Fourth Annual Conference on Large Hadron Collider Physics

Results from proton–lead collisions

André Mischke

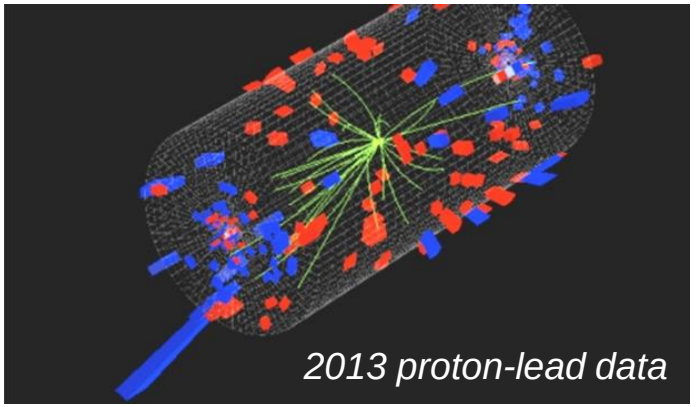
Utrecht University

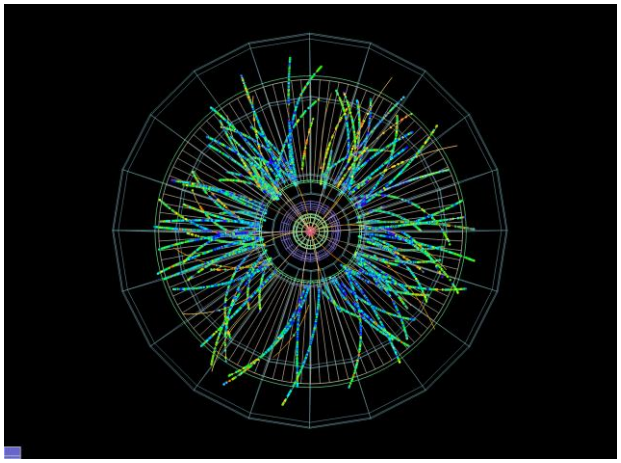
Netherlands Organisation for Scientific Research

Physics Utrecht EMMEΦ

Outline

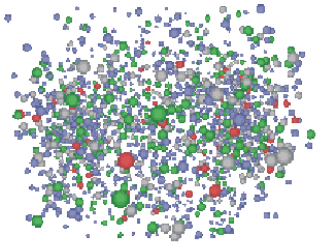
- Introduction
- Selected results from LHC experiments ALICE, ATLAS, CMS and LHCb
- Light flavour: strangeness
- Azimuthal correlations and jets
- Open and hidden heavy-flavour
- Summary and outlook



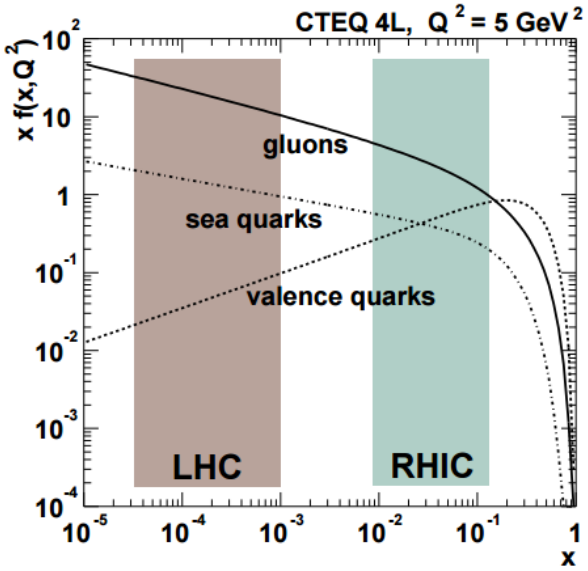


Cold nuclear matter (CNM) effects

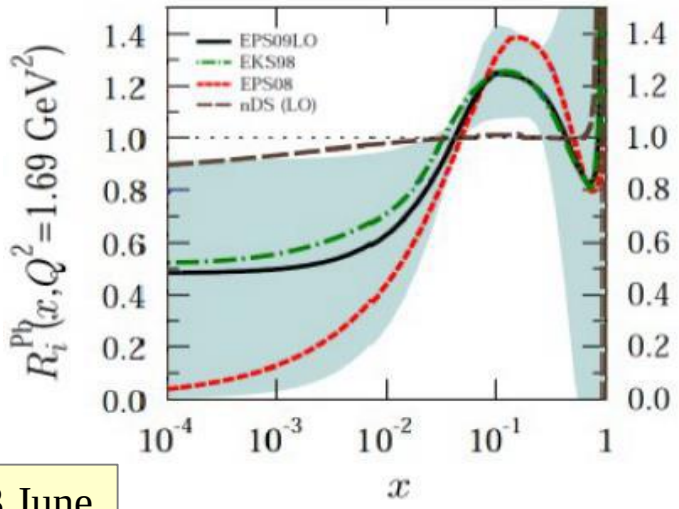
- Study cold nuclear matter effects (from initial state) such as
  - Nuclear modification of PDFs → **shadowing** at low Bjørken-x (dominant at LHC)
  - Gluon **saturation** from evolution equations (DGLAP and BFKL)
  - k_T broadening and Cronin enhancement from multiple parton scatterings
  - Initial-state energy loss



- Final-state effects
  - Energy loss?
  - Interactions between final-state particles (collective expansion?)
- Crucial for test of pQCD calculations and interpretation of heavy-ion results



K.J. Eskola, H. Paukkunen, C. A. Salgado, JHEP 0904, 65 (2009)



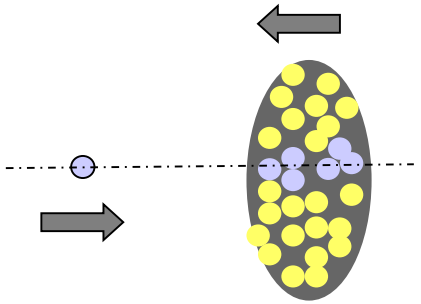
K. Mueller, QCD parallel, 13 June

Data sets

- Lead beam ($^{208}_{82}$Pb) with an energy of 1.58 TeV per nucleon and opposing proton beam with an energy of 4 TeV

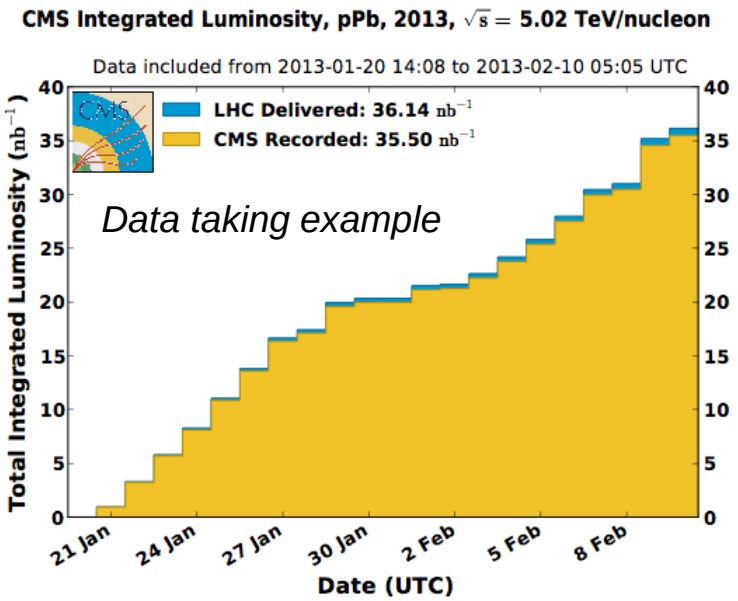
→ **p-Pb collisions with cms energy of $\sqrt{s_{NN}}$ = 5.02 TeV**

- 13 bunches were circulating with about 10^{10} protons and 6×10^{7} Pb ions per bunch
- Very successful end of LHC run-1 data taking in 2013



Δy_{cms} = 0.465 (in proton direction)

Experiment	Integrated luminosity
ALICE	~50 μb^{-1}
ATLAS	~30 nb^{-1}
CMS	~35 nb^{-1}
LHCb	~1.6 nb^{-1}



