QCD物理研讨会暨基金委重大项目学术交流会

课题2: 重味与奇异粒子产生

重味与STAR BES相关物理研究进展

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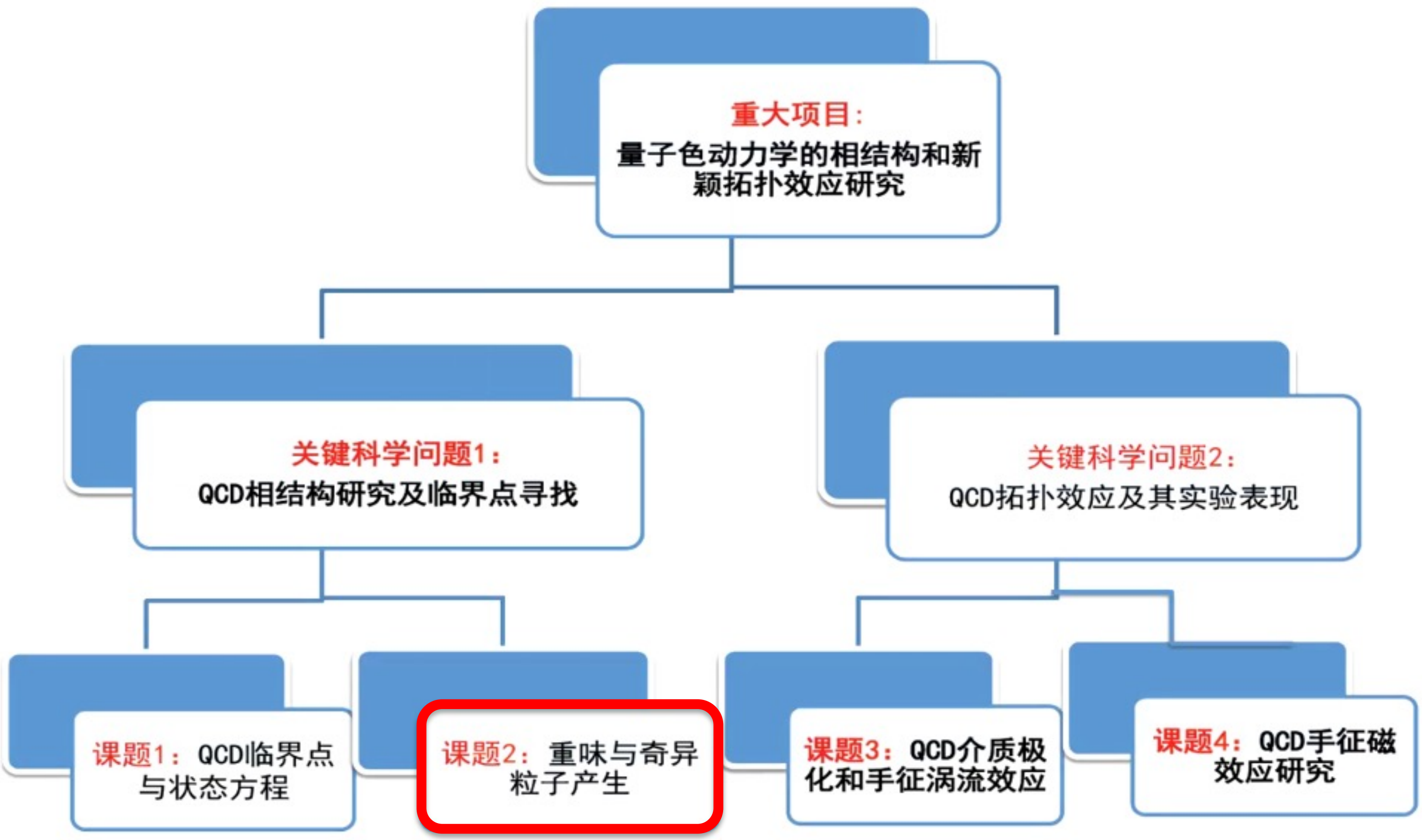
2022. 7. 29

提 纲

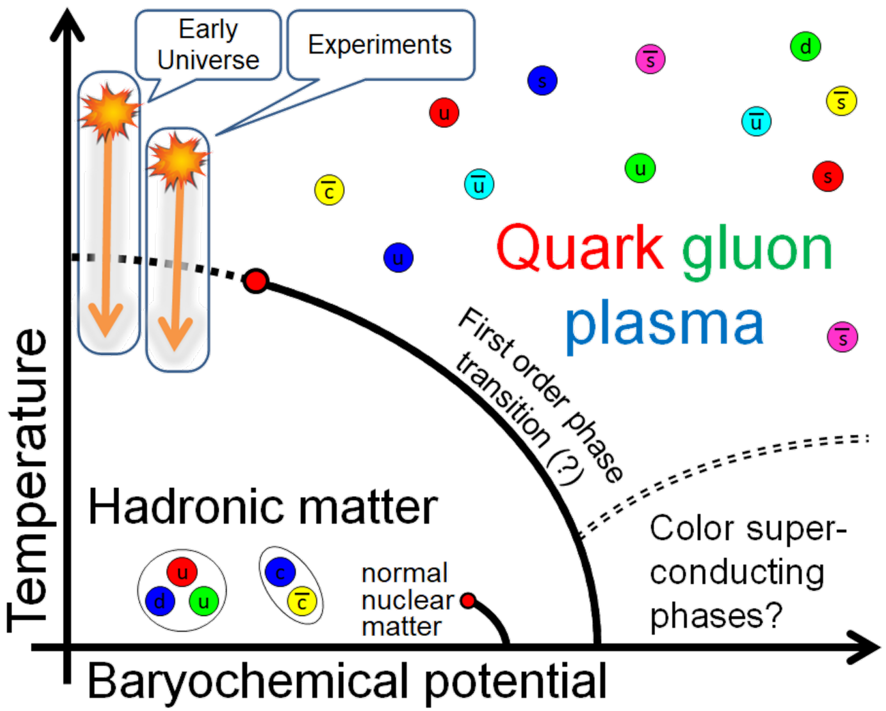
- 课题背景
- 工作汇报
  - 重离子碰撞中重味强子的产生
  - STAR BES能区的相关物理研究
- 总结

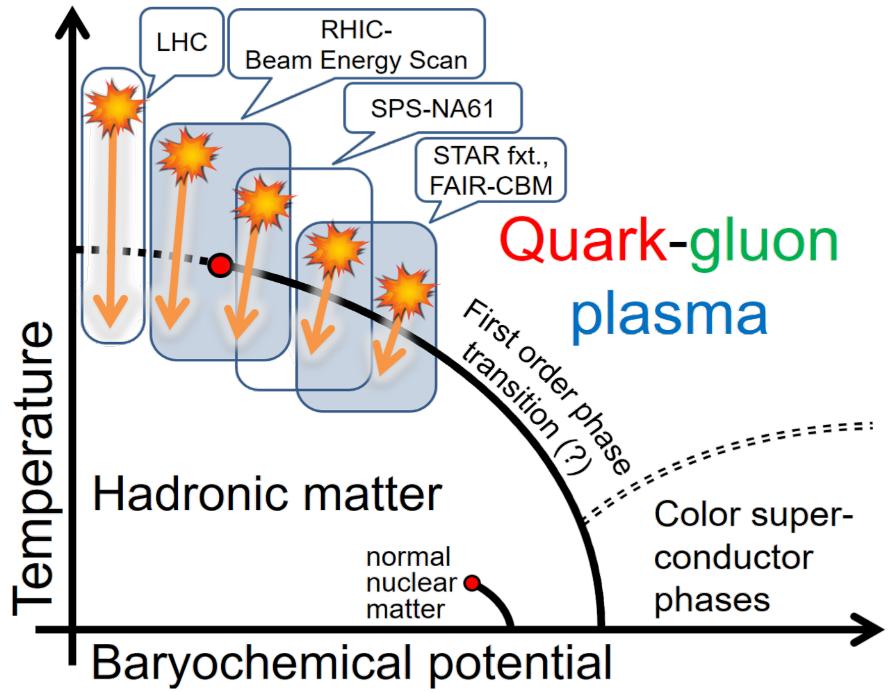
课题背景



关键科学问题1：QCD物质相结构研究及其临界点实验寻找

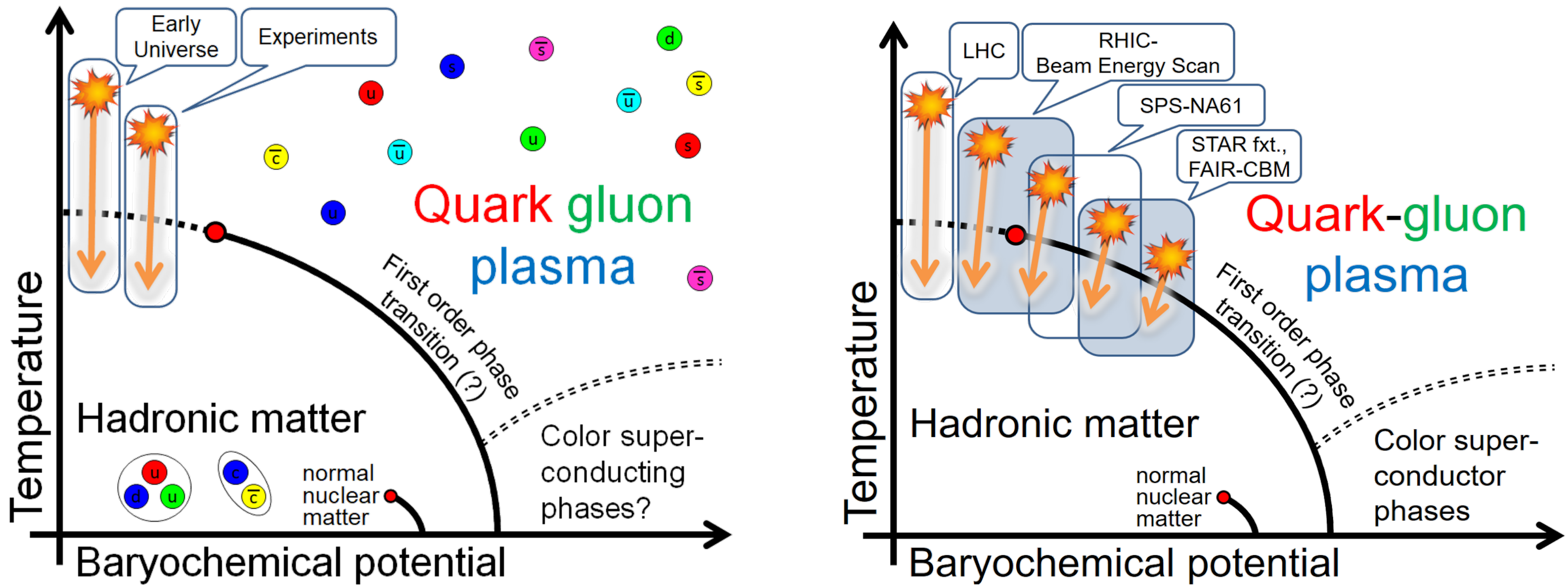
课题背景





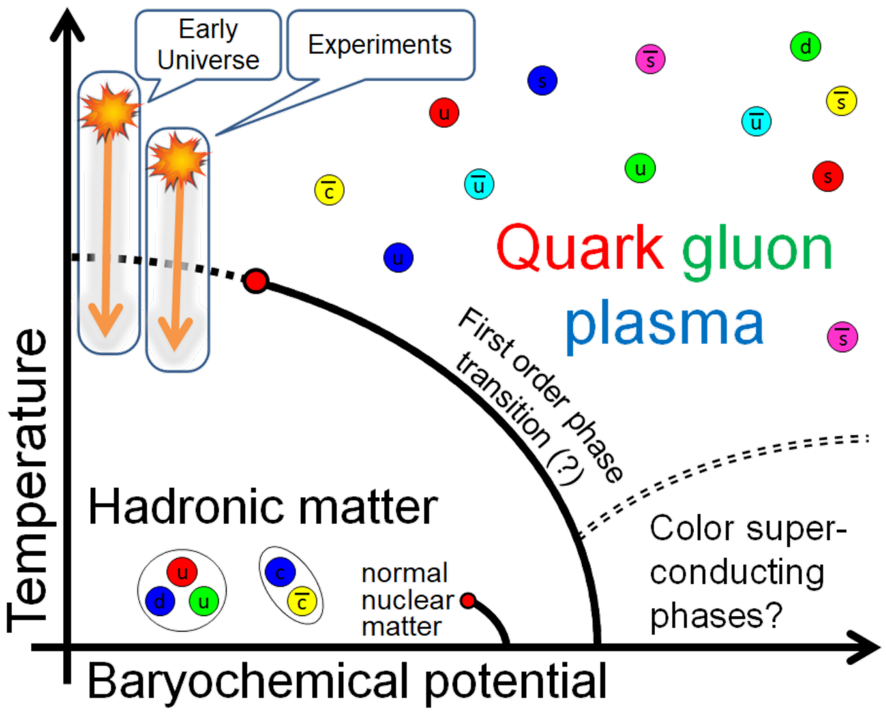
研究目标：深入准确的研究重味和奇异粒子在重离子碰撞中的产生以及与 QGP 的强关联，提取敏感的 QGP 信号，确定 QCD 相结构的临界点和相边界。

