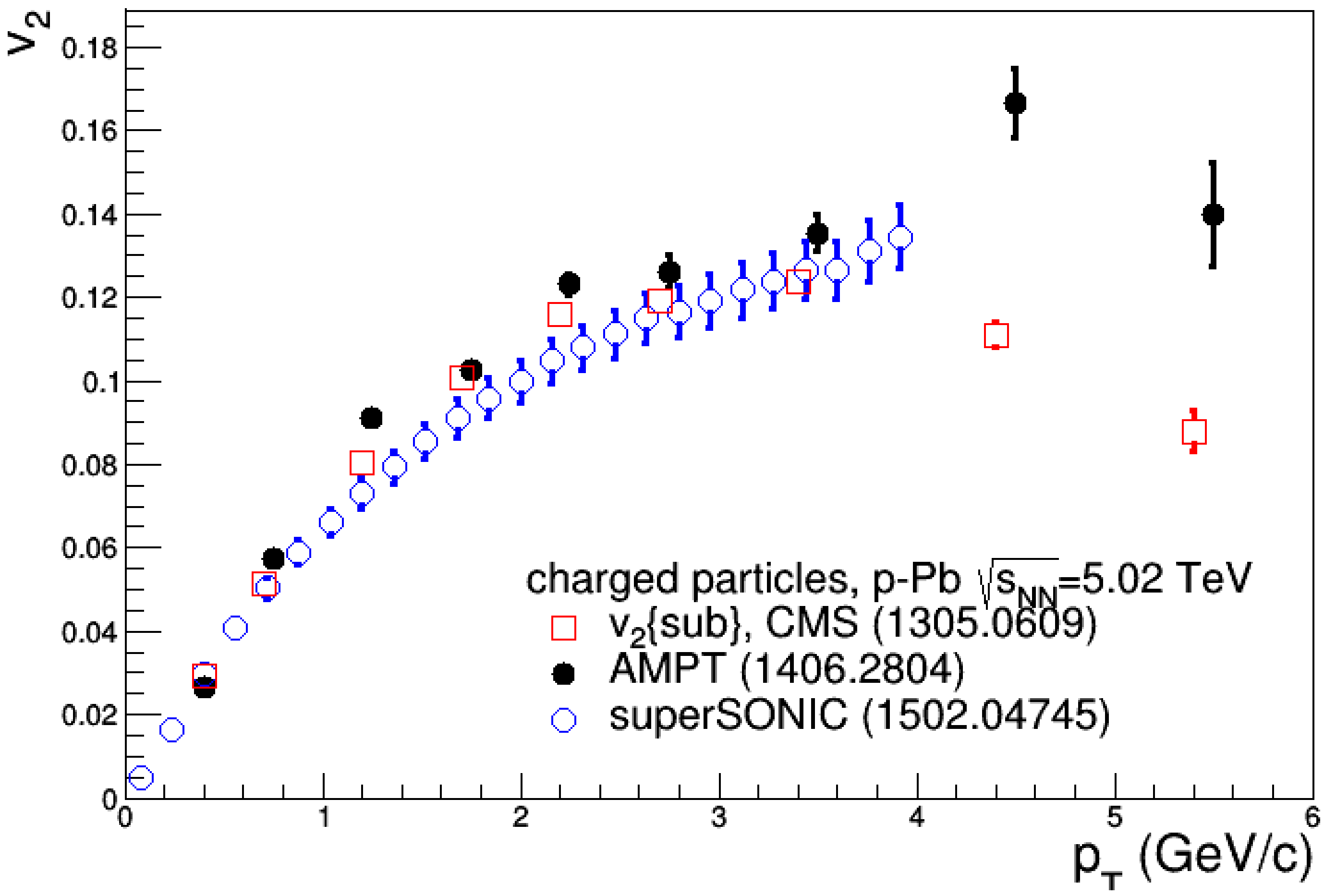
19 What is the underlying physics?

- Hypothesis:
  The Physics underlying the observed collectivity is the same
  - sQGP: thermo and hydrodynamics (maybe “at the edge”) (→Piotr)
    - Inconsistent with large v_2 and without direct evidence of jet quenching?
  - sMOG(*): non-equilibrium parton dynamics (maybe can drive the system from weak to strong collectivity?) (→Paul)
  - CGC + “evolution model” (→Soeren)
- Why bother with small systems?
  - Study “dynamics” instead of “equilibrium”
  - Validate, refine (or invalidate?) “perfect fluid” paradigm
  - Test fundamental QCD due to relevance of sub-nucleonic dof.

(*) J.Schukraft, Collectivity workshop, BNL 2015

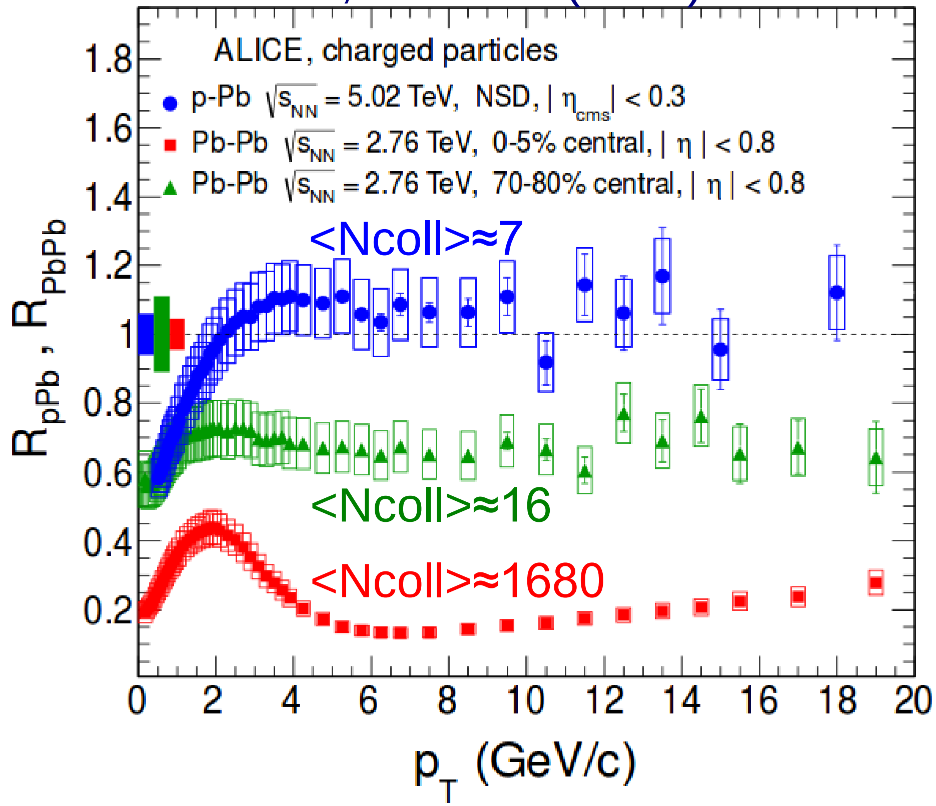
20 Extra

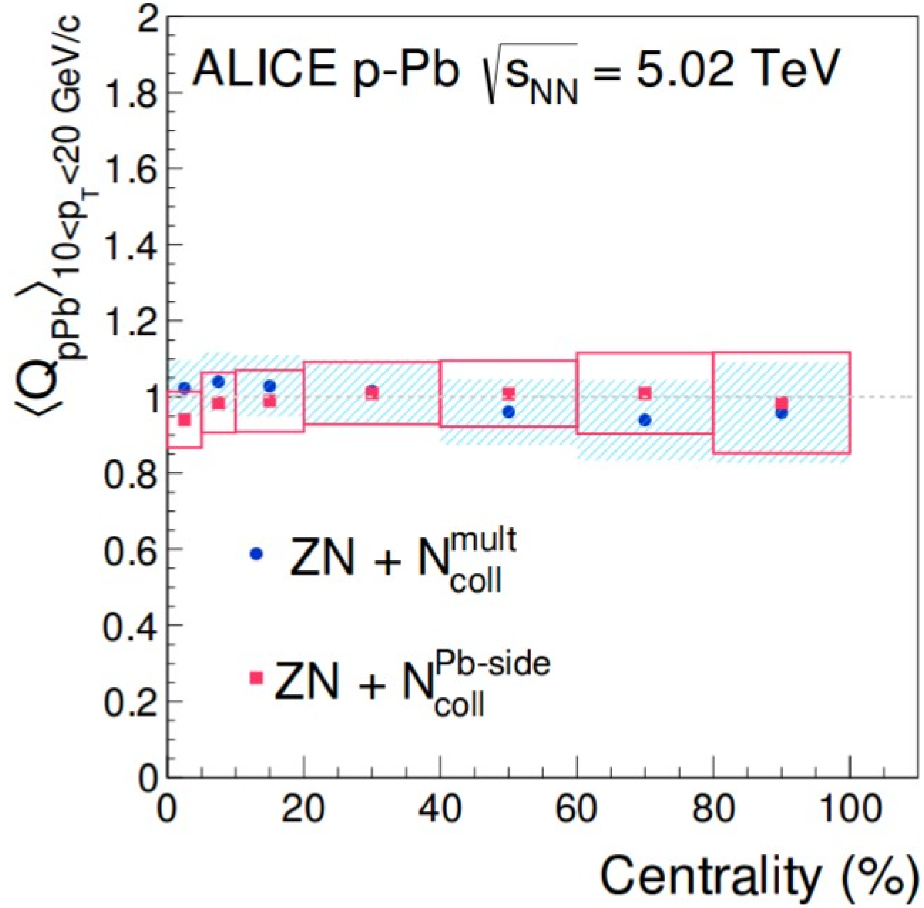
Example for AMPT and superSonic



Final state effects ?

ALICE, PRL 110 (2013) 082302

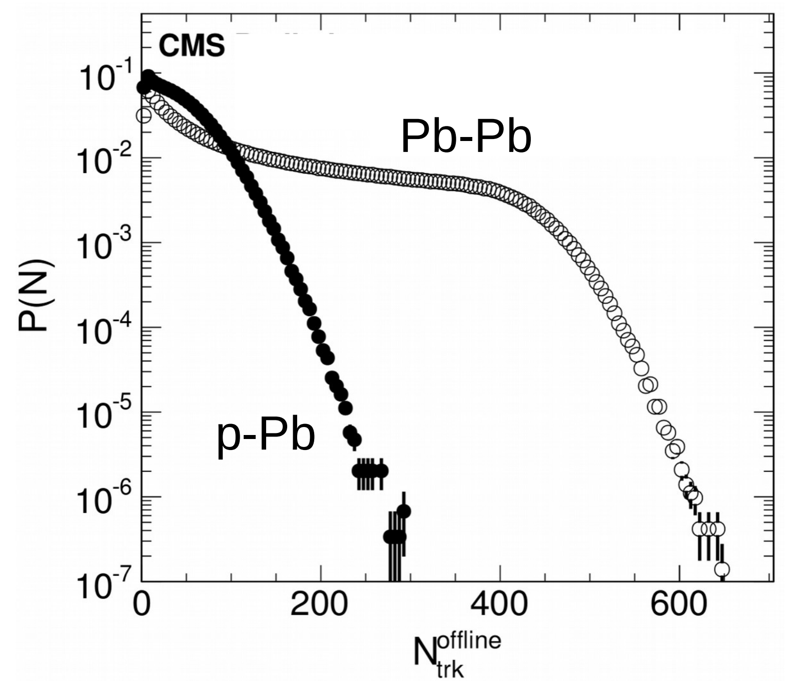


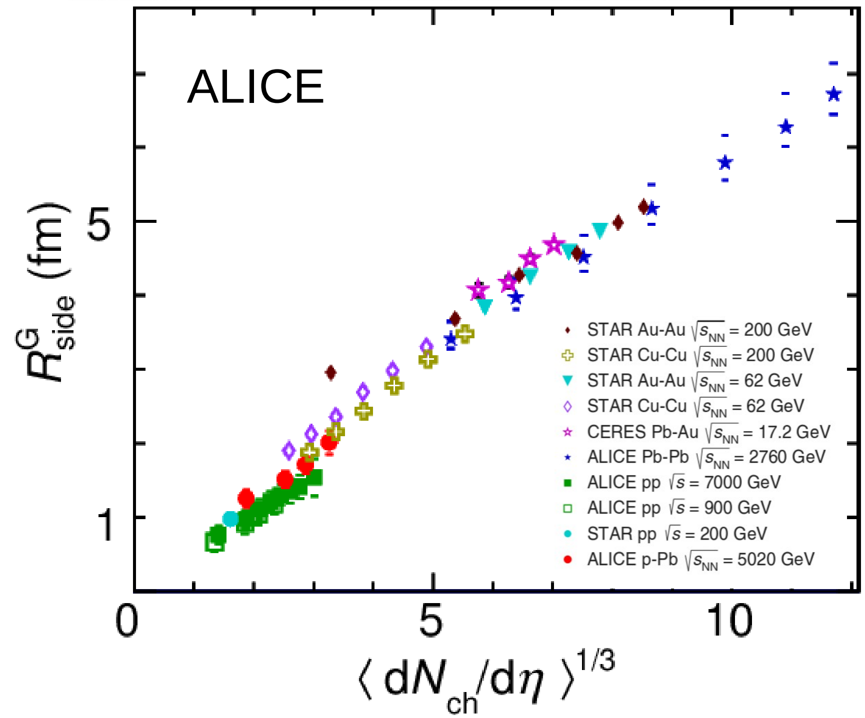


No sign of hadron suppression, but dynamic range of ZN estimator limited to about 2<dN/dη>

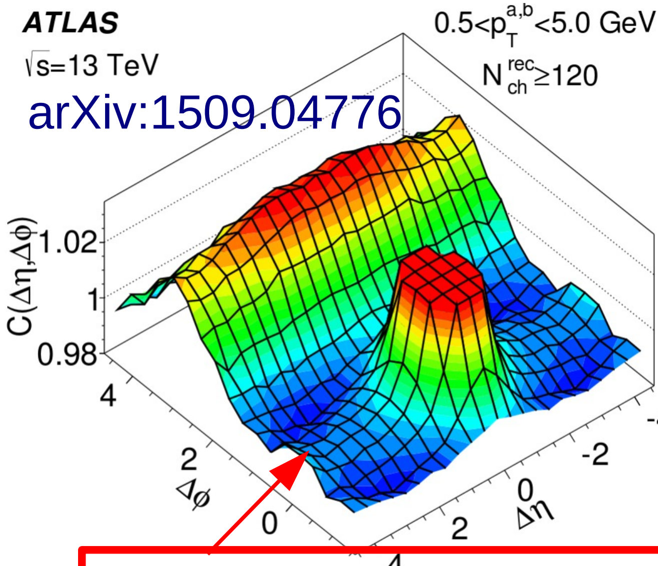
Measurements in “small” systems

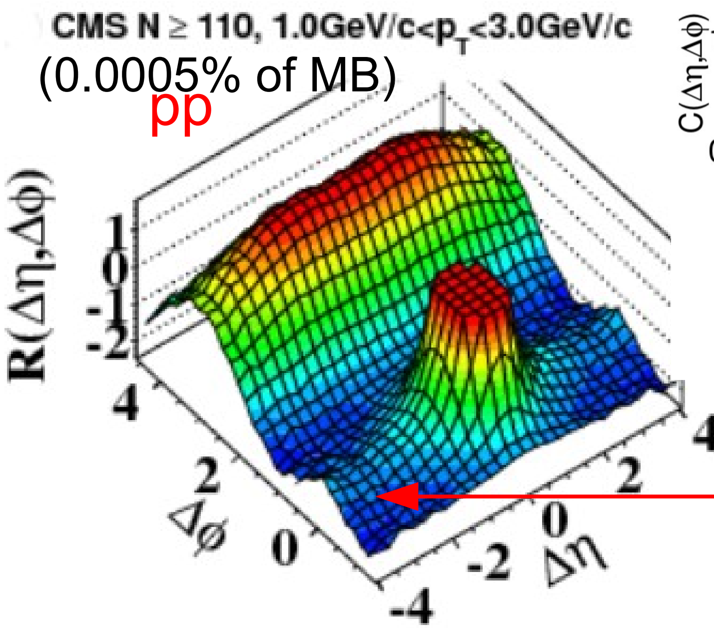
- Performed in bins of event activity
  - Tracks at mid-rapidity or multiplicity / energy in forward region
    - Also ZDC, but smaller dynamic range
  - Results can be affected by the event selection
    - Usually estimated by using selections in different kinematic ranges
- Unlike in Pb-Pb, in p-Pb (pp) high multiplicity is rare compared to MB
- Final system not small
  - Events with ~130 tracks (2%) similar multiplicity as 15-20% Cu-Cu 200 GeV
  - Transverse radius (R_{side}) similar for similar multiplicities across systems



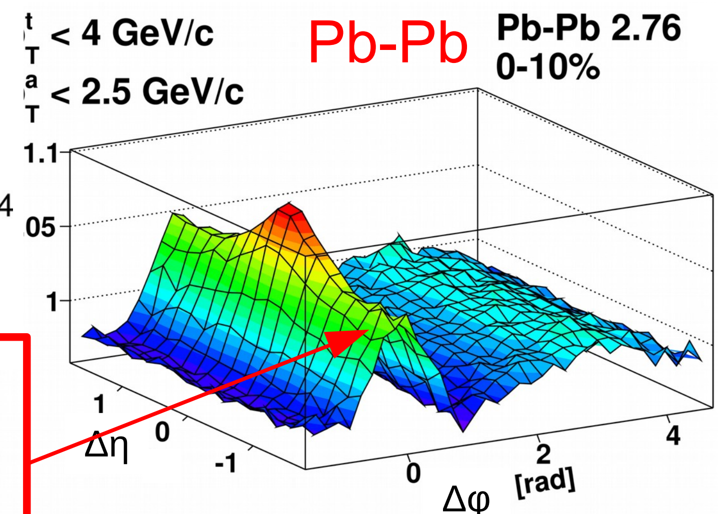


24 NS ridge str ar correlations



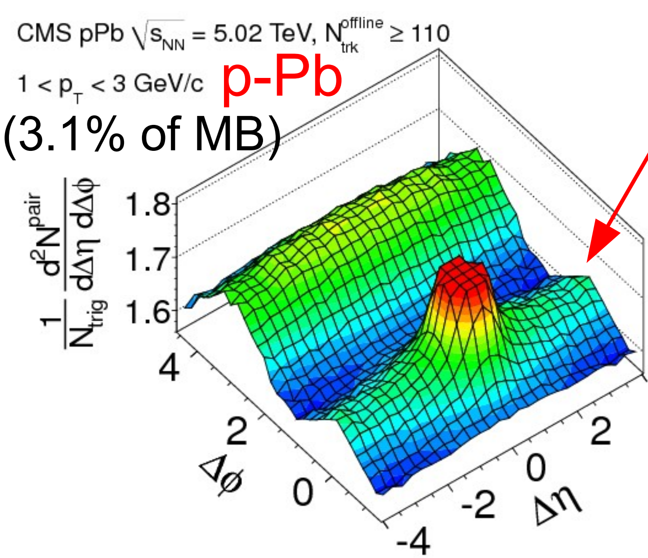


CMS, JHEP 1009 (2010) 91

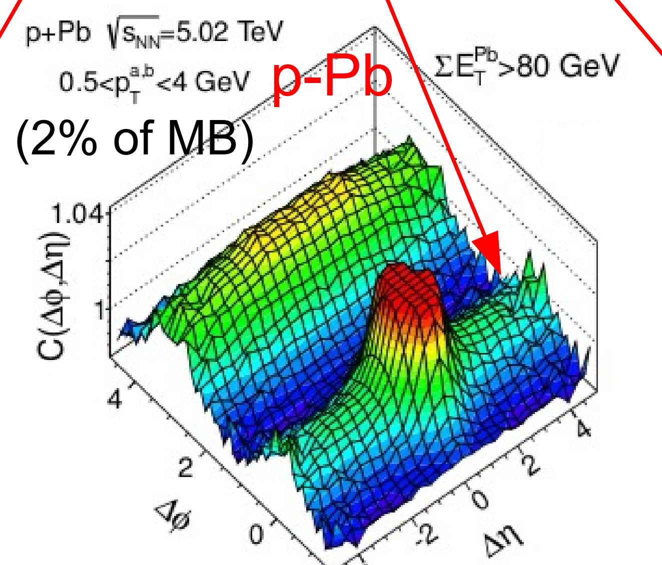


ALICE, PLB 708 (2012) 249

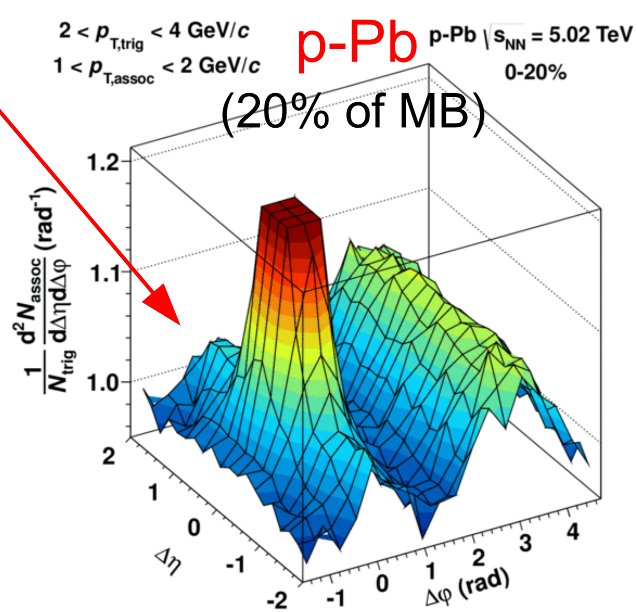
Near-side ridges (direct exp. evidence for long-range Δη correlations at Δφ≈0)



CMS, PLB 718 (2012) 795



ATLAS, PRL 110 (2013) 182302

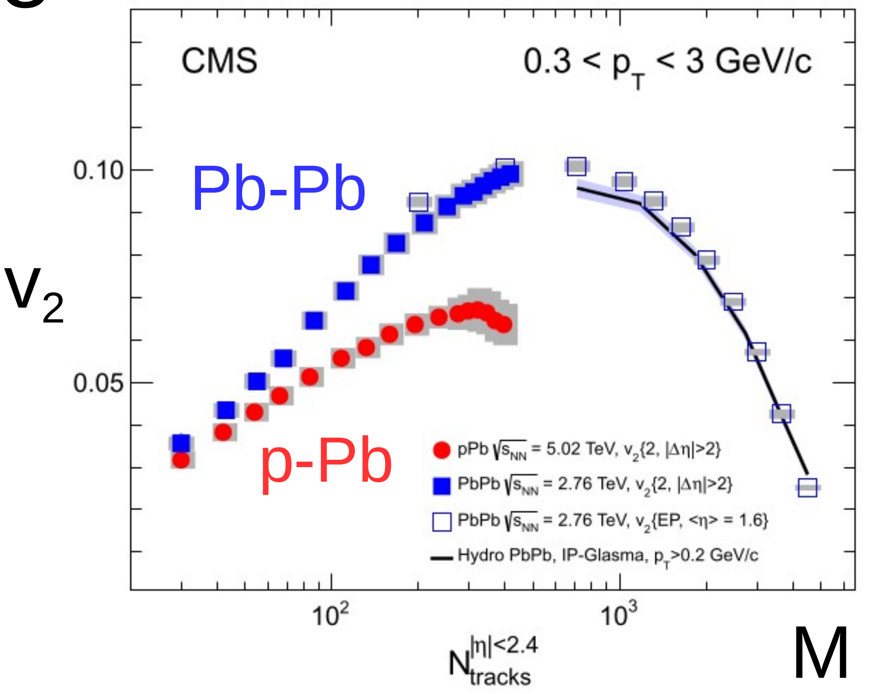


ALICE, PLB 719 (2013) 29

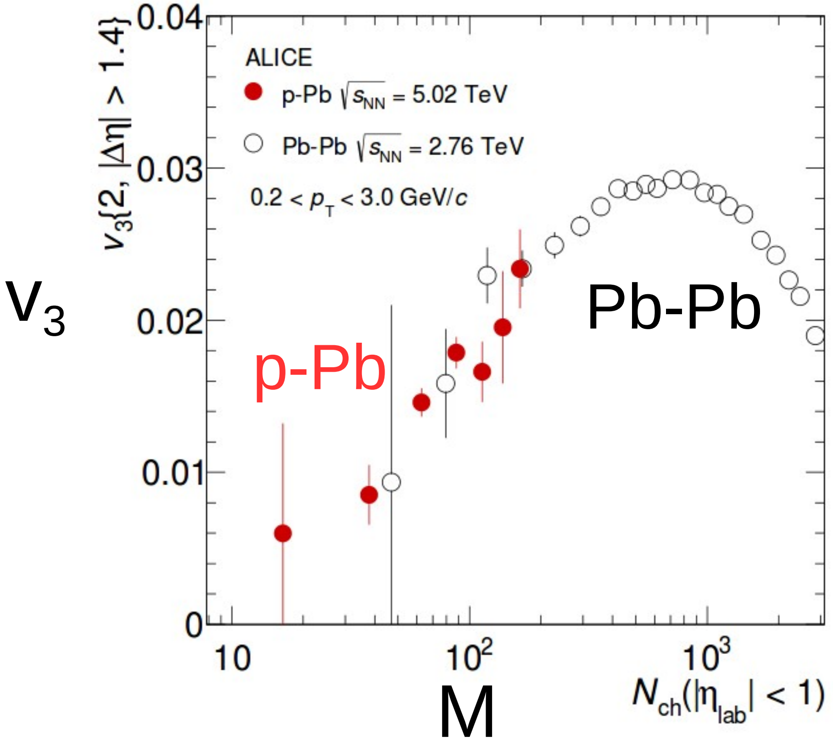
Multiplicity dependence

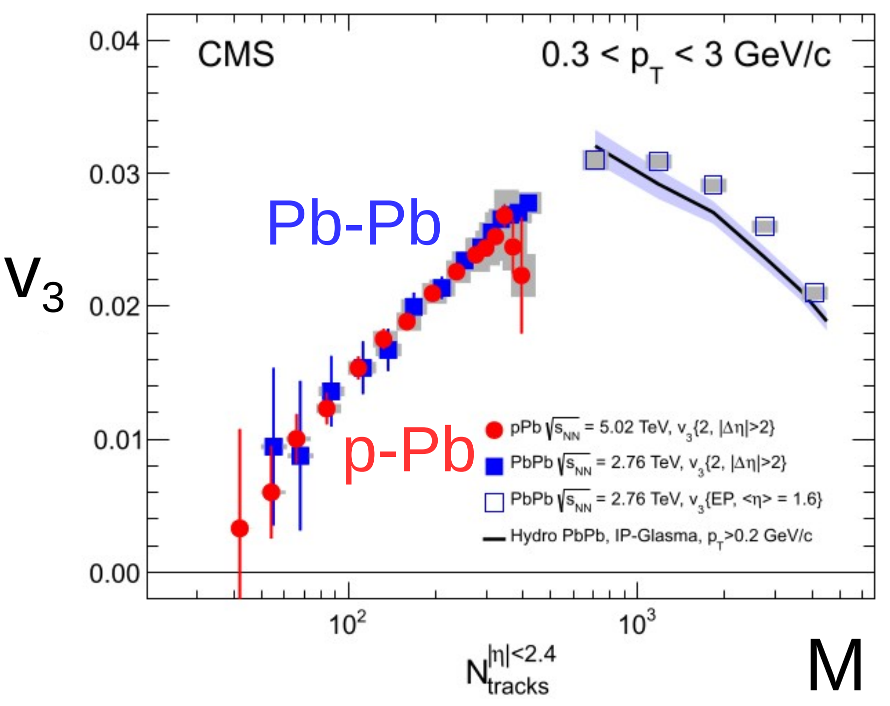
Continuous evolution from
"small" to "large" system

