Transverse momentum distributions of charged particles and identified hadrons in p-Pb collisions at the LHC

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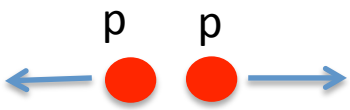
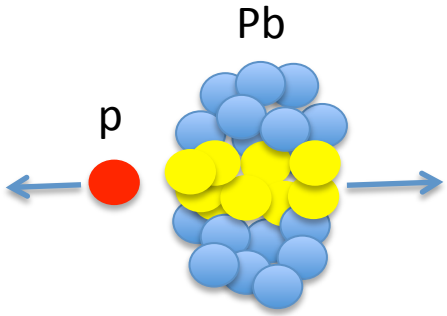
Particle production in pp, p-Pb and Pb-Pb

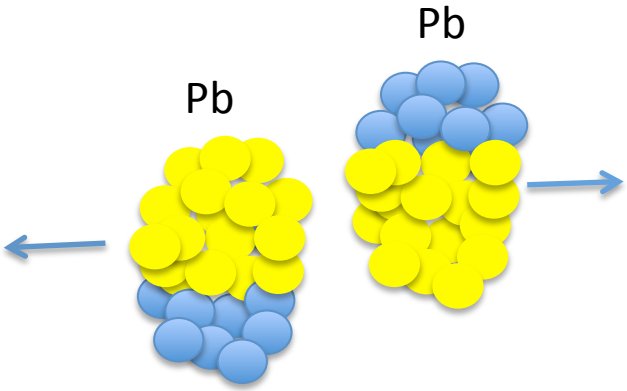
Several physics phenomena can be studied with light-flavor hadrons



Soft QCD and pQCD + fragmentation in vacuum. Reference for p-Pb and Pb-Pb.



Initial state effects (shadowing/gluon saturation). Reference for Pb-Pb.

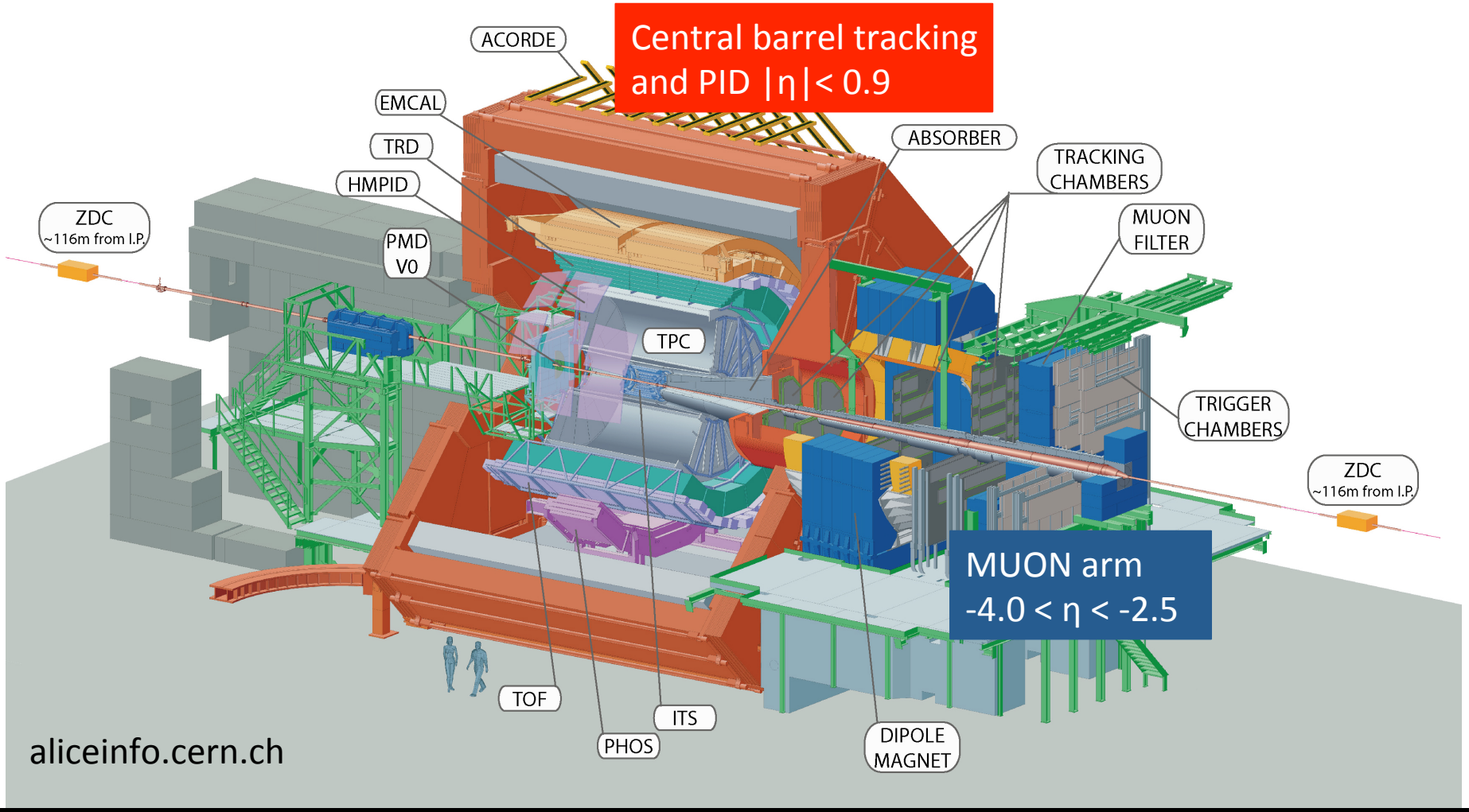


Thermal production, flow, recombination, jet quenching and fragmentation in the quark-gluon plasma (QGP).

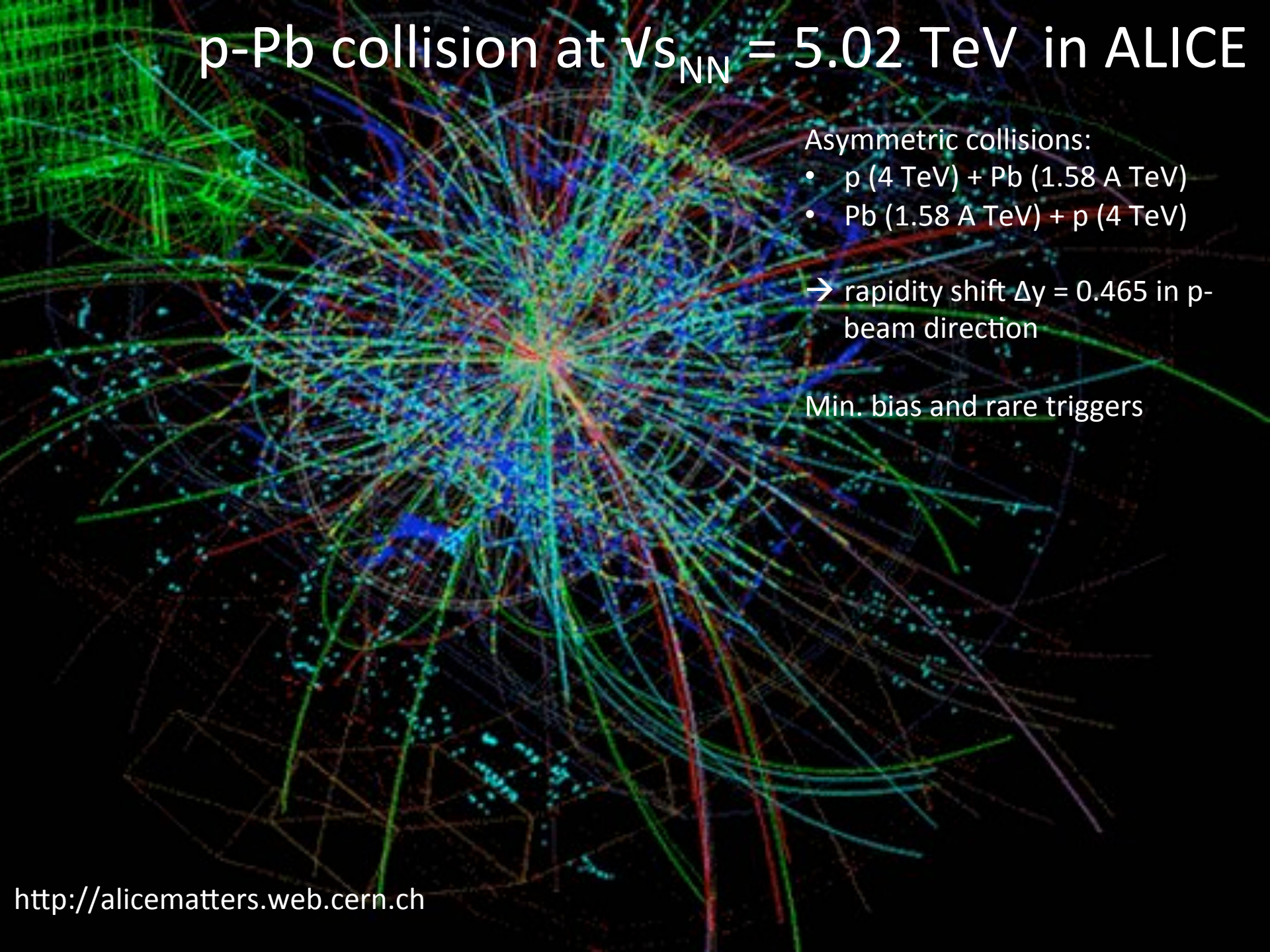
Surprising results in high multiplicity p-Pb collisions (ridge, flow like):
CMS: PLB 718 (2013) 795
ALICE: PLB 719 (2013) 29, PLB 726 (2013) 164
ATLAS: PRL 110 (2013) 182302

A Large Ion Collider Experiment

- Excellent particle identification capabilities in a large p_T range 0.1-20 GeV/c
- Good momentum resolution ~1-5% at p_T = 0.1-50 GeV/c



p-Pb collision at $\sqrt{s_{NN}}$ = 5.02 TeV in ALICE



Asymmetric collisions:

- p (4 TeV) + Pb (1.58 A TeV)
- Pb (1.58 A TeV) + p (4 TeV)

→ rapidity shift $\Delta y = 0.465$ in p-beam direction

Min. bias and rare triggers

http://alicematters.web.cern.ch

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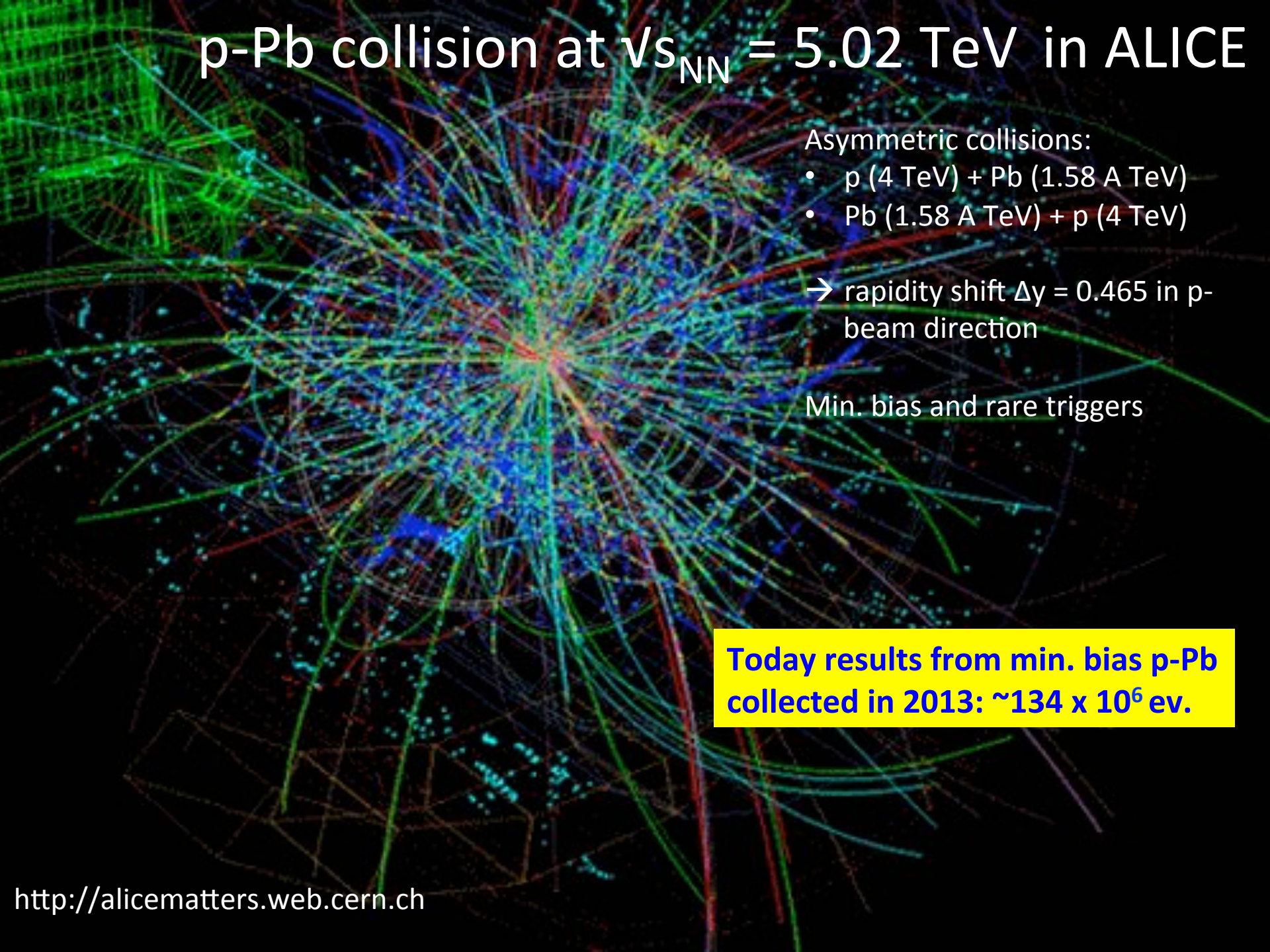

Asymmetric collisions:

