



A Large Ion Collider Experiment
aliceinfo.cern.ch



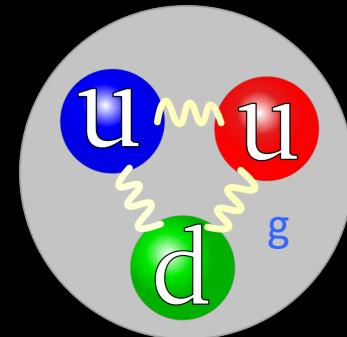
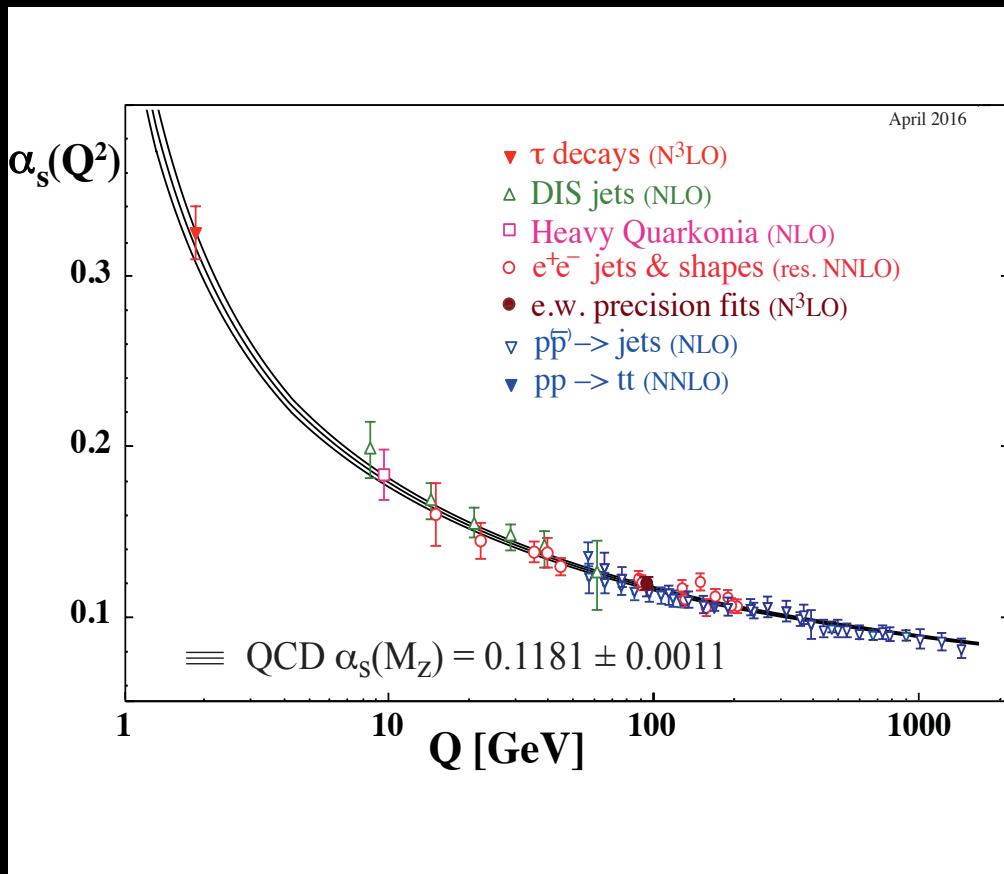
Study of the Quark-Gluon Plasma with Hard Probes at the LHC

Jacek Otwinowski
IFJ PAN, 1 March 2018



Asymptotic freedom

PDG: Chin. Phys. C40 (2016) 100001



Perturbative QCD

$$\alpha_s(Q^2) \equiv \frac{g_s^2(Q^2)}{4\pi} = \frac{12\pi}{(33 - 2N_f)\ln(Q^2/\Lambda_{\text{QCD}}^2)}$$

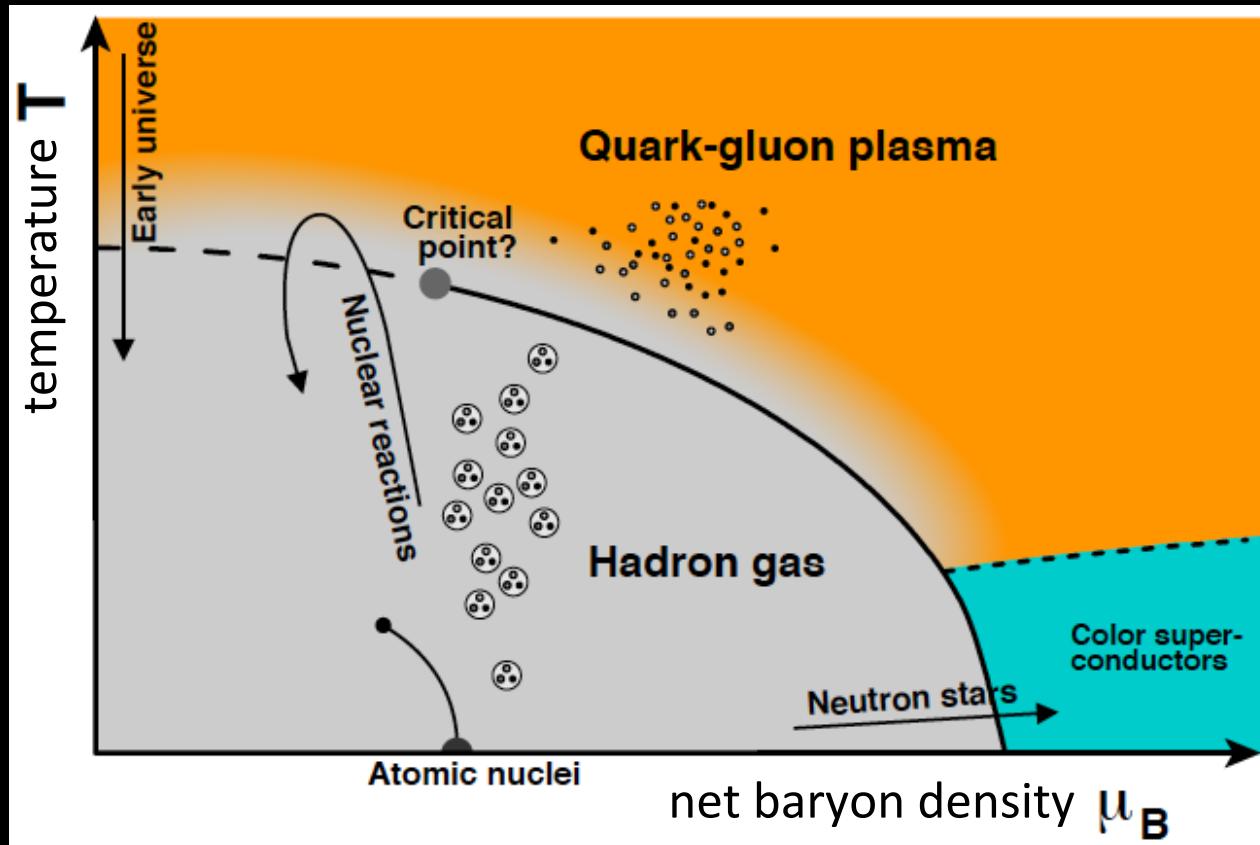
Politzer, Gross & Wilczek 1973

Possible transition (Cabibbo & Parisi 1975, Collins & Perry 1975)

Hadron gas \leftrightarrow state of deconfined quarks and gluons - Quark-Gluon Plasma (QGP)

Conjectured phase diagram of QCD matter

More than 30 years of experimental effort (nuclear collisions and astrophysical observations ...)

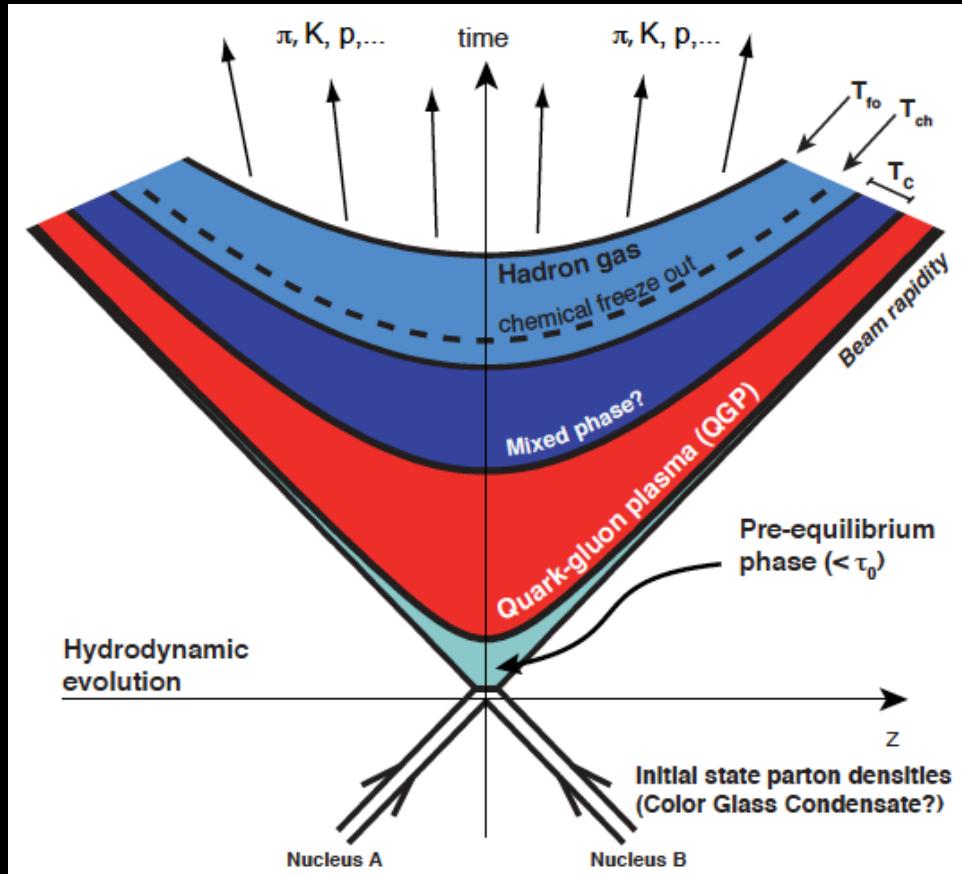


Small μ_B : Nuclear collisions; Lattice QCD ($\mu_B = 0$, $T_c \sim 155$ MeV, smooth crossover)

Large μ_B : Neutron stars observations to constrain models (gravitational waves...)

Relativistic heavy-ion collisions

Theoretically motivated picture: Bjorken 1983



Freeze-out

Hadronization ($T \sim T_c$)

Quark-Gluon (thermalized)
Plasma

Pre-equilibrium, fast
thermalization $\sim 1 \text{ fm}/c?$

Hard collisions

Lorentz-contracted ions
(gluonic matter)

- All stages in models of nuclear collisions
- QGP expansion modeled by relativistic hydrodynamics

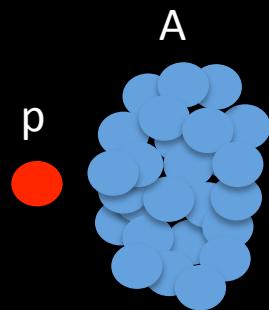
Models are crucial to characterize matter produced in heavy-ion collisions!

How do we measure?

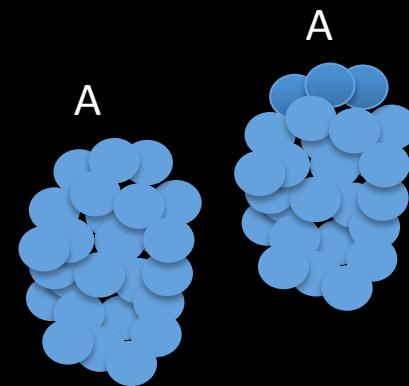
Collide A-A and compare results to reference measurements in pp and p-A



Soft QCD and perturbative QCD, fragmentation in vacuum. Reference for p-A and A-A.



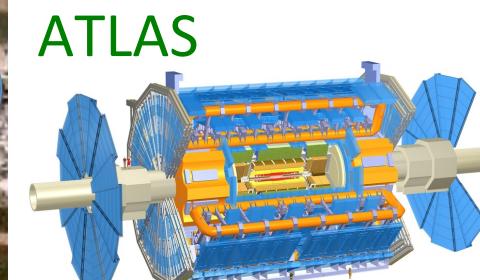
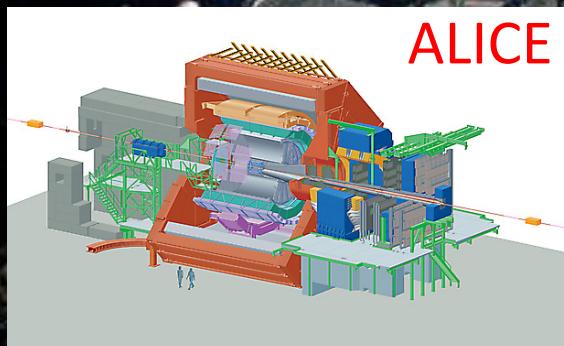
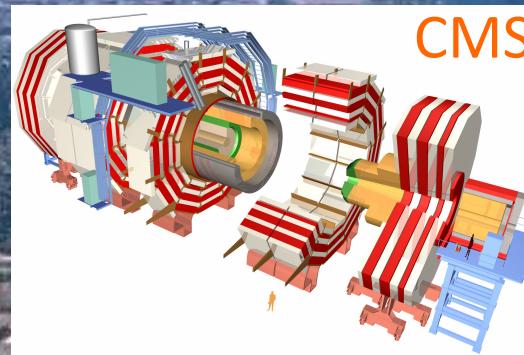
Initial state effects (shadowing/gluon saturation). Reference for A-A.



Thermal production, flow, recombination, jet quenching and fragmentation in the Quark-Gluon Plasma (QGP).

