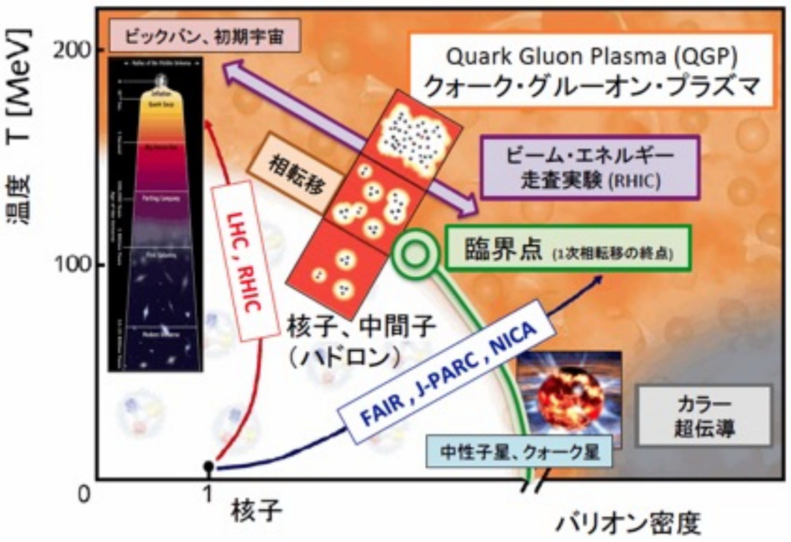
高エネルギー重イオン衝突の物理　チュートリアル研究会

臨界ダイナミクス（実験）



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筑波大学 数理物質系 物理学域
宇宙史研究センター
<u>江角晋一</u>

- Beam energy scan at high baryon density
- Temperature, partonic phase, phase transition
- Flow, correlation, fluctuation studies
- Summary and outlook

The STAR experiment
at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

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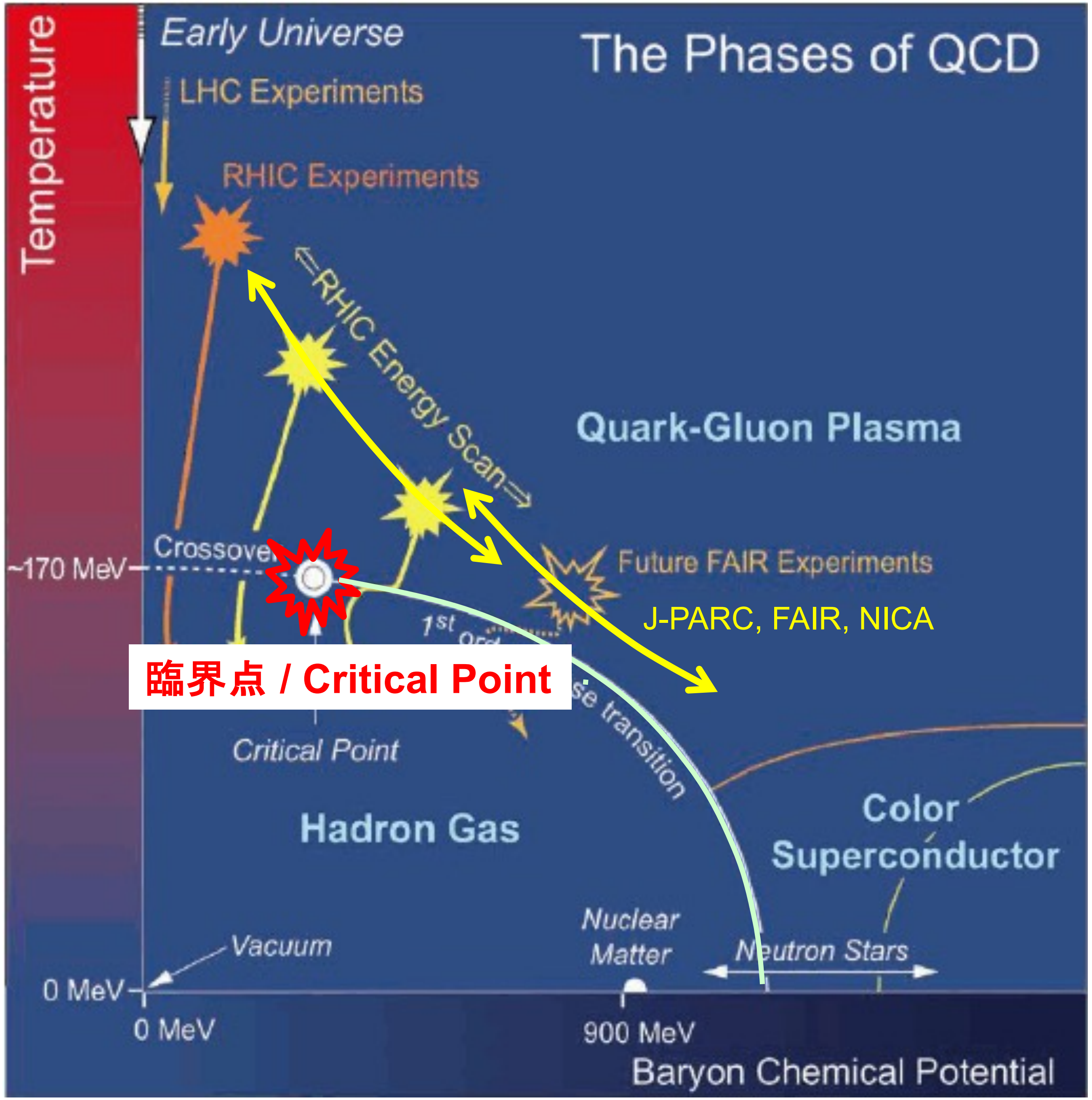
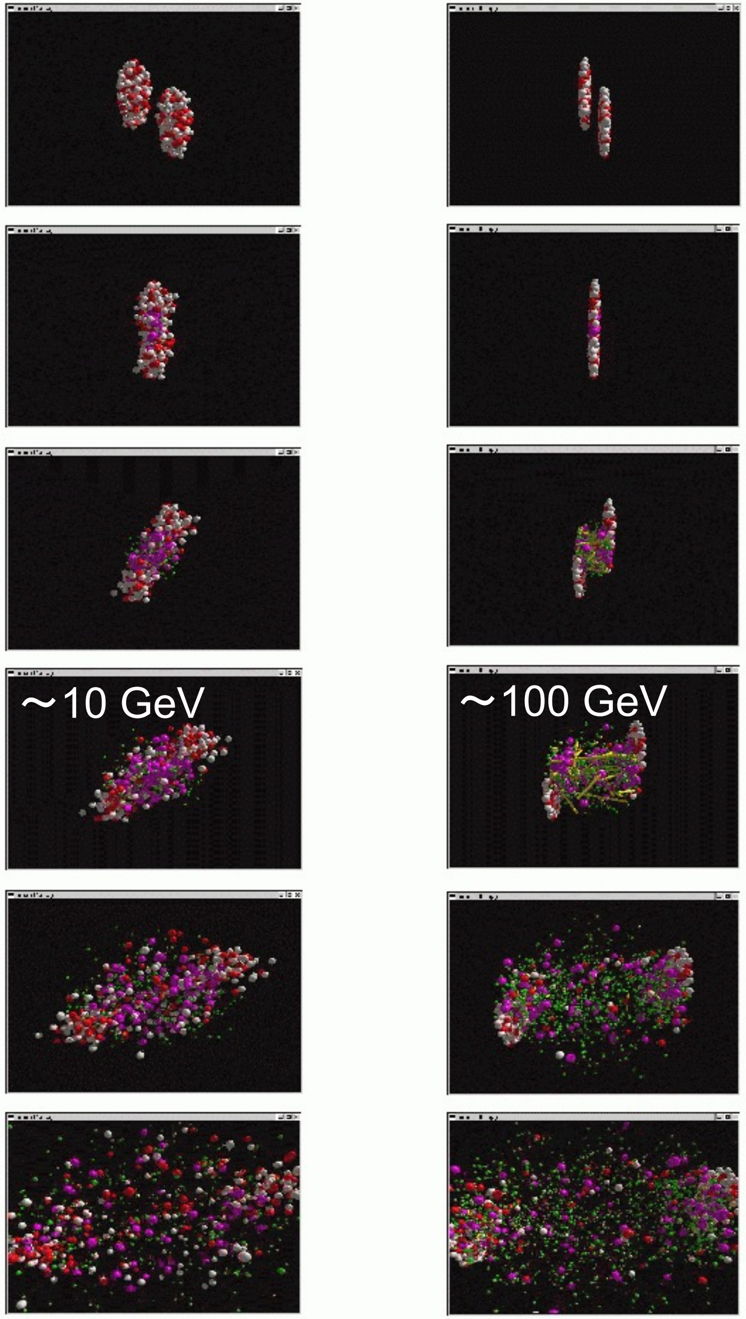
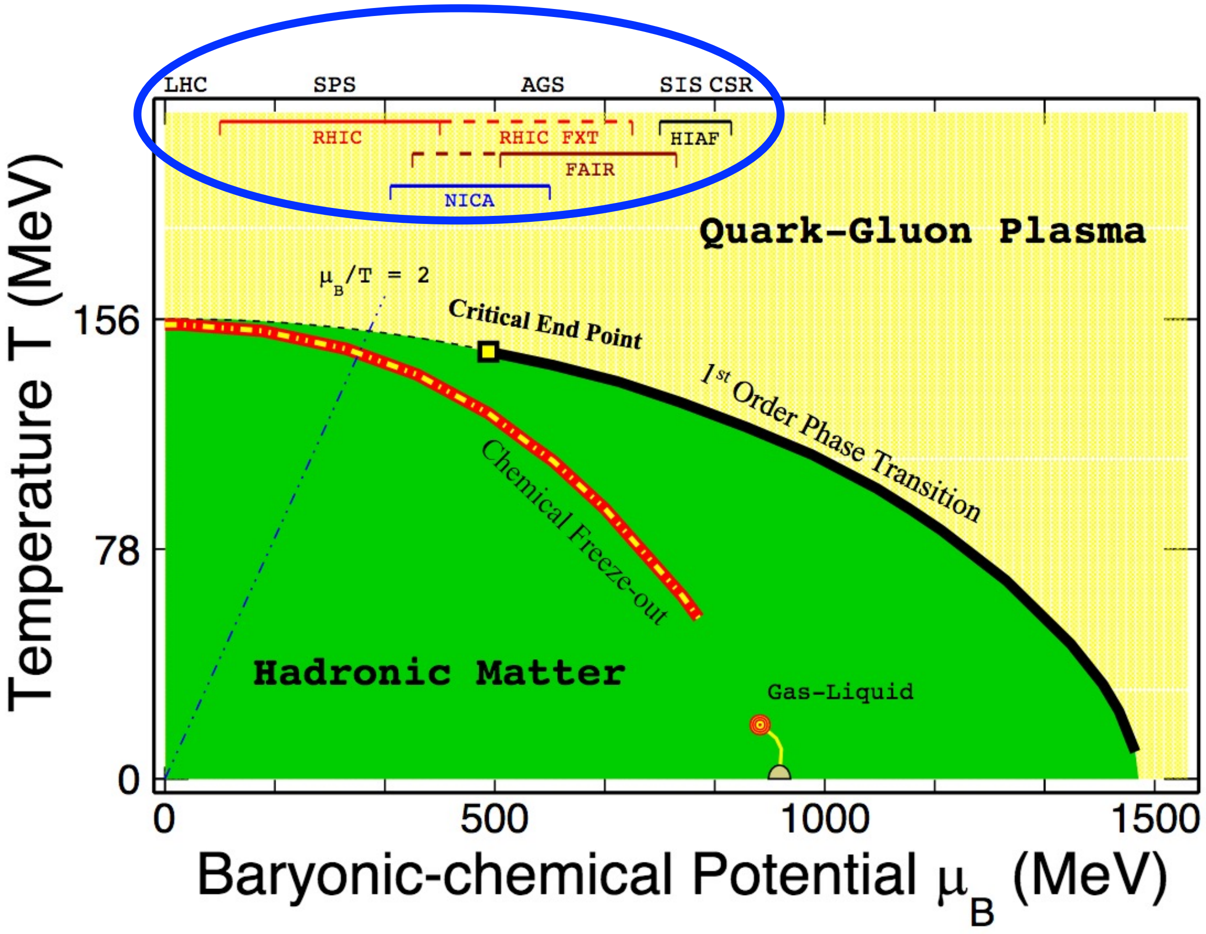
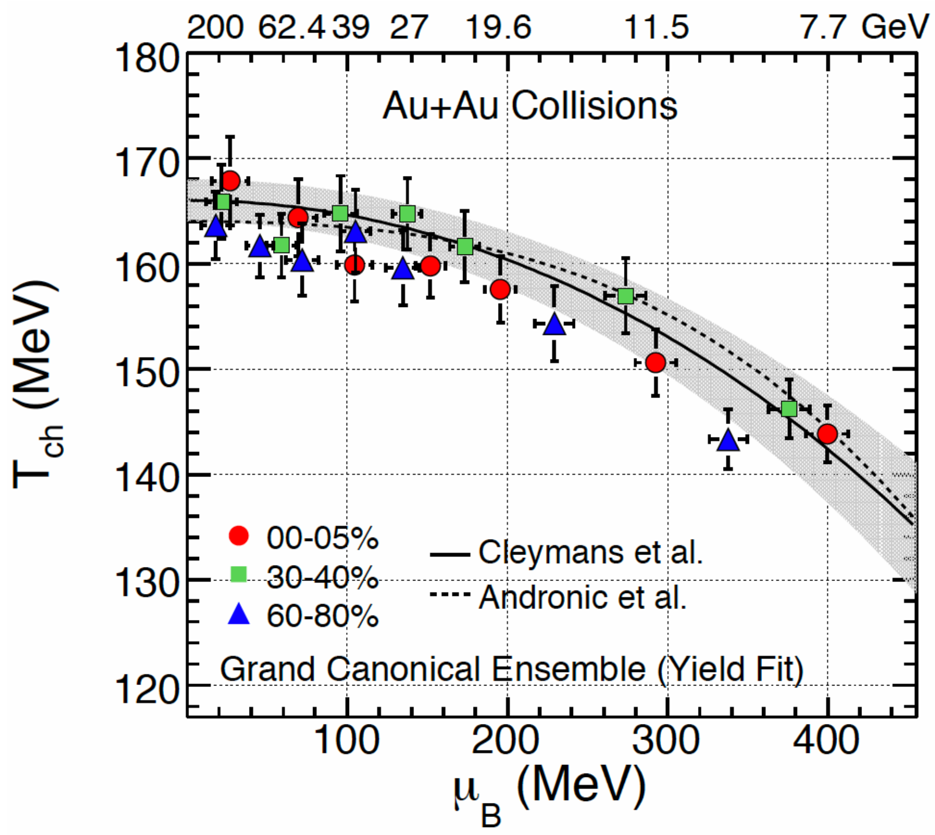

Early Universe
The Phases of QCD
LHC Experiments
RHIC Experiments
Temperature
RHIC Energy Scan
Quark-Gluon Plasma
Crossover
~170 MeV
Future FAIR Experiments
J-PARC, FAIR, NICA
臨界点 / Critical Point
Critical Point
Hadron Gas
Color
Superconductor
Nuclear
Matter
Neutron Stars
Vacuum
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential


～10 GeV
～100 GeV

QCD Phase diagram and Beam Energy Scan



PRC 96 (2017) 4, 044904



Thermal (Chemical Freeze-out) model

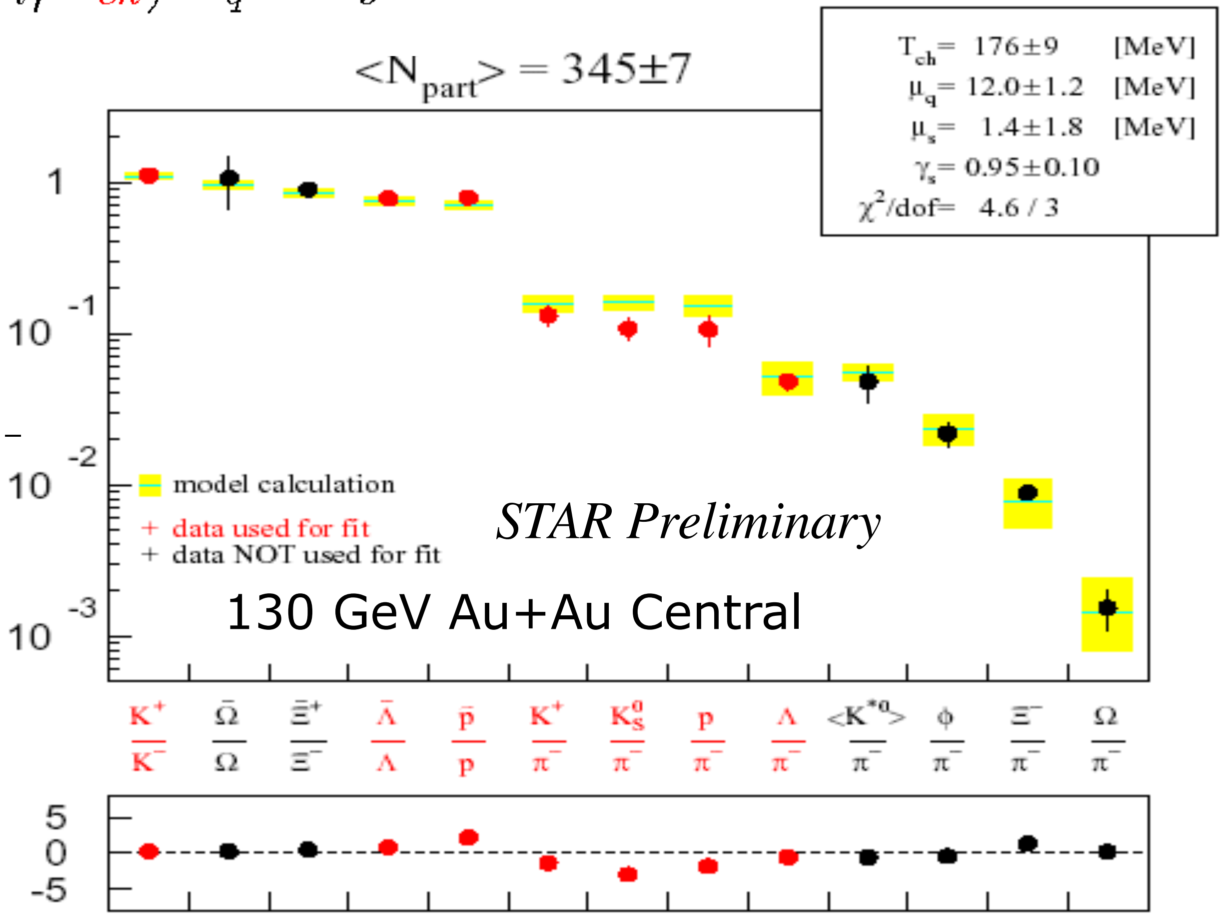
$$\rho_i = \gamma_s^{|s_i|} \frac{g_i}{2\pi^2} T_{ch}{}^3 \left(\frac{m_i}{T_{ch}}\right)^2 K_2(m_i/T_{ch})\ \lambda_q{}^{Q_i}\ \lambda_s{}^{s_i}$$

$$\lambda_q = \exp(\mu_q/T_{ch}), \quad \lambda_s = \exp(\mu_s/T_{ch})$$

M. Kaneta and N. Xu, J. Phys. G**27** (2001) 589

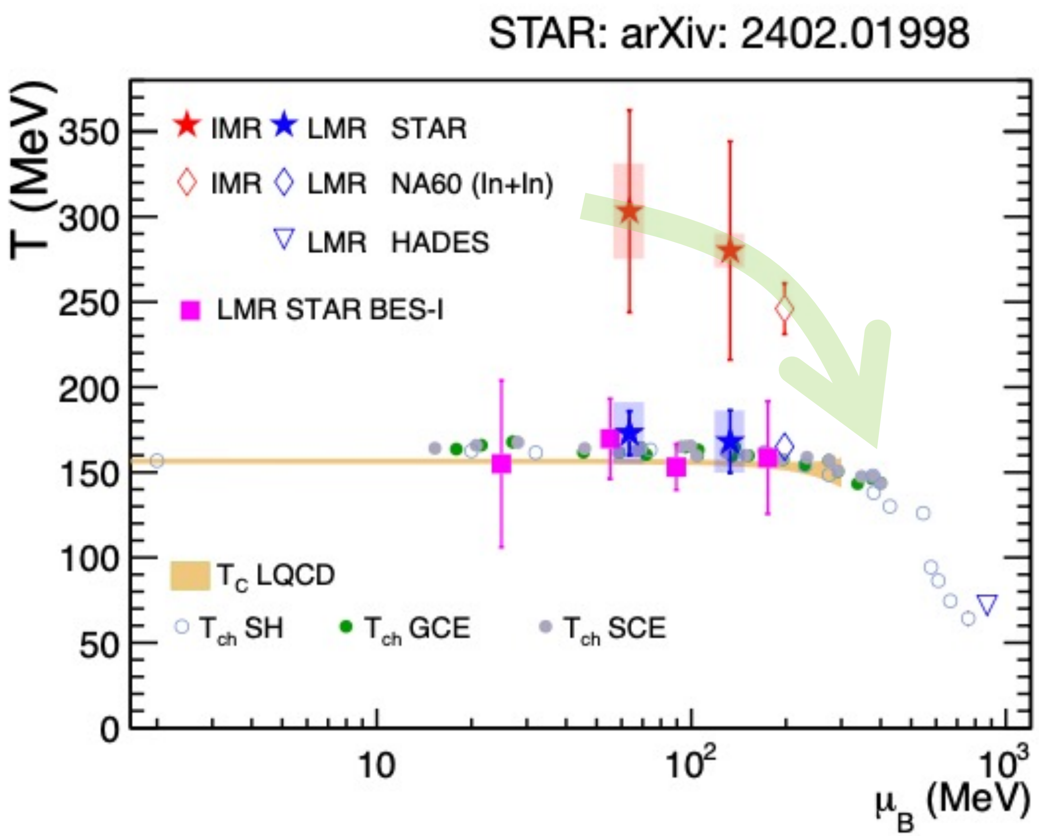
T_{ch} : Chemical freeze-out temperature
μ_q : light-quark chemical potential
μ_s : strangeness chemical potential
γ_s : strangeness saturation factor

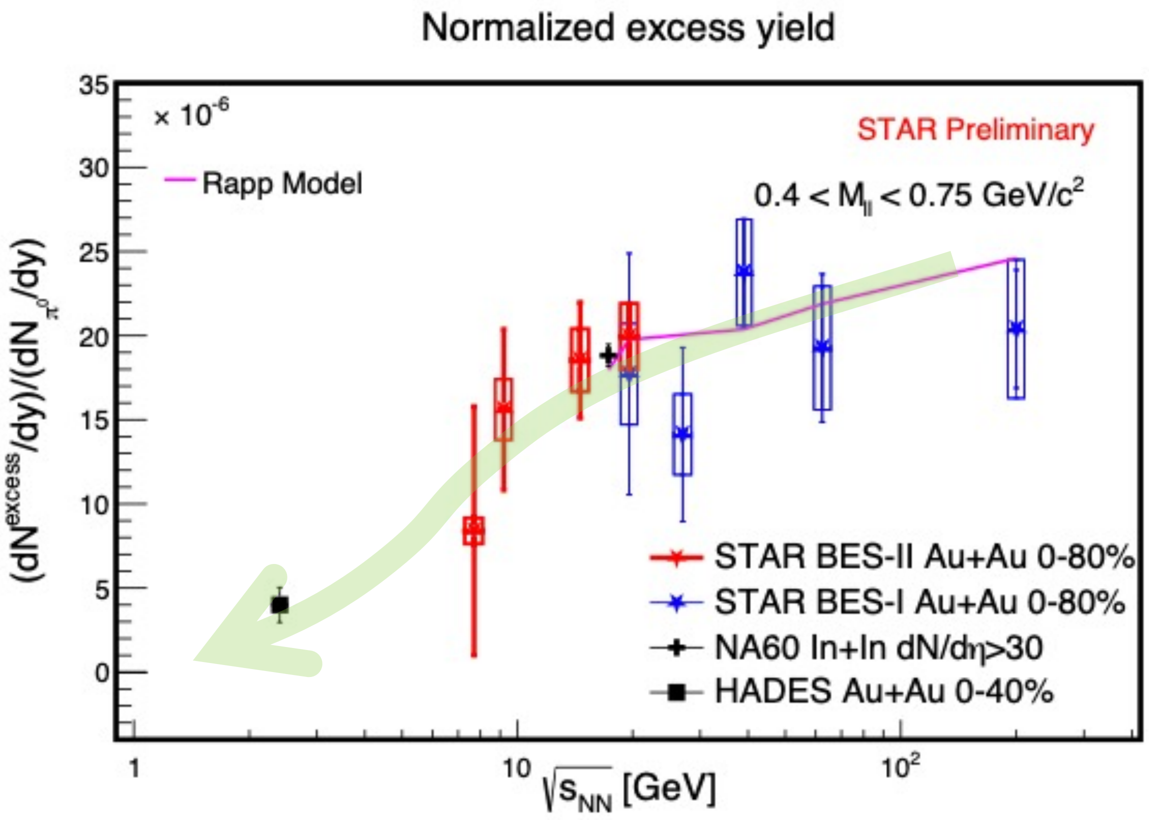
Q_i : 1 for u and d, -1 for $\bar{u}$ and $\bar{d}$
s_i : 1 for s, -1 for $\bar{s}$
g_i : spin-isospin freedom
m_i : particle mass
K_2 : the second-order modified Bessel function



Simple chemical freeze-out model remarkably well agrees with data.

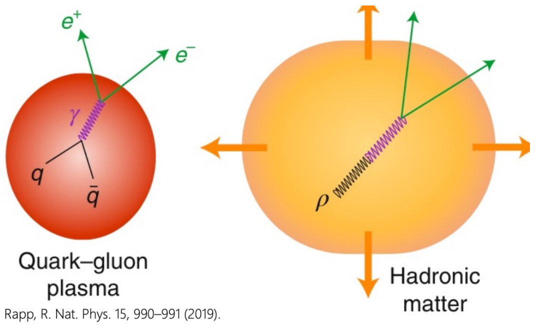
Thermal di-lepton measurements

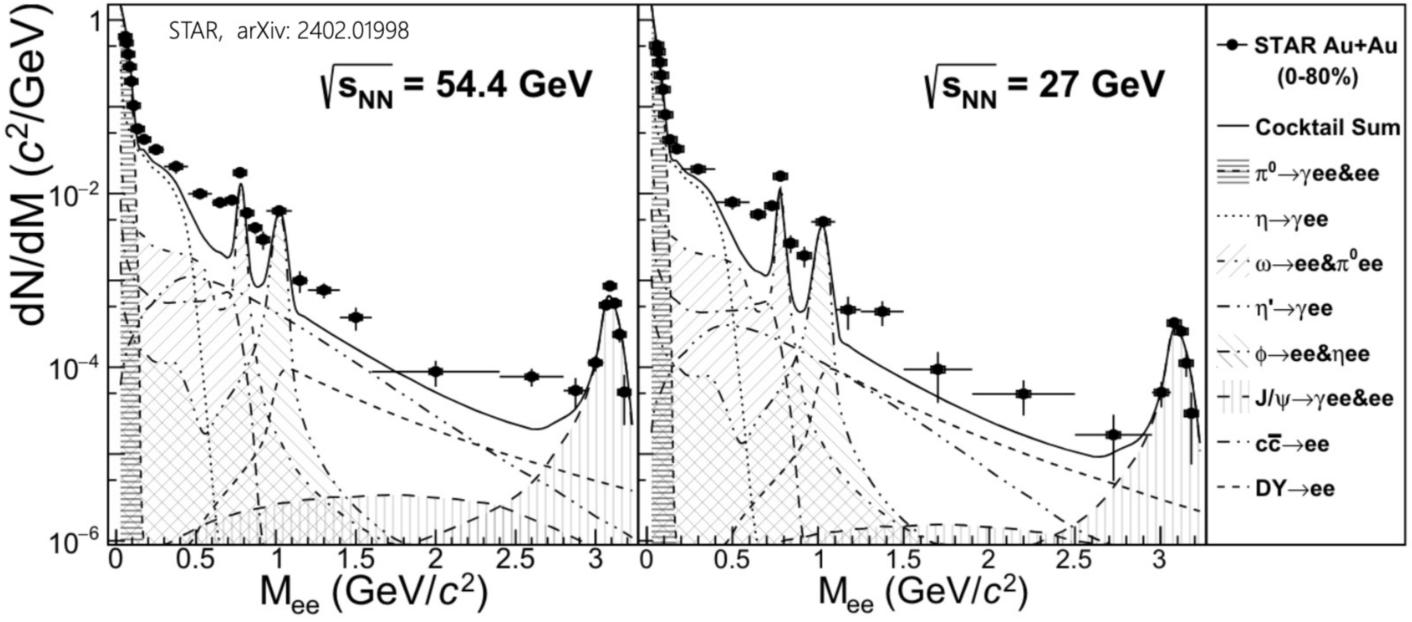


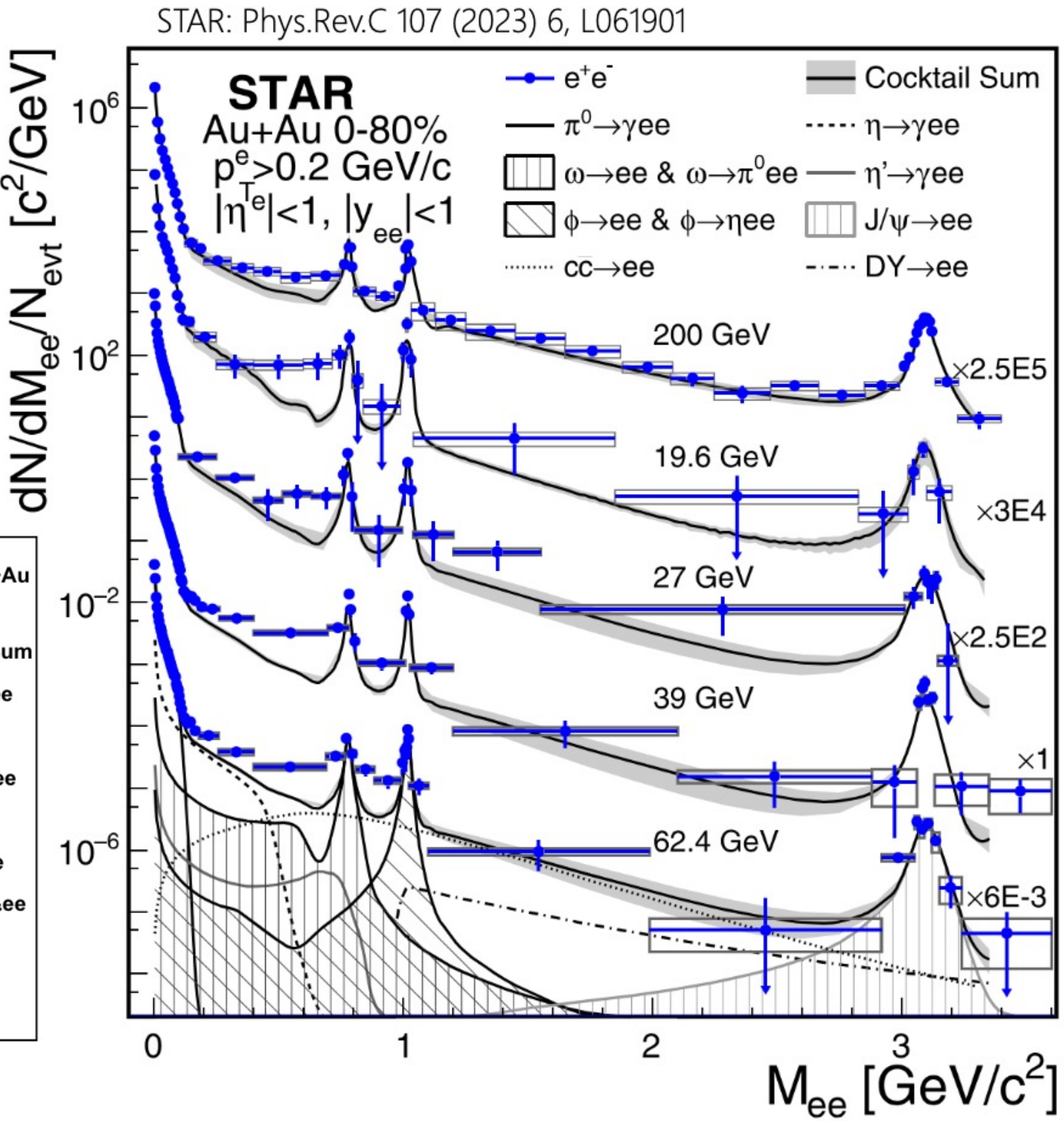


Di-electron mass spectra

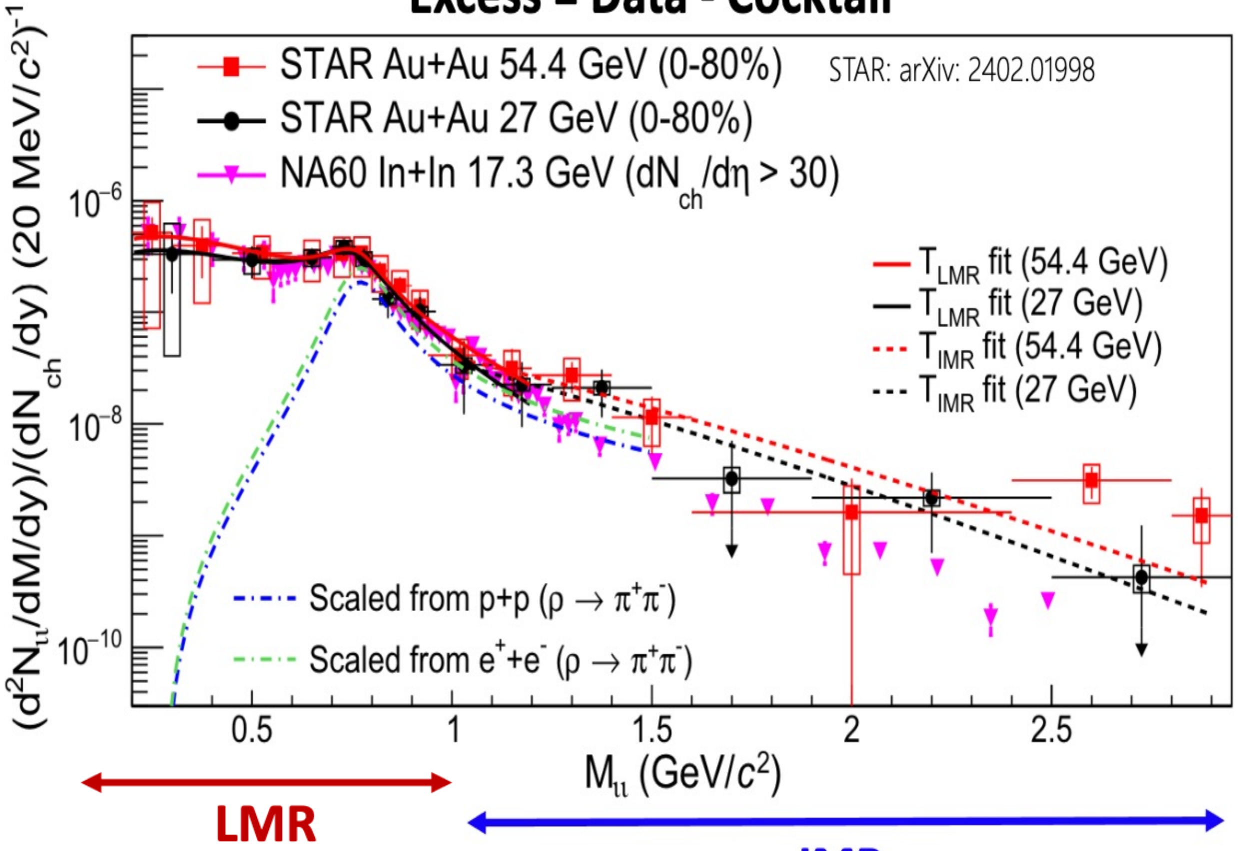
- π^0, η, (ρ), ω, η', ϕ mesons, J/ψ
- Thermal radiation
- ρ modification







Excess = Data - Cocktail



$T_{LMR}^{54.4\,GeV} = 172 \pm 12(stat.) \pm 18(sys.)$ MeV

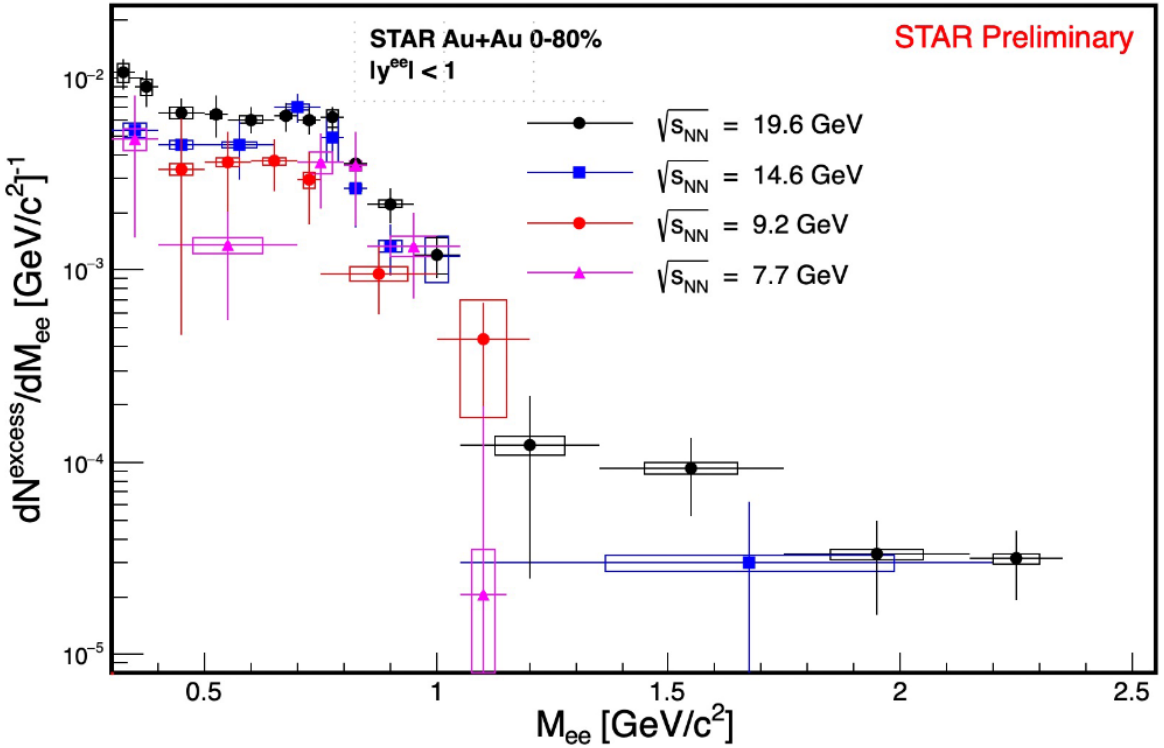
$T_{LMR}^{27\,GeV} = 167 \pm 21(stat.) \pm 18(sys.)$ MeV

