Post-QM2022:

Results from Beam Energy Scan
(ビームエネルギー走査、渦等の実験結果)

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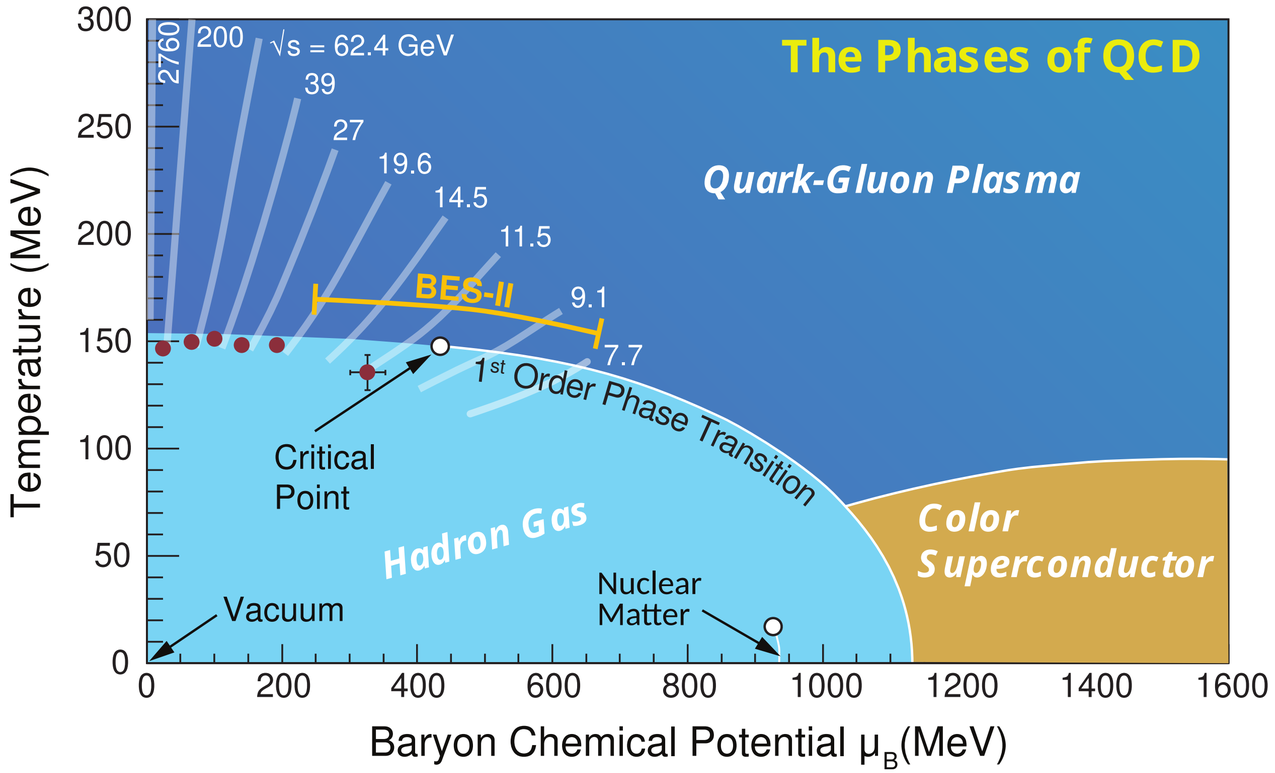
第39回Heavy Ion Cafe & 第35回Heavy Ion Pub合同研究会「ポストQM2022」
@名古屋大学, 4/30/2024

Beam Energy Scan (BES)

"Conjectured" QCD phase diagram



A. Bzdak et al., Phys. Rep. 853 (2020) 1-87

Main purposes of BES program:
- Identify location of critical point (CP)
- Search for the first-order phase transition
- Search for onset/turn-off of QGP formation