Experiments at the LHC

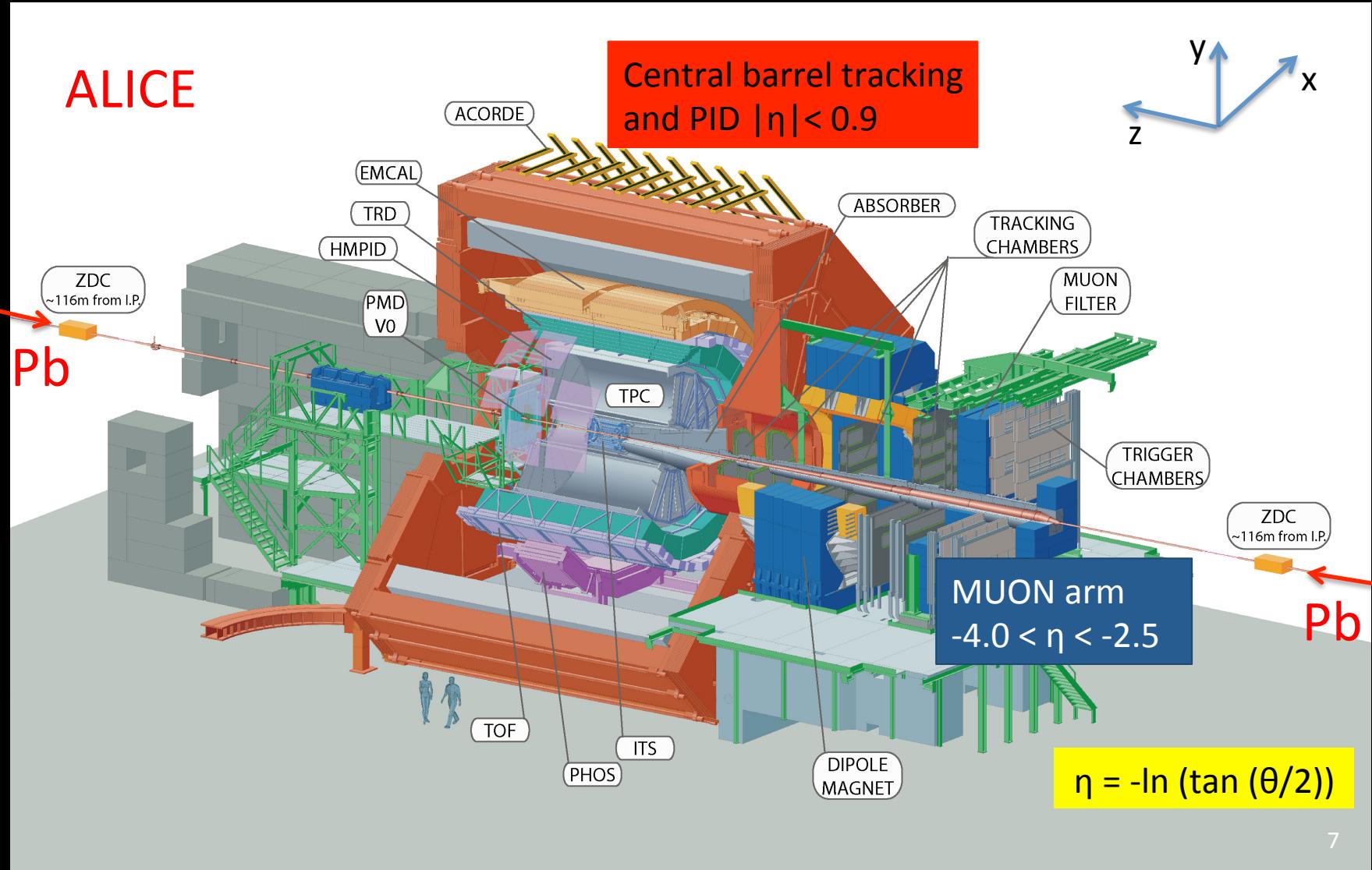
ALICE, CMS, ATLAS and LHCb measure heavy-ion collisions

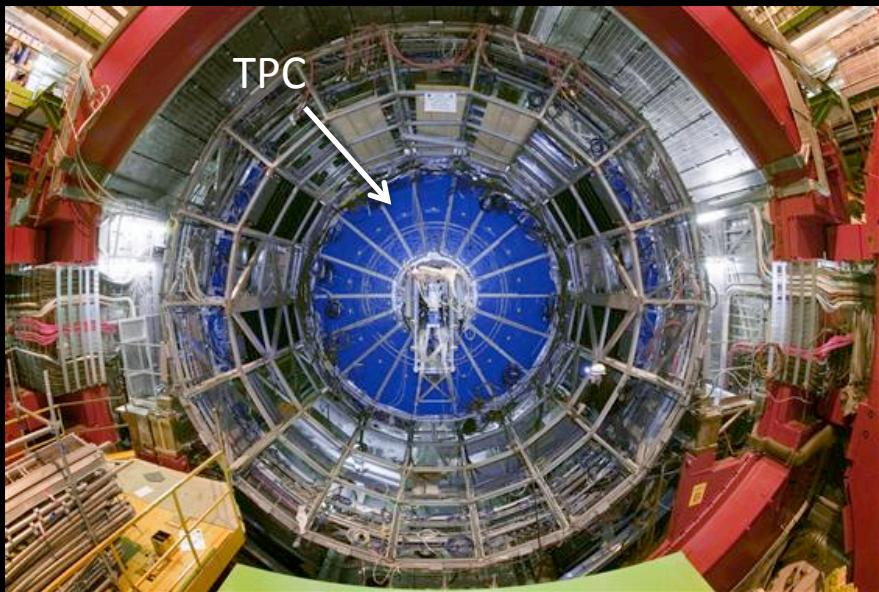
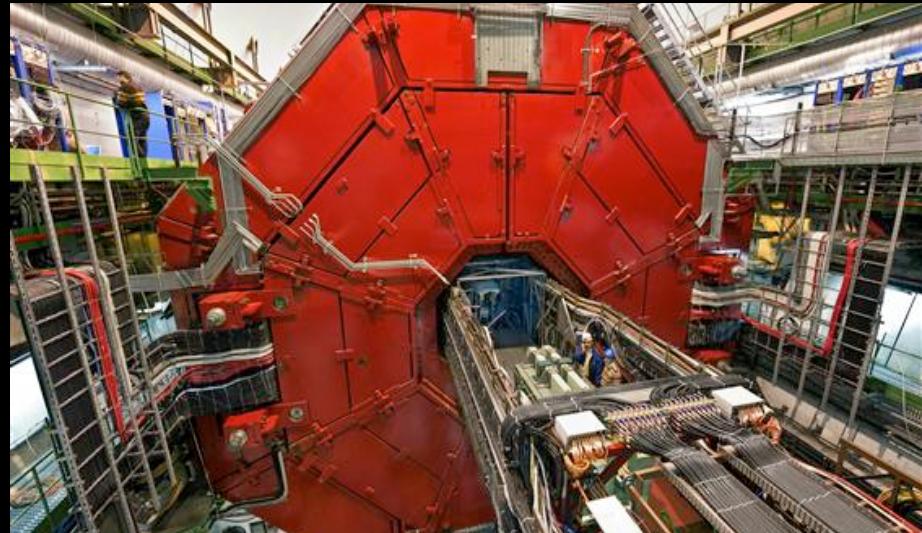


pp (max $\sqrt{s} = 14 \text{ TeV}$) p-A and
A-A (Pb-Pb max $\sqrt{s_{\text{NN}}} = 5.5 \text{ TeV}$)

A Large Ion Collider Experiment

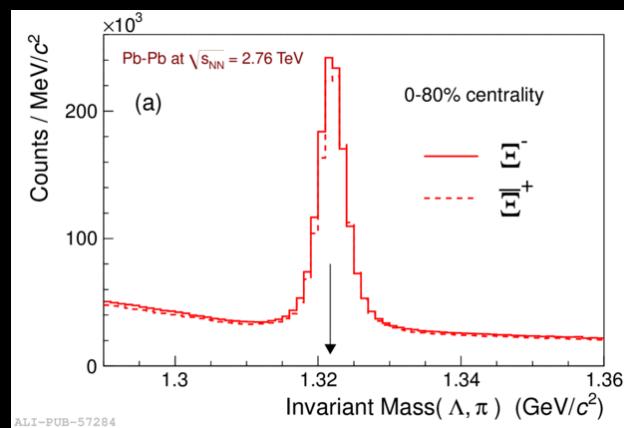
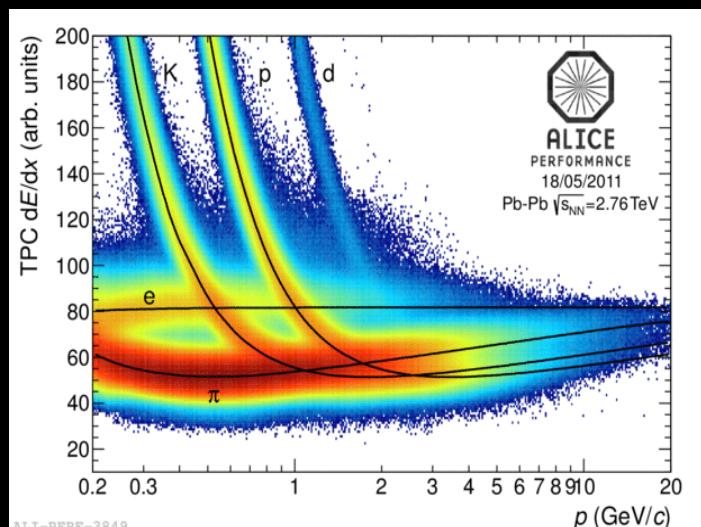
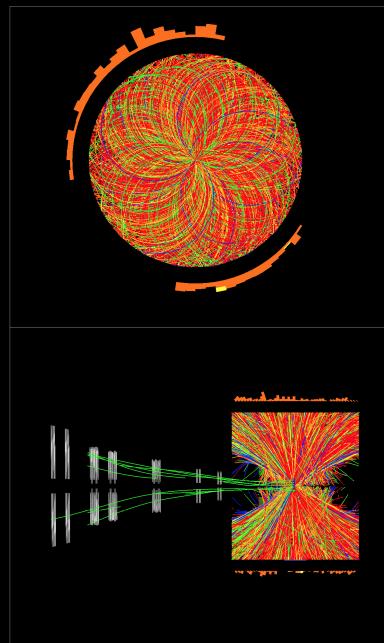
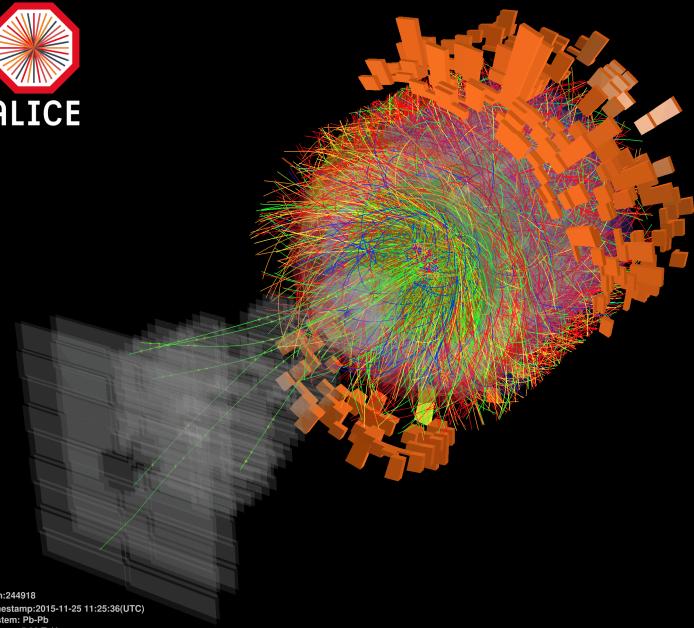
- Excellent particle identification capabilities in the large p_T range 0.1-20 GeV/c
- Good momentum resolution $\sim 1\text{-}5\%$ at $p_T = 0.1\text{-}50$ GeV/c





Size: $16 \times 16 \times 26 \text{ m}^3$
Weight: $\sim 10000 \text{ tons}$

ALICE at work



Run 1 (2009 - 2013)

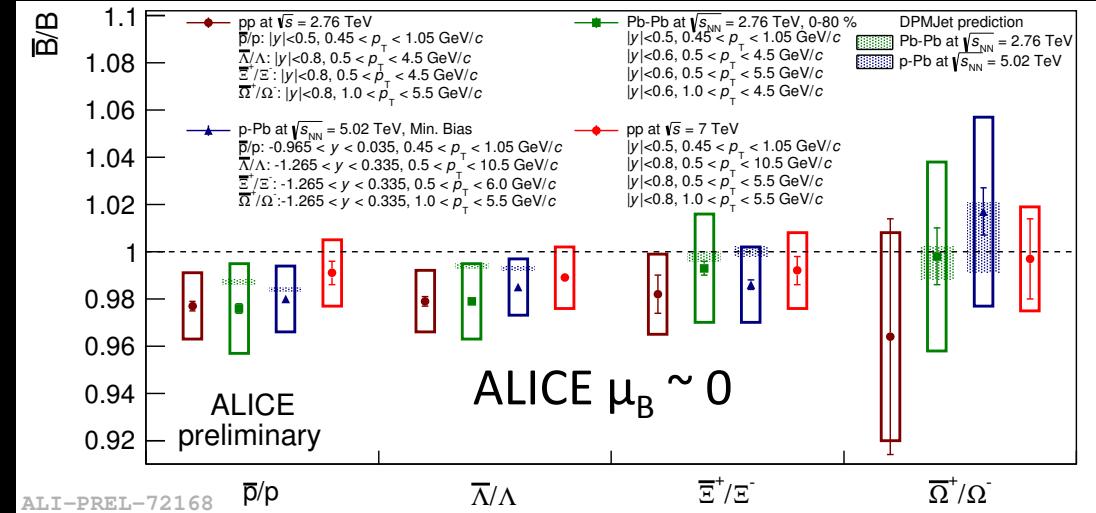
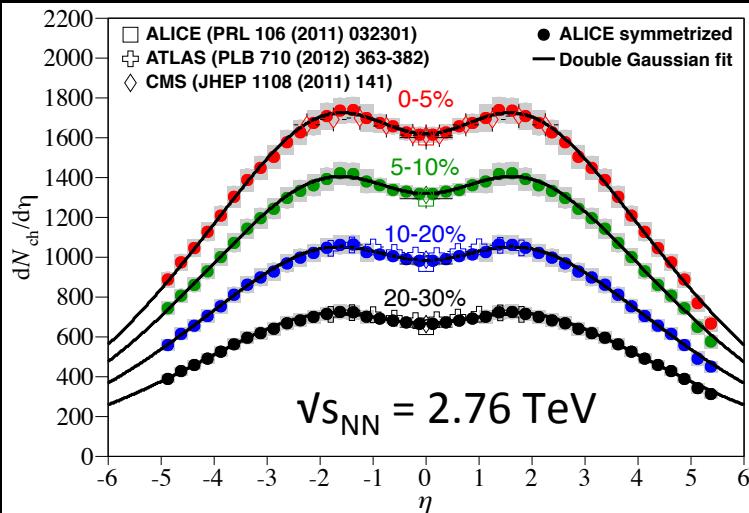
$p\text{-}p \sqrt{s}=0.9, 2.36, 2.76, 7, 8\text{ TeV}$
 $p\text{-}Pb \sqrt{s_{NN}}= 5.02\text{ TeV}$
 $Pb\text{-}Pb \sqrt{s_{NN}}=2.76\text{TeV}$

Run 2 (2015 - now)

$p\text{-}p \sqrt{s}=5.02, 13\text{ TeV}$
 $P\text{-}Pb \sqrt{s_{NN}}= 8.16\text{ TeV}$
 $Pb\text{-}Pb \sqrt{s_{NN}}=5.02\text{ TeV}$
 $Xe\text{-}Xe \sqrt{s_{NN}}=5.44\text{ TeV}$

