# Meson properties and production in nuclear medium

Hengne Li
(South China Normal University)

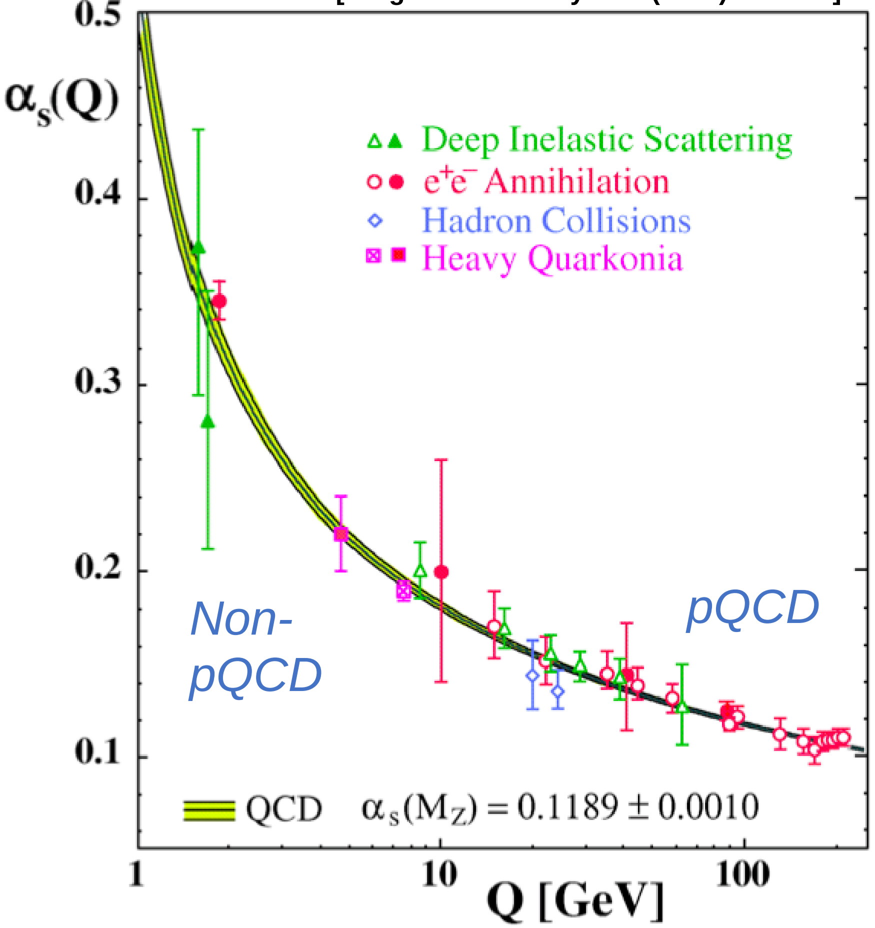
MESON 2021

# QCD: Color confinement, asymptotic freedom, and QGP

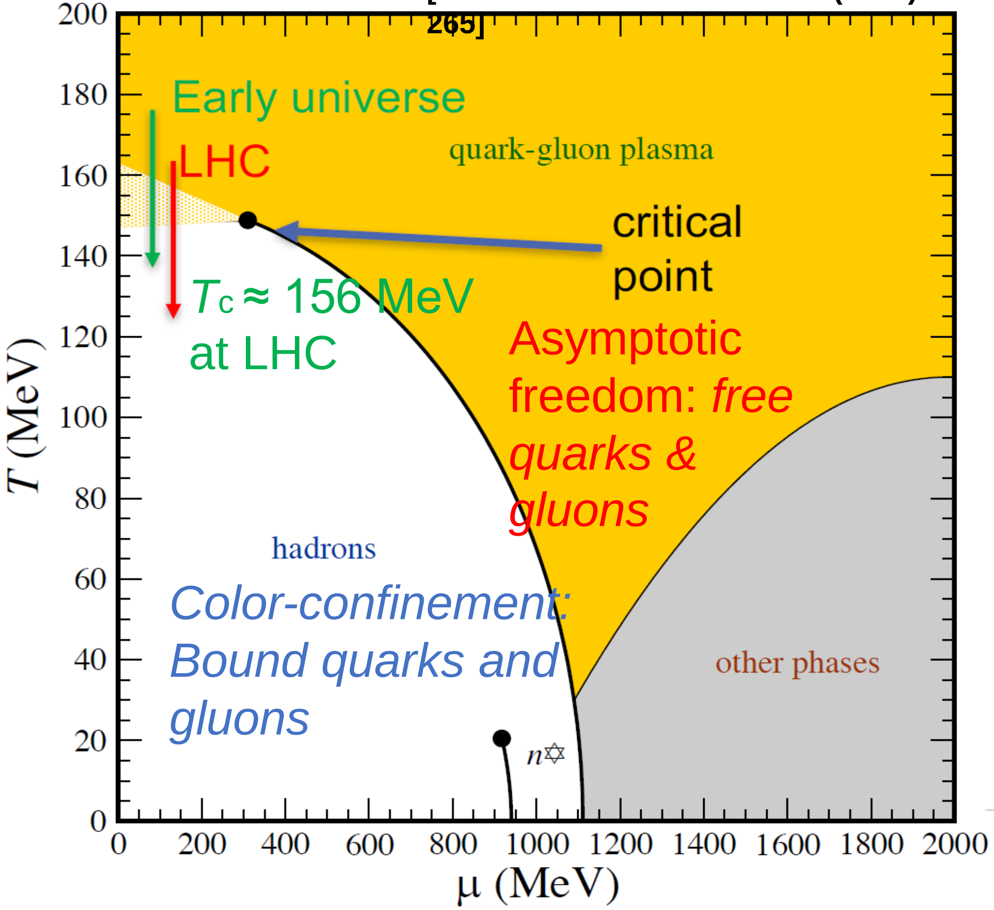
Heavy-ion physics: *high energy density QCD*

Quark-Gluon-Plasma (QGP): at extreme temperature and density, quarks and gluons behave quasi-free and are not confined in individual hadrons.

[Prog.Part.Nucl.Phys. 58 (2007) 351-386]




[Ann. Rev. Nucl. Part. Sci. 62 (2012) 265]



# Evolution of a heavy ion collision

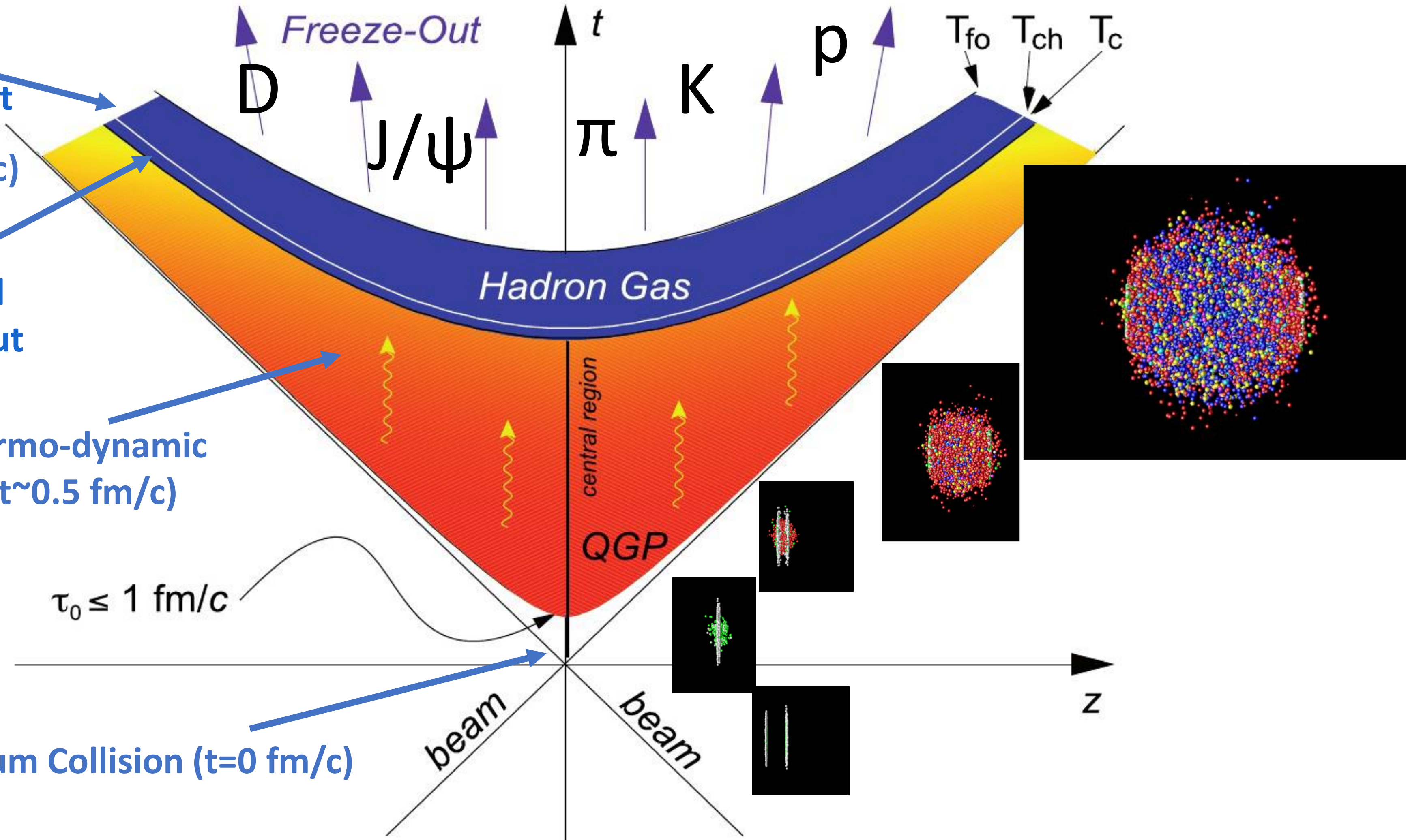
Thermodynamic (hydrodynamic) are employed to describe the QGP medium

Kinetic freeze-out

(t=10 fm/c)

Chemical freeze-out

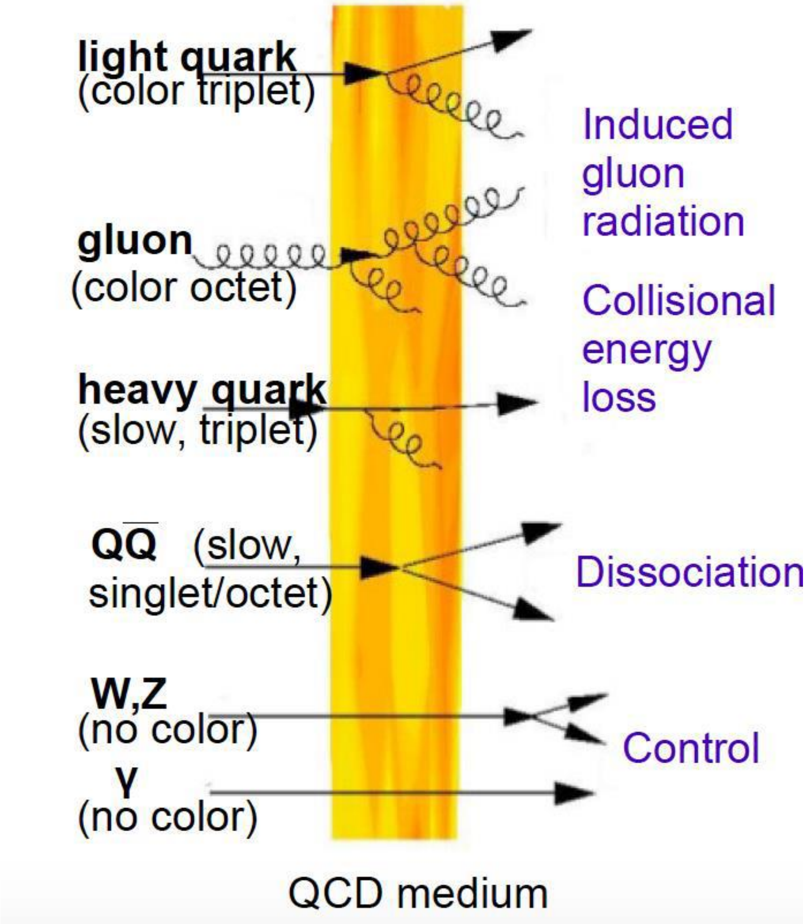
Hydro/thermo-dynamic evolution (t~0.5 fm/c)




Pre-equilibrium Collision (t=0 fm/c)

# Role of mesons in heavy ion collisions

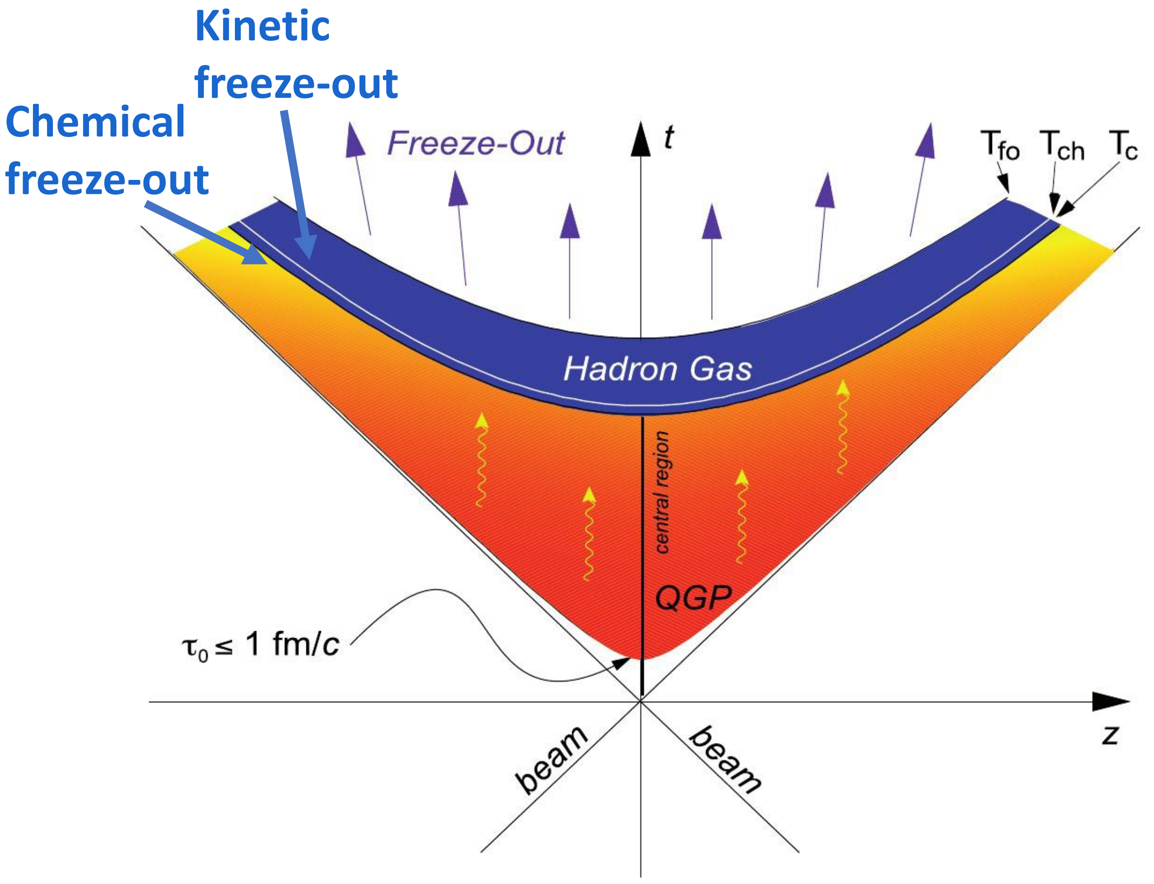
- The main goal (at the moment) of the heavy ion physics is to study QGP properties. Mesons are served as “probes”.
- Light flavor (u, d, s) mesons, soft probes to study QGP properties:
  - Particle chemistry, QCD critical point,
  - QCD thermodynamics, collectivity (radial & elliptic flows), etc.
- Heavy flavor mesons (open charm/bottom & quarkonium), hard probes to study:
  - Initial states: cold nuclear matter effects (CNM), PDF/nPDFs…
  - QGP properties, how hadrons interact with QGP: thermalization & coalescence, dissociation & recombination, etc..