Lattice QCDによると

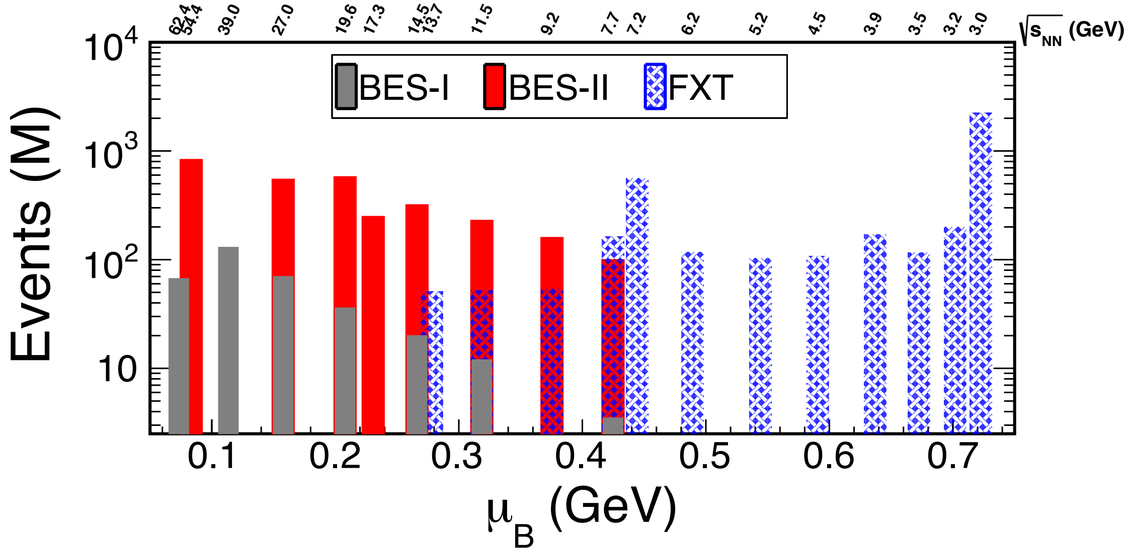
- A smooth crossover near μ_B~0 (μ_B<300 MeV)
- Pseudo-critical temperature at $\mu_B = 0$: $T_{pc} = 156.5 \pm 1.5$ MeV

Y. Aoki et al., Nature 443, 675 (2006)
A. Bazavov et al., PLB795 (2019) 15

Outline

- Particle production
- Fluctuations
- (a bit on) Femtoscopy ←maybe covered by 関口さん
- Vorticity and polarization
- (a bit on) Dilepton ←maybe covered by 八野さん

Data taken by STAR BES-I&II + Fixed-Target program



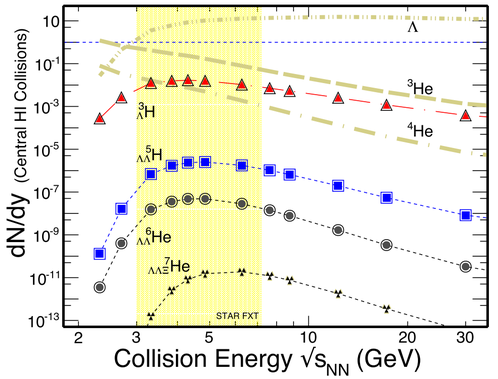
＊Mostly based on STAR results but a few from other experiments