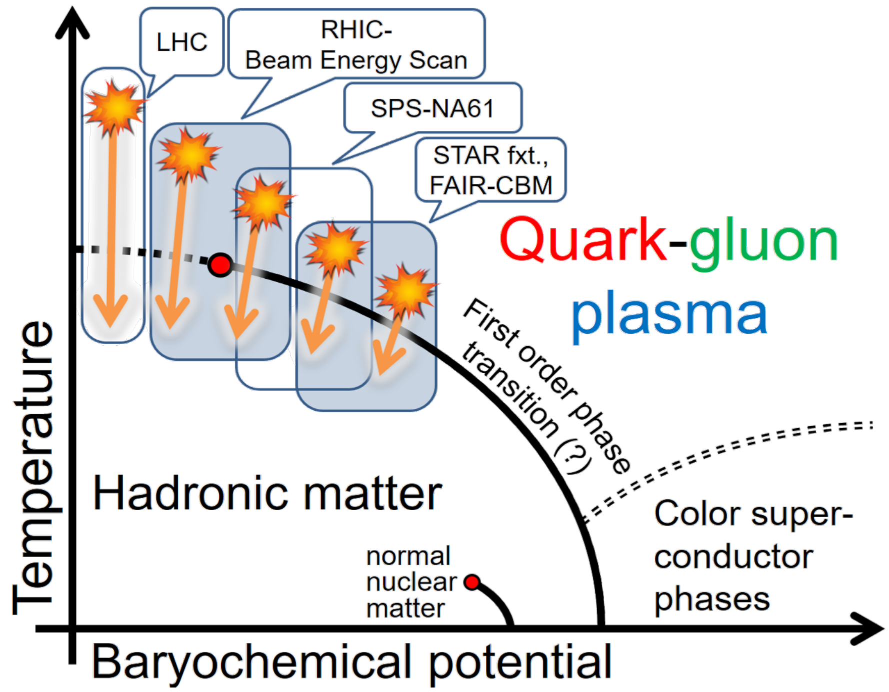
课题背景



- Crossover, extremely high T ➡ study key feature of the hot QCD matter
- Varying collision energies for wide baryon density region ➡ mapping QCD phase structure and search for critical point

课题背景



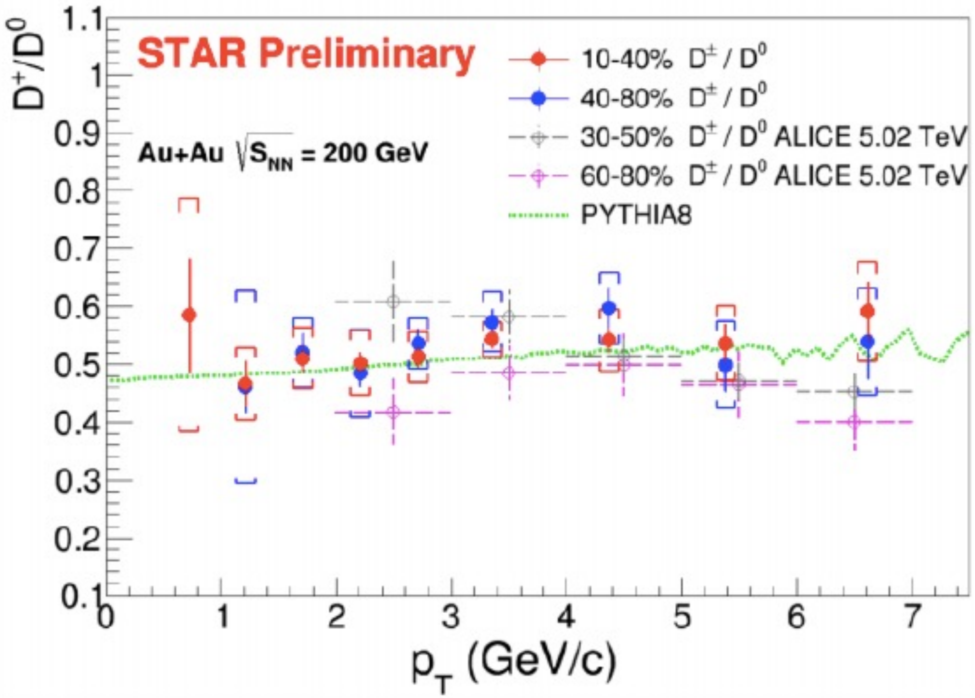


Heavy flavor production

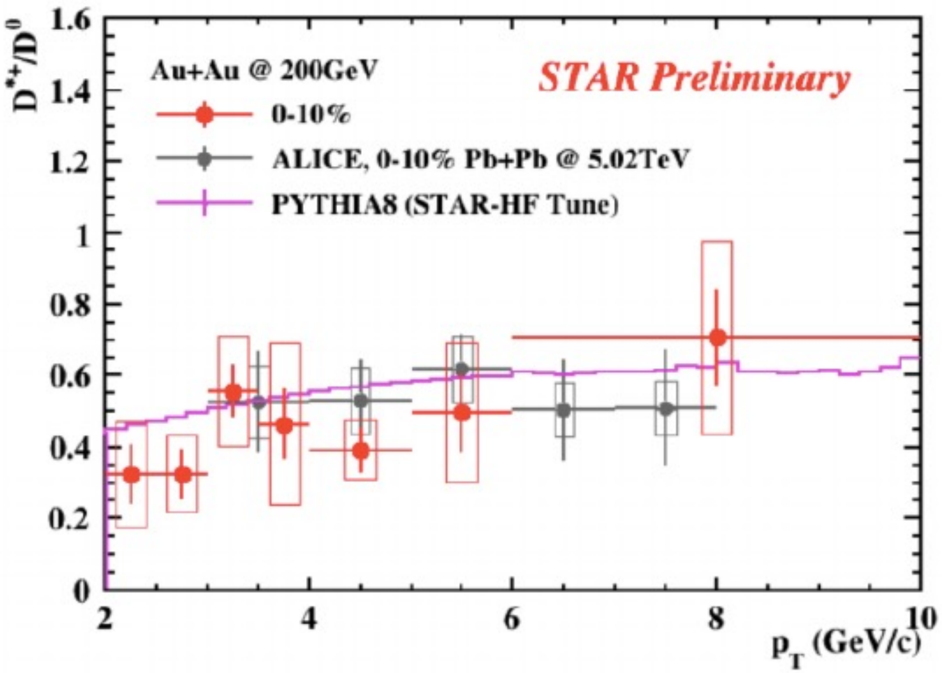
Higher-order fluctuations
Hypernuclei production

Charm-light mesons in Au+Au 200 GeV at STAR

$D^+ \to K^- \pi^+ \pi^+$



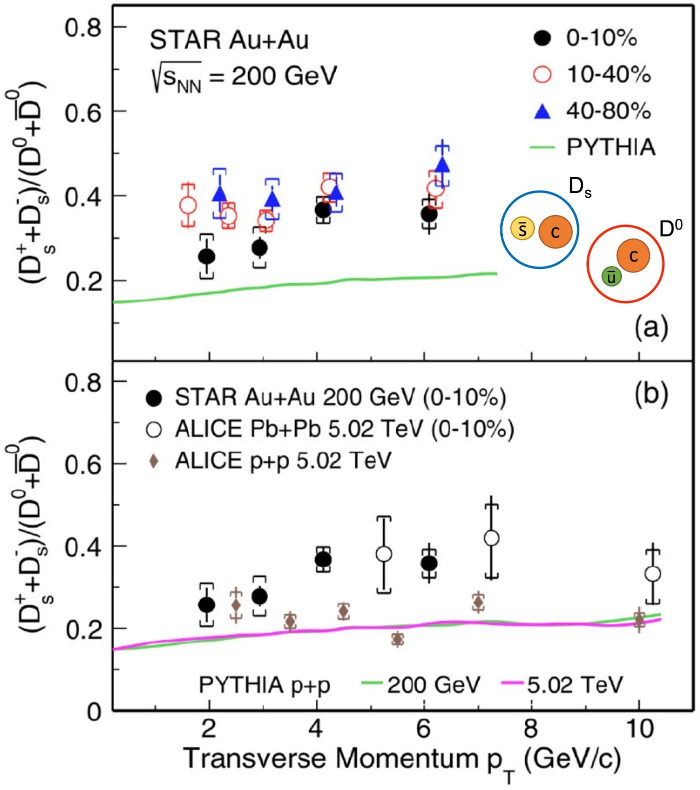
$D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi^+$



- D^+/D^0, D^*/D^0 ratios consistent with PYTHIA model calculations
- No significant modification to charm-light meson production in A+A collisions

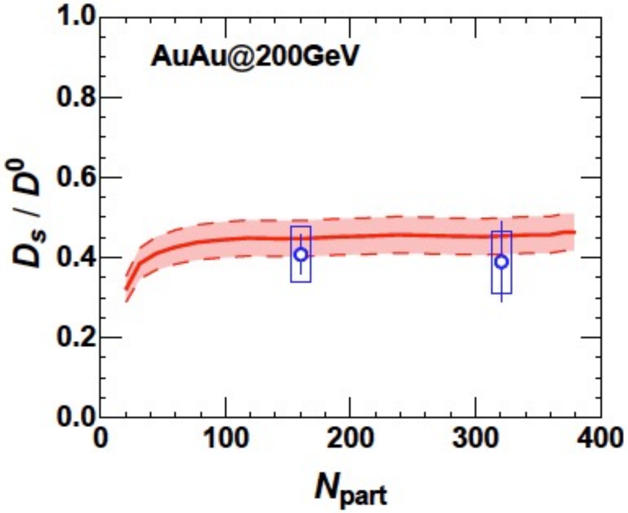
Paper in PWG review

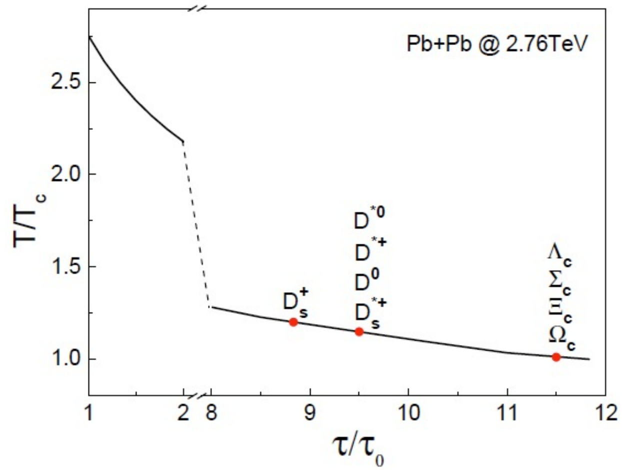
D_s enhancement in Au+Au 200 GeV at STAR

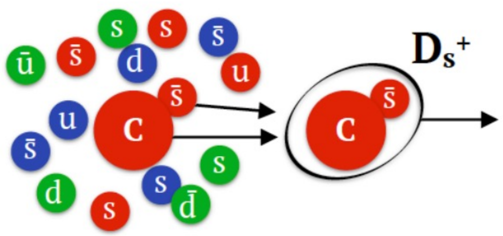


STAR: PRL127, 092301 (2021)

ALICE: EPJC 77, 550 (2017)
JHEP 2018, 174 (2018)







C. Ko, et al., PRC 79 (2009) 044905.

S. Plumari, et al., EPJC 78 (2018) 348.

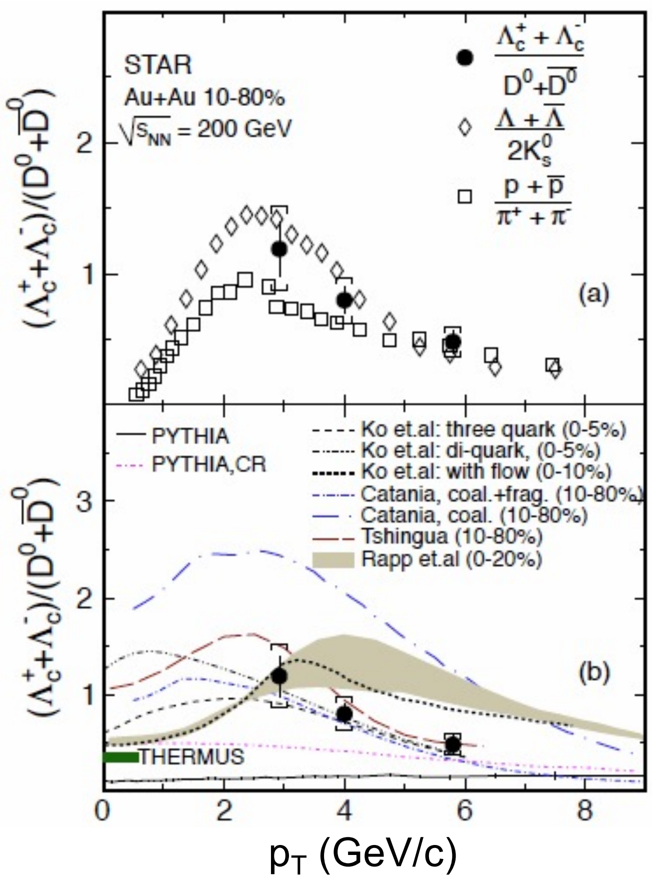
M. He, et al., PRL 110 (2013) 112301.

