42nd International Symposium on Physics in Collision

PIC2023

PHYSICS IN COLLISION

42nd International Conference on Physics in Collision

October 10 – 13, 2023
Universidad de Tarapacá, Arica, Chile

Recent experimental results on heavy-ion collisions at RHIC and LHC

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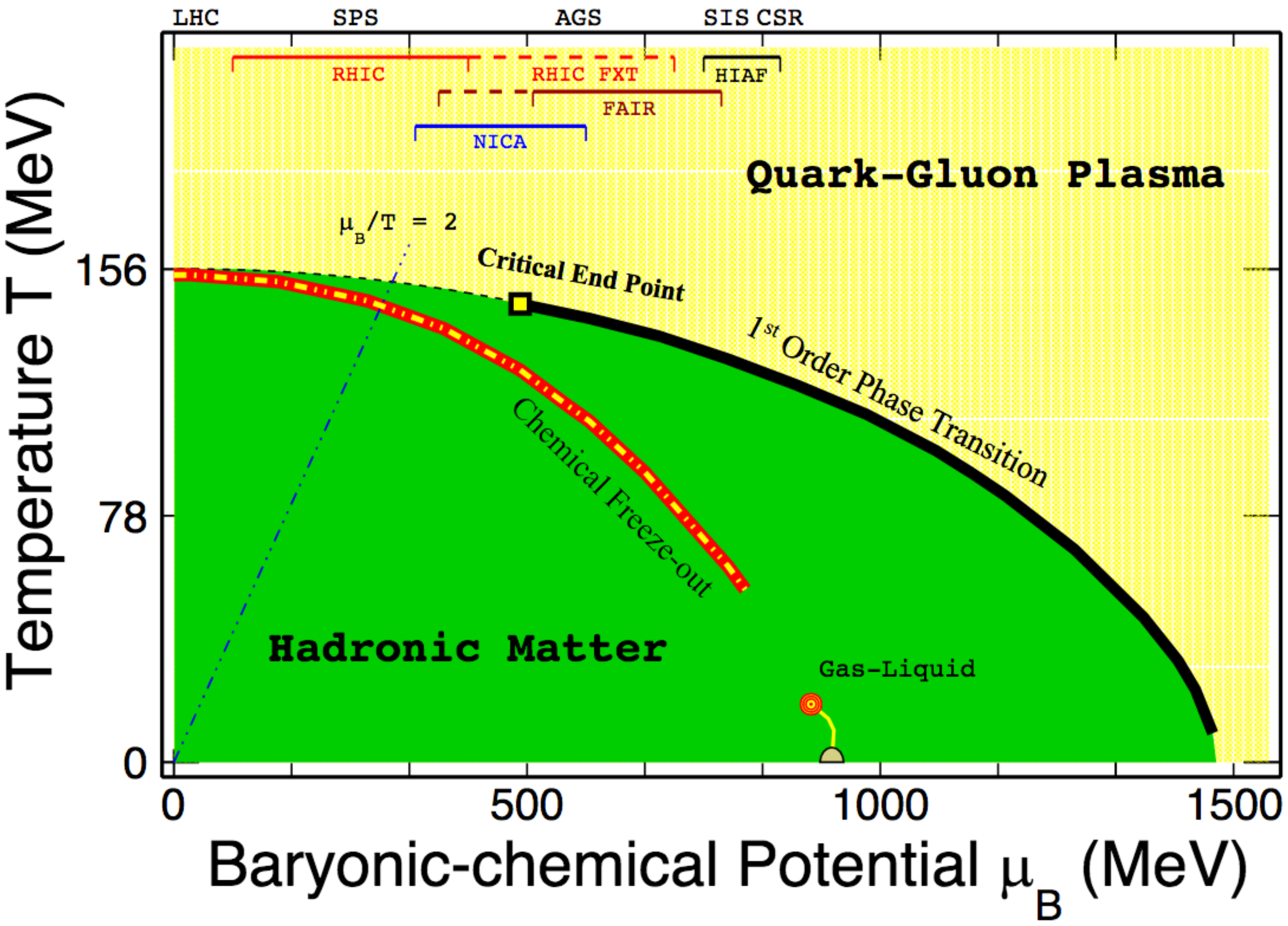
PIC 2023, Aric, Chile, October 13, 2023

BERKELEY LAB

KENT STATE UNIVERSITY

Heavy-ion collisions: QCD and more

Nuclear matter transitions into the deconfined QGP phase at high temperatures



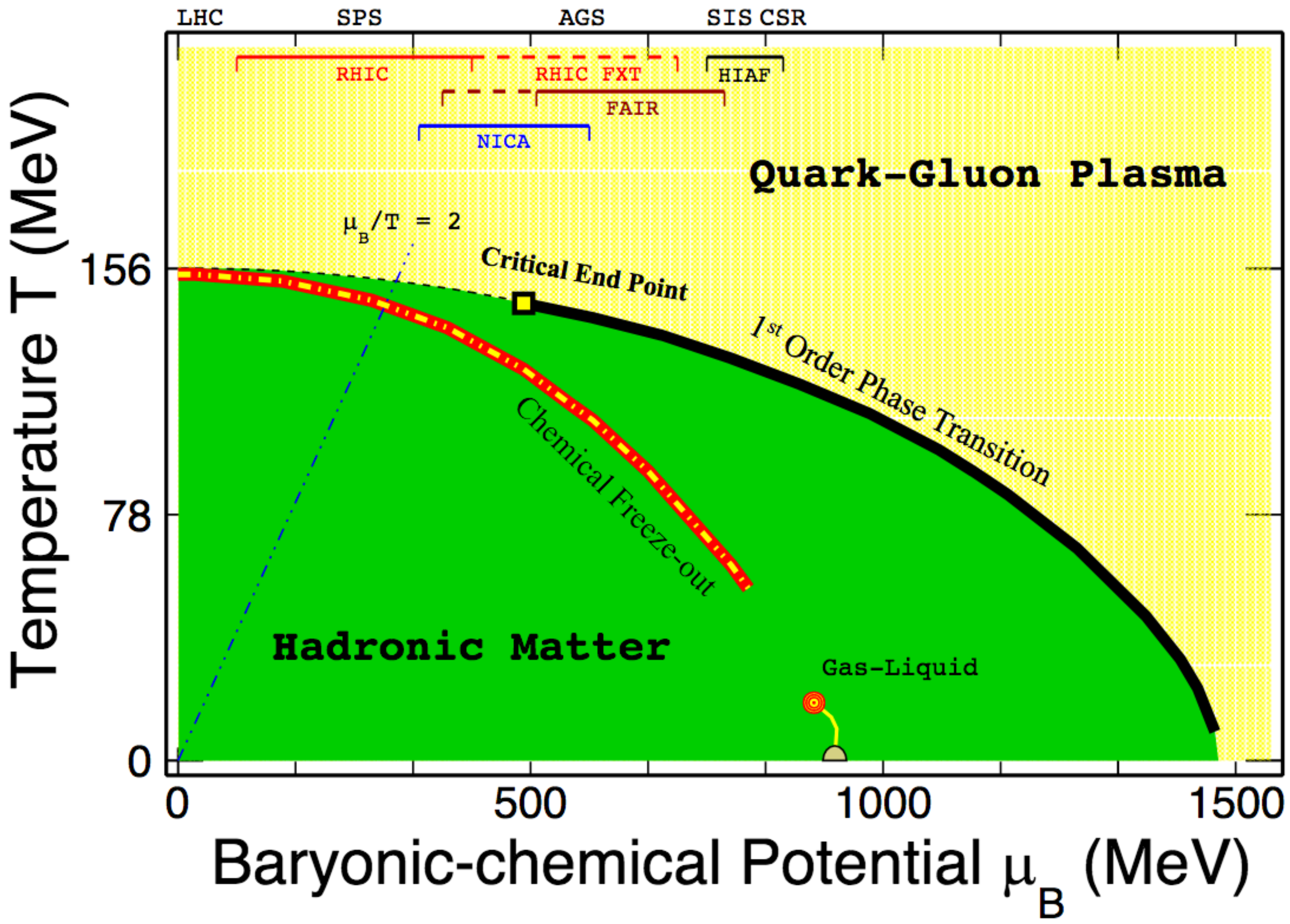
STAR: Phys. Rev. Lett.126 (2021), 092301

- Understand the properties of the QGP phase
- Study QCD phase structure, nature of phase transition

- Also,
  - Non perturbative QCD - hadronization, baryon transport ..
  - Nuclear matter properties at high μ_B, relevant for study of neutron stars
  - Internal structure of hadrons
  - UPCs, beyond SM physics, ….

Heavy-ion collisions: Experimental programs

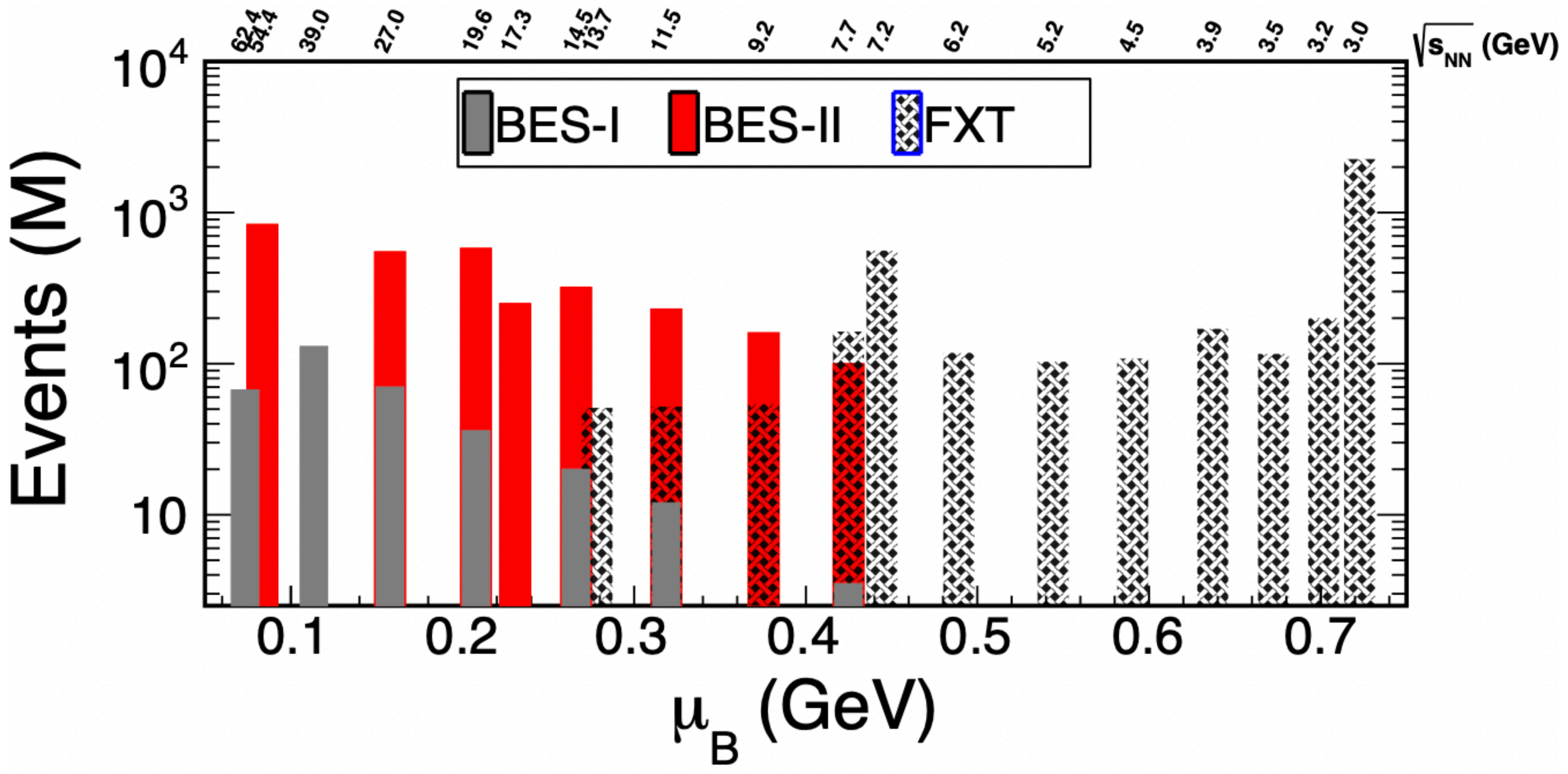
Experimental programs over a wide region of phase space



STAR: Phys. Rev. Lett.126 (2021), 092301

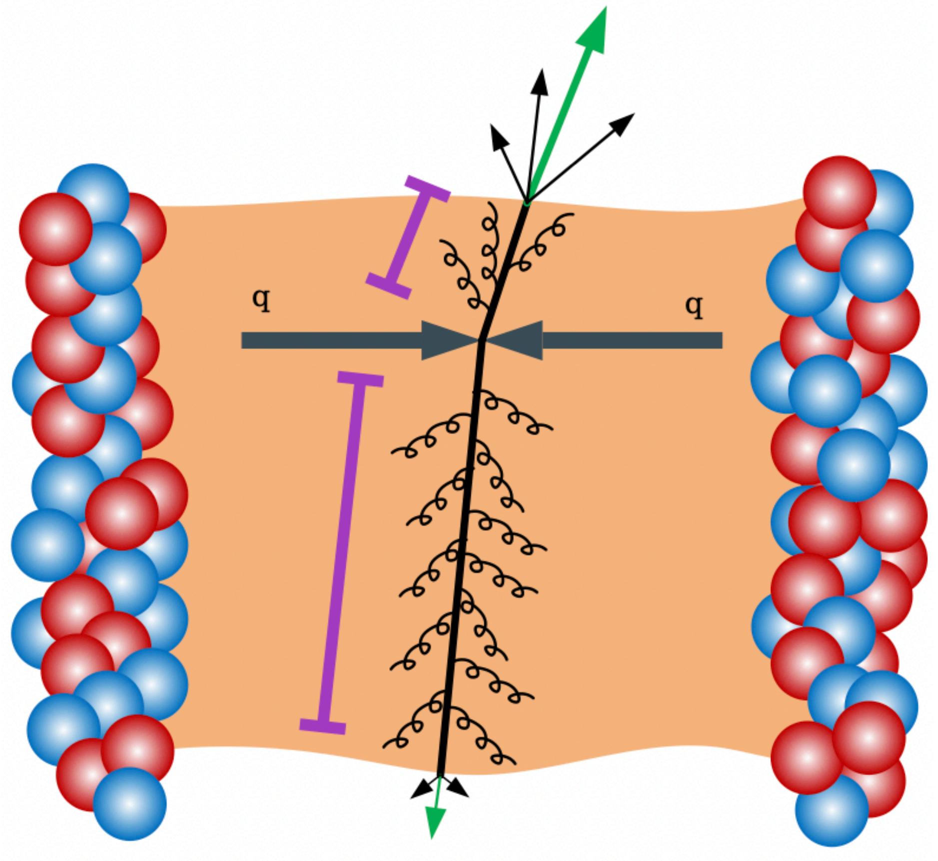
- LHC, top RHIC energies
- RHIC Beam Energy Scan Phase I, II
- FAIR, SPS, NICA ..

BES-II at STAR



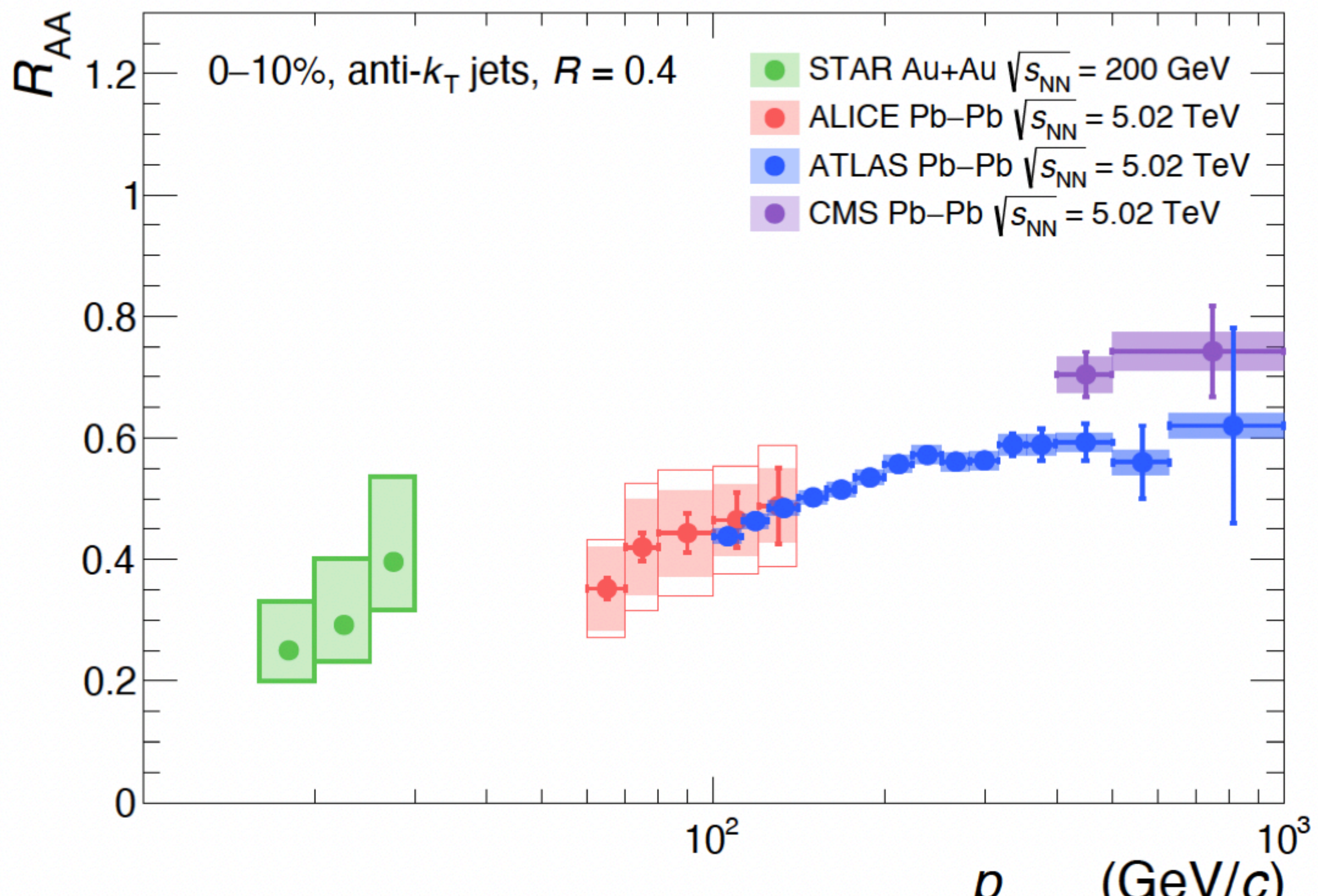
Understanding the Quark Gluon Plasma

Advances in jet quenching measurements



- Suppression of high p_T jets a feature of color charged QGP
- Understand energy loss mechanism, transport properties of QGP

$$R_{AA}(p_T) \equiv \frac{dN_{AA}/dp_T}{N_{binary}^{AA} \times dN_{pp}/dp_T}$$



Muller, Harris arXiv:2308.05743

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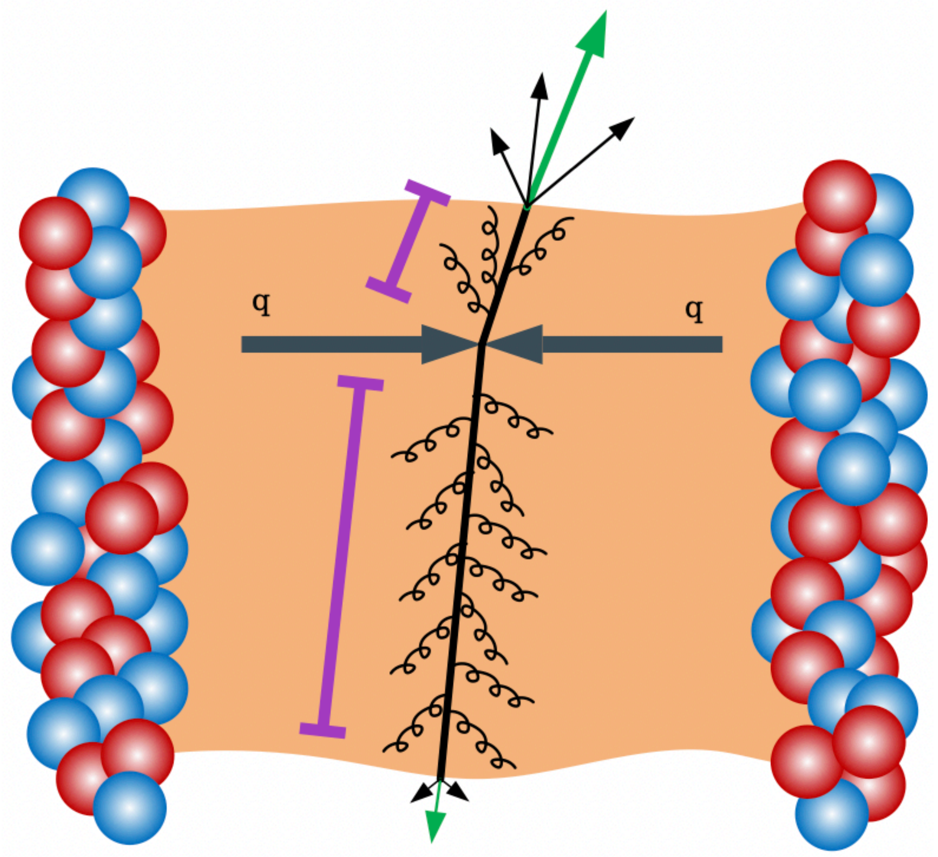

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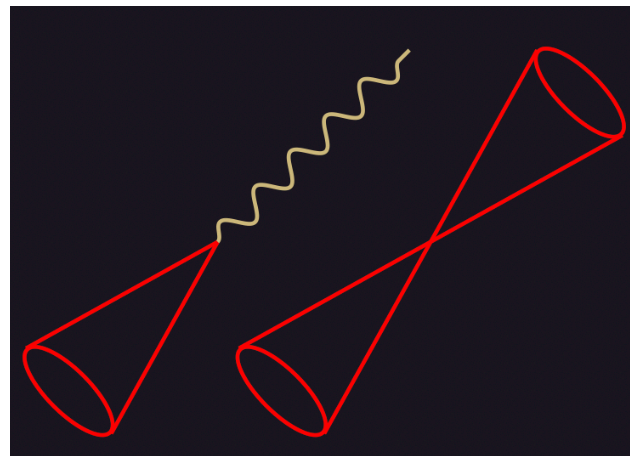
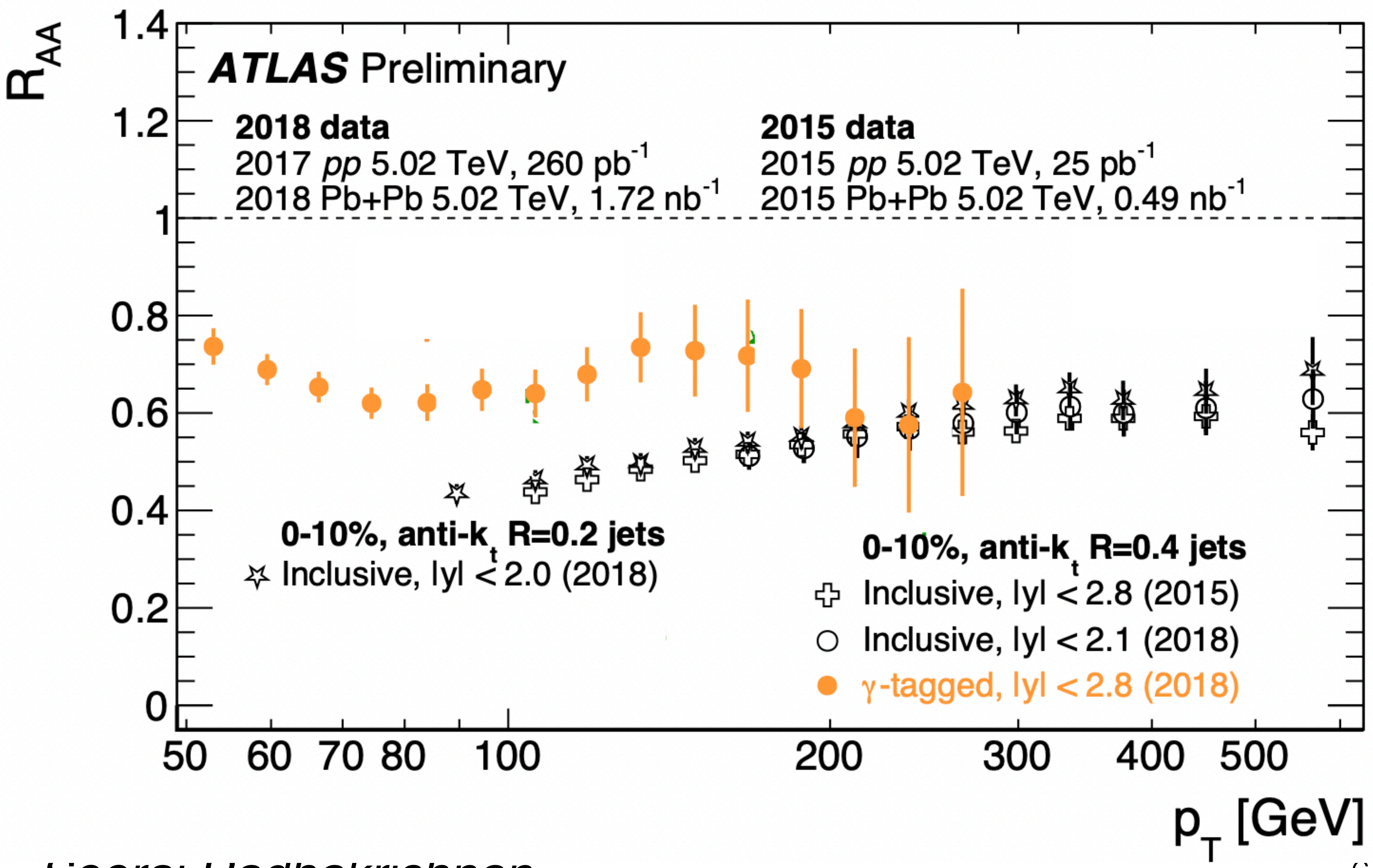




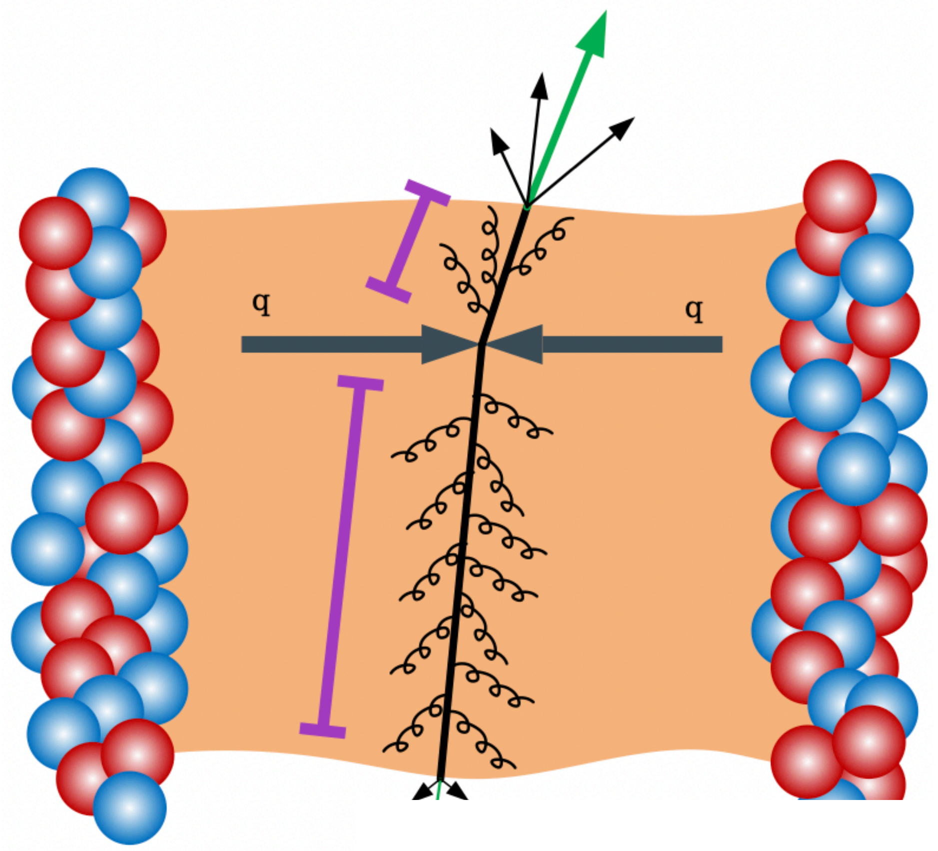
Photon tagged ~ 80% quark jets
Inclusive ~ 40-50% quark jets

$E_{loss}^{g} > E_{loss}^{q} > E_{loss}^{HQ}$

- Flavor dependence of suppression
- Photon tagged jets — more quark jets
- Difference more than from the Casimir color factor?

