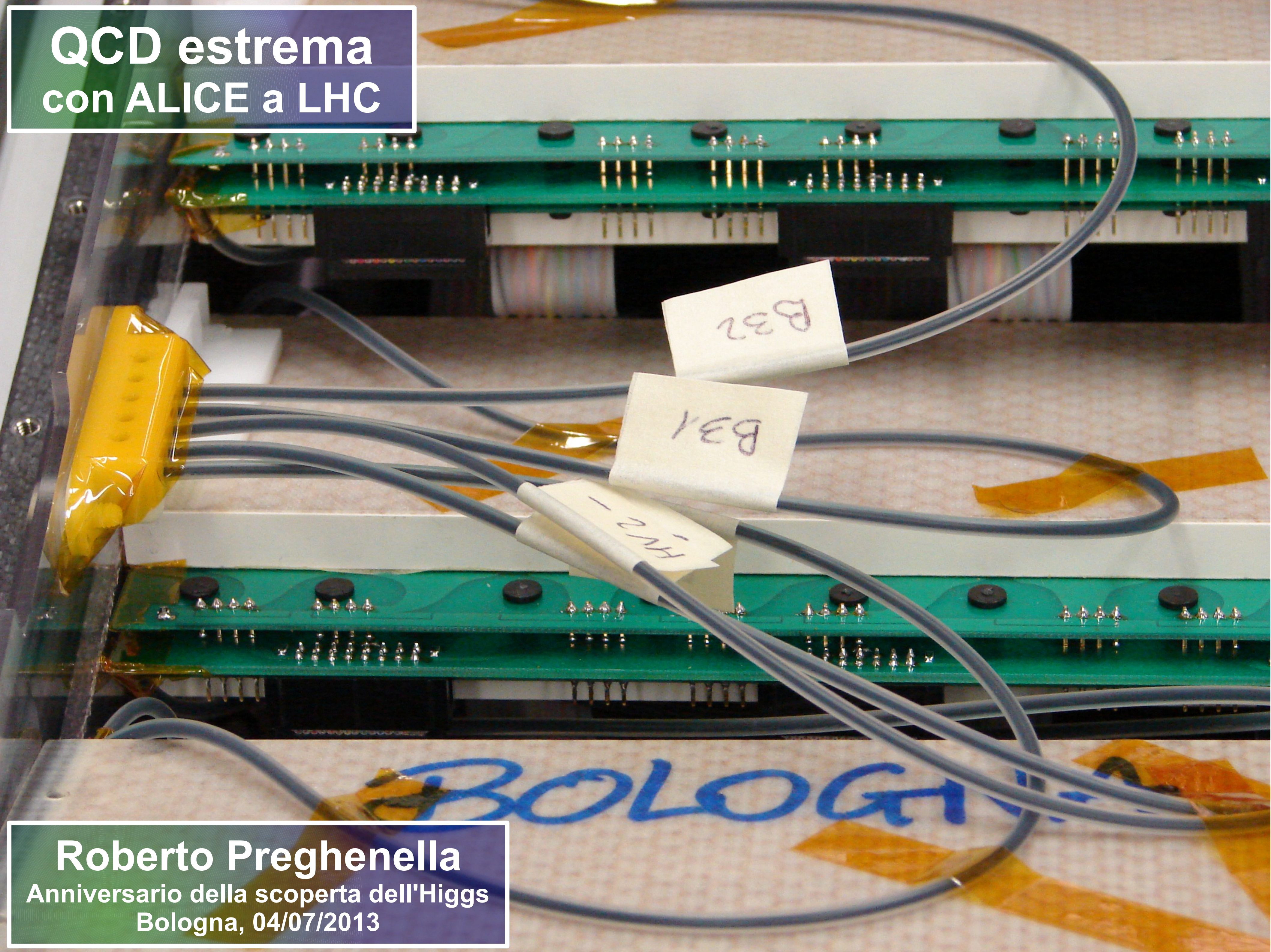
QCD estrema con ALICE a LHC



Roberto Preghenella

Anniversario della scoperta dell'Higgs

Bologna, 04/07/2013

Heavy-ion collisions at the LHC

The CERN LHC can accelerate also lead ions:
Pb-Pb collisions @ $\sqrt{s} = 2.76$TeV per nucleon pair

QCD matter @ high temperature and energy-density
is expected to undergo a phase transition

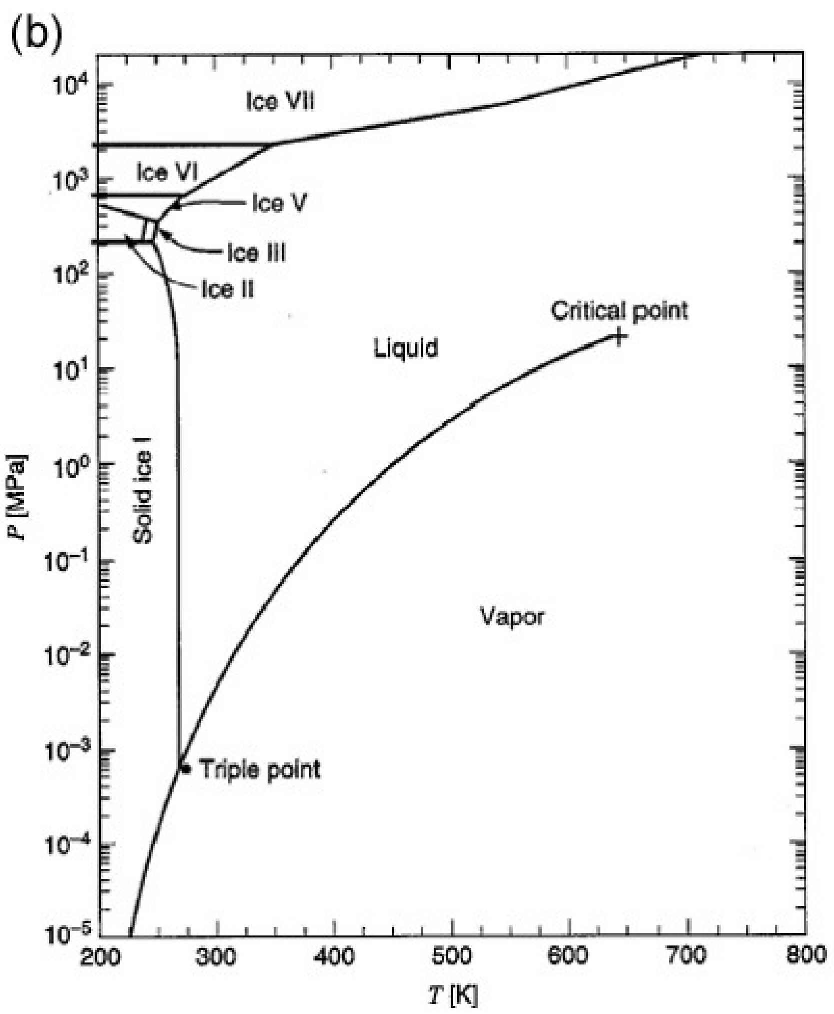
hadronic matter ⇨ deconfined state of quark and gluons

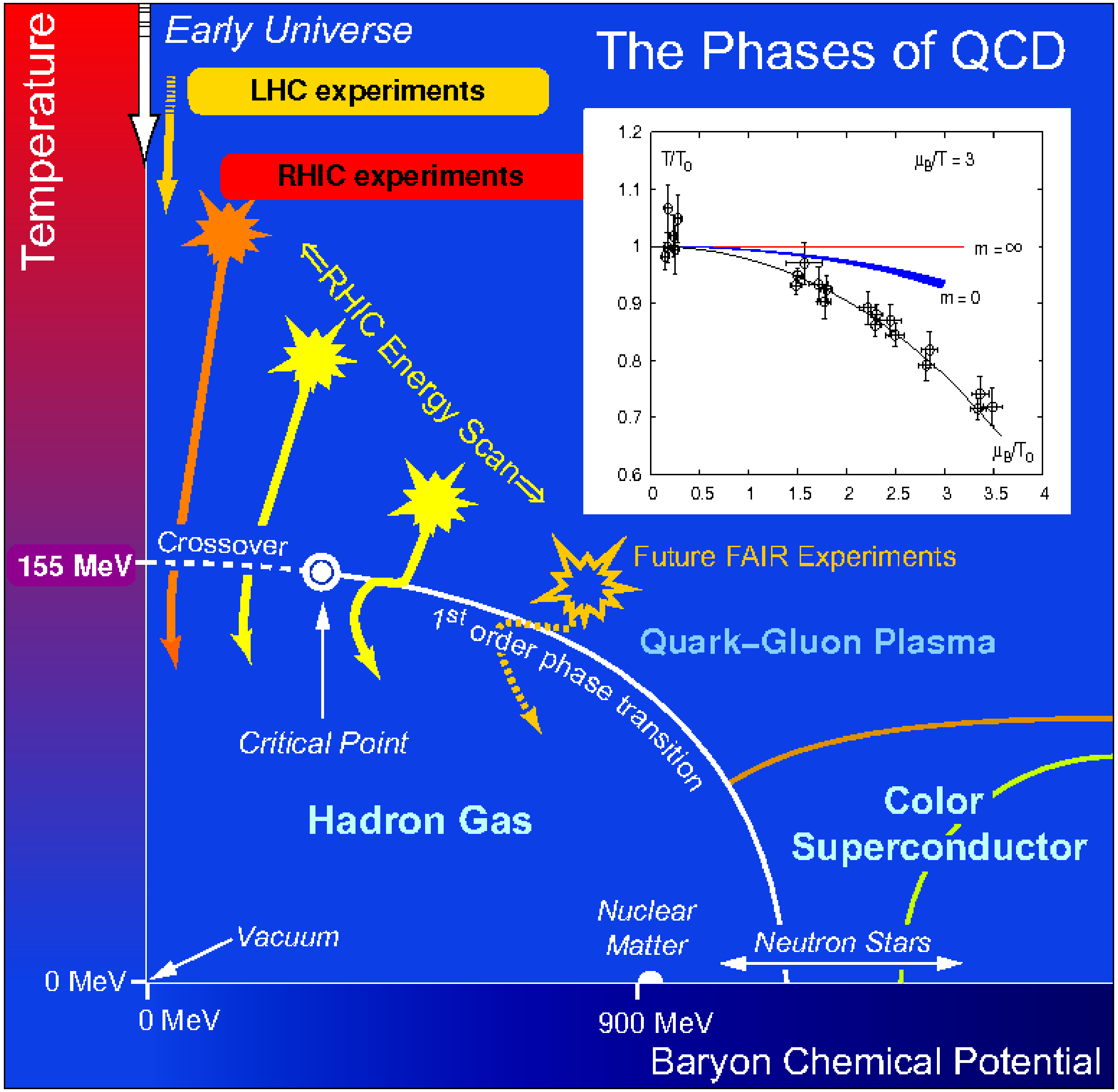
so far, a rich ultrarelativistic heavy-ion programme

past:	GSI-SIS	(~ 2 GeV)	
	BNL-AGS	(~ 5 GeV)	
	CERN-SPS	(~ 20 GeV)	first signals of new state of matter
present:	BNL-RHIC	(~ 200 GeV)	further evidence of deconfined partonic matter
future:	GSI-FAIR	(~ 45 GeV)	will study equation of state at high density ρ_B

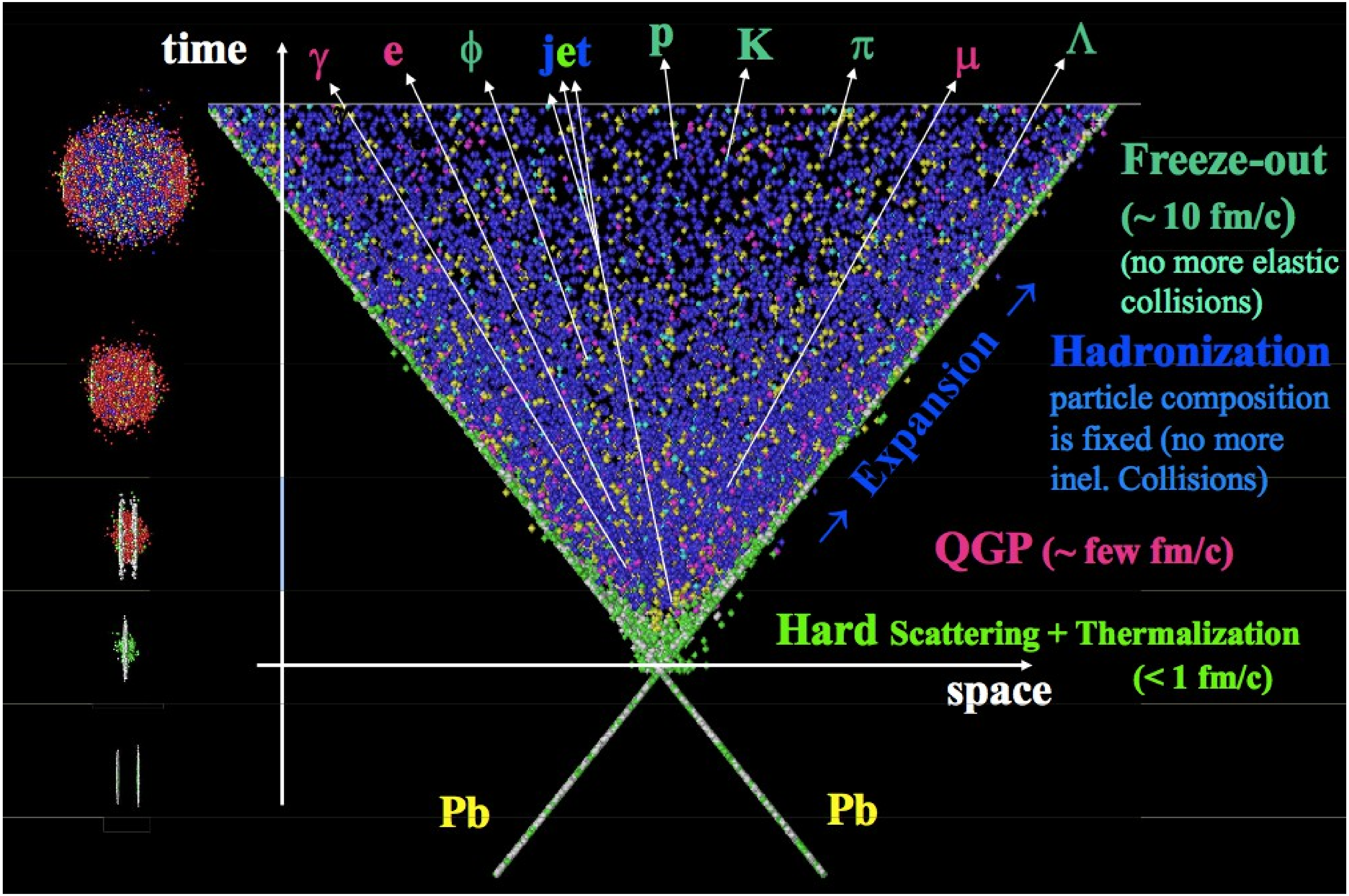
evidence at RHIC for a liquid quark-gluon matter (sQGP)
(Scientific American, May 2006)

QCD phase diagram

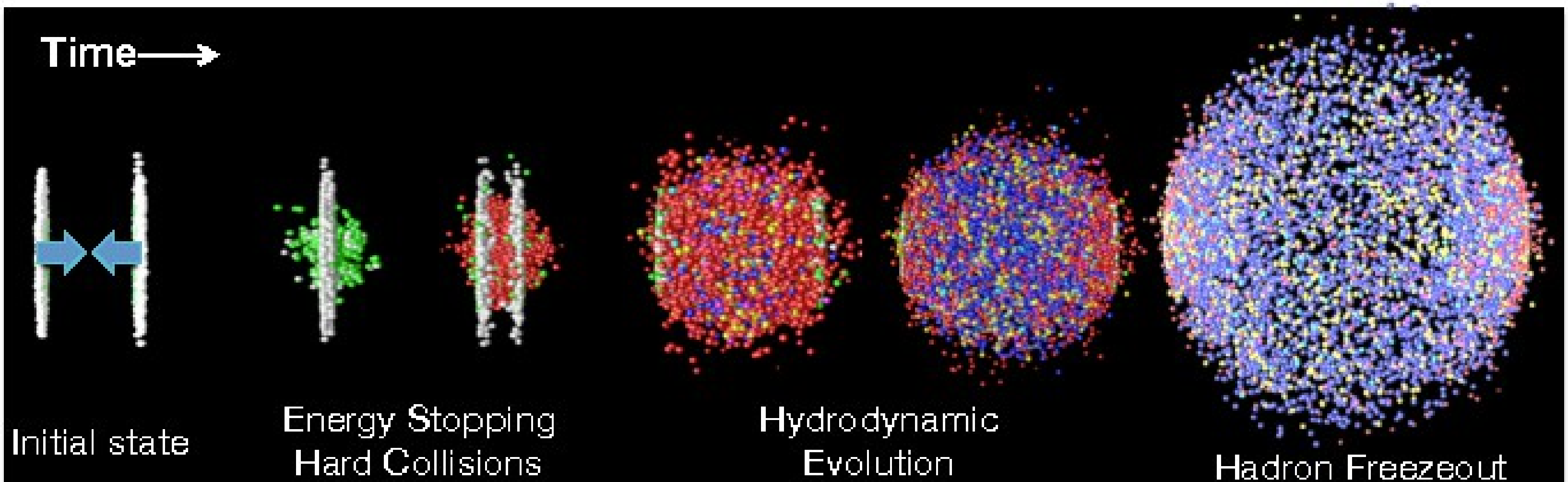


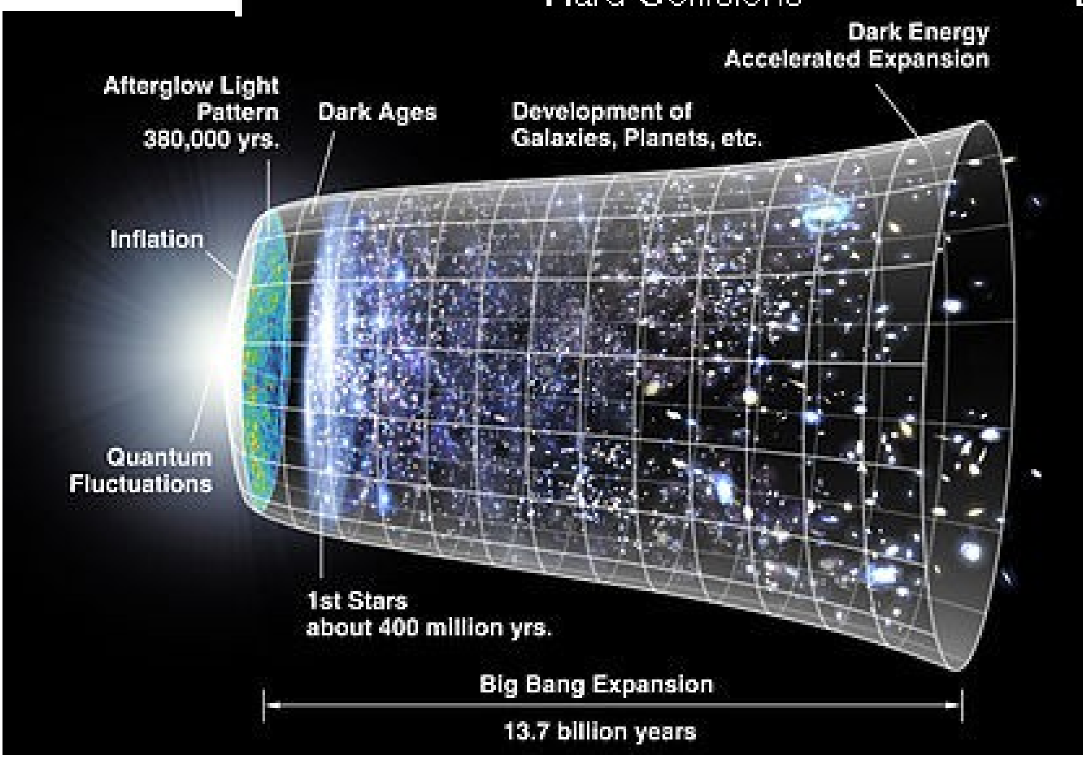


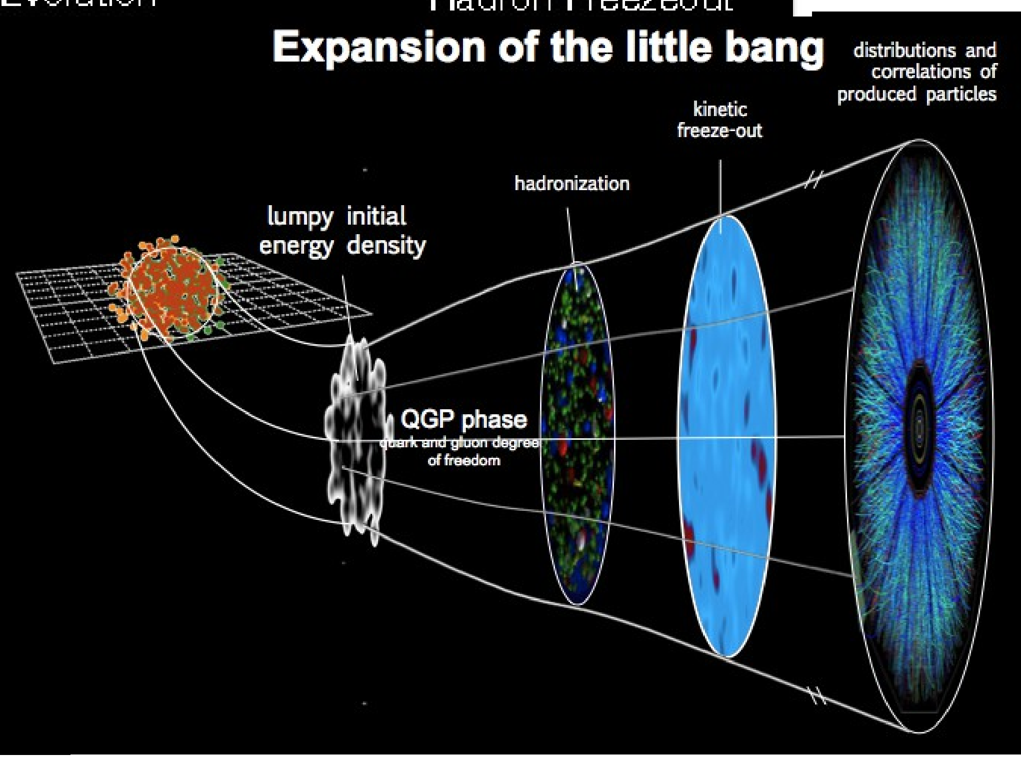
Heavy-ion collision and evolution



Analogies with the early universe







QGP experimental observables

properties of the bulk of the matter:

$dN_{ch}/d\eta$	⇨	energy density ϵ
chemical composition	⇨	chemical freeze-out
hadron spectra	⇨	kinetic freeze-out

electromagnetic probes:

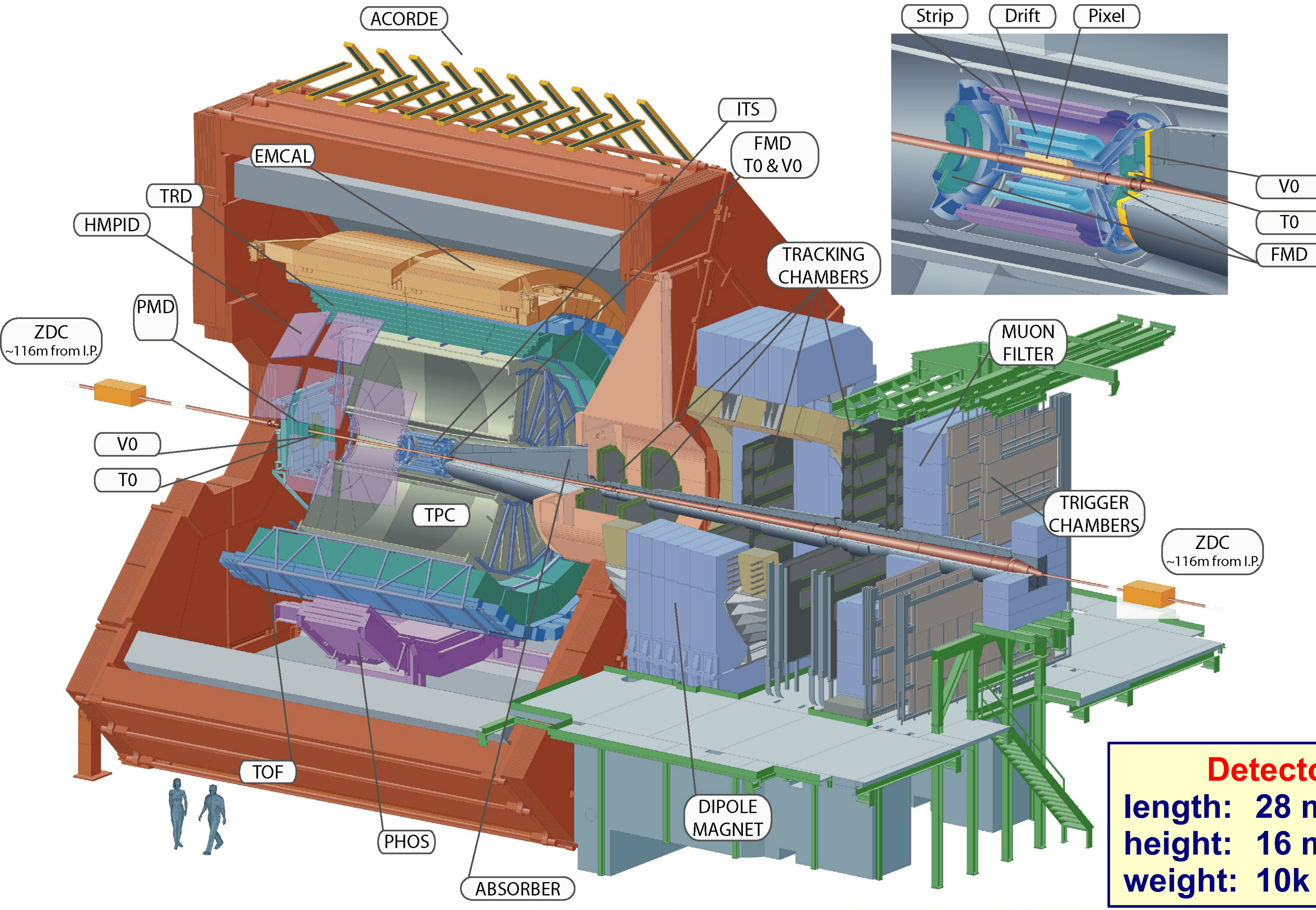
thermal radiation	⇨	plasma temperature
dilepton production	⇨	

⚠ large background ("prompt" γ, $\pi^0 \rightarrow \gamma\gamma$, $\pi^0 \rightarrow e^+e^-\gamma$)

heavy-quark (c, b) and quarkonium production:

production	⇨	perturbative phenomenon
long life-time	⇨	live through thermalization phase
energy loss	⇨	probes the matter produced
J/ψ suppression	⇨	colour screening (deconfinement)