J. Zhao et al., EPJ Web Conf. 202 (2019) 06004; arXiv: 2004.12305.

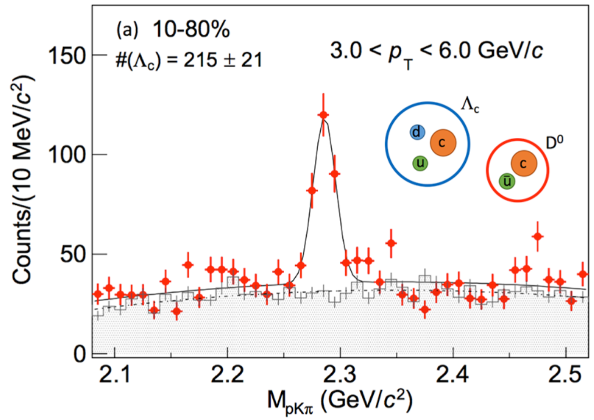
Significant D_s/D^0 enhancement in Au+Au collisions w.r.t fragmentation baseline or p+p

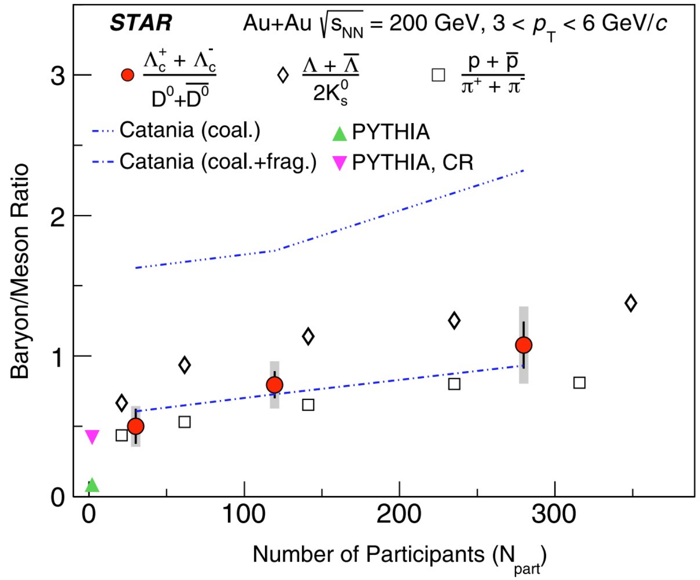
- (sequential) coalescence + strangeness enhancement
- compatible with SHM prediction (ratio ~ 0.35-0.4)

Λ_c enhancement in Au+Au 200 GeV at STAR



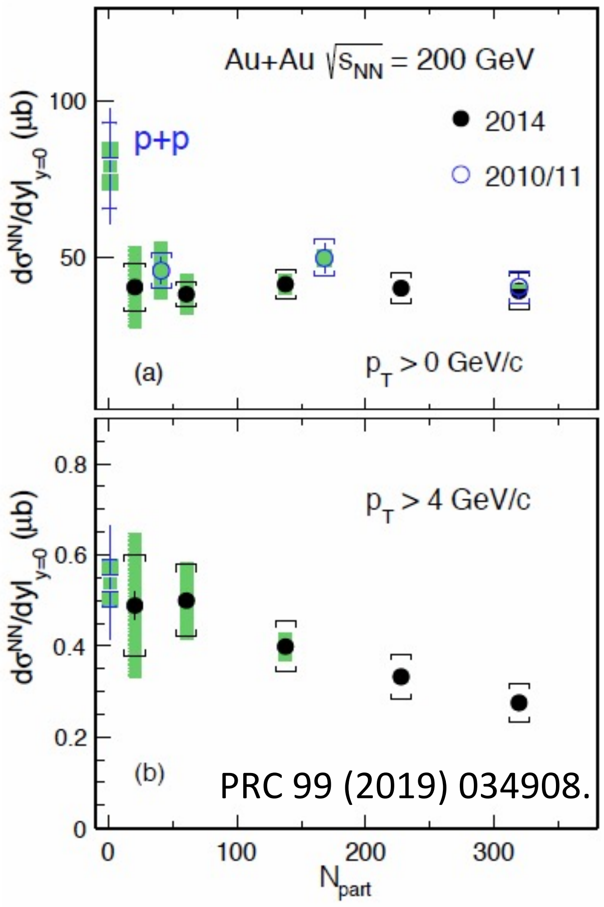
STAR PRL 124 (2020) 172301.
X. Luo et al., Particles 3 (2020) 278.





- Significant enhancement in Λ_c/D^0 compared to PYTHIA/fragmentation baseline.
- The Λ_c/D^0 ratio is compatible with light flavor baryon-to-meson ratios.
- Consistent with coalescence + thermalized charm quarks, higher at high p_T.

Charm production cross section in Au+Au 200 GeV



STAR Preliminary

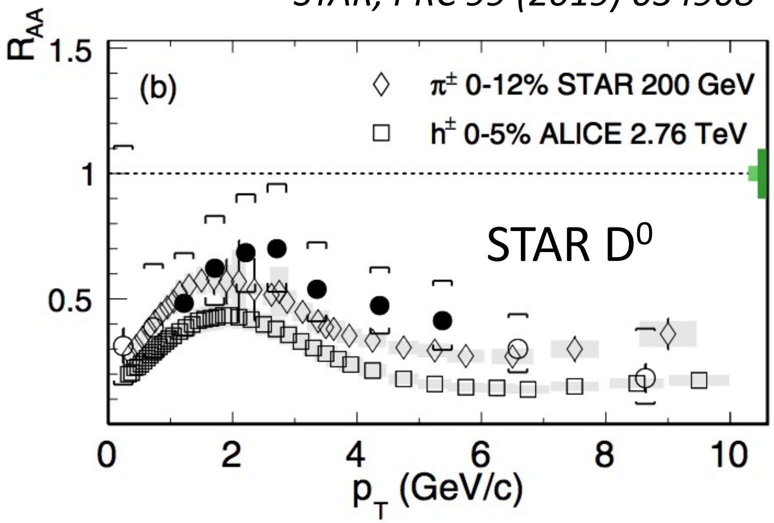
Collision system	Hadron	$d\sigma/dy$ [μb]
Au+Au 200 GeV 10-40%	D^0	39.0 ± 0.6(stat) ± 1.1(sys)
	$D^{\pm}$	19.2 ± 0.9(stat) ± 3.1(sys)
	D_s	15.4 ± 1.7(stat) ± 3.6(sys)
	Λ_c	39.7 ± 5.8(stat) ± 26.7(sys)
	Total:	113.3 ± 6.2(stat) ± 27.2(sys)
p+p 200 GeV	Total:	130 ± 30(stat) ± 26(sys)

Charm numbers are still conserved at RHIC!

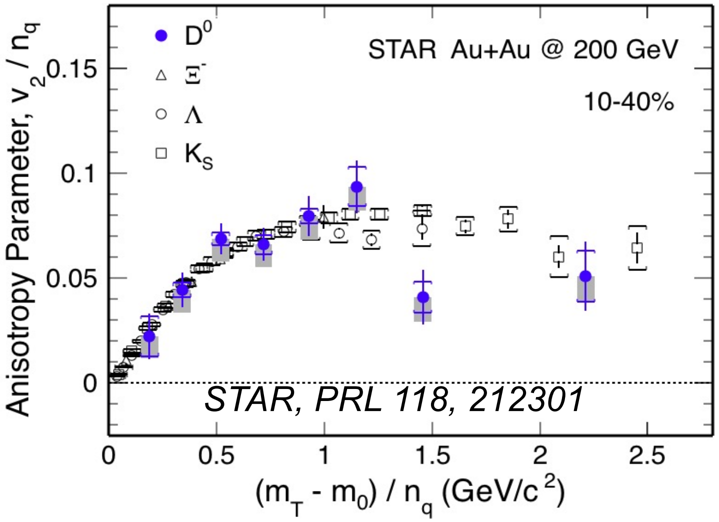
Total charm cross section in Au+Au collisions is consistent with p+p value within uncertainties, but redistributed among different charm hadron species.

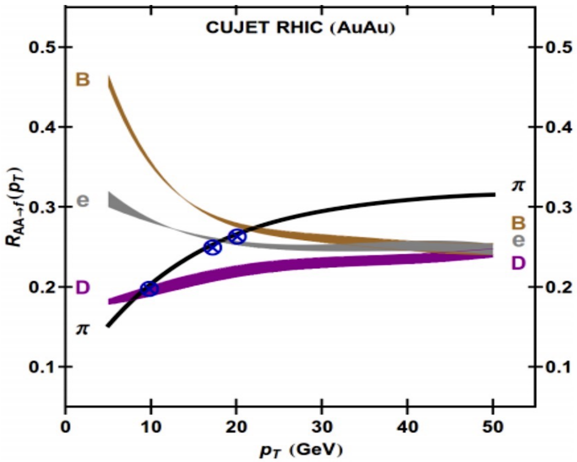
What about heavier bottom quark?

STAR, PRC 99 (2019) 034908



Moeraki boulders were moved to the beach by storm waves in Austrilia.





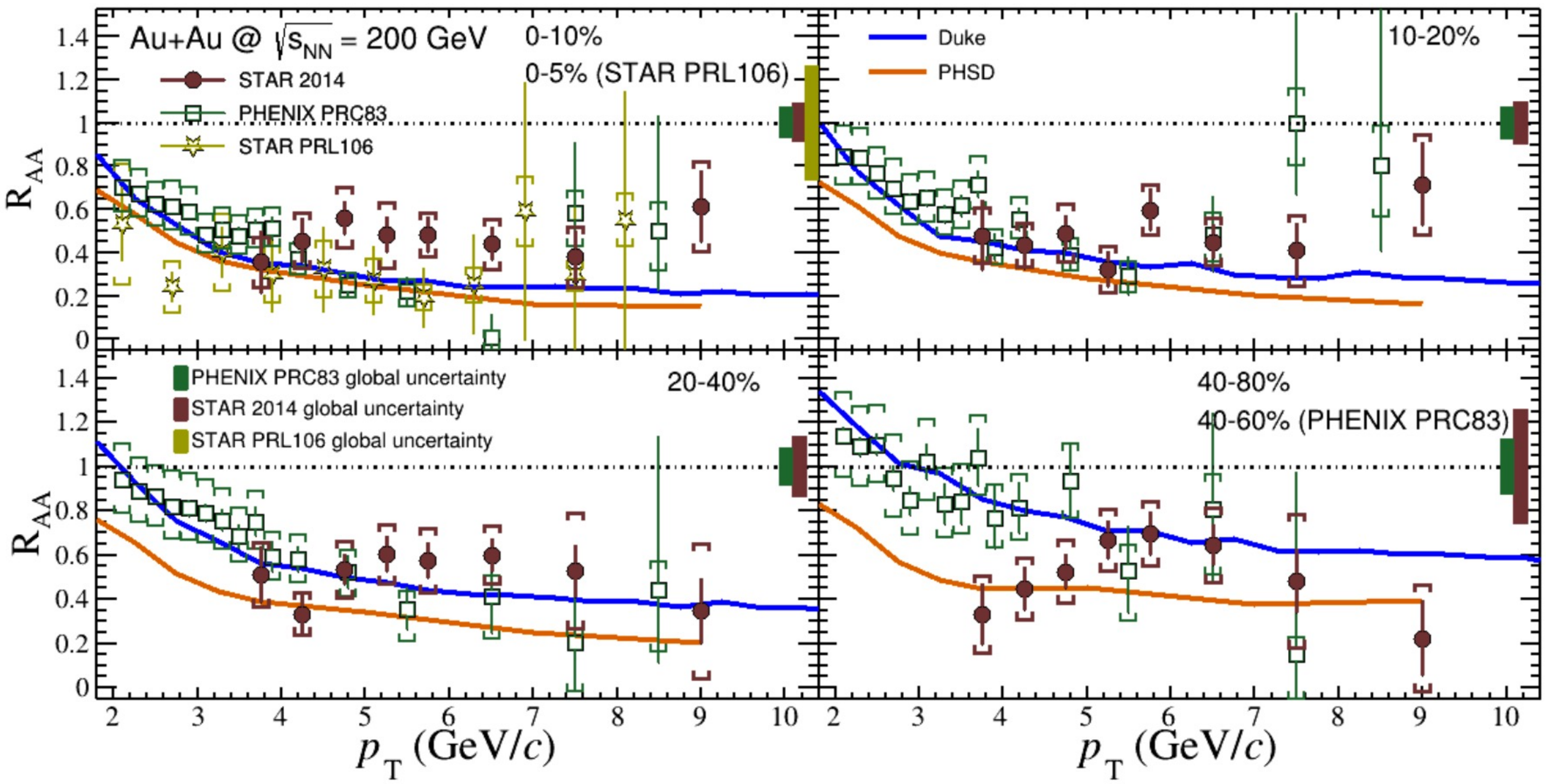
PRL 108 (2012) 022301

$M_b \sim 4.8$ GeV
$M_c \sim 1.3$ GeV

Charm is as ordinary as light quarks!