$T_{IMR}^{54.4\,GeV} = 303 \pm 59(stat.) \pm 28(sys.)$ MeV

$T_{IMR}^{27\,GeV} = 280 \pm 64(stat.) \pm 10(sys.)$ MeV

Excess = Data - Cocktail

Thermal dielectron spectra with STAR BES-II



Low mass region：

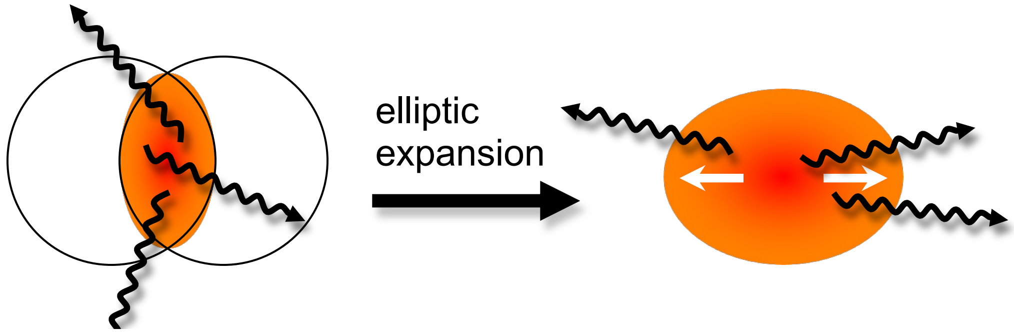
$(a*BW + b*M^{3/2}) * e^{-M/T}$

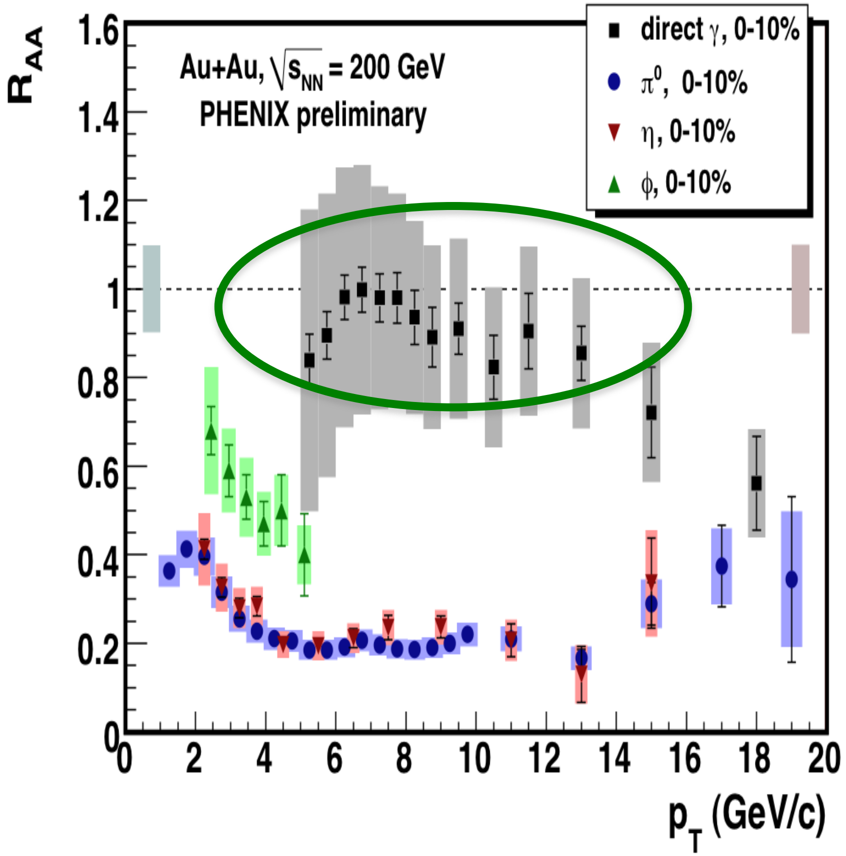
Intermediate mass region：

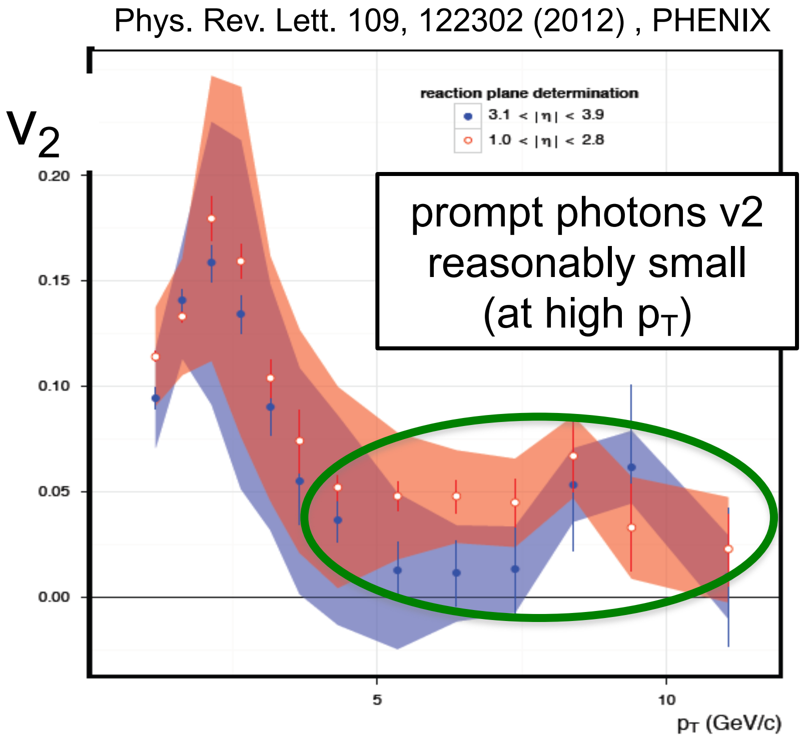
$M^{3/2} * e^{-M/T}$

High p_T prompt photon

- R_{AA} ~ 1 and v_2 ~ 0
- consistent with small interaction
- as a penetrating probe of QGP

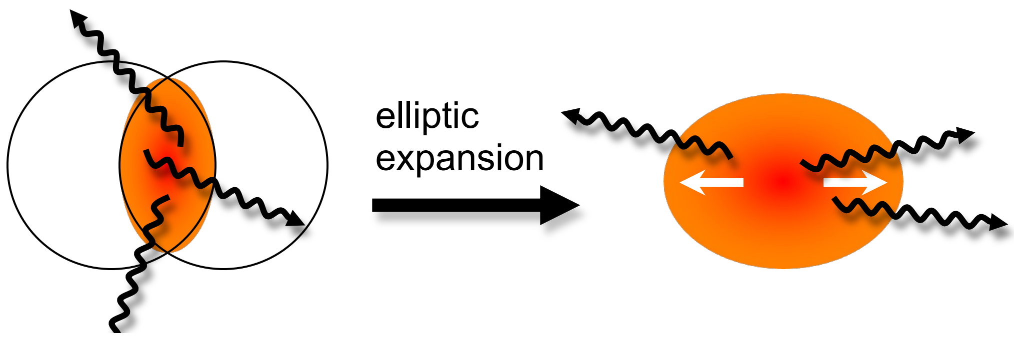




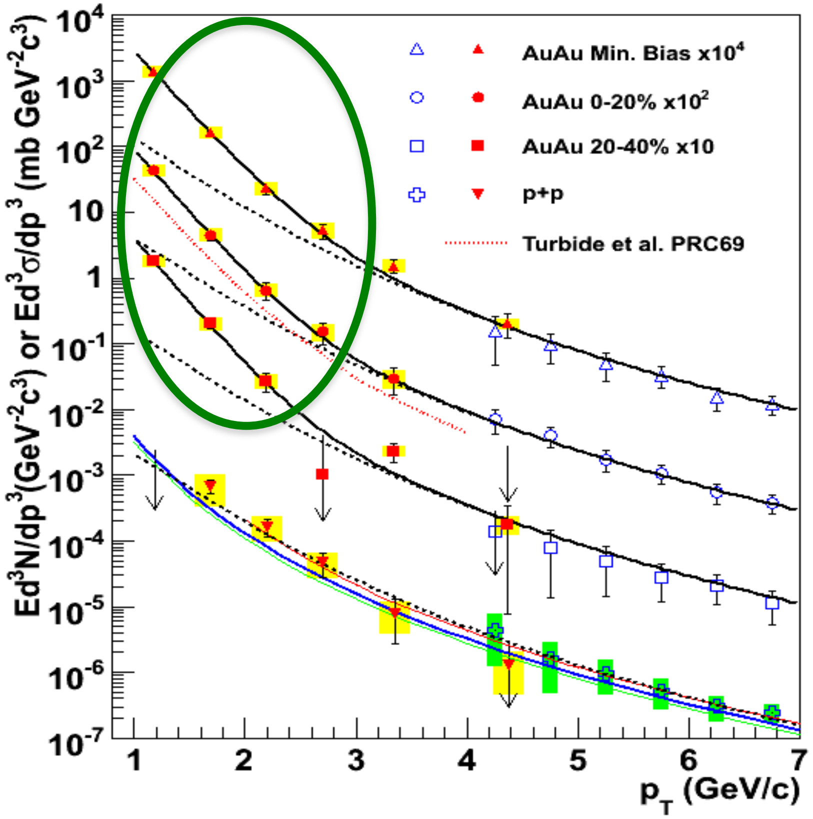


Thermal photon radiation and collective flow

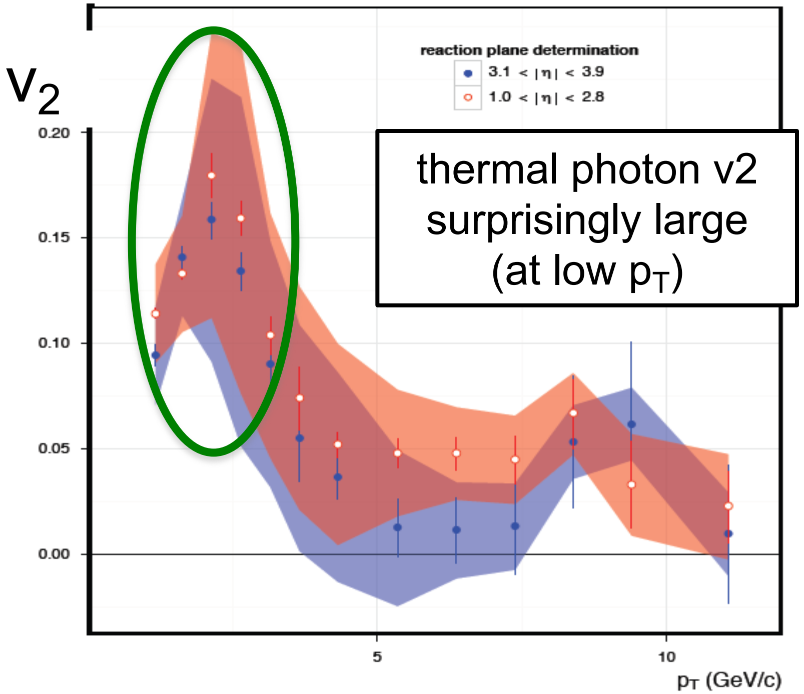
- significant low p_T photon excess
- Initial temperature 300-600MeV
- comparable v_2 with hadrons



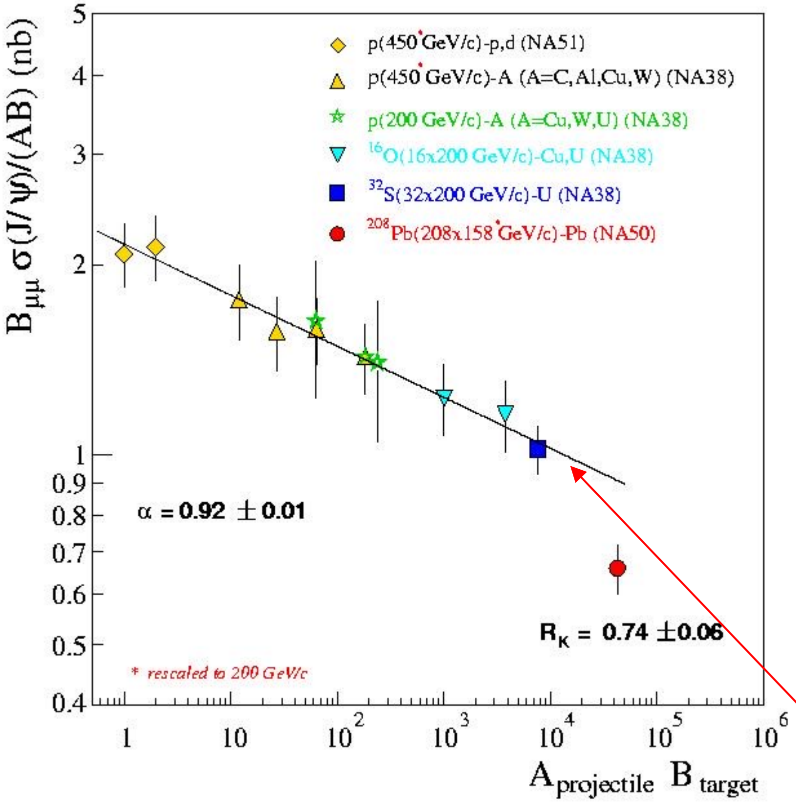
Phys. Rev. Lett. 104, 132301 (2010) , PHENIX

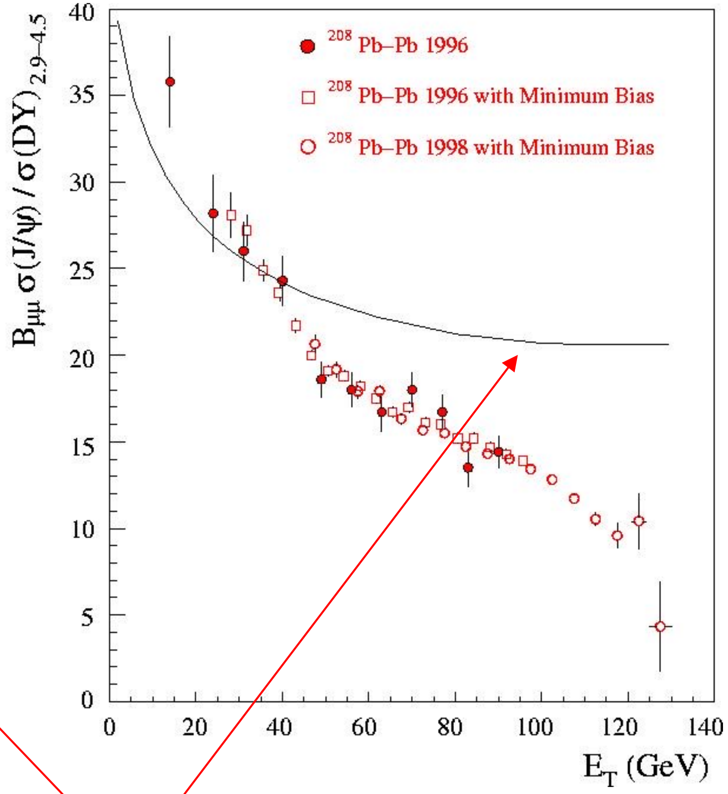


Phys. Rev. Lett. 109, 122302 (2012) , PHENIX



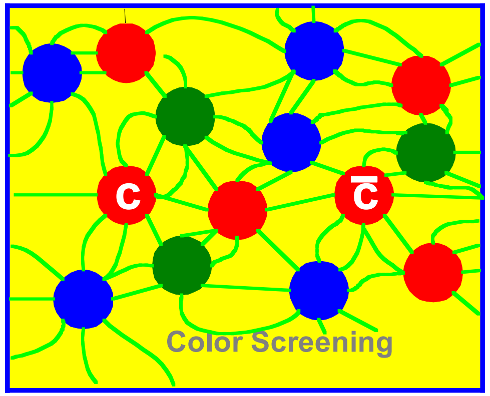
通常の核吸収から更にJ/ψの減少





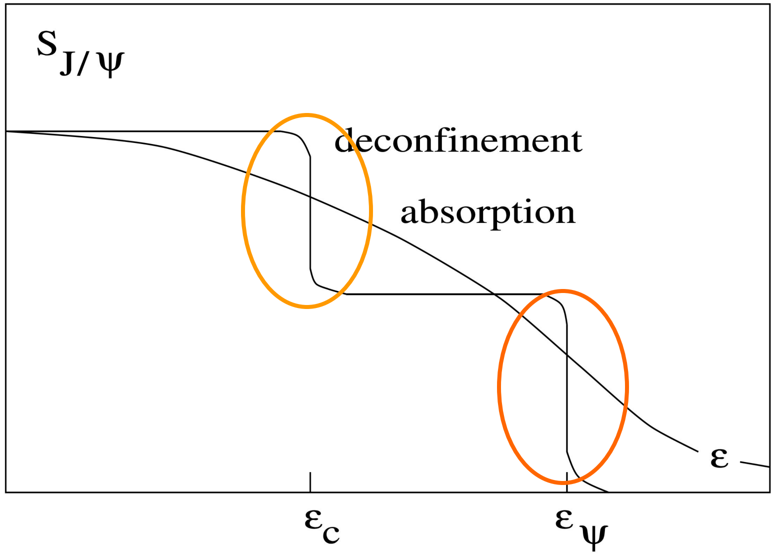
Normal nuclear absorption
6.4 +- 0.8 mb

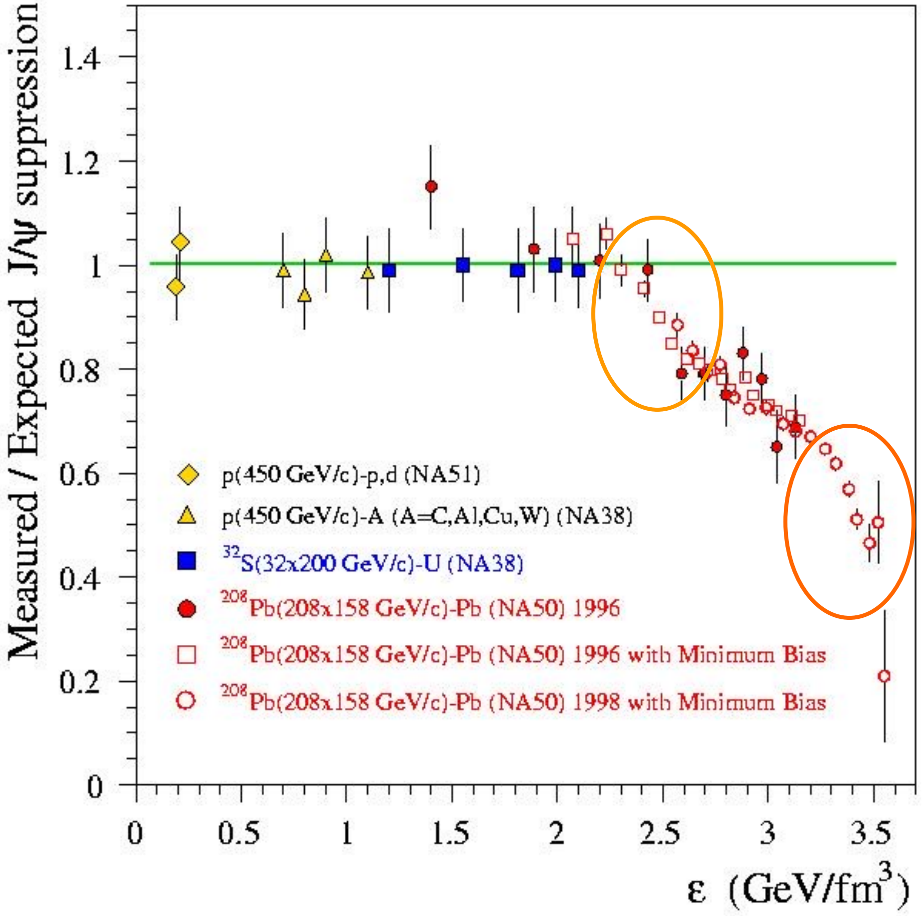
J/ψ ($c\bar{c}$) の
QGP中での消滅



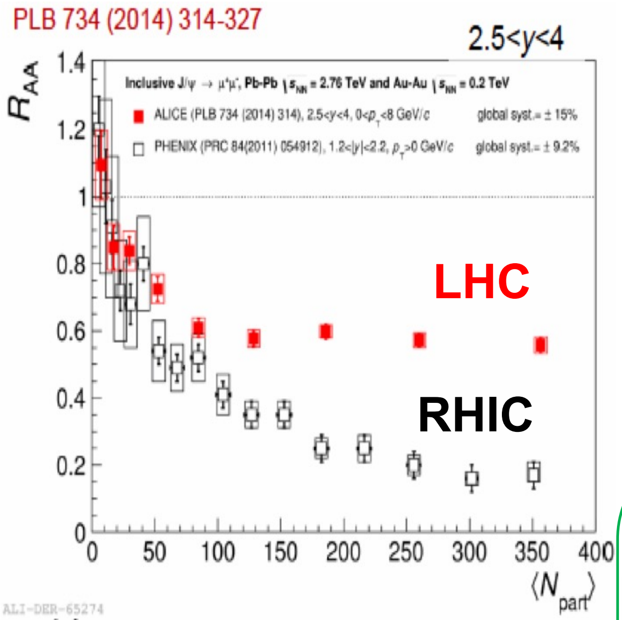
カラー遮蔽

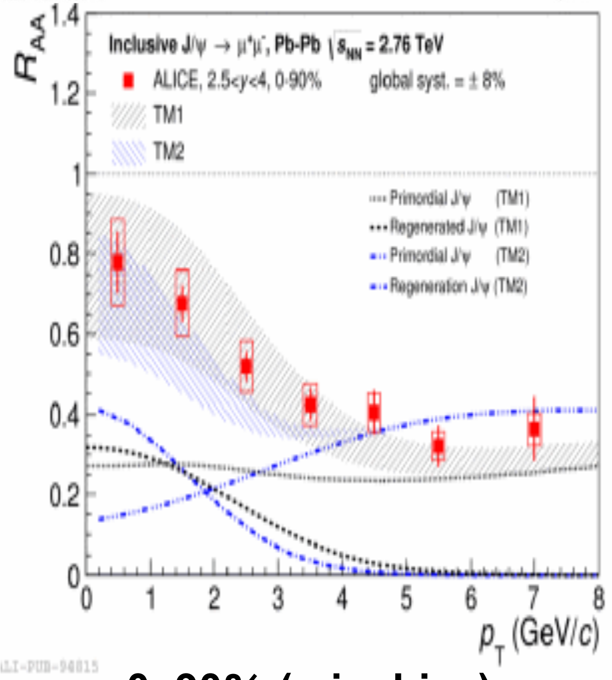
J/ψ suppression and threshold-like behavior





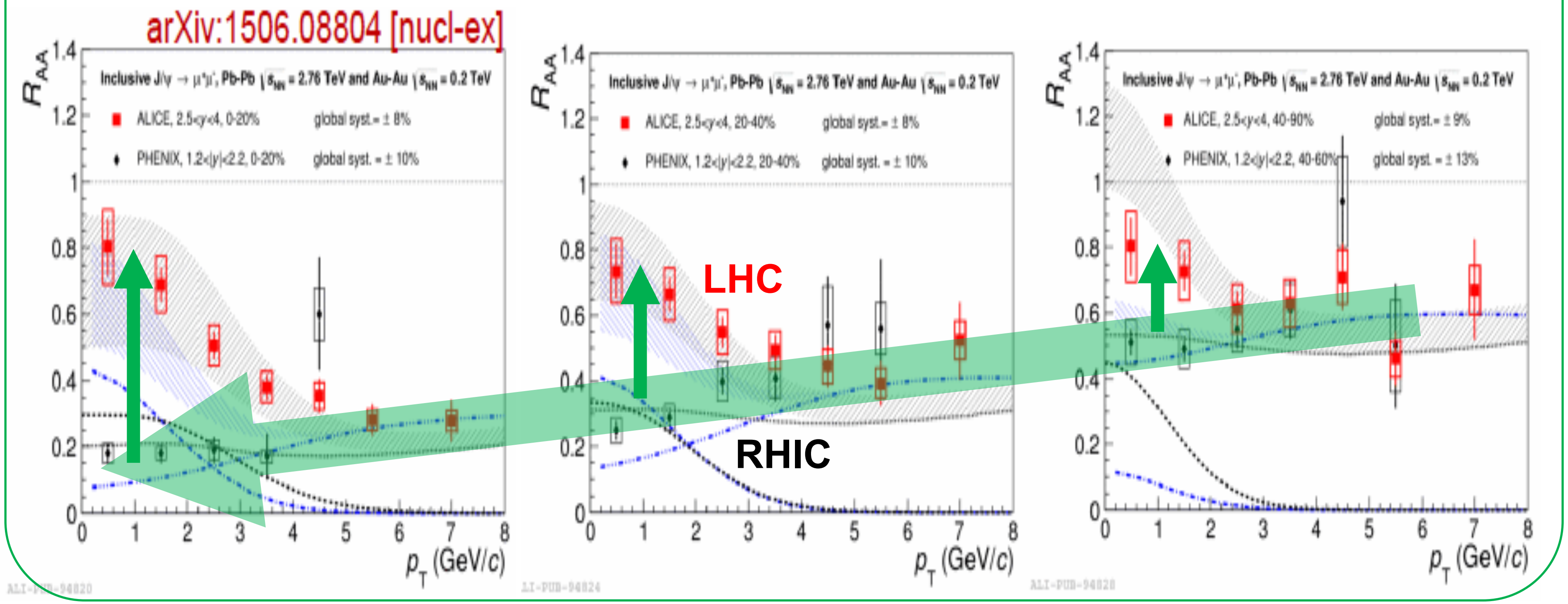
J/ψ suppression and re-generation





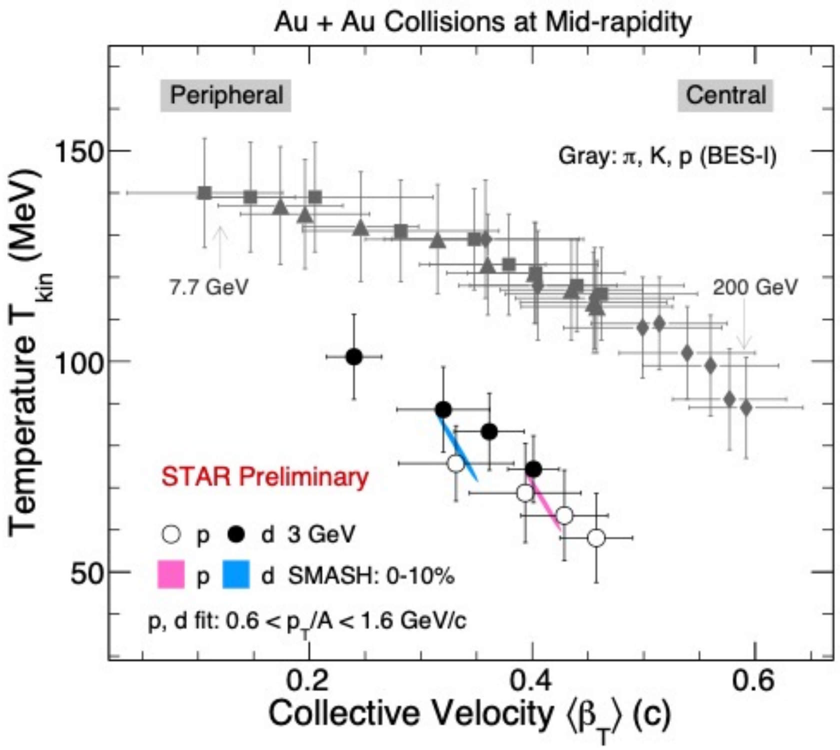
0−90% (min. bias)

0−20% (central) | 20−40% (semi-central) | 40−90% (peripheral)



Transition from Quark Matter back to Hadronic Matter

Thermal freeze-out

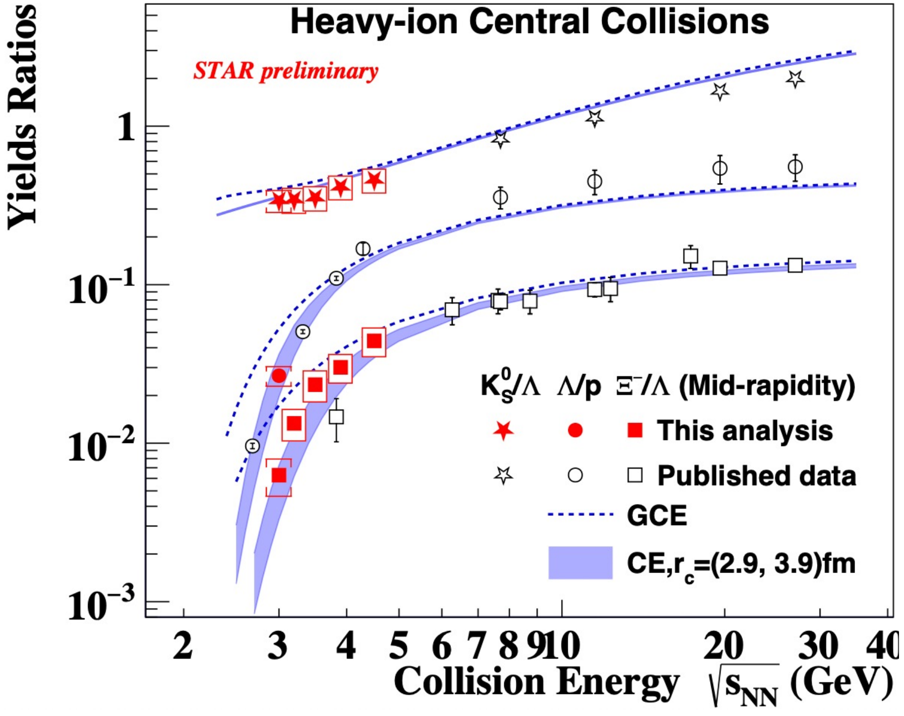


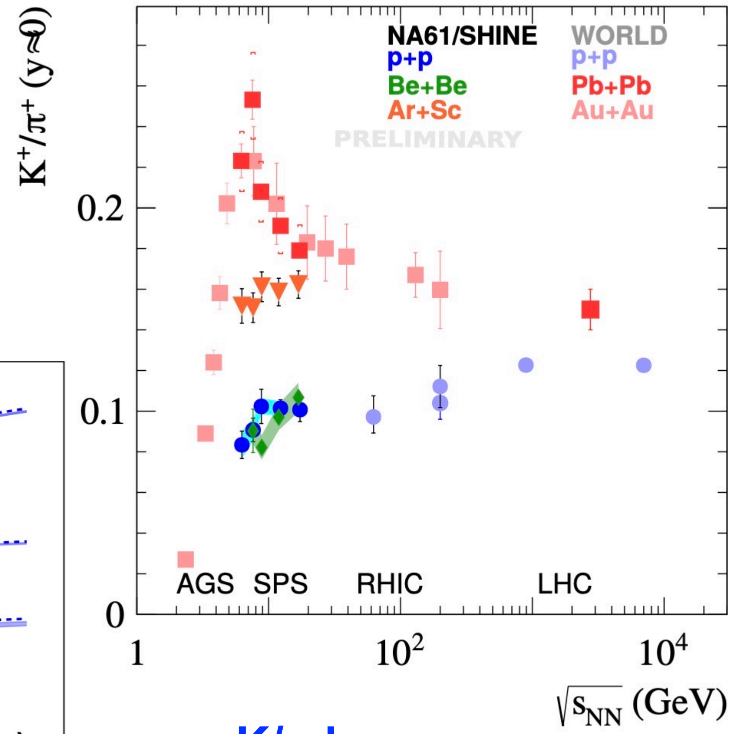
Blast Wave model (T_{kin}, β_T)

- radial flow

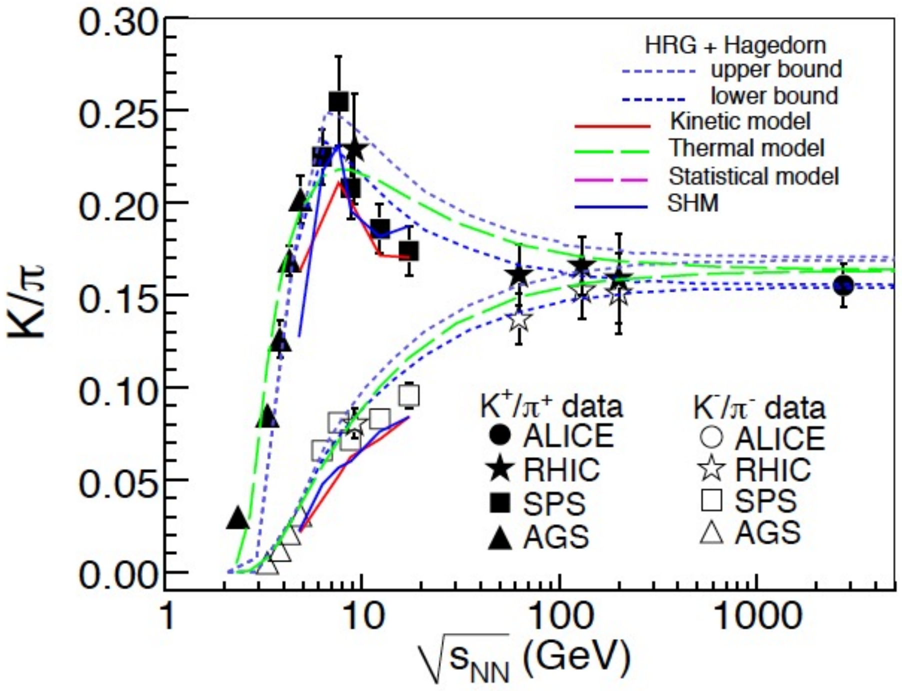
- hydro-base

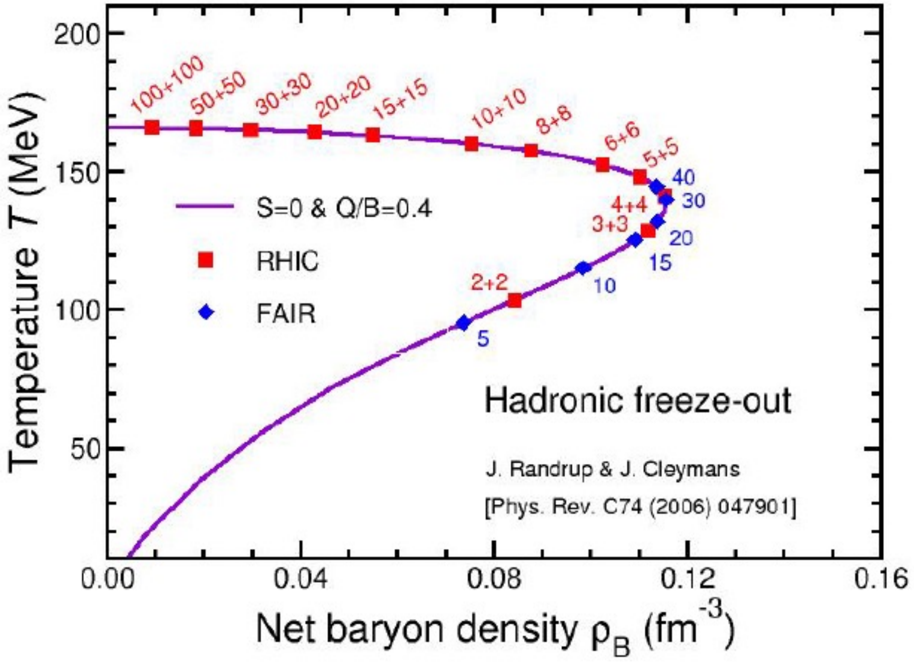
Strangeness





K/π horn



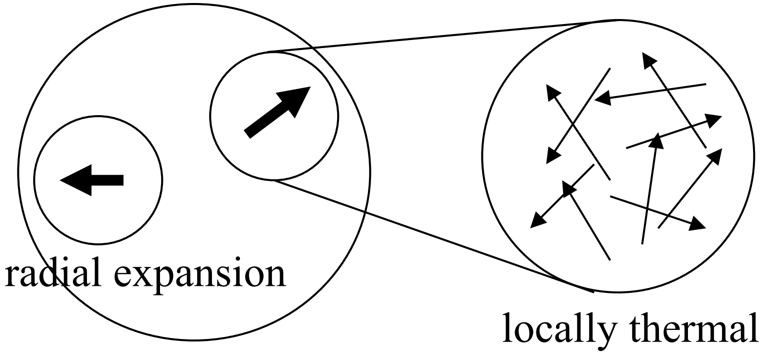


1) The **K^+/π** ratio peaks at $\sqrt{s_{NN}}$ ~ 8 GeV,
   K^-/π ratio merges with **K^+/π** at higher collision energy
2) Model: **Baryon density peaks at $\sqrt{s_{NN}}$ ~ 8 GeV**
3) At **$\sqrt{s_{NN}}$ > 8 GeV,** pair production becomes important

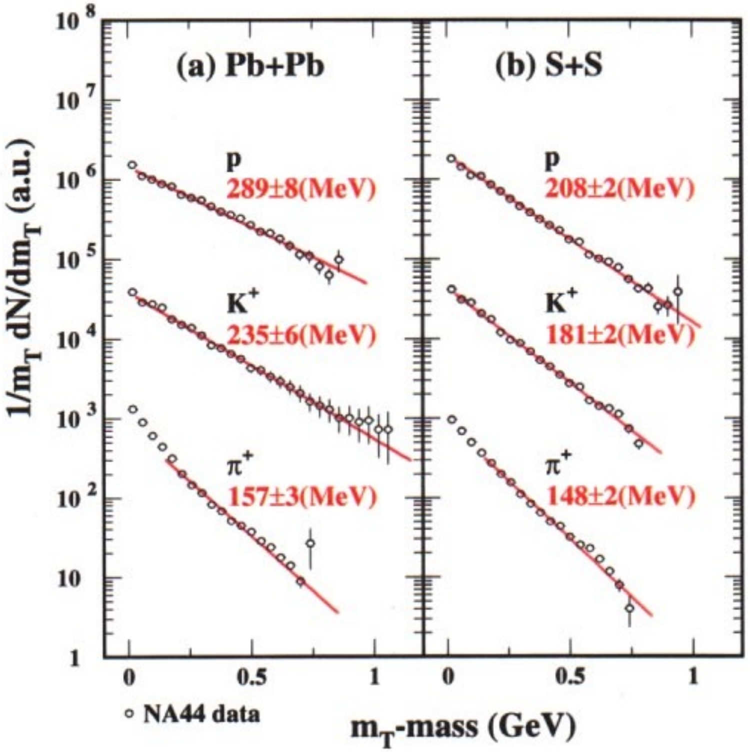
STAR: 1701.07065; J. Randrup and J. Cleymans, Phys. Rev. **C74**, 047901(2006)

