# Highlights from nuclear collisions studied by the STAR experiment

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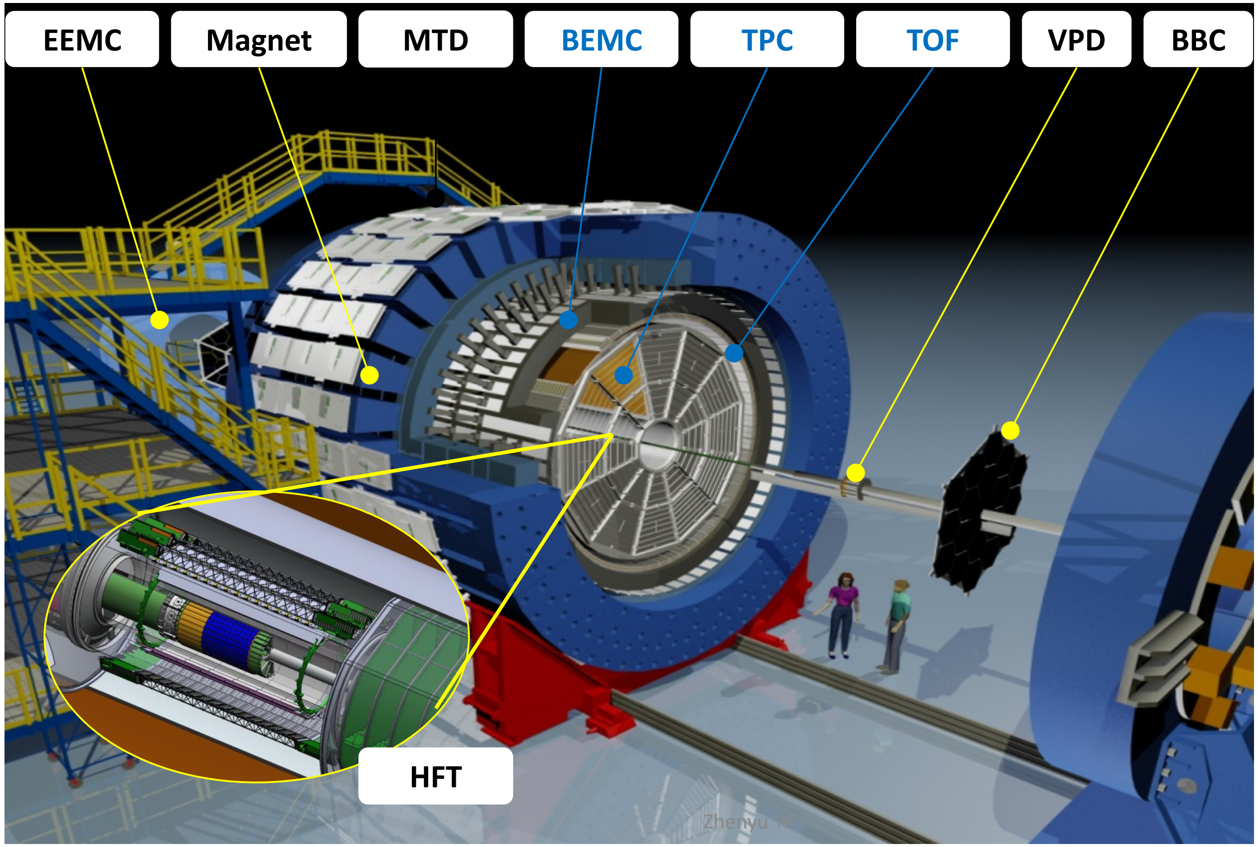
# Outline

- ☑ Introduction to the STAR experiment
- ☑ Selected results on hadrons in hot and nuclear environment including hypernuclei
  - – Heavy and light hadron production in hot medium
  - – Hypertriton binding energy and mass diff. measurement
  - – Search for nOmega bound state
- ☑ Summary and Outlook
  - – BES-II and fixed target

