



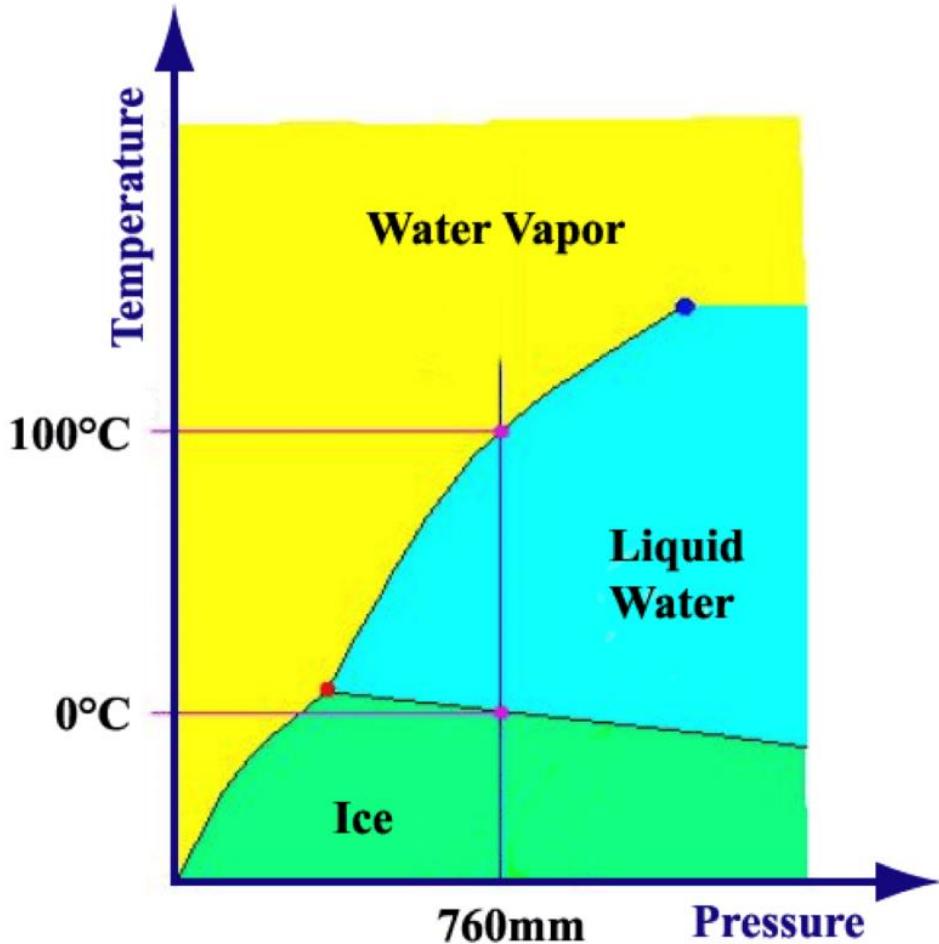
高能重离子碰撞实验中的奇异和重味探针

朱相雷

清华大学

6/30/2022

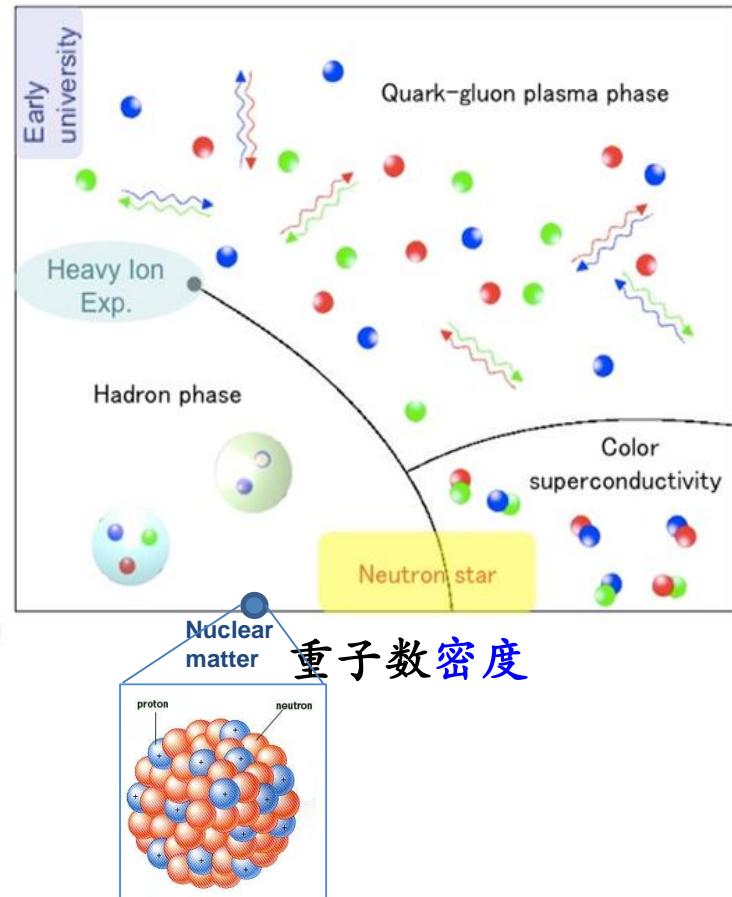
水的相图



- 水分子之间存在复杂的相互作用力
- 水的相图 (phase diagram) 描述水分子在不同的外部条件 (温度、压强) 下组成的宏观物质形态
- 相变: 不同相之间的转化
冰 \leftrightarrow 水 \leftrightarrow 水蒸气

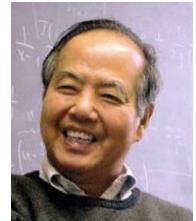
QCD相图

温度



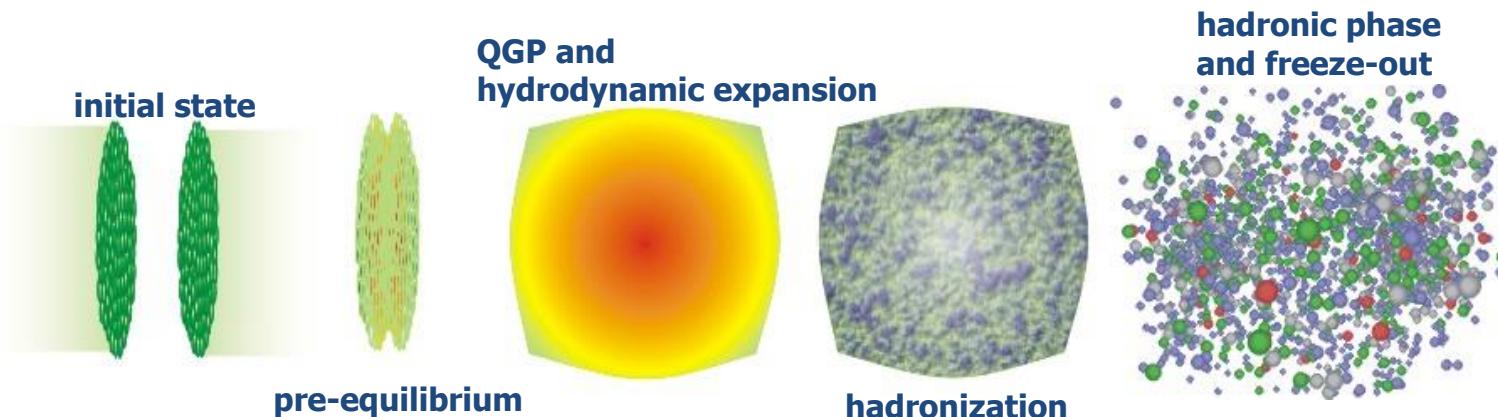
- 夸克：物质世界基本组分
- QCD：量子色动力学（Quantum Chromodynamics）
- QCD相图：描述由夸克胶子构成的，在不同温度、密度条件下的宏观物质形态
 - 低温、低密：夸克囚禁在强子内
 - 高温、高密：新物态——夸克胶子等离子体（Quark-Gluon Plasma, QGP）
- 与其它领域的联系：
宇宙学、天体物理，宇宙起源与演化

相对论重离子碰撞



李政道

- 高能（相对论）重离子碰撞可在实验室中产生极高温或高密条件



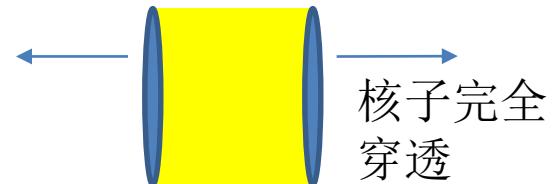
- 热密物态快速膨胀并冷却 (**mini-bang**)，需根据末态粒子的信息 (**信号**) 反推热密物态特性
- 重离子碰撞实验：BNL/AGS, CERN/SPS, **BNL/RHIC**, **CERN/LHC**

不同能区的重离子碰撞实验

- LHC和RHIC:

$$\sqrt{s_{NN}} \geq 200 \text{ GeV}$$

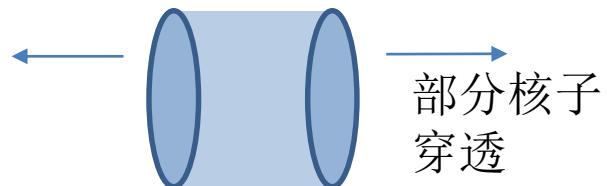
中心区温度高，净重子数密度低（化学势接近0）



- SPS, RHIC/STAR BES:

$$\sqrt{s_{NN}} \sim 10 - 20 \text{ GeV}$$

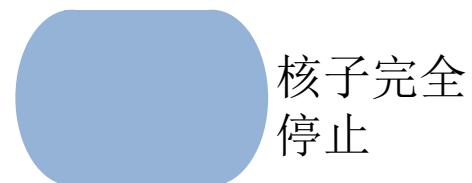
温度低，重子数密度较高（化学势大）



- STAR-FXT, AGS, NICA, FAIR, HIAF, JPARC...

$$\sqrt{s_{NN}} \sim 3 \text{ GeV}$$

温度低，重子数密度高



奇异强子是QCD相变的重要探针

Rafelski & Müller, 1982

- 奇异夸克

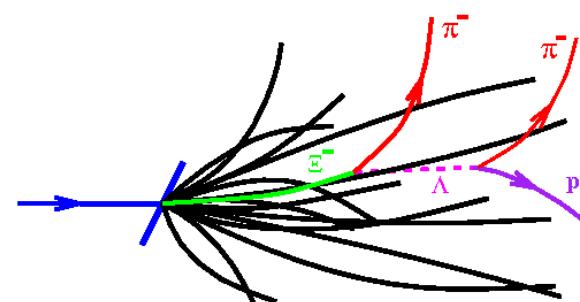
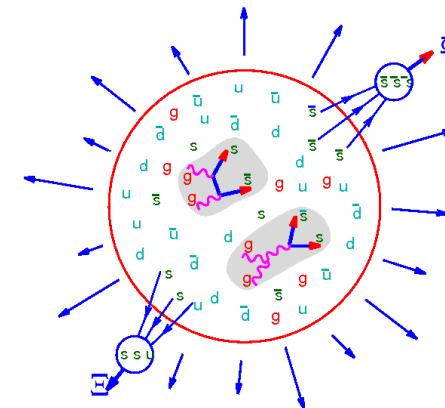
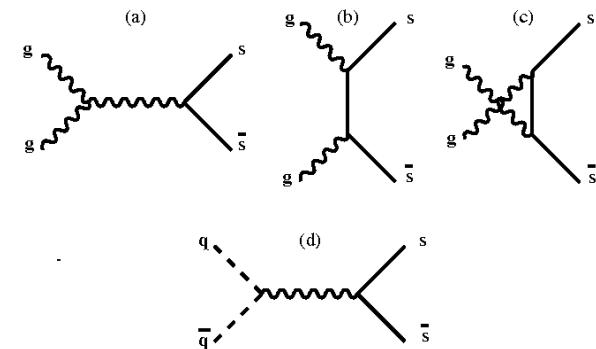
- 在对撞核中不存在其价夸克
- 流质量 $\sim 100 \text{ MeV} < T_c$
- 容易在退禁闭的QGP介质中对产生

→ 奇异性增强！

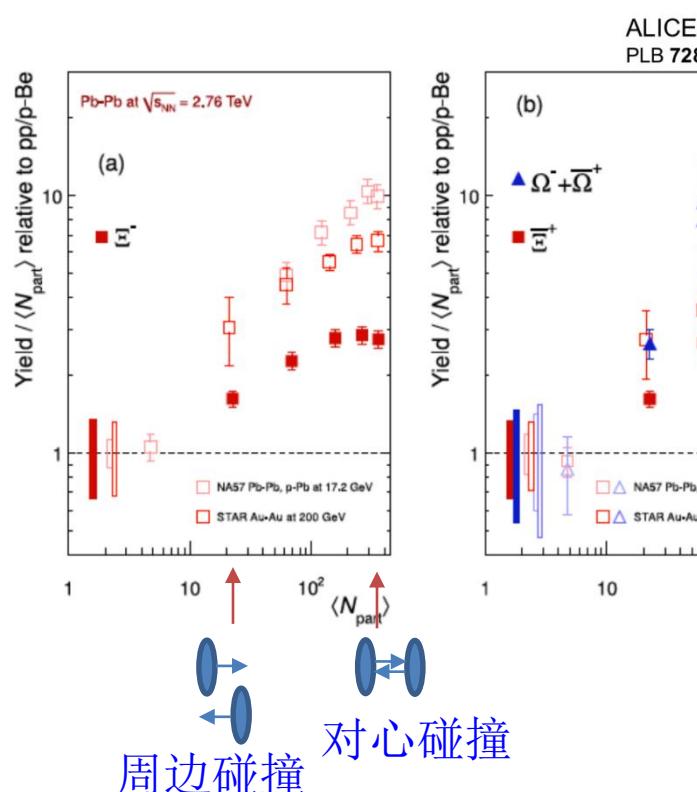
- 带有（多个）奇异夸克的强子

- 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！

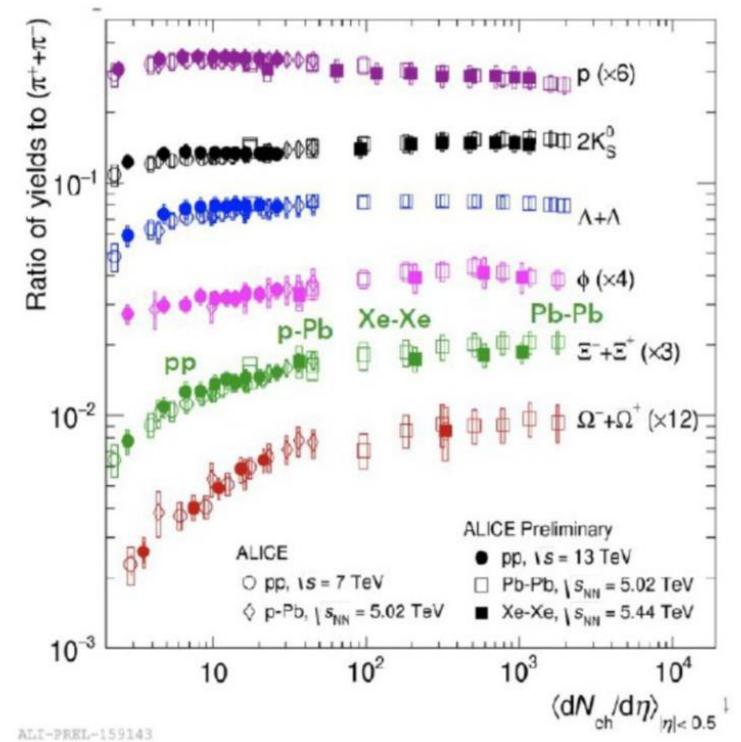


不同能区的奇异性增强



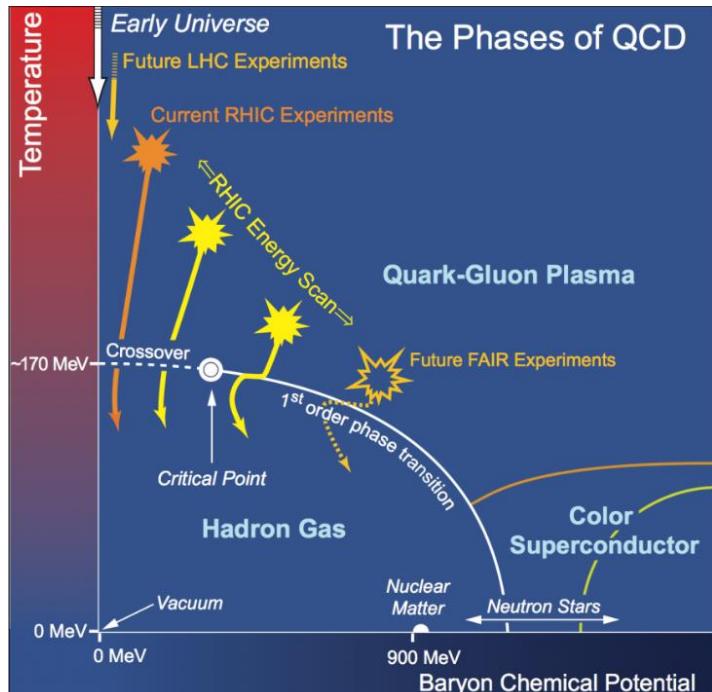
$$\text{Enhancement factor: } E = \frac{2}{N_{part}} \left[\frac{dN}{dy} (Pb + Pb) \Big|_{y=0} \right] / \left[\frac{dN}{dy} (p + p) \Big|_{y=0} \right]$$

Enhancement factor for Ω : (in central collisions)	SPS	20
	RHIC	12
	LHC	6



ALICE coll., Nature Phys. 13 (2017) 535-539
arXiv: 1606.07424 [nucl-ex]

QCD相图 (2007)



- 2007年，RHIC已确认QGP在200 GeV的金核-金核碰撞中产生！

- 待解决的关键物理问题：

- 1) QCD相变在什么能量开始发生？
高密区一级相变?
QCD临界点?

