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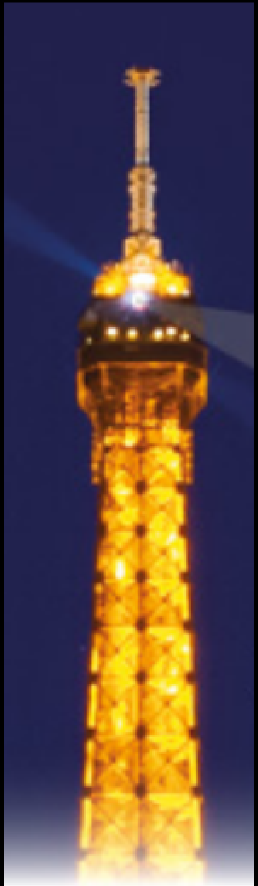
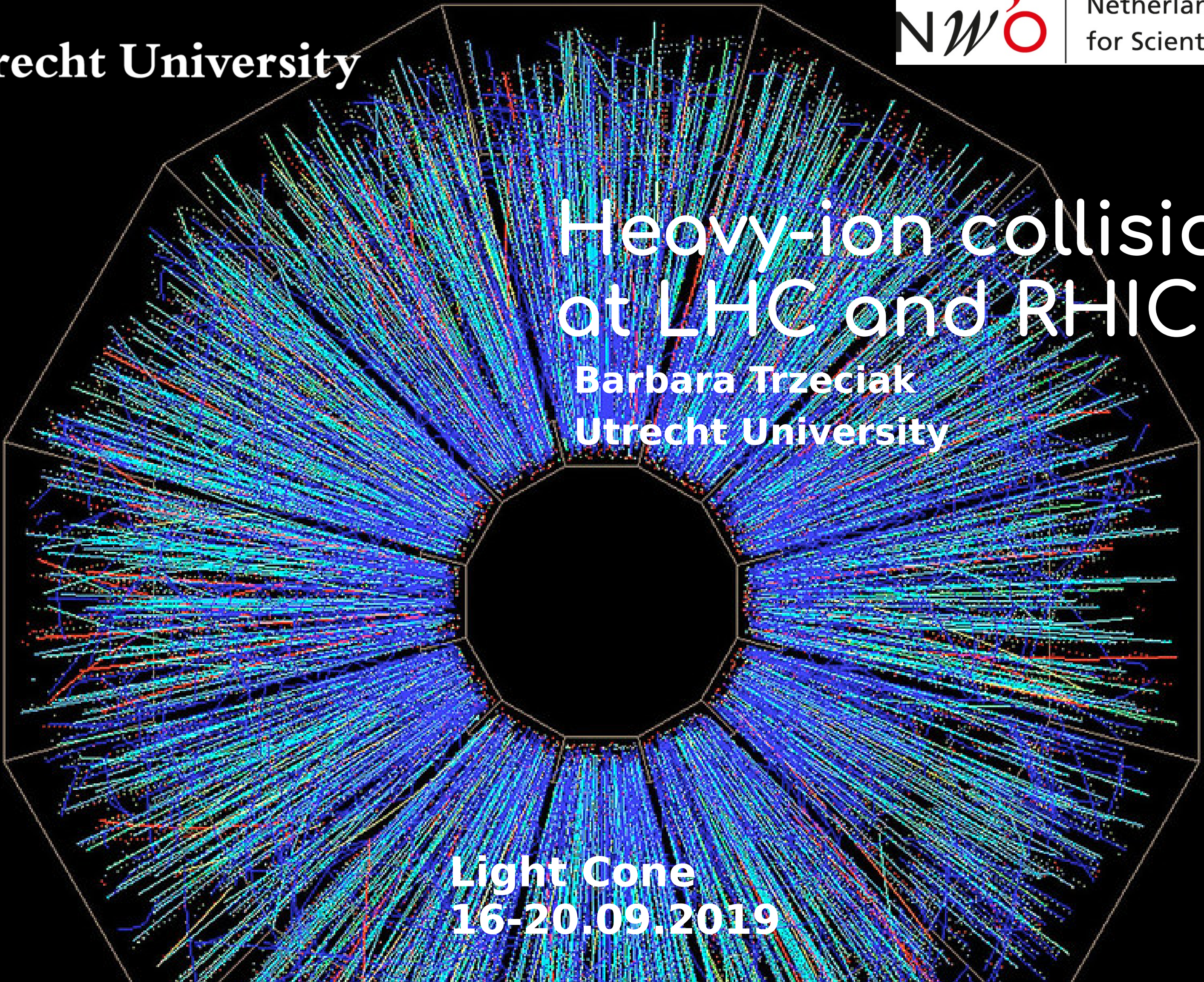


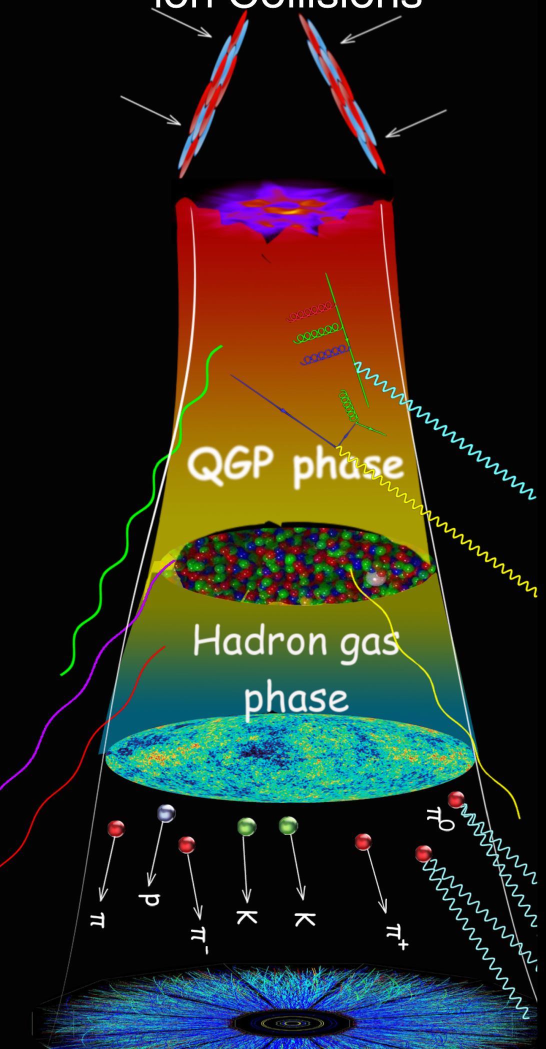


Heavy-ion collisions at LHC and RHIC

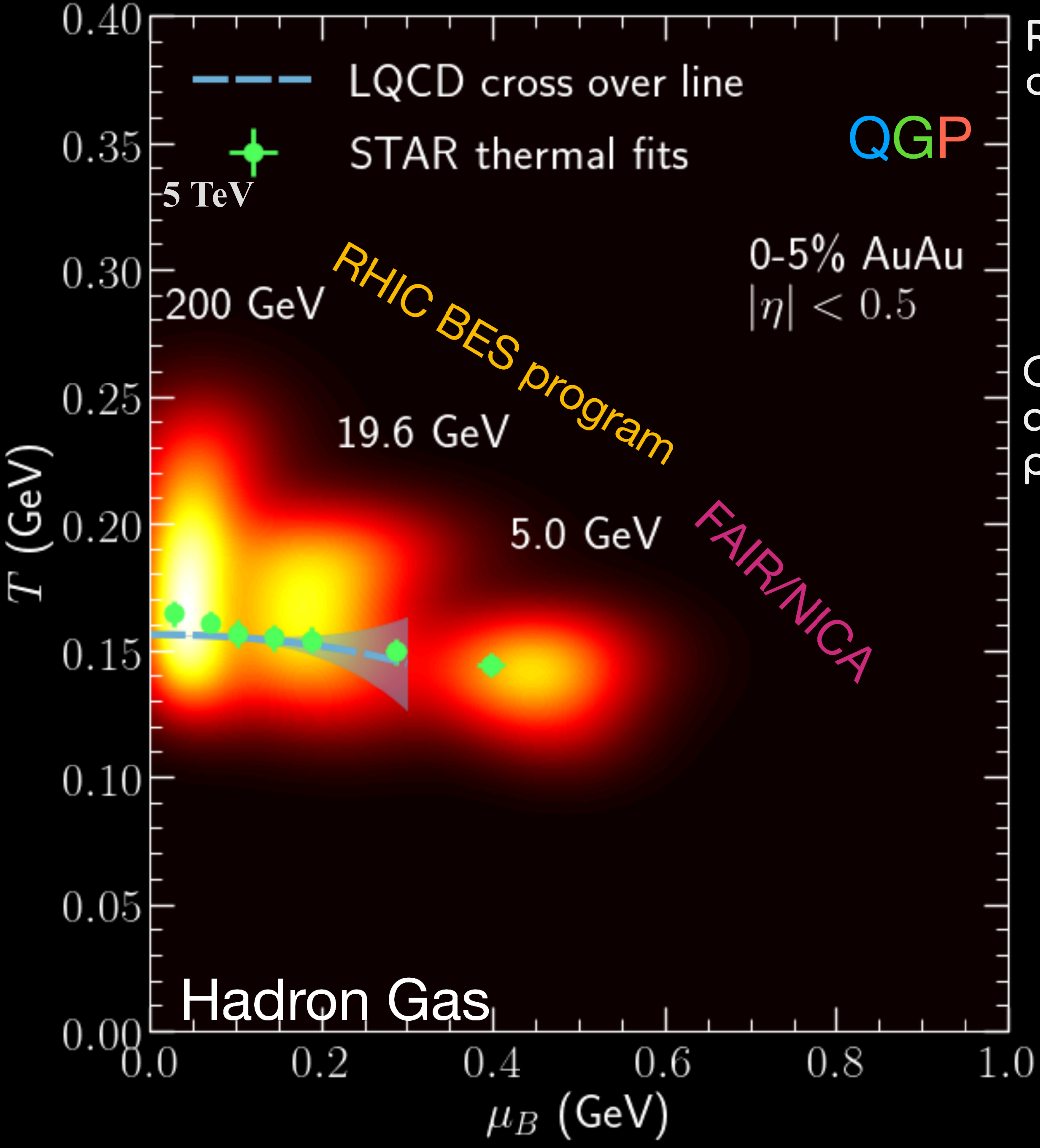
Barbara Trzeciak
Utrecht University

Light Cone
16-20.09.2019

Relativistic Heavy-ion Collisions



made by Chun Shen



Relativistic Heavy-ion collisions:

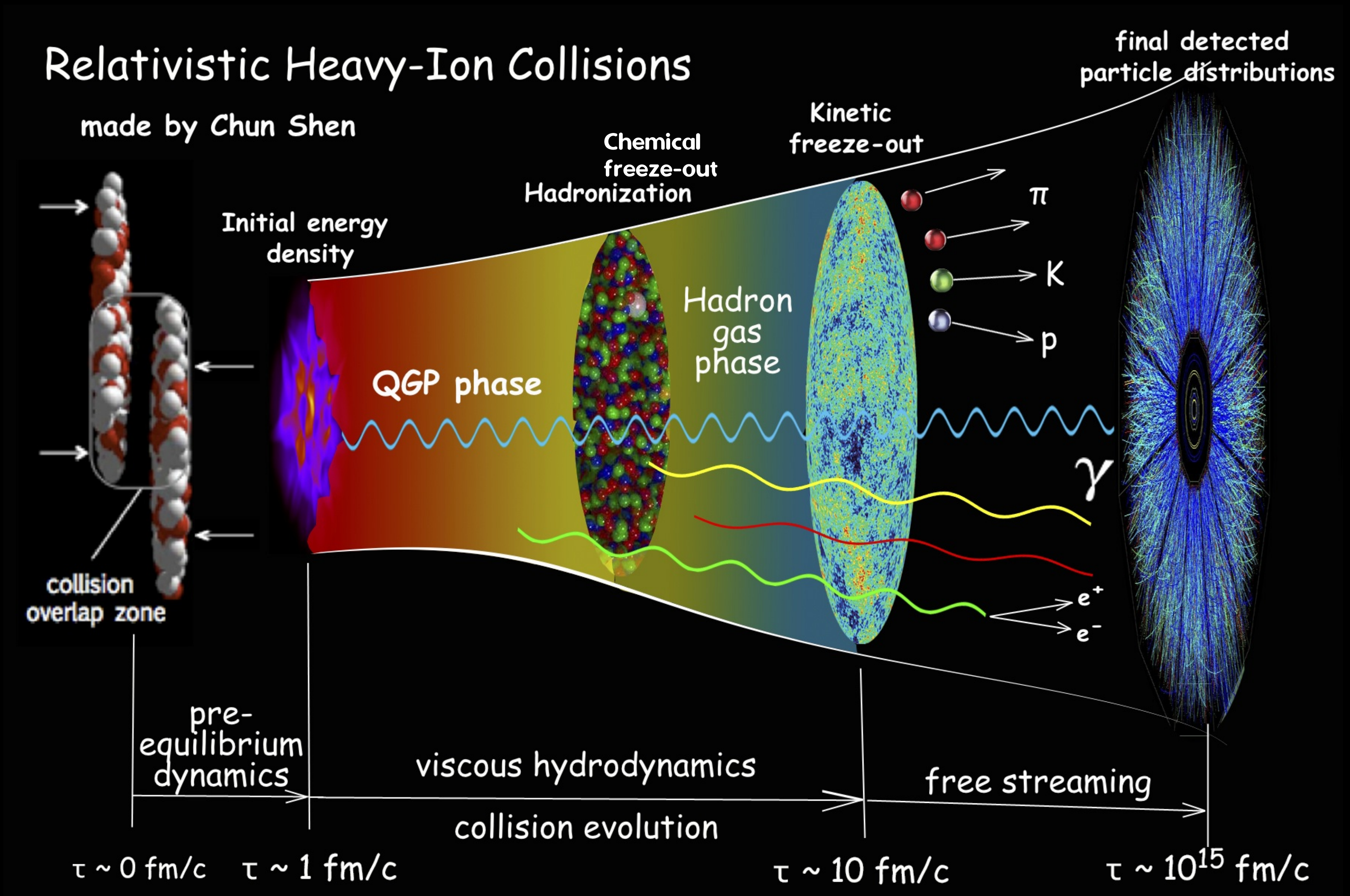
- unique tool to create and study hot QCD matter and its phase transition under controlled conditions

One of the fundamental questions in QCD phenomenology:

- *what are properties of strongly-interacting matter at extreme conditions of temperature and energy density*

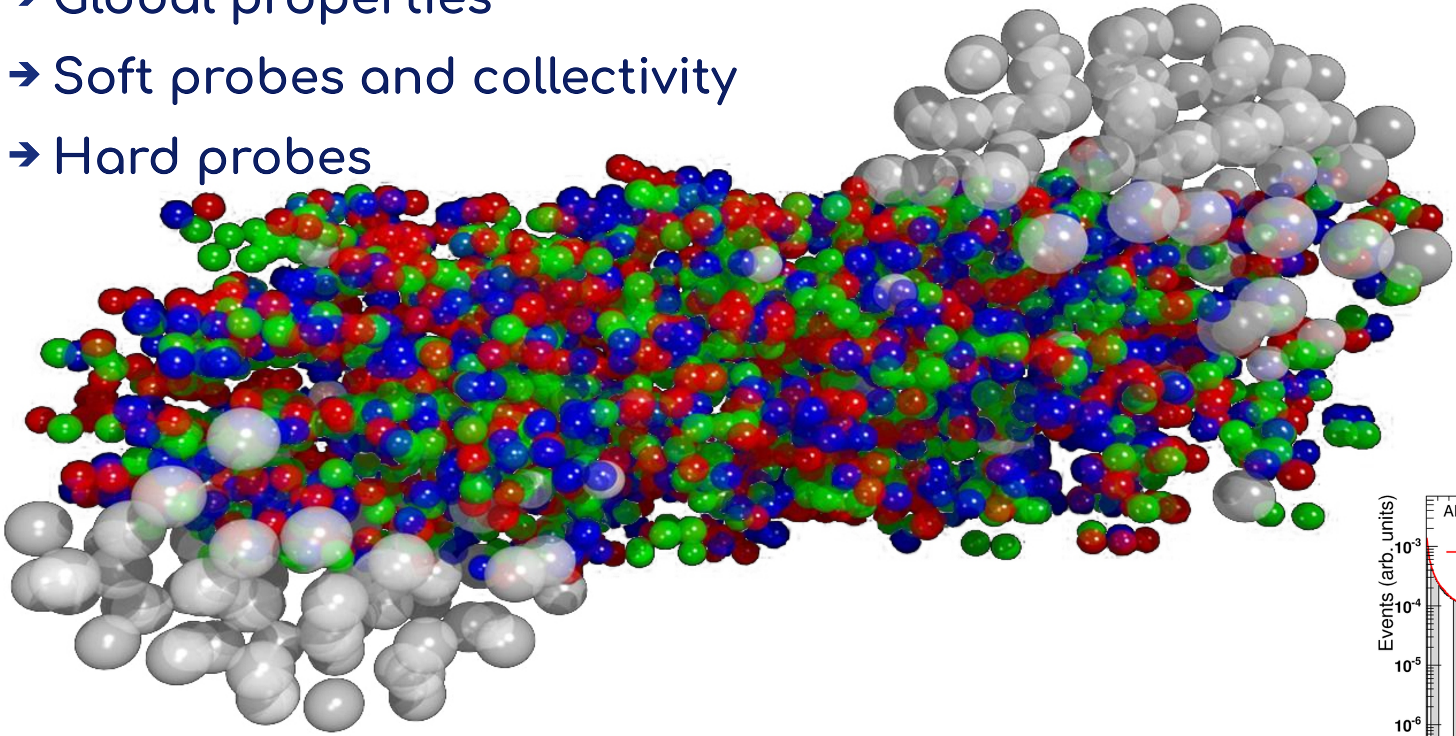
Nearly perfect fluid discovery at RHIC
Nucl. Phys. A 757 (2005)

RHIC: 130-200 GeV
LHC: Pb-Pb: 2.76-5.02, Xe-Xe: 5.44 TeV


Relativistic Heavy-Ion Collisions
made by Chun Shen
collision overlap zone
Initial energy density
QGP phase
Hadronization
Chemical freeze-out
Hadron gas phase
Kinetic freeze-out
final detected particle distributions
π
K
p
γ
e+
e-
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Outline

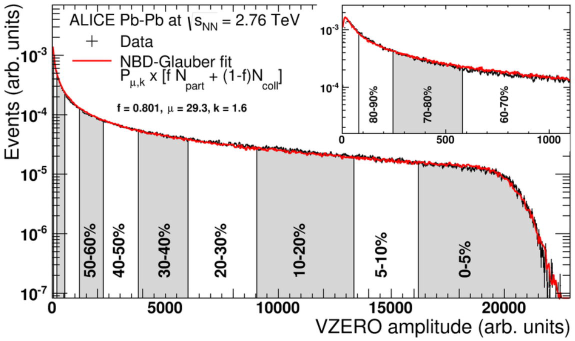
- ➔ Introduction
- ➔ Global properties
- ➔ Soft probes and collectivity
- ➔ Hard probes



b – impact parameter → collision centrality

N_{part} – number of participants

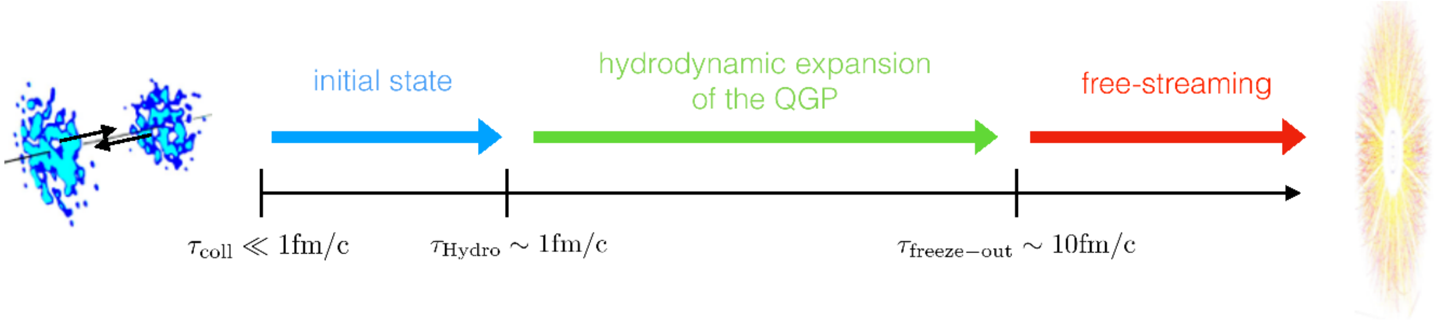
N_{coll} – number of binary collisions



➔ Selection of topics

Evolution of heavy-ion collisions

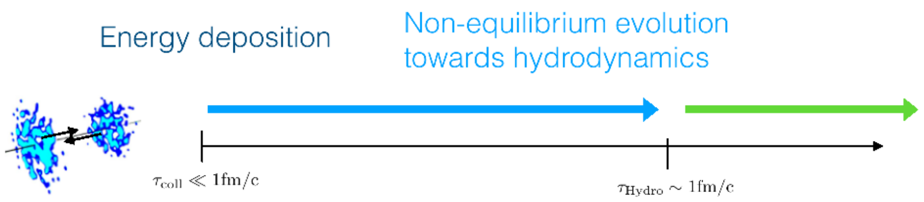
- Description of the heavy-ion collision dynamics from the underlying QCD still challenging

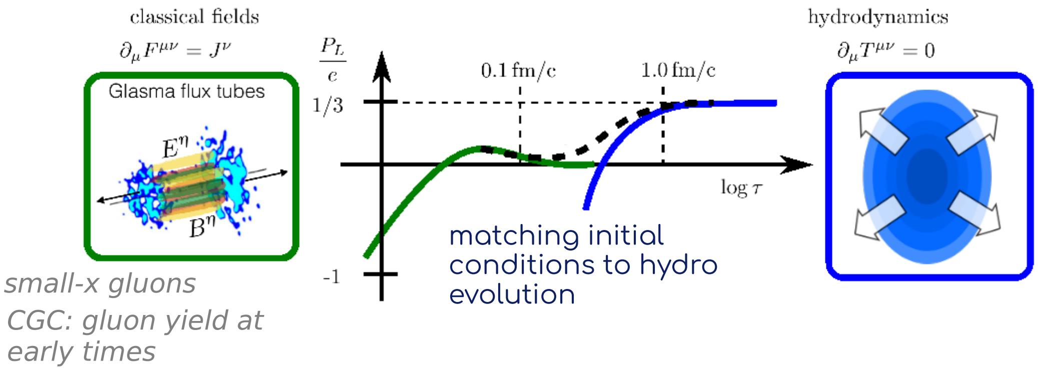


- Bulk dominated by the hydrodynamic expansion
  - Knowledge of the initial state required

Small systems → increased sensitivity to initial state

Early times, Pre-equilibrium



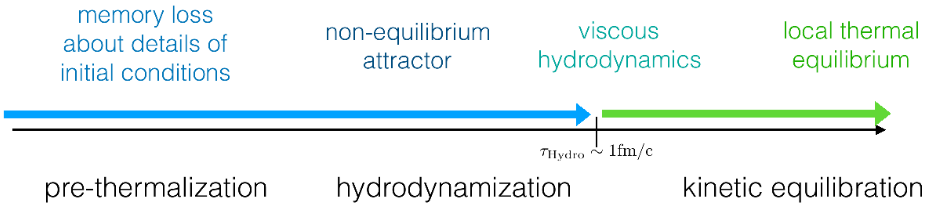


- Early times → classical field evolution
- Energy deposition models, based on:

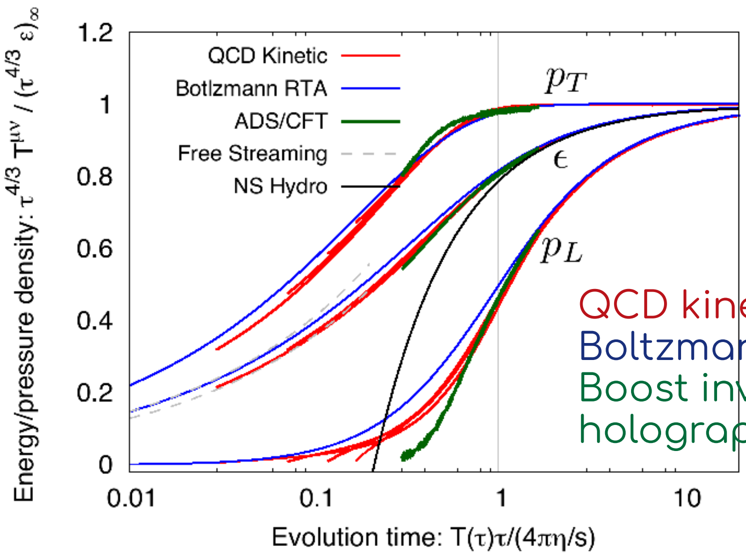
CGC,
phenomenology,
AdS/CFT (Shockwave collisions)

Non-equilibrium models:

QCD kinetic theory,
Boltzmann RTA,
Boost invariant holography AdS/CFT

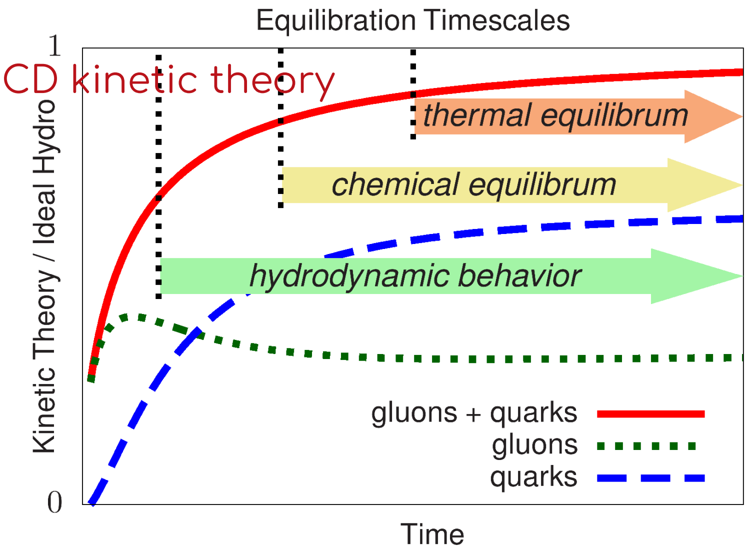


Pre-equilibrium



QCD kinetic theory,
Boltzmann RTA,
Boost invariant
holography AdS/CFT

QCD kinetic theory



- Consequences of pre-equilibrium: bulk isotropisation, entropy production, chemical equilibration
- In thermal equilibrium: conservation of entropy per unity rapidity (Bjorken)
- Entropy production ($dN_{ch}/d\eta$) dominated by the initial state,
  pre-equilibrium dynamics spoils sensitivity

$$\left\langle \frac{dE_\perp}{d\eta} \right\rangle_{\tau_{\rm coll}} \rightarrow \left\langle \frac{dS}{d\eta} \right\rangle_{\tau_{\rm Hydro}} \rightarrow \left\langle \frac{dS}{d\eta} \right\rangle_{\tau_{\rm freeze-out}} \approx$$

$$\left\langle \frac{dS}{d\eta} \right\rangle_{\tau_{\rm Hydro}} \rightarrow \left\langle \frac{dN_{\rm ch}}{d\eta} \right\rangle \approx \left\langle \frac{S}{N_{\rm ch}} \right\rangle \left\langle \frac{dS}{d\eta} \right\rangle_{\tau_{\rm freeze-out}}$$

-> strong sensitivity to global features of initial conditions (ε_n,Ψ_n,$dS/d\eta$,…)

-> small effects of pre-equilibrium dynamics on typical observables (v_n,<p_T>,…)

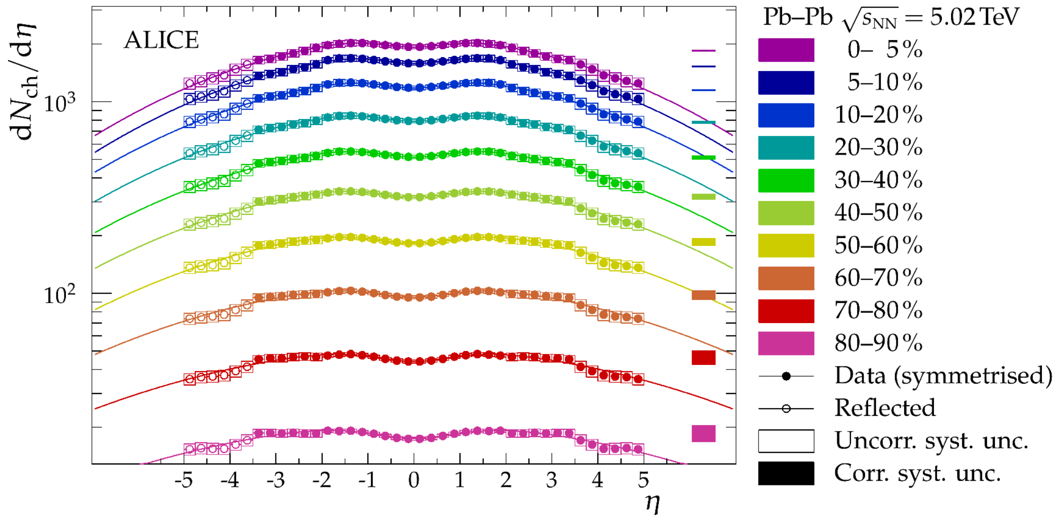
Schlichting, Mazeliauskas, IS 2019

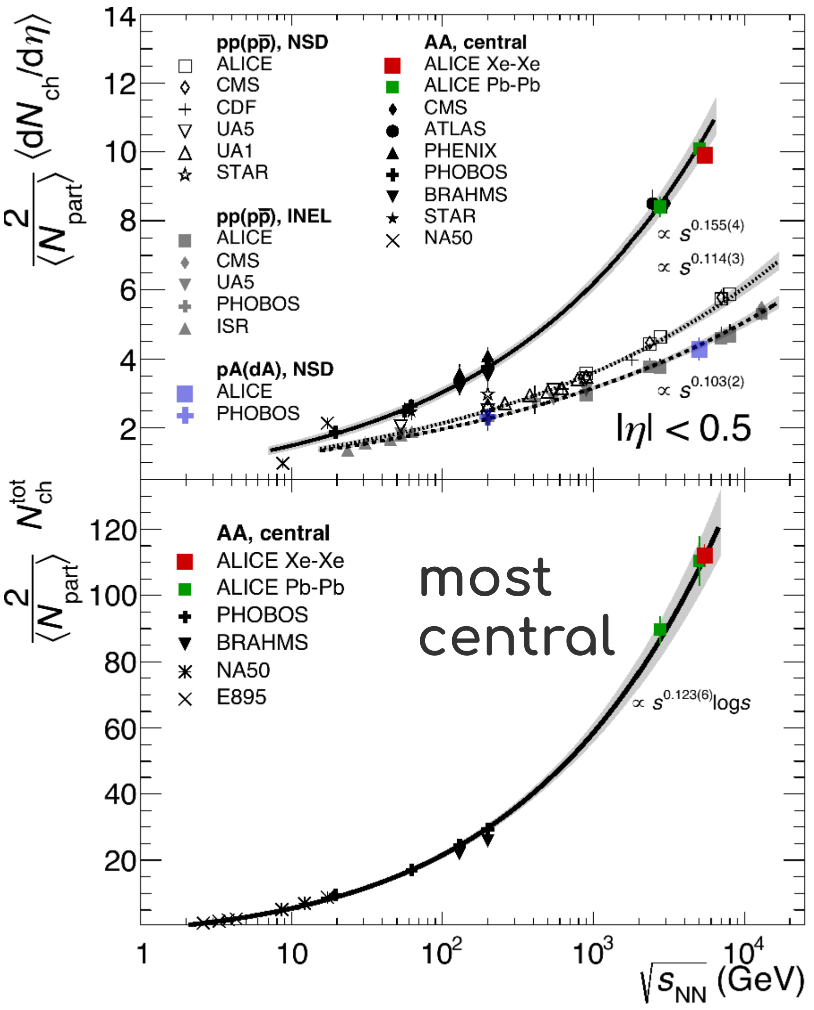
Global properties, soft probes

- Soft probes
  - Charged-particle multiplicity, particle yields, elliptic flow, transverse momentum spectra
  - Bulk matter properties, thermodynamic and transport properties of matter

Charged-particle multiplicity, dN/dη

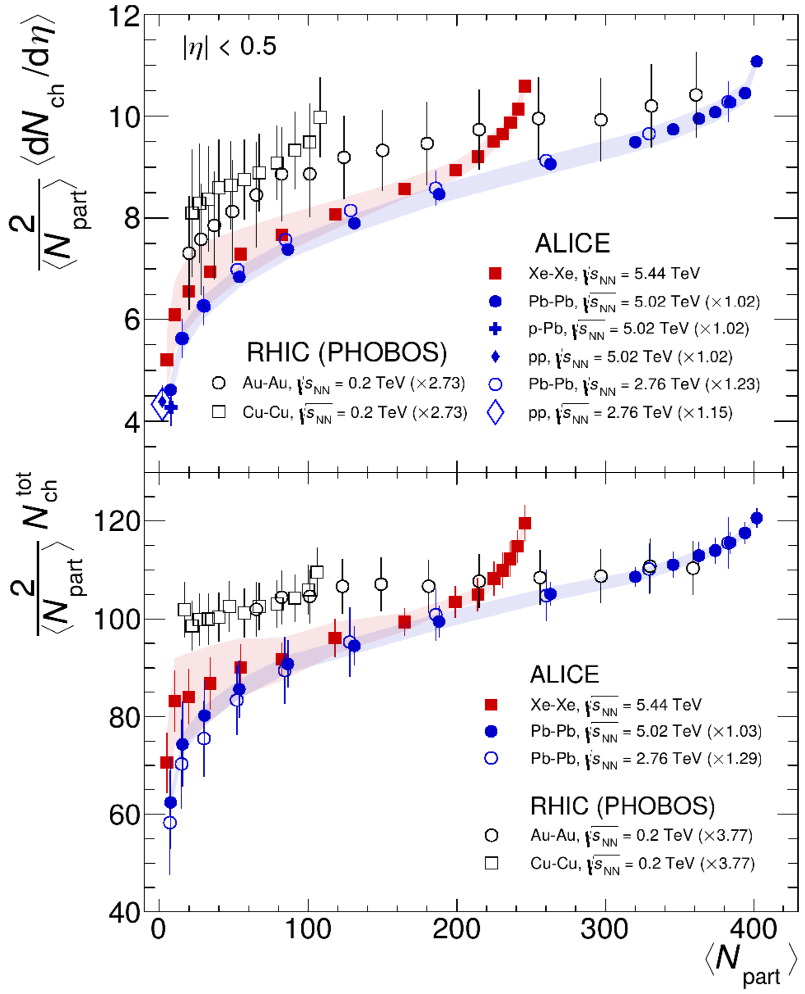
- ➔ Related to the initial energy density and collision geometry
- ➔ Large energy density of the created medium
  - ε~12 GeV/fm³ at t=1 fm/c (2.76 TeV) *PRC 94 (2016) 034903*
- ➔ N_{ch} ~21000 particles produced in central Pb-Pb collisions at 5.02 TeV



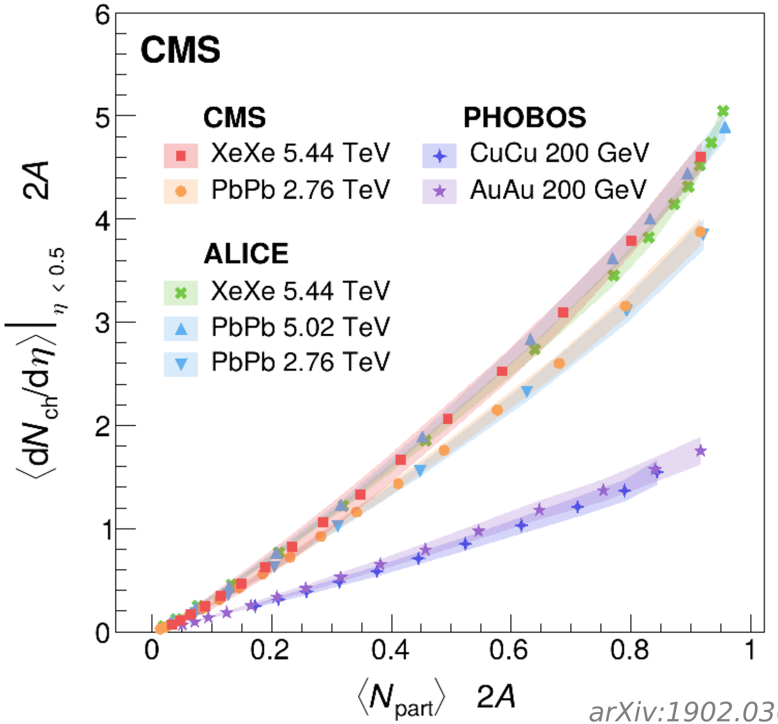


dN/dη vs N_{part}

- ➔ Deviation from N_{part} scaling at RHIC and LHC
- ➔ Steeper rise in most central collisions
- ➔ Collision geometry plays an importation role in particle production

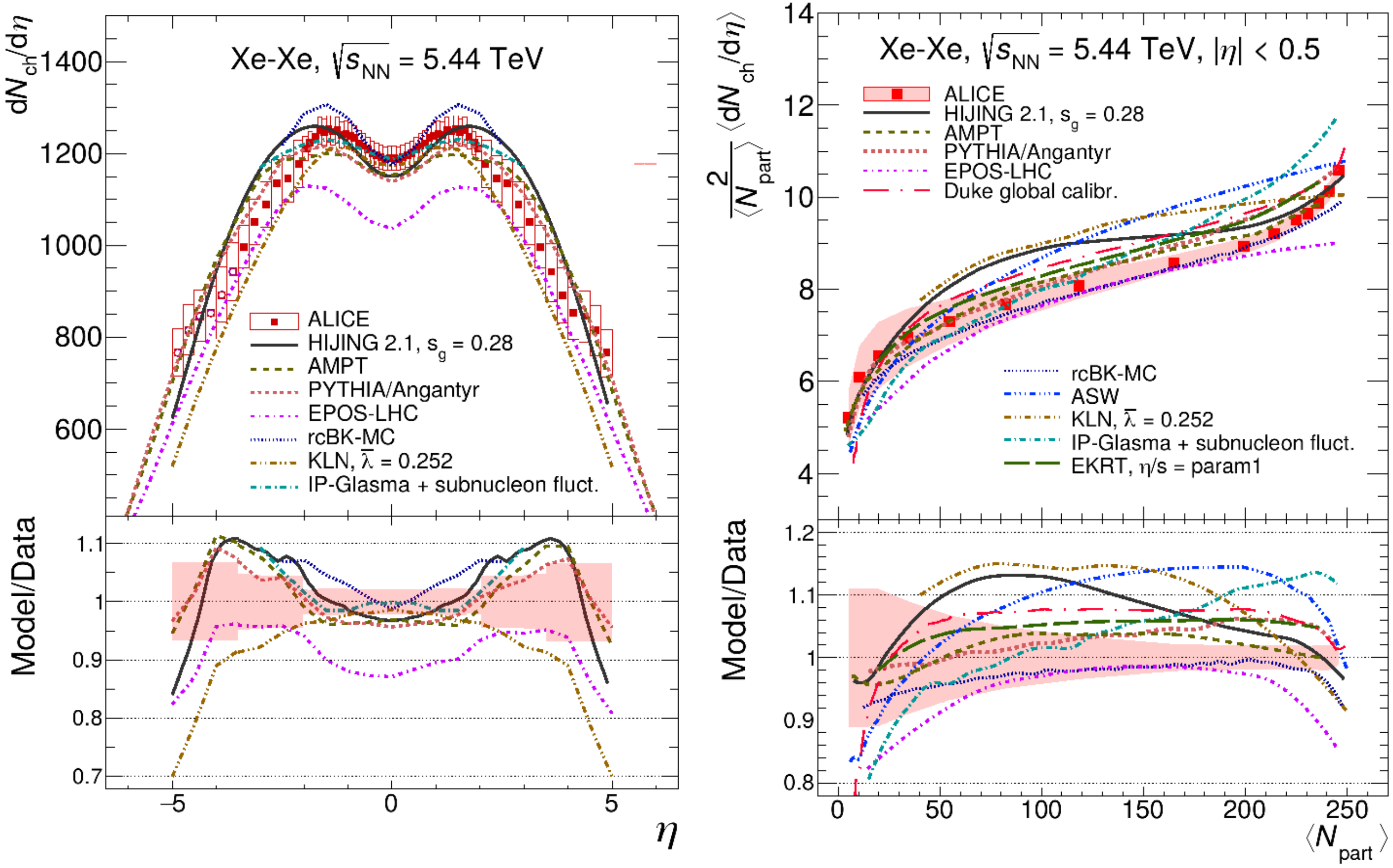


PLB 790 (2019) 35



arXiv:1902.03603

dN/dη vs models



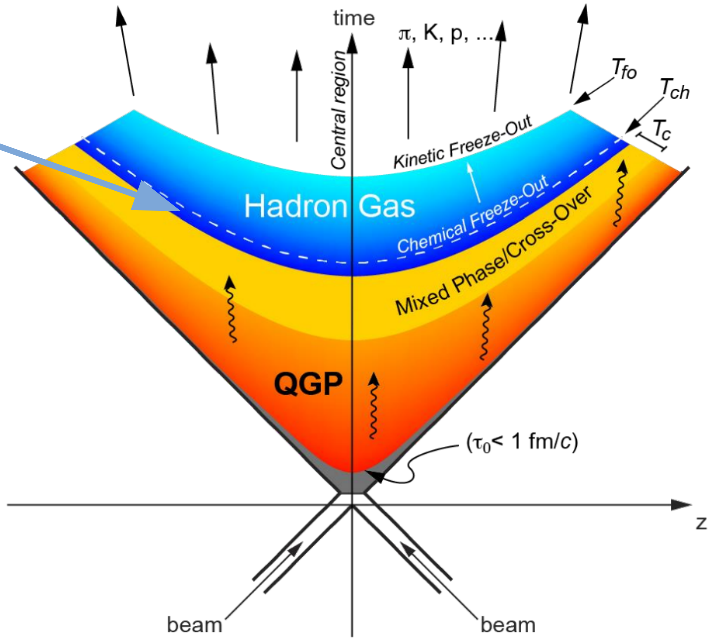
- Models **do not describe** charged-particle production in the whole rapidity range
- N_{part} dependence described by rcBK-MC: CGC saturation model based on Balitsky-Kovchegov gluon evolution equation

PLB 790 (2019) 35

Chemical composition

➔ Production at **chemical freeze-out**

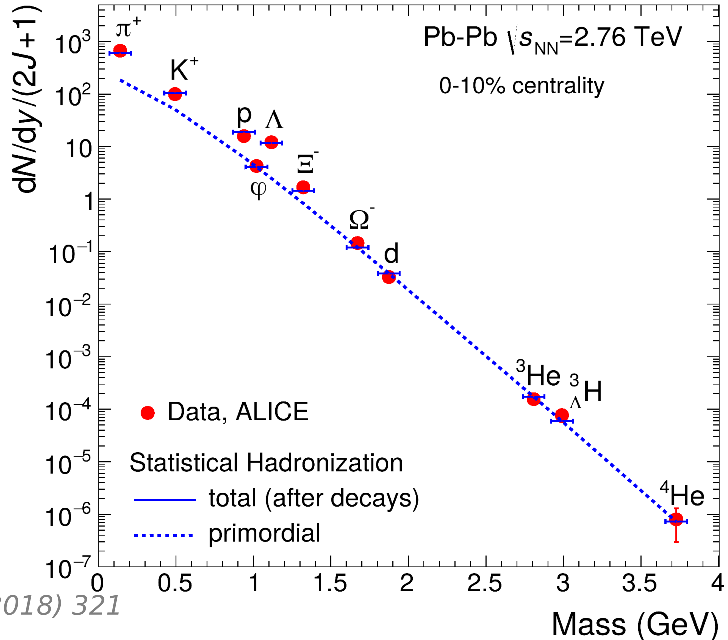
- Inelastic collisions cease
- Abundances of different hadron species fixed
- Integrated particle yields → conditions at chemical freeze-out



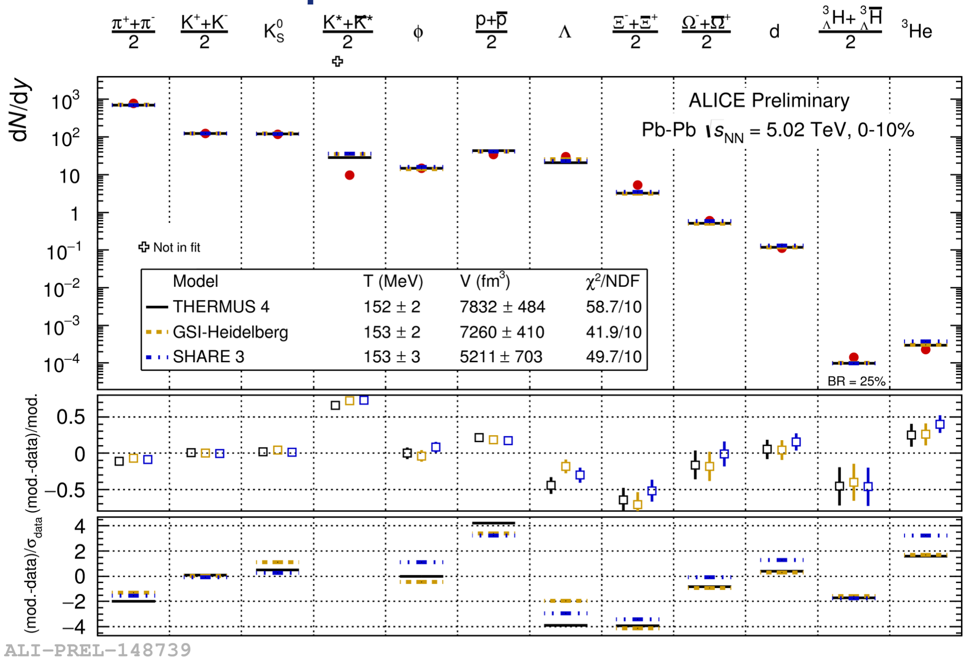
Chemical composition

- ➔ Production at **chemical freeze-out**
  - Inelastic collisions cease
  - Abundances of different hadron species fixed
  - Integrated particle yields → conditions at chemical freeze-out
- ➔ Described by statistical/thermal models with grand canonical ensemble
  - Roughly

$$\frac{dN}{dy} \sim e^{-m/T_{ch}}$$



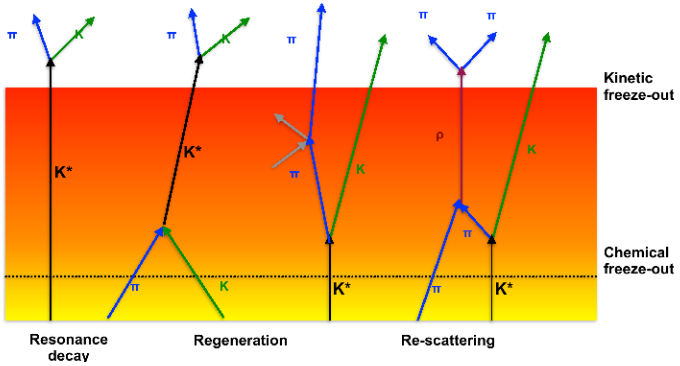
Nature, 561(2018) 321

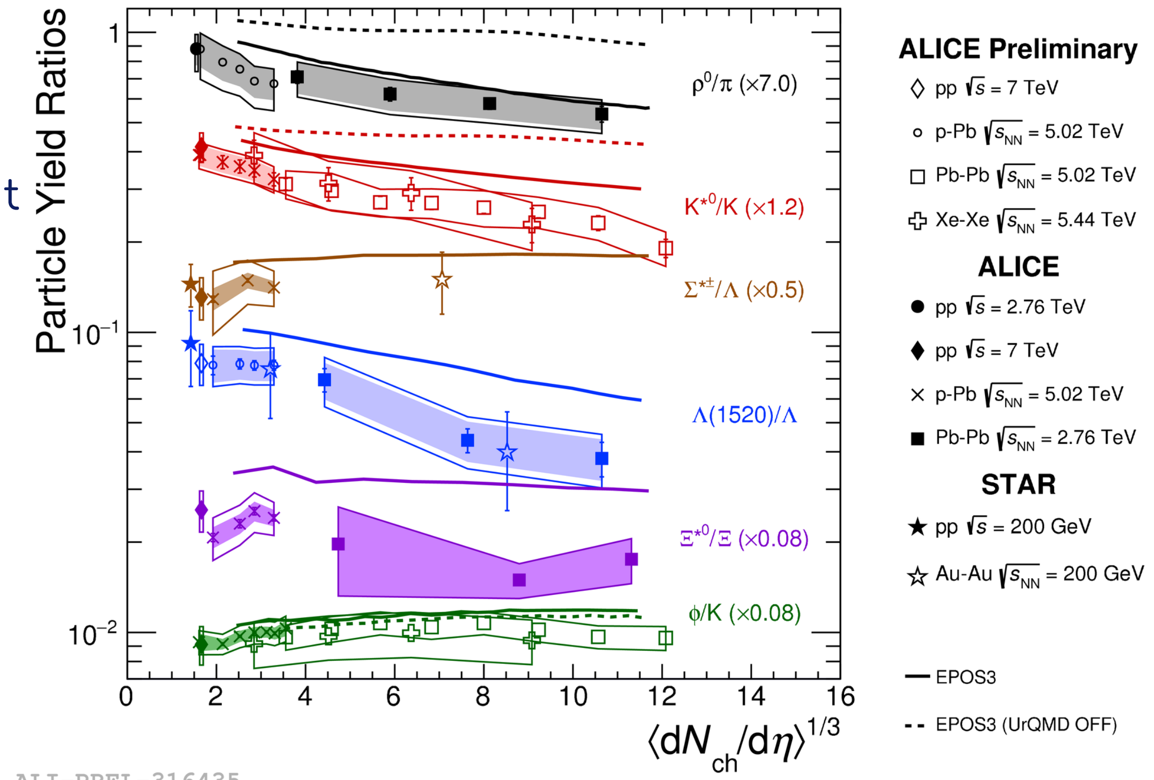


S. Wheaton et al., Comp. Phys. Comm. 180, 84 (2009)
A. Andronic et al., Phys. Lett. B 673, 142 (2009), erratum ibid 678, 516 (2009)
G. Torrieri et al., Comp. Phys. Comm. 167, 229 (2005); 175, 635 (2006); 185, 2056 (2014)

Final state interactions

- Described by statistical/thermal models with grand canonical ensemble.
- Particle yields measured at kinetic freeze-out. Depend on:
  - Initial yields after chemical freeze-out
  - Lifetime of hadronic phase
  - Resonance decays
  - Scattering cross-section of decay products
  - Baryon final state annihilation ?