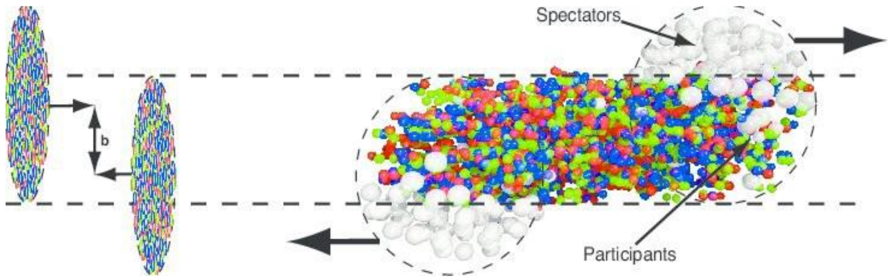
# Light flavor mesons

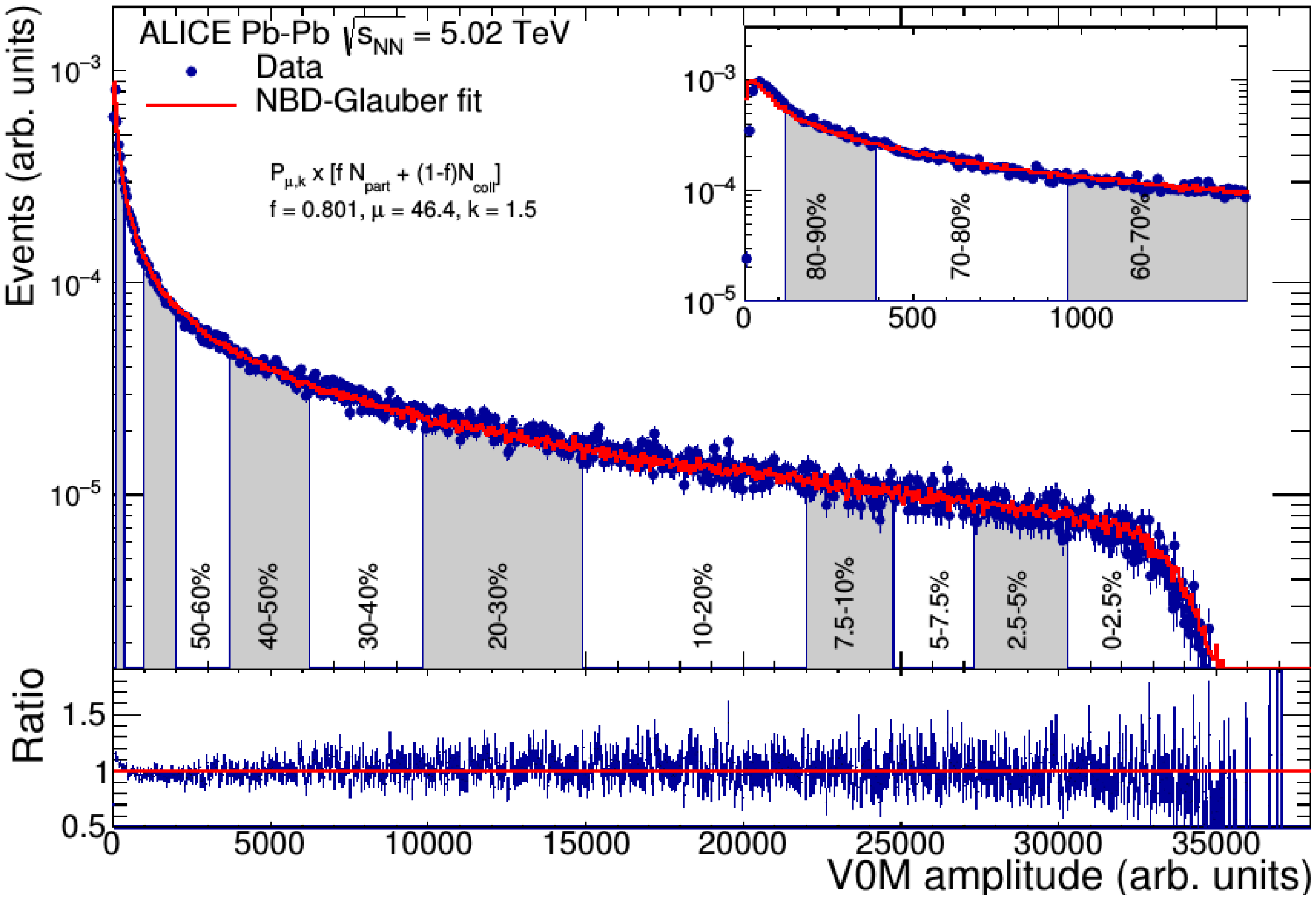
# Light flavor mesons

- Light flavor (u, d, s) mesons: π, K, ..
- Soft probes of QGP
- Light flavor hadrons constitute > 95% of the final state hadrons (< 2 GeV/c) at LHC for pp and PbPb collisions.
- Thermodynamics and hydrodynamics are employed to describe the “bulk” particles production in the QGP medium:
  - Production yields of different hadrons (different quark flavors u, d, or s) are described by (can be used to examine) the thermodynamic models (chemical)
  - Collectivity features, spectral shapes and azimuthal anisotropies (such as radial and elliptic flows) are described by (can be used to test) the hydrodynamic models (kinetic)



# Centrality: Geometry of heavy ion collisions



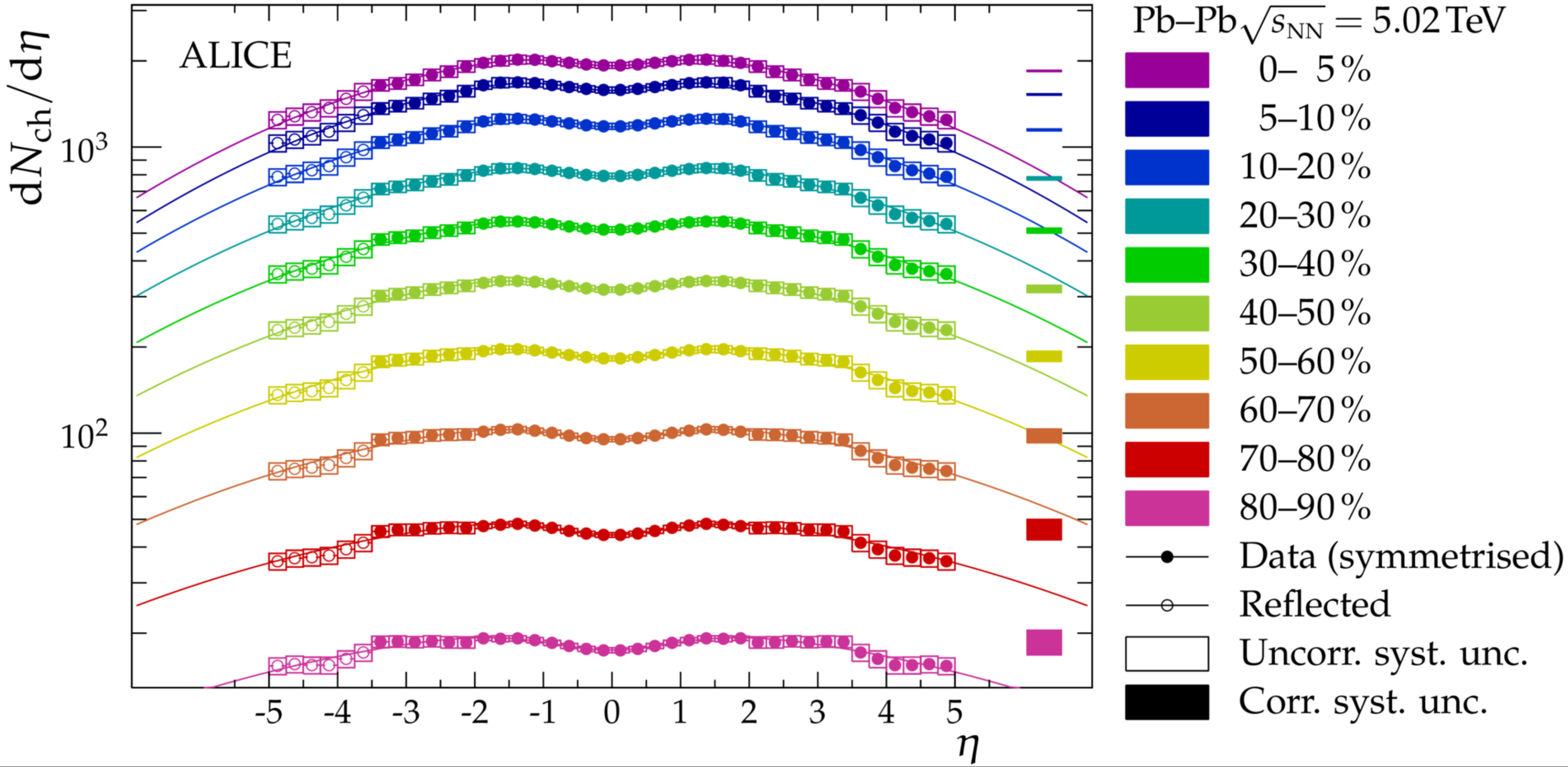

**Centrality Variables:**

- ***N*coll**: Number of nucleon-nucleon collisions
- ***N*part**: Number of participating nucleons

**Percentile of hadronic cross-section:**

0-5% => central (“many particles”)
80-90% => peripheral (“few particles”)

# $dN_{ch}/d\eta$ in 5.02 TeV Pb Pb collisions at LHC




ALI-PUB-115086 [arXiv:1612.08966]

$dN_{ch}/d\eta \approx$ 1943 ± 54 at midrapidity.

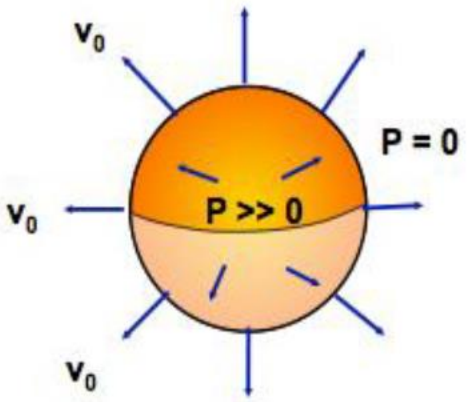
→ Even at LHC energies, 95% of all particles are produced with $p_T$ < 2 GeV/$c$ in pp and Pb-Pb collisions.

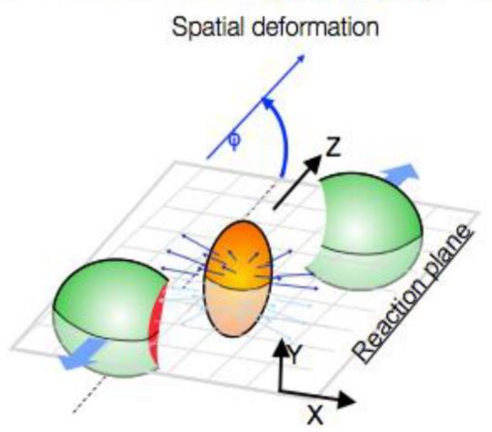
→ Bulk particle production and the study of collective phenomena are associated with ***"soft" physics*** in the non-perturbative regime of QCD.

# Bulk particle production and collectivity

- Low $p_T$ hadrons composed of light flavor quarks define the collective behavior of the QGP.
- Described using a “fireball” model in local thermodynamic equilibrium, where the observables are:
  - Hadrochemistry (the hadrons’ composition of different quark flavors) to verify the predictions by thermodynamic models.
  - The $p_T$ spectra and v2 to examine radial and elliptic hydrodynamic flow.

**Isotropic (Radial) flow** **Anisotropic (Elliptic) flow**



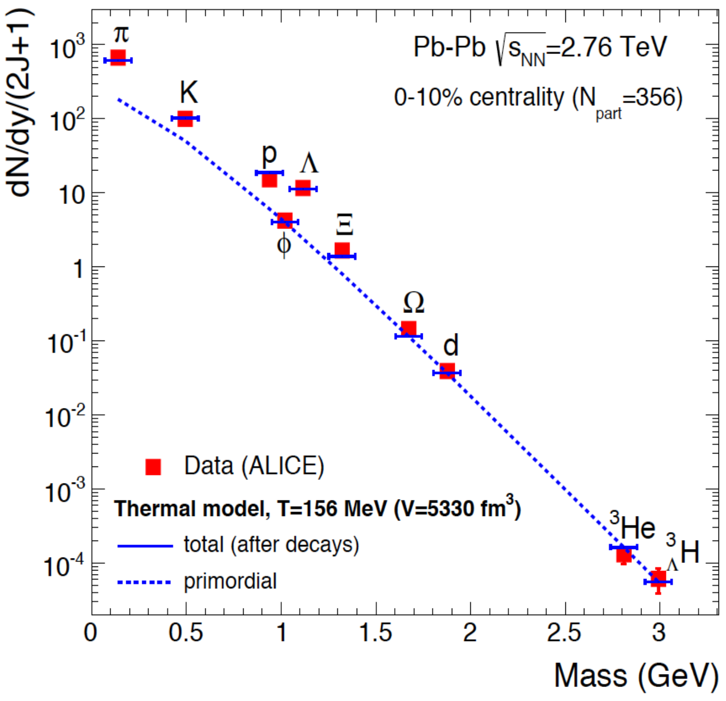




$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left\{1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos[n(\varphi - \psi_n)]\right\}$$

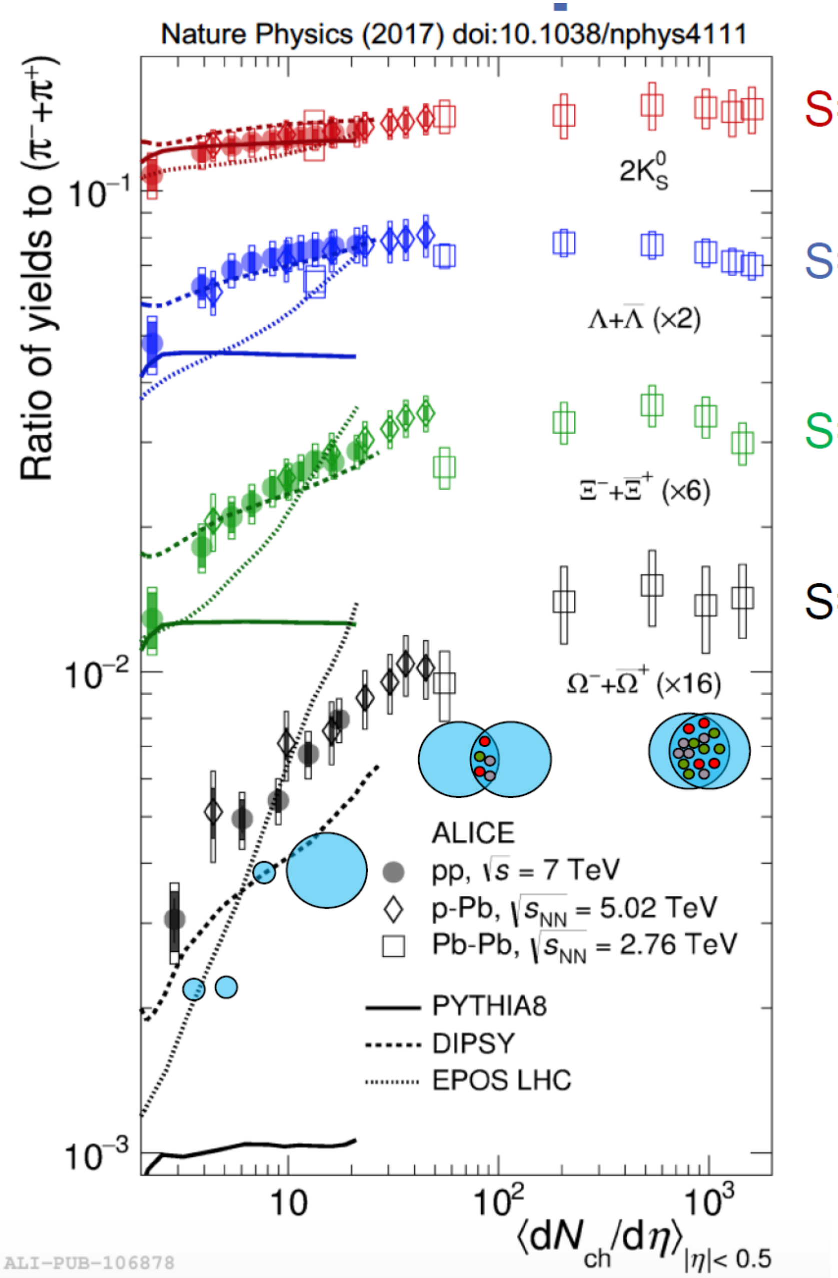
Radial flow $v_1$ – direct flow, **$v_2$- elliptic flow**

# Hadrochemistry: hadrons yields

- The production yields of different hadrons from a chemically equilibrated fireball can be calculated by statistical thermodynamic models (hadro-chemistry).
- Smooth evolution of hadrochemistry observed from pp to pPb to PbPb collisions as a function of charged particle multiplicity.
- Significant enhancement of strange to non-strange particle production observed in pp collisions.
- Non of the generators shown here can give a perfect prediction yet.




