Experimental Constraints on the QCD Phase Diagram based on RHIC and LHC results

R. Bellwied (University of Houston)

with a little help from my friends

The 5th International Symposium on Non-Equilibrium Dynamics

Oct.31– Nov 5, 2016

Phuket, Thailand

Outline

- The most recent results of RHIC and LHC with a focus on particle production in order to answer questions on two major open issues in our field:
  - Hadronization and Chiral Symmetry Restoration

    from RHIC to LHC, from HI to pp – global effects

    from RHIC to LHC, from HI to pp - chirality

    from RHIC to LHC, from HI to pp – particle production

    from RHIC to LHC, from HI to pp - hadronization

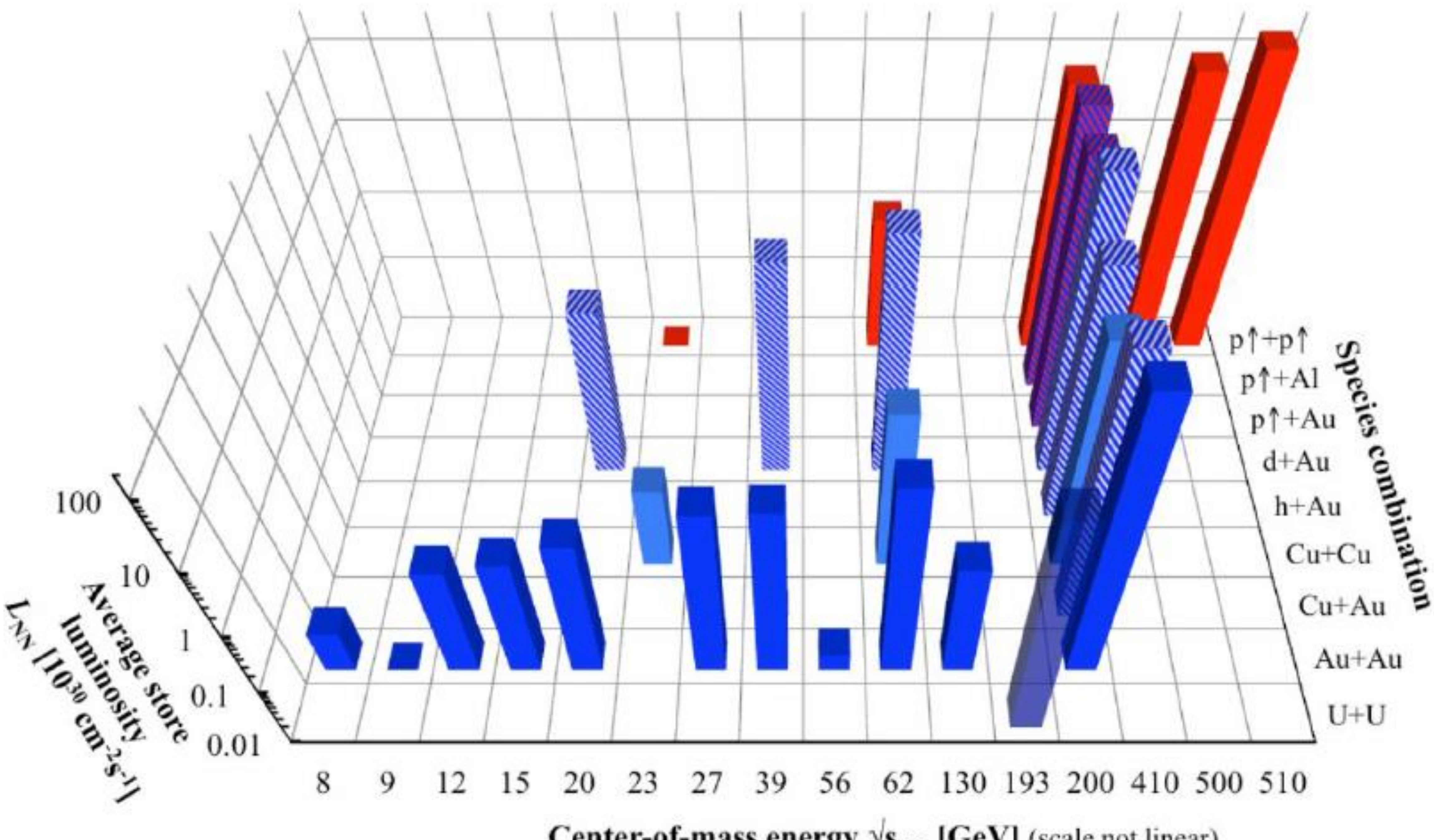
- I will not cover much of:
  - Flow (Raimond)
  - Heavy Flavor (Andre)
  - Hadronic Resonances (Christina)

Global effects

Versatility of RHIC

RHIC Amazing QCD Machine: Many Species and Many Energies!

RHIC energies, species combinations and luminosities (Run-1 to 16)



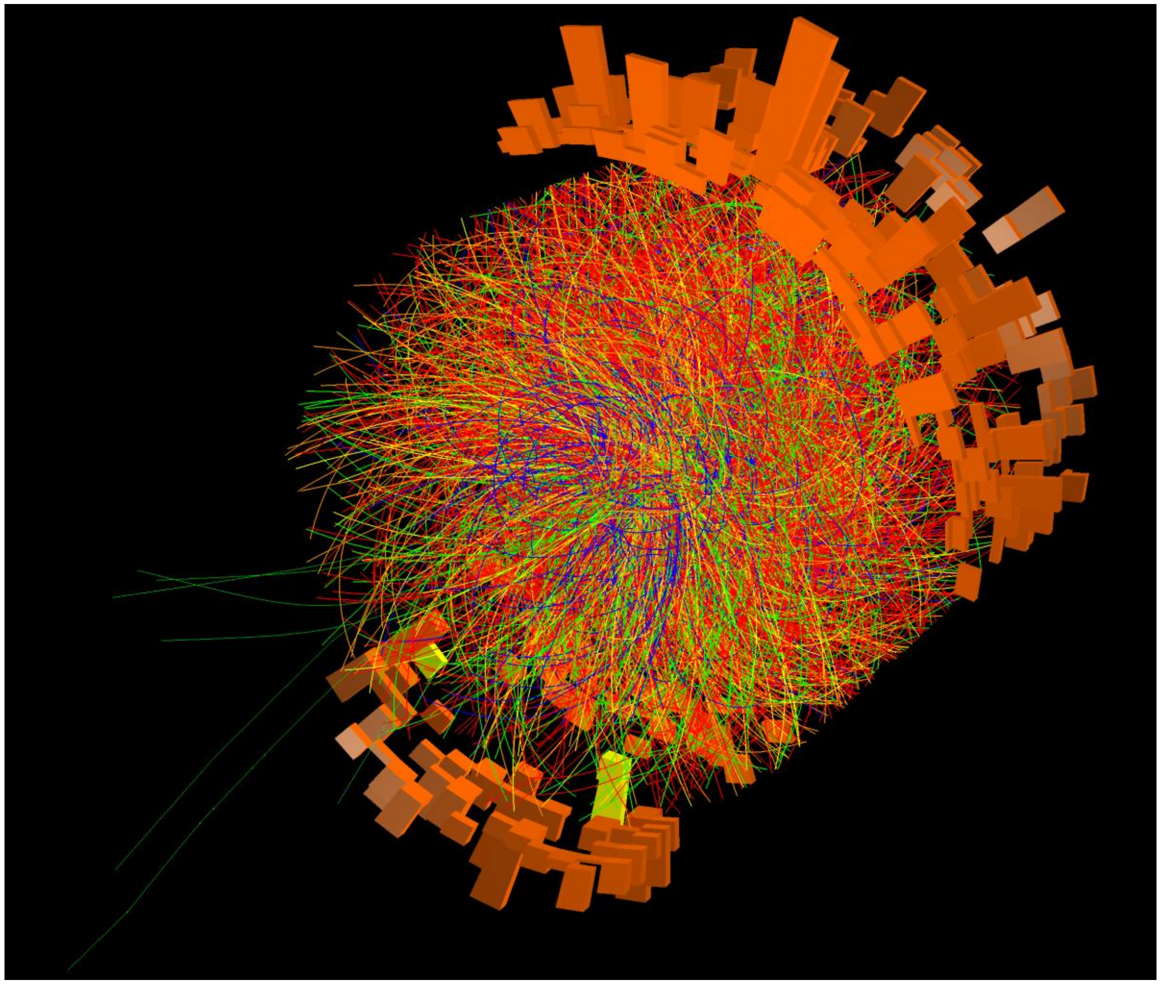
RHIC BES-I

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	#Events	#Weeks	Year
200	20	350 M	11	2010
62.4	70	67 M	1.5	2010
39.0	115	130 M	2	2010
27.0	155	70 M	1	2011
19.6	205	36 M	1.5	2011
14.5	260	20 M	3	2014
11.5	315	12 M	2	2010
7.7	420	4 M	4	2010

BES-II scheduled for 2018/2019

The power of the LHC

(the 5.02 TeV era has begun)



The ALICE setup now contains a fully functional back-to-back calorimeter

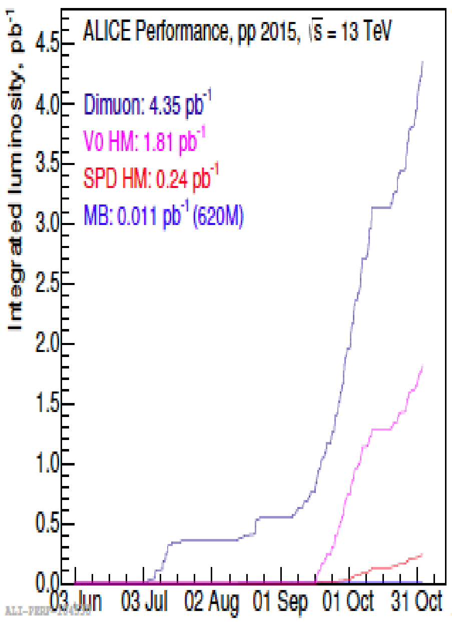
RUN-I milestone (2009 – 2013)

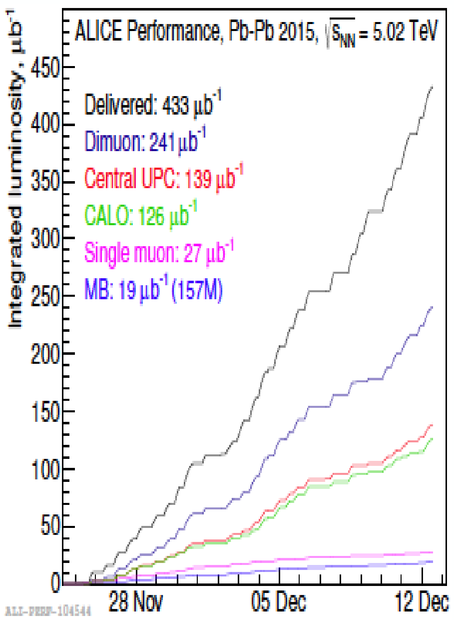
Year	System	Energy $\sqrt{s_{NN}}$ (TeV)	Integrated luminosity (nb^{-1})
2010	Pb–Pb	2.76	~ 0.01
2011	Pb–Pb	2.76	~ 0.1
2013	p–Pb	5.02	~ 30

- pp collisions at 0.9, 2.76, 7 and 8 TeV, total integrated luminosity up to ~20 pb^{-1}

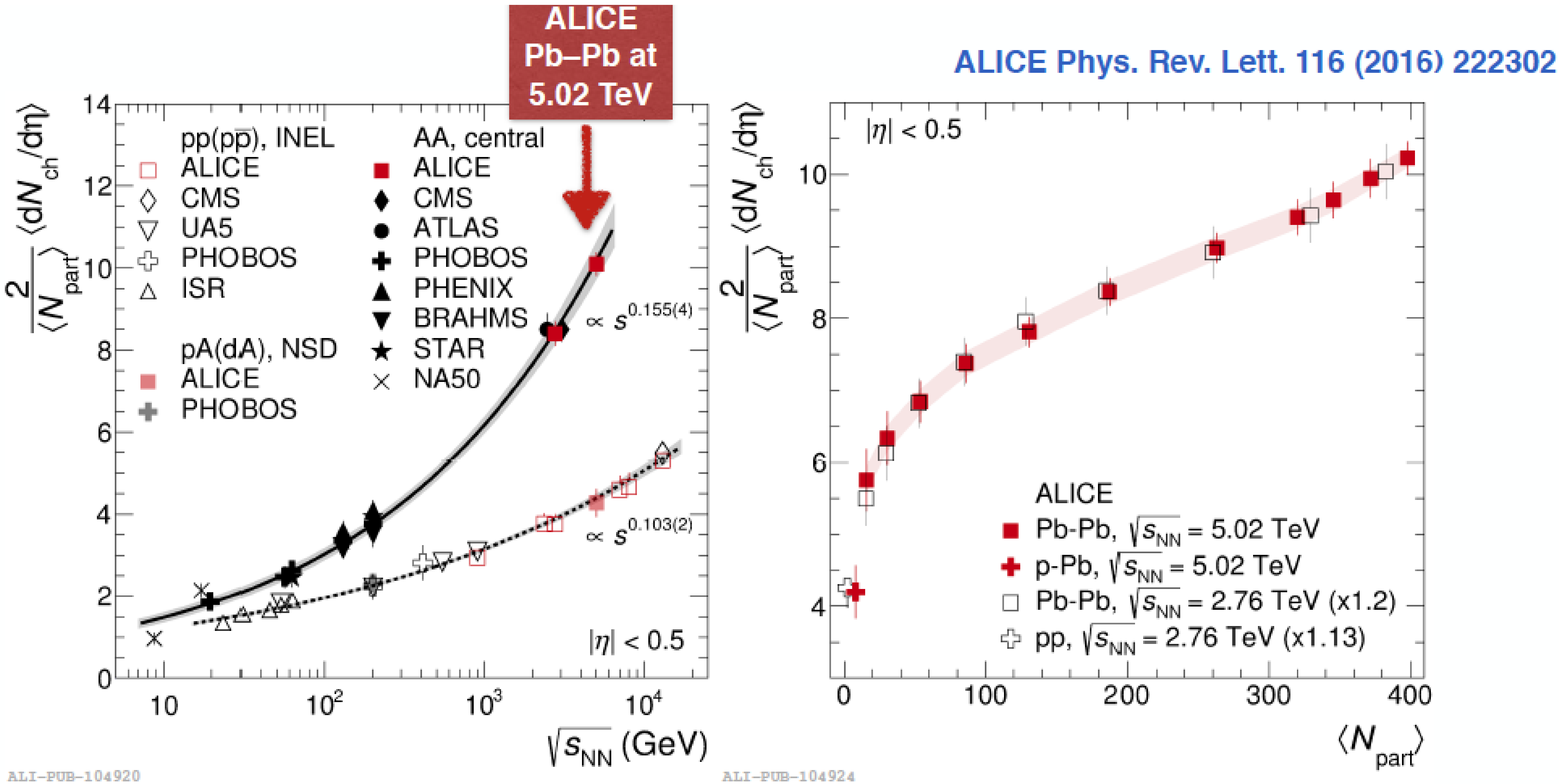
RUN-II, since 2015

- Pb–Pb at 5.02 TeV: up to 0.5 nb^{-1}
- pp at 13 TeV and 4 days at 5.02 TeV (~100 nb^{-1})
- Upcoming p–Pb at 5.02 and 8 TeV: 10 times more statistics than in RUN-I



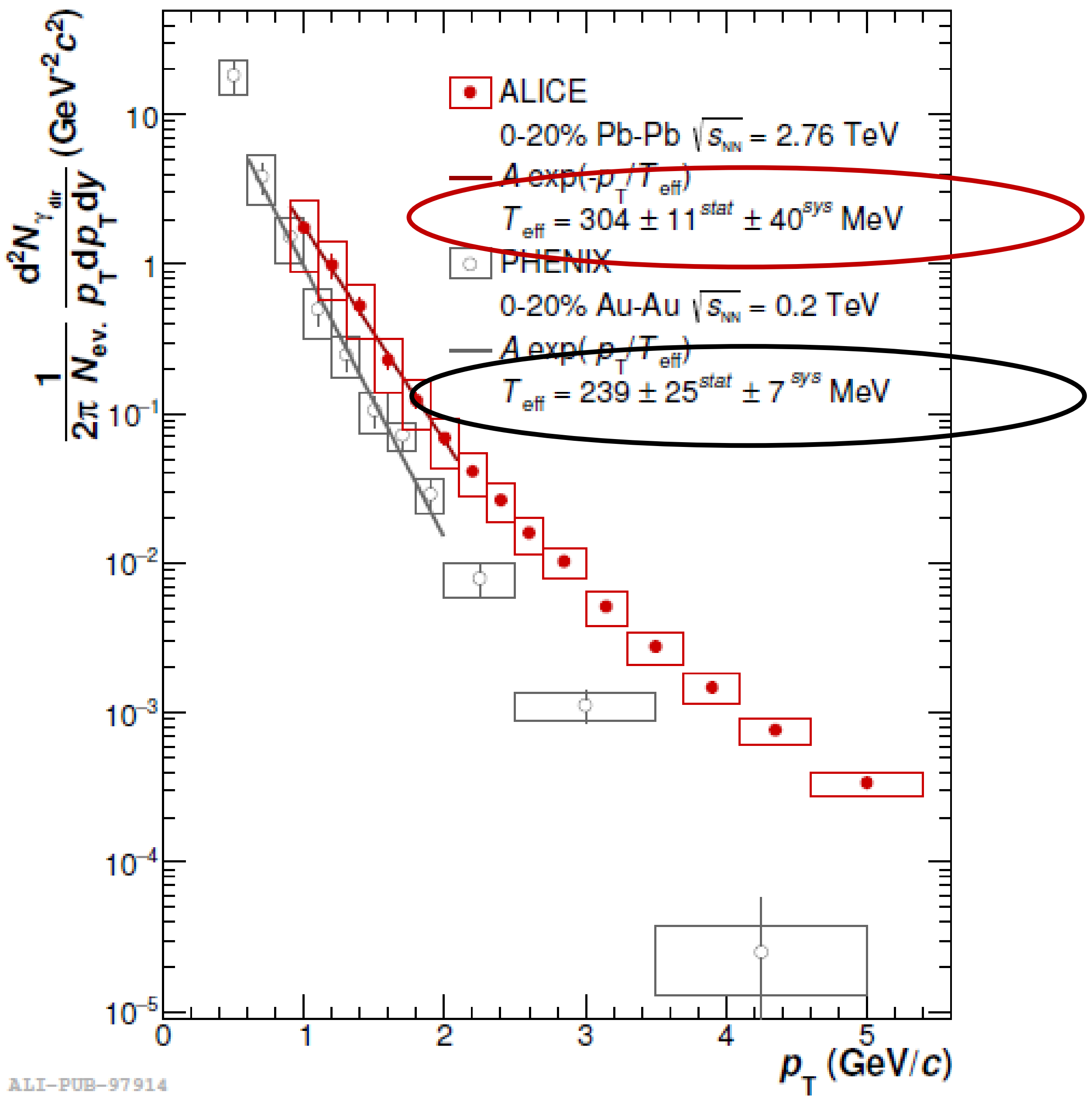


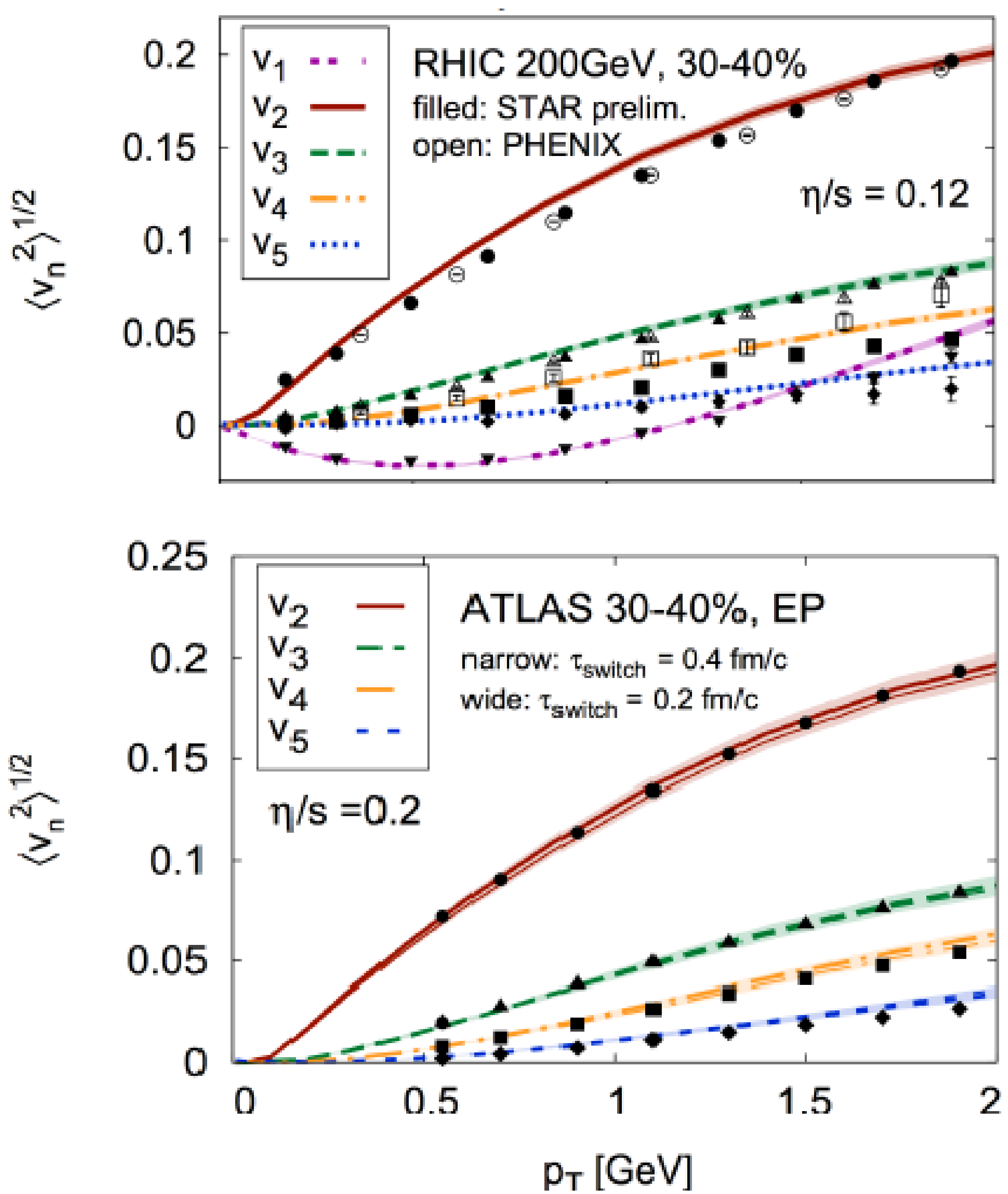
RHIC vs. LHC: charged particle multiplicity



- ALICE: Pb–Pb at 5.02 TeV — highest energy so far
  - For 0–5% most central collisions, confirms trend from lower energies
- $\langle dN_{ch}/d\eta \rangle$ vs. $\langle N_{part} \rangle$: similar evolution with centrality between 5.02 and 2.76 TeV
  - ~20% increase going from 2.76 to 5.02 TeV
  - Provides further constraints for models

RHIC vs. LHC: photon spectra and charged particle flow





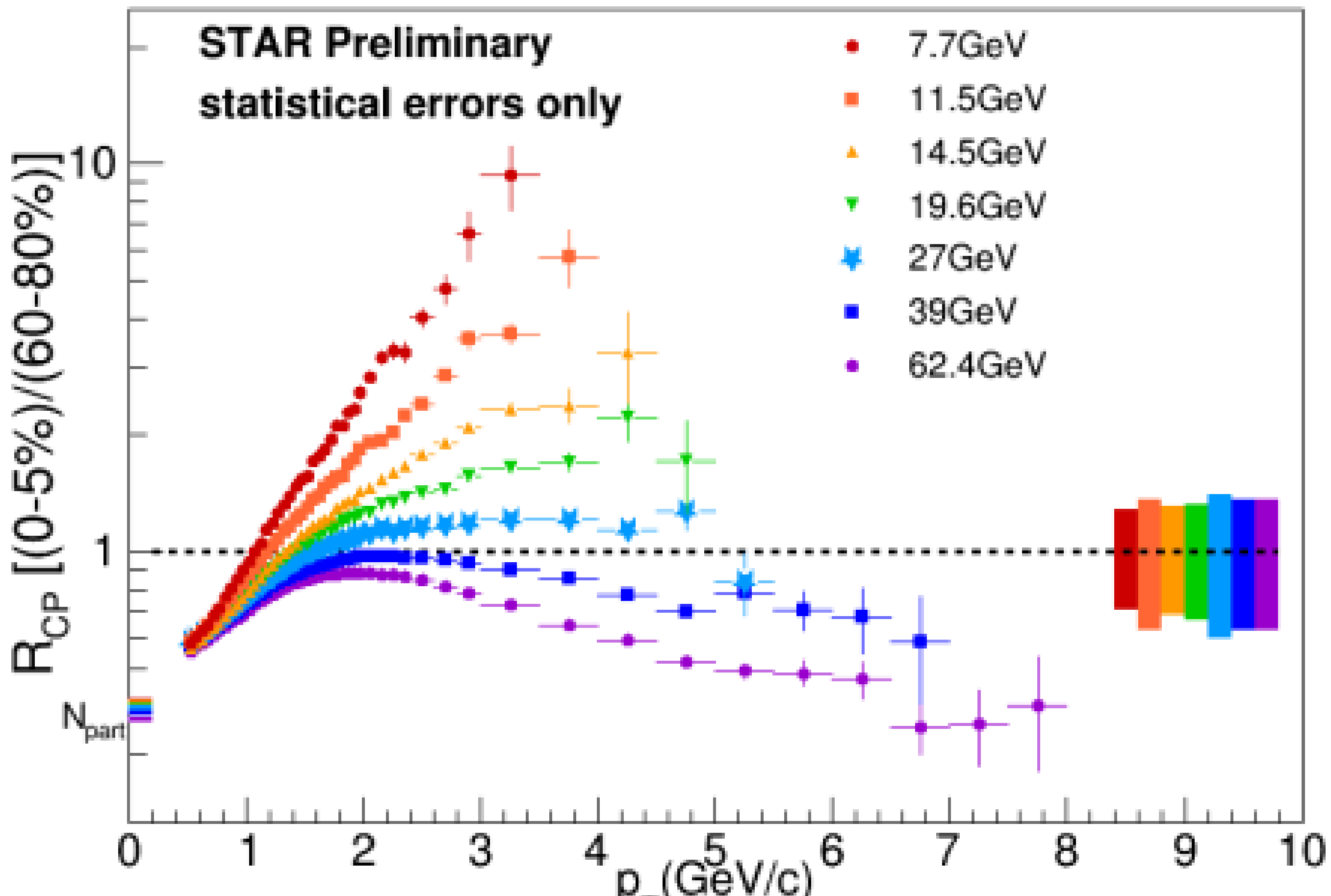
ALICE:Phys. Lett. B 754 235-248
PHENIX:*Phys. Rev. Lett.* **104** 132301

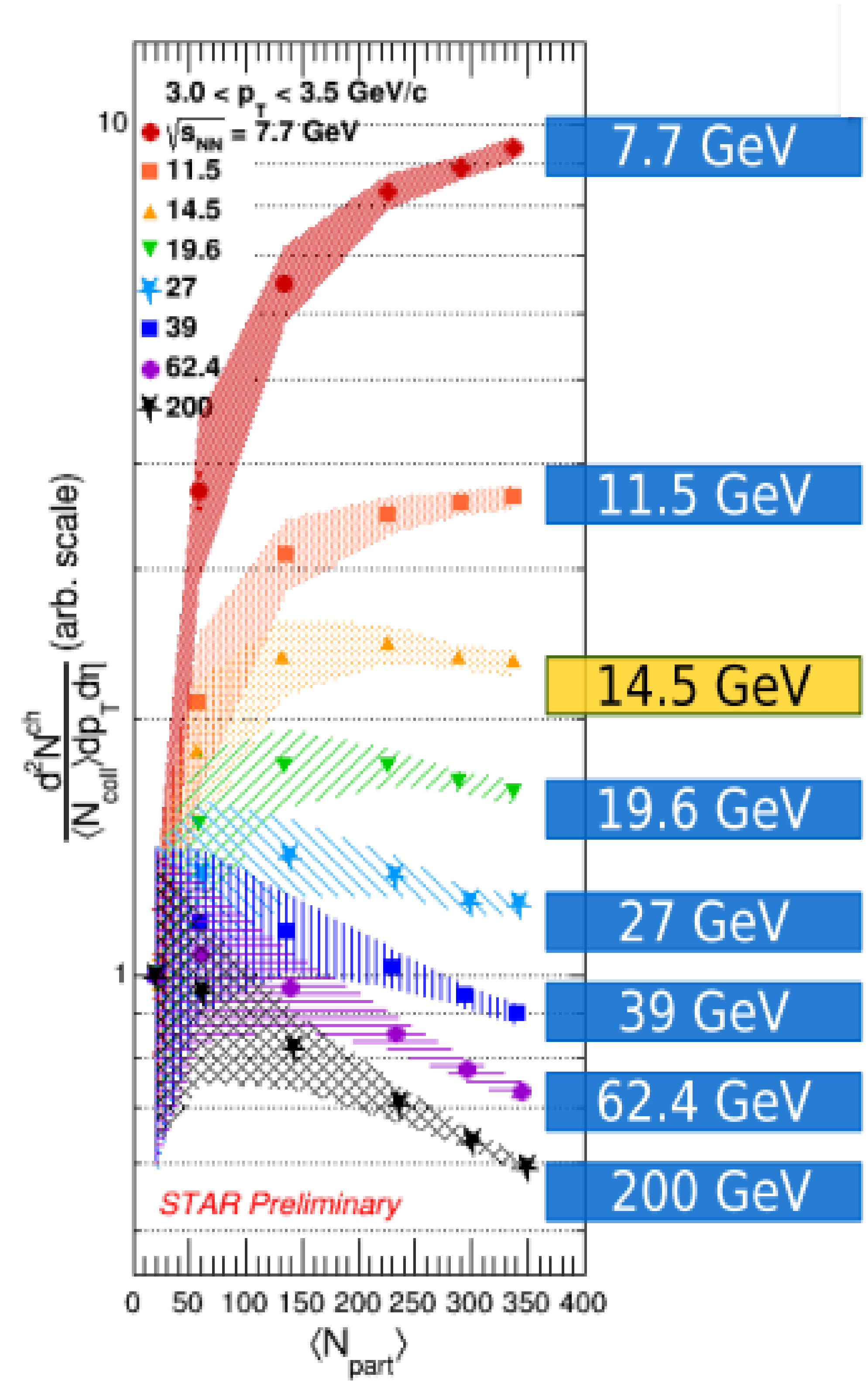
PRL. 110 012302

Effective Temperature over 200MeV

Anisotropy described by hydro

RHIC: onset of QGP signatures





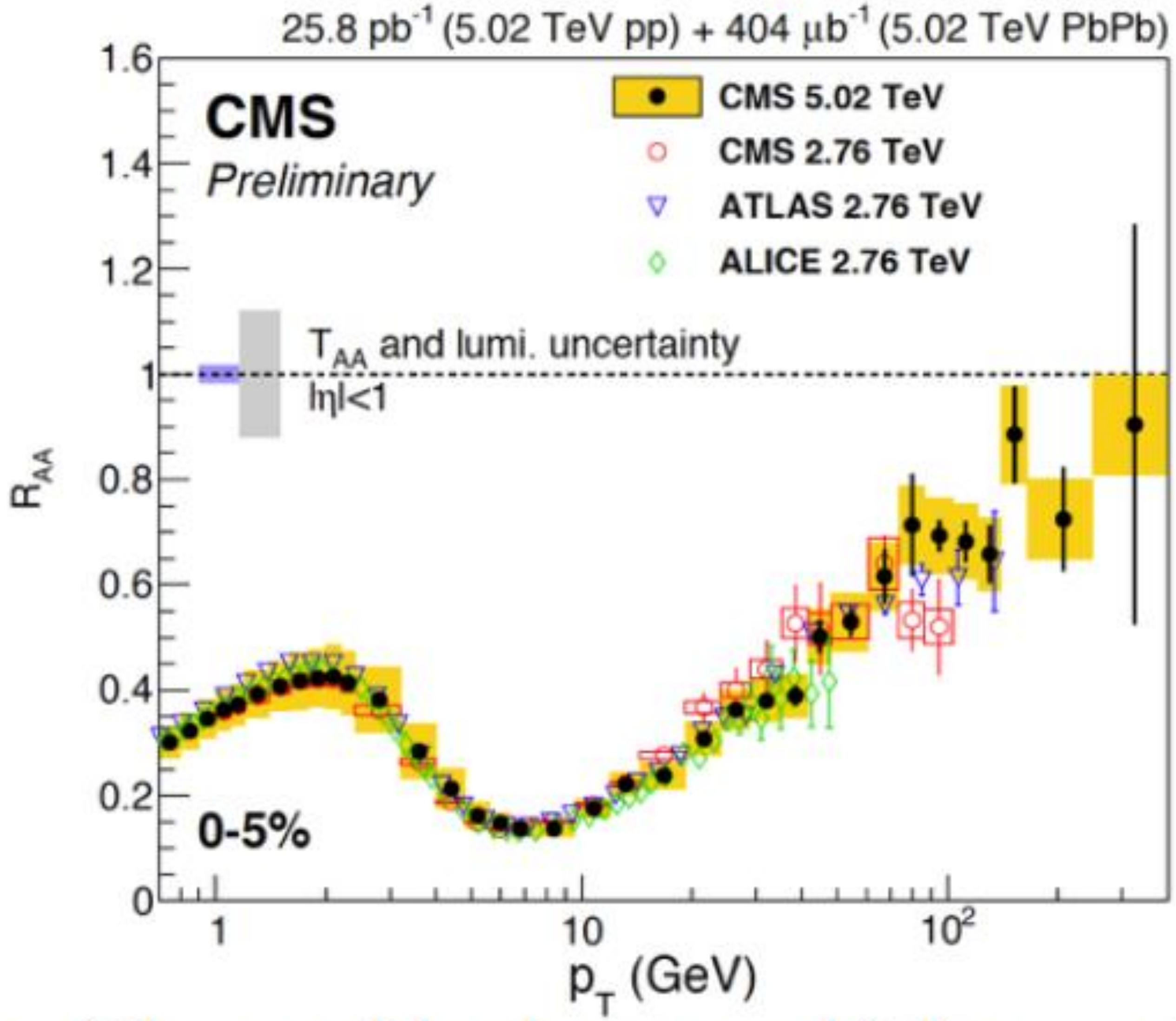
R_{CP} exhibits suppression down to 39 GeV

Cronin effects more prominent at lower energies

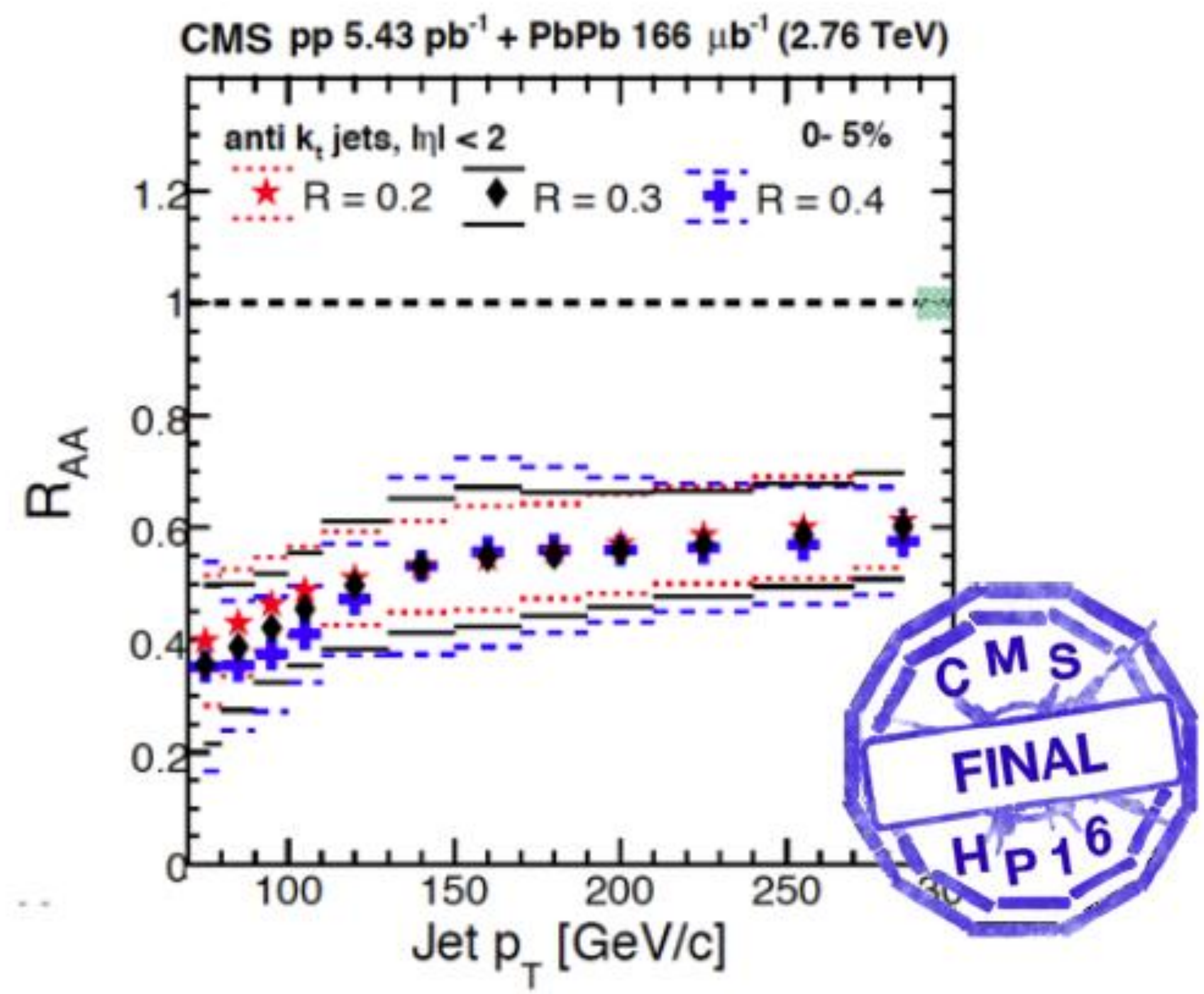
Yields per binary collision show indicate a balance of enhancement and suppression effects at $\sqrt{s_{NN}}$ = 14.5 GeV.