CMS, PLB 724 (2013) 213



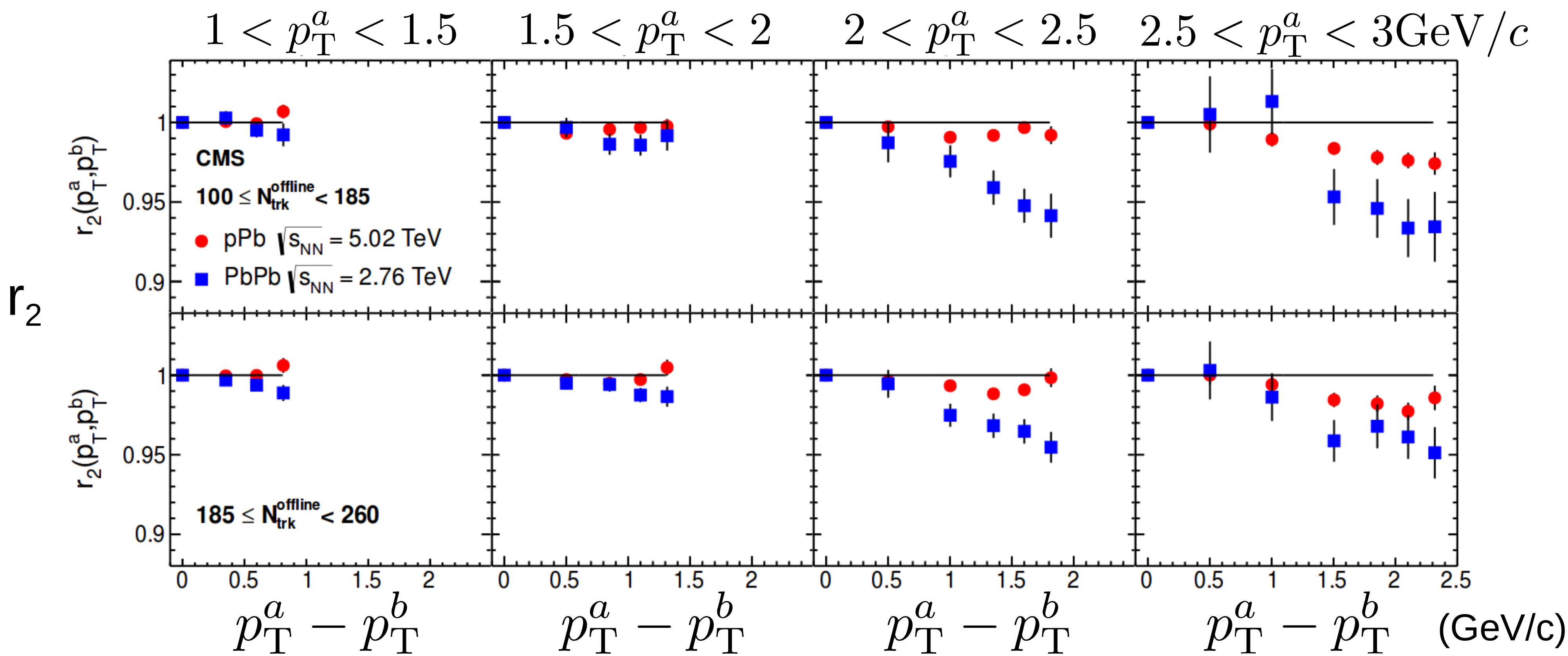
ALICE, PRC 90 (2014) 054901





Factorization-breaking in p-Pb

CMS, arXiv:1503.01692



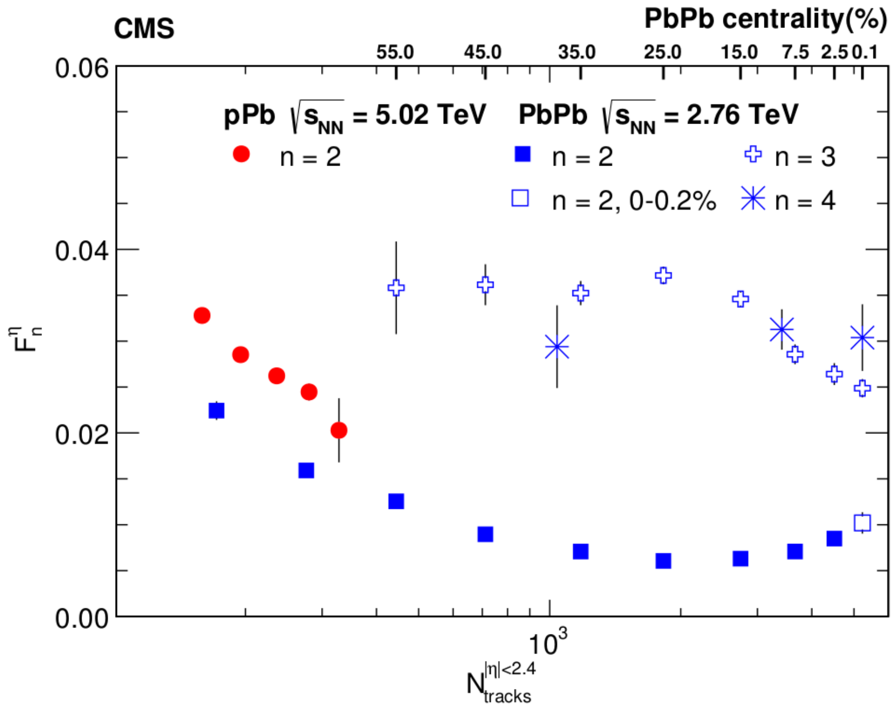
$$r_n \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}}$$
$$\sim \left\langle \cos[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))] \right\rangle$$

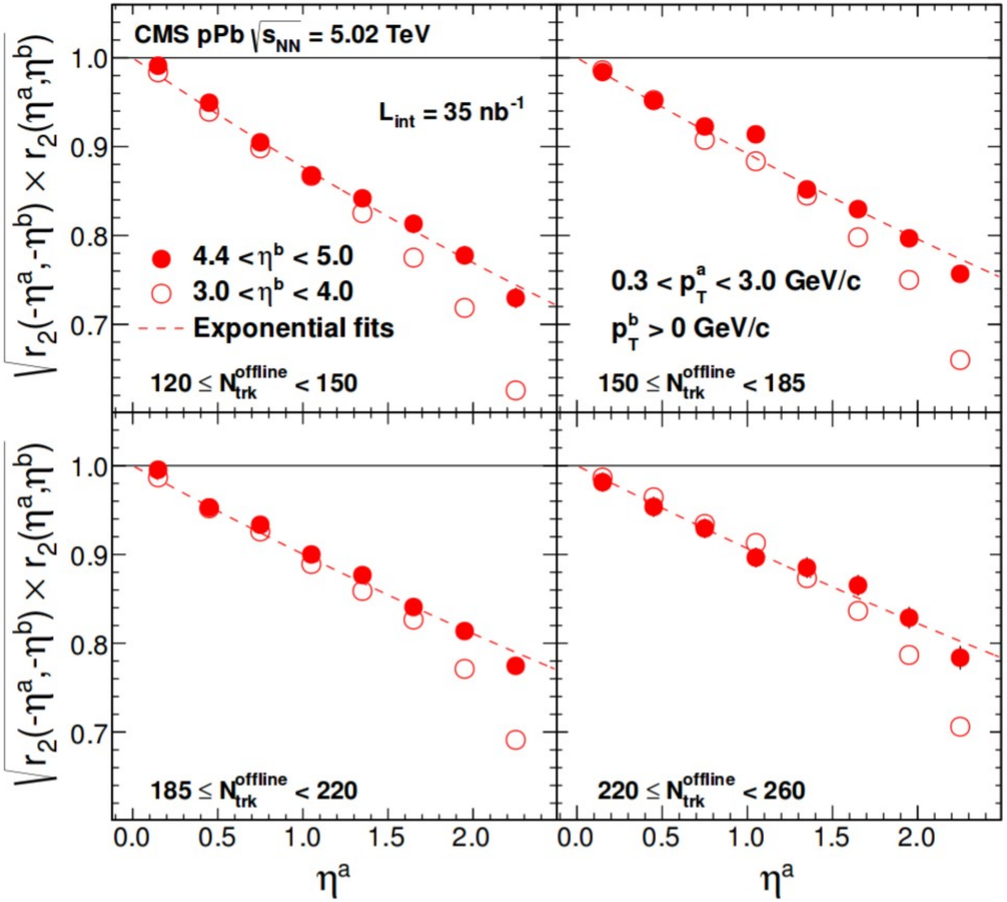
Slightly less broken than in Pb-Pb

Decorrelation in η

CMS, arXiv:1503.01692

$$r_n(\eta^a, \eta^b) \approx e^{-2F_n^{\eta}\eta^a}$$



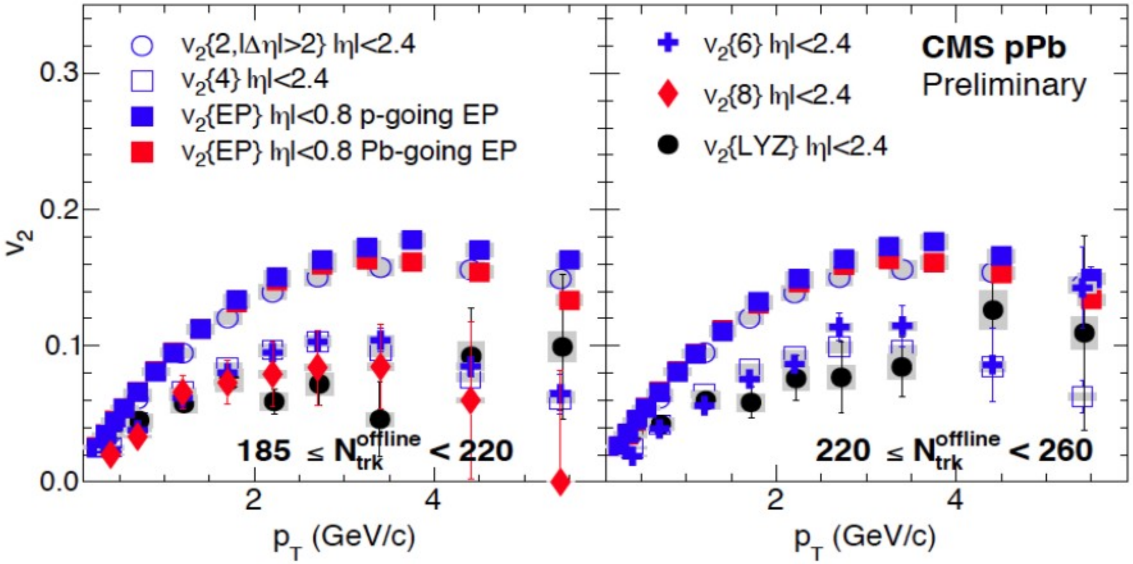


Observe larger decorrelation in η for p-Pb

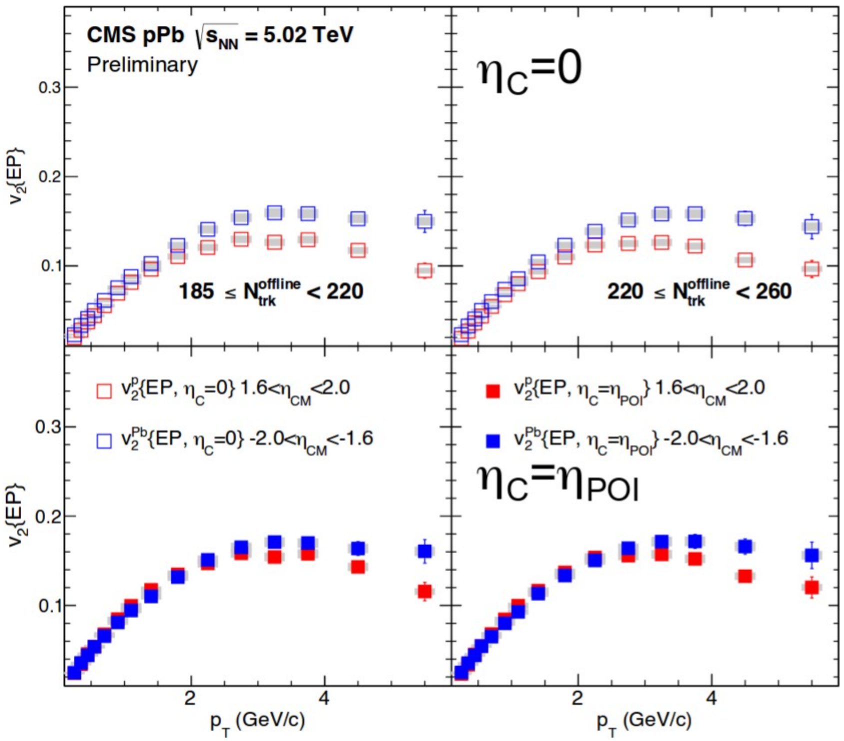
$$\sqrt{r_n(\eta^a,\eta^b) \times r_n(-\eta^a,-\eta^b)} \approx \sqrt{\frac{\langle \cos\left[\Psi_n(-\eta^a) - \Psi_n(\eta^b)\right]\rangle}{\langle \cos\left[\Psi_n(\eta^a) - \Psi_n(\eta^b)\right]\rangle} \frac{\langle \cos\left[\Psi_n(\eta^a) - \Psi_n(-\eta^b)\right]\rangle}{\langle \cos\left[\Psi_n(-\eta^a) - \Psi_n(-\eta^b)\right]\rangle}}$$

Extended p_T and η range

CMS-PAS-HIN-15-008

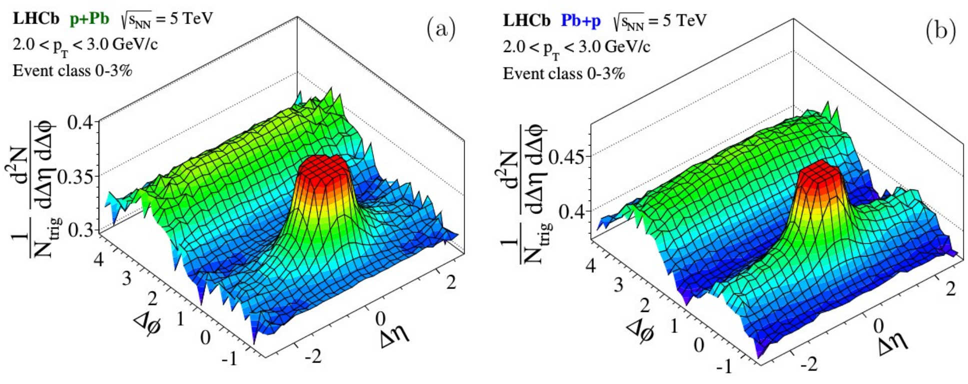


Cumulant method now up to 6 GeV.

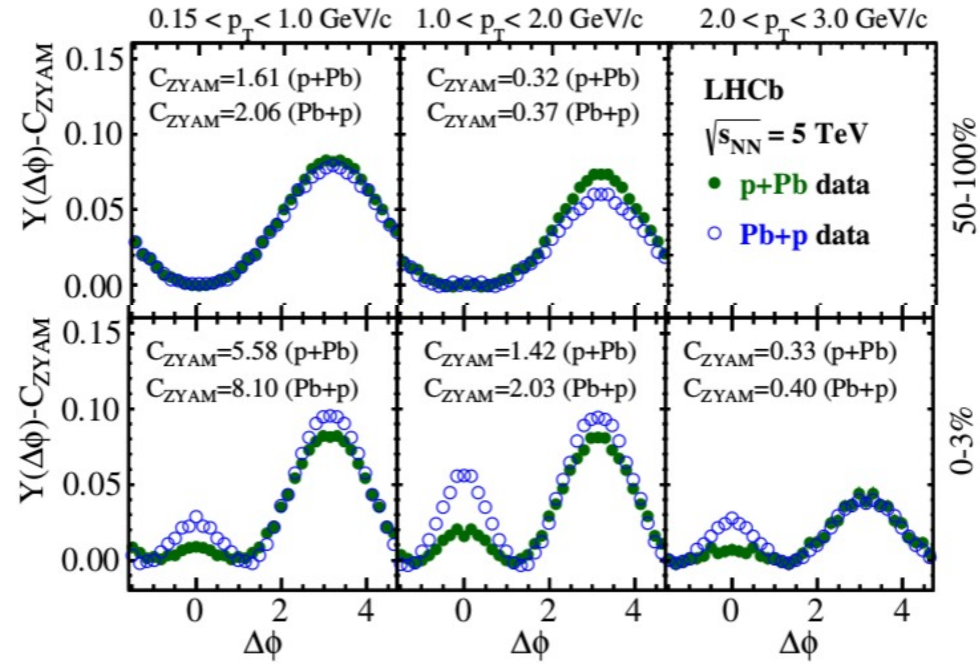


Similar dependence in forward and backward direction for low p_T

LHCb $2<\eta_{lab}<4.9$

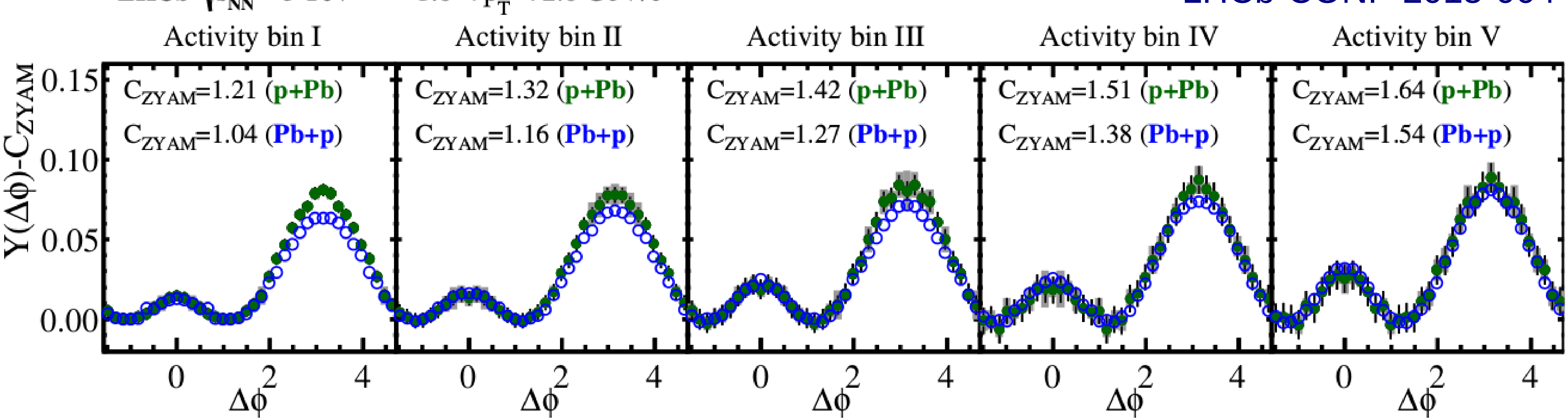


LHCb-CONF-2015-004

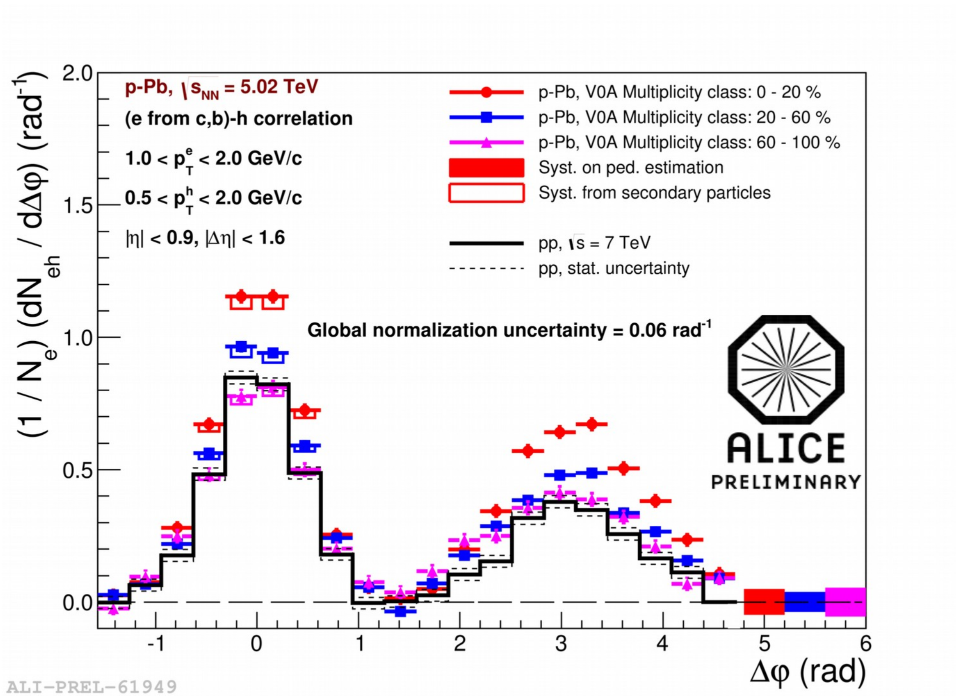


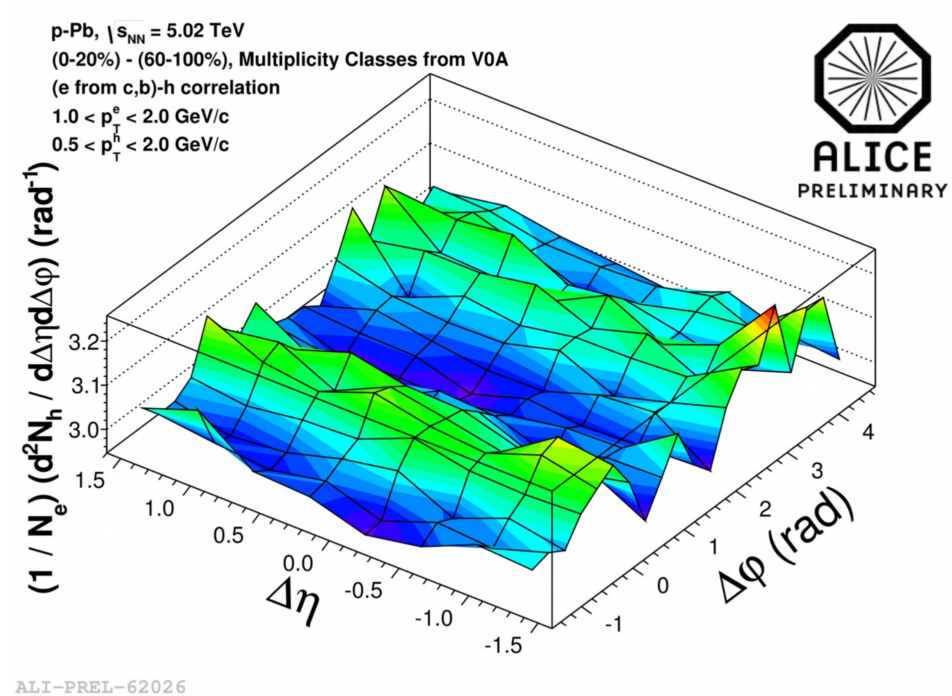
In same absolute activity bins find similar NS yield