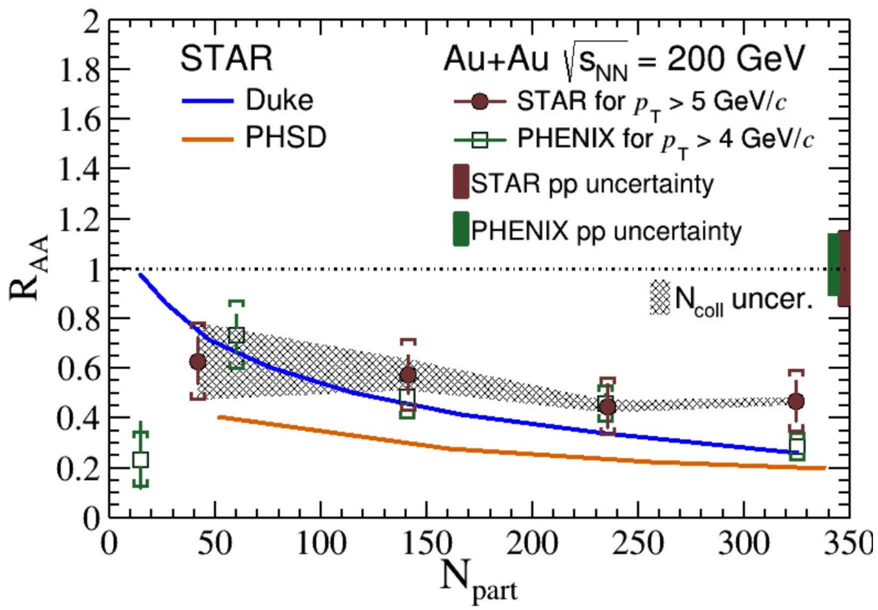
Is there a "big stone" too heavy to be moved in QGP storm?

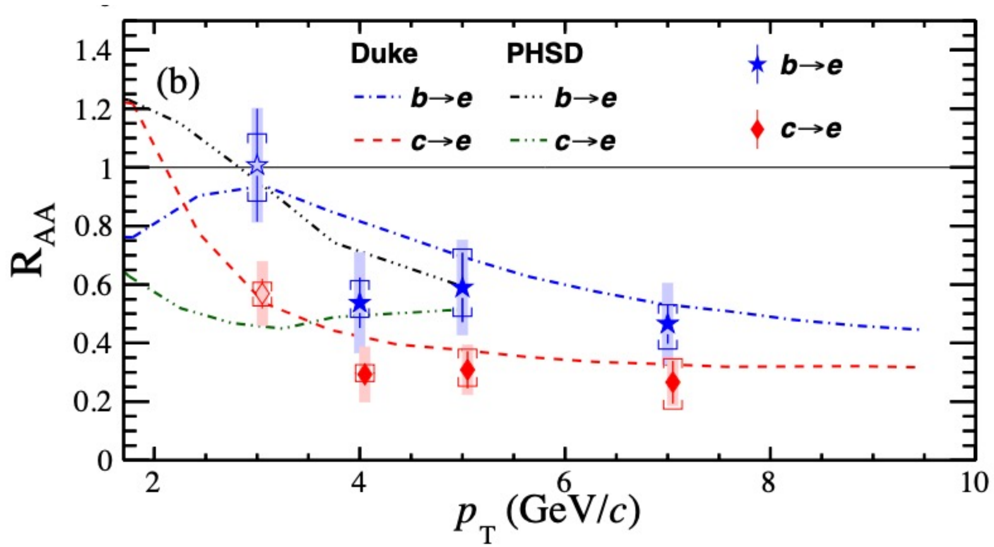
HFE measurement in Au+Au 200 GeV



- Improve measurements of HFE suppression with better precision at high p_T.
- ~x2 suppression is observed in central and mid-central collisions above 3.5 GeV/c, suggesting significant energy loss of heavy quarks in the hot-dense medium

HFE measurement in Au+Au 200 GeV

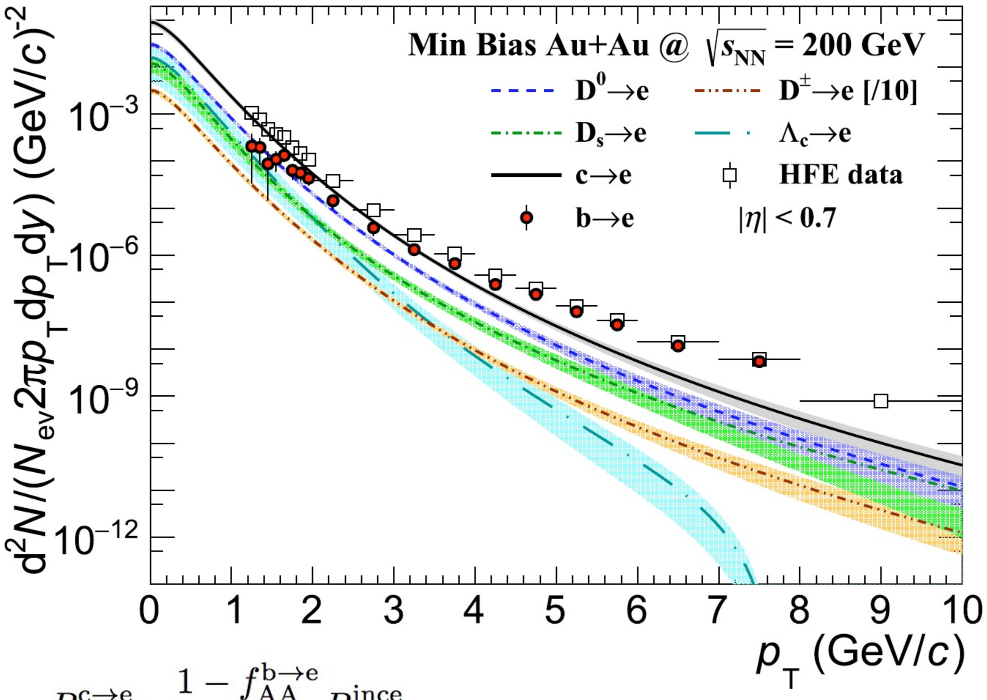


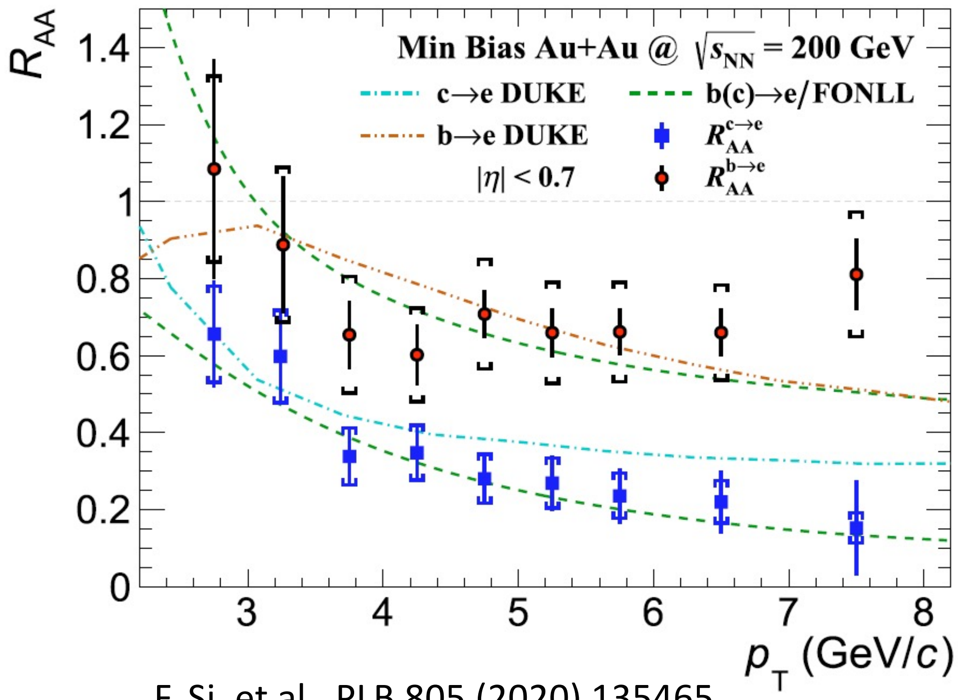


Paper in PWG review

- More suppression in more central collisions but not significant.
- Better consistent with Duke model calculations.
- Charm- and bottom-hadron decayed electrons separated in heavy-ion collisions, which provides evidence of mass ordering of heavy quark energy loss in the strongly coupled medium created in heavy-ion collisions.

B->e in Au+Au 200 GeV





$$R_{AA}^{c\to e} = \frac{1 - f_{AA}^{b\to e}}{1 - f_{pp}^{b\to e}} R_{AA}^{ince},$$

$$R_{AA}^{b\to e} = \frac{f_{AA}^{b\to e}}{f_{pp}^{b\to e}} R_{AA}^{ince},$$

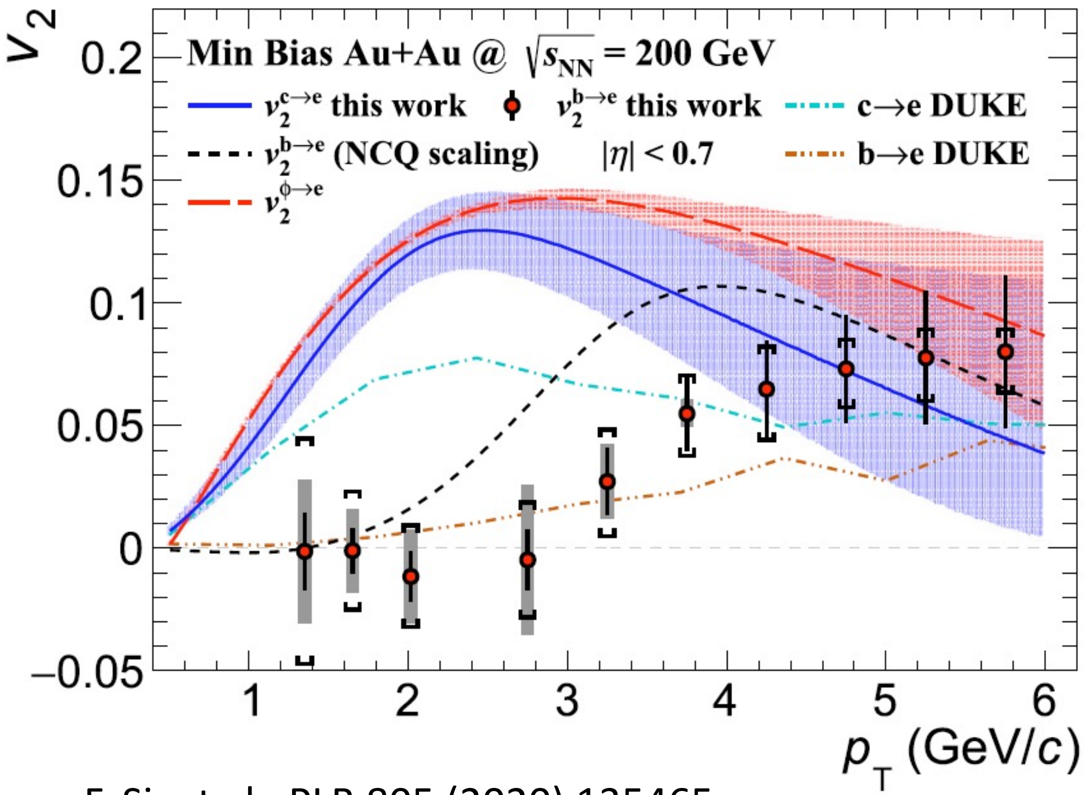
F. Si, et al., PLB 805 (2020) 135465.

DUKE: PRC 92, 024907 & Private Communication

FONLL: M. Cacciari, et al., PRL 95, 122001.

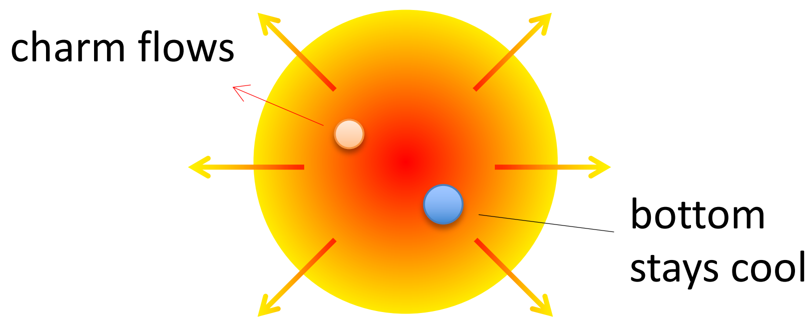
- b->e obtained by subtracting charm contributions from inclusive HFE.
- R_{AA}(c->e) < R_{AA}(b->e) at p_T > 4 GeV/c - mass dependent energy loss.
- Consistent with Duke model, except high p_T c->e (1-σ deviation).
- Consistent with b(c)->e/FONLL by definition.

