Overview of recent experimental highlights in heavy-ion collisions

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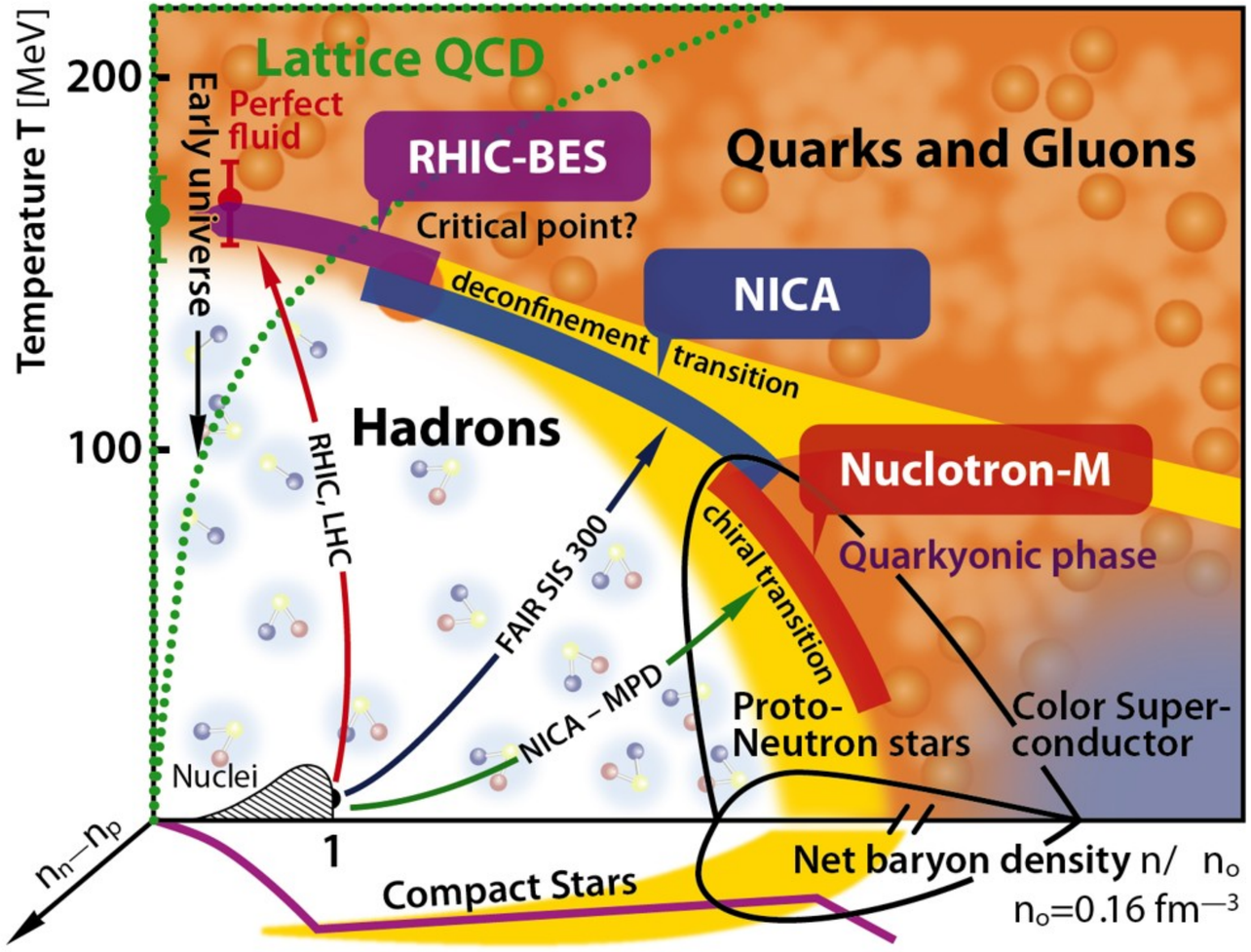
Central China Normal University

With personal bias

The 5th China LHC Physics Workshop
23–27 October 2019
Dalian Liaolin China

Heavy-ion program



High temperature and low μ_B: LHC, RHIC

- Global properties (T, η/s…) and collectivity
- Hard probes (jets, heavy quarks…)

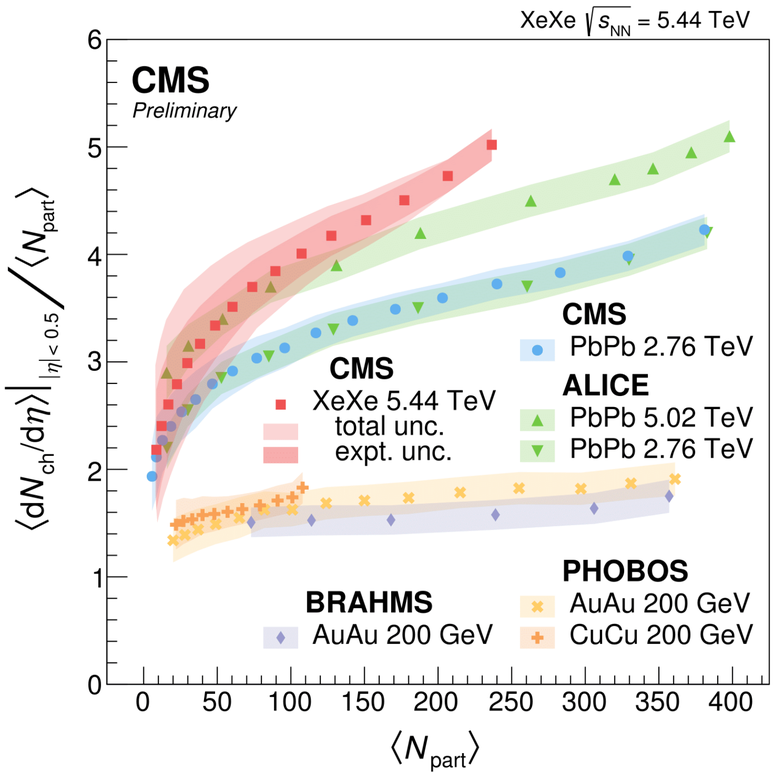
Finite temperature and μ_B: RHIC-BES, NICA

- Critical point search
- Correlations, di-lepton production…

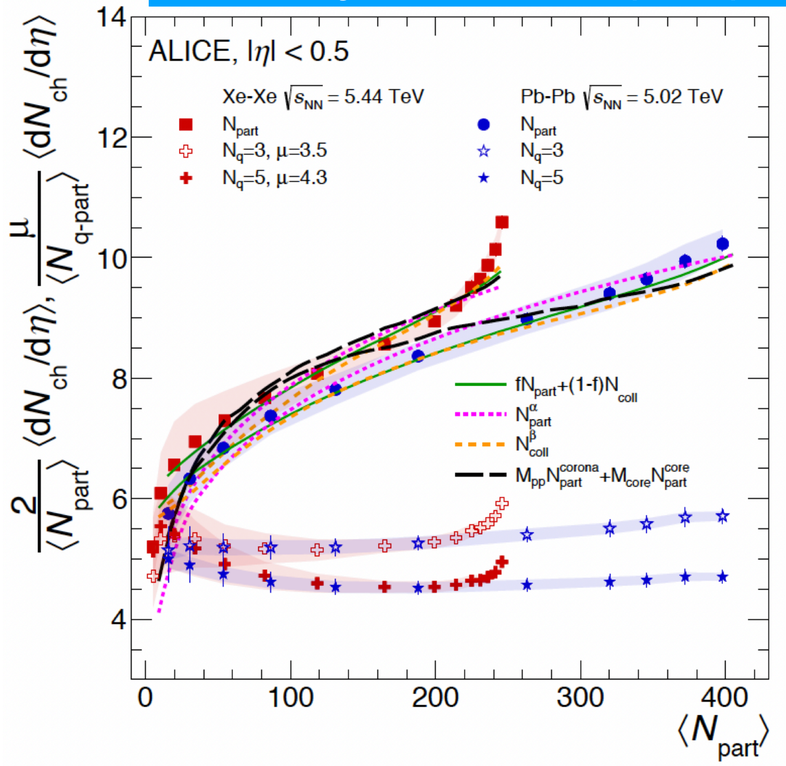
Low temperature and large μ_B: NICA, FAiR

- Search rich structure of QCD phase diagram
- Equation-of-state at large μ_B, chiral symmetry…

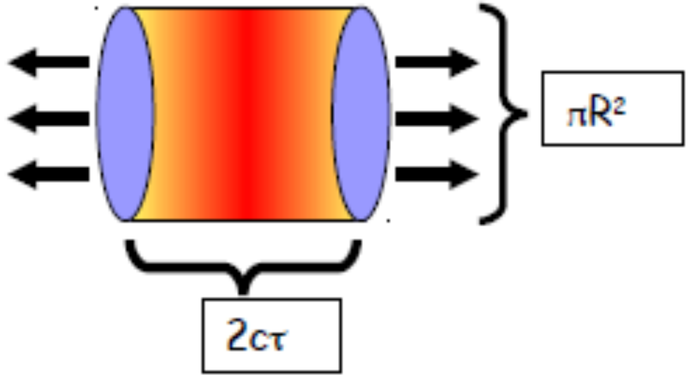
Charge particle multiplicity



ALICE *Phys. Lett.* B790 (2019) 35



Bjorken estimate:



$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y} \longleftrightarrow \mathrm{dN/d\eta}$$

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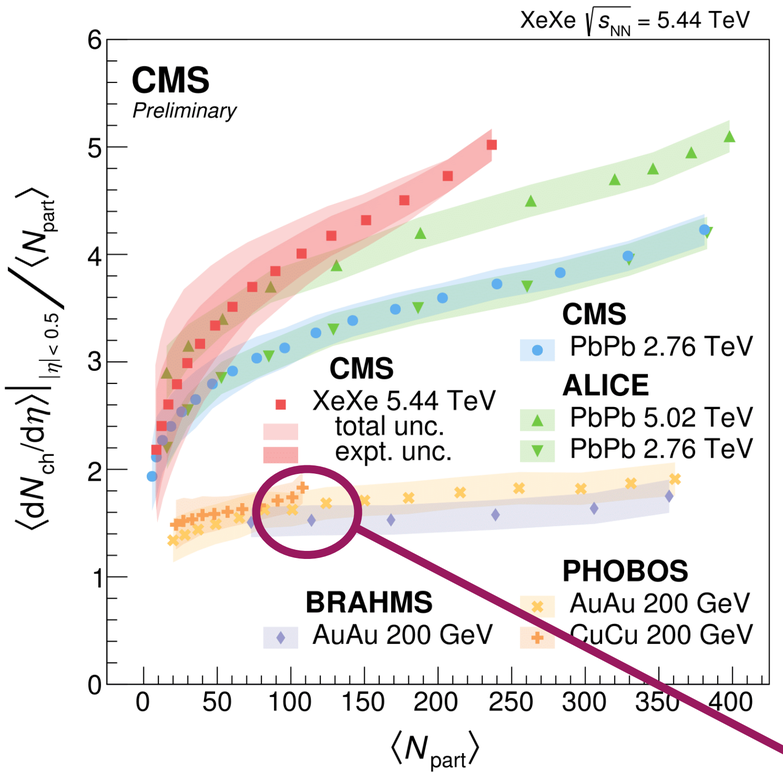

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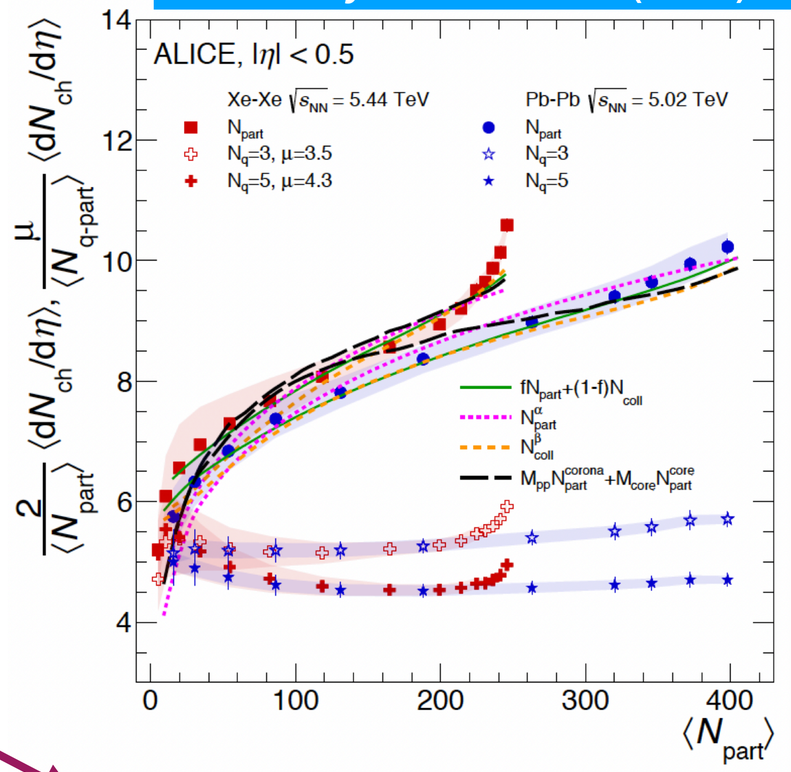

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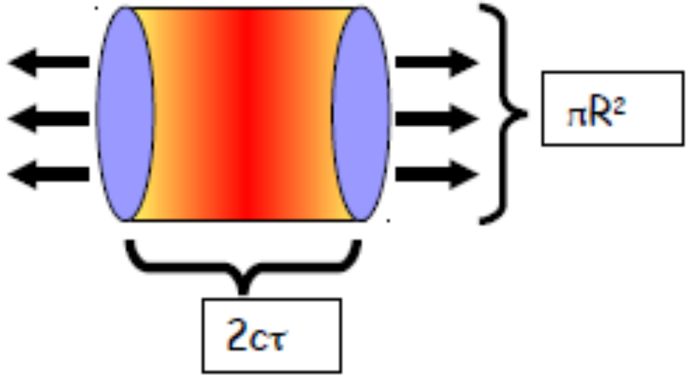

$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}y} \longleftrightarrow \mathrm{dN/d\eta}$$

- N_{part} scaling violation: known since long time ago

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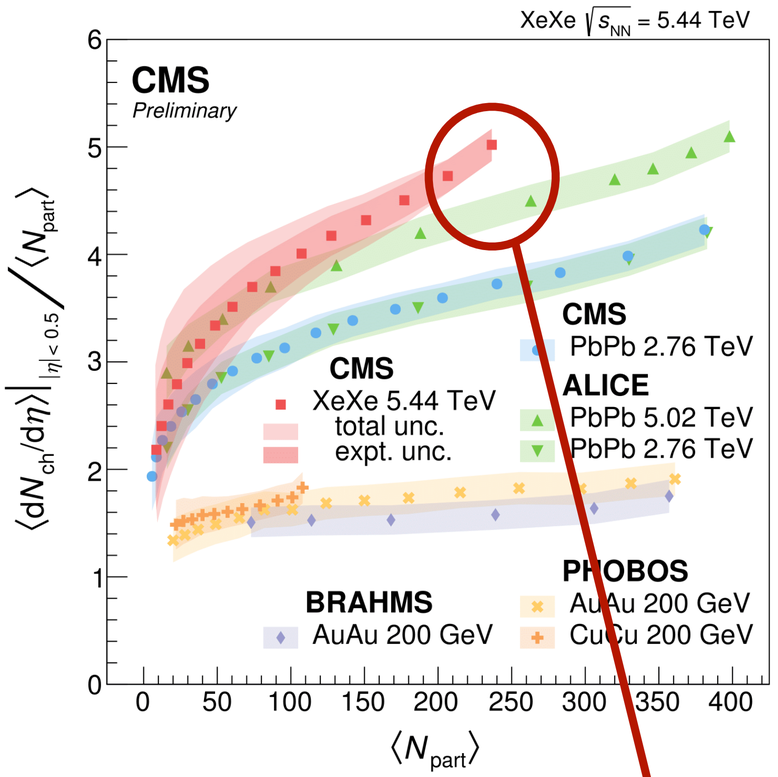

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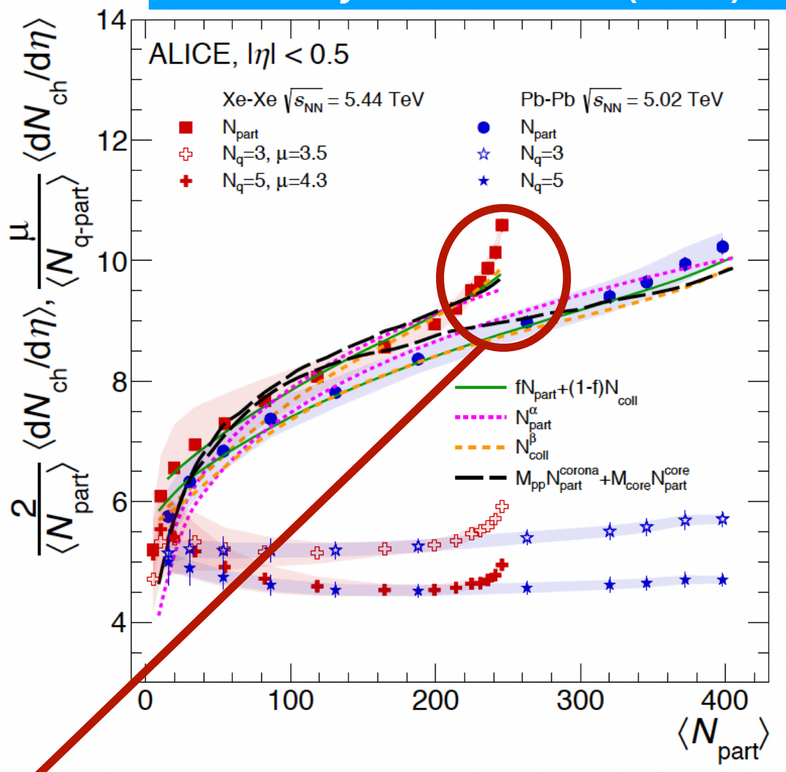

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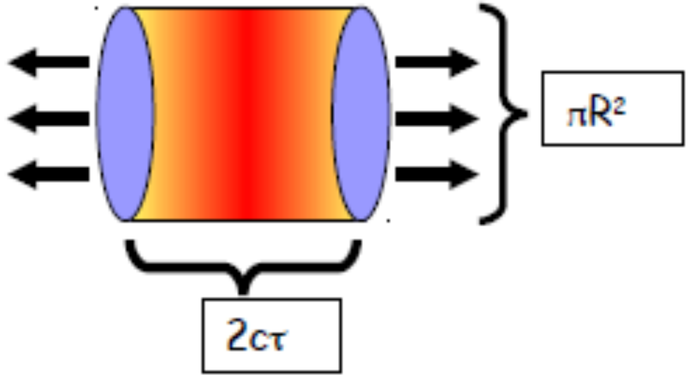

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- Confirmed by new Xe–Xe data