LHCb-CONF-2015-004



Heavy-flavor electron ridge

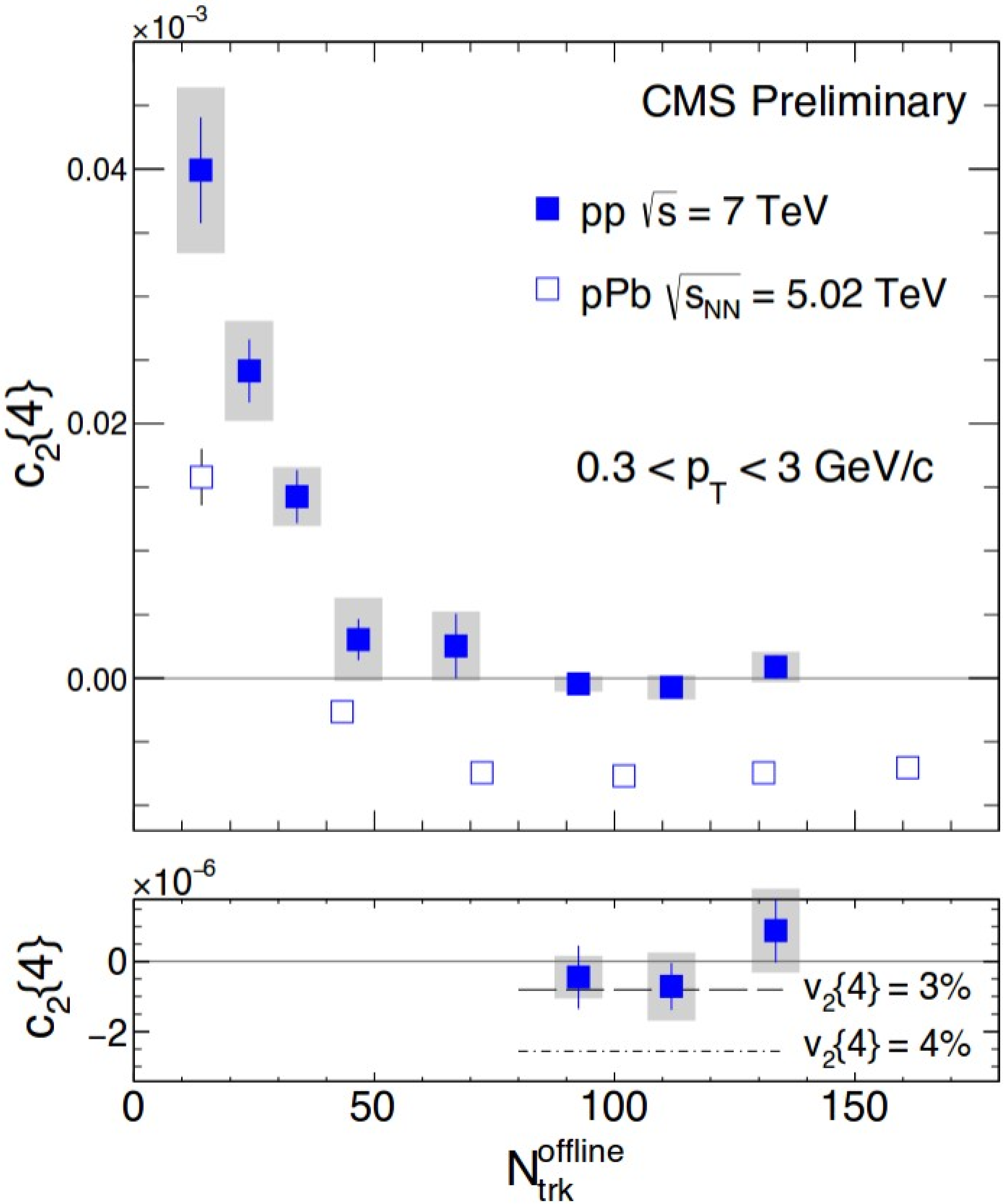




At mid-rapidity, double ridge for electrons from HF decays observed

Four-particle cumulant

CMS-FSQ-PAS-15-002



- Q-cumulant 4-particle correlation

$$\langle\langle 4 \rangle\rangle \equiv \left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle\right\rangle$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

related to v_2 as

$$v_2\{4\}^4 = -c_2\{4\}$$

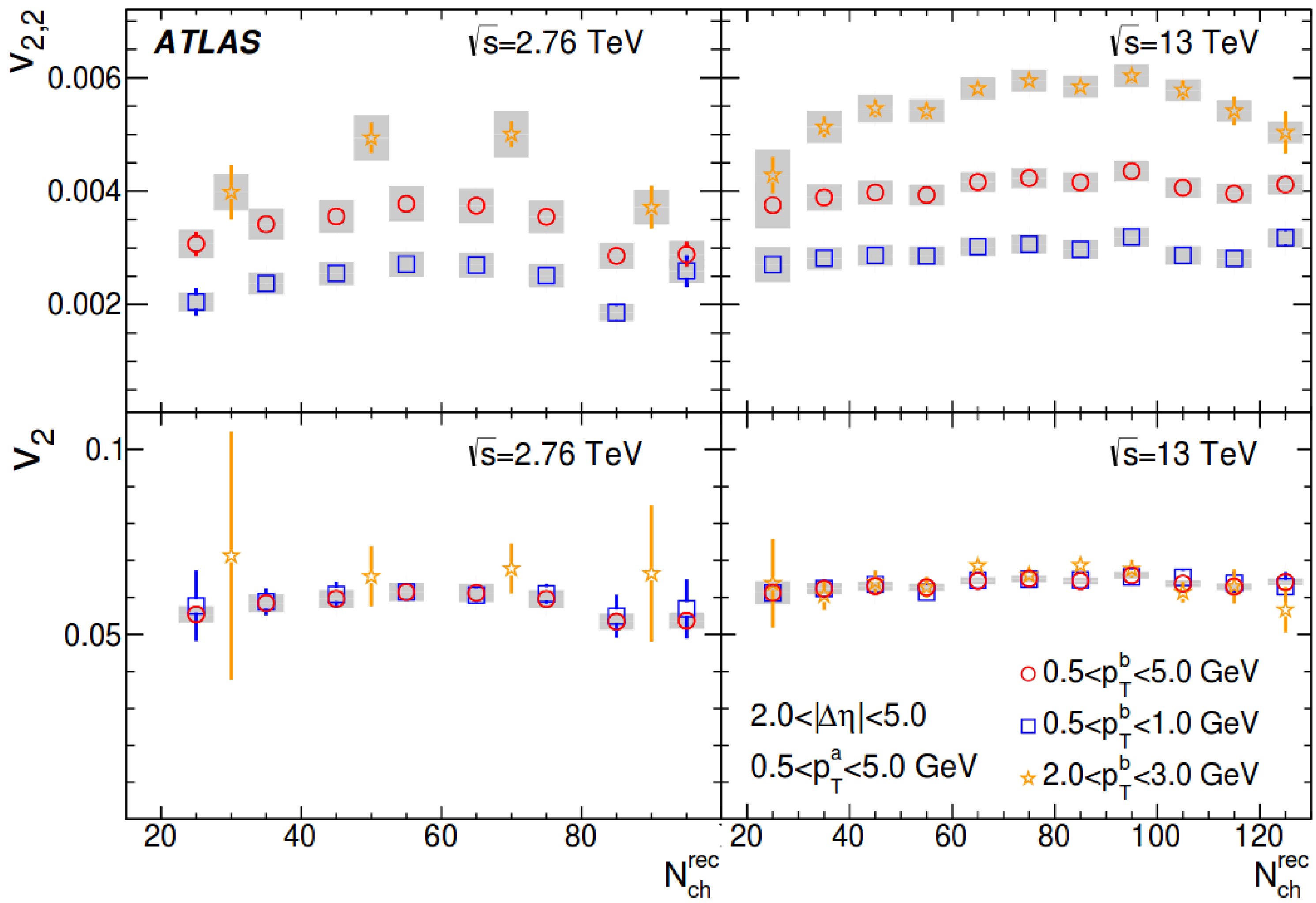
- $c_2\{4\}$ decrease with multiplicity, same behavior as in pPb

- Indication of negative $c_2\{4\}$ at high multiplicity, stay tuned!

(from Zhenyu Chen)

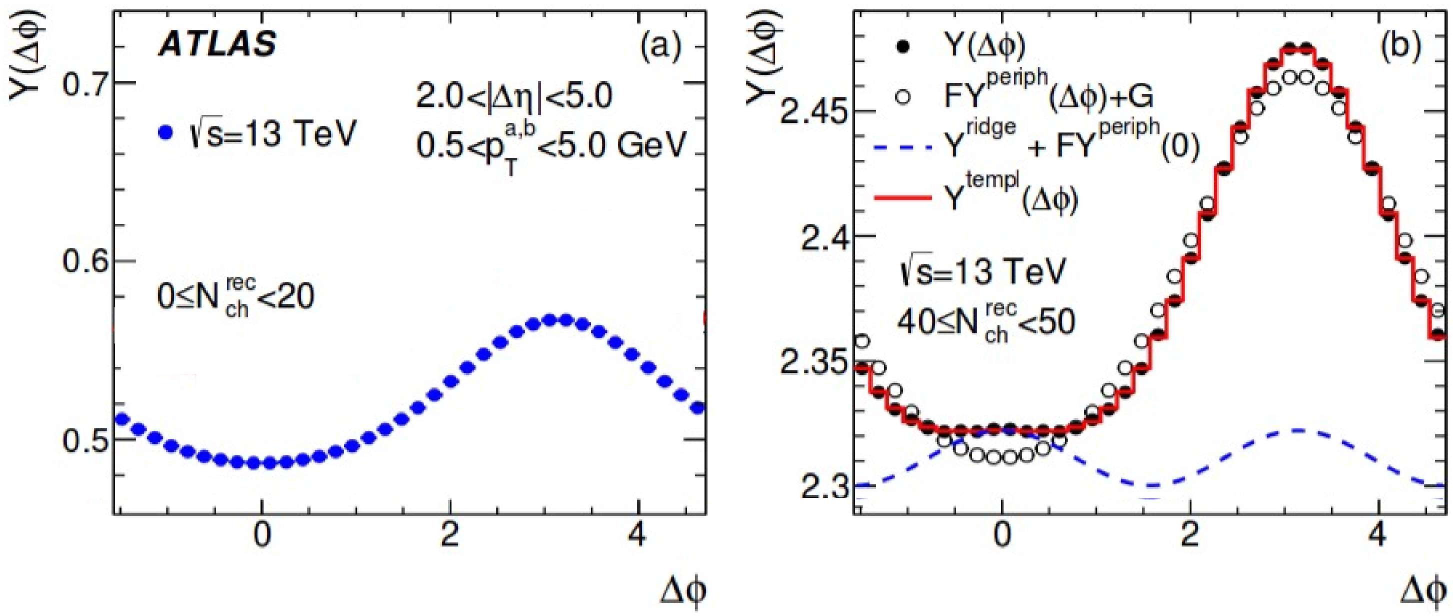
Factorization

ATLAS, arXiv:1509.04776



Template fit

ATLAS, arXiv:1509.04776



$$Y^{\rm temp}(\Delta\Phi) = F\,Y^{\rm periph} + Y^{\rm ridge}$$

$$Y^{\rm ridge}(\Delta\Phi) = G(1 + v_{2,2}\cos(2\Delta\Phi))$$

$$F\,Y^{\rm periph}(\Delta\Phi) = FY^{\rm hard}(\Delta\Phi) + F\,G_0\,(1 + 2v^0_{2,2}\cos(2\Delta\Phi))$$

Assuming there is no flow in the peripheral bin: $v^0_{2,2} = 0$

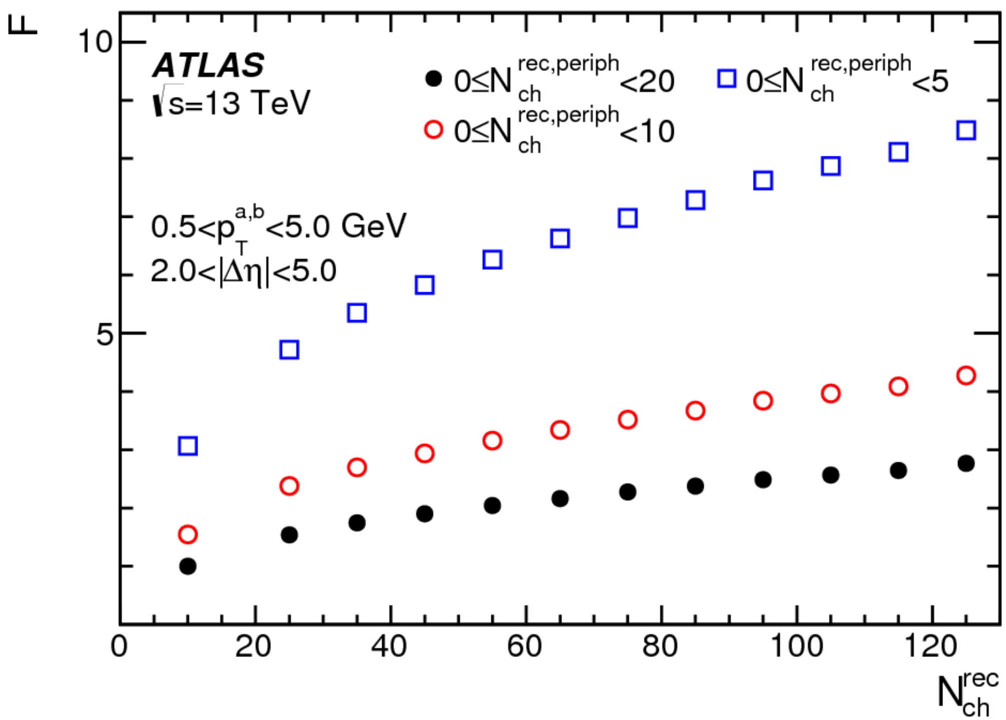
$$Y^{\rm temp}(\Delta\Phi) = FY^{\rm hard}(\Delta\Phi) + (\mathrm{F}\,\mathrm{G}_0 + G)\,(1 + 2v_{2,2}\frac{G}{FG_0+G}\cos\,(2\Delta\Phi))$$

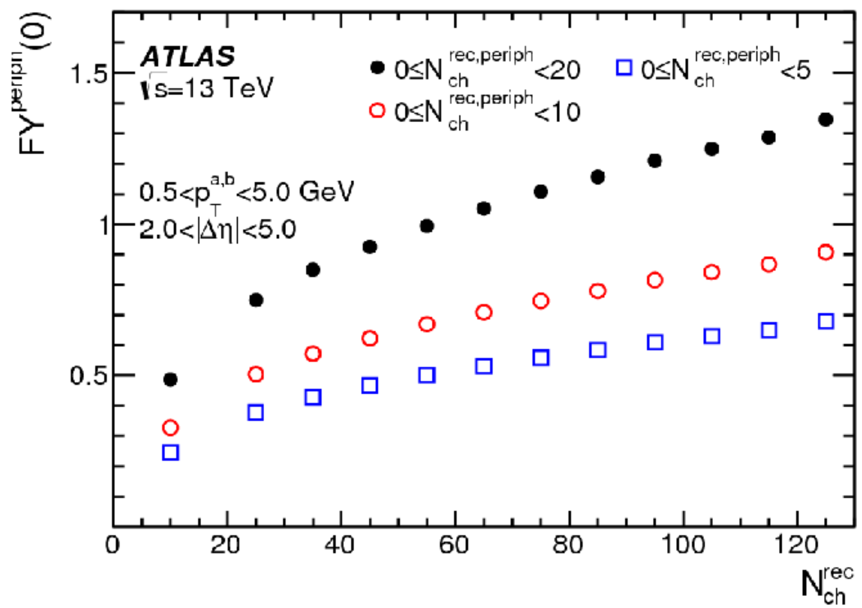
Assuming there is flow of similar magnitude: $v^0_{2,2} \approx v_{2,2}$

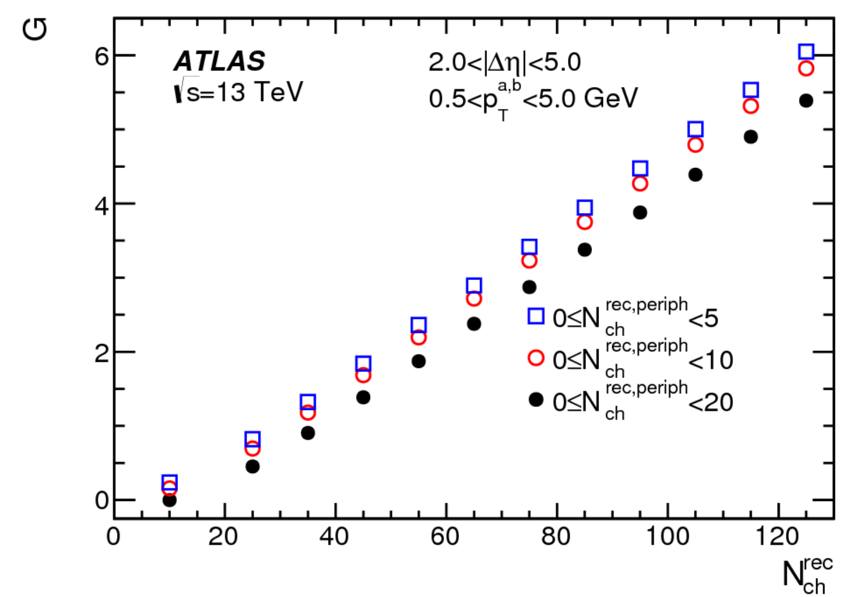
$$Y^{\rm temp}(\Delta\Phi) = FY^{\rm hard}(\Delta\Phi) + (\mathrm{F}\,\mathrm{G}_0 + G)\,(1 + 2v_{2,2}\cos\,(2\Delta\Phi))$$

Template parameters

ATLAS, arXiv:1509.04776





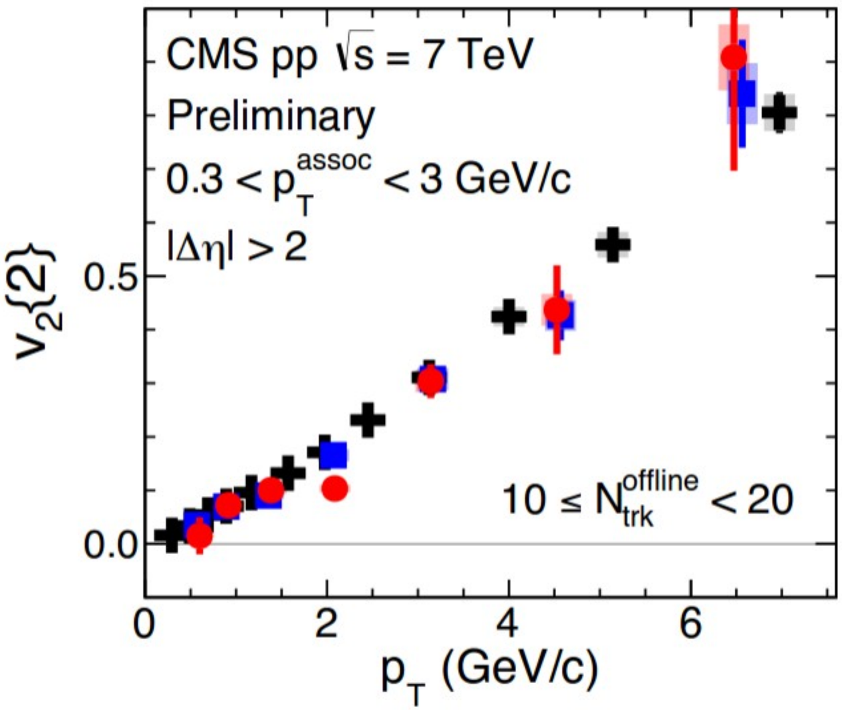


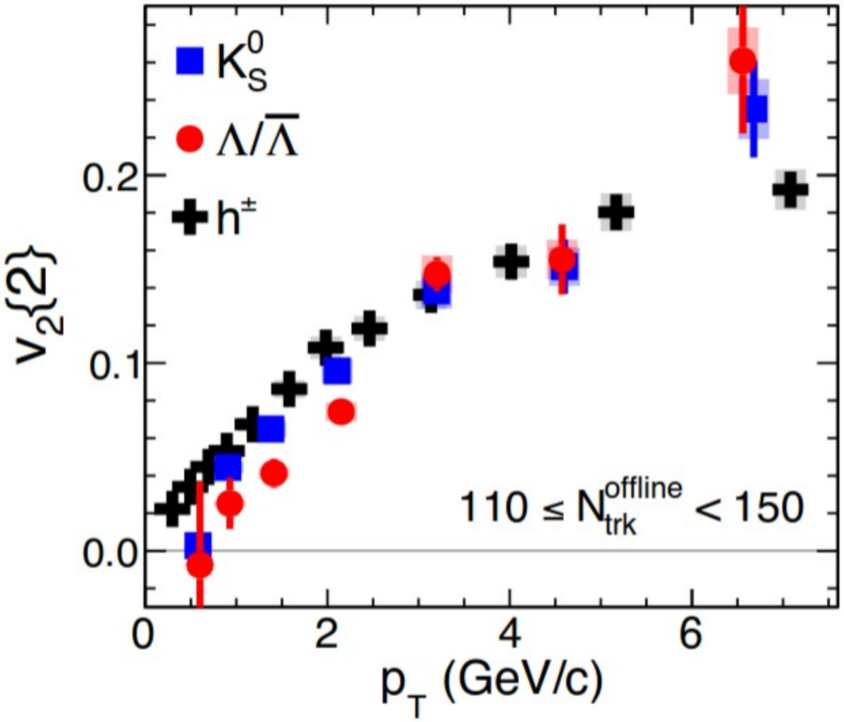
$$Y^{\mathrm{temp}}(\Delta\Phi) = F\,Y^{\mathrm{periph}} + Y^{\mathrm{ridge}}$$

$$Y^{\mathrm{ridge}}(\Delta\Phi) = G(1 + v_{2,2}\cos(2\Delta\Phi))$$

PID dependence of v_2

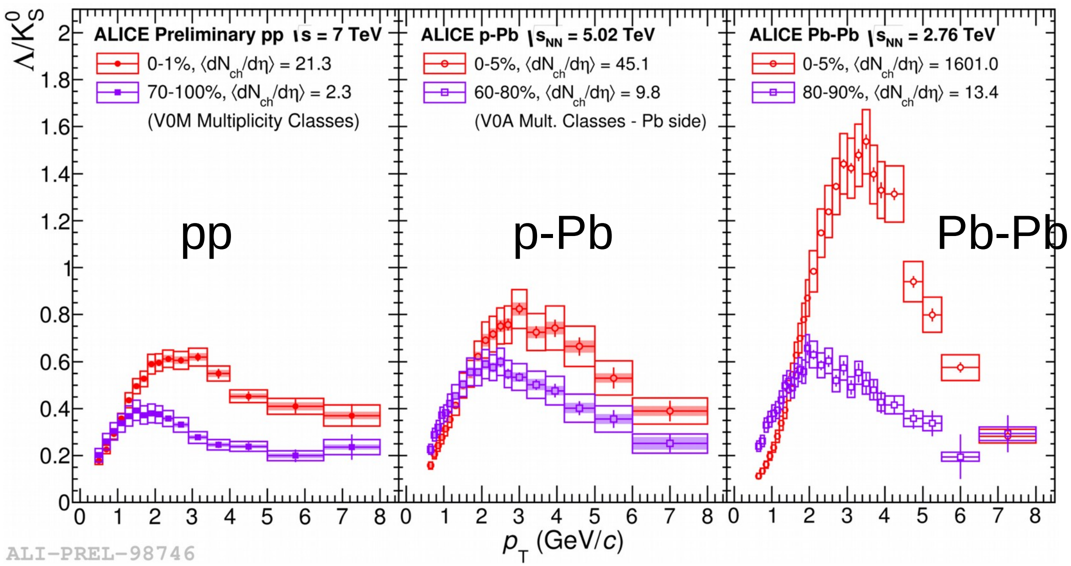
CMS-FSQ-PAS-15-002



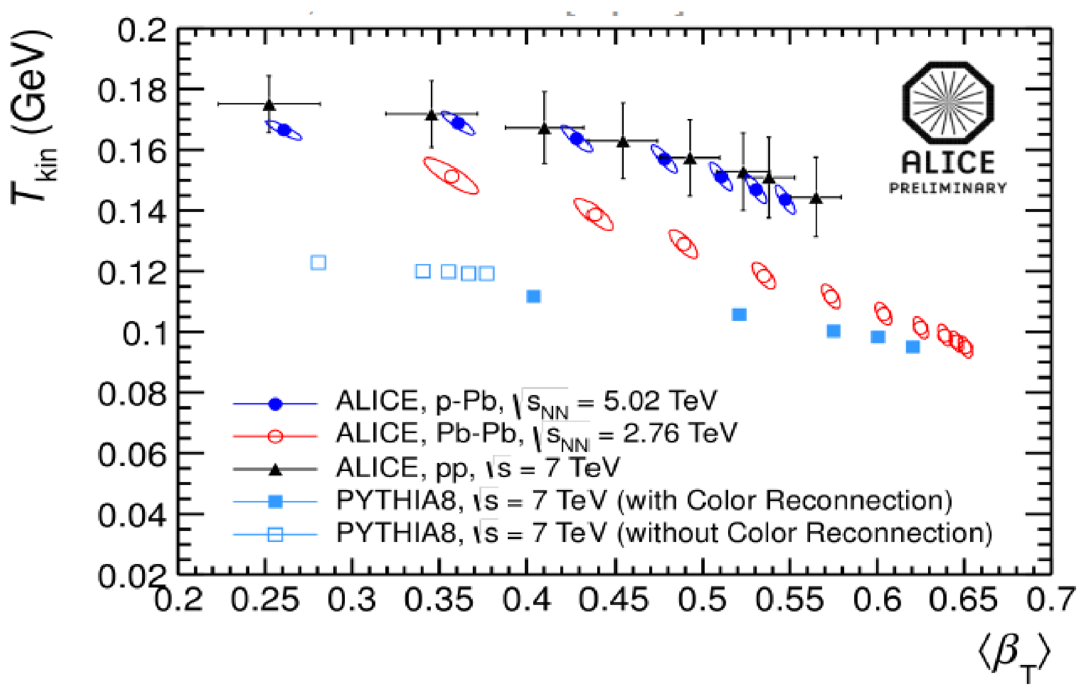


No mass dependence of v_2 from jet correlation at low multiplicity

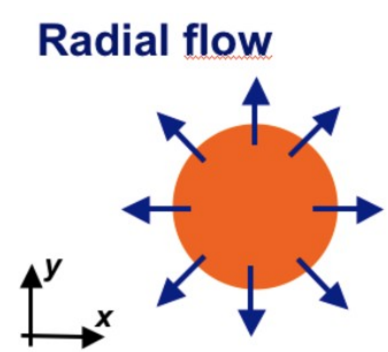
Spectra at low p_T in pp (7 TeV)



Increase and move of maximum with increasing multiplicity (measured with V0M to avoid trivial bias at low mult.)



