Overview of high-energy heavy-ion physics international cooperation

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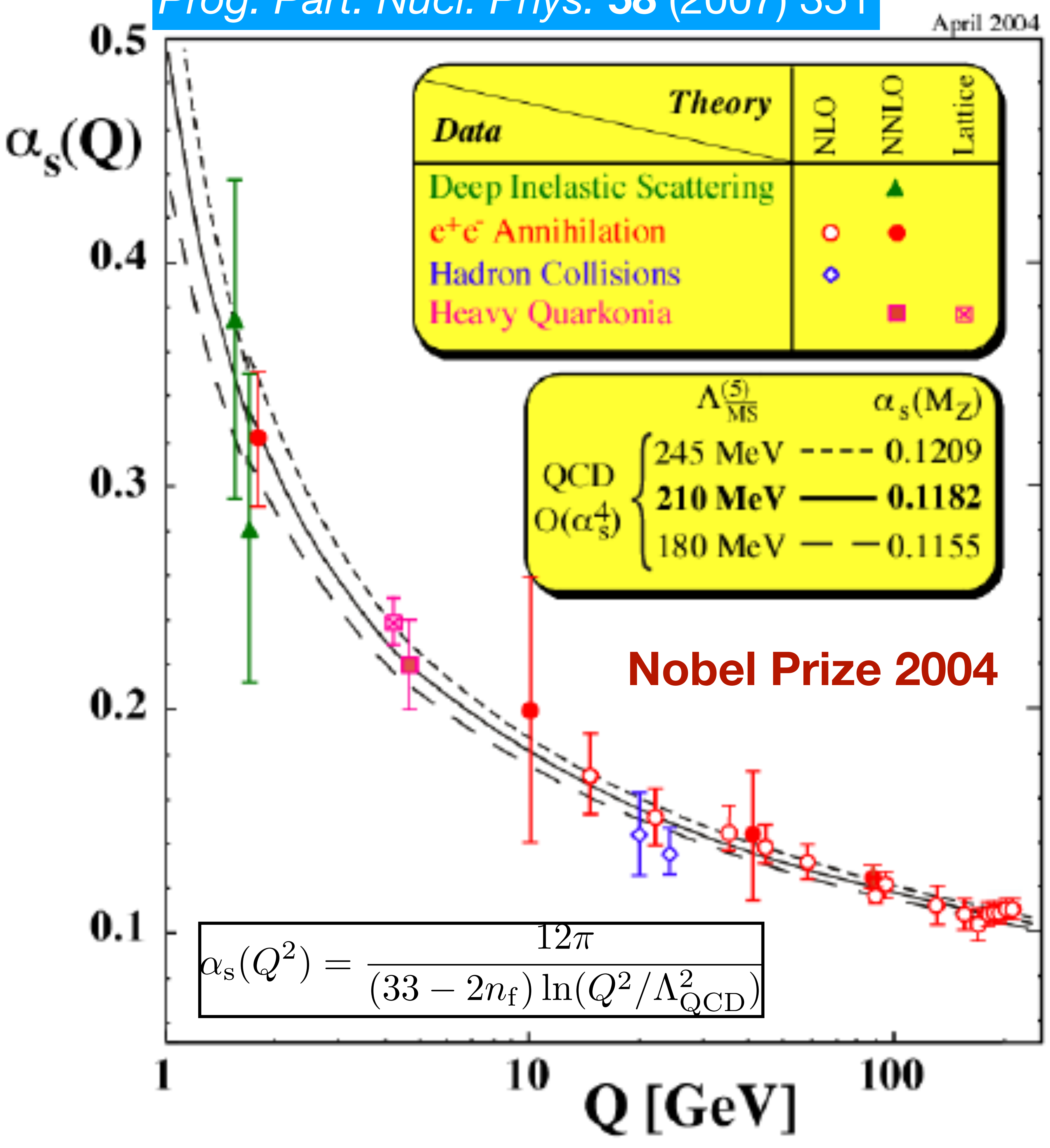
With personal bias

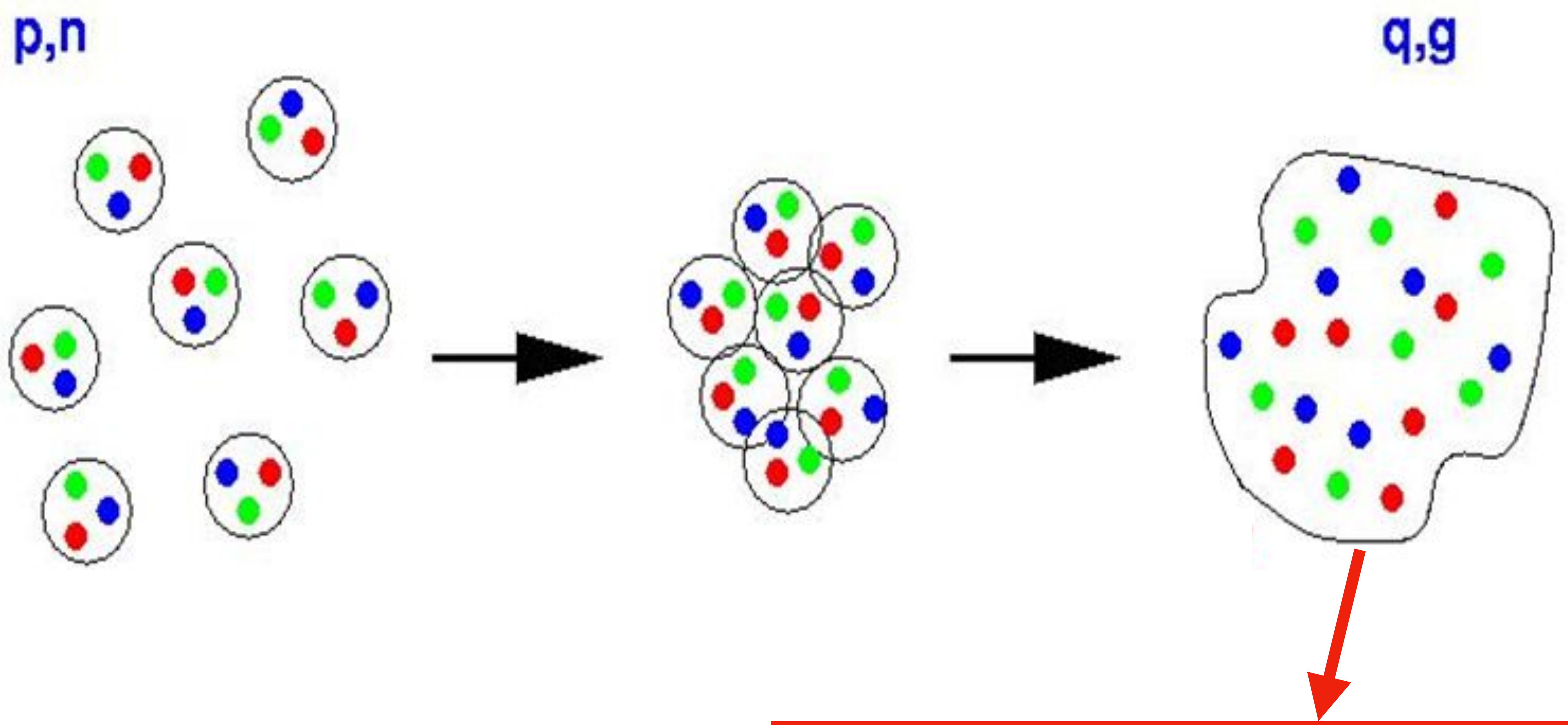
QCD phase transition

Prog. Part. Nucl. Phys. **58** (2007) 351



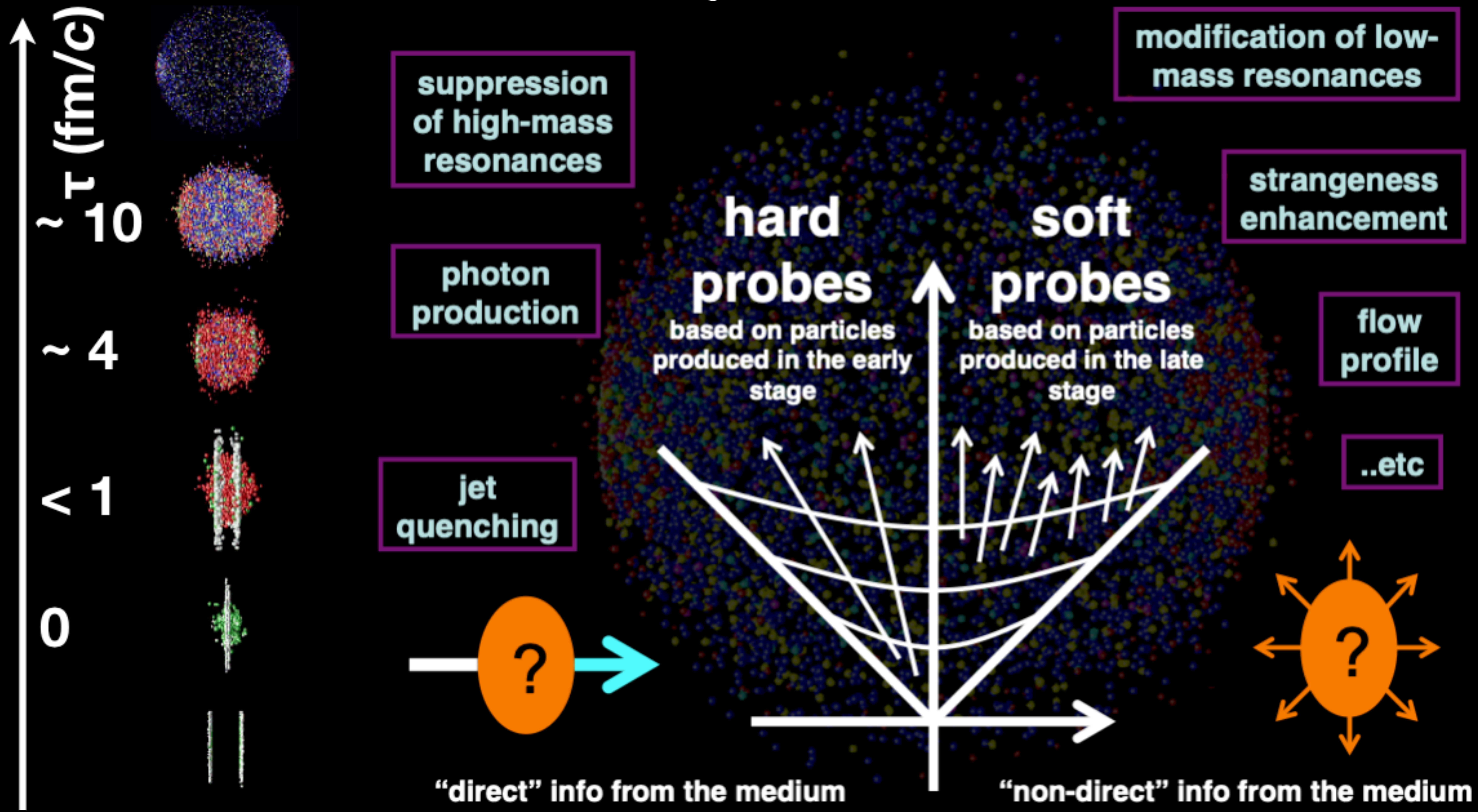
- QCD running coupling constant

➡ Quark confinement and asymptotic freedom



Quark-gluon plasma (QGP)

Ultra-relativistic heavy-ion collisions



Heavy-ion program

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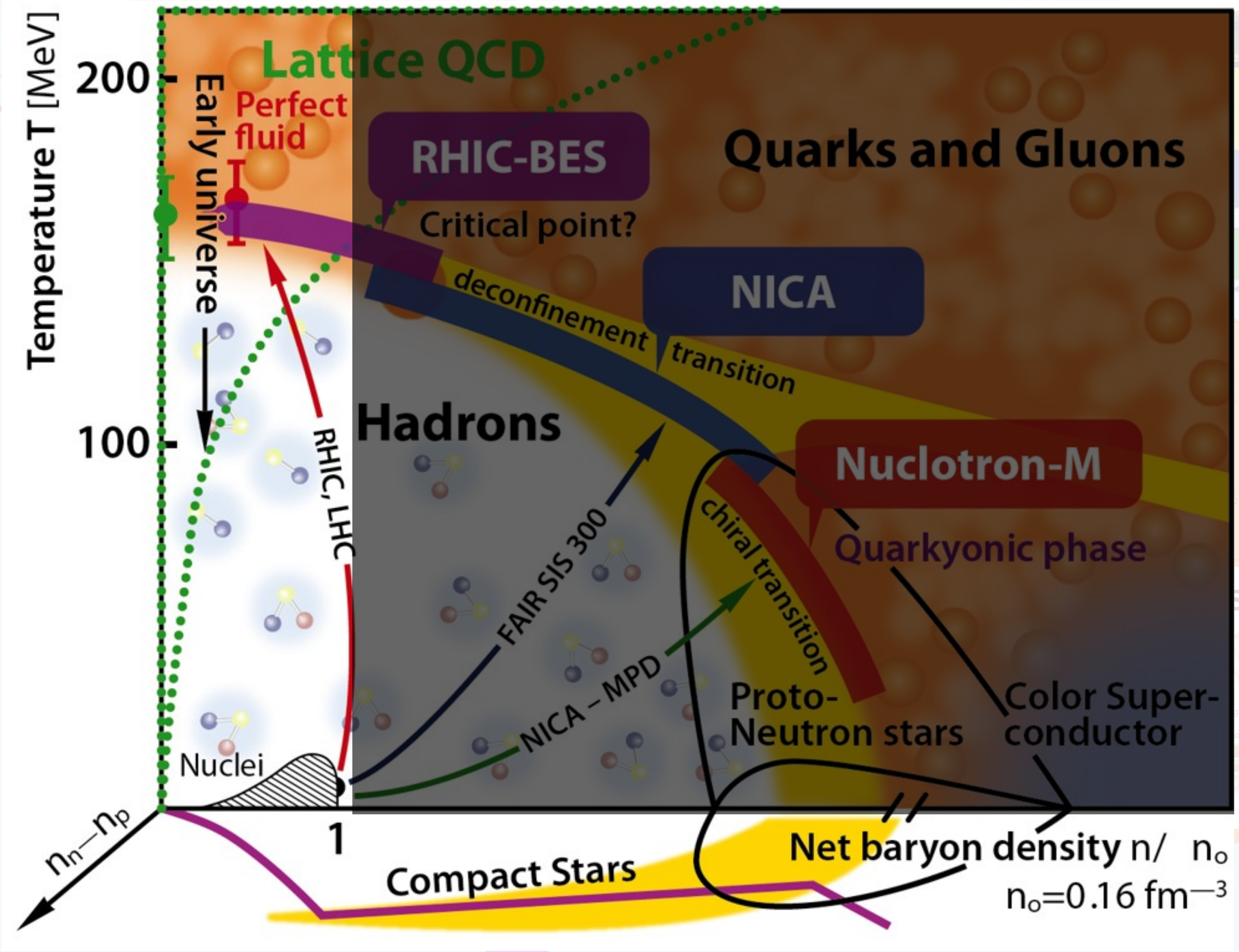


High temperature and low μ_B: LHC, RHIC

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

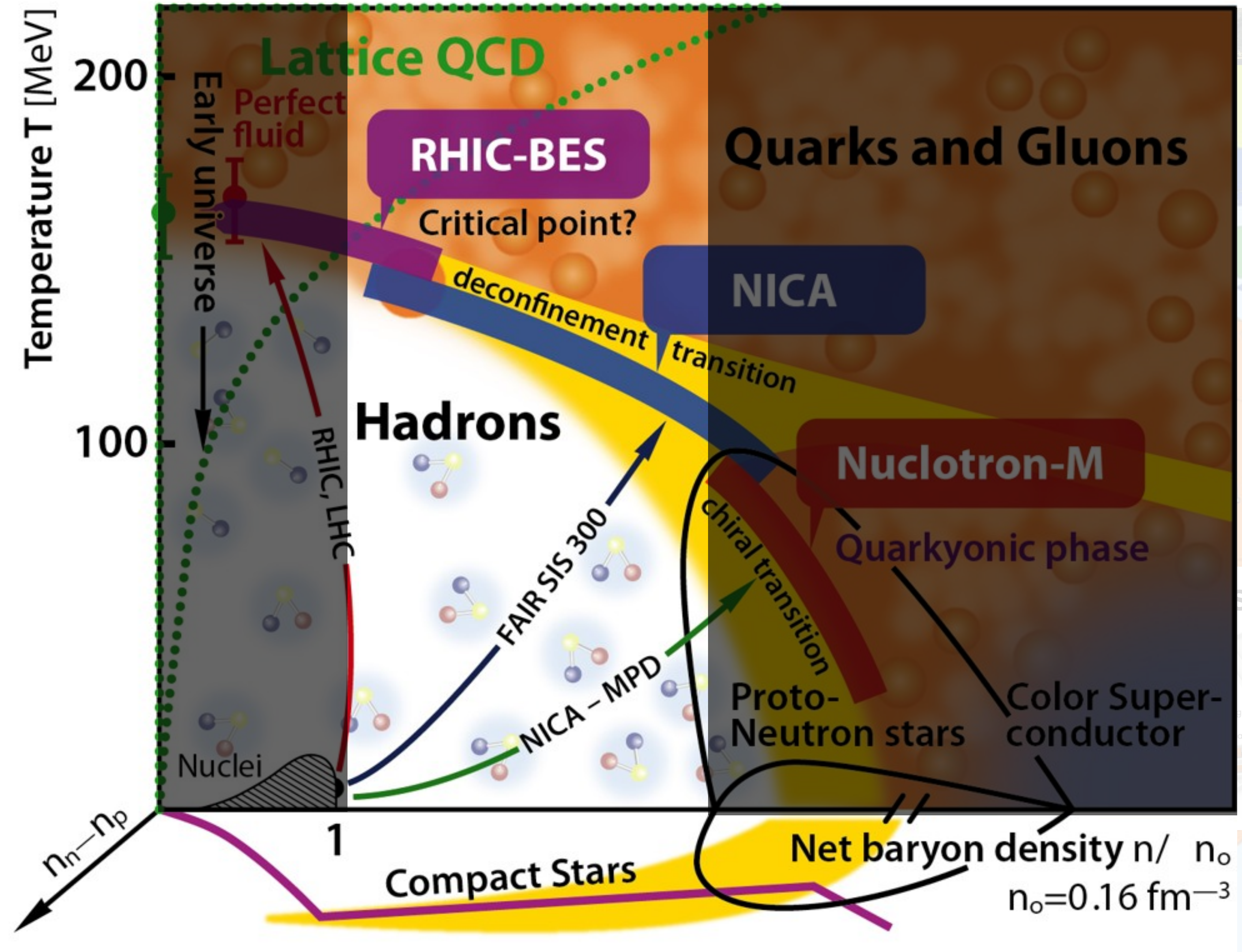
Finite temperature and μ_B: RHIC-BES, NICA

- 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…

Heavy-ion program



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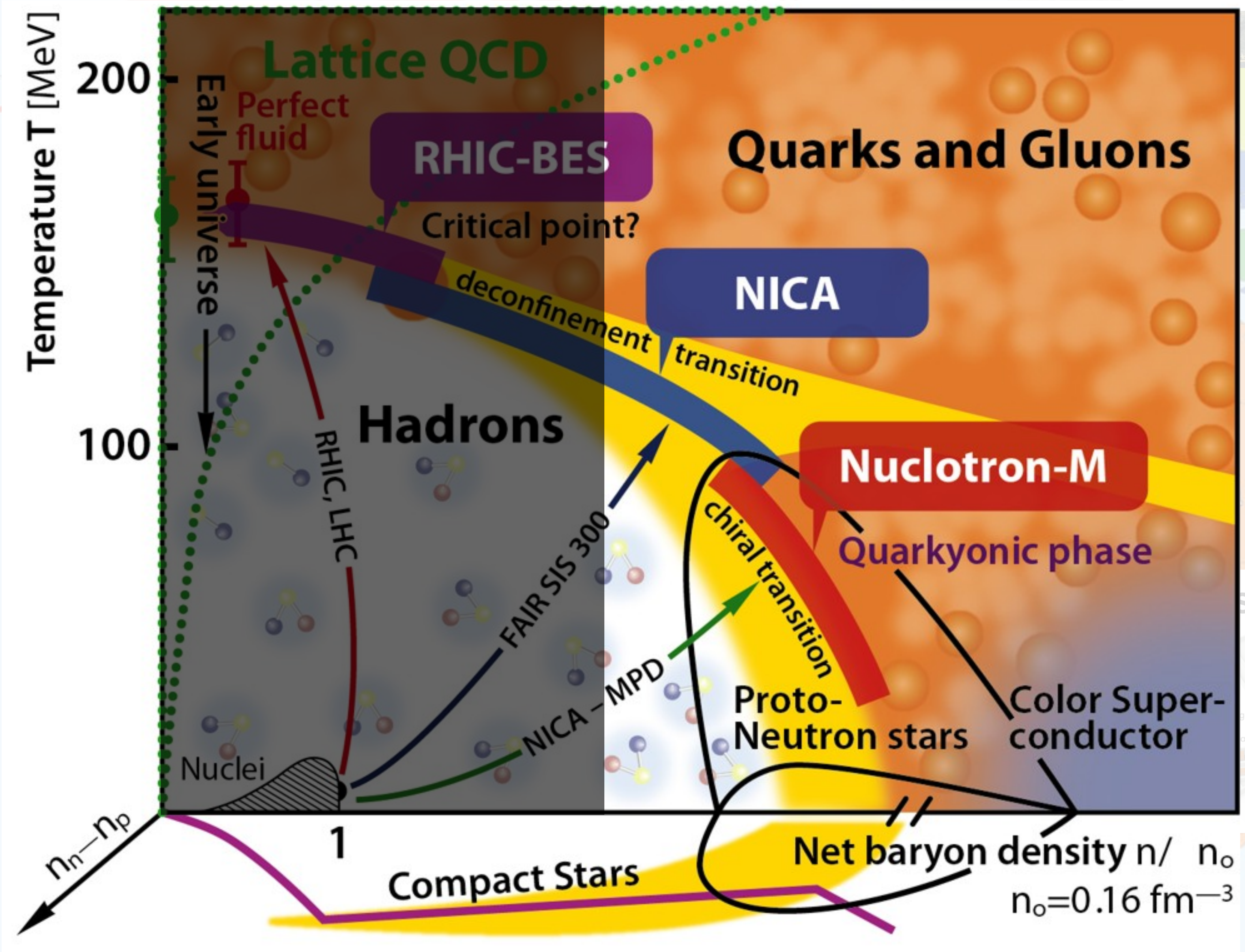

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Collaboration of China

RHIC-STAR
- 华中师范大学
- 复旦大学
- 湖州师范学院
- 中科院近代物理研究所
- 中国科学技术大学
- 山东大学
- 中科院应用物理研究所
- 清华大学

FAiR-CBM
- 三峡大学
- 华中师范大学
- 清华大学
- 重庆大学
- 中国科学技术大学
- 中科院近代物理研究所

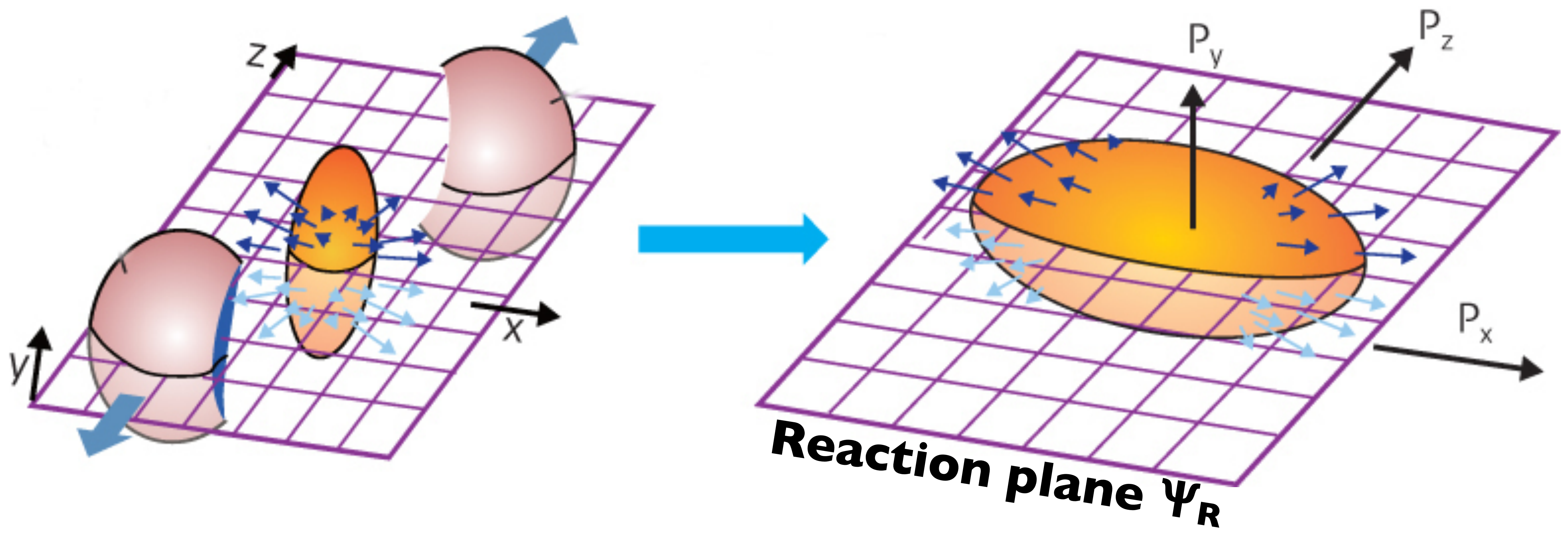
RHIC-PHENIX
- 北京大学

NICA-MPD
- 华中师范大学
- 湖州师范学院
- 中科院高能物理研究所
- 中科院近代物理研究所
- 山东大学
- 中科院应用物理研究所
- 三峡大学
- 清华大学
- 南华大学
- 中国科学技术大学

LHC-ALICE
- 华中师范大学
- 中国科学技术大学
- 复旦大学
- 中国原子能研究院

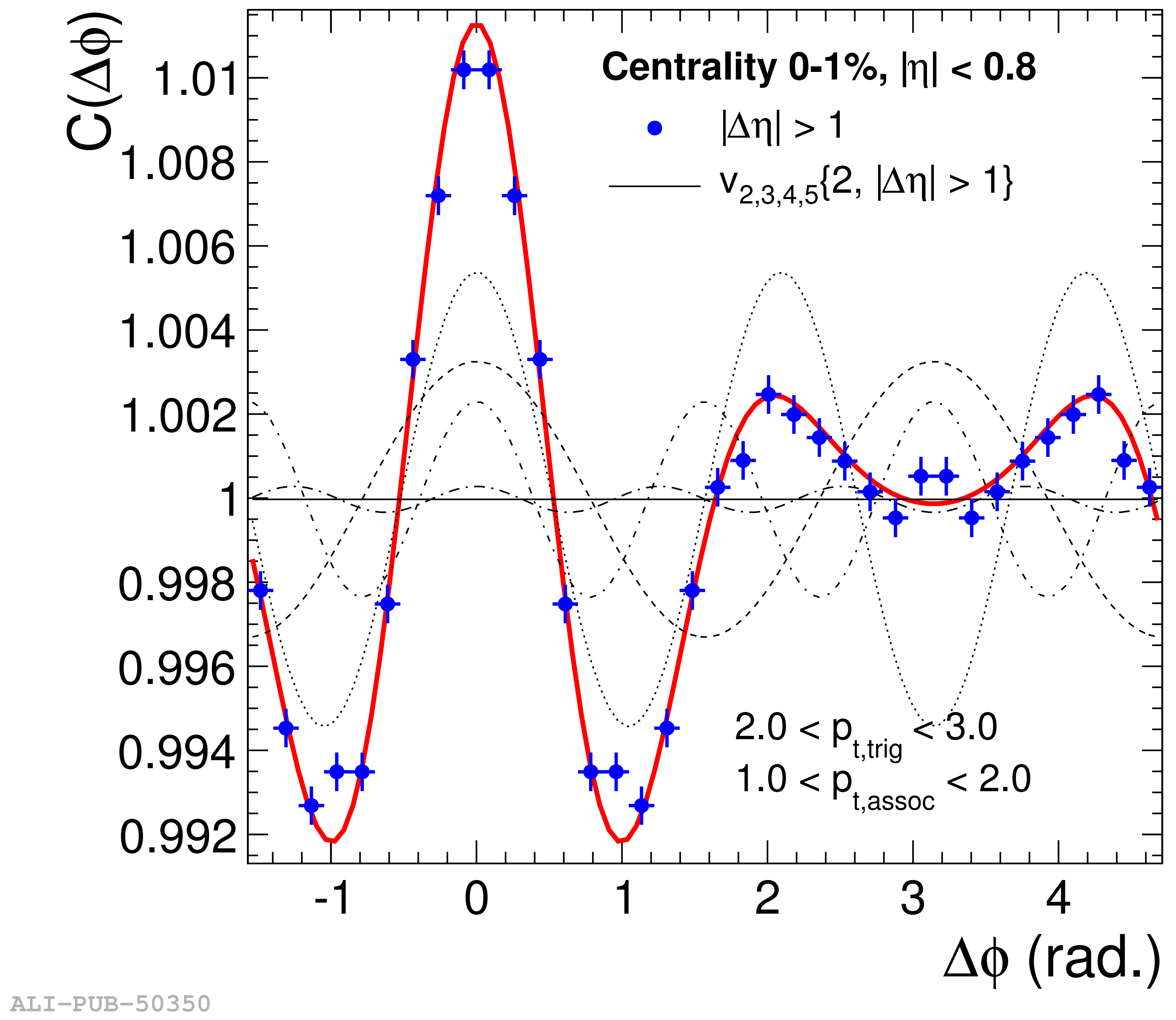
LHC-LHCb
- 清华大学
- 华南师范大学（NEW）
- 华中师范大学
- 武汉大学

Azimuthal anisotropy



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

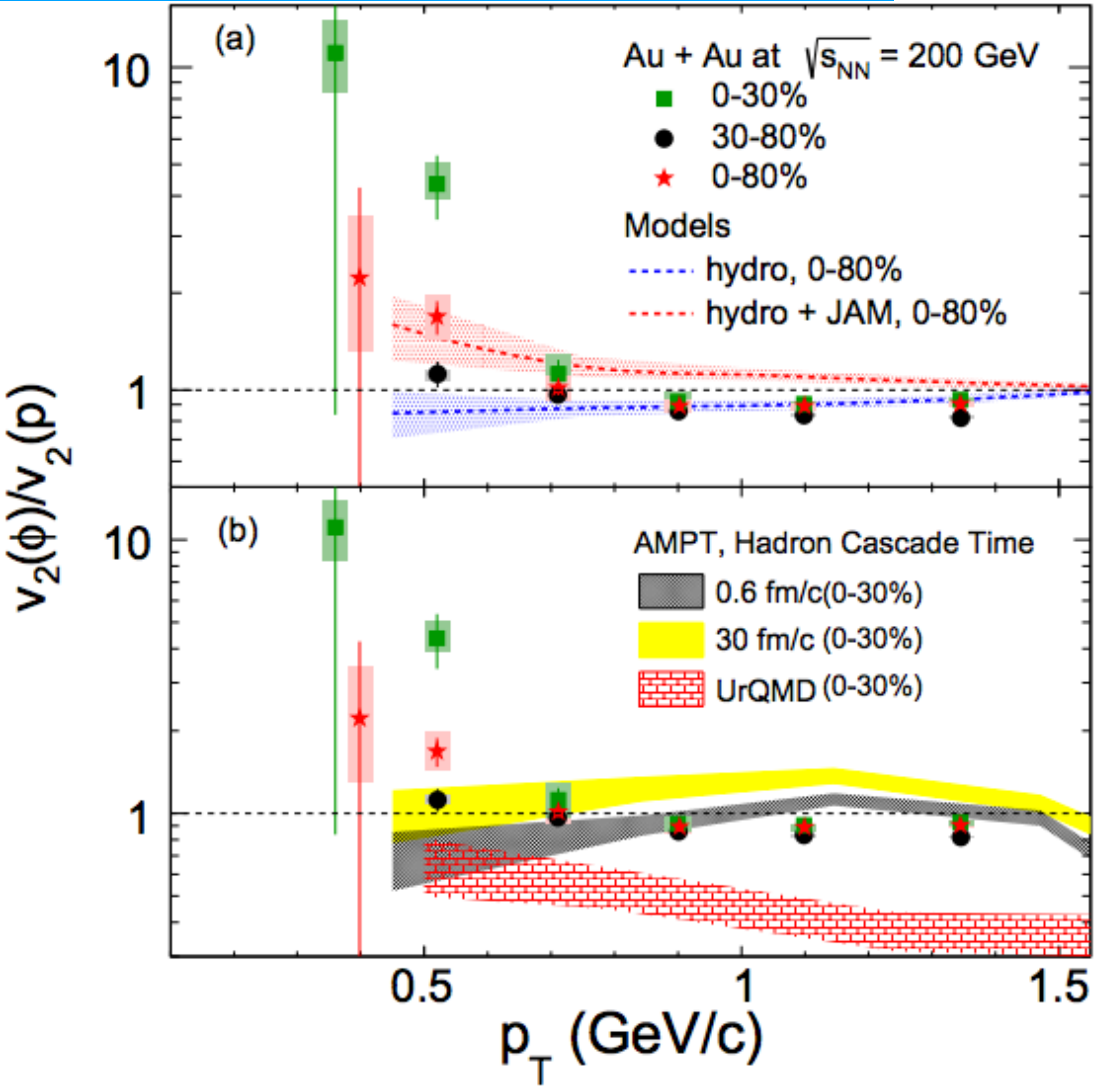
ALICE *Phys. Rev. Lett.* 107 (2013) 032301

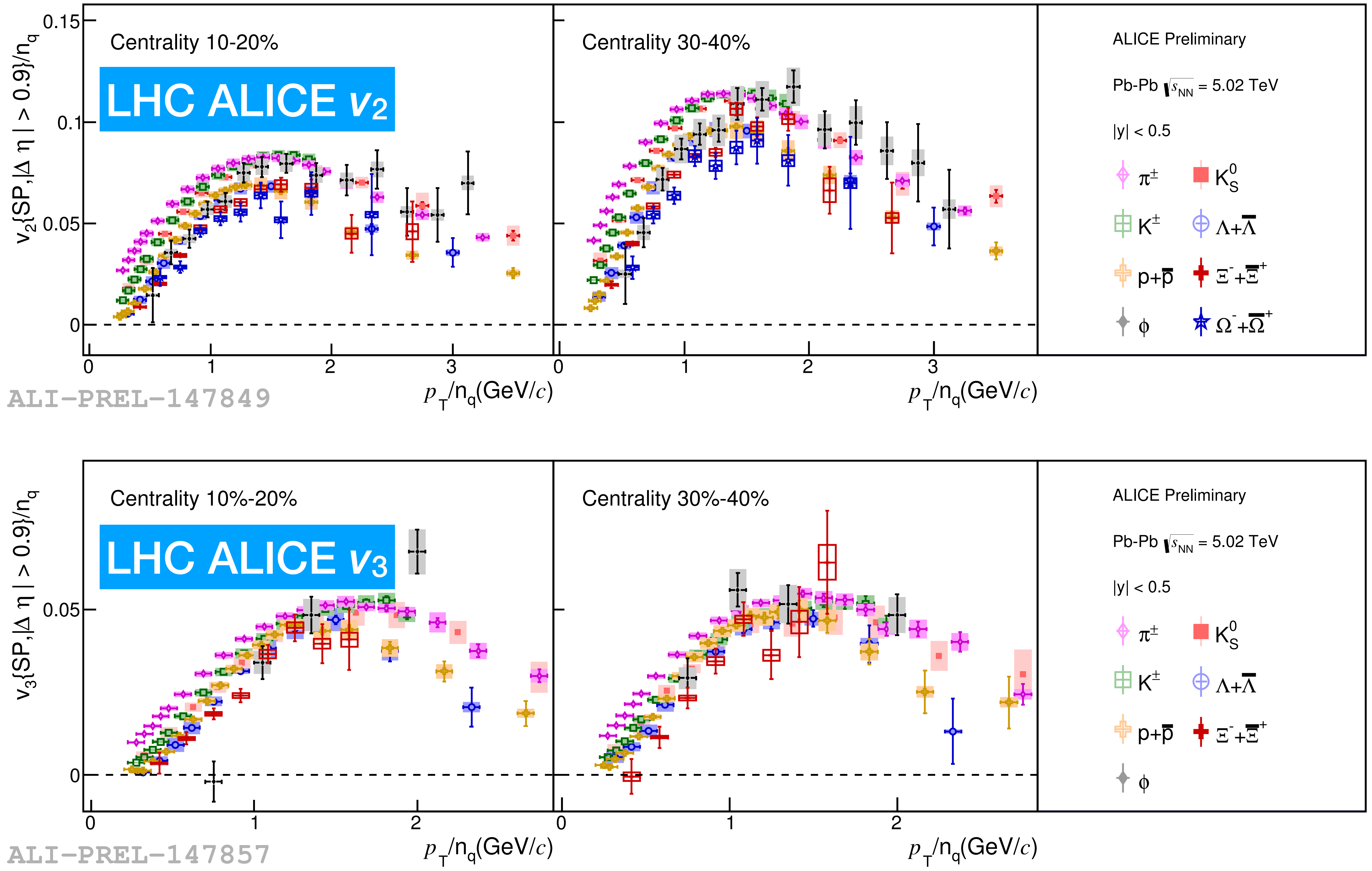


- Quantify anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP}) — coefficients v_2, v_3, v_4… v_n
- Elliptic flow (v_2): spatial anisotropy — pressure gradients leads to momentum anisotropy — hydrodynamics
- Higher order flow: bring additional constraints on the initial conditions, η/s, EoS, freeze-out conditions…