**[A. Andronicet *al.*, arXiv:1407.5003]**




S=1

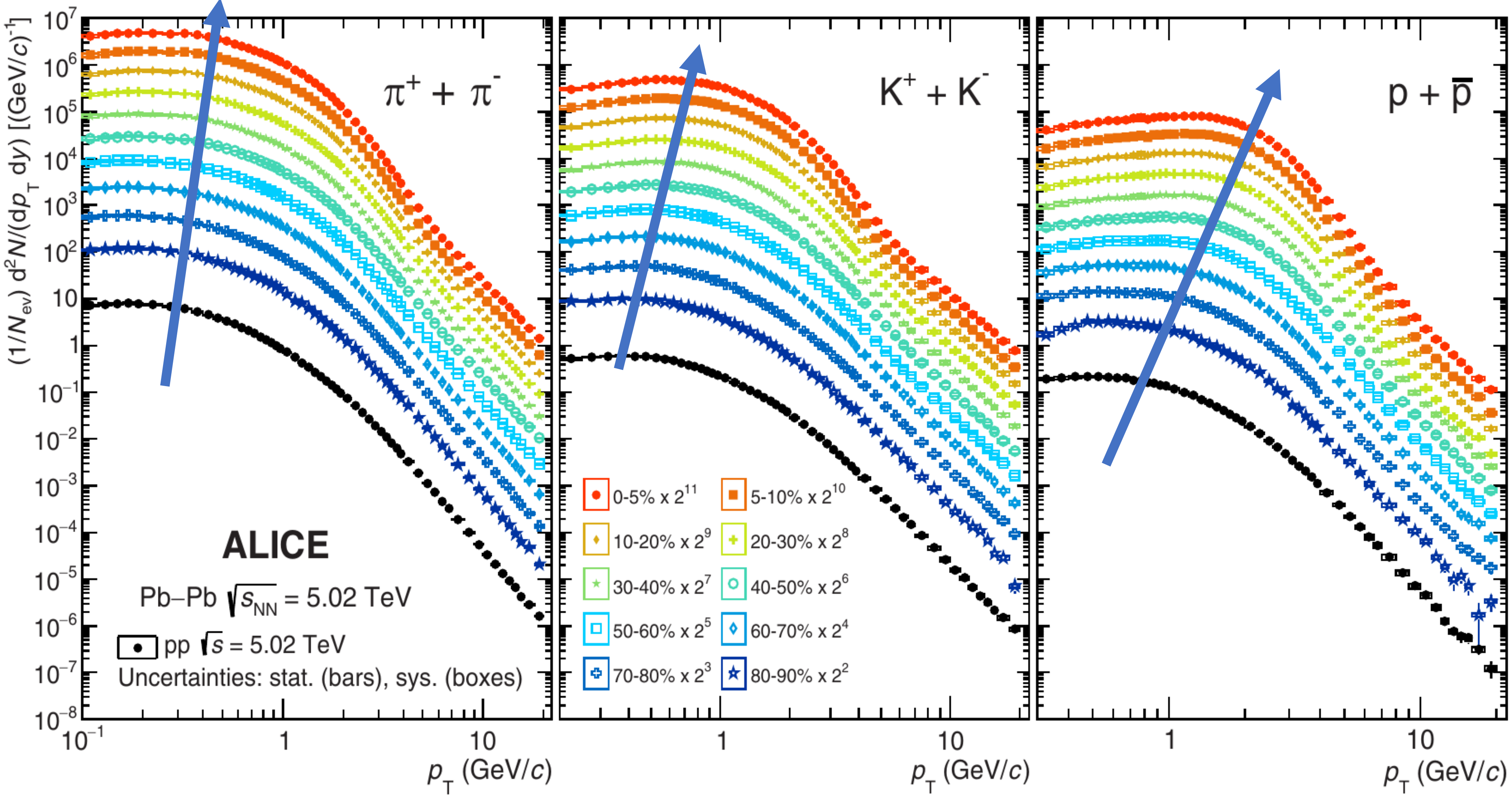
S=1

S=2

S=3

# Hydrodynamics: Radial flow Pb-Pb

Phys. Rev. C 101, 044907 (2020)

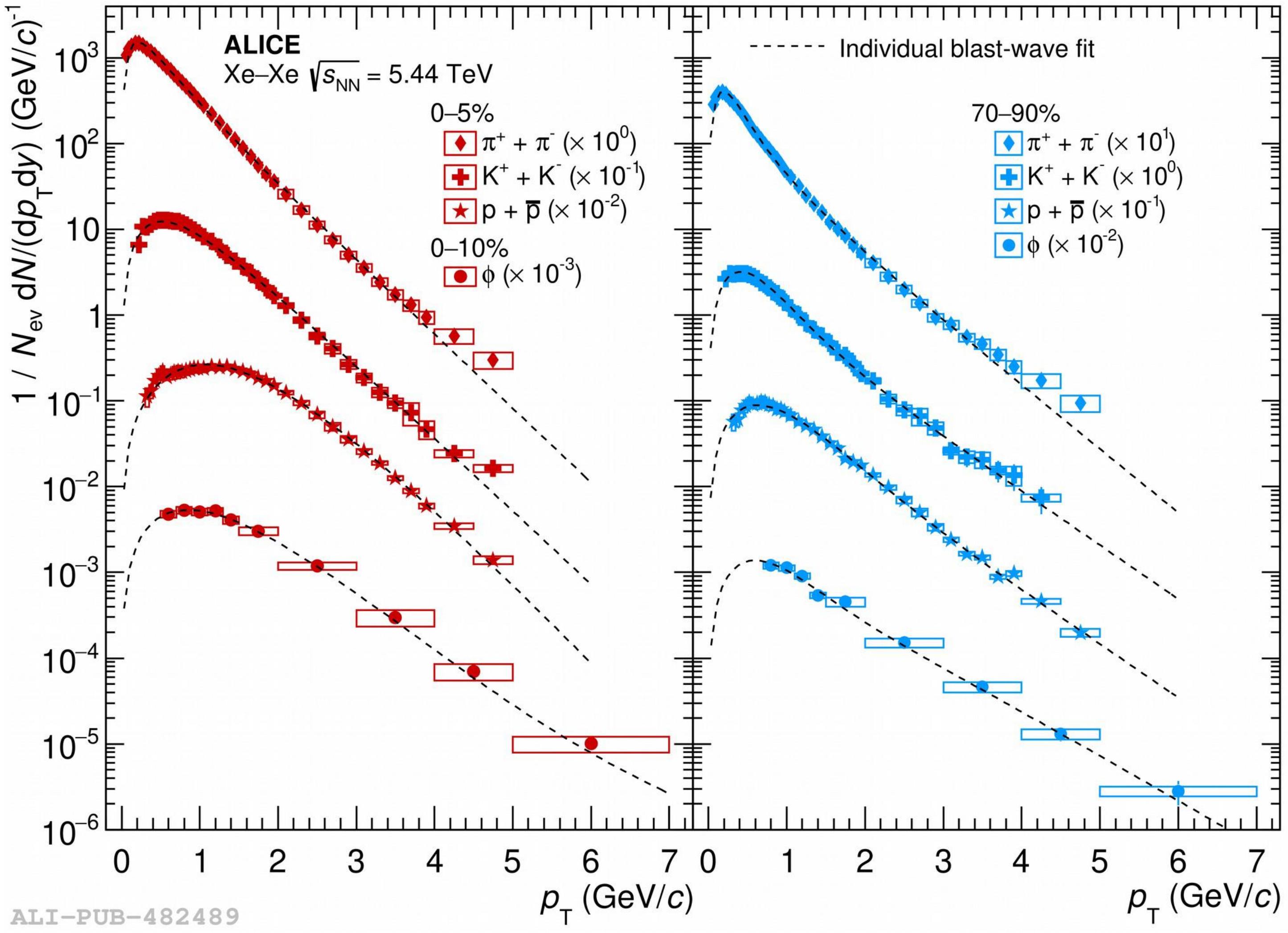



- Mass-dependent hardening of the soft part with increasing centrality due to the collective evolution (radial flow)

# Hydrodynamics: Radial flow Xe-Xe

arXiv:2101.03100

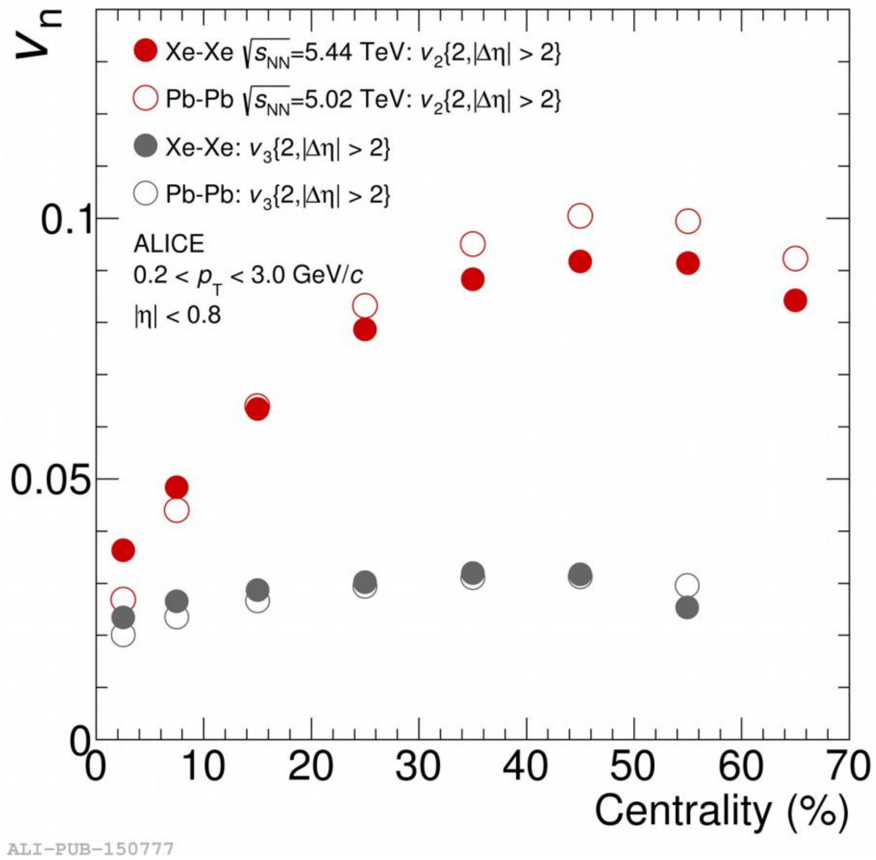
- Same observation as in PbPb collisions: harder spectra in central collisions due to radial flow
- Spectra hardening driven by particle mass: heavier particles are more shifted towards higher $p_T$

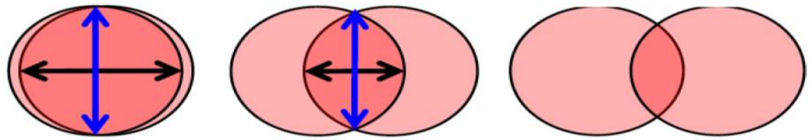


# Hydrodynamics: Anisotropic elliptic flow v2 and v3

- The anisotropic flow describes the "fireball" evolution shapes.
- v2 exhibits a strong centrality dependence, Pb-Pb is a little bit different than Xe-Xe, due to the different charges of the colliding system
- Spatial anisotropy very small in central collisions
- Largest anisotropy in mid central collisions at around 40-50%
- In peripheral collisions: increase in v2 (mostly driven by collision geometry) is larger than in v3 (mostly driven by fluctuations)

Phys. Lett. B784 (2018) 82

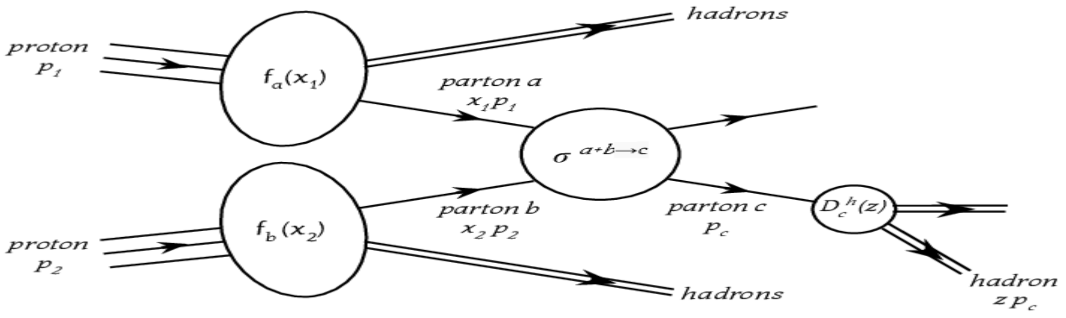


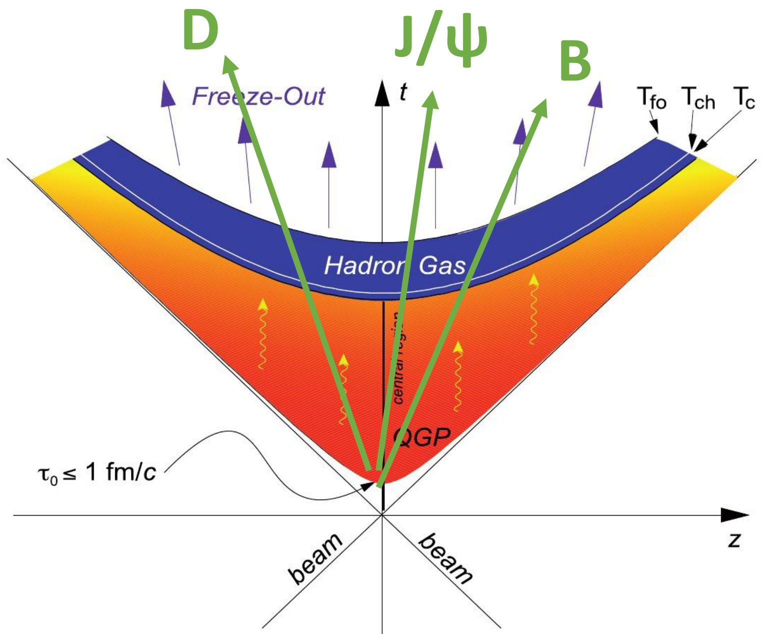
# Heavy flavor mesons:
# open charm/bottom & quarkonium

# Heavy flavor mesons: open charm/bottom & quarkonium

- Heavy flavor (c, b) mesons: dominantly produced in initial hard scattering then interact with the QGP medium.
  - $\tau_{HF}$ (≈ 0.05 – 0.1 fm/c) < $\tau_{QGP}$ (≈ 0.3 fm/c at LHC)
- Production in small system (pp, pA):
  - Probes the initial state cold nuclear matter (CNM) effects: Nuclear shadowing, gluon saturation, $k_T$ broadening, etc., constraining nPDFs.
- Production in large system (AA):
  - Hard probes of the QGP medium through in-medium suppression and enhancement of the production yields
- Observables to quantify the interactions with QGP:
  - Hydrodynamic collectivity observables such and radial flow ($p_T$) and elliptic flow (v2).
  - Nuclear modification factors: $R_{AA}$ .

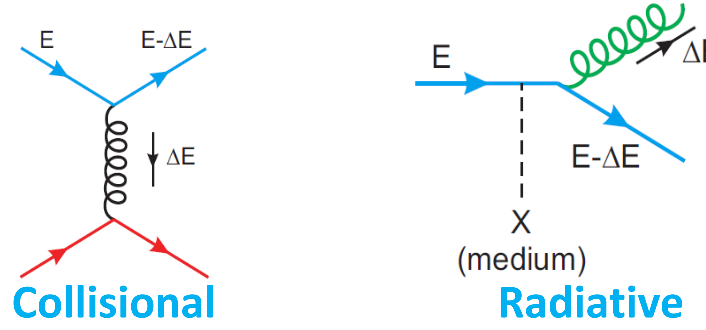


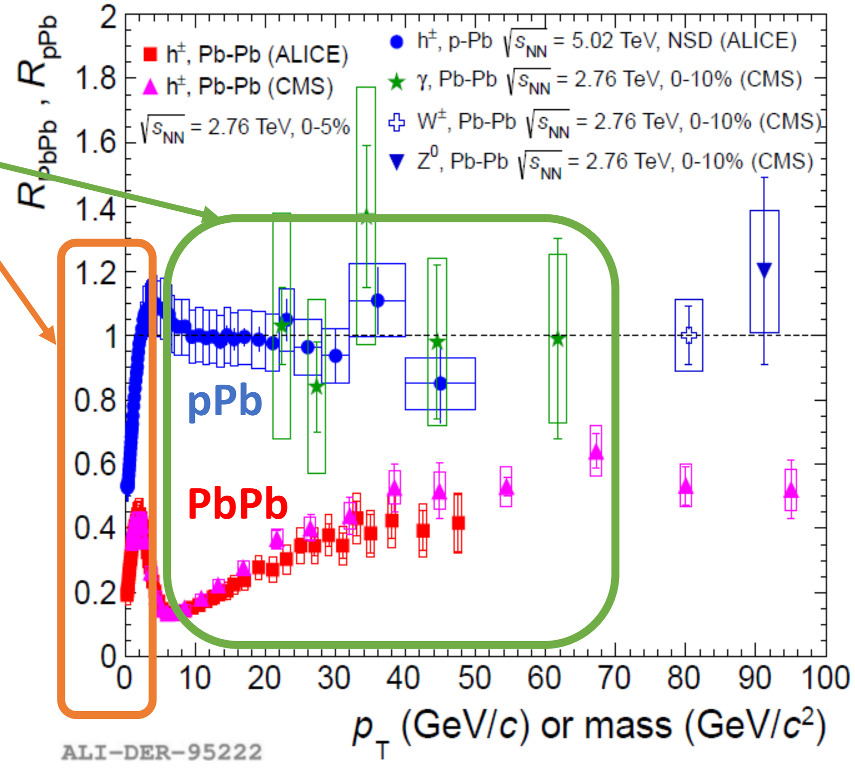

PDFs/nPDFs Non-perturbative ⊗ Hard scatter perturbative ⊗ Fragmentation Non-perturbative



# Interactions with QGP: open charm/bottom

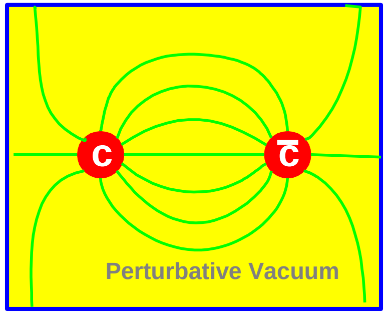
- Open charm and bottom:
  - Suppression: energy loss (thermalization):
    - Collisional energy loss: elastic scattering, dominate at low momentum, not only in QGP, pA small system also.
    - Radiative energy loss: inelastic scattering, gluon bremsstrahlung, dominate at high momentum, QGP medium effects.
    - Quark mass and color charge dependence, energy loss $b < c < u, d, s < g$
  - Enhancement: coalescence/recombination depends on enriched surrounding quarks in the medium, e.g.
    - Bulk of u/d quarks enhanced $D$ and $\Lambda_c$, compensate part of the suppression.
    - QGP enables gluon fusion process ($gg \rightarrow s\bar{s},\ c\bar{c}, ..$) => enriches s and c quarks in the QGP medium => larger enhancement of $D_s$ than non-strange D mesons.