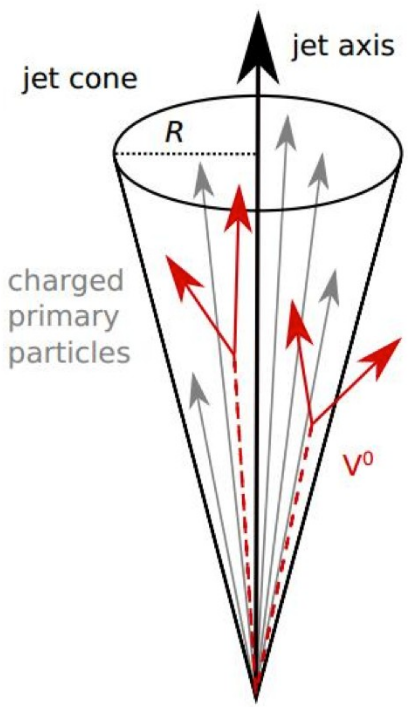
Larger common velocity in pp/pPb at similar N_{ch}



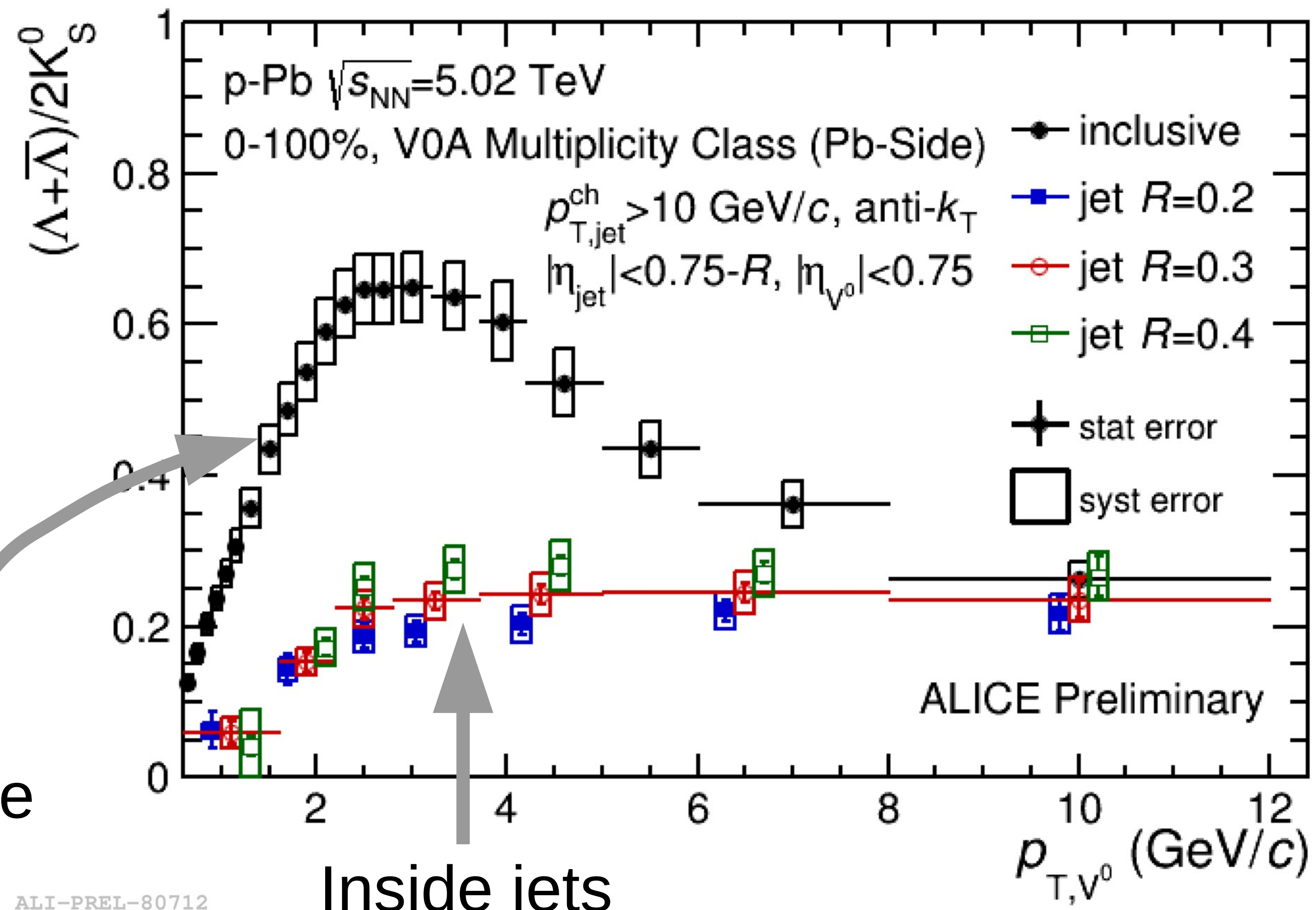
$$p_T^{flow} = p_T + m\,\beta_T^{flow}\,\gamma_T^{flow}$$

Shuryak and Zhirov, PLB 89 (1979) 253

Λ/K0s enhancement in/out jets



Λ over K_S^0 ratio inclusive vs inside jets

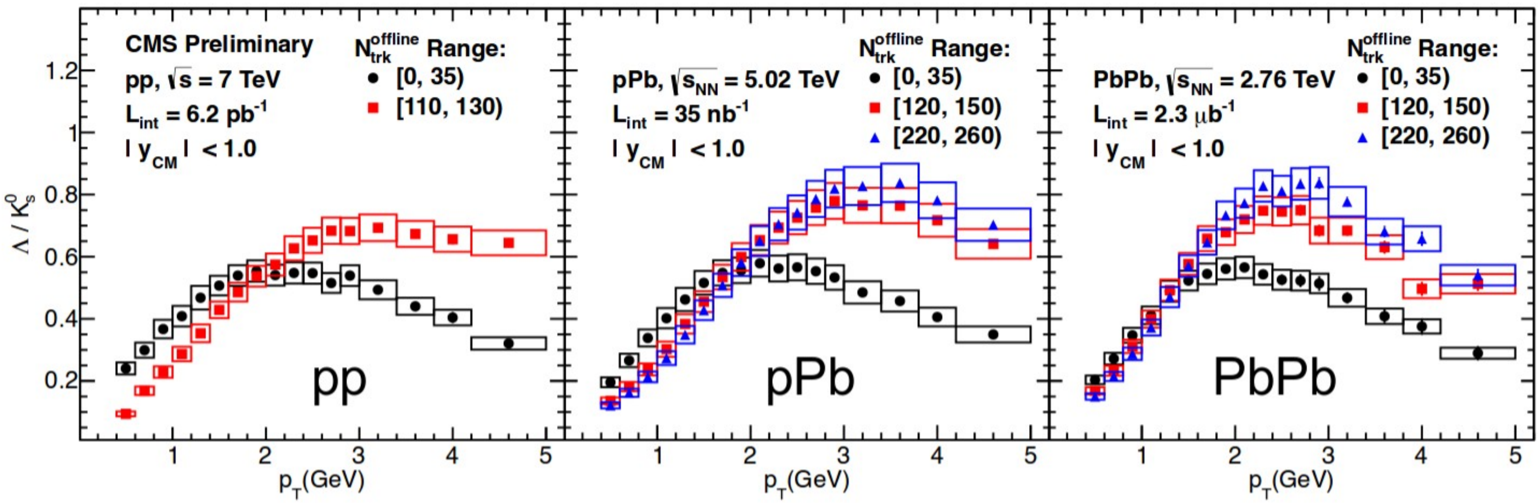


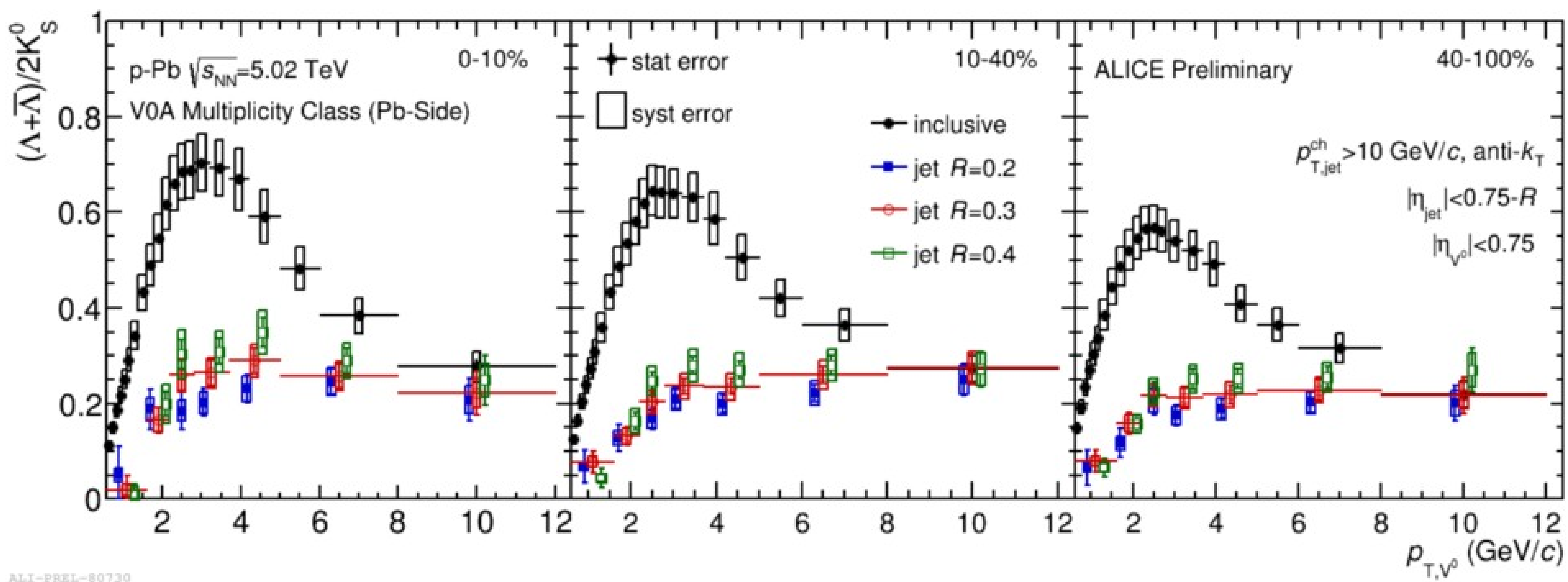
Inclusive

Inside jets

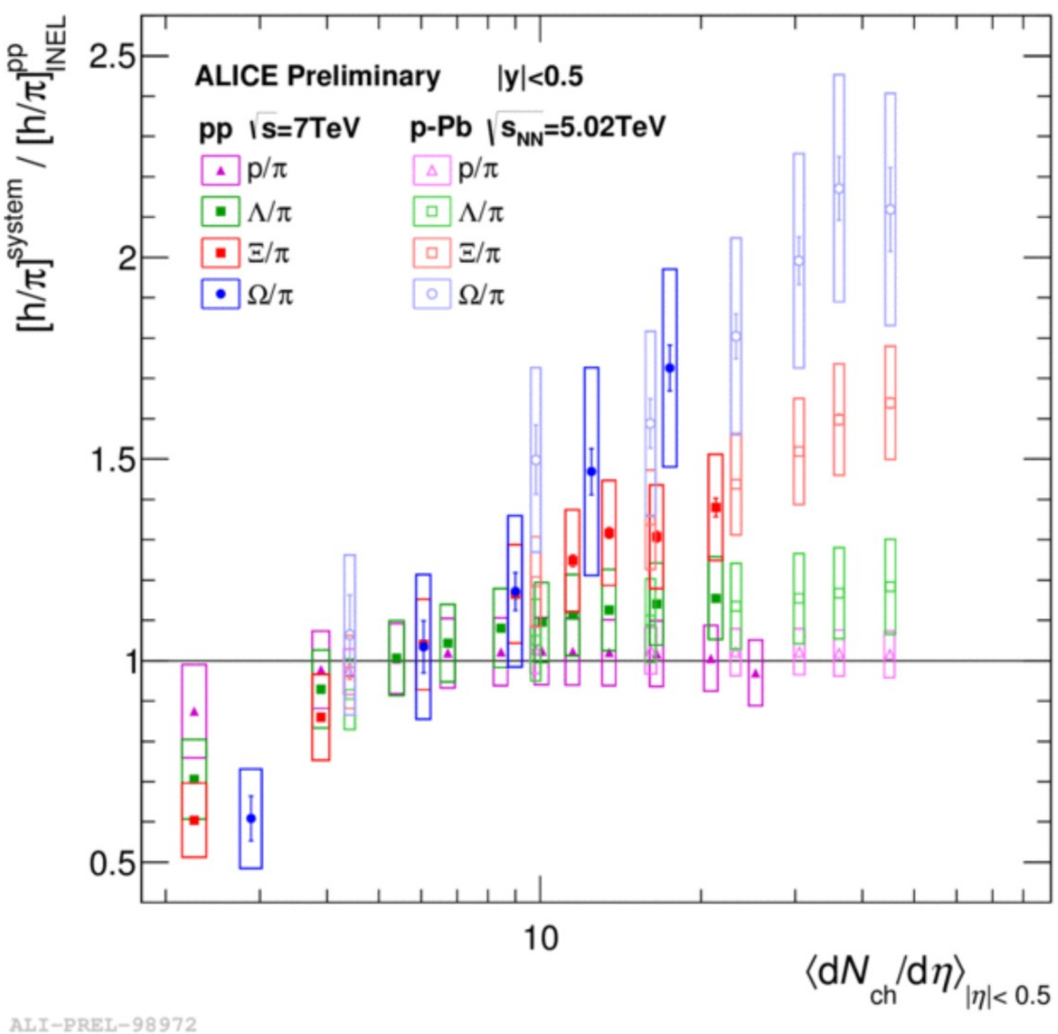
The enhancement is not coming from jets

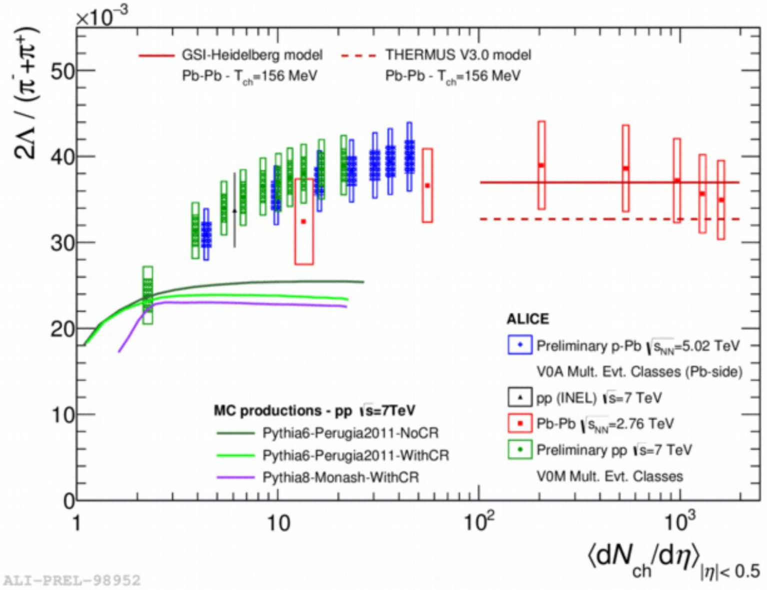
Λ/K0s

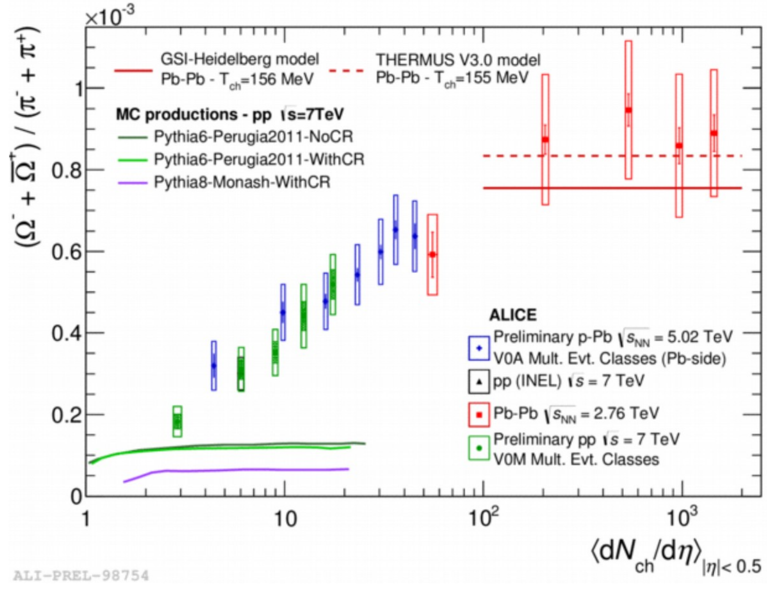

CMS Preliminary
pp, √s = 7 TeV
L_int = 6.2 pb^-1
| y_CM | < 1.0
N_trk^offline Range:
[0, 35)
[110, 130)
pp
pPb, √s_NN = 5.02 TeV
L_int = 35 nb^-1
| y_CM | < 1.0
N_trk^offline Range:
[0, 35)
[120, 150)
[220, 260)
pPb
PbPb, √s_NN = 2.76 TeV
L_int = 2.3 μb^-1
| y_CM | < 1.0
N_trk^offline Range:
[0, 35)
[120, 150)
[220, 260)
PbPb
Λ / K^0_S
p_T(GeV)


p-Pb √s_NN=5.02 TeV
V0A Multiplicity Class (Pb-Side)
0-10%
stat error
syst error
10-40%
inclusive
jet R=0.2
jet R=0.3
jet R=0.4
ALICE Preliminary
40-100%
p^ch_T,jet >10 GeV/c, anti-k_T
|η_jet|<0.75-R
|η_V0|<0.75
(Λ+Λ̄)/2K^0_S
p_T,V0 (GeV/c)
ALI-PREL-80730

