STRANGENESS AT INTERMEDIATE BARYON DENSITY

David Tlusty (Rice University)

Office of Science
U.S. DEPARTMENT OF ENERGY

RICE

OUTLINE

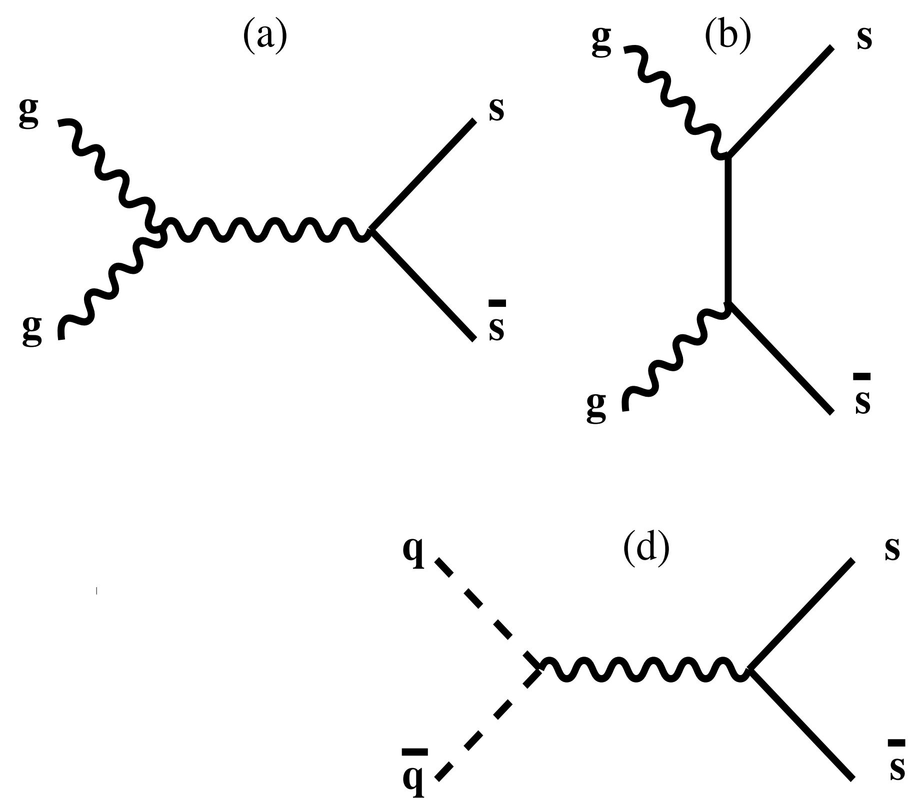
- main goals of beam energy scans
- importance of strangeness
- QCD phase diagram
- NA61 and STAR experiment
- selected experimental results
- future beam energy scans
- summary

EXPLORING THE QCD PHASE DIAGRAM

- main goals of beam energy scans [H. Petersen, QM2017]
  - what is the temperature and the density?
  - what are relevant degrees of freedom?
  - what type of phase transition and existence of critical point?
  - what are the transport properties?
  - chance to learn about QCD thermodynamics not (yet) accessible by lattice techniques
- turn off QGP signals
- chiral symmetry restoration

WHY IS STRANGENESS SO IMPORTANT?

- in QGP, strangeness can be easily produced as $s\bar{s}$ pairs in gg or $q\bar{q}$ fusion [Rafelski, Müller, PRL 48 1066 (1982)]
  - min Q≈200 MeV (while reaction n+n → n+Λ+K needs at least 670 MeV)
  - reactions fast enough to produce enough strange quarks to produce (Ξ, Ω) through coalescence

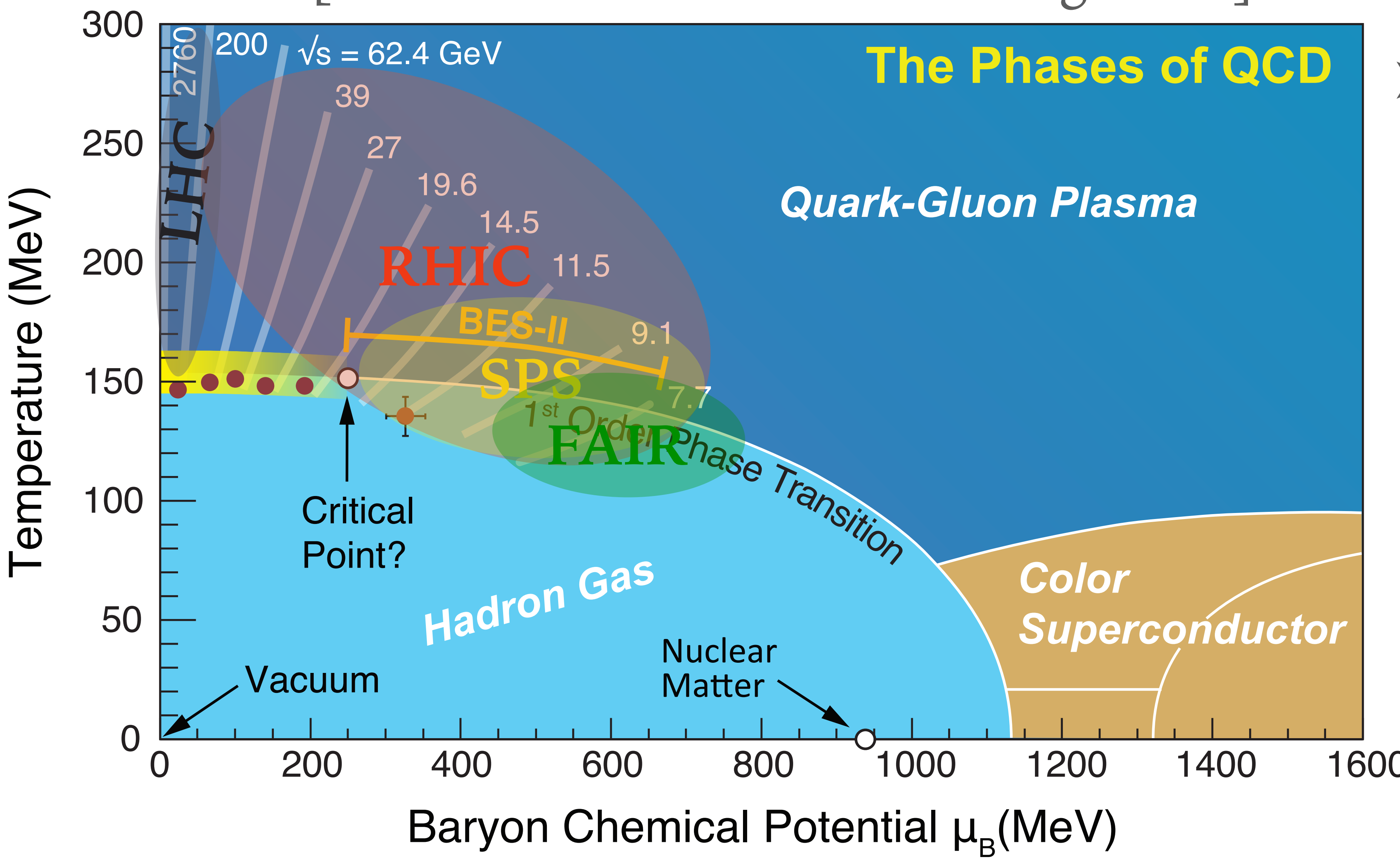


[Blume, Markert: PPNP 66, 834 (2011)]

- nearly 20% of all energy content of QGP is transferred to the production of strangeness when chemical equilibrium is reached [Rafelski, APP B 43 829 (2012)]

QCD PHASE DIAGRAM

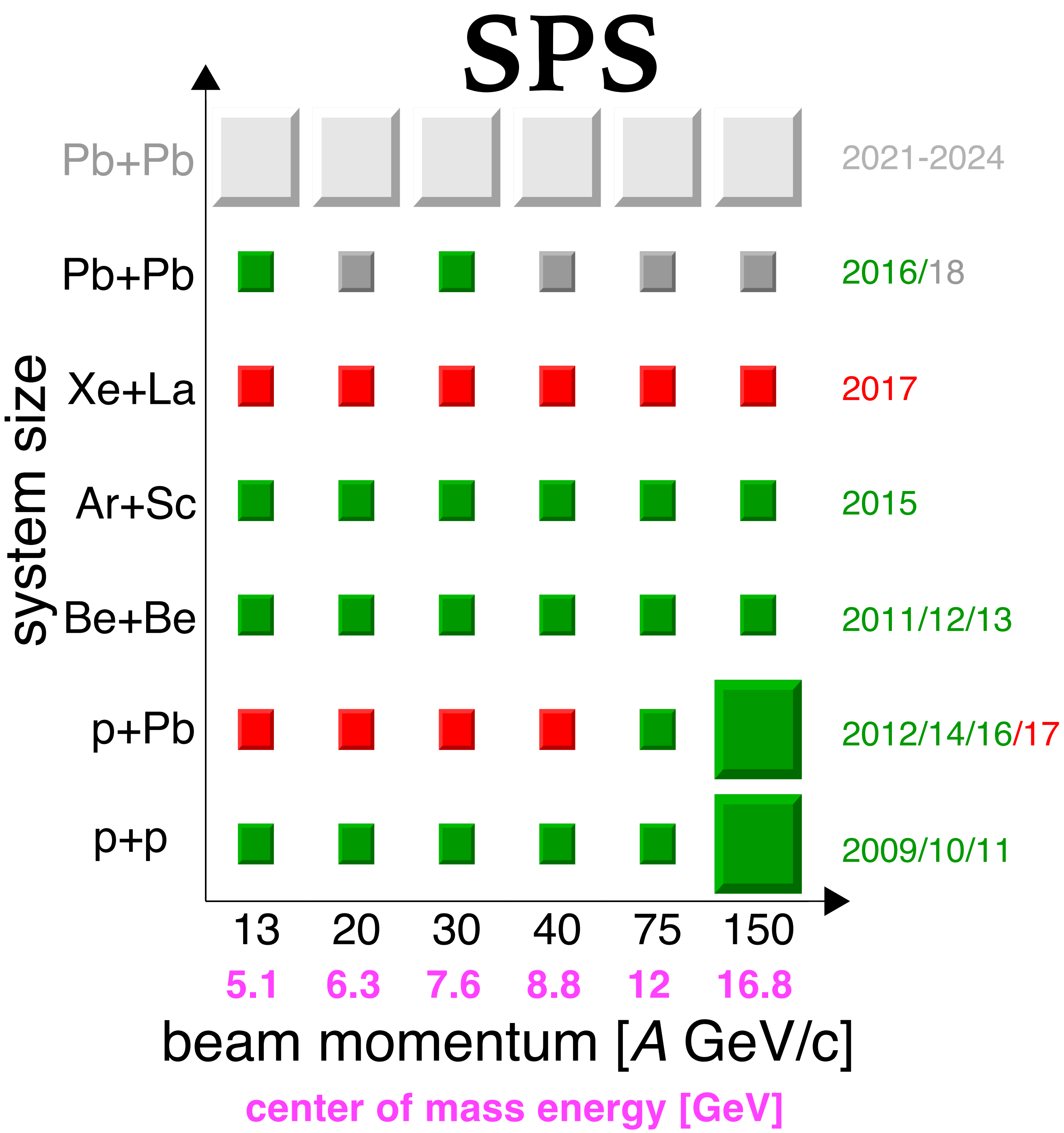
[B. Müller: BEST Col. Meeting 2016]



- accessible through experiments at LHC, RHIC, SPS, FAIR

- the region of intermediate baryon density covers the largest μ_B range including possible critical point

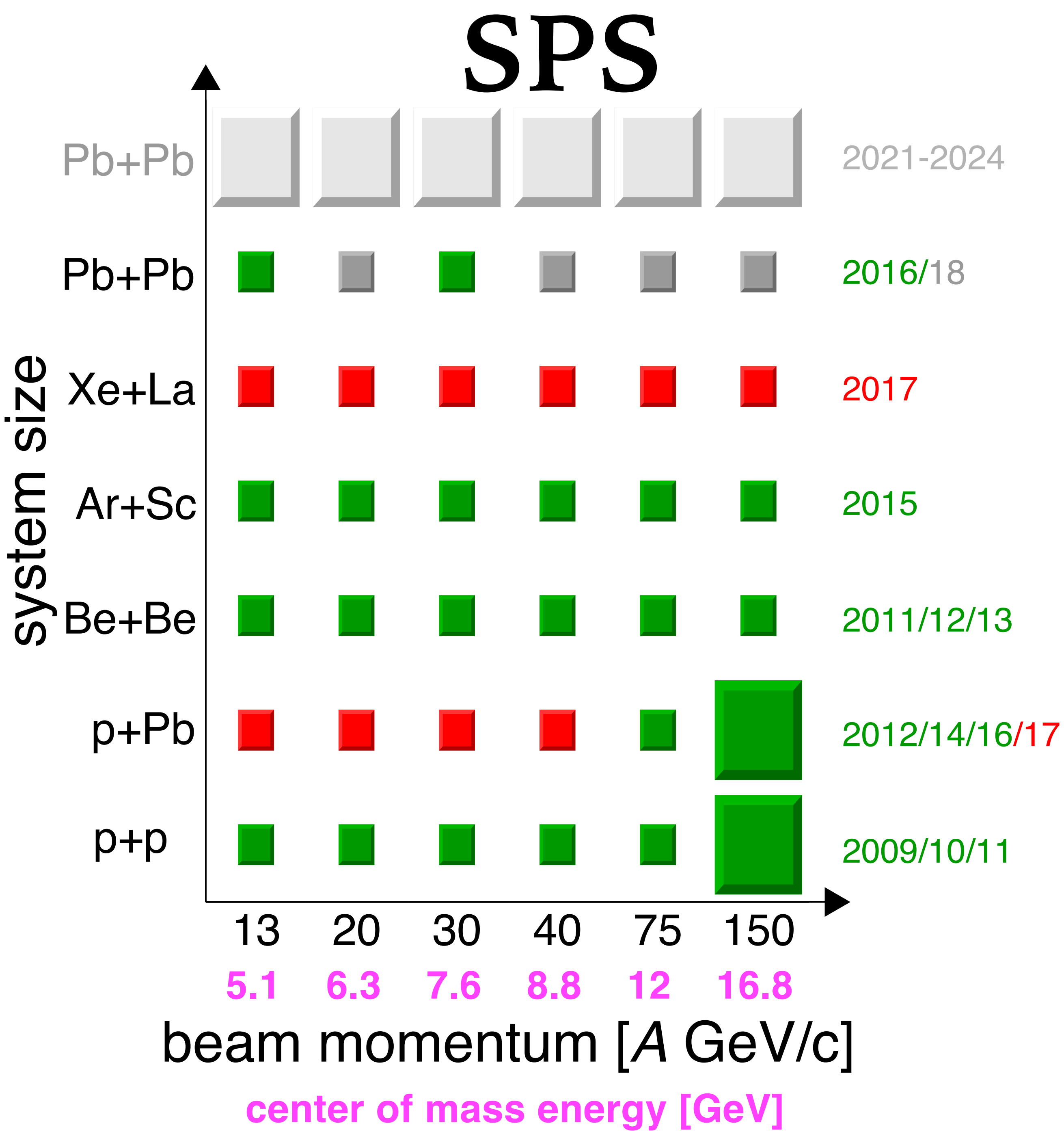
SPS AND RHIC BEAM ENERGY SCANS – EXPLORE INTERMEDIATE μ_B



