Strangeness and quarkonium production with STAR BESII program

Shuai Yang

South China Normal University

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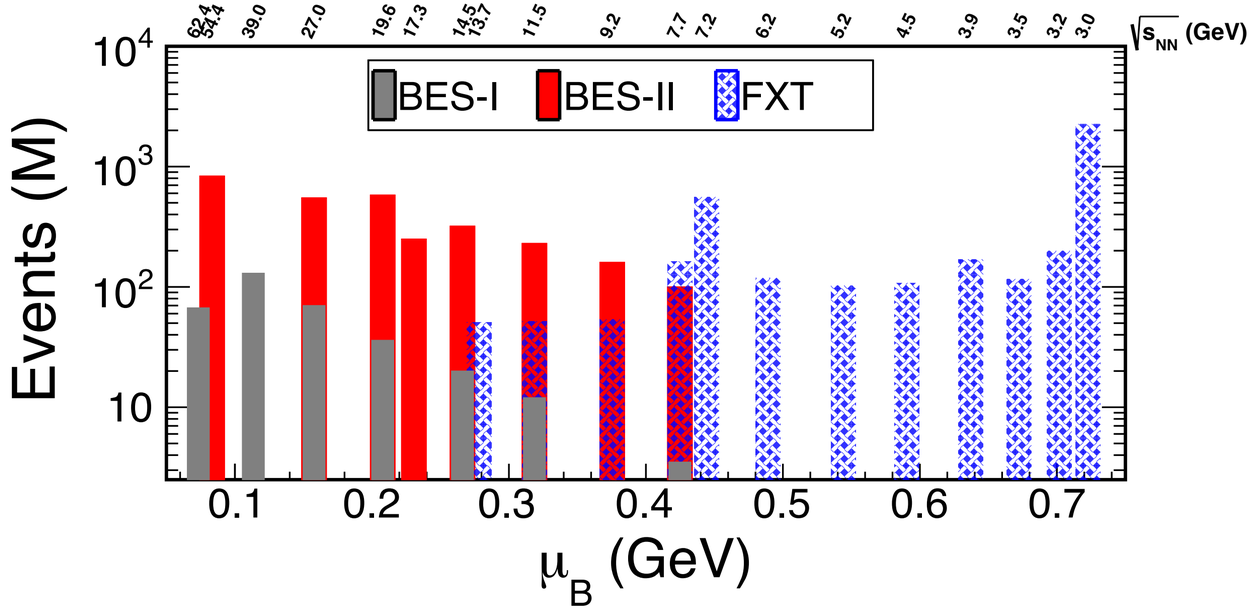
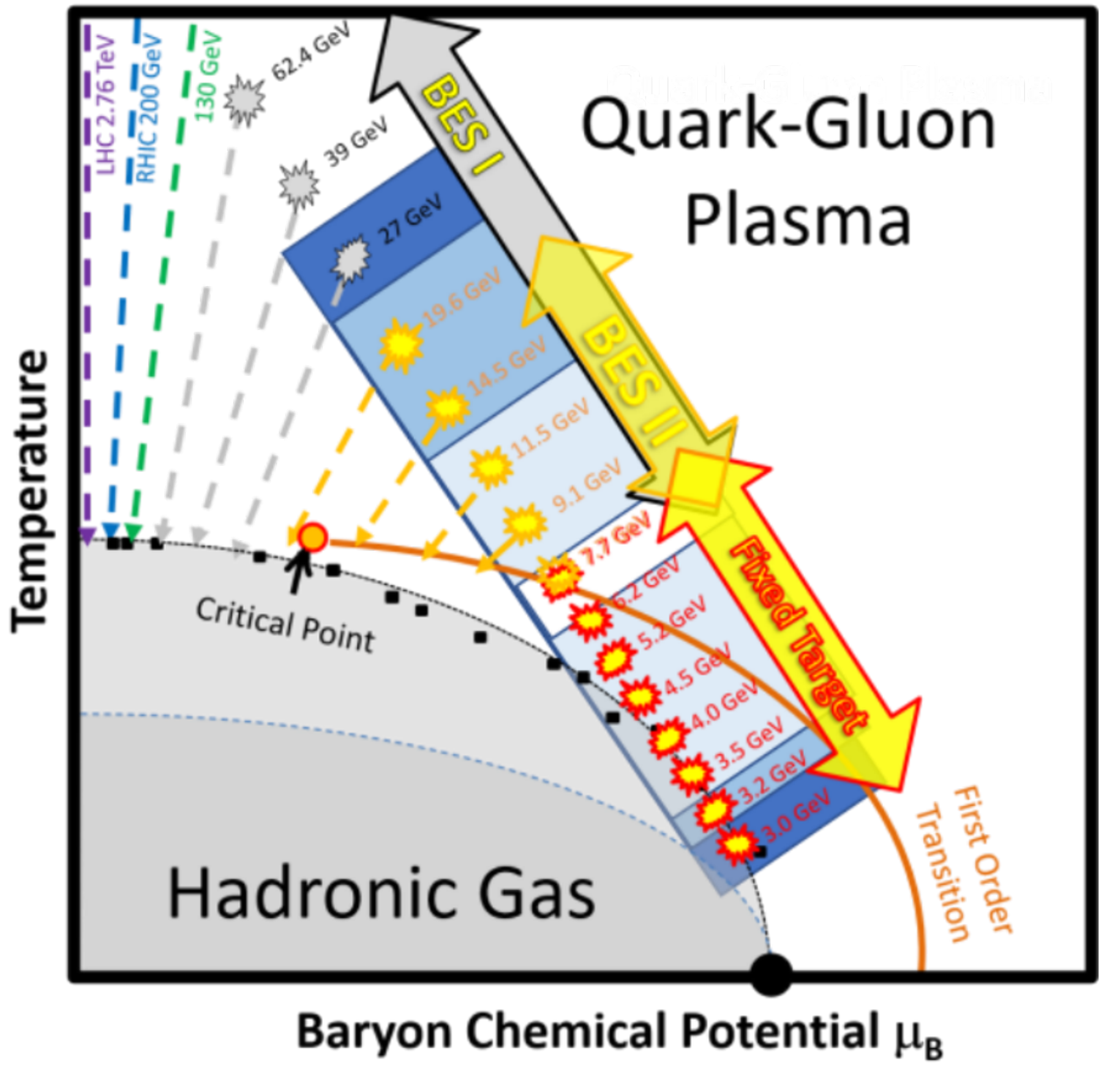
Motivation

- Beam Energy Scan (BES) program to study the QCD phase diagram
  - The onsite of deconfinement
  - The first-order phase transition
  - The critical point

BES-II ~ 10-20 × BES-I statistics

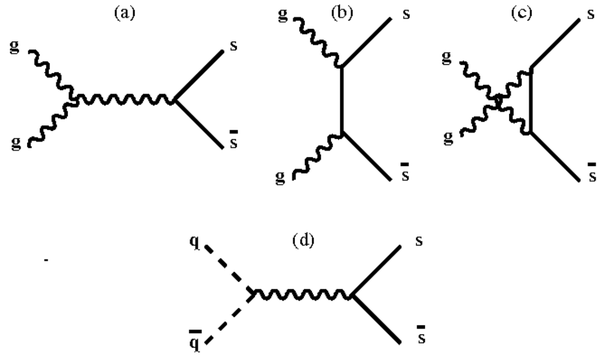




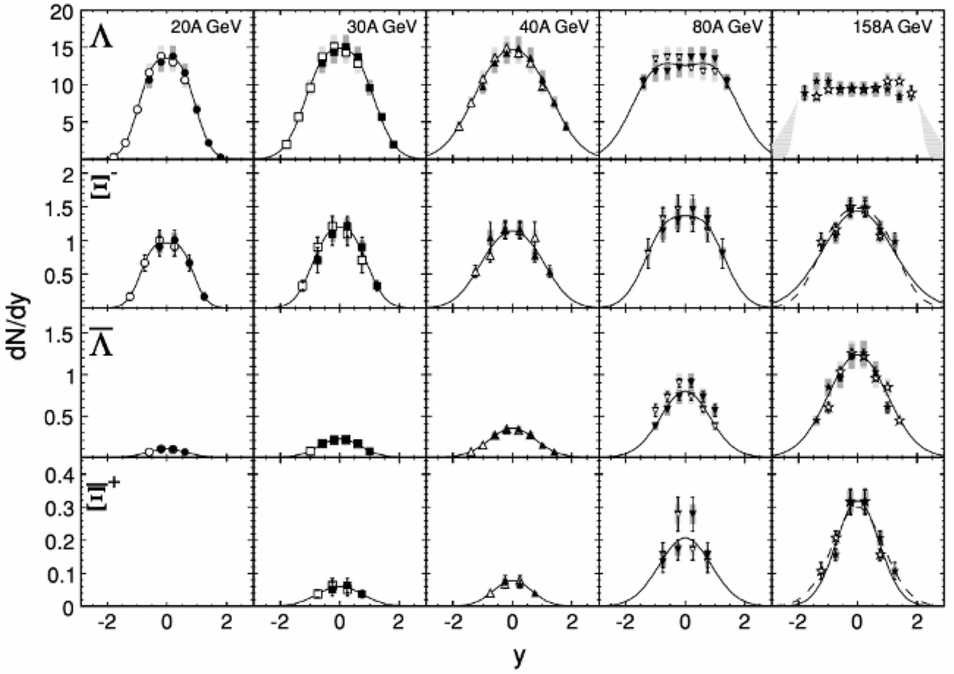
Why strangeness?

- Traditional probe for QGP formation
  - Strange baryon-to-meson ratio can be utilized to probe deconfinement

Koch, Müller, Rafelski, Phys. Rep. 142 (1986) 167



- Rapidity density of (anti-)strange baryons may give insight on the baryon stopping mechanism
  - Crucial ingredient to estimate the feed-down contribution for identified hadrons



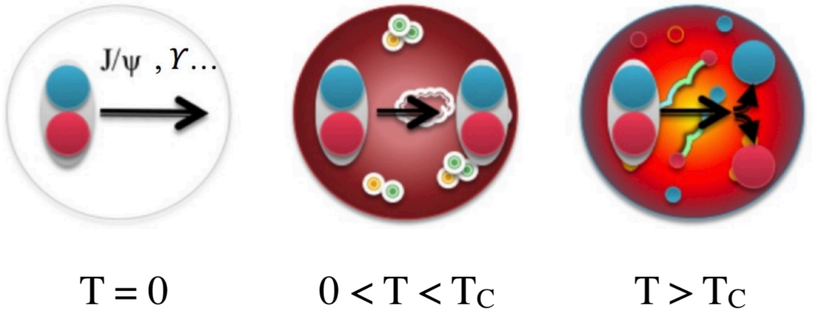
NA49, PRC 78 (2008) 034918

Why heavy quarkonium?