- p (4 TeV) + Pb (1.58 A TeV)
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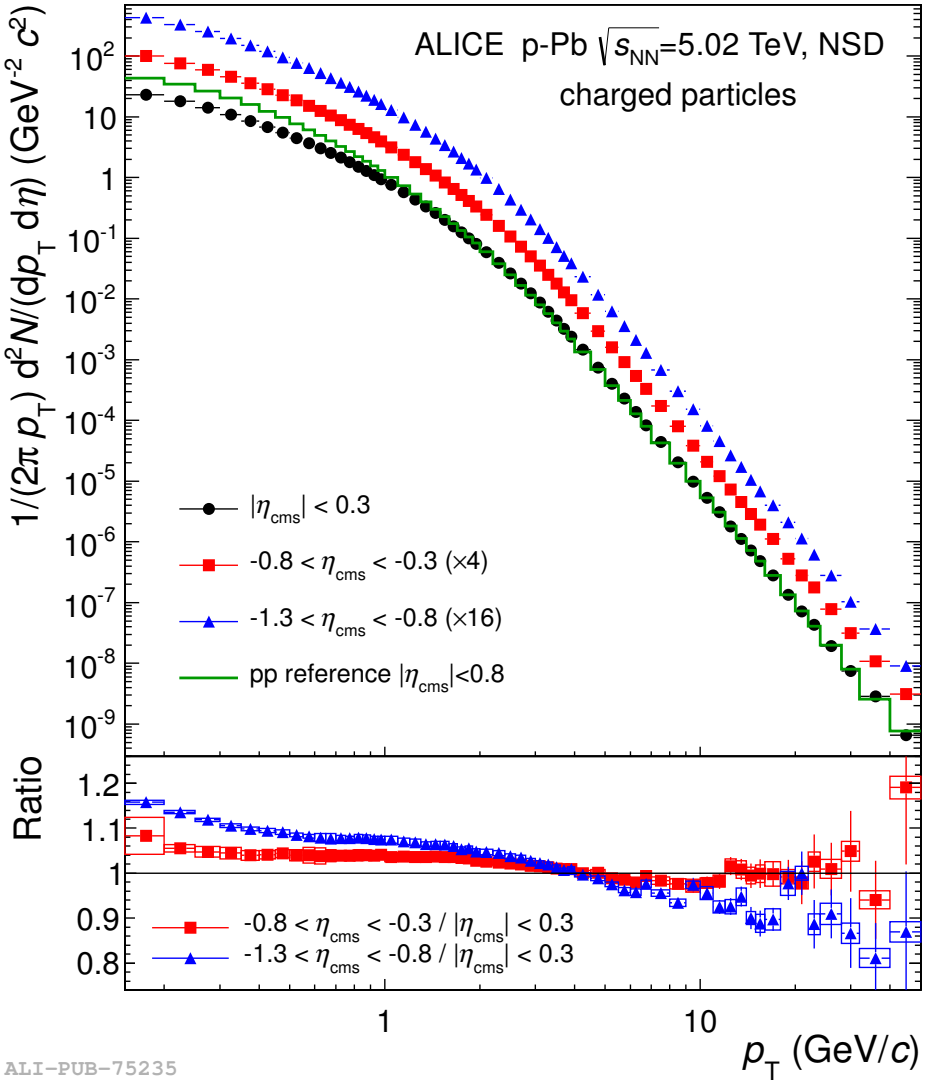
Min. bias and rare triggers

Today results from min. bias p-Pb collected in 2013: ~134 x 10^6 ev.

http://alicematters.web.cern.ch

Charged particle p_T spectra in p-Pb



p-Pb min. bias, non-single diffractive (NSD)

- p_T range: 0.15 – 50 GeV/c
- 3 pseudorapidity ranges

- $\eta_{cms} = \eta - 0.465$ using Jacobian ($dy/d\eta$) with measured identified hadrons (π, K, p) by ALICE

- pp reference at $\sqrt{s_{NN}}$ = 5.02 TeV constructed from pp at 2.76 and 7 TeV (no pp measurement available at this energy)

ALICE, arXiv:1405.2737

Nuclear modification factors

$$R_{pPb} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb}/dp_T}{dN_{pp}/dp_T}$$

$$\langle N_{coll} \rangle = A \cdot \frac{\sigma_{pN}}{\sigma_{pA}} = 6.9 \pm 0.6$$

σ_{pN} = 70±5 mb (interpolation)
σ_{pA} = 2.1±0.6 b (ALICE, arXiv:1405.1849)

p-Pb (minimum bias, NSD):

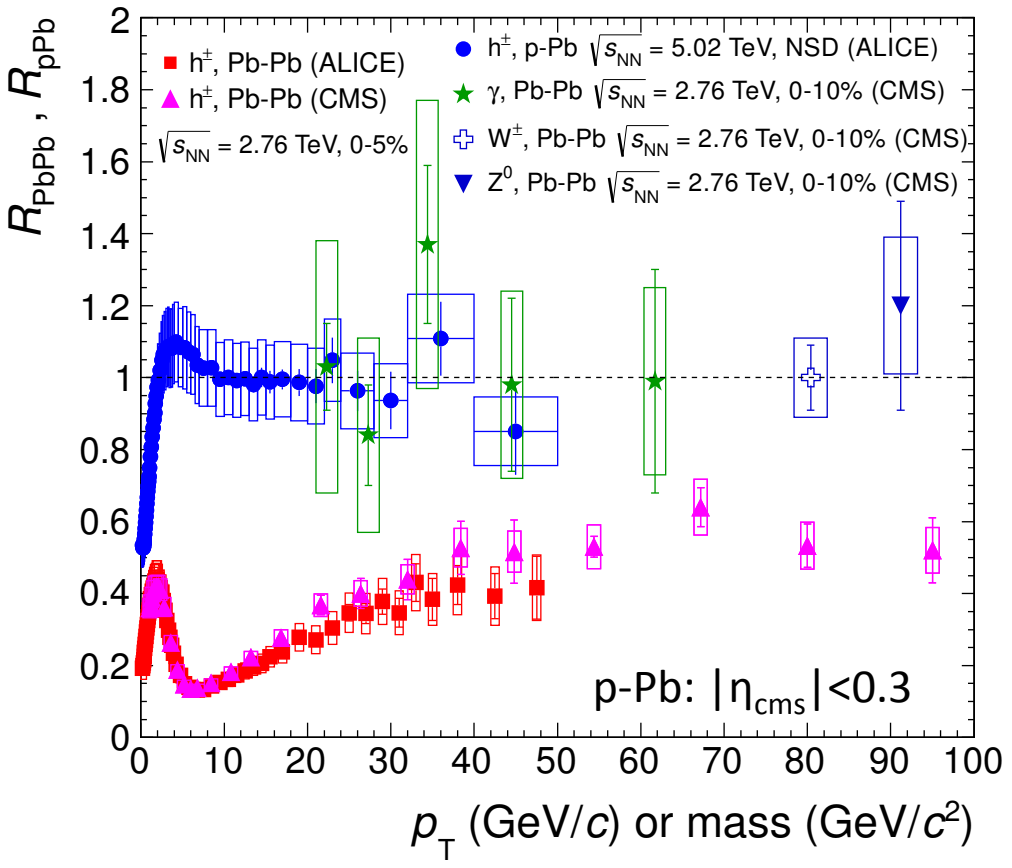
- No modification at high p_T (R_{pPb} = 1)

→ Particle suppression in Pb-Pb related to final state effects

Confirmed by jet measurements

p-Pb at central rapidity:
$x = p_{parton} / p_{Pb} \sim 10^{-2}$–$10^{-3}$

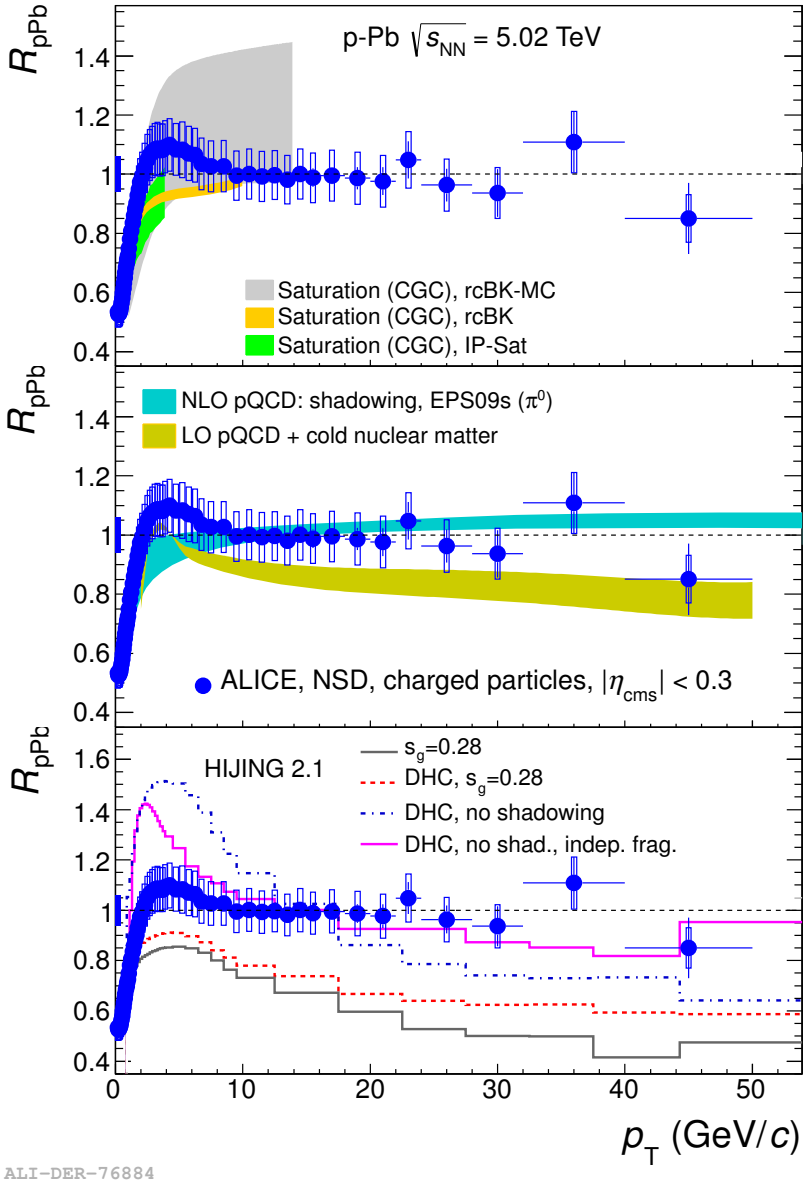
ALICE, arXiv:1405.2737



Smaller Q^2 and x

Larger Q^2 and x

R_{pPb} vs. models



ALI-DER-76884

Comparison with model predictions

- Saturation (CGC) models consistent with data (large systematic uncertainties)

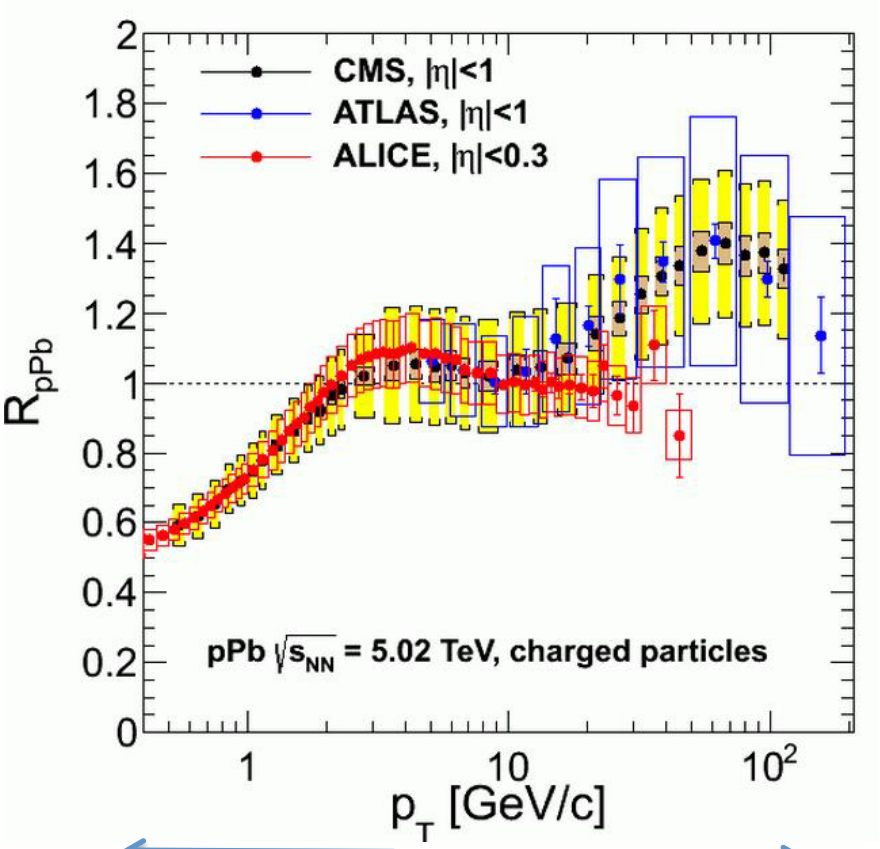
- NLO pQCD (shadowing, PDF EPS09a) for π^0 consistent with data
- LO pQCD + cold nuclear matter effects decreasing trend not confirmed by data

- HIJING 2.1 does not describe data at low p_T

ALICE, arXiv:1405.2737

R_{pPb} at very high p_T

- Surprising enhancement at very high-p_T measured by CMS and ATLAS
- ALICE data shows different trend – difference mostly in pp reference



→ Necessity to measure pp reference at $\sqrt{s_{NN}}$ = 5.02 TeV!

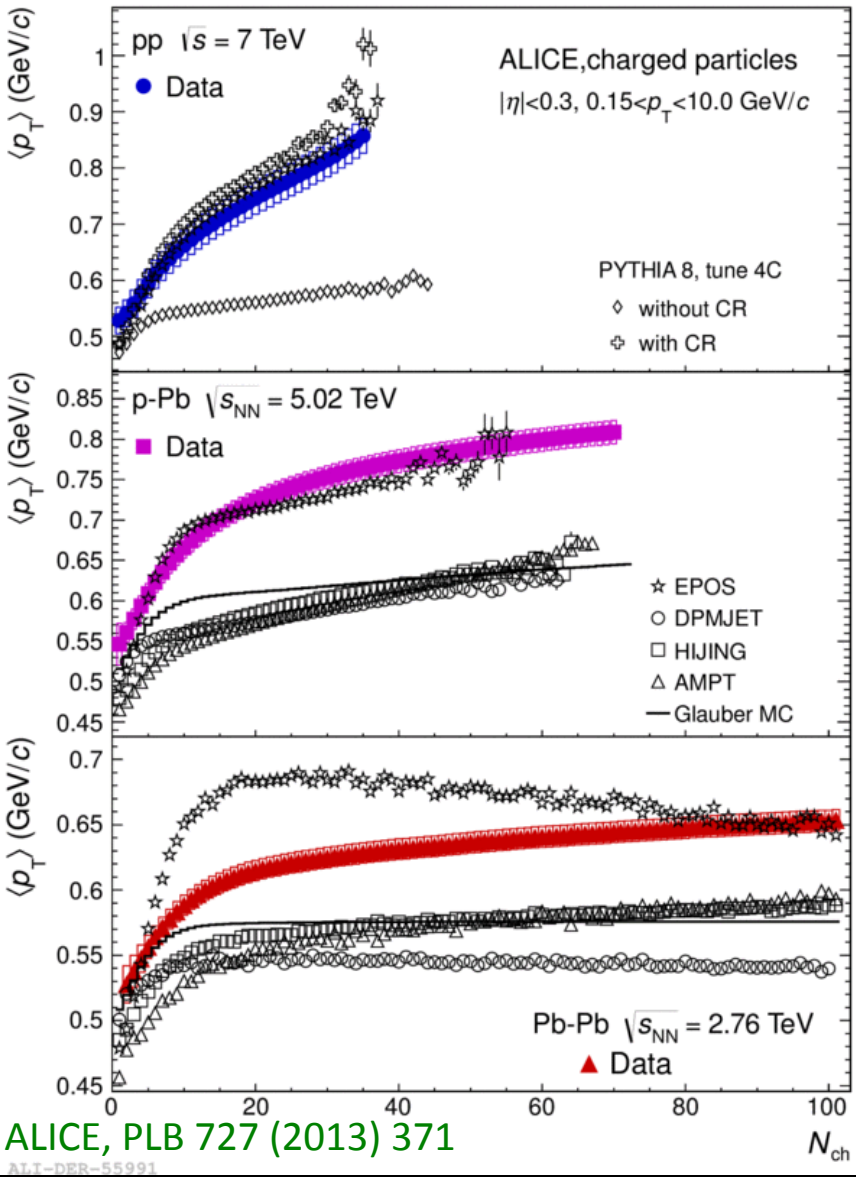
Enhancement at very high p_T not seen for jets

→ Modification of fragmentation function?