LHC: intriguing R_{AA} pattern at high pT

2.76 and 5 TeV charged hadrons

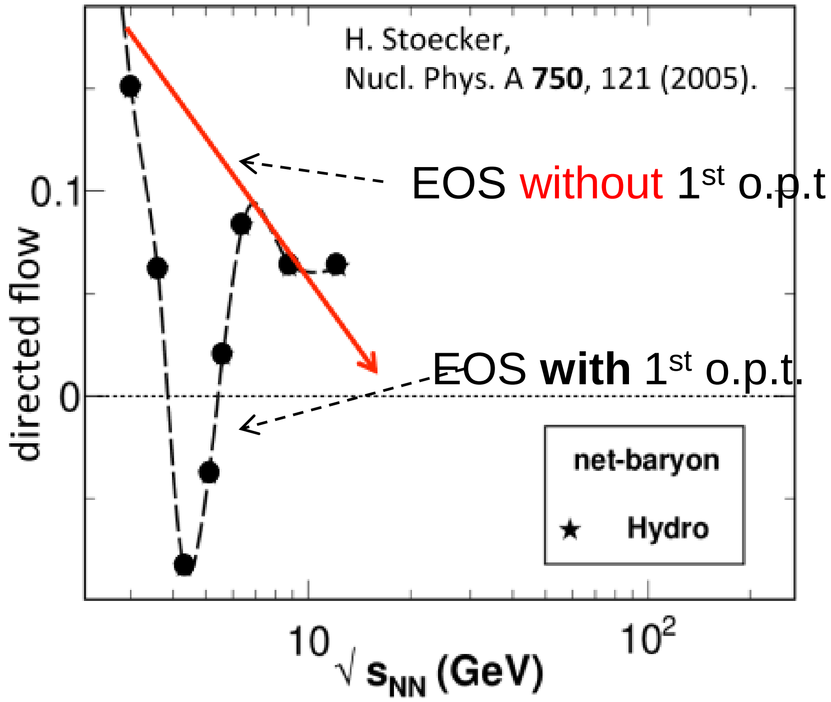


2.76 TeV jets



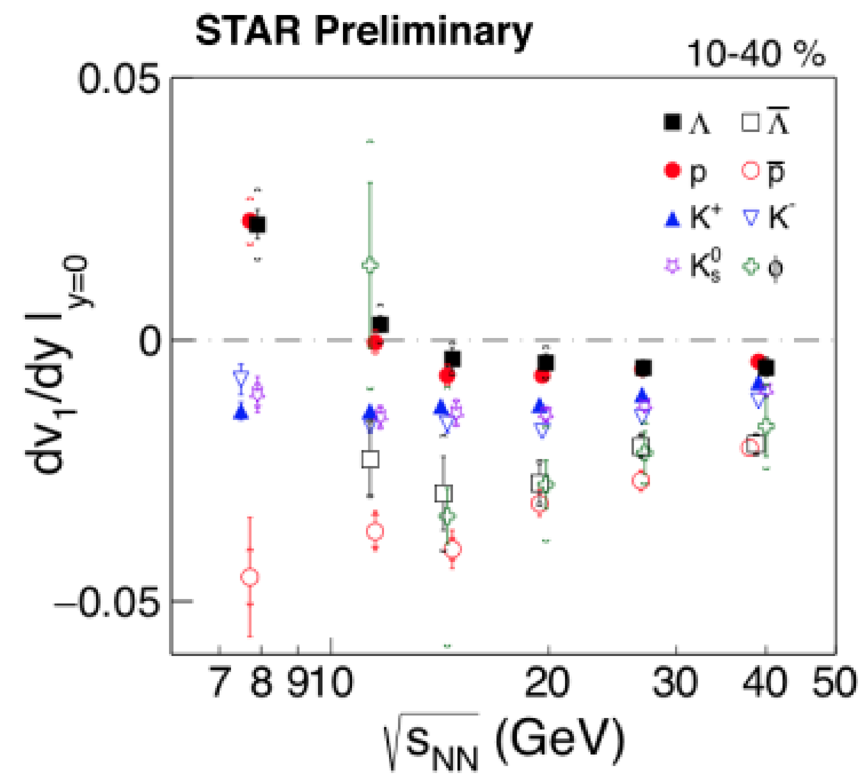
- Charged hadrons at high p_T → hard fragmenting high p_T jets
- Energy loss at high p_T *Rising trend as a function of p_T up to 400 GeV → approaching 1*
- Center of mass energy dependence *Slightly larger E_{loss} → higher T and density*

RHIC: onset of QGP signatures



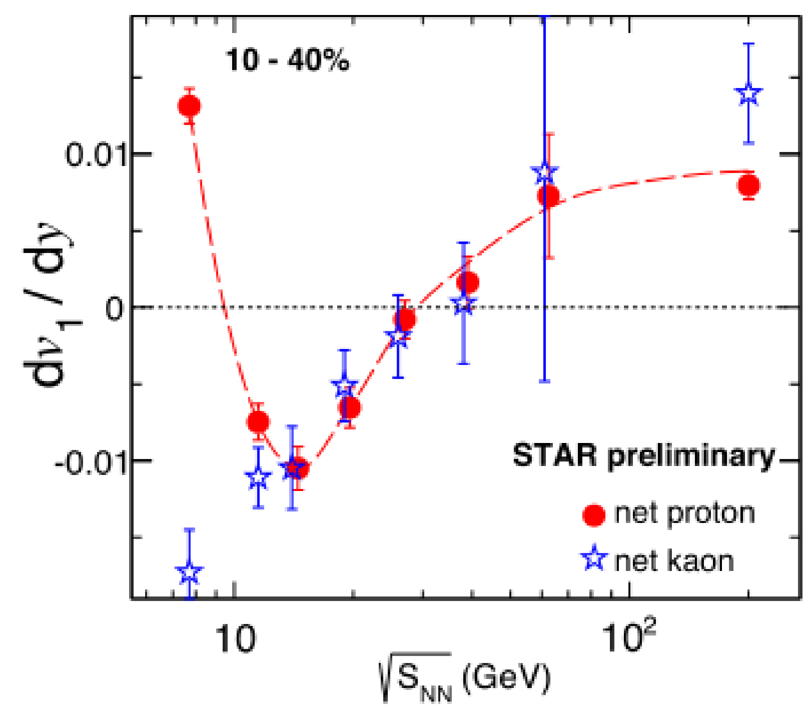
Directed flow v_1

- Sensitive to the pressure
- Sensitive to EoS
- Dip in dv_1/dy – softening of EOS



Minimum in $dv_1/dy|_{y=0}$ –hydro and baryon transport interplay

(Anti)-Lambdas follow those of (anti)-protons



Net-K and net-p are consistent with each other down to ~14.5 GeV. Net-K stays negative below14.5 GeV

RHIC: search for critical point

At critical point susceptibilities and correlation length diverge leading to large fluctuations

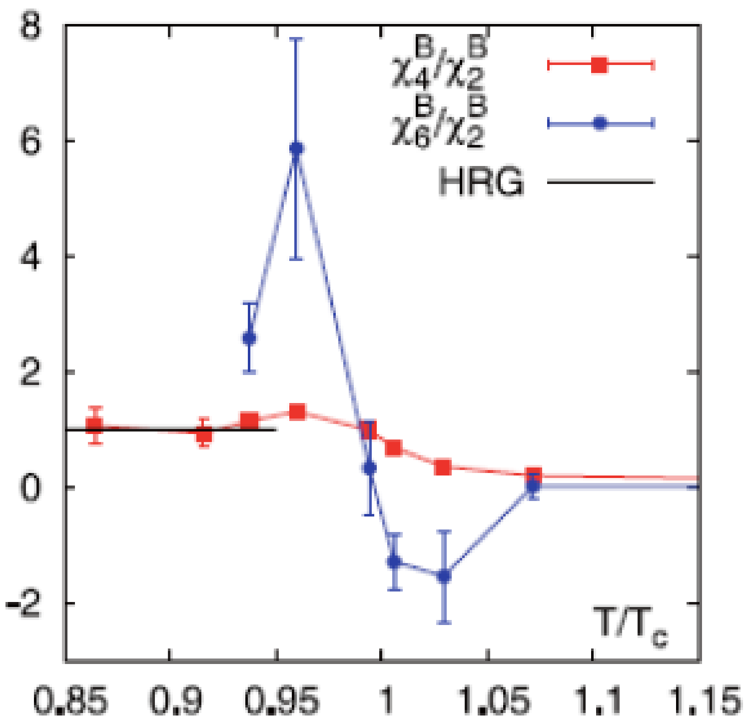
$$\frac{\chi_2^i}{\chi_1^i} = (\sigma^2/M)^i = \frac{c_2^i}{c_1^i}$$

Observables: Higher moments of conserved quantum numbers (Q, S, B)

$$\frac{\chi_3^i}{\chi_2^i} = (S\sigma)^i = \frac{c_3^i}{c_2^i}$$

Direct link between theory and moments of distributions (cumulant ratios)

$$\frac{\chi_4^i}{\chi_2^i} = (\kappa\sigma^2)^i = \frac{c_4^i}{c_2^i}$$

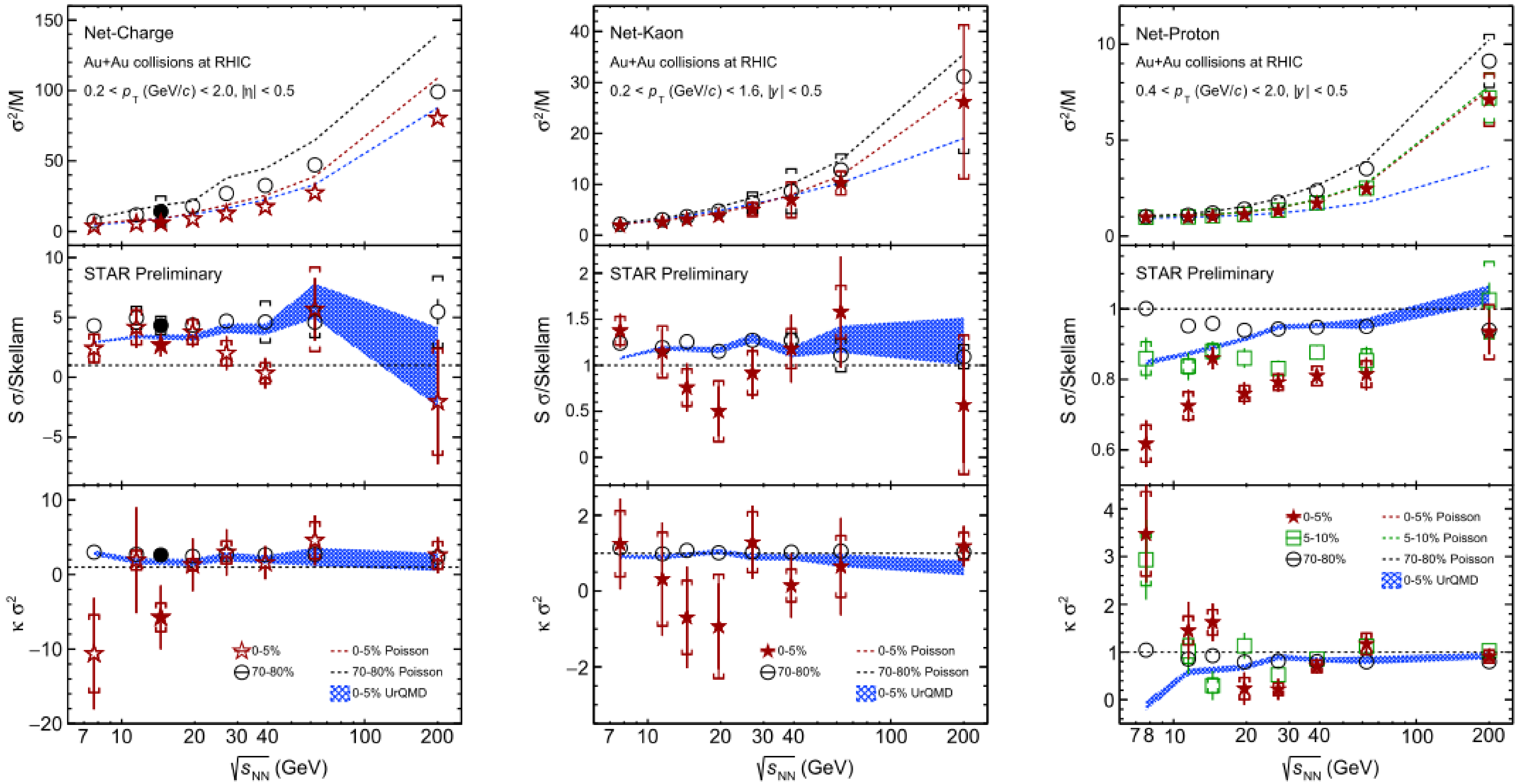


$$i = B, Q, S$$

$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial(\mu_q)^n}, q = B, Q, S$$

S. Ejiri et al, Phys.Lett. B 633 (2006) 275.
Cheng et al, PRD (2009) 074505. B. Friman et al., EPJC 71 (2011) 1694.
F. Karsch and K. Redlich , PLB 695, 136 (2011).
S. Gupta, et al., Science, 332, 1525(2011).
A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // P. Alba et al., arXiv:1403.4903

Net-charge,kaon,proton fluctuations
search for non-monotonic behavior in higher moments



Largest deviation from Poisson and uRQMD in net-protons around 19.6 GeV

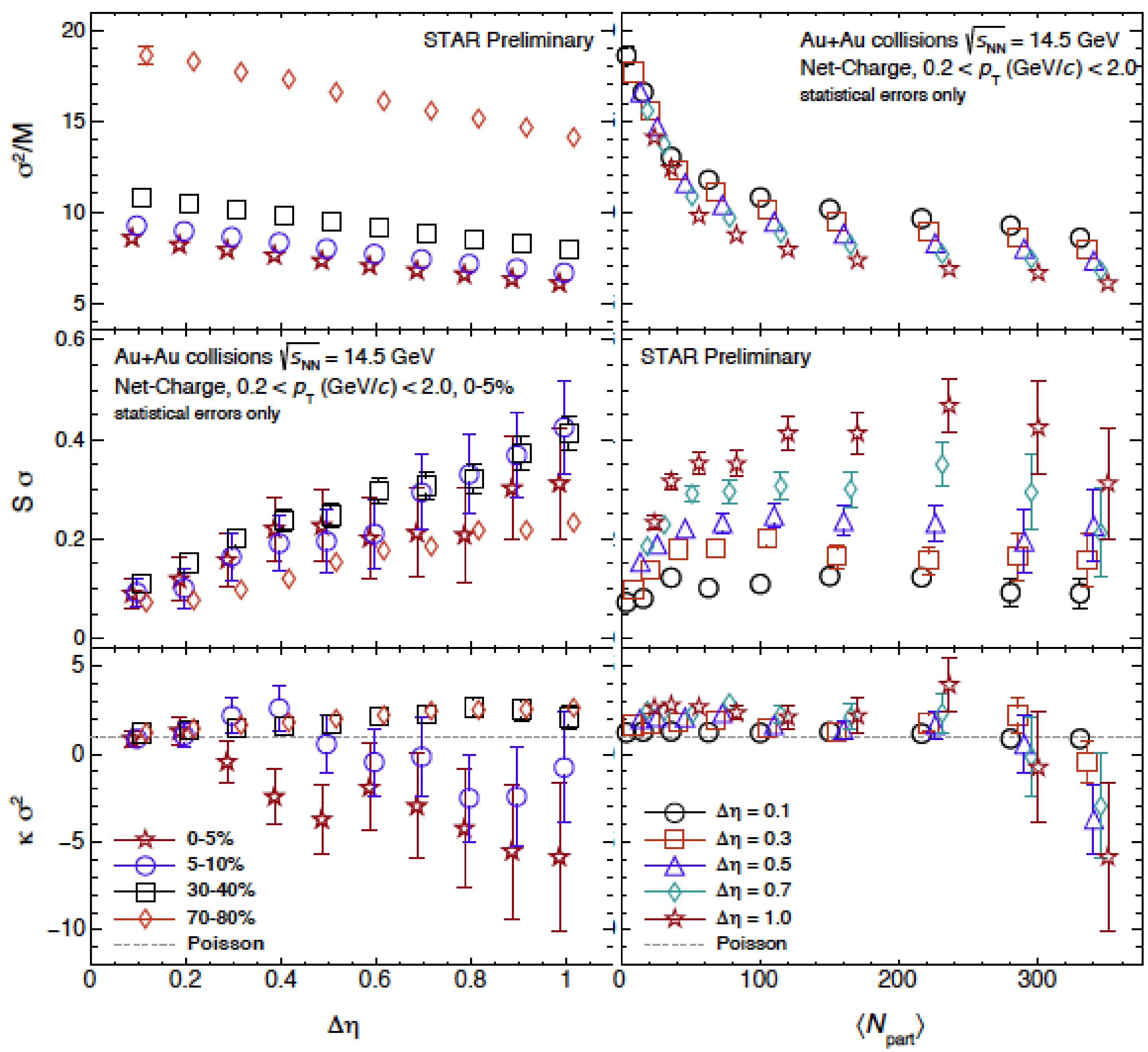
Need more precise measurements below 20 GeV, finer steps in μ_B, increase accepted rapidity window = BES-II

Fluctuation measurements are acceptance dependent

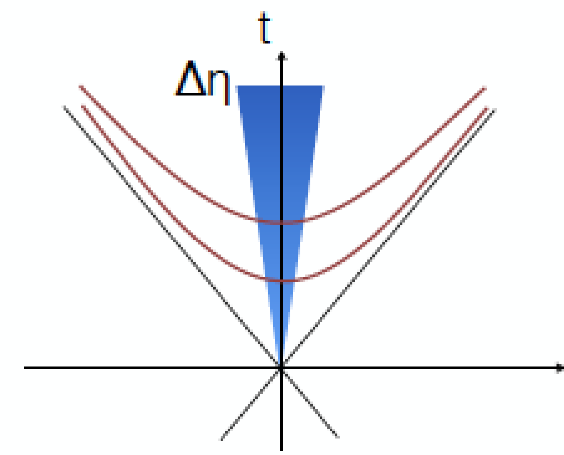
S. Jeon, V. Koch, arXiv:hep-ph/0304012
V. Koch, arXiv:0810.2520
M. Kitazawa, Nucl. Phys. A942 (2015) 65-96
M. Sakaida et al, PRC90 (2014) 6, 064911

Net-Charge – Δη Dependence

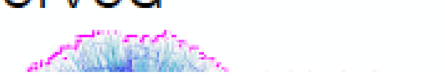
Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV



- Δη dependence of fluctuation observables encode history of the hot medium



- Smooth trend for σ^2/M, Sσ and $\kappa\sigma^2$ with increasing Δη
  - Different trend of $\kappa\sigma^2$ for central and peripheral collisions vs Δη
- The smaller the Δη window, the closer to poisson expectation
- Ordering in Δη vs $\langle N_{part}\rangle$ for σ^2/M, Sσ and $\kappa\sigma^2$ observed



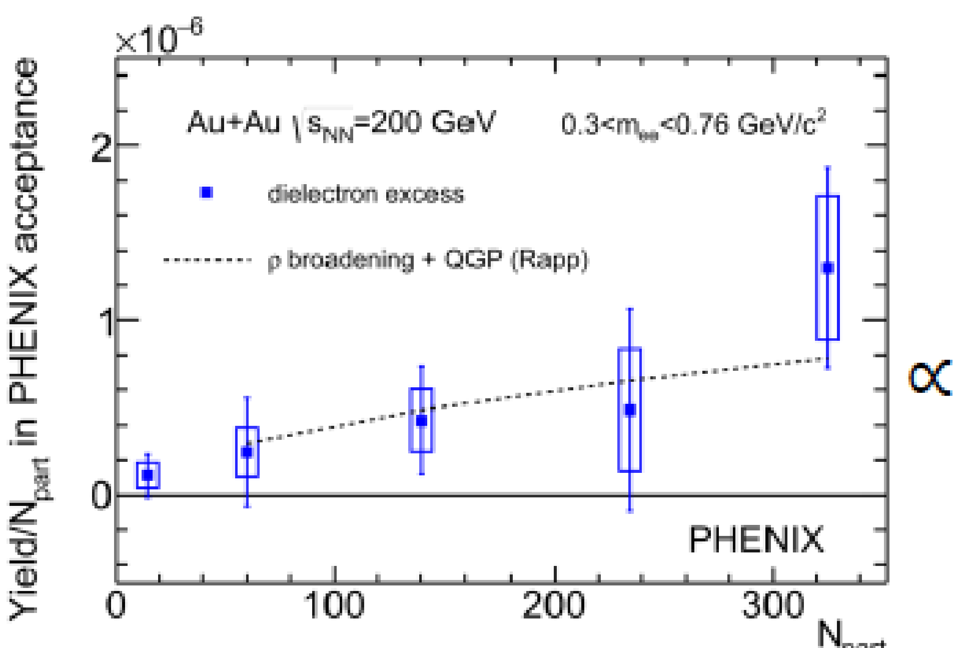
Chiral Symmetry

Broadened ρ spectral function at RHIC

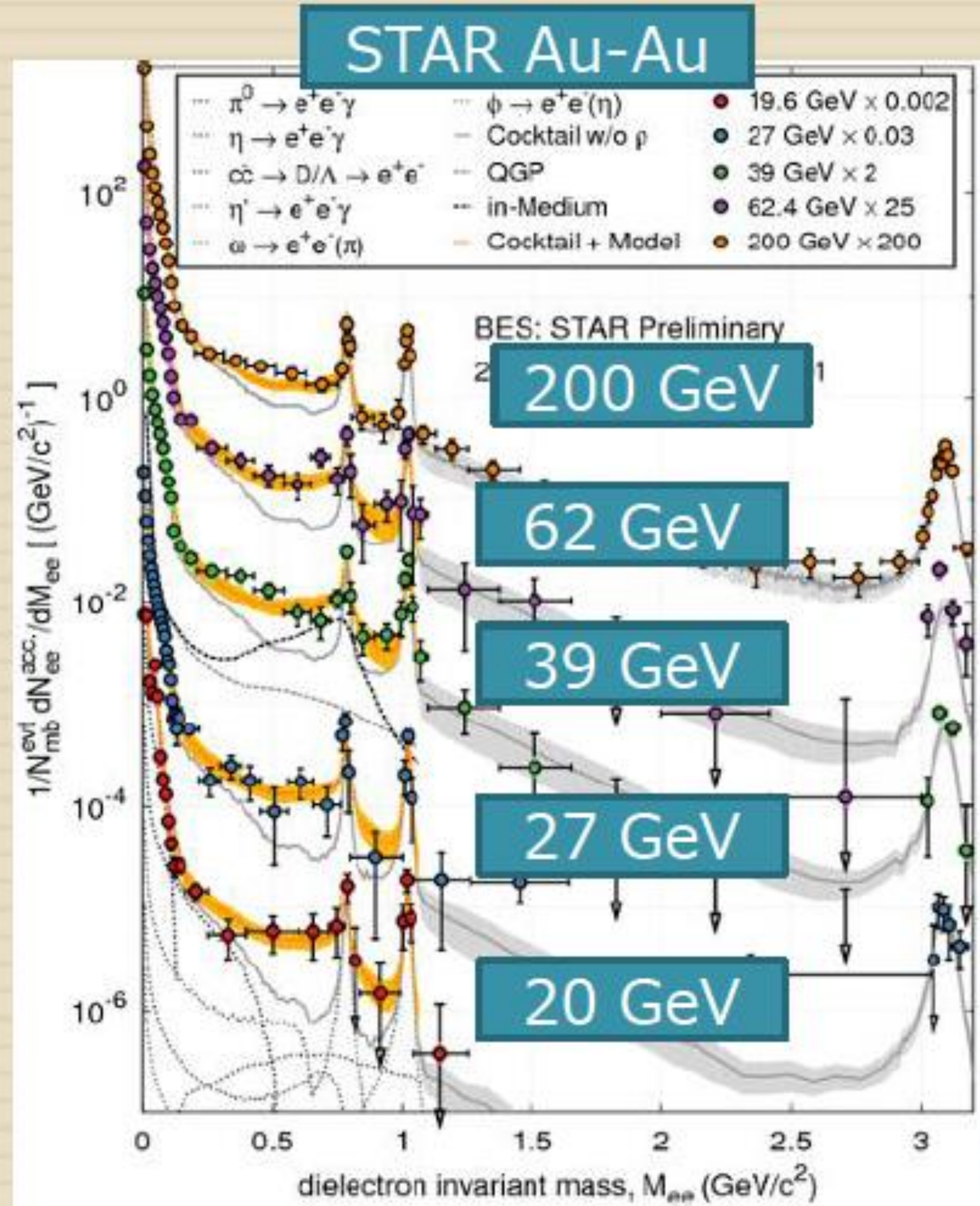
STAR and PHENIX are
Now consistent after
HBD results from PHENIX
(2016)

Data/cocktail ($0.3 < m_{ee} < 0.76$ GeV/c²)

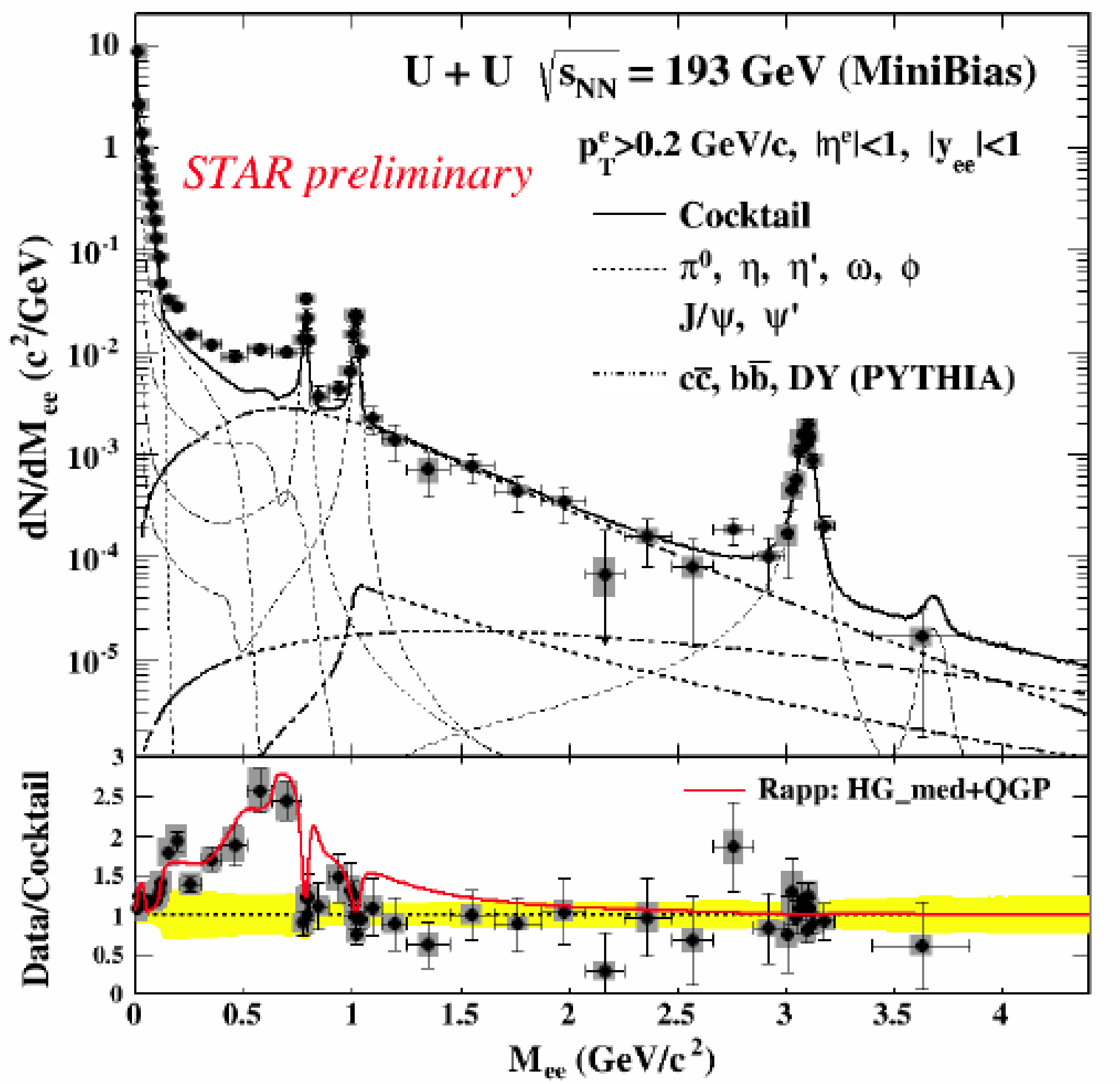
	value±stat ±syst ±model
PHENIX (New)	$2.3 \pm 0.4 \pm 0.4 \pm 0.2$
STAR	$1.76 \pm 0.06 \pm 0.26 \pm 0.29$

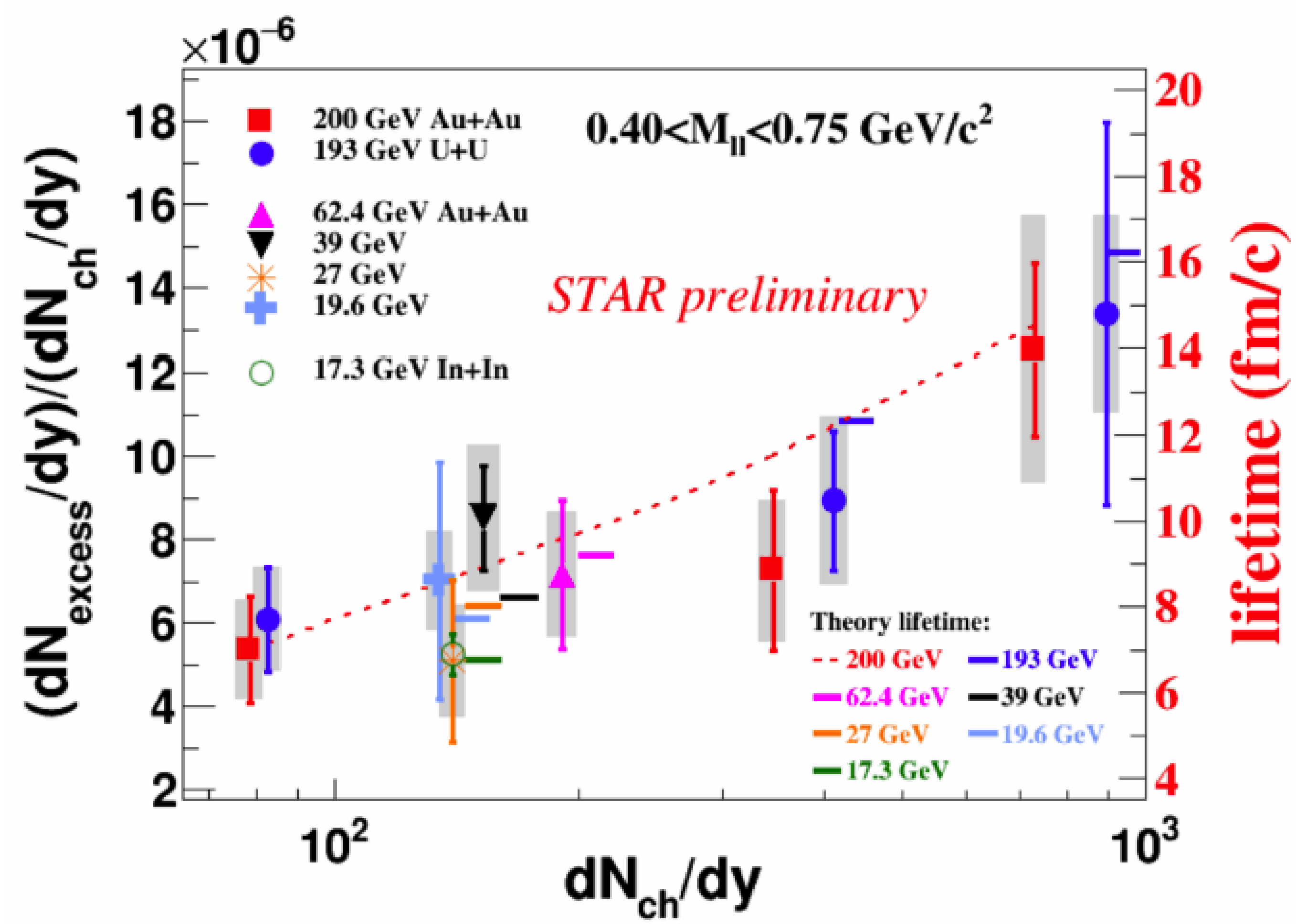


$\propto N_{part}^{1.45}$



Measurement extended to U+U and related to fireball lifetime





- Integrated excess yield, normalized by dN_{ch}/dy, is proportional to lifetime of fireball from 17.3 – 200 GeV.

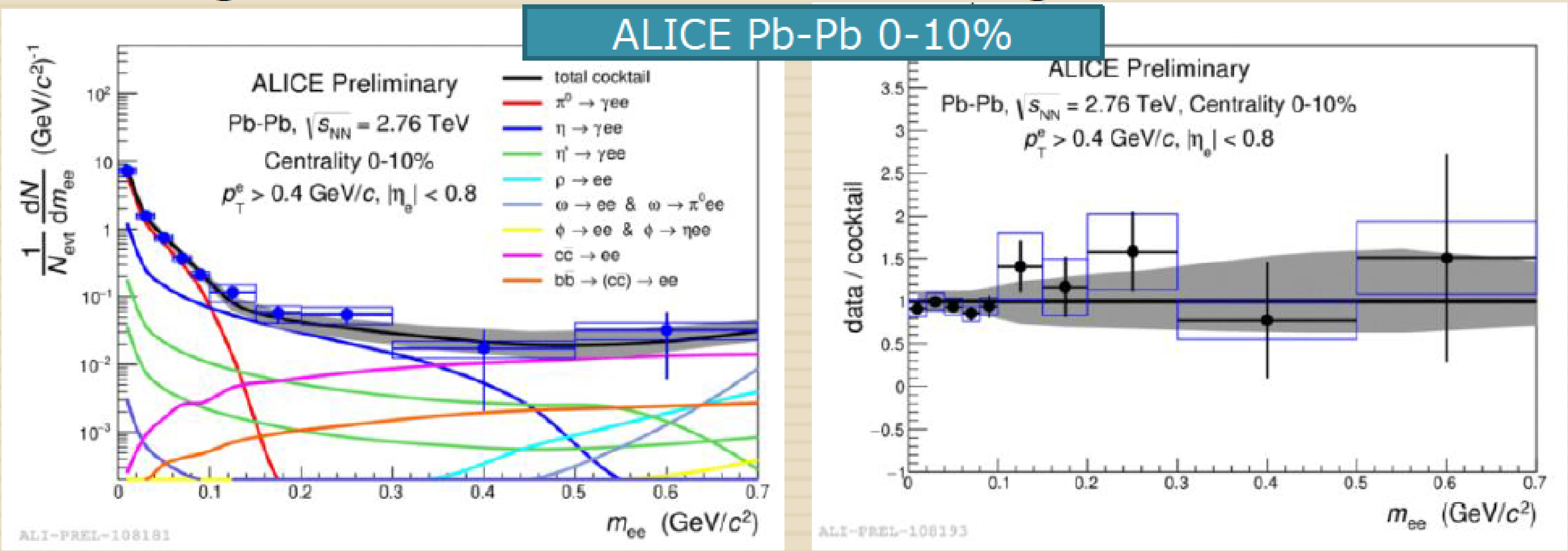
Given that total baryon density is nearly constant and emission rate is dominant in the near$-T_c$ region.

R. Rapp, H. van Hees PLB 753 (2016) 586-590

No excess at the LHC ?