- J/ψ suppression was proposed as a direct proof of QGP formation
  - Color screening ⟶ dissociation

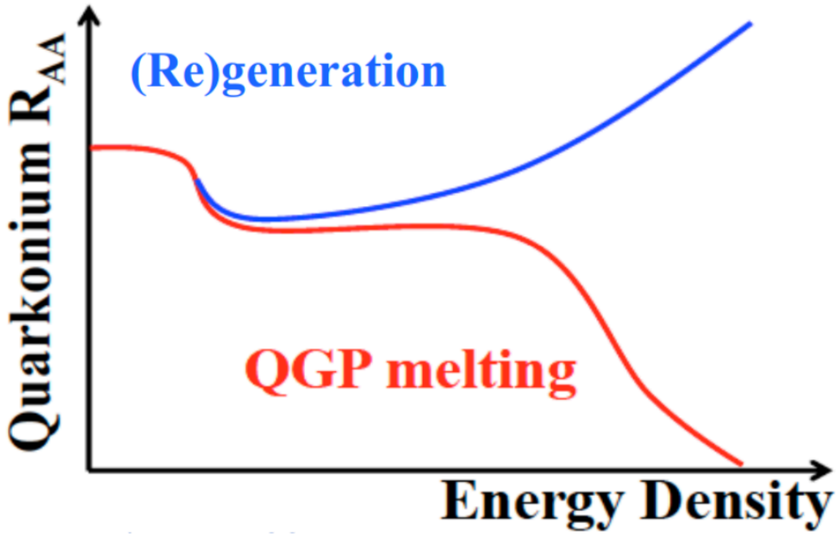
Matsui and Satz, PLB 178 (1986) 416

Credit: A. Rothkopf



- However, different effects in play
  - Regeneration
  - Cold nuclear matter effects
  - Feed down contributions
  - ...

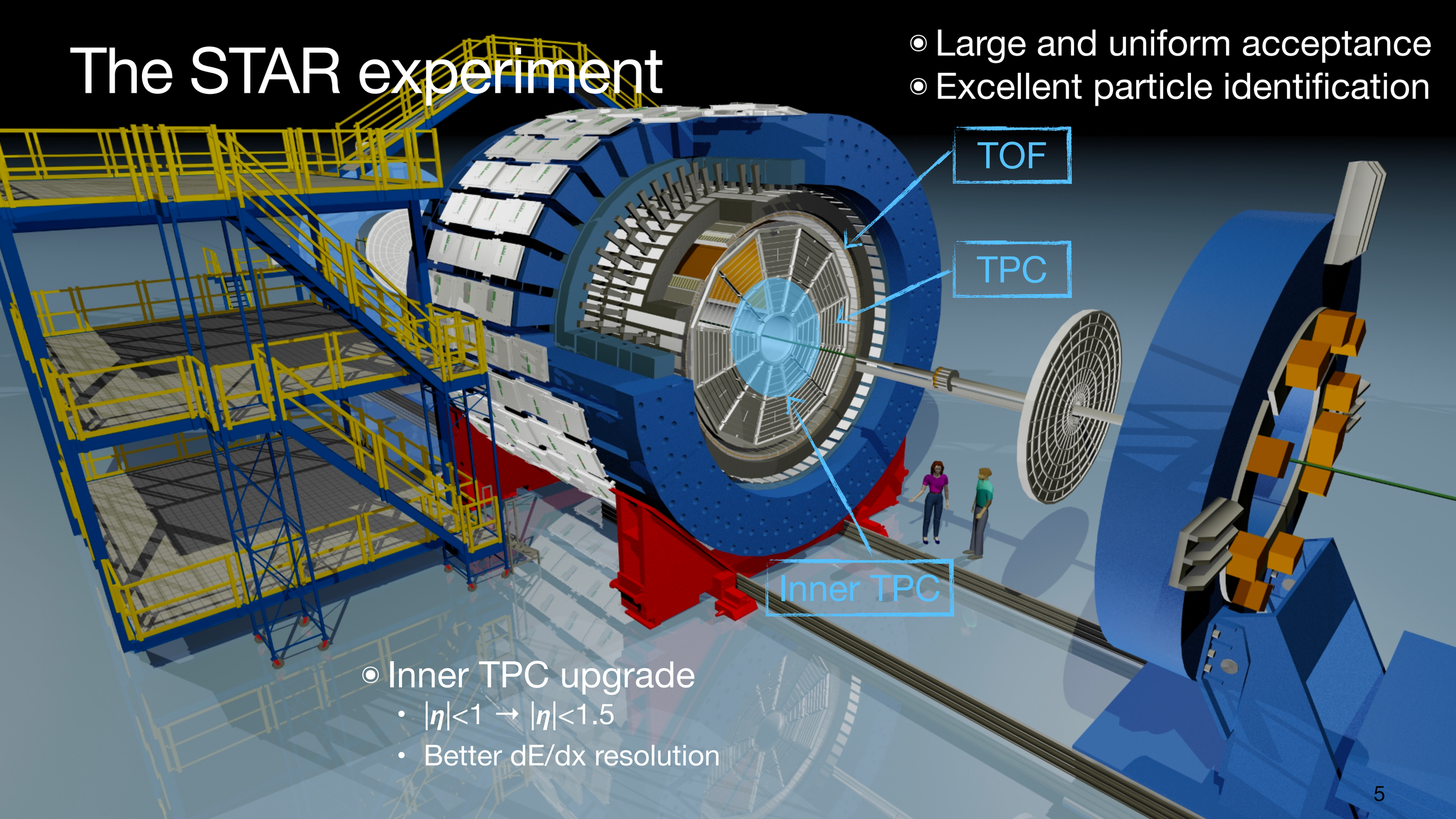
Ferreiro *et al.*, PRC 81 (2010) 064911
Gavin *et al.*, PRL 78 (1997) 1006
Capella and Ferreiro, EPJC 42 (2005) 419



- Systematically study the J/ψ production
  - Centrality, p_T differential measurements
  - Energy dependence

The STAR experiment

- Large and uniform acceptance
- Excellent particle identification

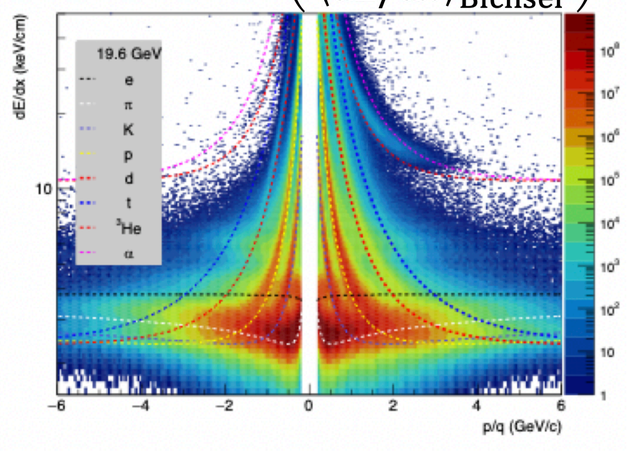


- Inner TPC upgrade
  - $|\eta|<1 \rightarrow |\eta|<1.5$
  - Better dE/dx resolution

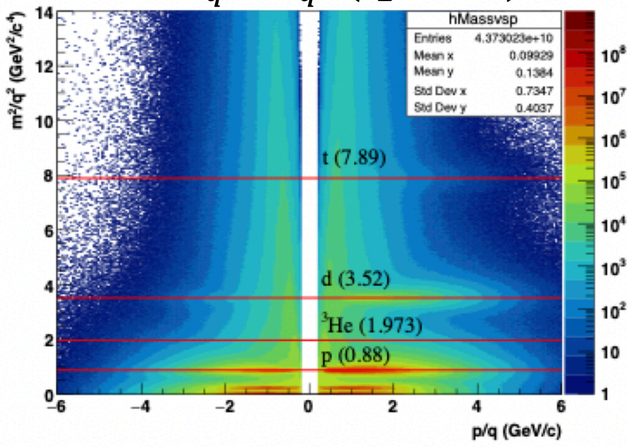
Strangeness production

Strangeness reconstruction

TPC: $z = \log\left(\frac{\langle \mathrm{dE/d}x\rangle_{\mathrm{measure}}}{\langle \mathrm{dE/d}x\rangle_{\mathrm{Bichsel}}}\right)$