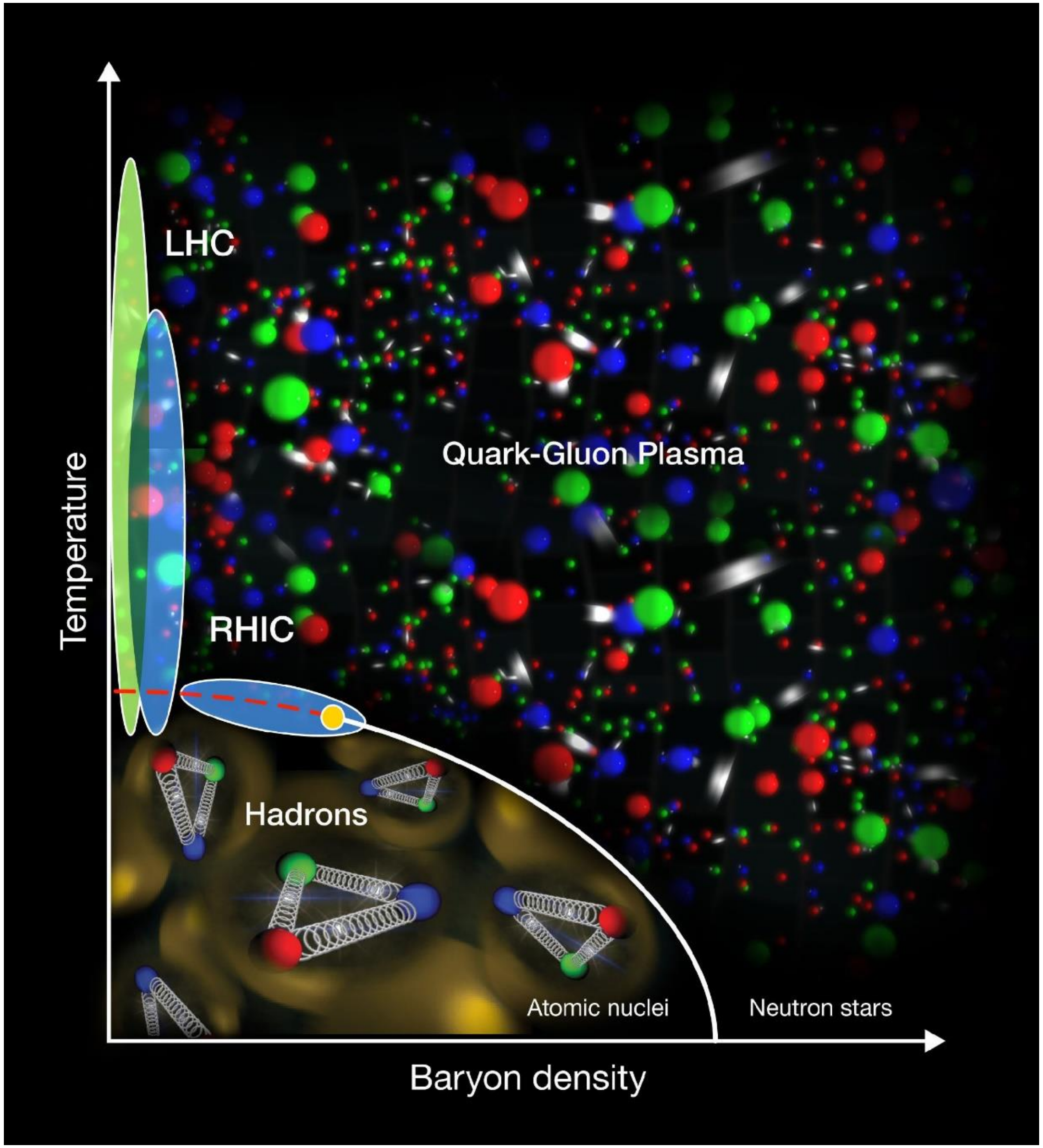
# The STAR detectors




- **Tracking and PID (full $2\pi$)**
  TPC: $|\eta| < 1$
  TOF: $|\eta| < 1$
  BEMC: $|\eta| < 1$
  EEMC: $1 < \eta < 2$
  HFT (2014-2016): $|\eta| < 1$
  MTD (2014+): $|\eta| < 0.5$
- **MB trigger and event plane reconstruction**
  BBC: $3.3 < |\eta| < 5$
  FMS: $2.5 < \eta < 4$
  VPD: $4.2 < |\eta| < 5$
  ZDC: $6.3 < |\eta|$
- **On-going/future upgrades**
  EPD (2018): $2.1 < |\eta| < 5.1$
  iTPC (2019): $|\eta| < 1.5$
  eTOF (2019): $-1.6 < \eta < -1$
  FCS (2021+): $2.5 < \eta < 4$
  FTS (2021+): $2.5 < \eta < 4$

☑ STAR: a complex set of various detectors, a wide range of measurements and a broad coverage of different physics topics

# The STAR experiment and physics




☑ RHIC top energy
p+p,p+Al,p+Au,$^{3}$He+Au,Cu+Cu,Cu+Au,Ru+Ru,Zr+Zr,Au+Au,U+U

- QCD at high energy density/ temperature
- Properties of QGP,EoS
- Polarized proton: nucleon structure…

☑ Beam energy scan
Au+Au vs. sqrt(s)

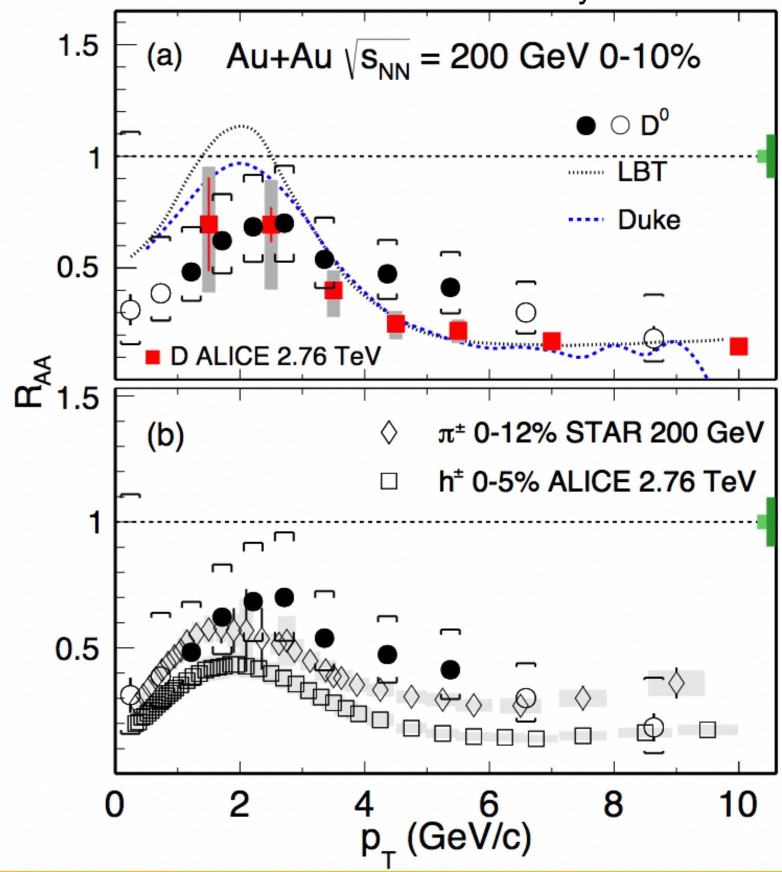
- QCD phase transition
- Search for critical point
- Turn-off of QGP signatures