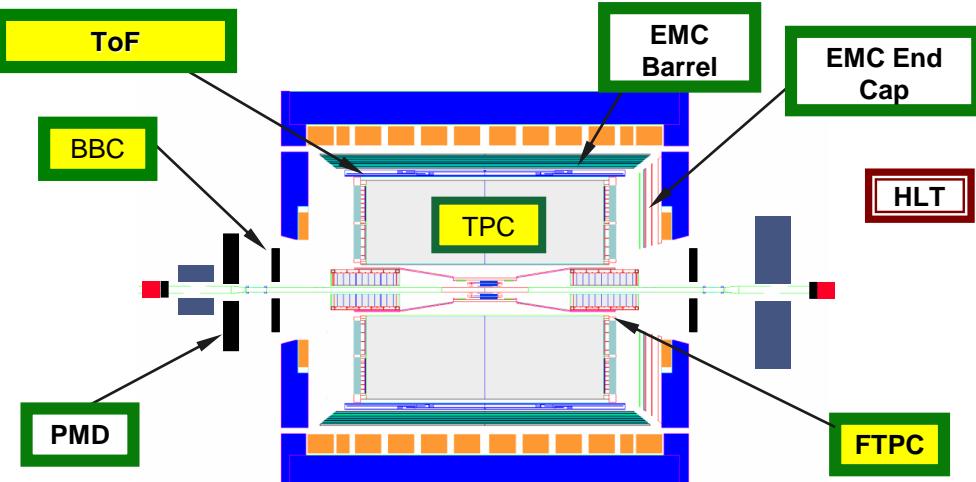
2010-2014年进行能量扫描实验
(7.7 – 62.4 GeV)，探测高密区

- 2) QGP物态的定量特性
在200 GeV提升亮度升级探测器
精确测量

2007年美国能源部科学局核科学顾问委员会长期规划报告
2007, DOE Office of Science, NSAC, Long Range Plan

<http://science.energy.gov/np/nsac/>

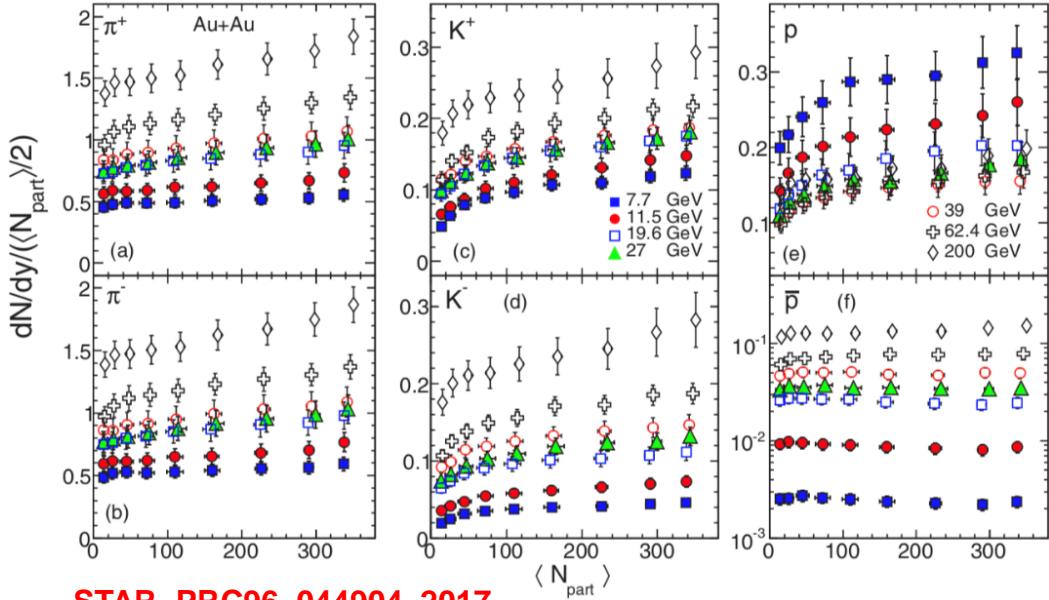
STAR 能量扫描实验



- 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)
 $\text{Au+Au } \sqrt{s_{\text{NN}}} = 62.4 - 7.7 \text{ GeV}$

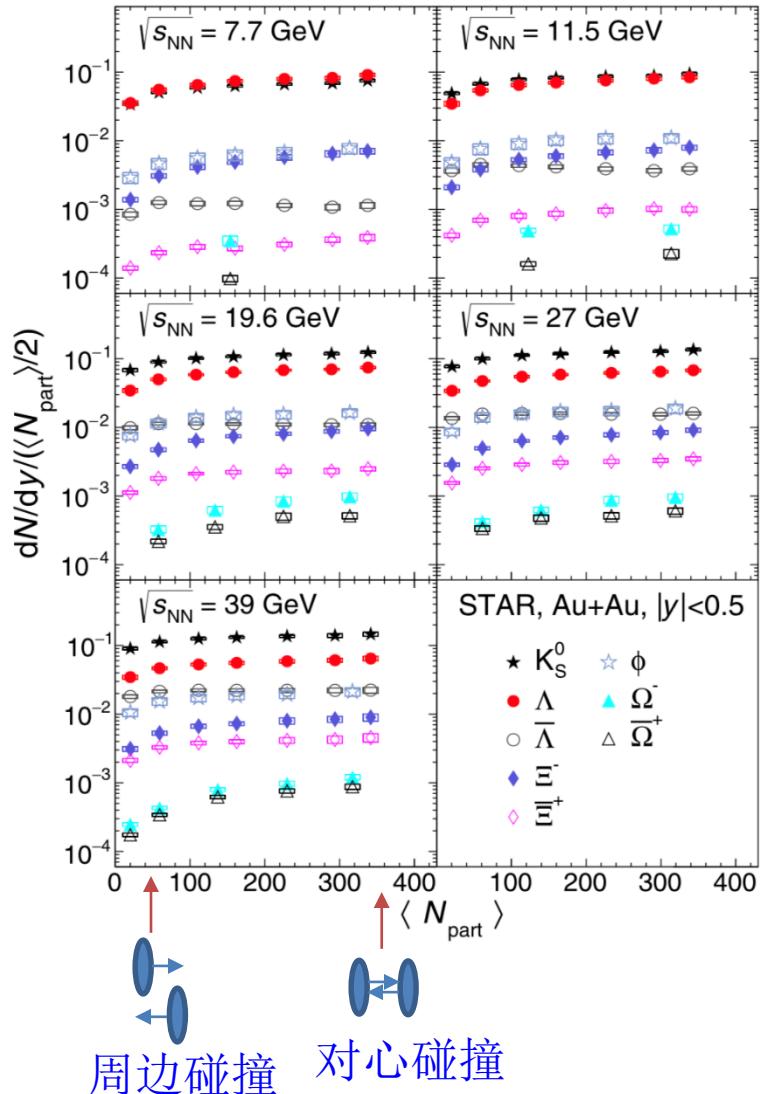
Year	Collisions	$\sqrt{s_{\text{NN}}}$ (GeV)	Minimum bias events
2010	Au+Au	7.7	$\sim 4 \text{ M}$
2010	Au+Au	11.5	$\sim 12 \text{ M}$
2014	Au+Au	14.5	$\sim 13 \text{ M}$
2011	Au+Au	19.6	$\sim 36 \text{ M}$
2011 / 2018	Au+Au	27	$\sim 70 \text{ M} / \sim 560 \text{ M}$
2010	Au+Au	39	$\sim 130 \text{ M}$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

STAR能量扫描中奇异强子产额 (dN/dy)

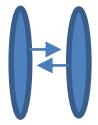


STAR, PRC96, 044904, 2017

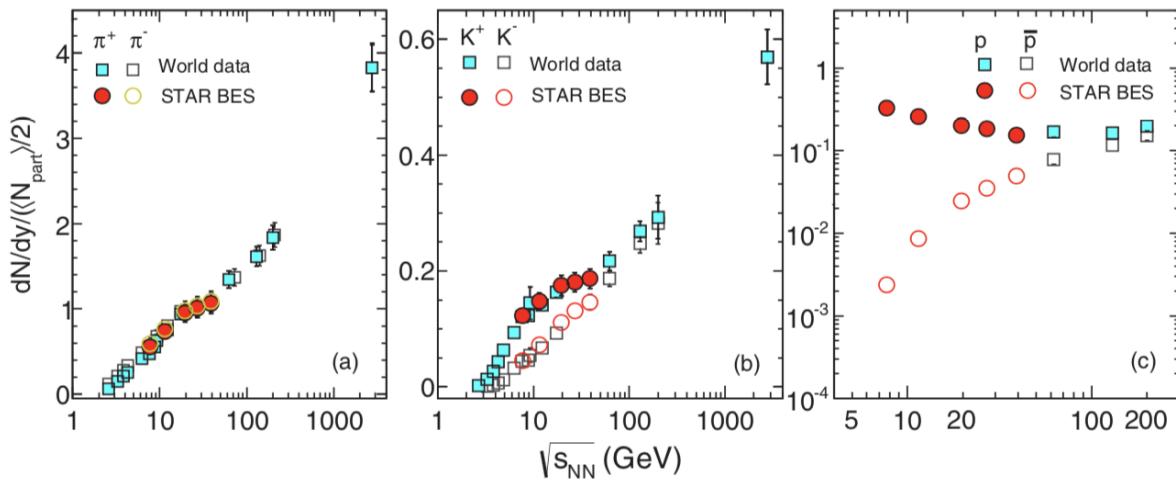
- (每参与碰撞核子对的) 各个强子产额随着碰撞更对心以及能量更高而增加
- 例外：
 - p 和 Λ 产额随能量提高而下降
 - \bar{p} 和 $\bar{\Lambda}$ 产额不随碰撞对心度变化



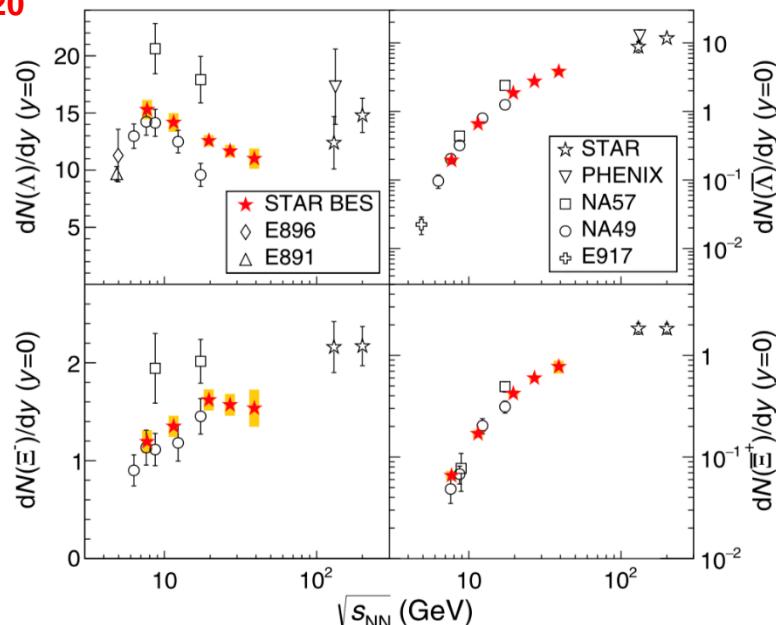
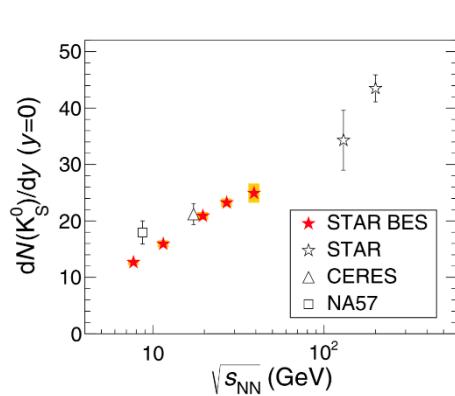
STAR, PRC102, 034909, 2020



对心碰撞中的强子产额随能量的变化

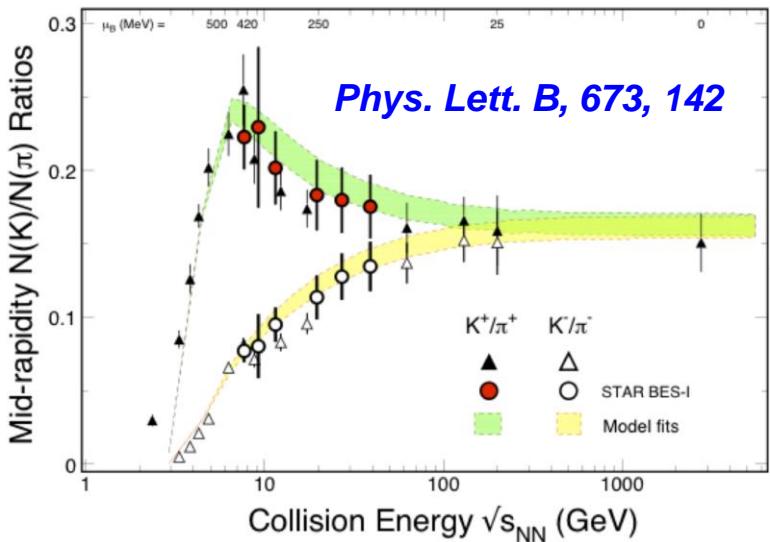
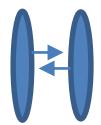


STAR, PRC96, 044904, 2017
STAR, PRC102, 034909, 2020

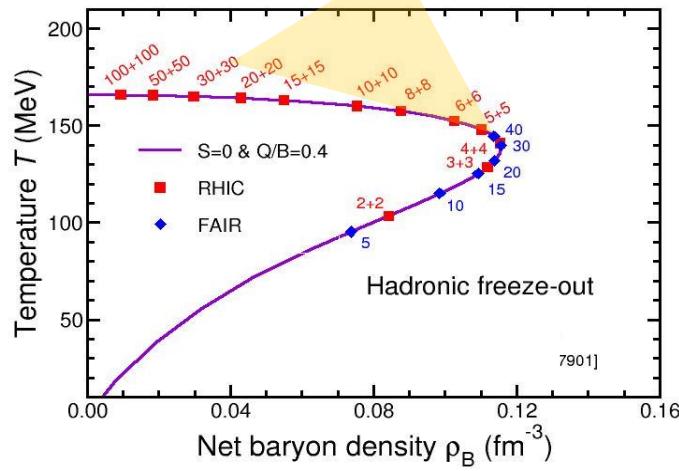


- STAR BES-I 数据与其他实验数据基本一致
- 各强子产额随能量的变化表现出丰富的结构
- p 和 Λ 产额在 39 GeV 附近最小:
 - 小于 39 GeV, 主要来源于碰撞核的重子停止
 - 大于 39 GeV, 主要来源于重子反重子对产生

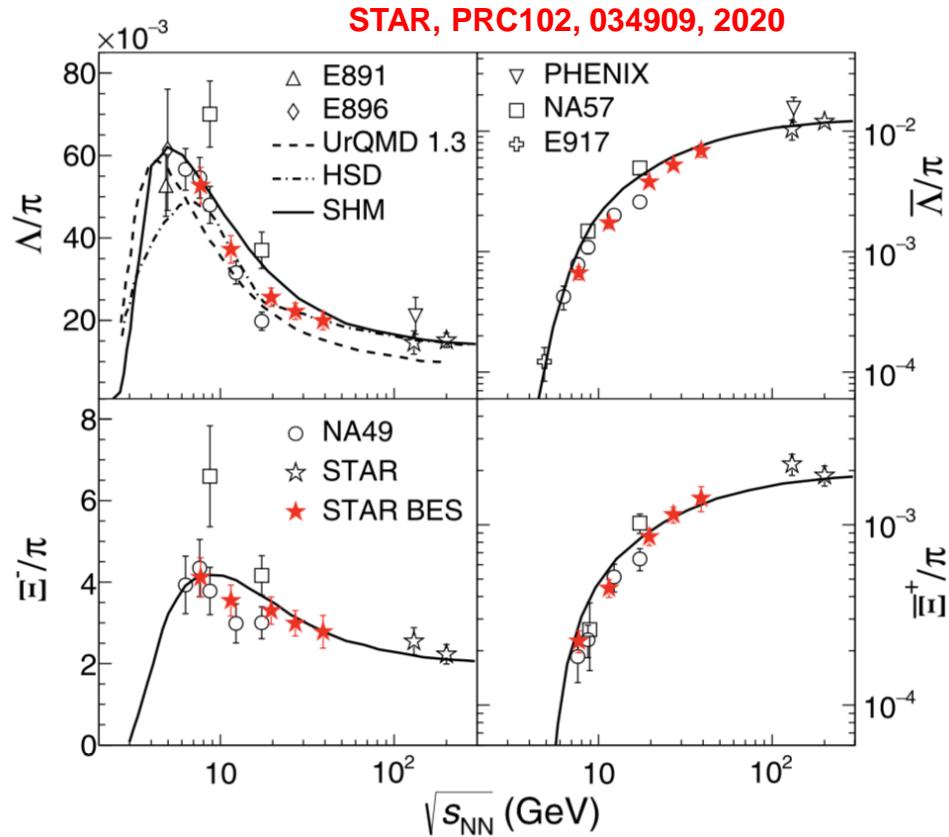
奇异强子和 π 介子产额比



RHIC BES-I



J. Randrup et al., PRC 74, 047901 (2006)



- 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。

统计模型

(hadron gas, grand canonical ensemble)

Partition function
(particle species i):

$$\ln Z_i = \frac{Vg_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$$

$g_i = (2J_i + 1)$ spin degeneracy factor
 “-” for bosons, “+” for fermions
 $E_i^2 = p^2 + m^2$

Particle densities:

$$n_i = N/V = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp((E_i - \mu_i)/T) \pm 1}$$

For every conserved quantum number there is a chemical potential:

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i}$$

Use conservation laws to constrain V, μ_s, μ_{I_3}

strangeness: $\sum_i n_i S_i = 0 \rightarrow \mu_s$

charge: $V \sum_i n_i I_{3,i} = \frac{Z - N}{2} \rightarrow \mu_{I_3}$

baryon number: $V \sum_i n_i B_i = Z + N \rightarrow V$

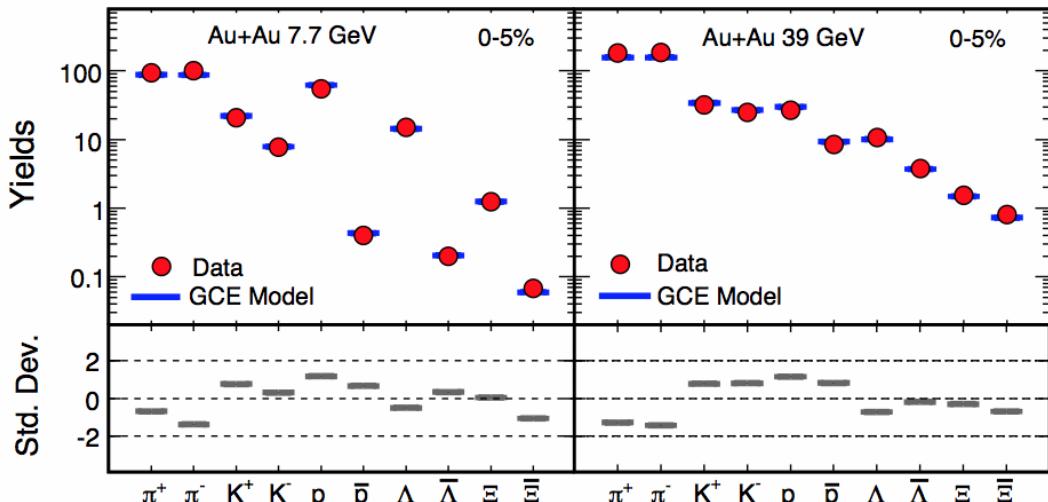
Only two parameters left (T, μ_B)