B->e in Au+Au 200 GeV



$$v_2(p_T) = \frac{p_0 n}{1+\exp\left(\frac{p_1 - \frac{p_T}{n}}{p_2}\right)} - \frac{p_0 n}{1+\exp\left(\frac{p_1}{p_2}\right)} - p_3 n p_T,$$

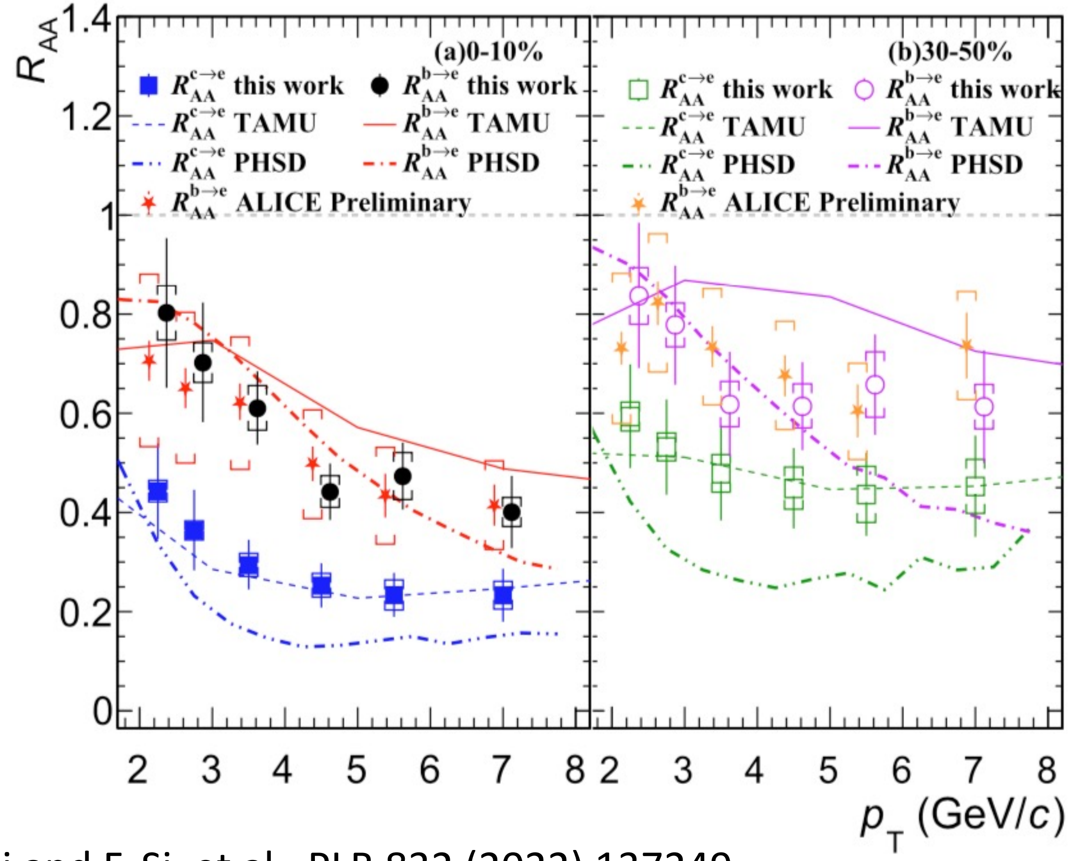
$$v_2^{b\to e} = \frac{v_2^{ince} - \left(1 - f_{AA}^{b\to e}\right) v_2^{c\to e}}{f_{AA}^{b\to e}},$$

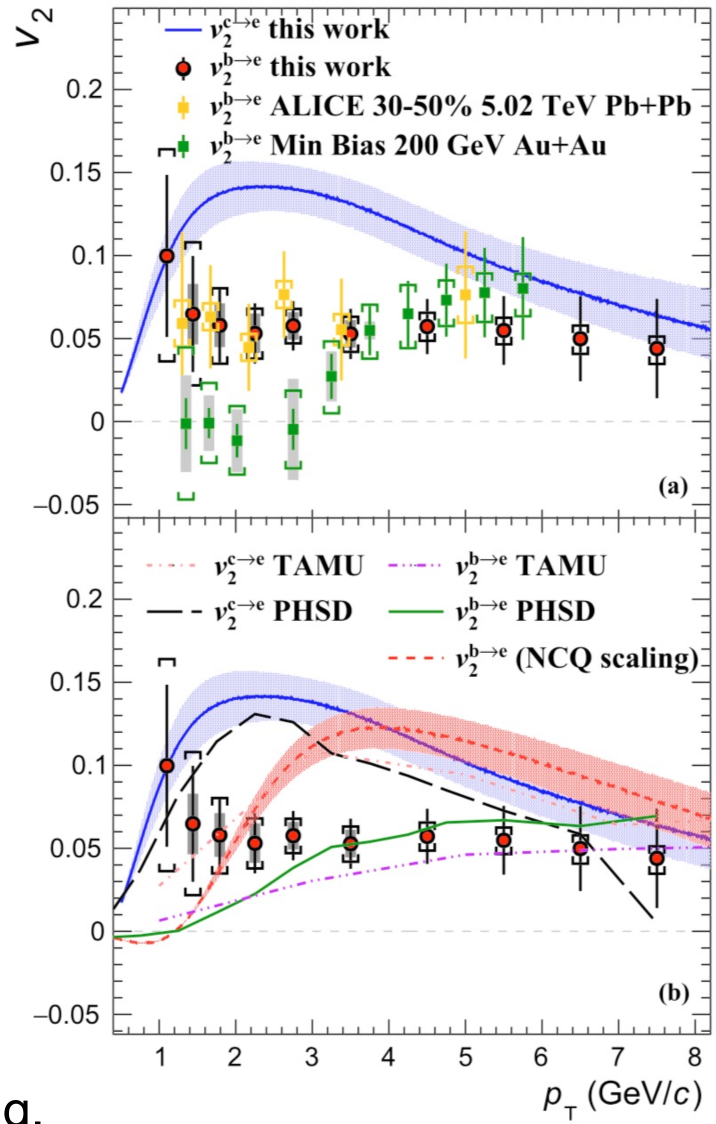


F. Si, et al., PLB 805 (2020) 135465.

- Non-zero b->e v_2 observed at p_T > 3 GeV/c.
- Much smaller v_2 compared with c->e at p_T < 4 GeV/c.
- Less flow compared with NCQ scaling hypothesis at 2.5 < p_T < 4.5 GeV/c assuming only mass effect, indicating bottom is unlikely thermalized at RHIC.

B->e in Pb+Pb 5.02 TeV

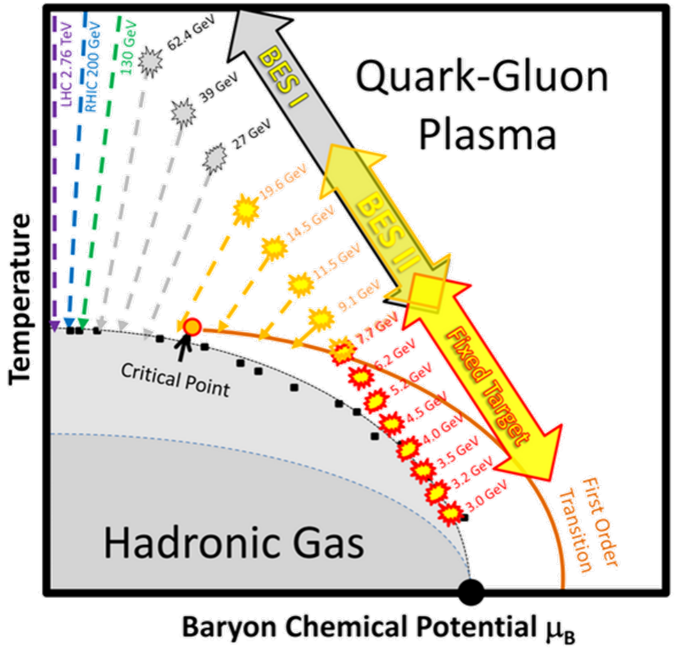


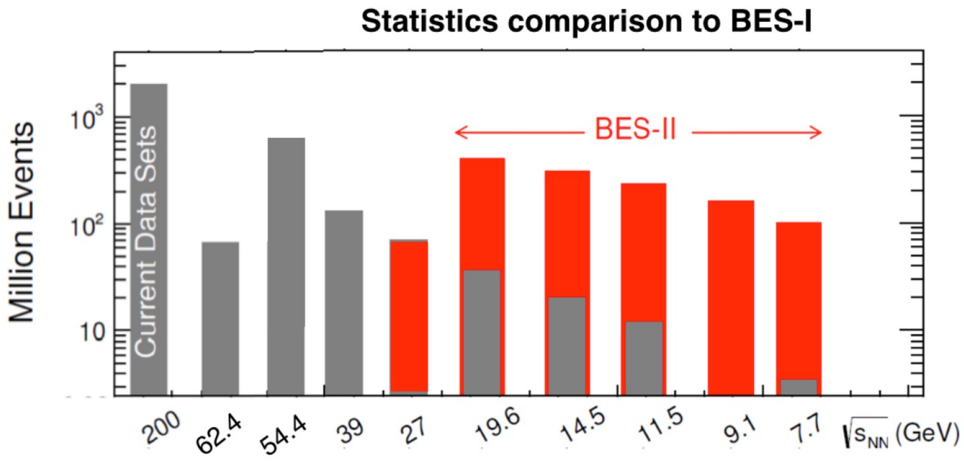


D. Li and F. Si, et al., PLB 832 (2022) 137249.

- Similar mass dependent energy loss.
- More suppression in more central collisions.
- Non-zero b->e v_2, smaller than c->e and NCQ scaling.
- Hint of energy dependence at $p_T < 3$ GeV/c => degree of thermalization?

STAR BES program



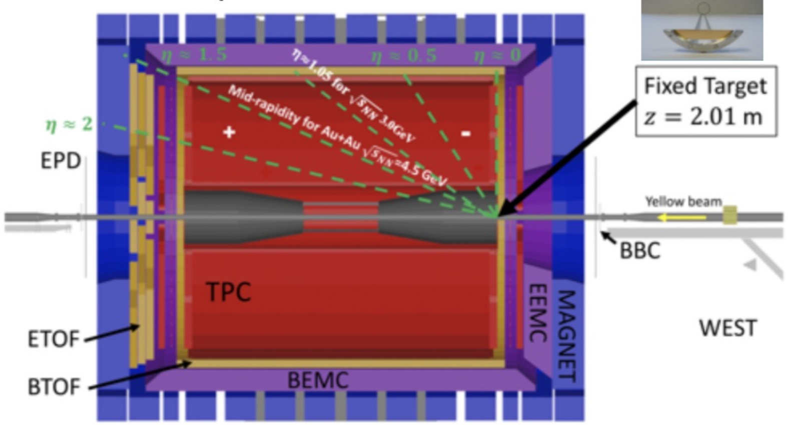


BES I/II: 7.7 – 200 GeV

Fixed target: 3.0 – 7.7 GeV

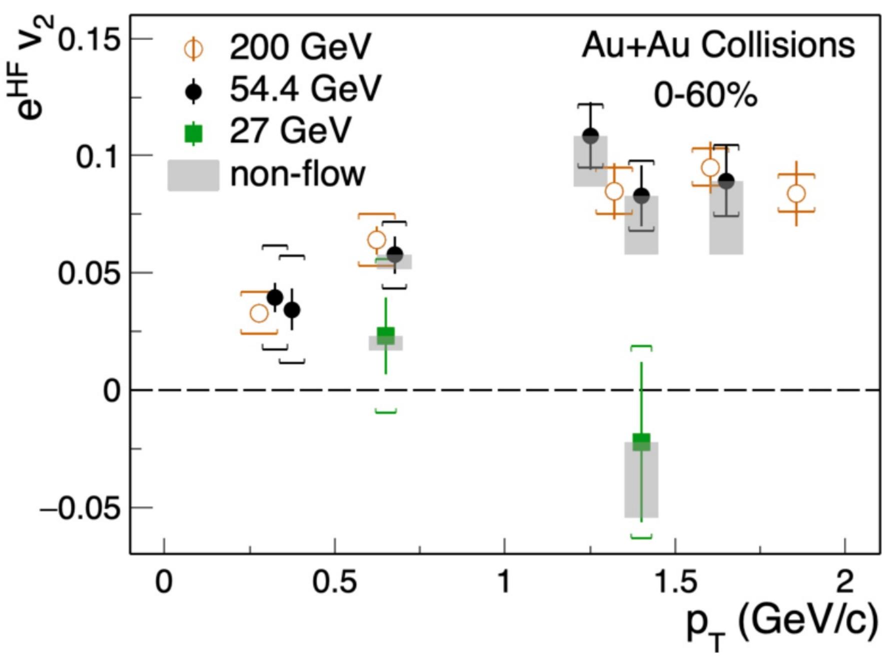
extends STAR's physics reach to region of compressed baryonic matter