Flavor dependence of jet suppression

$$R_{AA}(p_T) \equiv \frac{dN_{AA}/dp_T}{N^{AA}_{binary} \times dN_{pp}/dp_T}$$



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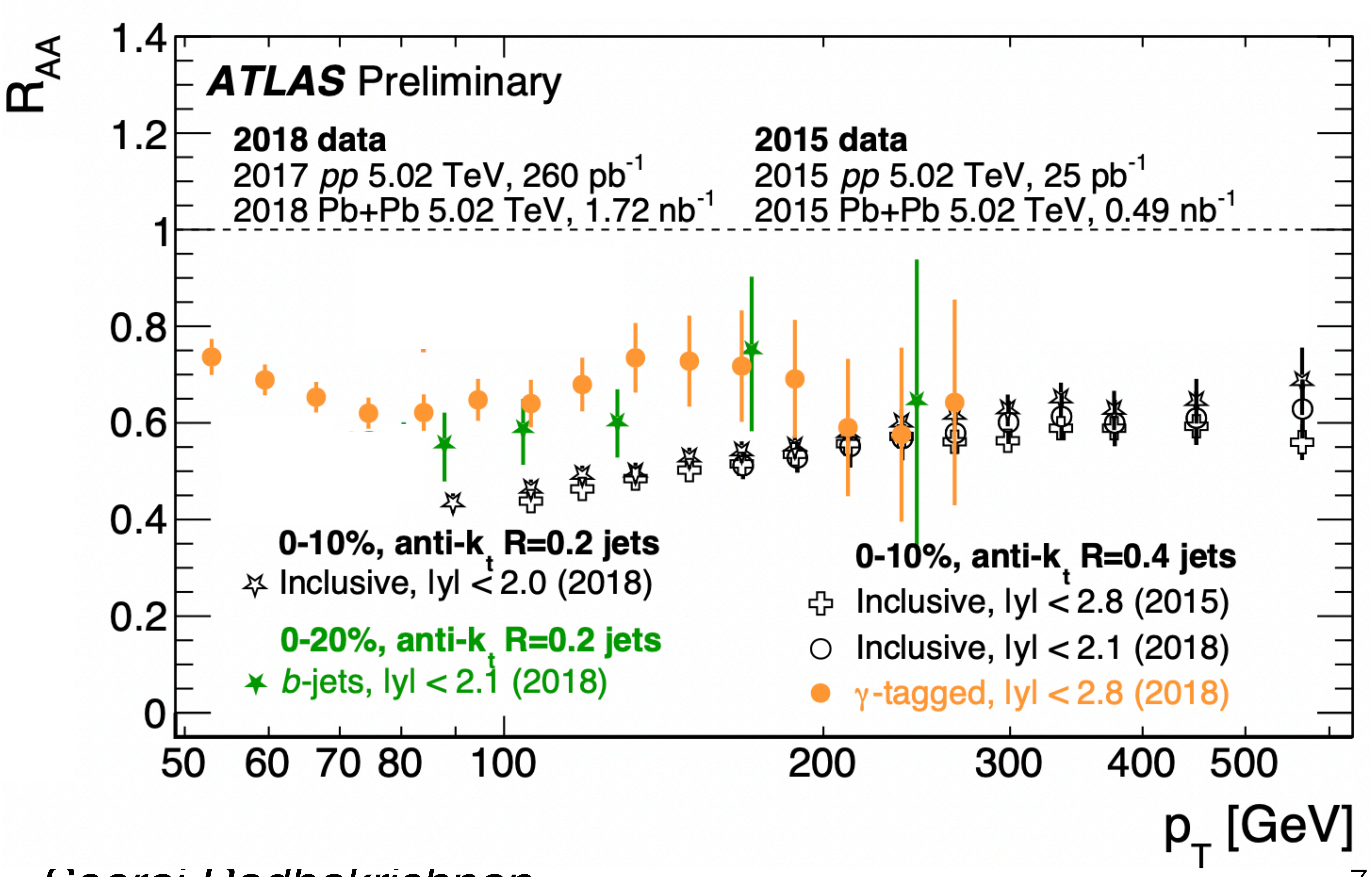


Dead cone effect for HQs, less suppression

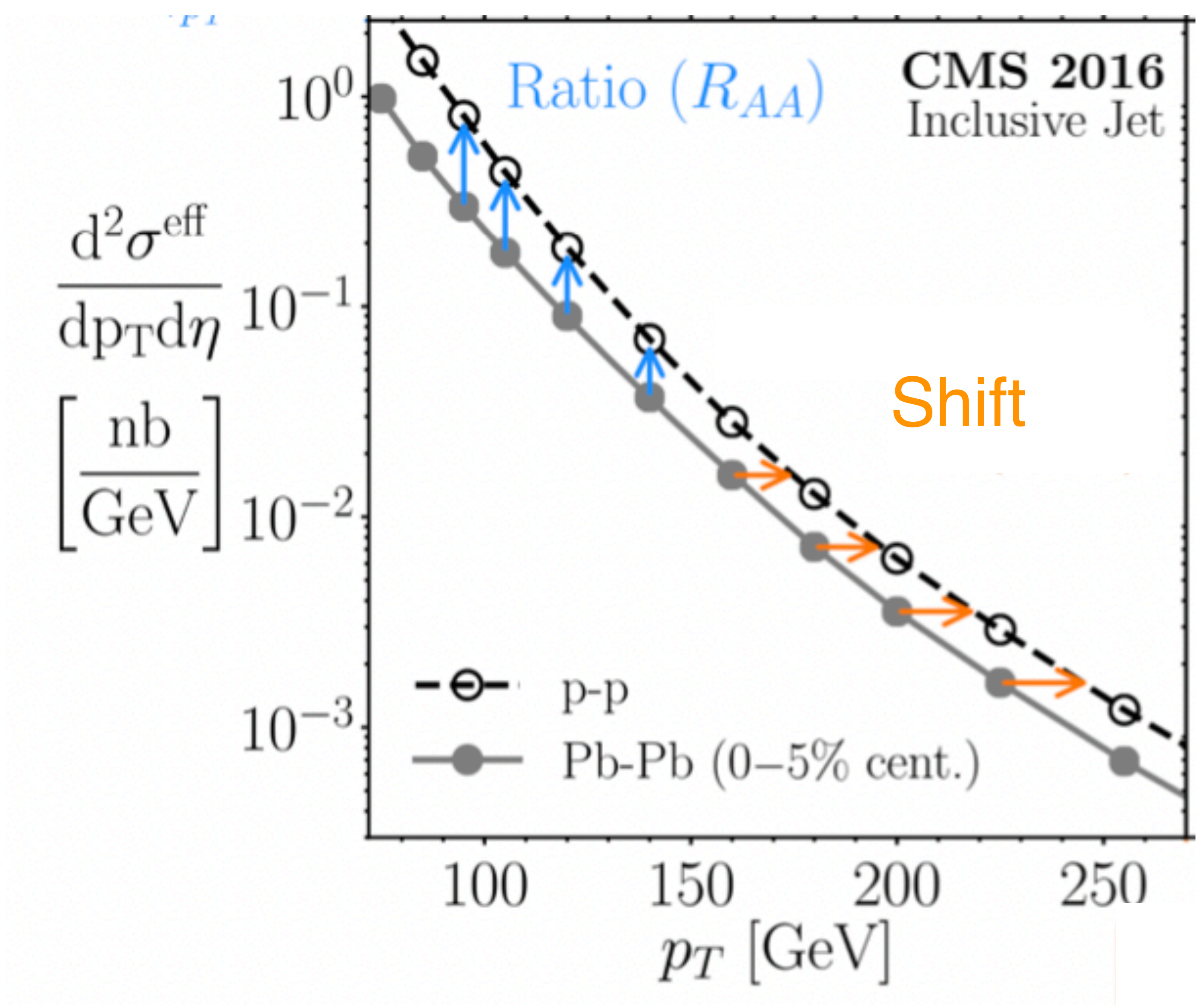
$$E_{loss}^{g} > E_{loss}^{q} > E_{loss}^{HQ}$$

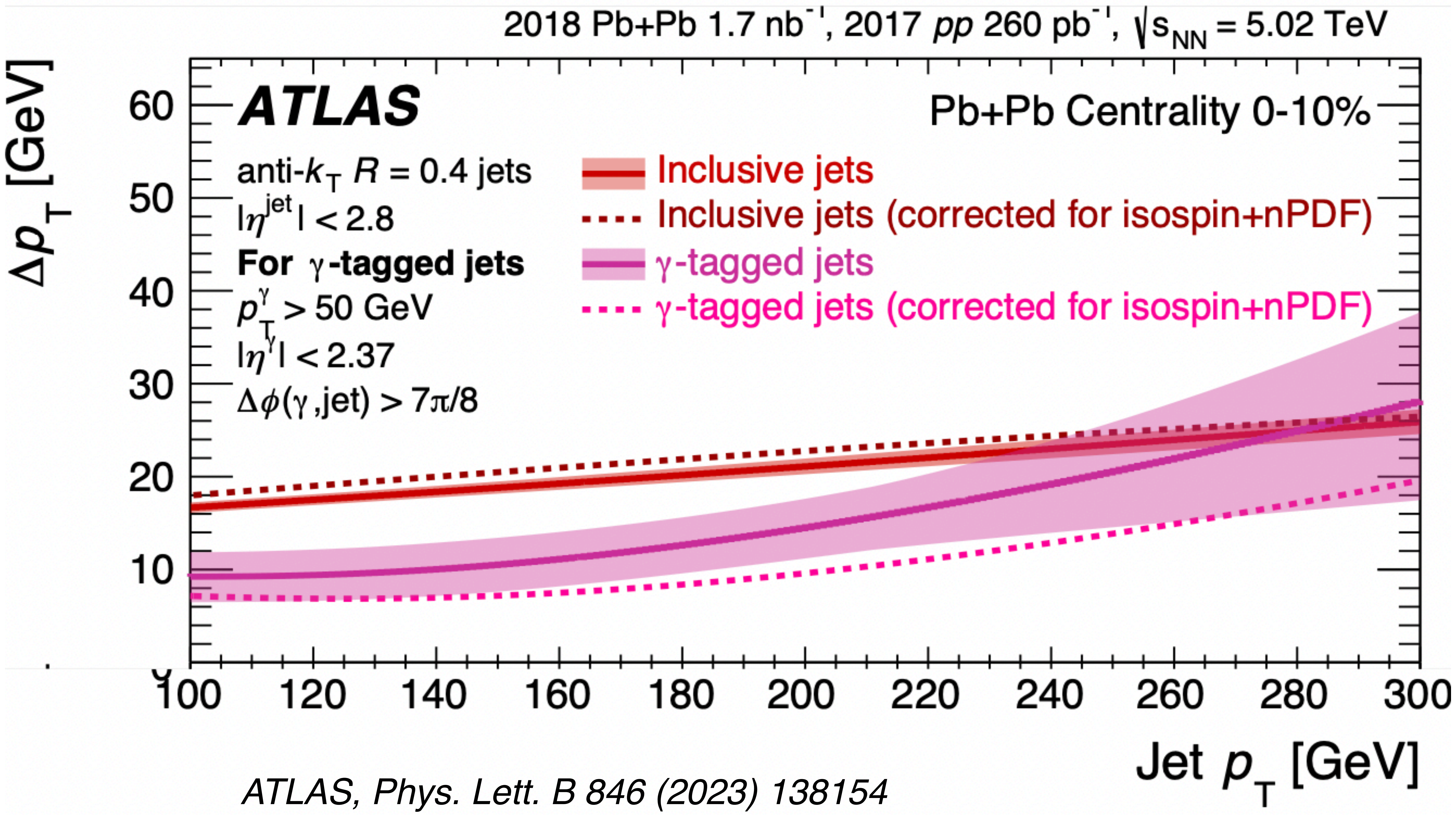
- Flavor dependence of suppression
- b-tagged jets less suppressed than gluon jets
- Comparable to suppression for photon tagged jets

Flavor dependence of jet energy loss

$$R_{AA}(p_T) \equiv \frac{dN_{AA}/dp_T}{N_{binary}^{AA} \times dN_{pp}/dp_T}$$

- Steepness of p_T distributions in p+p different for different flavors
- Alternate ways, look at p_T shift

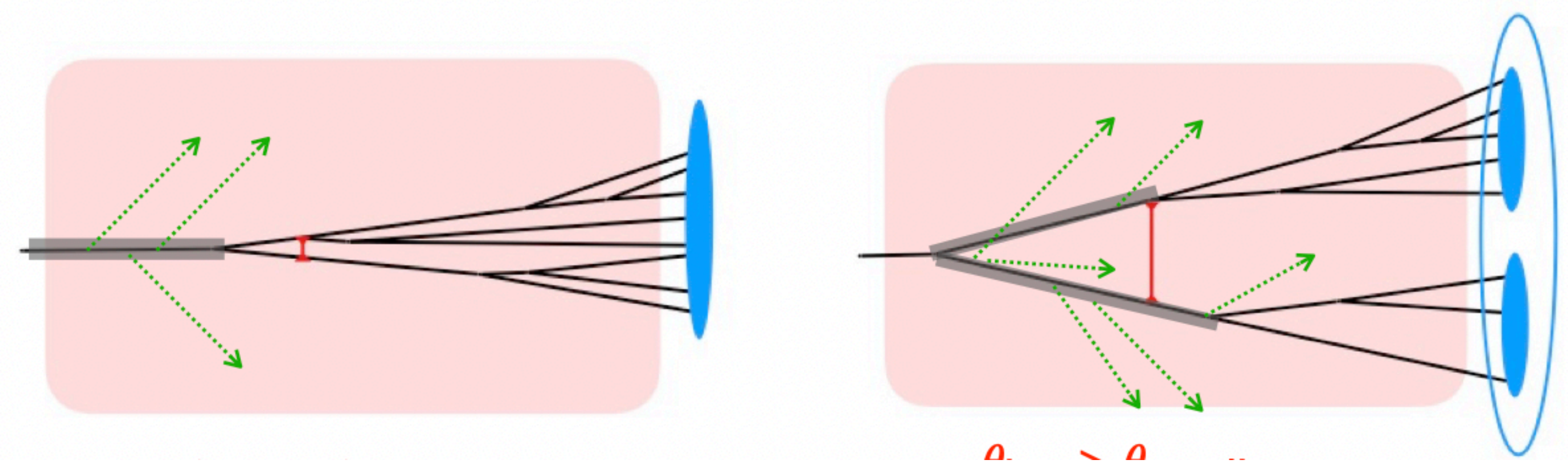




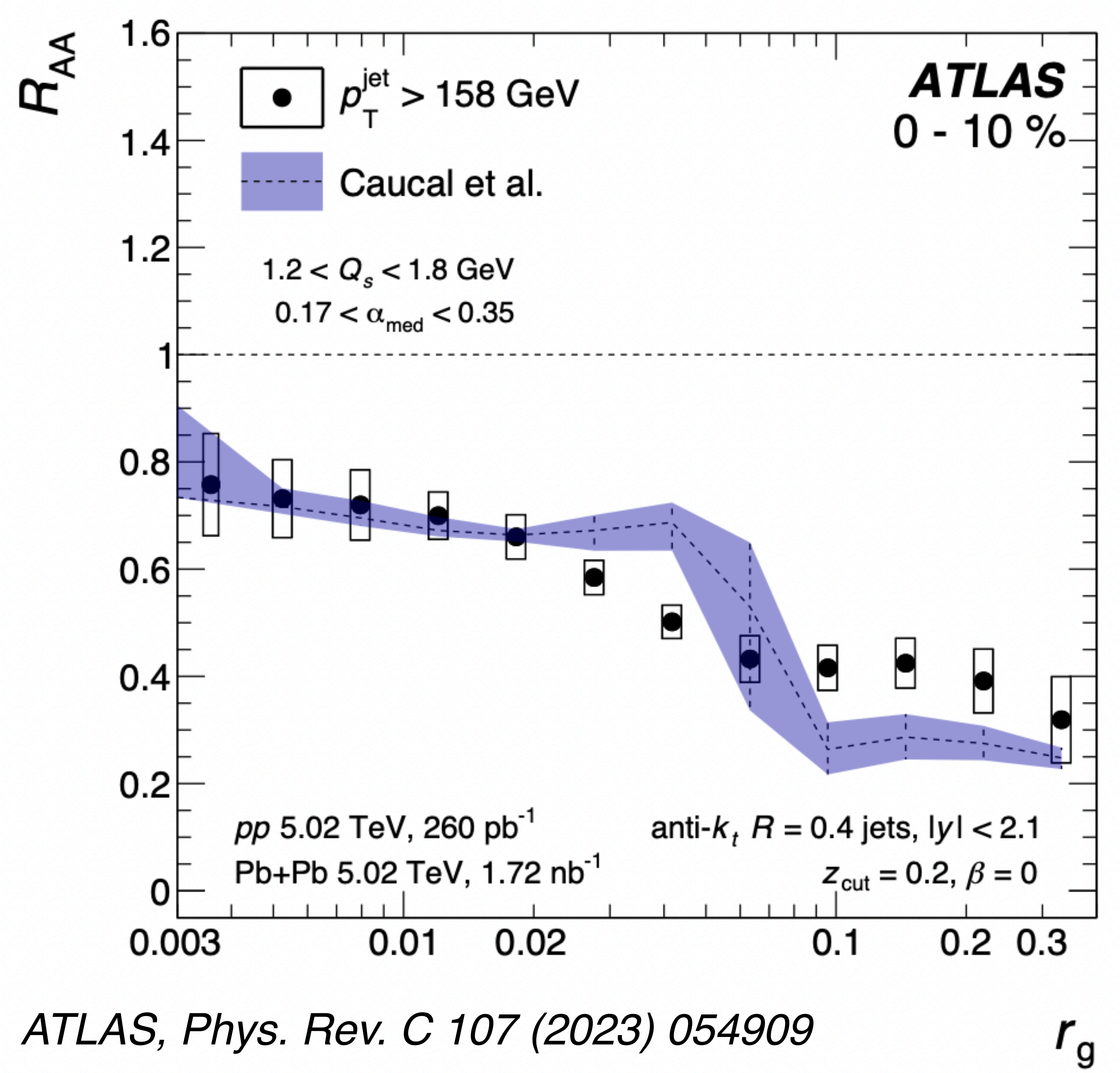
ATLAS, Phys. Lett. B 846 (2023) 138154

- Flavor dependence of suppression
- Photon tagged jets — more quark jets, less suppressed
- Difference more than from the Casimir color factor?

Jet sub-structure modifications

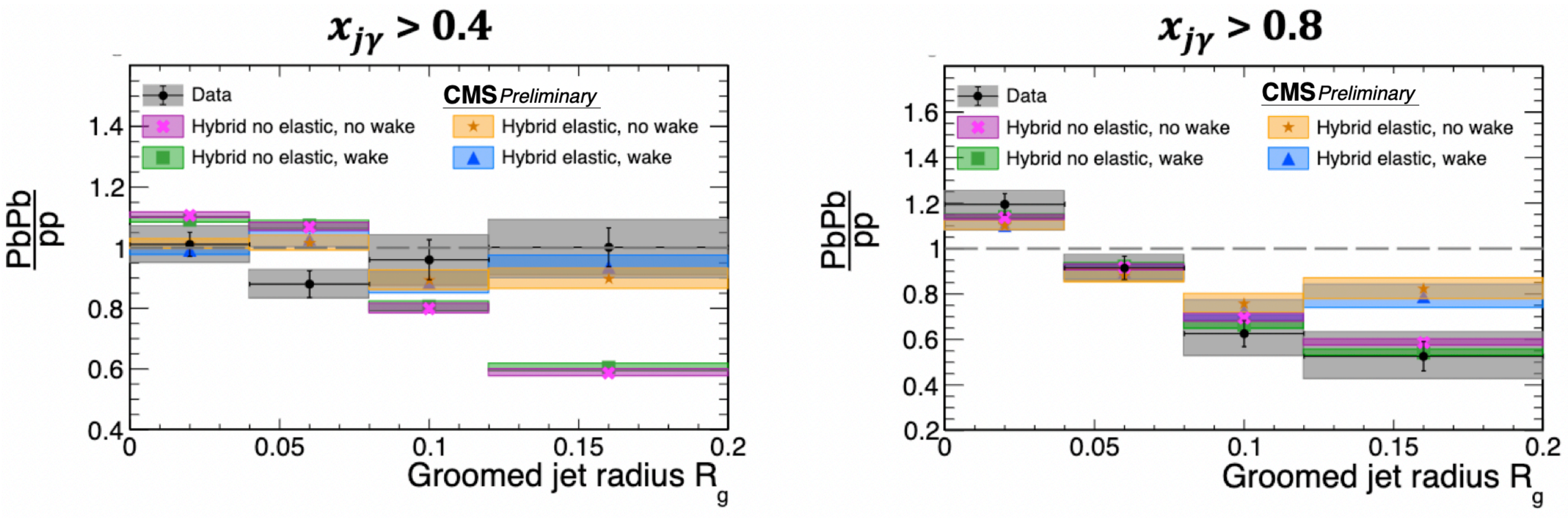


- Do jets with different sub-structure see different modification?
- r_g — angular scale of hardest splitting



ATLAS, Phys. Rev. C 107 (2023) 054909

- Increase in suppression towards larger r_g
- Models with medium induced decoherence describe data
- However, need to understand biases in selection



- For photon triggered jets no r_g dependence of suppression seen, unless selected for recoil jets with large energy loss