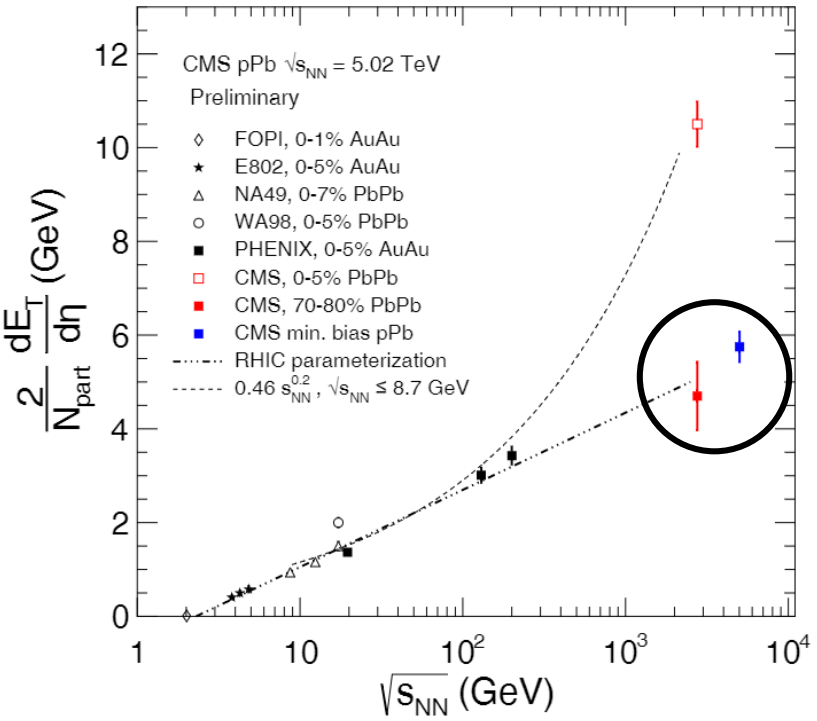
Light flavour

Global event properties

Transverse energy density

$(dE_T/d\eta)/(N_{part}/2) \sim 5.8$ GeV

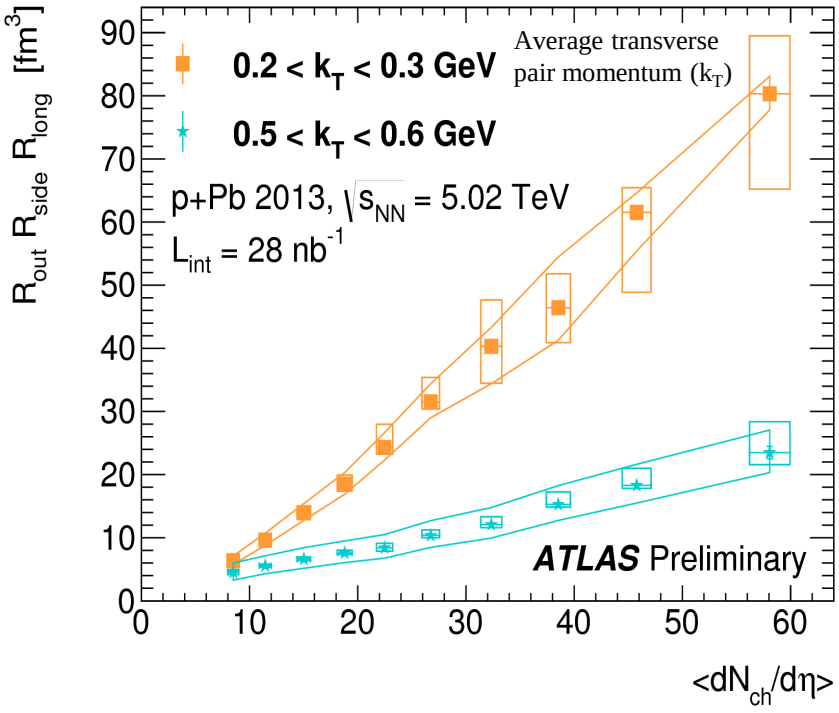
CMS-HIN-14-014



Charged pion HBT measurements:

size of particle emitting source

ATLAS-CONF-2015-054



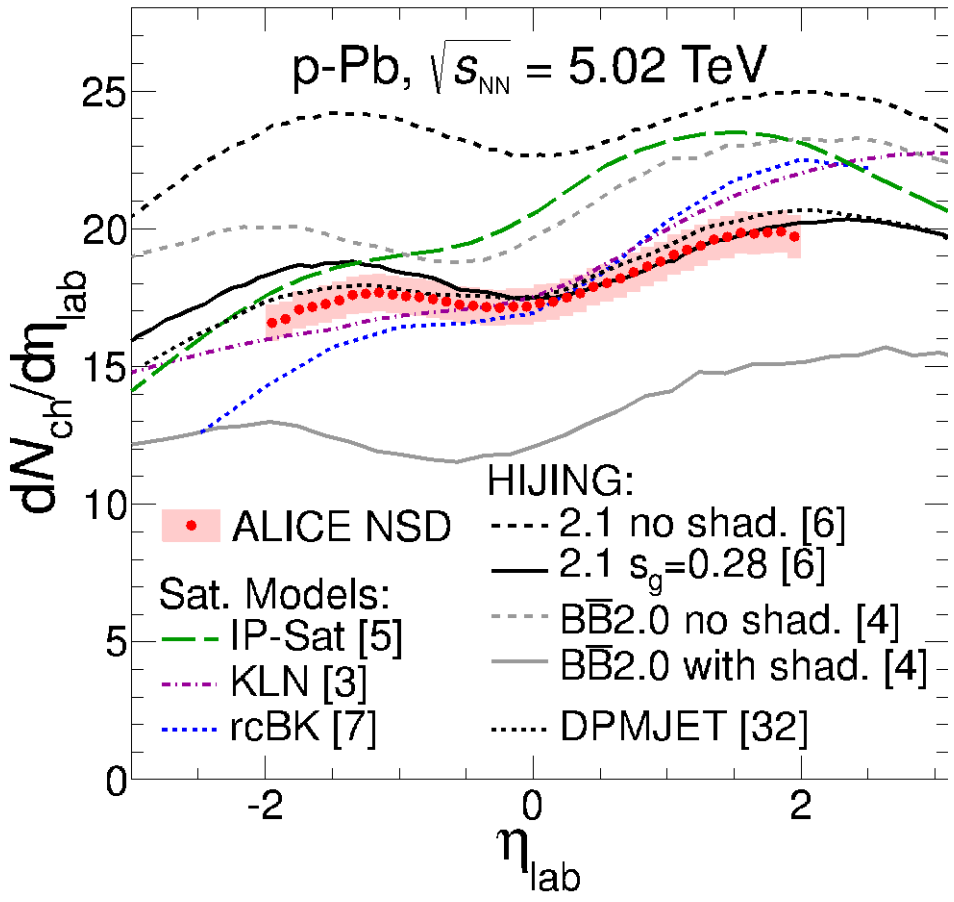
Transverse energy density per participant pair in p-Pb at 5.02 TeV is bigger than 70-80% Pb-Pb at 2.76 TeV

Source volume ~ $\langle dN/d\eta \rangle$

→ Indicating a constant source density at the moment of freeze-out

Pseudorapidity density of charged particles

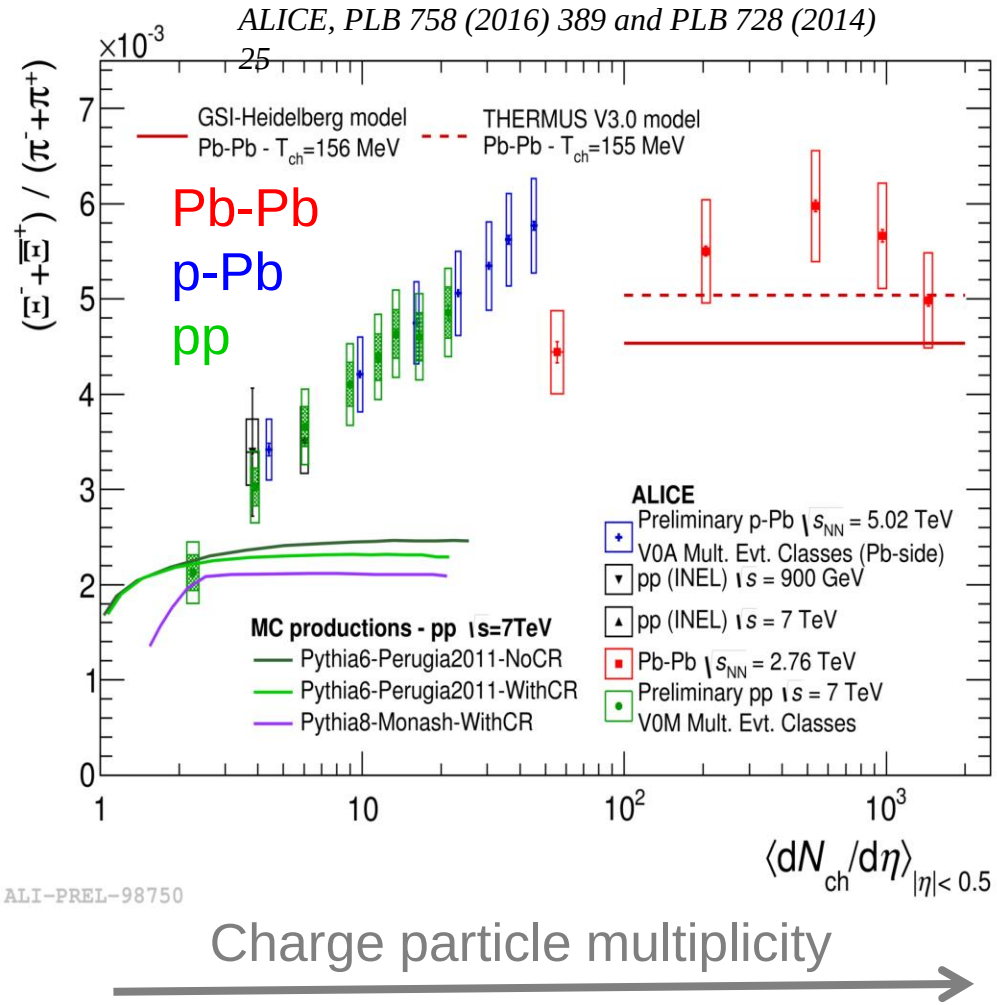
ALICE, Phys. Rev. Lett. 110, 032301 (2013)



$$\eta_{lab} = -\ln \tan(\theta/2)$$

- Measured over 4 units of pseudorapidity in non-single diffractive (NSD) p-Pb collisions
- Most model predictions within 20% of data
- **Saturation Models** rise too steeply with η_{lab}
- **pQCD-based Monte Carlo models** (HIJING and DPMJET) describe $dn_{ch}/d\eta_{lab}$