EPOS, Phys. Rev. C 93 (2016) 014911

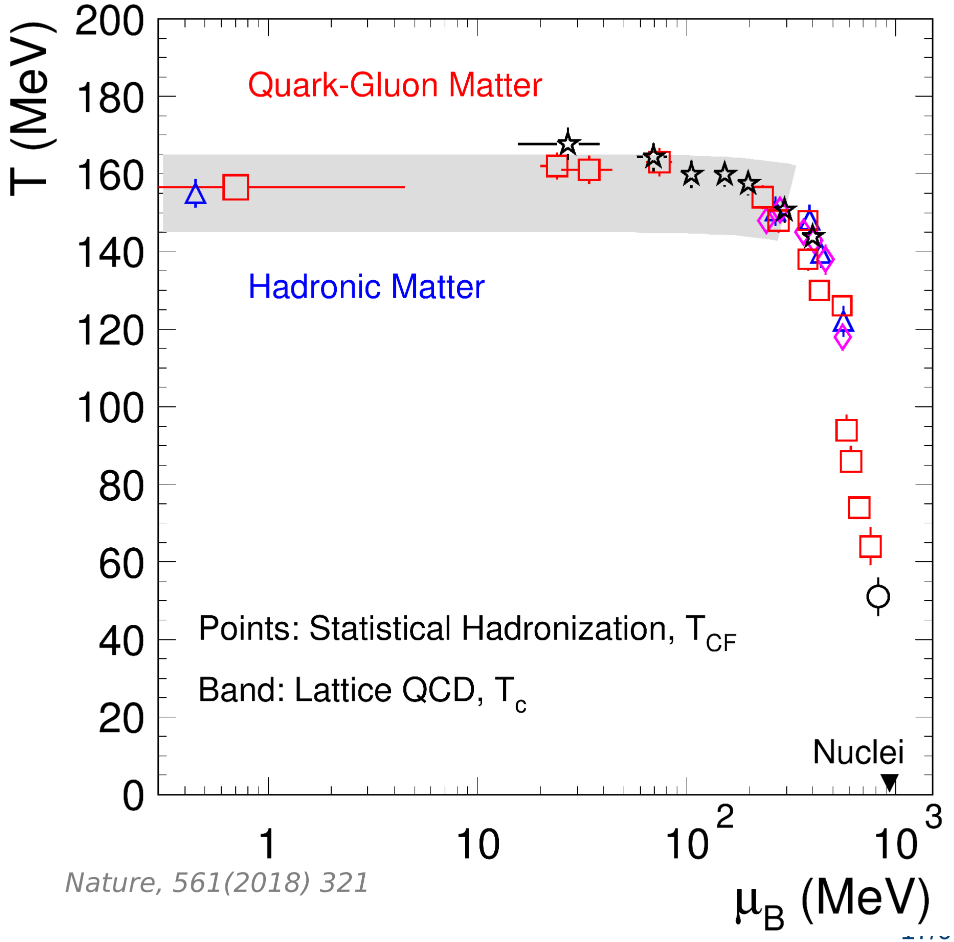
Lifetime (fm/c)

$\rho^0 < K^{*0} < \Lambda^* < \phi$

1.3 < 4.2 < 12.6 < 46.2

Thermodynamic properties

- Described by statistical/thermal models with grand canonical ensemble.
  - Three parameters: T_{ch}, μ_B, V
- With increasing $\sqrt{s_{NN}}$:
  - μ_B decreases, vanishes at LHC
  - T_{ch} increases up to SPS energies then saturated at ~160 MeV, close to the QGP phase boundary temperature from lattice QCD

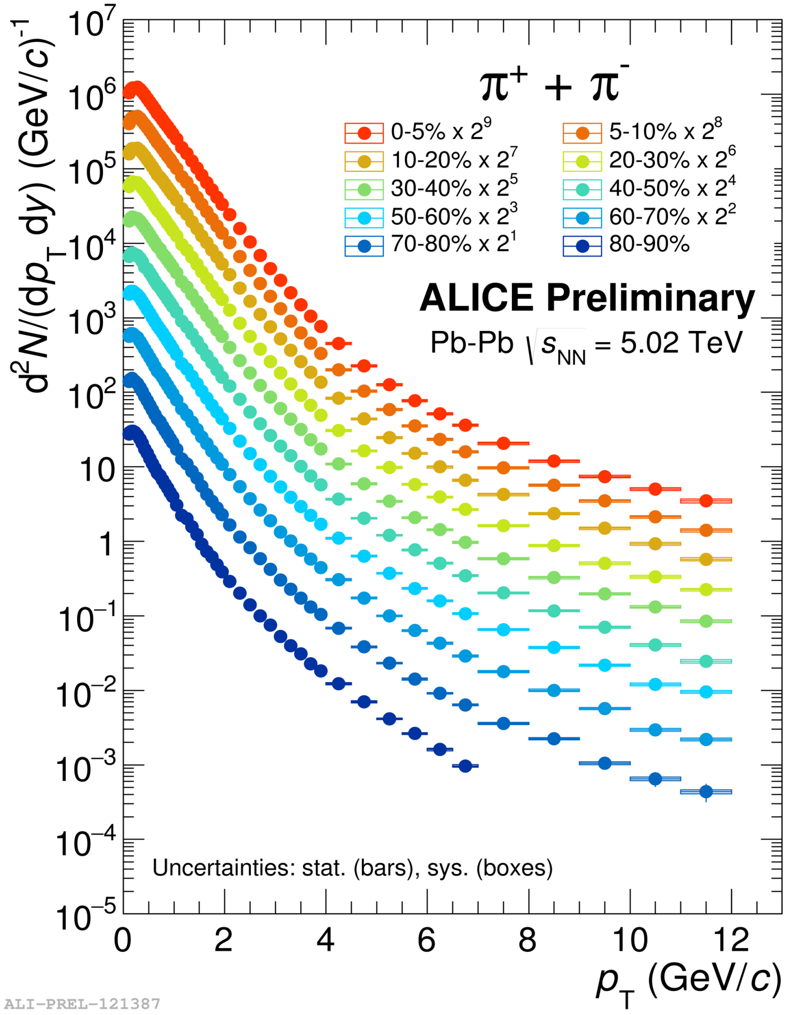


Nature, 561(2018) 321

p_T distributions

- ➔ **Low p_T** (< 2,3 GeV):
  - Bulk-matter (collective phenomena)
    LHC > 95% of the produced particles,
    non-perturbative QCD regime
- ➔ **Intermediate p_T:**
  - Fragmentation vs recombination
- ➔ **High p_T** (> 8-10 GeV):
  - Hard processes, energy loss

➔ Hardening of the spectra with centrality

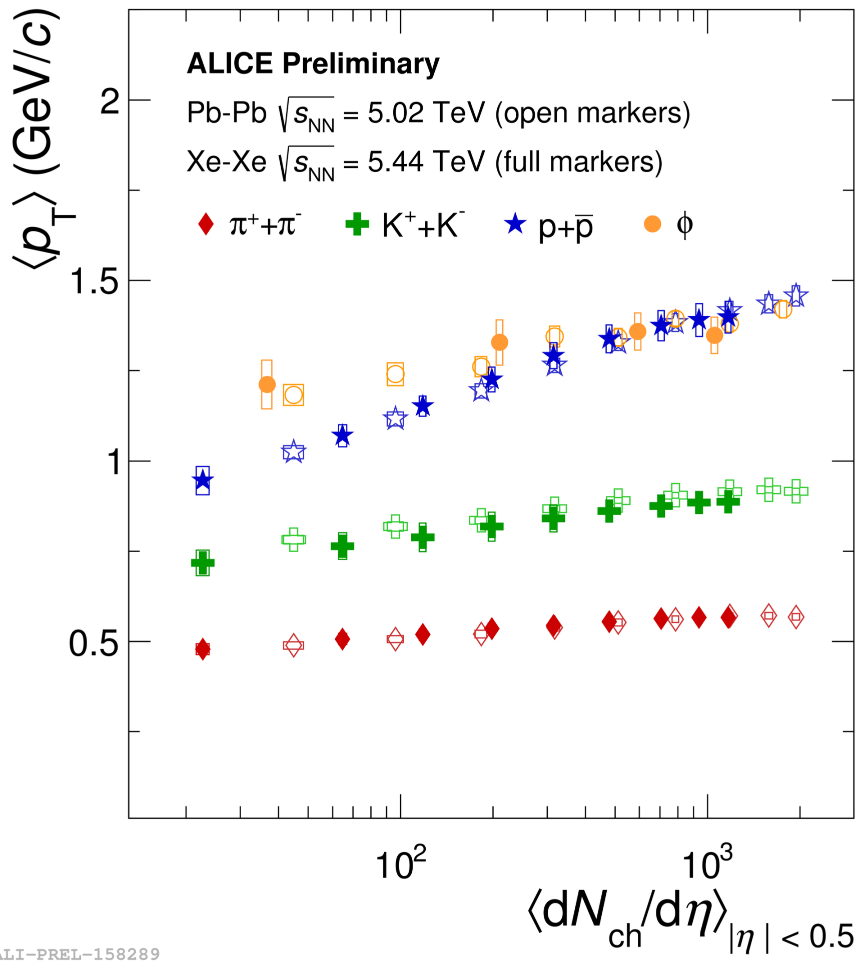


p_T distributions, mean p_T

- **Low p_T** (< 2,3 GeV):
  - Bulk-matter (collective phenomena)
    LHC > 95% of the produced particles,
    non-perturbative QCD regime
- **Intermediate p_T:**
  - Fragmentation vs recombination
- **High p_T** (> 8-10 GeV):
  - Hard processes, energy loss

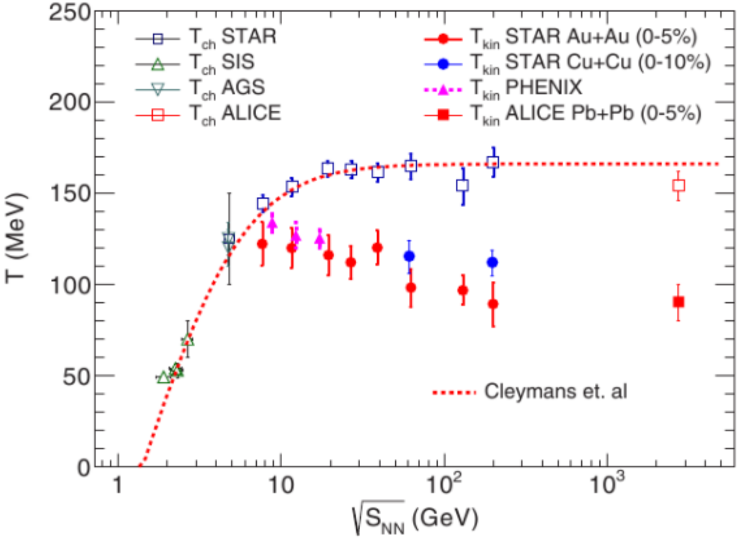
- Hardening of the spectra, increase in mean p_T with centrality
  - mass ordering of $\langle p_T \rangle$

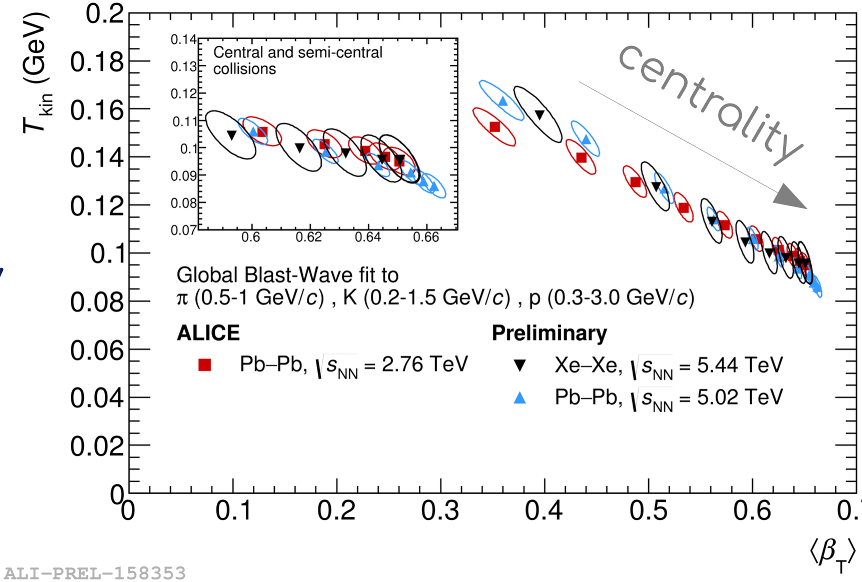
- Described by models of hydrodynamic expansion of the medium
  (radial expansion of the medium)



Kinetic freeze-out

- ➔ p_T distributions described by models of hydrodynamic expansion of the medium (radial flow)
- ➔ Fluido-dynamical description via blast-wave
  - Flow velocity $\langle\beta_T\rangle$, increases with centrality
  - T_{kin} decreases with centrality and energy





- Blast-wave: simplified hydrodynamic model
- Description of p_T spectra with three parameters m_T, $\langle\beta_T\rangle$ and T_{kin}

  β_T → radial flow velocity, T_{kin} → kinetic freeze-out temperature

- Fit depends on particle species and used ranges

Phys. Rev. C48 (1993) 2462
Phys. Rev. C 94, 044901 (2016)

Strangeness production

- Strangeness enhancement: QGP signature

➔ **Significant enhancement** of strange to non-strange particle production

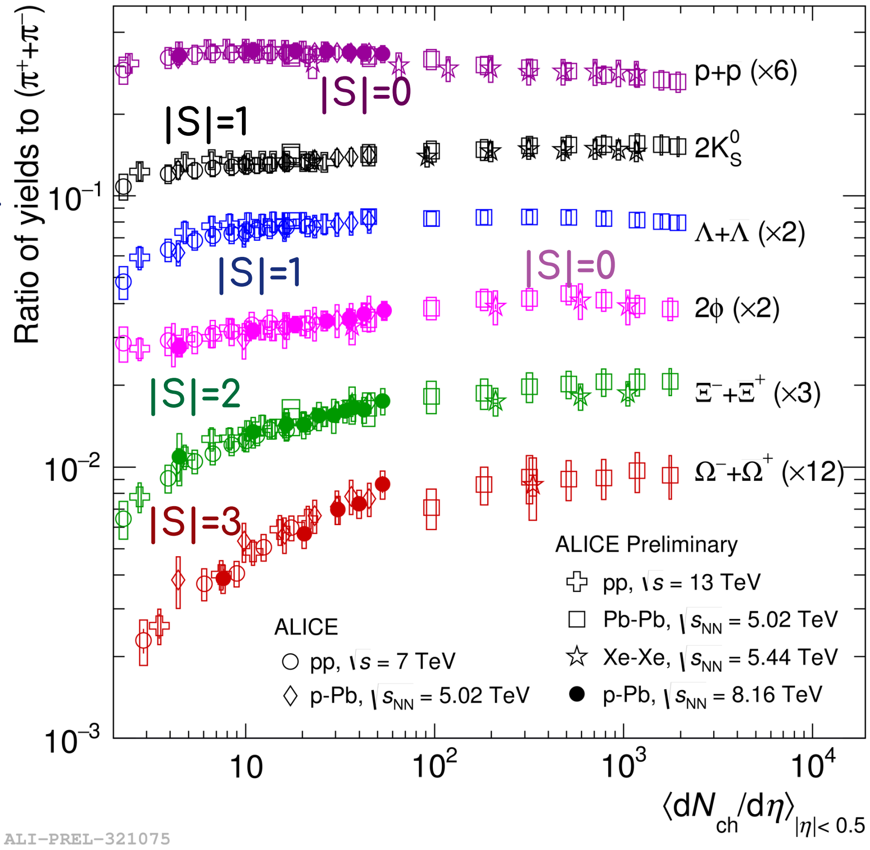
➔ **Smooth evolution with multiplicity**, from small to large systems

➔ Plateau in Pb-Pb – consistent with statistical hadronisation model expectations

➔ Magnitude of strangeness enhancement increases with strange-quark content

➔ **Hadron chemistry driven by multiplicity (system size)**

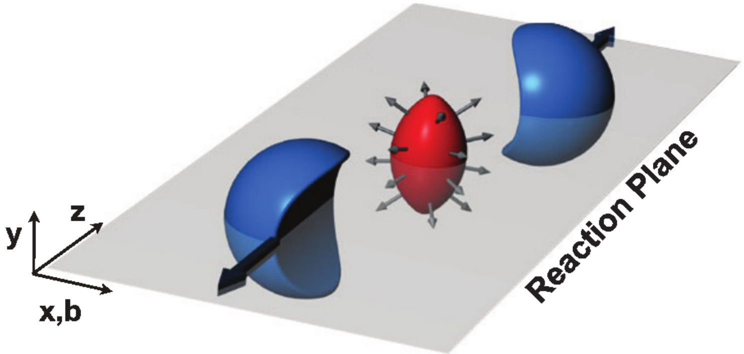
➔ **Effect related to strangeness content rather that mass**



Nature Physics 13 (2017) 535-539
PLB 758 (2016) 389-401

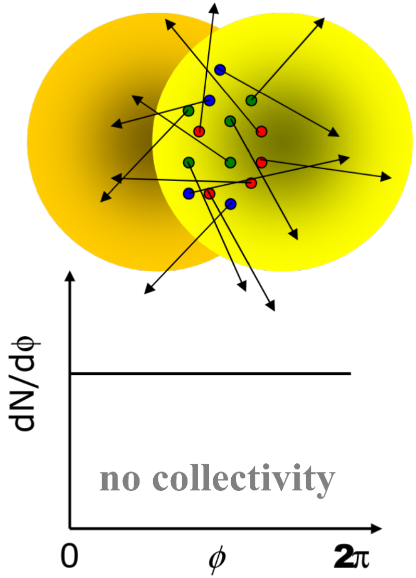
QGP: Collectivity in the system

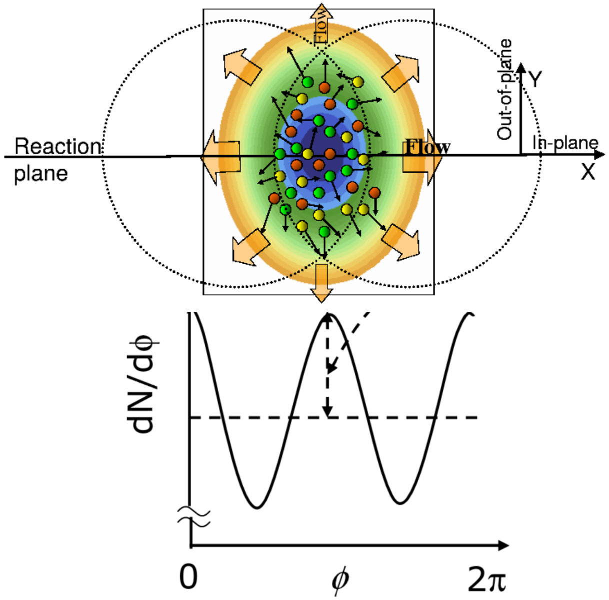
non-central HI collision



➔ Multiple interactions between the constituents of the medium → **flow**

➔ Common velocity field for all particles induced during the expansion → **radial flow**

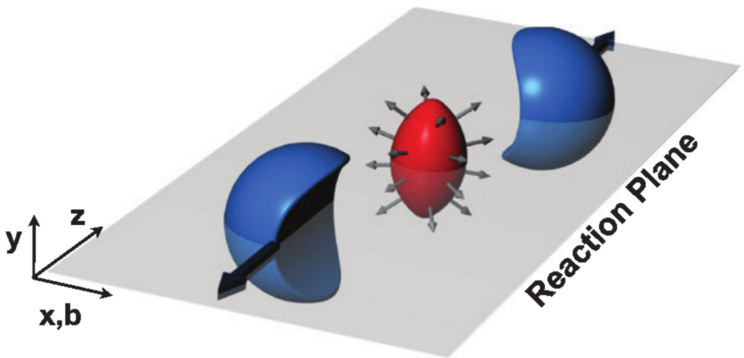




- Collision geometry: initial spacial anisotropy
  - ➔ initial spacial anisotropy → **azimuthal anisotropies** in particle momentum distributions

QGP: Collectivity in the system

non-central HI collision

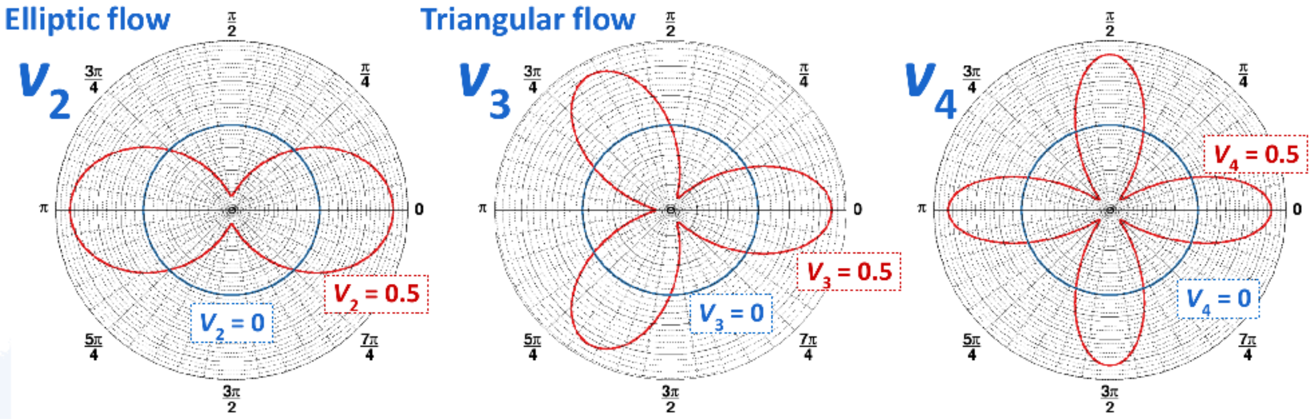


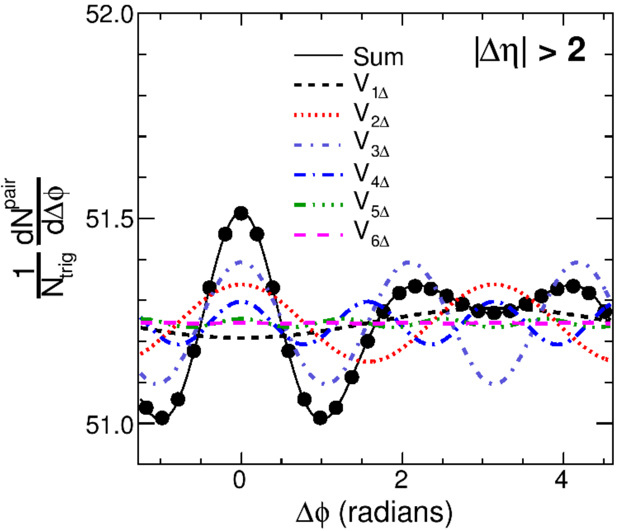
- initial spacial anisotropy → **azimuthal anisotropies** in particle momentum distributions
- Fourier expansion:

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

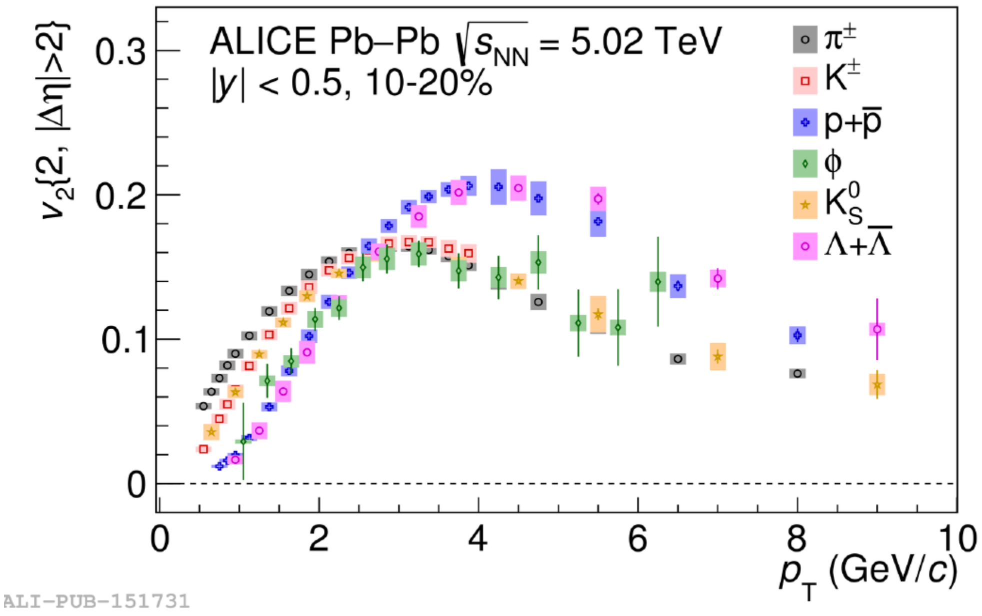
$$v_n(p_T, y) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

v_1: directed flow v_2: elliptic flow v_3: triangular flow





Azimuthal anisotropy – elliptic flow



- **Low p_T (<2 GeV/c): mass ordering**

  collective radial flow velocity, isotropic expansion

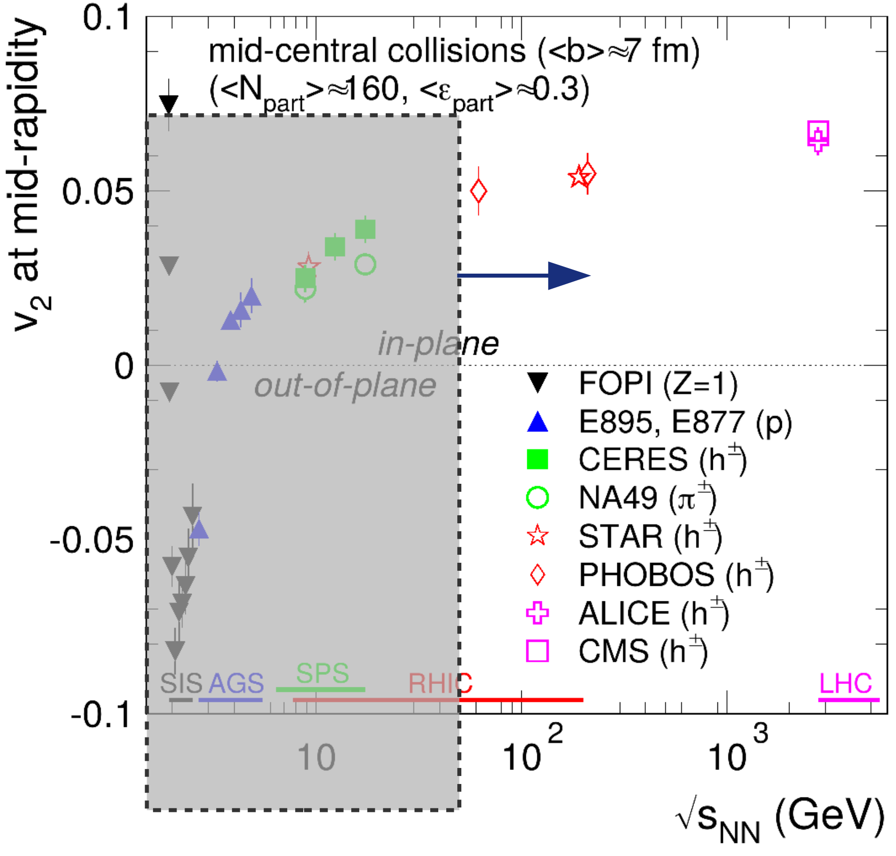
- **p_T ~2.5 GeV/c**: crossing between v_2 of mesons and baryons
- **p_T > 2.5~8 GeV/c: baryon-meson grouping**

  baryon v_2 > meson v_2,
  flow driven by quark content

- **Φ meson** follows mass ordering at low p_T and quark contents at intermediate p_T