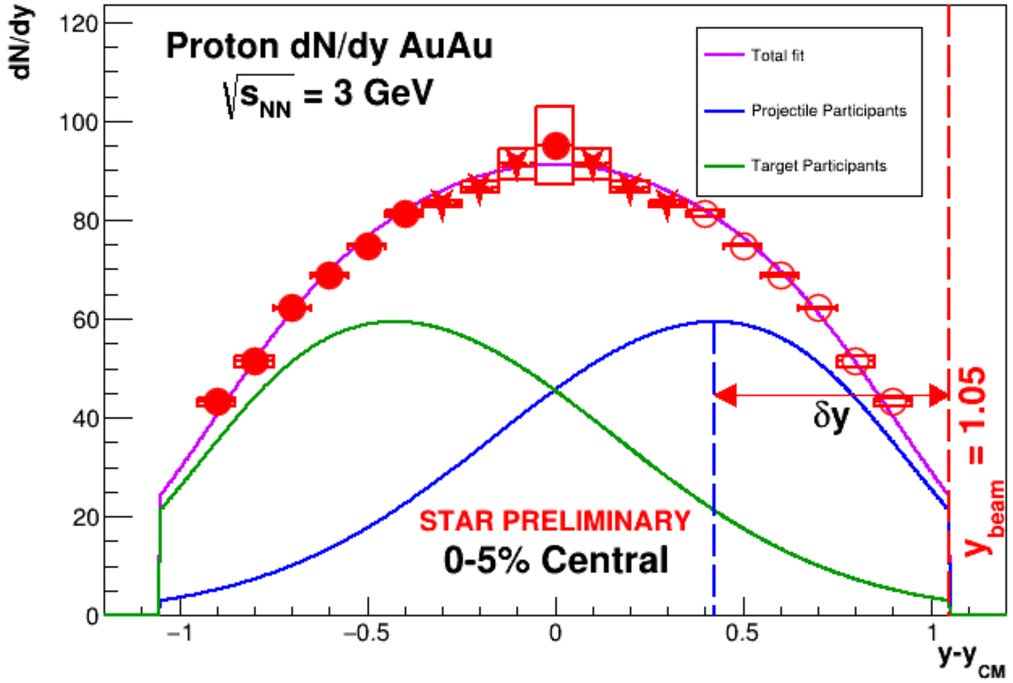
＊Sorry for a mixture of English and Japanese

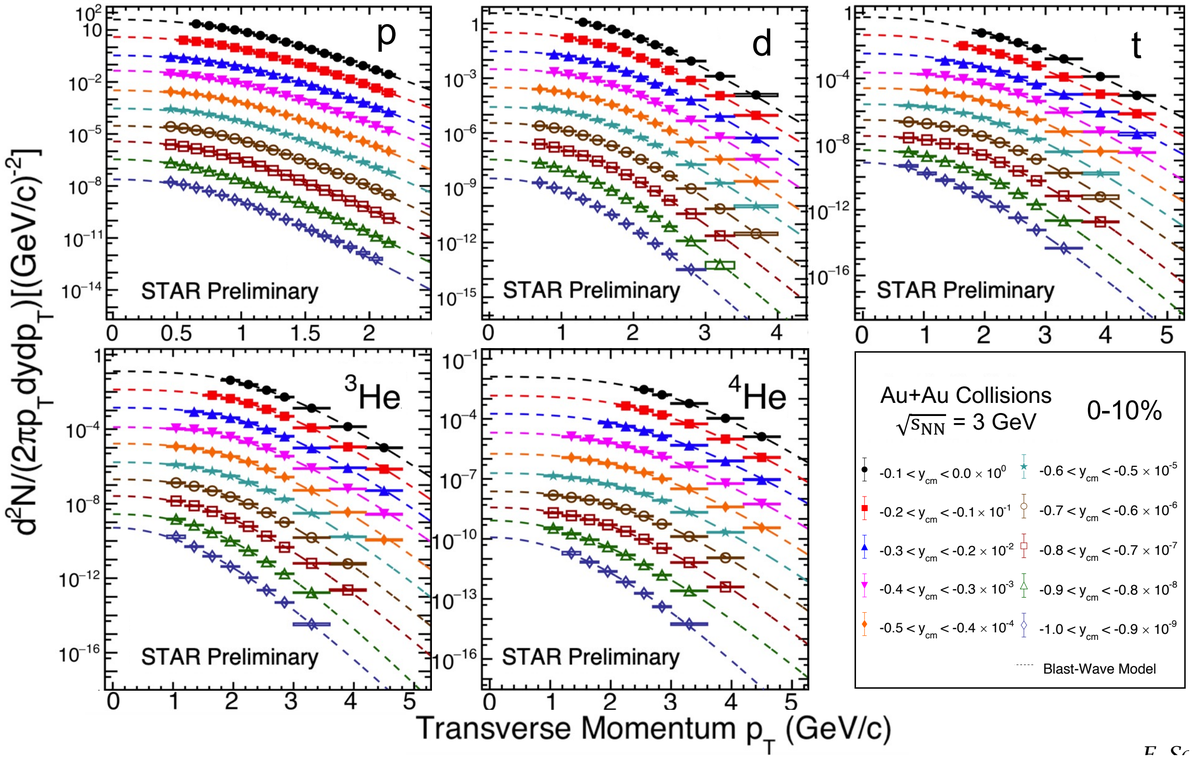
Particle production at 3 GeV

Talks by H. Liu (STAR) and B. Kimelman (STAR)

