



(部分) 奇异与重味实验研究进展

朱相雷

清华大学

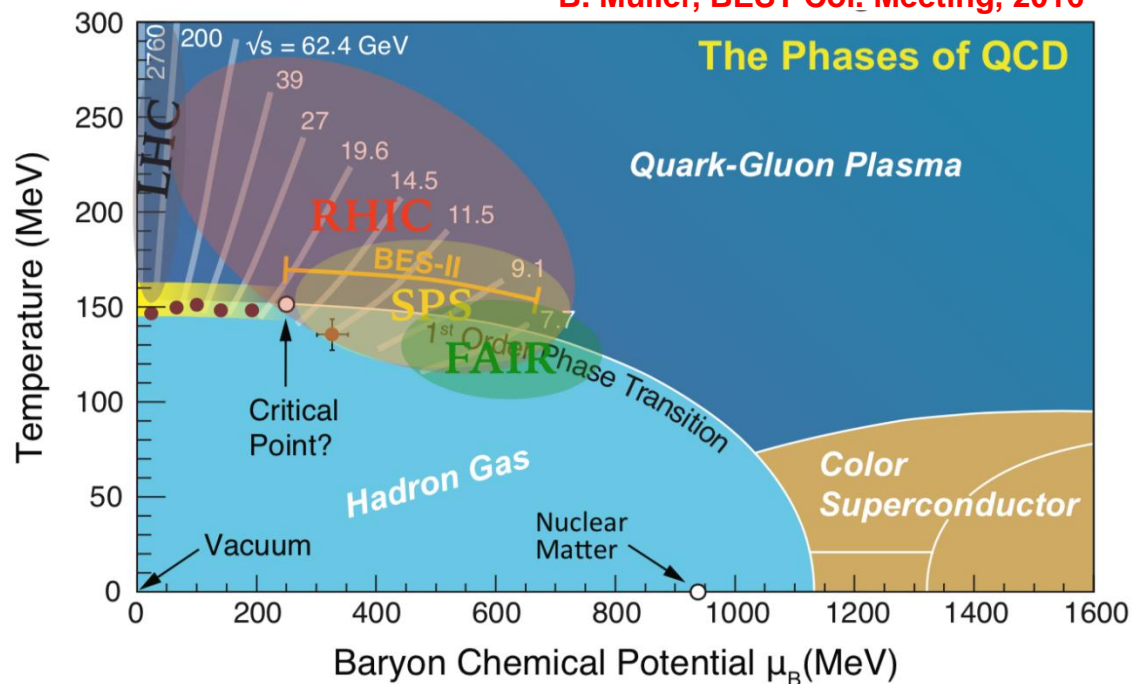
7/29/2022

QCD物理研讨会暨基金委重大项目学术交流会

2022.7.29-31, 山东大学青岛校区

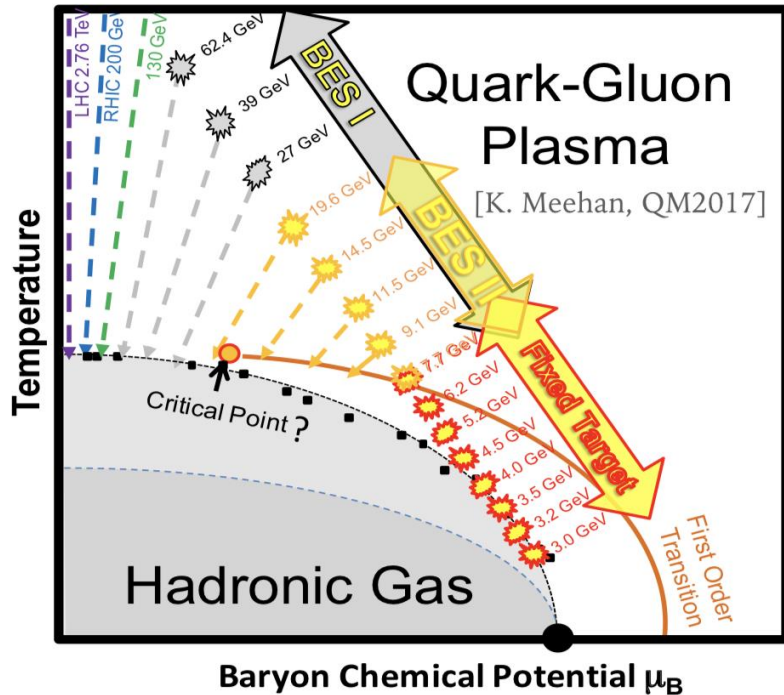
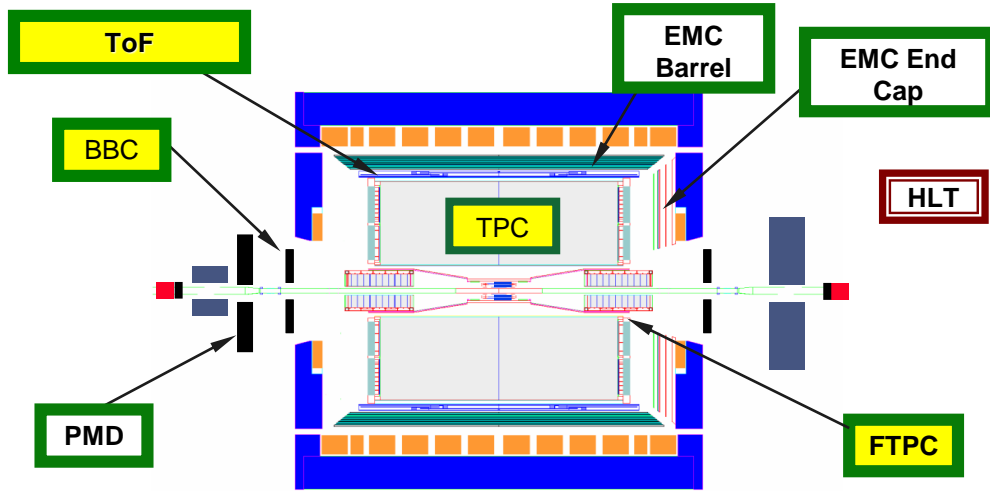
QCD 相图

B. Müller, BEST Col. Meeting, 2016



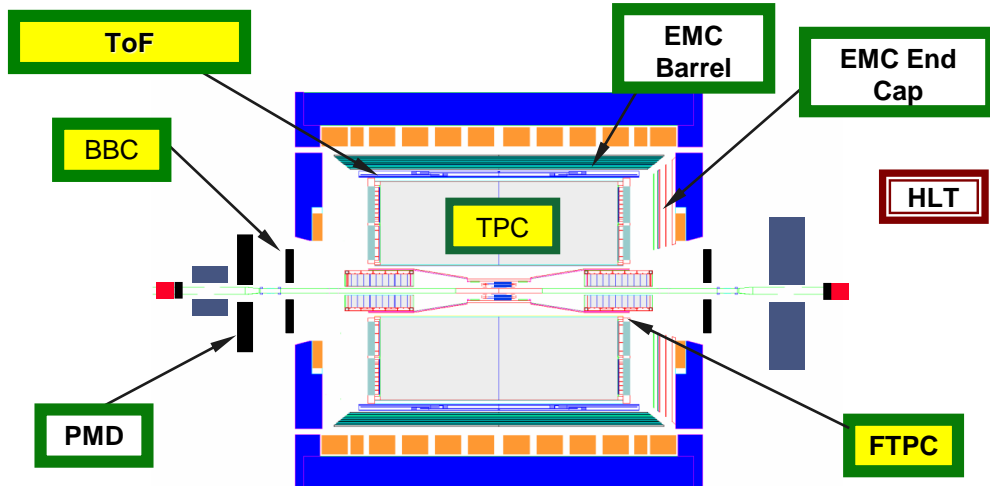
- **RHIC能量扫描实验 (beam energy scan, BES)**
覆盖中等重子数密度区，寻找退禁闭相变起始能量点、一级相变的相边界和临界端点。
- **RHIC和LHC的高能重离子碰撞**
低重子数密度区，定量研究QGP物态特性。

STAR 能量扫描实验



- STAR:
RHIC上的对撞机实验
- 在中心快度区 ($|\eta| < 1$) 具有 2π 方位角覆盖
- 第一阶段能量扫描(BES-I)
 $Au+Au \sqrt{s_{NN}} = 62.4 - 7.7$
GeV
- 第二阶段能量扫描(BES-II)
 $Au+Au \sqrt{s_{NN}} = 19.6 - 7.7$
GeV
- 固定靶(Fixed-target)
 $Au+Au \sqrt{s_{NN}} = 7.7 - 3.0$
GeV
重子化学势 μ_B 最大可达
721 MeV

STAR BES-I 已获取数据



- STAR:
RHIC上的对撞机实验
- 在中心快度区 ($|\eta| < 1$) 具有 2π 方位角覆盖
- 第一阶段能量扫描(BES-I)
 $\text{Au+Au } \sqrt{s_{NN}} = 62.4 - 7.7$
GeV

Year	Collisions	$\sqrt{s_{NN}}$ (GeV)	Minimum bias events
2010	Au+Au	7.7	~ 4 M
2010	Au+Au	11.5	~ 12 M
2014	Au+Au	14.5	~ 13 M
2011	Au+Au	19.6	~ 36 M
2011 / 2018	Au+Au	27	~ 70 M / ~ 560 M
2010	Au+Au	39	~ 130 M
2017	Au+Au	54.4	~ 556 M
2010	Au+Au	62.4	~ 46 M

奇异强子是QCD相变的重要探针

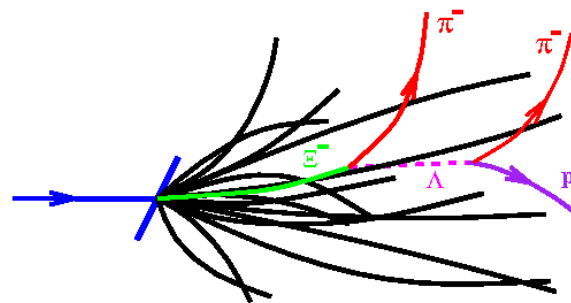
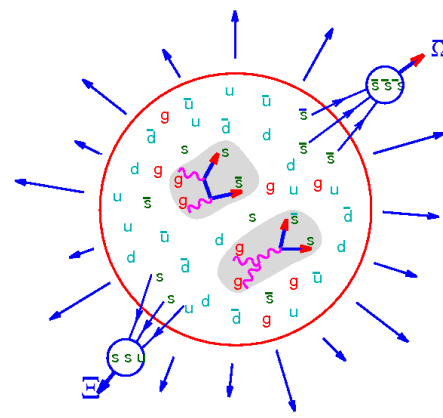
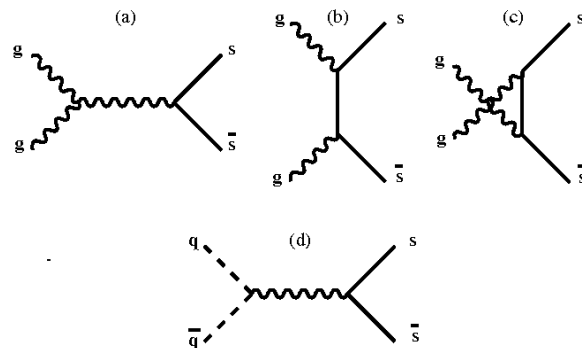
Rafelski & Müller, 1982

- 奇异夸克
 - 在对撞核中不存在其价夸克
 - 流质量 $\sim 100 \text{ MeV} < T_c$
 - 容易在退禁闭的QGP介质中对产生

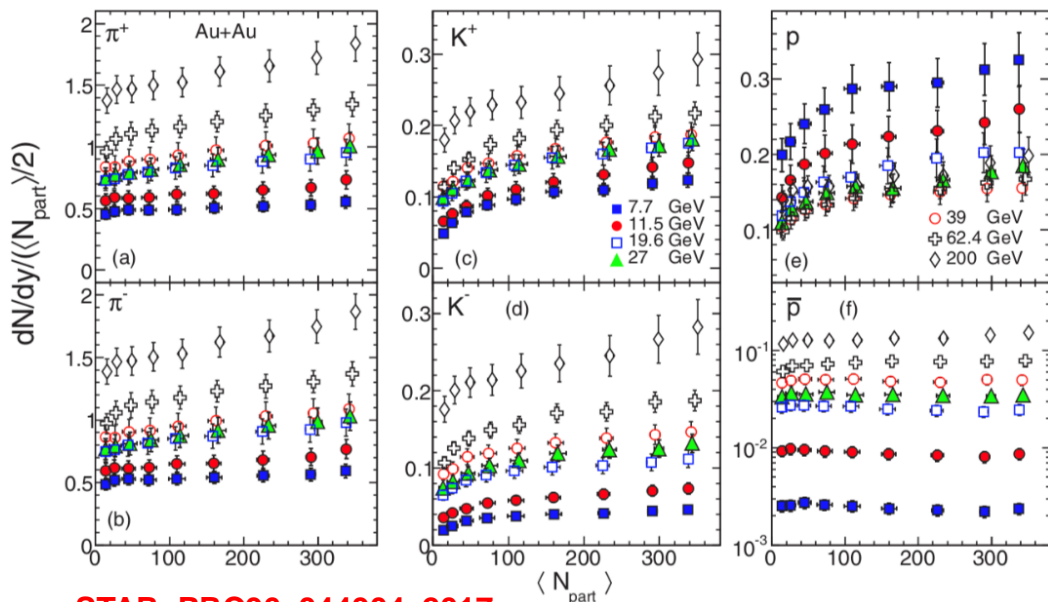
→ 奇异性增强！

- 带有（多个）奇异夸克的强子
 - 在QGP强子化阶段通过夸克重组并和产生
 - 强子散射截面较小
 - 对介质早期演化动力学较敏感
 - 实验上容易重建，并在所有 p_T 范围进行测量

