ALICE Experimental Results

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for the ALICE Collaboration

IFJ PAN, Kraków

XX Cracow Epiphany Conference

on the Physics at the LHC

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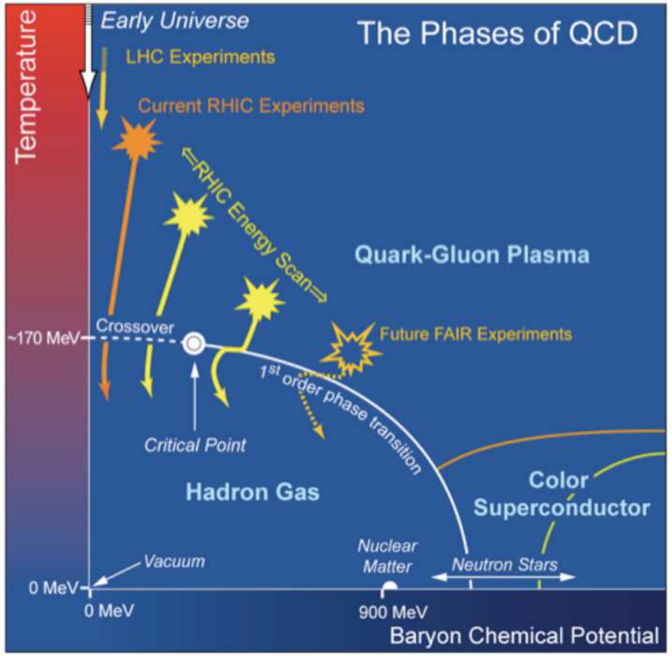
Outline

- Motivation
- Experimental apparatus
- Centrality determination
- Bulk properties from Pb-Pb collisions
  - Multiplicity
  - Particle production
  - Chemical (kinetic) freezeout temperature
  - Collective expansion
- News from p-Pb collisions
  - Double ridge structure
  - Identified particles spectra
  - Barion to meson ratio
- Jet quenching
  - Charged hadrons
  - Identified particles
    - Light flavours
    - Open and hidden charm
  - Reconstructed jets
- Summary

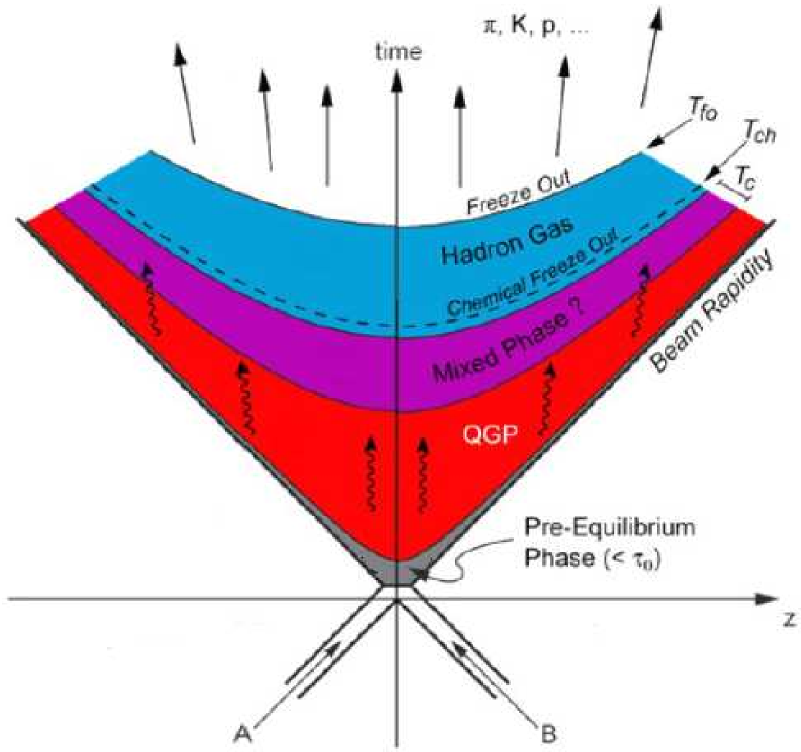
Motivation

- Investigate properties of nuclear matter at high temperature and density
- Important input for the understanding confinement and chiral symmetry restoration (transition from quark to hadronic matter)
- < 10^{-6} s after Big Bang
- Explore QCD in unknown regimes → study QCD phase diagram
- We should search for QGP phase and measure its properties
- LHC gives us the great opportunity via heavy ion collisions



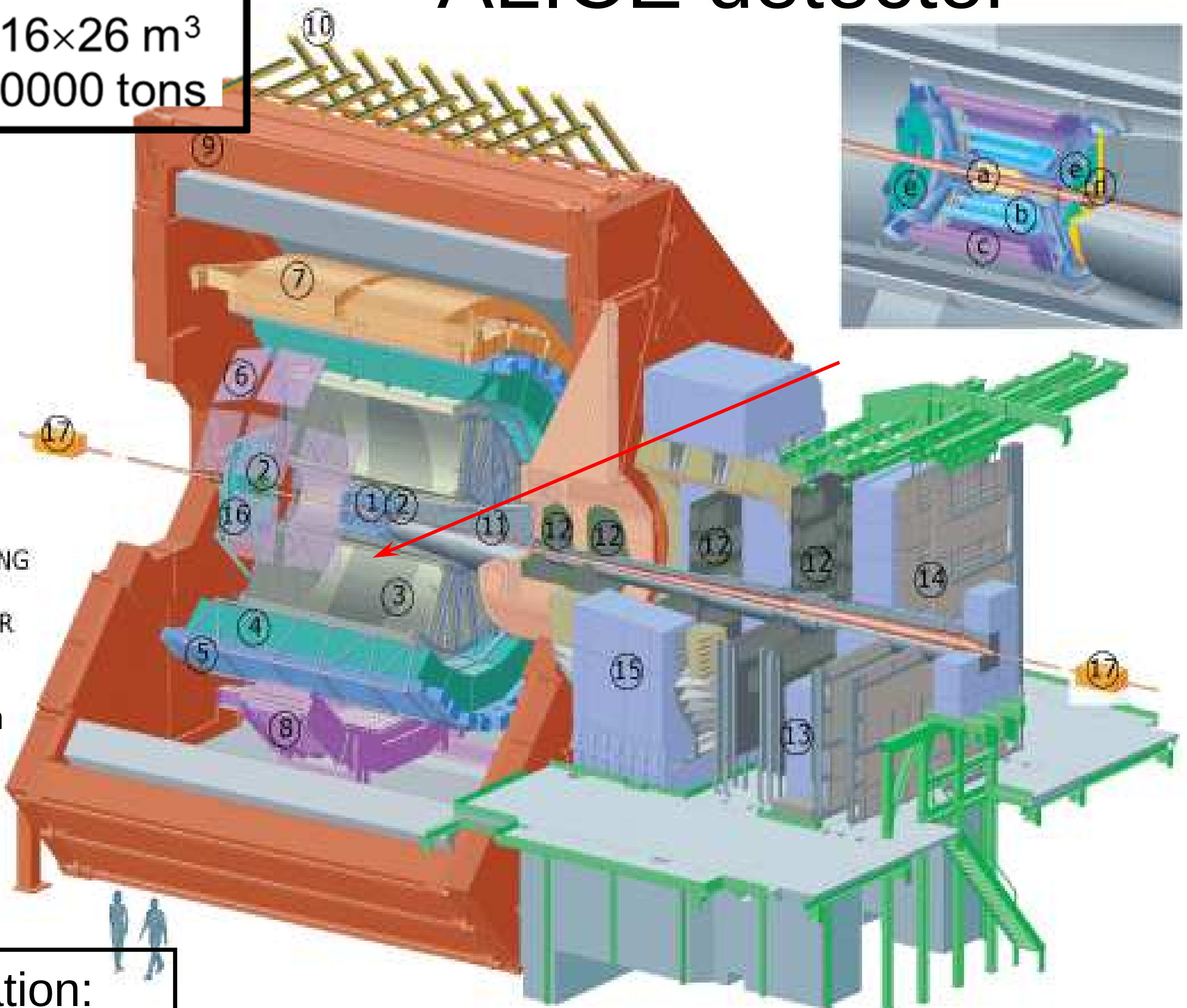
Observables

- Global observables
  - Flow, temperature
  - Measures bulk properties
- Hard probes
  - high p_T hadrons, heavy flavour, jets
  - Produced early in collision
  - Probe partonic energy loss in the medium



ALICE detector

Detector:
Size: 16×16×26 m^3
Weight: 10000 tons



1. ITS
2. FMD , T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCAL
8. PHOS CPV
9. MAGNET
10. ACORDE
11. ABSORBER
12. MUON TRACKING
13. MUON WALL
14. MUON TRIGGER
15. DIPOLE
16. PMD
17. ZDC ± 114 m

a. ITS SPD Pixel
b. ITS SDD Drift
c. ITS SSD Strip
d. V0 and T0
e. FMD

Collaboration:
36 countries
131 institutes
>1200 members

Central Tracking System:
- ITS + TPC
- Very high resolution
- $|\eta| < 0.9, \quad 0 < \phi < 2\pi$

Vertex:
- Pixel

Particle ID:
- CTS, TRD, TOF, HMPID

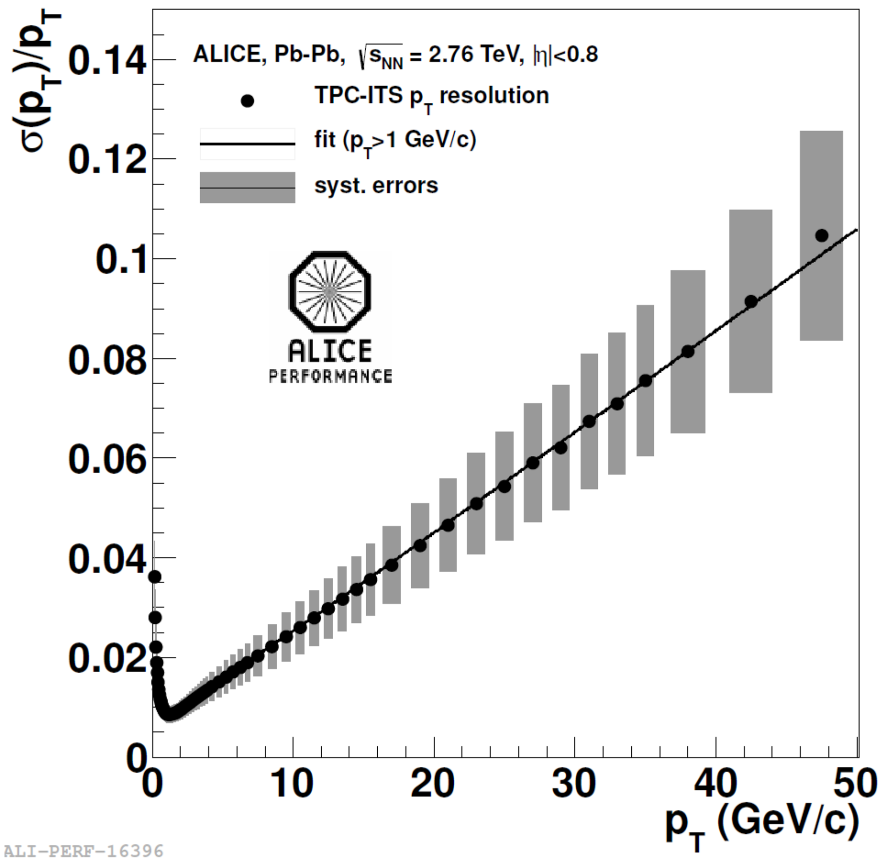
Calorimeters:
- EMCAL, PHOS

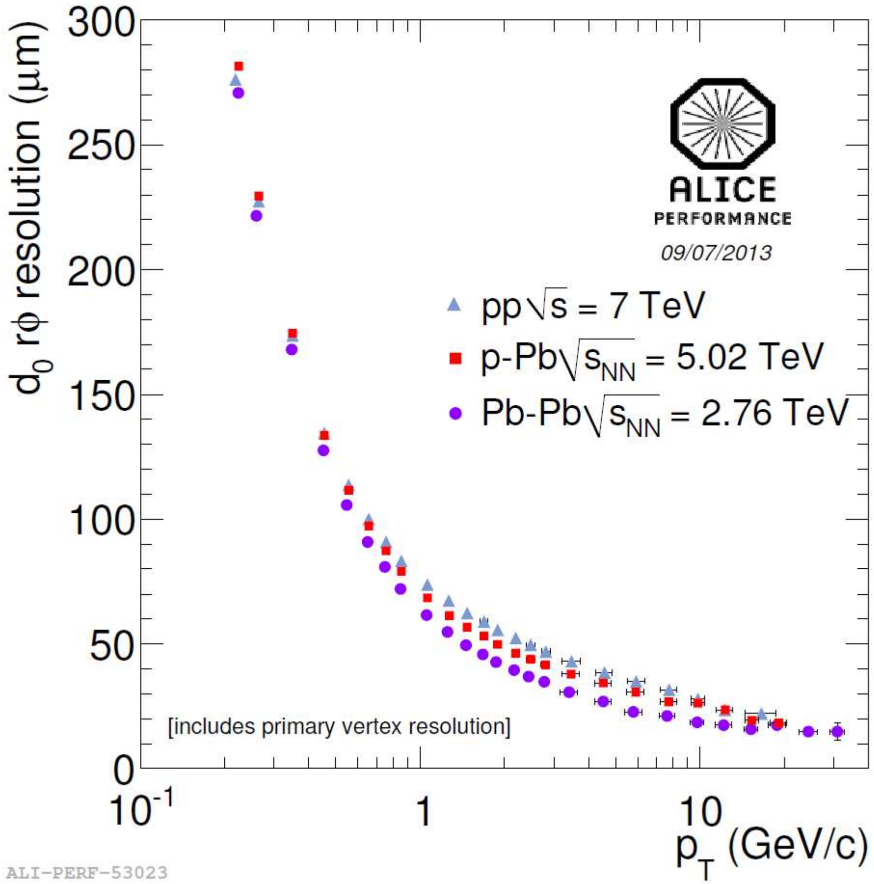
Muon Arm:
- $-4 < \eta < -2.5$

Trigger:
- Minimum Bias = SPD + V0
- MUON = Muon Arm + MB
- RARE triggers

Centrality:
- ZDC,V0 (resolution ~ 1ns)

Tracking in ALICE

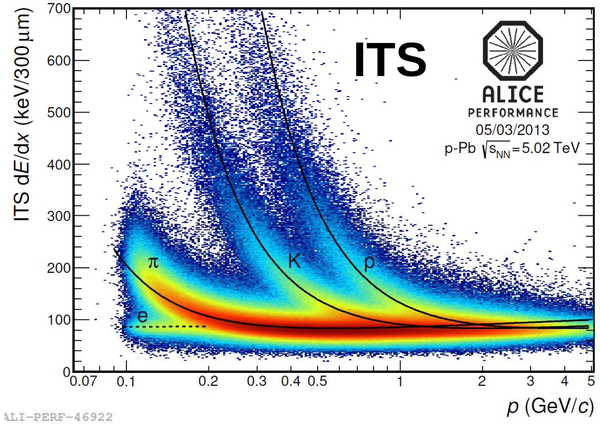


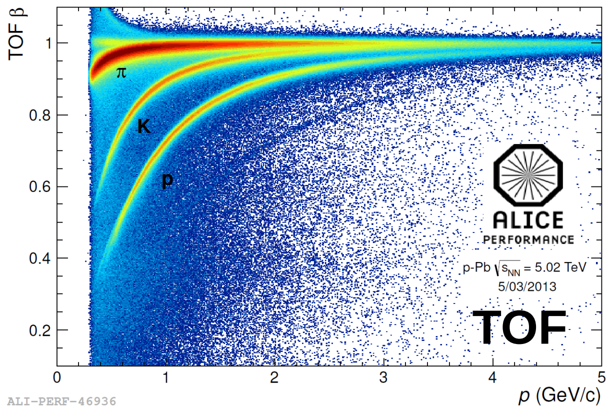


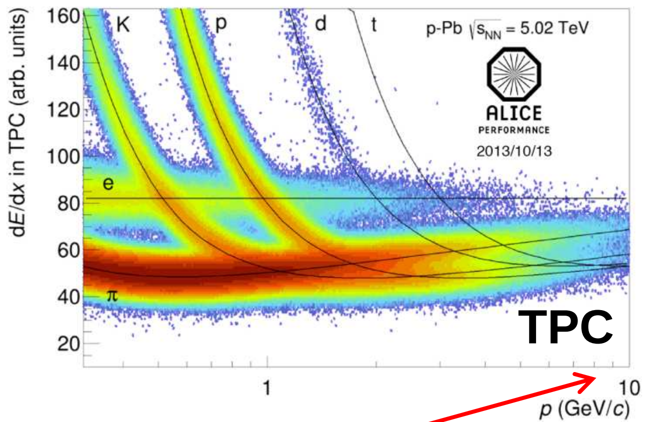
Charged track reconstruction in |η| < 0.9
TPC + ITS
Low momentum tracking down to ~100 MeV/c

High precision vertexing
High resolution of track impact parameter with ITS
Allows to decide: decay vertex of charm or beauty