N. Xu et al., AAPPS Bull.31(2021)1





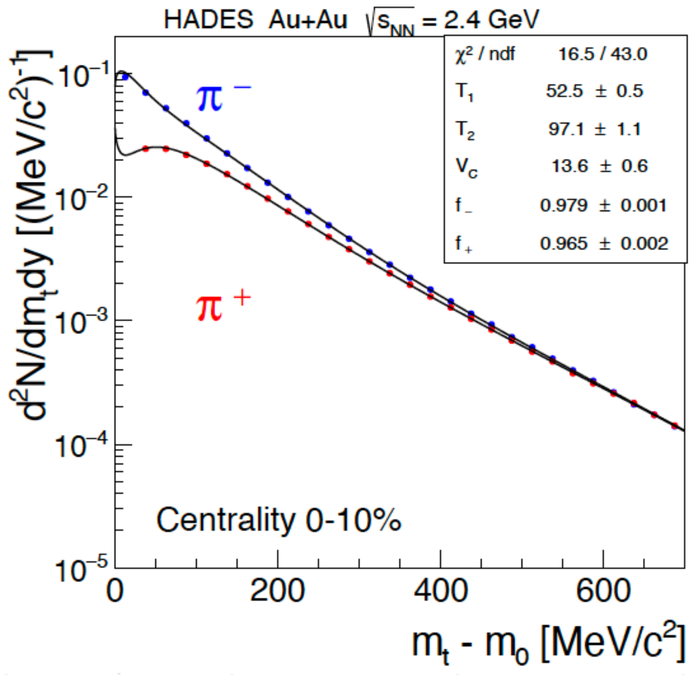


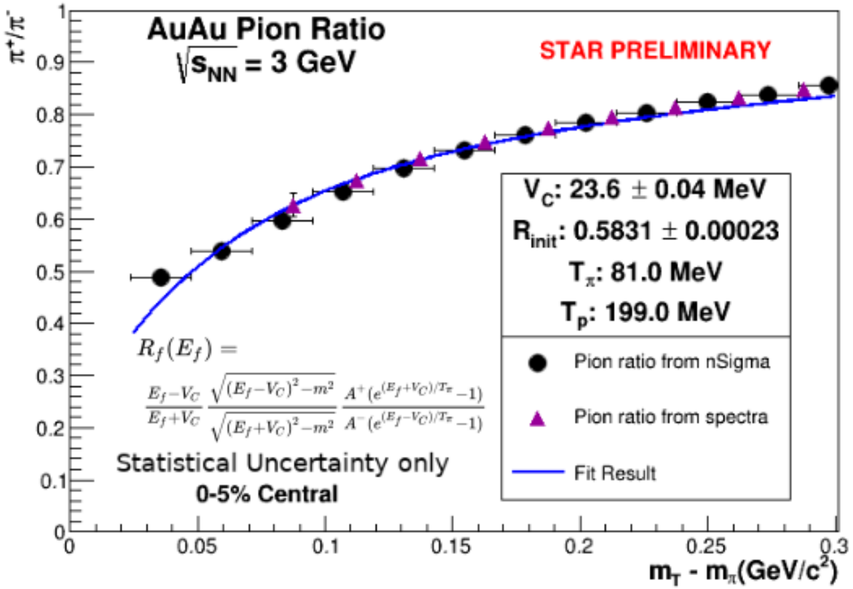
3 GeVでは、バリオンストッピングにより、バリオンが支配的な領域。

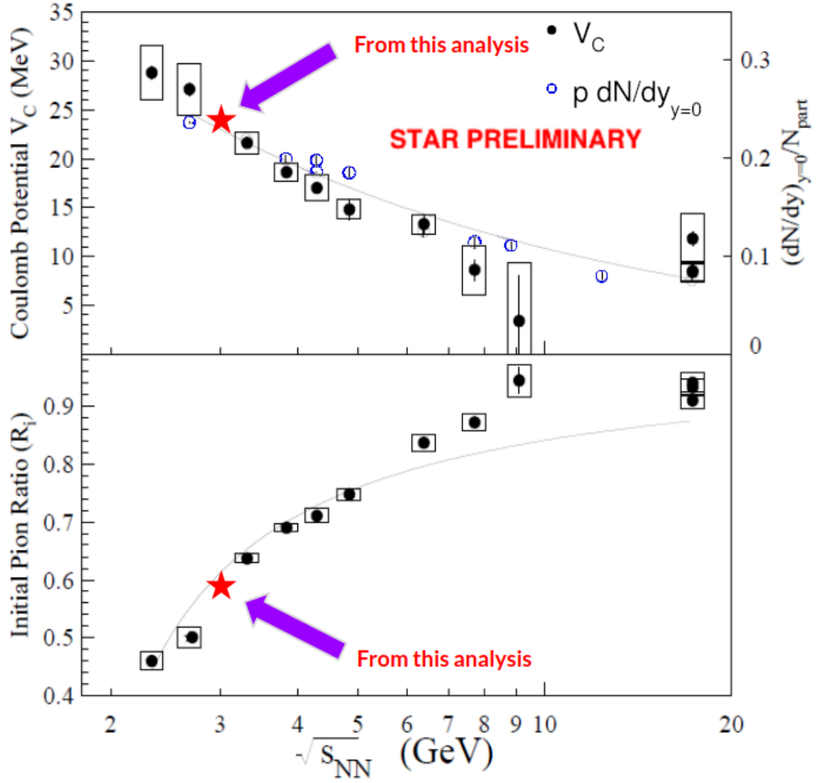
それに伴い、軽い原子核やハイパー核などがより多く生成されるようになる。

Effect of Coulomb potential

Talks by S. Harabasz (HADES) and B. Kimelman (STAR)