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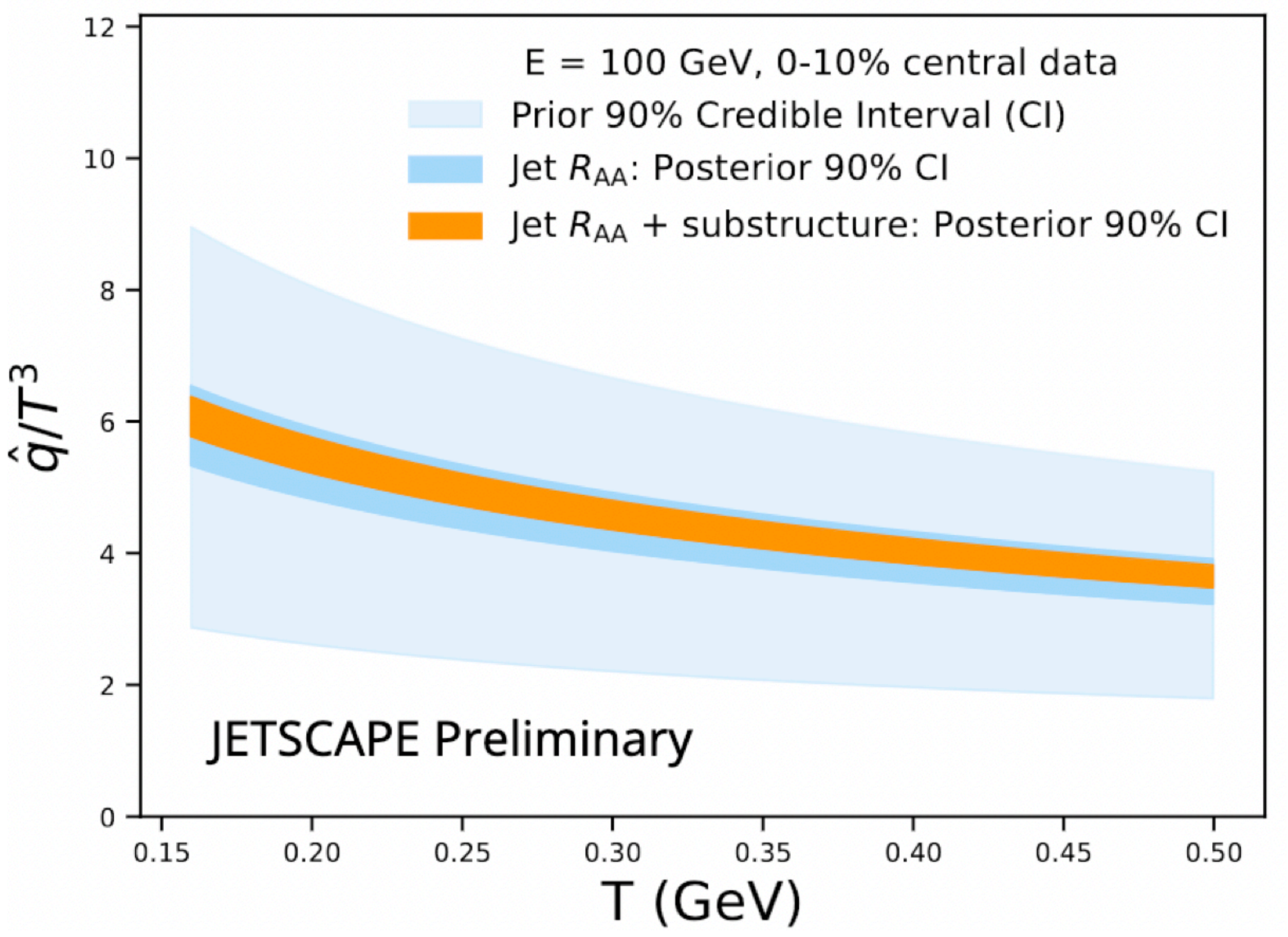
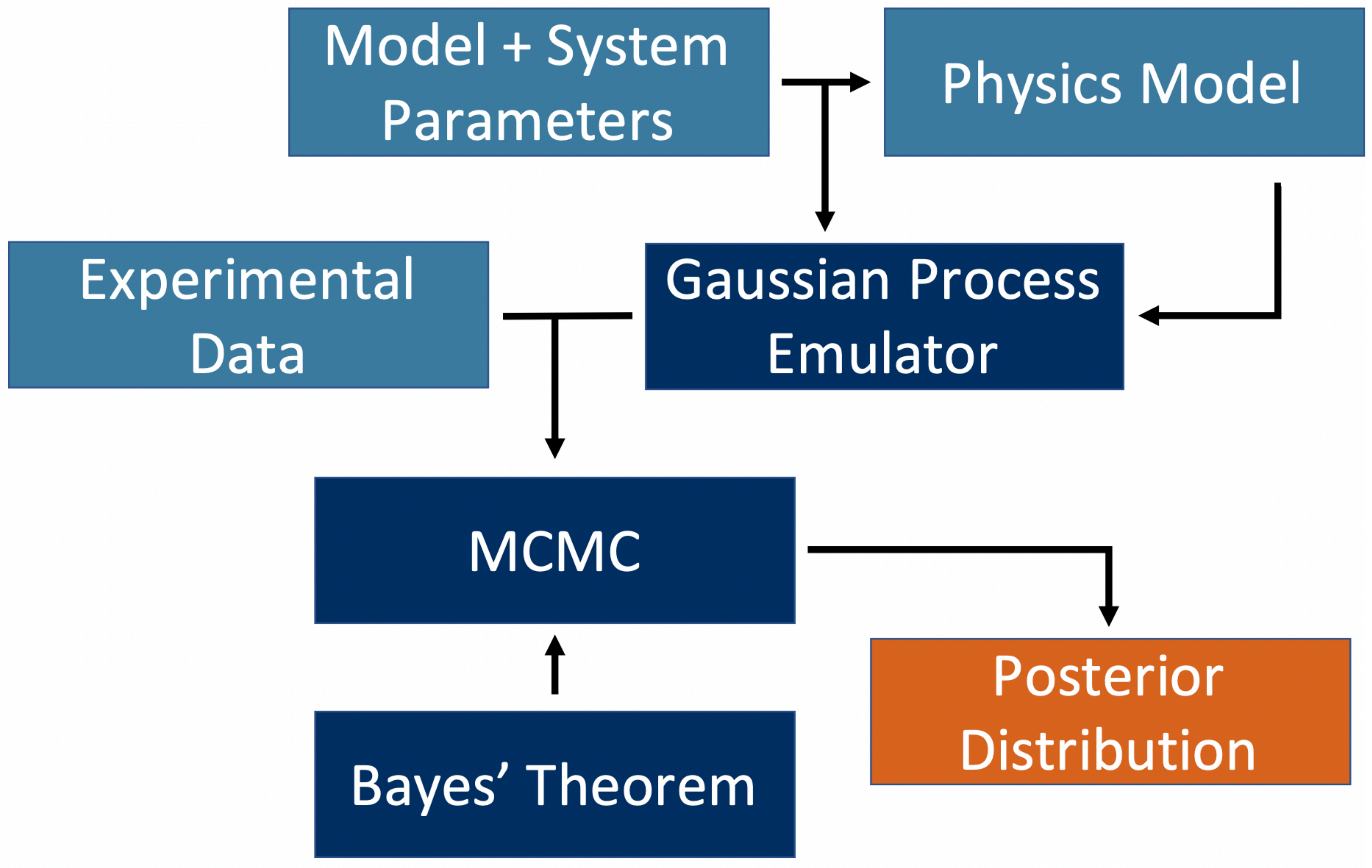
Constraints on QGP transport properties





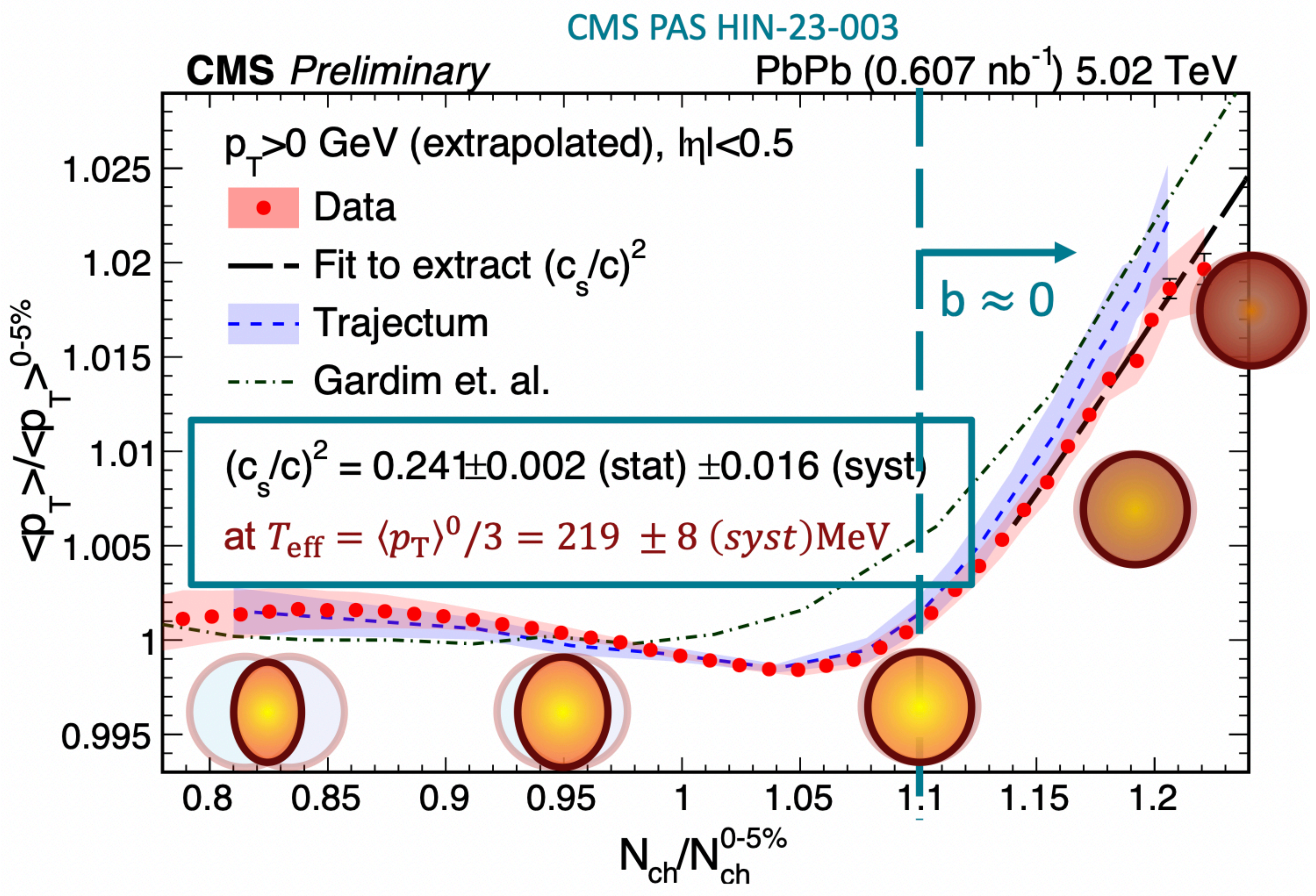
- Using Bayesian analysis to constrain the QGP transport properties

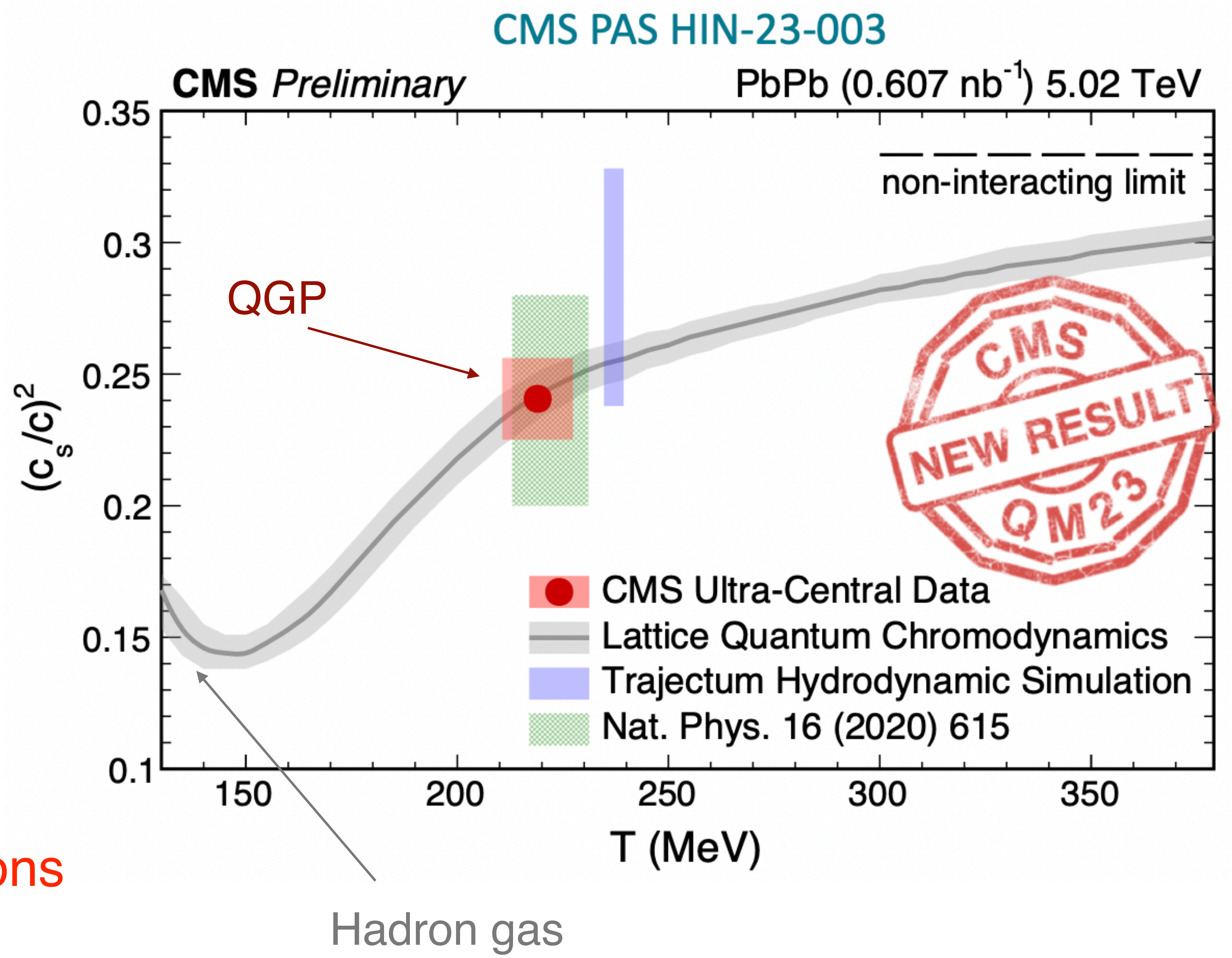
- Transport coefficient for energy loss well constrained by data
- Caveats: Modeling uncertainties, biases in observable selection

Speed of sound in the QGP

- High statistics, look at ultra central collisions
- Fixed volume, temperature fluctuation vs entropy

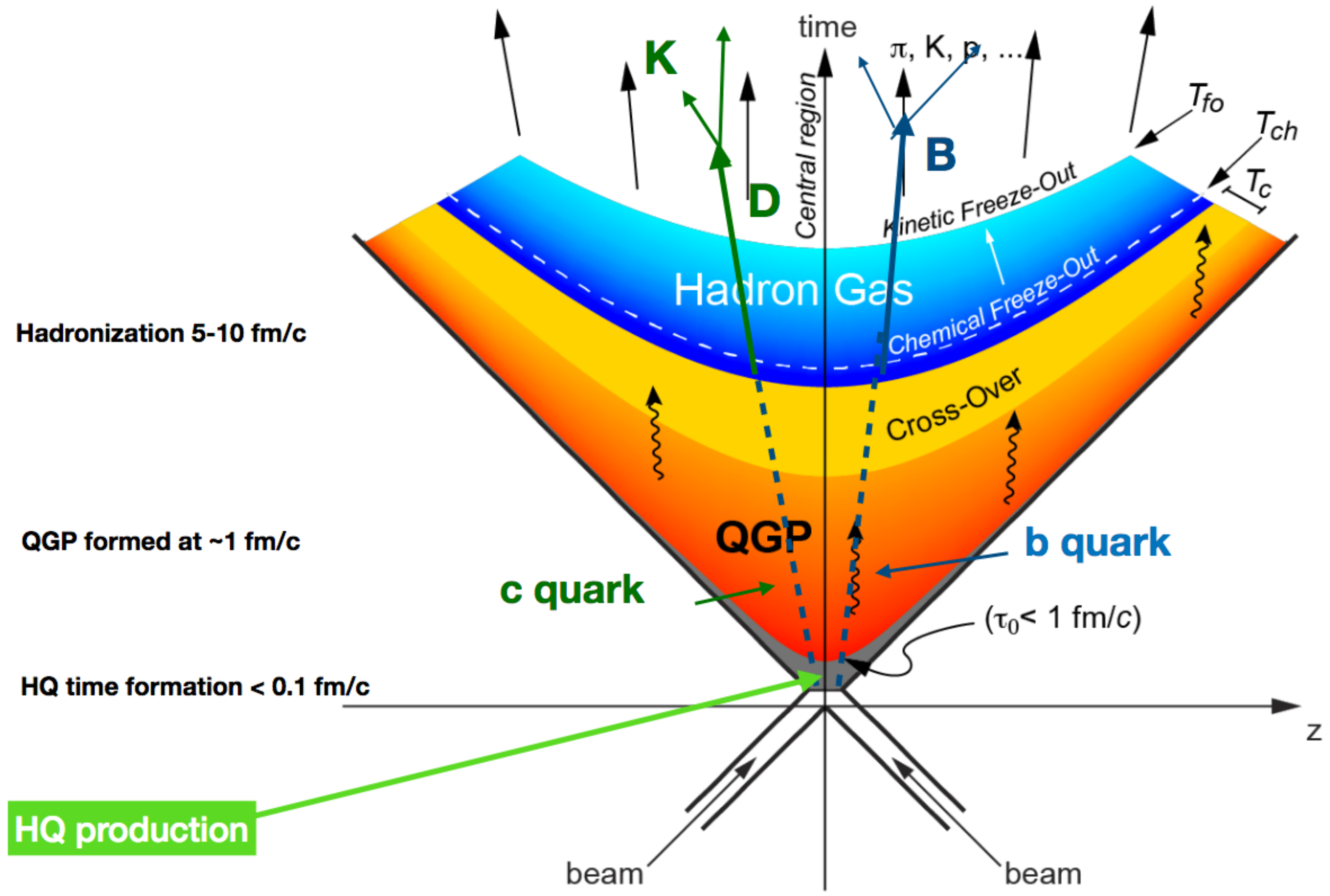
$$c_s^2 = \frac{dP}{d\varepsilon} = \frac{d\ln T}{d\ln s} = \frac{d\ln\langle p_T\rangle}{d\ln N_{ch}}$$





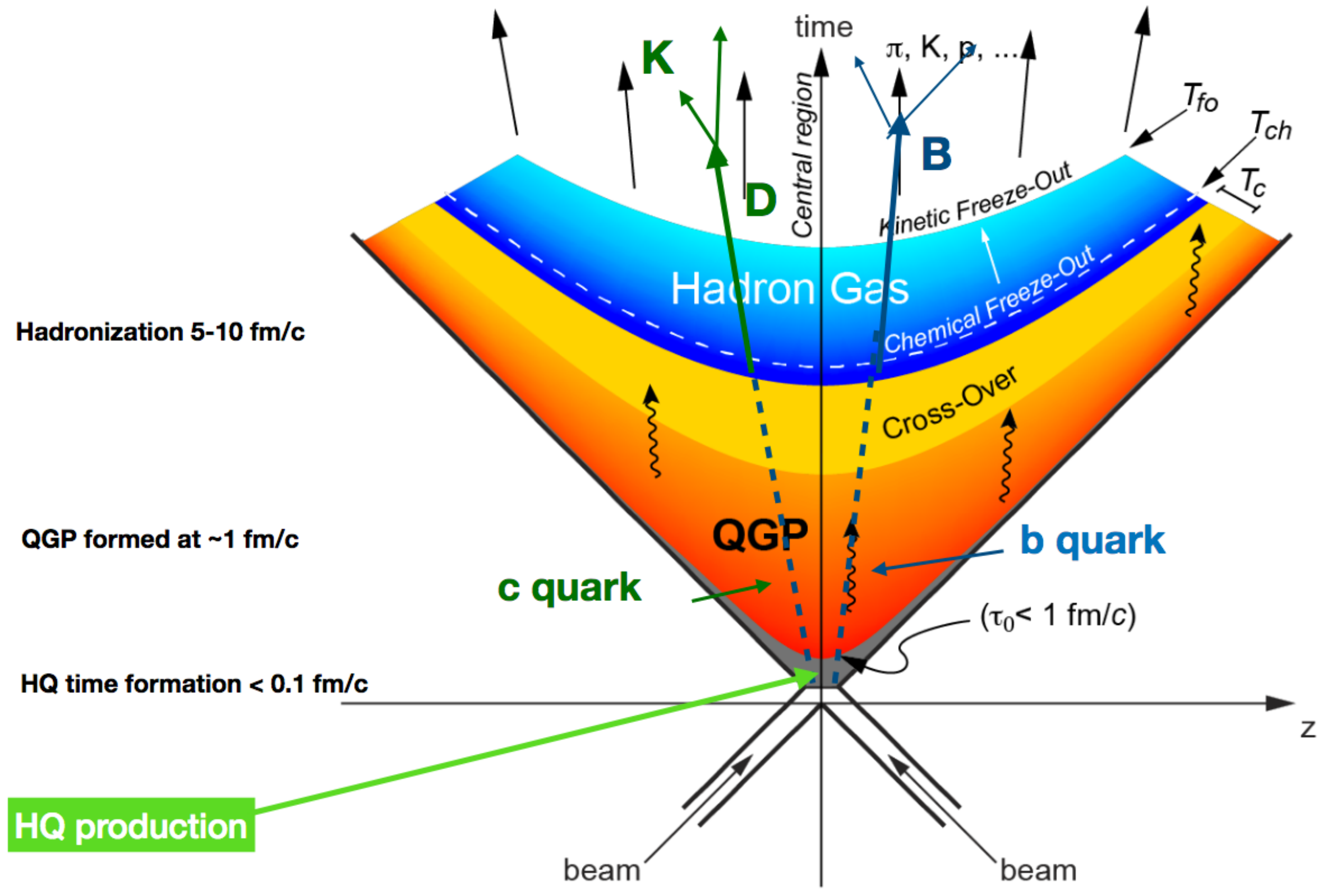
- Extracted c_s. Consistent with lattice predictions

Heavy flavor: study hadronization



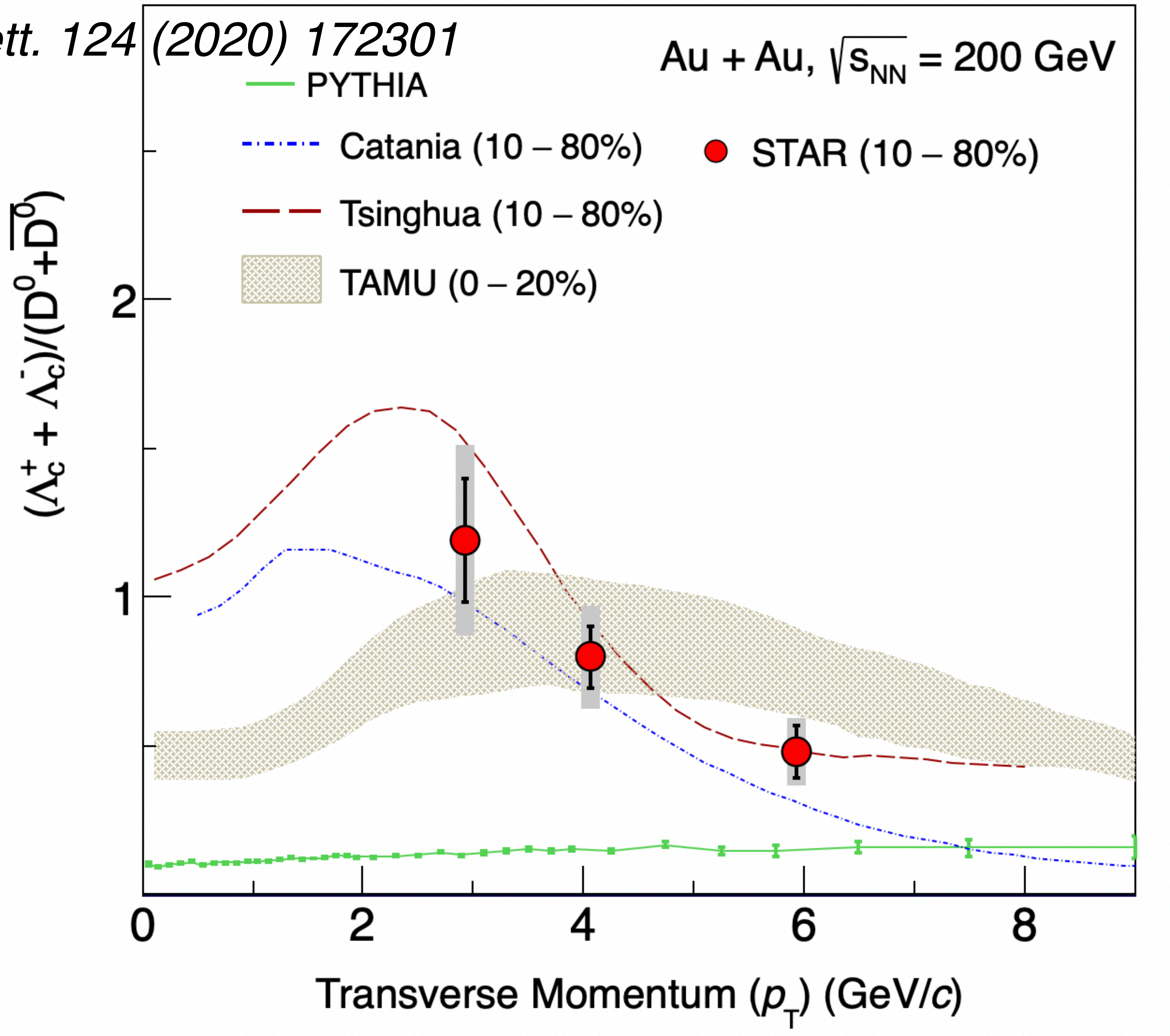
- HQs — produced in initial hard scatterings, mass >> T_{QGP}
- Ideal to study hadronization and its modification in presence of QGP

Heavy flavor: Λ_c enhancement



- Enhancement of baryon production
- Significantly higher than fragmentation ratios measured in e^+e^-

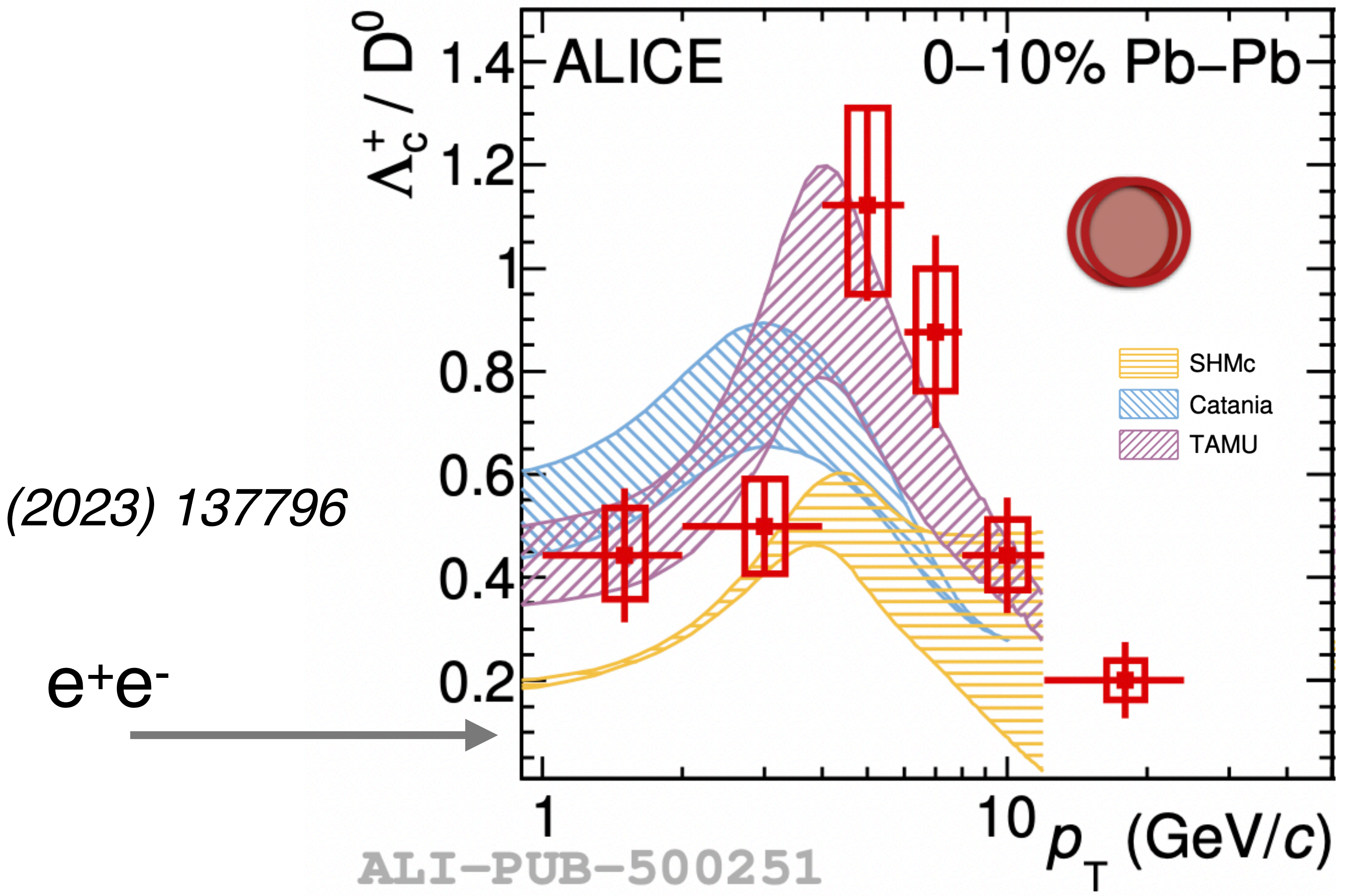
STAR, Phys. Rev. Lett. 124 (2020) 172301