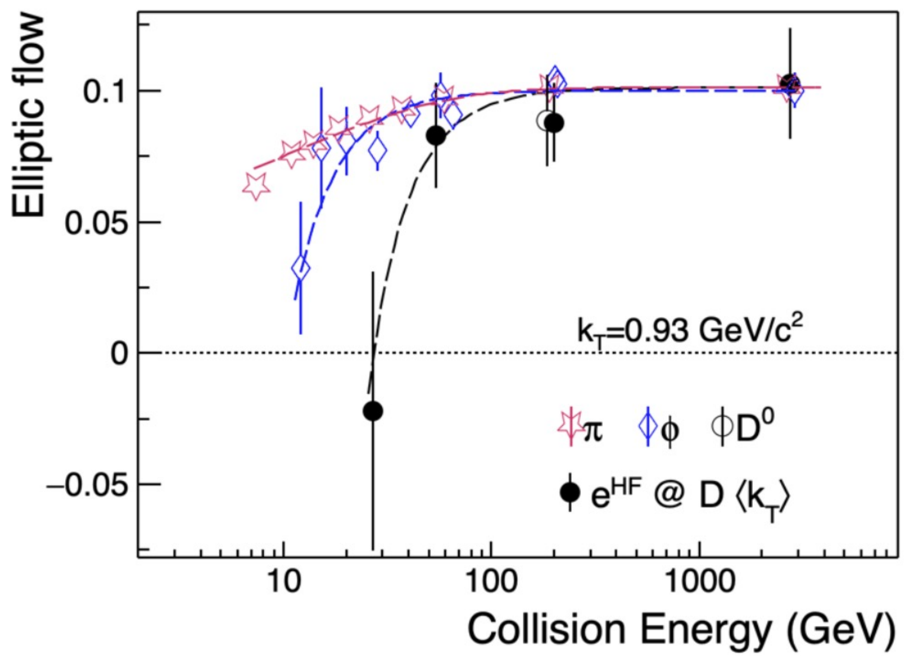
FXT mode setup:



- Mapping the QCD phase diagram with wide μ_B coverage: (20-720 MeV)
- Large and homogeneous acceptance, excellent particle identification, especially important for fluctuation analysis

Heavy flavor electron at lower energies

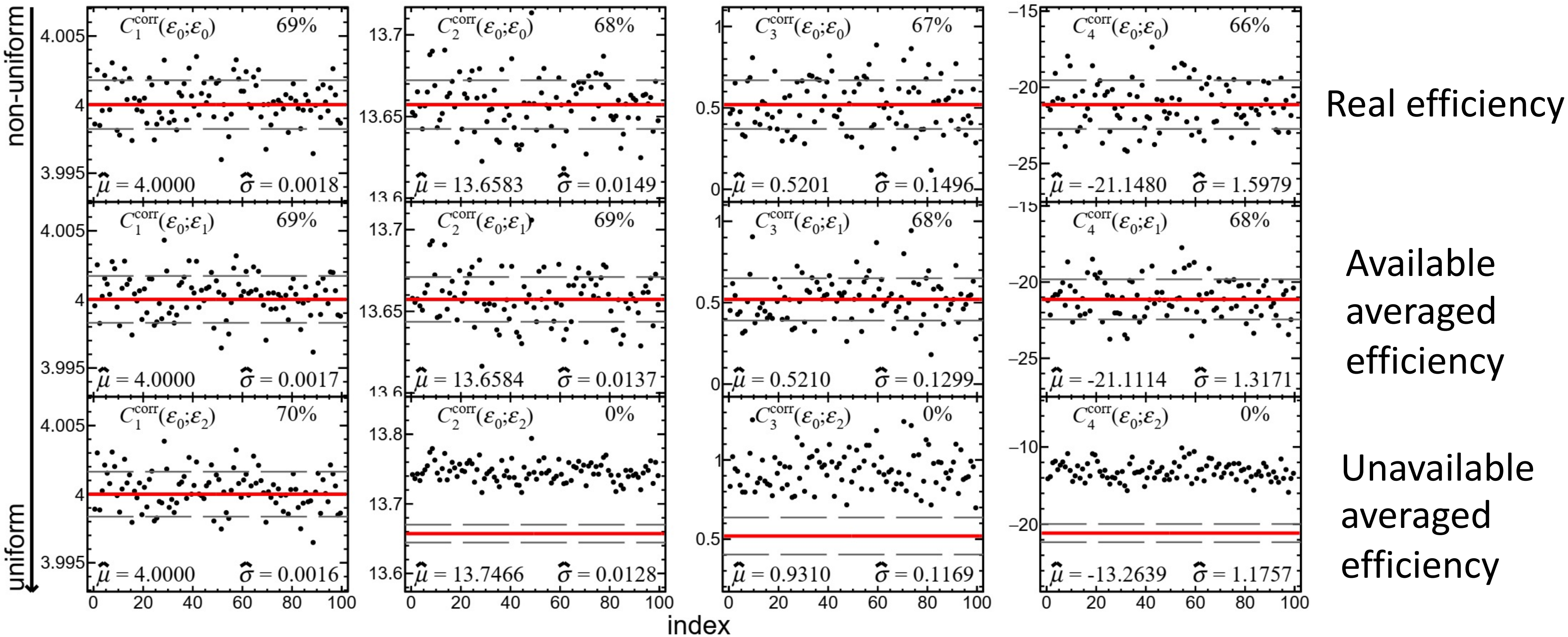




Paper in PWG review

- HFE v_2 in 54.4 GeV is consistent with 200 GeV result.
- Hint of smaller v_2 in 27 GeV.
- No flavor dependence at high energy, but clear flavor dependence at low energy.
- Mesons v_2 follow the same $<k_T> = <m_T - m_0> = 0.93$ GeV/c^2.

Non-uniform efficiency correction for higher-order cumulants

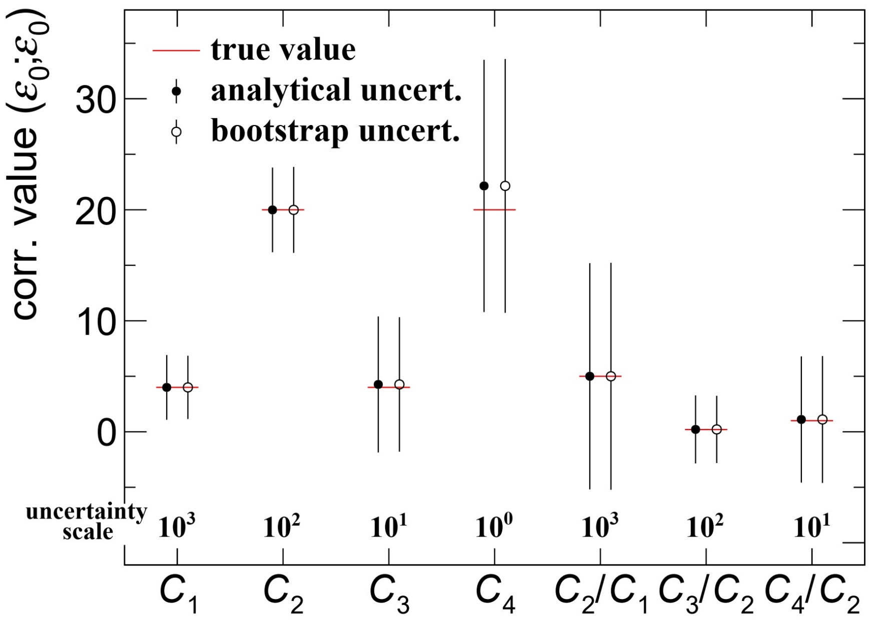


F. Si, ZYF, X. Luo, CPC 45 (2021) 124001.

- Study the non-uniformity effect of efficiency correction for higher-order cumulants.
- Analytic proof and MC test for validation of averaged efficiency correction.
- Reduce uncertainties from efficiency fluctuations.

Statistical uncertainties of higher-order cumulants

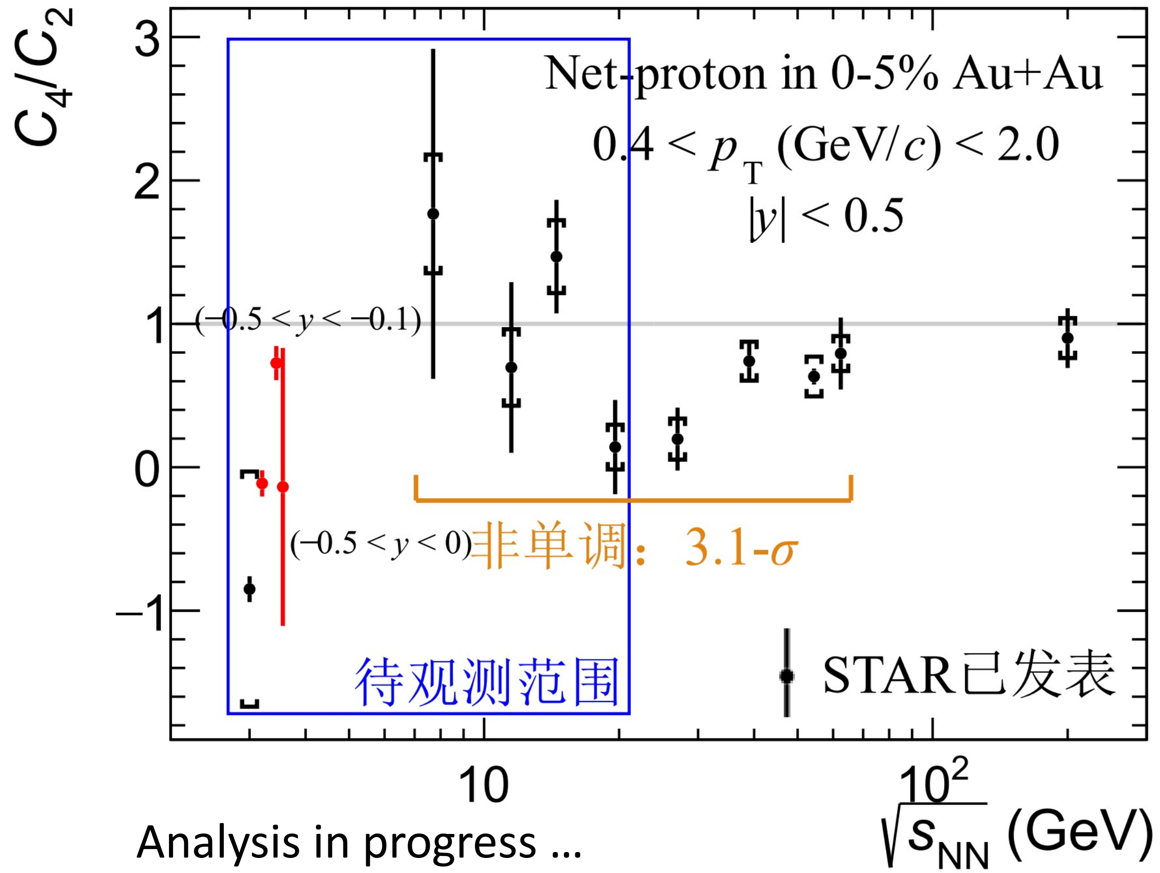
$$
\begin{aligned}
n\mathrm{Var}(\widehat{C}_4^{\mathrm{corr}}) =& \langle q_{(1,1)}^8\rangle_c + 16\langle q_{(1,1)}^6\rangle_c\langle q_{(1,1)}^2\rangle_c + 48\langle q_{(1,1)}^5\rangle_c\langle q_{(1,1)}^3\rangle_c + 34\langle q_{(1,1)}^4\rangle_c^2 \\
&+ 72\langle q_{(1,1)}^4\rangle_c\langle q_{(1,1)}^2\rangle_c^2 + 144\langle q_{(1,1)}^3\rangle_c^2\langle q_{(1,1)}^2\rangle_c + 24\langle q_{(1,1)}^2\rangle_c^4 \\
&+ 36(\langle q_{(1,1)}^4 q_{(2,1)}^2\rangle_c + \langle q_{(1,1)}^4\rangle_c\langle q_{(2,1)}^2\rangle_c + 4\langle q_{(1,1)}^3 q_{(2,1)}\rangle_c\langle q_{(1,1)} q_{(2,1)}\rangle_c + 4\langle q_{(1,1)}^2 q_{(2,1)}^2\rangle_c\langle q_{(1,1)}^2\rangle_c \\
&+ 4\langle q_{(1,1)}^3\rangle_c\langle q_{(1,1)} q_{(2,1)}^2\rangle_c + 5\langle q_{(1,1)}^2 q_{(2,1)}\rangle_c^2 + 2\langle q_{(1,1)}^2\rangle_c^2\langle q_{(2,1)}^2\rangle_c + 4\langle q_{(1,1)}^2\rangle_c\langle q_{(1,1)} q_{(2,1)}\rangle_c^2) \\
&+ 36(\langle q_{(1,1)}^4 q_{(2,2)}^2\rangle_c + \langle q_{(1,1)}^4\rangle_c\langle q_{(2,2)}^2\rangle_c + 4\langle q_{(1,1)}^3 q_{(2,2)}\rangle_c\langle q_{(1,1)} q_{(2,2)}\rangle_c + 4\langle q_{(1,1)}^2 q_{(2,2)}^2\rangle_c\langle q_{(1,1)}^2\rangle_c \\
&+ 4\langle q_{(1,1)}^3\rangle_c\langle q_{(1,1)} q_{(2,2)}^2\rangle_c + 5\langle q_{(1,1)}^2 q_{(2,2)}\rangle_c^2 + 2\langle q_{(1,1)}^2\rangle_c^2\langle q_{(2,2)}^2\rangle_c + 4\langle q_{(1,1)}^2\rangle_c\langle q_{(1,1)} q_{(2,2)}\rangle_c^2) \\
&+ 16(\langle q_{(1,1)}^2 q_{(3,1)}^2\rangle_c + \langle q_{(1,1)}^2\rangle_c\langle q_{(3,1)}^2\rangle_c + \langle q_{(1,1)} q_{(3,1)}\rangle_c^2) \\
&+ 144(\langle q_{(1,1)}^2 q_{(3,2)}^2\rangle_c + \langle q_{(1,1)}^2\rangle_c\langle q_{(3,2)}^2\rangle_c + \langle q_{(1,1)} q_{(3,2)}\rangle_c^2) + 64(\langle q_{(1,1)}^2 q_{(3,3)}^2\rangle_c + \langle q_{(1,1)}^2\rangle_c\langle q_{(3,3)}^2\rangle_c + \langle q_{(1,1)} q_{(3,3)}\rangle_c^2) \\
&+ 9(\langle q_{(2,1)}^4\rangle_c + 2\langle q_{(2,1)}^2\rangle_c^2) + 36(\langle q_{(2,1)}^2 q_{(2,2)}^2\rangle_c + \langle q_{(2,1)}^2\rangle_c\langle q_{(2,2)}^2\rangle_c + \langle q_{(2,1)} q_{(2,2)}\rangle_c^2) \\
&+ 9(\langle q_{(2,2)}^4\rangle_c + 2\langle q_{(2,2)}^2\rangle_c^2) + \langle q_{(4,1)}^2\rangle_c + 49\langle q_{(4,2)}^2\rangle_c + 144\langle q_{(4,3)}^2\rangle_c + 36\langle q_{(4,4)}^2\rangle_c \\
&+ 12(\langle q_{(1,1)}^6 q_{(2,1)}\rangle_c + 4\langle q_{(1,1)}^5\rangle_c\langle q_{(1,1)} q_{(2,1)}\rangle_c + 8\langle q_{(1,1)}^4 q_{(2,1)}\rangle_c\langle q_{(1,1)}^2\rangle_c + 14\langle q_{(1,1)}^4\rangle_c\langle q_{(1,1)}^2 q_{(2,1)}\rangle_c \\
&+ 16\langle q_{(1,1)}^3 q_{(2,1)}\rangle_c\langle q_{(1,1)}^3\rangle_c + 24\langle q_{(1,1)}^3\rangle_c\langle q_{(1,1)}^2\rangle_c\langle q_{(1,1)} q_{(2,1)}\rangle_c + 12\langle q_{(1,1)}^2 q_{(2,1)}\rangle_c\langle q_{(1,1)}^2\rangle_c^2) \\
&- 12(\langle q_{(1,1)}^6 q_{(2,2)}\rangle_c + 4\langle q_{(1,1)}^5\rangle_c\langle q_{(1,1)} q_{(2,2)}\rangle_c + 8\langle q_{(1,1)}^4 q_{(2,2)}\rangle_c\langle q_{(1,1)}^2\rangle_c + 14\langle q_{(1,1)}^4\rangle_c\langle q_{(1,1)}^2 q_{(2,2)}\rangle_c \\
&+ 16\langle q_{(1,1)}^3 q_{(2,2)}\rangle_c\langle q_{(1,1)}^3\rangle_c + 24\langle q_{(1,1)}^3\rangle_c\langle q_{(1,1)}^2\rangle_c\langle q_{(1,1)} q_{(2,2)}\rangle_c + 12\langle q_{(1,1)}^2 q_{(2,2)}\rangle_c\langle q_{(1,1)}^2\rangle_c^2) \\
&+ 8(\langle q_{(1,1)}^5 q_{(3,1)}\rangle_c + 4\langle q_{(1,1)}^4\rangle_c\langle q_{(1,1)} q_{(3,1)}\rangle_c + 4\langle q_{(1,1)}^3 q_{(3,1)}\rangle_c\langle q_{(1,1)}^2\rangle_c + 6\langle q_{(1,1)}^3\rangle_c\langle q_{(1,1)}^2 q_{(3,1)}\rangle_c)
\end{aligned}
$$