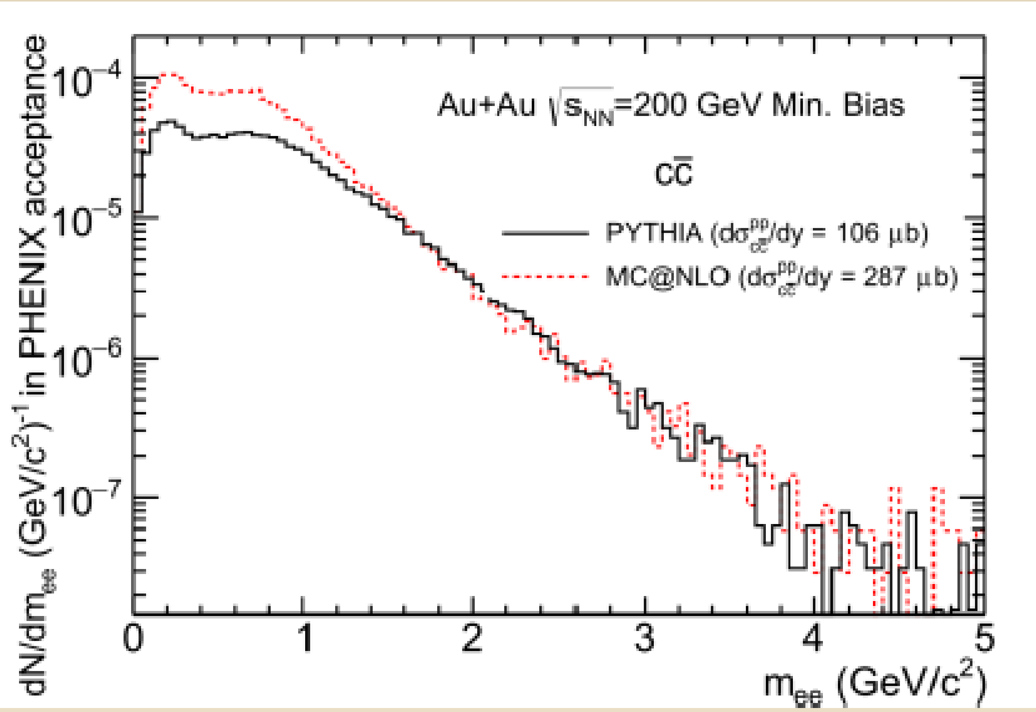
- Dielectron spectra in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV are presented
  - ALICE p_T^e>0.4 GeV/c, PHENIX/STAR: p_T^e > 0.2 GeV/c
- Consistent with no enhancement
  - Extracted limits compatible with ALICE real photon measurements and previous results from PHENIX and STAR
  - Large charm cross sections at LHC energies

ALICE Pb-Pb 0-10%



$c\bar{c}$ in cocktail

- Understanding of the charm contributions in cocktail is crucial to study in-medium ρ spectra
- New PHENIX result: PYTHIA and MC@NLO
  - 40% difference in data/cocktail ($0.3 < m_{ee} < 0.76$ GeV/c^2)
    - PYTHIA: 2.3 ±0.4±0.4±0.2, MC@NLO: 1.7 ±0.3±0.3±0.2
  - Cross sections are derived using IMR of d-Au collisions
  - Uncertainty in extrapolation to m~0
    - Lack of understanding in $c\bar{c}$ cross section and correlation
- Vertex detectors (PHENIX, STAR, ALICE) and MTD (STAR)

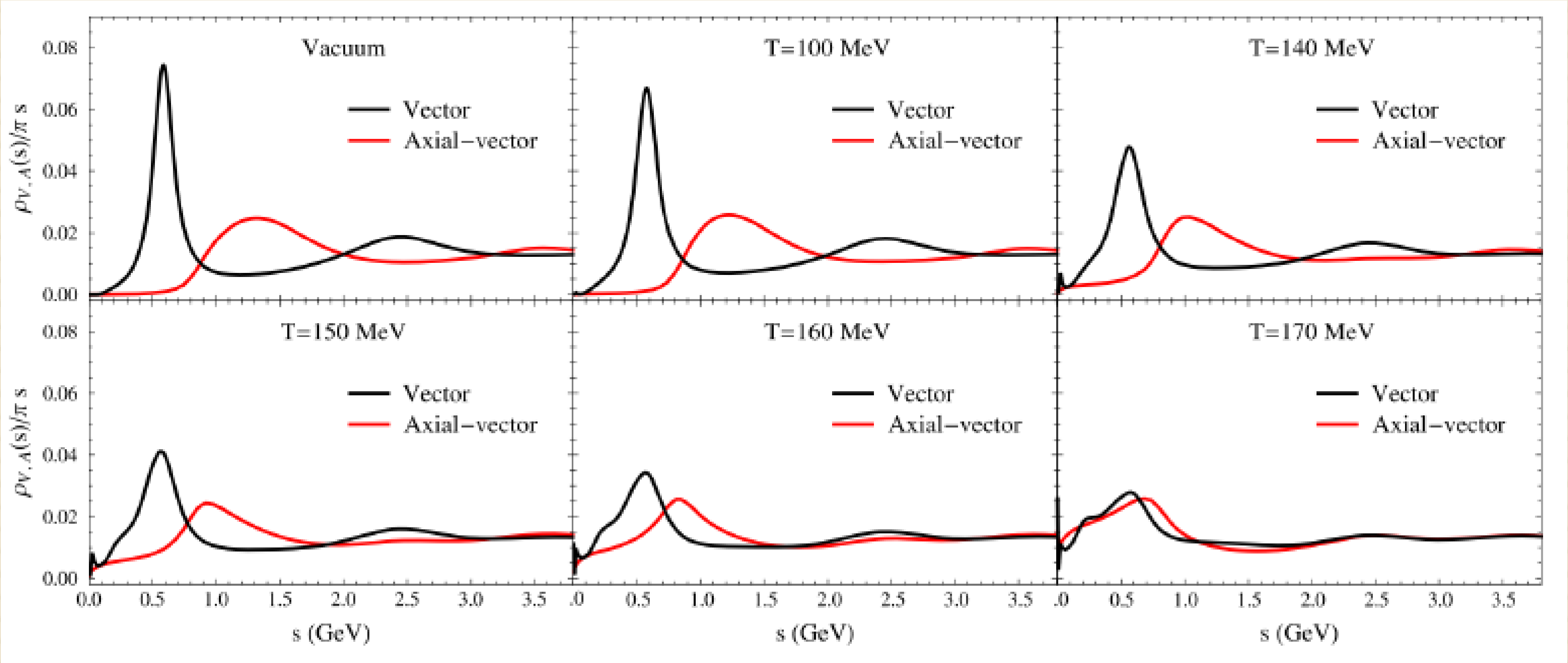


	$d\sigma^{pp}_{c\bar{c}}/dy$ (μb)
PYTHIA	$106 \pm 9^{stat} \pm 33^{syst}$
MC@NLO	$287 \pm 29^{stat} \pm 100^{syst}$
STAR (D meson) PRL 113(2014)022301	171 ± 26

PRC 93 (2016) 014904

Link to chiral symmetry restoration

- In-medium ρ spectra are well described by the models with "ρ broadening"
- Measurement of the a_1 meson is experimentally difficult
- According to PLB 731 (2014) 103, the medium-modified ρ and a_1 meson degenerate with each other at high T

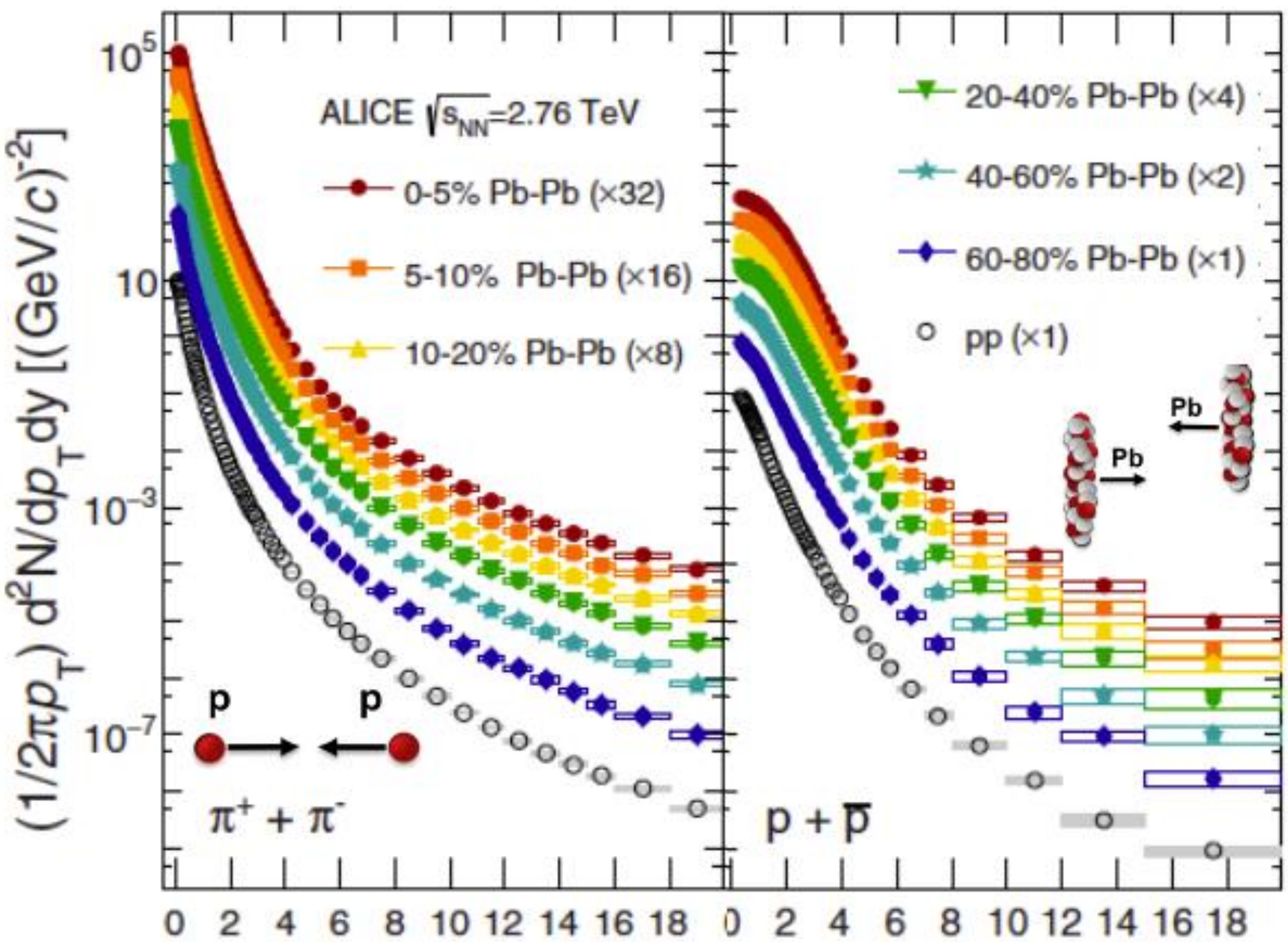


R. Rapp, PLB 731 (2014) 103

No further evidence in ω or ϕ measurements at RHIC or LHC

Particle production as a function of collision energy and system size

LHC: identified spectra out to high pT



Phys. Rev. C 93 (2016) 034913
(High-p_T π,K,p and R_{AA})

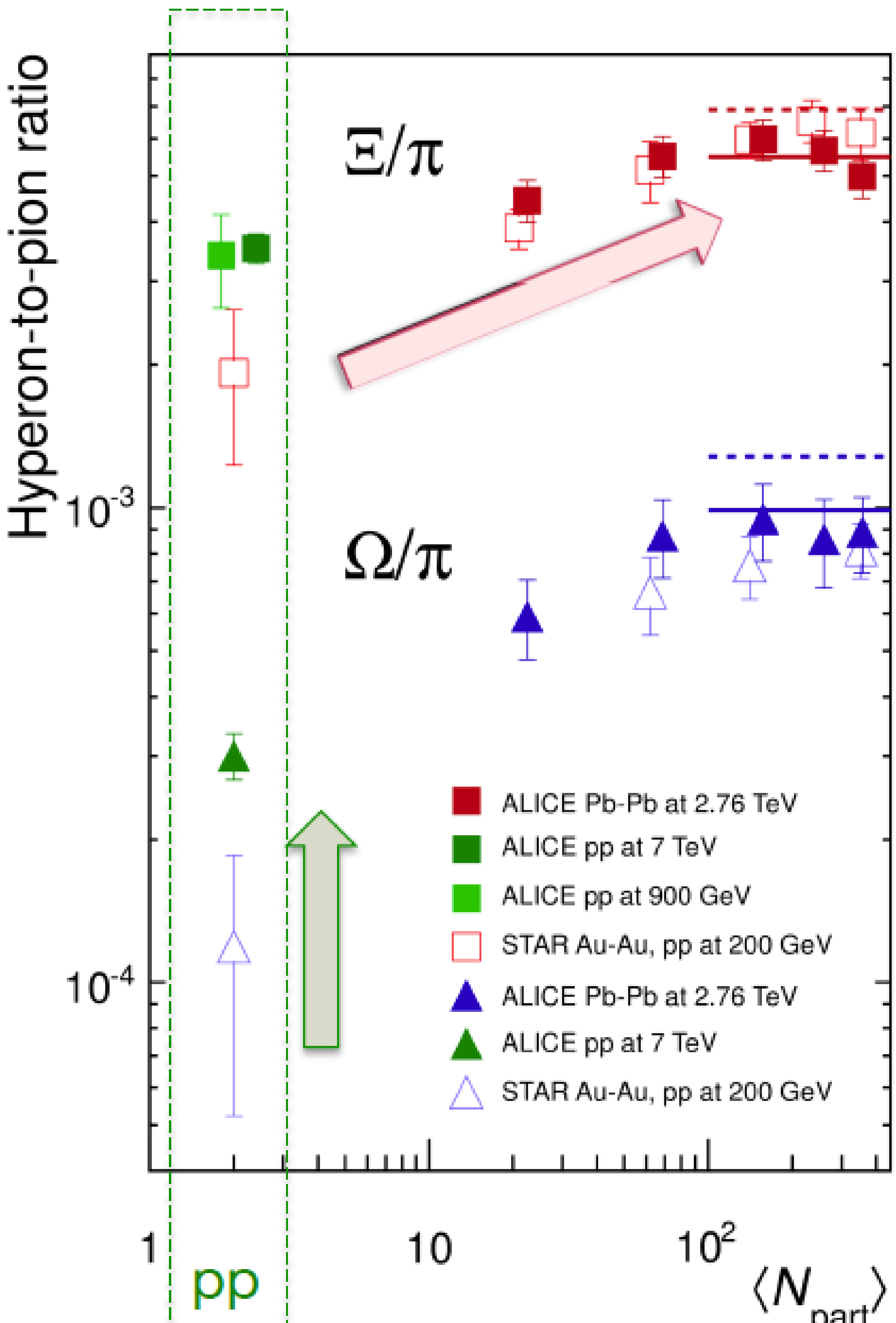
Low p_T (p_T < 3 GeV/c)
→ Study collective phenomena (radial flow)

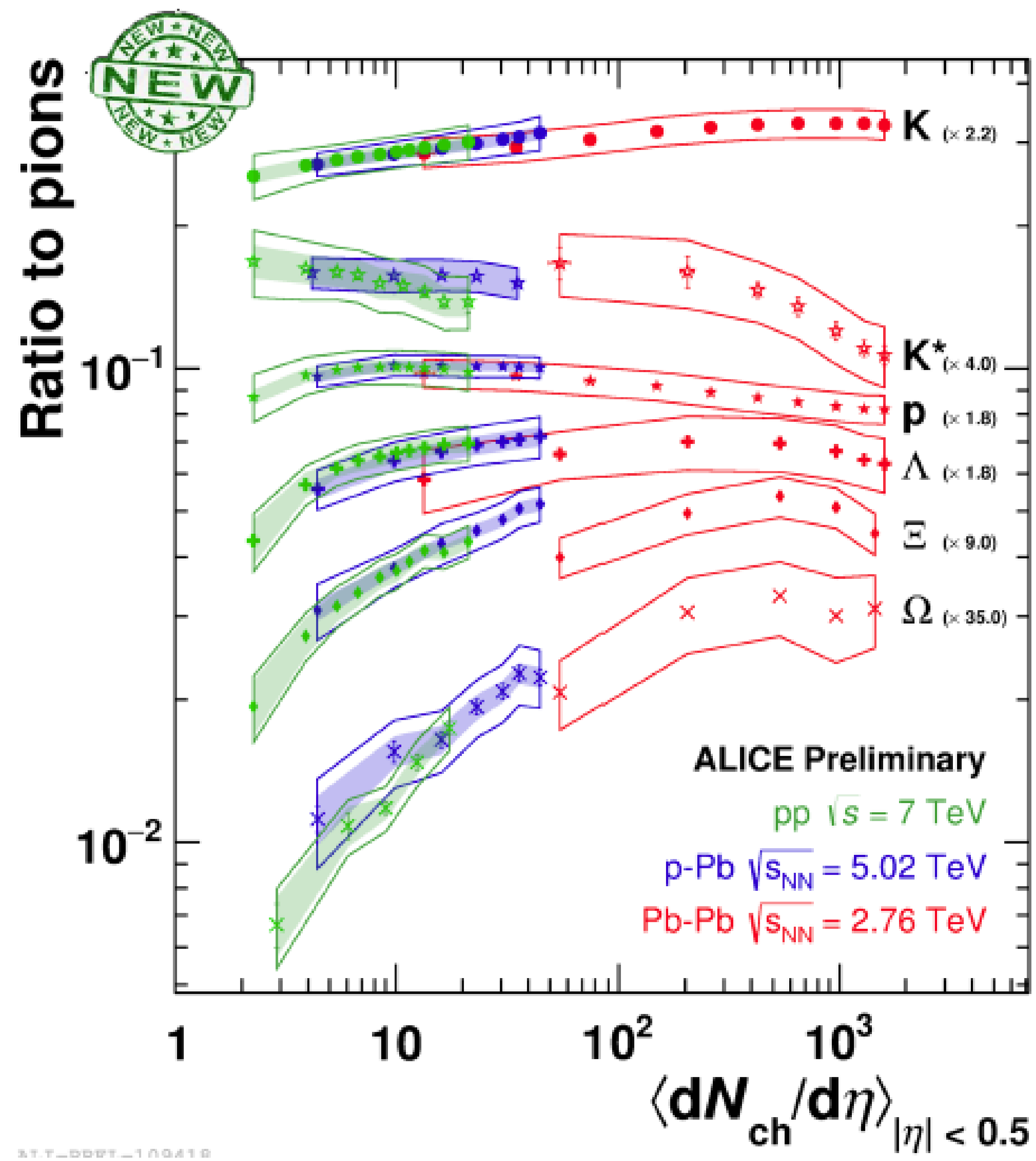
Mid-p_T (3 < p_T < 8-10 GeV/c)
→ Study fragmentation vs recombination

High p_T (p_T > 8-10 GeV/c):
→ Study jet quenching and energy loss nuclear via nuclear modification factors

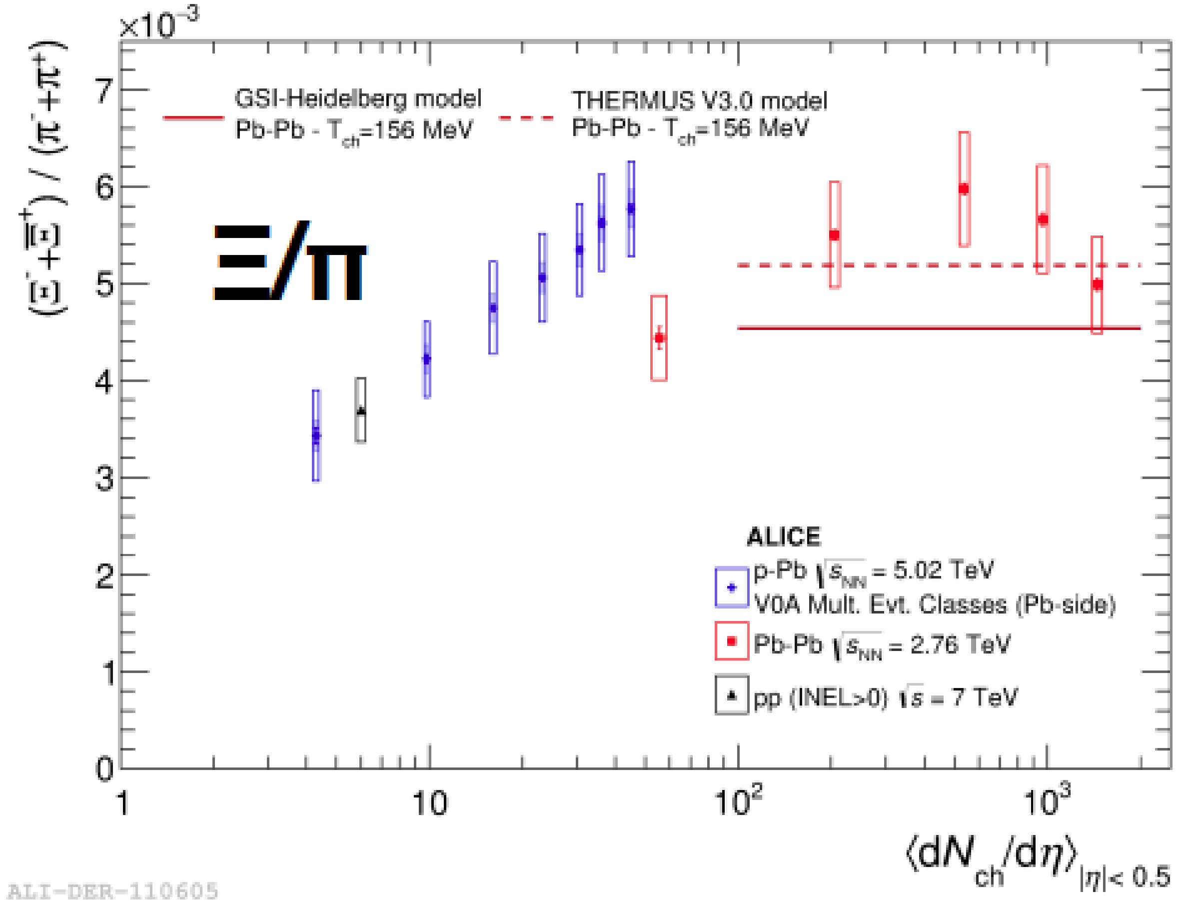
Strangeness production from pp to PbPb

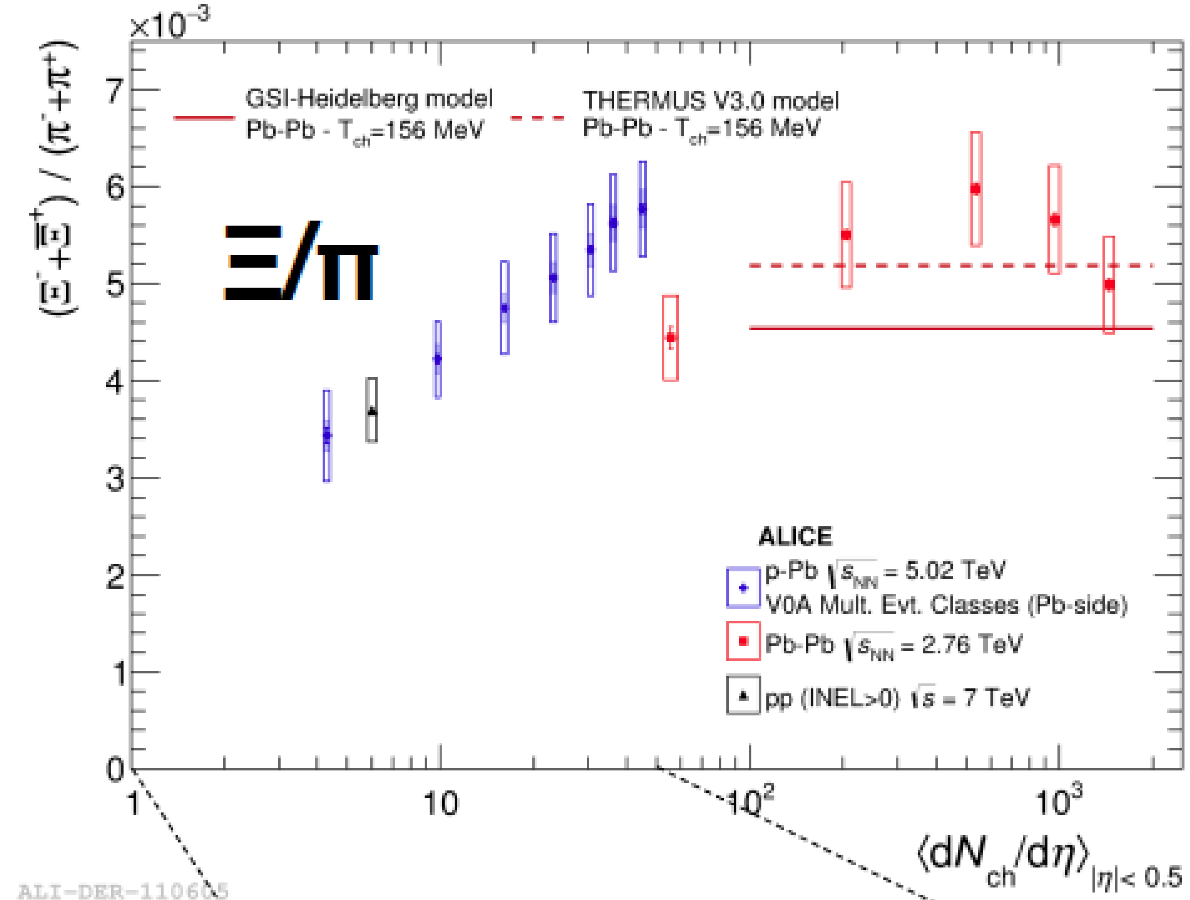
Pb-Pb $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
pp $\sqrt{s}$ = 0.9, 2.76, 5.02, 8, 13 TeV
$\sqrt{s}$ = 7 TeV (multip. dep.)