Example: $n(\bar{p})/n(p) = \exp(-2\mu_B/T)$
Boltzmann approximation

\rightarrow determine (T, μ_B) for different $\sqrt{s_{NN}}$ from fits to data

介质化学冻结热力学参数: T_{ch} vs. μ_B

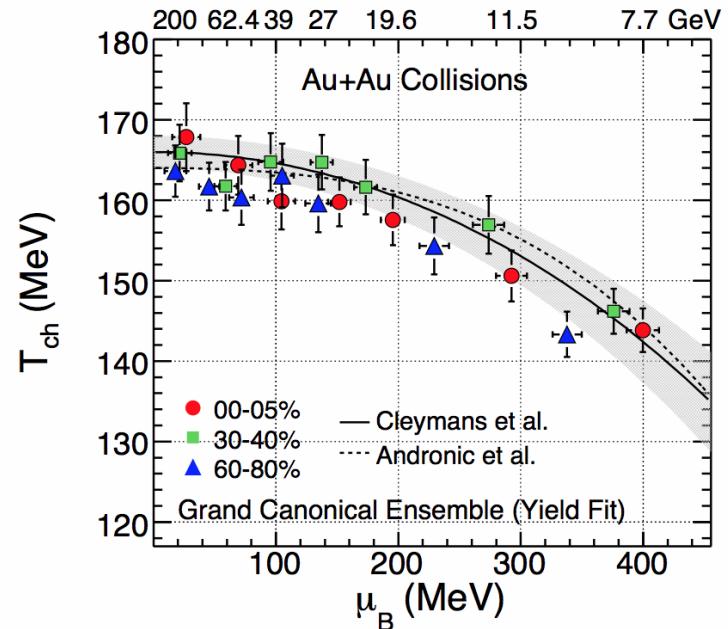
STAR, Phys. Rev. C 96, 044904, 2017



- ✓ 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！

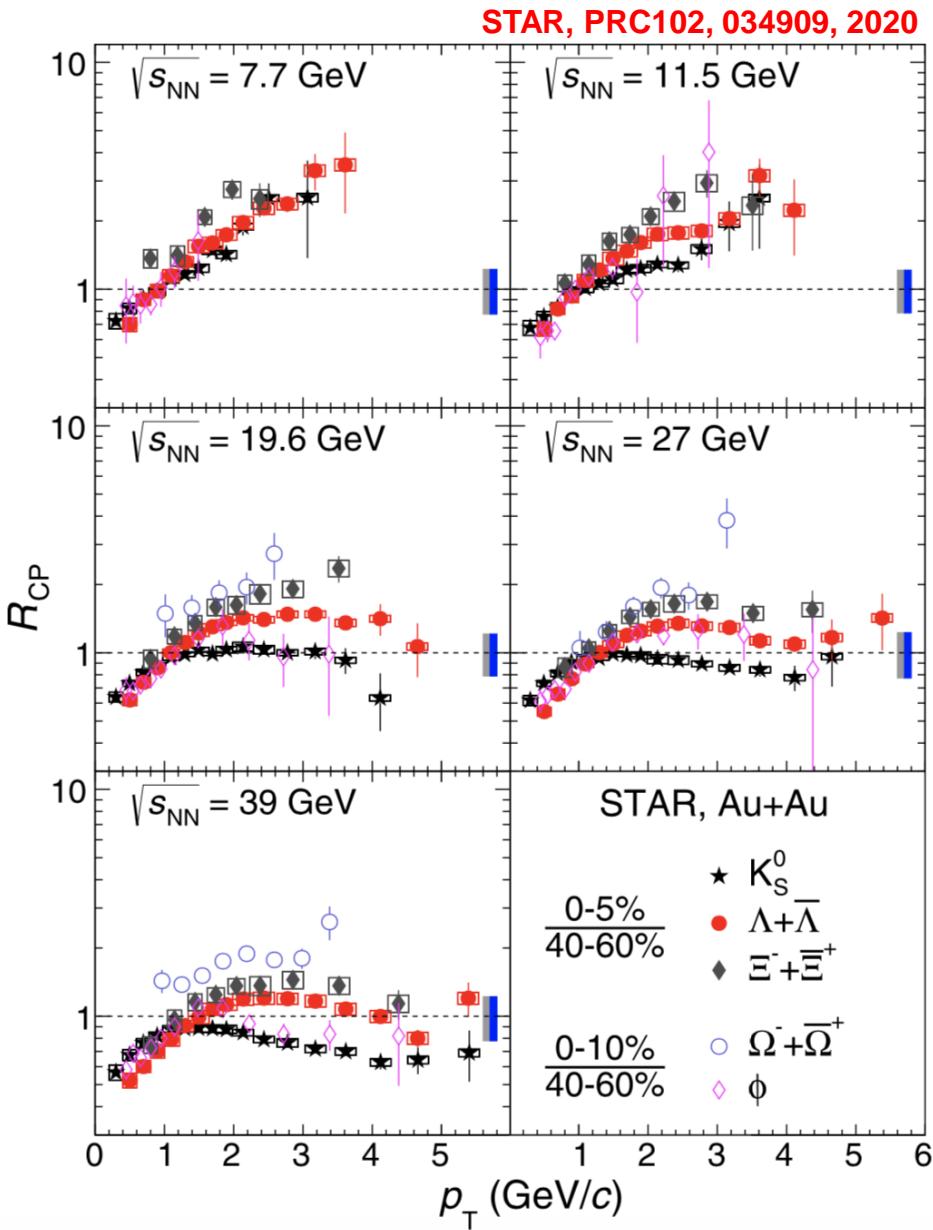


Andronic: NPA 834 (2010) 237

Cleymans: PRC 73 (2006) 034905

Au+Au 200 GeV : Phys. Rev. C 83 (2011) 24901

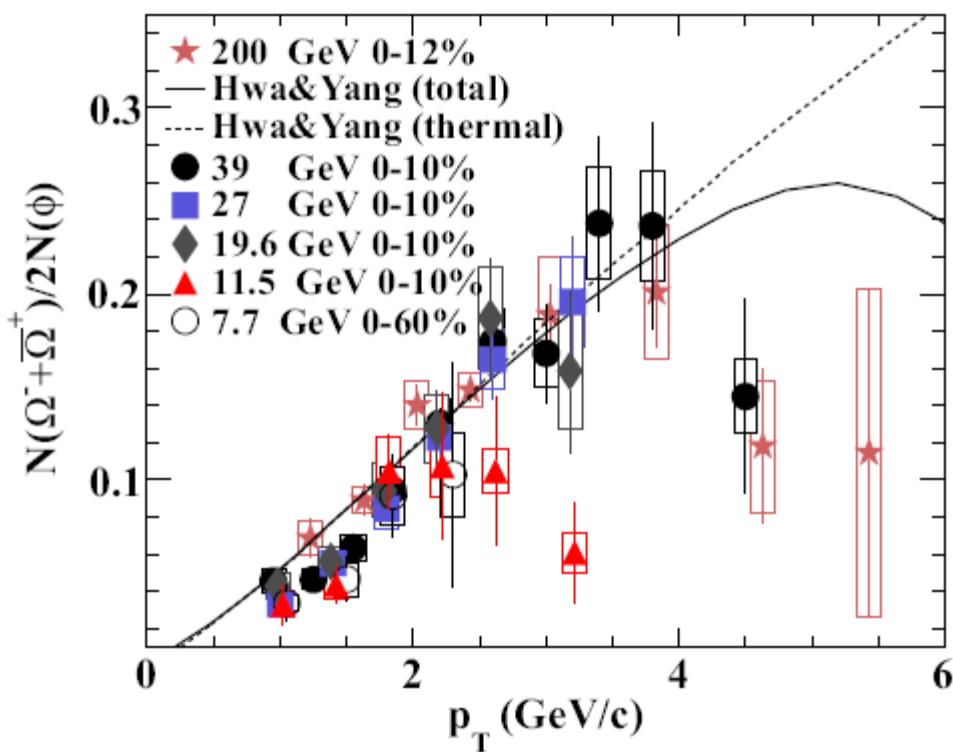
QGP信号随碰撞能量的变化：核修正因子 R_{CP}



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

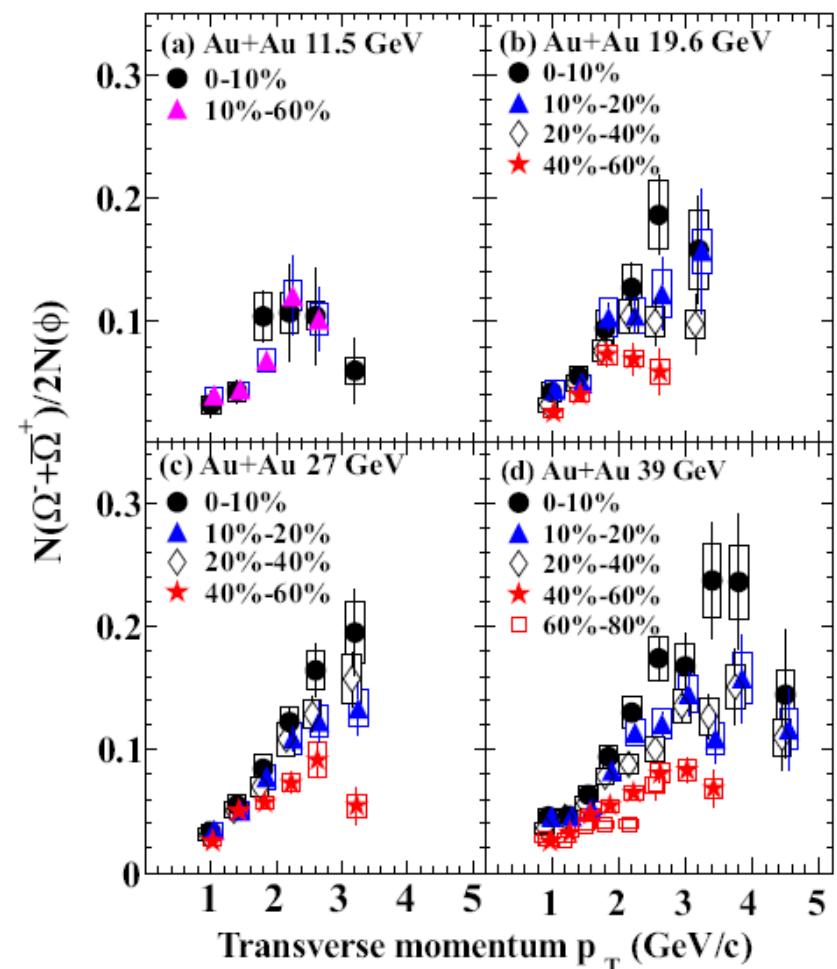
- 高能重离子碰撞中，高 p_T 的粒子 $R_{\text{CP}} < 1$ 是 QGP 的典型信号：**喷注淬火**
- STAR BES-I 数据显示：
 - 能量在 39 GeV, K_S^0 的 R_{CP} 小于 1, 喷注淬火!
 - 能量小于 11.5 GeV, 高横动量 K_S^0 和其它强子的 R_{CP} 显著大于 1!
 - 低能下, Cronin 效应或径向流效应会与部分子能损存在竞争

QGP信号随碰撞能量的变化：重子介子比 Ω / ϕ

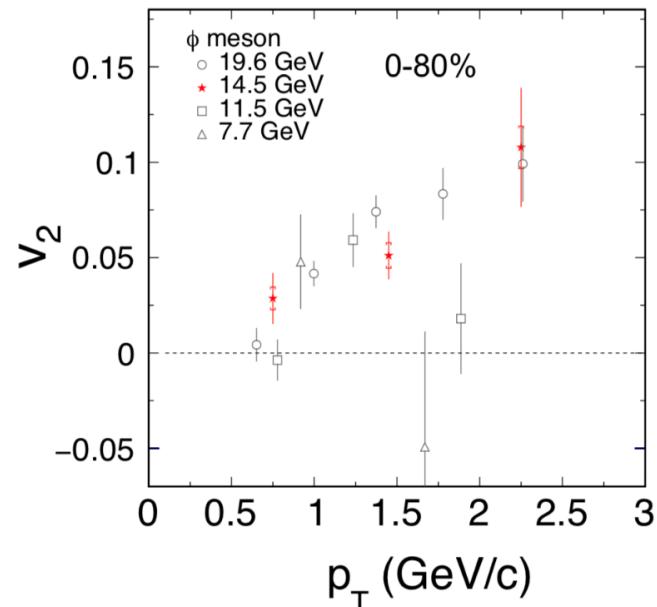
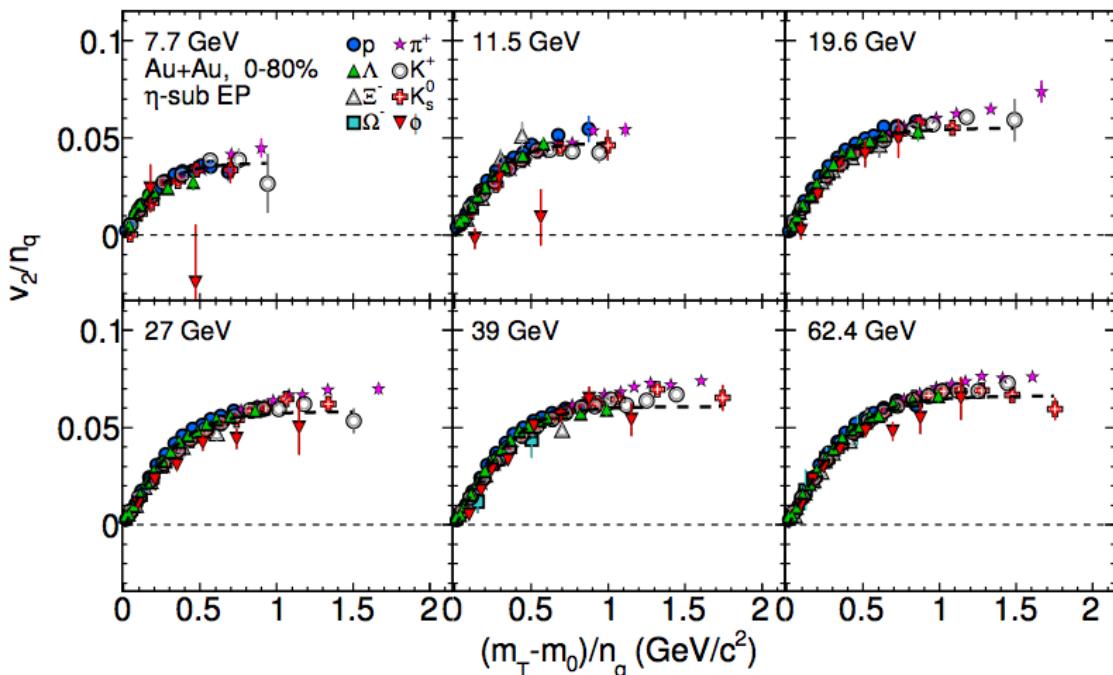
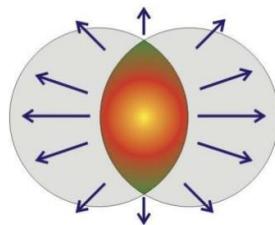


STAR, Phys. Rev. C 93, 021903 (R), 2016

- 中等 p_T Ω/ϕ 比：
低能 (11.5 GeV) 与较高能 ($\geq 19.6 \text{ GeV}$) 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



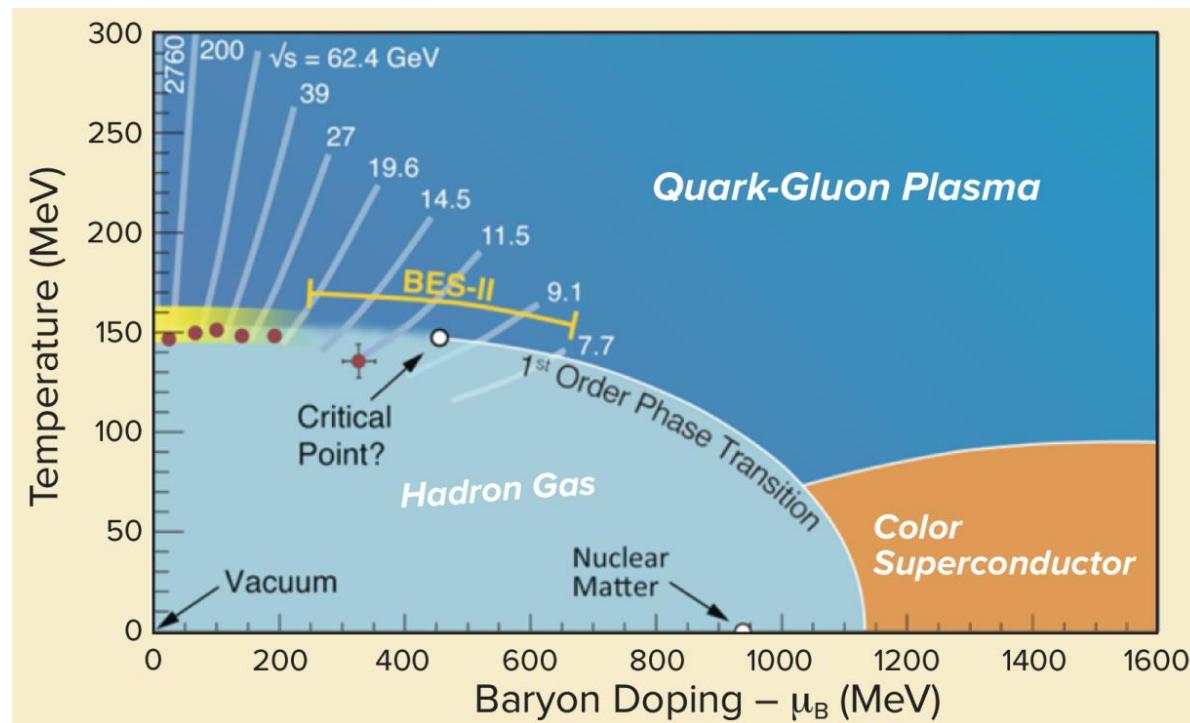
QGP信号随碰撞能量的变化：椭圆流 v_2



**STAR, Phys.Rev.Lett.110 (2013) 142301; Phys. Rev. C88 (2013) 014902;
Phys. Rev. C93 (2016) 014907**

- 低能（11.5GeV以下）碰撞中 ϕ 介子椭圆流可能偏离组分夸克数标度
- 14.5 GeV的碰撞中 ϕ 介子 v_2 与 19.6 GeV 接近
- 需要提高20 GeV以下数据的统计量以及增加能量点确定退禁闭相变的起始能量点！