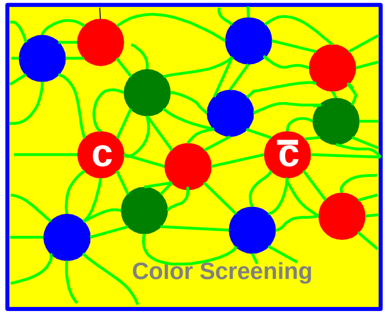


# Interactions with QGP: quarkonium

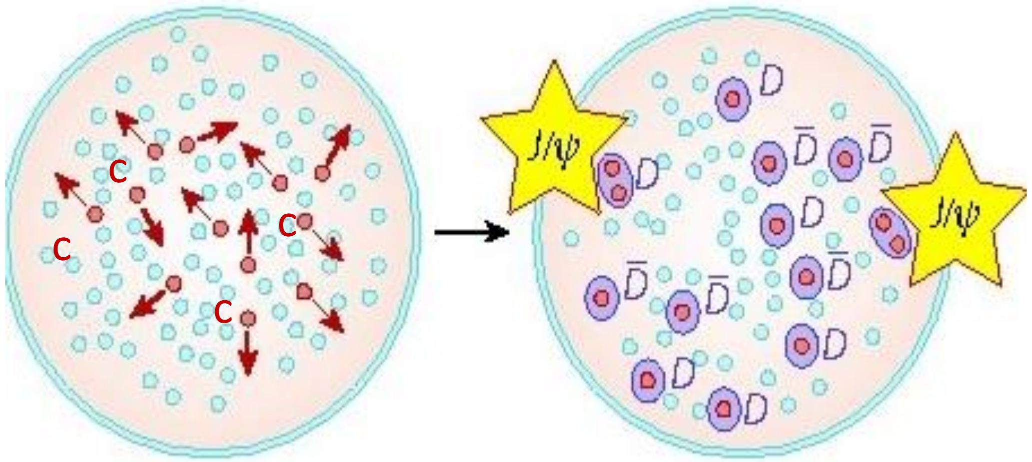
- Charmonium and bottonium
  - Suppression: dissociation (not energy loss!)
    - Color (Debye) screening: smaller screening radius $\lambda_D$ is needed to against the surrounding color charge
      => binding to a quarkonium become more difficult.
  - Enhancement: coalescence/recombination depends on surrounding charm and bottom quarks in the medium, e.g.
    - QGP enables gluon fusion process ($gg \to s\bar{s},\ c\bar{c},\ b\bar{b}$ ...)
      => Enriches c quarks in the medium, larger chance to (re)combine to more $\mathrm{J}/\Psi$
      => Mass dependence, $\sigma(gg \to s\bar{s}) > \sigma(gg \to c\bar{c}) > \sigma(gg \to b\bar{b})$,
      => enhancement for $\mathrm{J}/\Psi > \Upsilon(1\mathrm{S}, 2\mathrm{S}, ..)$




$$V(r) = -\frac{\alpha}{r} + kr$$

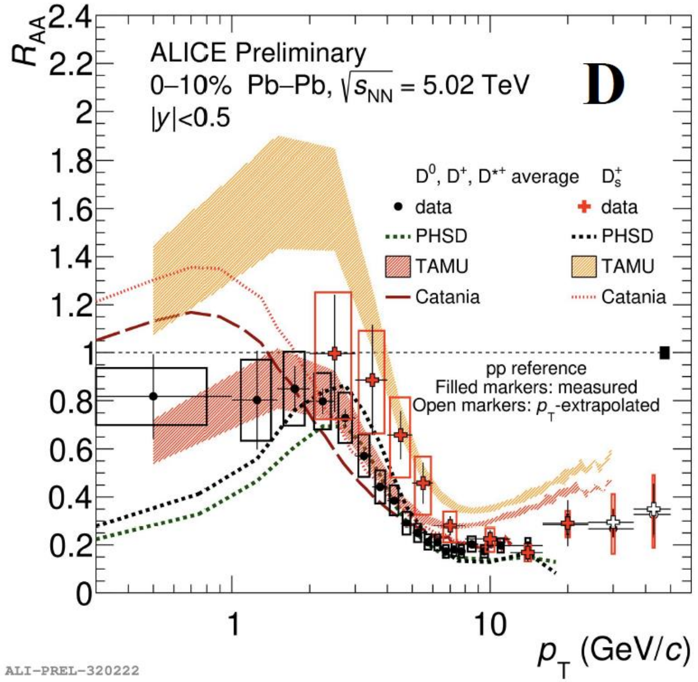
$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

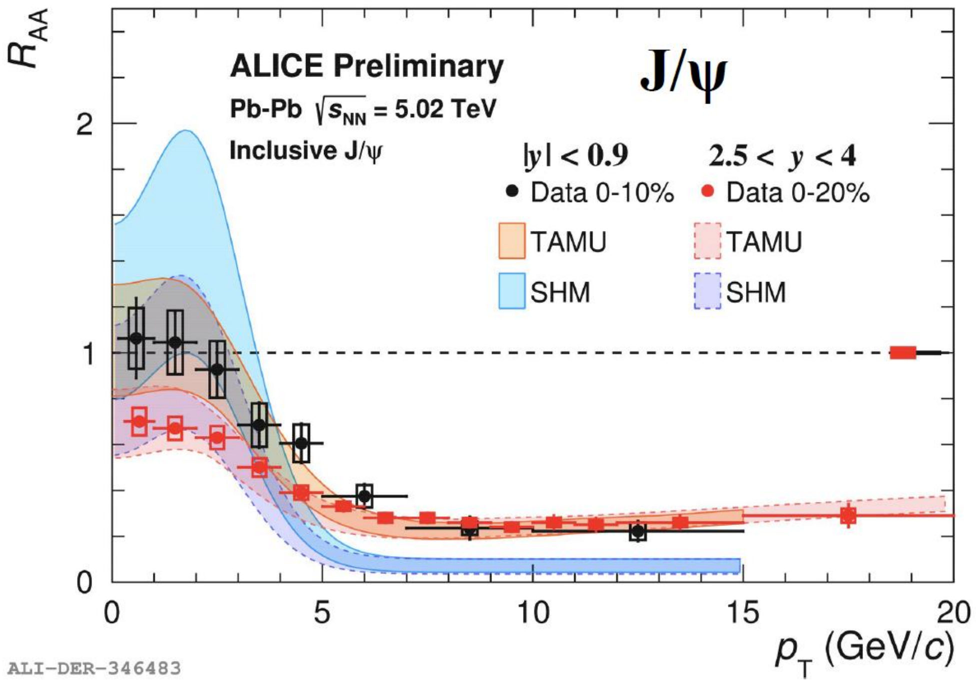


# Open charm and J/ψ $R_{AA}$ in Pb-Pb

PHSD: PRC 93 (2016) 034906
Catania: EPJC (2018) 78:348
TAMU: PRL 124 (2020) 042301
SHMc: arxiv:2104.12754

- Strong suppression of D meson $R_{AA}$ can be observed in central PbPb collisions at high $p_T$:
  - due to energy loss in the QGP medium
- A reduced suppression (or enhanced coalescence) of $D_S$ can be observed w.r.t. non-strange D meson at low $p_T$ :
  - due to the enhanced strangeness in the QGP medium
- For J/ψ, suppression and regeneration mechanisms describe the data: regeneration dominates at low $p_T$, stronger at midrapidity

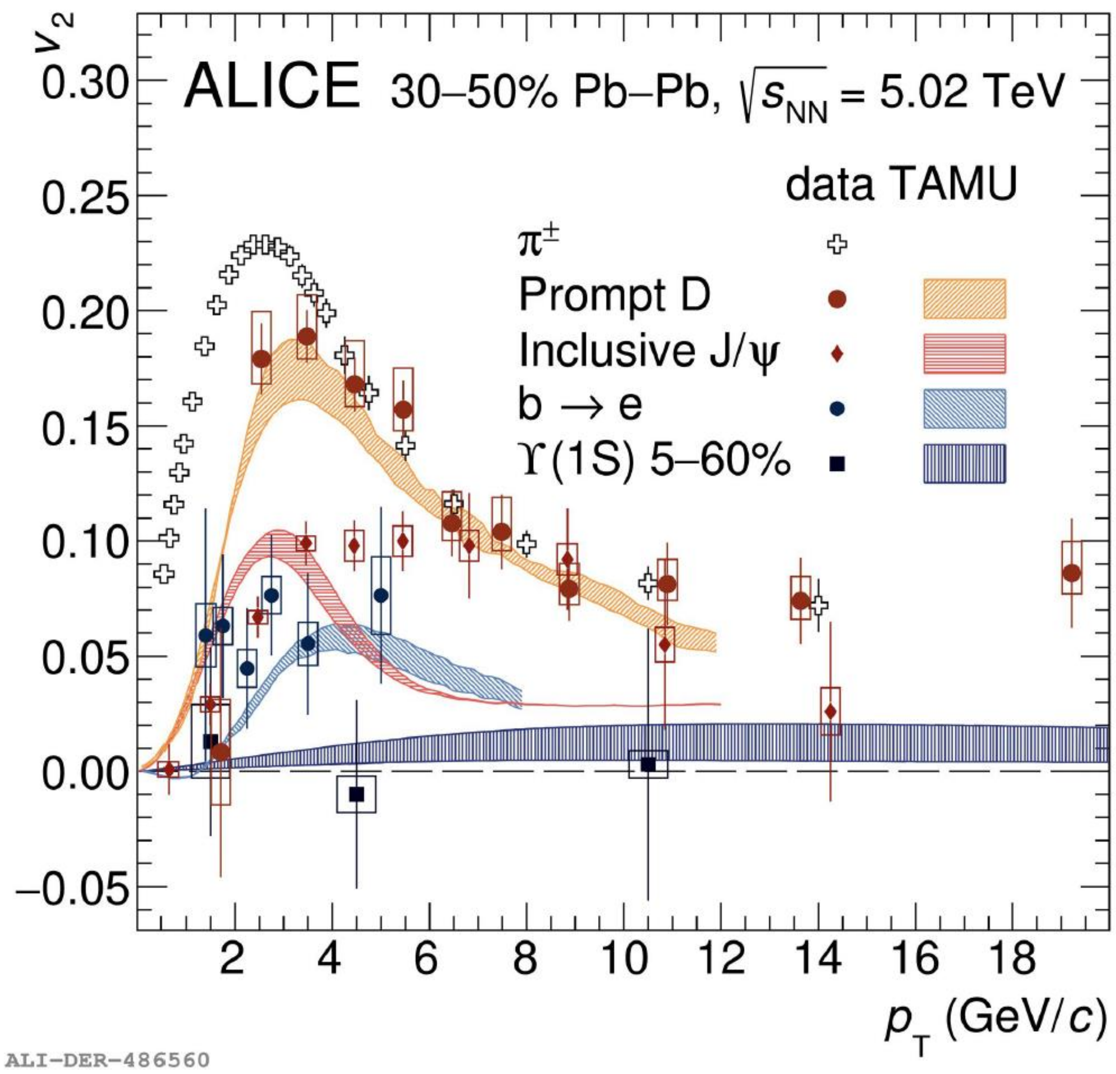


# Open charm and quarkonium v2

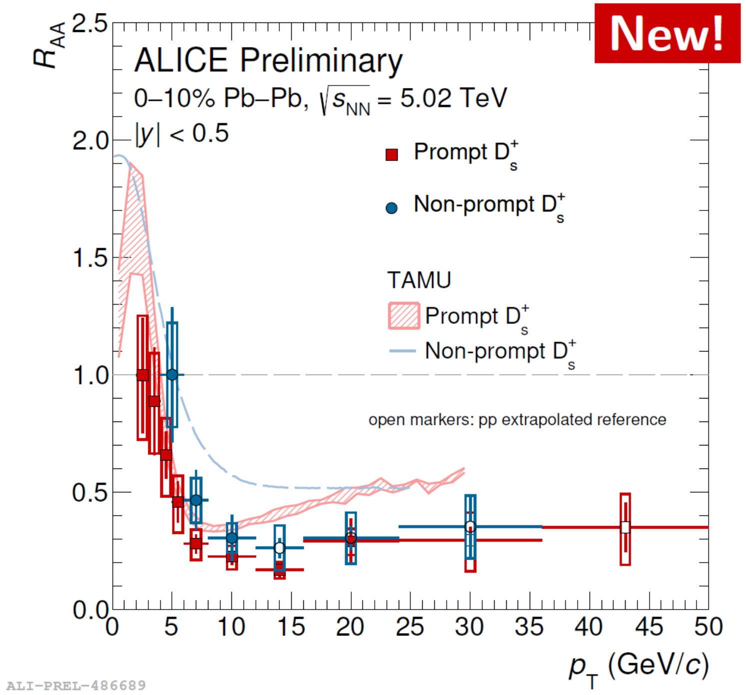
TAMU: M. He et al. PRL 124 042301 (2020) PHSD: T. Song et al. PRC 92 014910 (2015)

- The positive elliptic flow ($v_2$) of D and J/ψ mesons, shows they are strongly affected by the surrounding medium, participate in the collective motion
- $p_T$ dependence for D is similar to that for light flavor meson
- B->e also seems to flow
- But for Y(1S), v2 compatible with zero

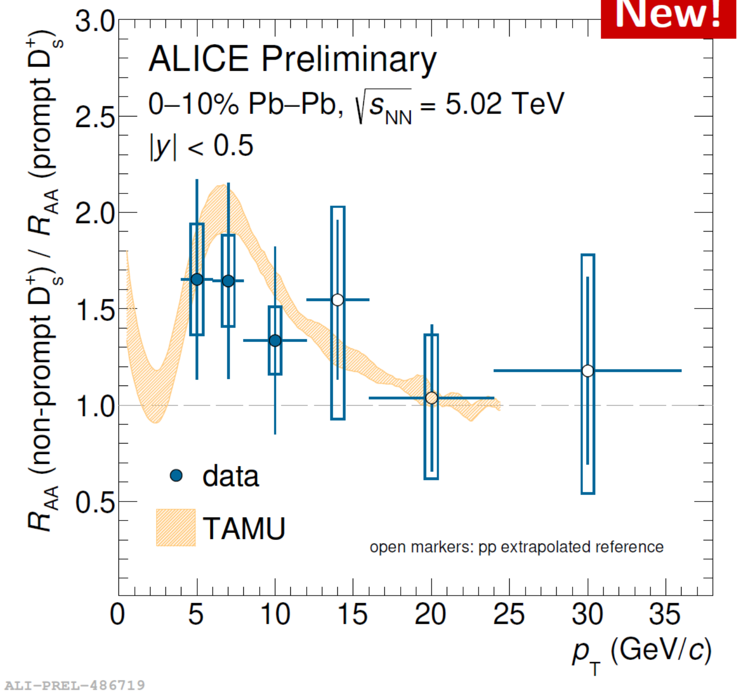


# Non-prompt (from B decay) D meson at ALICE

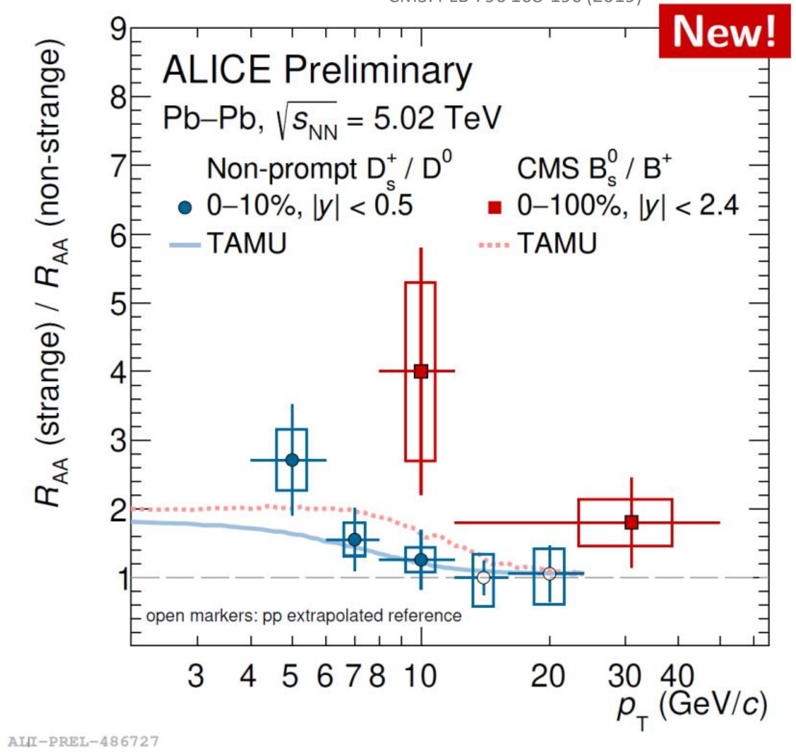
- A smaller suppression of the B-decay D meson $R_{AA}$ can be observed in central PbPb collisions
  - Interplay of charm and beauty energy loss in the medium
- Look B-decay (strange D)/(non-strange D) and (strange B)/(non-strange B):
  - both of the two ratios are above one, a double-enhancement.
  - Strange B has a larger enhancement than strange D




TAMU: M. He et al. PLB 735 445-450 (2014)