☑ Fixed target program
Au+Au @ 4.5 GeV, Al+Au @ 4.9 GeV

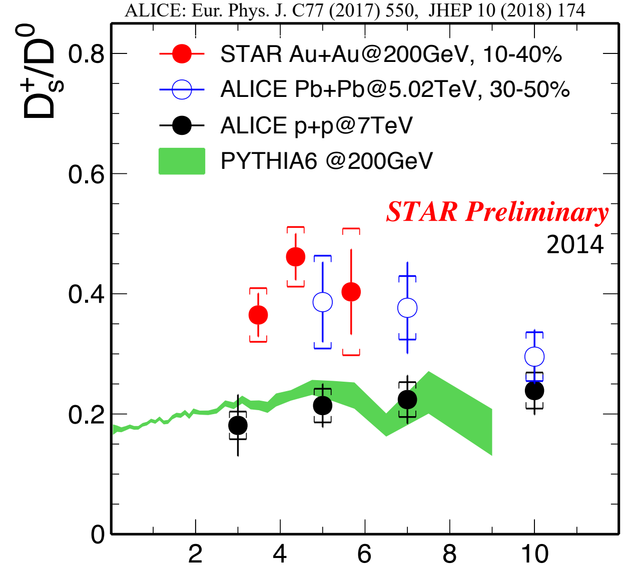
- High baryon density regime

# Open heavy flavor production

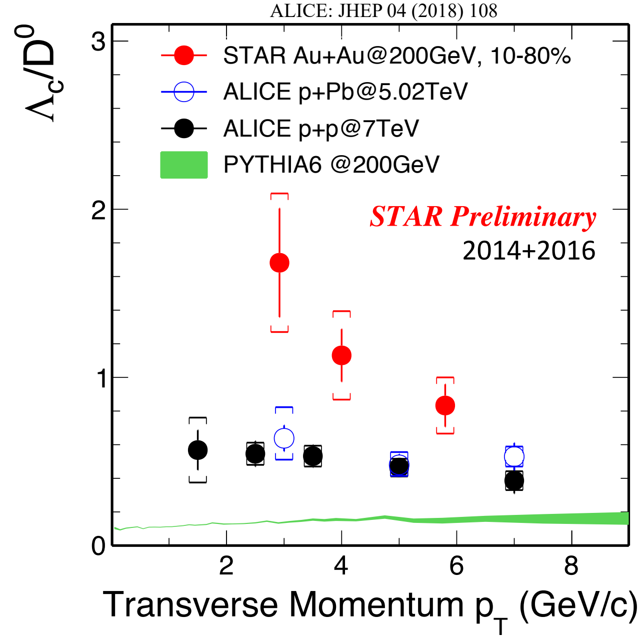
STAR Col. Phys. Rev. C 99.034908(2019)




ALICE: Eur. Phys. J. C77 (2017) 550, JHEP 10 (2018) 174



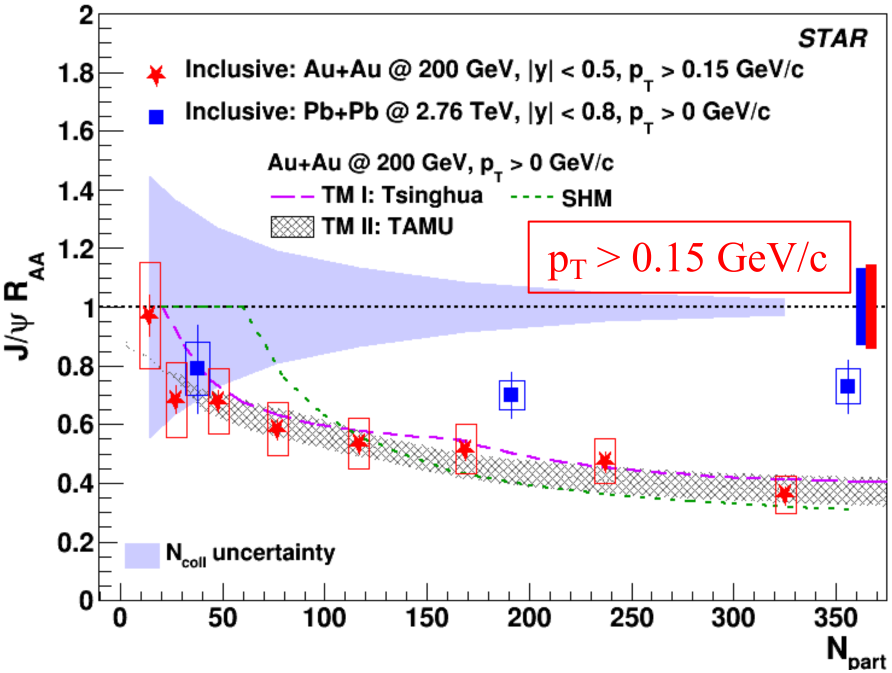

ALICE: JHEP 04 (2018) 108



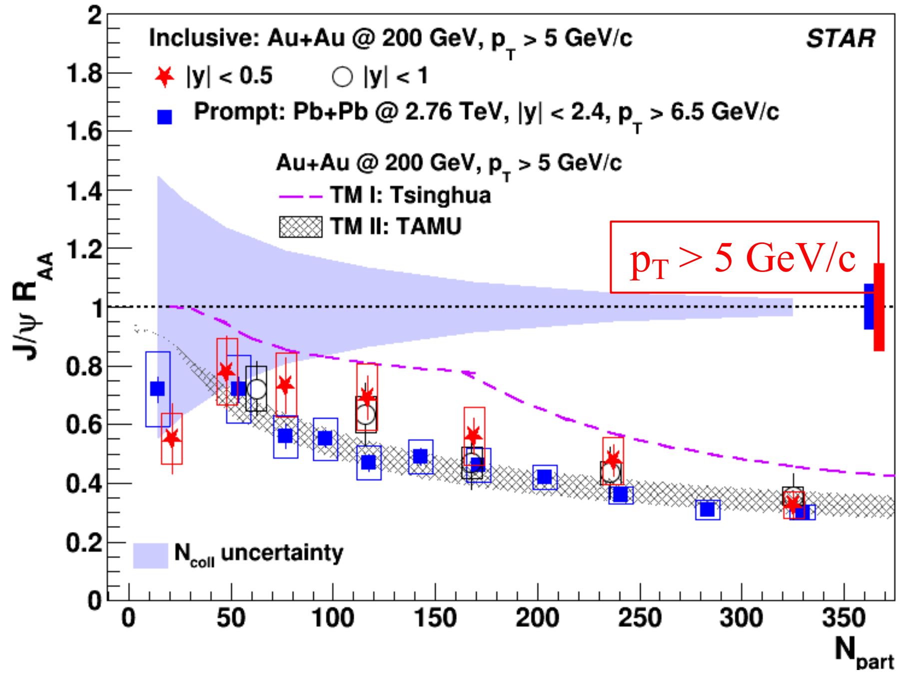

- ☑ Strong suppression of high $p_T$ $D^0$ in central AA Collisions: e-loss
- ☑ The open charm hadron ratio are significantly higher than p+p collisions: charm quark hadronization by coalescence with light flavors