Multi-strange particles vs. multiplicity

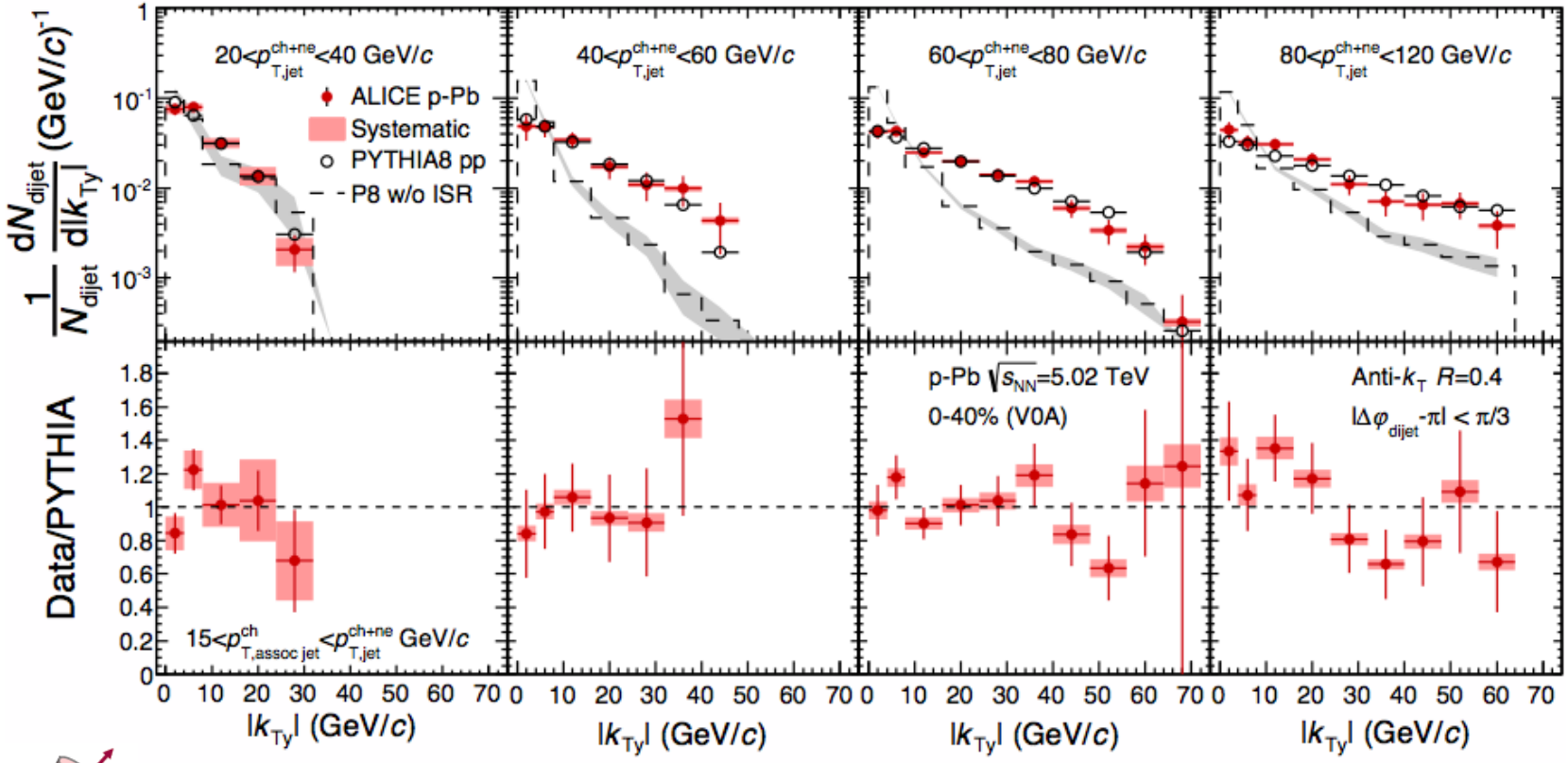


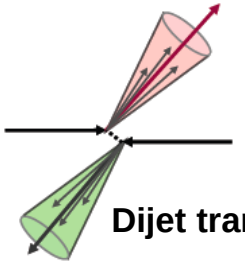
- Looser concept of ‘centrality’ in pp collisions
  - fluctuations in momentum transfer
  - internal proton structure
- Similar multiplicity dependence in pp and p-Pb
- Neither PYTHIA 6 nor 8 reproduce data in any of the tunes tested
- Continuous reduction of **canonical suppression** with increasing multiplicity

Jets

Acoplanarity between full and charged jets

ALICE, Phys. Lett. B746 (2015) 385





Dijet transverse momentum

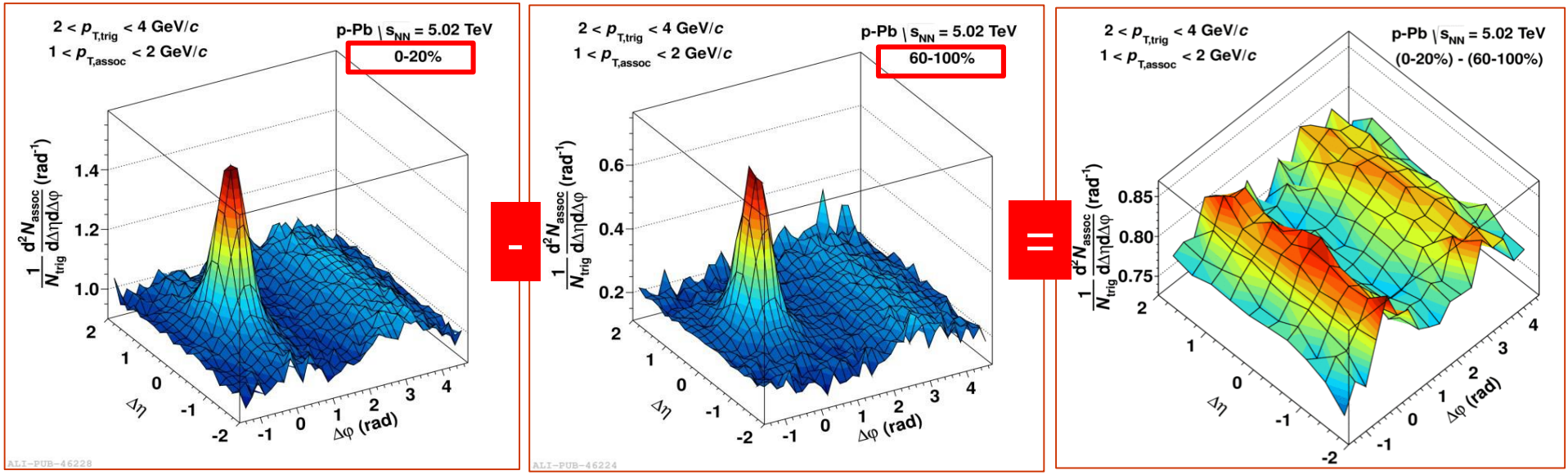
$$k_{Ty} = p_{T,jet}^{ch+ne} \sin(\Delta\varphi_{dijet}),$$

Di-jet k_{Ty} consistent with Pythia predictions (with ISR)

→ No strong nuclear matter effects in measured kinematic range

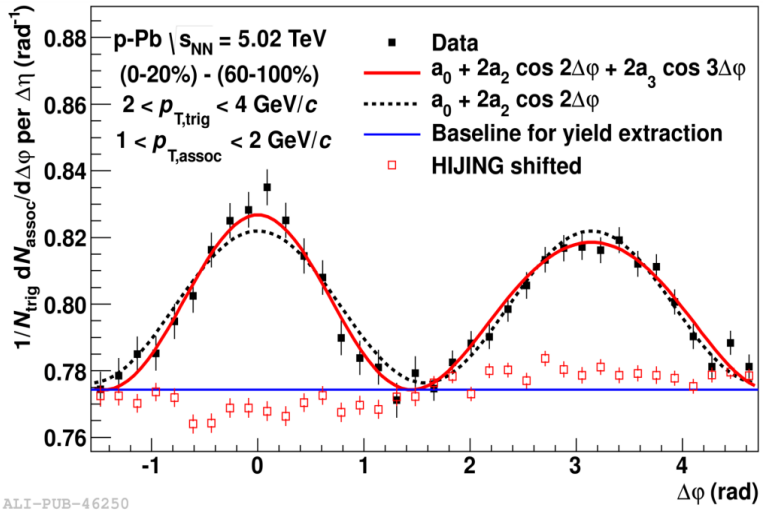
→ For large Q^2 mainly sensitive to increased available phase-space for QCD radiation processes

Di-hadron azimuthal correlations



ALICE, PLB 719, 29 (2013)

Two long-range (double ridge) structures described by
- colour glass condensate (initial state effect)
- hydrodynamics (final state effect)