Azimuthal anisotropy

STAR *Phys. Rev. Lett.* 116 (2016) 062301





- Flow is dominated by hydrodynamic evolution of the QCD medium
- At RHIC and LHC: $1 < (\eta/s)_{QGP} \lesssim 0.2$ — prefect fluid

Hard probes: medium tomography

- Produced in the early stage of heavy-ion collisions

  ➡ Experience the full evolution of the QCD medium, and interact with particles in the medium and loss energy

- Efficient probes for understanding the transport properties of the medium

Nuclear modification factor: R_{AA} — sensitive to the presence of the medium

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

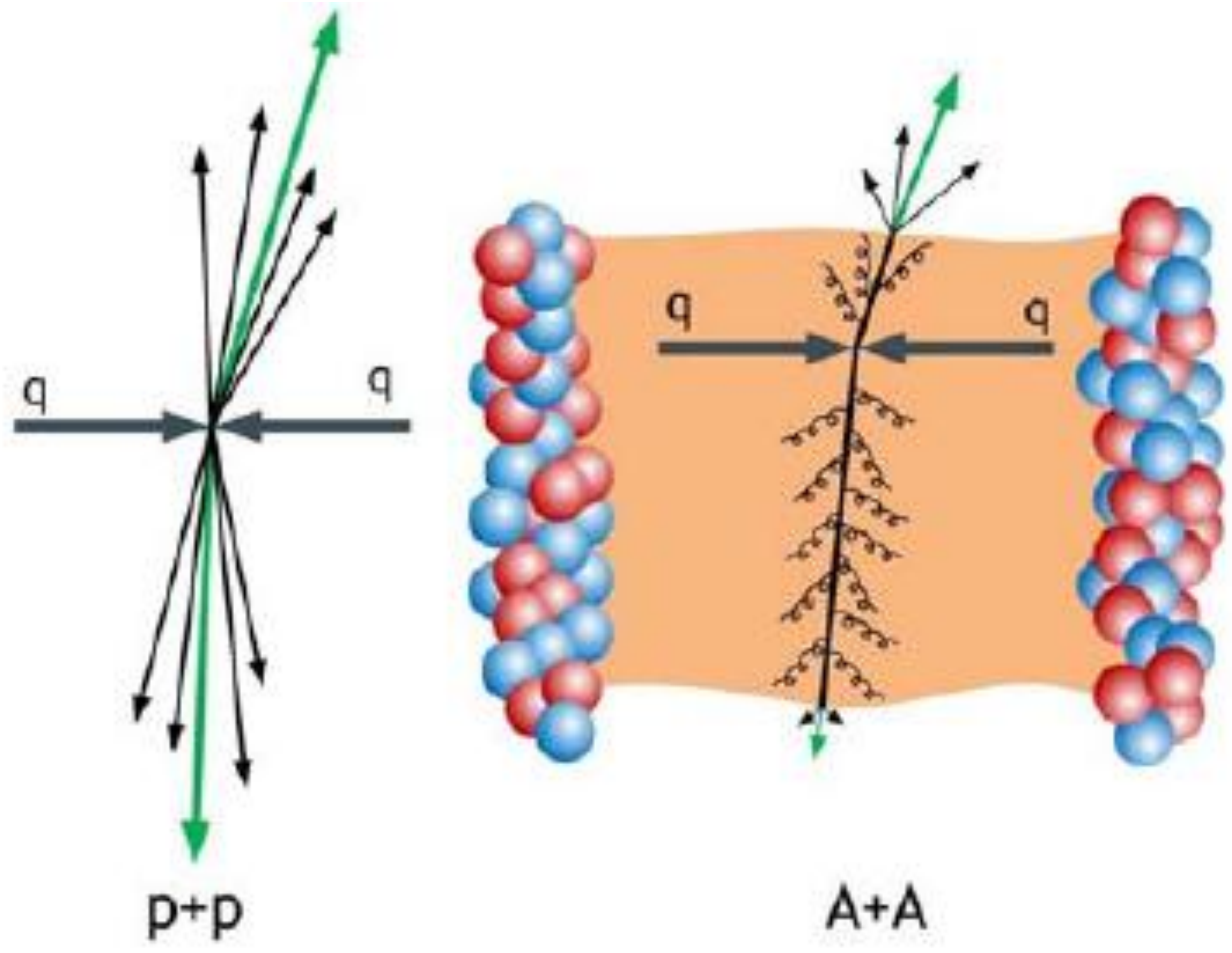
QCD medium

QCD vacuum

- R_{AA} = 1, if there is no medium modification

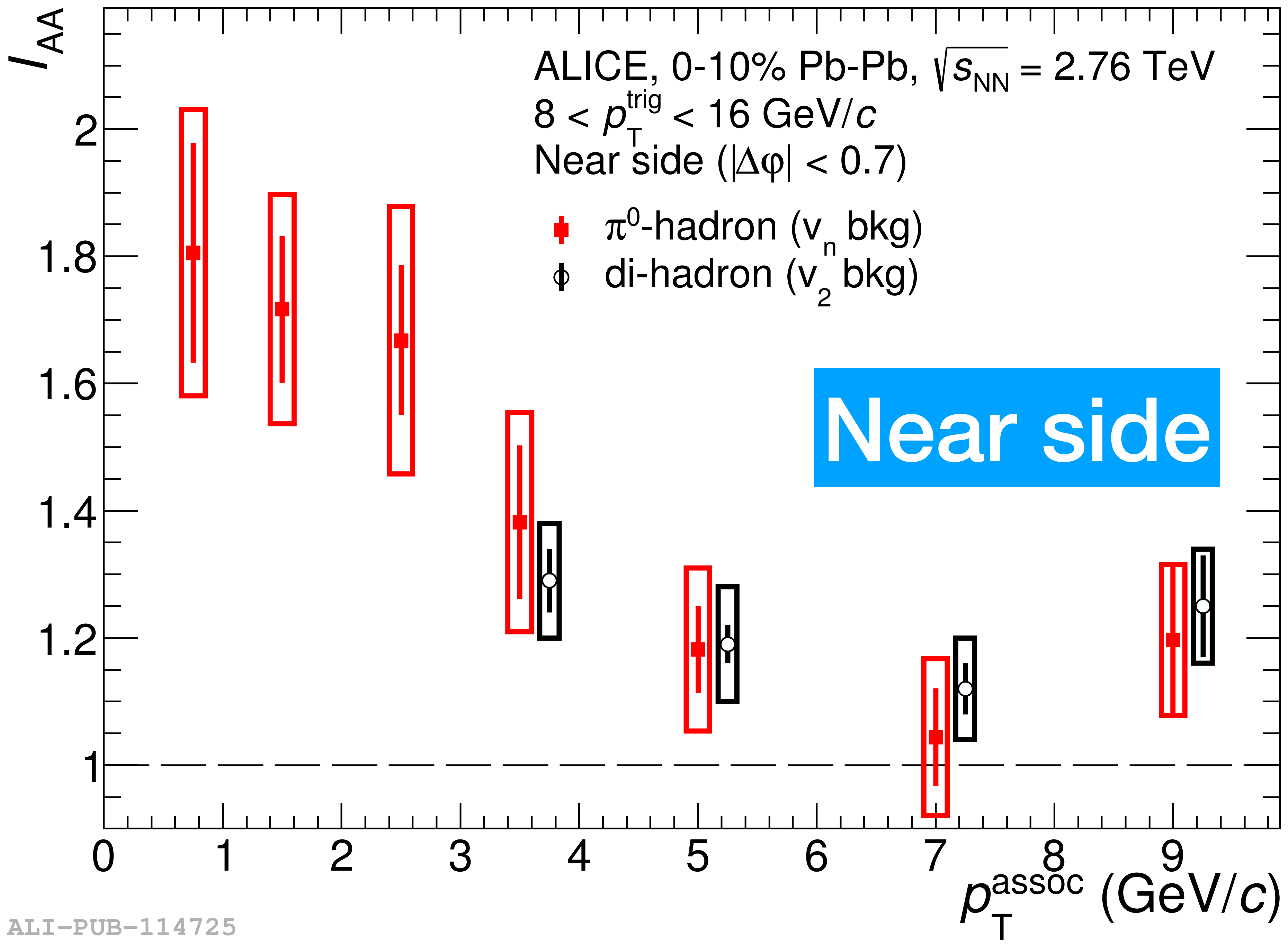
Shopping list

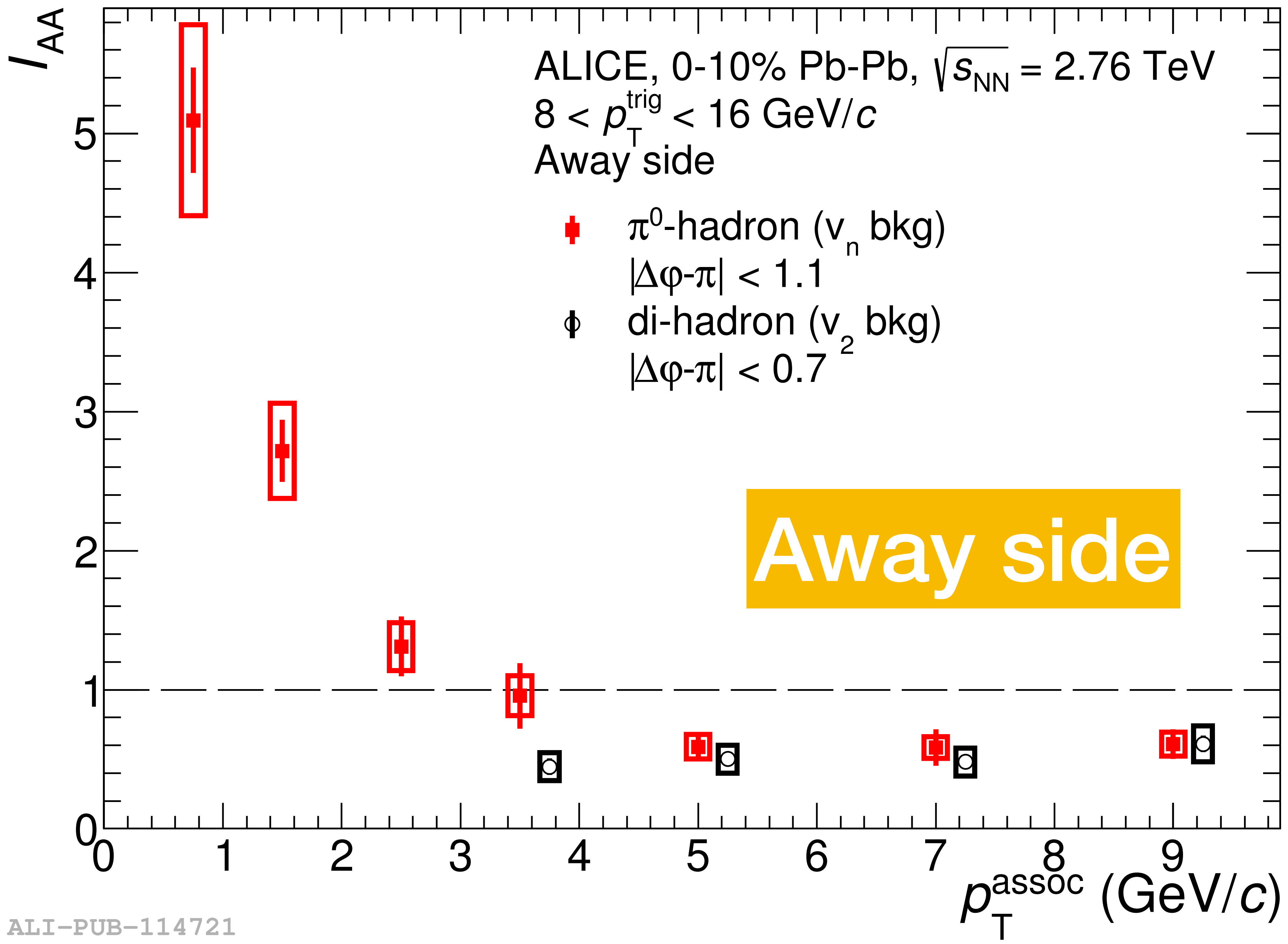
- High p_T particles, jets
- Open heavy flavours, quarkonia (J/ψ, ψ’… Υ…)

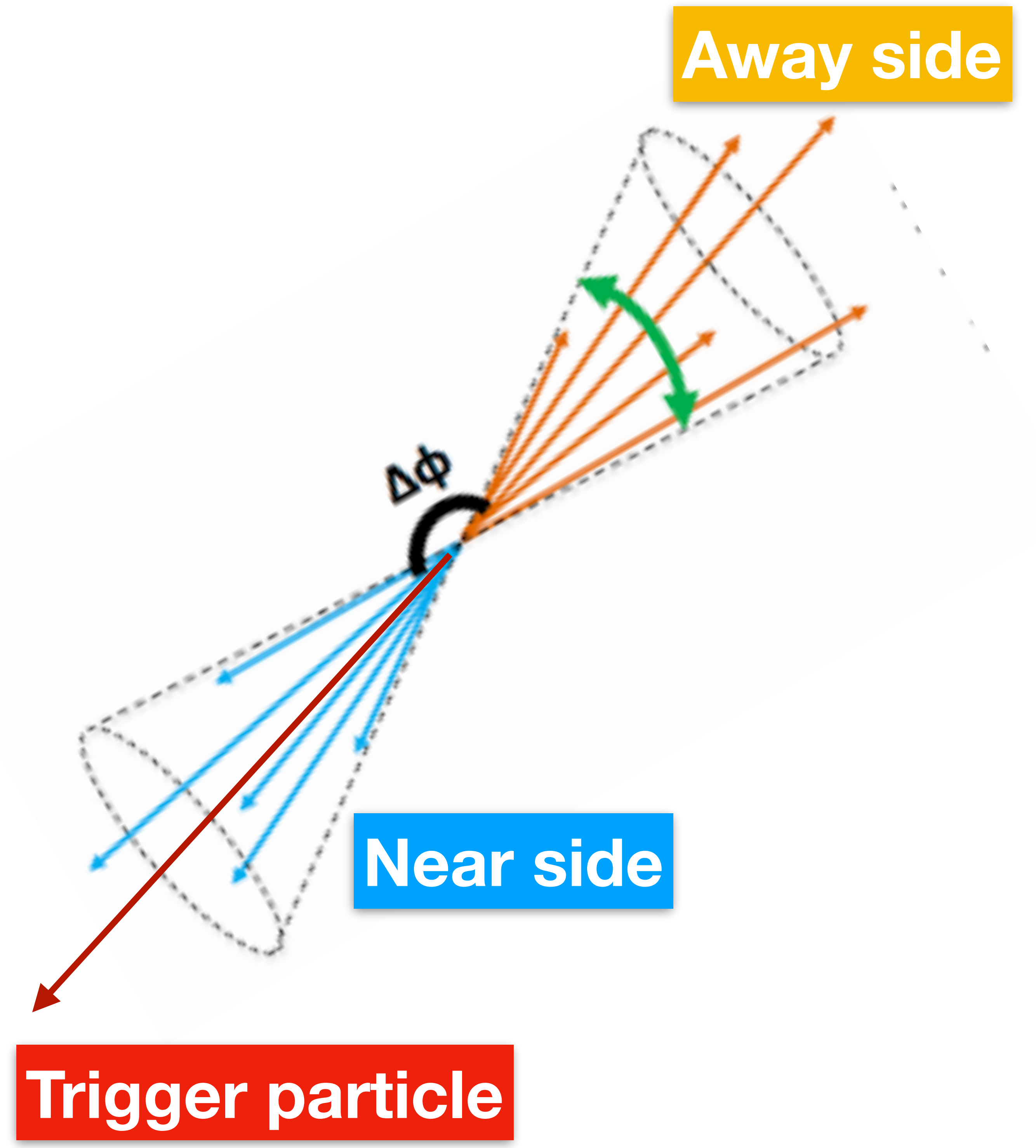


π^0-hadron correlations

ALICE *Phys. Lett.* **B763** (2016) 238

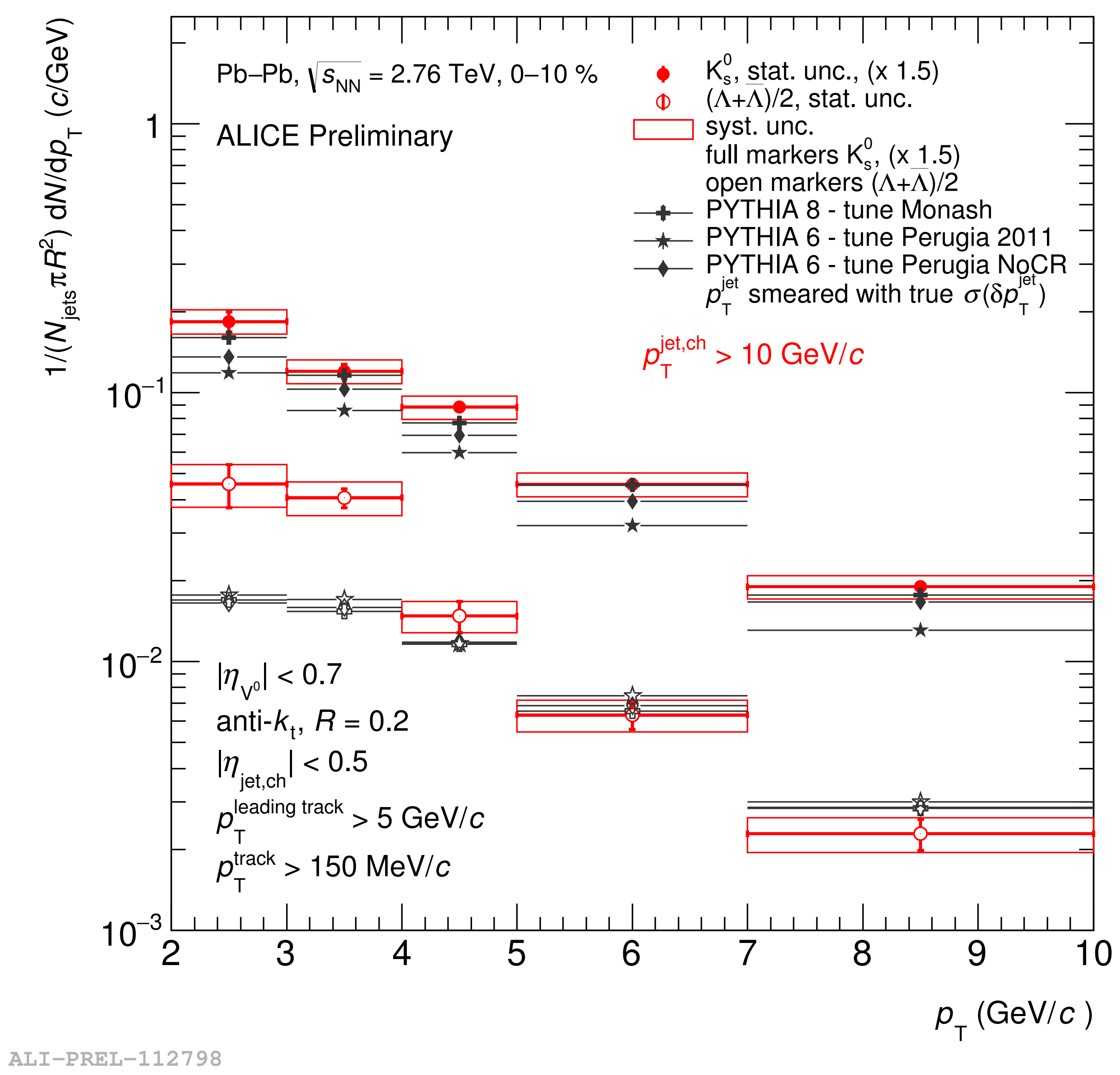


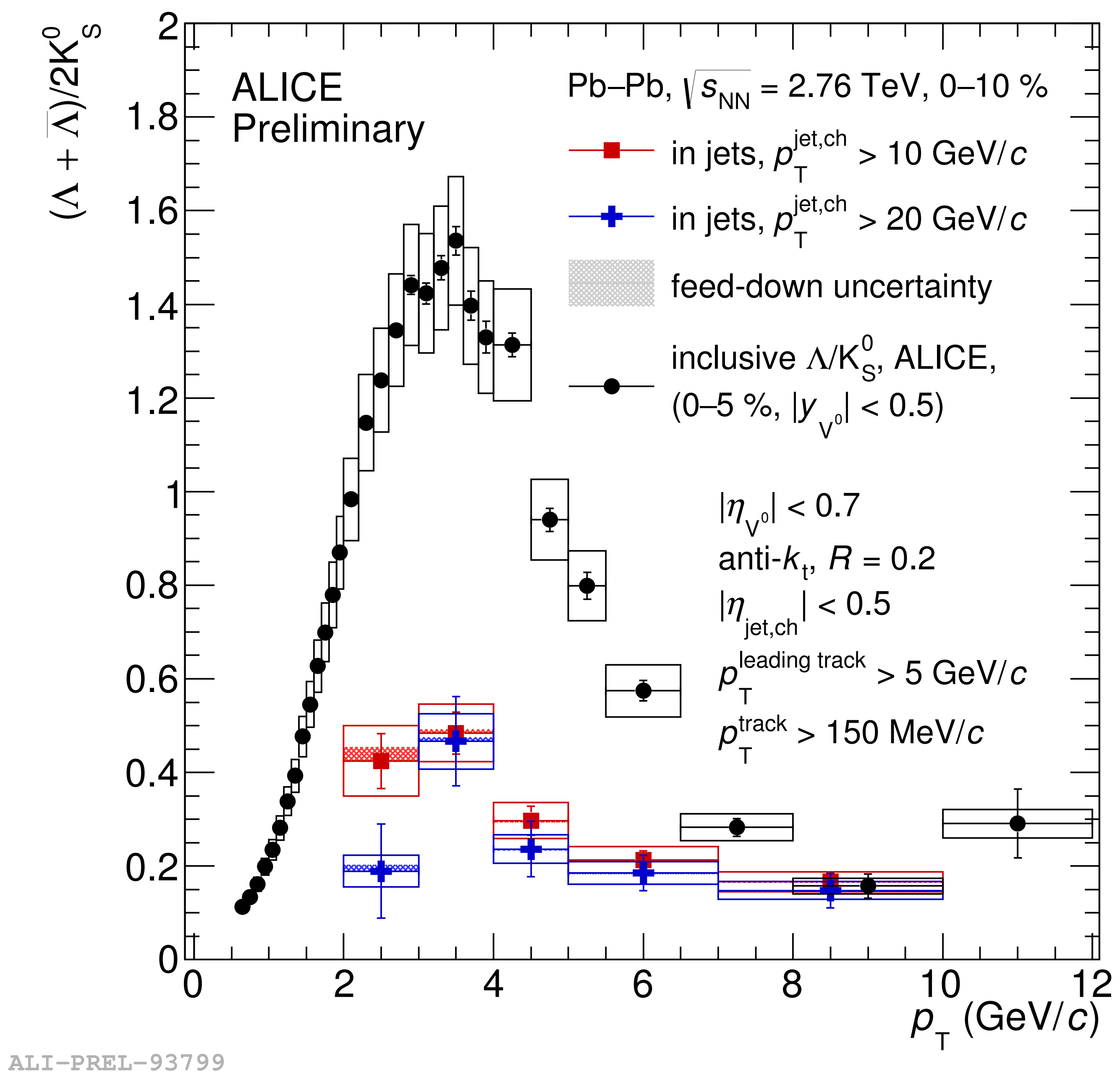




- Measurement has been extended to lower p_T w. r. t. di-hadron correlations
  - ➡ Near side enhancement: modification of jet fragmentation, quark- / gluon-jet ratio and / or the bias on parton p_T spectra…
  - ➡ Away side suppression at high p_T: hard parton energy loss
  - ➡ Away side enhancement at low p_T: favor the jet-medium excitation scenario

Particle production in jets

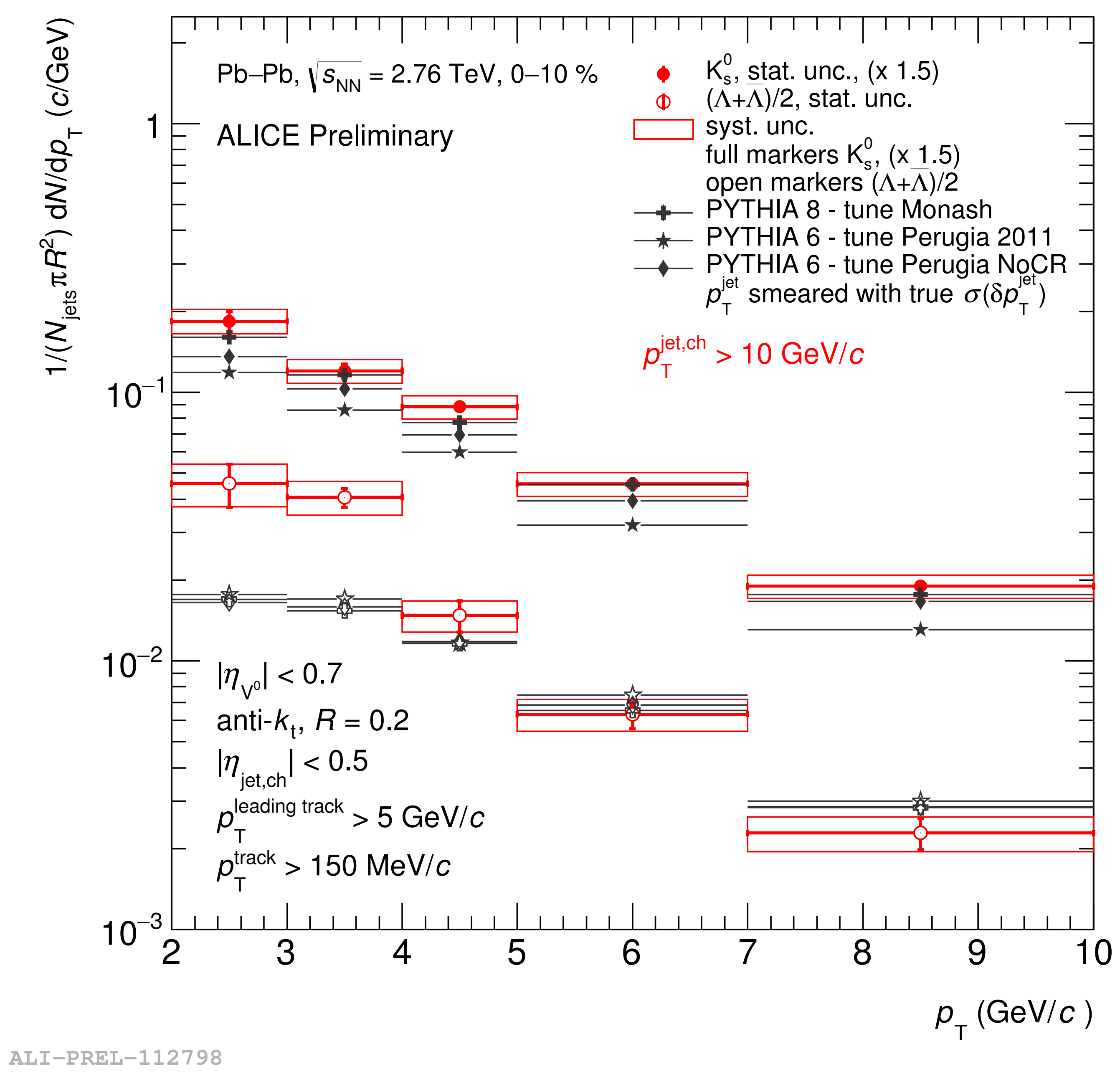


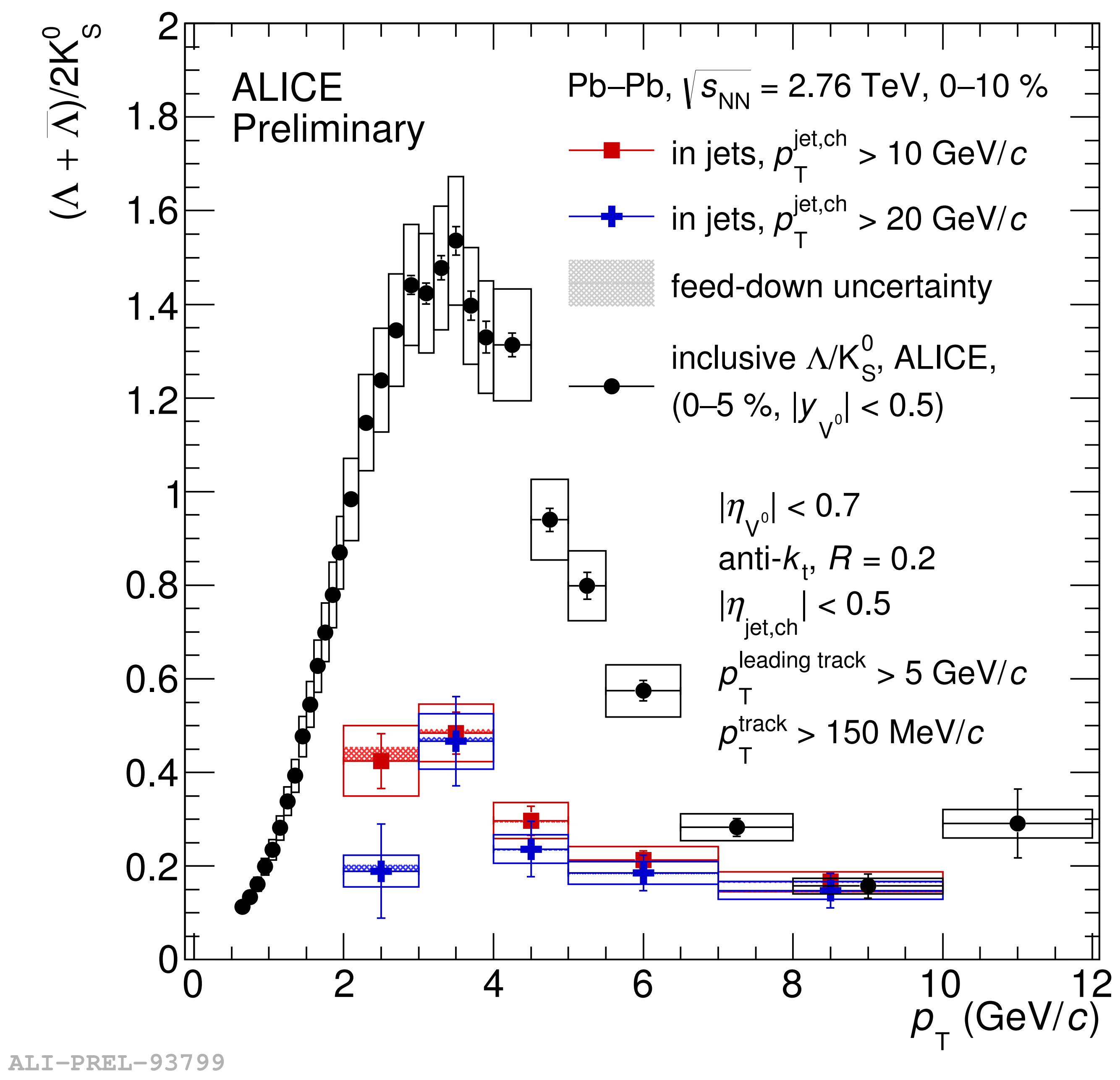


- Reference: PYTHIA smeared with background fluctuations
- K_S^0: consistent with PYTHIA within errors — hint of low-p_T enhancement
- Λ: data significantly higher than PYTHIA at low p_T

- Investigating medium modified fragmentation, effect seems to differ between baryons and mesons — further constraints on reference from data needed

