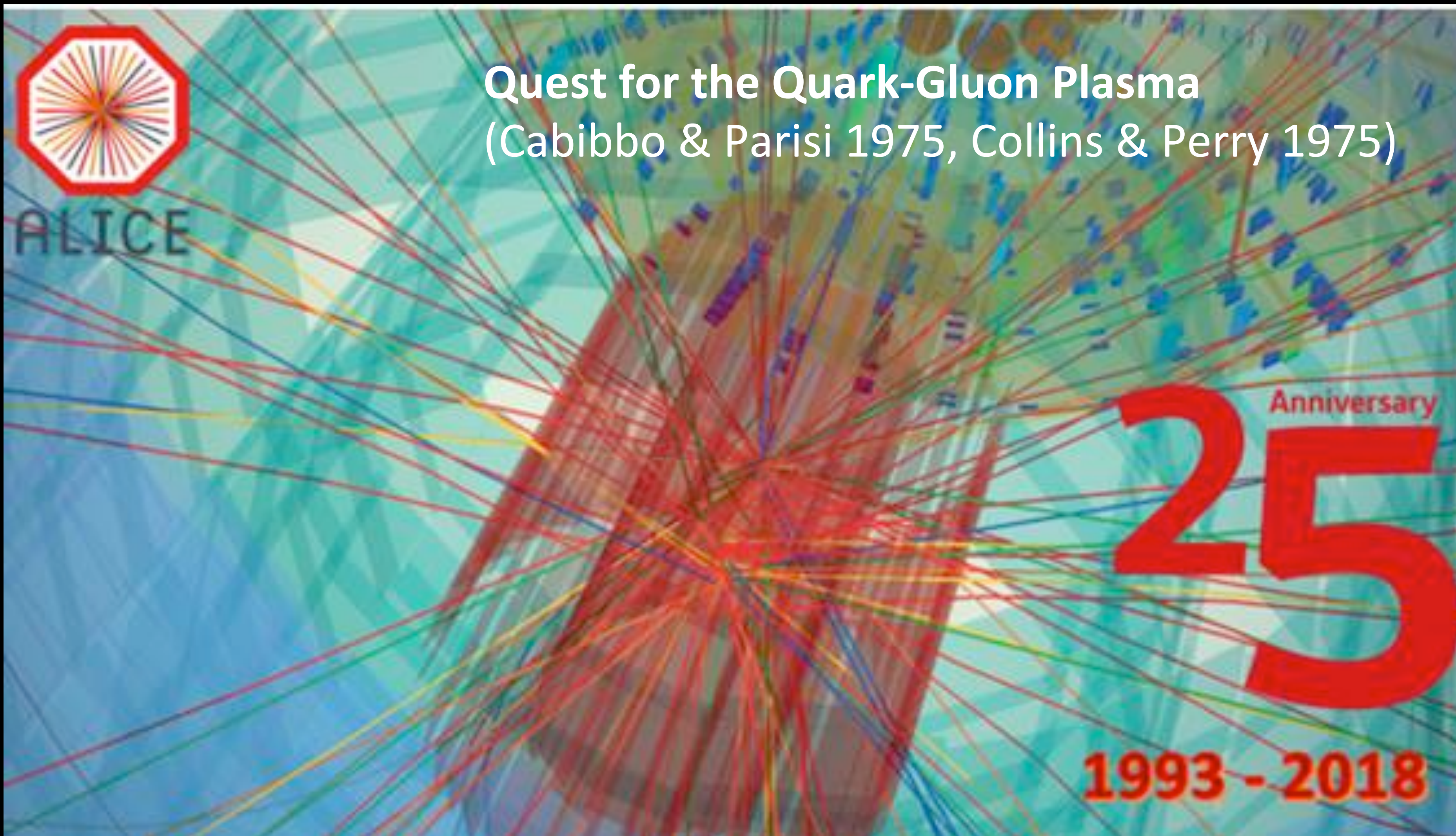
Energy and system dependence of light- and heavy-hadron production in pp, p-Pb, Xe-Xe and Pb-Pb collisions at the LHC

Jacek Otwinowski (IFJ PAN, Kraków)
On behalf of the ALICE Collaboration

A Large Ion Collider Experiment
aliceinfo.cern.ch

www.ifj.edu.pl

25 years of ALICE Collaboration

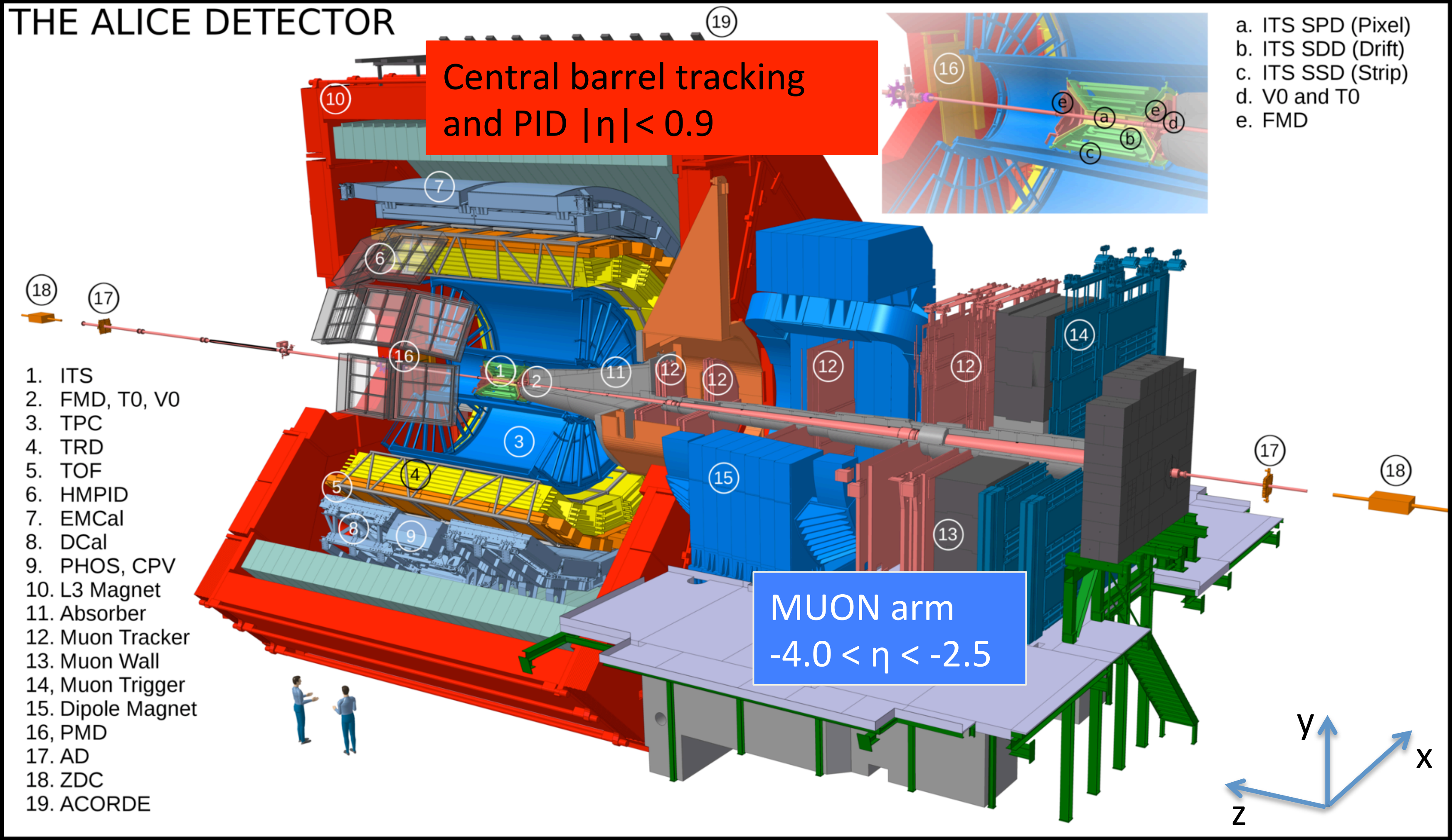


Quest for the Quark-Gluon Plasma
(Cabibbo & Parisi 1975, Collins & Perry 1975)

https://indico.cern.ch/event/653848/

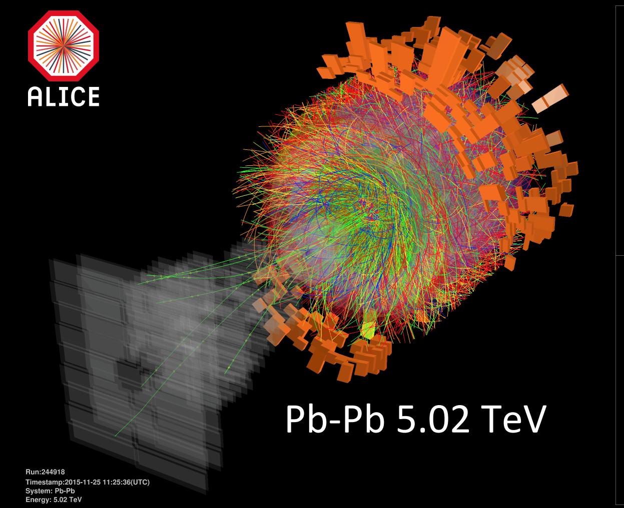
A Large Ion Collider Experiment

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



ALICE at work since 2009

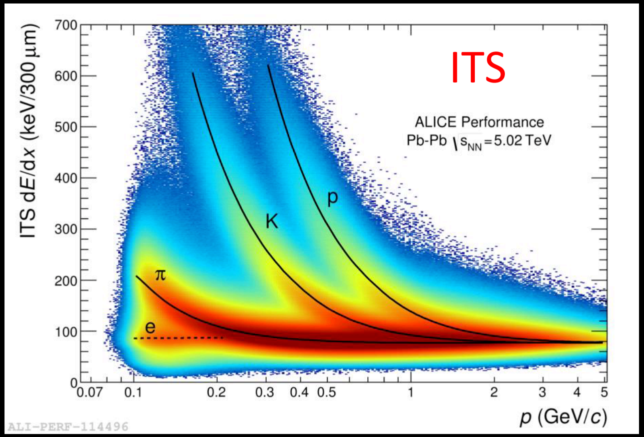
System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011 2015 *by the end of 2018*	2.76 5.02 5.02	~75 μb^{-1} ~250 μb^{-1} *~1* nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015-2017	0.9, 2.76, 7, 8 5.02, 13	~200 μb^{-1}, ~100 μb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1} ~1.3 pb^{-1}, ~25 pb^{-1}

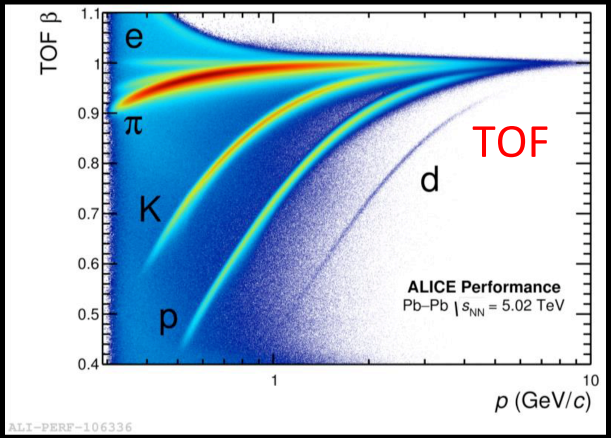


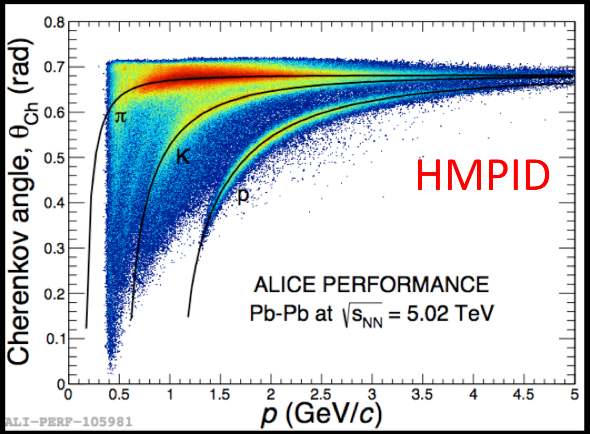
- Energy and system dependence studies of particle production are possible
- Large statistics of pp, p-Pb and Pb-Pb collisions at the same $\sqrt{s_{NN}}$
  → precise comparison studies

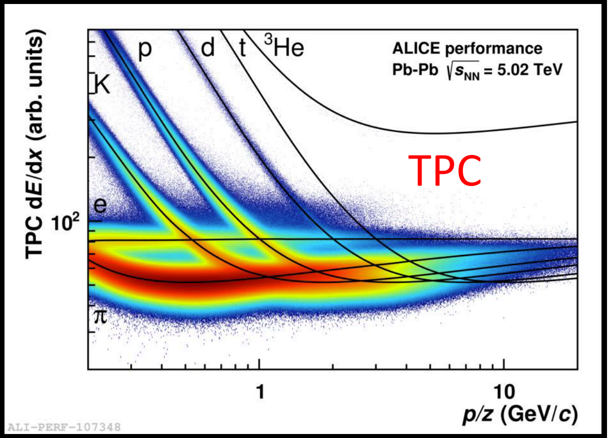
Particle identification with ALICE

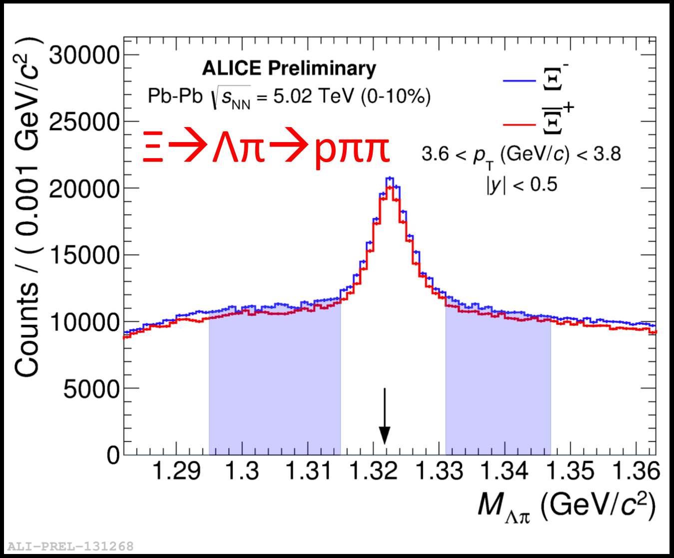
Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

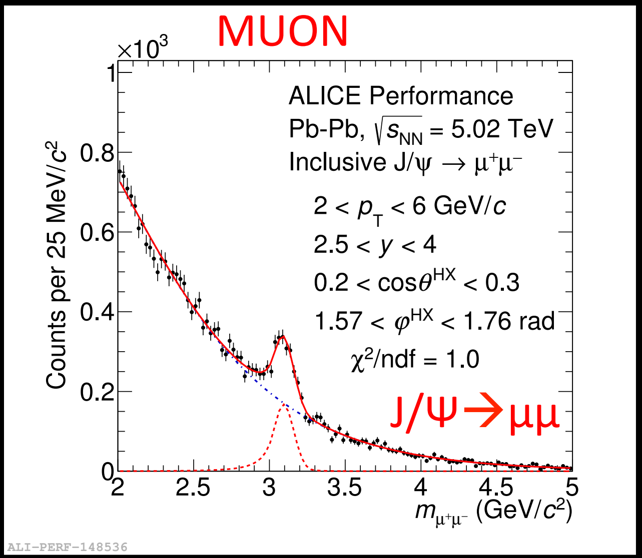






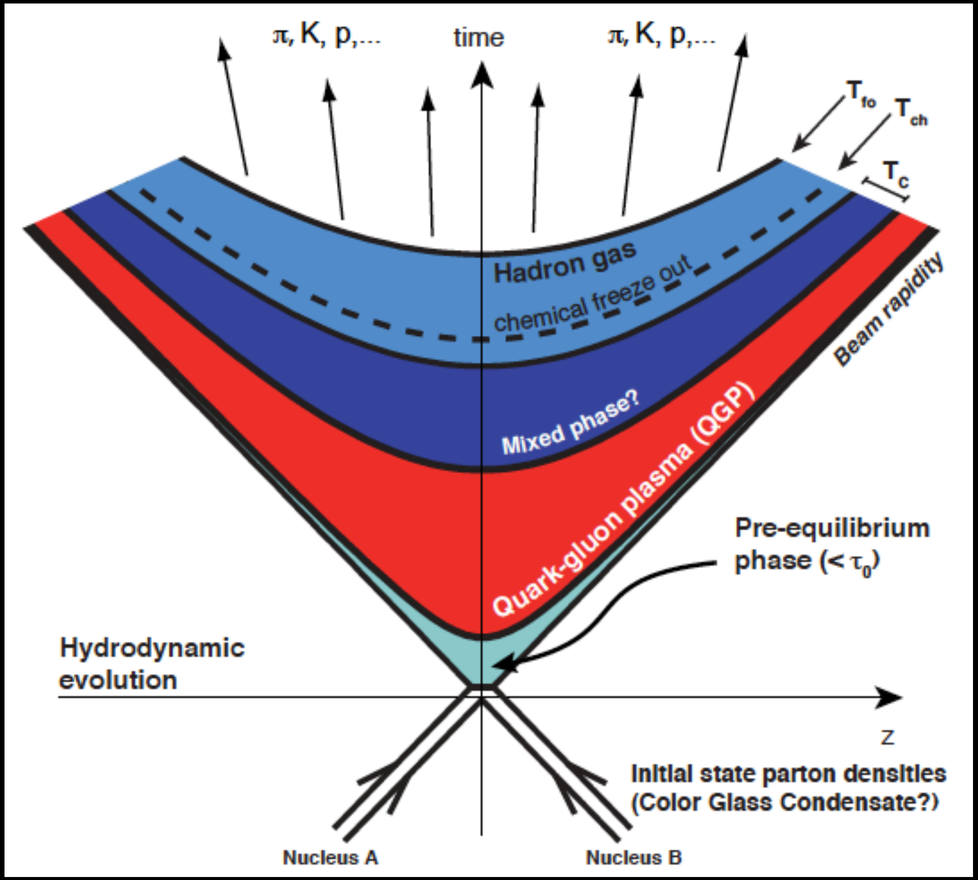






Stages of the relativistic heavy-ion collision

Bjorken 1983



Chemical and thermal freeze-out

Hadronization (T ~ T_C)

Quark-Gluon Plasma (thermalized matter)

Pre-equilibrium, fast thermalization ~ 1 fm/c, glasma?

Hard collisions

Lorentz-contracted ions (dense gluonic matter, Color Glass Condensate?)

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

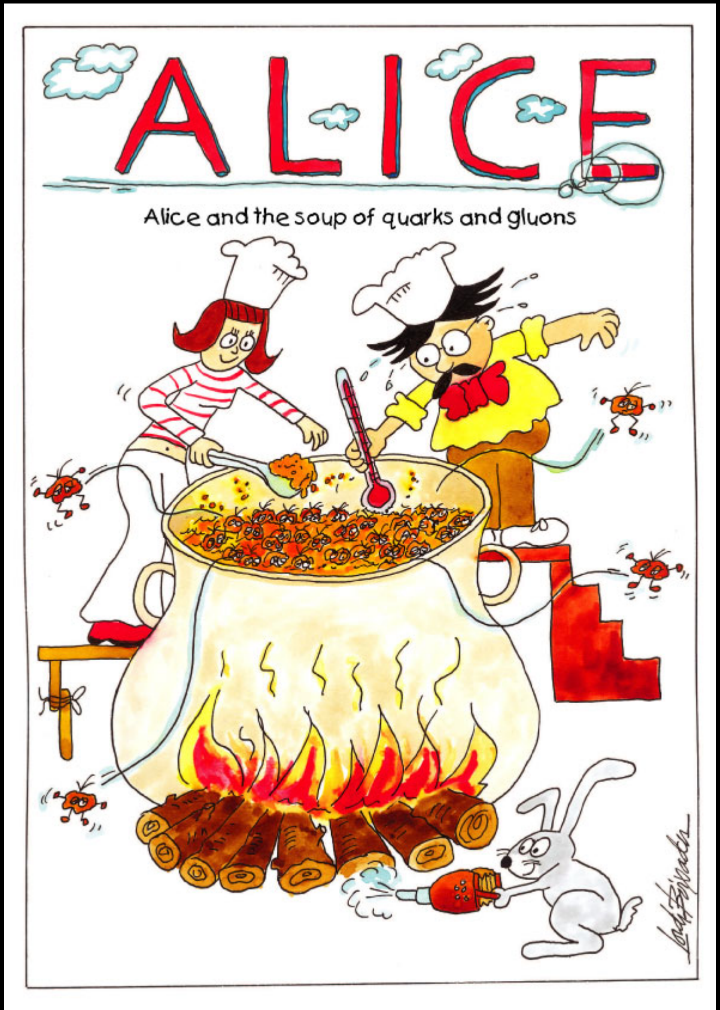
Models are crucial to characterize matter produced in heavy-ion collisions!