JHEP09 (2018) 006

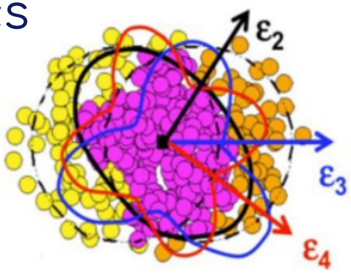
Azimuthal anisotropy – elliptic flow



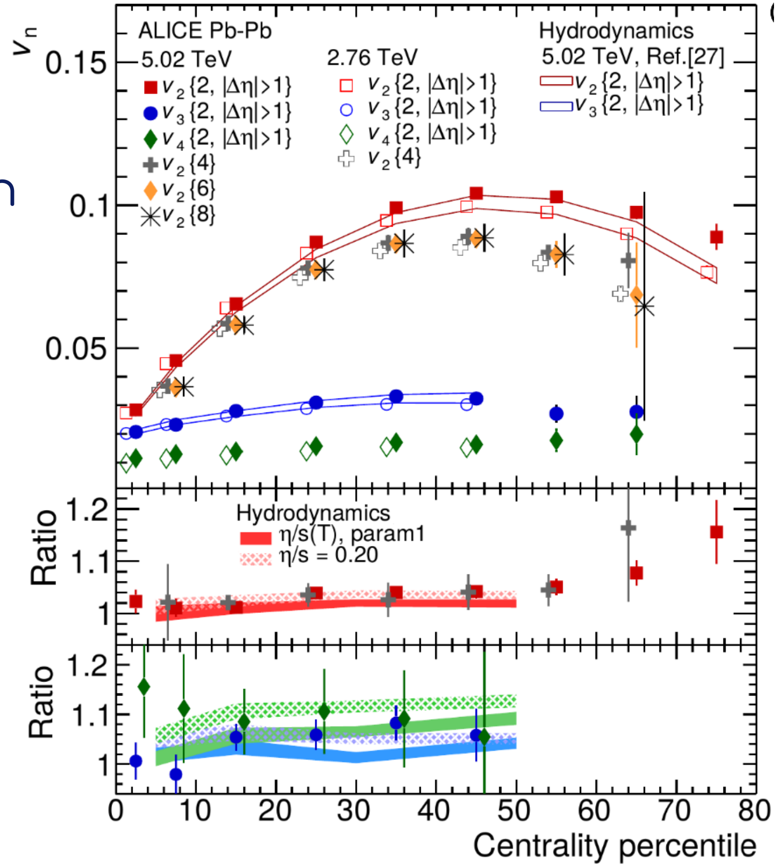
- **Low ρ_T (<2 GeV/c): mass ordering**
  - collective radial flow velocity, isotropic expansion
- **ρ_T ~2.5 GeV/c**: crossing between v_2 of mesons and baryons
- **ρ_T > 2.5~8 GeV/c: baryon-meson grouping**
  - baryon v_2 > meson v_2, flow driven by quark content
- **Φ meson** follows mass ordering at low ρ_T and quark contents at intermediate ρ_T
- v_2 increase with collision energy
  - Increase of the average transverse momentum of the hadrons; described by hydrodynamics

Fluctuations in the initial geometry

- ➔ **Fluctuations in initial geometry,** nucleon position and their fluctuations dictate the eccentricity → development of higher harmonics
  - important in central collisions



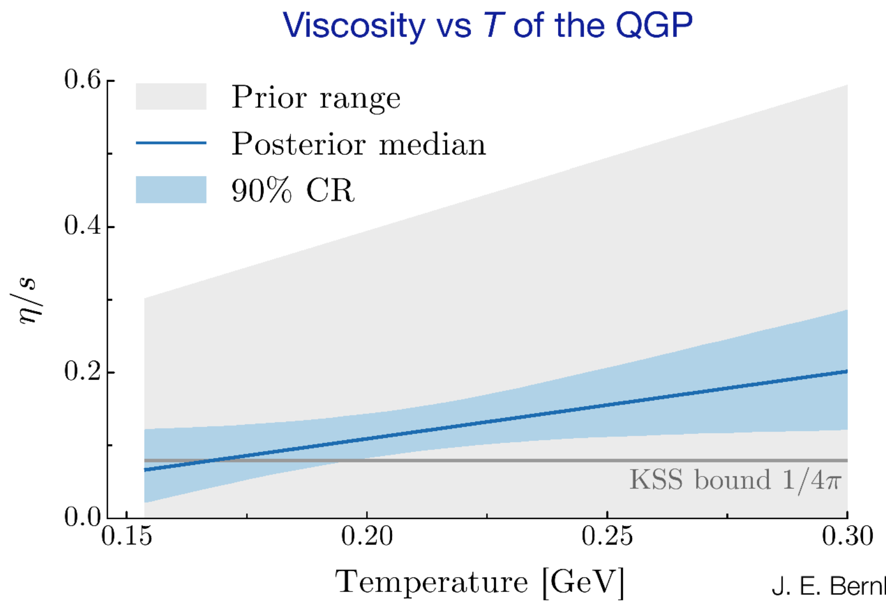
- ➔ Low p_T v_2 described by (viscous) hydrodynamic models
- ➔ Constrains on medium transport properties – shear and bulk viscosity (η,ζ/s) + initial state



JHEP09 (2018) 006

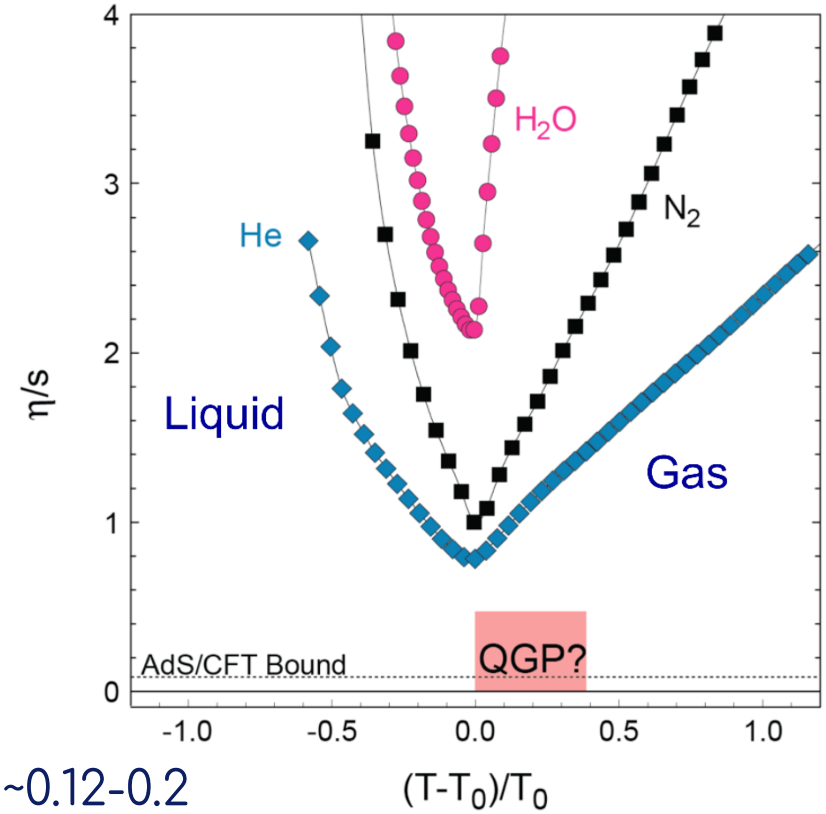
QGP viscosity

- ➔ **Constraining QGP viscosity and the initial state – Bayes approach**
  - ➔ Input from measurements at different energies: multiplicity, flow, p_T spectra



J. E. Bernhard et al, PRC 94, 024907

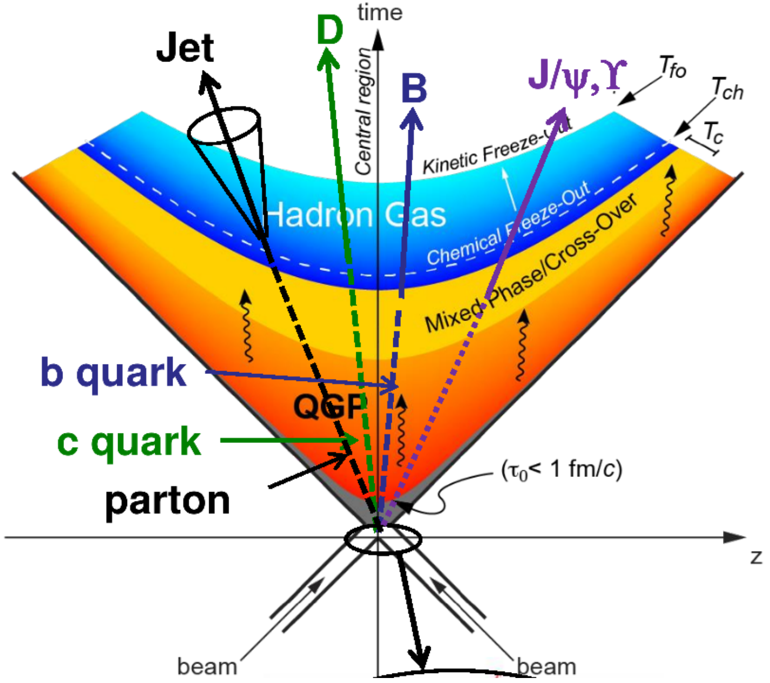
Bayesian fit: 9 parameters constraining initial state and viscosity



- ➔ Very small shear viscosity (η/s) ~0.12-0.2
- ➔ Bulk viscosity still hard to constrain (and understand)

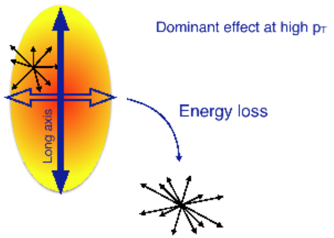
J. E. Bernhard et al, PRC 94, 024907

Hard probes

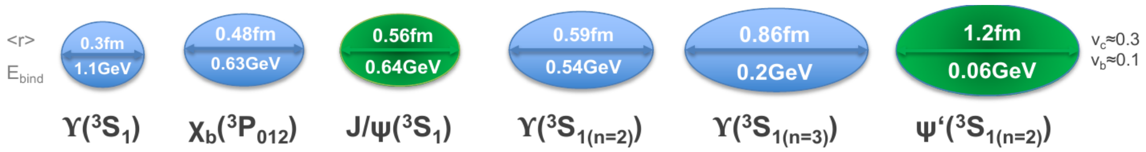


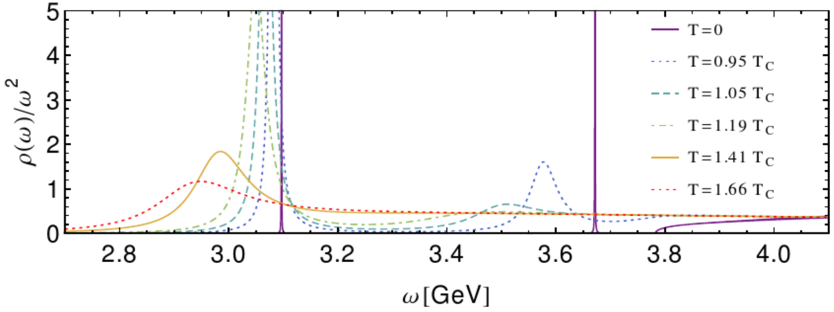
- Medium properties studied via parton modification in the medium

➔ High-p_T partons and heavy quarks
  - Collisional and radiative parton energy loss, flavour and mass dependence
  - Dependence on medium properties and traversed path lengths



➔ Quarkonia: suppression of different states due to colour screening
  - "QGP thermometer"



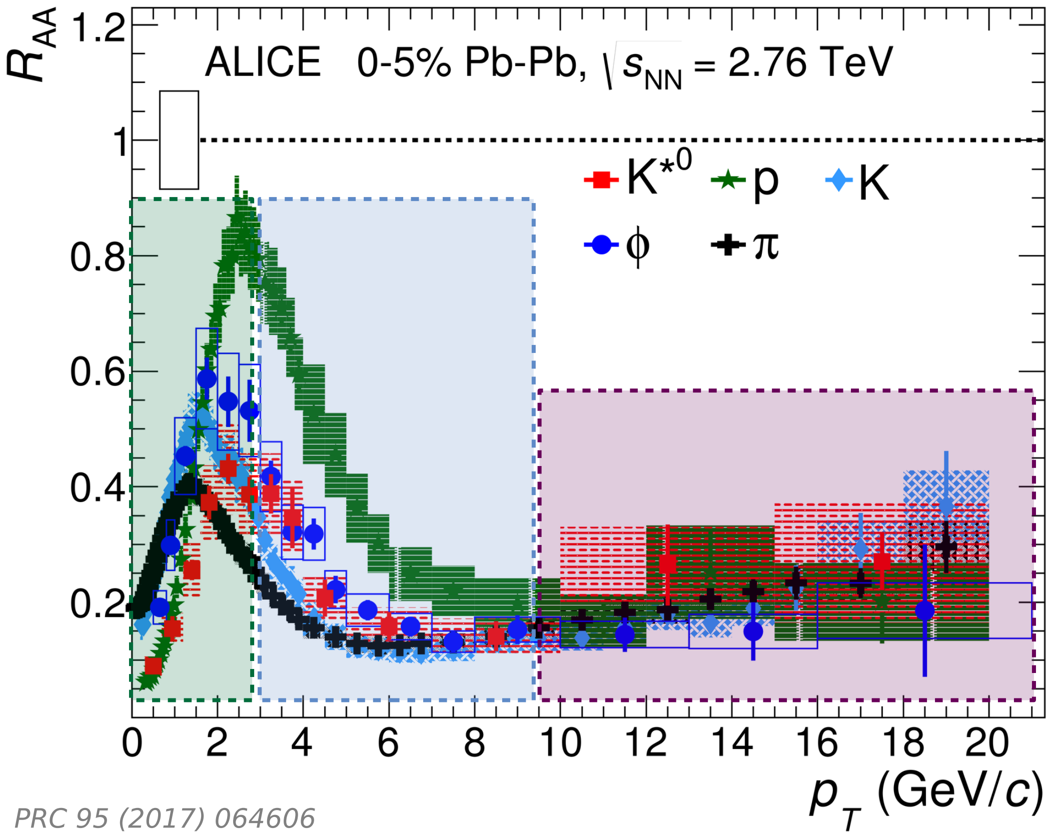


Charged-particle R_{AA}

- **Nuclear modification factor, R_{AA}**

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

T_{AA}: nuclear overlap function



PRC 95 (2017) 064606

→ **Low p_T** (< 2,3 GeV):
- Thermal regime
- Hydrodynamic expansion driven by pressure gradients
- Radial flow peak, mass ordering

→ **Intermediate p_T**:
- Kinetic regime (not described by hydro)
- Different R_{AA} for different hadron species
- Features described with in-medium hadronization via quark recombination

→ **High p_T** (> 8-10 GeV):
- Partons from hard scatterings
- Lose energy while traversing the QGP
- Hadronisation via fragmentation → same R_{AA} for all species

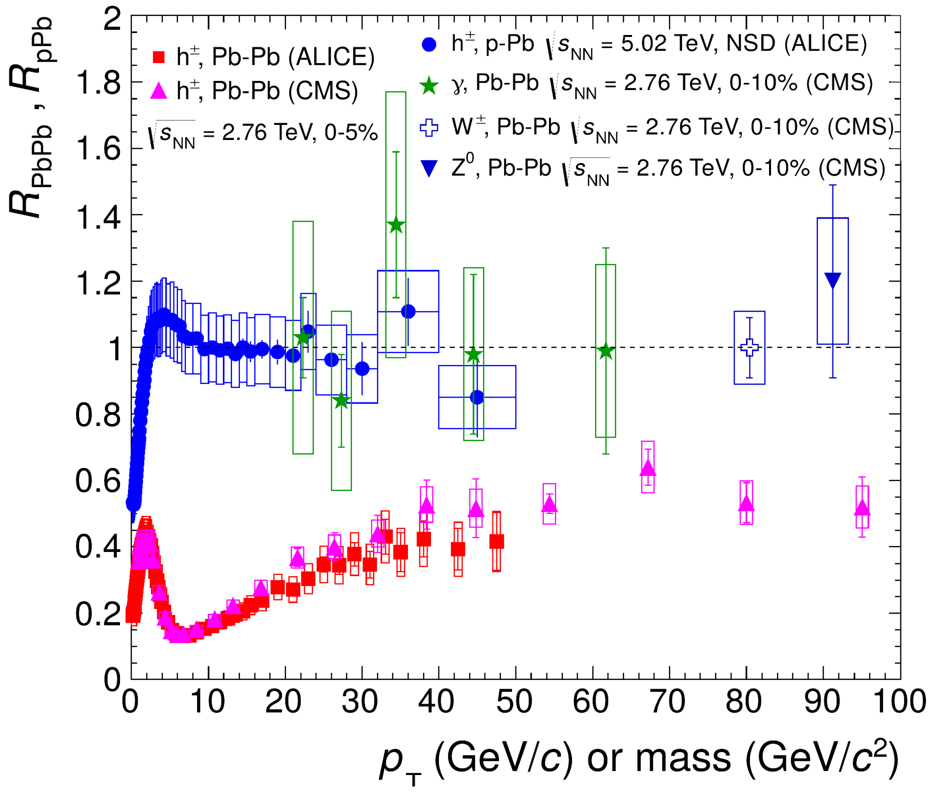
Charged-particle R_{AA}

- Nuclear modification factor, R_{AA}

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

➔ Suppression in AA due to final state effects

  - Control experiment: no suppression for photons, W and Z^0 bosons



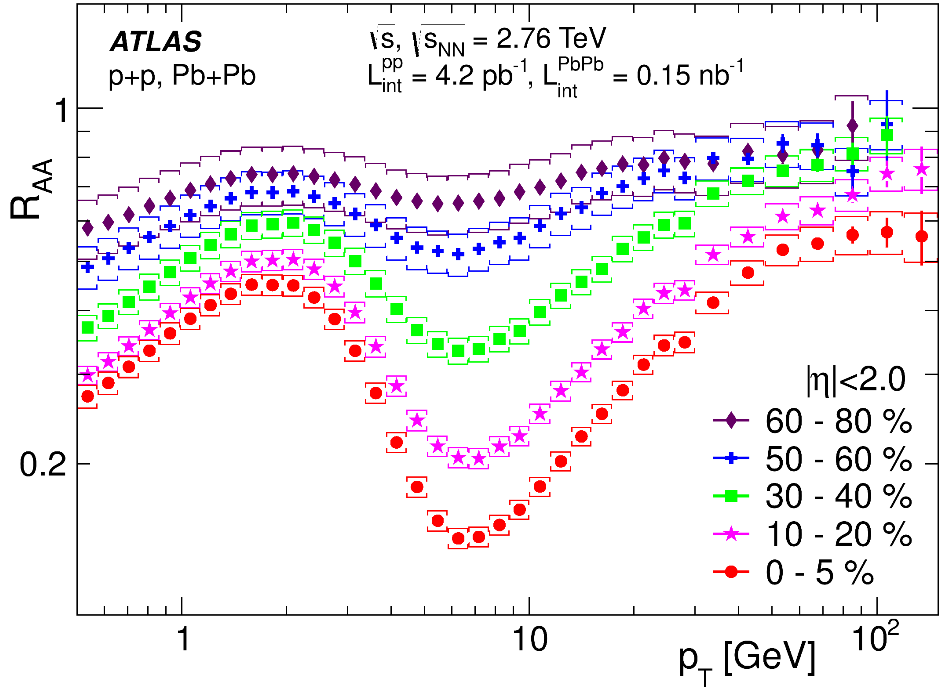
Charged-particle R_{AA}

- Nuclear modification factor, R_{AA}

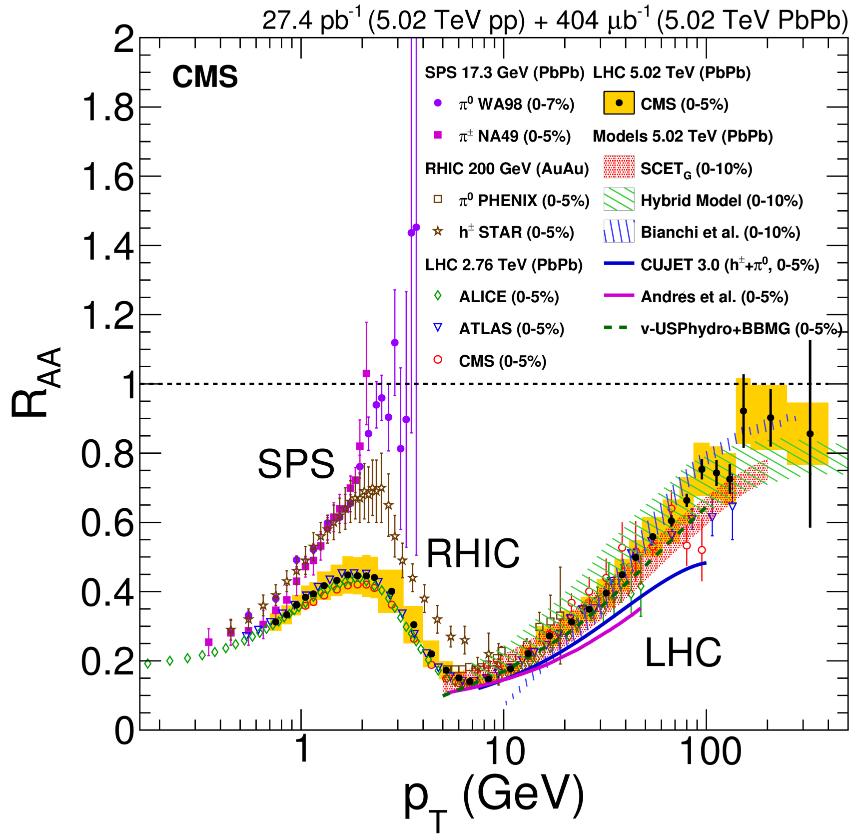
➔ Suppression in AA due to final state effects

➔ Increases with centrality and energy

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



JHEP 09 (2015) 050

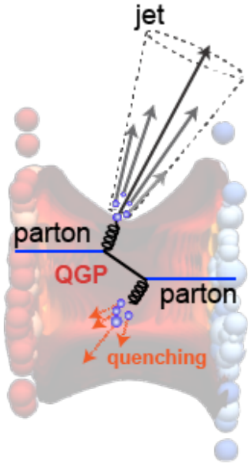


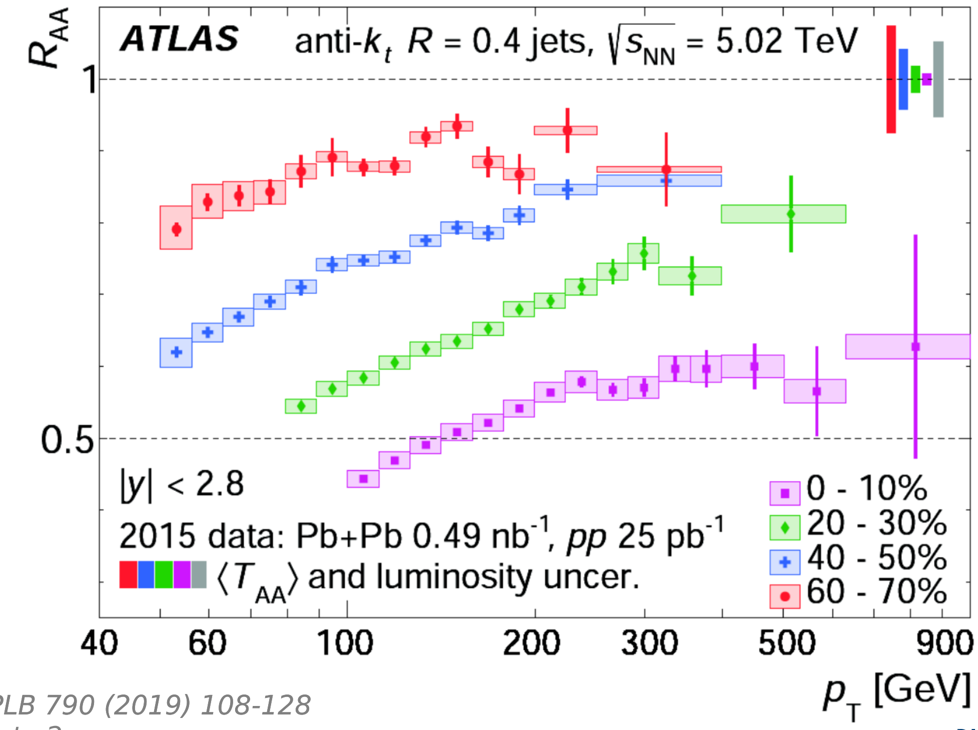
Jets

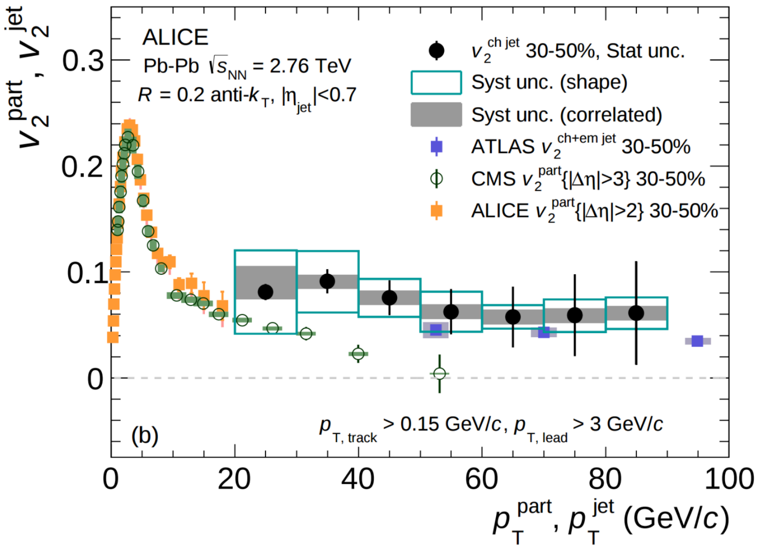
- More direct connection between the p_T and direction of the measured jet and the ones of the initial parton