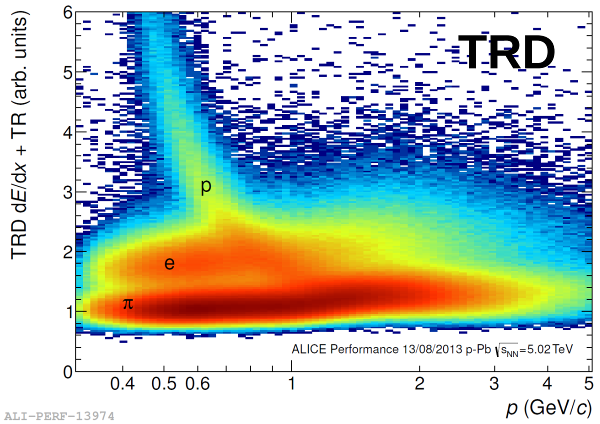
Particle Identification

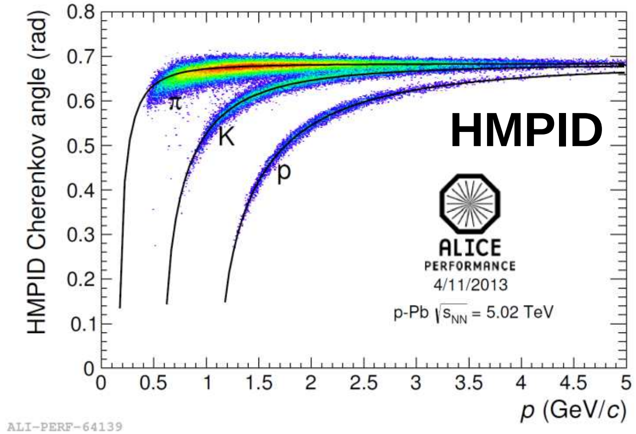


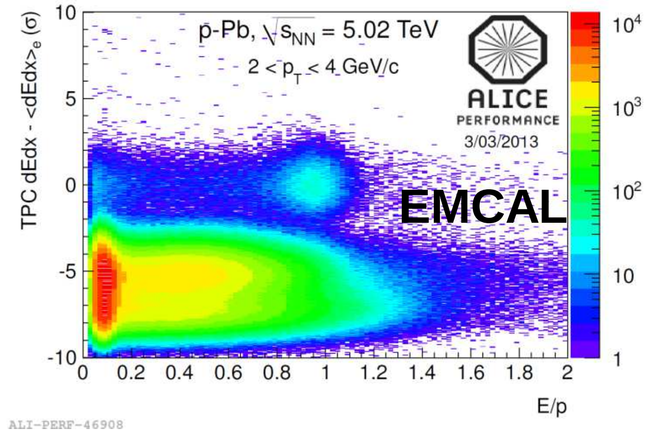




Statistical separation in the relativistic rise region

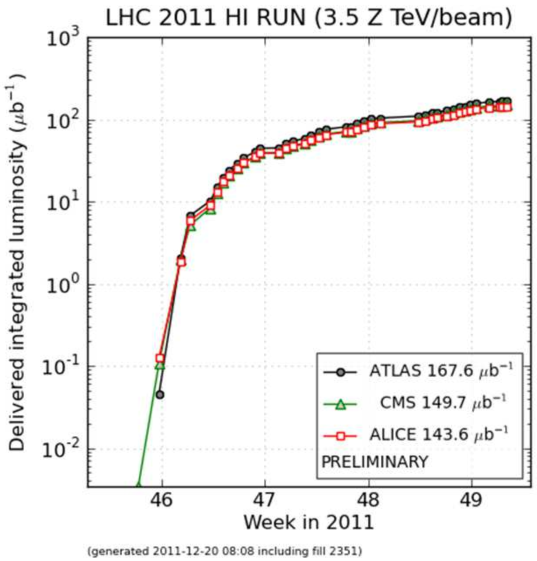


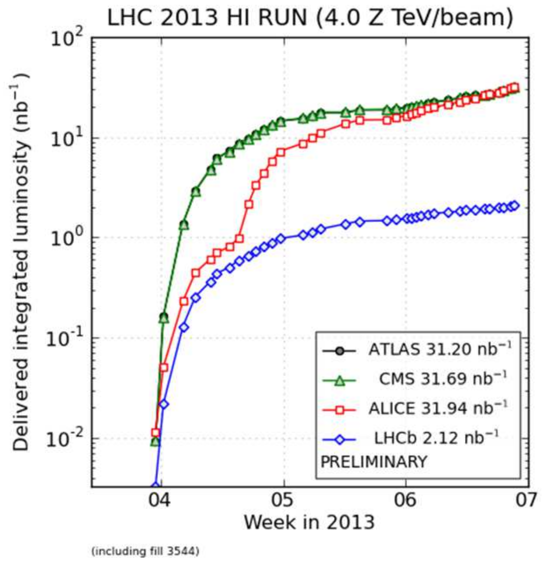




Almost all known techniques

Data samples





System	Year	Energy $\sqrt{s_{NN}}$ [TeV]	Integrated luminosity	Goal
Pb-Pb	2010	2.76	~ 10 μb^{-1}	Commissioning and the first data taking Study of hot and dense QCD matter
	2011	2.76	~ 100 μb^{-1}	
p-Pb	2012	5.02	~ 0.8 μb^{-1}	Check for cold nuclear matter effects Test for initial state signatures (e.g. CGC – low x gluons saturation)
	2013	5.02	~ 15 nb^{-1}	
Pb-p	2013	5.02	~ 15 nb^{-1}	
pp	2009 -2013	0.9, 2.36, 2.76, 7, 8		Used as a reference for Pb-Pb, p-Pb Commissioning

Centrality estimation in Pb-Pb

Phys. Rev. C 88, 044909 (2013)

- Centrality observables
  - Charge particle multiplicity in VZERO
  - Forward energy in ZDC
  - SPD for systematics
- Number of particle sources

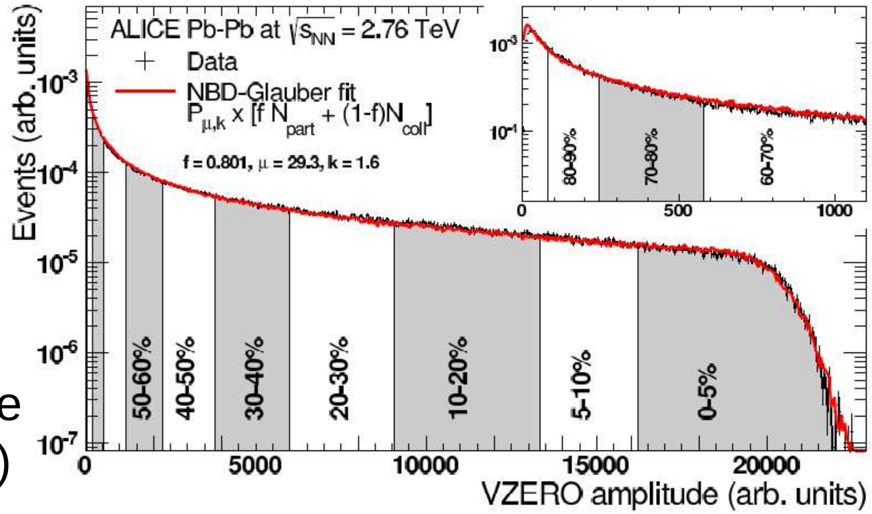
  $f \times N_{part} + (1 - f) \times N_{coll}$
- Number of particles produced by each source given by Negative Binomial Distribution (μ, κ)
- Glauber model fits to cross-section
  - 100% trigger efficiency
  - Background is negligible

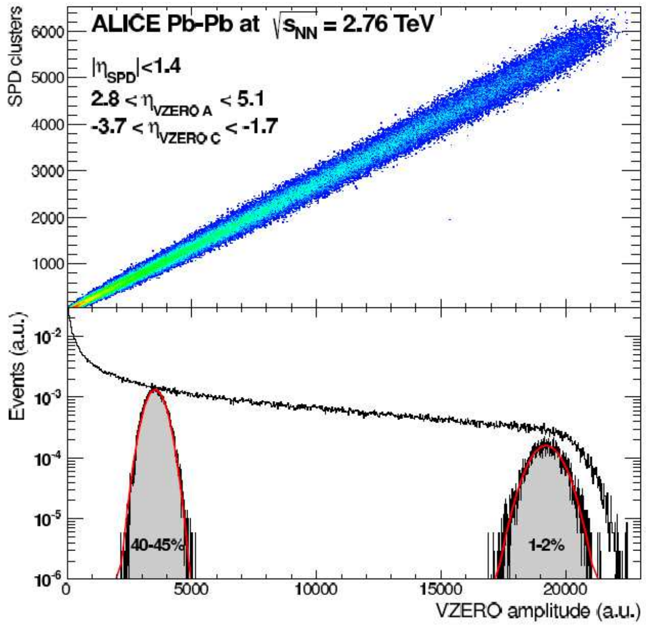
  → ~ 90% of total cross-section

  with $\sigma_{INEL}^{NN} = 64 \pm 5$ mb

  <1% agreement (0-70%) N_{part} with Glauber fit

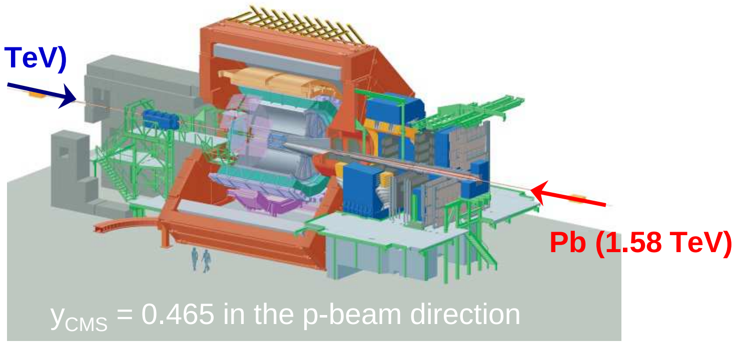
  3.5 % for peripheral (>70%)
- Define centrality classes corresponding to fractions of the inelastic Pb-Pb cross-section

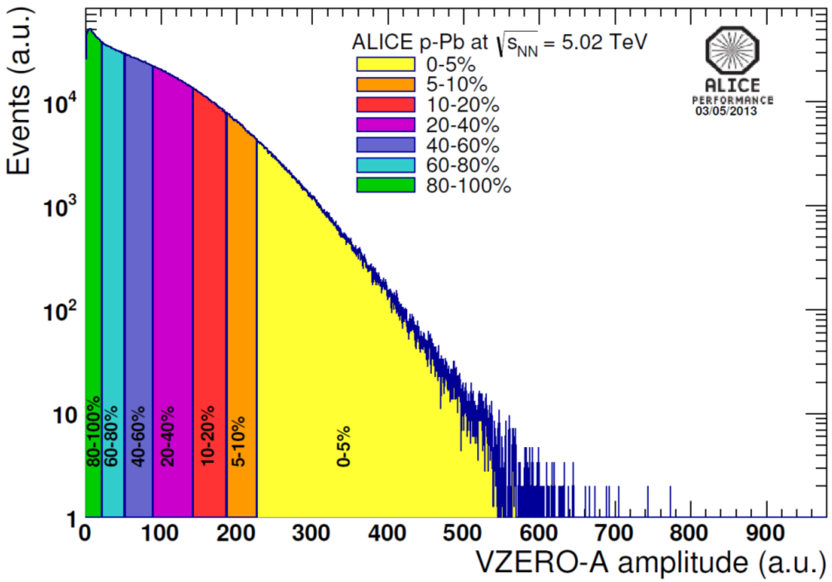


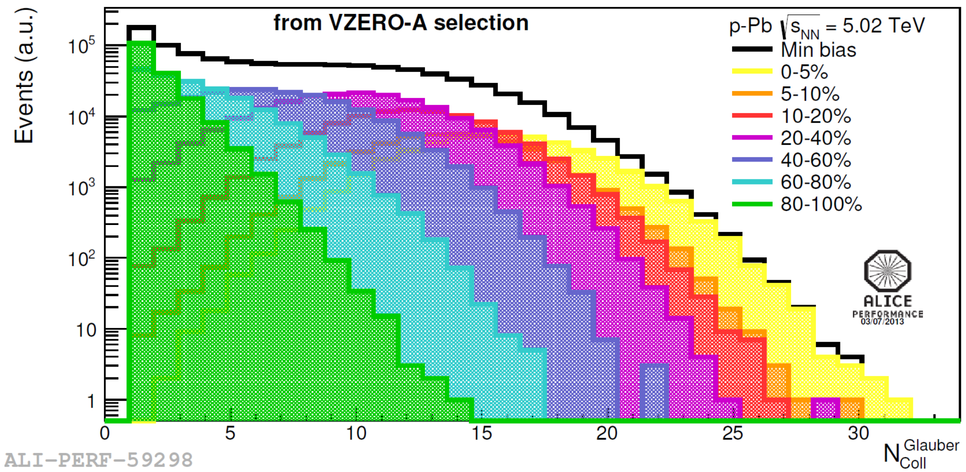


"Centrality" in p-Pb

- Estimator: V0A
  - In p-Pb: multiplicity in Pb hemisphere
- Multiplicity → geometry (Glauber)
  - Number of binary collisions
  - Large RMS → events with same N_{coll} fall in different multiplicity classes
- Bias in binary scaling for multiplicity classes

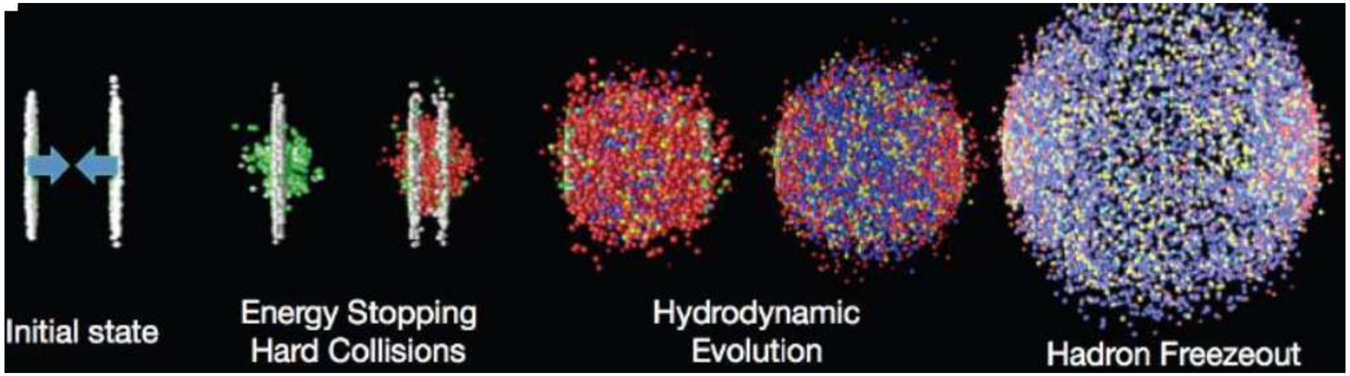






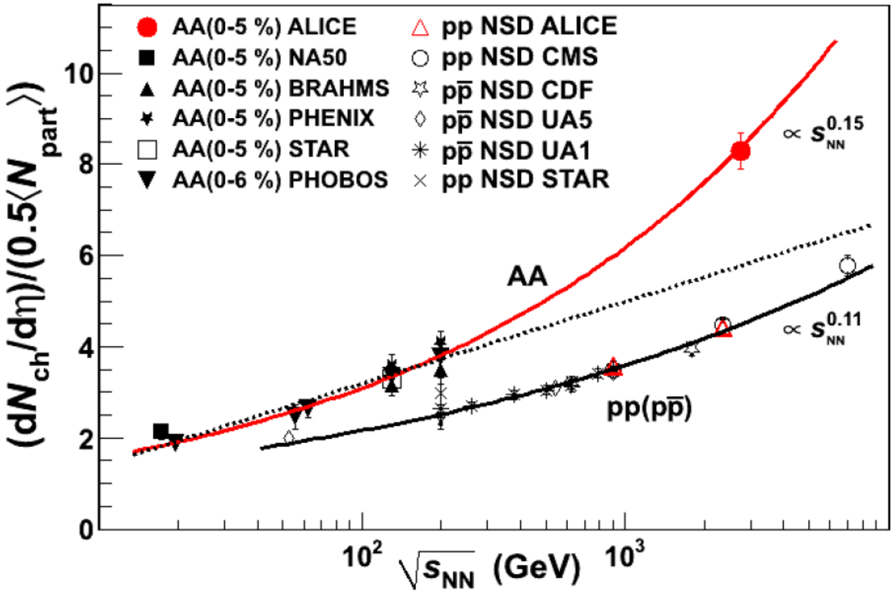
Correlation between geometry and multiplicity is very weak!
For p-Pb we present results in
V0A multiplicity intervals

Bulk properties

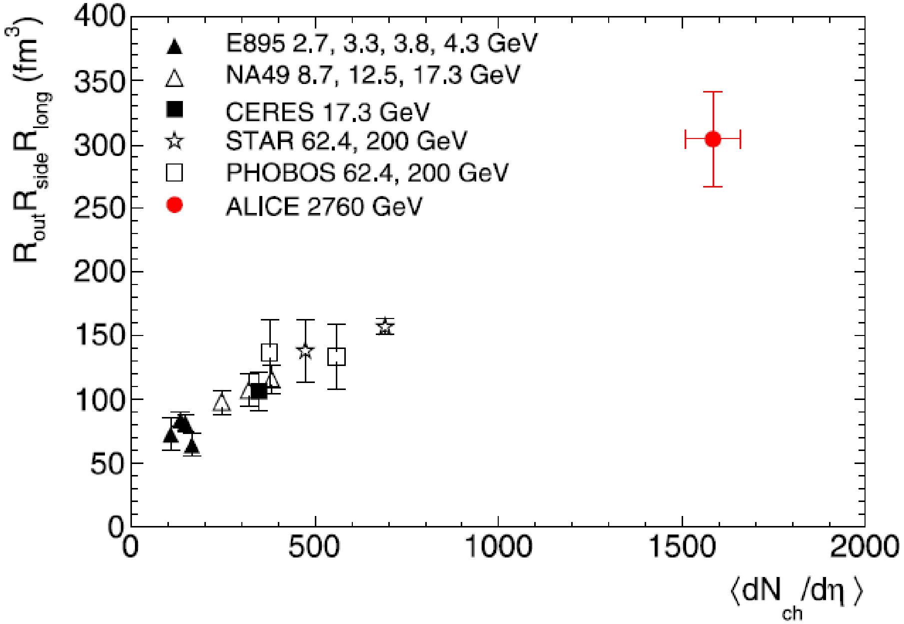


Particle multiplicity and system size

PRL105 (2010) 252301



PLB696 (2011) 328



For $\sqrt{s_{NN}}$=2.76 TeV Pb+Pb, 0-5% central, |η|<0.5

2 dNch/dη / <Npart> = 8.3 ± 0.4 (sys.)

for the most central collisions: ~ 1600 charged particles per unit of η

log extrapolation fails

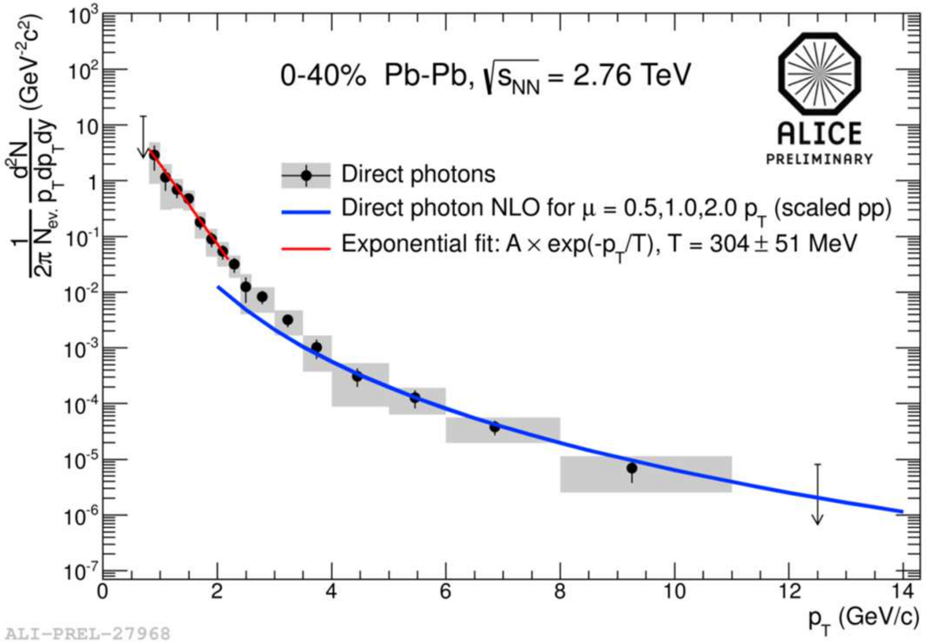
Multiplicity ~ 2 x N_{RHIC}
Energy density ~ 3 × ε_{RHIC}