The ALICE experiment

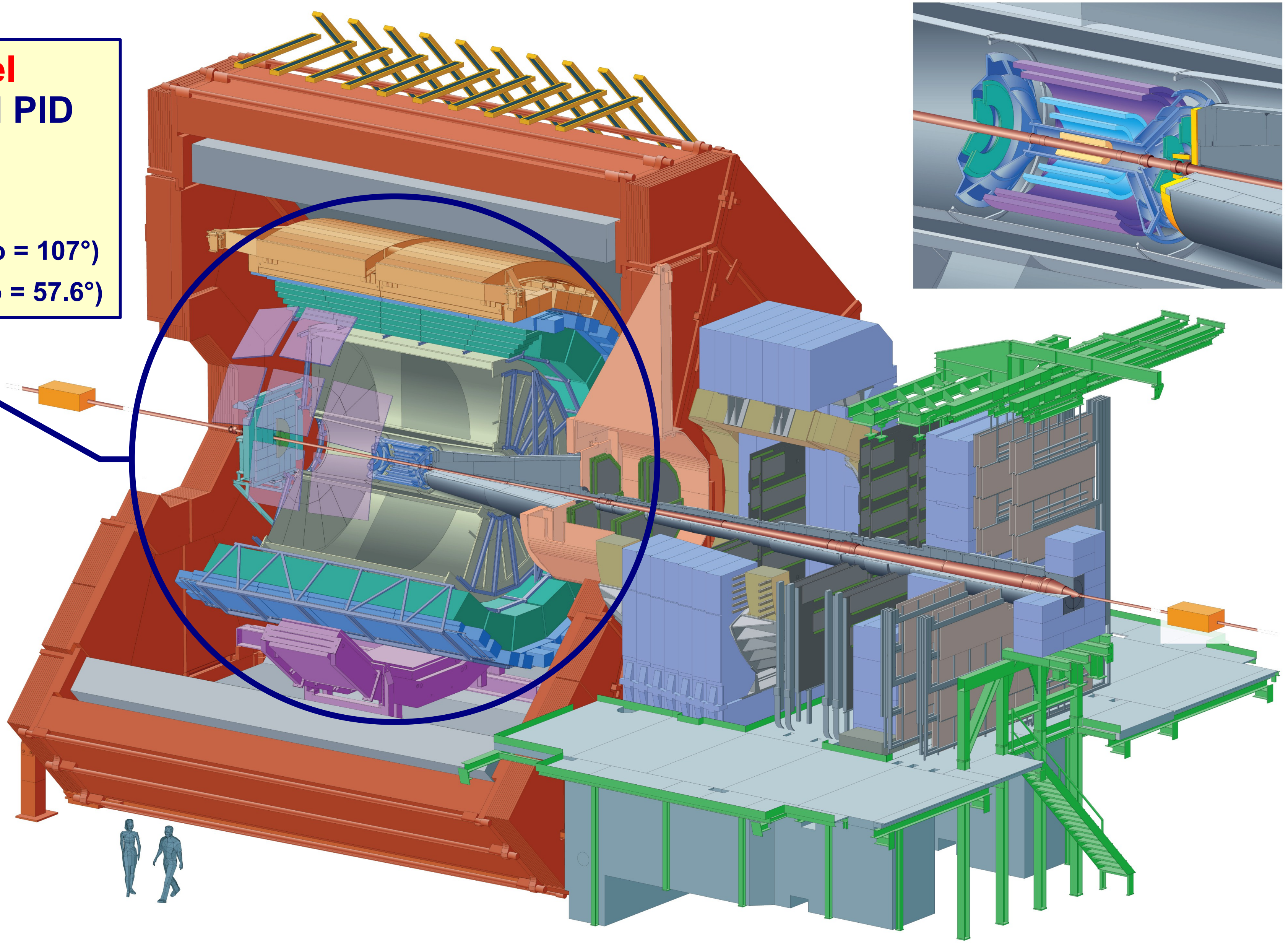


Detector:
length: 28 metres
height: 16 metres
weight: 10k tons

The ALICE detector

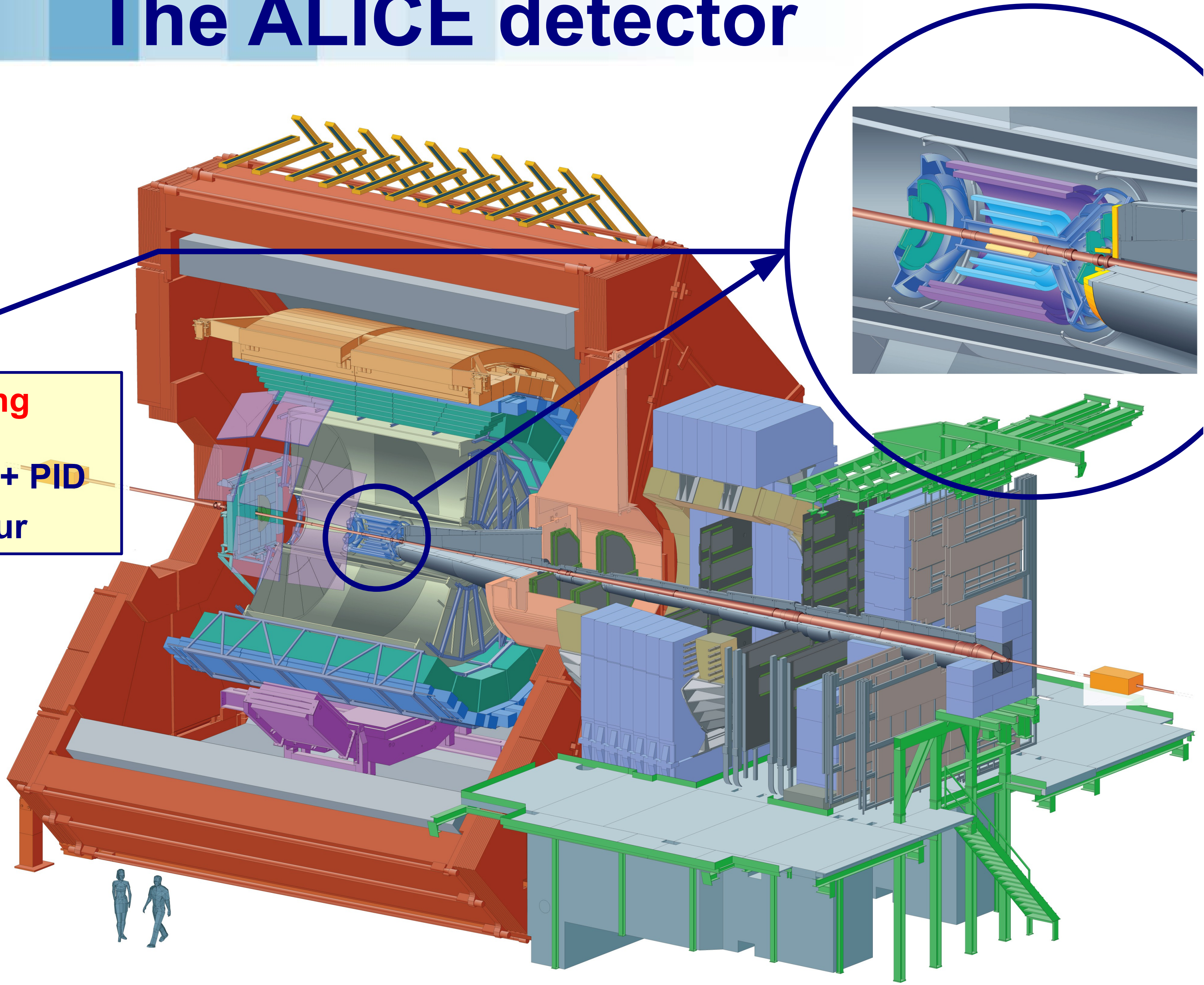
central barrel
2π tracking and PID
|η| < 1
B= 0.5 T

EM cal. (|η| < 0.7, Δϕ = 107°)
RICH (|η| < 0.6, Δϕ = 57.6°)

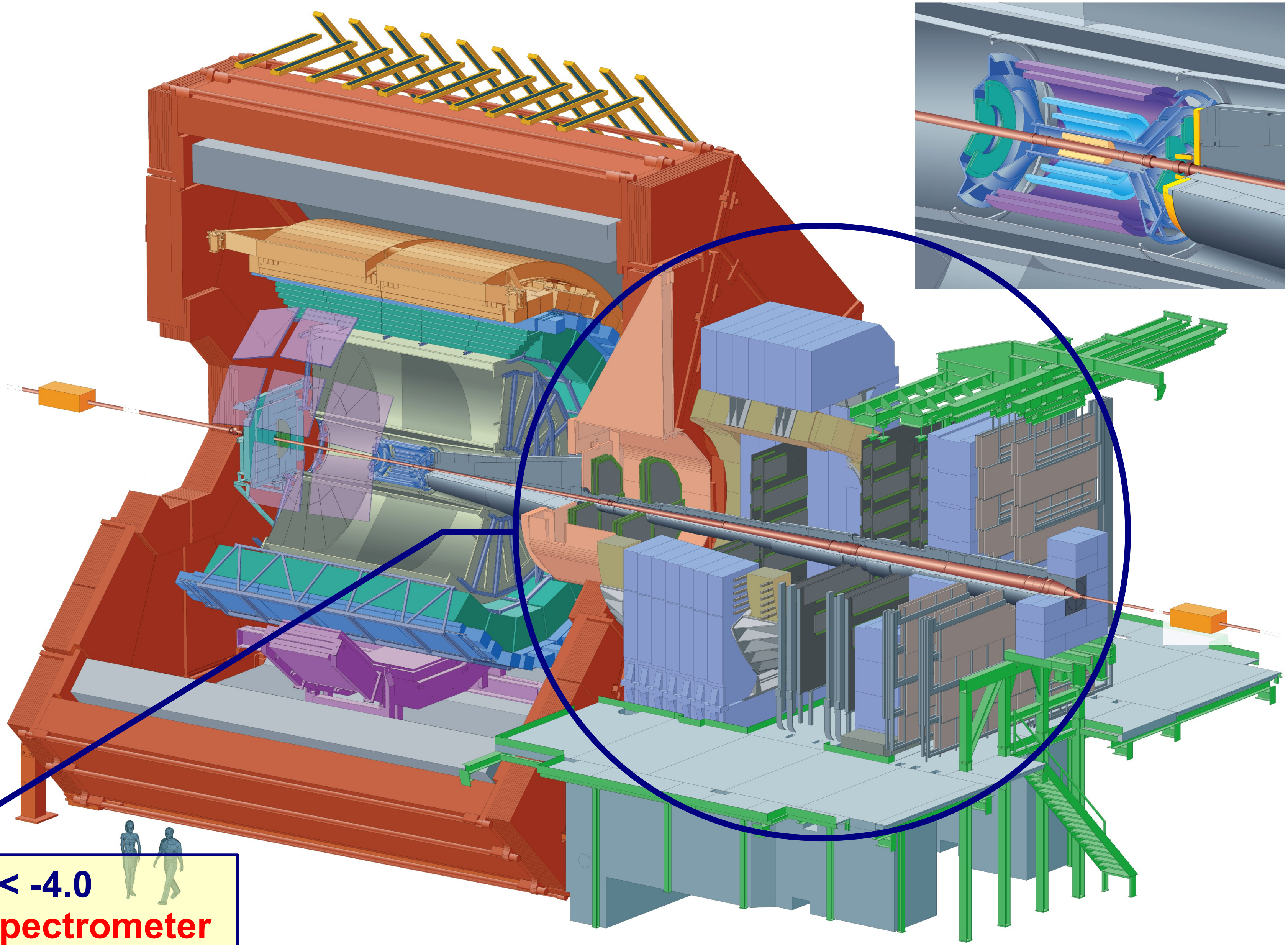


The ALICE detector

Inner-tracking
vertexing
low-p_T tracking + PID
heavy-flavour

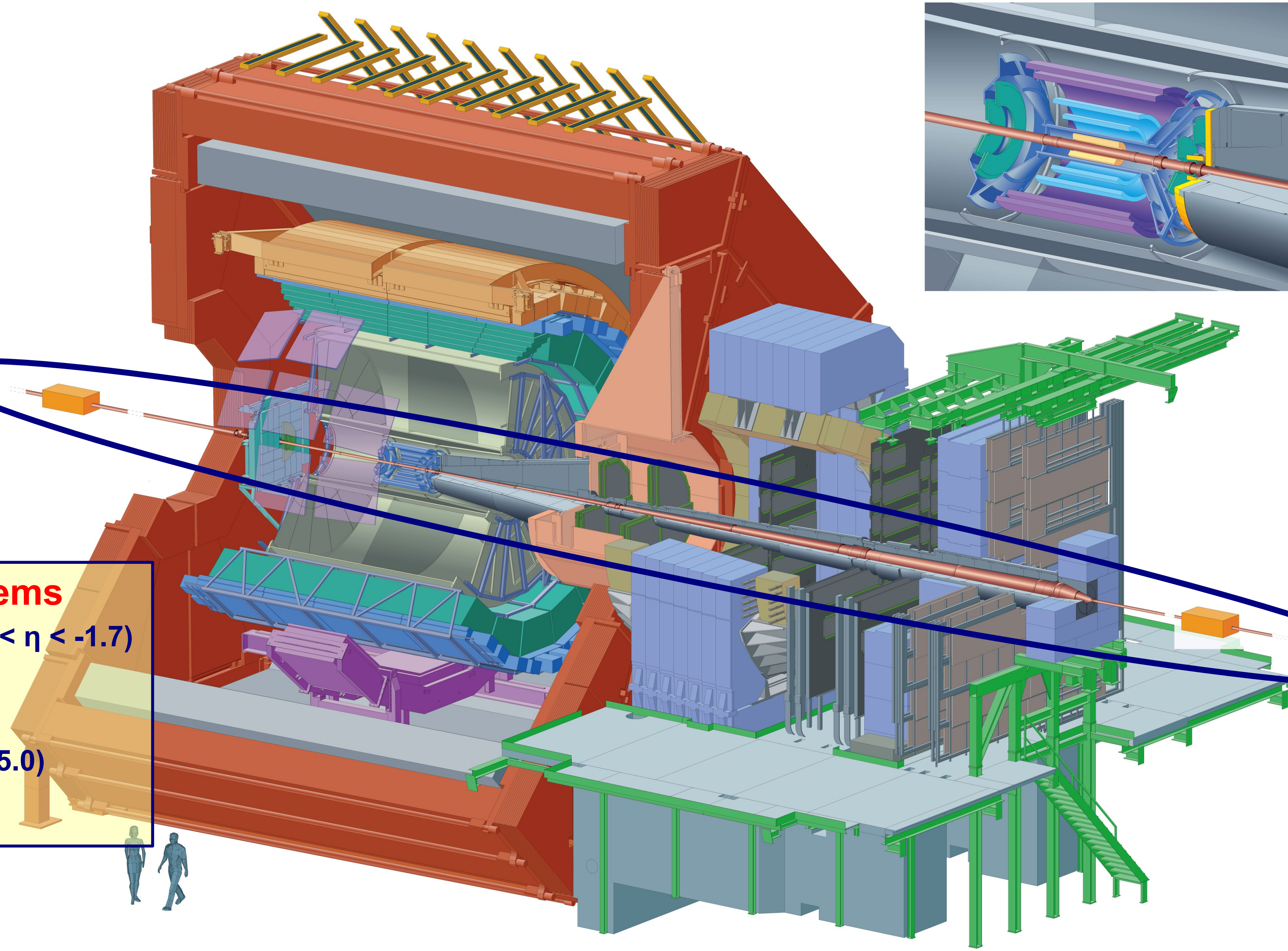


The ALICE detector



-2.5 < |η| < -4.0
forward-muon spectrometer

The ALICE detector



forward systems

V0 (2.8 < η < 5.1, -3.7 < η < -1.7)

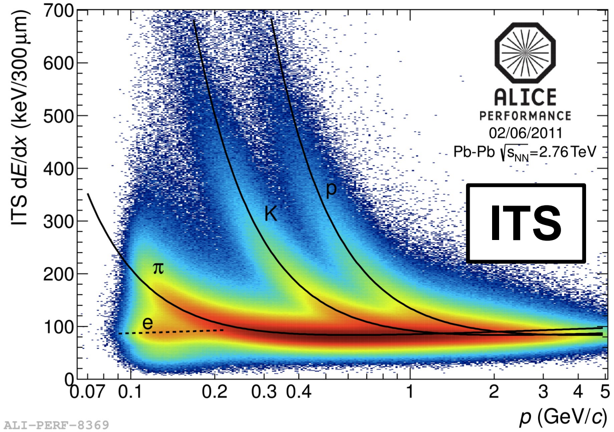
T0 (timing)

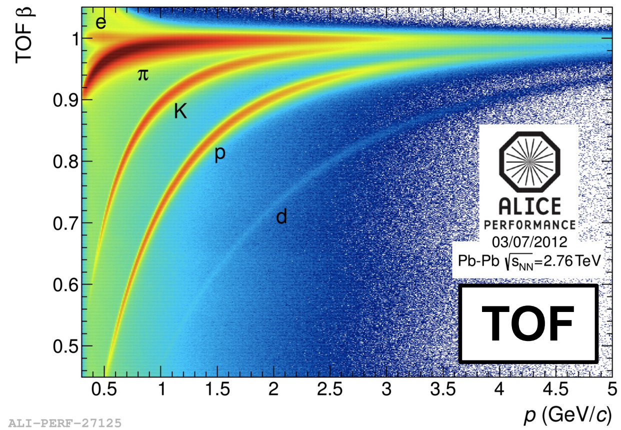
ZDC (centrality)

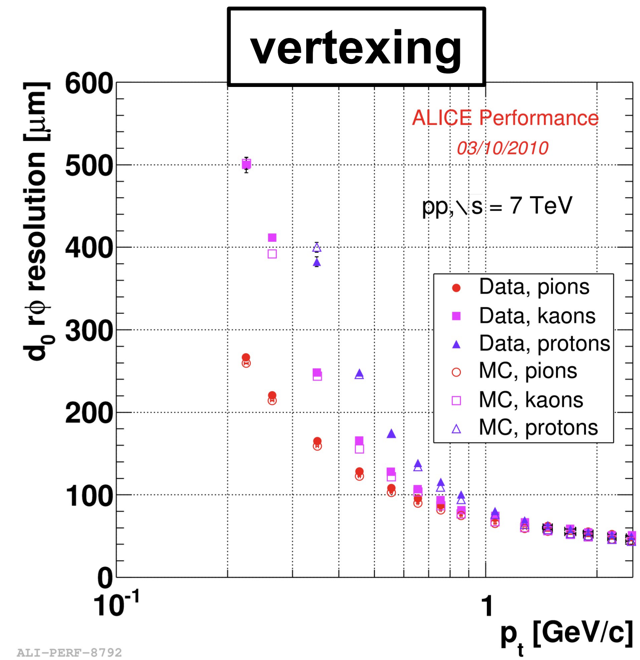
FMD (N_{ch}, -3.4 < η < -5.0)

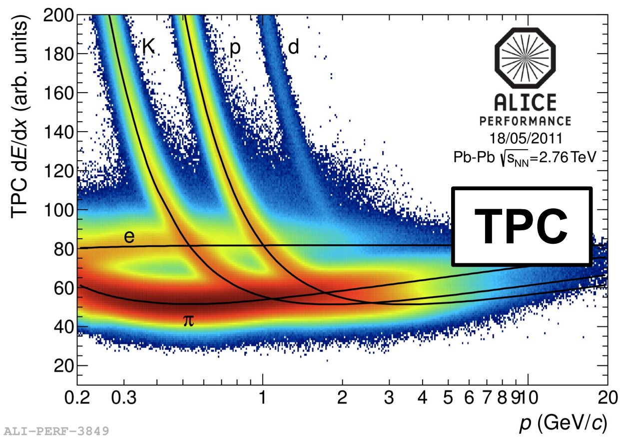
PMD (N_{γ}, N_{ch})

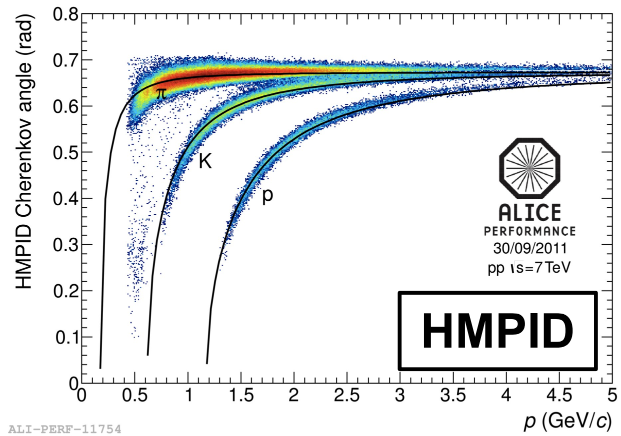
ALICE main features

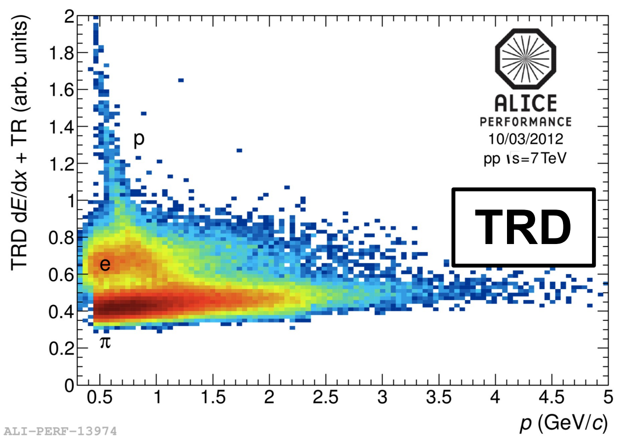








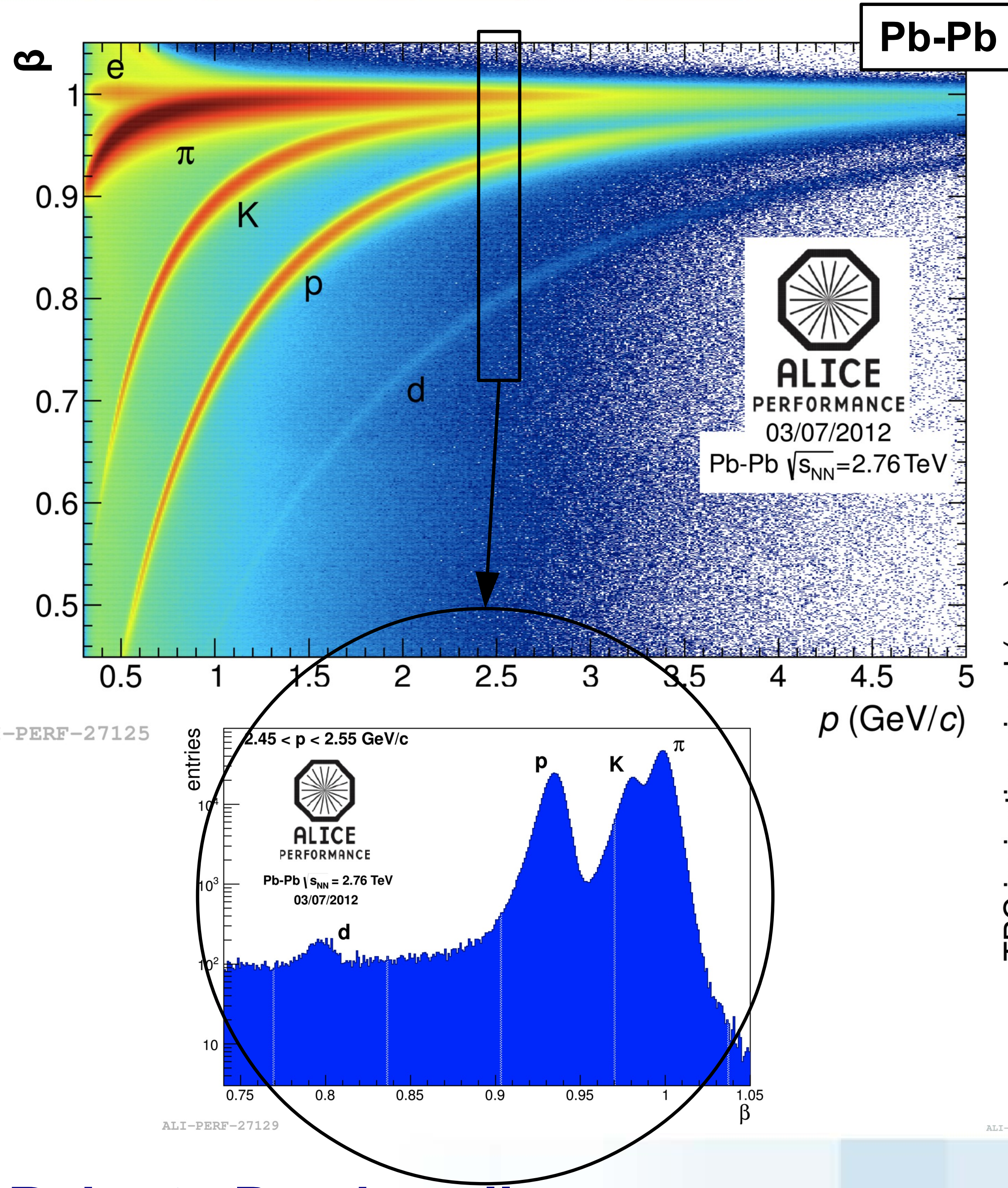




- **particle identification** (all known techniques)
- **excellent vertexing capability**
- **extremely low-mass tracker** (~10% of X_0)
- **efficient low-momentum tracking** (down to ~100 MeV/*c*)
- **particle detection over large rapidity range**
- **quarkonia detection down to p_T = 0**

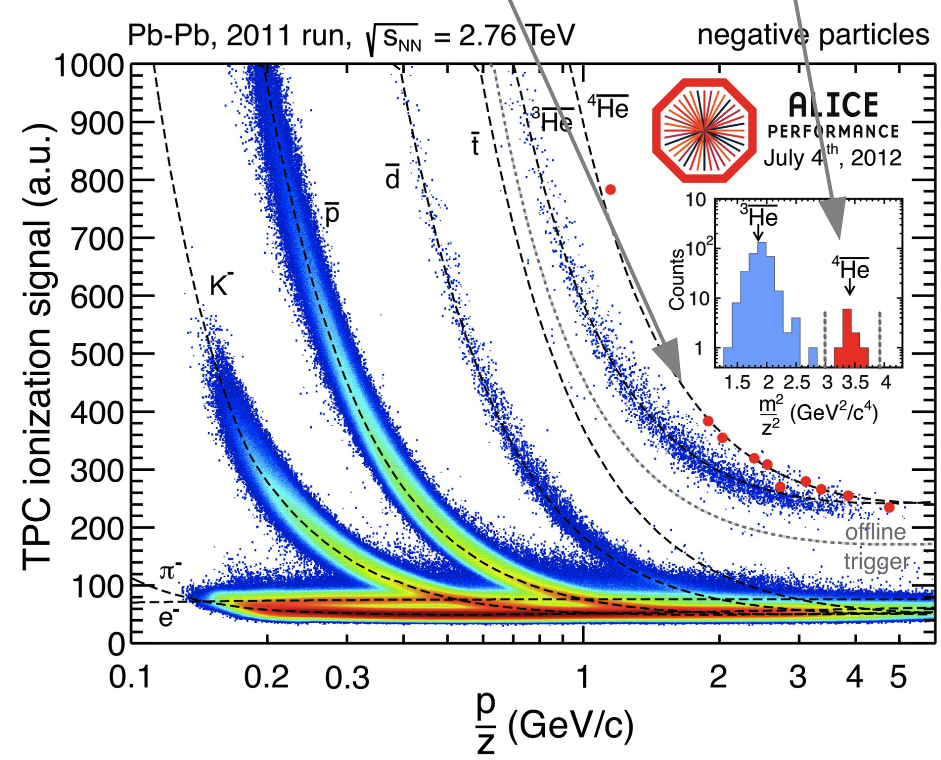
Particle-identification example: TOF

Particle-identification example: TOF

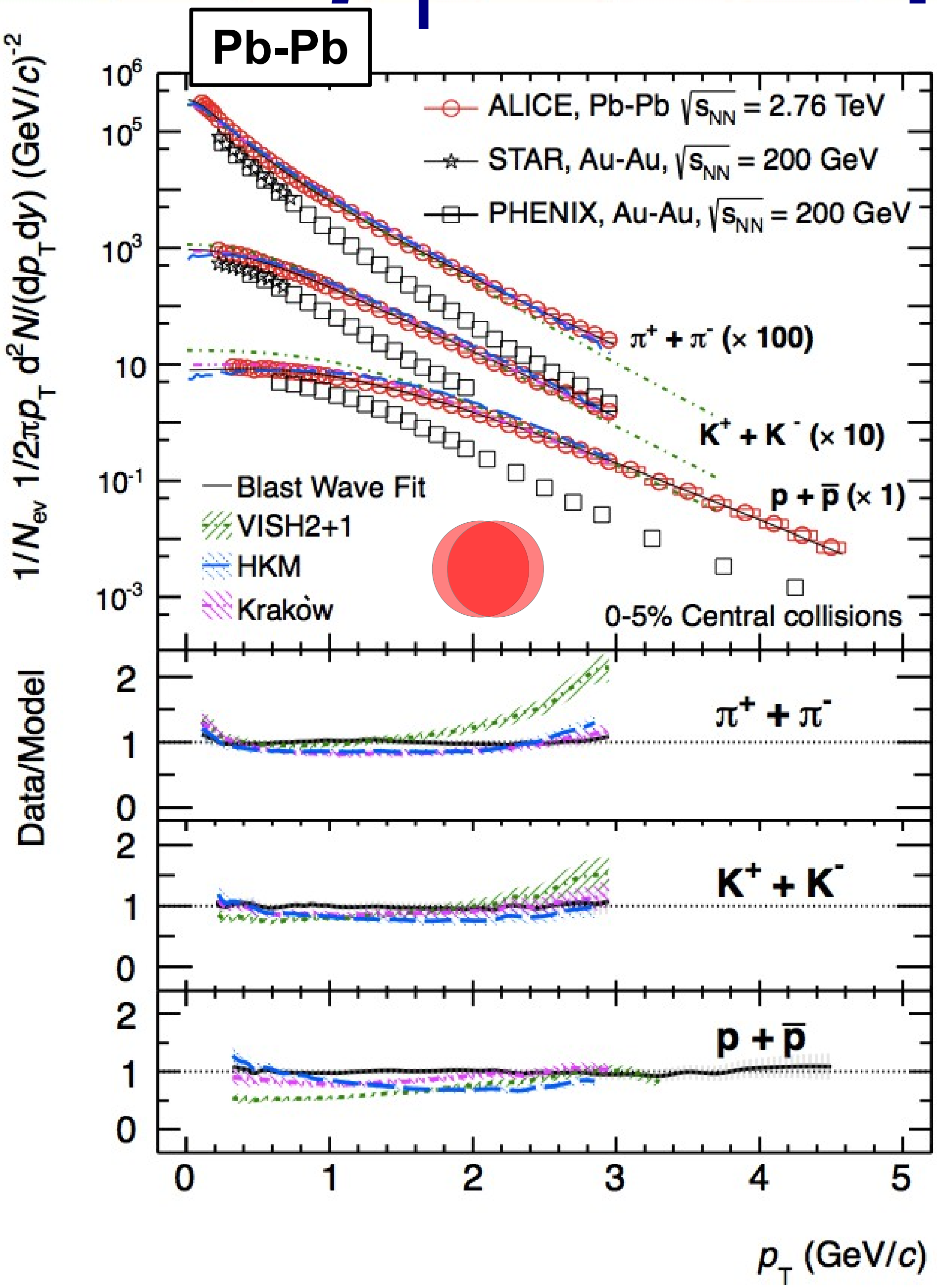


TOF: PID at intermediate momenta
PID via time-of-flight technique
σ < 100 ps
3σ *K/π* separation up to 2.5 GeV/c
3σ *p/π* separation up to 4.0 GeV/c

light (anti)nuclei ($\bar{d}$, $\bar{t}$, $^3\overline{He}$, $^4\overline{He}$)
combining TPC *d*E/*dx* + TOF mass