➔ Strong suppression persists up to 1 TeV

➔ Jet v_2 up to 100 GeV

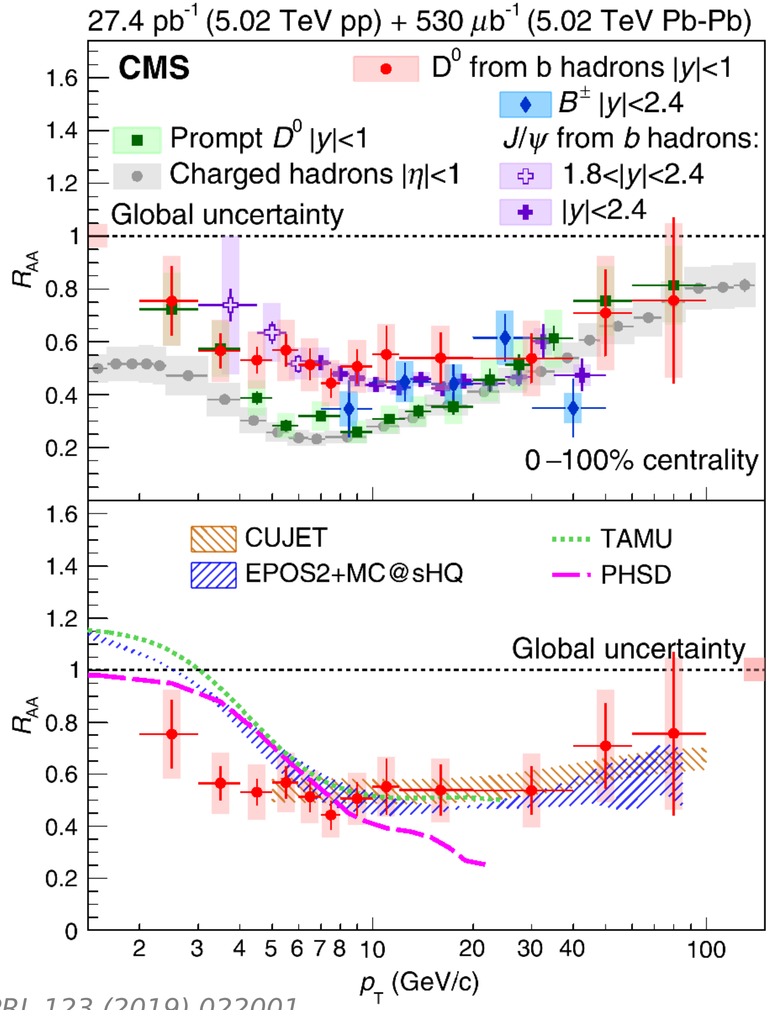






PLB 790 (2019) 108-128
Jet v2

Heavy-flavour probes

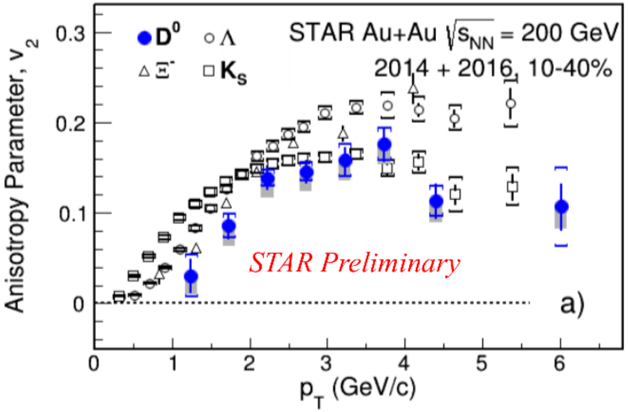


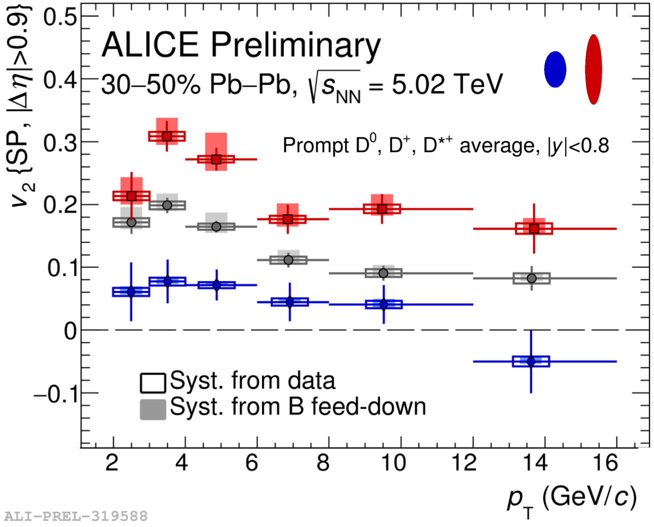
- Produced at early stage of the collisions, m > Λ_{QCD}, experience the whole medium evolution

➔ Intermediate p_T: **indication of flavour dependence** of the energy loss (sensitivity to fragmentation, p_T shape)

➔ High p_T: **flavour independent** suppression

➔ Charm *feels the shape* of the QGP





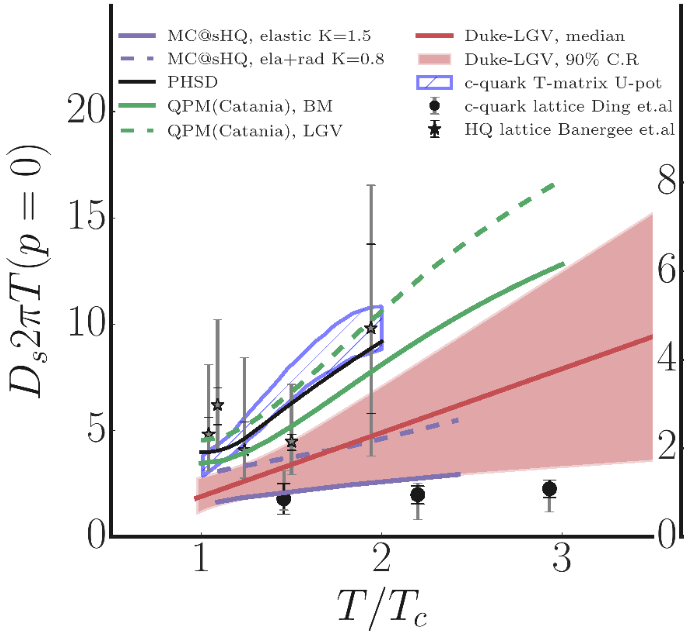
PRL 123 (2019) 022001

Transport properties of the QGP

➔ Comparison of R_{AA} and v_2 measurements to models

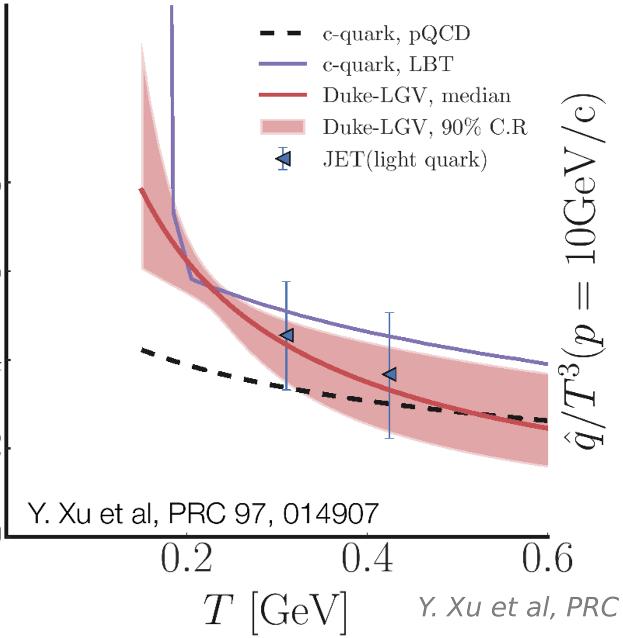
Diffusion coefficient

governs low momenta



Transport coefficient

governs high momenta



Y. Xu et al, PRC 97, 014907

Agrees with light flavour:

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

Burke et al, JET Collaboration, PRC 90, 014909

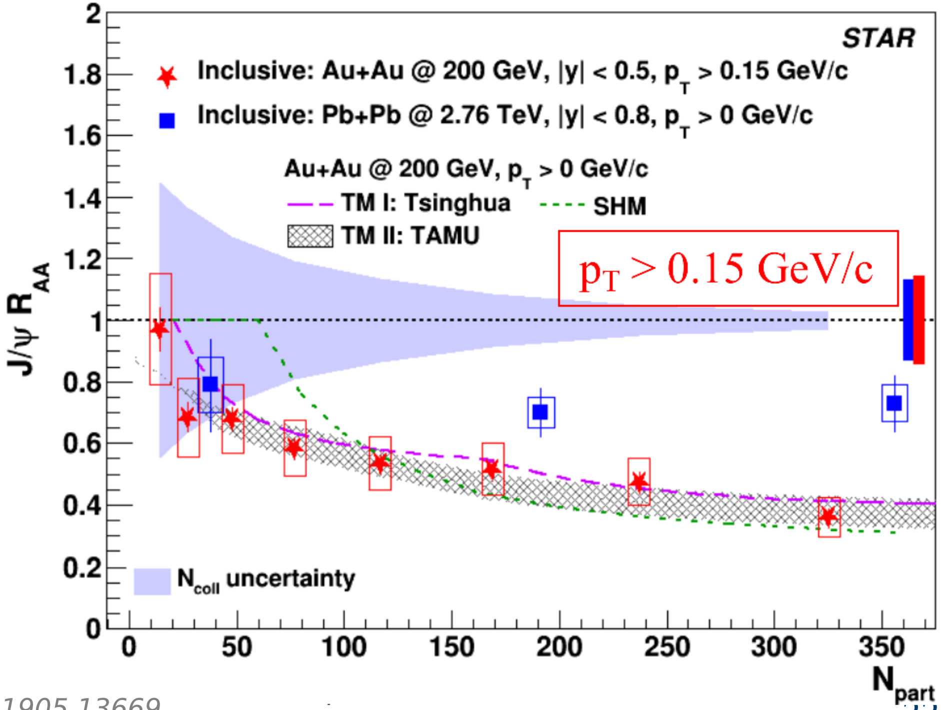
➔ Data provide significant constraints on T, p dependence of q̂ and D_s

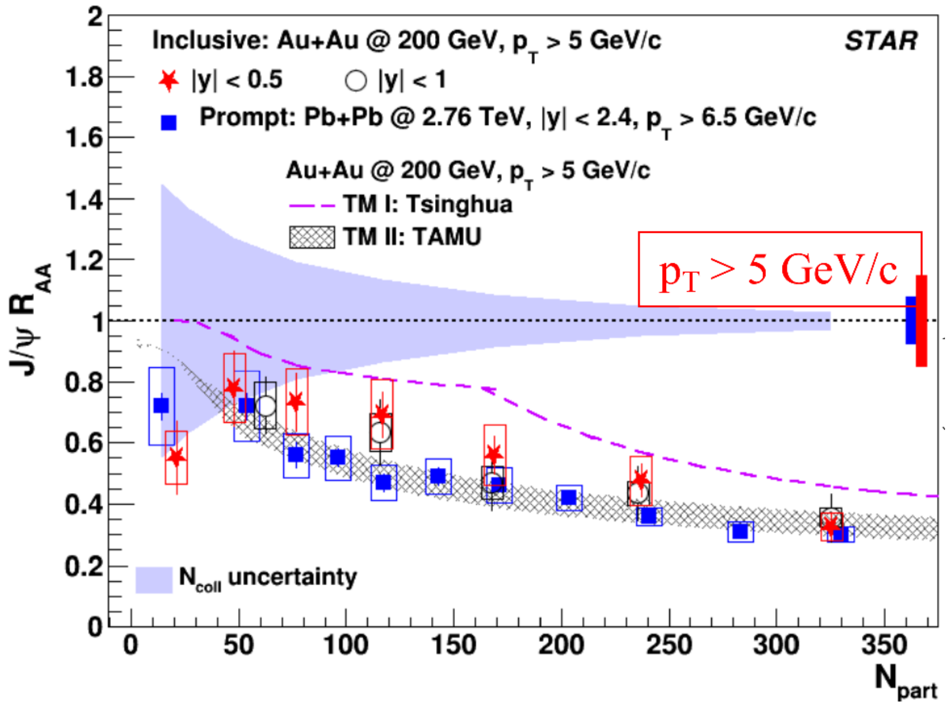
- More data available for the fits

➔ Emerging consistent understanding of light and heavy-flavour, medium expansion and transport

J/ψ suppression

- ➔ Low p_T: more suppressed at RHIC in central and semi-central
- ➔ High p_T: hint of smaller suppression at RHIC, higher temperature ?
- Significant regeneration contribution to charmonia production at low p_T, central collisions, especially at LHC
- Contribution from feed-down

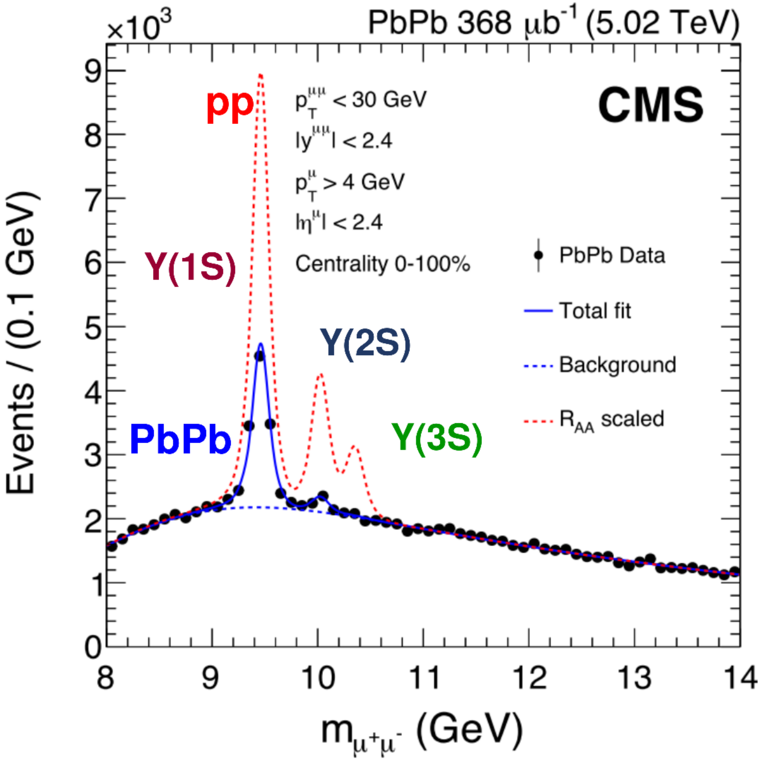


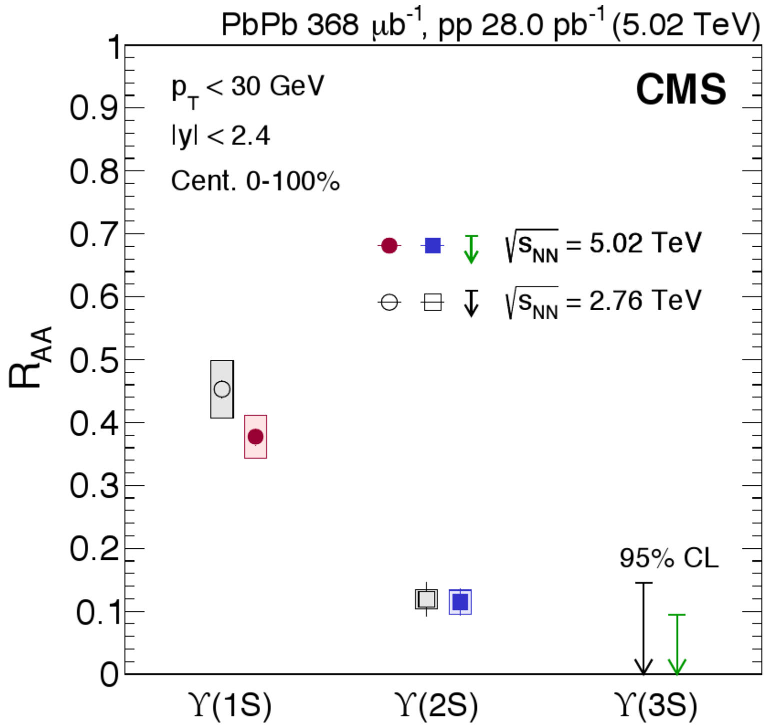


arXiv:1905.13669

Upsilon sequential suppression

- ➔ Negligible (small) regeneration component
- ➔ Sequential suppression of Upsilon states ?
- ➔ Contribution from feed-down





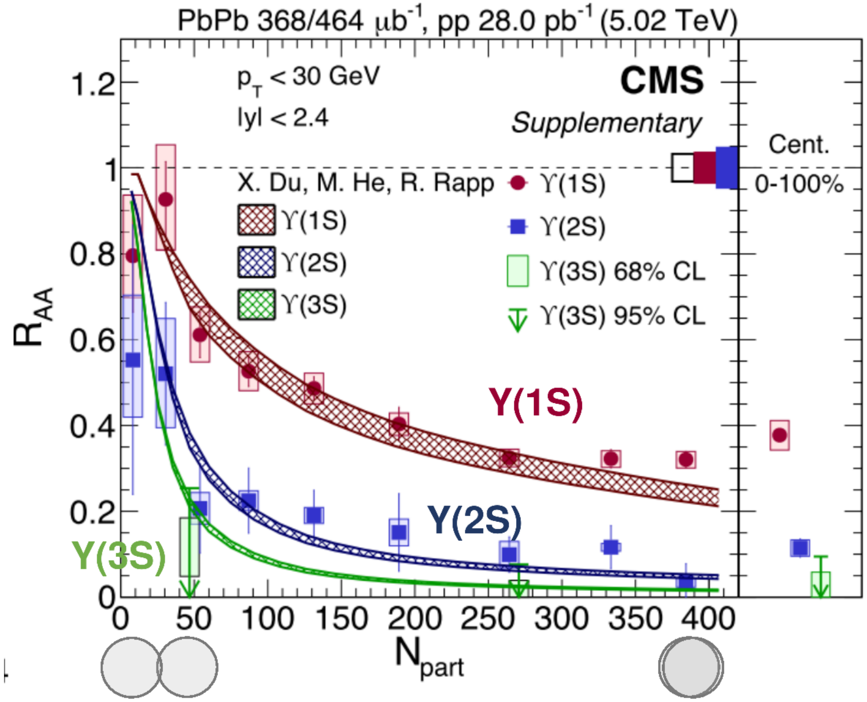
PLB 790 (2019) 270

Upsilon suppression

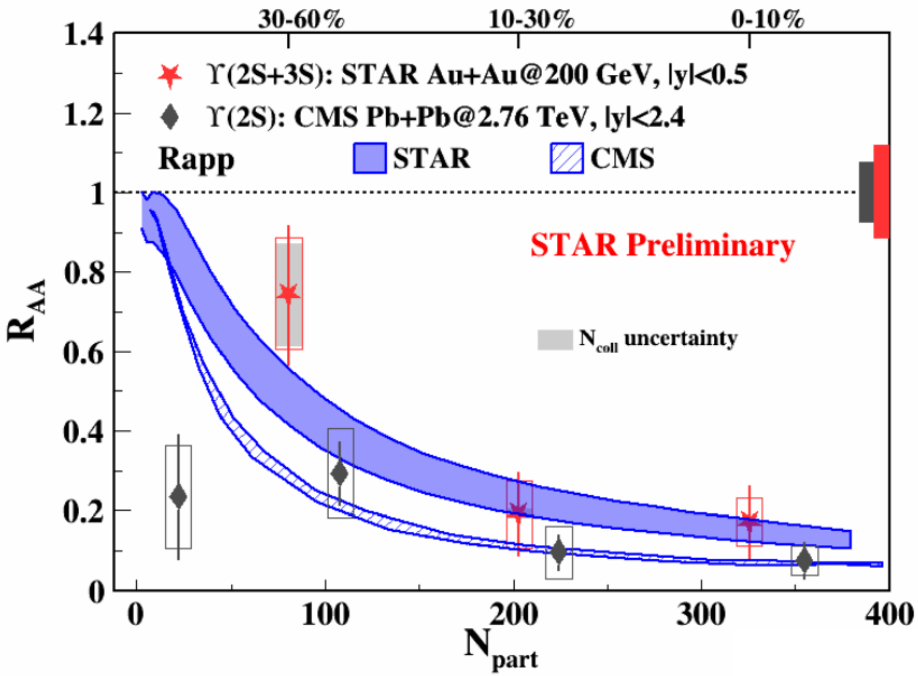
- ➔ Agreement with model using anisotropic hydrodynamics evolution with different initial temperatures
- ➔ And with CNM and small regeneration component

550 < T_0 < 800 MeV

T_0 (MeV)			
4πη/s	0.2	2.76	5.02 TeV
1	442	552	641
2	440	546	632
3	439	544	629



PLB 790 (2019) 270



PRD 97, (2018) 016017
PRC 96, (2017) 054901

Summary

- ➔ Consistent picture of QGP emerging
- ➔ Important step forwards in the understanding of QCD at extreme conditions of high temperature and energy density
  - Wealth of results from RHIC and LHC experiments in the last years
  - Tremendous progress also on the theoretical side towards an “heavy-ion standard model”

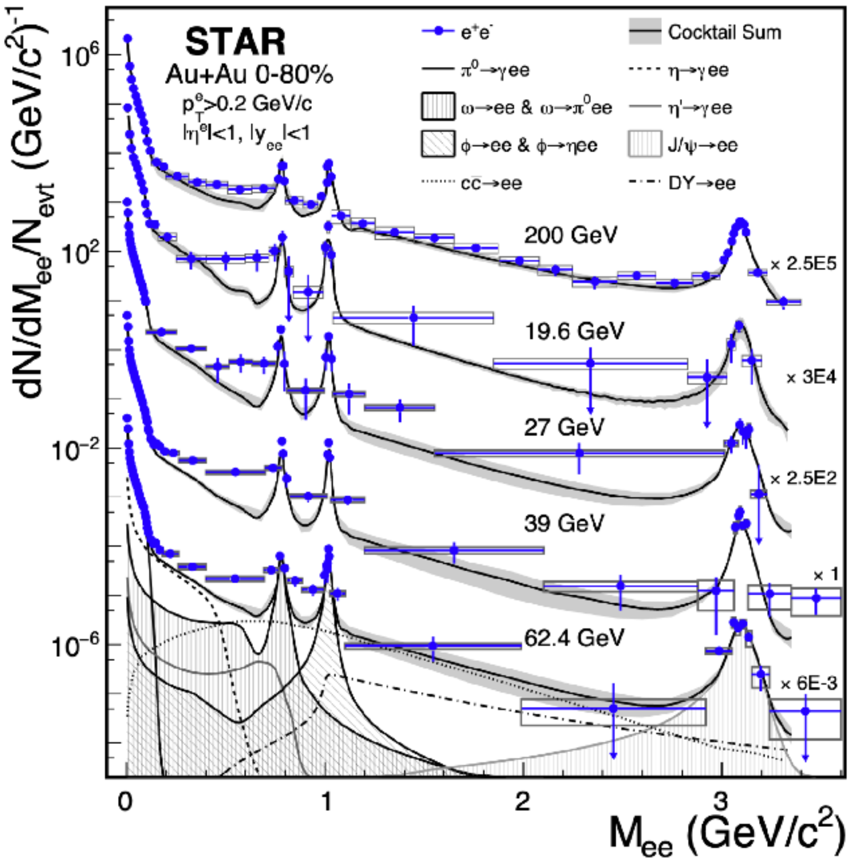
- ➔ Small systems important for HI studies: pp/pA → AA evolution

Backup

Low mass dielectrons, STAR

- ➔ Measurements of e–e+ distributions over broad momentum range, Au+Au at different energies
- ➔ Compared to cocktail from known sources (excluding vacuum rh0)
- ➔ Clear excess seen in low-mass region