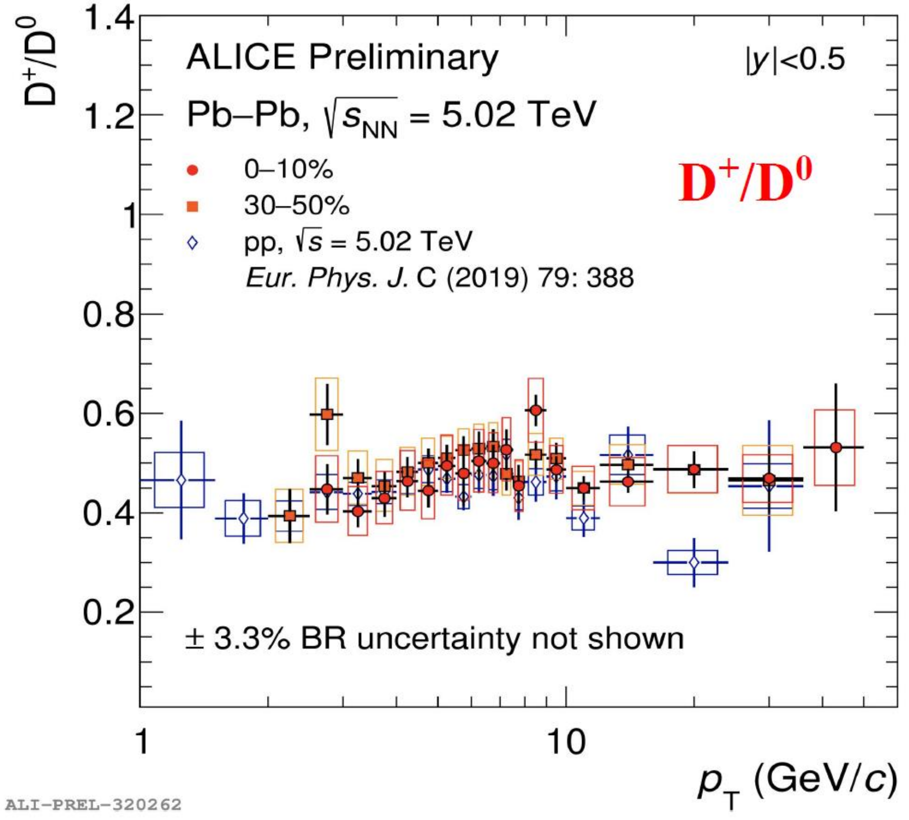


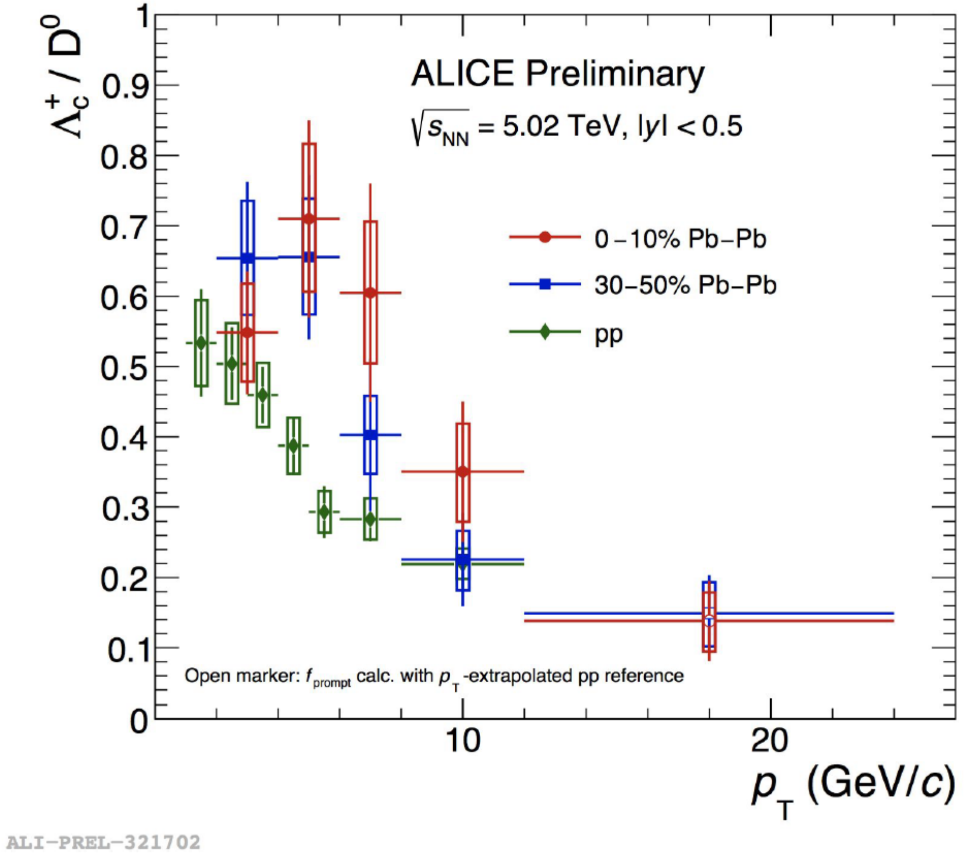

CMS: PLB 796 168-190 (2019)



# $D_s^+/D^0$ ratio and $\Lambda_c/D^0$ ratio

- Larger $D_s^+/D^0$ in Pb-Pb: due to the strangeness enriched QGP medium
- Λc/D0 ratio shows a large enhancement in QGP=> enhanced recombination with light quarks.

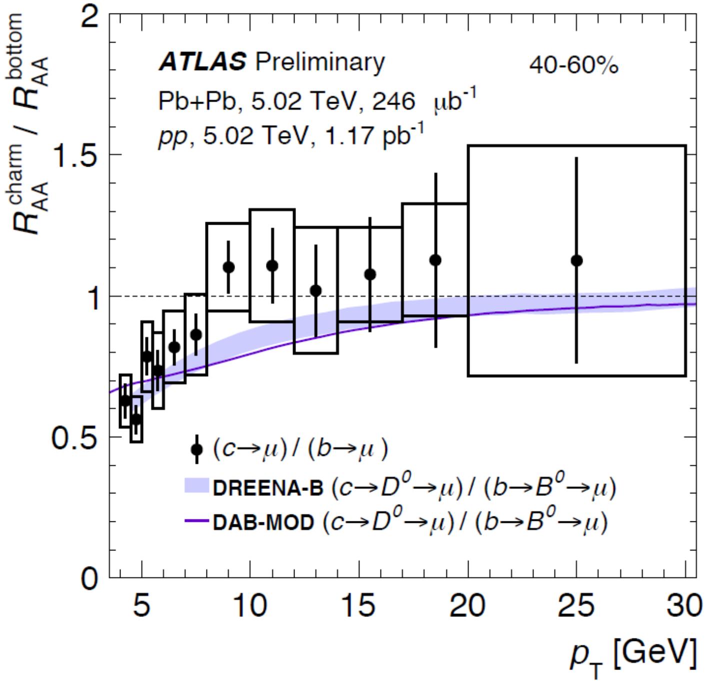


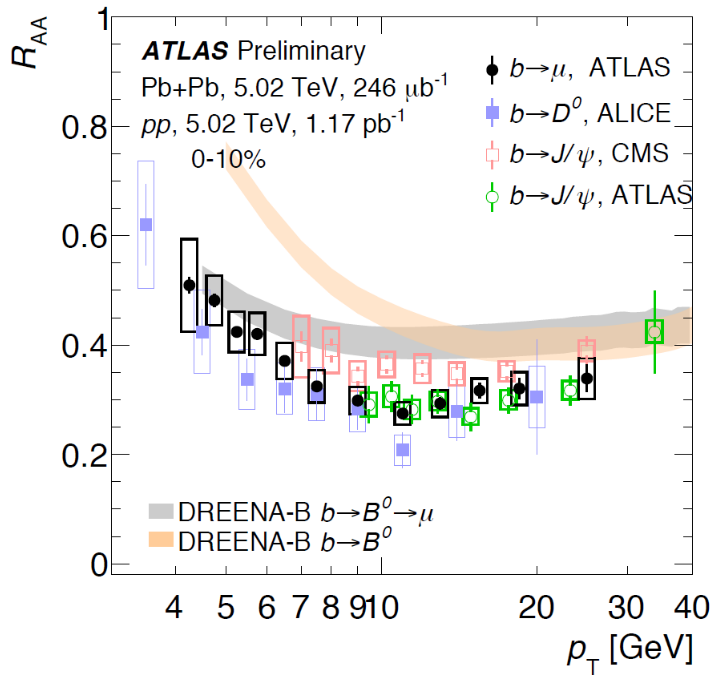



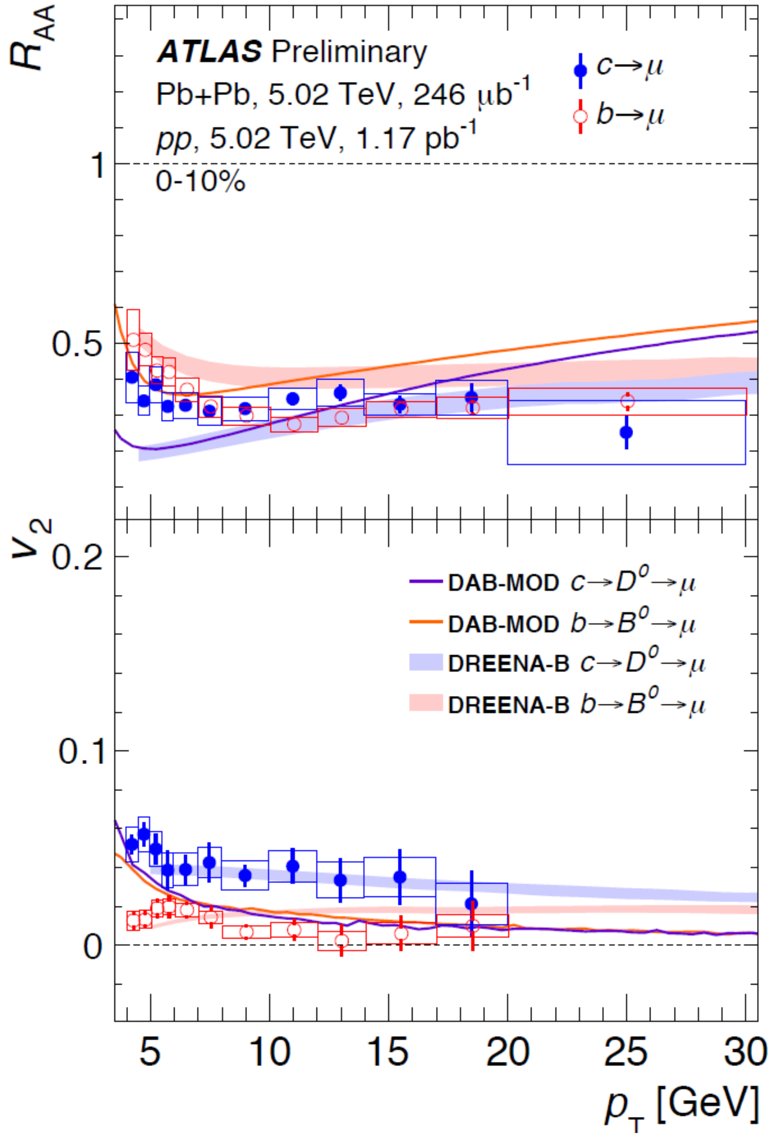
# Charm and bottom at ATLAS

**0-10%**

- Simultaneous measurement of $R_{AA}$ and v2.
- Suppression is stronger in high pT for both charm and bottom
- Bottom is less suppressed than charm, similar observation as in ALICE
- Less suppressed ⇔ smaller interaction with QGP, thus the elliptic flow v2 for bottom is smaller than charm.



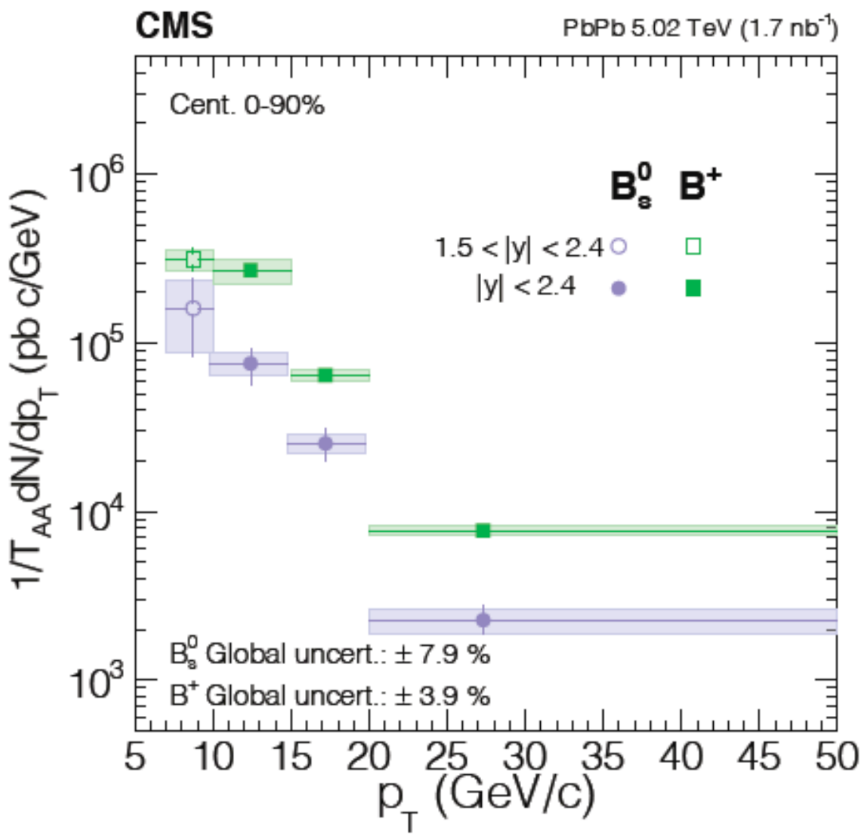



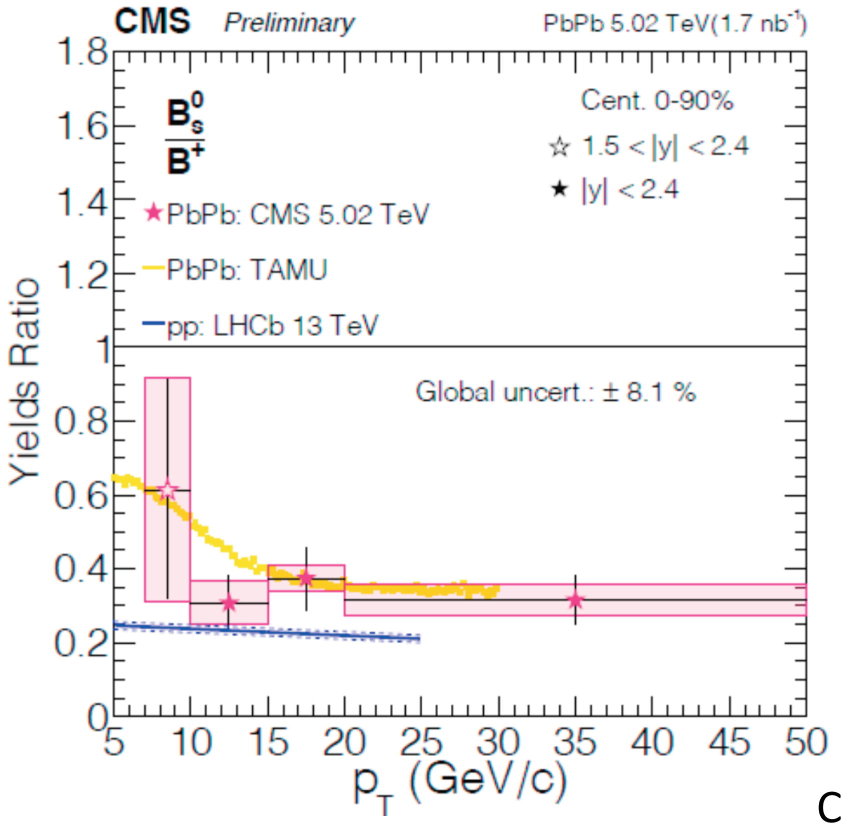




*Phys. Lett. B 807 (2020) 135595 ($v_2$, $v_3$) ATLAS-CONF-2021-020* ($R_{AA}$)

# Strange bottom and non-strange bottom at CMS

- Similar to the charm, strange bottom and non-strange bottom are also measured.
- The first result from CMS shows the ratio of the yields between strange bottom and non-strange bottom is statistical compatible with each other.
- No direct $R_{AA}$ comparison is given yet.



