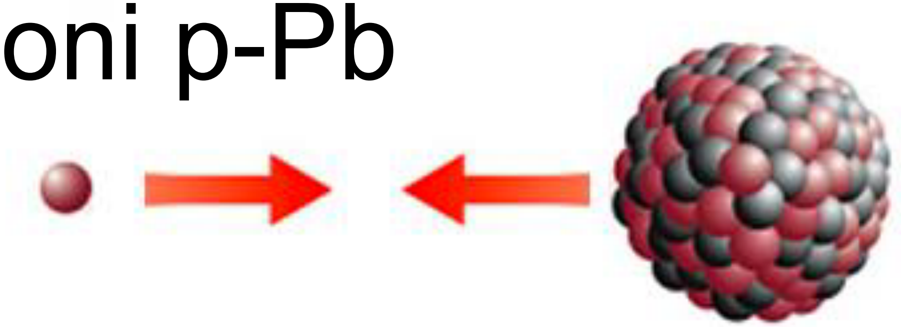
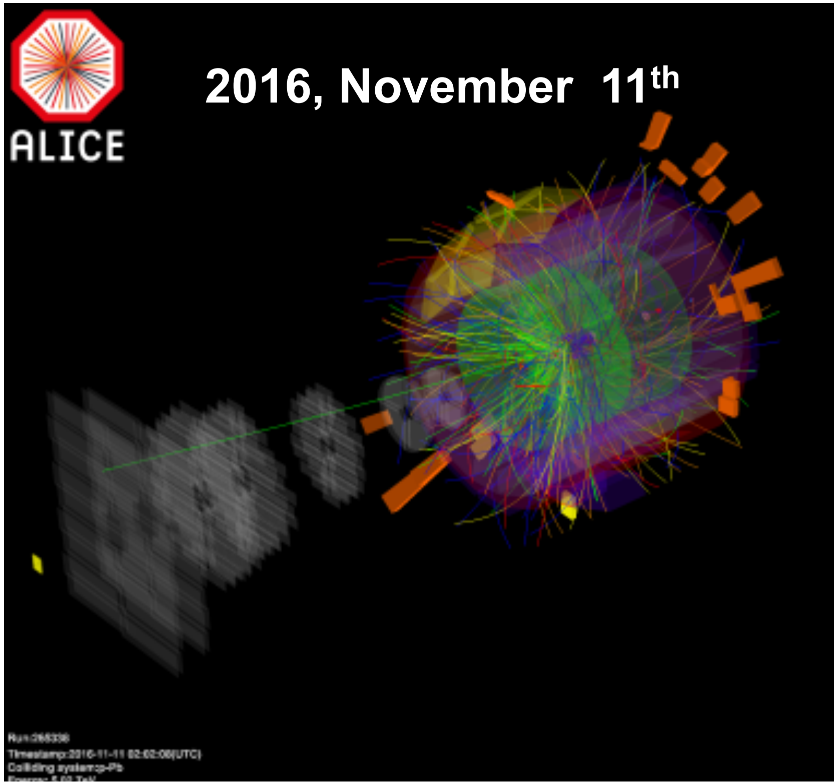
Ultimi risultati dell’esperimento ALICE nelle collisioni p-Pb




2016, November 11th

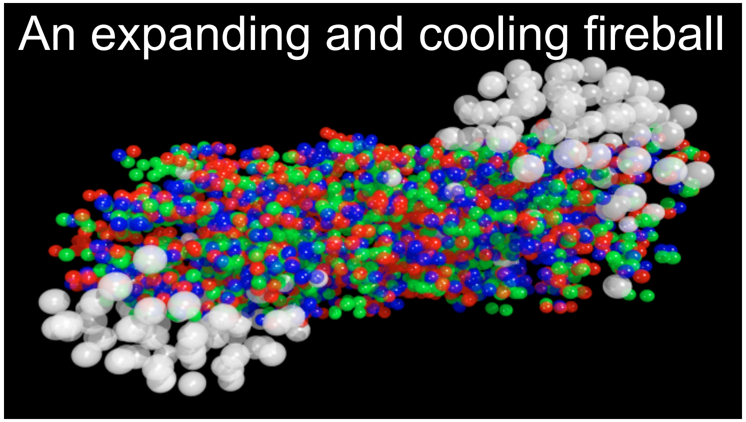
A. Rossi, Padova University & INFN

on behalf of the ALICE Collaboration

Outline

- Physics motivations
- The ALICE detector
- p-Pb as the control experiment: high-energy observables
- Quarkonia
- Soft probes and the revelation of collective-like effects
- Conclusions

A Large Ion Collider Experiment to study the QGP



An expanding and cooling fireball

Heavy-Ion Collisions at ultrarelativistic energies (e.g. Pb-Pb at the LHC) produce a system of strongly-interacting matter

- Extended size
- High temperature, high pressure
- Local thermodynamical equilibrium

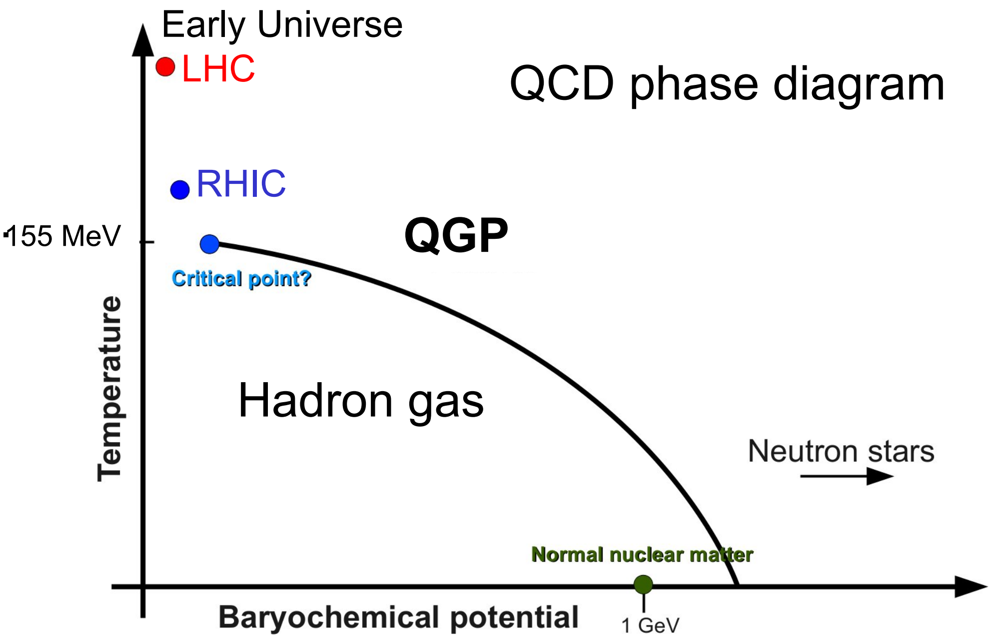
➜ Phase transition to a deconfined state:

Quark Gluon Plasma (QGP)

Thanks to several measurements performed at SPS, RHIC, and LHC the existence of QGP is established (e.g. J/ψ suppression and regeneration, see R. Arnaldi at INFN2014, https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=6771)

⇩

From "discovery phase" to detailed characterization of QGP properties



Soft and hard probes

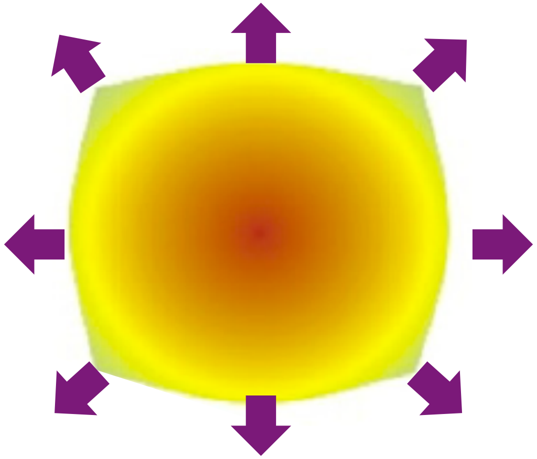
N.b. a simplistic and incomplete classification!

“Soft” probes

(e.g. light-flavour particle spectra and flow at low p_T)

Probe system as a whole

Test hydrodynamic description to extract
global properties of the medium and of its evolution (e.g.
temperature, density, homogeneity, viscosity, expansion velocity)



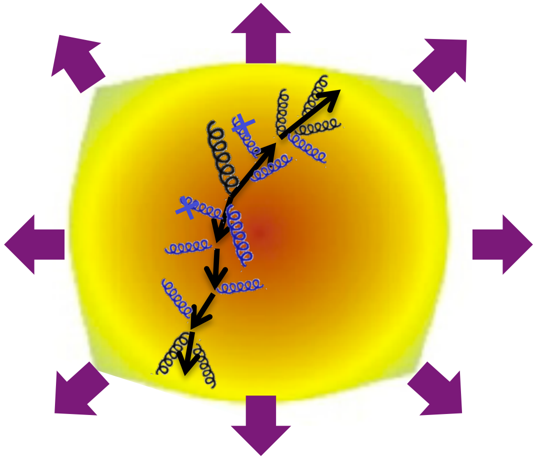
“Hard” probes

(e.g. high p_T particles, heavy flavours, quarkonia, jets)

Access **microscopic processes in the medium**

Resolve medium constituents (quarks and gluons)

Study spectra (e.g. transport coefficients, mean free path)
quantities



⇩

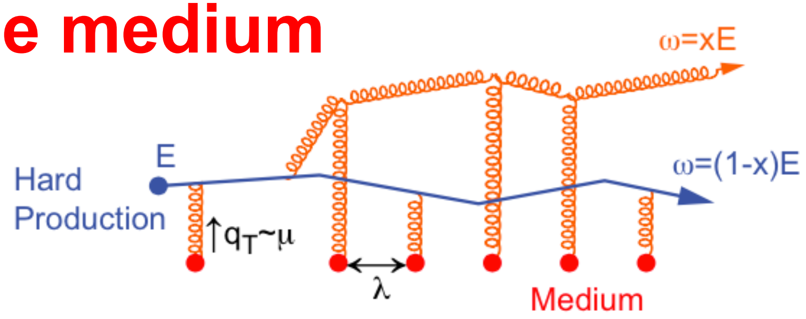
Connection of global medium properties with “local” interactions

Microscopic description of the medium

QGP tomography with high-energy partons

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium

⇨ **“Calibrated probes” of the medium**



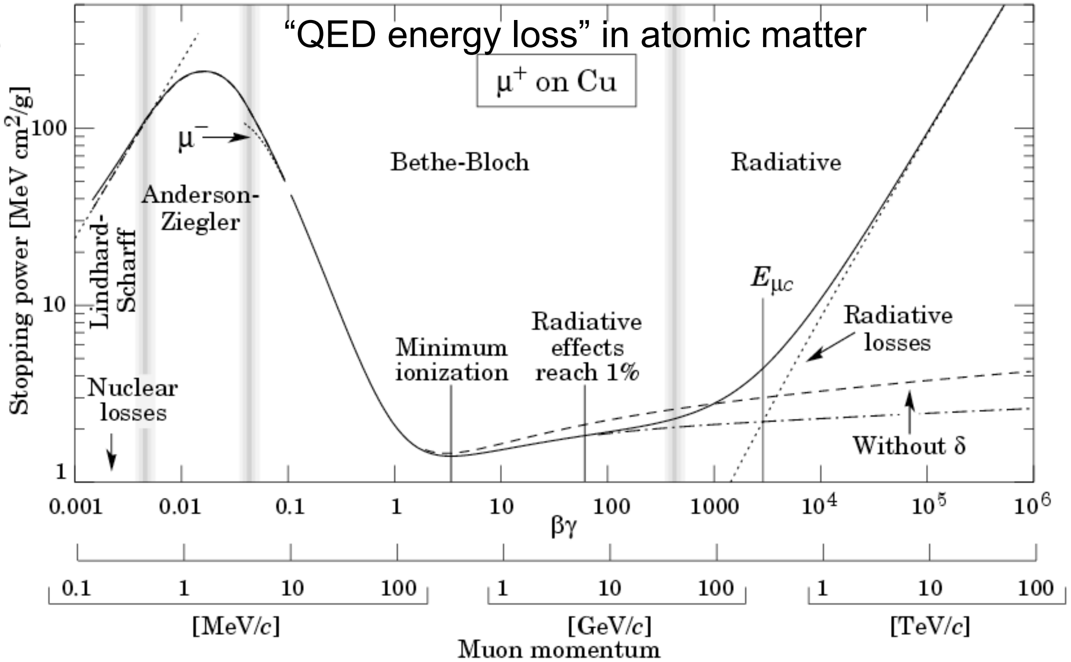
Study parton interaction with the medium

- **energy loss via radiative** (“gluon Bremsstrahlung”)
  collisional processes

~ Study QCD “Bethe-Block” curve for partons in the QGP

⇩

Connection of “local” interactions with global medium properties


“QED energy loss” in atomic matter

How can we measure medium effects?

Nuclear modification factor (R_{AA}): compare particle production in Pb-Pb with that in pp scaled by a “geometrical” factor (from Glauber model) to account for the larger number of nucleon-nucleon collisions

$$R_{AA}(p_{\mathrm{T}}) = \frac{dN_{AA}/dp_{\mathrm{T}}}{\langle N_{coll} \rangle \times dN_{pp}/dp_{\mathrm{T}}}$$

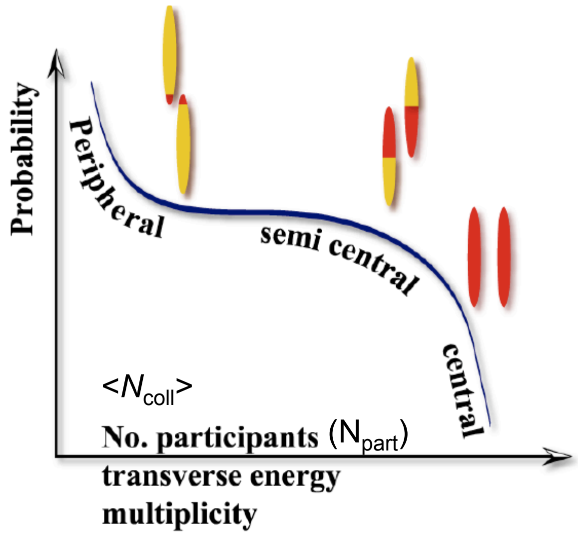
Pb-Pb

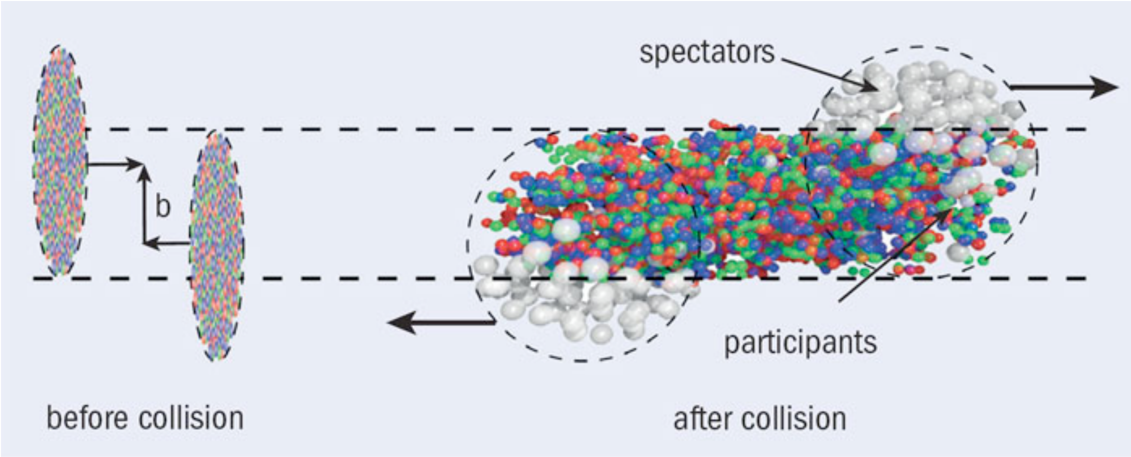
pp

Binary nucleon-nucleon collisions, encodes collision geometry

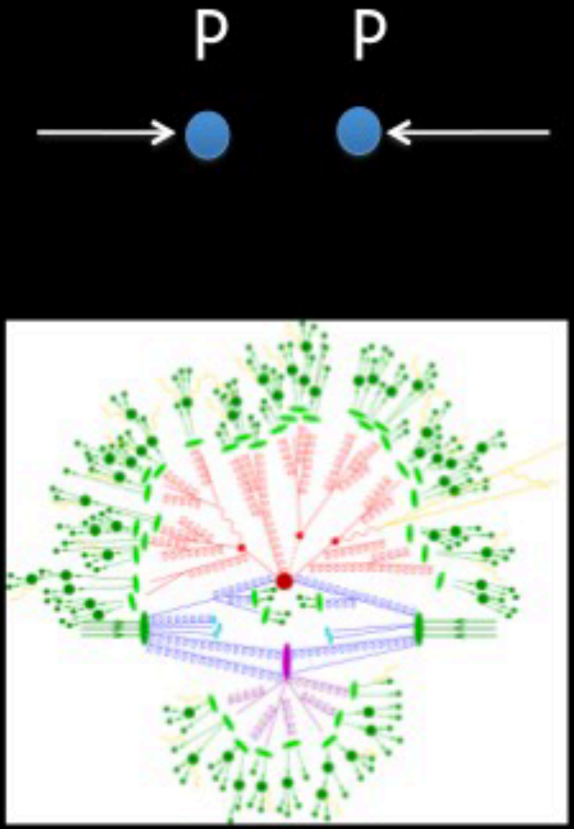
If $R_{AA}=1$ → no nuclear effects
If $R_{AA} \neq 1$ → nuclear effects

“Cold nuclear-matter effects”
→$R_{AA} \neq 1$ even w/o the formation of a QGP
→ need to measure them

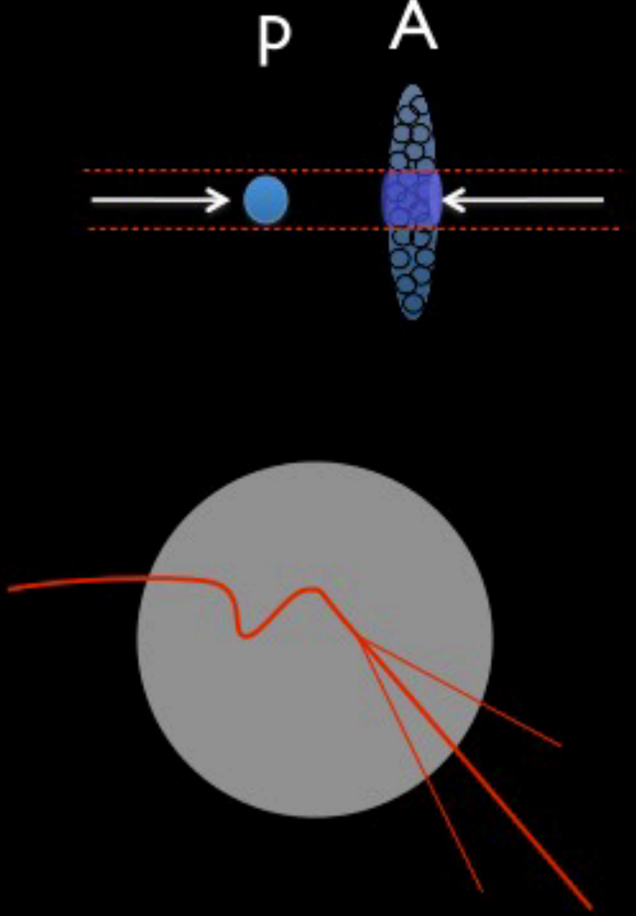




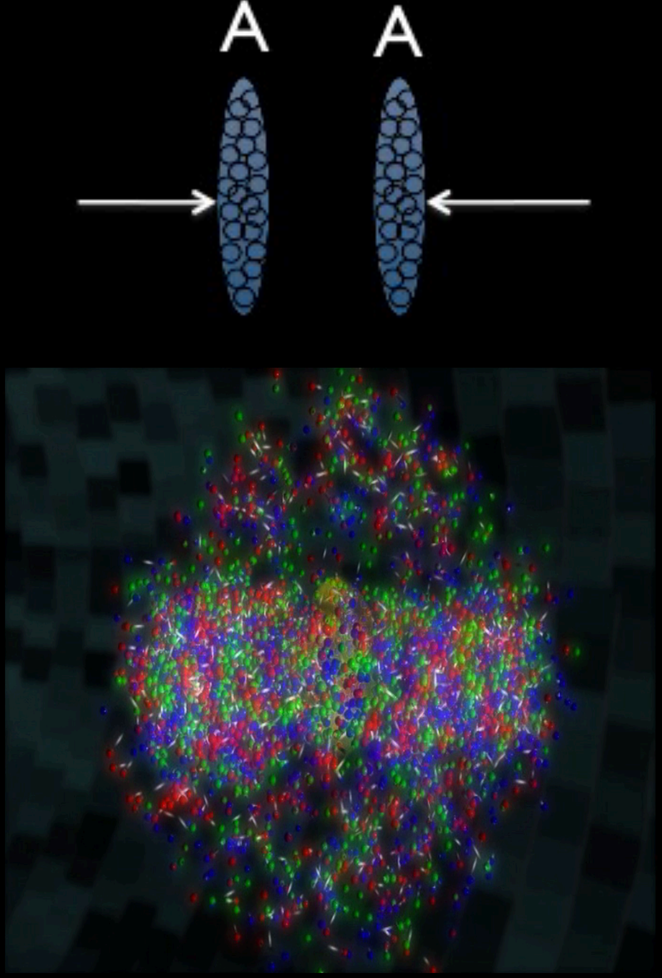
The multi collision-system experimental approach: the initial design



Local structure of QCD vacuum



Local QCD
+
initial state/cold nuclear matter

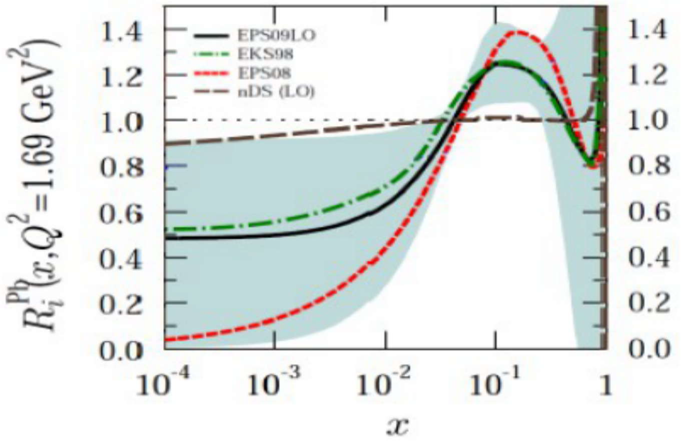


Local QCD
+
initial state/cold nuclear matter
+
Quark-Gluon Plasma

Copied by. C. Loizides who adapted it from G. Roland

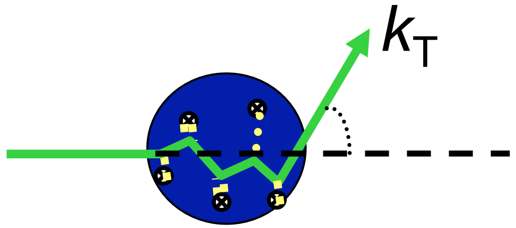
p-Pb to probe cold nuclear matter effects

Effects, not due to QGP formation, that can modify the yield of hard probes in nuclear collisions:



K. J. Eskola et al: JHEP04(2009)065

- **Nuclear modification of the PDFs**
  - shadowing at low Bjorken-*x* is the dominant effect at LHC energies
  - gluon saturation?



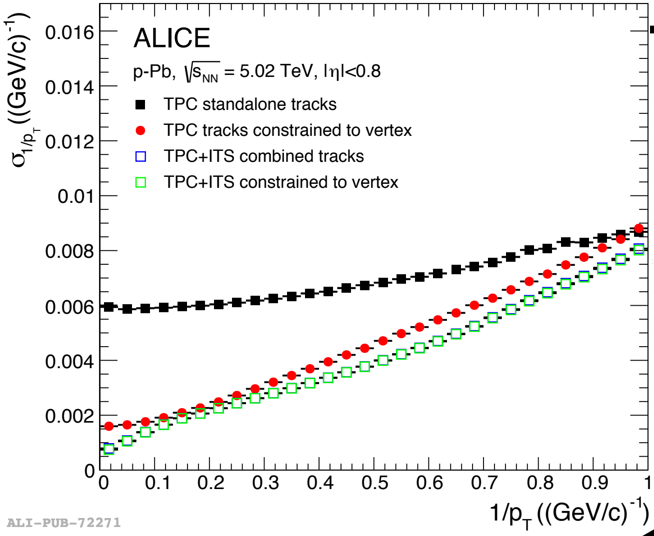
- ***k*$_T$-broadening**
  Due to multiple elastic collisions of the parton before the hard scattering

- **energy loss in cold nuclear matter**

Other final-state effects? (e.g. from system collectivity/hydro)
Are they possible in p-Pb?