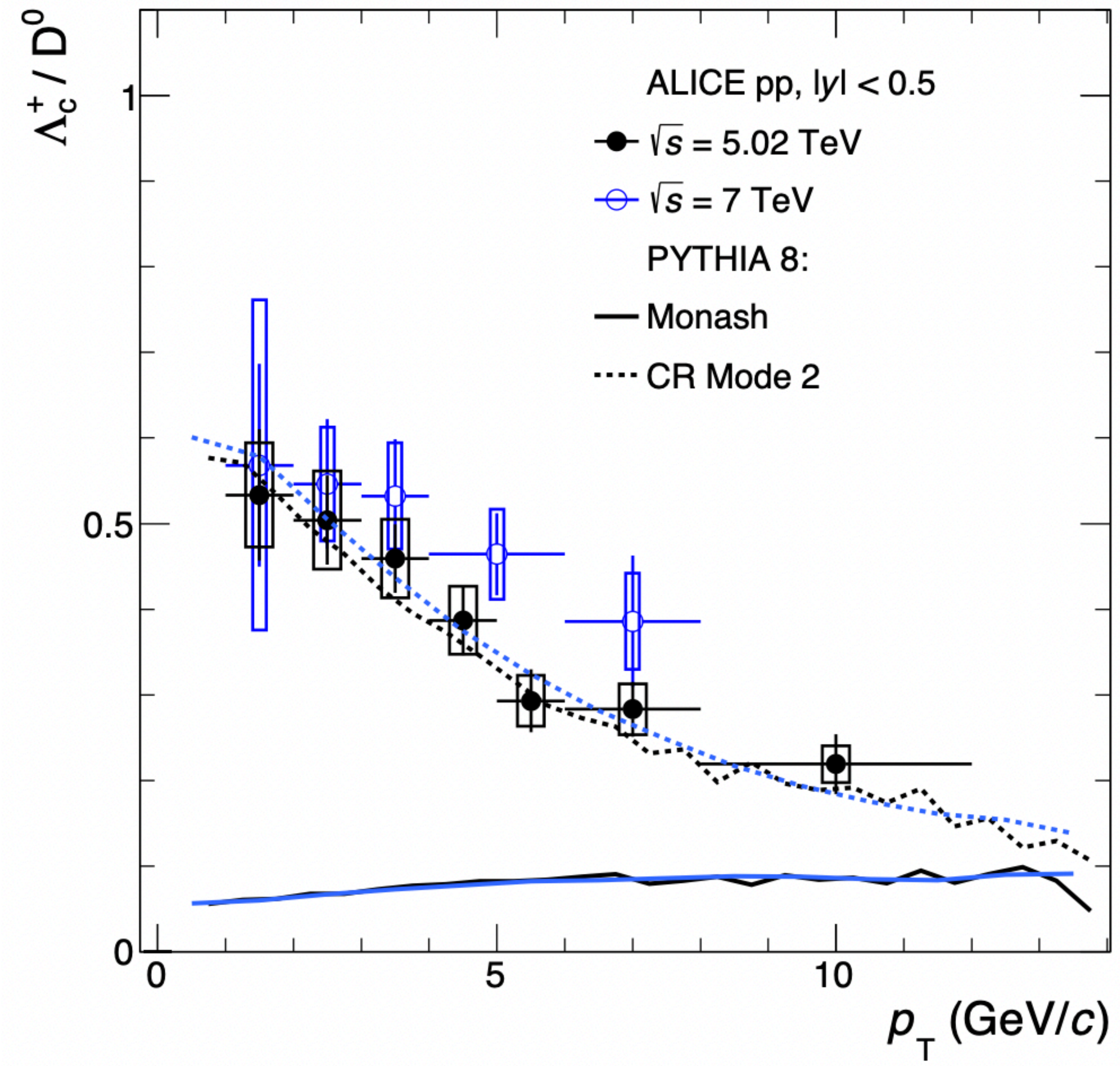
- Seen at both RHIC and LHC
- Described by coalescence model calculations

- HQs — produced in initial hard scatterings, mass >> T_{QGP}
- Ideal to study hadronization and its modification in presence of QGP

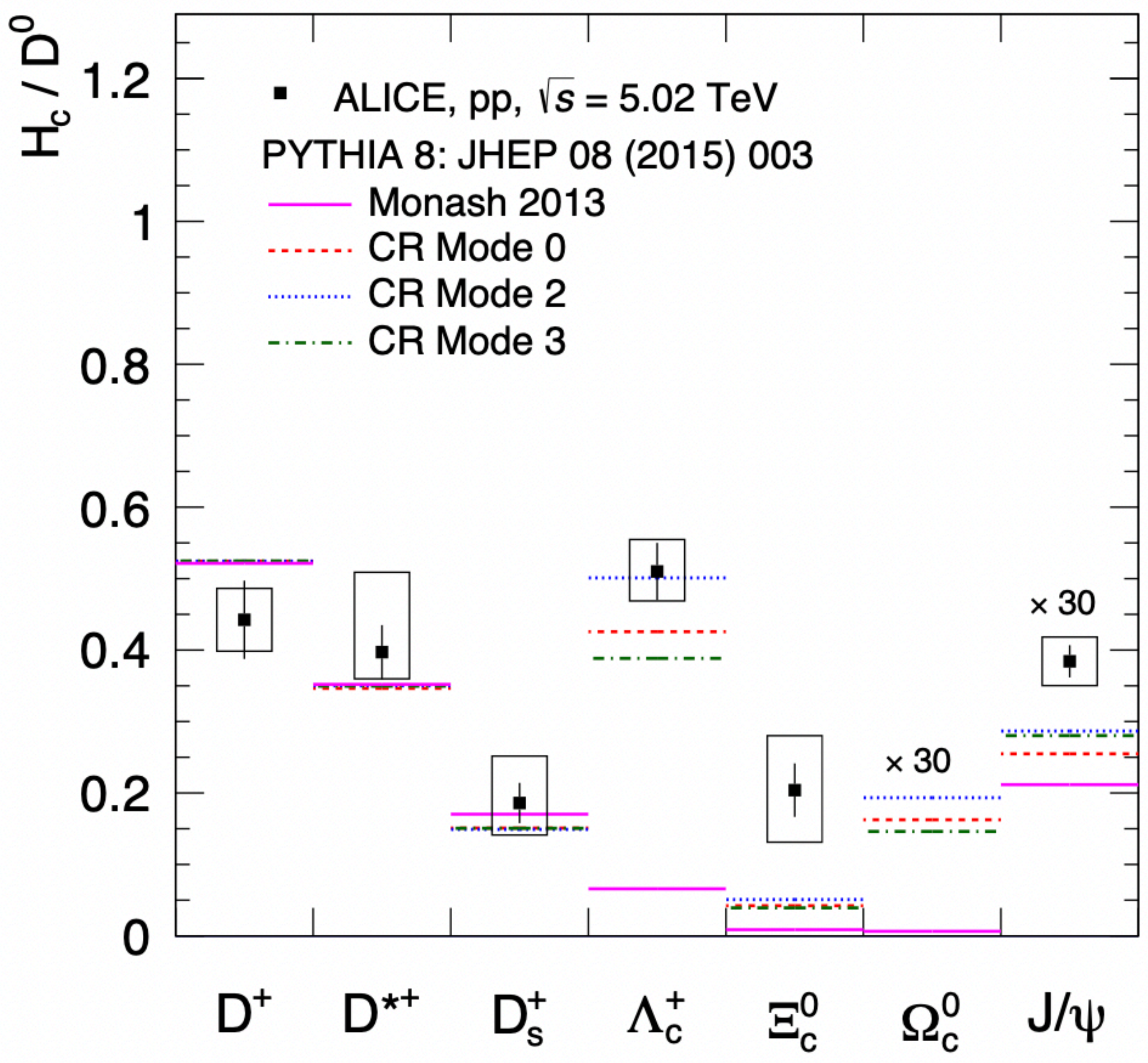
ALICE, Phys. Lett. B 839 (2023) 137796



Non-universality of HQ hadronization

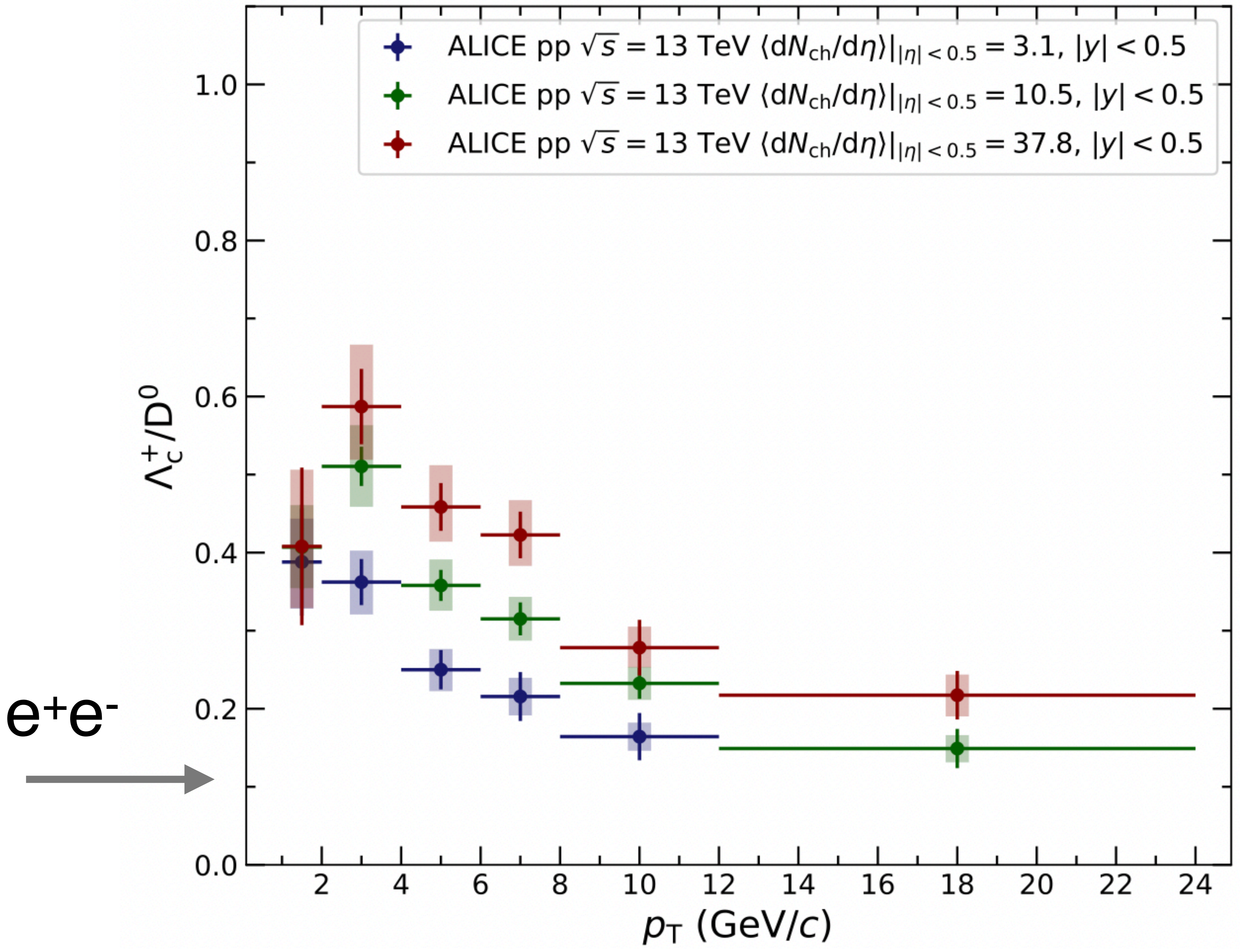


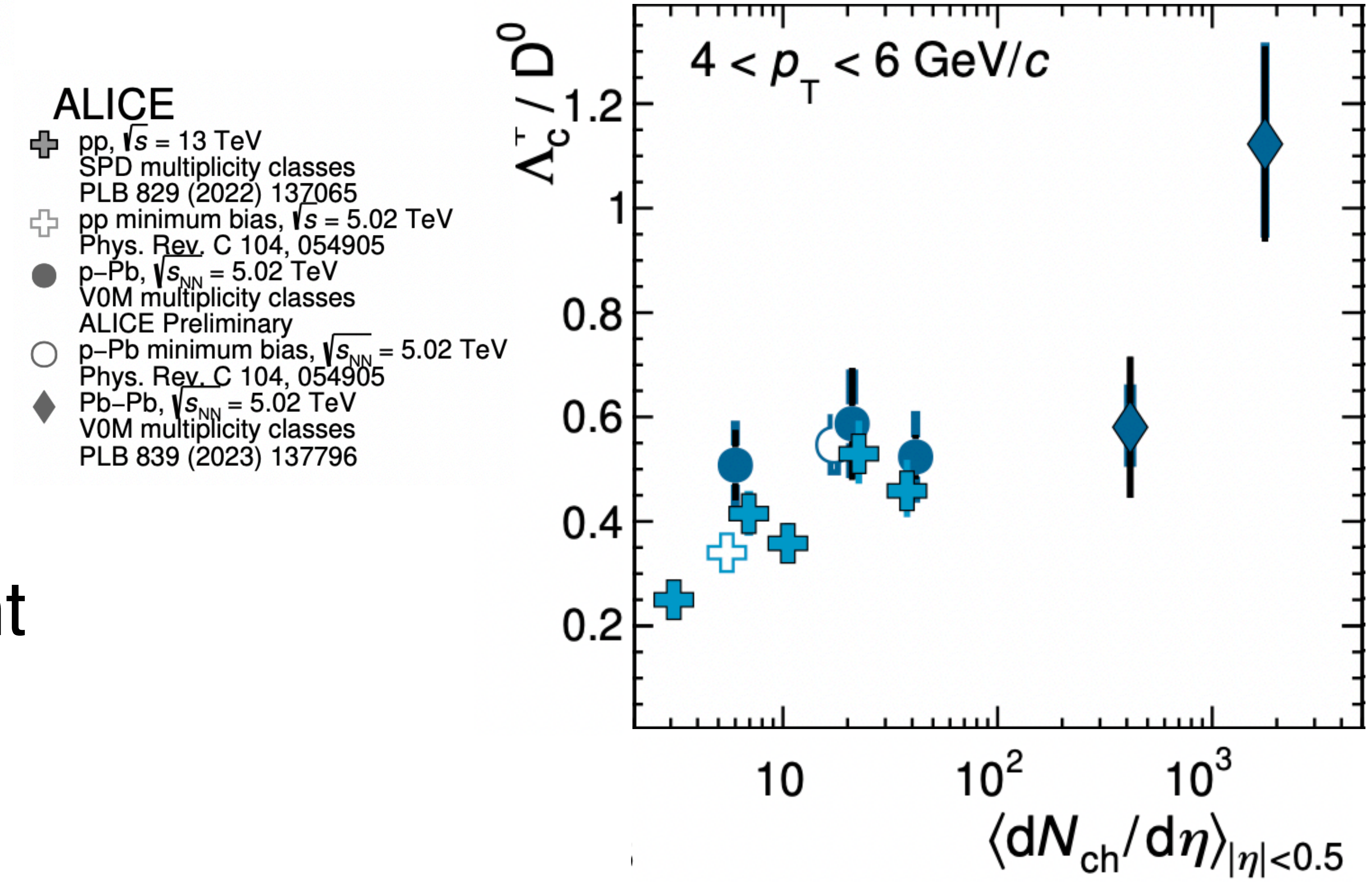
ALICE, Phys. Rev. Lett. 127 (2021) 202301



ALICE, Phys. Rev. D 105, L011103 (2022)

ALICE, Phys. Lett. B 829, 137065 (2022)

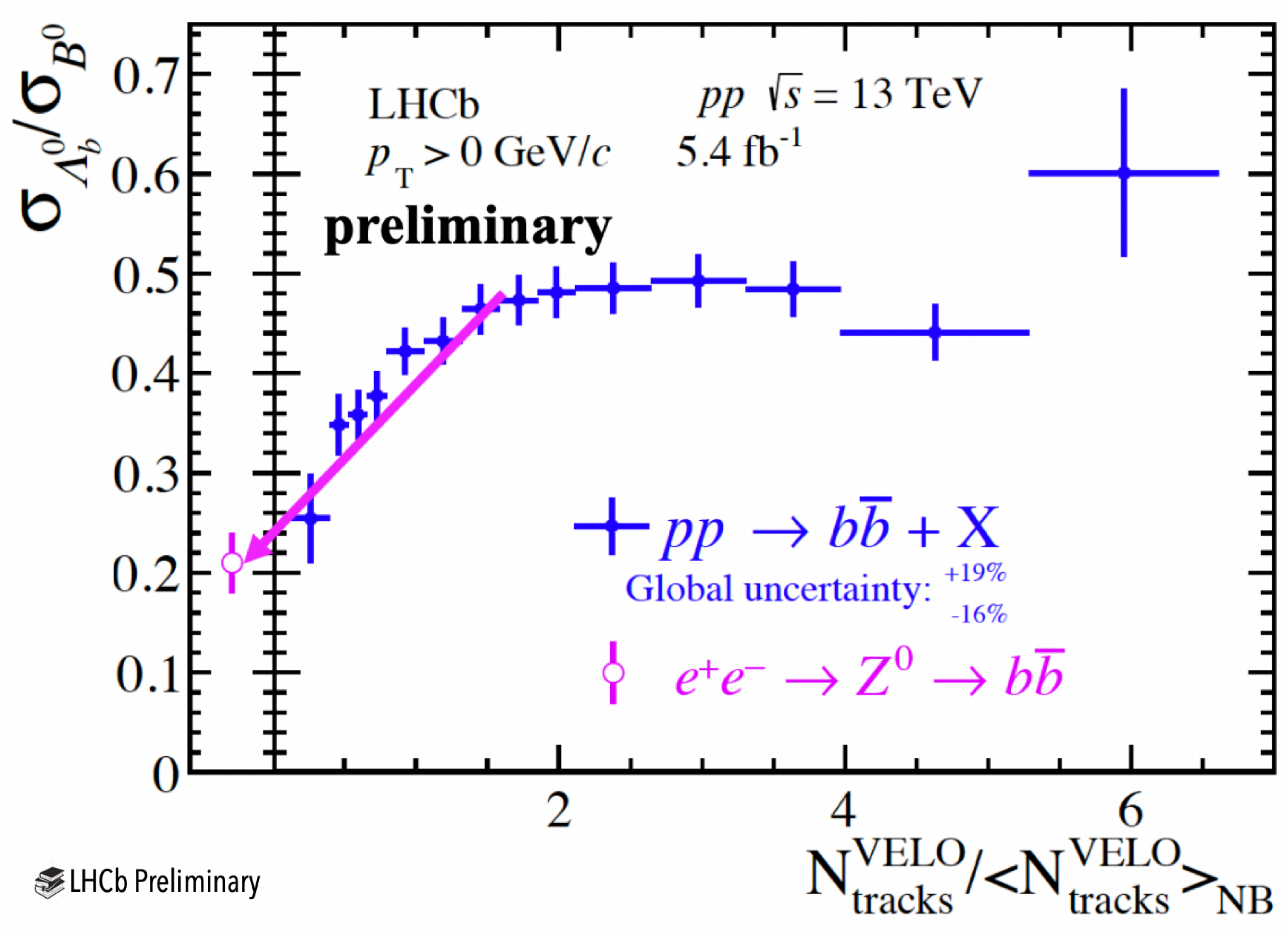




- Enhancement already in p+p collisions
- Non-universality of c-quark fragmentation
- Enhancement seen for Ξ_c as well
- PYTHIA with CR can describe Λ_c enhancement

- Multiplicity dependence for enhancement
- AA and p+p not directly comparable

Bottom baryon enhancement in p+p

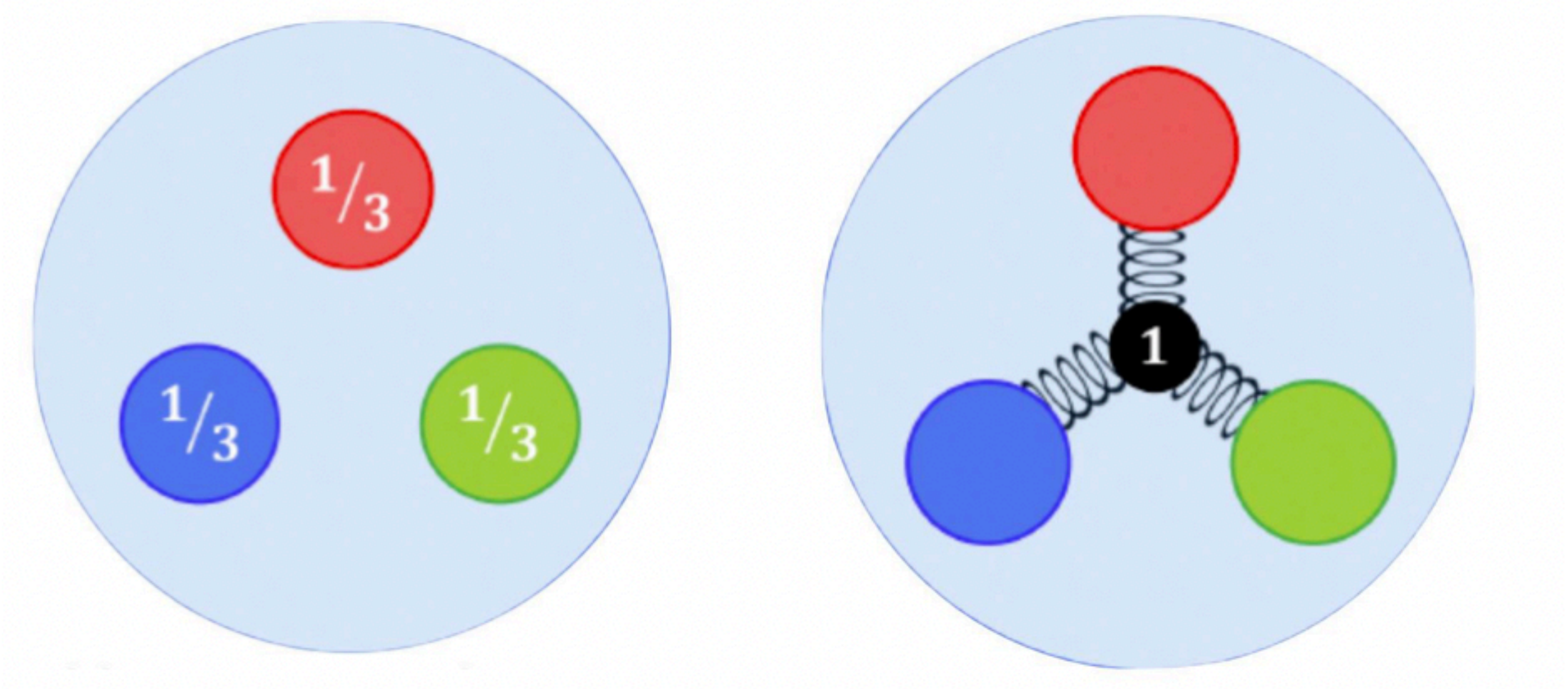


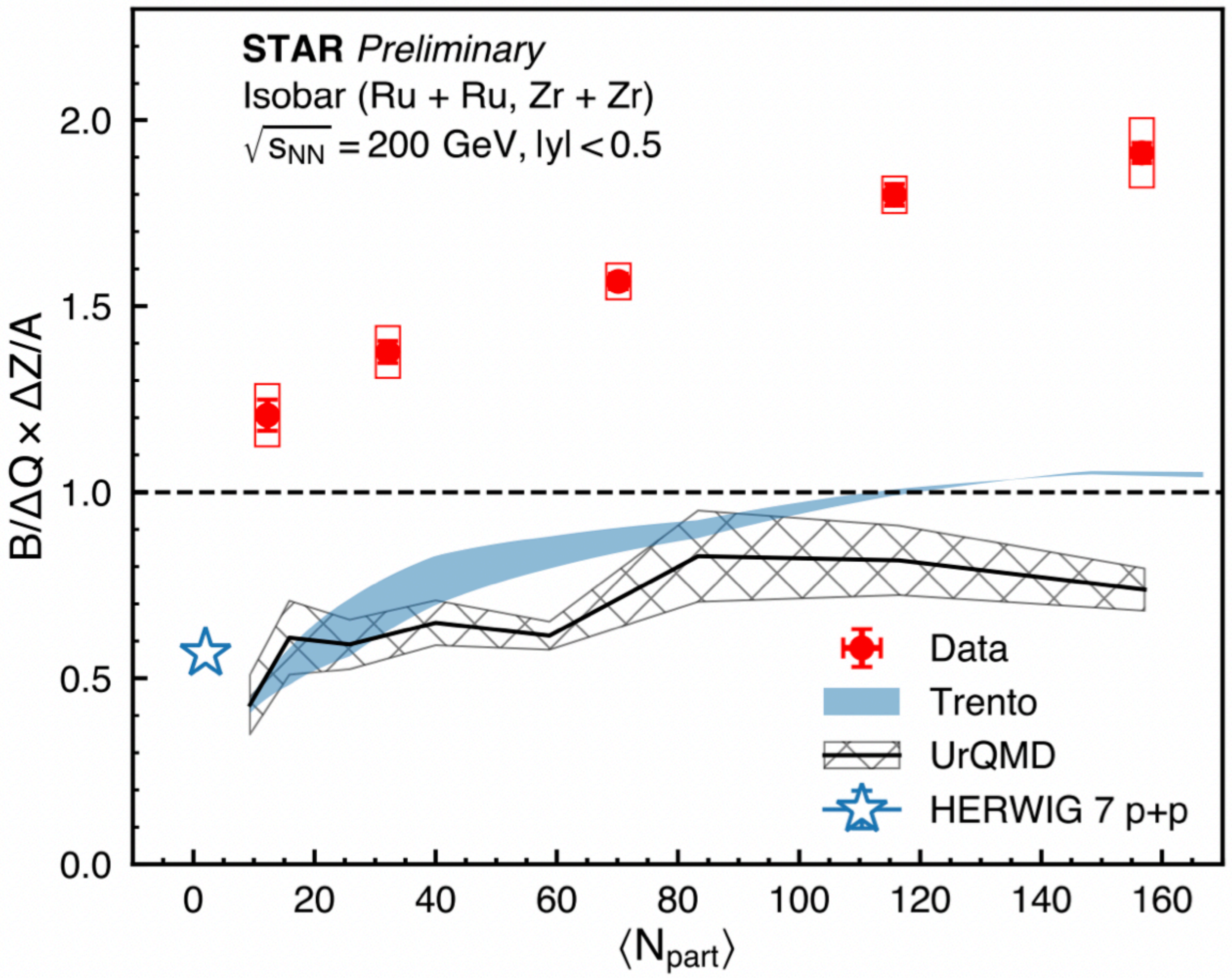
- Bottom baryons also enhanced in p+p
- Multiplicity dependence
- Approaches e^+e^- value at very low multiplicity

- Higher statistics data to come from LHC Run3 - more precise measurements in A+A, more differential measurements, heavier baryons

What carries baryon number?