Phys. Lett. B 728 (2014) 216

ALICE case



Initial energy density (Bjorken formula)

$$\varepsilon \geq \frac{dE_T/d\eta}{\tau_0 \pi R^2} = \frac{3}{2} (E_T/N) \frac{dN_{\text{ch}}/d\eta}{\tau_0 \pi R^2}$$

Central collisions:

$$\varepsilon \sim 14 \text{ GeV/fm}^3 \gg \varepsilon_c$$

→ Large enough to produce QGP

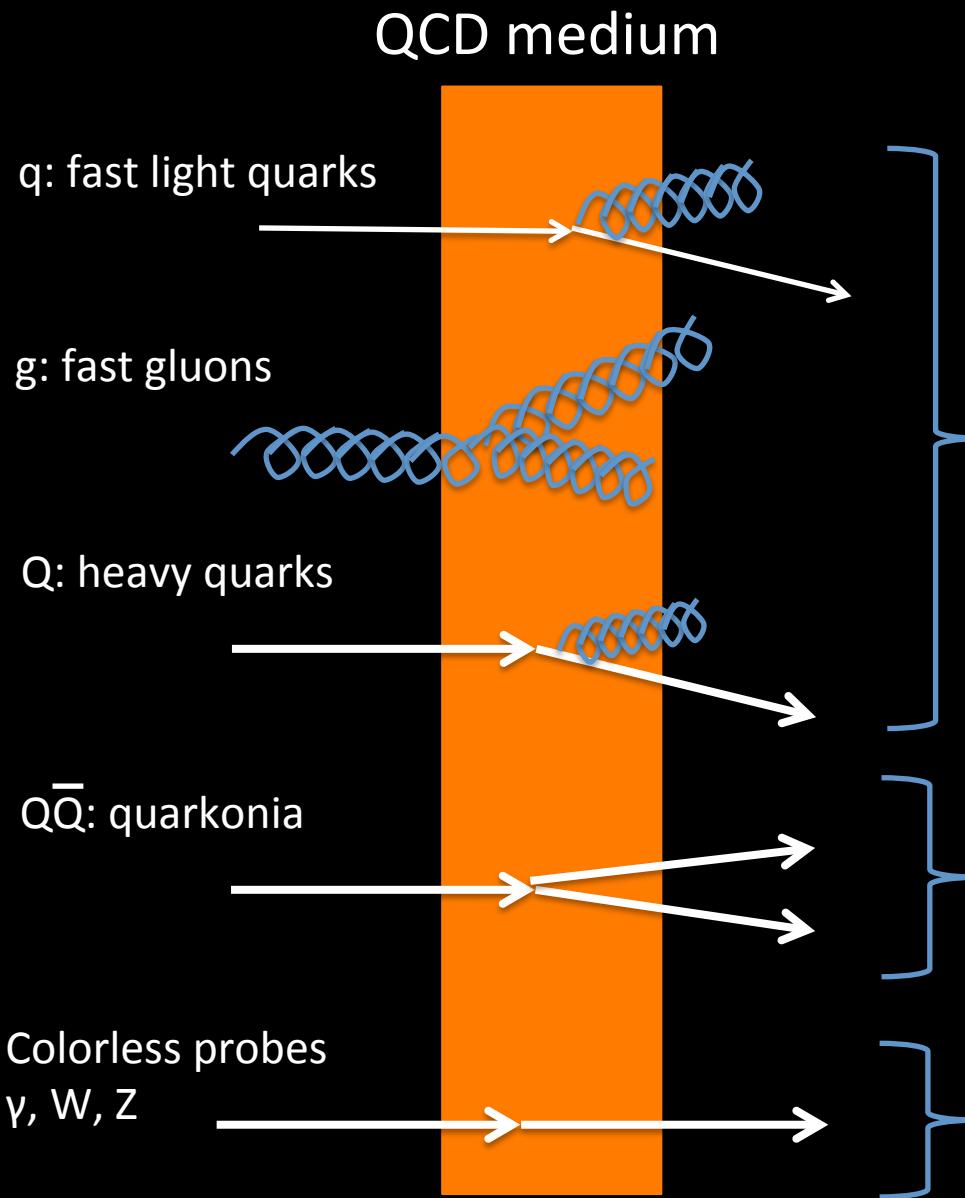
Lattice QCD ($\mu_B = 0$):

- $T_c = 145-163 \text{ MeV}$
- $\varepsilon_c = (0.18-0.5) \text{ GeV/fm}^3, (1.2-3.1) \varepsilon_{\text{nuclear}}$

Bazavov et al.
Phys. Rev. D 90 (2014) 094503

PROBING QGP WITH HARD PROBES

Hard Probes of the QCD medium



Hard probes: particles (partons) with large momenta or/and mass: $M, p_T \gg \Lambda_{QCD}$

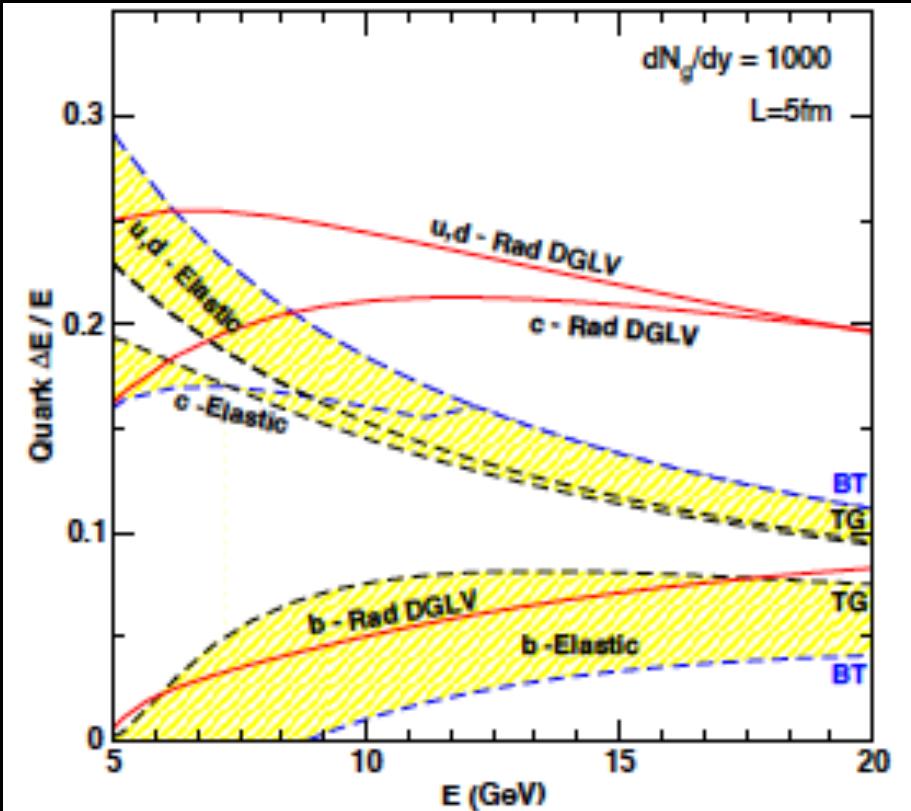
- Collisional and radiative energy loss:
- Medium transport properties
 - Medium density

- Quarkonia dissociation and recombination:
- Critical temperature T_c and energy density ϵ_c

- Colorless probes:
- Control measurements

Parton Energy Loss in QCD medium

Radiative and collisional parton energy loss: $\Delta E = \Delta E_{\text{coll}} + \Delta E_{\text{rad}}$, $\Delta E (E, m, C_R; \rho_g, \alpha_s, T, L)$



Medium: Longitudinally expanding QGP plasma

Radiative energy loss dominate at high- p_T :

- Color charge dependence C_R : $C_{R,g} > C_{R,q,Q}$
→ $\Delta E_g > \Delta E_{q,Q}$
- Mass dependence m “dead cone”: gluon radiation suppression at $\Theta < m_Q/E$
→ $\Delta E_q > \Delta E_Q$

$$\rightarrow \Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$$

Radiative including “dead cone” (DGLV):

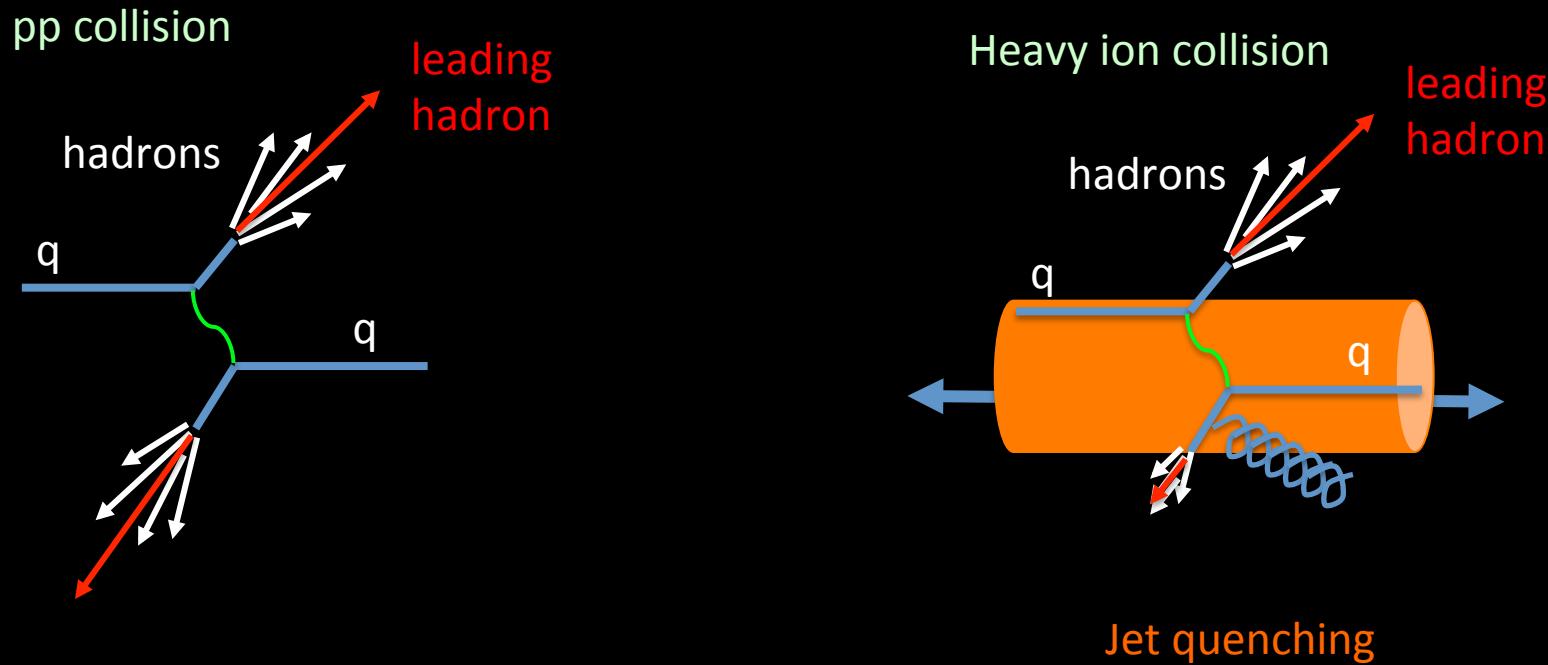
- Djordjevic & Gyulassy, NPA 733 (2004) 265
- Dokshitzer& Kharzeev, PLB 519 (2001) 199

Elastic:

- TG: Thoma & Gyulassy, NPB 351 (1991) 491
- BT: Braaten & Thoma, PRD 44 (1991) 1298

Parton Energy Loss and Jet Quenching

High p_T particles (partons): $\tau_{\text{prod}} \sim 1 / p_T$ ($\tau_{\text{prod}} \sim 0.1 \text{ fm}/c$ for $p_T = 10 \text{ GeV}/c$)

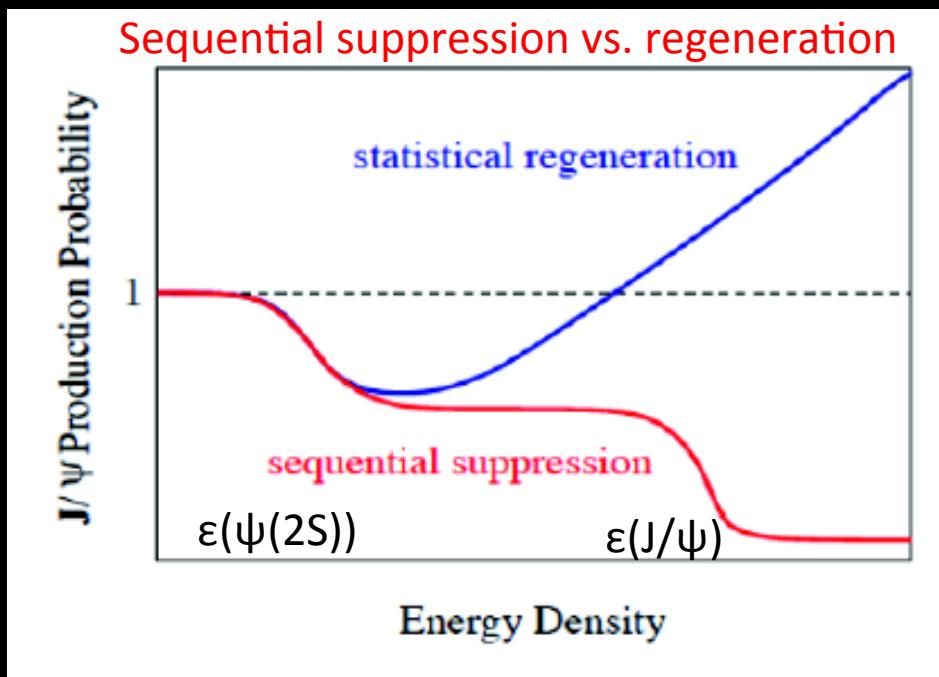
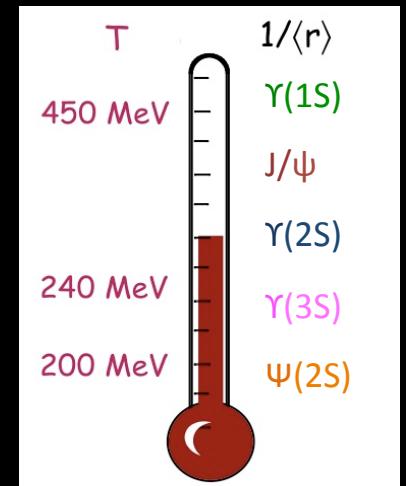


Characterize medium properties via parton energy loss

→ Modification of leading hadron and jet spectra

Quarkonia production in heavy-ion collisions

- Quarkonia ($c\bar{c}$, $b\bar{b}$) produced in the early stage of HI collisions
- Quarkonia sequential suppression in QGP due to color screening
Matsui & Satz PLB 168 (1986) 415; Karsch & Satz, ZPC 51 (1991) 209
- Charmonia production via regeneration ($c\bar{c}$ combination) in the QGP or at the phase boundary ($T \sim T_c$) Braun-Munzinger & Stachel PLB 490 (2000) 196; Thews et al. PRC 63 (2000) 054905