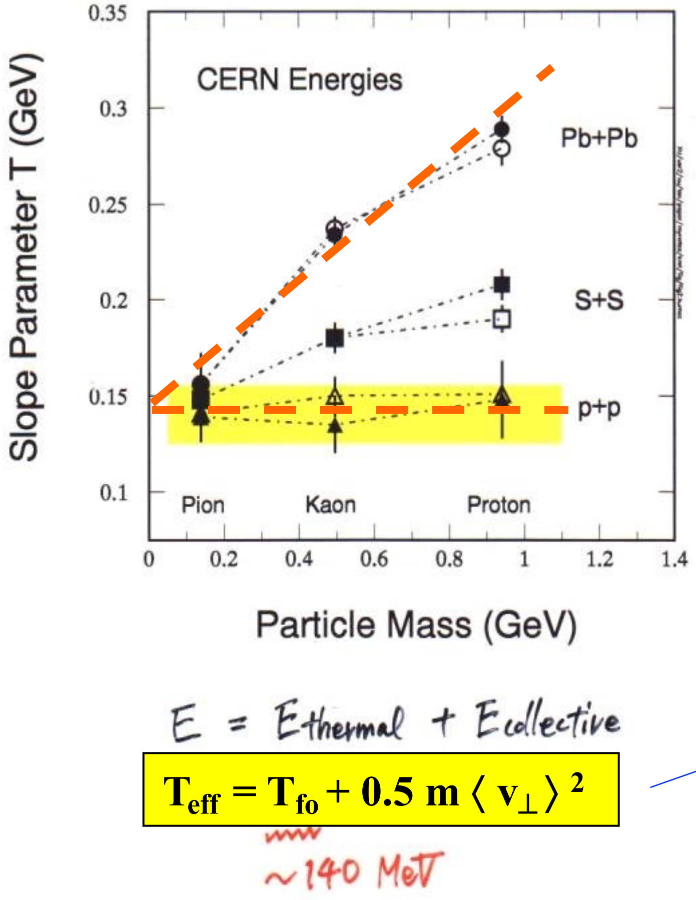
Thermal (Kinetic) Freeze-out with radial flow

- end of elastic interactions
- end of inelastic interactions (Chemical freeze-out)



π K p : p_T spectra





$T_{eff} = T_{fo} + 0.5\ m \langle v_{\perp} \rangle^2$

Blast Wave model (T_{kin} , β_T)

- radial flow
- hydro-base

↕

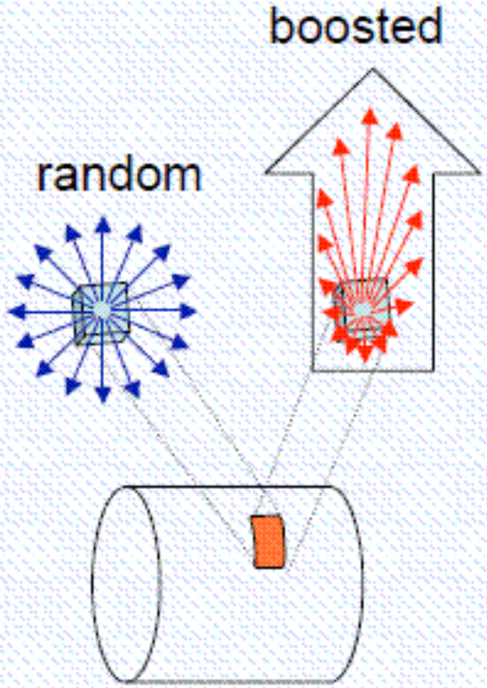
(T_{fo} , v_T)

E.Schnedermann, J.Sollfrank, and U.Heinz, Phys. Rev. ***C48****, 2462(1993)*

$$E\frac{d^3N}{dp^3} \propto \int_\sigma e^{-(u^\mu p_\mu)/T_{fo}} p d\sigma_\mu \Rightarrow$$

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right)$$

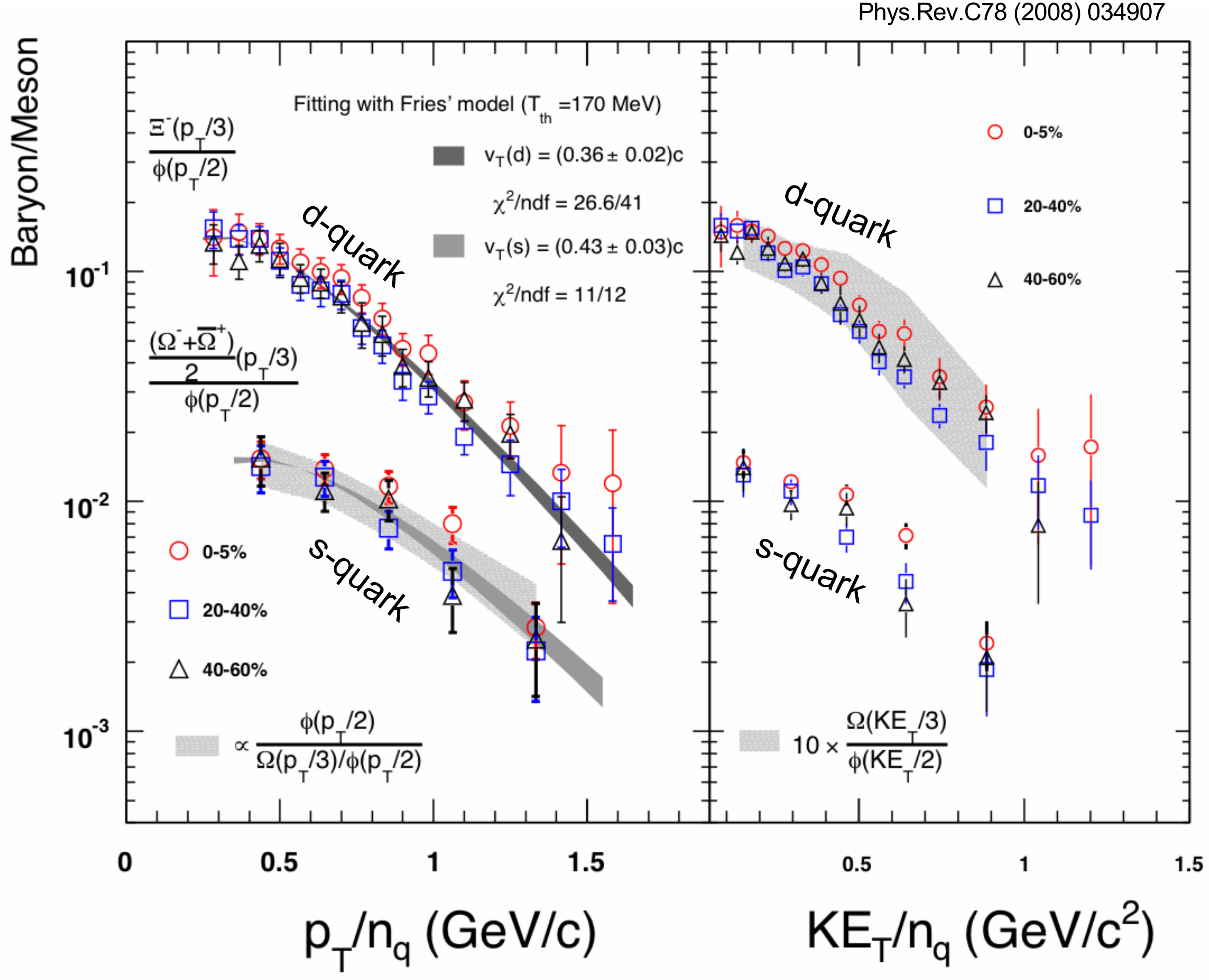
$$\rho = \tanh^{-1}\beta_T \qquad \beta_T = \beta_S\left(\frac{r}{R}\right)^\alpha \qquad \alpha = 0.5,\ 1,\ 2$$

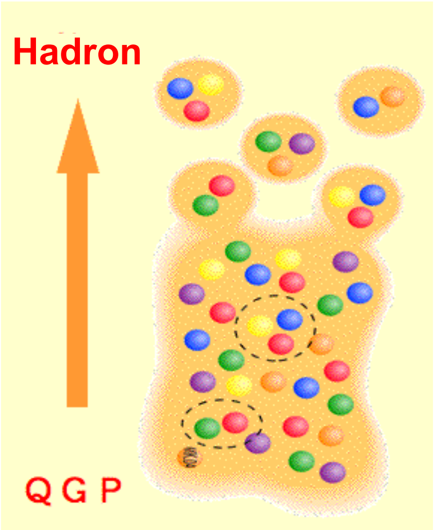


Extract thermal temperature T_{fo} and velocity parameter $\langle\beta_T\rangle$

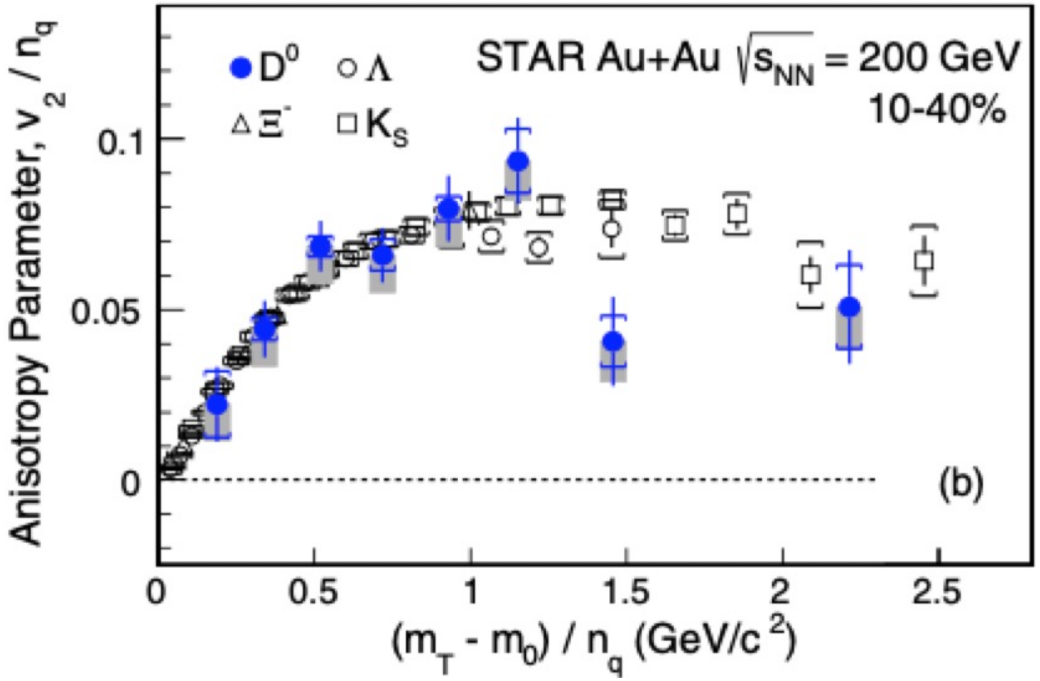
Radial flow of quark (quark coalescence)

Phys.Rev.C78 (2008) 034907



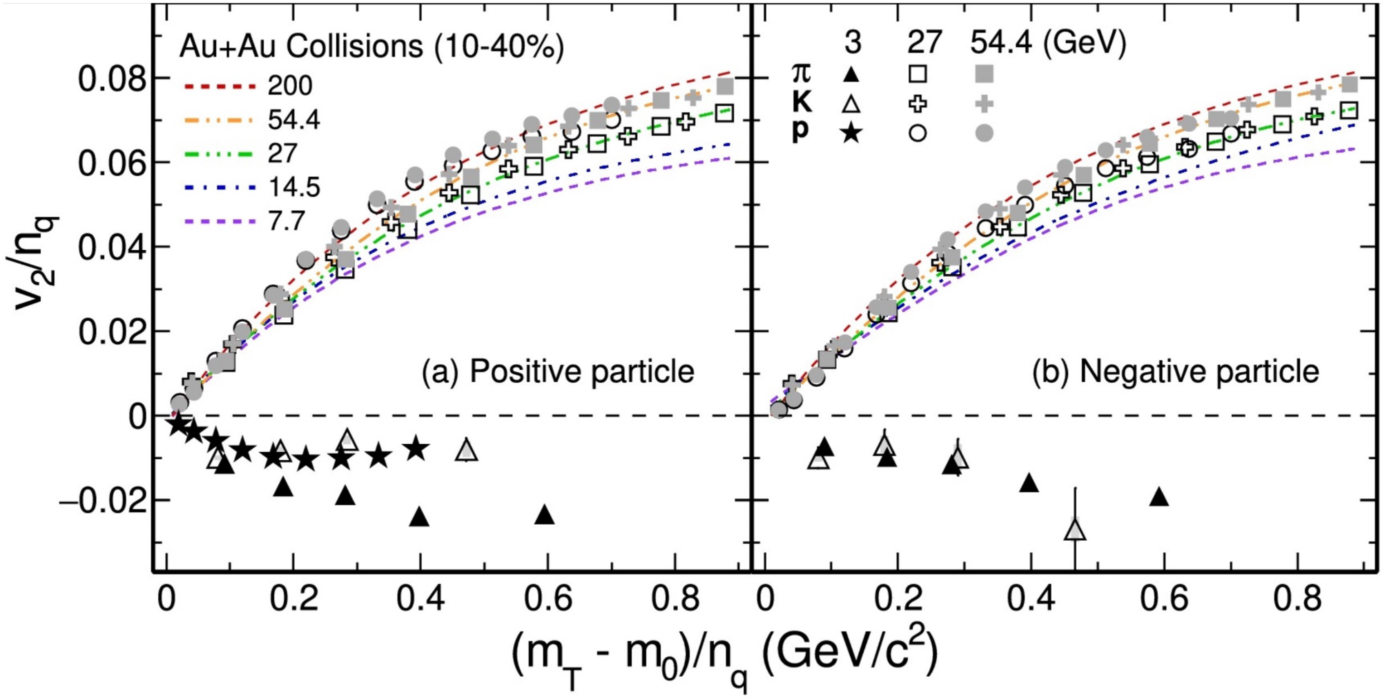


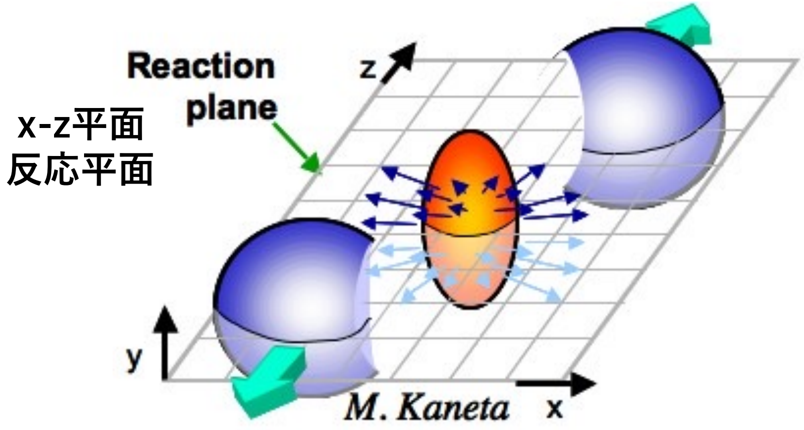
STAR, Phys. Rev. Lett. 118, 212301 (2017)



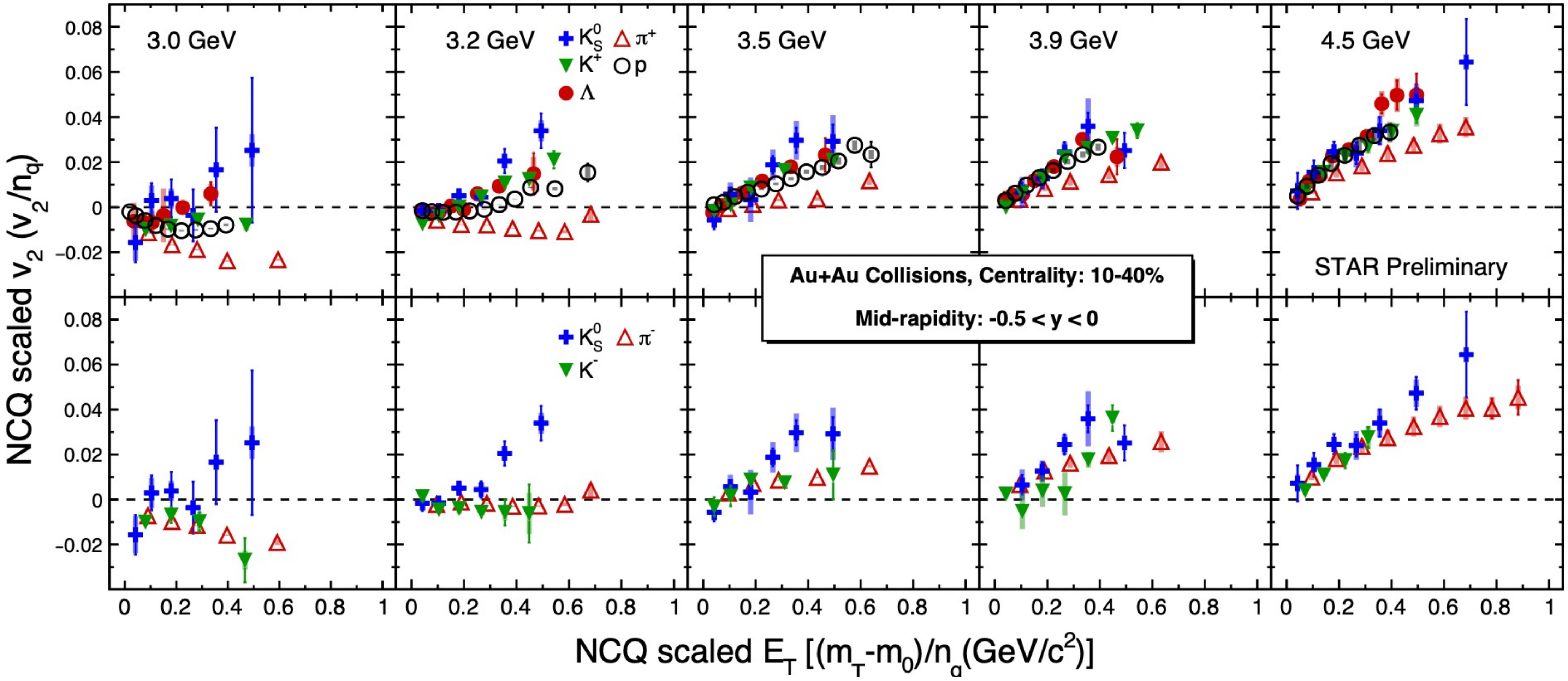
Departure from the Quark Number Scaling of v_2

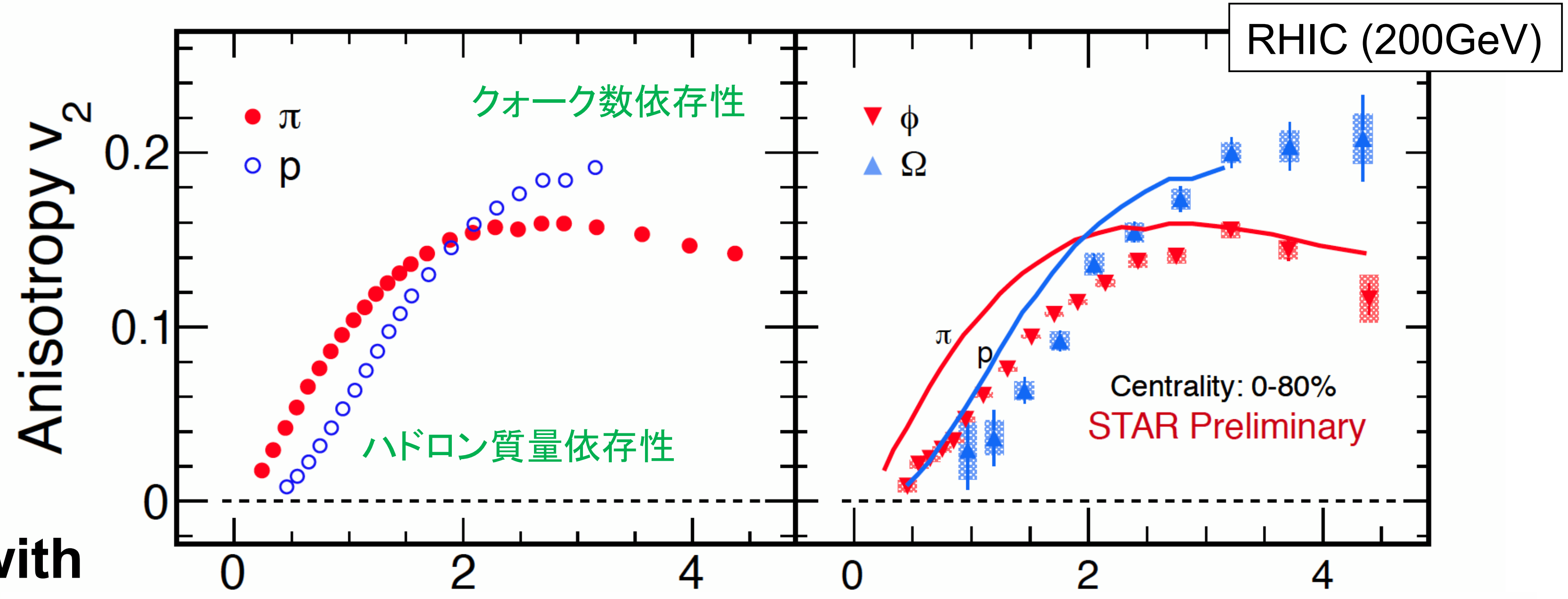
STAR, Phys. Lett. B 827, 137003 (2022)



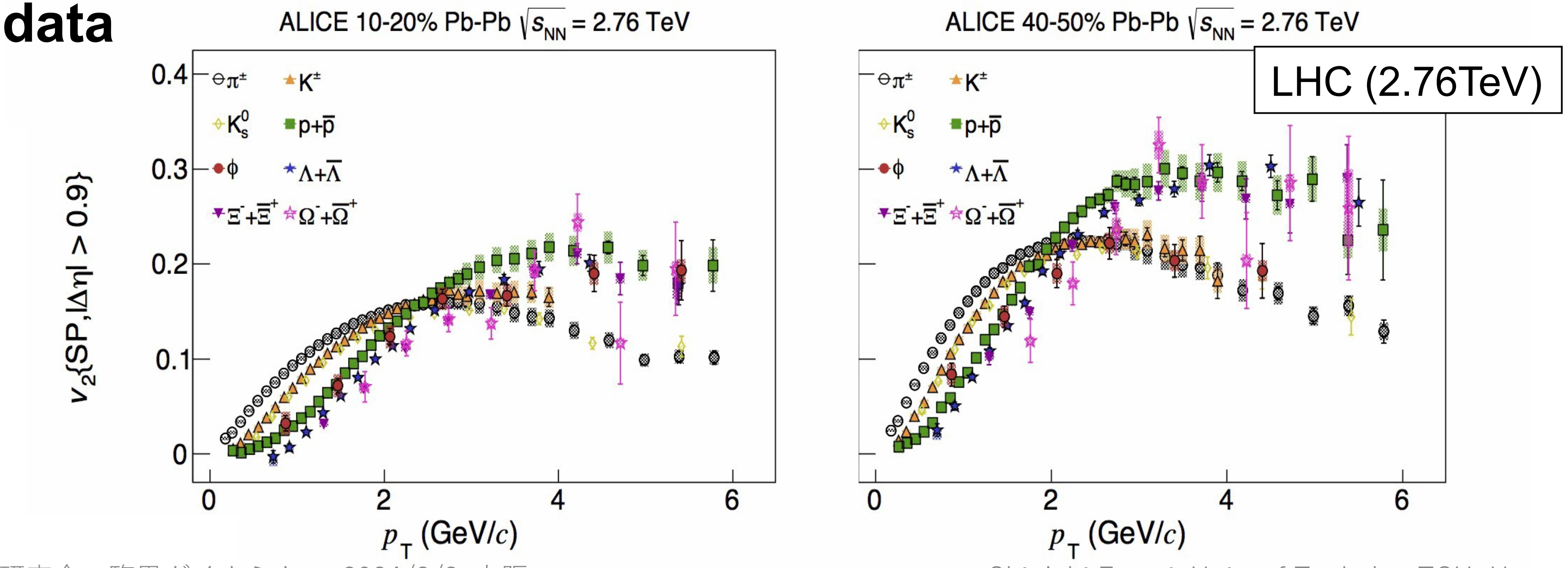


Quark Number Scaled v_2 at FXT beam energies (3.0 ~ 4.5 GeV)

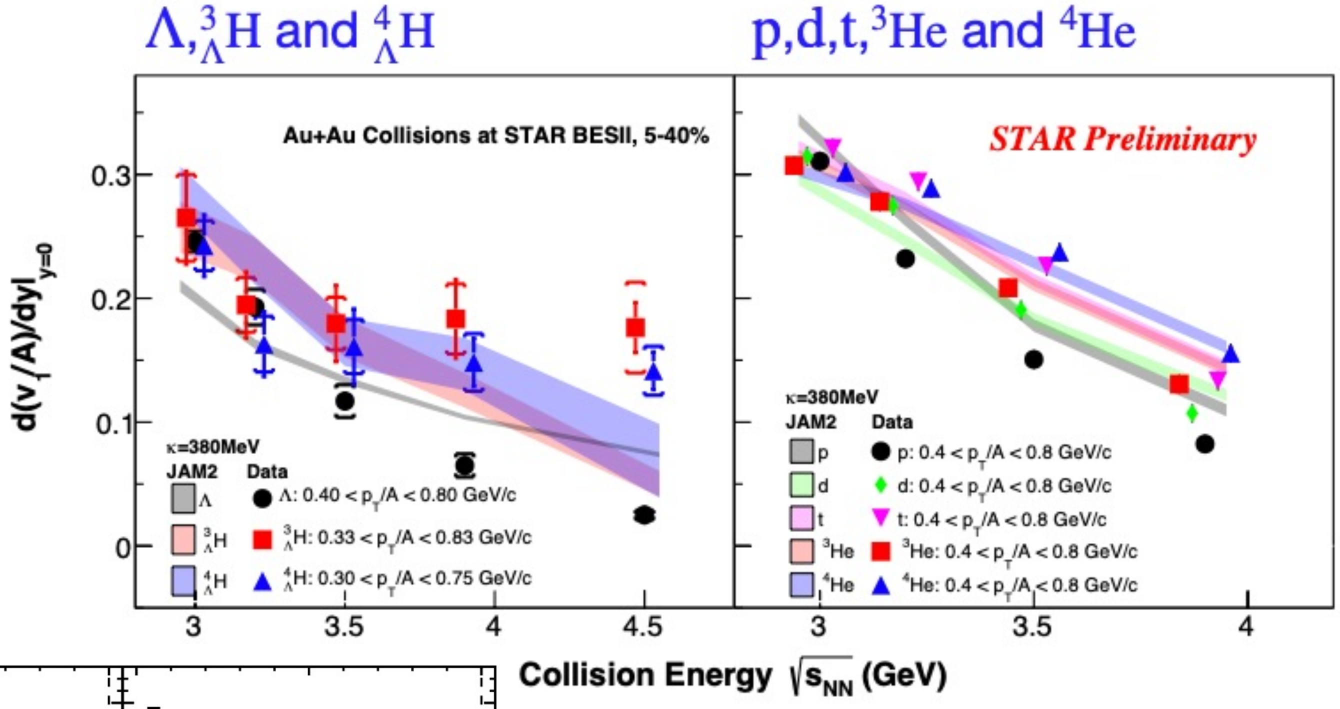


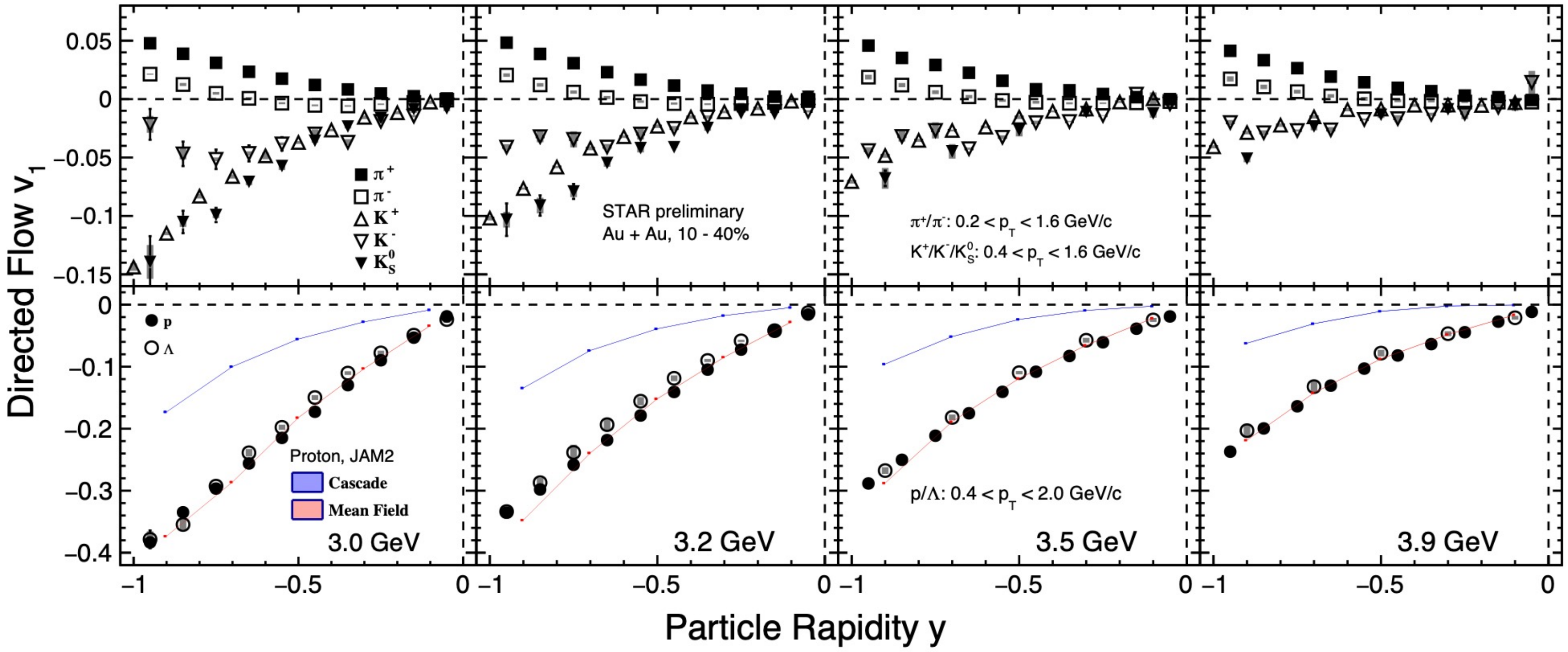


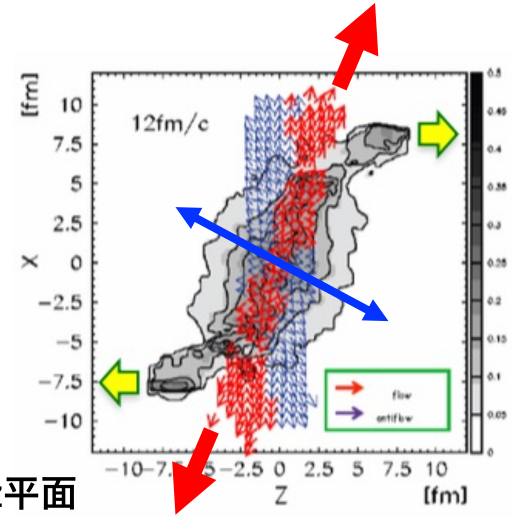
Test of NCQ scaling with high stat. RHIC/LHC data



v_1 vs rapidity and v_1 slope of hyper-Nuclei at FXT beam energies





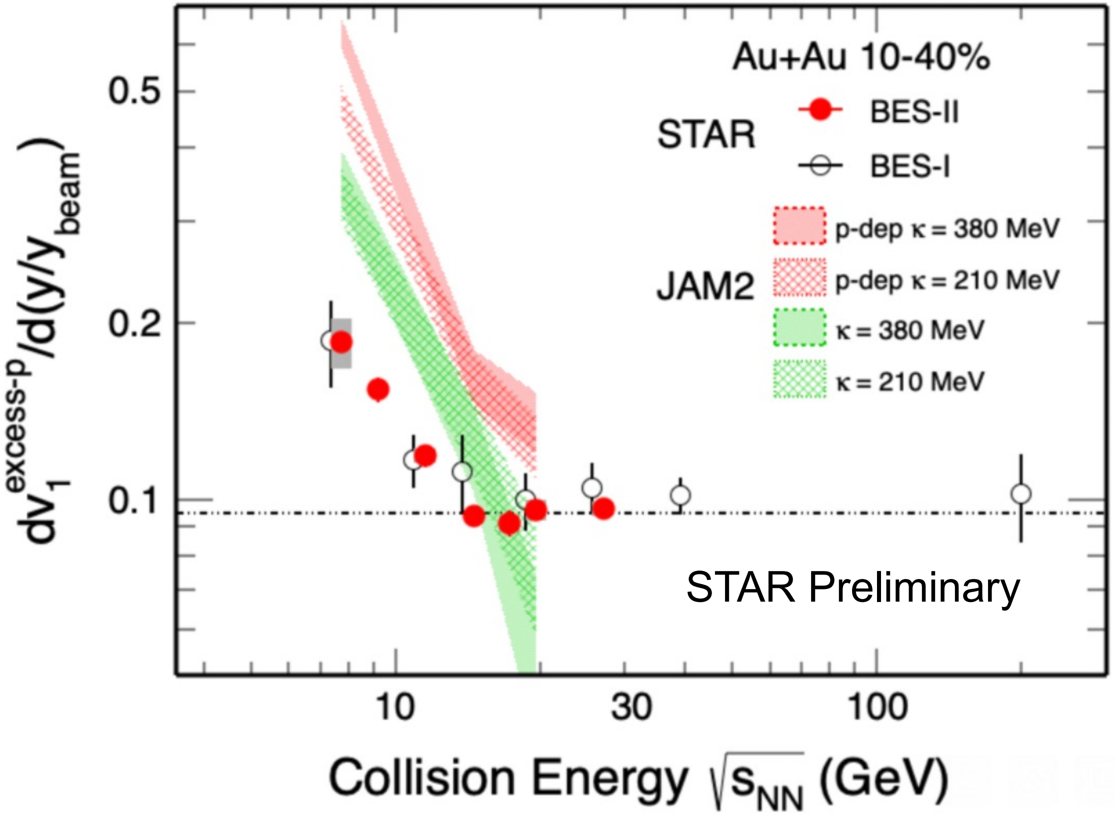


x-z平面
反応平面

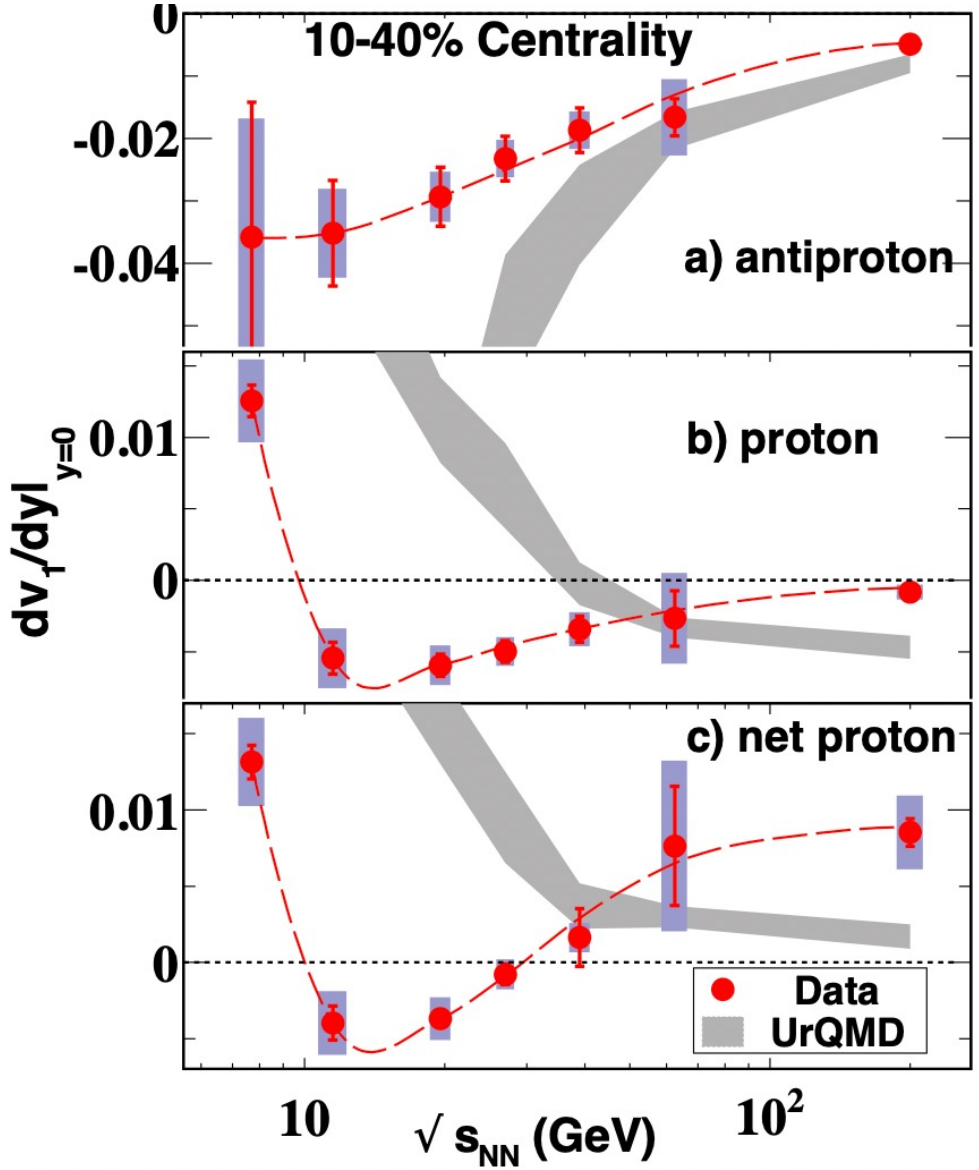
Excess-proton v_1 or Net-proton v_1

$$v_1^{excess-p} = \frac{v_1(p) - v_1(pbar)}{1-r} \qquad v_1^{net-p} = \frac{v_1(p) - r\, v_1(pbar)}{1-r}$$