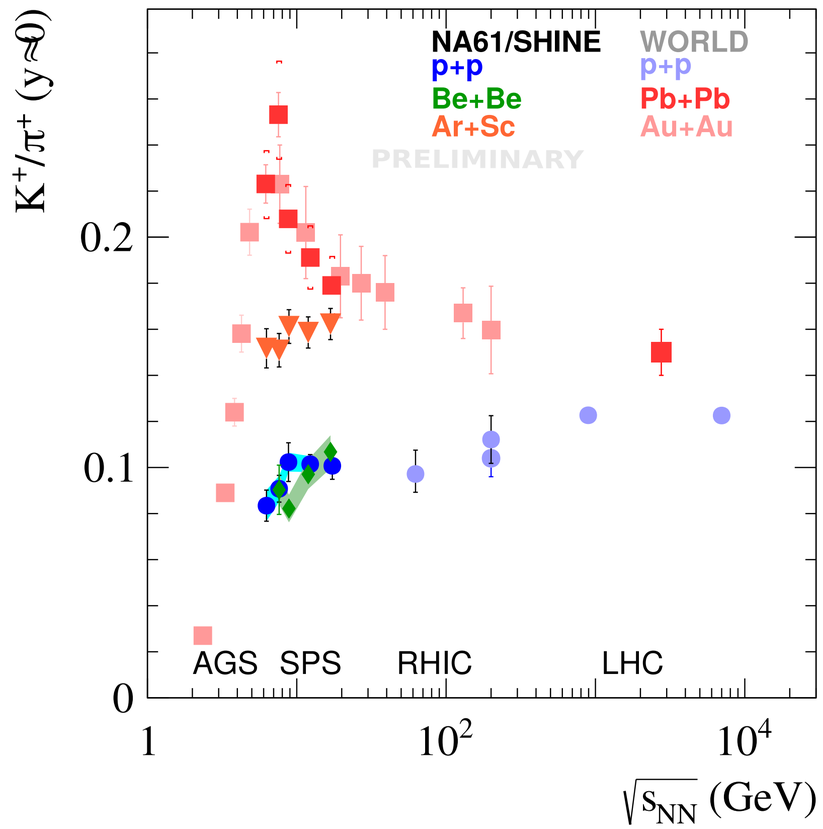




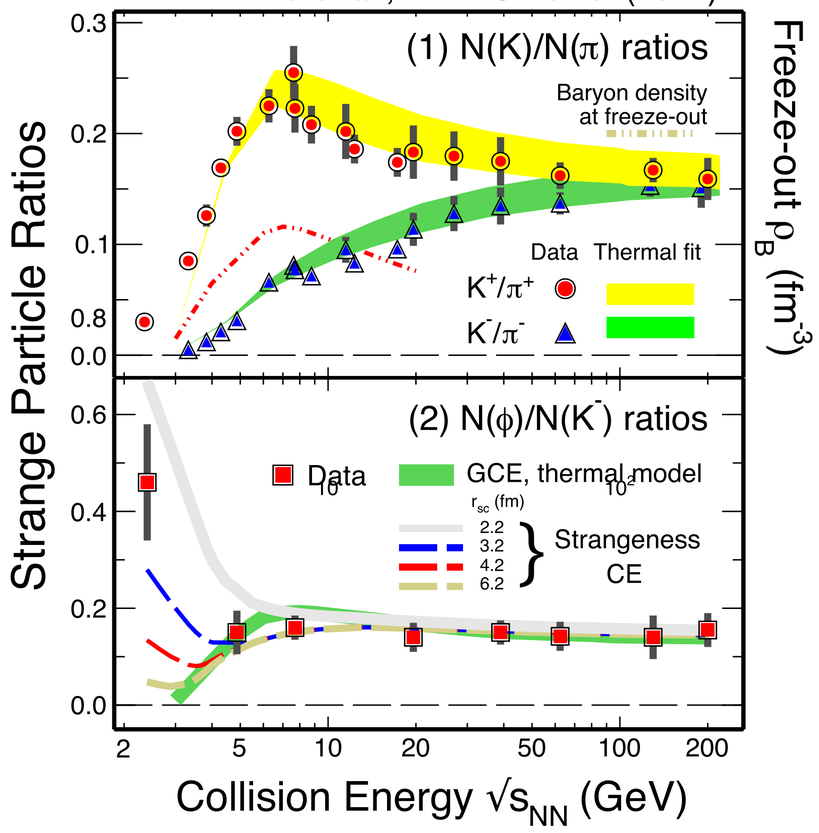
バリオンストッピングにより、正味電荷は正となり、クーロン場が生成される。
クーロン場によって、正と負電荷粒子のスペクトルが変化する。

Strangeness production

Talks by A. Marcinek (NA61)



N. Xu et al., AAPPS Bull.31(2021)1