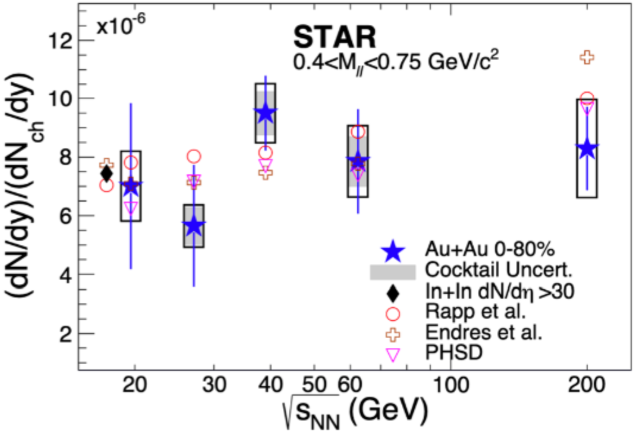
arXiv: 1810.10159



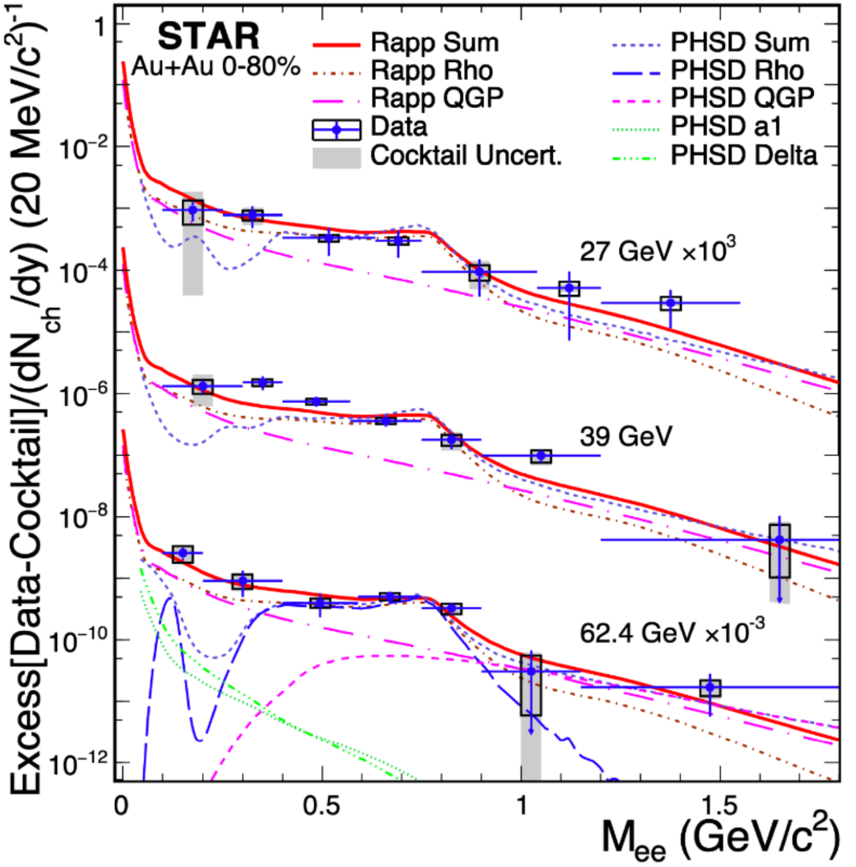
Low mass dielectrons, STAR

- ➔ Excess compared to Rapp & PHSD calculations
  - Contributions from broadened rh0, other decays, QGP radiation
  - Both calculations describe excess well for $0.4<M_{ee}<0.75$ GeV
  - Good agreement over broad energy range (also for NA60 In+In)
- ➔ But: low-mass e– e+ yield for p_T < 0.15 GeV/c not explained by cocktail w/ broadened r

PRL 121 132301 (2018)



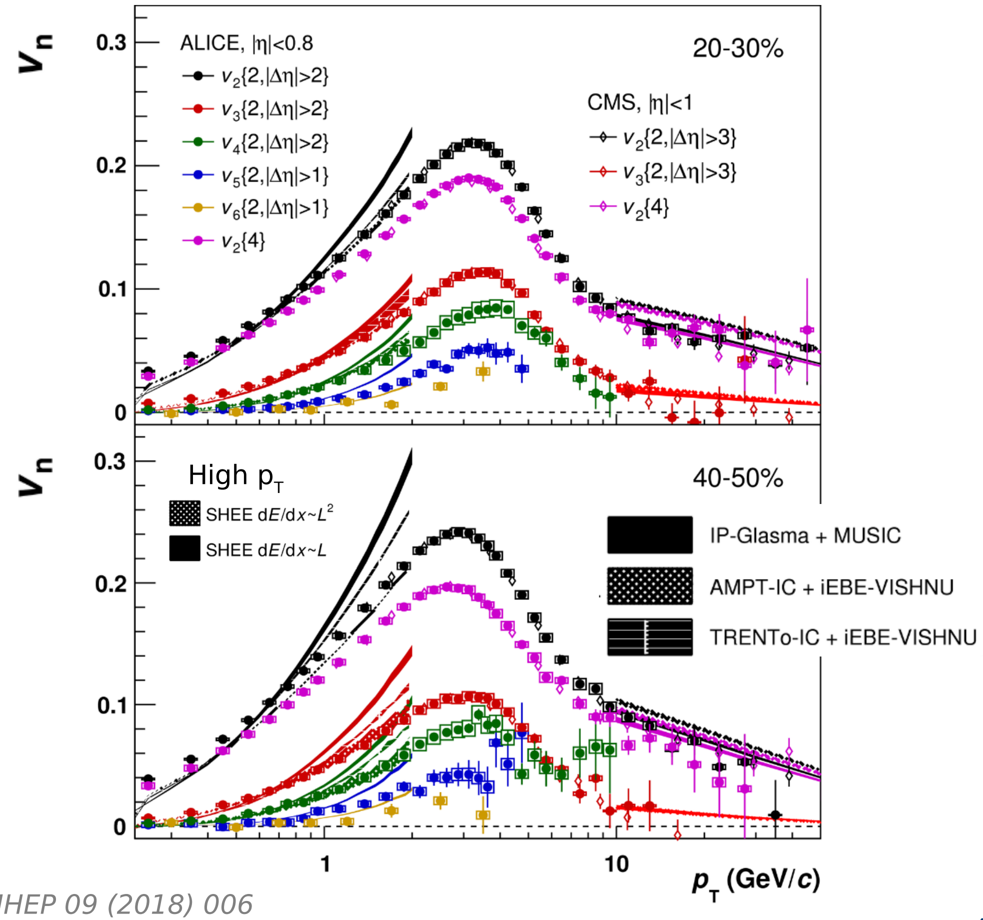
arXiv: 1810.10159

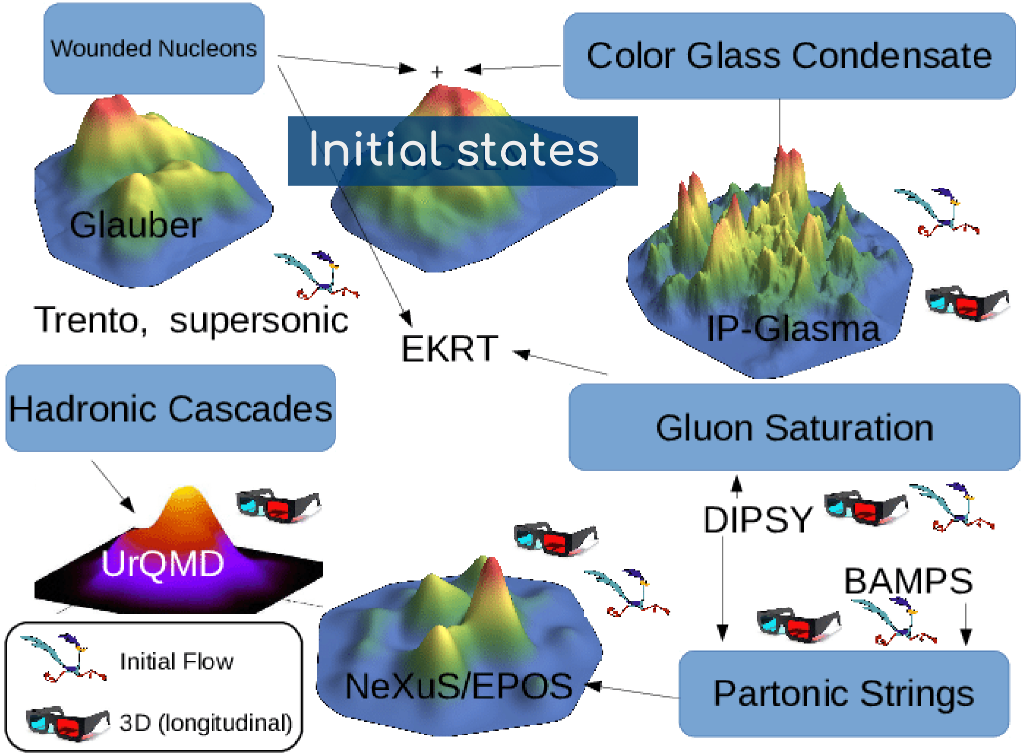


Also: PRC 99 024002 (2019)
PRC 81 034911 (2010)

Sensitivity to the initial state

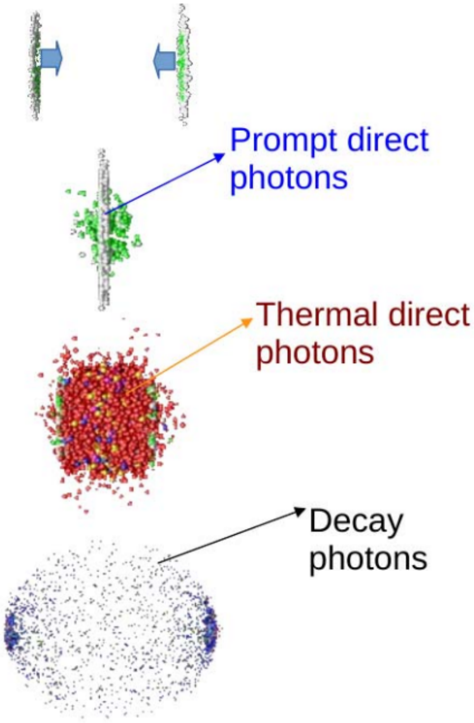
➔ Dependent on fine details of the initial energy density distribution



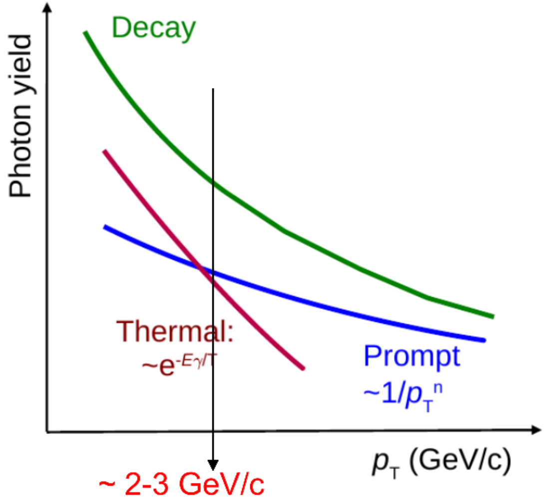


JHEP 09 (2018) 006
JHEP 1807 (2018) 103

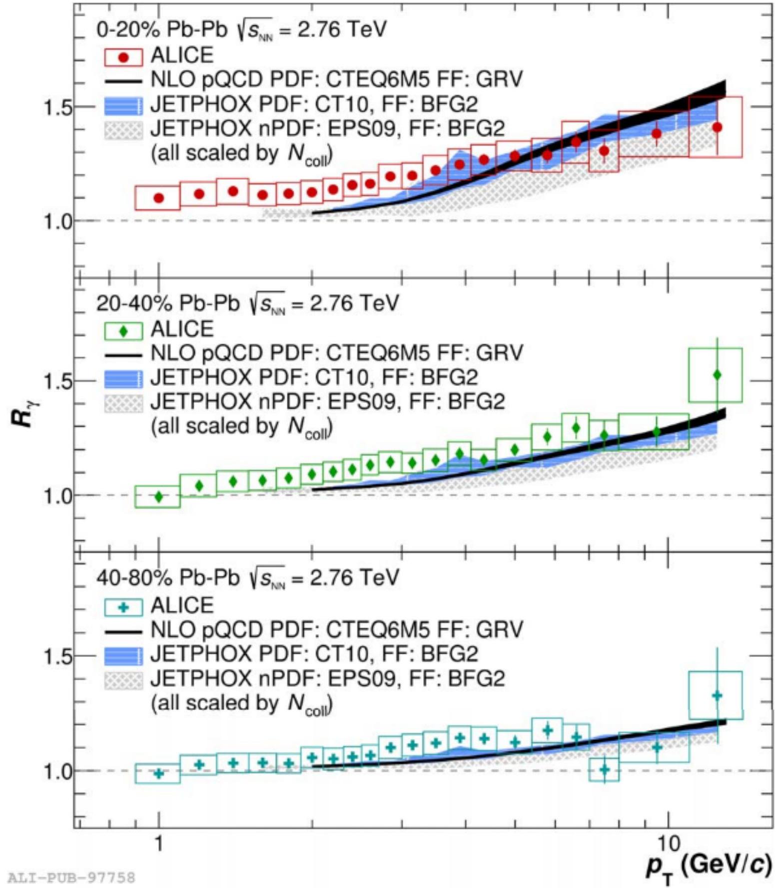
Direct photons



- Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision
- Photons are produced at different collision times
- Photons don't interact strongly and carry out information about collision, even the earliest stage

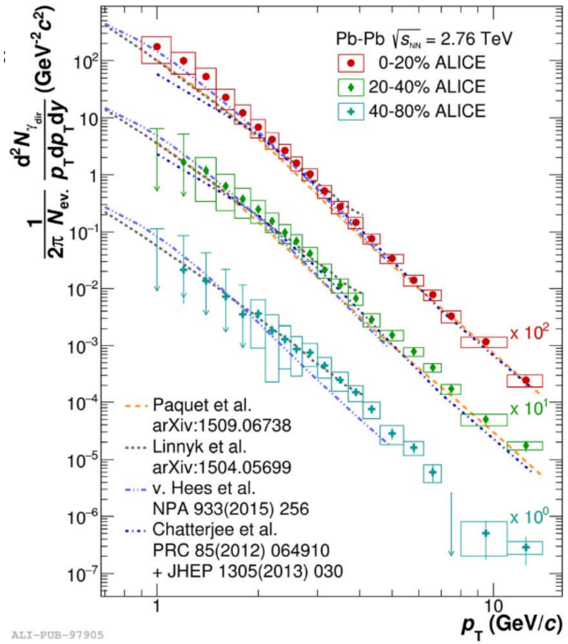


Direct photons in ALICE



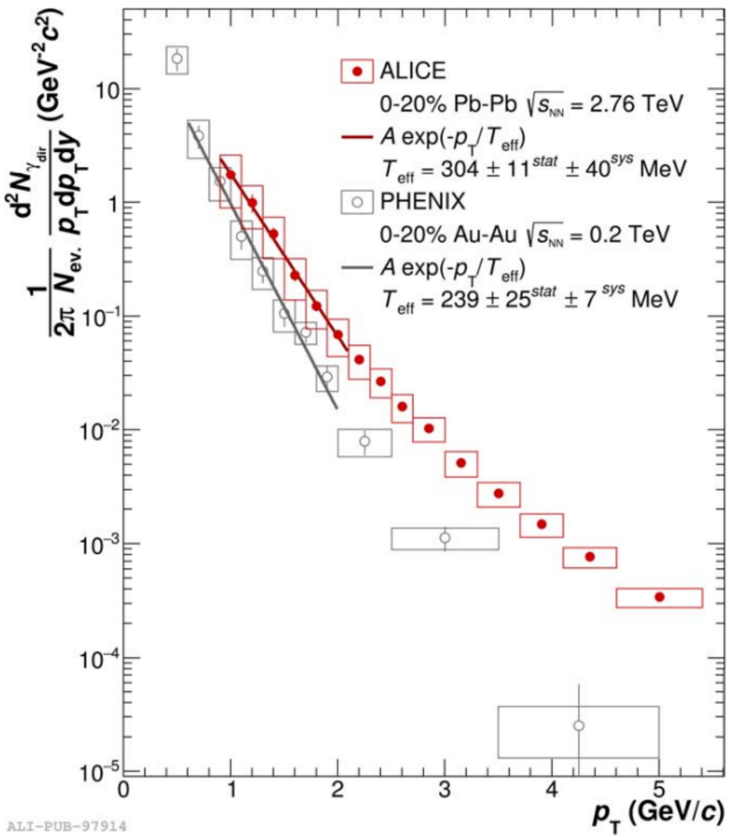
Phys. Lett. B 754 (2016) 235

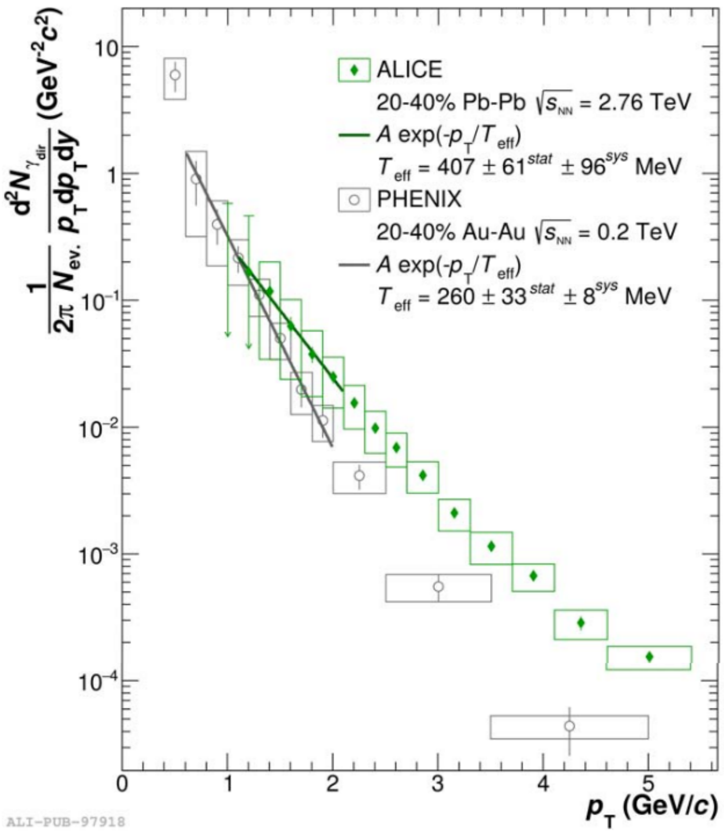
- At low p_T 2-3 GeV/c
  ~ 8%-15% excess in 0-20% ;
  ~ 8%-9% in 20-40%
- At high p_T above ~5 GeV/c in agreement with NLO pQCD and JETPHOX
- Agreement with hydro models



Effective temperature

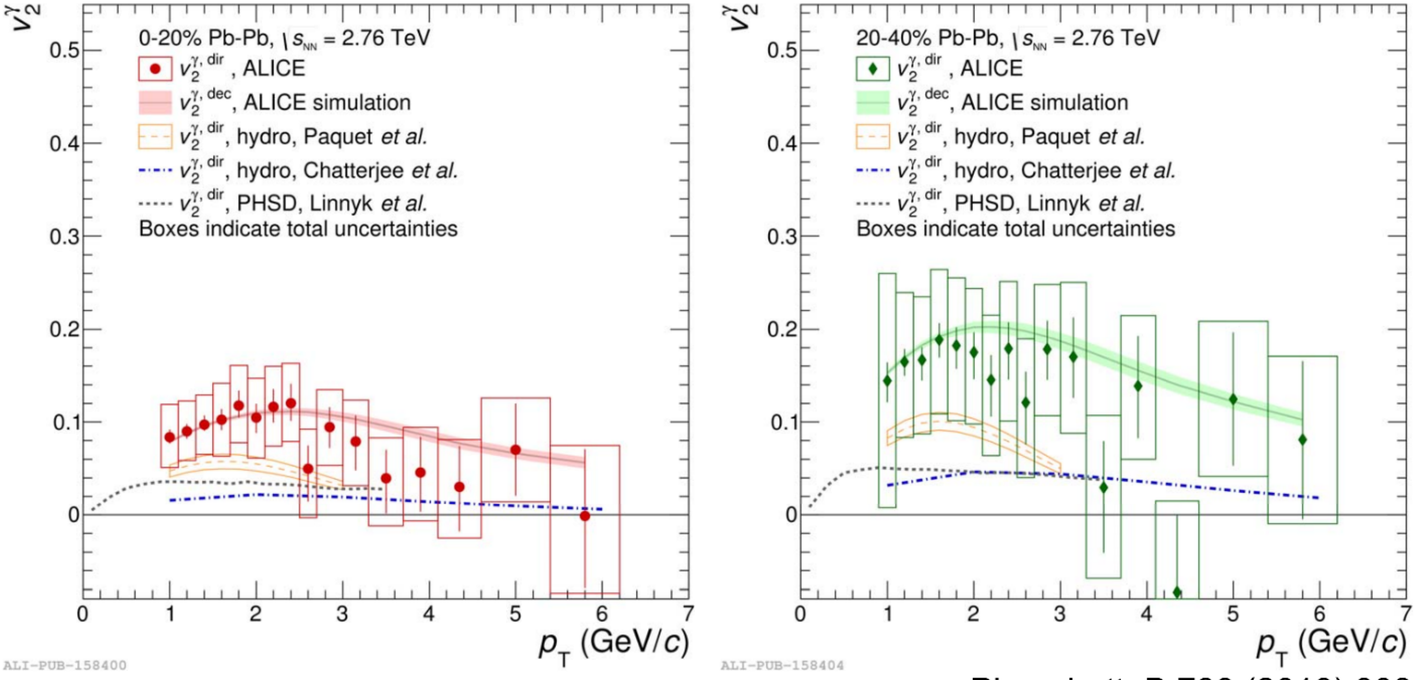
- ➔ Effective temperature can be extracted from the low-p_T part of the spectrum
- ➔ Both absolute yield of direct photons and effective slope increase with increasing of the collision energy





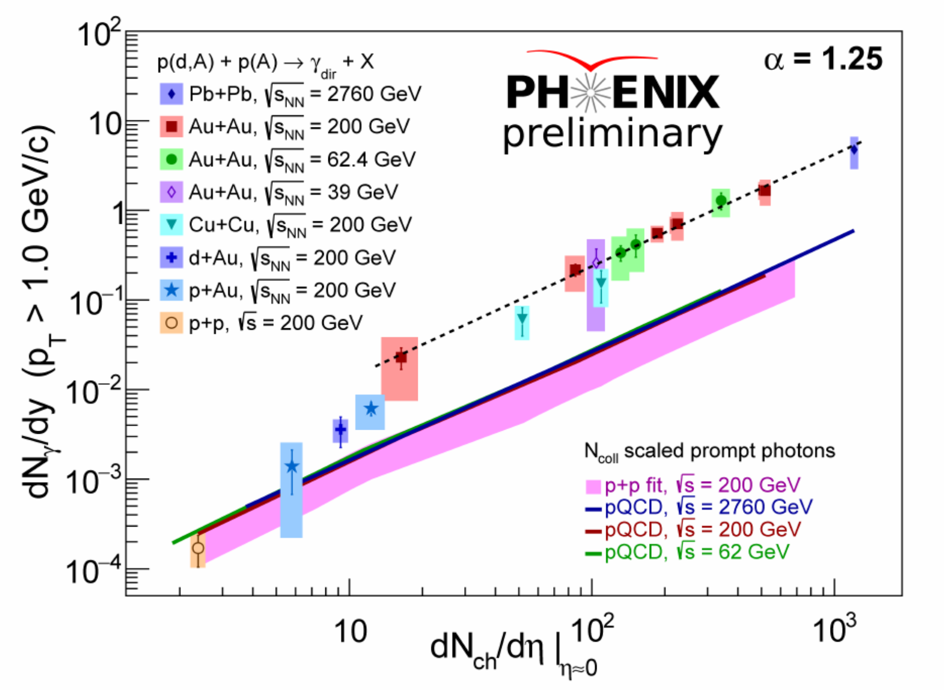
Direct photon flow in Pb-Pb

- ➔ Large v_2 for p_T < 3 GeV/c, comparable to hadron flow for 20-40% - too large uncertainties for conclusions
- ➔ Hydro models underpredict direct photon low → models need further development
- ➔ Hint for late direct photons production, and early flow formation