ALICE, arXiv:1405.2737
CMS-PAS-HIN-12017
ATLAS-CONF-2014-029

Yen-Jie Lee (Quark Matter 2014)

$\langle p_T \rangle$ vs. N_{ch}: Data vs. Models

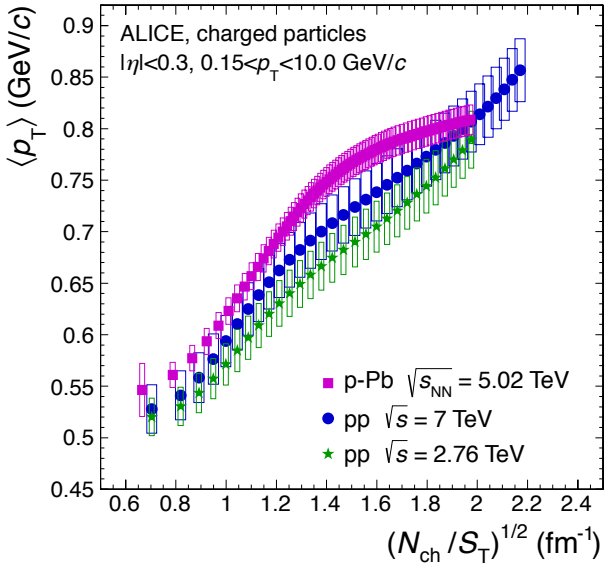


ALICE, PLB 727 (2013) 371

ALI-DER-55991

Comparison with model predictions

- **EPOS** describes pp and is consistent with p-Pb data but with tension (parameterizations of collective effects)
- **PYTHIA8** with color reconnection (CR) consistent with pp data
- **Glauber MC** does not describe p-Pb and Pb-Pb data (incoherent superposition of nucleon-nucleon collisions)

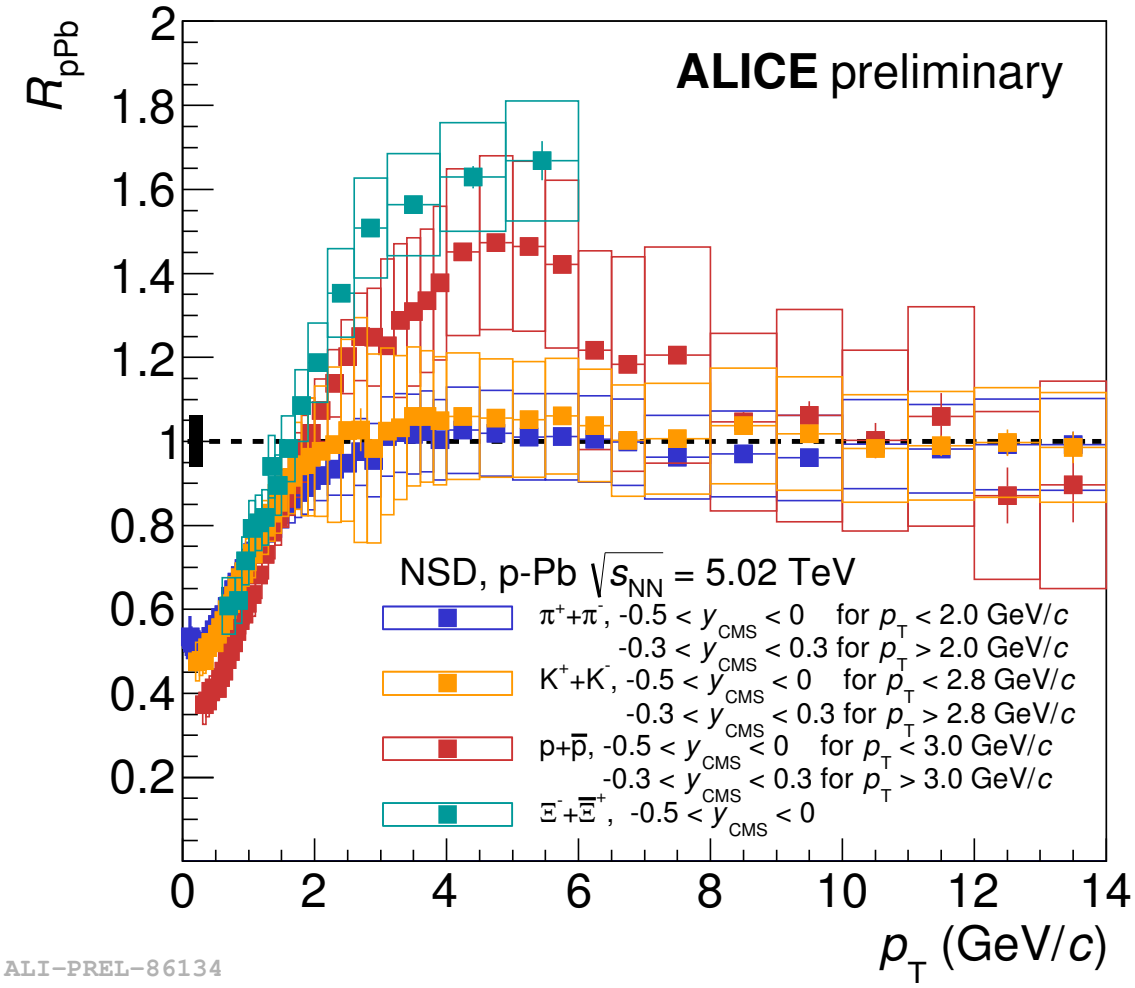


Scaling with transverse area S_T based on CGC model

Works but with tension for pp and p-Pb

Identified particle spectra in p-Pb

R_{pPb} for identified hadrons



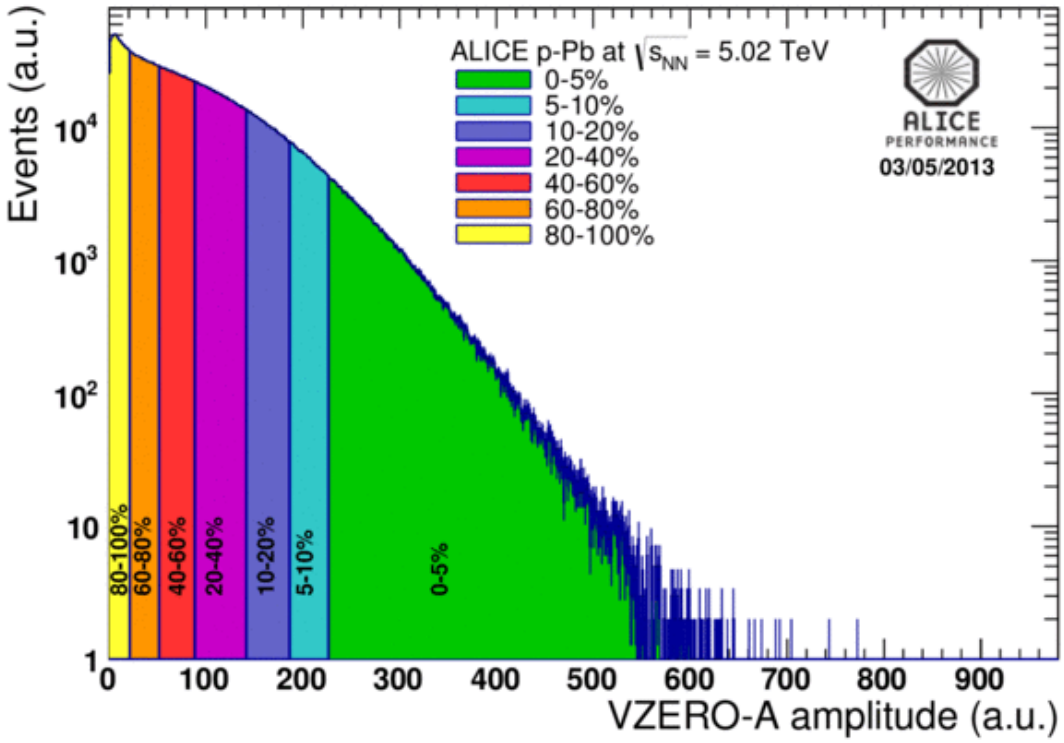
$$R_{pPb} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb}/dp_T}{dN_{pp}/dp_T}$$

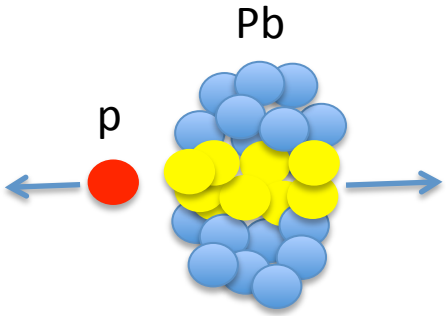
- **Low p_T < 2 GeV/c**: depletion similar for all particle species
- **Intermediate 2 < p_T < 7 GeV/c:** enhancement for protons and Xi - "Cronin" like effect or flow
- **High p_T > 7 GeV/c:** R_{pPb} ~ 1 (no modification)

Event centrality/multiplicity selection in p-Pb

At the LHC, the correlation between geometry and track multiplicity in p-Pb is not as straightforward as in Pb-Pb (e.g A. Toia at Quark Matter 2014)

→ Event centrality selection based on track multiplicity in VZERO-A detector ($2.8<\eta_{lab}<5.1$) – Pb-side

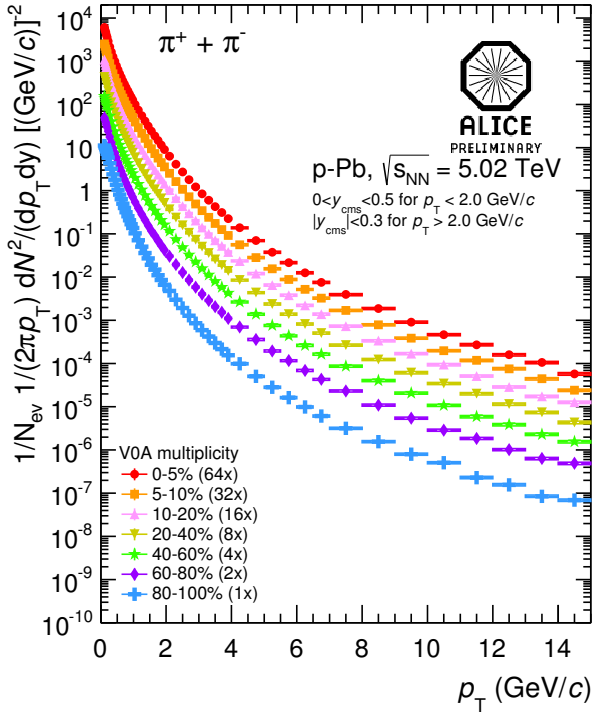


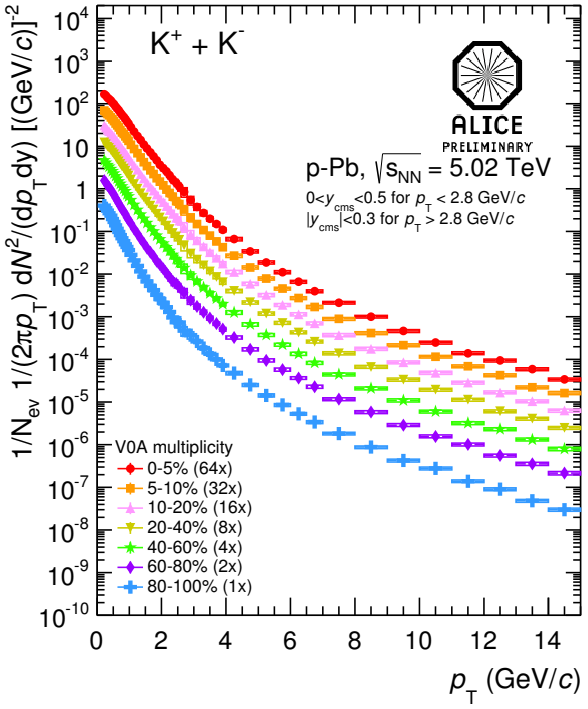


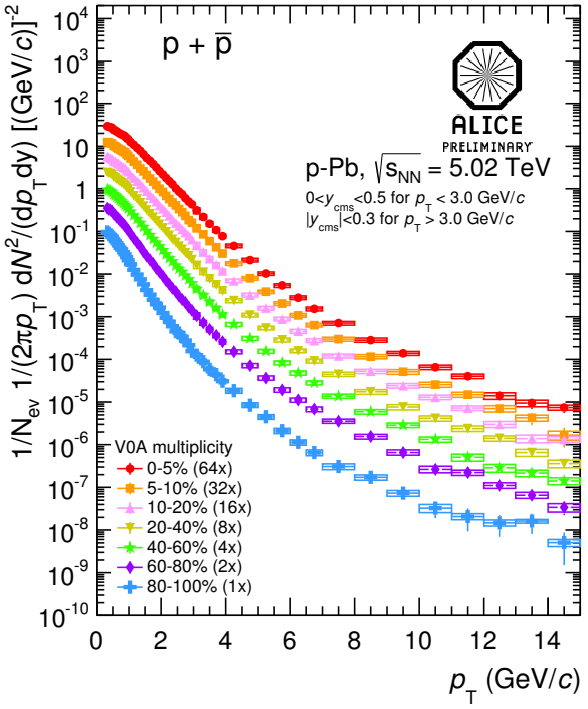
ALI-PERF-51387

Pions, kaons and protons in p-Pb

- Harder spectra with increasing multiplicity and with increasing particle mass
- Flattening of proton spectra at low p_T with increasing multiplicity → indication of flow

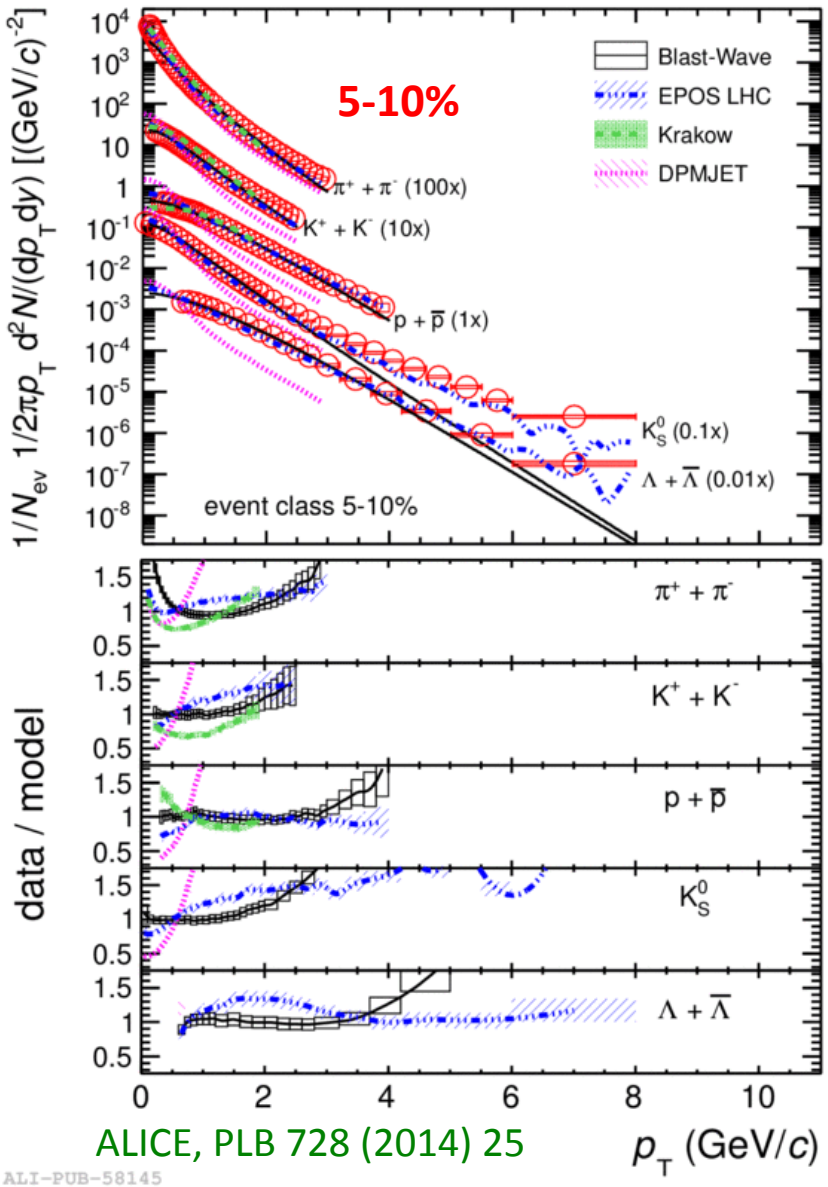






Results for low p_T: ALICE, PLB 728 (2014) 25

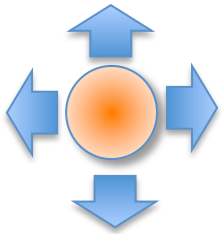
Low-p_T hadron production in p-Pb vs. models