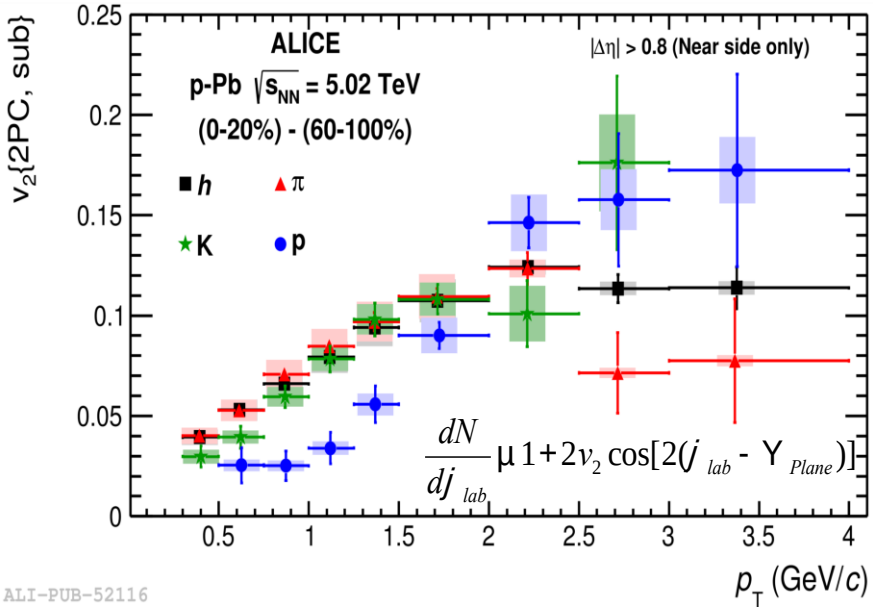
- Unexpected collective (?) behaviour in high-multiplicity events at low p_T seen even in the small p-Pb system
- Jets suggest no significant CNM effects

*Also measured by **LHCb**, arXiv:1512.00439 and **CMS**, PLB 718 (2012) 795 and **ATLAS**, PRL 110 (2013) 182302*

Di-hadron correlations in p-Pb (cont'd)

hadron – (π, K, p) correlations

Phys. Lett. B 726, 164 (2013) Also for Λ and K_s^0, *CMS-HIN-15-006*

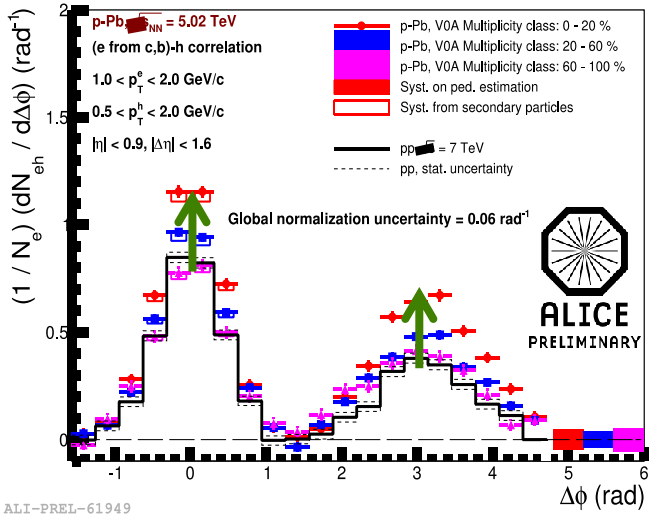


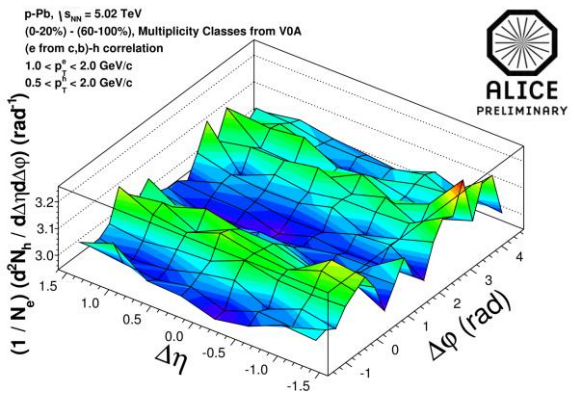
- v_2 obtained from two-particles correlations
  - Mass ordering at low p_T
  - Crossing at p_T ~ 2 GeV/c
- Qualitatively similar to Pb-Pb and consistent with hydro calculations

→ Suggests similar physics (collectivity?) at place?

Small Systems session, Heavy Ion, 14 June

b,c→e – hadron correlations

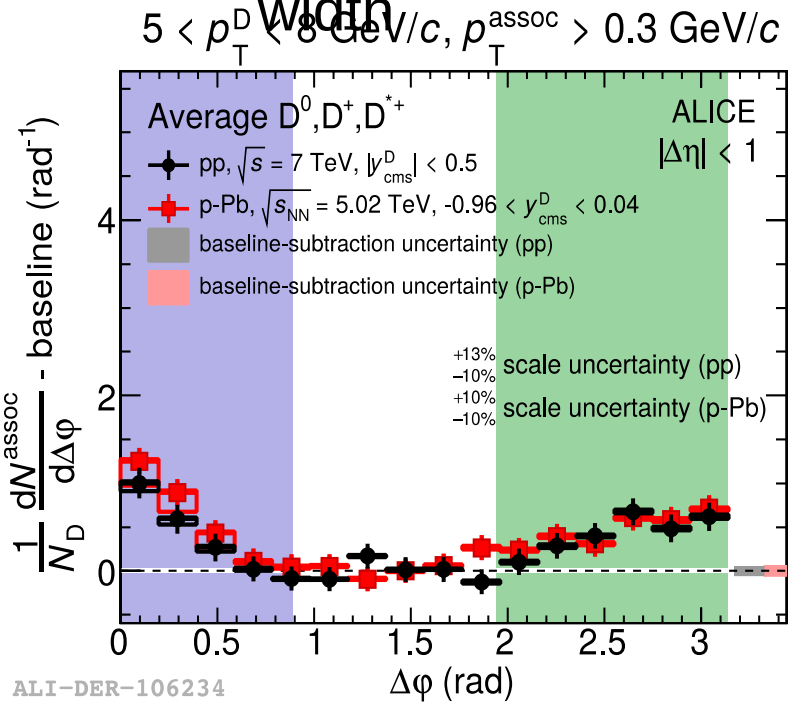




- Double ridge structure also present
- Suggests same mechanism as for light-flavour correlations
- Theoretical interpretation ongoing

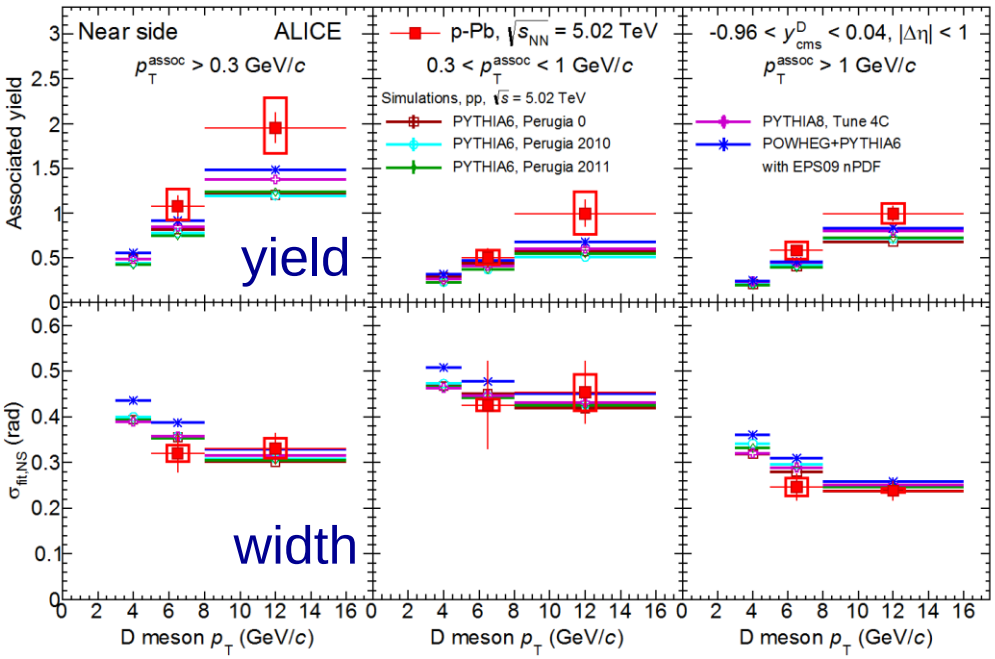
D-tagged charged particle azimuthal correlations

$\Delta\phi$ distribution



Near-side correlation yield & width

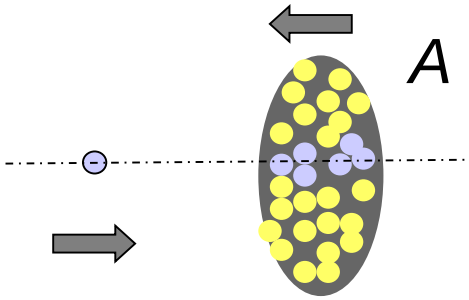
ALICE, subm. to EPJC (arXiv:1605.06963)



- First D meson - charged hadron correlation measurement at the LHC
- Near-side correlation peak is sensitive to characteristics of jet containing D meson
- Similar yields for p-Pb and pp (not shown)
- Data well reproduced by PYTHIA (in all kinematic ranges)

Quantification of nuclear effects

- Proton-lead collisions: single proton hits multiple nucleons, number depends on impact parameter b ($\langle N_{coll} \rangle \approx 7$)
- Nuclear modification factor R_{pPb}
- Centrality/multiplicity-dependent nuclear modification factor Q_{pPb}
  - Collision centrality expressed in terms of nuclear overlap function T_{pPb}
  - T_{pPb} and N_{coll} determination relies on assumption that charged-particle multiplicity at mid-rapidity scales linearly with N_{part}
- pp reference data at $\sqrt{s}$ = 7 TeV
  (if not indicated otherwise)
- **If R_{pPb} and Q_{pPb} = 1 → no nuclear matter effects → binary collision scaling**