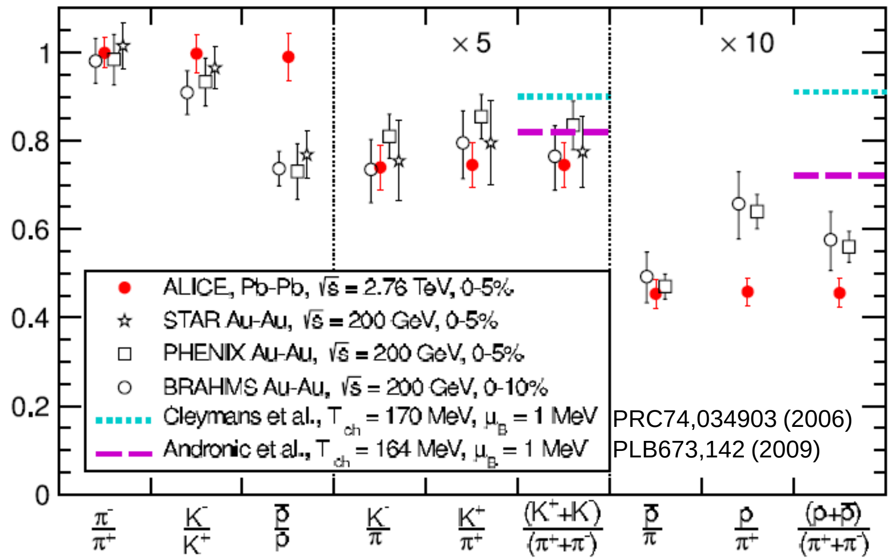
Volume at freeze out
$(2\pi)^{3/2} R_{out} R_{side} R_{long}$ ~ 5000 fm^3
Lifetime from collision to freeze out extracted from R_{long} ~ 10 fm/c

Volume ~ 2 x V_{RHIC}
Lifetime ~ 20 % longer than at RHIC

Direct photon spectrum and particle species

PRL 109, 252301 (2013)





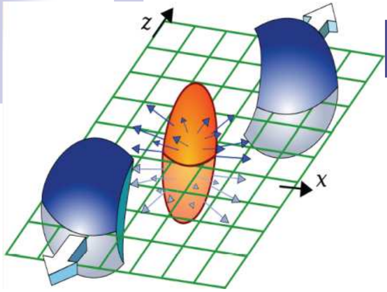
- For 0-40% Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
- Exponential fit for p_T < 2.2 GeV/c

⇒ inv. slope T = 304 ± 51 MeV

⇒ Initial temperature T_{init} = 500-600 MeV

- "temperature" ~ 300 MeV → largest ever man-made
- PHENIX: T = 221±19±19 MeV for 0-20% Au-Au at $\sqrt{s_{NN}}$ = 200 GeV

- Hadron species abundances described by thermal model
- But "tension" for protons
- Proton yield does not follow the results from statistical hadronization model when assuming a common chemical freeze-out temperature



Flow

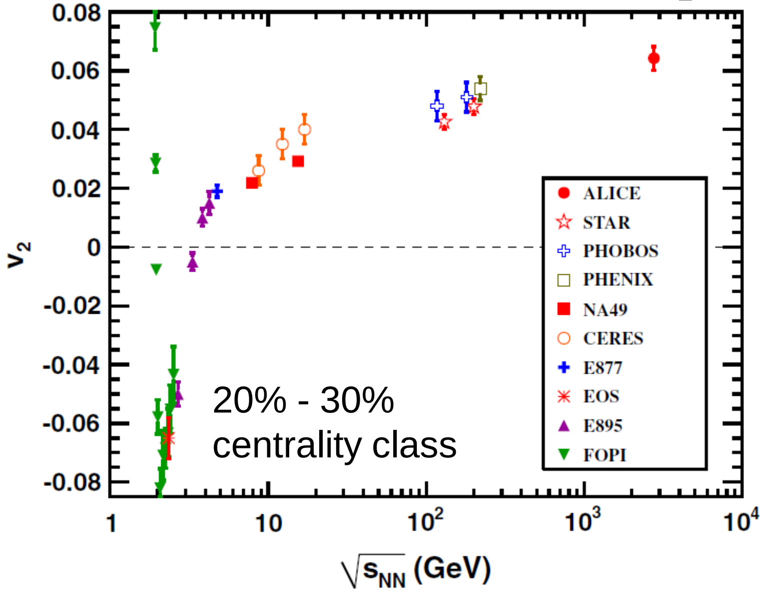
Larger flow than at RHIC
For anisotropic flow: larger p_T integrated v_2
For radial flow: 10% larger expansion velocity

- Spatial asymmetry → pressure gradients → momentum anisotropy
- To quantify the asymmetry:

  → Fourier expansion of the angular distribution:

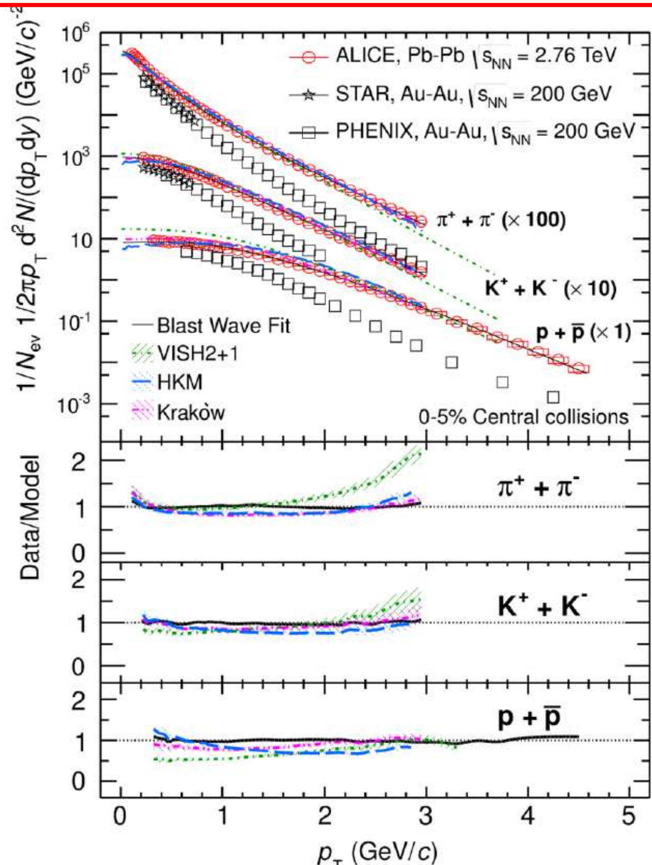
$$\frac{d^2N}{dp_T d\varphi} \approx 1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots$$

  - in the central detector region (~ 90º) → v_1 ~ 0 → asymmetry quantified with v_2



PRL 105, 252302 (2010)

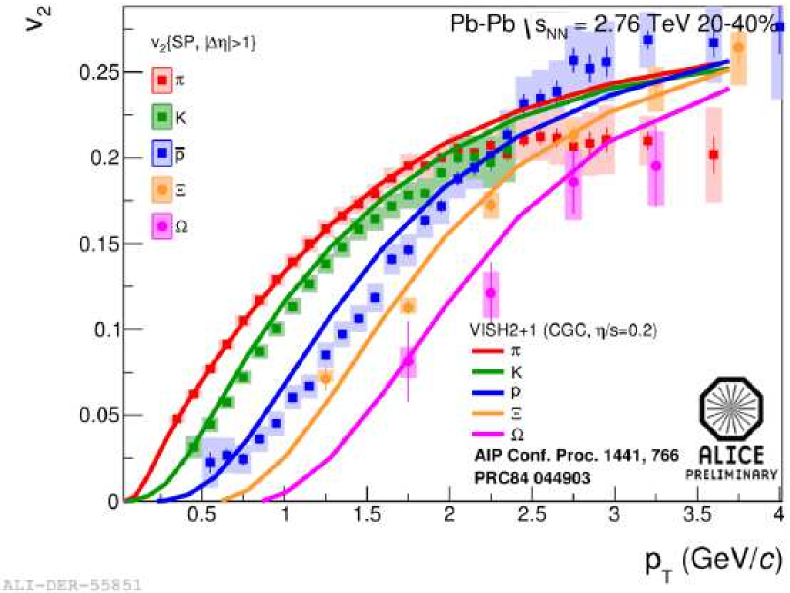
PRL 109,252301 (2013)

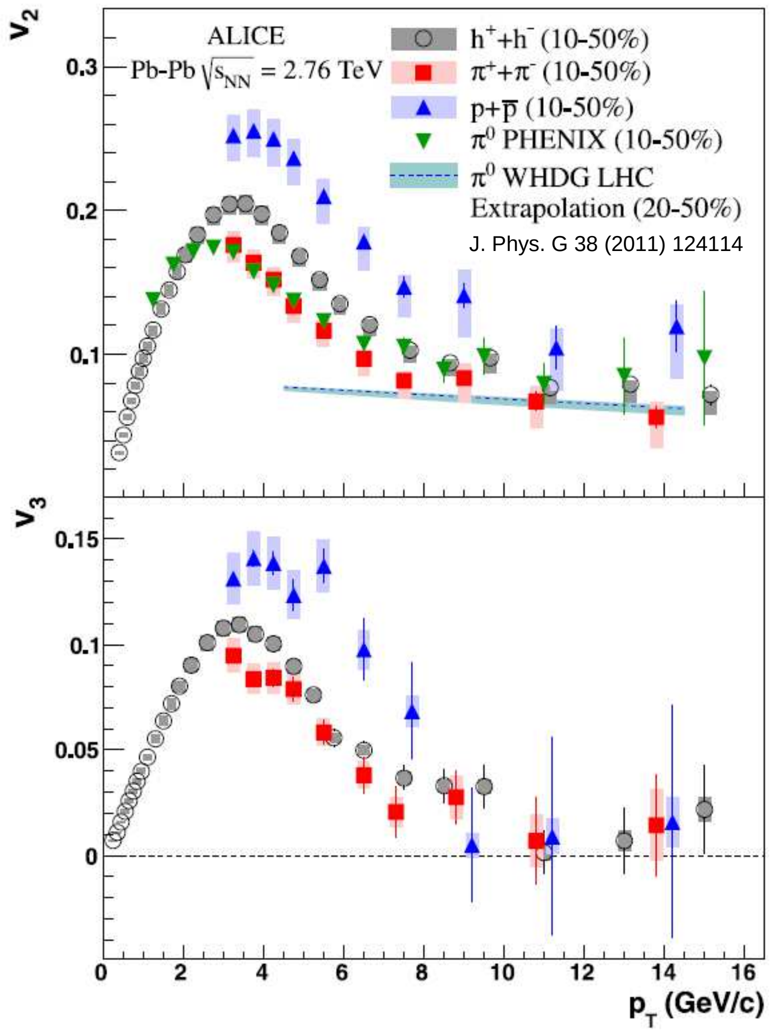


Blast Wave: PRC48,2462 (1993)
VISH2+1: PRC 84,044903 (2011)
HKM: JPG38,124059 (2011),arXiv:1204.5351
Krakow: PRC85,034901 (2012)

Identified particle v_n

PLB 719,18 (2013)

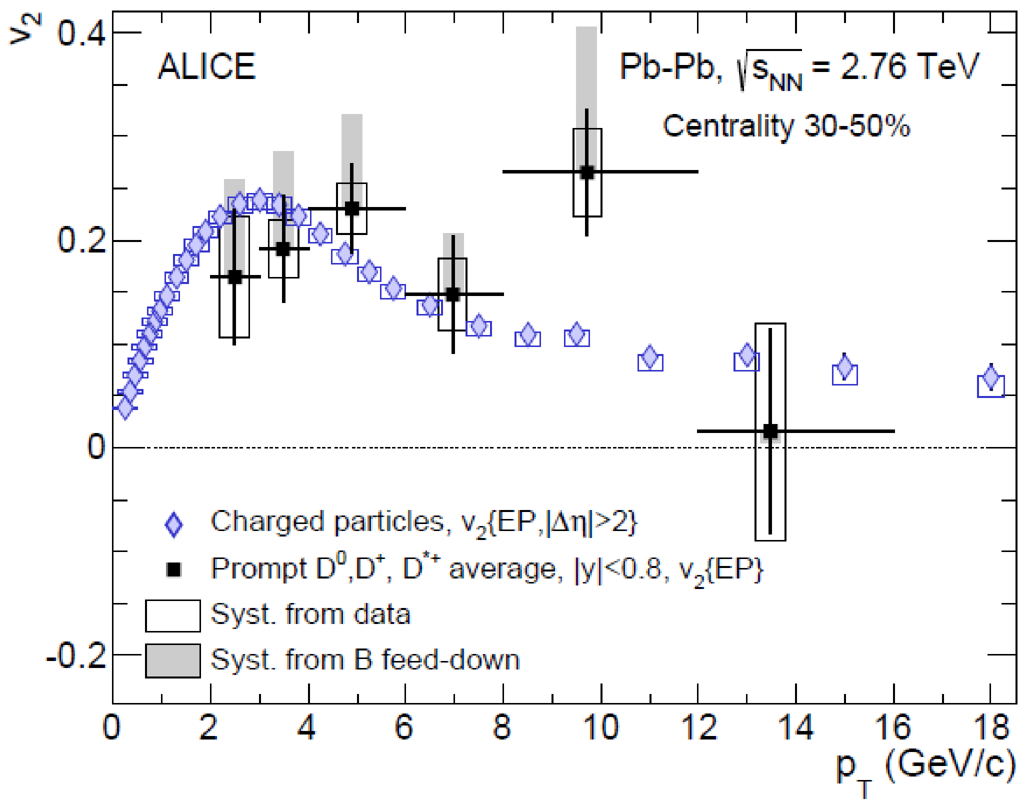




- Identified particle elliptic flow
  - Mass ordering at low pT described by hydrodynamics
  - Particle species dependence persists up to p_T=8 GeV/c
- Small increase of flow in comparison to RHIC

Charm Quarks Flow

PRL 111,102301 (2013)

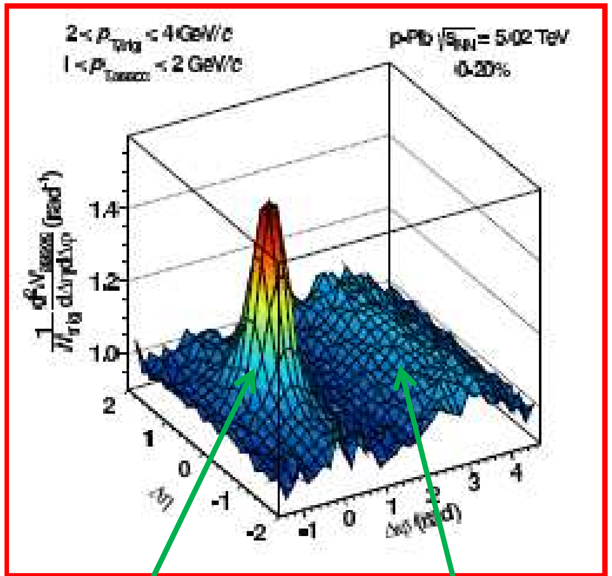


- D meson $v_2>0$
- Similar v_2 as pions
- Charm quarks also flow:
  - At low p_T due to the initial spatial anisotropy
  - At high p_T due to energy loss

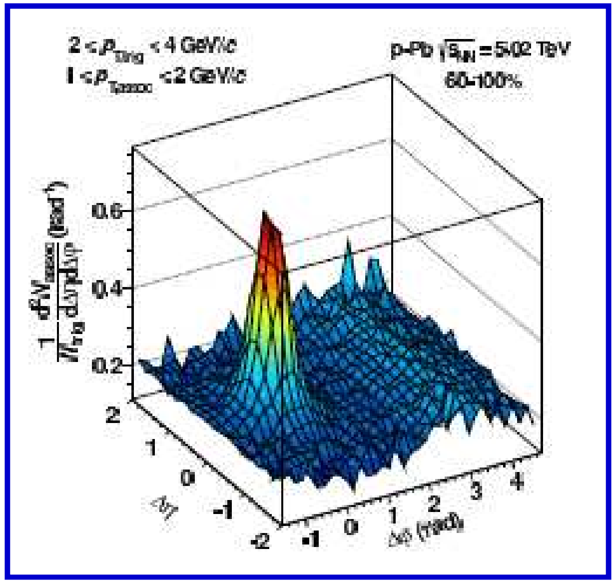
p-Pb news

Hadron-hadron correlations in p-Pb

High multiplicity

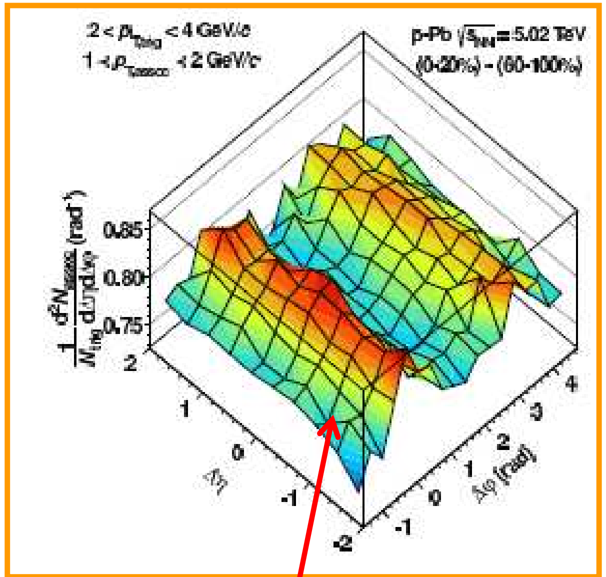


Low multiplicity

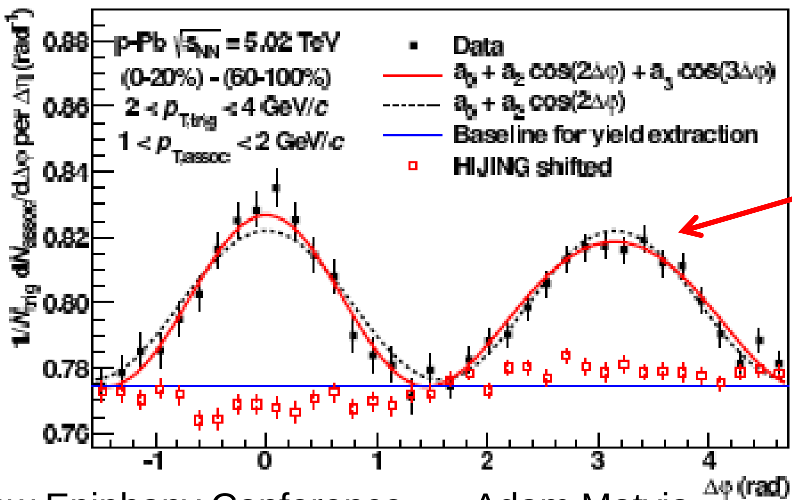


PLB719,29 (2013)

High – Low multiplicity



near side away side



Effect can be explained by both hydro and CGC

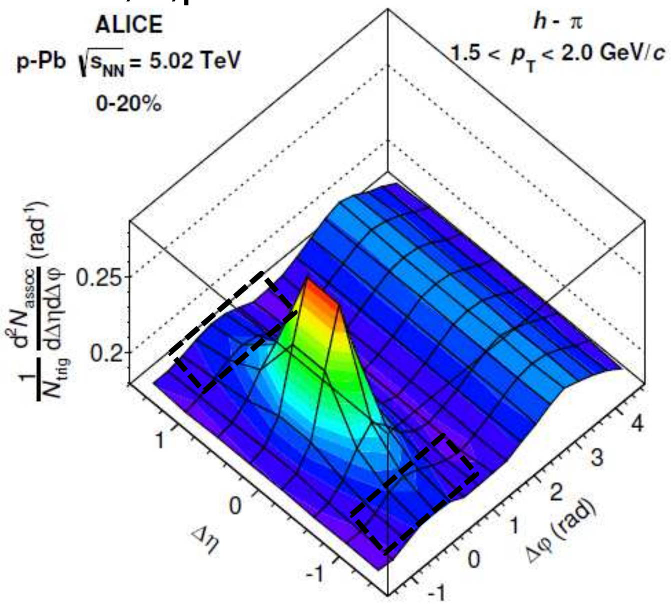
Bozek et al., PLB718,1557 (2013)