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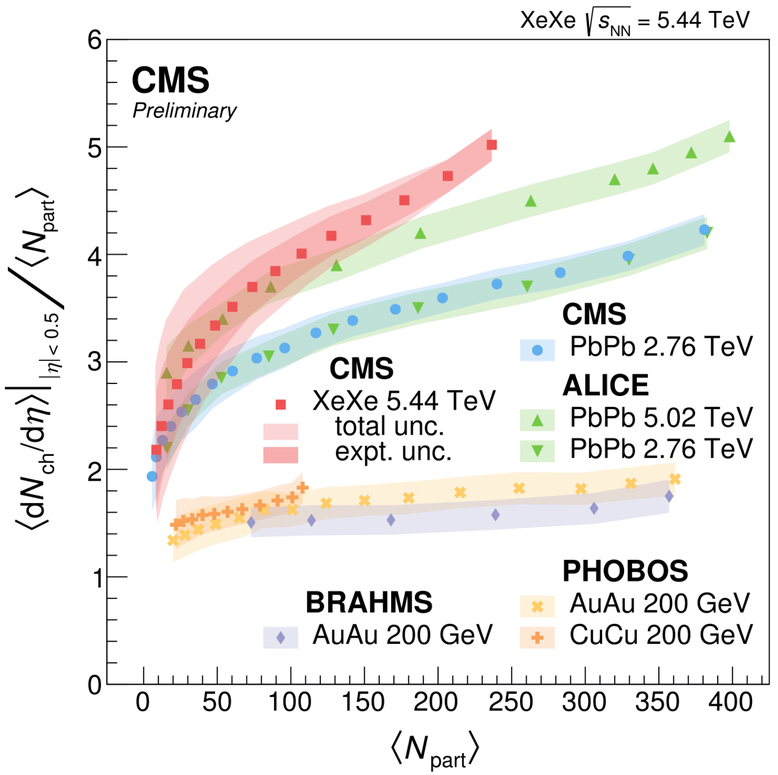

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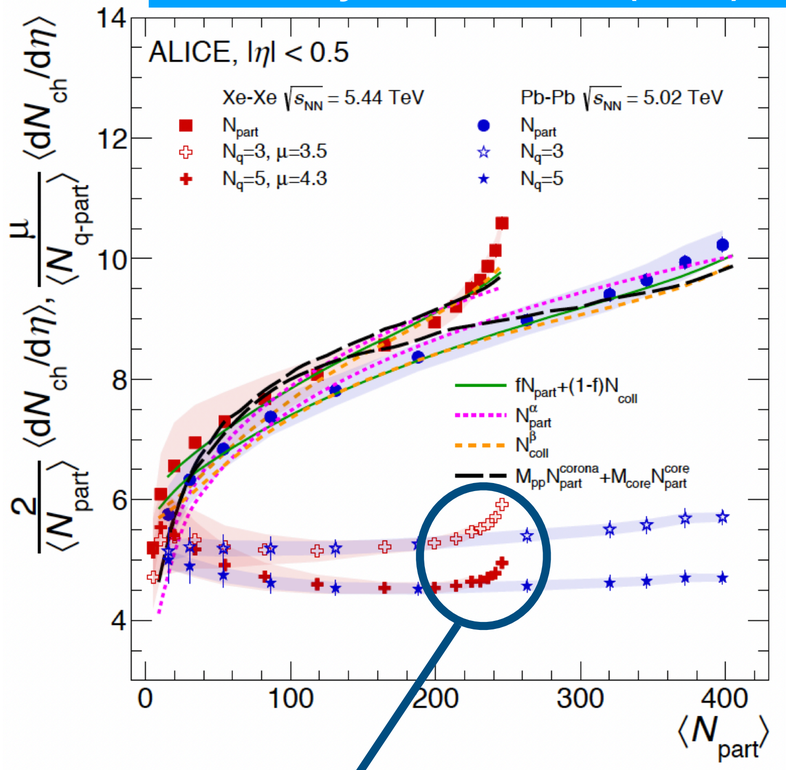

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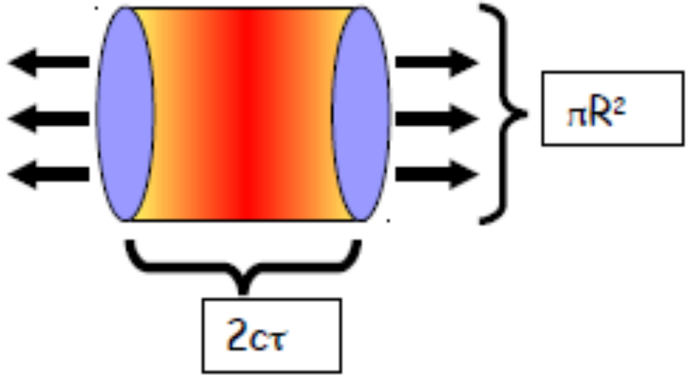

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- Neither explained by participant quark scaling nor fully reproduced by models

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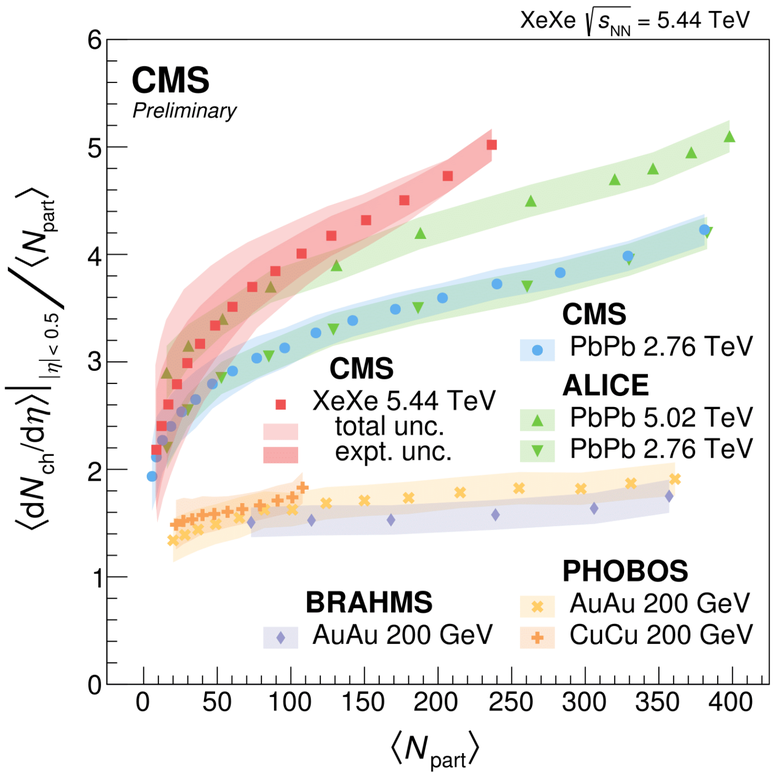

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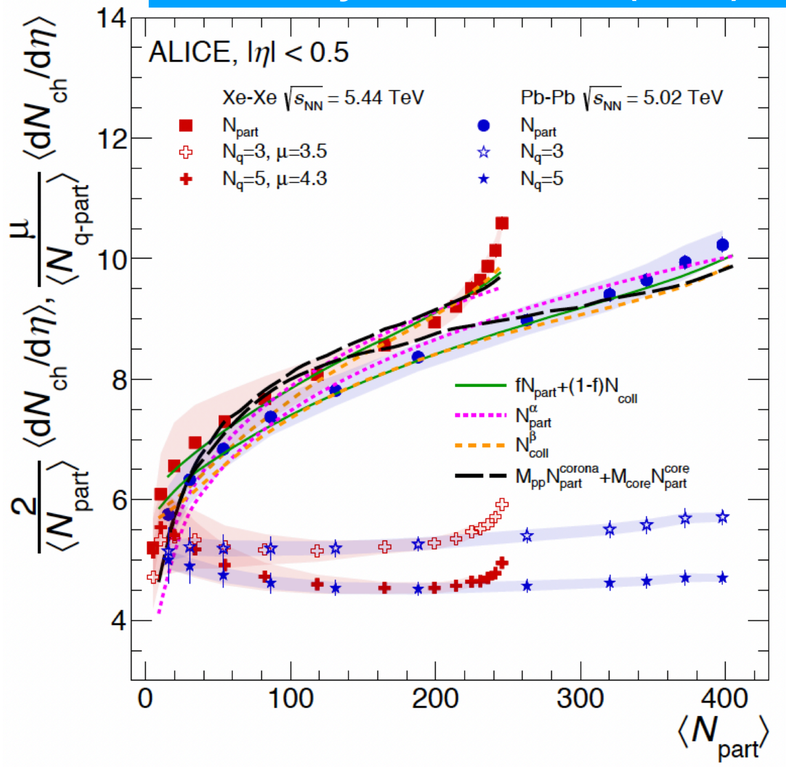

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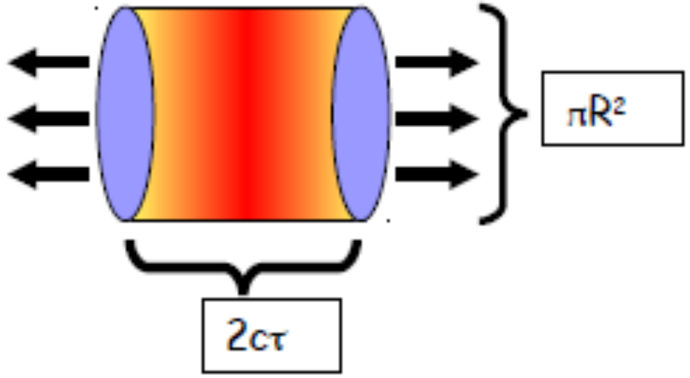

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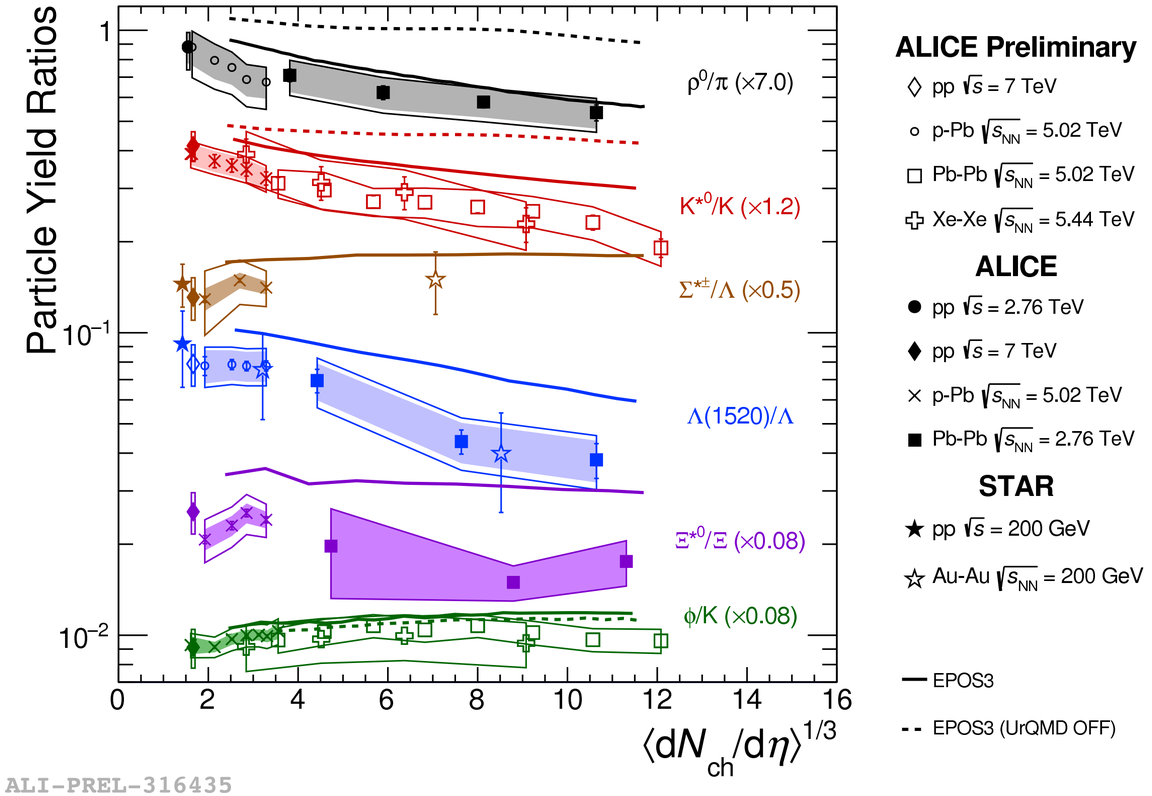
- N_{part} scaling violation: known since long time ago
- Confirmed by new Xe–Xe data
- Neither explained by participant quark scaling nor fully reproduced by models
- Collision geometry plays an important role on particle production

Particle production vs. multiplicity



ALI-PREL-316435

Where all this comes from?

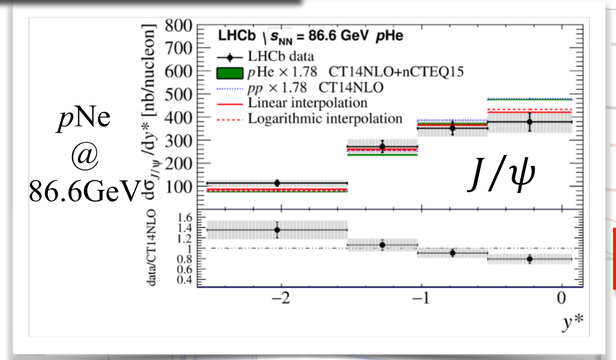
- Initial and / or stages effects?
- Common mechanism of particle production?
- Better understanding of the observables we use in heavy-ion for small systems?

- Similar trend seen in all collision systems
- Smooth evolution of particle production from small to large systems vs multiplicity

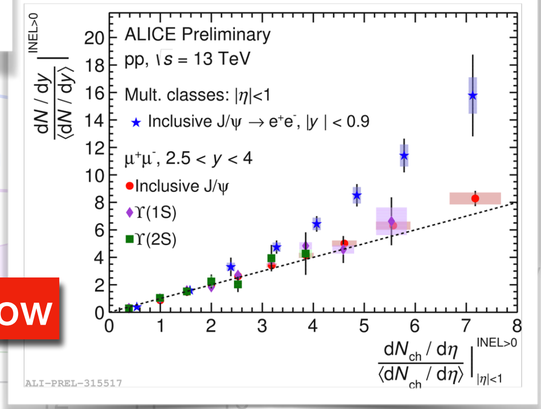
  ➡ Increases with strangeness content
- No significant energy and system dependence is observed at similar multiplicity

Particle production in small systems

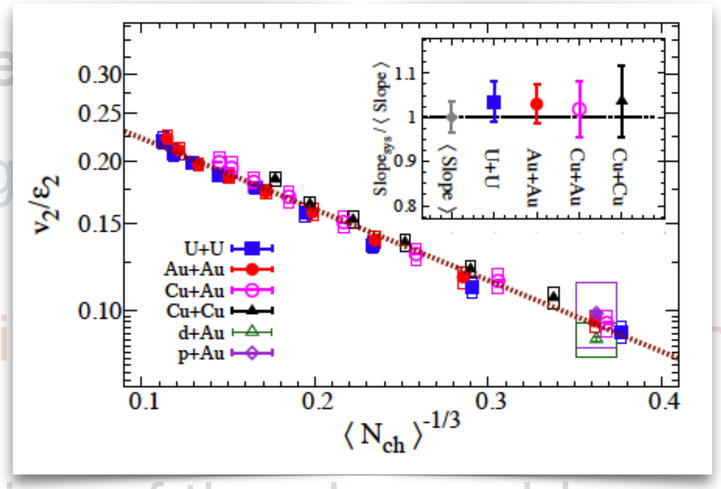
LHCb Fix target



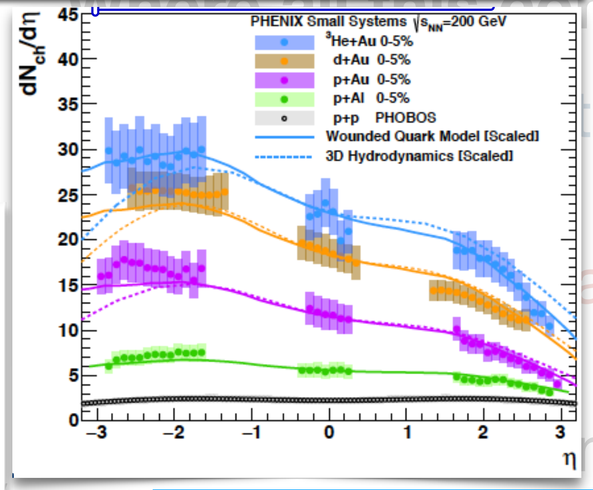
ALICE Y(1S) and Y(2S)



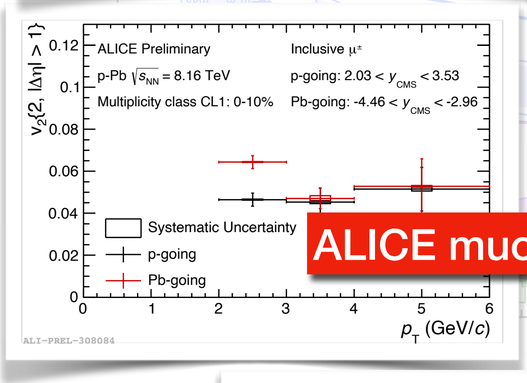
STAR *Phys. Rev. Lett.* 122 (2019) 172301



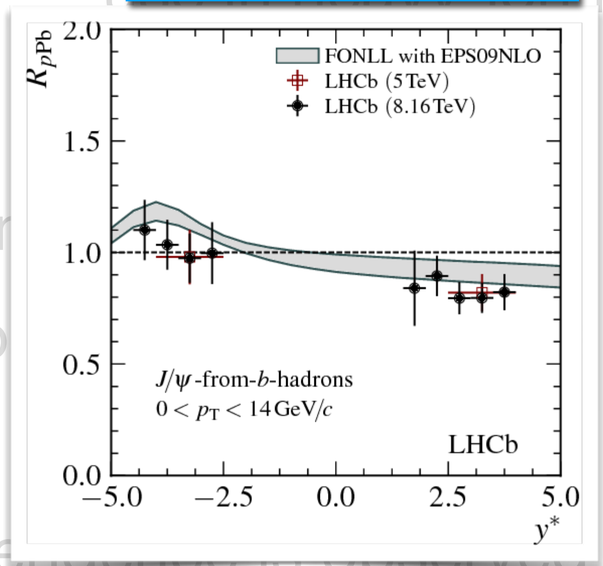
PHENIX *Phys. Rev. Lett.* 121 (2018) 222301



ALICE muon flow



LHCb non-prompt J/ψ



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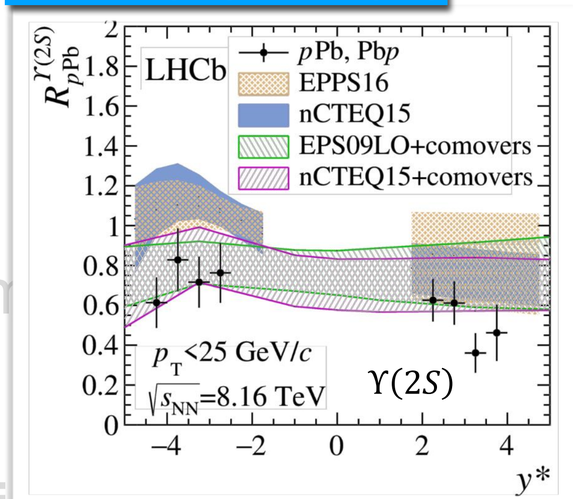
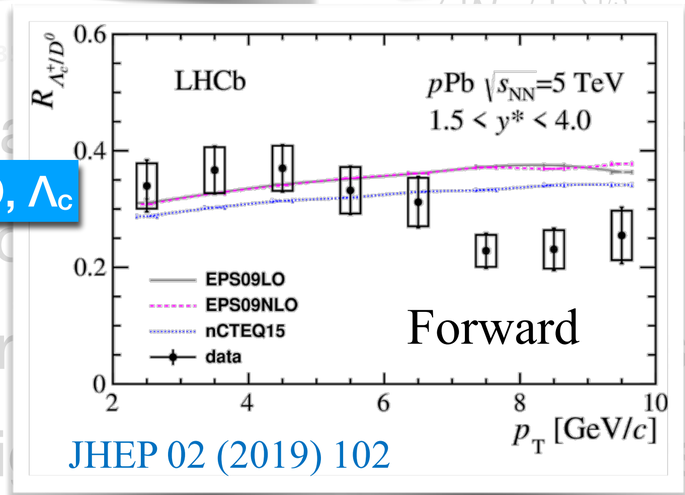