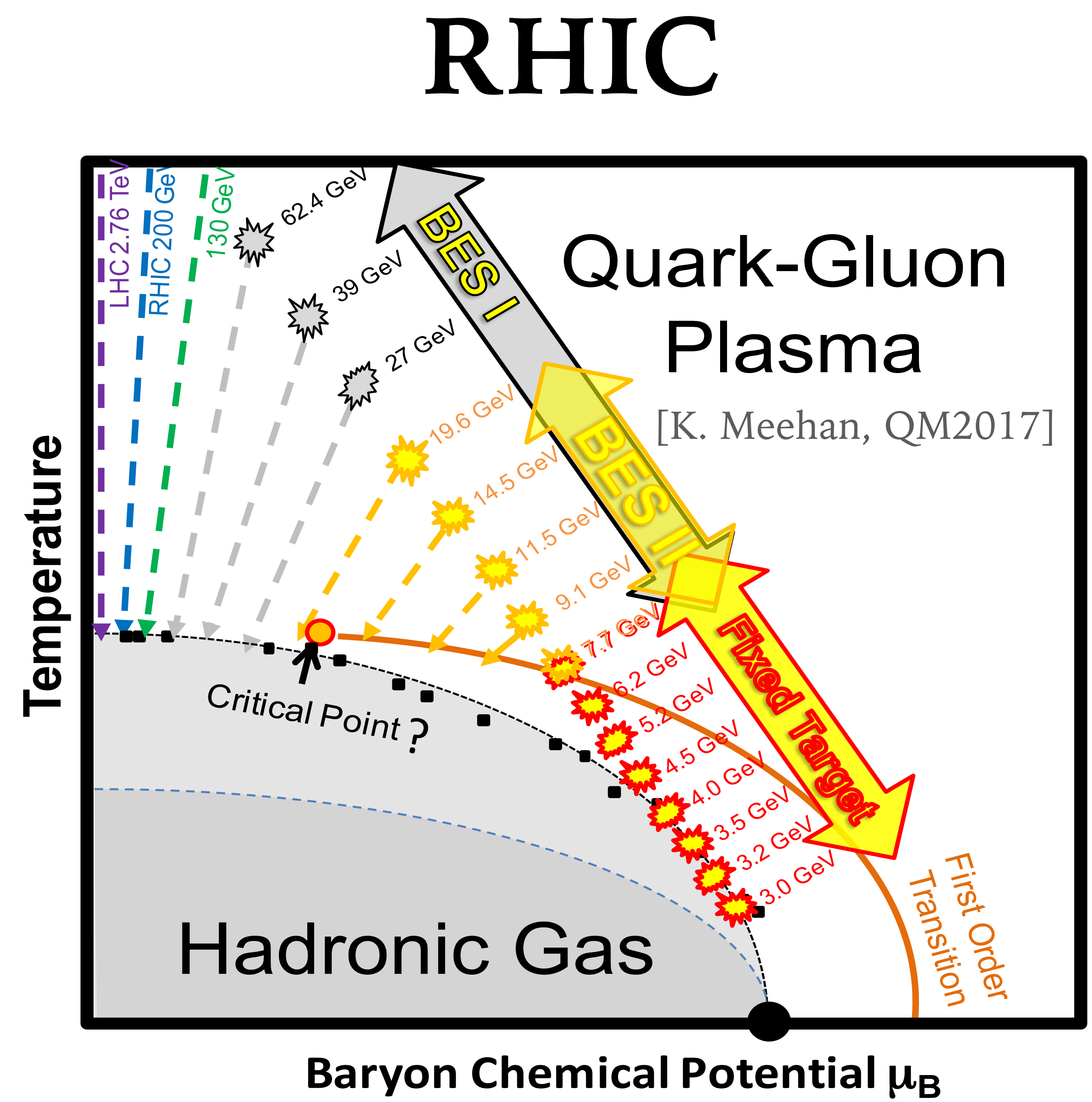
[A. Aduszkiewicz, QM2017]

Star Note 598

SPS AND RHIC BEAM ENERGY SCANS – EXPLORE INTERMEDIATE μ_B



[A. Aduszkiewicz, QM2017]

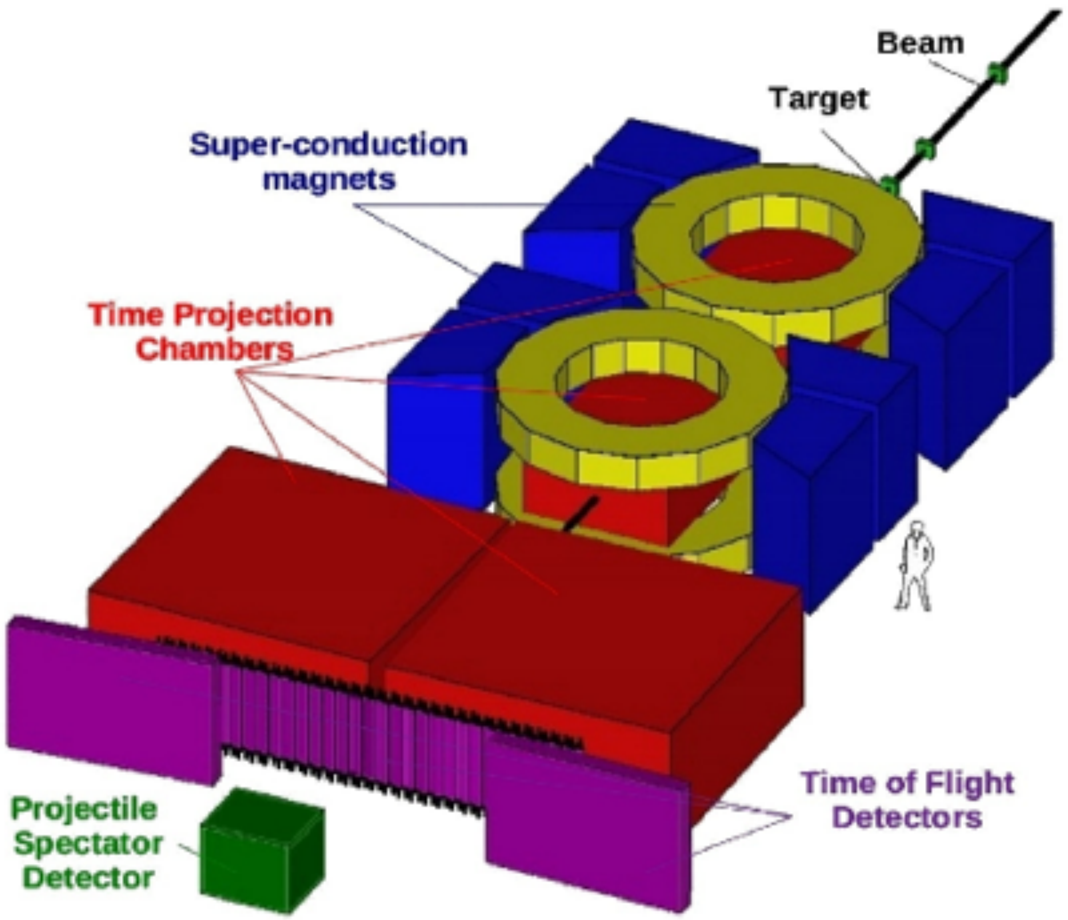


$\sqrt{s_{NN}}$ [GeV]	7.7	11.5	14.5	19.6	27.0	39.0
$\sim\mu_B$ (central) [MeV]	420	315	260	205	155	115

Star Note 598

NA61 AND STAR EXPERIMENTS

SPS: NA61/SHINE



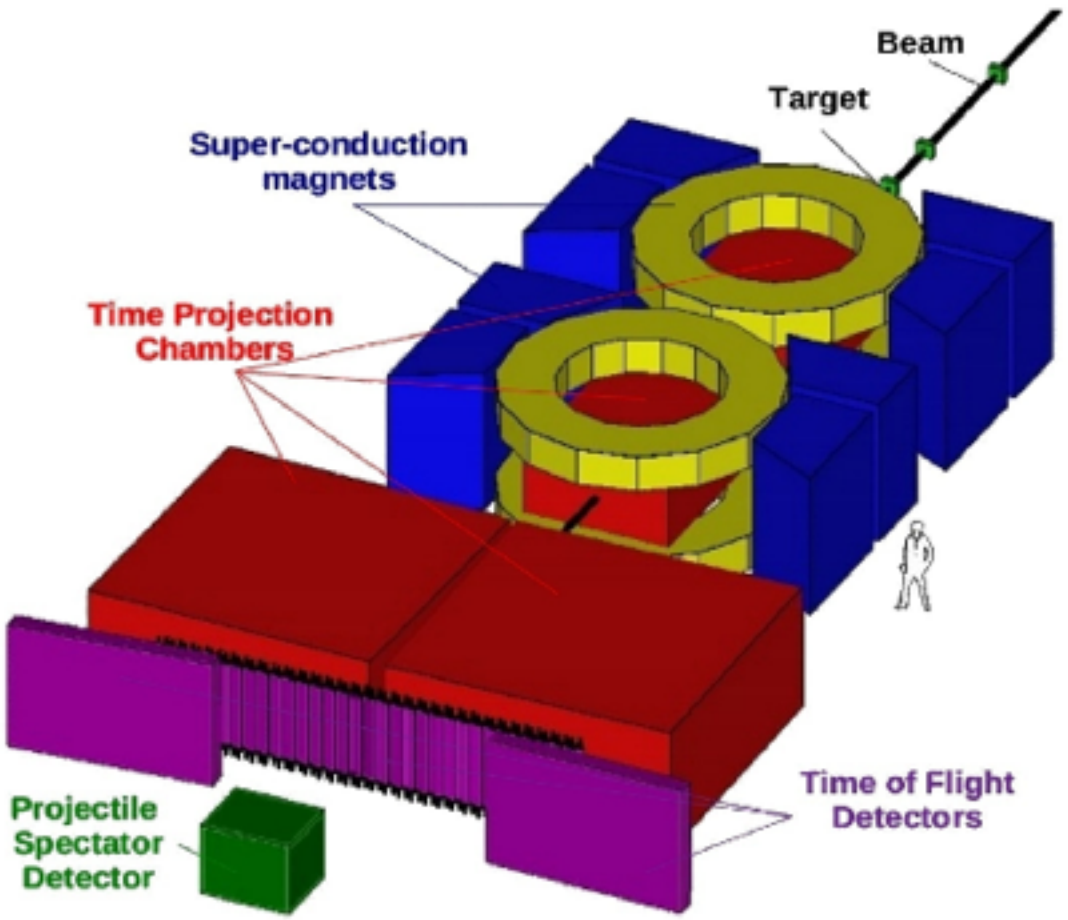
[M. Unger, EPJWC 52, 01009 (2013)]

fixed target

coverage of the full forward hemisphere

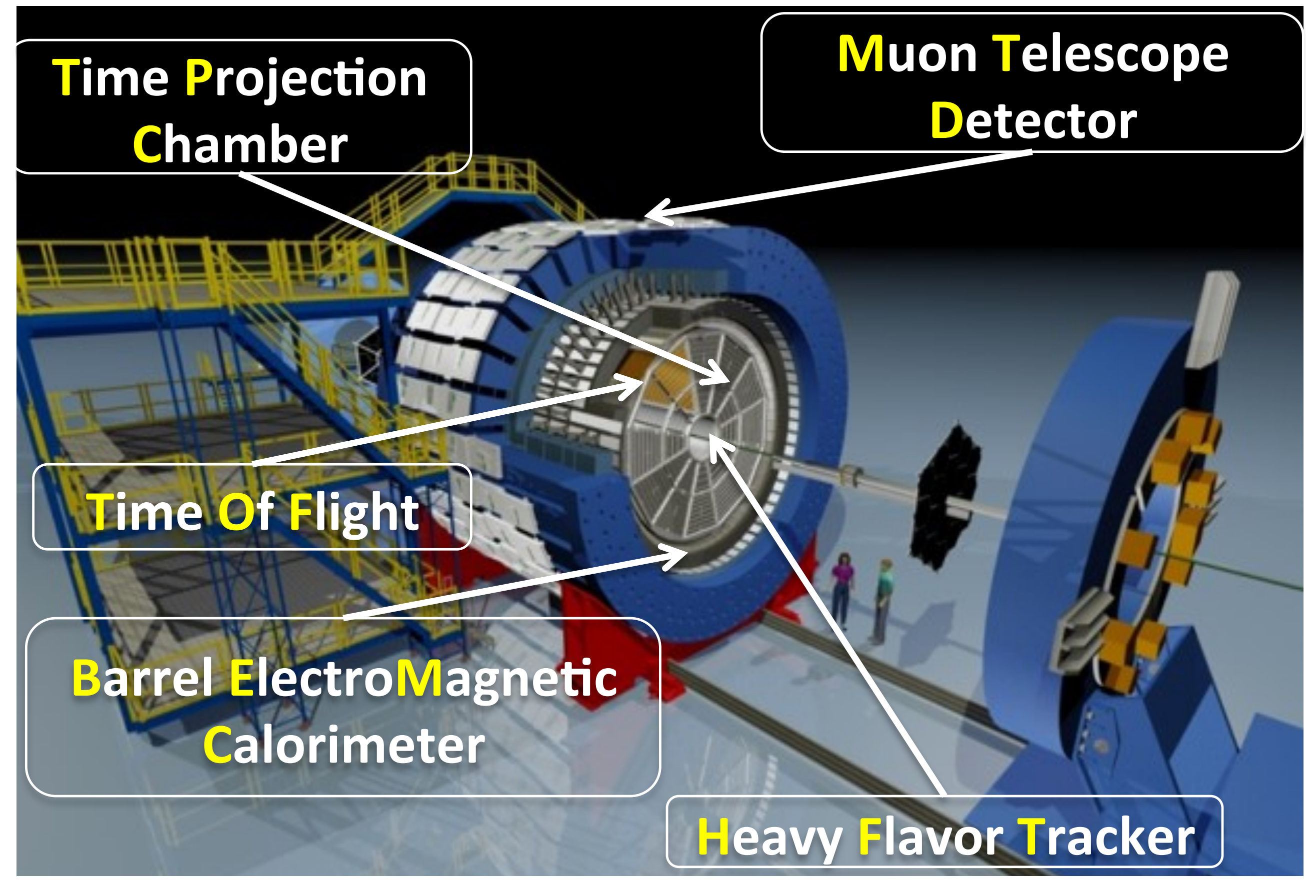
NA61 AND STAR EXPERIMENTS

SPS: NA61/SHINE



[M. Unger, EPJWC 52, 01009 (2013)]

RHIC: STAR



[R. Ma, Moribond QCD 2017]