F. Si, ZYF, PRC 105 (2022) 024907.

- Analytical formula for statistical uncertainties of cumulants upto 4th-order.
- ~x10^6 faster than bootstrap method.

Net-proton higher-order cumulants in BES-II



- 3.2 and 3.5 GeV FXT analysis is in progress.
- Detailed work on acceptance is ongoing.

Hypernuclei production in BES energies

Hypernuclei: bound nuclear systems of non-strange and strange baryons

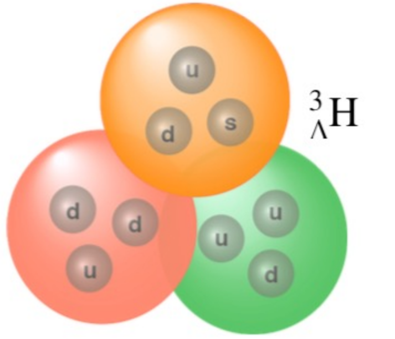
- Probe hyperon-nucleon(Y-N) interaction
  - Strangeness in high density nuclear matter
    - EoS of neutron star
- Experimentally, we can make measurements related to:

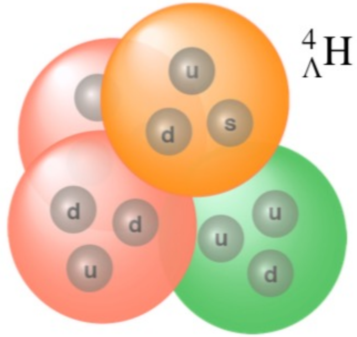
1. Internal structure
    - Lifetime, binding energy, branching ratios etc.

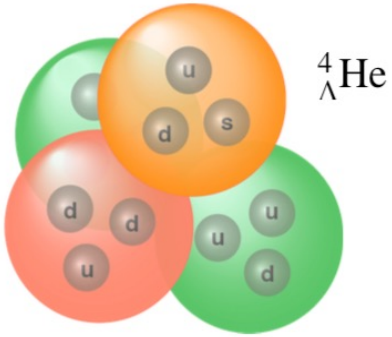
   Understanding hypernuclei structure may give more constraints on the Y-N interaction

2. Production in heavy-ion collisions
    - Spectra, collectivity etc.

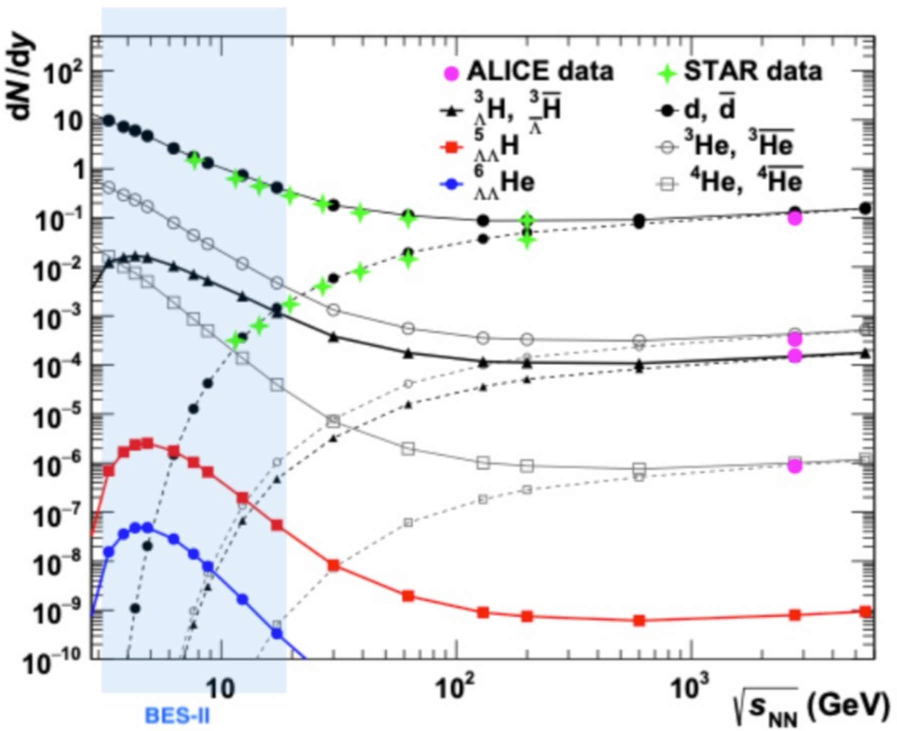
   The formation of loosely bound states in violent heavy-ion collisions is not well understood







Hypernuclei production in BES energies



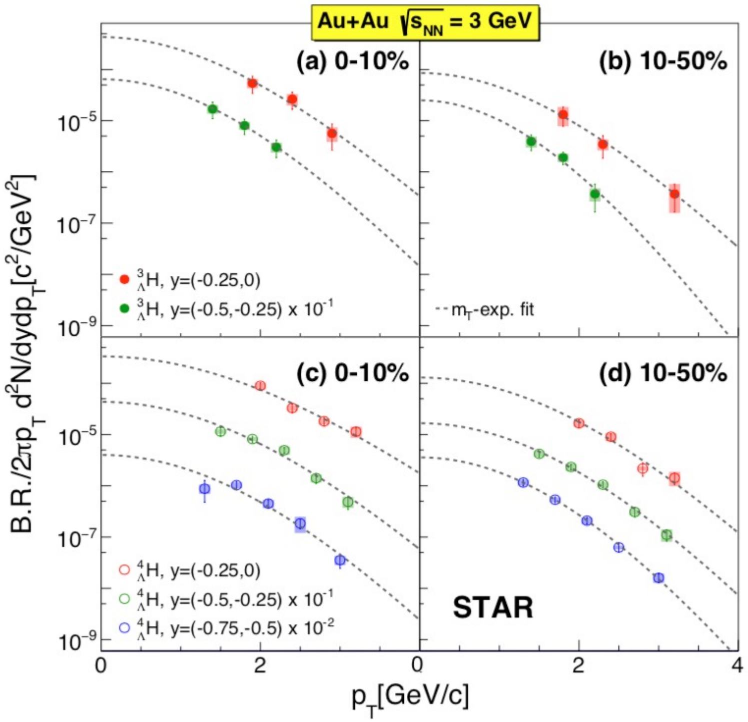
B. Dönigus, Eur. Phys. J. A (2020) 56:280

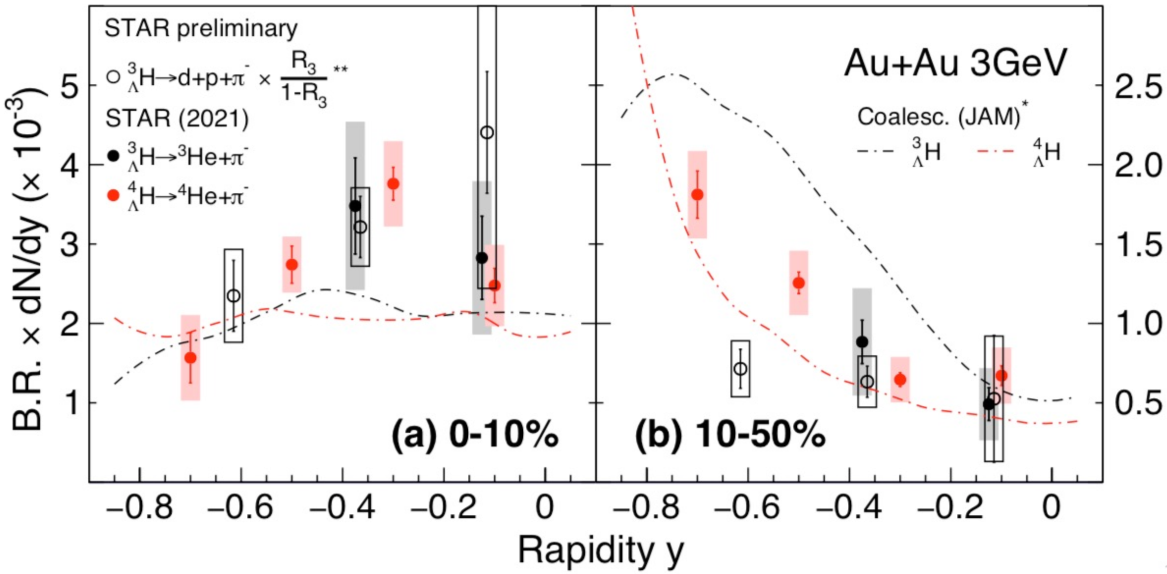
Year	$\sqrt{s_{NN}}$ [GeV]	Events
2018	27	555 M
	3.0	258 M
	7.2	155 M
2019	19.6	478 M
	14.6	324 M
	3.9	53 M
	3.2	201 M
	7.7	51 M
2020	11.5	235 M
	7.7	113 M
	4.5	108 M
	6.2	118 M
	5.2	103 M
	3.9	117 M
	3.5	116 M
	9.2	162 M
	7.2	317 M

Year	$\sqrt{s_{NN}}$ [GeV]	Events
2021	7.7	101 M
	3.0	2103 M
	9.2	54 M
	11.5	52 M
	13.7	51 M
	17.3	256 M
	7.2	89 M

- At lower energies, hypernuclei yield is enhanced due to high baryon density.
- STAR BES-II with large statistics data provide great opportunity to study hypernuclei production.