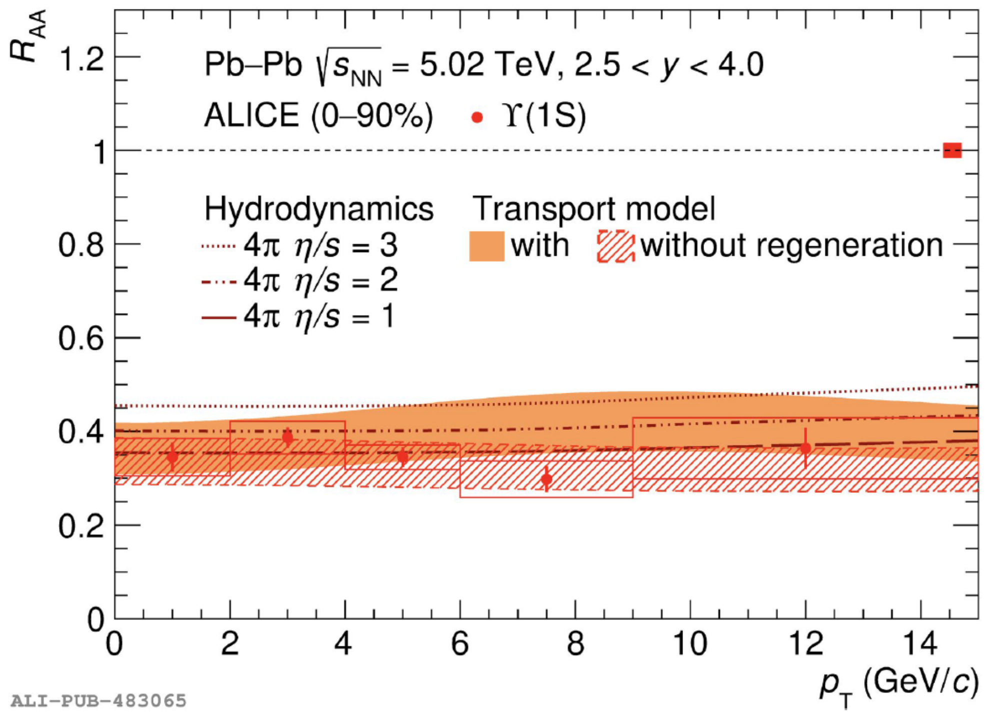



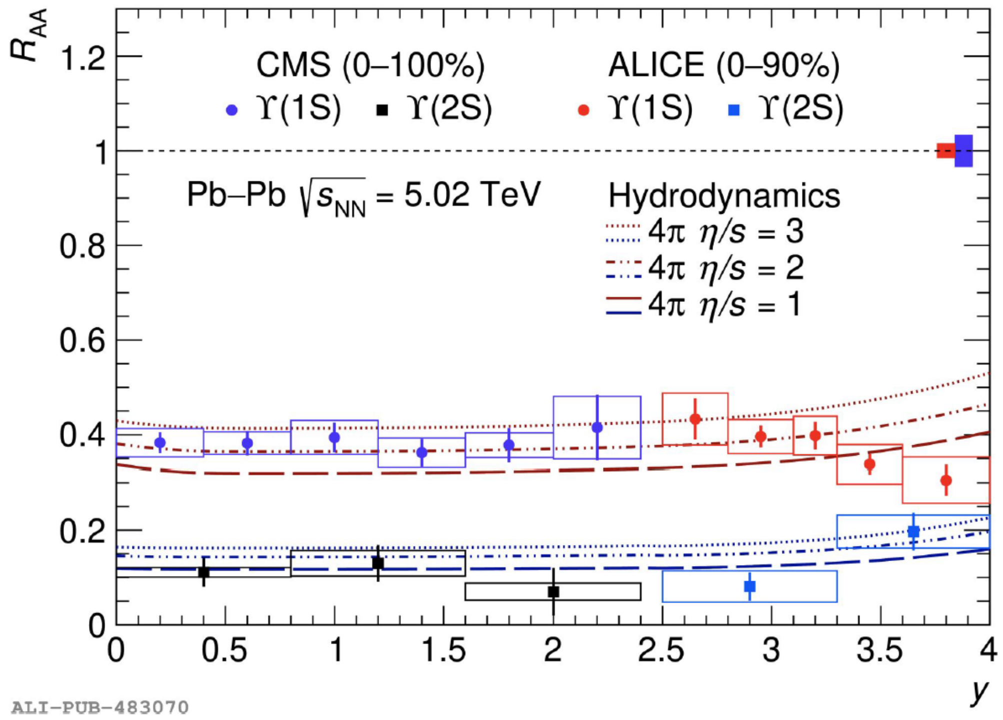

CMS-HIN-19-011

# Υ(1S) and Υ(2S) $R_{AA}$ in Pb-Pb

ALICE: arxiv:2011.05758
TAMU: PRL 124 (2020) 042301
Hydro: Universe 2016, 2(3), 16

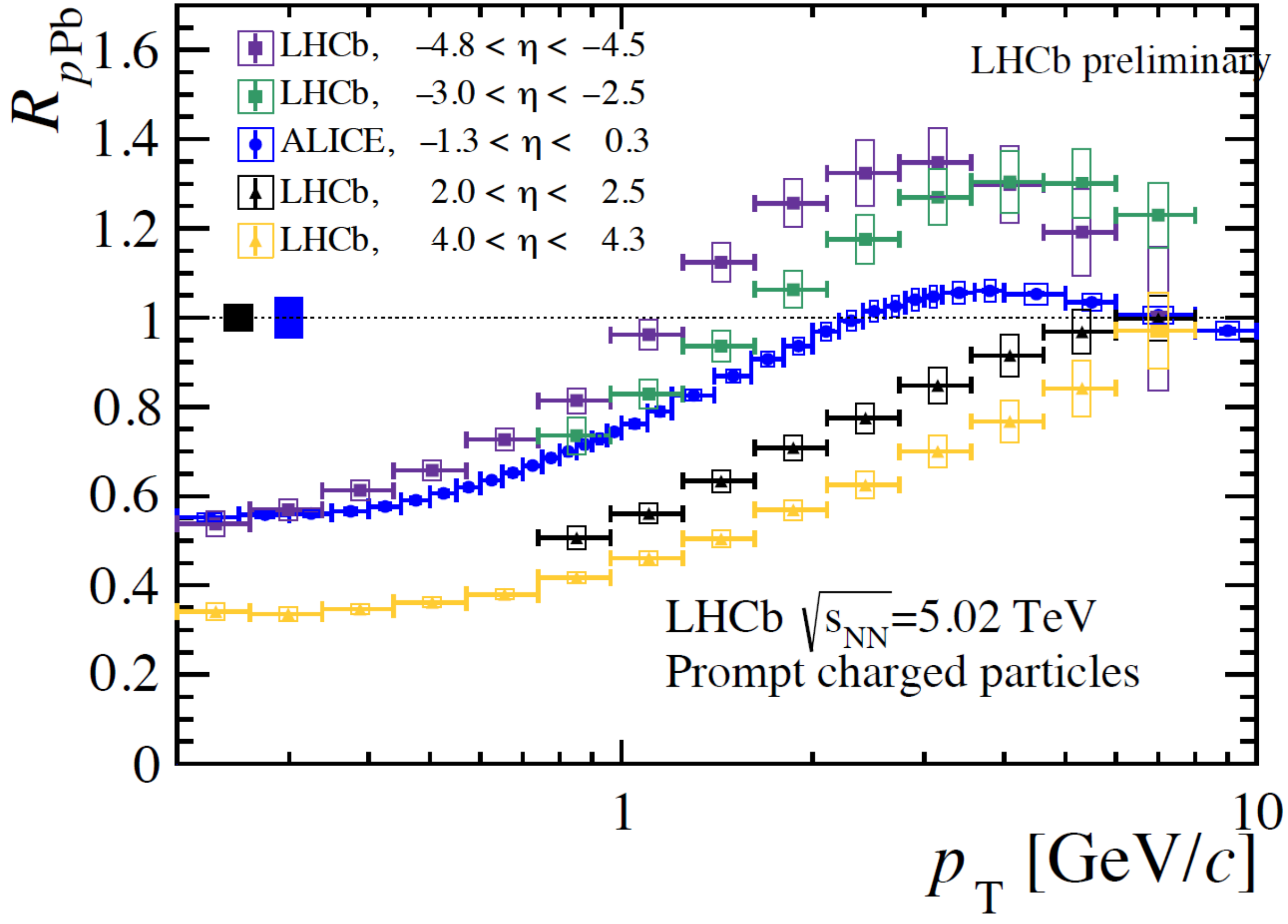
- Flat suppression vs pT for Υ(1S) - transport and hydro models describe the data
- ALICE data complement CMS results,
- Large suppression for both Υ(1S) and Υ(2S) , and Υ(1S) < Υ(2S).



# Small system: Prompt charged hadrons production in pPb and pp collisions at 5 TeV

- Since the heavy flavor hadrons are produced in the initial hard scattering, it is important to well constrain the initial states.
- Charged hadron production in pPb/pp collisions:
  - Probes the initial state cold nuclear matter (CNM) effects, such as nuclear shadowing, gluon saturation, kT broadening, etc., constraining nPDFs
- New results from LHCb highly extended the $R_{pPb}$ coverage from very backward rapidity to very forward rapidity.




*LHCb-PAPER-2021-015, in preparation*

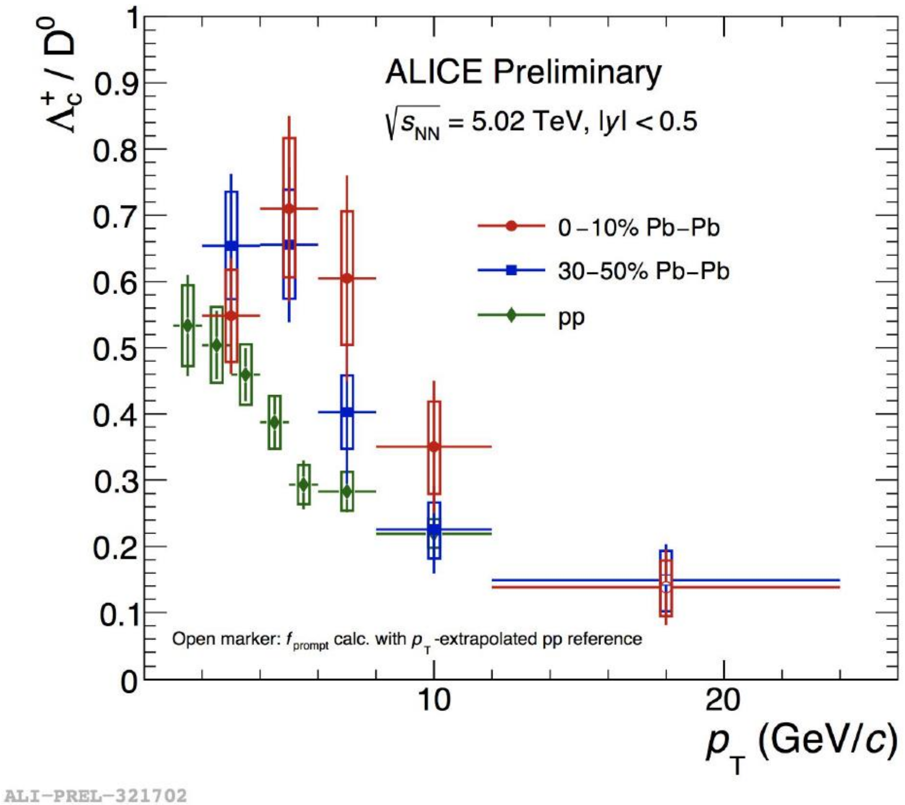
# Summary

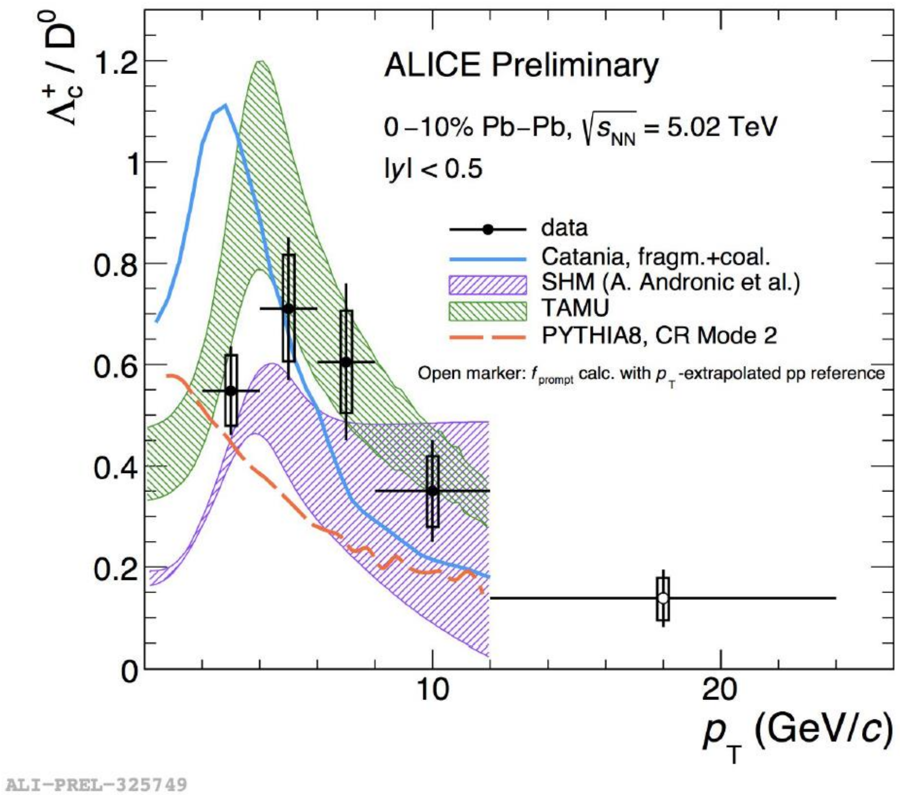
- The main goal (at the moment) of heavy ion physics is to study the properties of QGP and how it interacts with particles.
- Mesons are major probes for heavy ion studies:
  - Light flavor (u, d, s) mesons: soft probes of the QGP contents and dynamics.
  - Heavy flavor mesons (open charm/bottom & quarkonium): Hard probes of initial state and QGP properties:
- A short review of the role of mesons in heavy ion collisions and how they are produced in and interacting with the quark matter. A selection of recent results from LHC experiments are presented.
- There are of course many interesting topics concerning mesons and heavy ion physics not able to be included in this talk, such as
  - Reach program of probing the CNM, collectivity also studied in small systems, study the X(3872) in heavy ion env, and the important light-induced UPC physics., etc…

# Backups

# Λc/D0 yield ratio in Pb-Pb

- Λc/D0 ratio in heavy-ion collisions allows investigating the possible modification of the charm fragmentation → hint of an enhancement wrt pp via recombination with light quark in the QGP
- The Λc/D0 ratio is best described by models which implement heavy-quark hadronisation via coalescence and fragmentation in the QGP