The ALICE detector: central barrel

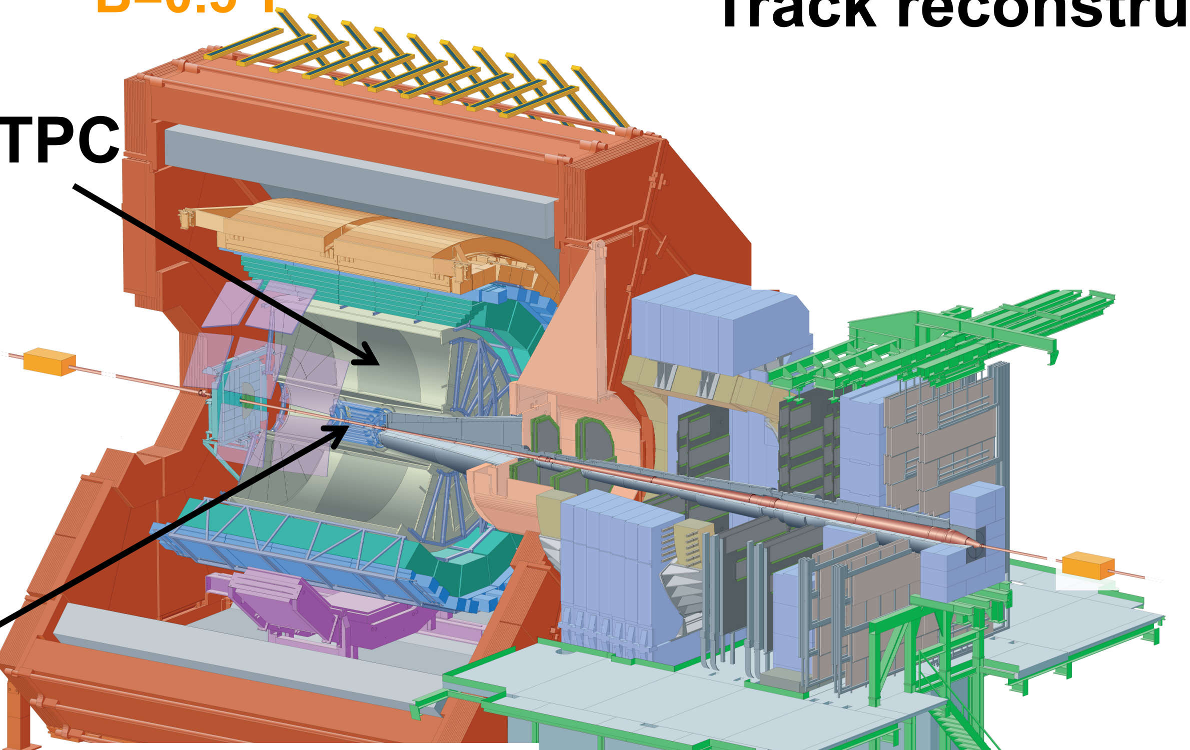
Transverse momentum (p_T) resolution: 0.8% (2%) at 1 (10) GeV/c

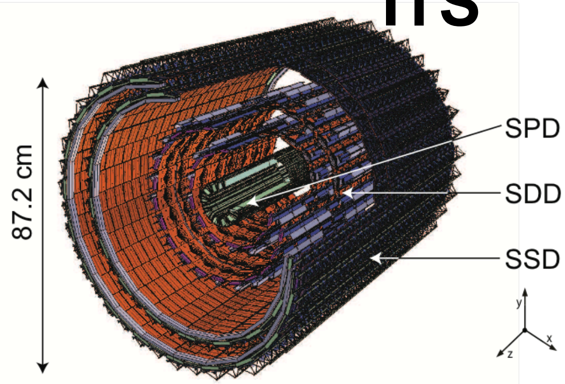


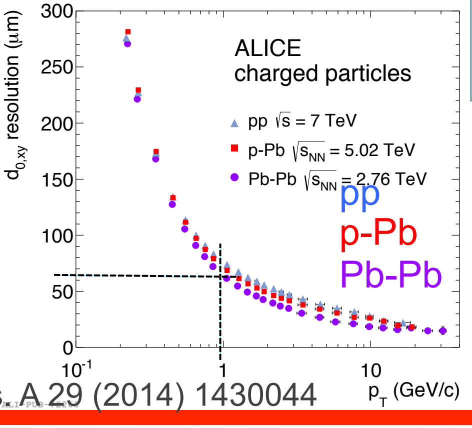
|η|<0.9

B=0.5 T

Track reconstruction







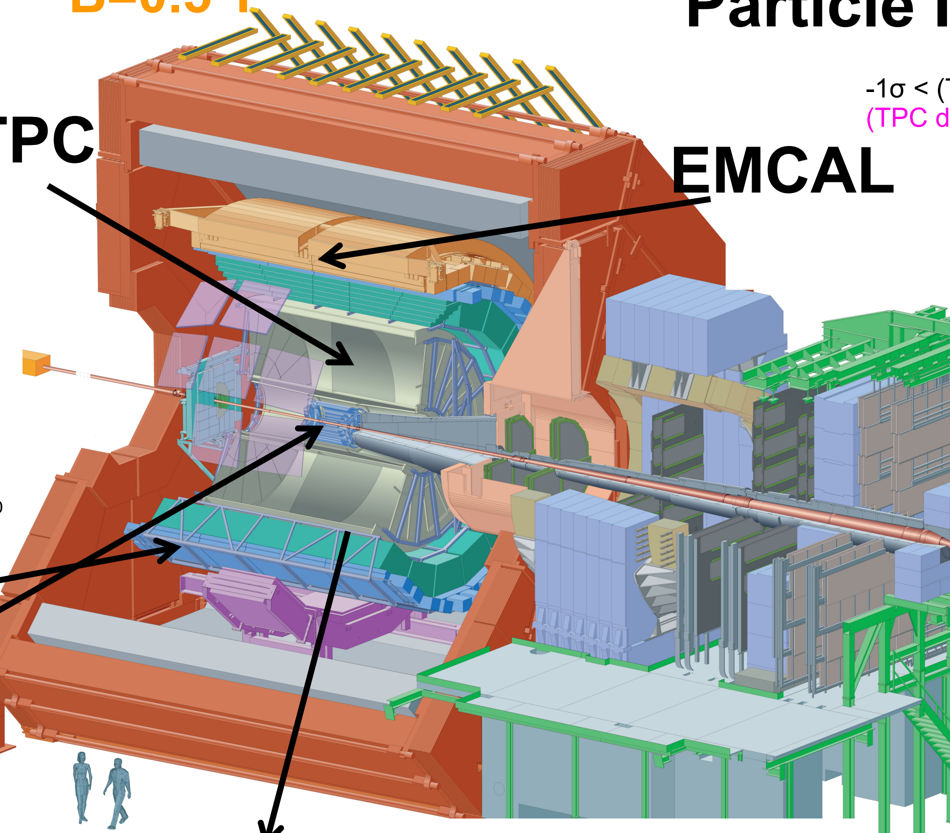
Int. J. Mod. Phys. A 29 (2014) 1430044

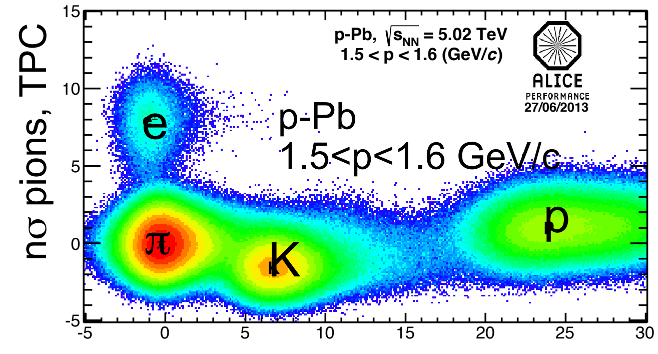
Resolution on track position at the primary vertex better than 70 micron for p_T>1 GeV/c (crucial for D-meson reconstruction)

The ALICE detector: central barrel

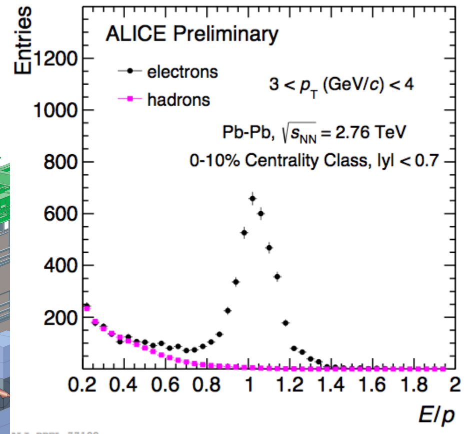
|η|<0.9
B=0.5 T

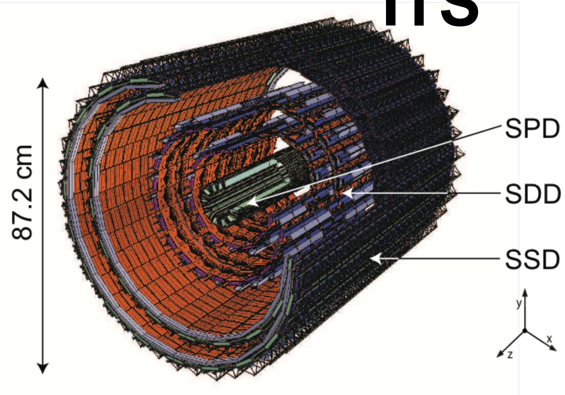
Particle Identification

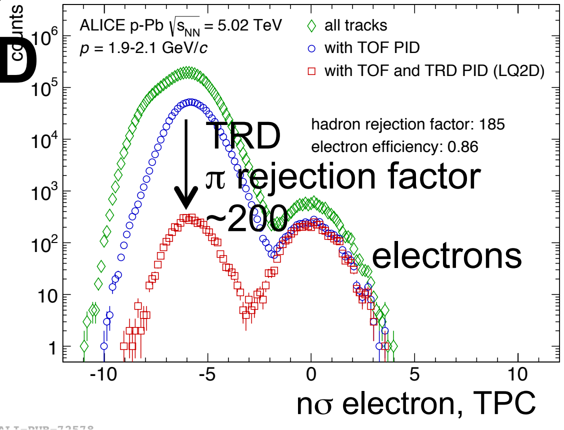




-1σ < (TPC dE/dx – <TPC dE/dx>e)TPC < 3σ
(TPC dE/dx – <TPC dE/dx>e)TPC < -4σ







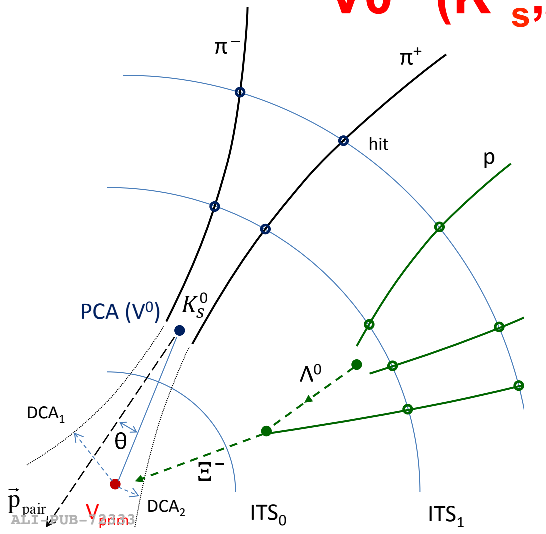
TRD
π rejection factor
~200

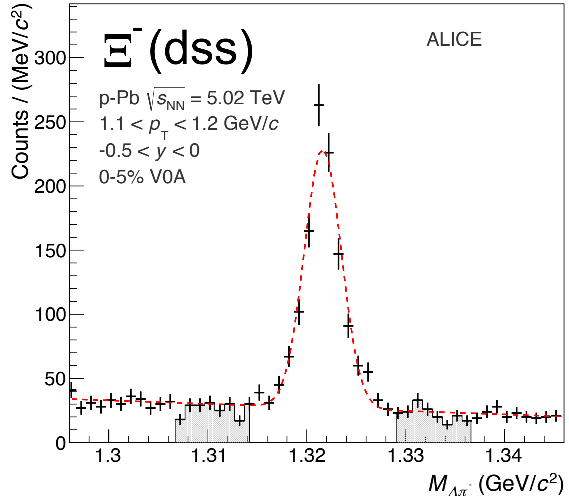
electrons

N.B. only detectors used for the measurements that are shown

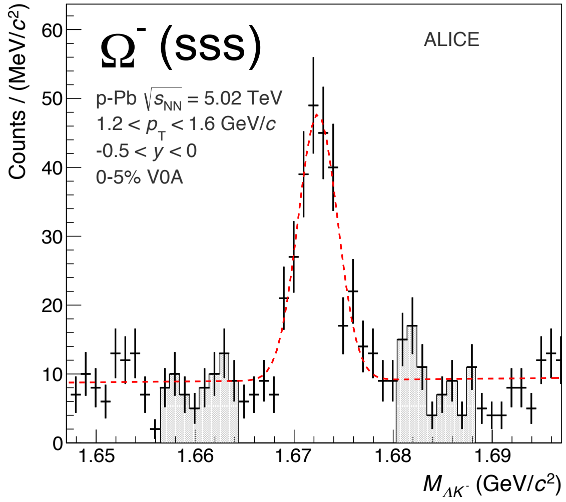
Signals reconstructed with central barrel

“V0” (K^0_s,Λ^0) and “Cascades” (Ξ,Ω)

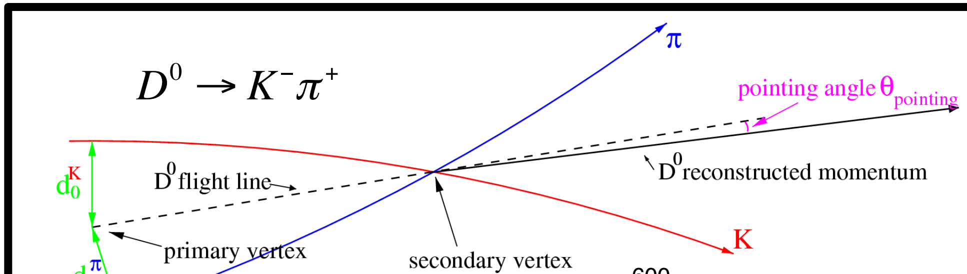




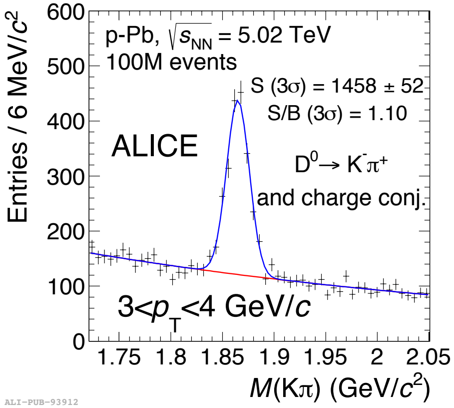
ALI-PUB-103594



ALI-PUB-103602

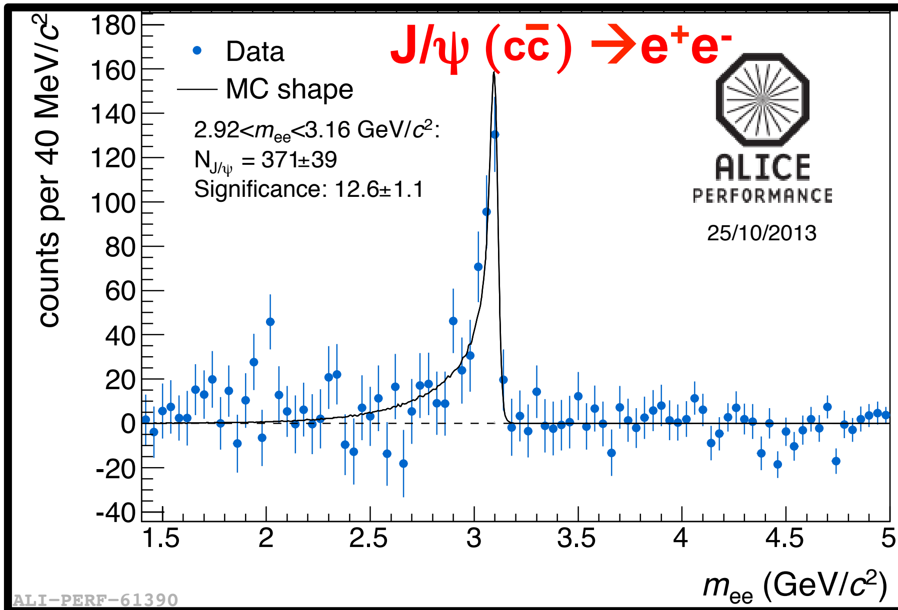


D mesons (e.g. $D^0(c\bar{u})$)



ALI-PUB-93912

J/ψ ($c\bar{c}$) → e^+e^-

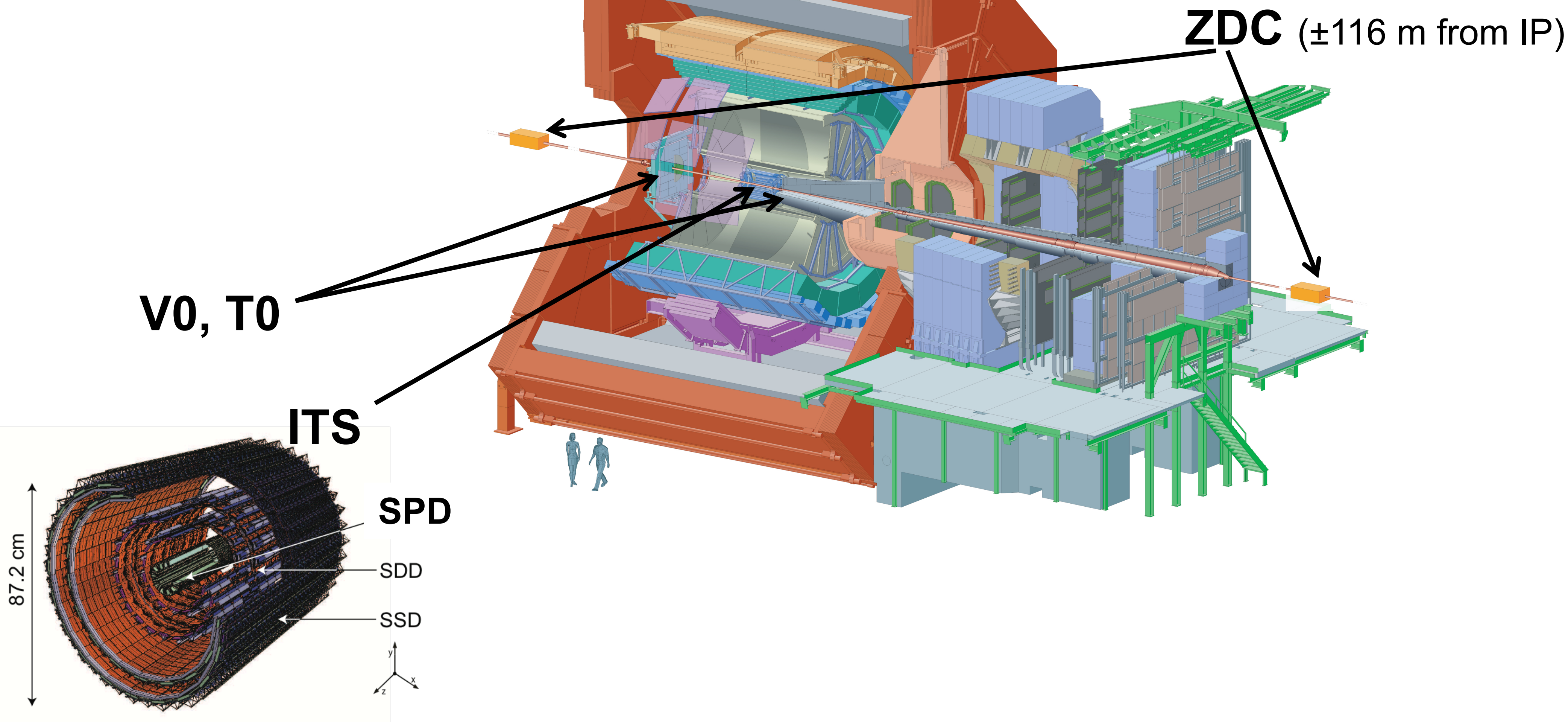


ALI-PERF-61390

+ spectra of identified particles

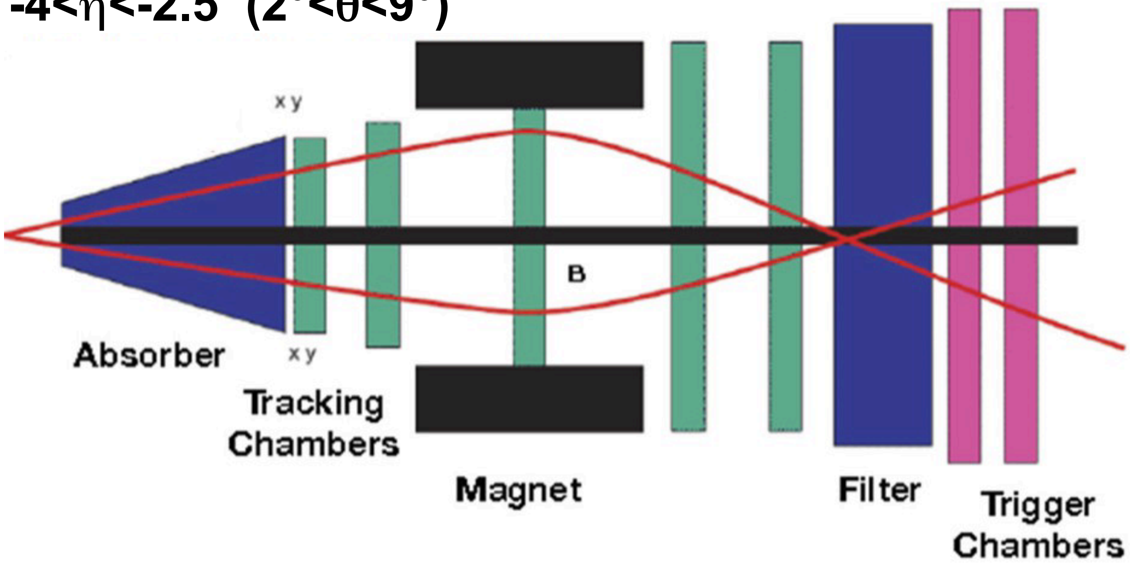
The ALICE detector: “small-angle” detectors

Event selection (min bias) + centrality determination

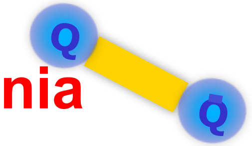


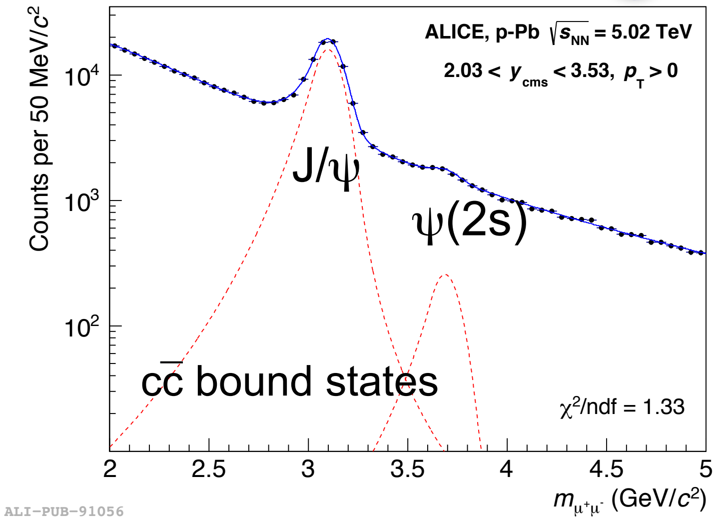
The ALICE detector: forward muon spectrometer

MUON SPECTROMETER
$-4<\eta<-2.5$ ($2°<\theta<9°$)



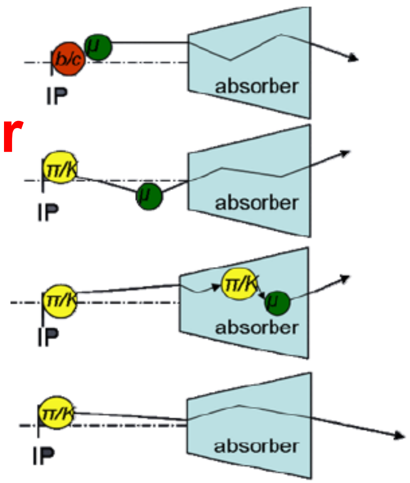
Quarkonia





Muons from semi-leptonic heavy-flavour hadron decays

D,B, Λ_c,..→ μ X
(after subtraction of muons from non-HF sources)

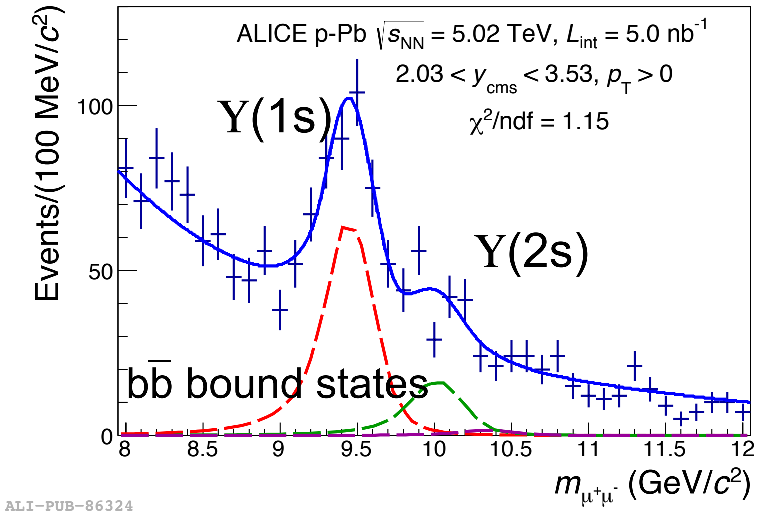


μ from heavy flavours

μ from primary π, K

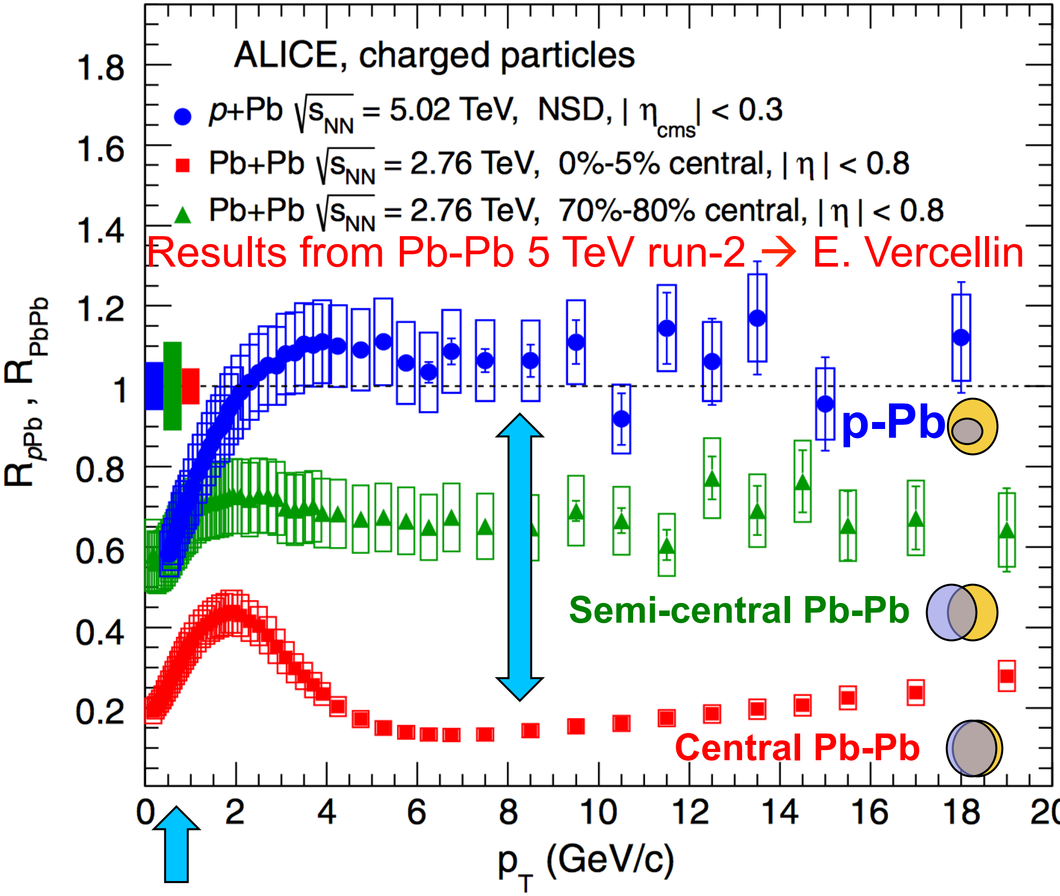
μ from secondary π, K

punch through hadrons



The high-energy regime: charged particles at high p_T

ALICE, PRL 110 (2013) 082302



Results from Pb-Pb 5 TeV run-2 → E. Vercellin

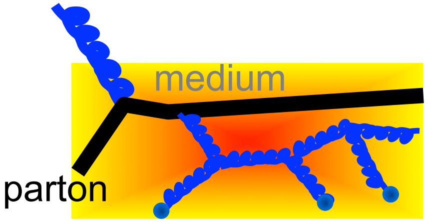
$$R_{PbPb[pPb]}(p_T) = \frac{dN_{PbPb[pPb]}/dp_T}{\left\langle N_{coll}^{PbPb[pPb]} \right\rangle \times dN_{pp}/dp_T}$$