Hypernuclei production at 3 GeV

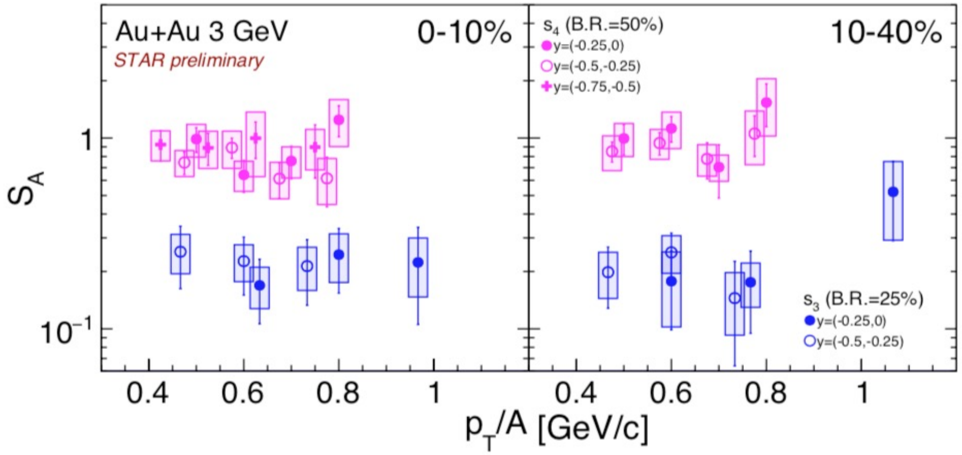


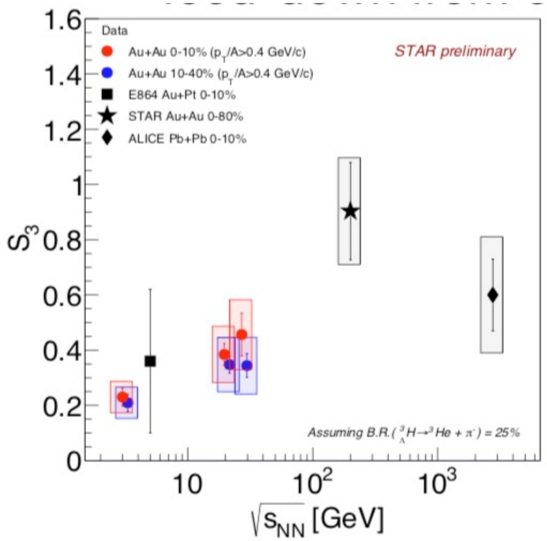


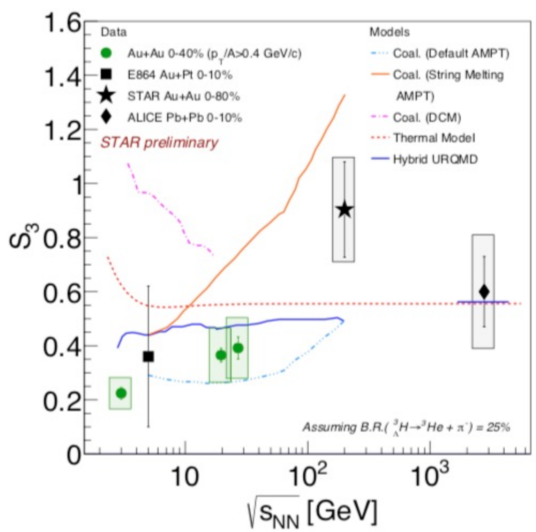
- First measurement of dN/dy of hypernuclei in heavy-ion collisions
- Different trends in the $^{4}_{\Lambda}\mathrm{H}$ rapidity distribution in central (0-10%) and mid-central (10-50%) collisions
- Transport model (JAM) with coalescence reproduces trends of $^{4}_{\Lambda}\mathrm{H}$ rapidity distributions seen in data

Relative yield S_3 and S_4

- S_A: relative suppression of hypernuclei production compared to light nuclei production
  $$S_A = \frac{{}^{A}_{\Lambda}H}{{}^{A}He \times \frac{\Lambda}{p}}$$
  - Expect ~1 if no suppression naively
    - $S_3 < 1 \rightarrow$ relative suppression of ${}^{3}_{\Lambda}H$ to ${}^{3}He$
    - $S_4 > S_3 \rightarrow$ enhanced ${}^{4}_{\Lambda}H$ production due to feed-down from excited state



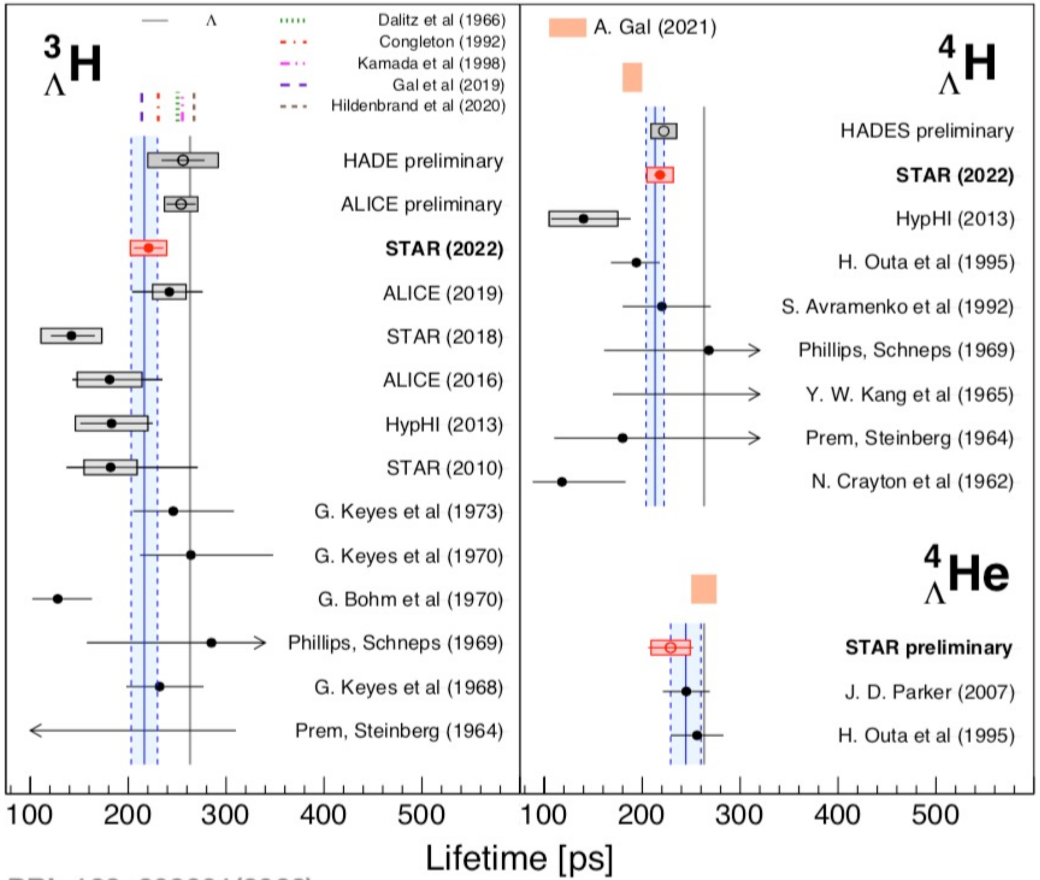




- No clear centrality dependence
- Hint of an increasing trend from $\sqrt{s_{NN}}$ = 3.0 GeV to 2.76 TeV
- None of the models describe the S_3 data quantitatively

STAR, Science 328 (2010) 58
ALICE, PLB 754 (2016) 360
E864, PRC 70 (2004) 024902
NA49, J.Phys.Conf.Ser.110(2008)032010
A. Andronic et al, PLB 697 (2011) 203 (Thermal model)
J. Steinheimer et al, PLB 714 (2021) (H. URQMD, Coal.(DCM))
S. Zhang PLB 684(2010)224 (Coal.+AMPT)

Hypernuclei lifetime measurement at 3 and 7.2 GeV



PRL 128, 202301(2022)

$^{3}_{\Lambda}$H: $\tau = 221 \pm 15(\text{stat.}) \pm 19(\text{syst.})$[ps]

$^{4}_{\Lambda}$H: $\tau = 218 \pm 6(\text{stat.}) \pm 13(\text{syst.})$[ps]

$^{4}_{\Lambda}$He: $\tau = 229 \pm 23(\text{stat.}) \pm 20(\text{syst.})$[ps]

- Lifetime of light hypernuclei $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He are shorter than that of free Λ (with 1.8σ, 3.0σ, 1.1σ respectively)
- Consistent with former measurements (within 2.5σ for $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H
- $\tau_{^{3}_{\Lambda}\text{H}}$ result consistent with calculation including pion FSI (2019) and calculation under Λd 2-body picture (1992) within 1σ

$^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H results with improved precision

→ Provide tighter constraints on models.

Summary

- Heavy flavor hadrons D+, Ds, Λc over D^0 ratios are measured in top energy at STAR and consistent with fragmentation or quark coalescence hadronization mechanisms.
- HFE R_{AA} are measured and with c/b separation for both RHIC and LHC, consistent with mass-dependent energy loss picture.
- The measured b->e v2 indicates bottom is unlikely thermalized and first seen the energy dependence in between RHIC and LHC.
- Some progress in net-proton higher-order cumulants analysis in STAR BES energies, looking for more detailed study and new data.
- Hypernuclei production in some of the BES energies are measured, some detailed study is ongoing and new data will come soon for more energies

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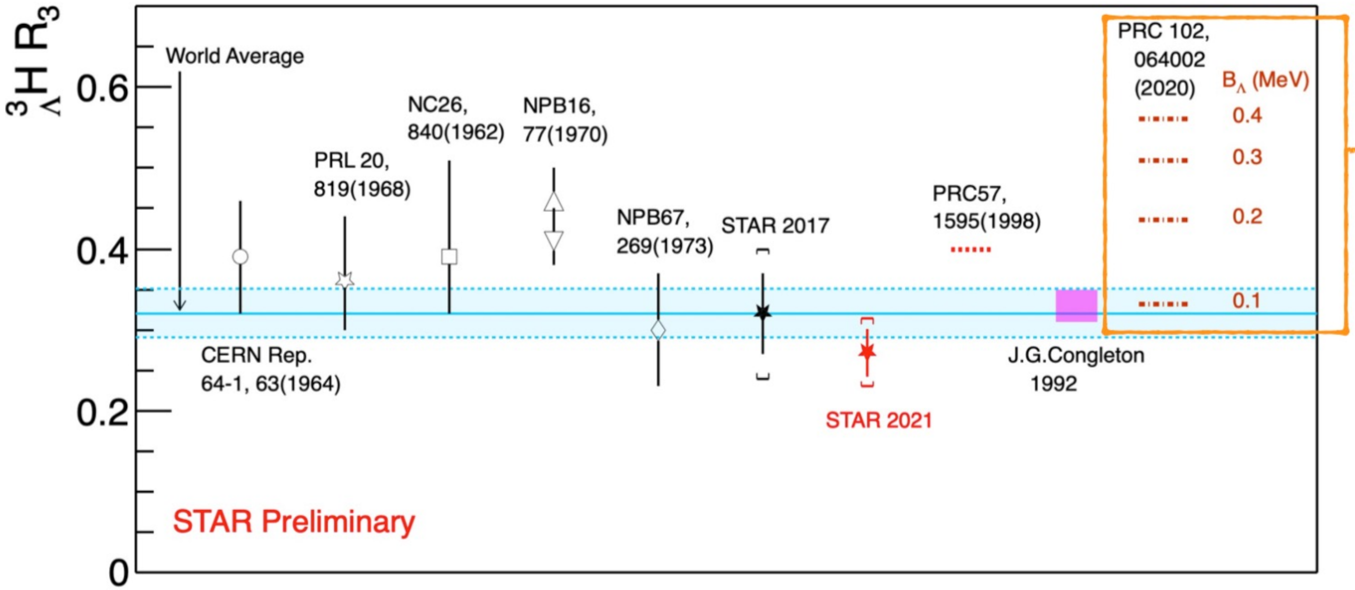
Thank you for your attention!

Backup slides

Hypertriton branching ratio R_3

Relative branching ratio: $R_3 = \dfrac{B.R.({}^3_\Lambda H \to {}^3He\pi^-)}{B.R.({}^3_\Lambda H \to {}^3He\pi^-) + B.R.({}^3_\Lambda H \to dp\pi^-)}$



R_3 may be sensitive to the binding energy of ${}^3_\Lambda H$

- STAR 2021 (preliminary): $R_3 = 0.272 \pm 0.030 \pm 0.042$
  - Updated world average R_3 is consistent with theory calculation assuming B_Λ~ 0.1 MeV

- Improved precision on R_3
  - Stronger constraints on hypernuclear interaction models used to describe ${}^3_\Lambda H$
  - Stronger constraints on absolute B.R.s