Low-p_T hadron production in Pb-Pb



arXiv:1208.1974 [hep-ex]

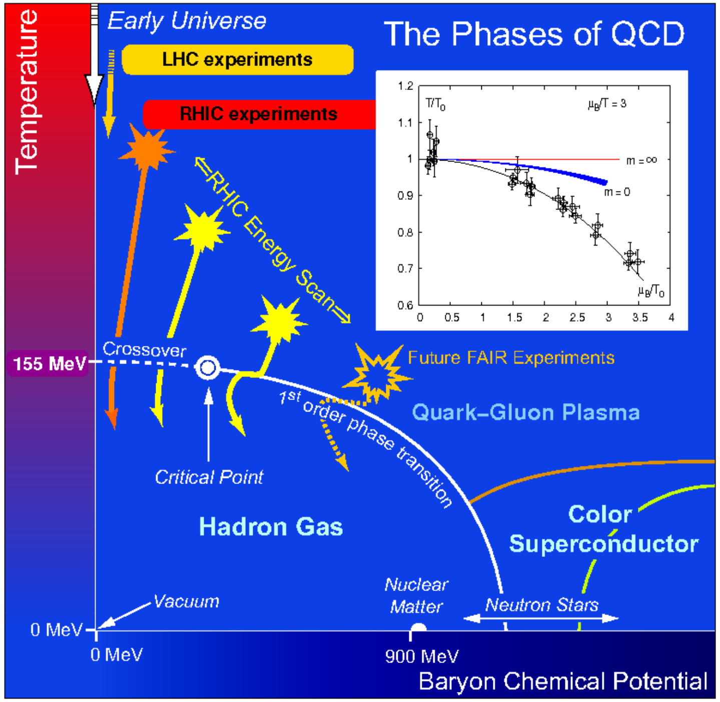
p_T spectra → from thermal sources expanding with a collective transverse radial flow velocity β_T

Fit to the data with Blast-Wave model
Schnedermann et al., PRC 48, 2462 (1993)

$\langle\beta_T\rangle$ = 0.65 ± 0.02
~10% higher than at RHIC

T_{kin} = 96 ± 10 MeV
compatible within errors

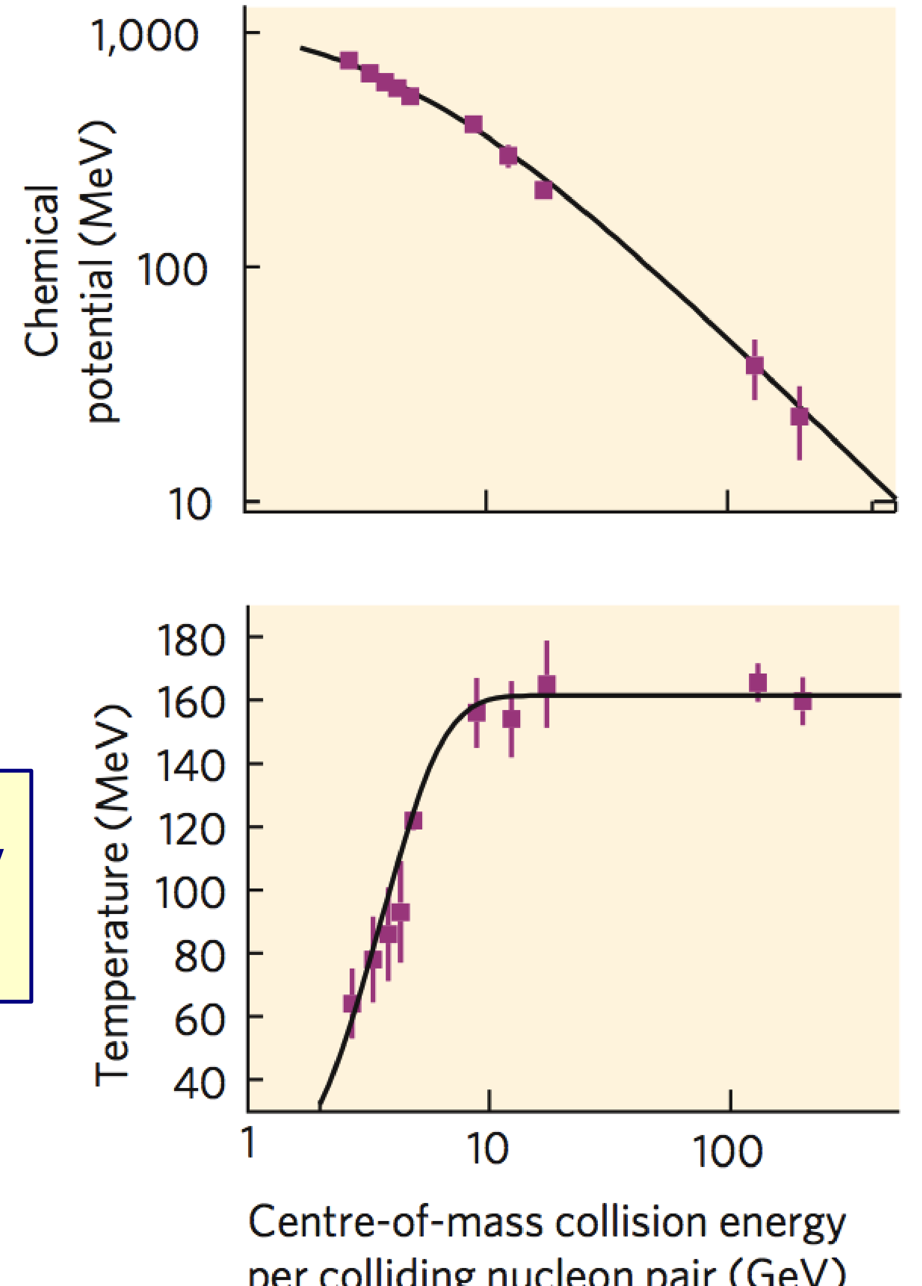
Hadron abundances in A-A collisions



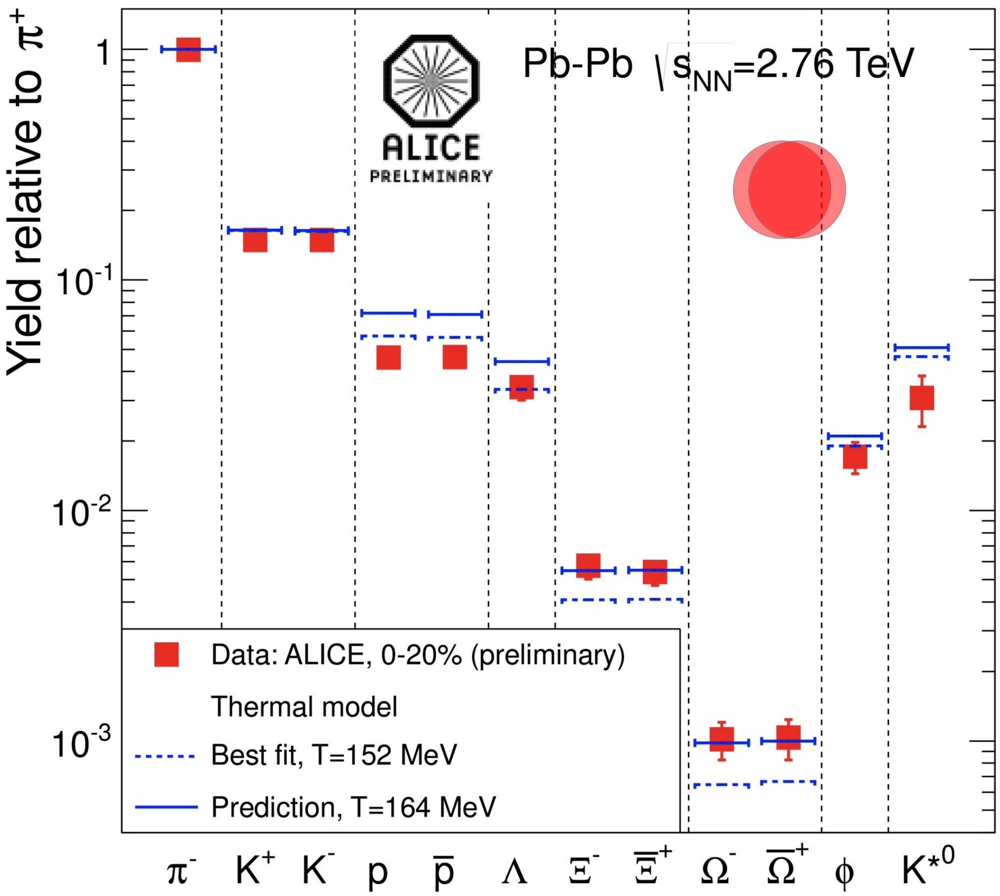
successfully described by statistical (thermal) model in a wide range of energies, $\sqrt{s_{NN}}$ = 2-200 GeV

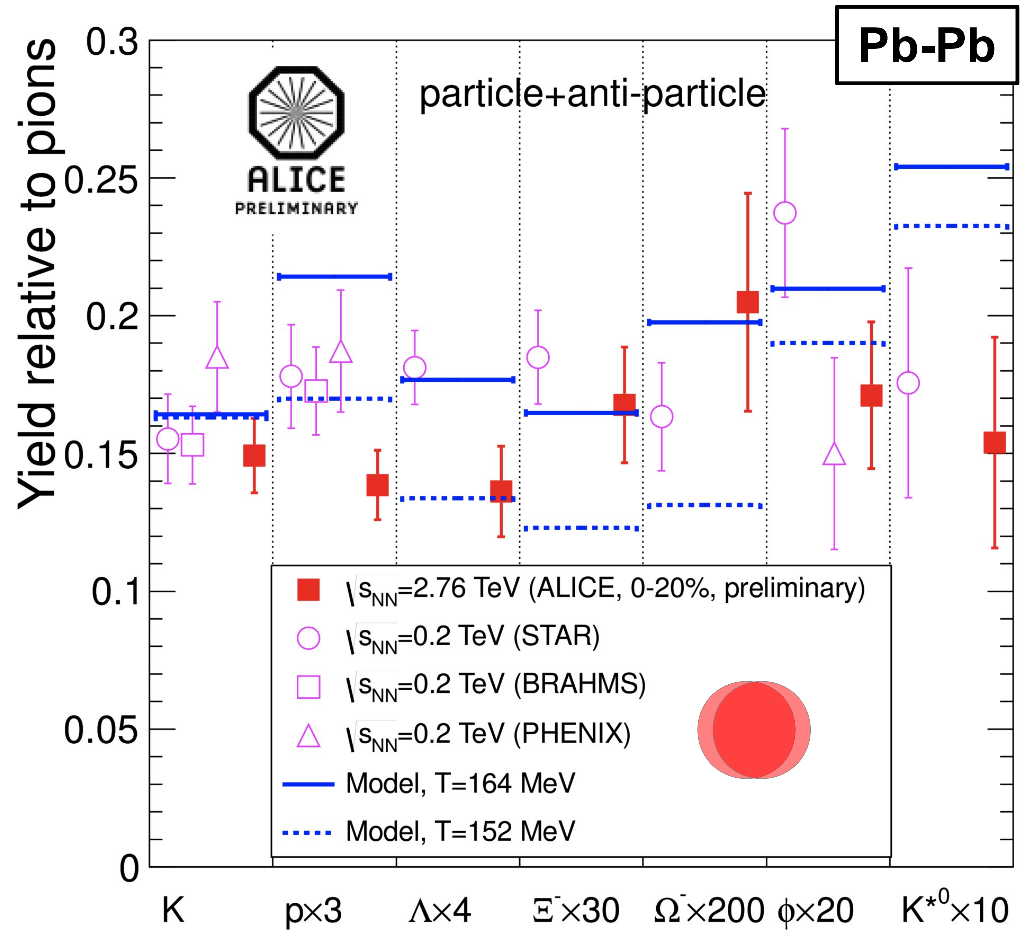
consistent with equilibrium population → (T_{ch}, μ_B)

Predicted temperature at the LHC:
Andronic et al., NPA 772, 167 (2006)
T_{ch} = 164 MeV



Hadron yields and ratios in Pb-Pb





Predicted temperature at the LHC:
Andronic et al., NPA 772, 167 (2006)

T_{ch} = 164 MeV

Best fit (without resonances):

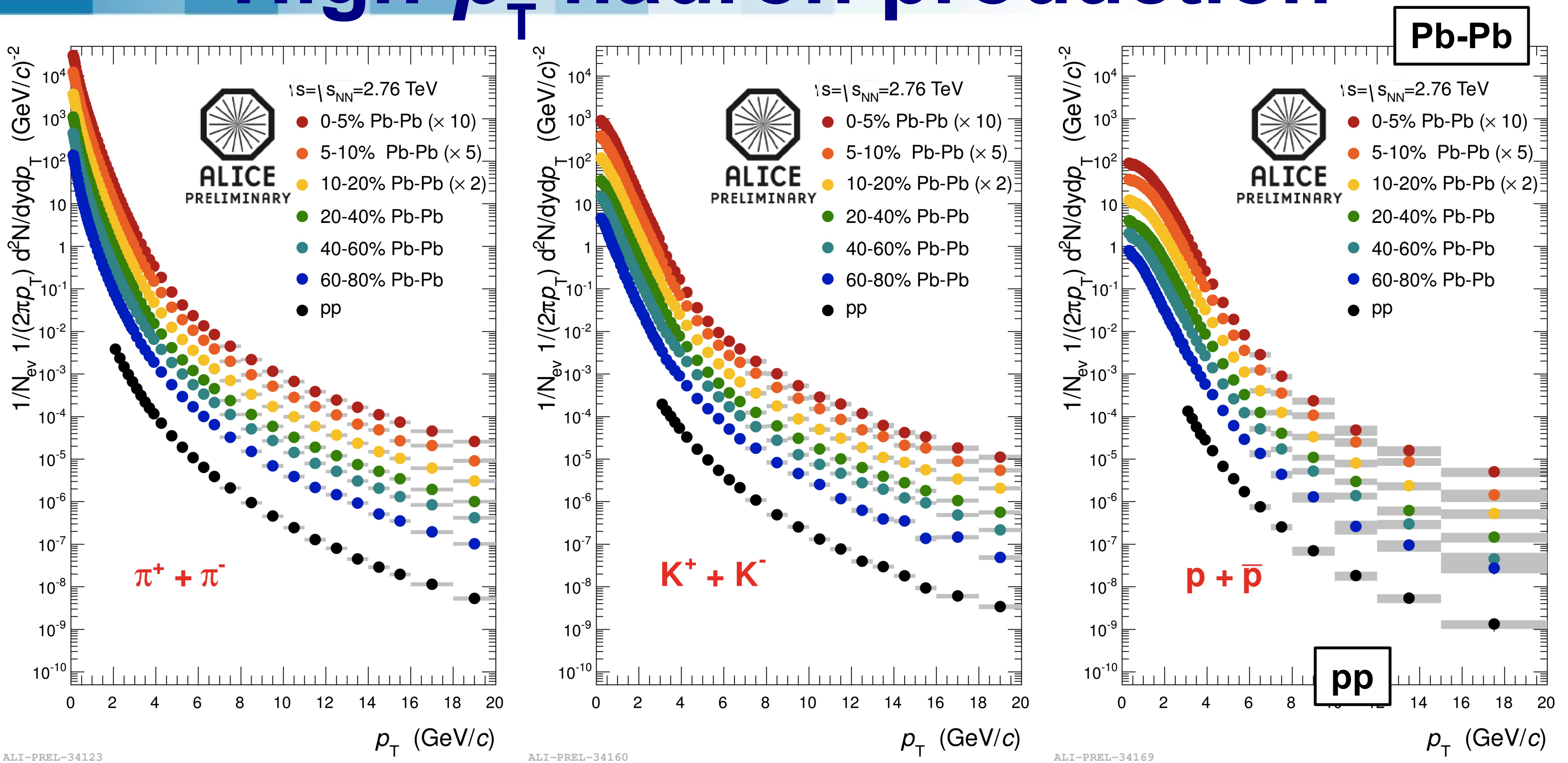
T_{ch} = 152 MeV (χ^2/ndf = 40/9)

p/π and Λ/π production ratios at LHC lower than at RHIC
significant ~1.5x deviation still puzzling

Increasing hadronic re-scattering?

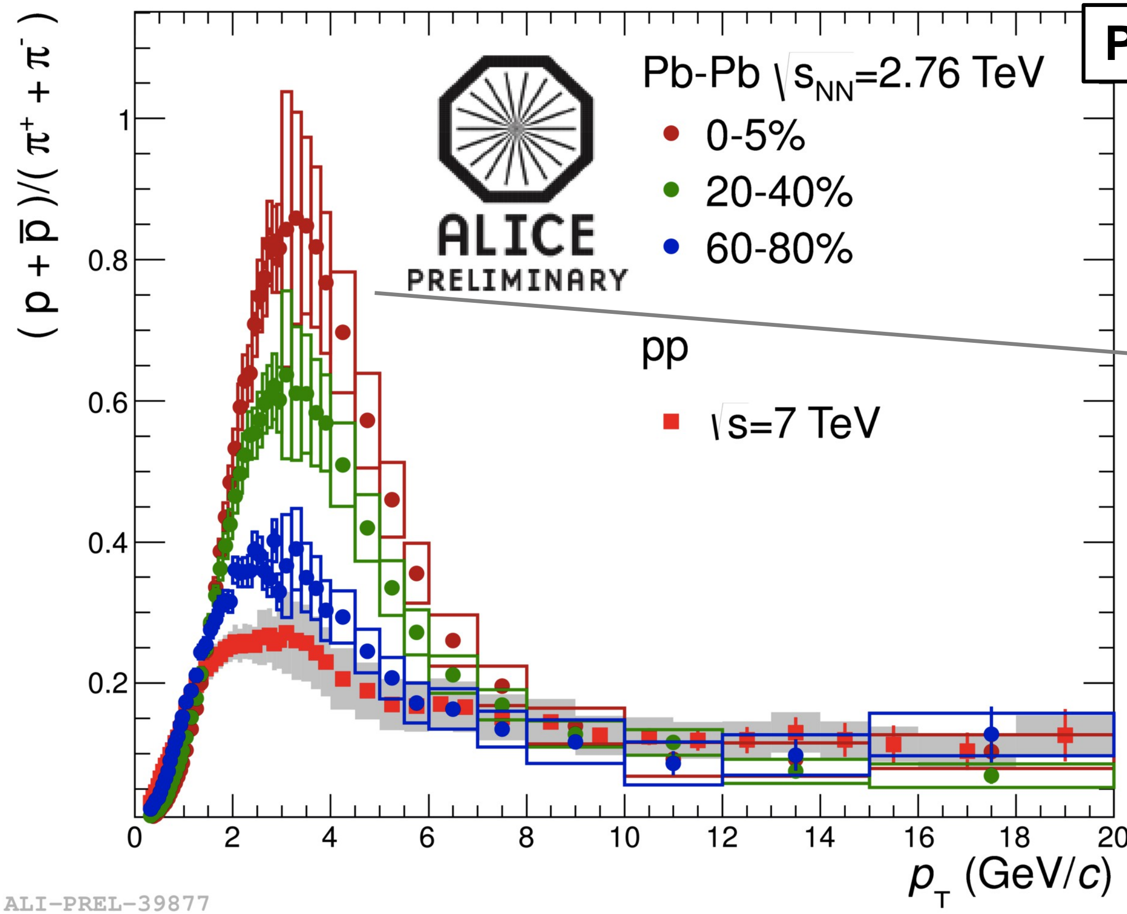
Becattini et al., PRC 85, 044921 (2012)
Steinheimer et al., arXiv:1203.5302 [nucl-th]

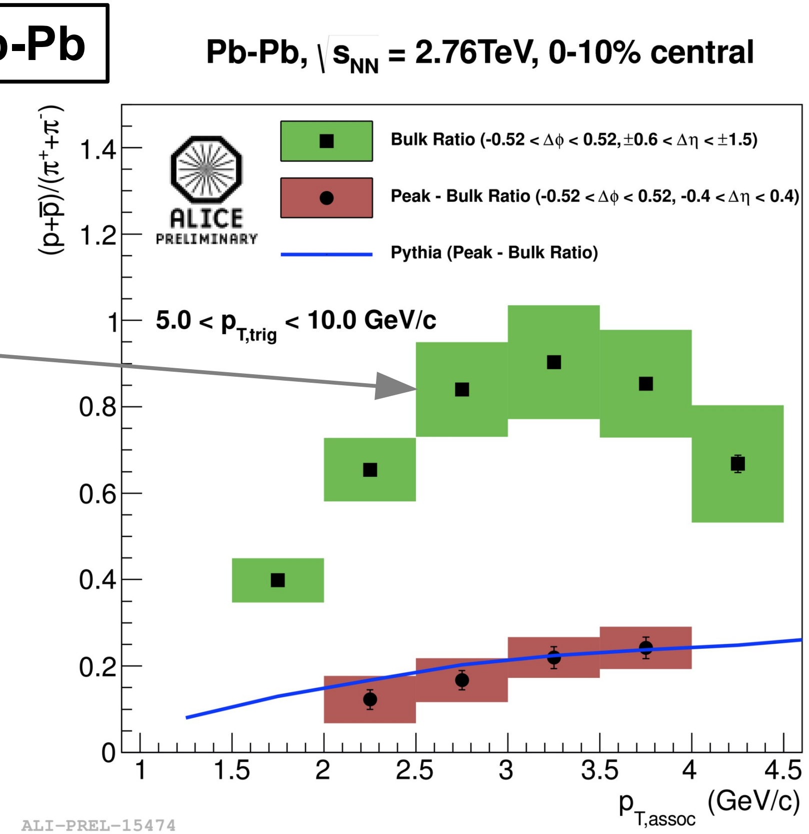
High-p_T hadron production



Identified-particle p_T spectra measured over a wide momentum range in pp $\sqrt{s}$ = 0.9, 2.76, 7 TeV and in Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV

Baryon-to-meson ratio: p/π





Enhancement of the baryon-to-meson ratio at intermediate p_T (3–7 GeV/c)
p/π ratio at p_T ≈ 3 GeV/c in most central (0-5%) Pb-Pb is ~3x higher than in pp
→ seems to be a bulk effect: recombination, radial flow?

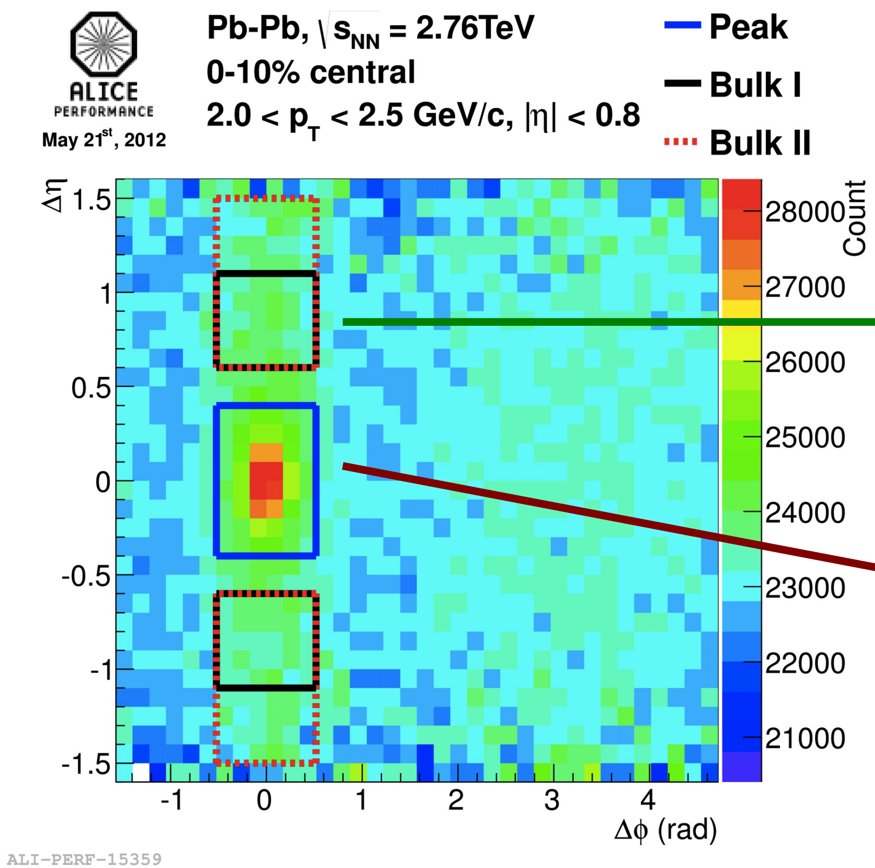
For p_T larger than ~10 GeV/c the ratio goes back to “normal” pp value
parton fragmentation (jet chemistry) not modified by the medium

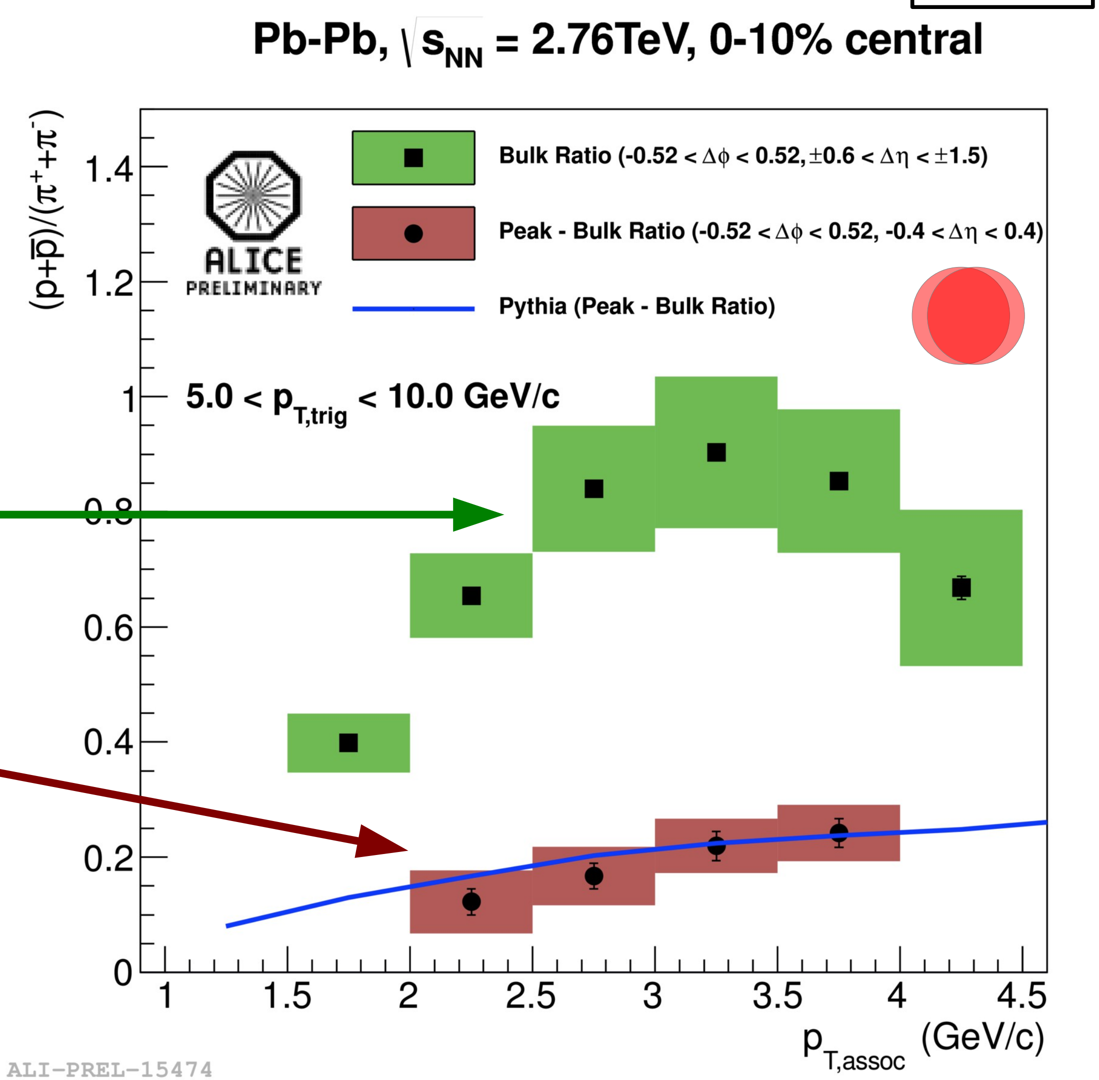
arXiv:1210.6995 [hep-ex]