Charged particles R_{pPb} compatible with unity from larger than ~1 GeV/c

→ Confirms that suppression of intermediate/ high p_T particles in central Pb-Pb collisions is a final-state effect

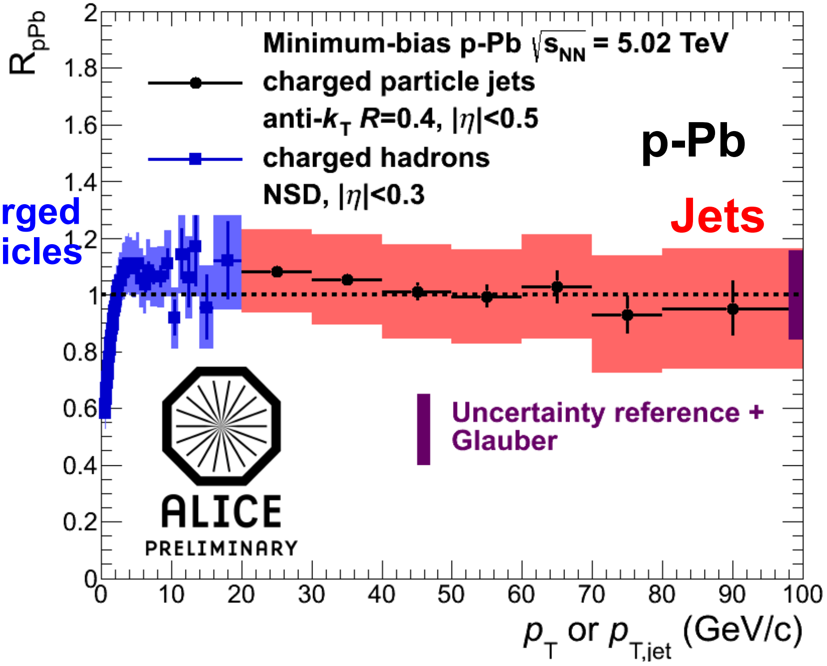
→ Evidence of in-medium partonic energy loss

Low p_T: shadowing + bulk of particle production from soft processes whose cross section is not expected to scale with N_{coll}



The high-energy regime: jets

Charged particles



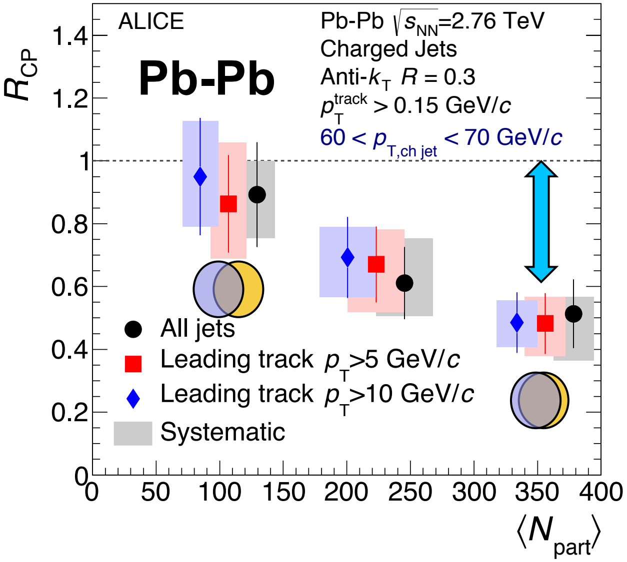
ALI-DER-63814

$$R_{PbPb[pPb]}(p_T) = \frac{dN_{PbPb[pPb]}/dp_T}{\left\langle N_{coll}^{PbPb[pPb]}\right\rangle \times dN_{pp}/dp_T}$$

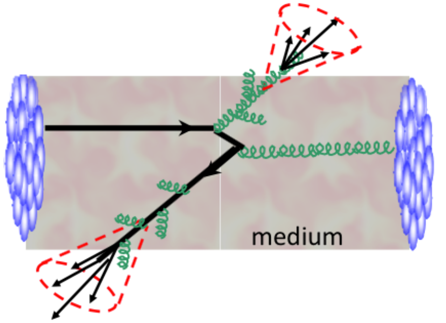
Same conclusion for jets…

N.B. Jets are "extended" and composite objects → complementary information w.r.t. single particles, e.g. address spatial distribution of radiated energy in Pb-Pb collisions

"Central-to-peripheral" ratio

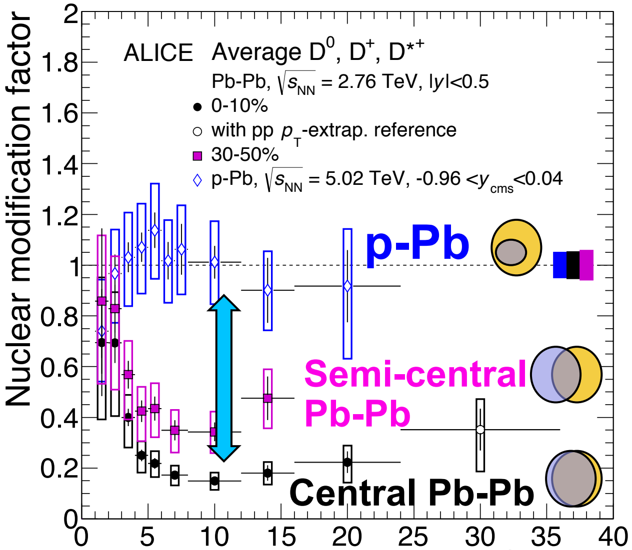


ALI-PUB-64299



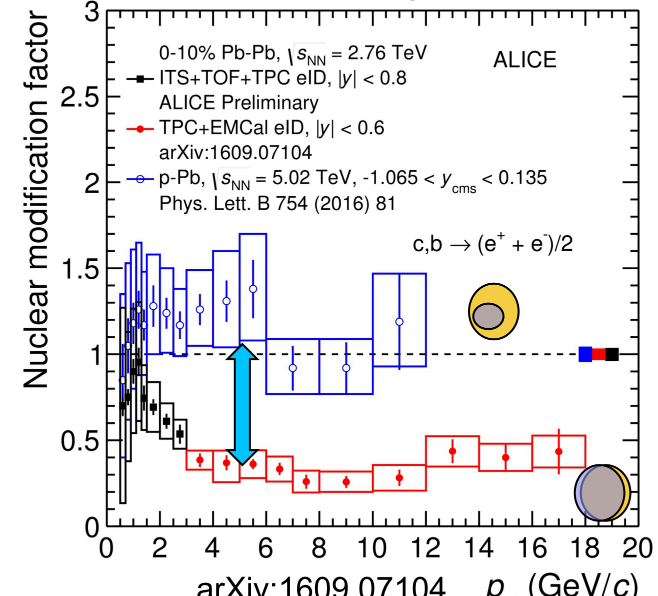
The high-energy regime: open heavy-flavour at mid-rapidity

D mesons



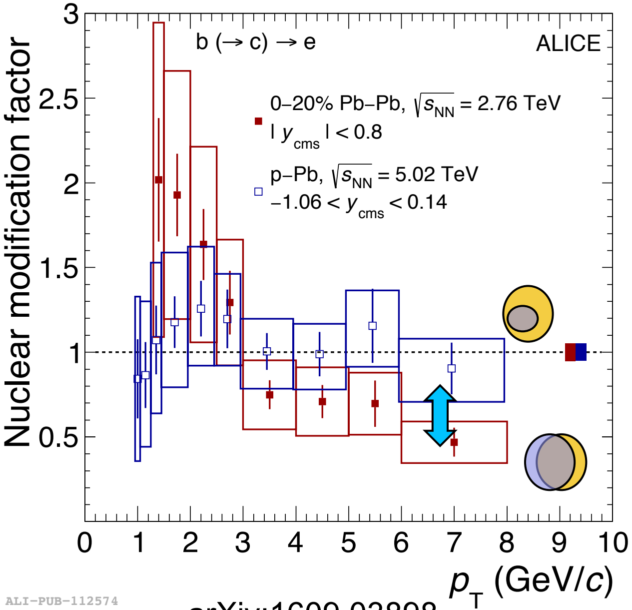
arXiv:1605.07569
JHEP1603 (2016) 081

Charm & beauty electrons



arXiv:1609.07104
Phys. Lett. B 754 (2016) 81-93

Beauty electrons



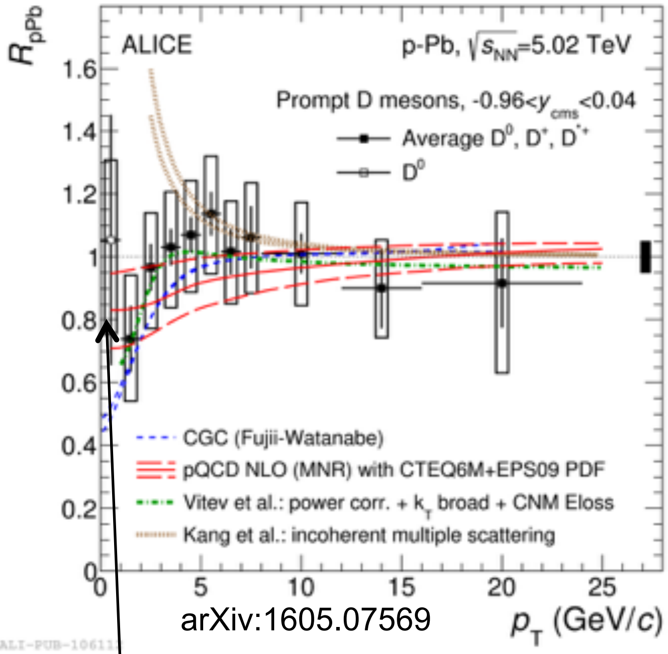
arXiv:1609.03898

D-meson, charm- and beauty-electron R_{pPb} compatible with unity within uncertainties

Confirm that charm and beauty suppression at intermediate/high p_T in Pb-Pb collisions is due to charm and beauty quark energy loss in the medium

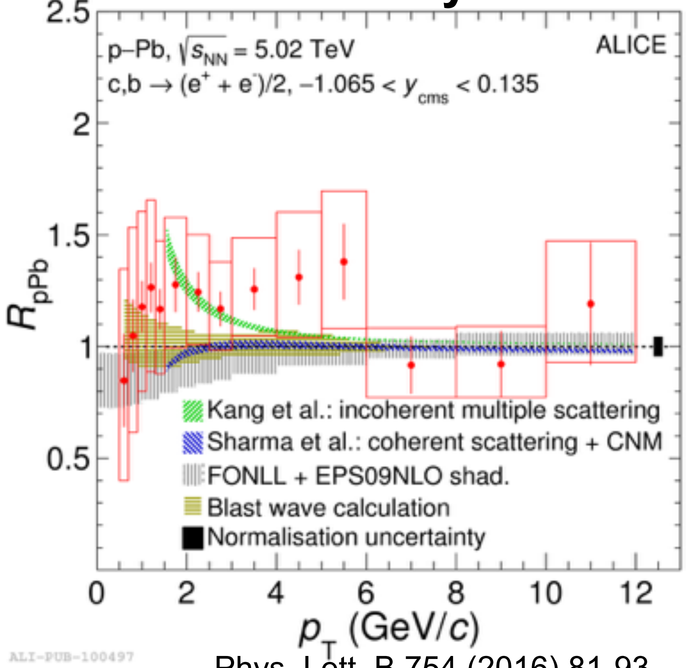
The high-energy regime: open heavy-flavour at mid-rapidity

D mesons



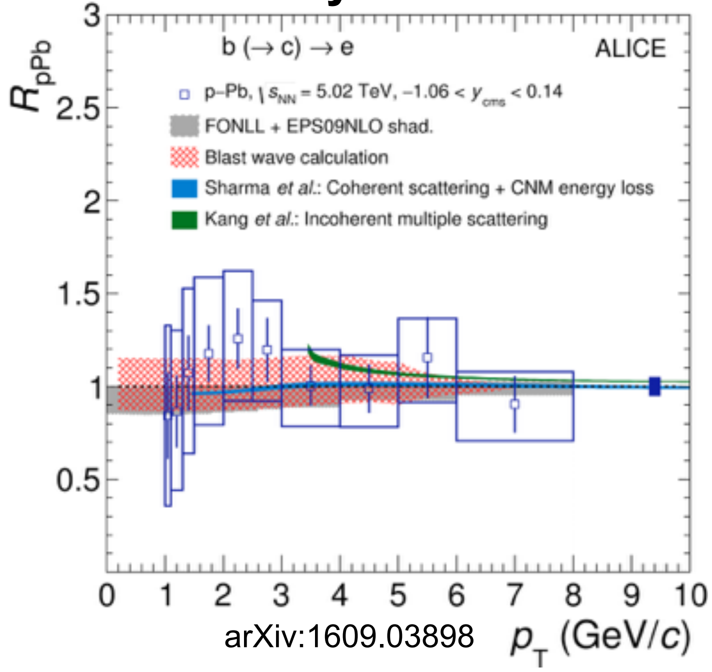
arXiv:1605.07569

Charm & beauty electrons



Phys. Lett. B 754 (2016) 81-93

Beauty electrons



arXiv:1609.03898

Data described by pQCD+nuclear PDF and models including initial-state and cold nuclear-matter effects

D mesons down to p_T=0 (n.b. massive quarks → high energy down to p_T=0)

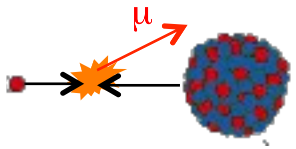
- a milestone for measuring total charm cross-section and initial-state effects for charm
  - Very important also for the interpretation of charmonia results
- p_T region where model predictions differentiate more
  - → Looking forward to larger dataset from ongoing p-Pb run (x10 more statistics)

HF-decay μ at forward/backward rapidity

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

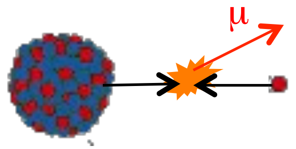
y_{cms}=0.465 (towards p beam)

p-Pb, “Forward”



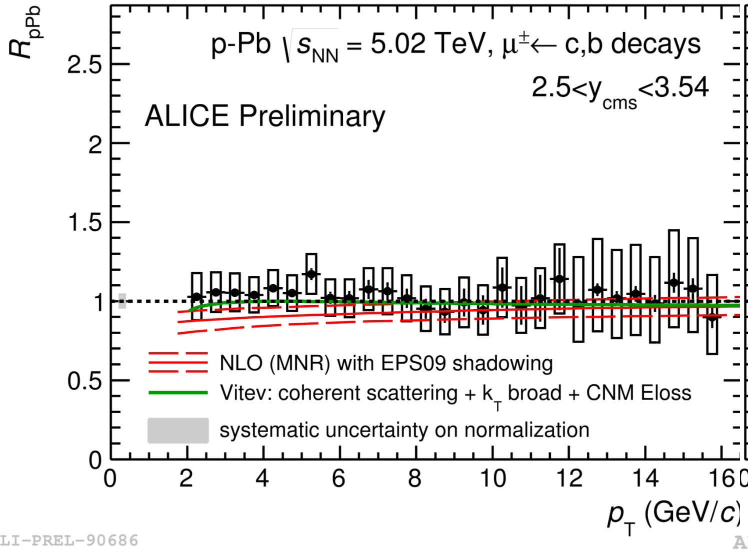
Probing low-x in Pb nucleus

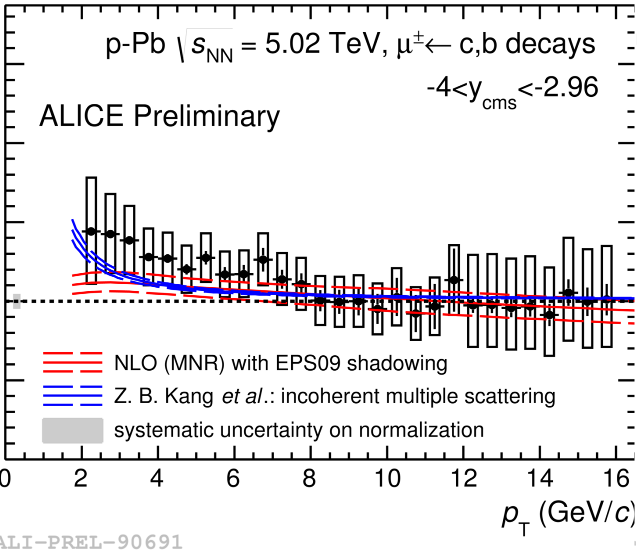
Pb-p, “Backward”

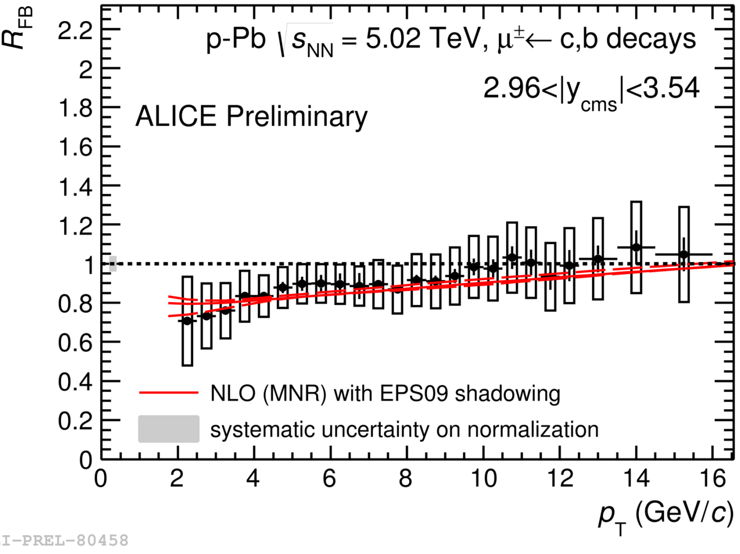


Probing large-x in Pb nucleus

Forward/backward ratio







***R_{pPb}* compatible with unity** within uncertainties

***R_{Pbp}* slightly larger than unity**, forward/backward ratio slightly smaller than unity at low p_T

→ **small cold nuclear matter effects, if any, for p_T>2 GeV/*c***

Data well described by pQCD + shadowing

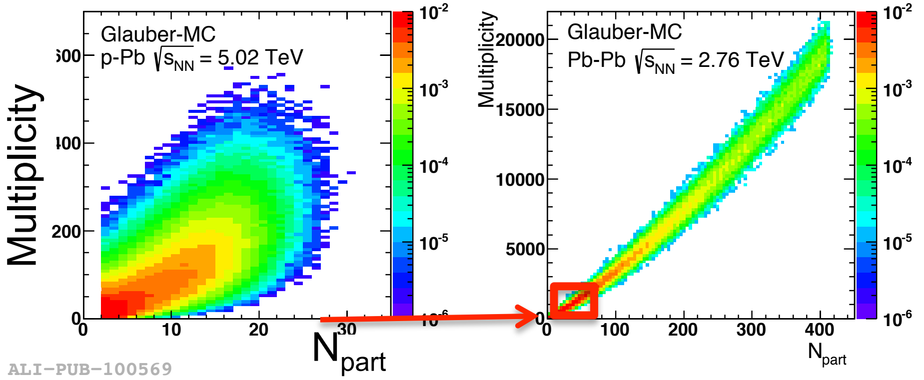
As well as by a model including coherent scattering, k_T broadening and CNM energy loss

And by a model including incoherent multiple scattering

(Parenthesis)Centrality in p-Pb collisions

- Intrinsic fluctuation of nucleon-nucleon multiplicity + small number of nucleon-nucleon collisions

→ Broad correlation between event activity and geometry.



ALI-PUB-100569

- Events with high-p_T particles contribute to event multiplicity shifting estimated centrality to higher values, especially if multiplicity measured in the same acceptance of measurement

Unable to define an unbiased R_{pPb} → define Q_{pPb}

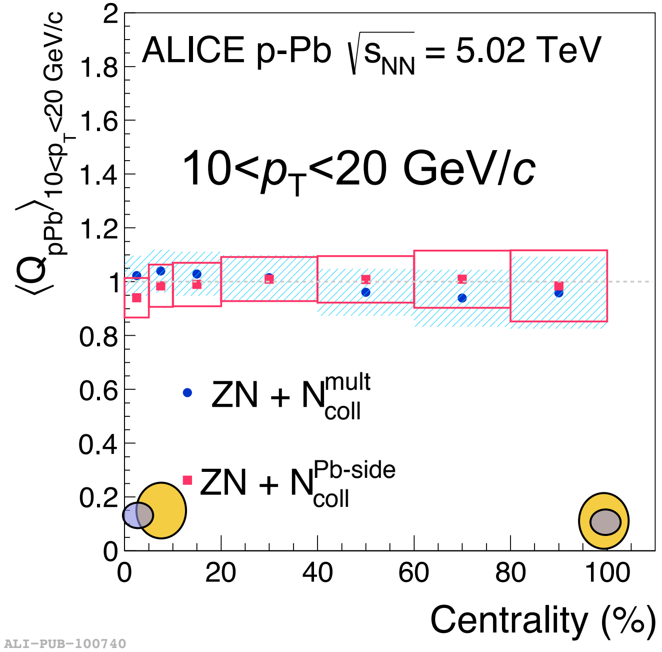
$$Q^{i}_{pA} = \frac{dN_{pA}/dp_T}{\langle N_{coll}\rangle_i \, dN_{pp}/dp_T}$$

Least bias estimator:

ZDC + assumptions of scaling of particle production

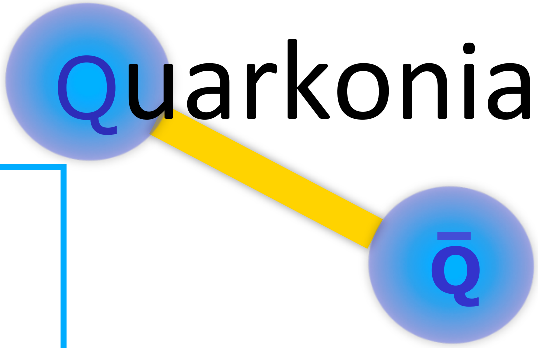
→ Q_{pPb} ~ 1 at high p_T

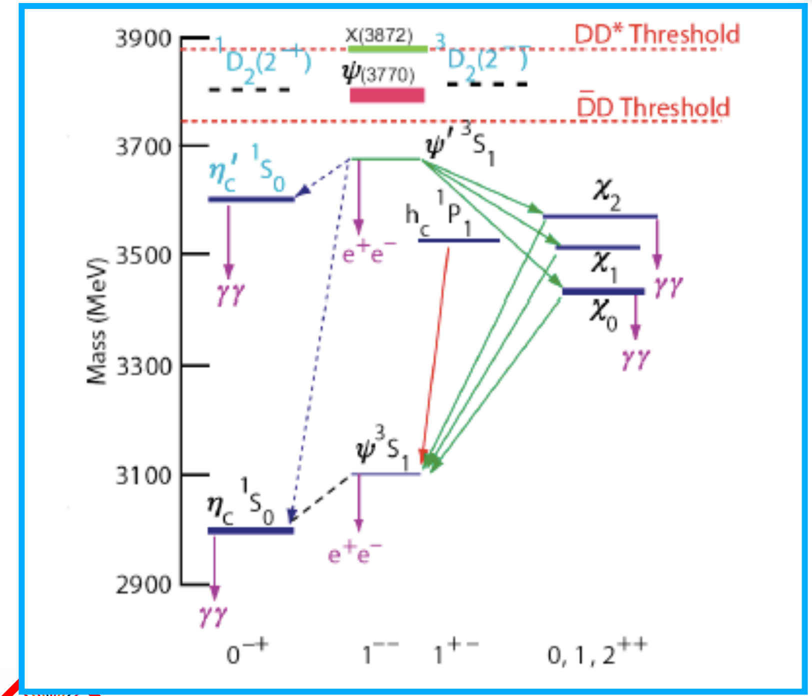
Phys. Rev. C 91 (2015) 064905



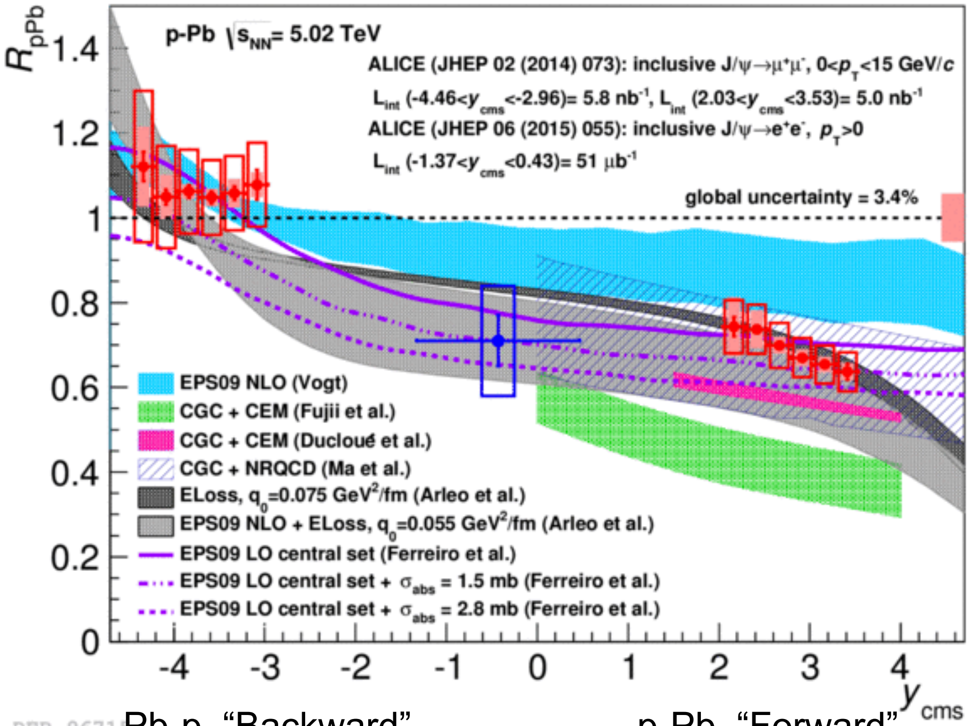
ALI-PUB-100740

Quarkonia


Q
Q̄


Mass (MeV)
3900
3700
3500
3300
3100
2900
X(3872)
DD* Threshold
D̄D Threshold
$^1D_2(2^{-+})$
$^3D_2(2^{--})$
ψ(3770)
$\psi'\ ^3S_1$
$\eta_c'\ ^1S_0$
$h_c\ ^1P_1$
χ_2
χ_1
χ_0
e^+e^-
$\gamma\gamma$
$\psi\ ^3S_1$
$\eta_c\ ^1S_0$
0^{-+}
1^{--}
1^{+-}
$0, 1, 2^{++}$