TOF: $\frac{m^2}{q^2} = \frac{p^2}{q^2}\left(\frac{c^2t^2}{L^2} - 1\right)$



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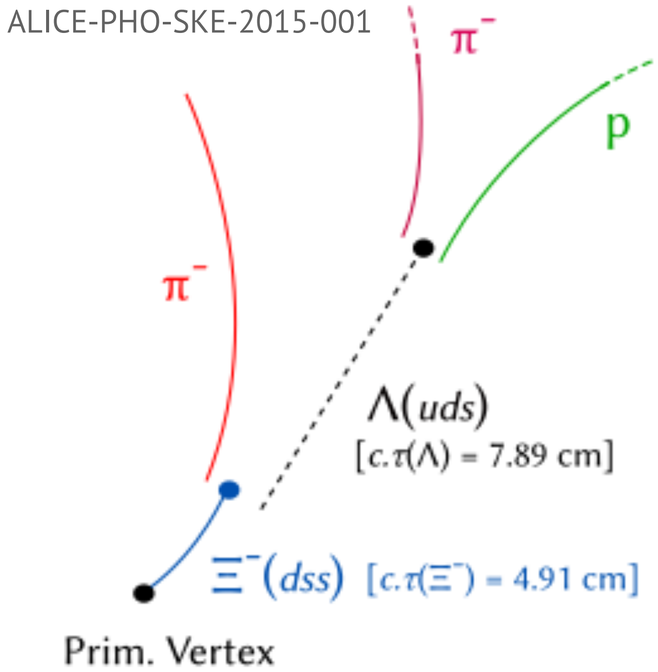
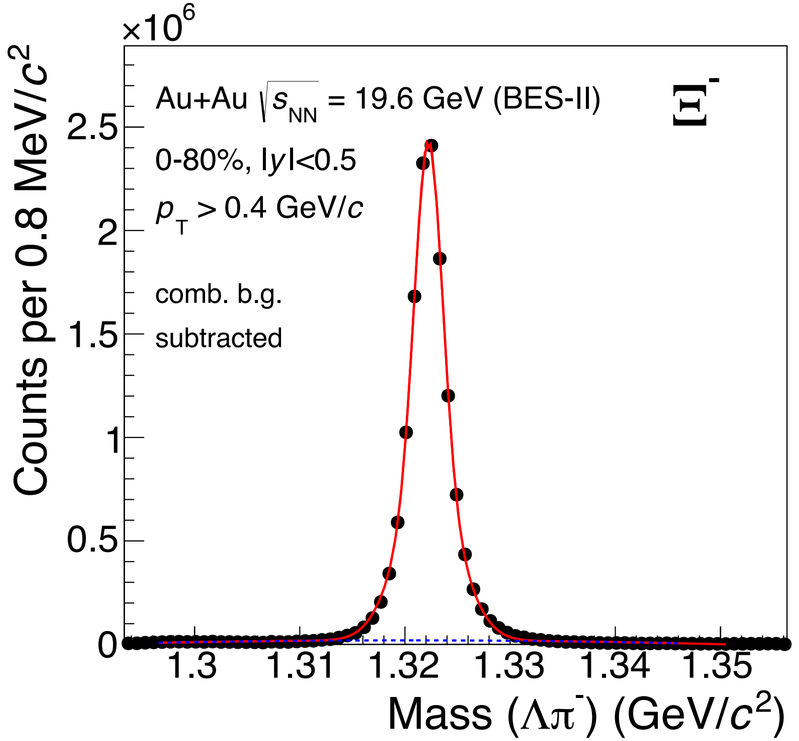
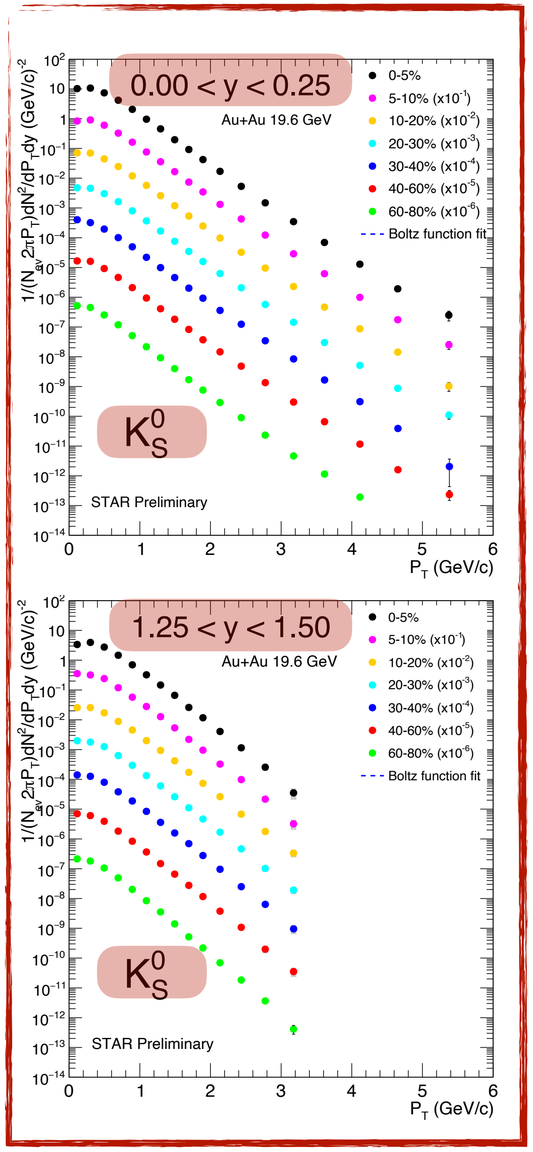
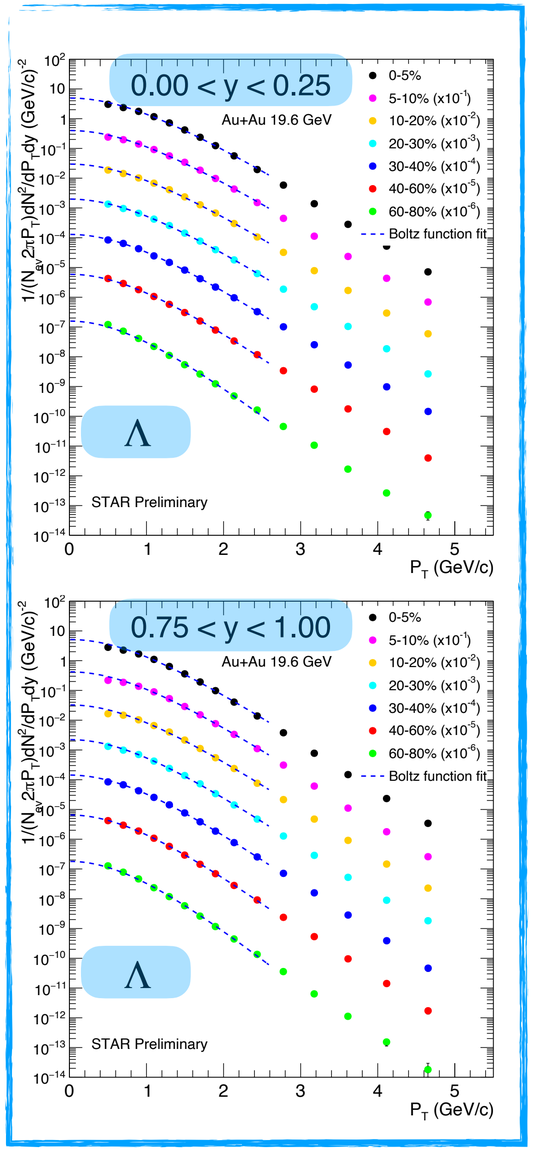


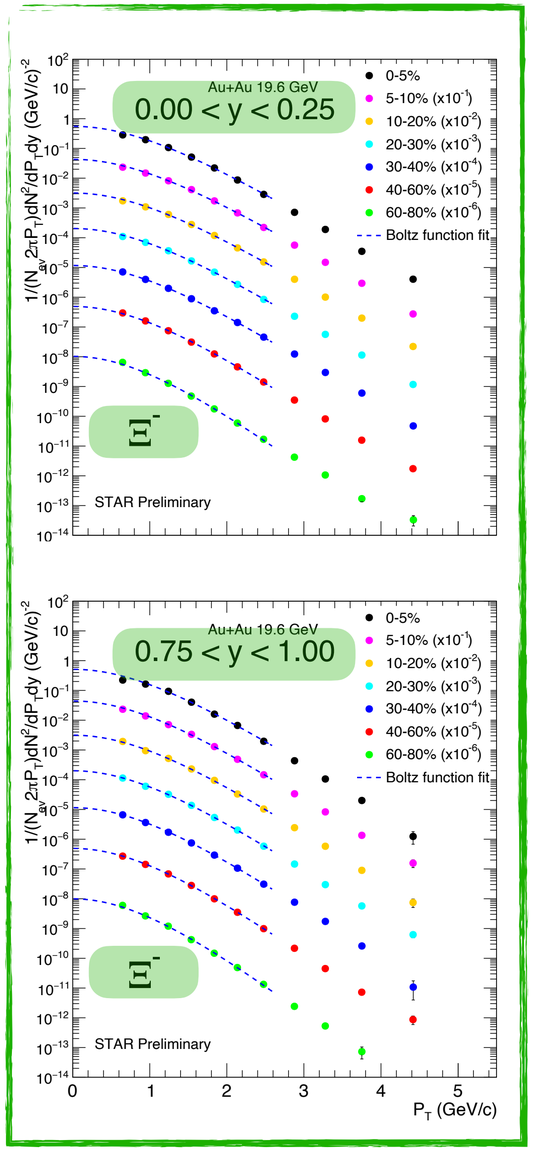


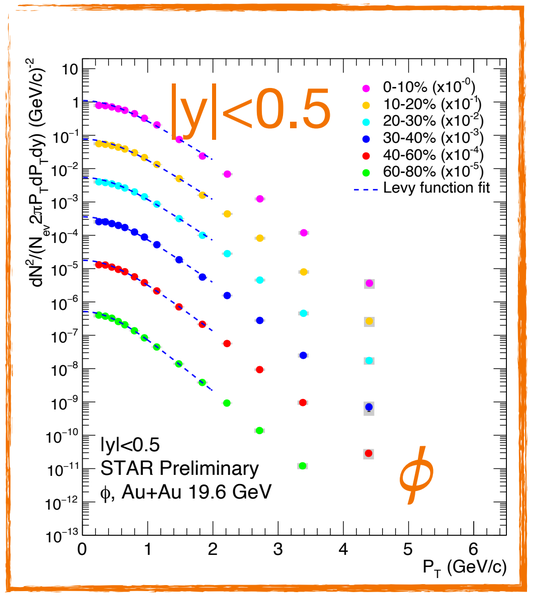
$$\mathrm{K}^0_{\mathrm{S}} \to \pi^+ + \pi^-(\mathcal{B} = 69.2\%)$$
$$\Lambda(\bar{\Lambda}) \to p(\bar{p}) + \pi^-\left(\pi^+\right)(\mathcal{B} = 63.9\%)$$
$$\Xi^-\left(\bar{\Xi}^+\right) \to \Lambda(\bar{\Lambda}) + \pi^-\left(\pi^+\right)(\mathcal{B} = 99.9\%)$$
$$\Omega^-\left(\bar{\Omega}^+\right) \to \Lambda(\bar{\Lambda}) + K^-\left(K^+\right)(\mathcal{B} = 67.8\%)$$
$$\phi \to \mathrm{K}^+ + \mathrm{K}^-(\mathcal{B} = 49.1\%)$$