Particle production in jets





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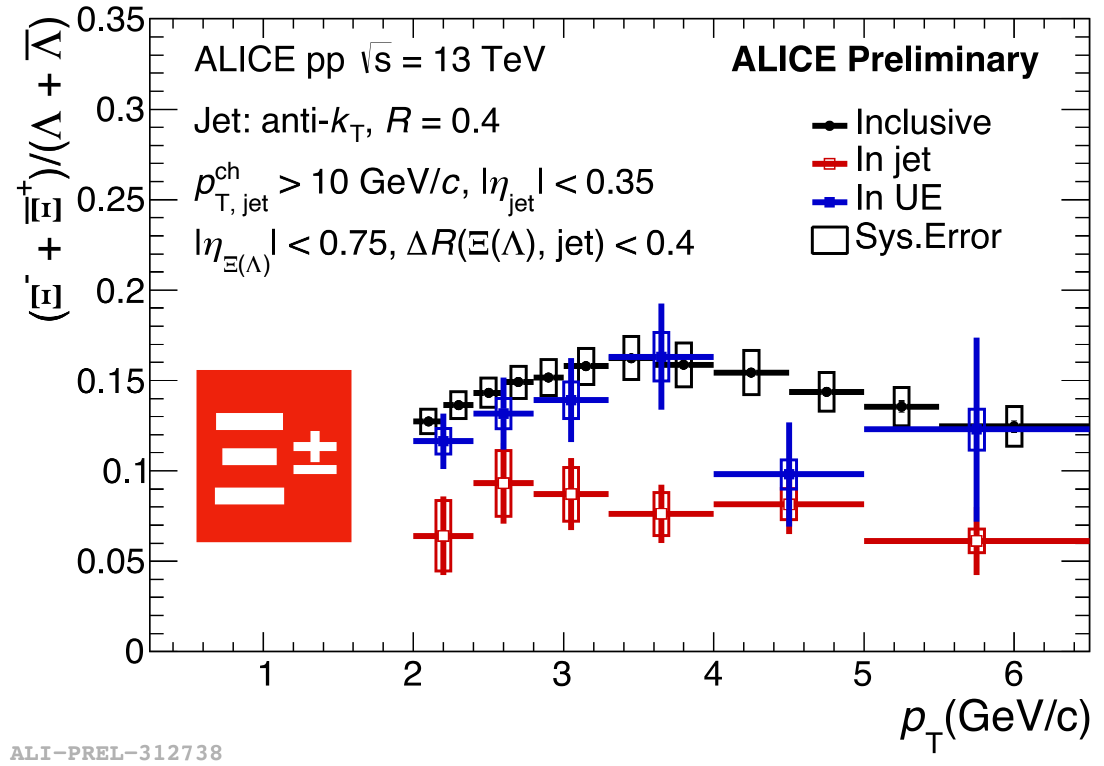
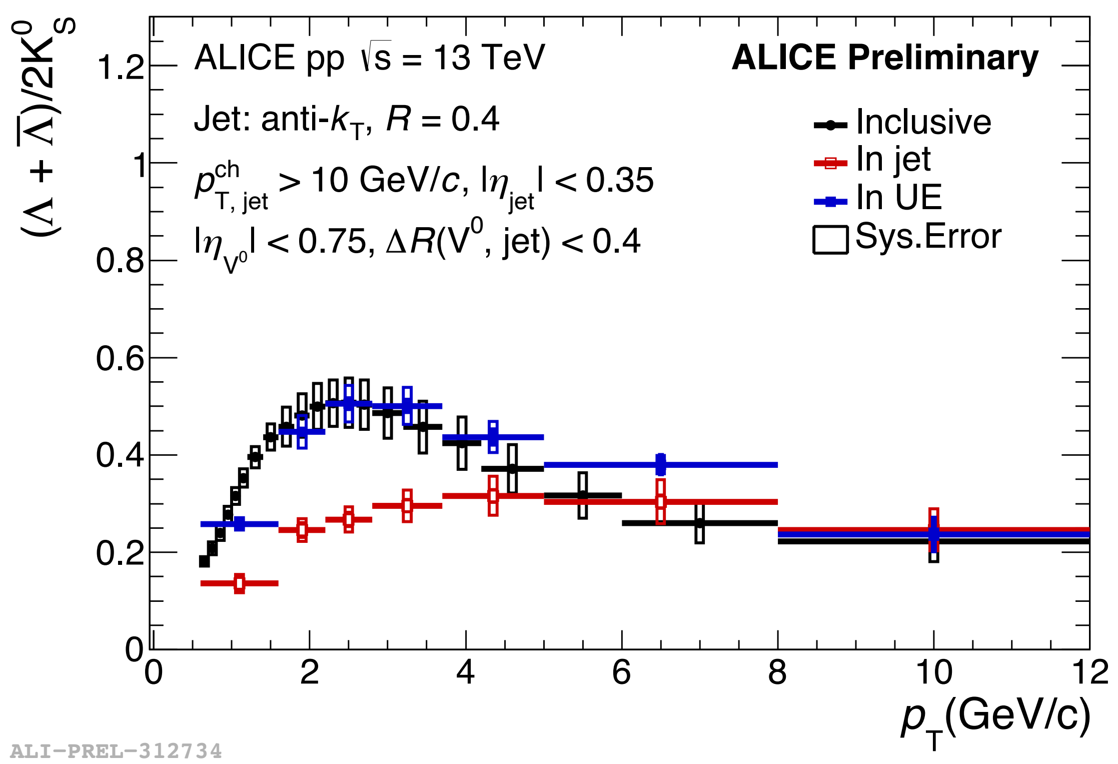
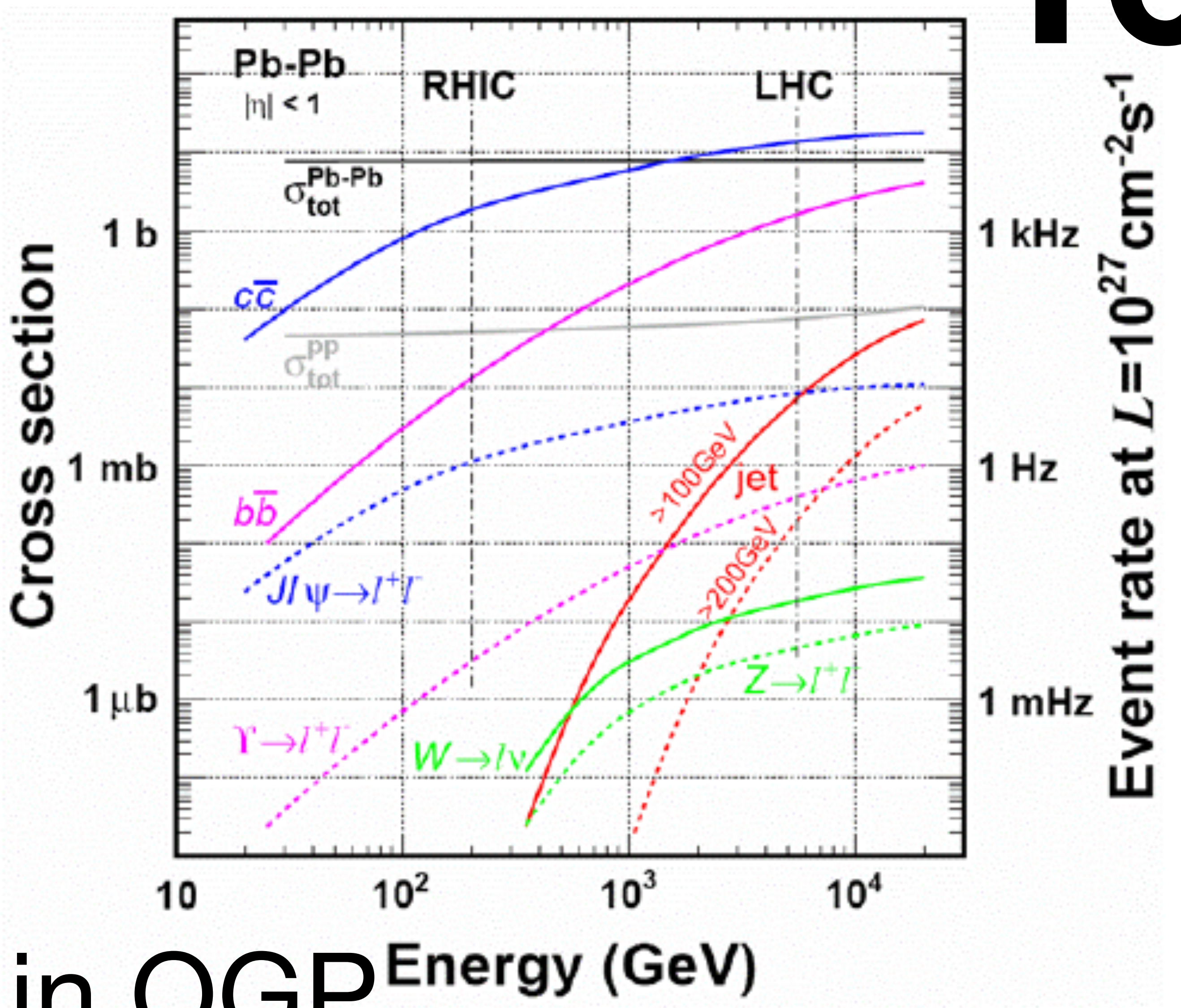




NEW ALICE LHC RUN-II data

- Higher statistics, precise measurements
- Extend to multi-strangeness sector

Open heavy-flavour production



Open heavy-flavours (open charm and beauty particles)

- R_{AA}: Radiative energy loss vs. collisional energy loss
  - ➡ Mass and color charge dependence
- Elliptic flow
  - ➡ Low-p_T: initial conditions and degree of thermalization of HF in QGP
  - ➡ High-p_T: path-length dependence of HF in-medium energy loss

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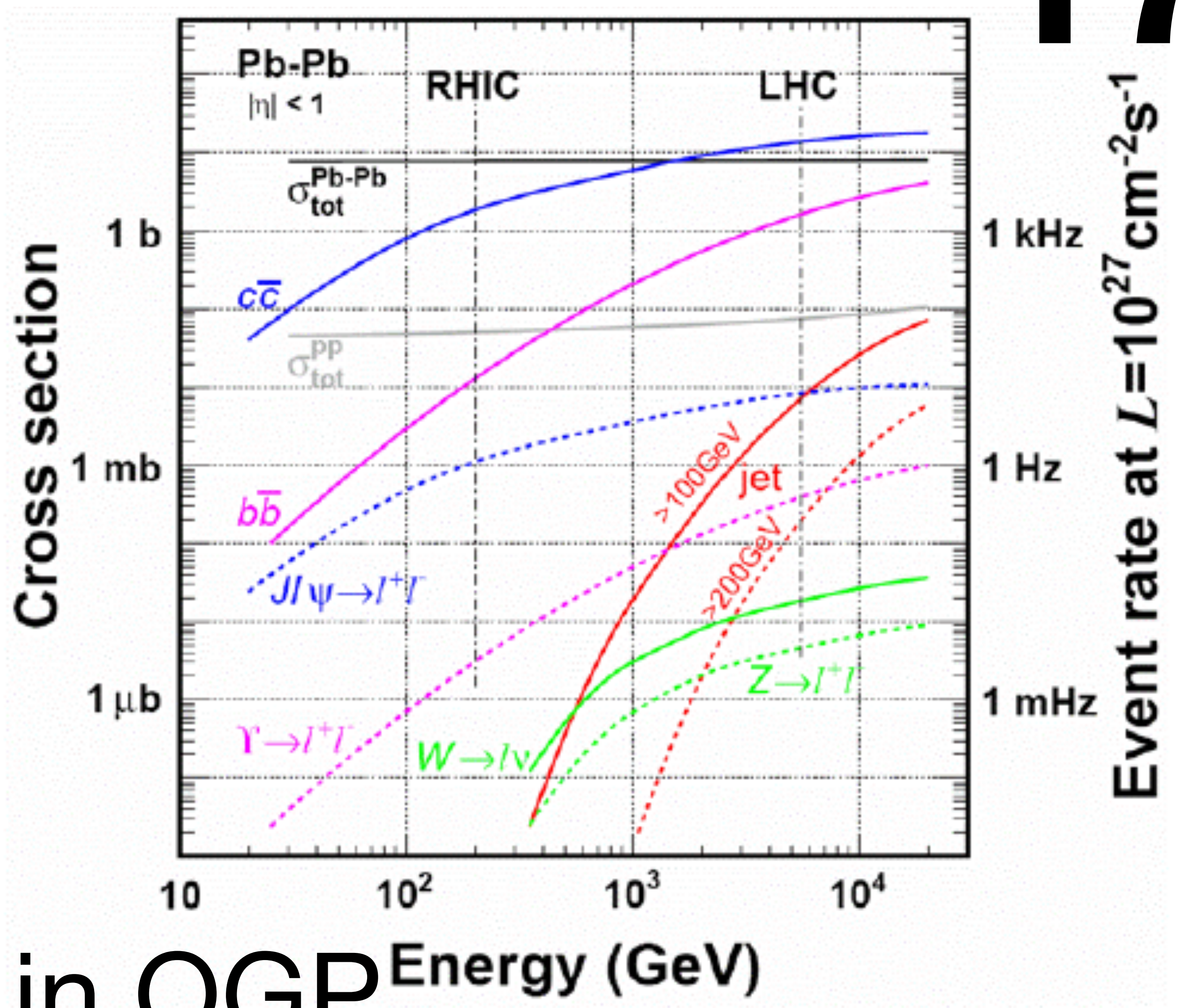
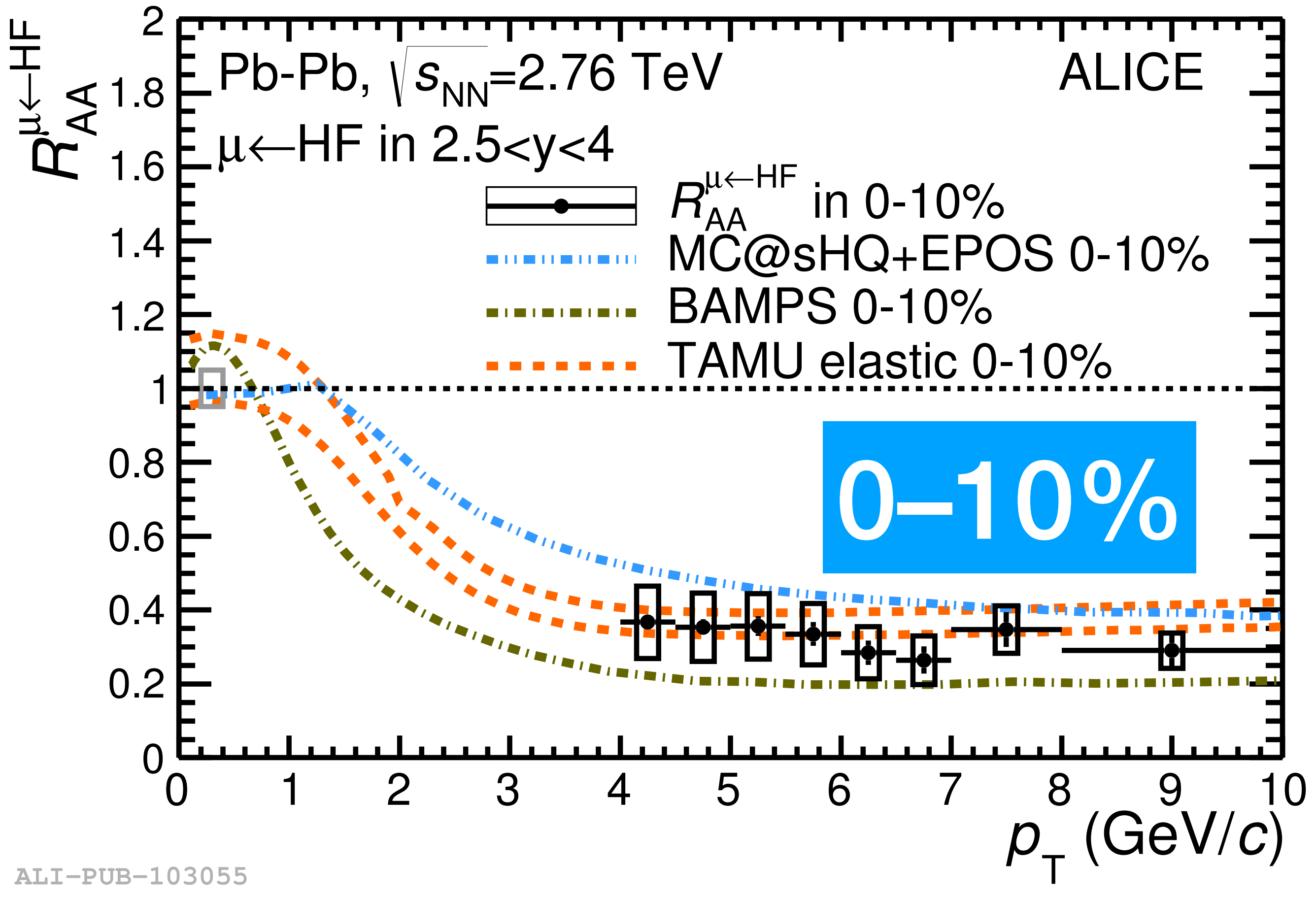
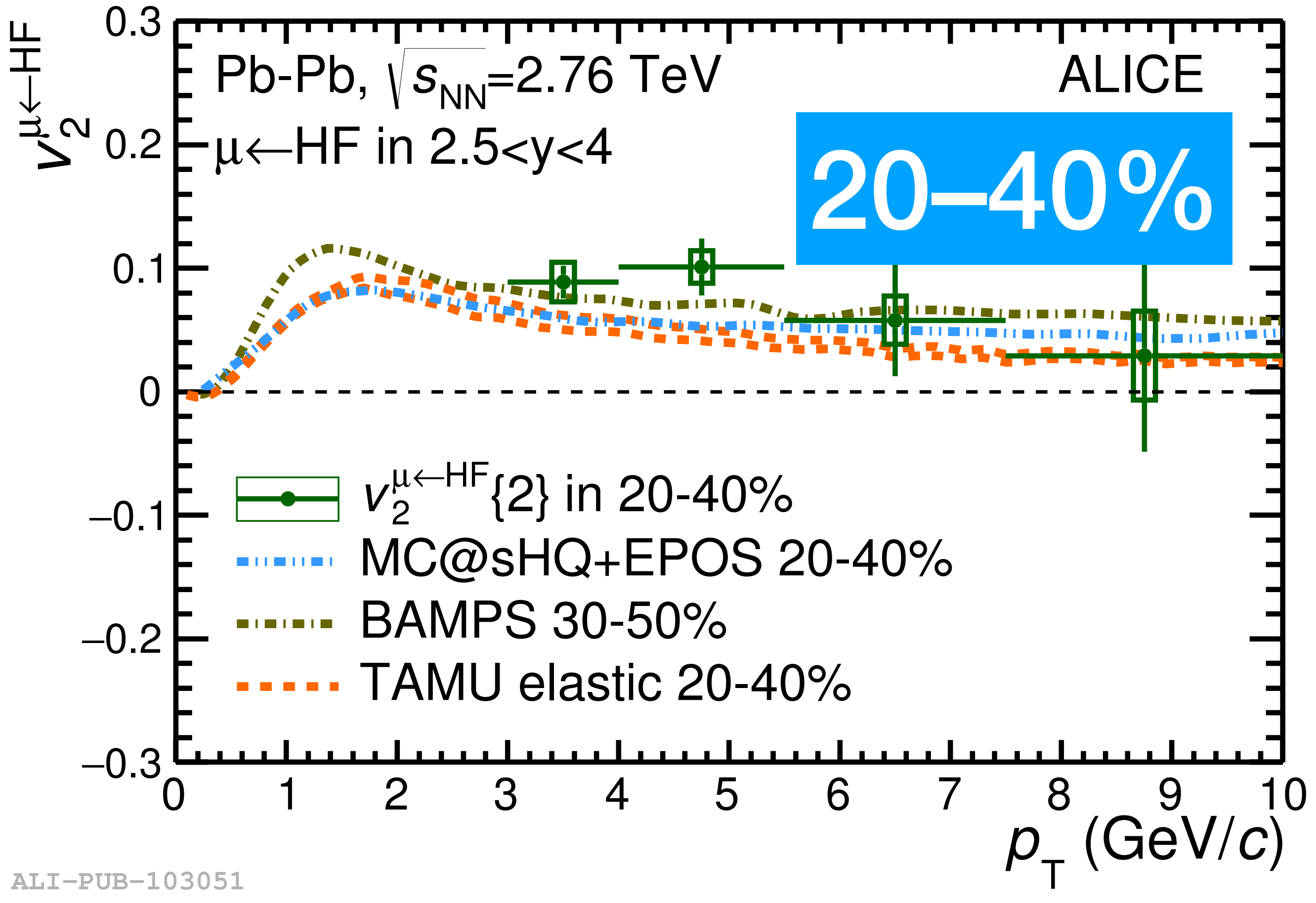


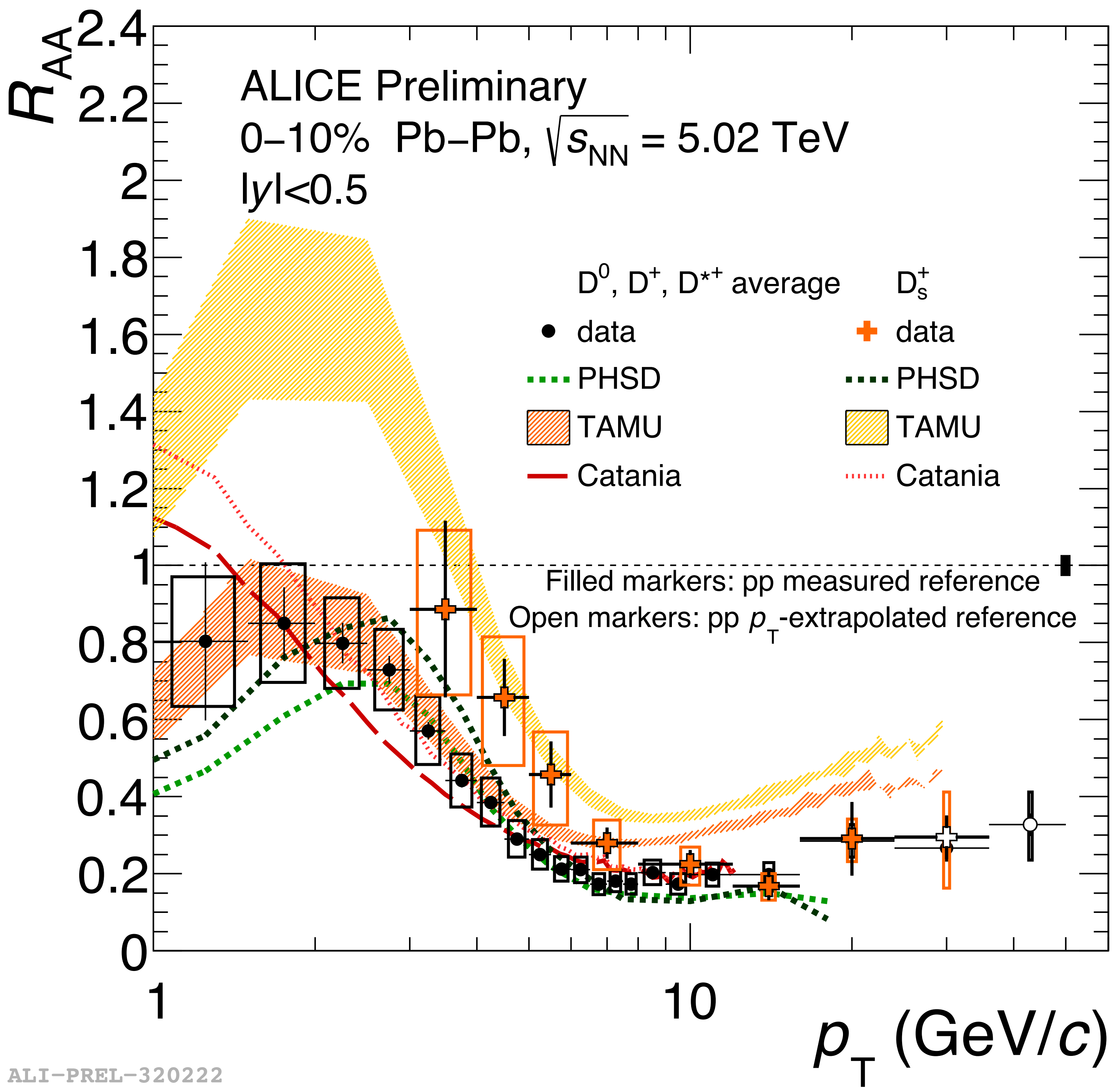
ALICE *Phys. Lett.* **B753** (2016) 41, *Phys. Rev. Lett.* **109** (2012) 112301

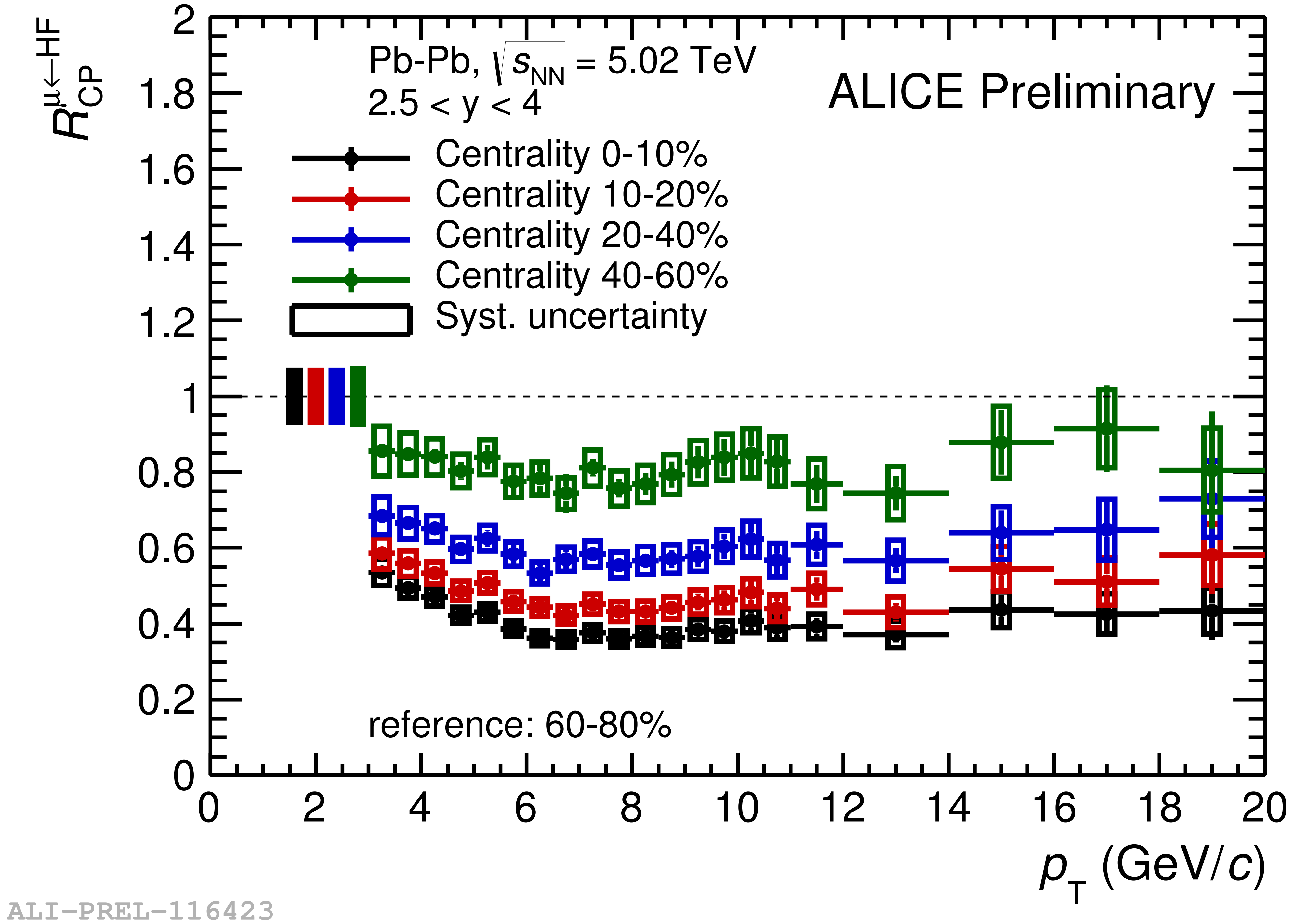




- HF decay muons in $2.5 < y < 4$
- Strong suppression in central collisions
- Non-zero flow in semi-central collisions
- Heavy quarks undergone significant interaction in the QCD medium

Open heavy-flavour production

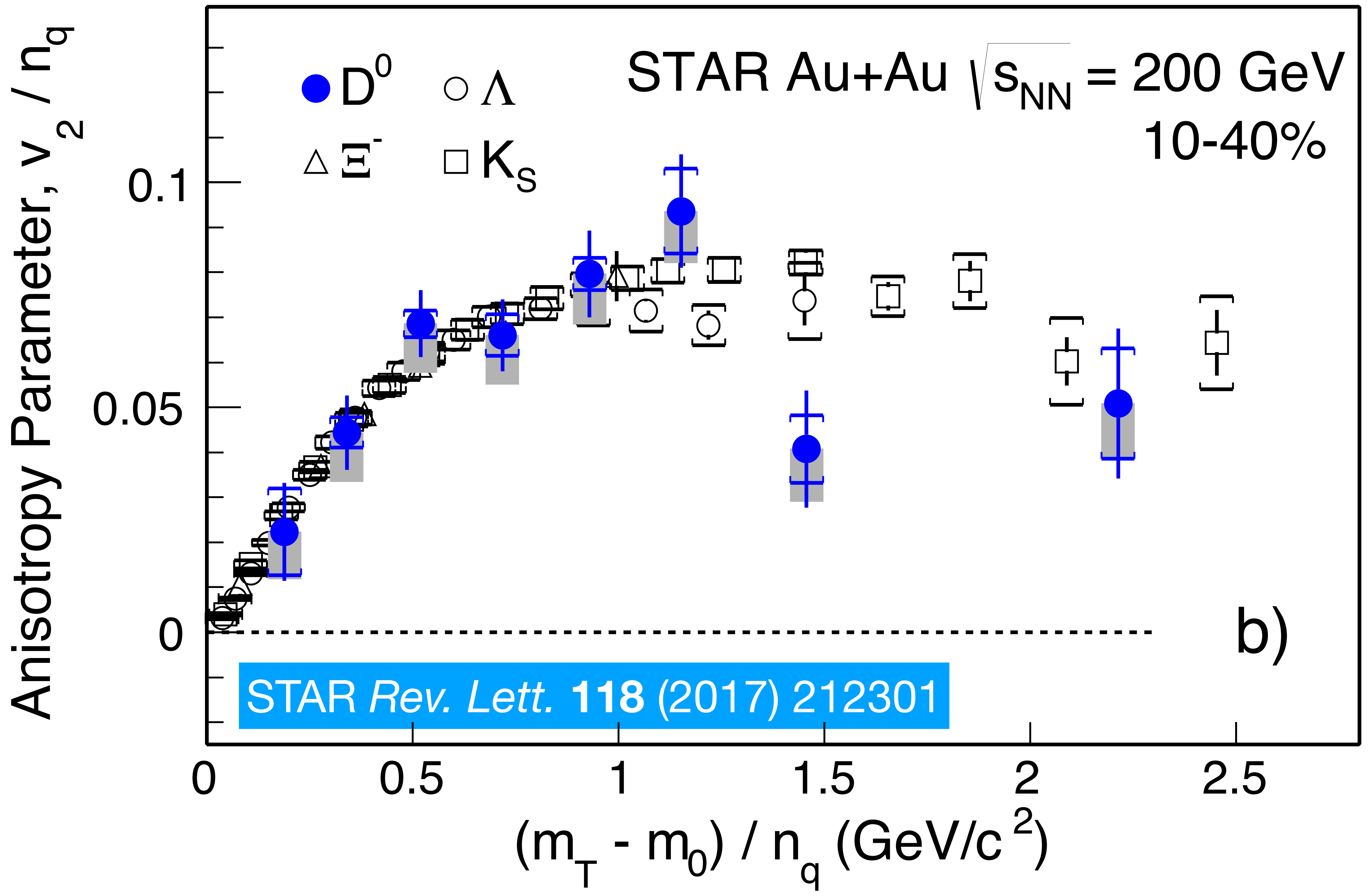


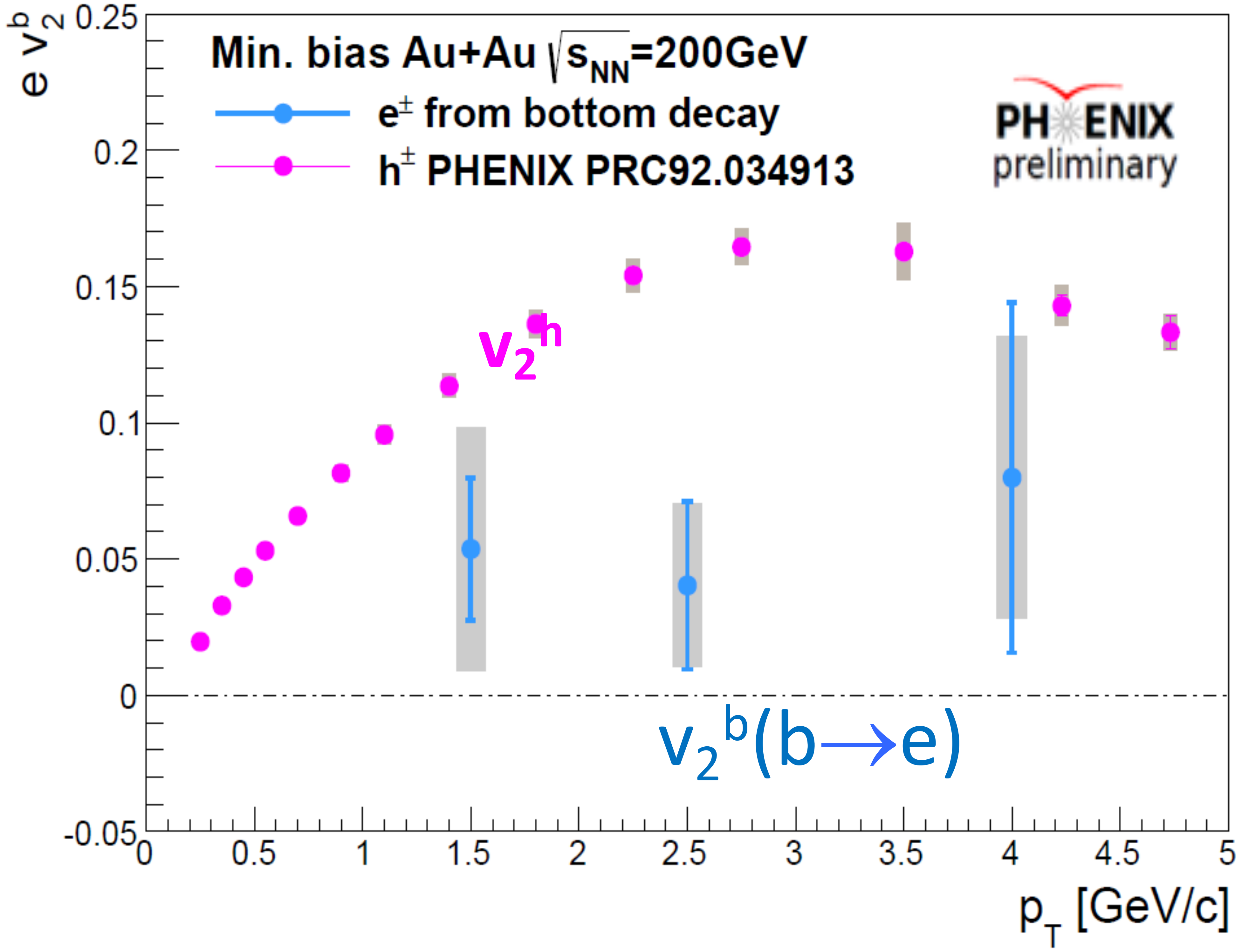


NEW ALICE LHC RUN-II data

- Higher statistics, precise measurements
- R_{AA} of D mesons: collisional and radiative energy loss, coalescence and realistic medium evolution required to describe data
- HF decay muons: the most precise measurement of b-quark energy loss at high p_T