K+/pi+ “horn” was considered as a possible signature of phase transition. But with BES-I data, it is rather smooth transition with energy. No peak in smaller systems (Ar+Sc, Be+Be) by NA61/SHINE.

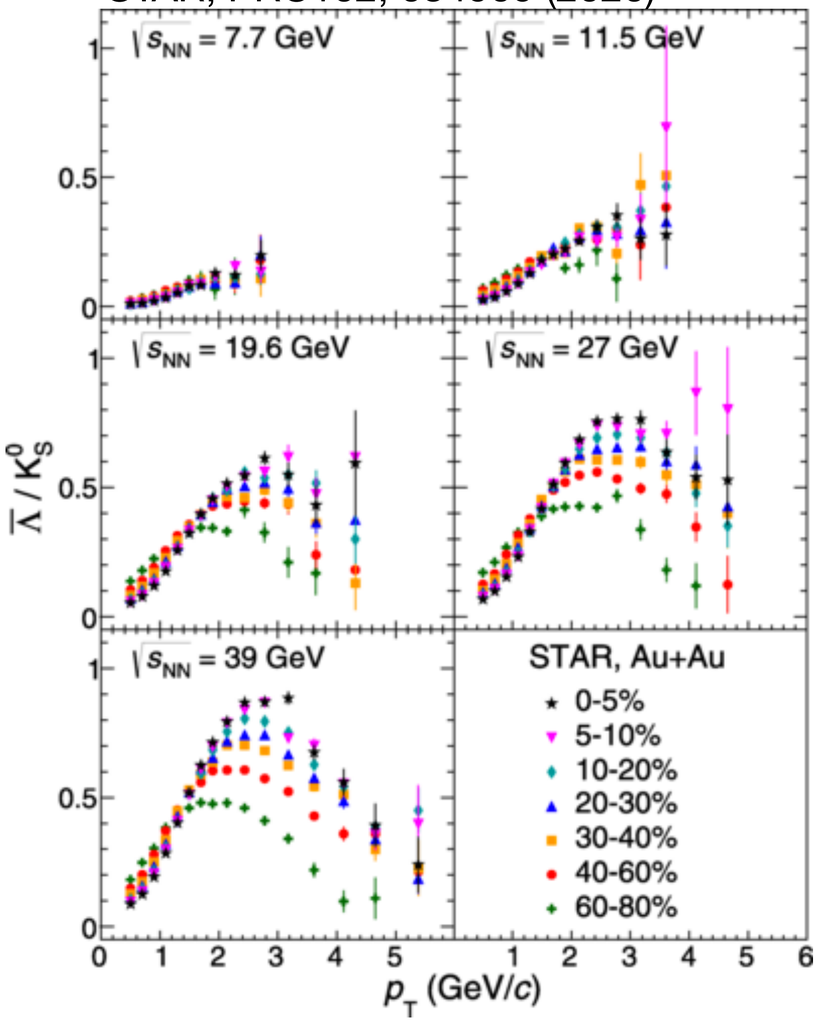
＊バリオン密度が$\sqrt{s_{NN}}$~7 GeVで最大、K+とΛのassociate production (N+N->N+Λ+K+)が支配的、