p_T spectra of strange hadrons at 19.6 GeV



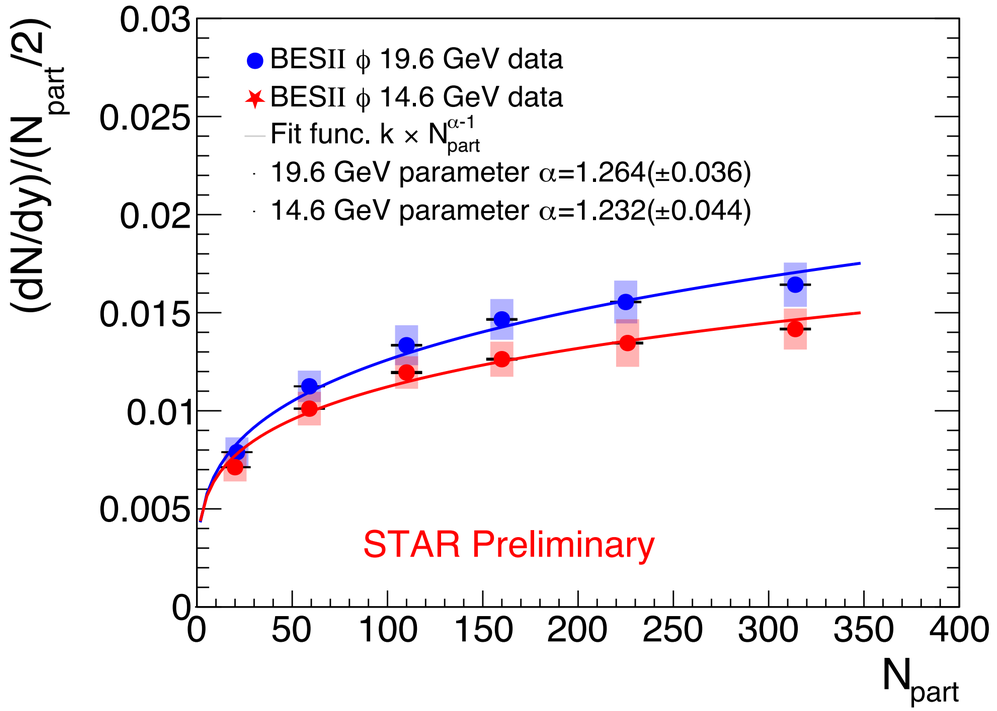


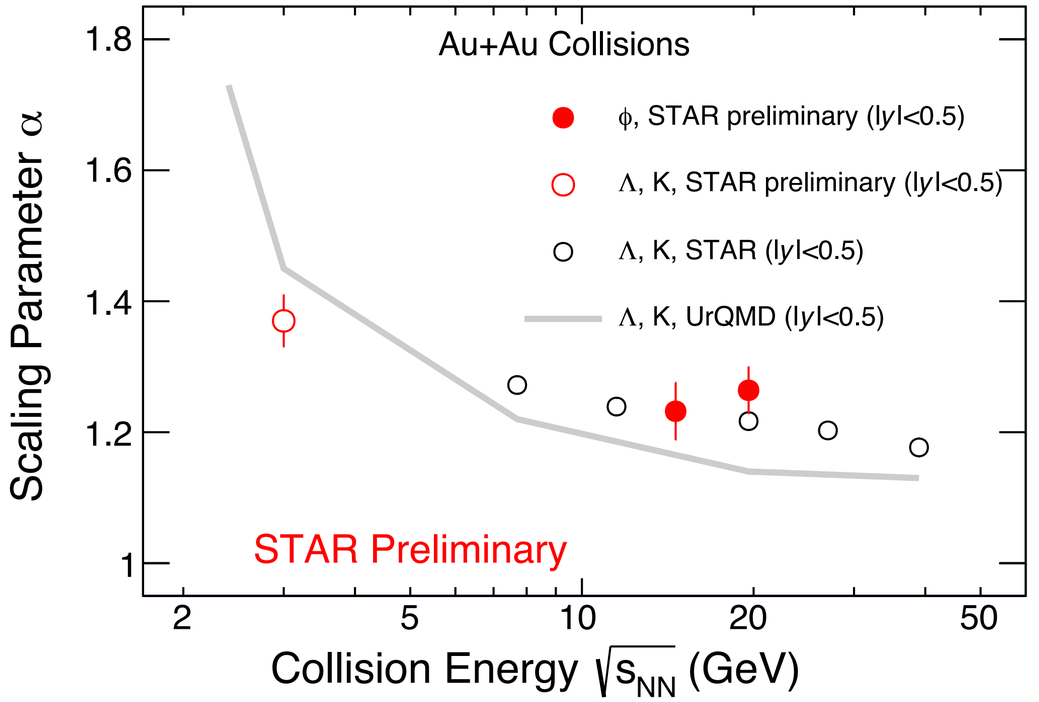




- K_S^0 measurements down to 0 p_T
- **Λ&Ξ**: Boltzmann function is employed for low p_T extrapolation
- ϕ: Levy function is used for low p_T extrapolation

Energy and centrality dependence of ϕ production

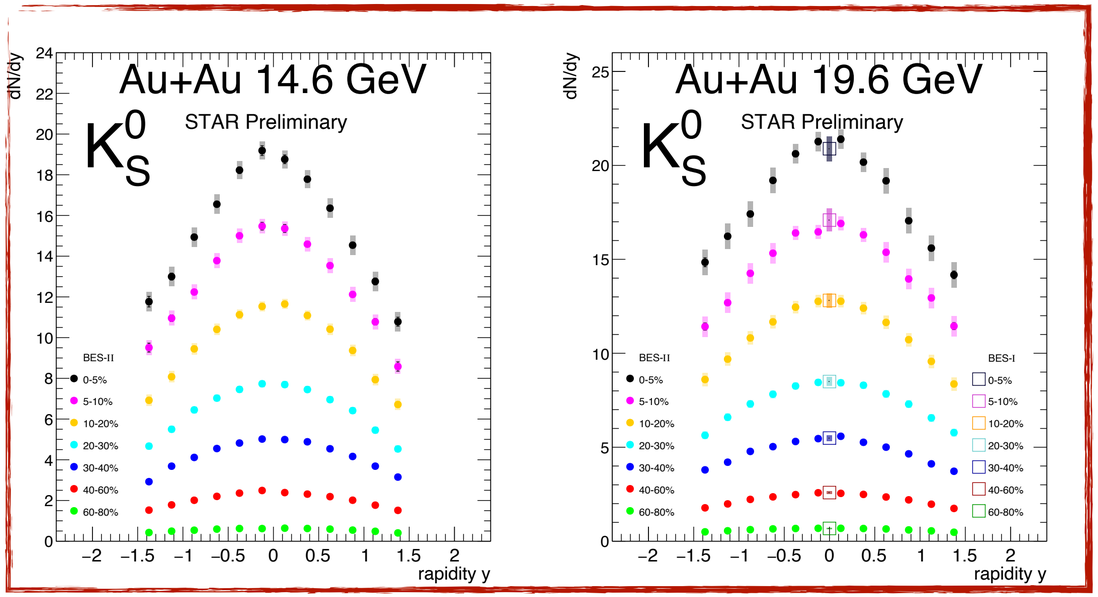


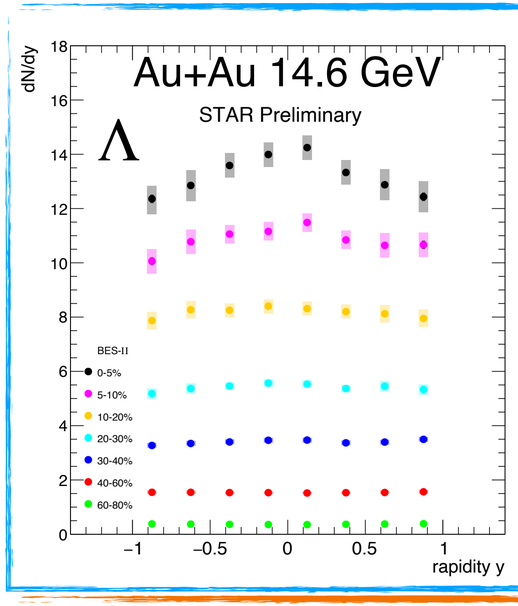


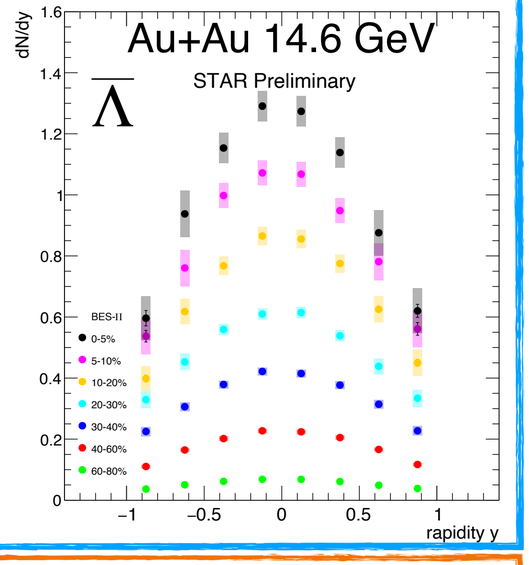
STAR, PRC 102 (2020) 034909
Bleicher *et al.*, JPG 25 (1999) 1859

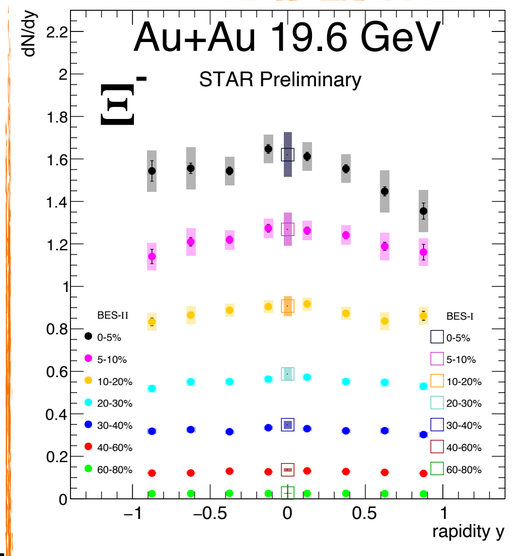
- Fit functions: $dN/dy = k \times \langle N_{part} \rangle^{\alpha}$
- Common centrality dependence for ϕ, Λ, K production at 19.6 GeV
- Above 7.7 GeV, data indicates a steeper increase on strangeness yields compared to UrQMD
  - Thermal production of strangeness in the QGP is not included in UrQMD

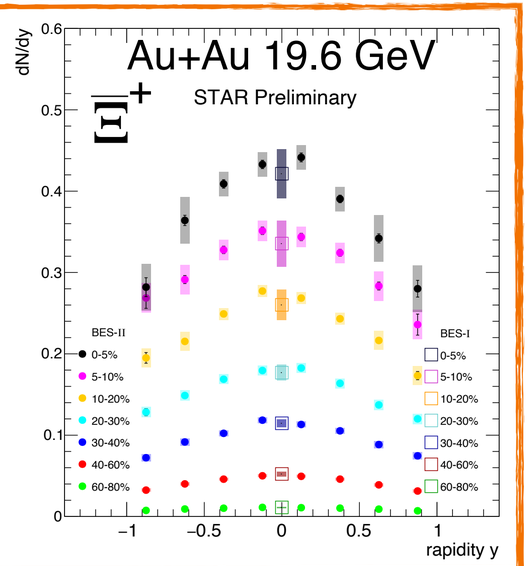
Rapidity distributions of strange hadrons