PID in jet structures

Pb-Pb

Studied in 2-particle Δη-Δφ correlations
- **non-ID trigger particle (5-10 GeV/*c*)**
- **ID associated π, K, p (1.5-4.5 GeV/*c*)**





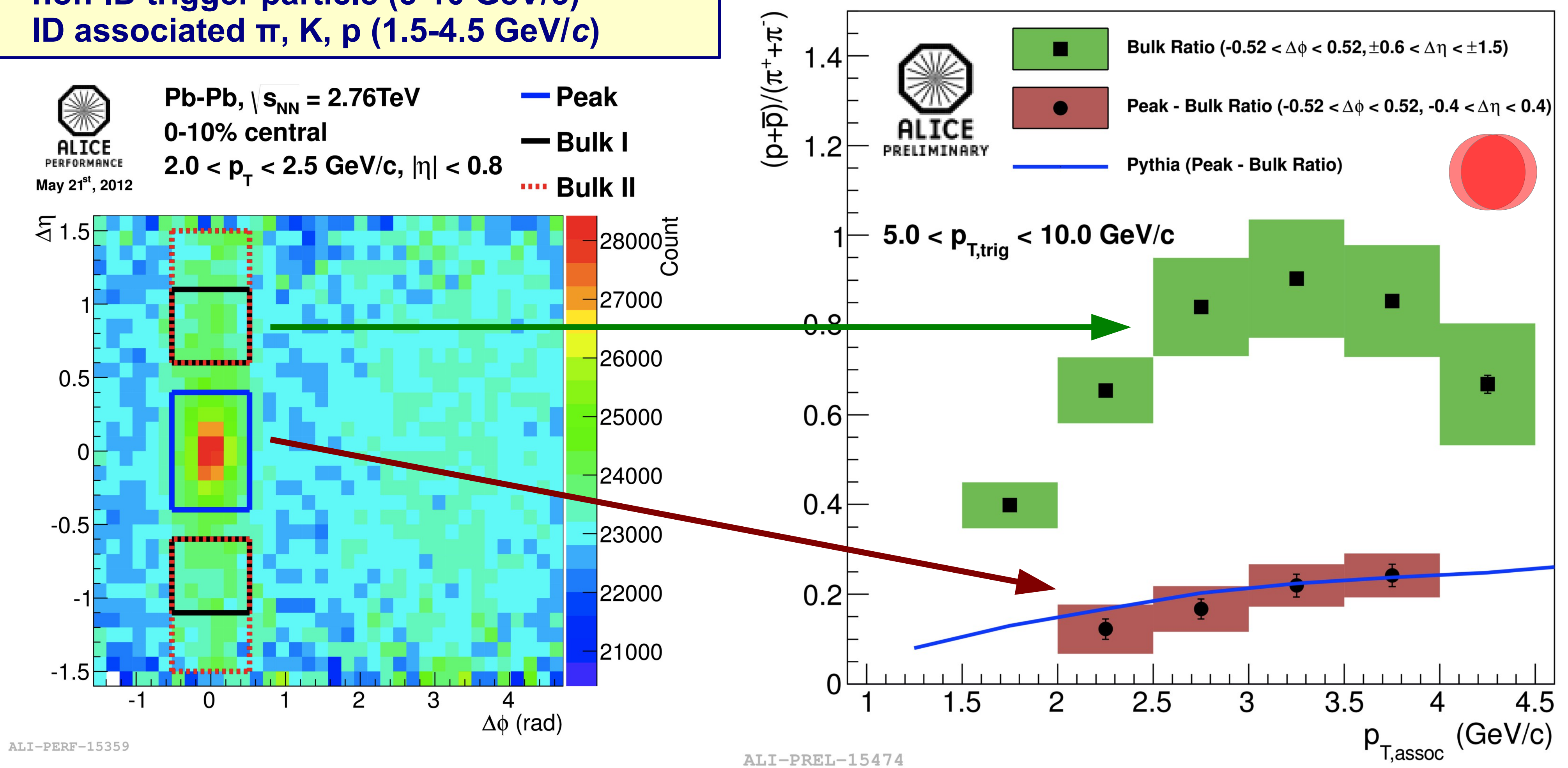
Near-side peak (after bulk subtraction):
p/π ratio similar to pp (PYTHIA)

Bulk region:
p/π ratio strongly enhanced
compatible with overall baryon enhancement

PID in jet structures

Pb-Pb

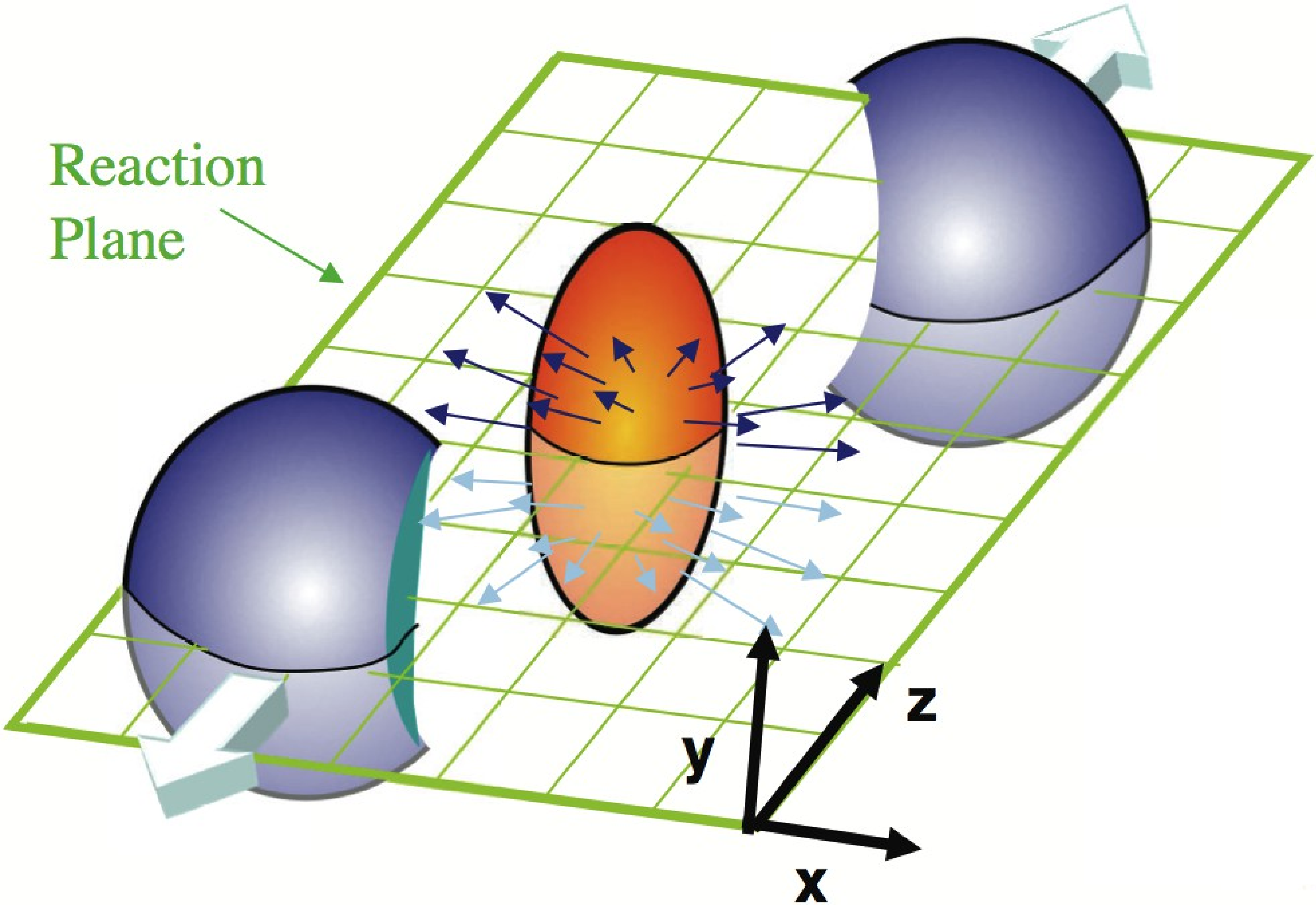
Studied in 2-particle Δη-Δφ correlations
- **non-ID trigger particle (5-10 GeV/*c*)**
- **ID associated π, K, p (1.5-4.5 GeV/*c*)**



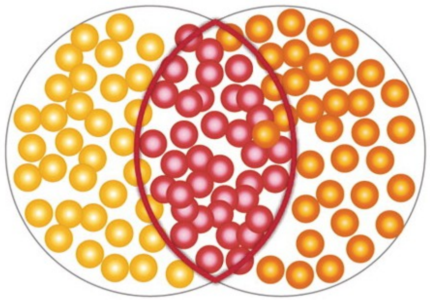
no medium-induced modification of jet particle ratios (jet chemistry)

baryon enhancement is from the bulk, not from jets

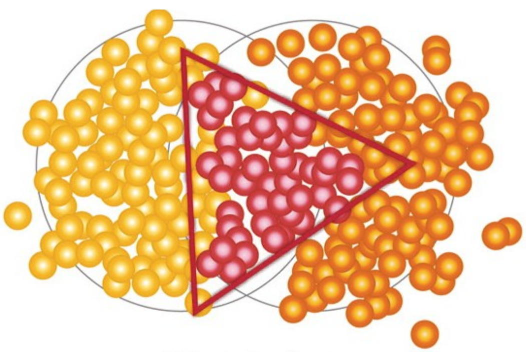
Anisotropic transverse flow



Anisotropic transverse flow



Elliptic flow



Triangular flow

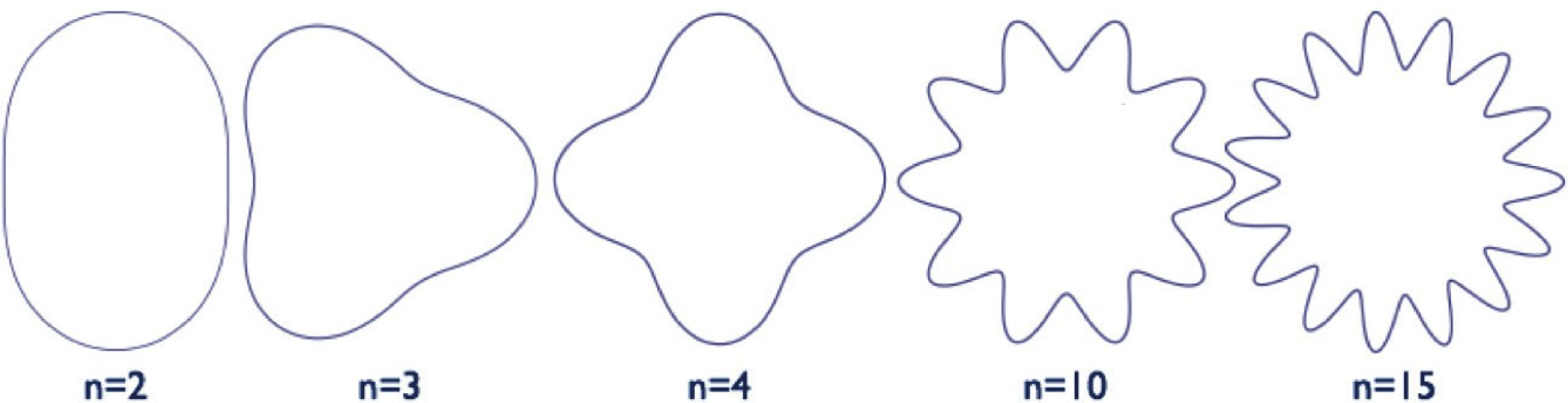
azimuthal distribution of particles wrt. plane perpendicular to the beam

anisotropic momentum distributions

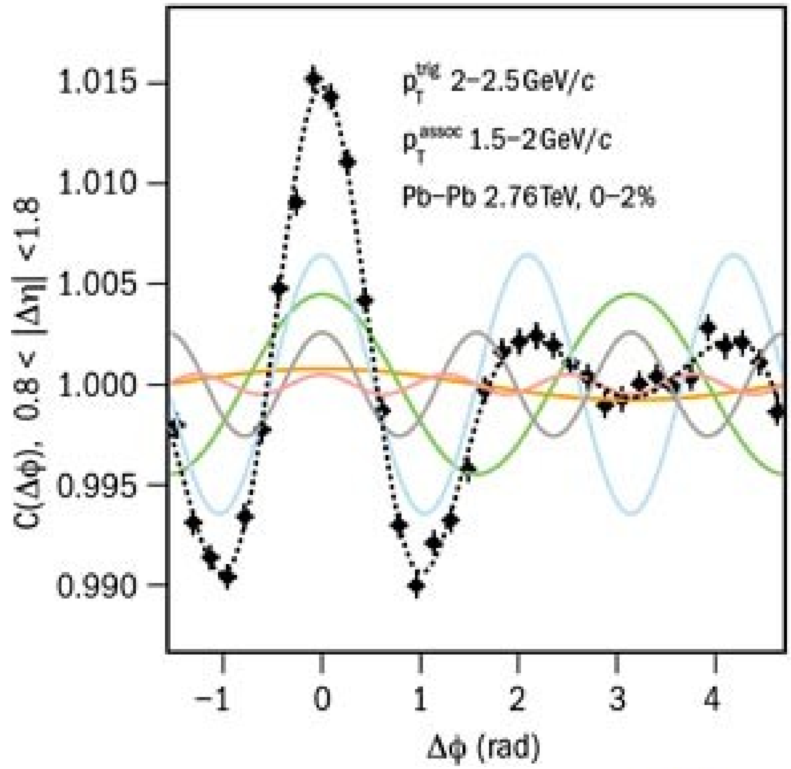
azimuthal dependence can be written in the form of a Fourier series

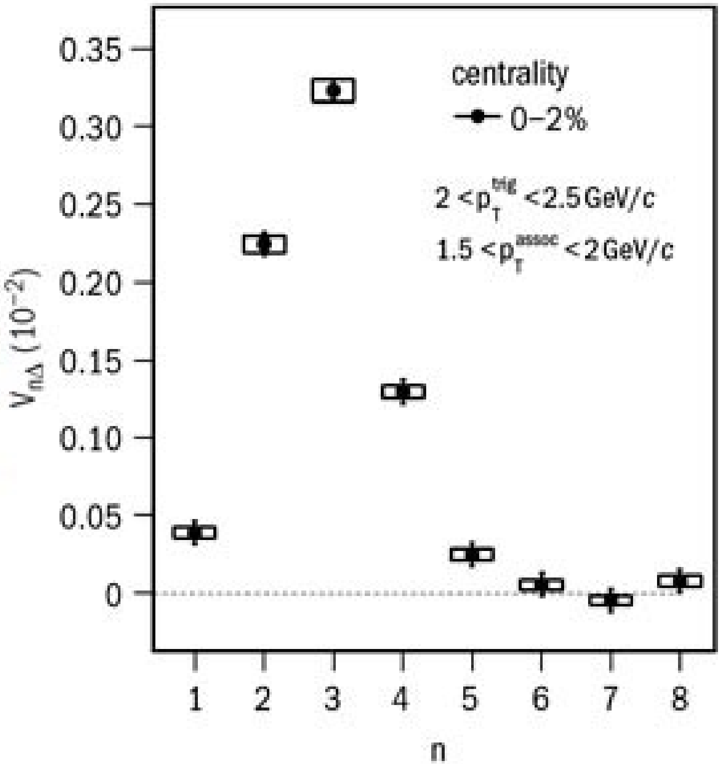
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)]\right)$$

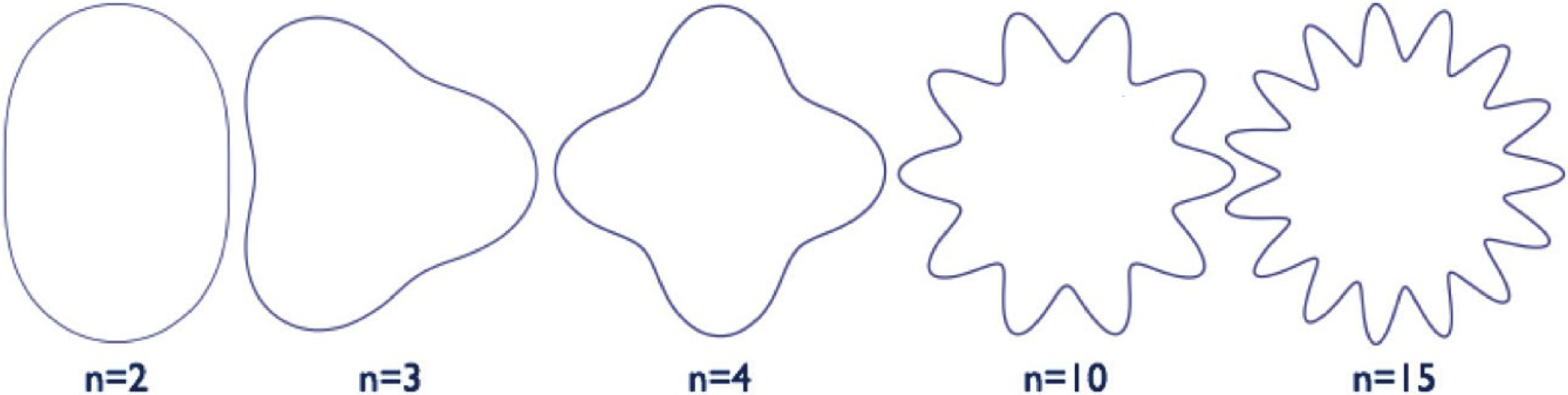
the magnitude of the anisotropic flow is characterized by the coefficients v_n of the Fourier expansion



Anisotropic transverse flow

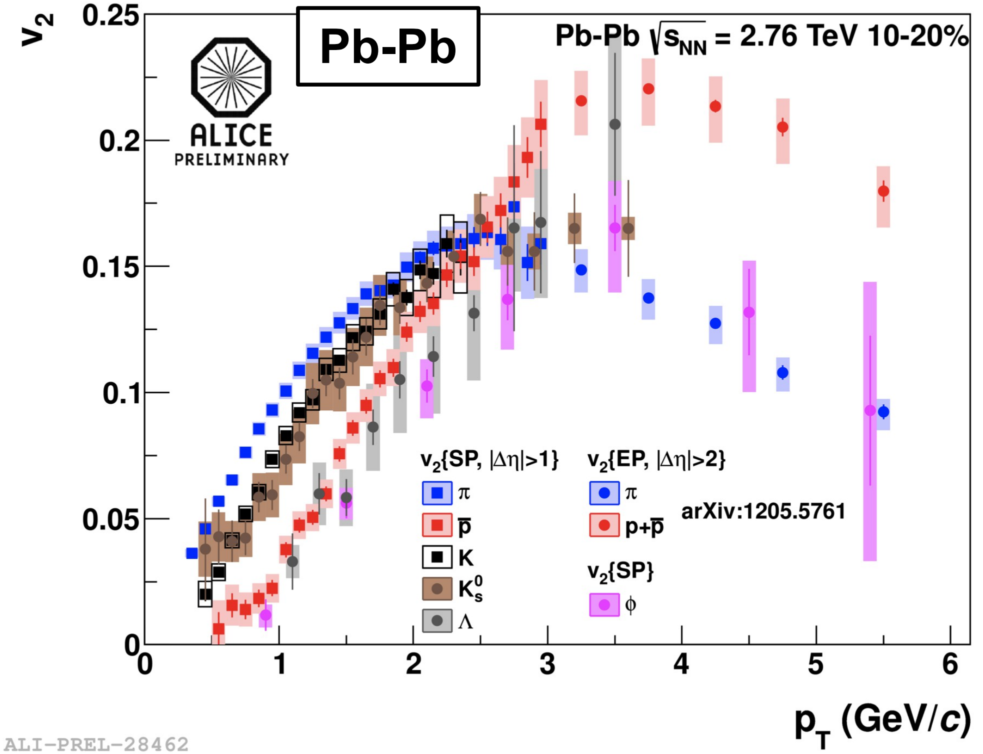


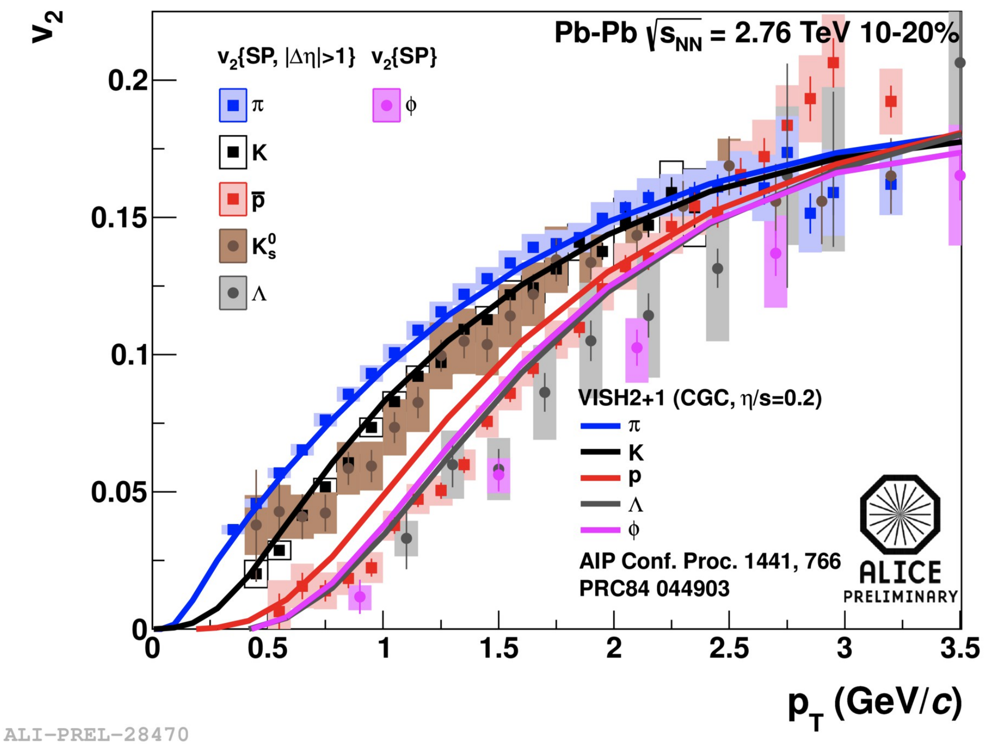




Elliptic flow of identified particles

sensitive to the partonic degrees of freedom at early times in HI collisions





Elliptic flow (v_2) measured for:

$\pi^\pm$, $K^\pm$, K_s^0, p, Λ, ϕ and (not shown) Ξ, Ω

mass ordering observed at low p_T

<u>ϕ-meson elliptic flow</u>

follows mass hierarchy at low p_T < 3 GeV/*c*

follows flow of mesons at higher p_T

Overall qualitative agreement with viscous hydro calculations at low p_T

Adding hadronic rescattering phase improves the agreement

Heinz et al., AIP Conf Proc 1441, 766 (2012)

Direct photon production

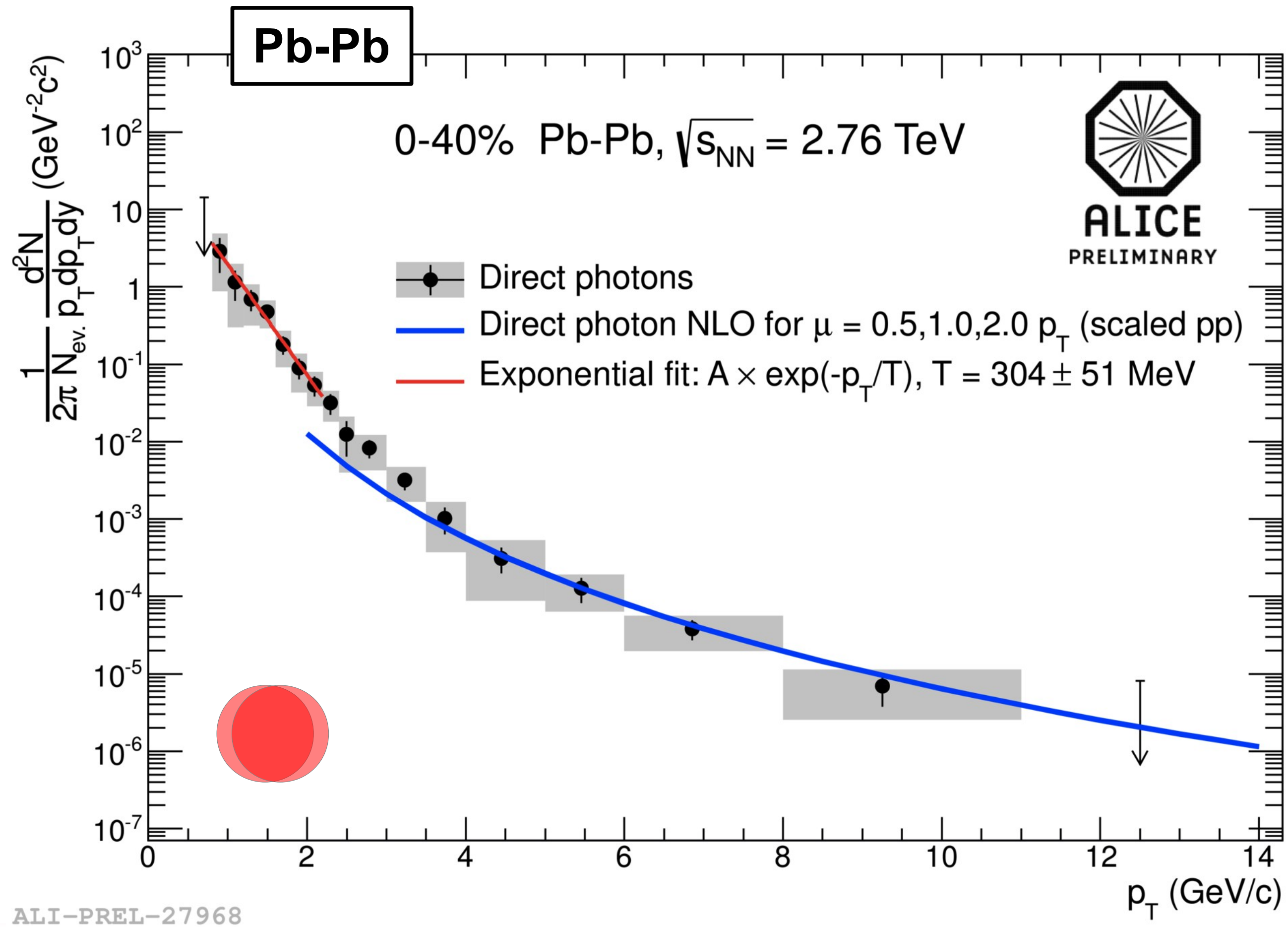
p_T < 2 GeV/*c*
~20% excess of direct photons
p_T > 4 GeV/*c*
agreement with N_{coll} scaled NLO

Exponential fit for p_T < 2.2 GeV/*c*

ALICE inverse slope:
***T* = 304 ± 51 MeV**
in 0-40% central Pb-Pb
$\sqrt{s_{NN}}$ = 2.76 TeV