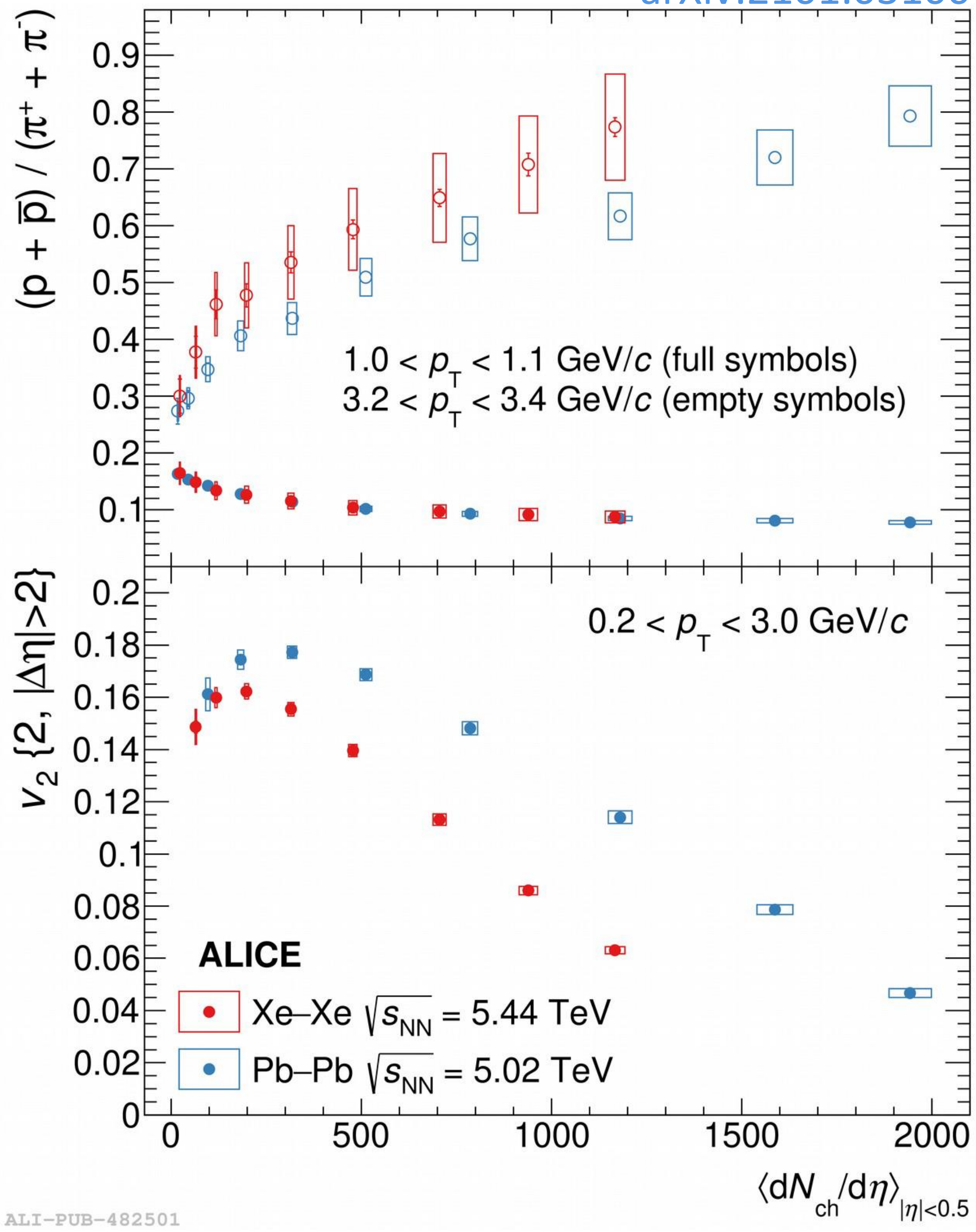




Catania: EPJC (2018) 78:348
SHMc: arxiv:2104.12754
TAMU: PRL 124 (2020) 042301

arXiv:2101.03100

# Testing elliptic vs radial flow

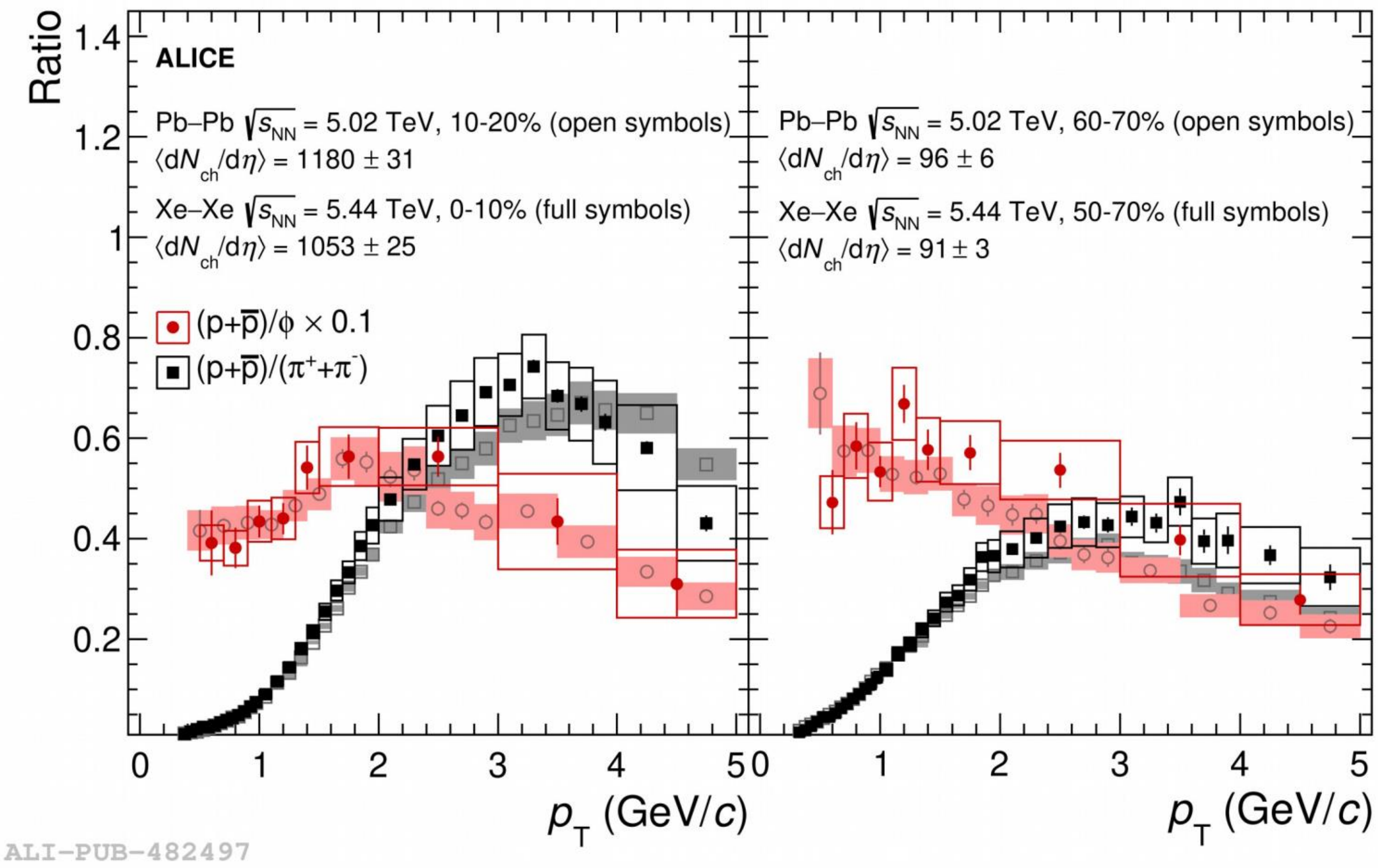
- Depletion/enhancement of the p/pi ratio as a proxy to account for the radial flow
- Radial flow in Xe-Xe and Pb-Pb at the same multiplicity is in agreement
- Elliptic flow in the two systems at the same multiplicity is quite different (different geometry)



# Baryon/meson ratio: Pb-Pb vs Xe-Xe

- At the same multiplicity baryon/meson ratios agree in Pb-Pb and Xe-Xe
- Radial flow independent on the collision system
- Flat p/ϕ ratio: radial flow driven by particle mass instead of quark content
- Radial flow magnitude decreases in peripheral collisions (lower multiplicity)

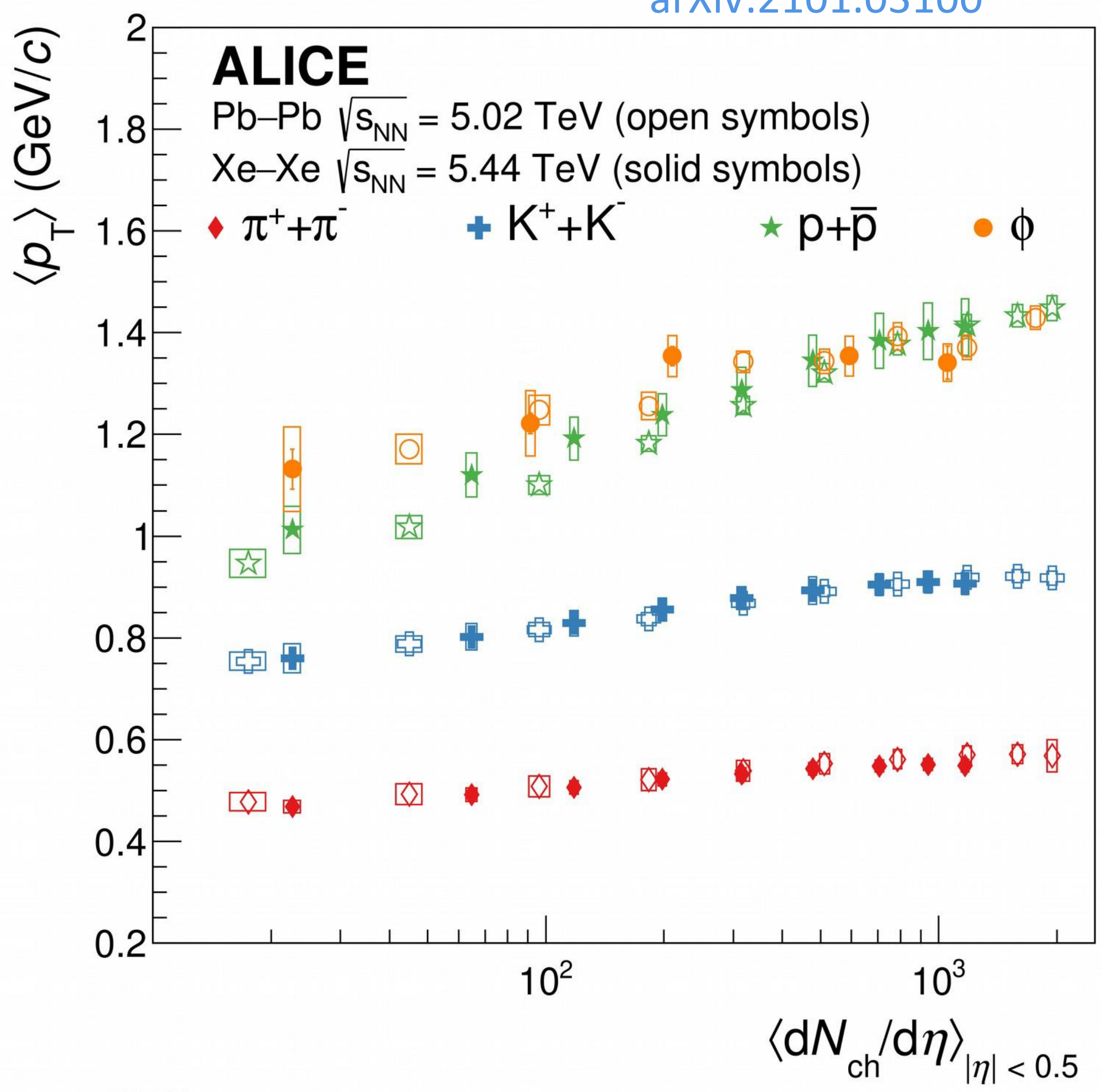
arXiv:2101.03100



# <pT> Pb-Pb vs Xe-Xe and mass dependence

- <pT> increases with charged particle multiplicity: more radial flow at high multiplicity
- Larger relative increase for heavier particles (steeper rise): mass dependent hardening
- Similar <pT> trend for p and ϕ (mp ~ 0.938 GeV/c2 mf ~ 1.019 GeV/c2)
- The comparison to Pb-Pb shows that charged particle multiplicity is the scaling property: same dynamics in different systems

arXiv:2101.03100

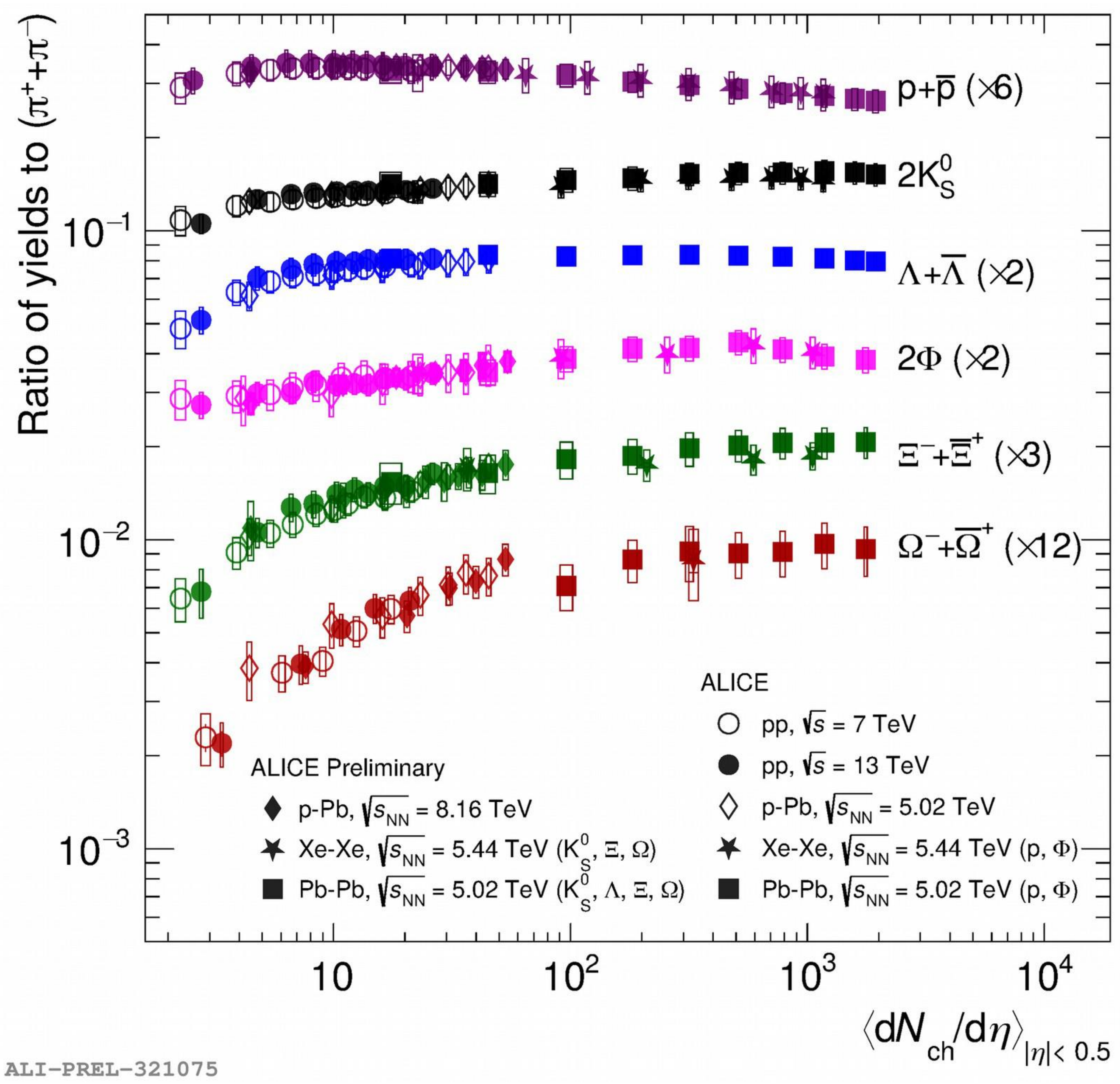


# Mesons are discussed almost everywhere in the heavy ion physics!

- Mesons are major probes for heavy ion studies:
  - Soft probes of the QGP dynamics:
    - Light flavor (u, d, s) mesons
  - Hard probes of initial state and QGP properties:
    - Heavy flavor mesons (open charm/bottom & quarkonium)
- A short review of the role of mesons in heavy ion collisions, and how they are produced in and interacting with the quark matter.
- A selection of results from LHC experiments will be presented.

# Hadrochemistry: from small to large systems

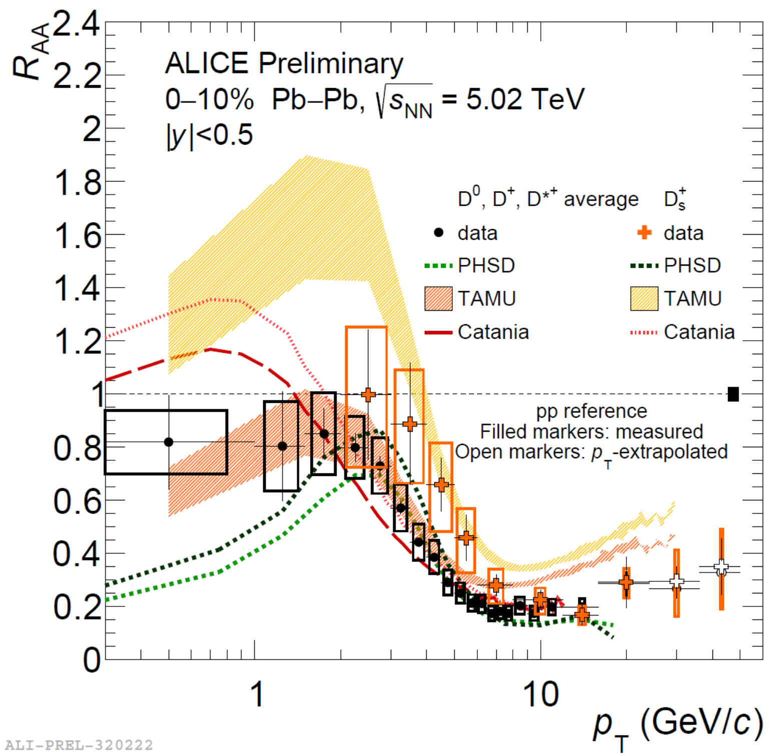
- At LHC energies continuous evolution is observed also when considering small systems (pp and p-Pb)
- In pp, p-Pb, Xe-Xe and Pb-Pb the charged particle multiplicity is a good scaling observable to describe particle production
- Steeper increase in particles with more strangeness content indicating that the strangeness enhancement starts at the
- charged particle multiplicity reached in small systems

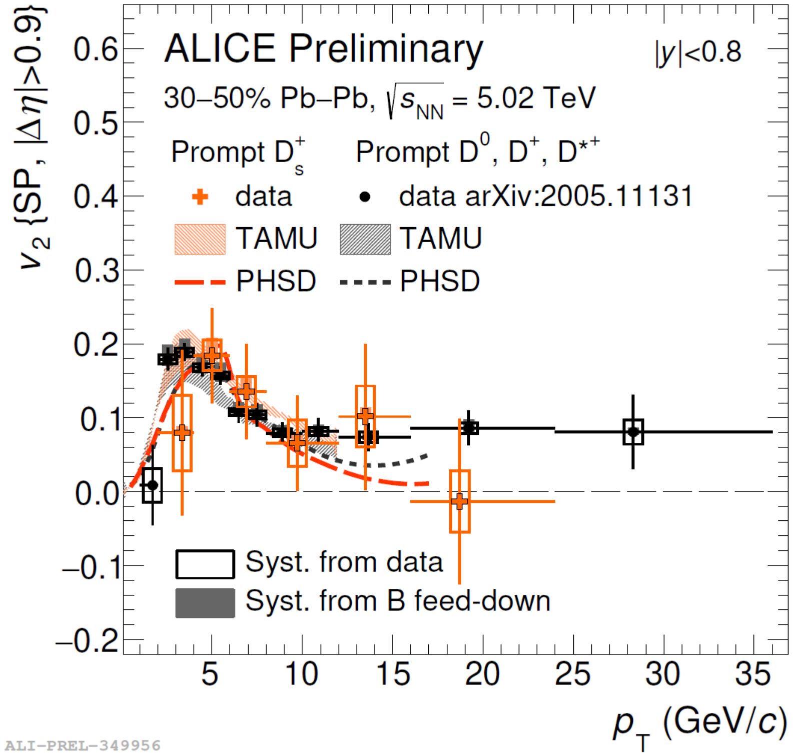


# Strange and non-strange D meson at ALICE

TAMU: M. He et al. PRL 124 042301 (2020) PHSD: T. Song et al. PRC 92 014910 (2015)

- Strong suppression of D meson $R_{AA}$ can be observed in central PbPb collisions at high $p_T$:
  - due to energy loss in the QGP medium
- A reduced suppression (or enhanced coalescence) of $D_s$ can be observed w.r.t. non-strange D meson at low $p_T$ :
  - due to the enhanced strangeness in the QGP medium
- The positive elliptic flow ($v_2$) of the D meson is a clear indication that the D mesons inherited the collectivity motion of the QGP



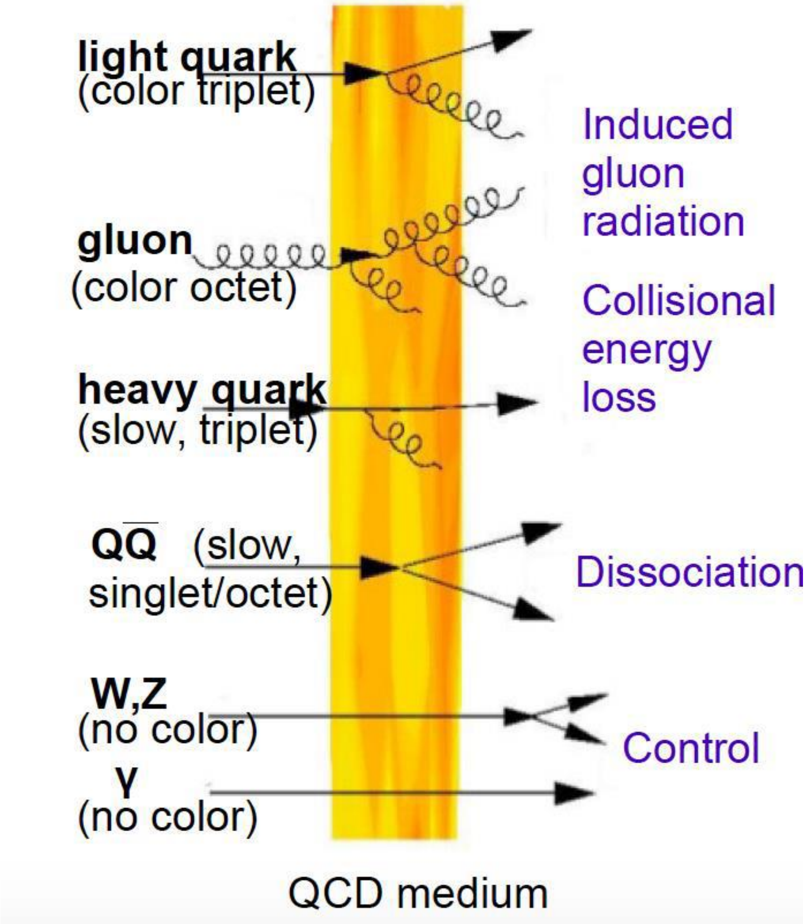



# Mesons are discussed almost everywhere in the heavy ion physics!

- Mesons are major probes for heavy ion studies:
  - Soft probes of the QGP dynamics:
    - Light flavor (u, d, s) mesons
  - Hard probes of initial state and QGP properties:
    - Heavy flavor mesons (open charm/bottom & quarkonium)
  - Photon induced production to probe cold nuclear matter effects:
    - Mesons from ultra- peripheral collisions (UPC)
- A short review of the role of mesons in heavy ion collisions, and how they are produced in and interacting with the quark matter.
- A selection of results from LHC experiments will be presented.