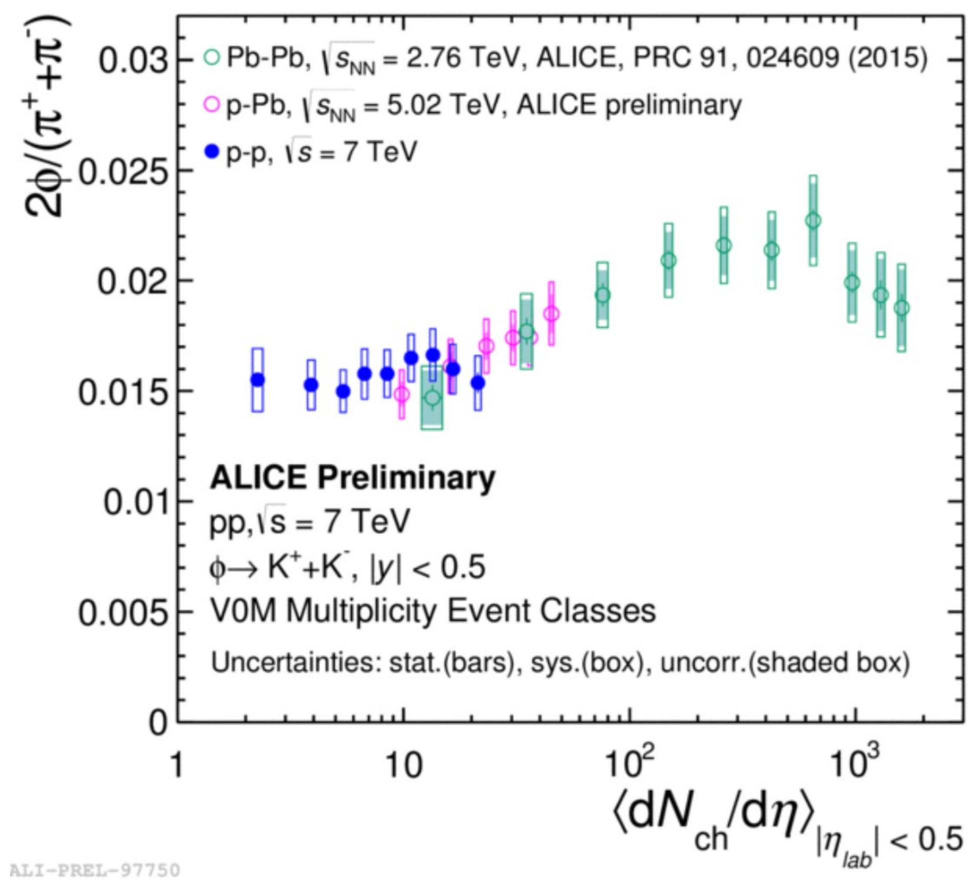
Particle ratios vs multiplicity

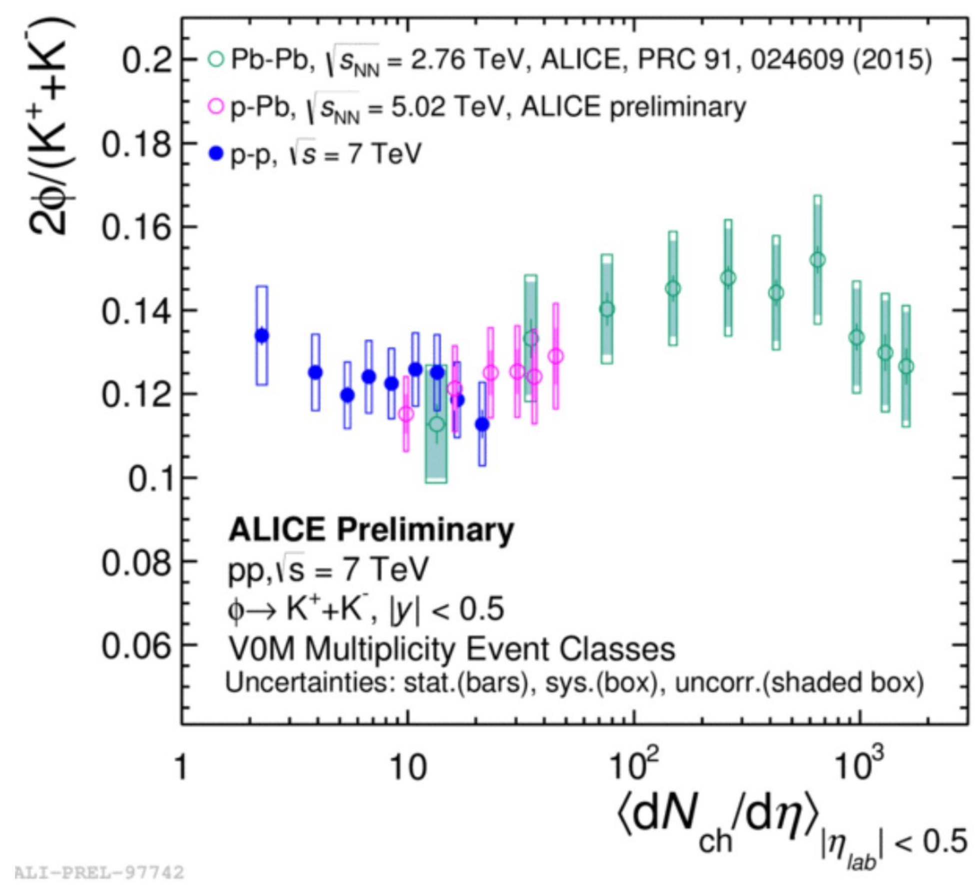






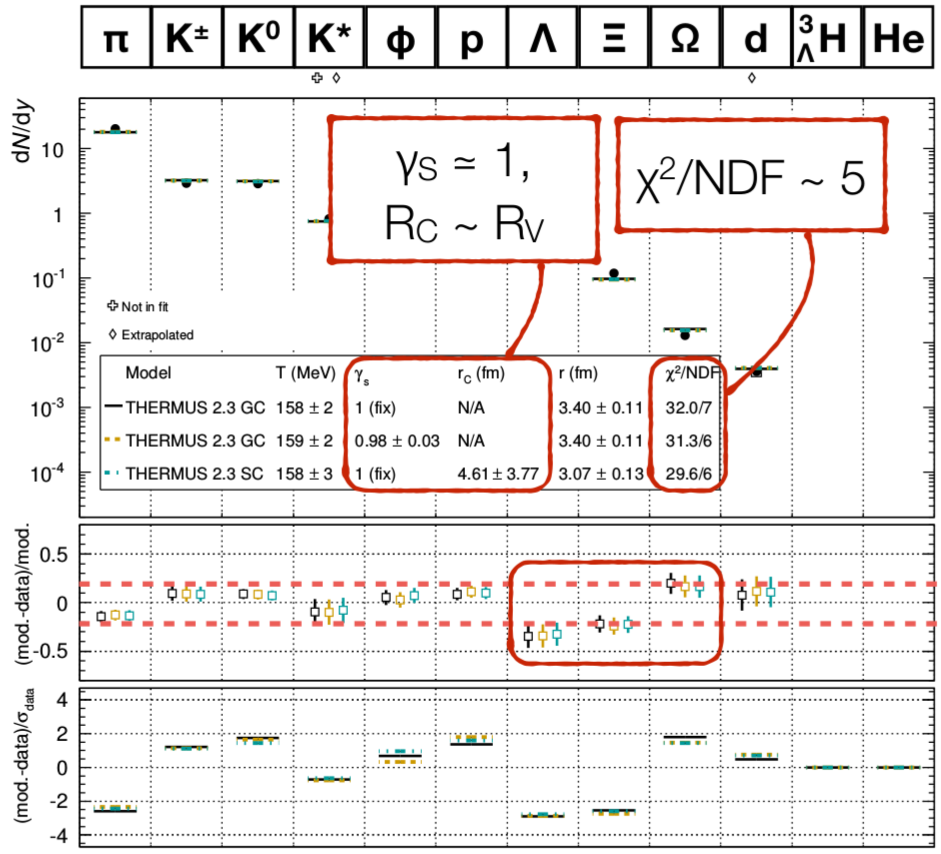
Multiplicity dependence of the Φ meson





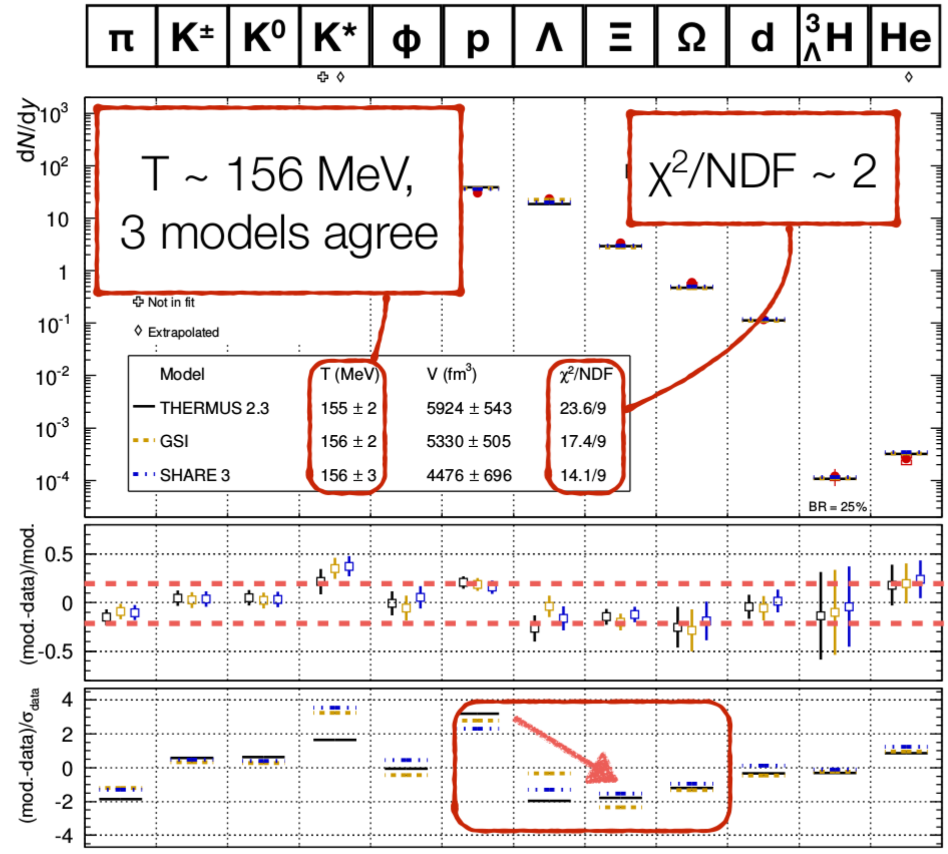
Statistical model fits

0-5% p-Pb



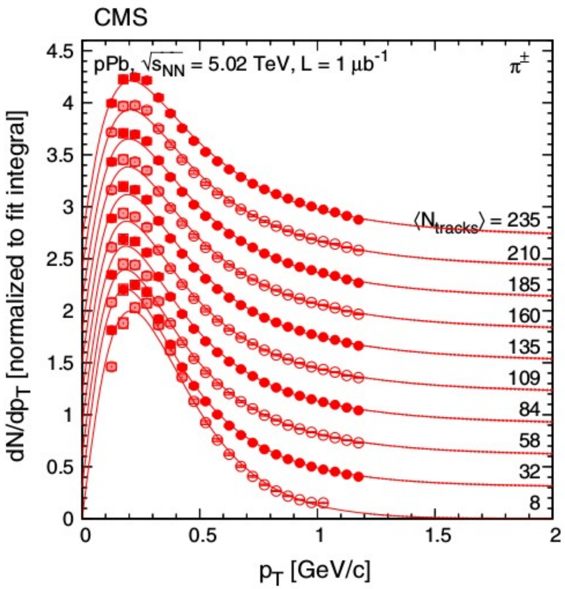
ALI-PREL-74510

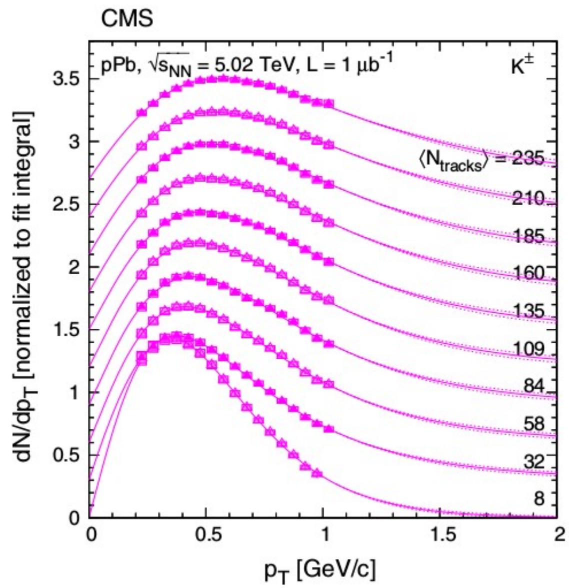
0-10% Pp-Pb

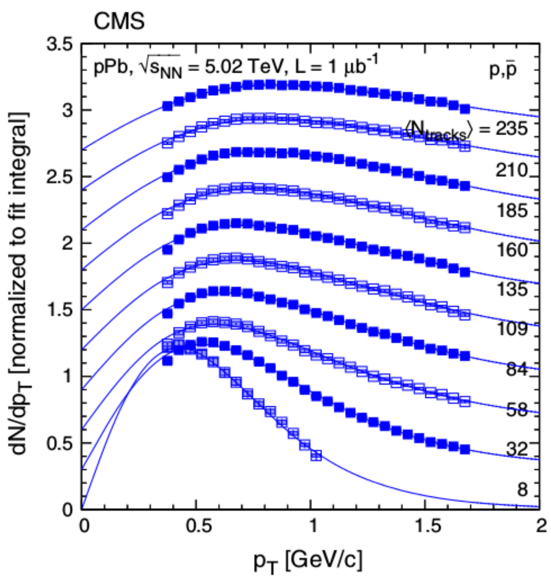


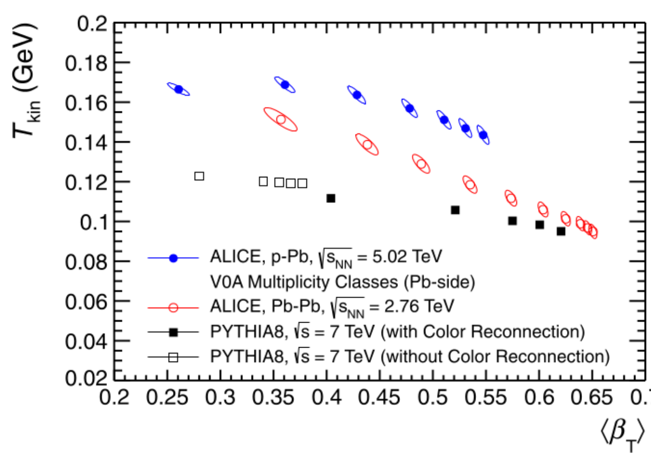
ALI-PREL-74463

42 Spectra in p-Pb

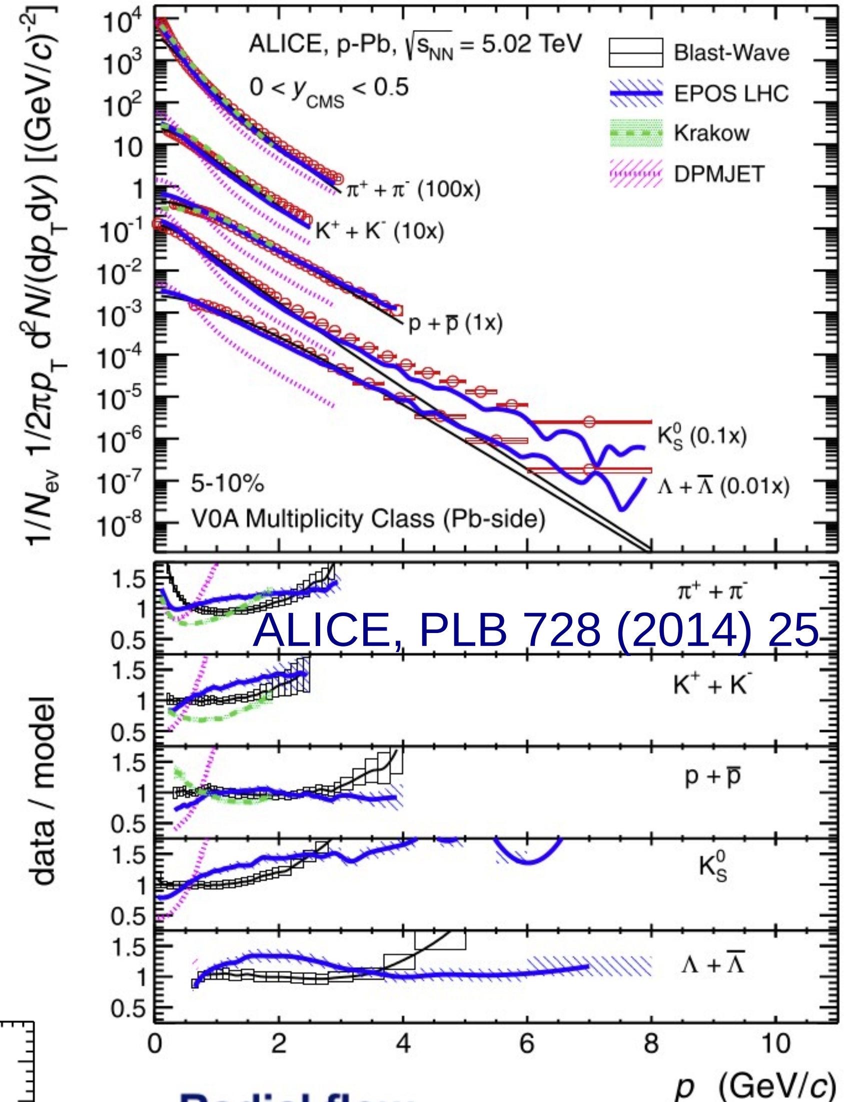






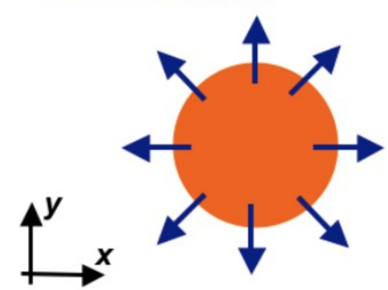


CMS, EPJC 74 (2014) 2847



ALICE, PLB 728 (2014) 25

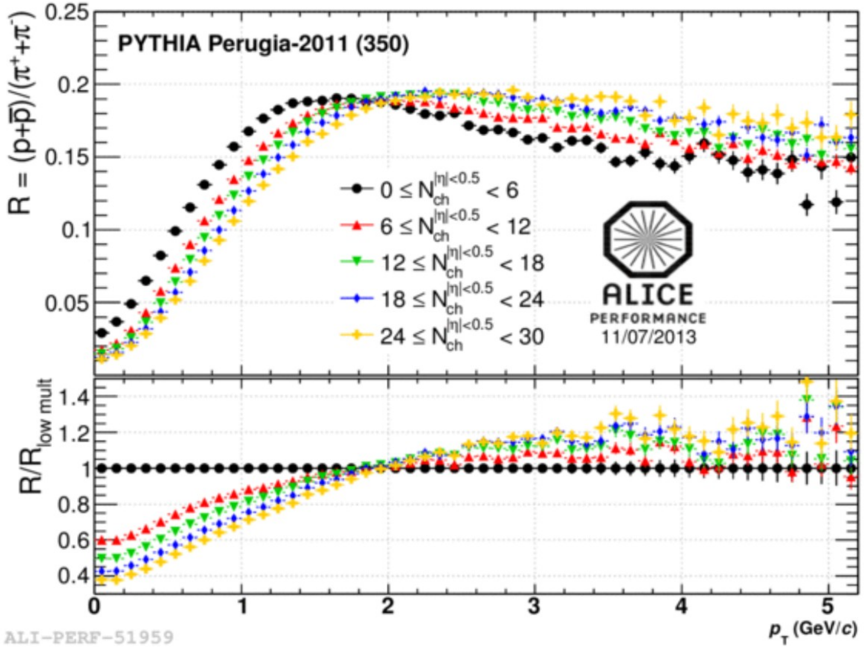
Radial flow

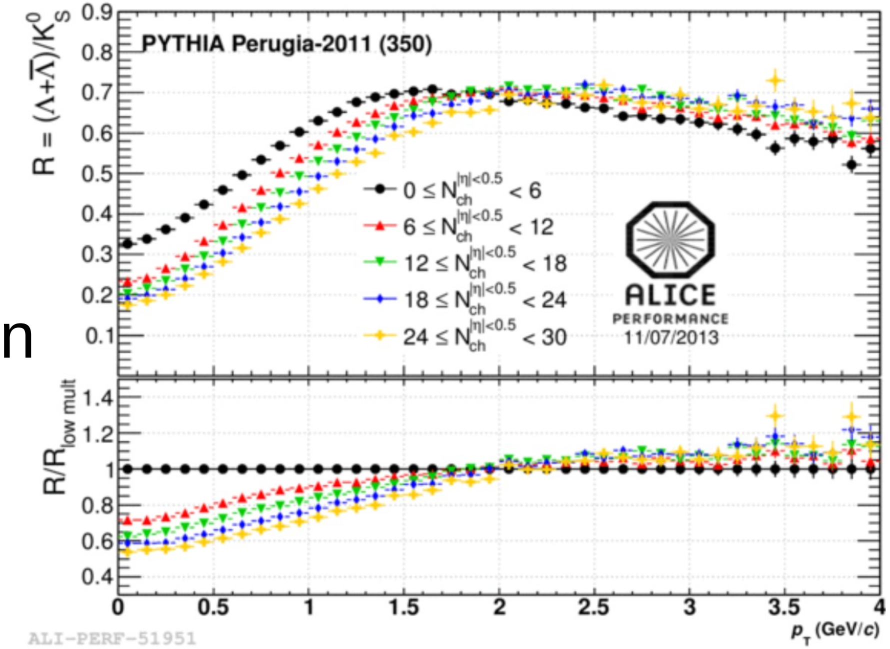


$$p_T^{flow} = p_T + m\beta_T^{flow}\gamma_T^{flow}$$

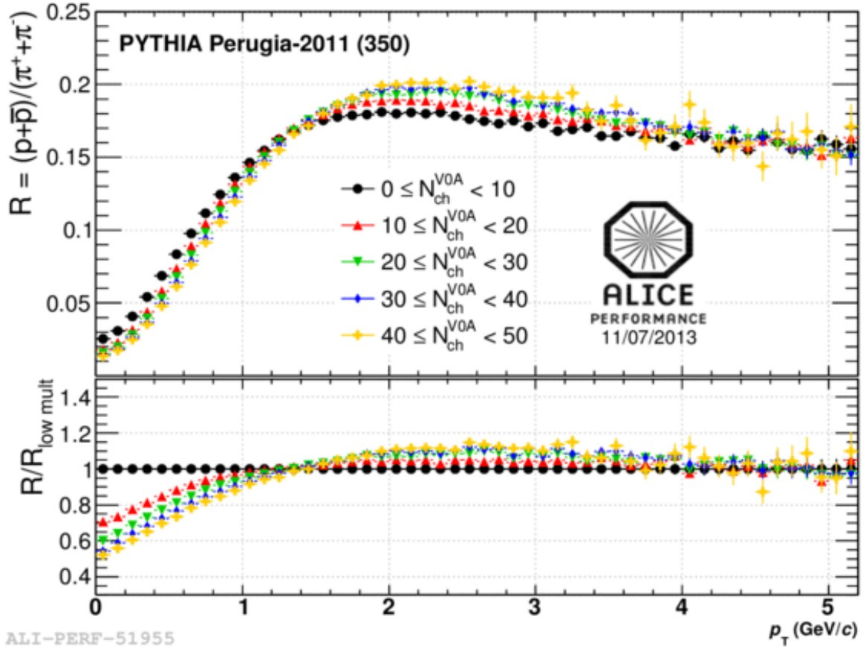
Shuryak and Zhirov, PLB 89 (1979) 253

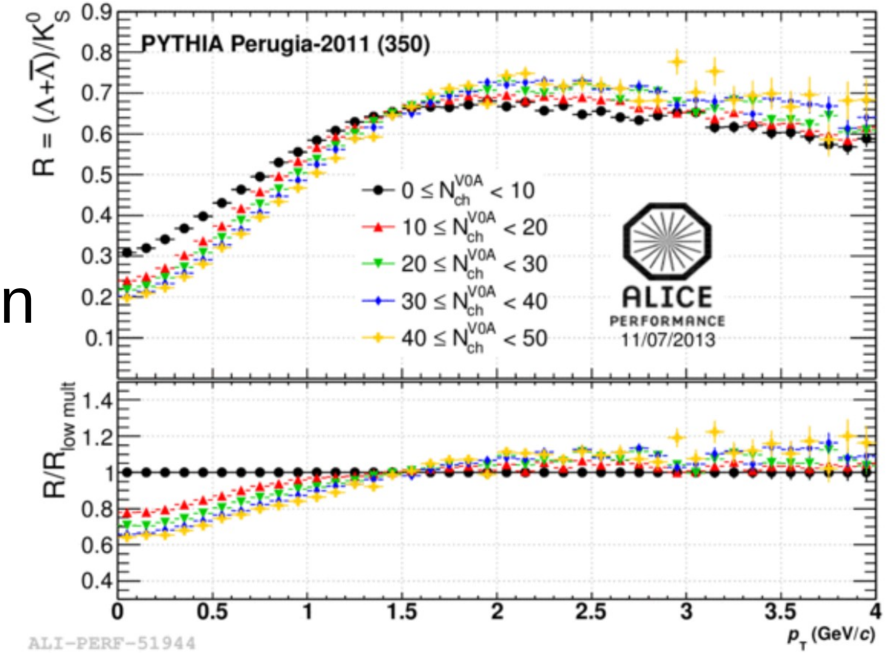
Selection bias (examples for 7 TeV)





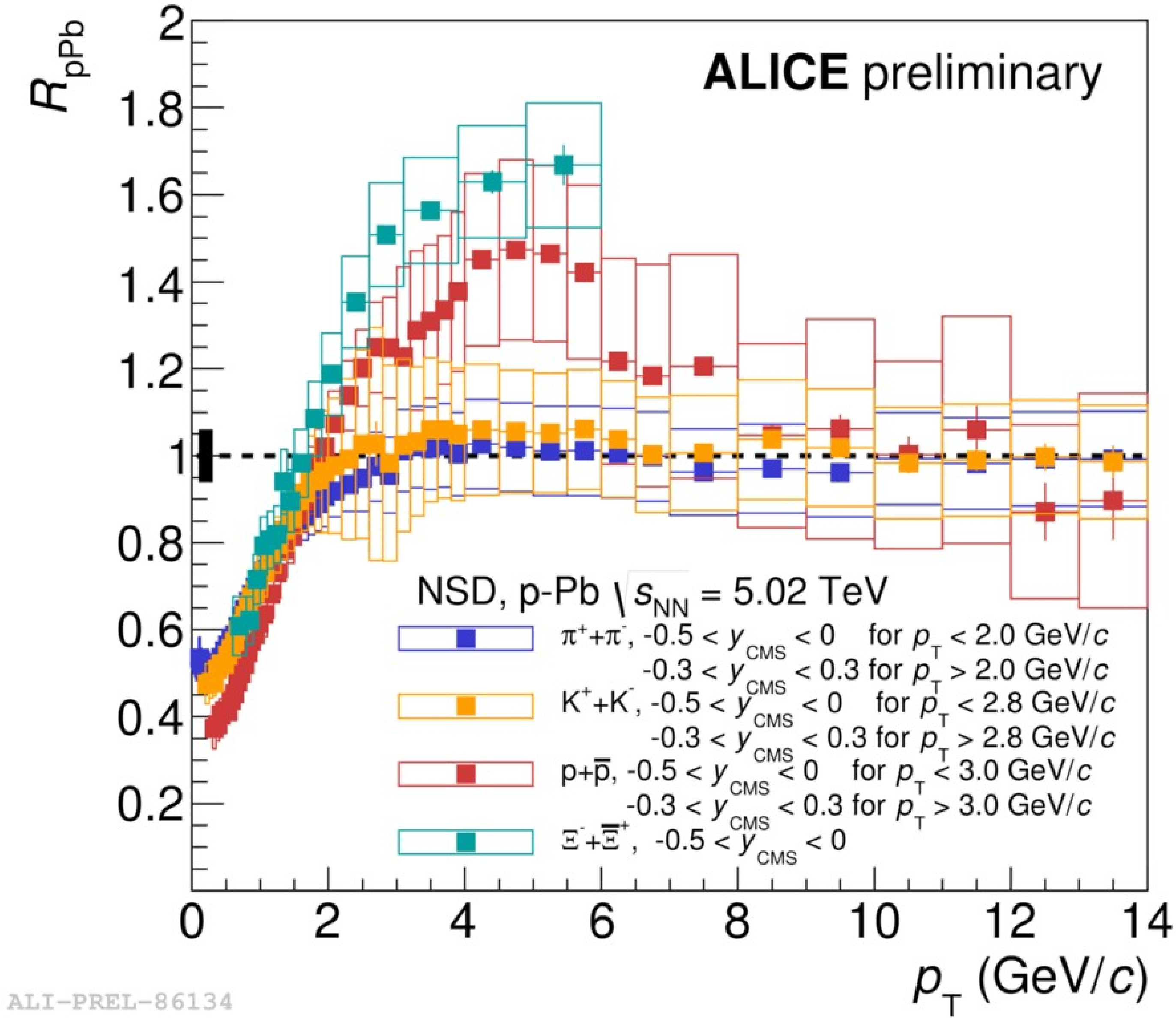
N_{ch} selection





V0A selection

Nuclear modification factor



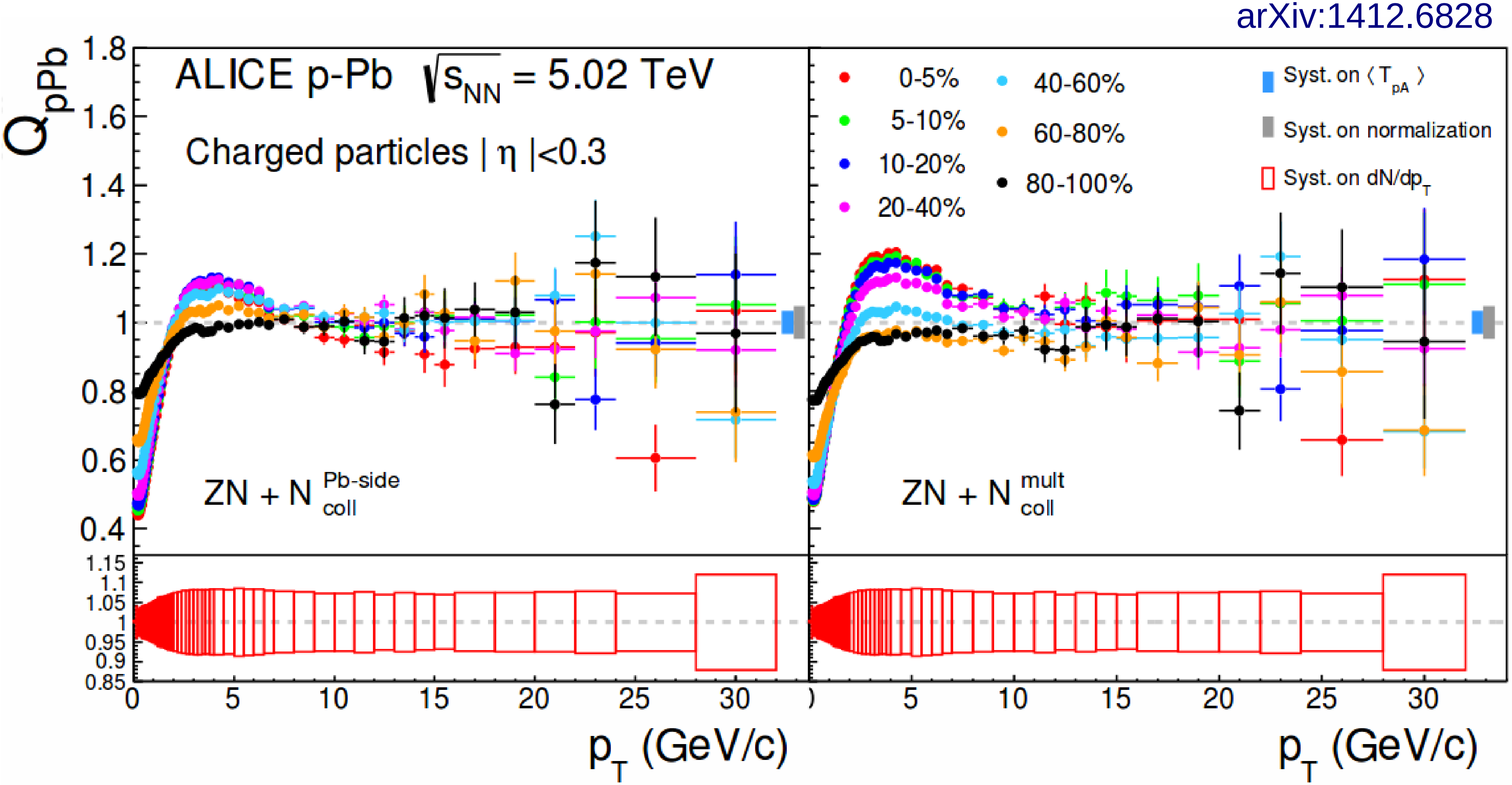
At intermediate p_T (Cronin region):