THE HIGHEST MAN-MADE TEMPERATURE

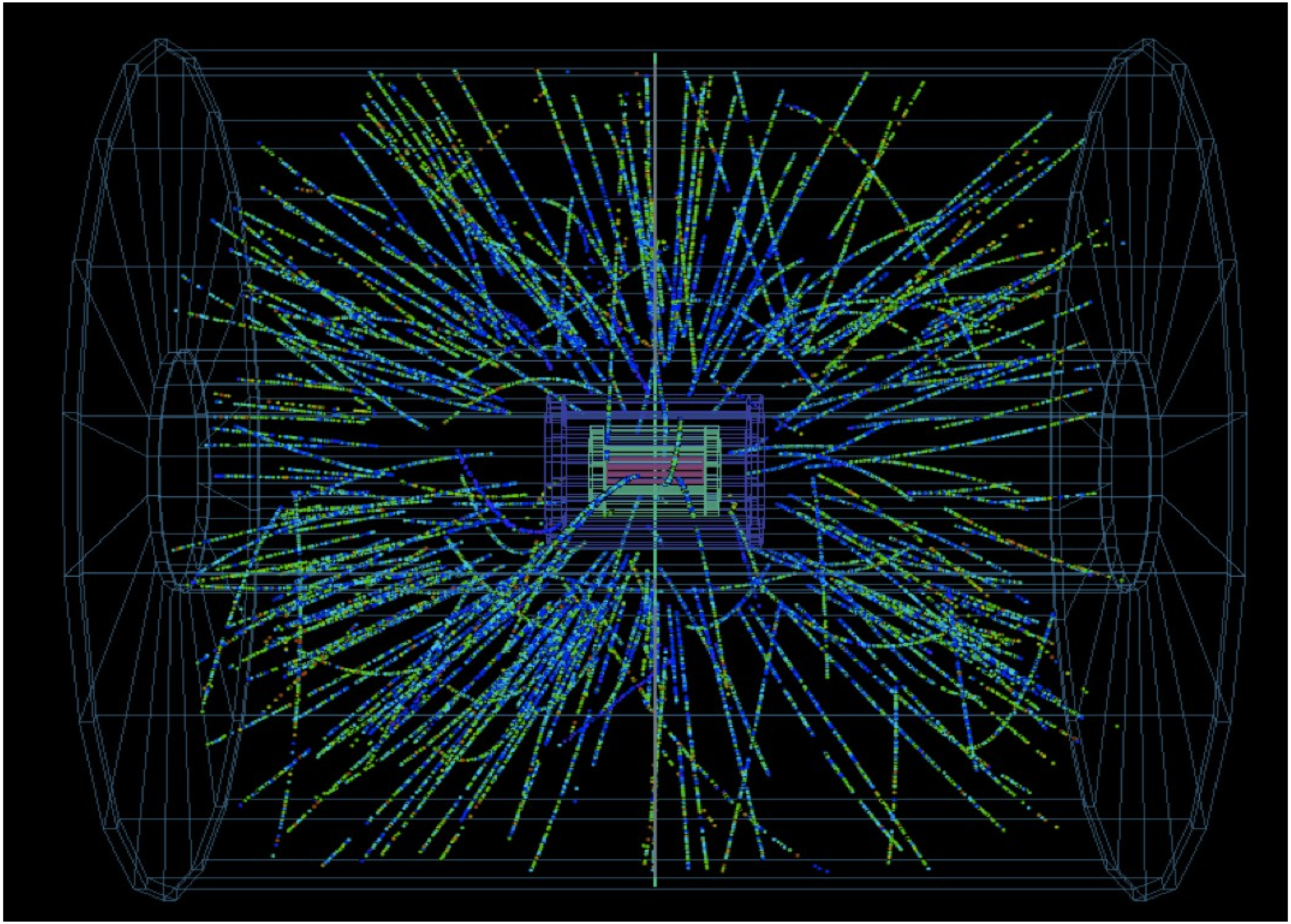
PHENIX:
***T* = 221 ± 19 ± 19 MeV**
in 0-20% central Au-Au
$\sqrt{s_{NN}}$ = 200 GeV
PHENIX, PRL 104, 132301 (2010)



arXiv:1210.5958 [nucl-ex]

p-Pb collisions

first p-Pb collisions during LHC pilot run, 12 September 2012



R_{AA} in p-Pb collisions

arXiv:1210.4520 [nucl-ex]

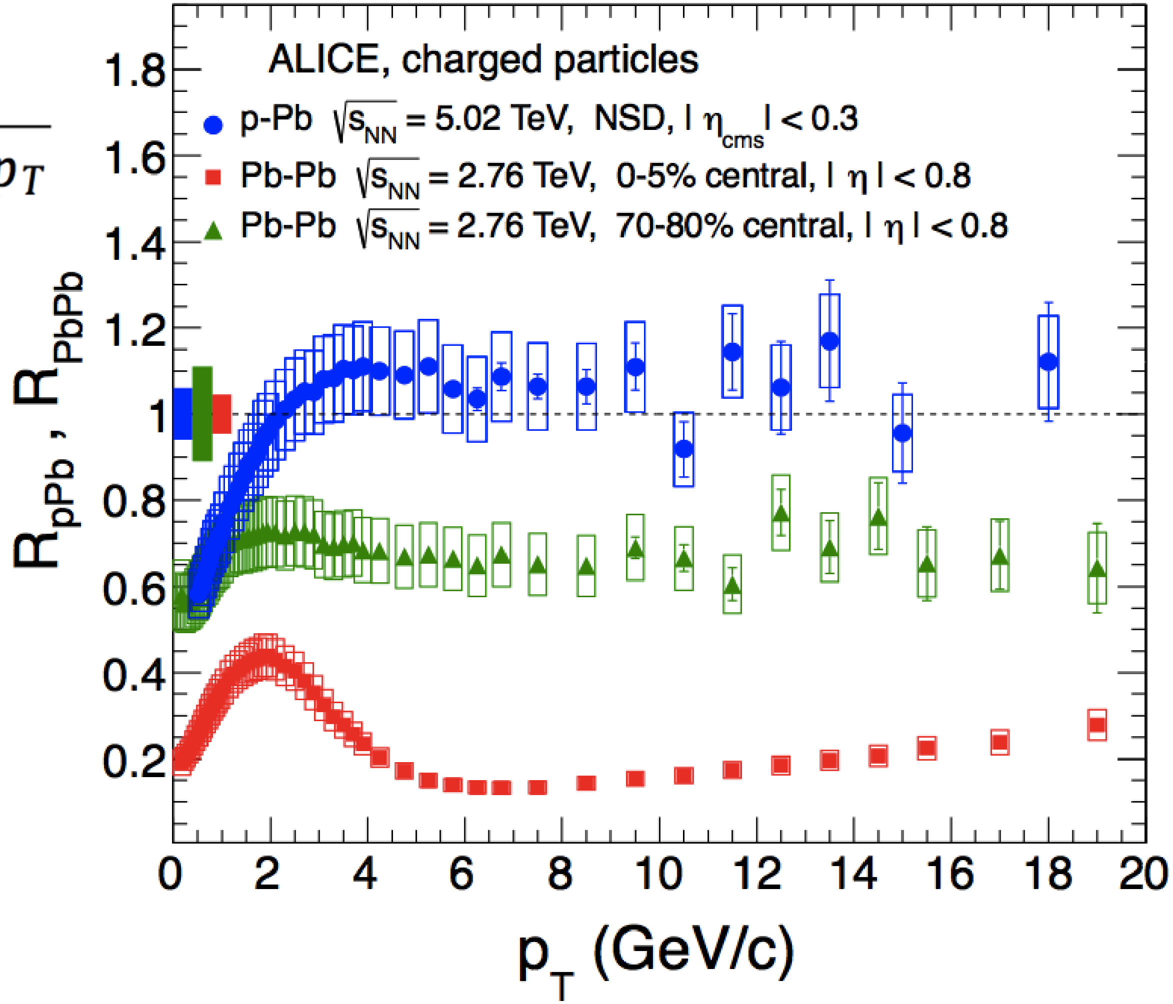
PLB 696, 30 (2011)

→ **unity for hard-processes with binary collision scaling in the absence of nuclear modifications**

confirmed in Pb-Pb collisions at the LHC (direct-γ, Z^0 and $W^{\pm}$ production)

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta\, dp_T}$$

p-Pb



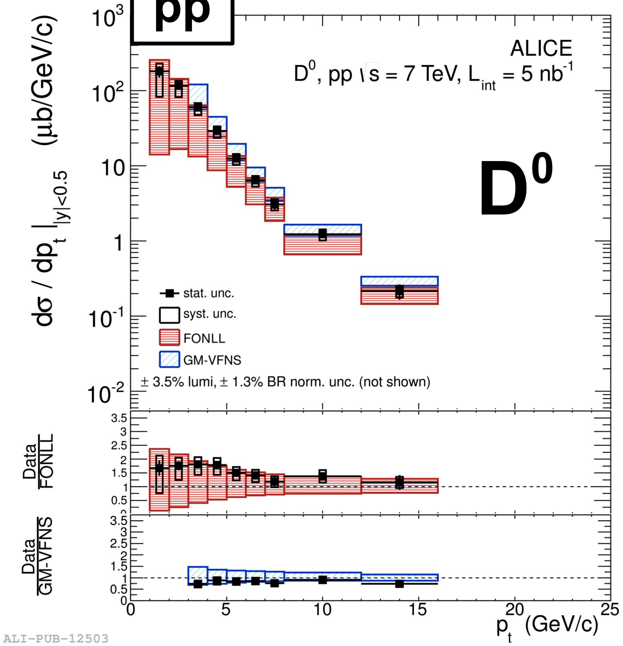
consistent with unity for p_T > 2 GeV/*c*

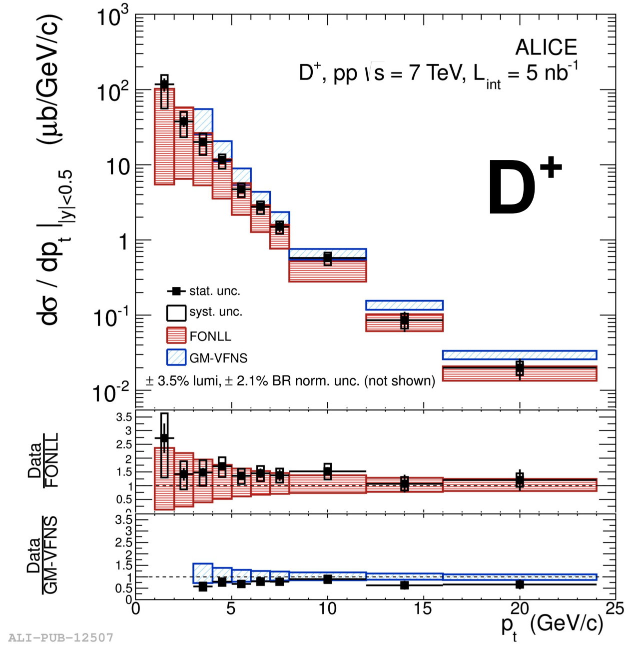
the strong suppression observed in Pb-Pb is NOT an initial-state effect → hot QCD matter effect

Heavy flavour

Heavy flavour production

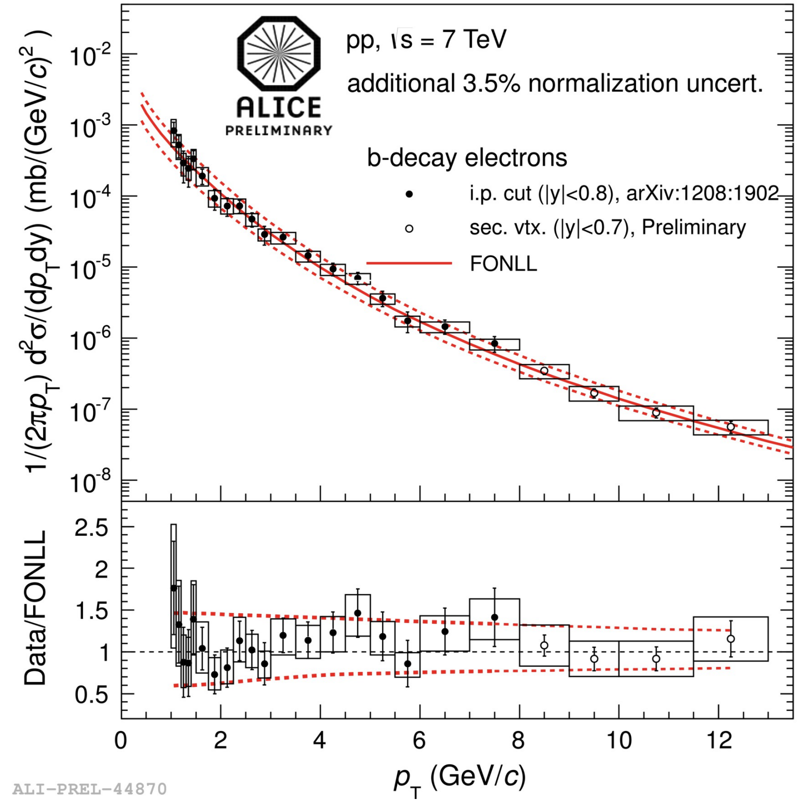
pp

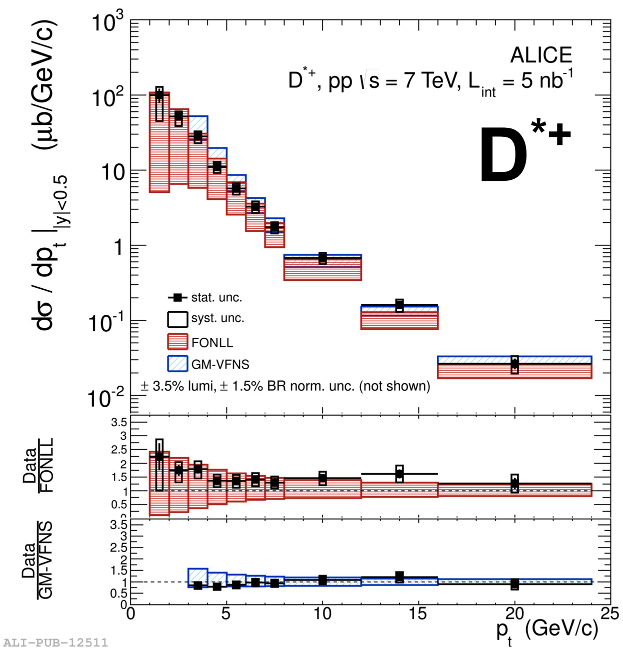


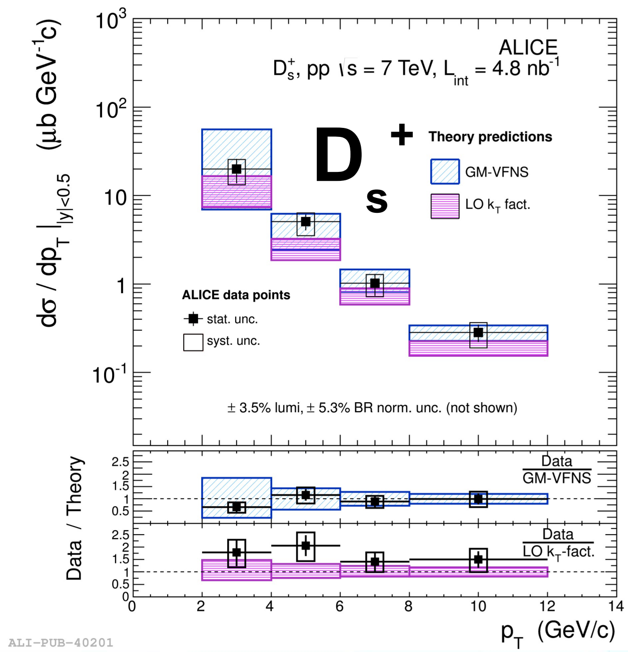


σ measurements in pp well described by pQCD

b → (c →) e

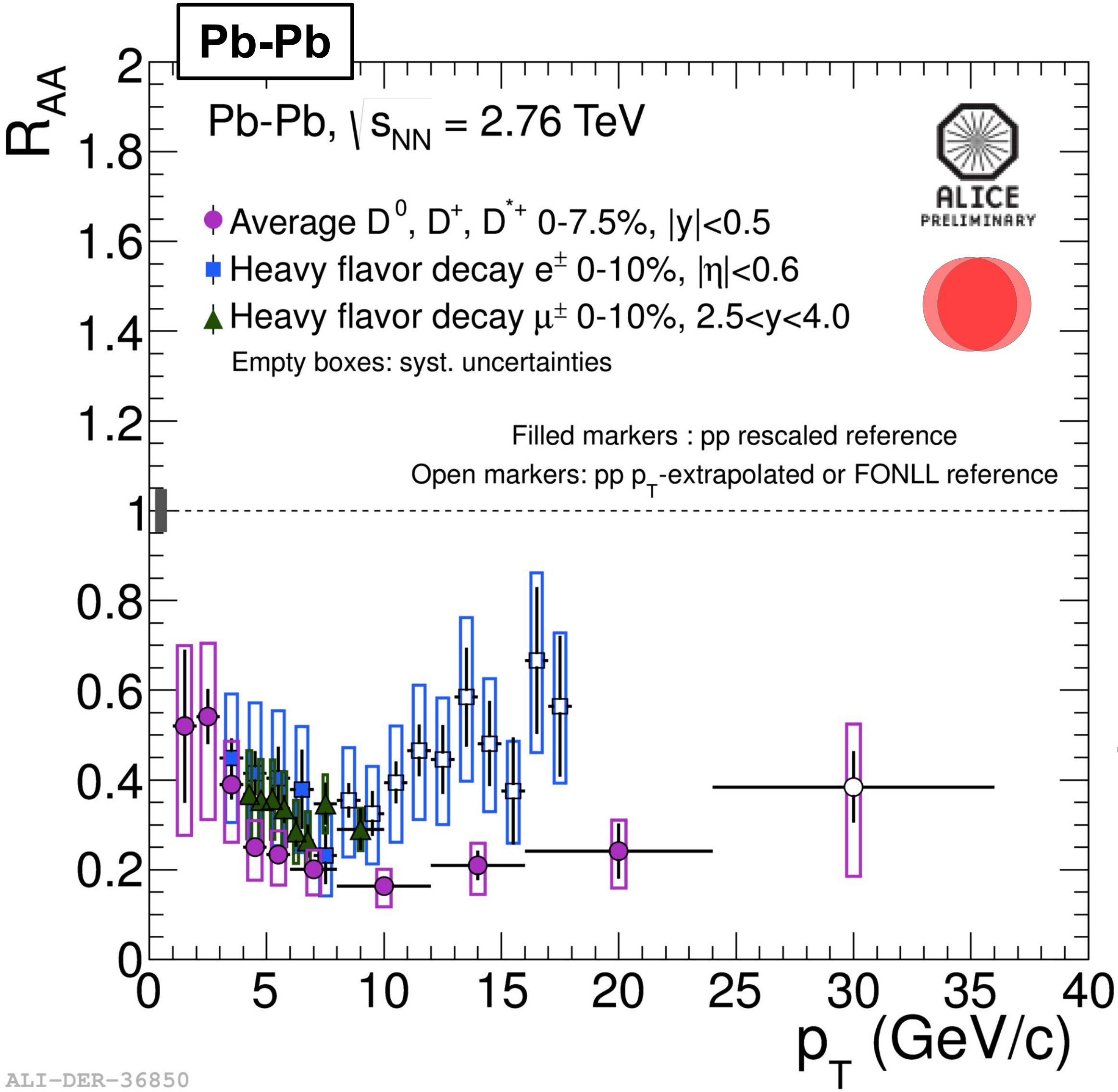


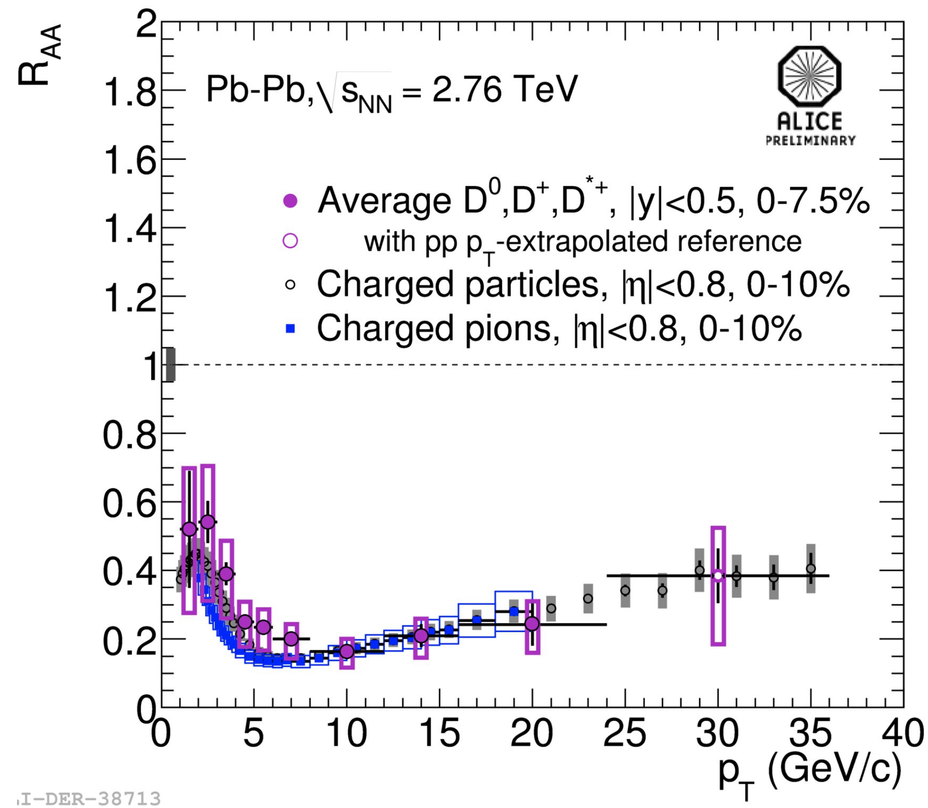




JHEP 01, 128 (2012)
arXiv:1208.1948 [hep-ex]
arXiv:1208.1902 [hep-ex]

Heavy-flavour R_{AA}



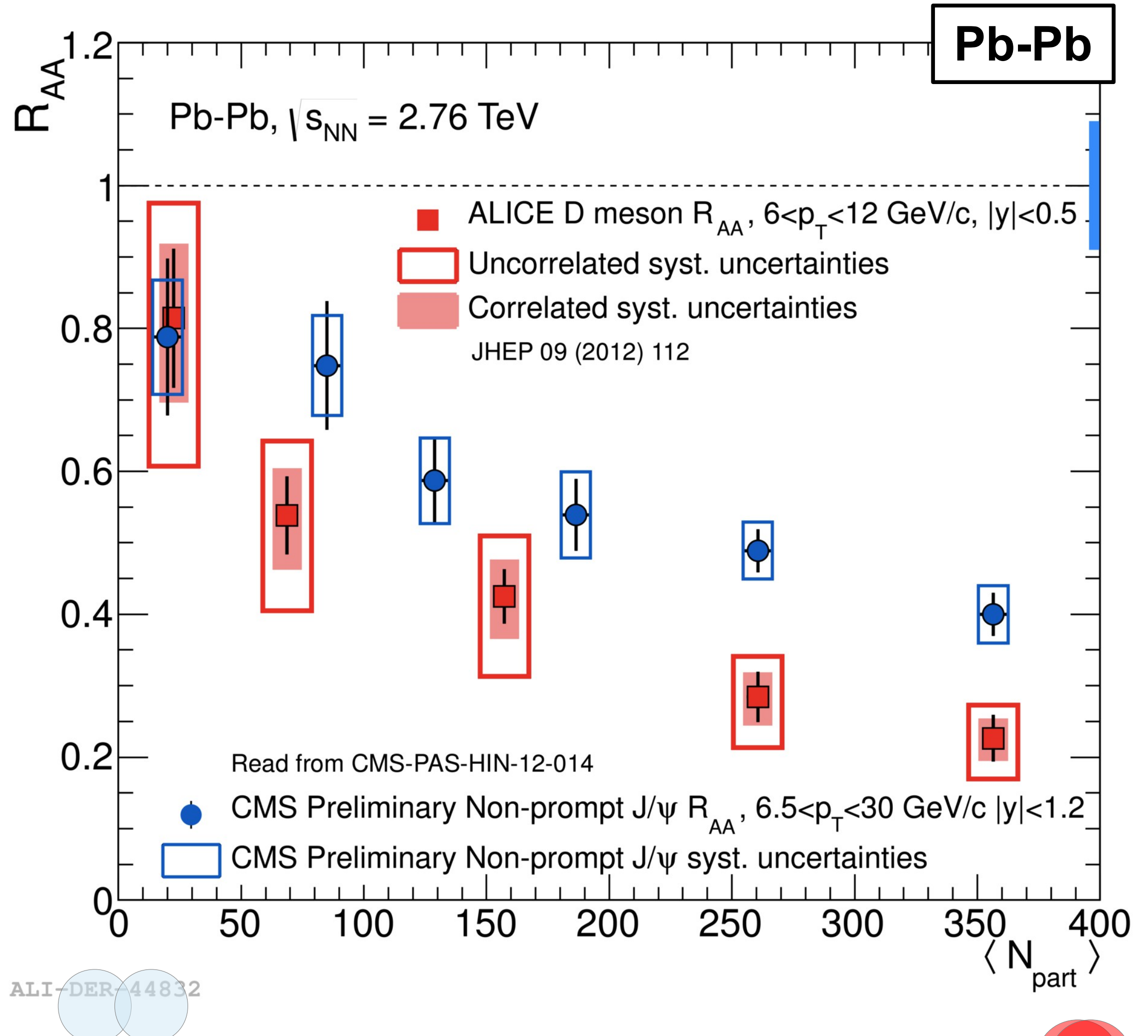


Average D-meson R_{AA} shows similar trend as charged particles and $\pi^{\pm}$ (mostly from gluon fragmentation)

→ not possible to conclude on the expected q vs. g different in energy loss

Heavy-flavour R_{AA}

CMS non-prompt J/ψ (from B-meson decays)
R_{AA} reflects b-quark energy loss in medium



parton energy loss by medium-induced gluon radiation collisions with medium gluons predicts $\Delta E_c > \Delta E_b$

indication of different suppression for charm and beauty in central collisions

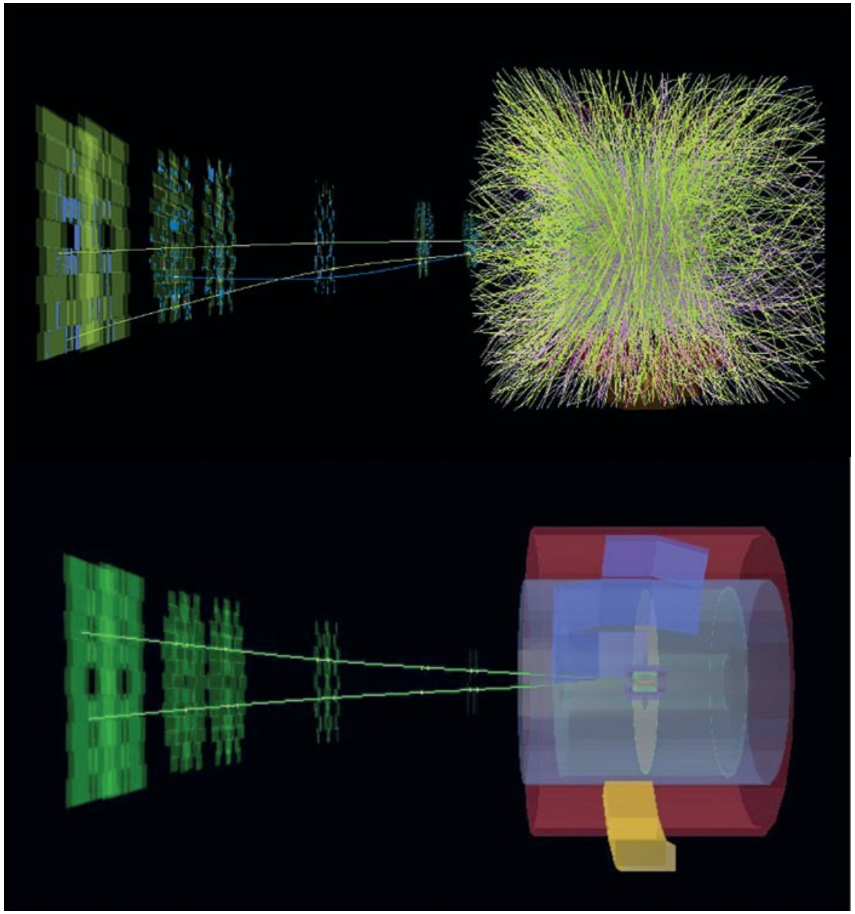
JHEP 09, 112 (2012)