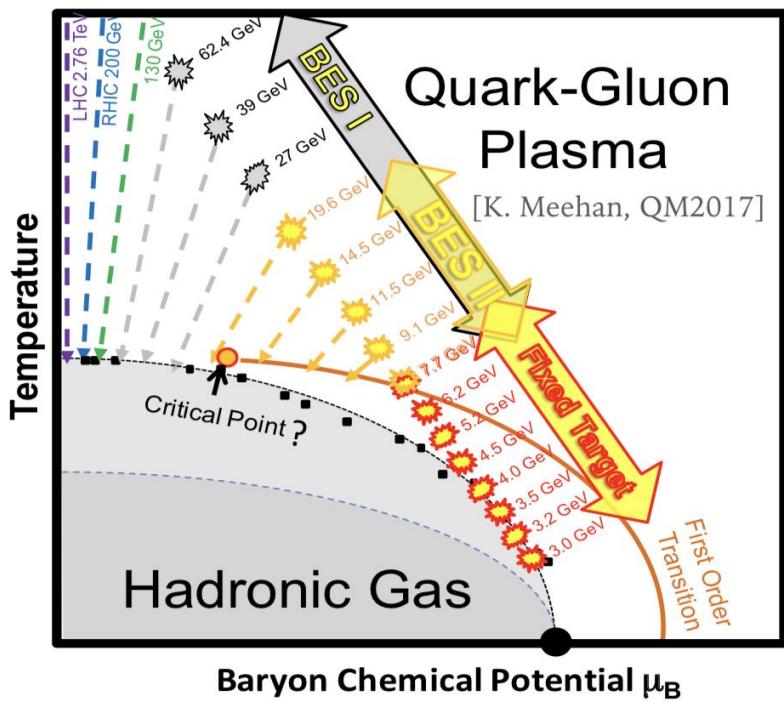
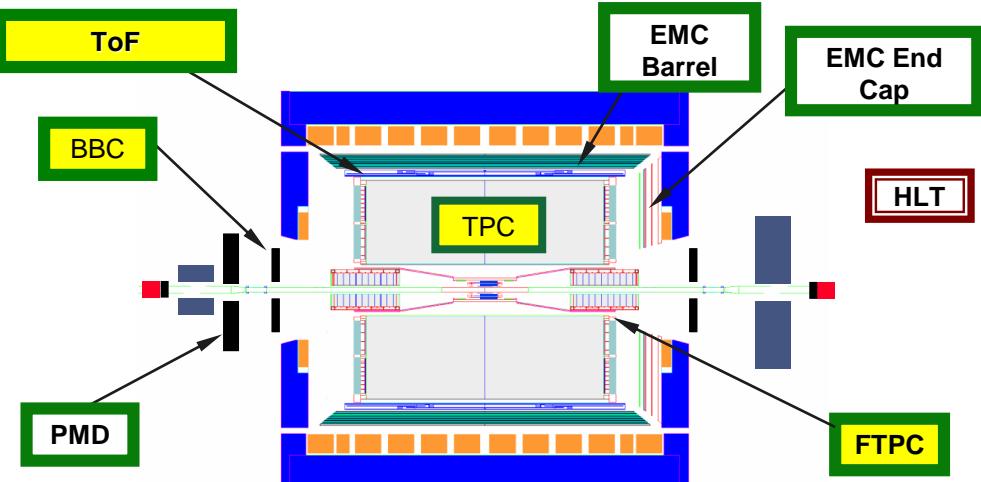
QCD相图 (2015)



2015年美国能源部科学局核科学顾问委员会长期规划报告
2015, DOE Office of Science, NSAC, Long Range Plan

<http://science.energy.gov/np/nsac/>

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-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)
- 2)
- 3)

Enlarge rapidity acceptance
Improve particle identification
Enhance centrality/EP resolution

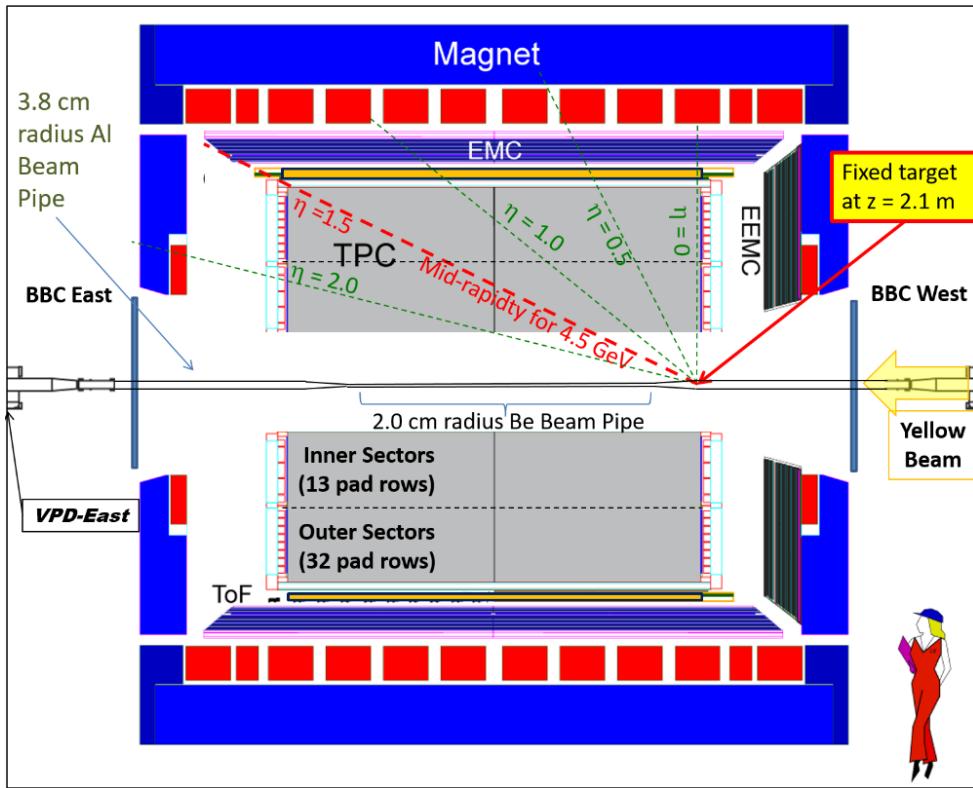
这三个探测器已经在2019年（Run-19）全部安装完毕并参与
STAR BES-II对撞取数。

STAR BES-II 获取的对撞数据 (2019-2021)

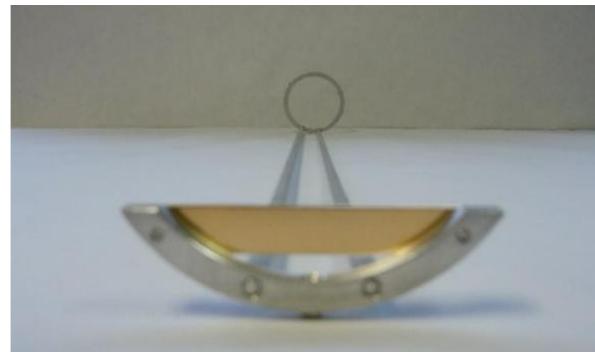
Year	<i>Collisions</i>	\sqrt{s}_{NN} (GeV)	Good events
2019	Au+Au	19.6	~ 582 M
2019	Au+Au	14.5	~ 324 M
2020	Au+Au	11.5	~ 235 M
2020	Au+Au	9.2	~ 162 M
2021	Au+Au	7.7	~ 100 M
2021	Au+Au	17.3	~ 250 M

STAR BES-II对撞取数已经在去年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。

STAR固定靶实验

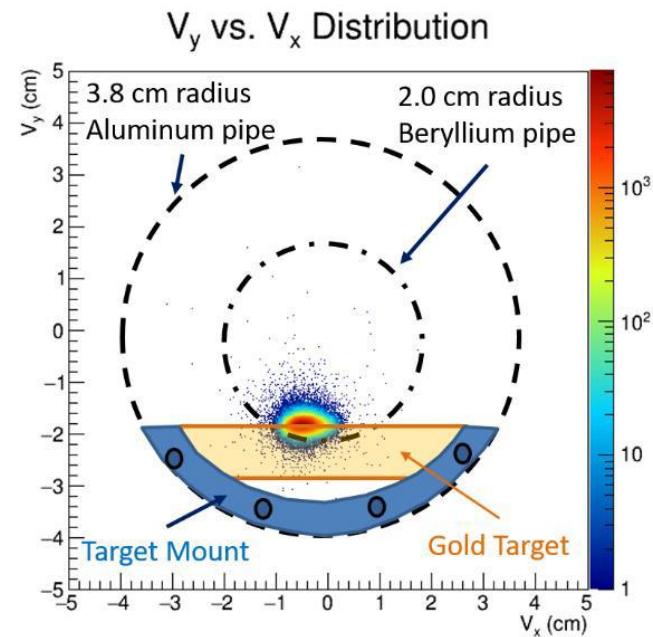


1 mm thick (4% inter. prob.) gold target (2015)
 → 1/4 mm thick gold target in FXT phys. program



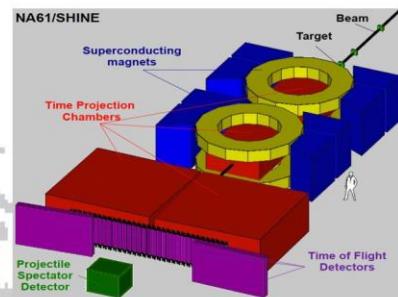
1.3M events from **half hour test run**, top 30%
 central trigger, Au+Au $\sqrt{s_{NN}}=4.5 \text{ GeV}$

3.4M events from **two hour test run**, top 30%
 central trigger, Al+Au $\sqrt{s_{NN}}=4.9 \text{ GeV}$

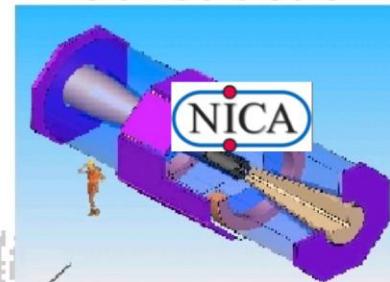


高密度区重离子碰撞实验

CERN SPS

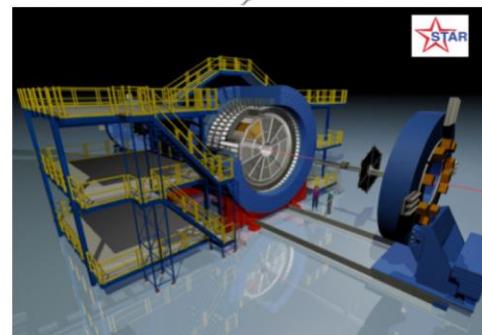


Construction....



BNL/RHIC STAR

BES-I (2010-2017)
BES-II (2018-2021) is ongoing.



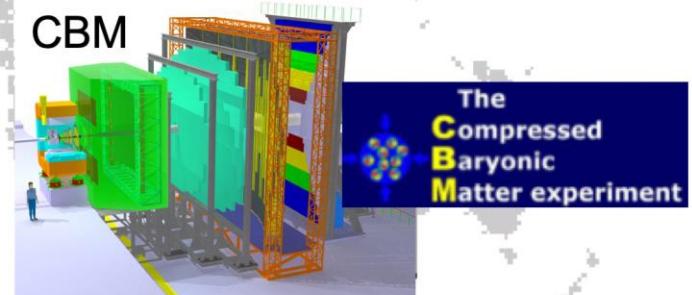
Collider $\sqrt{s_{NN}} = 7.7\text{-}200 \text{ GeV}$

Fix target

$\sqrt{s_{NN}} = 5\text{-}17 \text{ GeV}$

SPS

CBM



Fix target

$\sqrt{s_{NN}} = 2\text{-}5 \text{ GeV} (2025\text{-})$

Collider

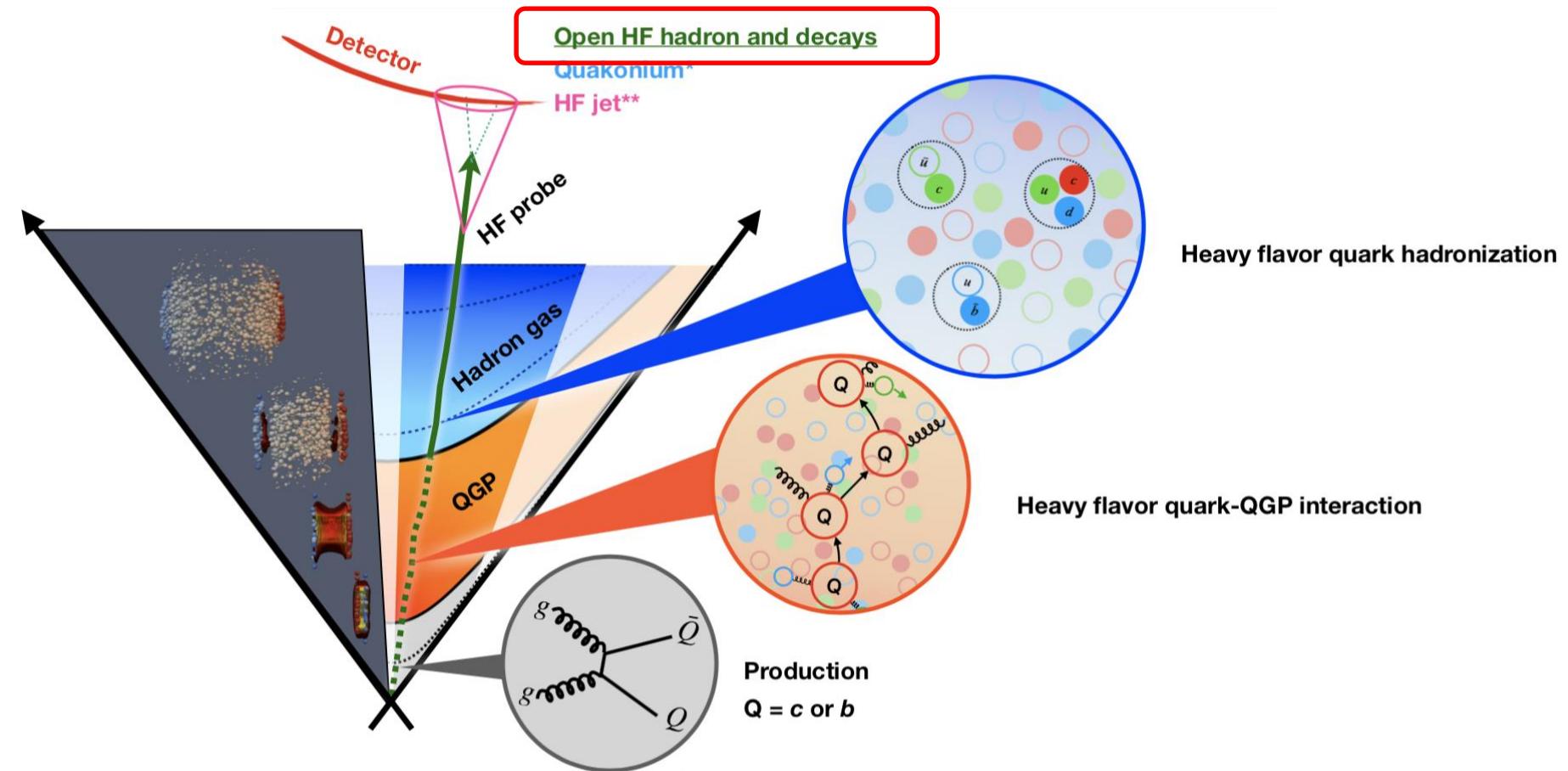
$\sqrt{s_{NN}} = 4\text{-}11 \text{ GeV} (2023\text{-})$

CEE@Lanzhou

JPARC@Japan

Construction....