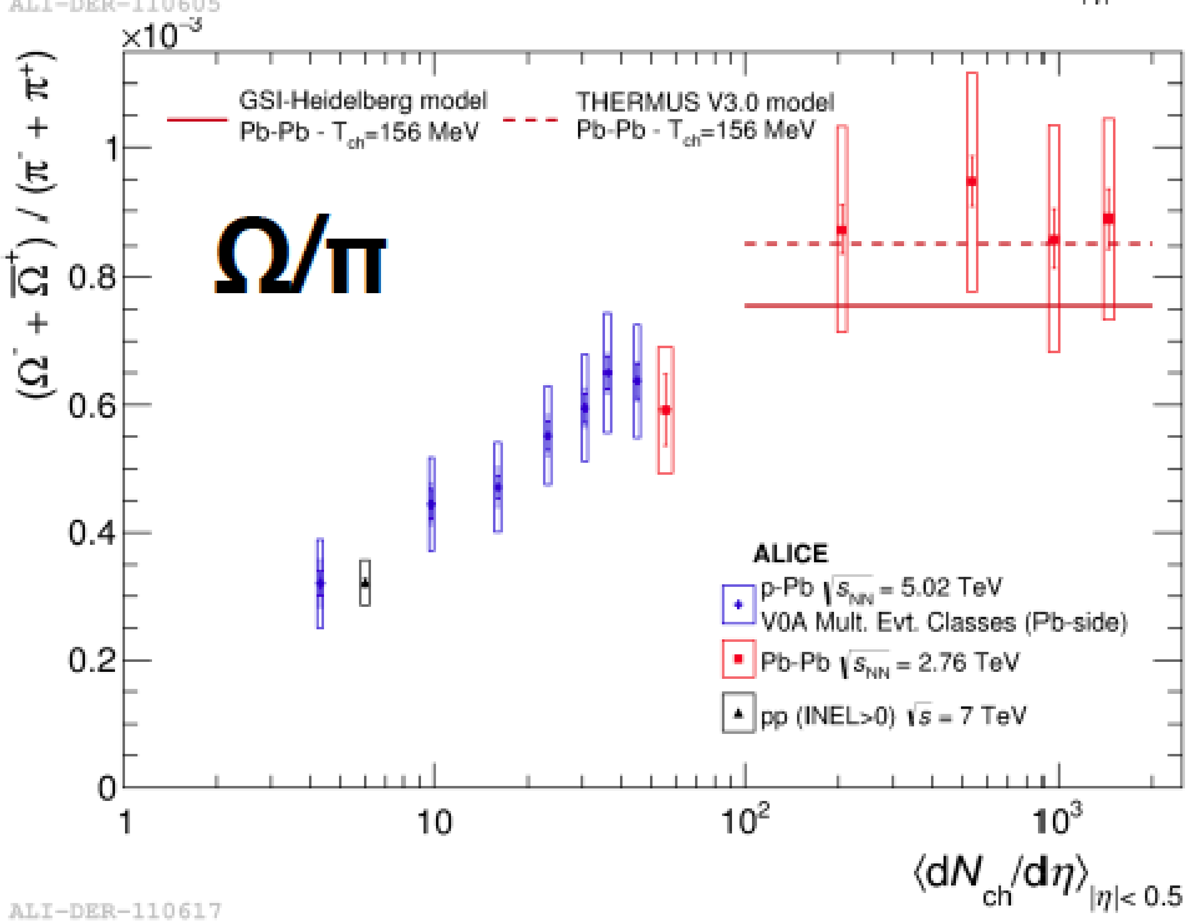


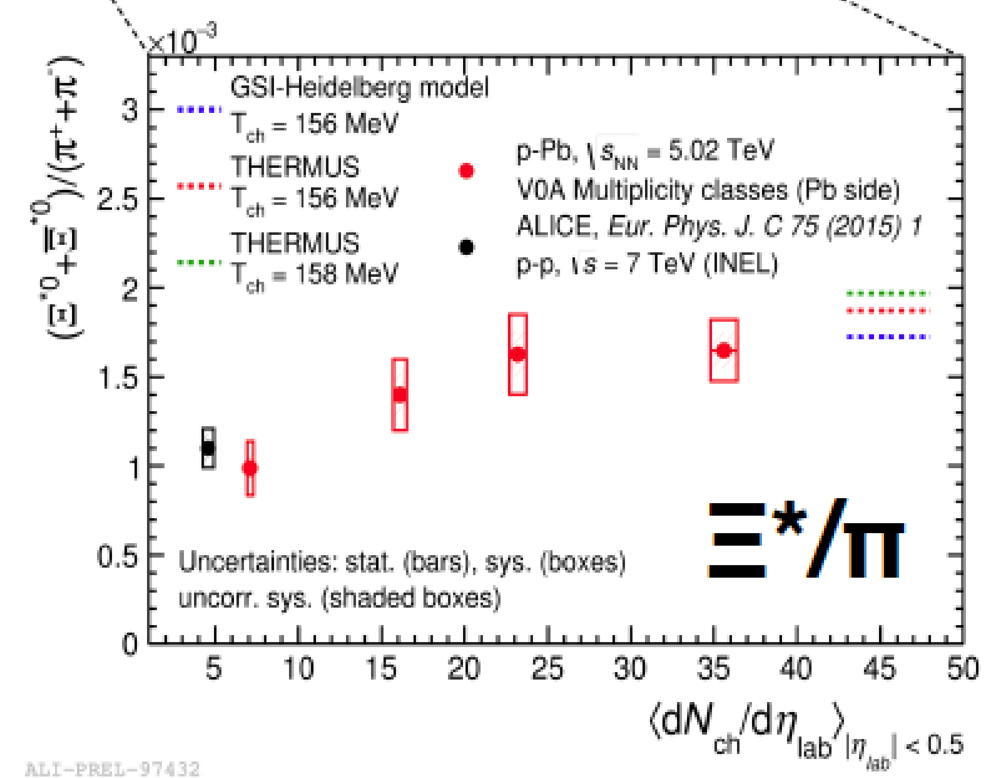


Strangeness production in pPb

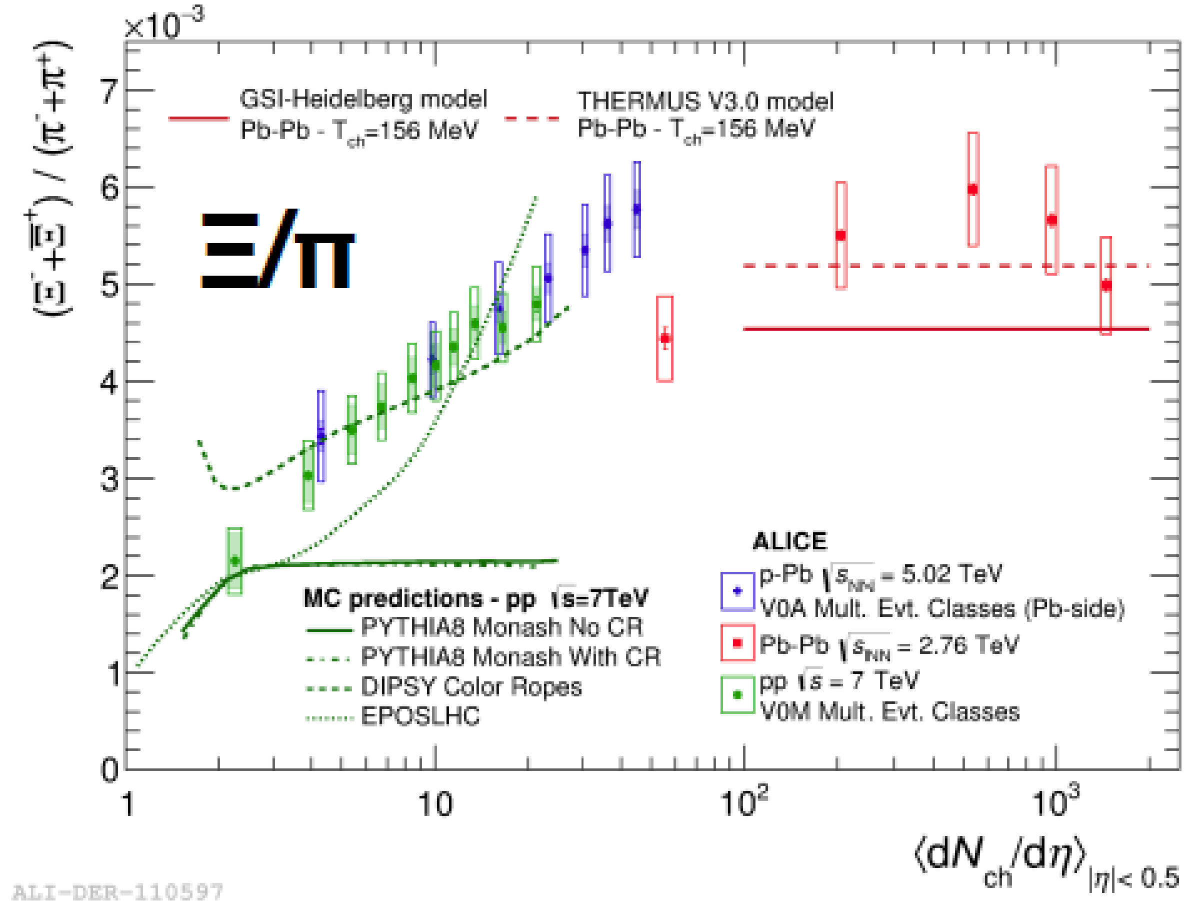


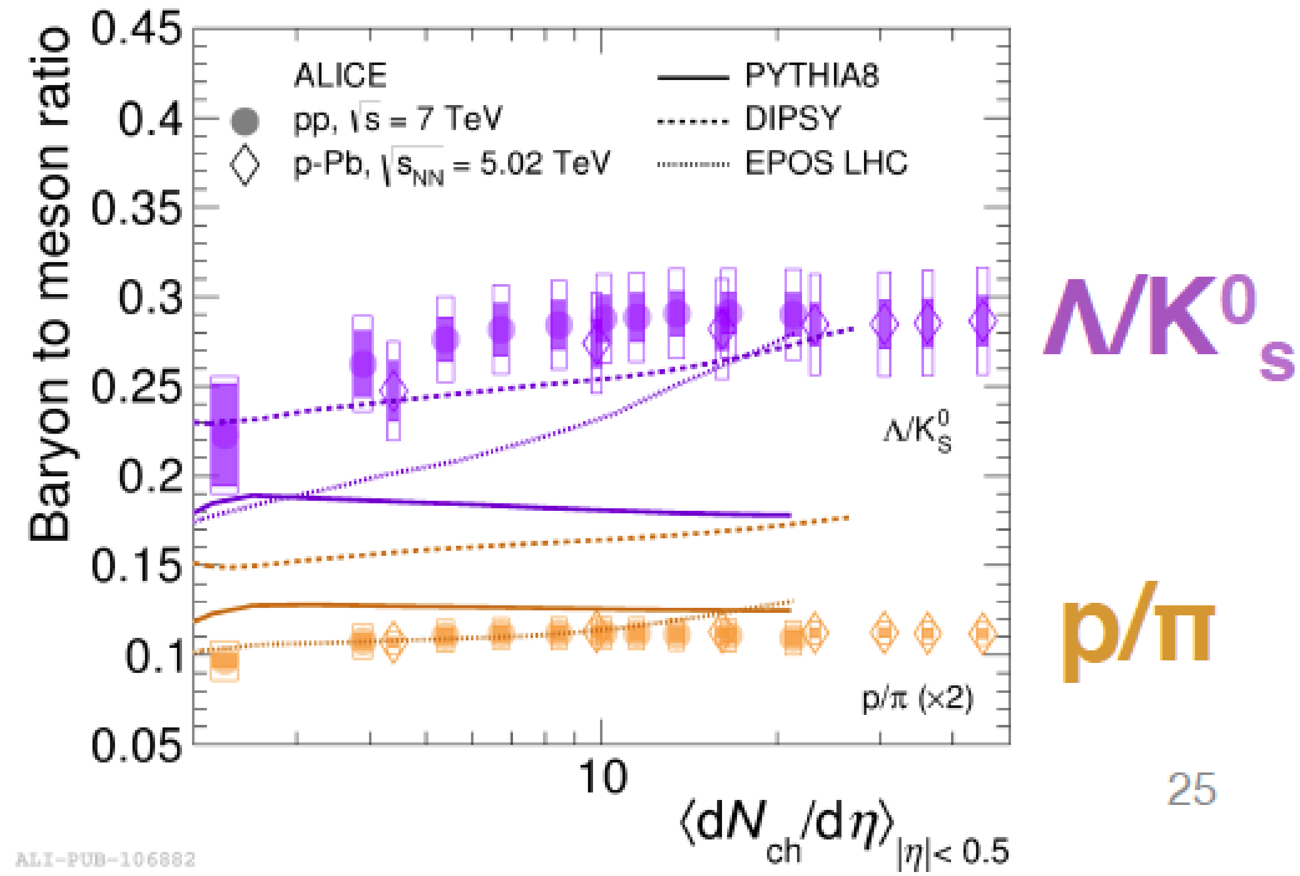


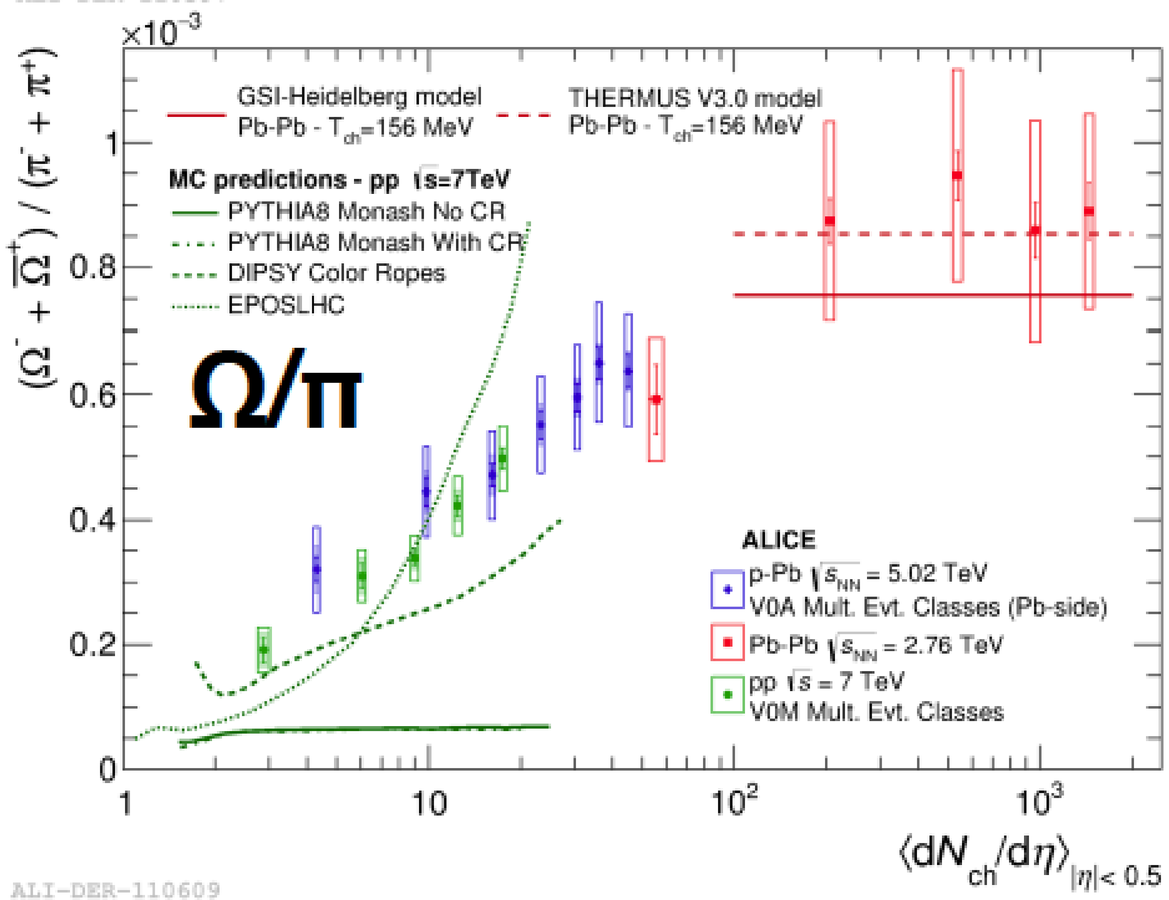


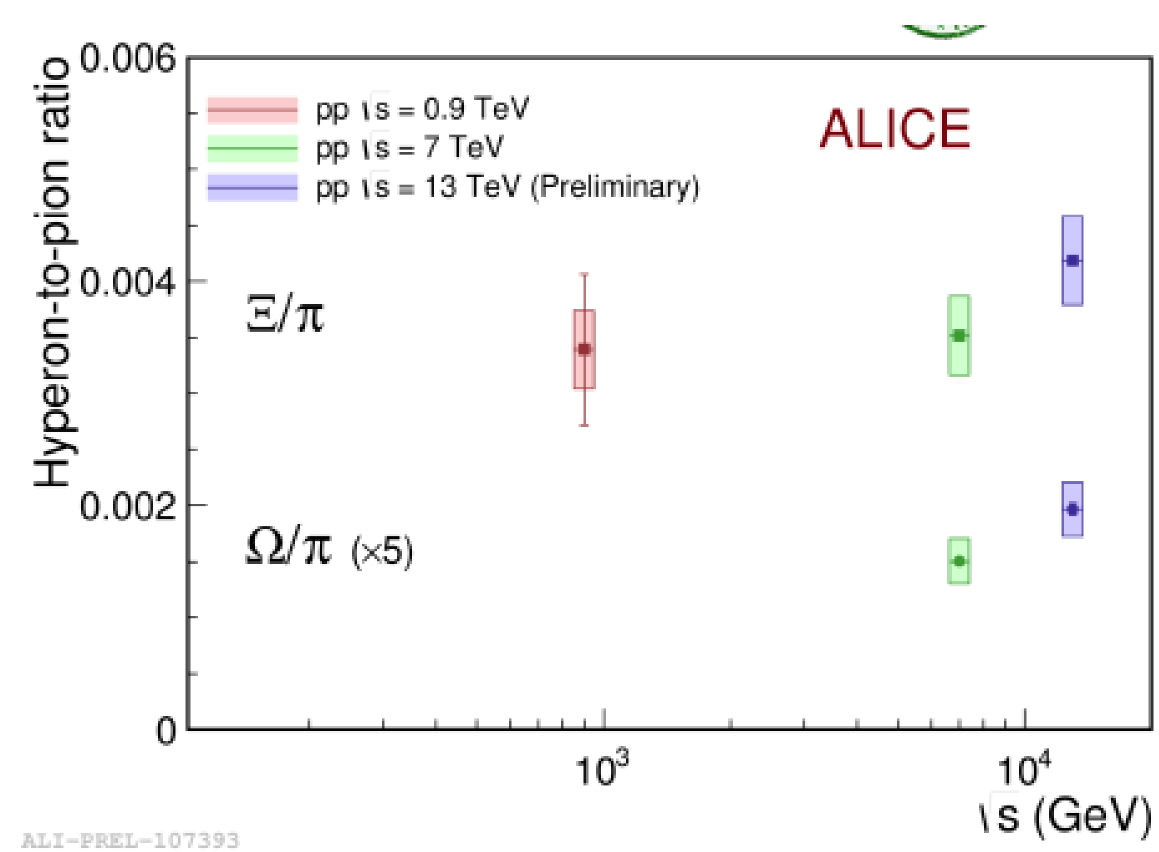


Strangeness production in pp

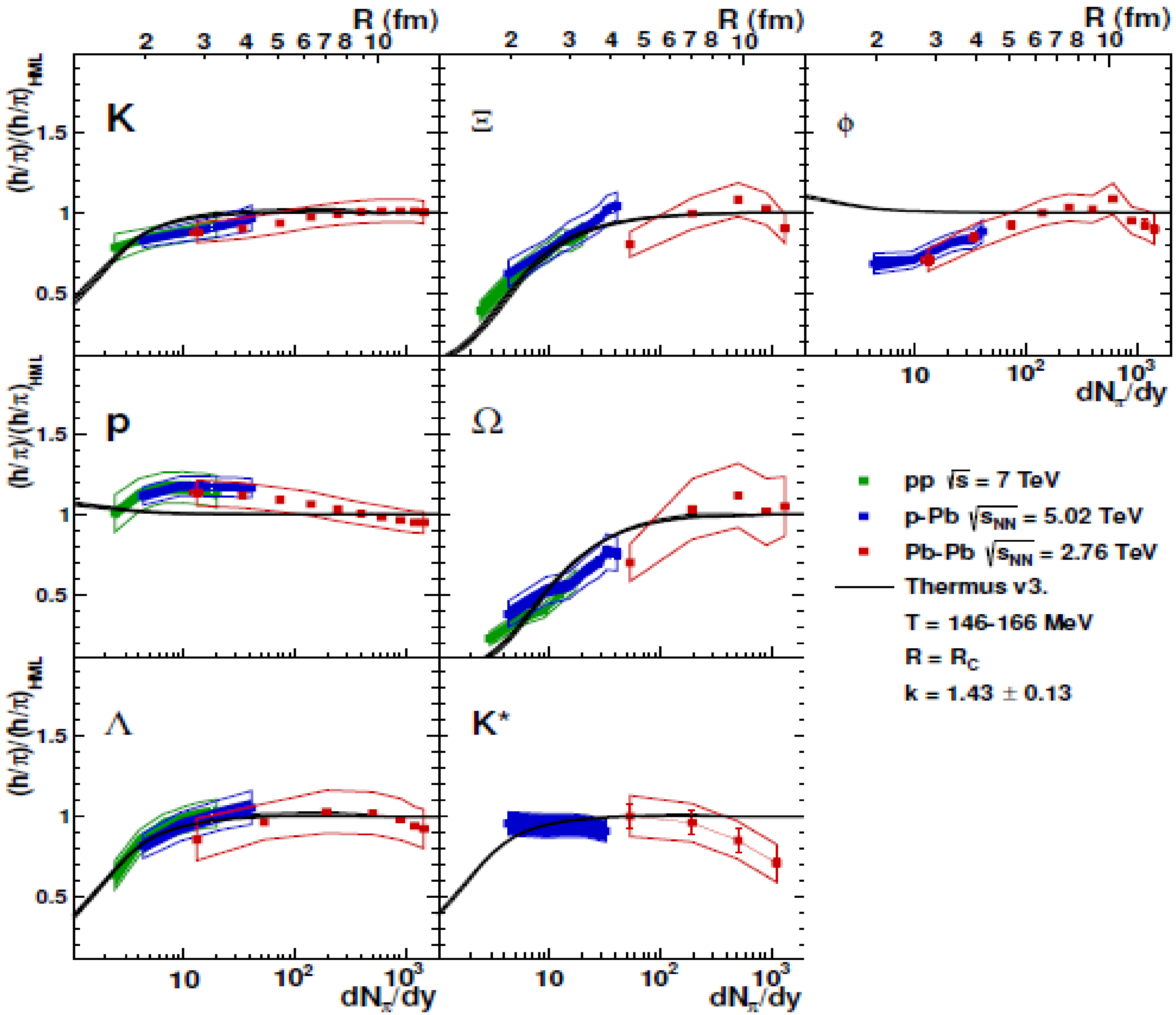




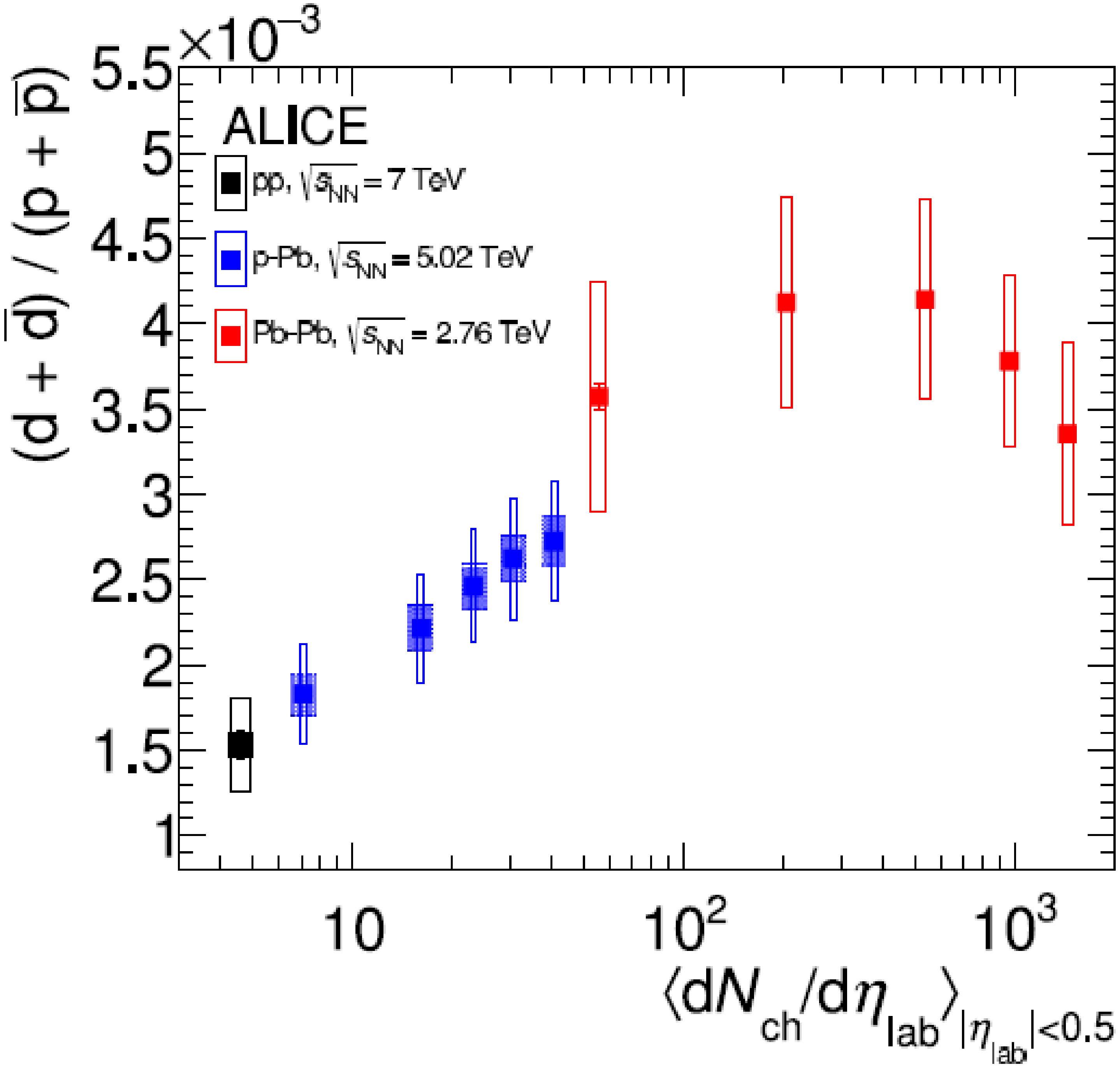




Canonical Suppression Model
(Vislavicius, Kalweit, arXiv:1610.03001)

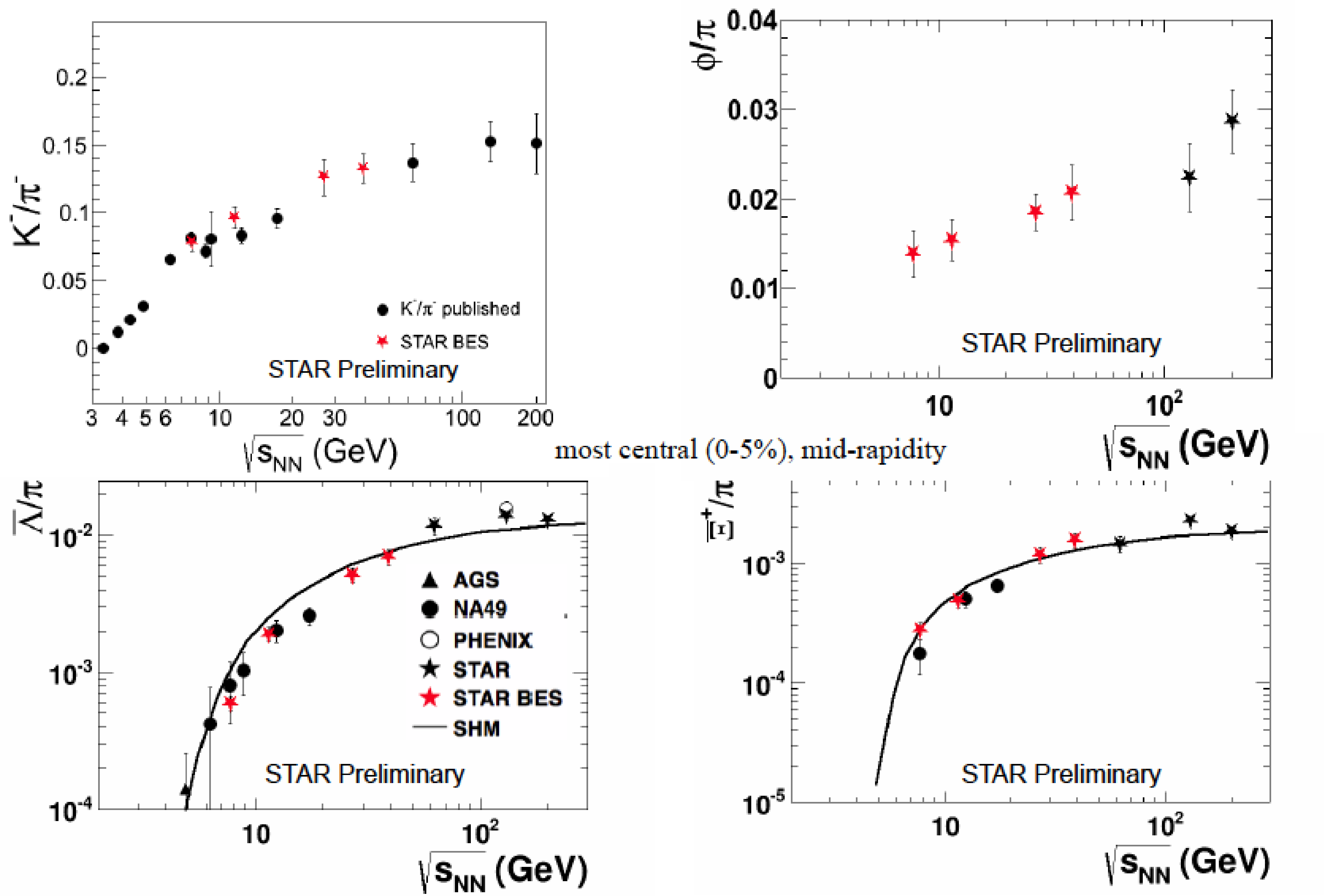


Deuteron production in pPb



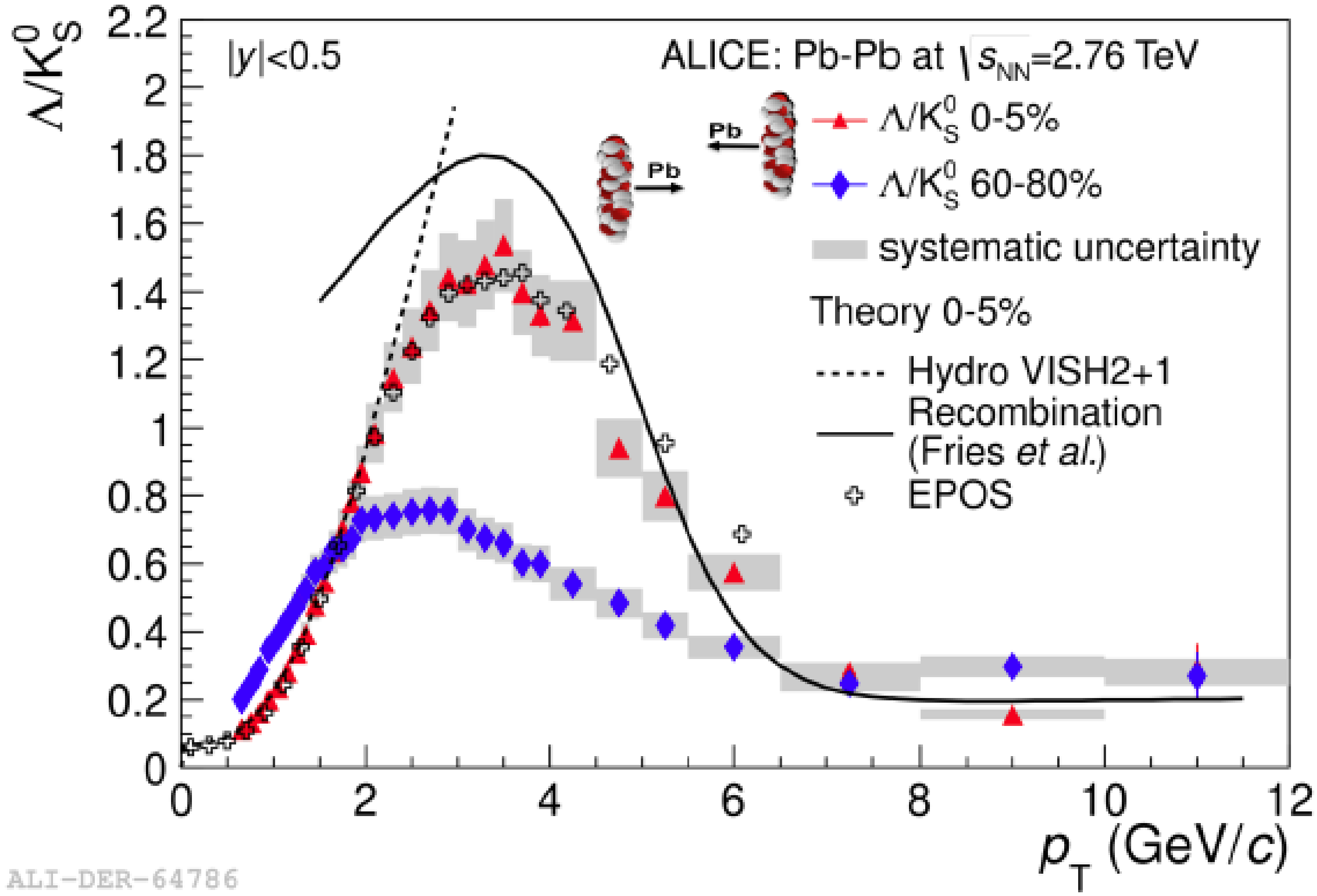
Very similar trend than strangeness enhancement.
Is deuteron produced directly in partonic medium ?

Strangeness enhancement as a f(beam energy)



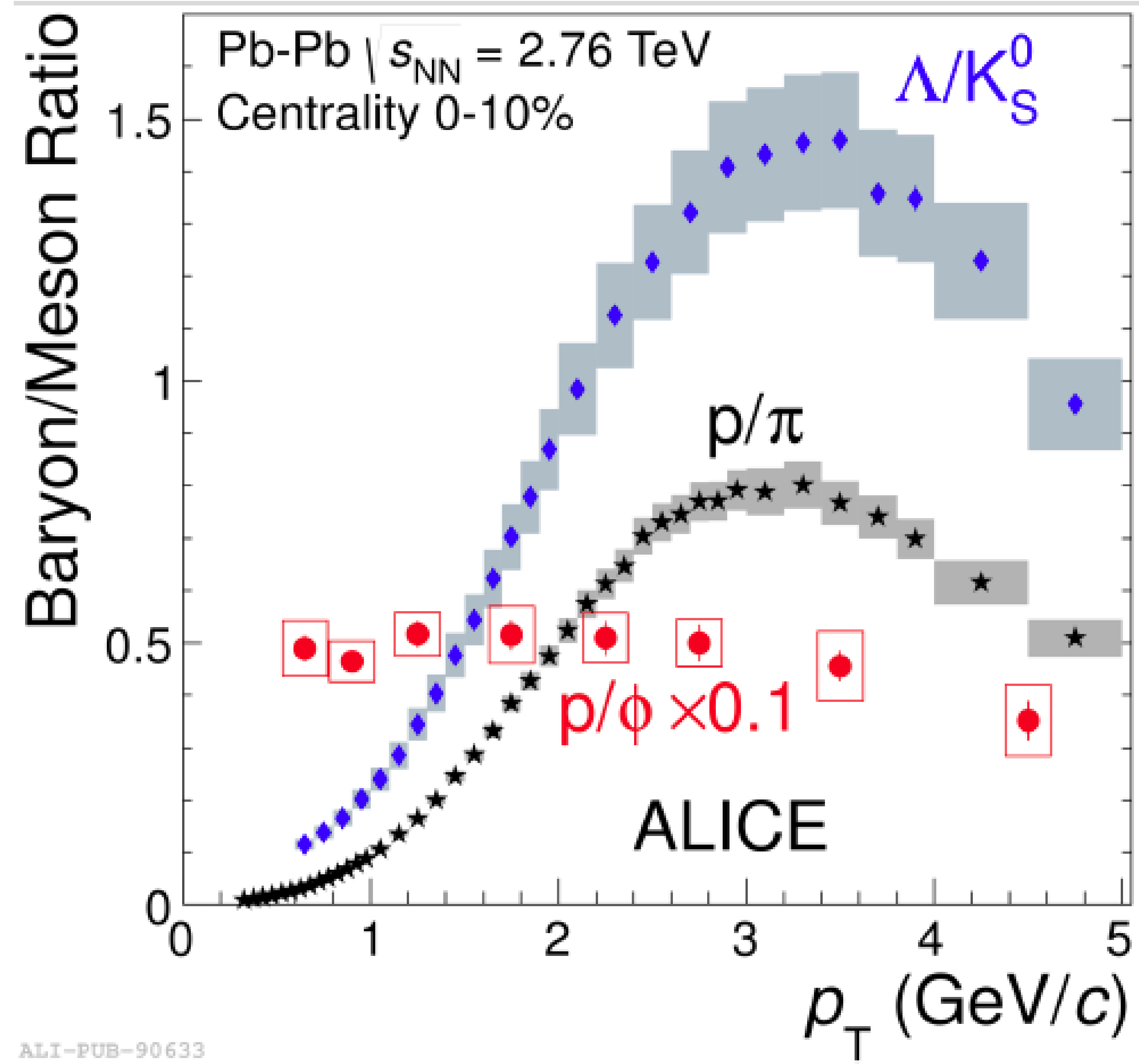
Statistical Hadron gas Model: A. Andronic et al., Nucl. Phys. A 772, 167 (2006)

Baryon to meson ratios at LHC



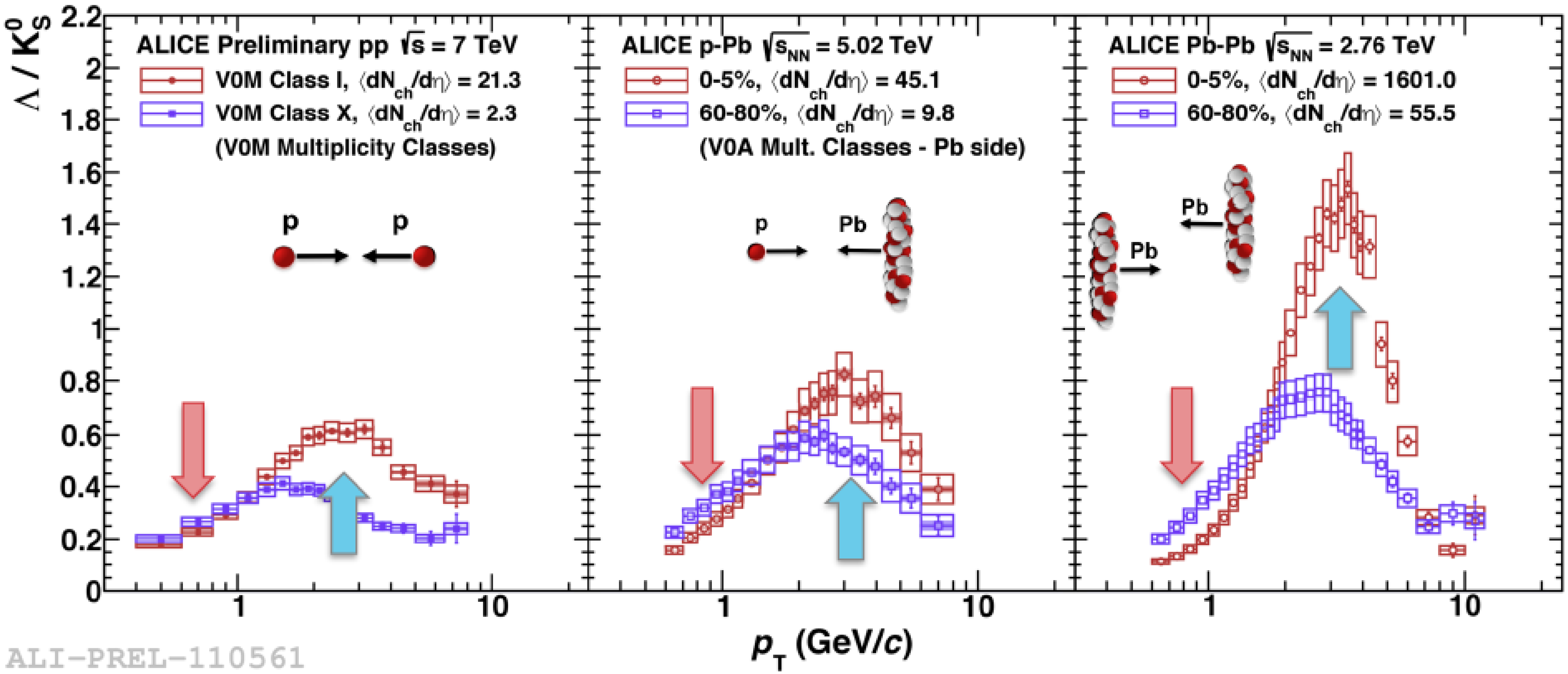
B/M enhancement at intermediate p_T

- **Hydrodynamics** describes only the rise < 2 GeV/*c*
- **Recombination** reproduces effect but overestimates
- **EPOS** gives good description of the data (with **flow**)



p/ϕ have similar mass
p/ϕ ratio is flat in central Pb-Pb
→ **Mass determines the spectral shapes** (as in hydrodynamics)

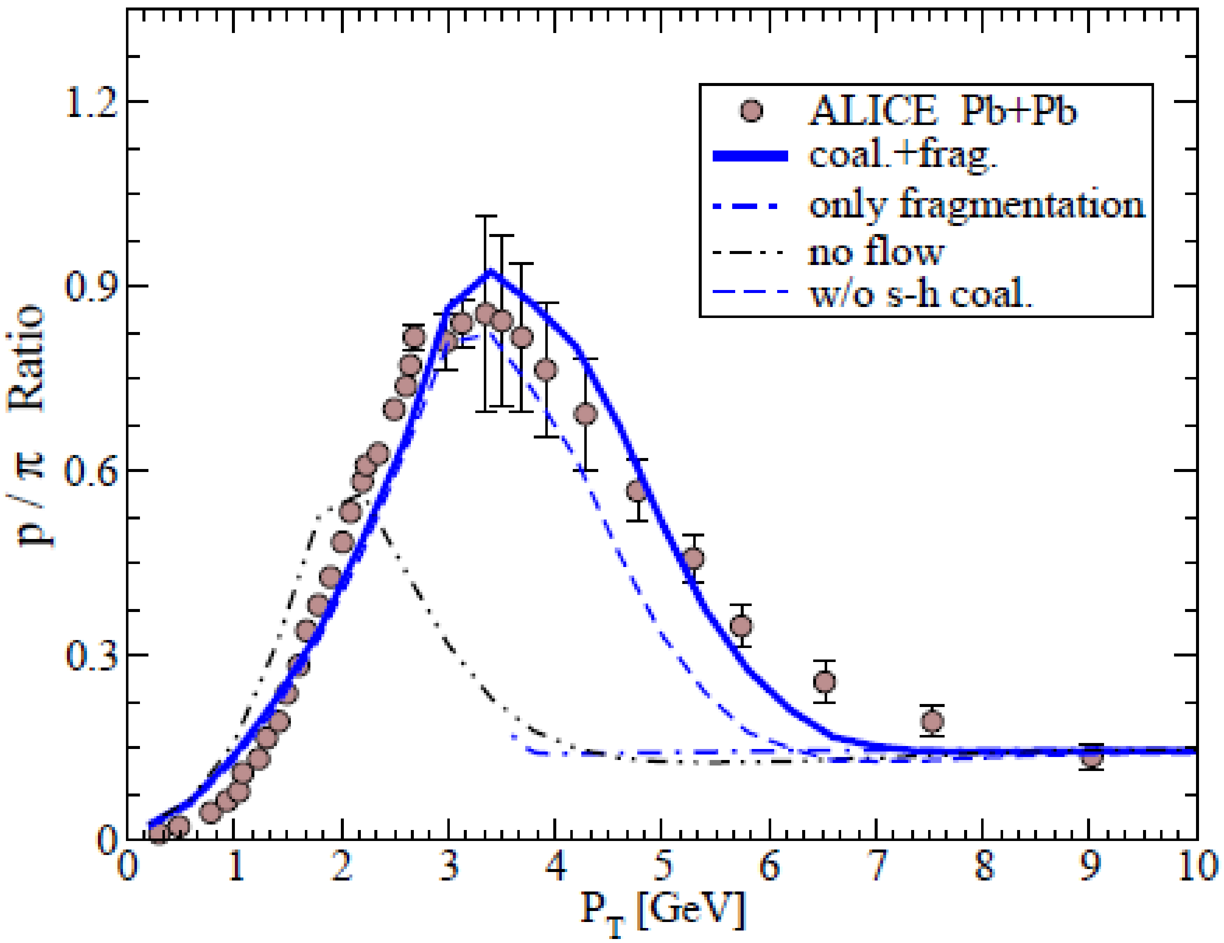
Baryon to meson ratio as a f(system size)



In pp, p-Pb and Pb-Pb collisions the B/M ratio as a function of multiplicity is

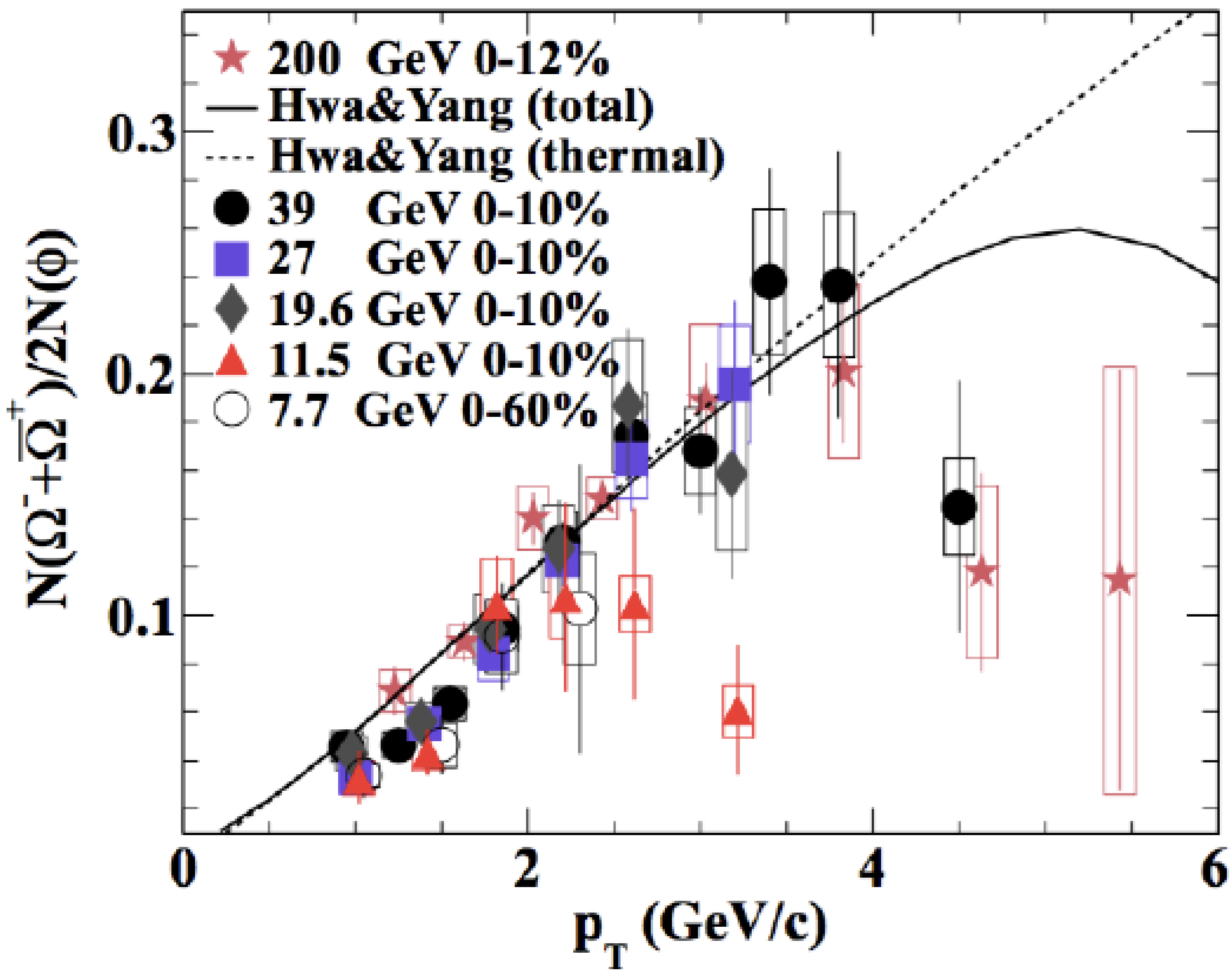
- qualitatively similar: **depletion** at low p_T, **enhancement** at intermediate p_T
- quantitatively different in the three systems

Latest recombination model results
(Minissale, Scardina, Greco, arXiv:1502.06213)

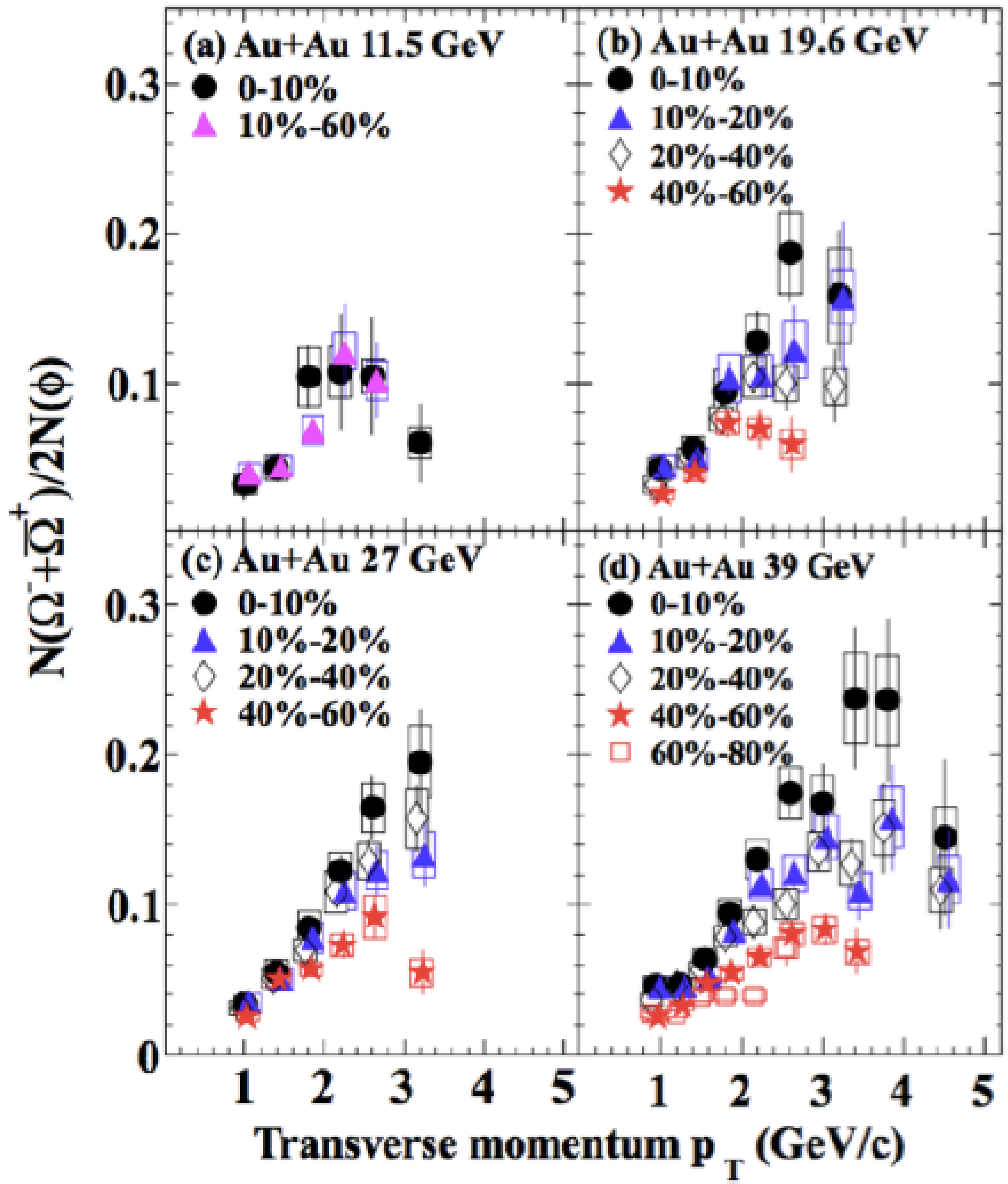


Good agreement with strange and non-strange B/M ratios

Ω/ϕ ratio at RHIC-BES

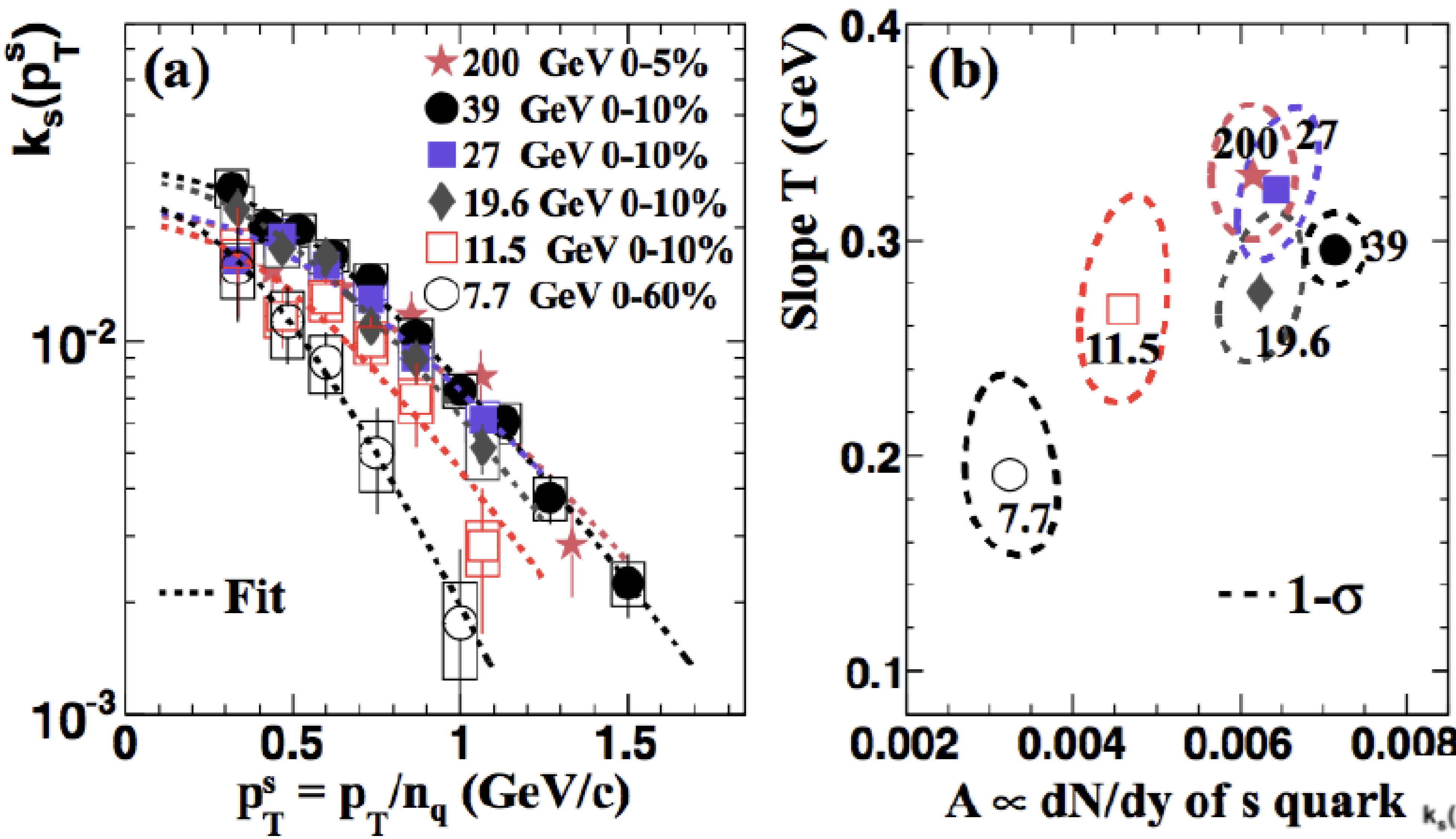


STAR: Phys. Rev. C 93, 021903 (2016)



- ➢ The ratios at 11.5 GeV seem to *deviate* from the trend observed at higher beam energies for p_T > 2.4 GeV/c
- ➢ 40%-60% peripheral < 0-10% central for 19.6, 27 and 39 GeV
- ➢ Need more statistics at lower beam energies