Exclusive J/ψ photoproduction

Studied in ultra-peripheral (UPC) heavy-ion collisions

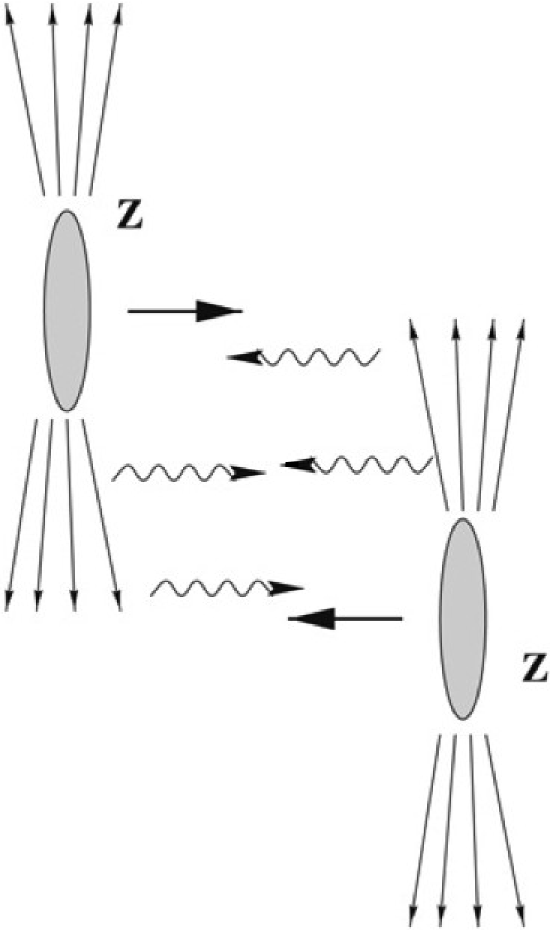
impact parameter *b* larger than sum of the two radii 2R
→ hadronic interactions strongly suppressed

high photon flux ~ Z^2
→ high σ for γ-induced reactions



inclusive J/ψ
central PbPb

exclusive J/ψ
UPC

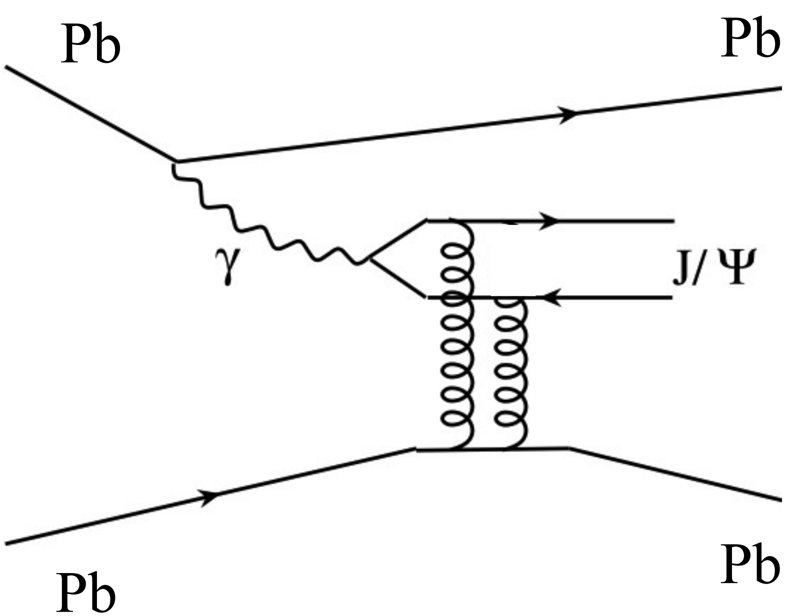


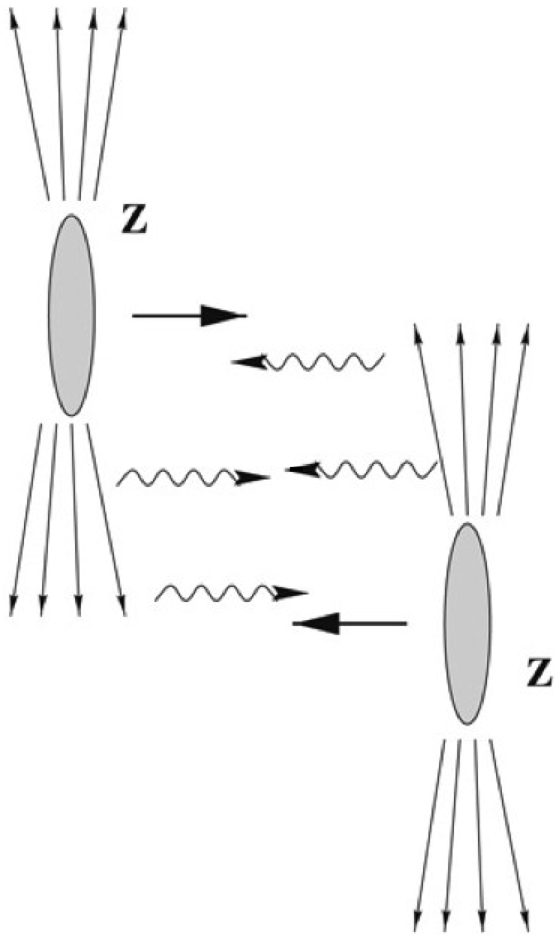
Exclusive J/ψ photoproduction

Studied in ultra-peripheral (UPC) heavy-ion collisions

impact parameter *b* larger than sum of the two radii 2R
→ hadronic interactions strongly suppressed

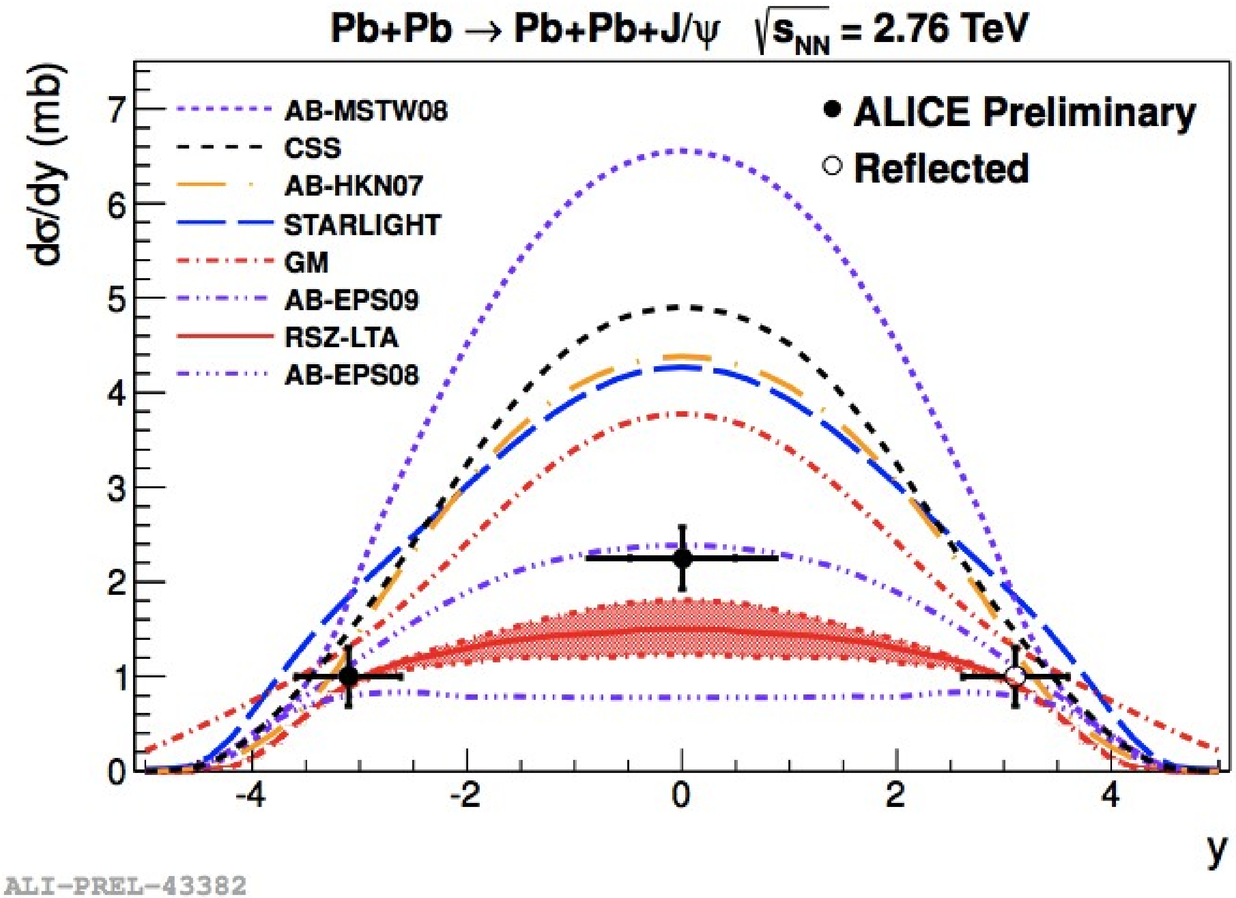
high photon flux ~ Z^2
→ high σ for γ-induced reactions





Successfully modeled in pQCD via two-gluon exchange
→ probes nuclear gluon distribution of the nucleus
poorly known in the low-x region

Exclusive J/ψ photoproduction

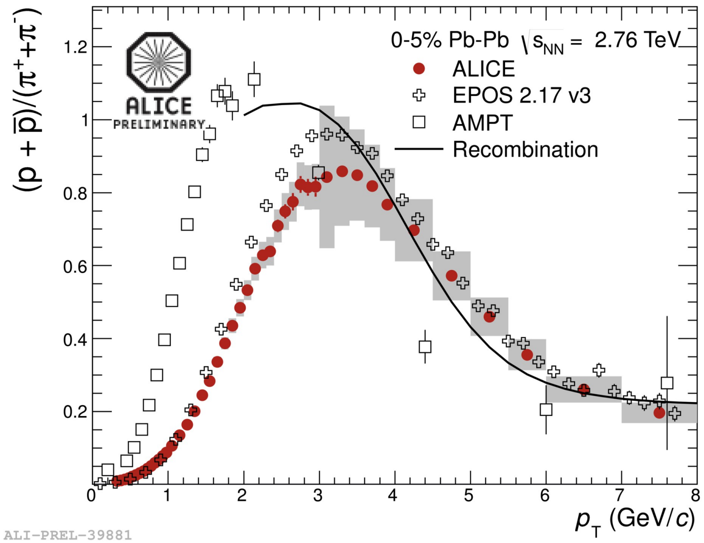


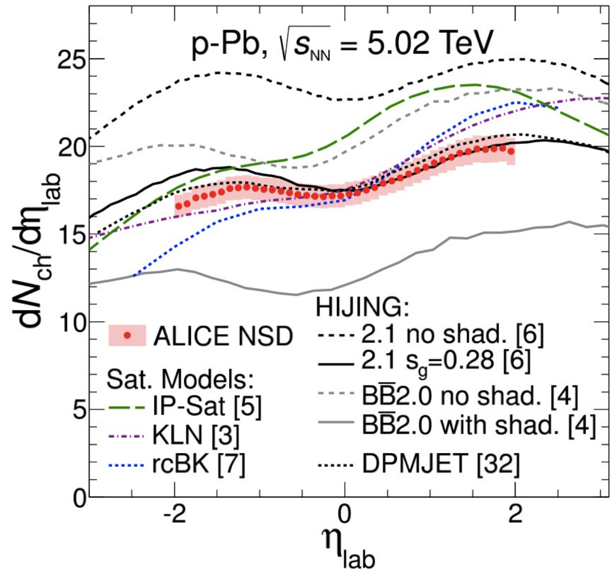
Data is found in **good agreement with** pQCD models with $\sigma \sim [G(x,Q^2)]^2$ which include **gluon shadowing**

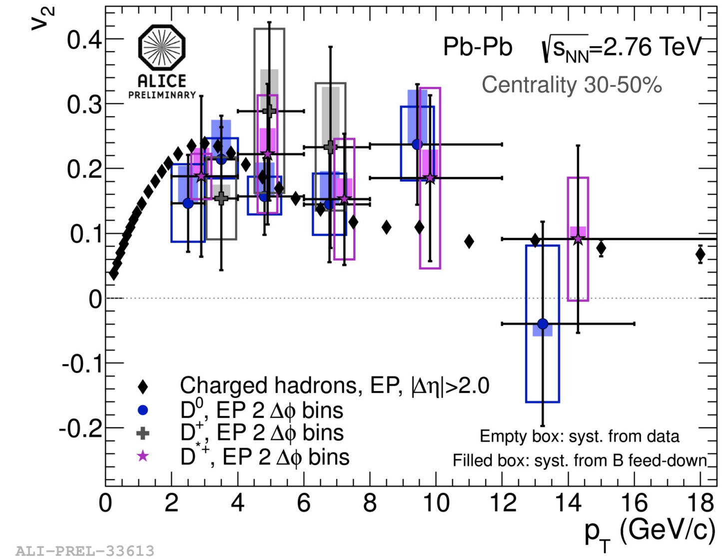
best agreement with EPS-09 parametrization both in central and forward region

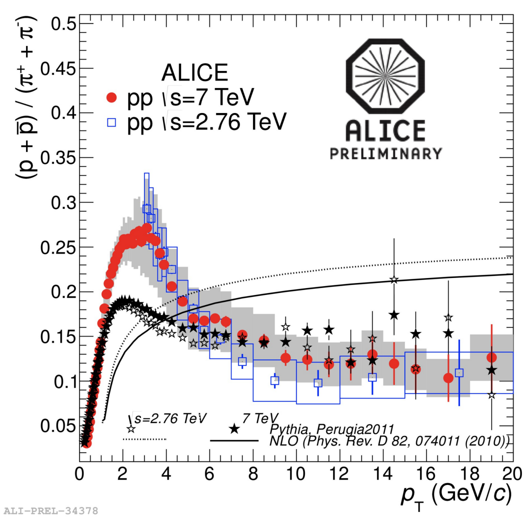
arXiv:1209.3715 [nucl-ex]

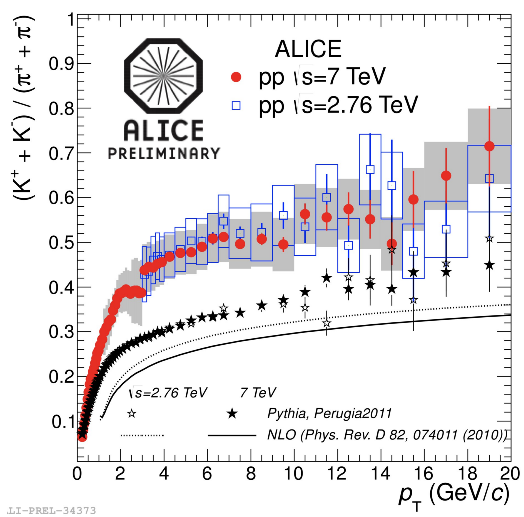
...and much more

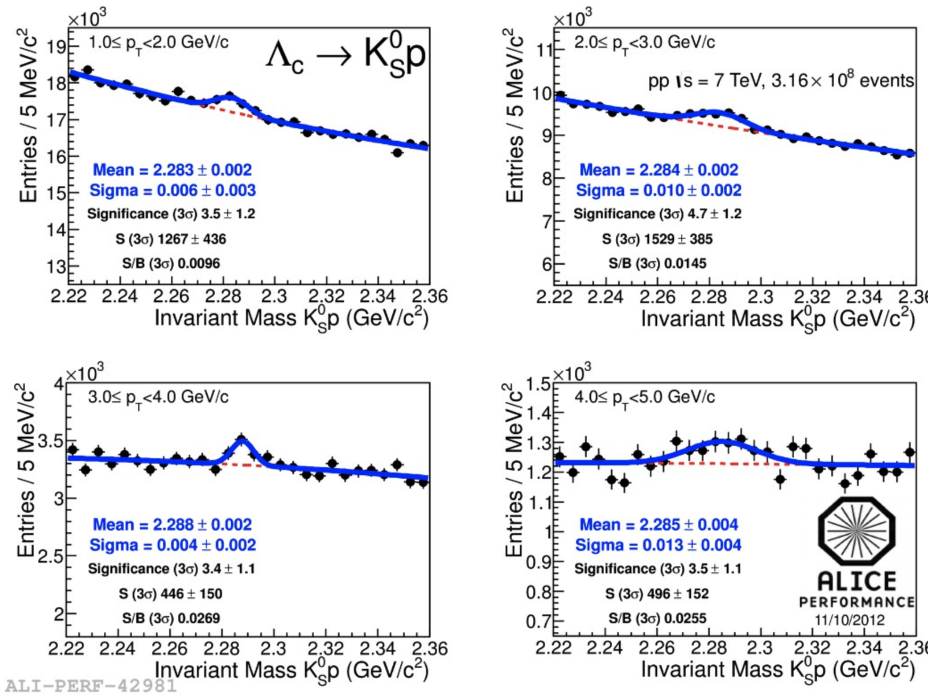












Summary and conclusions

ALICE is obtaining a wealth of physics results both from proton-proton collisions and from the first two LHC heavy-ion runs

Bulk and soft probes

Low-x with exclusive vector-meson production

High-p_T probes

Heavy-flavour physics

Now entering in the precision measurement era

- p-Pb collisions clarify the role of the initial-state
- further Pb-Pb collisions before LHC LS2
- clear detector upgrade plan for hi-lumi LHC

END

The ALICE experiment at LHC

a dedicated heavy-ion experiment at the LHC

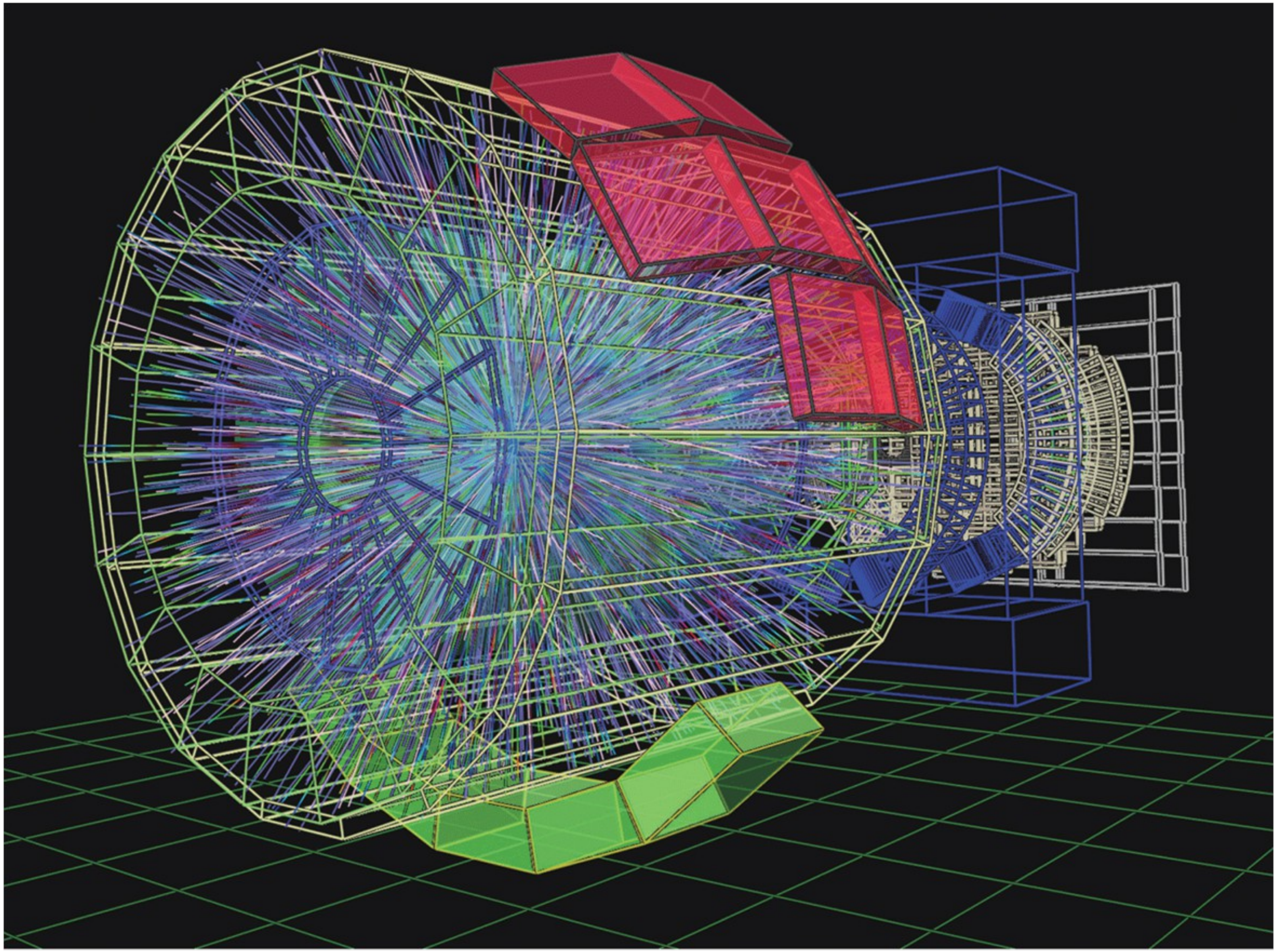
designed to cope with **very high charged-particle multiplicities** $dN_{ch}/d\eta \leq 8000$

3D **tracking with TPC**

moderate B = 0.5 T
thin materials
for low-p_T particles

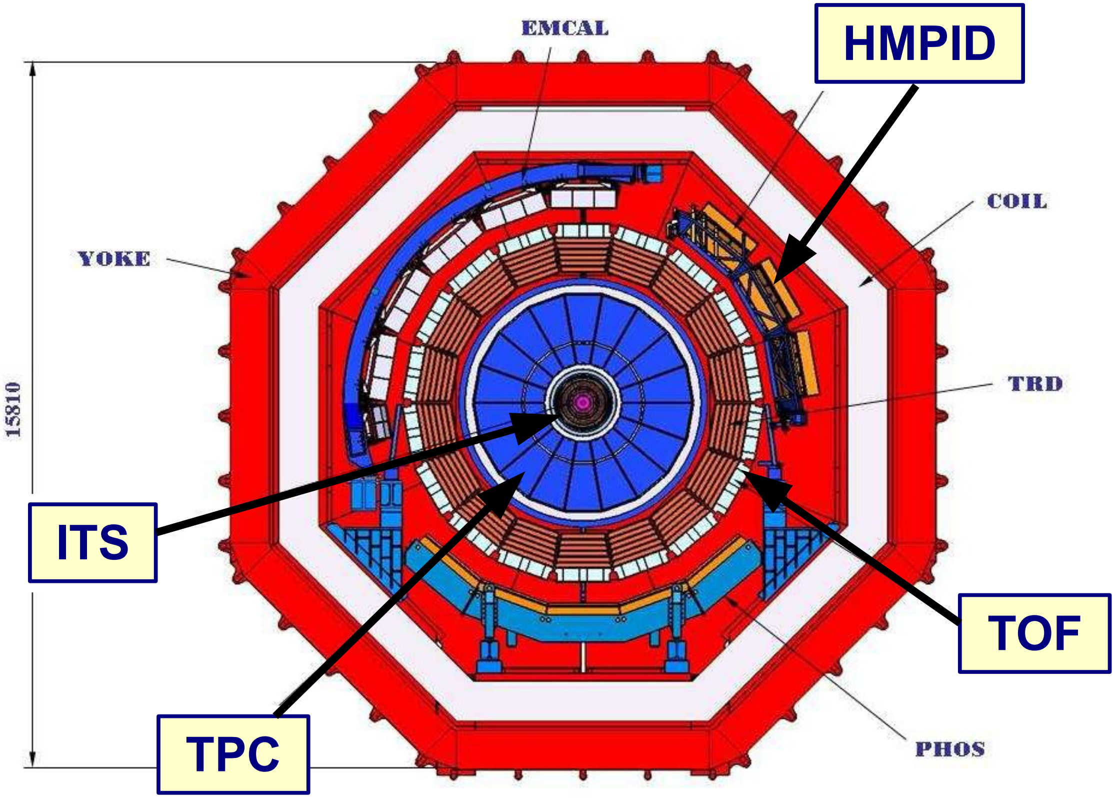
uses **all known PID techniques**

- dE/dx
- time-of-flight
- transition radiation
- Cherenkov radiation
- calorimetry
- muon filters
- topological decay

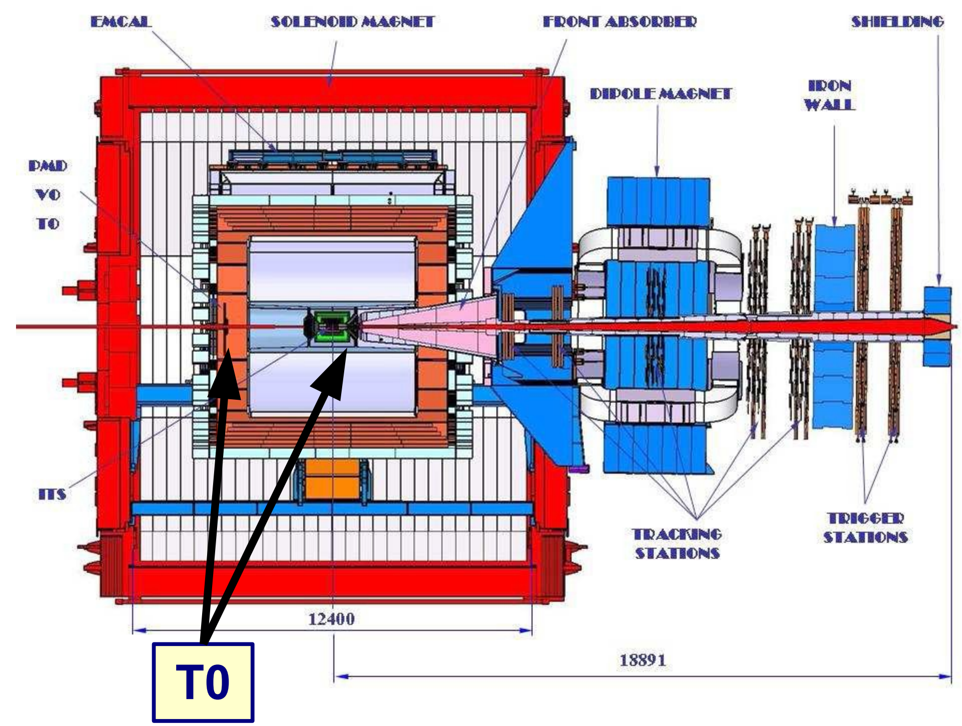


Central-barrel particle identification

front view



side view

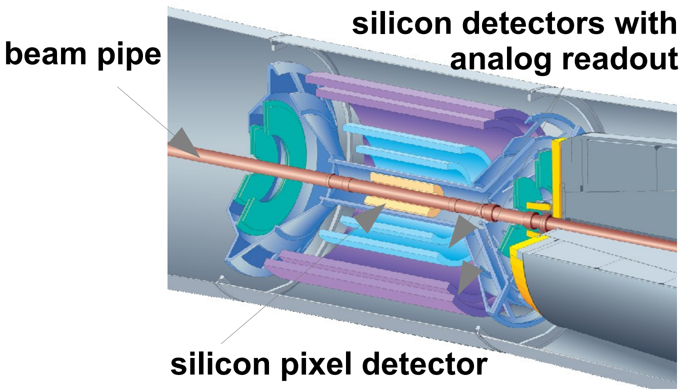


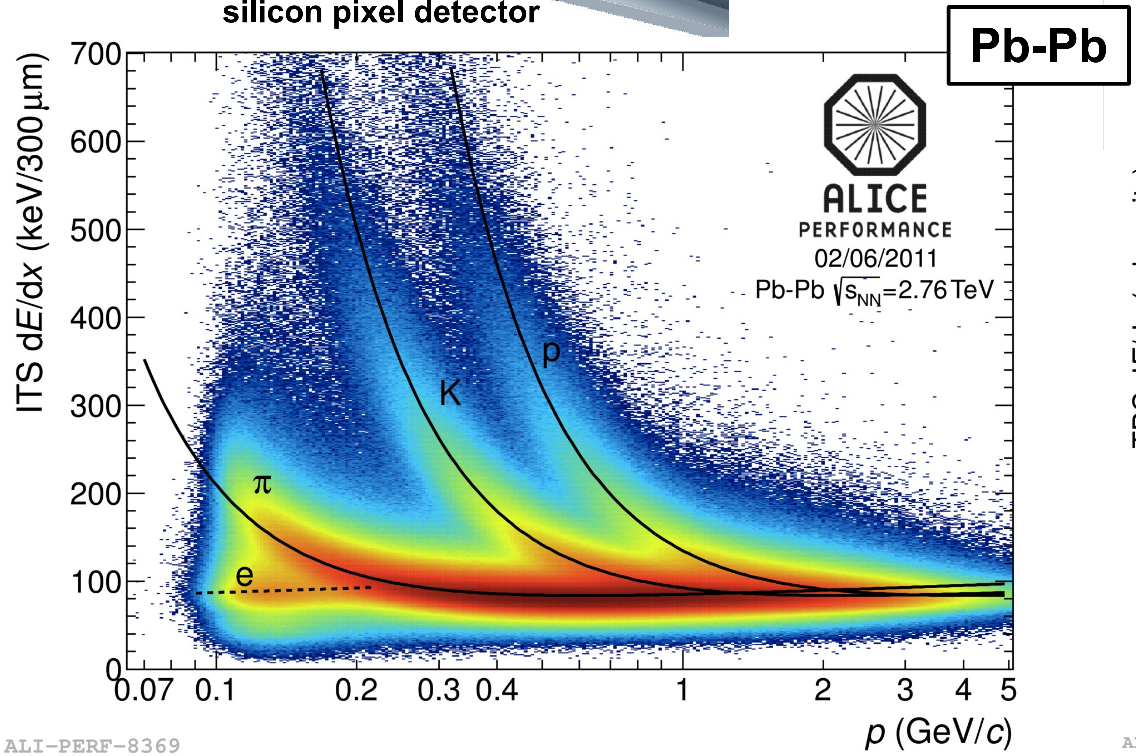
ALICE sub-detectors used for direct <u>hadron identification</u>