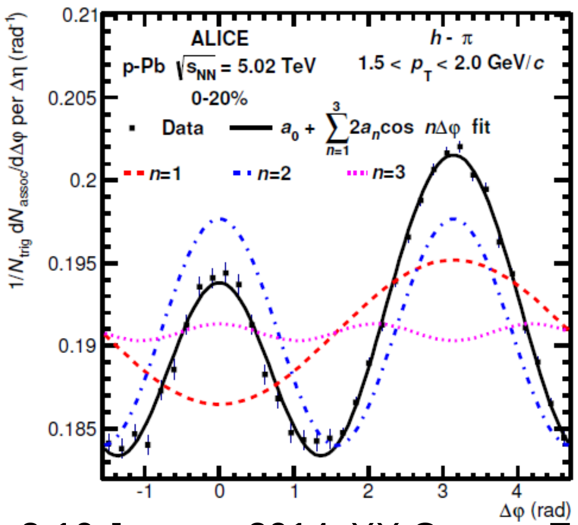
Dustling et al., PRD87,094034 (2013)

Double ridge structure = long-range angular correlations in the near and away side

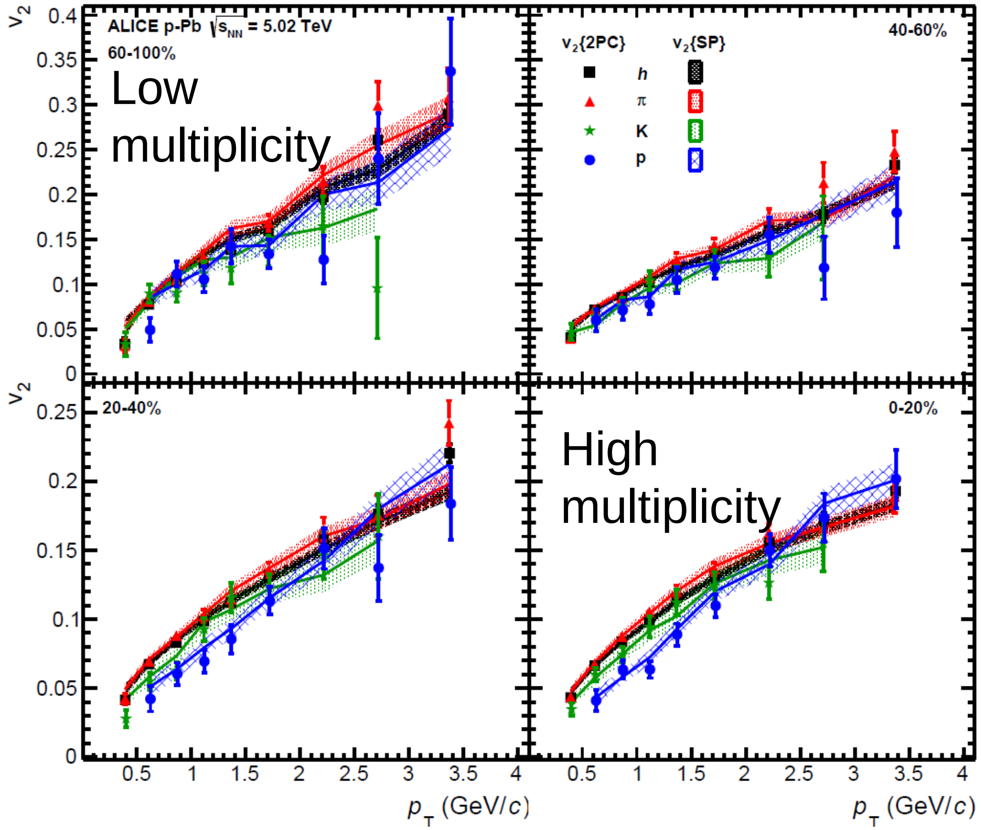
Double ridge studies

h - π,K,p correlations



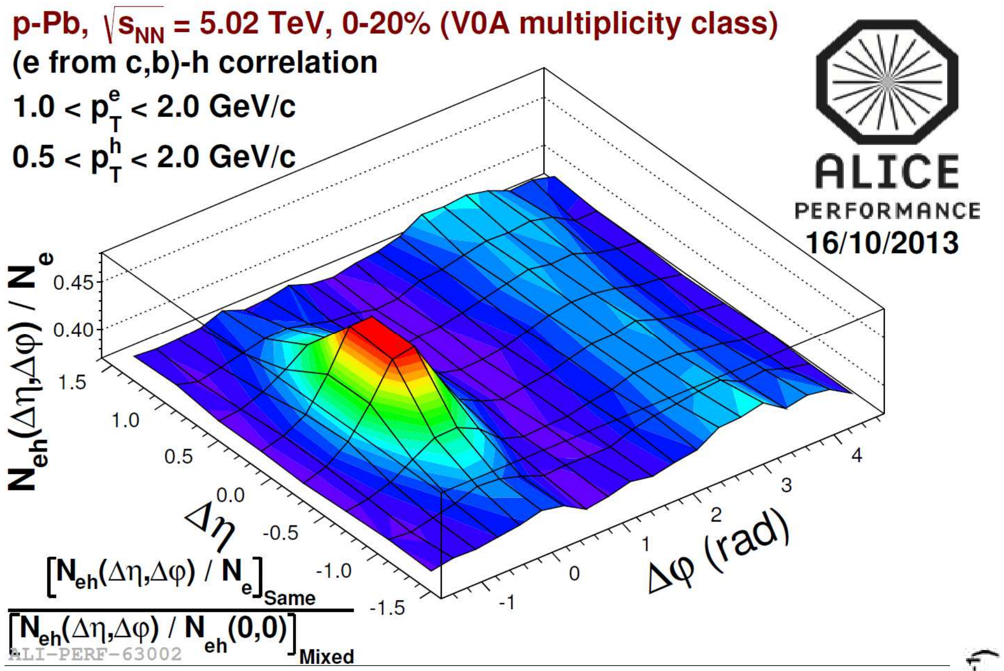


PLB 726 (2013) 164



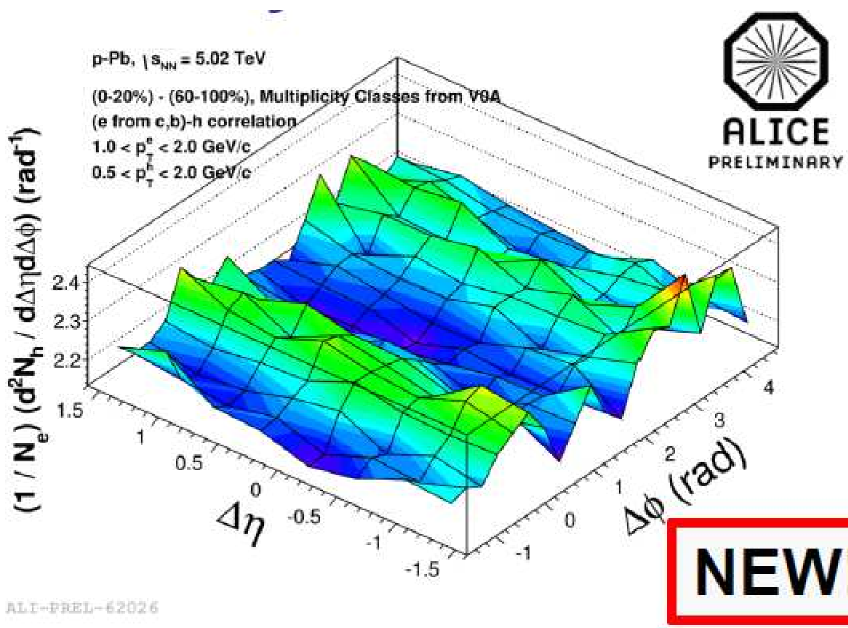
- Mass ordering at low pT
- Crossing at $p_T \approx 2$GeV/c
- Silimar to Pb-Pb

HF decay $e^{\pm}$ – h correlations



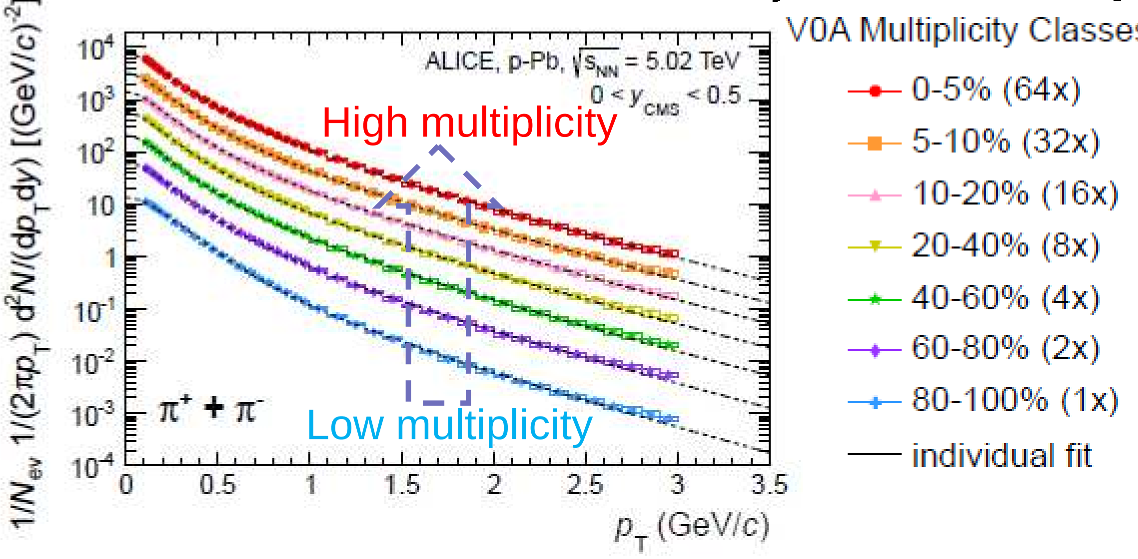
Double ridge seen also in the correlation of heavy flavour decay electrons with hadrons

$\Rightarrow$ mechanism responsible for double ridge also works for heavy flavours

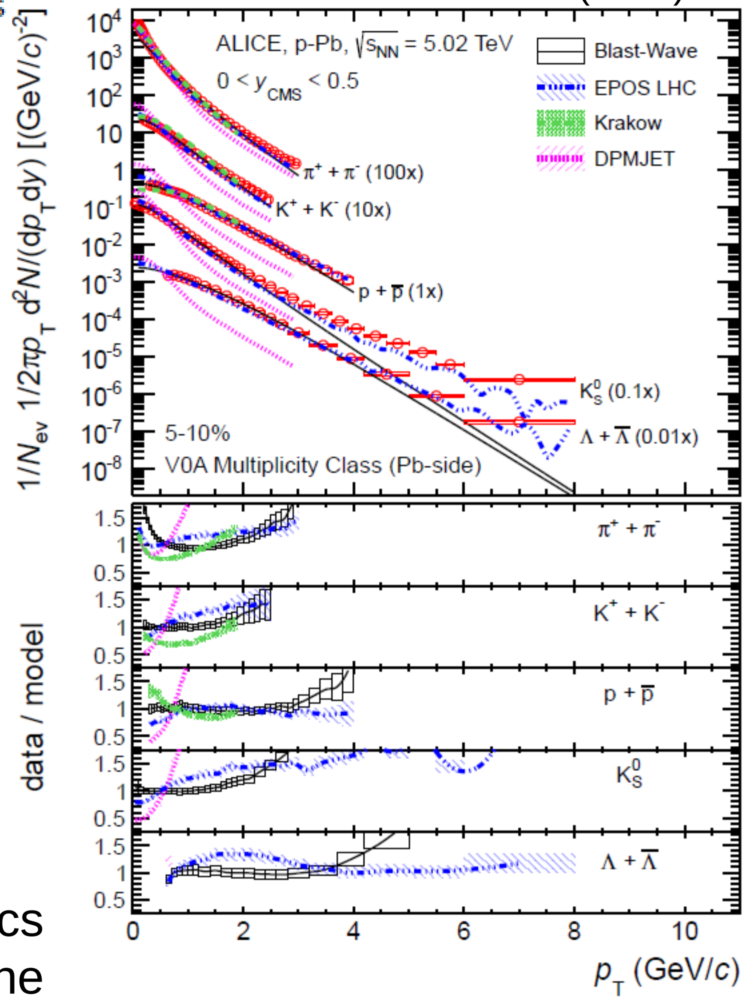


NEW!

Identified particles p_T spectra



PLB 728 (2014) 25



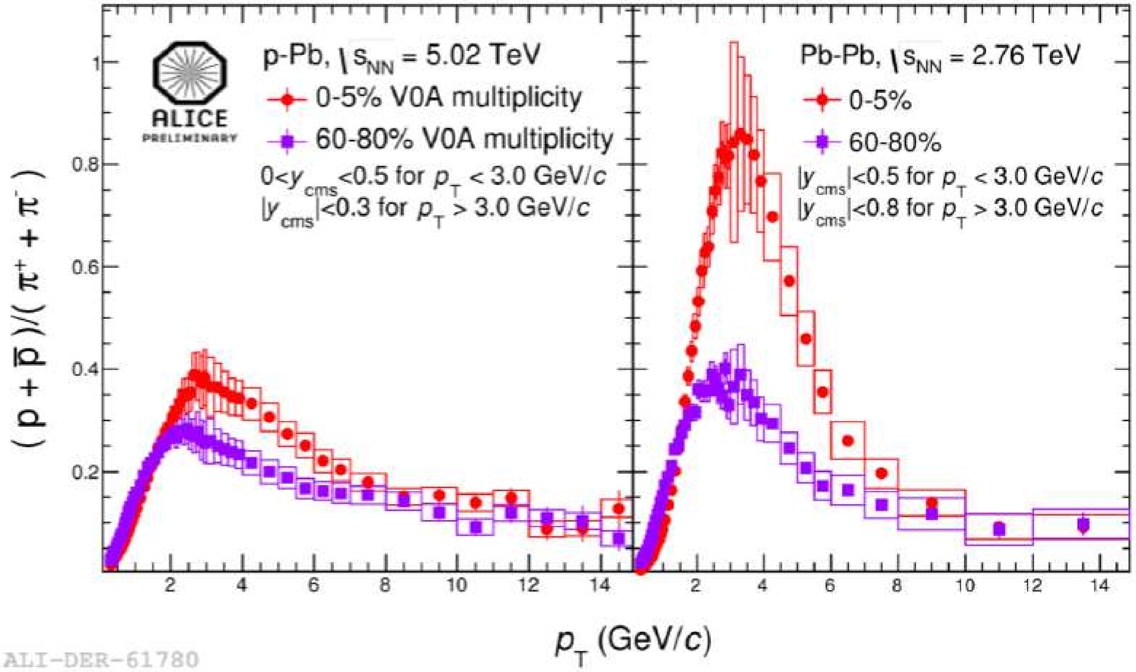
- Spectra becomes harder with multiplicity
- Effect increases with the mass of the particle

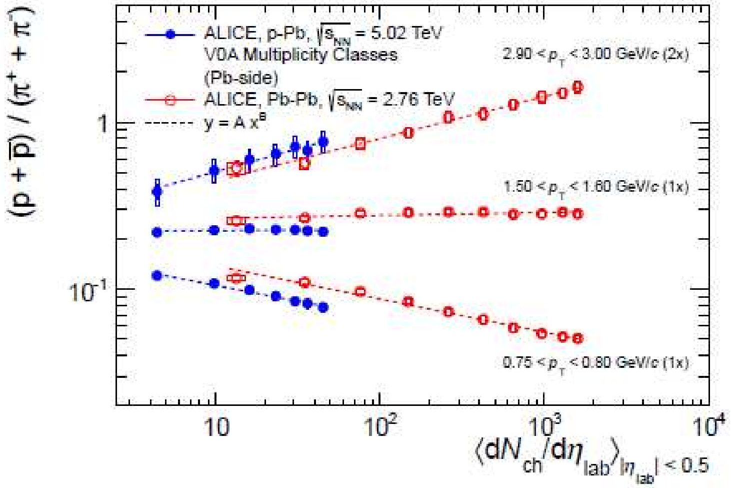
Models including hydrodynamics give a better description of the spectra

Blast-Wave: PRC 48,2462 (1993)
EPOS LHC: arXiv:1306.0121 [hep-ph]
Krakow: PRC 85,014911 (2012)
DPMJET: arXiv:hep-ph/0012252

PRC 88,044910 (2013)

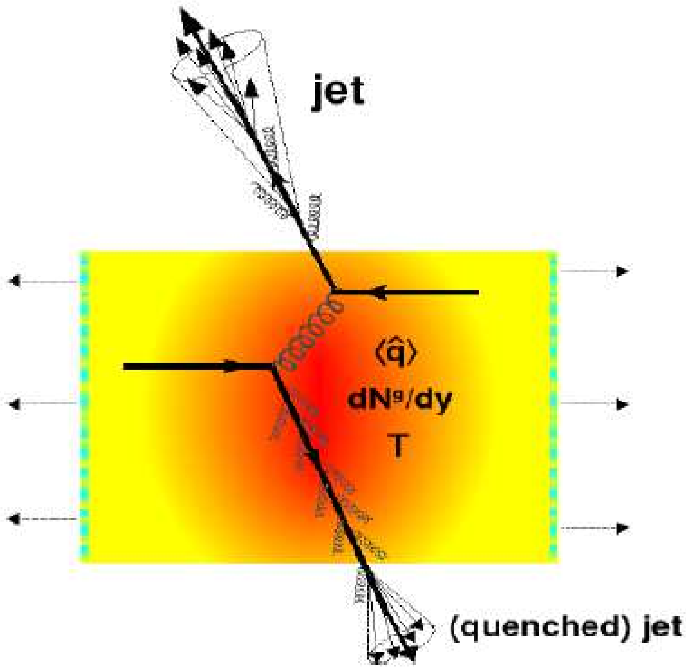
Barion to meson ratio





- Similar evolution of barion/meson ratio vs. p_T with multiplicity in Pb-Pb and p-Pb collisions
  - Enhancement at intermediate p_T
  - Pb-Pb results understood in term of collective radial expansion and hadronization via quark recombination
  - Different magnitude of the effect on p-Pb and Pb-Pb
  - Medium effect disappears at large p_T
  - In a given p_T bin the ratio as a function of $dN_{ch}/d\eta$ follows a power law with the same exponent in p-Pb and Pb-Pb