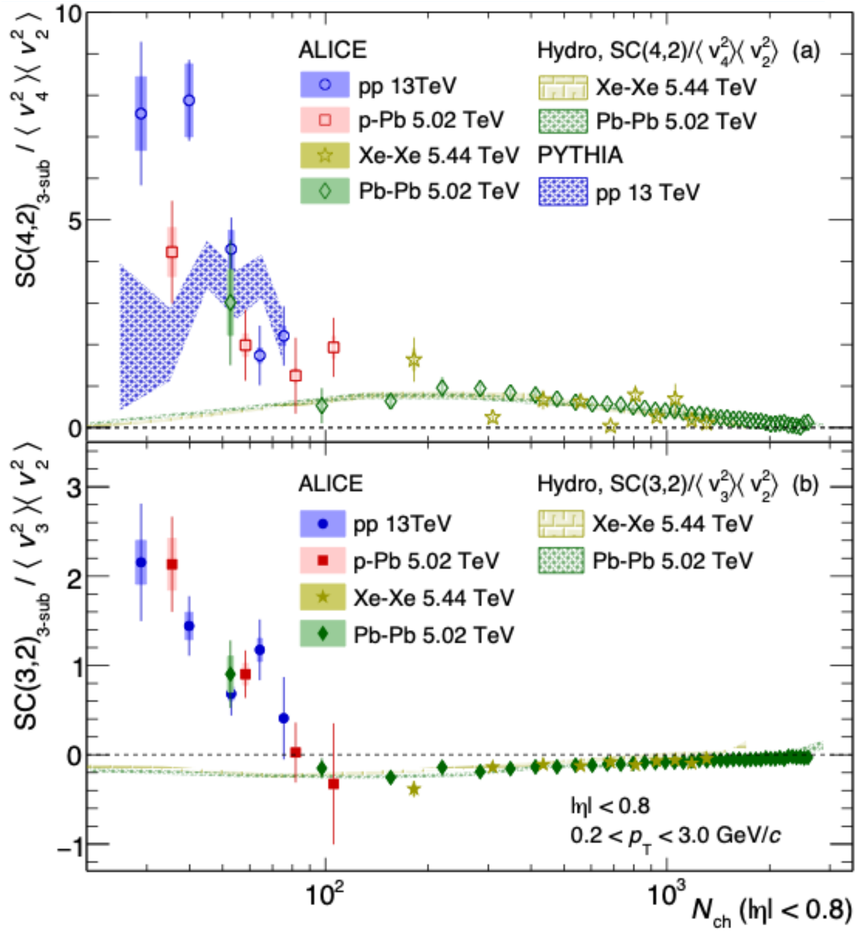
LHCb D, Λ_c



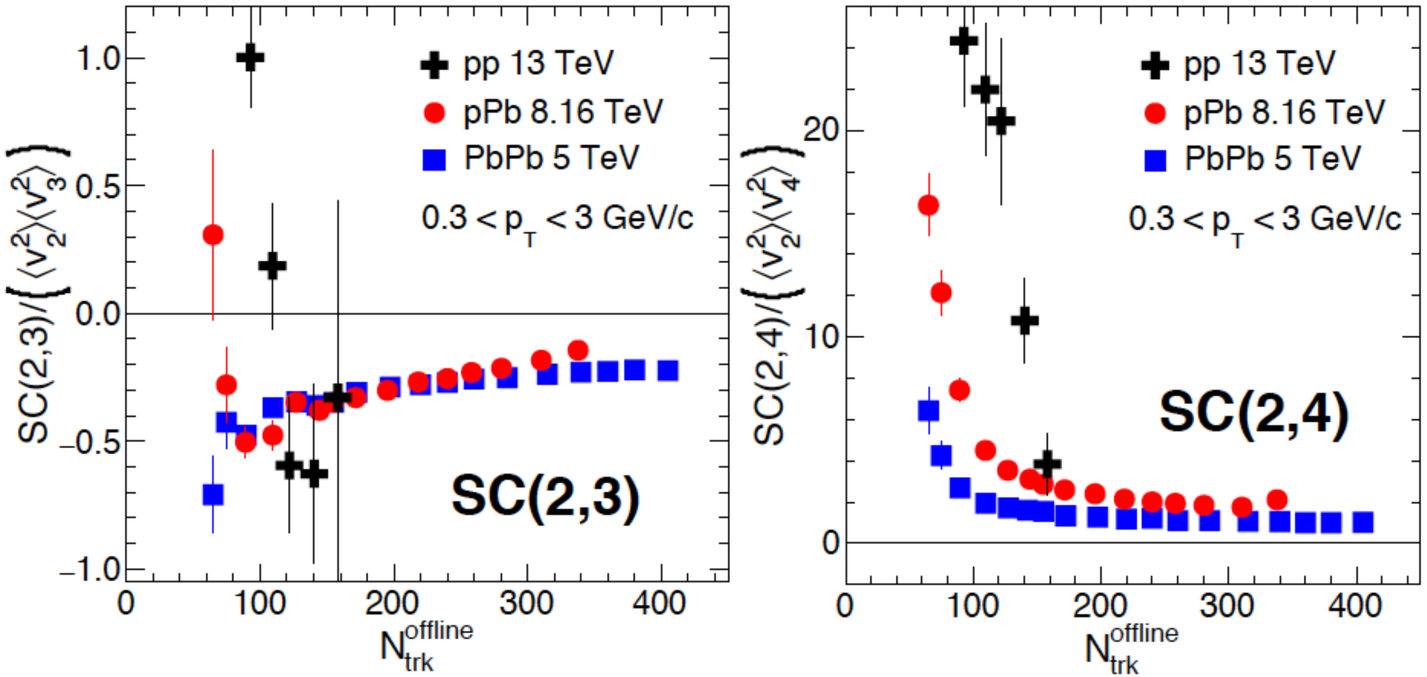
JHEP 02 (2019) 102

Particle correlations

ALICE *Phys. Rev. Lett.* **123** (2019) 142301

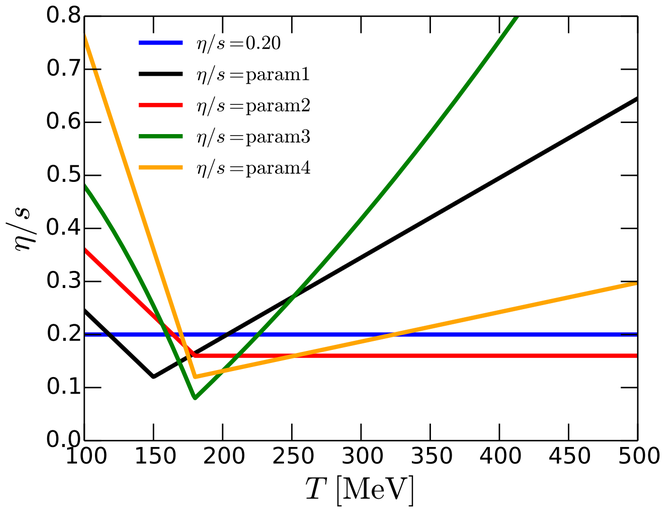


CMS *Phys. Rev. Lett.* **120** (2018) 092301



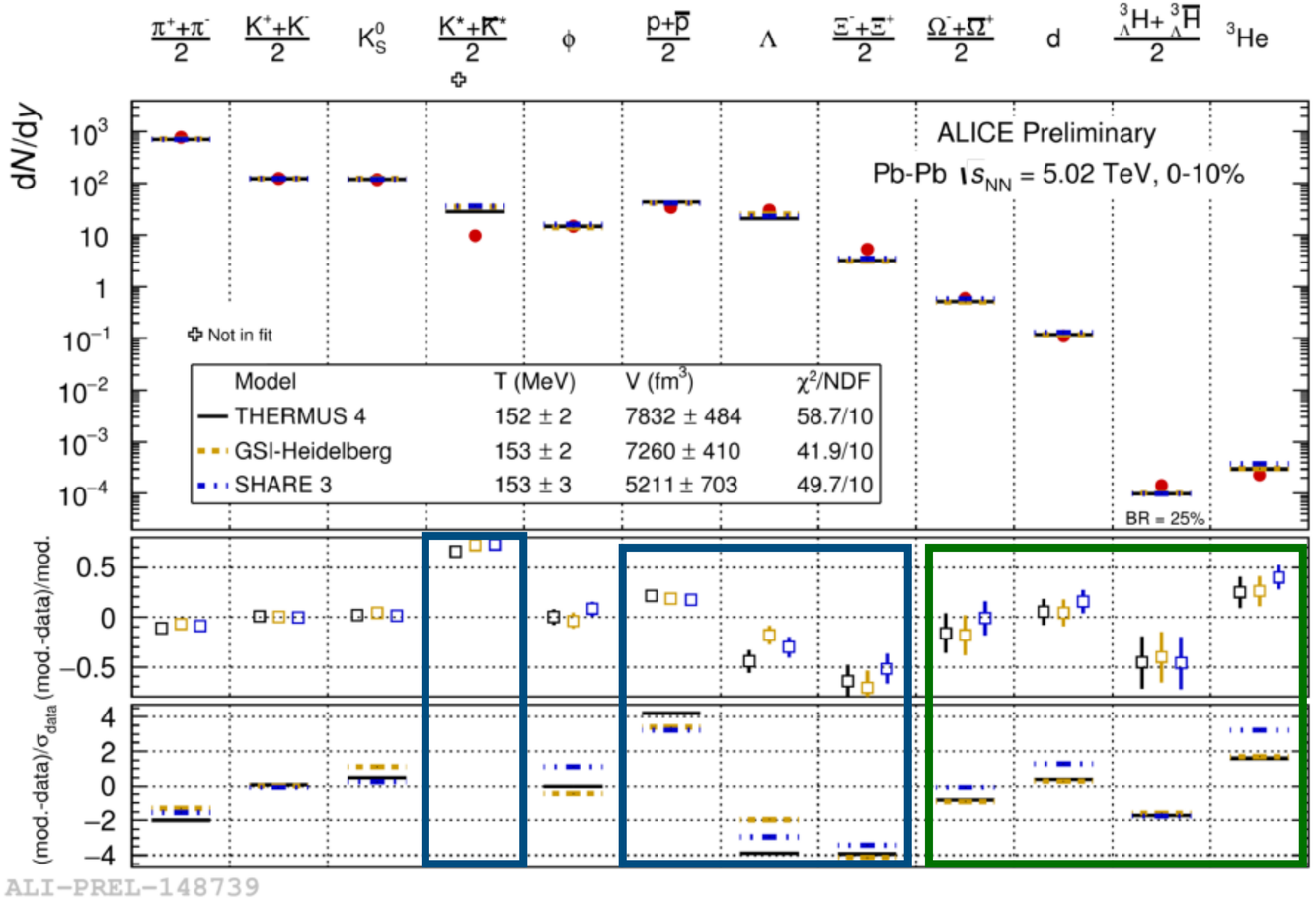
Symmetric Cumulants (SC)

- **SC(3,2)** Sensitive to initial conditions (IC)
- **SC(4,2)** Sensitive to both IC and η/s



- **SC(3,2)** Hint of similarity between small and large systems
- **SC(4,2)** Clearly higher correlations in smaller systems

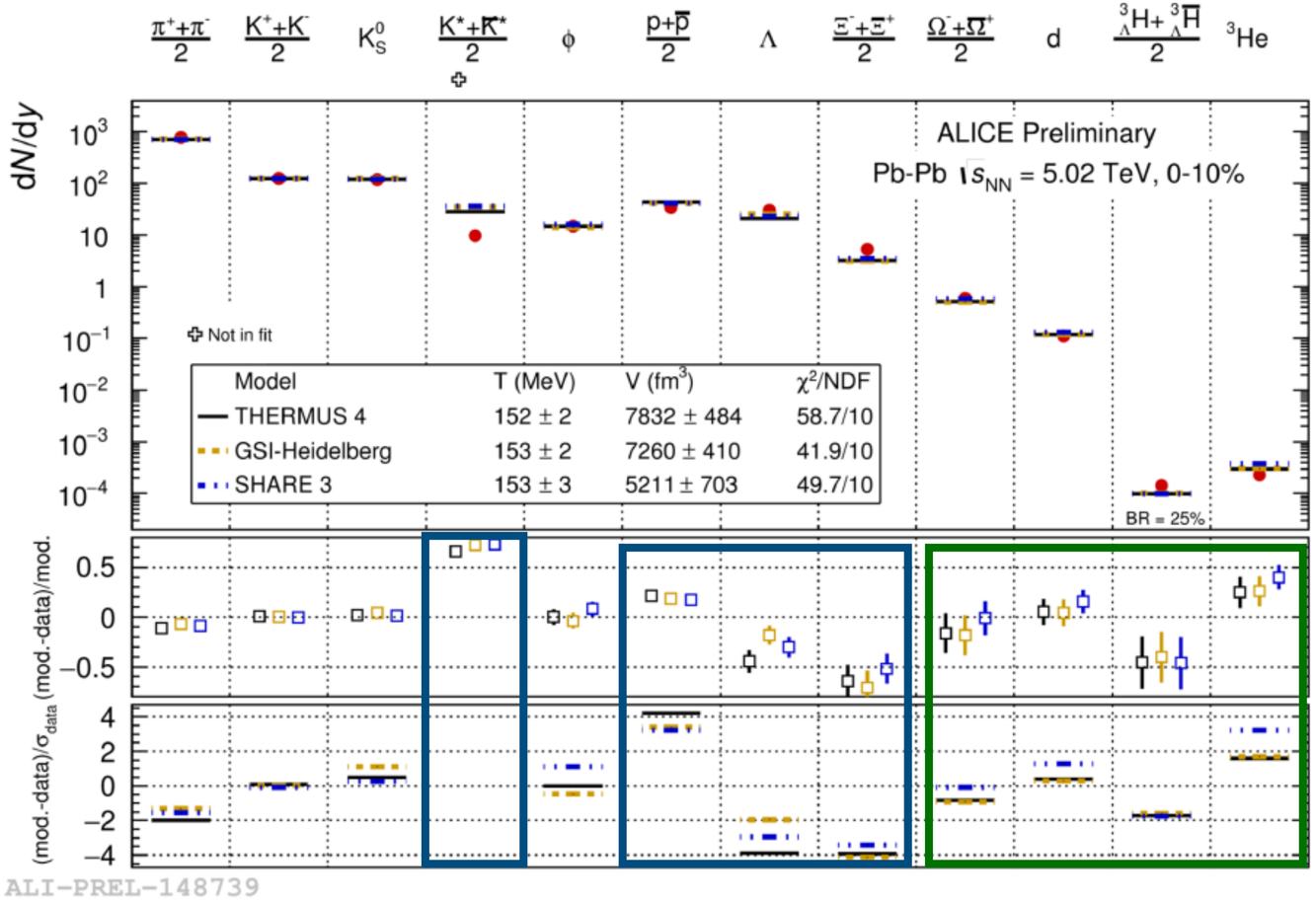
Particle yields vs thermal models



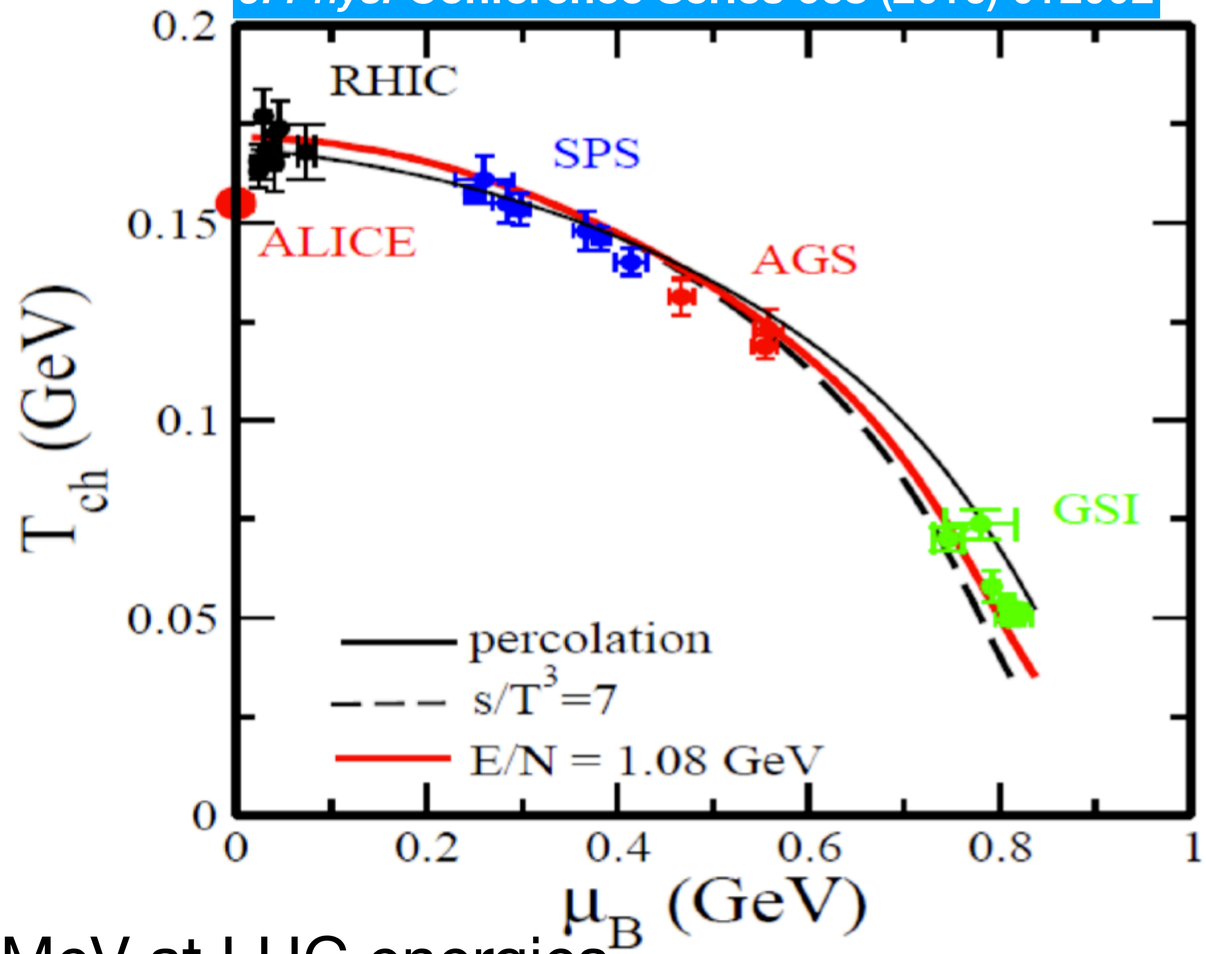
- Thermal models describe yields of light flavor hadrons qualitatively well over 7 orders of magnitude
  - ➡ Including $^3_\Lambda$He and ^{3}He
- Tension for protons and multi-strange baryons
  - ➡ Binding energy << T_{ch} (?)