Outline

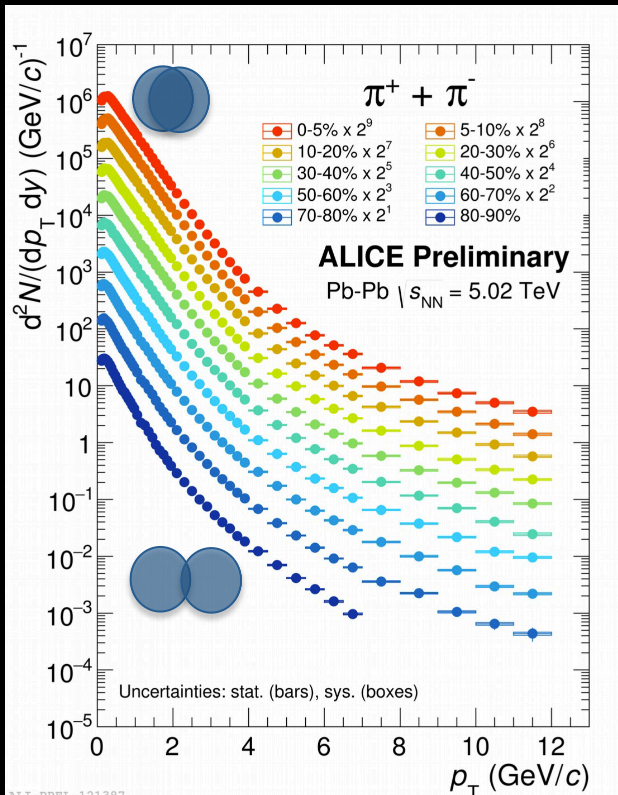
Recent results from ALICE

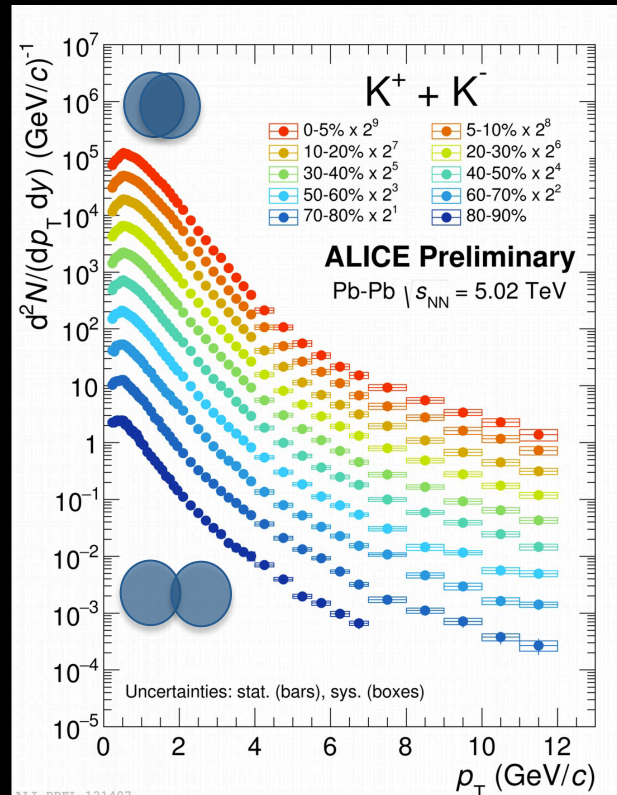
- Light-flavor hadrons production
  - Collective effects on p_T spectra
  - Thermal production
  - Strangeness and resonances

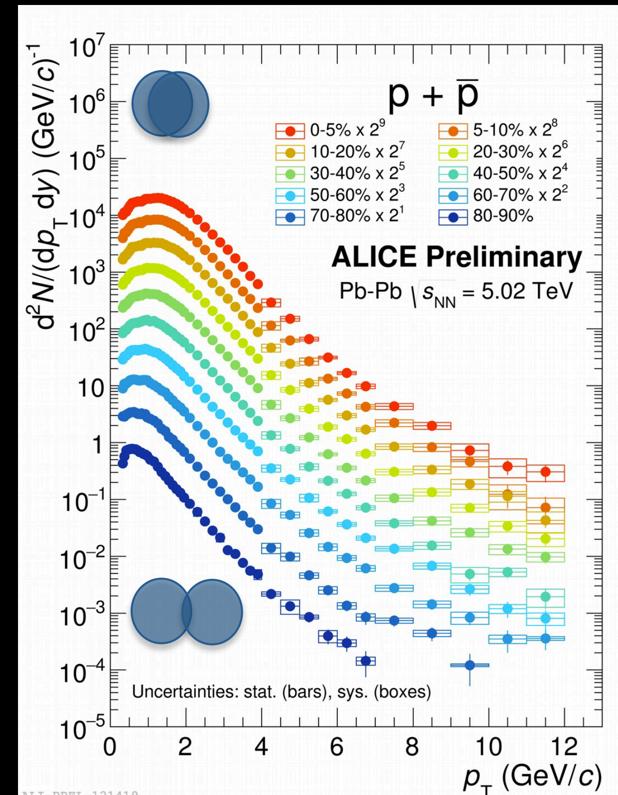
- Heavy-flavor hadron and quarkonia production
  - D meson and Λ_C baryon production
  - Quarkonia sequential suppression and regeneration
  - J/ψ photoproduction



Charged π, K and p spectra



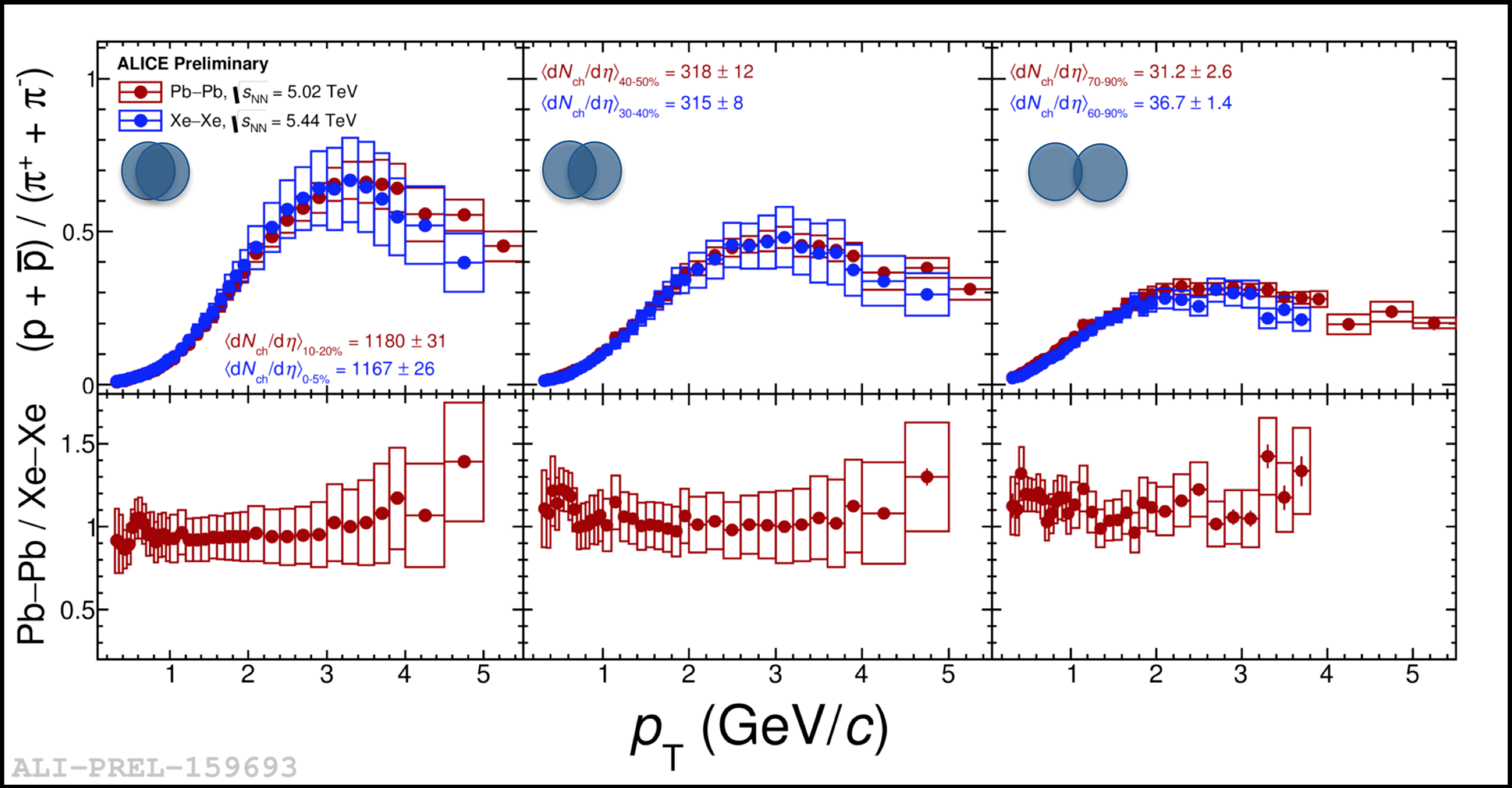




- Measured and identified with different analysis techniques: ITS, TPC, TOF, HMPID and topological identification of decaying charged kaons
- Mass dependent hardening of the spectra with increasing centrality

→ Suggests common radial expansion

p / π ratio in Pb-Pb and Xe-Xe



- Maximum in the p/π ratio due to radial flow
- Similar values for Pb-Pb and Xe-Xe at similar multiplicity

Blast-Wave model fit to hadron spectra

$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{Kin}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{Kin}}\right) r\,dr$$

$$m_T = \sqrt{m^2 + p_T^2} \qquad \rho = \tanh^{-1}(\beta_T) \qquad \beta_T = \beta_s \left(\frac{r}{R}\right)^n$$

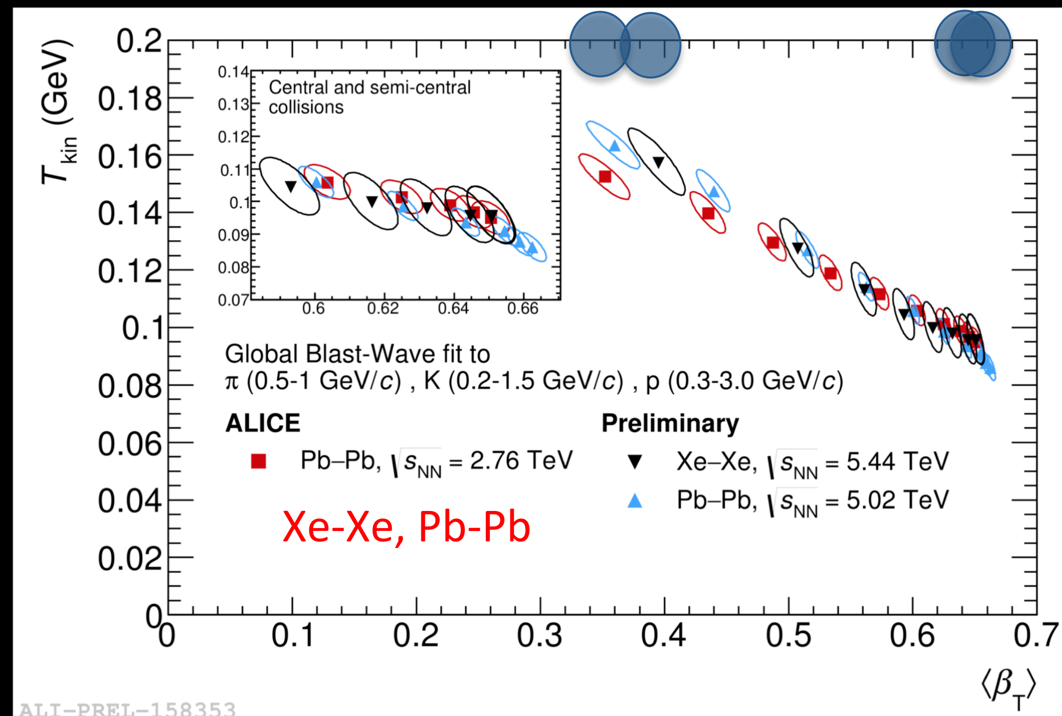
Schnedermann, Sollfrank and Heinz Phys. Rev. C 48, 2462

Simplified hydrodynamic model with 3 parameters:

- β_T - radial expansion velocity
- T_{kin} – kinetic freeze-out temperature
- n – velocity profile

→ Blast-Wave fit parameters are consistent for Pb-Pb and Xe-Xe at similar multiplicity

Simultaneous fit to the π, K, p spectra



p–Pb Phys. Lett. B 760 (2016) 720
Pb–Pb 2.76 TeV, Phys. Rev. C88 (2013) 044910

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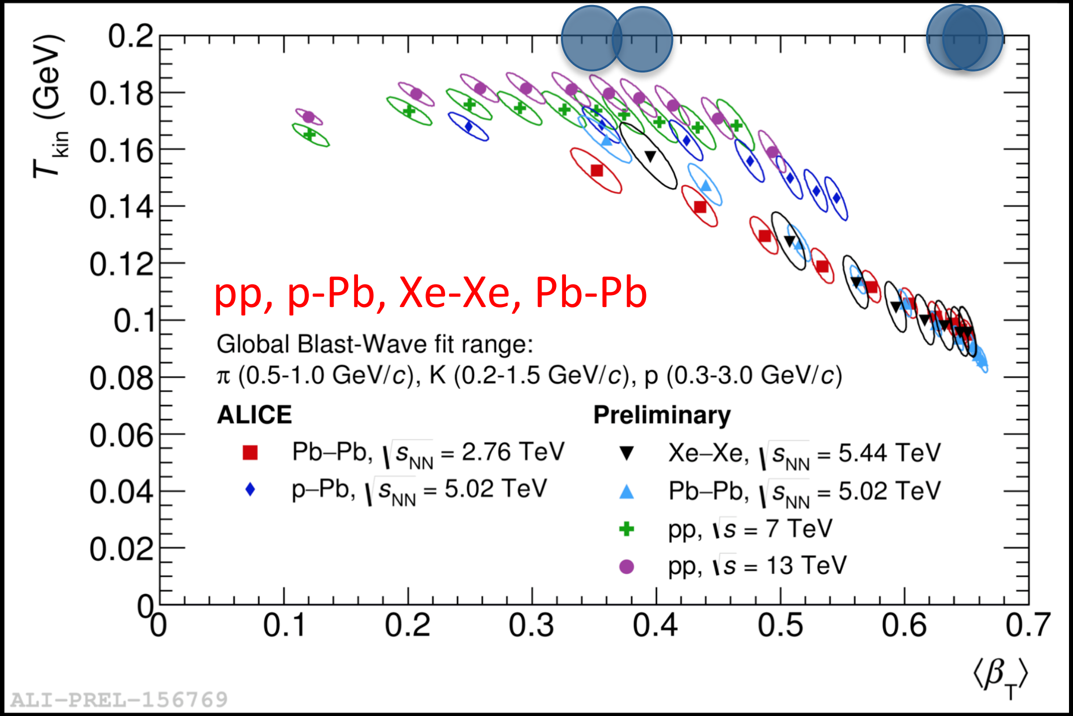


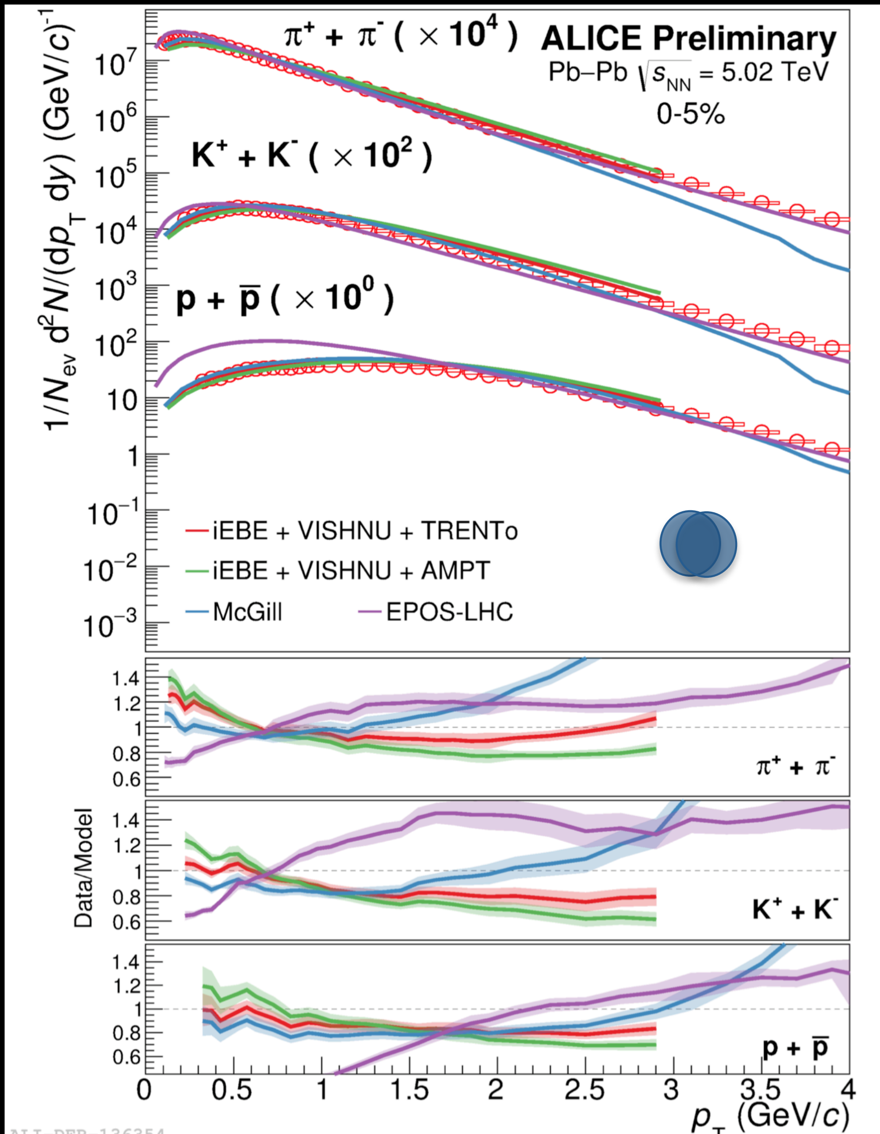
→ Blast-Wave fit parameters are consistent for Pb-Pb and Xe-Xe at similar multiplicity

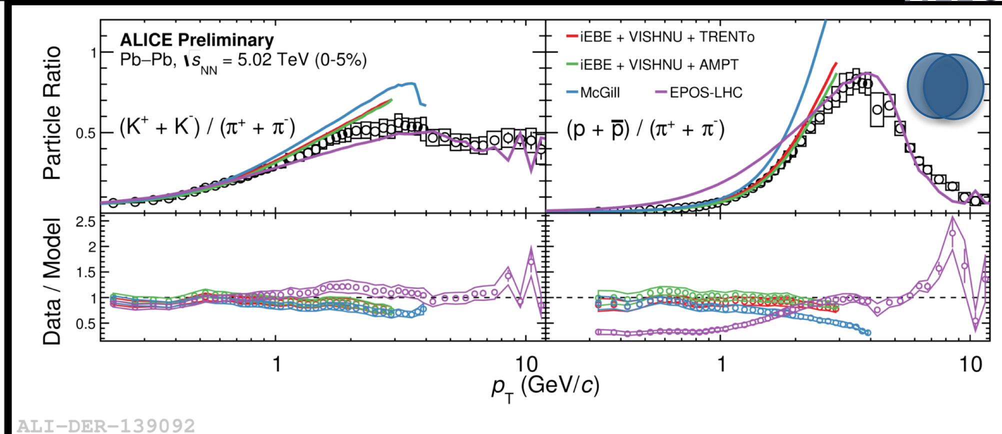
→ Similar trend observed in pp and p-Pb collisions

→ Larger β_T in small systems at similar multiplicity

p–Pb Phys. Lett. B 760 (2016) 720
Pb–Pb 2.76 TeV, Phys. Rev. C88 (2013) 044910

Comparison to hydro models – Pb-Pb (0-5%)





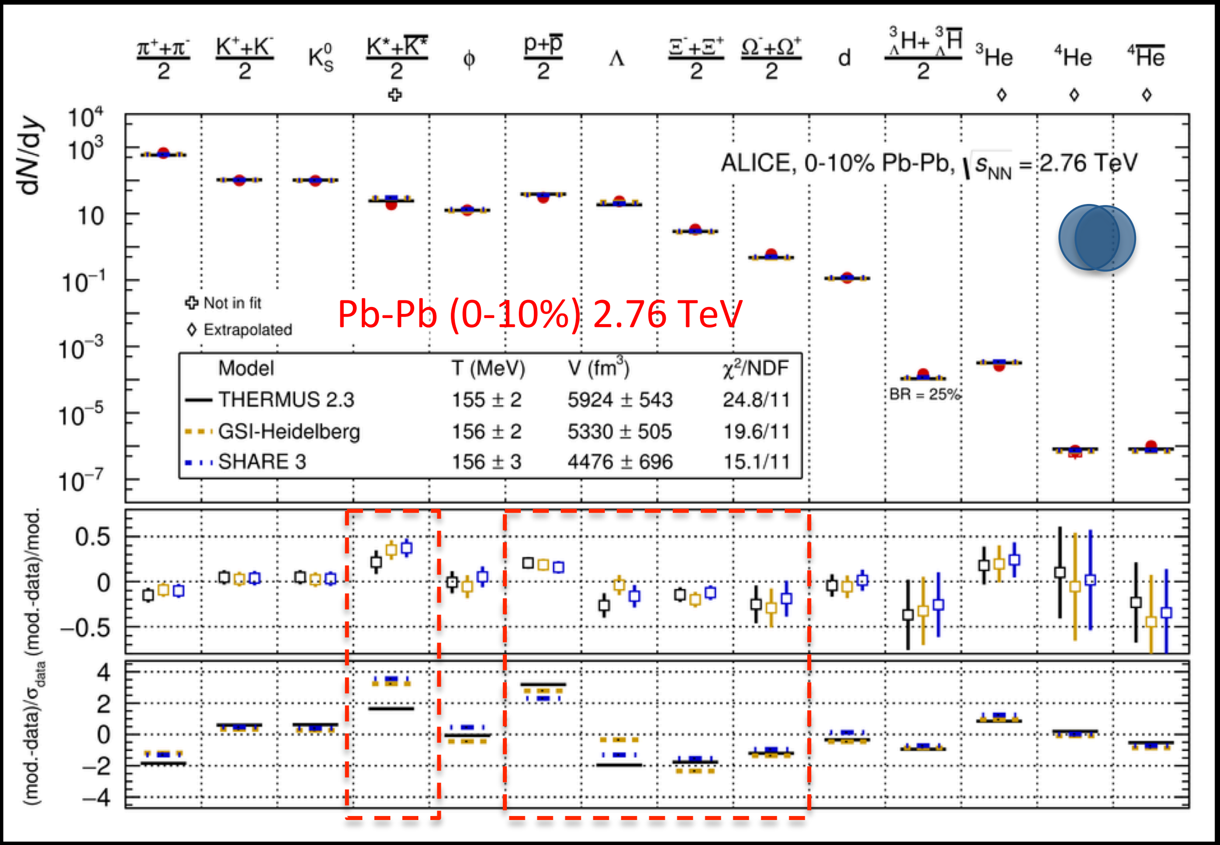
- iEBE-VISHNU (hydro+UrQMD) + TRENTo/AMPT initial conditions [1]
- McGill: MUSIC (hydro) + IP glasma initial conditions [2]
- EPOS LHC: hydro param. + hadronzation [3]
- Models description within 20-40% for Pb-Pb central collisions
- Presented models give much worse description in peripheral collisions

radial flow (hydro) - Navier-Stokes equations

[1] Eur. Phys. J C77 (2017) 645
[2] Phys. Rev. C95 (2017) 064913
[3] Phys. Rev. C92 (2015) 034906