Jet quenching

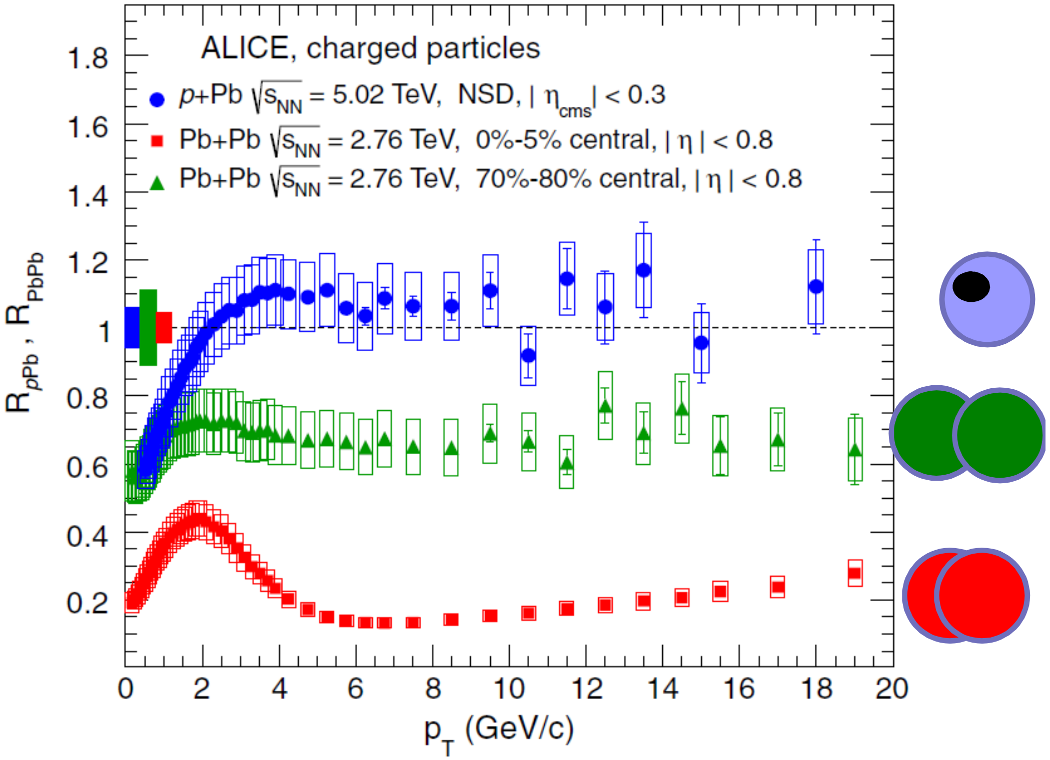


Nuclear Modification Factor

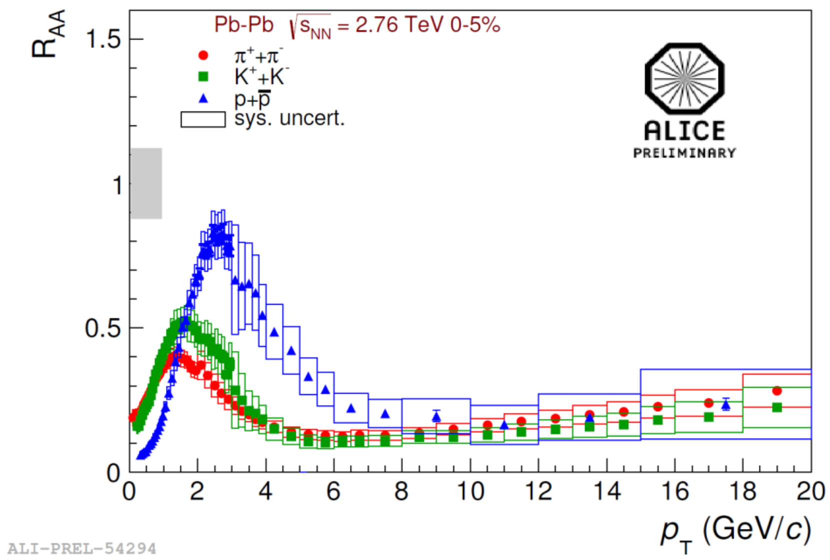
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \, dN_{pp}/dp_T}$$

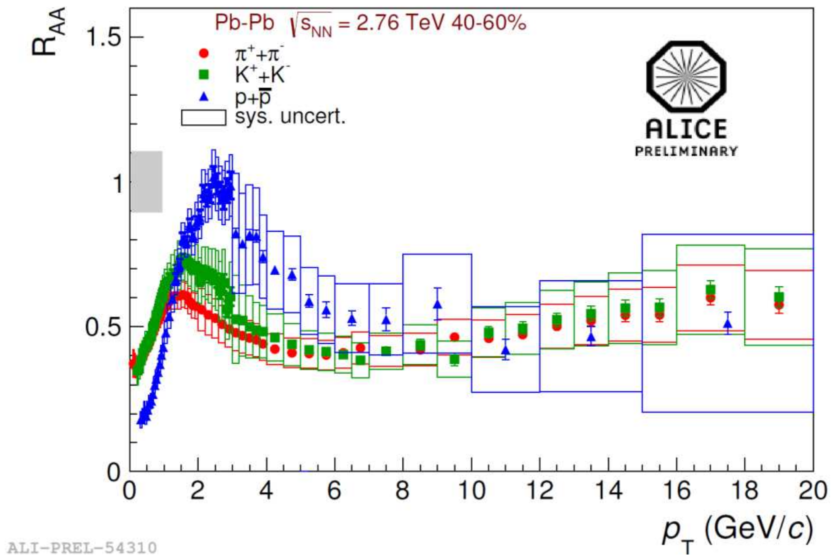
- Judges medium effect
- $R_{AA}=1 \rightarrow$ no modification
- Suppression observed in Pb-Pb collisions
  - Centrality dependent
  - Energy loss
- p-Pb result indicates that suppression is a final state effect

PRL 110, 082302 (2013)



Suppression of π/K/p



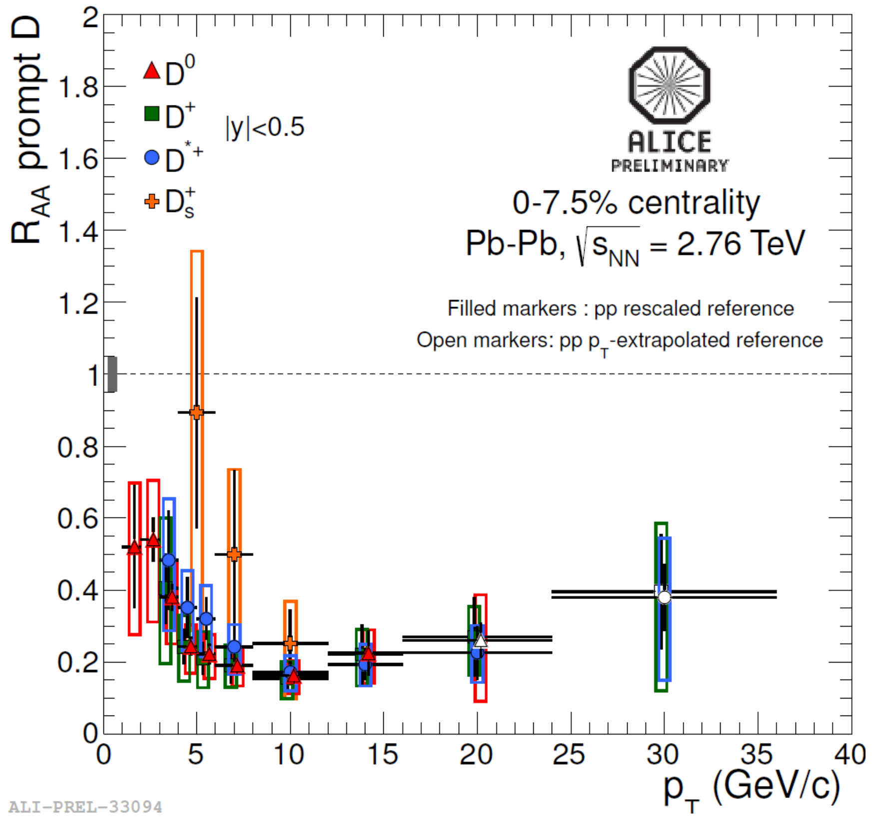


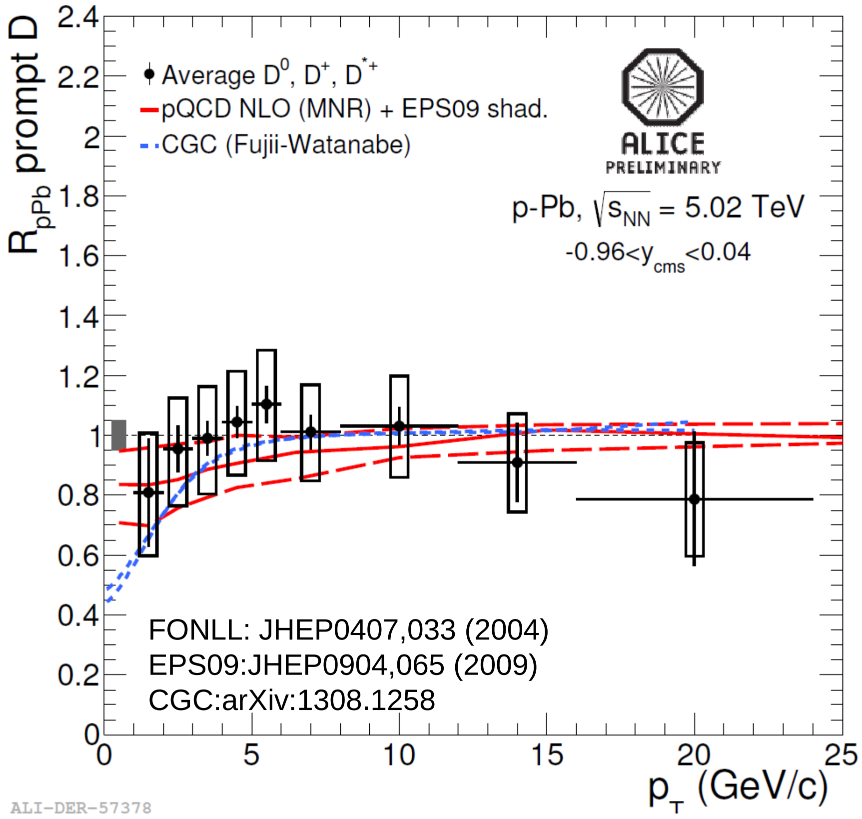
- Equal suppression for pions, kaons and protons for $p_T > 8$ GeV/c

⇒ Particle composition at high p_T not affected by the medium

Heavy flavours

More in Cristina Bedda talk



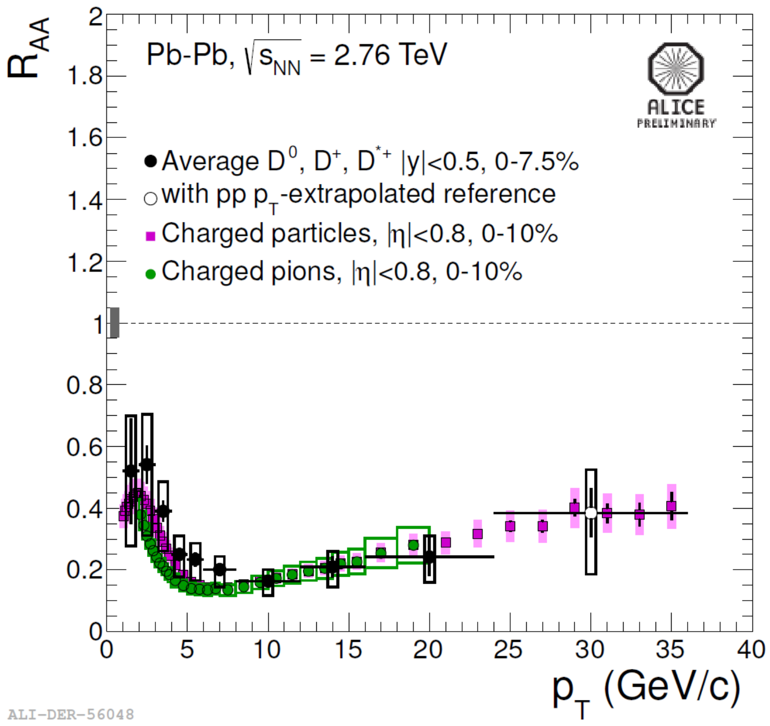


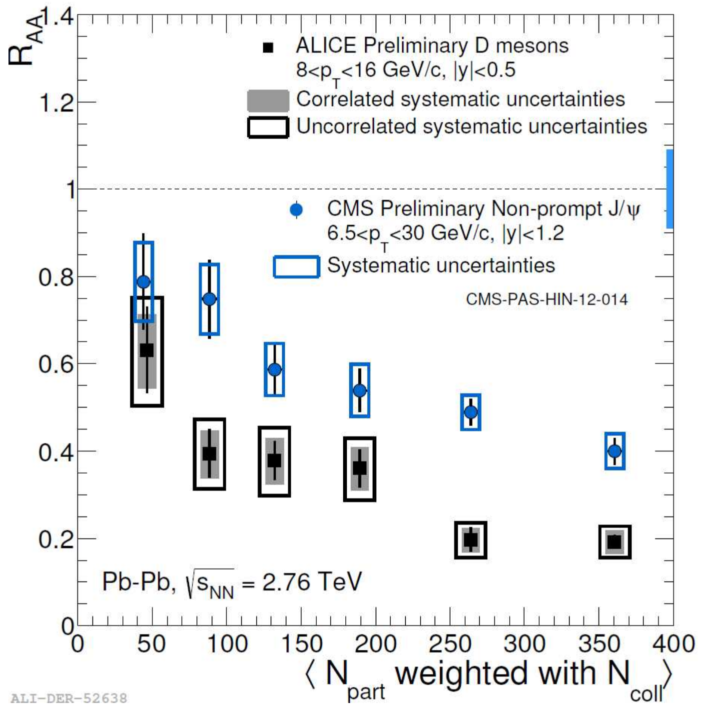
- Suppression of all prompt D meson yield
- No conclusion on expected enhancement of D_S/D at low p_T

- Consistent with unity
- Consistent with models that include CNM effects (CGC, shadowing)

Hierarchy in energy loss?

- Expectation from radiative energy loss: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Could be reflected in hierarchy of R_{AA}: $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$



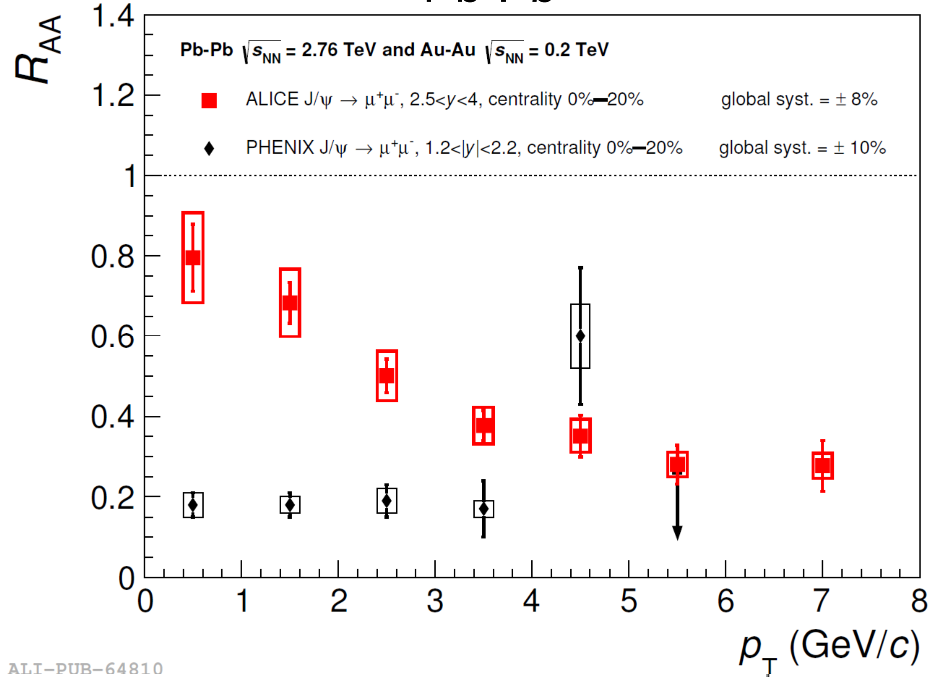


$R_{AA}(D) \sim R_{AA}(\pi)$
(but different fragmentation and p_T spectra)

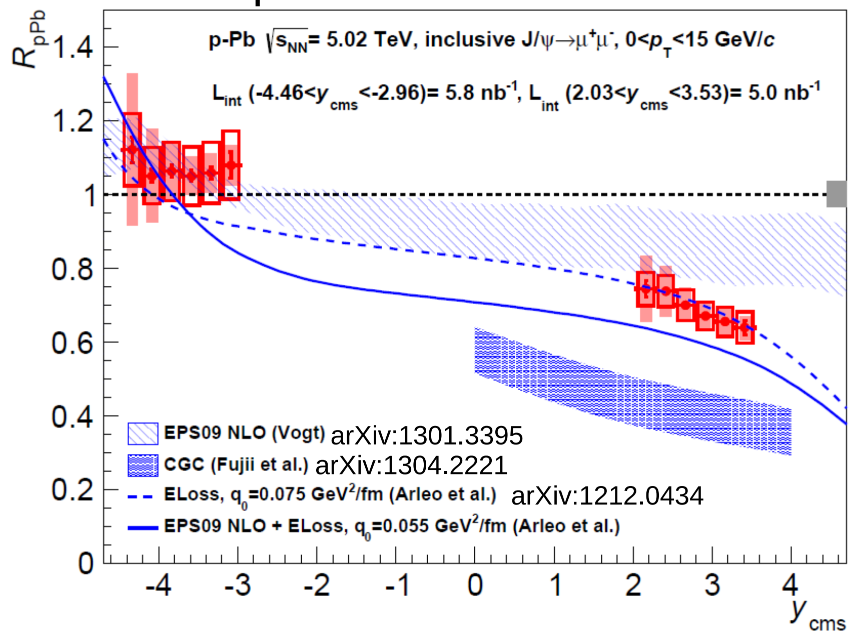
$R_{AA}(B) > R_{AA}(D)$
(but different fragmentation and p_T spectra)