- Indication of mass ordering
  - No enhancement for pions and kaons
  - Pronounced peak for protons
  - Even stronger for cascades

Particle species dependence points to relevance of final state effects

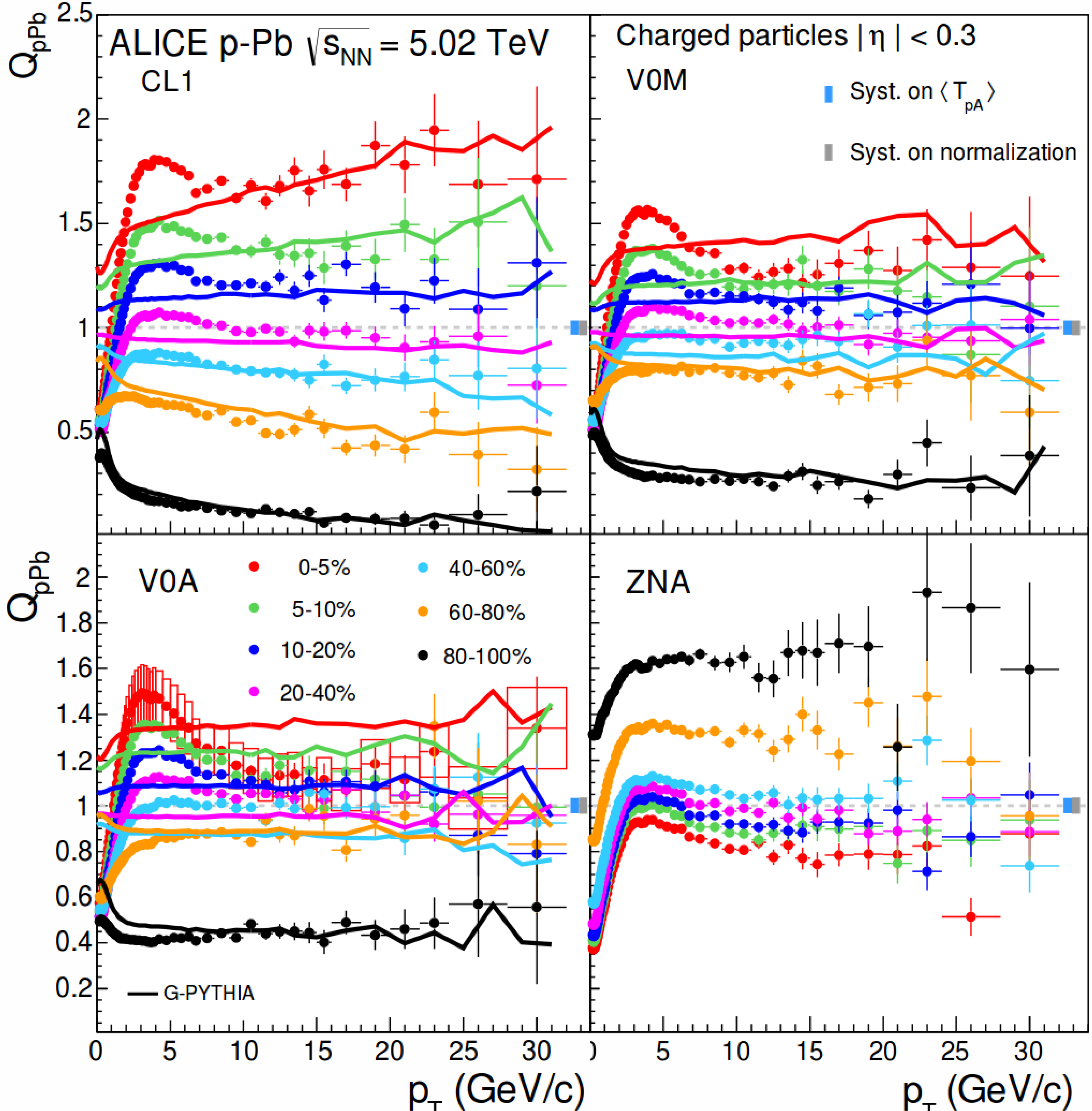
QpPb using ZN hybrid method

arXiv:1412.6828

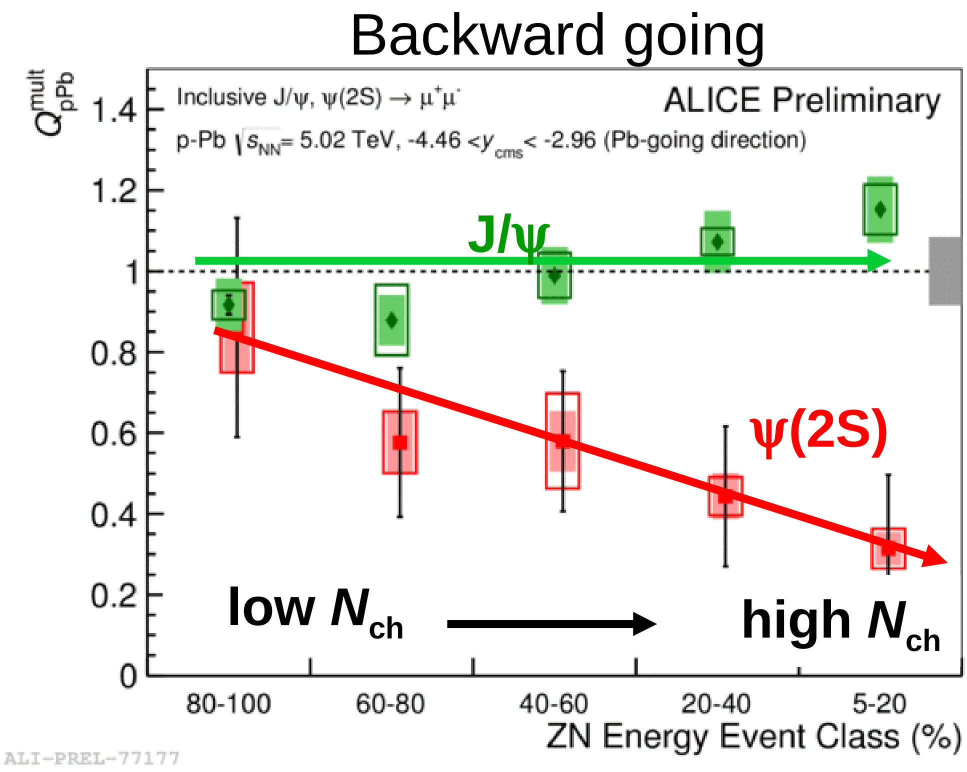


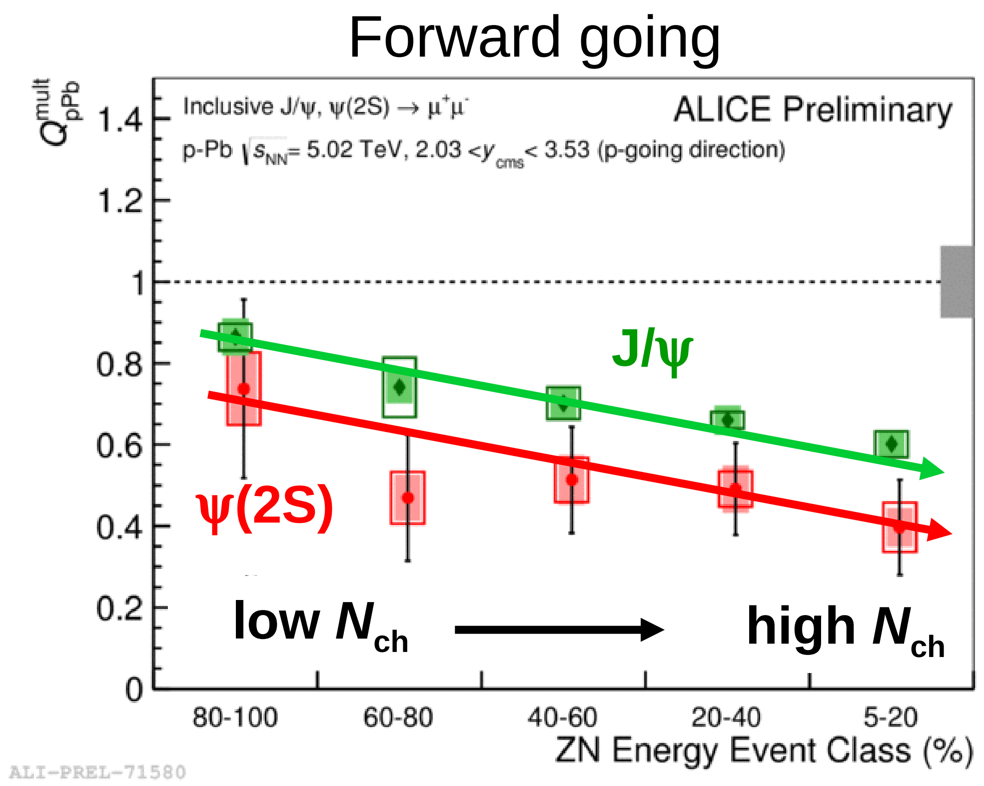
QpPb

arXiv:1412.6828



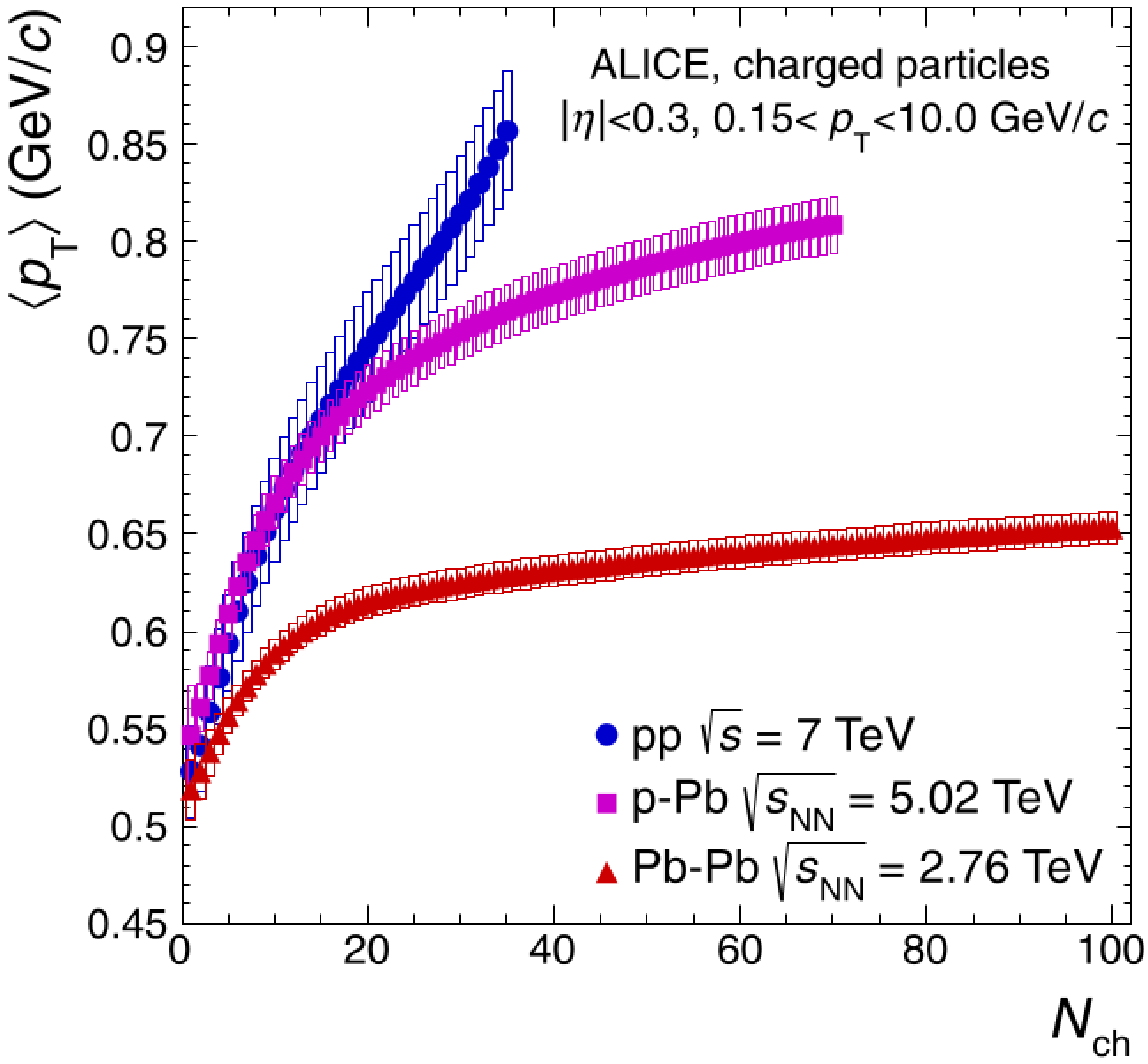
J/Ψ and Ψ(2S) suppression





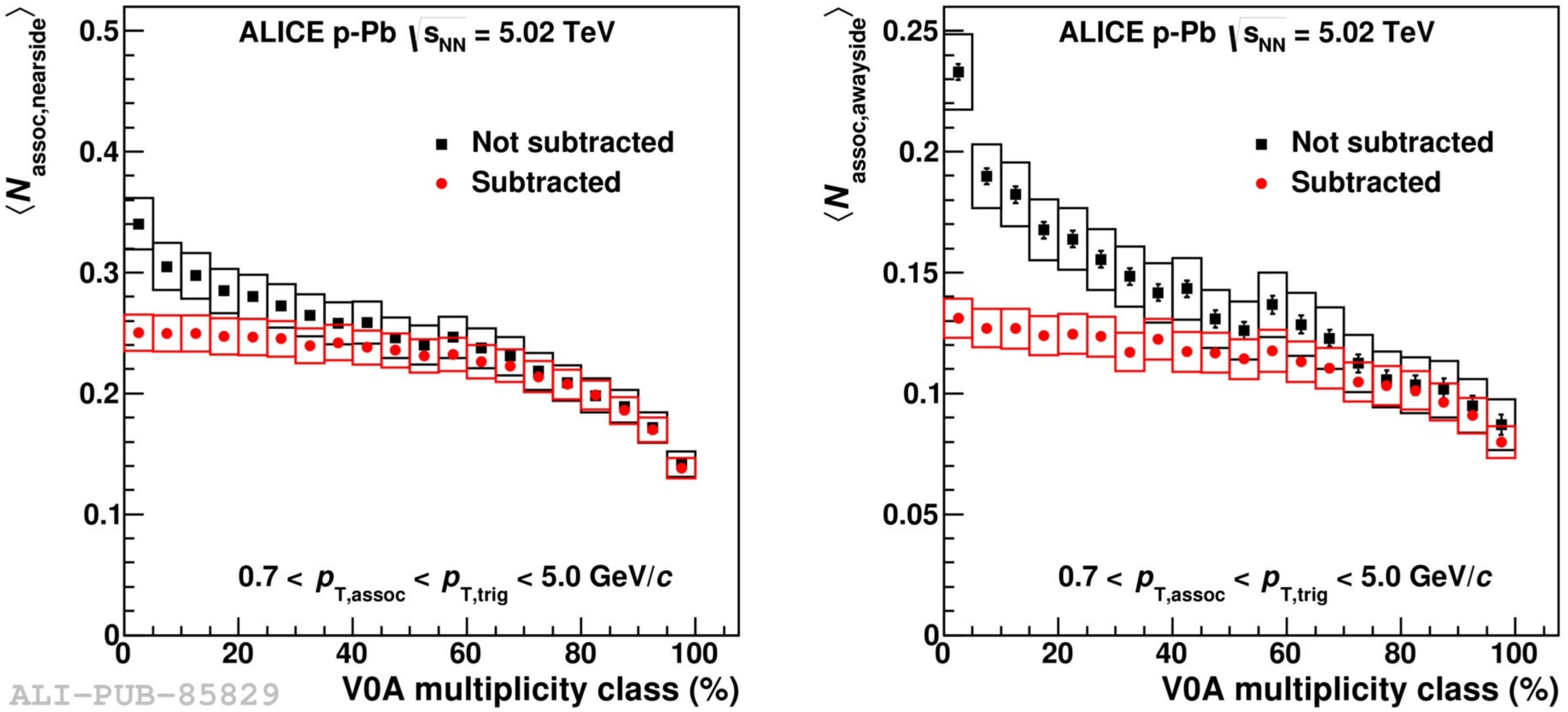
- J/ψ → μμ: Multiplicity dependent suppression in p-going direction, and no suppression in Pb-going direction
  - Consistent with shadowing
- ψ(2S) → μμ: Multiplicity dependent suppression in both directions
  - Needs additional effect (Final state?)

Average transverse momentum



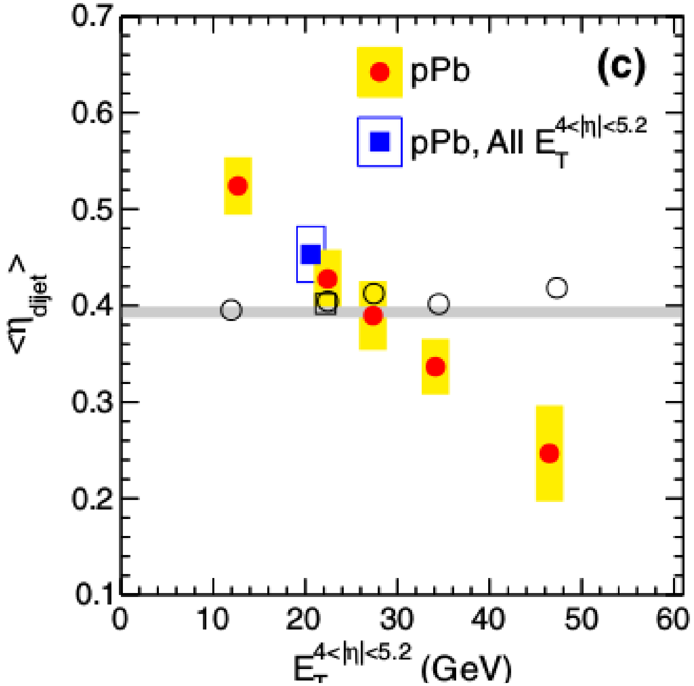
Associated yields

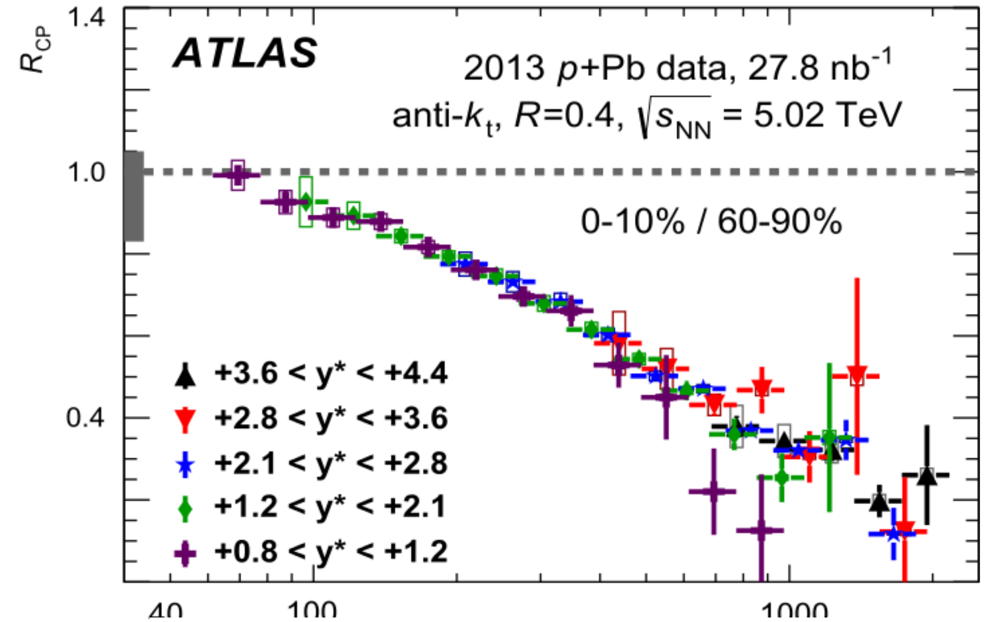
ALICE, arXiv:1406.5463

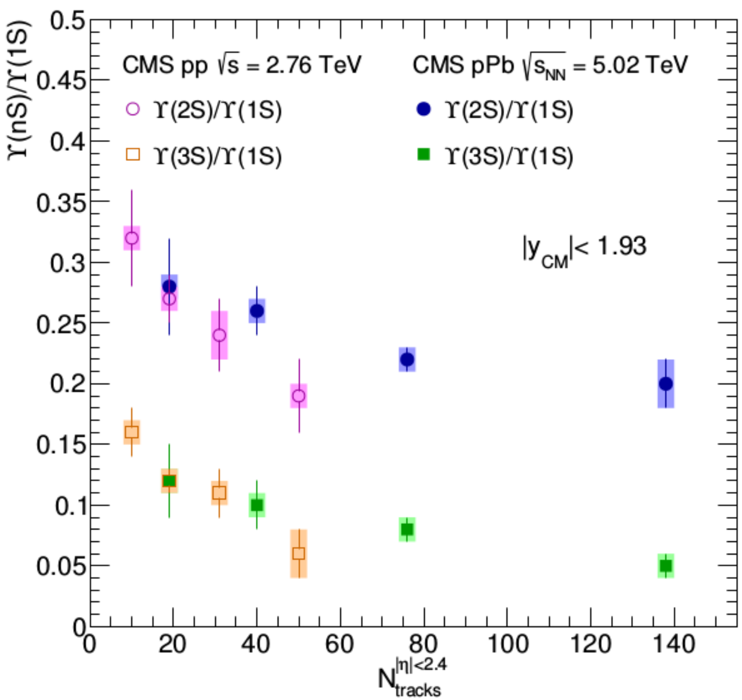


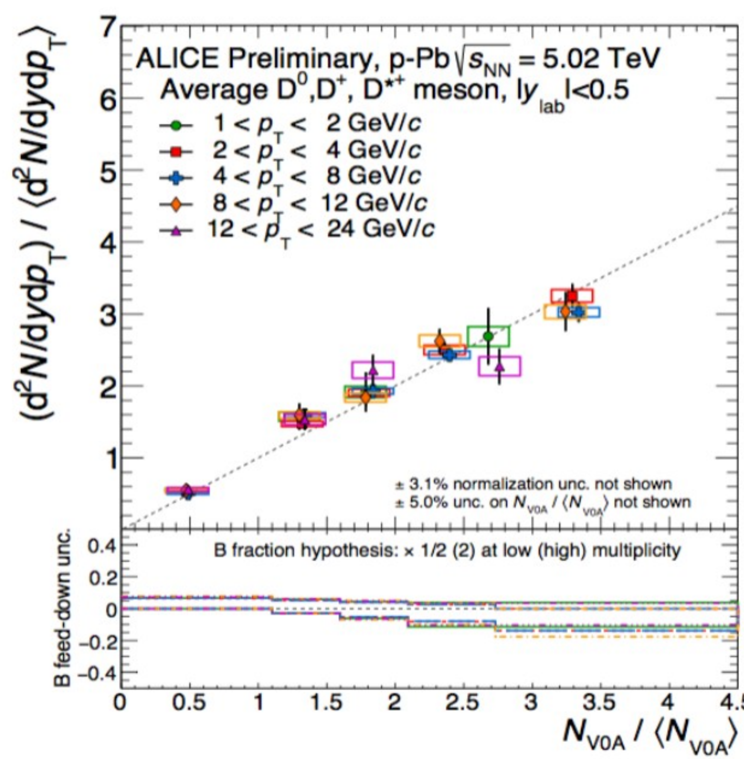
Associated yields after long range subtraction approx. flat, except for low multiplicity classes