ALICE, PLB 728 (2014) 25

ALI-PUB-58145

p-Pb high multiplicity events



Blast-wave
- Hydro inspired model

EPOS LHC
- hard/soft scattering contribute to jet/bulk
- bulk matter described with hydro

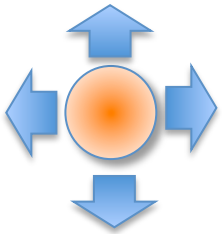
Kraków
- initial conditions from Glauber MC
- viscous hydrodynamic expansion
- statistical hadronization at freeze-out

DPMJET
- QCD-inspired model based on Gribov-Glauber approach
- reproduces $dN_{ch}/d\eta$ in NSD p-Pb

Hydro models reasonably well describe data in p-Pb → indication of flow

Blast-wave comparison of p-Pb and Pb-Pb

p-Pb and Pb-Pb data in multiplicity bins



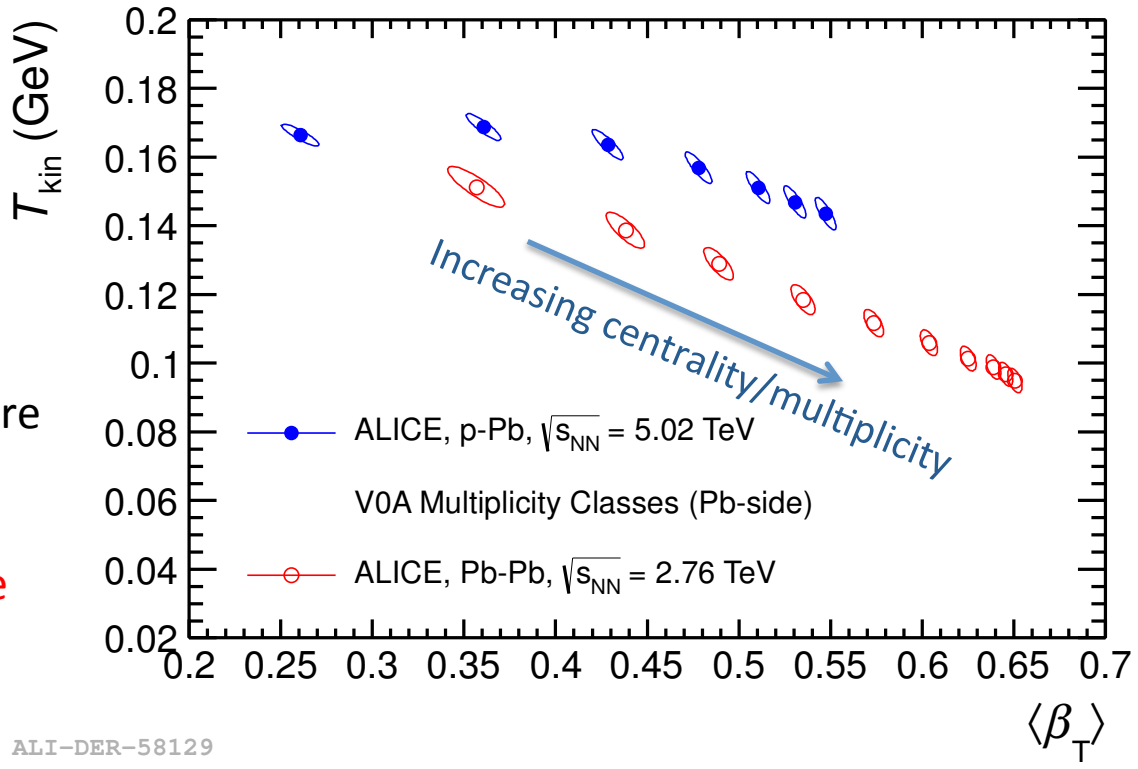
Blast-wave fit parameters:

T_{kin} – kinetic freeze-out temperature

$\langle\beta_T\rangle$ - radial flow velocity

Similar evolution of the blast-wave parameters with increasing multiplicity

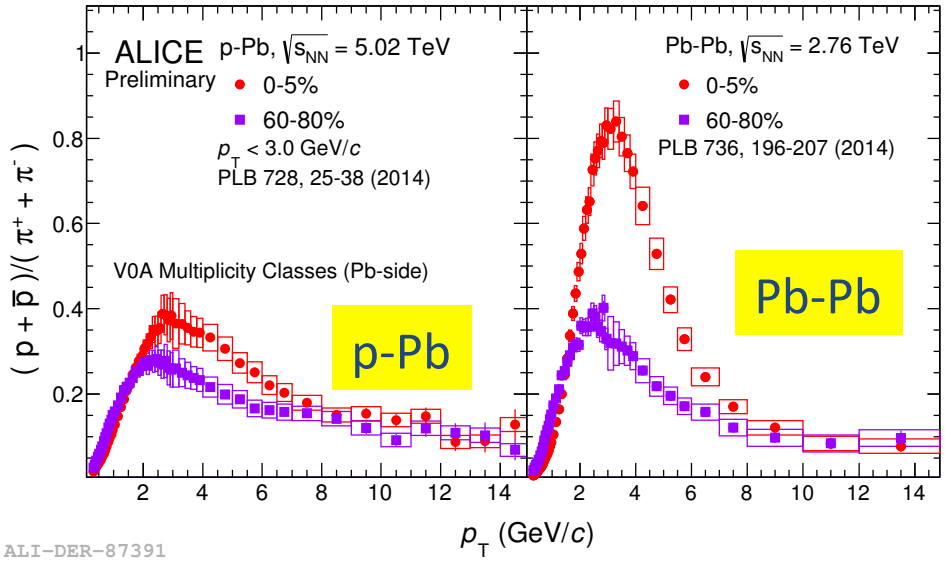
ALICE, PLB 728 (2014) 25



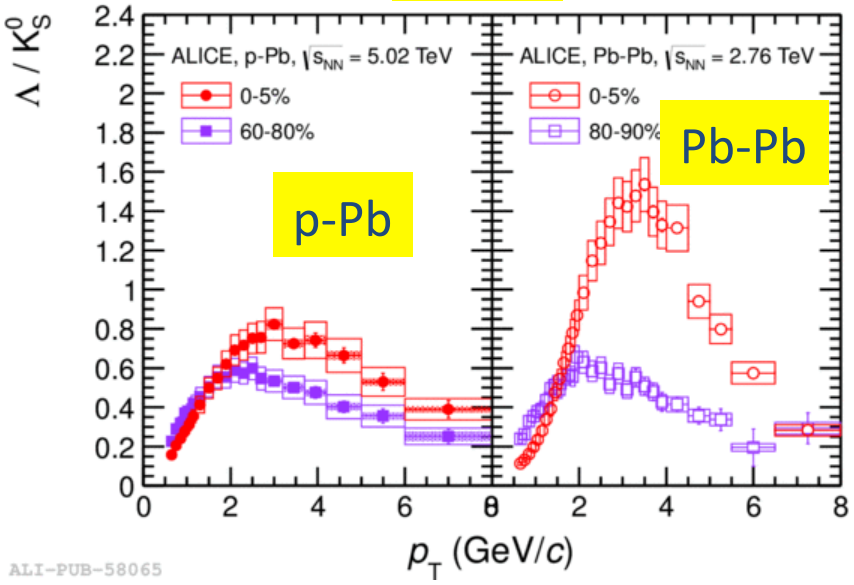
NB: Multiplicity selection introduces bias on p_T spectra in p-Pb.

Baryon to meson ratios

p/π



Λ /K⁰s



Baryon to meson ratio increases with multiplicity

- p-Pb: flow?
- Pb-Pb: flow and recombination

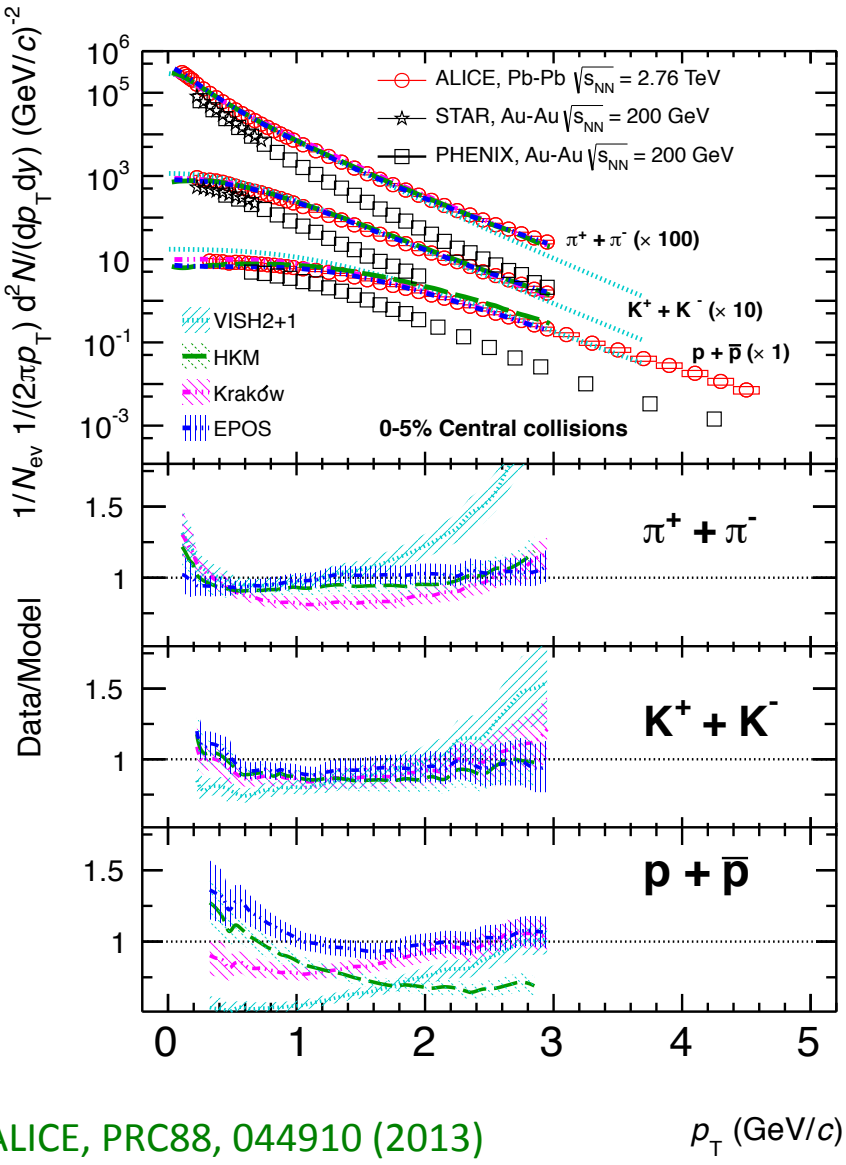
ALICE, PLB 728 (2014) 25
ALICE, PLB 736 (2014) 196

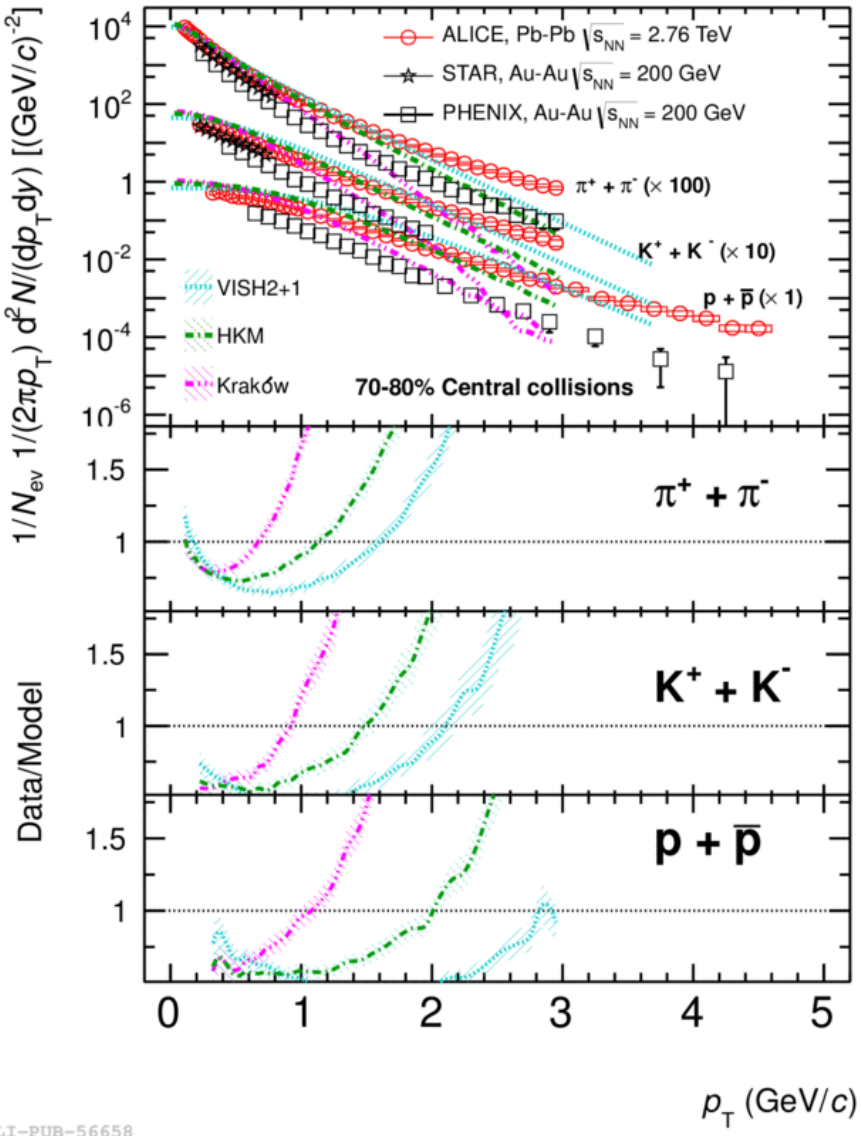
Summary

- Charged particles in min. bias p-Pb collisions
  - $R_{pPb} < 1$ at low p_T consistent with CGC models
  - R_{pPb} ~1 for $2 < p_T < 50$ GeV/c consistent with NLO pQCD with shadowing models
  - Suprising enhancement (R_{pPb} ~ 1.4) for $p_T > 50$ GeV/c seen by CMS and ATLAS
  - $\langle p_T \rangle$ vs N_{ch} data are consistent with EPOS (flow) and CGC but with tension
- Identified light-flavor hadrons
  - R_{pPb} in min. bias p-Pb
    - Similar depletion for $p_T < 2$ GeV/c
    - Mass dependent enhancement at intermediate p_T: "Cronin" like effect or flow
    - No modification for $7 < p_T < 14$ GeV/c
  - Indication of flow in high multiplicity p-Pb collisions