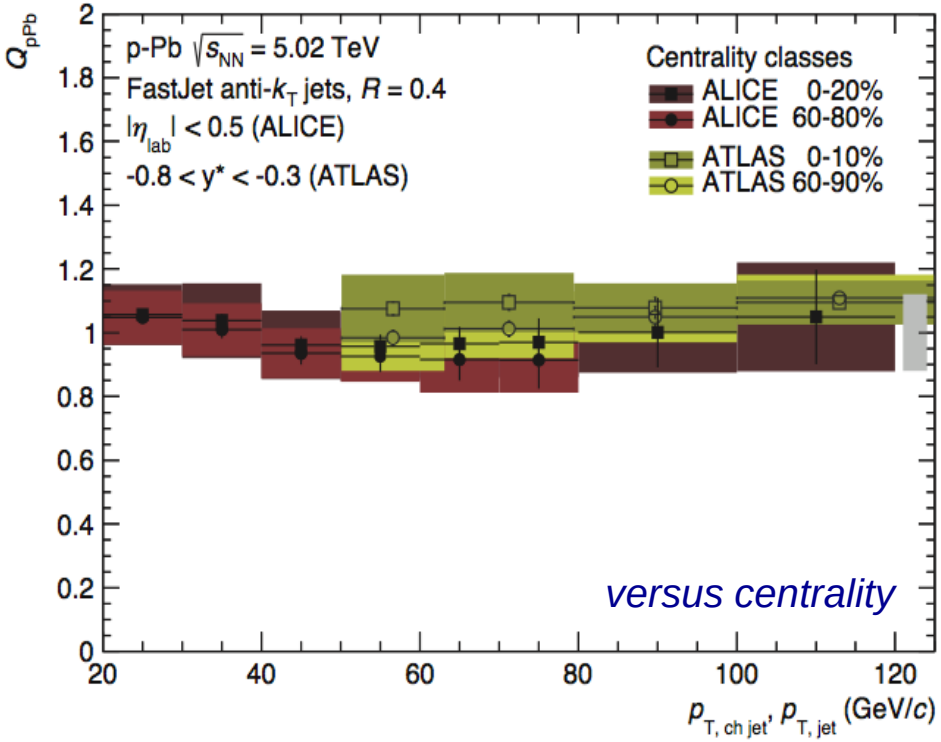


$$R_{pA} = \frac{ds_{pPb}/dp_T}{A' \, ds_{pp}/dp_T}$$

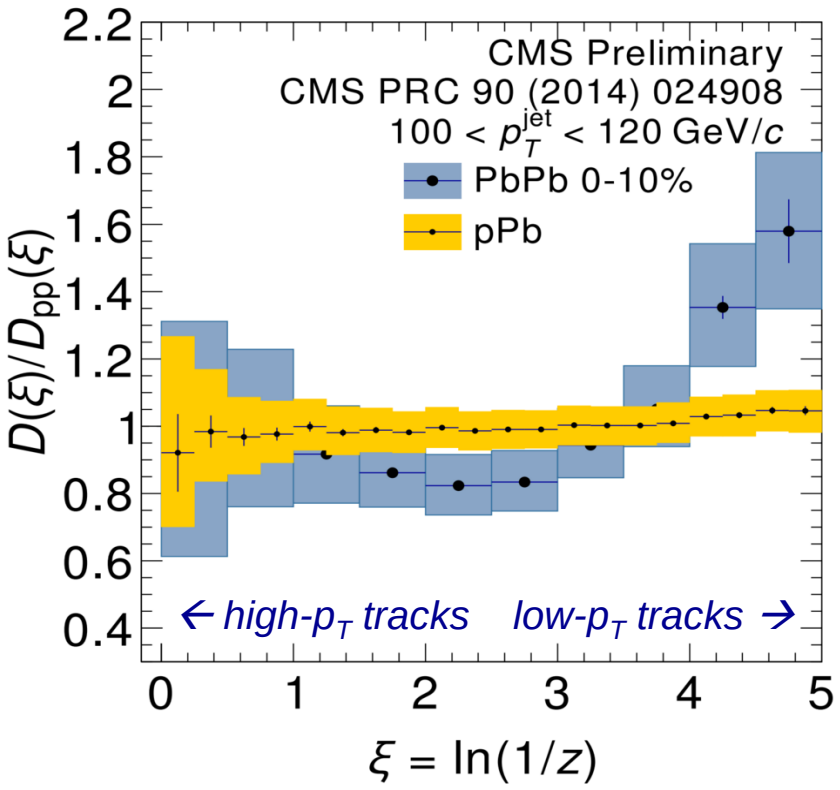
$$Q_{pA} = \frac{dN_{pPb}/dp_T}{\langle T_{pPb}^{mult} \rangle' \, ds_{pp}/dp_T}$$

Full and charged jet production

ALICE, Eur. Phys. J. C76, 271 (2016), Phys. Rev. C91, 064905 (2015)
ATLAS, Phys. Lett. B 748, 392 (2015)



CMS-PAS-HIN-15-004



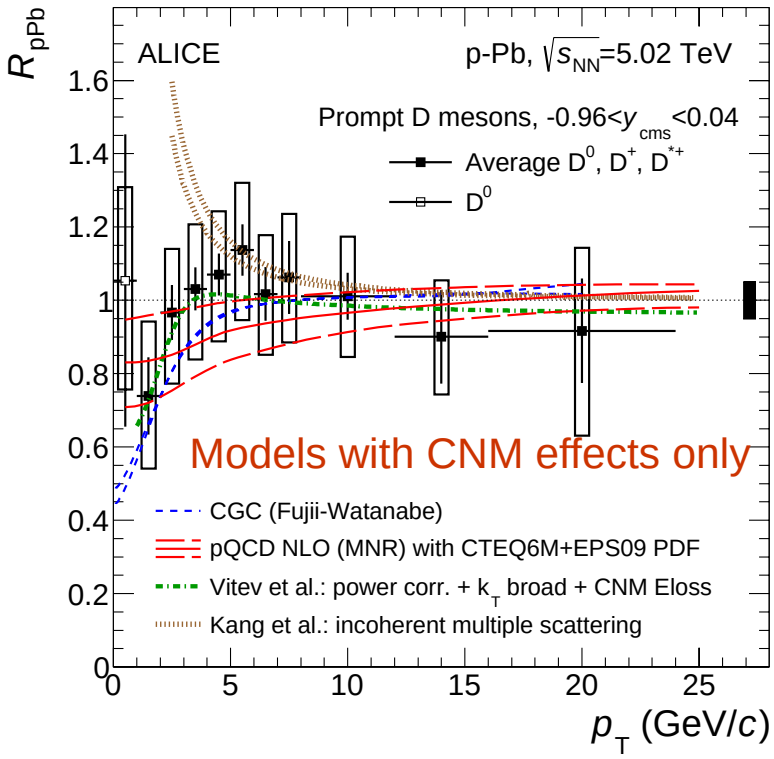
- Q_{pPb}~1 for all centralities and independent on jet p_T
- Dependence on resolution parameter R as expected in pp
- **Jet fragmentation function** is unmodified with respect to the interpolated pp reference → no CNM effects

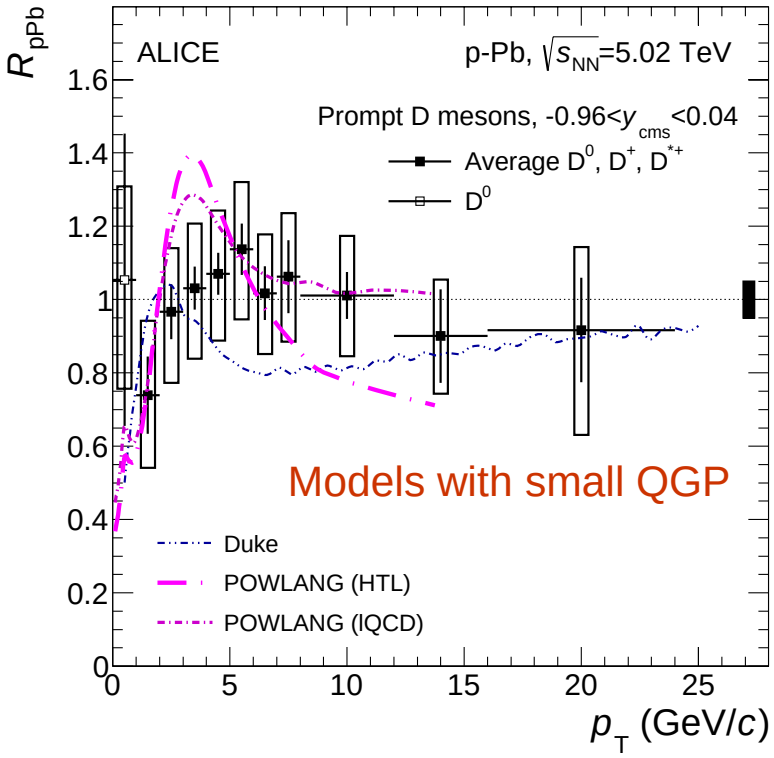
*Also **ATLAS** measurement, PLB 748 (2015) 392*