- Chemical freeze-out temperature (T_{ch}) ~153 MeV at LHC energies
  - ➡ Driven by protons (before was 156 MeV), K* resonances are not included

Particle yields vs thermal models



J. Phys. Conference Series 668 (2016) 012002



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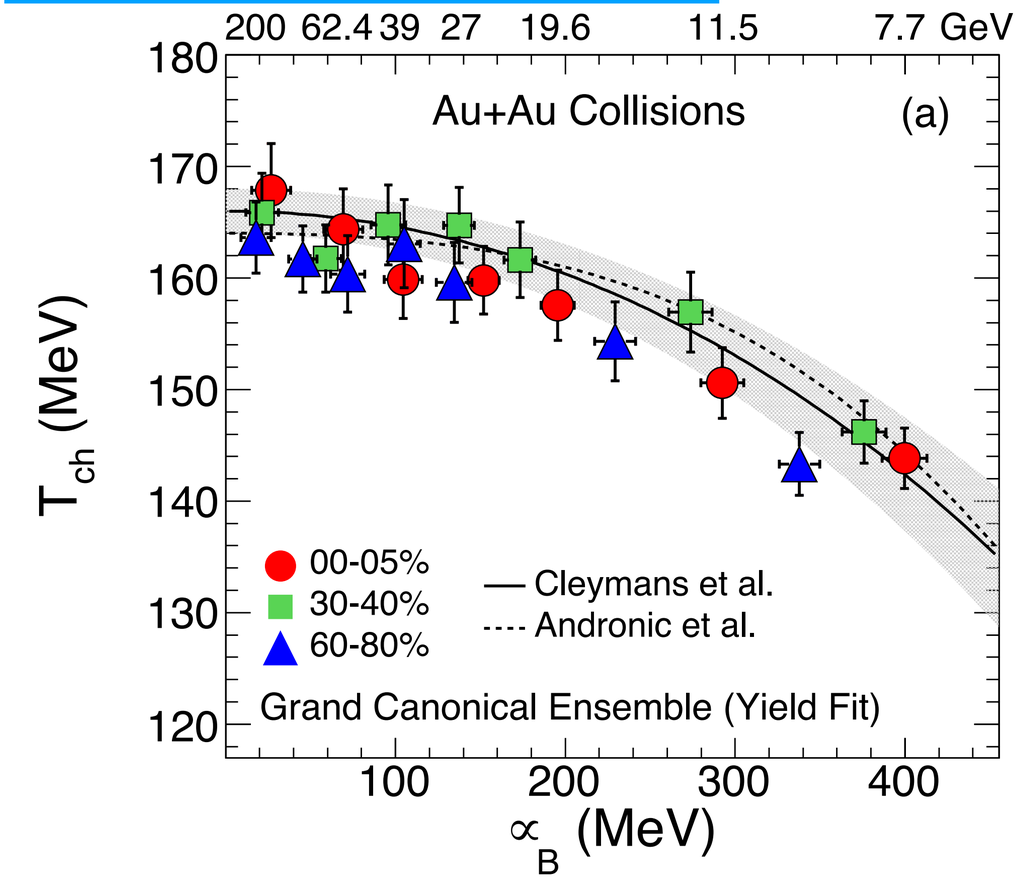
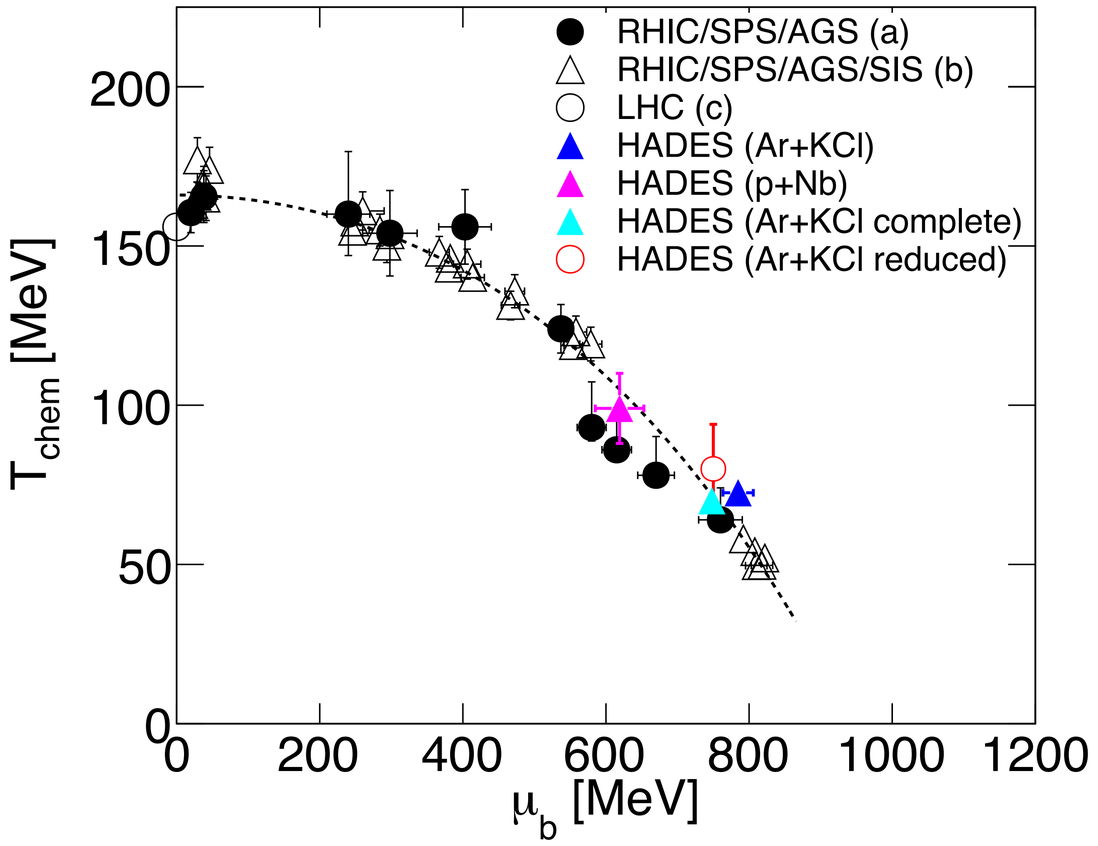
Mapping μ_B — T_{ch} plane

STAR *Phys. Rev.* **C96** (2017) 044904



HADES *Eur. Phys. J.* **A52** (2016) 178



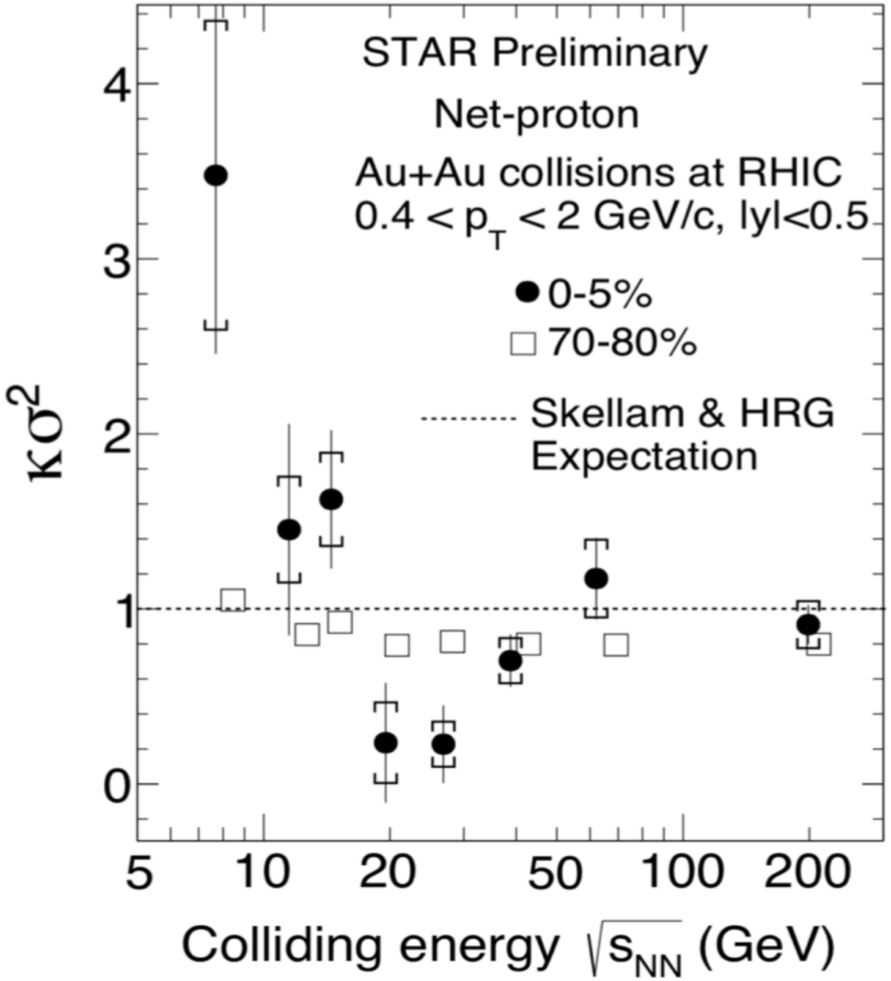
Beam energy scan RHIC and SIS 18

- **RHIC** Region of intermediate μ_B covers possible critical point
- **SIS 18** Explores the denser nuclear matter

Fourth order net-proton fluctuations

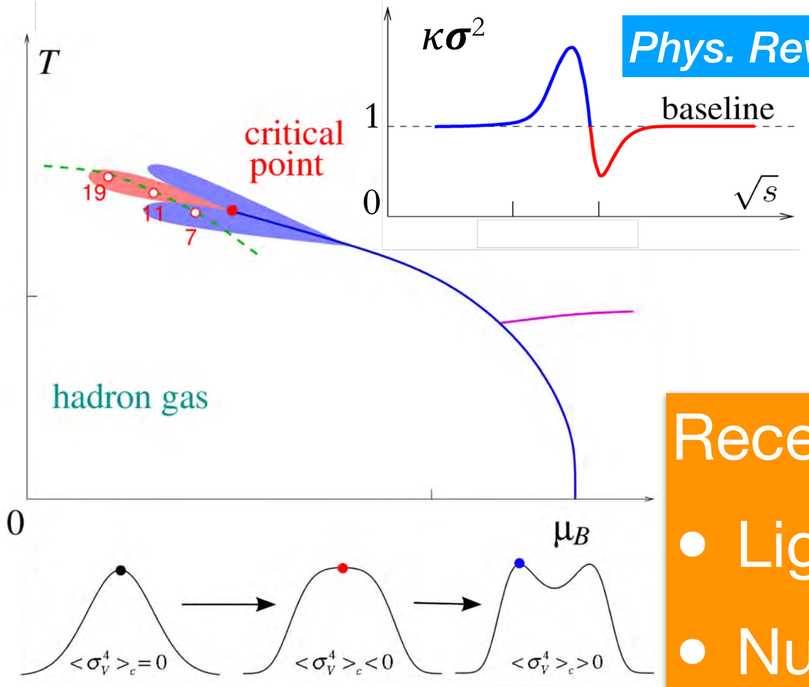
STAR *Phys. Rev. Lett.* **105** (2010) 022302

Phys. Rev. Lett. **112** (2014) 032302



- First observation of the non-monotonic energy dependence of 4th order net-proton fluctuations

➡ Hint of entering Critical Region?

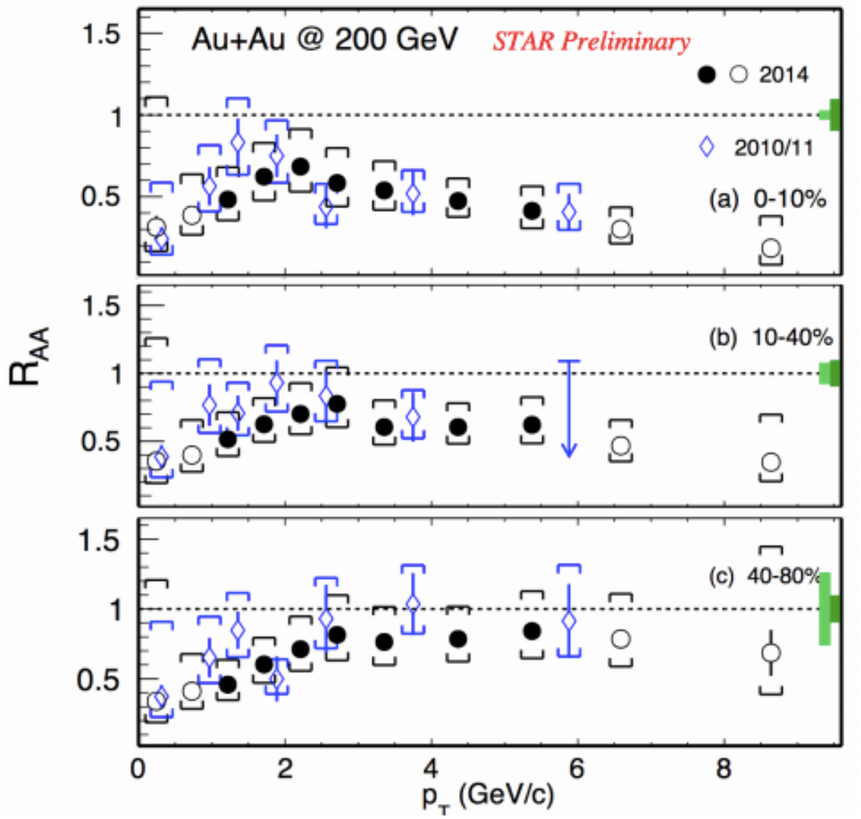


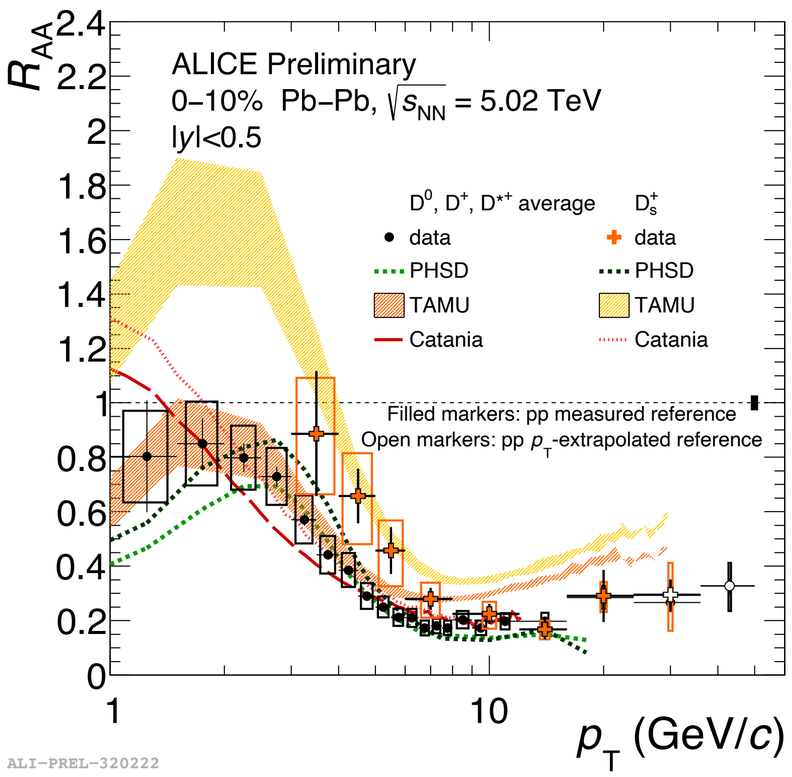
Phys. Rev. Lett. **107** (2011) 052301

Recent established observables

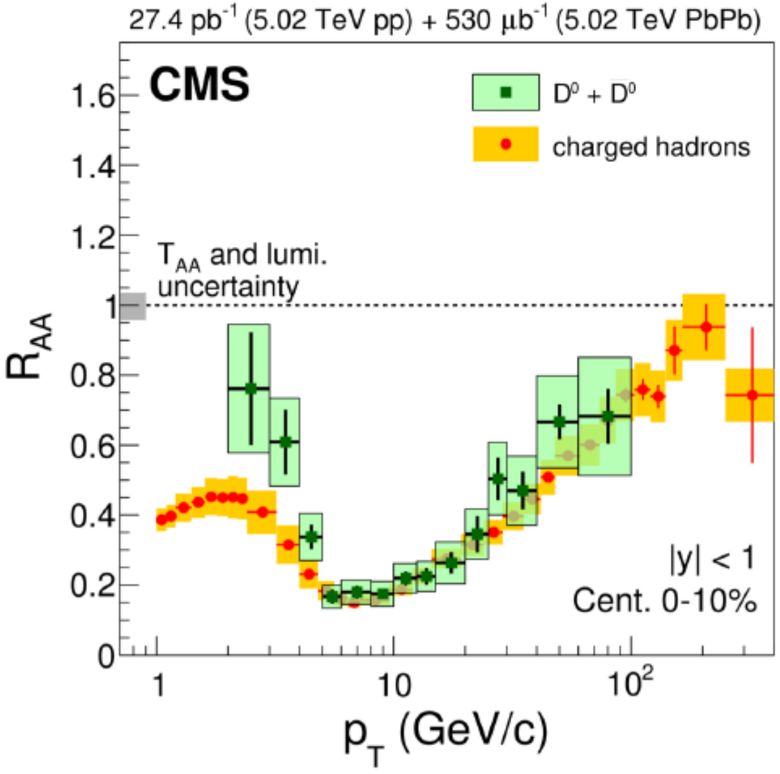
- Light nuclei production
- Nucleon density fluctuations
- …

Charm quarks energy loss





CMS *Phys. Lett.* **B782** (2018) 474

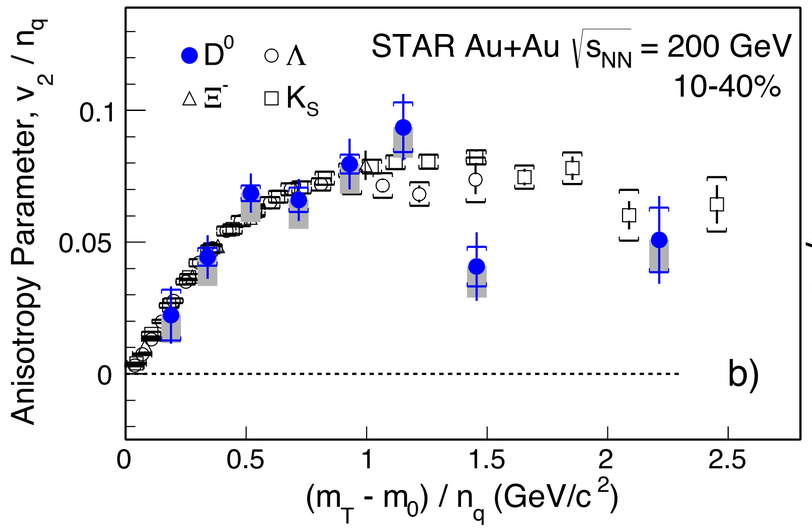


- Strong suppression of D meson production observed in the most 10% central collisions at both RHIC and the LHC

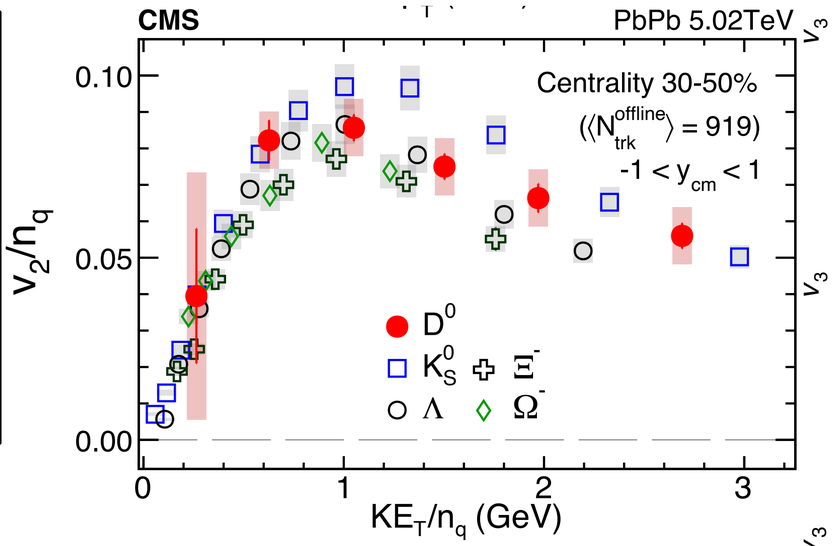
➡ Charm quark undergo significant interactions with the QCD medium