BACKUP

Comparison to hydro models

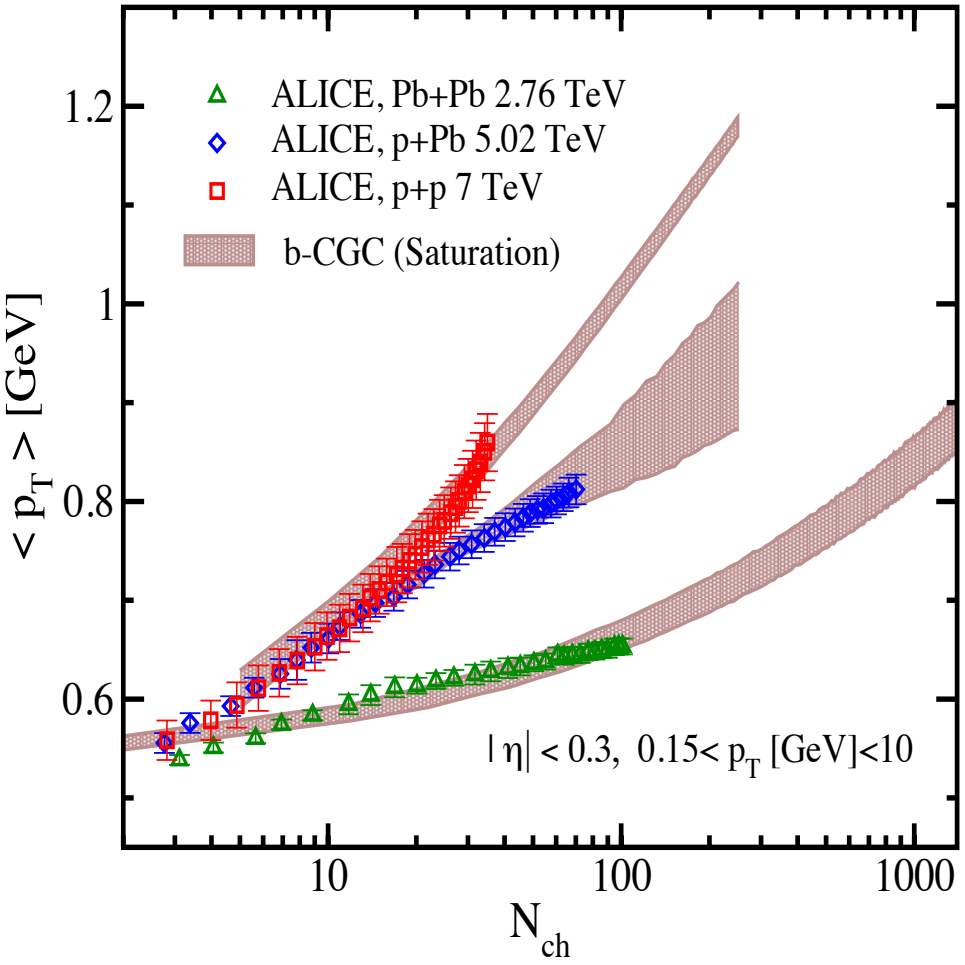




ALICE, PRC88, 044910 (2013)

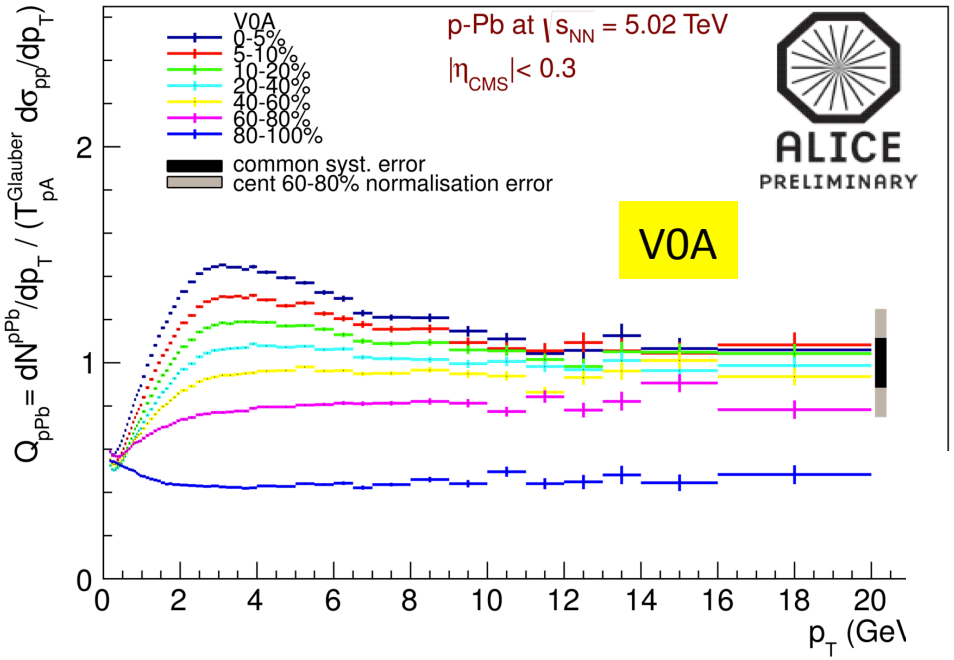
ALI-PUB-56658

$\langle p_T \rangle$ vs. N_{ch} vs. CGC model



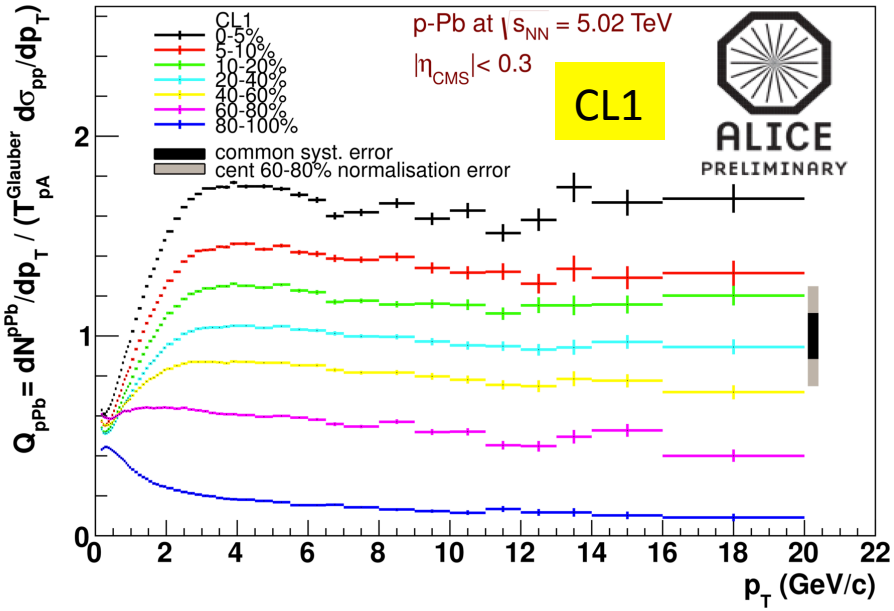
A. Razeian, arXiv:1308.4736

Q_{pPb} – biased R_{pPb}



ALI-PREL-53981

A. Toia at Quark Matter 2014

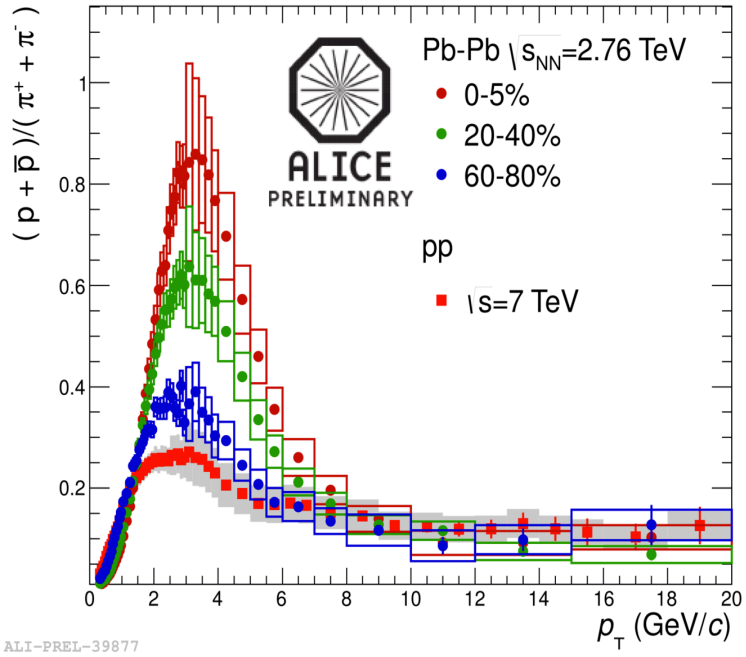


ALI-PREL-53973

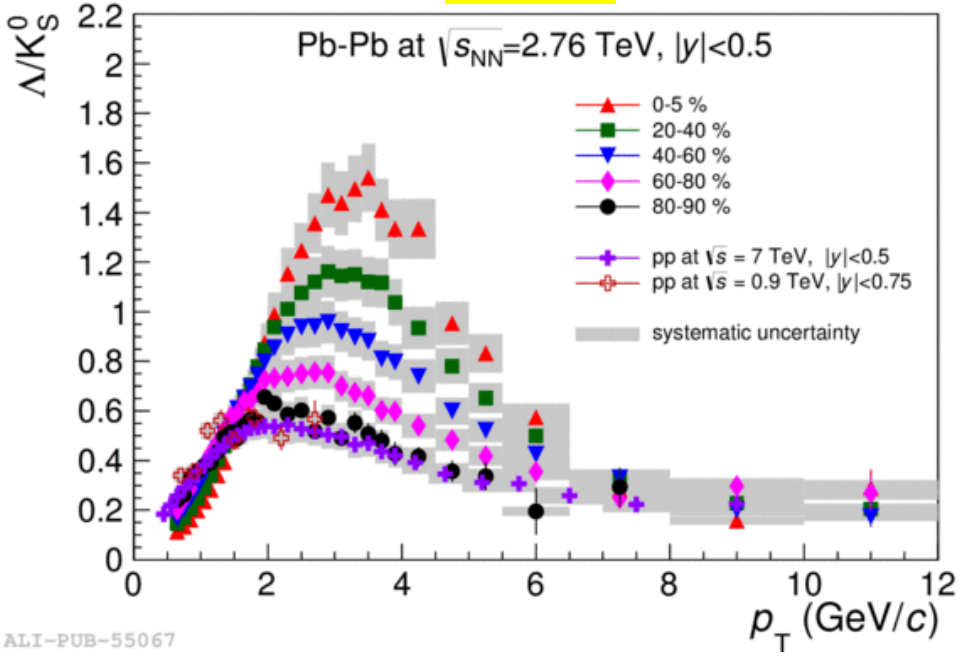
Baryon-meson "anomaly"

Ratios of hadrons with different mass

p/π



Λ /K⁰s

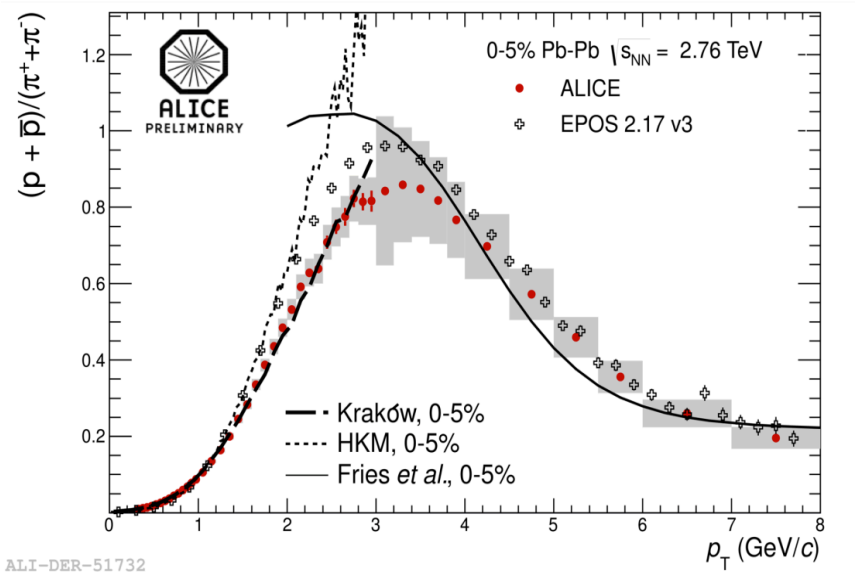


ALICE, PRL 111, 222301 (2013)

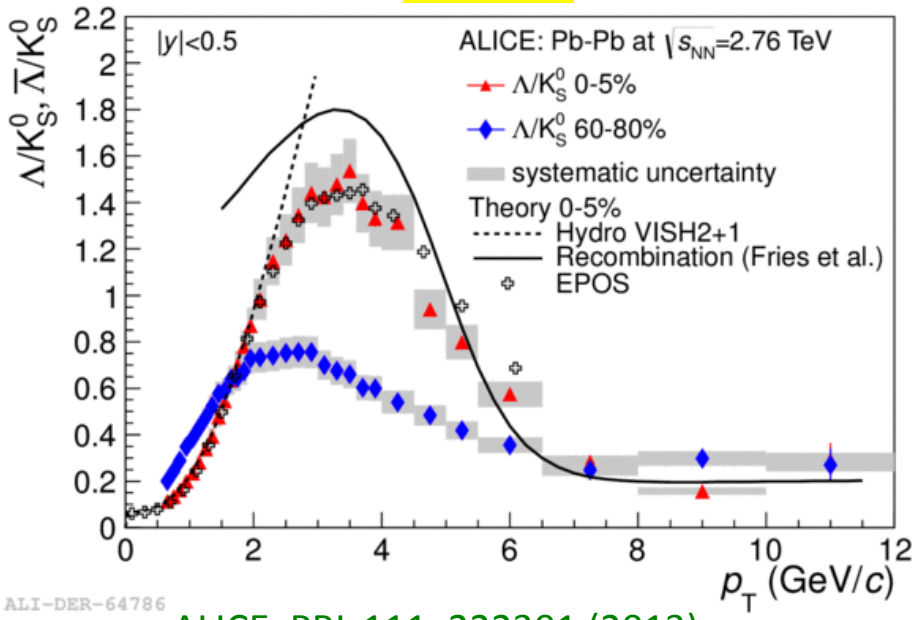
- Baryon to meson ratio increasing with centrality for $p_T < 8$ GeV/c
- Similar baryon to meson ratio in peripheral Pb-Pb and pp collisions
- For $p_T > 8$ GeV/c no dependence on centrality and collision system

Baryon-meson "anomaly" vs. models

p/π



Λ /K⁰S



ALICE, PRL 111, 222301 (2013)

- Hydro models (**Kraków, HKM, VISH2+1**): good agreement at low p_T < 2 GeV/c
- Recombination models (**Fries et al.**): work for p_T > 3-5 GeV/c