# Quarkonium production

*arXiv:1905.13669 , submitted to P.L.B*

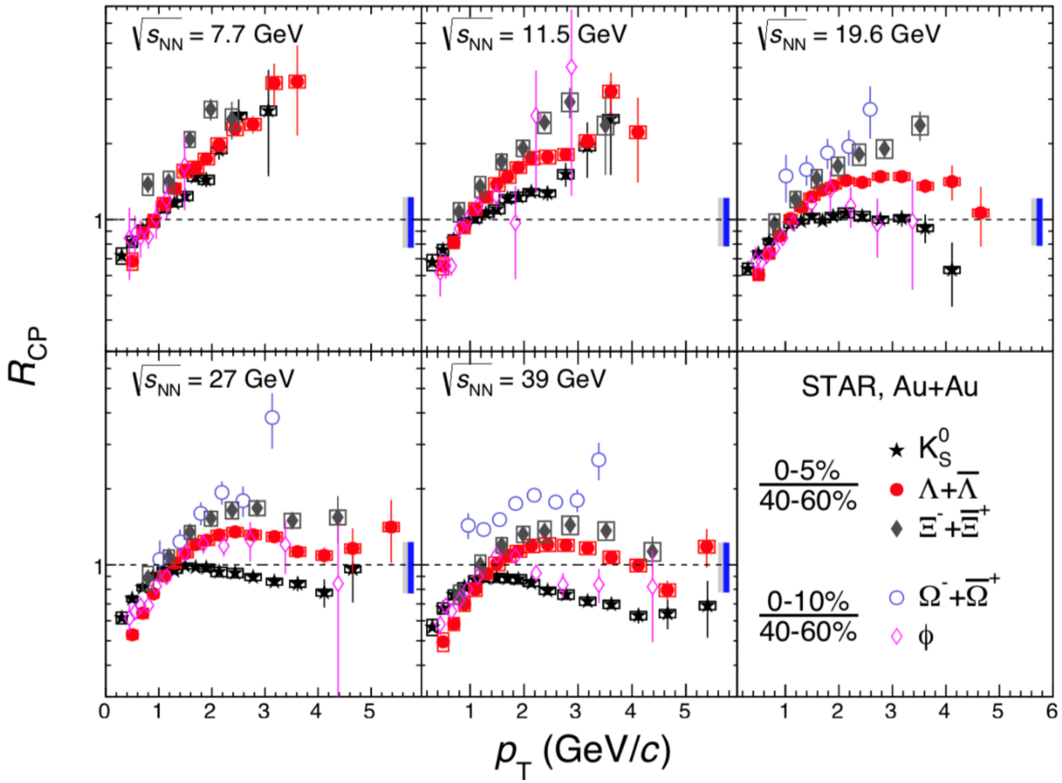



Inclusive J/ψ from STAR

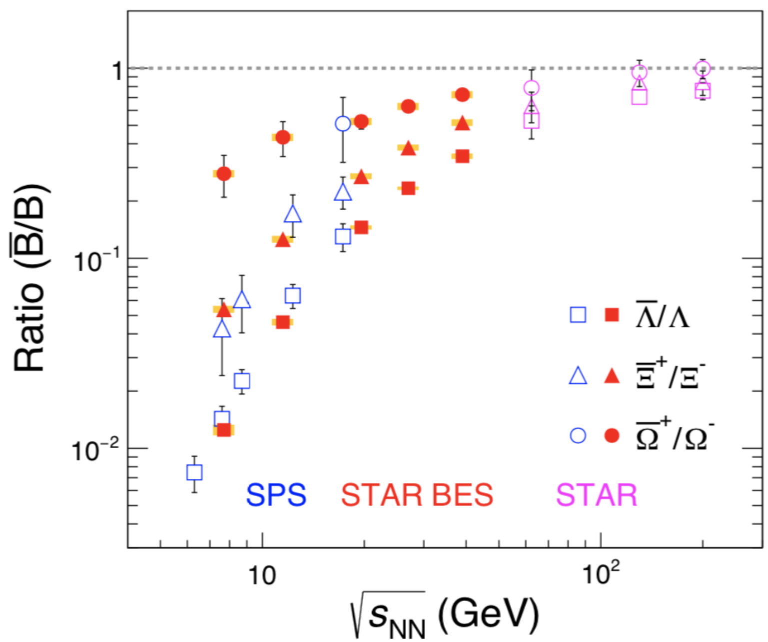



- Both, low and high $p_T$, $R_{AA}$ decreases from peripheral to central collisions
- Low $p_T$ : more suppressed at RHIC in central and semi-central
  → Less regeneration due to lower charm production
- High $p_T$ : hint of systematically less suppression at RHIC for semi-central
  → Probably stronger dissociation at LHC due to high temperature

# Strange hadron production in BES-I




STAR Col. arXiv: 1906.03732

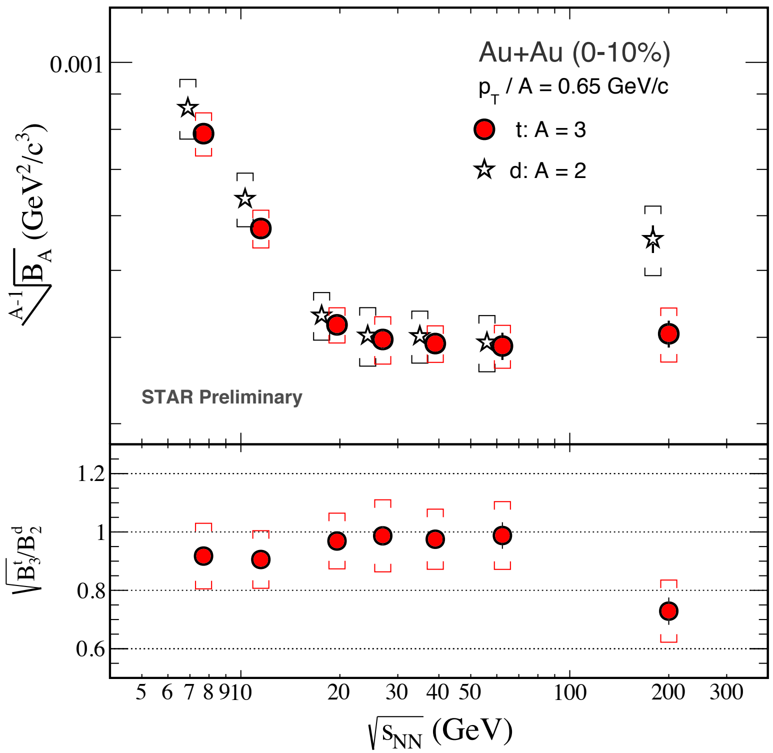



- No $K^0_S$ suppression in Au+Au 7.7 and 11.5 GeV
- Cronin effect and other effects (radial flow) compete with partonic energy loss
- Intermediate $p_T$, particle $R_{CP}$ difference becomes smaller @ 7.7 and 11.5 GeV