ITS	tracking + vertexing + PID *(dE/dx in silicon)*
TPC	tracking + vertexing + PID *(dE/dx in gas)*
TOF (+T0)	PID *(Time-Of-Flight)*
HMPID	PID (R*ing Imaging Cherenkov*)

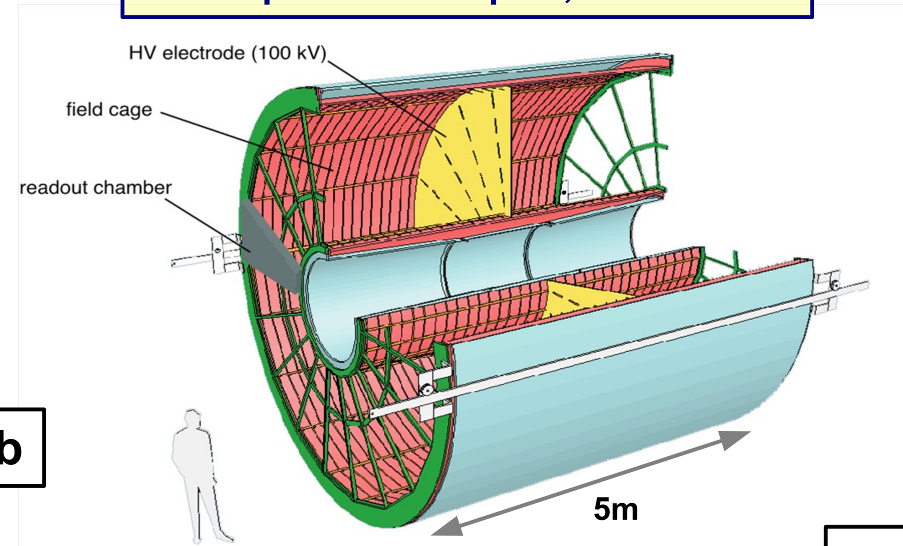
Particle-identification: dE/dx technique

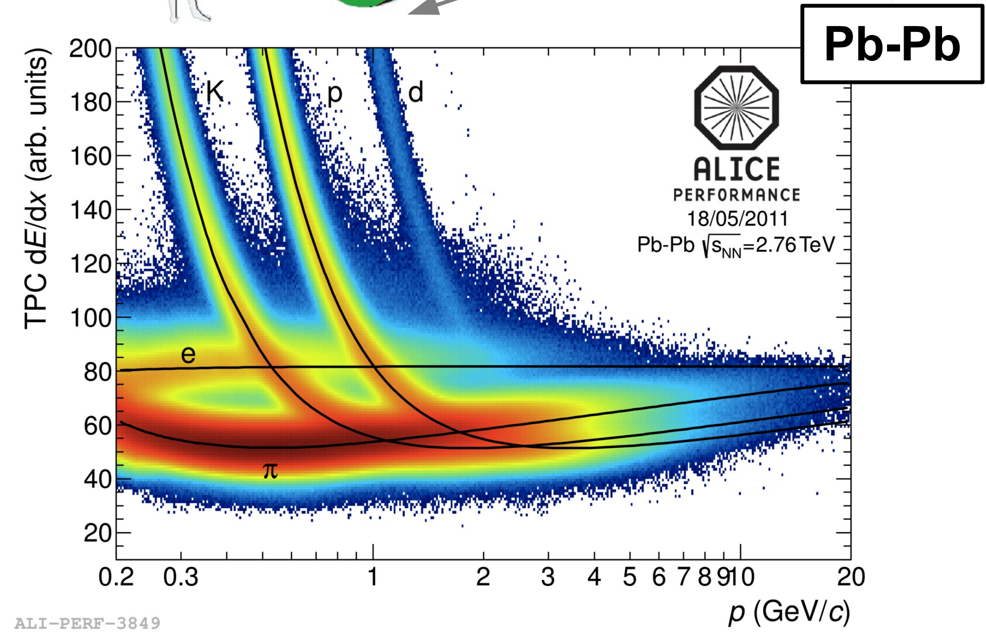
ITS: PID at low momenta
PID via *d*E/*dx* in silicon
up to 4 samples, σ ~10-15%



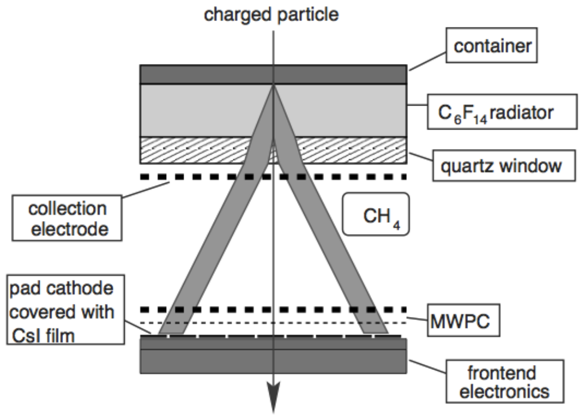


TPC: main tracking detector
PID via *d*E/*dx* in gas
up to 159 samples, σ ~5%





Particle-identification: Cherenkov

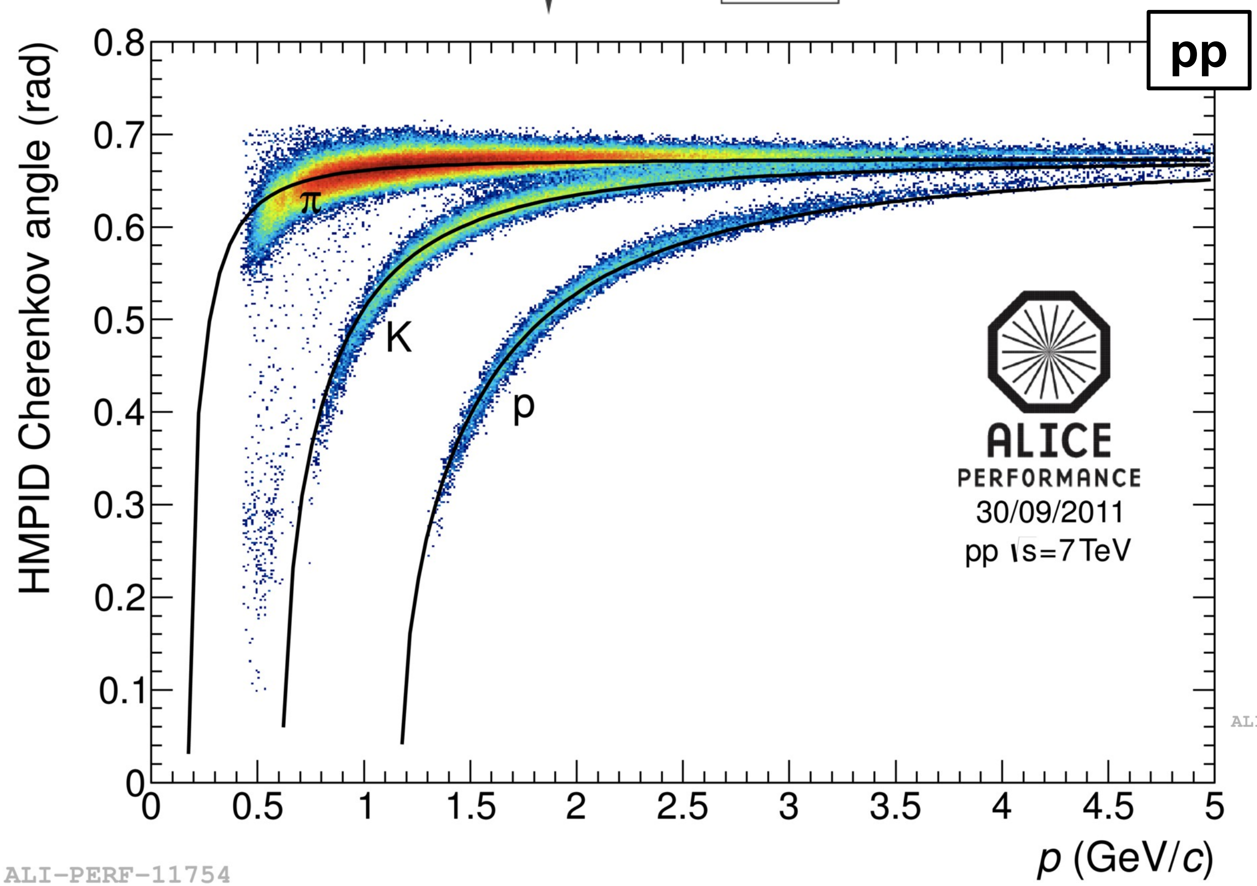


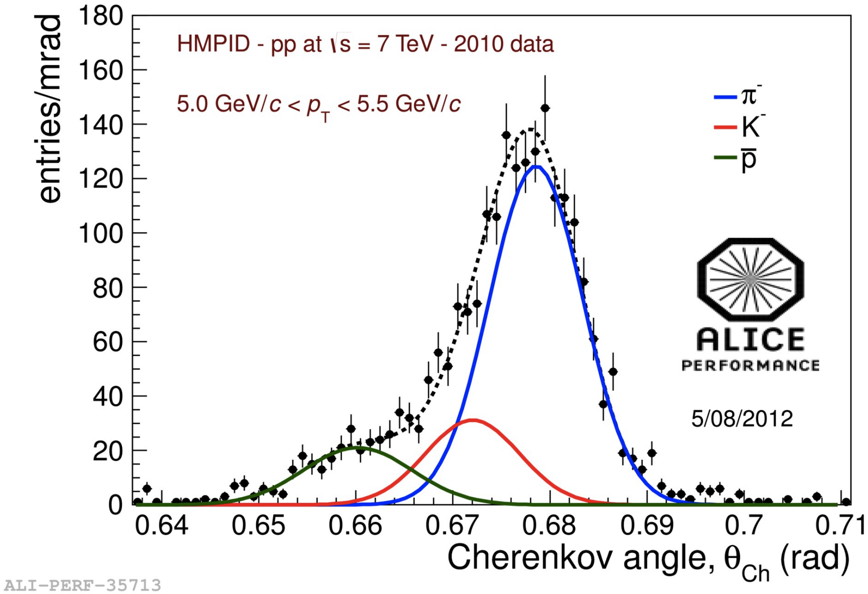
HMPID: extends PID at higher p_T

PID via Cherenkov angle θ_{Ch}

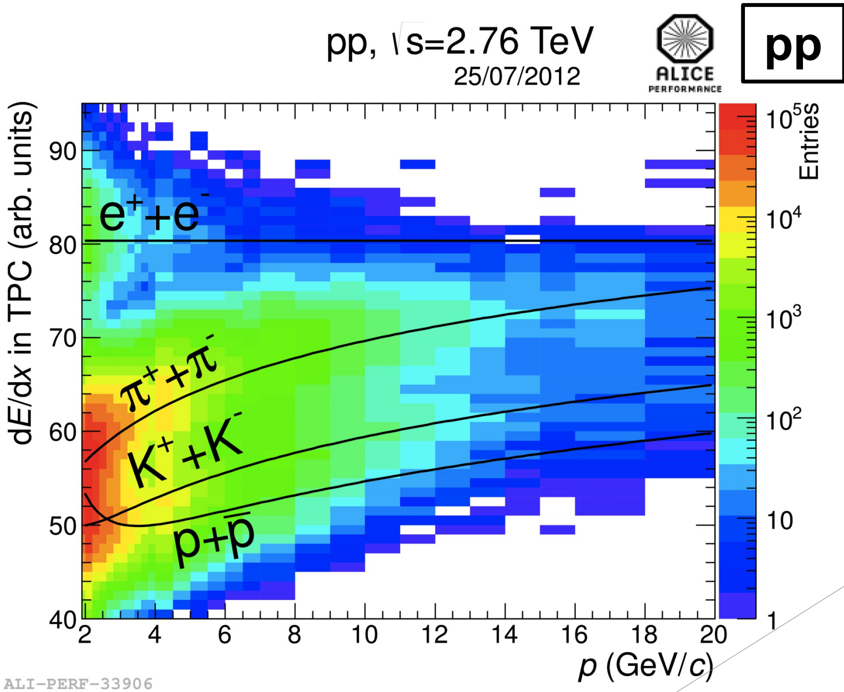
proximity-focus RICH technique

3σ proton separation up to 5.0 GeV/c
2σ proton separation up to 6.0 GeV/c





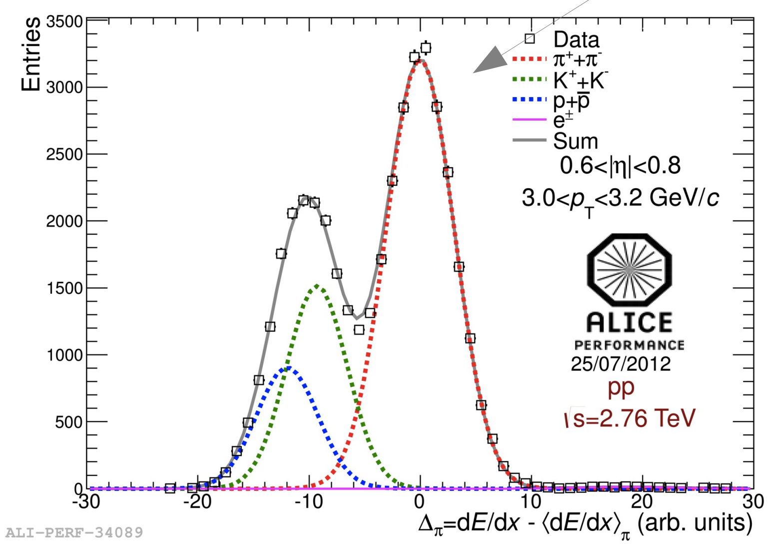
Particle-identification: relativistic rise

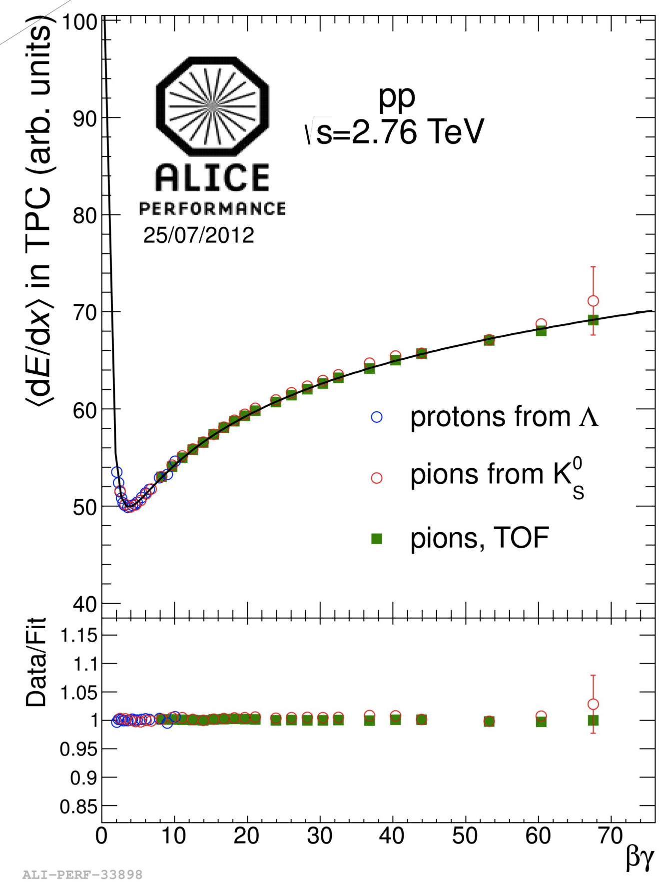


TPC relativistic rise: extends PID at even higher p_T

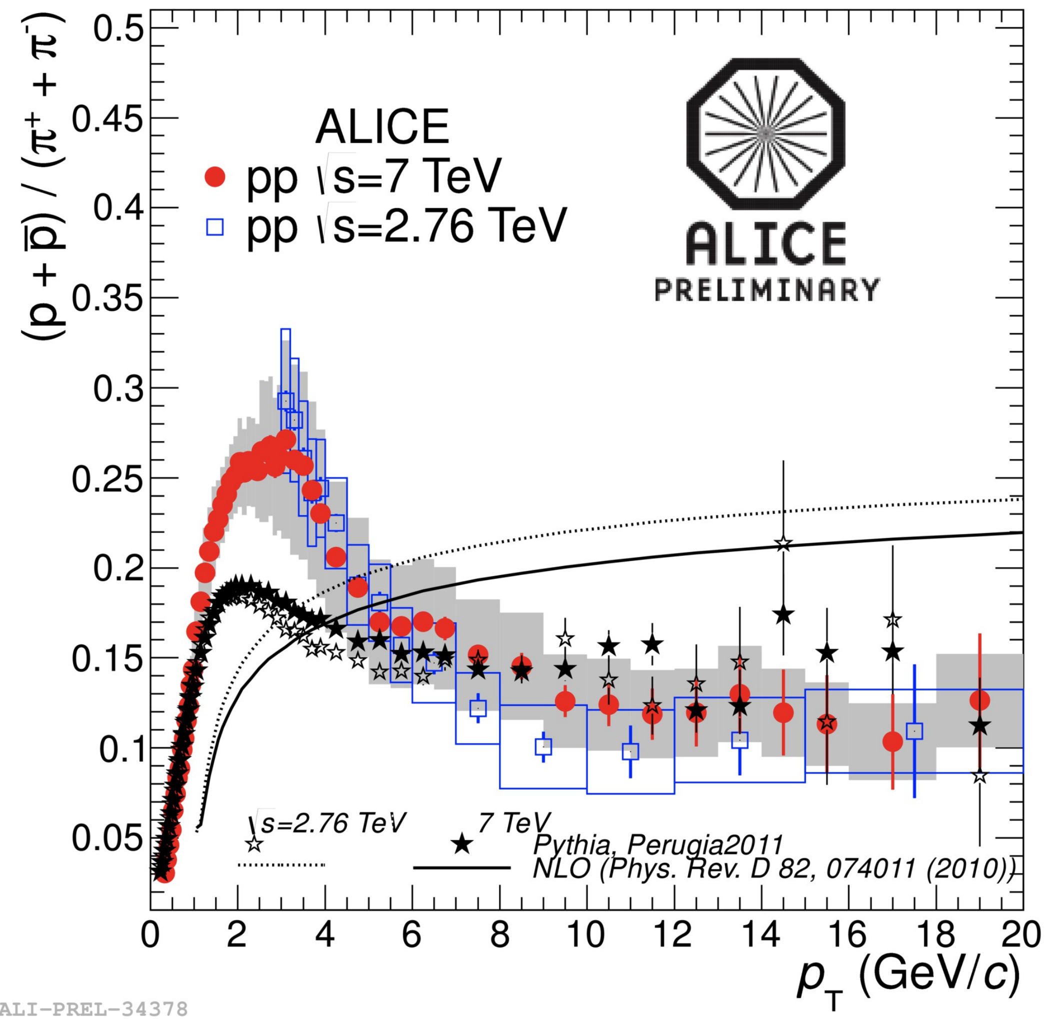
particles are not well separated, though statistical PID is possible

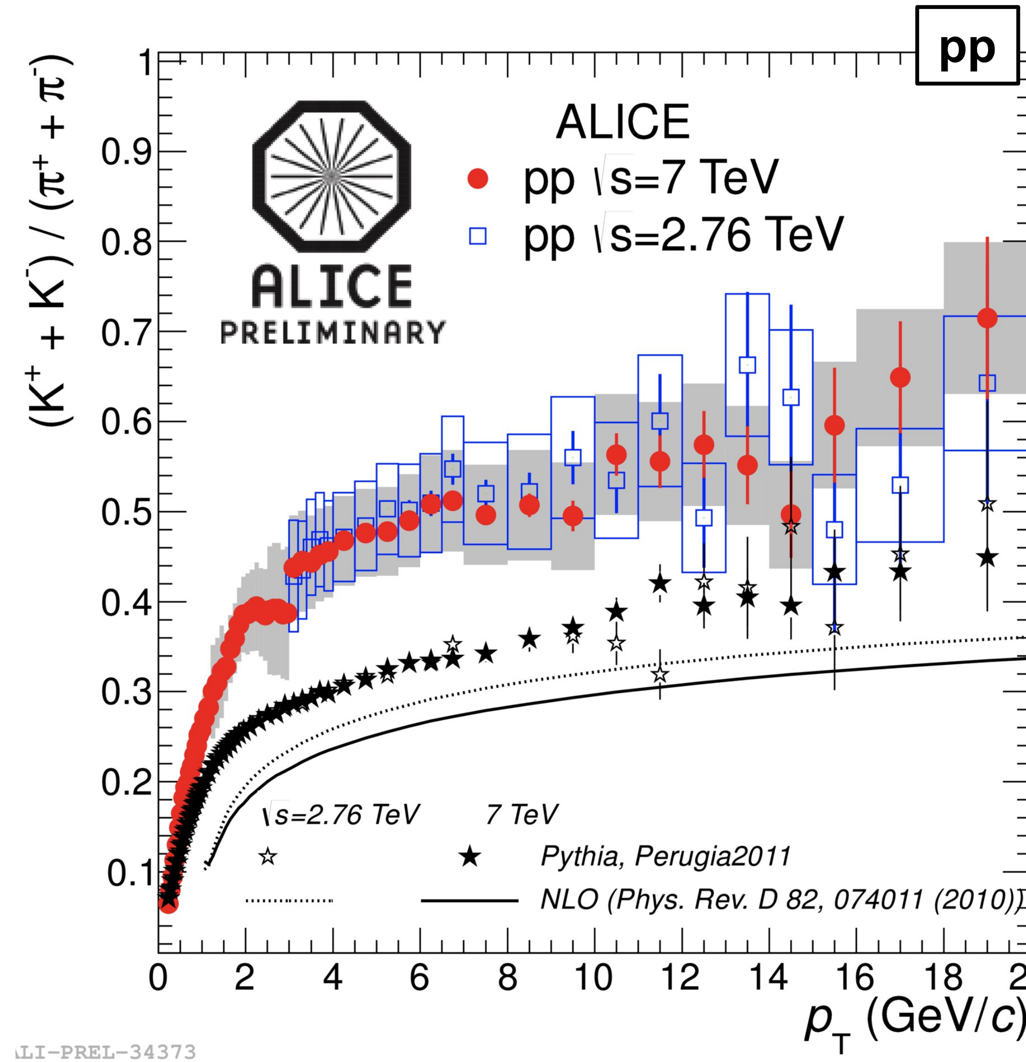
all particles described by a common Bethe-Bloch curve





Particle ratios in pp



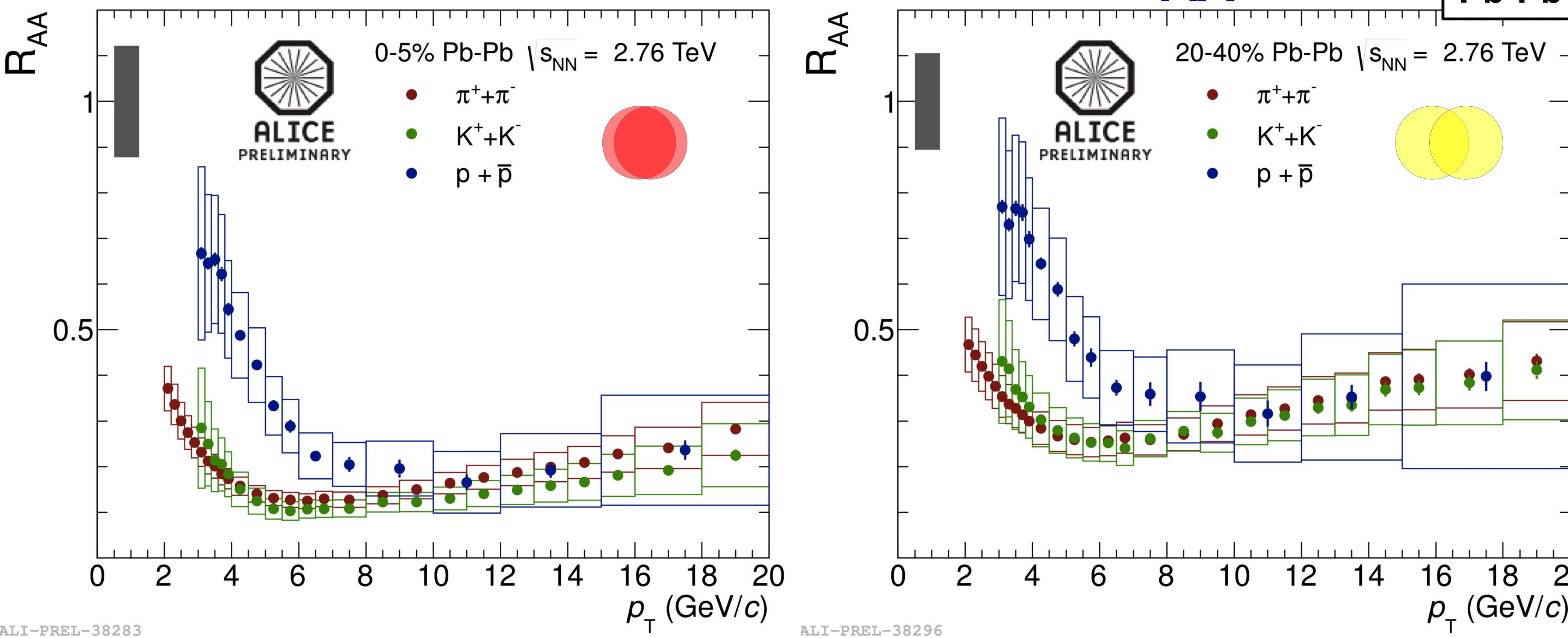


No energy dependence observed

ratios not reproduced by NLO calculations
Pythia (Perugia2011) underpredicts p/π at intermediate p_T

Identified-hadron R_{AA}

Pb-Pb



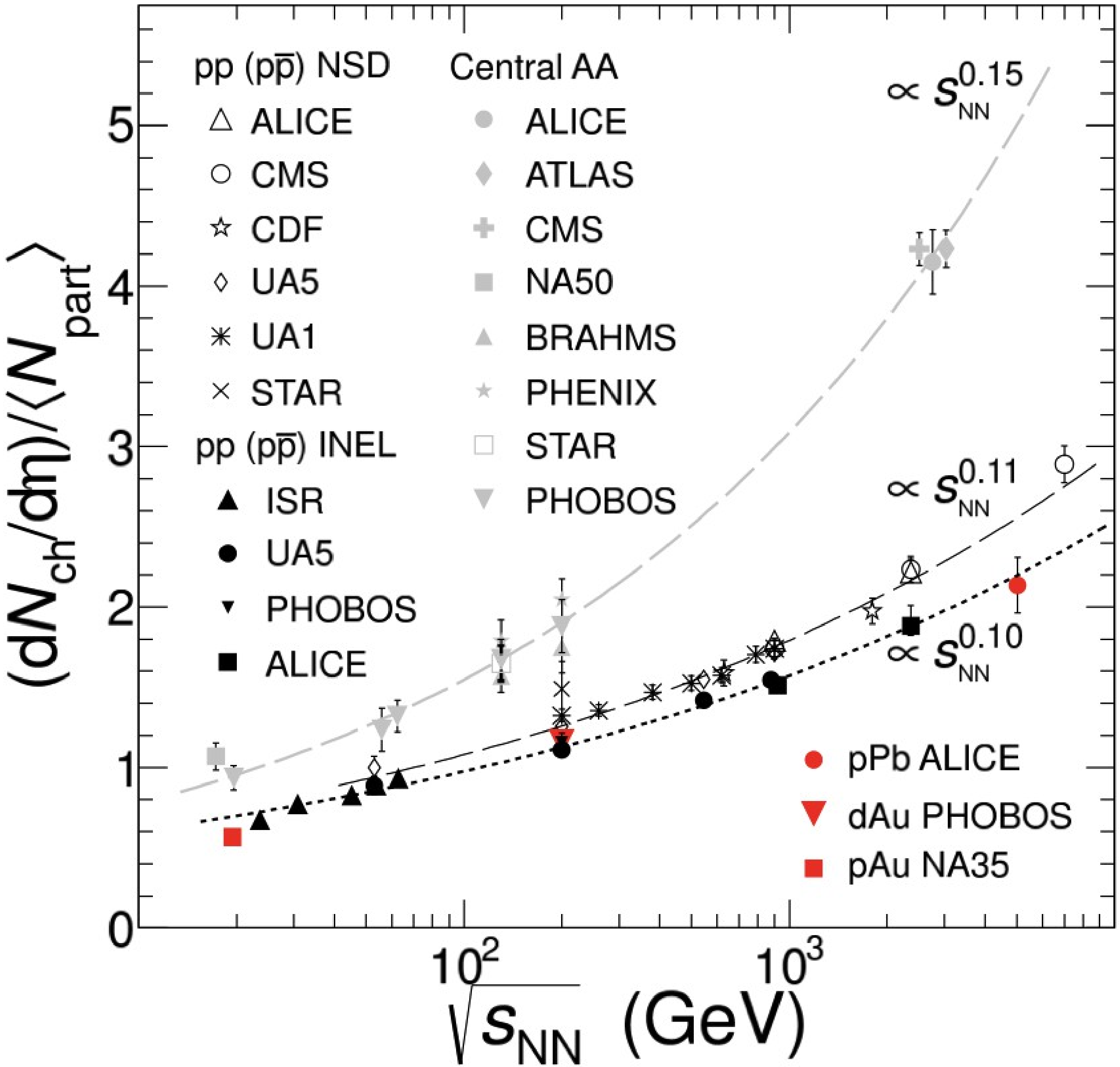
R_{AA} of π/K/p are compatible at high p_T (> 7-8 GeV/c)