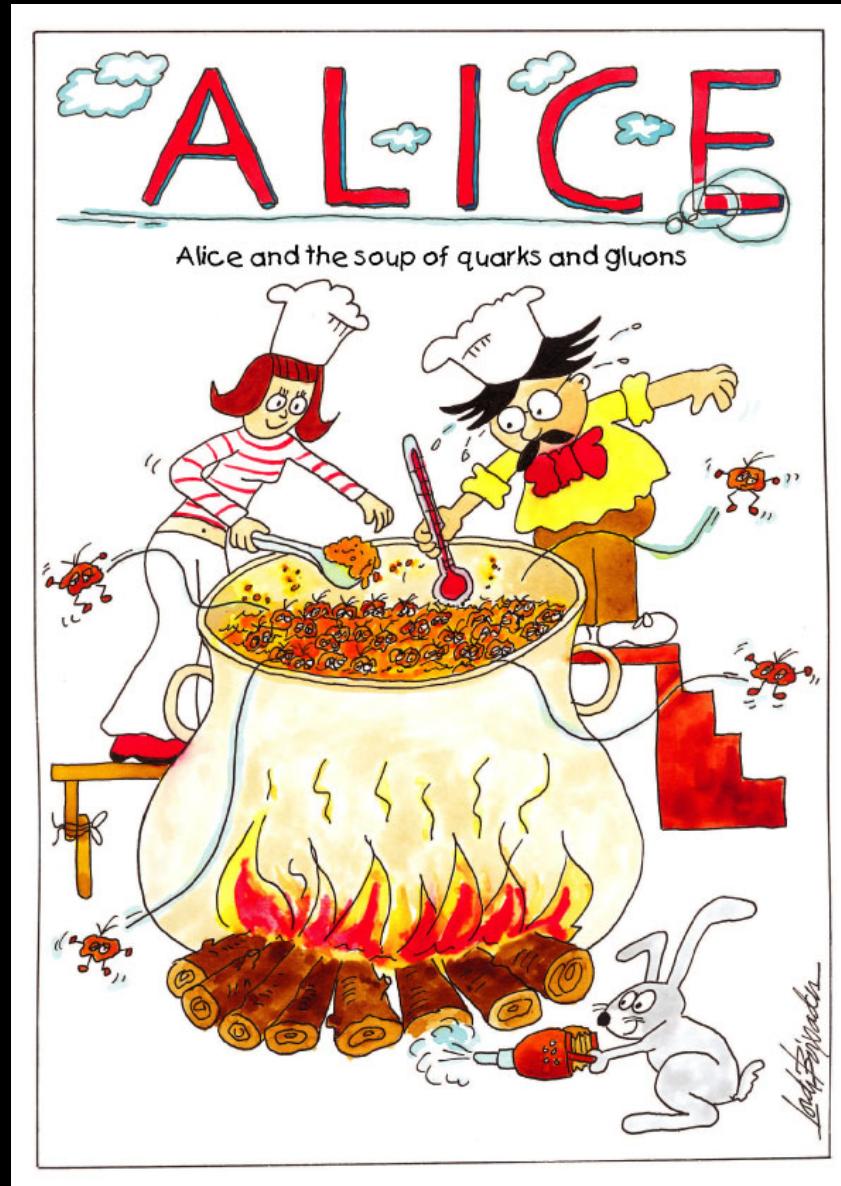
- Central Pb-Pb collisions at LHC:
- $N_{c\bar{c}}/\text{event} \sim 115$, $N_{b\bar{b}}/\text{event} \sim 3$ (10x more than at RHIC)
 - Enhancement of charmonium production via regeneration (depending on open charm cross section)
 - Evidence for charm thermalization

Selected results

Hard probes

- Single particle spectra
 - Charged particles
 - Identified hadrons
- Jets
- Quarkonia

Focus on measurement of nuclear modification factors



Nuclear Modification Factors

Quantify medium effects on particle production at high- p_T

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA} / dp_T}{d\sigma_{pp} / dp_T} \equiv \frac{[medium]}{[vacuum]}$$

$$\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{NN}$$
 from Glauber MC

$R_{AA} > 1$ enhancement

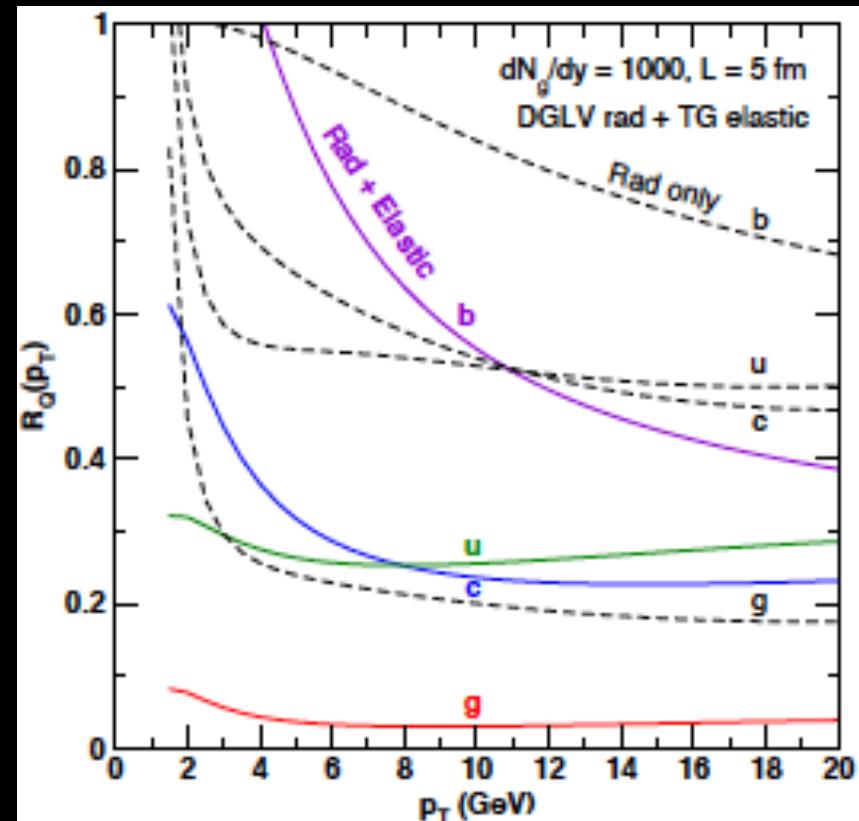
$R_{AA} = 1$ no modification

$R_{AA} < 1$ suppression

Requires reference spectra in pp collisions

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$$

$$\rightarrow R_{AA,g} < R_{AA,q} < R_{AA,c} < R_{AA,b}?$$



CHARGED PARTICLE NUCLEAR MODIFICATION FACTORS

R_{AA} of charged particles

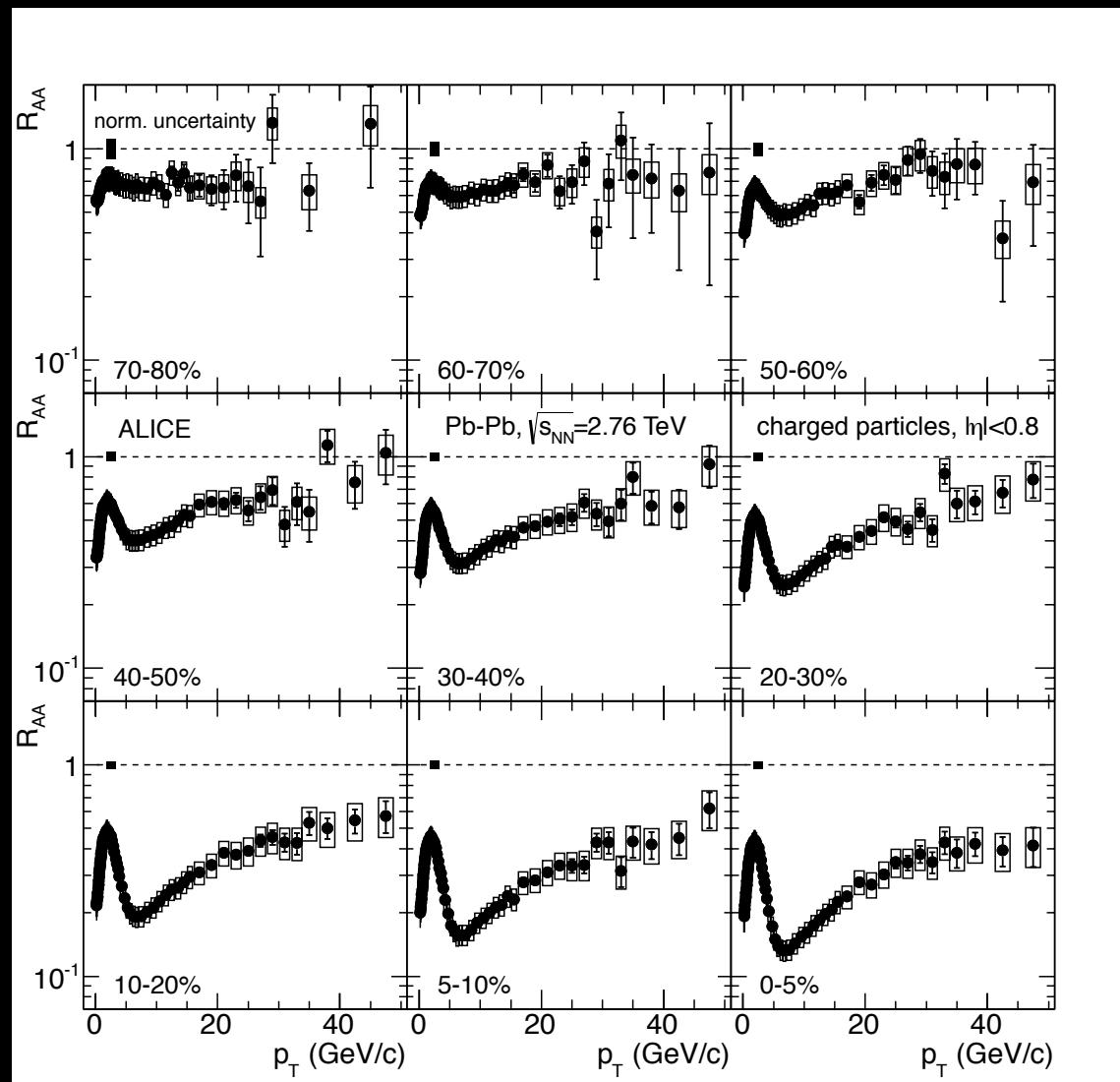
Phys. Lett. B720 (2013) 52

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA} / dp_T}{d\sigma_{pp} / dp_T} \equiv \frac{[medium]}{[vacuum]}$$

R_{AA} vs. p_T measured in Pb-Pb collisions in nine centrality intervals

Strong suppression of particle production in central Pb-Pb collisions (0-5%) about factor of 2-7