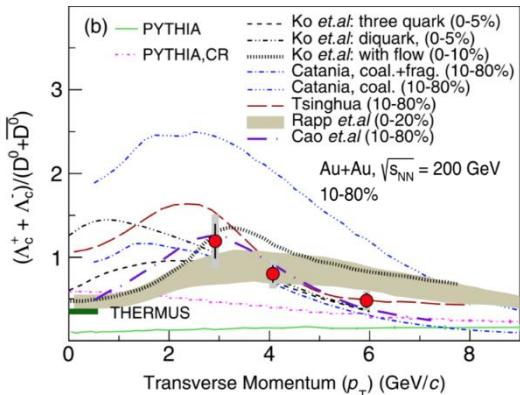
重味强子——QGP特性的探针



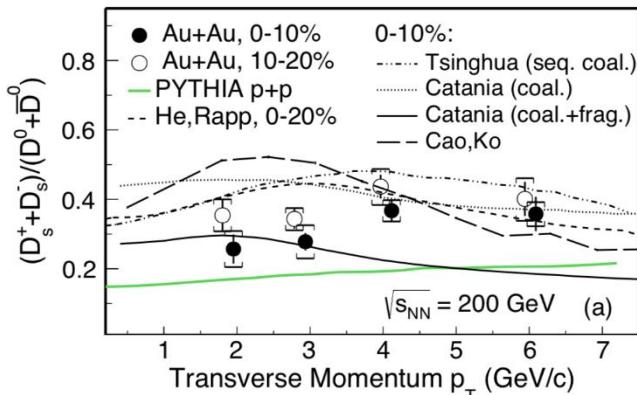
Qipeng Hu, SQM2022

Open charm in Au+Au at 200 GeV

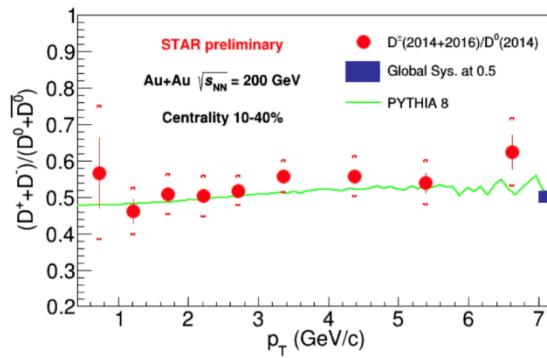
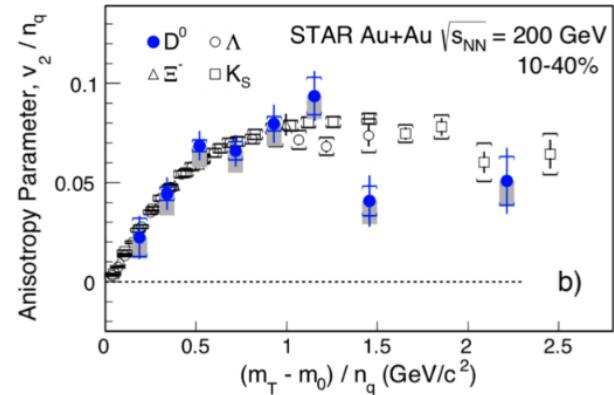
PRL 124, 172031 (2020)



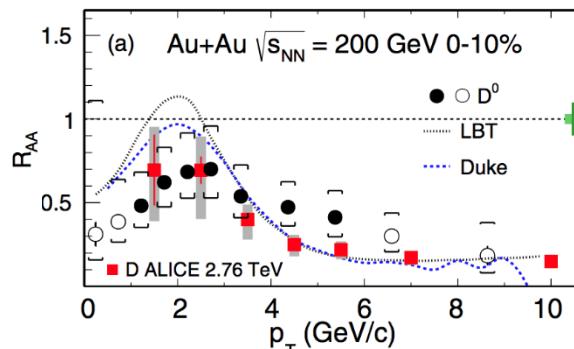
arXiv:2101.11793, accepted by PRL



PRL 118, 212301 (2017)



J. Vanek, HP2020



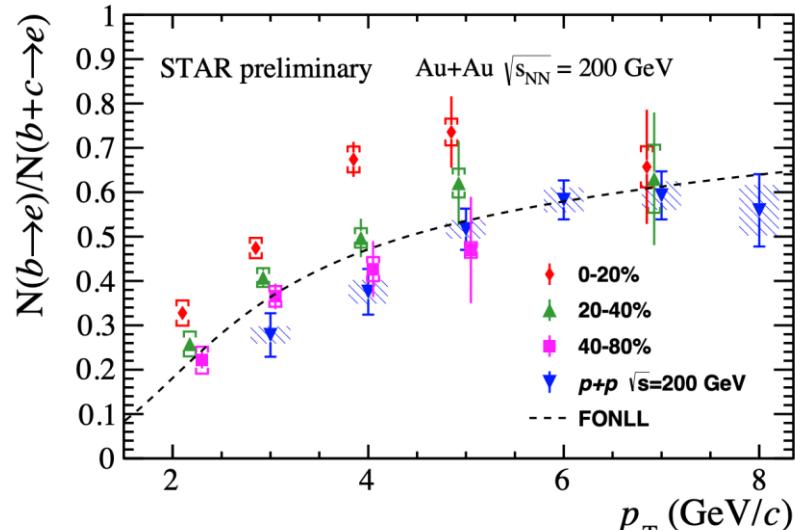
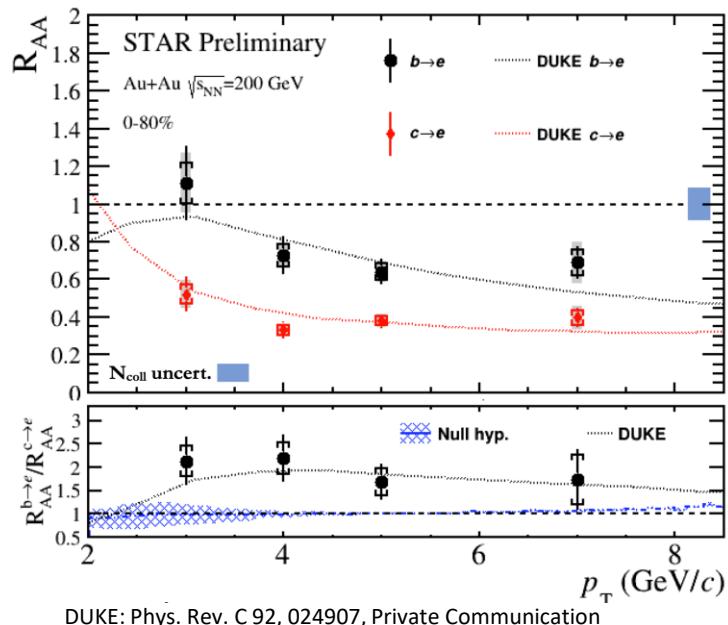
PRC 99, 034908 (2019)

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

production yields in AA collisions
production yields in pp collisions
binary nucleon-nucleon collisions

- Data suggest both charm quark thermalization with the medium and charm quark coalescence hadronization at top RHIC energy

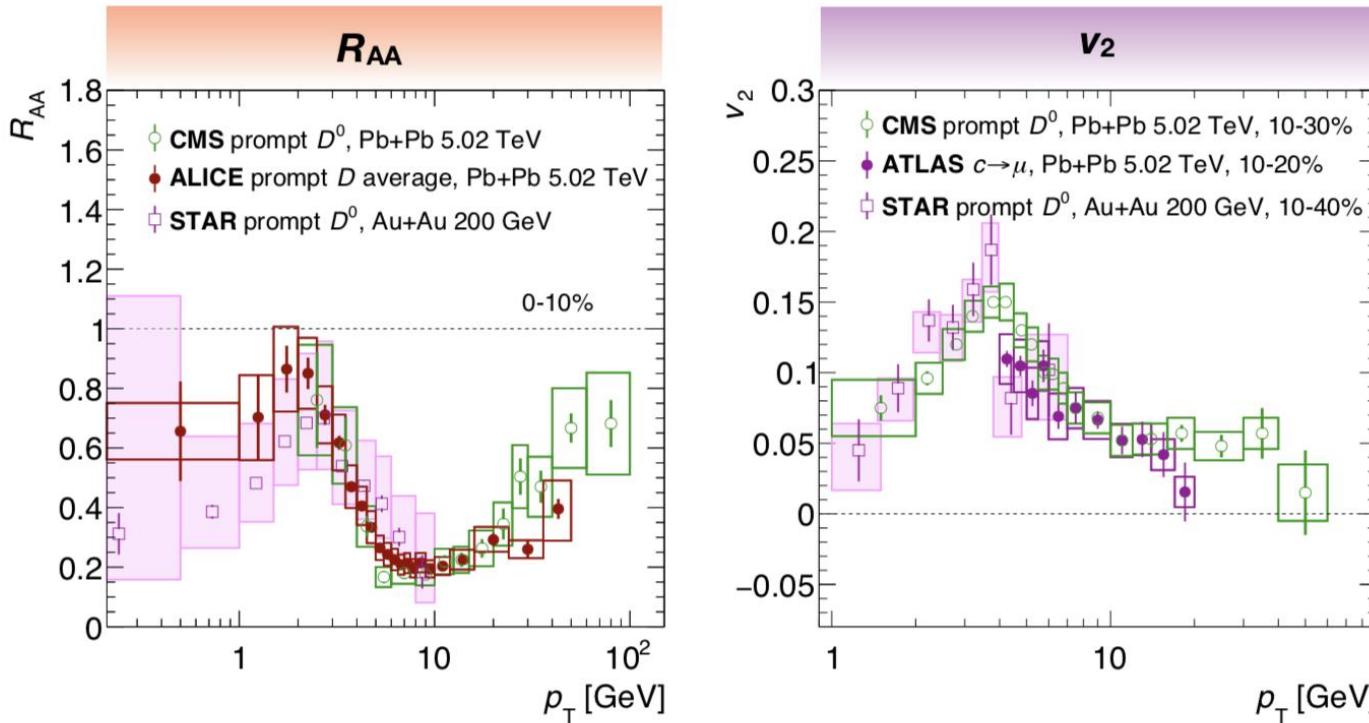
$c \rightarrow e$ and $b \rightarrow e$ in Au+Au at 200 GeV



- $R_{AA}(b \rightarrow e) > R_{AA}(c \rightarrow e) (>3\sigma)$: bottom is less suppressed than charm
- Bottom fraction significantly enhanced in central collisions, approach p+p data towards peripheral

Y. Zhou, HP2020

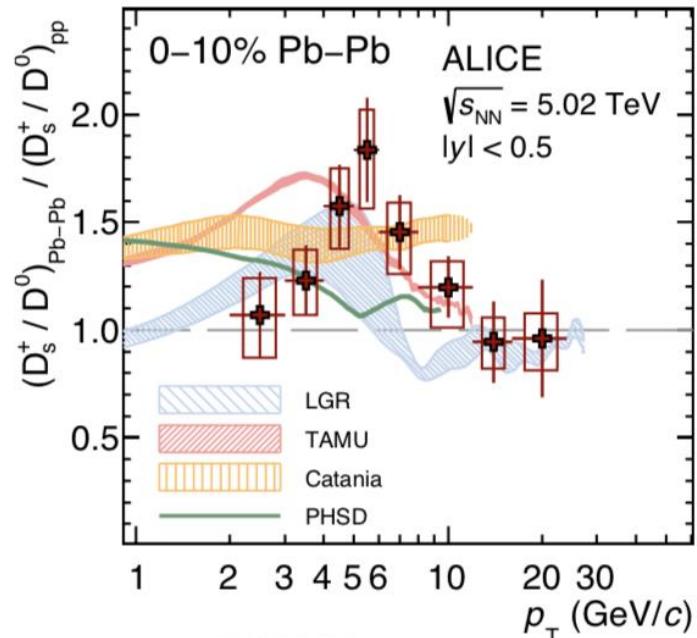
Open charm in Pb+Pb at LHC



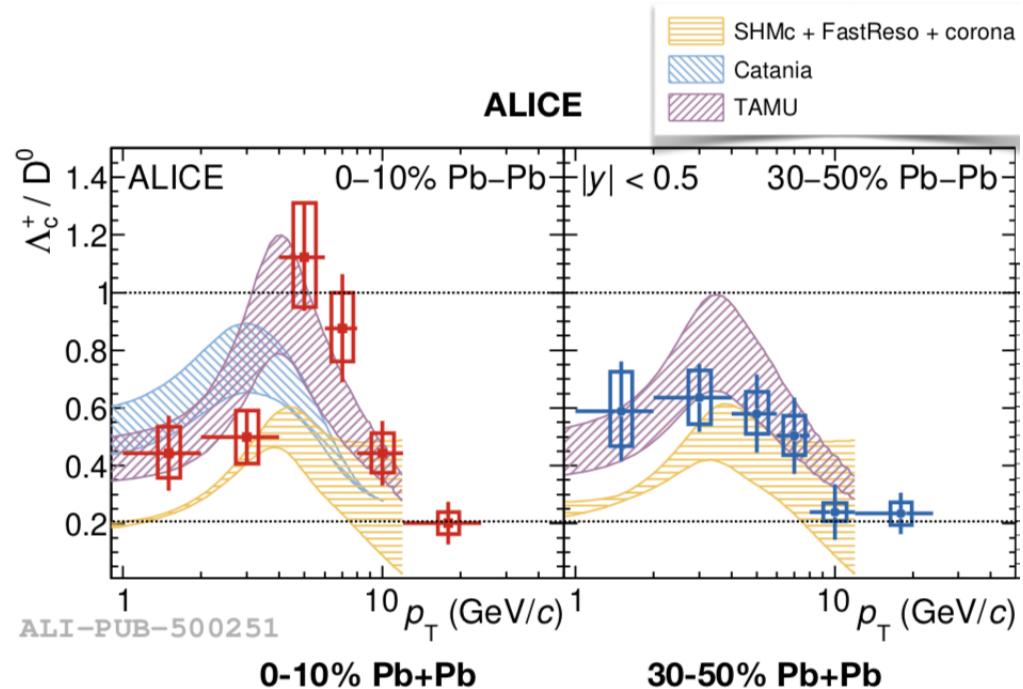
ALICE R_{AA} , JHEP 01 (2022) 174
 CMS R_{AA} , PLB 782 (2018) 474
 STAR R_{AA} , PRC 99 (2019) 034908

- Precise R_{AA} and v_2 measured down to $p_T \sim 0$ GeV. Open charm is strongly modified in a p_T dependent way
- Perfect consistency between LHC experiments: ALICE, CMS, ATLAS
- Similarity between LHC and RHIC

Open charm in Pb+Pb at LHC



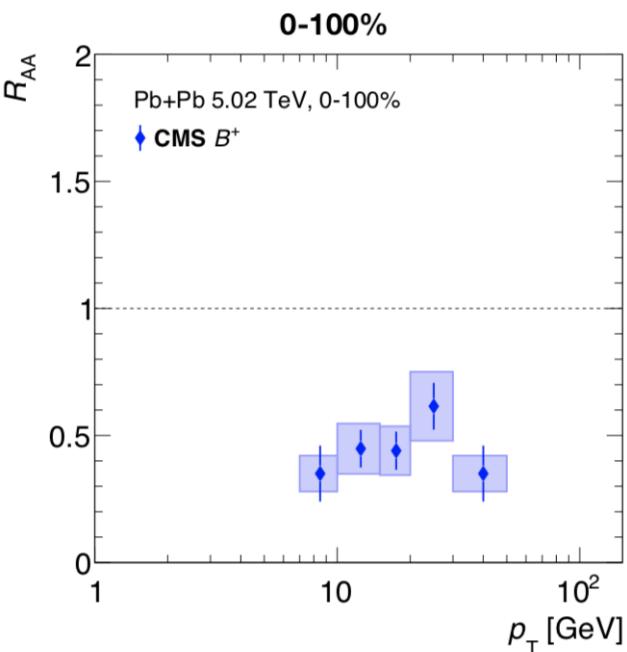
ALI-PUB-522154



- D_s^+ is significantly enhanced compared to D^0 in Pb+Pb at LHC and RHIC
- Qualitatively captured by different models with coalescence
- Λ_c^+ / D^0 show increasing trend with increasing $\langle N_{\text{part}} \rangle$ at low $4 < p_T < 6$ GeV

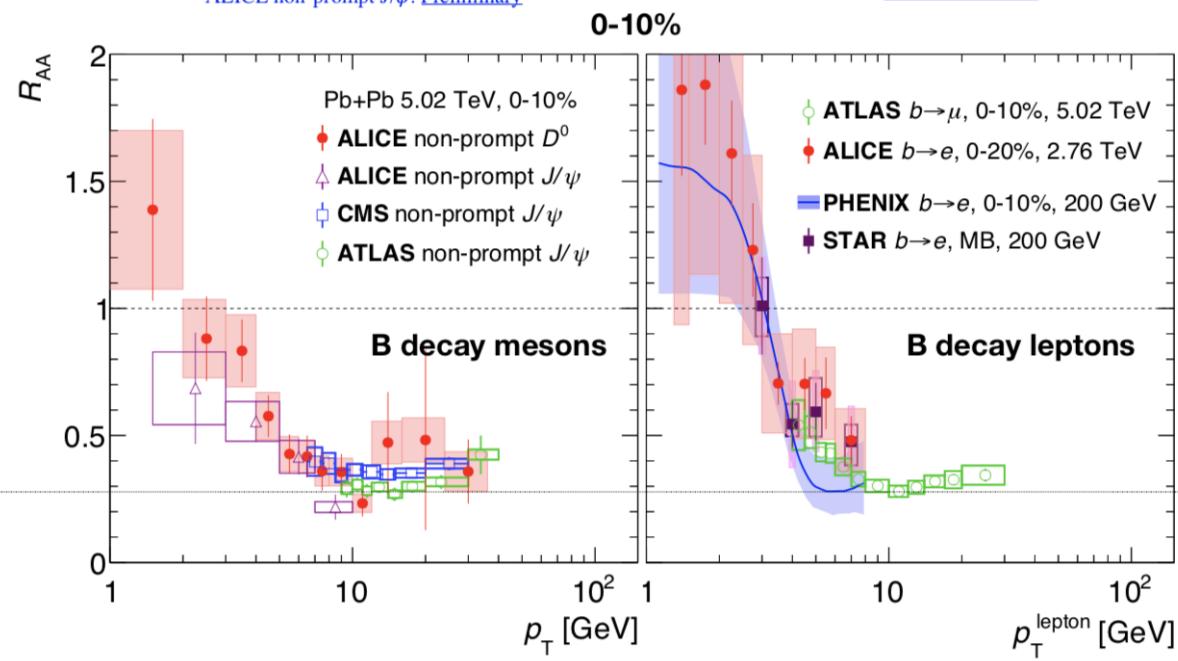
Open bottom in Pb+Pb at LHC

CMS B^+ : PRL 119 (2017) 152301



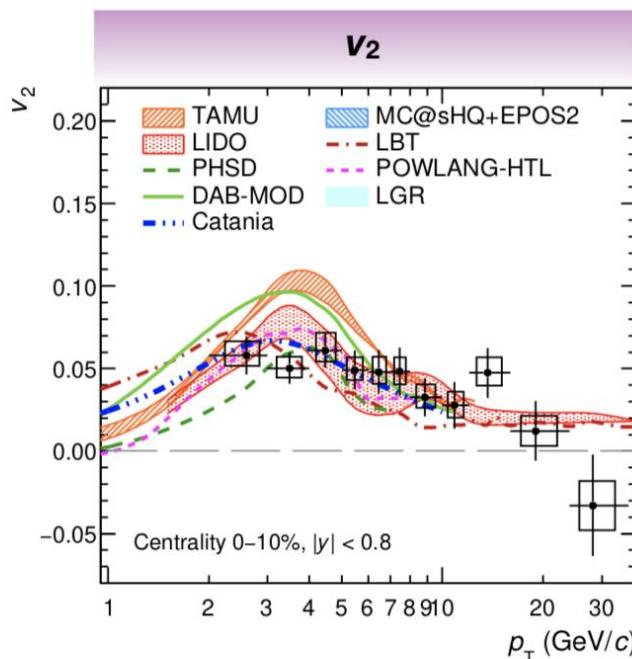
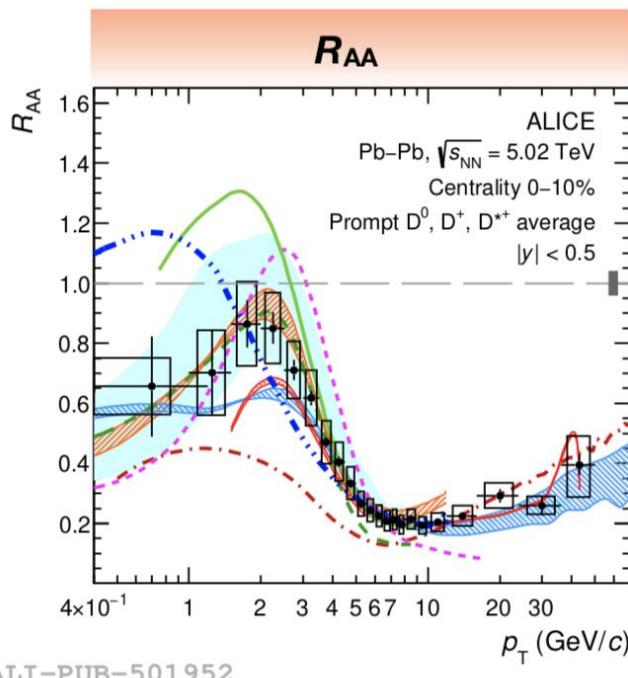
ALICE non-prompt D^0 : arXiv:2202.00815
 CMS non-prompt J/ψ : EPJC 78 (2018) 509
 ATLAS non-prompt J/ψ : EPJC 78 (2018) 762
 ALICE non-prompt J/ψ : Preliminary