J/ψ nuclear modification factor



Small CNM effects at backward
Strong effects at forward rapidity

Pb-p, “Backward”

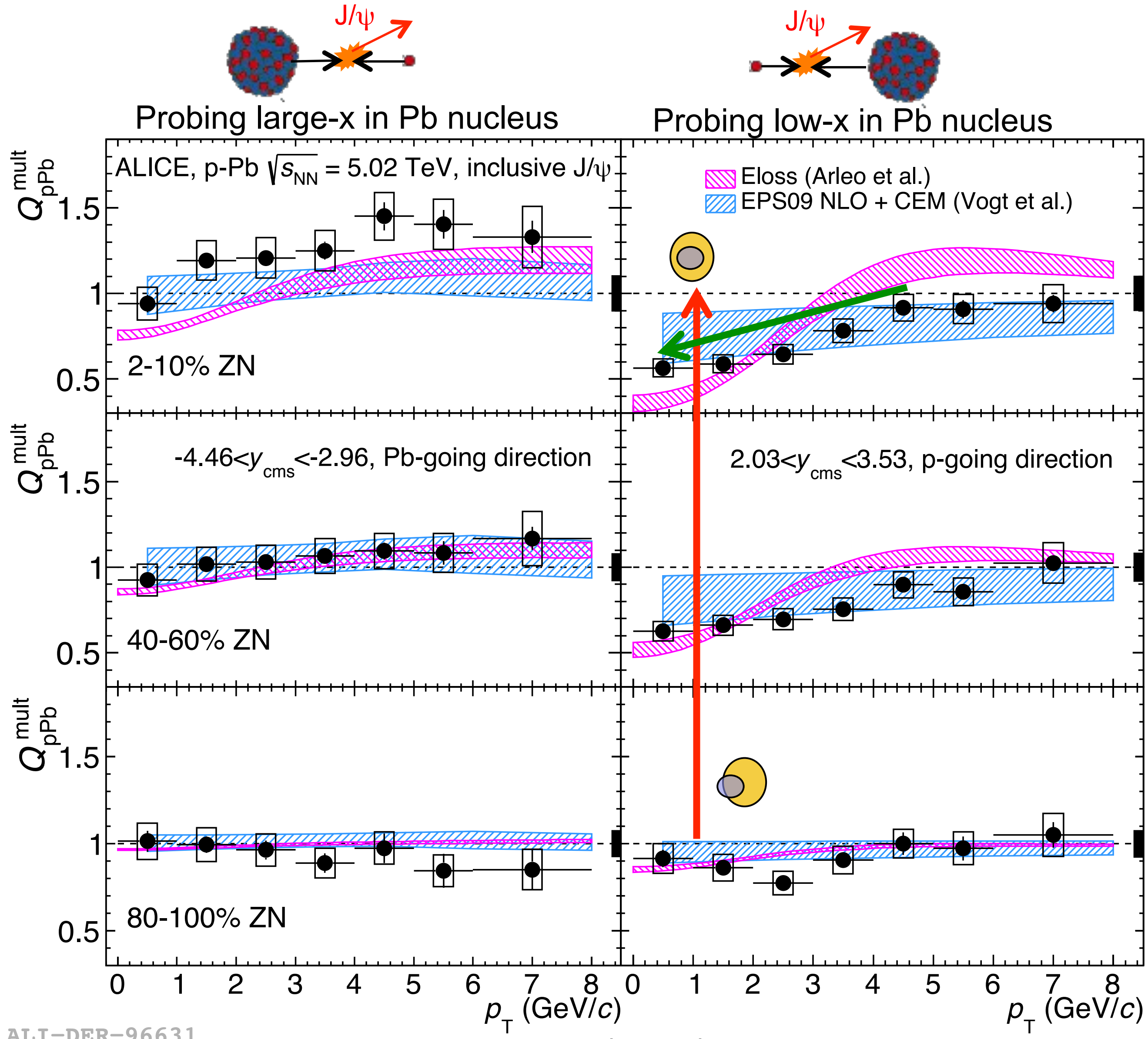
p-Pb, “Forward”

Probing large-x in Pb nucleus

Probing low-x in Pb nucleus

see R. Arnaldi at INFN2014, https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=6771

J/ψ “Q_{pPb}”: centrality and p_T dependence



JHEP 1511 (2015) 127

Suppression at forward rapidity:

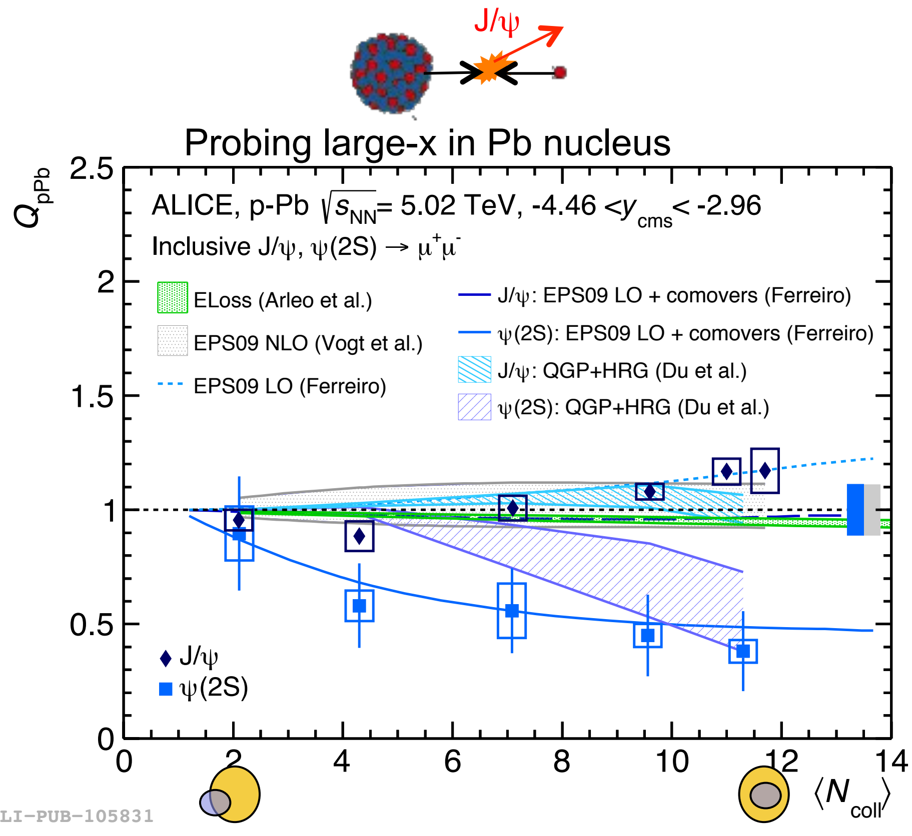
- Maximum at low p_T
- Increases for more central events

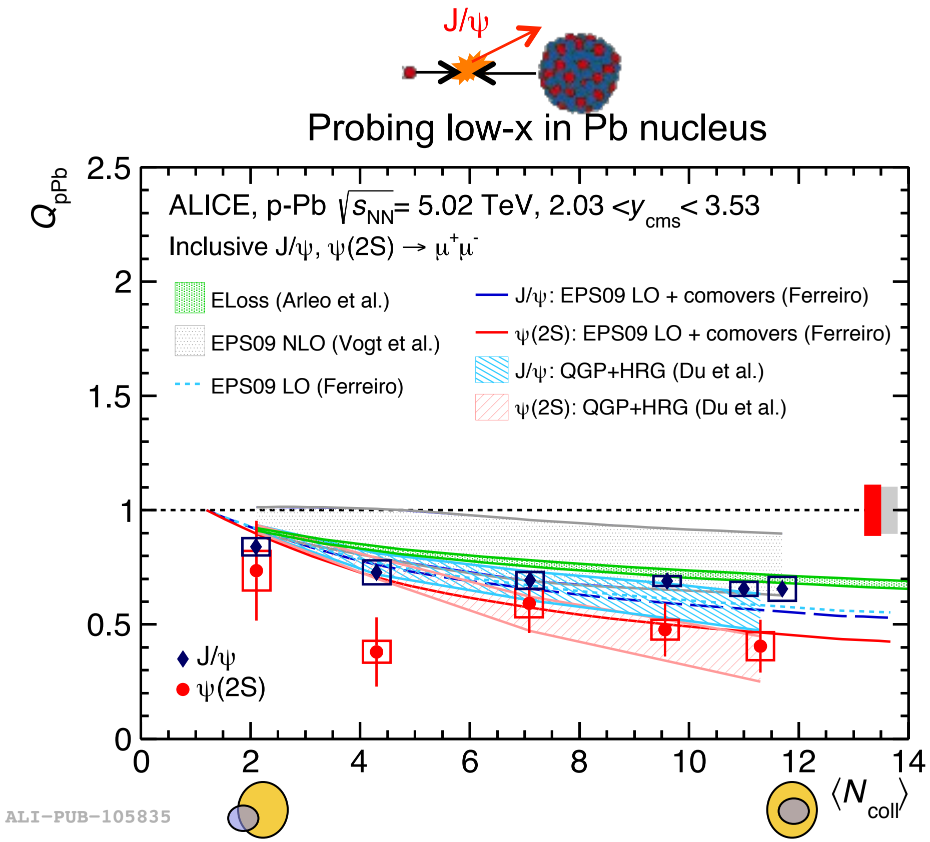
CNM effects predicted to be stronger for more central events

No model is able to reproduce precisely all observables

Though shadowing and coherent energy loss work quite well

ψ(2s) suppression in p-Pb


Probing large-x in Pb nucleus


Probing low-x in Pb nucleus

ψ(2s), less tightly bound than J/ψ, is suppressed!

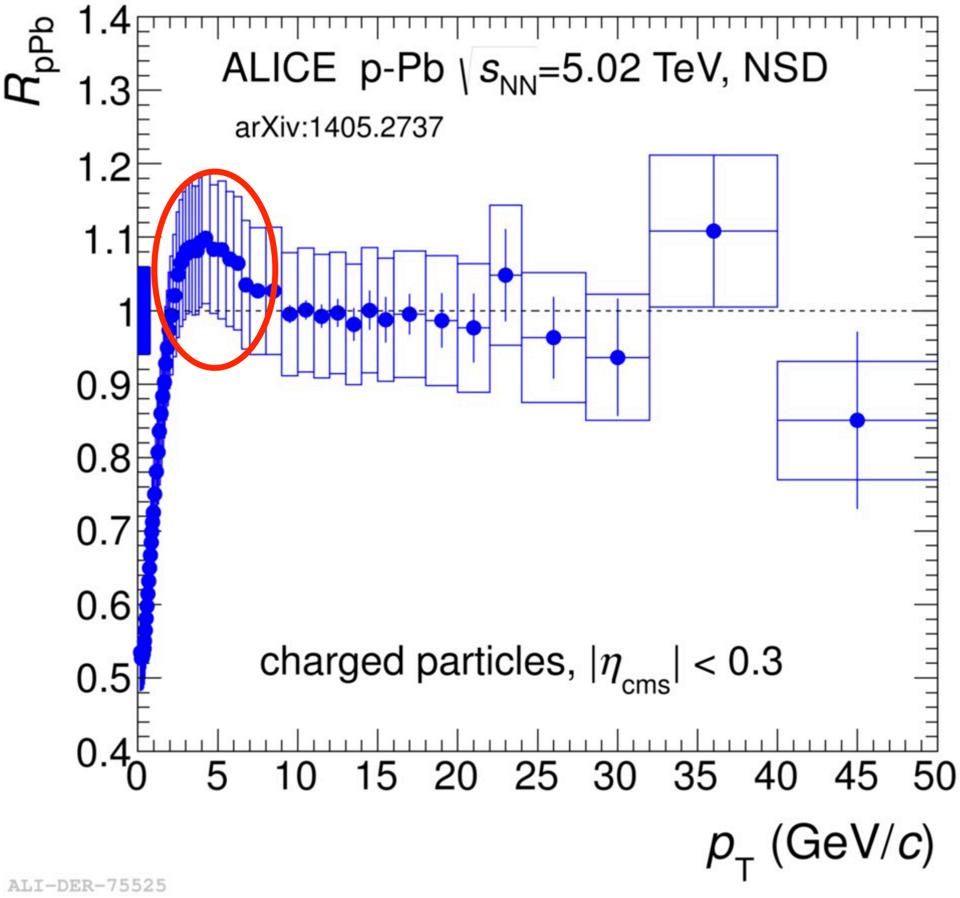
→ Indication of final-state effects

Interactions with co-moving hadrons (and QGP?) + dissociation of fully-formed resonance in nuclear matter ?

JHEP 06 (2016) 50, JHEP 1511 (2015) 127

Soft probes and the revelation of collective-like effects

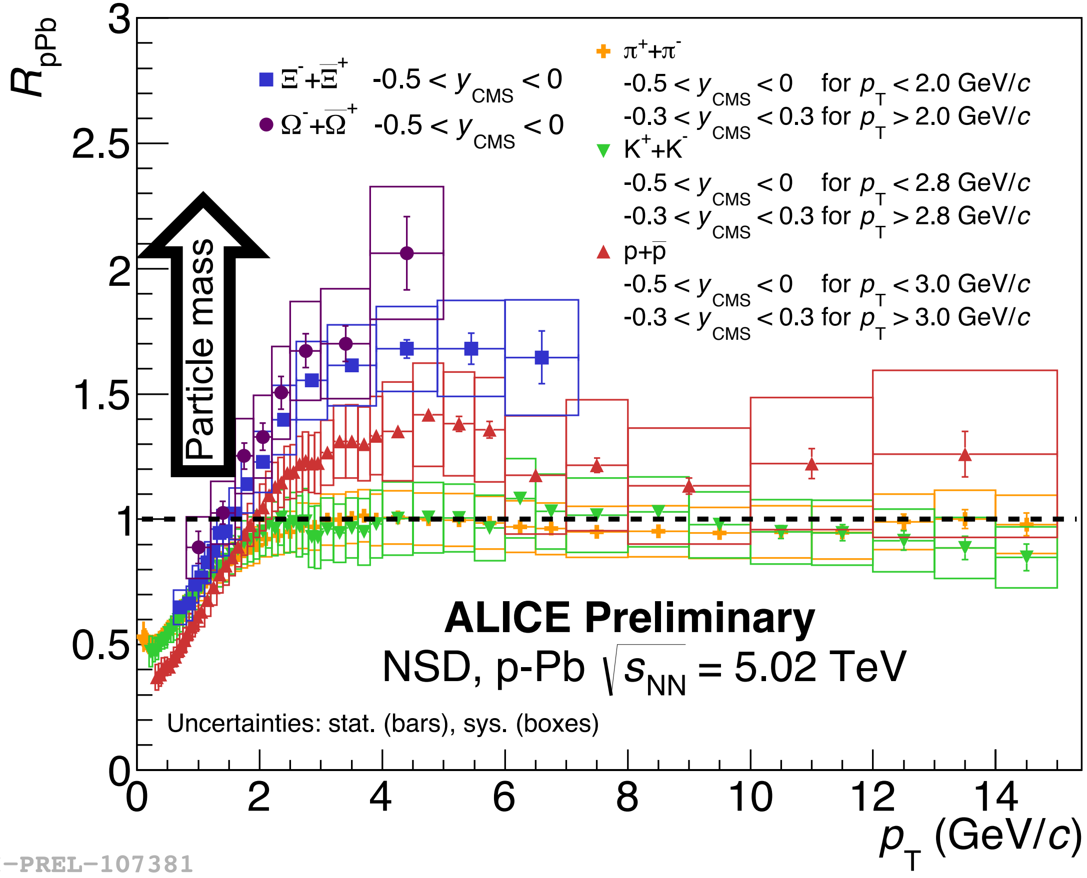
More on R_{pPb}: a look at low p_T



“Cronin”-enhancement
First observed by Cronin (PRD 11 (1975) 3105)

Traditional explanation:
multiple-soft scattering in initial state before hard scattering (arXiv:hep-ph/0212148)

More on R_{pPb}: a look at low p_T



At intermediate p_T (Cronin region)

Indication of mass ordering

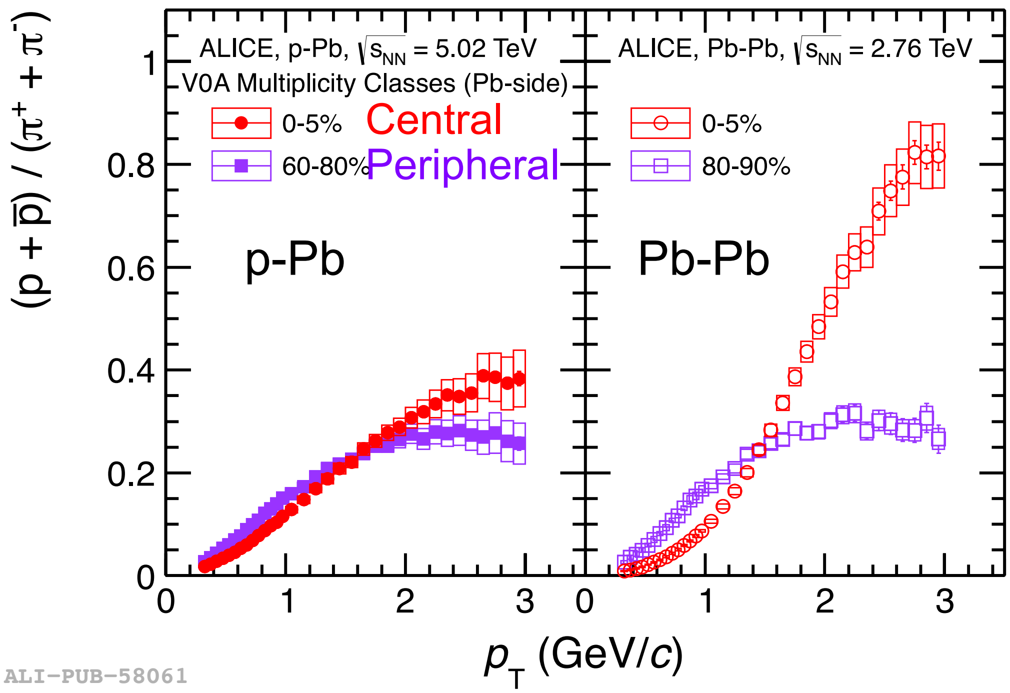
- No enhancement for pions and kaons
- Pronounced peak for protons
- Even stronger for cascades

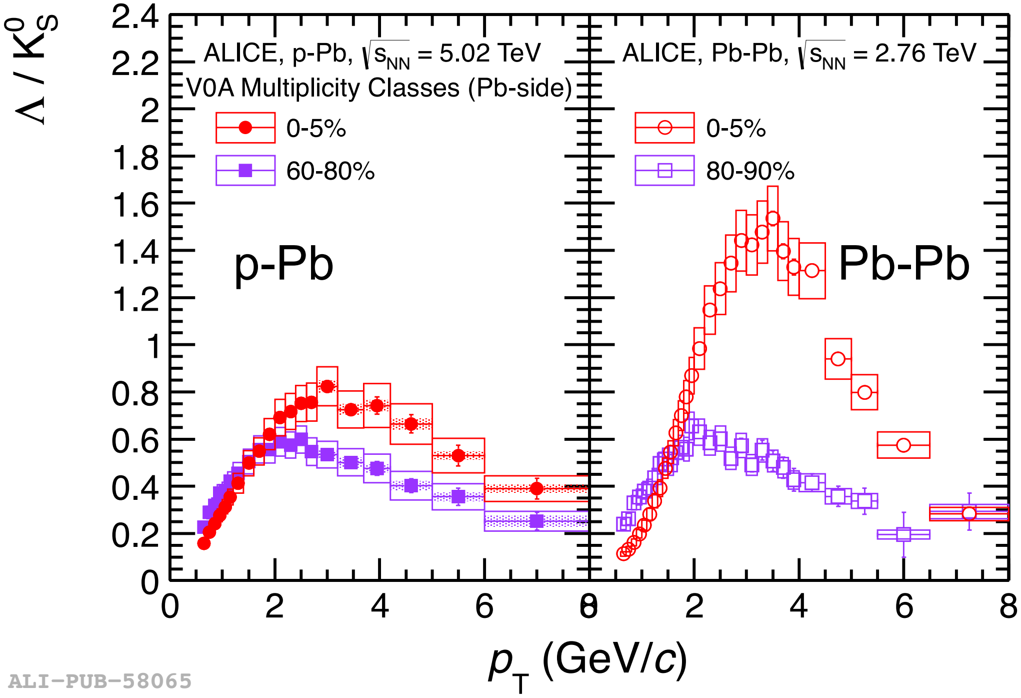
Resembling **radial flow** effect? (medium expansion → collective particle motion in common velocity field→ larger momentum for heavier particles)

Particle species dependence points to relevance of final-state effects

Baryon-over-meson enhancement

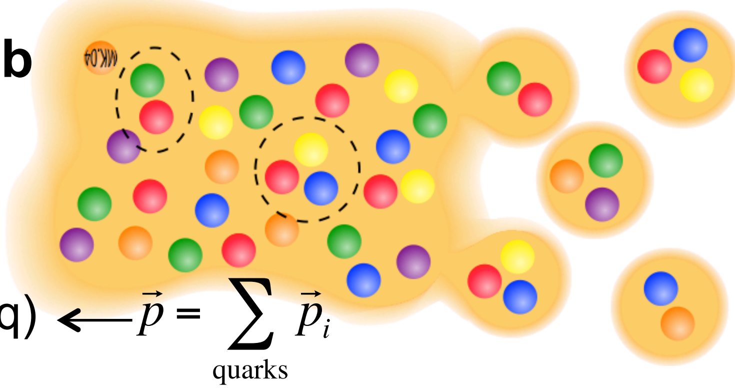
Phys. Lett. B 728 (2014) 25-38





Significant multiplicity dependence of proton over pion and Λ over K^0_s ratio:

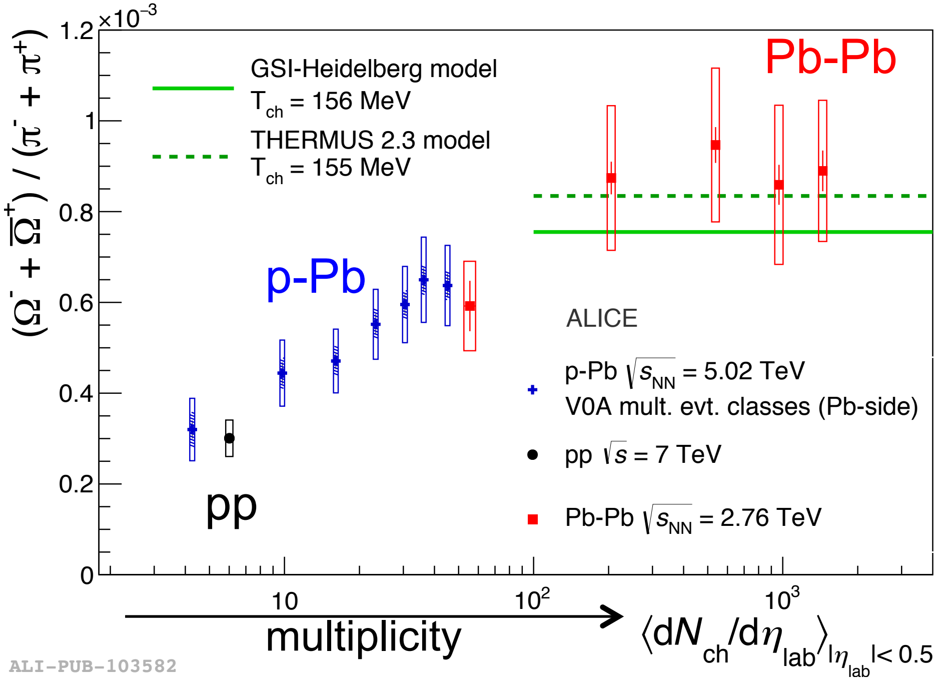
- **Reminiscent enhancement of observations in Pb-Pb**
  - usually attributed to **radial flow** or hadron formation via **coalescence** of deconfined and thermalized quarks