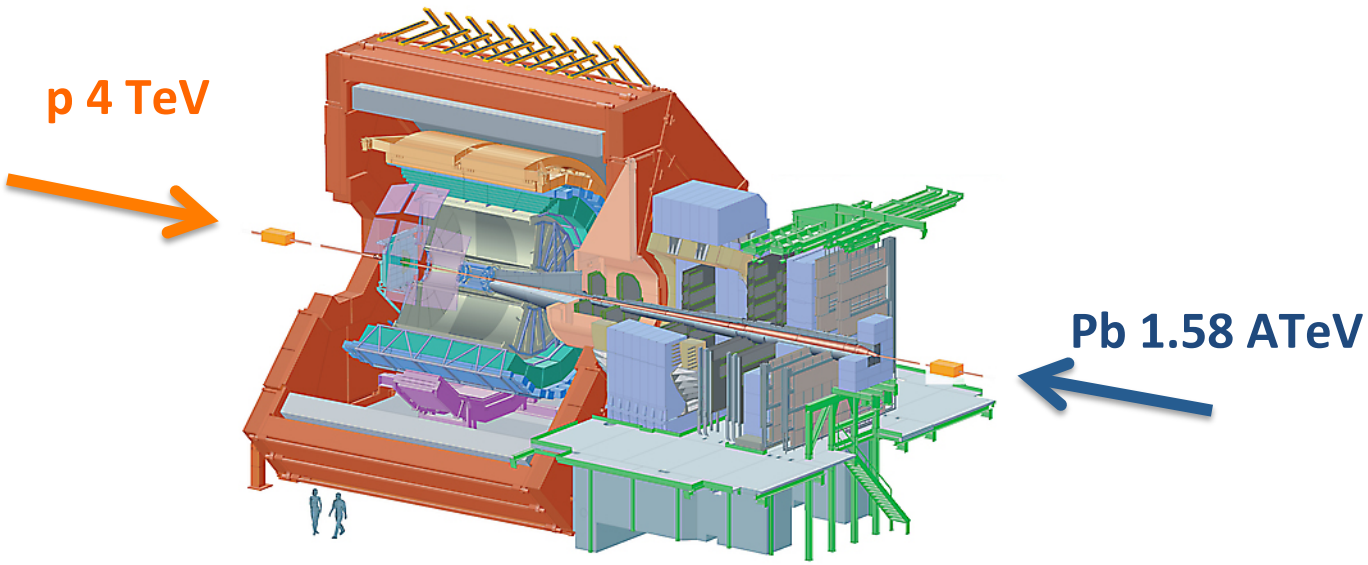
EPOS best agreement with data at whole p_T range:

- Hydro at low p_T
- Medium modified jet fragmentation at intermediate p_T
- Vacuum jet fragmentation at high p_T

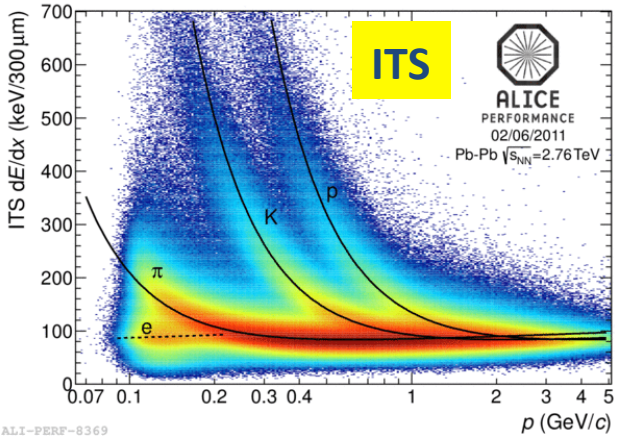
p-Pb collisions at the LHC

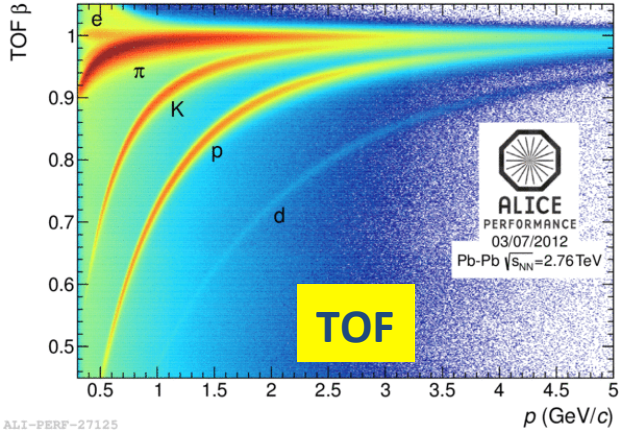
Asymmetric p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

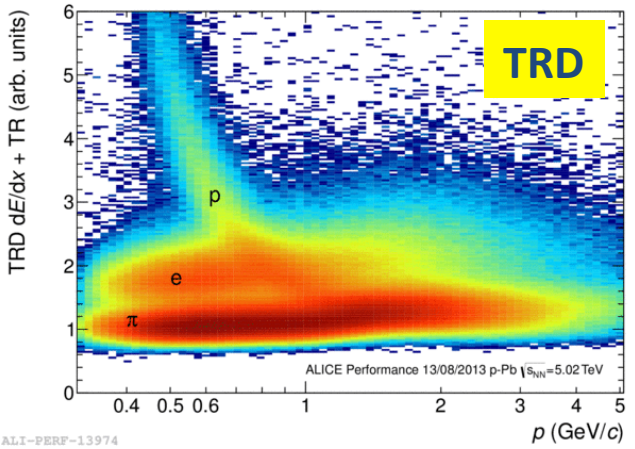
Δy_{NN} = 0.465 in the p-beam direction

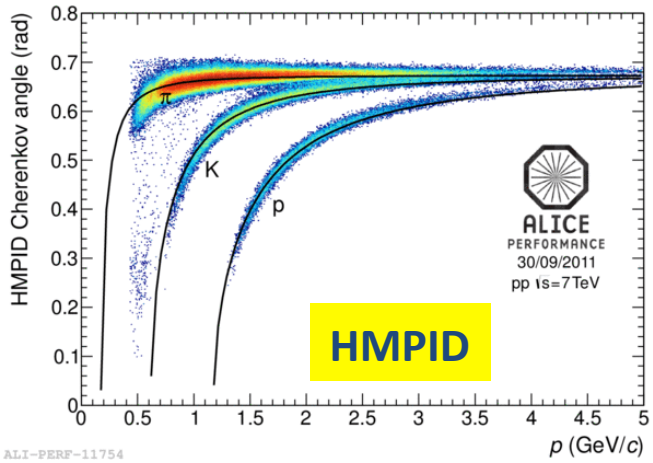


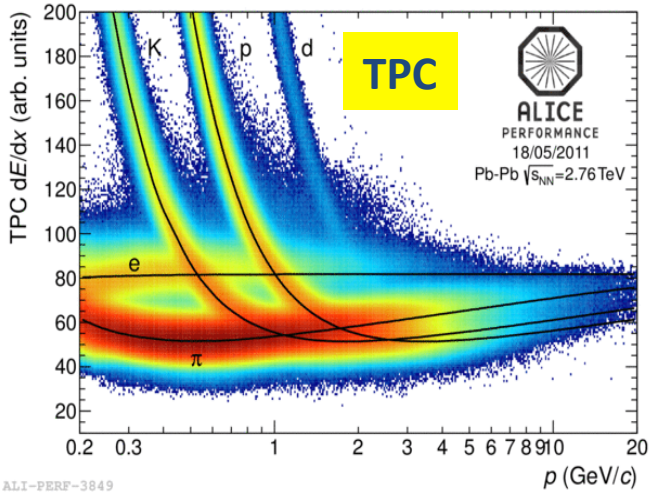
Charged hadron and electron ID at central rapidity







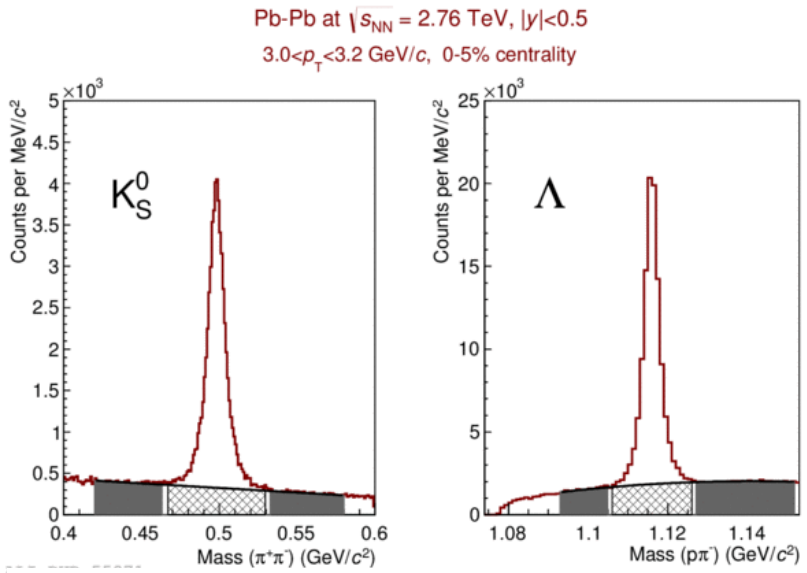




Strange hadron ID at central rapidity

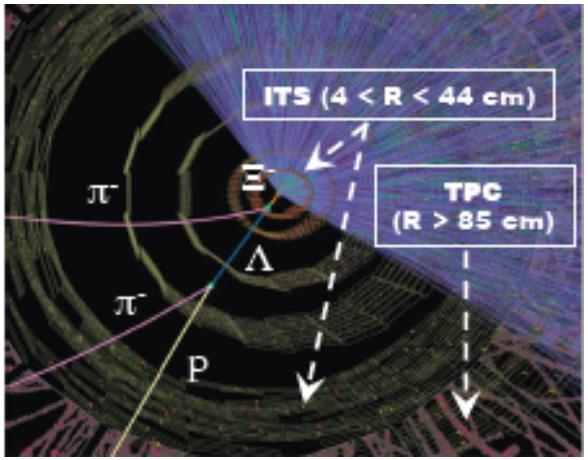
- Strange hadron reconstruction via decay topology plus hadron identification
- Invariant mass analysis:

$K^0_S \rightarrow \pi\pi$
$\Lambda \rightarrow p\pi$
$\Xi \rightarrow \Lambda\pi$

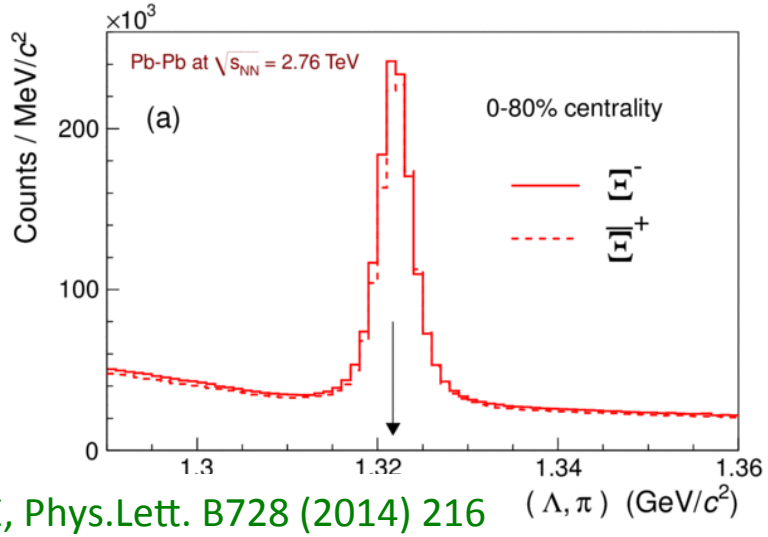


ALICE, PRL 111 (2013) 222301

Ξ decay topology



ALICE, JPG32, 1295 (2006)



ALICE, Phys.Lett. B728 (2014) 216

Blast-wave comparison of pp, p-Pb and Pb-Pb

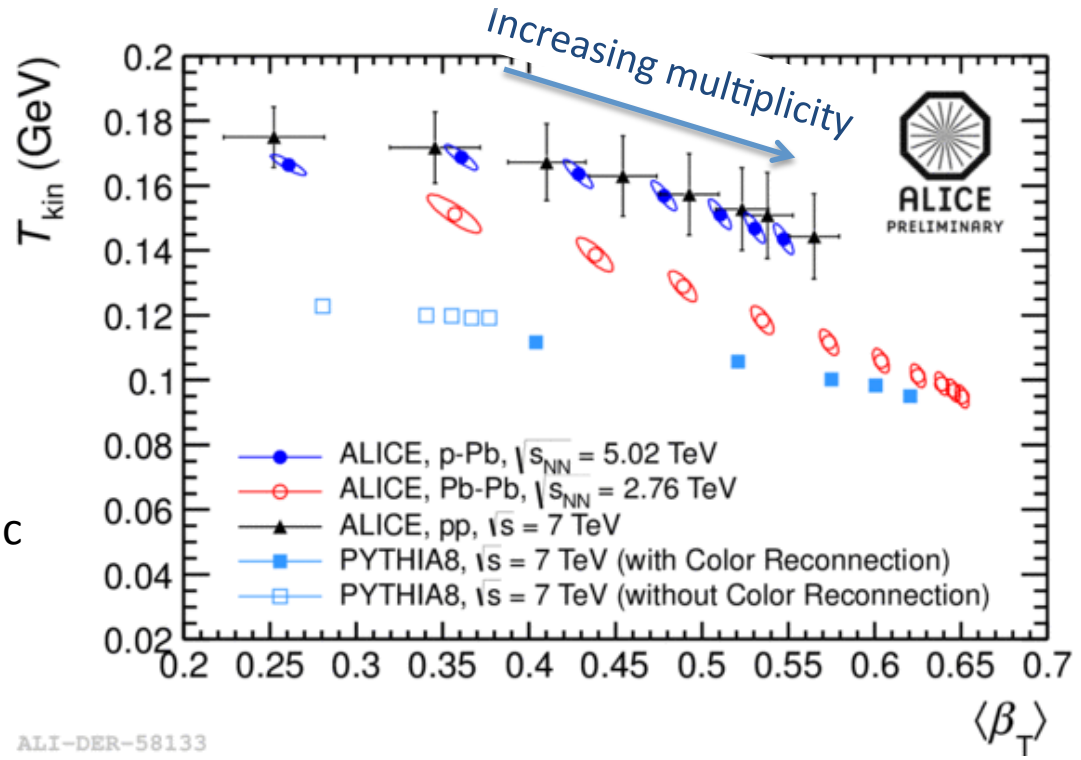
- pp, p-Pb and Pb-Pb data in multiplicity bins
- pp PYTHIA8 MC in multiplicity bins

Blast-wave fit parameters:
T_{kin} – kinetic freeze-out temperature
$\langle\beta_T\rangle$ - radial flow velocity

Similar evolution of the blast-wave parameters with increasing multiplicity

PYTHIA8 pp events (no hydrodynamic evolution) also show the same trend

- Color reconnection causes similar effect as flow



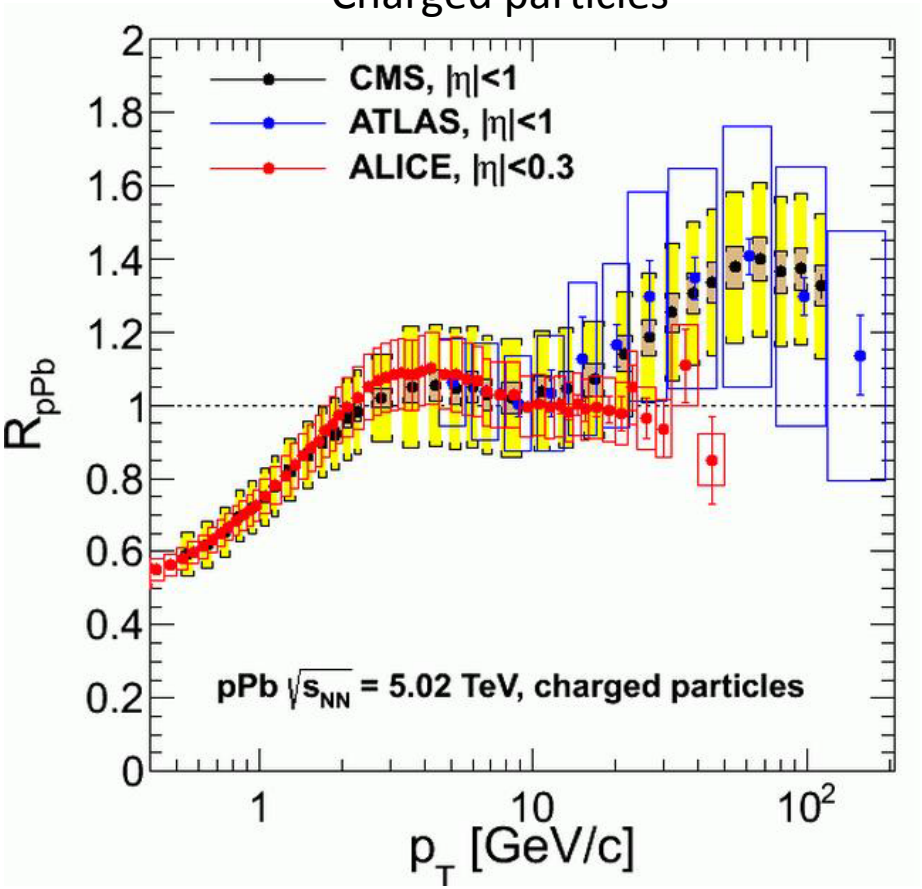
Published p-Pb and Pb-Pb results: ALICE, PLB 728 (2014) 25

NB: Multiplicity selection introduces bias on p_T spectra in pp and p-Pb.