Degree of thermalization of charm

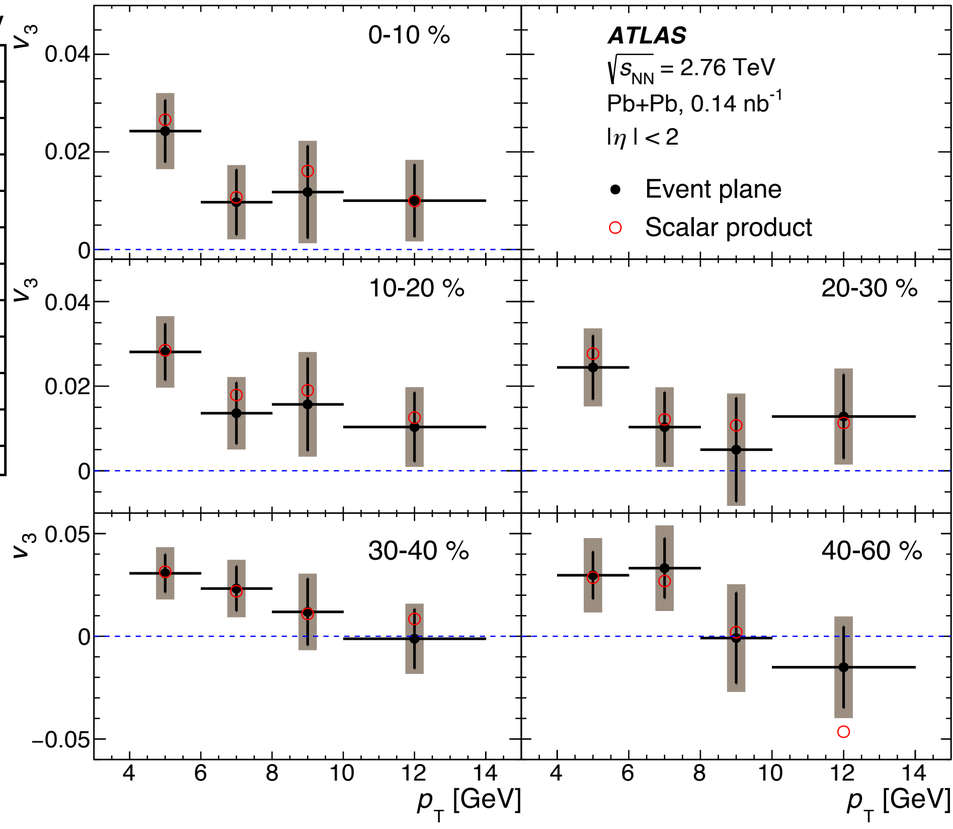
STAR *Phys. Rev. Lett.* **118** (2017) 212301



CMS *Phys. Rev. Lett.* **121** (2018) 082301



ATLAS *Phys. Rev.* **C98** (2018) 044905



- D mesons seem to follow the same number of constituent quarks (NCQ) and kE_T scaling as light hadrons — observed at both RHIC and LHC

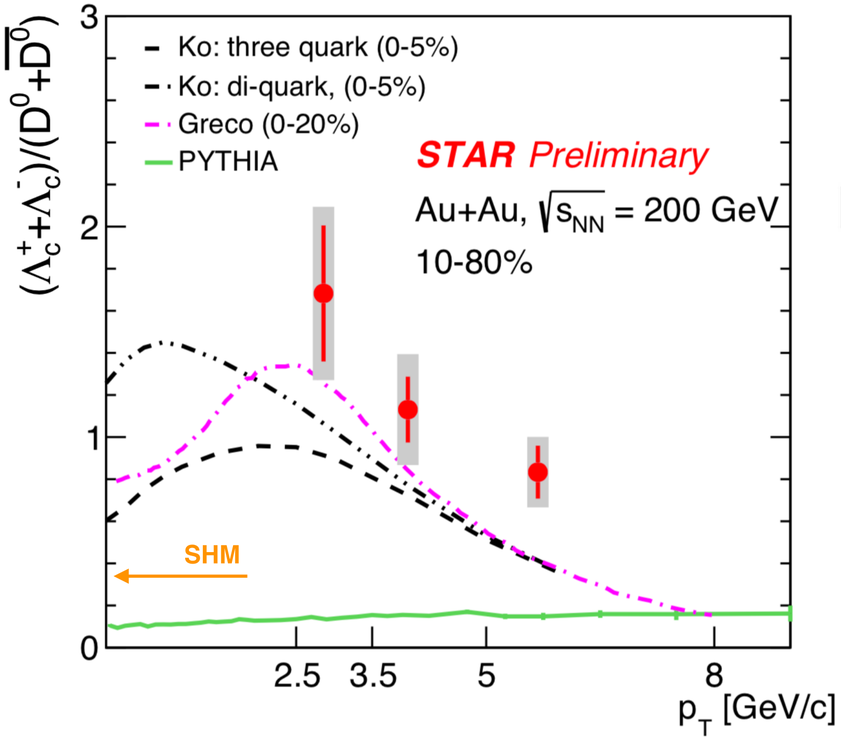
➡ Similar collective motion of charm and light quarks (?)

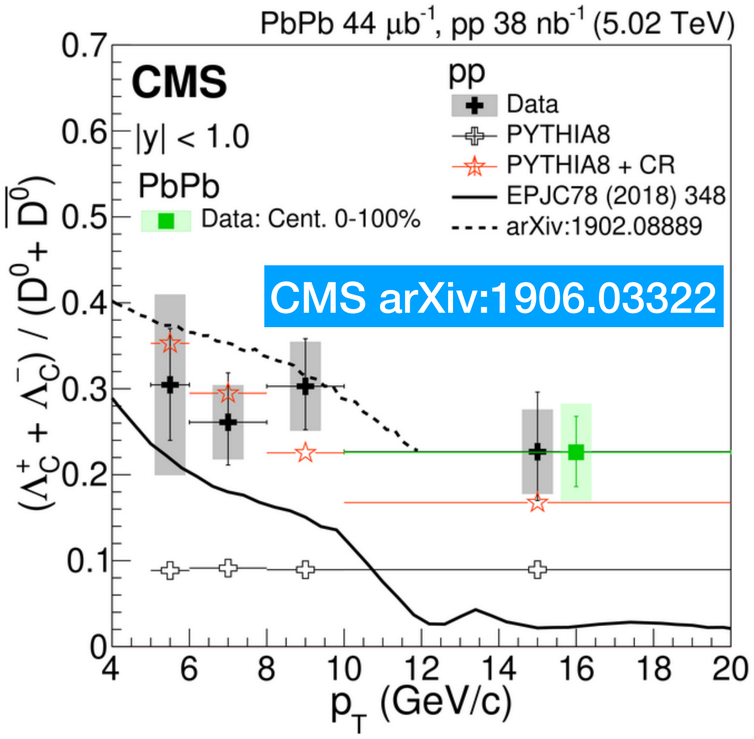
➡ Hint of charm thermalization (?)

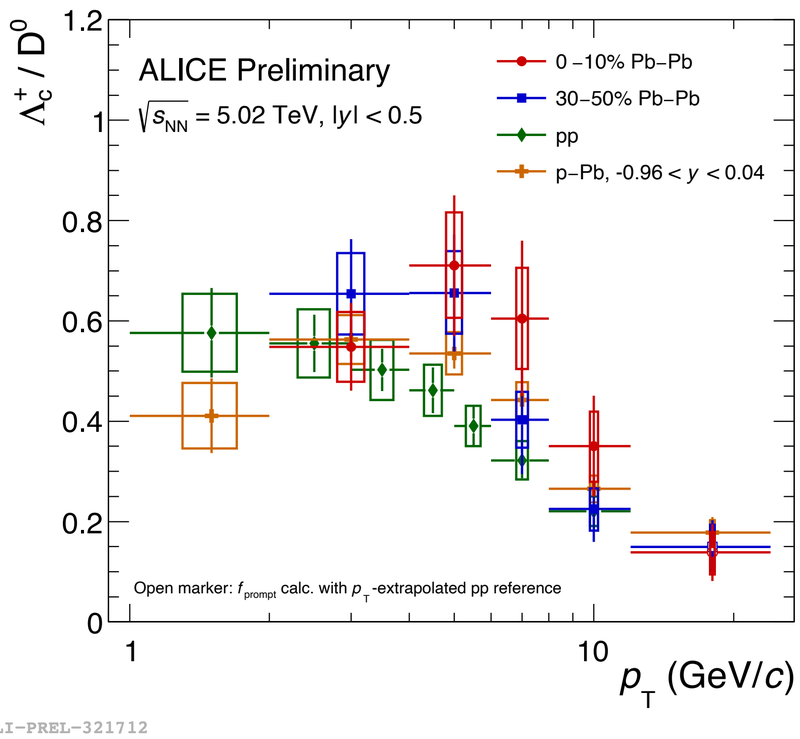
Triangle flow (v_3) of HF decay muons

- Additional constraints on initial conditions, η/s, EoS, freeze-out conditions…

Charmed baryon production



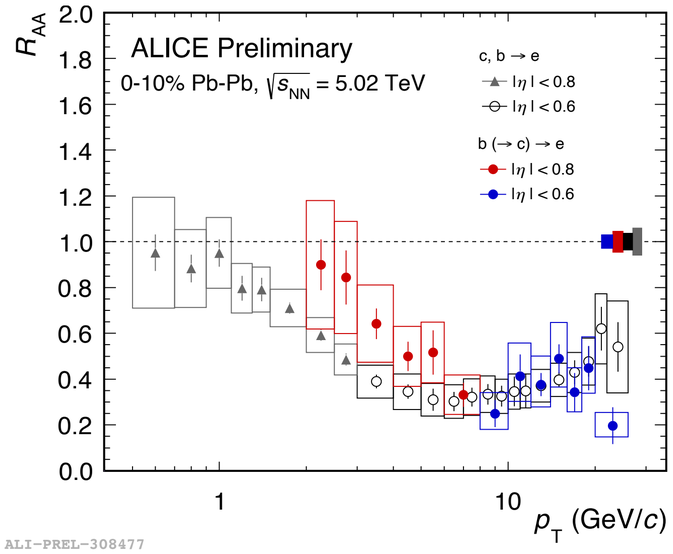


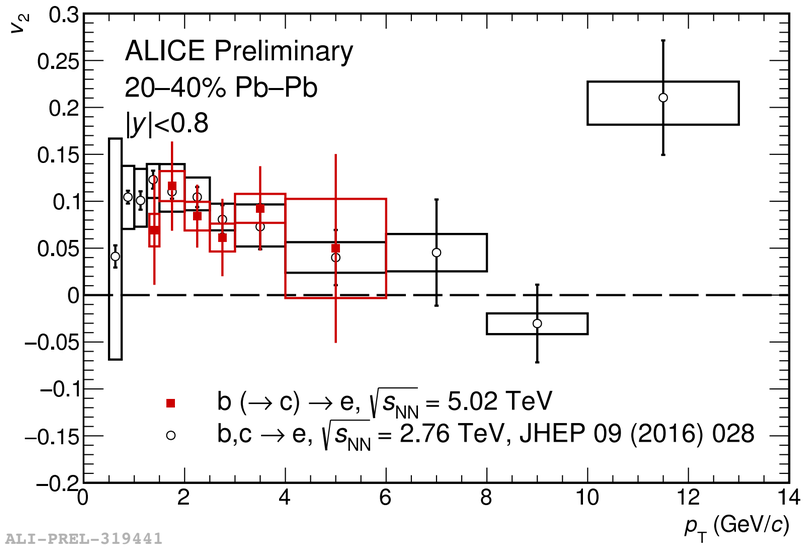


ALI-PREL-321712

- RHIC: Λ_c / D^0 ratio is strongly enhanced compared to PYTHIA — enhancement increases towards low p_T
- LHC: Hint of higher Λ_c / D^0 ratio in 0-10% Pb–Pb collisions w. r. t. pp collisions
- Understanding of pp data is fundamental: not granted that Λ_c is “enhanced” in the same way in heavy-ion and pp (w. r. t. e^+e^-)

Open beauty production





- Hint of smaller suppression for beauty-decay electrons

  ➡ Mass dependence of energy loss (?)

- $v_2 > 0$ (~3.5σ effect) for e←b in 20-40% centrality

  ➡ Beauty thermalization (?)

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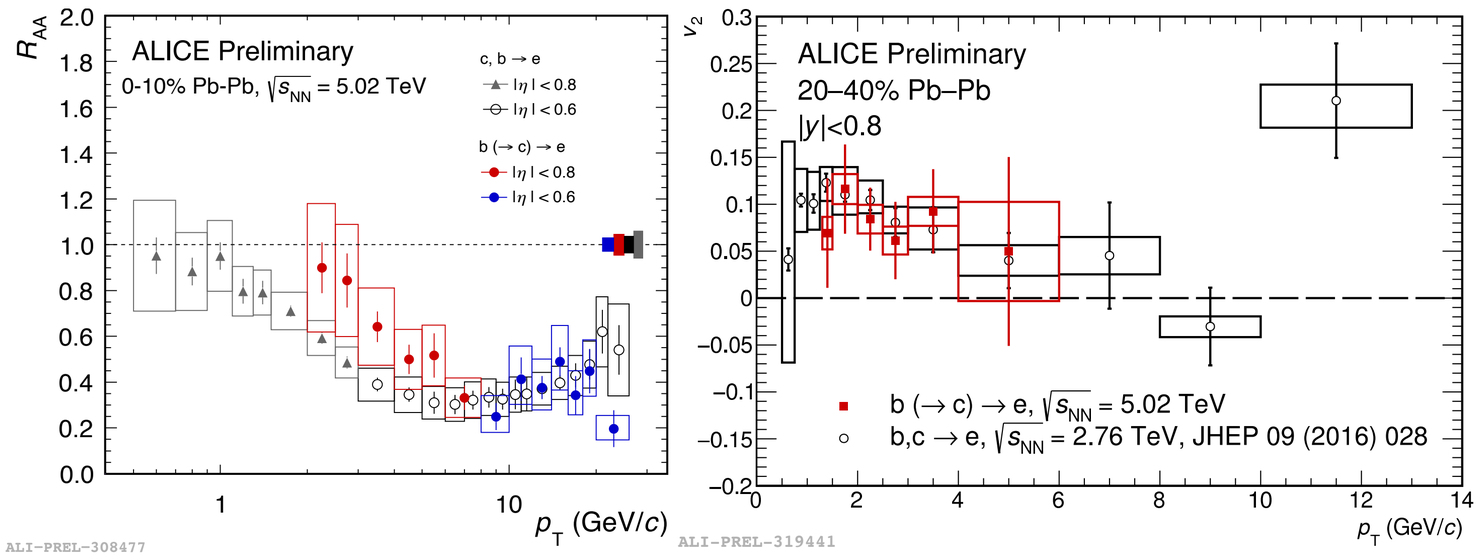

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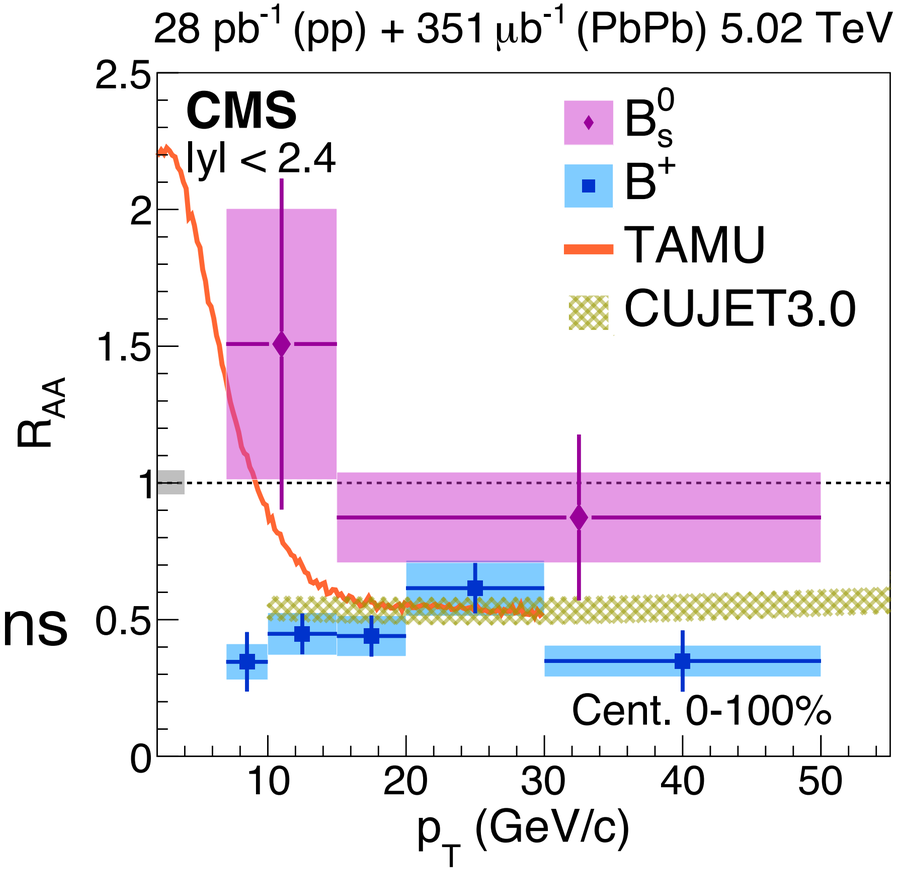
  - ➡ Beauty thermalization (?)

CMS *Phys. Lett.* **B796** (2019) 168

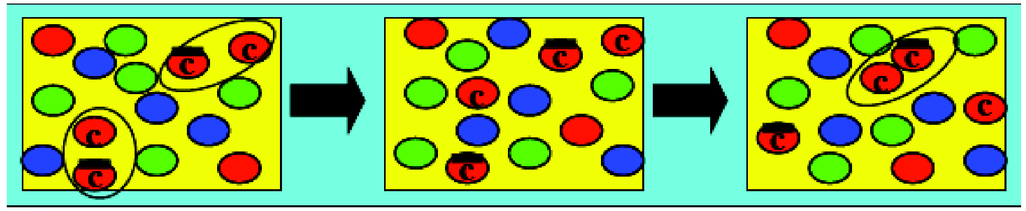


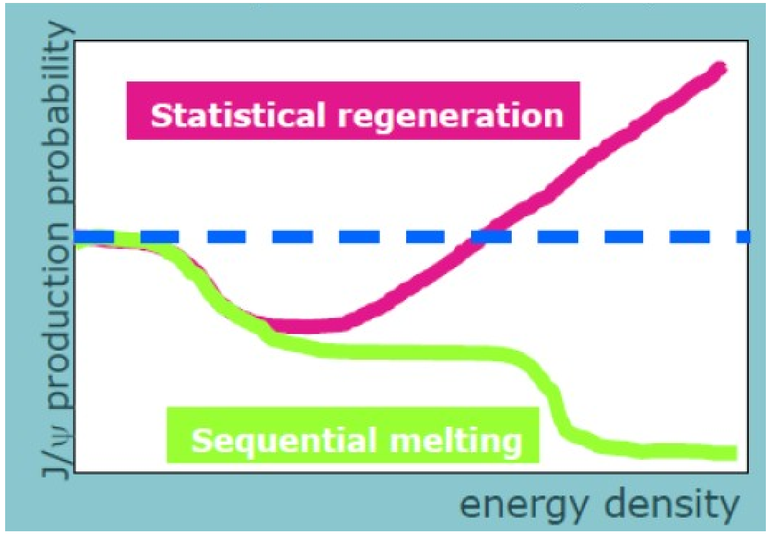
- Indication of less B_s suppression
  - ➡ Coalescence (?)