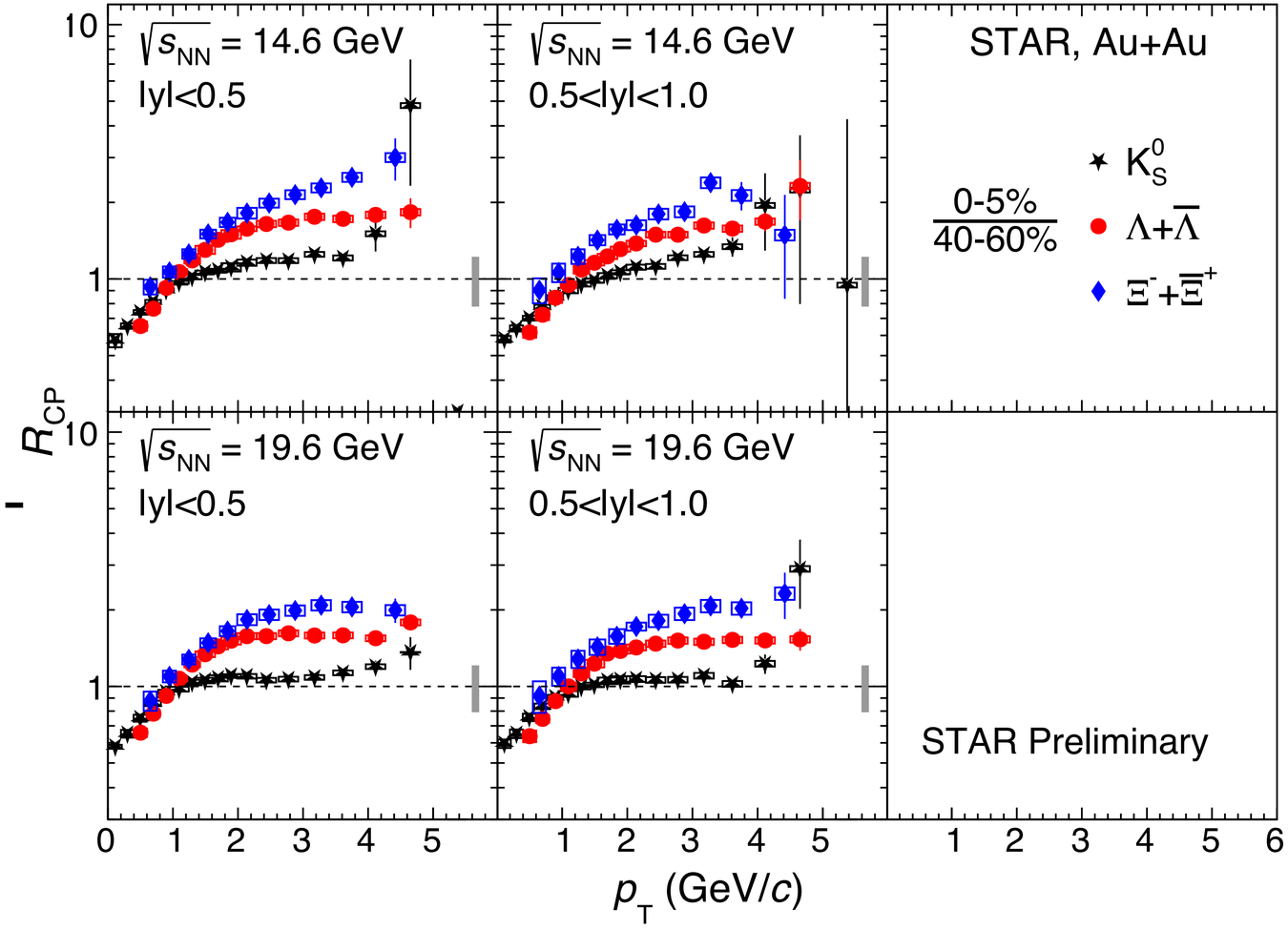
- New results for K^0_S, $\Lambda(\bar{\Lambda})$, $\Xi^-(\bar{\Xi}^+)$ for 14.6 and 19.6 GeV at BES-II
  - Consistent with BES-I results within uncertainty
  - Extended p_T and rapidity region
- Wider rapidity distributions for baryons compared to anti-baryons
  - Extra contributions from stopped baryons

Nuclear modification factor

- R_{CP} tends to be flat and larger than unity at $p_T > 2$ GeV/c
  - Radial flow
  - Quark coalescence

- The enhancement is stronger for multi-strange particles compared to K^0_S & Λ
  - A signature for QGP formation

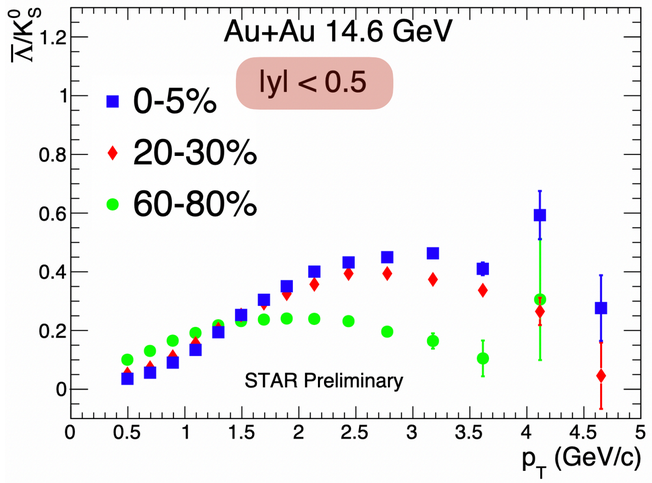
$$R_{\mathrm{CP}} = \frac{[(dN/dp_T)/\langle N_{\mathrm{coll}}\rangle]_{\mathrm{central}}}{[(dN/dp_T)/\langle N_{\mathrm{coll}}\rangle]_{\mathrm{peripheral}}}$$

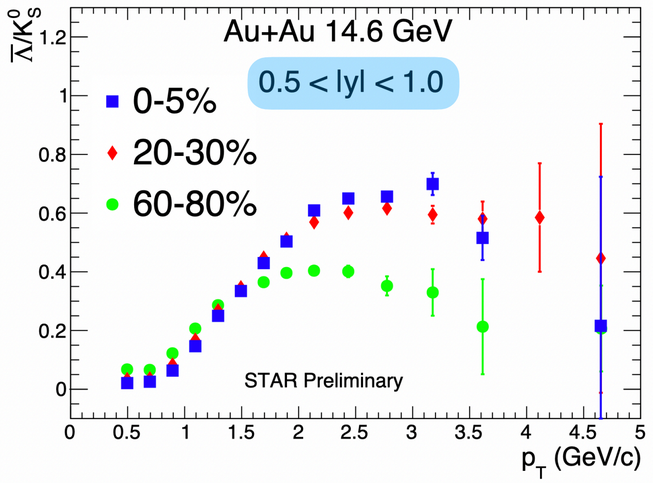


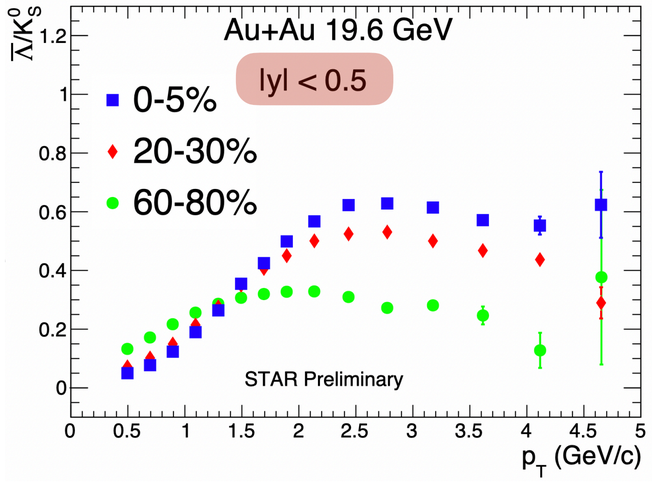
Baryon-to-meson ratios

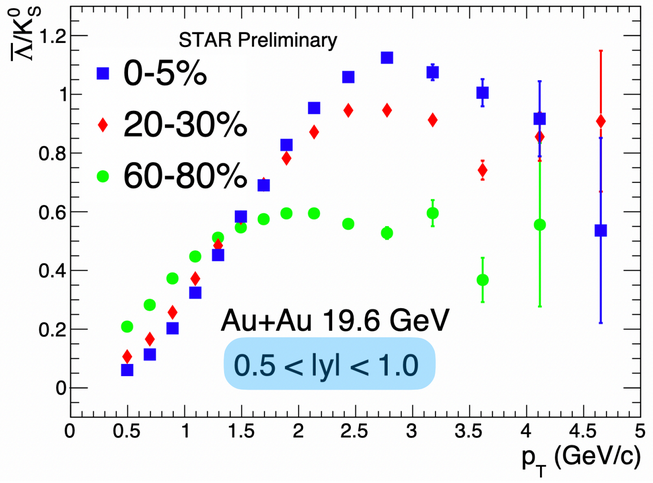
- Baryon-to-meson ratios: often utilized to probe deconfinement

- Baryon enhancement observed at 14.6 and 19.6 GeV in all measured rapidity regions
  - Consistent with QGP formation in central 14.6 and 19.6 GeV collisions
  - Clear centrality and rapidity dependence



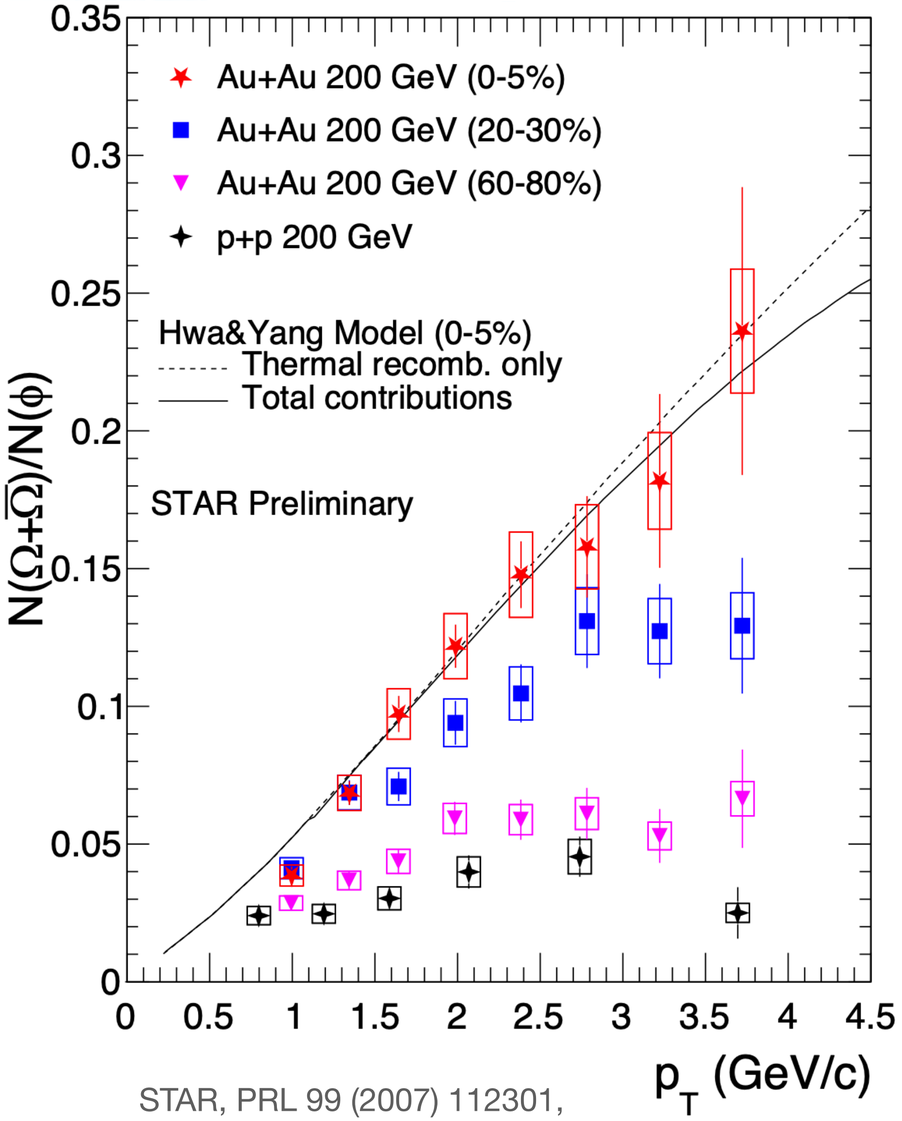






Baryon-to-meson ratios

- Good agreement between data and recombination models
  - Ω and ϕ are predominantly produced through the recombination of thermalized strange quarks in QGP
- Significant Ω enhancement over ϕ is observed at intermediate p_T with increasing system size
- Ω/ϕ ratio in p+p collisions is closed to that in peripheral Au+Au collisions
  - Hint of smooth transition from p+p collisions to Au+Au collisions