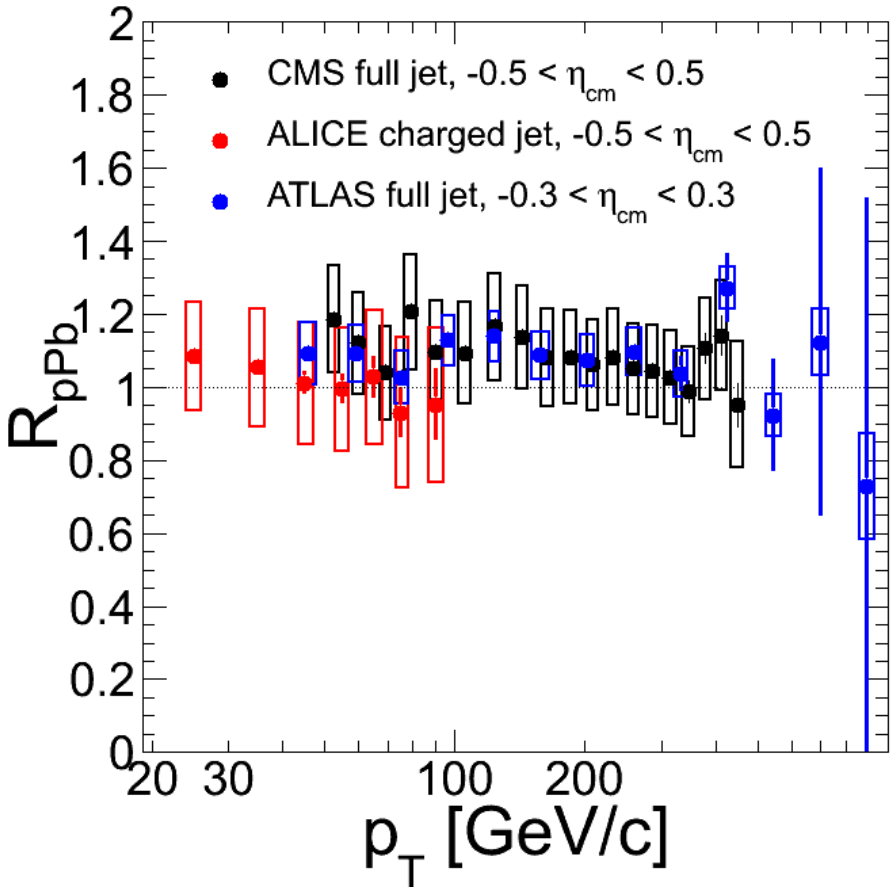
R_{pPb} at very high-p_T

- Surprising enhancement at very high-p_T measured by CMS and ATLAS
- ALICE data shows different trend – different pp reference
- Jets are not modified → need to check fragmentation function in p-Pb!

Charged particles



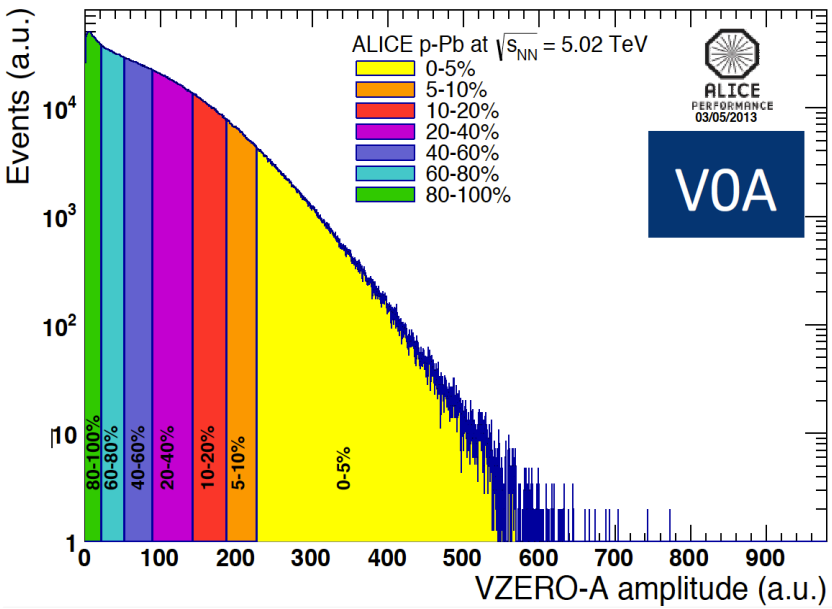
Jets



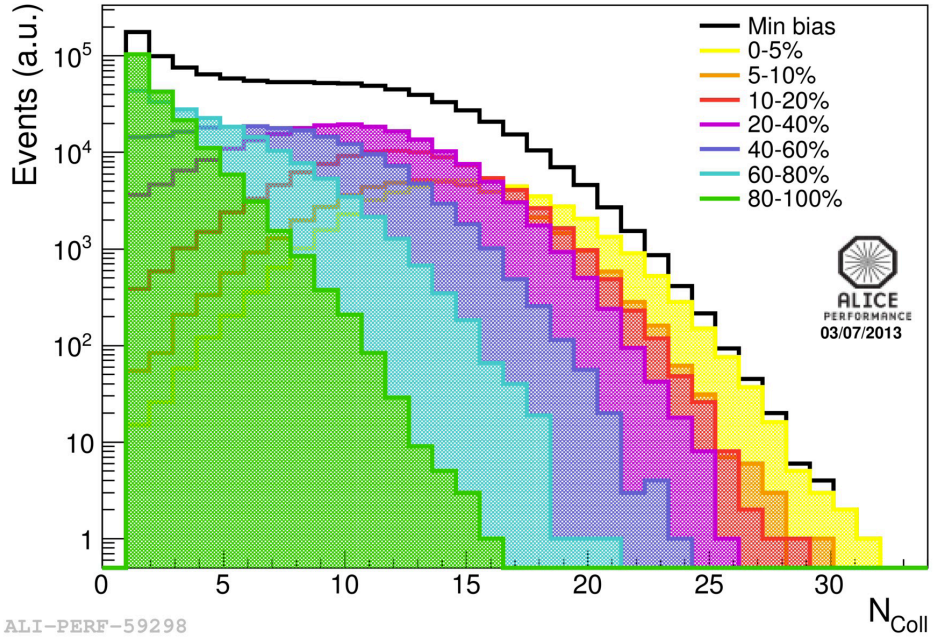
Yen-Jie Lee (Quark Matter 2014)

N_{coll} from Glauber MC in p-Pb

Slicing (percentiles)



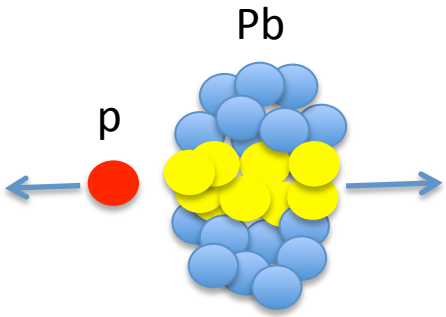
Corresponding N_{coll} from Glauber MC



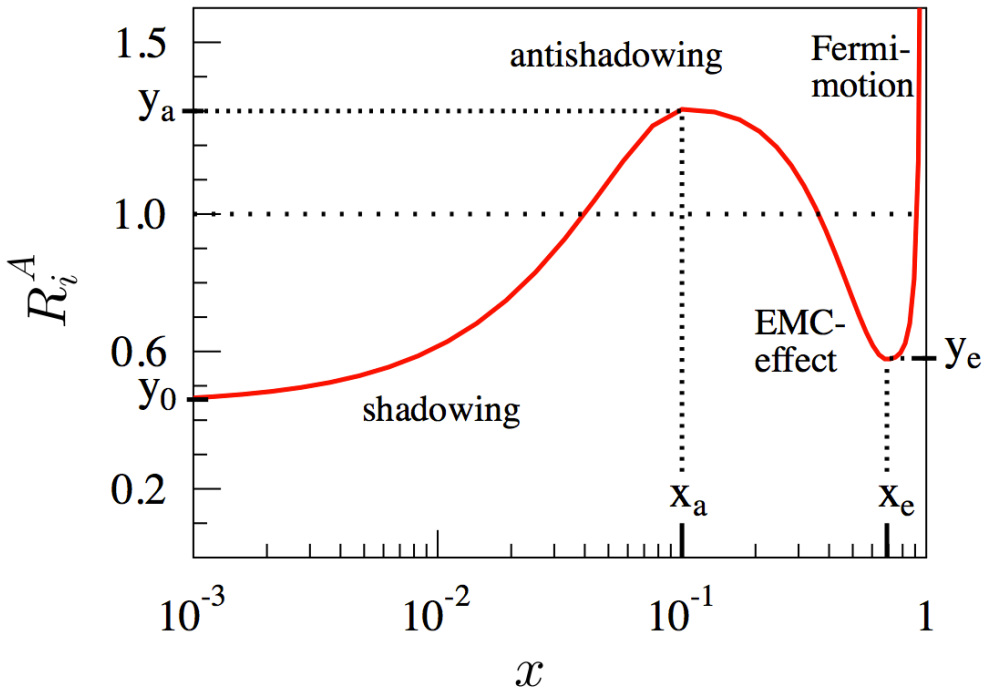
N_{coll} fluctuations within the same centrality class are large!

Shadowing / Gluon Saturation

- Nuclear modification of the parton distribution functions
  - Parton distribution in nucleus differs from that in hadron



$$R_i^A\left(x,Q^2\right) \equiv f_i^A\left(x_1,Q^2\right) / f_i^p\left(x,Q^2\right)$$



Salgado et al. JHEP 0904:065,2009

LHC: x ~10^{-1}-10^{-5}
- shadowing
- antishdowing

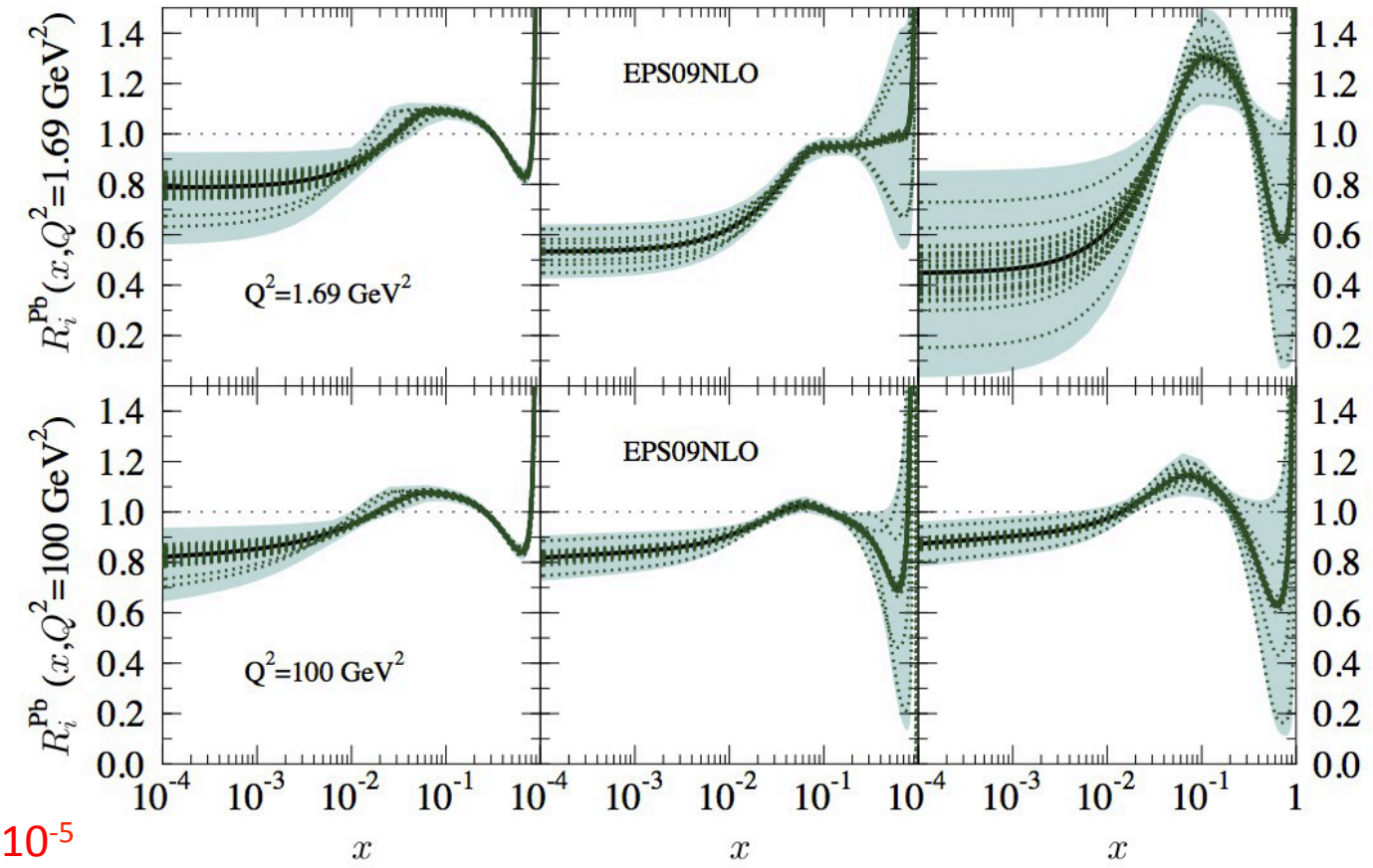
Nuclear Parton Distribution Functions – EPS09

$$R_i^{Pb}\left(x,Q^2\right) \equiv f_i^{Pb}\left(x_1,Q^2\right) / f_i^{p}\left(x,Q^2\right)$$