→ 可系统研究热密介质特性！

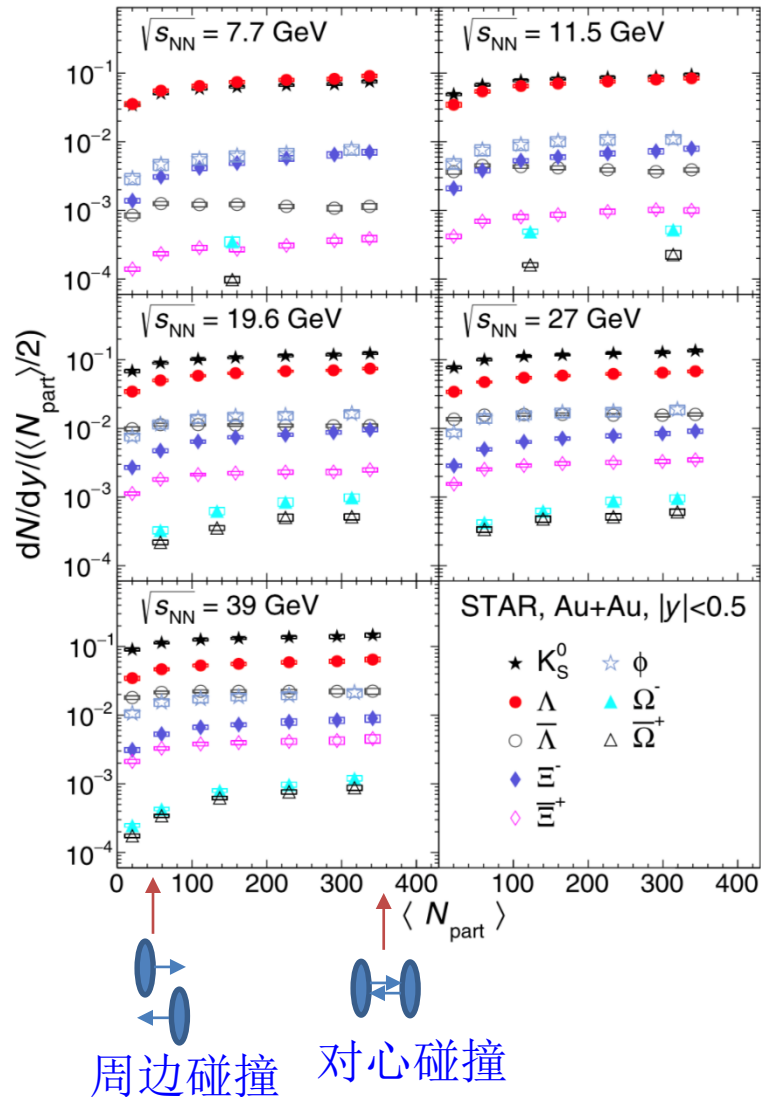


中心快度区的奇异强子产额 (dN/dy)



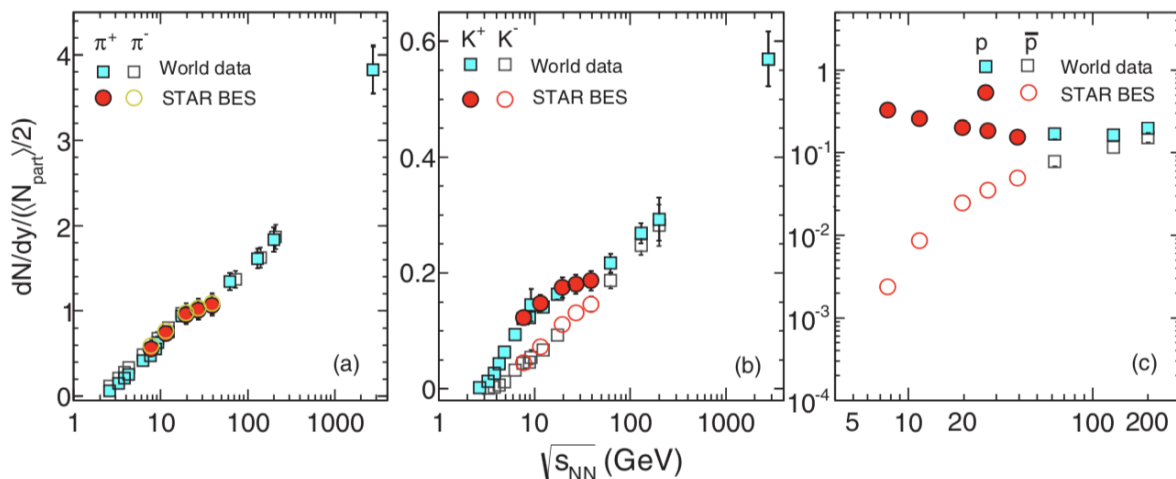
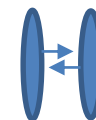
STAR, PRC96, 044904, 2017

- (每参与碰撞核子对的) 各个强子产额随着碰撞更对心以及能量更高而增加
- 例外:
 - p 和 Λ 产额随能量提高而下降
 - \bar{p} 和 $\bar{\Lambda}$ 产额不随碰撞对心度变化

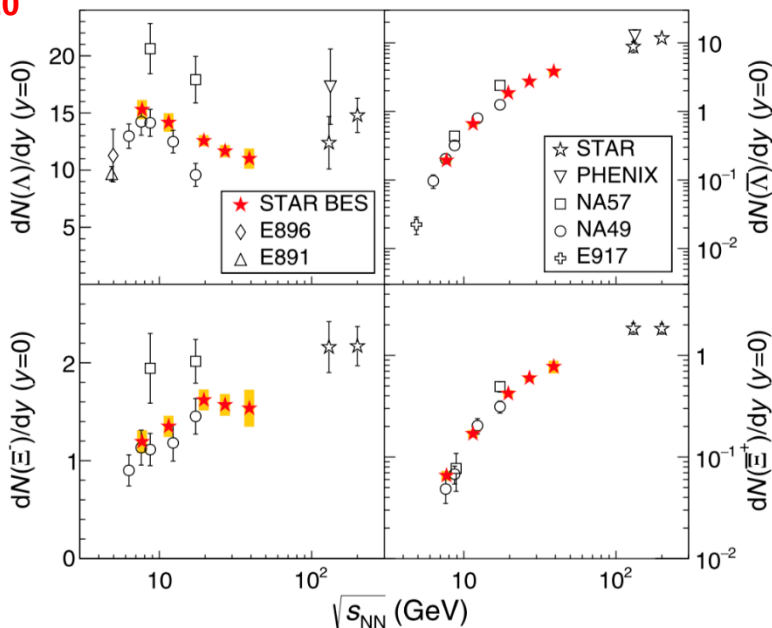
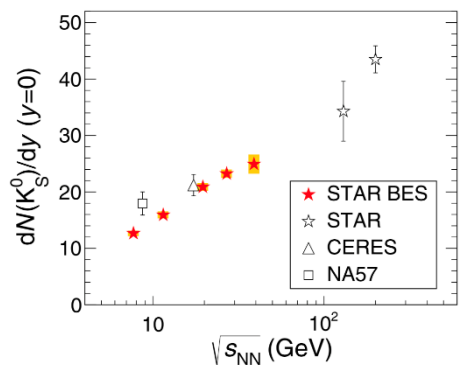


STAR, PRC102, 034909, 2020

对心碰撞中的强子产额随能量的变化

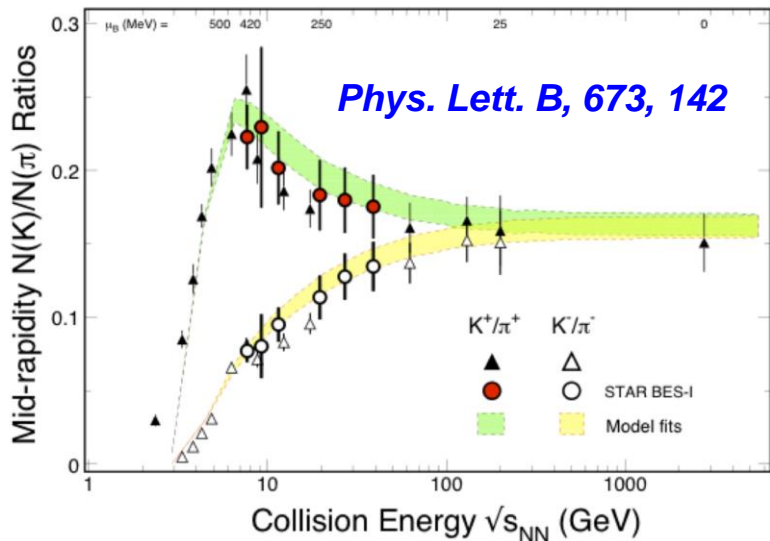
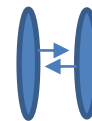


STAR, PRC96, 044904, 2017
 STAR, PRC102, 034909, 2020

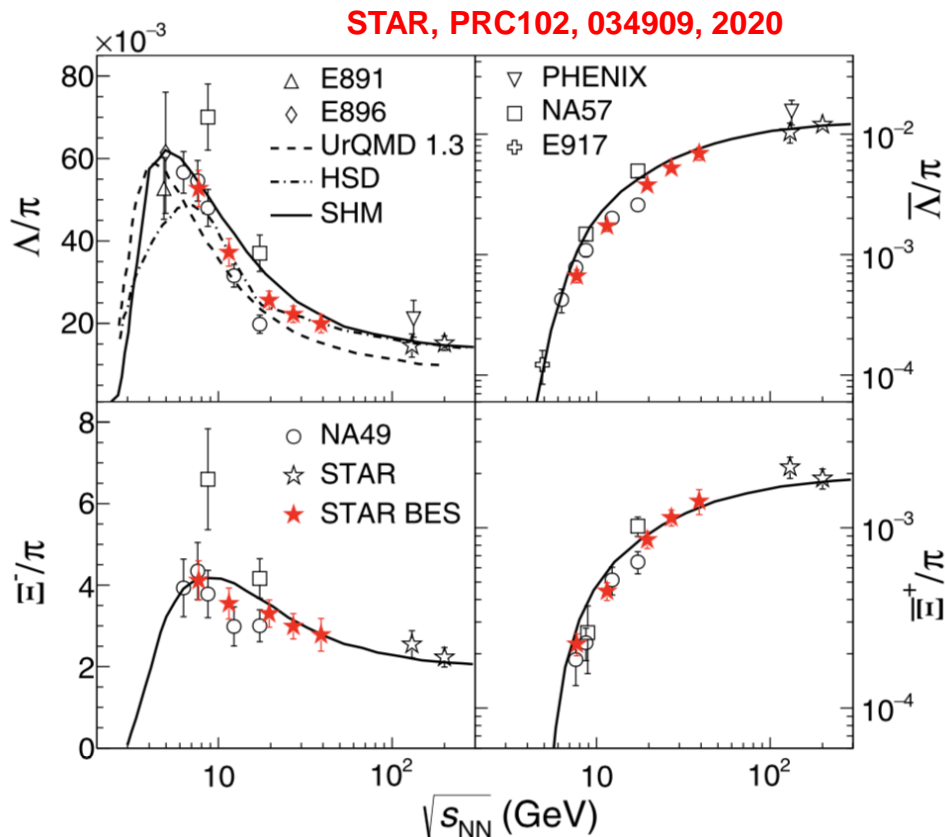
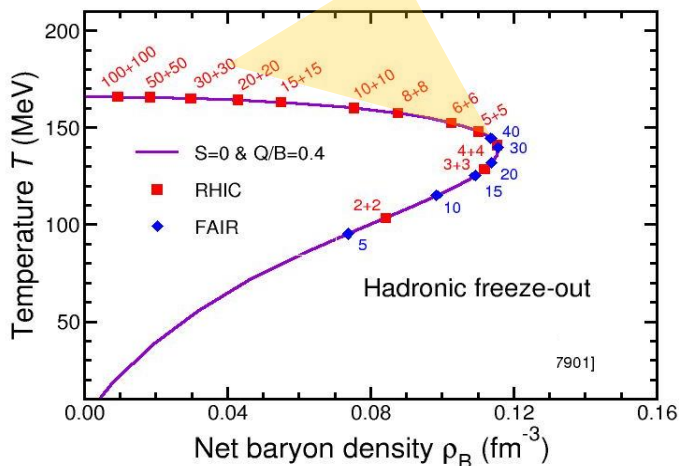


- STAR BES-I 数据与其他实验数据基本一致
- 各强子产额随能量的变化表现出丰富的结构
- p 和 Λ 产额在 39 GeV 附近最小：
 - 小于 39 GeV，主要来源于碰撞核的重子停止
 - 大于 39 GeV，主要来源于重子反重子对产生