ATLAS muon: PLB 829 (2022) 137077
 ALICE electron: JHEP 07 (2017) 052
 PHENIX electron: arXiv:2203.17058
 STAR electron: arXiv:2111.14615



- B^+ R_{AA} has limited kinematic coverage and precision
- Bottom R_{AA} measured via B decays can reach much higher precision

Open charm data-model comparison



JHEP 01 (2022) 174

Model ingredients:

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

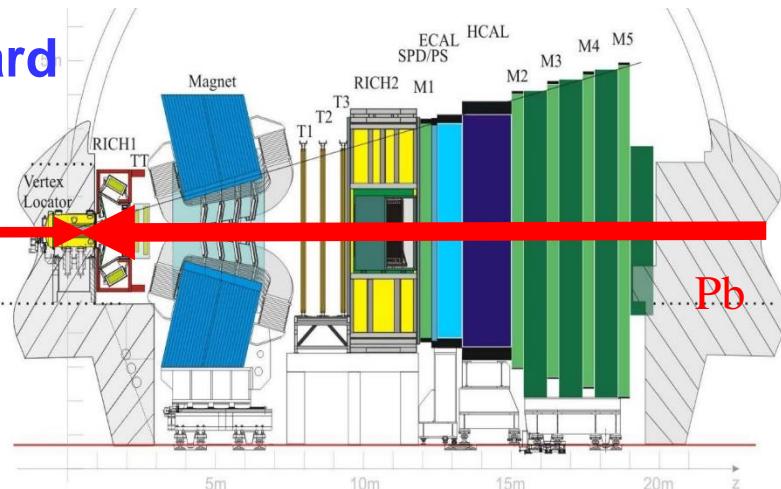
- Open charm experiences the entire QGP evolution; models also contain each stage of charm evolution
- Most models describe data over wide kinematic and centrality ranges

LHCb $p\text{Pb}$ datasets

Forward

$p\text{Pb}$

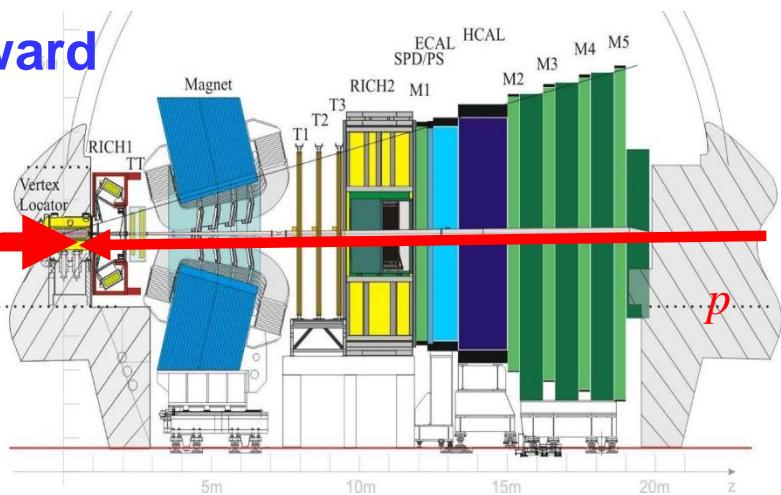
p



Backward

Pbp

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: $2.5 < |y^*| < 4.0$

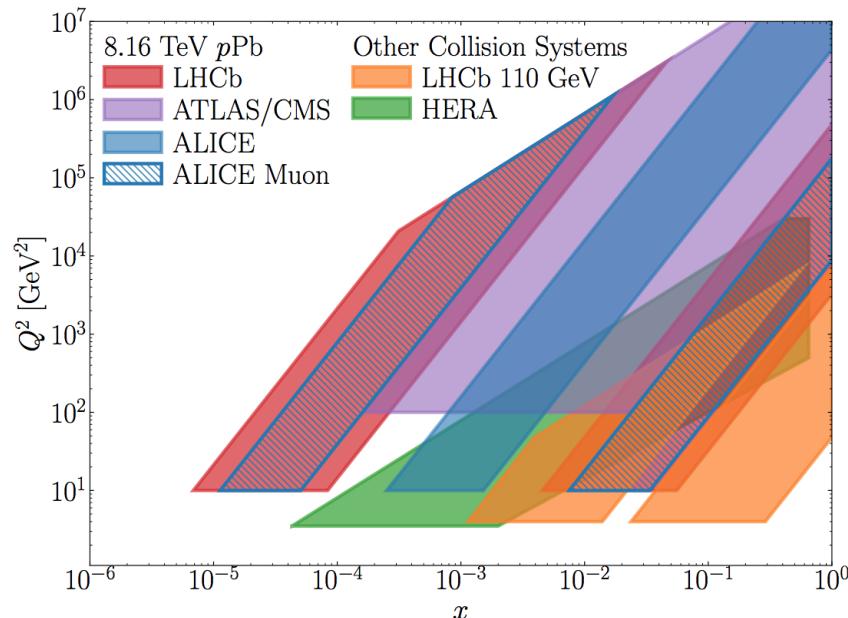
- ✓ $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ (2013, Run I)

- ✓ $p\text{Pb}$ (1.06 nb^{-1}) + Pbp (0.52 nb^{-1})

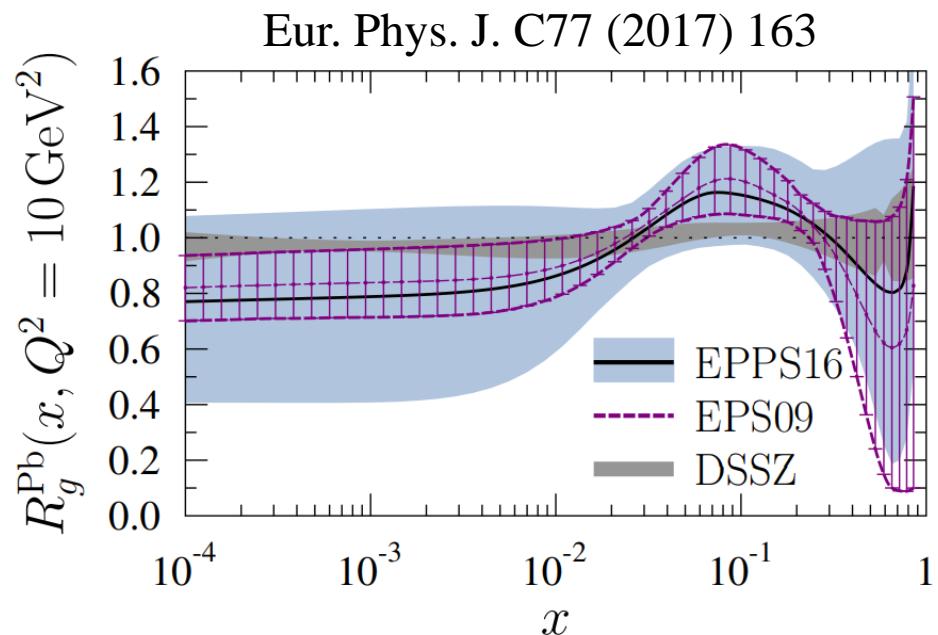
- ✓ $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$ (2016, Run II)

- ✓ $p\text{Pb}$ (13.6 nb^{-1}) + Pbp (21.8 nb^{-1})

LHCb: frontier experiment in phase space



Graphic by T. Boettcher

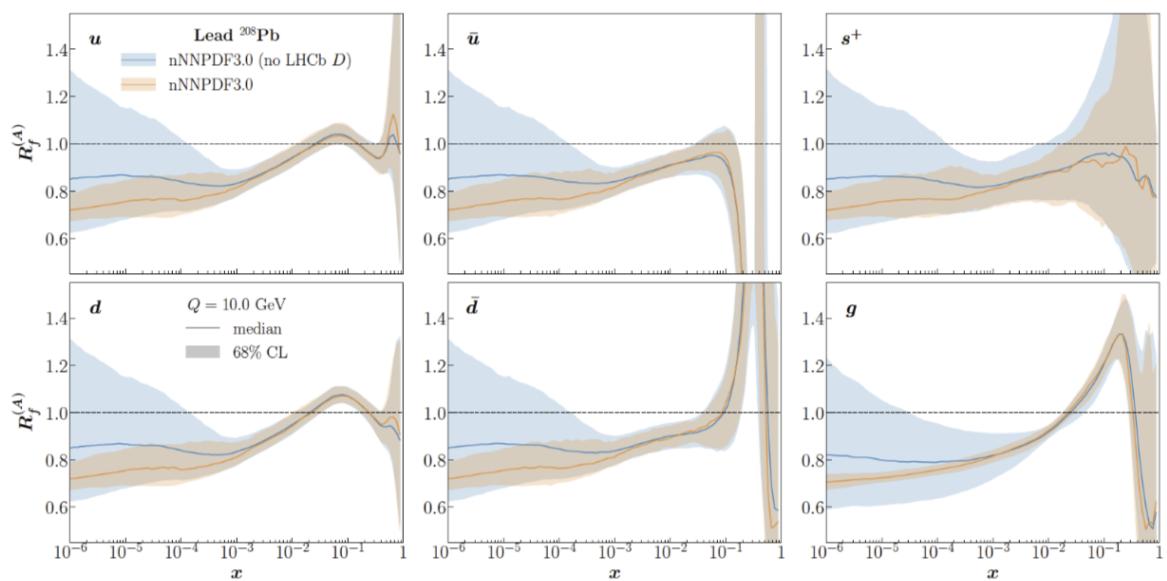
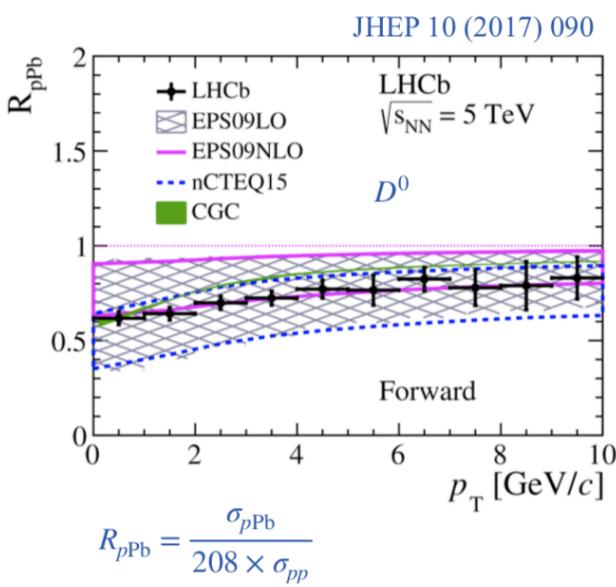


Thanks to the boost, the high resolution, the low- p_T reach and the fast read-out

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

LHCb D^0 data constrain nPDF

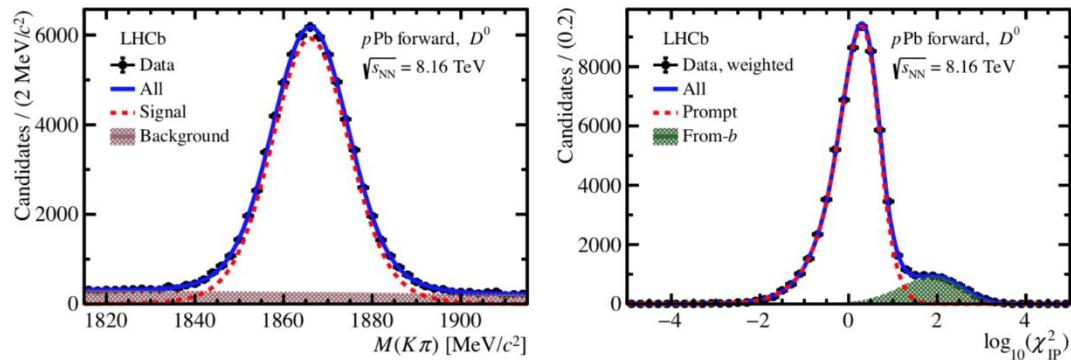
- nNNPDF3.0 [arXiv:2201.12363](https://arxiv.org/abs/2201.12363)
- LHCb measurement of prompt D^0 production in $p\text{Pb}$ collisions at 5 TeV makes an impressive impact on reducing nPDF uncertainty down to $x \sim 10^{-6}$



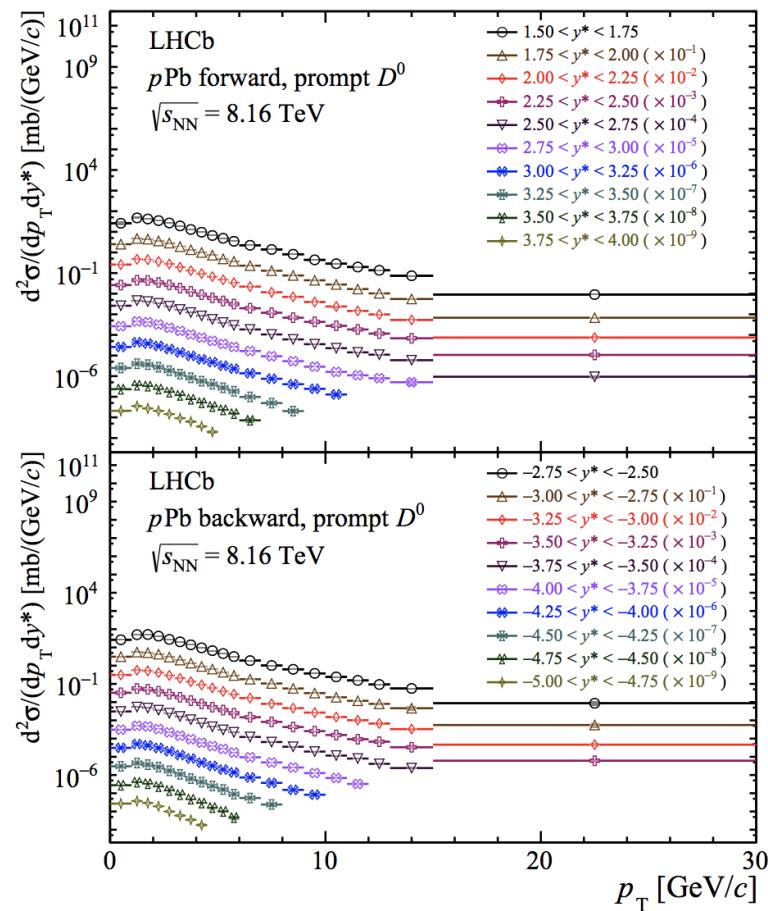
Jiayin Sun, LHC seminar

New D^0 measurement at 8.16TeV

arXiv:2205.03936

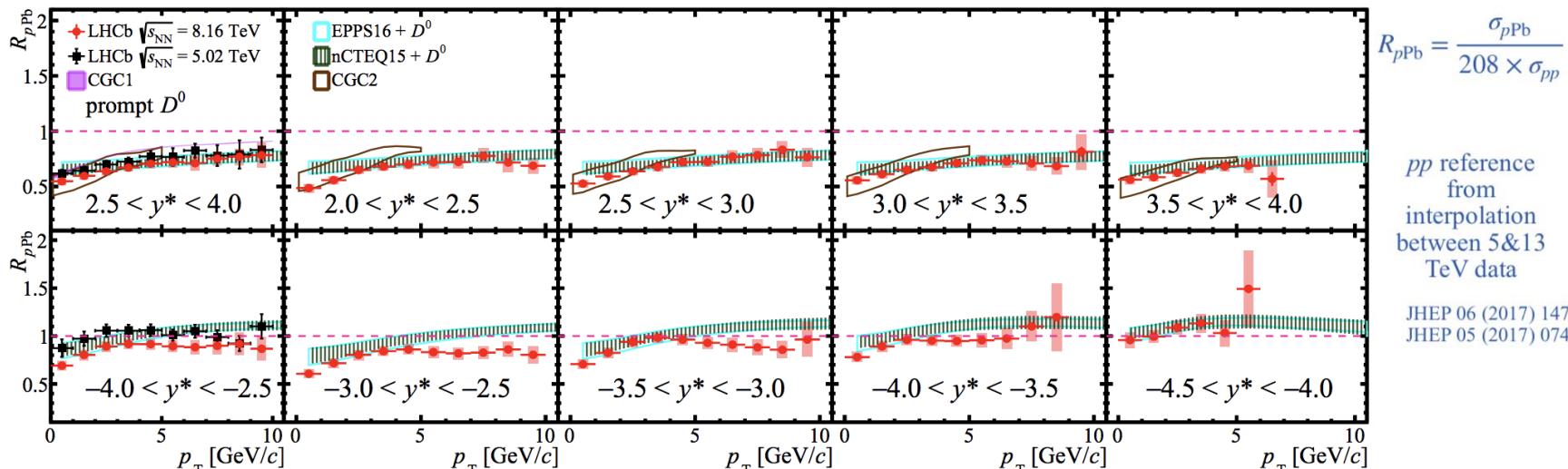


- Precise measurement of prompt D^0 production in $p\text{Pb}$ collisions
- 20 times larger statistics than previous LHCb D^0 result at 5TeV
- $D^0 \rightarrow K^-\pi^+$
- Use impact parameter to separate the prompt and b -decay components
- $0 < p_T < 30 \text{ GeV}/c$
- $p\text{Pb}: 1.5 < y < 4.0;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