- Study baryon transport vs charge transport
- Utilize isobar collisions at RHIC





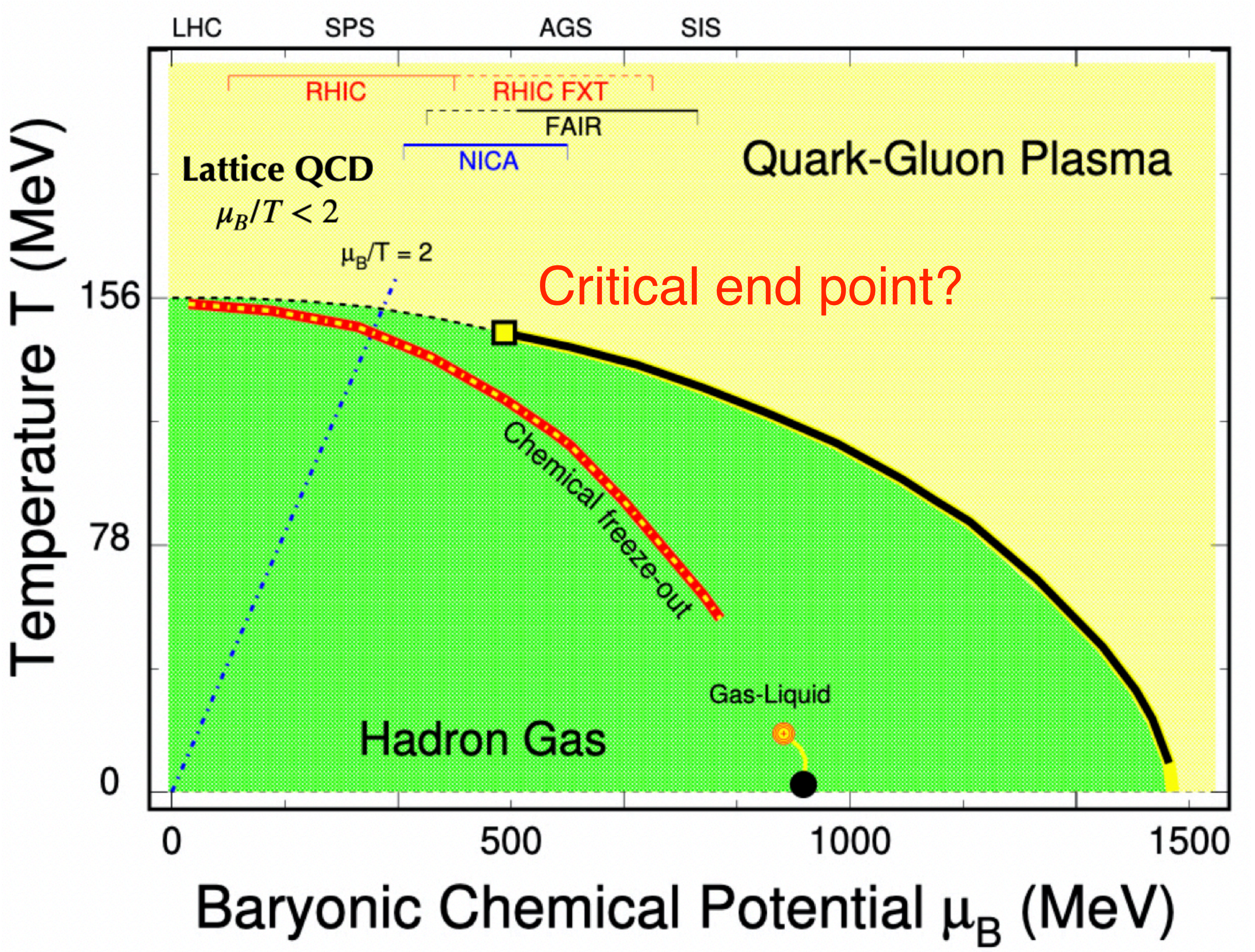
- Naive expectation $B/\Delta Q \times \Delta Z/A = 1$

- Models cannot describe both baryon transport and charge transport
- Is valence quark model insufficiency? baryon number carried by gluon junctions?

QCD Phase Structure

Search for the QCD critical point

$C_2 \sim \xi^2, C_4 \sim \xi^7$ $\quad C_4/C_2 \sim \chi_4^B/\chi_2^B \quad \chi_i^B = -\frac{\partial^i \hat{\varphi}}{\partial \hat{\mu}_B^i},$



- Cumulants of net-baryon number distributions related to correlation length in medium
- Cumulant ratios give ratio of susceptibilities
- Expect non-monotonous behavior near critical point

Search for the QCD critical point

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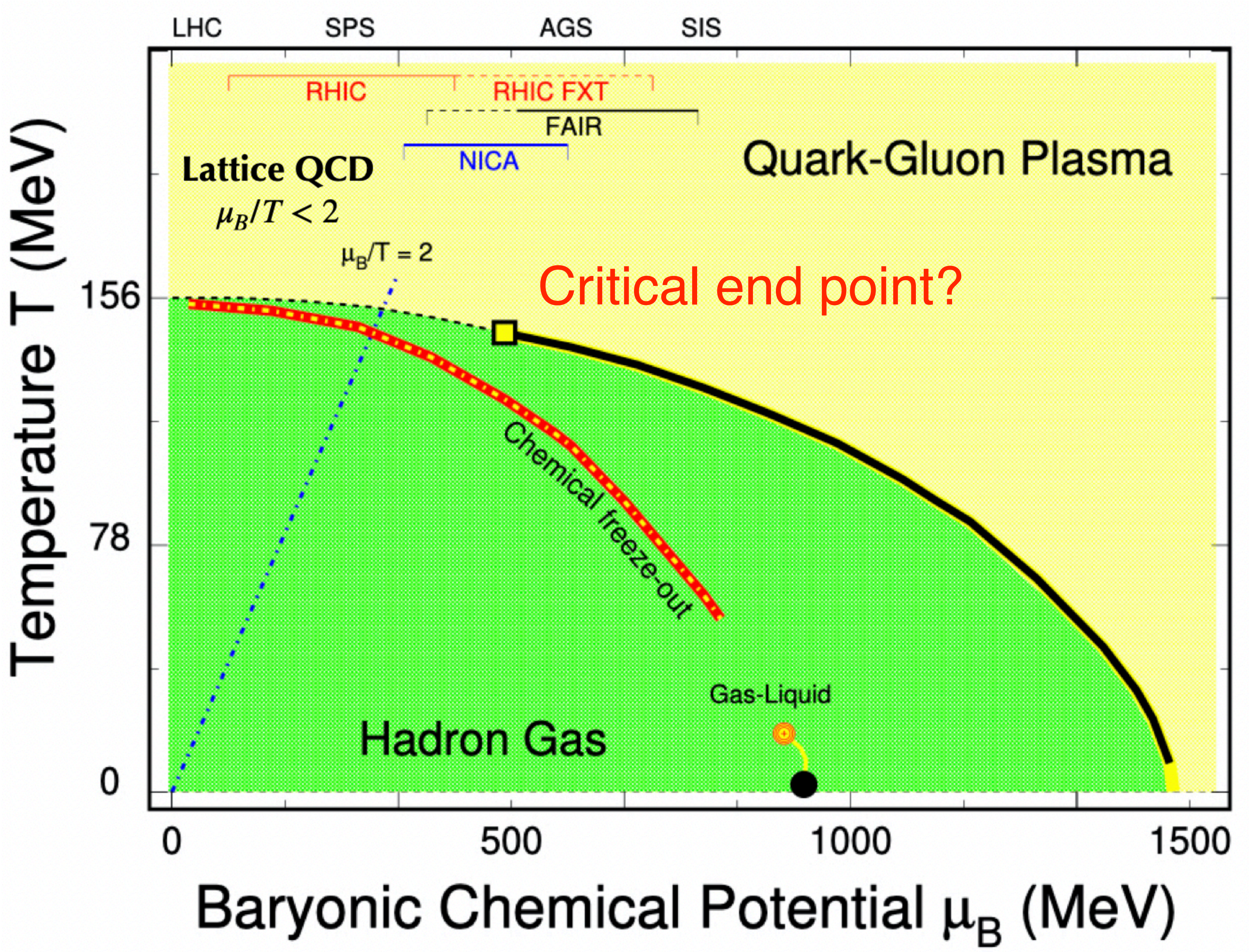

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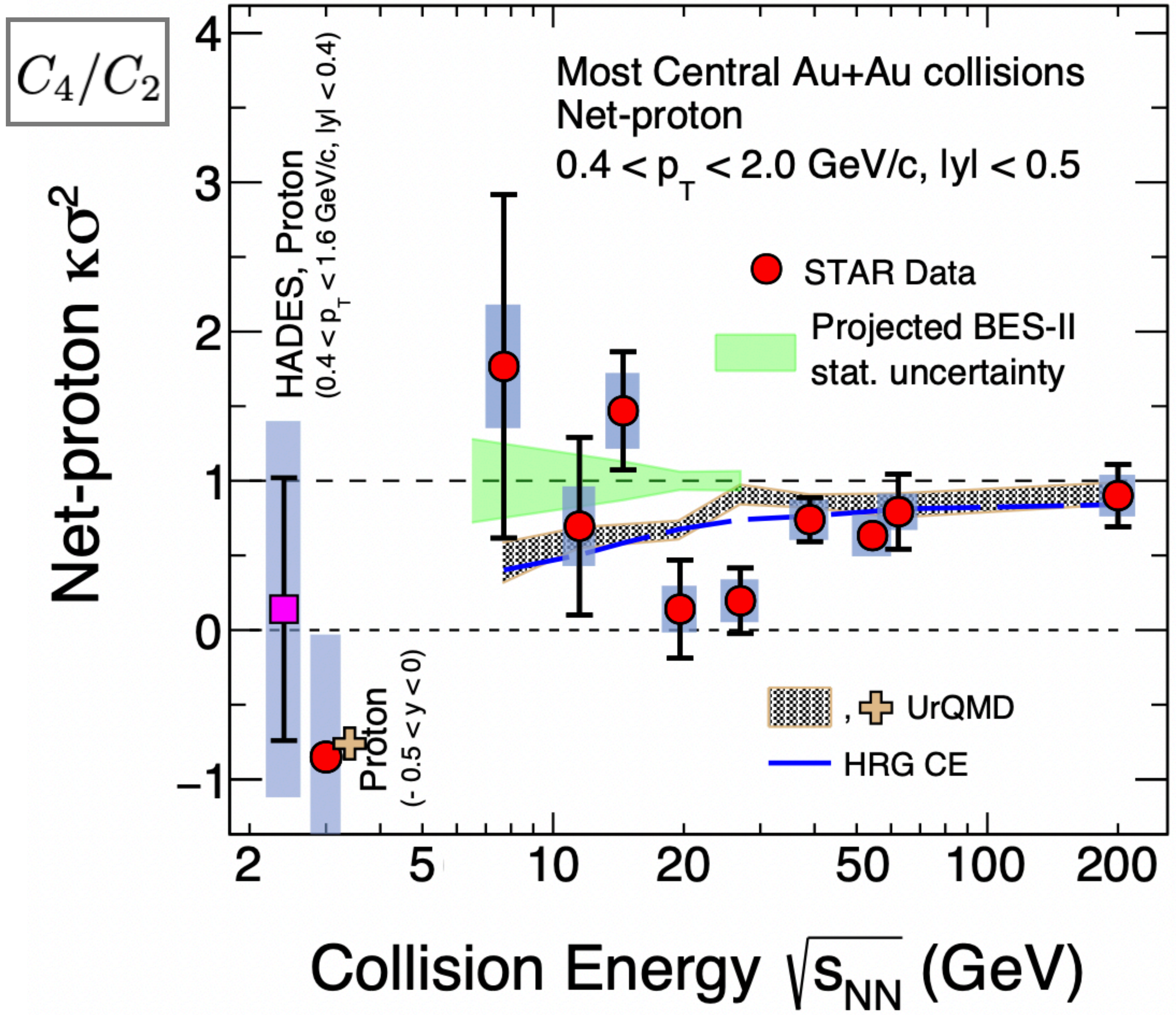
STAR, PRL 128, 202302 (2022)

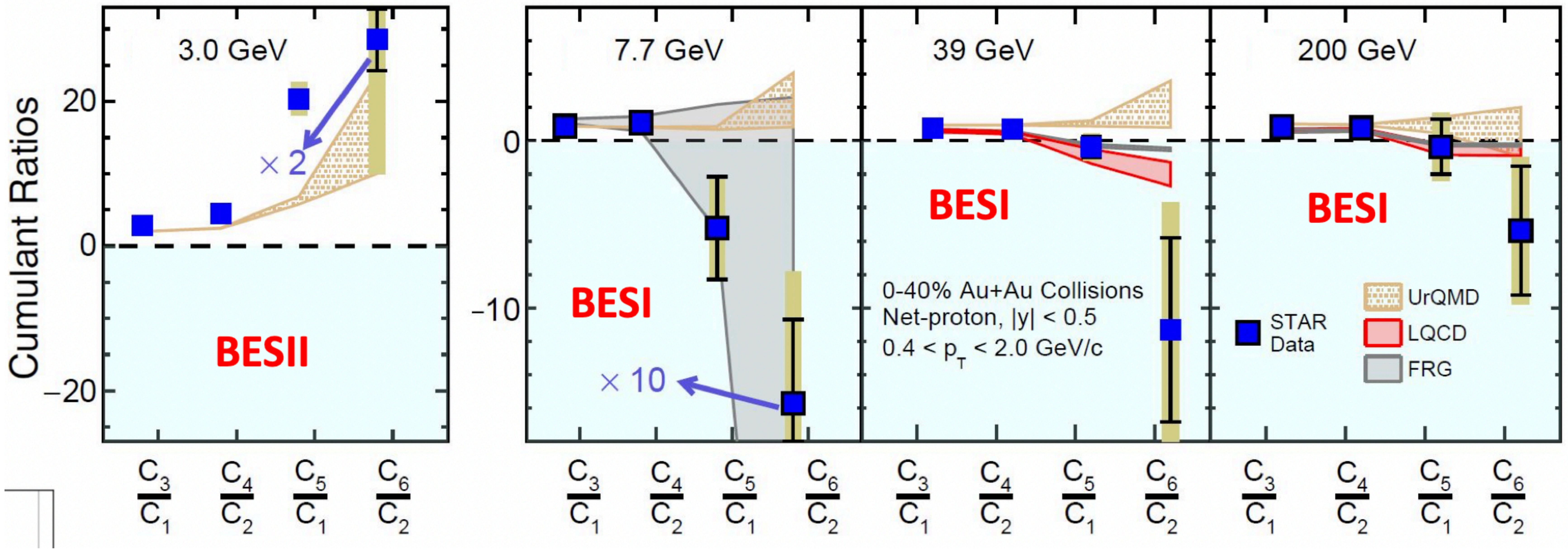


- Non-monotonous beam energy dependence seen at 3.1σ level from BES-I data
- Results from 3 GeV consistent with hadronic transport models
- Precision measurements from BES-II ongoing

Higher order cumulant ratios

- Ordering of cumulant ratios predicted by lattice QCD calculations

$$C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$$



10x more statistics from BES-II for 7.7 - 200 GeV

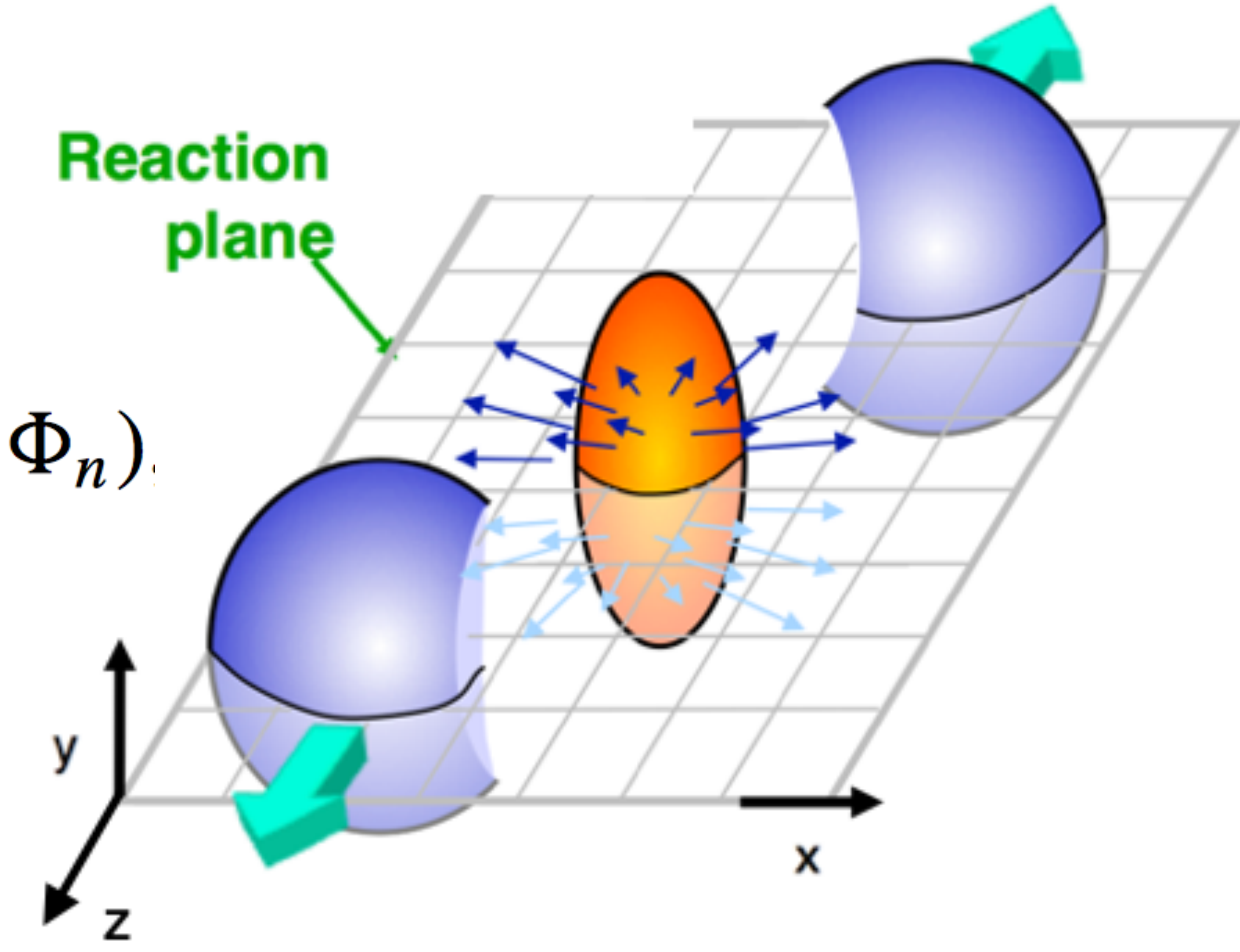
STAR, PRL 130, 082301 (2023)

- Cumulant ratios from data consistent with the ordering for $\sqrt{s_{NN}}$ = 7.7 - 200 GeV
- Ordering violated at 3 GeV; but reproduced by hadronic transport model calculations

Anisotropic flow, constituent quark scaling

- Anisotropic flow: from pressure driven expansion of produced matter
- Access to medium properties and EoS

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n).$$



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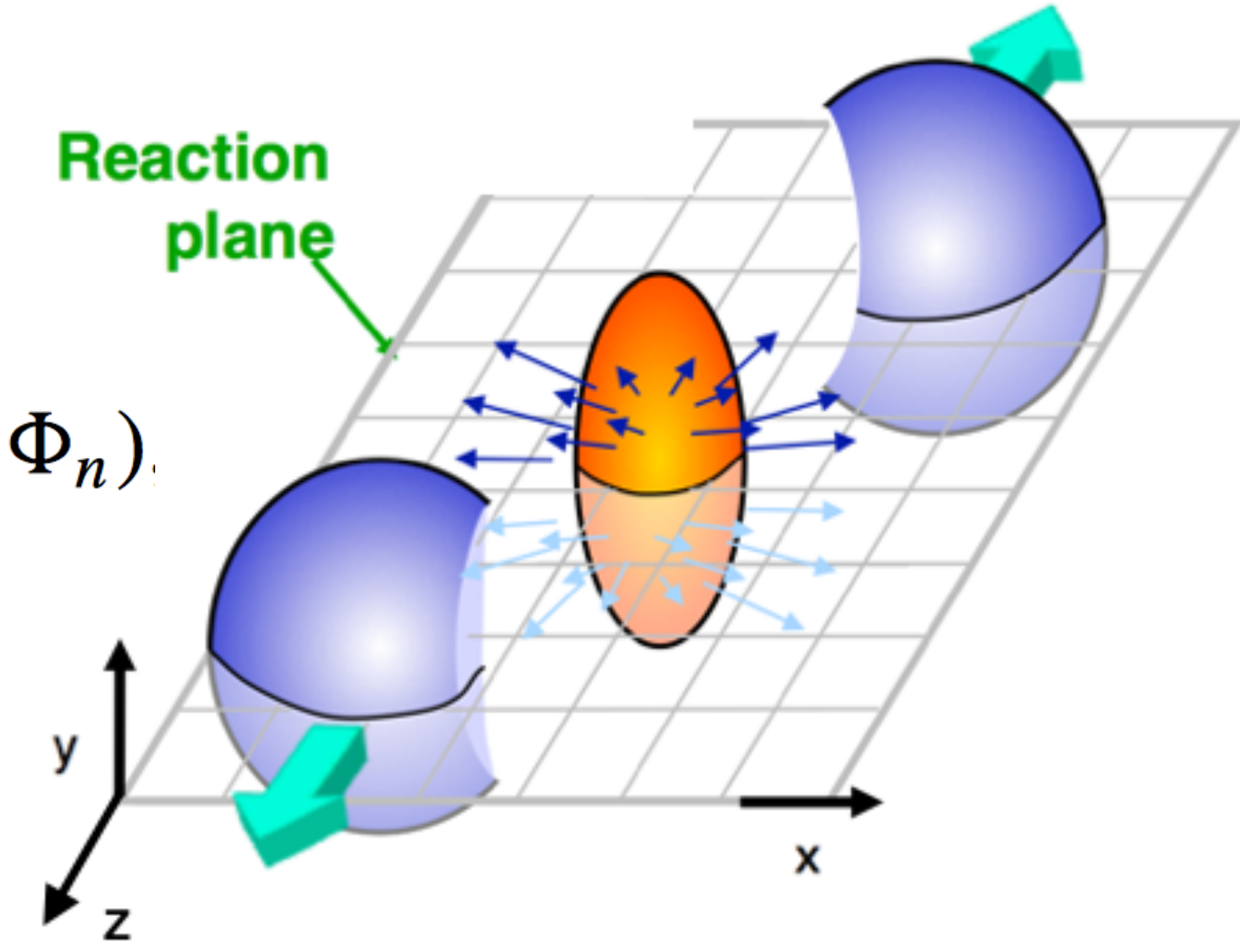
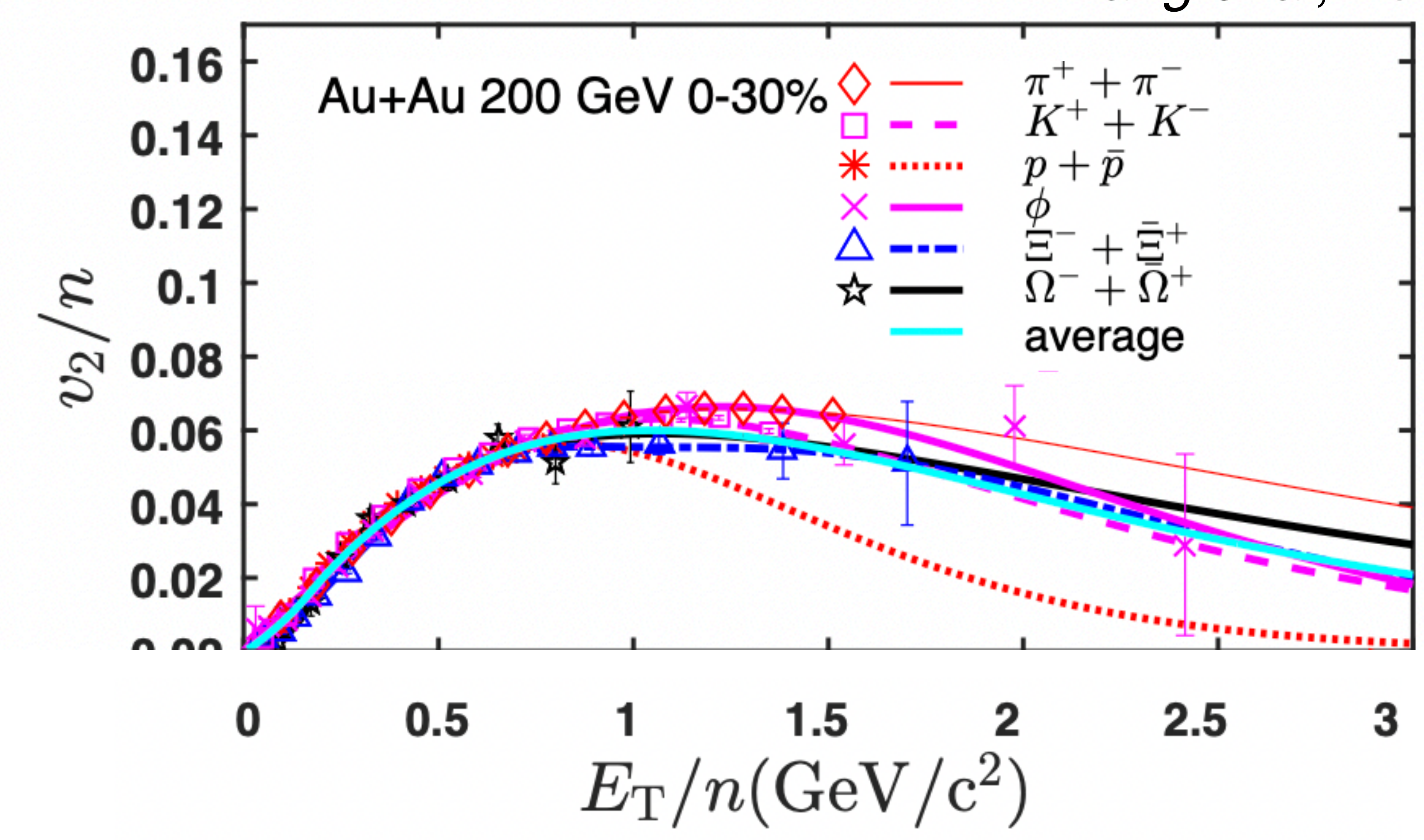
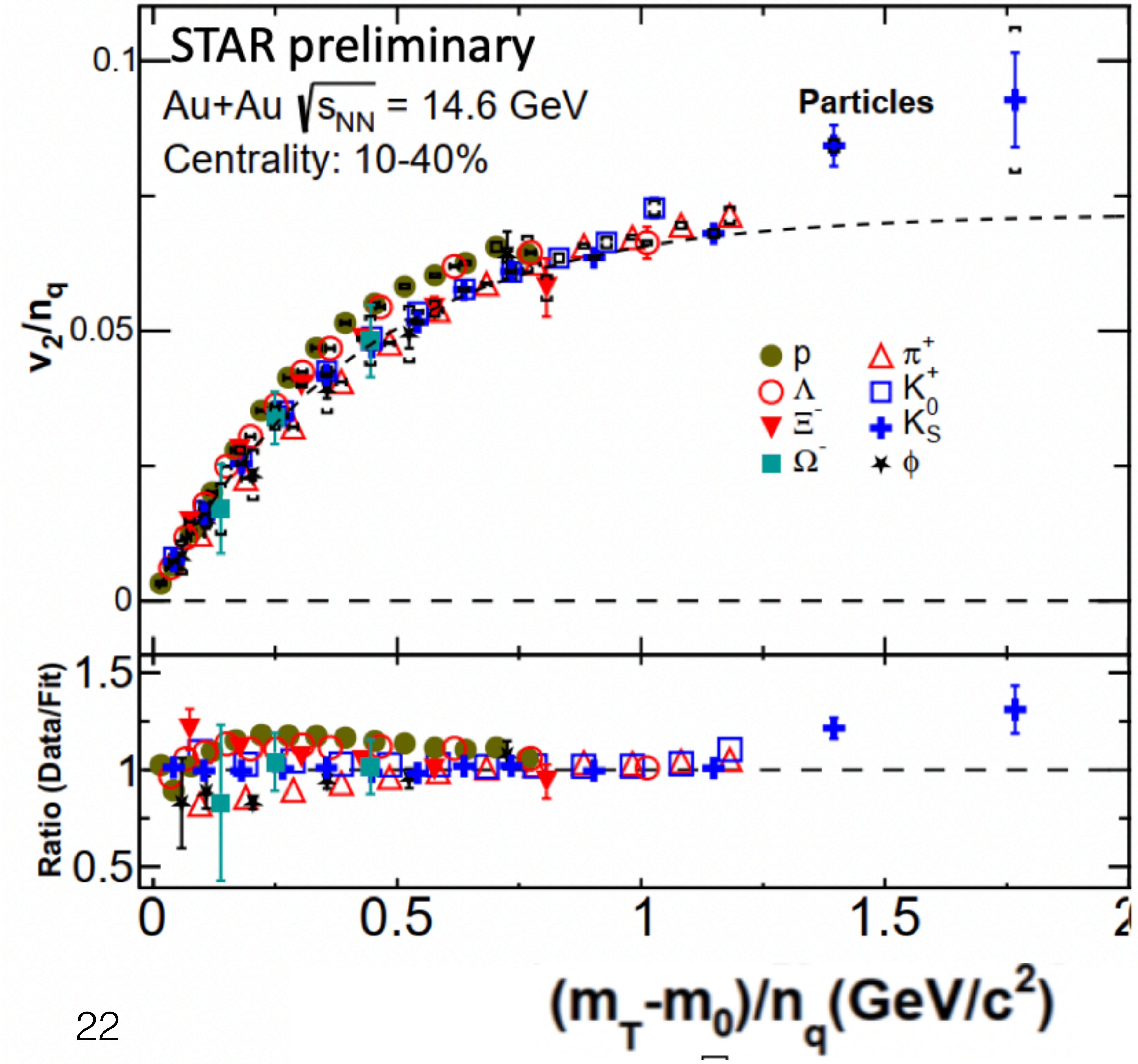