J/ψ production

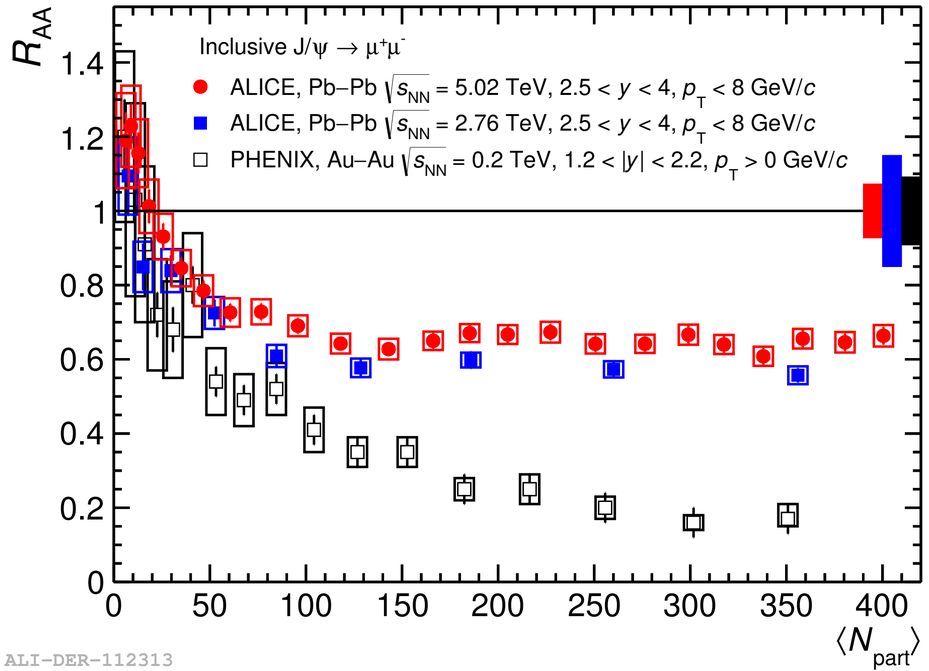
Quarkonia (J/ψ and Y families)

- Sequential melting (Debye screening) vs. recombination
- Sensitive to medium temperature





ALICE *Phys. Lett.* **B766** (2017) 212

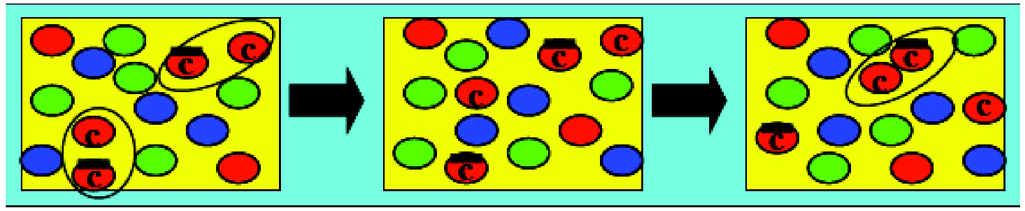


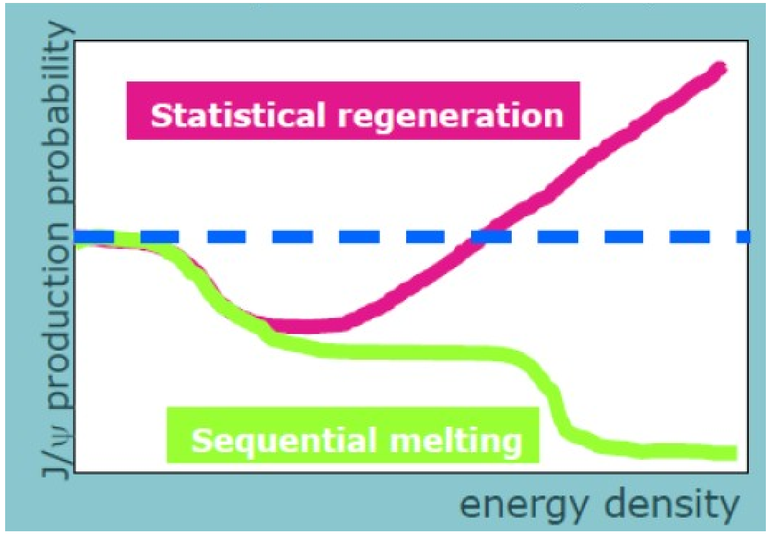
- Suppression is insensitive on centrality in central and semi-central collisions
- Recombination plays important roles on J/ψ production on top of the Debye screening at the LHC energies

J/ψ production

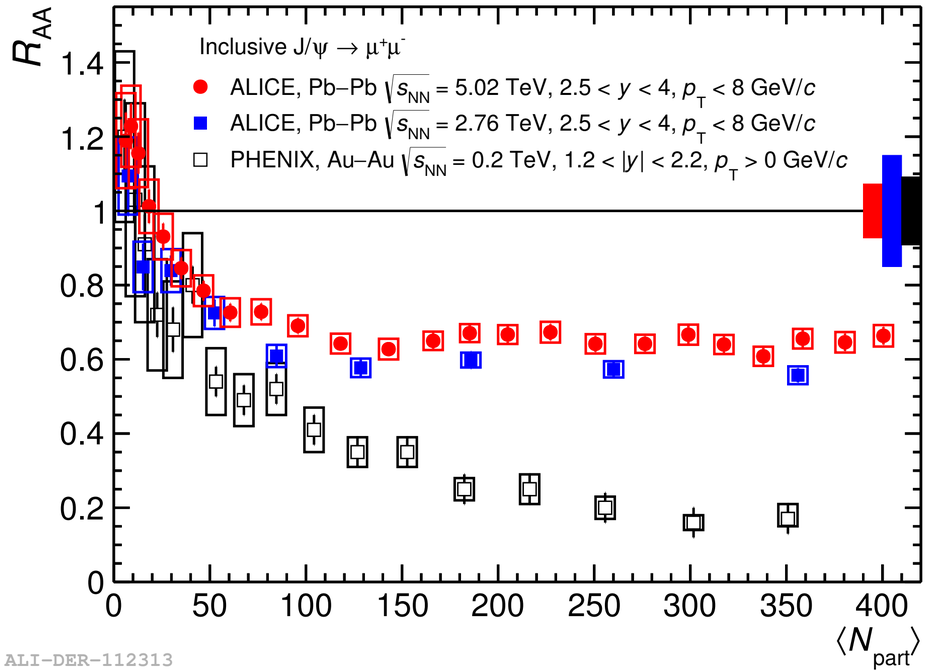
Quarkonia (J/ψ and Y families)

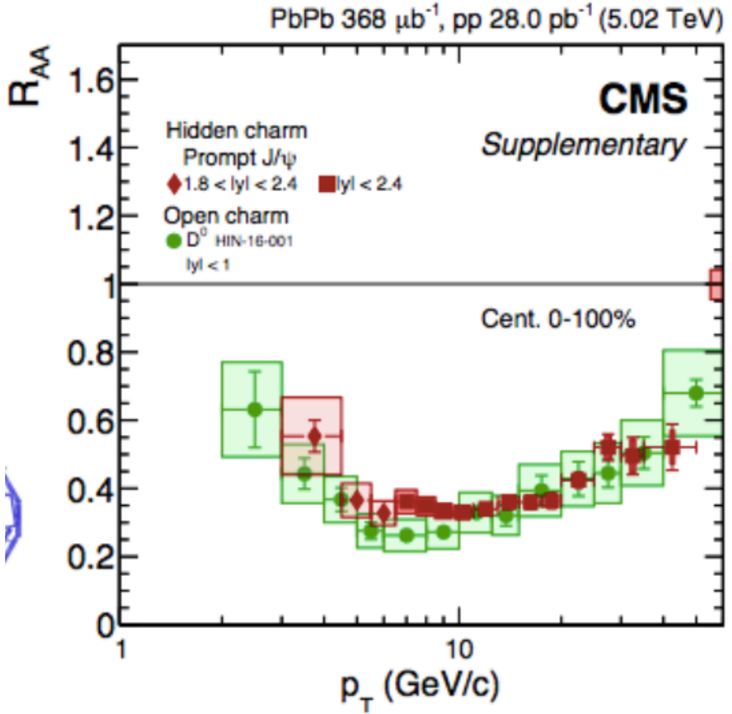
- Sequential melting (Debye screening) vs. recombination
- Sensitive to medium temperature





ALICE *Phys. Lett.* **B766** (2017) 212

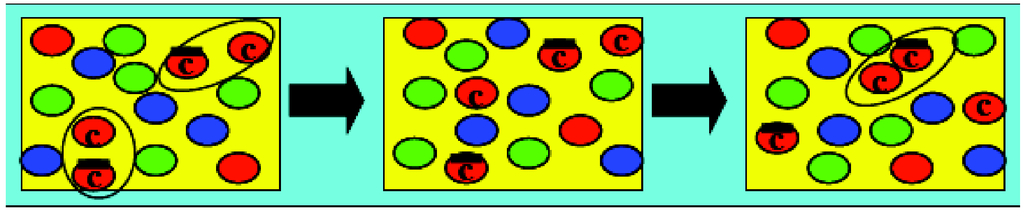


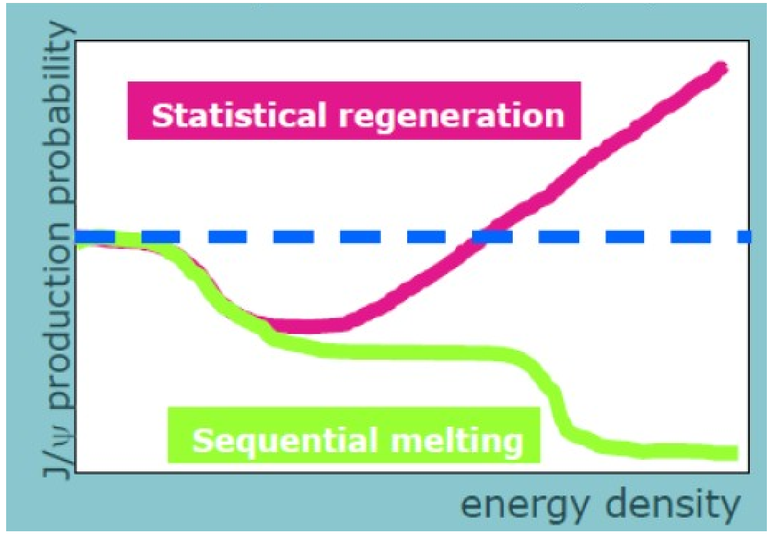


J/ψ production

Quarkonia (J/ψ and Y families)

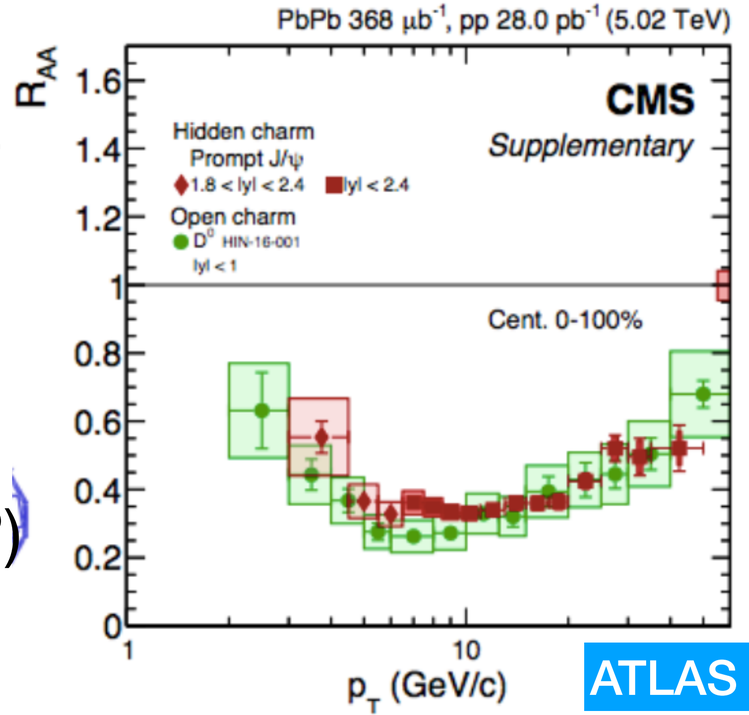
- Sequential melting (Debye screening) vs. recombination
- Sensitive to medium temperature

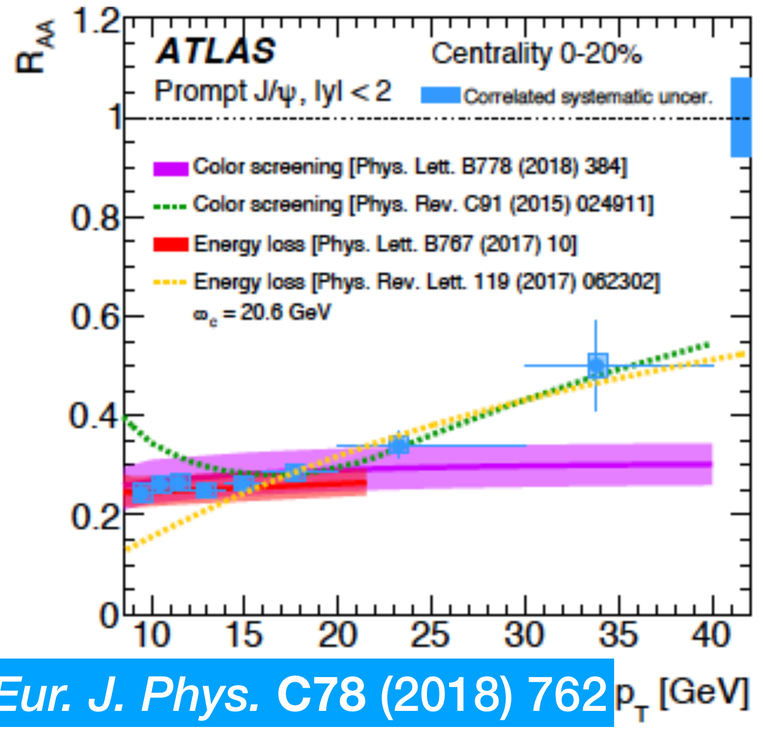




- High p_T: similar suppression of open and hidden charm

- Suppression of J/ψ at high p_T driven by parton energy loss (?)

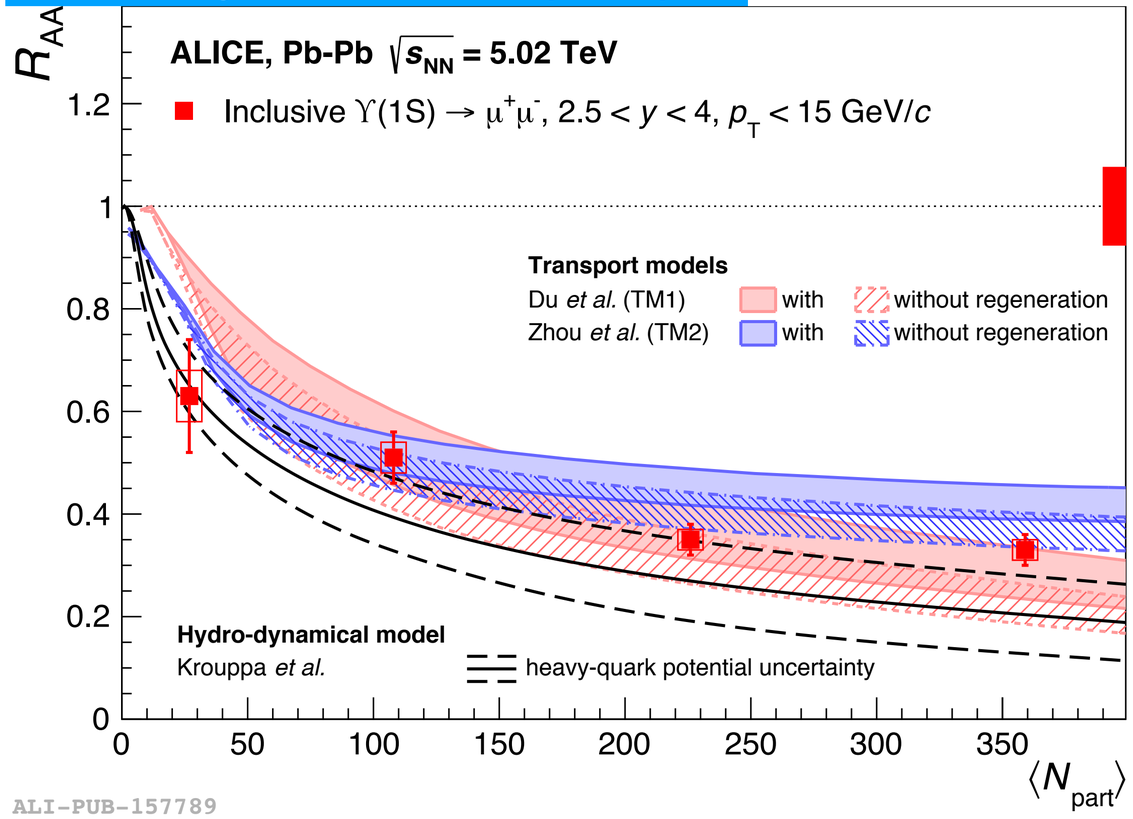




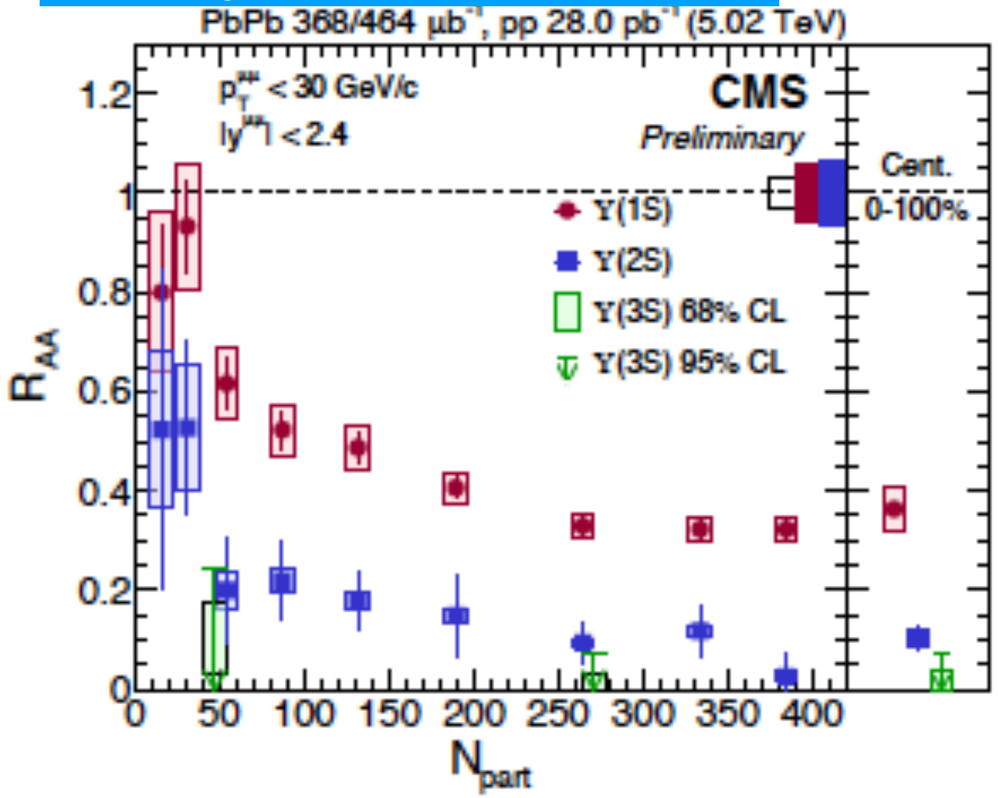
ATLAS *Eur. J. Phys.* **C78** (2018) 762

Bottomonia melting

ALICE *Phys. Lett.* B790 (2019) 89



CMS *Phys. Lett.* B790 (2019) 270



- Clear hierarchy of suppression, but no sudden turn-on

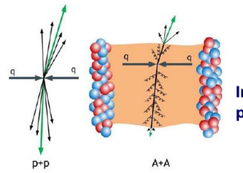
  ➡ *T* does not change rapidly with centrality (?)