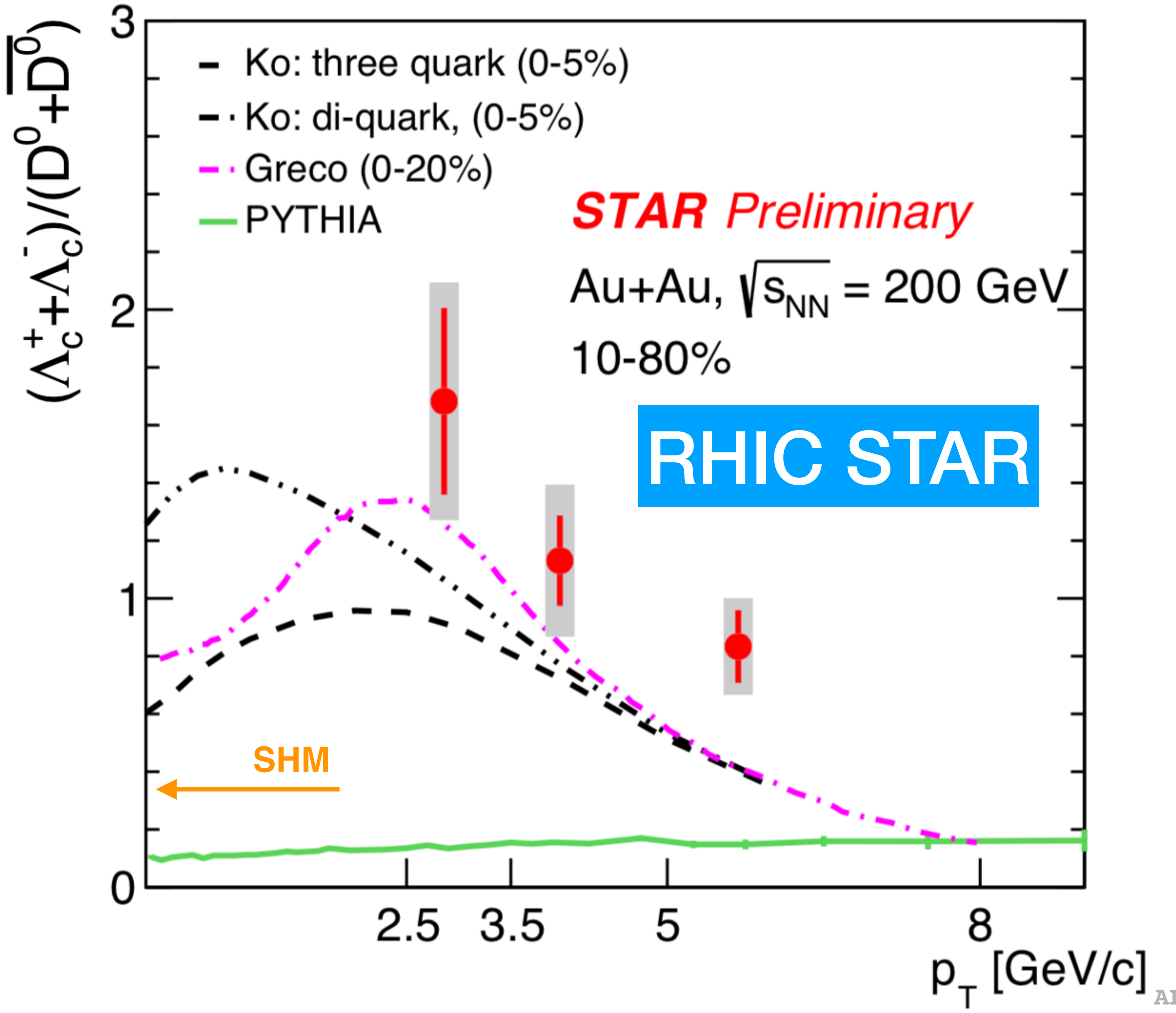
Open heavy-flavour production

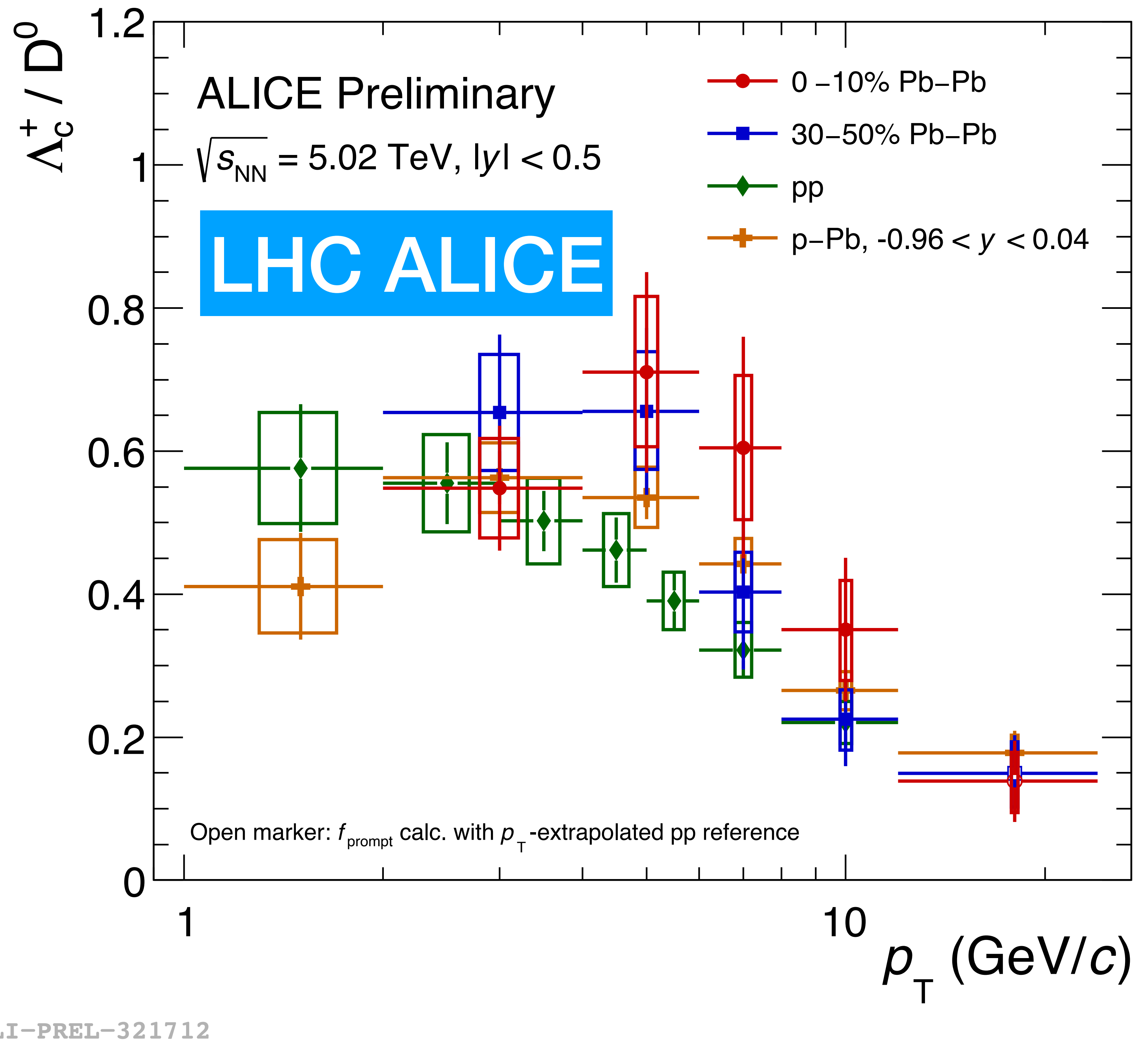




- **STAR** D mesons seem to follow the same number of constituent quarks (NCQ) and kE_T scaling as light hadrons — similar collective motion of charm quarks and light quarks (?) — charm thermalization (?)
  ➡ Measurement has been extended to the strange D mesons (D_s) sector
- **PHENIX** First v2(e←b) measurement at RHIC — hint of bottom flow, too

Charmed baryon production



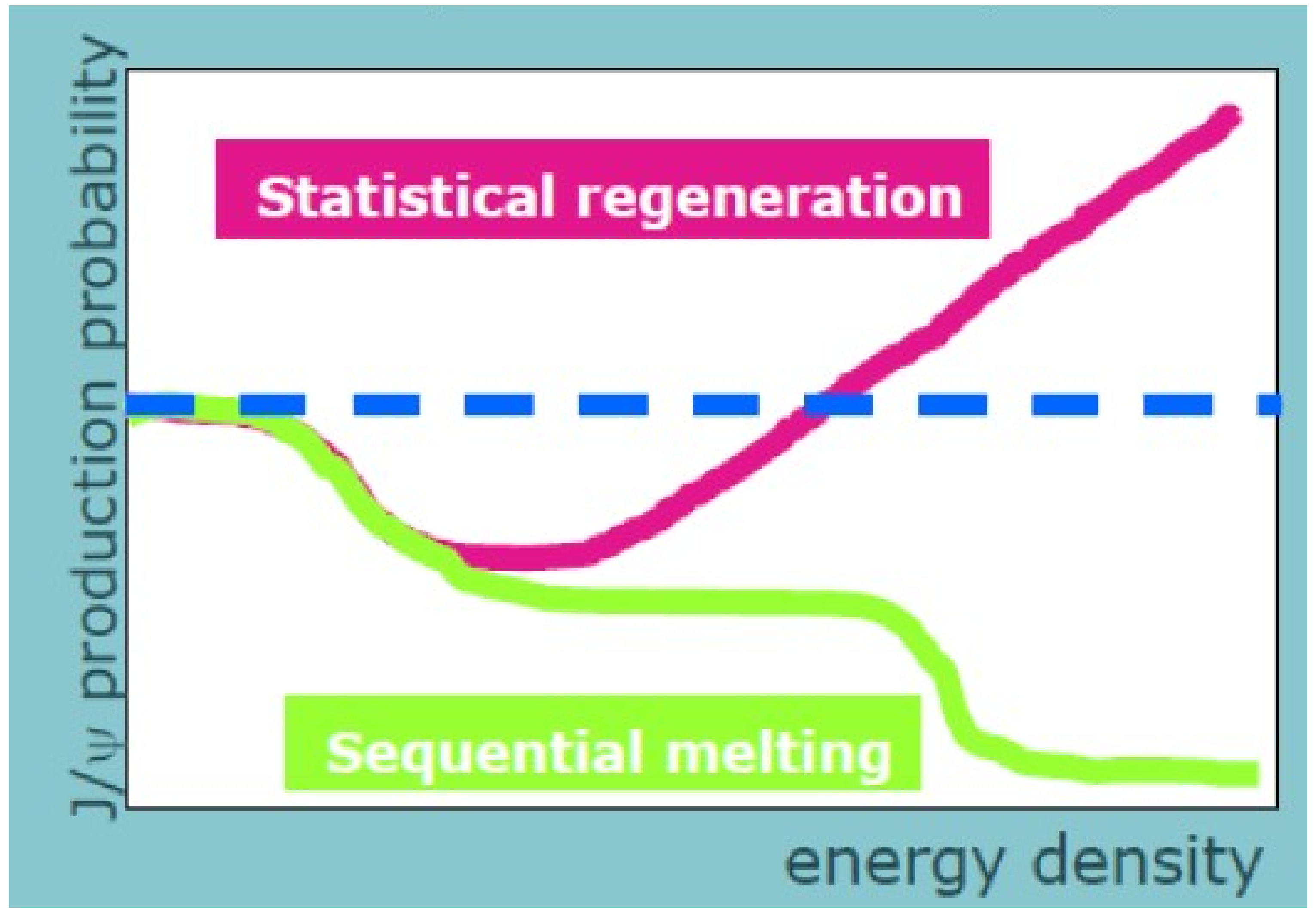


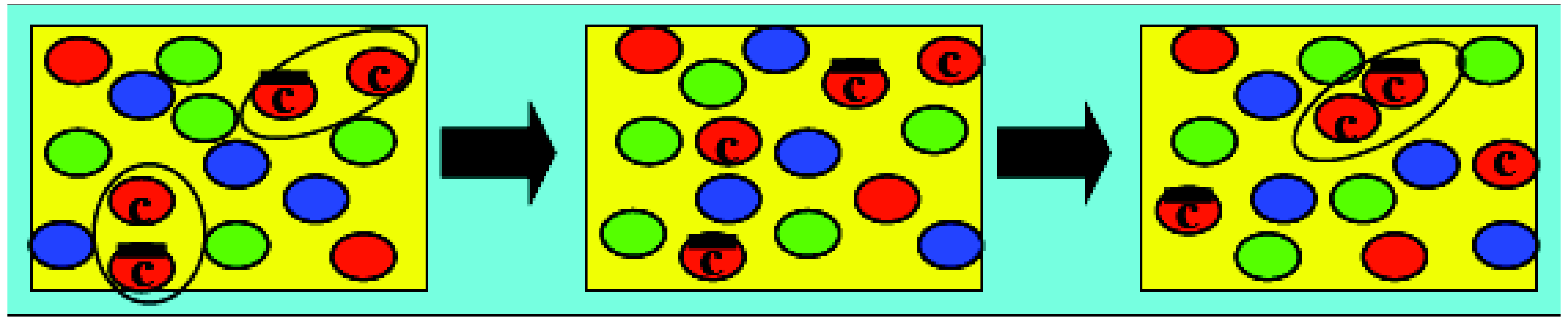
- RHIC: Λ_c / D^0 ratio is strongly enhanced compared to PYTHIA — enhancement increases towards low p_T
- LHC: Hint of higher Λ_c / D^0 ratio in 0-10% Pb–Pb collisions w. r. t. pp collisions
- Understanding of pp data is fundamental: not granted that Λ_c is “enhanced” in the same way in heavy-ion and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

Quarkonia production

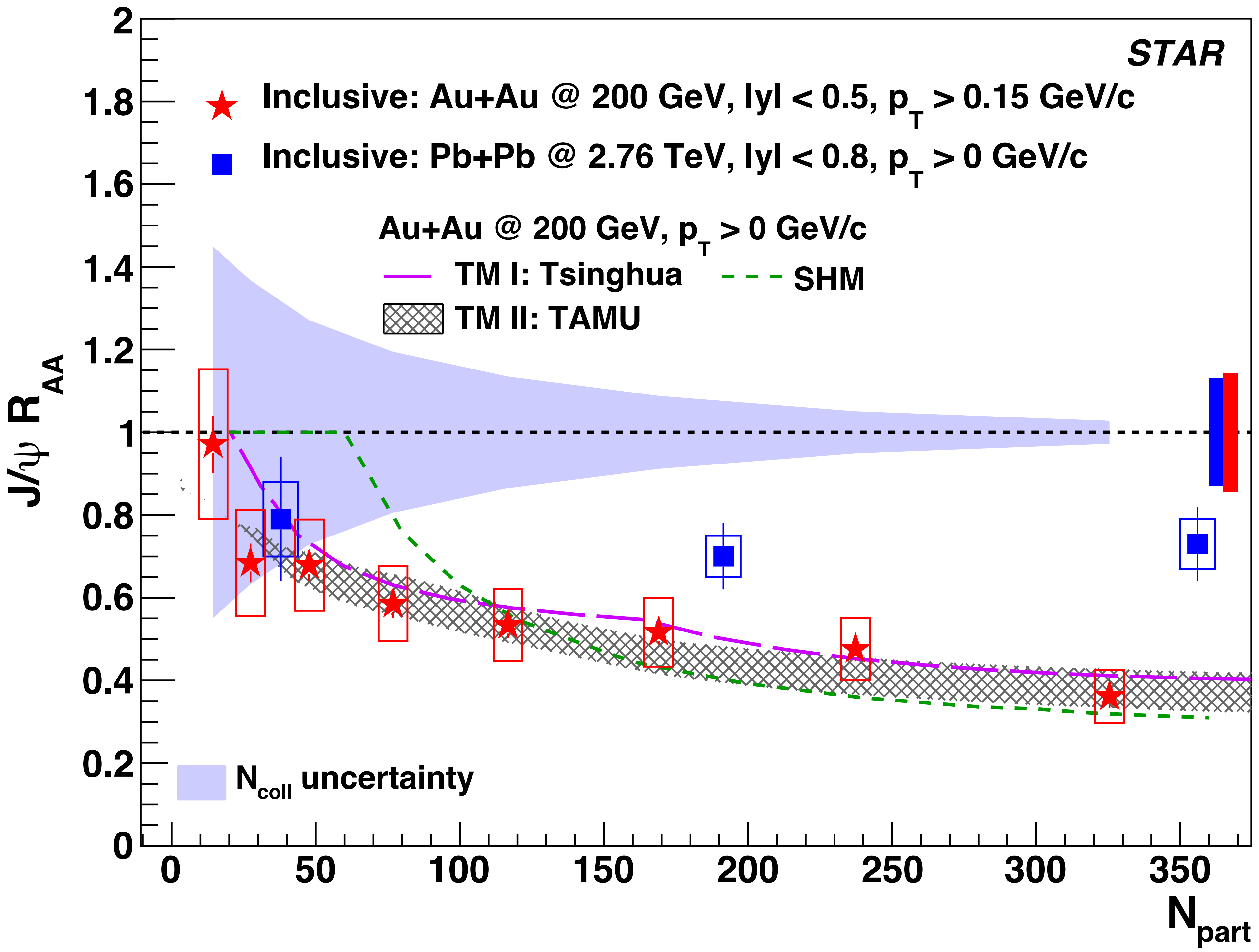
Quarkonia (J/ψ and Υ families)

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





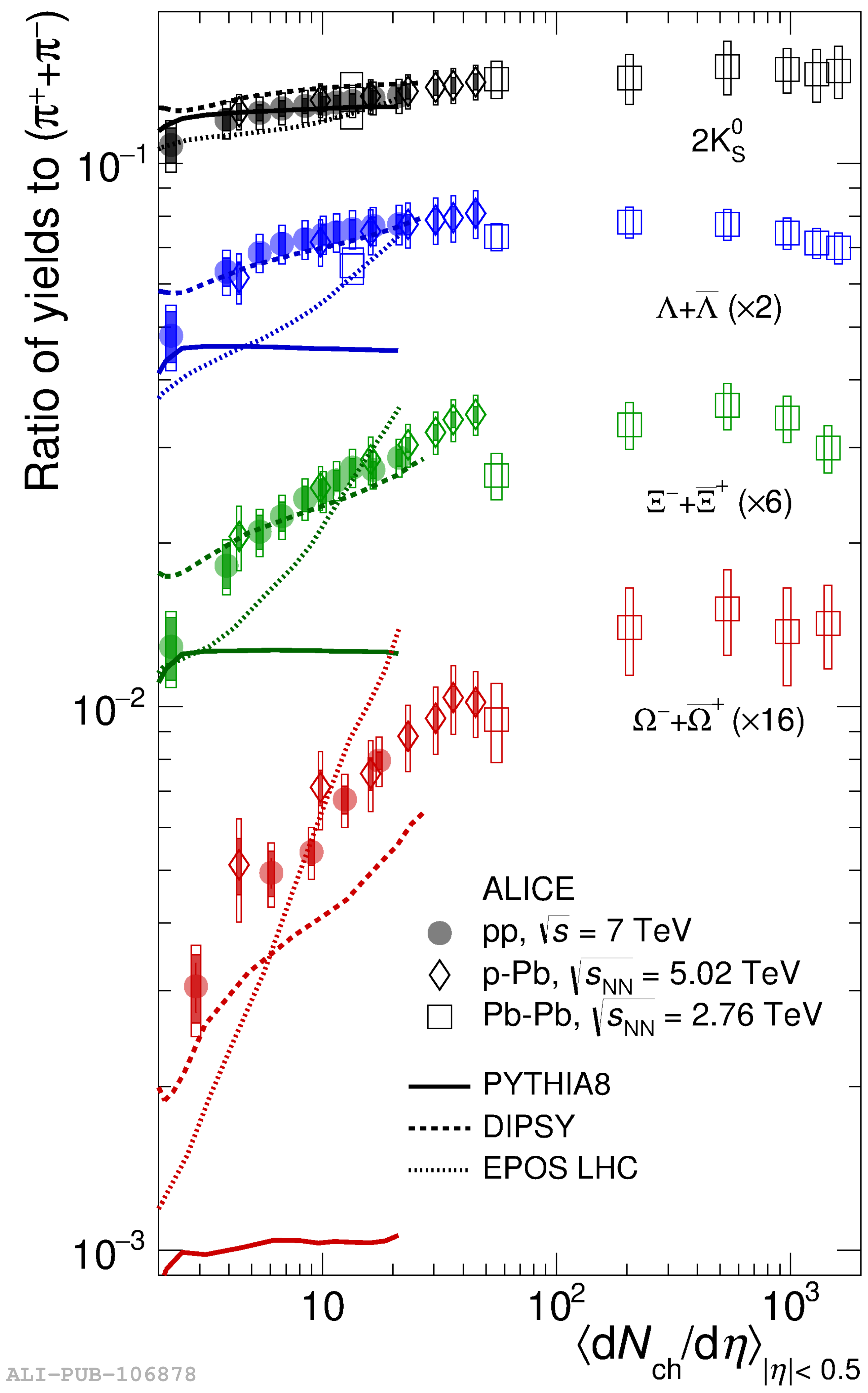
STAR *Phys. Lett.* **B797** (2019) 134917



- 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

The "pandora box" at the LHC

ALICE *Nature Physics* **13** (2017) 535

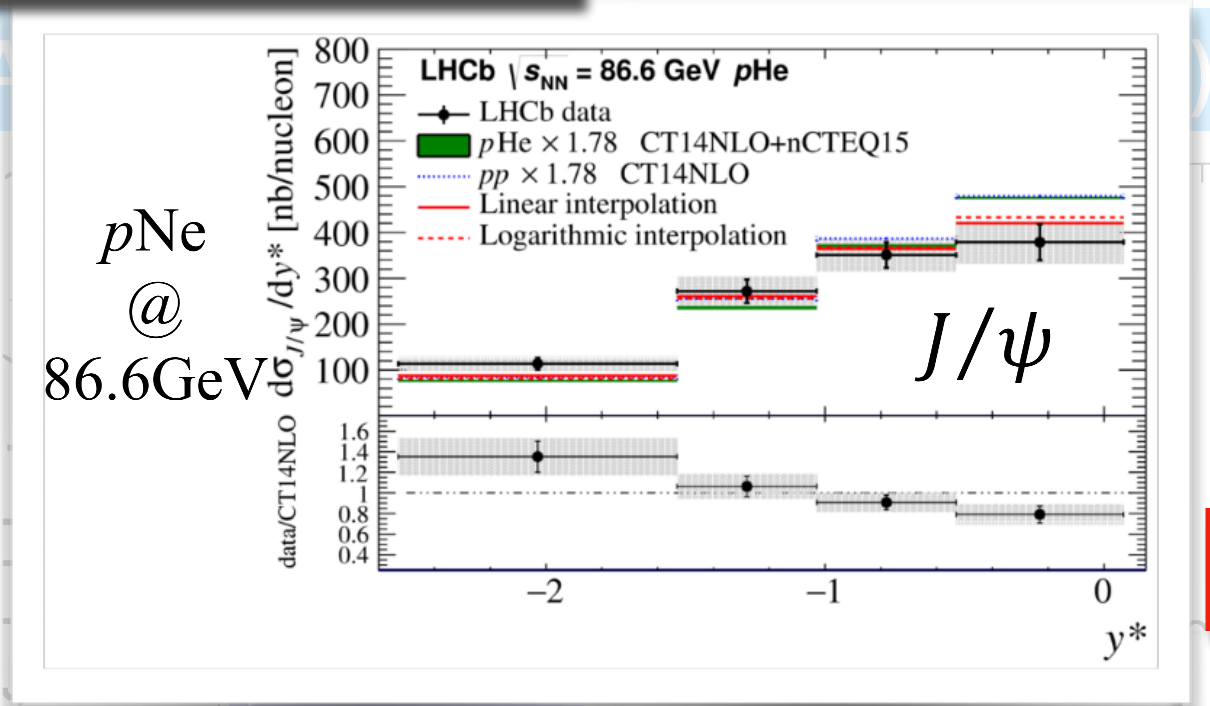


- Smooth evolution of particle production from small to large systems vs charge multiplicity
  - ➡ Strangeness enhancement considered defining feature of heavy-ions — now seen in high-multiplicity pp / p–Pb!

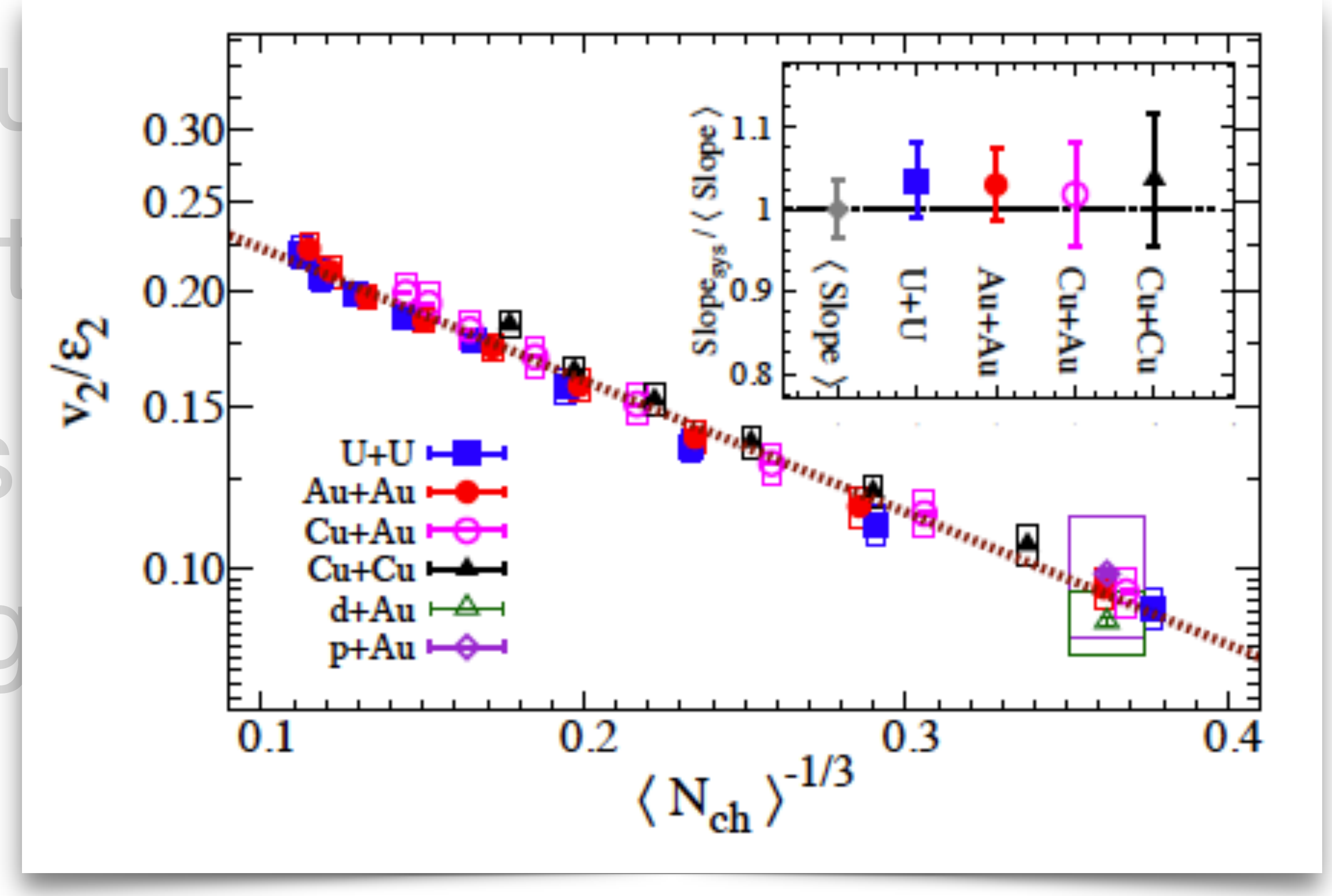
- Where all this comes from?
  - ➡ Initial stages effects?
  - ➡ Better understanding of the observables we use in heavy-ion for small systems?
  - ➡ Common mechanism of particle production?
  - ➡ Final state effects?

Particle production in small systems

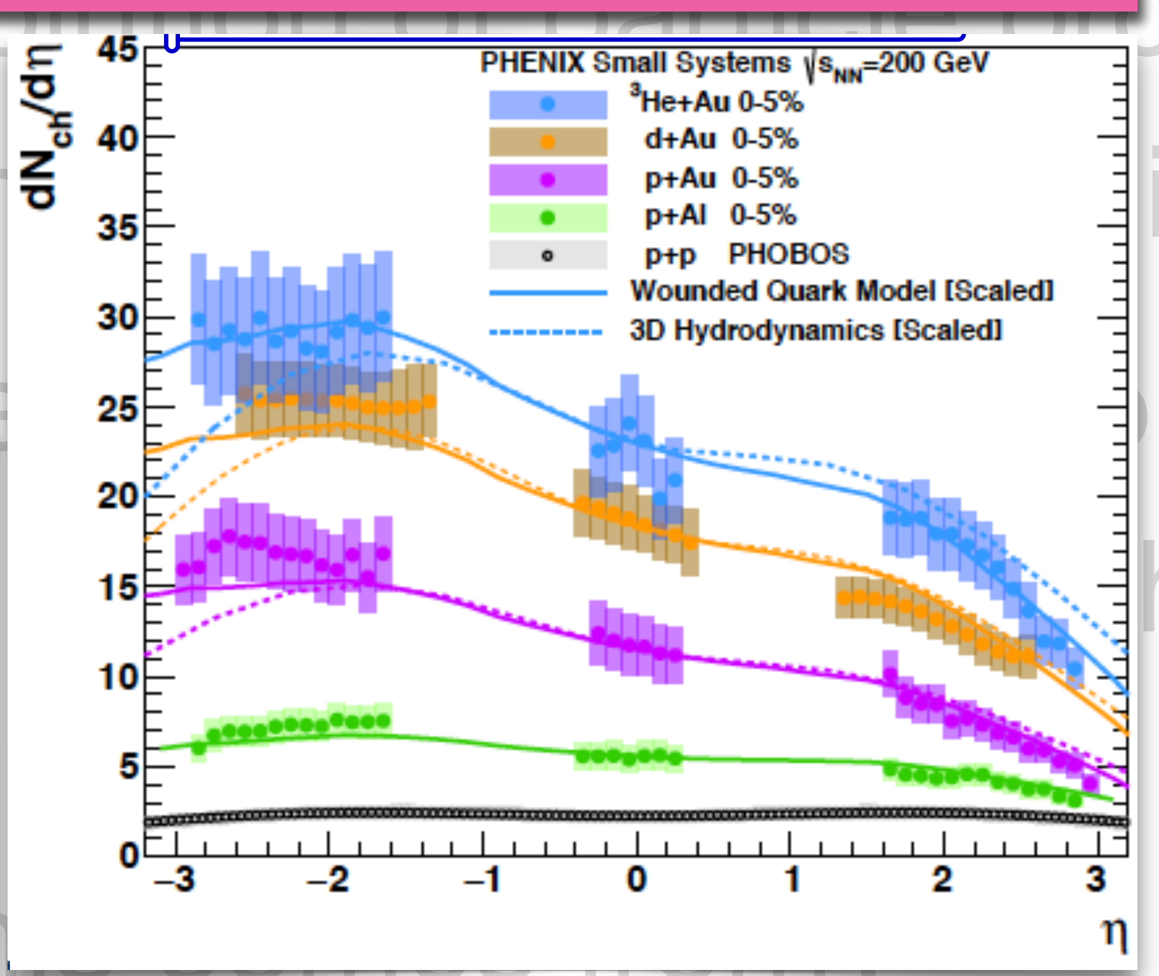
LHCb Fix target



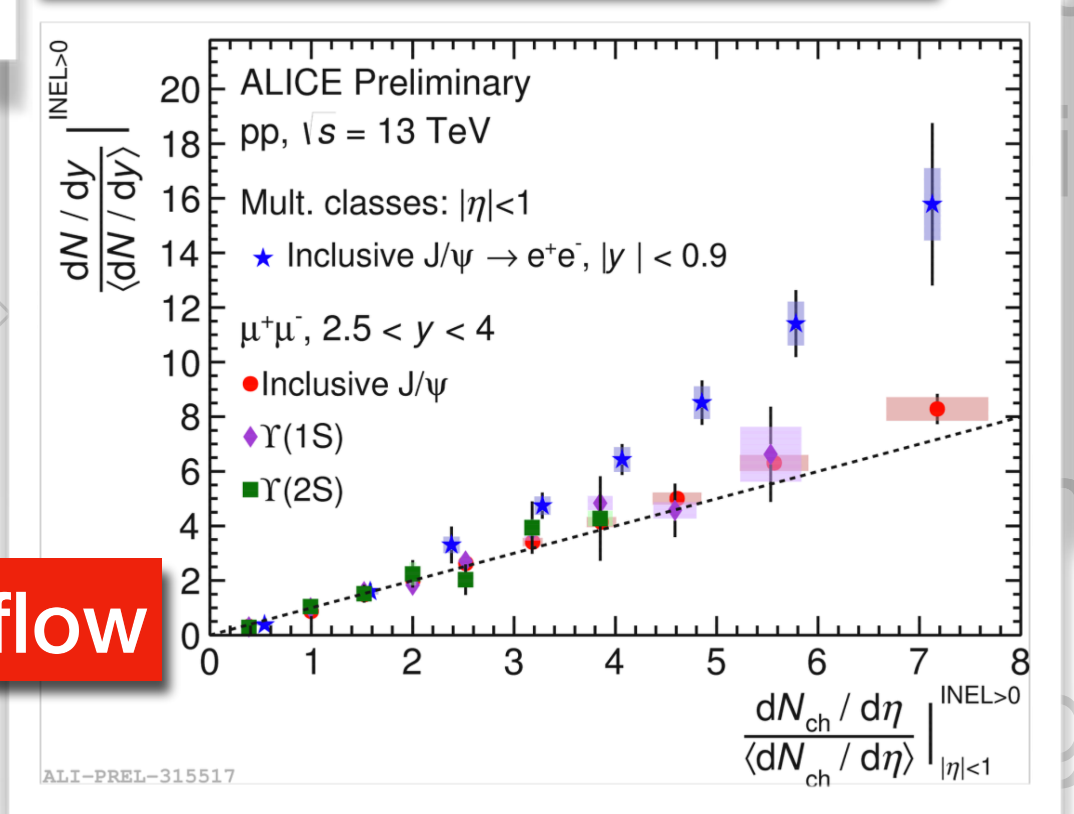
STAR *Phys. Rev. Lett.* **122** (2019) 172301



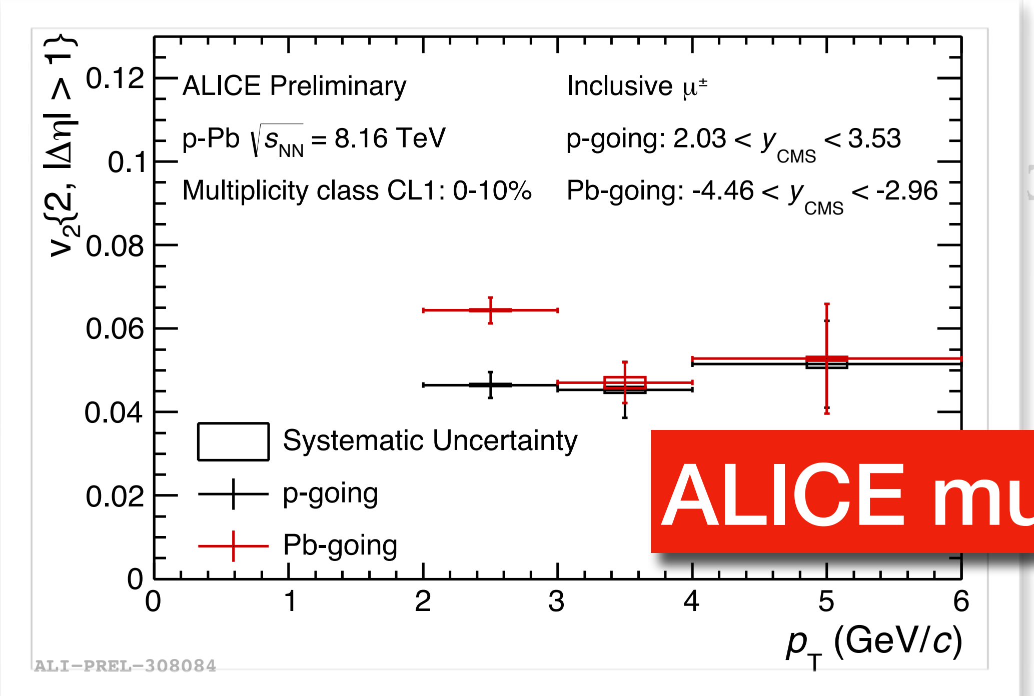
PHENIX *Phys. Rev. Lett.* **121** (2018) 222301