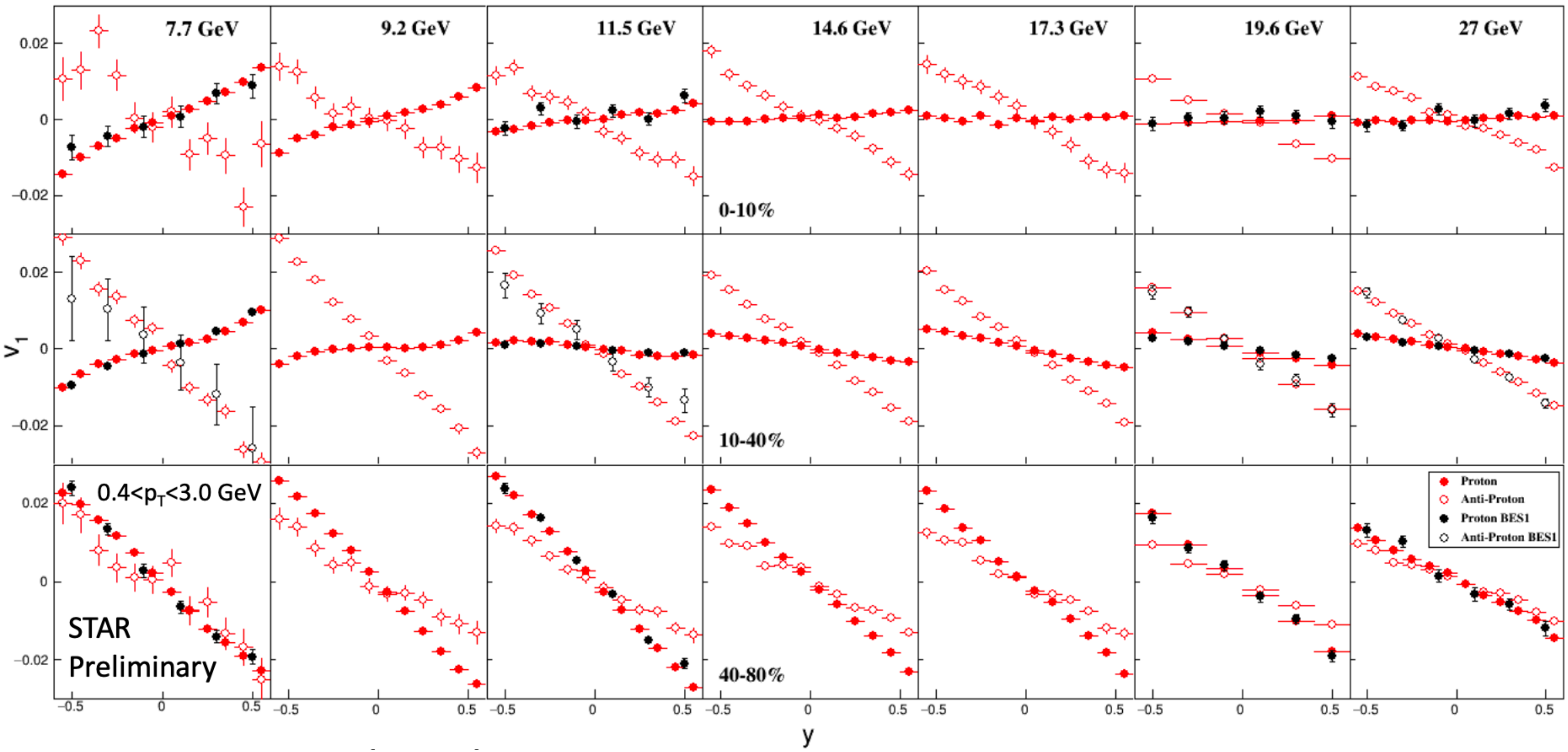
$$r = \frac{N_{pbar}}{N_p}$$



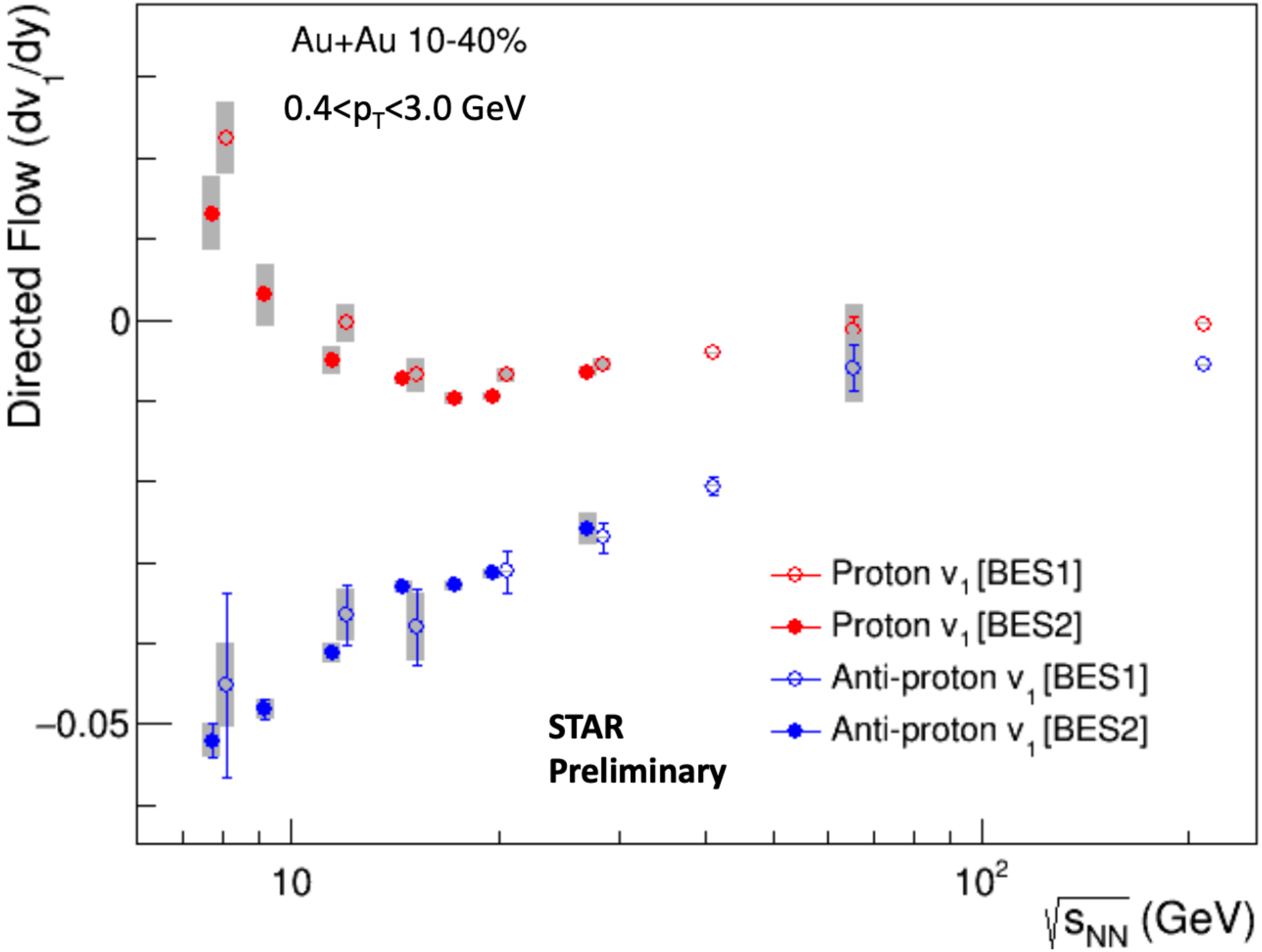
STAR, Phys. Rev. Lett. 112,162301 (2014)



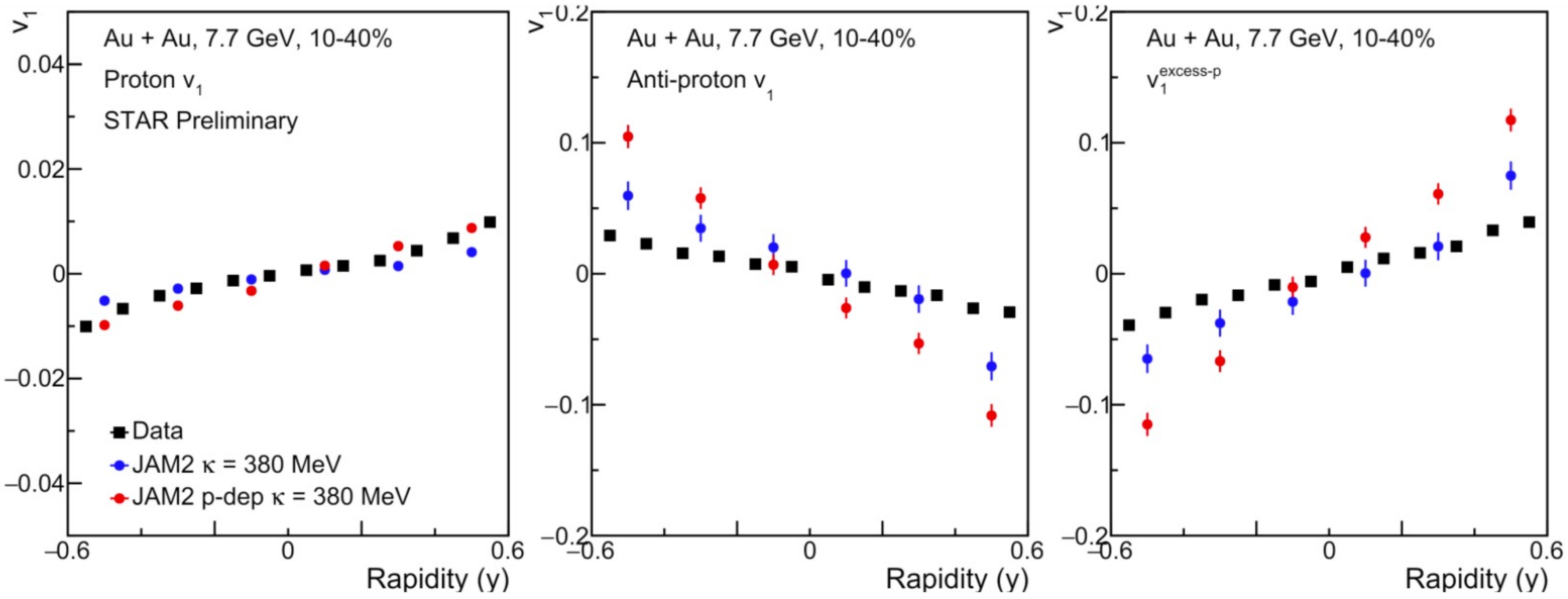
Proton and anti-proton v_1 vs rapidity



Proton and anti-proton dv_1/dy



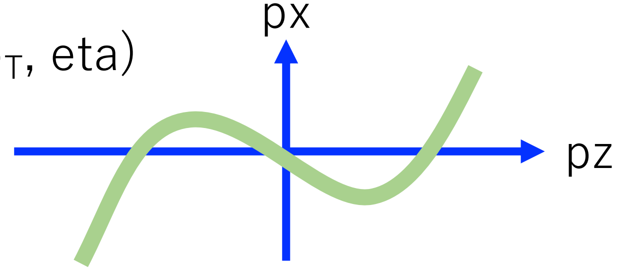
Comparison with JAM calculations

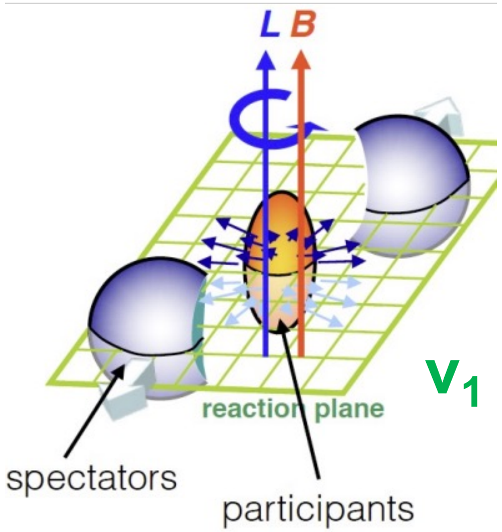


Various correlations studies

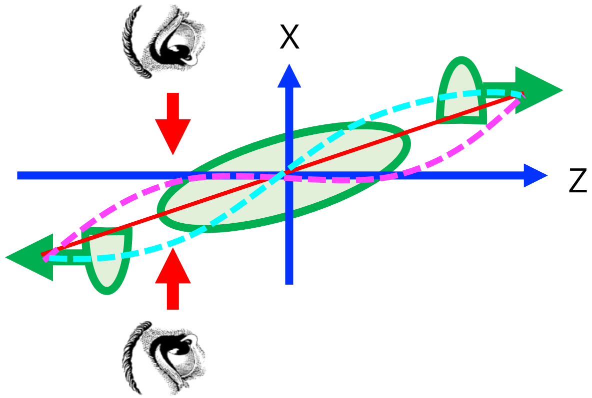
- **geometry, expansion, interaction**
- **identical, non-identical correlation**
- **meson-meson, baryon-baryon**
- **global/local polarization**
- **vorticity and EM-field**

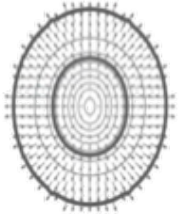
$v_n(p_T, \text{eta})$

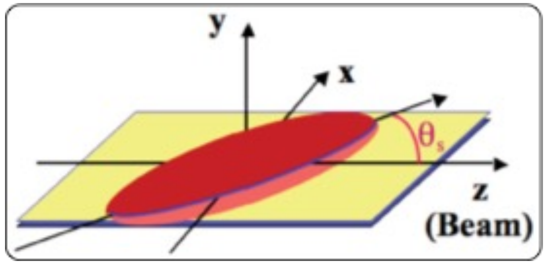


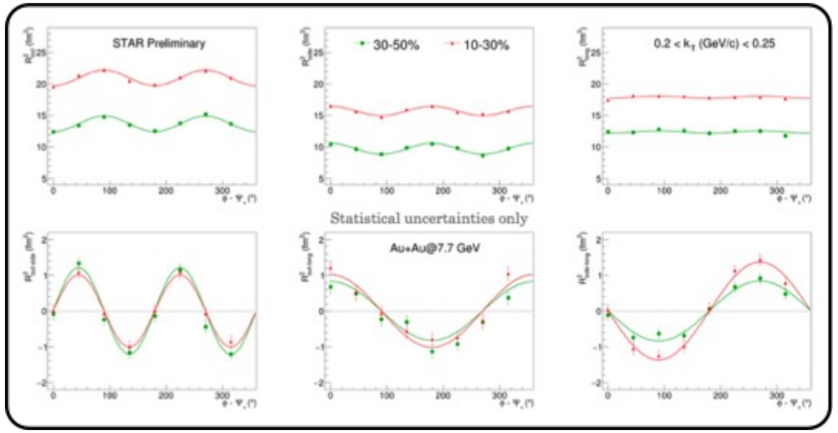


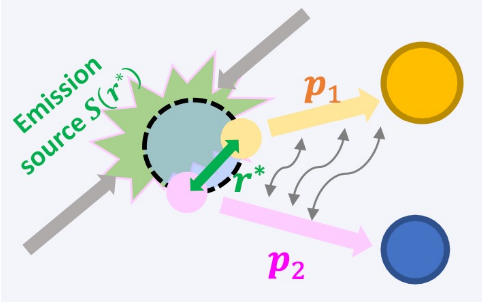
$\varepsilon_n(p_T, \text{eta})$

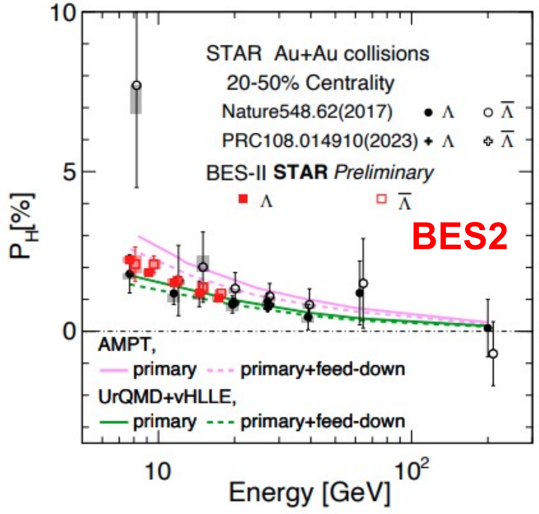


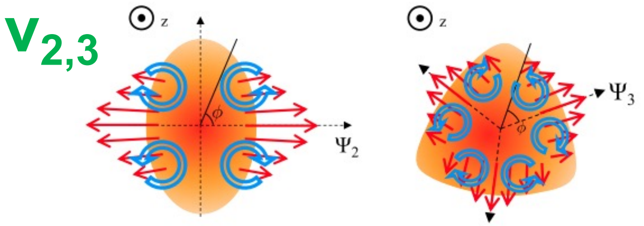






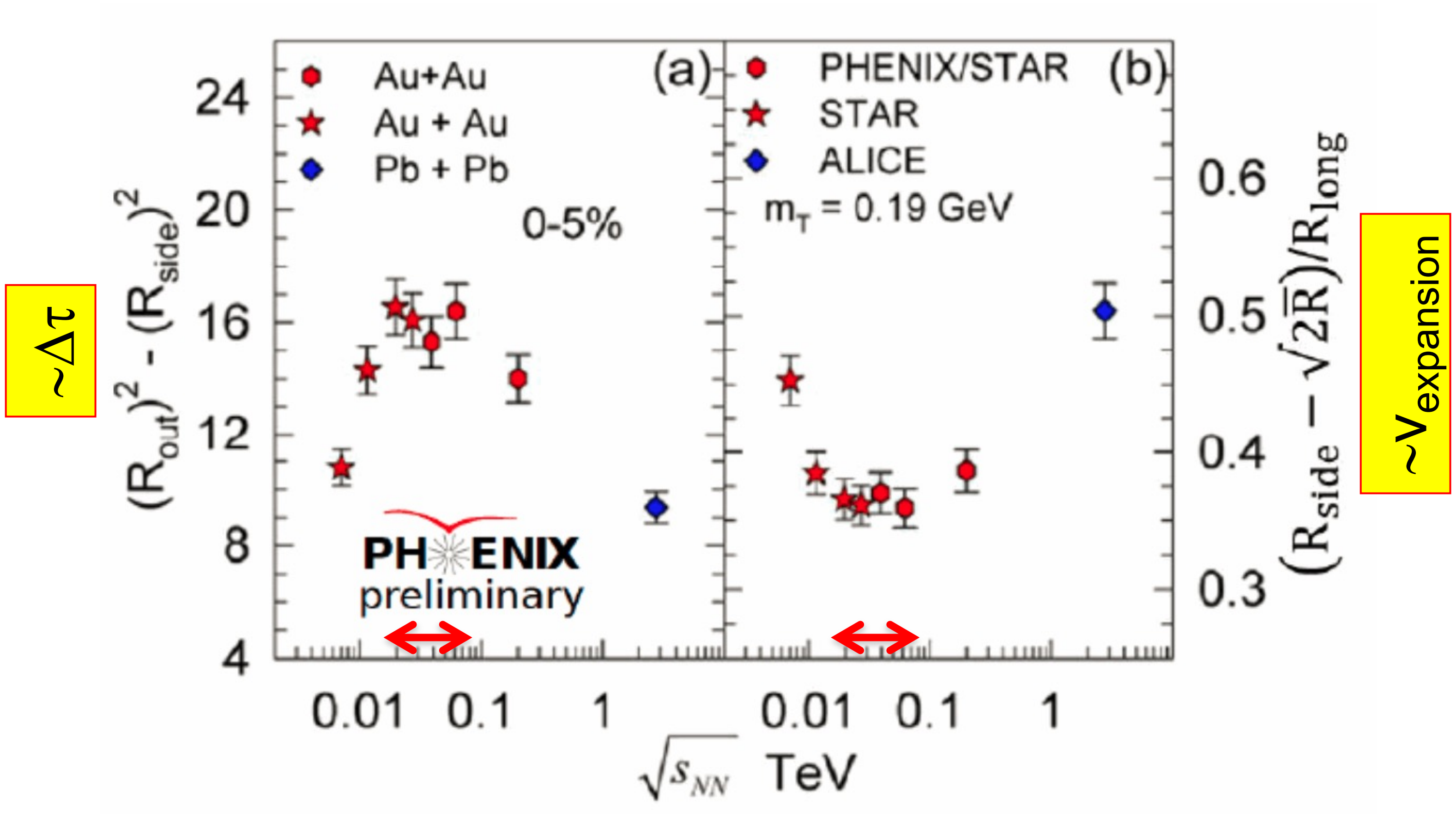


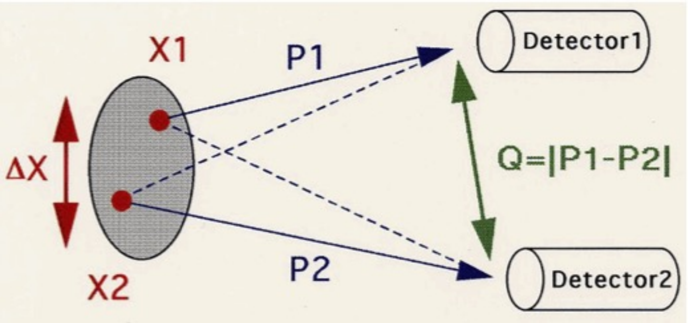


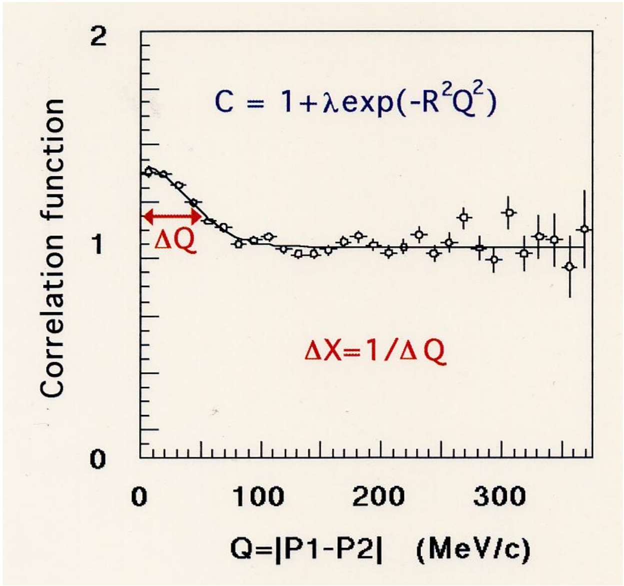


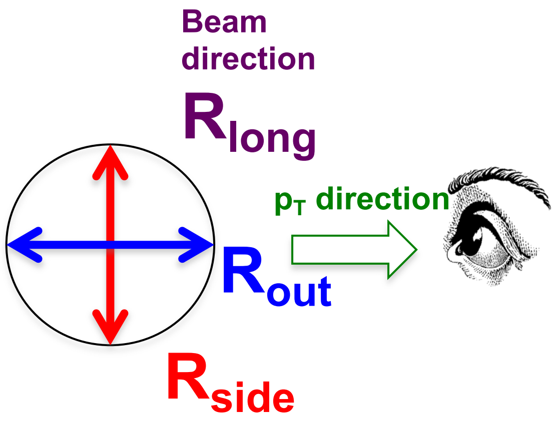
Beam energy dependence of 2-particle interferometry measurement (HBT effect)

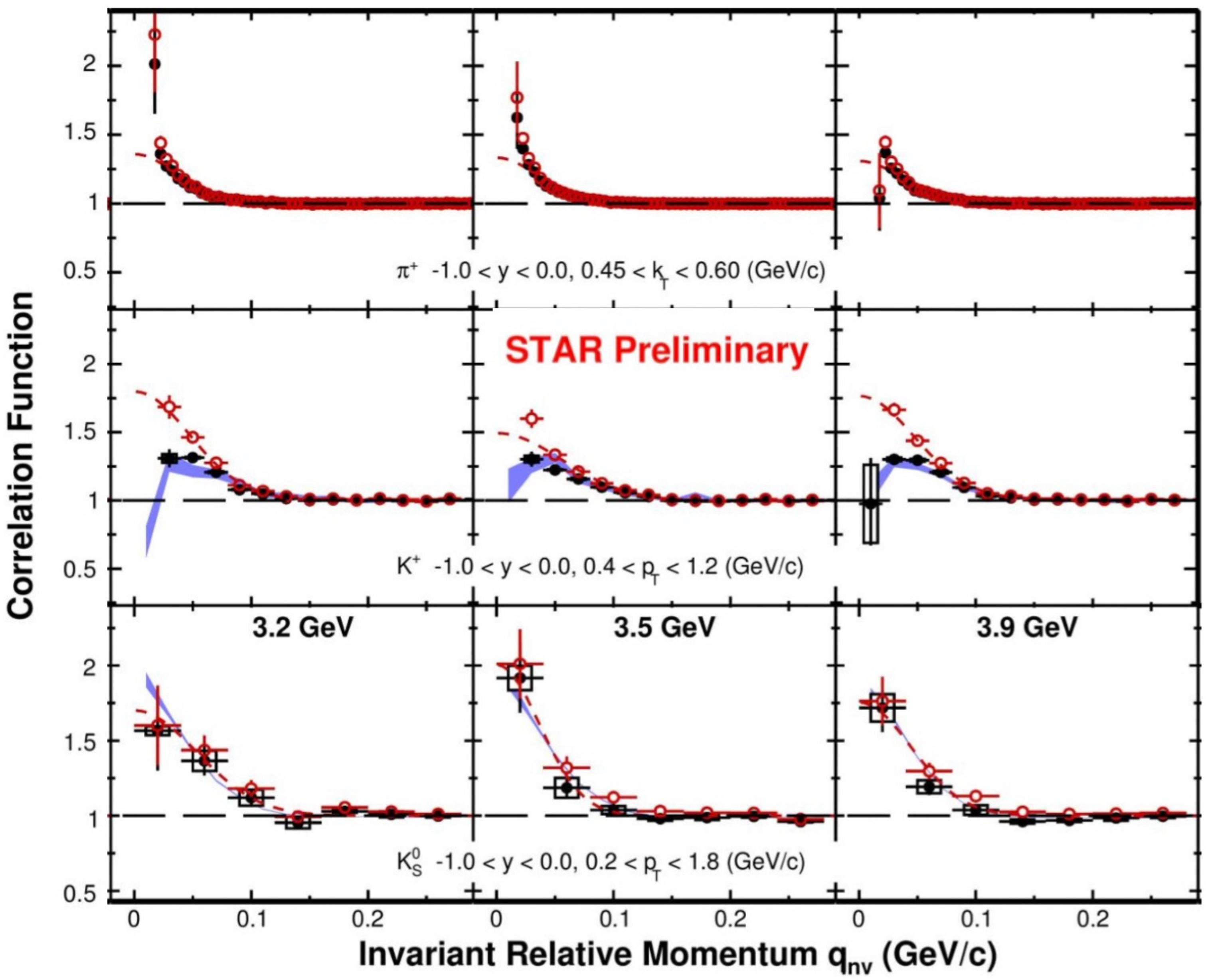
arXiv:1410.2559









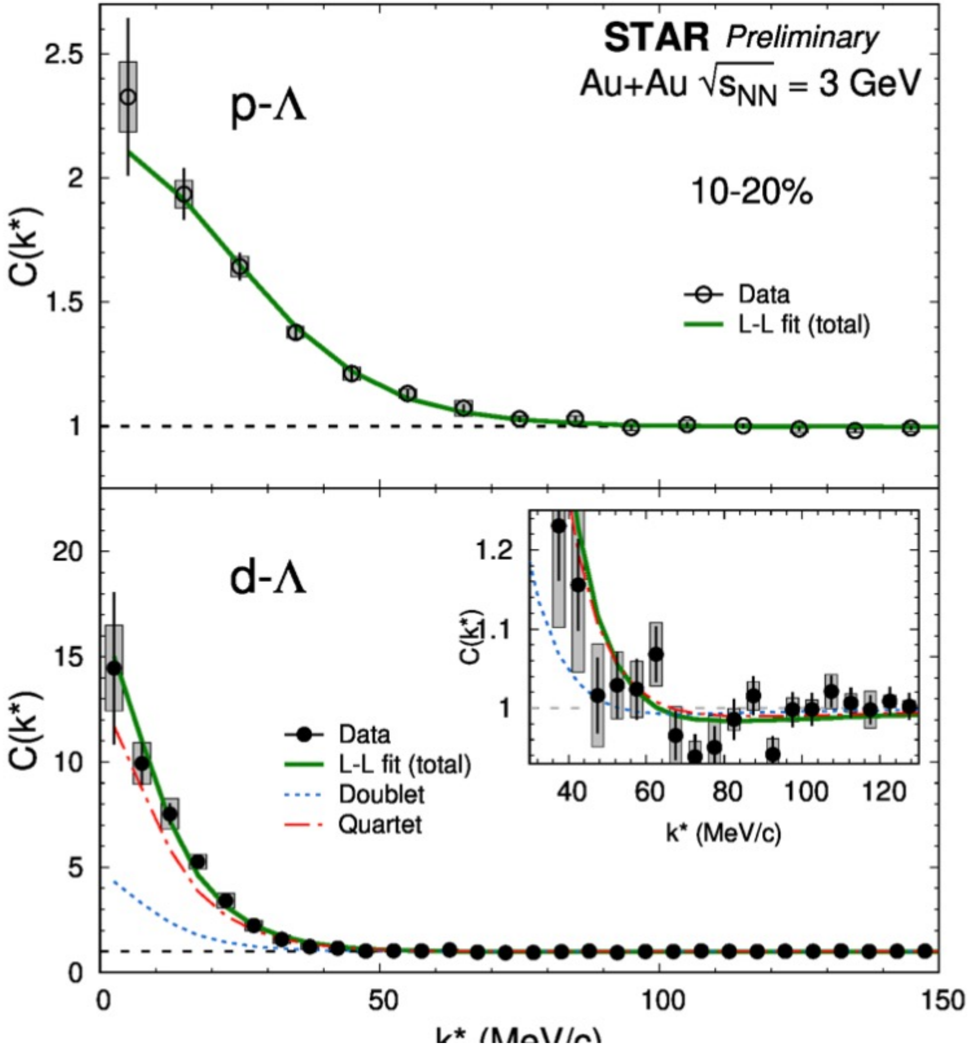


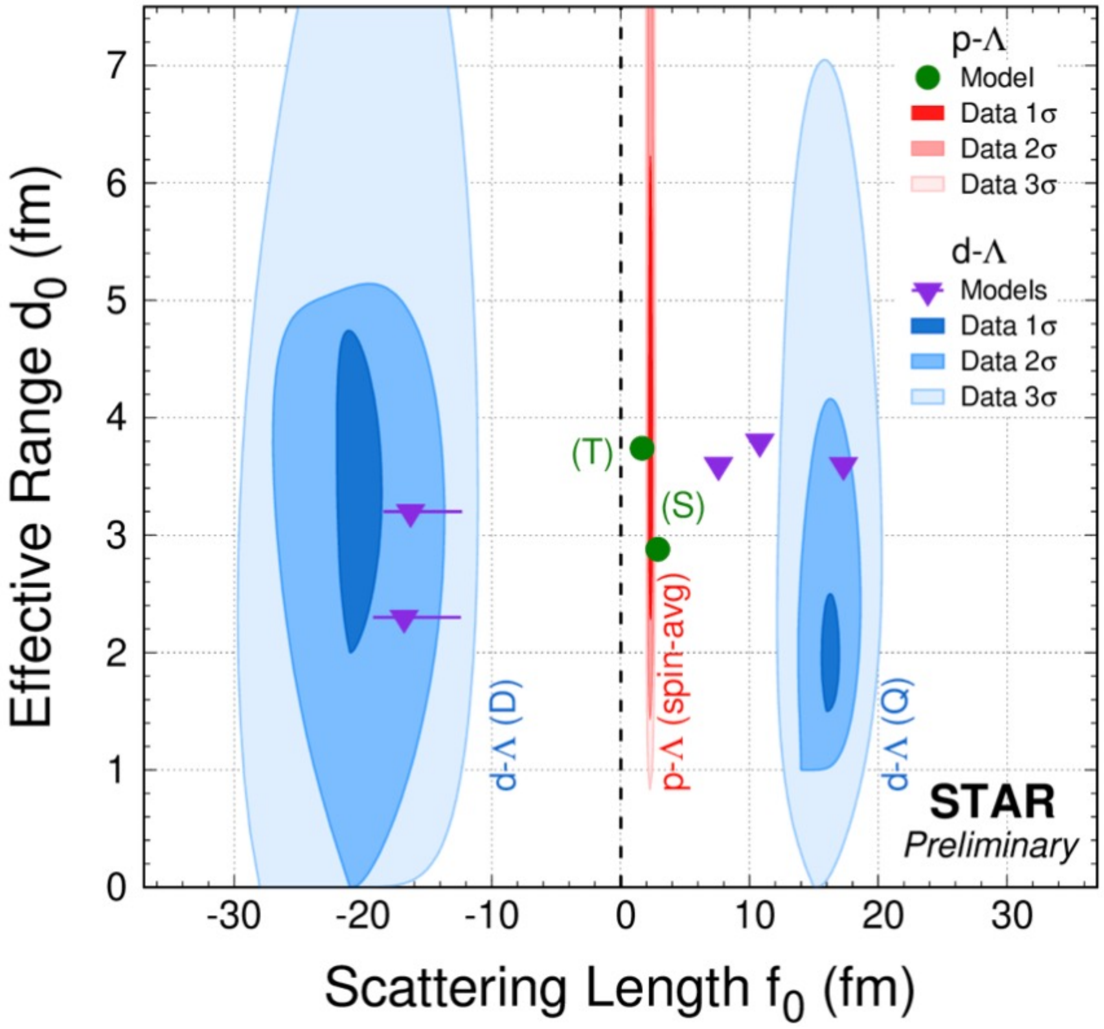
Charged pions
(coulomb corrected)

Charged Kaons
(coulomb corrected)

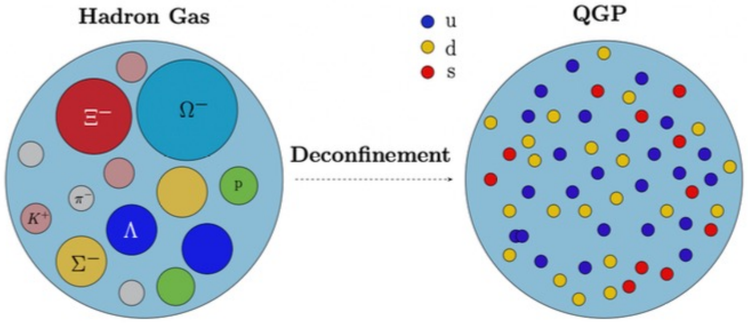
Neutral K^0_s
(strong corrected)

p-Λ, d-Λ correlations to determine f_0 and d_0



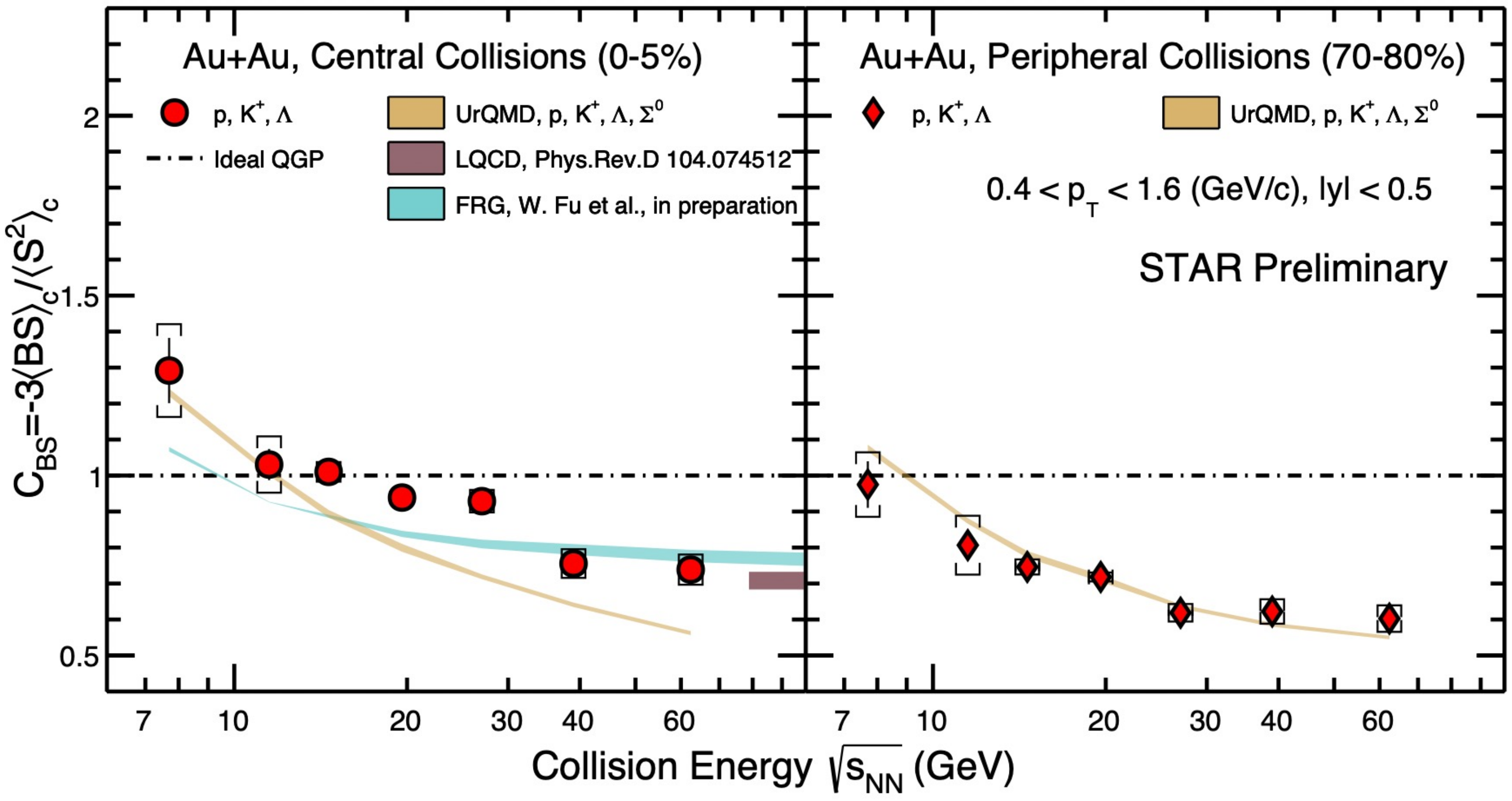


Baryon – Strangeness correlation

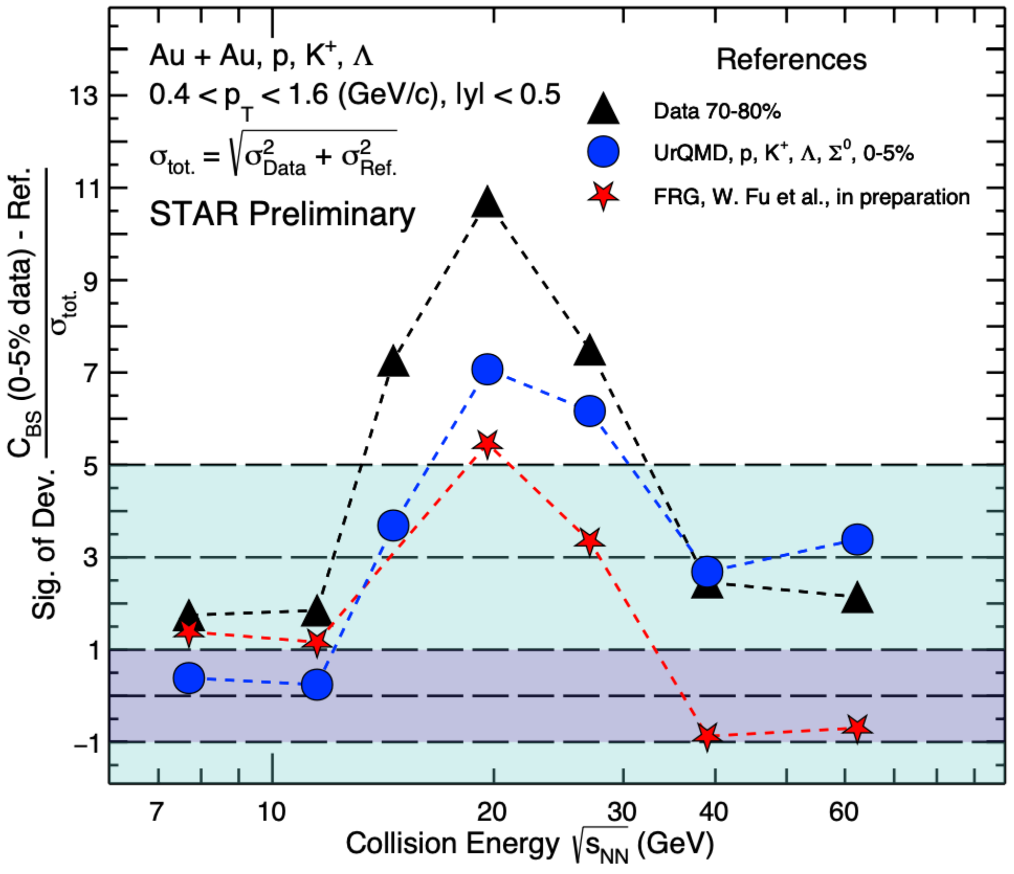


$$C_{BS} = -3\frac{\langle BS \rangle_c}{\langle S^2 \rangle_c} = -3\frac{\langle BS \rangle - \langle B \rangle \langle S \rangle}{\langle S^2 \rangle - \langle S \rangle^2}$$