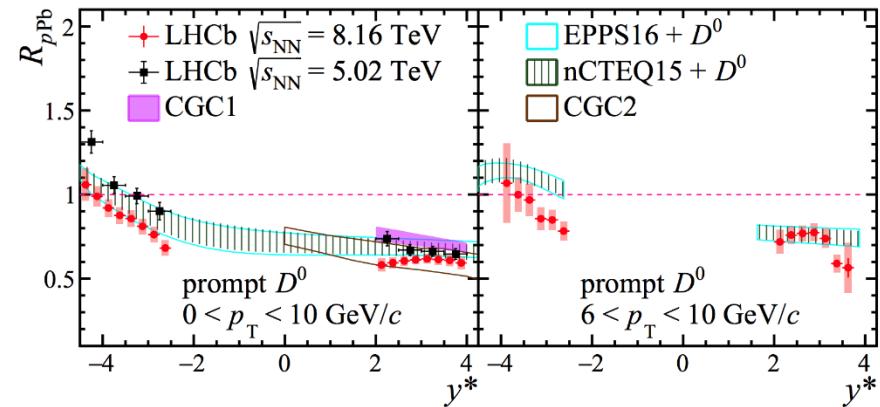


D^0 nuclear modification factor at 8.16 TeV

arXiv:2205.03936

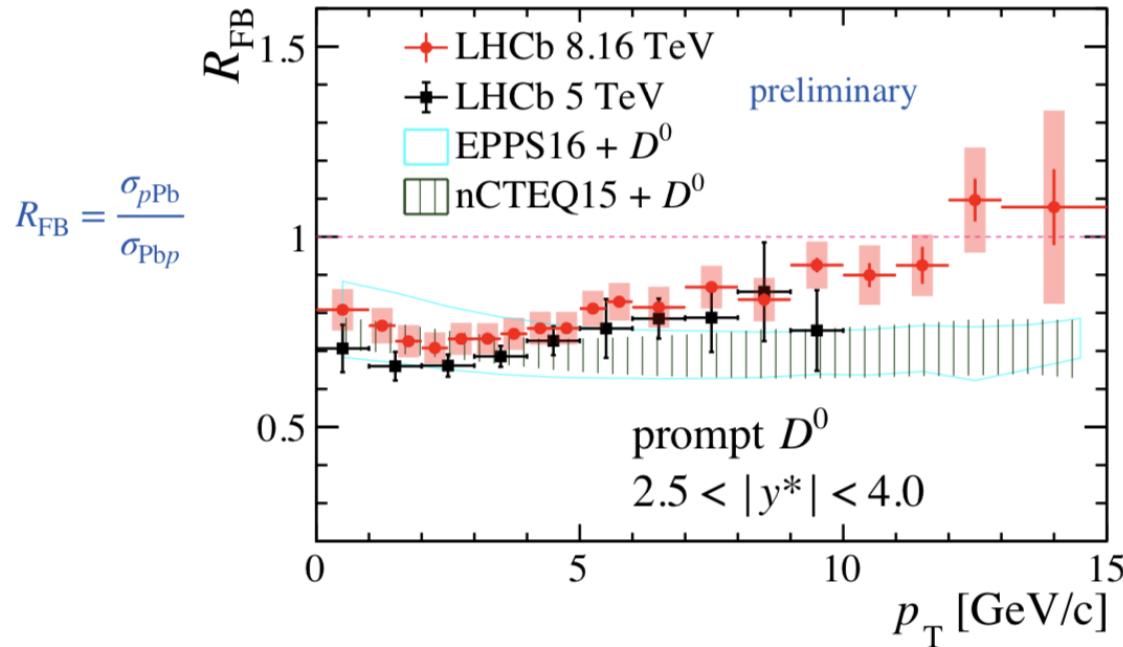


- Forward:
 - Suppression consistent with 5 TeV D^0 result
 - Consistent with nPDF and CGC
- Backward:
 - Data lower than nPDF at high p_T
 - Room for additional effects in the backward rapidity
 - **nPDF calculations do not describe data for h^\pm , π^0 and D^0**



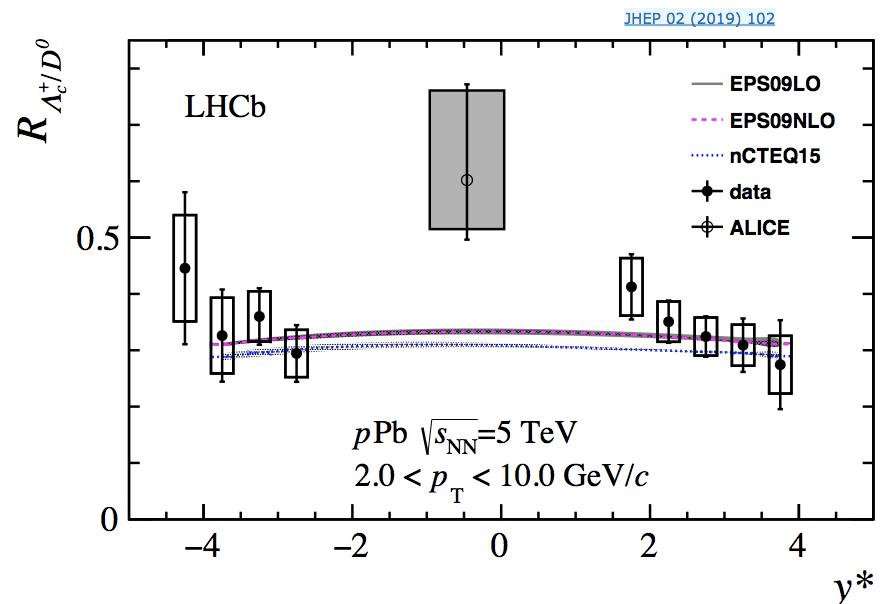
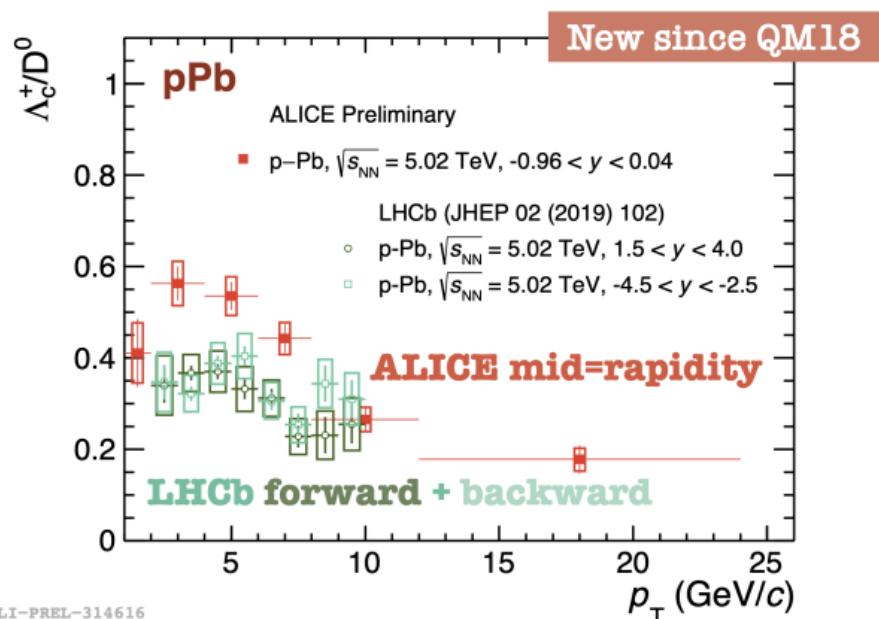
D^0 forward-backward production ratio

arXiv:2205.03936



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

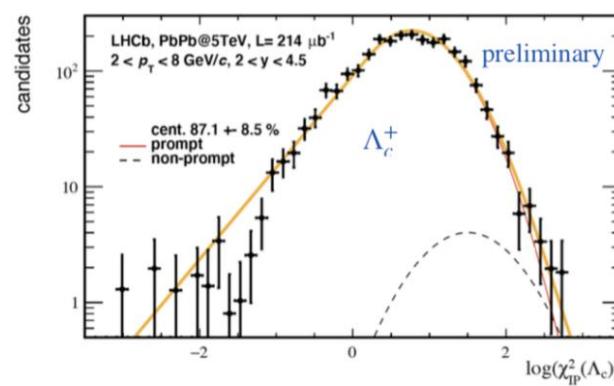
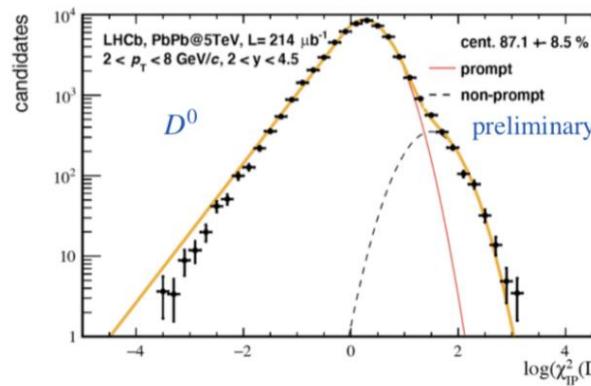
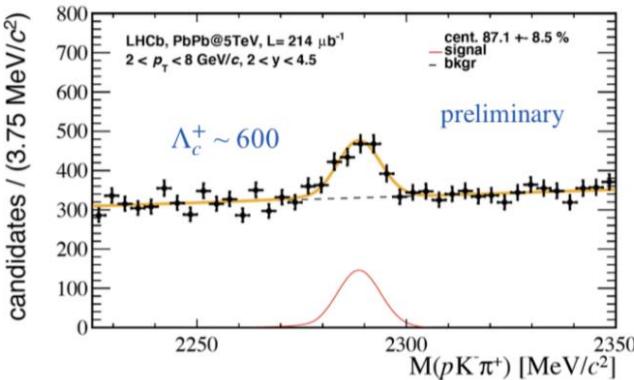
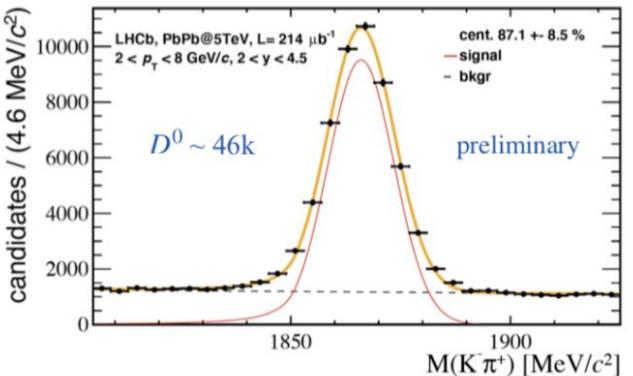
Λ_c/D^0 in pPb collisions



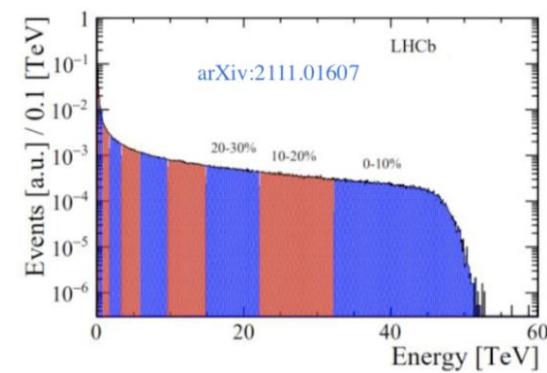
New LHCb Pb+Pb sample might give some insights ?

Λ_c/D^0 in peripheral Pb+Pb

LHCb-PAPER-2021-046

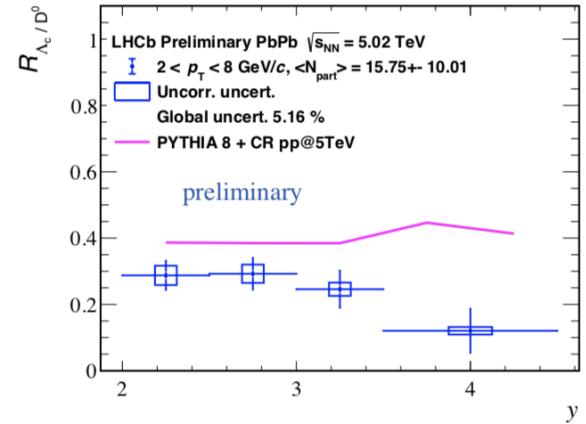
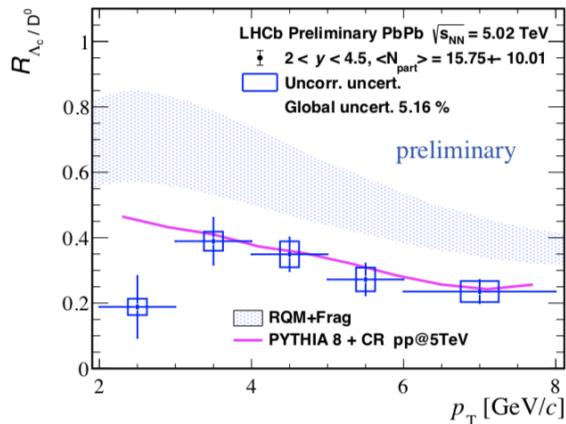
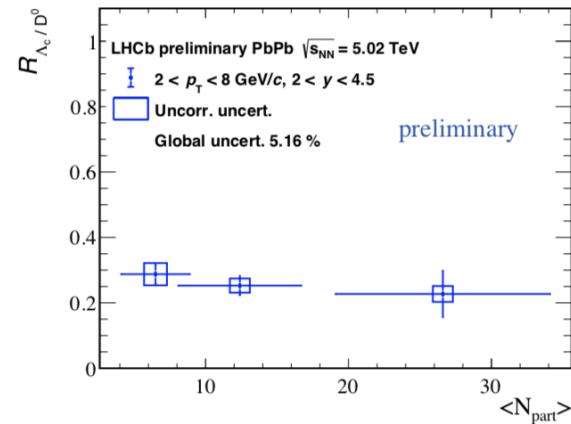


- One of the first LHCb PbPb results in hadronic collisions
- PbPb data collected in 2018
- Centrality determined by energy in Ecal
- Up to 60% centrality in hadronic collisions
- Separation of the prompt and b -decay components by impact parameter



Λ_c/D^0 in peripheral Pb+Pb

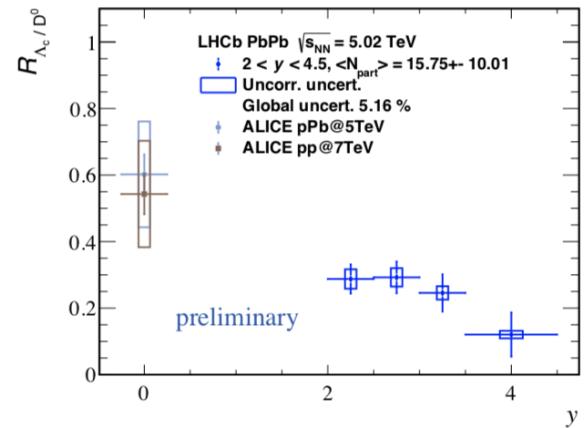
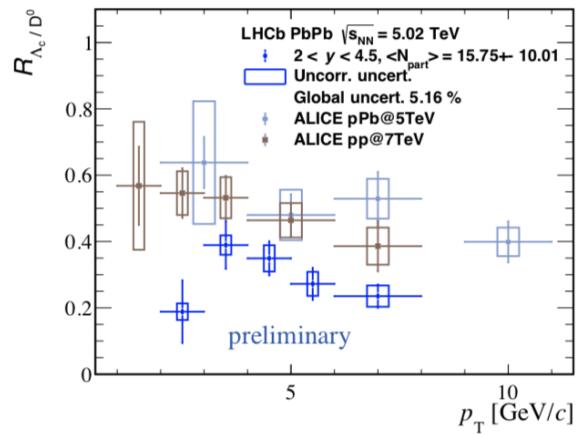
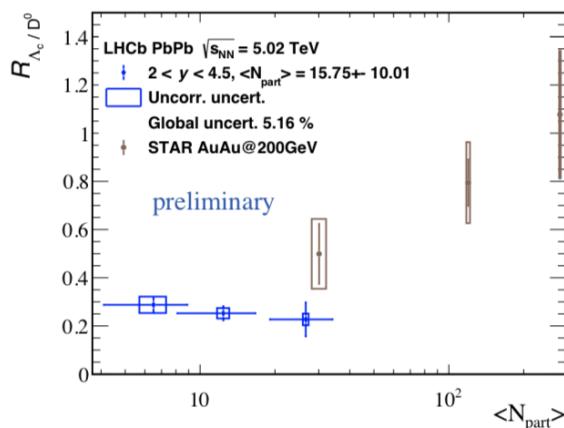
LHCb-PAPER-2021-046



- Flat dependence vs. $\langle N_{part} \rangle$
 - $\langle \Lambda_c^+/D^0 \rangle \sim 0.27$
 - PYTHIA8 + Color Reconnection: compatible with data within 3σ
 - Standard Hadronization Model is above the data
 - Needs better understanding of charm hadronization
- Enhancement at intermediate p_T
- Compatible with flat dependence vs. rapidity

Λ_c/D^0 in peripheral Pb+Pb

LHCb-PAPER-2021-046

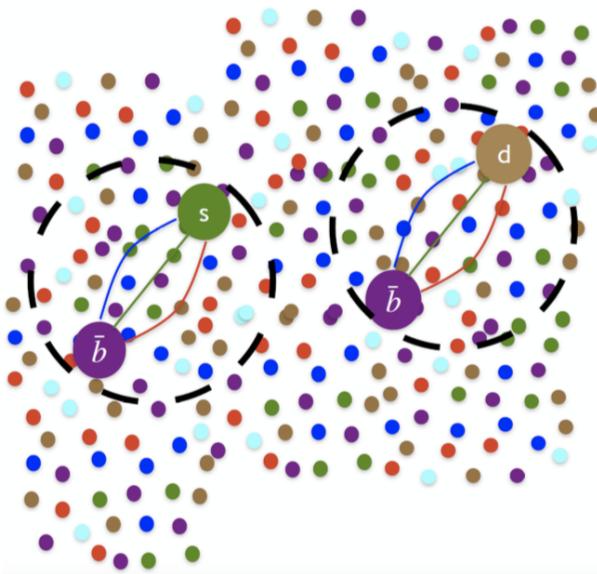


- Compatible with STAR at overlapping $\langle N_{part} \rangle$ values
 - Λ_c^+/D^0 ratio systematically lower than ALICE measurements in midrapidity
 - Λ_c^+/D^0 ratio dependence on rapidity?
- Similar decreasing trend at $p_T > 4$ GeV/c
- Lower values than ALICE in midrapidity