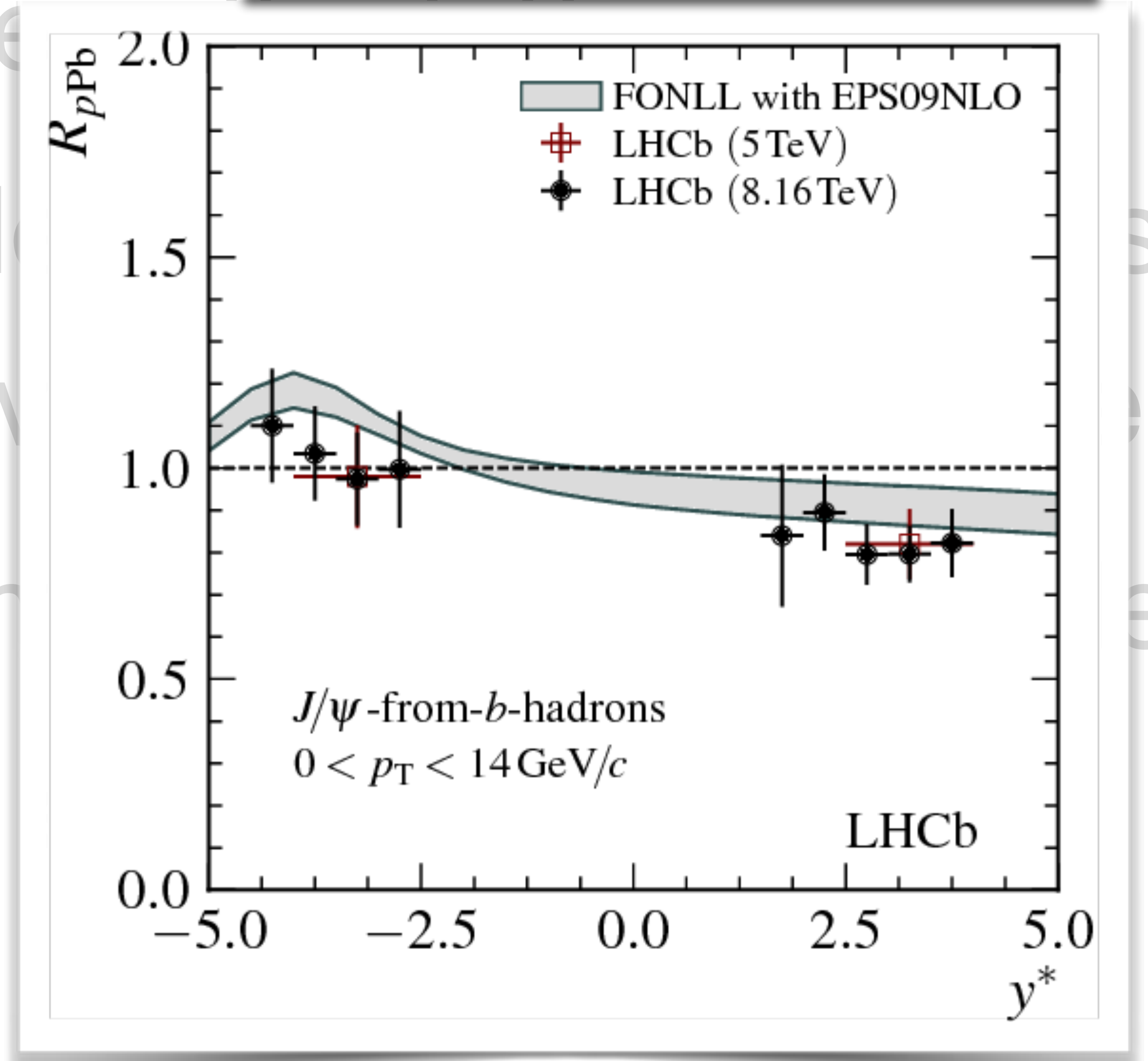
ALICE Υ(1*S*) and Υ(2*S*)



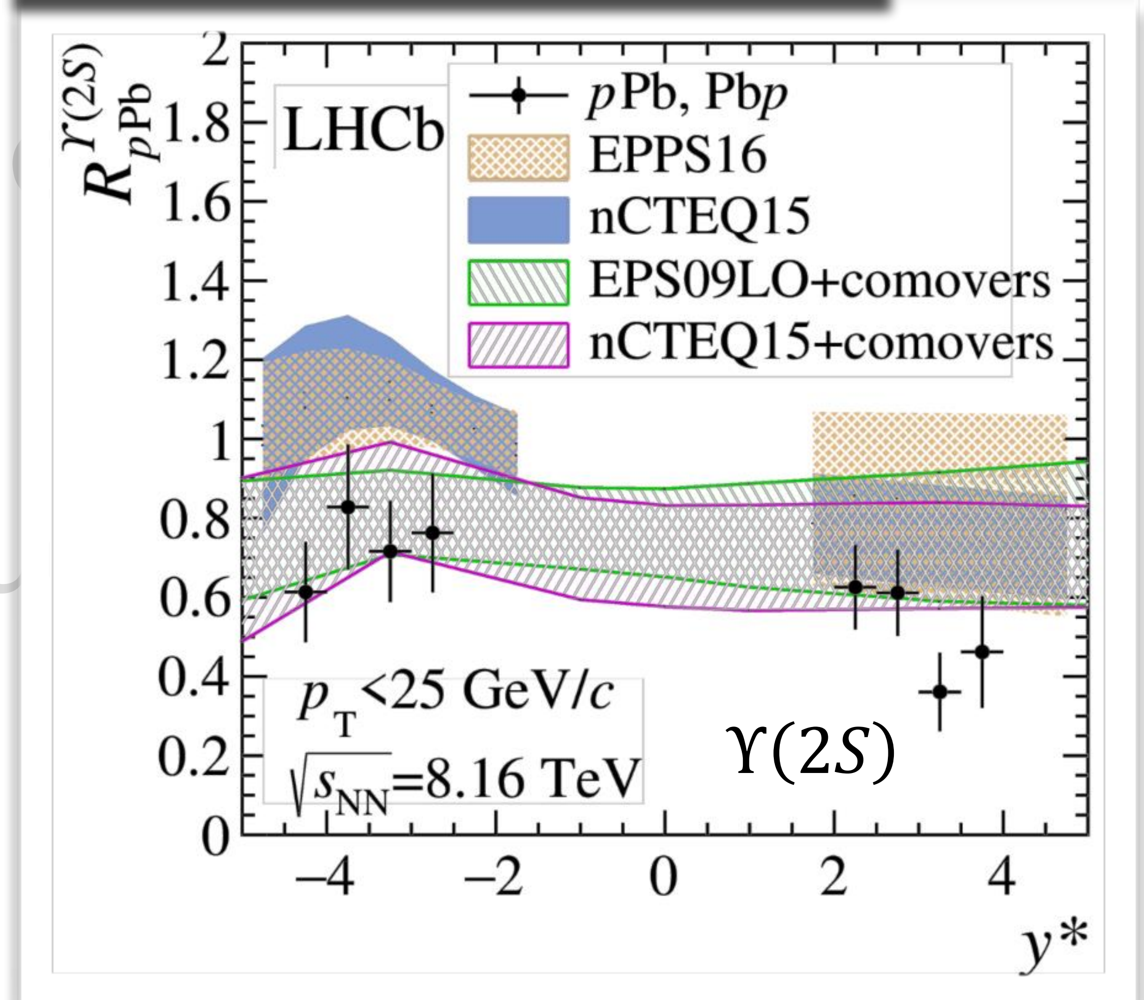
ALICE muon flow



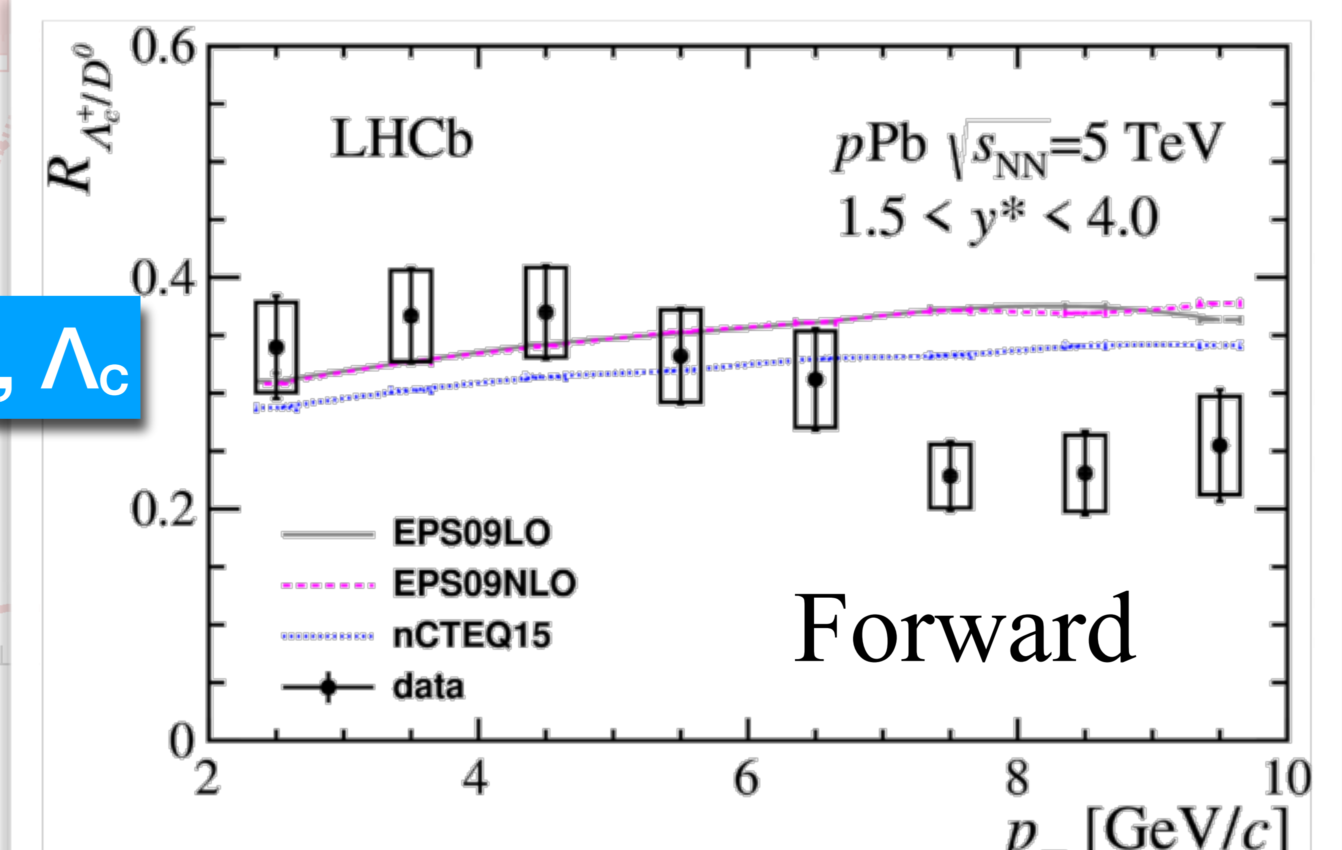
LHCb non-prompt J/ψ



LHCb Y(1*S*) and Y(2*S*)



LHCb D, Λ_c

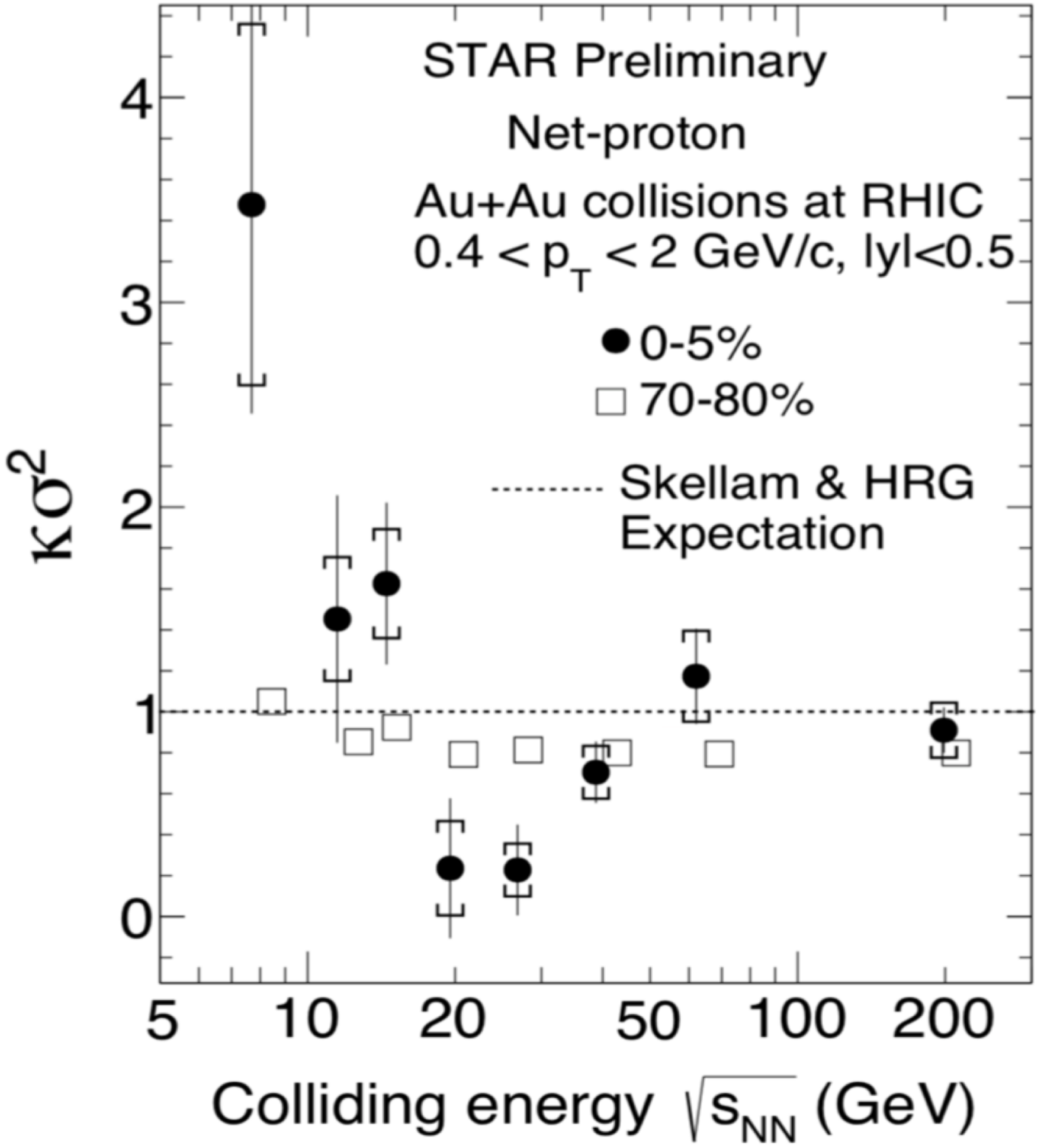


JHEP 02 (2019) 102

Fourth order net-proton fluctuations

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

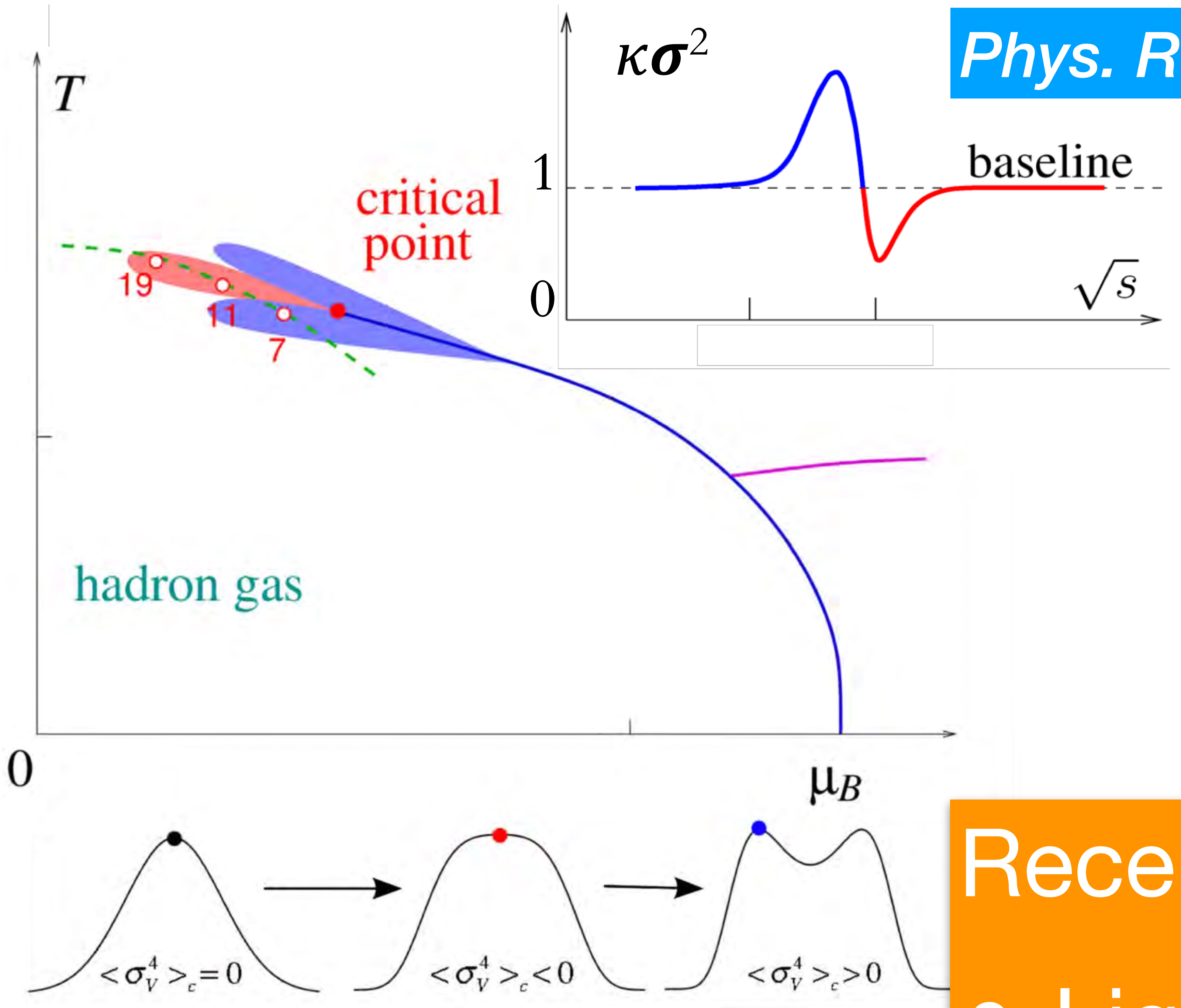
Phys. Rev. Lett. 112 (2014) 032302



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

➡ Hint of entering Critical Region?

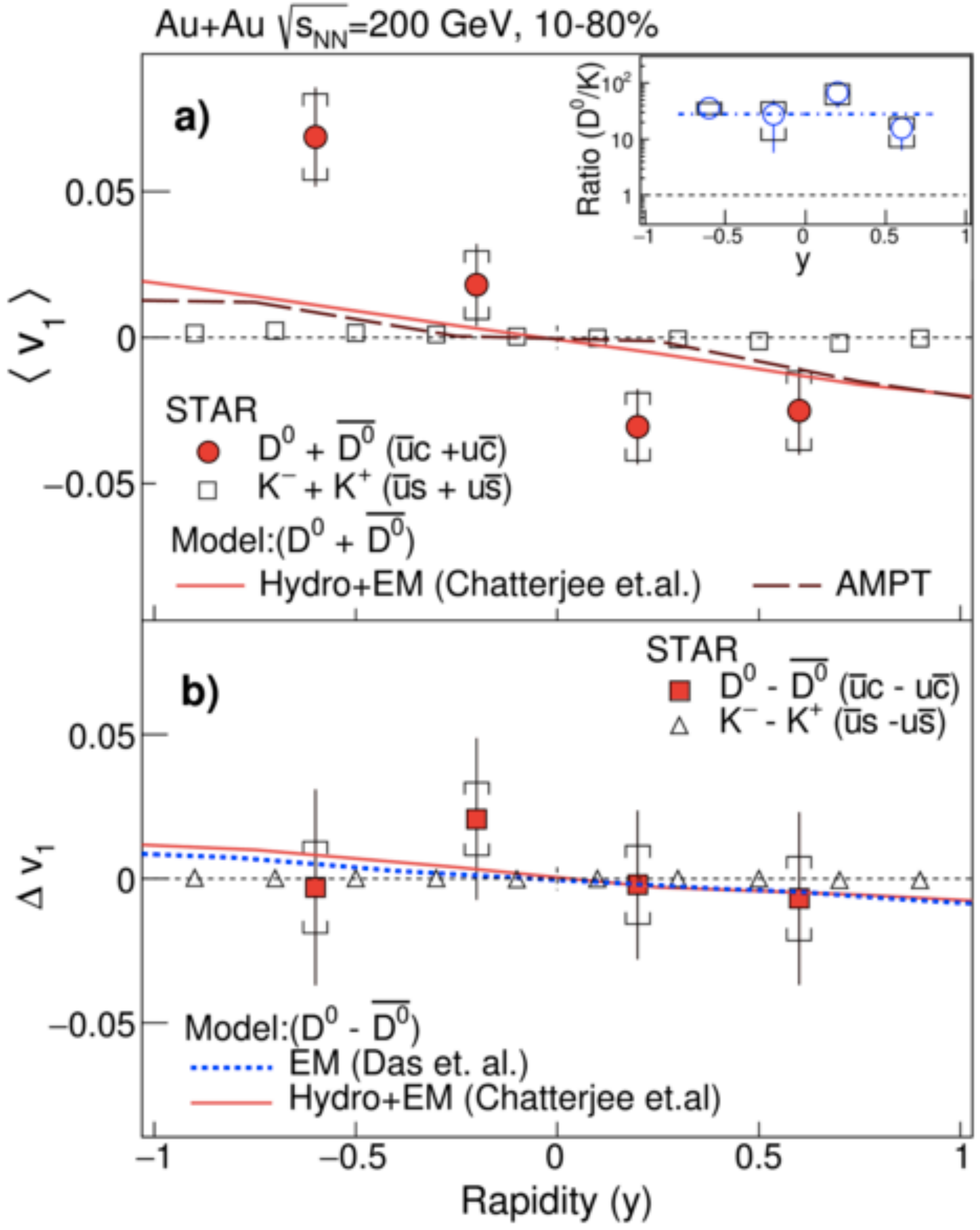
Phys. Rev. Lett. 107 (2011) 052301



Recent established observables

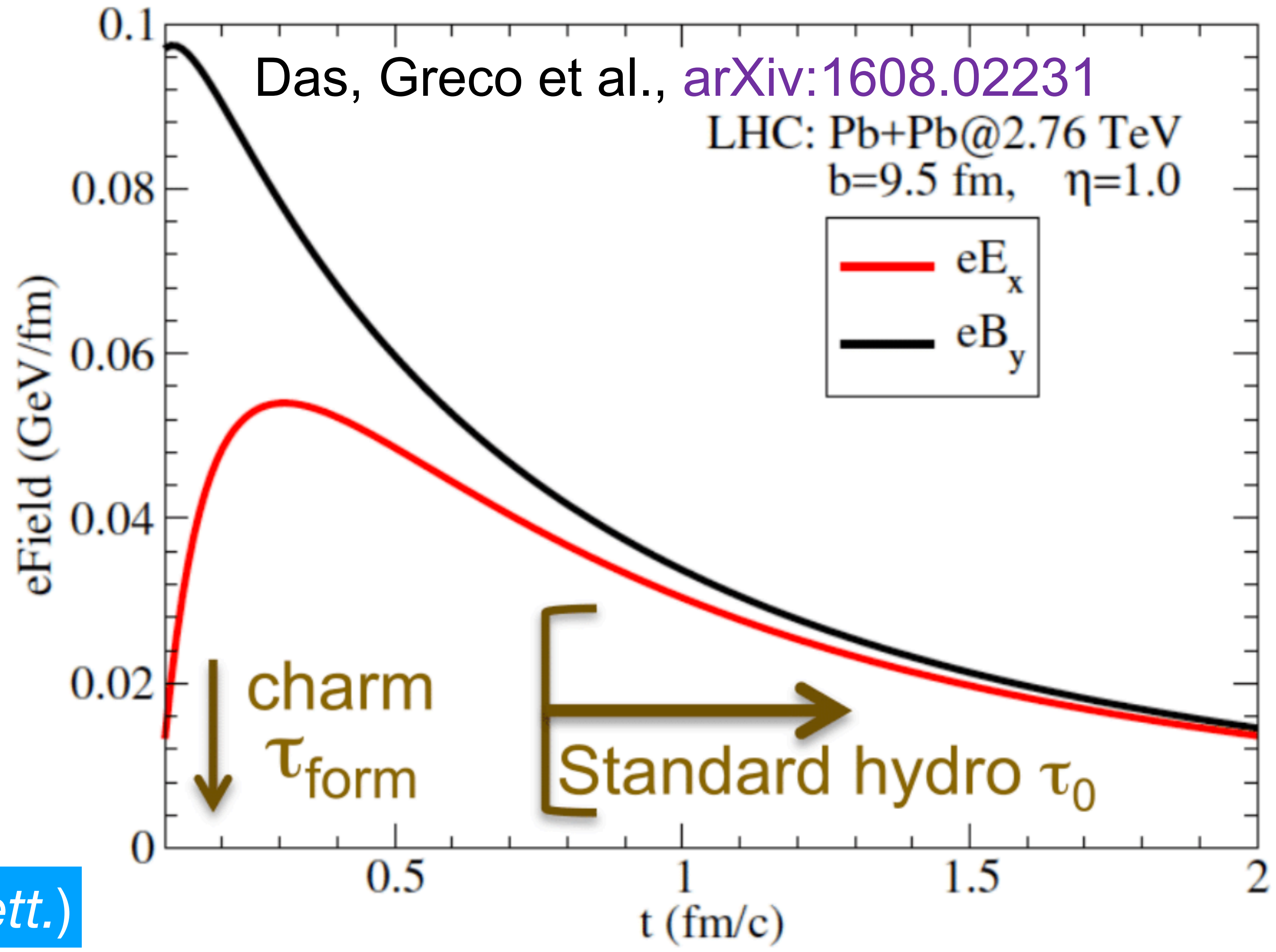
- Light nuclei production
- Nucleon density fluctuations
- …

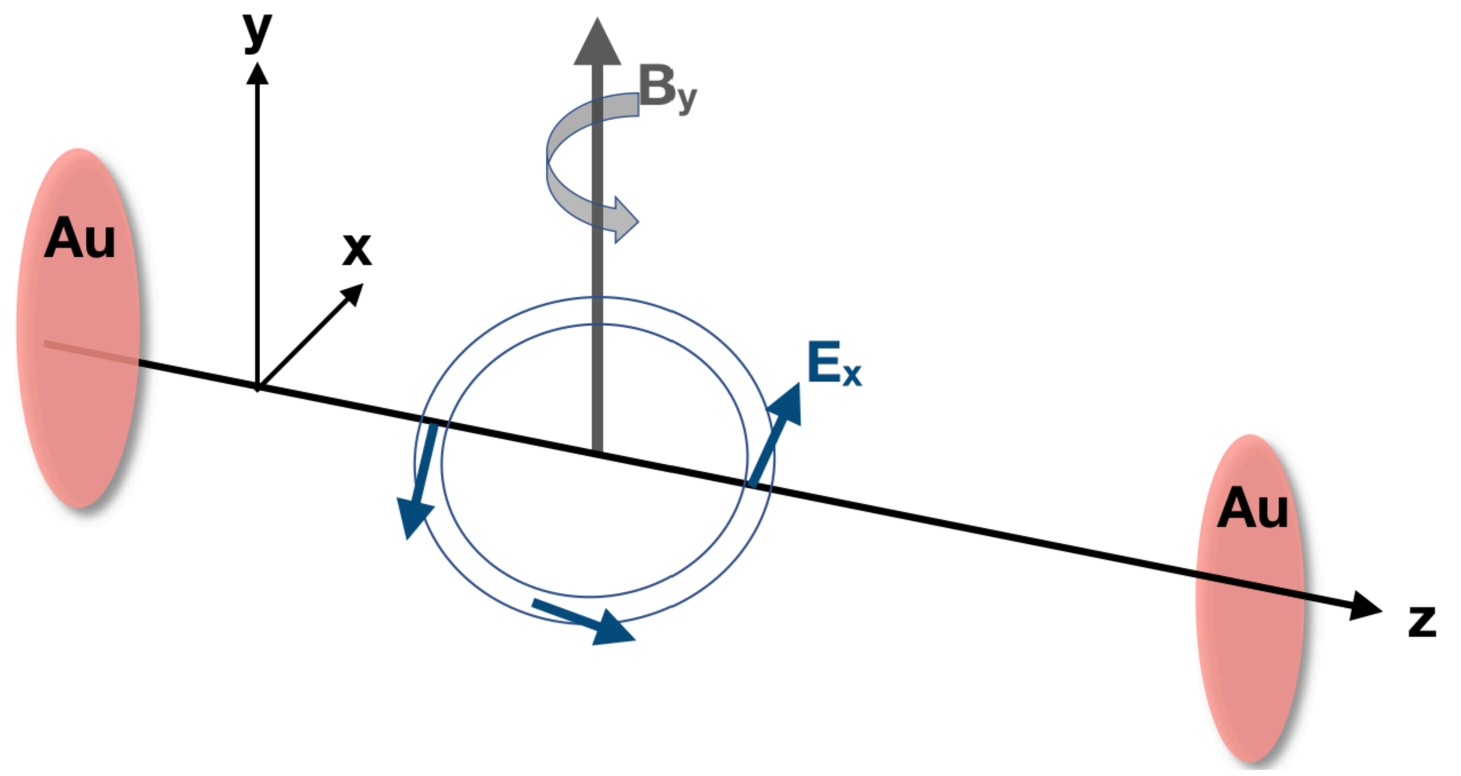
Charge dependence of direct flow

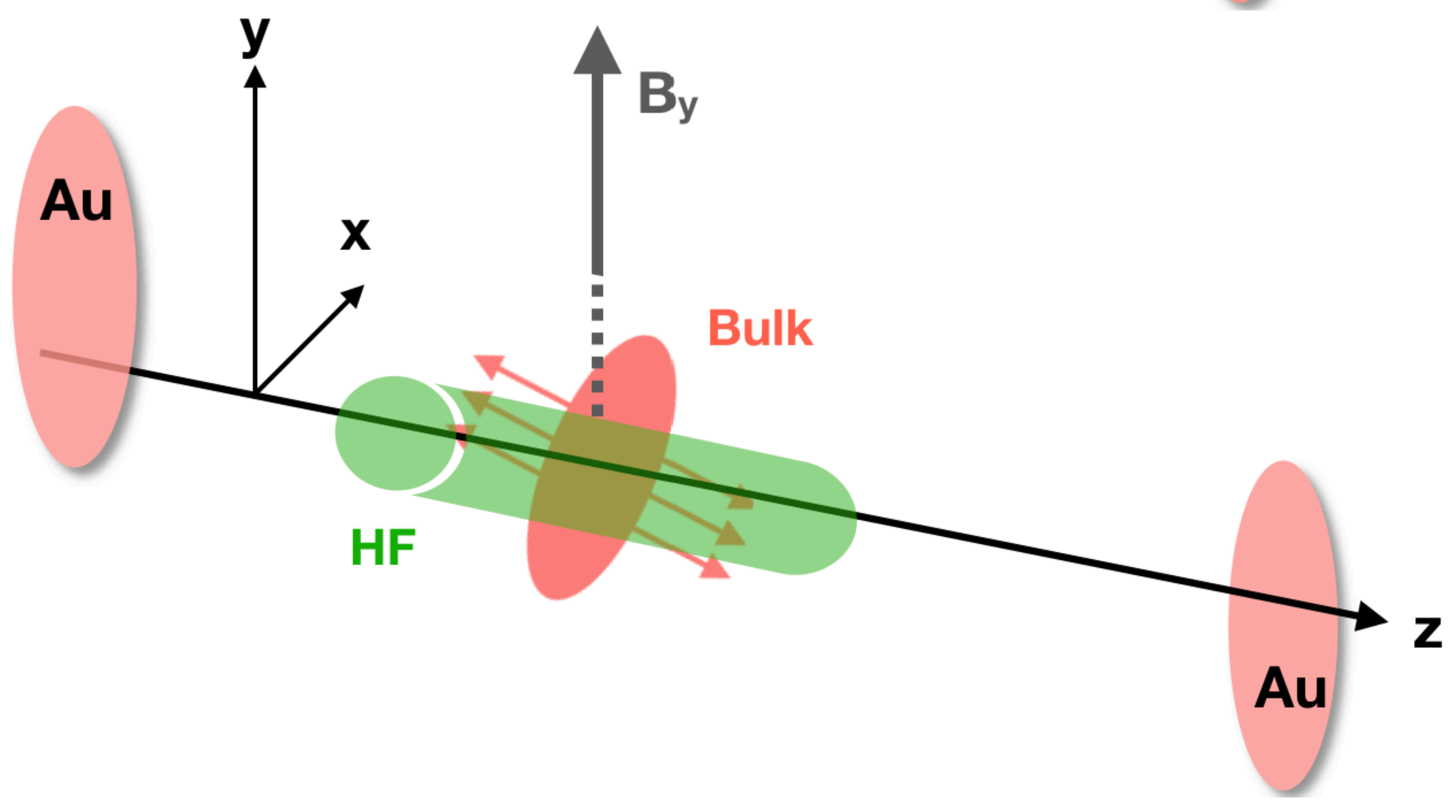


STAR arXiv:1905.02052 (submitted to *Phys. Rev. Lett.*)

- Sensitive to the early time EM fields in the collisions
  ➡ Provide constraint for CME related physics
- Charm dragged by tilted bulk: production points are shifted from the bulk at $y \neq 0$ — probe the longitudinal profile of the initial matter

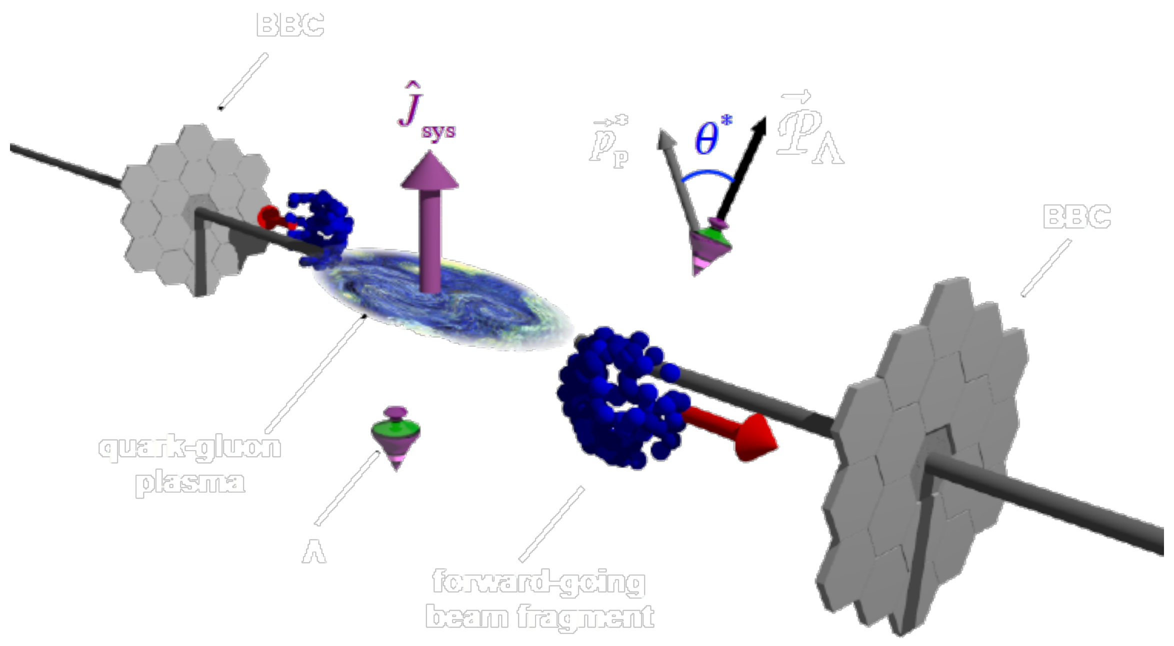




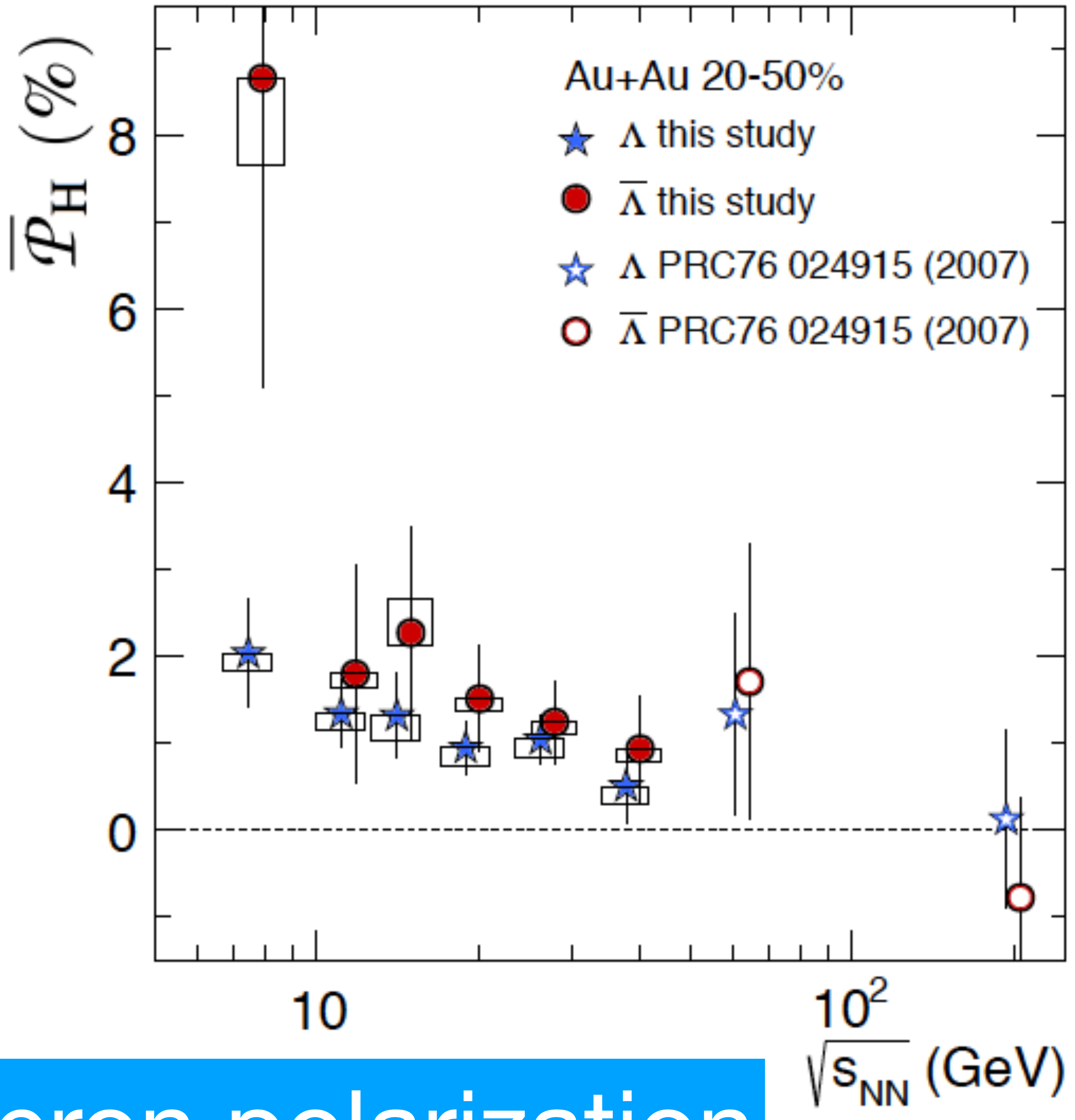


Most vertical fluid ever observed

- Non-central heavy-ion collisions produce a state of matter with strong vortical fluid
- Restoration of fundamental symmetries of quantum chromo-dynamics is expected to produce novel physical effects in the presence of strong vorticity [*Prog. Part. Nucl. Phys.* **88** (2016) 1]