Sign of leveling off for $p_T > 30$ GeV in 0-5% central collisions



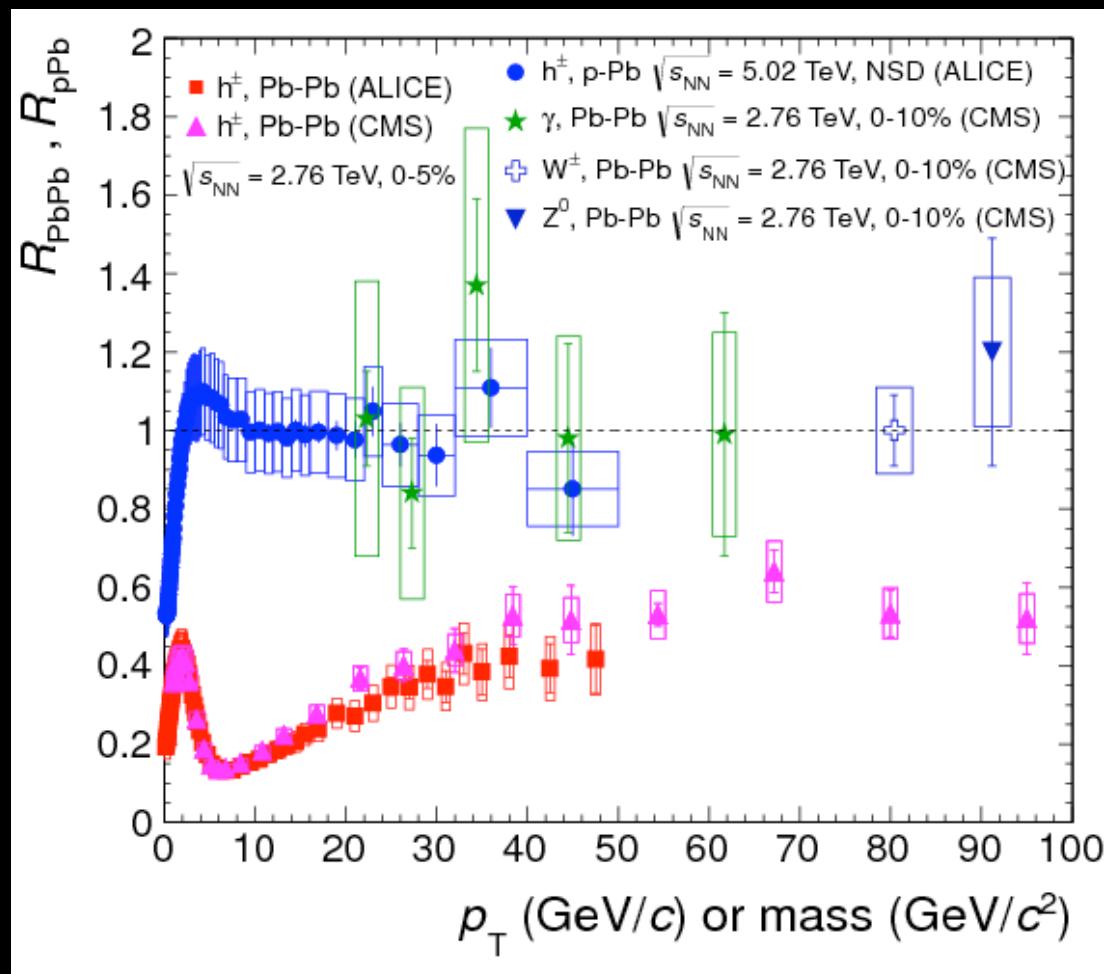
R_{pPb} and R_{PbPb} at LHC

ALICE, Eur.Phys.J. C74 (2014) 9

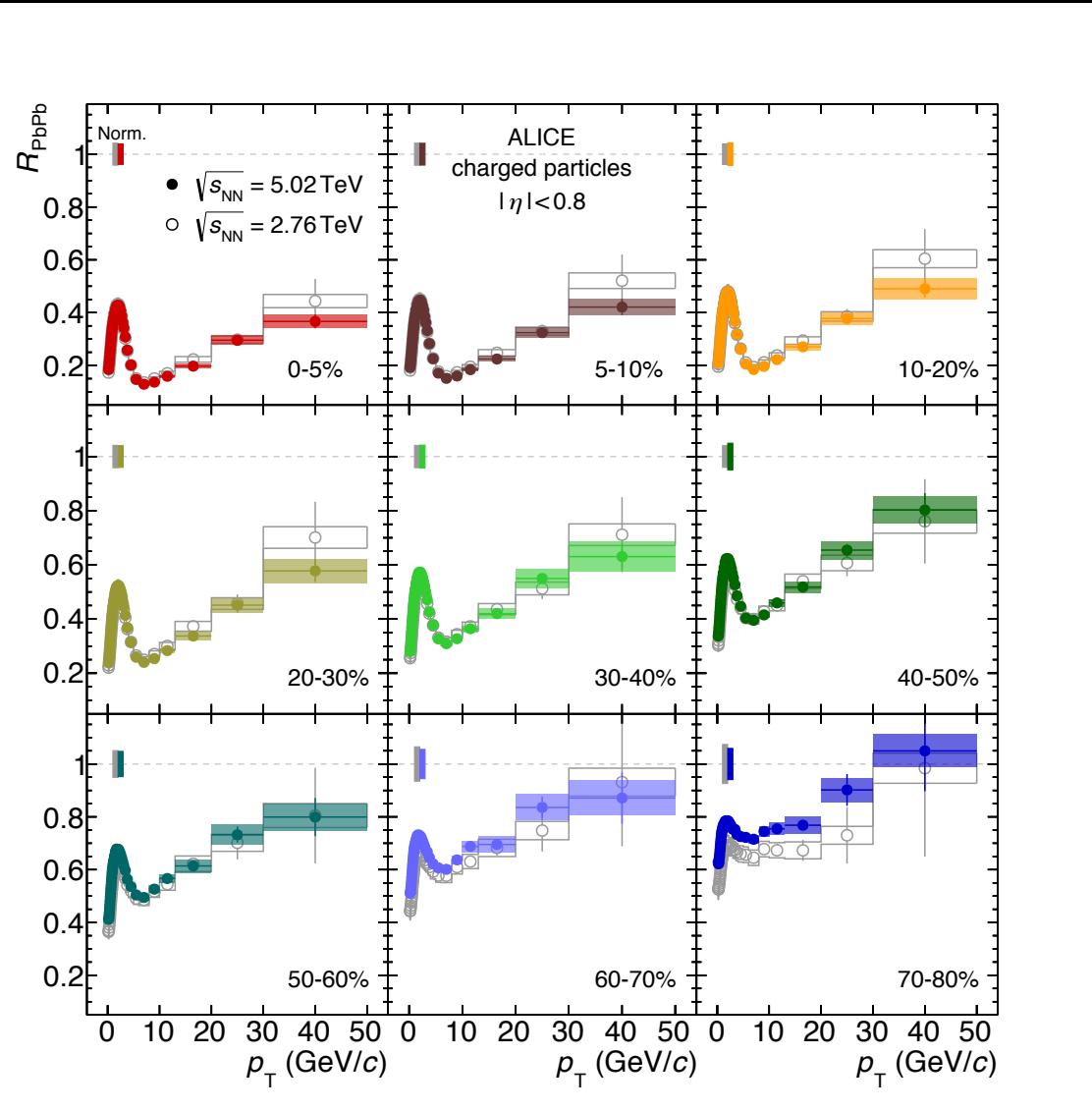
For $p_T > 8 \text{ GeV}/c$

- Strong suppression in central Pb-Pb collisions (ALICE and CMS data)
- No modification for colorless probes (CMS)
- No modification in p-Pb collisions (ALICE, no centrality selection)

→ Suppression in Pb-Pb collisions is due to final state effects!



R_{PbPb} energy dependence at LHC



arXiv:1802.09145

Similar suppression at both energies

Harder spectra at larger energy

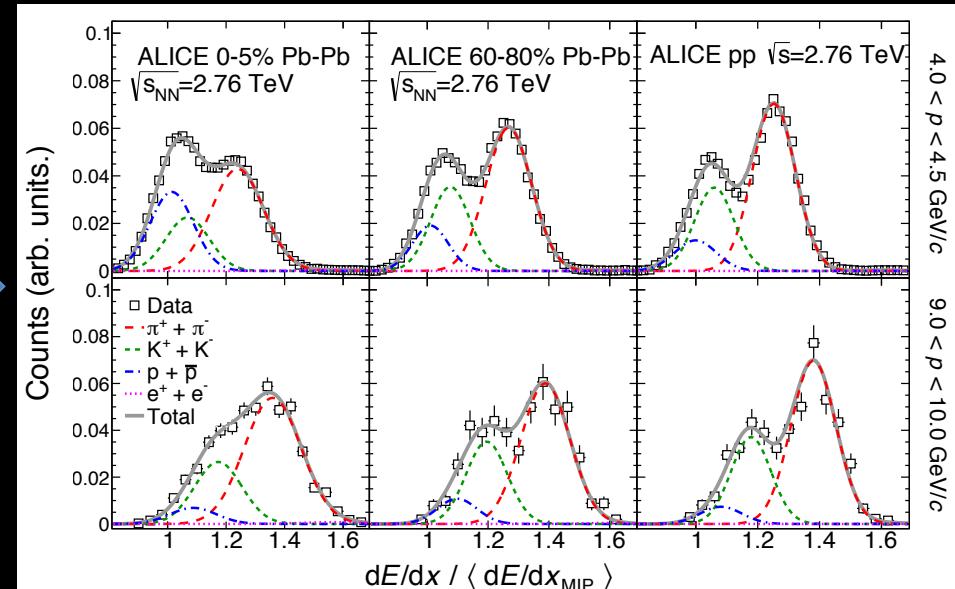
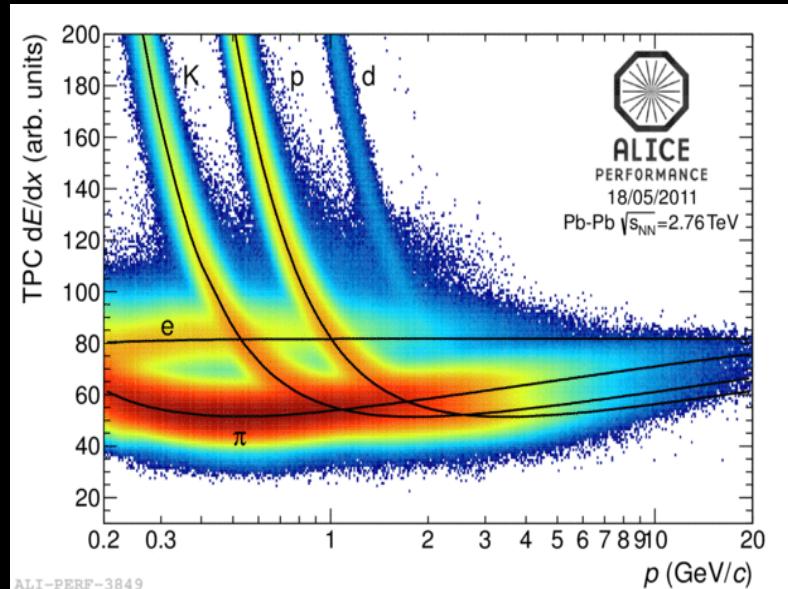
→ Indication of larger parton energy loss at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

IDENTIFIED PARTICLE NUCLEAR MODIFICATION FACTORS

- Charged pions, kaons and protons
- D mesons

Pion, kaon and proton identification at high- p_T

Based on measured p_T spectra for charged particles and TPC dE/dx information.



$$\frac{d^2N_{\pi/K/p}}{dp_T dy} = J_{\pi/K/p} \frac{d^2N_{ch}}{dp_T d\eta} \frac{\epsilon_{ch}}{\epsilon_{\pi/K/p}} f_{\pi/K/p}(p_T)$$



Jacobian
($\eta \rightarrow y$)



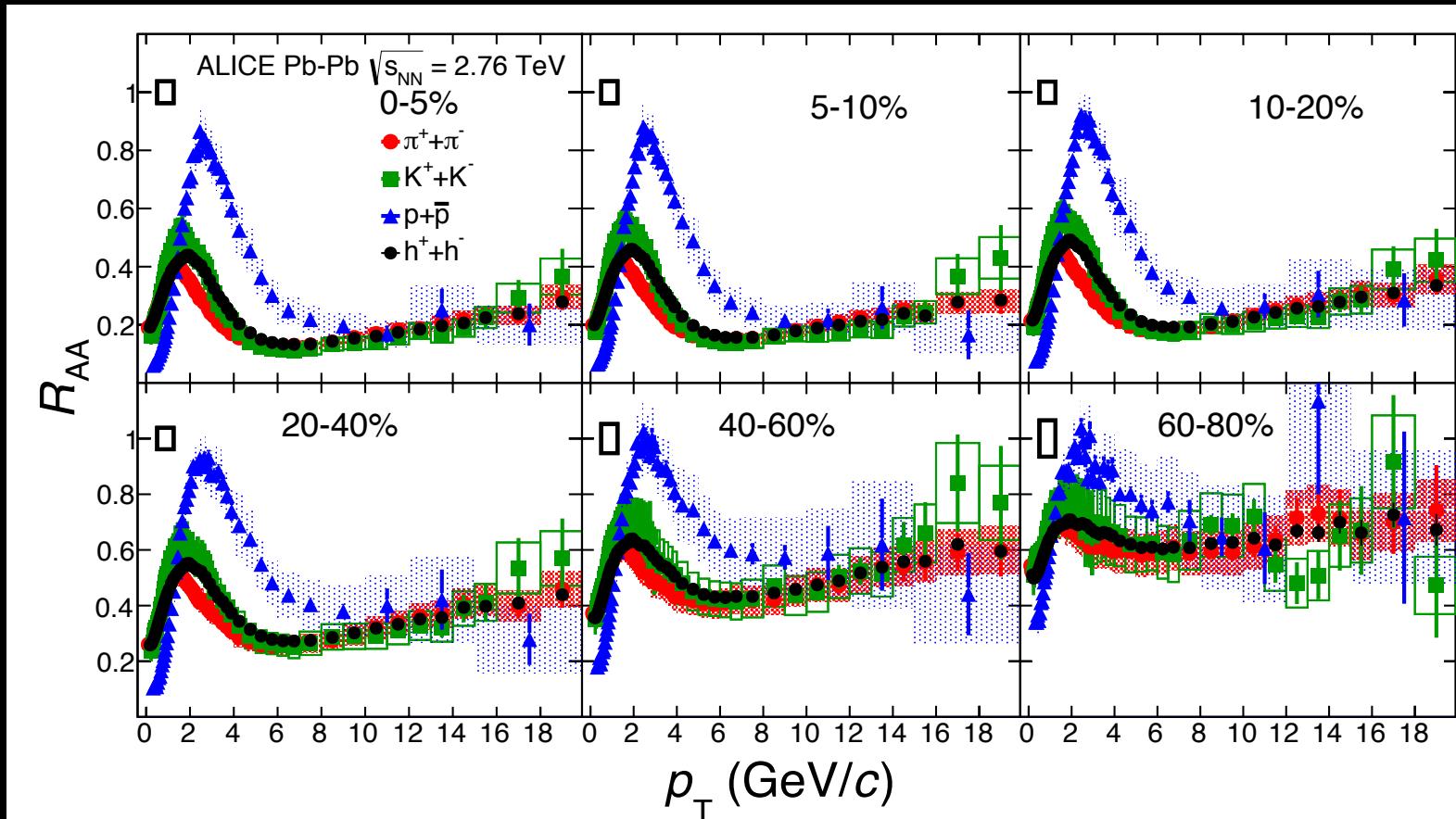
Efficiency
ratio



Particle
fractions

R_{AA} of π , K , p at $\sqrt{s}_{NN} = 2.76$ TeV

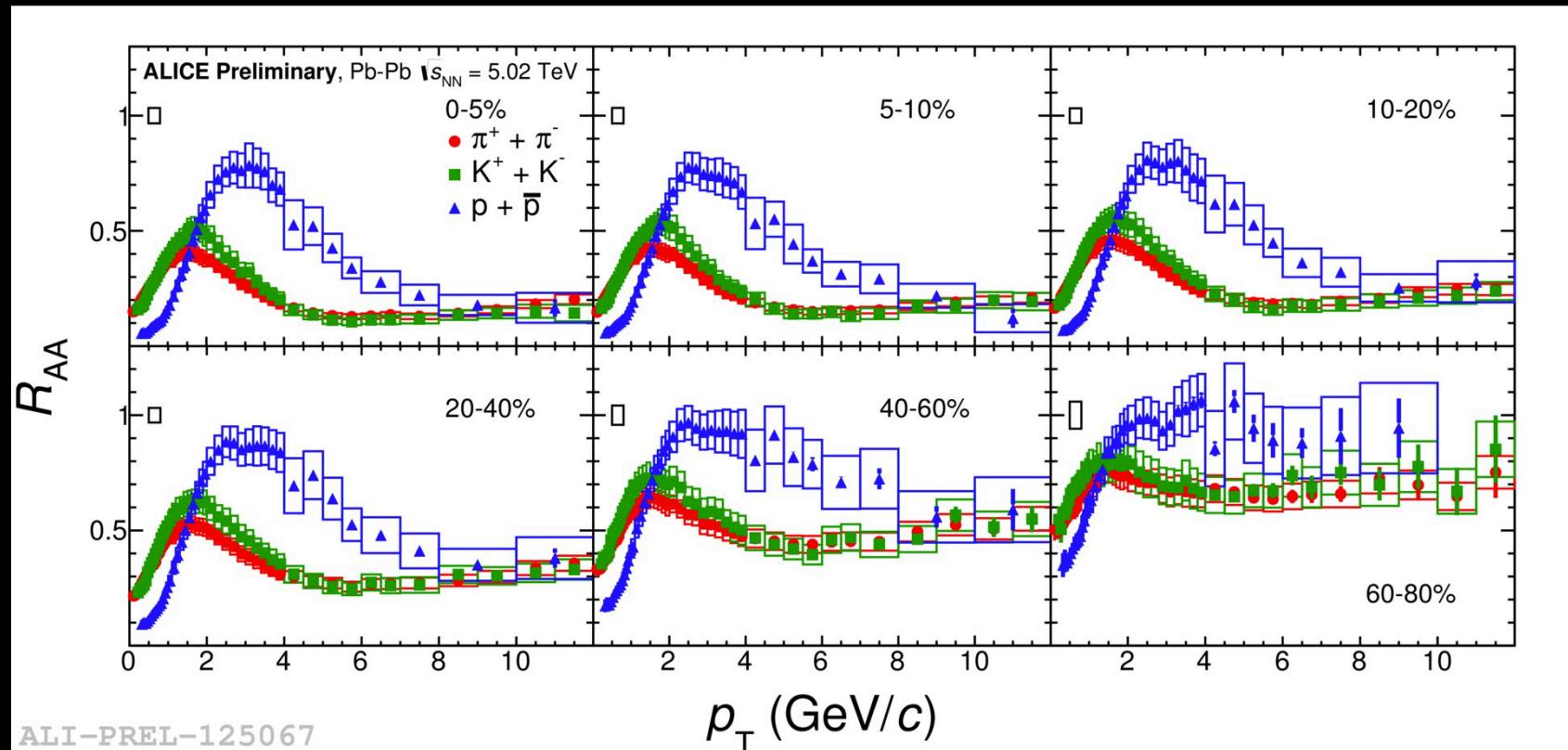
Phys. Rev. C93 (2016) 034913



For $p_T > 8$ GeV/c, the same suppression for pions, kaons, protons and charged particles
 \rightarrow Fragmentation function at high p_T is not affected by the medium