# Role of mesons in heavy ion collisions

- Light flavor (u, d, s) mesons
  - Soft probes of QGP properties: particle chemistry, QCD critical point, radial & elliptic flows, etc.
- Heavy flavor mesons (open charm/bottom & quarkonium):
  - Hard probes of the initial state and QGP properties: PDF/nPDFs, thermalization & coalescence, dissociation & recombination, etc..
- Mesons ultra- peripheral collisions:
  - Photon induced production, to probe cold nuclear matter effects such as nuclear shadowing, etc..



# Mesons produced in ultra-peripheral collisions (UPC)

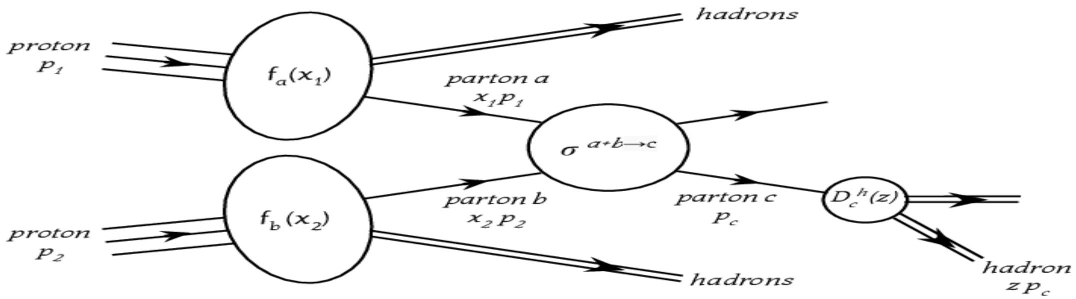
# Interactions with QGP: open charm/bottom & quarkonium

- Open charm and bottom:
  - Suppression: energy loss (thermalization):
    - Collisional energy loss: elastic scattering, dominate at low momentum
    - Radiative energy loss: inelastic scattering, gluon bremsstrahlung, dominate at high momentum
    - Quark mass and color charge dependence, energy loss: b < c < u,d,s < gluon
  - Enhancement: coalescence/recombination depends on enriched surrounding quarks in the medium, e.g.
    - $D$ and $\Lambda_c$ compensate part of the suppression.
    - QGP enables gluon fusion process (gg->ss/cc)<br>=> enriches s and c quarks in the medium<br>=> larger enhancement of $D_s$ than non-strange D mesons.

- Charmonium and bottonium
  - Suppression: dissociation (not energy loss!)
    - Collisional energy loss: elastic scattering, dominate at low momentum
    - Radiative energy loss: inelastic scattering, gluon bremsstrahlung, dominate at high momentum
    - Quark mass and color charge dependence, energy loss: b < c < u,d,s < gluon
  - Enhancement: coalescence/recombination depends on enriched surrounding quarks in the medium, e.g.
    - $D$ and $\Lambda_c$ compensate part of the suppression.
    - QGP enables gluon fusion process (gg->ss/cc)<br>=> enriches s and c quarks in the medium<br>=> larger enhancement of $D_s$ than non-strange D mesons.

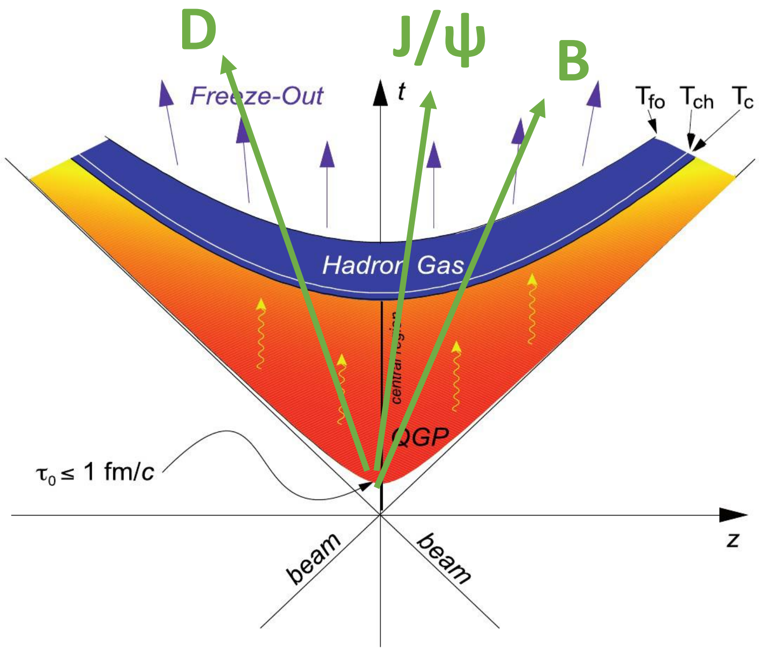
# Heavy flavor mesons: open charm/bottom & quarkonium

- Heavy flavor (c, b) mesons are produced in initial hard scattering before the QGP formation.
    - $\tau_{HF}$ (≈ 0.05 – 0.1 fm/c) < $\tau_{QGP}$ (≈ 0.3 fm/c at LHC)
- Production in small system (pp, pA) probes the initial state cold nuclear matter (CNM) effects:
    - Nuclear shadowing, gluon saturation, $k_T$ broadening, etc., constraining nPDFs.
- Production in large system (AA), hard probes of the QGP properties.
- Open charm/bottom:
    - Suppression through energy loss (thermalization):
        - Low pT, collisional elastic scattering
        - High pT, radiative inelastic (gluon bremsstrahlung)




**PDFs/nPDFs** ⊗ **Hard scatter** ⊗ **Fragmentation**

**Non-perturbative** **perturbative** **Non-perturbative**

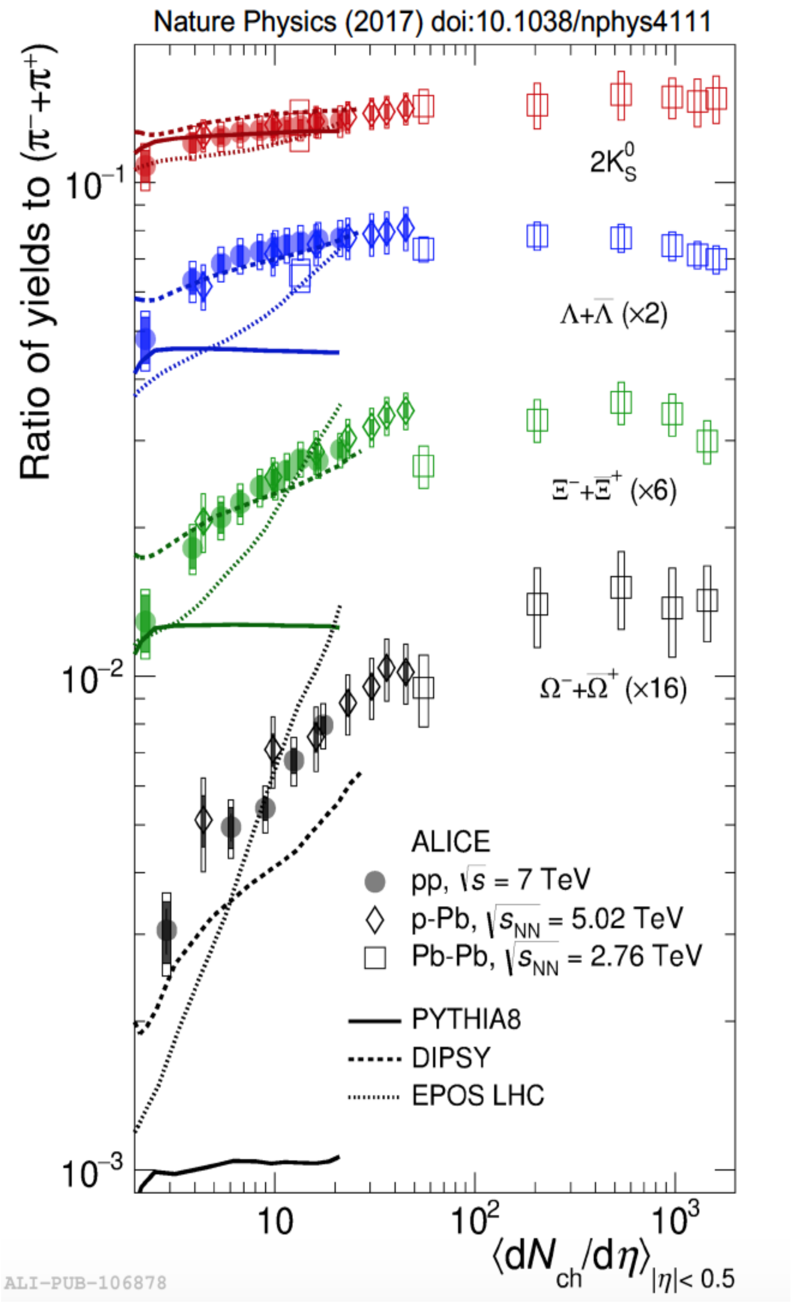


# Scope of this talk

- This scope I received from the organizers is big!
- A short overview of the meson properties and the role/application of mesons in ultra-relativistic heavy ion collisions
- A selection of recent results from LHC (cannot show all of them).
- Mesons are major probes for heavy ion studies:
  - Light flavor (u, d, s) mesons :
    - Soft probes of QGP properties: particle chemistry, QCD critical point, radial & elliptic flows, etc.
  - Heavy flavor mesons (open charm/bottom & quarkonium):
    - Hard probes of initial state and QGP properties: PDF/nPDFs, thermalization & coalescence, dissociation & recombination, etc..
  - Mesons from Ultra- peripheral collisions:
    - Photon induced production, to probe cold nuclear matter effects such as nuclear shadowing, etc..

# Scope of this talk

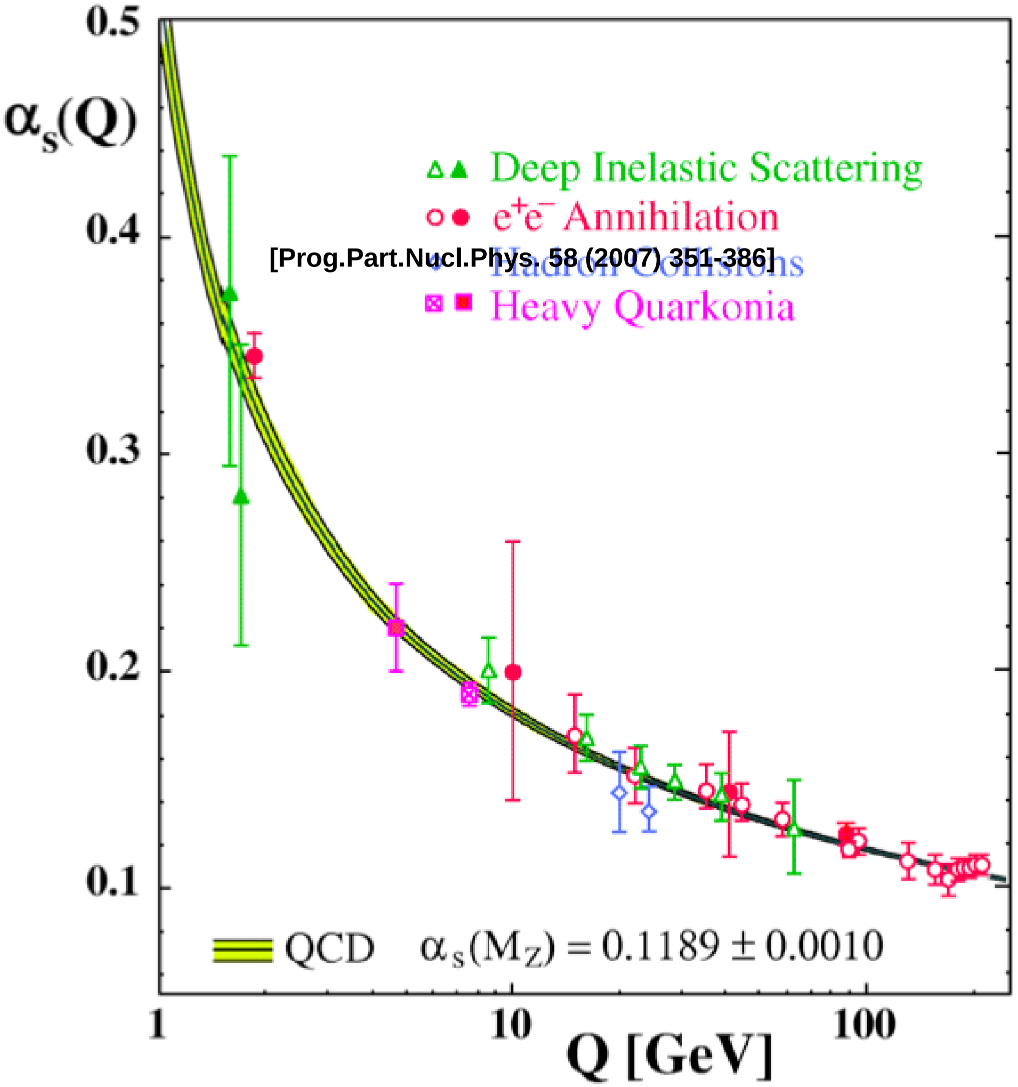
- This scope I received from the organizers is big!
- A short overview of the meson properties and the role/application of mesons in ultra-relativistic heavy ion collision physics.
- A selection of recent results from LHC (cannot show all of them).
- Mesons are major probes for heavy ion studies:
  - Light flavor (u, d, s) mesons :
    - Soft probes of QGP properties
  - Heavy flavor mesons (open charm/bottom & quarkonium):
    - Hard probes of initial state and QGP properties
  - Mesons from Ultra- peripheral collisions:
    - Photon induced production to probe cold nuclear matter effects

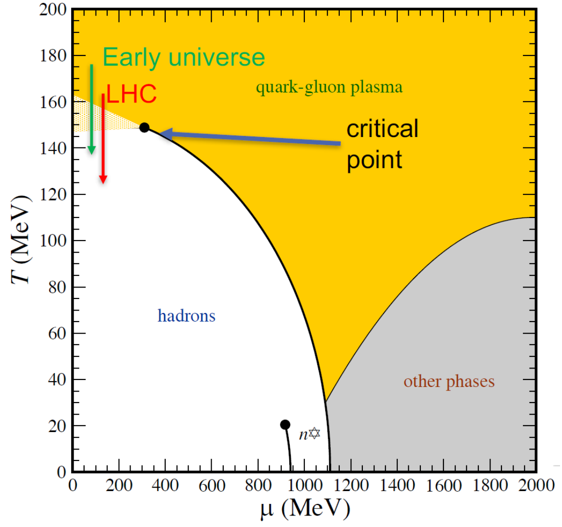

Nature Physics (2017) doi:10.1038/nphys4111
Ratio of yields to $(\pi^-+\pi^+)$
$2K^0_S$
$\Lambda+\bar{\Lambda}$ (×2)
$\Xi^-+\bar{\Xi}^+$ (×6)
$\Omega^-+\bar{\Omega}^+$ (×16)
ALICE
pp, $\sqrt{s}$ = 7 TeV
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
PYTHIA8
DIPSY
EPOS LHC
$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$
ALI-PUB-106878

# QCD, color confinement, asymptotic freedom, and QGP

- Heavy ion physics: high energ
QCD.
- Quark-Gluon-Plasma (QGP): a
temperatures and densities c
gluons behave quasi-free anc
localized to individual hadror

*Confinement: Quarks and gluons are bound in color neutral mesons or baryons*



# Introductory remarks

- LHCb-CONF-2019-003, Twiki page, LHCb-ANA-2019-037,
- As concluded in the Collaboration Approval of the CONF note above, the following tasks are requested to be finished before going to paper:
  - [done] Change to use nVeloClusters for multiplicity reweighting (a better variable)
  - [done] Understood and fixed the issue that two methods double-counted part of the background contributions.
  - [preliminary] Provide results in rapidity bins
  - [ongoing] Add RpA in rapidity bins
  - [done] Fix issue in nPDF uncertainties in FEWZ theoretical prediction, i.e. default FEWZ codes cannot use PDF for proton beam and nPDF for Pb beam at the same time. (CONF note quoted PbPb uncertainties instead of pPb uncertainties)
- Beside the requested tasks, we also plan to add the following results:
  - [ongoing] add diff x-sec and RpA in pT(Z) bins and phi* bins.