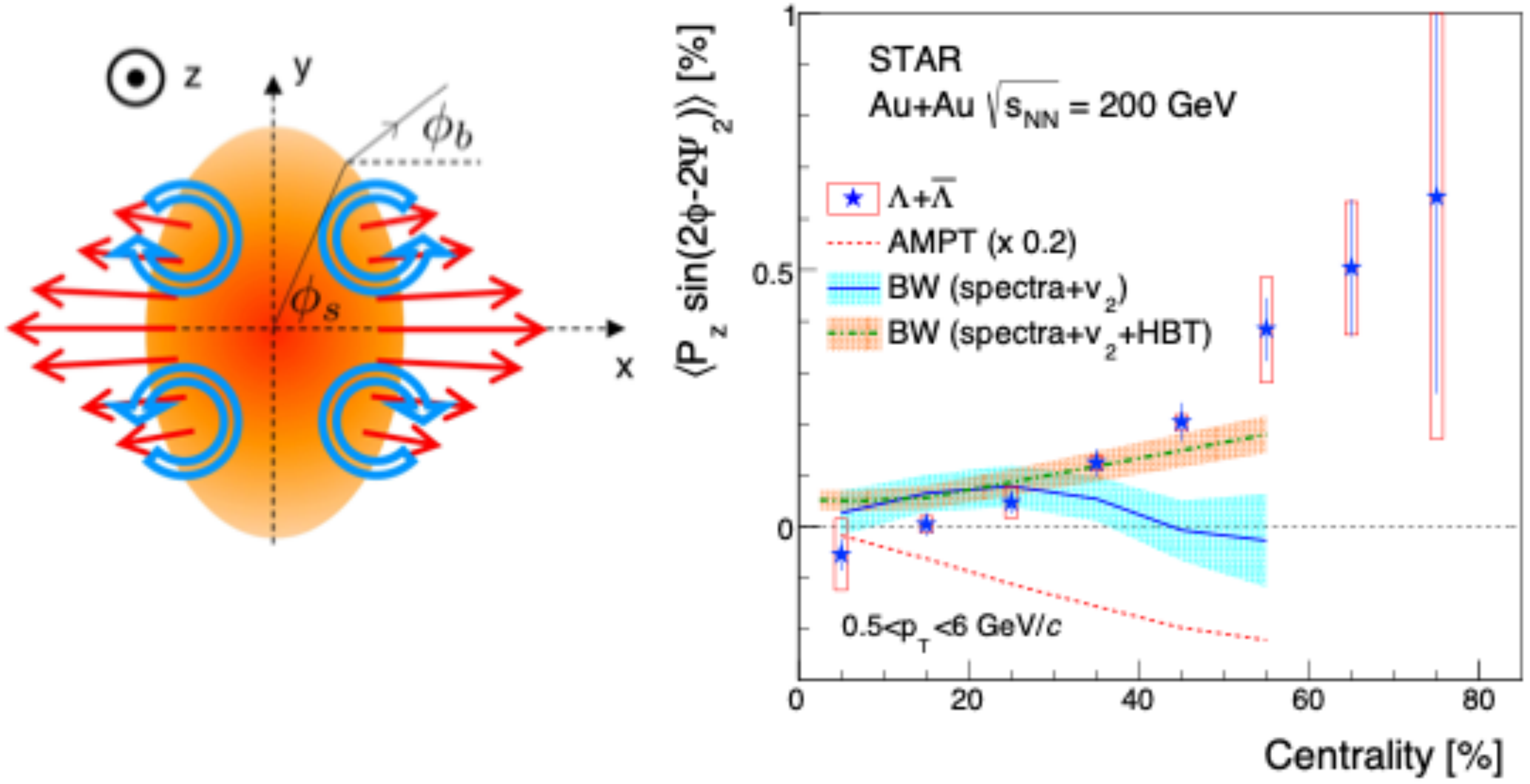


STAR *Nature* **548** (2017) 62



Global Λ hyperon polarization

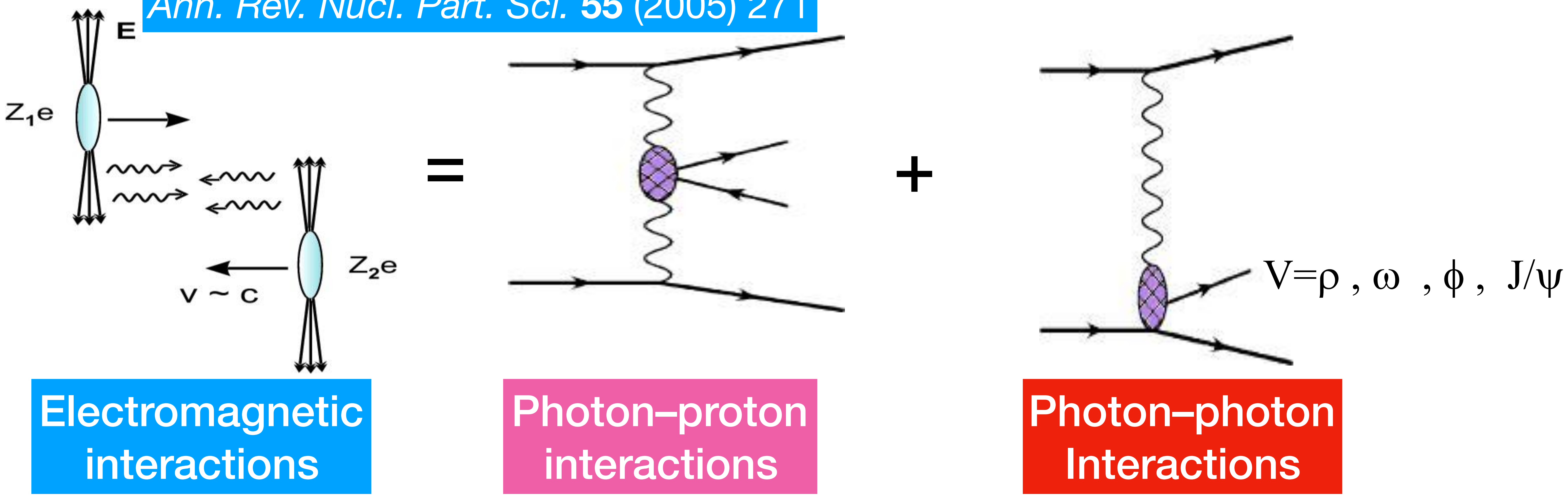
STAR *Phys. Rev. Lett.* **123** (2019) 132301

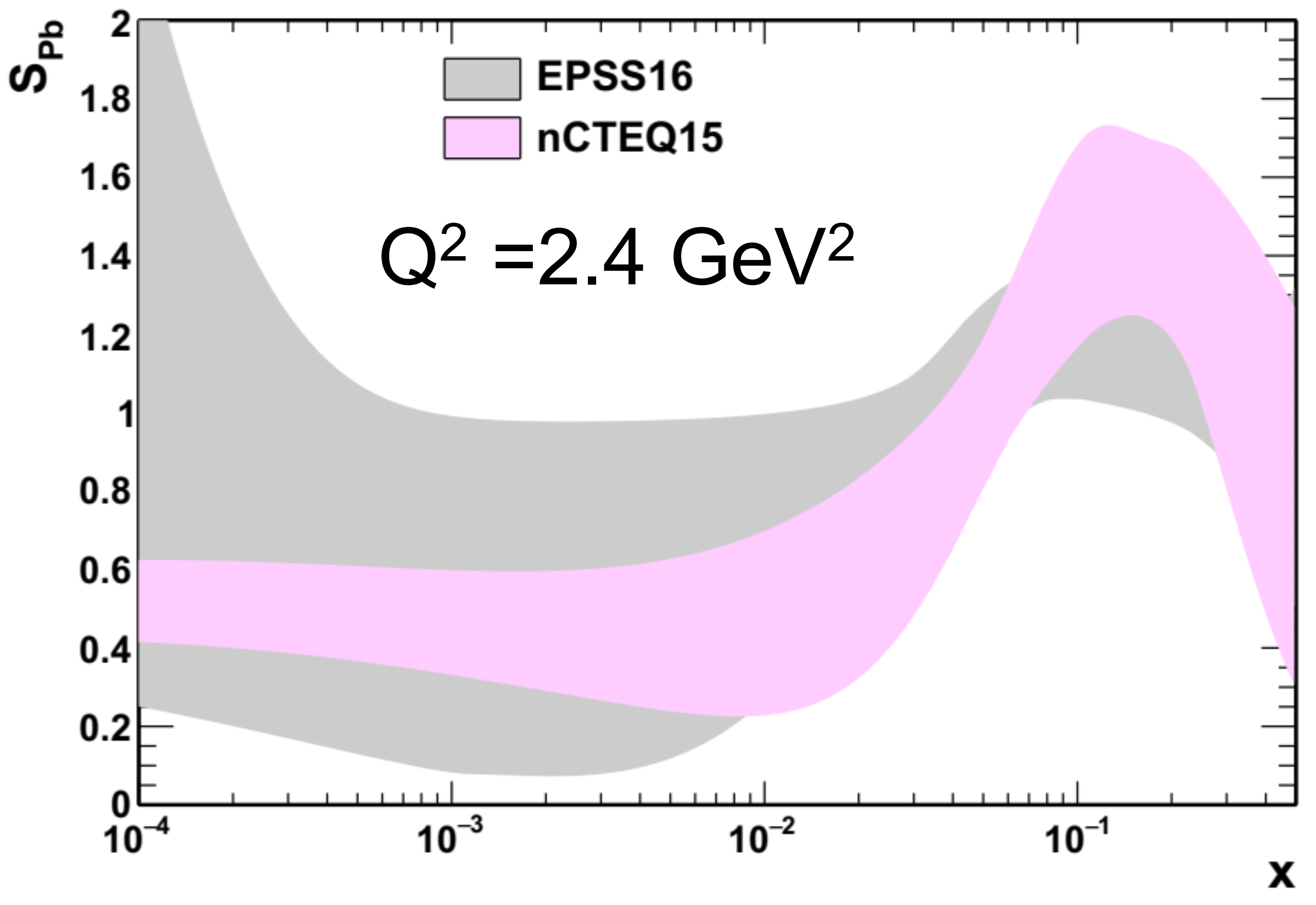


Λ polarization alone beam axis

Photon interactions in heavy-ion collisions

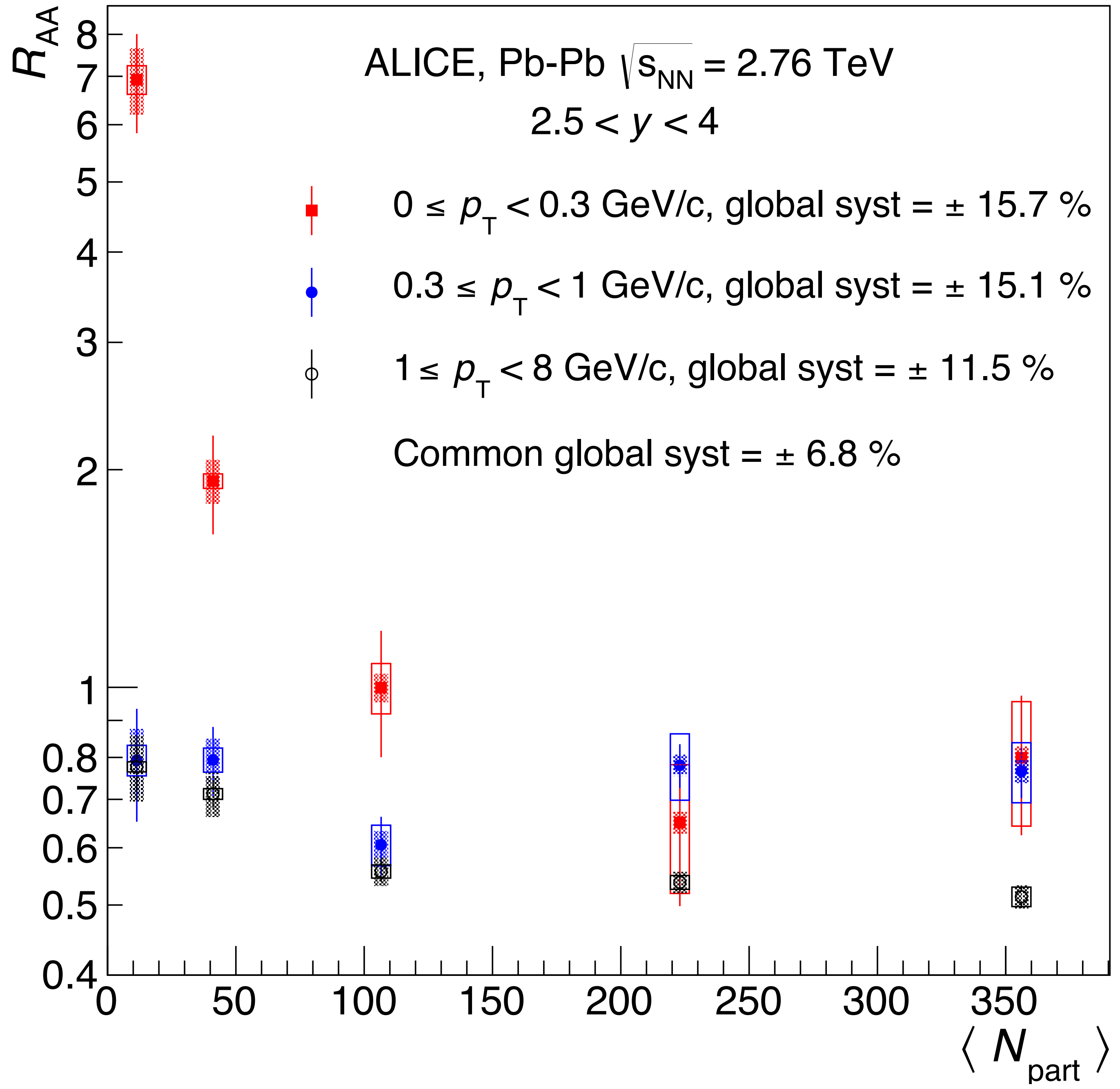
Ann. Rev. Nucl. Part. Sci. **55** (2005) 271



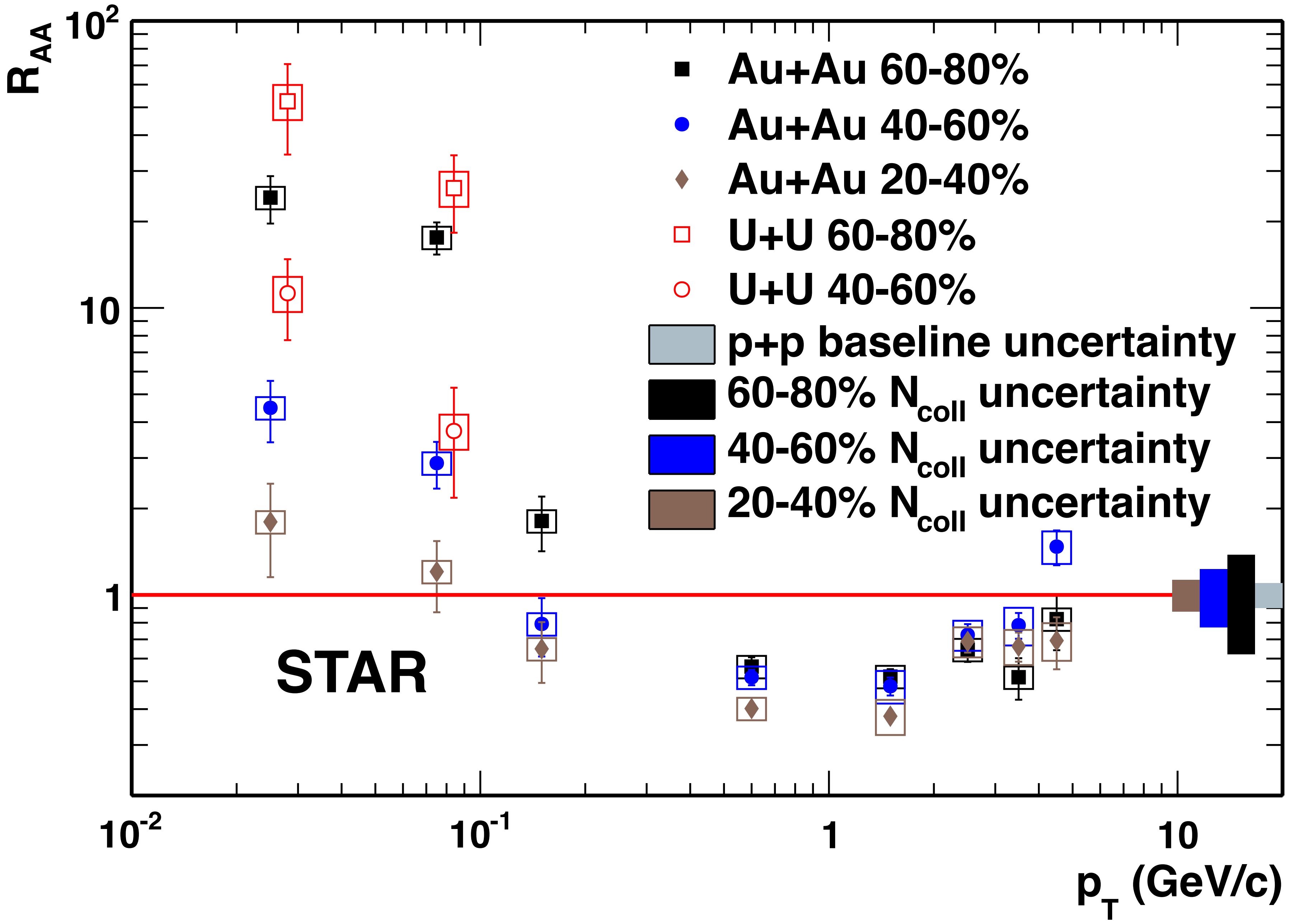


Eur. Phys. J. **C77** (2017) 163

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



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

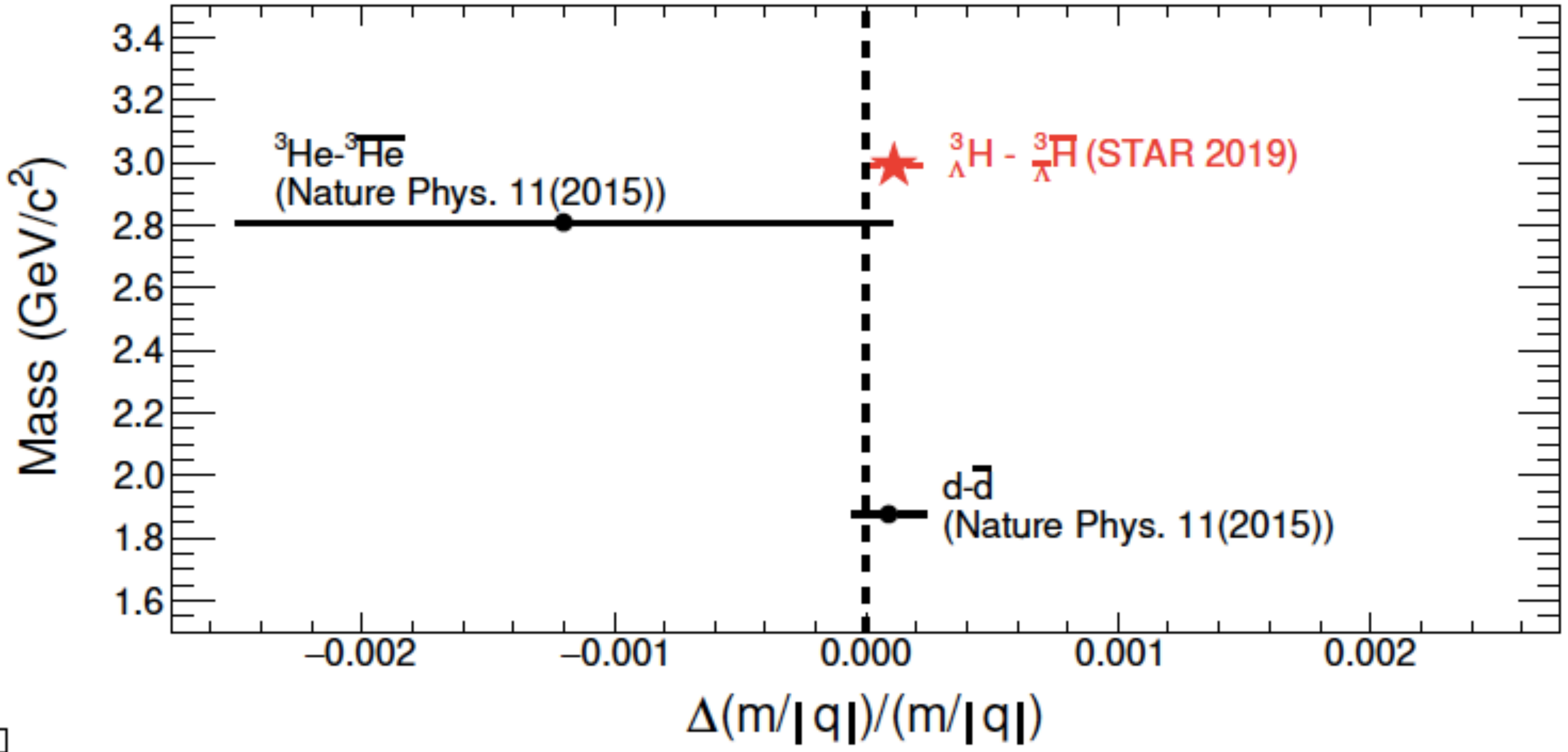


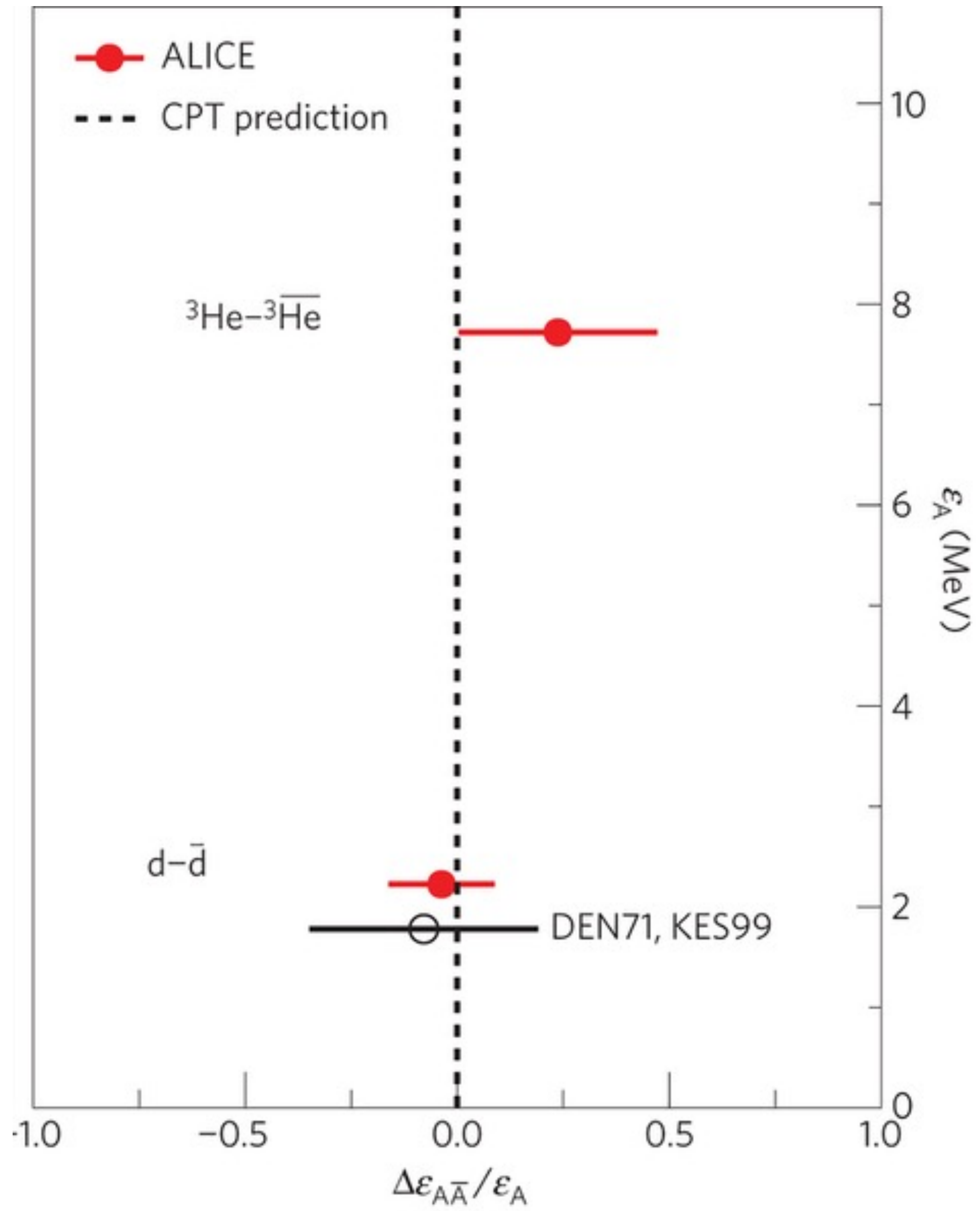
- Exceed J/ψ at low-p_T: coherent photo-production
- Sensitive to gluon distribution function at very low Bjorken-*x*