Heavy-flavour

Prompt D mesons at mid-rapidity

ALICE, subm. to JHEP (arXiv:1605.07569)
and Phys. Rev. Lett. 113 (2014) 232301



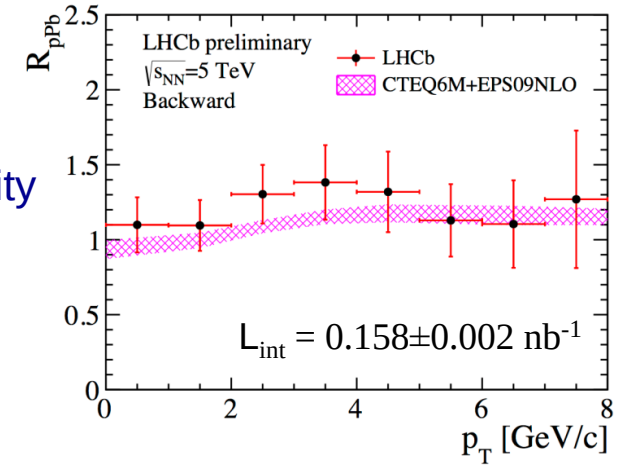


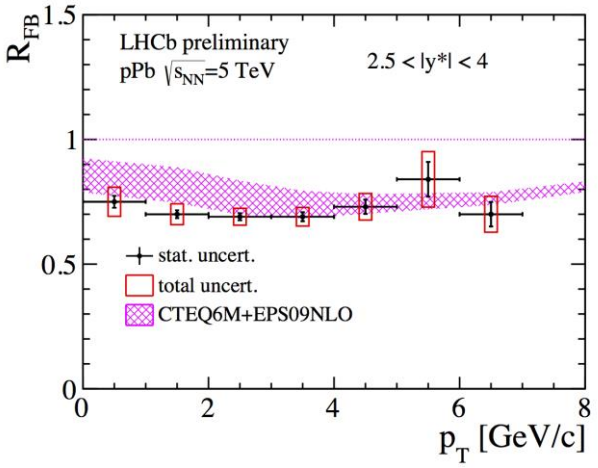
- R_{pA} (measured down to p_T = 0) compatible with unity; no centrality dependence (not shown)
  - Consistent with predictions from shadowing and CGC model
- Data disfavour suppression larger than 15% at high p_T

Prompt D^0 mesons at for/backward rapidity

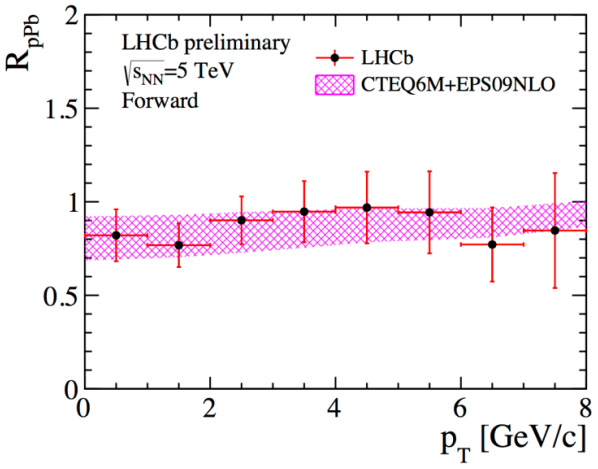
LHCb-CONF-2016-003

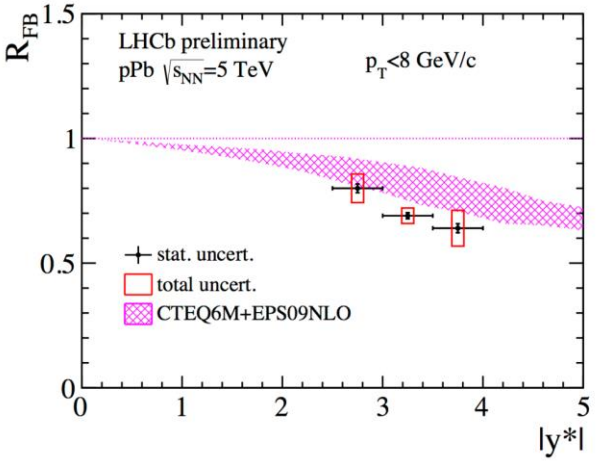
Backward rapidity
-2.5 > y > -4.0
(Pb-going side)





Forward rapidity
2.5 < y < 4.0
(p-going side)



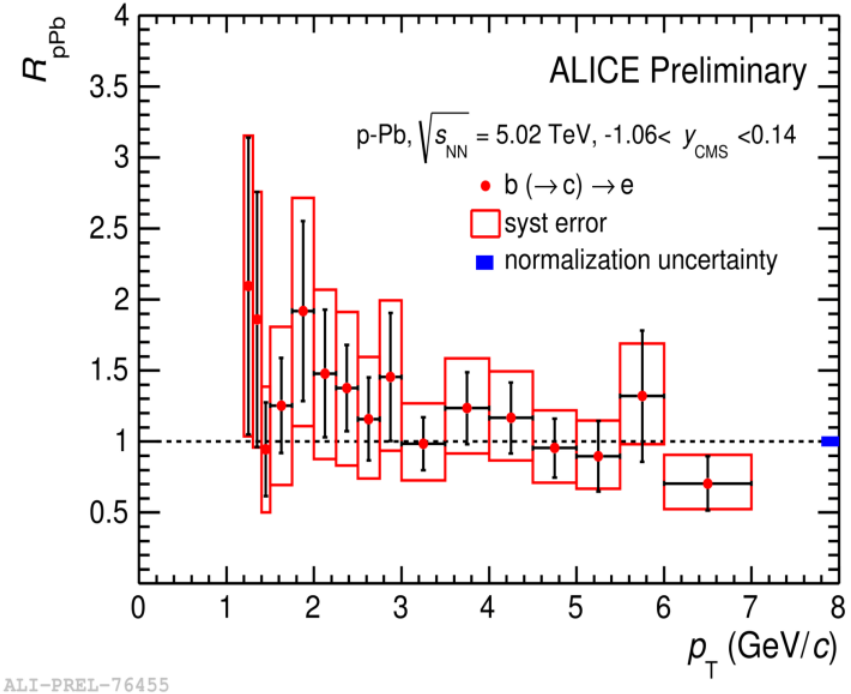


- Charm production described by pQCD calculations including nPDF
- Large asymmetry in forward-backward production is observed, suggesting non negligible CNM effect
- Indication that data is slightly more suppressed at high-y*