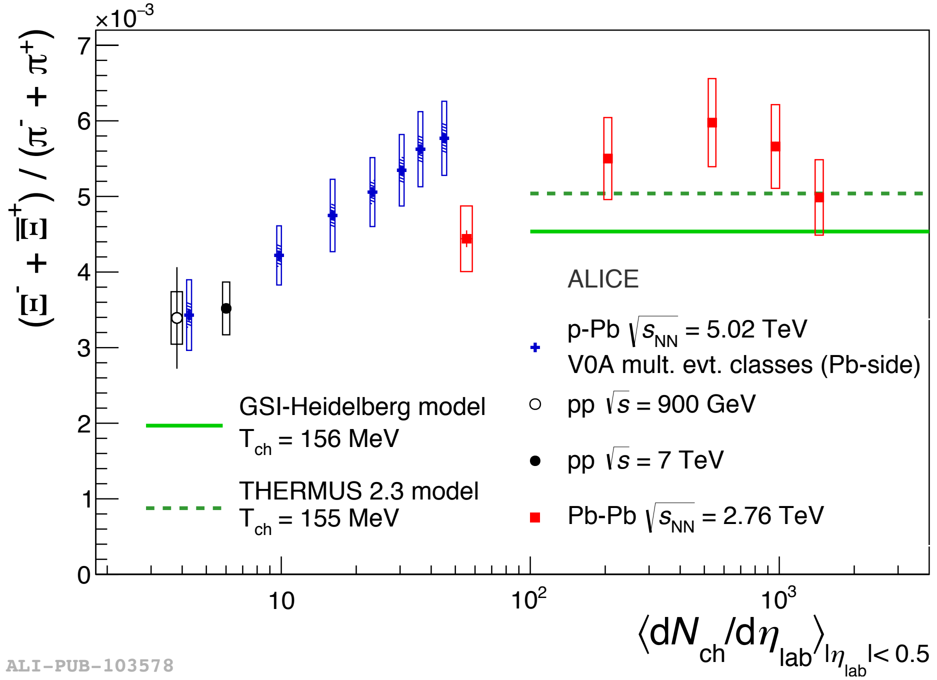


$$p(qqq) > p(qq) \longleftarrow \vec{p} = \sum_{\text{quarks}} \vec{p}_i$$

Hyperon production vs. multiplicity

Phys. Lett. B 758 (2016) 389-401





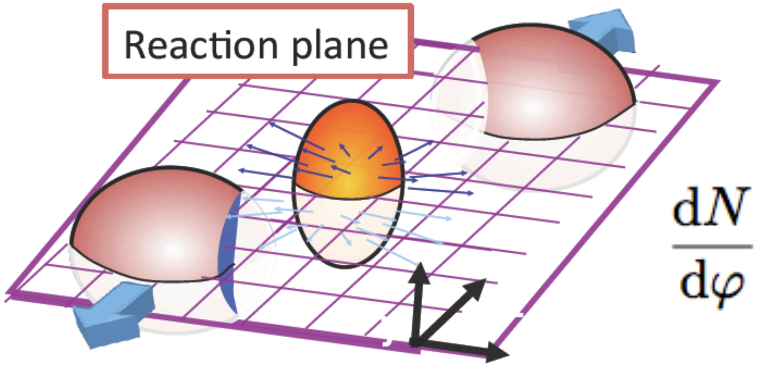
- Hyperon-to-pion ratio increases with multiplicity from values compatible to pp to those observed for Pb-Pb
- Rate of increase is higher for particles with higher strangeness content

→ Qualitatively consistent with the lifting of canonical suppression with increasing multiplicity expected from statistical hadronisation models

Azimuthal anisotropy (Elliptic flow)

-- idea "inherited" from nucleus-nucleus collisions --

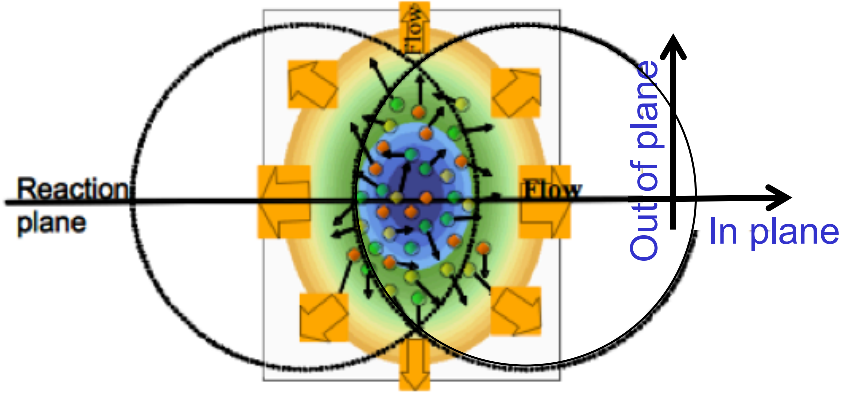
Study azimuthal distribution of produced particles w.r.t. the reaction plane (Ψ_{RP})



Initial spatial anisotropy
→ momentum anisotropy

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi-\Psi_1) + 2v_2\cos[2(\varphi-\Psi_2)] + \ldots\right)$$

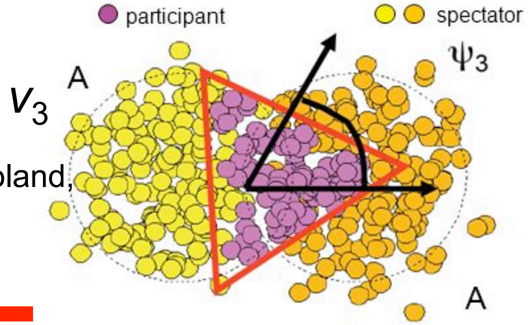
$$v_n = \left\langle \cos(n[\varphi-\psi_n]) \right\rangle$$



$v_2>0$

→ Thermalization/collective motion (at low p_T)

→ Path length dependence of energy loss (at high p_T)



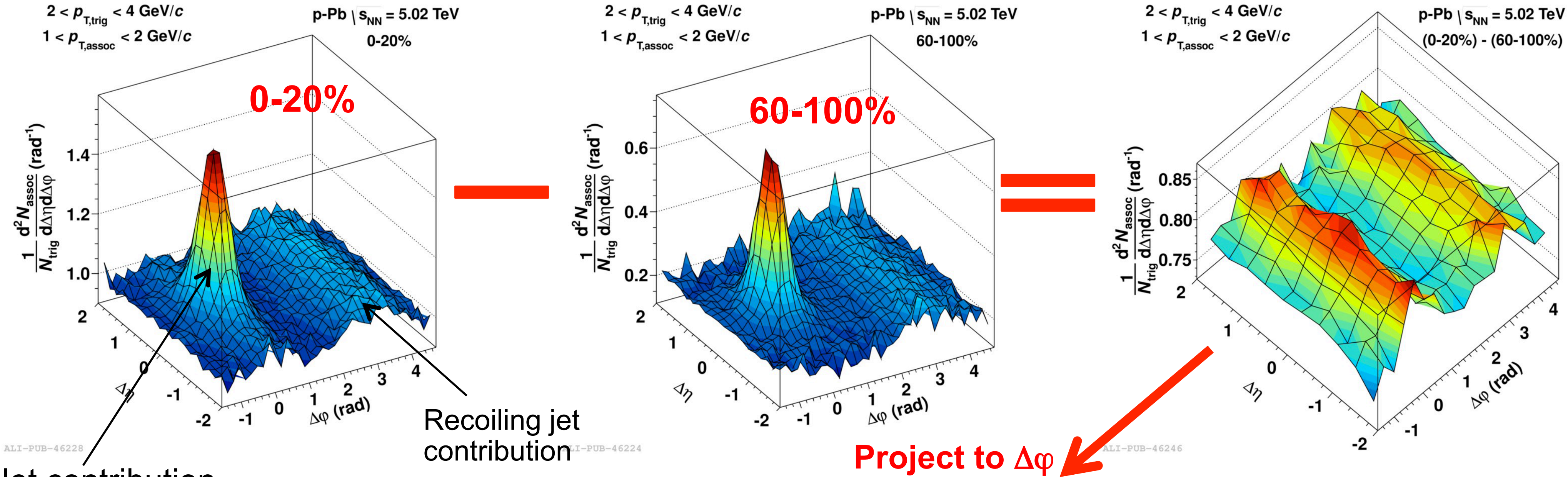
B. Alver, G. Roland, PRC81 (2010) 054905

$v_n>0$

Higher harmonics → transformation of initial-state fluctuations into final-state anisotropy

Azimuthal anisotropy (Elliptic flow)

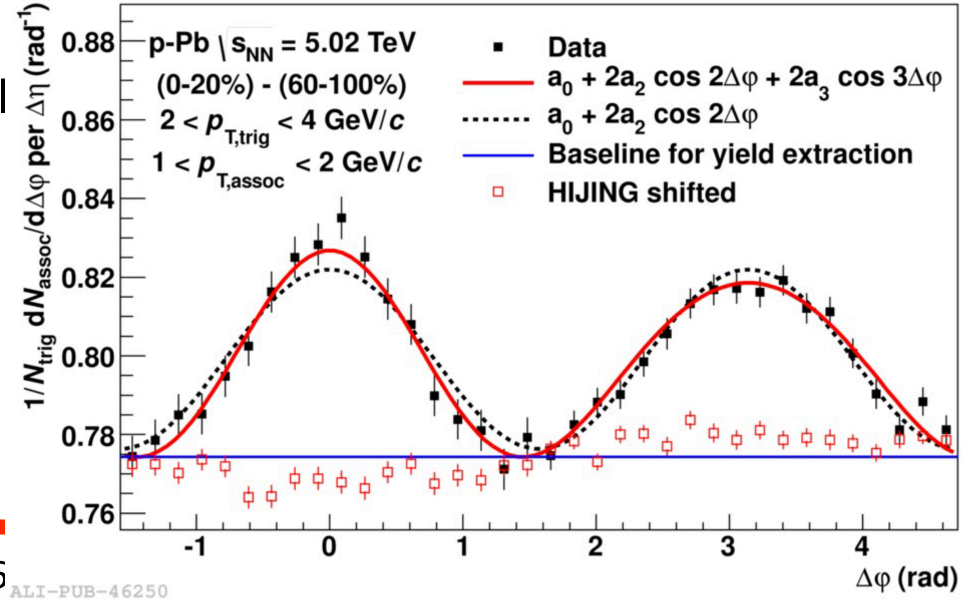
2-particle angular correlations (→Δφ,Δη distributions) to probe existence of symmetry planes



Recoiling jet contribution

Jet contribution

Project to Δφ

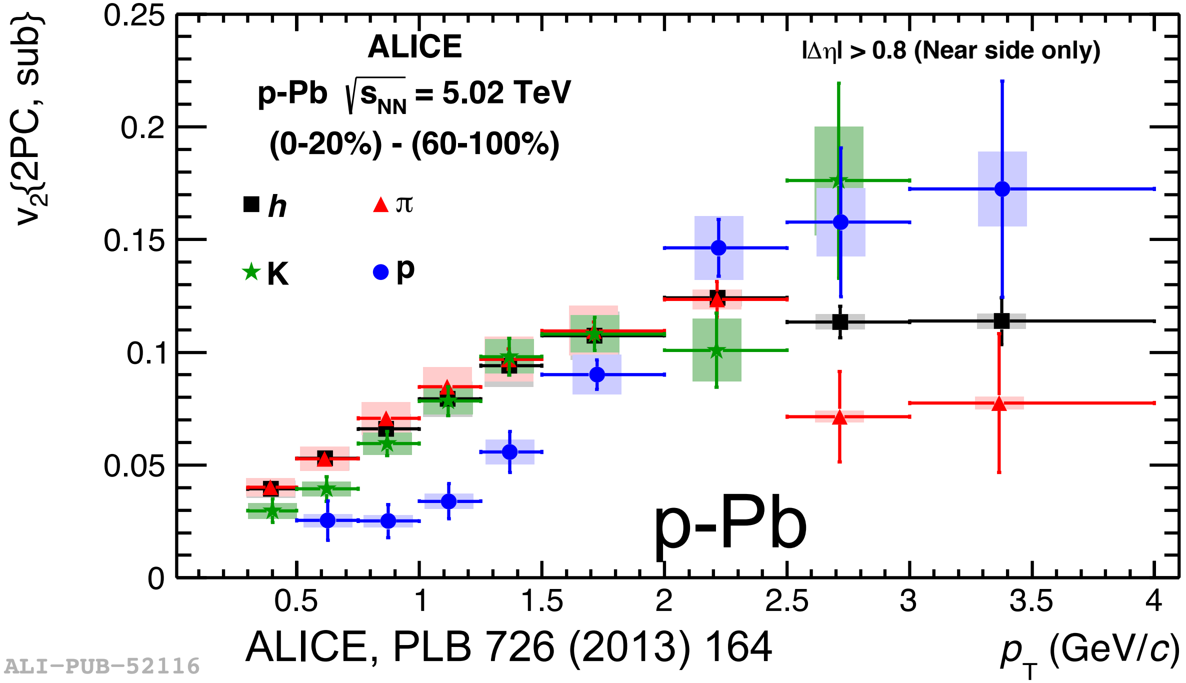


Unexpected modulation of the baseline after removal of jet contributions

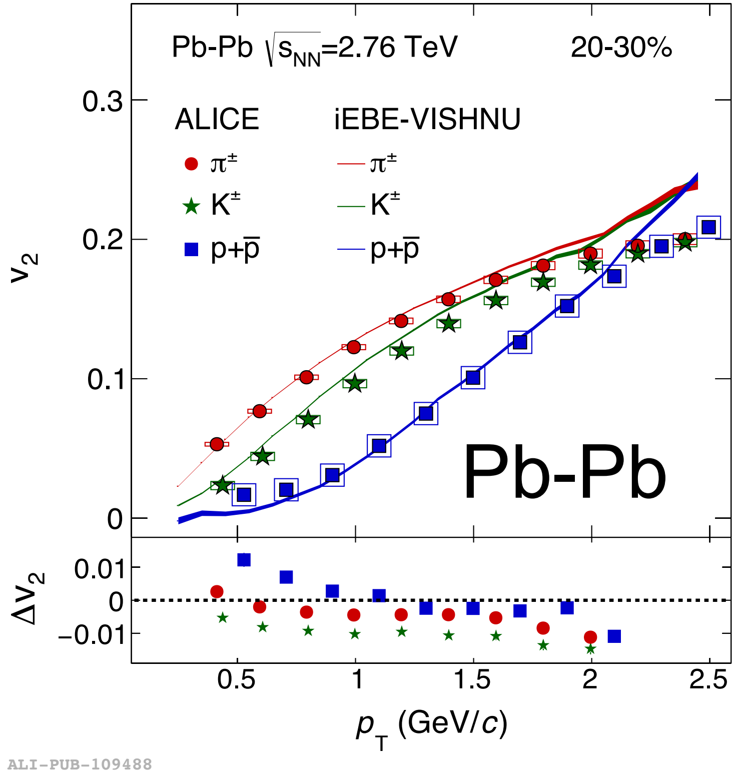
- **“double-ridge” structure** resembling what seen in Pb-Pb and typically attributed to elliptic flow
  •…as well as in very-high multiplicity pp… still not understood

ALICE, PLB 719 (2013) 29

Azimuthal anisotropy (Elliptic flow)



ALICE, PLB 726 (2013) 164



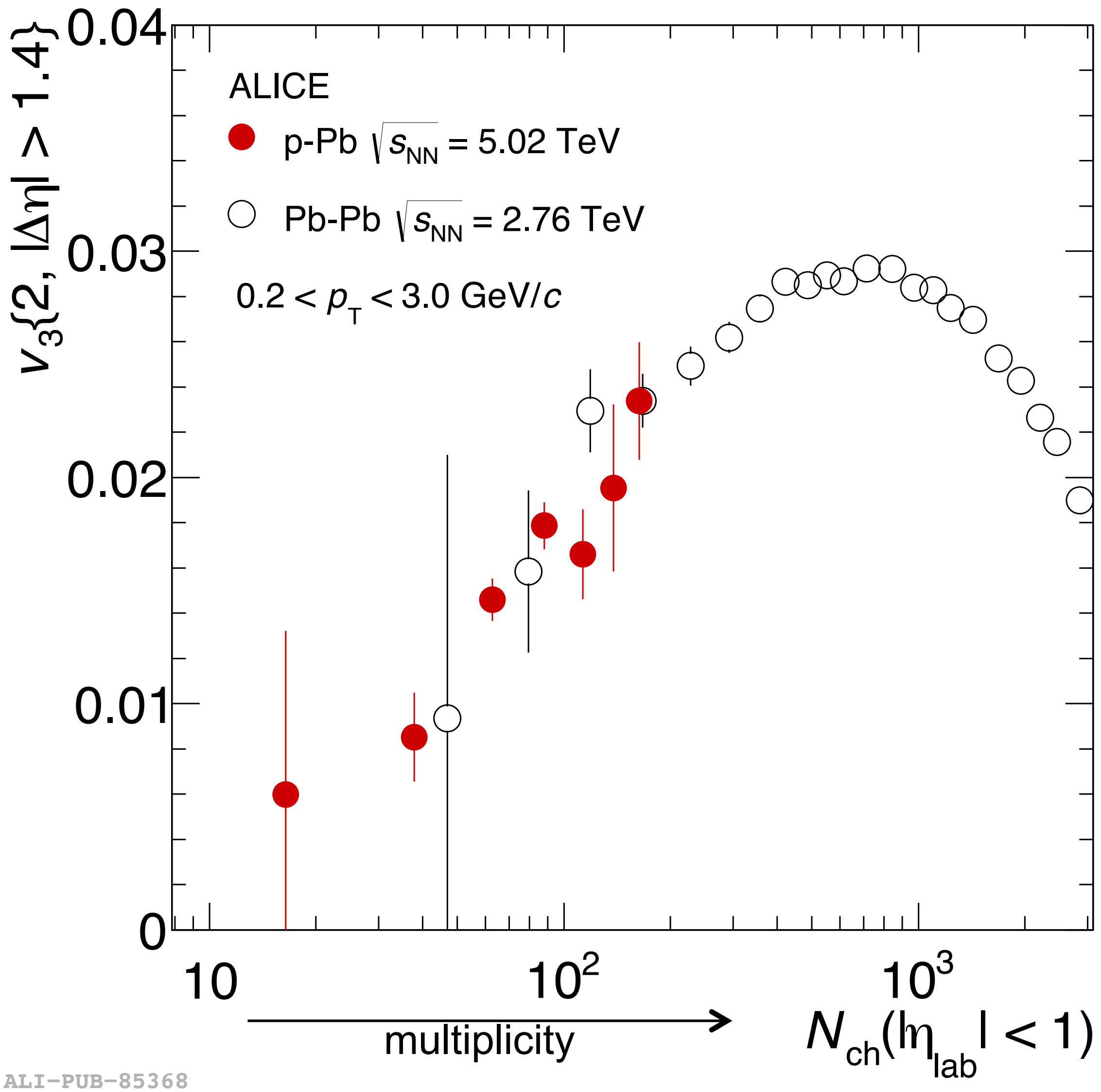
arxiv:1606.06057

Large v_2 values!

Mass ordering and "crossing" similar to Pb-Pb, where data are reproduced by hydrodynimical models

see also Salvo Plumari (this afternoon)

Azimuthal anisotropy: triangular flow



Phys. Rev. C 90, 054901 (2014)

v_3 (p_T-integrated) similar in p-Pb and Pb-Pb for overlapping multiplicities

Similar initial-state third harmonic eccentricities in the two systems?

Has the v_3 in p-Pb and Pb-Pb the same origin?

Conclusions

First p-Pb run at the LHC was extremely successful for ALICE

High-energy regime

✓ Binary scaling works in p-Pb

✓ Small cold nuclear-matter effects if any at mid-rapidity

Several indications supporting final-state effects (baryon/meson enhancement, double ridge, ψ(2s) suppression)

... QGP formed in p-Pb? (and what about high-multiplicity pp?)

... is it possible to have collective effects and no (signs of) energy loss?

... that would be a spectacular unexpected news... but would it imply that we lost our "control experiment"?

Particle multiplicity emerging as a scale to connect different collision systems

→possibility to study **onset of collectivity?**

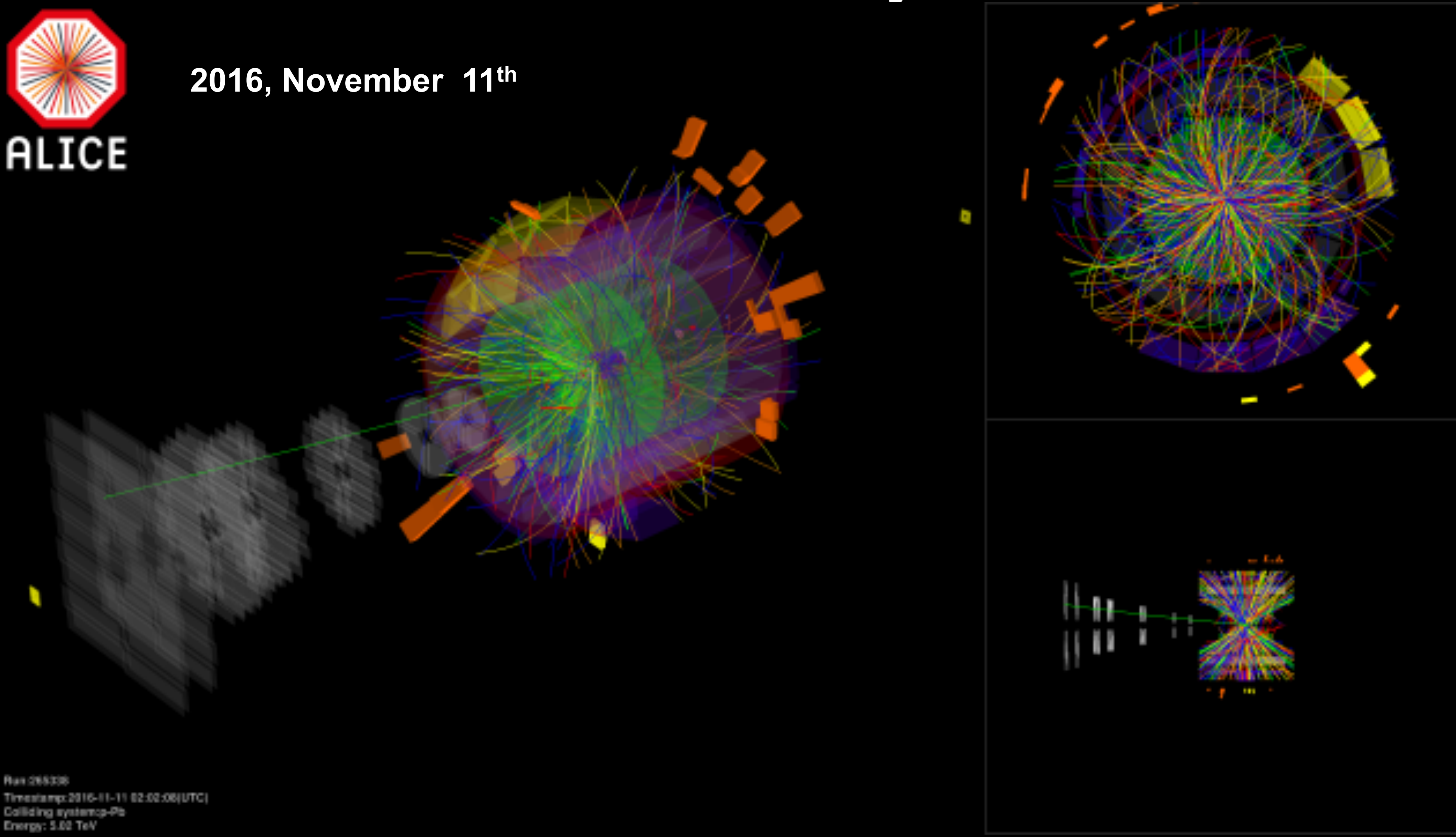
Look forward to new data from ongoing p-Pb run:

- **x10 stat for min. bias data at 5 TeV**
- **New energy explored (p-Pb at 8 TeV)**

Thanks and… stay tuned!