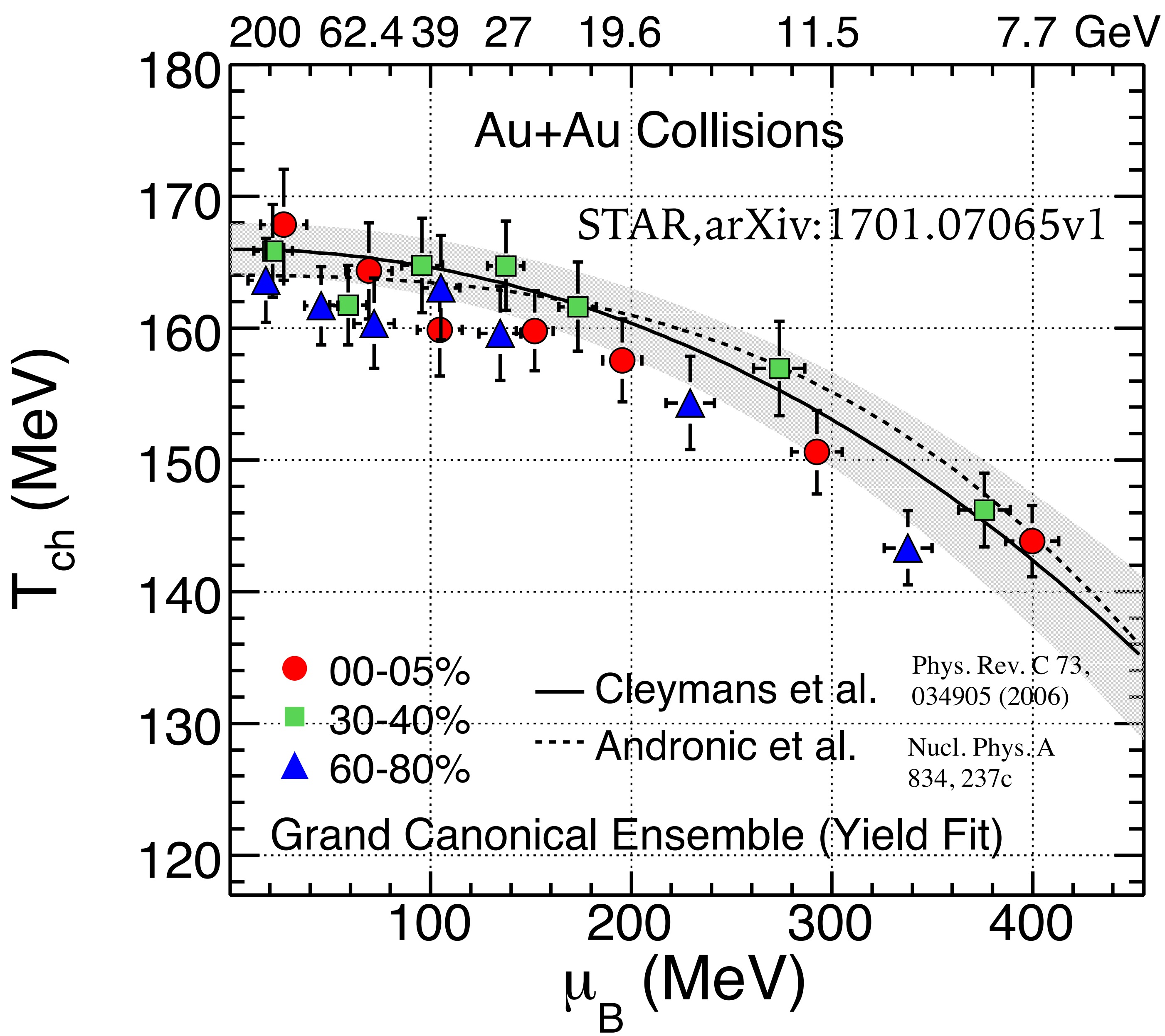
fixed target

coverage of the full forward hemisphere

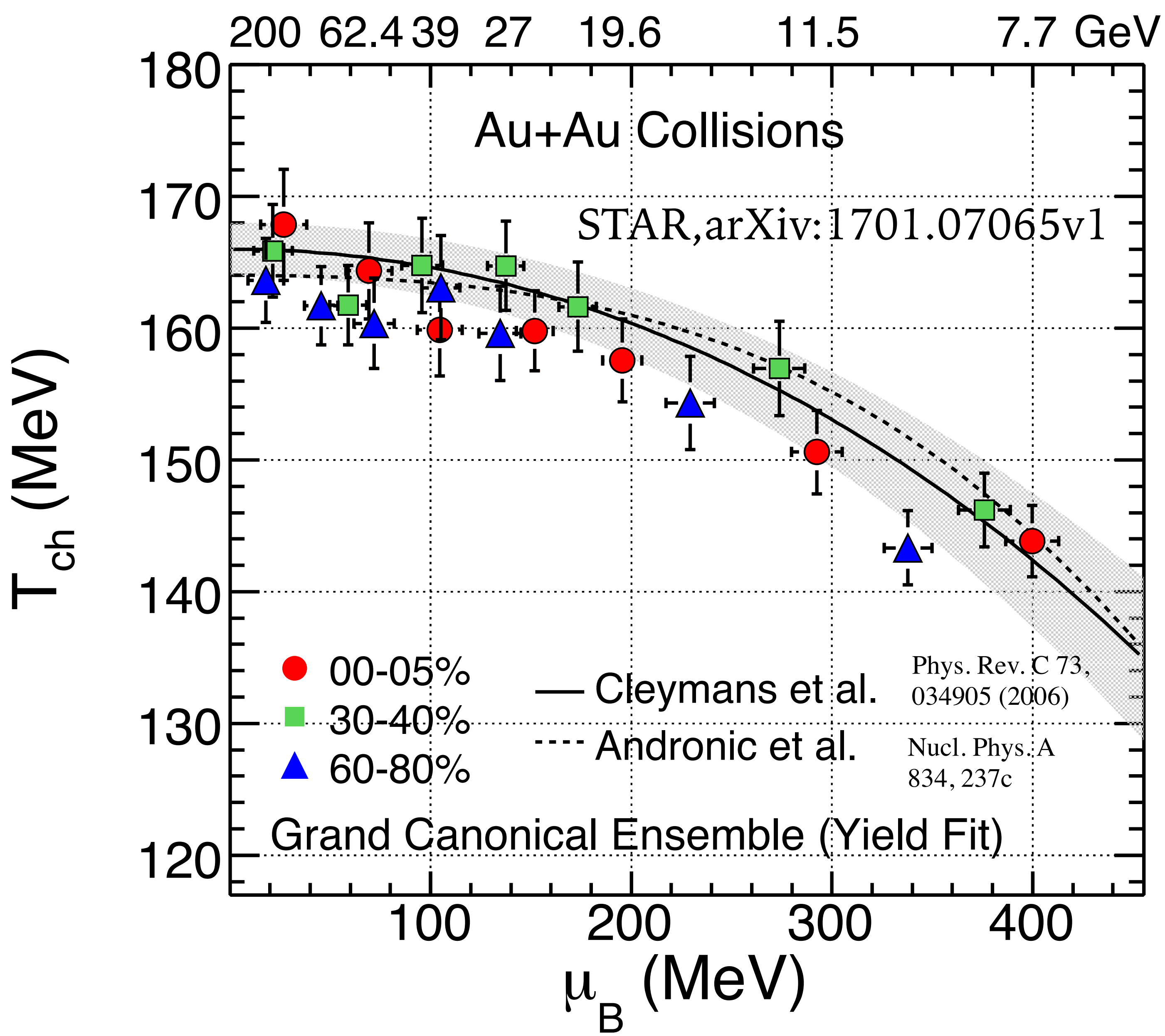
collider experiment with fixed target option

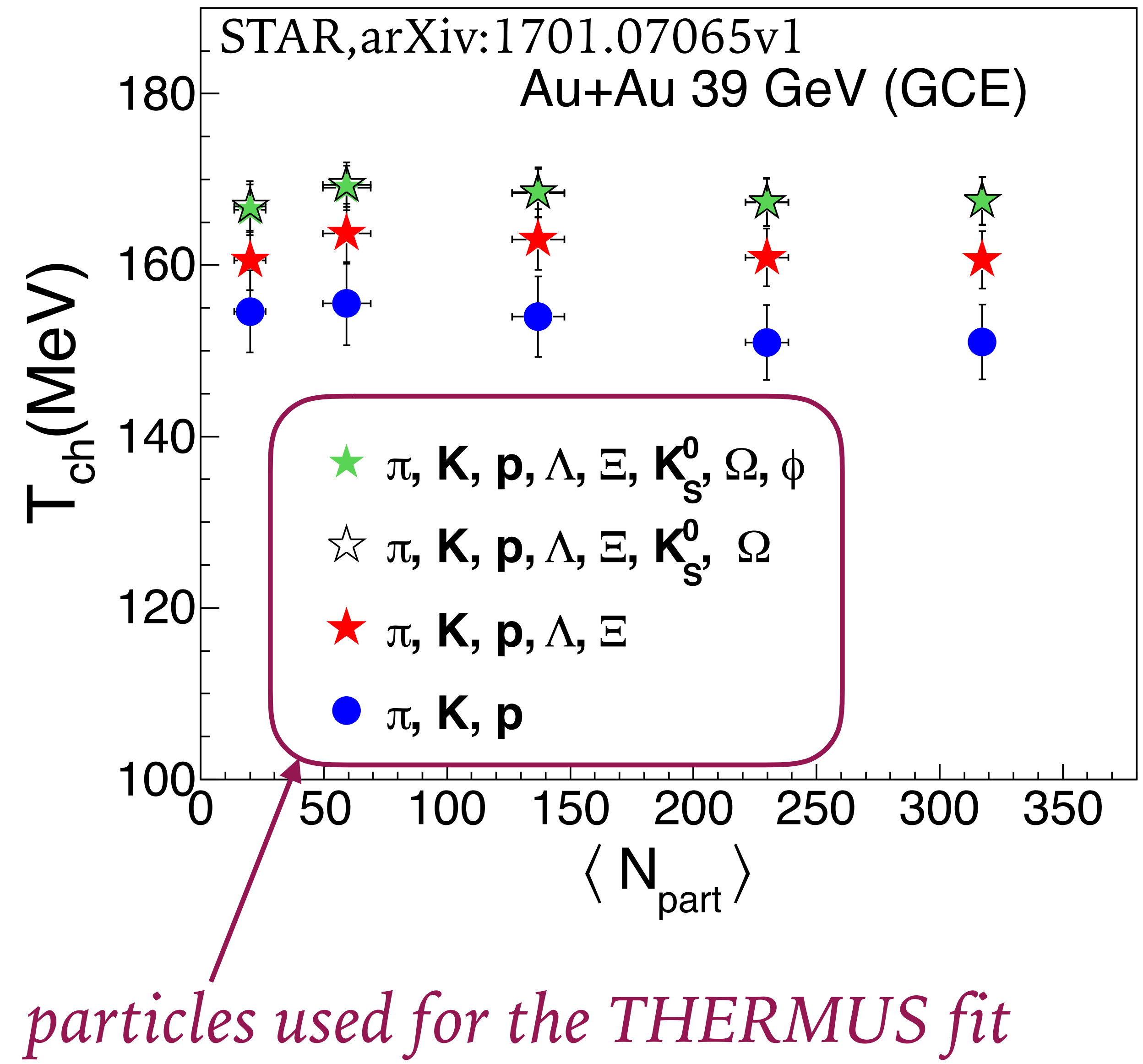
full azimuthal coverage

TEMPERATURE OF CHEMICAL FREEZE-OUT AND BARYON DENSITY



TEMPERATURE OF CHEMICAL FREEZE-OUT AND BARYON DENSITY





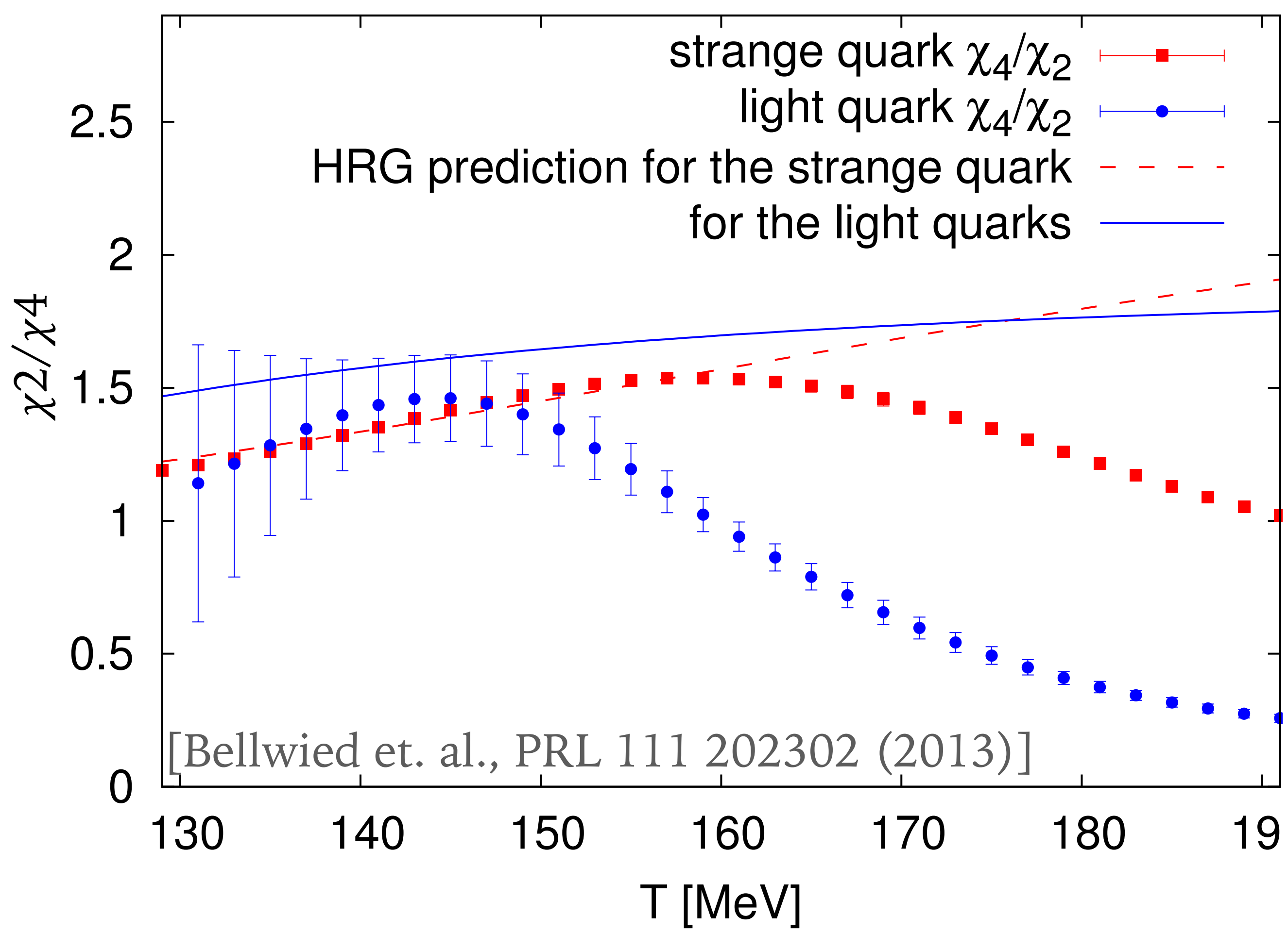
➤ particles included in the THERMUS model fit were π, K, p, $\bar{p}$, Λ, and Ξ