Thermal models vs particle yields in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

Nucl. Phys. A 971 (2018) 1



THERMUS: Wheaton et al., Comput. Phys. Commun, 180 (2009) 84
GSI-Heidelberg: Andronic et al., Phys. Lett. B 673 142
SHARE: Petran et al., Comp. Phys. Commun. 195 (2014) 2056

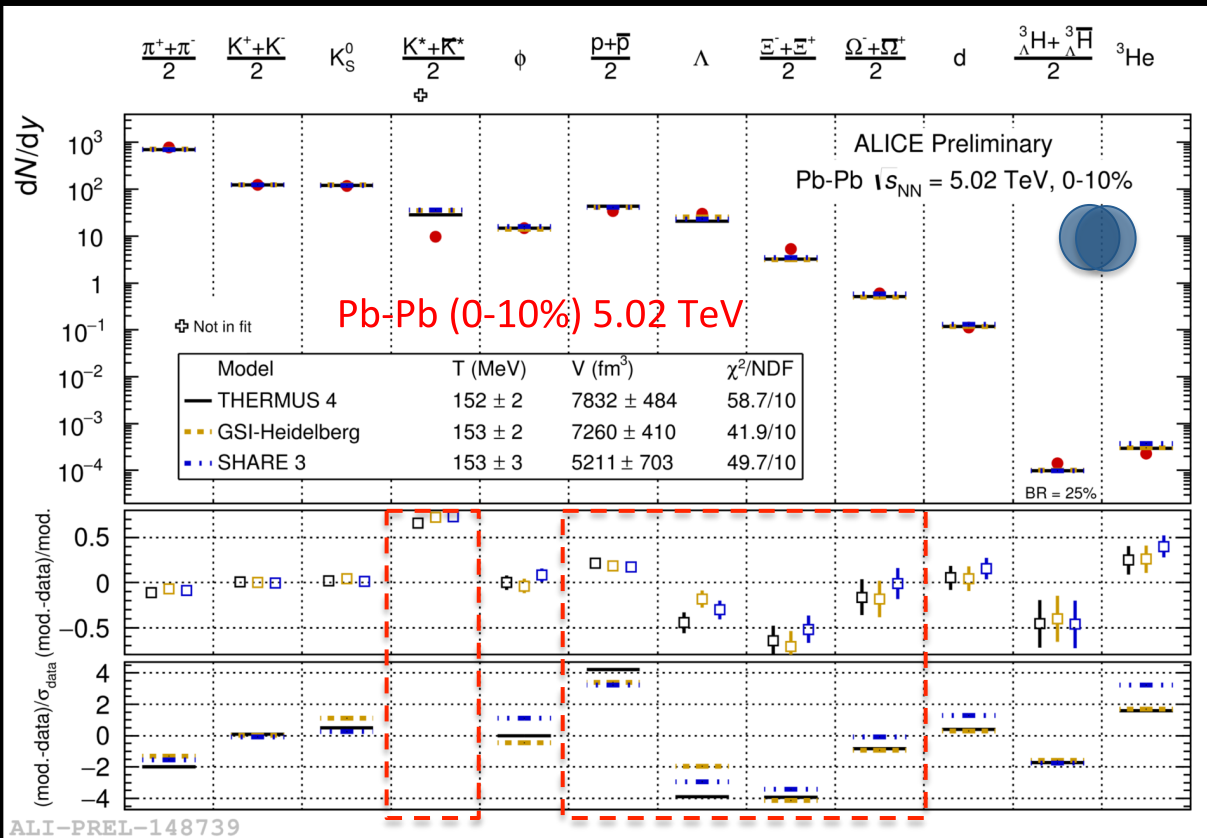
Hadron production in chemical equilibrium

Production of (most) hadrons well described at freeze-out temperature T_{ch}~ 155 MeV

Tension for protons and multi-strange baryons: incomplete hadron spectrum, baryon annihilation in hadronic phase, interacting hadron gas, ...?

K^{*0} resonance production overestimated by thermal models (rescattering in the hadronic phase?)

Thermal models vs particle yields in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



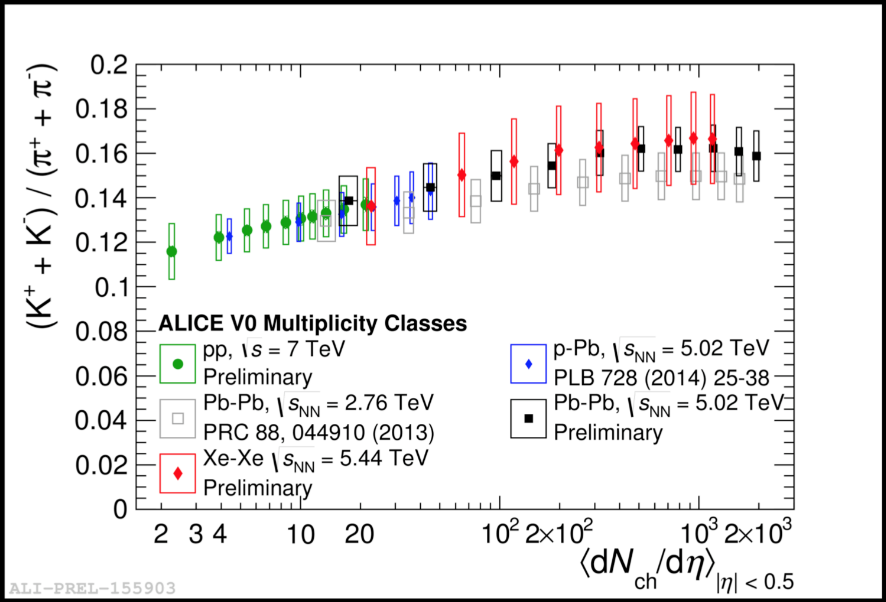
Production of (most) hadrons well described at freeze-out temperature T_{ch} ~ 152 MeV (lower than at $\sqrt{s_{NN}}$ = 2.76 TeV)

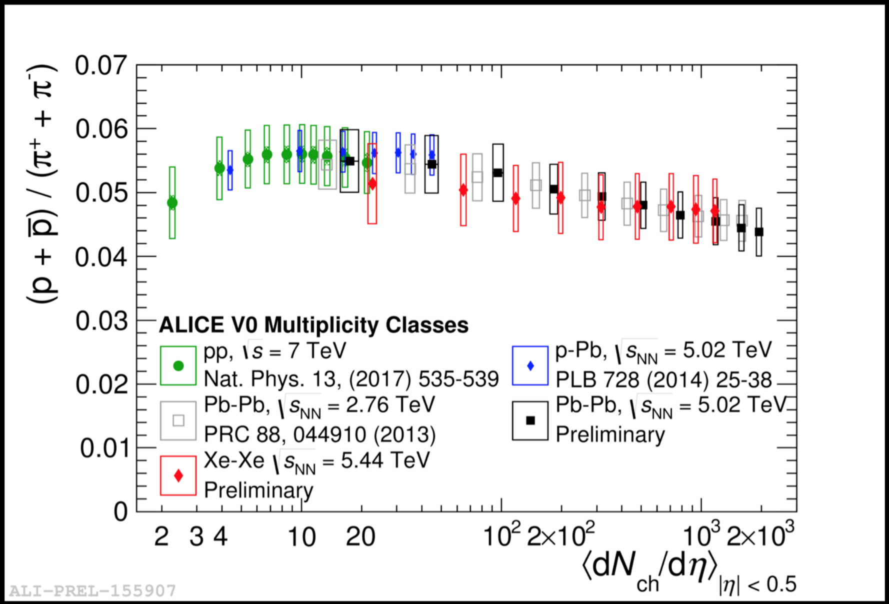
Tension for protons and multi-strange baryons confirmed at higher energy

K^{*0} resonance production overestimated by thermal models confirmed at higher energy

THERMUS: Wheaton et al., Comput. Phys. Commun, 180 (2009) 84
GSI-Heidelberg: Andronic et al., Phys. Lett. B 673 142
SHARE: Petran et al., Comp. Phys. Commun. 195 (2014) 2056

Ratios of p_T integrated yields in pp, p-Pb, Xe-Xe and Pb-Pb



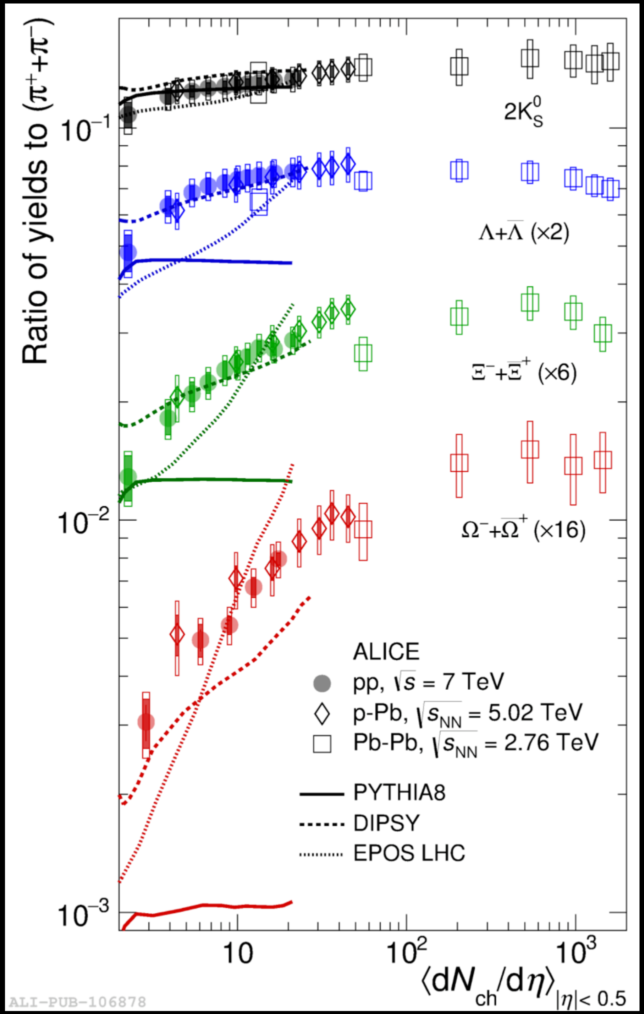


- No significant energy dependence is observed
- K/π and p/π are consistent for all collision systems at similar multiplicity

→ relative particle yields are driven by energy density?

Relative strangeness production in pp, p-Pb and Pb-Pb

Nature Physics 13 (2017) 535

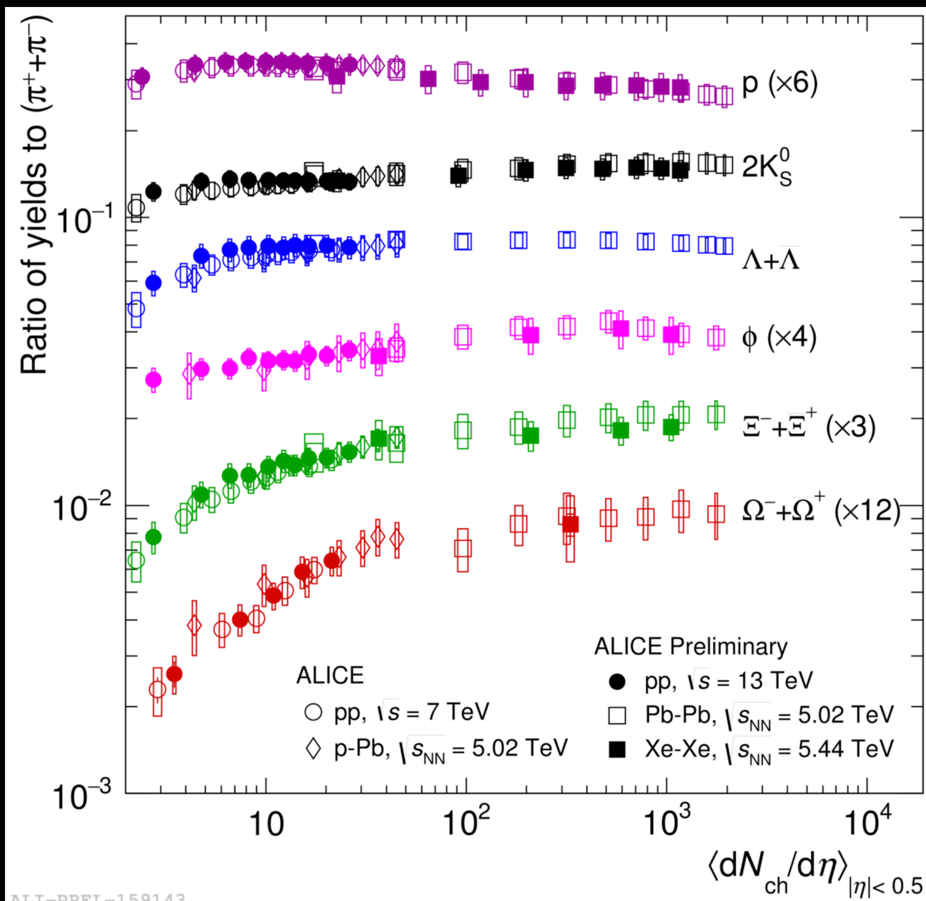


Historically a signature of the QGP
Rafelski & Mueller, PRL 48 (1982) 1066

- Smooth evolution from pp to Pb-Pb
- Enhancement observed in A-A which increases with strangeness content
- Enhancement also seen in the smaller systems pp and p-Pb
- No significant energy and system dependence is observed at similar multiplicity
- DIPSY model (rope hadronization) describes data best

PYTHIA 8: Comput. Phys. Commun. 178 (2008) 852867
EPOS LHC: PRC92 (2015) 034906
DIPSY: PRD92(2015) 094010

Relative strangeness production in pp, p-Pb, Xe-Xe and Pb-Pb



pp 7 TeV, p-Pb 5.02 TeV
ALICE, Nature Physics 13 (2017) 535

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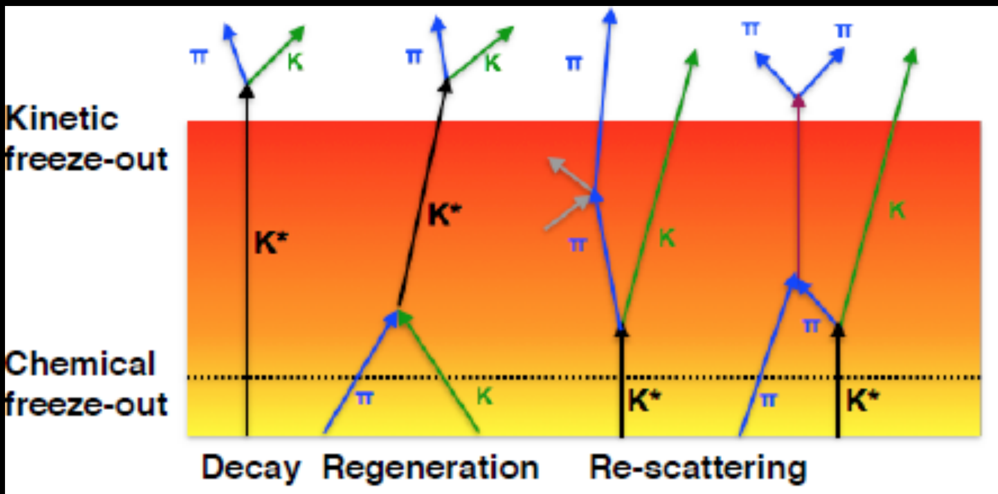
- Smooth evolution from pp to Pb-Pb
- Enhancement observed in A-A which increases with strangeness content
- Enhancement also seen in the smaller systems pp and p-Pb

- Xe-Xe results in agreement with previous measurements
- No significant energy and system dependence is observed at similar multiplicity

→ strangeness production is driven by the characteristic of final state

Resonance production



Rescattering and regeneration in the hadronic phase influence on the measured resonance yields

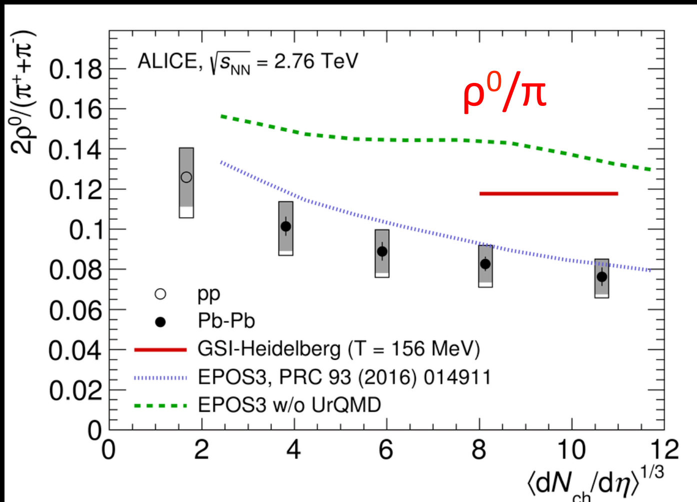
Final yields at kinetic freeze-out depend on:

- Initial yield after chemical freezeout
- Lifetime of hadronic phase
- Resonance lifetime
- Scattering cross-section of decay products

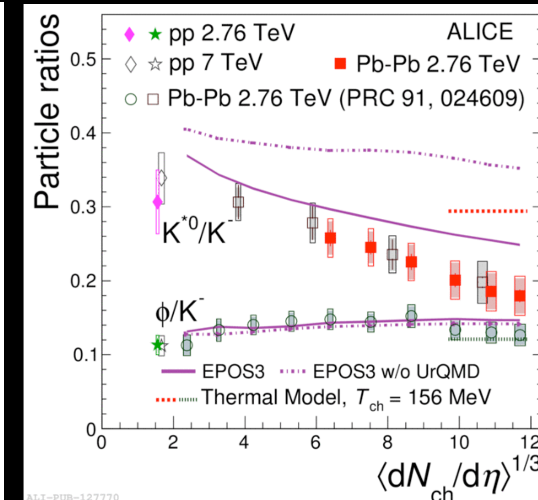
Resonance	ρ^0	K^{*0}	Λ(1520)	Φ
Lifetime (fm/c)	1.3	4.16	12.6	46.2

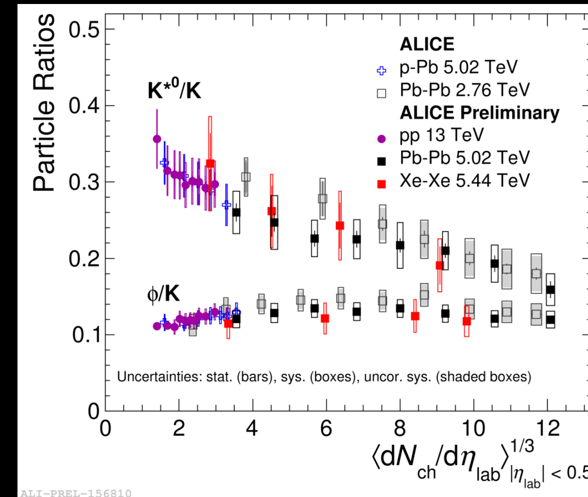
Relative resonance production in pp, p-Pb, Xe-Xe and Pb-Pb collisions

arXiv: 1805.04365

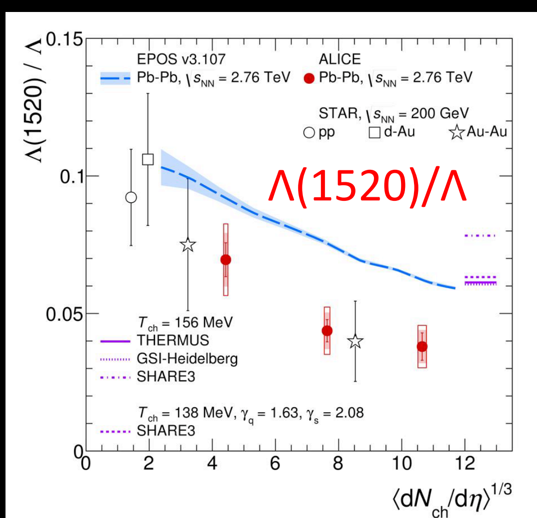


Phys. Rev. C 95, 064606 (2017)





arXiv: 1805.04361



- Suppression of short-lived resonances (ρ^0, K^{*0}, $\Lambda(1520)$) production with collision centrality is observed
- Φ/K is independent of collision centrality
- Similar trend seen in all collision systems
- Thermal models overestimate production in central collisions
- EPOS3 describes Φ/K^- and trend of K^{*0}/K^-, ρ^0/π (with UrQMD included)

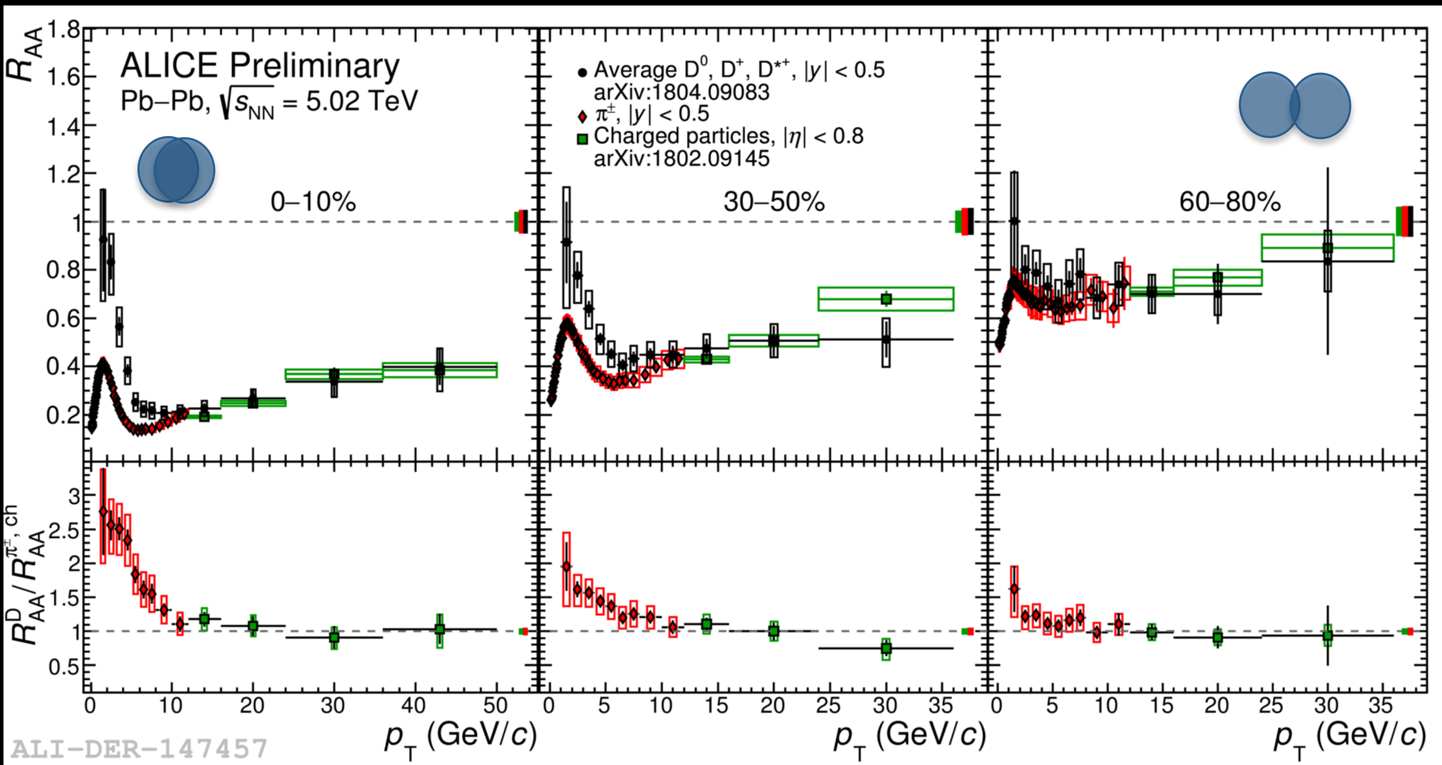
→ Dominance of rescattering over regeneration in hadronic phase