NCQ scaled Ω/ϕ ratio at RHIC-BES



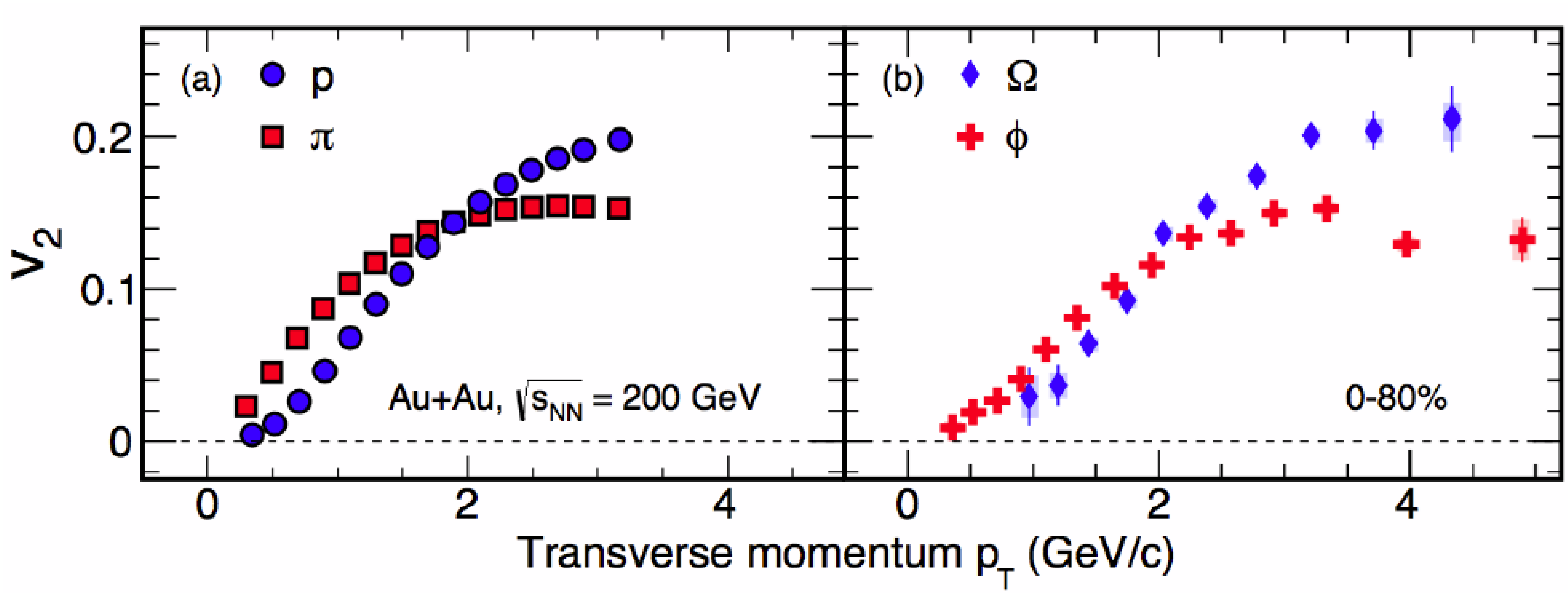
$$k_s(p_T^s) = \frac{N(\Omega^- + \overline{\Omega}^+)(p_T^\Omega = 3p_T^s)}{2N(\phi)(p_T^\phi = 2p_T^s)}$$

STAR: Phys. Rev. C 93, 021903 (2016)

- One single strange quark distribution describes both Ω and ϕ spectra-> quark coalescence production
- Slope (T) from Boltzmann fit changes at 7.7 GeV. *Centrality difference?*
- Decreasing *s* quark density below 19.6 GeV -> *Possible phase transition*

Ω and ϕ v_2 at RHIC

Ω and ϕ: good probes of early partonic stage of collision

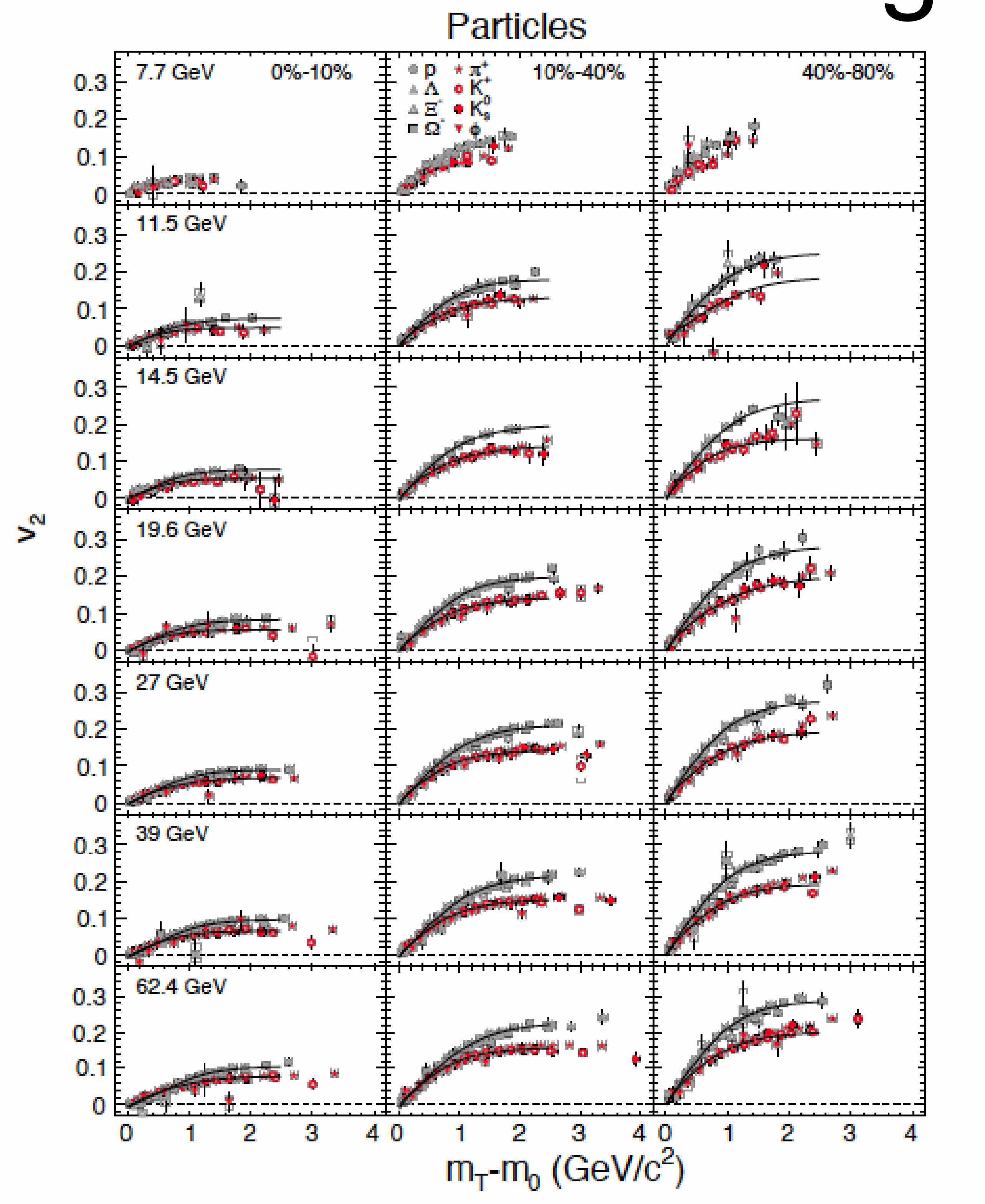


STAR: Phys. Rev. Lett.116, 062301 (2016)

- **Proton and pion v_2 compared with Ω baryon and ϕ meson v_2**
- **High precision data prove that Ω follows the baryon/meson splitting at intermediate p_T range, $2 < p_T < 5$ GeV/c .** ***First time!***

The major part of collectivity has been built-up at partonic stage!

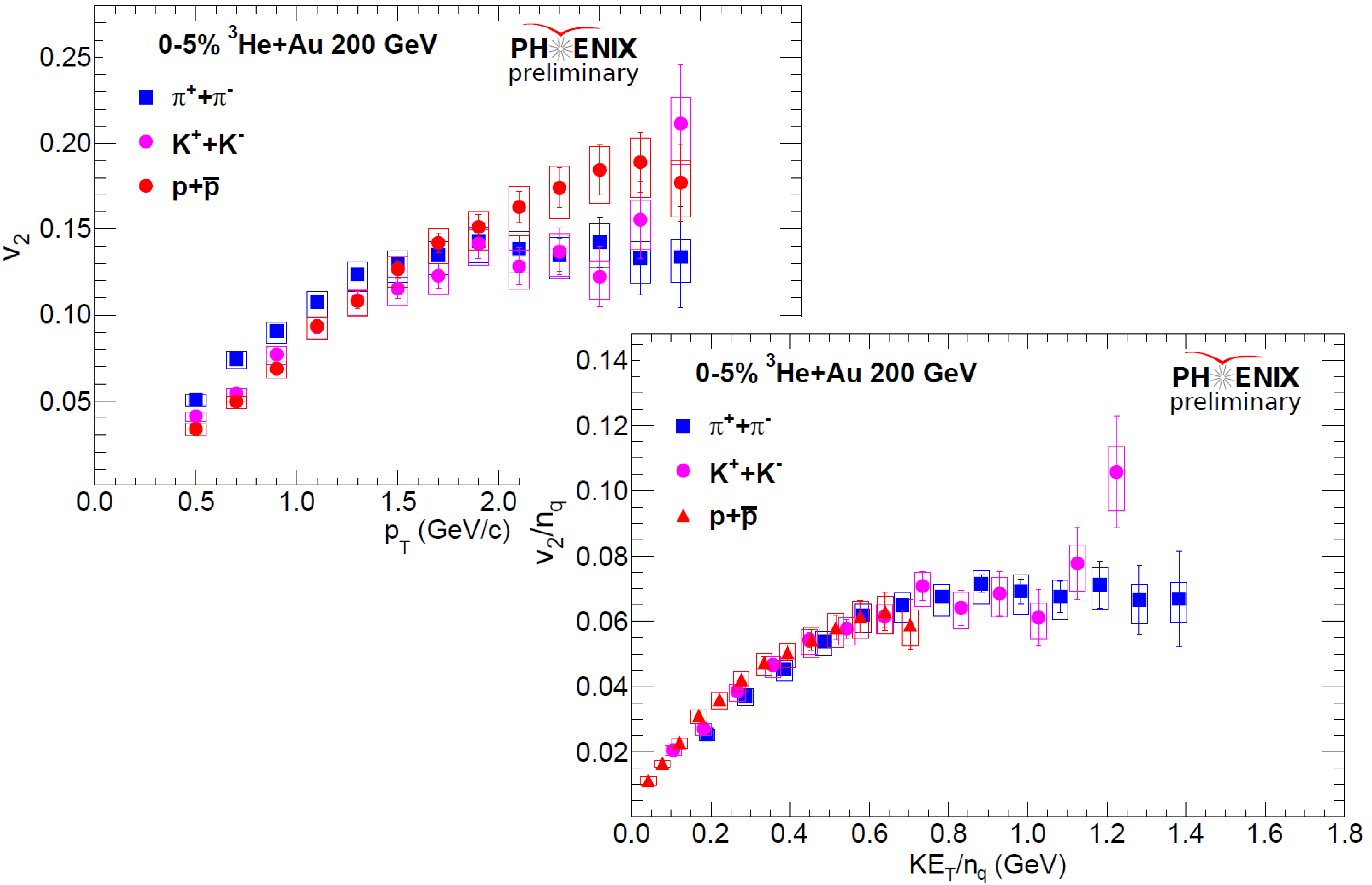
Baryon to meson splitting persists at all energies….



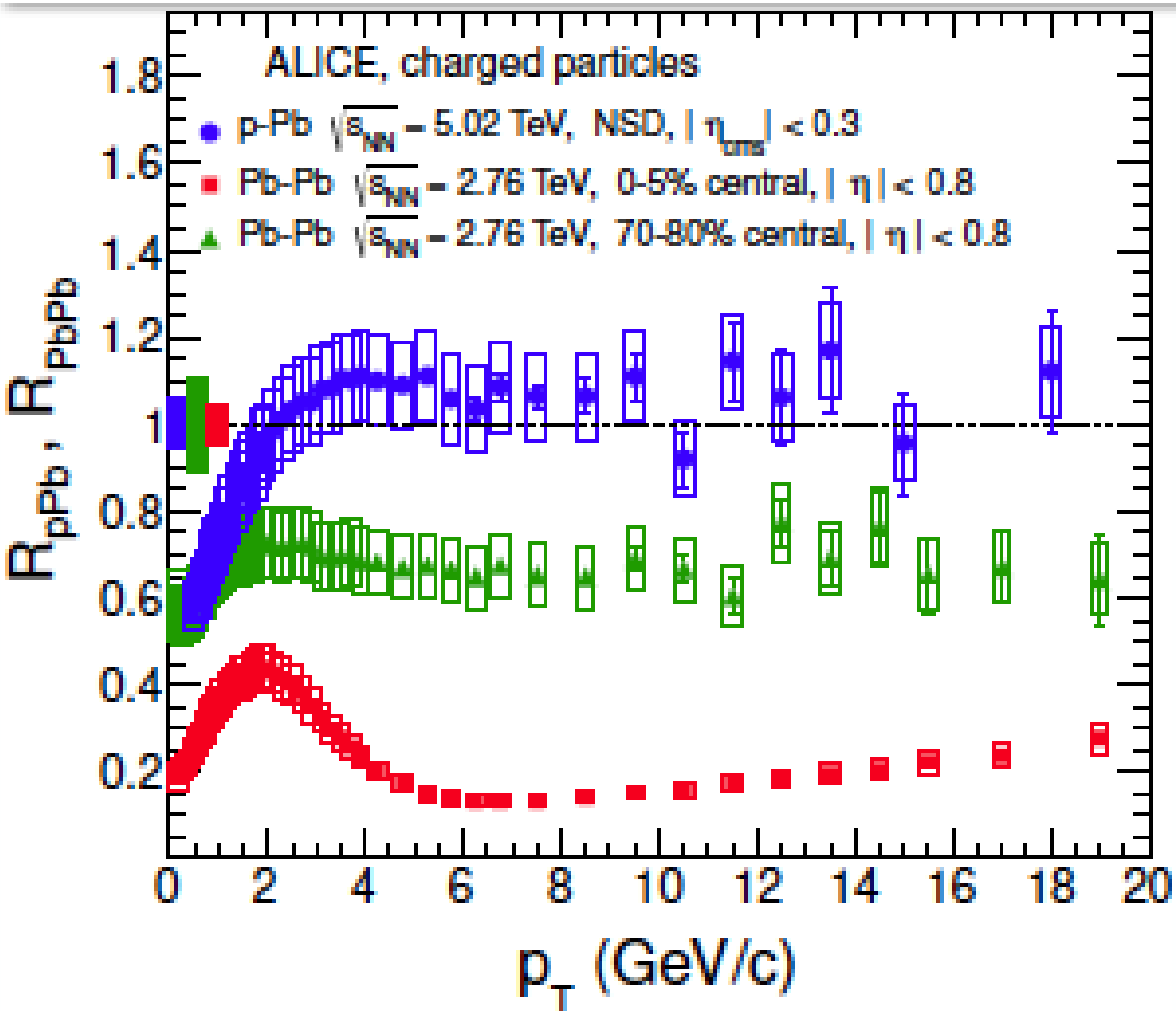
- **A splitting between baryons and mesons is observed at all energies except 7.7 GeV and all centralities.**
- **At 7.7 GeV we are limited by the number of events.**

STAR: Phys. Rev. C 93, 014907(2016)

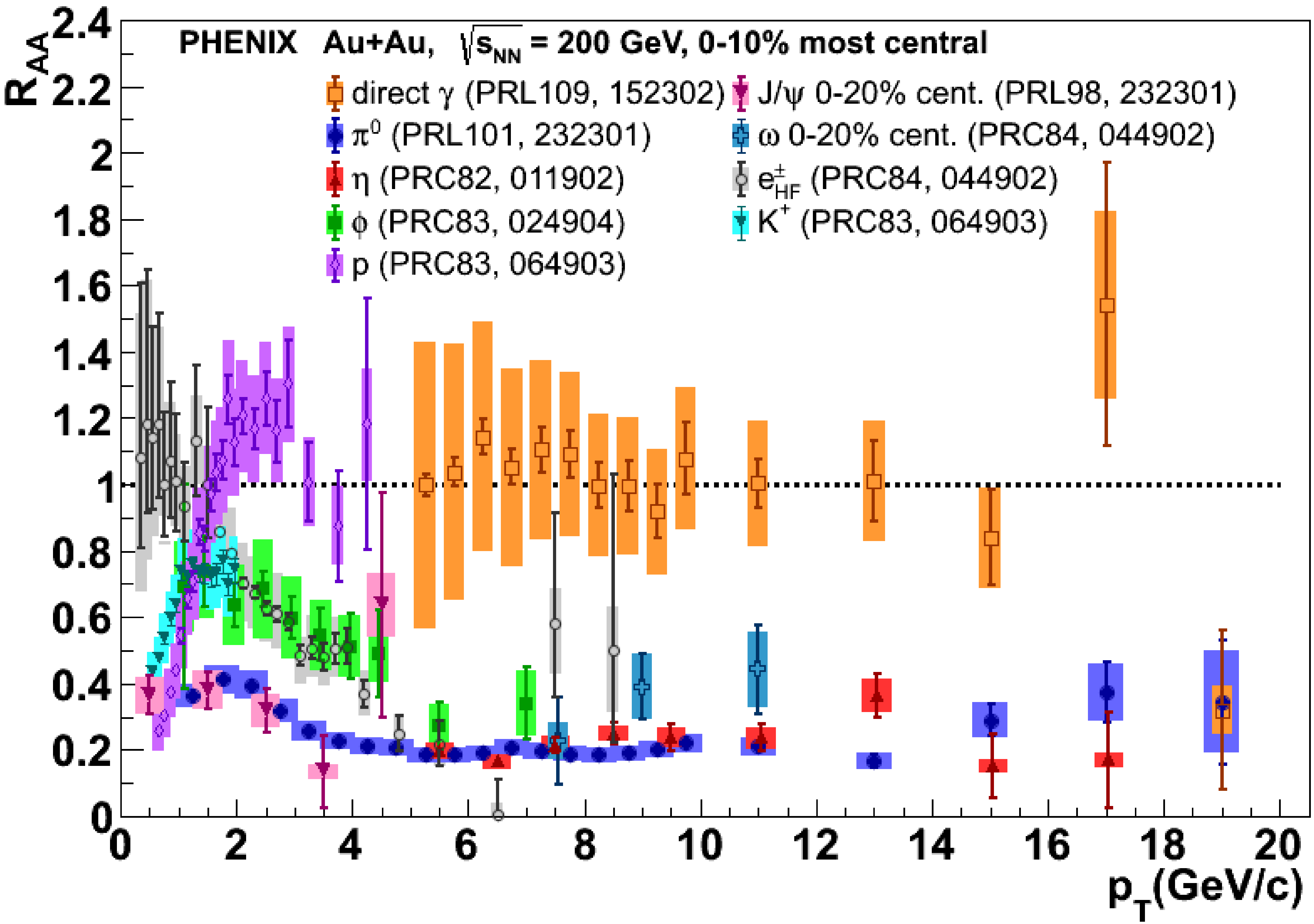
..and for all system sizes



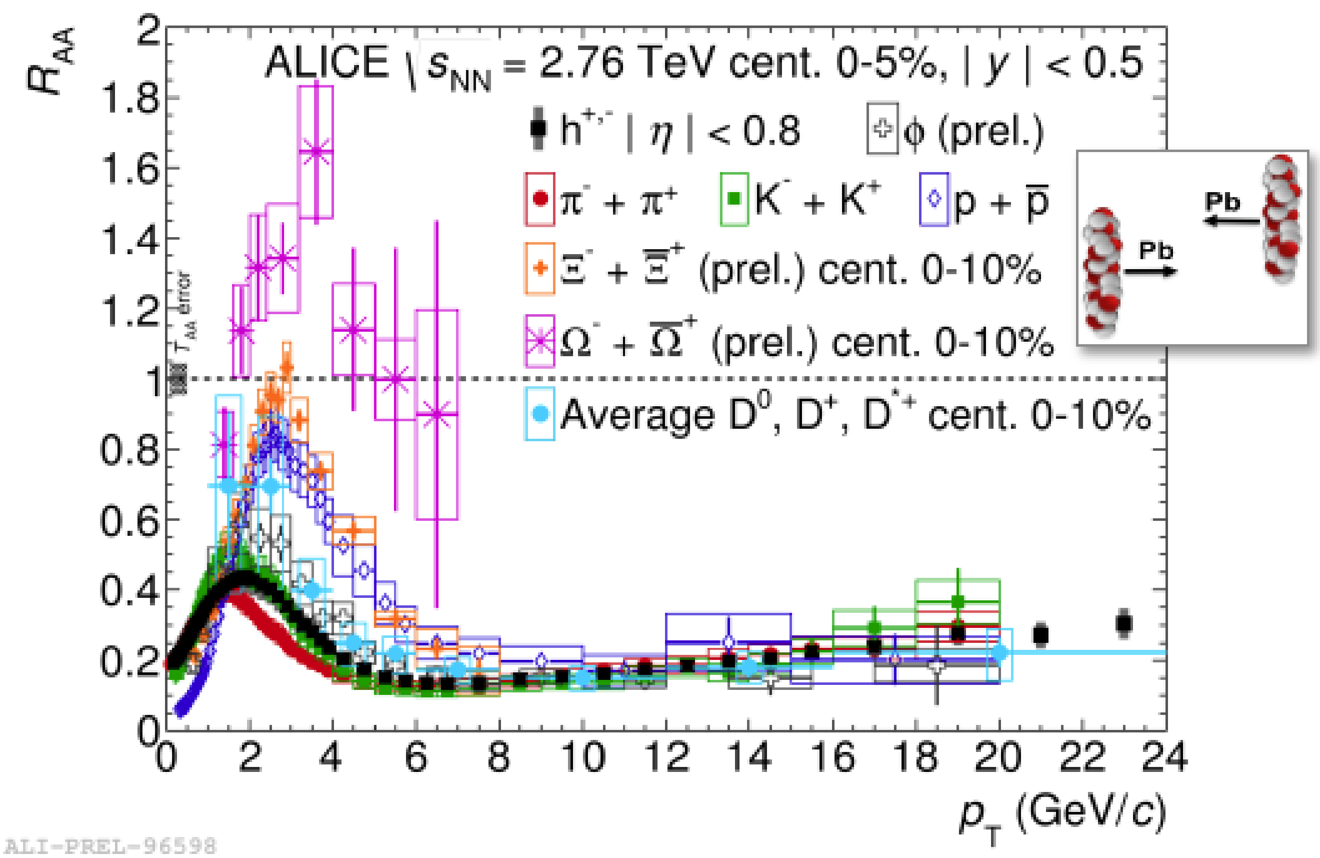
Nuclear suppression does NOT persist for all system sizes



Identified particle R_{AA} at RHIC



Identified particle R_{AA} at LHC (incl. charm)

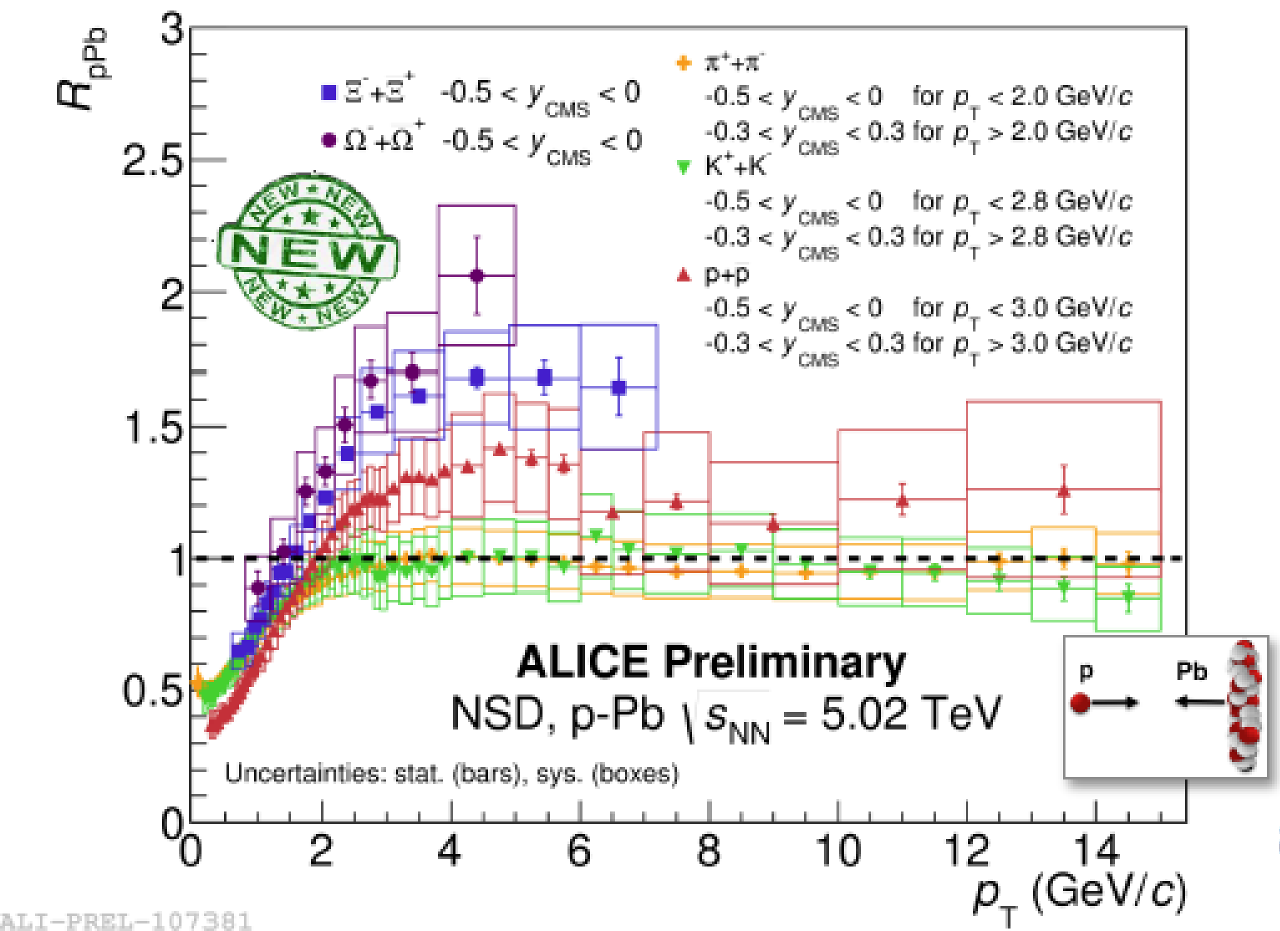


$$R_{xA}(p_T) = \frac{d^2N_{ch}^{xA}/d\eta dp_T}{\langle T_{xA}\rangle d^2\sigma_{ch}^{pp}/d\eta dp_T}$$

At **high-p_T** (>8-10 GeV/c):

- strong **flavour-independent suppression** in **central Pb-Pb** with respect to pp
- **no suppression** observed **in p-Pb** for π,K,p above 6-8 GeV/c

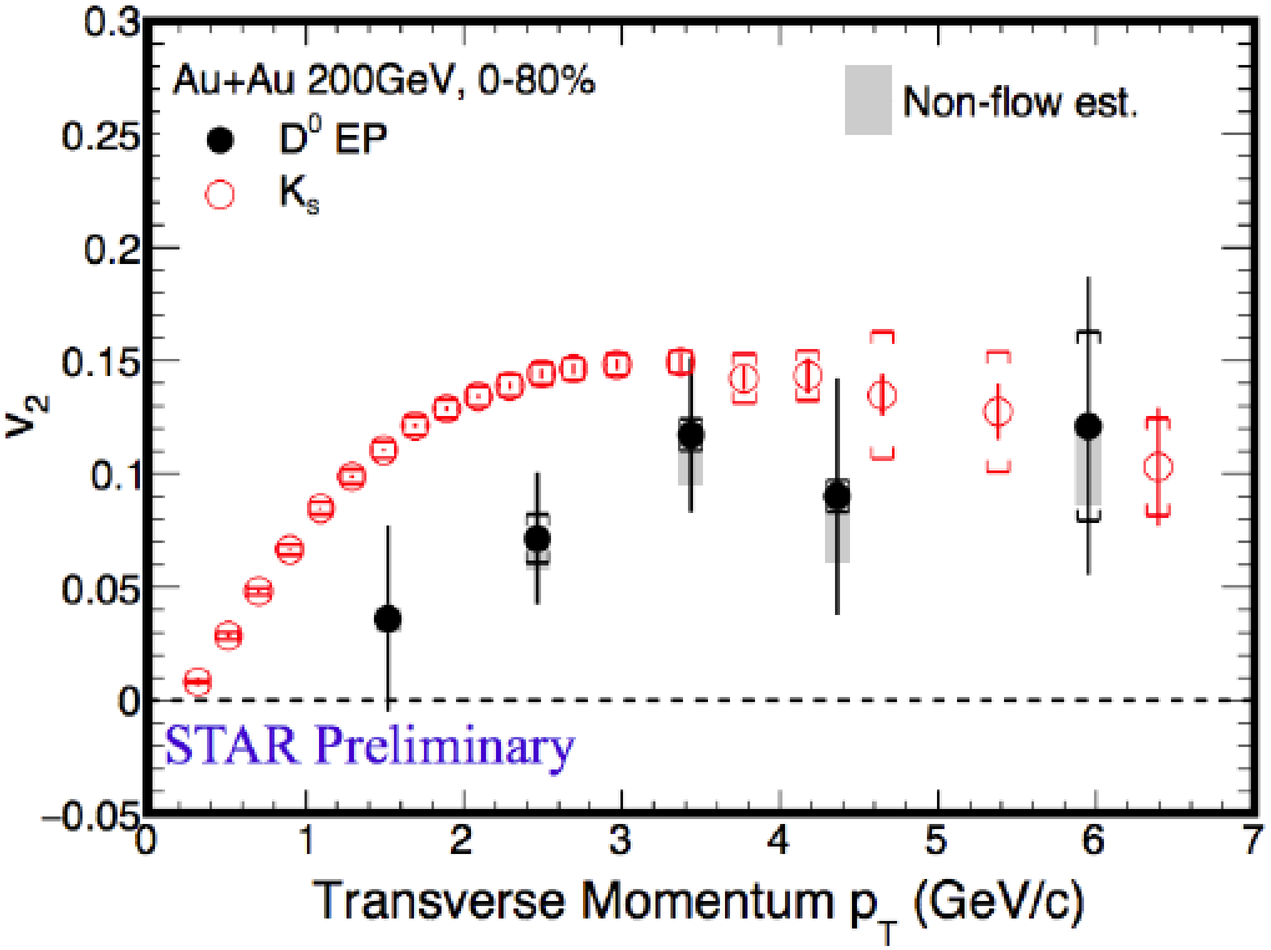
→ In Pb-Pb, due to **parton energy loss in the hot nuclear matter**



arXiv:1601.03658

(High-p_T π,K,p and R_{pPb})

Charm R_{AA} and v_2 at RHIC (w. STAR-HFT)

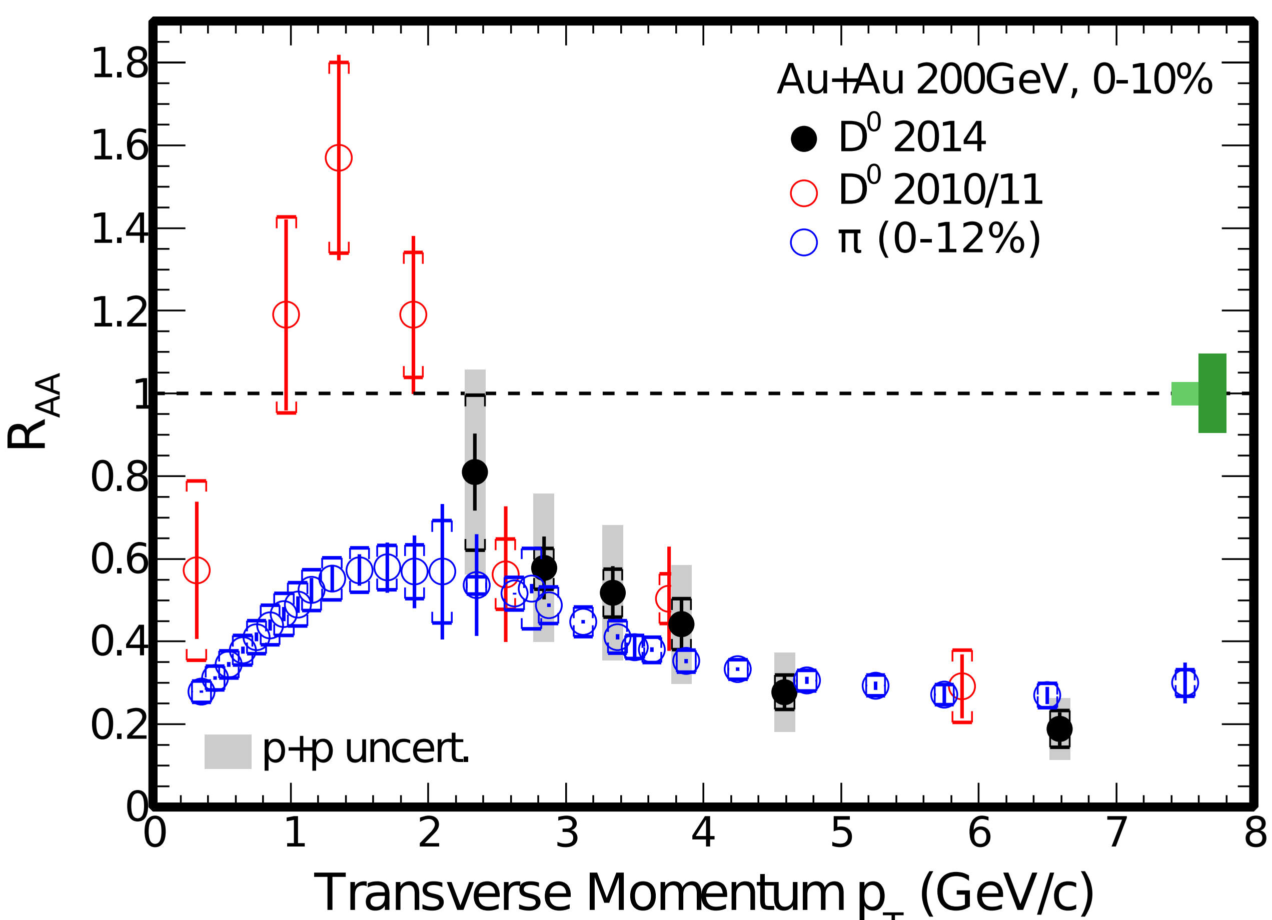


$R_{AA} > 1$ for $p_T \sim 1.5$ GeV/c

Charm coalescence with the flowing medium

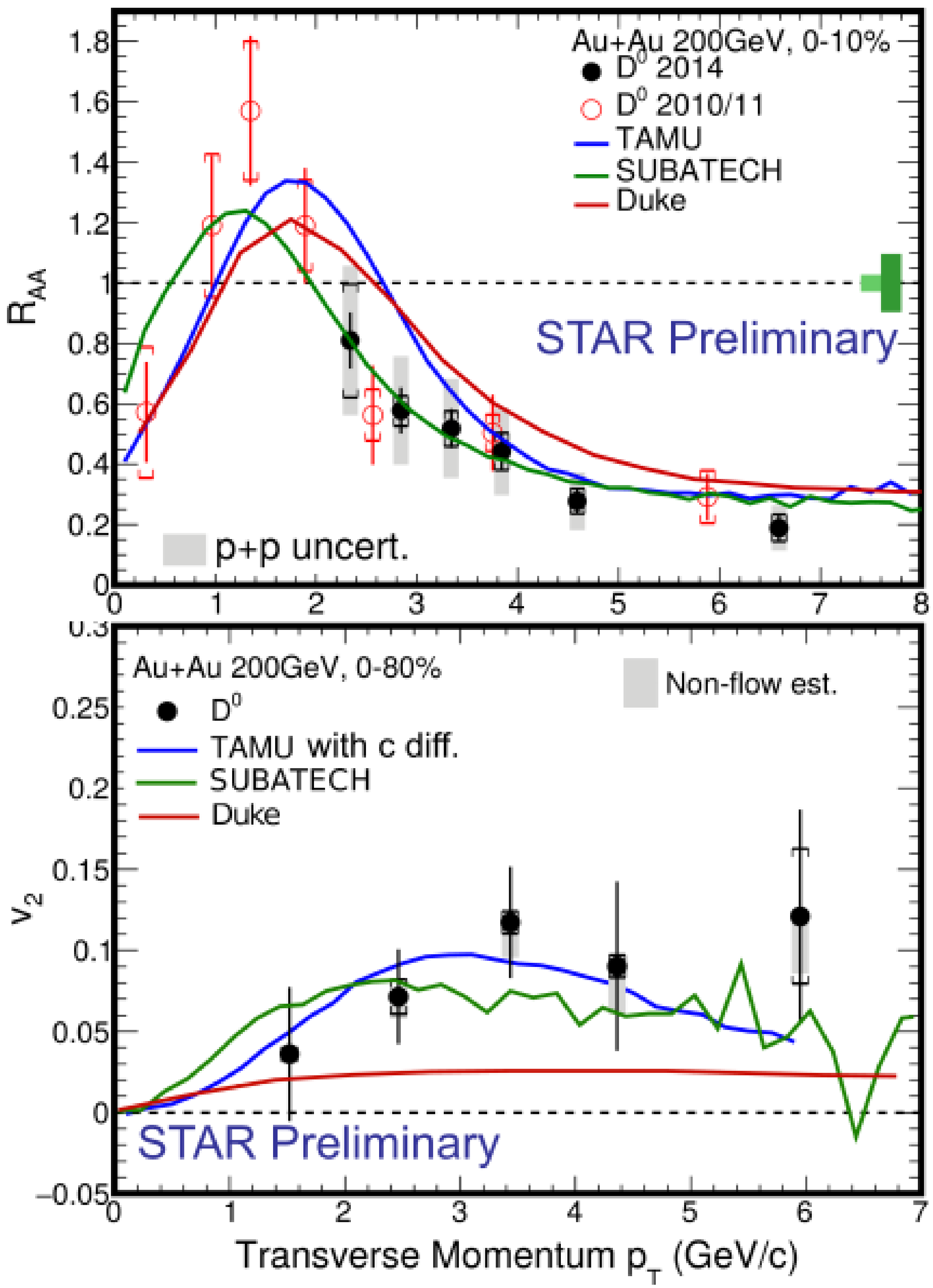
- $R_{AA} << 1$ for $p_T > 2.5$ GeV/c

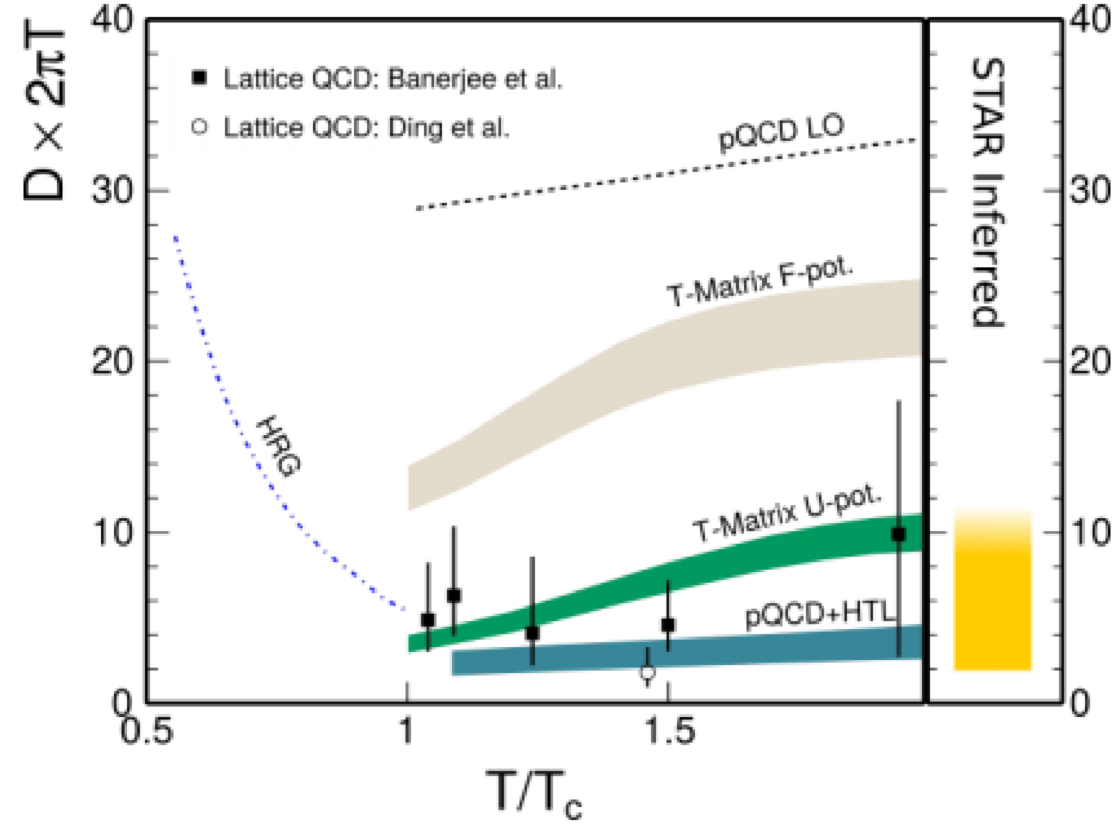
Strong charm-medium interaction leading to sizable energy loss



- Similar suppression as pions at high p_T
  - Collisional energy loss is important
  - Shapes of parton spectrum & fragmentation function need to be taken into account.