J/ψ

Submitted to arXiv Pb-Pb



p-Pb arXiv:1308.6726

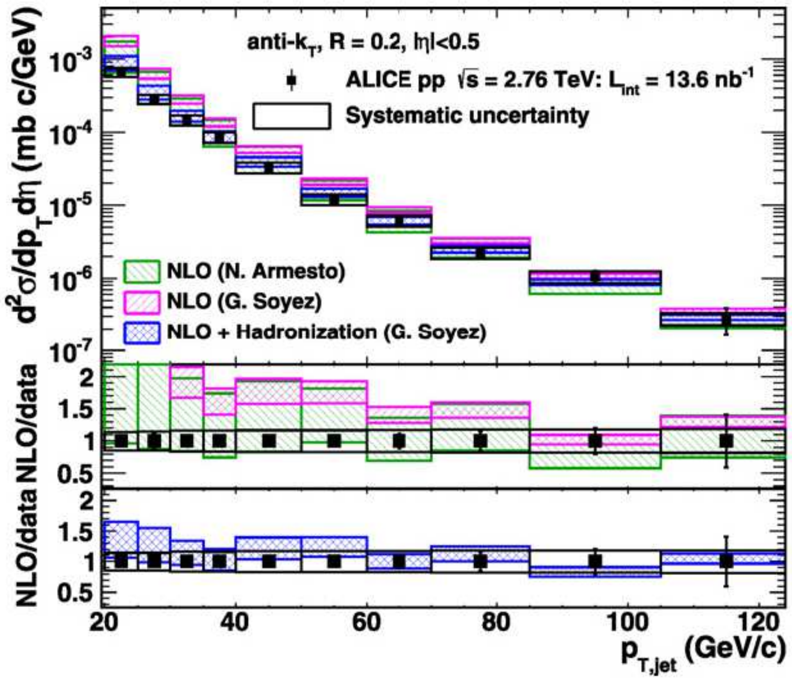


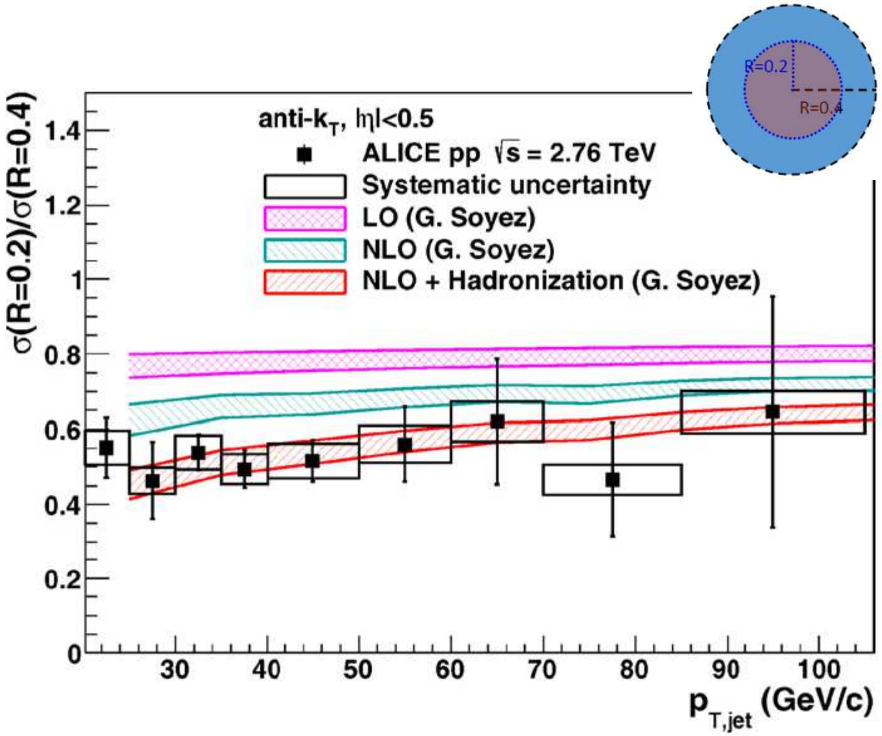
- J/ψ less suppressed at low p_T than at high p_T
- Different p_T dependence of R_{AA} at RHIC and LHC

- R_{pPb} = 1 for Pb going side (backward)
- Suppression observed at forward and mid rapidity
- Rapidity dependence qualitatively described by models
- CGC less favored

Jet cross-section in pp $\sqrt{s_{NN}}=2.76$

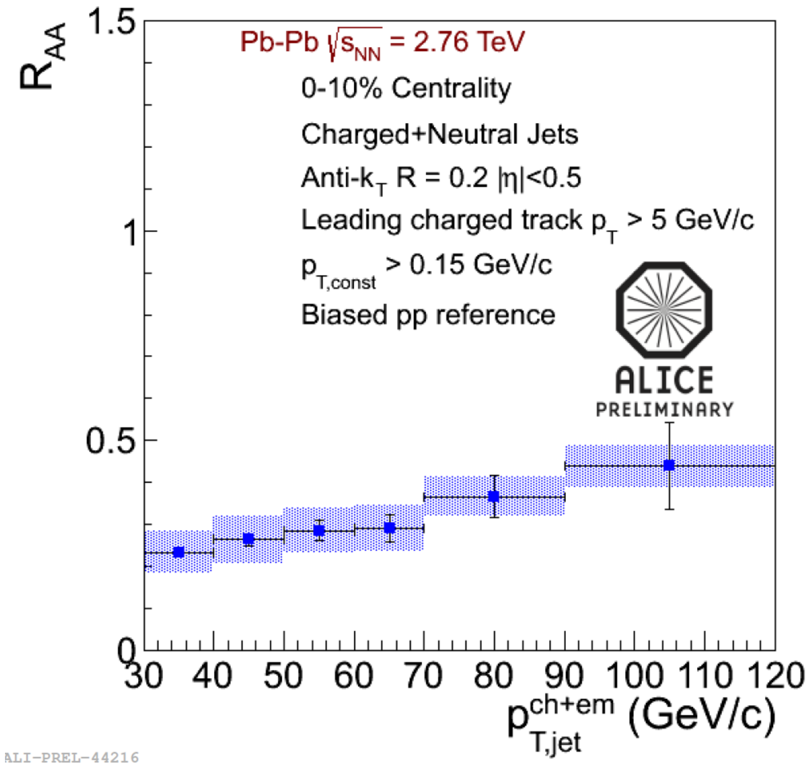
PLB 722, 4 (2013)

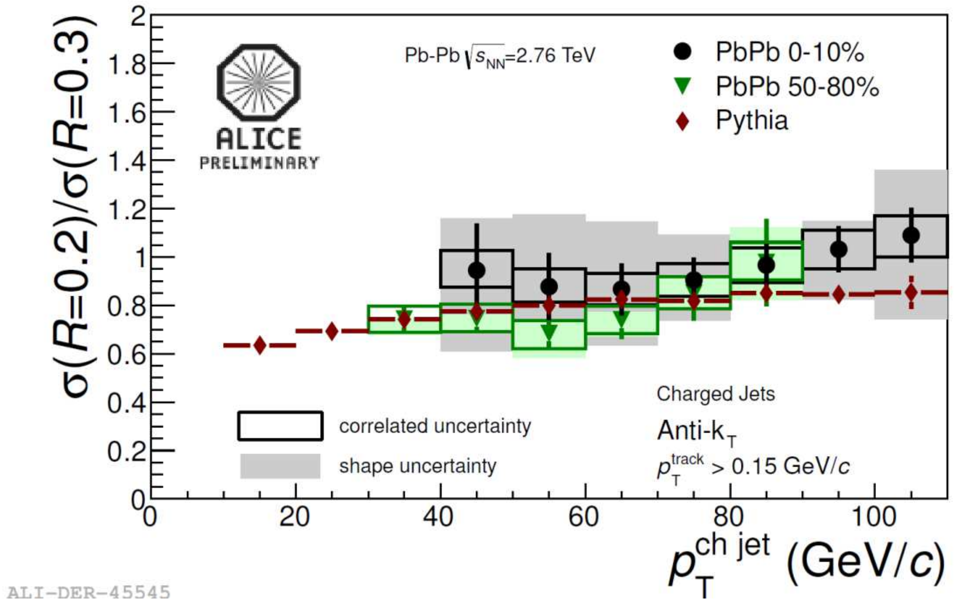




- Reference for Pb-Pb data
- Ratio is a sensitive observable to jet broadening
- Hadronization is needed to describe data

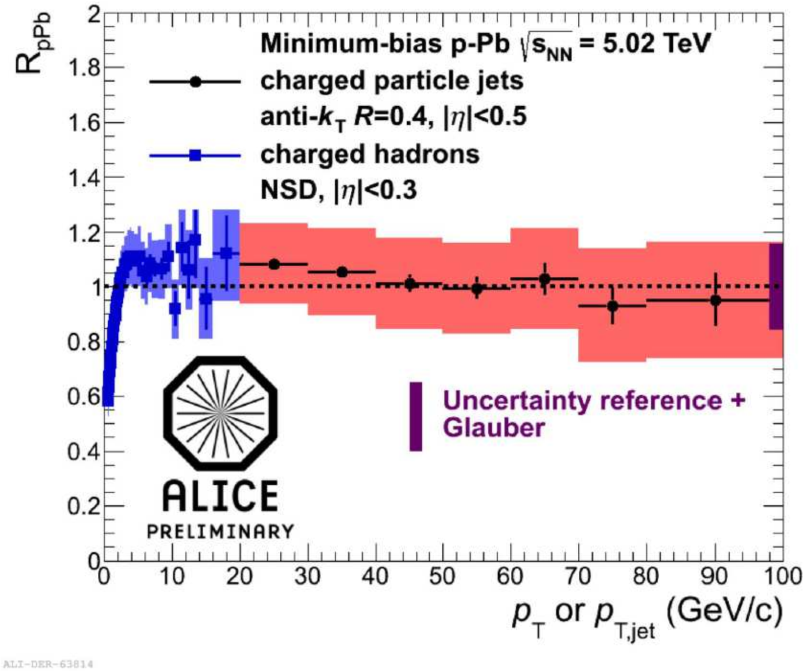
Jets in Pb-Pb

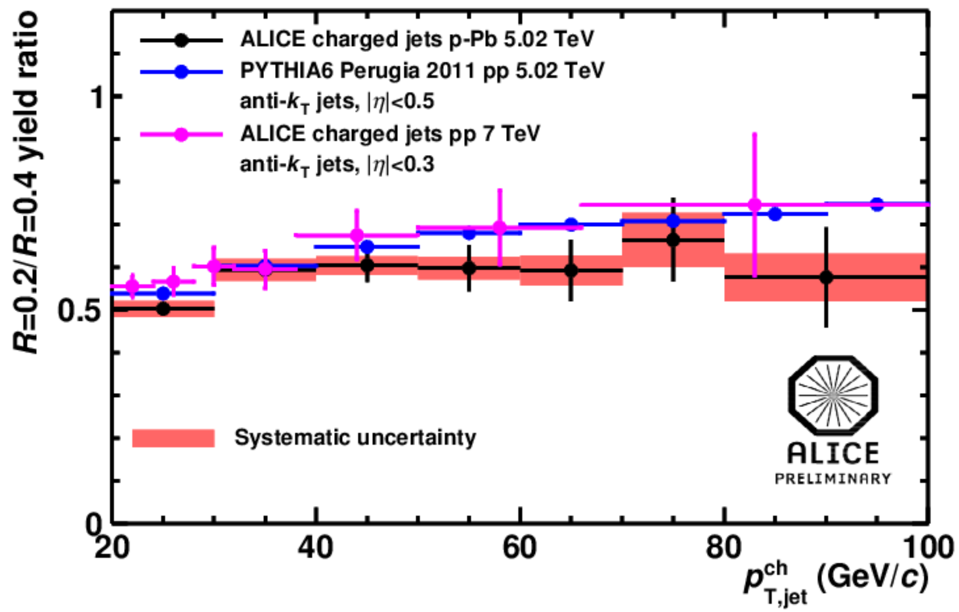




- Unique low p_T range
- Strong suppression of jet yield in most central collisions
- Ratio of jet cross-sections compatible with fragmentation in vacuum (PYTHIA)
  - Sensitive to the profile of jet energy density
  - No evidence of jet shape modification in jet core

Jets in p-Pb





- Nuclear modification factor consistent with unity within uncertainties
- Jet structure ratio consistent with pp one (different energies)
- No CNM effect observed
- Comparison hadrons to jets
  - → Binary scaling holds
  - → Apple to pinaple comparison

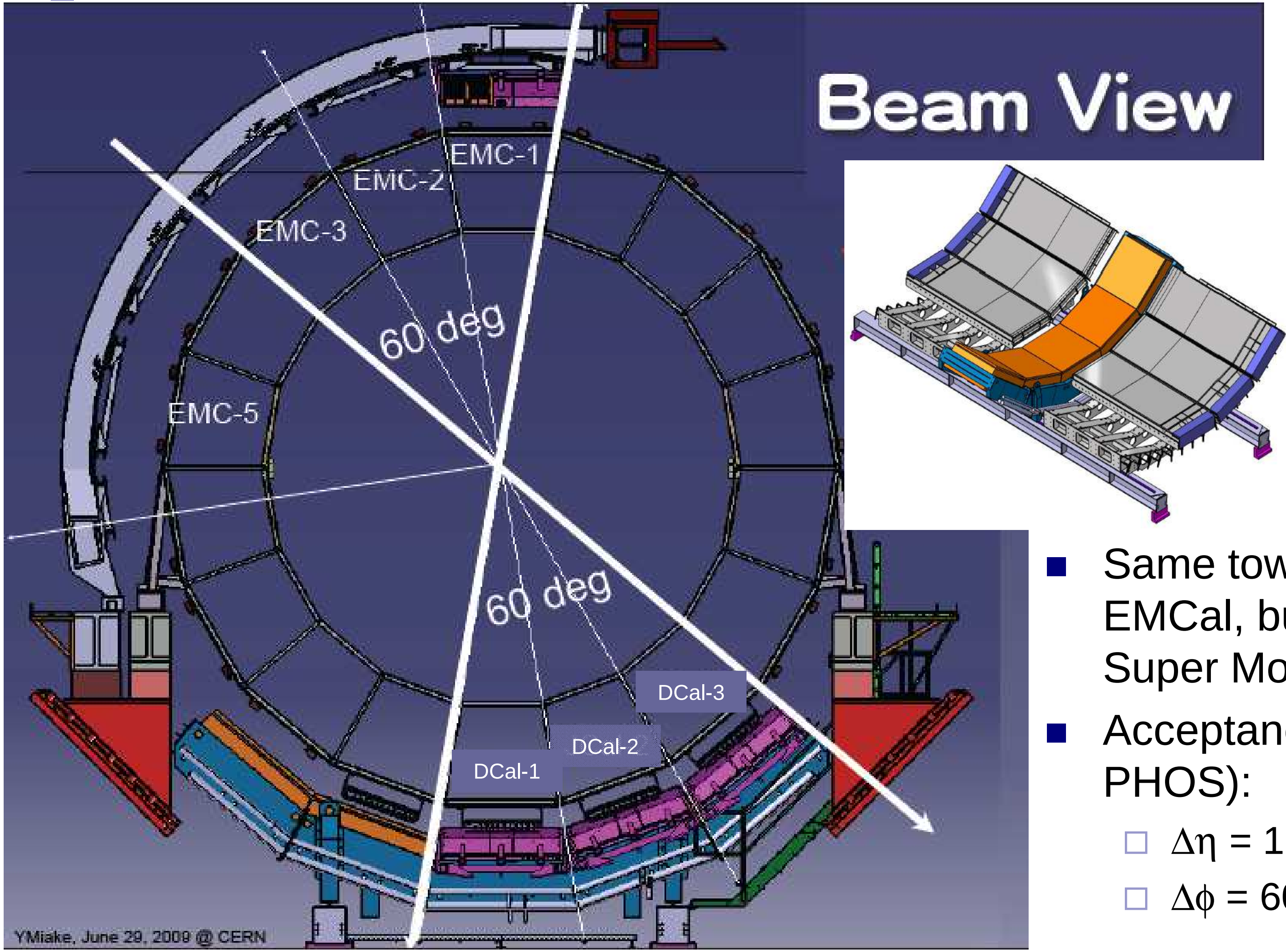
Summary

- Small sample of ALICE results was presented
- Significant progress in QCD matter studies in Pb-Pb collisions
  - bulk production shows the expected strongly collective medium similar to RHIC
  - Strong suppression for hadrons, heavy flavours and jets observed
  - Hints of flavour hierarchy in the QCD transition
  - Jet quenching has little effect on hadr-chemistry and jet structure
  - Hints of b/c energy loss difference
  - v_2 vs p_T mass ordering
- p-Pb
  - More than just a control experiment
  - No evidence of quenching, similar effect were found in pp high multiplicity collisions
  - A symmetric ridge under the jet found in 2 particle correlations
  - Jets are not quenched and are similar to pp jets
- There are a lot of analysis ongoing

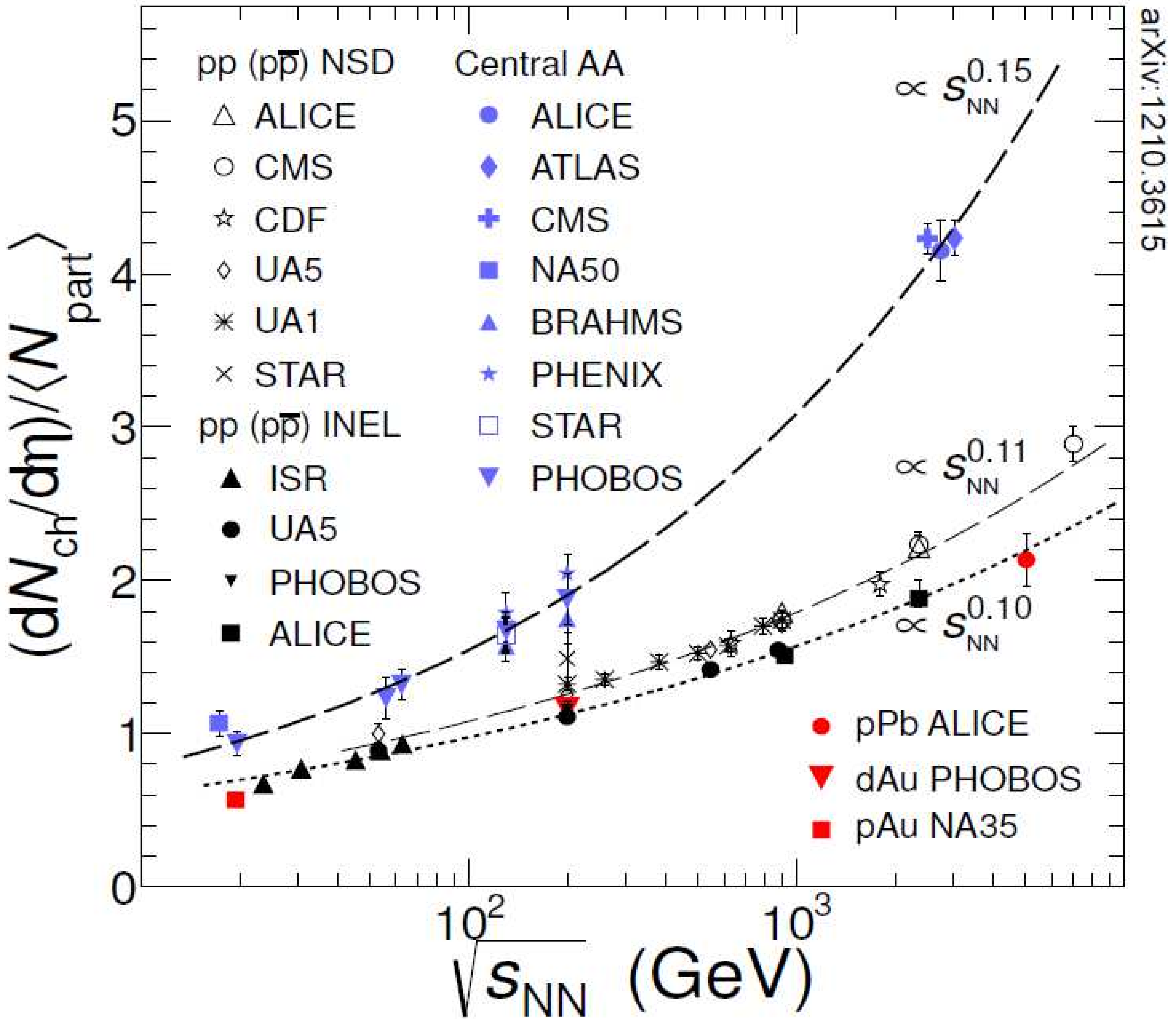
Thank you!