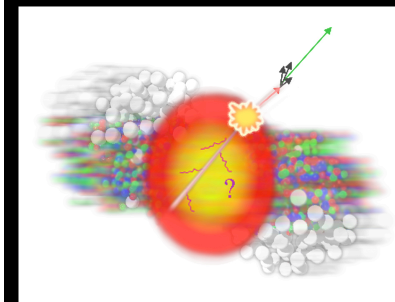
Heavy-flavor hadron and quarkonia production

R_{AA} of D mesons and light hadrons in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

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

arXiv:1804.09083

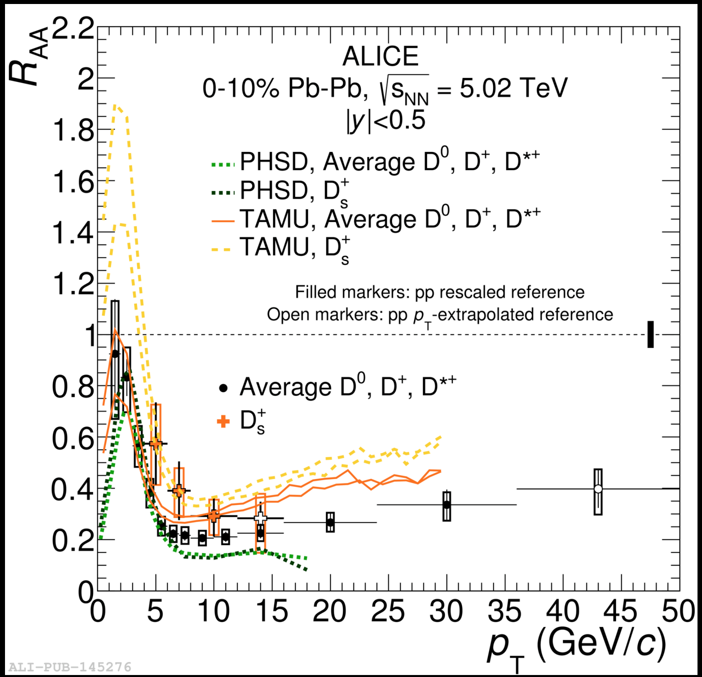


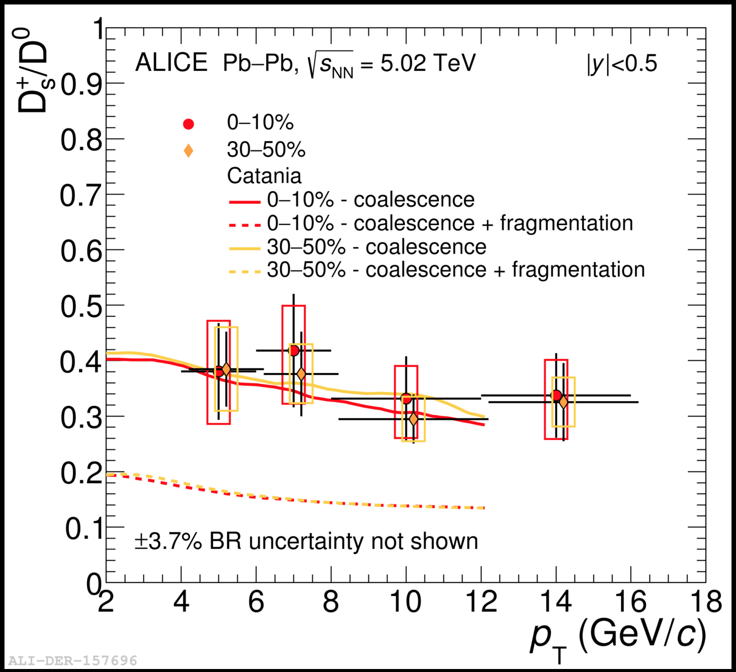


- For p_T > 10 GeV/c: the same suppression of light-flavor and D mesons in Pb-Pb collisions → similar energy loss of heavy and light partons in the QGP?
- For p_T < 10 GeV/c: smaller suppression of D mesons than light-flavor hadrons (difficult to interpret due to other effects e.g. radial flow, recombination,…)

Strange and non-strange D meson production in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

arXiv:1804.09083

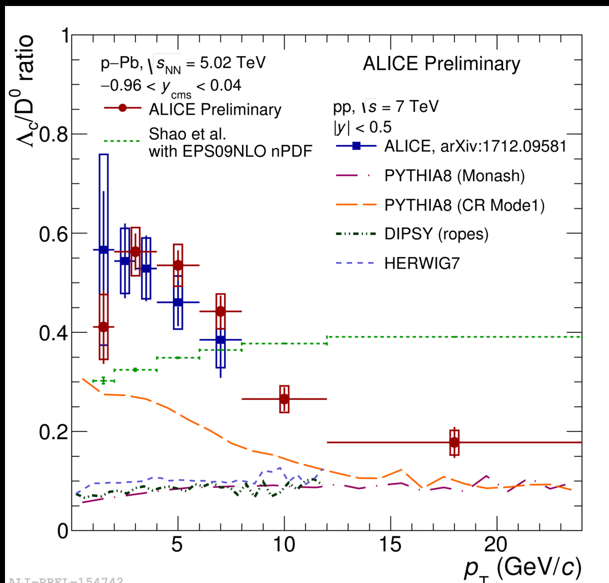


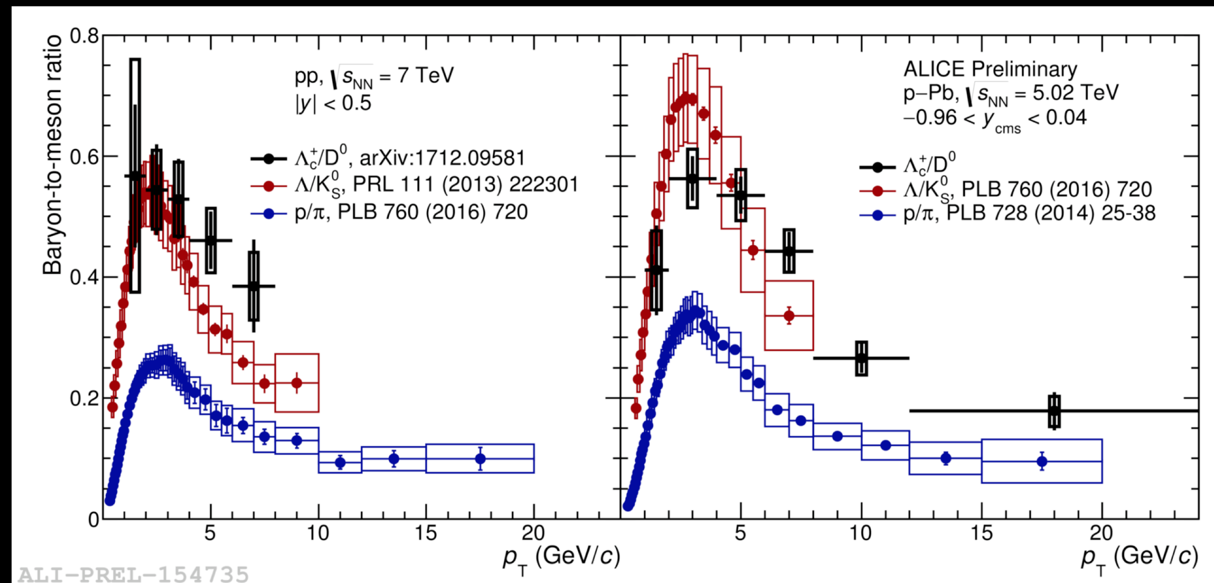


- R_{AA}: hint of enhanced D_s meson production compared to non-strange mesons
- Transport models (TAMU PRC93 (2016) 034906, PHSD PLB735 (2014)445) predict enhancement but fail to describe data at high p_T (TAMU contains only elastic parton energy loss)

- D^+_s/D^0 shows no dependence on centrality
- Well described by model (Catania EPJC78 (2018) 348) with only coalescence included

Λ^+_c production in pp and p-Pb

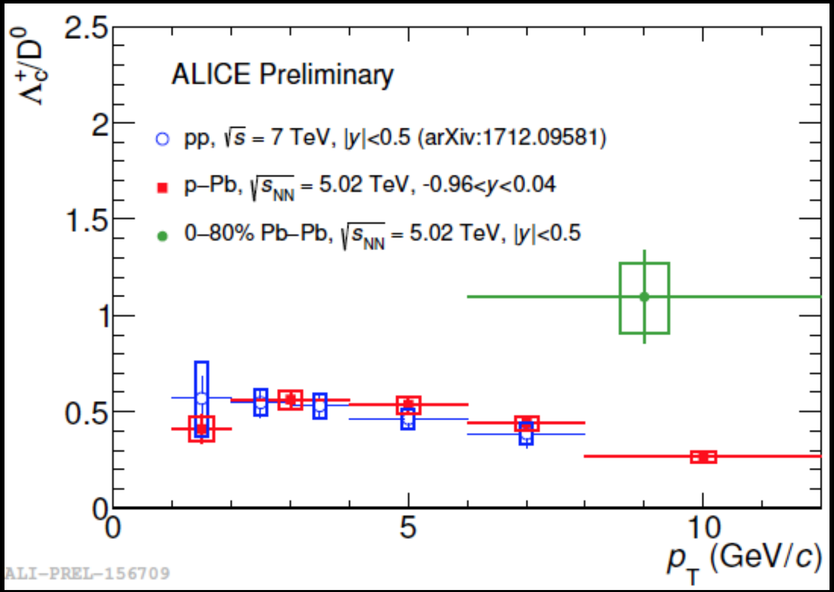


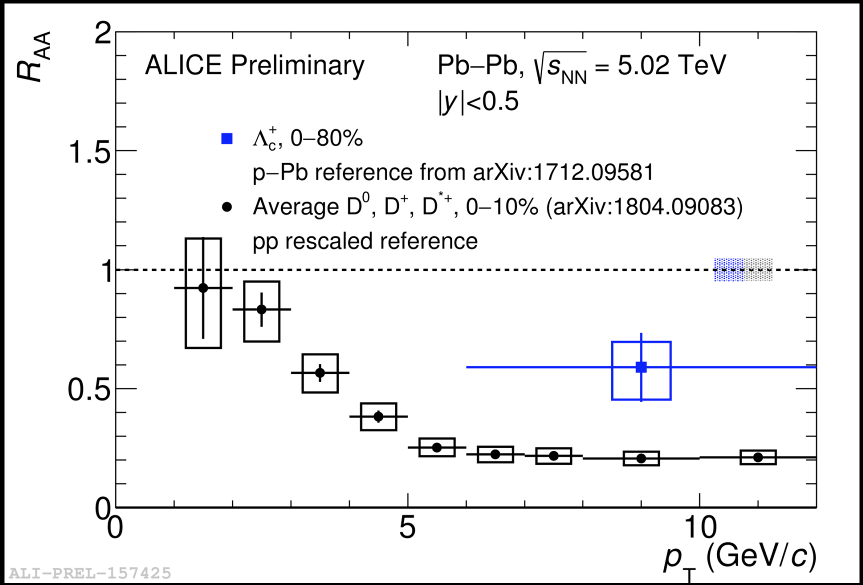


- Λ^+_c/D^0 ratio larger than expected from measurements at e^+e^- and ep colliders
- Λ^+_c/D^0 show similar values in pp and p-Pb and is similar to Λ/K^0_s
- Λ^+_c/D^0 ratio in pp and p-Pb are not described by models

PYTHIA8: JHEP 08 (2015) 003
DIPSY: Phys. Rev. D92 (2015) 094010
HERWIG: Eur. Phys. J. C58 (2008) 639
Shao et al. Eur. Phys. J. C77 (2017) 1

Λ^+_c production in pp, p-Pb and Pb-Pb

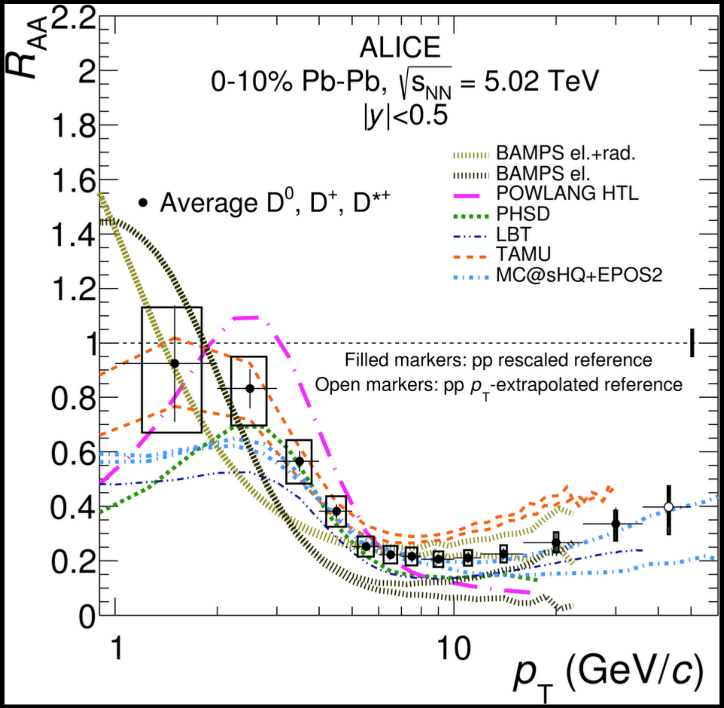




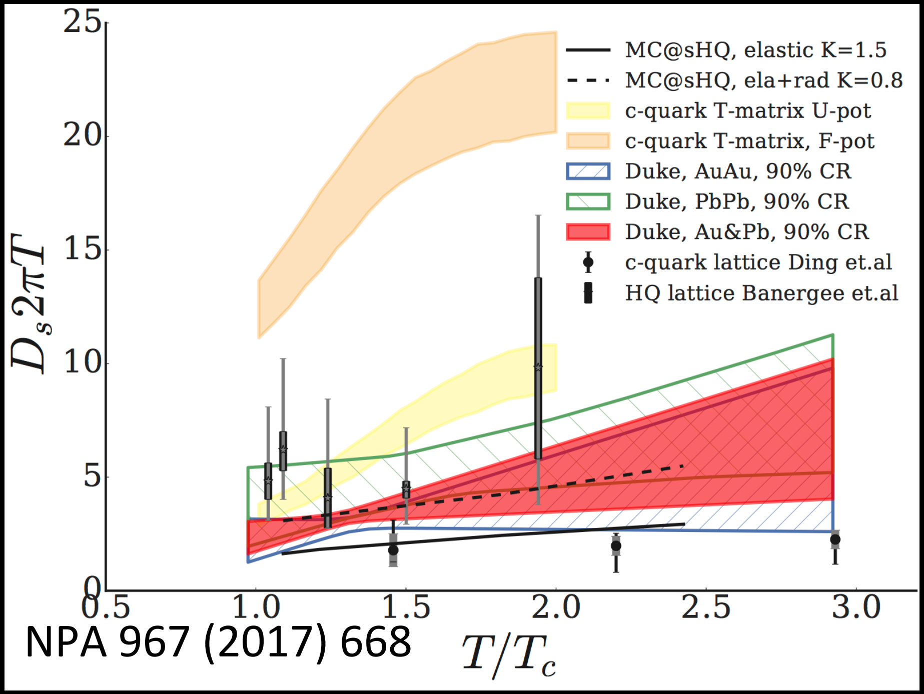
- Λ^+_c/D^0 in Pb-Pb is ~1 at high p_T and is higher than in pp and p-Pb
- R_{AA}: Enhanced Λ^+_c production compared to D mesons

Charm: constraining the QGP transport properties

arXiv:1804.09083



Diffusion coefficient vs T (Run-1 ALICE data)

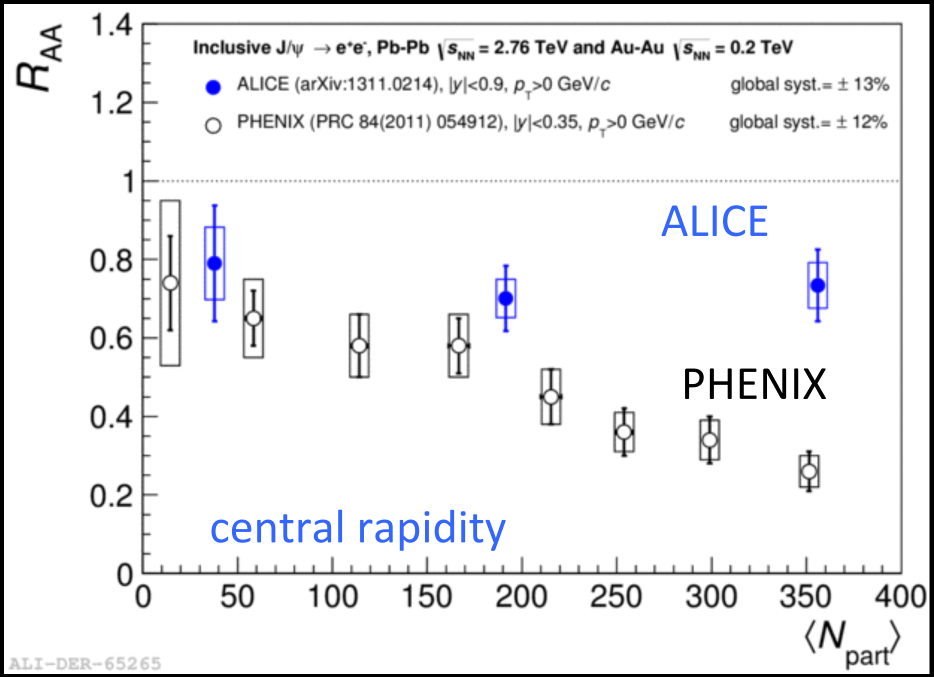


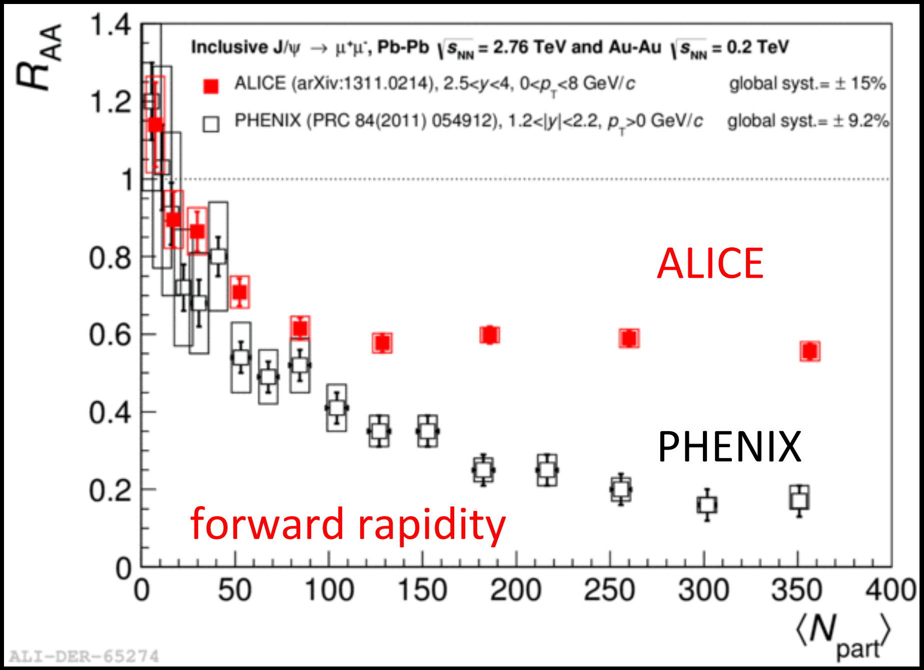
- Further constraints on the QGP transport properties from charm flow measurements
- Same approach for high-p_T light-flavor hadrons [Phys. Rev. C90(2014) 014909]

R_{AA} of J/Ψ at LHC vs RHIC

Sequential suppression vs regeneration

PLB 743 (2014) 314





- Different suppression vs centrality compared to RHIC at central and forward rapidity

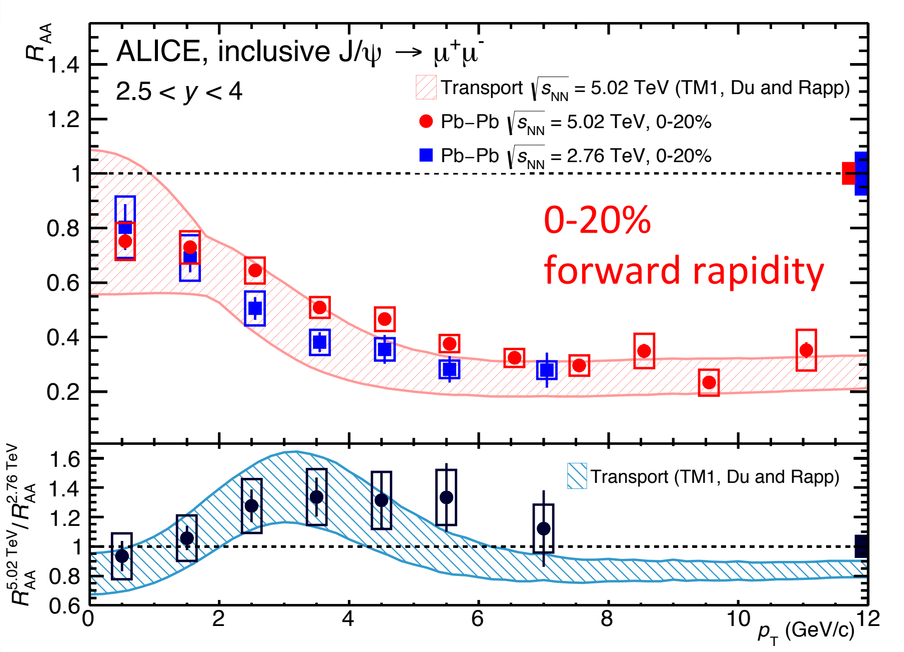
→ Different source of J/ψ in central collisions at the LHC