B-S correlations



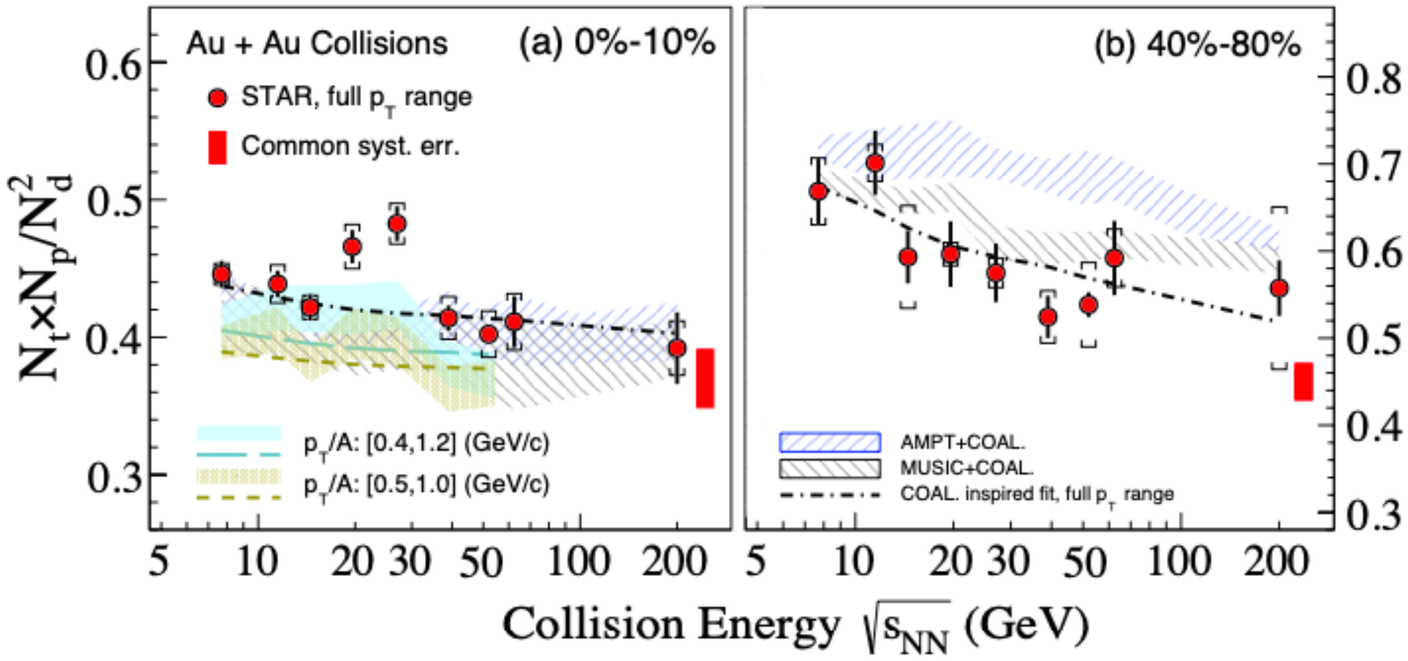
Baryon – Strangeness correlation and Neutron Density Fluctuation



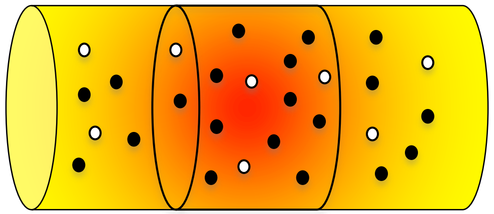
$$\frac{N_t N_p}{(N_d)^2} = \frac{(pnn)(p)}{(pn)(pn)}$$

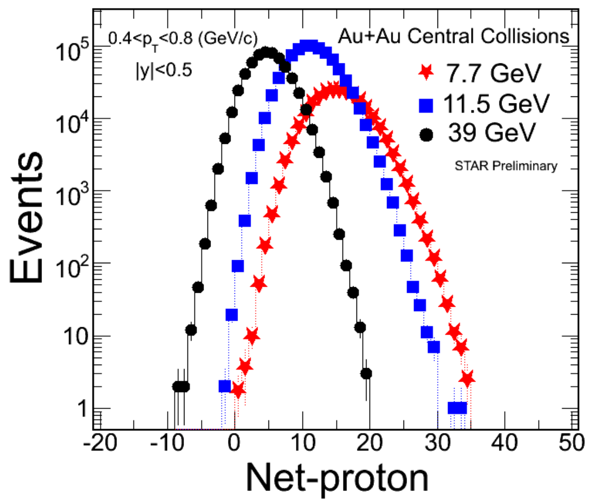
light nuclei coalescence
(locally) neutron rich system

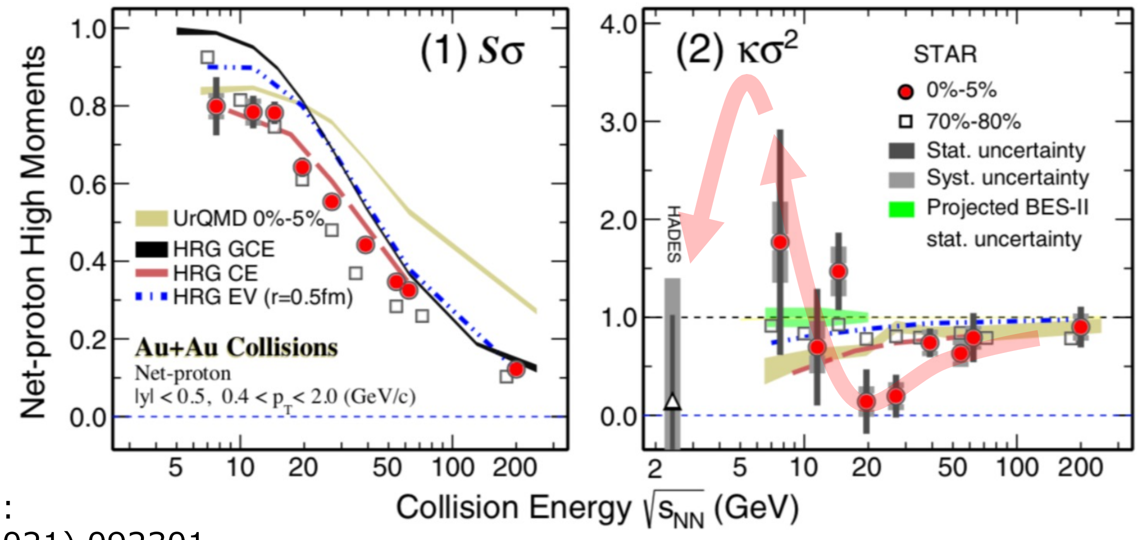
STAR, Phys. Rev. Lett. 130, 202301 (2023)

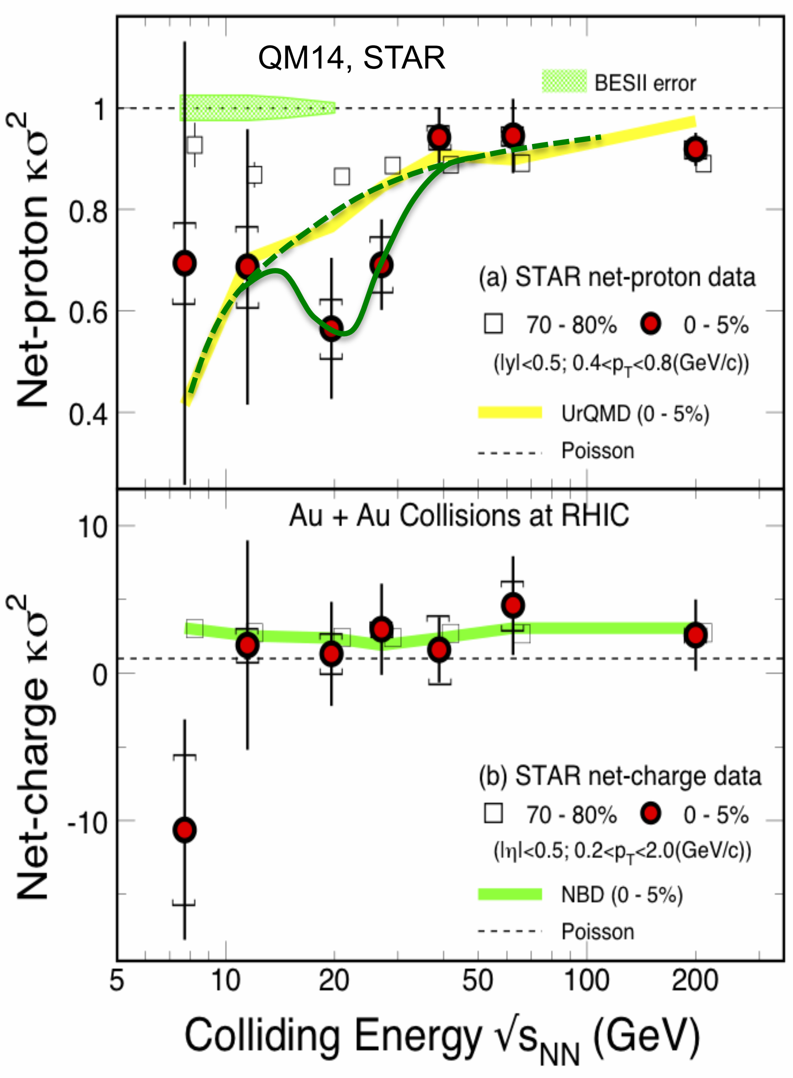


Beam energy dependence of net-proton, net-charge distribution



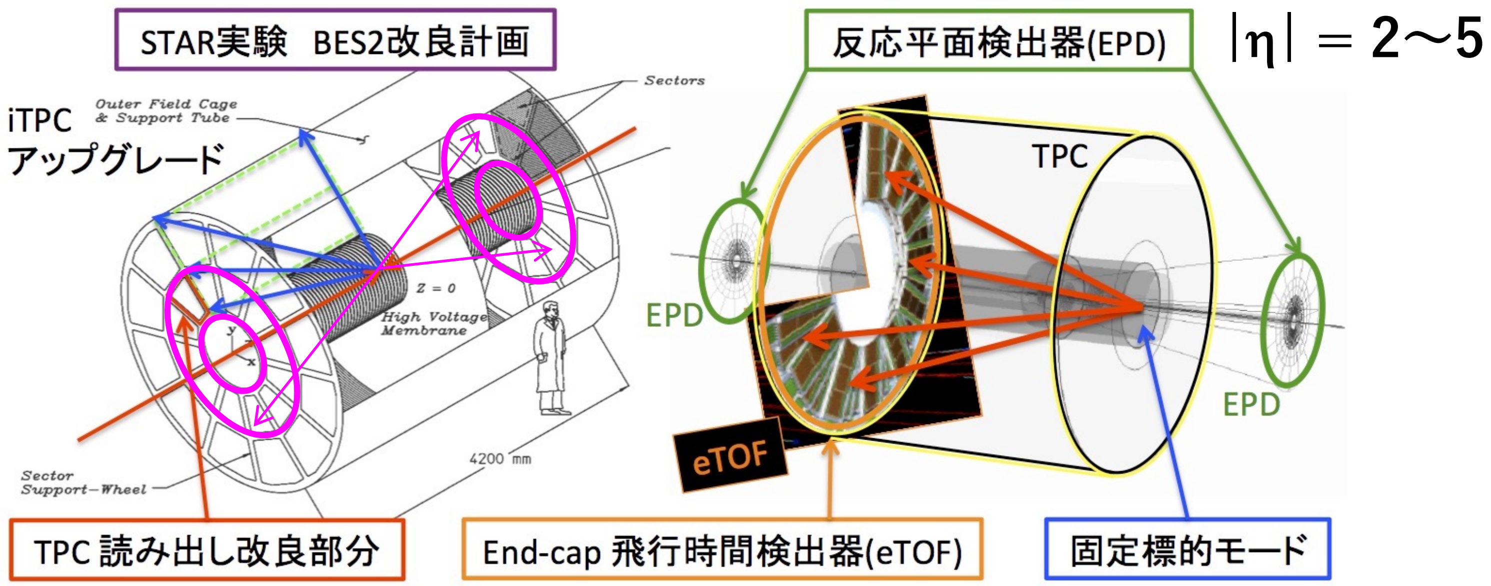


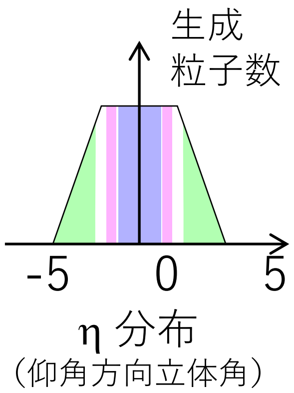




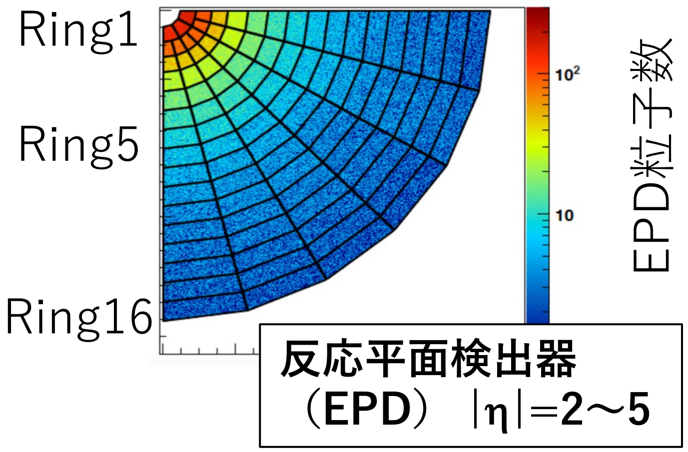
BES-I final :
PRL 126 (2021) 092301

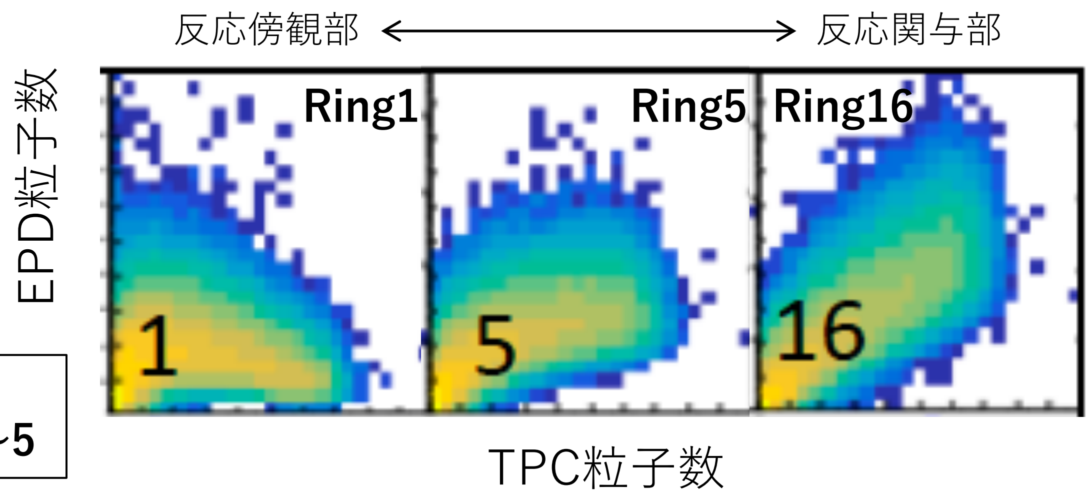
|η| < 1.0
→ 1.5





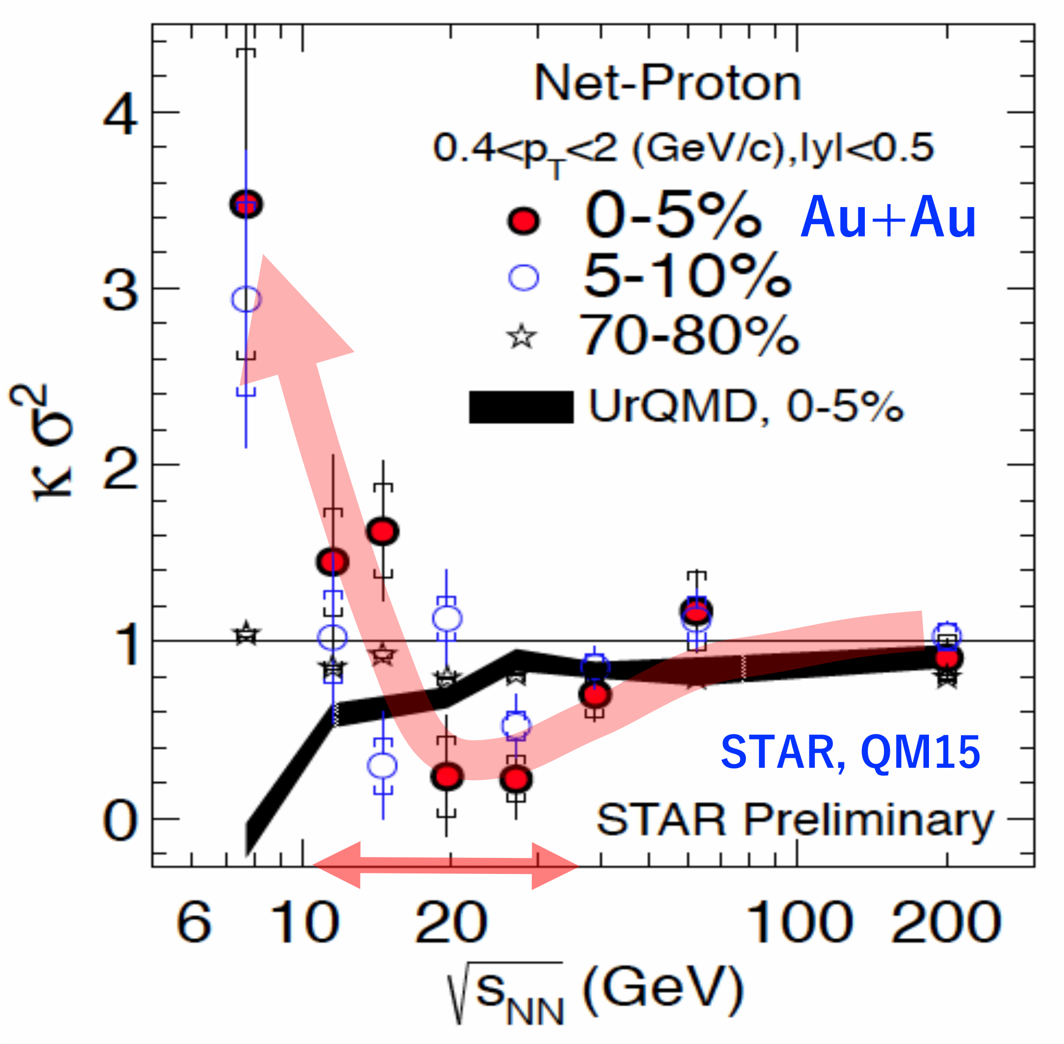
- **立体角の拡大**
- **統計量の増大**
- **物理的感度の改善**

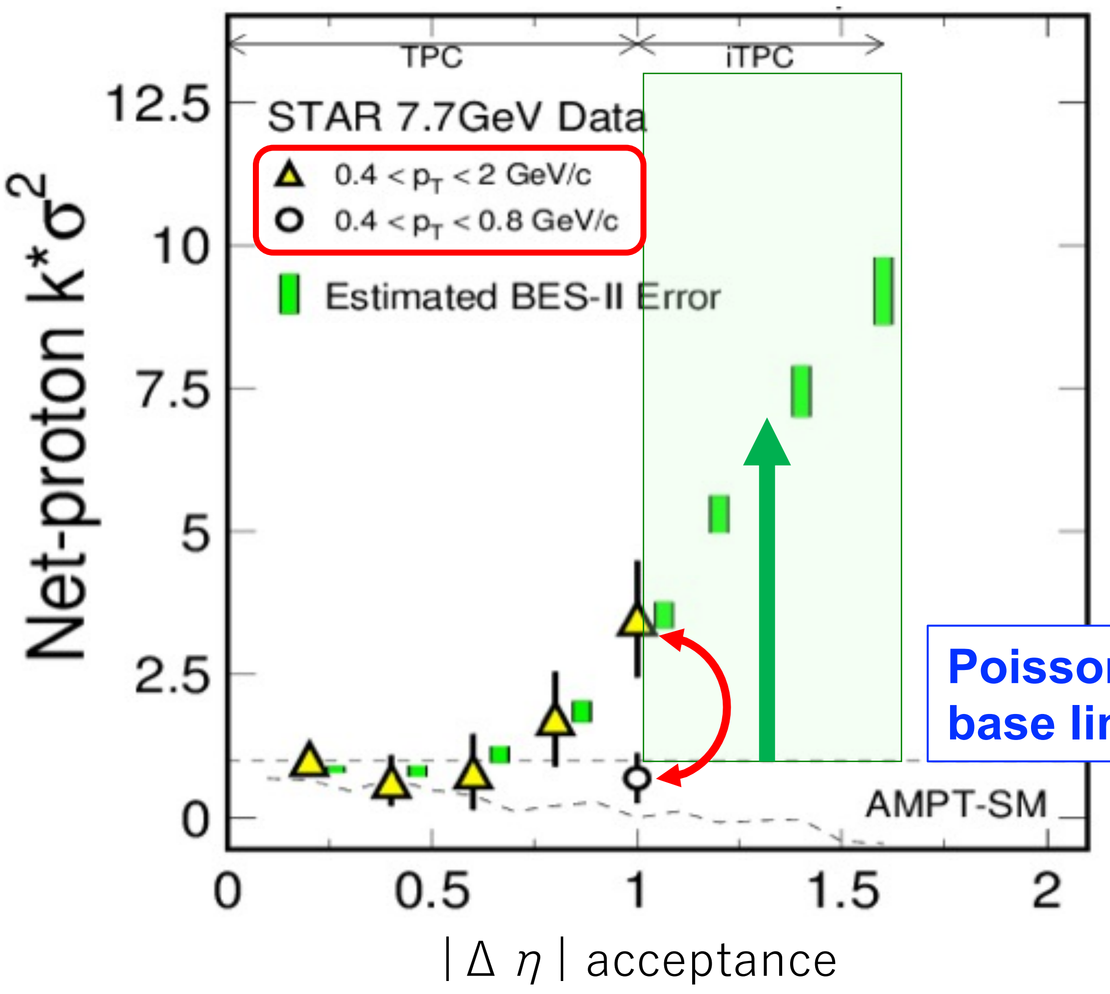




Sensitivity improvement expected !?

$N_{baryon} \sim N_{proton} + N_{neutron} + N_{hyperon}$
$\sim 2 \times N_{proton}$

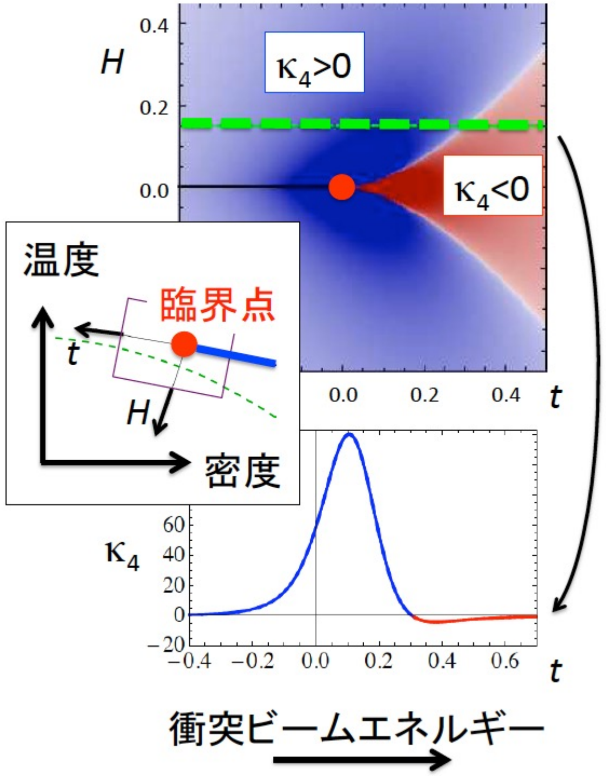




Poisson base line = 1

At critical point with an infinite system
- correlation length should diverge
- susceptibilities should diverge

$$\chi_n^B = -\frac{1}{3^n}\frac{\partial^n f/T^4}{\partial \hat{\mu}_q^n}$$

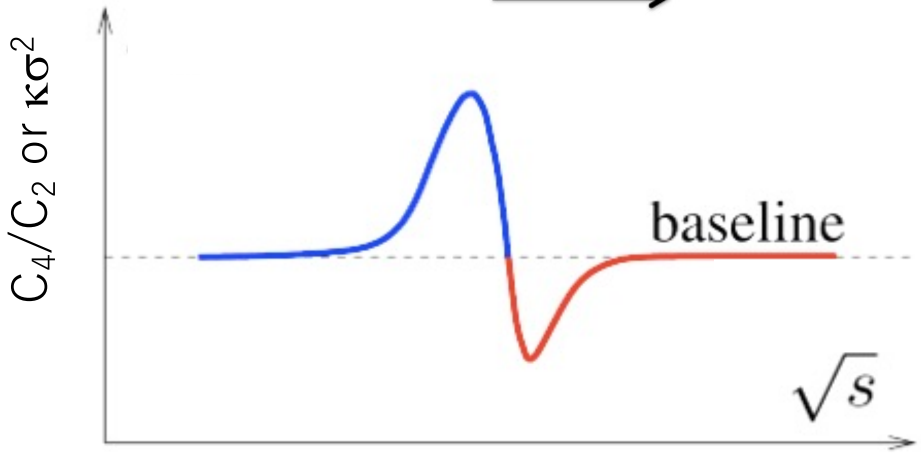


PRL107 (2011) 052301

Proposed Experimental Observables:

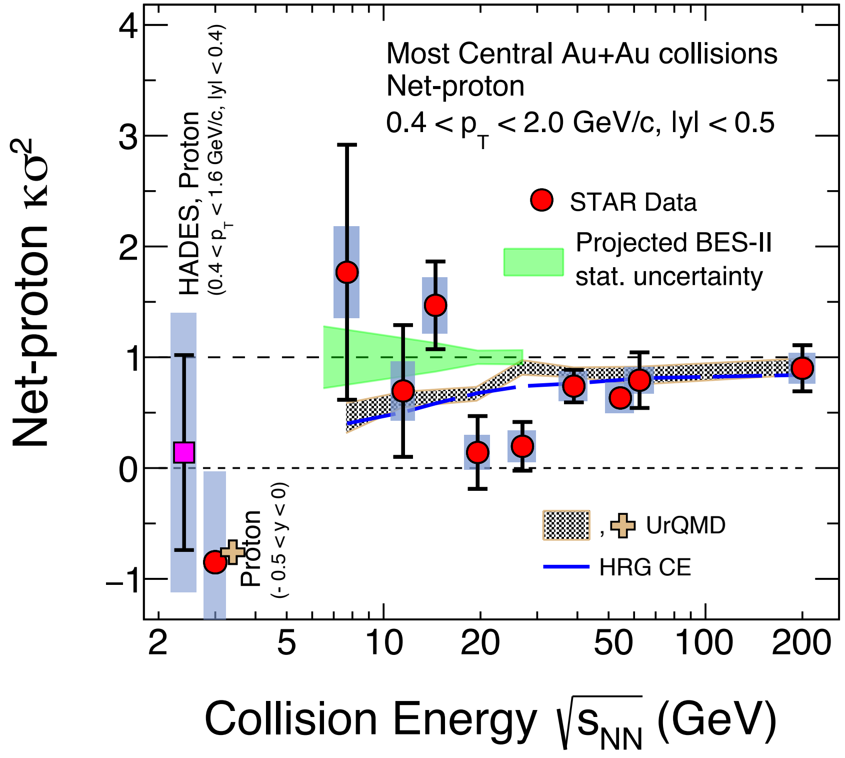
Moments of conserved quantities: net-***B***, net-***S***, net-***Q*** etc.
- directly related to the susceptibility ratios (calculable from Lattice QCD)
- sensitive to correlation lengths *(M. A. Stephanov, PRL 102 (2009) 032301)*

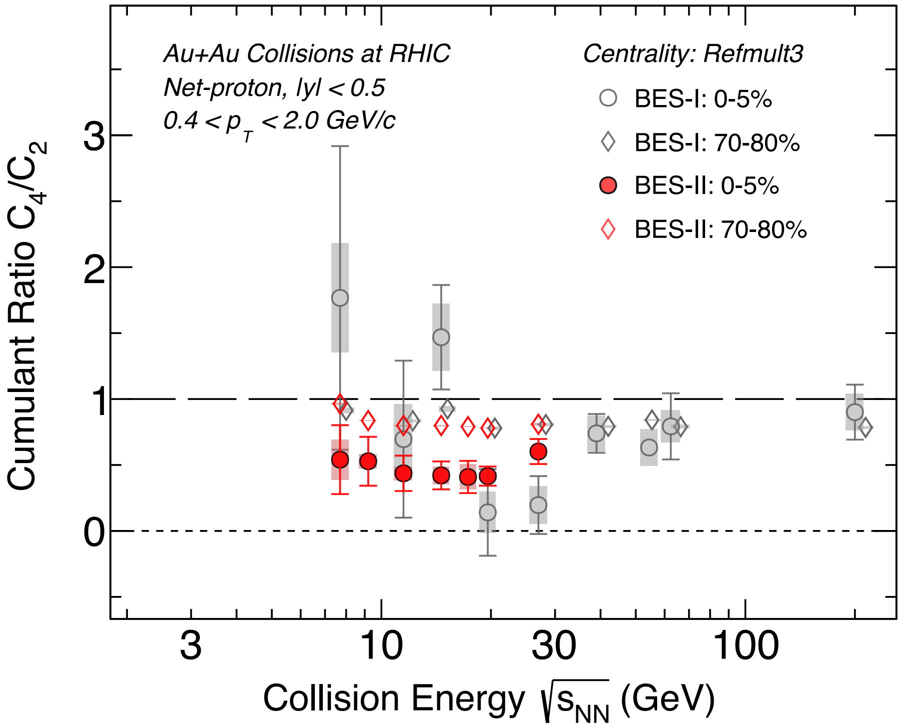
$$\begin{aligned}
\text{mean} : \mathrm{M} = \langle N \rangle &= C_1, \\
\text{variance} : \sigma^2 = \langle (\delta N)^2 \rangle &= C_2, \\
\text{skewness} : \mathrm{S} = \langle (\delta N)^3 \rangle / \sigma^3 &= C_3/C_2^{3/2}, \\
\text{kurtosis} : \kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 &= C_4/C_2^2.
\end{aligned}$$

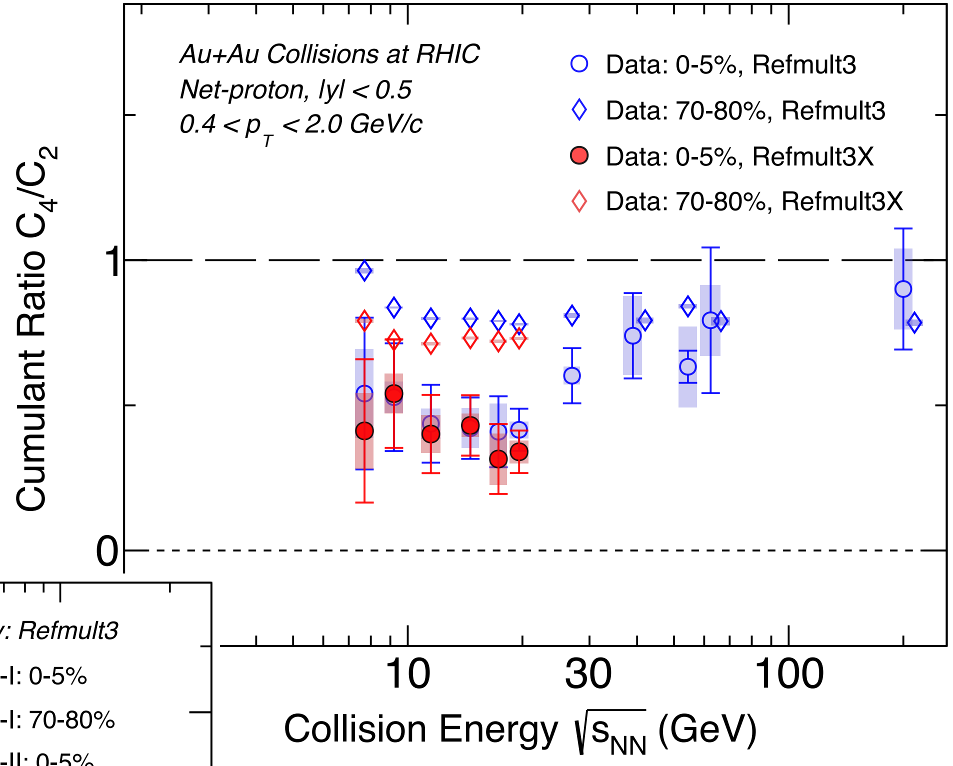


New Result on
Net-proton Cumulant Ratio C_4/C_2

STAR, Phys. Rev. Lett. 127, 262301 (2021)
STAR, Phys. Rev. Lett. 128, 202302 (2022)