M. Wang et al, Nucl. Sci. Tech. 33, 37 (2022)





- Also holds for down to 14.6 GeV collisions
- BES-II data

- v_2 of all hadrons fall on one curve when scaled by Number of Constituent Quarks
- Taken to indicate flow develops in the partonic phase

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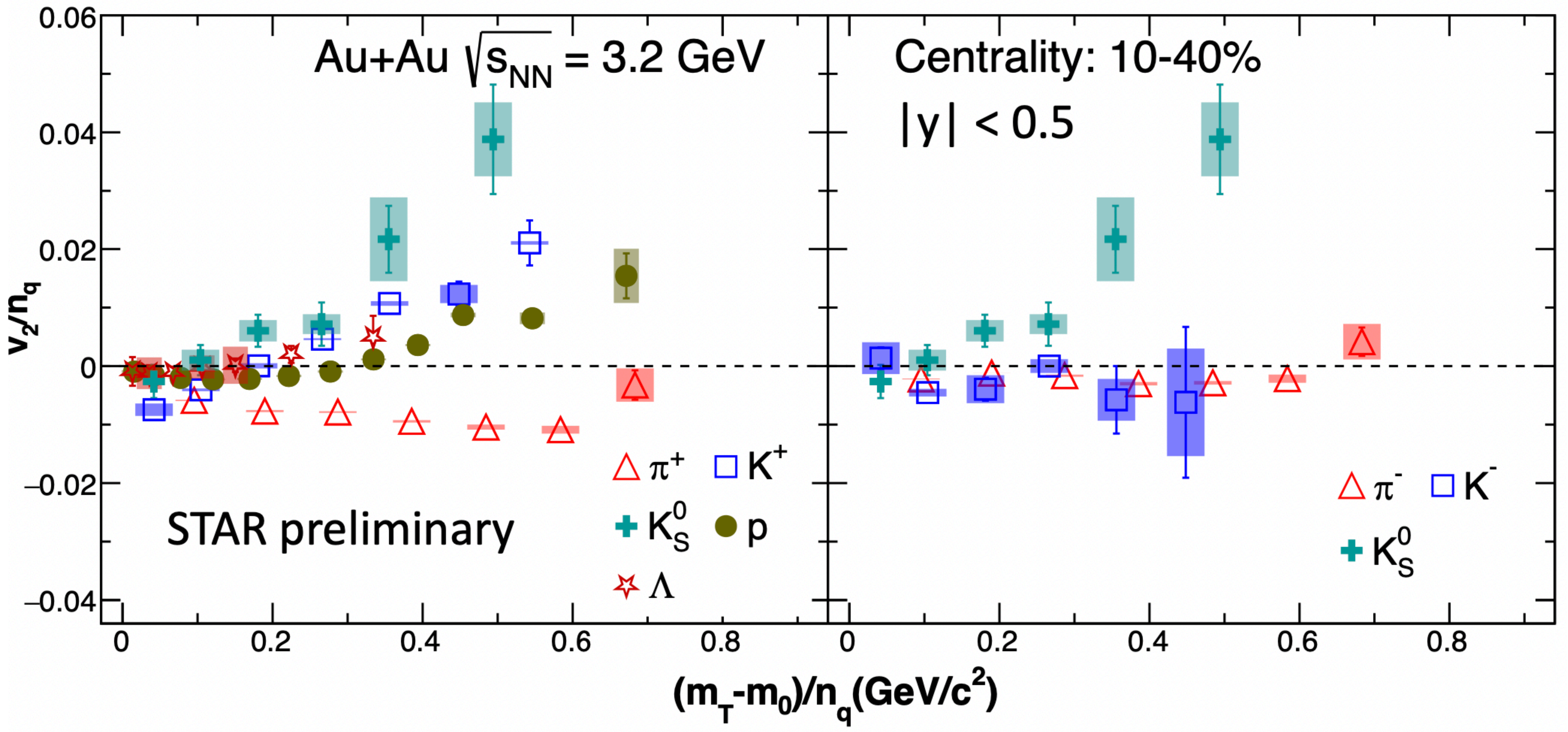
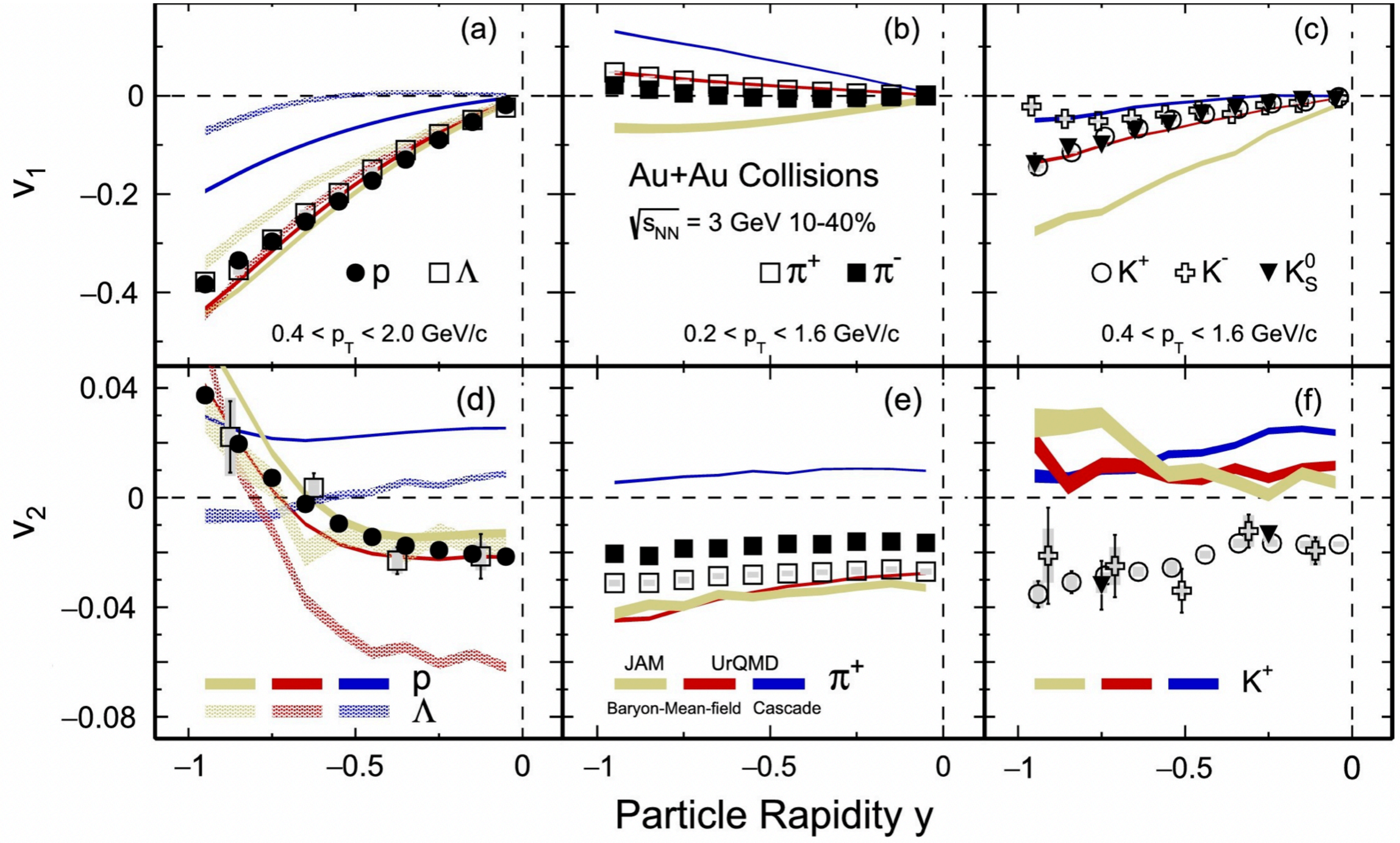
NCQ scaling breaking, disappearance of partonic collectivity



- NCQ scaling breaks for 3.2 GeV and below — disappearance of partonic collectivity

STAR, PLB 827, 137003 (2022)



- v_1, v_2 well described by hadronic transport model calculations with baryonic meanfield interactions
- Hadronic interactions dominate the matter produced in lower energy collisions

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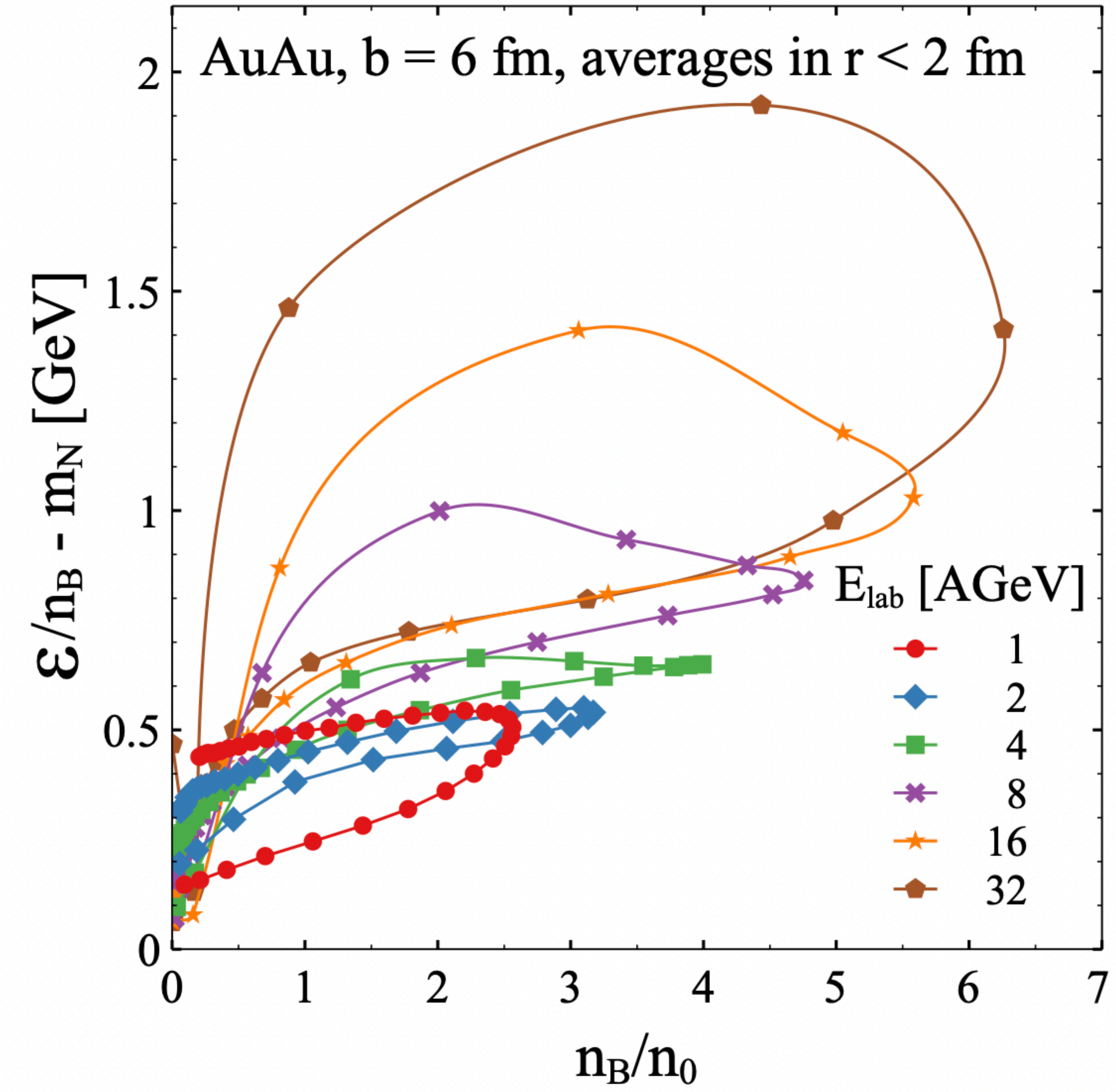
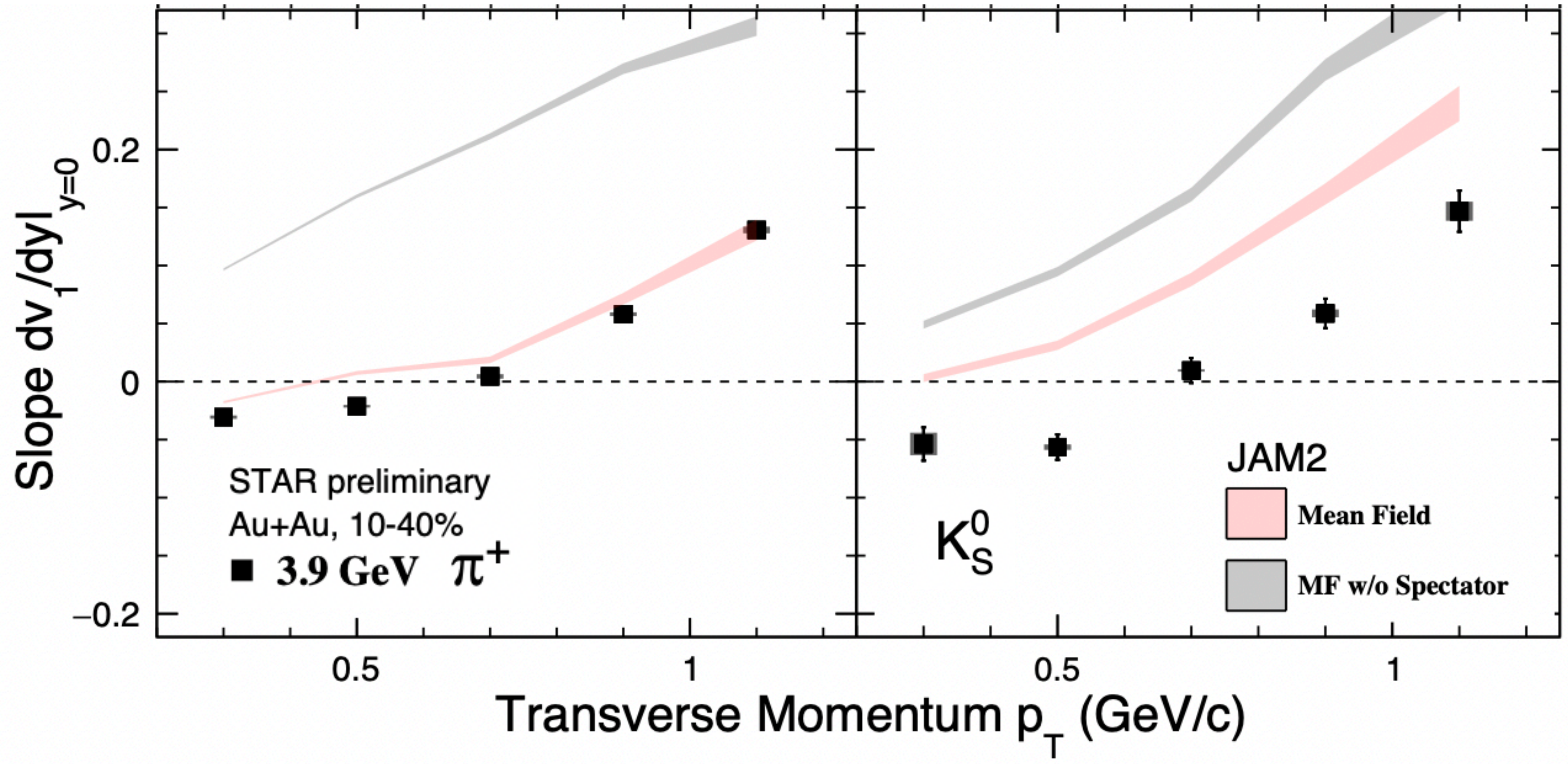
EoS of high μ_B matter and neutron stars

- HIC only way to reach densities few times saturation density on earth, comparable to densities of neutron stars



D. Oliinychenko et al, PRC 108, 034908 (2023)

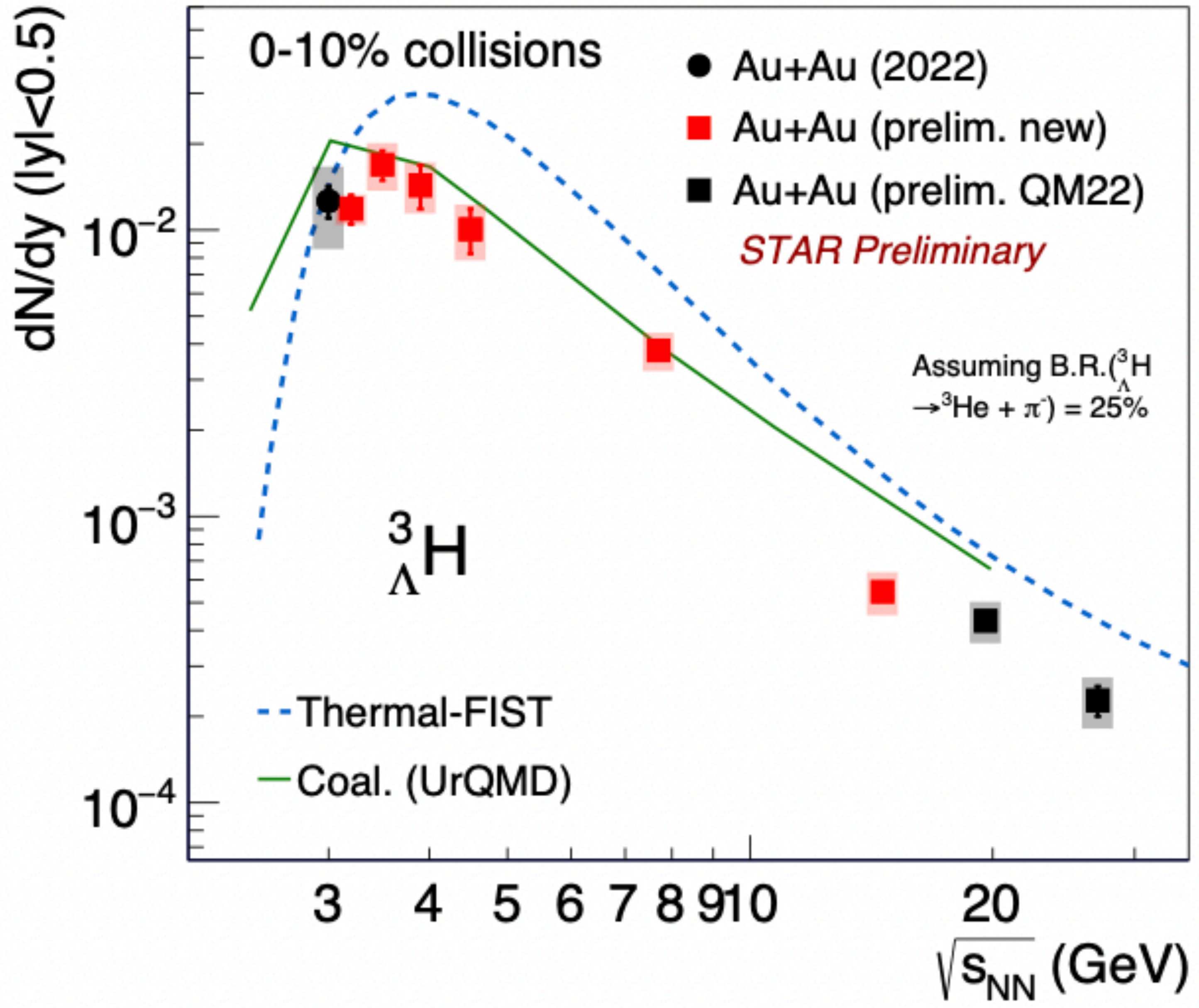


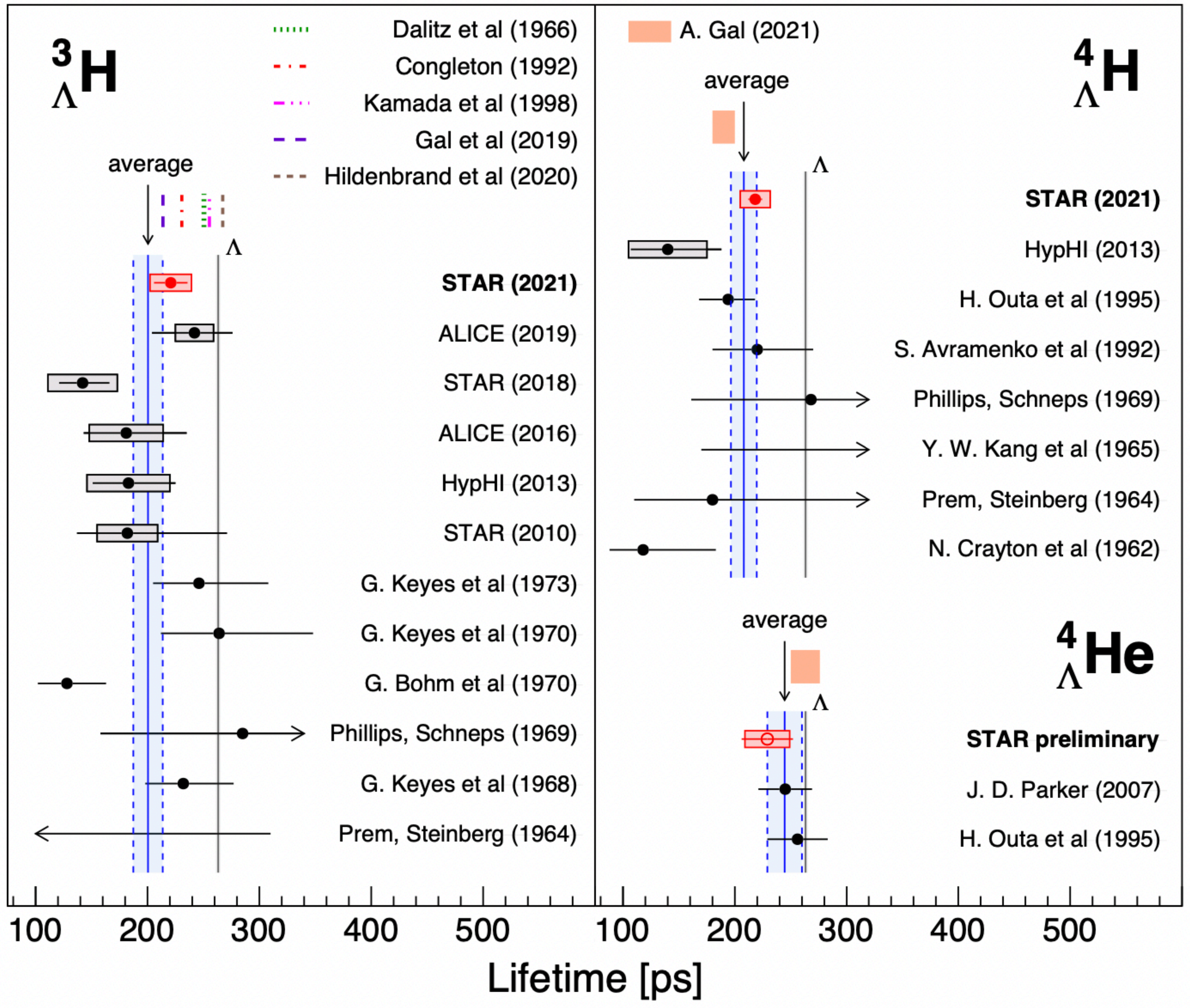
- Multiple observables and energies —> should allow extraction of EoS with a Bayesian analysis