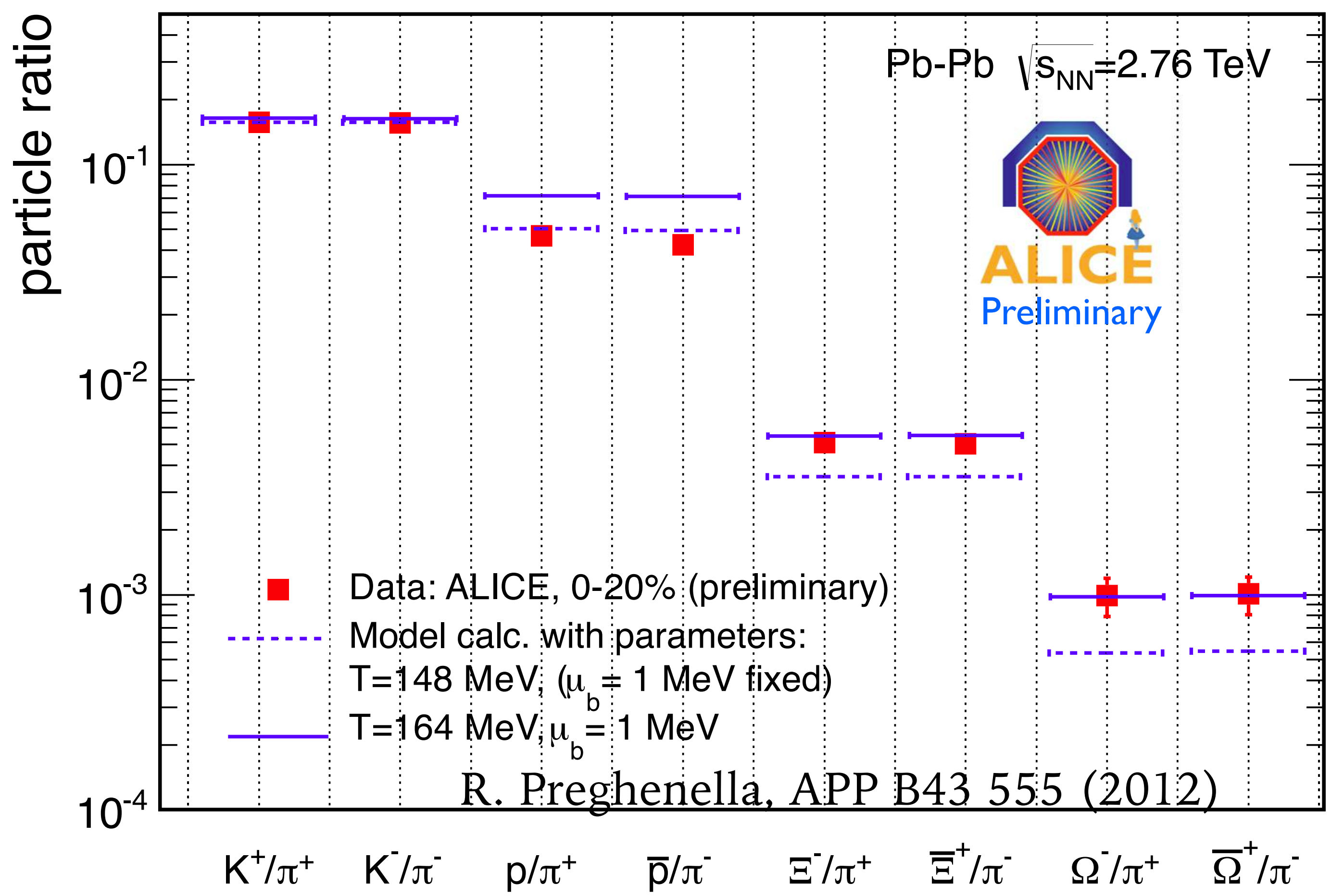
[Wheaton et al., CPC180, 84 (2009)]

➤ T_{ch} appears to be lower when strange particles were excluded from the fit

DO STRANGE QUARKS REALLY FREEZE-OUT AT HIGHER T?

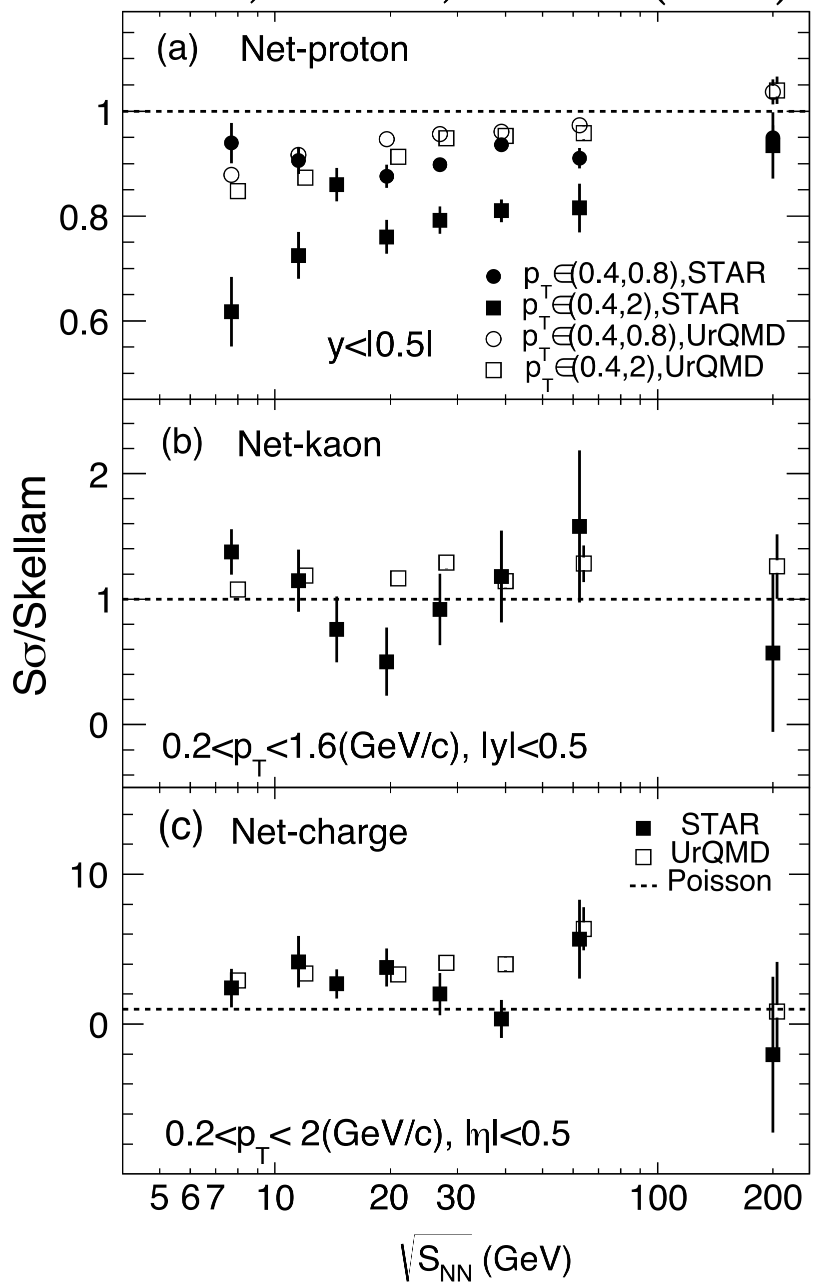
- Lattice QCD calculation predicts T_{ch}~160 MeV for strange quarks and T_{ch}~145 MeV for light quarks at $\mu_B = 0$ [Bellwied et al., PRL 111 202302 (2013)]

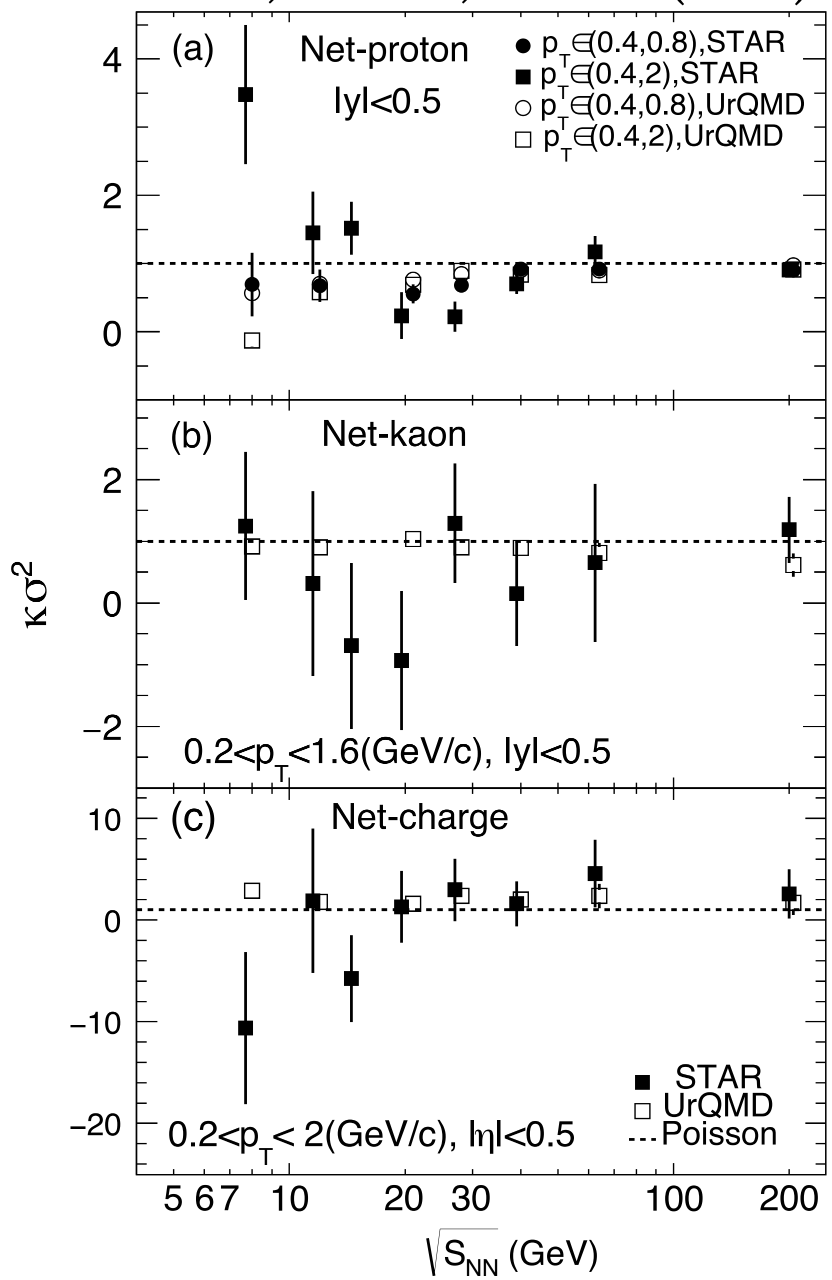




- thermal model fits to particle ratios from ALICE show T_{ch}(s-quark) = 164 MeV and T_{ch}(u,d - quark) = 148 MeV [Andronic et al., PLB673, 142 (2009)]
- could we do the same Lattice QCD calculation at μ_B ~ 100 MeV?

CUMULANT RATIOS OF NET-PROTON(KAON,CHARGE) MULTIPLICITY





$$\kappa\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}} \qquad S\sigma = \frac{\chi^{(3)}}{\chi^{(2)}}$$

$$S\sigma = \frac{\langle (N - \langle N \rangle)^3 \rangle}{\langle (N - \langle N \rangle)^2 \rangle}$$

$$\kappa\sigma^2 = \frac{\langle (N - \langle N \rangle)^4 \rangle - 3\langle (N - \langle N \rangle)^2 \rangle}{\langle (N - \langle N \rangle)^2 \rangle}$$

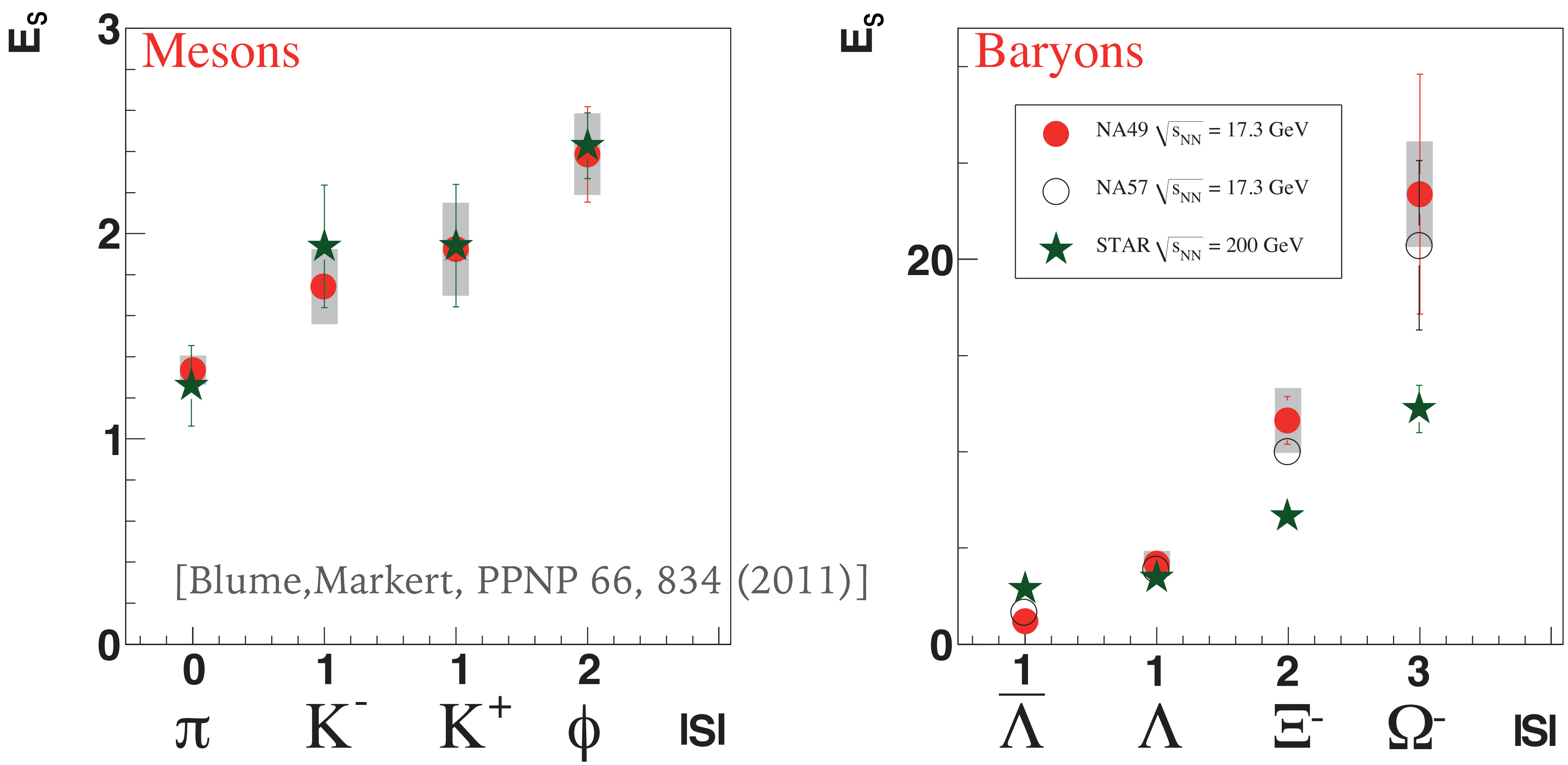
- non-monotonic energy dependence of net-proton $\kappa\sigma^2$ and net-kaon Sσ
  - need more statistics
- no critical physics implemented in UrQMD

STRANGENESS ENHANCEMENT MEASUREMENTS

$$E_S = \left(\frac{1}{\langle N_{\mathrm{part}} \rangle} \frac{\mathrm{d}N(A+A)}{\mathrm{d}y}\bigg|_{y=0} \right) \bigg/ \left(\frac{1}{2} \frac{\mathrm{d}N(p+p)}{\mathrm{d}y}\bigg|_{y=0} \right)$$