This suggests that the medium does not affect the fragmentation

Jet hadron-chemistry effects foreseen in some models are small, if present

EPJC 55, 293 (2008)

$dN_{ch}/d\eta$ in p-Pb collisions



arXiv:1210.3615 [nucl-ex]

p-Pb crucial to discriminate between initial (cold nuclear matter) and final state (QGP) effects

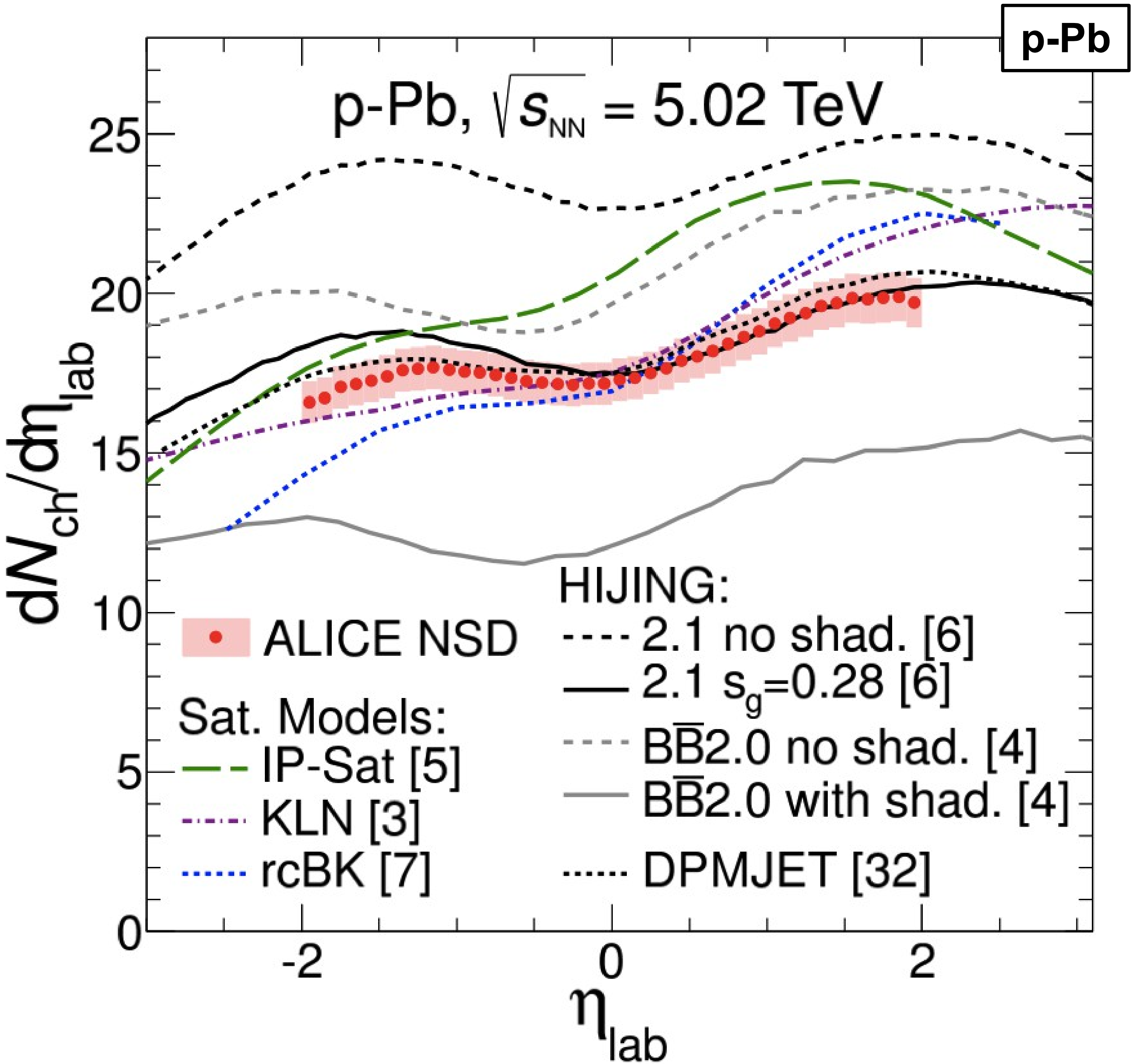
p-Pb at LHC → probe nuclear wave-function at small x

QCD at high gluon density: parton shadowing, gluon saturation?

mid-rapidity $\langle N_{part} \rangle$ normalized $\langle dN_{ch}/d\eta \rangle$

p-Pb similar trend to pp

dN_{ch}/dη in p-Pb collisions



arXiv:1210.3615 [nucl-ex]

p-Pb crucial to discriminate between initial (cold nuclear matter) and final state (QGP) effects

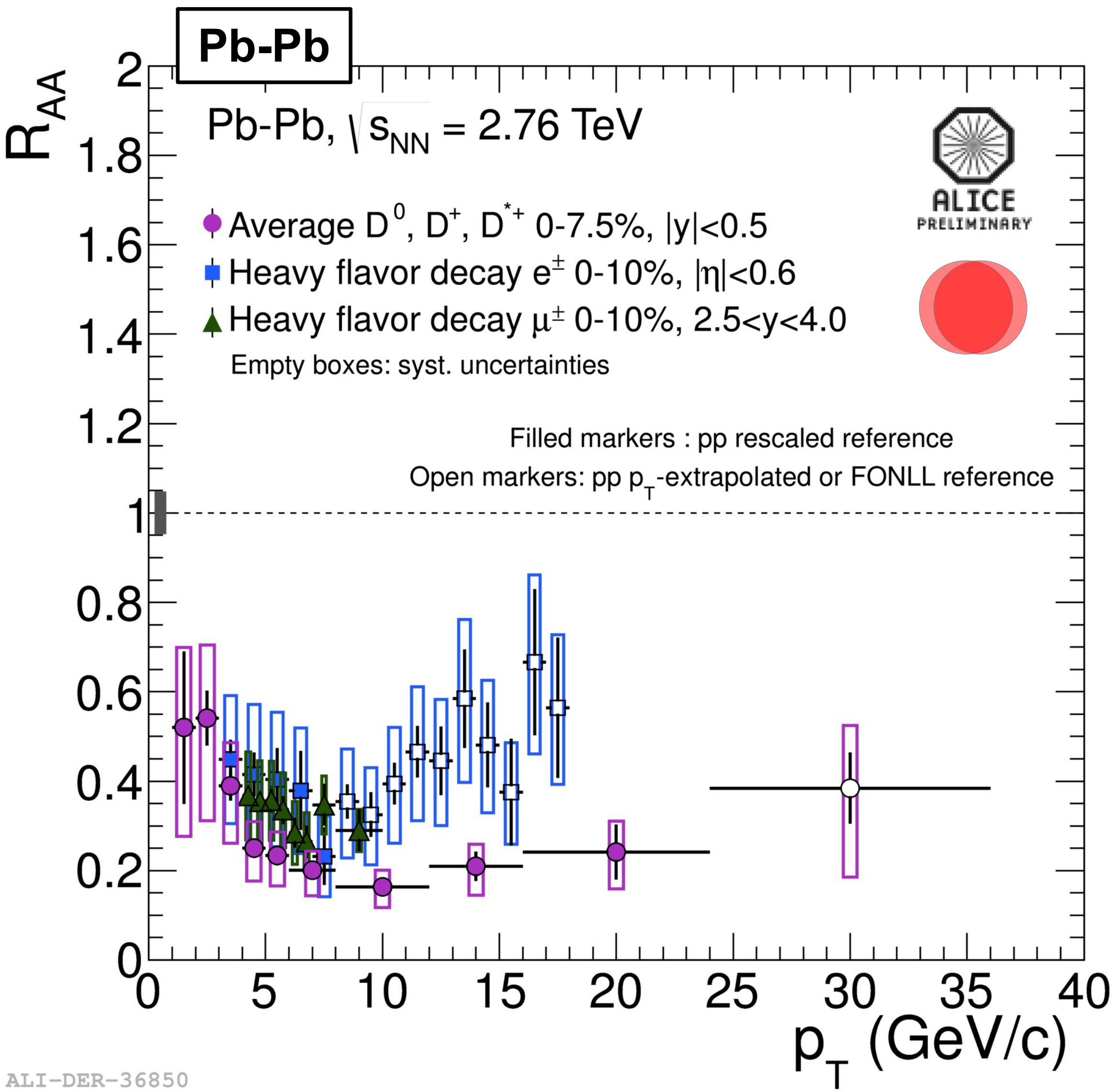
p-Pb at LHC → probe nuclear wave-function at small x

QCD at high gluon density: parton shadowing, gluon saturation?

gluon saturation models: steeper η_{lab} dependence than the data

HIJING (parton shadowing) and DPMJET: describe the rapidity shape rather well

Heavy-flavour R_{AA}



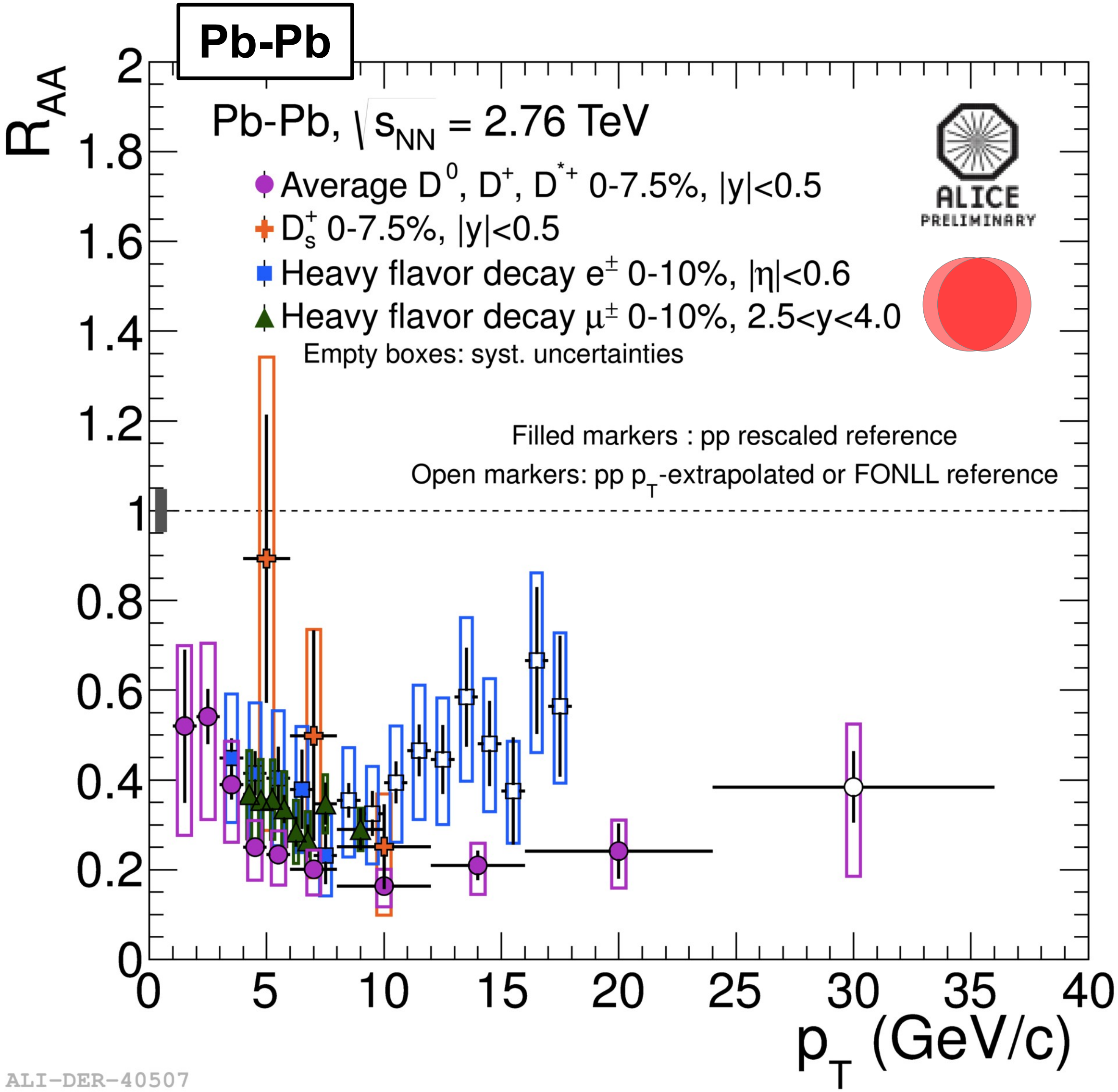
Average D-meson R_{AA} (|y| < 0.5)
(D^0, D$^+$, D^{*+} are compatible within errors)
large suppression in a wide p_T range
factor 4-5 in 5 < p_T < 15 GeV/c

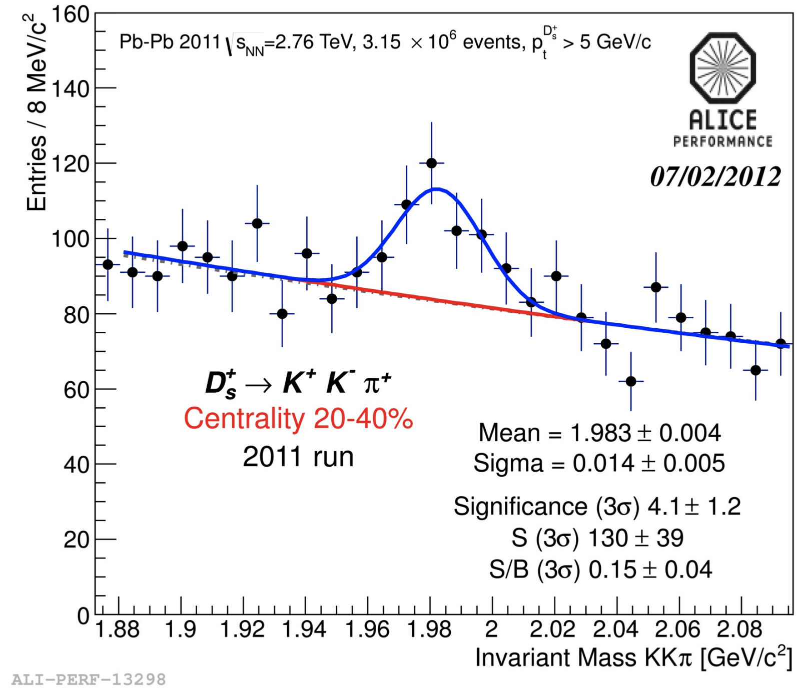
Heavy-flavour electrons R_{AA} (|y| < 0.6):
strong suppression up to 18 GeV/c
ongoing effort to separate beauty...

Heavy-flavour muons (2.5 < y < 4.0):
suppression in the forward region
similar to that of electrons

JHEP 09, 112 (2012)
arXiv:1210.7332 [hep-ex]
arXiv:1205.6443 [hep-ex]

Heavy-flavour R_{AA}





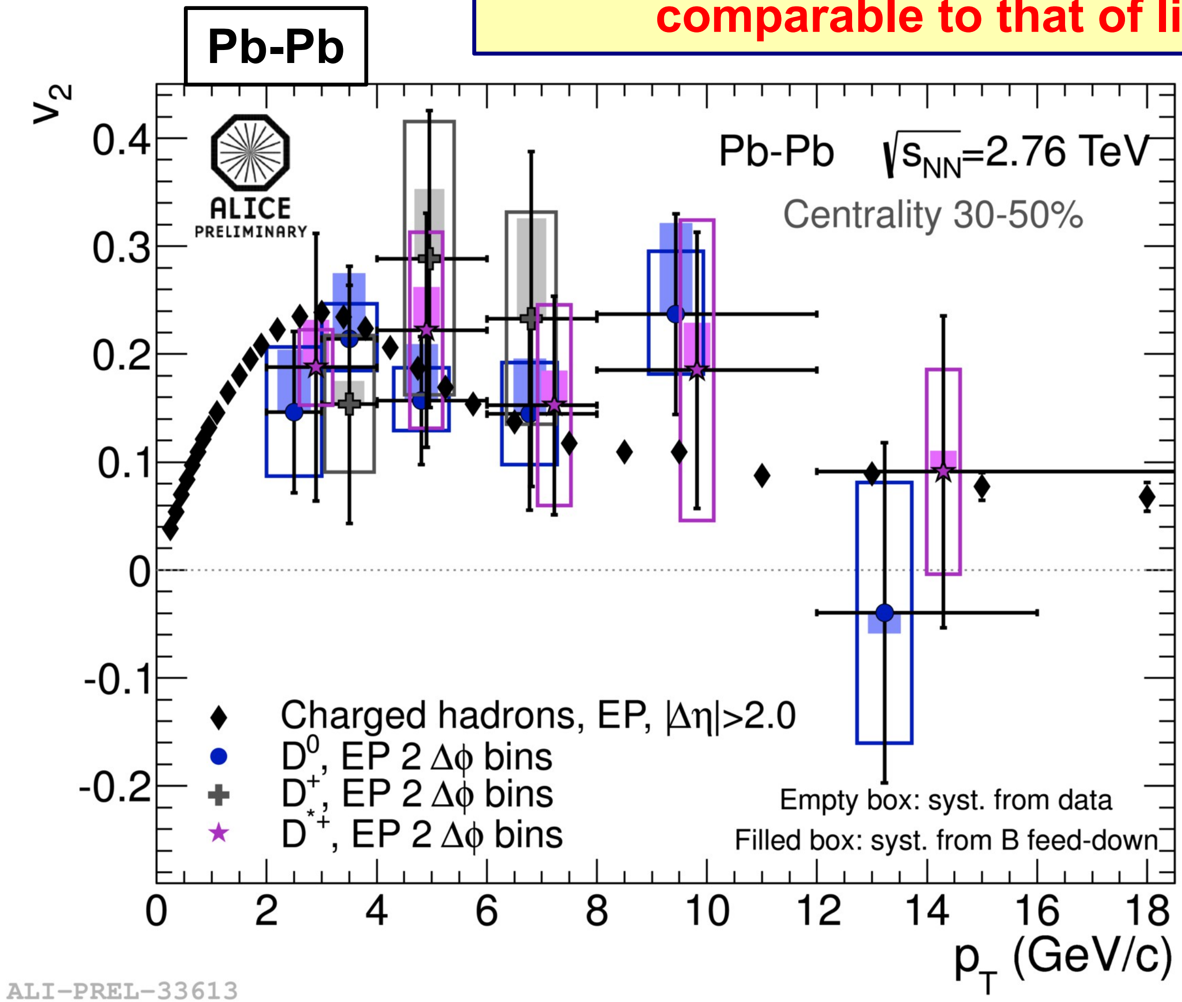
Adding D_s to charm R_{AA}:
strong suppression for p_T > 8 GeV/c

more statistics needed to conclude on expected enhancement at low p_T

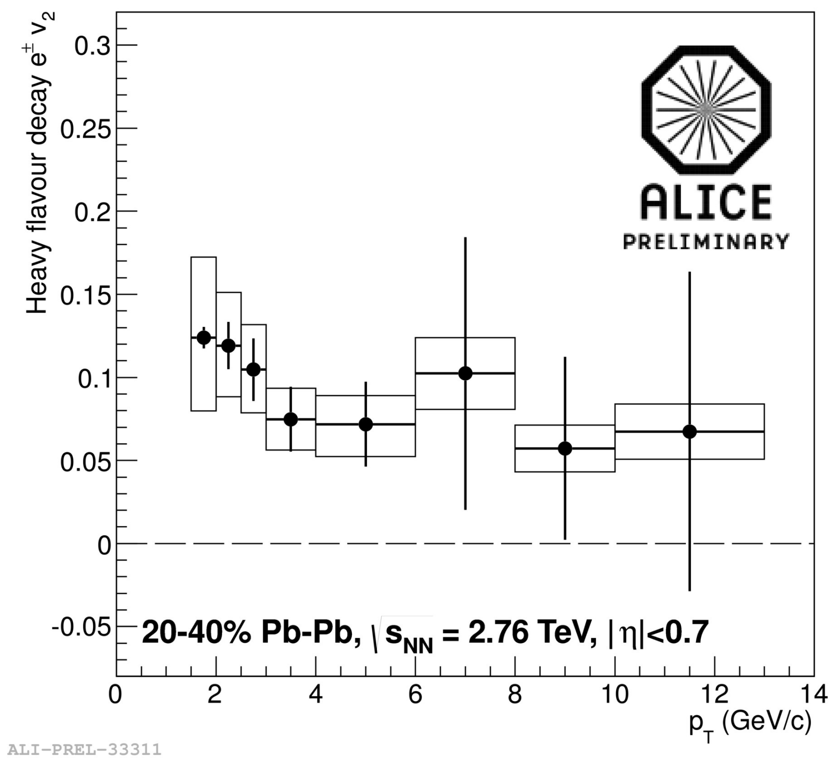
uncertainty will improve with future pp and Pb-Pb data taking

D-meson elliptic flow

Non-zero D-meson elliptic flow (v_2) observed:
consistent among D-meson species (D^0, D^+, D^{*+})
comparable to that of light hadrons



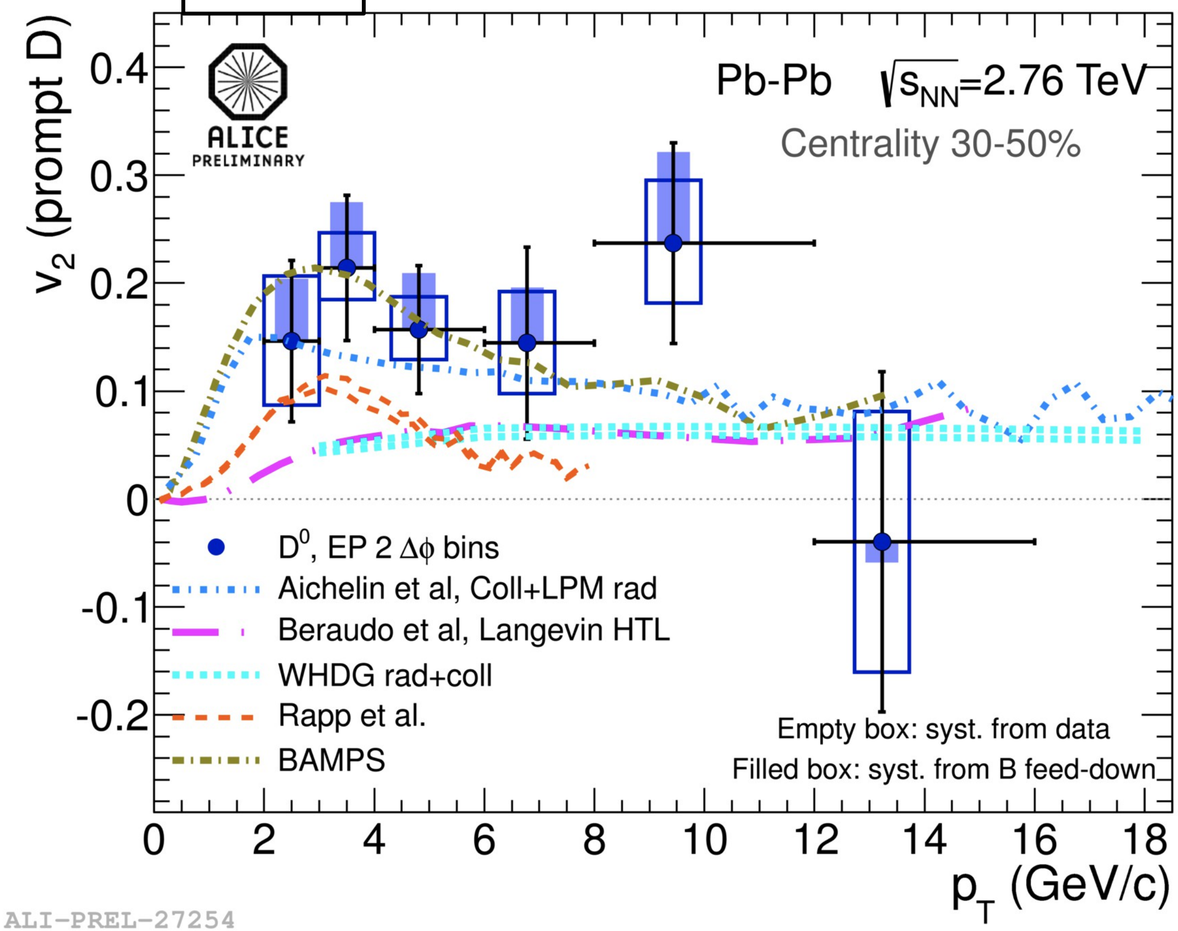
also HF-electrons show v_2 > 0
3σ effect for 2 < p_T < 3 GeV/c

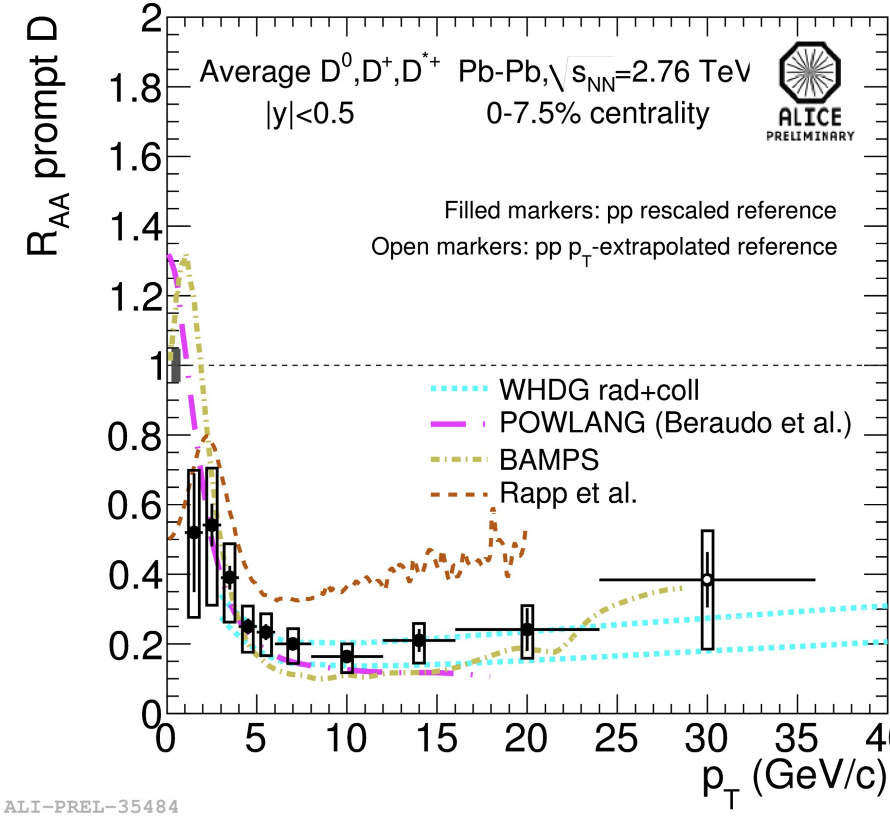


D-meson elliptic flow and models

Non-zero D-meson elliptic flow (v_2) observed:
consistent among D-meson species (D^0, D^+, D^{*+})
comparable to that of light hadrons

Pb-Pb





the simultaneous description of v_2 and R_{AA} is challenging