奇异强子和 π 介子产额比



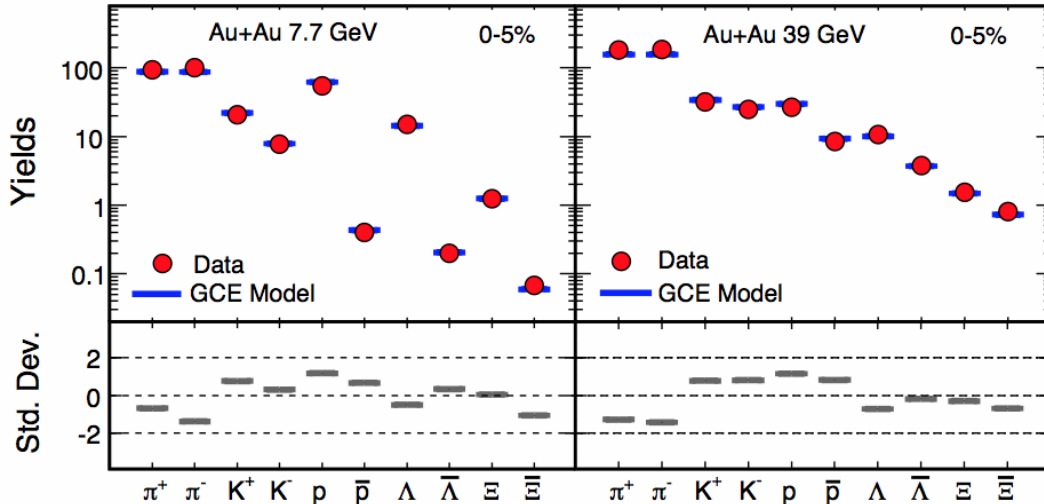
RHIC BES-I



- 各个奇异强子和 π 介子产额比显示 $\sqrt{s_{NN}} \sim 8 \text{ GeV}$ 的重离子碰撞中产生的热密介质在化学冻结时刻的净重子数密度最大。

介质化学冻结热力学参数: T_{ch} vs. μ_B

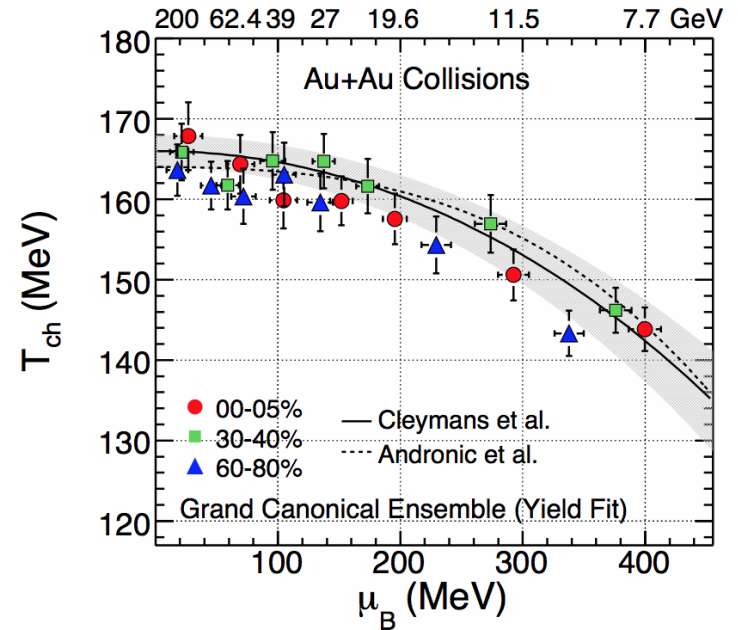
STAR, Phys. Rev. C 96, 044904, 2017



- ✓ Particles used : π , K , p , Λ , Ξ
- ✓ Ensemble used: **Grand canonical (GCE)**
- ✓ Fit parameters: T_{ch} , μ_B , μ_S and γ_S

Thermus, S. Wheaton & J. Cleymans, Comput. Phys. Commun. 180: 84-106, 2009.

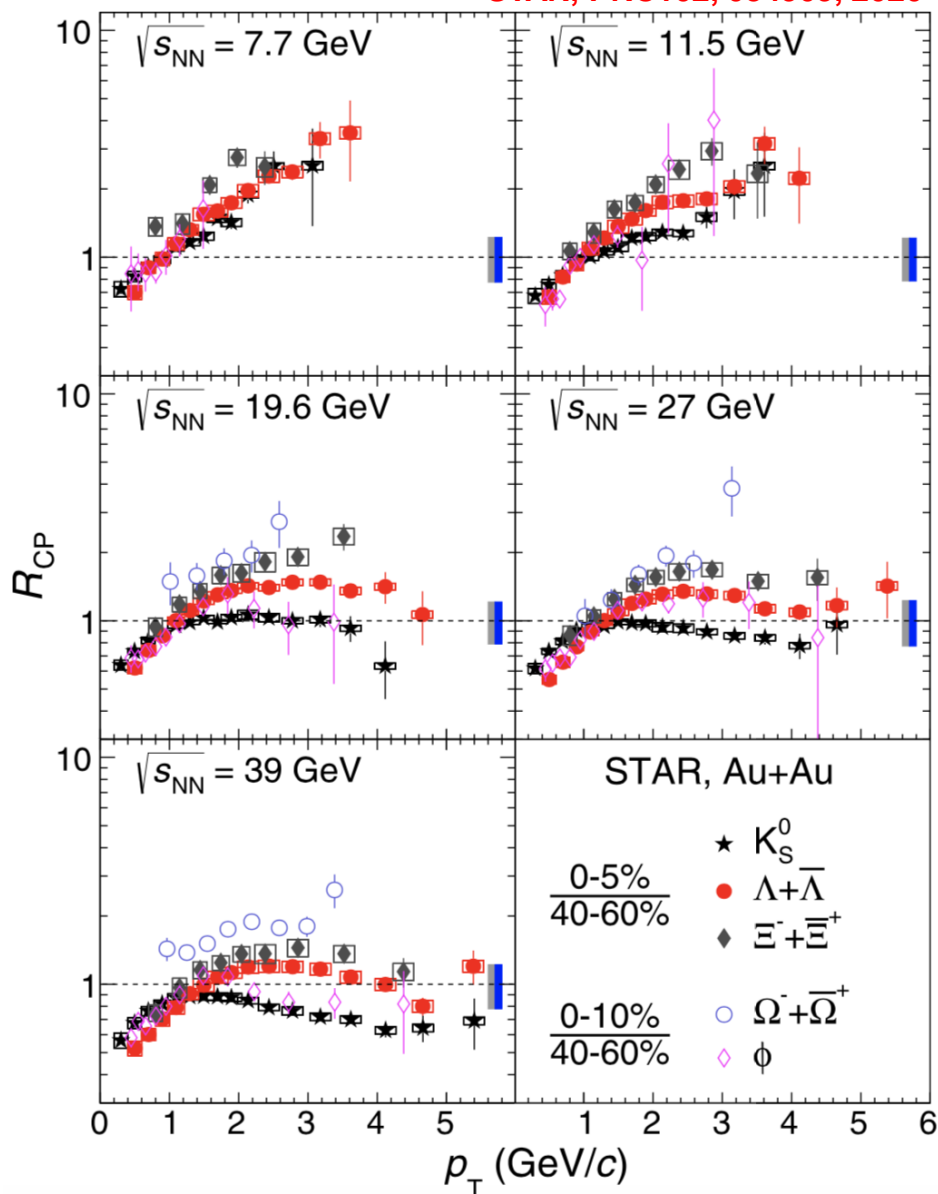
- 利用统计模型直接拟合多种强子产额，提取STAR BES-I各能量Au+Au碰撞产生的介质的 T_{ch} , μ_B , μ_S 等热力学参数。
- 限定QCD相变的相边界！



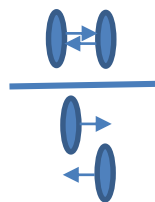
Andronic: NPA 834 (2010) 237
 Cleymans: PRC 73 (2006) 034905
 Au+Au 200 GeV : Phys. Rev. C 83 (2011) 24901

QGP信号随碰撞能量的变化：核修正因子 R_{CP}

STAR, PRC102, 034909, 2020

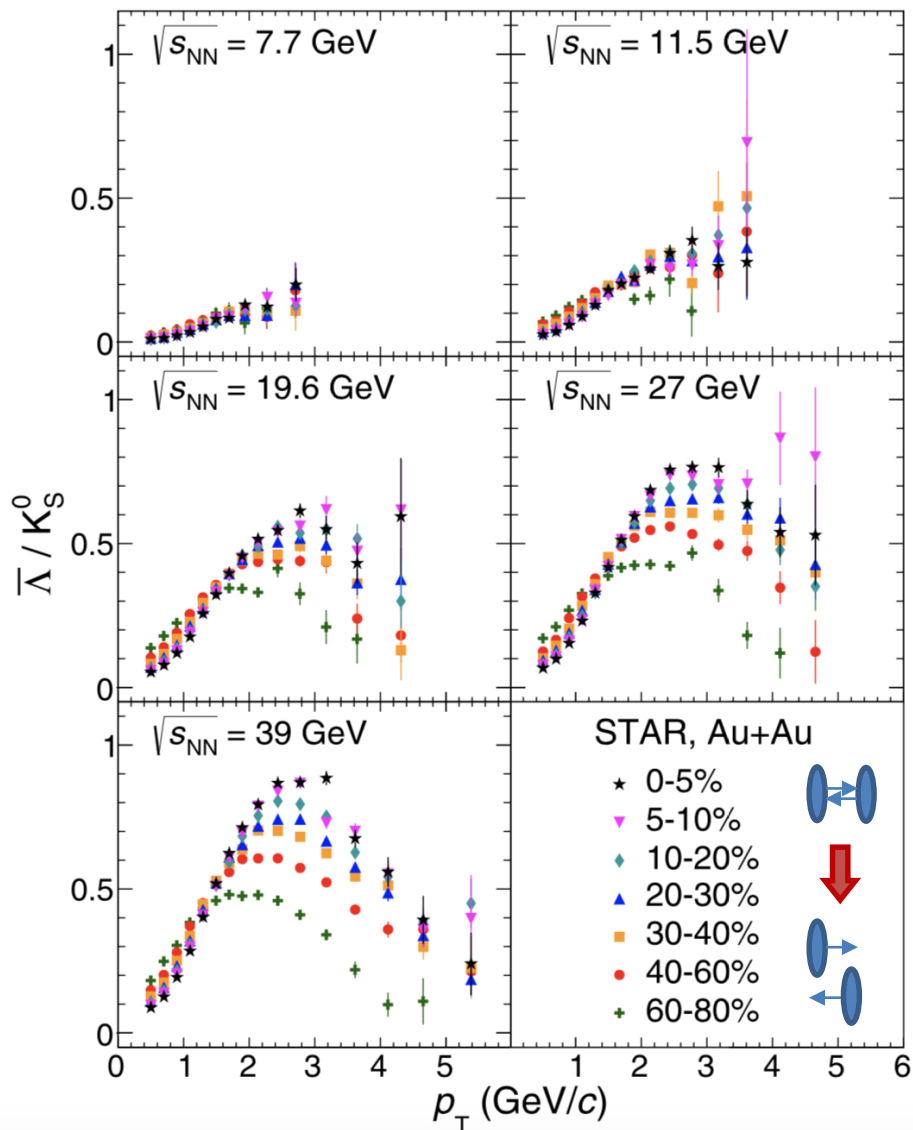


$$R_{CP}(p_T) = \frac{[d^2\sigma/(N_{bin}p_T dp_T dy)]_{central}}{[d^2\sigma/(N_{bin}p_T dp_T dy)]_{peripheral}}$$



- 高能重离子碰撞中，高 p_T 的粒子 $R_{CP} < 1$ 是 QGP 的典型信号：**喷注淬火**
- STAR BES-I 数据显示：
 - 能量在 39 GeV， K_S^0 的 R_{CP} 小于 1，喷注淬火！
 - 能量小于 11.5 GeV，高横动量 K_S^0 和其它强子的 R_{CP} 显著大于 1！
 - 低能下，Cronin 效应或径向流效应会与部分子能损存在竞争