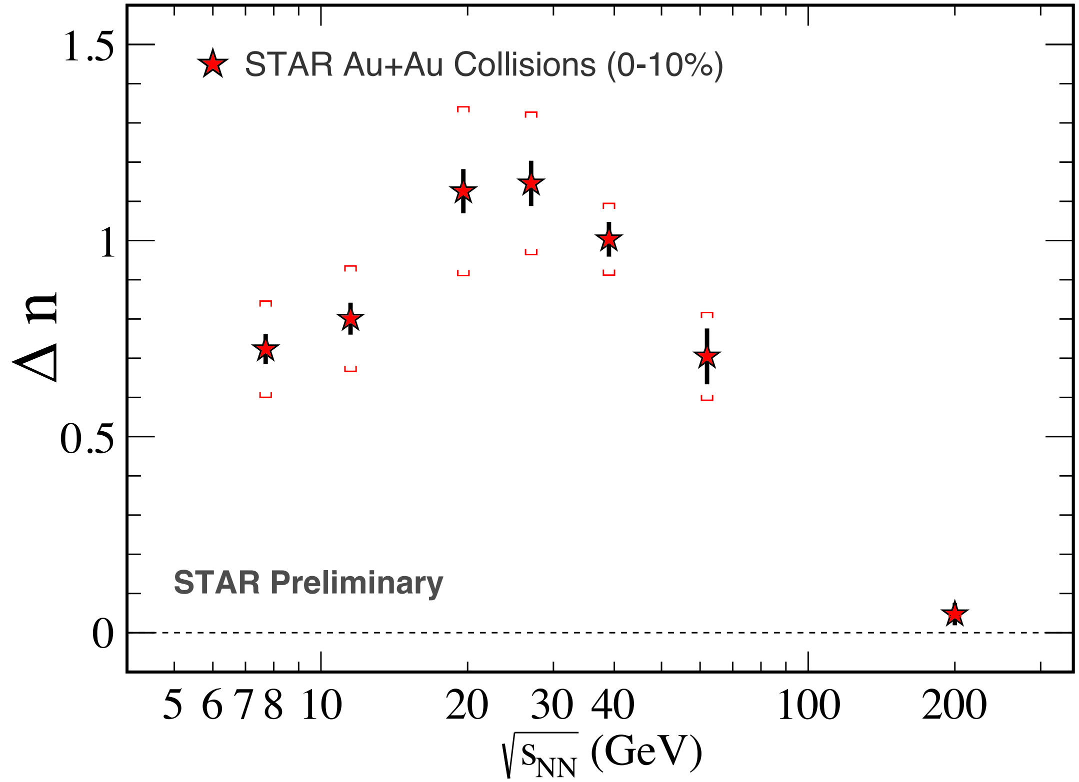
- Antibaryon/baryon ratios lie in a trend with NA49 data, and increase with strange quark at low energies

$$\bar{\Omega}^+/\Omega^- > \bar{\Xi}^+/\Xi^- > \bar{\Lambda}/\Lambda > \bar{p}/p$$

# Triton production in BES-I



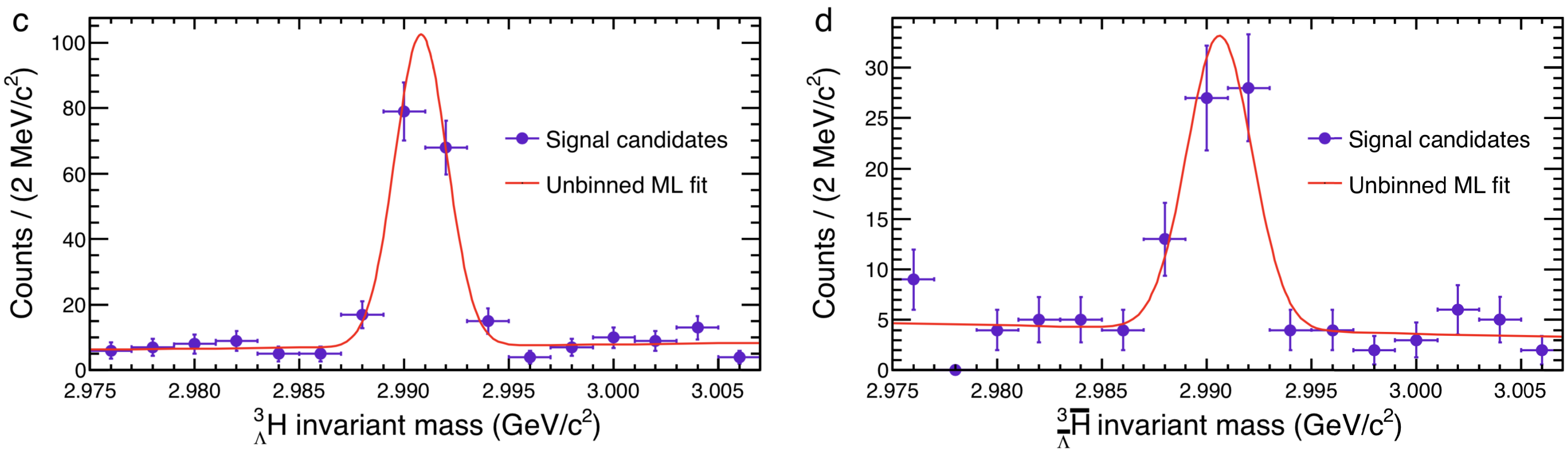

$$E_A \frac{d^3 N_A}{dp^3} \approx B_A \left( E_p \frac{d^3 N_p}{dp^3} \right)^A$$



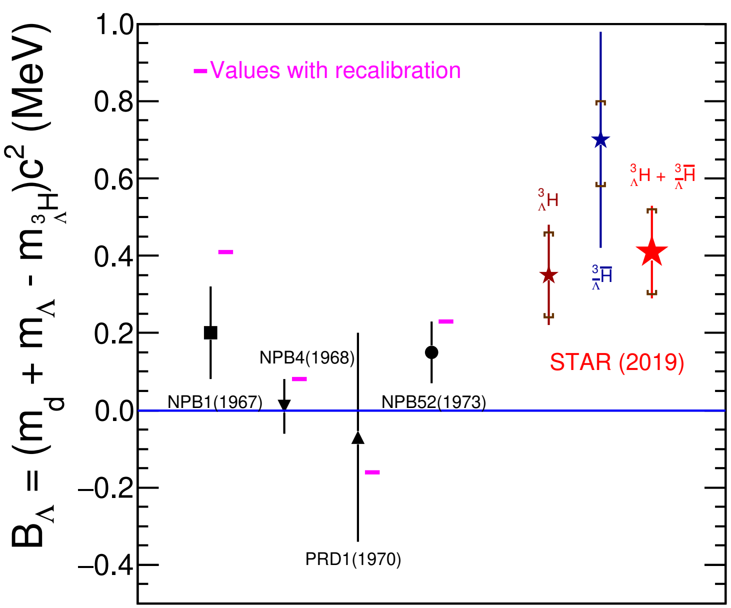

$N_t \cdot N_p / N_d^2 \approx g(1 + \Delta n)$, with g = 0.29

- Coalescence parameter $B_A \propto V_f^{1-A}$ in thermal model. $\sqrt{B_3^t}$ similar to $B_2^d$ for $\sqrt{s_{NN}} < 62$ GeV
- Non-monotonic energy dependence in neutron density fluctuation $\Delta n = \langle \delta_n^2 \rangle / \langle n^2 \rangle$