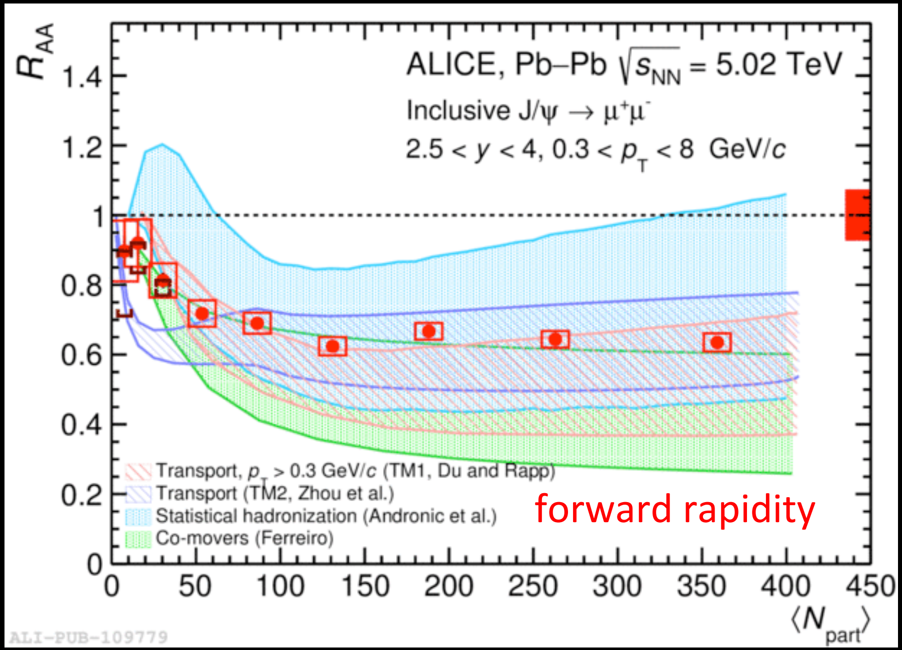
→ Indication of regeneration in central collisions

PHENIX, PRC 84 (2011) 054912

R_{AA} of J/Ψ in Pb-Pb vs models

Phys. Lett. B 766 (2017) 212



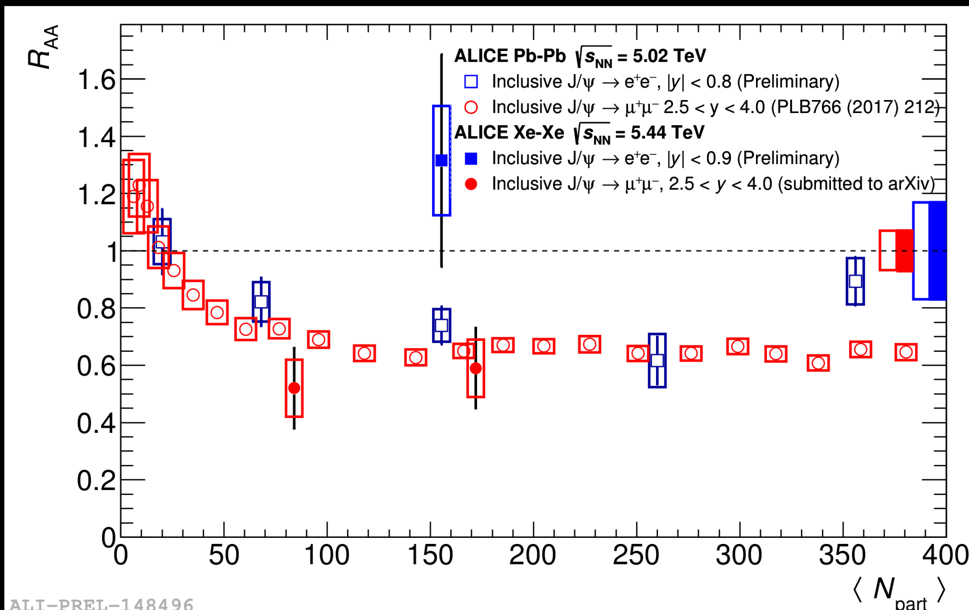


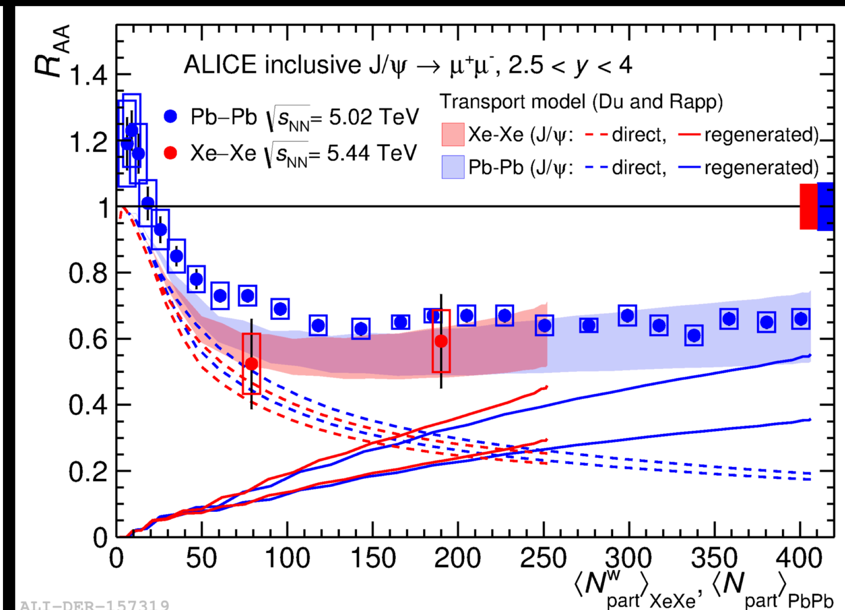
- Transport models (TM1, TM2): continuous interplay between dissociation and (re)generation
- Statistical harmonization model: all J/ψ are dissociated in the plasma (re)generation occurs at the phase boundary
- Comover model: J/ψ are suppressed via interaction with a parton co-moving medium; (Re)generation added as a gain term.

→ Measurement is precise enough to constrain the models

R_{AA} of J/Ψ in Xe-Xe and Pb-Pb

Xe-Xe, arXiv:1805.04383

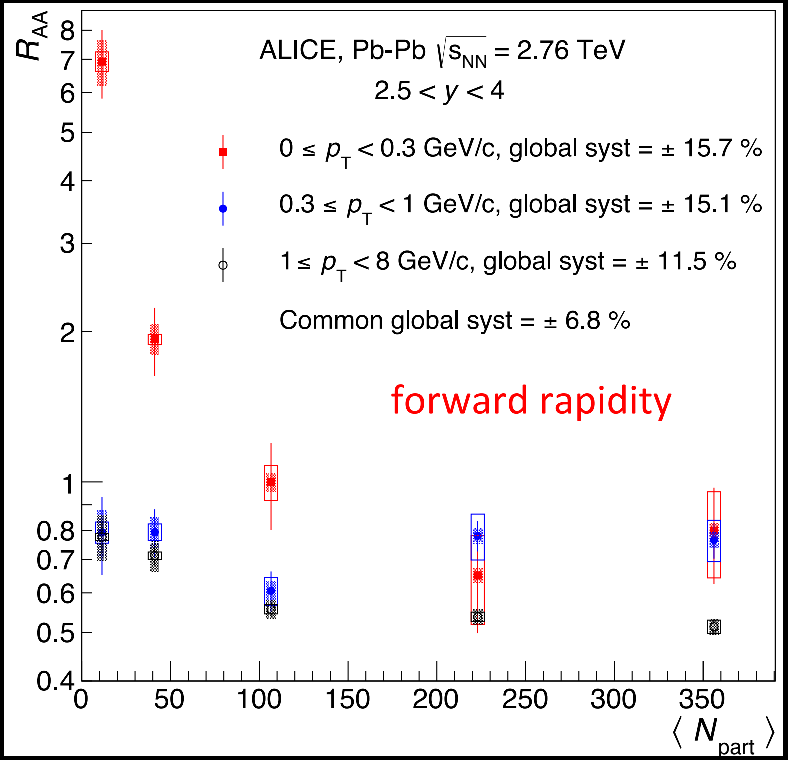




- R_{AA} in Xe-Xe confirms strong (re)generation at the LHC
- Transport model (TM1) predicts smaller R_{AA} in Xe-Xe compared to Pb-Pb

Excess in J/ψ R_{AA} at low p_T

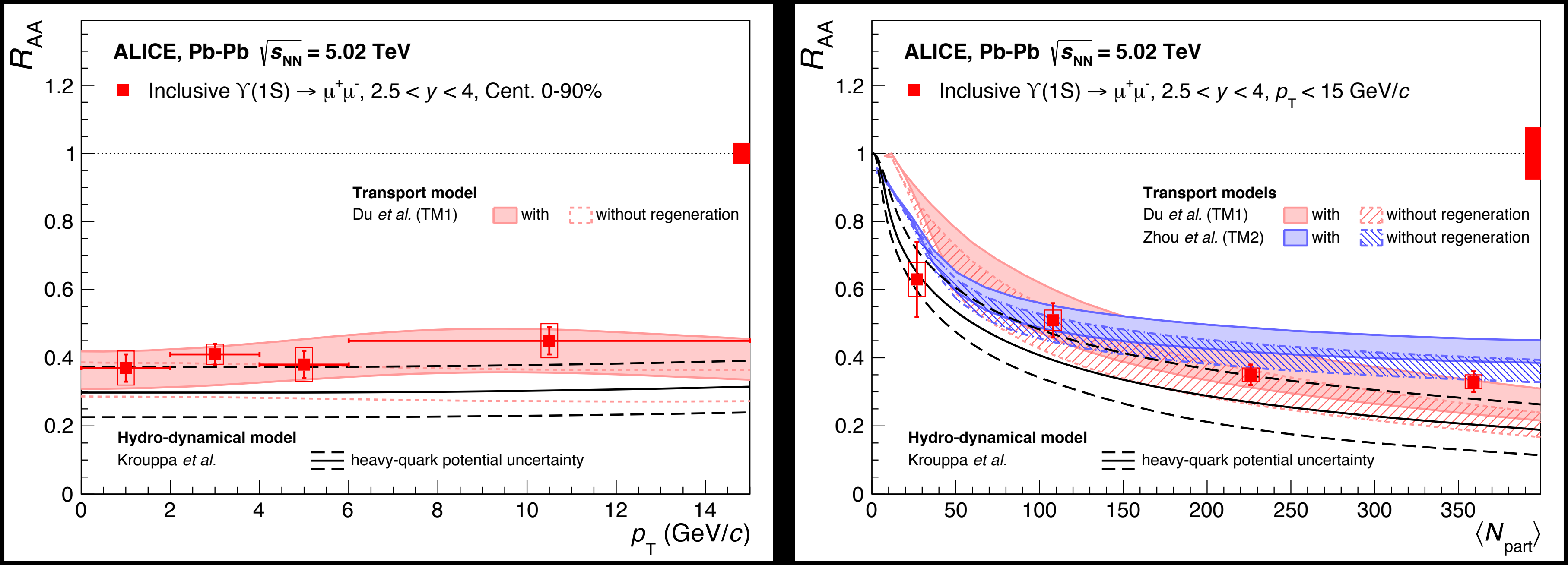
PRL 116 (2016) 222301



R_{AA} ~ 7 at low p_T in peripheral collisions → related to J/ψ photoproduction?

R_{AA} of Υ(1s) in Pb-Pb

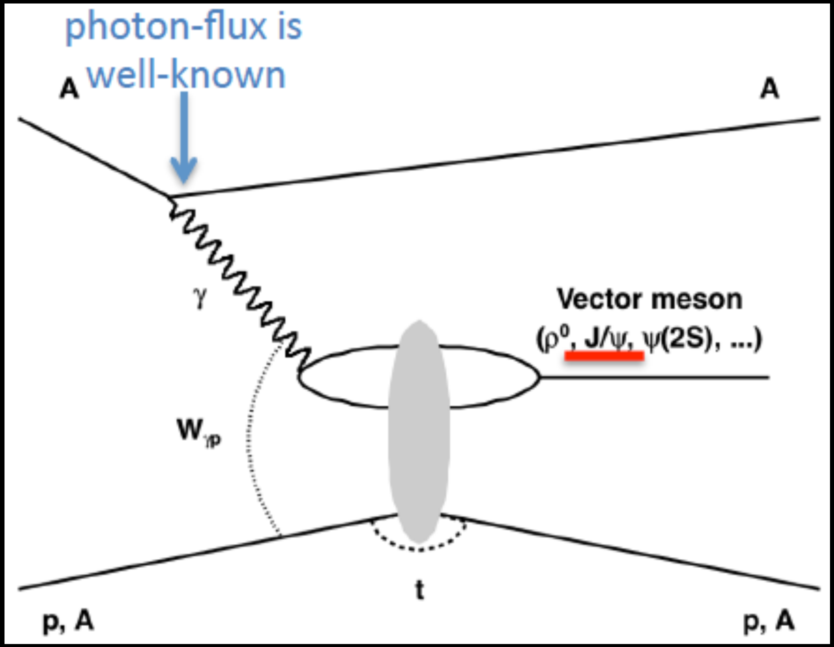
arXiv:1805.04387



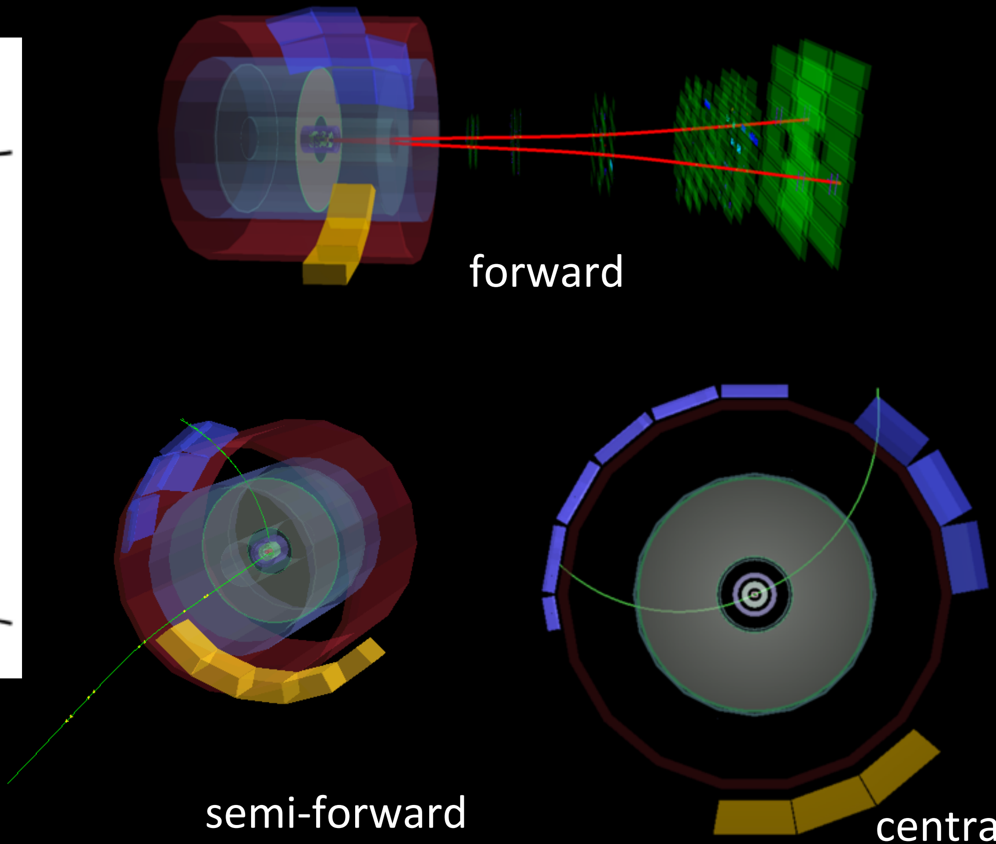
- Strong suppression of Υ(1s) in Pb-Pb at forward rapidity
- Transport model (TM1) with regeneration describe Υ(1s) production
- For integrated yields $R_{AA}^{Υ(2s)}$ / $R_{AA}^{Υ(1s)}$ ~ 0.28 → indication of sequential suppression

Exclusive J/ψ photoproduction in ALICE

Ultra-peripheral collisions (UPC):
impact parameter $b > R_1 + R_2$

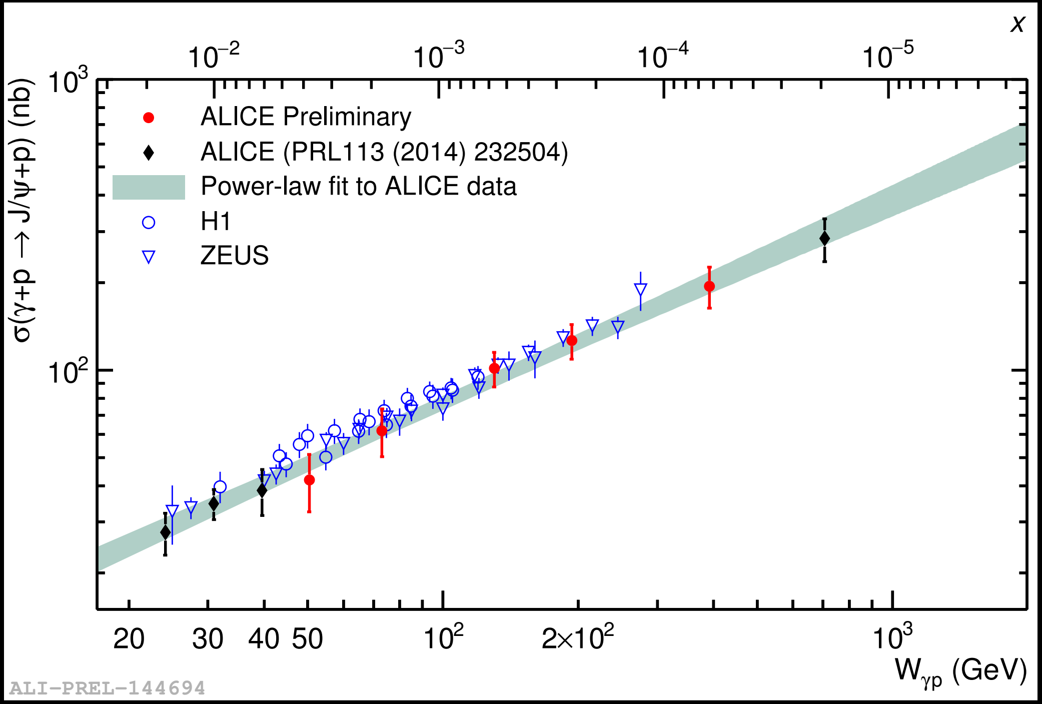


$J/\psi \rightarrow e^+e^-$ or $\mu^+\mu^-$
(measurement in different rapidity intervals)



Exclusive J/ψ photoproduction in p-Pb and Pb-p

$\sigma(W_{\gamma p})$ ~ square of the gluon PDF in the proton



- ALICE forward (published)
- ALICE semi-forward and central (preliminary)
- Power low fit: exponent = 0.70 ± 0.05
- Good agreement with HERA data (H1 and ZEUS)

- Large energy reach ~700 GeV
- Bjorken-x ~2×10^{-5}

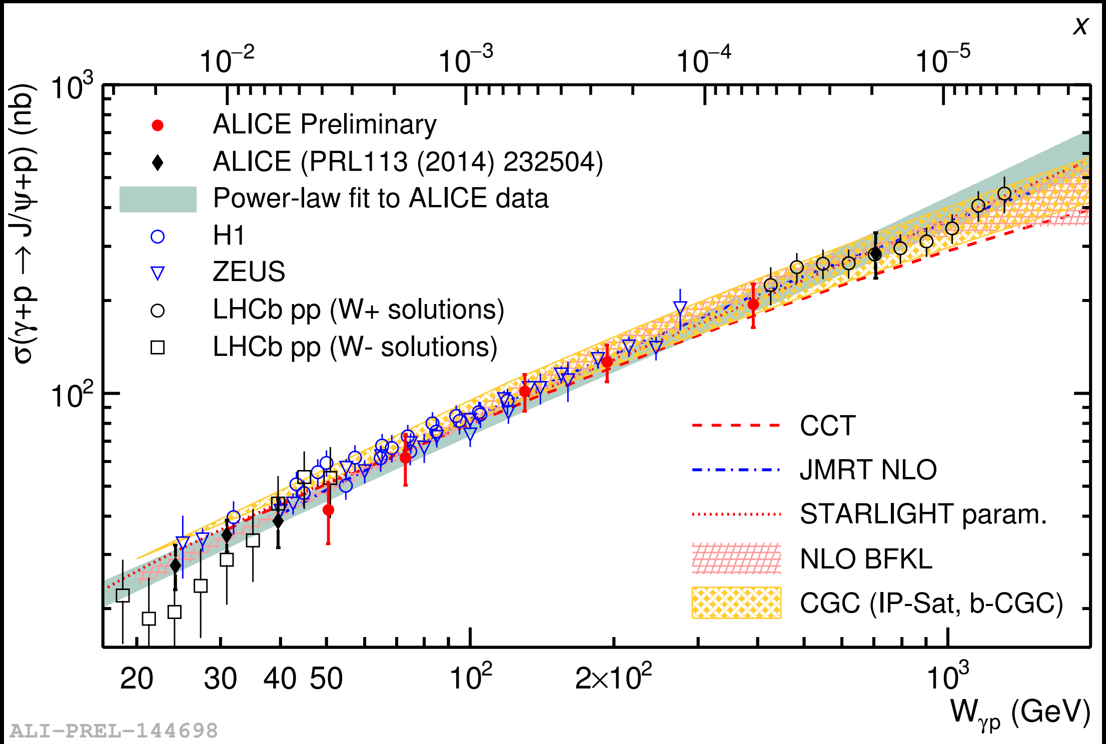
→ New constraints on the gluon PDF in the proton