Comparison to models





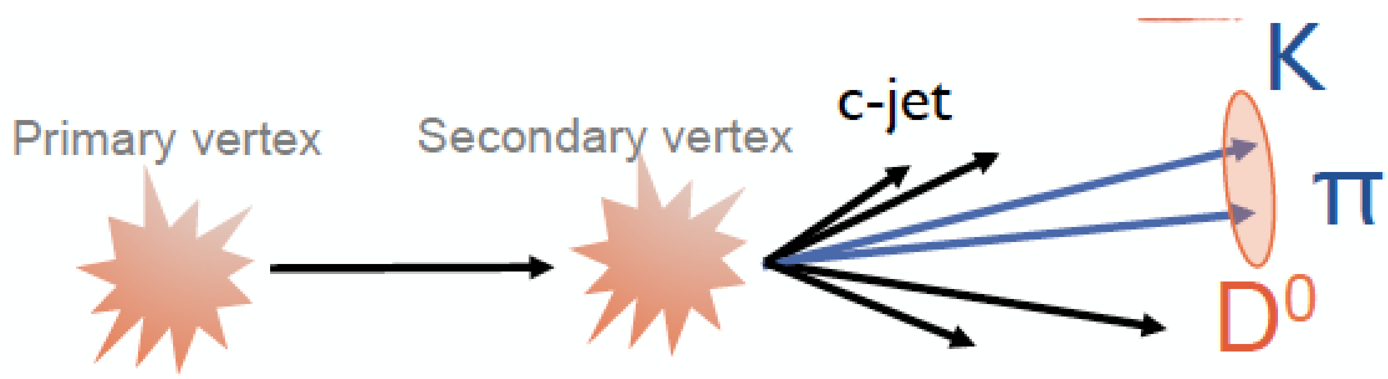
Values for the diffusion coeff. extracted from models and compared to STAR data

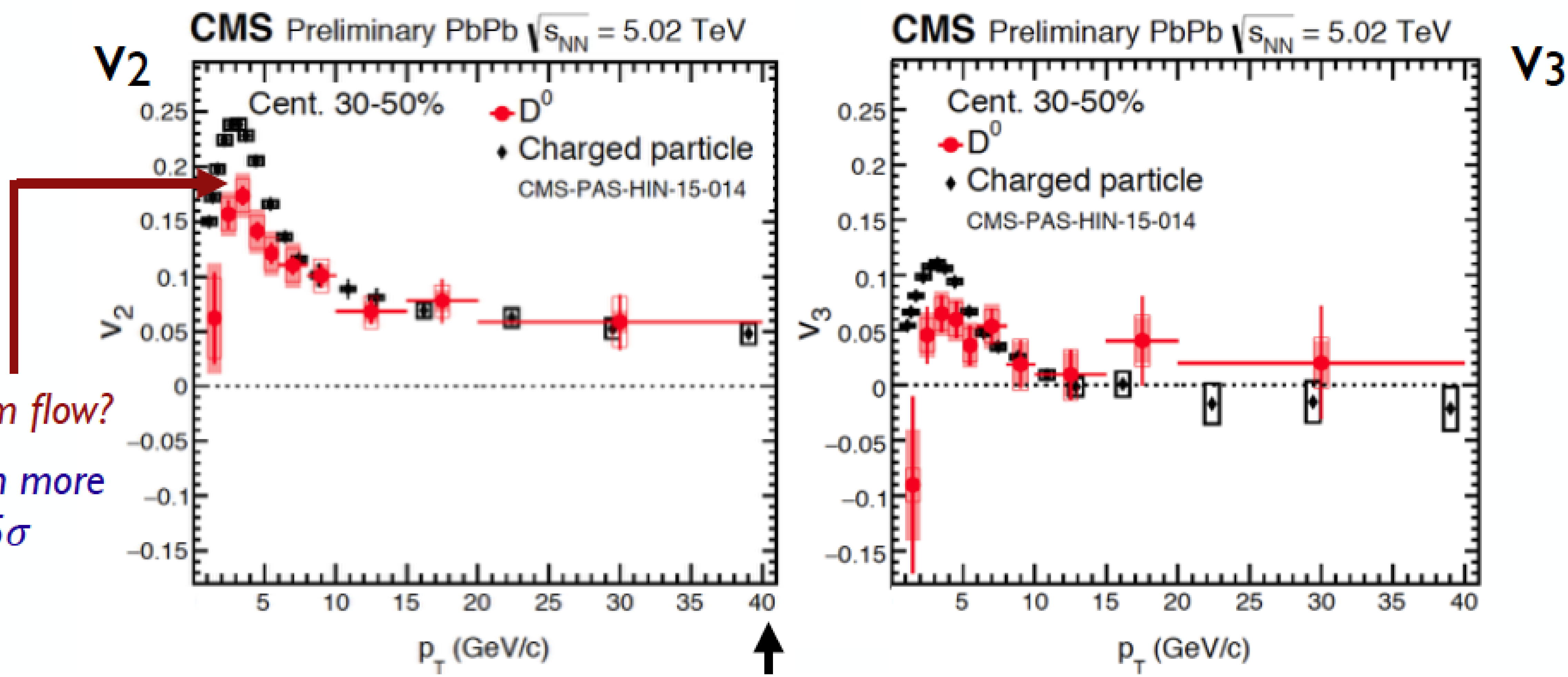
	$D \times 2\pi T$	Diff. Calculation
TAMU	2-11	T-Matrix
SUBATECH	2-4	pQCD+HTL
Duke	7	Free parameter

STAR D_0 2010/11: PRL 113 (2014) 142301
Theory curves private communications
DUKE: PRC 92 (2015) 024907
A.Andronic arXiv:1506.03981(2015)

Does charm flow and quench at LHC ?

- Low p_T differences
  Mass ordering
- Agreement at high p_T *No sign of difference in path length dependence of E_{loss} for inclusive flavor and charm*

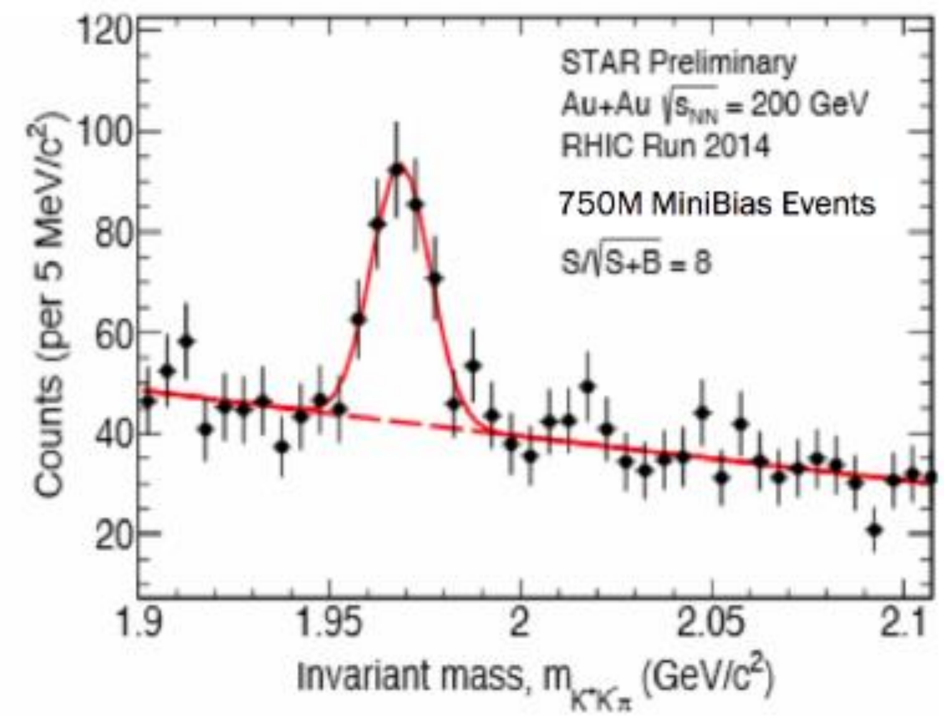


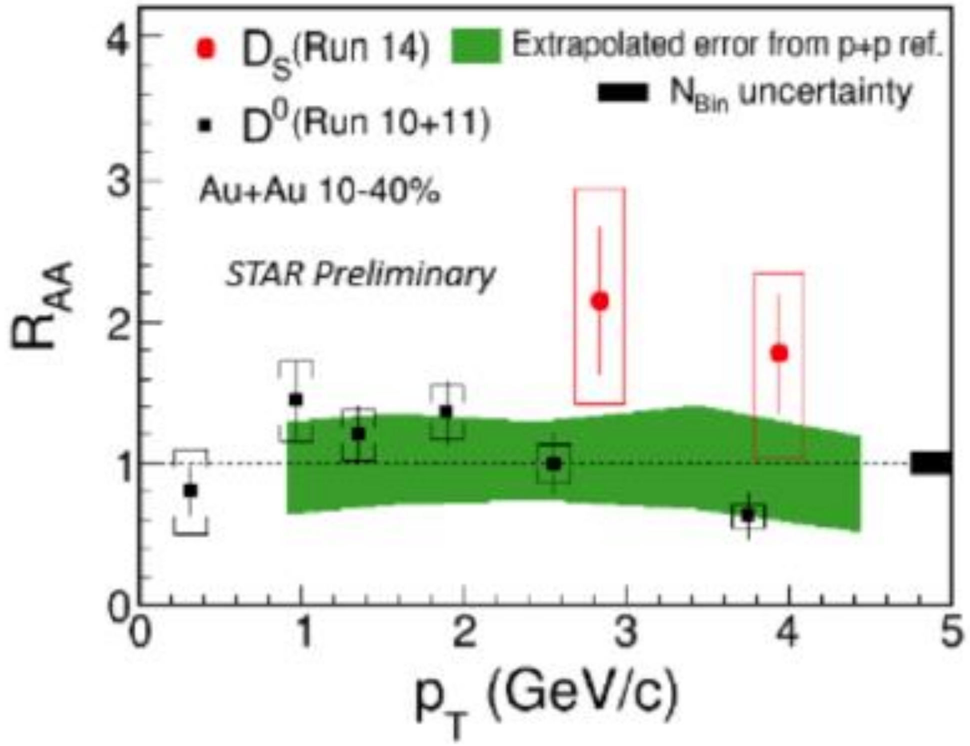


Does charm flow?

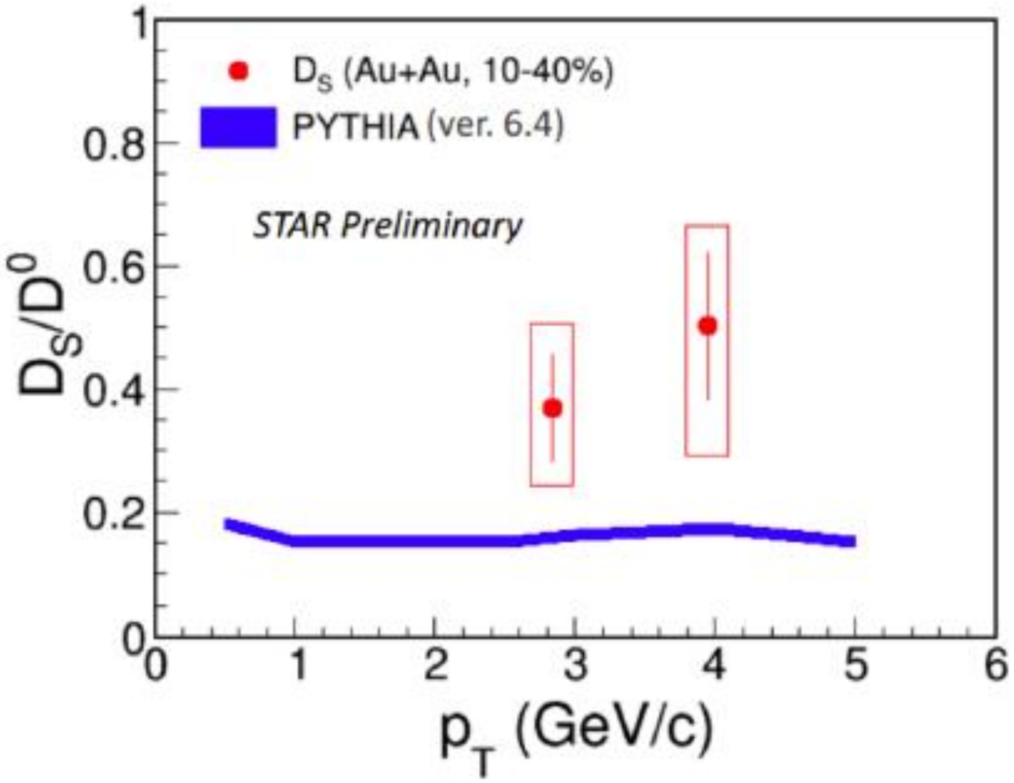
$v_2 > 0$ with more than 5σ

D_s R_{AA} and v_2 at RHIC

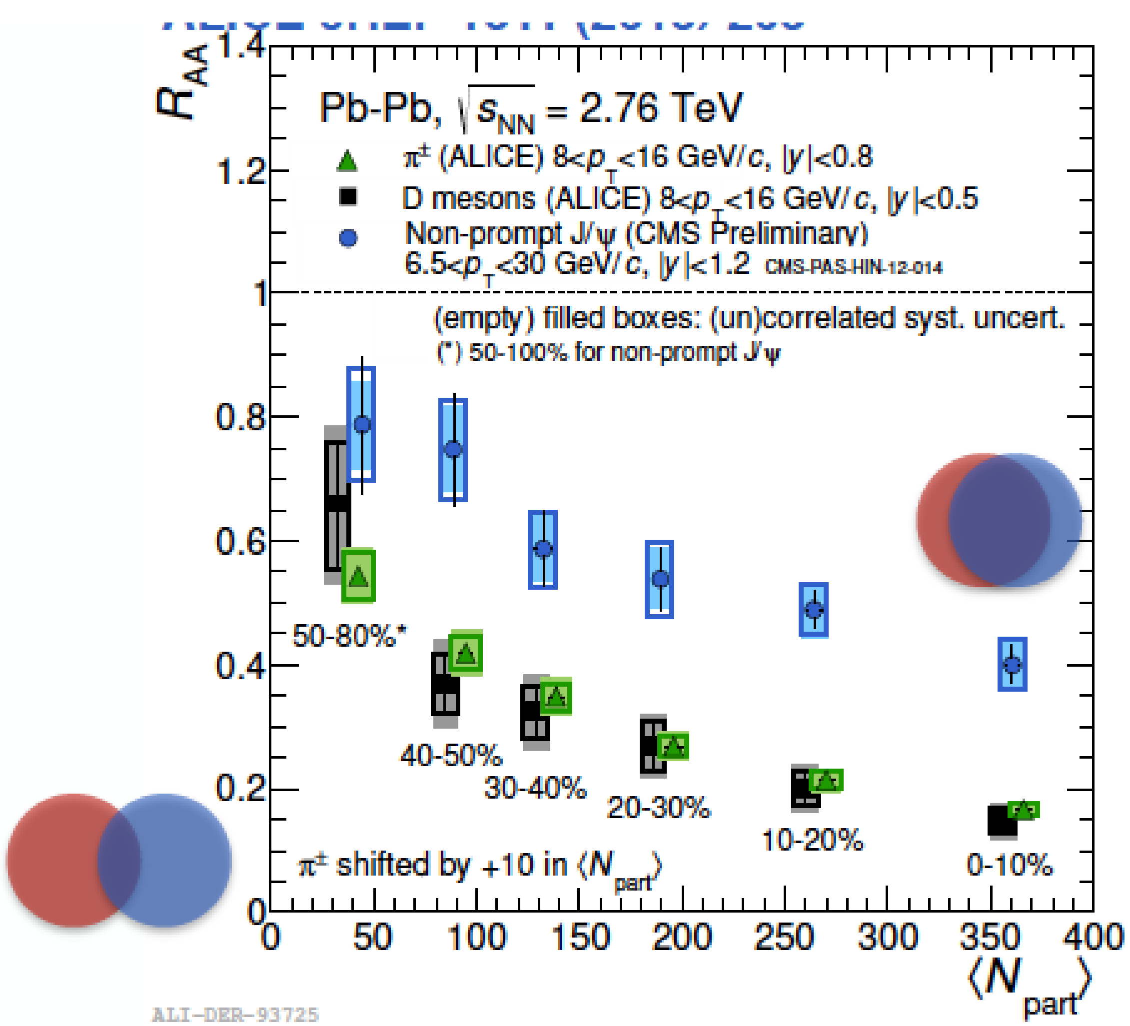


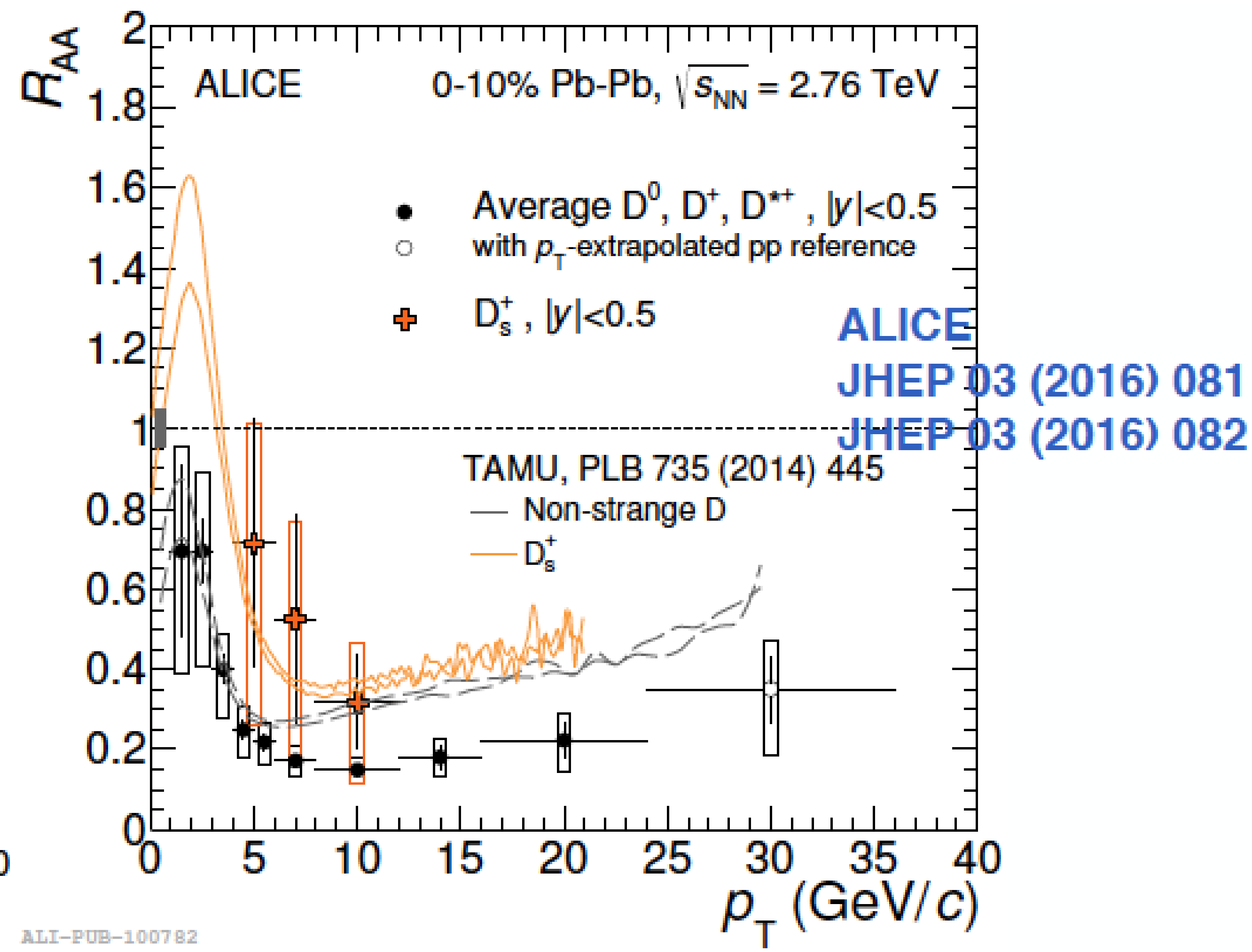


- D_s R_{AA} may be higher than D^0.
- Higher D_s/D^0 ratio wrt. PYTHIA?
- Will follow up with better precision measurements.



R_{AA} of D, D_s and B (through non-prompt J/ψ)

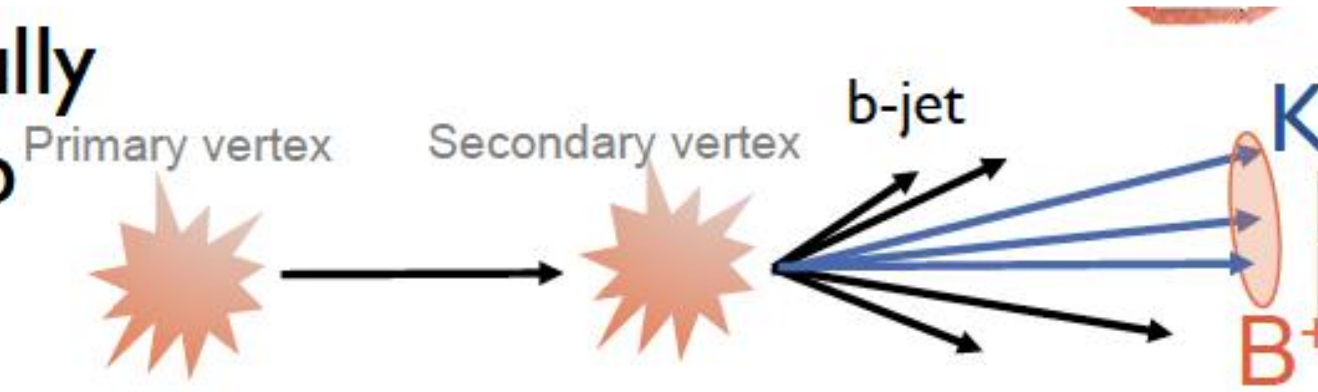


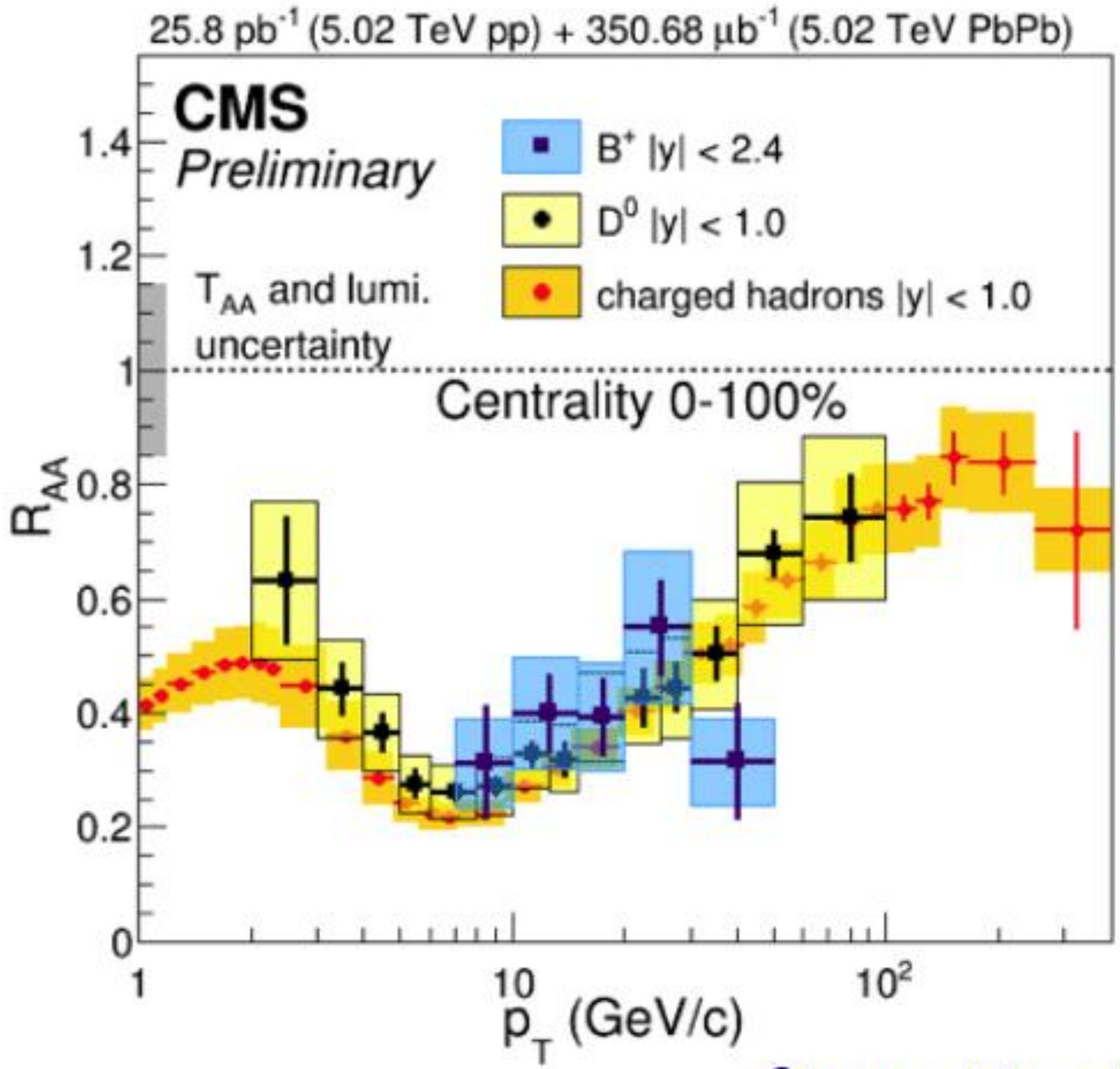


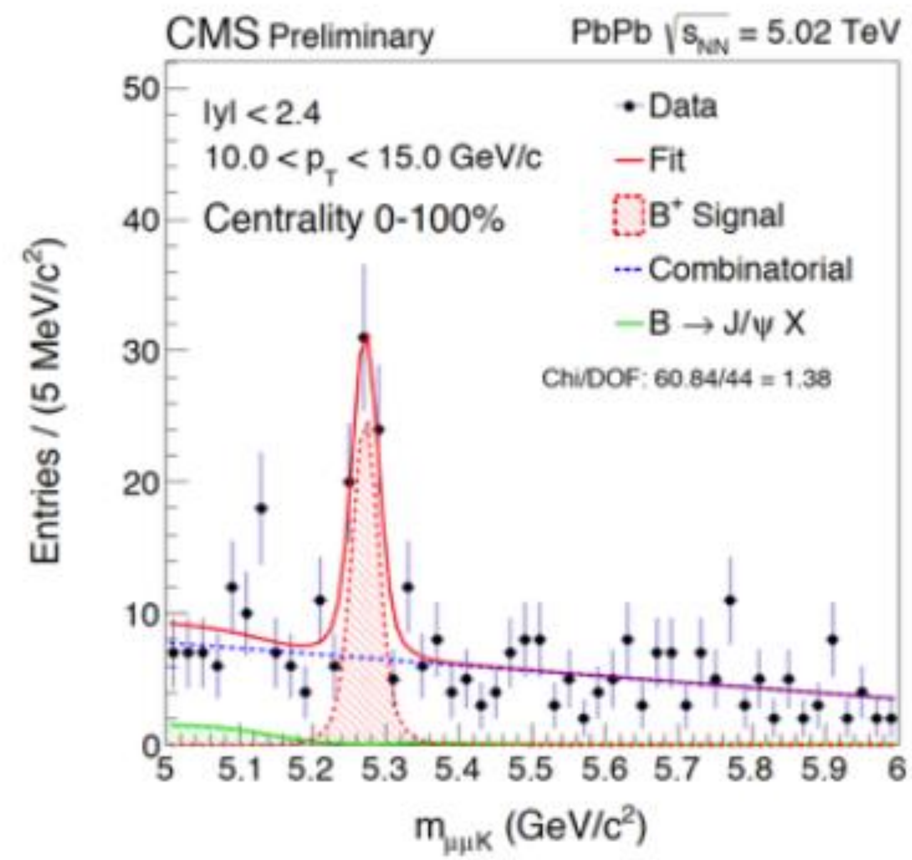
- R_{AA}(D)<R_{AA}(J/ψ←B): $\Delta E_c > \Delta E_b$ — mass dependence of HF energy loss
- R_{AA}(D)≈R_{AA}(π): $\Delta E_c \approx \Delta E_g$(?) or different parton p_T distributions and fragmentation functions
- Charm hadronization through recombination in medium (?) — predicted in models — hint of R_{AA}(D)<R_{AA}(D_s^+) in data — to be confirmed with higher precision measurements

B-meson suppression at the LHC

FIRST EVER measurement of fully reconstructed B meson in PbPb



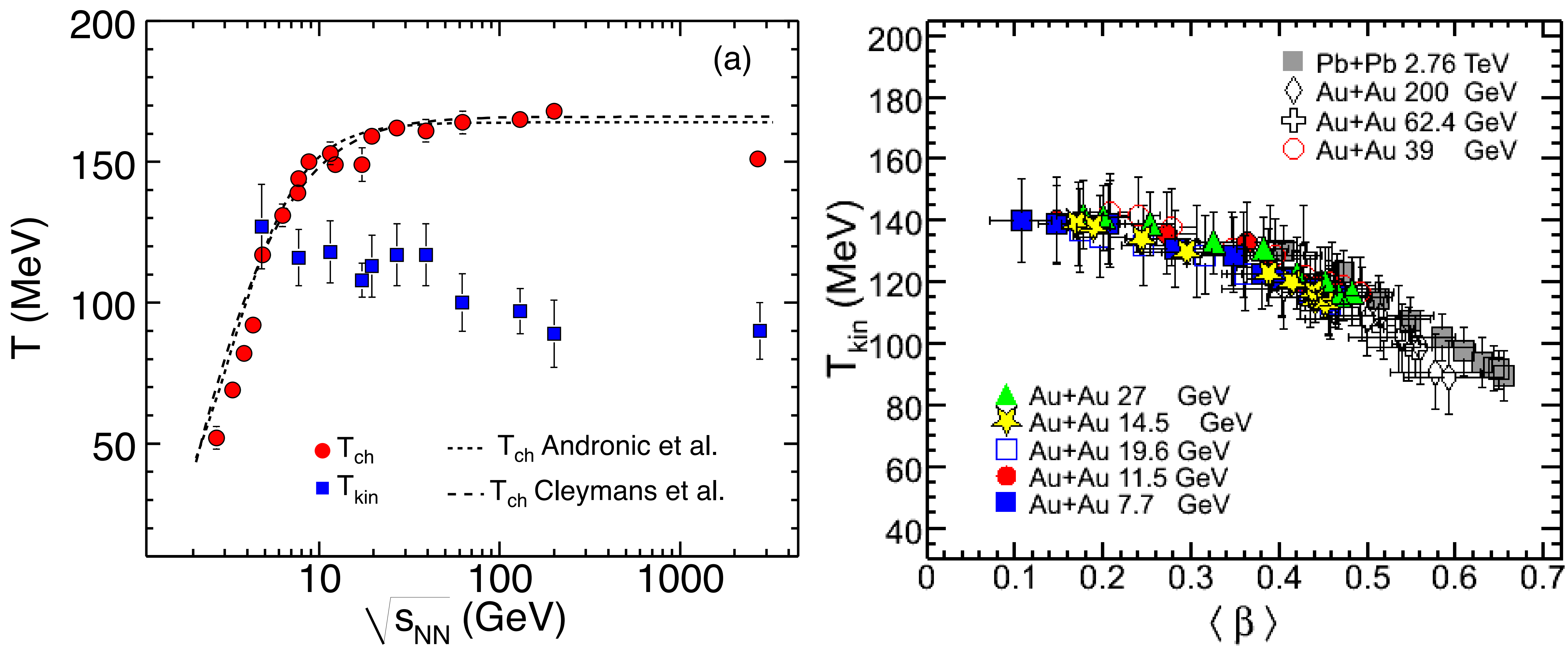




Strong suppression of 7-50 GeV B mesons

Freeze-out
/
Hadronization

Collision energy dependence of blast wave fits to π,k,p at RHIC



The higher the collision energy the longer the hadronic lifetime of the system (confirmed by resonance measurements) and the larger the radial expansion velocity

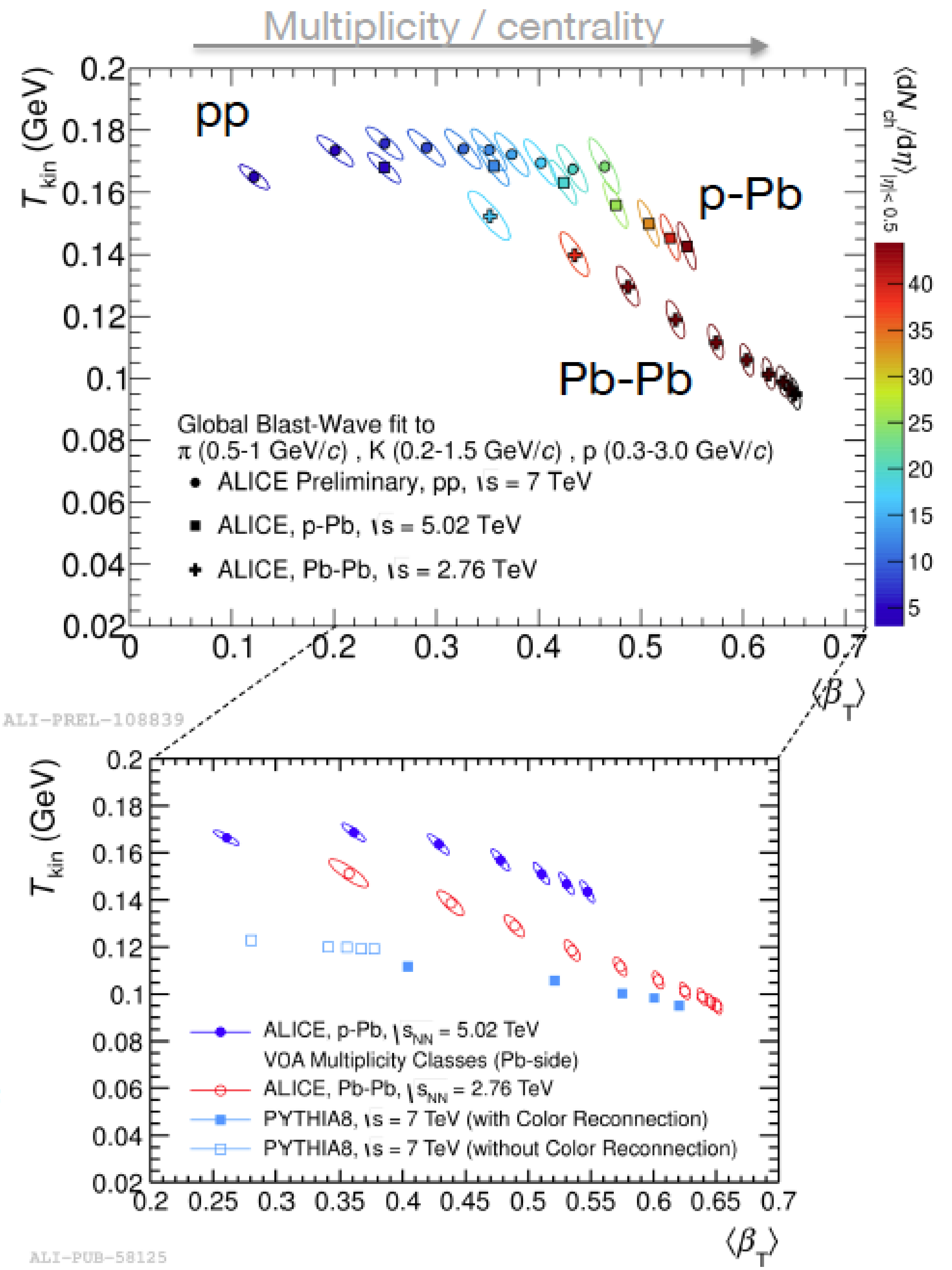
Blast wave fits to π,k,p as a function of system size and centrality at LHC

Simultaneous **Blast-Wave model** fit to the π, K, p spectra

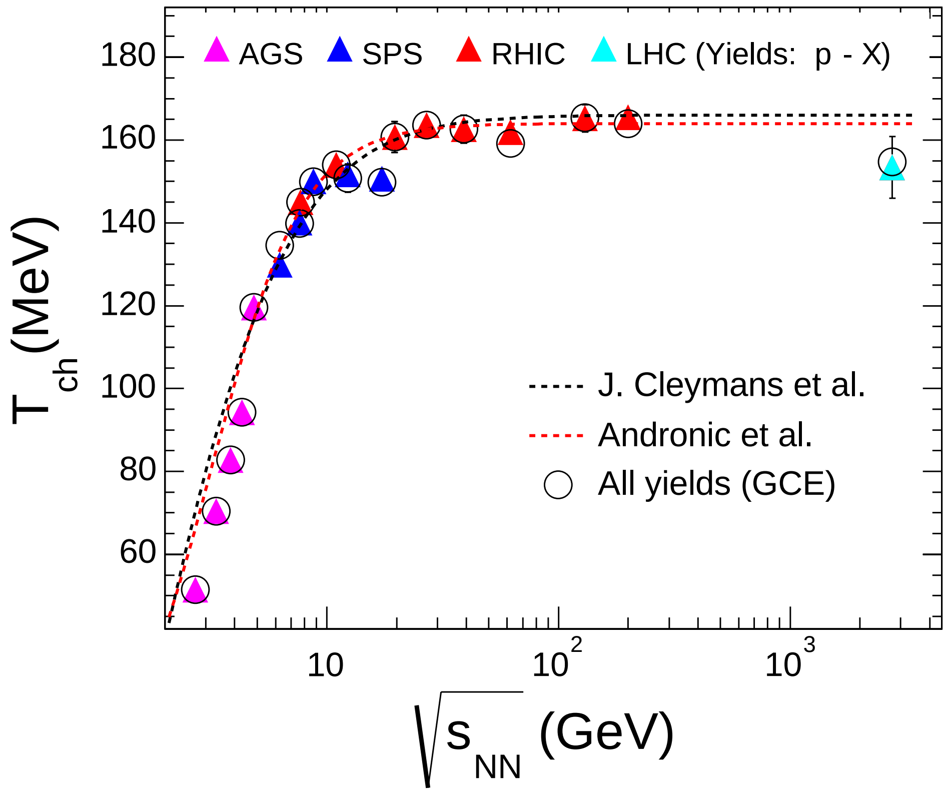
- In **Pb-Pb**: increase of radial flow with centrality
- In **pp** and **p-Pb**, similar evolution of the parameters towards high multiplicity
- **Stronger <β_T> for smaller systems at similar multiplicity**