# Hypertrion binding energy measurements




STAR Col. arXiv 1904.10520




$$m_{^3_\Lambda \mathrm{H}} = 2990.95 \pm 0.13(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}/c^2$$

$$m_{^3_{\bar{\Lambda}} \overline{\mathrm{H}}} = 2990.60 \pm 0.28(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}/c^2$$

$$B_\Lambda = 0.41 \pm 0.12(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}$$

- ☑ Almost bg free with STAR HFT/TPC
- ☑ STAR data differs from zero and larger than the commonly used results from 1973

# New data : stronger YNN interaction?

Hildenbrand, Hammer, arXiv: 1904.05818

- Three-body hypernuclei from Pionless EFT
  - The d-Lambda scattering length and hyper triton radius is strongly depend on the BE. At fixed cutoff an increase in the BE will require a more attractive three-body force

$$B_\Lambda = 0.13 \pm 0.05\mathrm{MeV}$$

$$a_{\Lambda d}^{y=0.086} = 13.80^{+3.75}_{-2.03}\ \mathrm{fm}$$

  - Our data require higher-order correction to the effective d-Lambda assumption

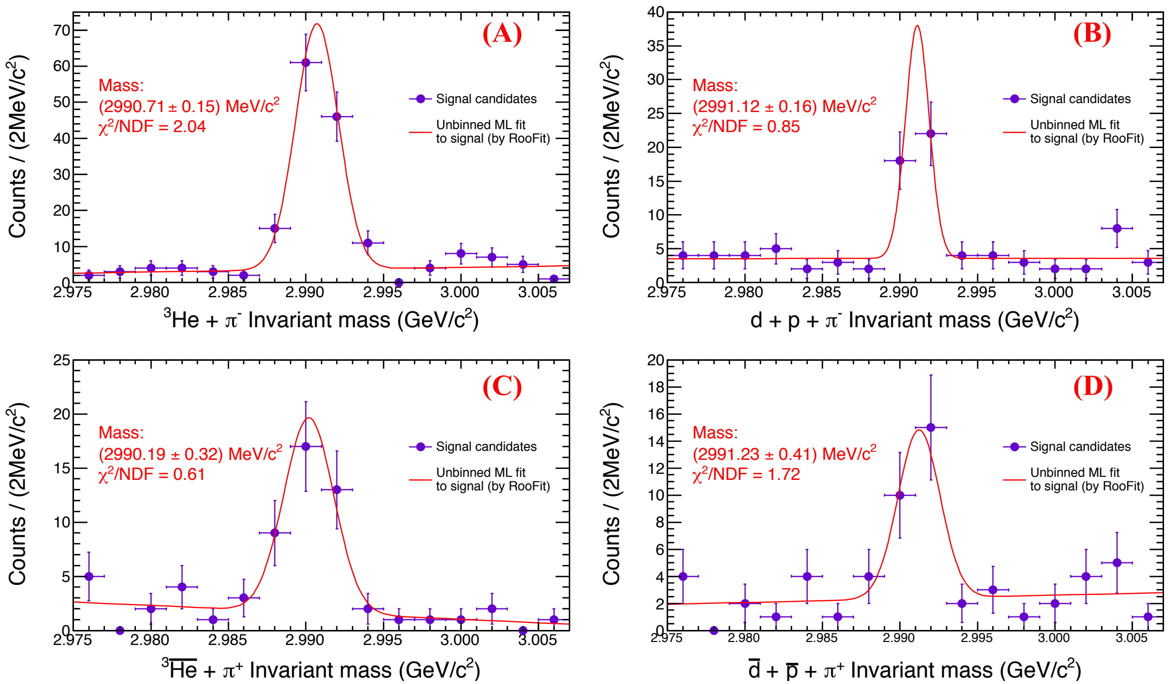
- Updated calculation on YN interaction within Chiral EFT: the in-medium interaction of the Lambda predicted by the new potential is now considerably more attractive and becomes repulsive at much higher nuclear densities

| YN interaction | ${}^{3}_{\Lambda}\mathrm{H}$ |
|---|---|
| NLO13(650) w/ $\Sigma$ | 0.087 |
| NLO13(650) w/o $\Sigma$ | 0.095 |
| NLO19(650) w/ $\Sigma$ | 0.095 |
| NLO19(650) w/o $\Sigma$ | 0.100 |
| Jülich'04 w/ $\Sigma$ | 0.046 |
| Jülich'04 w/o $\Sigma$ | 0.162 |
| NSC97f w/ $\Sigma$ | 0.099 |
| NSC97f w/o $\Sigma$ | 0.062 |

Haidenbauer, Meibner, Nogaa, arXiv: 1906.11681

"For a significantly larger BE, the excellent description of the LambdaN and SigmaN data can be maintained, by an approximate re-adjustment of the potential strengths in the LambdaN $^1S_0$ and $^3S_1$ partial waves - though at the expense of giving up the strict SU(3) constraints on the LECs between the LambdaN and SigmaN channels."

# Extend the nuclei sector with strangeness




- The STAR measurement is related to the knowledge of masses of its decay daughter and is carried out with the CPT assumption for decay products
- In the future, as the uncertainty in ³He mass diff. improves, our result under this assumption will remain constant and is therefore very useful