→ No sign of gluon saturation at this energy range

ZEUS: Eur. Phys. J. C 24, 345 (2002)
H1: Eur. Phys. J. C 46, 585 (2006),
Eur. Phys. J. C 73, 2466 (2013)

Exclusive J/ψ photoproduction vs models

H1, ZEUS, ALICE and LHCb data vs models



→ All models are consistent with data

LHCb data pp at $\sqrt{s_{NN}}$ = 13 TeV
LHCb-CONF-2016-007

Models:

CCT - energy dependent hot spot model [PLB766 (2017) 186]

JMTR NLO - DGLAP formalism at NLO [EPJC76 (2016) 633]

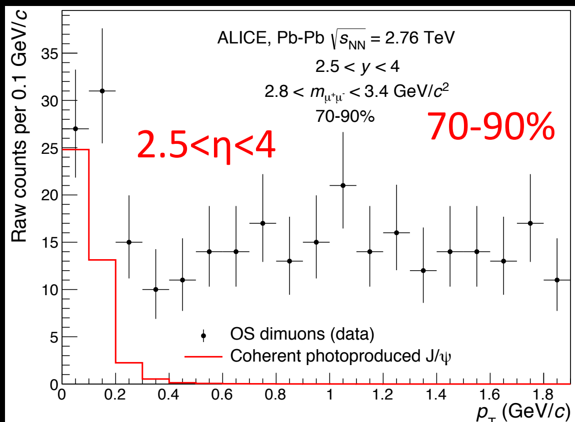
STARLIGHT parametrization of HERA data [CPhC 2012 (2017) 258]

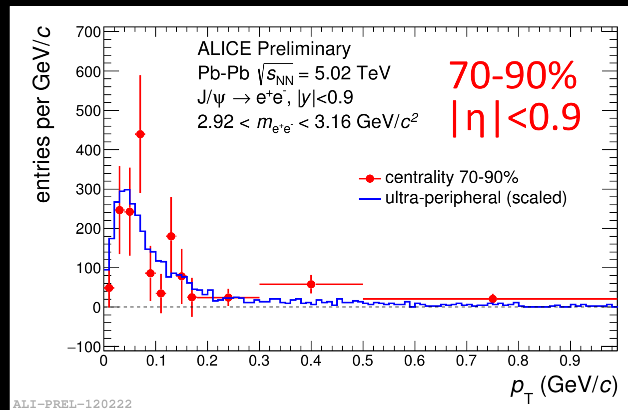
NLO BFKL - proton impact factor from F2 HERA data [PRD94 (2016) 054002]

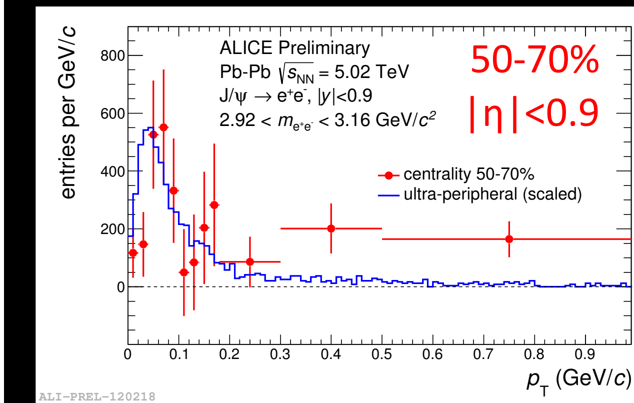
CGC – color glass condensate with gluon saturation [PRD90 (2014) 054003]

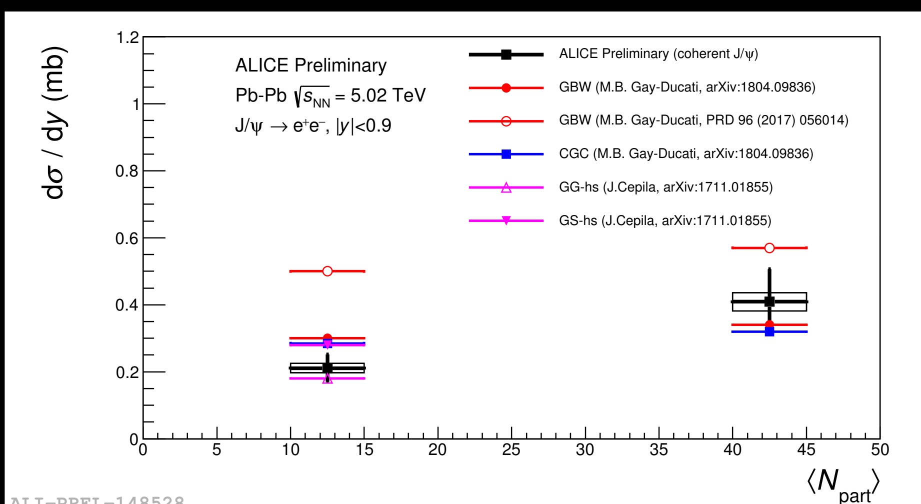
Low-p_T excess in the J/ψ yield in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

PRL 116 (2016) 222301









- GBW 2017: γ flux with nuclear overlap
- GBW 2018: γ flux corrected
- CGC: color glass condensate
- GC-hs, GS-hs: energy-dependent hot spot models

→ Excess should be taken into account for J/ψ R_{AA} at low p_T

Summary and Outlook

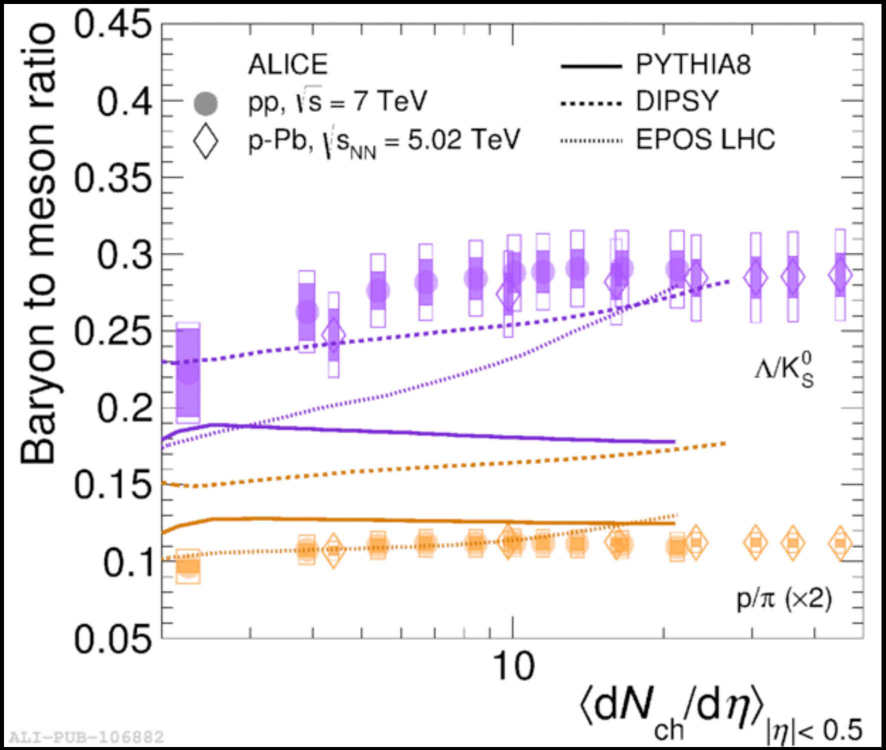
- Strong collectivity in Pb-Pb as well as in pp and p-Pb collisions
- Relative hadron production independent of collision energy and system for the same multiplicity events
- Strangeness enhancement increasing with multiplicity and strangeness content
- Rescattering of short-lived resonances in the hadronic phase

- Hint of enhanced D_s/D in Pb-Pb (no centrality dependence)
- Enhanced Λ^+_c/D^0 in Pb-Pb
- Similar suppression of D mesons and light-flavor hadrons a high p_T
- J/ψ and Υ sequential suppression and regeneration observed
- J/ψ photoproduction puts new constraints on the gluon PDF in proton
- Low-p_T J/ψ enhancement (R_{AA}) due to J/ψ photoproduction

Backup

Baryon to meson ratios in pp and p-Pb

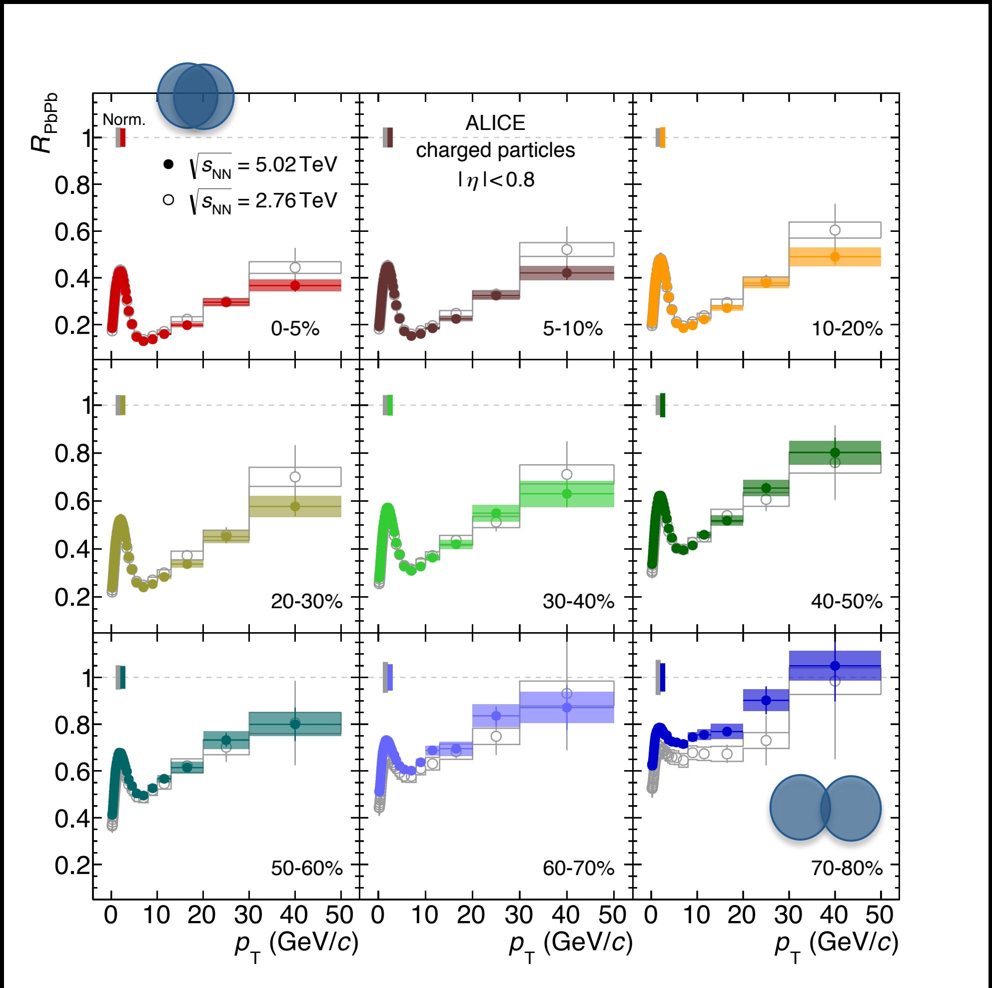
Nature Physics: 10.1038/nphys4111



- Baryon to meson ratios do not change significantly with multiplicity
- DIPSY model describes data best

Charged-particle R_{AA} at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

arXiv: 1802.09145



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

N_{coll} from Glauber MC

- Different suppression pattern depending on Pb-Pb collision centrality
- Maximum suppression by a factor ~7 ($6 < p_T < 7$ GeV/c) in 0-5% collisions
- No significant evolution with collision energy is seen

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

Confirmed by jet measurements:
ATLAS, PRL 114 (2015) 072302

R_{pPb} and R_{PbPb} at the LHC

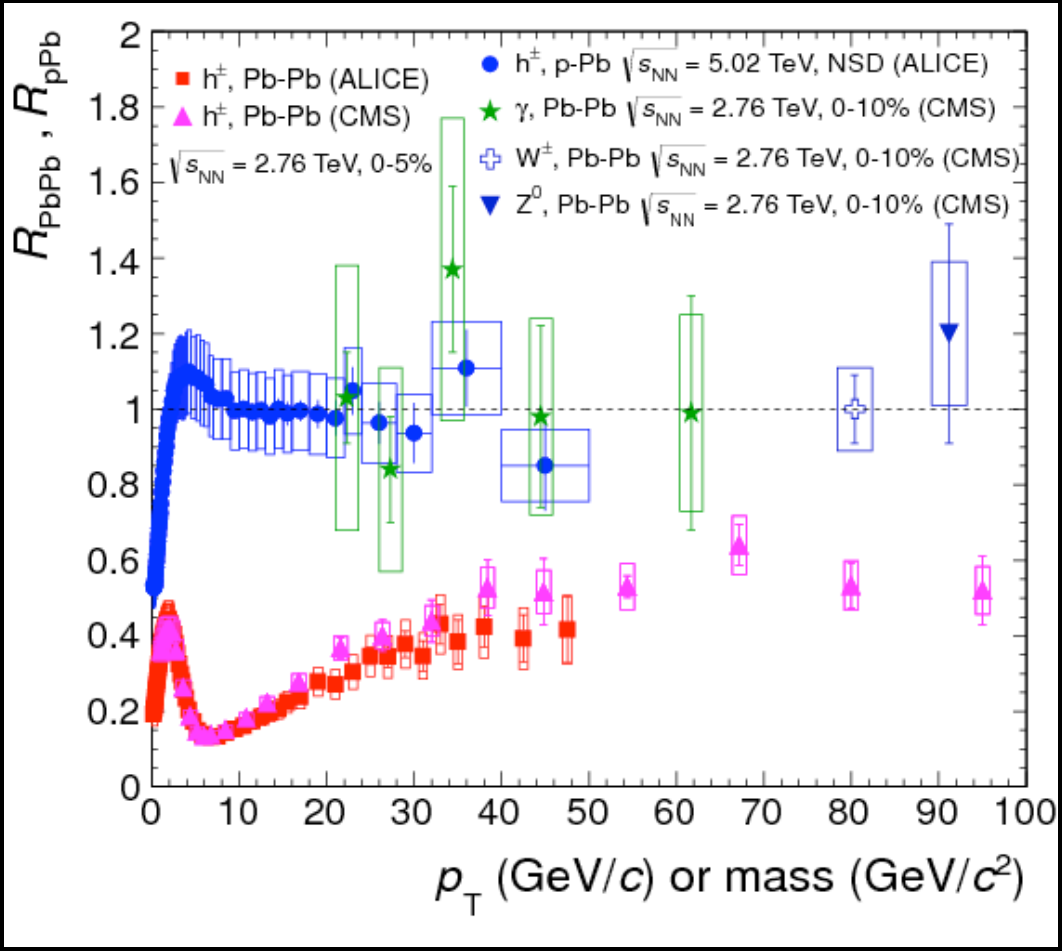
ALICE, Eur.Phys. .J. C74 (2014) 9

For p_T > 8 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!

Confirmed by jet measurements: Phys. Lett. B749 (2015) 68



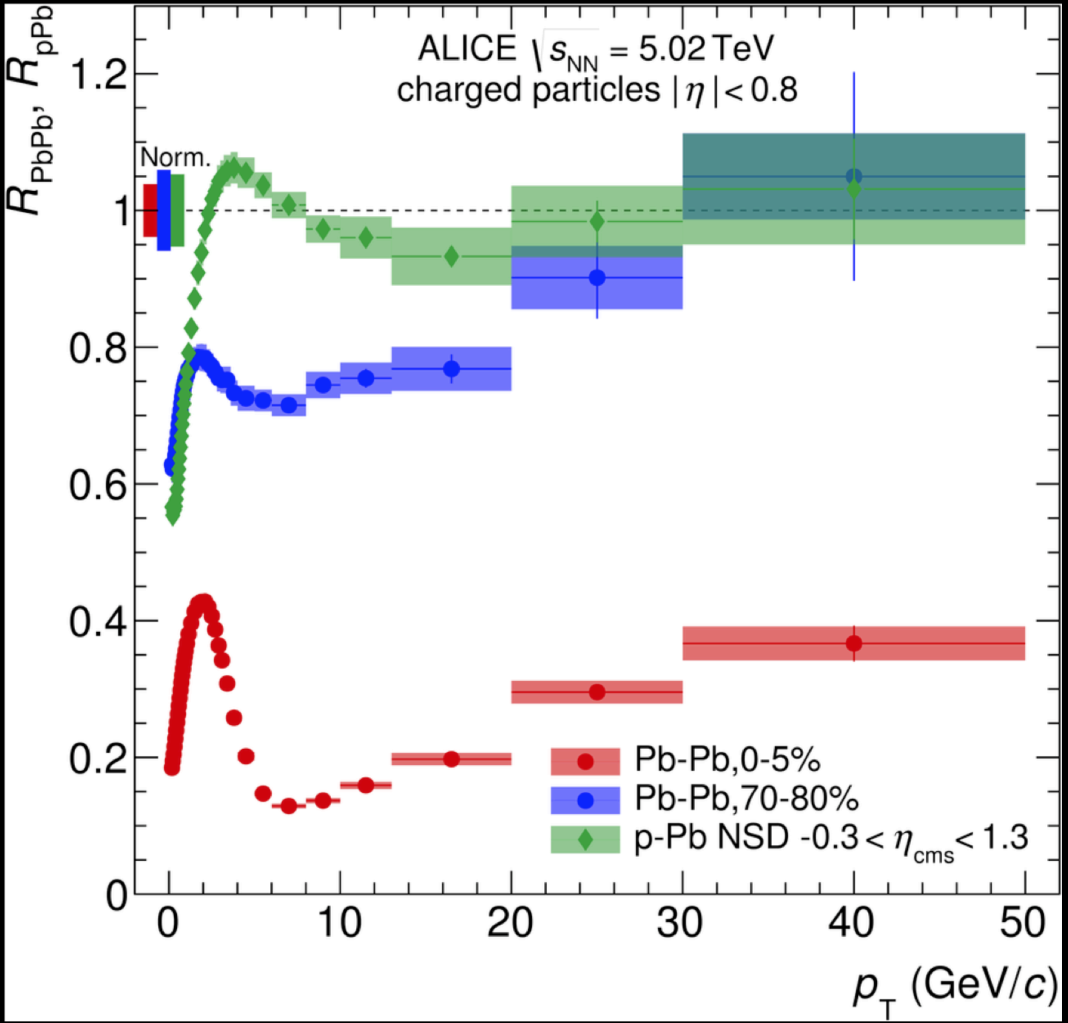
Charged-particle R_{pPb} and R_{PbPb} at the LHC

arXiv: 1802.09145

For $p_T > 8$ GeV/c
- Strong suppression in central Pb-Pb collisions
- Small suppression in peripheral Pb-Pb collisions (possible due to biased centrality selection)
- No modification in p-Pb collisions (no centrality selection)

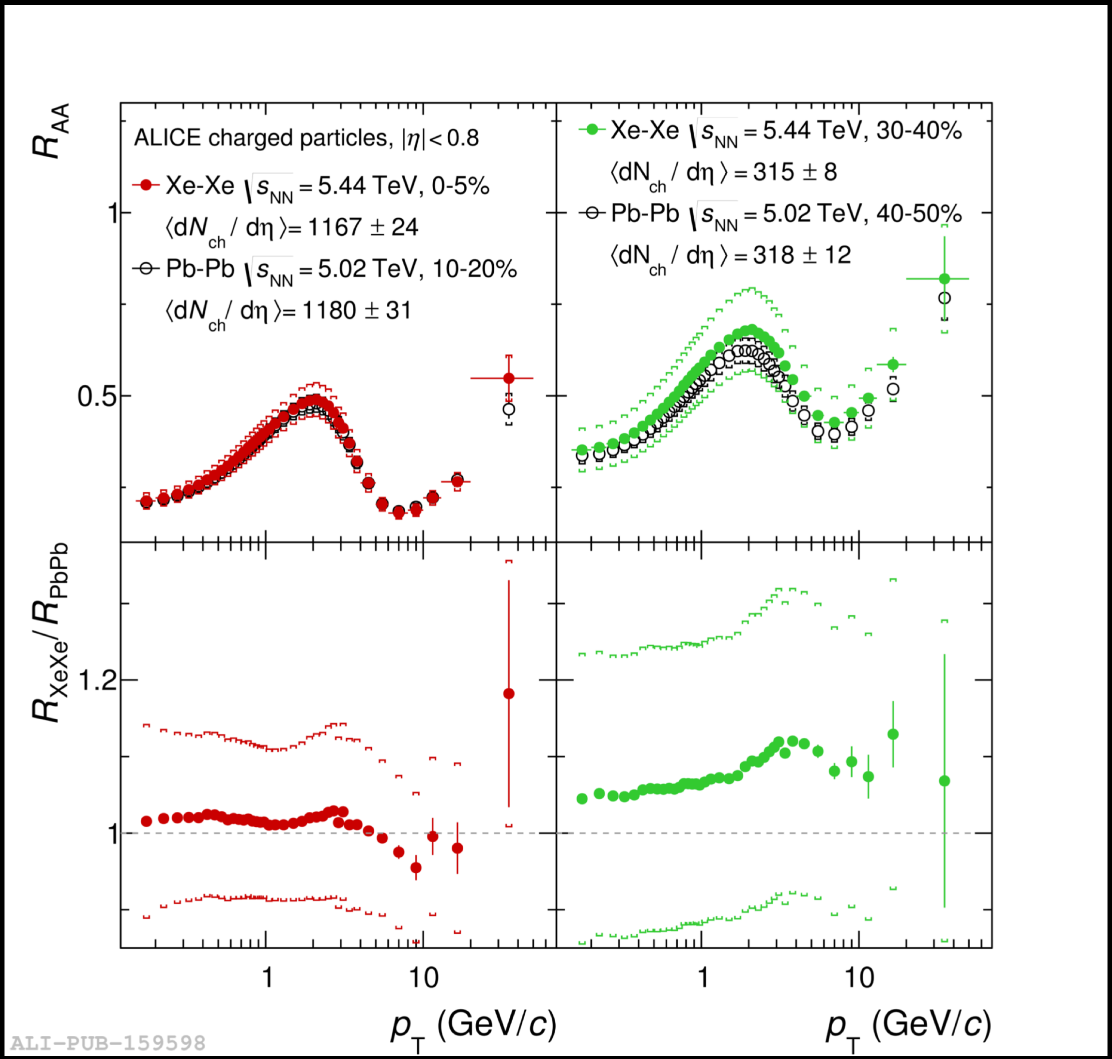
→ Suppression in central Pb-Pb collisions is due to final state effects!