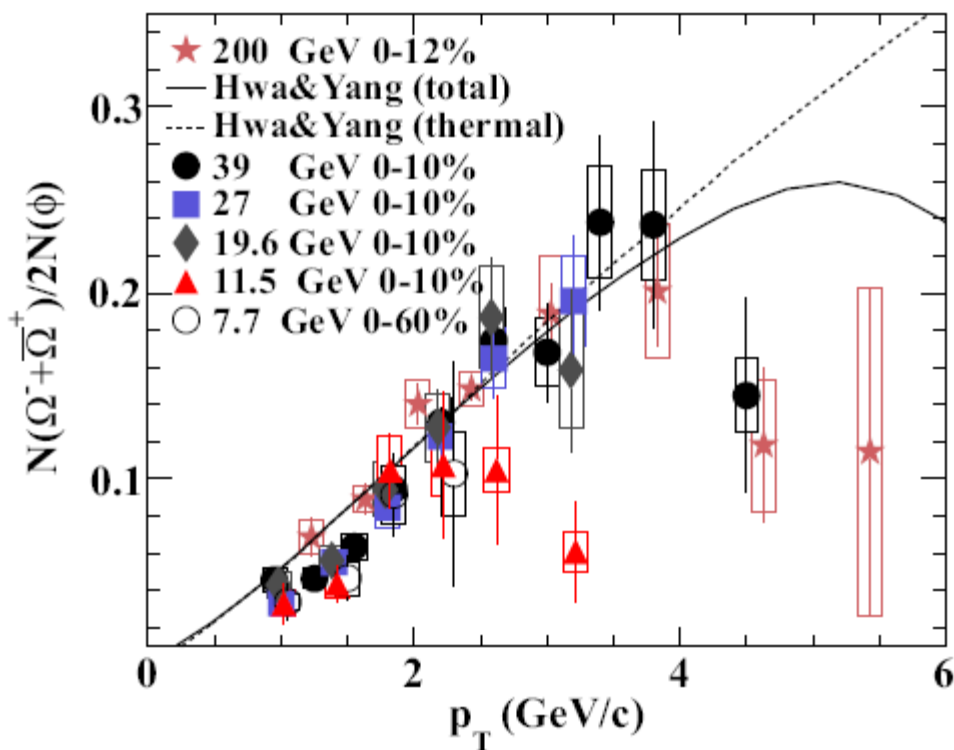
QGP信号随碰撞能量的变化：重子介子比 $\bar{\Lambda}/K_S^0$



STAR, PRC102, 034909, 2020

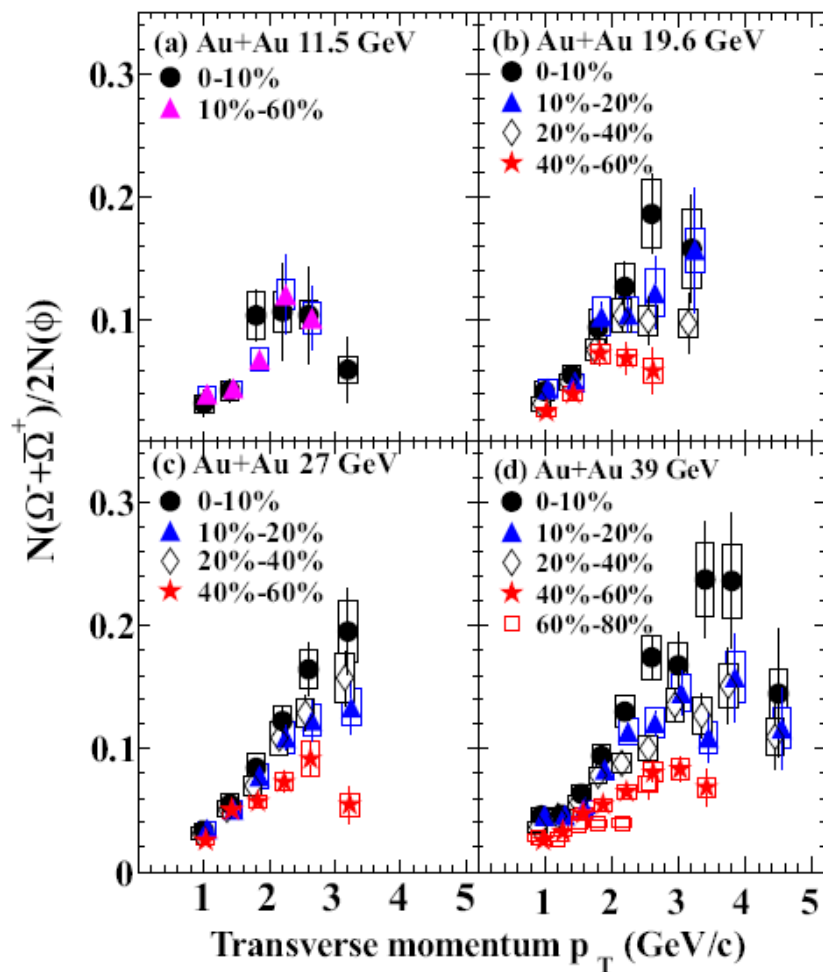
$\sqrt{s_{NN}} < 19.6$ GeV, 中等 p_T , 对心碰撞 (0-5%) 的 $\bar{\Lambda} / K_S^0$ 相对周边碰撞 (40-60%) 可能没有增强

QGP信号随碰撞能量的变化：重子介子比 Ω / ϕ

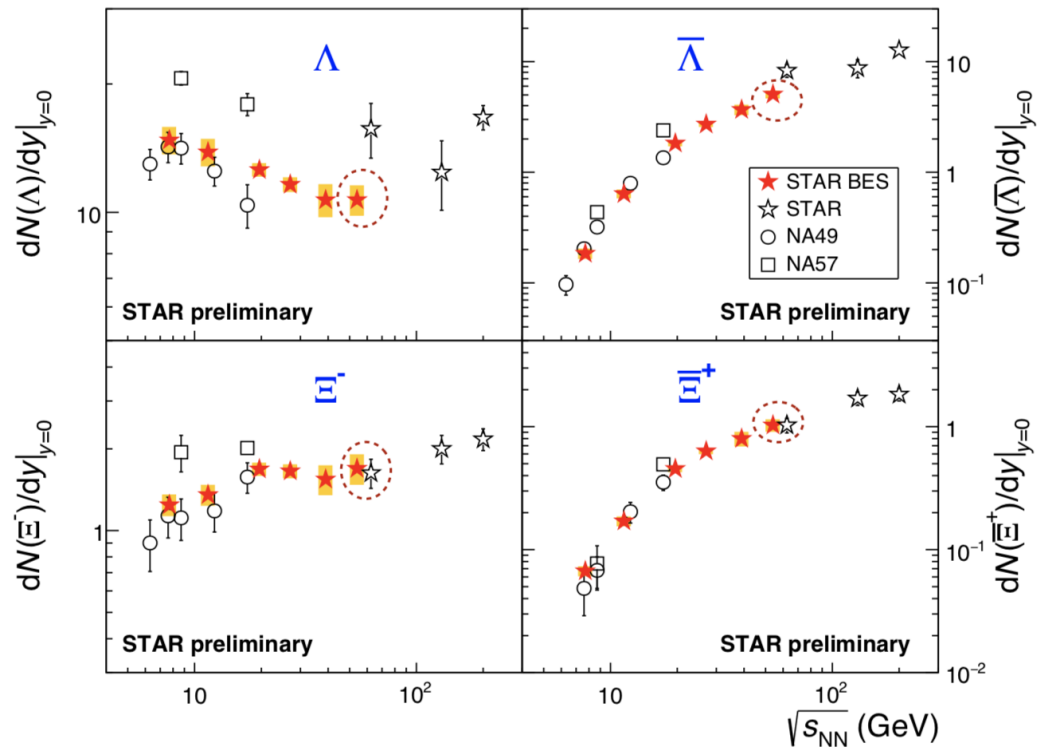
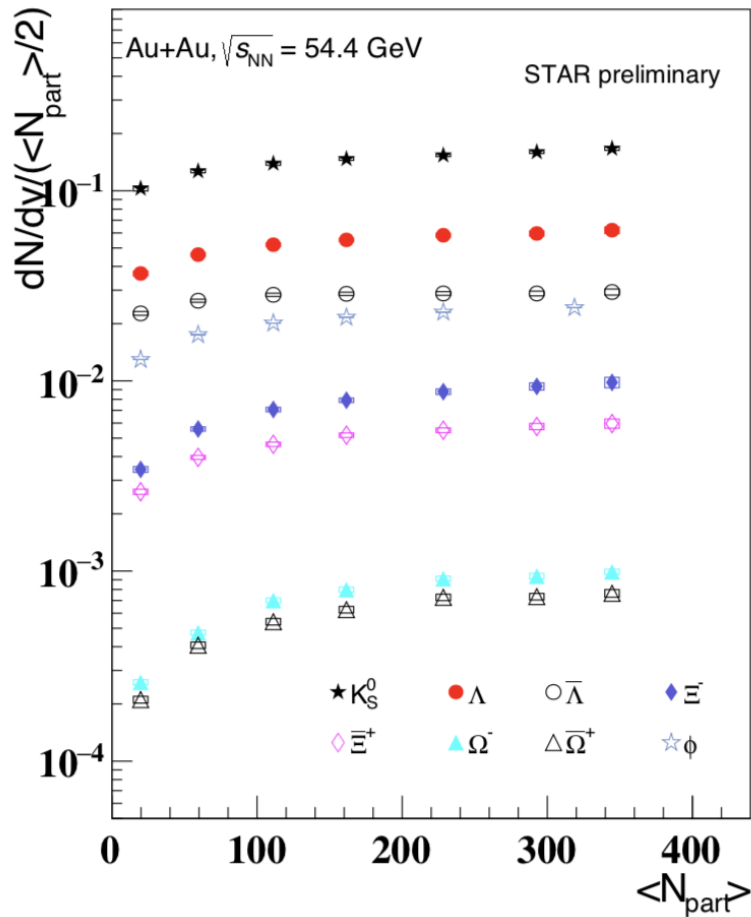


STAR, Phys. Rev. C 93, 021903 (R), 2016

- 中等 p_T Ω/ϕ 比：
低能（11.5 GeV）与较高能（ ≥ 19.6 GeV）碰撞可能存在偏离
- 19.6, 27和39 GeV对心碰撞中的 Ω/ϕ 比显著大于周边碰撞



Au+Au 54.4 GeV 奇异粒子初步结果

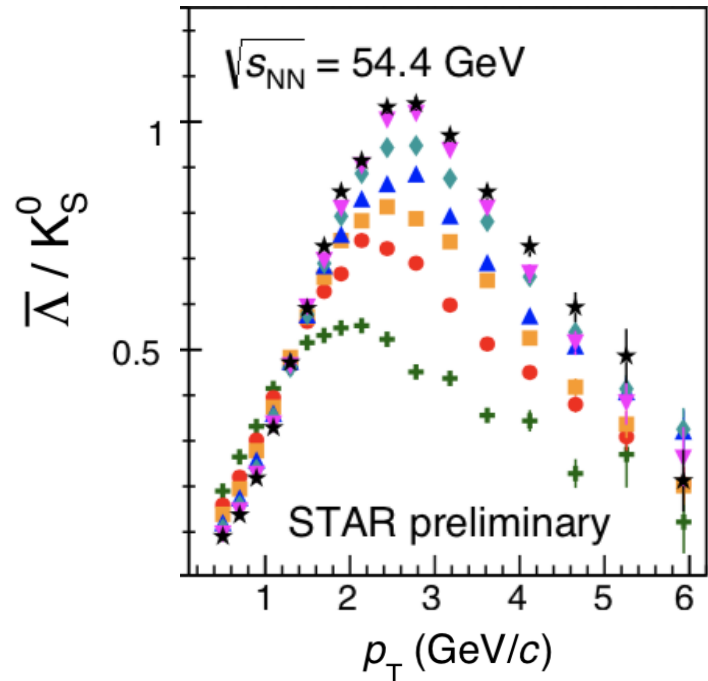
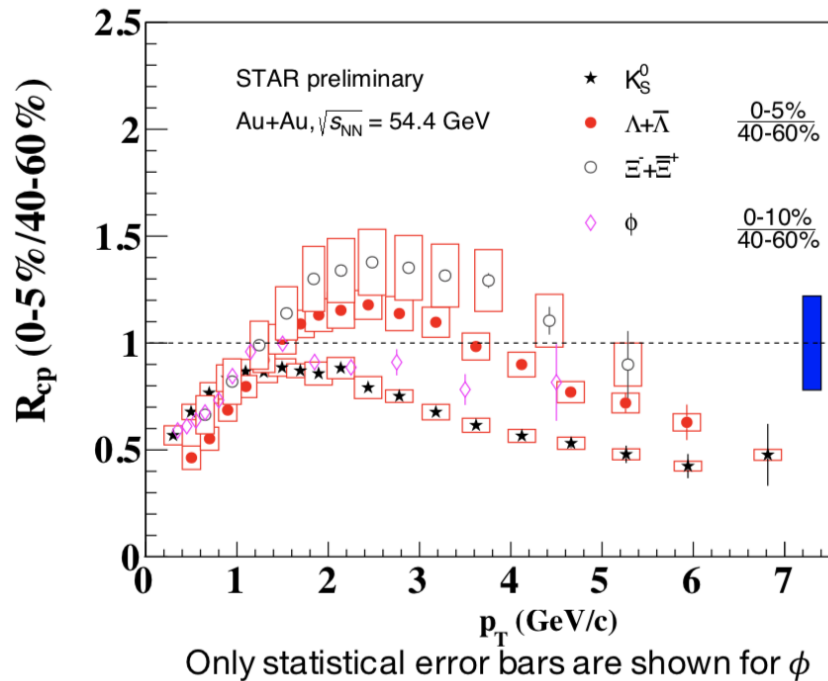


M.-U. Ashraf, QM2019
Y. Huang, SQM2021

The energy dependence of Λ :

- $\Lambda\bar{\Lambda}$ pair production at higher energy
- Associated production at lower energy
- Possible cross over between two mechanisms at ~ 54.4 GeV