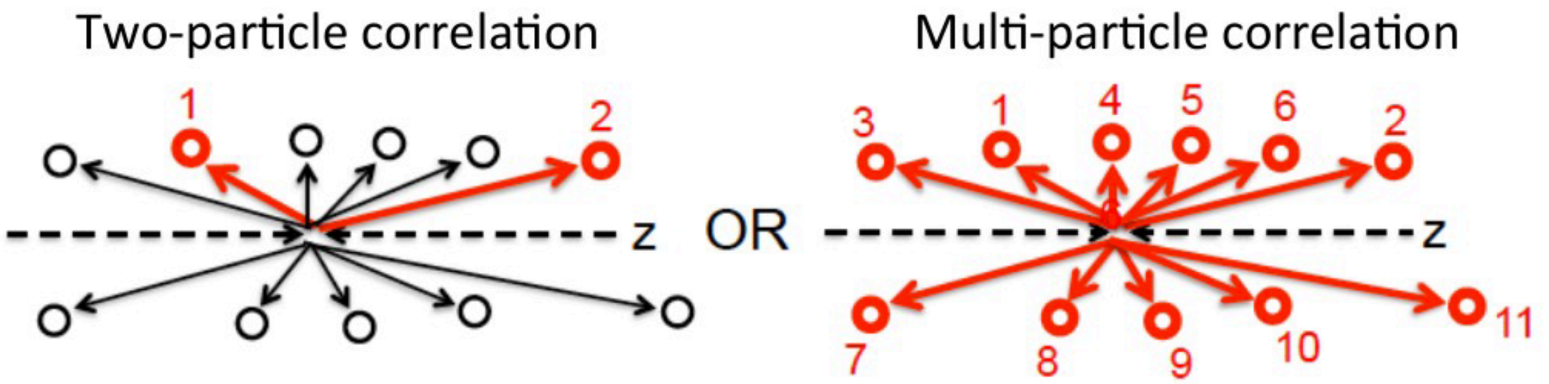
ALICE

2016, November 11th



Extra

Azimuthal anisotropy with multi-particle correlations



Multi-particle (>2) cumulants:

$$\langle\langle 6\rangle\rangle = \langle\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\rangle\rangle$$

$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\cdot\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\cdot\langle\langle 2\rangle\rangle^3$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

$$v_n\{6\} = \sqrt[4]{\frac{1}{4}c_n\{6\}}$$

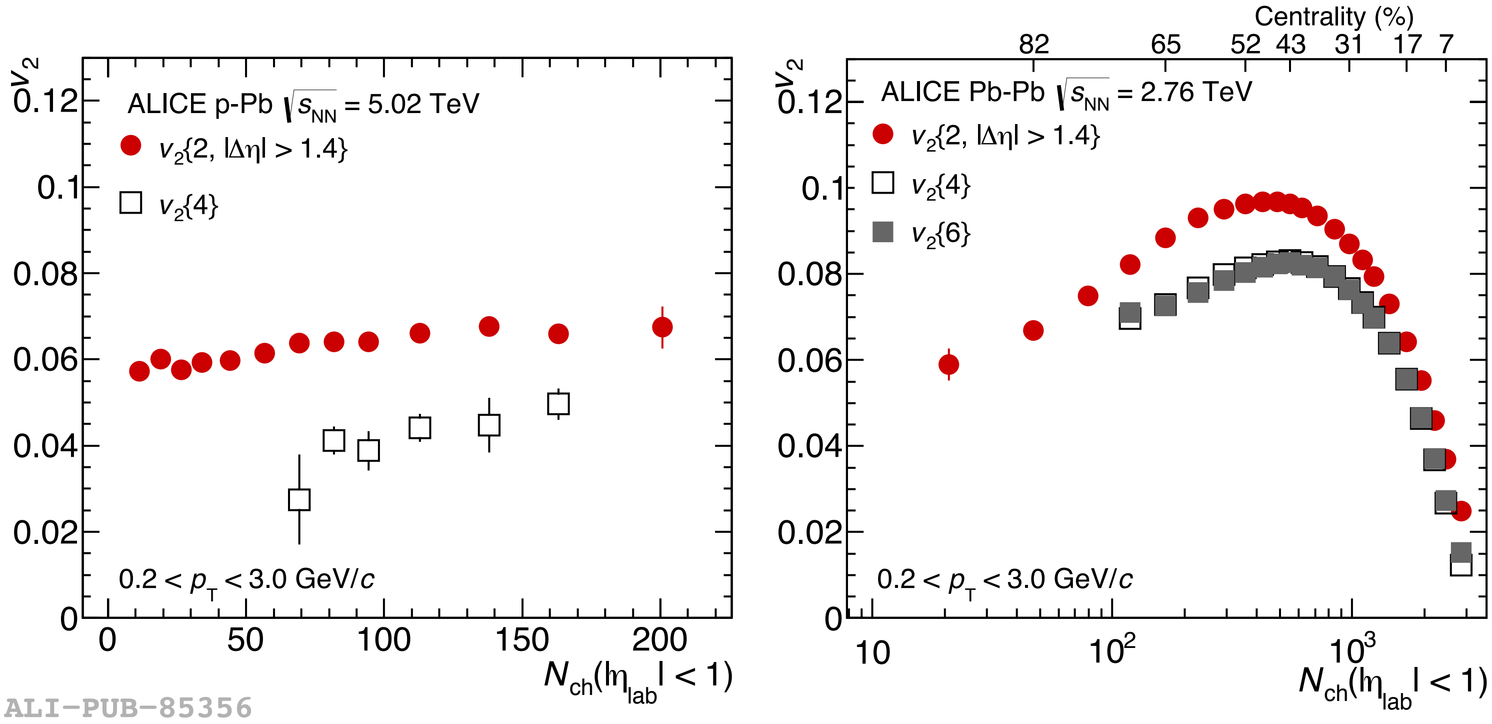
$$v_n\{8\} = \sqrt[4]{-\frac{1}{33}c_n\{8\}}$$

Insensitive to non-flow effect

Q-cumulant, PRC 83 (2011) 044913

In hydrodynamics expect: $v_2\{2\}>v_2\{4\}\approx v_2\{6\}\approx v_2\{8\}\approx v_2\{\infty\}$

Azimuthal anisotropy with multi-particle correlations

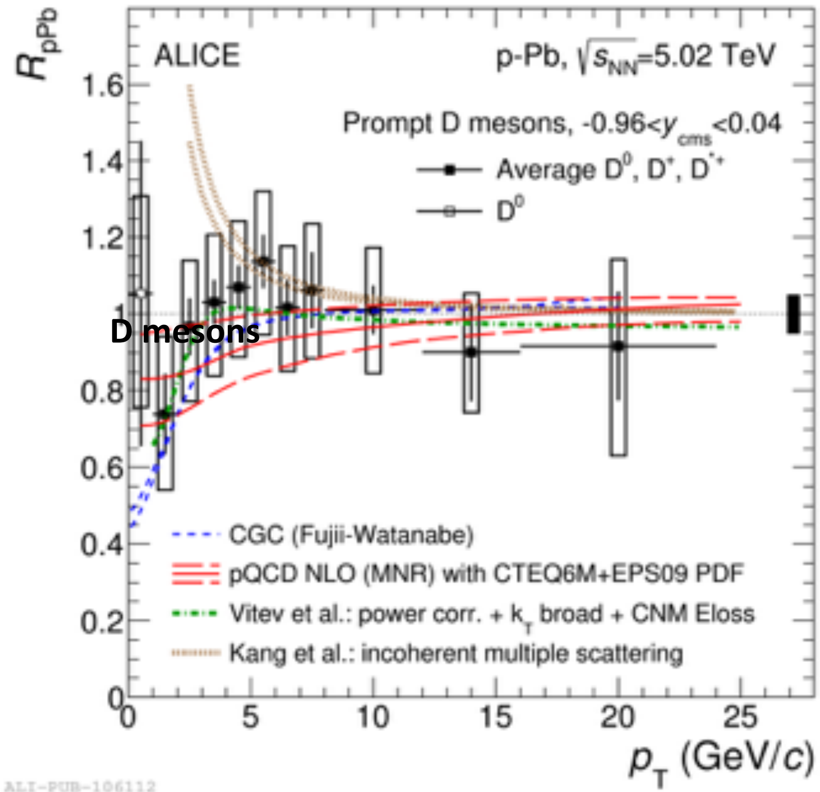


$v_2\{4\} > 0$ → support collective nature of correlations

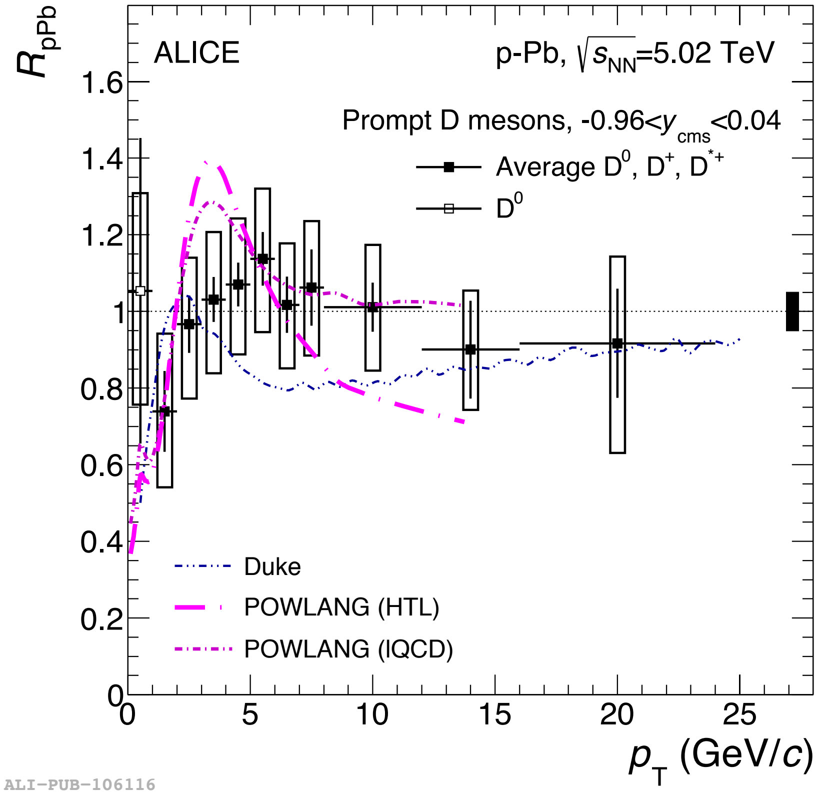
Phys. Rev. C 90, 054901 (2014)

The high energy regime: open heavy-flavour

arXiv:1605.07569



ALI-PUB-106112

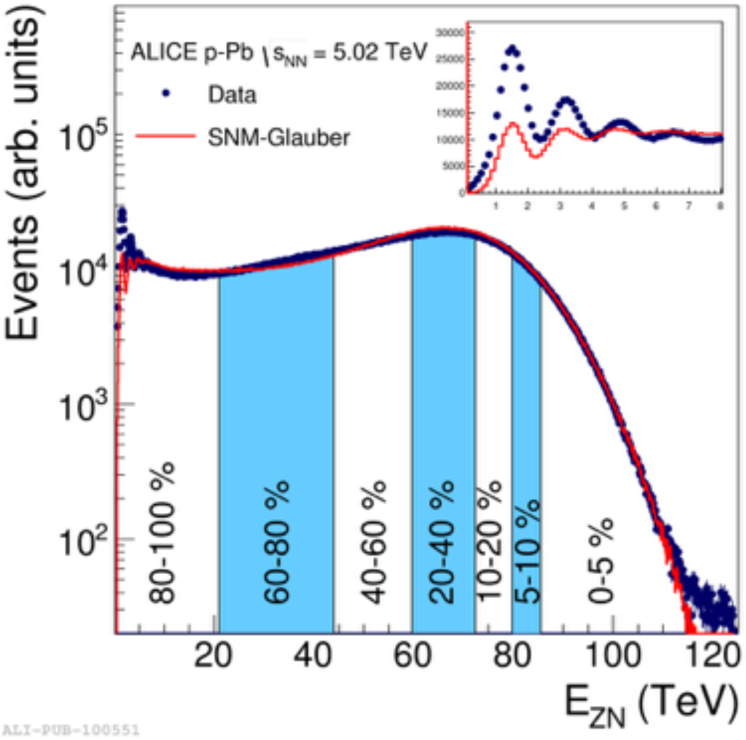


ALI-PUB-106116

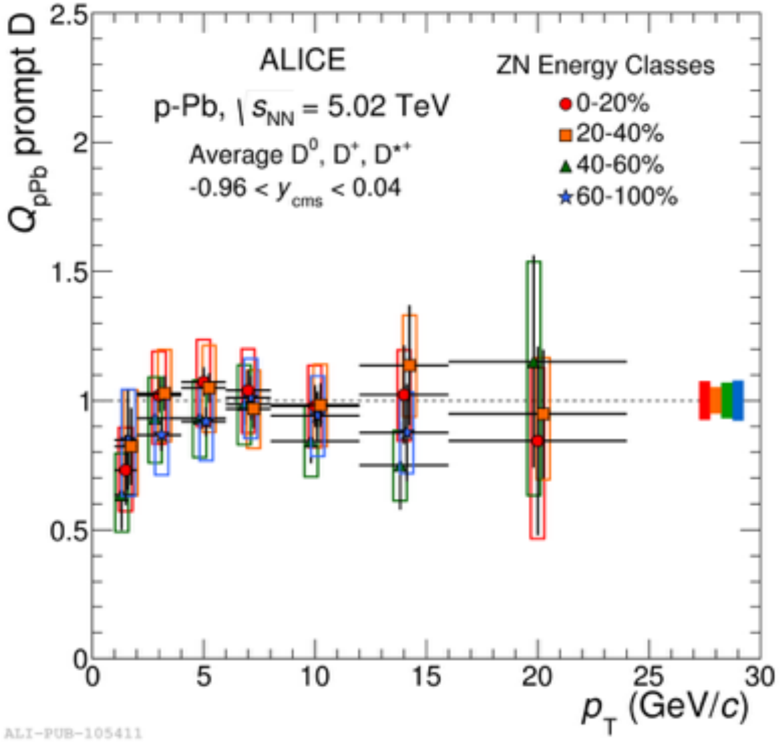
Also models which assume the formation of a small-size QGP can reproduced the D-meson data within uncertainties

D-meson in p-Pb vs. centrality: Q_{pPb}

Centrality estimated on the basis of the energy deposited in the neutron ZDC in the Pb-going direction



JHEP 08 (2016) 1

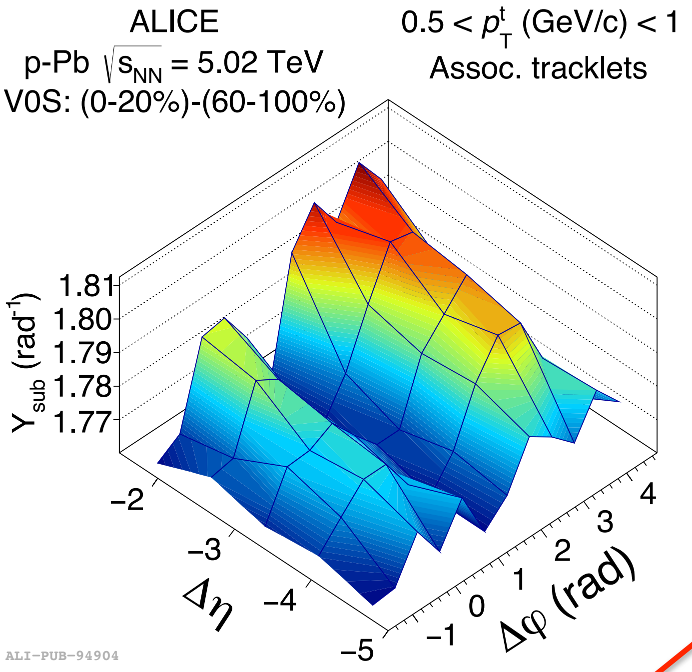


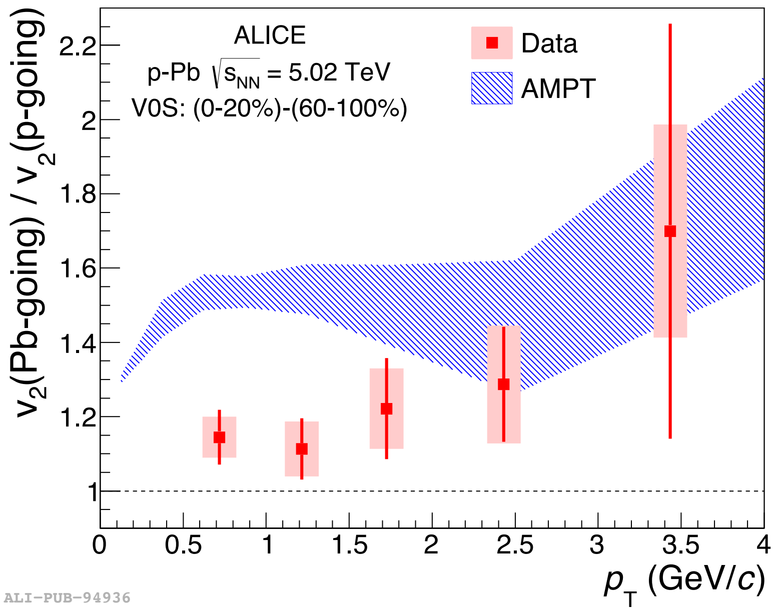
No centrality dependence observed within uncertainties

Double-ridge in p-Pb, a further look

μ-tracklet correlations with large Δη

Phys. Lett. B 753 (2016) 126-139





v_2 (Pb-going)/v_2(p-going)>1 ~independent of p_T

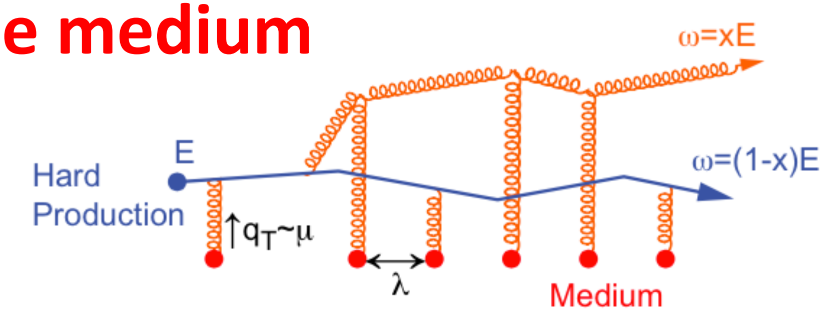
HF decay muons dominate for p_T>2 GeV/c. Suggests that:

- v_2>0 for HF decay muons
- Different cocktail and/or v_2 of trigger parent hadrons

QGP tomography with high-energy partons

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium

"Calibrated probes" of the medium



Study parton interaction with the medium
- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes

~ Study QCD "Bethe-Block" curve for partons in the QGP

Connection of "local" interactions with global medium properties

e.g. in BDMPS-Z formalism*, at intermediate energies

$$\langle \Delta E \rangle^{\mathrm{rad}} \propto \alpha_s C_R \hat{q} L^2$$

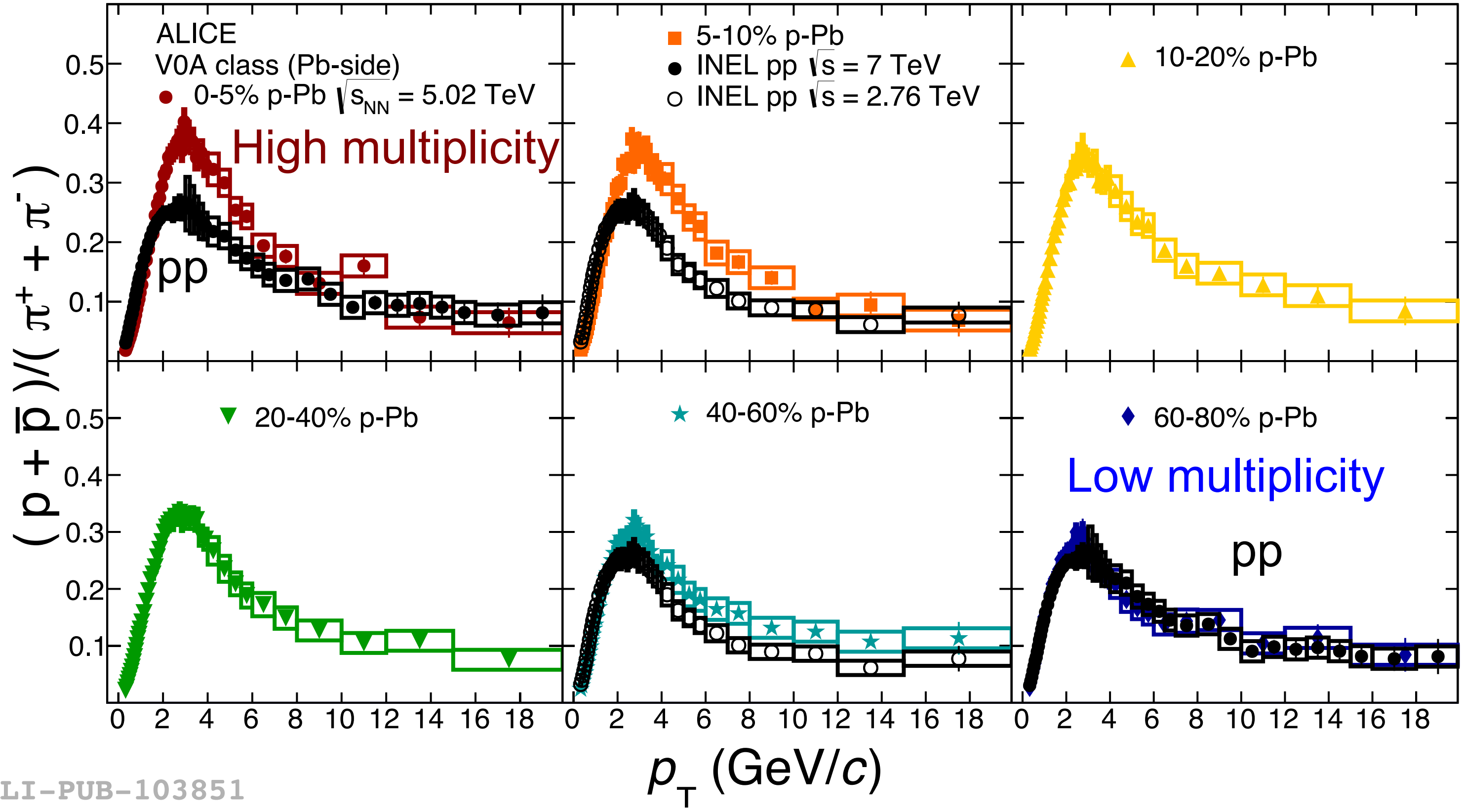
$$\hat{q} = \frac{\mu^2}{\lambda} = \mu^2 \rho \sigma$$

Transport coefficient(s)

*Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.