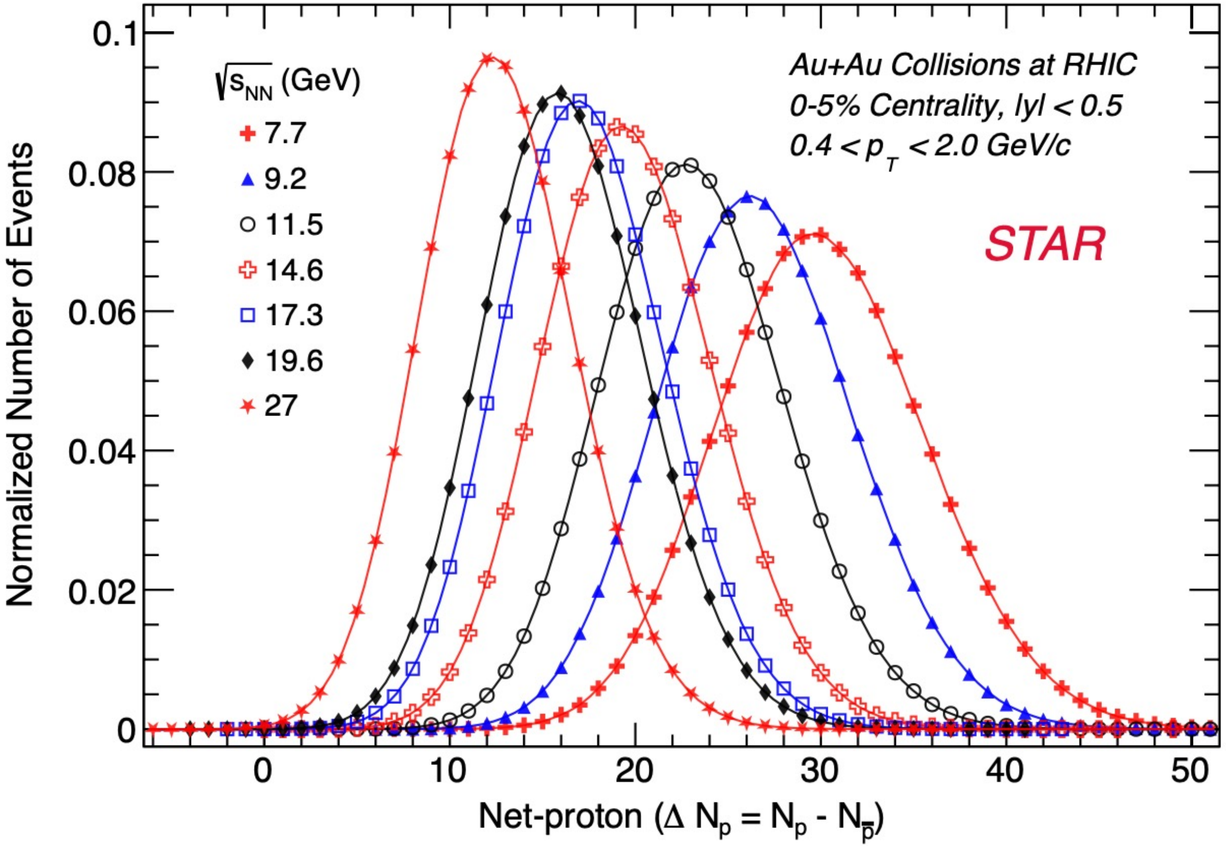


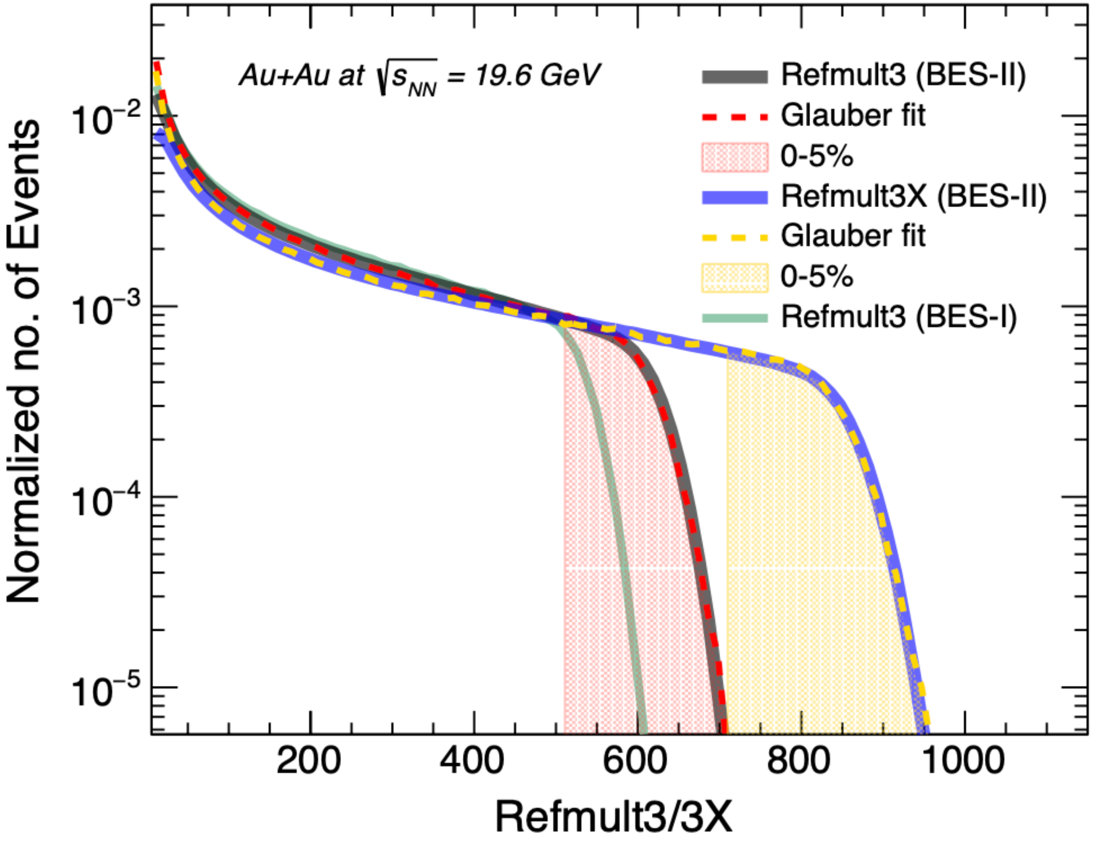


BES-I RefMult3
BES-II RefMult3
BES-II RefMult3X

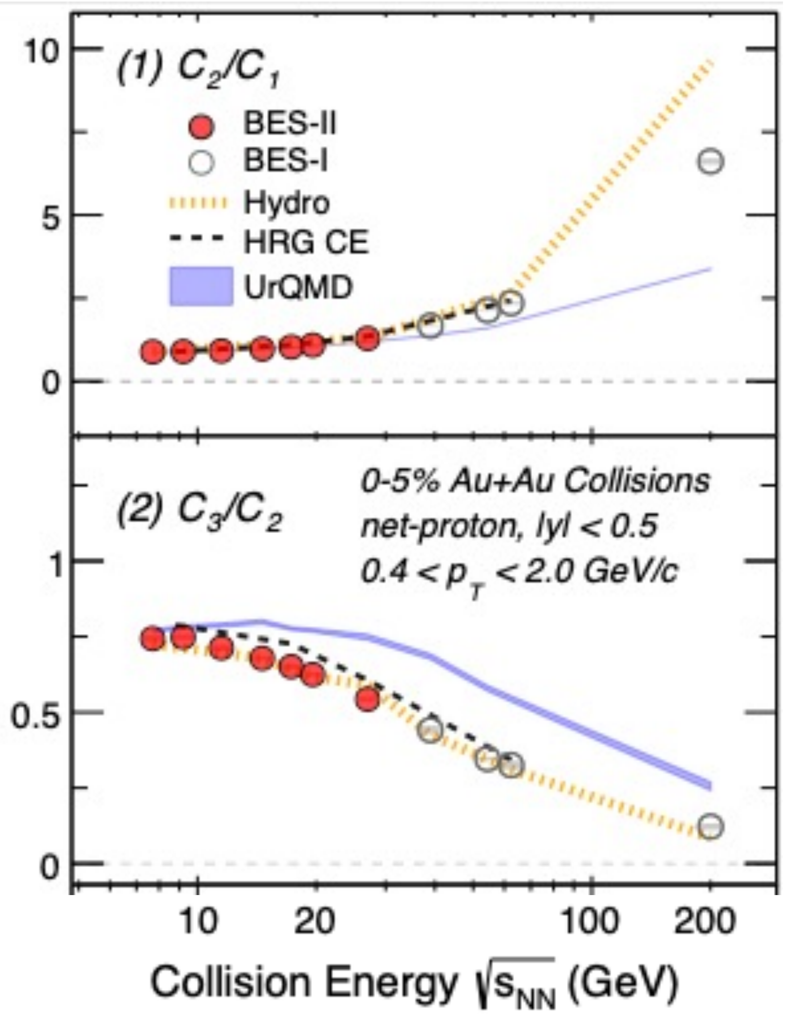
Net-proton distribution and Centrality determination

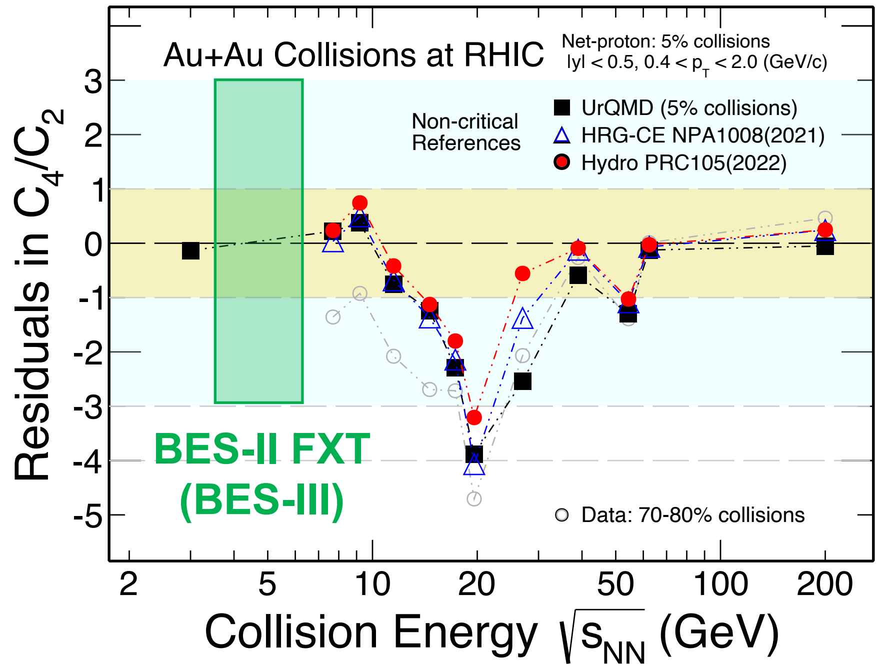
BES-I RefMult3
BES-II RefMult3
BES-II RefMult3X

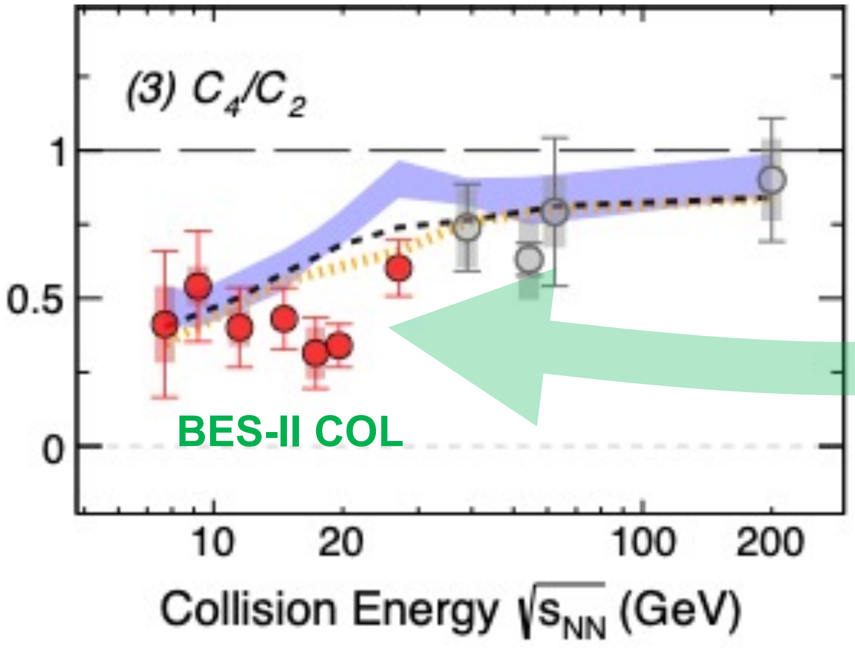


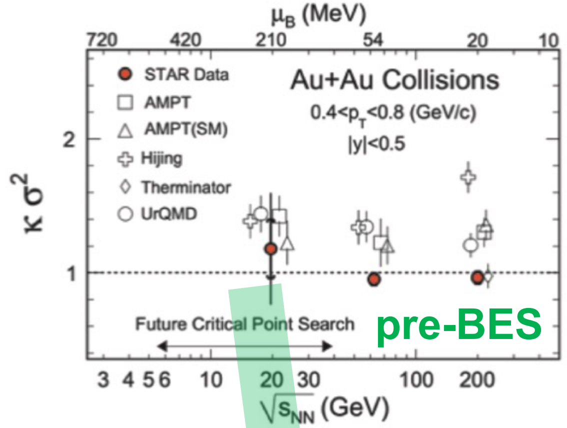


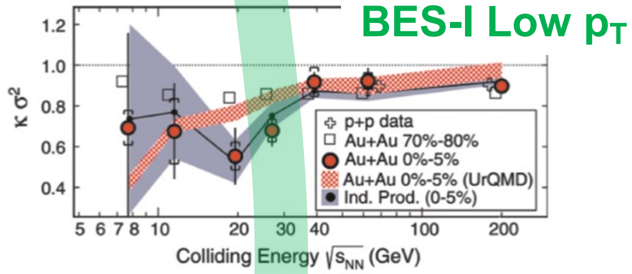
Peak is gone, Dip remains?

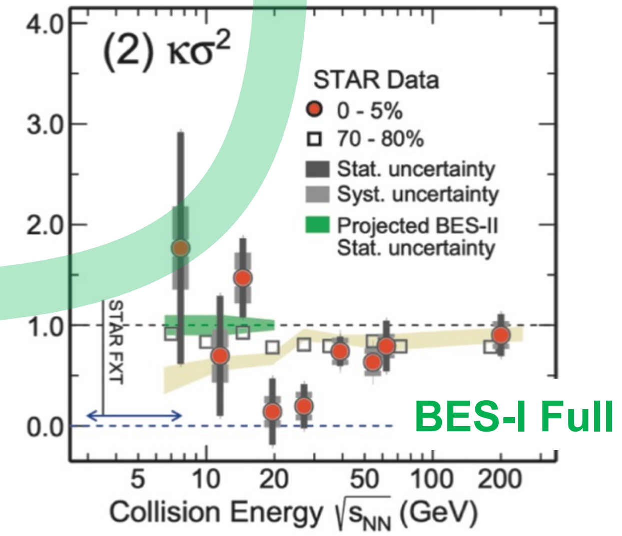




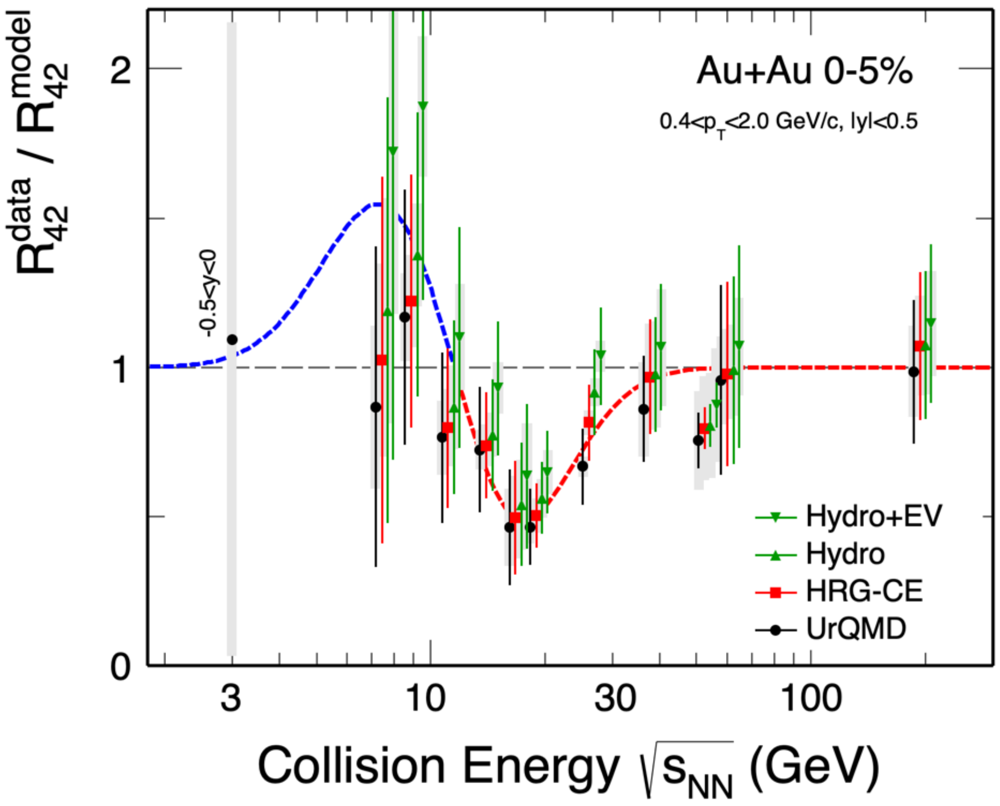




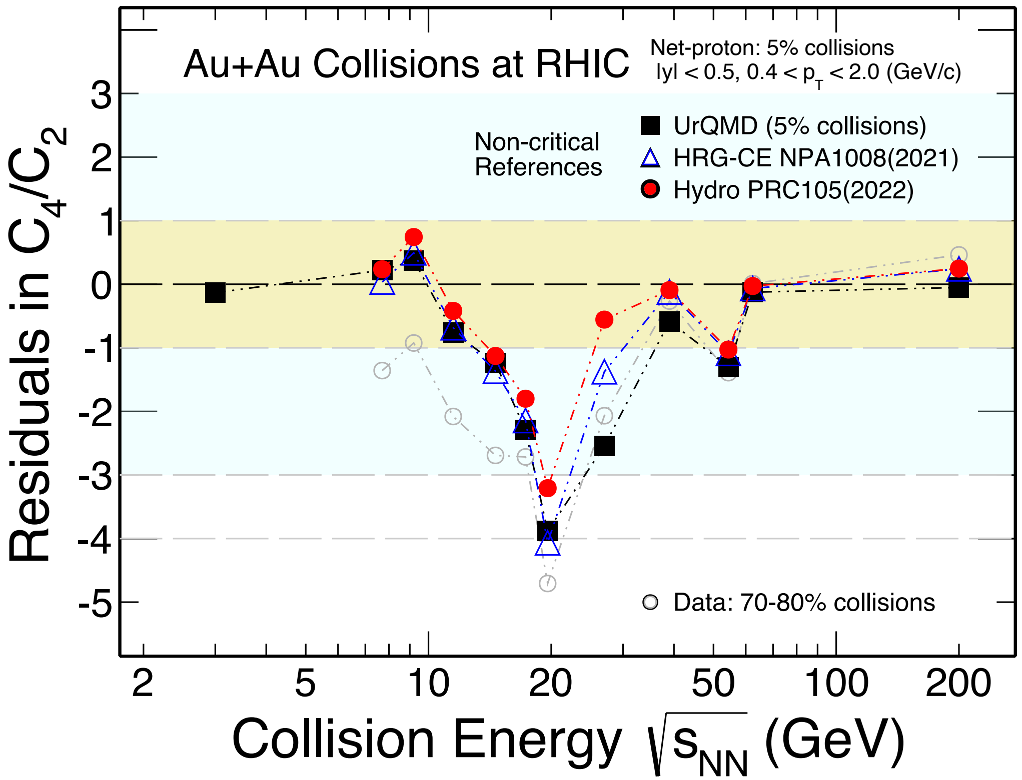




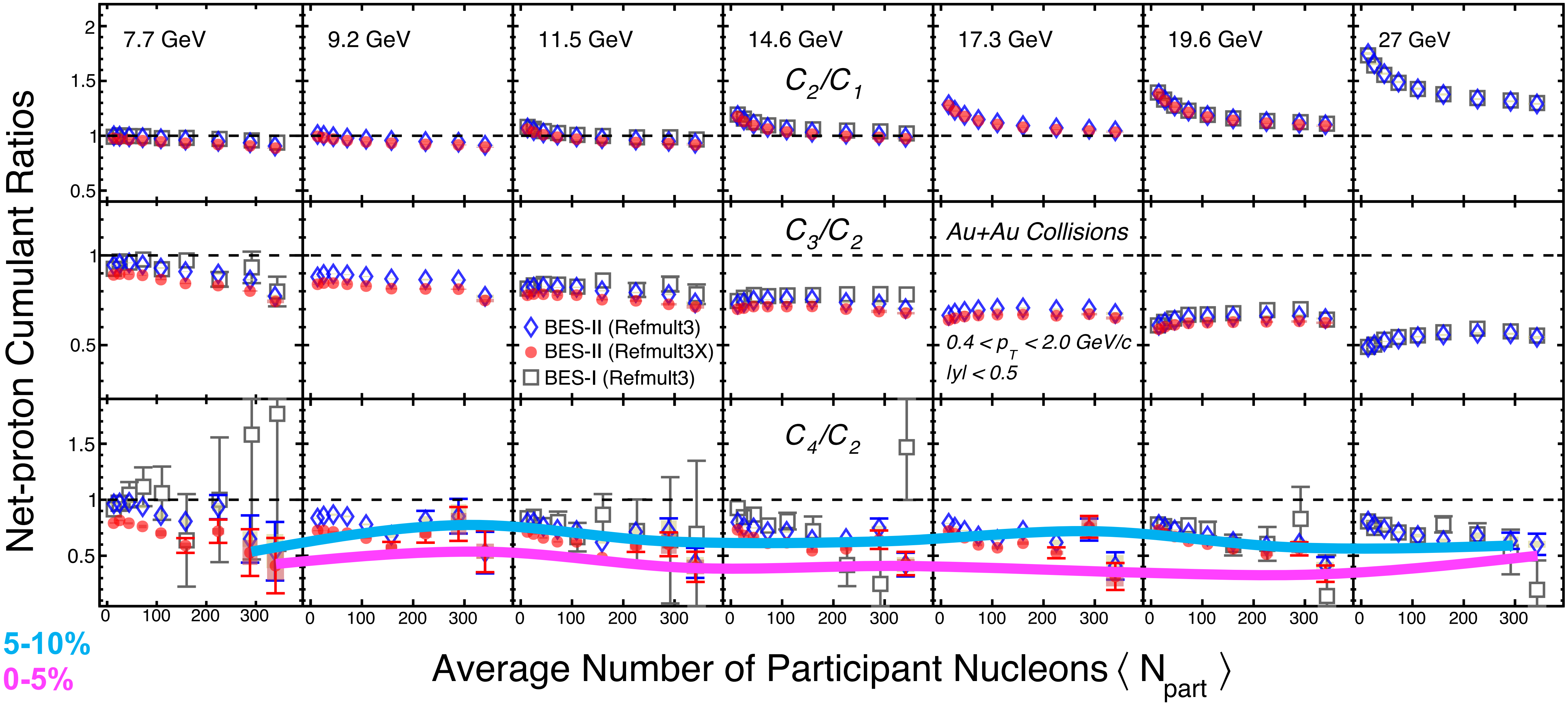
Data/Model Ratio



Residual = (Data – Model)/error



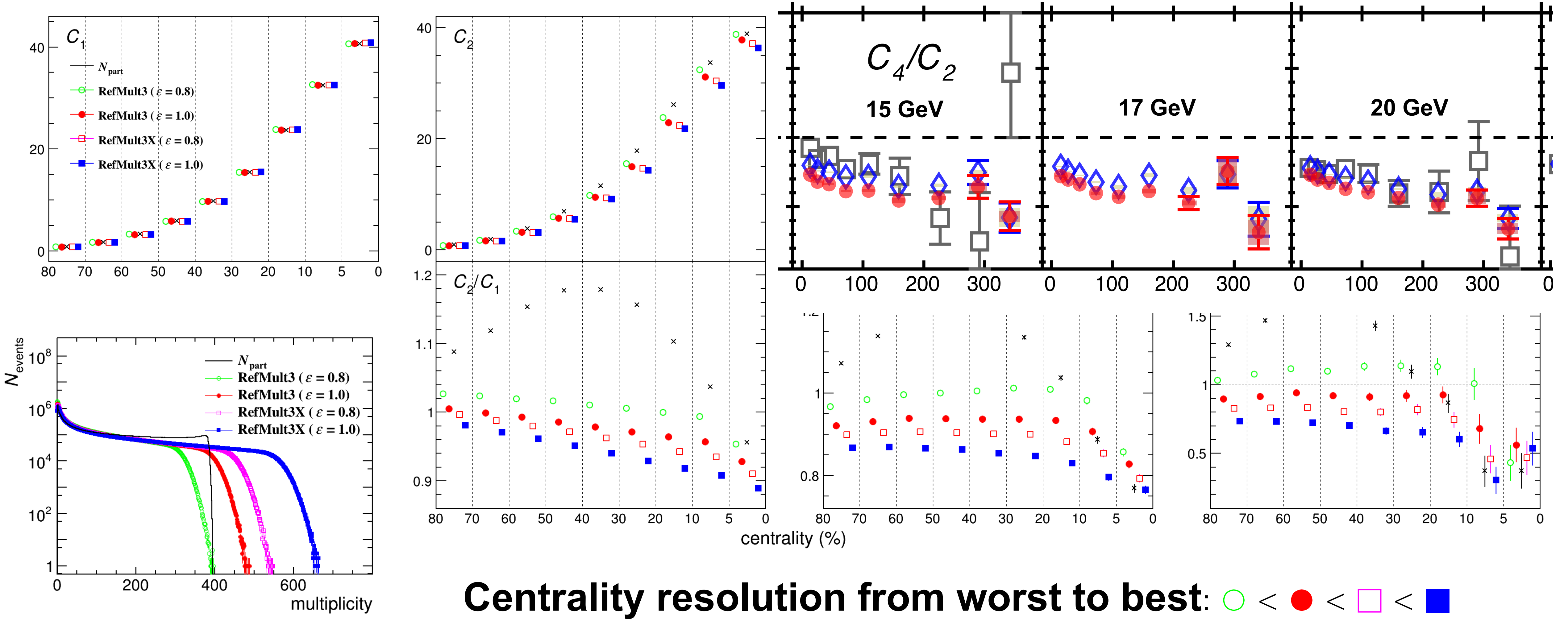
Net-proton Cumulant Ratio as a function of Centrality



5-10%
0-5%

Fan Si,
grad. student
USTC/Tsukuba

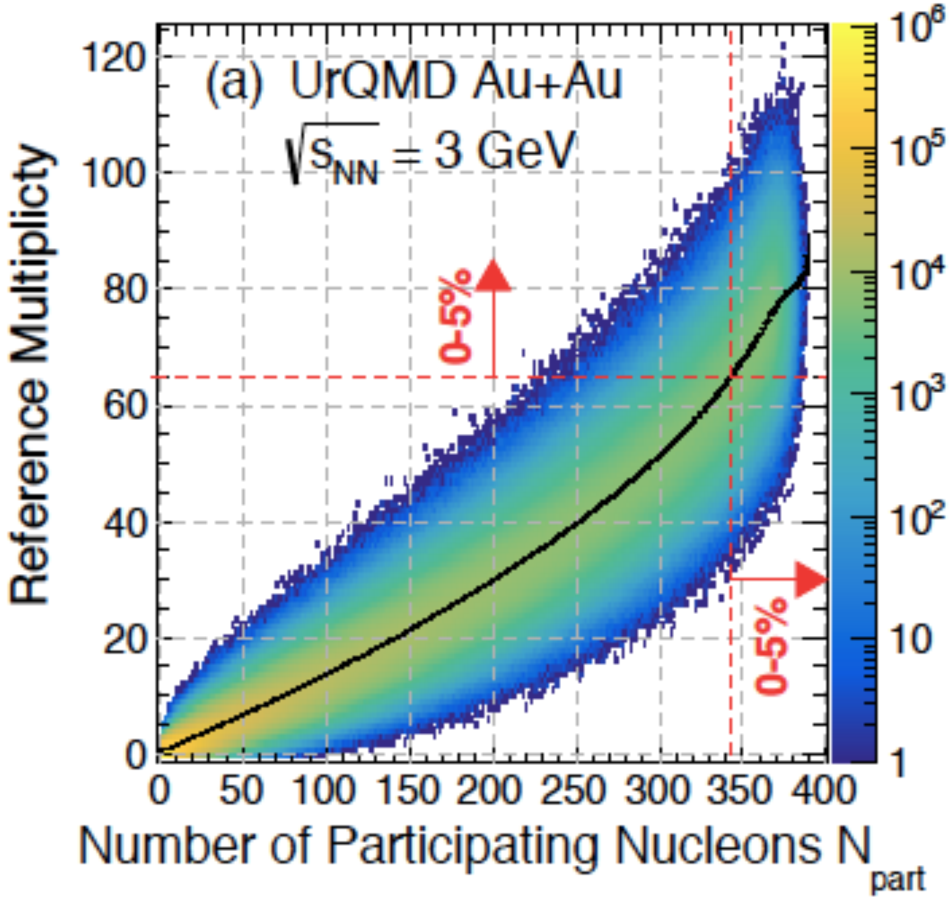
UrQMD simulation study : Au+Au at 7.7 GeV



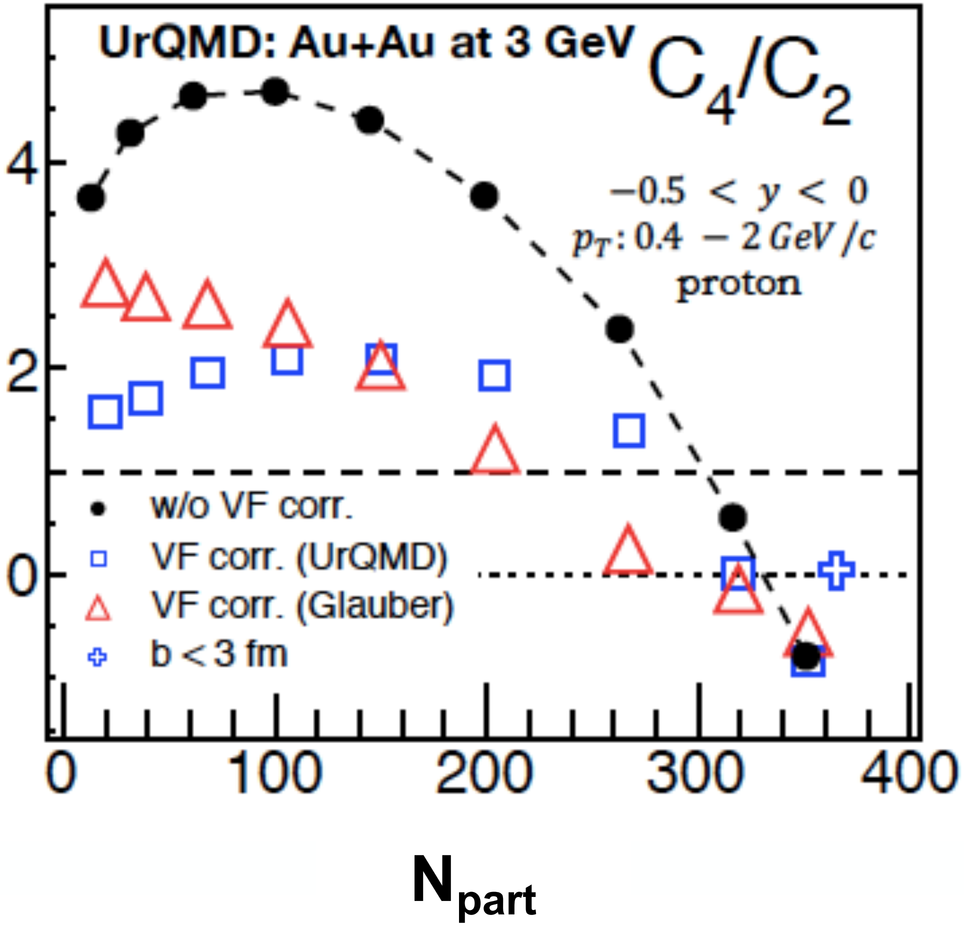
Centrality resolution from worst to best: ○ < ● < □ < ■

clear centrality resolution ordering: better resolution => lower cumulants/ratios

UrQMD simulation study : Au+Au at 3 GeV



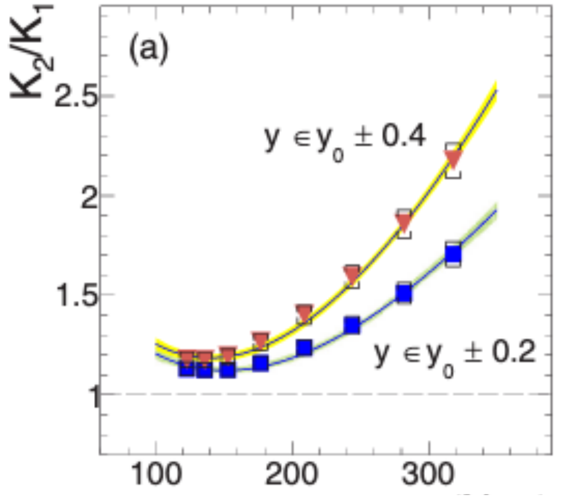
STAR, PRC 107 (2023) 024908

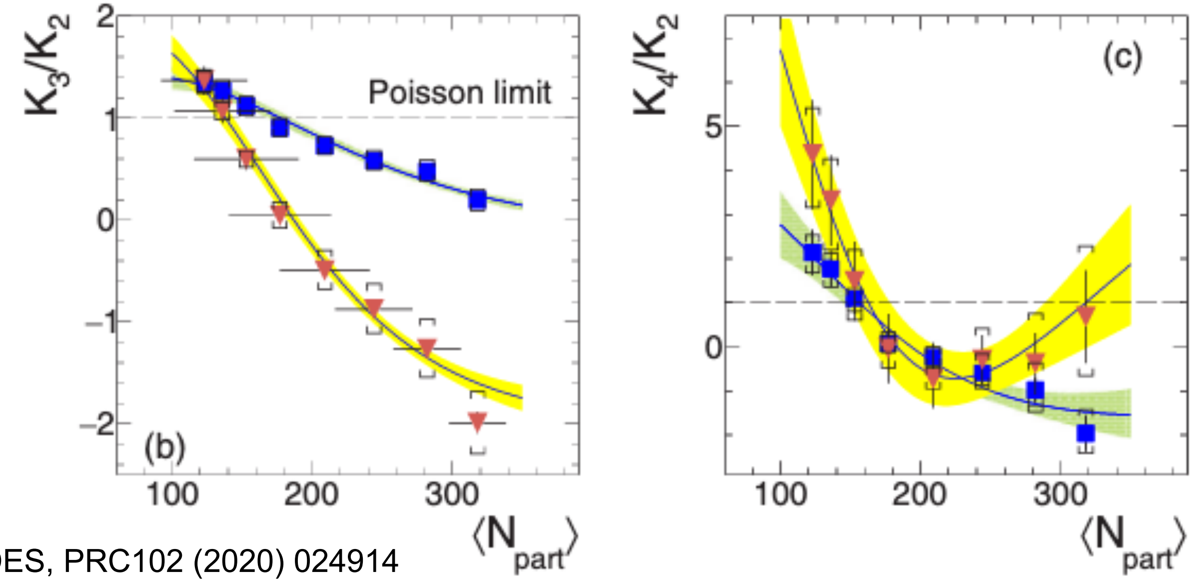


HADES at 2.4 GeV Au+Au collisions & STAR at 3.0 GeV

Au+Au 2.4 GeV HADES

with spectator based centrality
with volume correction

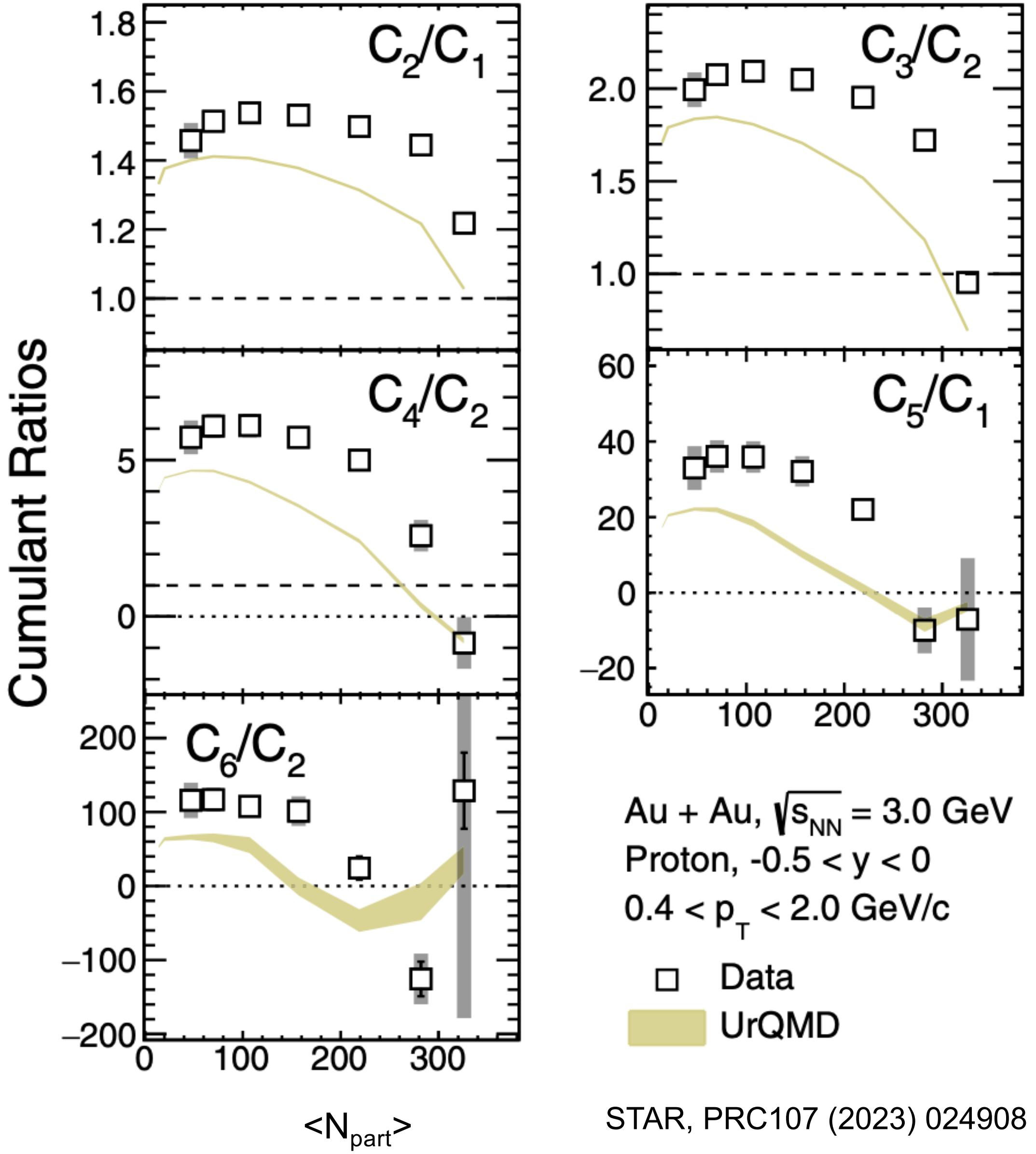




HADES, PRC102 (2020) 024914

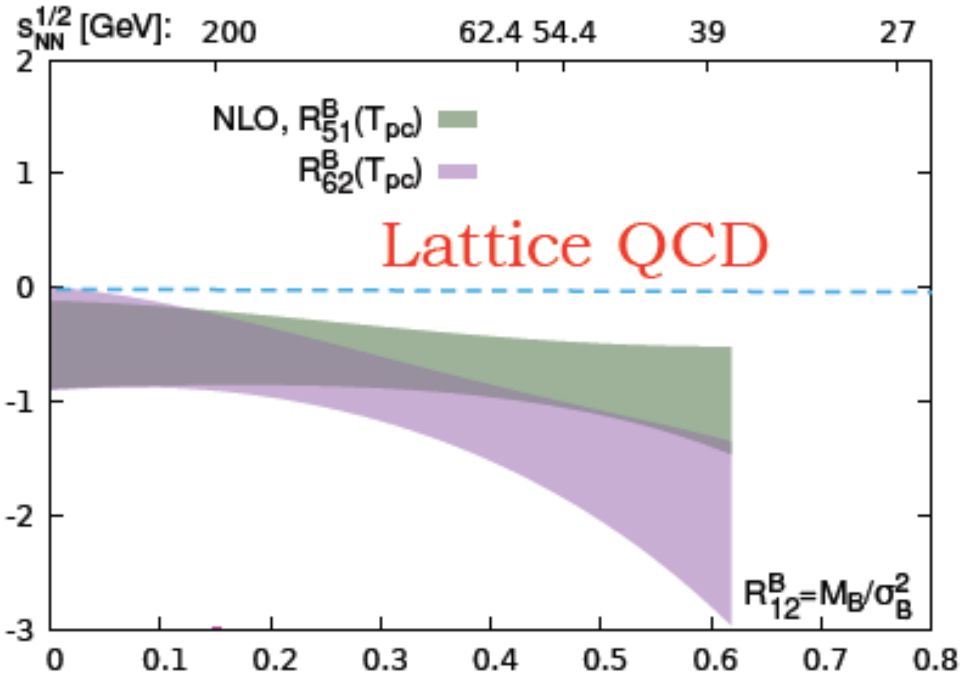
Au+Au 3 GeV STAR
CBWC only

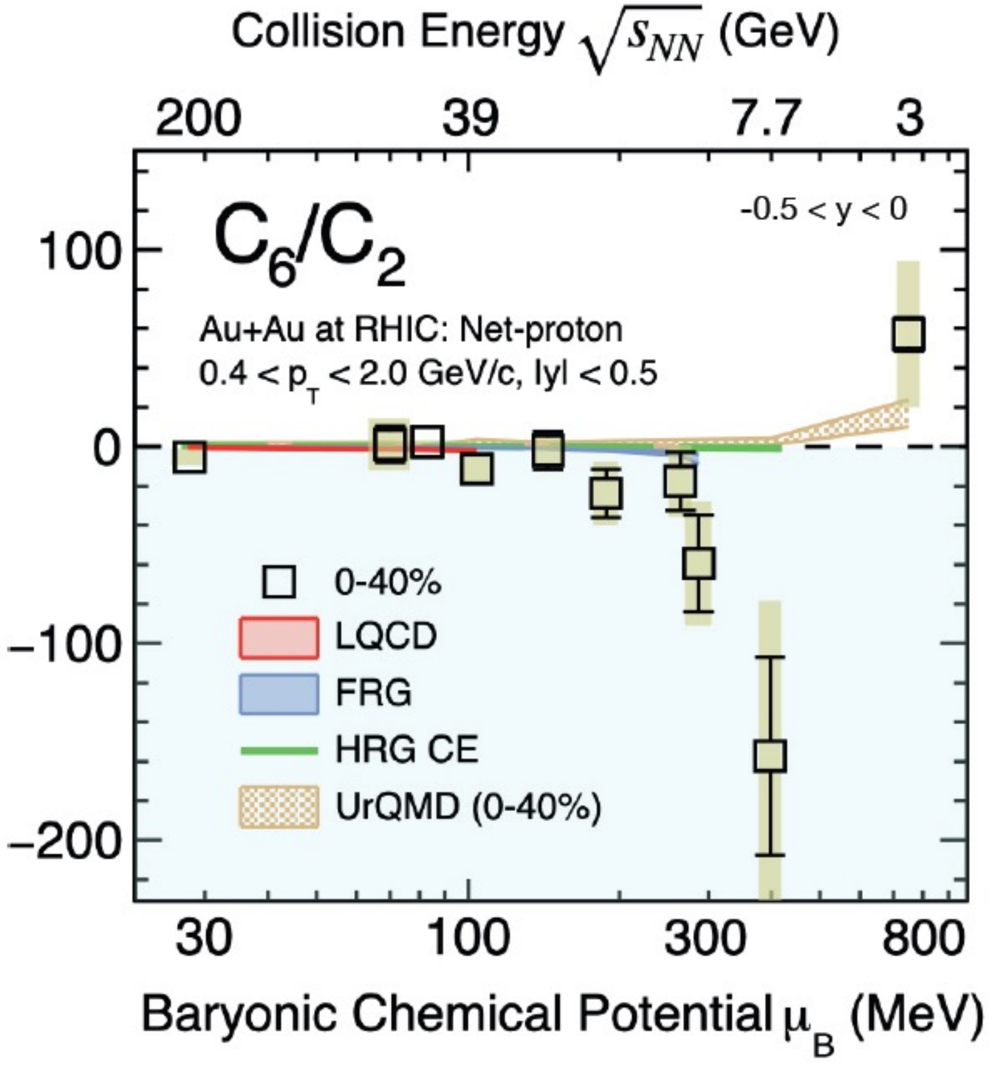
with participant based centrality
without volume correction