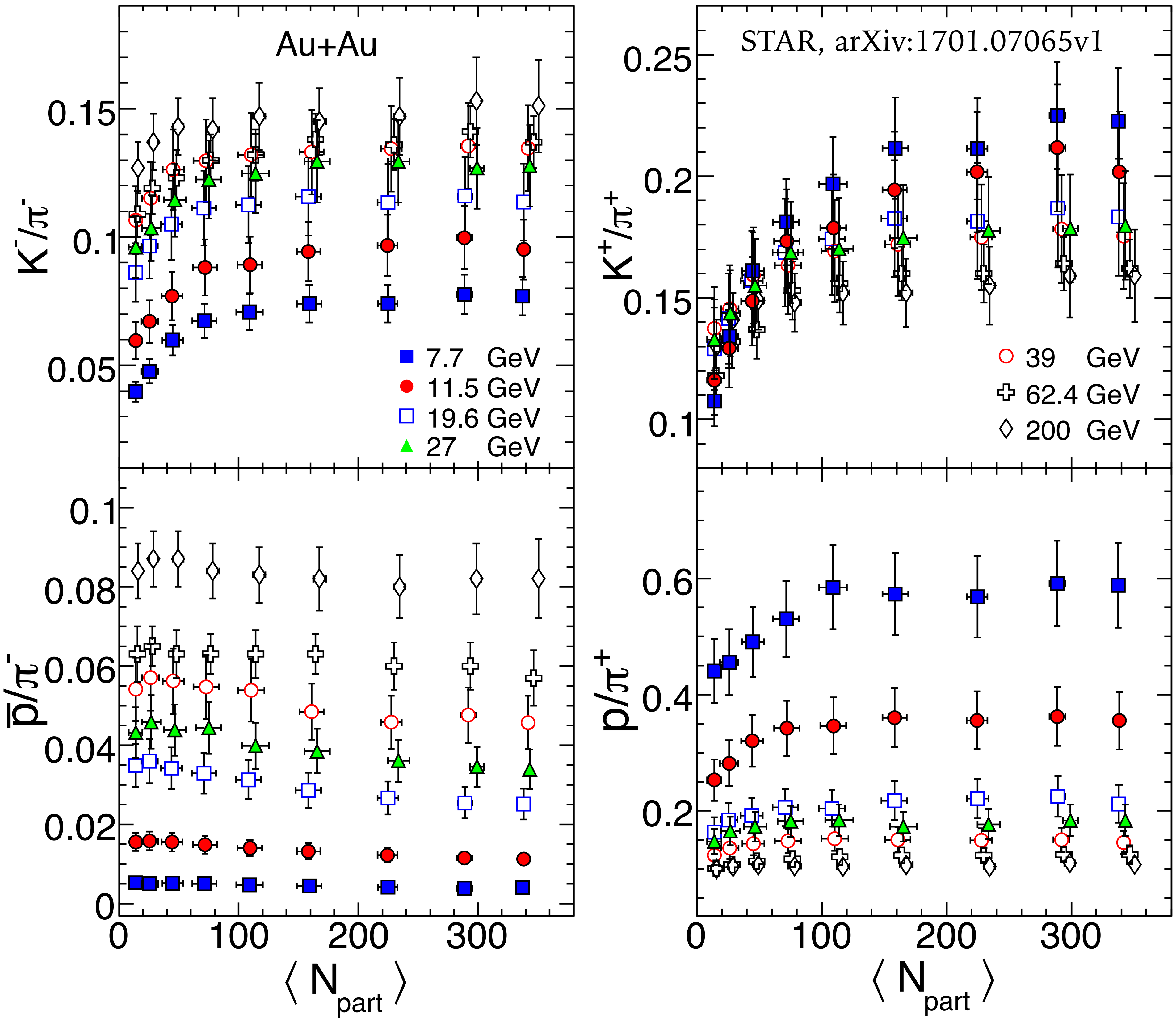
STRANGENESS ENHANCEMENT MEASUREMENTS

$$E_S = \left(\frac{1}{\langle N_{\rm part} \rangle} \frac{{\rm d}N(A+A)}{{\rm d}y} \bigg|_{y=0} \right) \bigg/ \left(\frac{1}{2} \frac{{\rm d}N(p+p)}{{\rm d}y} \bigg|_{y=0} \right)$$



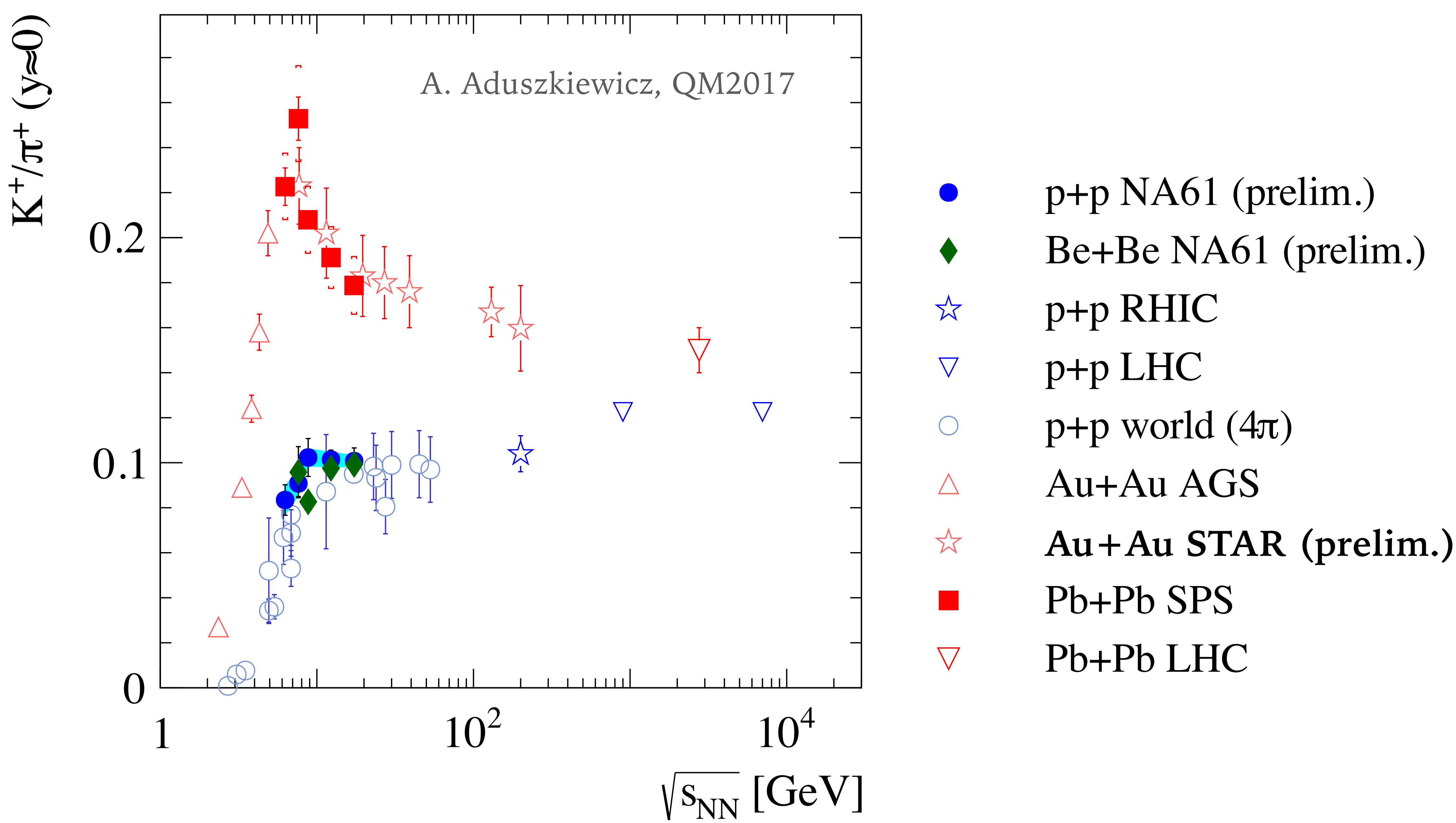
- hierarchy of enhancement with strangeness
- enhancement for baryons higher at SPS than at RHIC
- statistical models - strong reduction of the available phase space for strange particle

PARTICLE RATIOS AS A FUNCTION OF SYSTEM SIZE FROM STAR



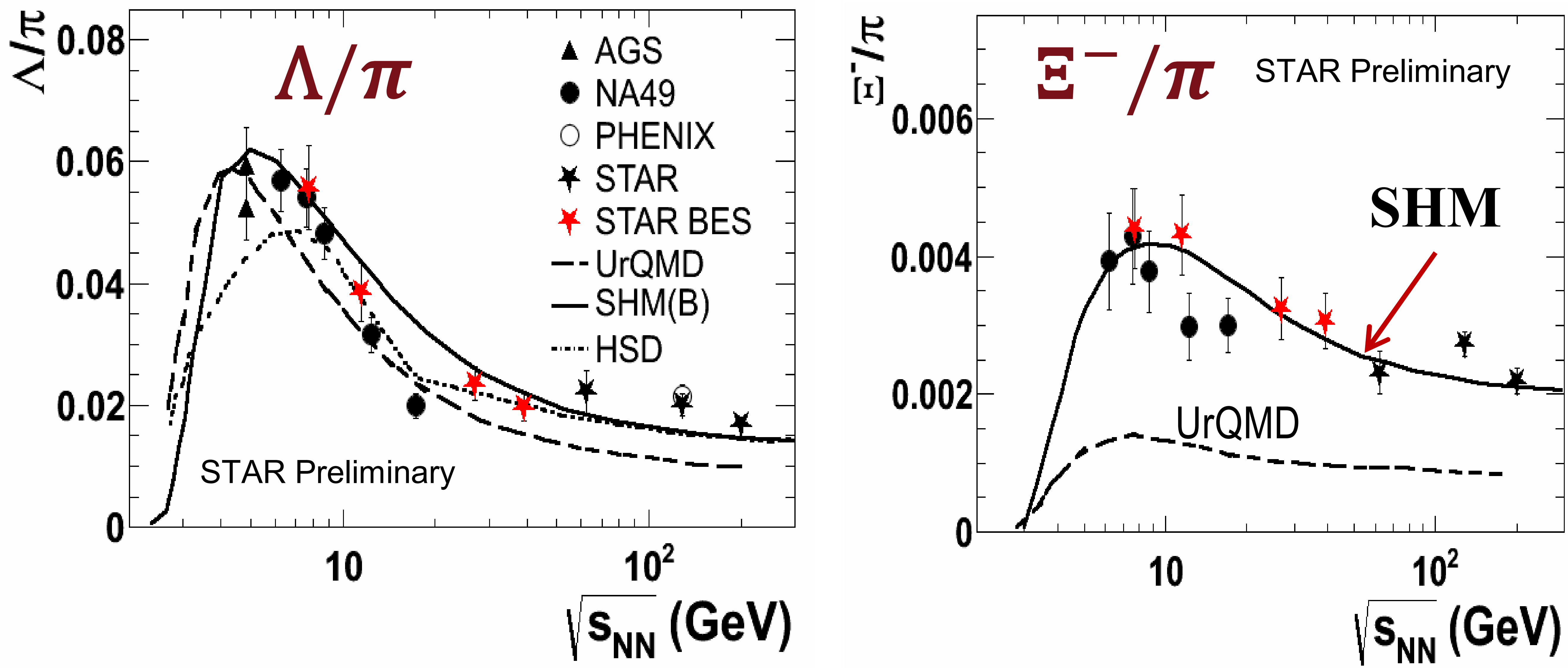
- strangeness production grows with the system size
  - expected result

K+/π+ FROM NA61 - p+p VS Be+Be



- blue circles vs green diamonds - no enhancement
- is Be+Be too small (N_{part} ≅ 10) for QGP formation at SPS energies?

STRANGE BARYON/PION RATIOS IN ENERGY SCANS



- Statistical Hadronization Models (SHM) successful in prediction
- maximum net baryon density of GCE~ 8 GeV [Randrup, Cleymans, PRC **74**, 047901 (2006)]
  - maximum in the production ratio is expected to shift toward higher energies with increasing strangeness content of the baryon

ANTI-BARYON TO BARYON RATIOS

- primordial density of hadron species i

  [Cleymans et al., PRC 71 054901 (2005)]:

$$n_i = \gamma_S \frac{g_i}{2\pi^2} m_i^2 T K_2(m_i/T) \exp(\mu_i/T)$$

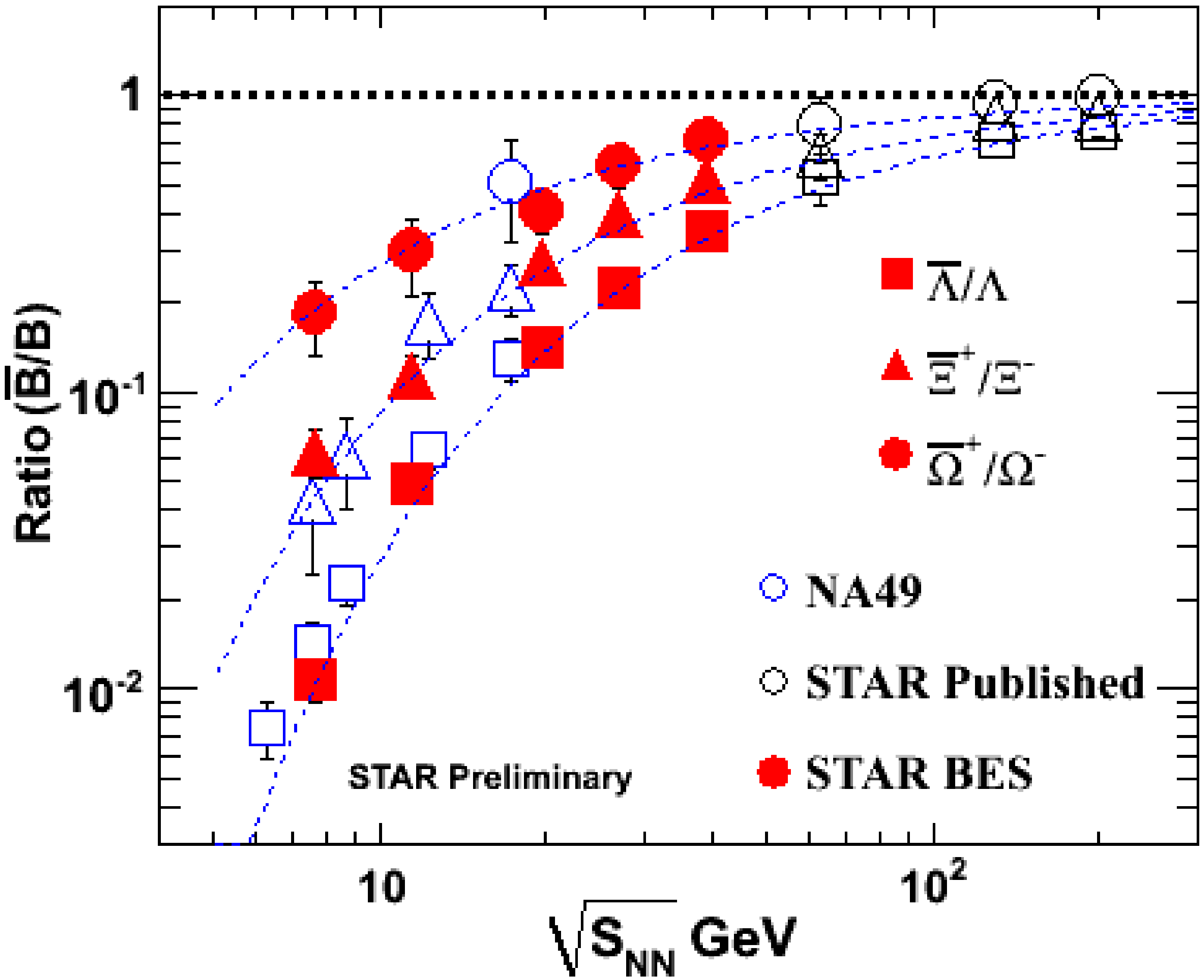
- which implies

$$\frac{n_{\overline{\Lambda}}}{n_{\Lambda}} = \exp\left(-\frac{2\mu_B}{T} + \frac{2\mu_S}{T}\right) \qquad \frac{n_{\overline{\Xi}^+}}{n_{\Xi^-}} = \exp\left(-\frac{2\mu_B}{T} + \frac{4\mu_S}{T}\right)$$

$$\frac{n_{\overline{\Omega}^+}}{n_{\Omega^-}} = \exp\left(-\frac{2\mu_B}{T} + \frac{6\mu_S}{T}\right)$$