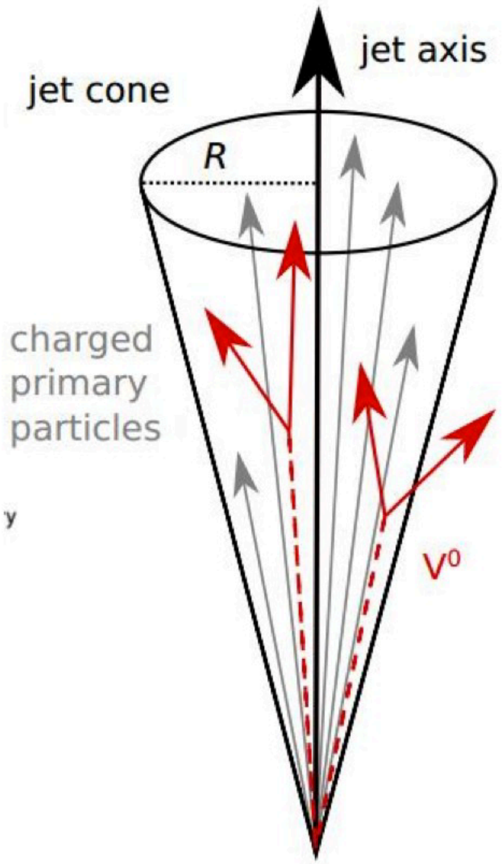
Baryon-over-meson enhancement

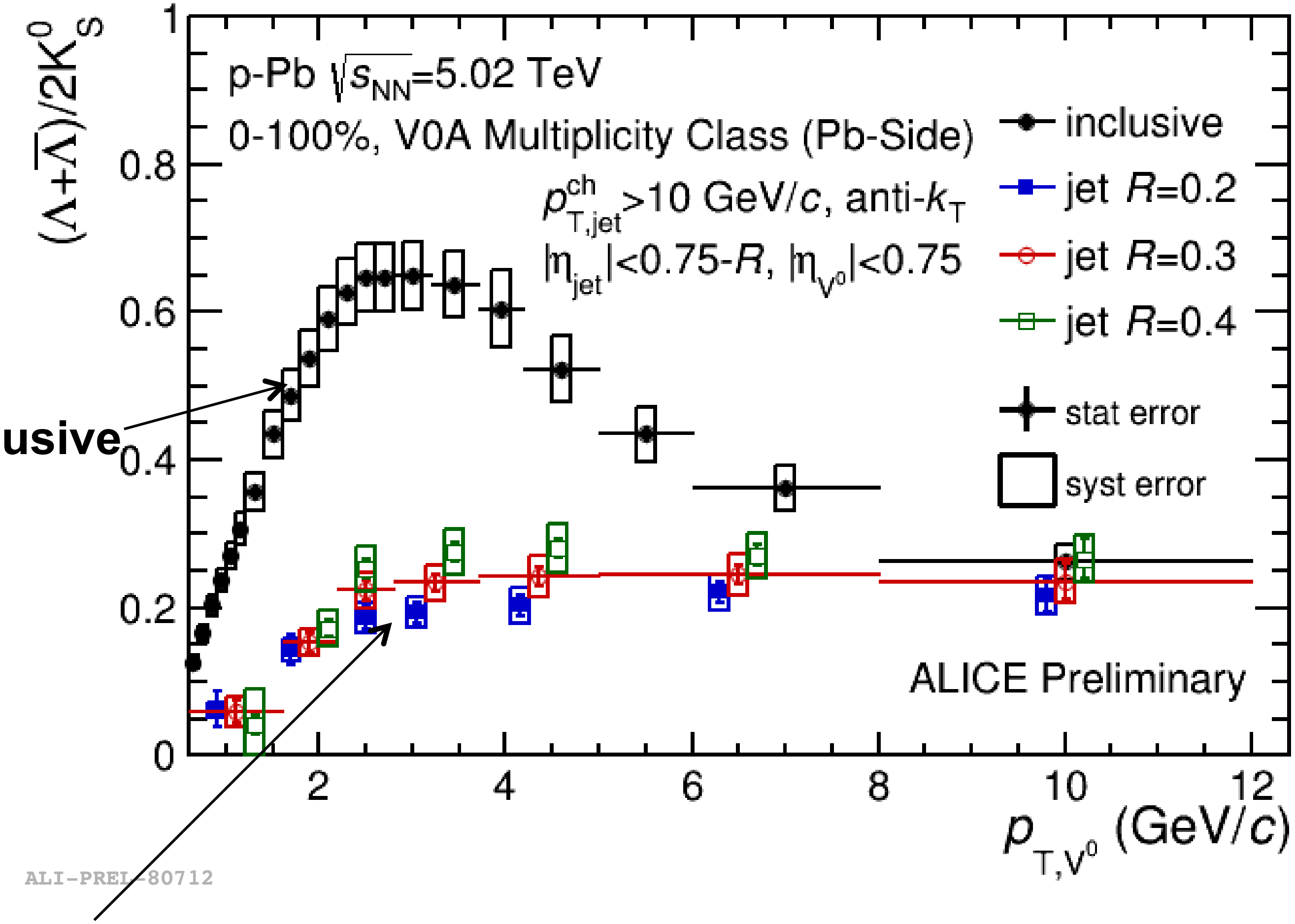
Phys. Lett. B 760 (2016) 720



High p_T unaffected

Baryon-over-meson enhancement … not in jets



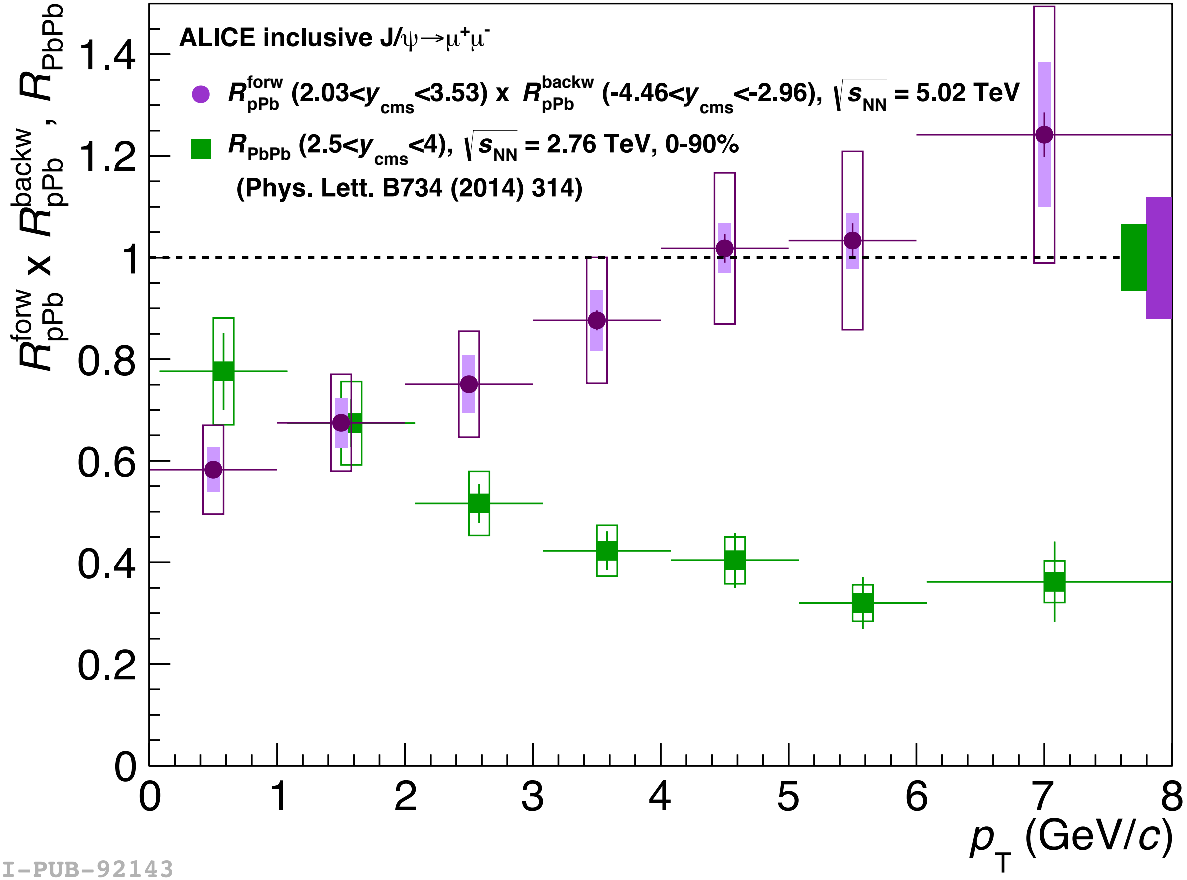


Inclusive

Inside jets

→ **Baryon-over-meson enhancement is a “bulk” effect**

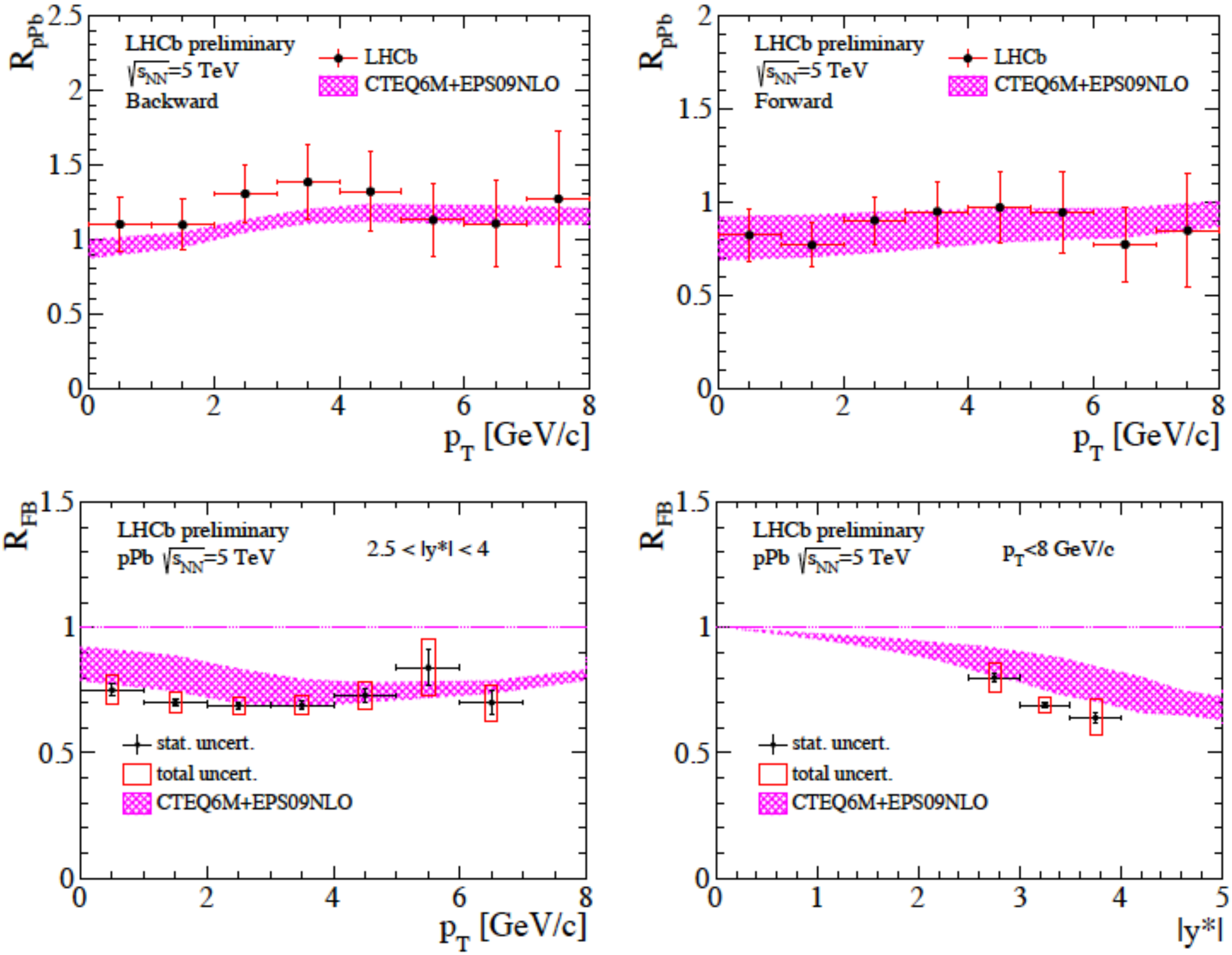
J/ψ R_{pPb} vs. R_{AA}



R_{pPb} x R_{Pbp} → Estimate of CNM effects in Pb-Pb based on p-Pb and Pb-p nuclear modification factors

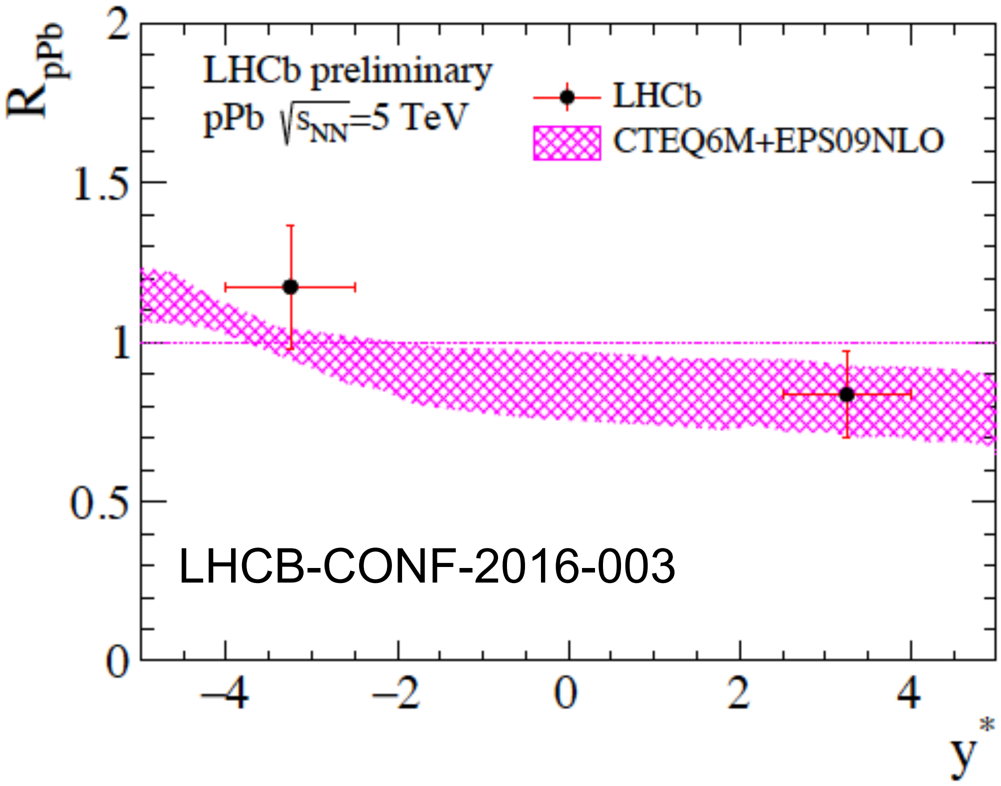
Consistent with picture of J/ψ suppression from Debye screening + recombination at low p_T

Open charm in p-Pb: LHCb

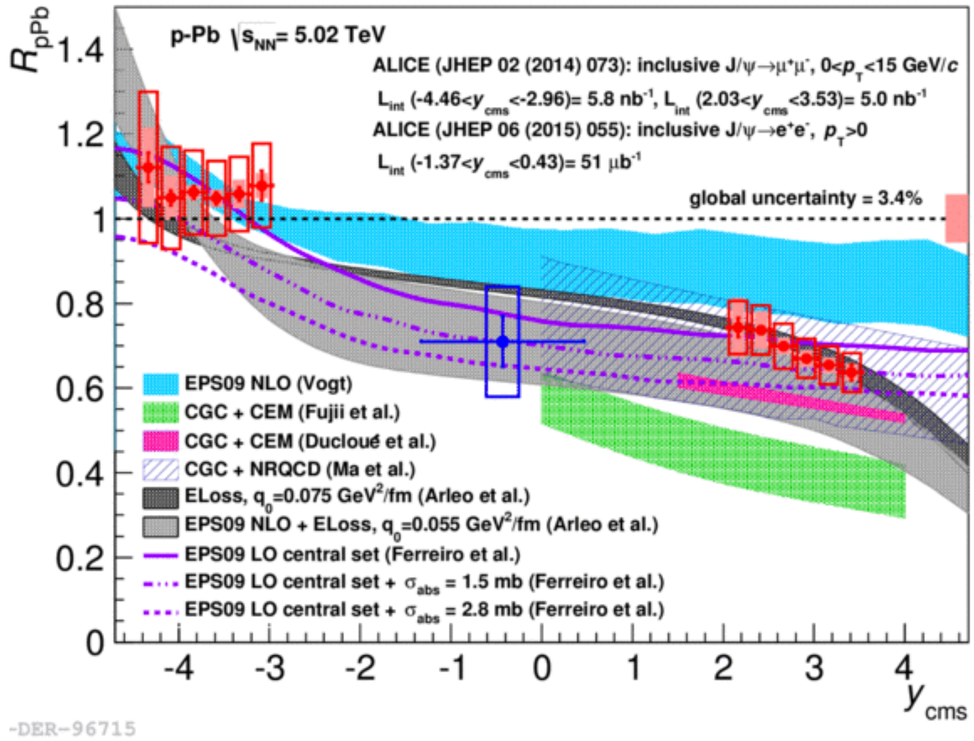


LHCB-CONF-2016-003

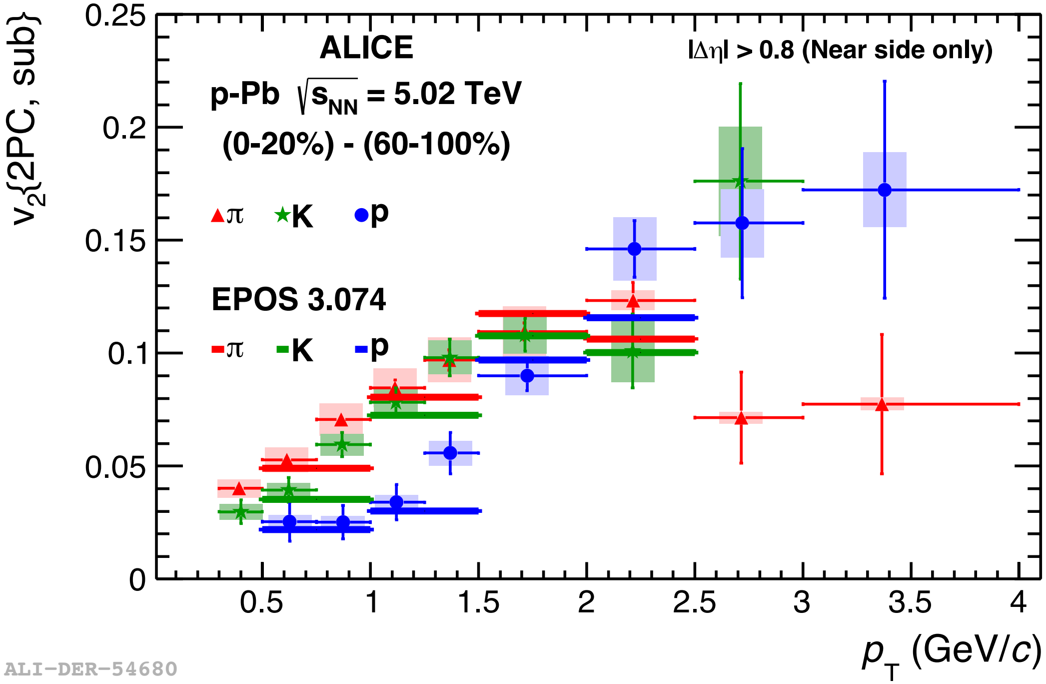
Open and hidden charm side-by-side

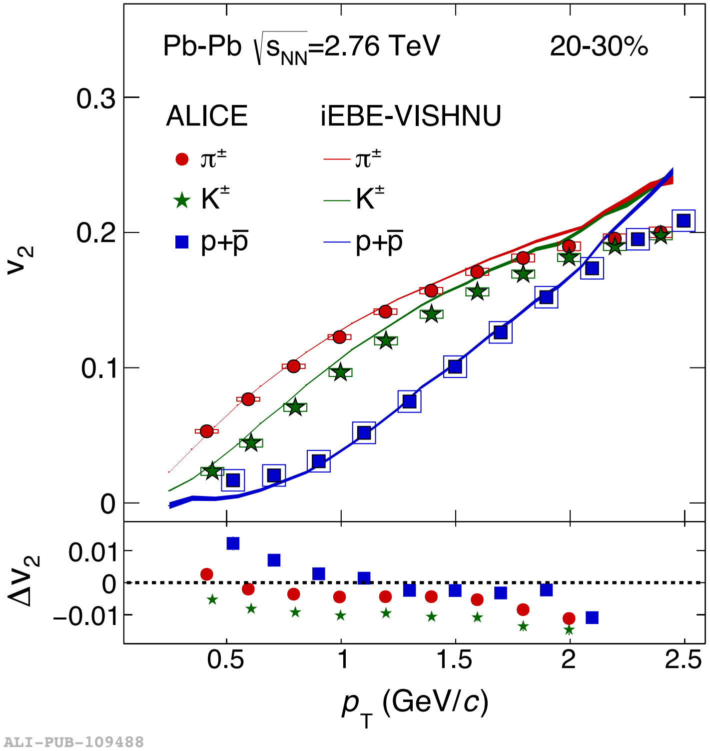


LHCB-CONF-2016-003



Azimuthal anisotropy (Elliptic flow)





Large v_2 values!

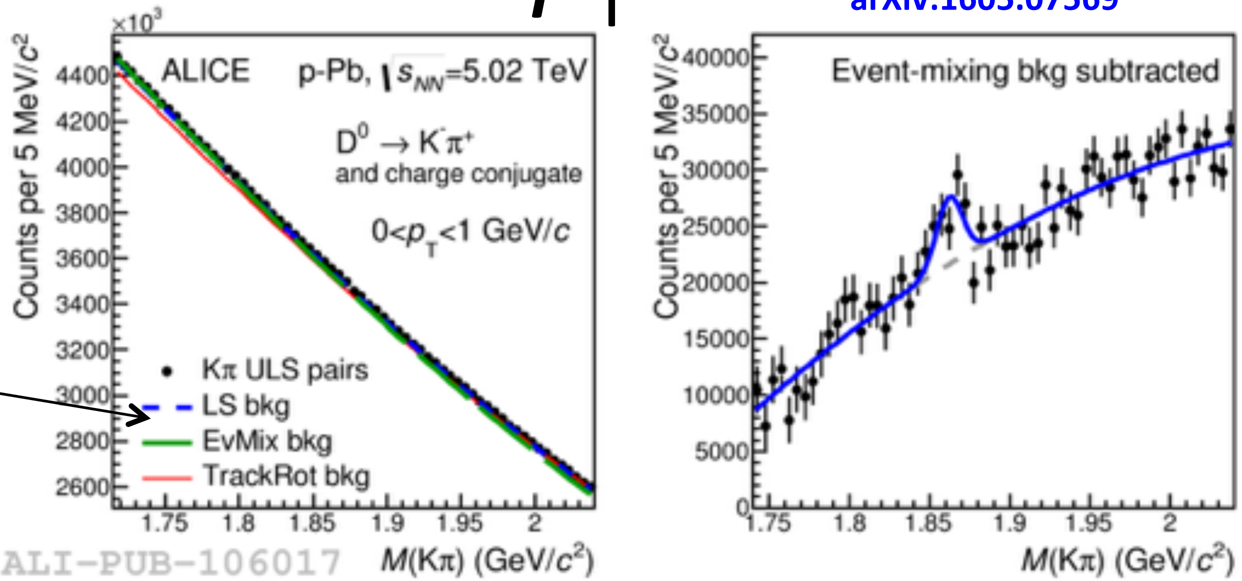
Mass ordering and "crossing" similar to Pb-Pb, where data are reproduced by hydrodynimical models

More details on expectations from models →Salvo Plumari (this afternoon)

D mesons down to p_T=0

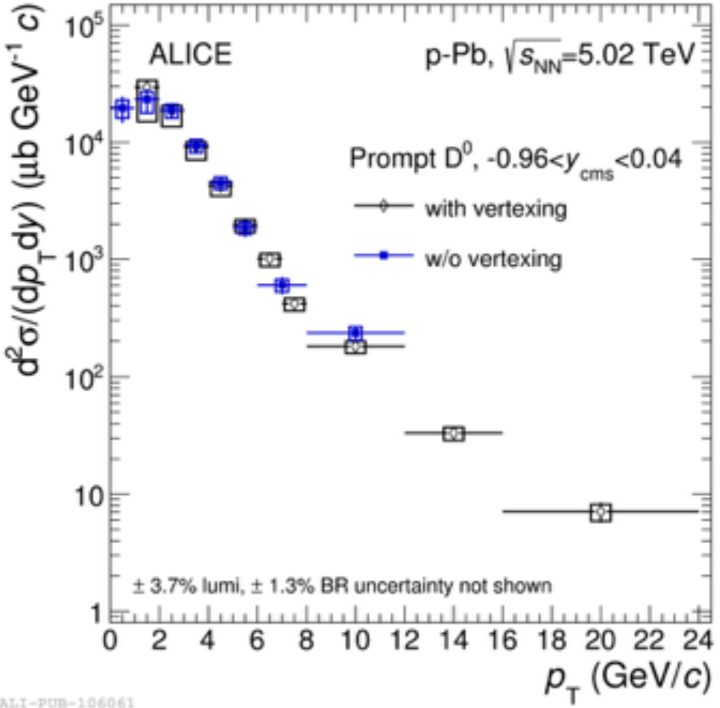
arXiv:1605.07569

- Effectiveness of standard analysis based on decay vertex reconstruction reduces for p_T<2 GeV/*c* (no boost)
- Alternative approach based on PID only
- Careful background subtraction with 4 different approaches

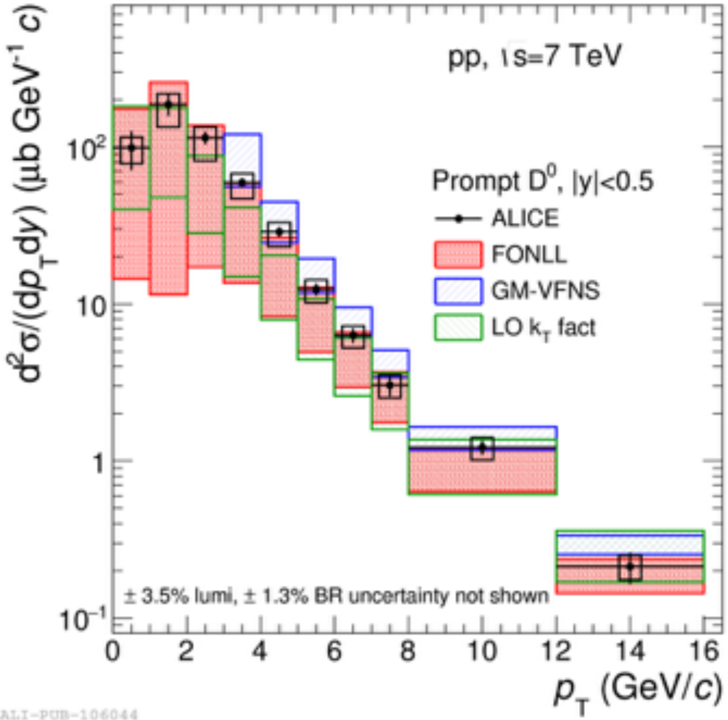


ALI-PUB-106017

- Compatible results w/ and w/o vertex reconstruction for p_T>1 GeV/*c*
- Better performance w/o vertex reconstruction for p_T<2 GeV/*c*
- pQCD-based theoretical calculations reproduce the data
- Data much more precise than theoretical calculations

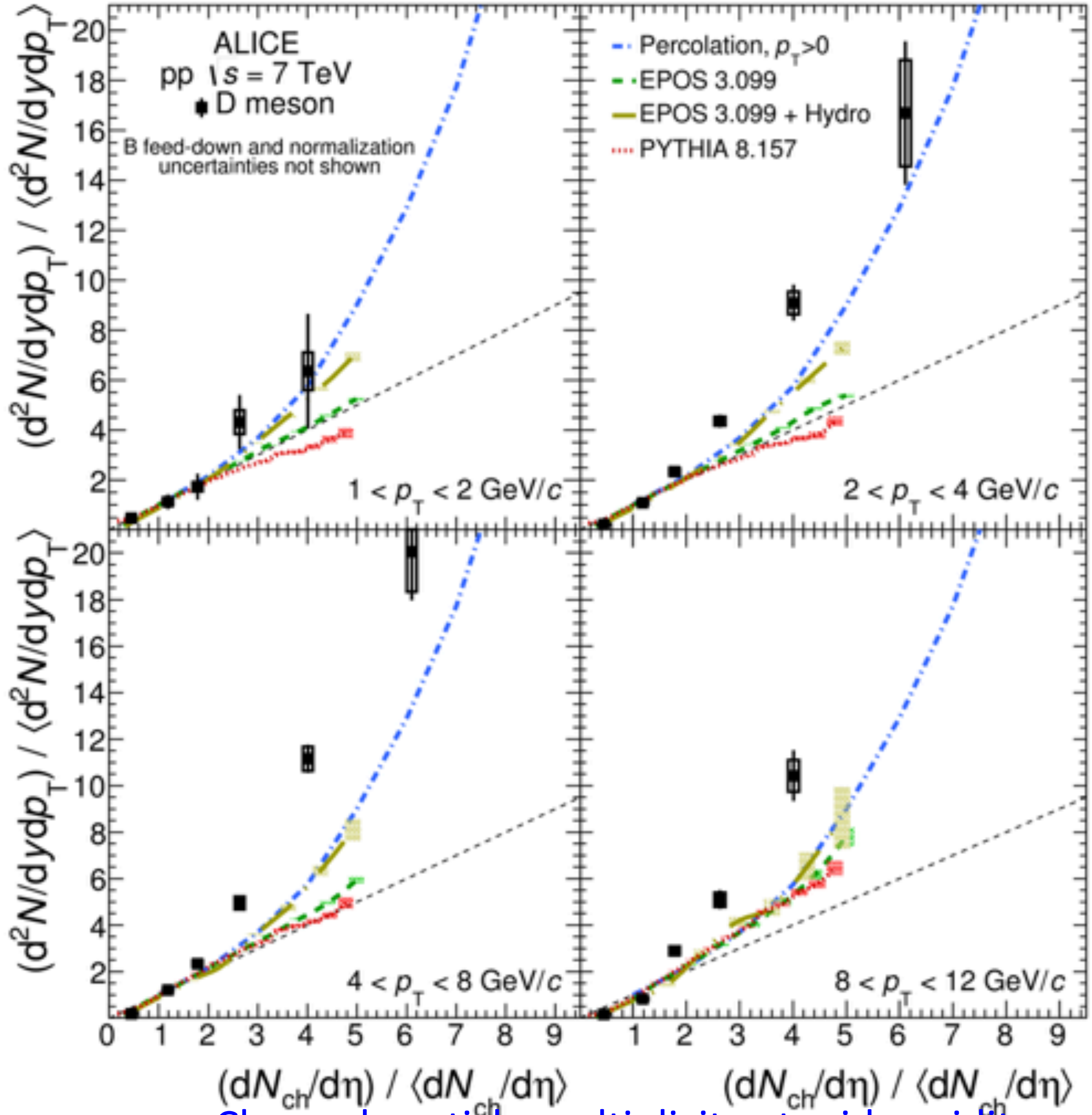


ALI-PUB-106061



ALI-PUB-106044

D-meson yields vs. multiplicity: comparison with models (pp)



Charged-particle multiplicity at mid-rapidity

JHEP 09 (2015) 148

Percolation **(Ferreiro, Pajares, PRC 86 (2012) 034903**

Particle production via exchange of colour sources between projectile and target (close to MPI scenario)

- Faster than linear increase

EPOS 3.099 **(Werner et al., PRC 89 (2014) 064903)**

Gribov-Regge multiple-scattering formalism
Saturation scale to model non-linear effects
Number of MPI directly related to multiplicity → slightly faster than linear
With hydrodynamical evolution applied to the core of the collision → faster than linear increase

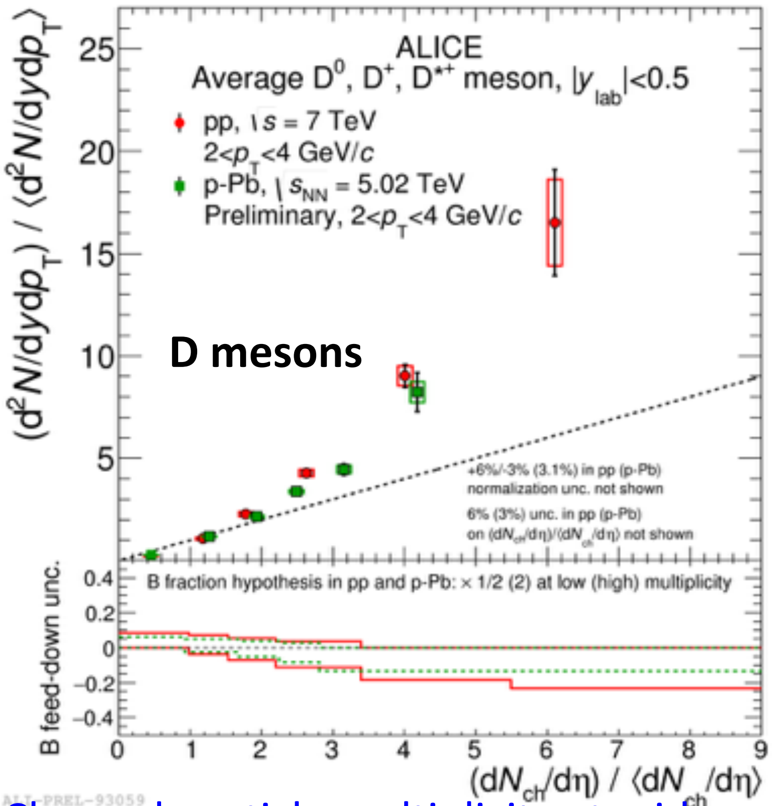
PYTHIA 8 **(Sjostrand et al., Comput. Phys. Commun. 178 (2008) 852)**