NLO fits to measured data

Salgado et al. JHEP 0904:065,2009

Valence quarks R_V^{Pb} See quarks R_S^{Pb} Gluons R_G^{Pb}



LHC: x ~10^{-1}-10^{-5}

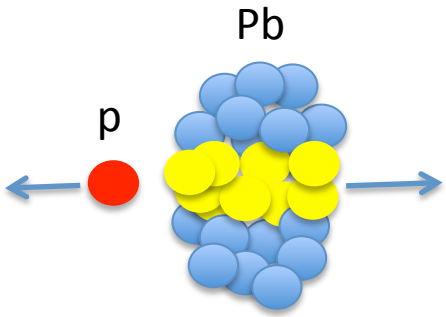
Possibility to reach gluon saturation at small x (Color Glass Condensate)

Cronin Effect

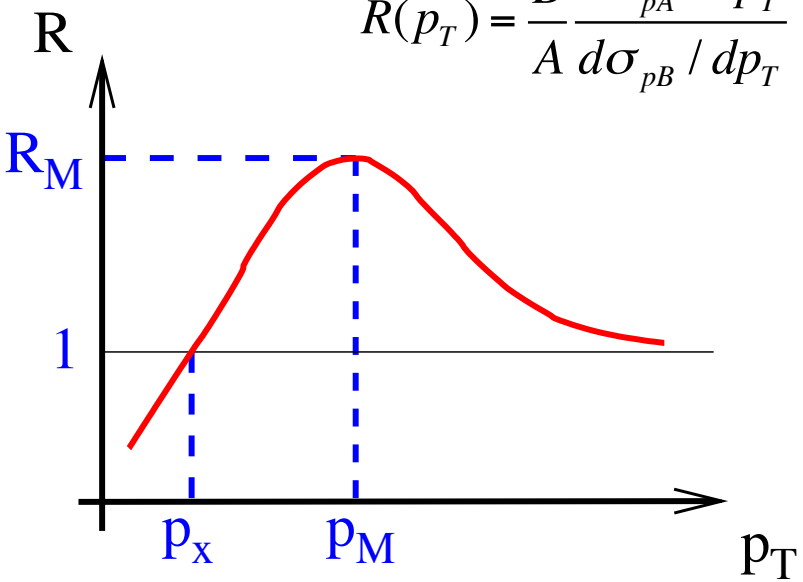
- **Cronin effect**: enhancement of particle production in p-A compared to p-B collisions (A heavier than B)

  Cronin et al. PRD 11 (1975) 3105

  – initial state scattering of incoming nucleon



$$R(p_T) = \frac{B}{A}\frac{d\sigma_{pA}/dp_T}{d\sigma_{pB}/dp_T}$$



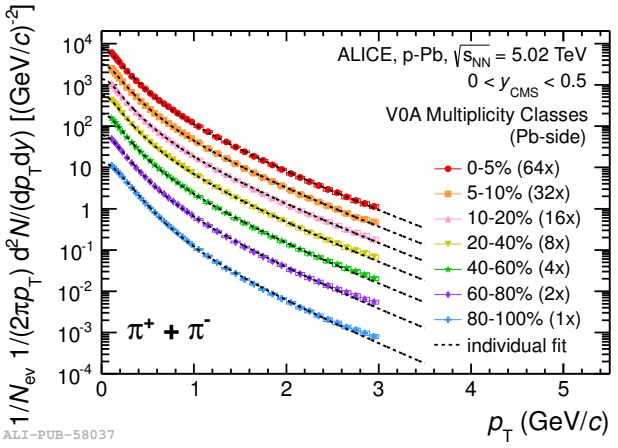
Predictions for minimum bias p-Pb collisions at LHC:

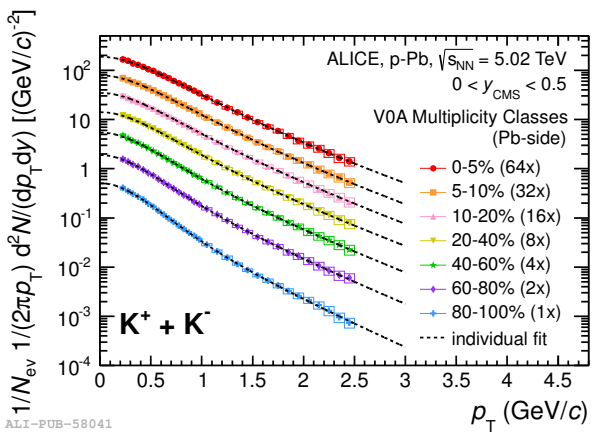
- R_M ~ 1.1
- p_M ~3-4 GeV/c

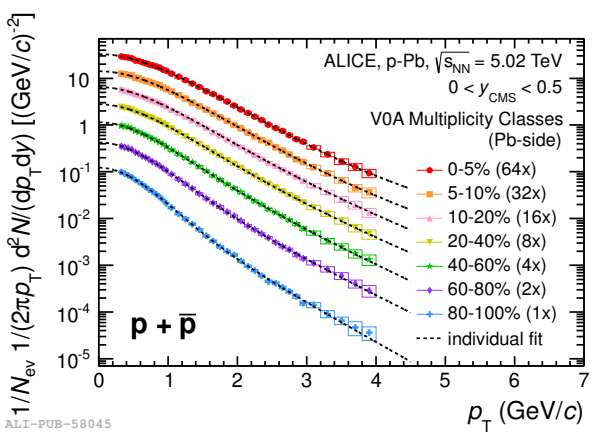
Accardi arXiv:hep-ph/0212128

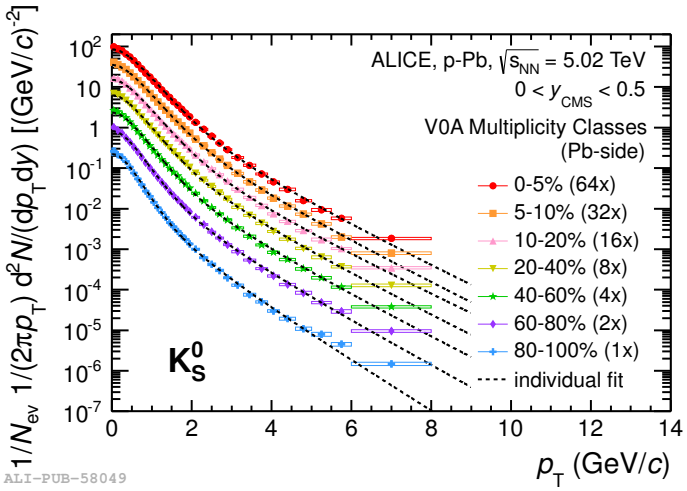
Larger effect expected in central p-Pb collisions.

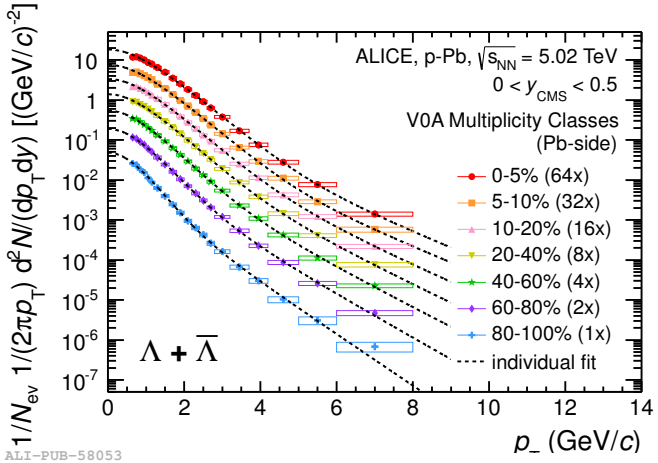
Blast-wave fits in p-Pb

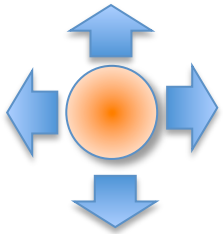










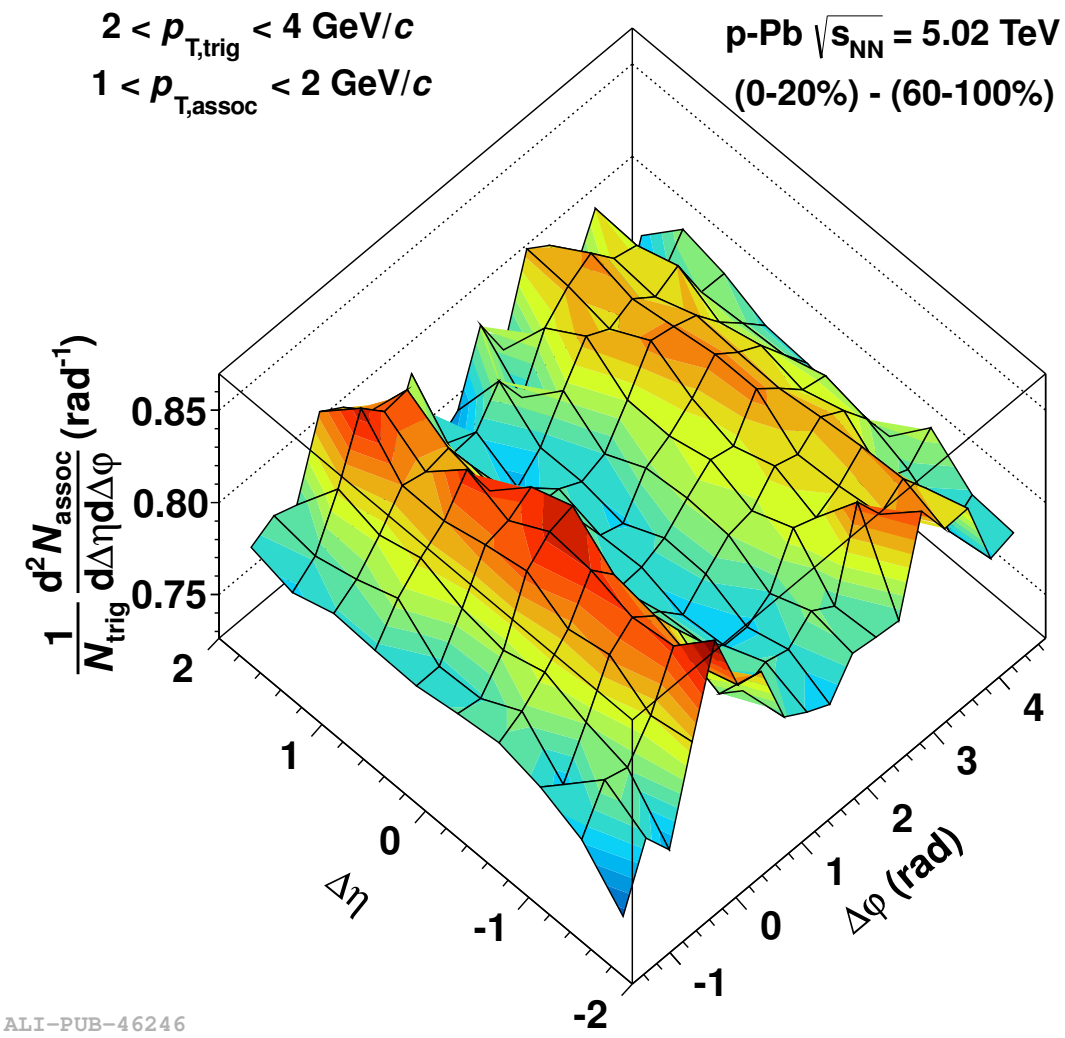


Blast-wave model (thermal + collective)

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

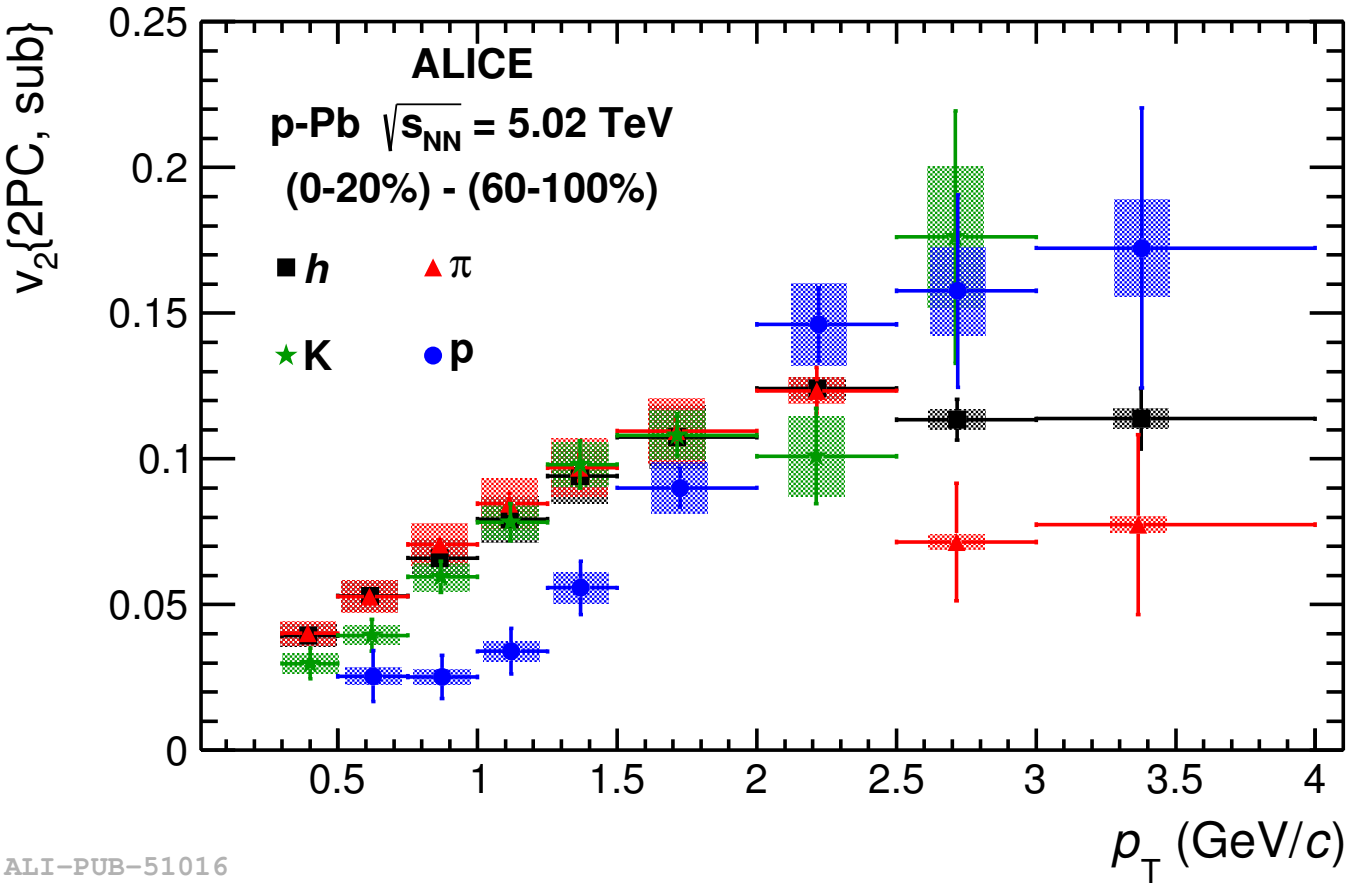
$$\rho = \tanh^{-1}\beta_T$$

Double ridge in high multiplicity p-Pb



ALICE: PLB 719 (2013) 29

Flow in high multiplicity p-Pb?



ALICE, PLB 726 (2013) 164