Open beauty

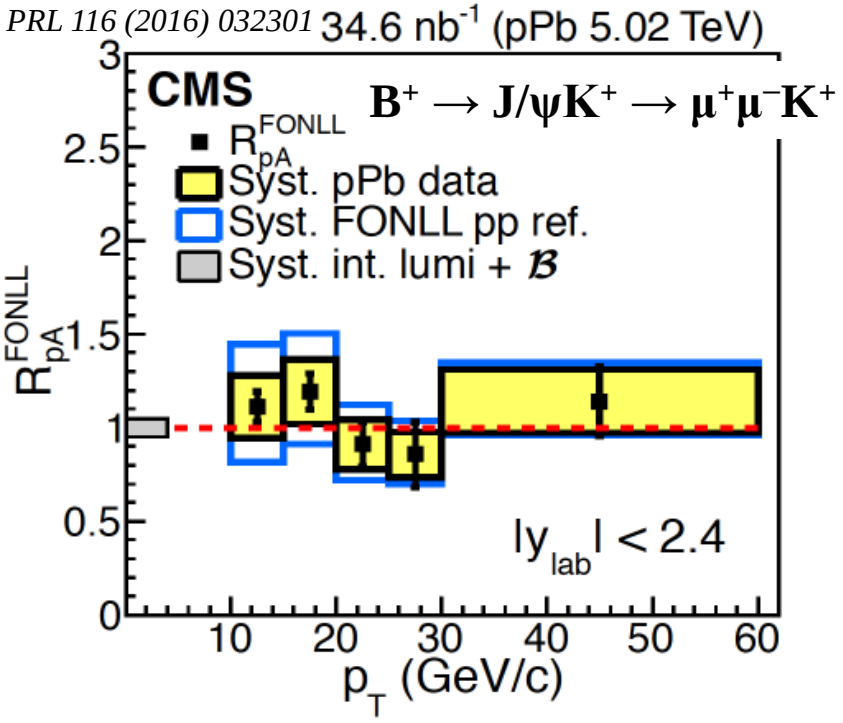
Beauty-decay electrons

ALICE, arXiv:1512.02892



B mesons

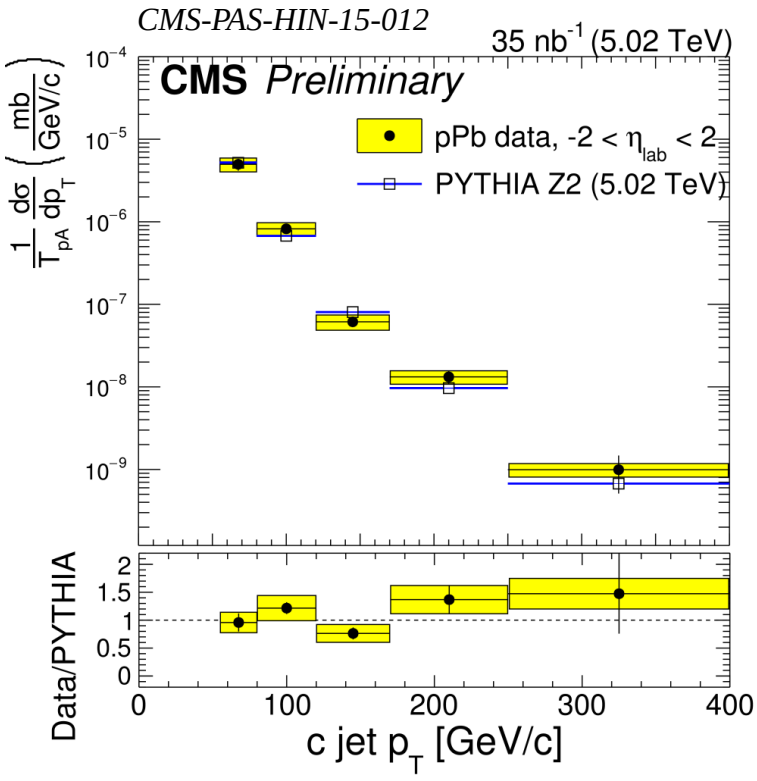
CMS, PRL 116 (2016) 032301



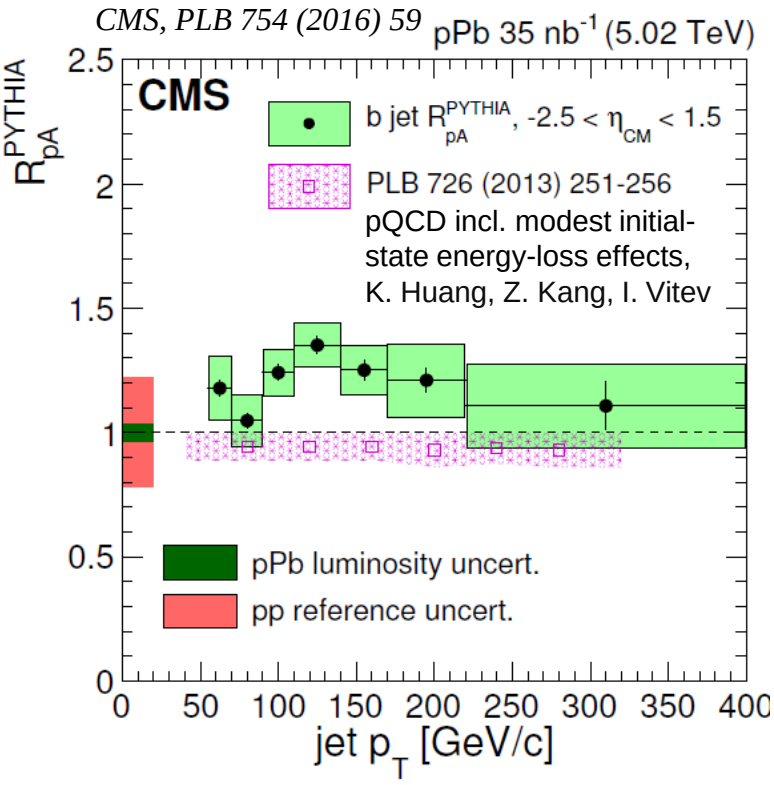
- R_{pPb} of beauty-decay electrons at low p_T and B mesons in $10 < p_T < 60$ GeV/c consistent with unity; same for B^0 and B_s^0 $R_{p\text{-}Pb}$ (not shown)
- No indication of significant cold nuclear matter effects on beauty production

Heavy-flavour jets

Charm jets



Beauty jets



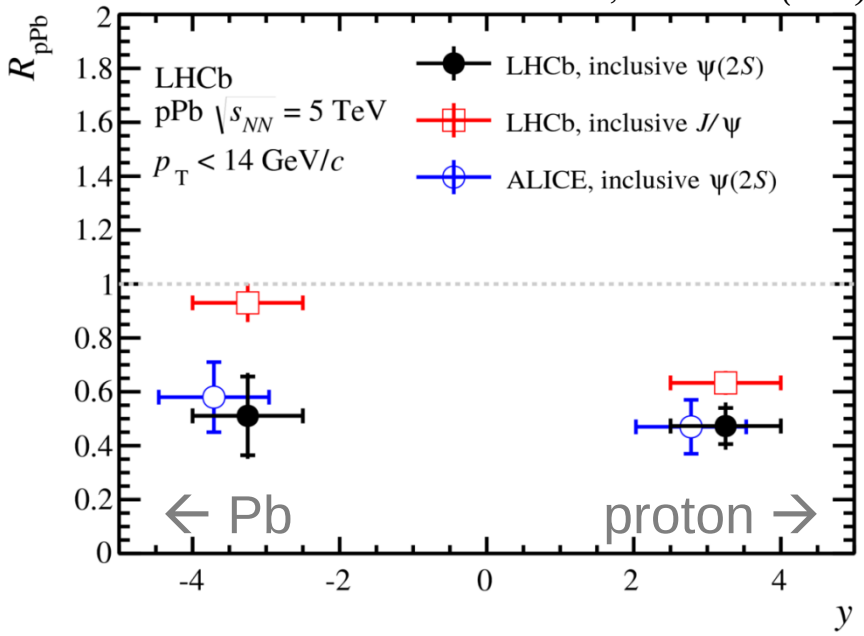
- Charm-jet p_T differential cross section consistent with PYTHIA
- Inclusive beauty jet $R_{p\text{-}Pb}$ in agreement with pp reference
- No significant CNM effects on heavy-flavour production at high p_T

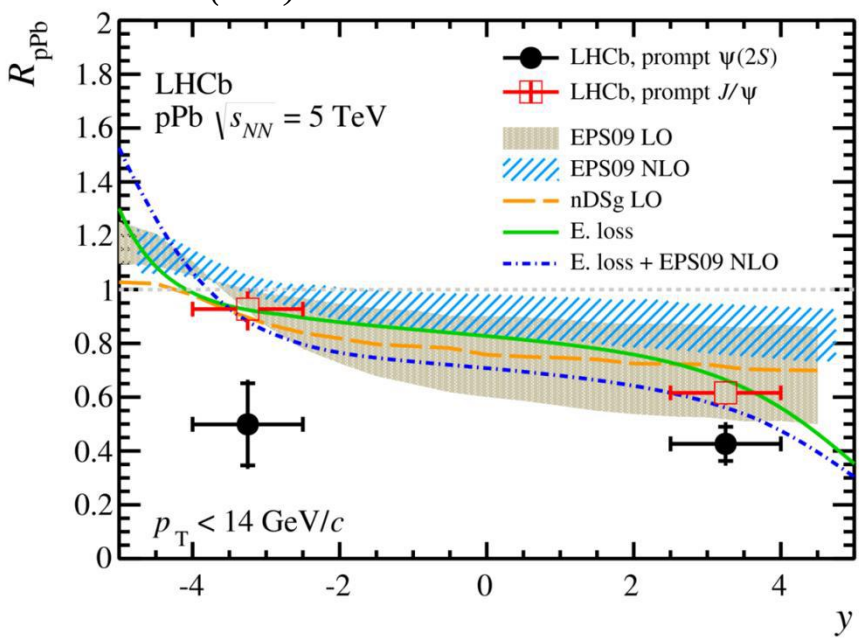
J/ψ and Ψ(2S)

Inclusive

Prompt

LHCb, JHEP 1402 (2014) 072 and JHEP 1603 (2016) 133
ALICE, JHEP 1402 (2014) 073 and JHEP 1412 (2014) 073





- **J/ψ** R_{pPb} described reasonably well by CNM effects
- **Ψ(2S)** production suppressed relative to J/ψ at both backward and forward rapidity

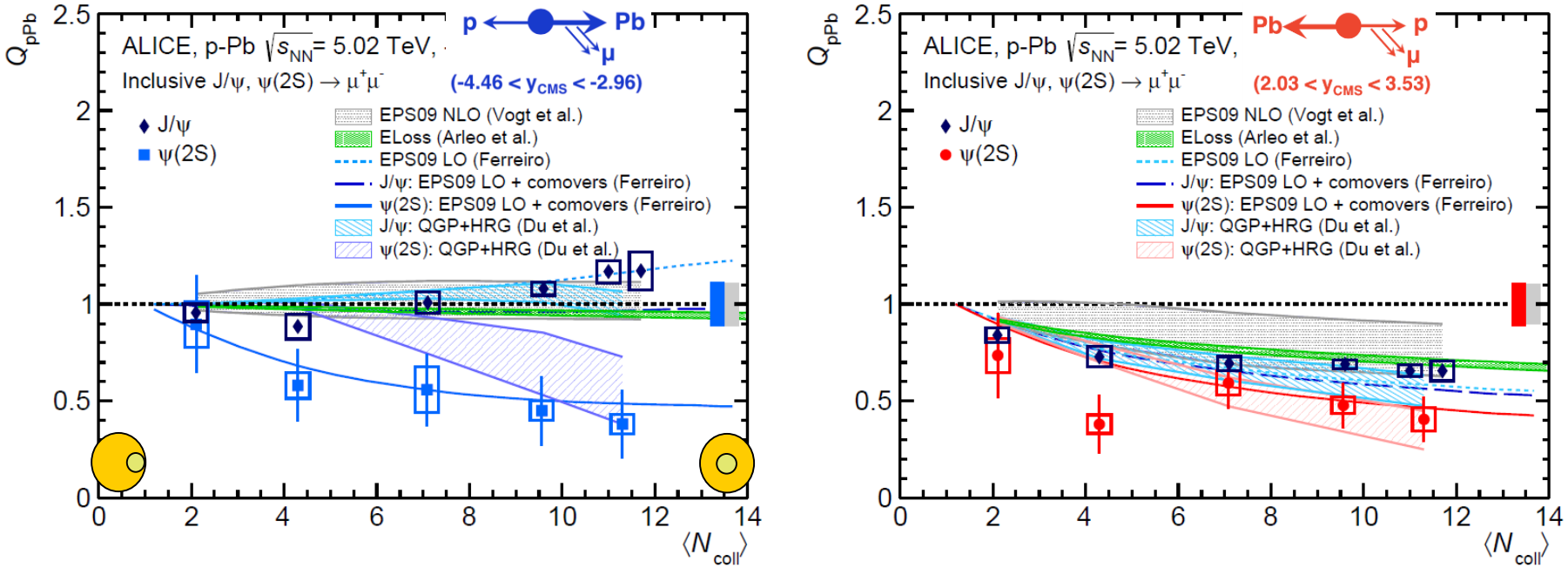
→ Shadowing & energy loss expected to be the same for J/ψ and Ψ(2S), thus these mechanisms cannot describe the different suppression