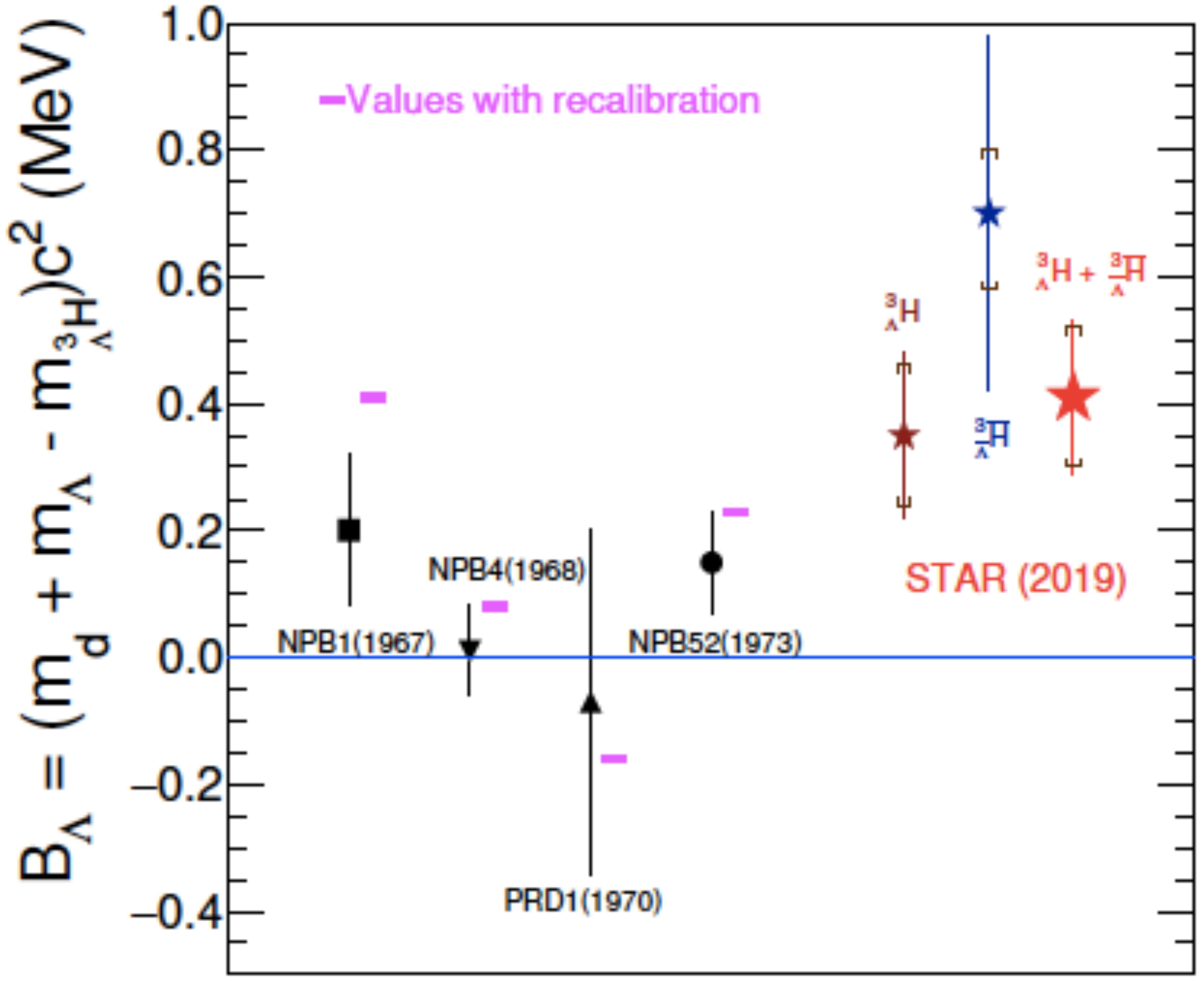
Mass difference of (anti-)nuclei

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

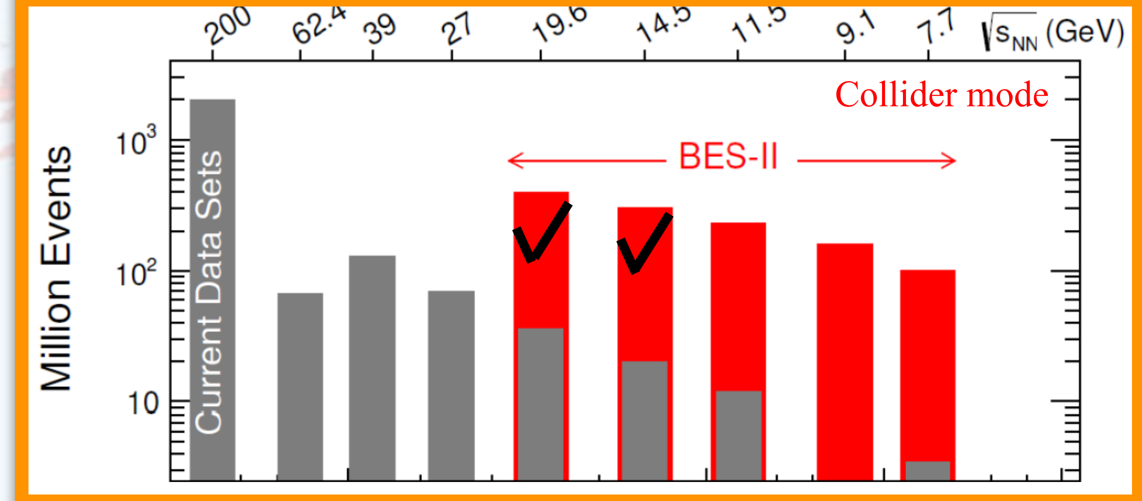
➡ Opened the hyper-nuclei window

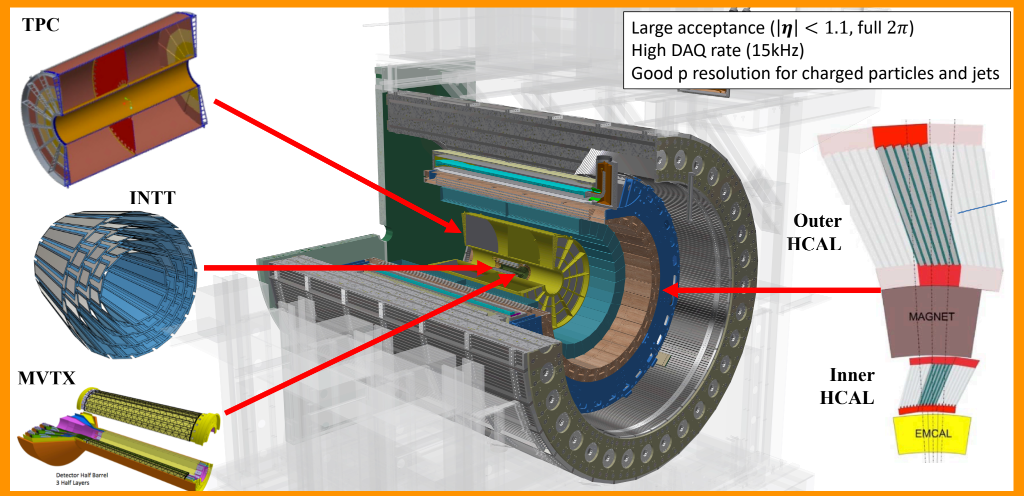
On going and upcoming projects…

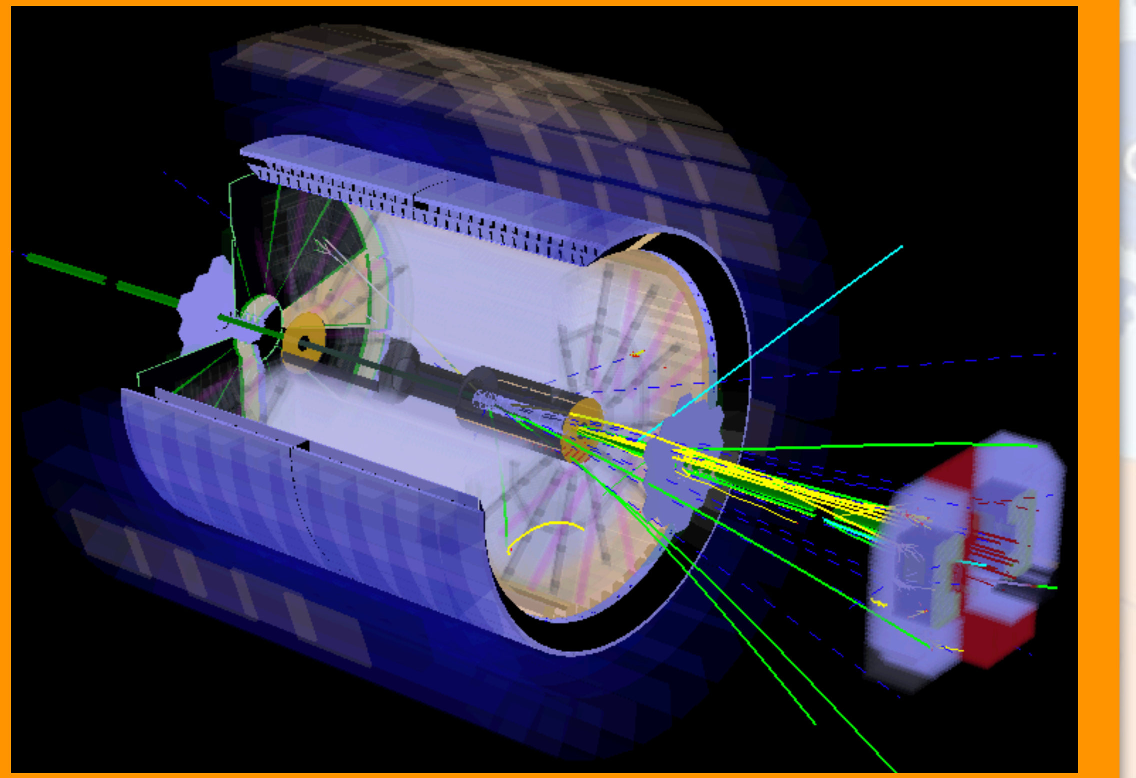
RHIC

STAR BES-II, iTPC, eTOF, Forward upgrade

sPHENIX…

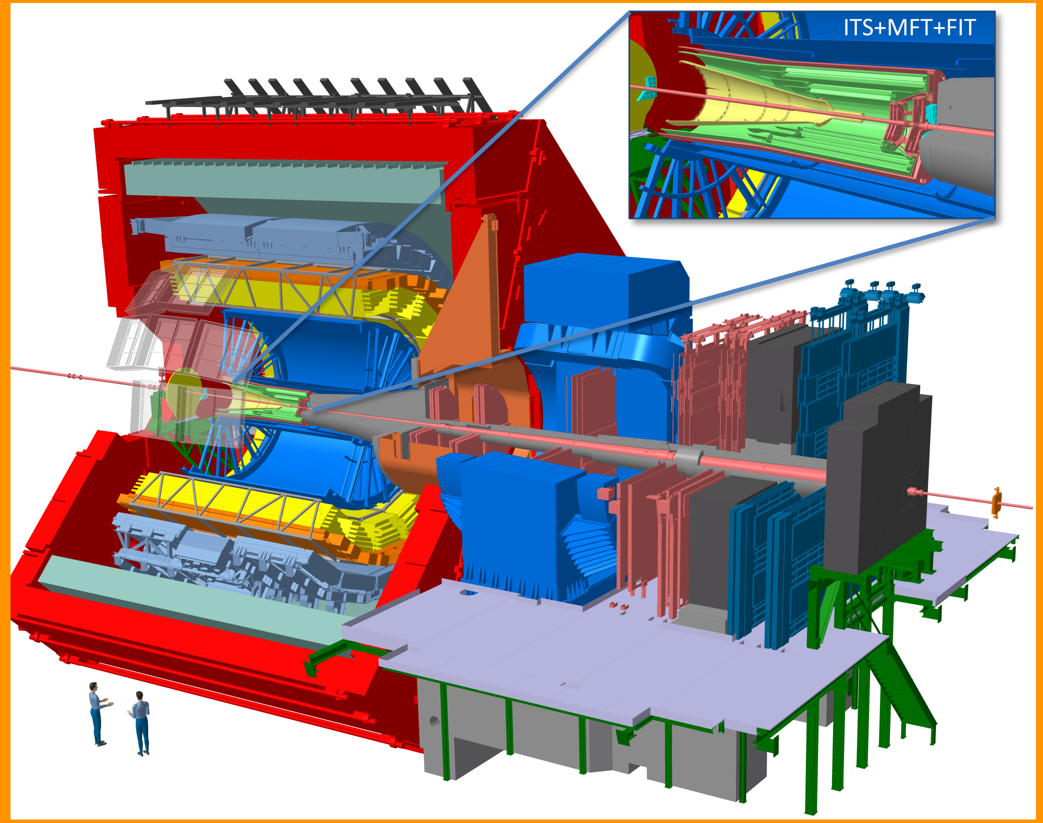


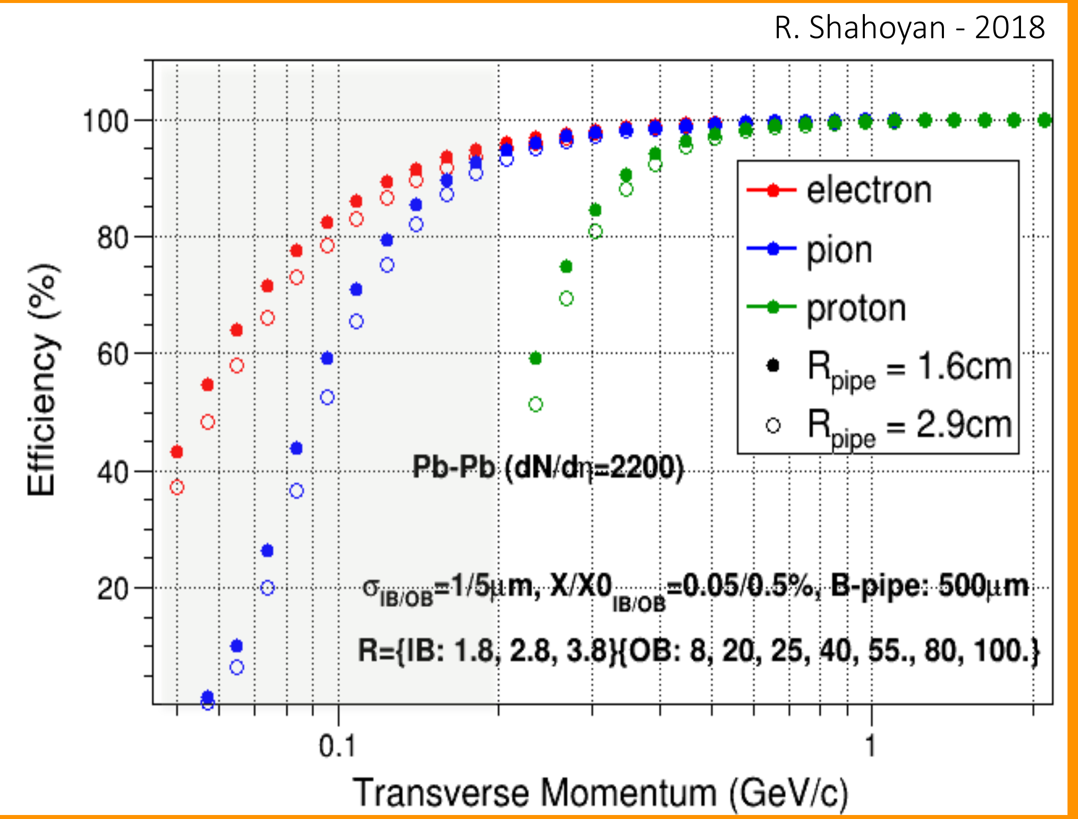




LHC

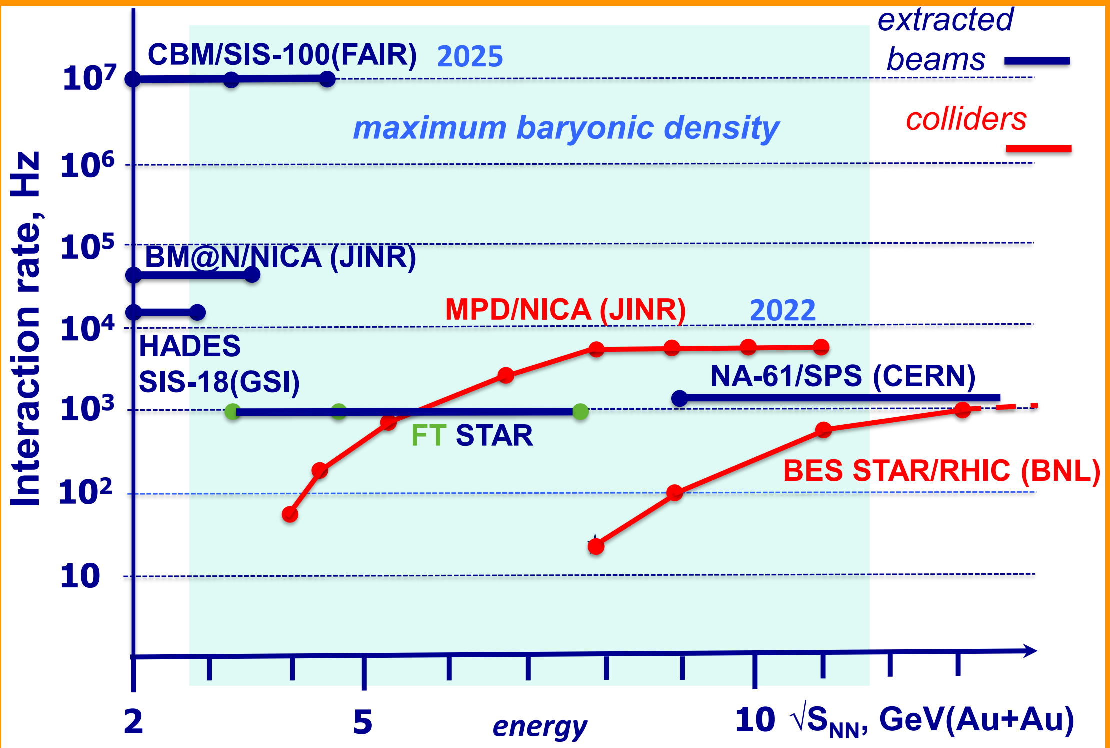
ALICE and LHCb RUN-III, beyond RUN-IV upgrade

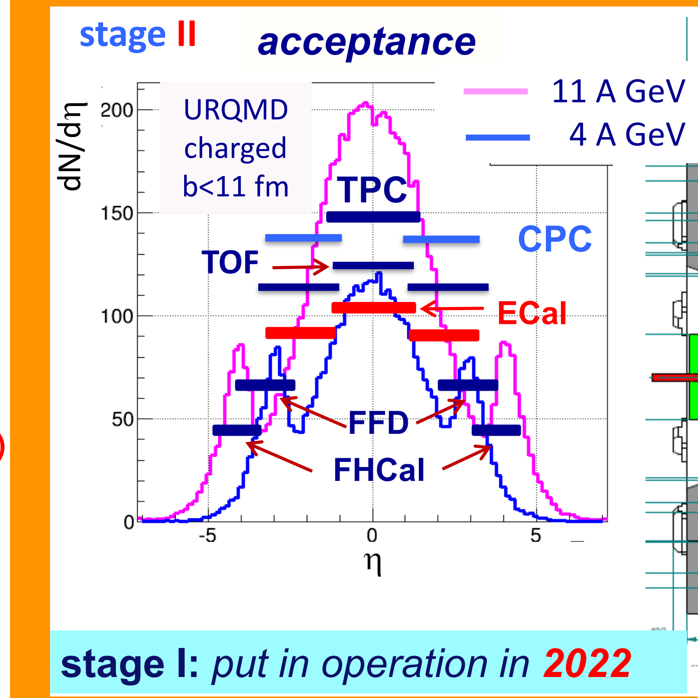


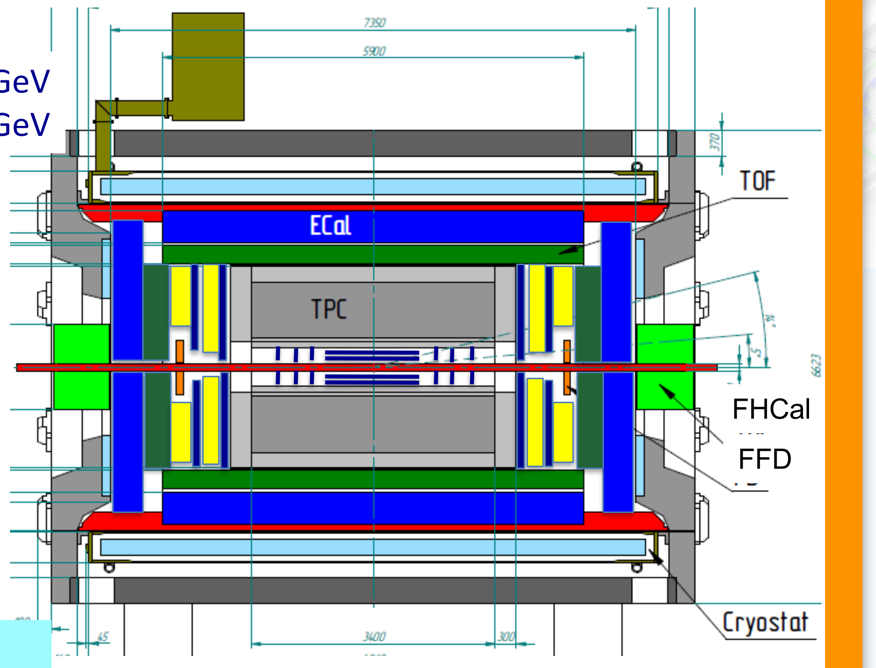


NICA-MPD

China contribution: ECal, TOF…



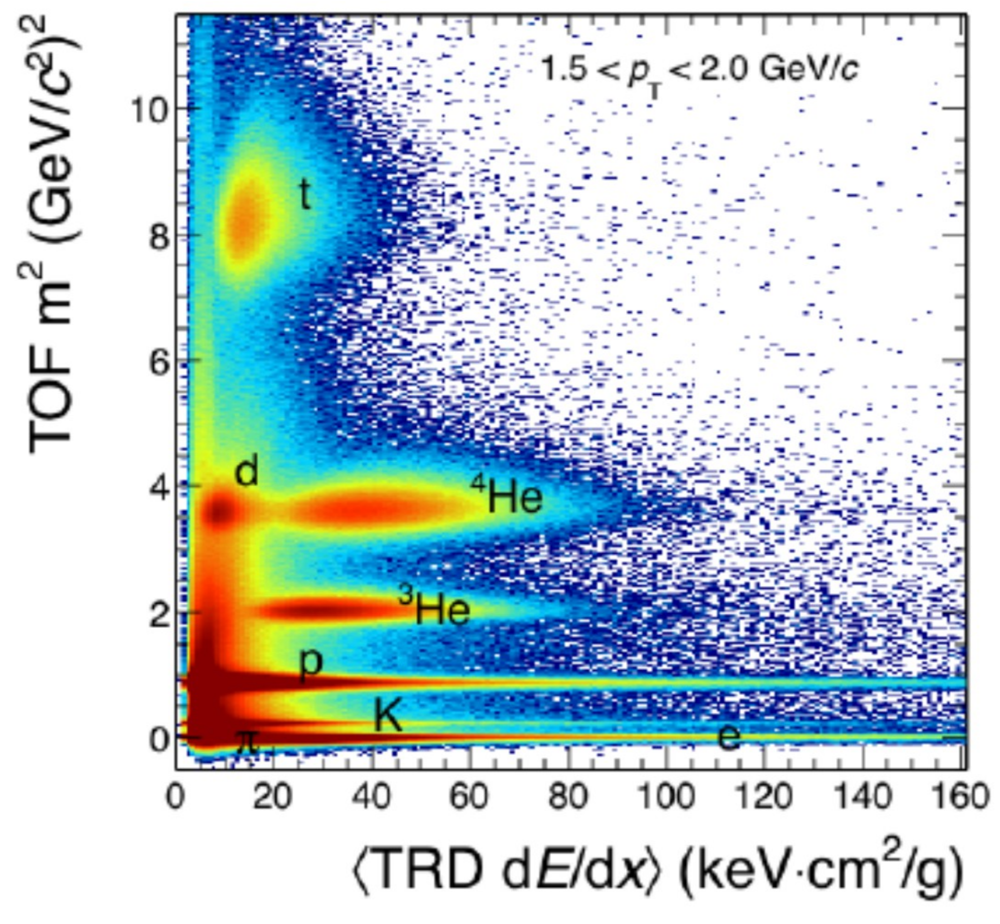


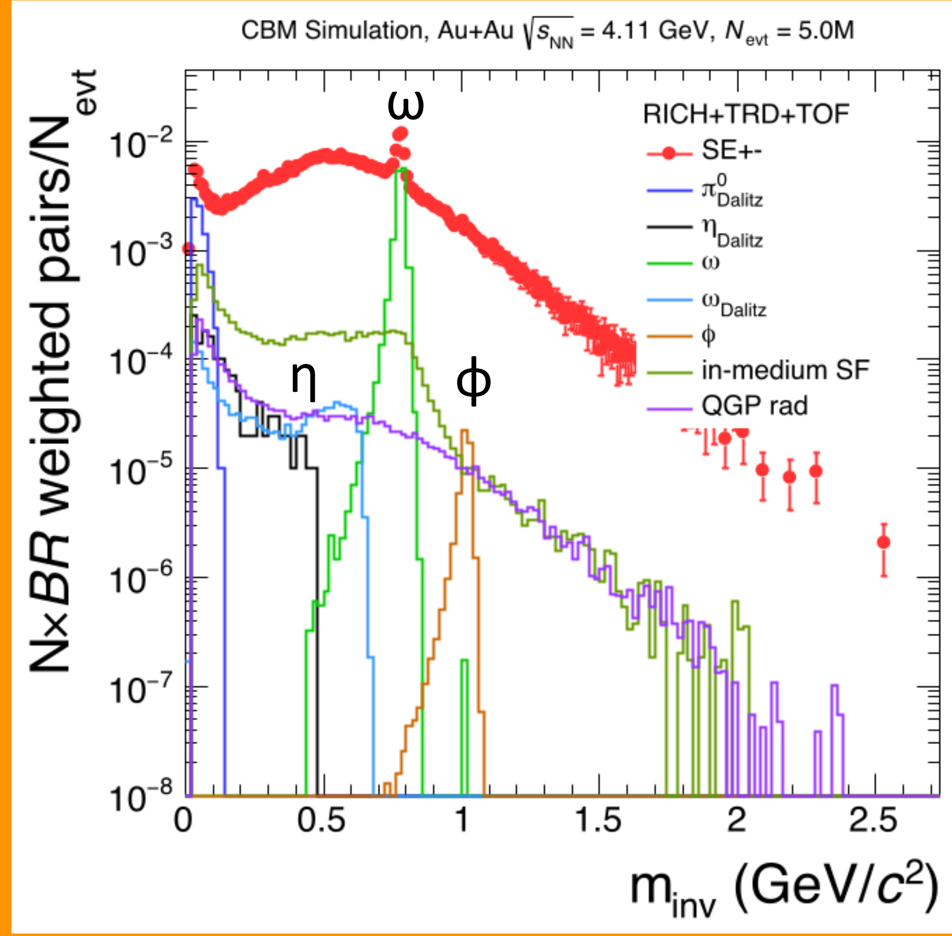


FAiR-CBM

Capability of particle identification

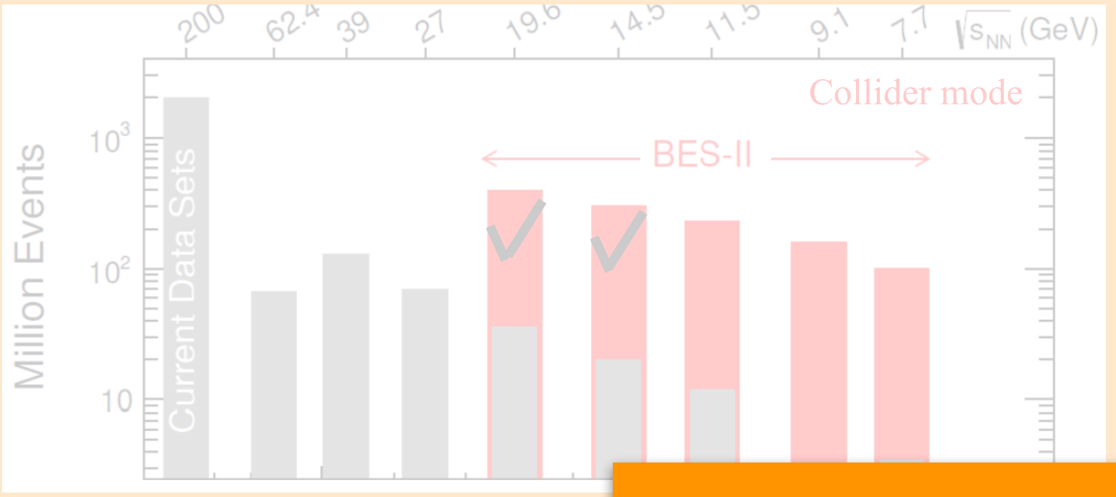
Performance of di-lepton measurments

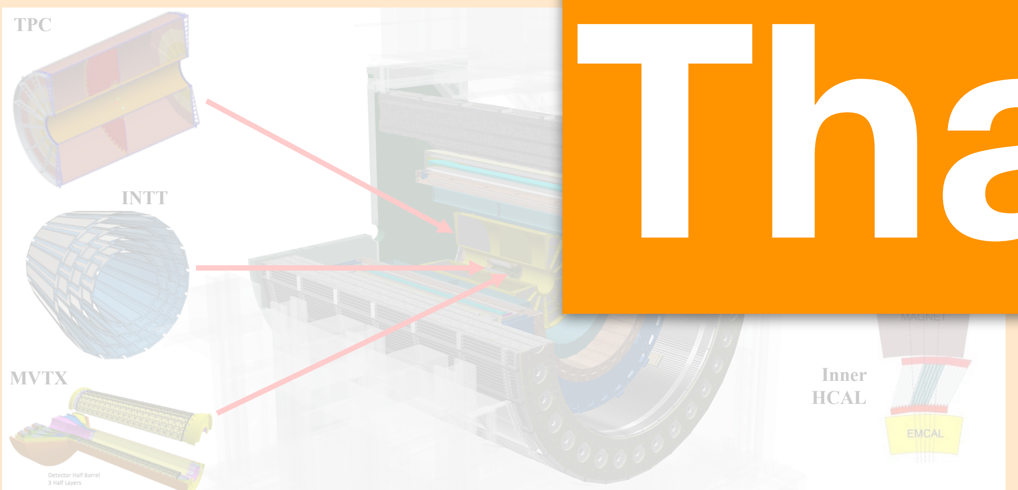




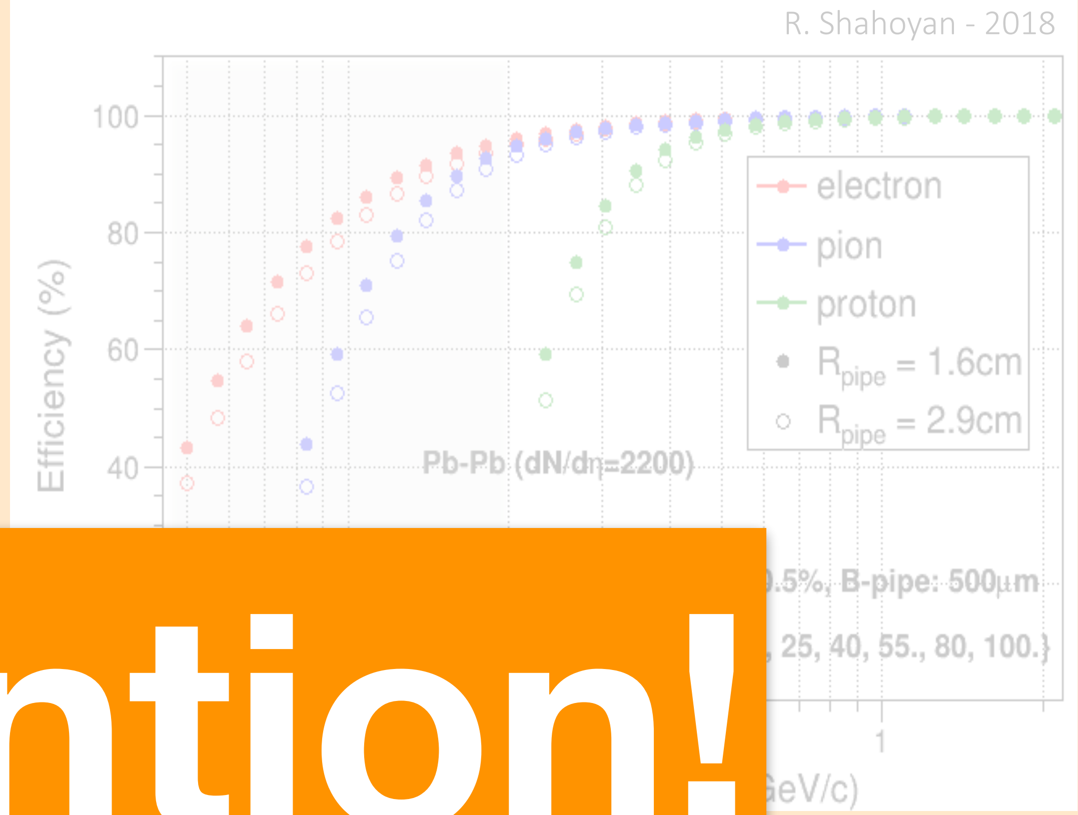
On going and upcoming projects…

RHIC
STAR BES-II, iTPC, eTOF, Forward upgrade
sPHENIX…





LHC
ALICE and LHCb RUN-III, beyond RUN-IV upgrade



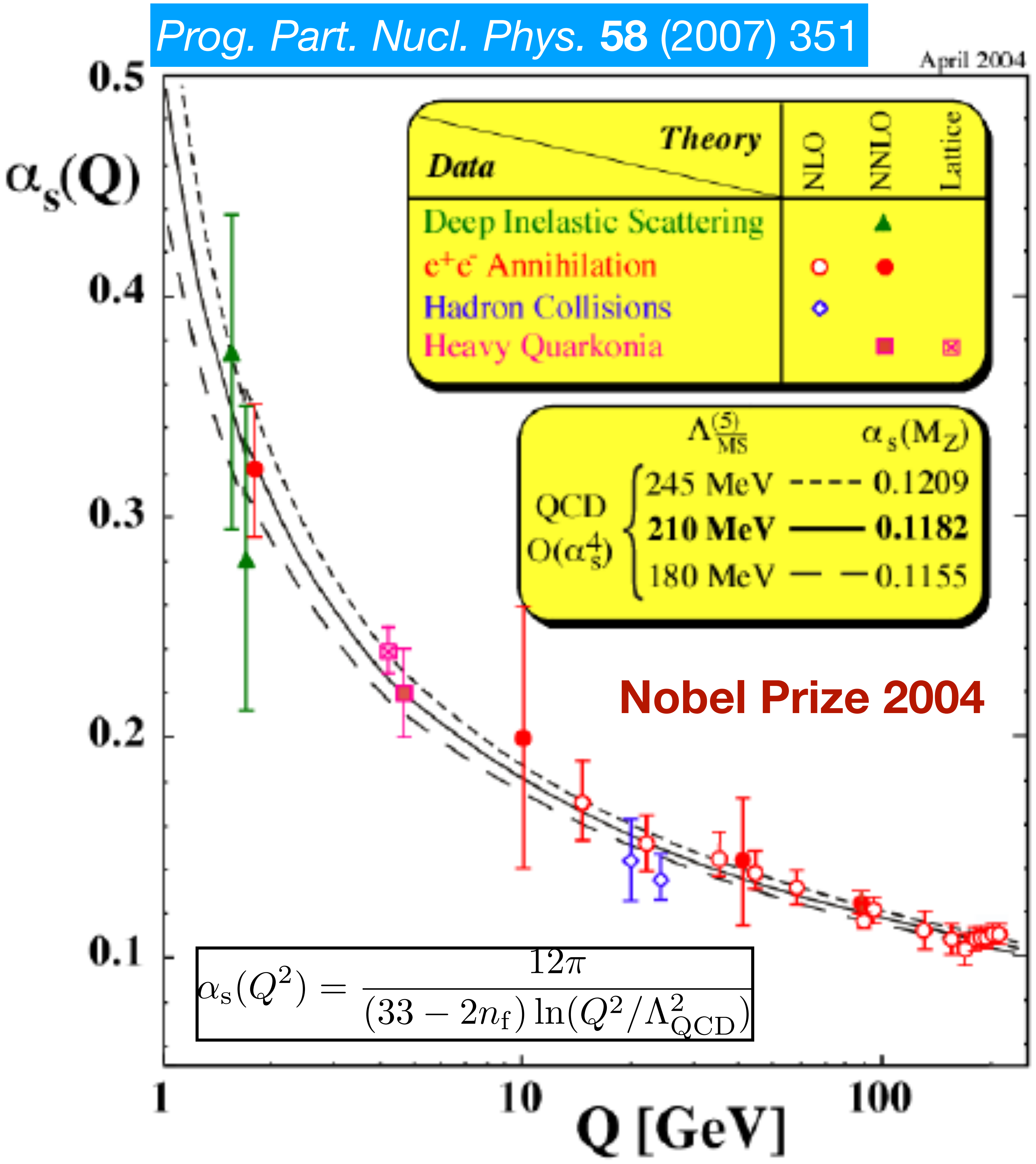
Thanks for your attention!

NICA-MPD
China contribution: ECal, TOF…

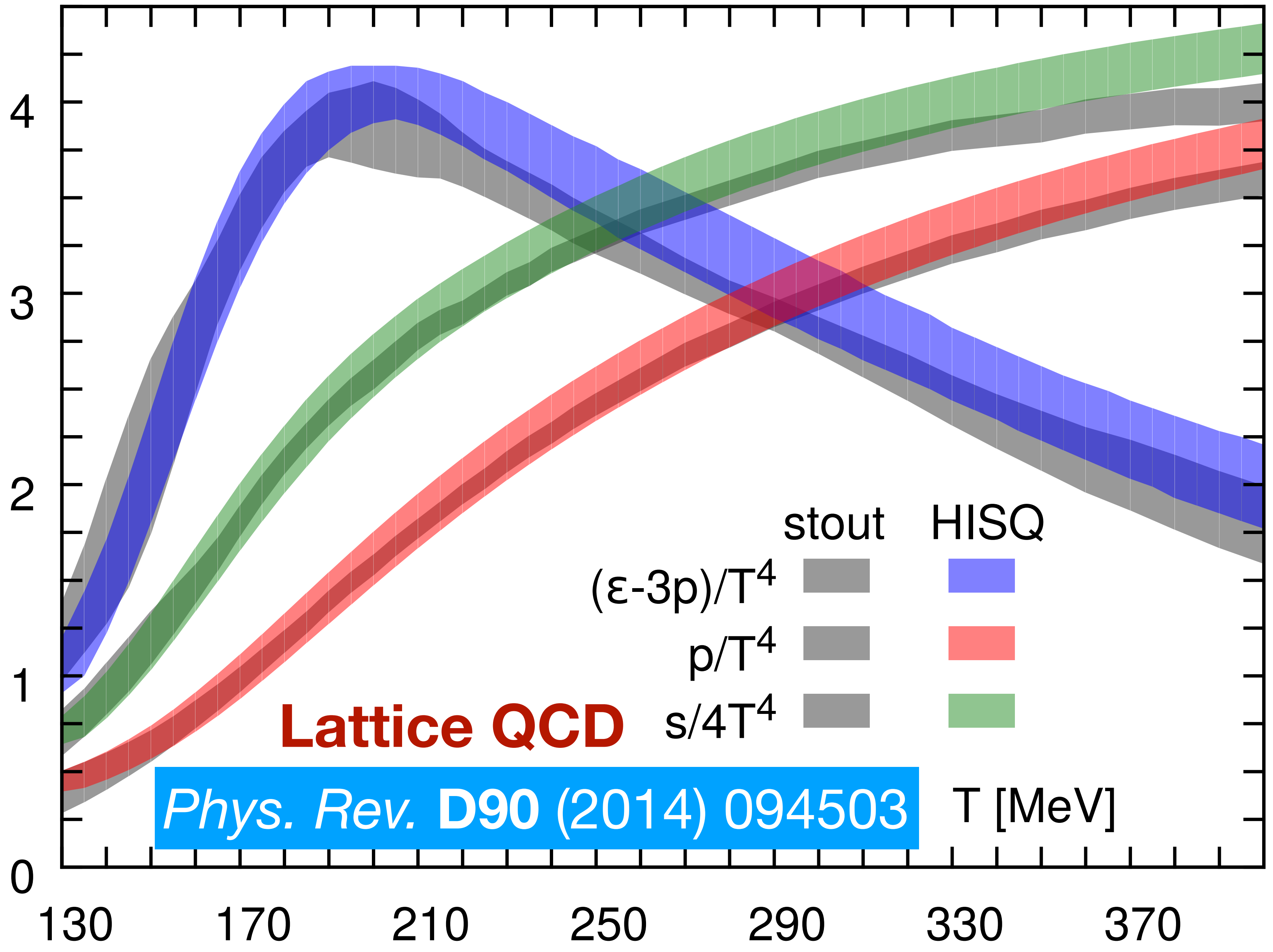
FAiR-CBM
Capability of particle identification
Performance of di-lepton measurments

Backup

QCD phase transition



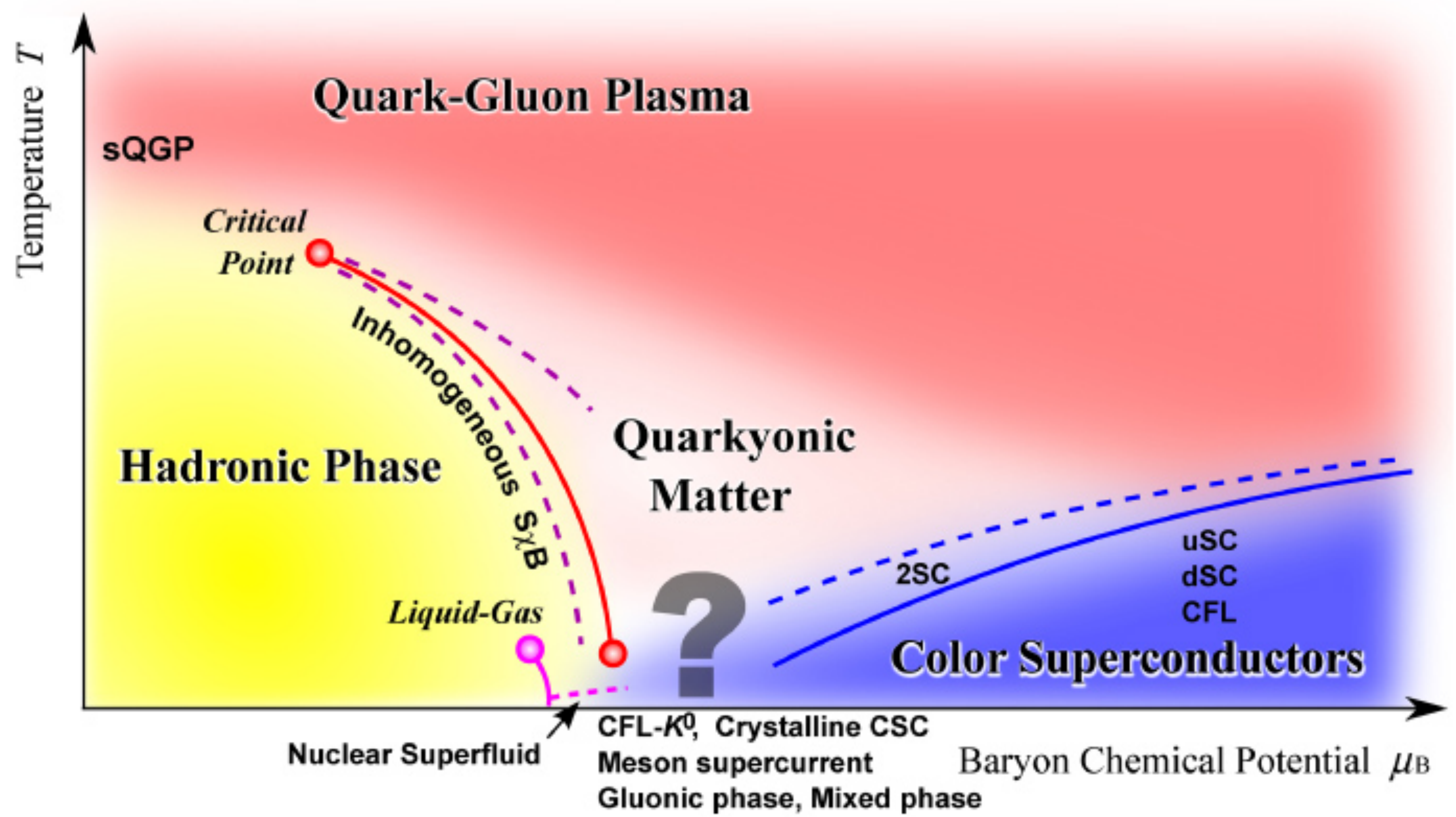
- QCD running coupling constant
  - ➡ Quark confinement and asymptotic freedom