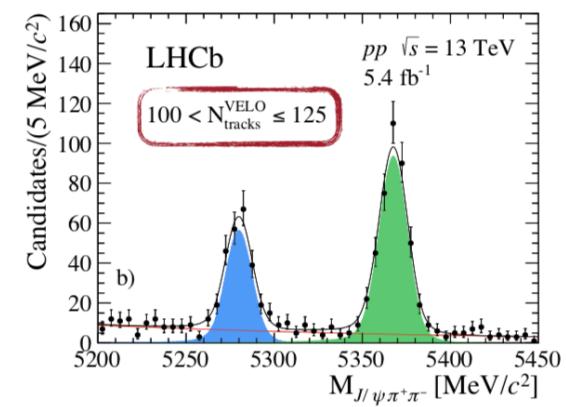
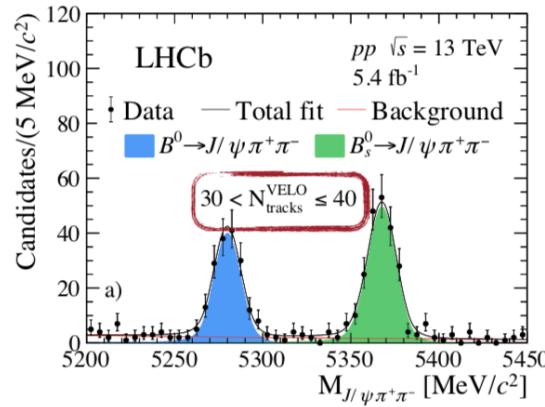
B_s^0/B^0 in high multiplicity pp at 13 TeV

arXiv:2204.13042

- Production of $b\bar{b}$ pairs at hadron colliders dominated by hard parton-parton interactions in the initial stages, well described by pQCD calculations
- Enhanced strangeness production in light-quark baryons and mesons observed by ALICE [Nature Phys. 13 \(2017\) 535](#)
- **Possible quark coalescence → enhanced B_s^0/B^0 ratio with increasing particle multiplicity, especially at low p_T**

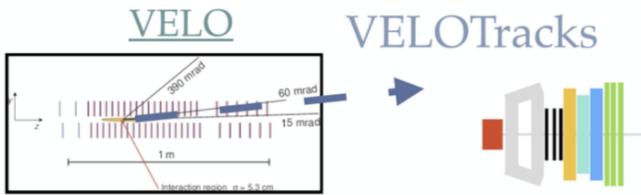


$$B_{(s)}^0 \rightarrow (J/\psi \rightarrow \mu^+\mu^-)\pi^+\pi^-$$

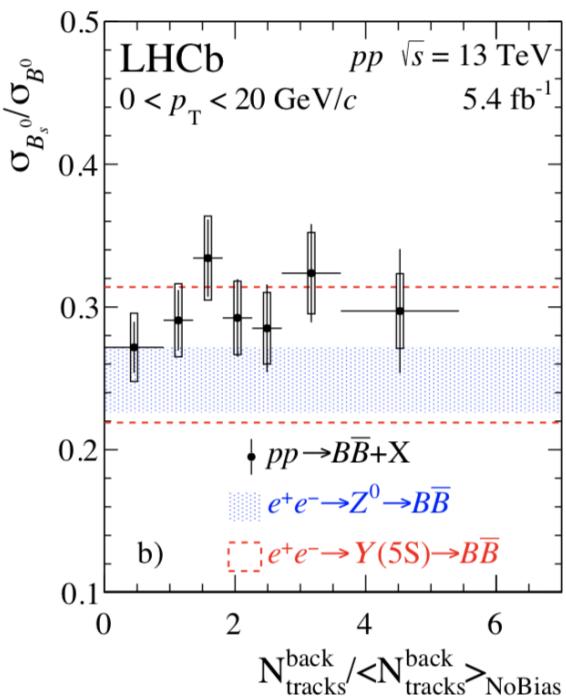
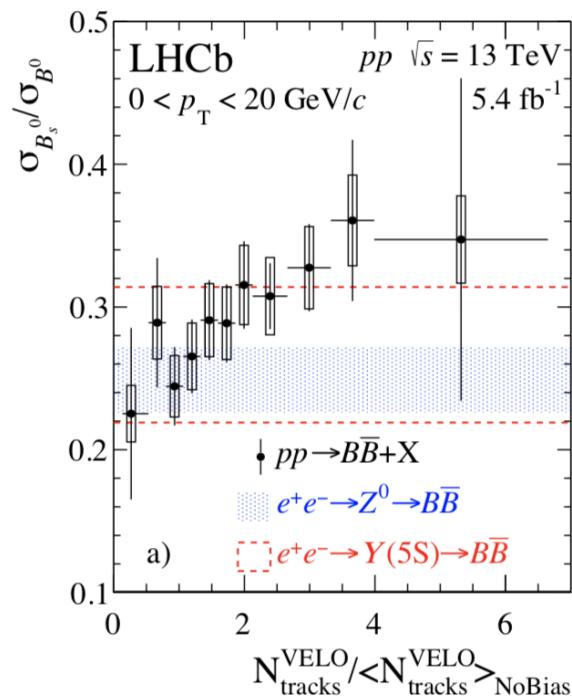


B_s^0/B^0 in high multiplicity pp at 13 TeV

arXiv:2204.13042

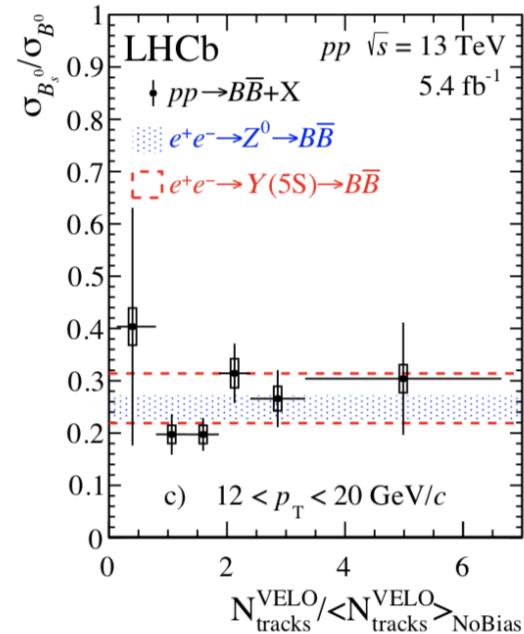
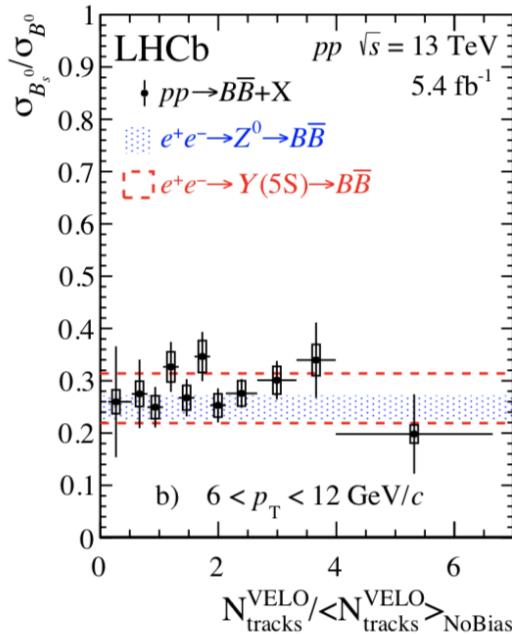
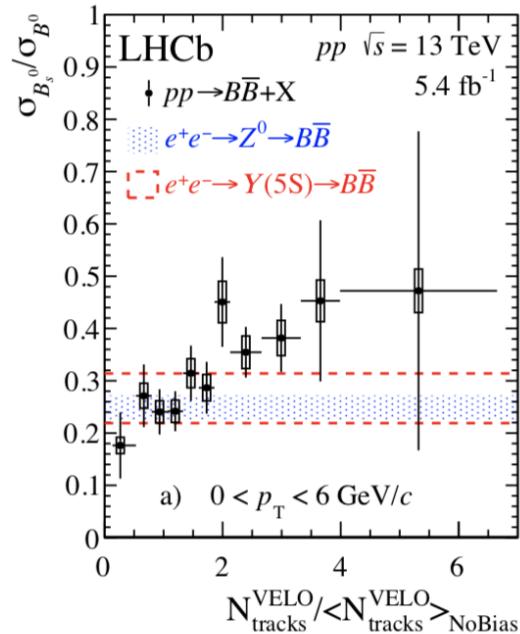


- Total VELO multiplicity:
 - Increasing trend
- Multiplicity measured in backward region:
 - No significant dependence
- Indicates B_s^0/B^0 increase related to the local particle density around the B mesons
- Compatible with expectations of coalescence



B_s^0/B^0 in high multiplicity pp at 13 TeV

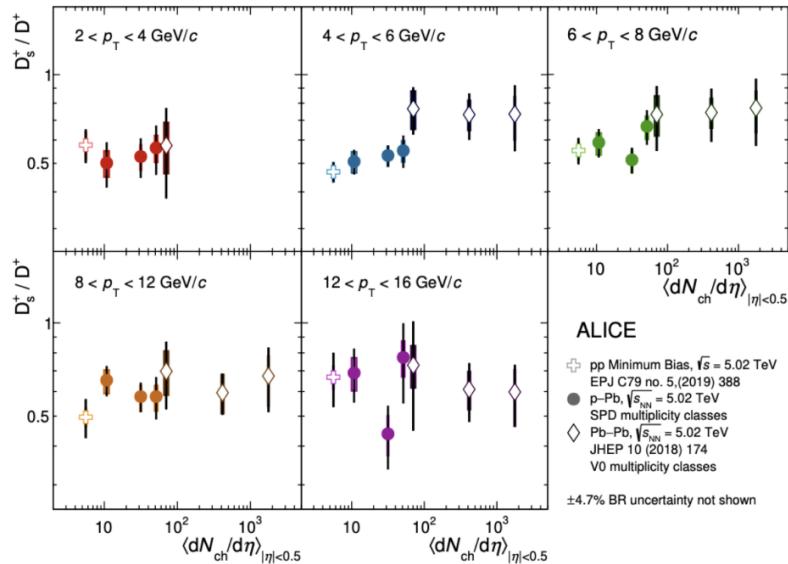
arXiv:2204.13042



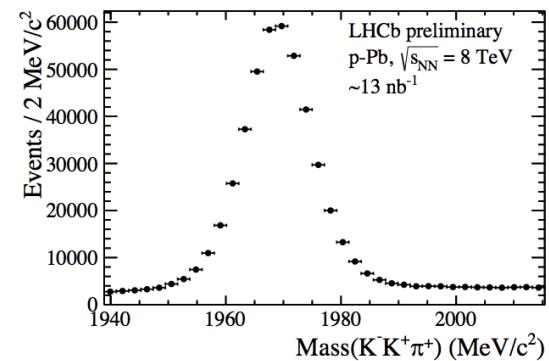
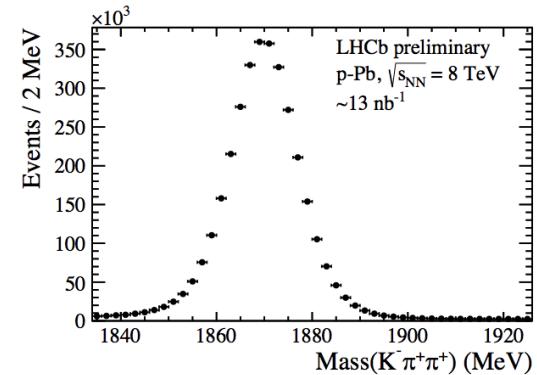
- Low multiplicity: consistent with values in e^+e^- collisions
- $0 < p_T < 6$: increases with increasing multiplicity, slope 3.4σ deviations from constant
- Higher p_T intervals: no significant dependence, consistent with e^+e^- data
- **Qualitatively consistent with expectations of coalescence**

Work in progress: D_s^+ / D^+ in pPb at 8.16 TeV

- We are studying strangeness enhancement in $p\text{Pb}$ collision by D_s^+ / D^+ ratio.
 - We use the same strategy as B analysis, the statistics of D mesons are larger.
- ALICE has studied in 5.02 TeV $p\text{Pb}$ collision.



$$R_{D_s^+/D^+}(p_T, y^*, \text{PV nTracks}) = \frac{N(D_s^\pm \rightarrow K^\mp K^\pm \pi^\pm)}{N(D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm)} \times \frac{\mathcal{B}(D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm)}{\mathcal{B}(D_s^\pm \rightarrow K^\mp K^\pm \pi^\pm)} \times \frac{\epsilon_{D^+}}{\epsilon_{D_s^+}}$$



Chenxi Gu, SQM2022

总结和展望

➤ (高密区) QCD相结构

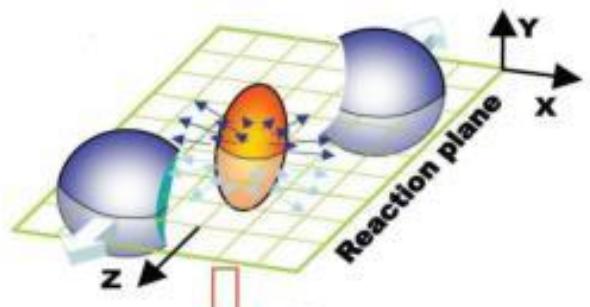
- STAR 第一期能量扫描实验 (7.7-39GeV的Au+Au碰撞) 系统测量了中等重子数密度区重离子碰撞的**奇异强子产生**
- 利用奇异强子产额以及统计模型提取了碰撞系统在化学冻结时刻的热力学参数
- 多个夸克胶子等离子体 (QGP) 信号在低能碰撞 (<20GeV) 中变得不显著，但需要更精确的测量予以确认
- STAR 第二期能量扫描将**精确测量**中高重子数密度区QCD相变和物态特性 (μ_B 最高达 721 MeV)

➤ QGP特性

- LHCb实验测量了pPb、周边PbPb和高多重数pp等碰撞系统中的**重味**粒子产生，为LHC上PbPb碰撞中QGP特性的定量研究提供参考
- 基于Run2数据的多项重味粒子产生结果将于近期公布
- Run3将可以进行PbPb碰撞中QGP特性的直接测量！

谢谢！

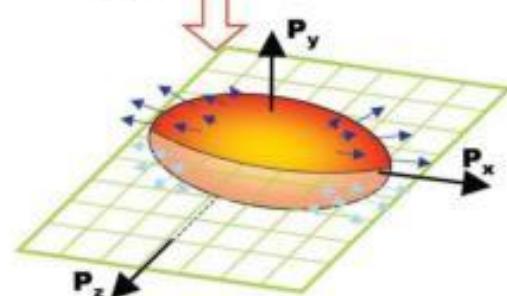
Elliptic Flow (v_2)



$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$



D

$\phi, \Omega, \Xi, \Lambda$

π, K, p

➤ **Elliptic flow** =>

➤ Initial spatial anisotropy (eccentricity ε)
->final momentum anisotropy v_2

➔ Interactions among constituents

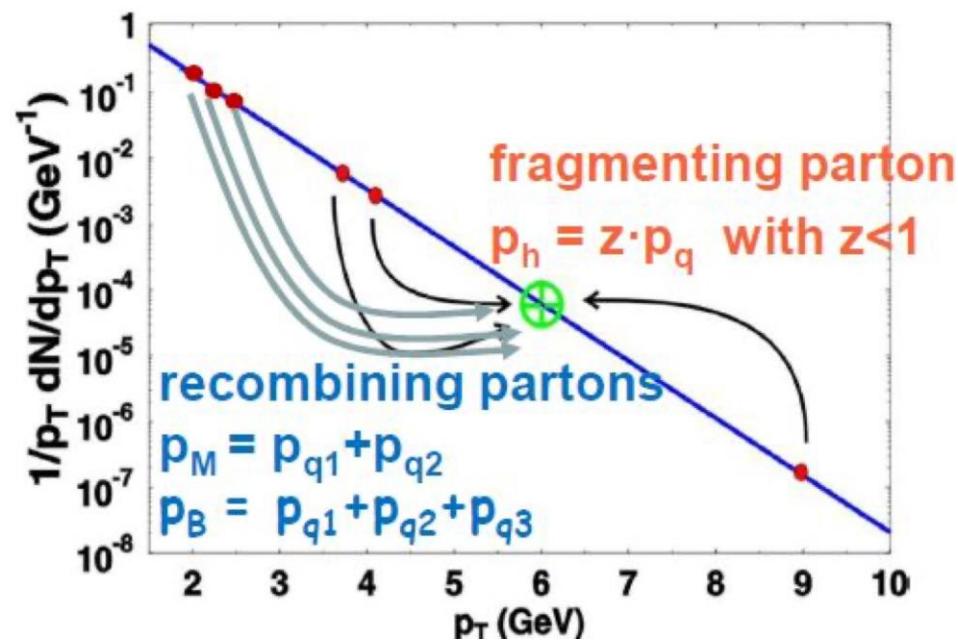
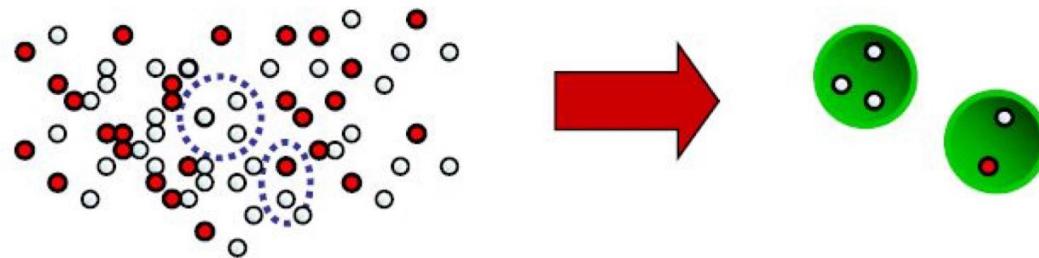
➤ Sensitive to degree of thermalization

➤ Self-quenching with time

➤ Sensitive to the early stages of the system evolution

➤ **Strange hadron => less sensitive to late hadronic rescattering**

Good probe of the early stage of the collision.



Greco et al., PRL 90 (2003) 202302