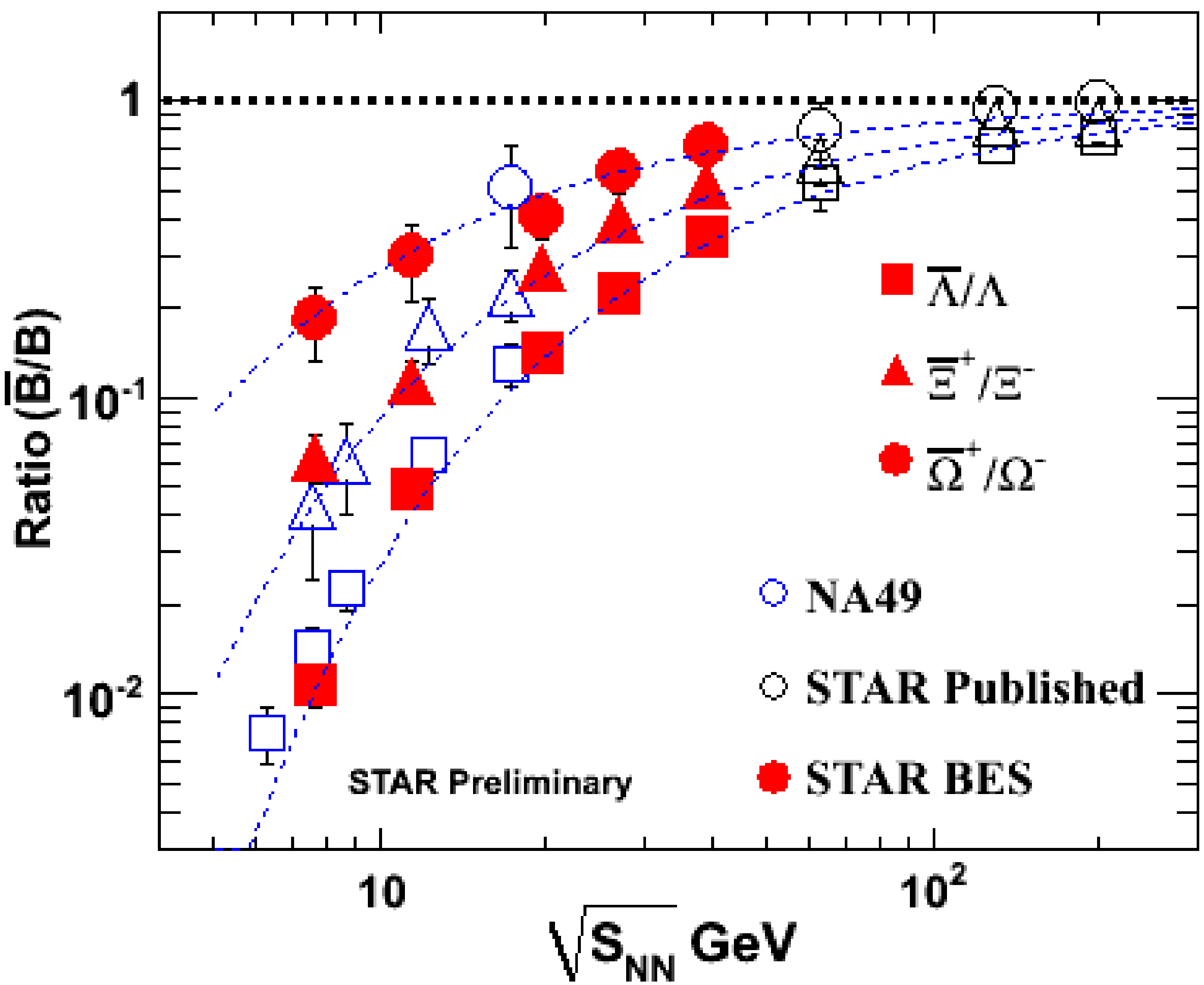
- T - temperature
- μ_B, μ_S - baryon, strangeness chemical potential
- γ_S - strangeness saturation factor (for not fully equilibrated systems)

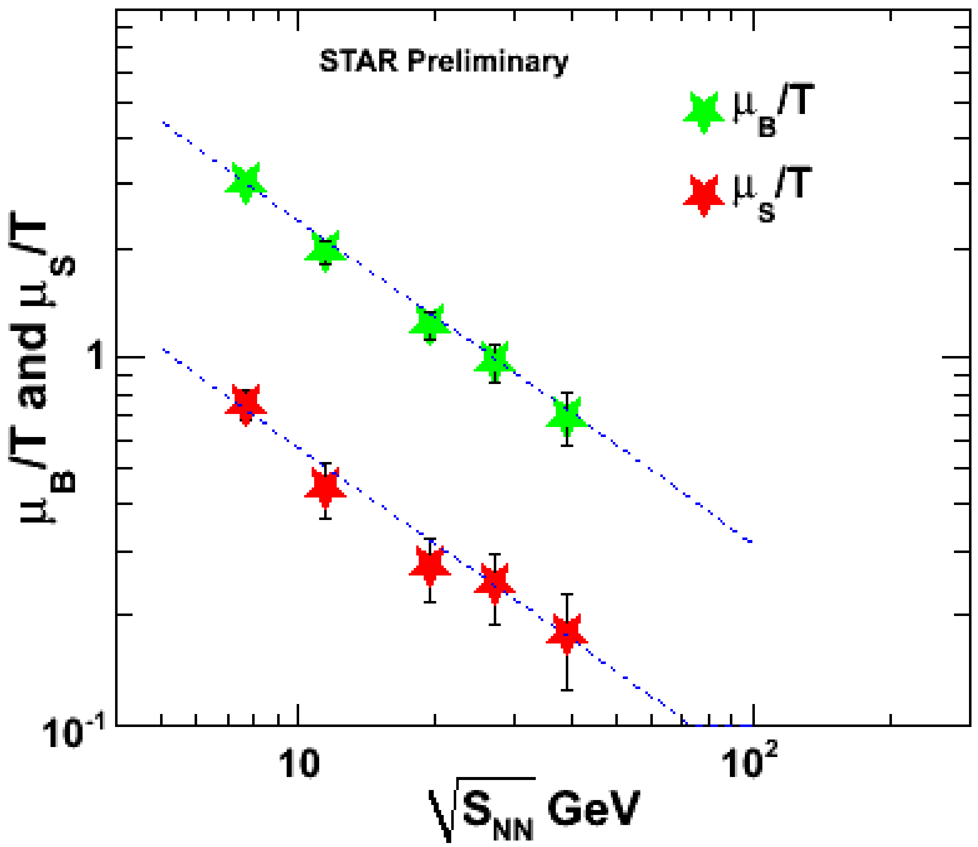
ANTI-BARYON TO BARYON RATIOS



[Andronic et. al., Nucl. Phys. A 772, 167 (2006)]

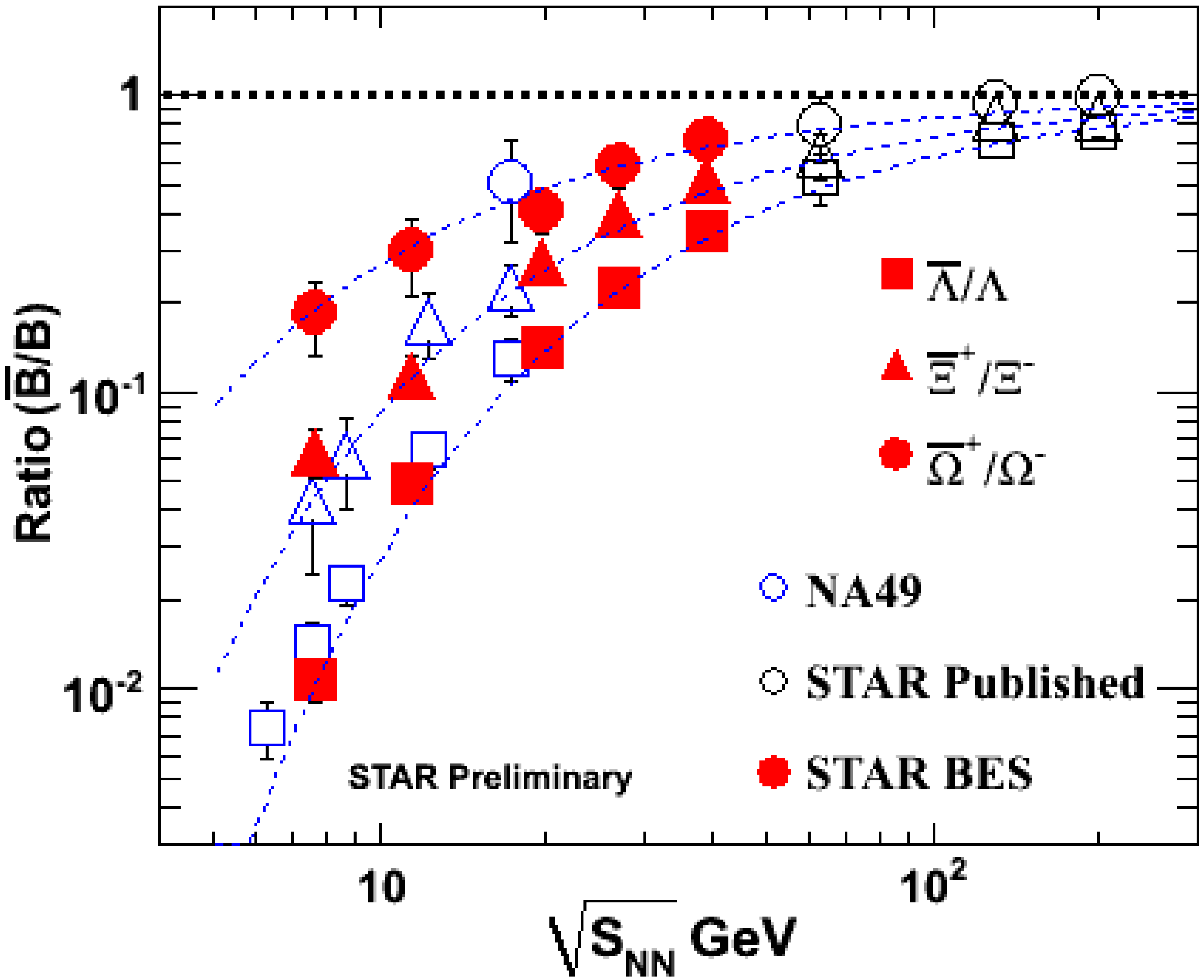
ANTI-BARYON TO BARYON RATIOS



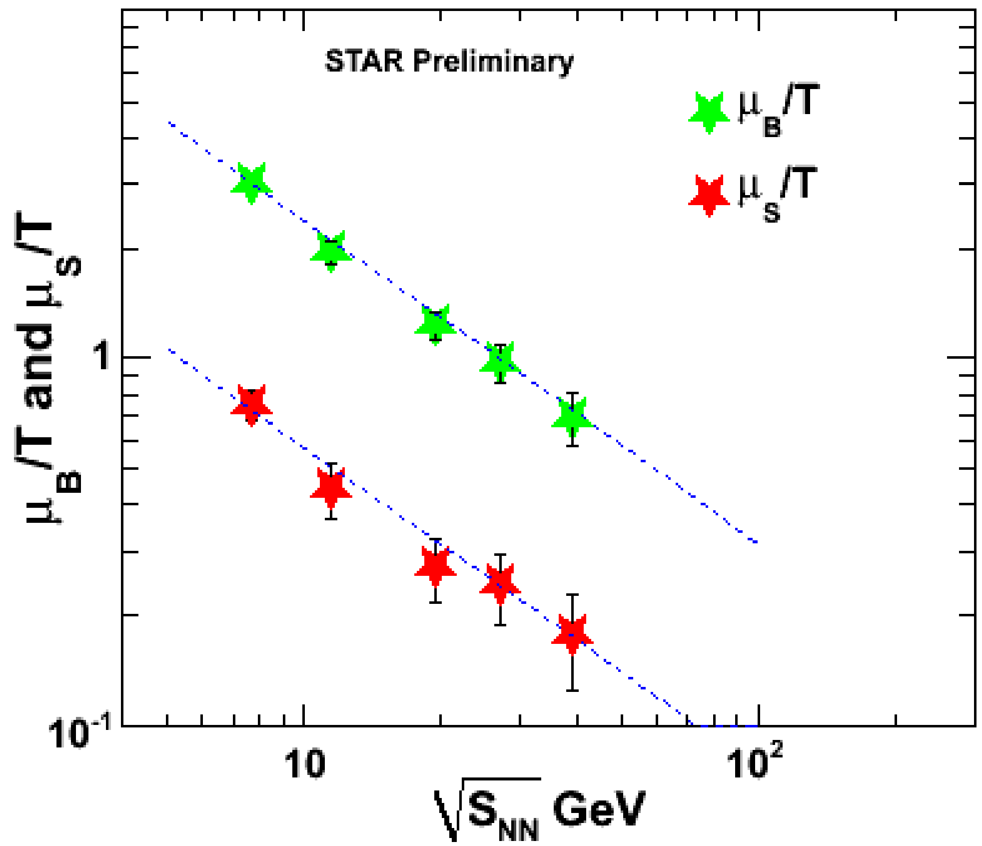


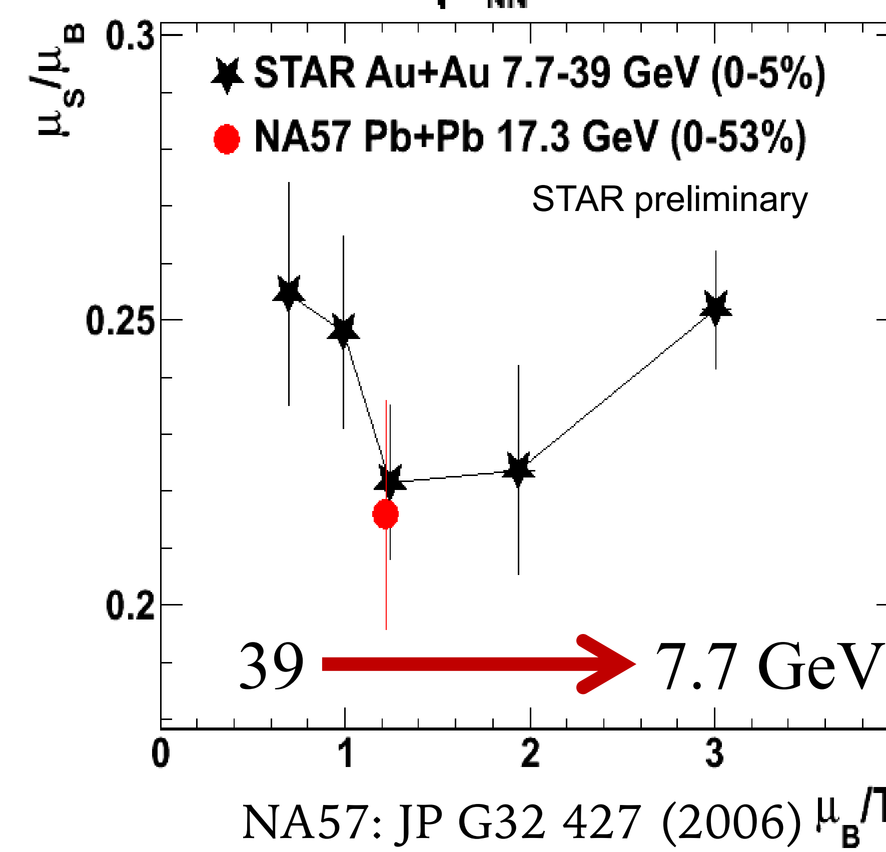
[Andronic et. al., Nucl. Phys. A 772, 167 (2006)]