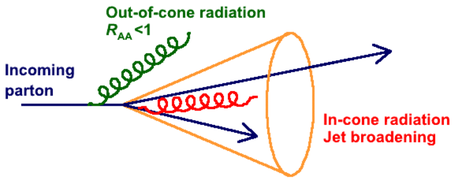
Topics which are not covered…

Jet and jet structure

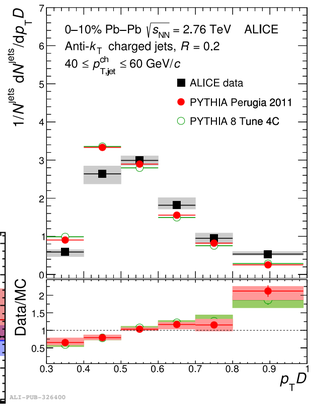
- Jet: a spray of particles from hard parton fragmentation

  ➡ Get closer access to parton energy

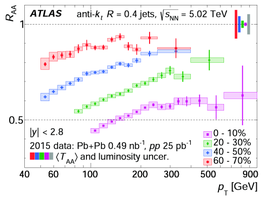




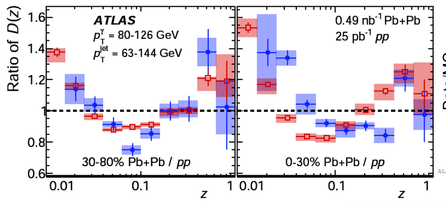
ALICE *JHEP* **10** (2018) 139



ATLAS *Phys. Lett.* **B790** (2019) 108



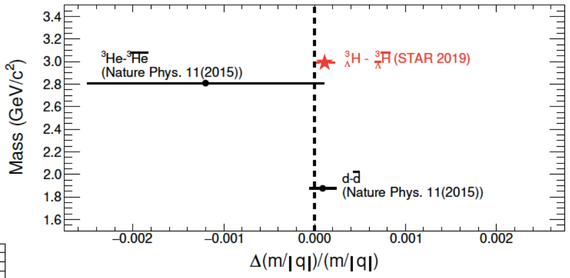
ATLAS *Phys. Rev. Lett.* **123** (2019) 042001

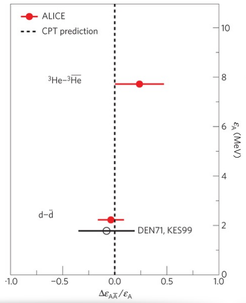


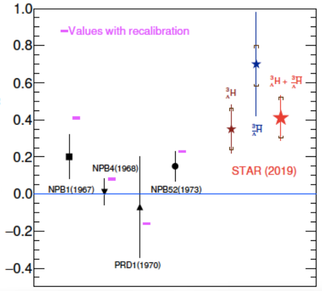
Exotic particle production

ALICE *Nature Phys.* **11** (2015) 811
STAR arXiv:1904.10520 (submitted to *Nature Phys.*)

- Test of CPT invariance of residual nuclear force by measuring mass difference in the nuclei sector
- Confirms CPT invariance for (light) nuclei



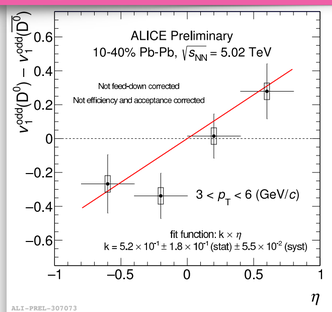


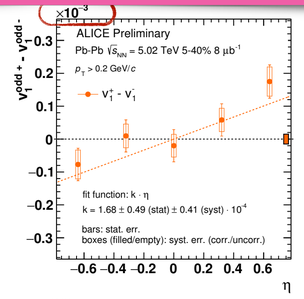


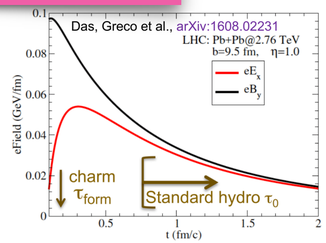
- **New STAR** Measure hypertriton binding energy (best ever) and systematically larger than previous measured

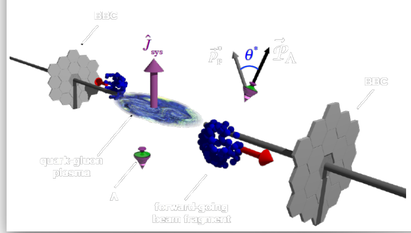
  ➡ Opened the hyper-nuclei window

Magnetic and vortical effects

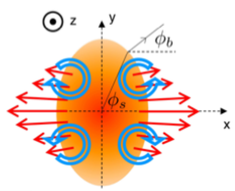


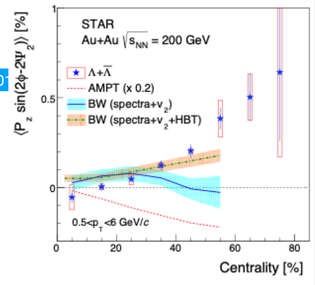






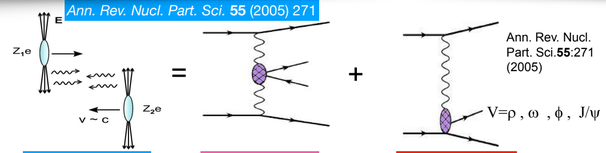
STAR *Phys. Rev. Lett.* **123** (2019) 132301



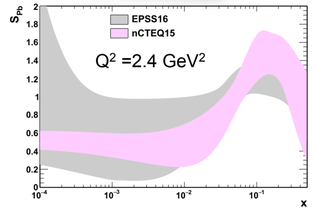


Photon–Photon interactions

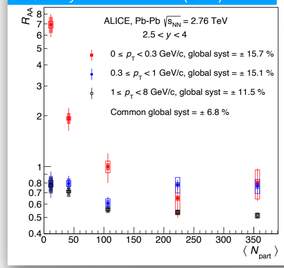
Ann. Rev. Nucl. Part. Sci. **55** (2005) 271



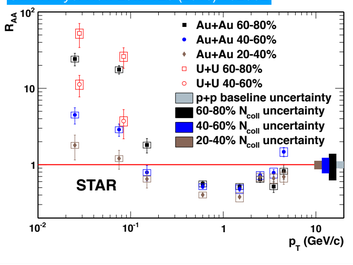
Electromagnetic interactions | Photon–proton interactions | Photon–photon Interactions



ALICE *Phys. Rev. Lett.* **116** (2016) 222301



STAR *Phys. Rev. Lett.* **123** (2019) 132302



Eur. Phys. J. **C77** (2017) 163

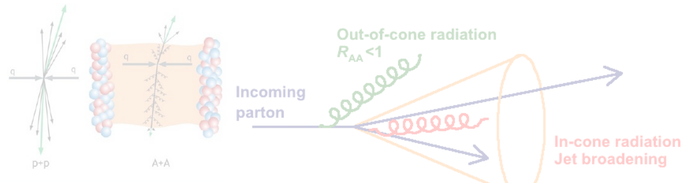
- Exceed J/ψ at low-p_T: coherent photo-production
- Sensitive to gluon distribution function at very low Bjorken-x

And many many others…

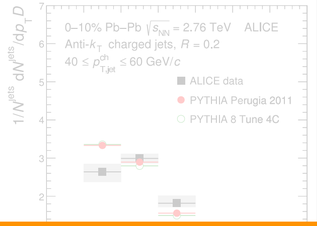
Topics which are not covered…

Jet and jet structure

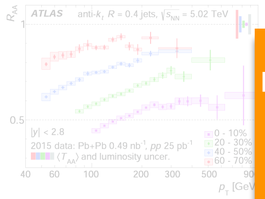
- Jet: a spray of particles from hard parton fragmentation
  - ➡ Get closer access to parton energy



ALICE *JHEP* **10** (2018) 139



ATLAS *Phys. Lett.* **B790** (2019) 108



ATLAS *Phys. Rev. Lett.* **123** (2019) 042001

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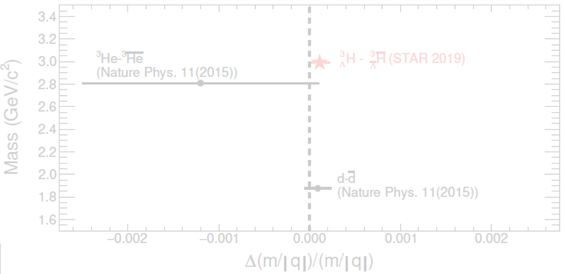
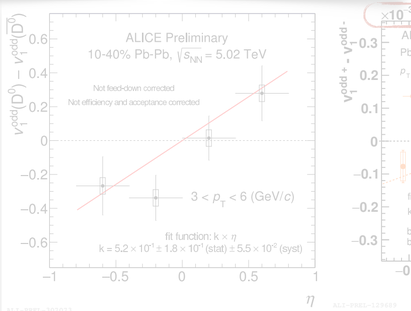
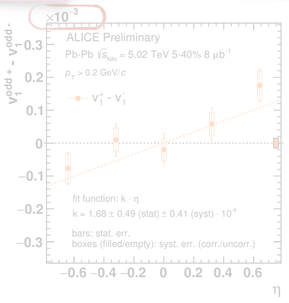
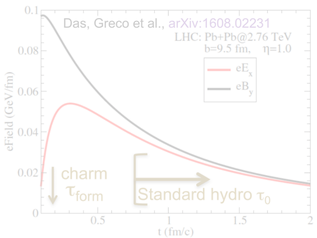


- ➡ Opened the hyper-nuclei window

Magnetic effect



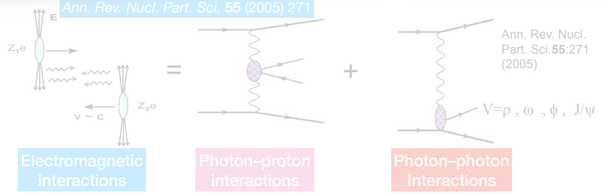




STAR *Phys. Rev. Lett.* **123** (2019) 132301

Photon–Photon interactions

Ann. Rev. Nucl. Part. Sci. **55** (2005) 271



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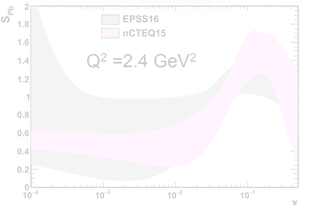
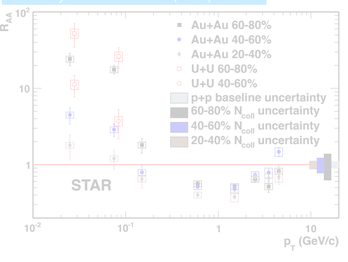


Eur. Phys. J. **C77** (2017) 163

ALICE *Phys. Rev. Lett.* **116** (2016) 222301

STAR *Phys. Rev. Lett.* **123** (2019) 132302



- Exceed J/ψ at low-p_T: coherent photo-production
- Sensitive to gluon distribution function at very low Bjorken-x

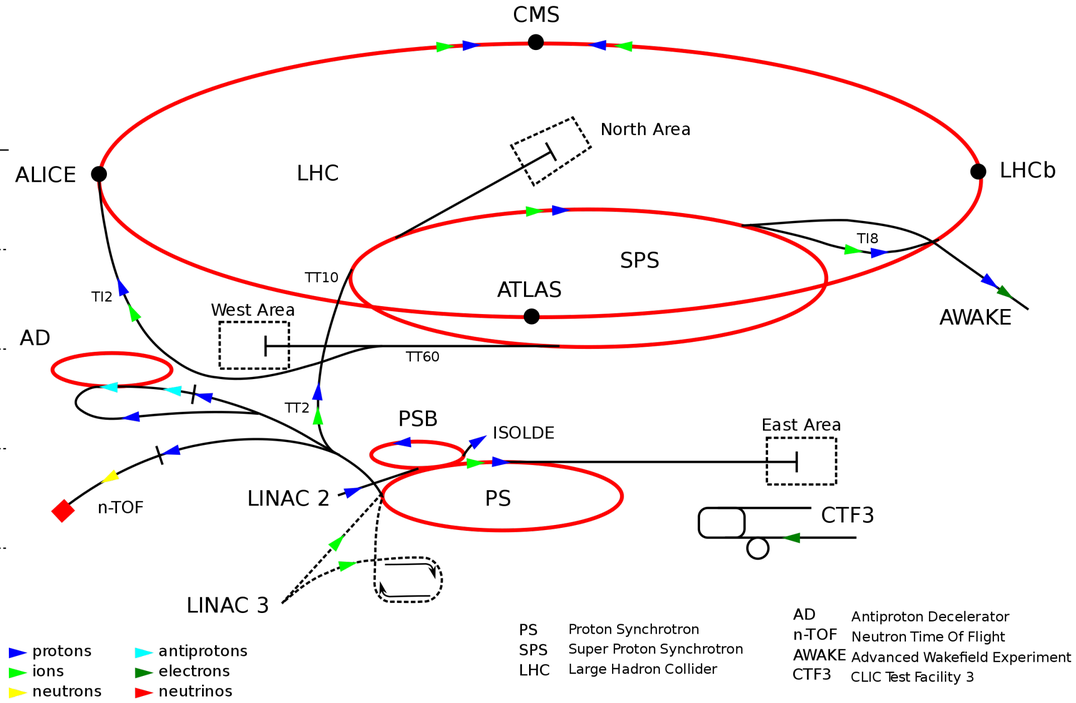
Thanks for your attention!

And many many others…

Backup

Experimental facilities: LHC

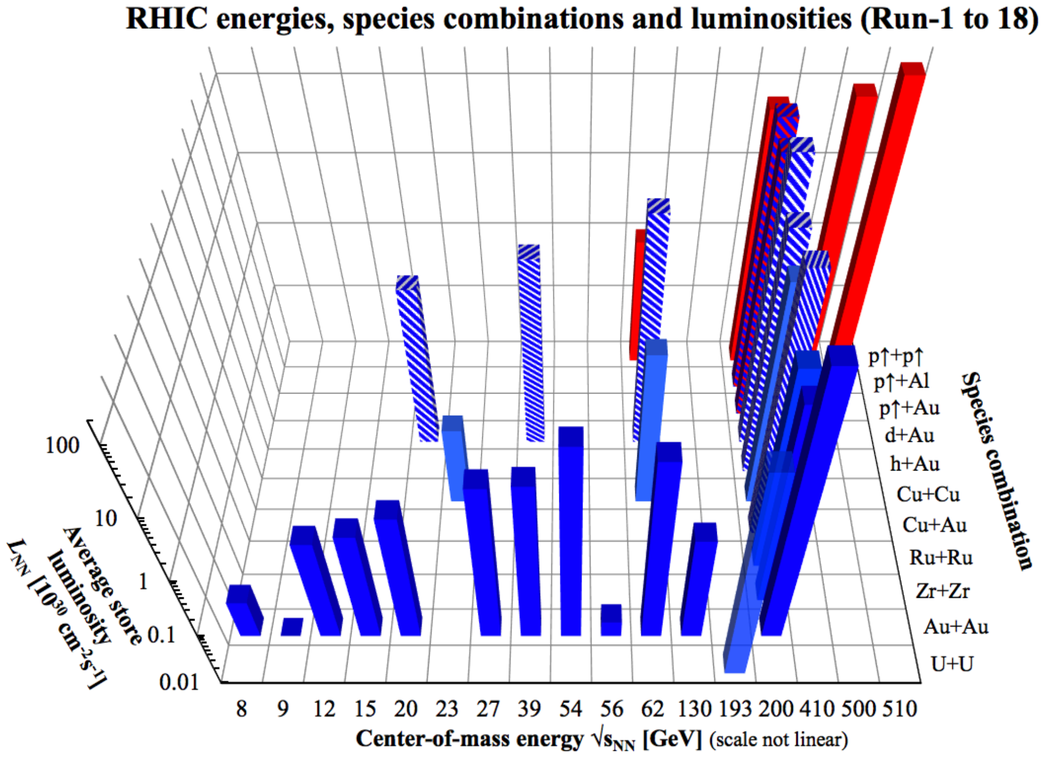
System	Central-of-mass energy (TeV)
Pb–Pb	2.76, 5.02
Xe–Xe	5.44
p–Pb	5.02, 8.16
pp	0.9, 2.76, 5.02, 7, 8, 13
Possibly other nuclei	O–O, S–S…



- **ALICE** Dedicated heavy-ion experiment
- **ATLAS and CMS** General-purpose detector with heavy-ion capabilities
- **LHCb** Forward beauty experiment, heavy-ion and fixed target capabilities

Experimental facilities: RHIC

System	Central-of-mass energy (GeV)
Au–Au	From 7.7 up to 200
Cu–Cu	22, 62, 200
U–U	193
Gu–Au, Zr–Zr, Ru–Ru	200
p–Au, He–Au	200
d–Au	19.7, 39, 62, 200
pp	62, 200, 400, 500, polarized
Possibly fixed target	Beam energy scan



- **STAR** Multipurpose heavy-ion detector, capability for hadron measurements
- **PHENIX** Multipurpose heavy-ion detector, capability for lepton measurements

Experimental facilities: SPS, SIS18…

CERN-SPS

- NA61 / SHINE Follow-up of NA49
- Pb–Pb collisions up to $\sqrt{s_{NN}}$ = 17 GeV, pp collisions up to $\sqrt{s}$ = 29 GeV

  ➡ Many other combinations from fragmented beams (energy scan)