Interplay between soft / hard production

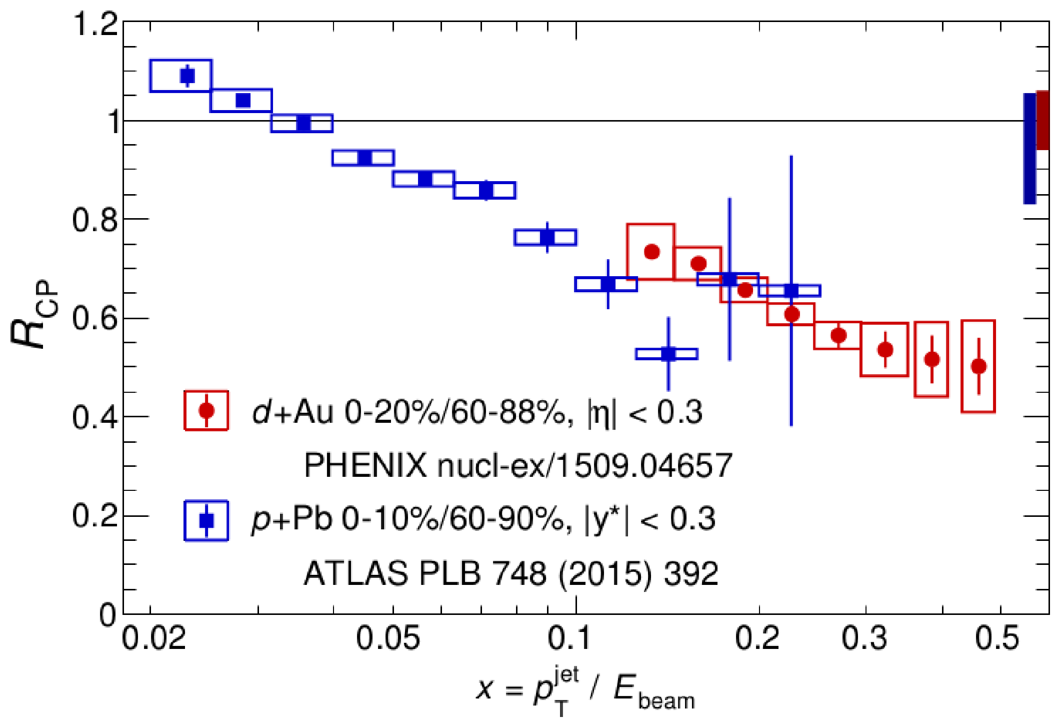


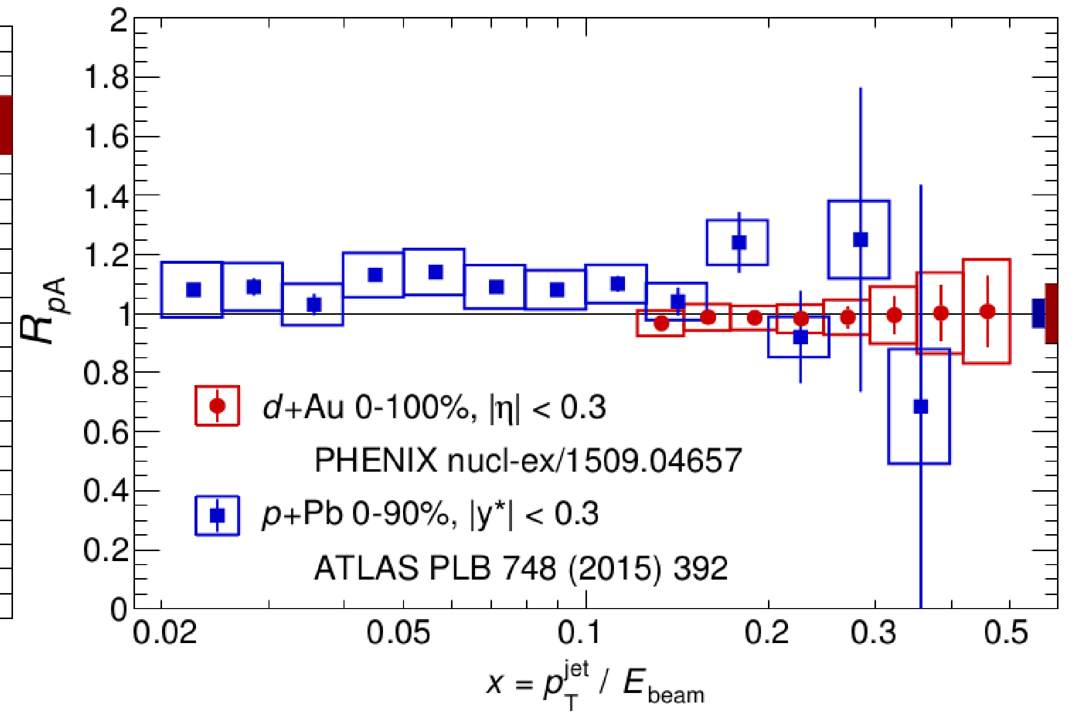






Proton color fluctuations

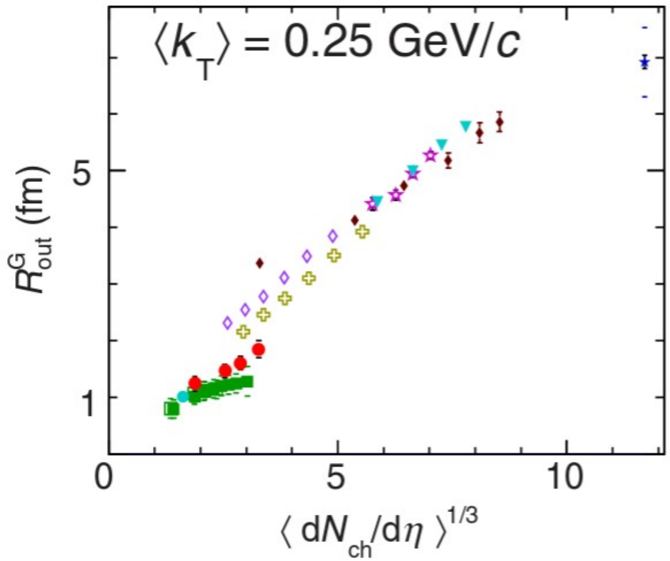


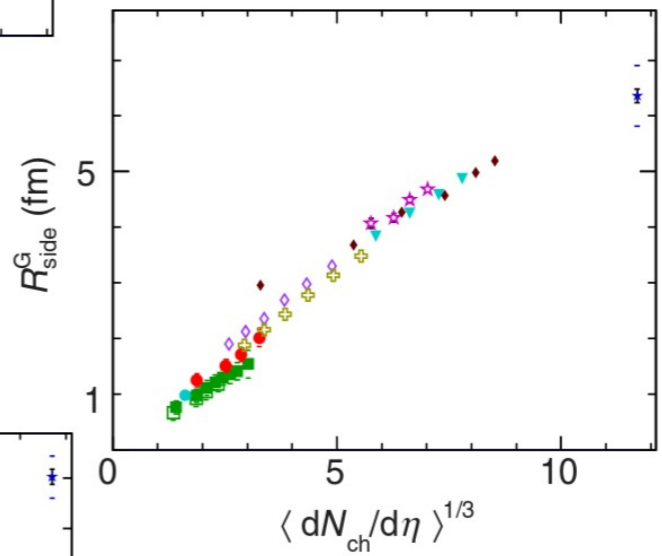


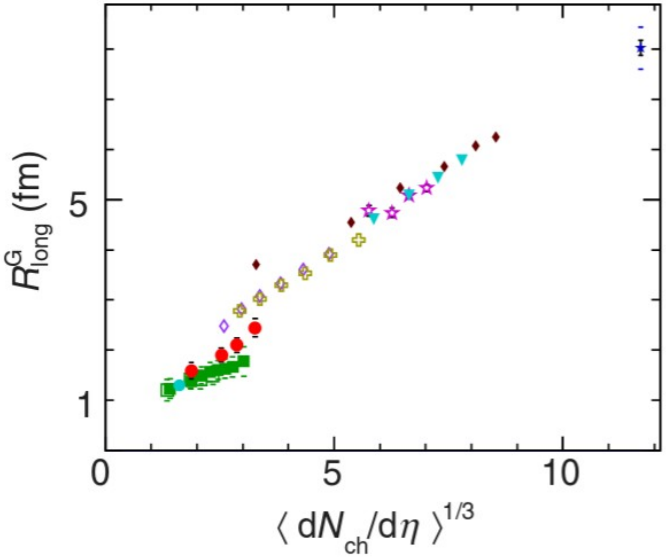
(from D.Perepelitsa)

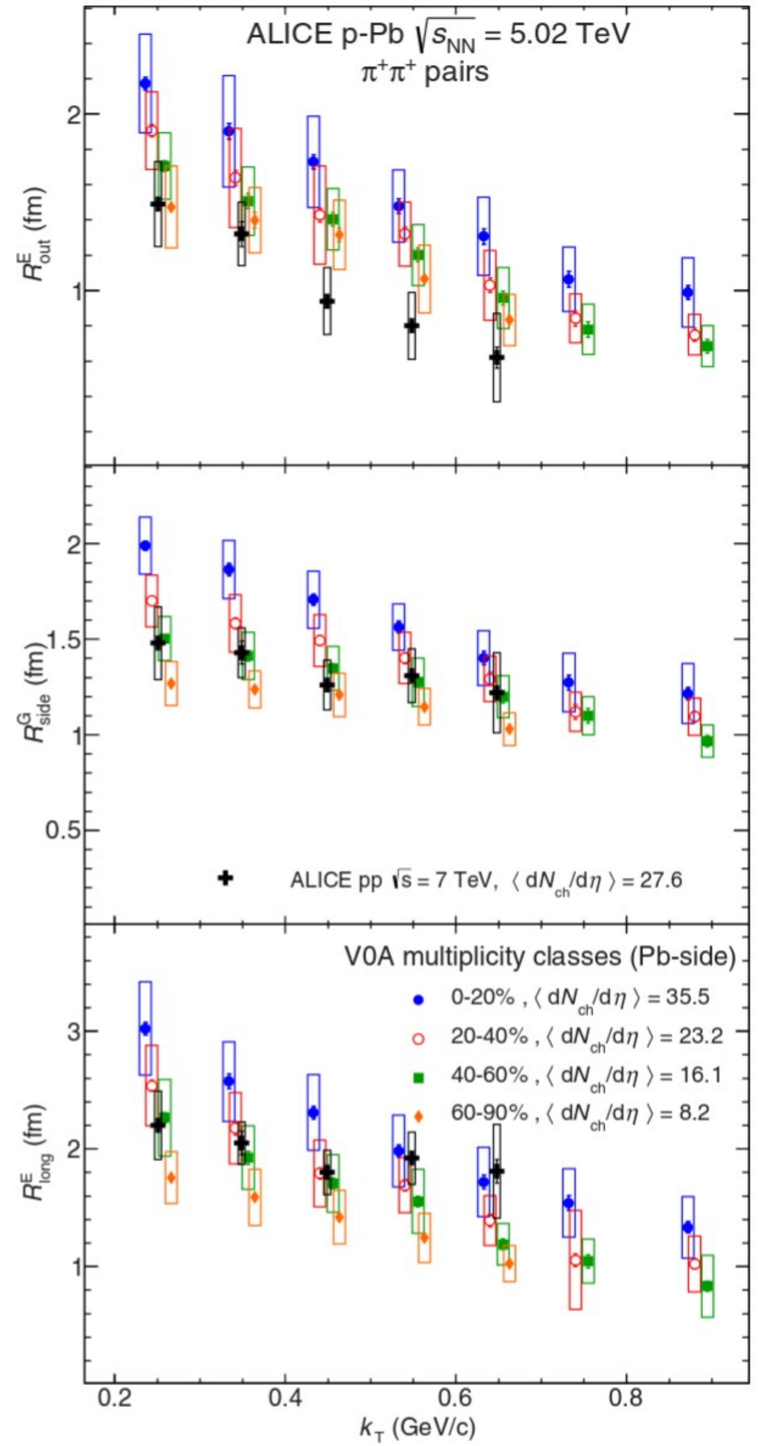
3d pion radii in p-Pb

ALICE, PRC 91 (2015) 034906

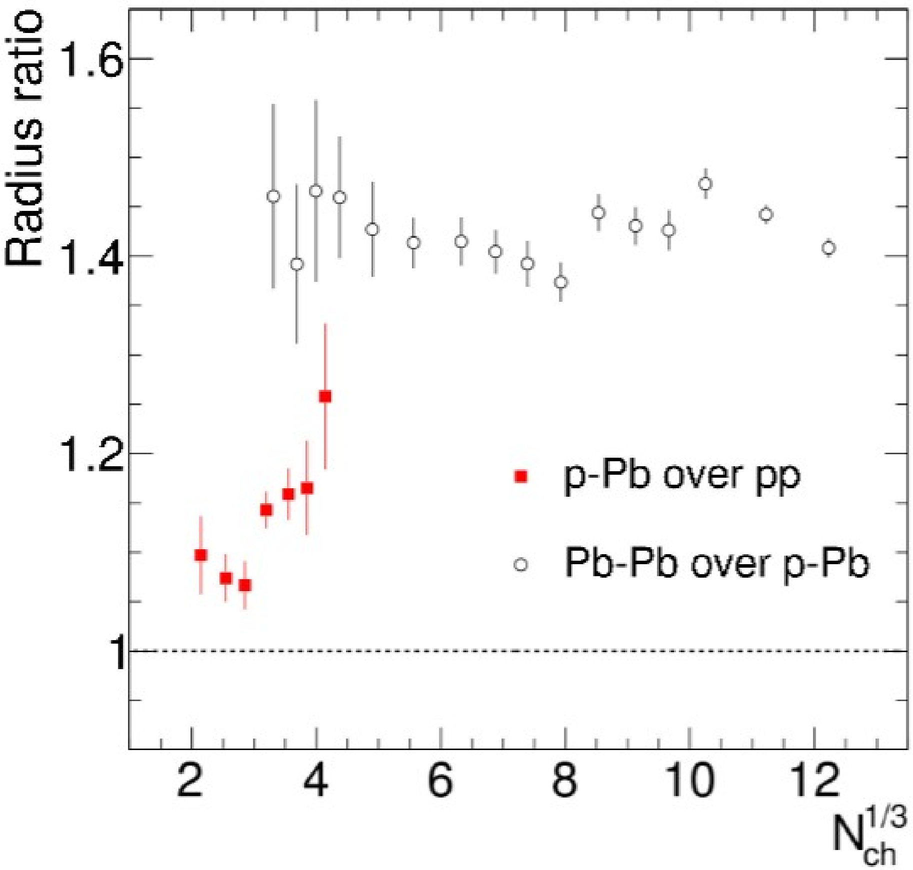


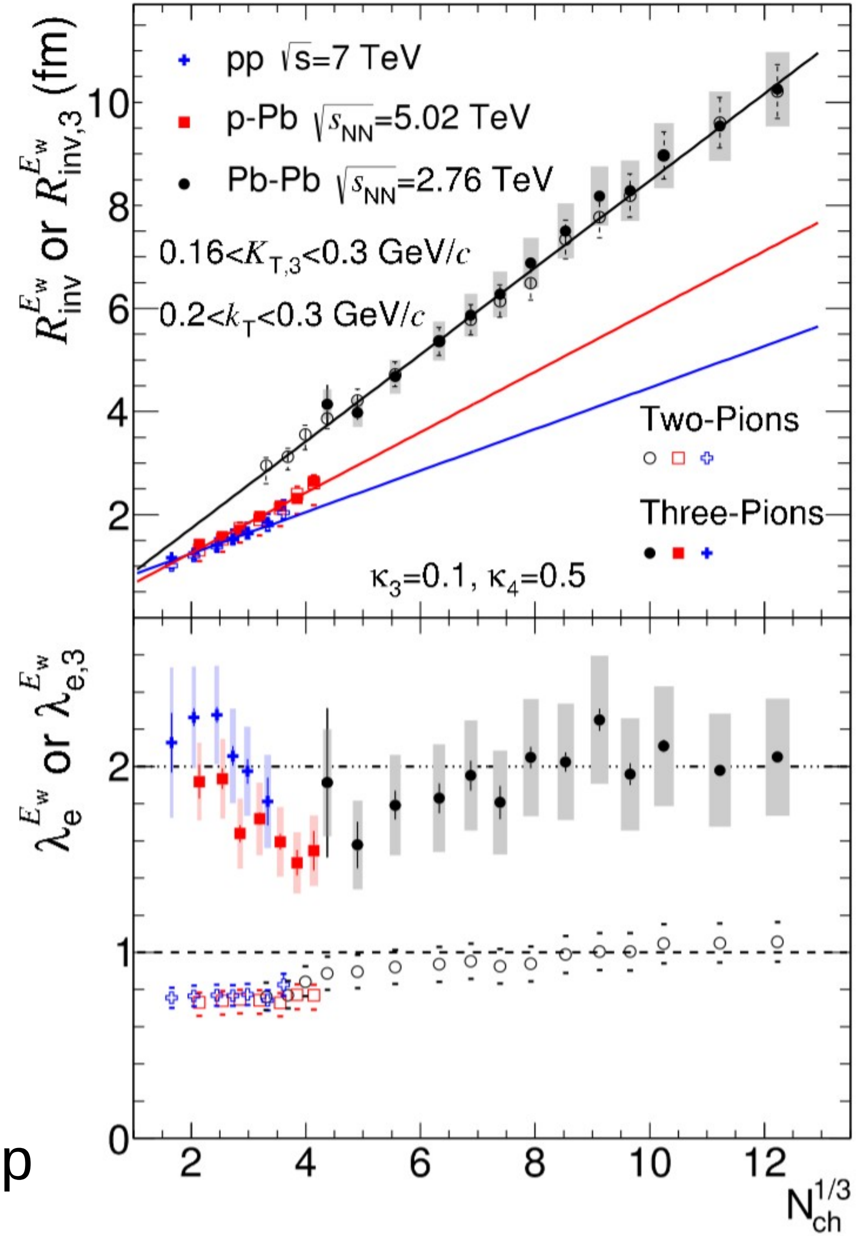






1d radii using 3 pion QS correlations

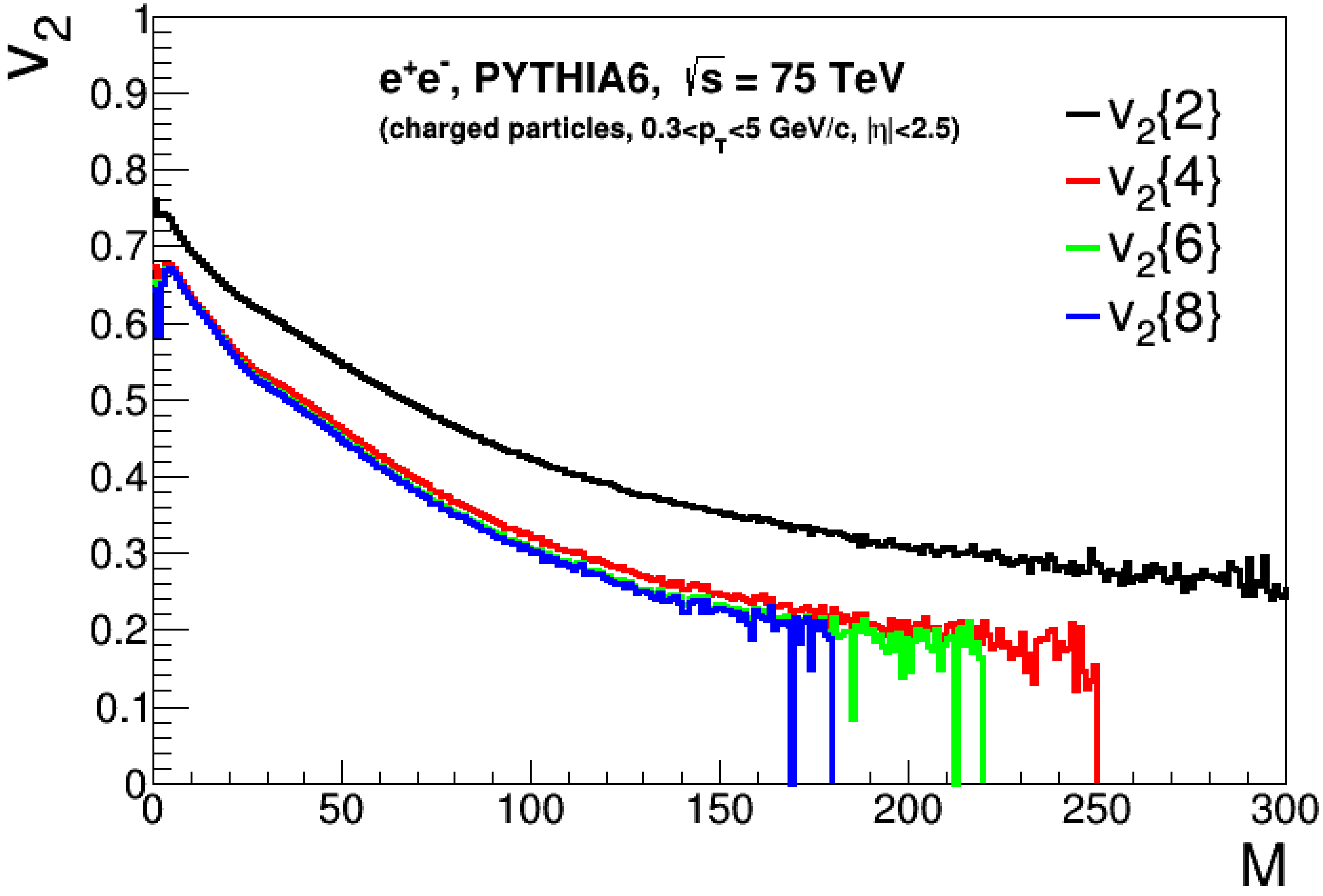




At the same measured Nch, 1d radius in pp more similar to p-Pb, than p-Pb to Pb-Pb

ALICE, PLB 739 (2014) 139

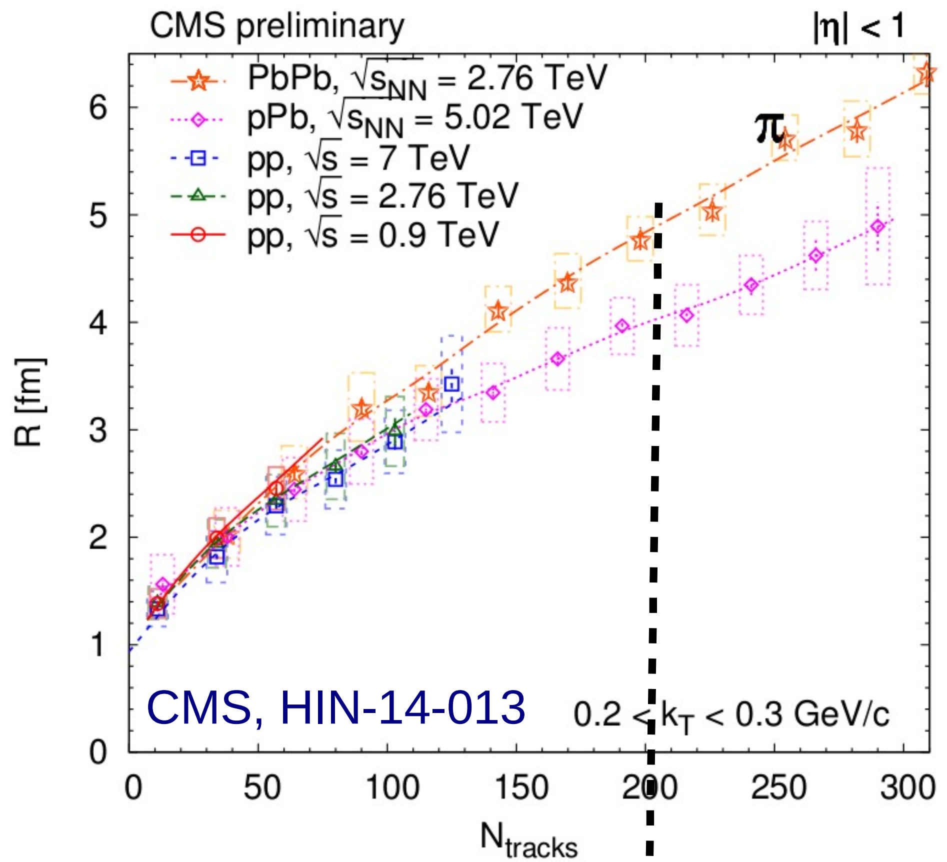
Weak collectivity



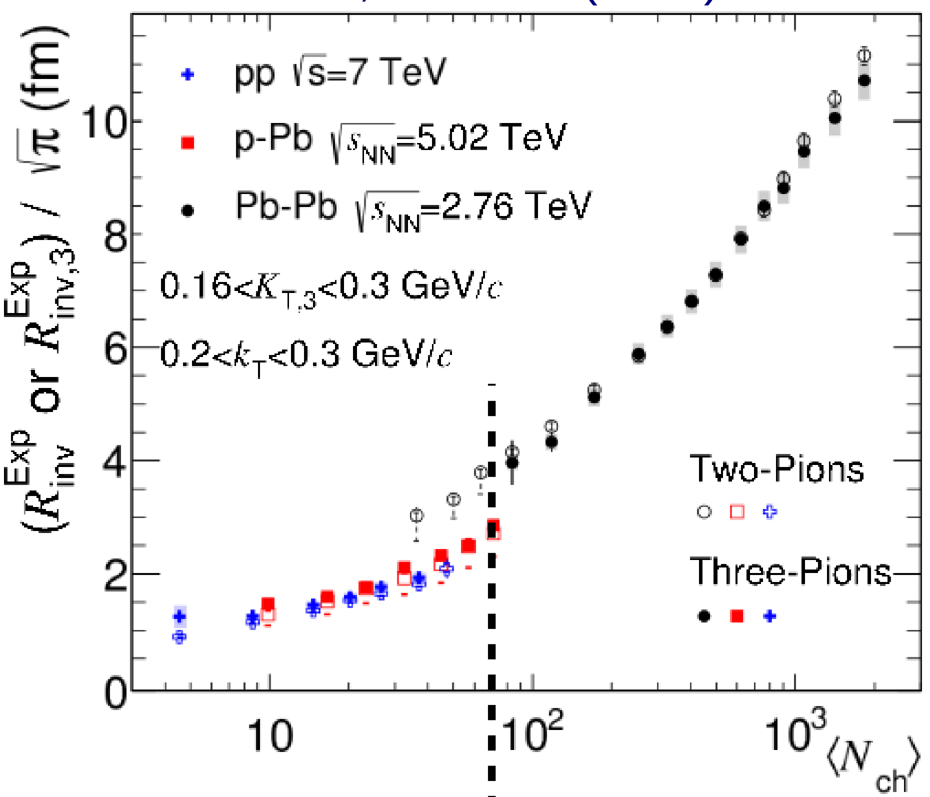
Particles produced in e+e- exhibit weak collectivity?