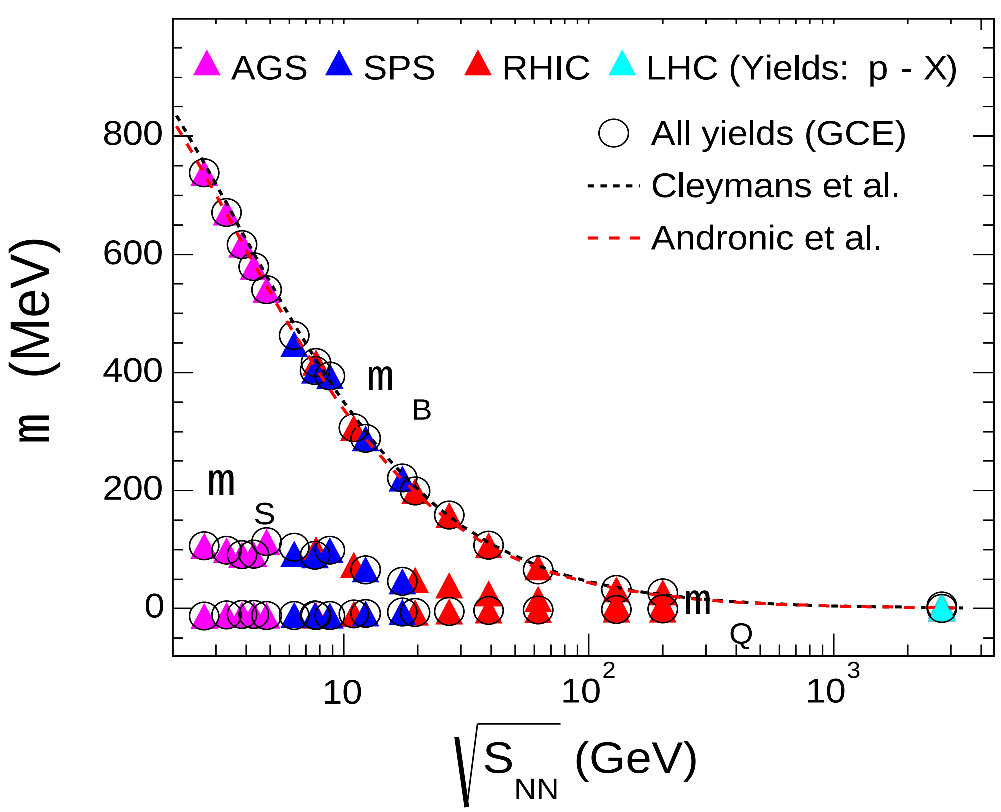
… but mind:

- Sensitivity to **fit range** and the set of **particles included in the fit**
- Mechanisms such as color reconnection in models of pp collisions can mimic the effects of radial flow

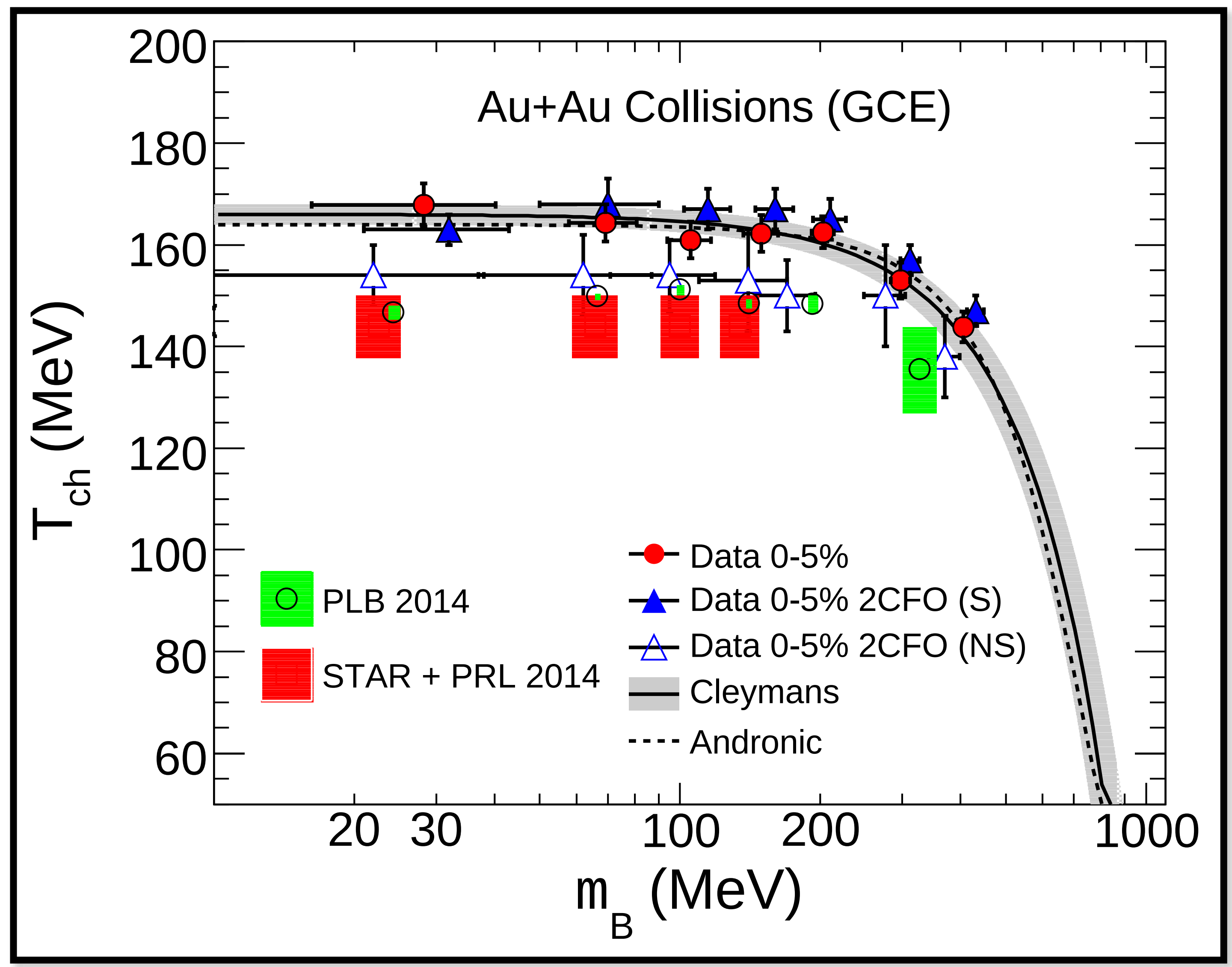


Collision energy dependence of chemical freeze-out fit to all particle yields

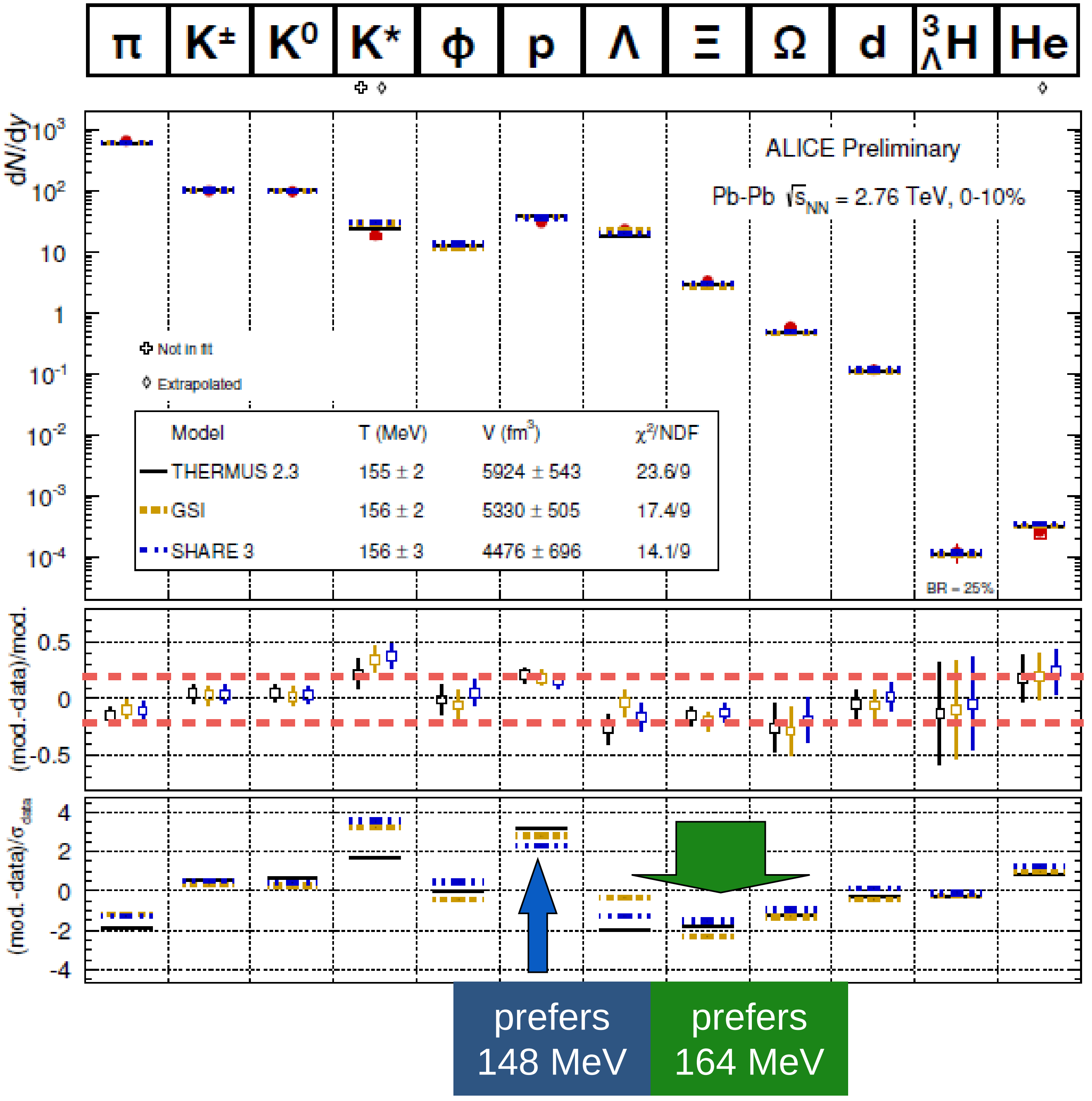


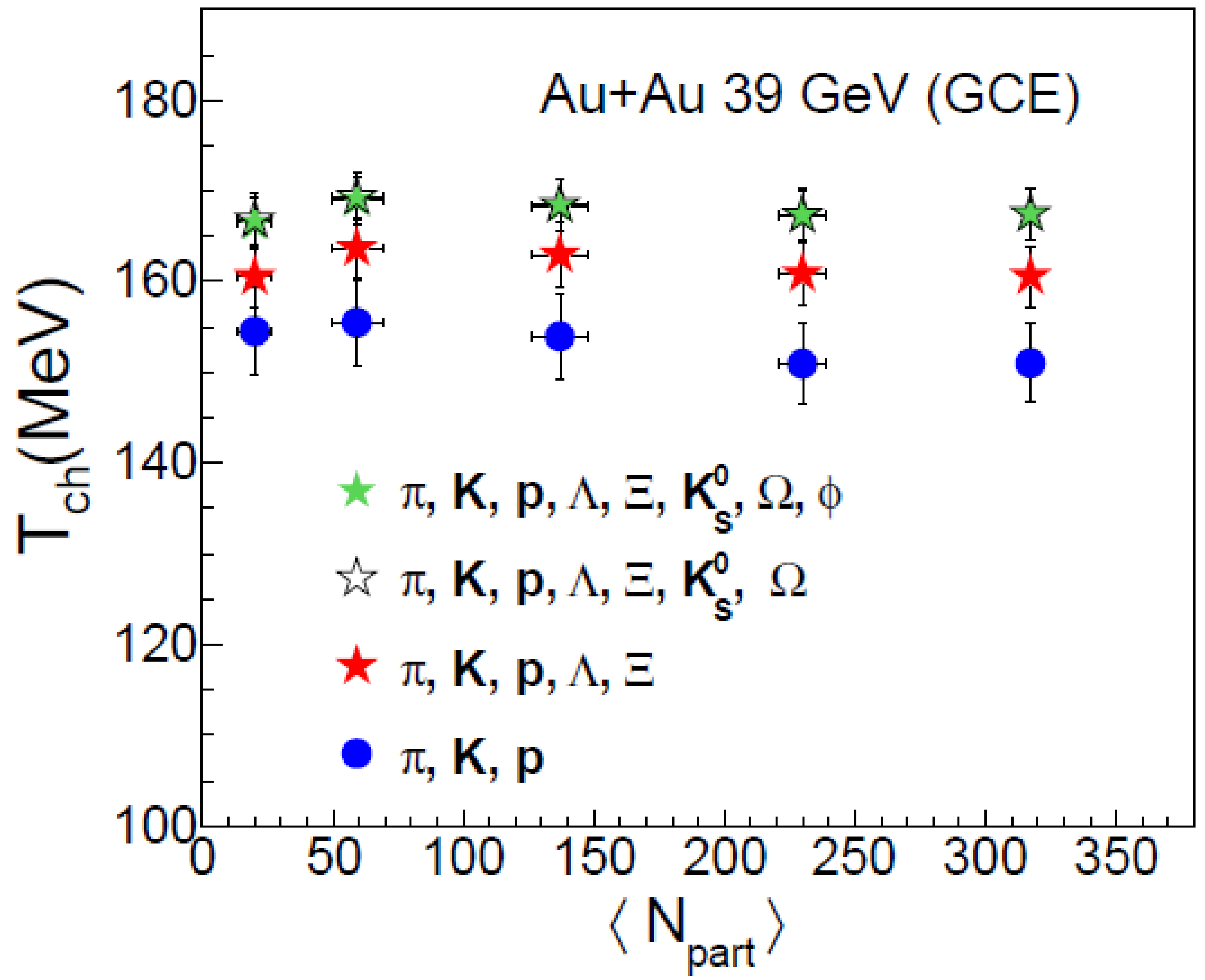


More detailed fit assuming two freeze-out surfaces for light and strange flavor:



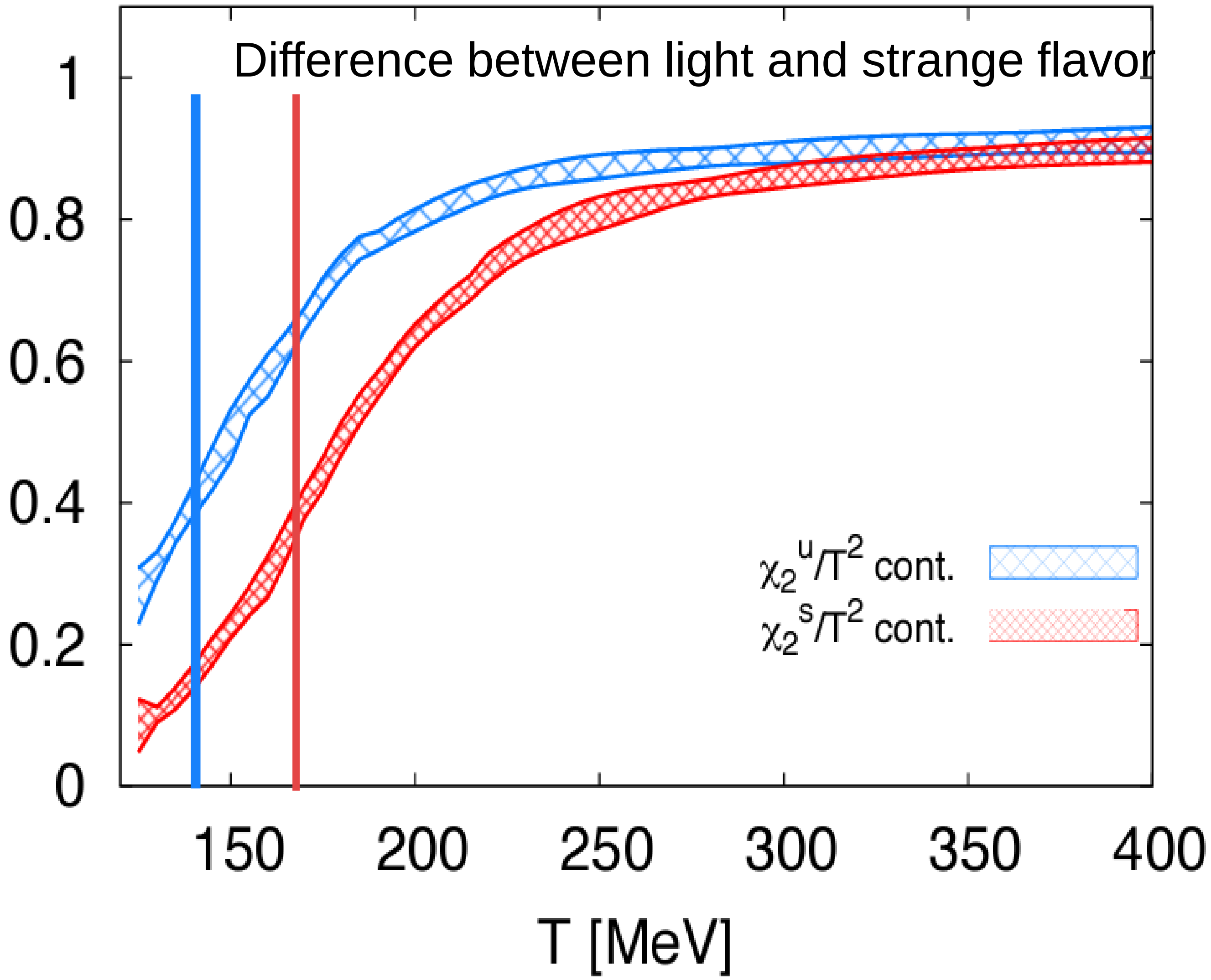
Relevant experimental results



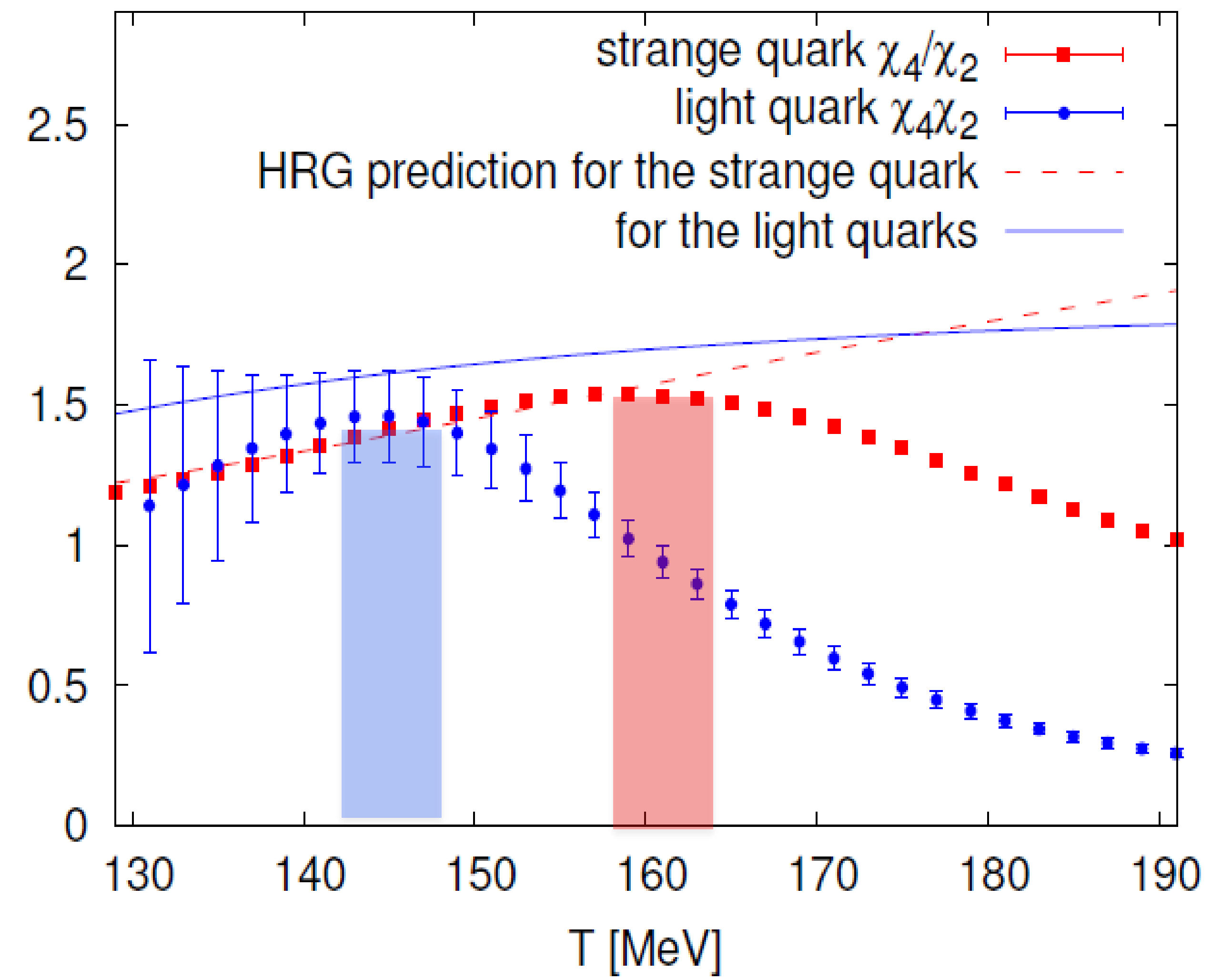


Separation of quark flavor freeze-out in yield fits at RHIC & LHC

Indication of flavor dependence in susceptibilities and susceptibility ratios



C. Ratti et al., PRD 85, 014004 (2012)
R. Bellwied, arXiv:1205.3625



R. Bellwied & WB Collab., PRL (2013), arXiv:1305.6297

Indication of sequential hadronization ?

$$\kappa_B\sigma_B^2 \equiv \frac{\chi^B_{4,\mu}}{\chi^B_{2,\mu}} = \frac{\chi^B_4(T)}{\chi^B_2(T)}\left[\frac{1+\frac{1}{2}\frac{\chi^B_6(T)}{\chi^B_4(T)}(\mu_B/T)^2+\ldots}{1+\frac{1}{2}\frac{\chi^B_4(T)}{\chi^B_2(T)}(\mu_B/T)^2+\ldots}\right]$$

Susceptibilities on the lattice map to measureable moments of the multiplicity distribution

In a thermally equilibrated system we can define susceptibilities χ as 2nd derivative of pressure with respect to chemical potential (1st derivative of ρ).

Starting from a given partition function we define the fluctuations of a set of conserved charges as:

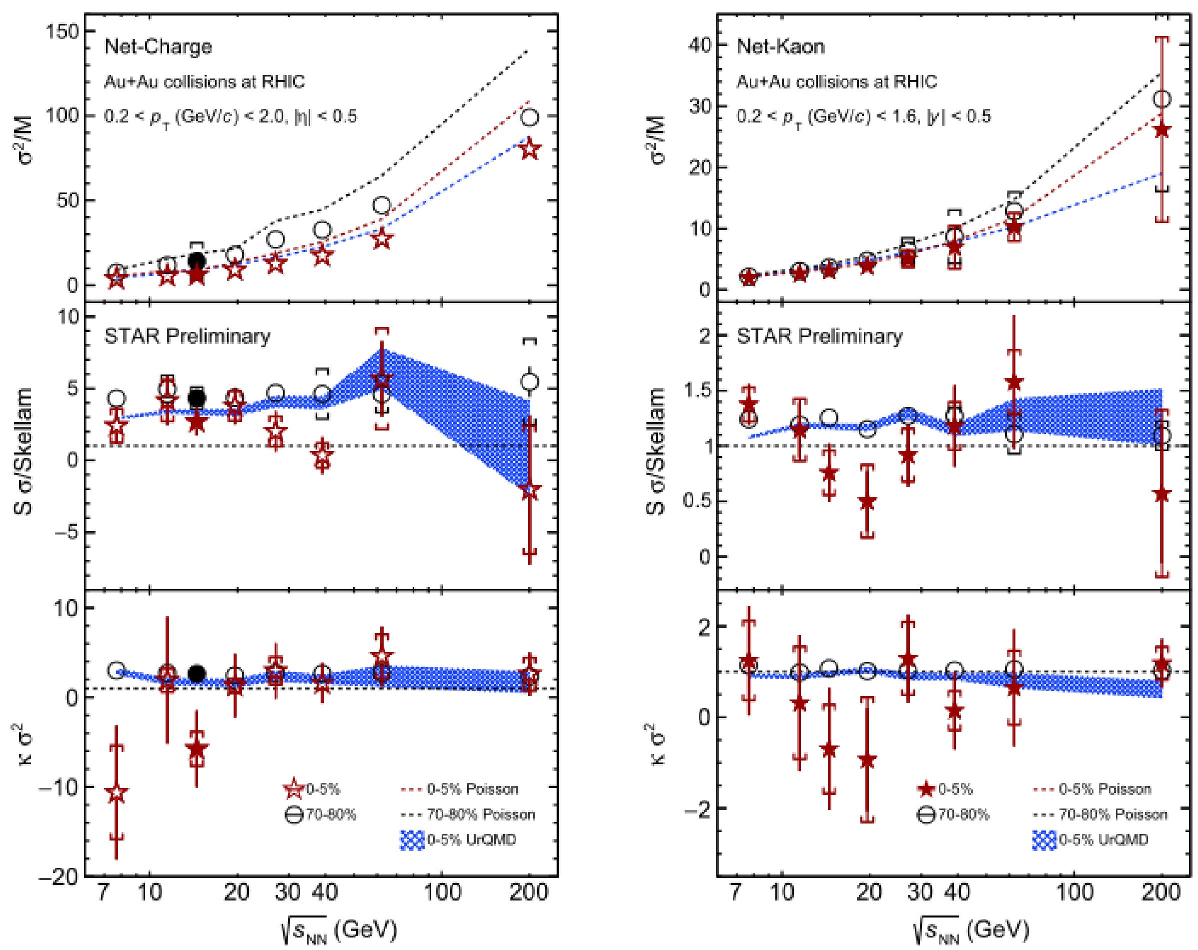
$$\chi^{BSQ}_{lmn} = \frac{\partial^{l+m+n}\left(p/T^4\right)}{\partial\left(\mu_B/T\right)^l \partial\left(\mu_S/T\right)^m \partial\left(\mu_Q/T\right)^n}$$

mean: $M = \langle N \rangle = VT^3\chi_1,$

variance: $\sigma^2 = \langle(\delta N)^2\rangle = VT^3\chi_2,$

skewness: $S = \frac{\langle(\delta N)^3\rangle}{\sigma^3} = \frac{VT^3\chi_3}{(VT^3\chi_2)^{3/2}},$

kurtosis: $k = \frac{\langle(\delta N)^4\rangle}{\sigma^4} - 3 = \frac{VT^3\chi_4}{(VT^3\chi_2)^2};$



Measurable ratios:

$$R_{32} = S\sigma = \frac{\chi_3^{(B,S,Q)}}{\chi_2^{(B,S,Q)}}$$

$$R_{42} = K\sigma^2 = \frac{\chi_4^{(B,S,Q)}}{\chi_2^{(B,S,Q)}}$$

To measure μ_B:

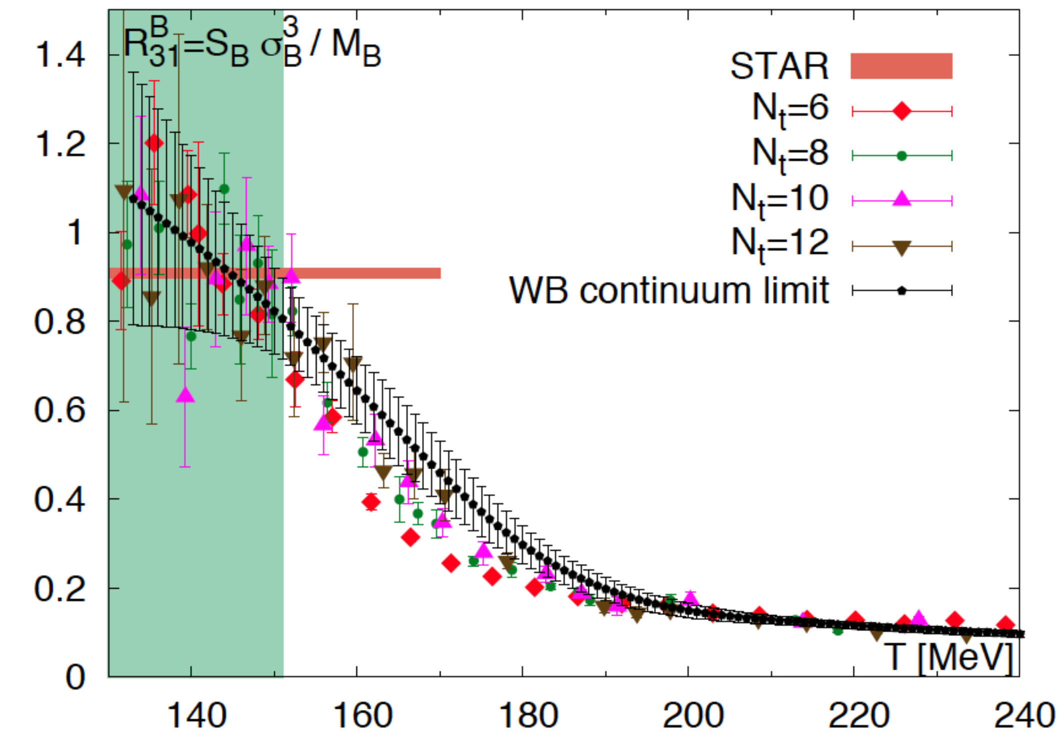
$$R_{12} = \frac{M}{\sigma^2} = \frac{\chi_1^{(B,S,Q)}}{\chi_2^{(B,S,Q)}}$$

To measure T:

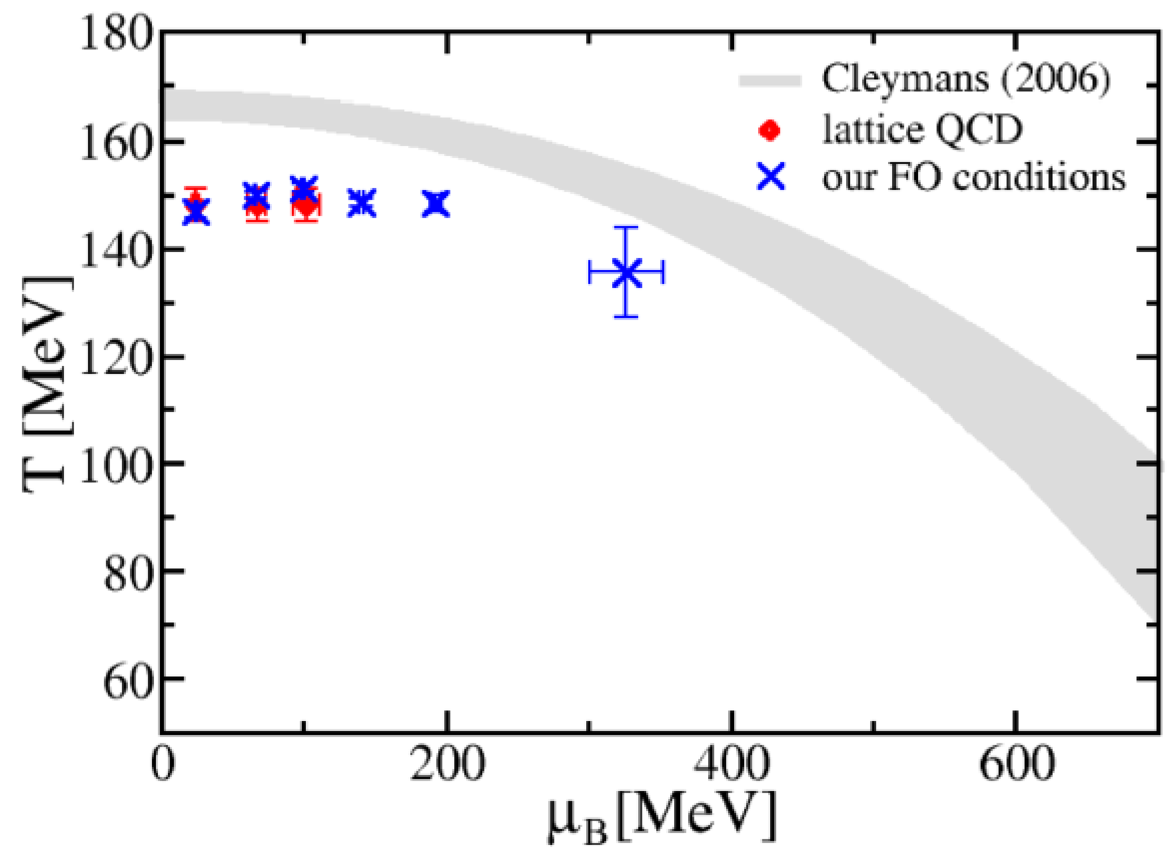
$$R_{31} = \frac{S\sigma^3}{M} = \frac{\chi_3^{(B,S,Q)}}{\chi_1^{(B,S,Q)}}$$

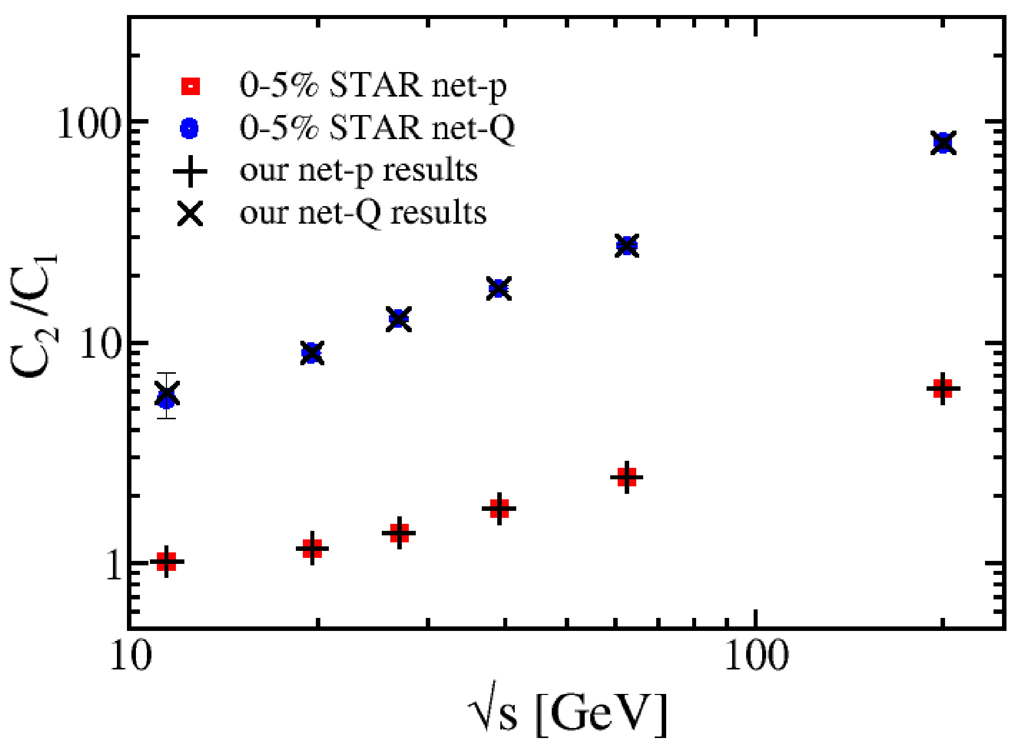
HRG and lattice QCD point at lower T_{ch}

(lQCD result based on simultaneous net-charge and net-proton fit)



(WB collaboration, PRL (2014) arXiv:1403.4576)

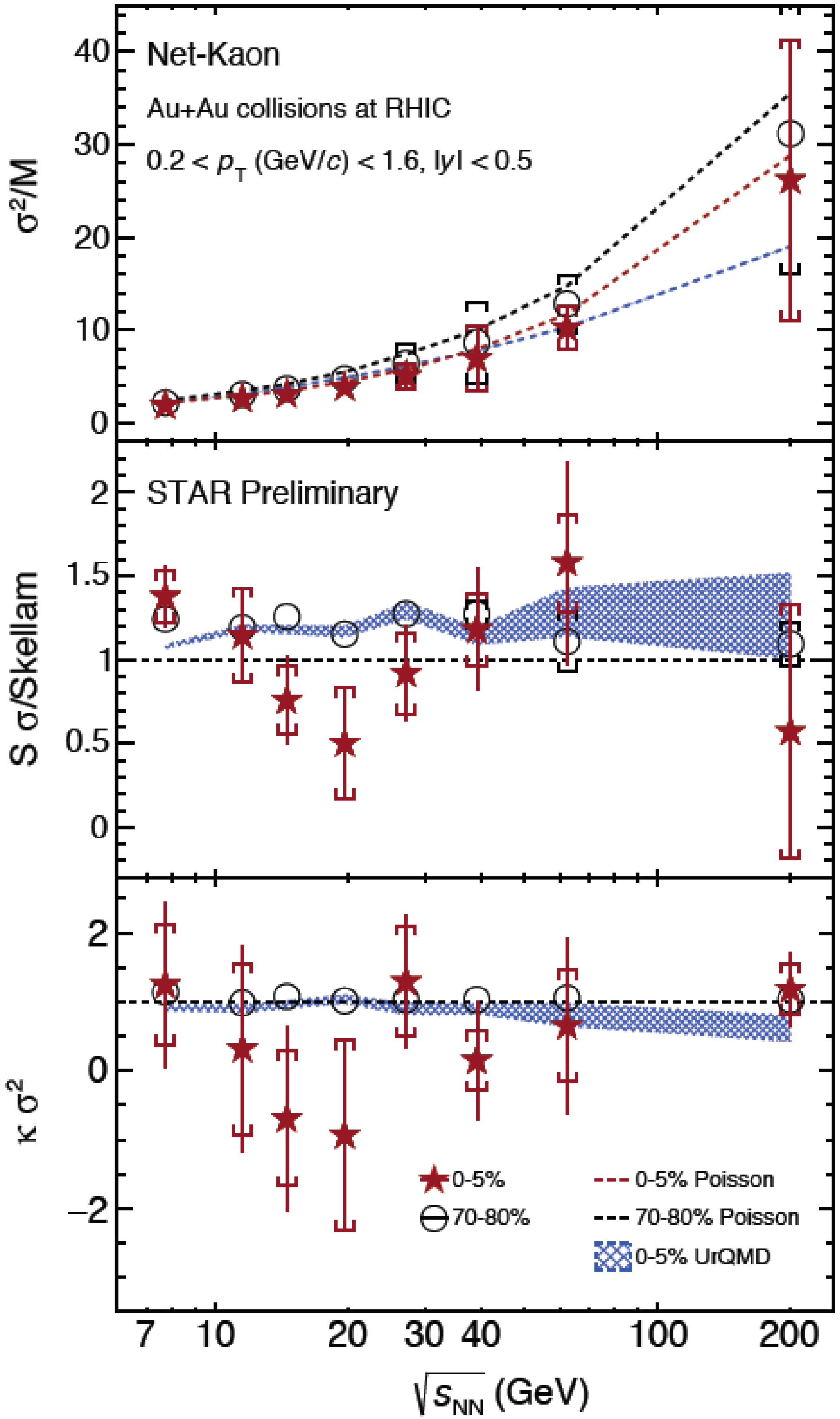


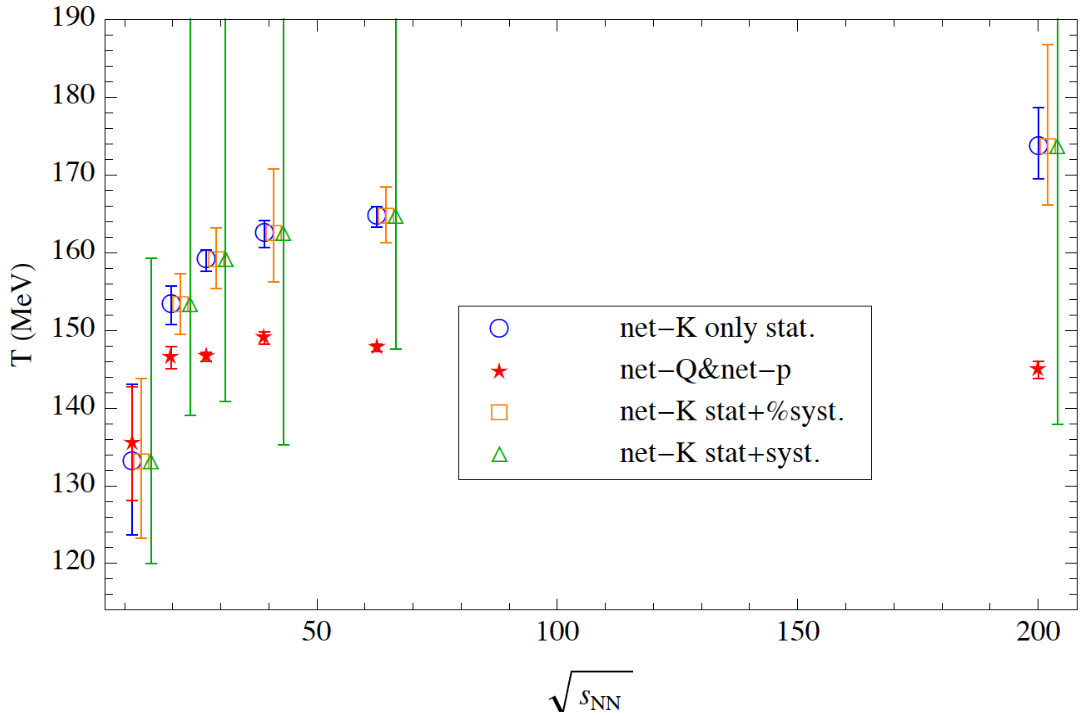


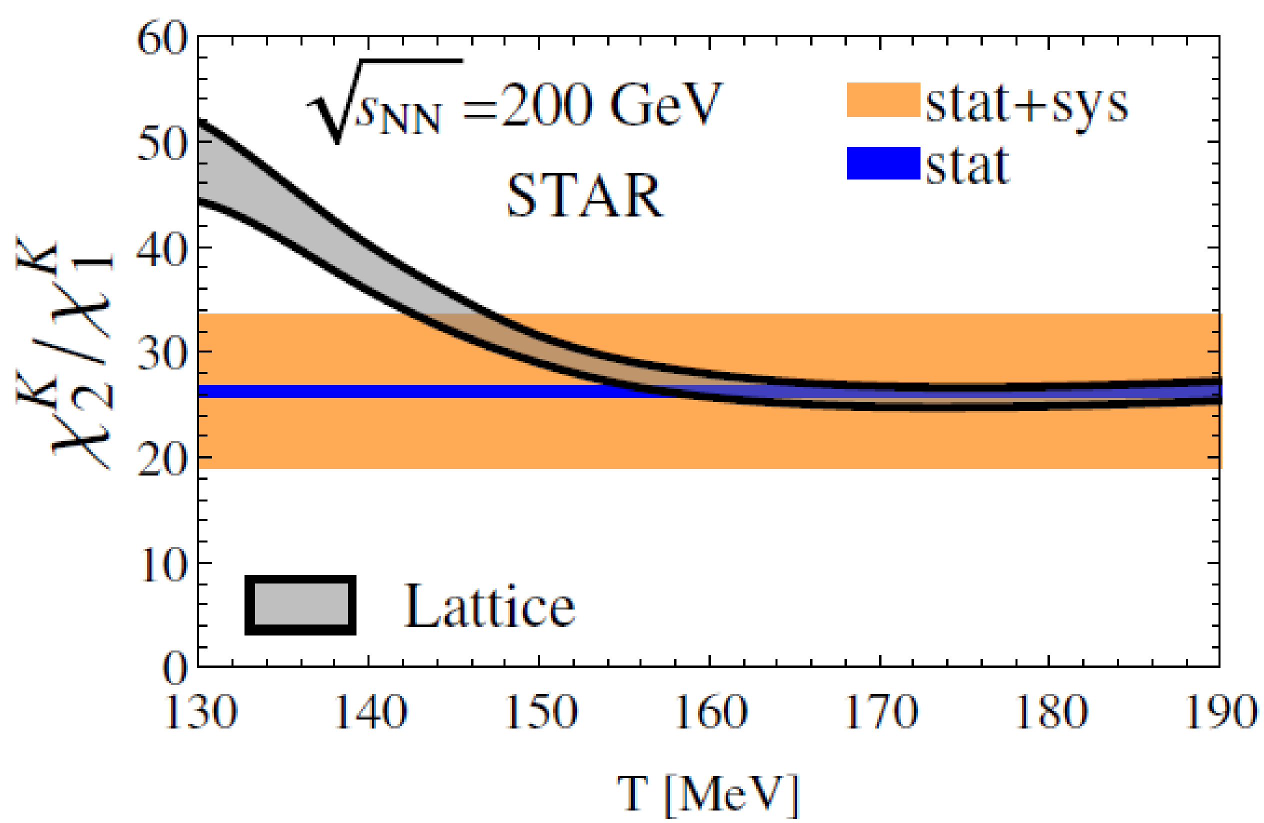
$\sqrt{s}$ [GeV]	$\mu_{B,ch}$ [MeV]	T_{ch} [MeV]
11.5	326.7±25.9	135.5±8.3
19.6	192.5±3.9	148.4±1.6
27	140.4±1.4	148.5±0.7
39	99.9±1.4	151.2±0.8
62.4	66.4±0.6	149.9±0.5
200	24.3±0.6	146.8±1.2

(Alba et al., PRL (2014) arXiv:1403.4903)

Fit σ^2/M for net-kaons in the same fashion than for net-proton and net-charge (Alba et al. in prep.)