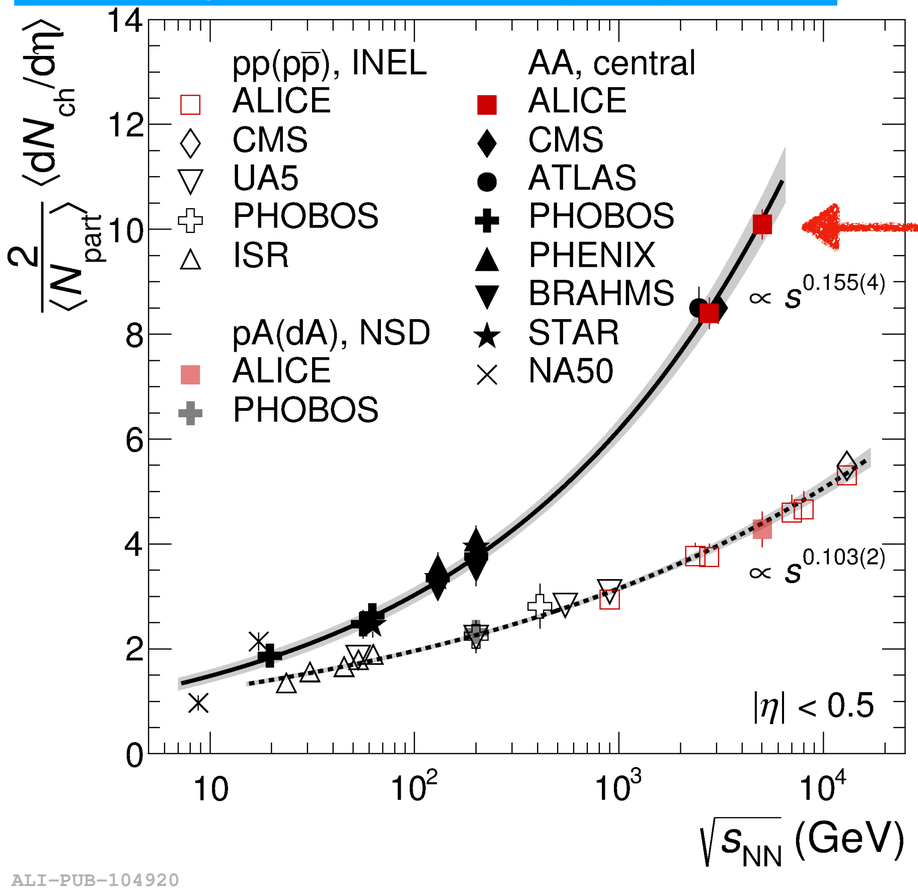
GSI-SIS 18

- HADES High acceptance spectrometer for di-electrons and hadrons
- FOPI 4π spectrometer, hadron identification
- U–U, Ne–Ne and pp collisions up to 1.4, 1.9 and 2.9 GeV, respectively

…

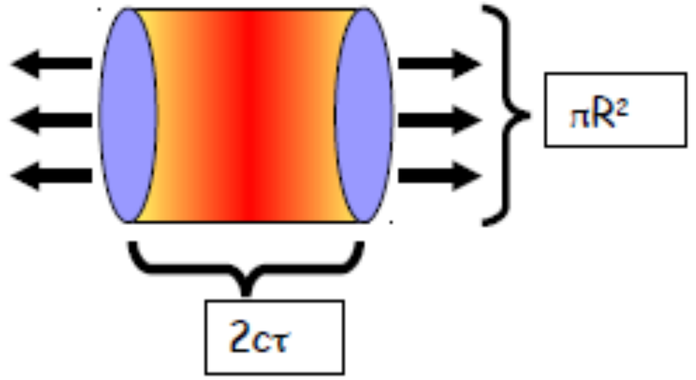
Charge particle multiplicity

ALICE *Phys. Rev. Lett.* 116 (2016) 222302



ALICE Pb–Pb at 5.02 TeV

Bjorken estimate:

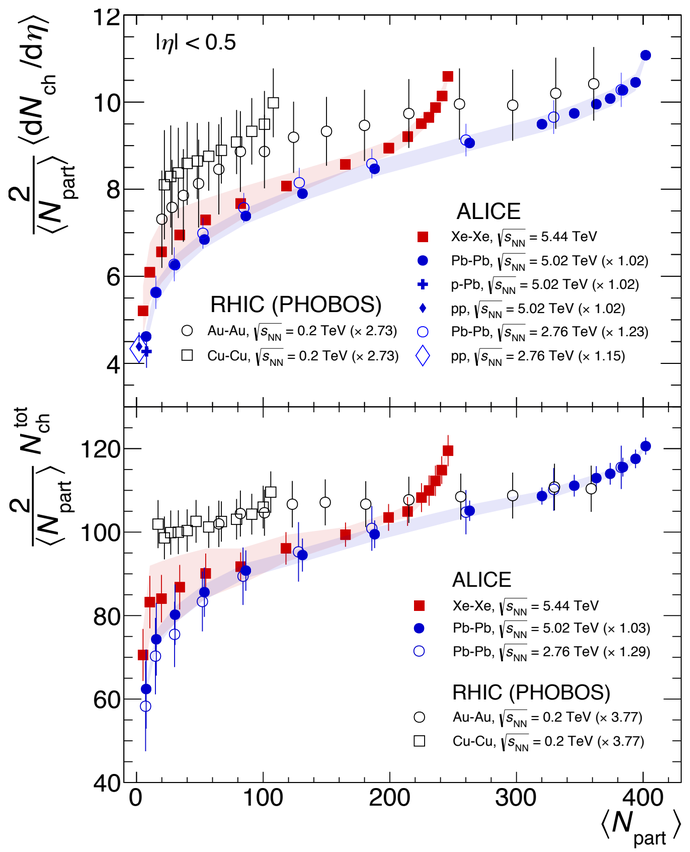


$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}y} \longleftrightarrow \mathrm{dN/d\eta}$$

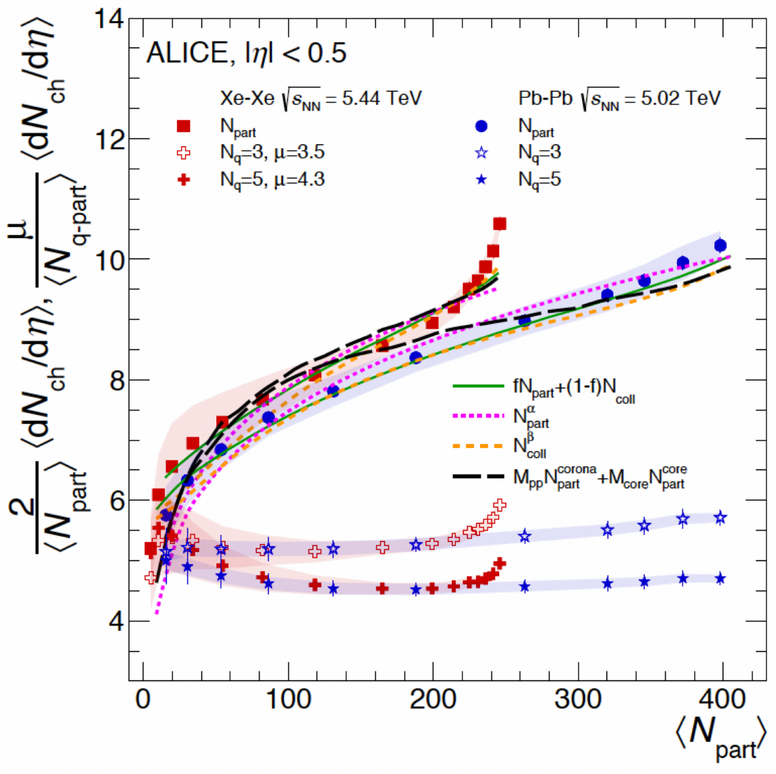
- Central Pb–Pb collisions at 5.02 TeV d*N*/dη ~ 2000
  - ➡ Energy density ε ~18 GeV/fm³
  - ➡ Above deconfinement transition (~1 GeV/fm³)

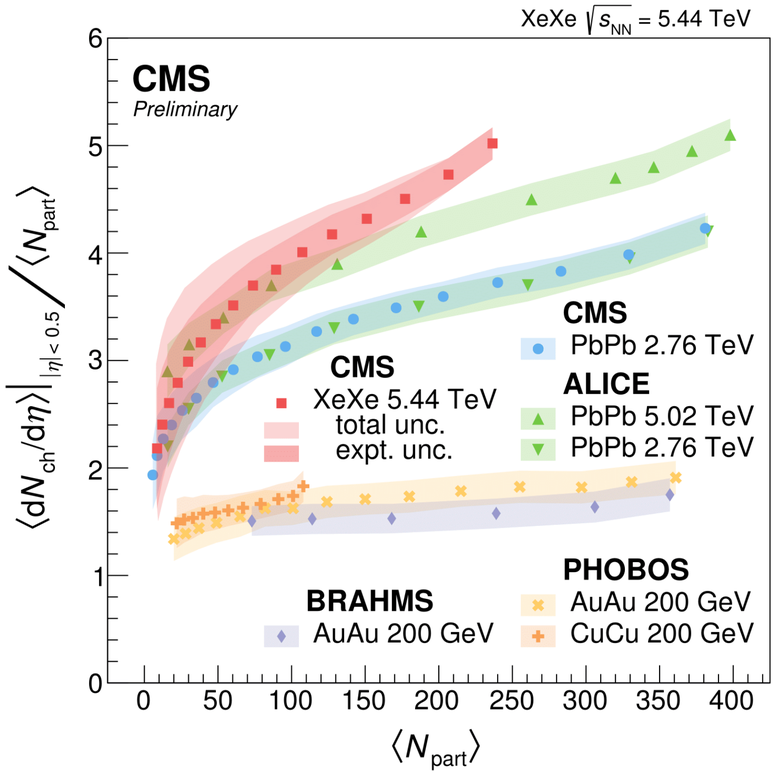
- ALICE: Pb–Pb at 5.02 TeV — highest energy so far
  - ➡ For 0–5% most central collisions, confirms trend from lower energies

Charge particle multiplicity



ALICE *Phys. Lett.* B790 (2019) 35

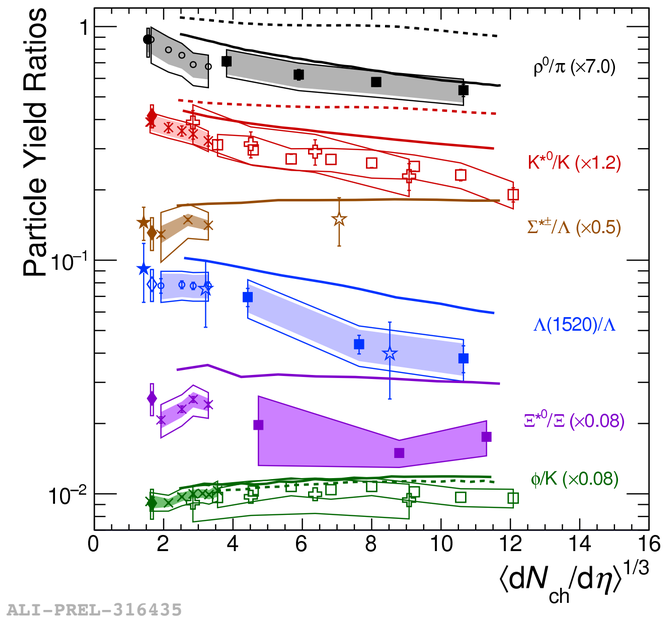


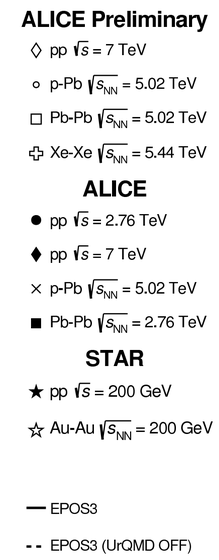


- Newest measurement in Xe–Xe collisions: confirms N_{part} scaling violation
- Central collisions of medium-size nuclei produce more particles per N_{part} than mid-central collisions of large nuclei at the same N_{part}

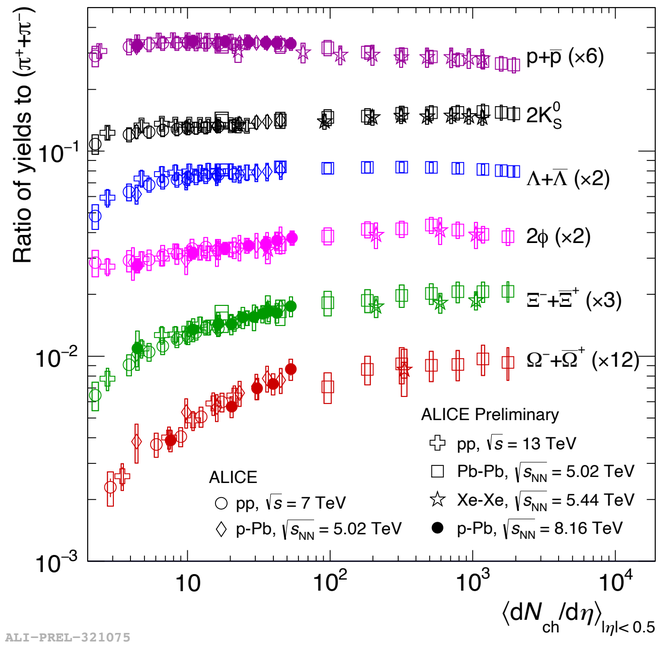
➡ Neither explained by participant quark scaling nor fully reproduced by models

Particle production vs. multiplicity





ALI-PREL-316435



ALI-PREL-321075

- Similar trend seen in all collision systems
- Smooth evolution of particle production from small to large systems vs charge multiplicity

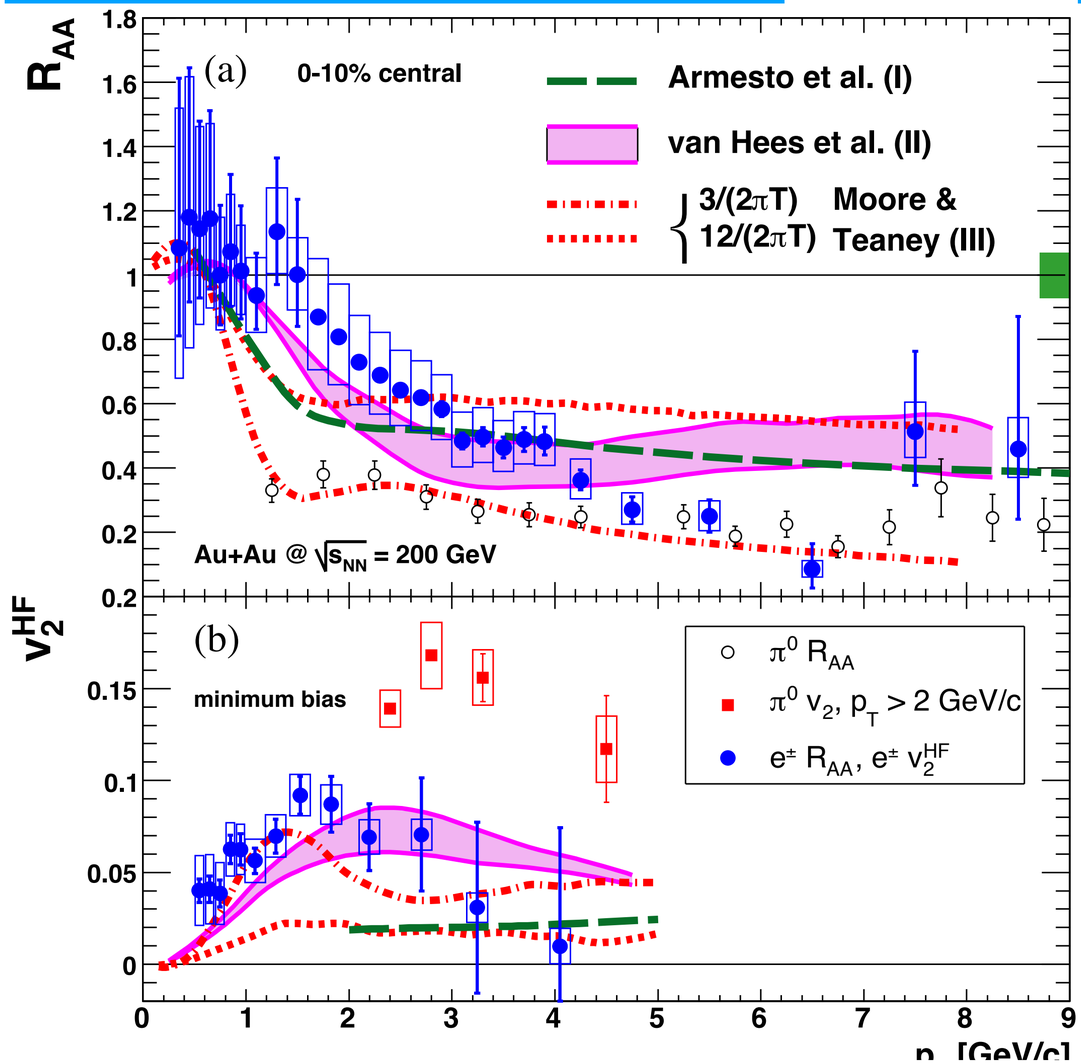
  ➡ Increases with strangeness content
- No significant energy and system dependence is observed at similar multiplicity

Where all this comes from?

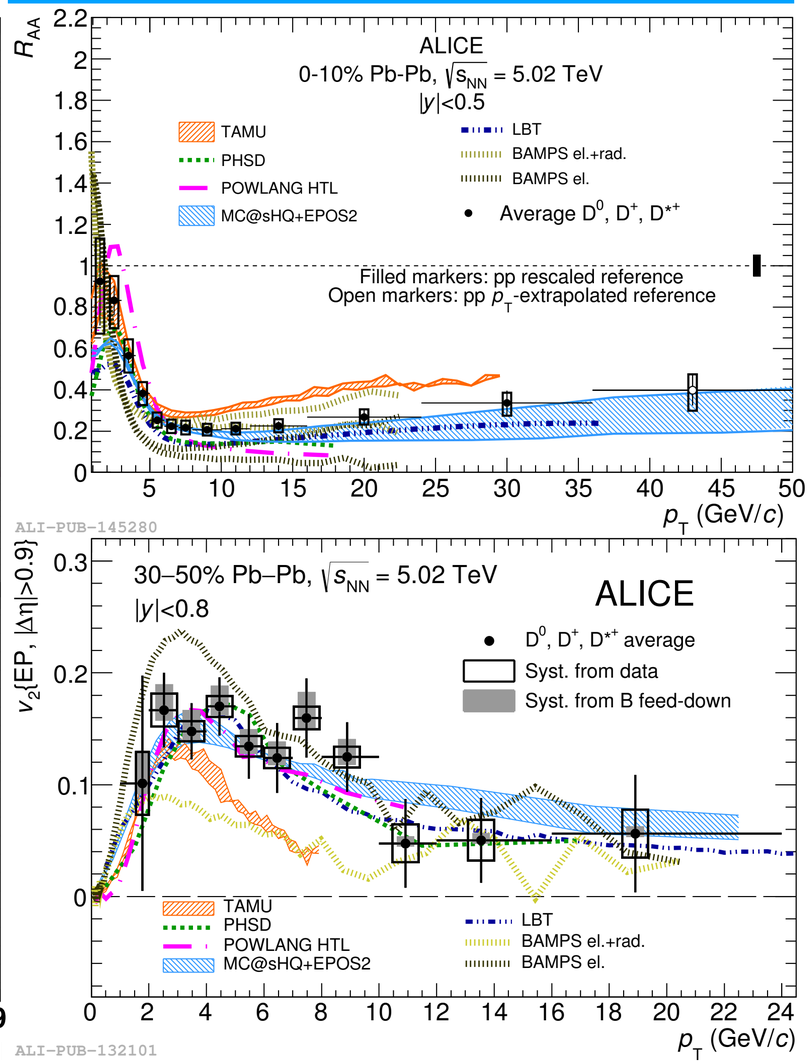
- Initial and / or stages effects?
- Common mechanism of particle production?
- Better understanding of the observables we use in heavy-ion for small systems?

Heavy quarks in heavy-ion collisions

RHIC *Phys. Rev. Lett.* **98** (2007) 172301



LHC *Phys. Rev. Lett.* **120** (2018) 102301



Heavy quark diffusion coefficient

- **RHIC** (4 – 6) / 2πT for 0.2 < T < 0.4 GeV
- **LHC** (1.5 – 7) / 2πT for $T = T_c$

- Heavy quarks — the unique probes of the QCD medium since ~20 years ago