- Lattice QCD prediction
  - ➡ A phase transition at $T_c \approx 175$ MeV

QCD phase diagram

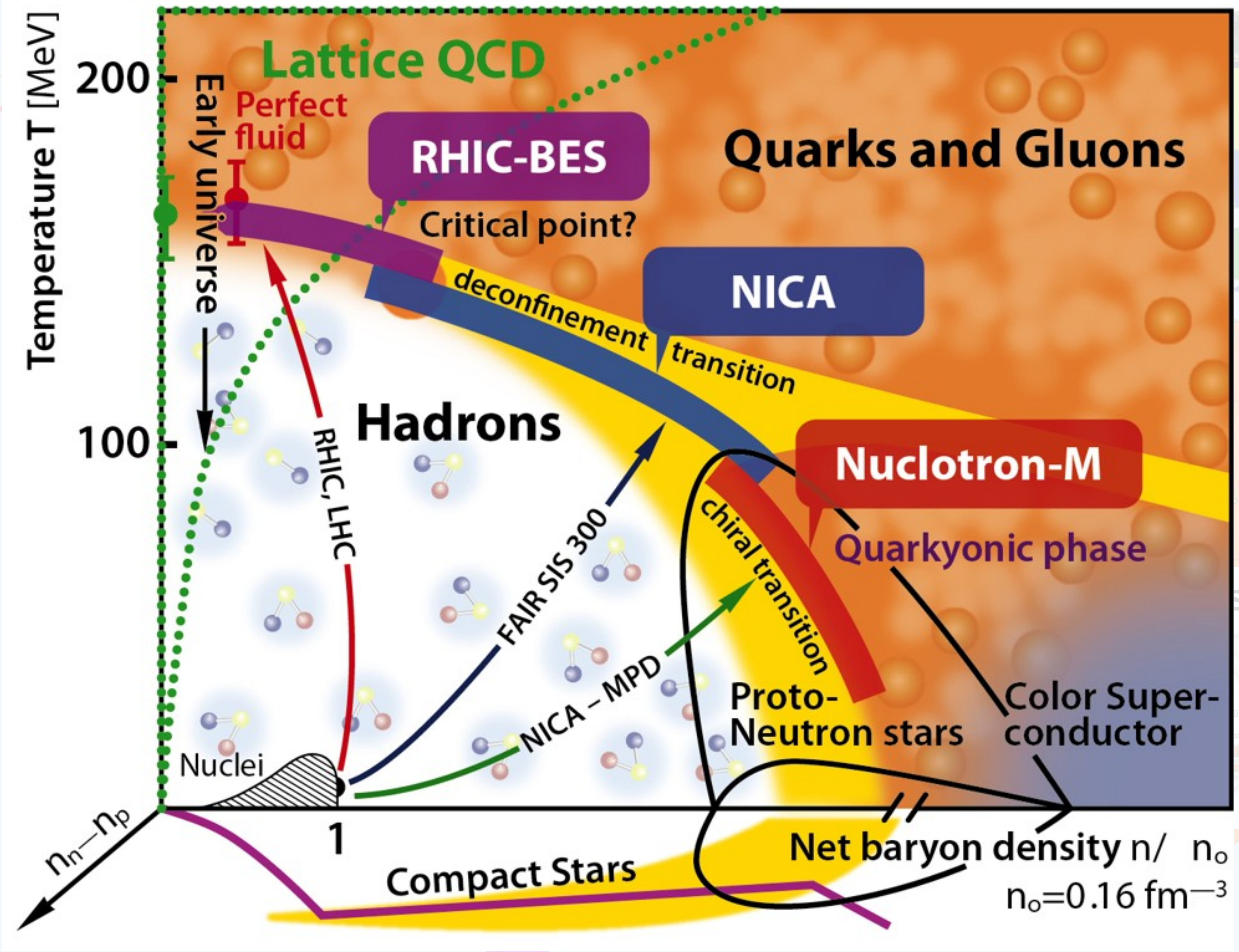
Prog. Part. Nucl. Phys. **72** (2013) 99



- High temperature at $\mu_B \approx 0$
  - ➡ Early universe
  - ➡ Chiral symmetry restoration
- Finite μ_B
  - ➡ Rich structure
  - ➡ Neutron star etc.
- Critical point (?)
  - ➡ 1st order phase transition or crossover (?)

- Continuous heating / compressing the hadronic matter — a phase transition into a new state of matter: the **quark-gluon plasma (QGP)**

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

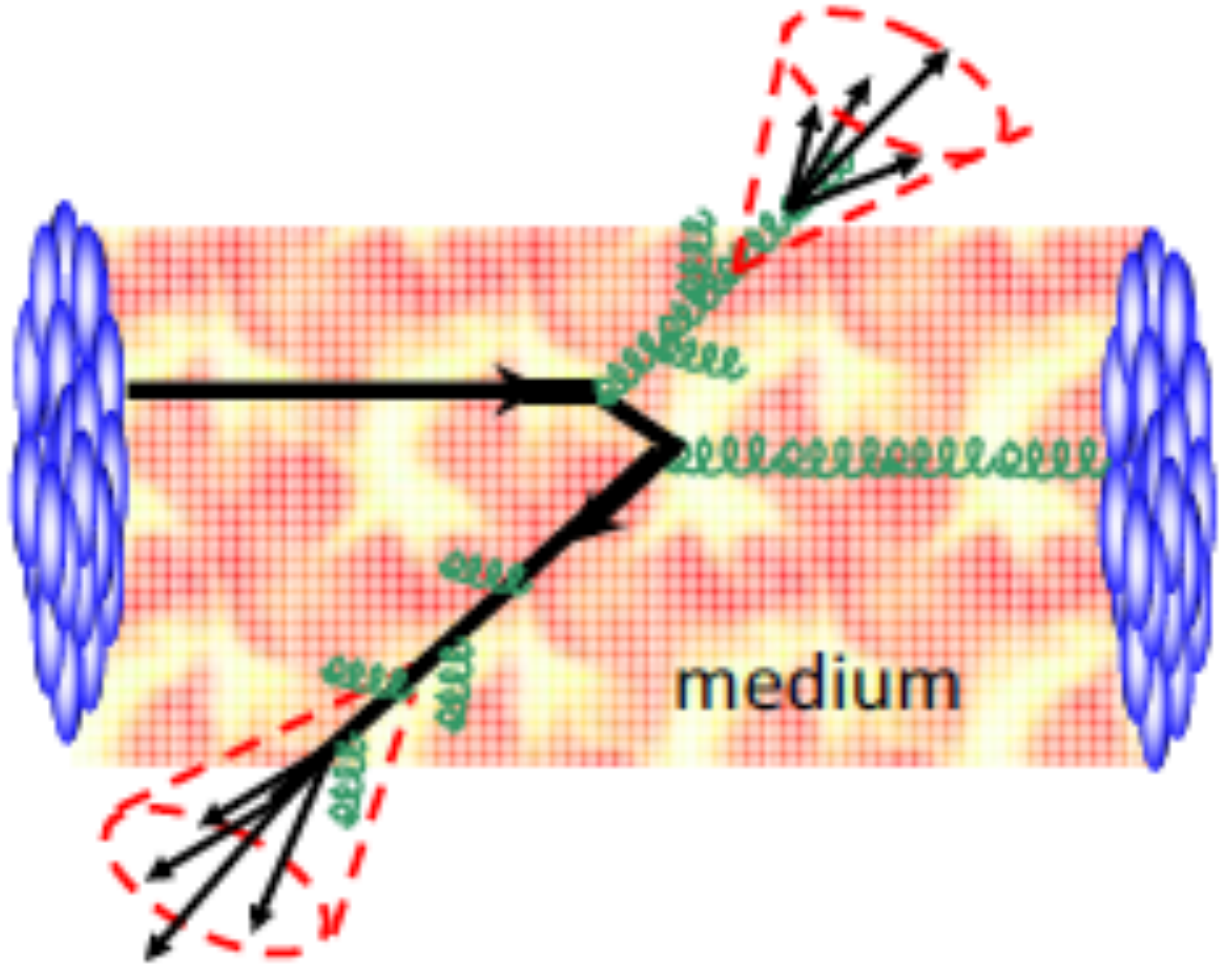
- Critical point search
- Correlations, di-lepton production…

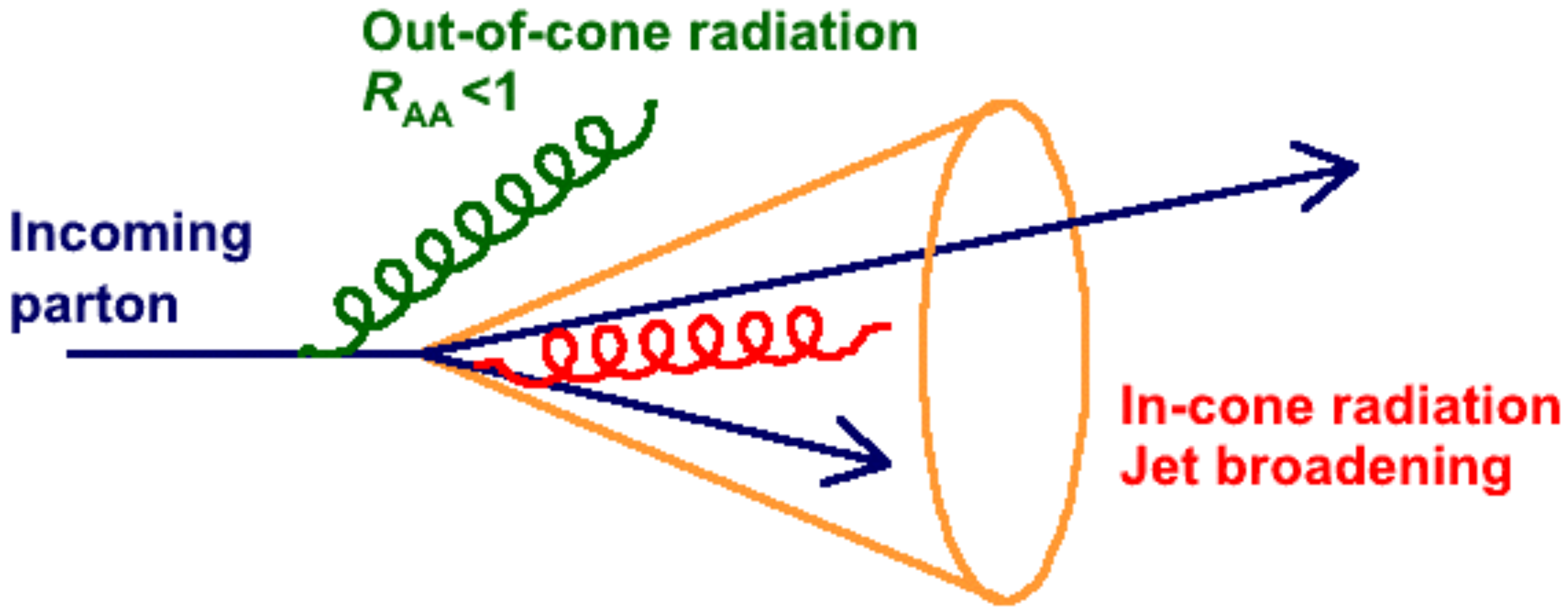
Low temperature and large μ_B: NICA, FAiR

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

Jet production at RHIC and LHC

- Jet: a spray of particles from hard parton fragmentation
  - ➡ Get closer access to parton energy
- Aim Hard partons produced before the QCD medium forms
- Interact with the hot and dense medium

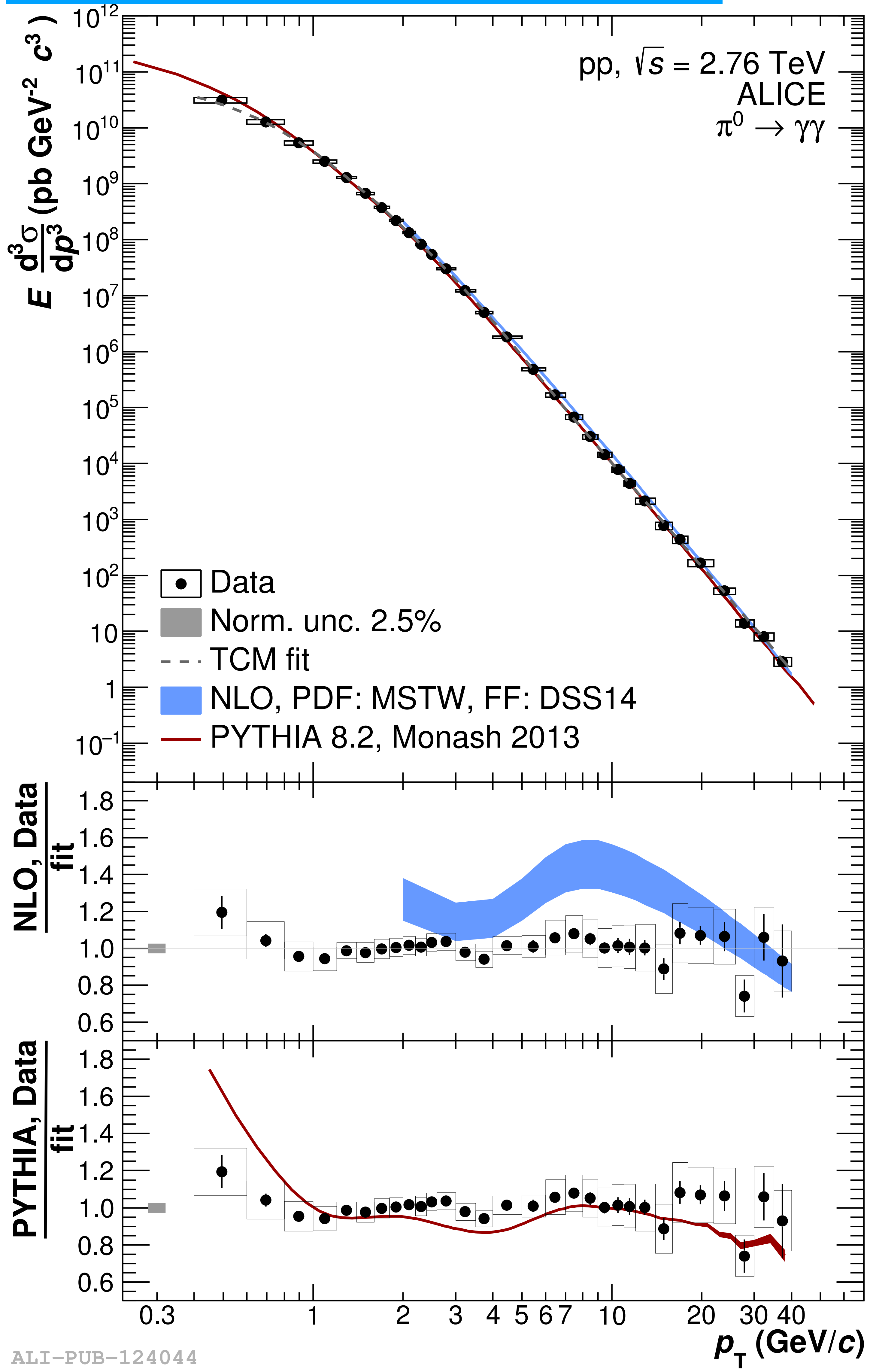




- Out-of-cone radiation: energy loss in jet cone
  - ➡ Jet yield suppression, dijet or hadron–jet acoplanarity…
- In-cone radiation: medium modified fragmentation
  - ➡ Jet shape broadening, modification of transverse energy profile…

Neutral pion production

ALICE *Eur. Phys. J.* **C77** (2017) 339



- Neutral pions — unique trigger particles for the gluon jet tagging, baseline for the γ-jet

- Neutral pion spectrum is measured up to p_T = 40 GeV/c

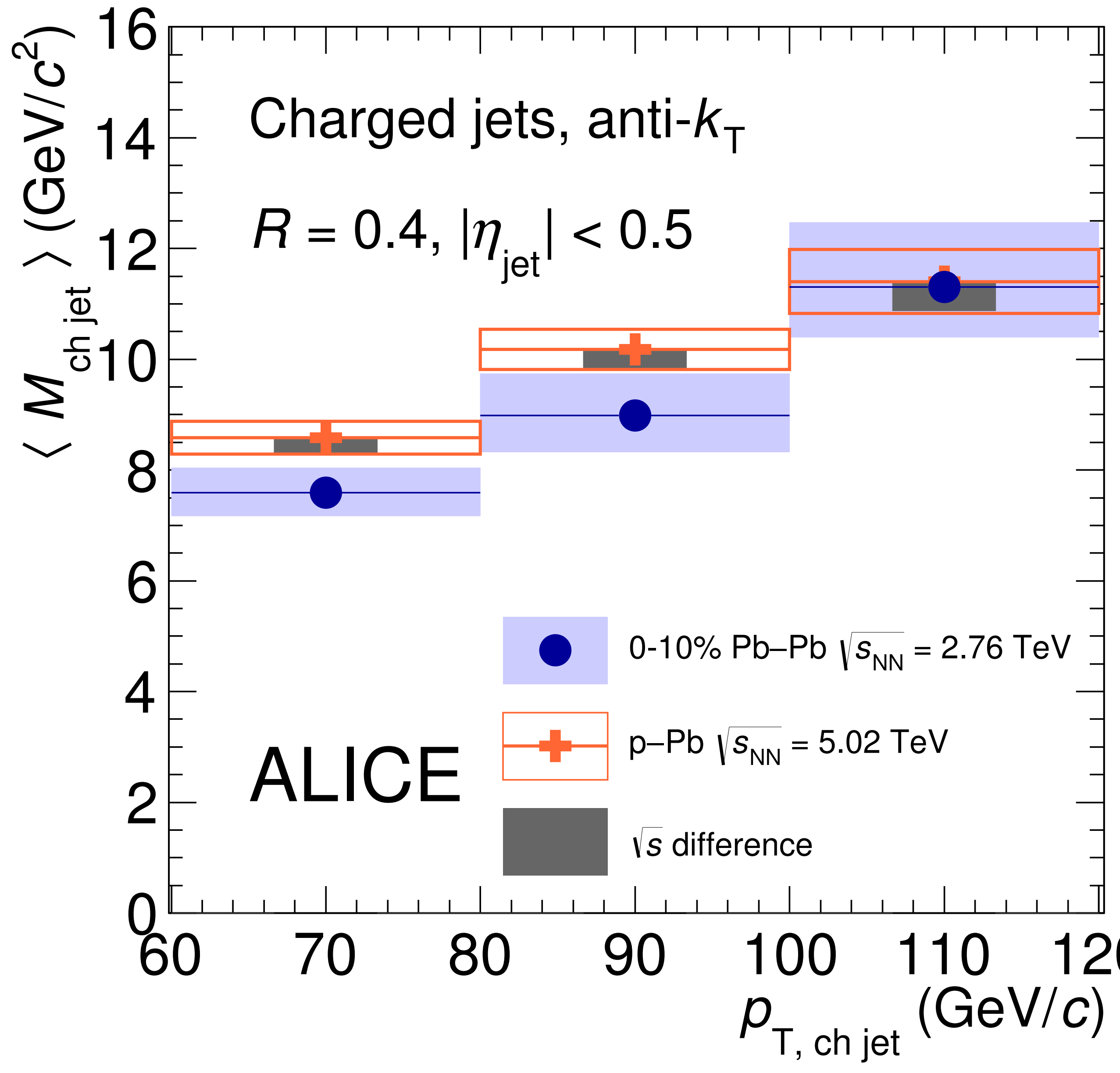
➡ Thanks to the new shower shape method for high-p_T π^0 identification developed by ALICE-China group

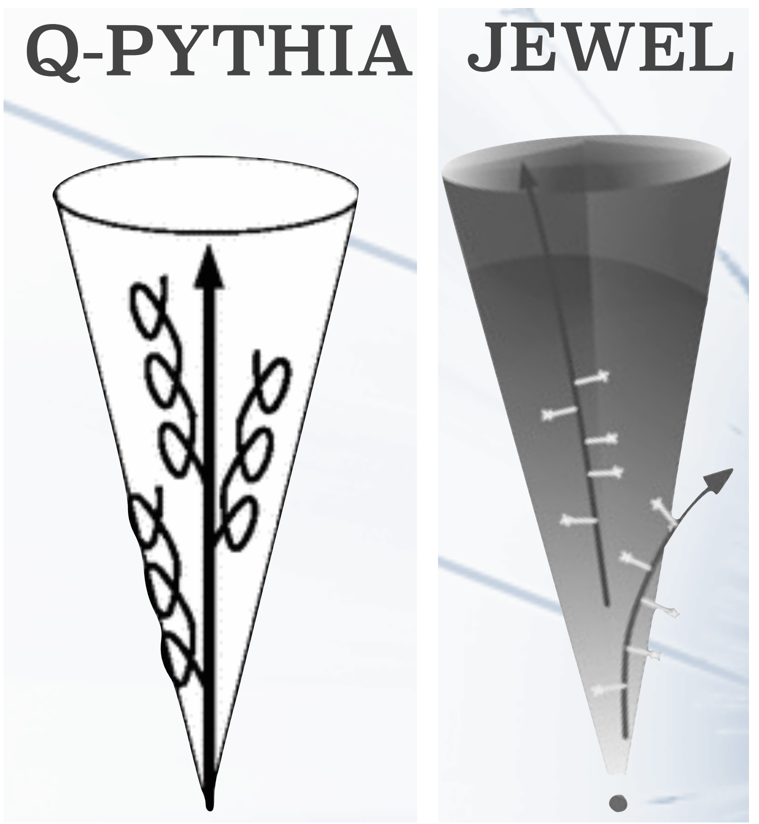
➡ New constraint on QCD predictions, especially on understanding the QCD long-range properties such as PDFs and vacuum FFs

➡ Important baseline for heavy-ion collisions

Jet structure

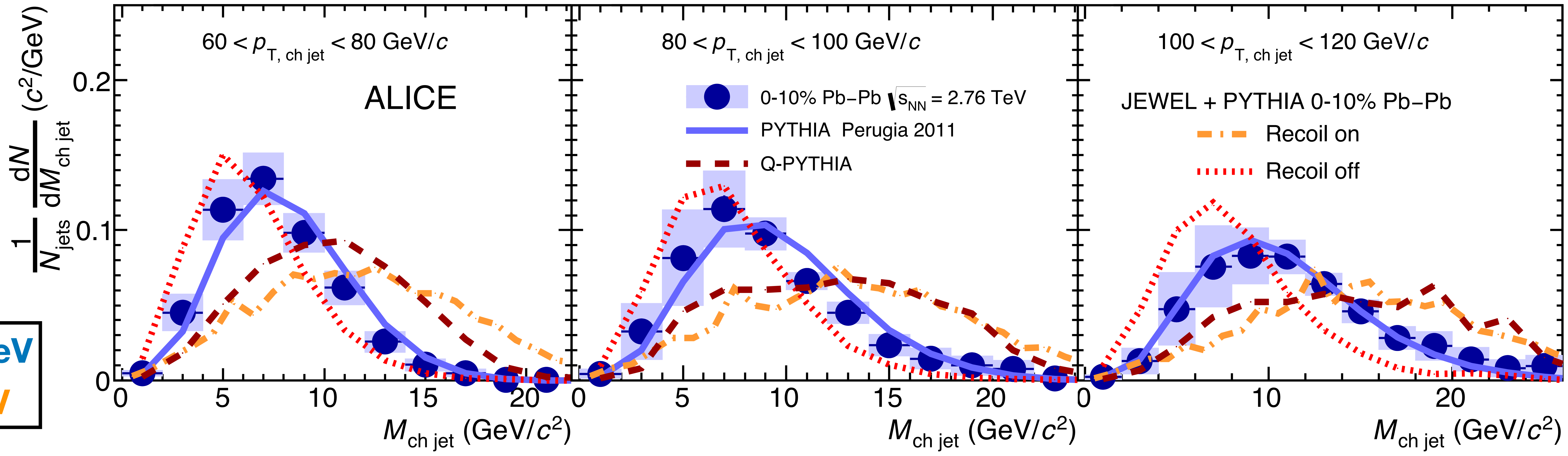
ALICE *Phys. Lett.* **B763** (2016) 238





Pb–Pb 2.75 TeV
p–Pb 5.02 TeV

- Jet mass: Pb–Pb distribution is shifted towards smaller masses w. r. t. p–Pb collisions
- Indicate large angle out-of-cone radiation in the medium

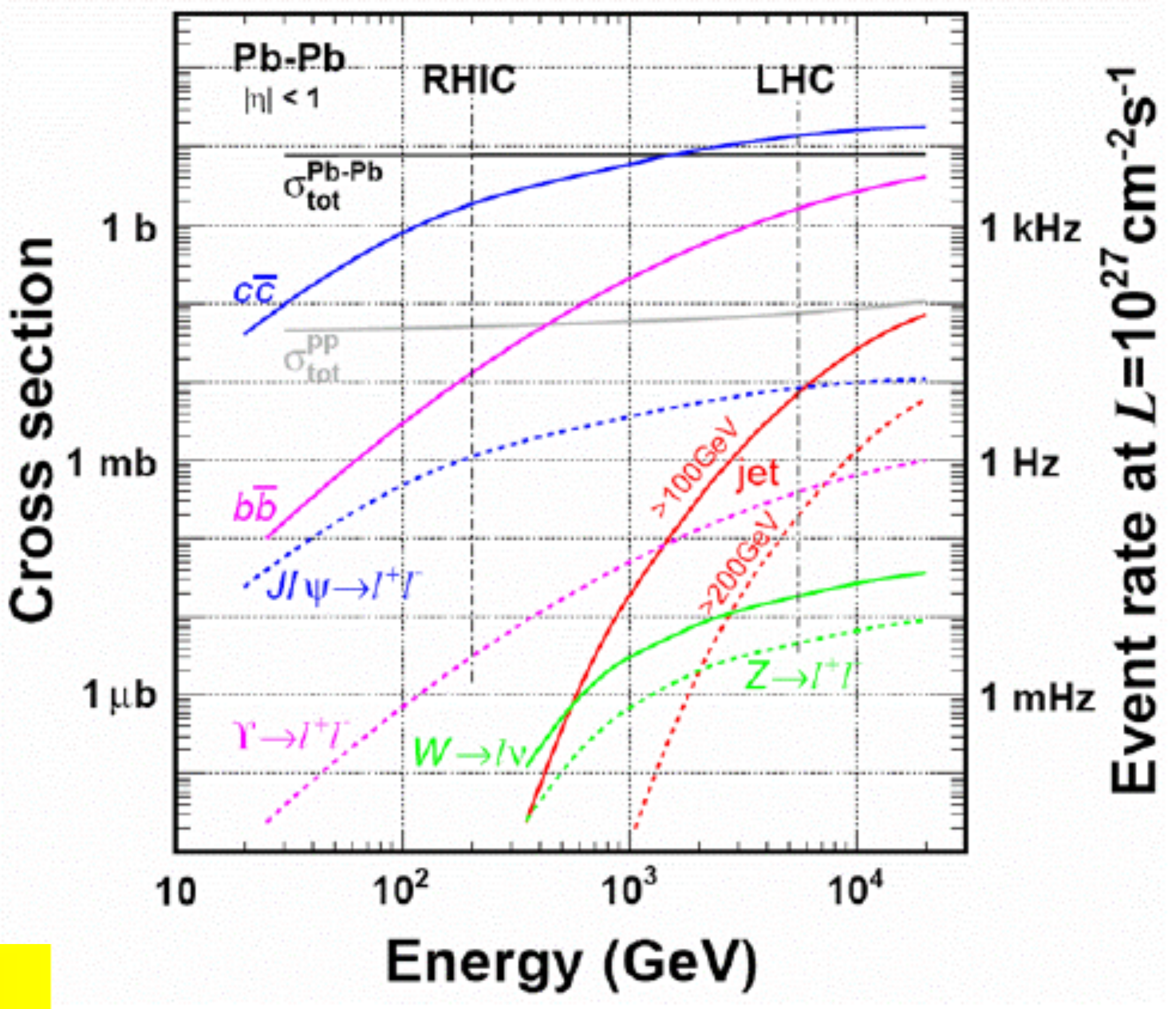


- Challenge to describe data by models
- Important constraints on jet in-cone radiations

- **Q-PYTHIA** Radiation energy loss of BDMPS-Z type — modification of parton splitting function in vacuum
- **JEWEL** Elastic + radiative energy loss — implemented the Landau-Pomeranchuck-Migdal effect

Open heavy-flavour production

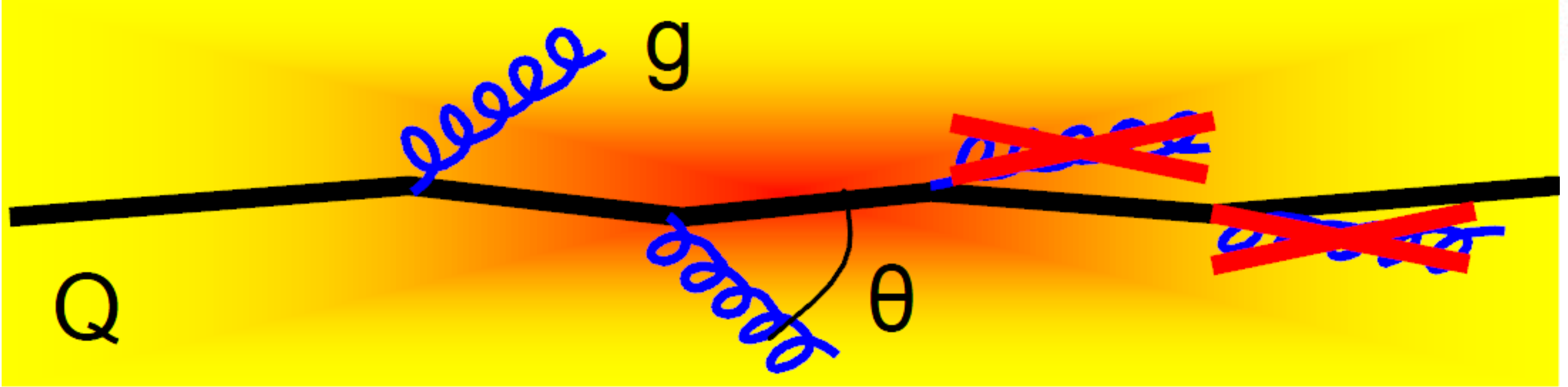
Open heavy-flavours (open charm and beauty particles)



- R_{AA}: Radiative energy loss vs. collisional energy loss
  - ➡ Mass and color charge dependence

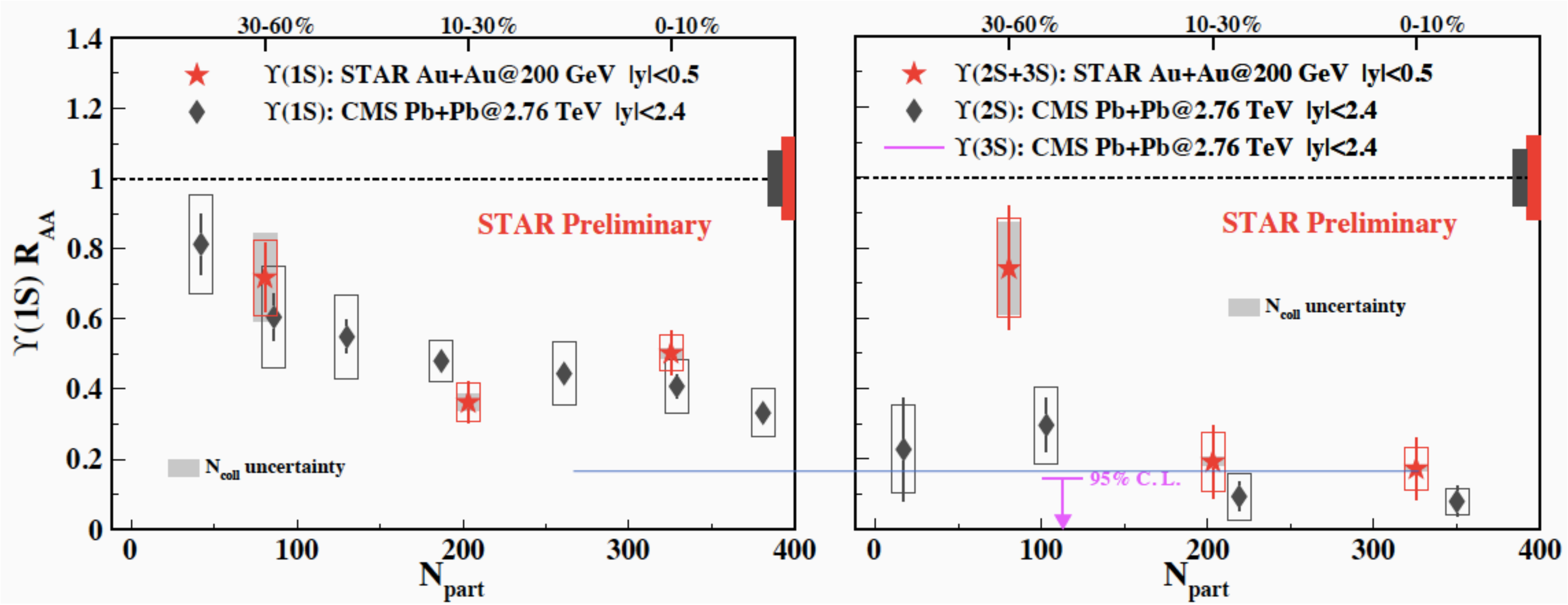
$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

➡ R_{AA}(light hadron) < R_{AA}(D) < R_{AA}(B) ?



- Elliptic flow
  - ➡ Low-p_T: initial conditions and degree of thermalization of HF in QGP
  - ➡ High-p_T: path-length dependence of HF in-medium energy loss
- Medium modification of heavy-flavour hadron formation
  - ➡ Hadronization via quark coalescence and / or enhancement of di-quark state

Υ suppression



Combined 2011 di-electron and 2014 + 2016 dimuon datasets

Consistent with sequential melting in QGP

- Υ(1*S*) R_{AA}: similar at RHIC and LHC
- Υ(2*S*+3*S*) R_{AA}: smaller than Υ(1*S*) in the most 10% central collisions

➡ Results at RHIC energies are systematically larger than Υ(2*S*) at the LHC