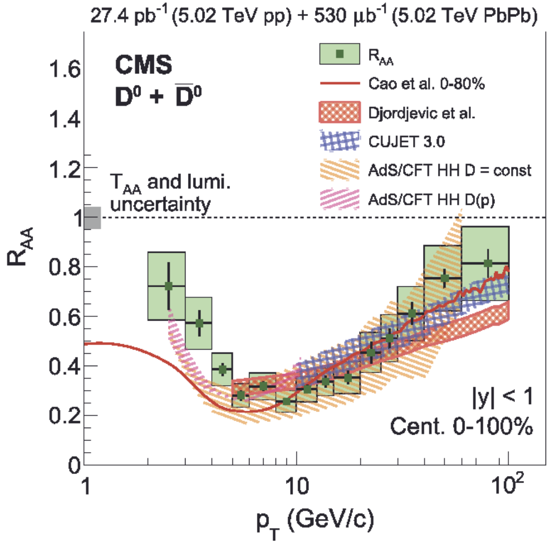
Phys. Lett. B 789 (2019) 308-322

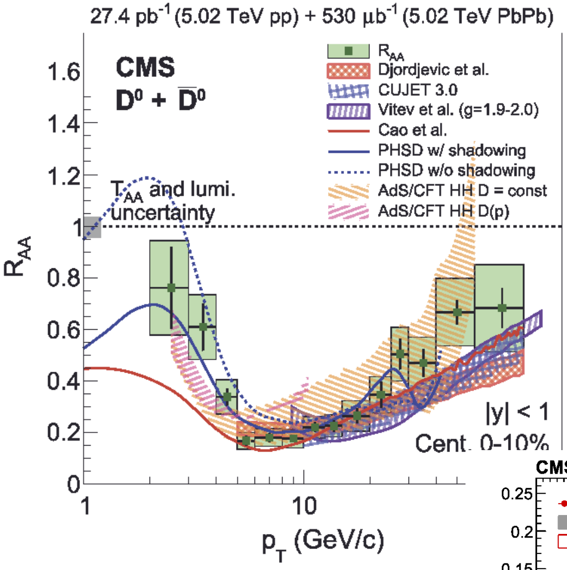
Photon yields

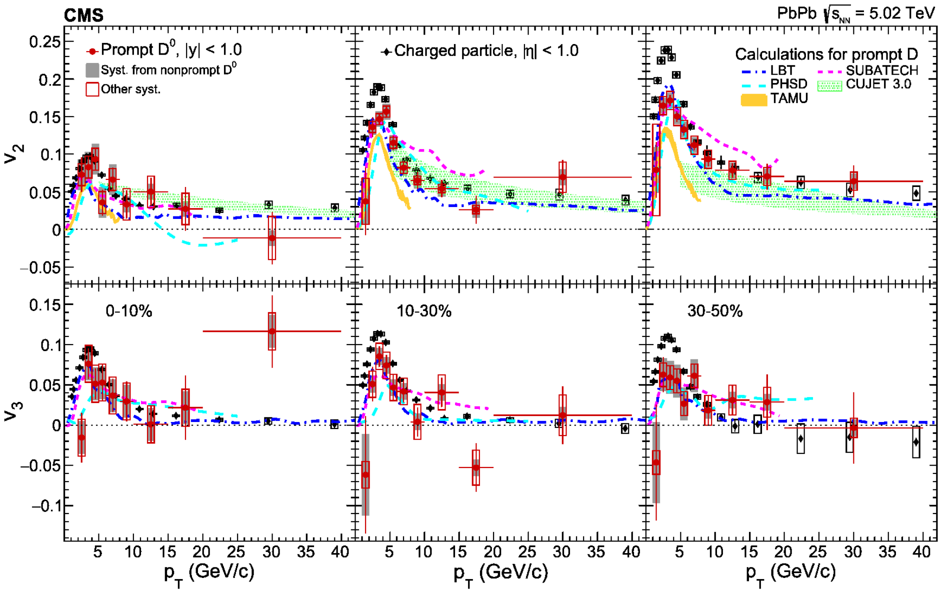


1805.04084 (PRL)