Confirmed by jet fragmentation function measurements: CMS Phys. Rev. C90, 024908 (2014)

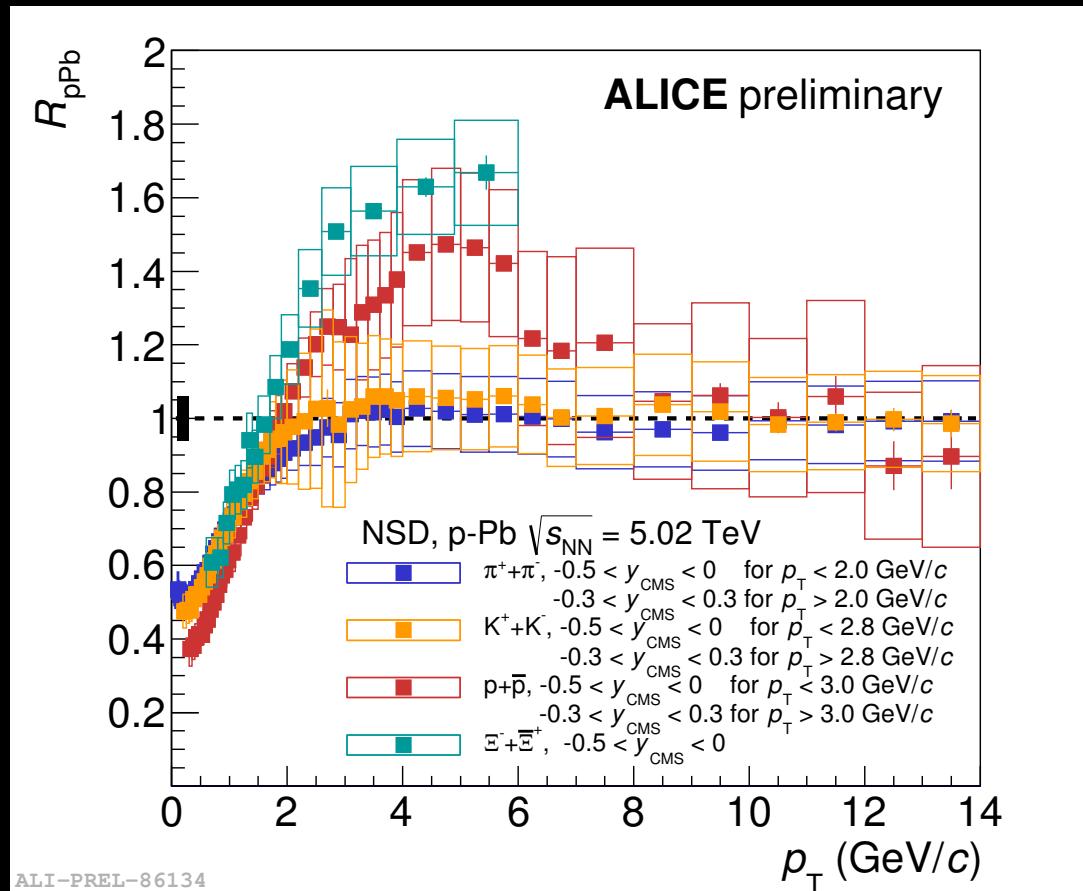
R_{AA} of π , K , p at $\sqrt{s}_{NN} = 5.02$ TeV



pp Phys. Lett. B760 (2016) 720

- For $p_T > 8$ GeV/c, all three species are equally suppressed for all centralities
- (Light-)flavor independent energy loss at high p_T as observed at $\sqrt{s}_{NN} = 2.76$ TeV

R_{pPb} of π , K , p



p-Pb (minimum bias, NSD)

High $p_T > 8 \text{ GeV}/c$: $R_{\text{pPb}} \sim 1$ (no modification)

→ Suppression in Pb-Pb collisions is due to final state effects!

D meson measurements in ALICE

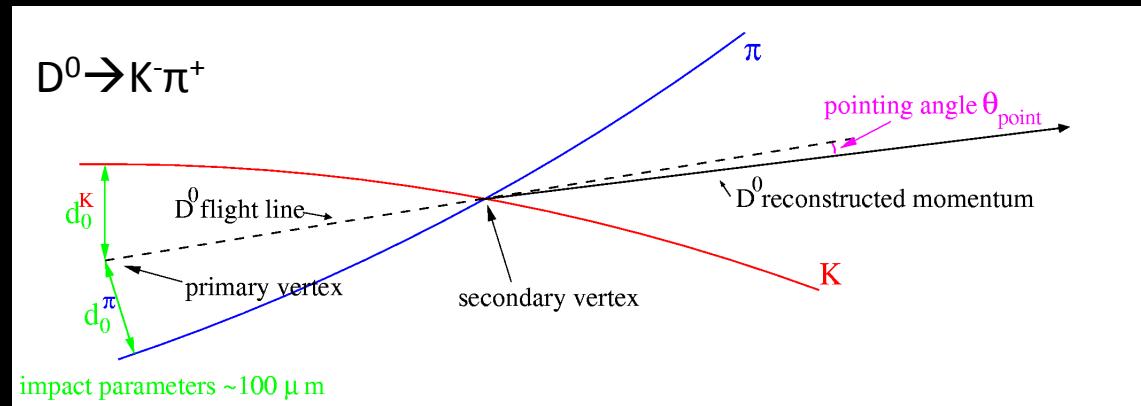
First measurement of D mesons in heavy-ion collisions! ALICE, JHEP 09 (2012) 112

$D^0 \rightarrow K^- \pi^+$
(BR=3.87%, $c\tau \sim 123 \mu\text{m}$)

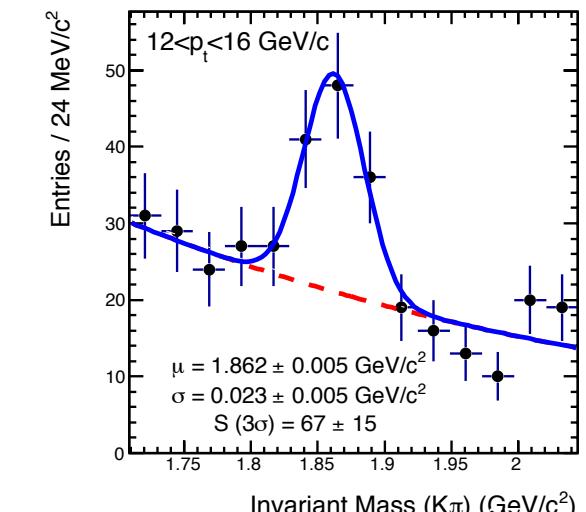
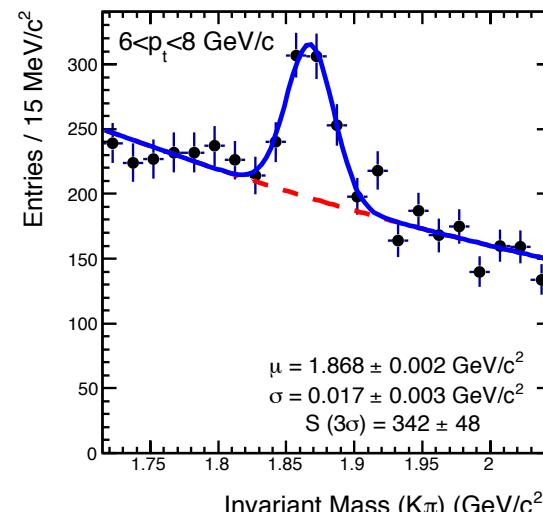
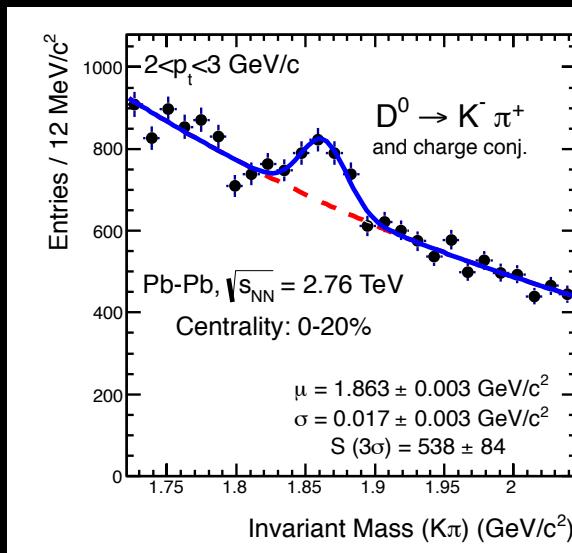
$D^+ \rightarrow K^- \pi^+ \pi^+$
(BR=9.13%, $c\tau \sim 312 \mu\text{m}$)

$D^{*+} \rightarrow D^0 \pi^+$
(BR=67.7%, strong decays)

Secondary vertex reconstruction in ALICE

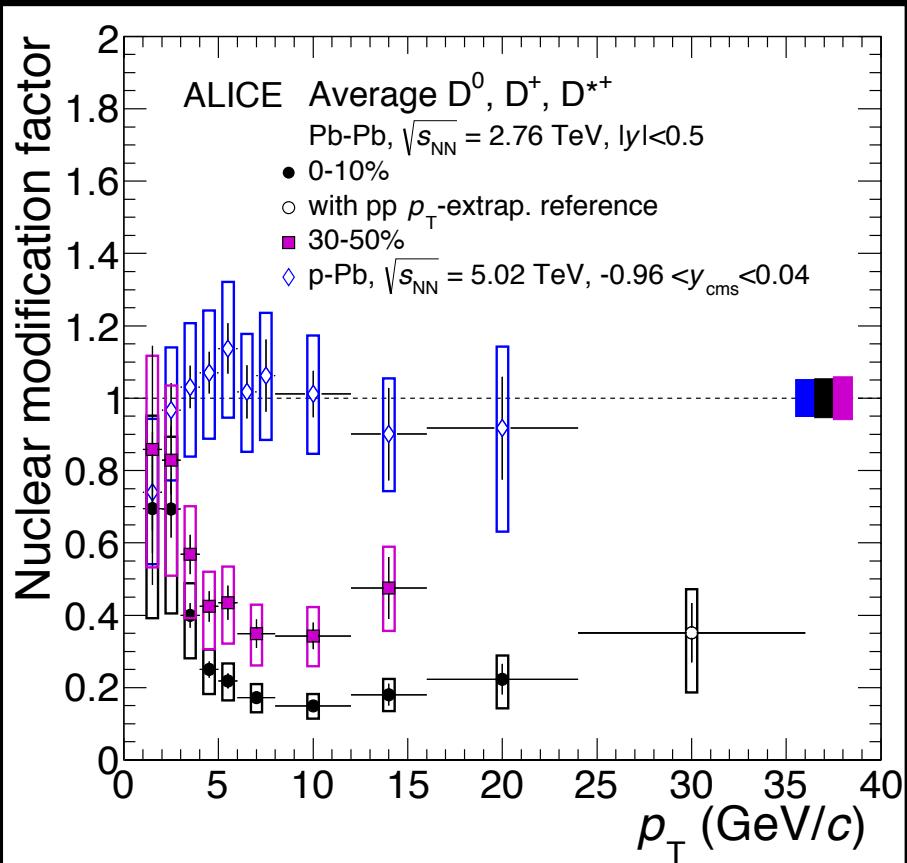
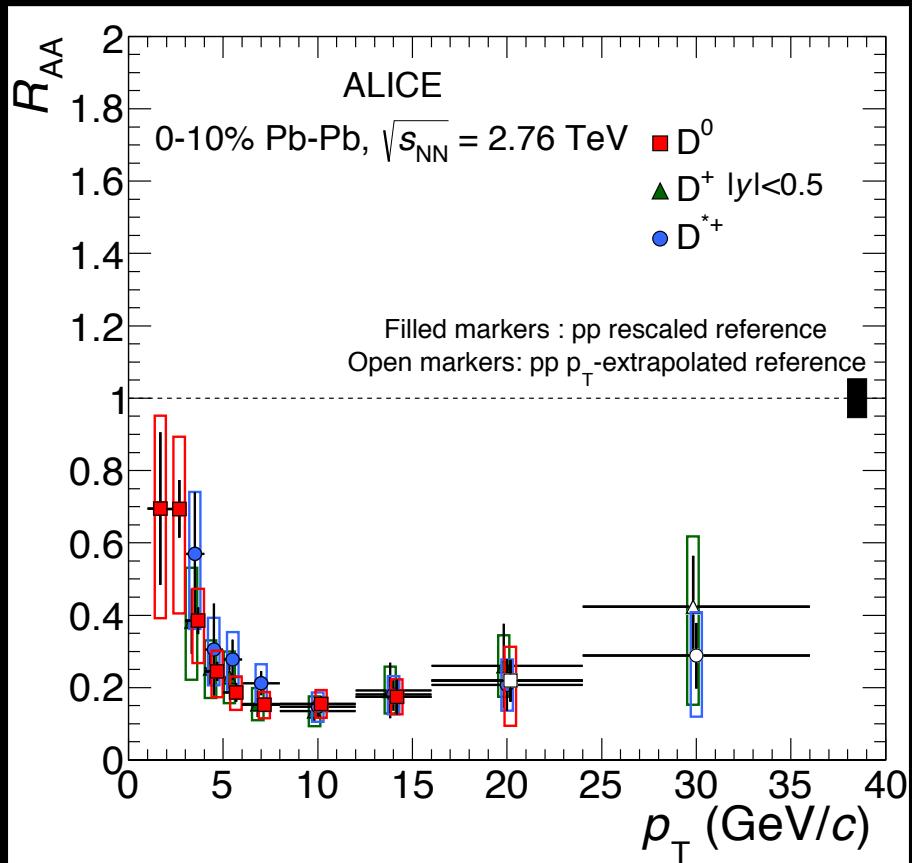