Confirmed by jet measurements: Phys. Lett. B749 (2015) 68



Charged-particle R_{AA} in Xe-Xe and Pb-Pb

arXiv:1805.04399

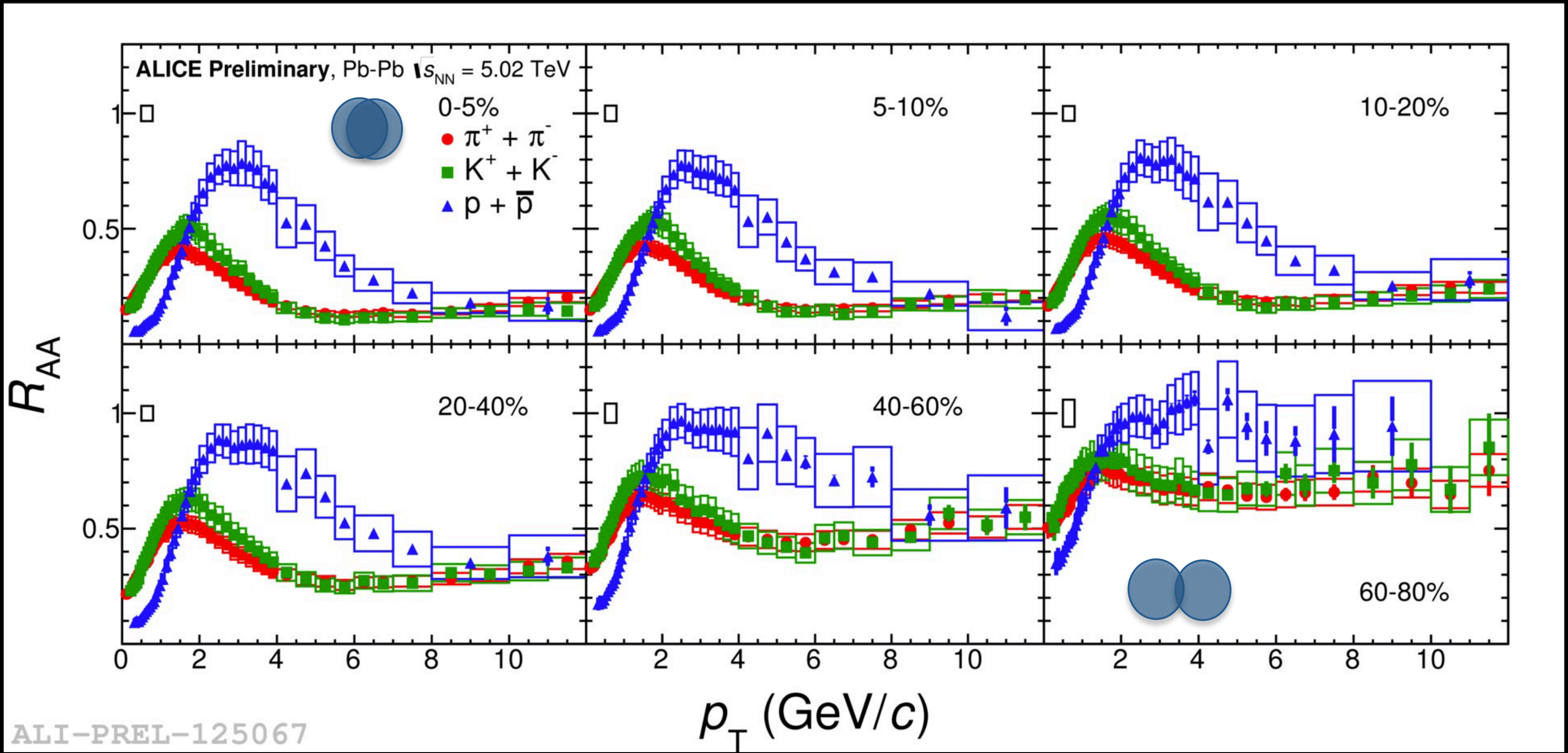


Similar R_{AA} in central Xe-Xe and Pb-Pb collisions at similar multiplicity

→ Result of interplay of geometry and path length dependence of parton energy loss

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

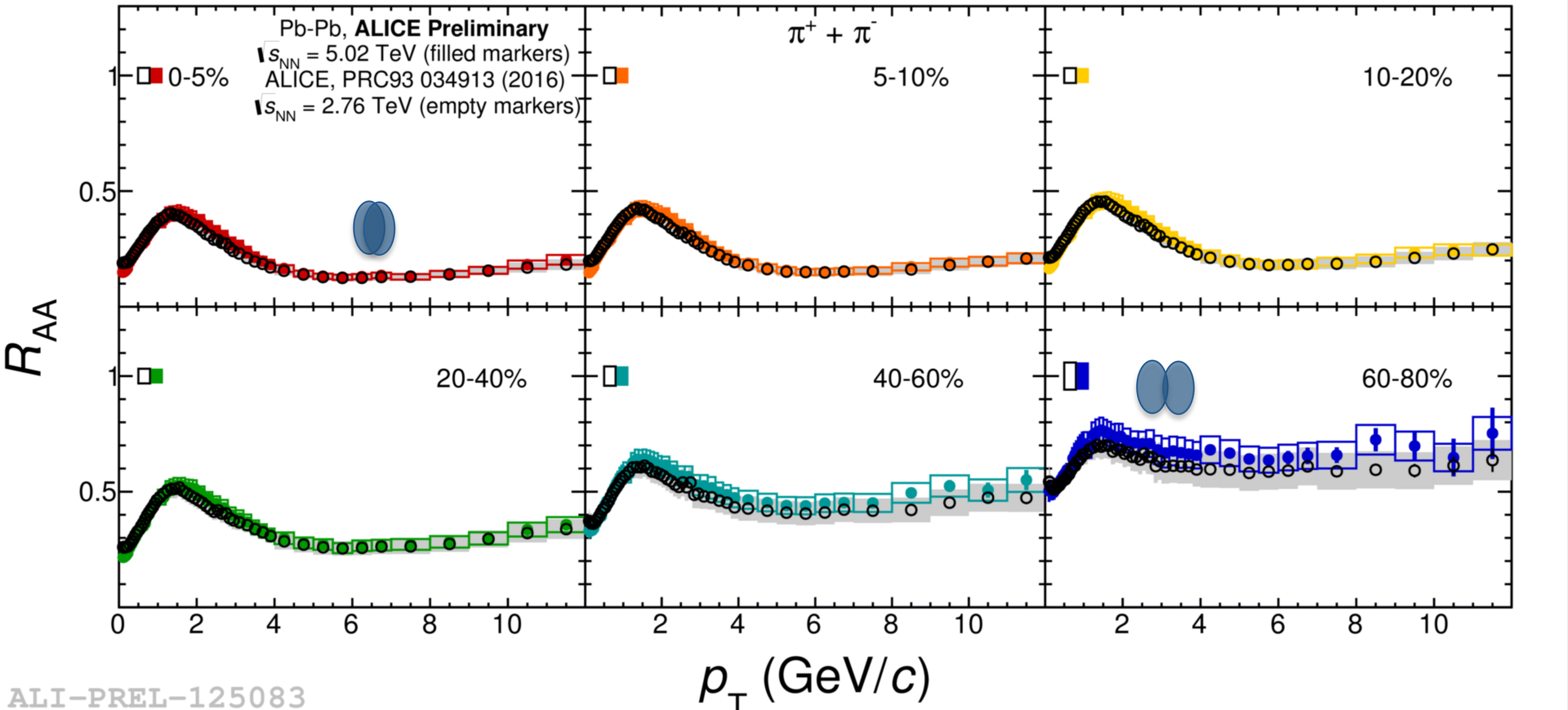
pp Phys. Lett. B 760 (2016) 720



- In Pb–Pb collisions all three species are equally suppressed for all centralities at high p_T > 8 GeV/c
- Similar suppression as observed at $\sqrt{s_{NN}}$ = 2.76 TeV [Phys. Rev. C93 (2016) 034913]

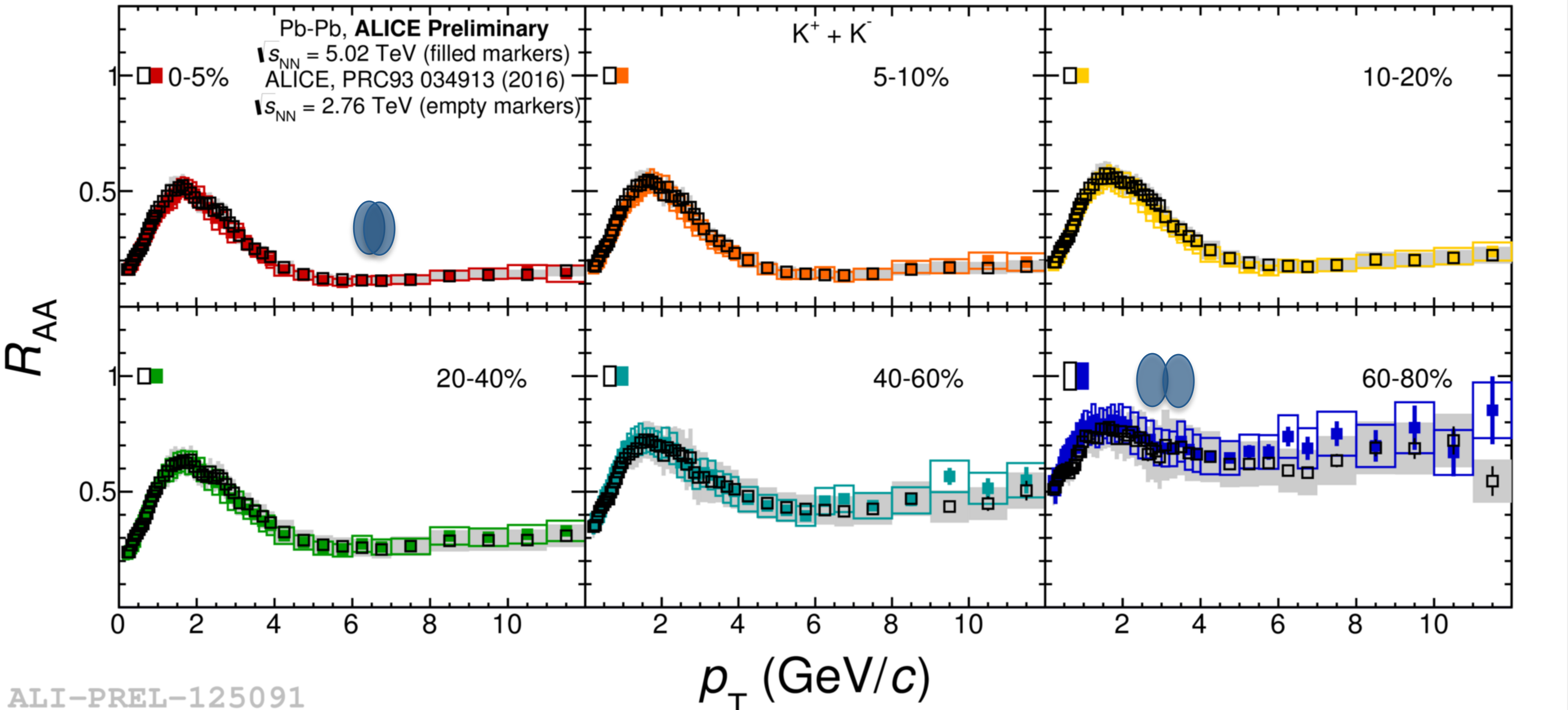
→ Fragmentation function at high p_T is not affected by the medium

R_{AA} energy dependence



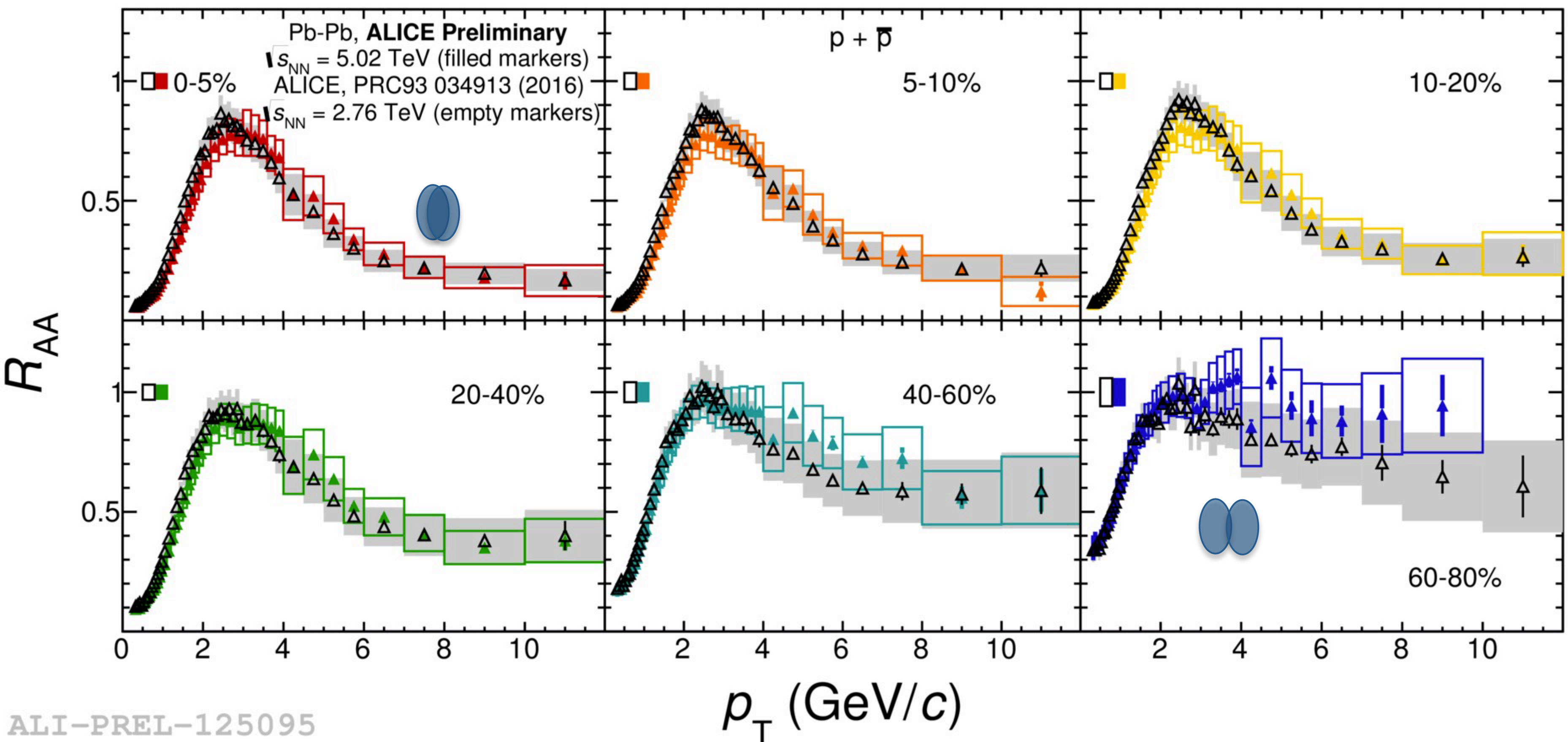
No significant evolution with collision energy is found

R_{AA} energy dependence



No significant evolution with collision energy is found

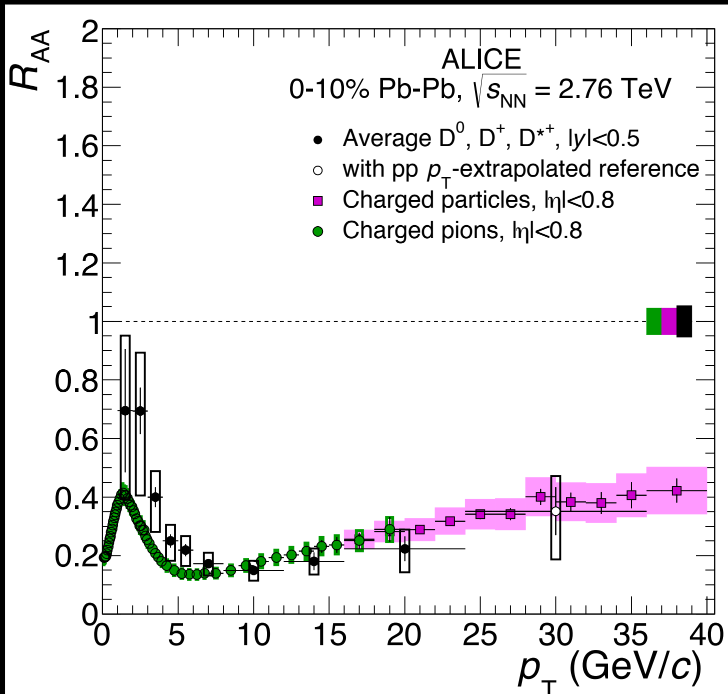
R_{AA} energy dependence

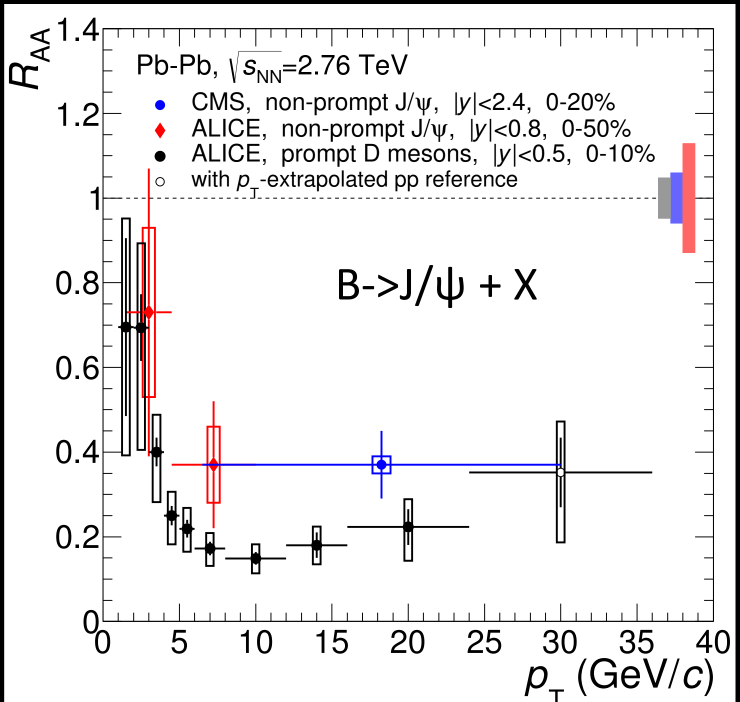


No significant evolution with collision energy is found

R_{AA} of identified hadrons comparison $\sqrt{s_{NN}}$ = 2.76 TeV

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:

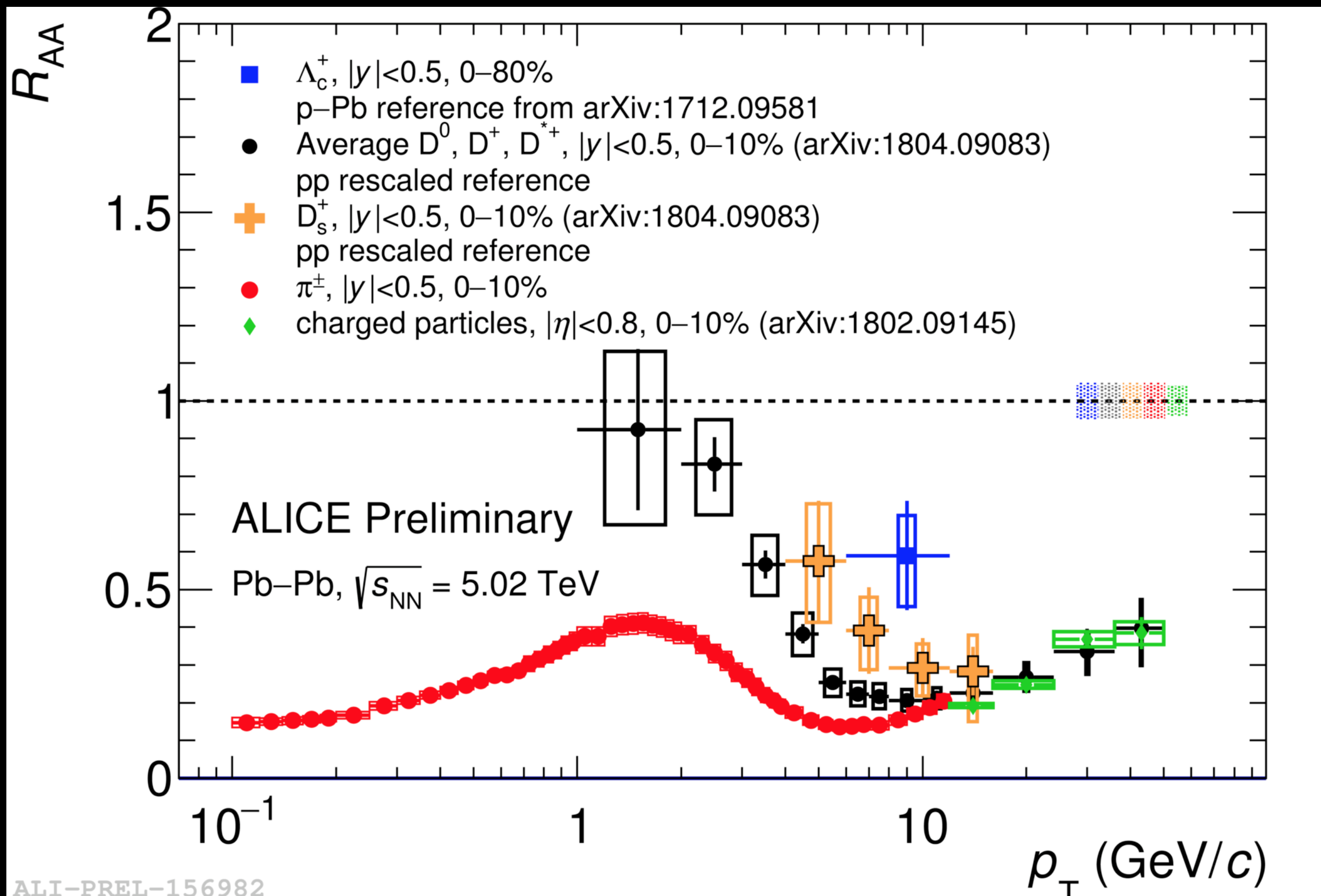
- $\Delta E_{g,q} \sim \Delta E_c$ at high p_T
- $\Delta E_b < \Delta E_c$?