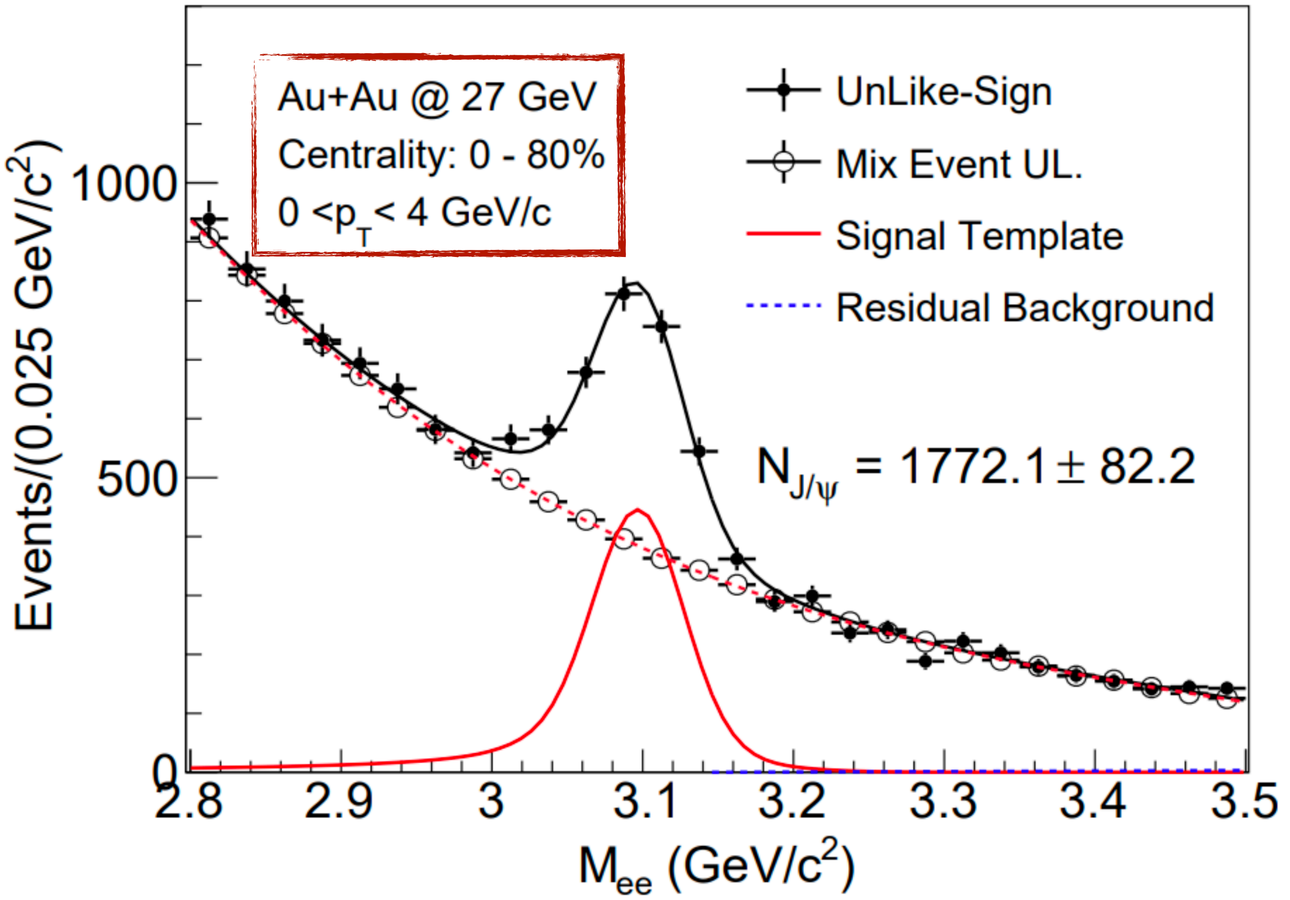


STAR, PRL 99 (2007) 112301,
STAR, PRC 79 (2009) 064903
Hwa and Yang, PRC 75 (2007) 054904

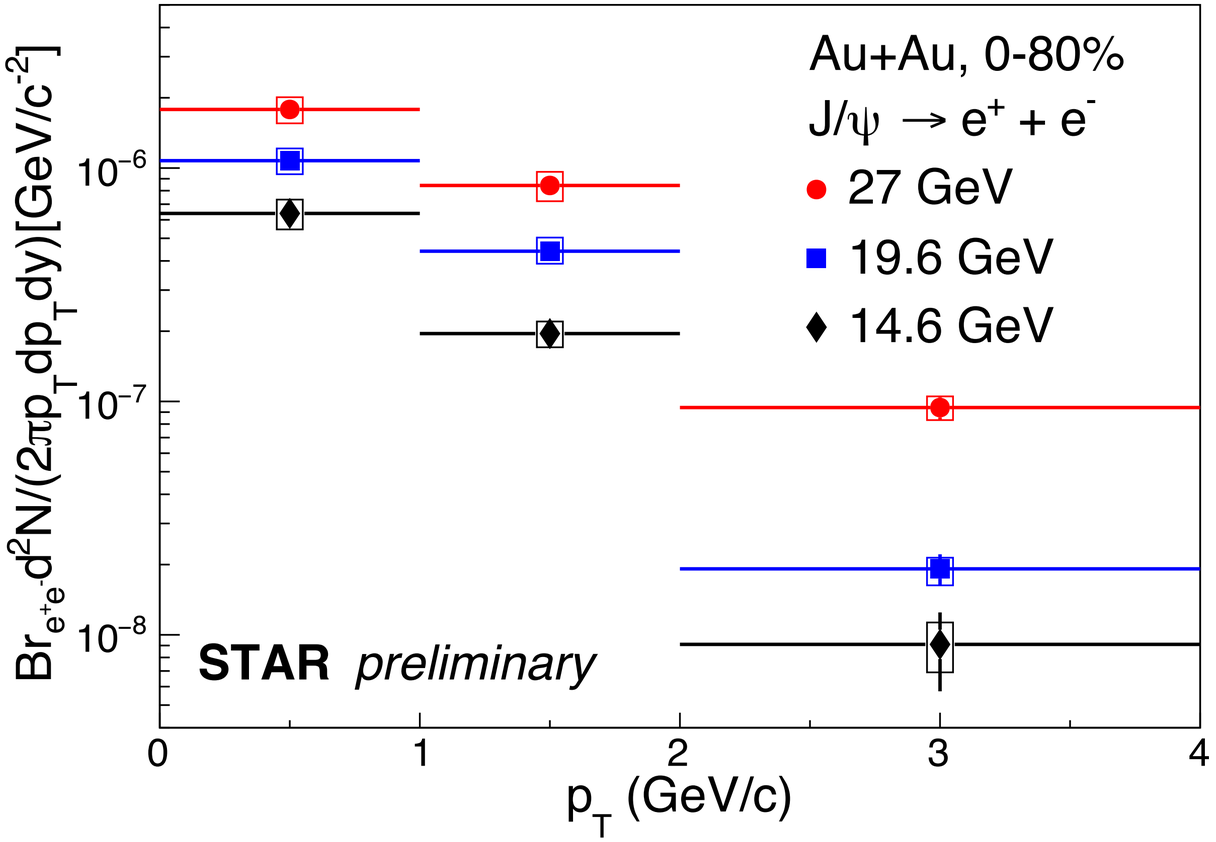
Quarkonium production

J/ψ signal extraction

- J/ψ template: MC simulation with detector effects
- Combinatorial background: mixed-event technique
- Residual background: a first order polynomial function



Inclusive J/ψ invariant yields

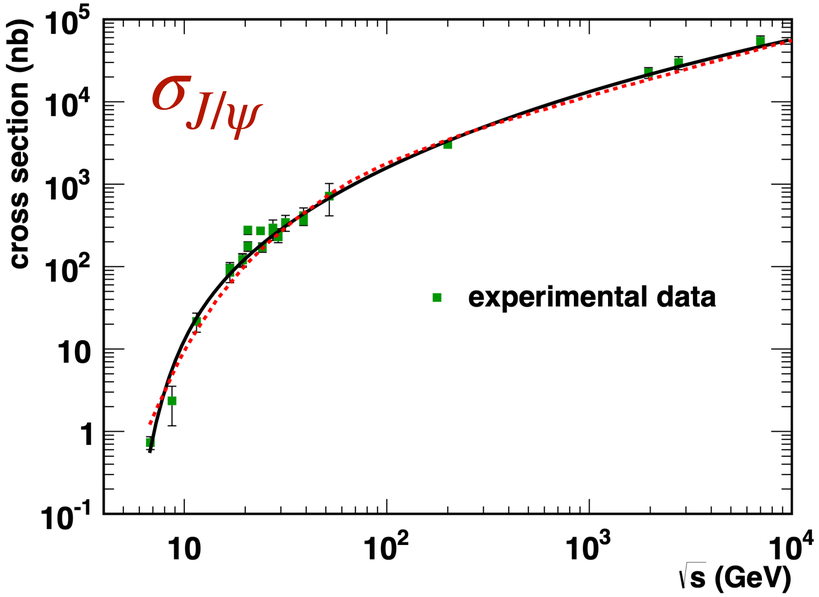


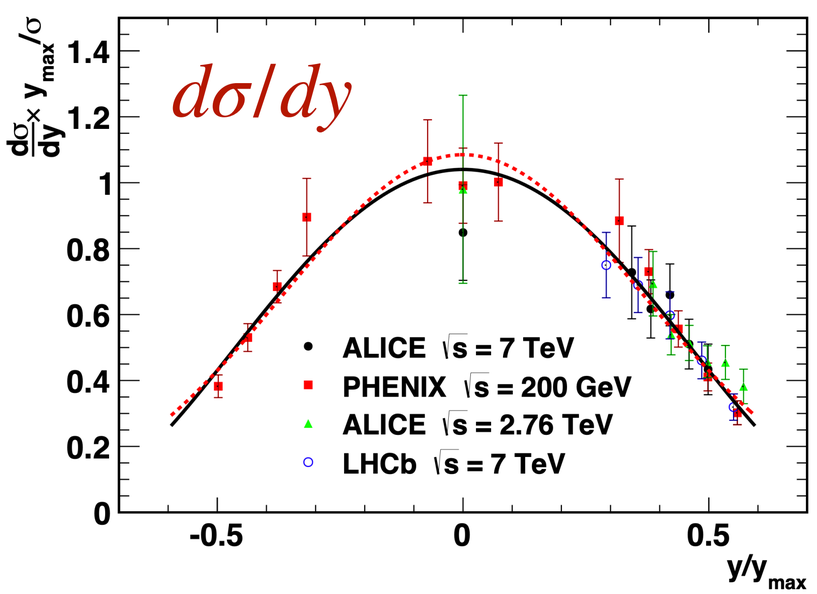
- Inclusive J/ψ yields as a function of p_T at mid-rapidity in Au+Au collisions at 14.6, 19.6 and 27 GeV