J/ψ and Ψ(2S) versus centrality

Backward rapidity (Pb-going side)

Forward rapidity (p-going side)

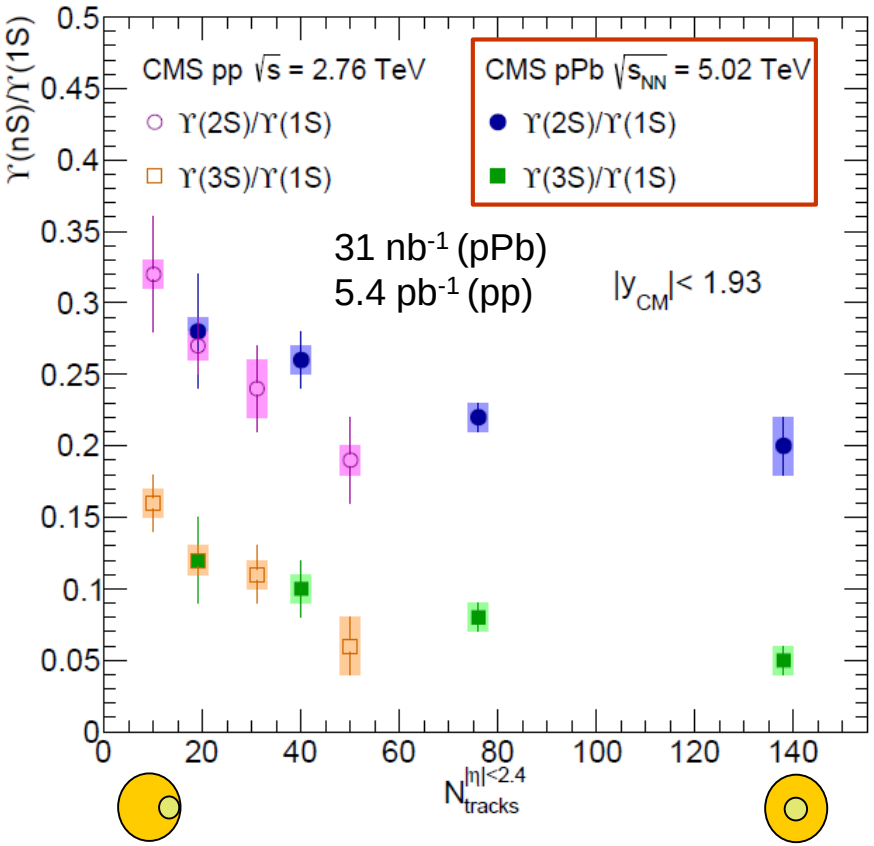
ALICE, JHEP 1606 (2016) 050 and JHEP 1511 (2015) 127



- **J/ψ**: Multiplicity dependent suppression in p-going direction, and no suppression in Pb-going direction → Consistent with shadowing
- **Ψ(2S)**: Multiplicity dependent suppression in both directions
  - Not described by (anti)shadowing and energy loss only
  - Needs additional effect (final state?), e.g., interactions with co-moving hadrons plus dissociation of fully-formed resonance in nuclear matter?

□(nS) states

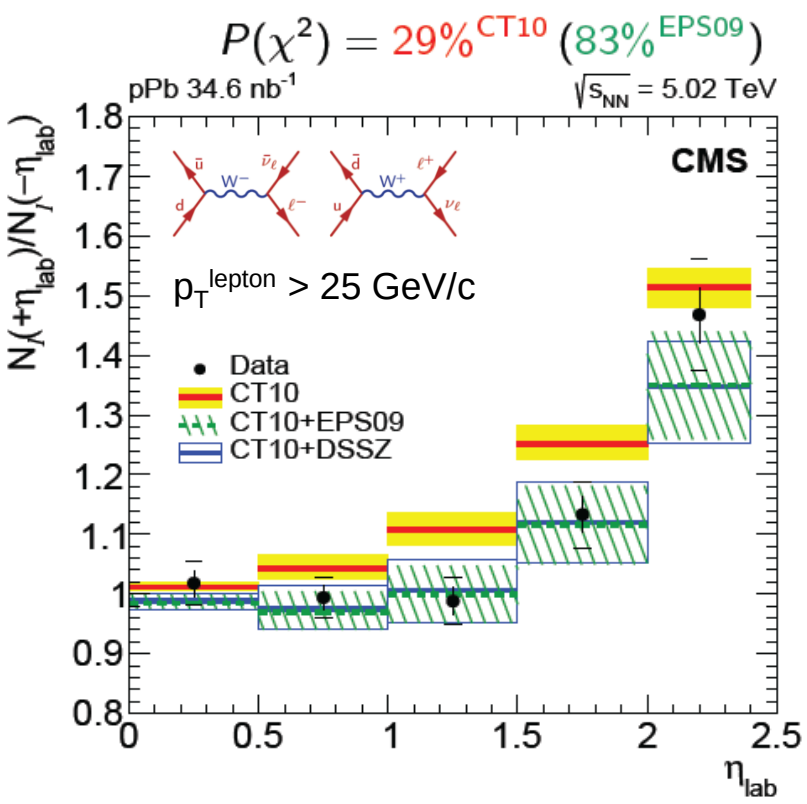
CMS, JHEP 1404 (2014) 103



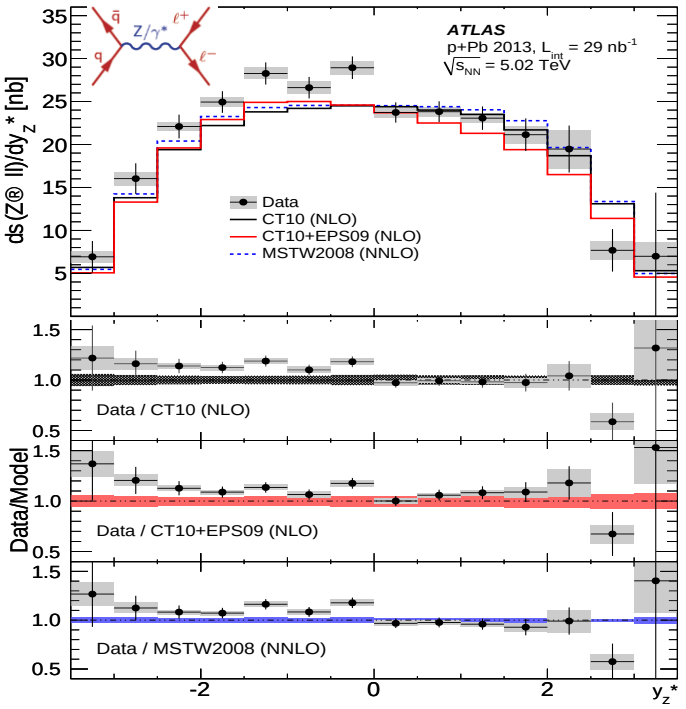
- Ratios of excited to ground state cross sections □(nS)/□(1S) are found to decrease with increasing charged-particle multiplicity
- Unexpected dependence suggests novel phenomena in quarkonium production(?)
  - Larger number of charged particles being systematically produced with ground state
  - Stronger impact of growing number of nearby particles on more weakly bound states
  - Excited states more easily dissociated by interactions with other particles?

W and Z production

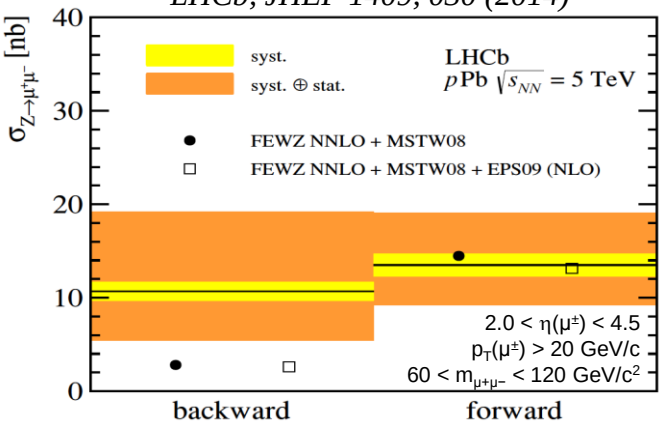
CMS, Phys. Lett. B750 (2015) 565



ATLAS, Phys. Rev. C 92, 044915 (2015)



LHCb, JHEP 1409, 030 (2014)



- Probing nuclear PDF for *q* and *qbar* in p-Pb
- Electroweak bosons favour the modification of nPDF
- Large statistical uncertainties yet prevent distinction among different nPDFs

Conclusions

- LHC p-Pb run at $\sqrt{s_{NN}}$ = 5.02 TeV yielded many (unexpected) results: different hadronic probes and observables
- Strangeness: Continuous reduction of canonical suppression with increasing multiplicity
- Jet fragmentation exhibits no modification
- Heavy flavour

  - No significant modification of production are observed for prompt D mesons, B mesons, charm and beauty jets

  - Quarkonia: J/ψ results consistent with shadowing, Ψ(2S) however not described by (anti)shadowing and energy loss only

→ No indication for substantial modification due to cold nuclear matter effects (except for quarkonia)

→ Indication for collective-like behaviour in small systems, reminiscent of that observed in Pb+Pb collisions

→ Final-state modifications in p-Pb collisions?

- Future: Run-2 p-Pb data taking at 5 and 8 TeV in 2016