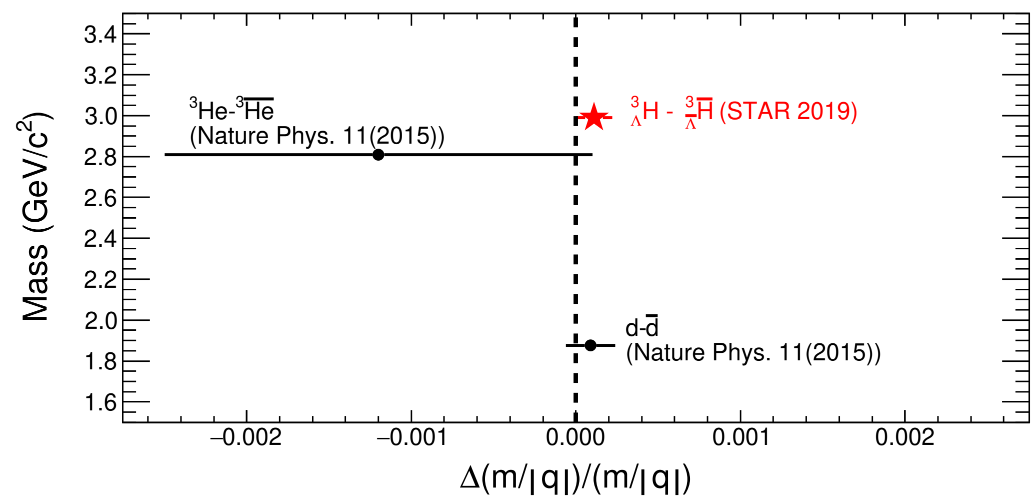
STAR Col. arXiv:1904.10520

A=3 with strangeness in nuclei

$$[\,1.1 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.})] \times 10^{-4}$$

A=3 from ³He (ALICE)

$$(-1.2 \pm 0.9(\text{stat.}) \pm 1.0(\text{syst.})) \times 10^{-3}$$

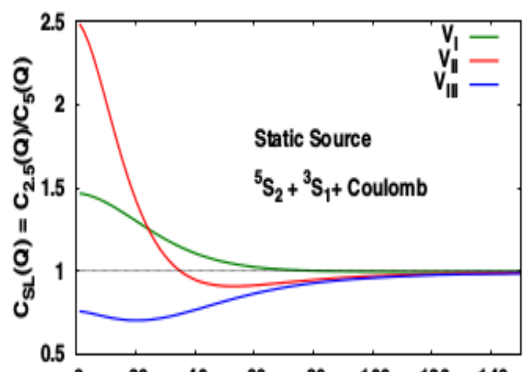


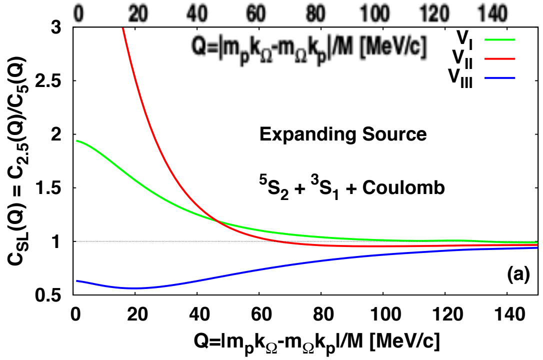
# Exotic hadron with multi-strangeness

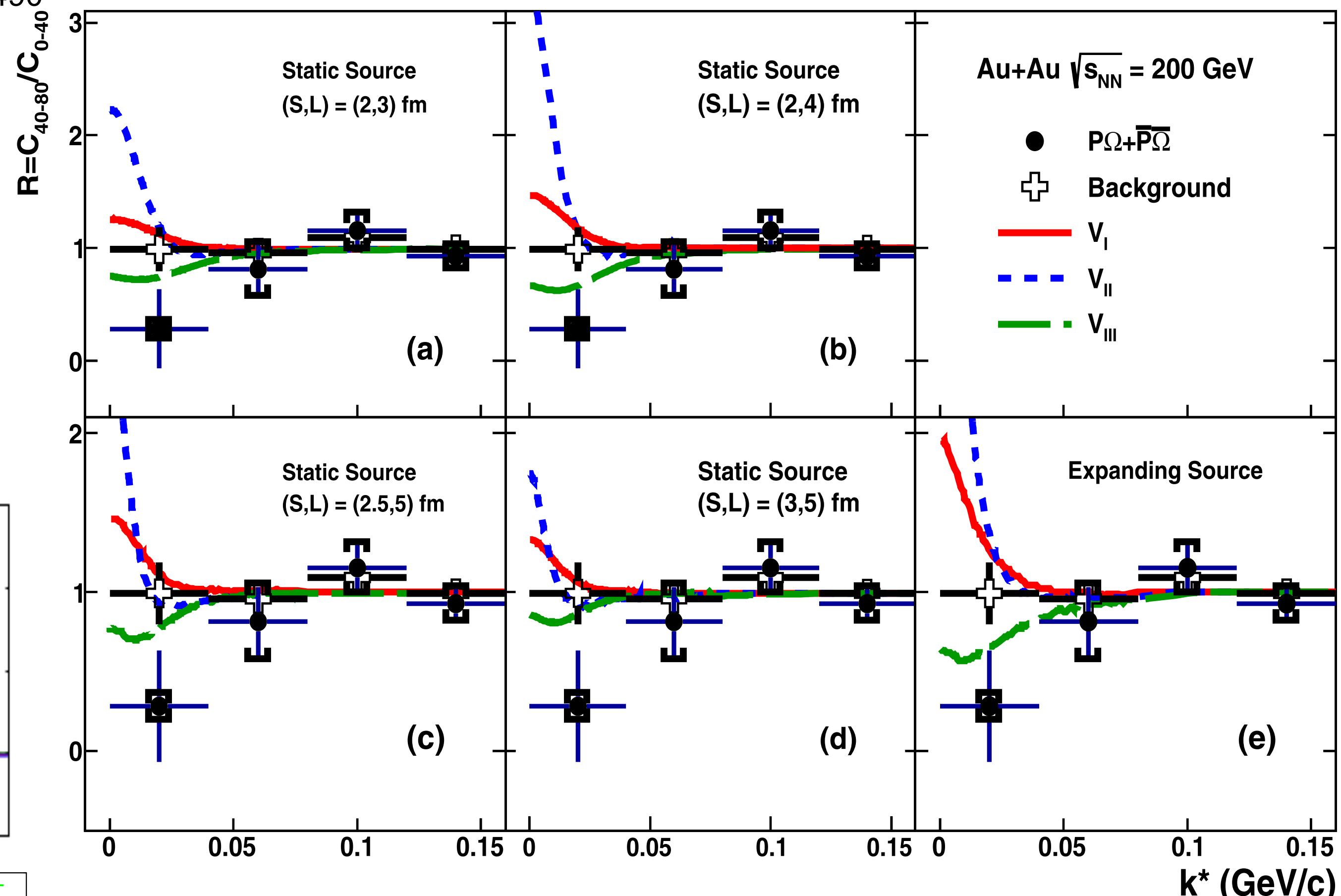
STAR Col. Phys. Lett. B 790 (2019) 490

- The ratio at low k*
  - <1.0 for data
  - close to 1.0 for bg
  - Compared with LQCD calculation favors $V_{III}$ potential scenario