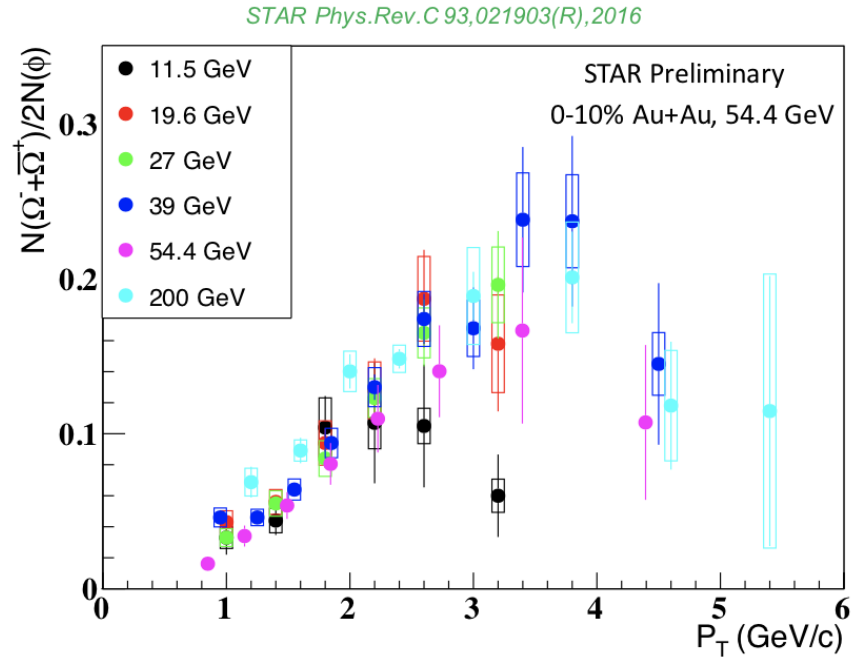
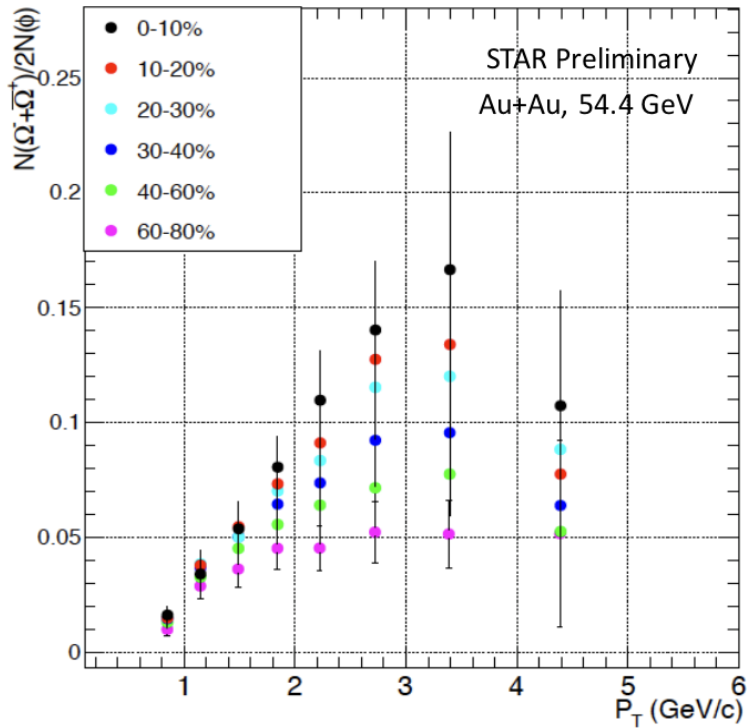
Au+Au 54.4 GeV 奇异粒子初步结果



- Strong suppression of K_S^0 R_{CP} at high p_T
→ partonic energy loss
- Baryon enhancement at intermediate p_T
→ Hadron formation through parton recombination

M.-U. Ashraf, QM2019
Y. Huang, SQM2021

Au+Au 54.4 GeV 奇异粒子初步结果



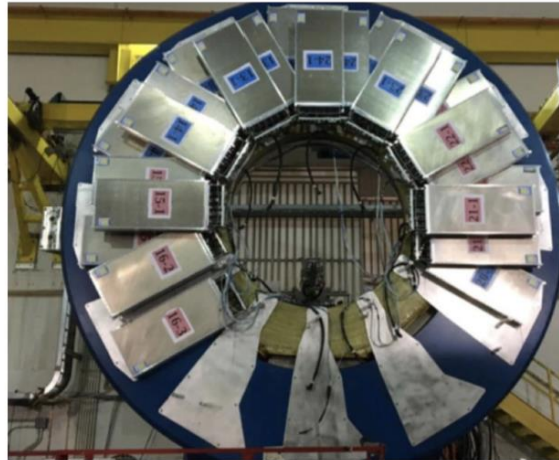
Ω/ϕ ratio enhancement at 54.4 GeV

→ Hadron formation through parton recombination

M.-U. Ashraf, QM2019

Y. Huang, SQM2021

STAR BES-II 探测器升级



iTPC:

- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c
- Ready in 2019

EndCap TOF:

- Forward rapidity coverage is critical
- PID at $\eta = 0.9$ to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR
- Ready in 2019

EPD:

- Improves trigger
 - Reduces background
 - Allows a better centrality and reaction plane measurement
- Ready in 2018

iTPC: <https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619>

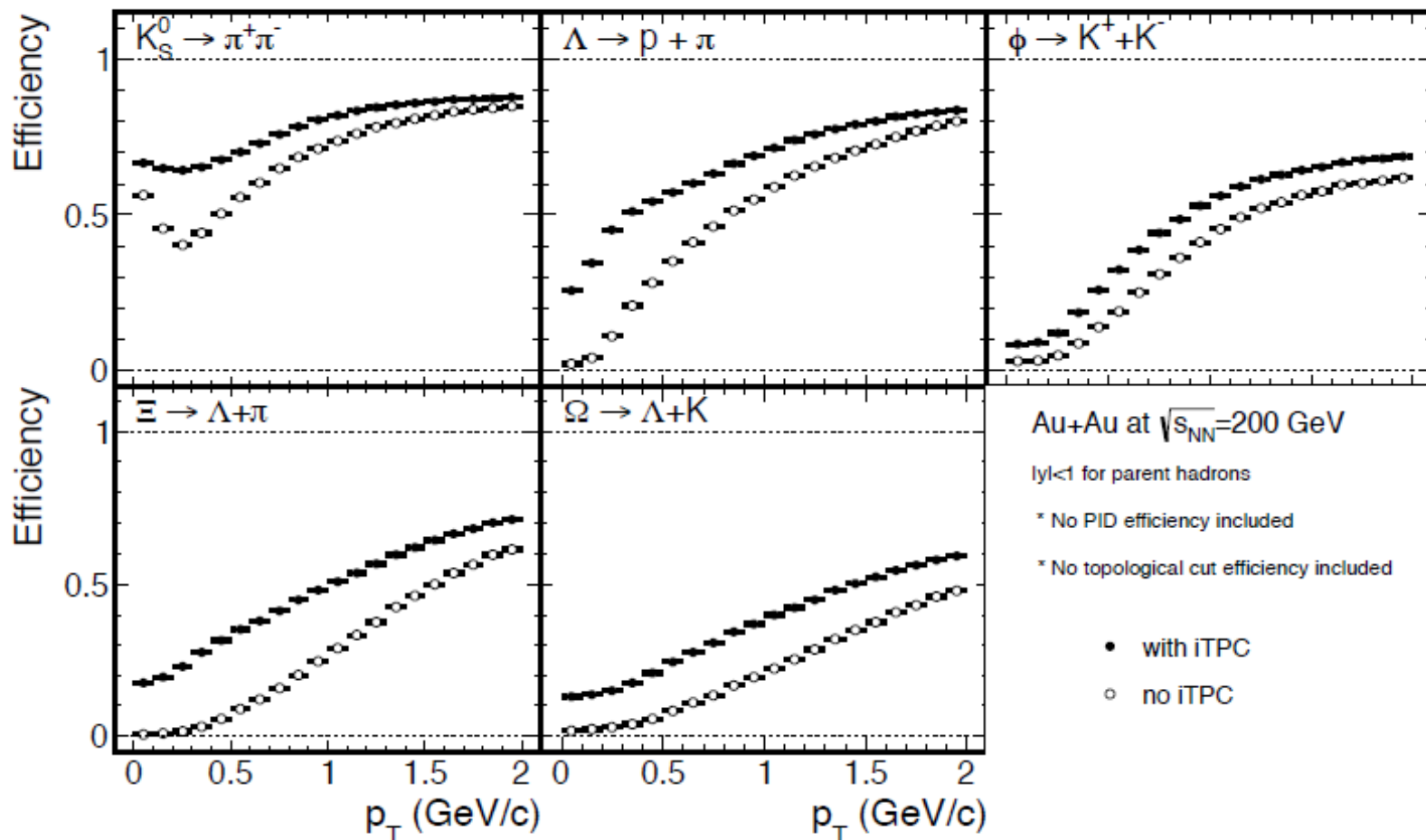
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102

EPD: J. Adams, et al. Nucl. Instr. Meth. A 968, 163970 (2020)

- 1) **Enlarge rapidity acceptance**
- 2) **Improve particle identification**
- 3) **Enhance centrality/EP resolution**

这三个探测器已经在2019年（Run-19）全部安装完毕并参与STAR BES-II对撞取数。

iTPC大幅提升了STAR探测器的奇异强子重建能力



- Significant improvement of efficiency especially for Ξ , Ω

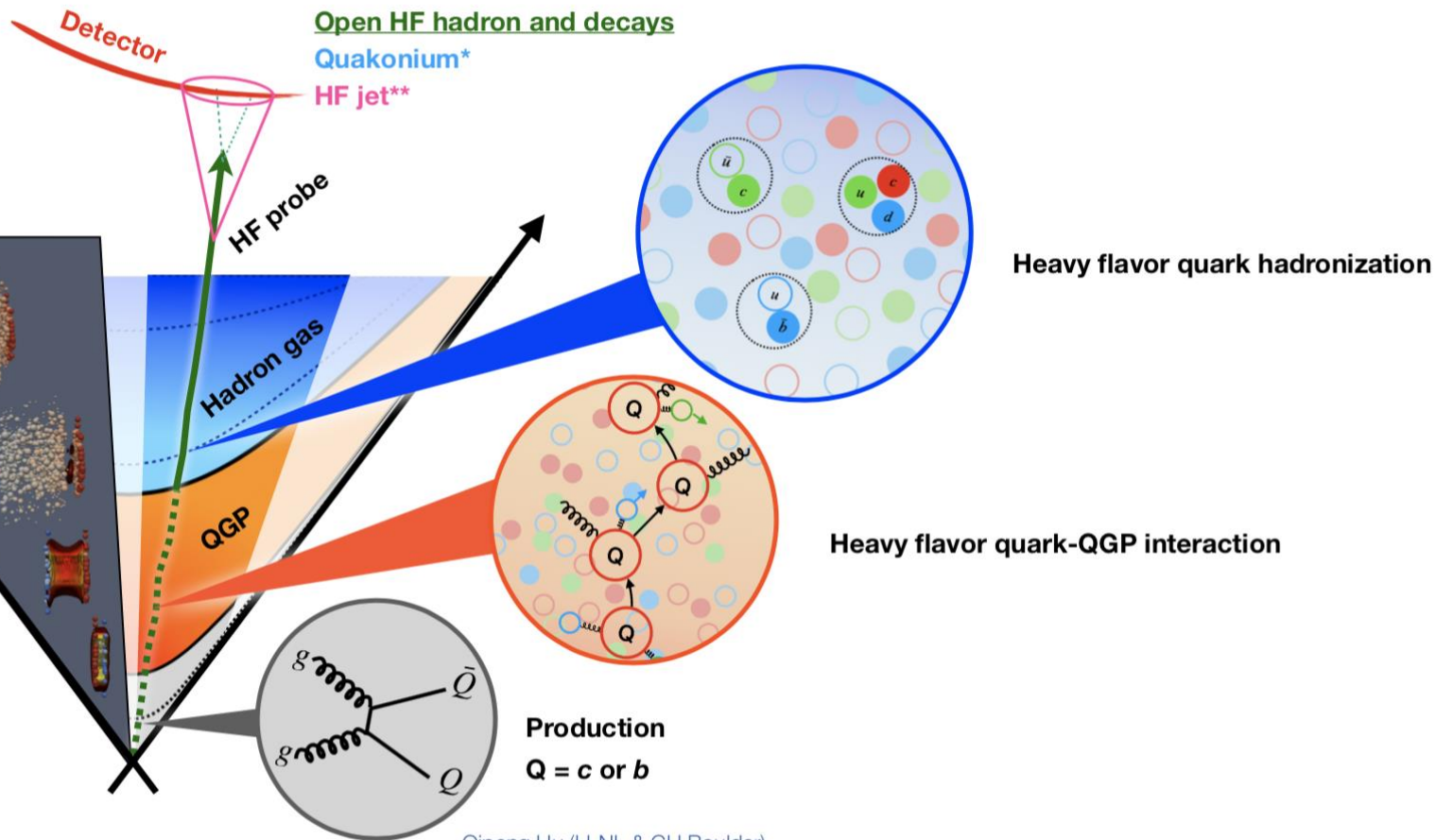
H. Masui, A. Schmah / LBNL

STAR BES-II 获取的对撞数据 (2019-2021)