Jet measurements show $\Delta E_{g,q} \sim \Delta E_b$?

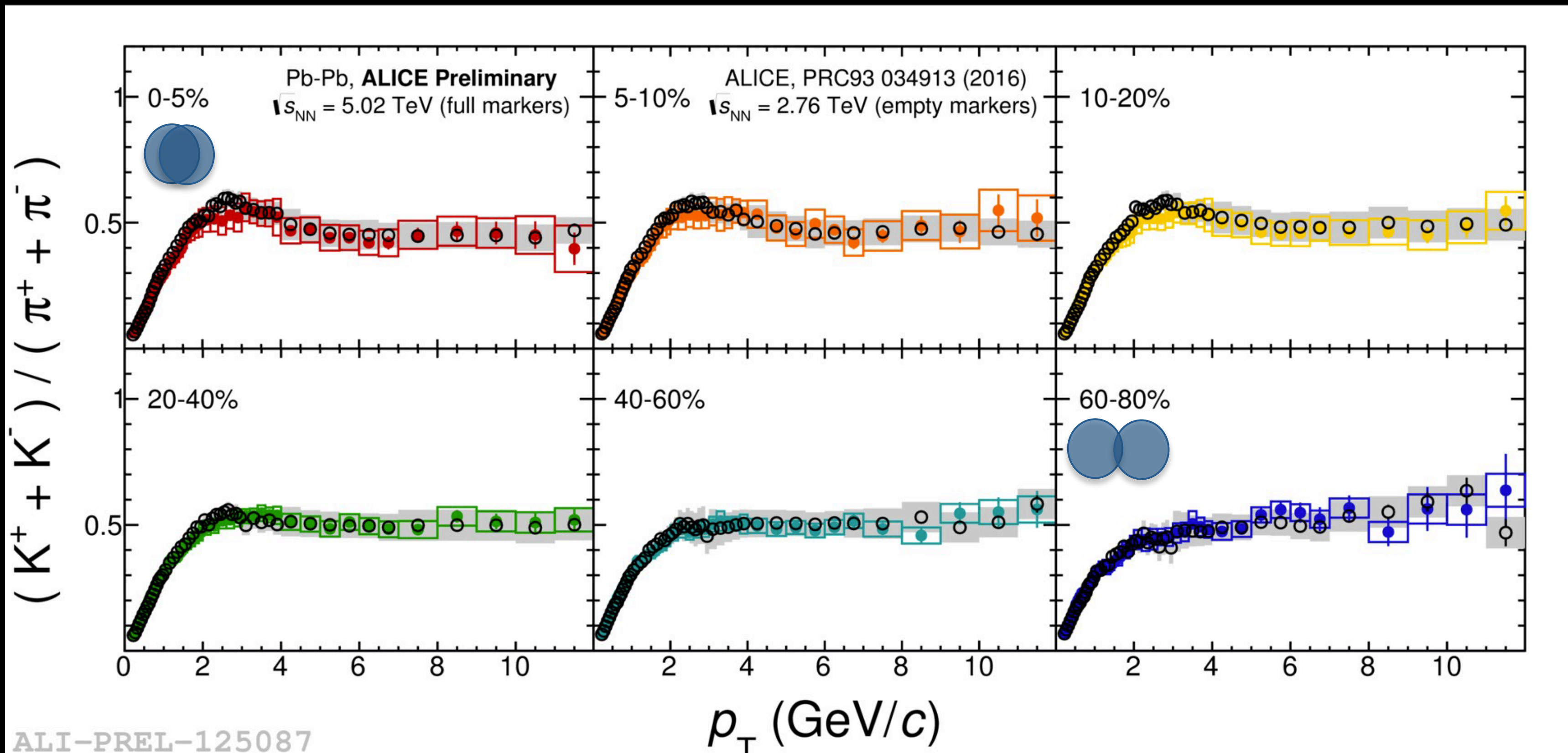
Non-prompt J/ψ (B->J/ψ + X):
ALICE, JHEP 1507 (2015) 051
CMS, JHEP 05 (2012) 063

Jets:
CMS, PRL 113, 132301 (2014)
ATLAS, PRL 114 (2015) 072302

R_{AA} of identified hadrons comparison at $\sqrt{s_{NN}}$ = 5.02 TeV

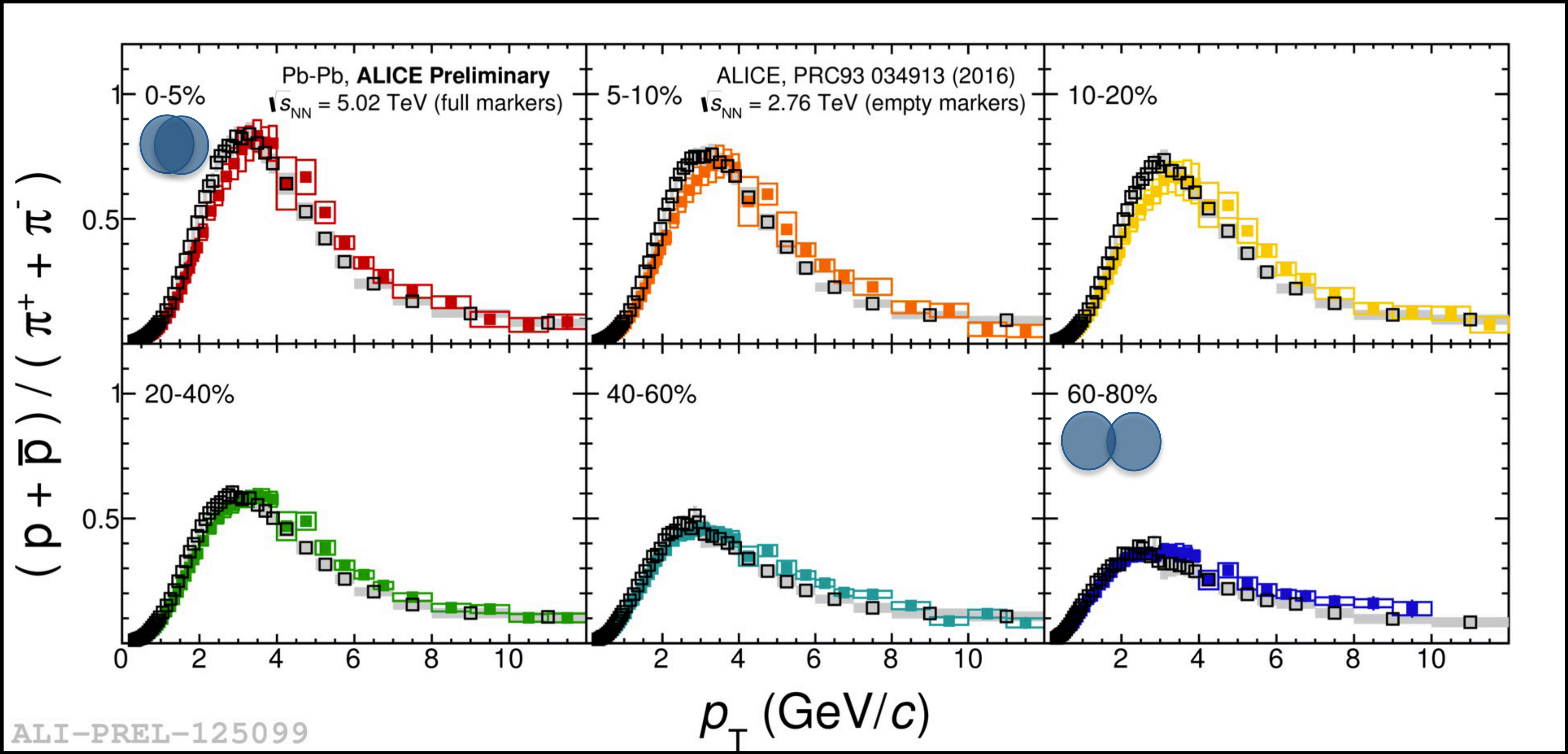


K / π ratio in Pb-Pb



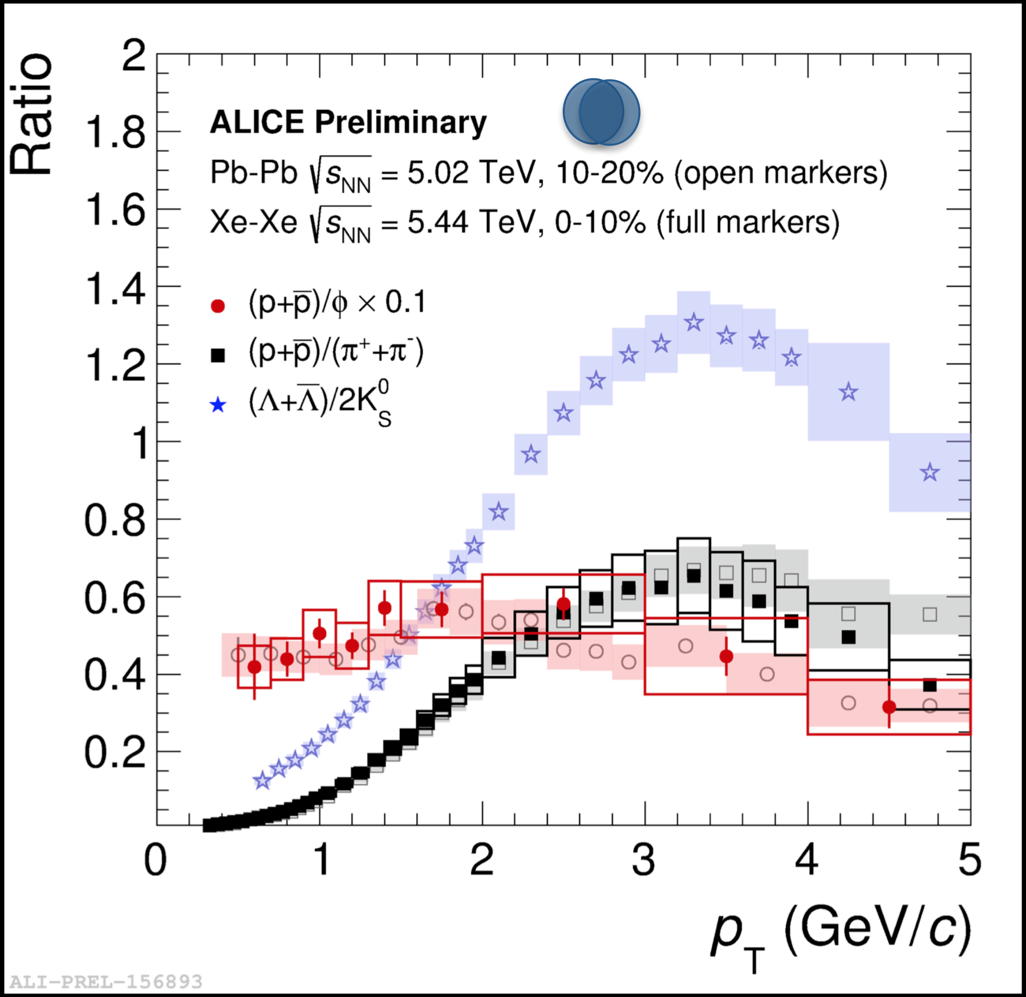
- Different pattern in the K/π ratio depending on centrality
- No significant change between the two energies $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV

p / π ratio in Pb-Pb



- Maximum in the p/π ratio due to radial flow
- Shift of the maximum of p/π to higher p_T with respect to lower energies due to stronger radial flow

Flow vs recombination at intermediate p_T



Baryon-to-meson ratios at intermediate p_T are sensitive to both effects: flow and recombination

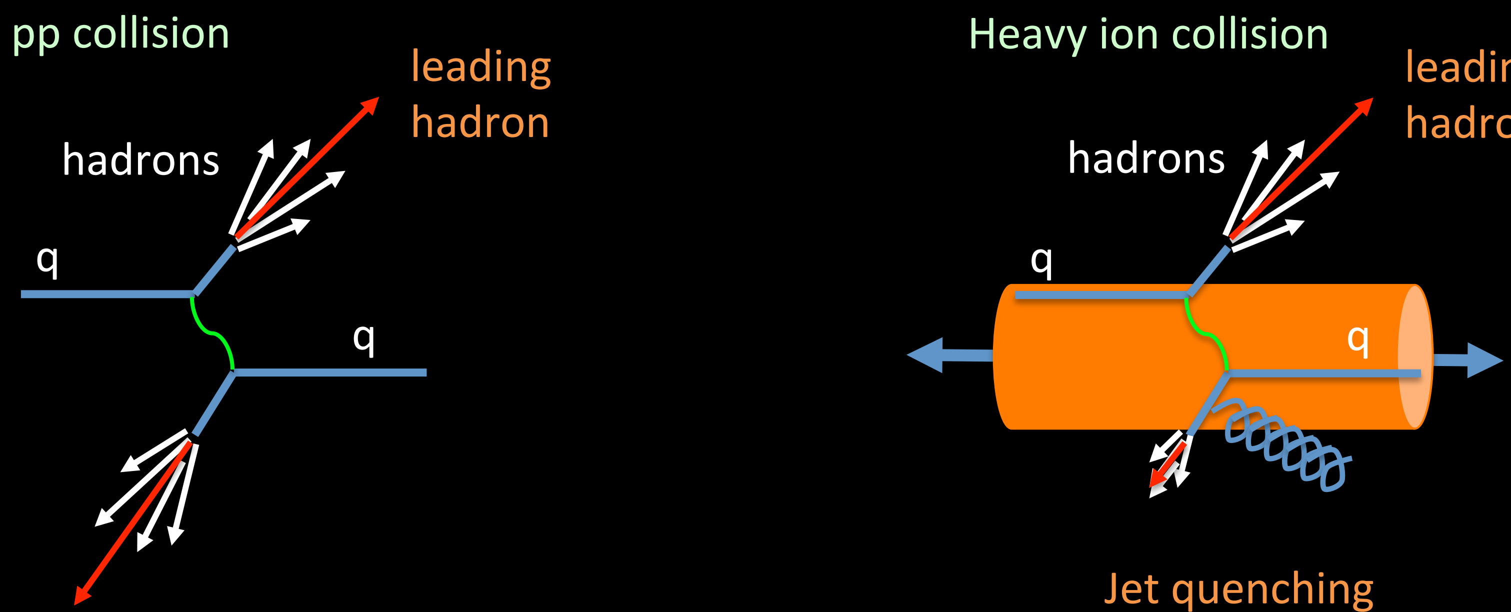
The same ratios observed in Pb-Pb and Xe-Xe at similar multiplicity

p/ϕ ratio is consistent with hydro predictions (particles with similar mass) but also with recombination [Greco et al., Phys. Rev. C92 (2015) 054904]

→ Still open question whether flow or recombination determines particle production at intermediate p_T

Parton energy loss and and jet quenching

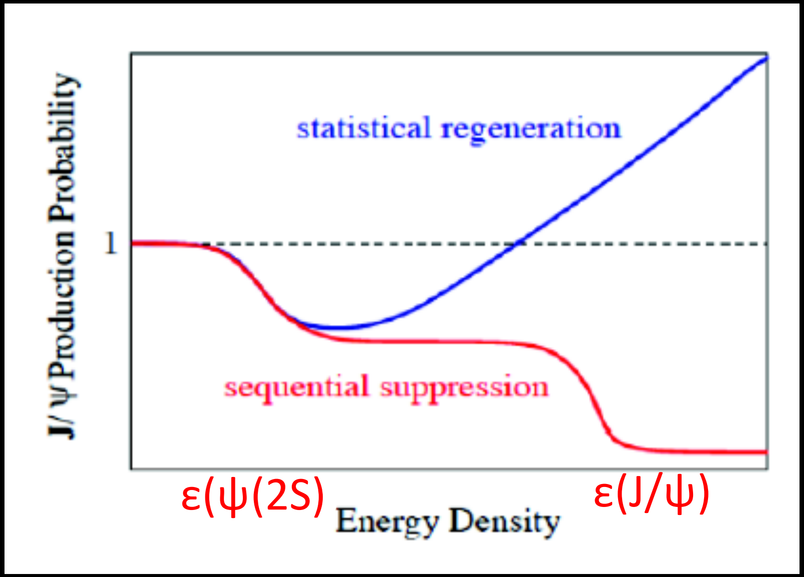
- Hard probes are produced in the early stage of collision (τ~1/Q) and can be used to probe dense and hot QCD matter

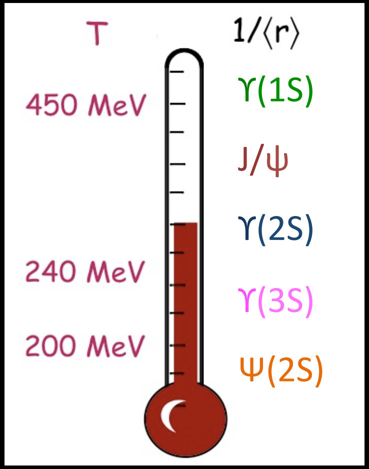


- Parton energy loss is expected to depend on its color charge and mass [Dokshitzer & Kharzeev, PLB 519 (2001) 199, Djordjevic & Gyulassy, NPA 733 (2004) 265]
  - $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$
- Characterize medium transport properties via parton energy loss
  - Modification of leading hadron and jet spectra is quantified by nuclear modification factors R_{AA}

Quarkonia sequential suppression vs (re)generation

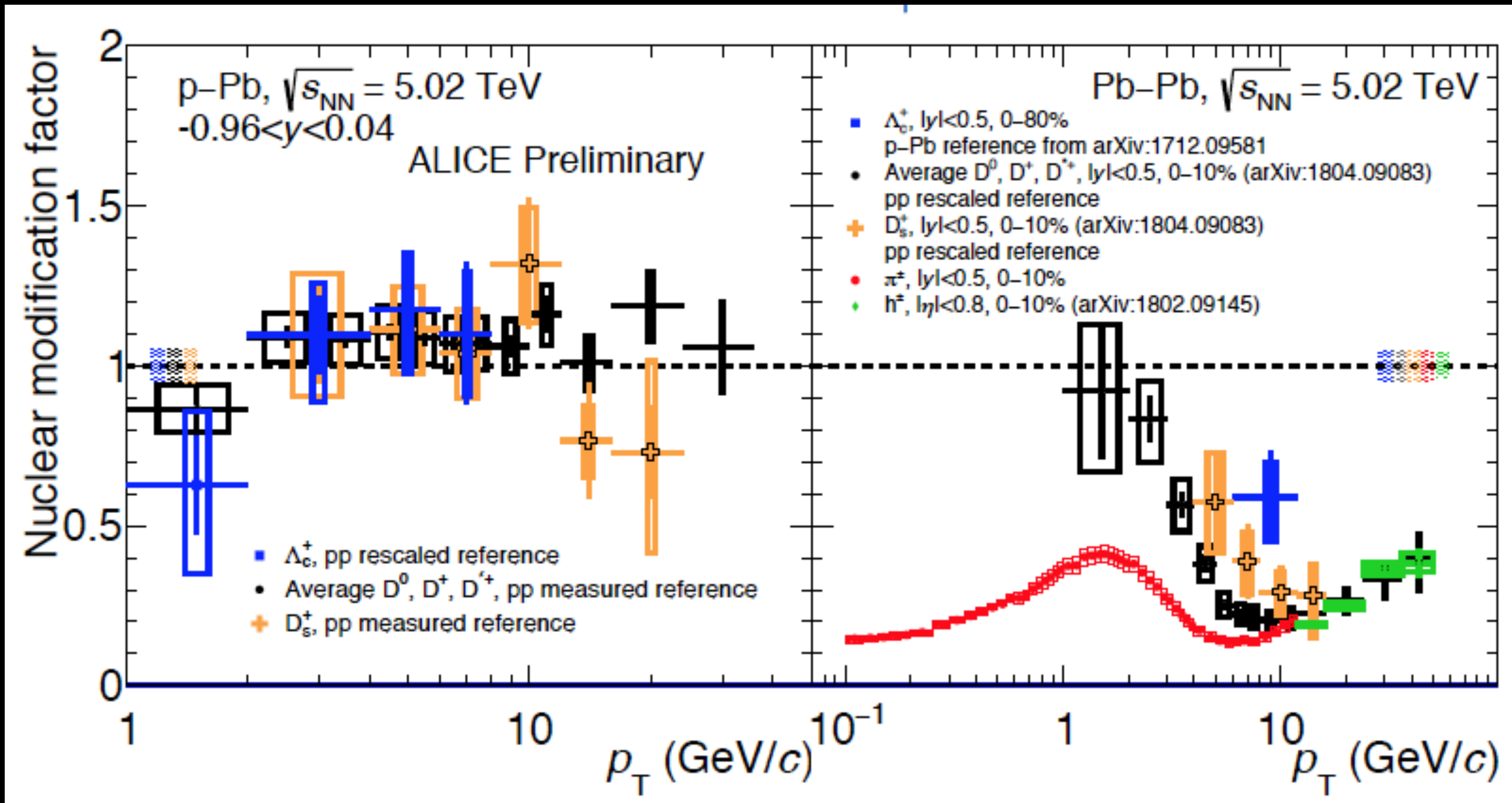
- Quarkonia - bound states of charm and bottom quarks produced in early stage of collision
- Quarkonia sequential suppression in the QGP due to color screening
  Matsui and Satz, PLB 168 (1986) 415; Karsch and Satz, ZPC 51, (1991) 209
- Quarkonia (re)generation at the phase boundary T ~ T_{ch}
  Braun-Munzinger and Stachel, PLB 490 (2000) 196; Thews et al., PRC 63 (2000) 054905





At LHC one can expect enhanced quarkonium production via (re)generation
→ Evidence for heavy quark thermalization in the QGP

Heavy-flavor R_{pPb} and R_{AA} at $\sqrt{s_{NN}}$ = 5.02 TeV



- R_{pPb} ~ 1: no modification of heavy-flavor production in p-Pb compared to scaled pp
- Strong suppression in Pb-Pb collisions (final state effect)
- R_{AA} ordering supports recombination of Ds from s+c quarks
- R_{AA} at high p_T is similar for D mesons and light-flavor hadrons