BACKUP

DCal



- Same towers as for EMCal, but shorter Super Modules in η
- Acceptance (including PHOS):
  - $\Delta\eta = 1.4$
  - $\Delta\phi = 60^{o}$

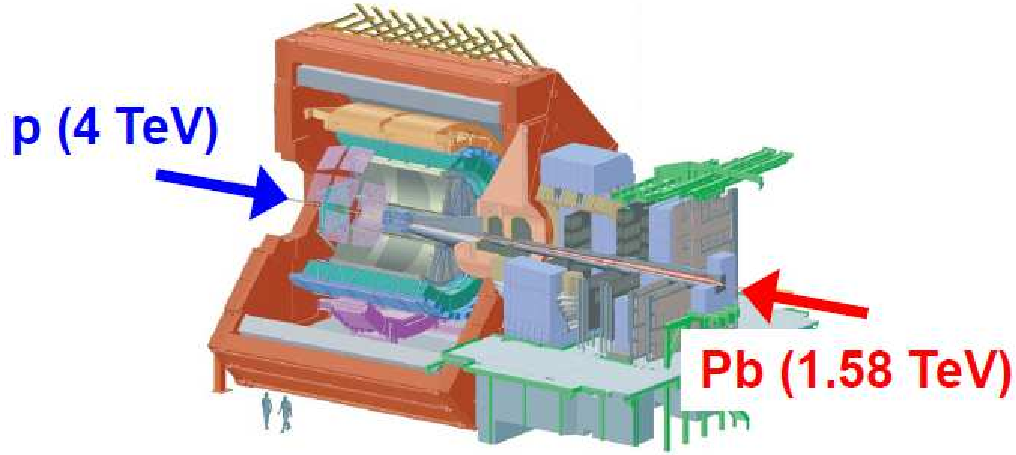


pp (p$\bar{p}$) NSD
ALICE
CMS
CDF
UA5
UA1
STAR
pp (p$\bar{p}$) INEL
ISR
UA5
PHOBOS
ALICE
Central AA
ALICE
ATLAS
CMS
NA50
BRAHMS
PHENIX
STAR
PHOBOS
$\propto s_{NN}^{0.15}$
$\propto s_{NN}^{0.11}$
$\propto s_{NN}^{0.10}$
pPb ALICE
dAu PHOBOS
pAu NA35
arXiv:1210.3615
$(dN_{ch}/d\eta)/\langle N_{part} \rangle$
$\sqrt{s_{NN}}$ (GeV)

p-Pb and Pb-p samples

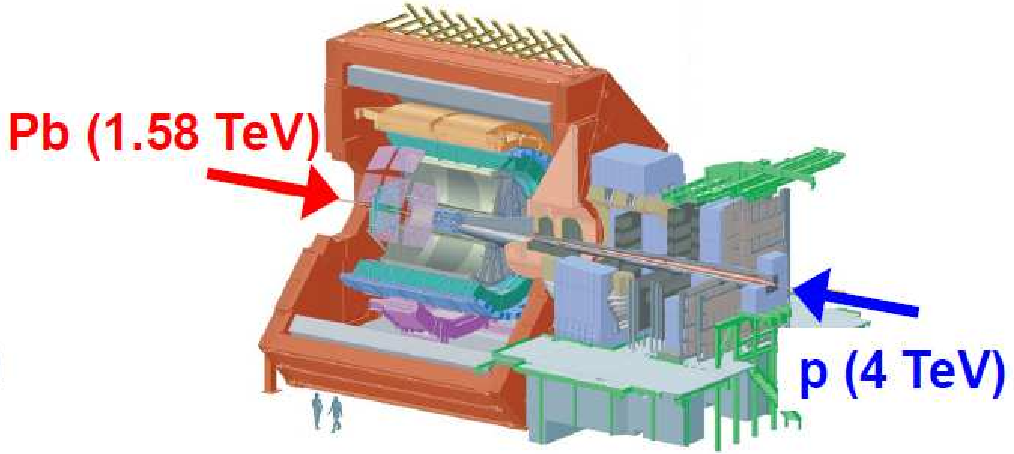
- p-Pb
  - ⇨proton going towards muon arm

Most of the results shown in this presentation from the p-Pb sample

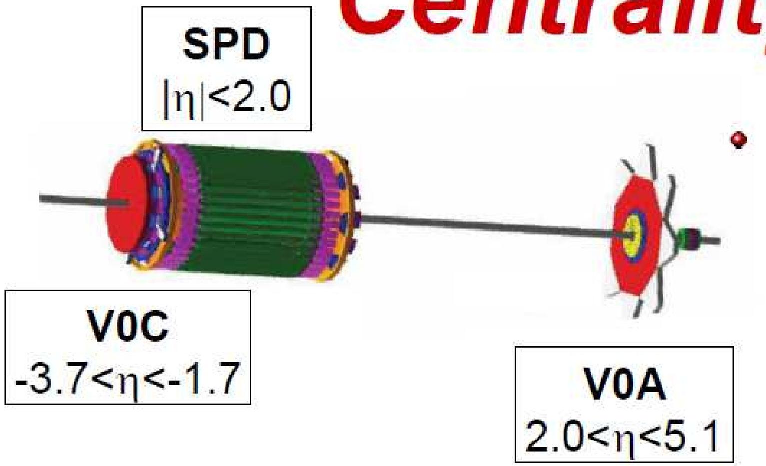


y_{CMS} = 0.465 in the p-beam direction

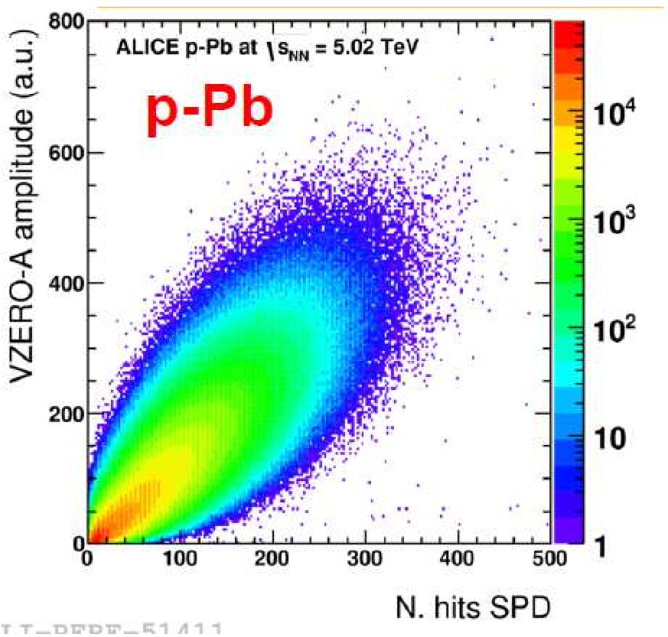
- Pb-p
  - ⇨Pb nucleus going towards muon arm

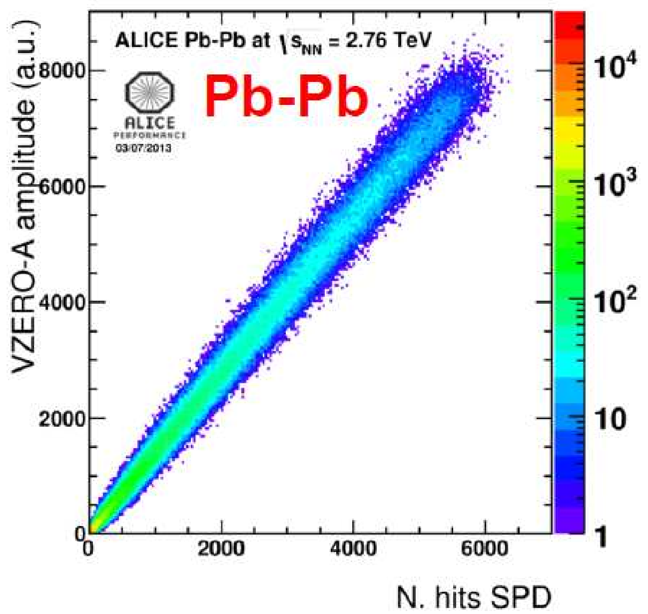


Centrality in p-Pb ?



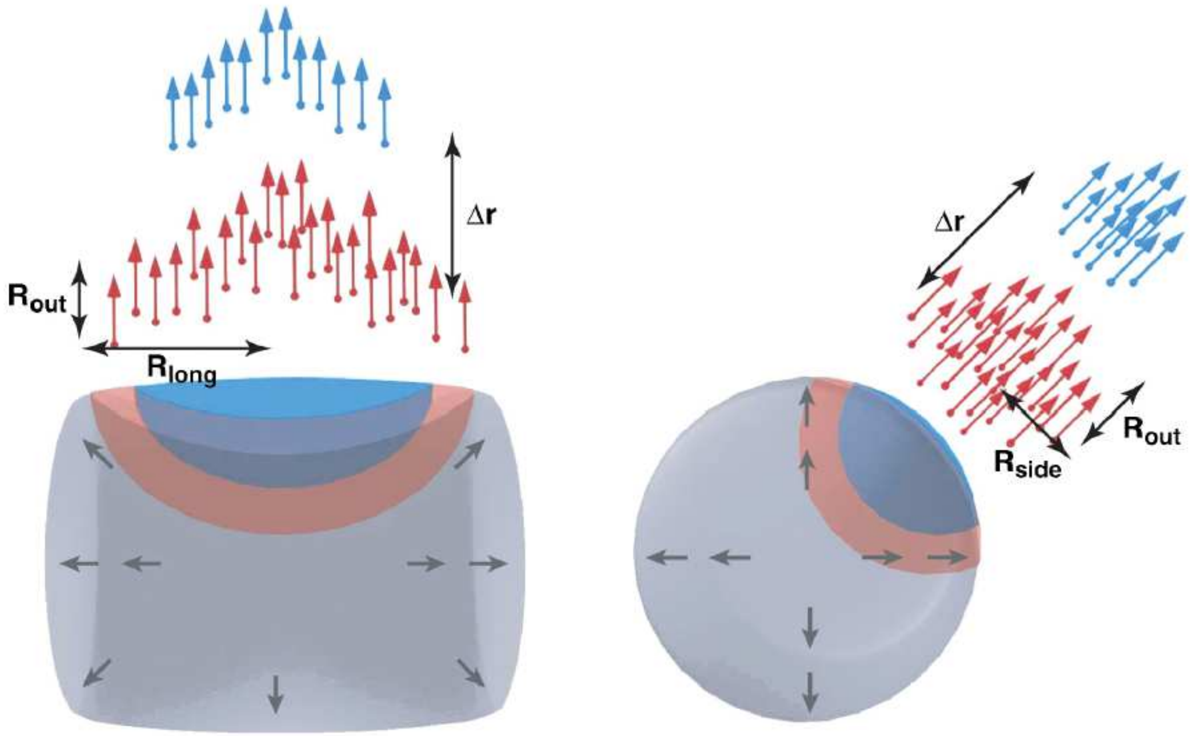
- Different bias on binary scaling for different multiplicity estimators
  - ⇨ correlations between high p_T particles in the tracker and measured multiplicity
    - ✓ *jet-veto effect at low multiplicity*
  - ⇨ bias reduced by η gap





10

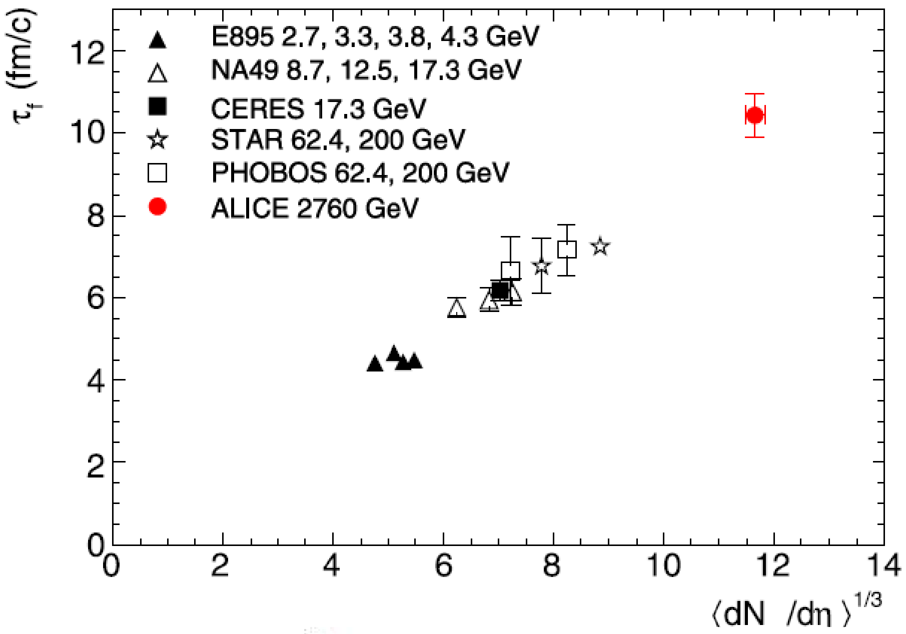
definition of out-side-long axes



Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

standard way to parametrize source size in 3-dim

HBT of identical pions



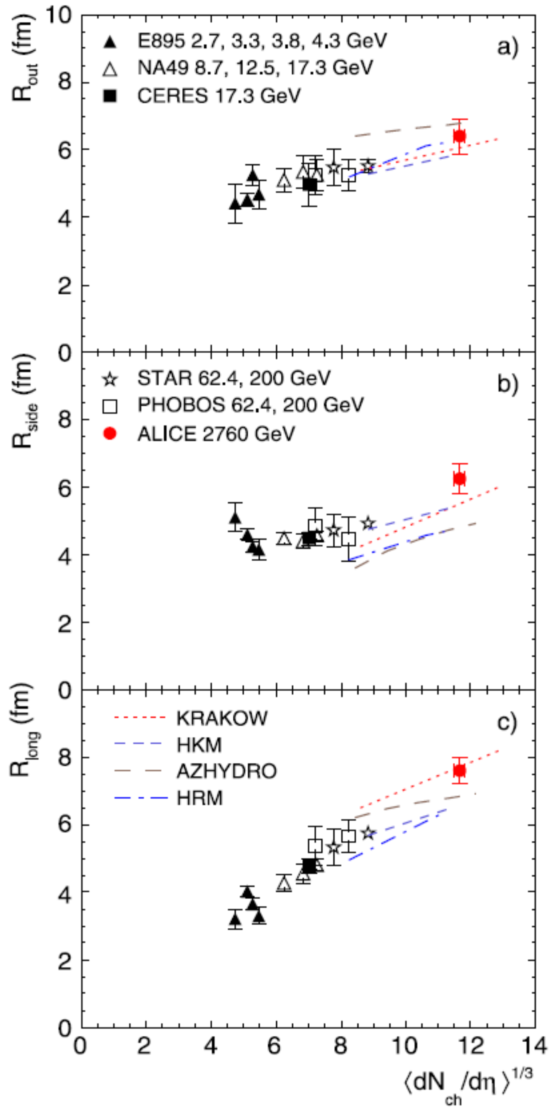
$$R^2_{\text{long}}(k_T) = \frac{\tau_f^2 T}{m_T} \frac{K_2(m_T/T)}{K_1(m_T/T)}, \quad m_T = \sqrt{m_\pi^2 + k_T^2},$$

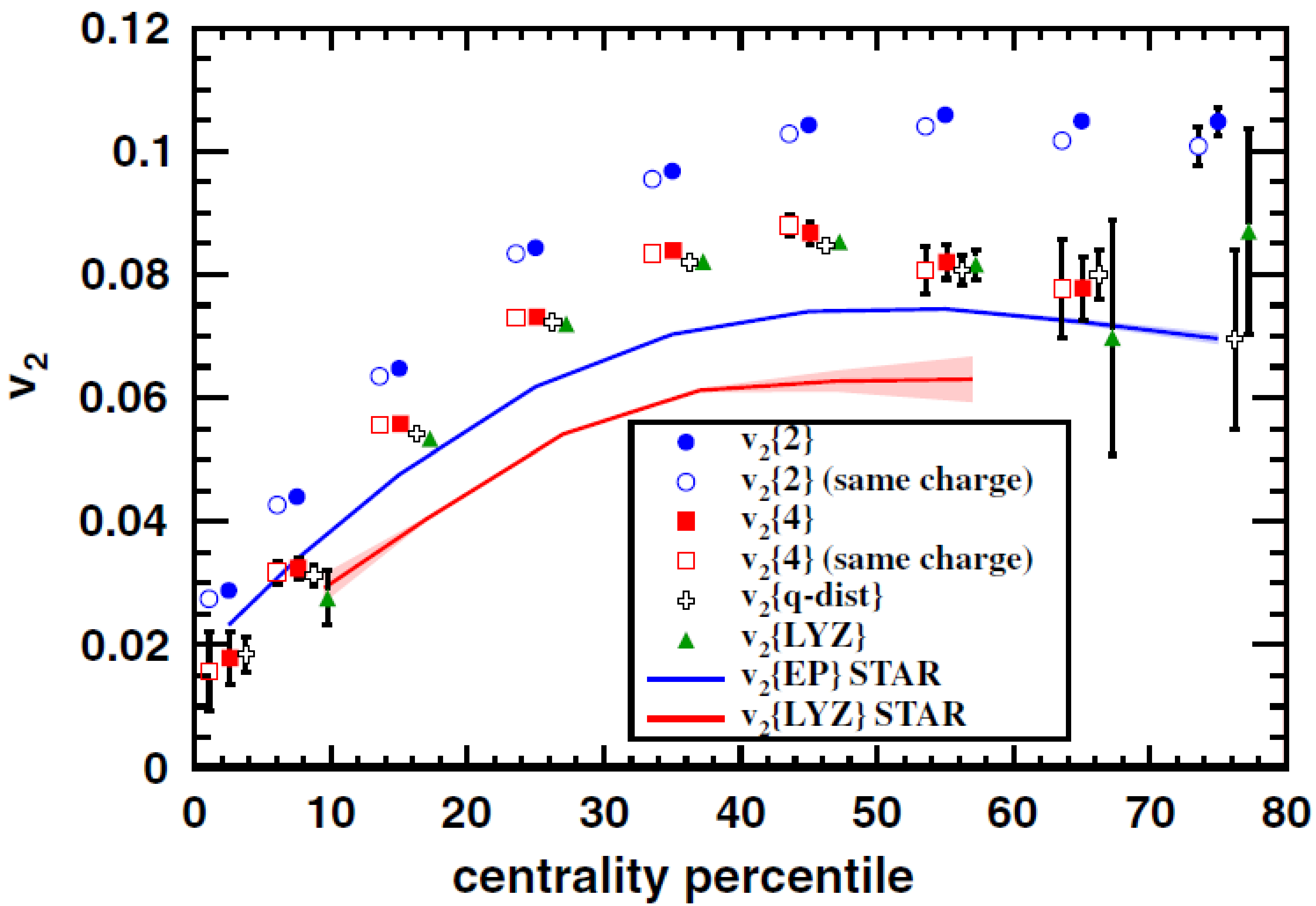
T – kinetic freeze out temperature= 0.12 GeV