STAR, PRC107 (2023) 024908

C_6/C_2 (hyper order fluctuation)



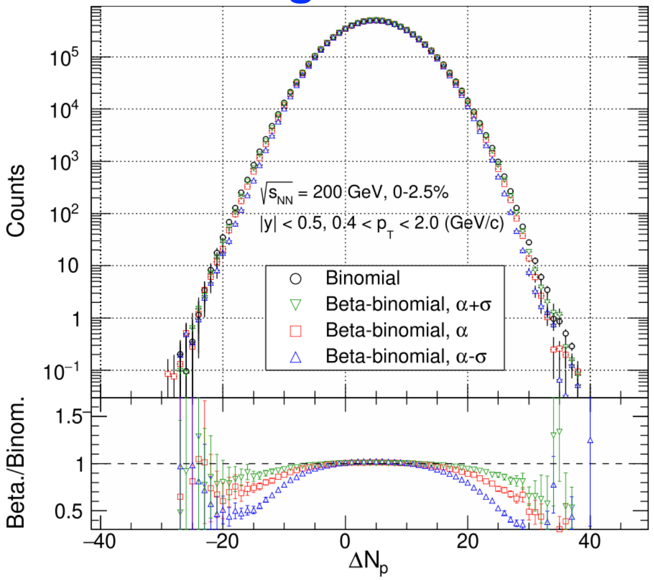


1) Increasingly negative C_6/C_2 down to 7.7 GeV (1.7σ) – consistent with LQCD

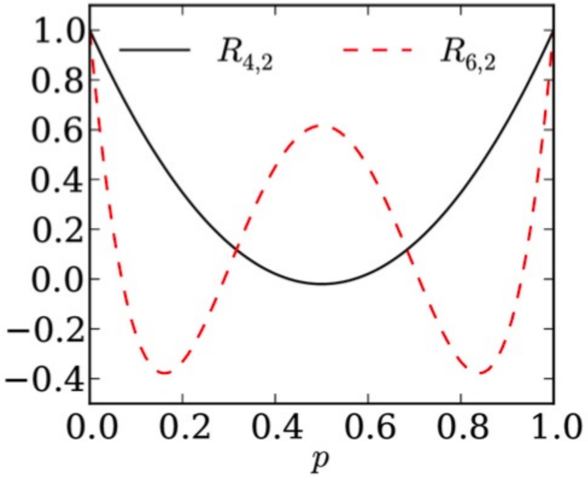
2) $C_6/C_2 > 0$ at 3 GeV, consistent with UrQMD calculation

STAR, PRL 127 (2021) 262301 (2021), PRL 130 (2023) 082301

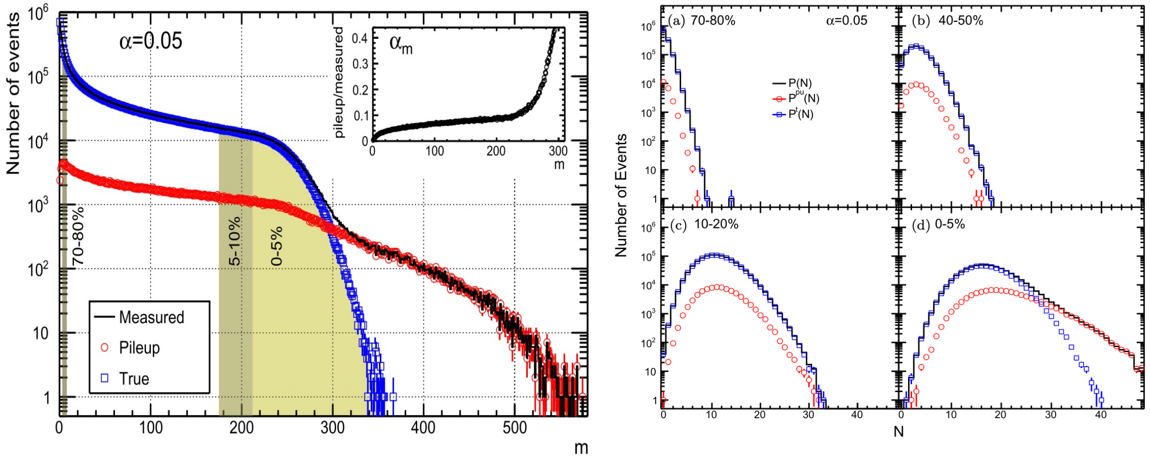
Unfolding eff. correction



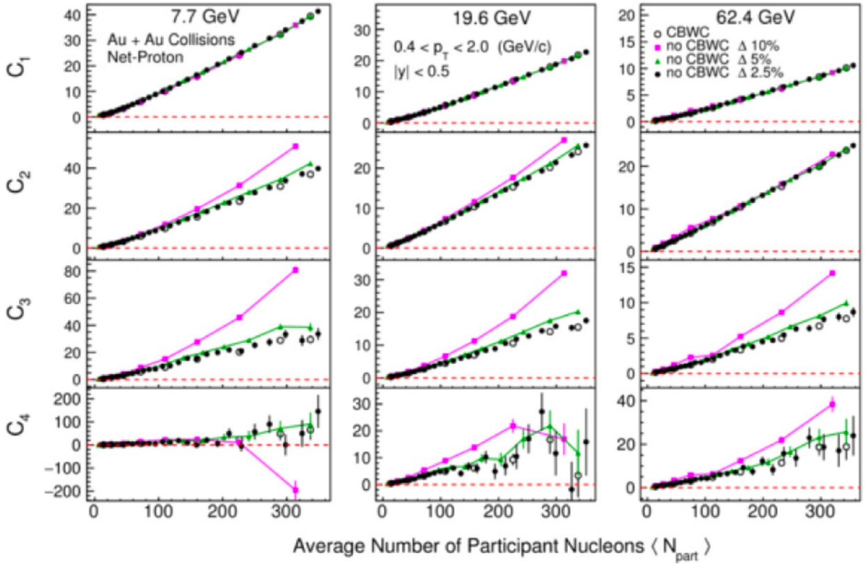
Baryon conservation



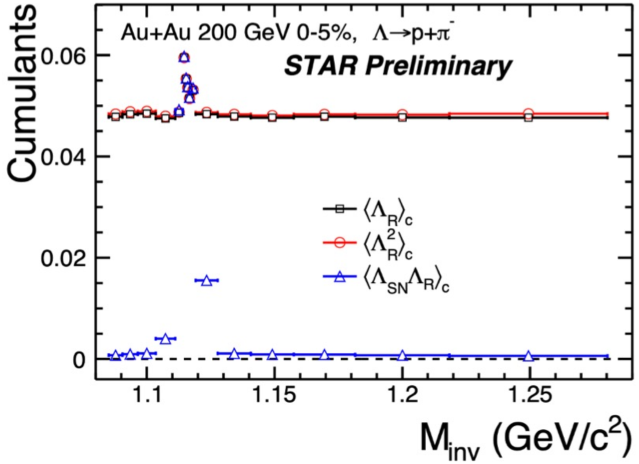
Pile-up correction

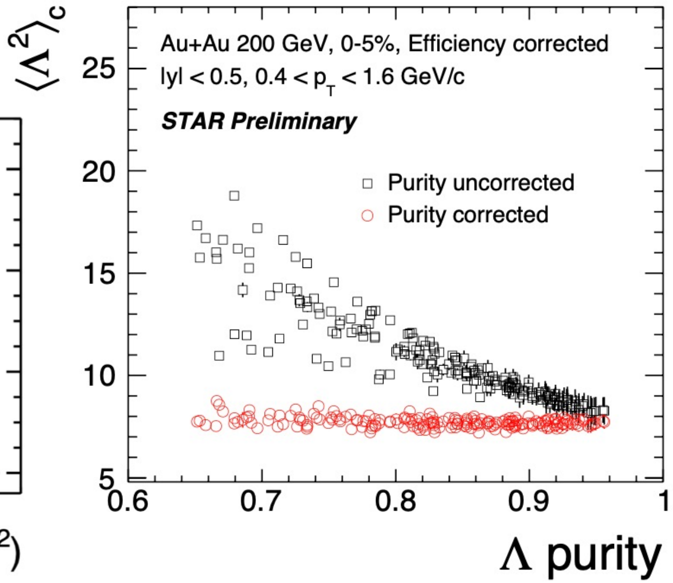


Centrality resolution correction (CBWC)



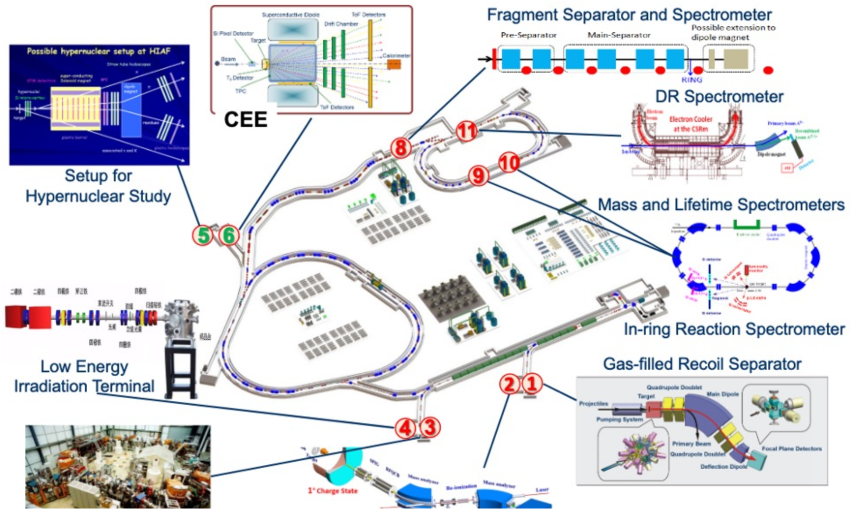
Purity correction





HIAF / HIRFL-CSR in China (2025~)

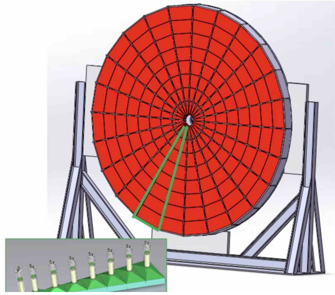
High Intensity heavy ion Accelerator Facility（HIAF）



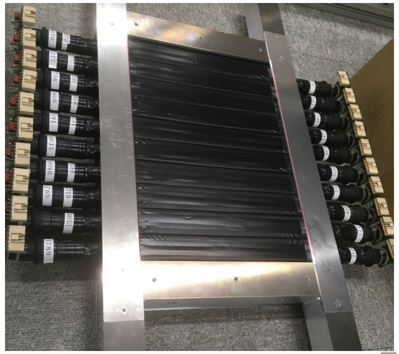
概述 – ZDC探测器介绍

- ZDC探测器安装在CEE的磁铁下游方向，为轮盘结构，前表面距磁铁中心2.95m，束流垂直从轮盘内径里穿过
- ZDC探测器采用“塑闪+光导+真空光电倍增管(PMT)”设计方案
- ZDC探测器测量前向区带电粒子在ZDC里的沉积能量和击中位置信息，确定核核碰撞中事件碰撞中心度和事件平面，为CEE以后的物理分析提供基本测量量

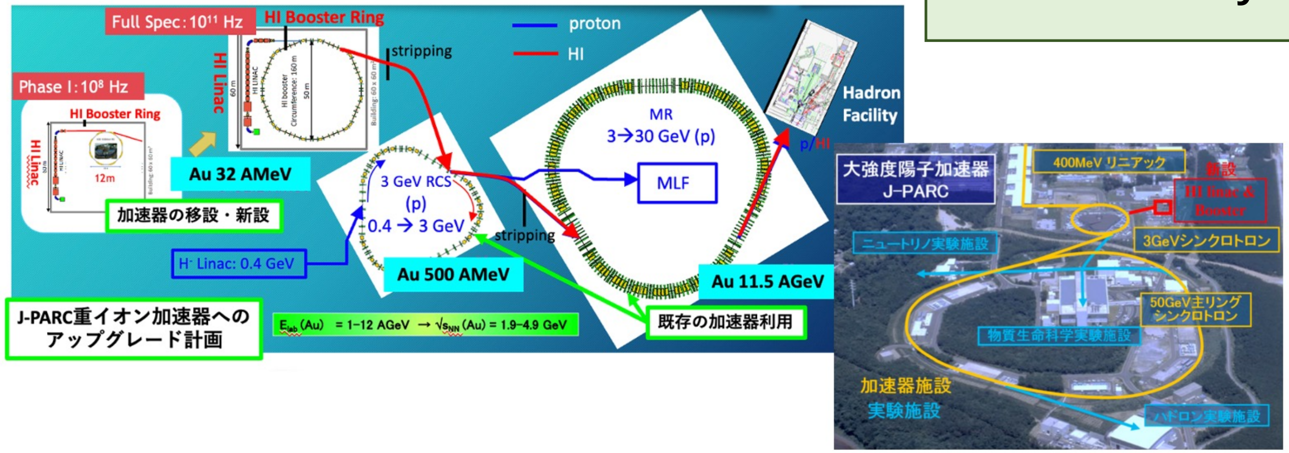
ZDC探测器的几何参数	
距磁铁中心距离	2.95 m
ZDC轮盘内径	5 cm
ZDC轮盘外径	100 cm
探测模块数	192 (24扇区 × 8模块/扇区)
电子学道数(双打拿极输出)	384
ZDC主要技术指标	
探测效率	> 95%
通道占有度	< 15%
有效面积	> 1m²



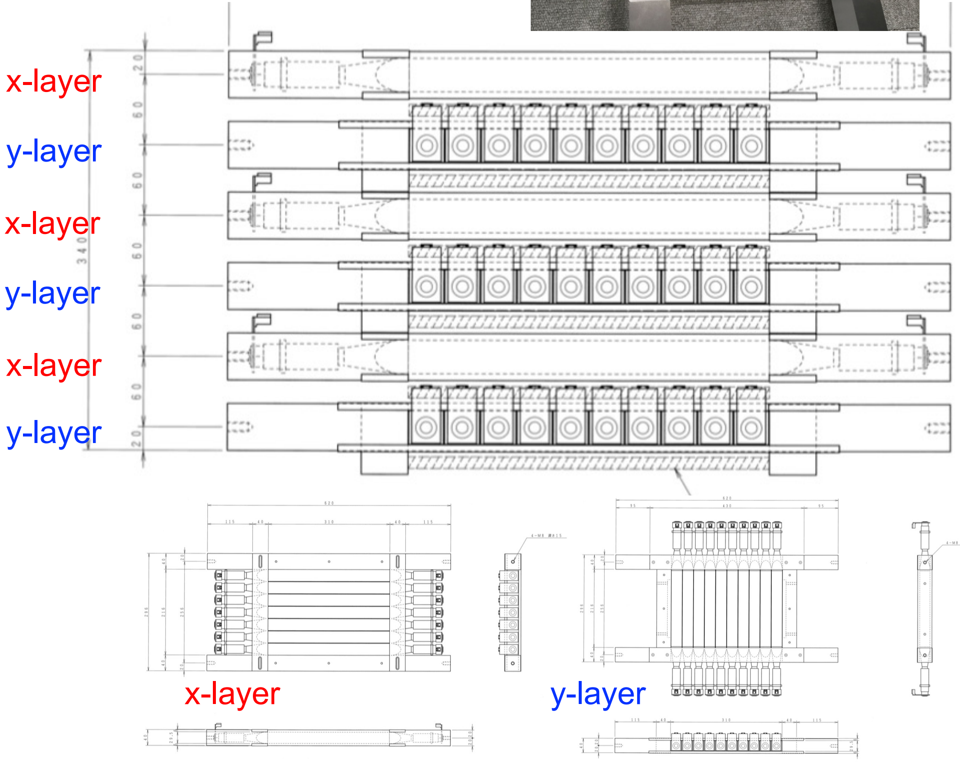
ZDC for centrality and event plane at CEE experiment



茨城県東海村　J-PARC（原研・KEK）

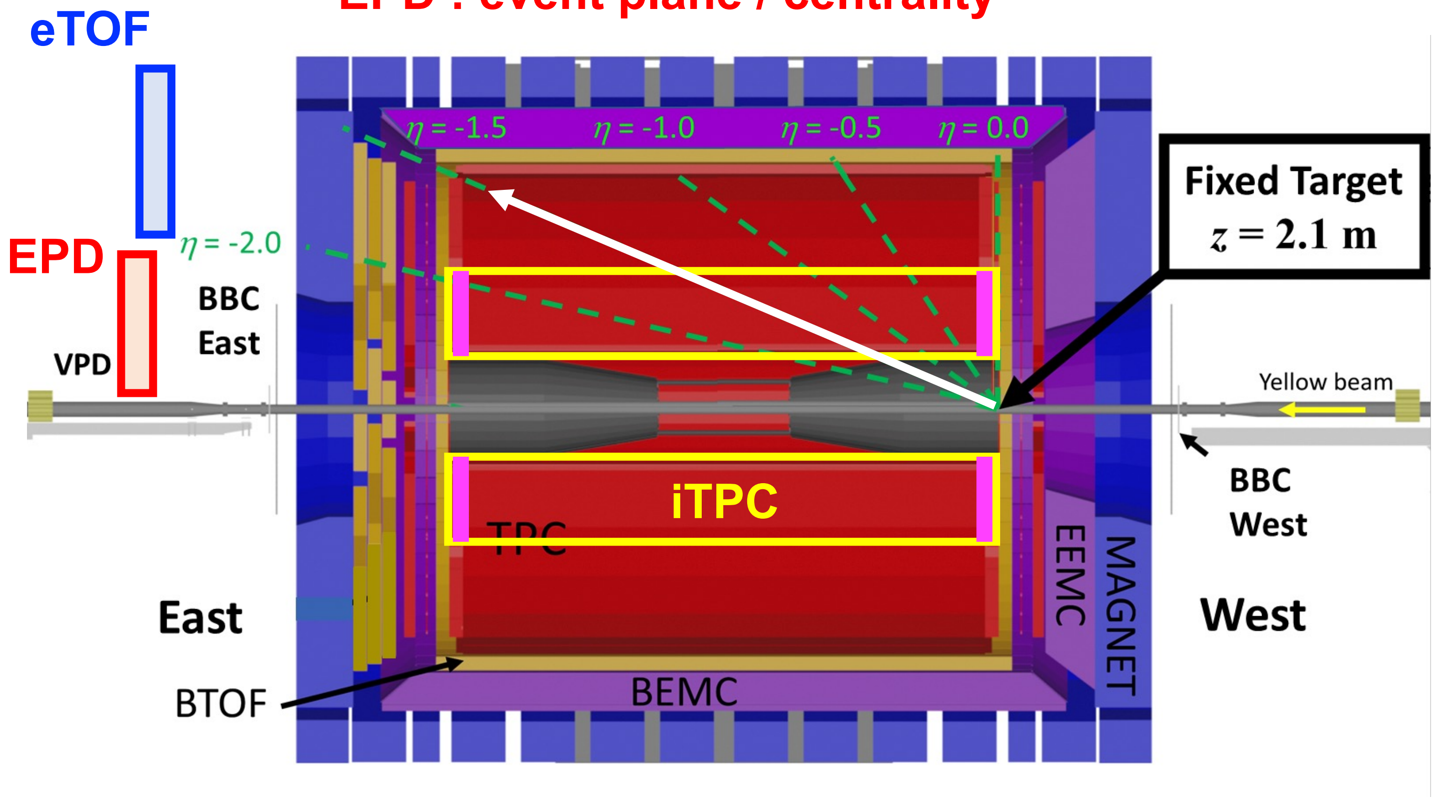


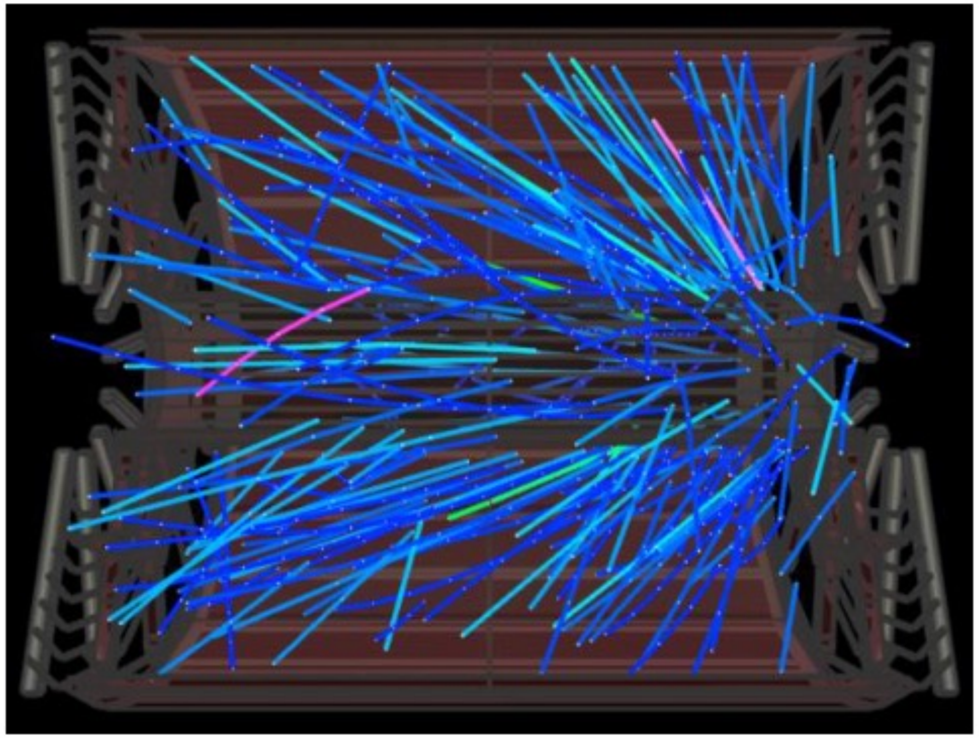
Neutron detector FAIR-CBM and J-PARC Heavy-Ion

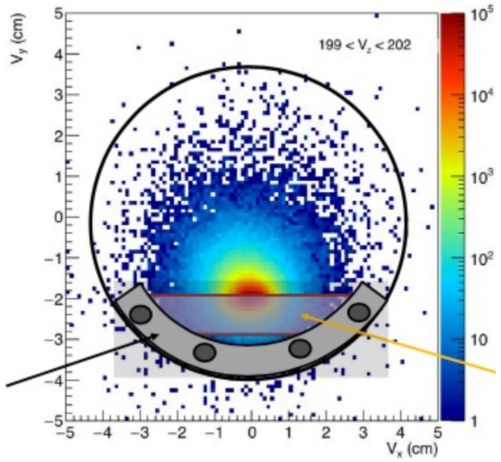


Fixed Target Set-up (FXT) at STAR Experiment

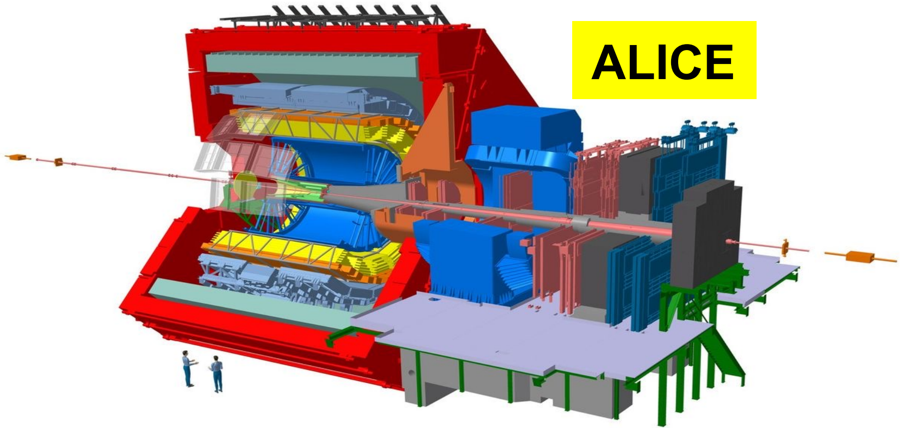
iTPC : inner TPC, forward tracking
eTOF : end-cap TOF, forward PID
EPD : event plane / centrality