ANTI-BARYON TO BARYON RATIOS



[Andronic et. al., Nucl. Phys. A 772, 167 (2006)]



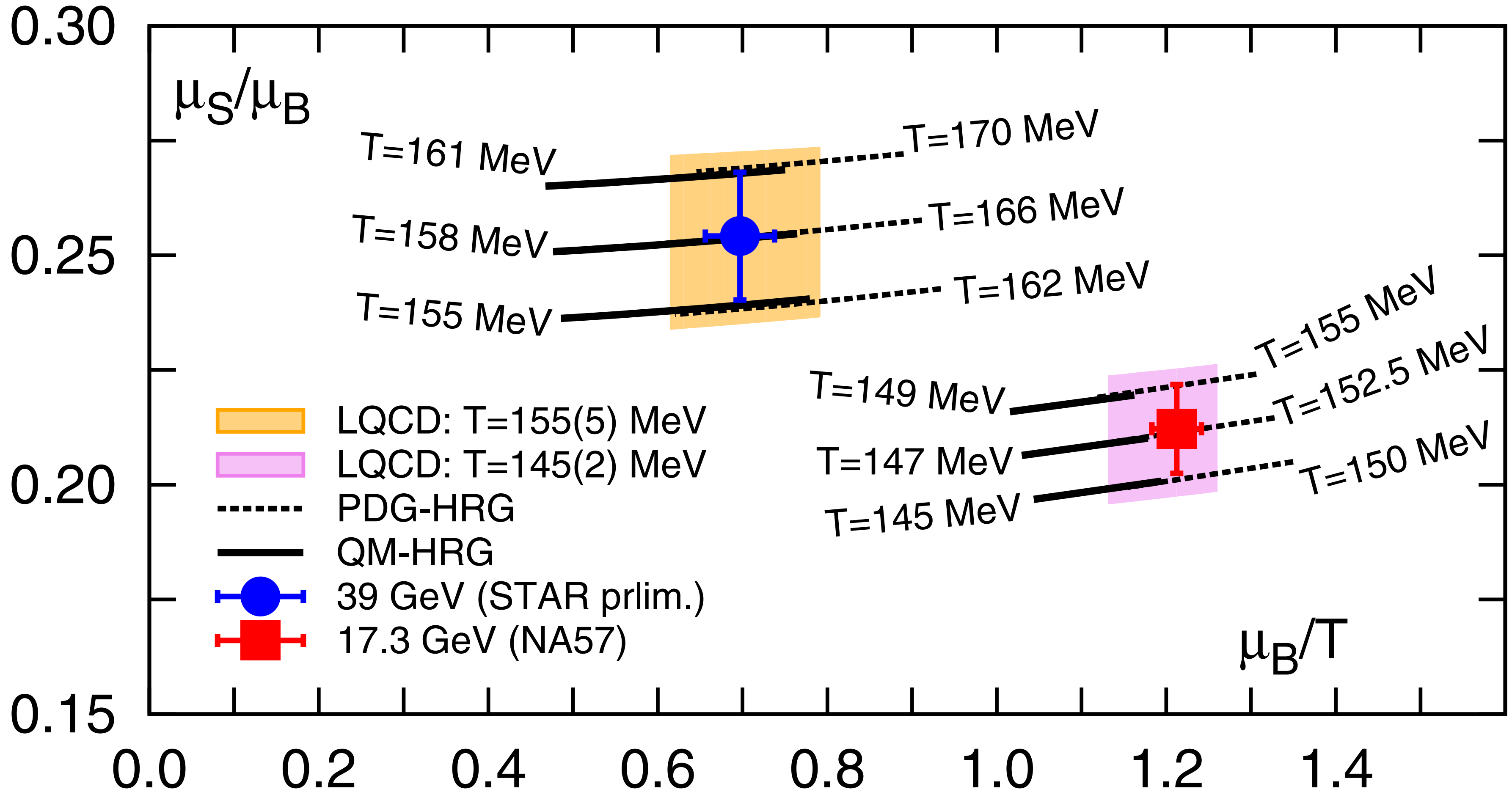


NA57: JP G32 427 (2006)

- minimum of μ_S/μ_B found for 19.6, and 11.5 GeV

LATTICE QCD PREDICTION FOR μ_S/μ_B RATIO

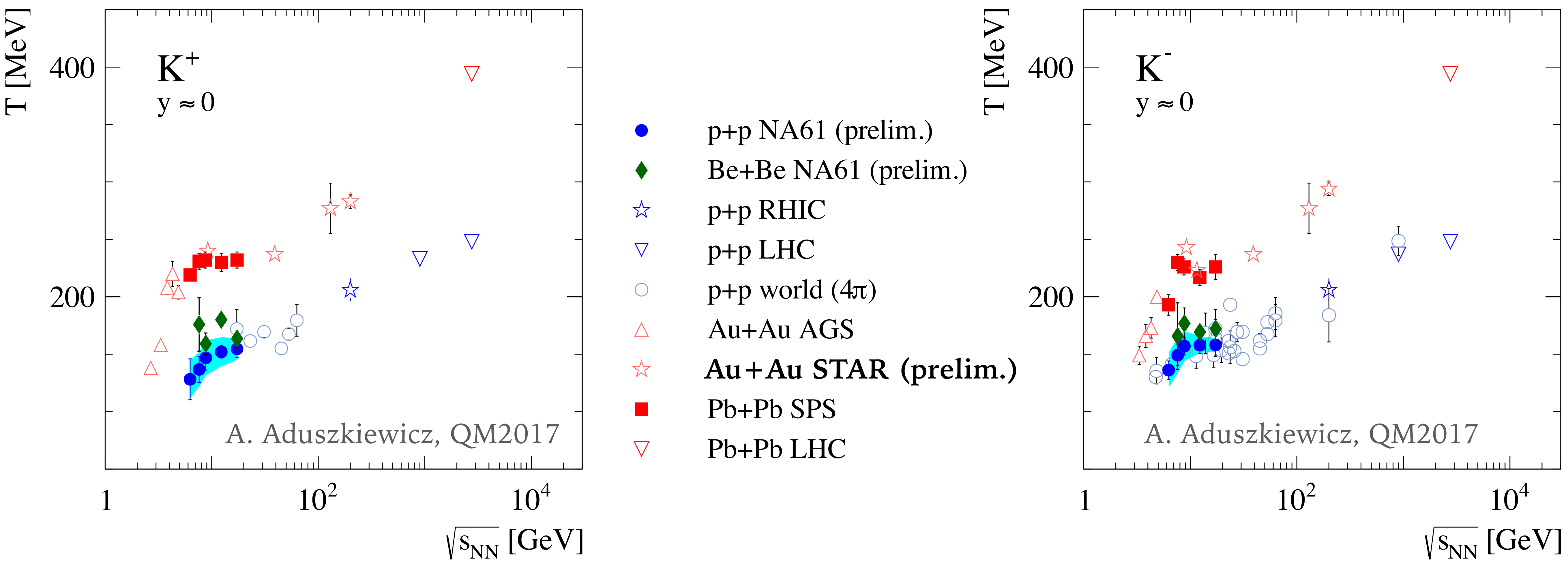
- LQCD and Hadron Resonance Gas (HRG) model prediction for T at 17.3 GeV and 39 GeV
- PDG-HRG includes all known strange hadrons while QM-HRG includes, in addition, predicted strange hadrons not yet observed
  - baryons [Capstick, Isgur, PRD 34 2809 (1986)], mesons [Ebert, et al., PRD 79 114029 (2009)]
- QM-HRG freeze-out temperatures much closer to LQCD than those from PDG-HRG
- **indication of more strange baryons at RHIC?**



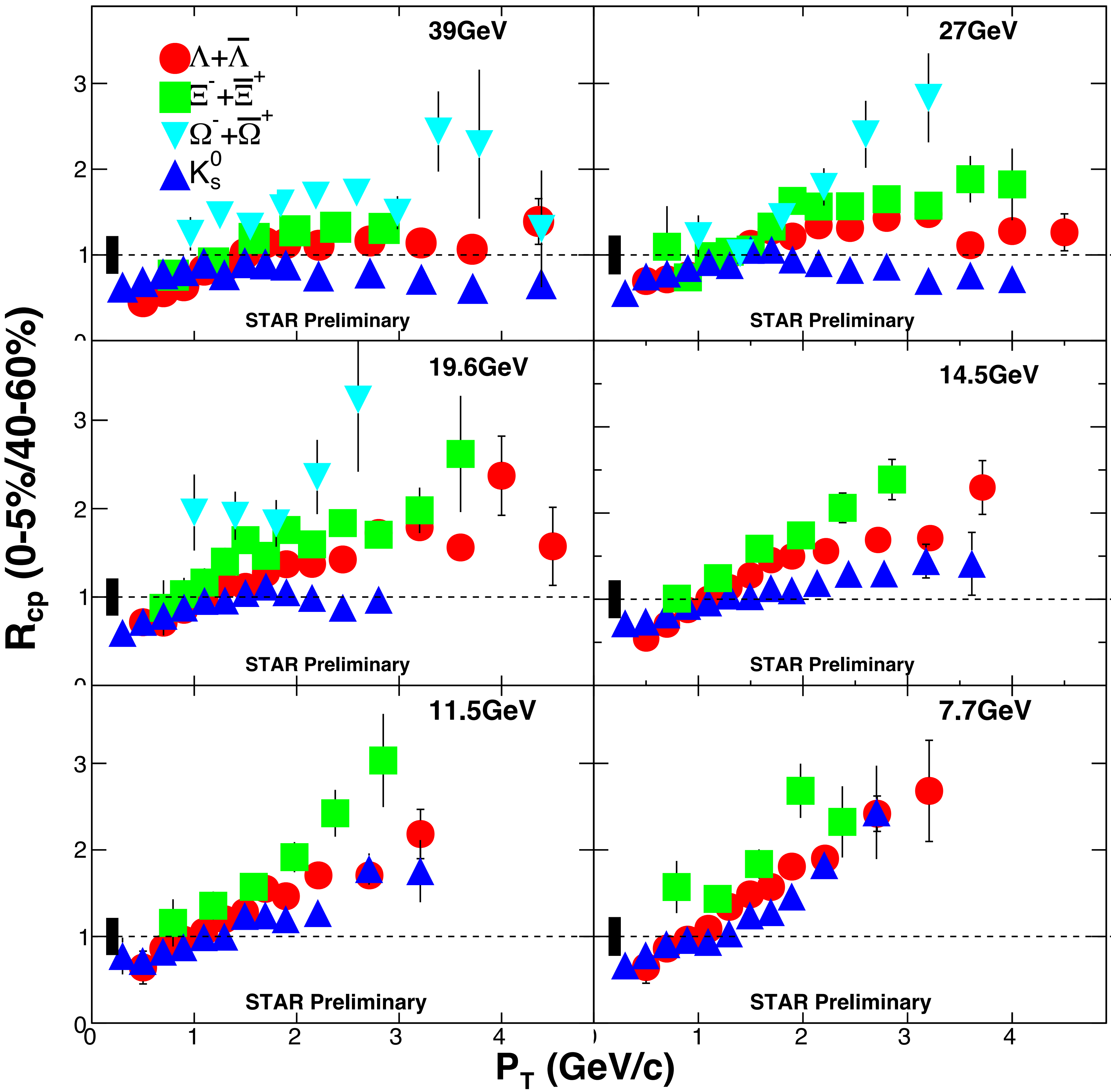
Bazavov, et al., PRL 113 072001 (2014)

TRANSVERSE MOMENTUM SPECTRA OF KAONS

- "step" reproduced by 3+1 Hydro model [Gaździcki et al., BJP 34 322 (2003)]
  - assumes 1st order phase transition (modification of EoS [Van Hove, PLB 118 138 (1982)])
- but also with UrQMD based [Petersen, et al., J. Phys. G 36 055104 (2009)]
  - either 1st order phase transition or EoS effectively softened due to non-equilibrium effects in the hadronic transport calculation