Data comparisons

Comparison CMS vs ALICE (1d radii)



ALICE, PLB 739 (2014) 139



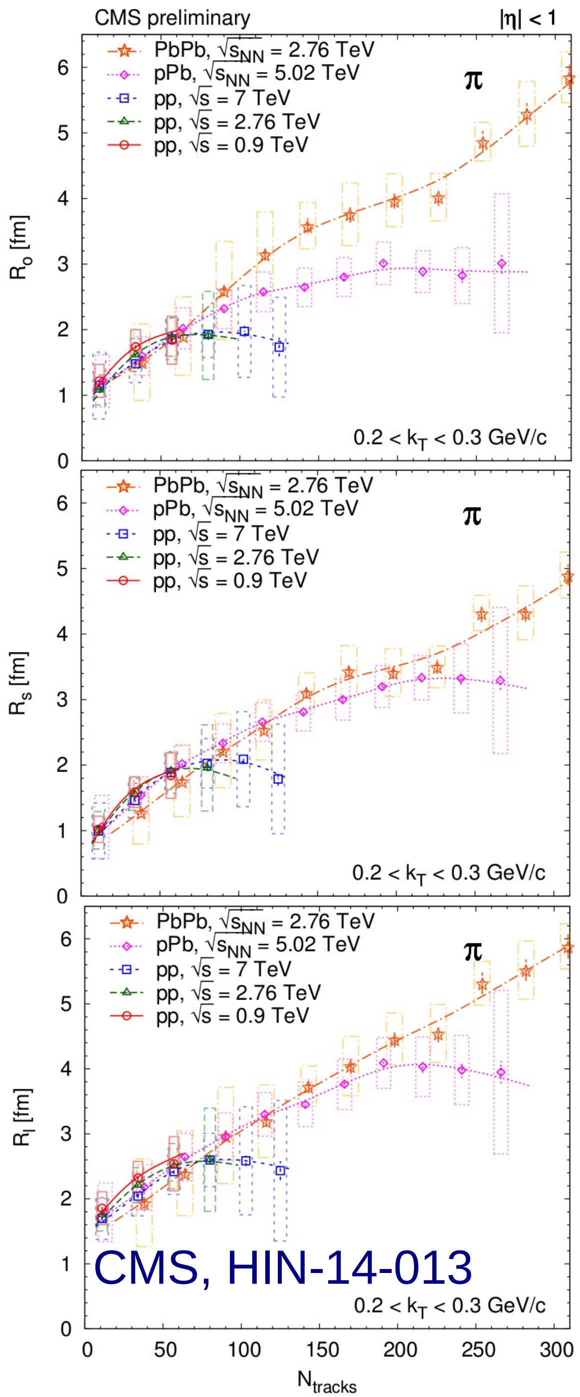
Corresponds to ~50 tracks for |η|<1

Corresponds to ~50 tracks for |η|<1

Qualitative similar result, but quantitatively different!

CMS: Corrected Nch in |η|<4.8 down to 0
ALICE: Corrected Nch in |η|<1.6 down to 0.16 GeV/c

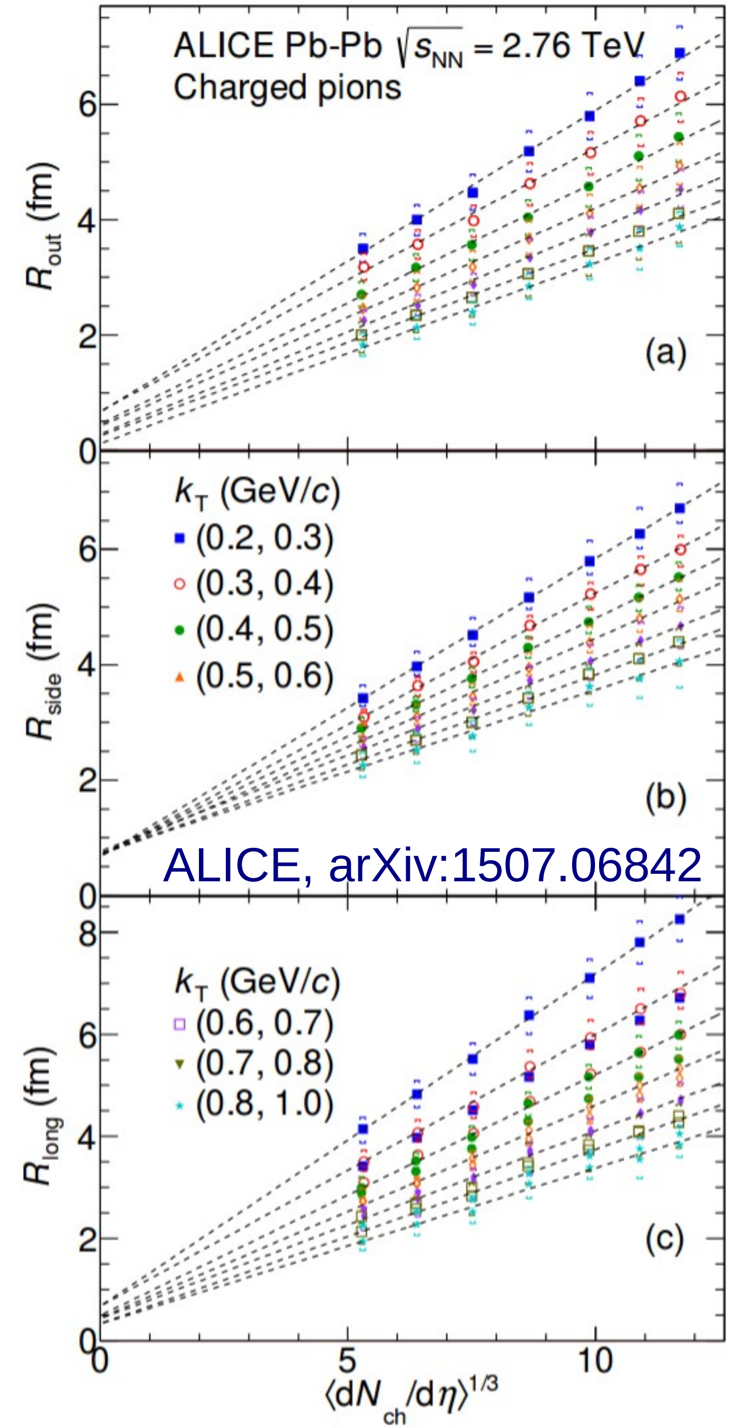
Comparison CMS and ALICE (3d radii)



CMS at Ntrack of 300, should be compared to ALICE at $dN/d\eta^{1/3}$ of ~4

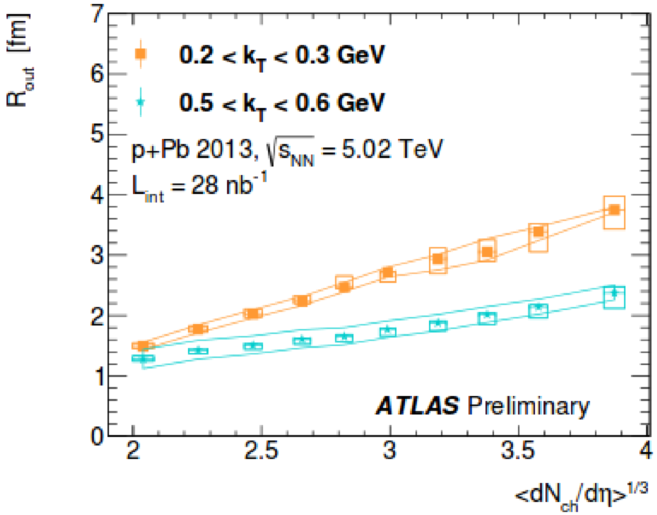
3d Pb-Pb radii are consistent

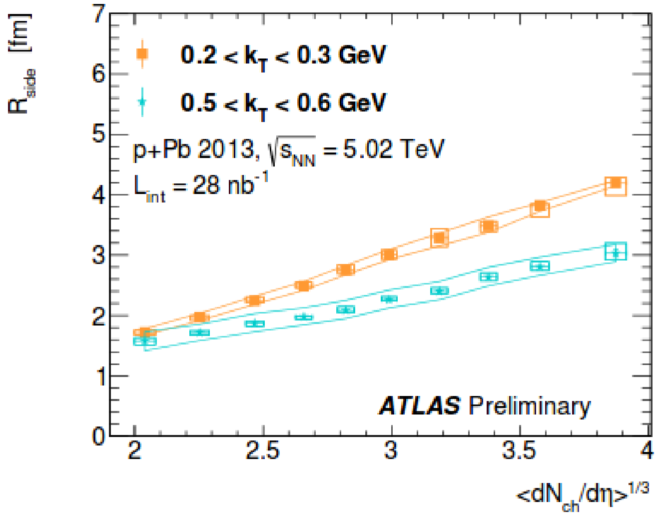
(CMS radii are exp in 3d, so scale by √π)

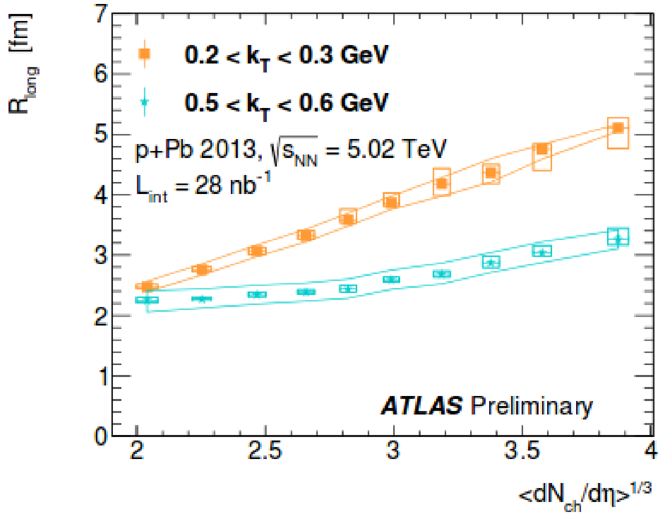


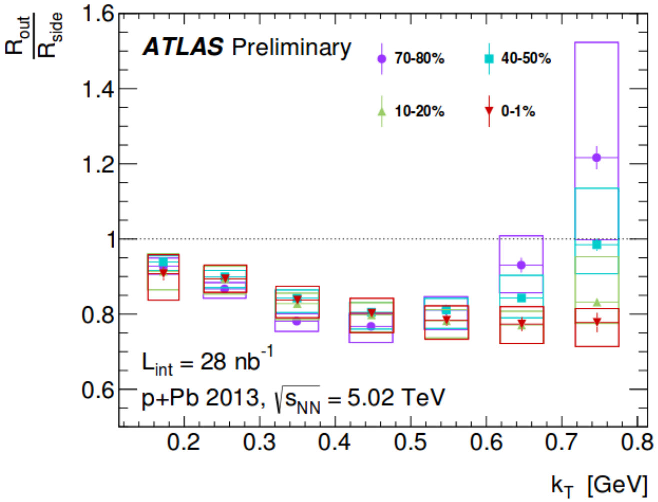
Radii from ATLAS

ATLAS-CONF-2015-054





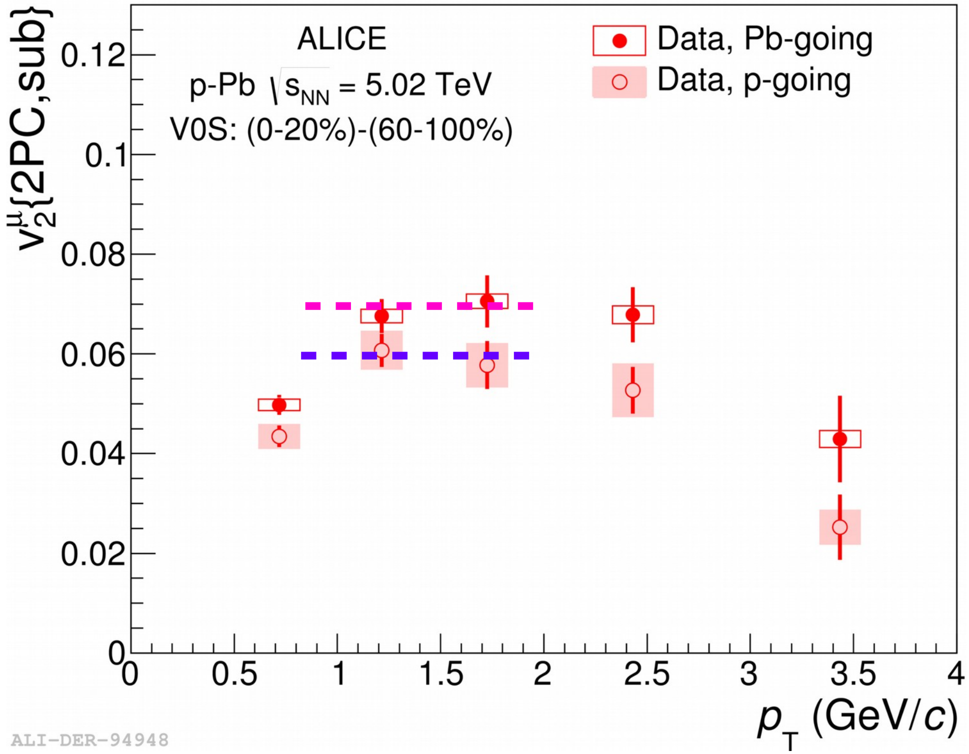




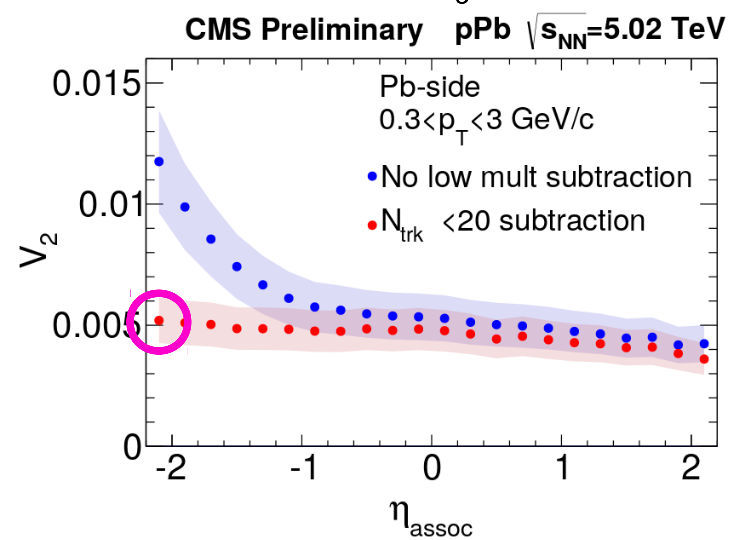
(Radii are exp in 3d, so scale by √π)

Comparison to prel. CMS

CMS-HIN-14-008



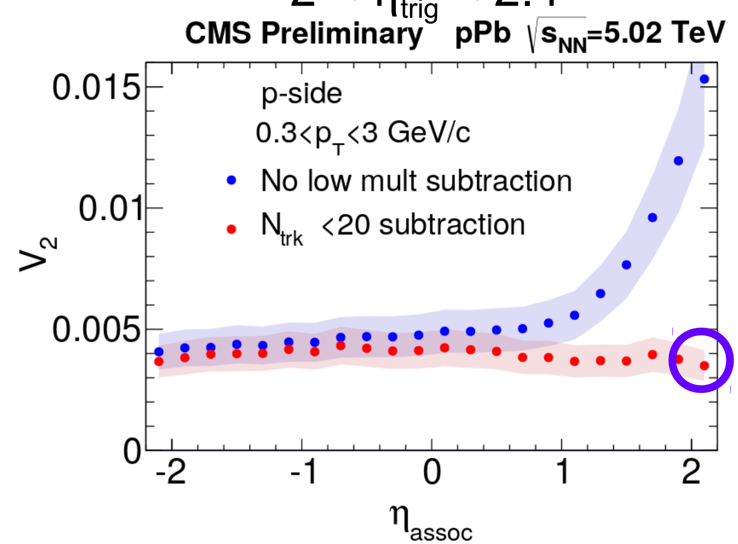
$-2.4 < \eta_{trig} < -2$



Δη: 0 2 4

V_2=0.005 ↓ v_2=0.07

$2 < \eta_{trig} < 2.4$



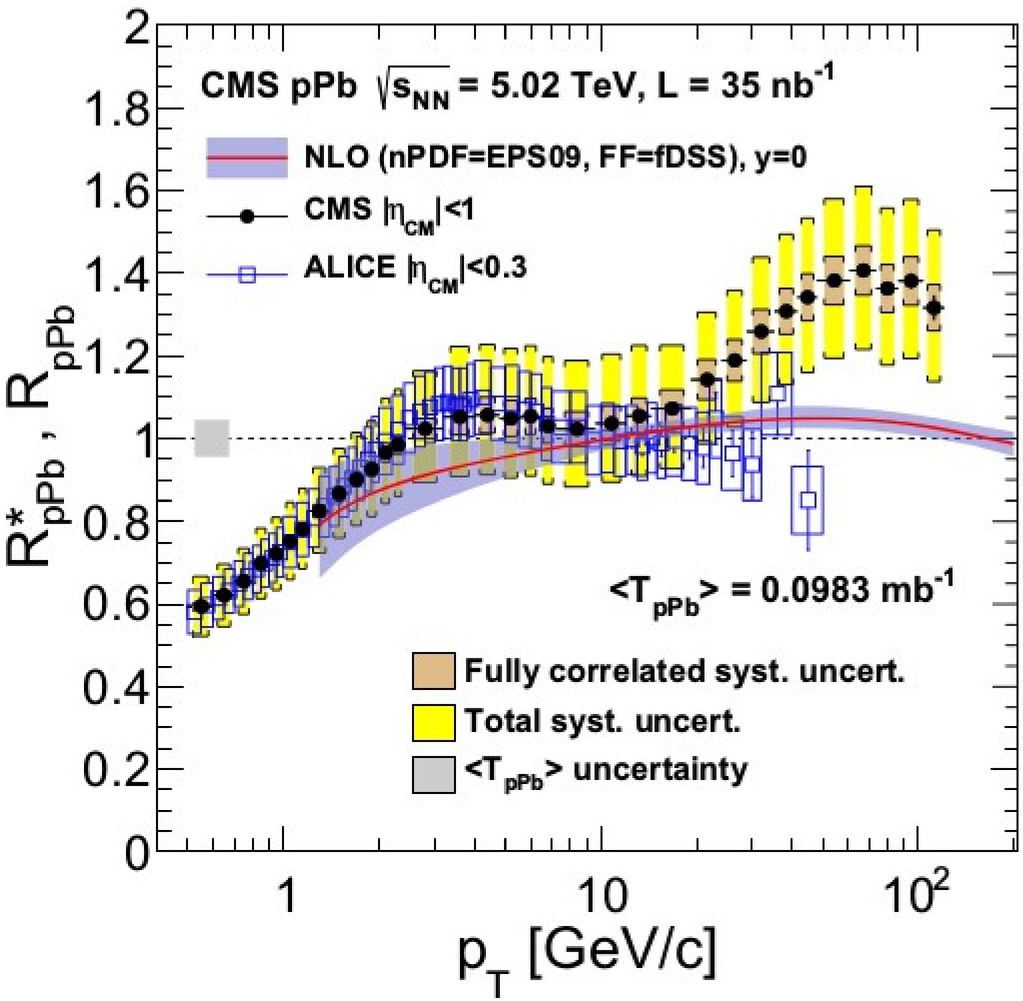
Δη: -4 -2 0

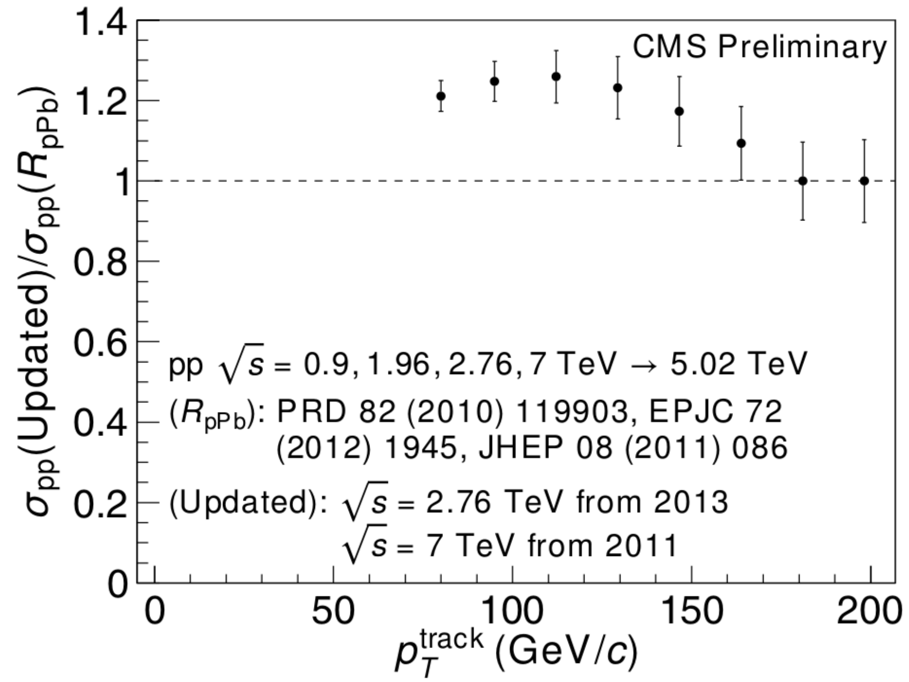
V_2=0.0035 ↓ v_2=0.06

- Resulting coefficients
  - of similar magnitude
  - with same asymmetry
- Not apples-to-apples comparison
  - Muons vs charged particles
  - Kinematic ranges + event selection

R_{pPb} at high p_T

CMS-HIN-15-004

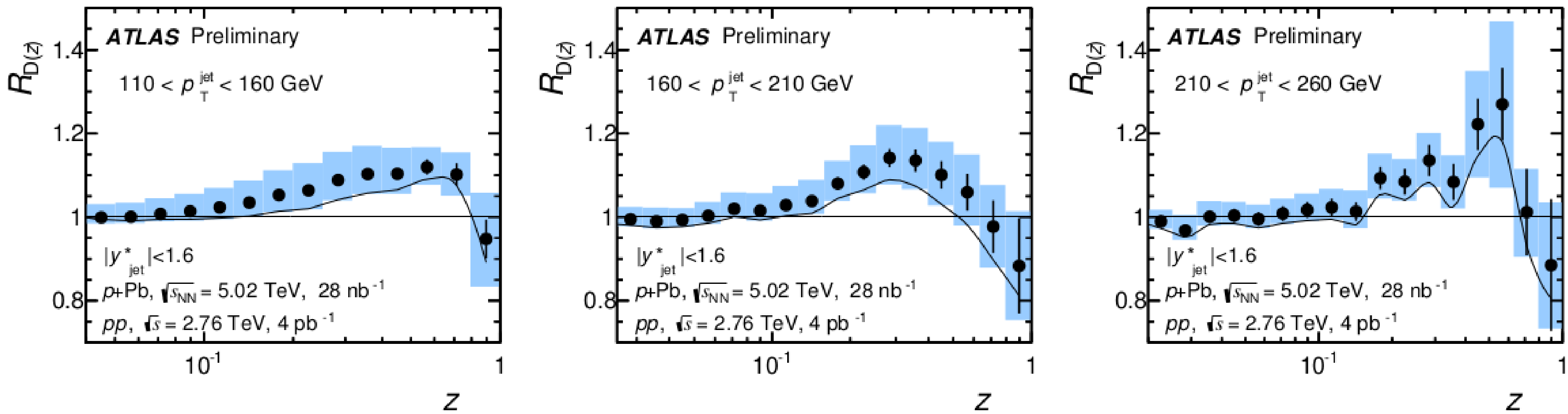


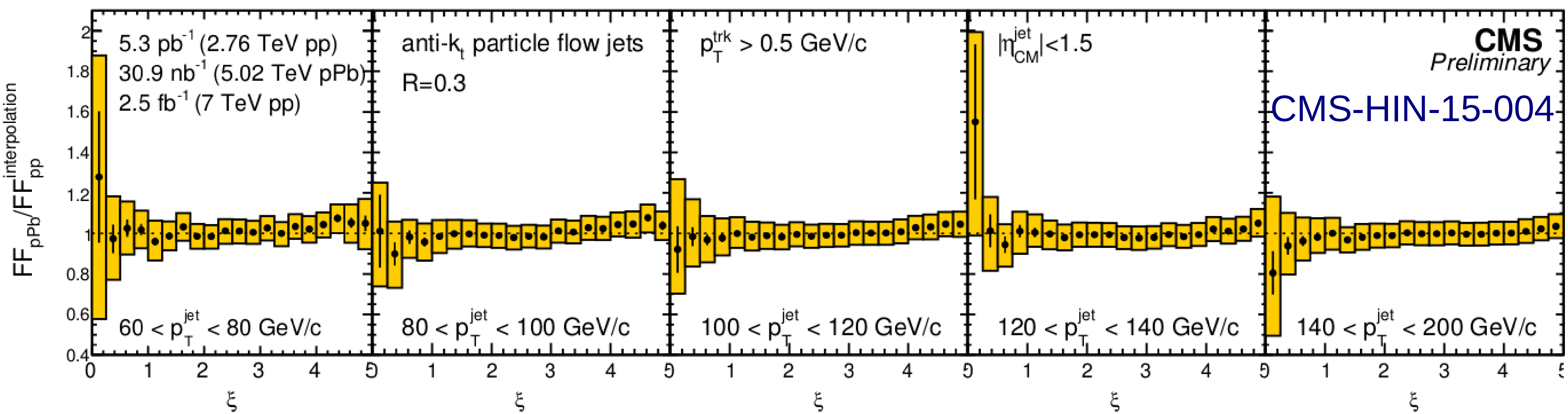


As suspected, the enhancement is from (interpolated) pp reference (pp data at 5 TeV will soon be taken!)

Fragmentation function in p-Pb vs pp

ATLAS-CONF-2015-022





Discrepancy with CMS, but both use interpolated pp references