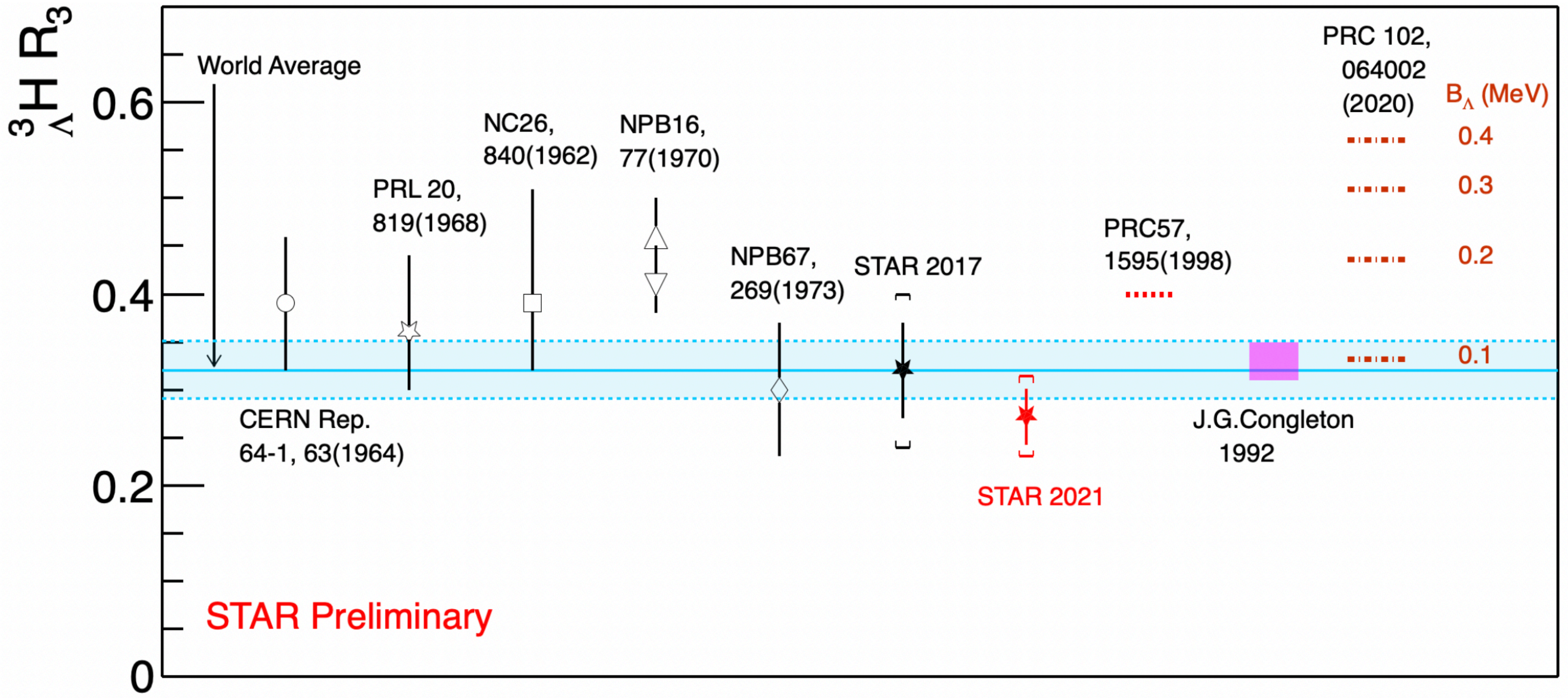
Hypernuclei production at high μ_B

- Hypernuclei — study YN interactions. Important for understanding neutron stars
- High μ_B enhanced production of hypernuclei

- High precision measurements of yields, branching ratio, lifetimes from BES-II







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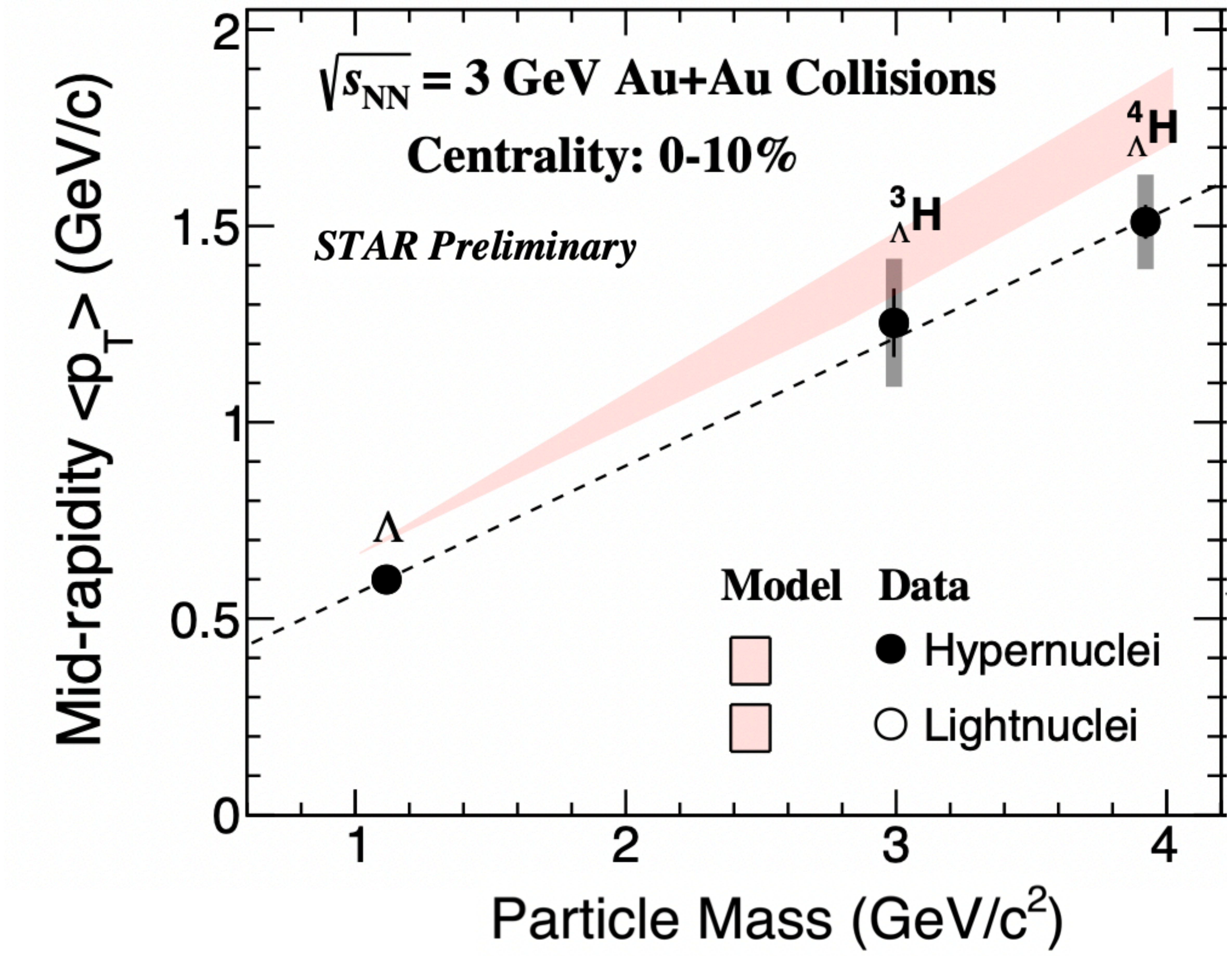
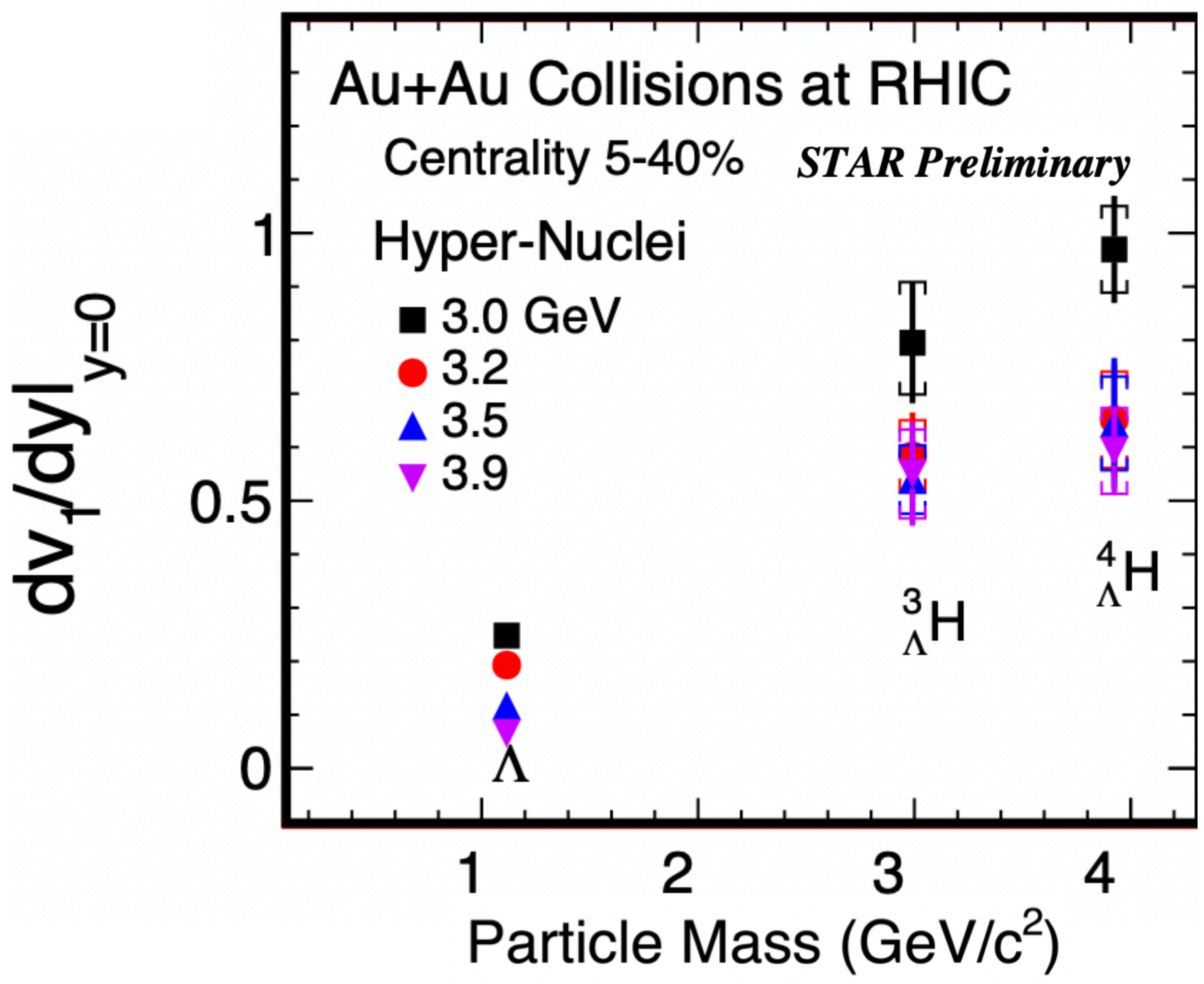
Hypernuclei collectivity

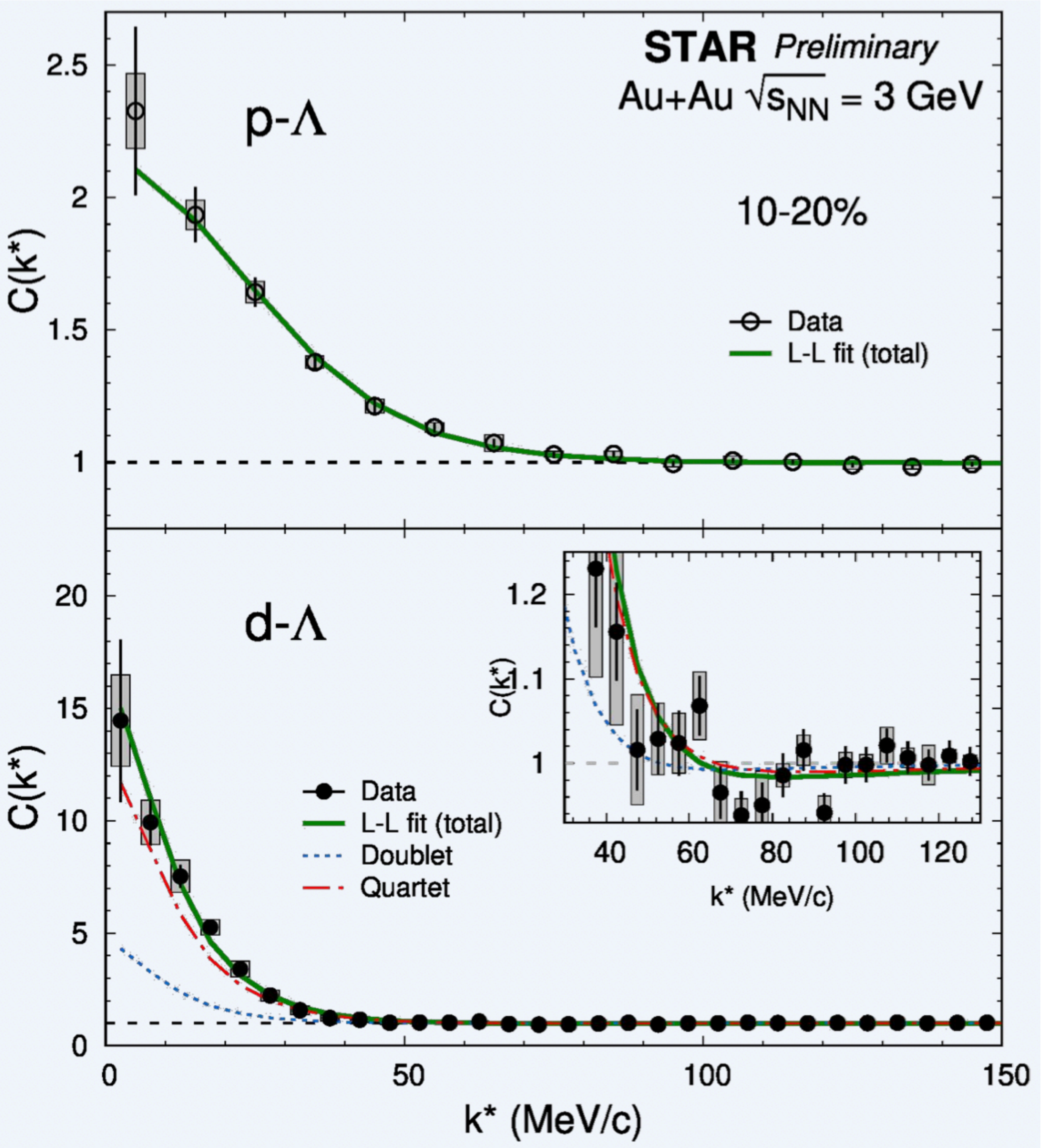


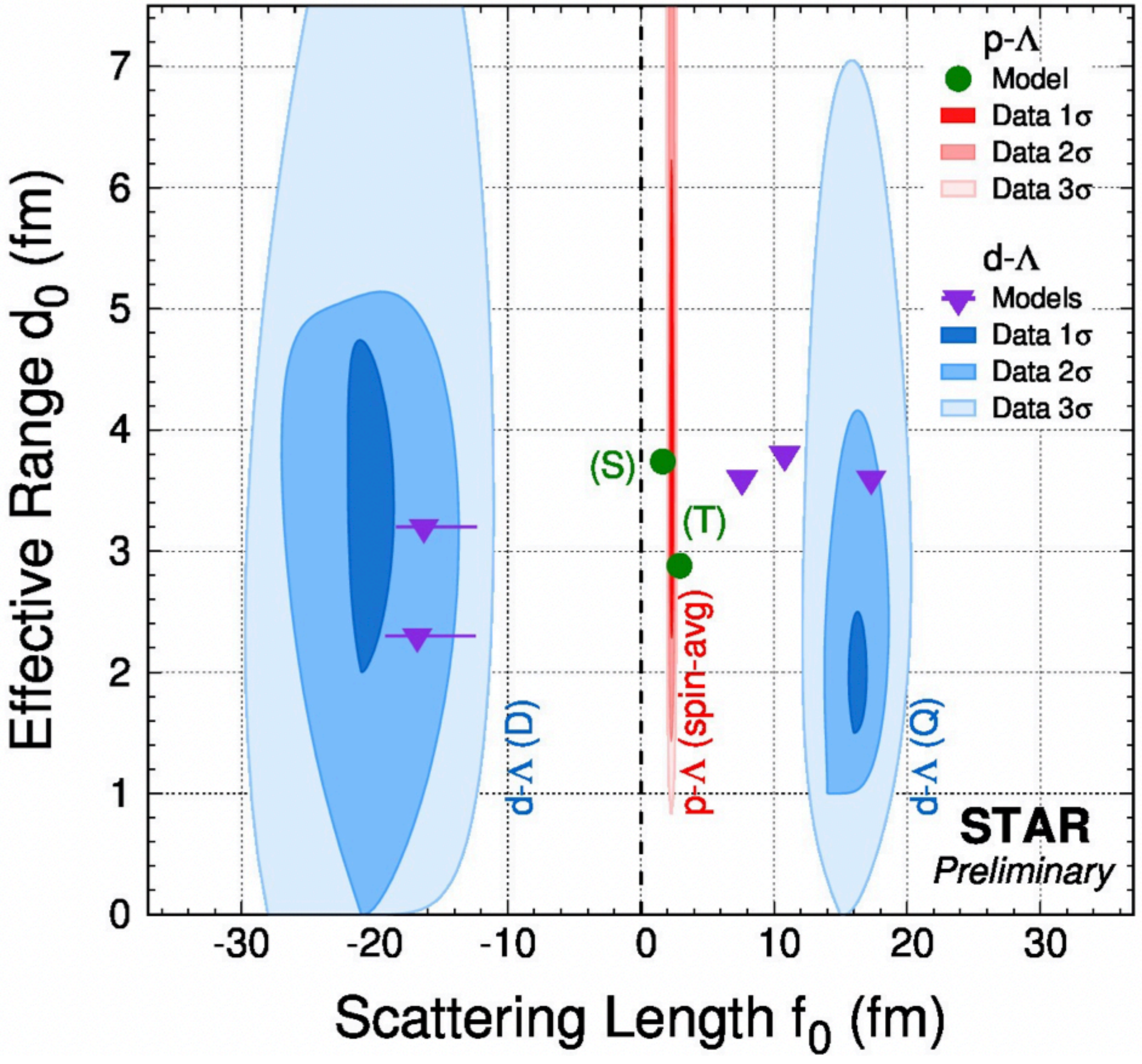


- Hypernuclei <p_T> and v_1 follow mass number scaling —> Coalescence production from light nuclei and Lambda
- Access to YN interactions

Light nuclei - Λ interactions from correlation femtoscopy

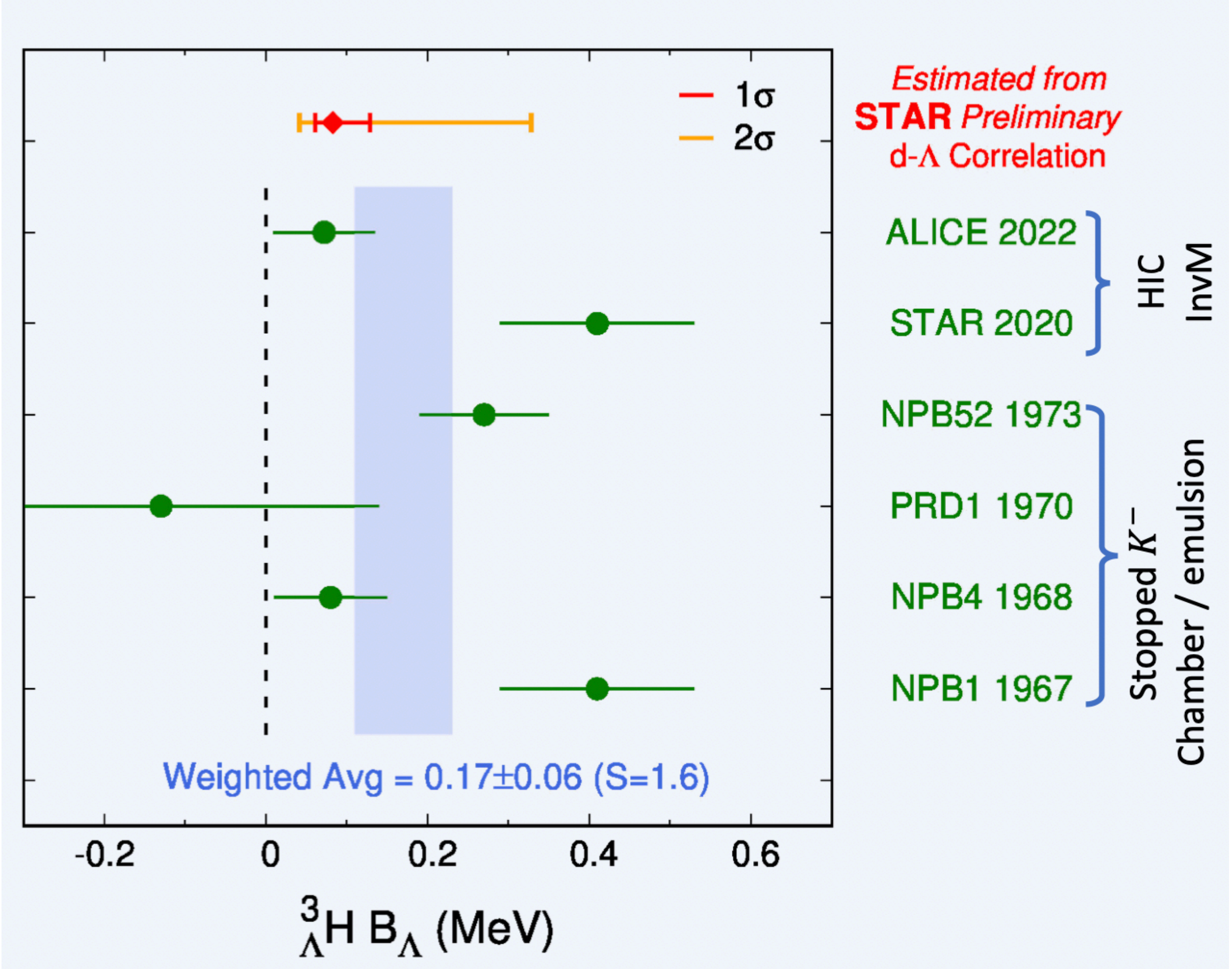
- Pair momentum correlations of light nuclei and Λ.
- Provides access to source size and final state interactions. Lednicky-Lyuboshits approach





- f_0, d_0 extracted for two spin states for d-Λ
- Bound state for doublet case

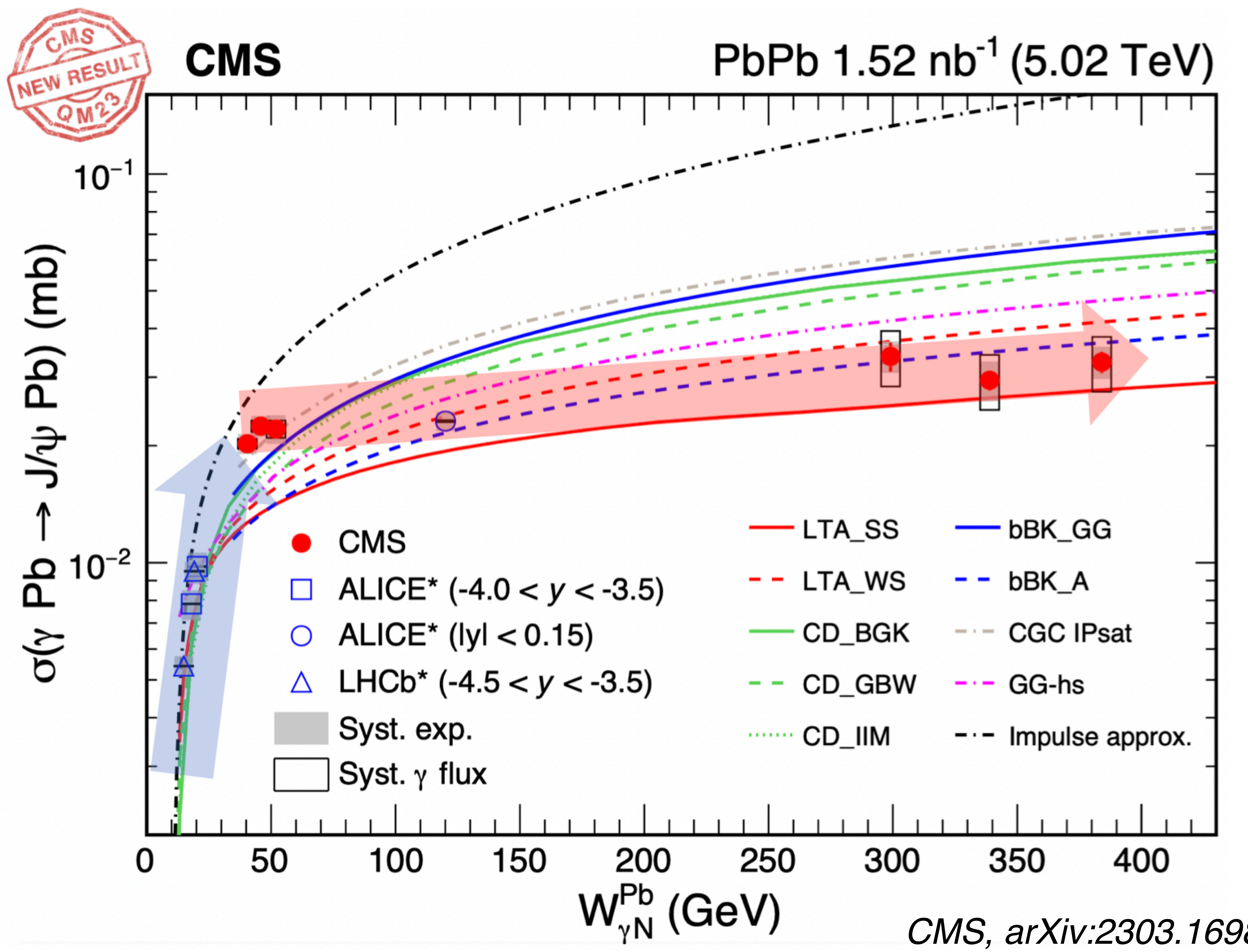
$$\frac{1}{-f_0} = \gamma - \frac{1}{2} d_0 \gamma^2$$