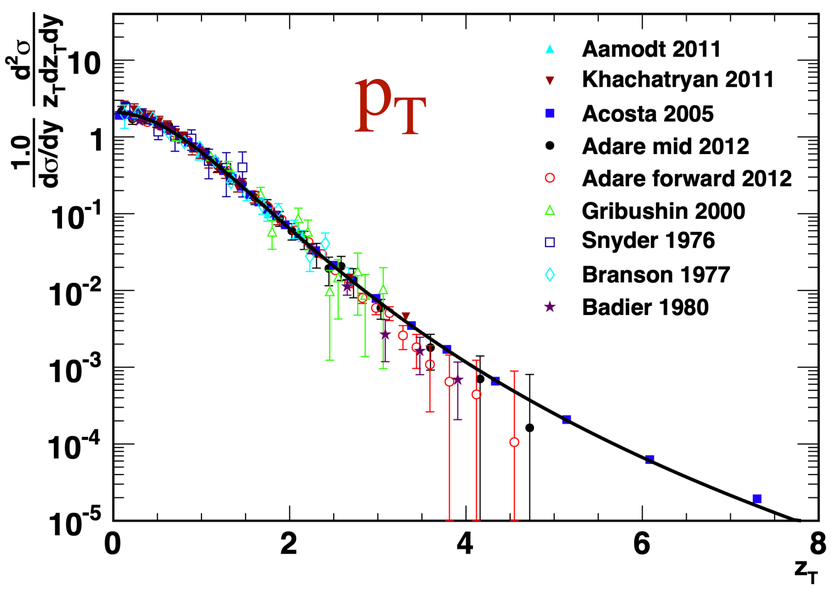
p+p baseline

- The p+p baselines at BES-II energies are extracted from world-wide data

Zha *et al.*, PRC 93 (2016) 024919







$$\sigma = \alpha \times \sigma_{CEM}$$

$$\frac{1}{\sigma}\frac{d\sigma}{dy/y_{max}} = ae^{-\frac{1}{2}(\frac{y/y_{max}}{b})^2}$$

$$\frac{1}{d\sigma/dy}\frac{d^2\sigma}{z_T dz_T dy} = a \times \frac{1}{(1+b^2 z_T^2)^n}$$

α: scaleing factor

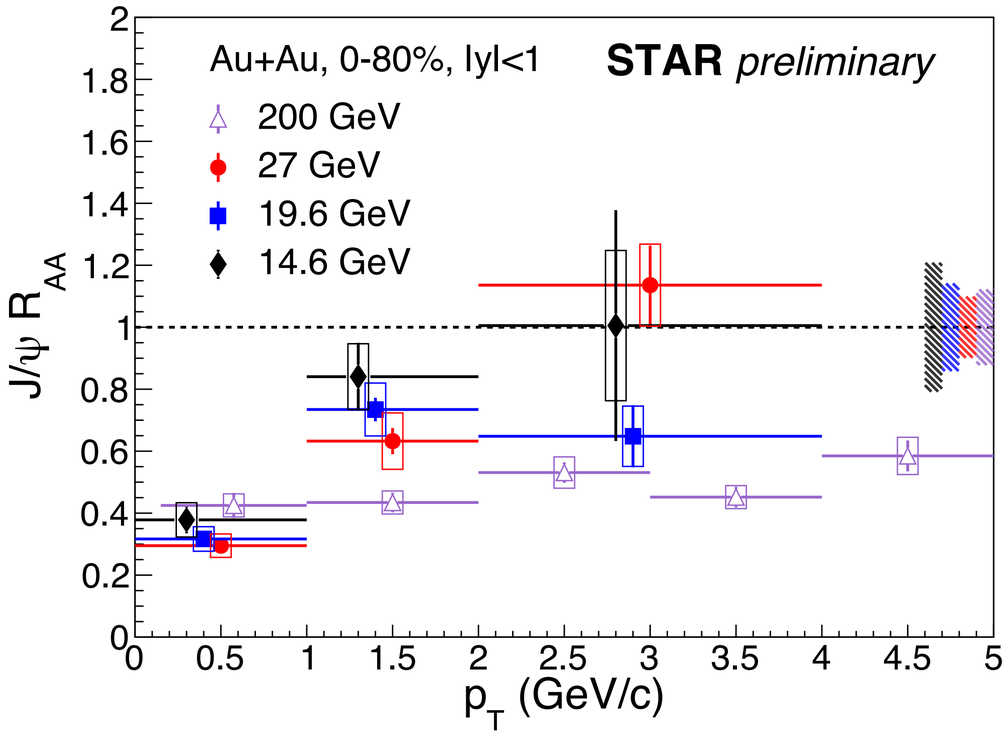
σ_{CEM}: σ from color evaporation model

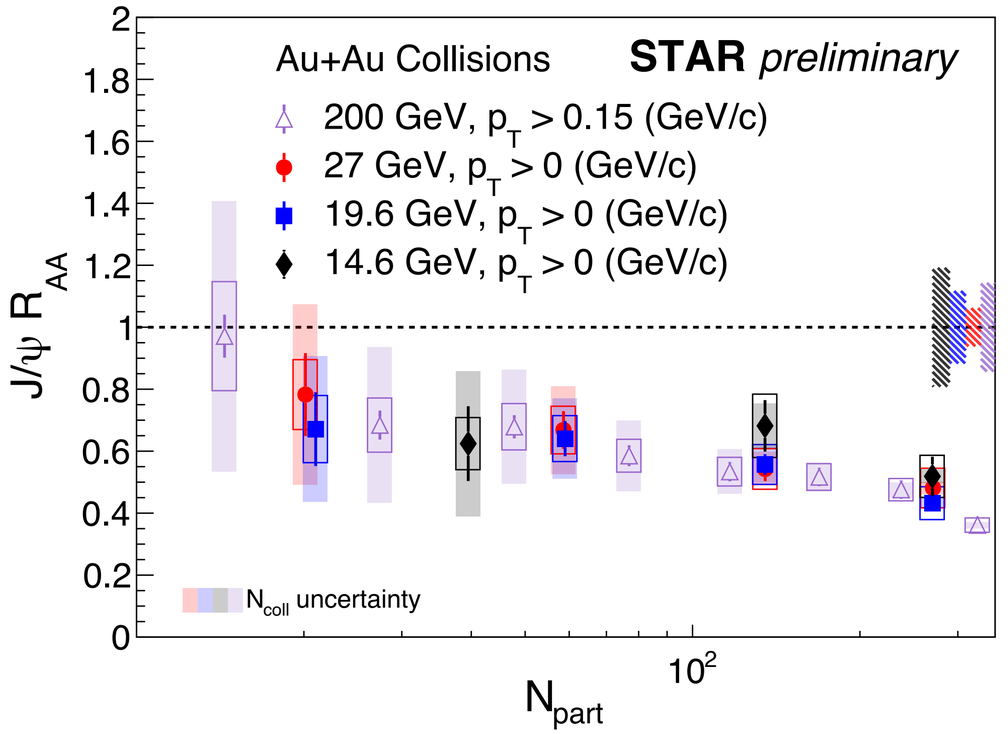
$$y_{max} = ln(\frac{\sqrt{s}}{m_{J/\psi}})$$

$$z_T = \frac{p_T}{\langle p_T \rangle}$$

The p_T and centrality dependence of J/ψ R_{AA}

STAR, PLB 797 (2019) 134917





- J/ψ is significant suppressed at low p_T
- R_{AA} increases with p_T at BES-II energies
- No significant p_T dependence at 200 GeV

$$R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

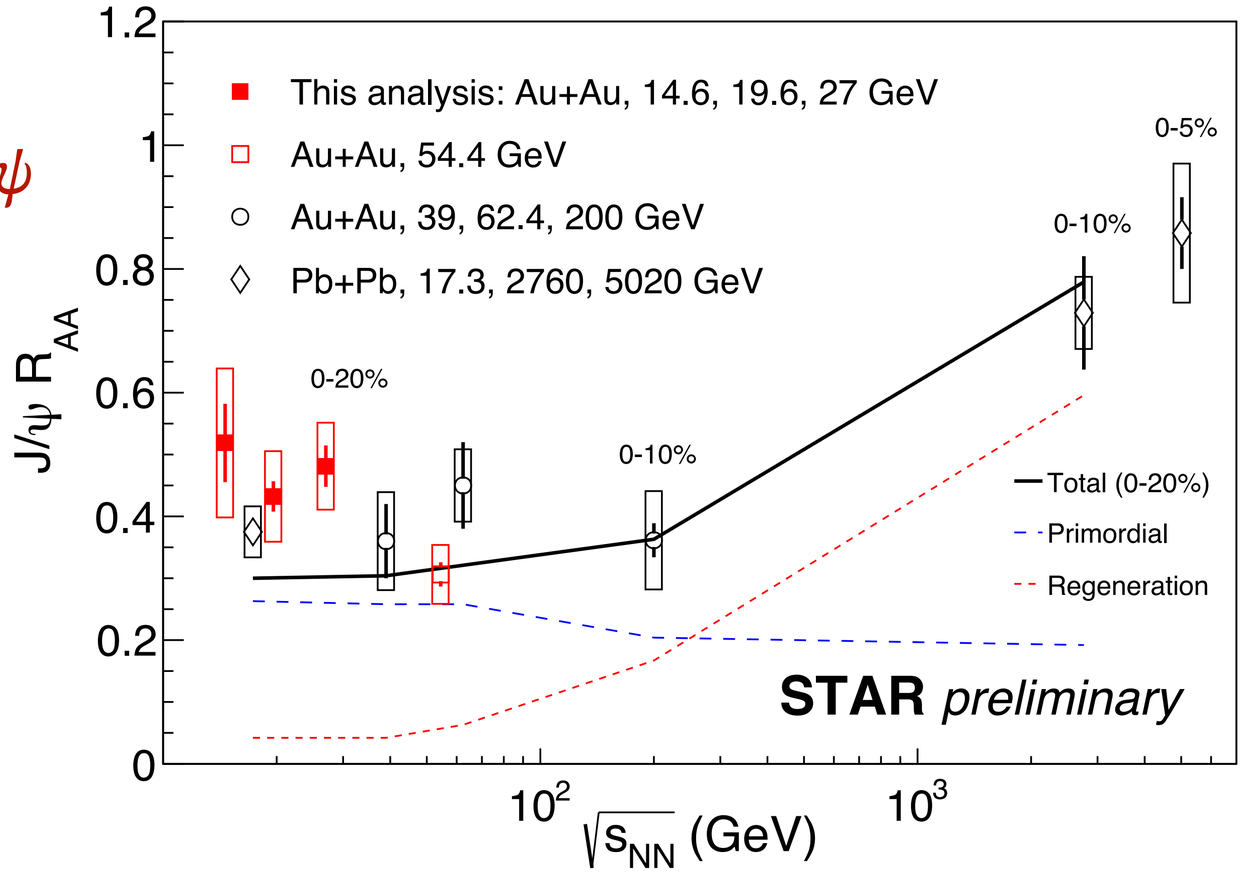
- Hint of decreasing trend towards central collisions
- R_{AA} shows no energy dependence at RHIC with similar system size