Morita:PRC 2016 and 1908.05414



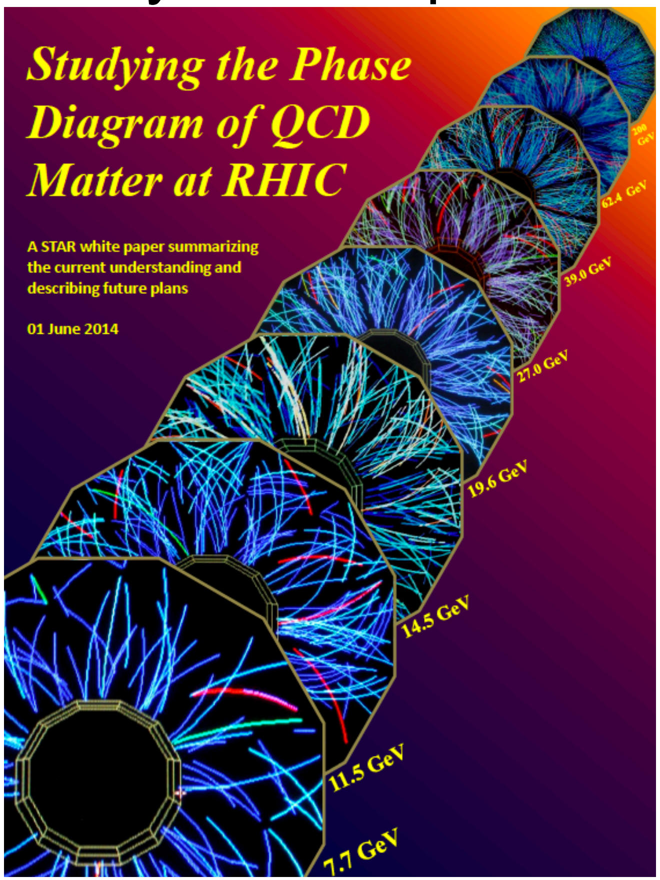



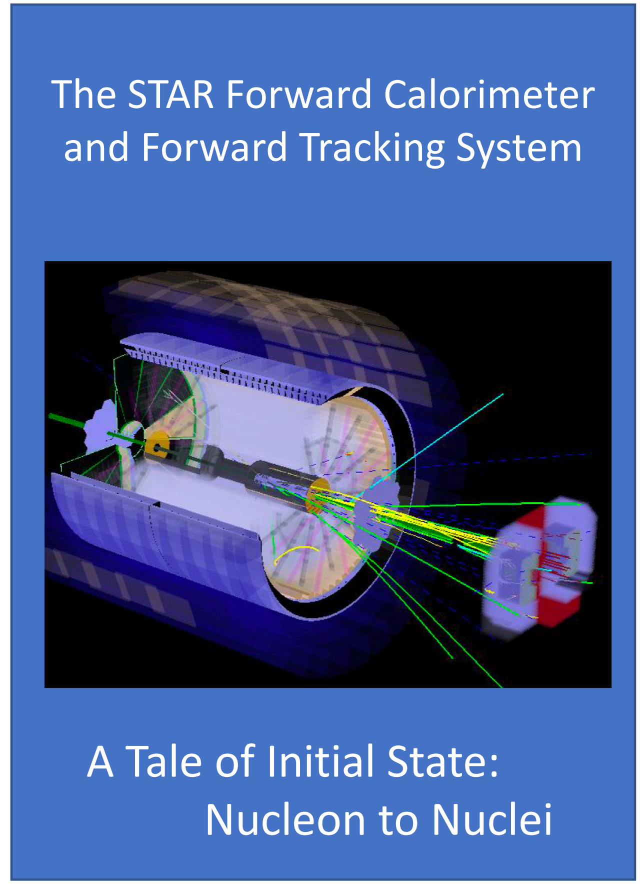




| k* (GeV/c) | R | Background |
|---|---|---|
| 0.20 | $0.28 \pm 0.35_{stat} \pm 0.03_{sys}$ | $0.96 \pm 0.13_{stat}$ |
| 0.60 | $0.81 \pm 0.22_{stat} \pm 0.08_{sys}$ | $0.97 \pm 0.05_{stat}$ |

# Summary and Outlook

- RHIC-STAR: a dedicated midrapidity collider for QCD matter at high density and temperature, with excellent data




- STAR BES-II: 2019-2021
- STAR forward upgrades: 2021-2025

# $^3$He mass data on hypertrion measurement

- Consider the mass difference of $^3$He and d from ALICE, our measurement is dominated by the 3-body decay channel:

$$\Delta m^{2-\mathrm{body}} = \Delta m_{\mathrm{HT}} - \Delta m_{^3\mathrm{He}}\left(1+\sqrt{\frac{m_{\pi^-}^2+p_{\pi^+}^2}{m_{^3\mathrm{He}}^2+p_{\mathrm{anti}-^3\mathrm{He}}^2}}\right)\frac{m_{^3\mathrm{He}}}{m} \approx \Delta m(\mathrm{HT}) - 1.01\Delta m(^3\mathrm{He})$$

$$\Delta m^{3-\mathrm{body}} = \Delta m_{\mathrm{HT}} - \Delta m_{\mathrm{d}}\left(1+\sqrt{\frac{m_{\pi^-}^2+p_{\pi^+}^2}{m_{\mathrm{d}}^2+p_{\mathrm{anti}-\mathrm{d}}^2}}+\sqrt{\frac{m_{\mathrm{p}}^2+p_{\mathrm{anti}-\mathrm{p}}^2}{m_{\mathrm{d}}^2+p_{\mathrm{anti}-\mathrm{d}}^2}}\right)\frac{m_{\mathrm{d}}}{m} \approx \Delta m(\mathrm{HT}) - 1.00\Delta m_{\mathrm{d}}$$

3-body channel: $0.13 \pm 0.63(\mathrm{stat.}) \pm 0.31(\mathrm{syst.})\mathrm{MeV}/c^2$

- The 2-body and 3-body channel measurements in conjunction with the ALICE d mass difference

$$\Delta m_{^3\mathrm{He}} = 0.99(\Delta m^{3-\mathrm{body}} - \Delta m^{2-\mathrm{body}}) + 0.99\Delta m_d$$
$$= -0.43 \pm 0.72(\mathrm{stat.}) \pm 0.34(\mathrm{syst.})\mathrm{MeV}/c^2$$