Year	<i>Collisions</i>	$\sqrt{s_{NN}}$ (GeV)	Good events
2019	Au+Au	19.6	~ 582 M
2019	Au+Au	14.5	~ 324 M
2020	Au+Au	11.5	~ 235 M
2020	Au+Au	9.2	~ 162 M
2021	Au+Au	7.7	~ 100 M
2021	Au+Au	17.3	~ 250 M

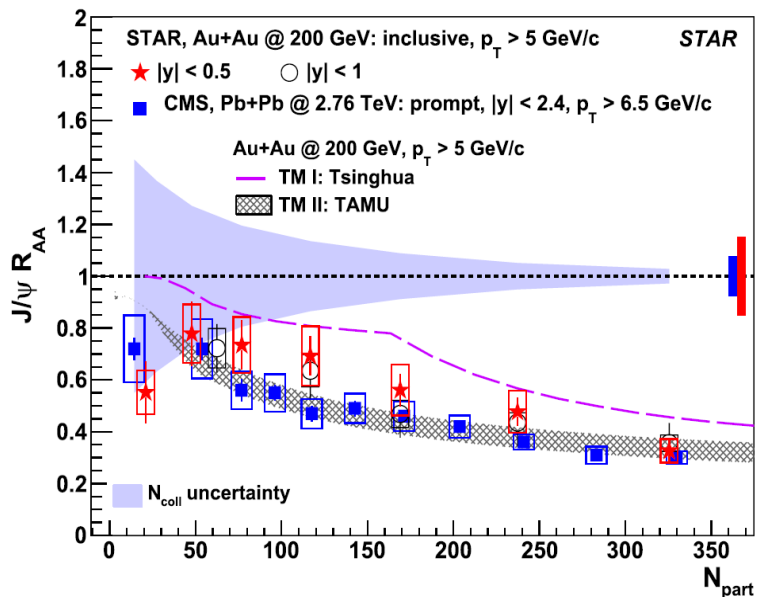
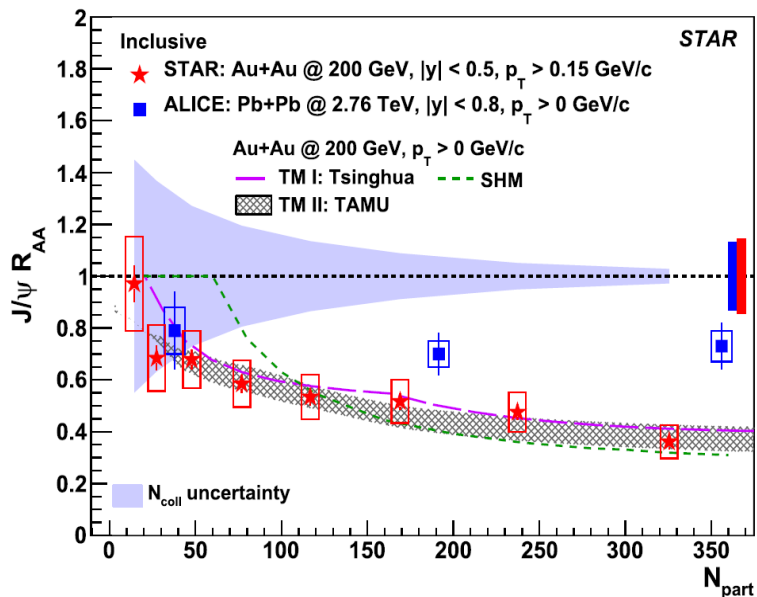
**STAR BES-II对撞取数已经在2021年6月底圆满完成！
在7.7-19.6 GeV能区多个能量点获取了大统计量实验数据。**

重味——QGP特性的探针



Qipeng Hu, SQM2022

STAR 200 GeV 金核-金核碰撞中 J/ψ 产额压低



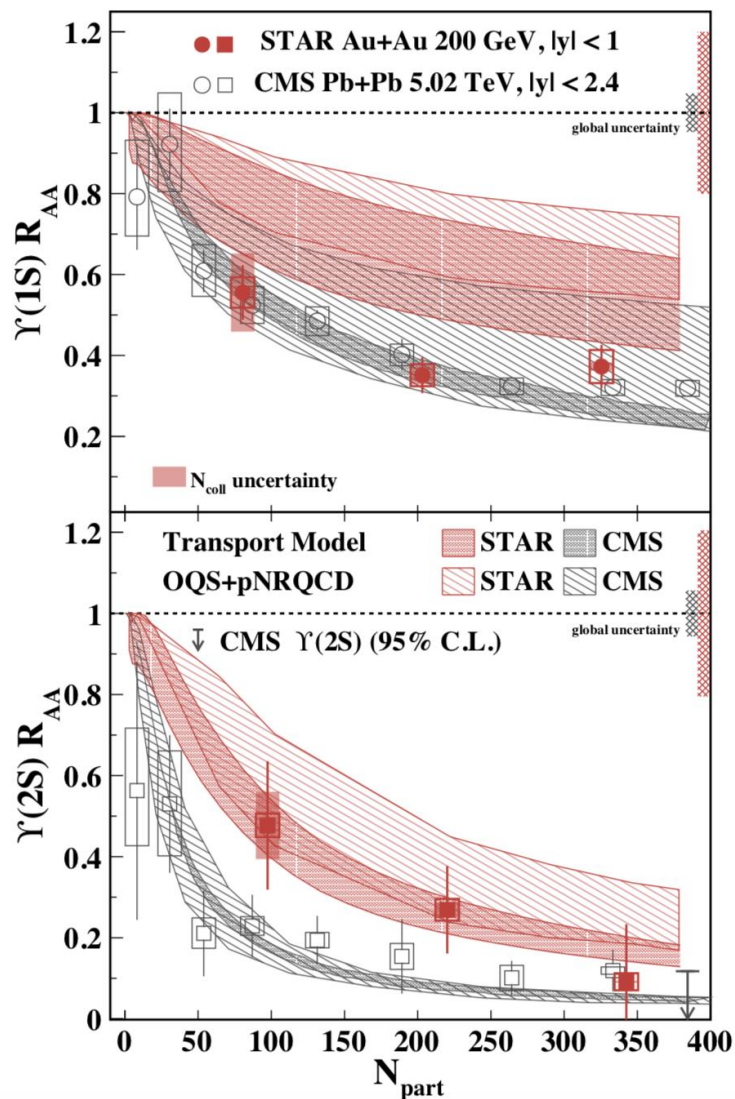
STAR, Phys. Lett. B 797 (2019) 134917

- 基于STAR升级MTD探测器利用双muon衰变道精确测量了RHIC能量下 J/ψ 产额压低
- 中心碰撞中较高横动量的 J/ψ 产额存在显著压低，暗示QGP中色屏蔽效应的存在

STAR 200 GeV金核-金核碰撞中 Υ 产额压低

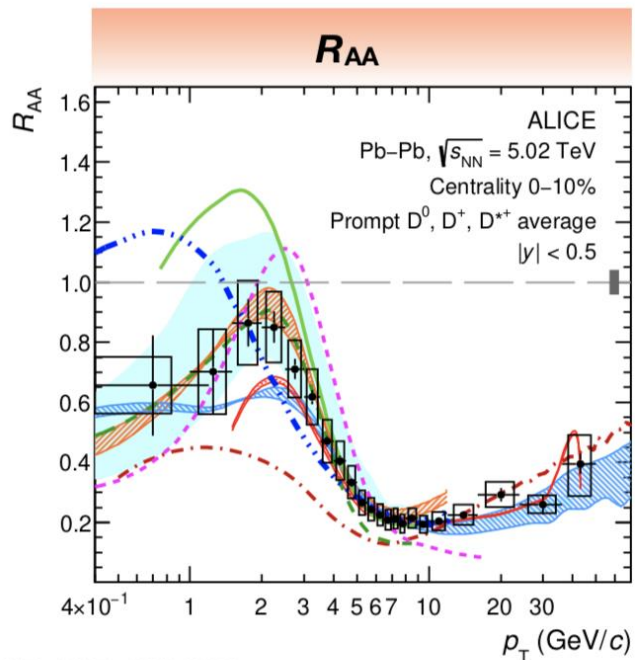
- 基于STAR升级MTD探测器在RHIC利用双muon道测量了 Υ 产额压低。
- RHIC能量下重离子碰撞中存在显著的 $\Upsilon(1S)$ 产额压低，压低幅度与LHC相近。
- 在中心碰撞中 $\Upsilon(2S)$ 产额压低程度比 $\Upsilon(1S)$ 更大，即顺次熔解现象。

STAR, arXiv: 2207.06568

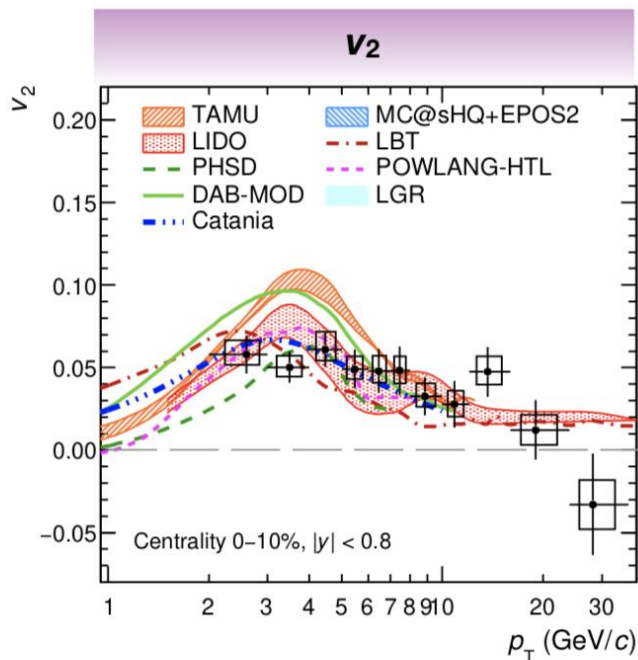


Open charm measurements in A+A

JHEP01(2022)174



ALI-PUB-501952

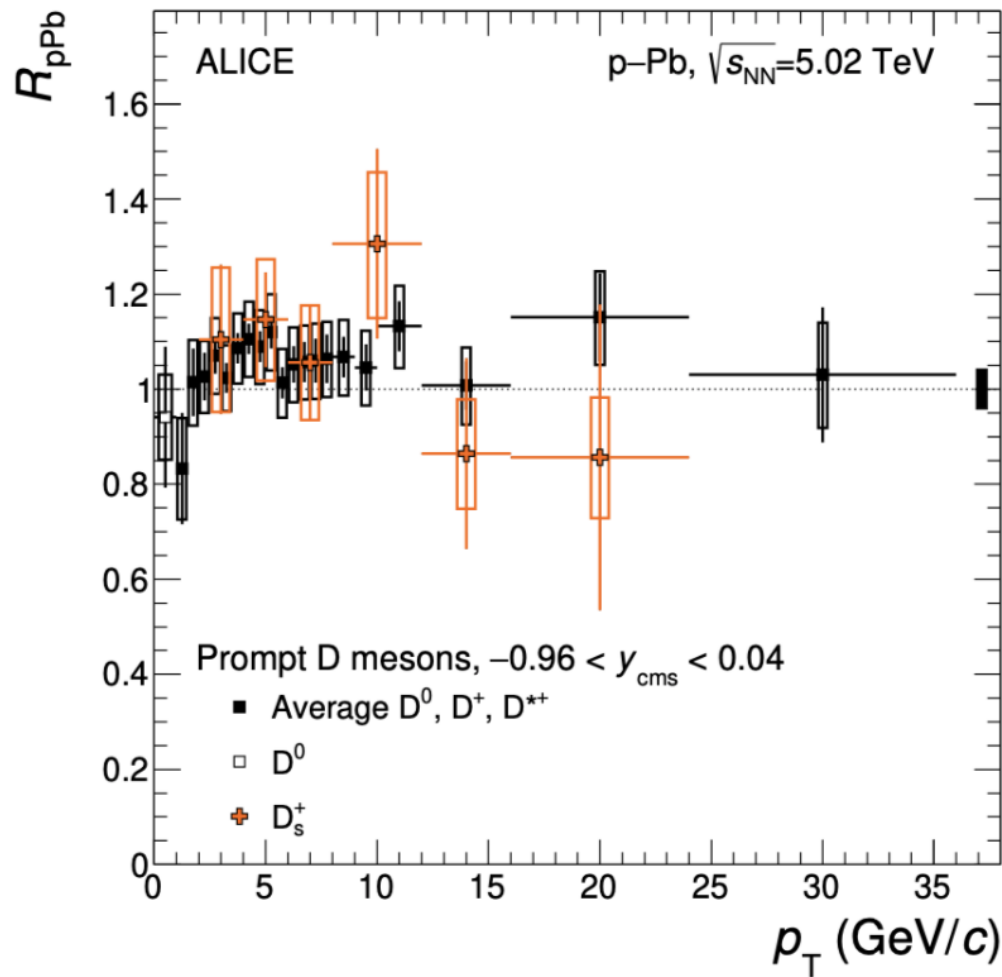


- Model ingredients:
- nPDF
 - Hydro medium
 - Coll. and Rad. scatterings (weakly coupled approach)
 - Coalescence hadronization

- Open charm experiences the entire QGP evolution; models also contain each stage of charm evolution
- Most models describe data over wide kinematic and centrality ranges

Qipeng Hu, SQM2022

Open charm in pPb collisions



JHEP12(2019)092

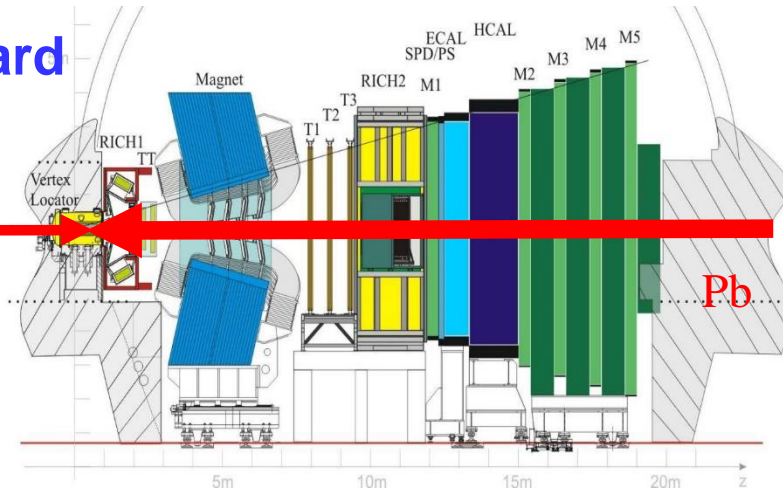
No sign of quenching for charm (with big uncertainties)!