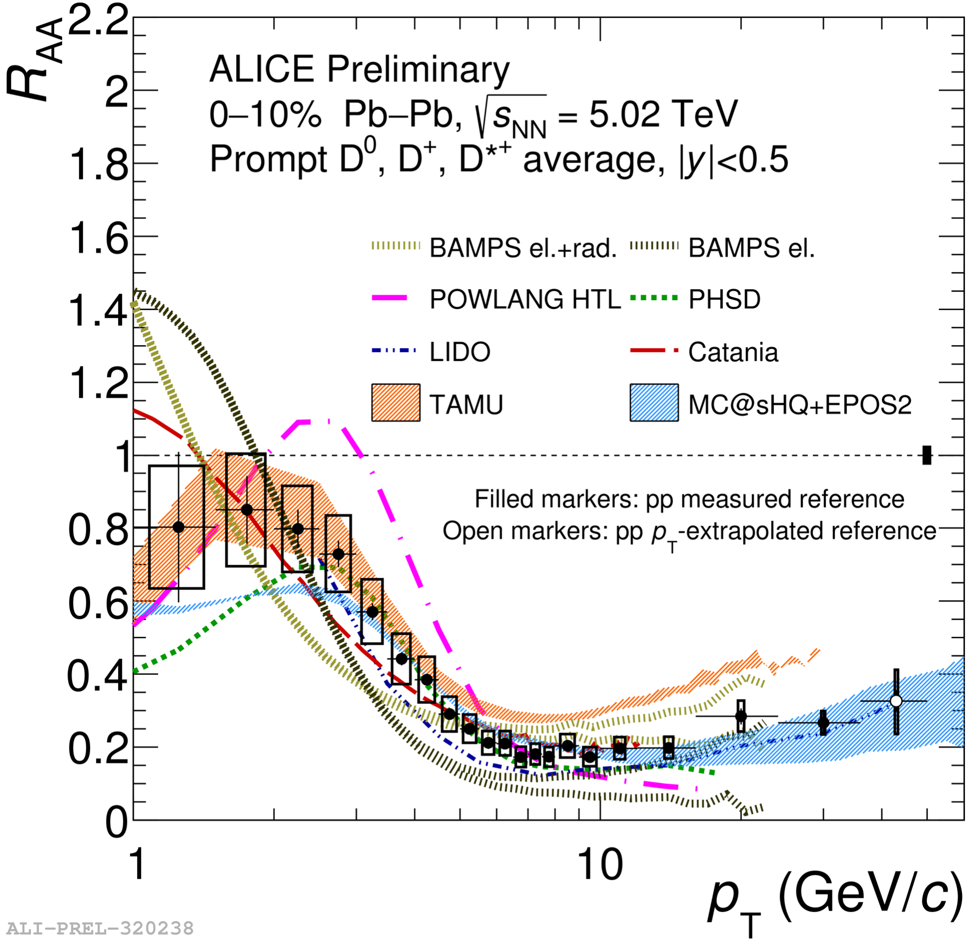
Open charm vs models – CMS

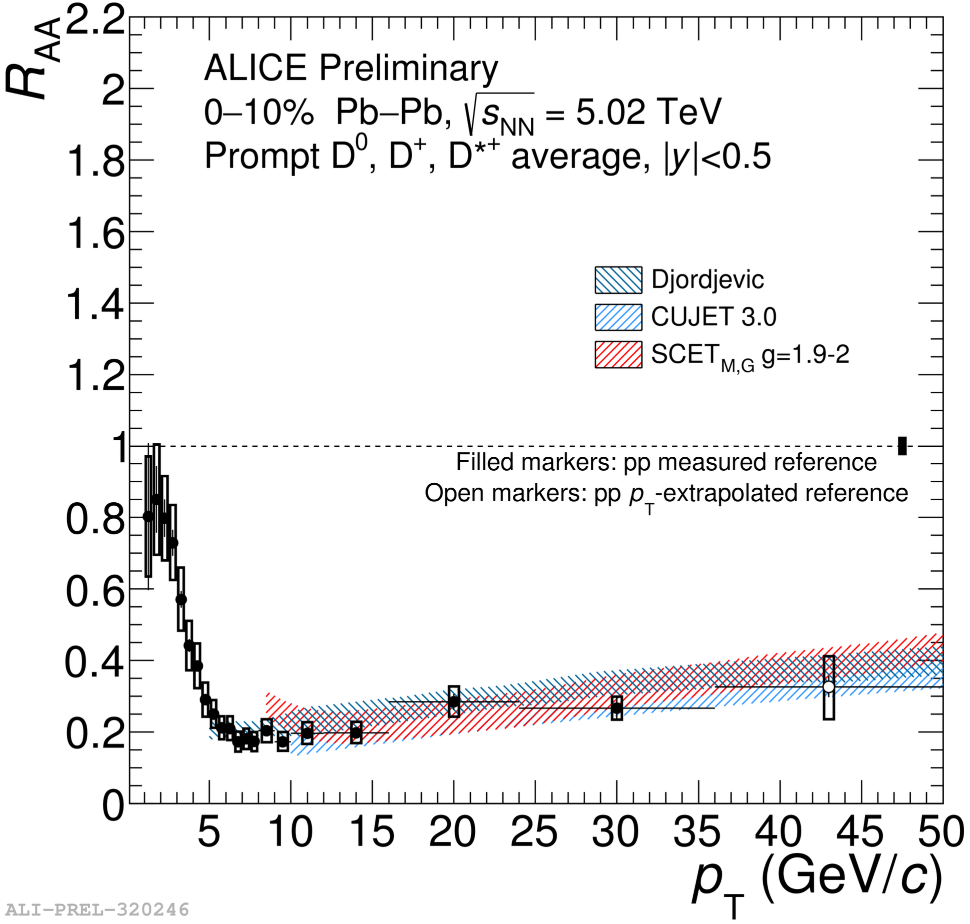






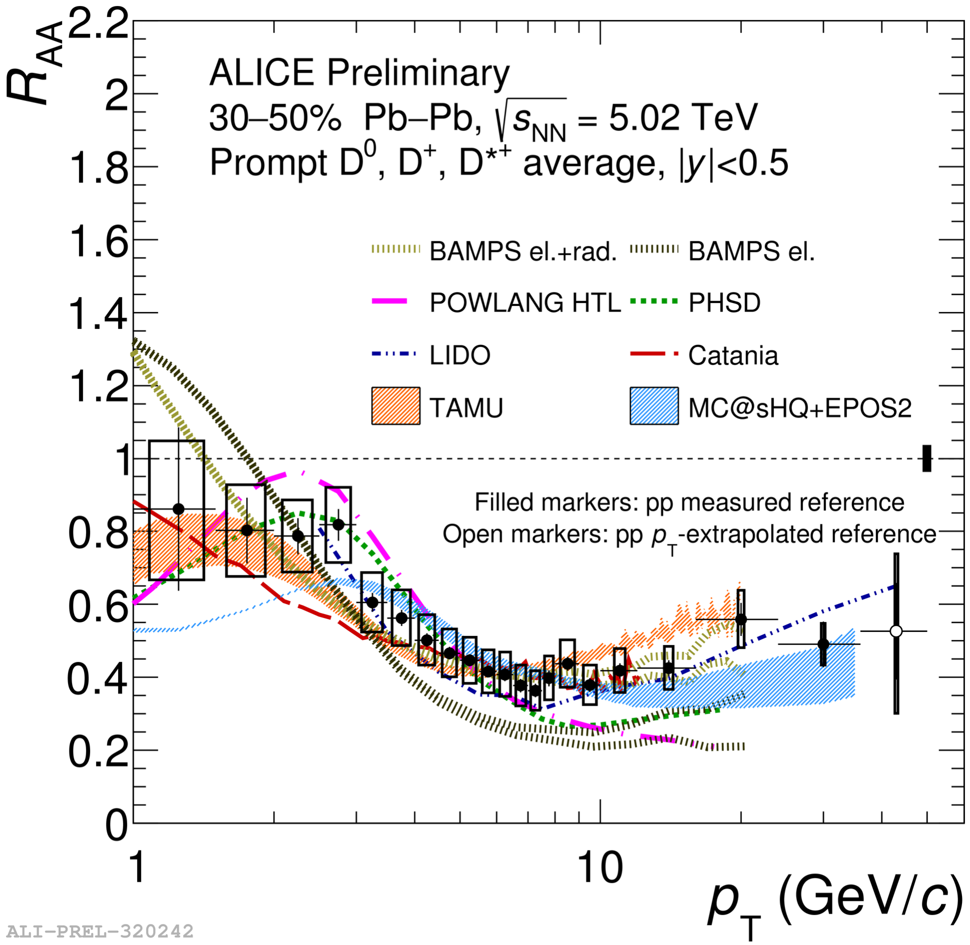
Open charm vs models – ALICE

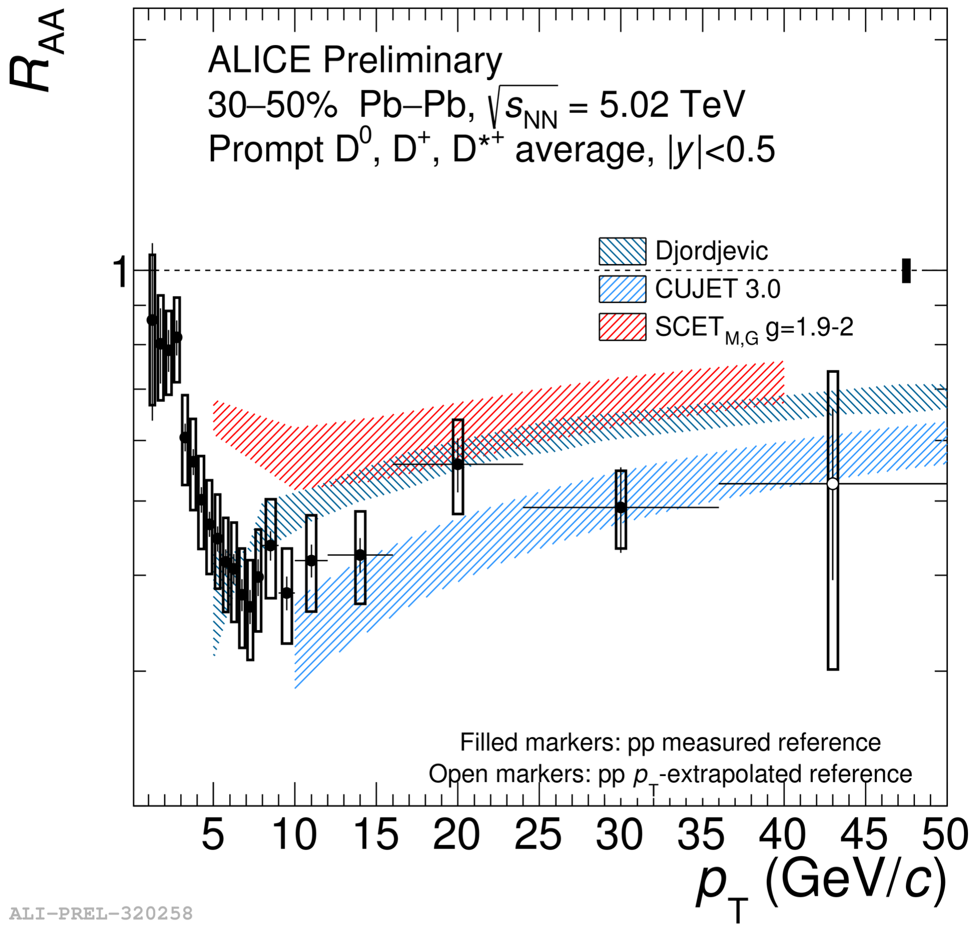




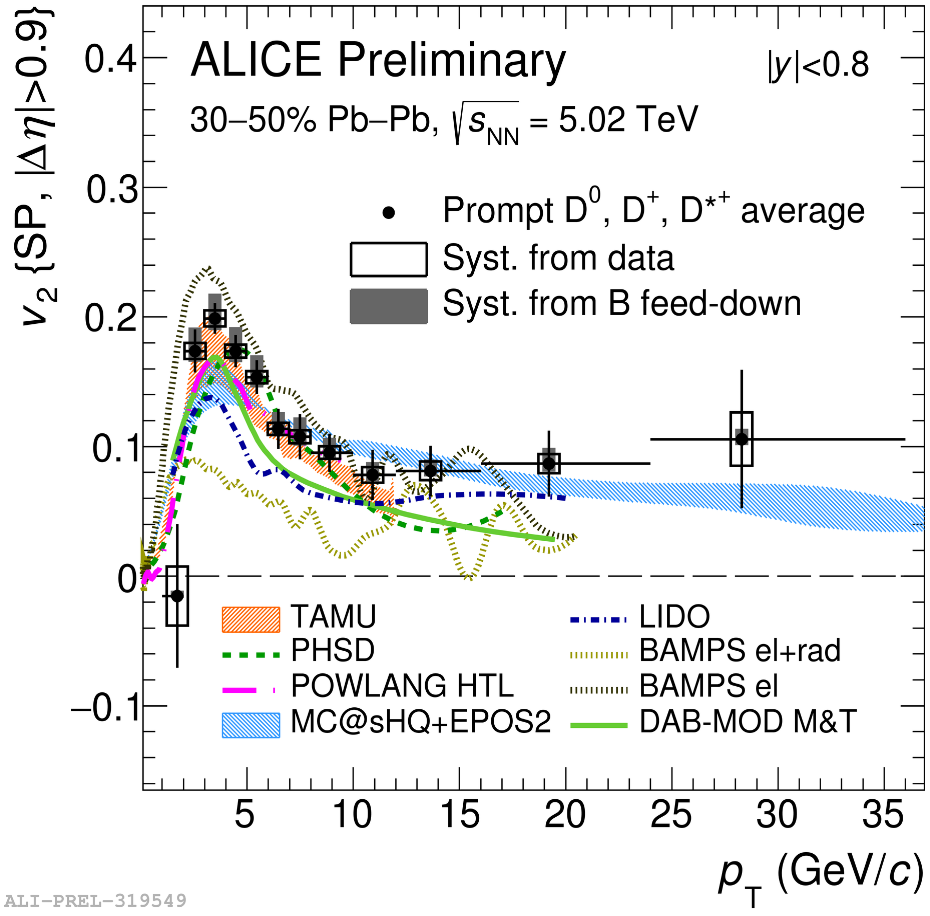
P

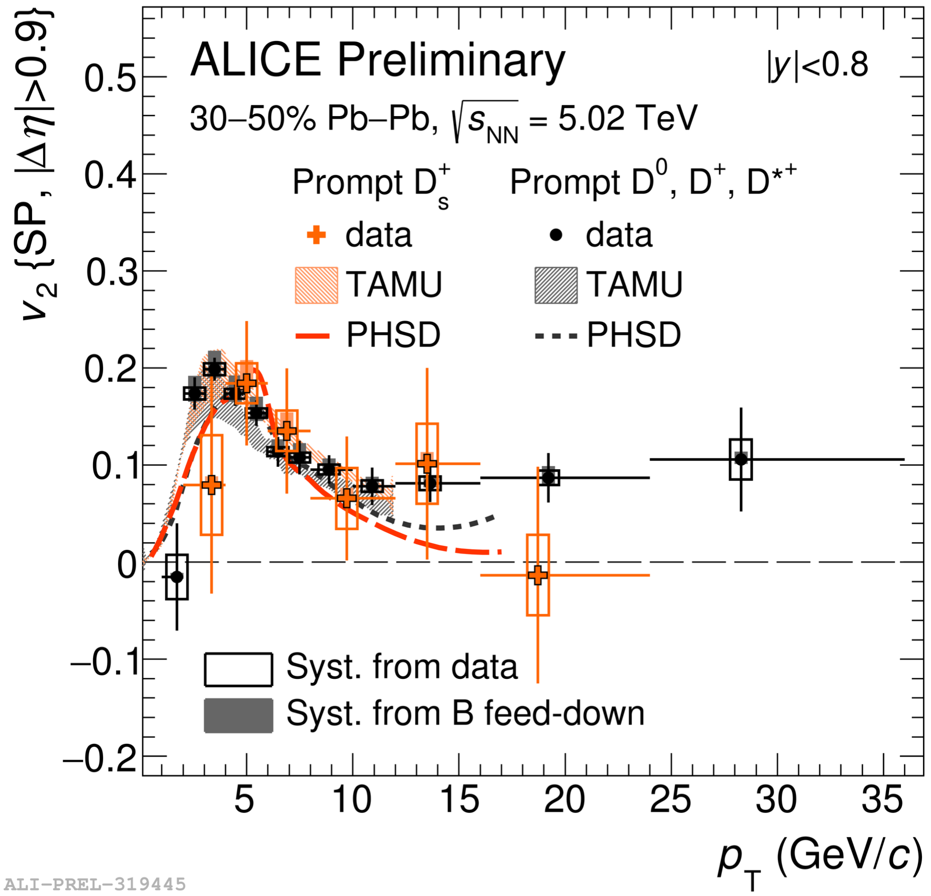
Open charm vs models – ALICE



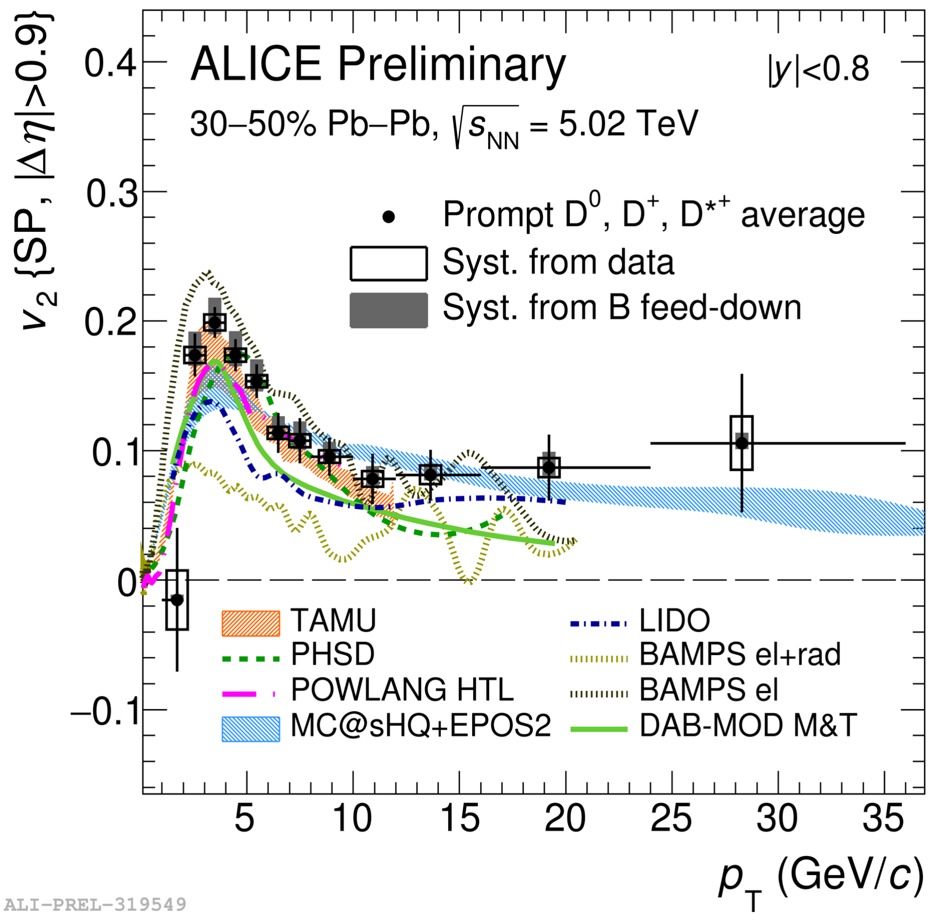


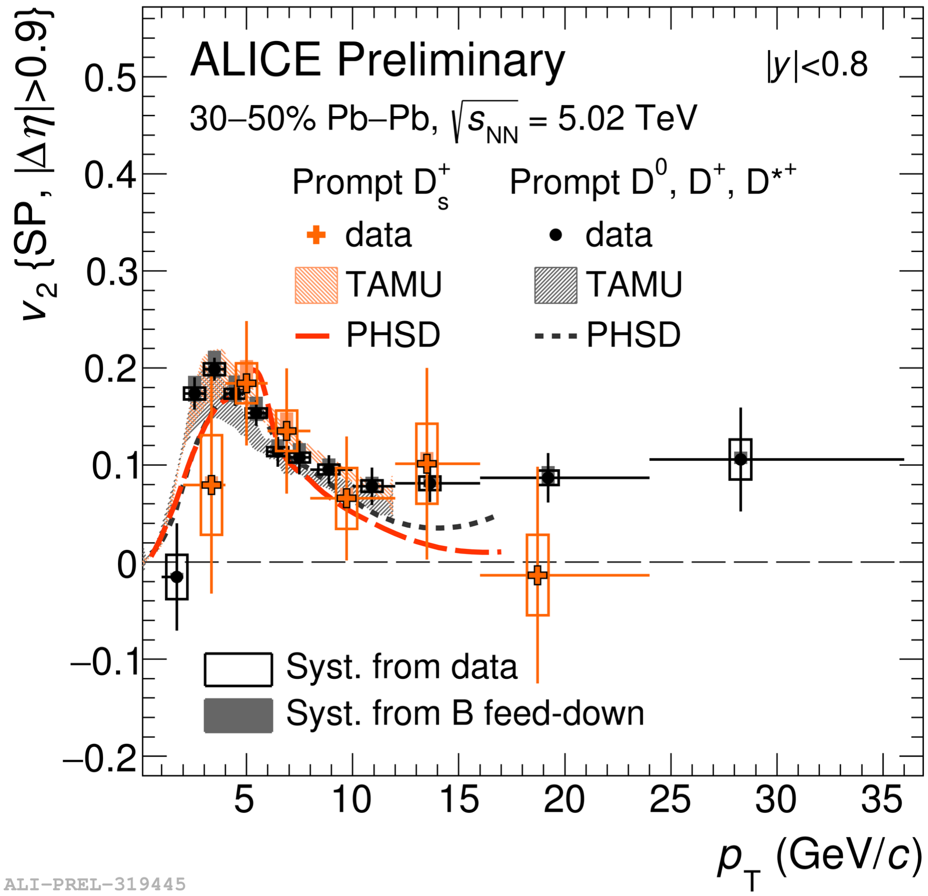
Open charm vs models – ALICE



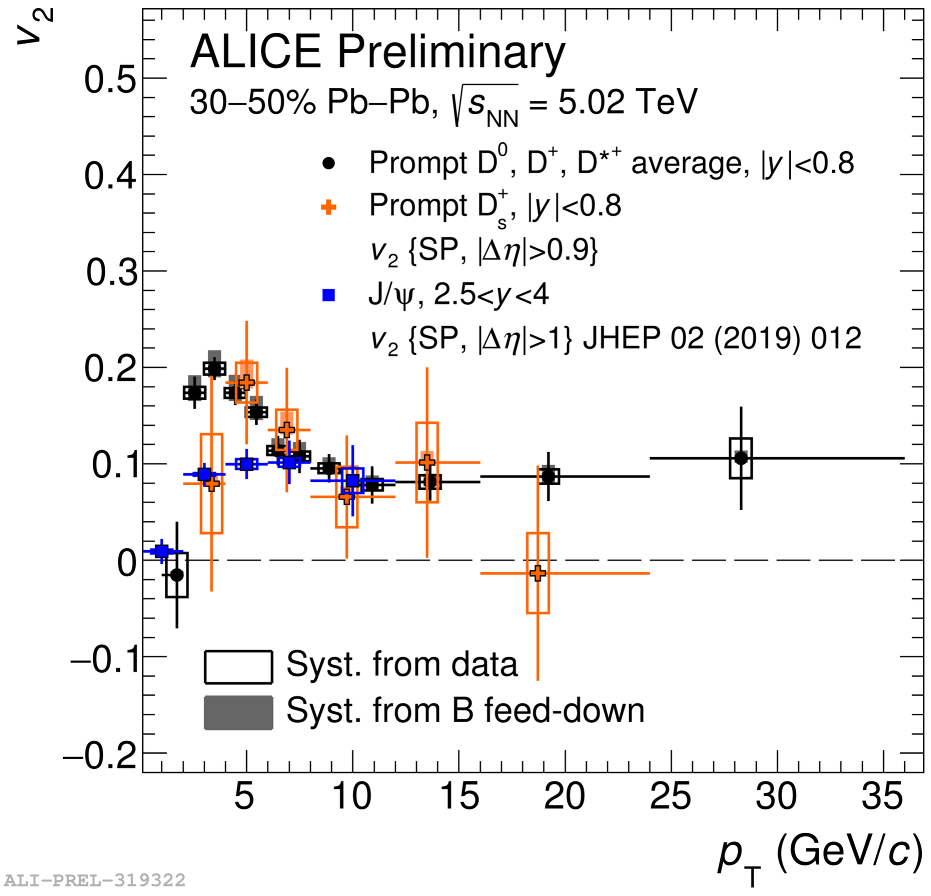


Open charm vs models – ALICE

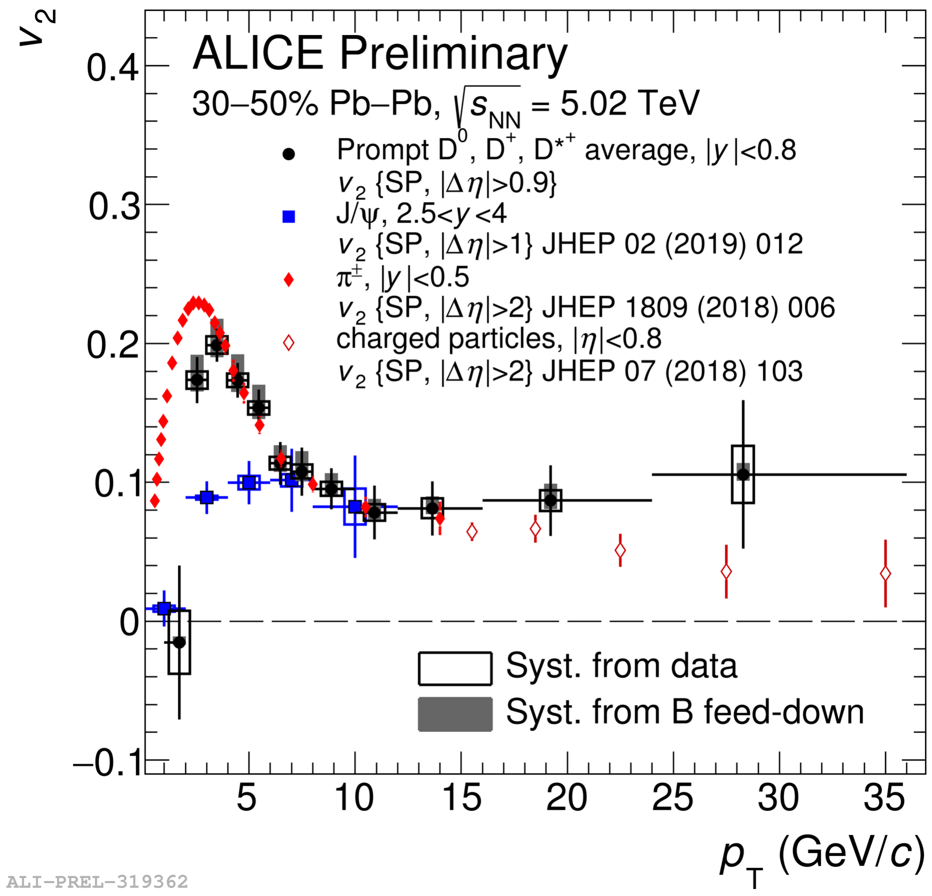




J/psi v_2



ALICE Preliminary
30–50% Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Prompt D^0, D^+, D^{*+} average, |y|<0.8
Prompt D_s^+, |y|<0.8
v_2 {SP, |Δη|>0.9}
J/ψ, 2.5<y<4
v_2 {SP, |Δη|>1} JHEP 02 (2019) 012
Syst. from data
Syst. from B feed-down
v_2
p_T (GeV/c)
ALI-PREL-319322



ALICE Preliminary
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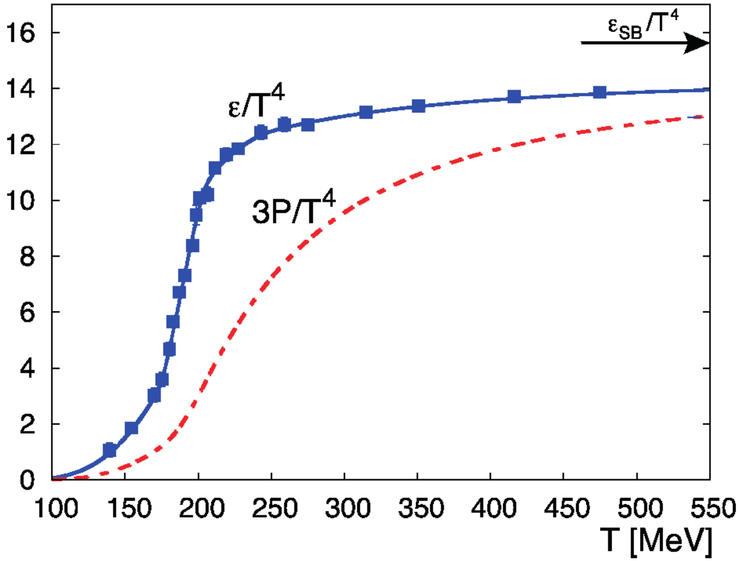
Prompt D^0, D^+, D^{*+} average, |y|<0.8
v_2 {SP, |Δη|>0.9}
J/ψ, 2.5<y<4
v_2 {SP, |Δη|>1} JHEP 02 (2019) 012
$\pi^{\pm}$, |y|<0.5
v_2 {SP, |Δη|>2} JHEP 1809 (2018) 006
charged particles, |η|<0.8
v_2 {SP, |Δη|>2} JHEP 07 (2018) 103
Syst. from data
Syst. from B feed-down
v_2
p_T (GeV/c)
ALI-PREL-319362

Probes

- It is mostly from the final state hadrons measured in the experimental apparatus that one tries to deduce information about the initial state and the collision history
- The investigation of the creation of the QGP and the study of its properties is thus relying on appropriate experimental observables (so-called “signatures”) and their comparison to models
- To extract the properties of the produced matter different experimental observables are being optimized to probe the dynamical evolution of the system and characterize the different stages of the collision.
- The characterization of the created partonic matter in terms of its initial conditions (eccentricity, volume, temperature, lifetime), equation-of-state (relating pressure and energy) and of its transport properties (viscosity and diffusion coefficients)
- Soft probes
  - Charged-particle multiplicity, elliptic flow: bulk matter properties
  - Transverse momenta spectra and nuclear modification factor: thermodynamic and transport properties of matter

Lattice QCD

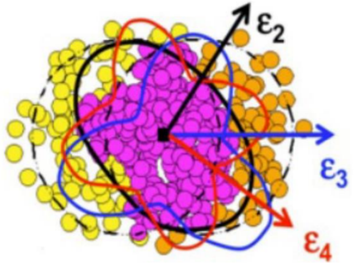


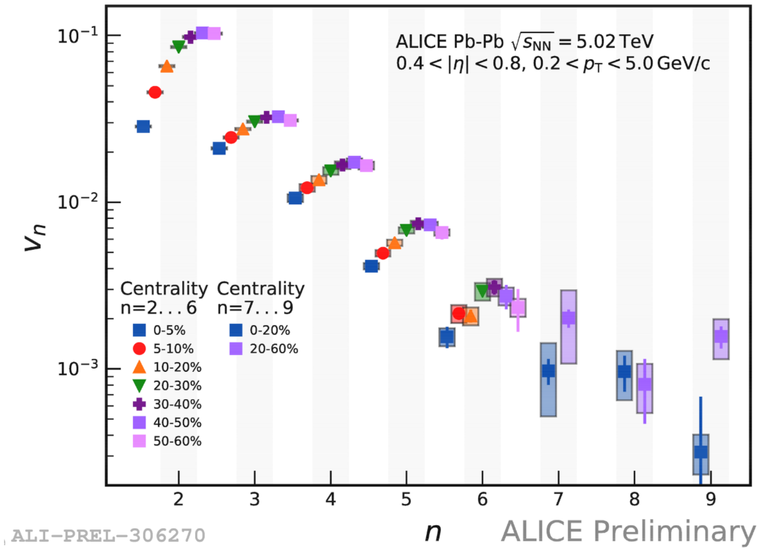
Phys. Rev. D 80 014504

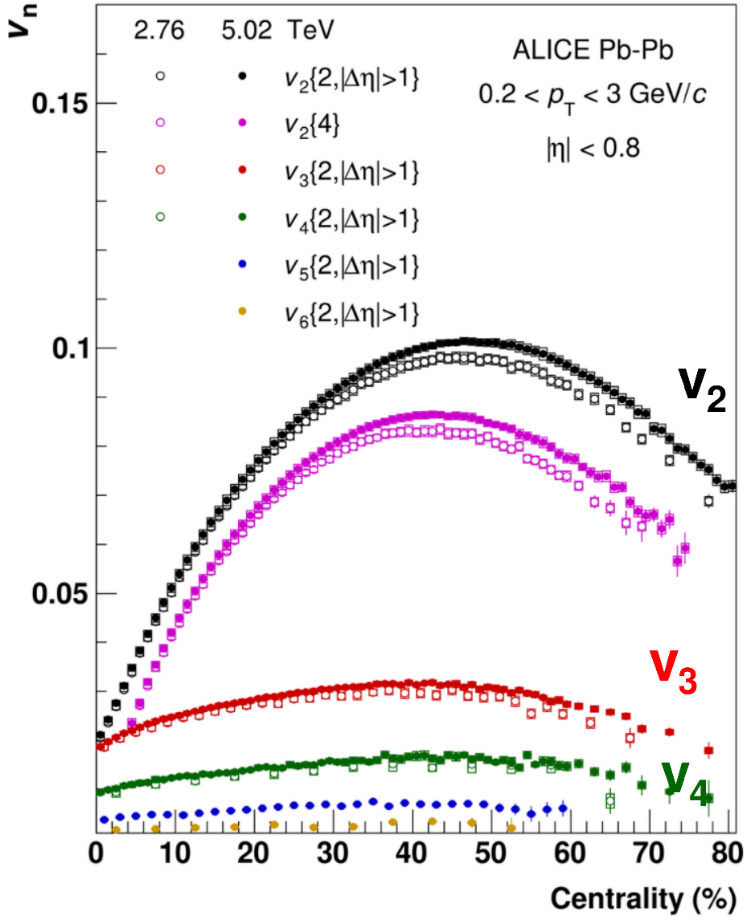
One of the fundamental questions in QCD phenomenology:

Fluctuations in the initial geometry – backup

- ➔ **Fluctuations in initial geometry,** nucleon position and their fluctuations dictate the eccentricity → development of higher harmonics
- ➔ Important in central collisions



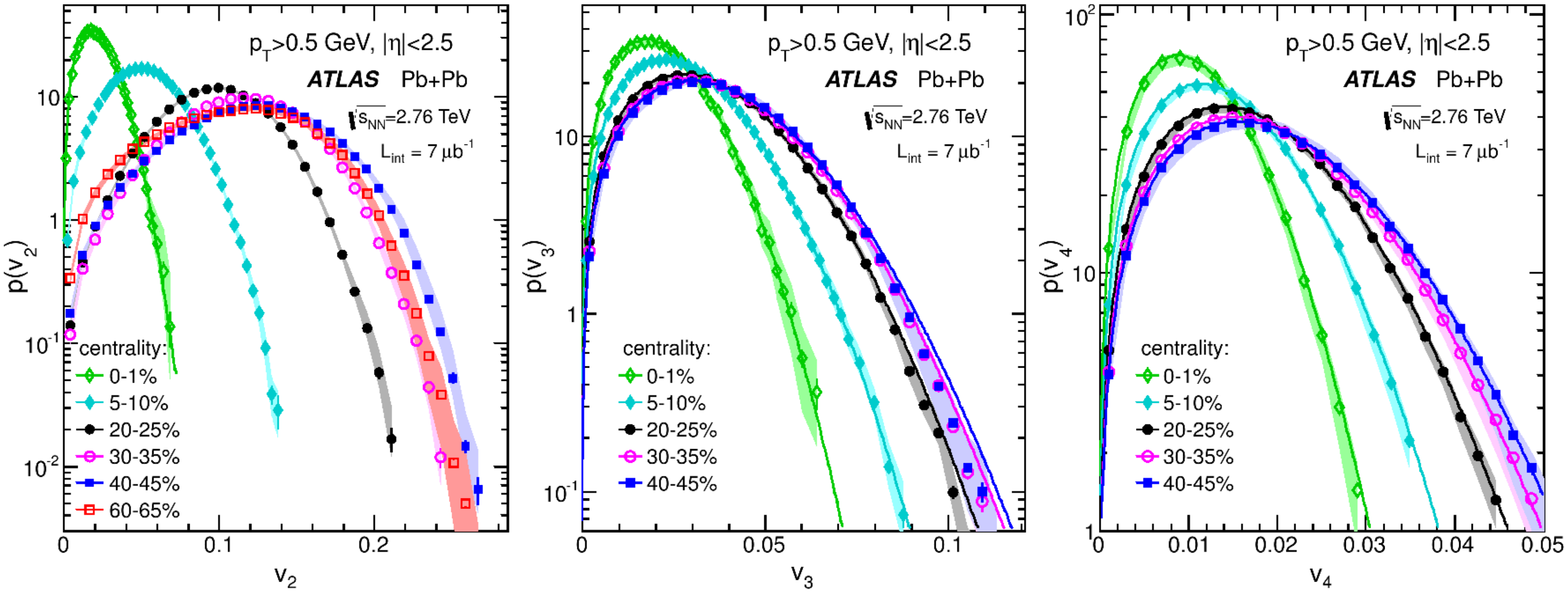




JHEP09 (2018) 006

Fluctuations in the initial geometry – backup

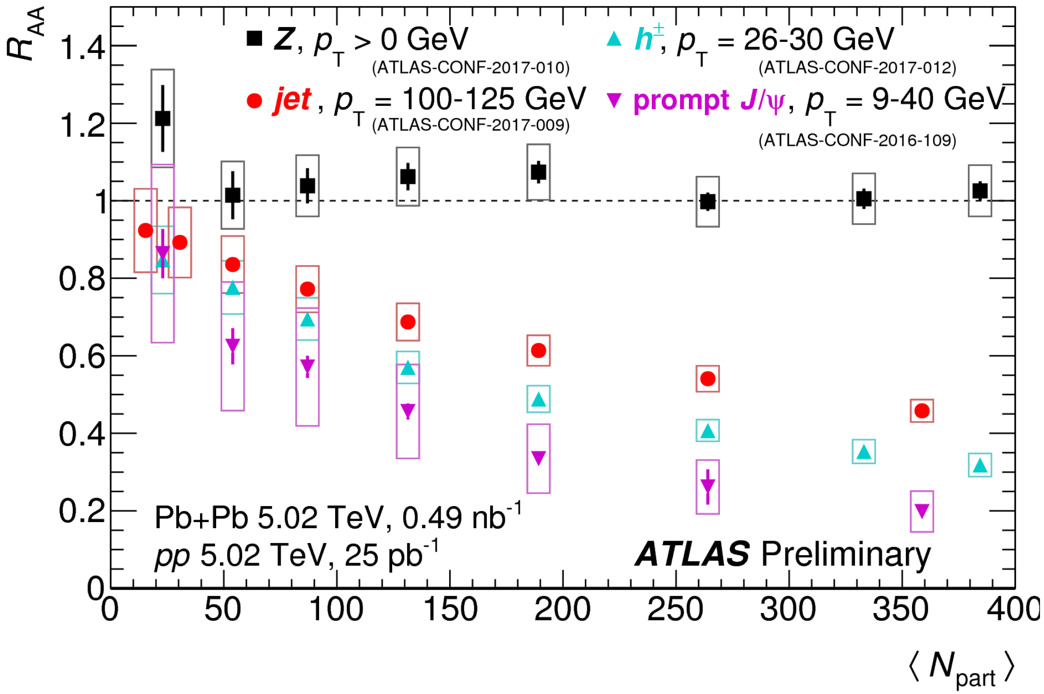
➔ **Fluctuations in initial geometry** → development of higher harmonics, v_3 …



JHEP 1311 (2013) 183

JHEP09 (2018) 006

Particle suppression



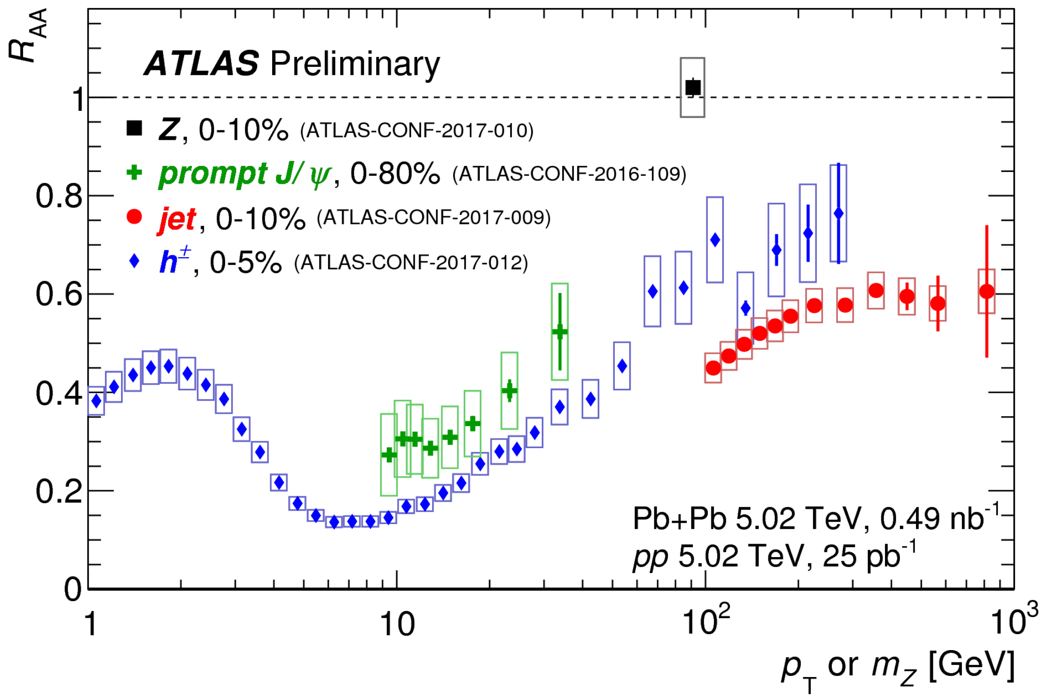
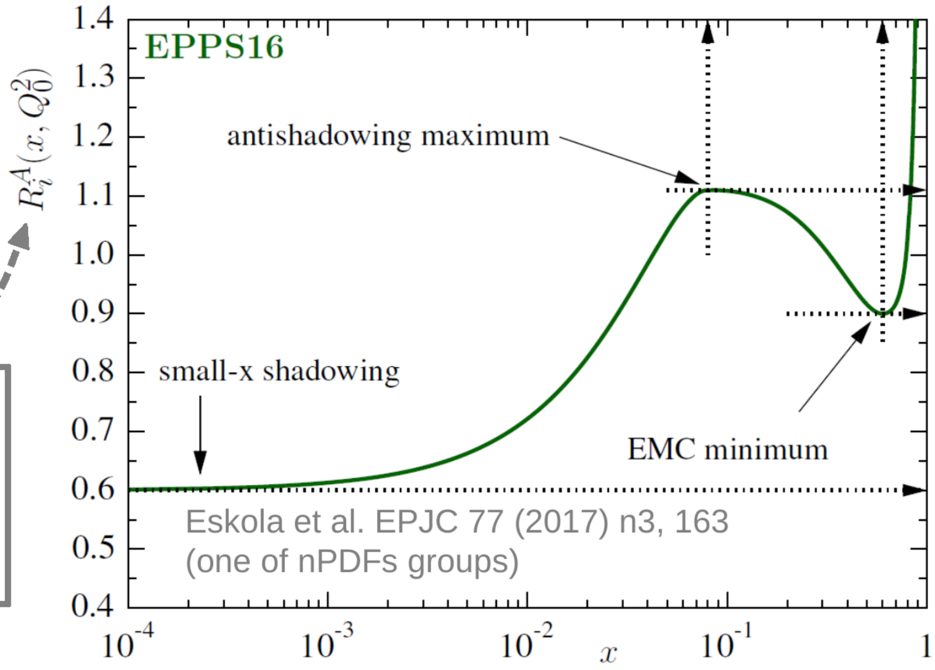


Photo-nuclear dijet production

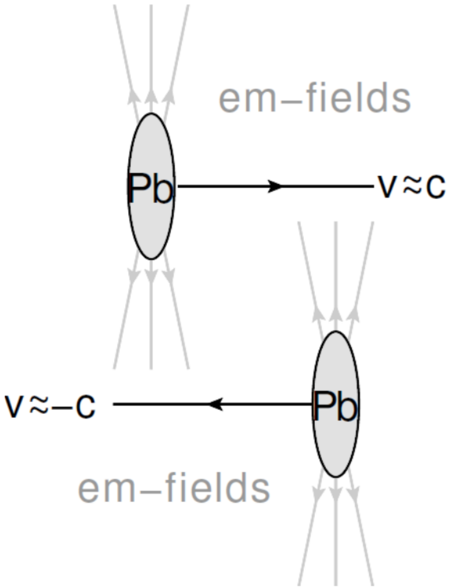
- Motivation: restrict nuclear parton distribution functions (nPDF) at low *x*
- **nPDF** exhibit **non-trivial behavior**:
  - suppression at low *x* called “shadowing“
  - enhancement at larger *x* called “anti-shadowing“
  - suppression at the largest *x* called “EMC effect“

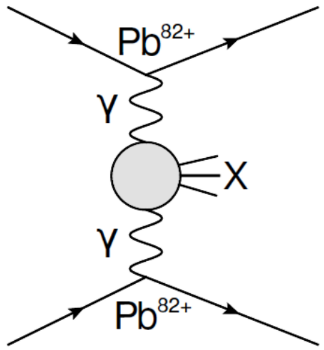
$$f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2)\, f_i^p(x, Q^2)$$



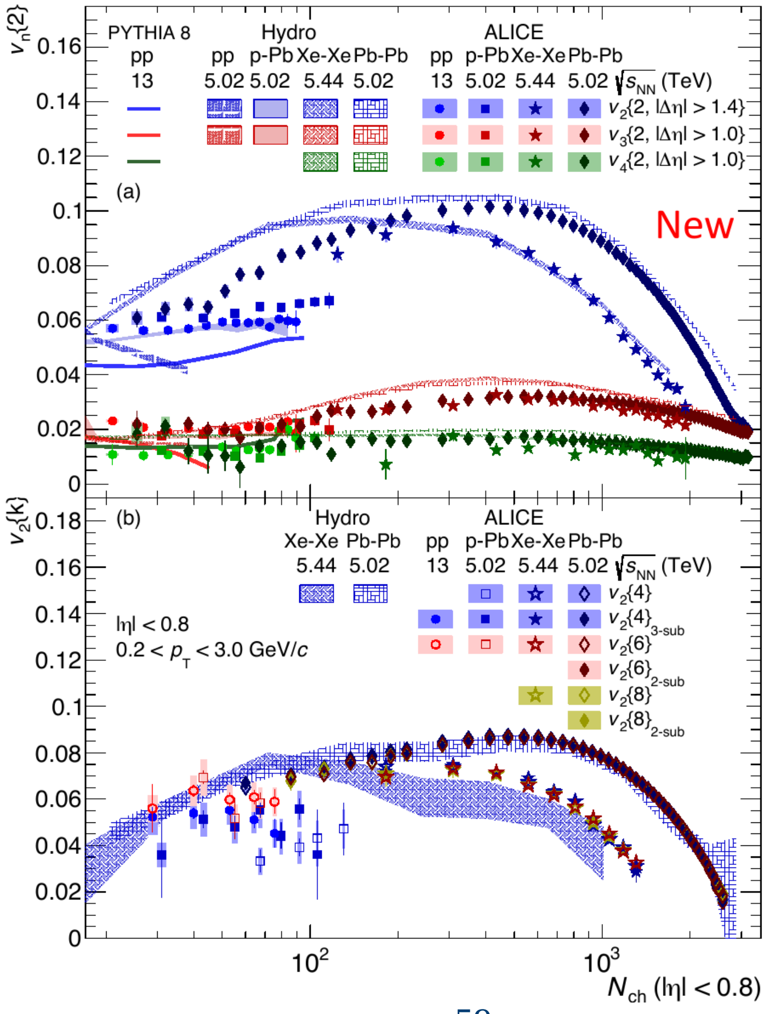
Spousta, SQM

UPC





v_n across systems



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