K_1,K_2 – integer order modified Bessel functions

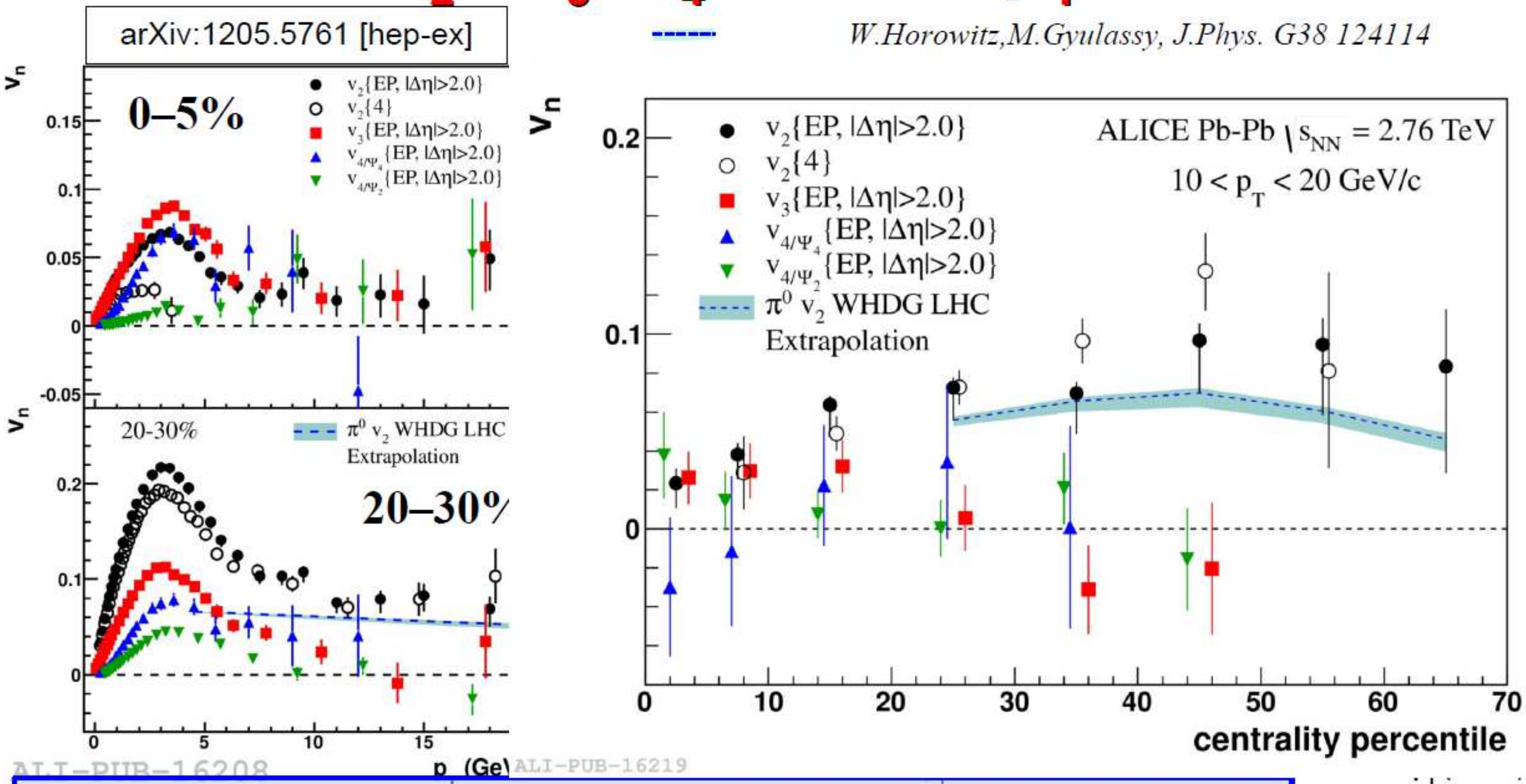
m_π - pion mass

$k_T = |p_{T1}+p_{T2}|/2$




0.12
0.1
0.08
0.06
0.04
0.02
0
v2
0
10
20
30
40
50
60
70
80
centrality percentile
v2{2}
v2{2} (same charge)
v2{4}
v2{4} (same charge)
v2{q-dist}
v2{LYZ}
v2{EP} STAR
v2{LYZ} STAR

v_2 , v_3, v_4 versus p_T



v_n measurements up to 20 GeV/c – where dominated by jet quenching
Non-flow effects suppressed by rapidity gap or using higher cumulants
Non-zero value of v_2 at high p_T both for $\Delta\eta > 2$ and 4-particle cumulant

v_3 and v_4 diminish above 10 GeV/c – indication of decrease of fluctuations at high p_T

Adam Kisiel (WUT) Kielce, 14 Dec 2013 20/30

Blast-Wave fit:

Schnedermann et al., PRC 48, 2462 (1993)

- spectral-shape analysis performed with hydro-inspired model
- allows characterization of ID-spectra with small set of parameters

EPOS LHC:

Pierog et al., arXiv:1306.0121 [hep-ph]

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

Krakow:

Bozek, PRC 85, 014911 (2012)

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

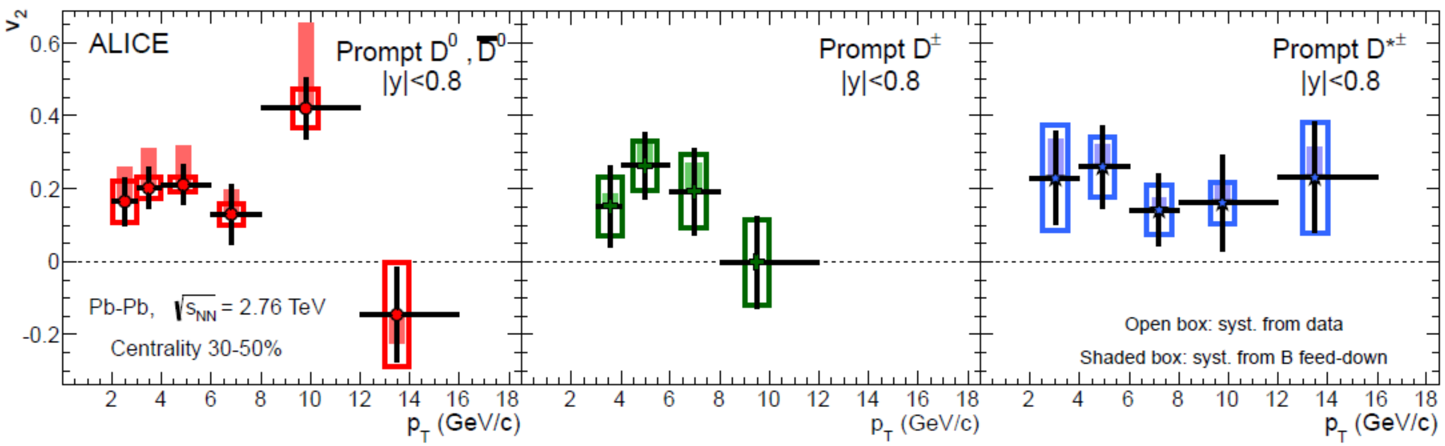
DPMJET:

Roesler et al., arXiv:hep-ph/0012252

- QCD-inspired model
- reproduces dNch/dη in NSD p-Pb.

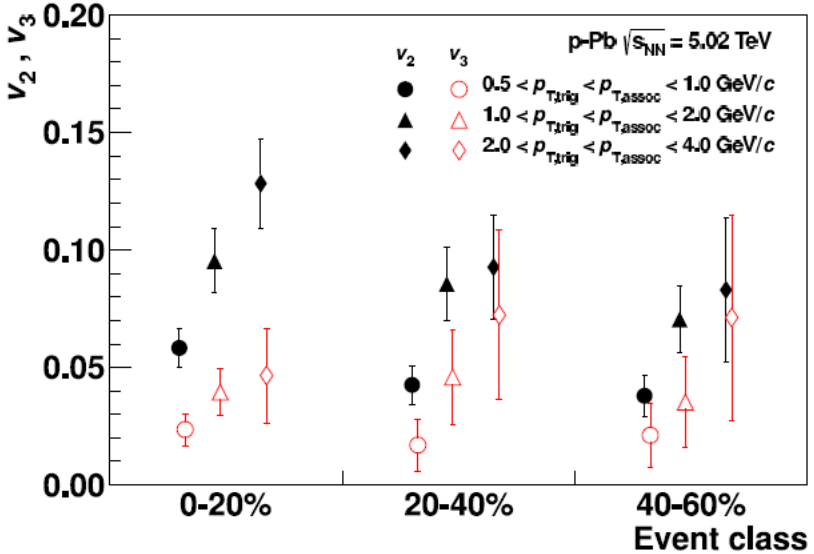
D meson elliptic flow

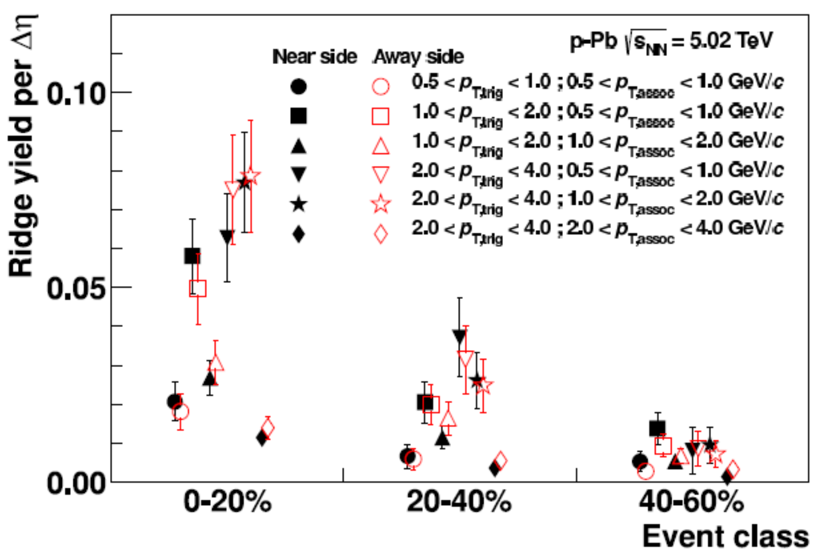
$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}.$$



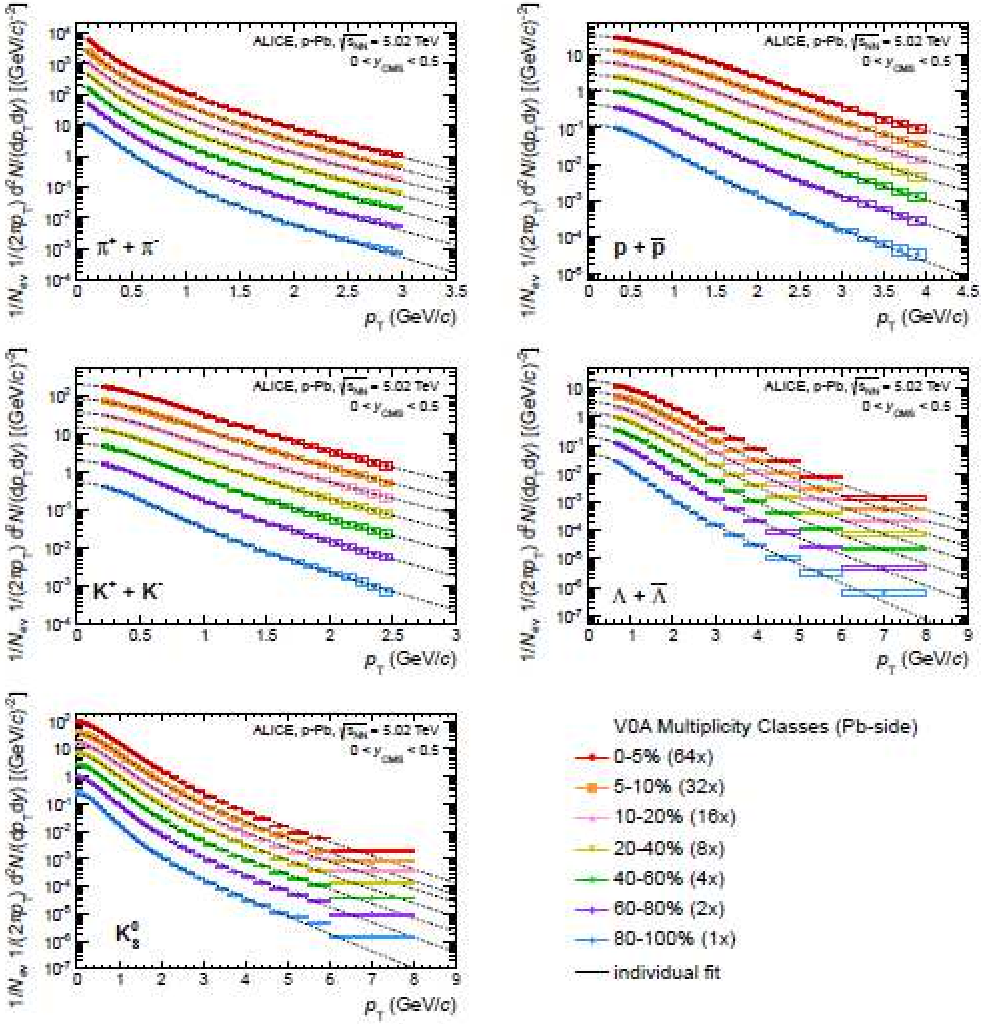
Double ridge structure p-Pb

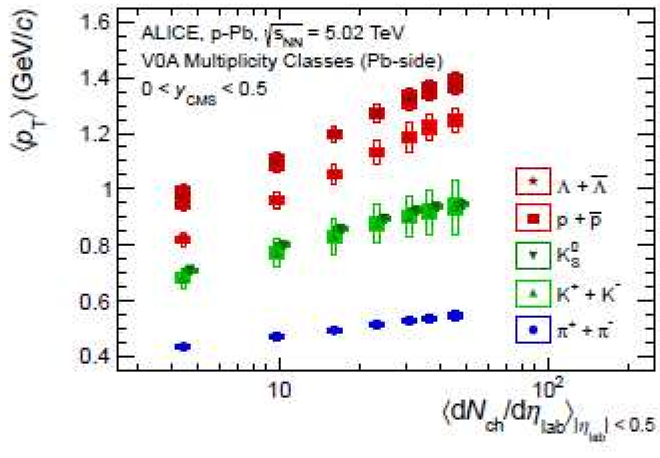
$$v_n = \sqrt{a_n / b}.$$



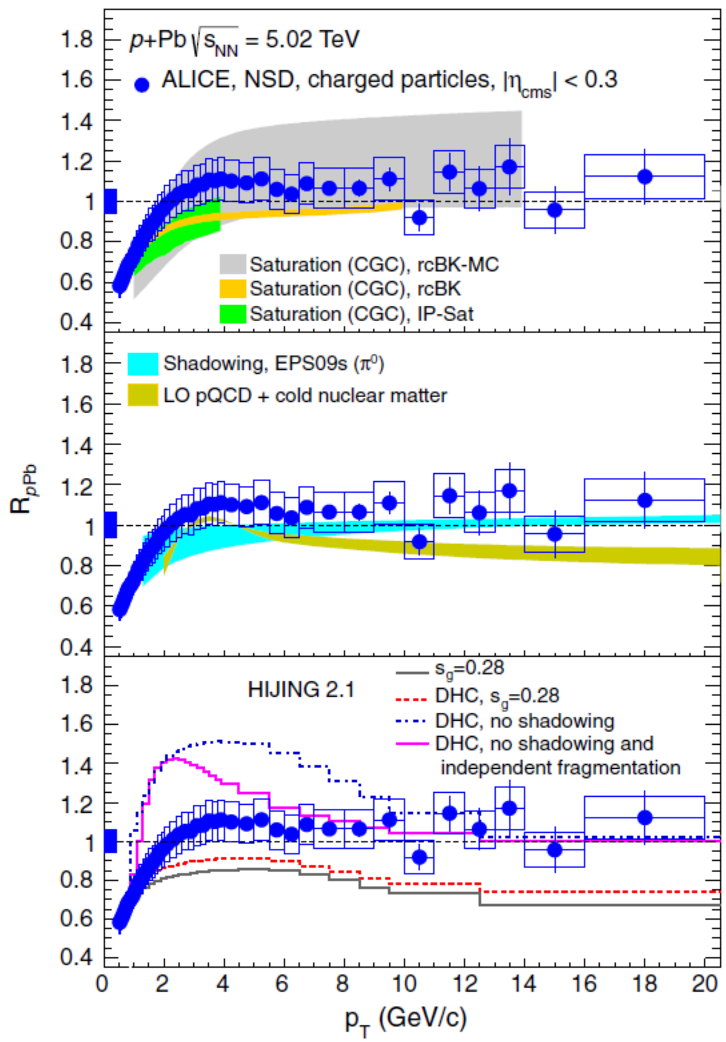


Identified particle spectra p-Pb

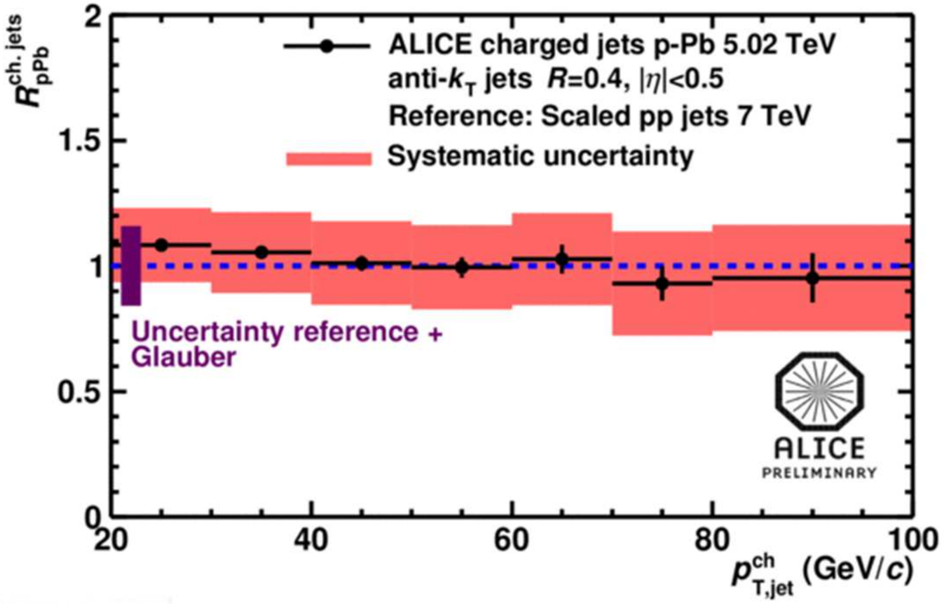




R_{AA} in p-Pb



p+Pb √s_NN = 5.02 TeV
ALICE, NSD, charged particles, |η_cms| < 0.3
Saturation (CGC), rcBK-MC
Saturation (CGC), rcBK
Saturation (CGC), IP-Sat
Shadowing, EPS09s (π⁰)
LO pQCD + cold nuclear matter
HIJING 2.1
s_g=0.28
DHC, s_g=0.28
DHC, no shadowing
DHC, no shadowing and independent fragmentation
R_pPb
p_T (GeV/c)



$R_{pPb}^{ch. jets}$
ALICE charged jets p-Pb 5.02 TeV
anti-k_T jets R=0.4, $|\eta|$<0.5
Reference: Scaled pp jets 7 TeV
Systematic uncertainty
Uncertainty reference +
Glauber
ALICE
PRELIMINARY
$p_{T,jet}^{ch}$ (GeV/c)