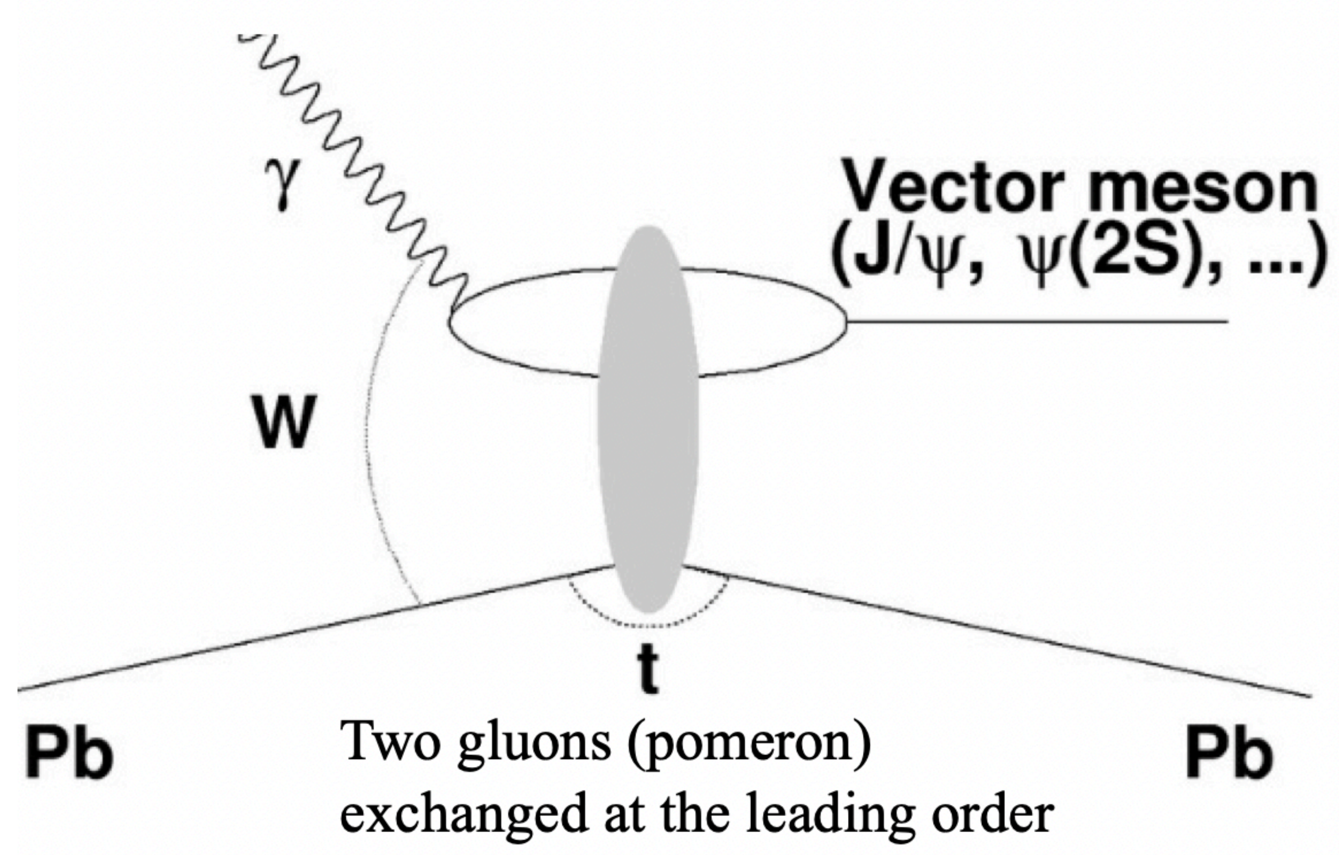
Consistent binding energy extracted for the H3L state

Ultra peripheral collisions: unique opportunity in HIC

- Large photon flux associated with ions, enhanced by Z^4
- γ - γ and γ - A interactions



CMS, arXiv:2303.16984



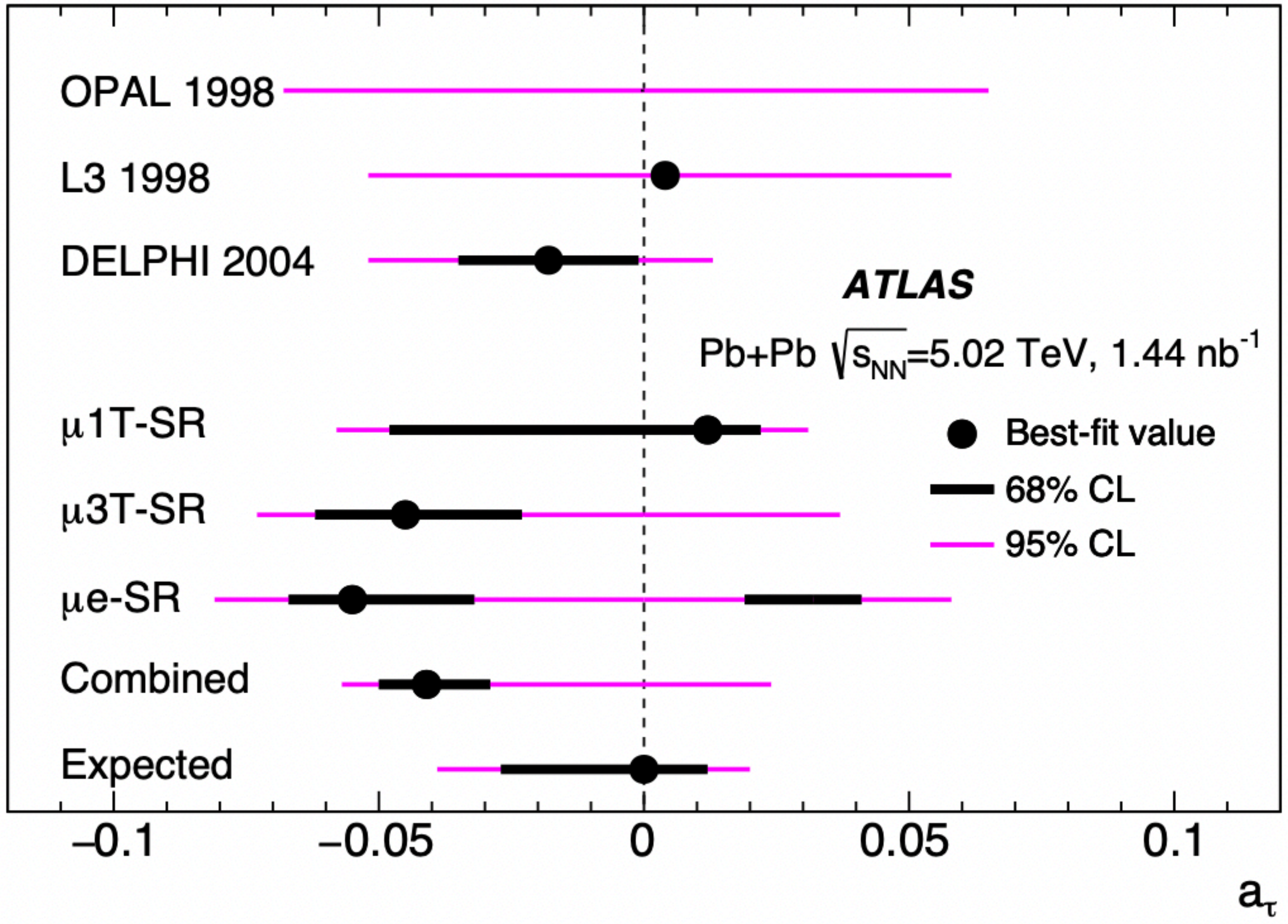
- J/Ψ photo production — probes gluon distribution

- Sharp increase followed by plateau
- Direct evidence of gluon saturation? Need more theory studies
- Current models can't describe

Ultra peripheral collisions: unique opportunity in HIC

- Large photon flux associated with ions, enhance by Z^4 n
- γ - γ and γ - A interactions

$a_l = 1/2(g - 2)l$

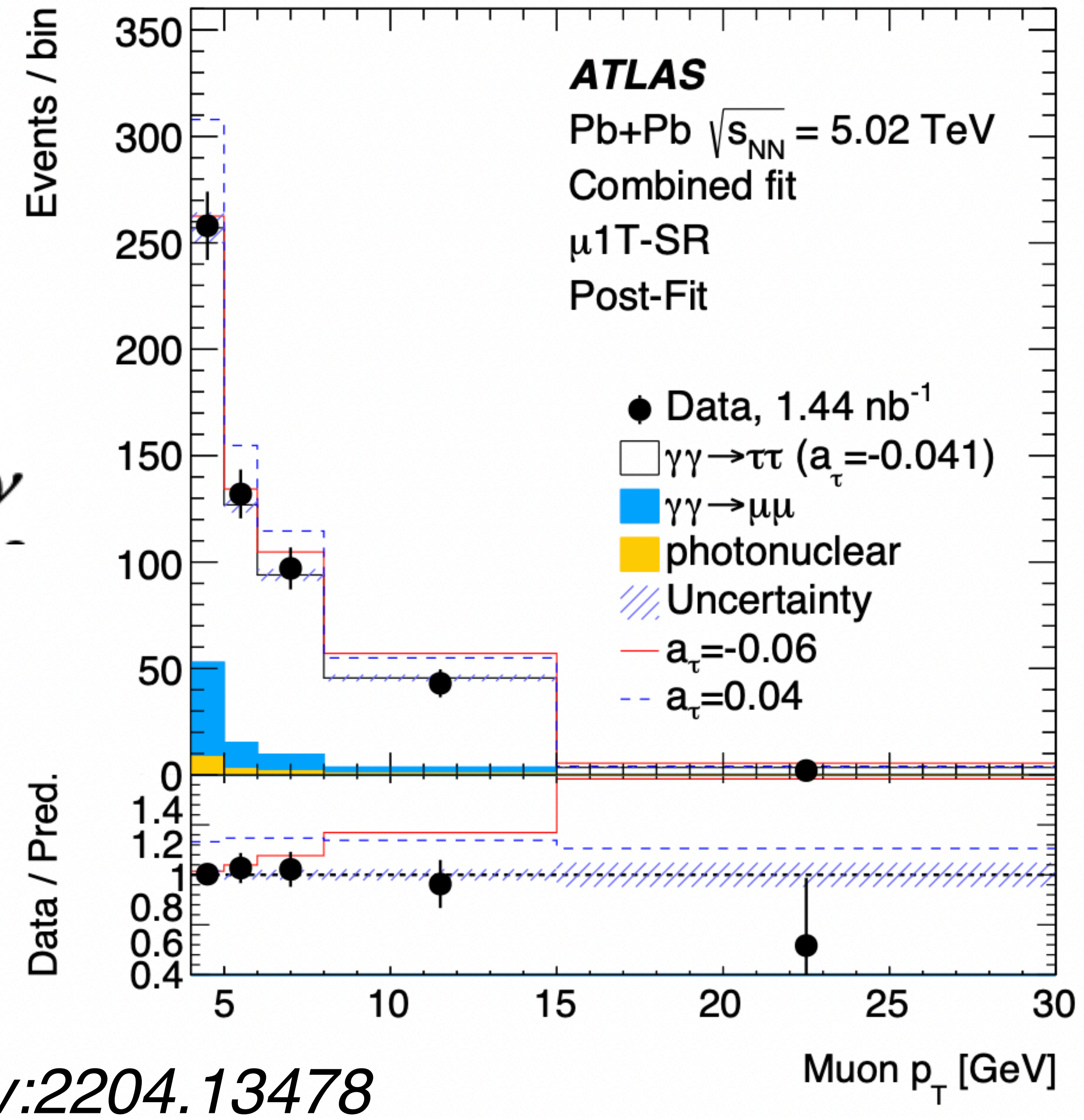


ATLAS, arXiv:2204.13478

ττγ coupling

$$F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i}{2m_\tau}\sigma^{\mu\nu}q_\nu$$

$$F_2(q^2 \to 0) = a_\tau$$



ATLAS, arXiv:2204.13478

- Anomalous magnetic moment of τ from photon photon interaction
- Could have a larger contribution to τ from larger mass
- Better precision measurements expected from Run3

Summary & Outlook

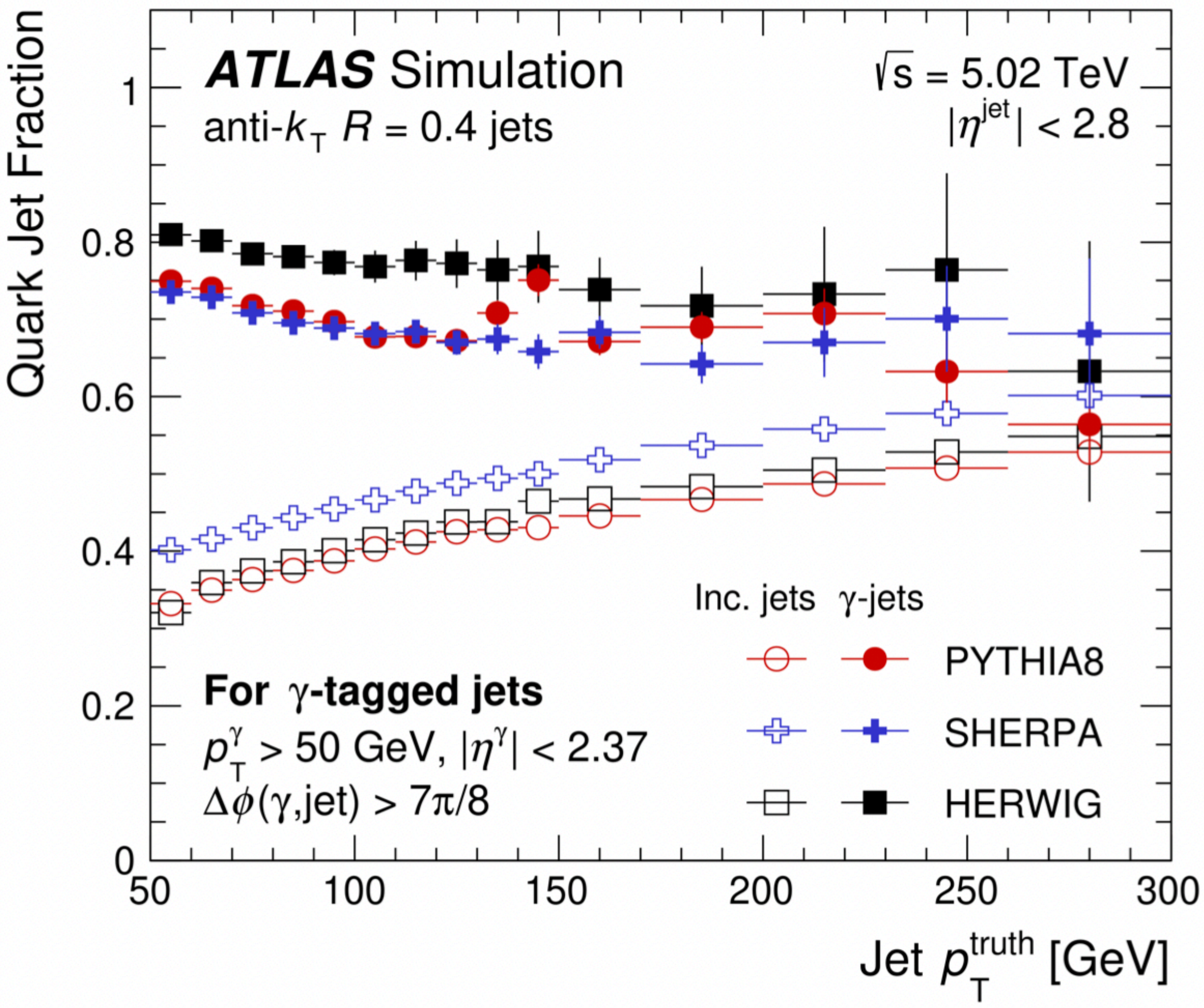
- Top energies, QGP properties
  - Flavor dependence of parton energy loss
  - Bayesian extraction of QGP transport properties
  - Speed of sound of QGP consistent with LQCD calculations
  - Modification of hadronization in p+p and A+A collisions

- Beam energy scan, QCD phase structure
  - Non-monotonous energy dependence of C_4/C_2 from BES-I. BES-II higher precision measurements awaited
  - Medium dominated by hadronic interactions at 3.2 GeV and below
  - Y-N interactions through hypernuclei measurements and correlation femtoscopy

- Outlook
  - RHIC runs 2023 - 25: High statistics A+A and p+p data, sPHENIX experiment
  - LHC Run3 2022 - 25: ALICE upgrades
  - HL LHC, Run4 and 5: ALICE, CMS, ATLAS upgrades. High precision measurements

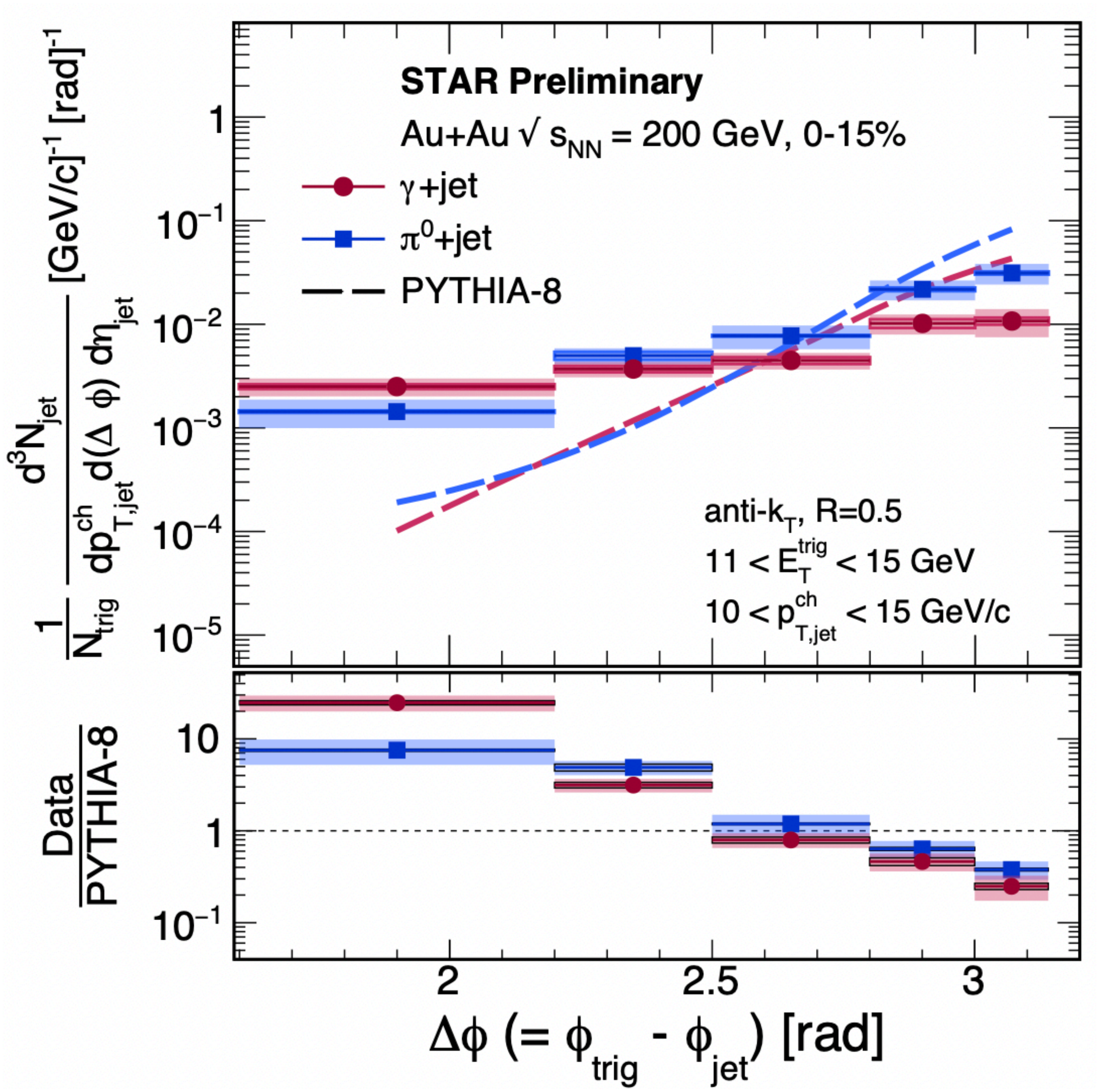
Back Up

Quark jet fractions - photon tagging

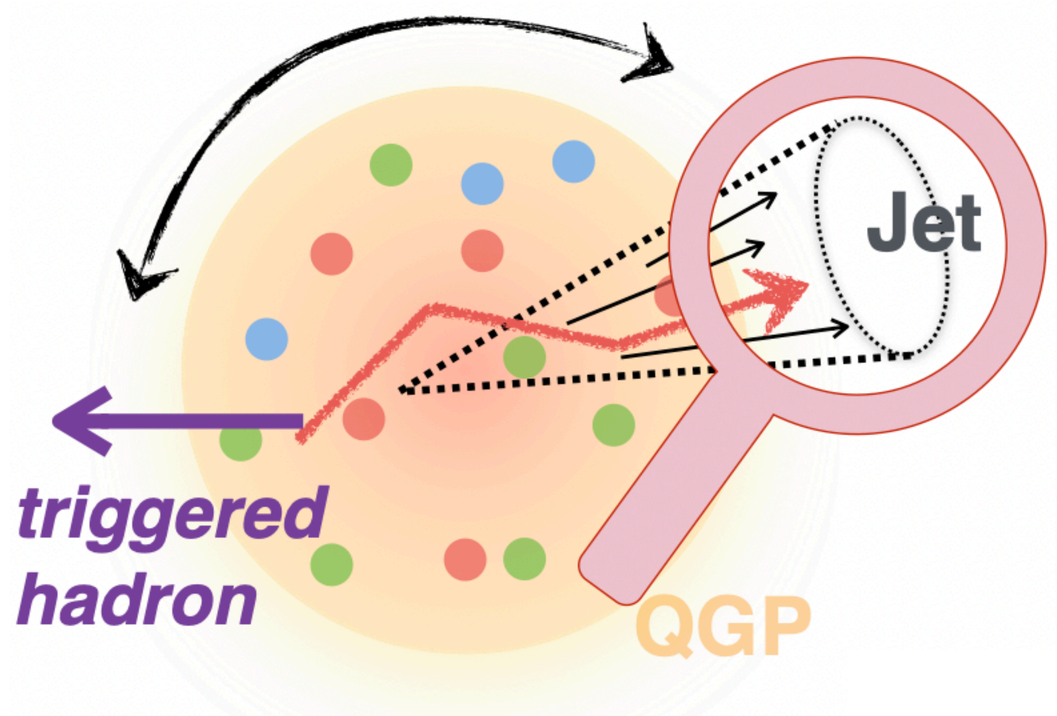


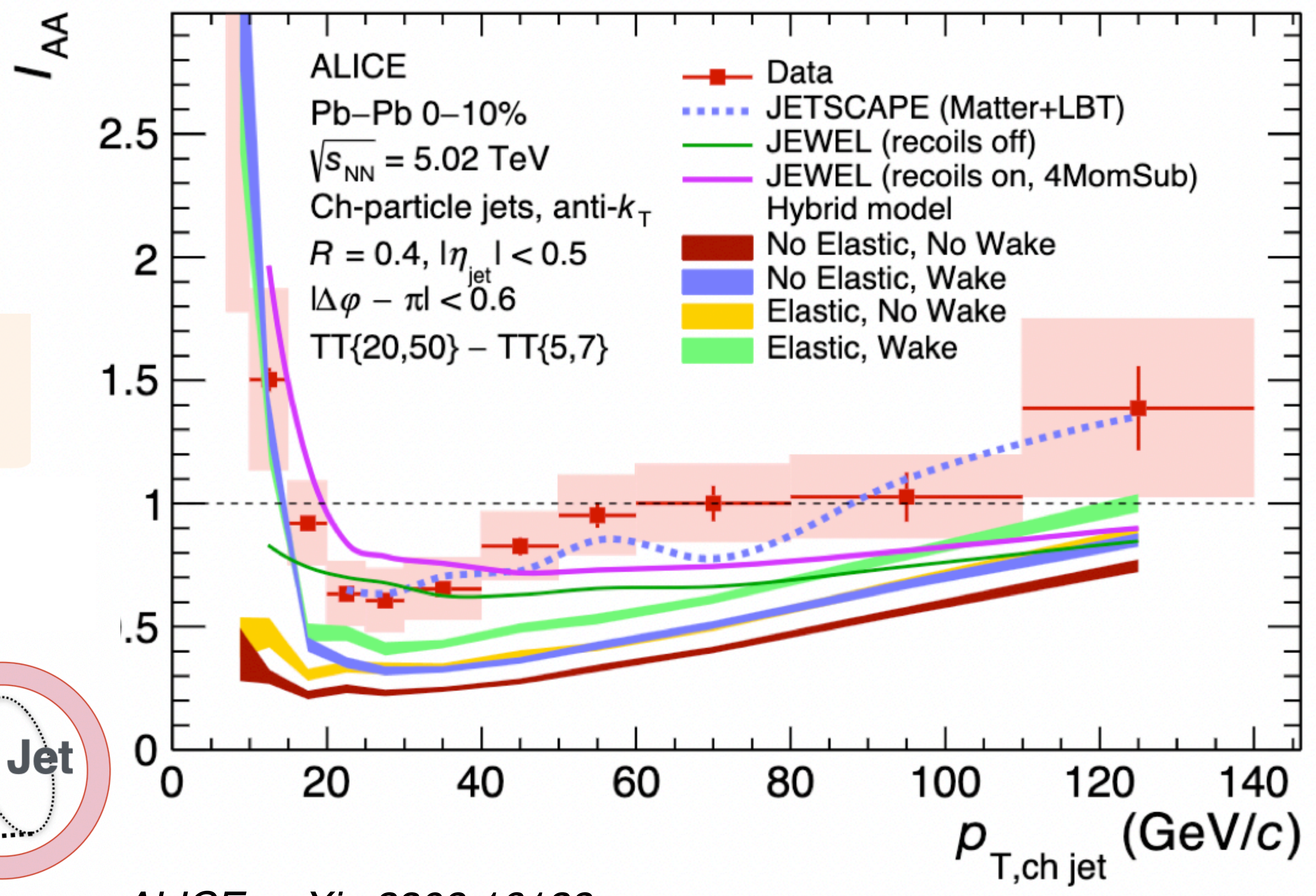
Medium response to jets

- Acoplanarity, angular distribution of recoil jets



$$I_{AA} = \frac{Y^{\rm jet}_{\rm Pb+Pb}/N^{\rm trig}_{\rm Pb+Pb}}{Y^{\rm jet}_{pp}/N^{\rm trig}_{pp}}$$





ALICE, arXiv:2308.16128

- Enhancement in the yield of lower p_T jets
- Sensitive to medium response. Medium wake? Need further understanding

- Significant dijet acoplanrity measured in AA
- Details of how jets lose energy in the medium