Invariant mass analysis



D meson R_{AA} and R_{pPb}

JHEP03 (2016) 081



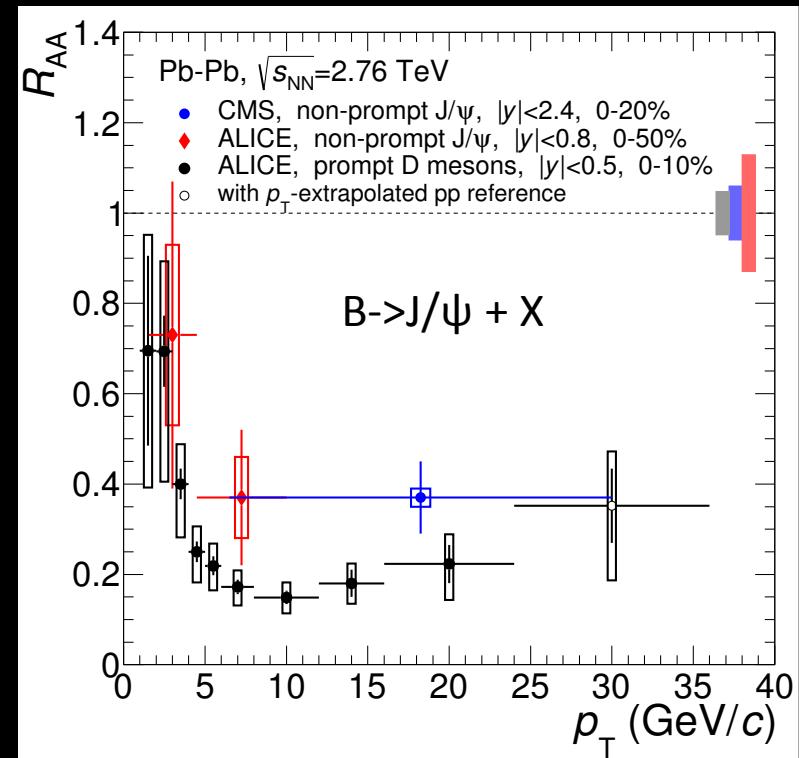
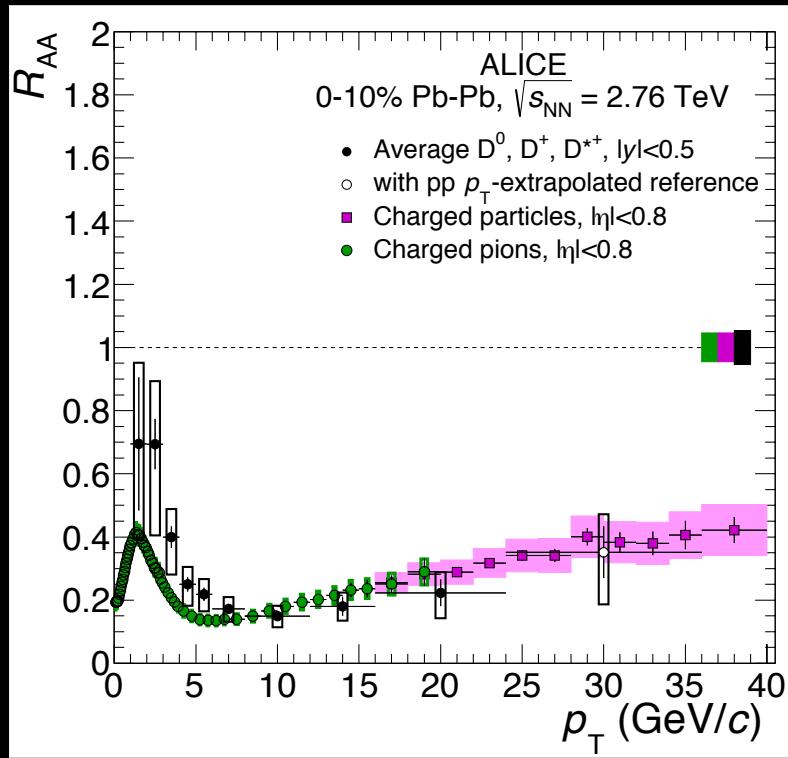
Pb-Pb: Strong suppression at high p_T

p-Pb: No modification at high- p_T

→ Suppression in Pb-Pb collisions is due to final state effects!

R_{AA} identified hadrons comparison

JHEP03 (2016) 081



- The same suppression of light-flavor and D mesons in central Pb-Pb collisions
- Stronger suppression of D than B mesons at high- p_T

→ Parton energy loss in the QGP:

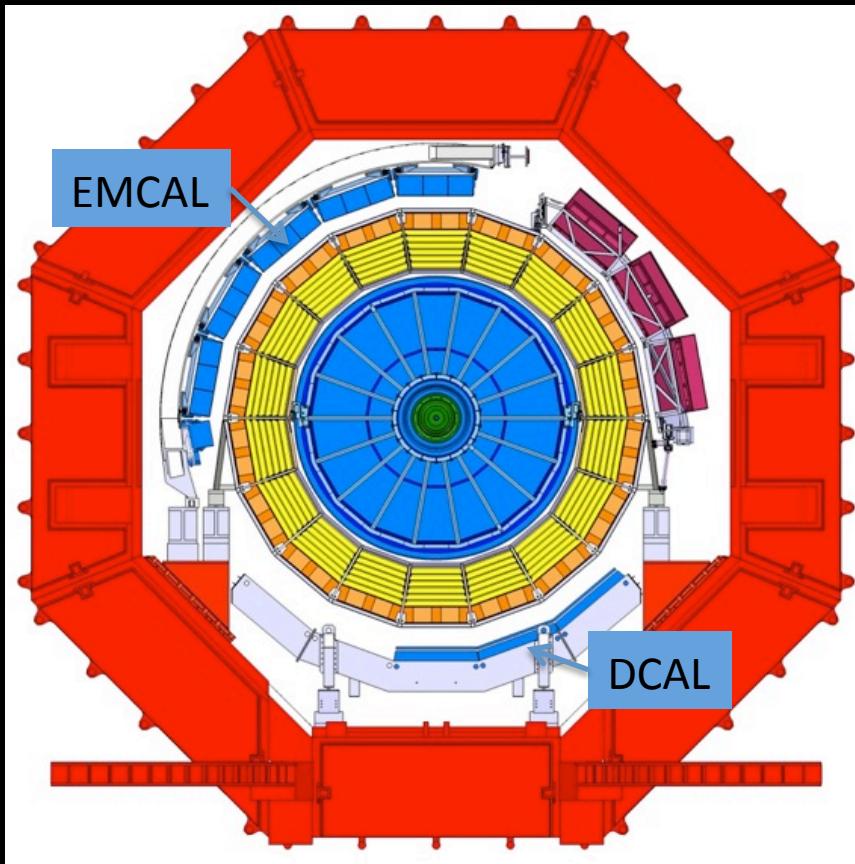
- $\Delta E_{g,u,d,s} \sim \Delta E_c$?
- $\Delta E_b < \Delta E_c$?

In order to conclude → jet measurements

Non-prompt J/ψ ($B \rightarrow J/\psi + X$):
ALICE, JHEP 1507 (2015) 051
CMS, JHEP 05 (2012) 063

JETS

Jet measurement in ALICE

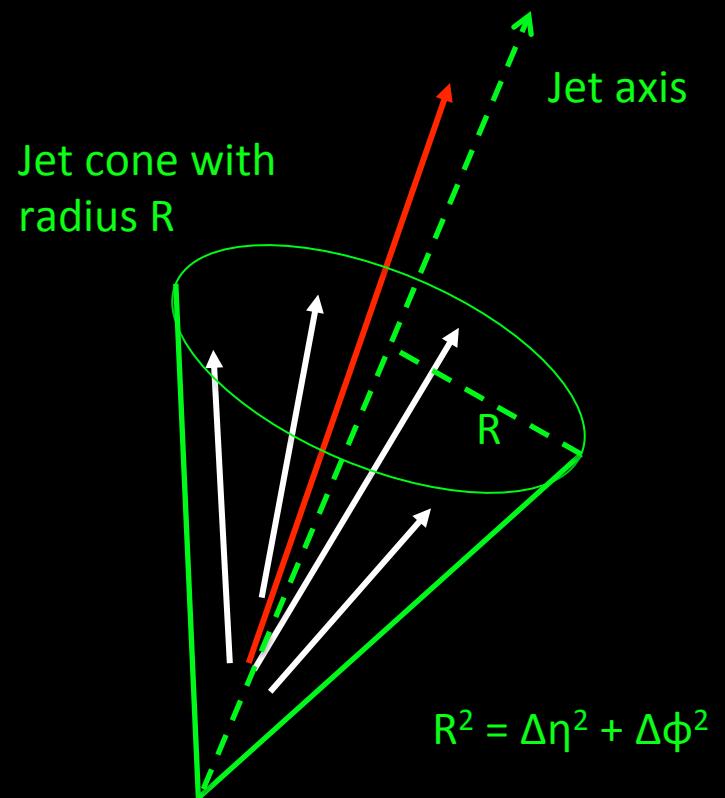


TPC+ITS: charged jets – charged jet constituents
TPC+ITS+EMCAL+DCAL: full jets – charged + neutral (π^0, γ)

Anti- k_t : Cacciari et al. Eur. Phys. J. C 72, 1896 (2012)

k_t : Cacciari and Salam Phys. Lett. B 659 (2008) 119

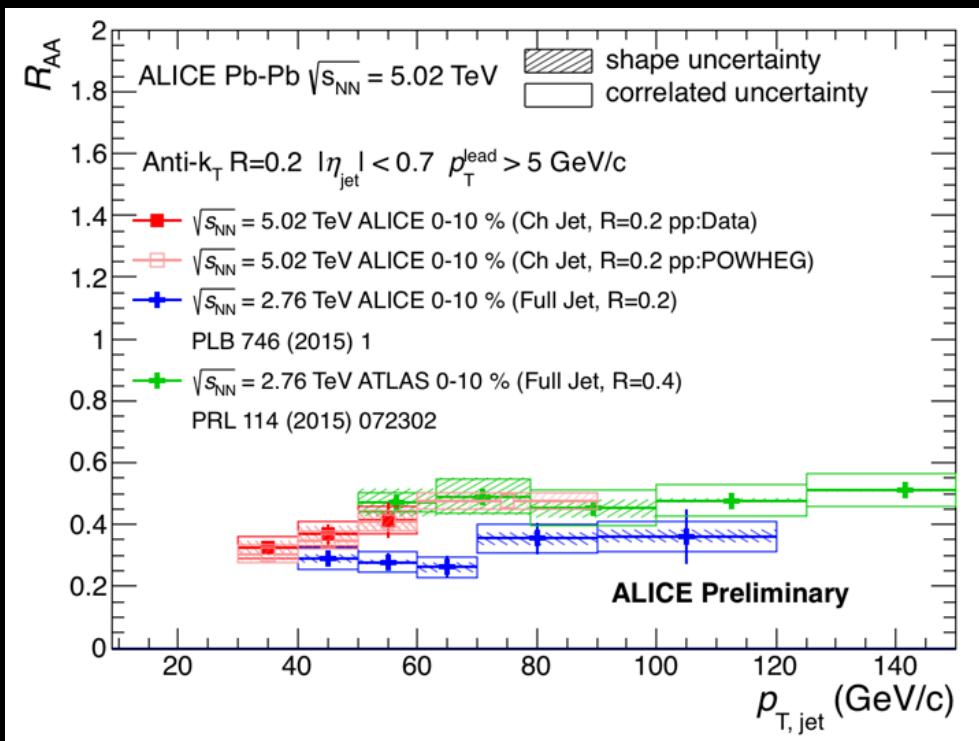
Background fluctuations: ALICE, JHEP 053 (2012) 1203



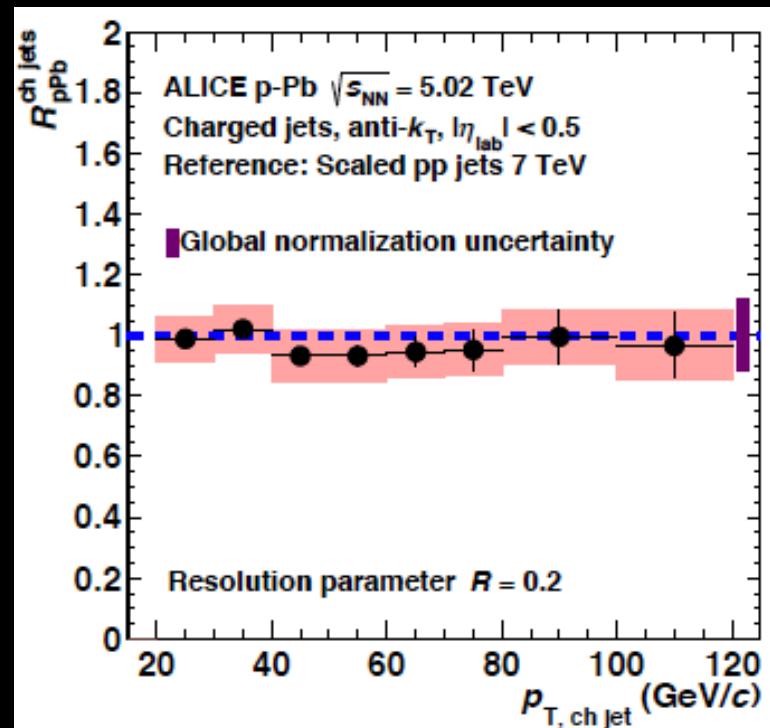
Jet finder: anti- k_t algorithm
Underlying Event (UE) background subtraction:

- Event wise (k_t algorithm)
 $p_{Tjet} = p_{Tjet,rec} - \rho \cdot A_{jet}$
- Fluctuations on statistical level
 $\delta p_{Tjet} = (p_{Tjet,rec} - \rho \cdot A_{jet}) - p_{Tjet,true}$