NUCLEAR MODIFICATION FACTOR

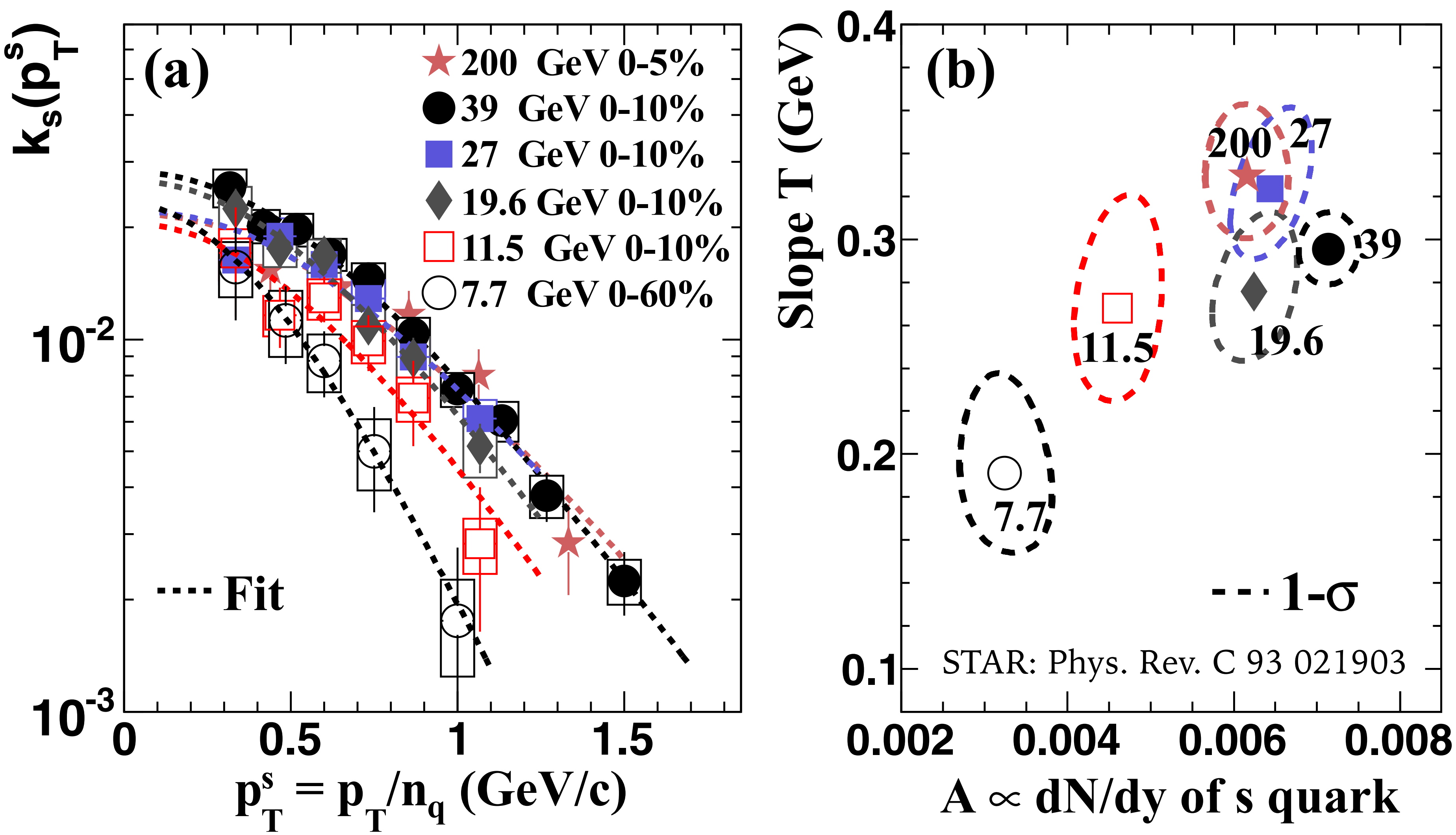


$$R_{CP} = \frac{[(dN/dp_T)/N_{\rm bin}]_{\rm central}}{[(dN/dp_T)/N_{\rm bin}]_{\rm peripheral}}$$

- how strong are cold nuclear matter effects?
  - NA61 preliminary results in p+Pb collisions could come in about half a year
  - d+Au energy scan collected by STAR in 2016
- similar pattern as for light hadrons

[STAR: arXiv:1707.01988]

NCQ SCALED Ω/φ RATIO



Assume approximately equal momentum of coalescing strange quarks

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

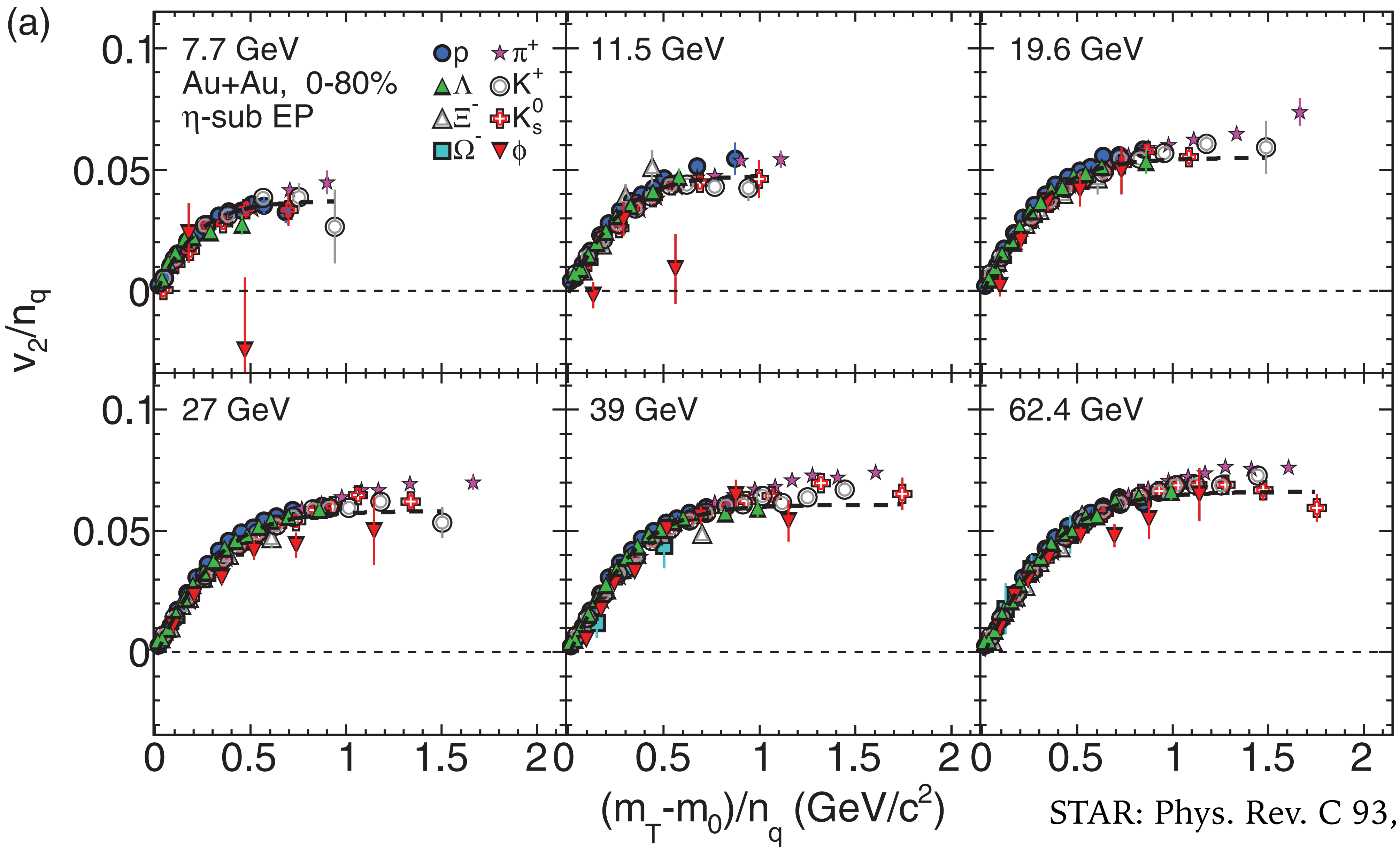
Parameter A from a Boltzmann distribution

$$\frac{g_s A m_T}{T(m_s + T)} e^{-(m_T - m_s)/T}$$

is proportional to s quark rapidity density

- strange quark coalescence test [Chen, et al., PRC78 034907 (2008)]
- strangeness density seems to start to drop ~ 11.5 GeV

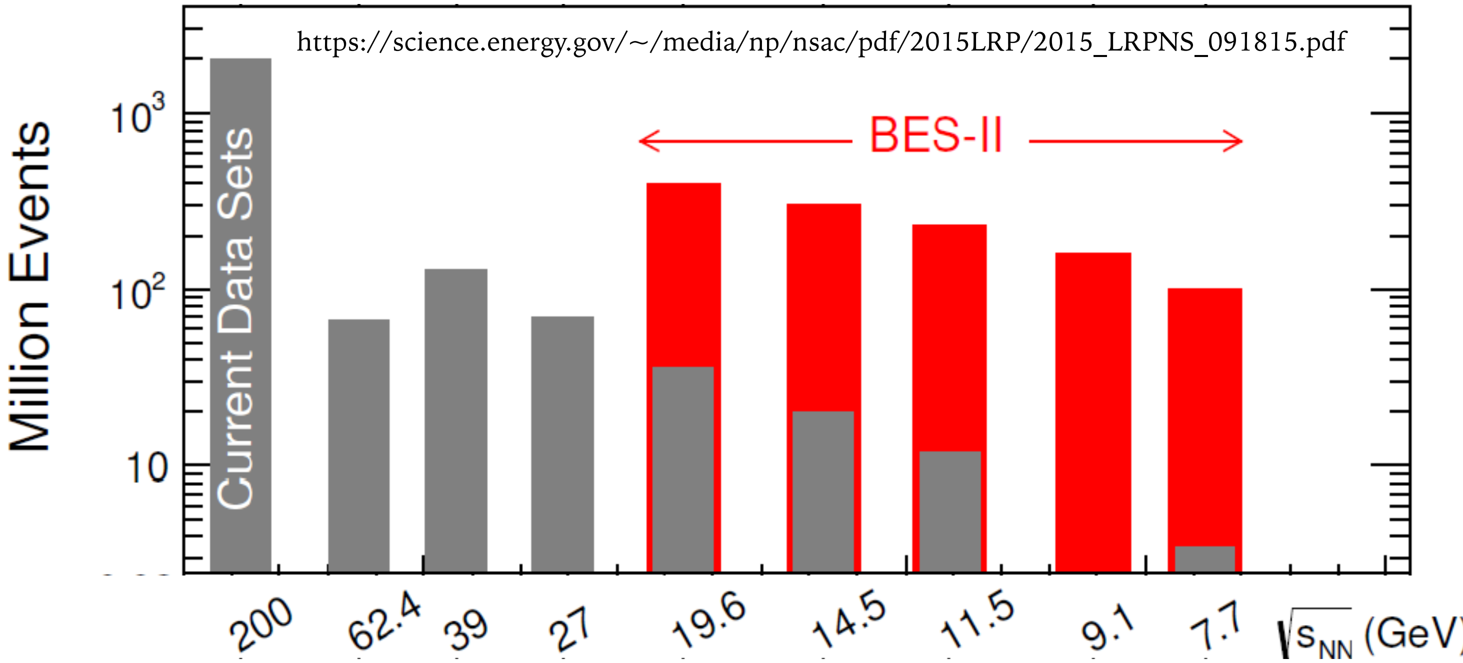
ELLIPTICAL FLOW OF IDENTIFIED HADRONS



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

- ϕ meson's NCQ scaling seems to break down at 11.5 and 7.7 GeV
- ϕ meson has significantly lower collision cross section in hadron gas
- but the statistics is insufficient - need BES-II

FUTURE PLANS



Collider Energy	Fixed-target Energy	Single beam AGeV	CMS Rapidity	μ_B [MeV]
62.4	7.7	30.3	2.10	420
39	6.2	18.6	1.87	487
27	5.2	12.6	1.68	541
19.6	4.5	8.9	1.52	589
14.5	3.9	6.3	1.37	633
11.5	3.5	4.8	1.25	666
9.1	3.2	3.6	1.13	699
7.7	3.0	2.9	1.05	721

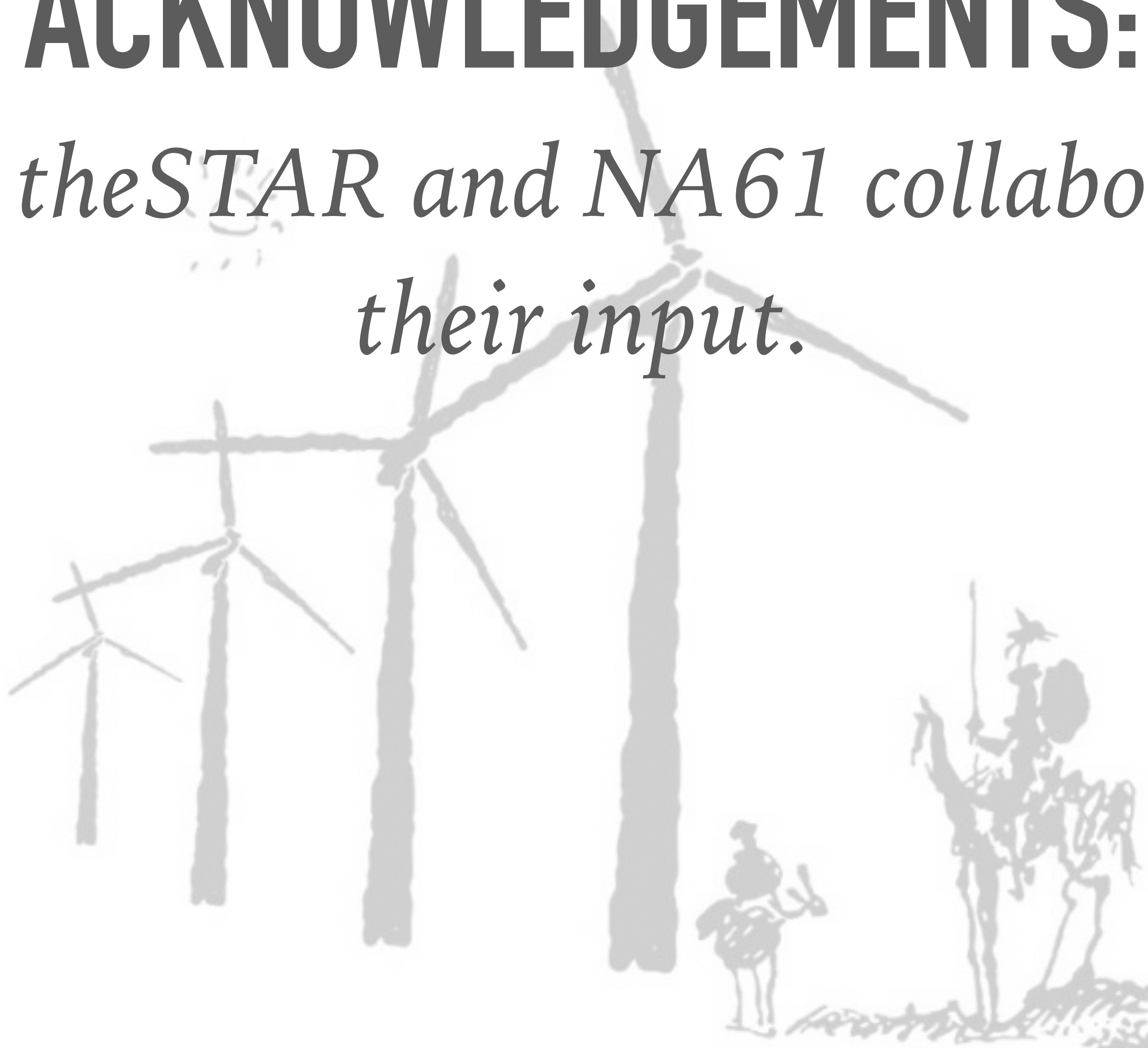
- 2019-2020: BES Phase II at RHIC
- improvement of statistical uncertainties
  - RHIC luminosity increase by a factor of ~25
- improvement of systematic uncertainties [STAR Internal Note SN-0598]
  - detector upgrades with better resolution,wider rapidity range,and wider p_T coverage at STAR
- Fixed-target at STAR
  - allows for QCD phase space diagram exploration extended to μ_B = 721 MeV
- At SPS, NA61 will have 1 kHz readout (2020)
  - high statistics beam momentum scan with Pb+Pb collisions for precise measurement of multi-strange hyperon production

QCD PHASE DIAGRAM AT INTERMEDIATE μ_B – CURRENT STATUS

- QGP signals appear to turn off at lower energies of beam energy scans; more statistics necessary
- indications of a flavor hierarchy in chemical freeze-out
- no strangeness enhancement in SPS Be+Be collisions at $\sqrt{s_{NN}}$ = 8-17 GeV
- in searching for a critical point and the type of phase transition, beam energy scan will provide further constraints
- at both SPS and RHIC, upgrades will be online soon
    - RHIC BES-II 2019-2020
    - SPS beam momentum scan 2021-2024

ACKNOWLEDGEMENTS:

Thanks to theSTAR and NA61 collaborations for their input.



THANK YOU