LHCb $p\text{Pb}$ datasets

Forward

$p\text{Pb}$

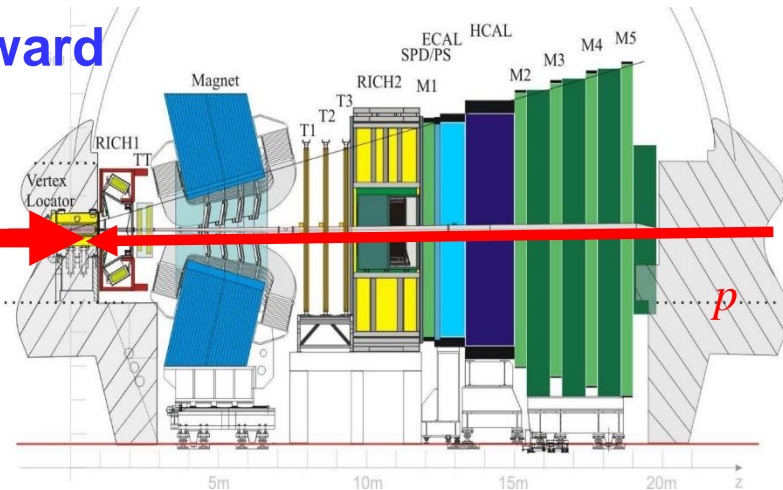
p



Backward

$\text{Pb}p$

Pb



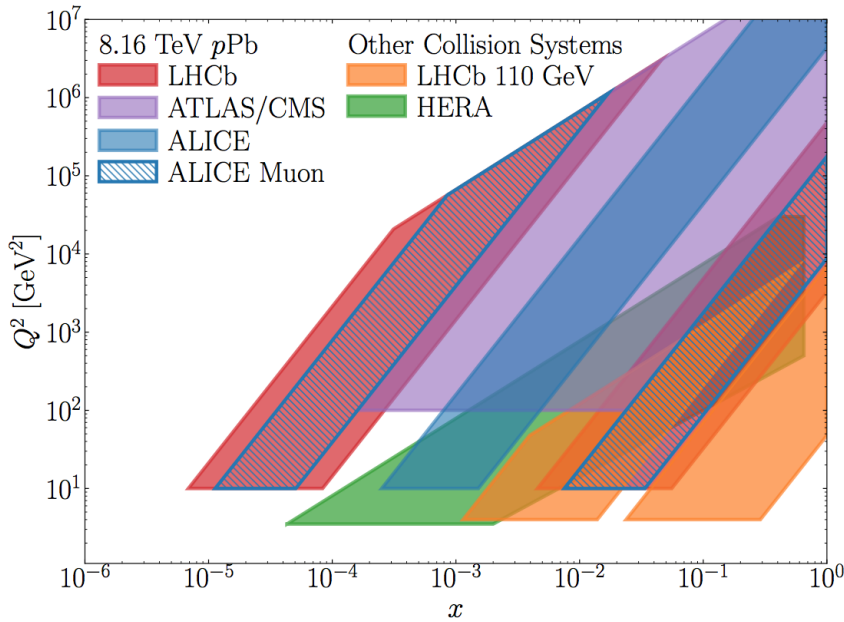
➤ Rapidity Coverage

- ✓ y^* : rapidity in nucleon-nucleon cms
- ✓ $y_{\text{cms}} = \pm 0.465$
- ✓ **Forward:** $1.5 < y^* < 4.0$
- ✓ **Backward:** $-5.0 < y^* < -2.5$
- ✓ Common region: $2.5 < |y^*| < 4.0$

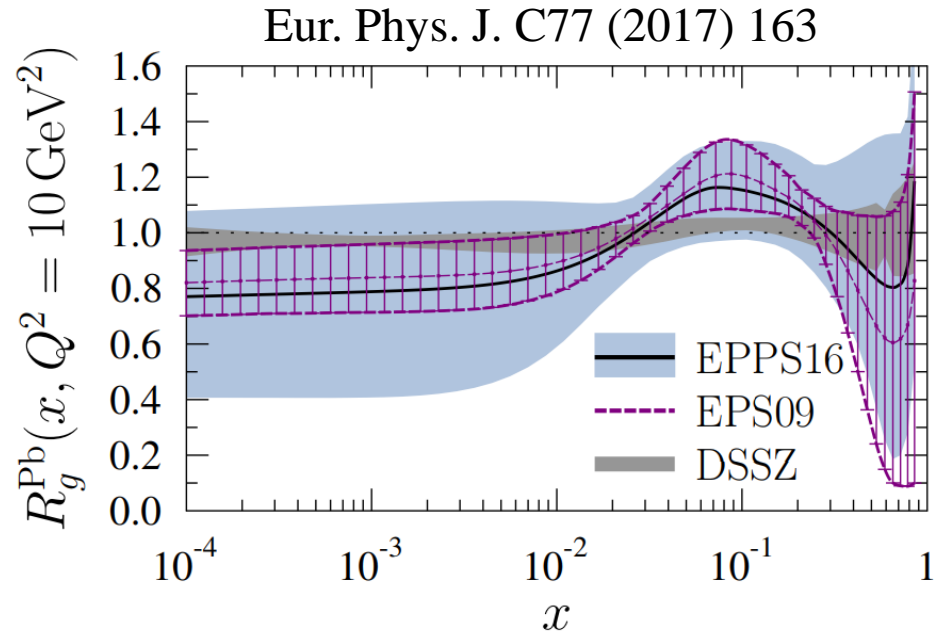
- ✓ $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ (2013, Run I)
- ✓ $p\text{Pb}$ (1.06 nb^{-1}) + $\text{Pb}p$ (0.52 nb^{-1})

- ✓ $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$ (2016, Run II)
- ✓ $p\text{Pb}$ (13.6 nb^{-1}) + $\text{Pb}p$ (21.8 nb^{-1})

LHCb: frontier experiment in phase space



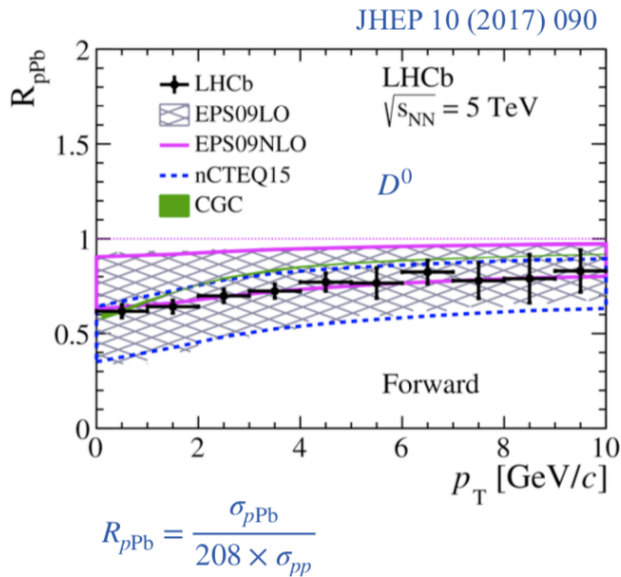
Graphic by T. Boettcher



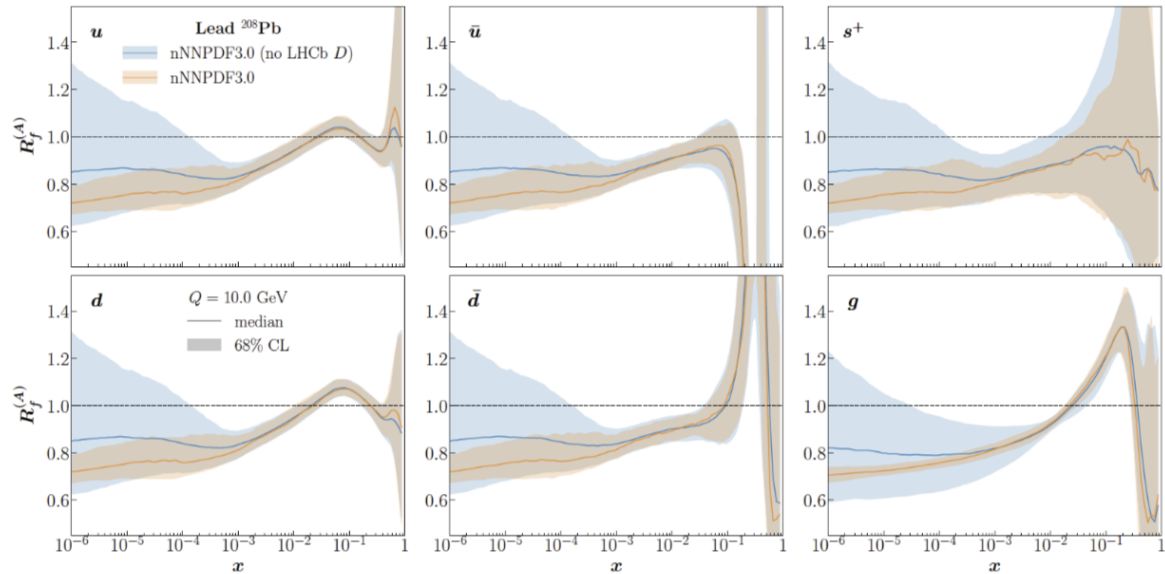
Thanks to the boost, the high resolution, the low- p_T reach and the fast read-out

- disentangle initial state from other phenomena
- constrain initial state
- sensitive to the physics on the saturation scale

LHCb D^0 data constrain nPDF



- nNNPDF3.0 [arXiv:2201.12363](https://arxiv.org/abs/2201.12363)
- LHCb measurement of prompt D^0 production in pPb collisions at 5 TeV makes an impressive impact on reducing nPDF uncertainty down to $x \sim 10^{-6}$