R_{AA} vs. $R_{p\text{Pb}}$ jets



ATLAS, Phys. Rev. Lett. 114 (2015) 072302

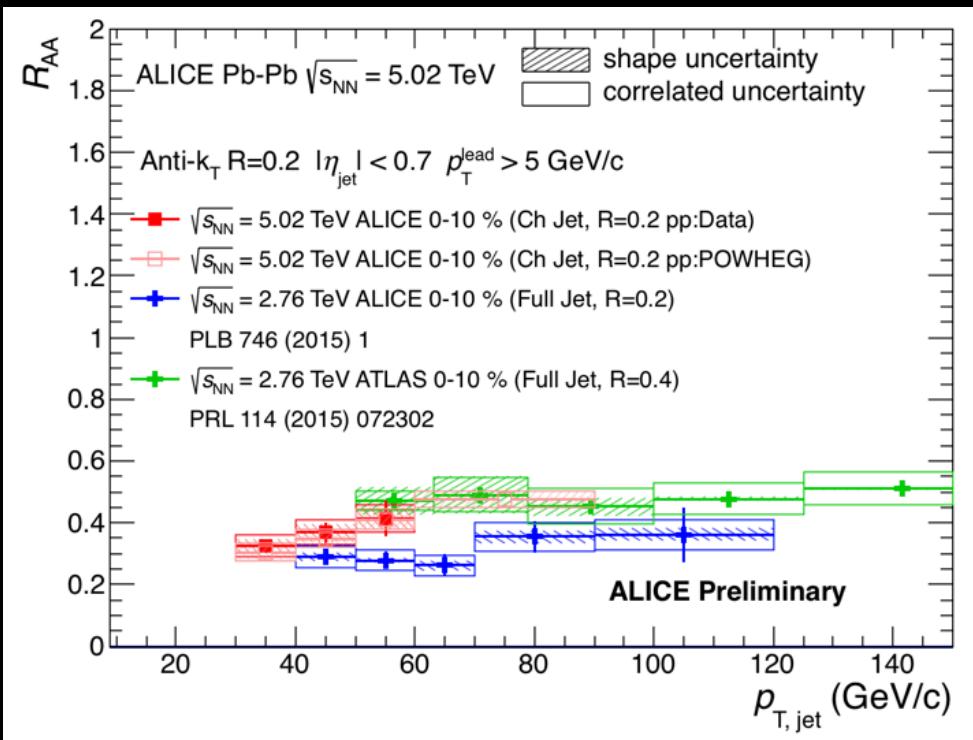


Phys. Lett. B749 (2015) 68

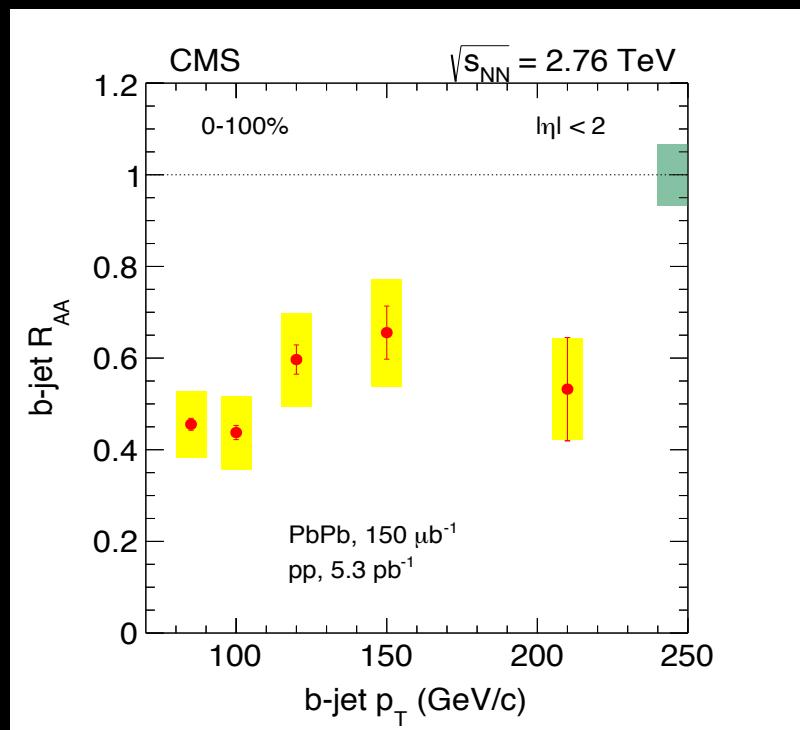
→ Jet production suppression in Pb-Pb central collisions related to final state effects

R_{AA} jets

g/q-jet R_{AA}



b-jet R_{AA}



- Strong suppression of g/q-jets in central Pb-Pb collisions
- The same suppression of g/q and b jets

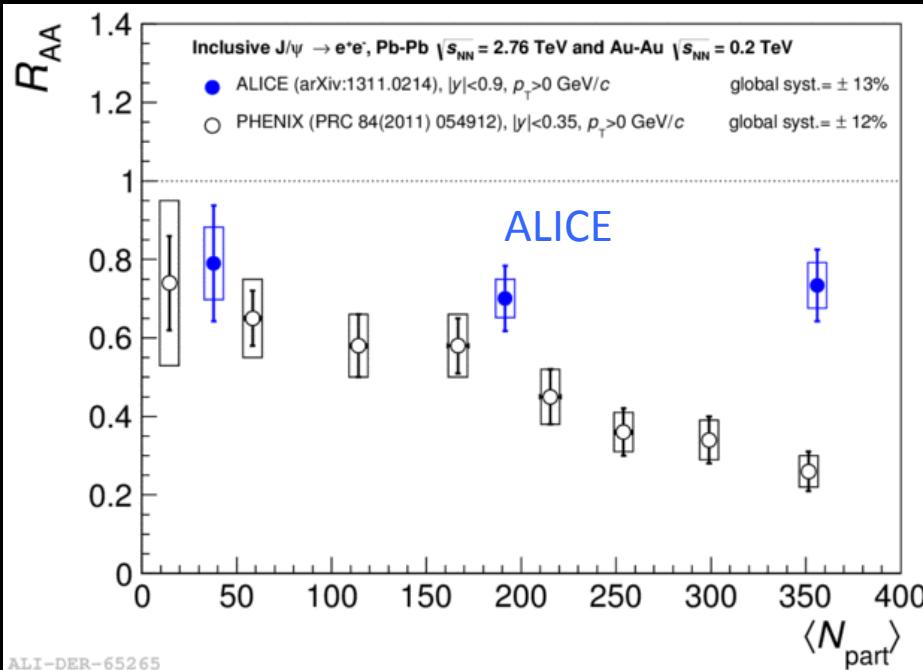
→ Parton energy loss in the QGP: $\Delta E_{g,u,d,s} \sim \Delta E_b$?

CMS, Phys. Rev. Lett. 113, 132301 (2014)
ATLAS, Phys. Rev. Lett. 114 (2015) 072302

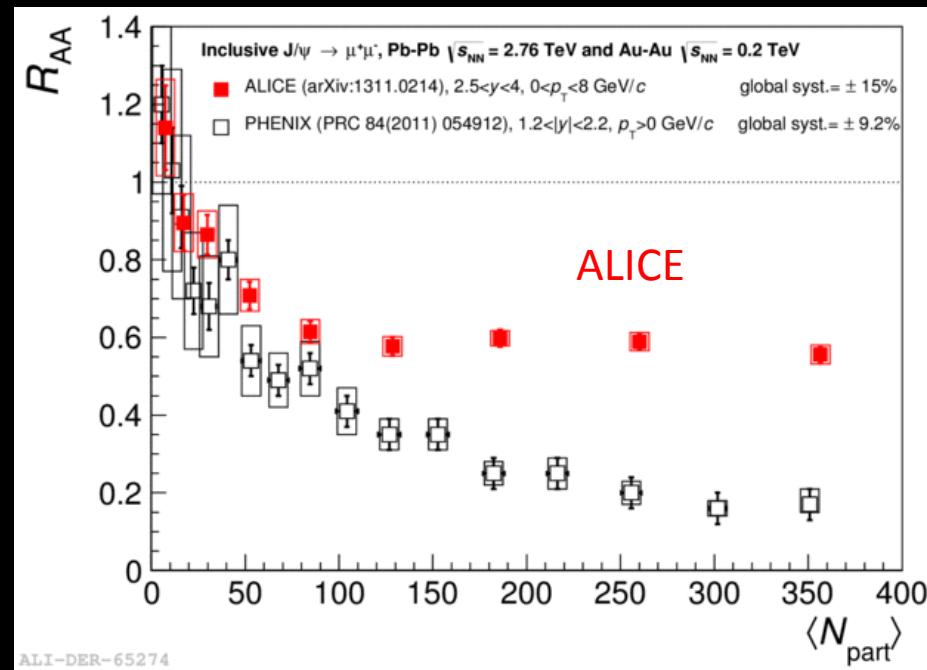
QUARKONIA

J/ Ψ at LHC vs RHIC

Central rapidity



Forward rapidity



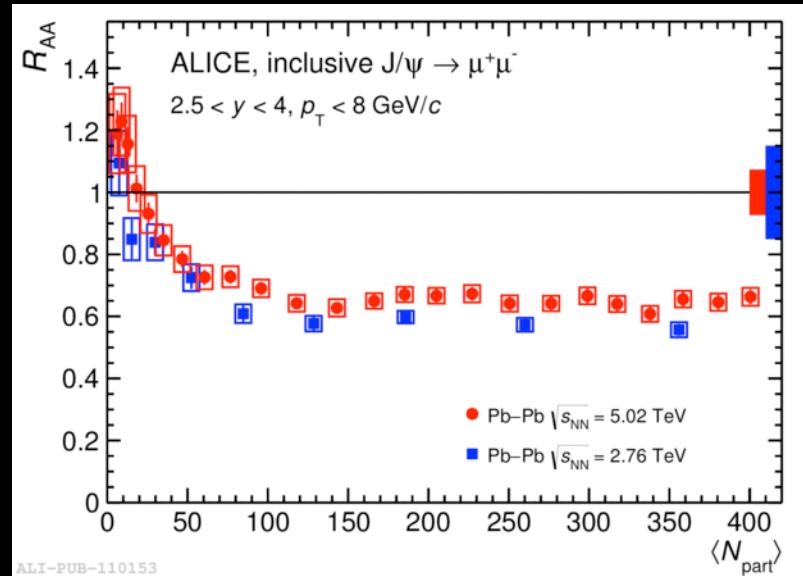
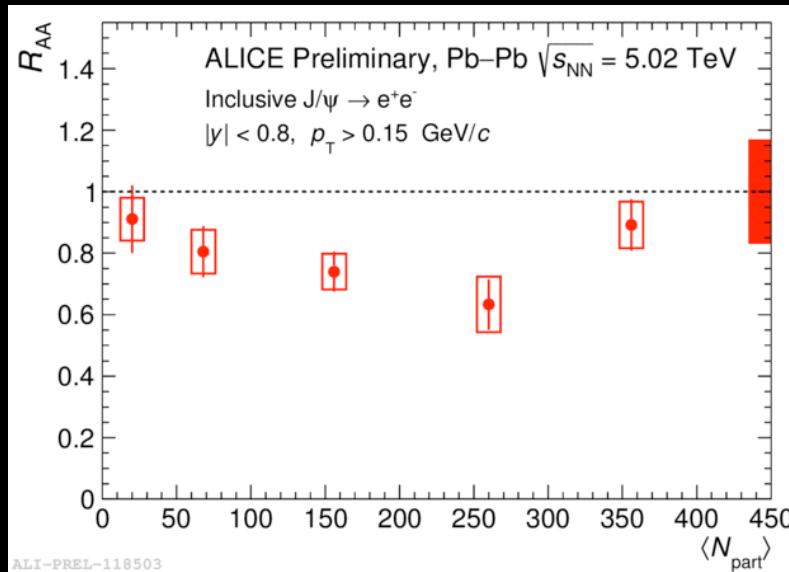
- Different suppression pattern compared to RHIC at central and forward rapidity
 → Different source of J/ Ψ in central collisions at the LHC
 → Indication of generation in central collisions

Sequential quarkonia suppression measured by CMS
 CMS Phys. Lett. B 770 (2017) 357

ALICE, PLB 743 (2014) 314-327
 PHENIX, PRC 84 (2011) 054912

R_{AA} of J/ ψ vs energy at LHC

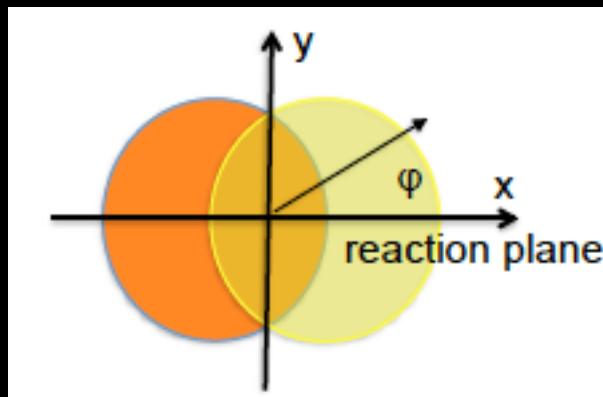
Phys. Lett. B 766 (2017) 212



- Similar suppression measured in central and forward rapidity
- Small dependence on energy visible but indication of increase

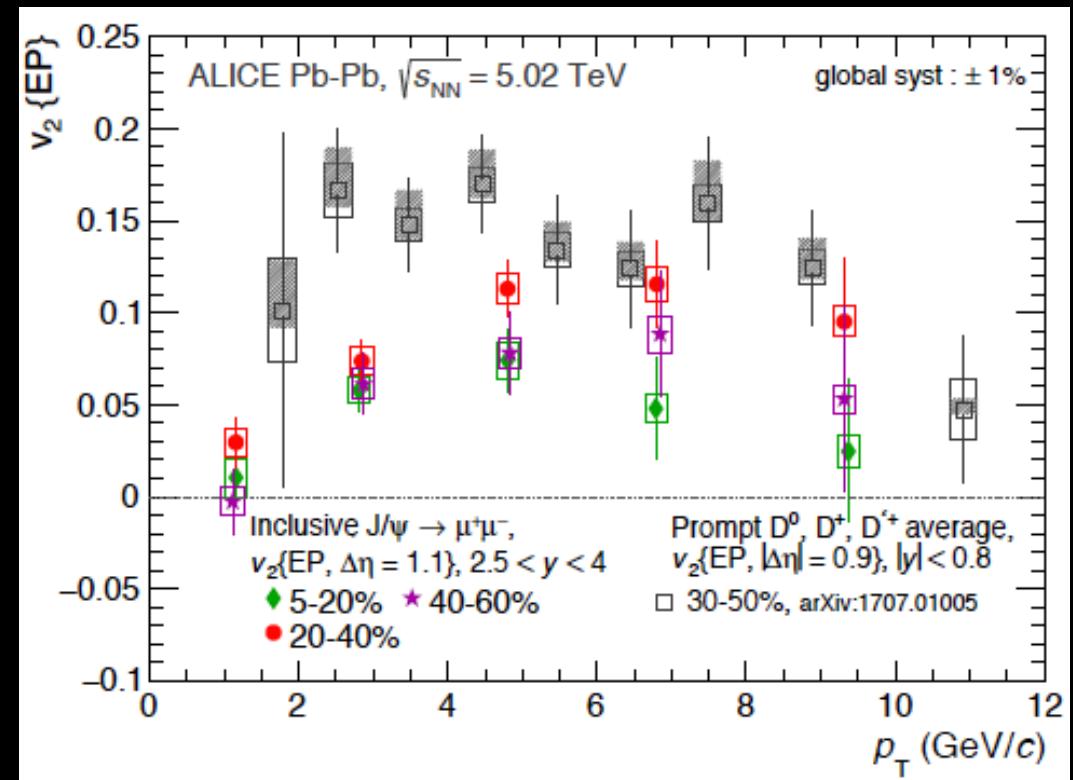
Extra slide: elliptic flow v_2

Noncentral A-A collision



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

Phys. Rev. Lett. 119 (2017) 242301



Non-zero elliptic flow measured for D and J/ψ mesons

→ Charm quarks are thermalized and flow