Energy dependence of J/ψ R_{AA}

- J/ψ R_{AA} at 14.6, 19.6 and 27 GeV follows the trend
- No significant energy dependence of J/ψ R_{AA} in central collisions up to 200 GeV
- Regeneration dominates at LHC energies
- Transport model qualitatively describes the observed energy dependence

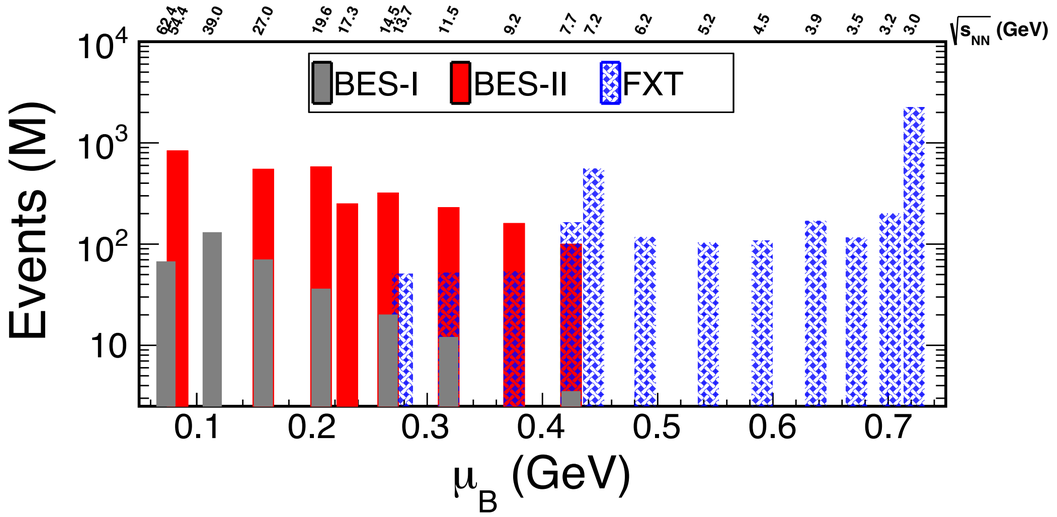
Zhao and Rapp, PRC 82 (2010) 064905
Kluberg, EPJC 43 (2005) 145
NA50, PLB 477 (2000) 28

STAR, PLB 771 (2017) 13
STAR, PLB 797 (2019) 134917
ALICE, PLB 734 (2014) 314
ALICE, NPA 1005 (2021) 121769



Summary and outlook

- Precise strangeness measurements with extended p_T and rapidity at BES-II
  - Wider rapidity distributions for baryons compared to anti-baryons
  - Baryon enhancement is observed from 14.6 to 200 GeV
  - Smooth trend in strangeness enhancement from small to large systems
- Systematically study J/ψ production at BES-II
  - No significant collision energy and system dependence of J/ψ R_{AA} at RHIC energy
  - J/ψ R_{AA} increases with p_T, hint of decreasing with centrality
- More strangeness results will be released in the coming sQM with BES-II data

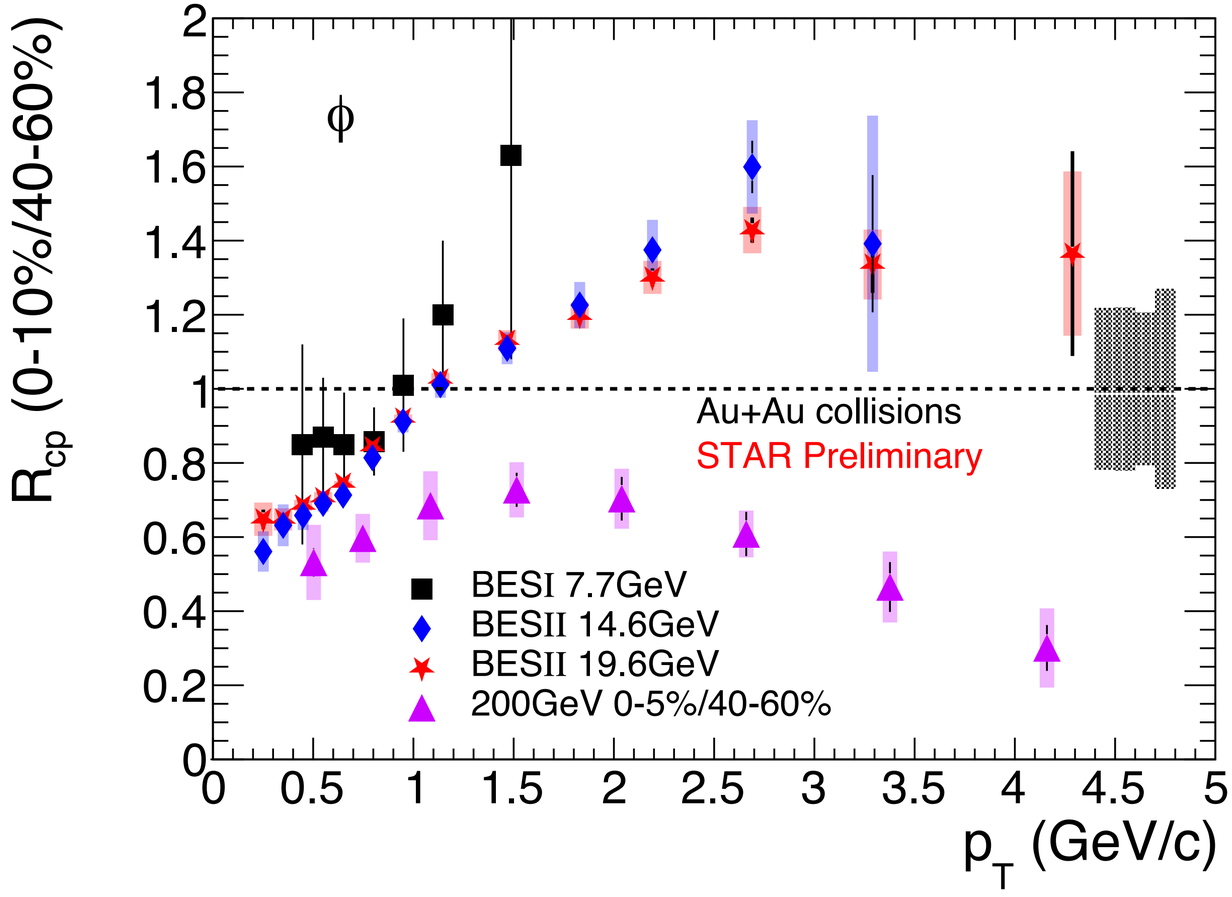


Backup

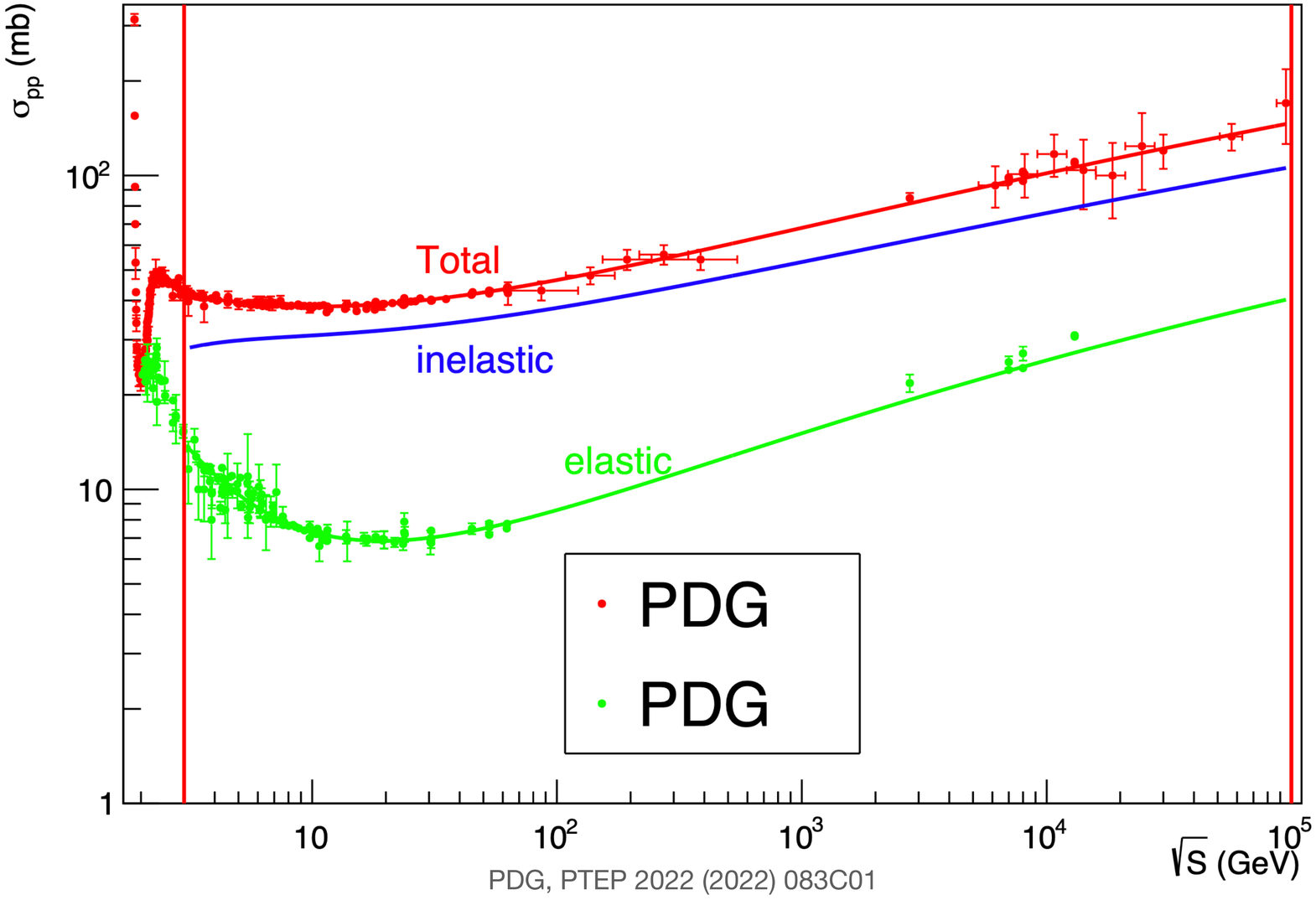
Energy dependence of R_{CP} for ϕ

- $R_{CP} > 1$ for higher p_T at 19.6 GeV and lower energies
- $R_{CP} < 1$ for the whole p_T region at top RHIC energy
  - Stronger energy loss in QGP

STAR, PRL 99 (2007) 112301



Inelastic pp cross section



PDG, PTEP 2022 (2022) 083C01