Jiayin Sun, LHC seminar

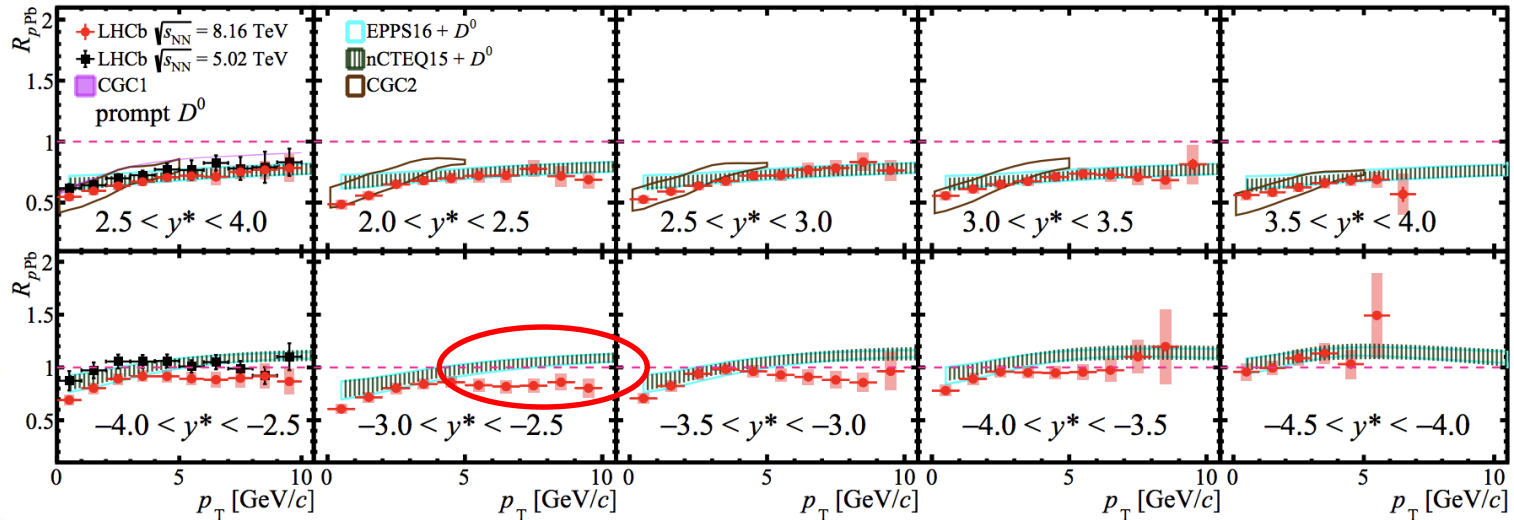
D^0 nuclear modification factor at 8.16 TeV

arXiv:2205.03936

$$R_{pPb} = \frac{\sigma_{pPb}}{208 \times \sigma_{pp}}$$

pp reference
from
interpolation
between 5&13
TeV data

JHEP 06 (2017) 147
JHEP 05 (2017) 074

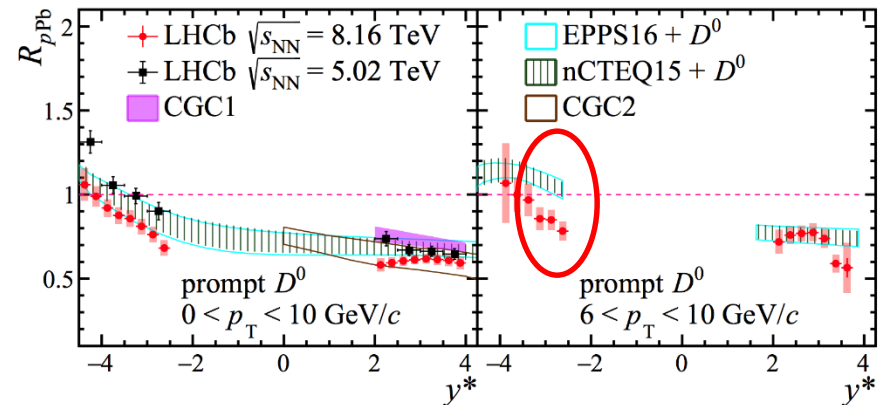


• Forward:

- Suppression consistent with 5TeV D^0 result
- Consistent with nPDF and CGC

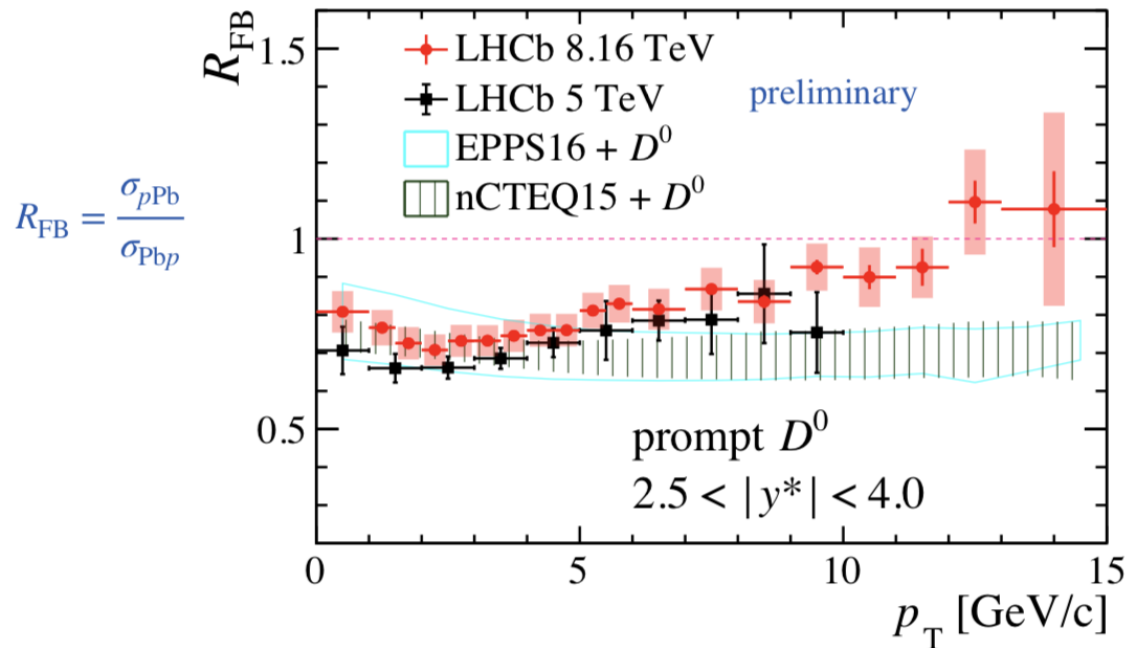
• Backward:

- Data lower than nPDF at high p_T
- Room for additional effects in the backward rapidity
- **nPDF calculations do not describe data for h^\pm , π^0 and D^0**



D^0 forward-backward production ratio

arXiv:2205.03936



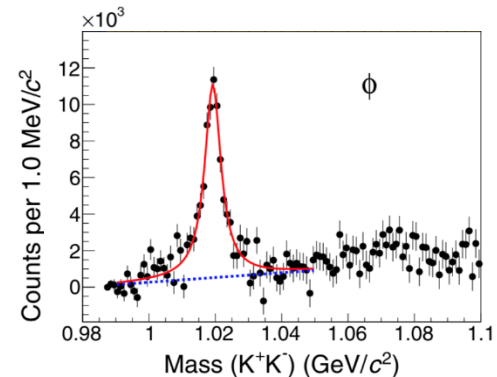
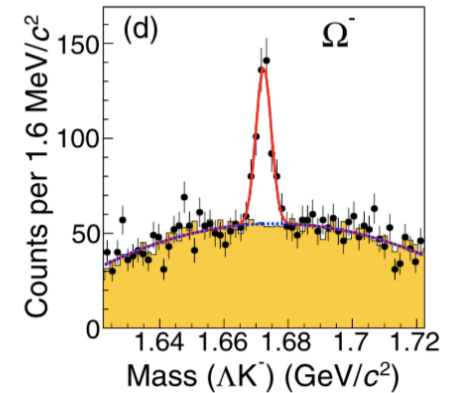
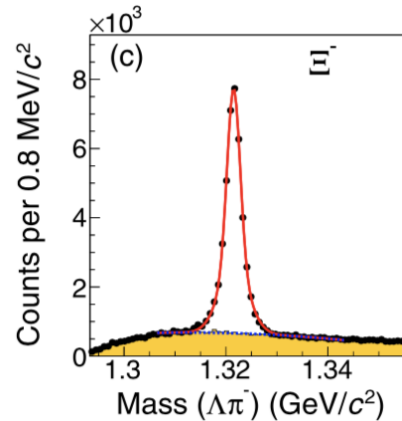
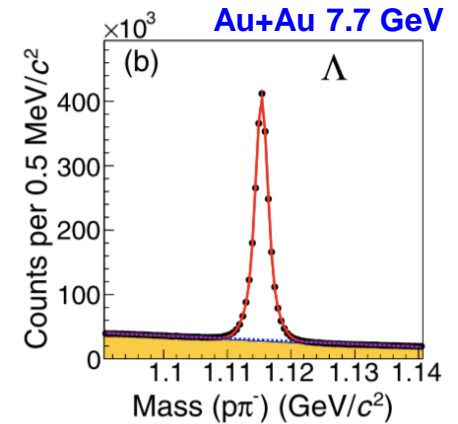
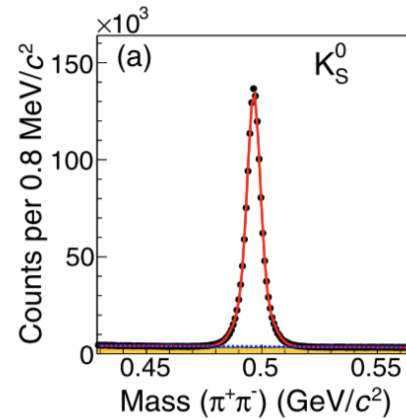
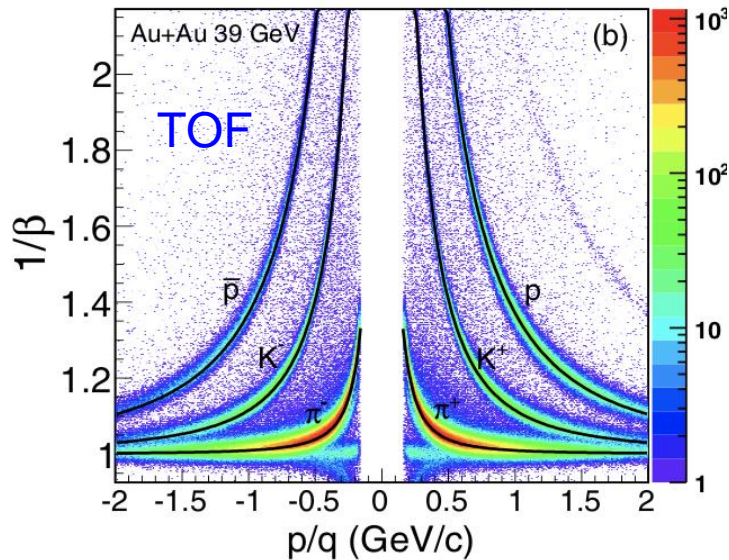
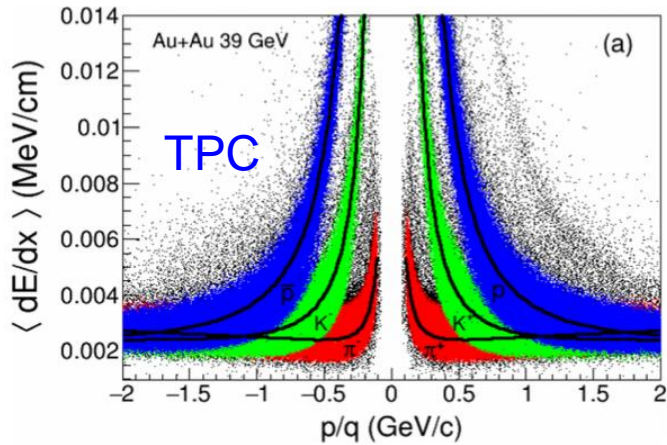
- Forward-backward production ratio R_{FB}
 - Low p_{T} : **consistent with nPDF expectations**
 - High p_{T} : **data > nPDF**

总结和展望

- STAR 第一期能量扫描实验（7.7-39GeV的Au+Au碰撞）系统测量了中等重子数密度区重离子碰撞的奇异强子产生
- 利用奇异强子产额以及统计模型提取了碰撞系统在化学冻结时刻的热力学参数
- 多个夸克胶子等离子体（QGP）信号在低能碰撞（<20GeV）中变得不显著，需要更精确的测量予以确认
- STAR 第二期能量扫描以及固定靶实验将**精确测量**中高重子数密度区QCD相变和物态特性 (μ_B 最高达 721 MeV)
- 利用重味定量研究QGP特性也需要理解和限定冷核物质效应！

谢谢！

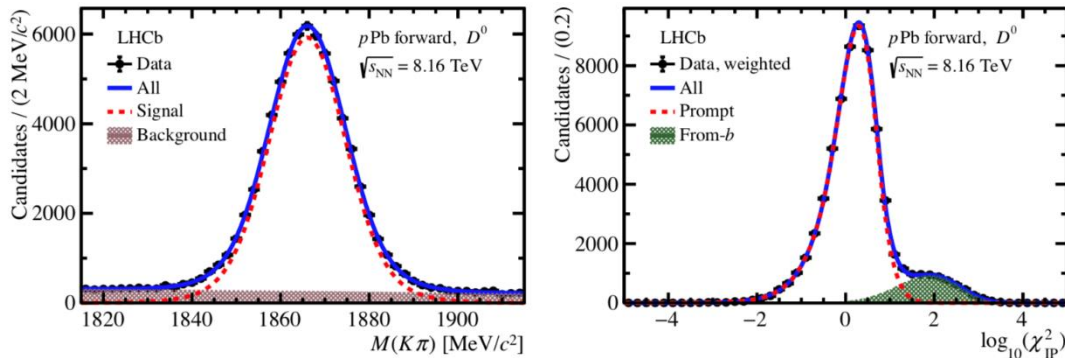
STAR实验粒子鉴别和奇异强子重建



STAR, PRC96, 044904, 2017
 STAR, PRC102, 034909, 2020

New D^0 measurement at 8.16 TeV

arXiv:2205.03936



- Precise measurement of prompt D^0 production in $p\text{Pb}$ collisions
- 20 times larger statistics than previous LHCb D^0 result at 5 TeV
- $D^0 \rightarrow K^- \pi^+$
- Use impact parameter to separate the prompt and b -decay components
- $0 < p_{\text{T}} < 30 \text{ GeV}/c$
- $p\text{Pb}$: $1.5 < y < 4.0$; $\text{Pb}p$: $-5.0 < y < -2.5$