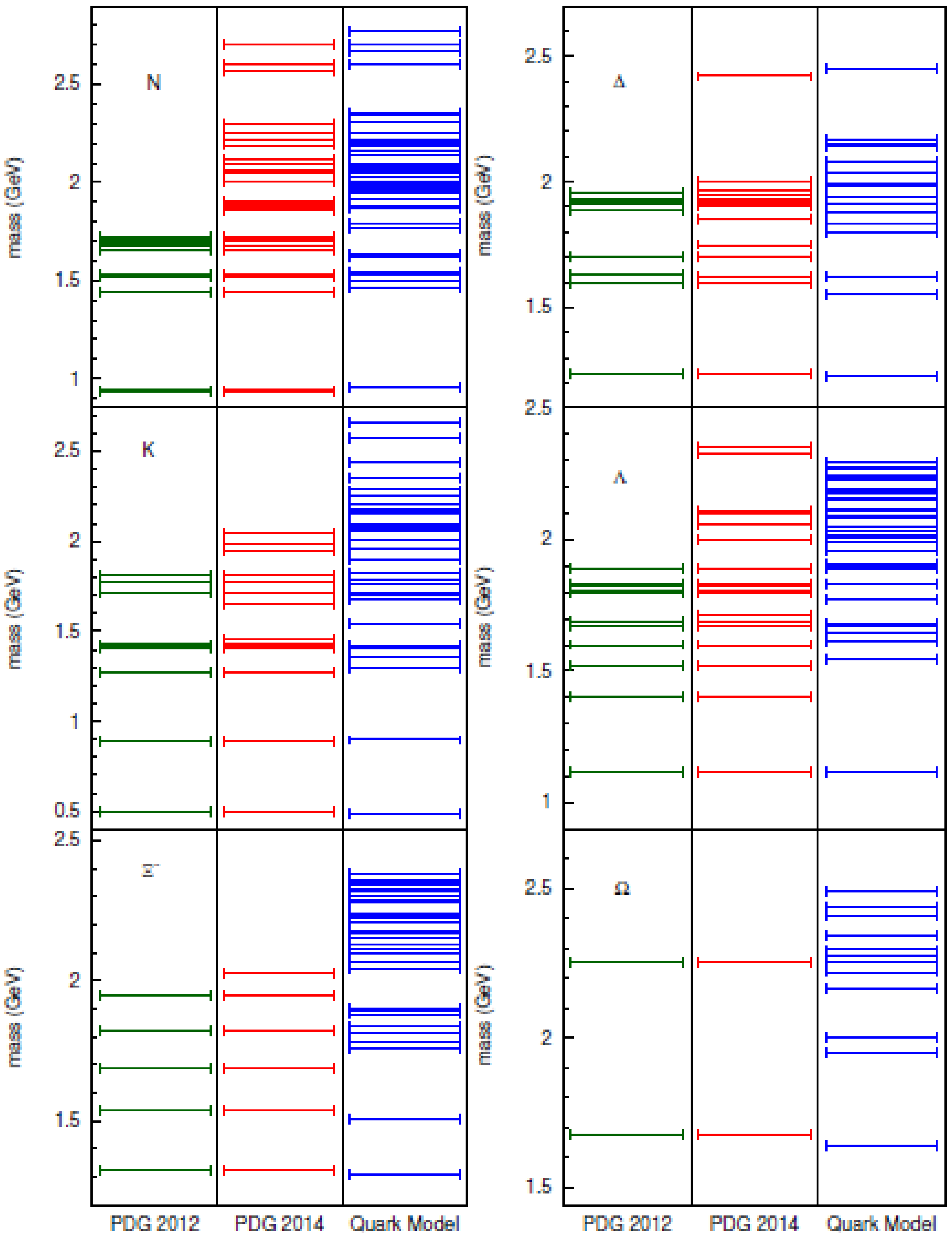






Hostler et al., arXiv:1607.02527

So what can happen between 148 and 164 MeV ?



A 20 MeV drop can be translated into a 2 fm/c time window

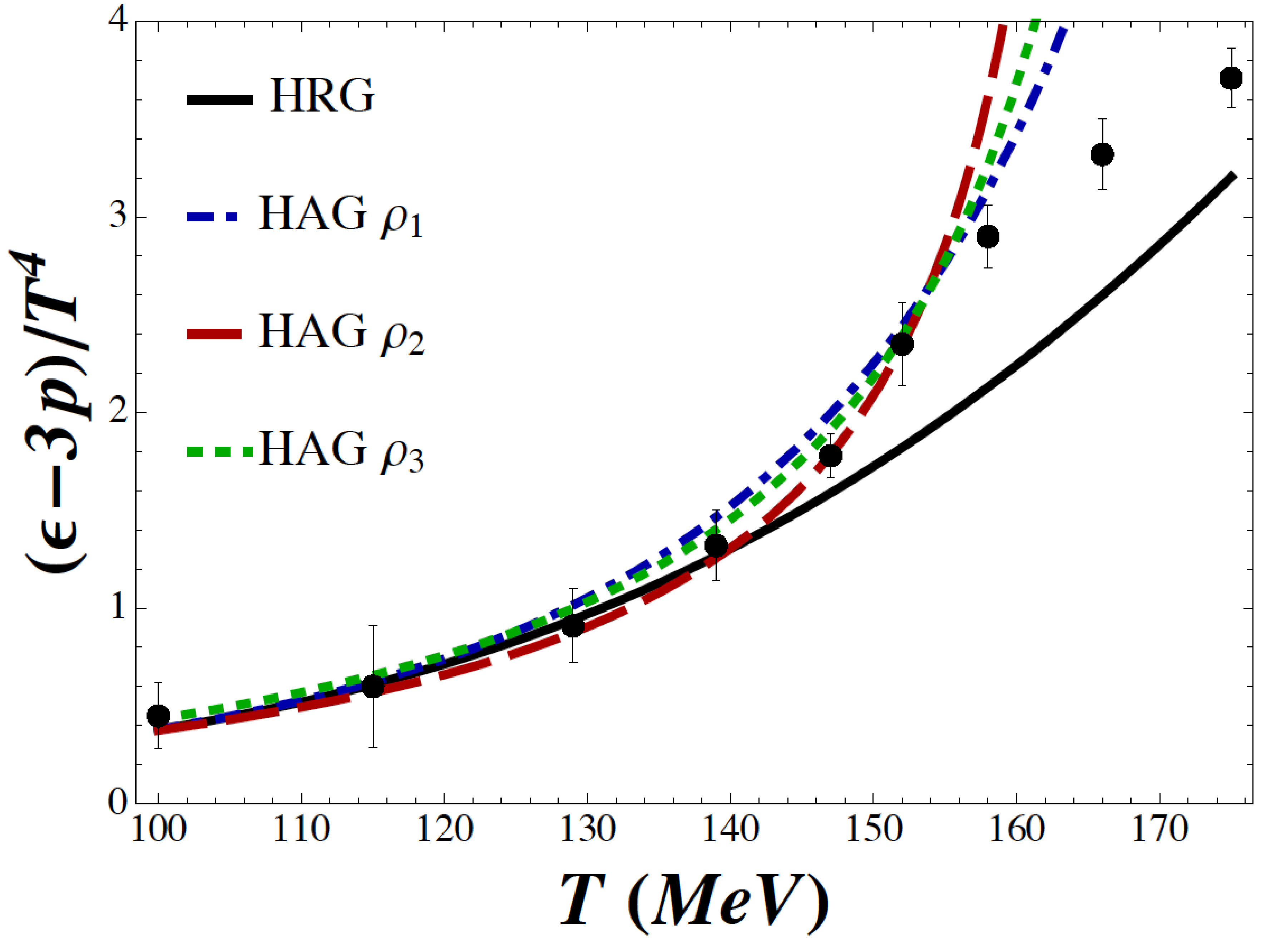
Strangeness wants to freeze-out, light quarks do not

Can there be measurable effects ?

Simple strangeness enhancement of the strange ground states or additional strange hadronic resonances or exotic quark configurations with strangeness ?

Evidence for exotic states: Comparison of trace anomaly from lattice to HRG spectrum expanded with Hagedorn States

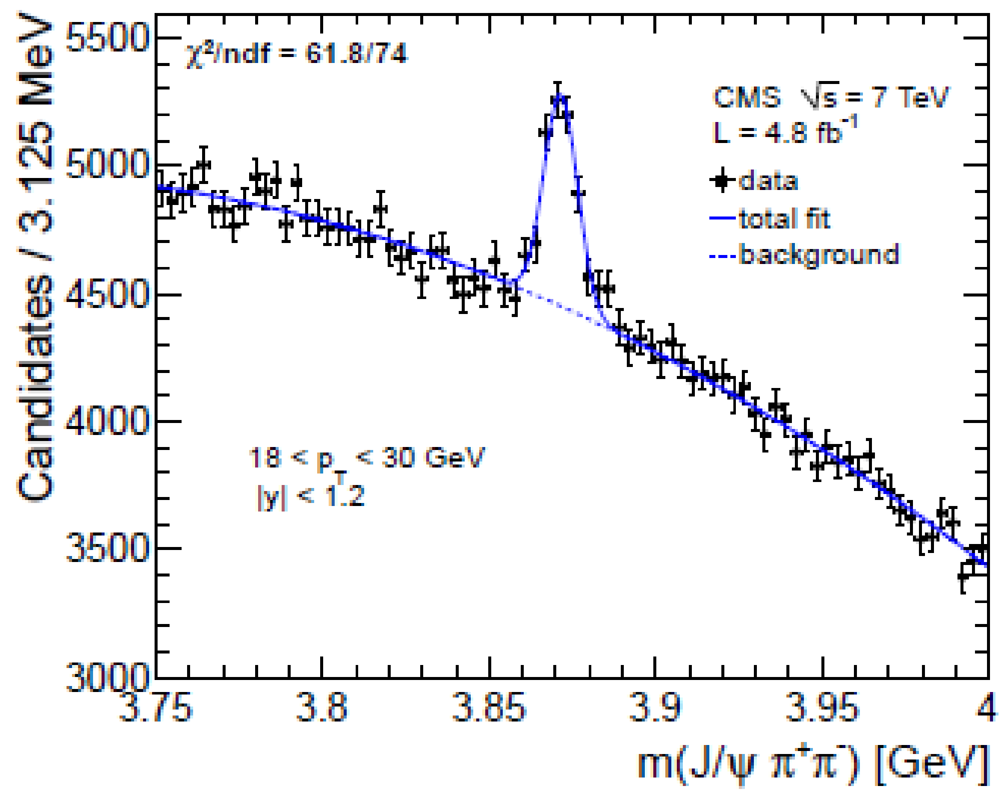
(J. Noronha-Hostler et al., PRC (2014), arXiv:1302.7038)



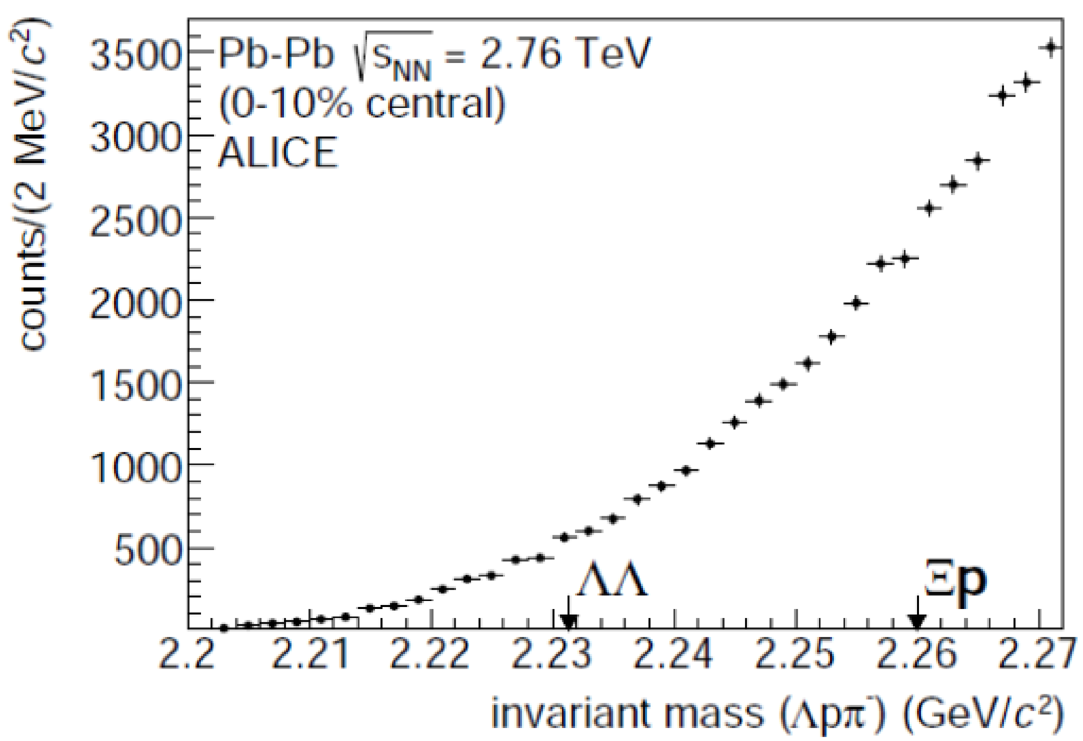
Inclusion of Hagedorn states seems to improve agreement with lattice near the transition temperature of 151+-4 MeV

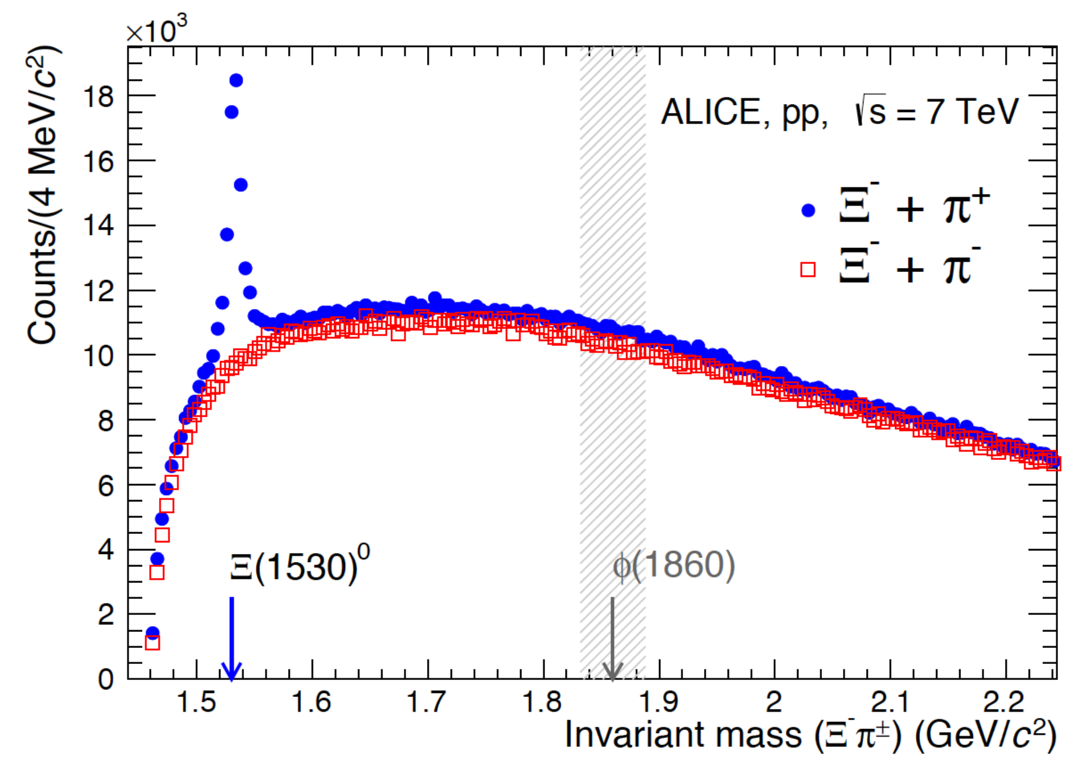
Exotic states within the Standard Model

Exotic states measured at LHC (in the charm sector)



But little evidence for strange pentaquarks or dibaryons in ALICE data



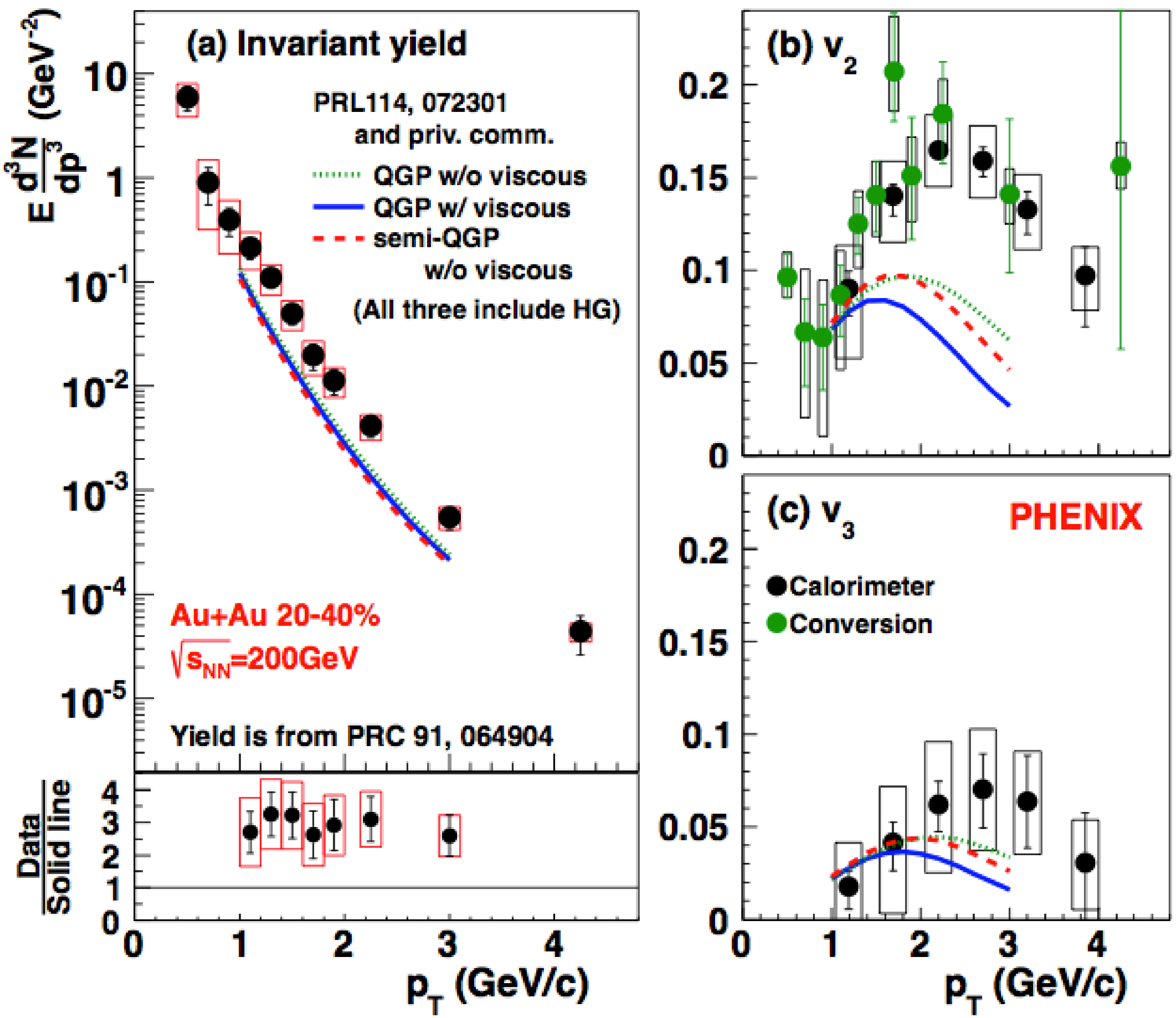


Conclusions / Outlook

- Amazing new data from RHIC and LHC for 9 different system at 11 different energies
- Mass broadening of the r-meson has been measured now at SPS and RHIC. The effect is lost at LHC (too much charm in the cocktail ?). No effects are measured in any other resonances. A link to chiral symmetry restoration will still require a chiral partner measurement.
- RHIC-BES has added an enormous wealth of data which clearly indicate that around the SPS energies the system transitions from a hadron dominated to a parton dominated system. The critical point is still elusive, but also still possible.
- Strangeness enhancement has become an exact science with interesting new features in the small system region.
- Small systems flow like large systems and they show partonic features in certain dynamic variables, but they don't generate comparable partonic energy loss. In the large system partonic energy loss seems path-length independent (not shown here), and flavor independent at high pT. The mid-pT region reveals interesting flavor and quark configuration dependencies. Recombination and NCQ scaling are well and alive.
- The higher the collision energy, the larger the radial flow, the longer the partonic and hadronic lifetimes of the system.
- Flavor hierarchy in hadronization will lead to a better understanding of the hadronization process, but it hopefully also leads to some more exotic states in the strangeness sector.

Backup

Photons flow at RHIC



arXiv:1509.07758

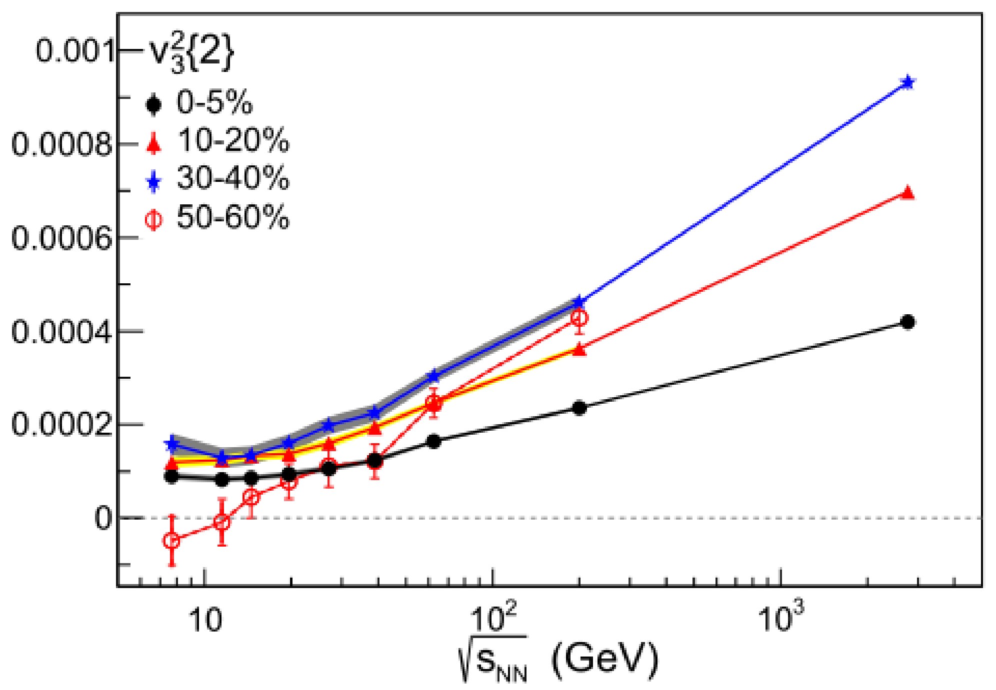
A sizable v2 and v3 is observed for direct photons.

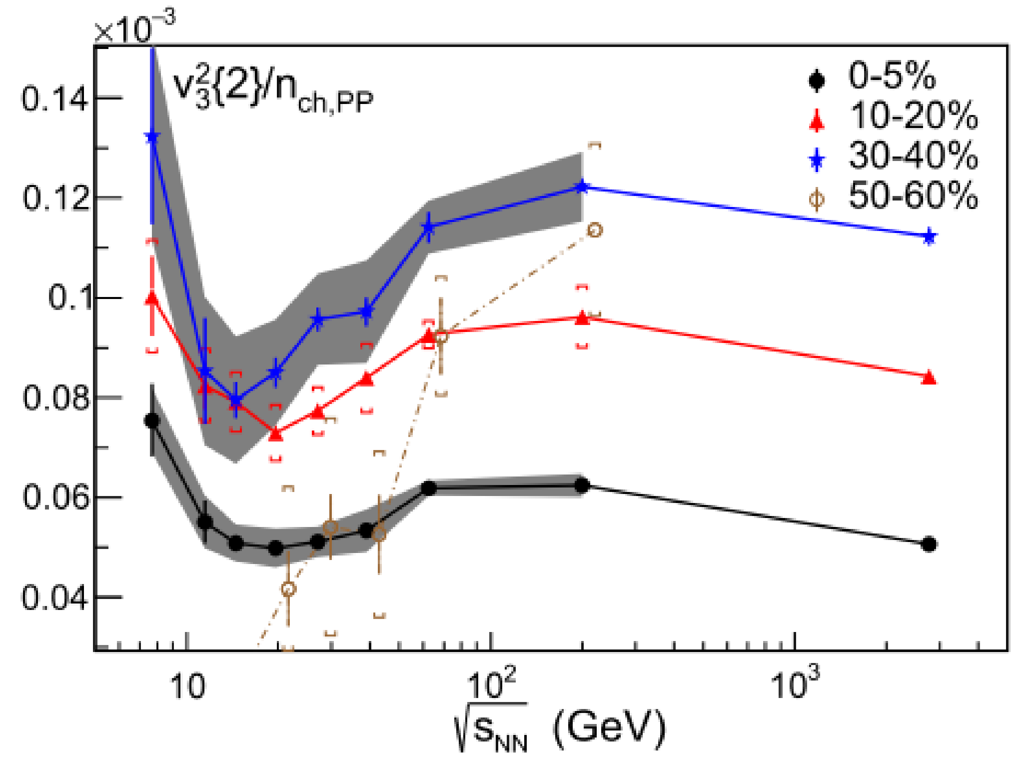
Theoretical picture still incomplete to describe large yield and v2 simultaneously.

RHIC: onset of QGP signatures

Triangular flow v_3 –is a sensitive indicator for the presence of a low viscosity QGP phase

Phys. Rev. Lett. **116** (2016) 112302





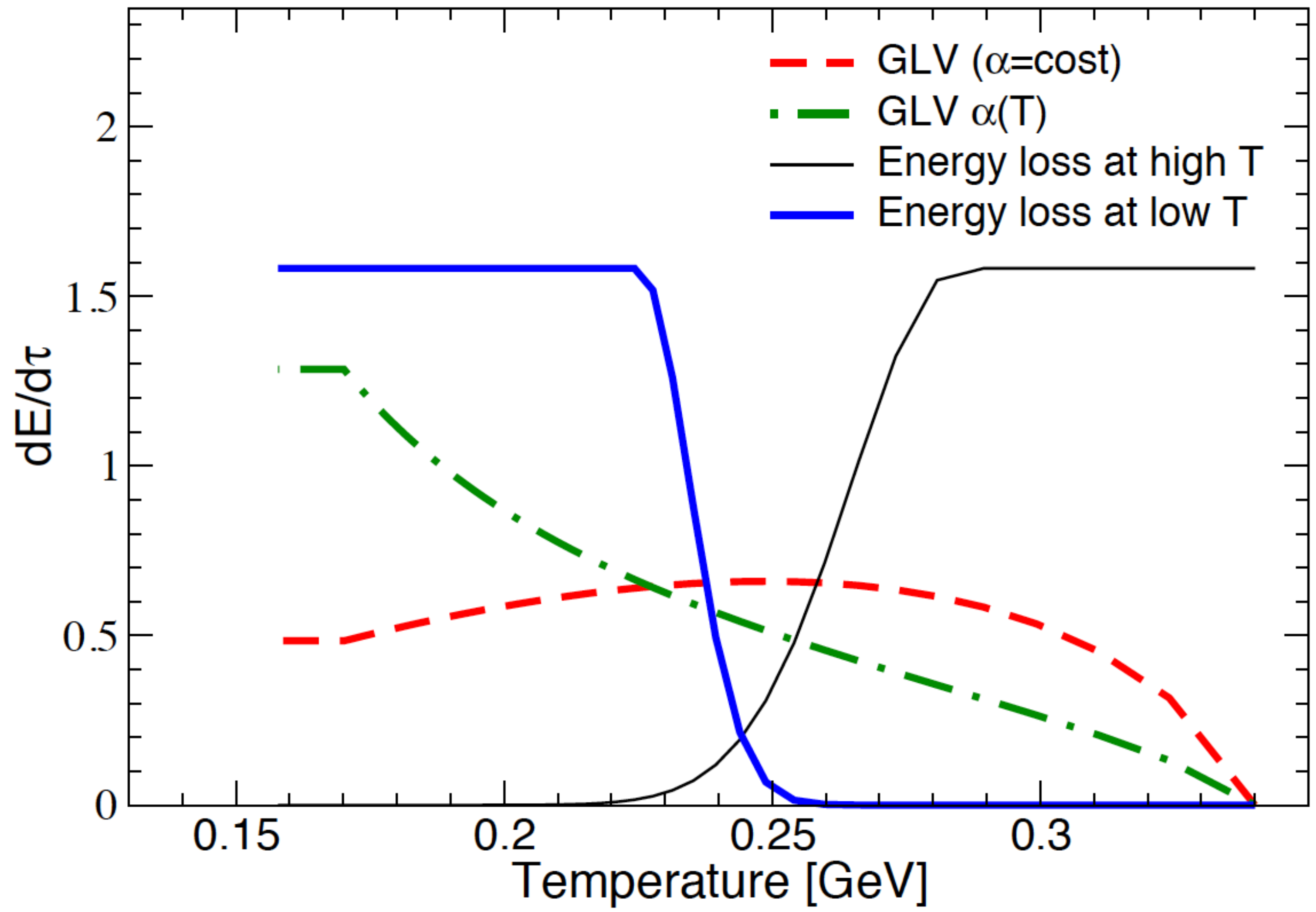
- Sizable v_3 at lower energies in central to mid-central centralities
- While the v_3 grows as ~log(√s) at higher energy, it is nearly independent of energy below 20 GeV.
- Peripheral collisions consistent with zero for $\sqrt{s_{NN}}$ less than 14.5 GeV

v_3 scaled by $n_{ch,PP} = dN_{ch}/d\eta/(N_{part}/2)$

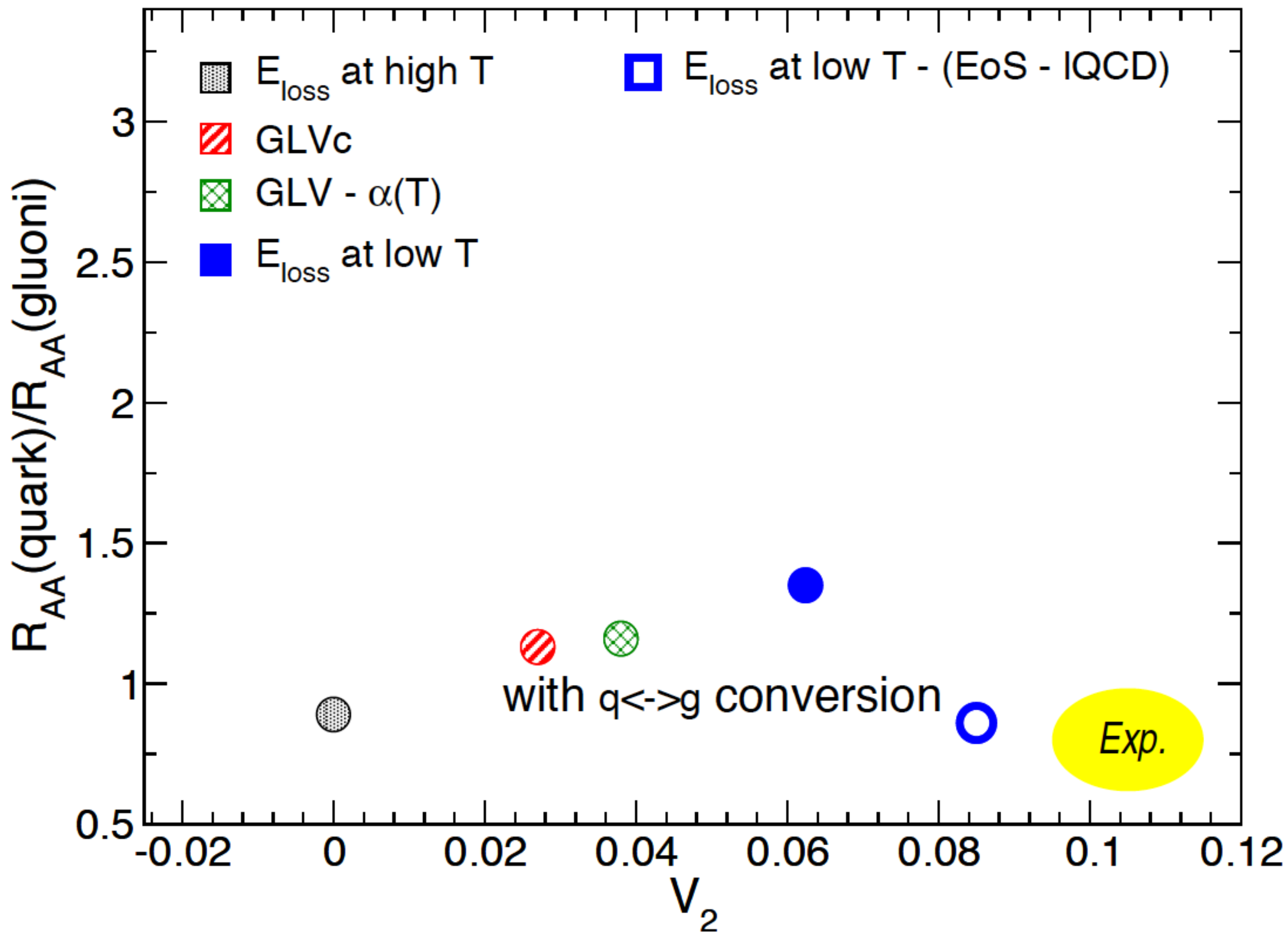
- Flat trend $\sqrt{s_{NN}}$ = 7.7 – 20 GeV
- Softening of EoS?

Can a flavor dependent freeze-out temperature T_{ch} cause such an effect ?

Yes, if R_{AA} is generated late (near T_{ch}) and v_2 is generated early (Greco et al., PRC82 (2010) 054901): combined fit to R_{AA} and v_2



All curves describe R_{AA} at RHIC 200 GeV…..



…but only the energy loss at low T comes close to describing R_{AA} and v_2