Soft-QCD tune
Colour reconnection
MPI

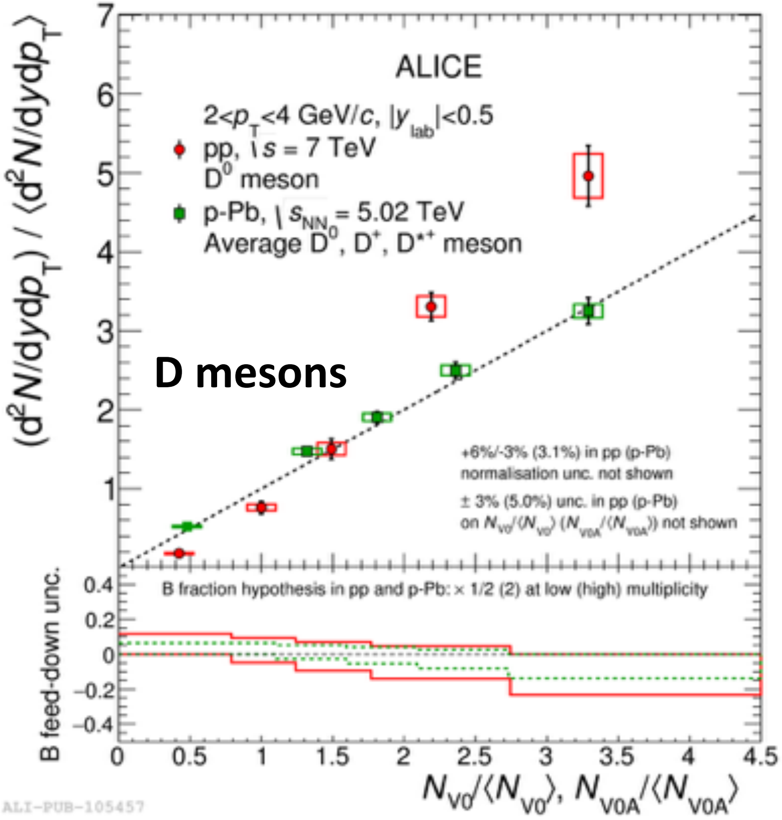
- Linear increase

D-meson yields vs. multiplicity in pp and p-Pb collisions

JHEP 09 (2015) 148
JHEP 08 (2016) 1



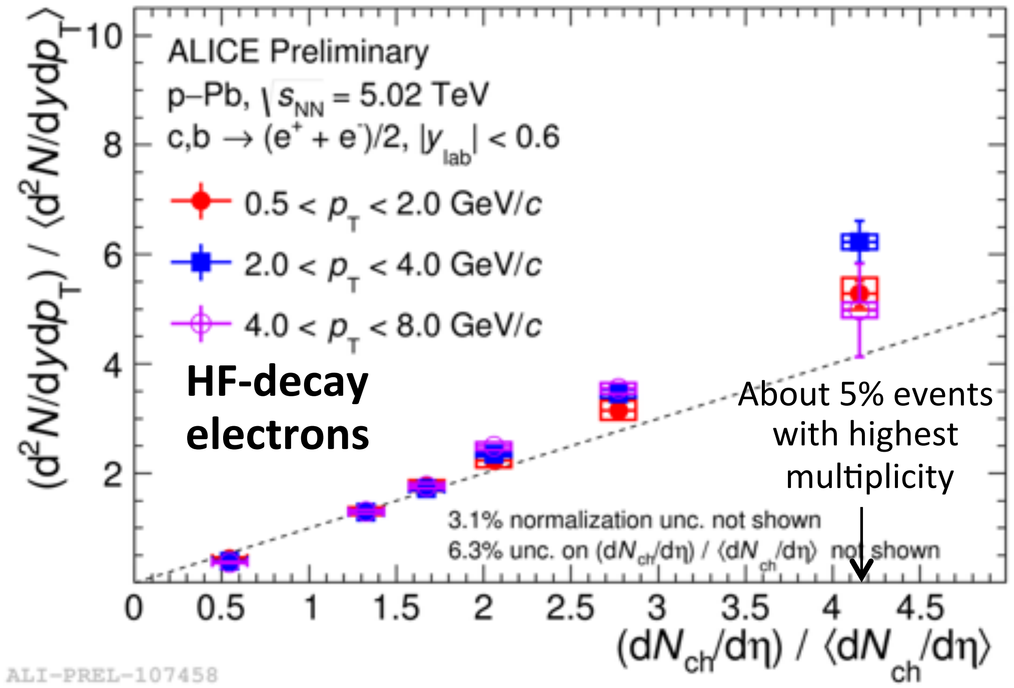
Charged-particle multiplicity at mid-rapidity



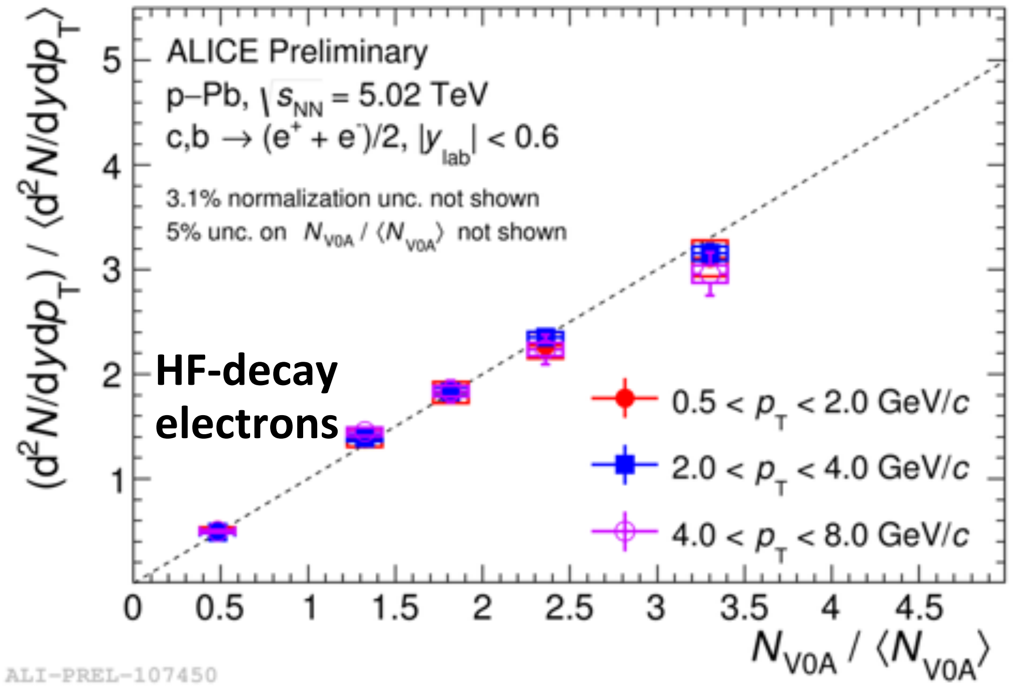
Charged-particle multiplicity at backward rapidity (Pb direction)

p-Pb: interplay of collision geometry (N_{coll}>1) and MPI, difficult to disentangle the two contributions
With event activity estimated at mid-rapidity (same region of D mesons): similar faster-than-linear increase in pp and p-Pb collisions
With event activity estimated at backward rapidity (|Δη|>1.9): faster increase in pp than in p-Pb

Heavy-flavour hadron decay electron yields vs. multiplicity in p-Pb collisions



Charged-particle multiplicity at mid-rapidity



Charged-particle multiplicity at backward rapidity (Pb direction)

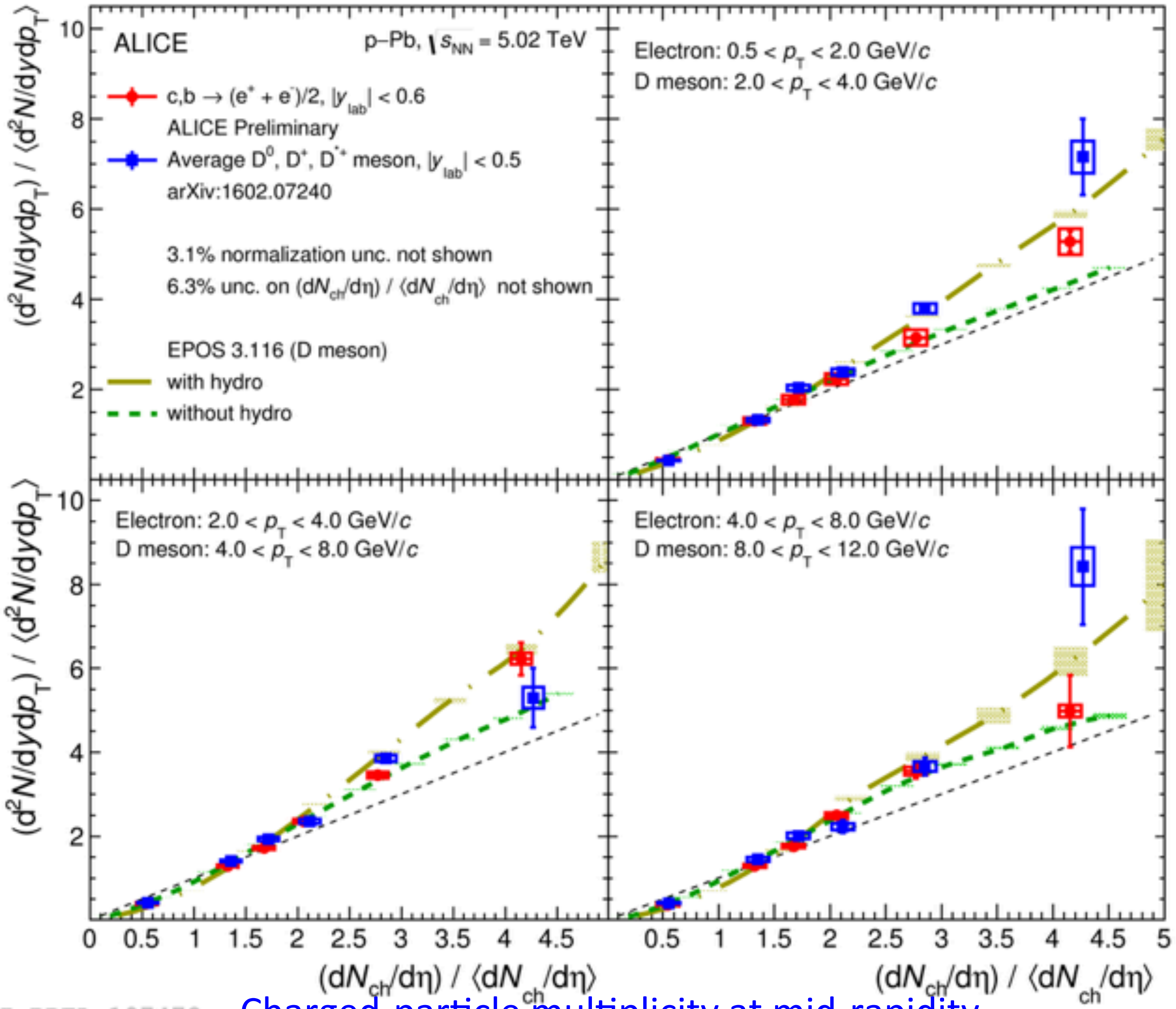
p-Pb: interplay of collision geometry (N_{coll}>1) and MPI, difficult to disentangle the two contributions

With event activity estimated at mid-rapidity (same region than HF-decay electrons): faster-than-linear increase

With event activity estimated at backward rapidity (|Δη|>1.9): ~ linear increase

No change for p_T>4 GeV/*c* where b→e^- contribution becomes larger than 50%

D-meson and HF-decay yields vs. multiplicity: comparison with models (p-Pb)



Charged-particle multiplicity at mid-rapidity

Momentum ranges compared are chosen to better match the electron parent-hadron momentum with the D-meson momentum range.

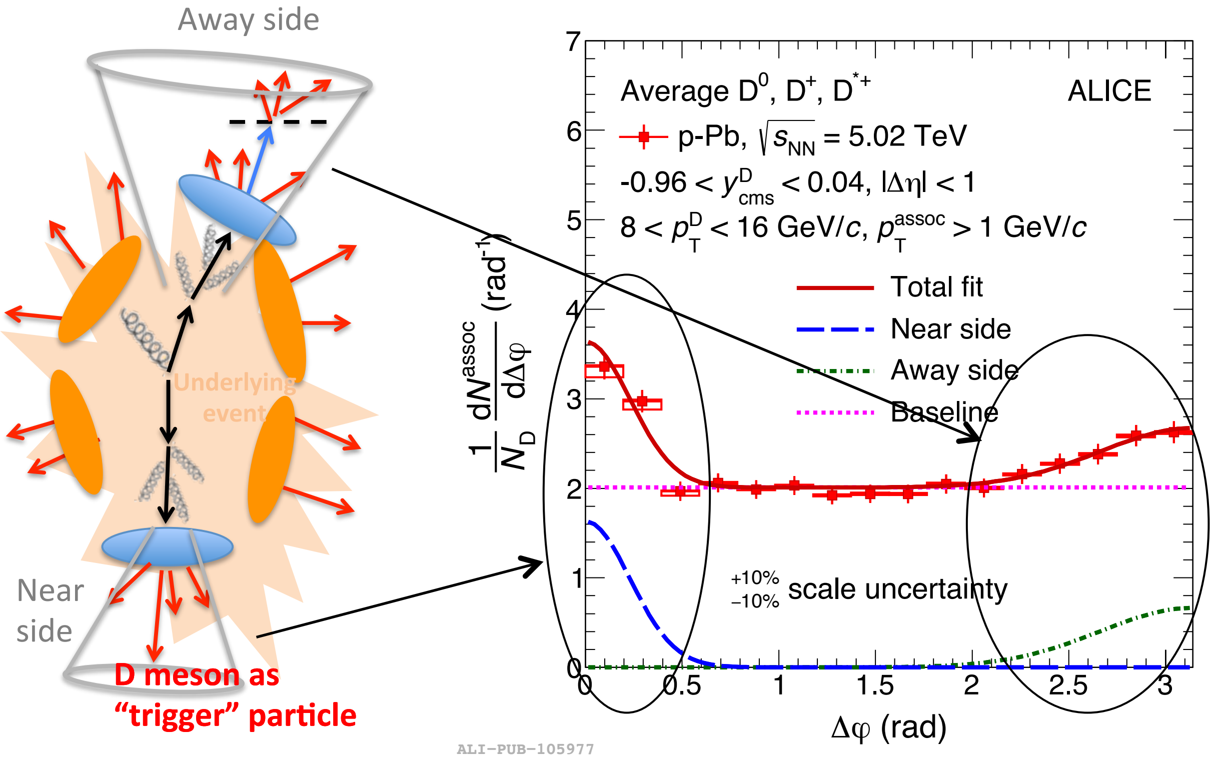
D meson and HF-decay electrons self-normalized yields compatible within uncertainties

EPOS 3.116

(Werner et al., PRC 89 (2014) 064903)

- Calculation for D mesons
- Initial conditions and hydrodynamical evolution
- Hint that D mesons are better reproduced by simulation with hydro

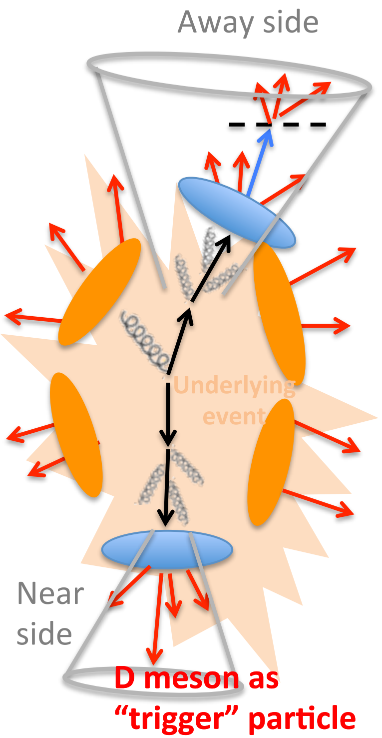
Azimuthal correlations of D mesons with charged particles

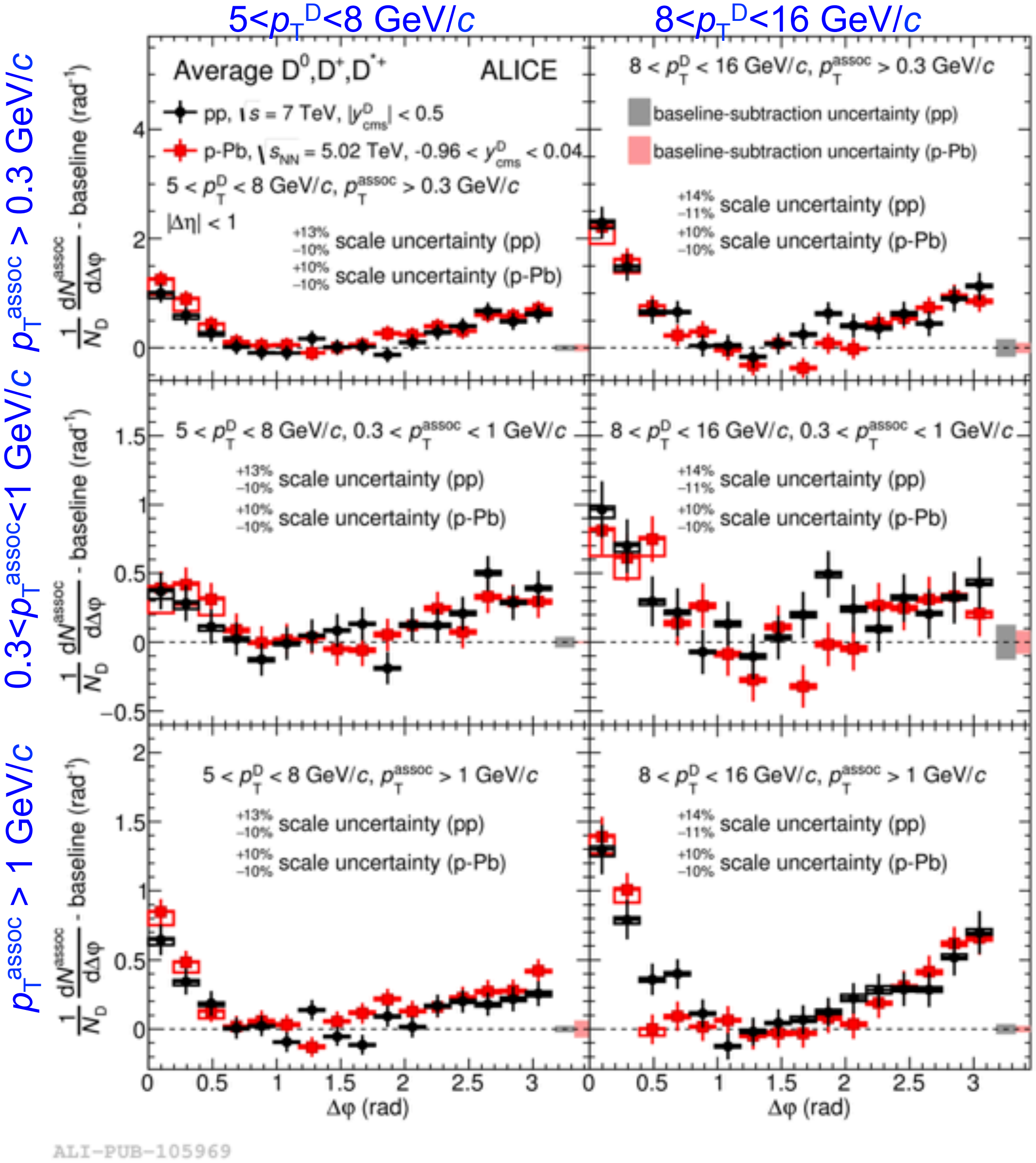


arXiv:1605:06963

Near-side peak properties (width, "associated yield") → address charm jet properties

Azimuthal correlations of D mesons with charged particles: pp vs. p-Pb





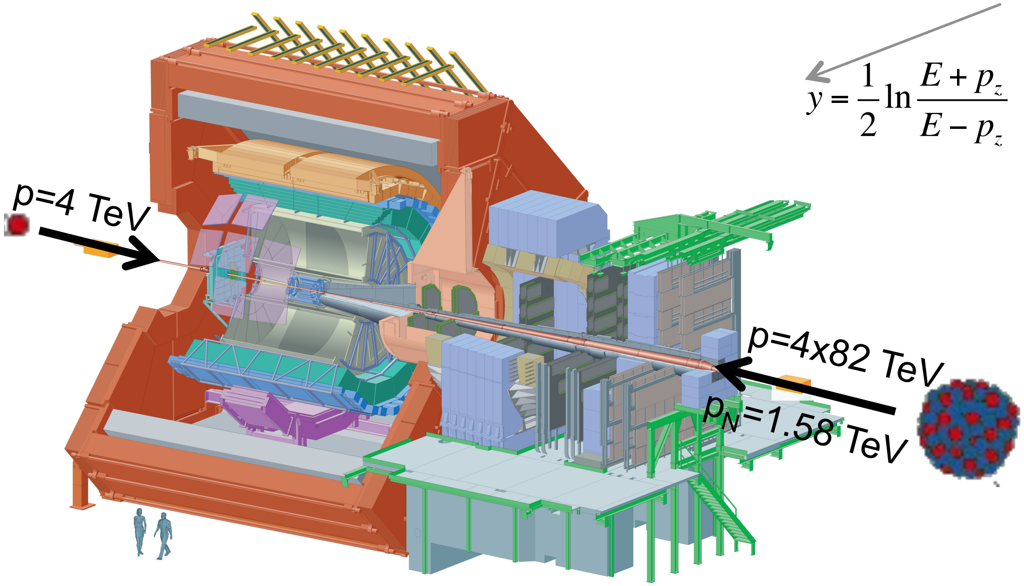
pp and p-Pb results compatible within uncertainties after the subtraction of the baseline

arXiv:1605:06963

Two p-Pb beam modes

Centre of mass of the nucleon-nucleon system moves towards the p-beam direction with rapidity Δy_{NN}=0.465

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

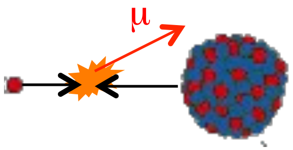


$\sqrt{s_{NN}}$= 5.02 TeV

N.B. not so relevant for measurements done at mid-rapidity

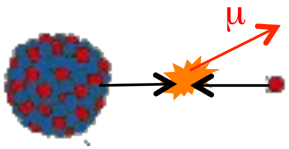
LHC operated with 2 beam modes

p-Pb, “Forward”, “p-going”



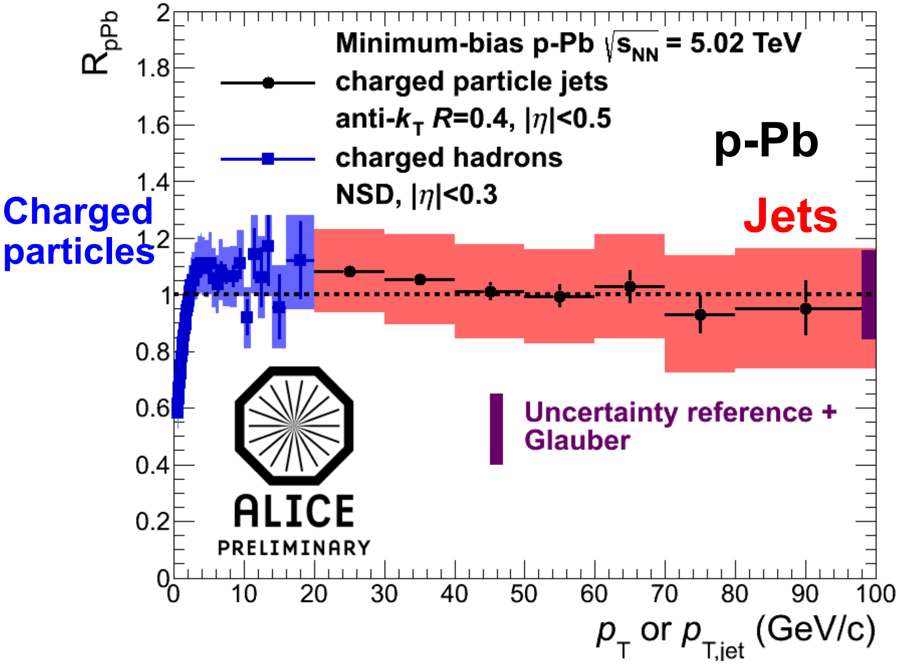
Probing low-x in Pb nucleus
Convention: positive *y* towards muon spectrometer

Pb-p, “Backward”, “Pb-going”



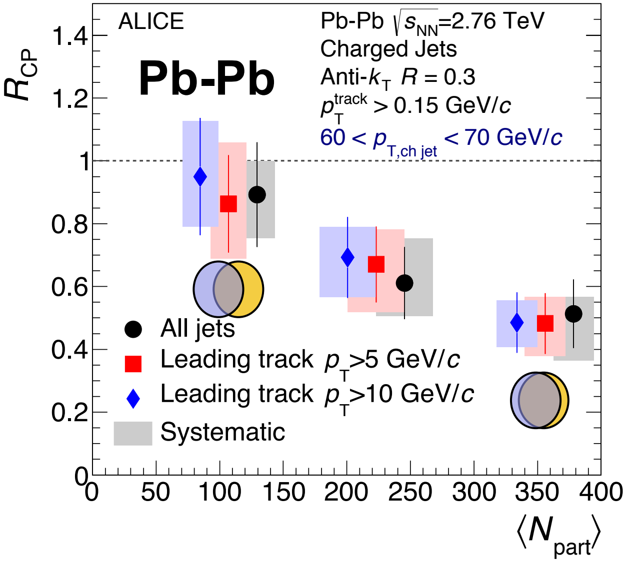
Probing large-x in Pb nucleus
Convention: negative *y* towards muon spectrometer

The high-energy regime: jets



ALI-DER-63814

“Central-to-peripheral ratio”



ALI-PUB-64299

$$R_{PbPb[pPb]}(p_T) = \frac{dN_{PbPb[pPb]}/dp_T}{\left\langle N_{coll}^{PbPb[pPb]} \right\rangle \times dN_{pp}/dp_T}$$

Jets R_{pPb} compatible with unity from p_T larger than ~1 GeV/c

→ Confirms that suppression of intermediate/ high p_T particles in central Pb-Pb collisions is a final-state effect

→ Evidence of in-medium partonic energy loss
→ Information on spatial distribution of radiated energy