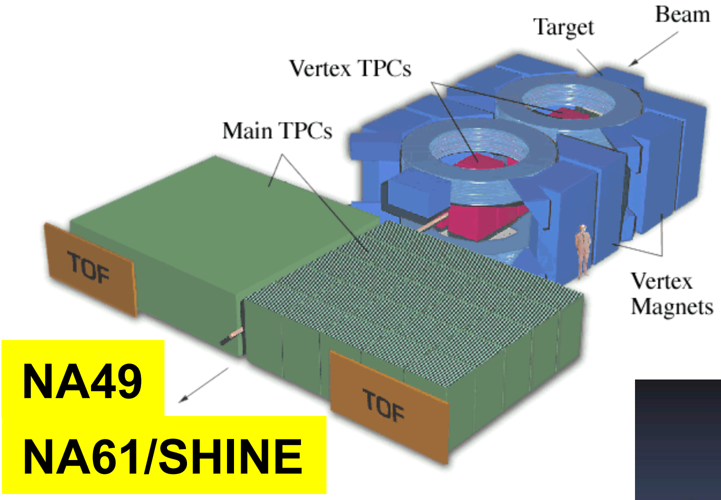


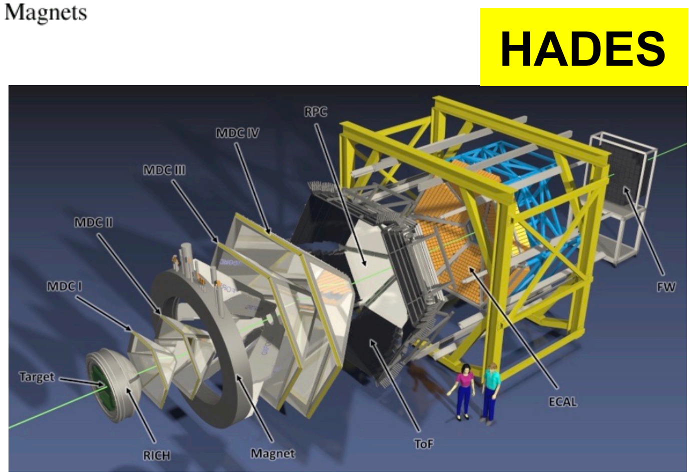


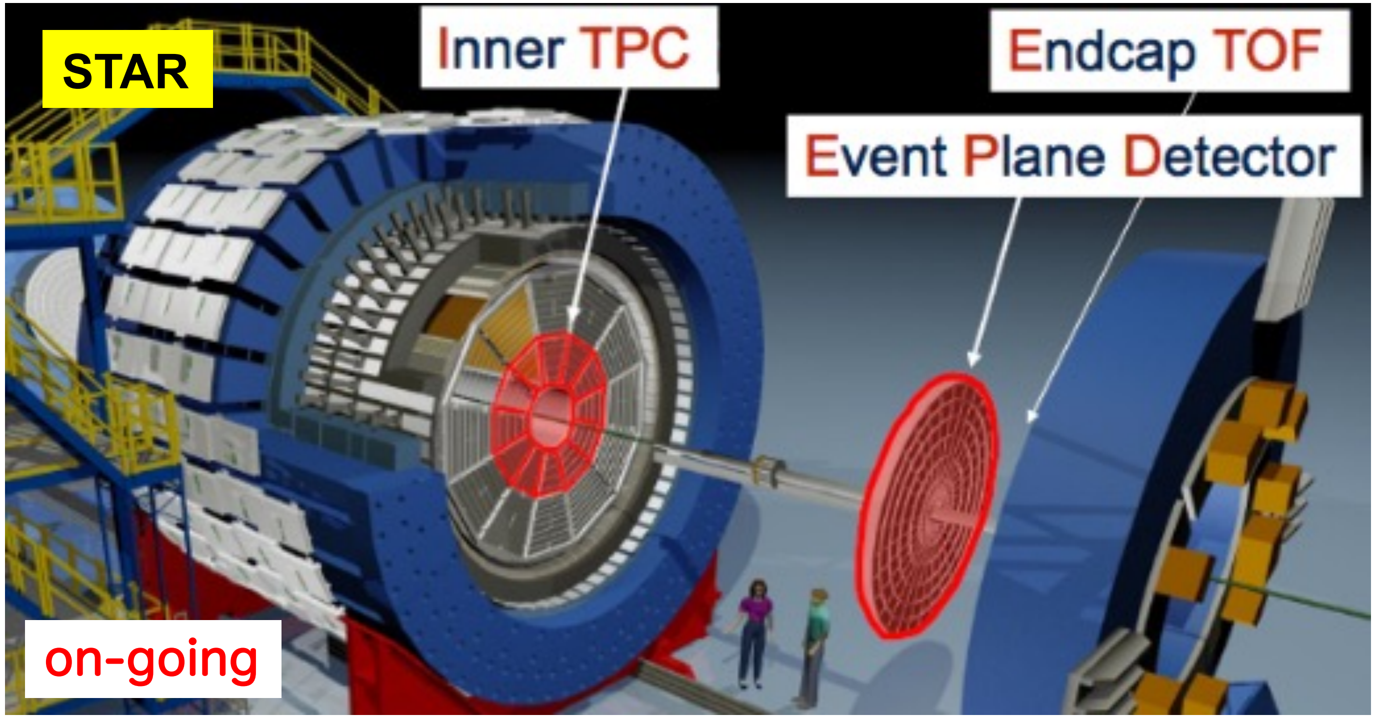


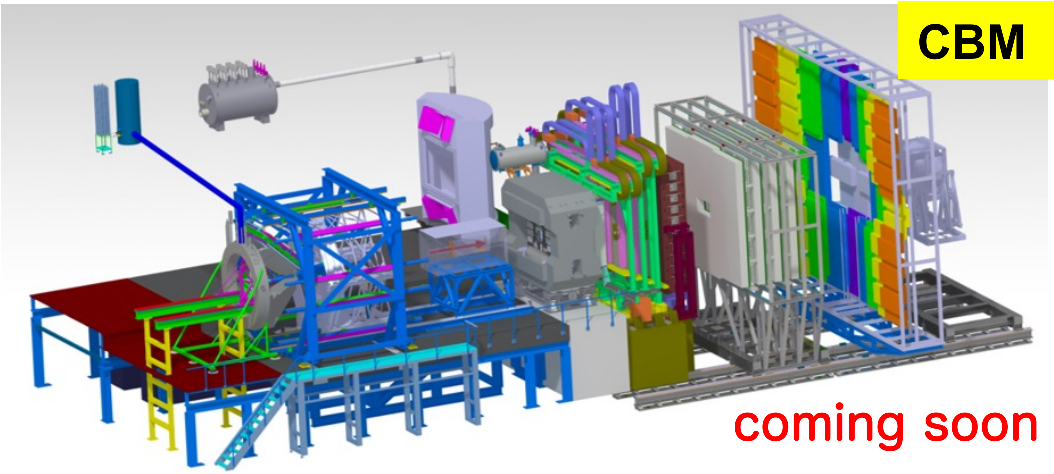
Experiments at CERN, GSI, BNL



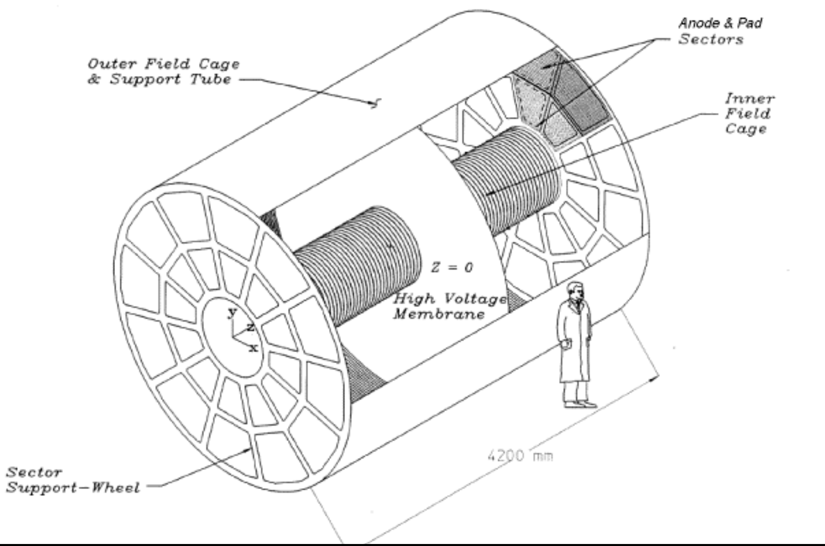


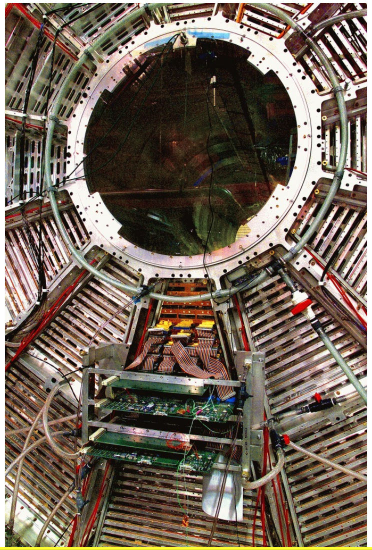


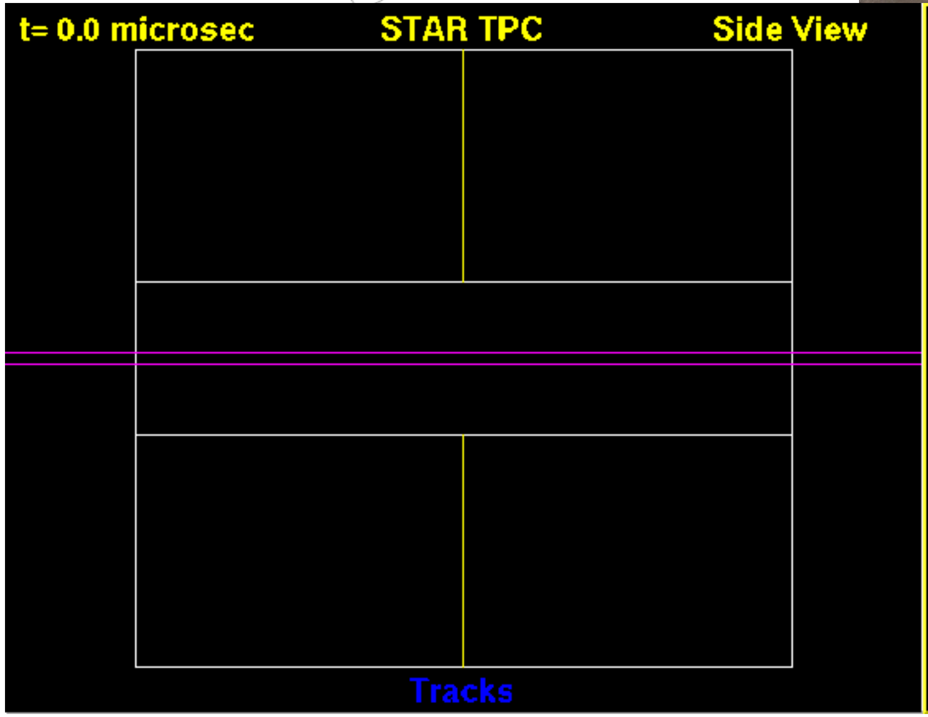


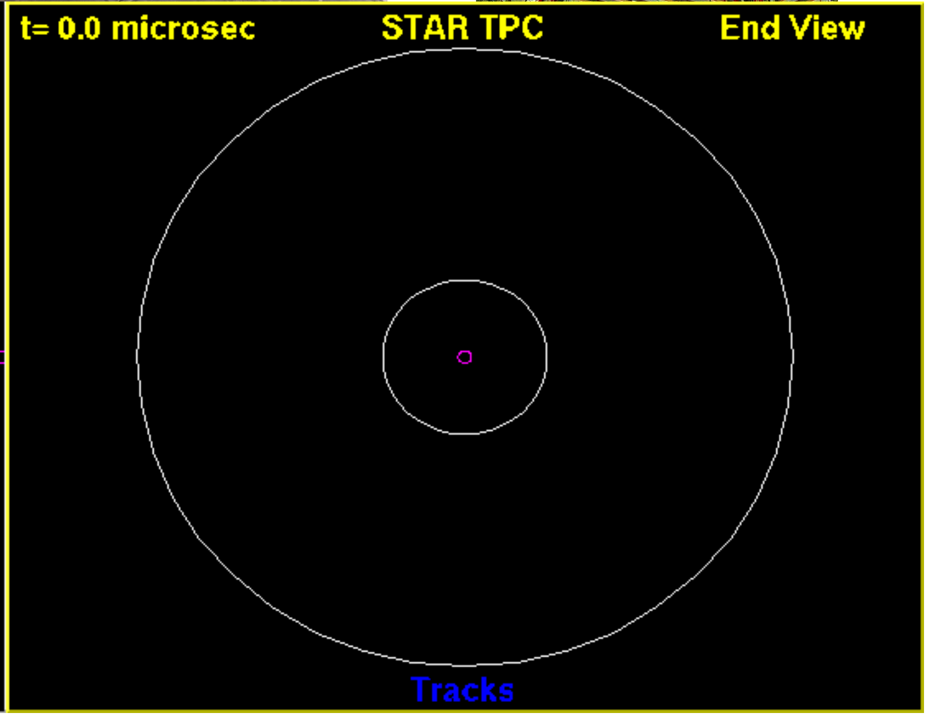


時間射影型粒子検出器(TPC) 3次元飛跡測定の原理





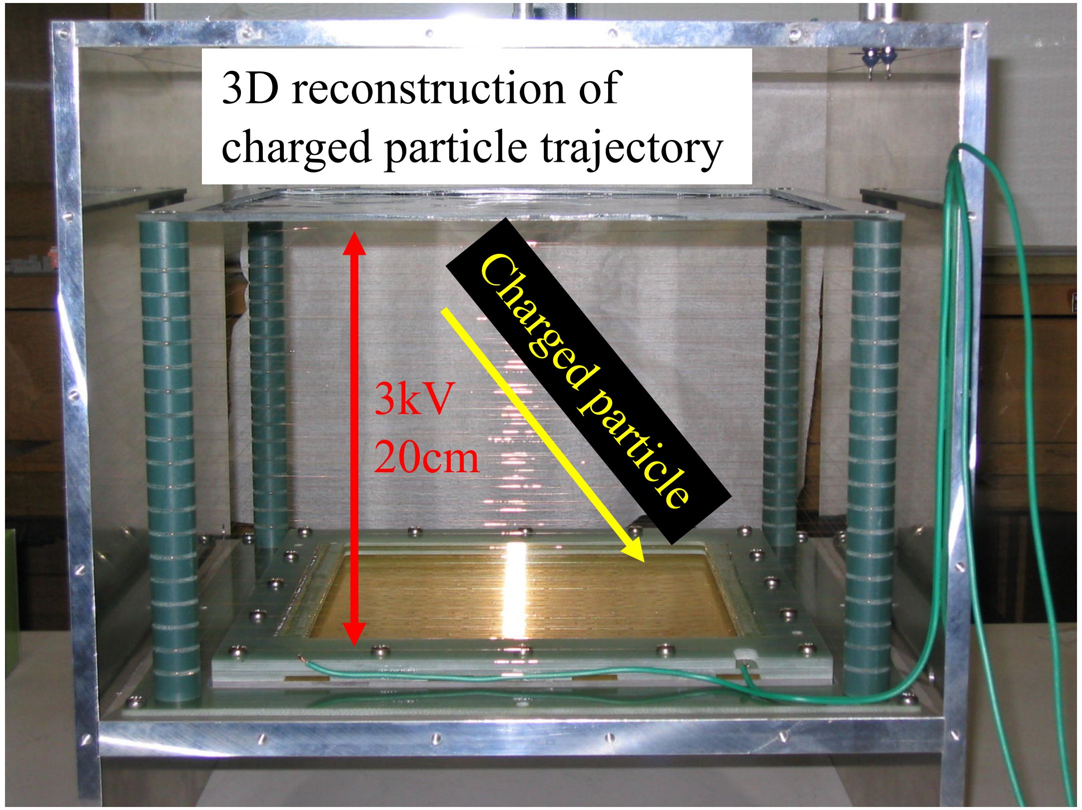


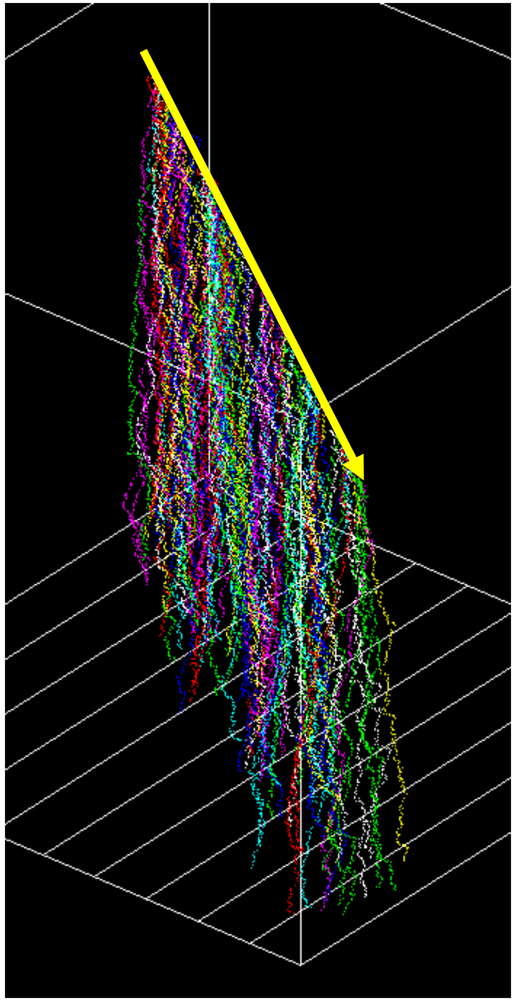


荷電粒子の飛跡検出器
時間射影型ガス検出器(TPC)
による3次元飛跡の再構成

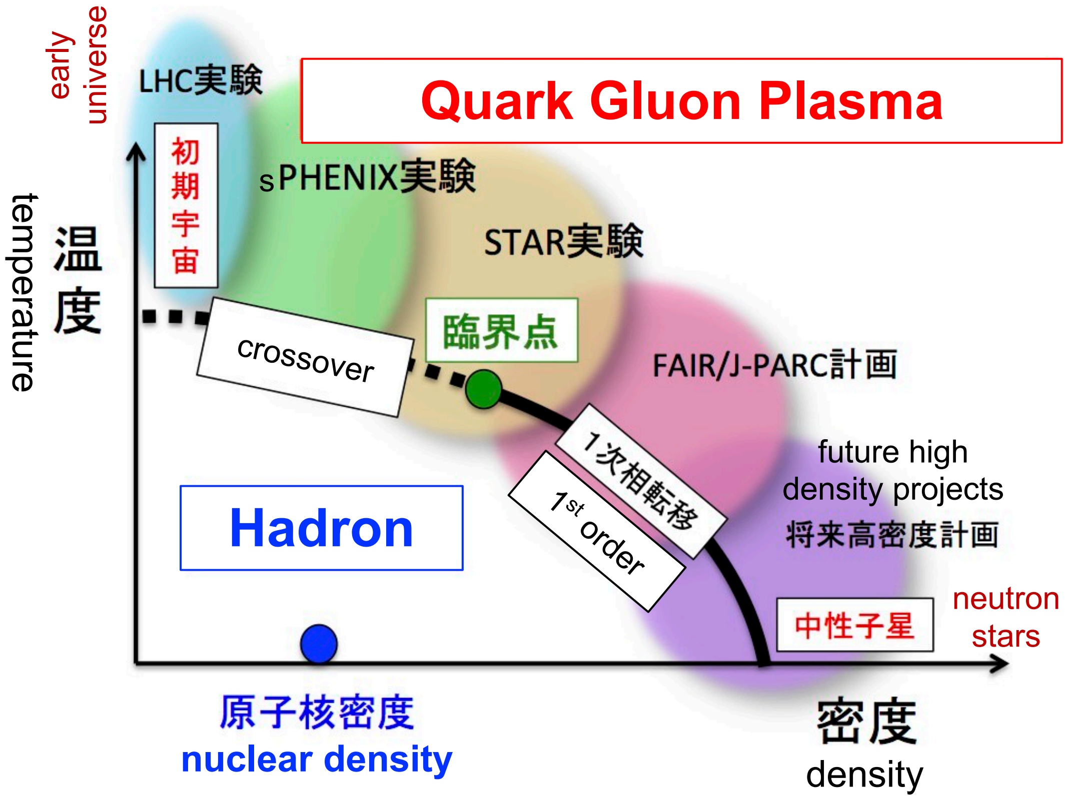
写真4.2.1　α線の飛跡の例

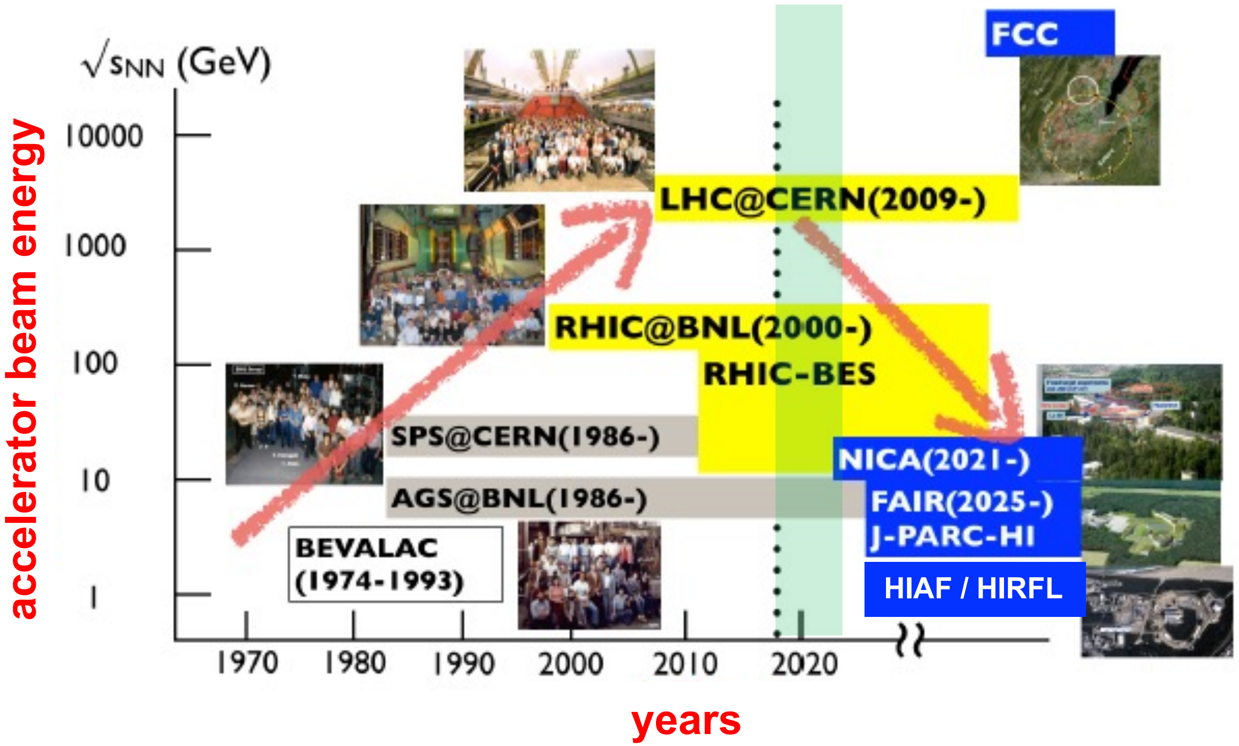
図4.3.1　β線の飛跡の例





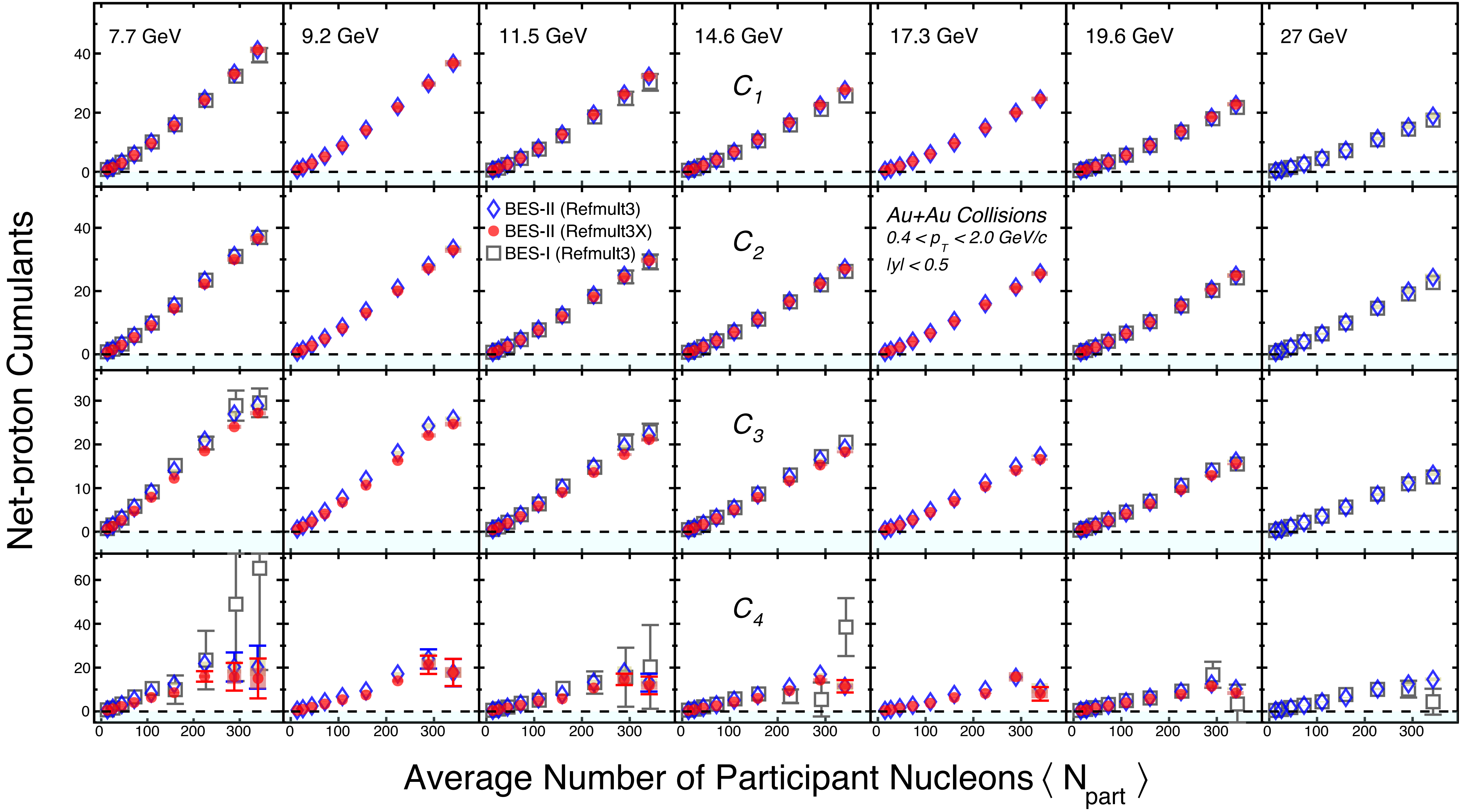
History of Heavy-Ion Facilities and My Interests …

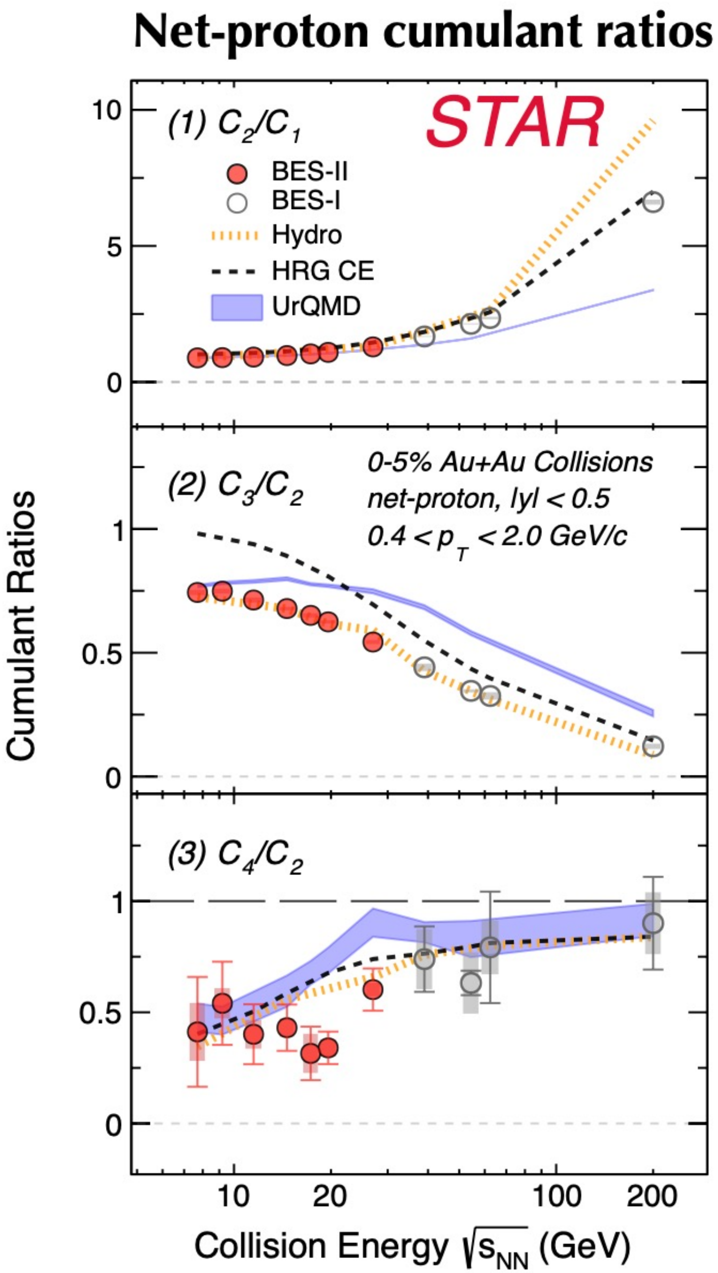


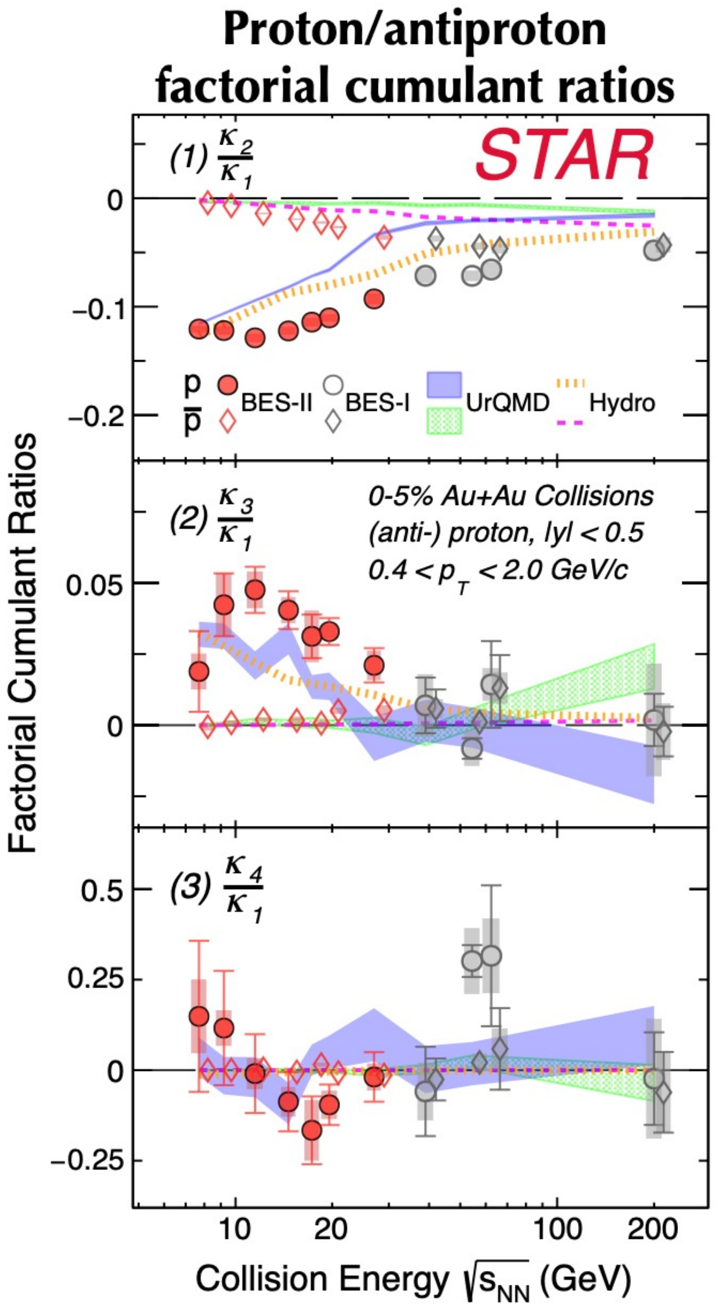


- **Beam Energy Scan at High Baryon Density**
- **Flow, correlation and fluctuation studies**

Back-up slides

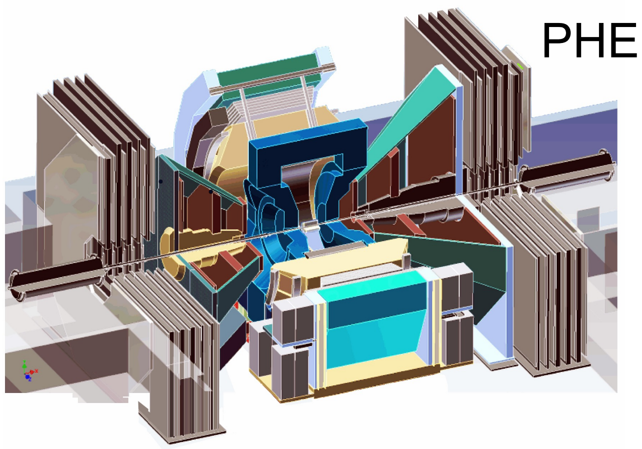

7.7 GeV
9.2 GeV
11.5 GeV
14.6 GeV
17.3 GeV
19.6 GeV
27 GeV
C1
C2
C3
C4
BES-II (Refmult3)
BES-II (Refmult3X)
BES-I (Refmult3)
Au+Au Collisions
0.4 < pT < 2.0 GeV/c
|y| < 0.5
Net-proton Cumulants
Average Number of Participant Nucleons ⟨ Npart ⟩


Net-proton cumulant ratios
(1) C2/C1
STAR
BES-II
BES-I
Hydro
HRG CE
UrQMD
(2) C3/C2
0-5% Au+Au Collisions
net-proton, |y| < 0.5
0.4 < pT < 2.0 GeV/c
(3) C4/C2
Cumulant Ratios
Collision Energy √sNN (GeV)

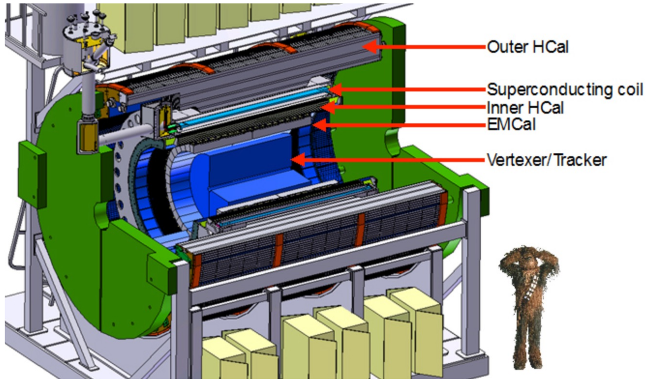

Proton/antiproton
factorial cumulant ratios
(1) κ2/κ1
STAR
p
p̄
BES-II
BES-I
UrQMD
Hydro
(2) κ3/κ1
0-5% Au+Au Collisions
(anti-) proton, |y| < 0.5
0.4 < pT < 2.0 GeV/c
(3) κ4/κ1
Factorial Cumulant Ratios
Collision Energy √sNN (GeV)

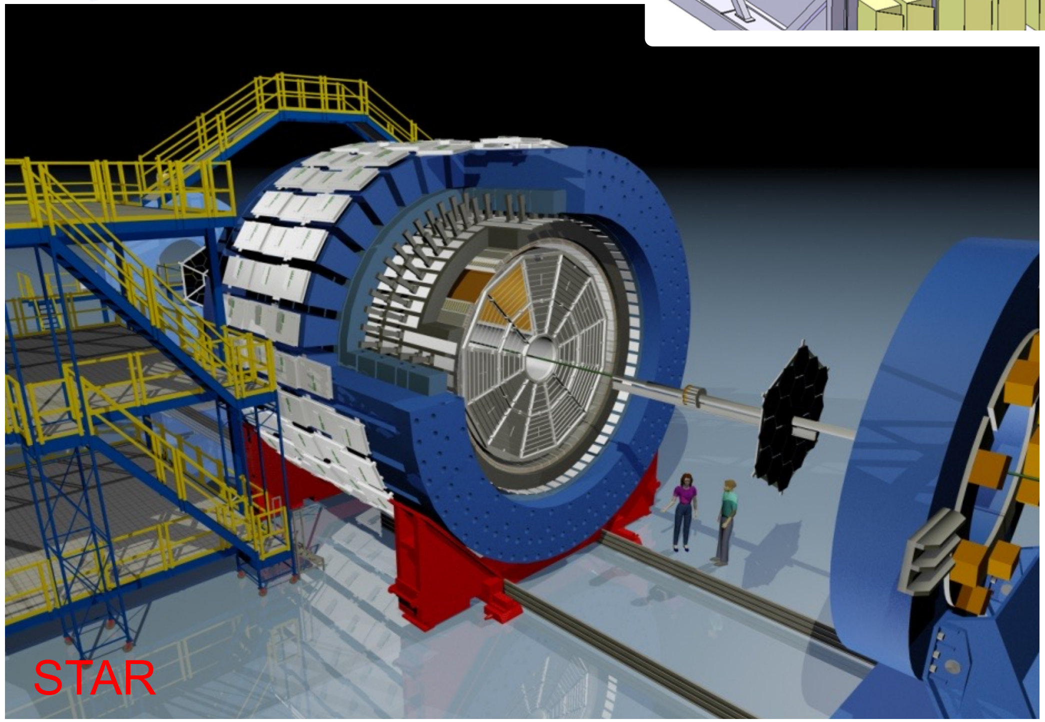
RHICやLHC加速器における実験

PHENIX

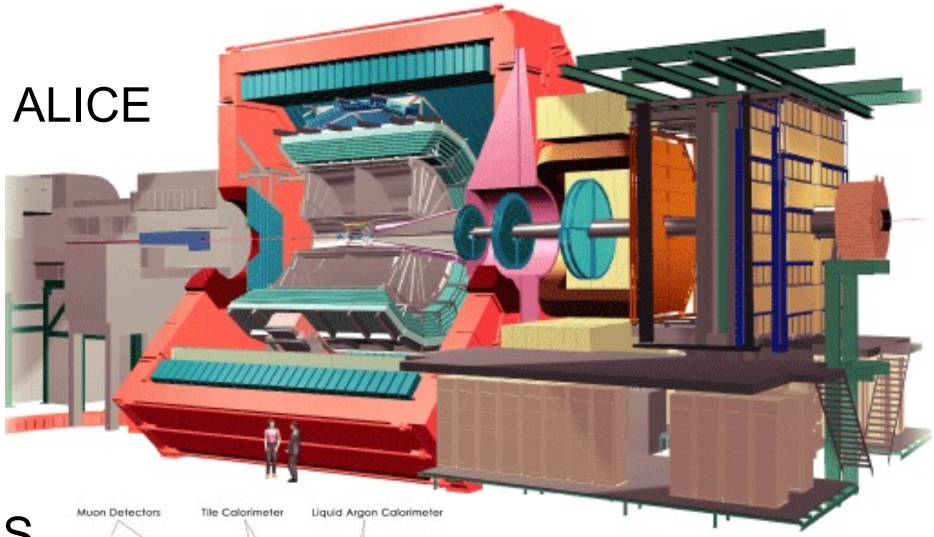


sPHENIX

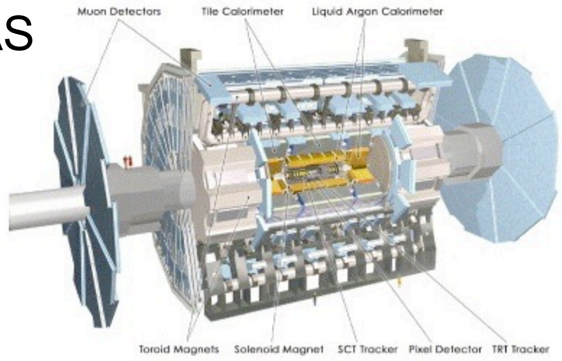




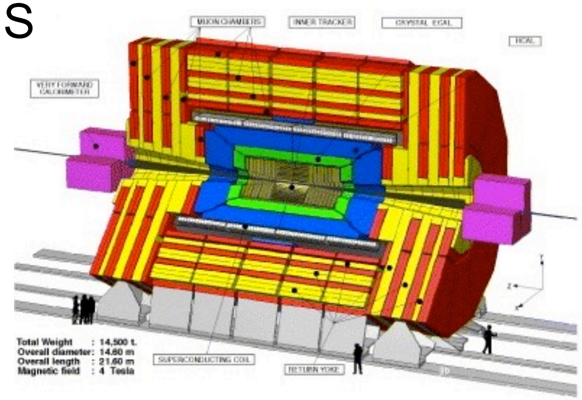
ALICE

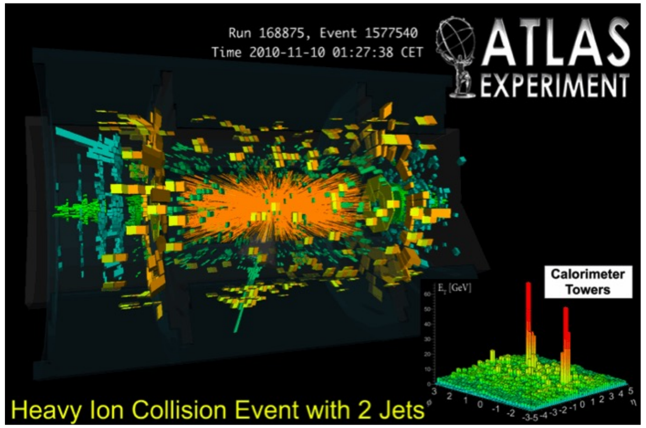


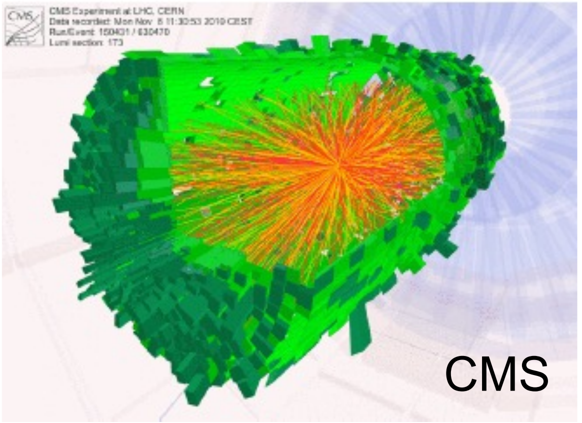
ATLAS

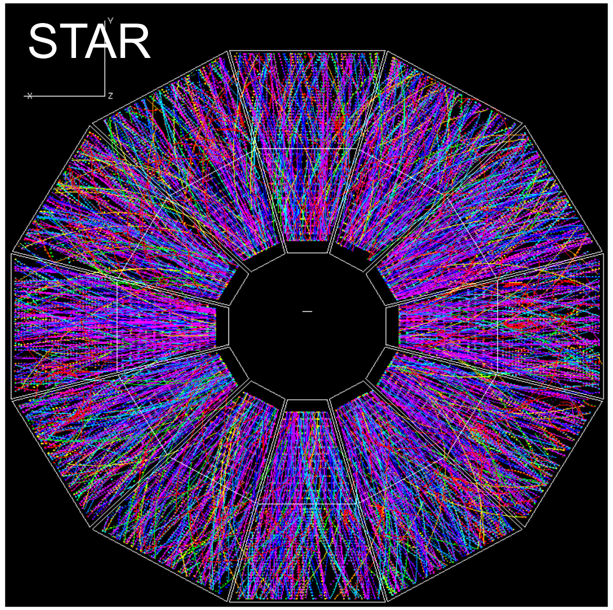


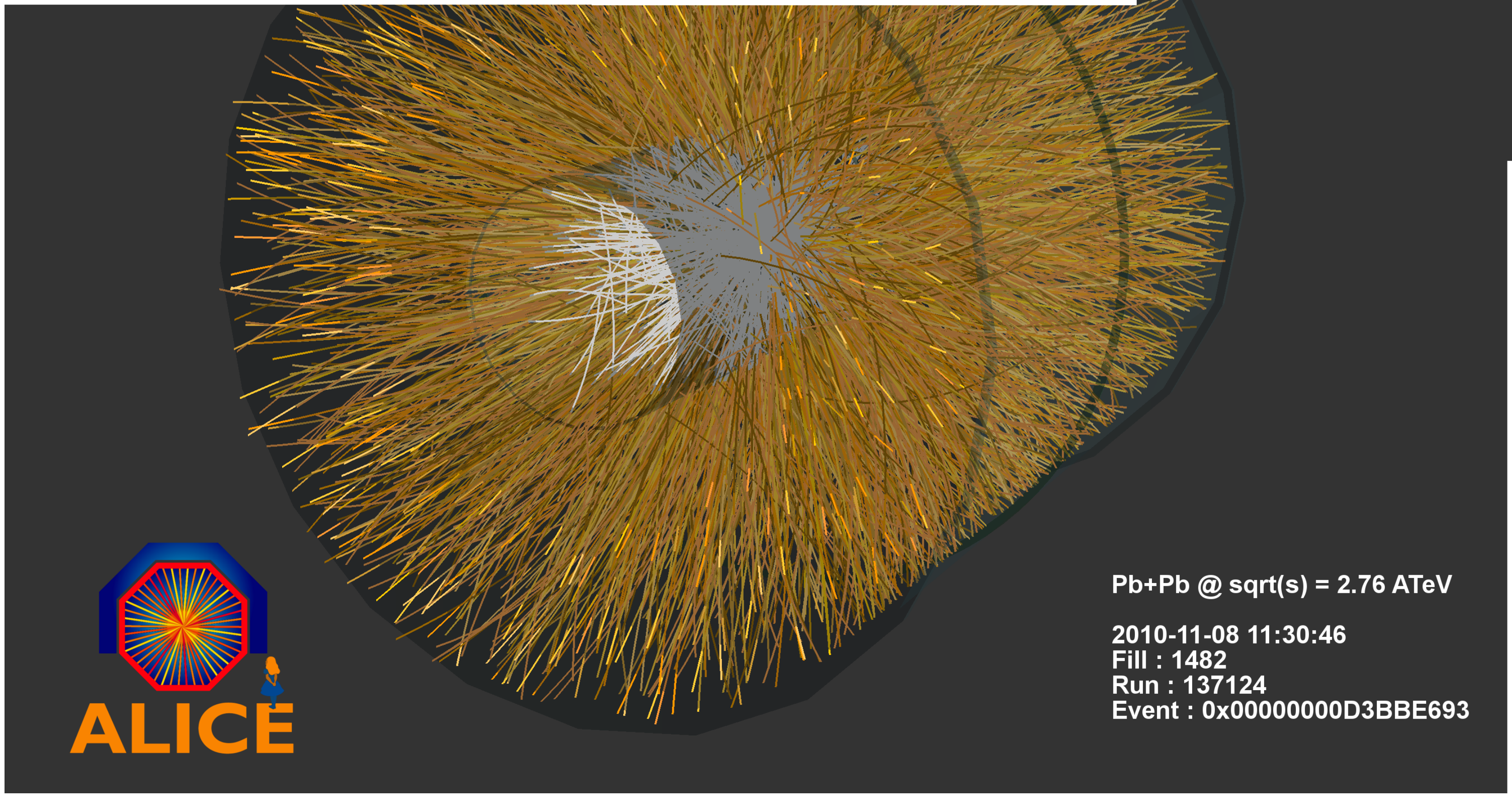
CMS

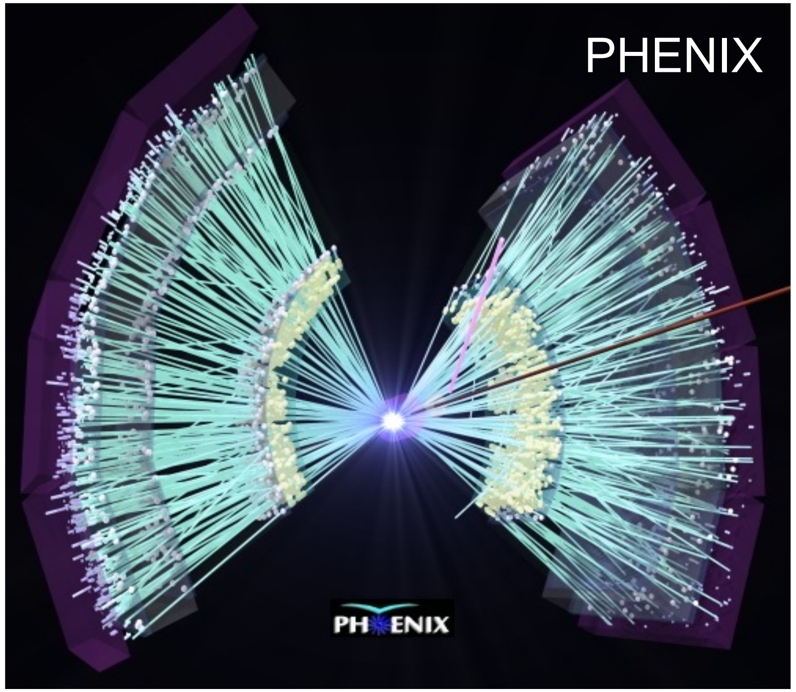



Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET
ATLAS
EXPERIMENT
Calorimeter
Towers
Heavy Ion Collision Event with 2 Jets


CMS


STAR


ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693


PHENIX