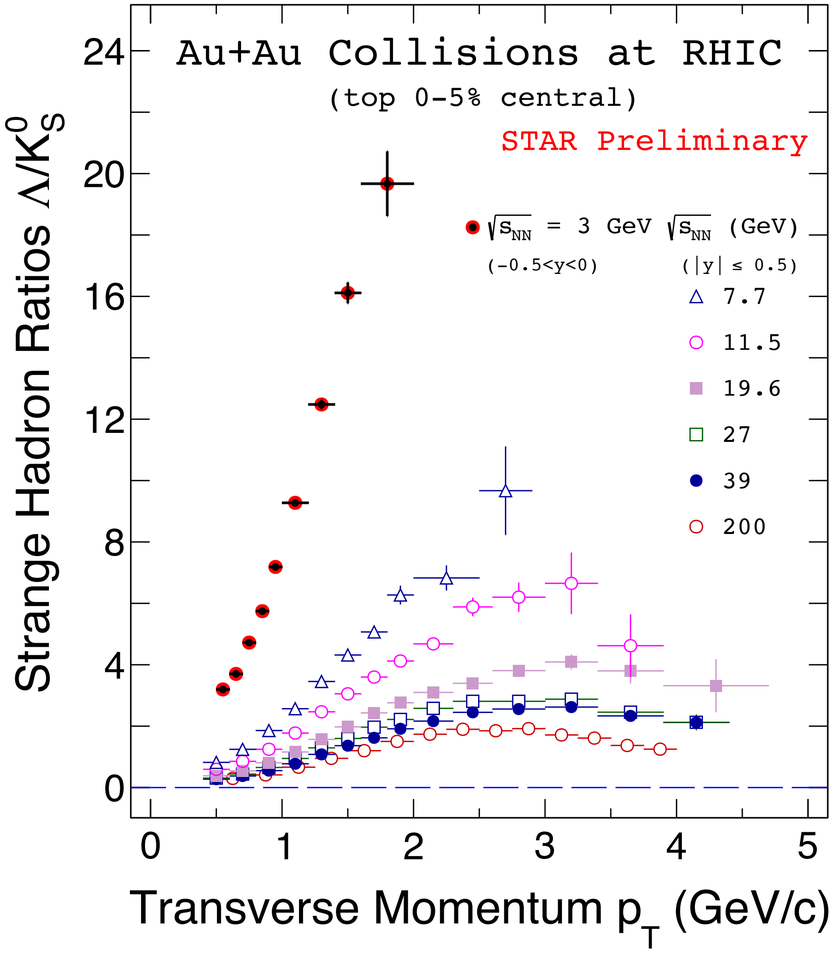
ということから7 GeV付近のピークは大体説明できる。

Baryon-to-meson ratio

Talk by A. Sahoo (STAR)

STAR, PRC102, 034909 (2020)





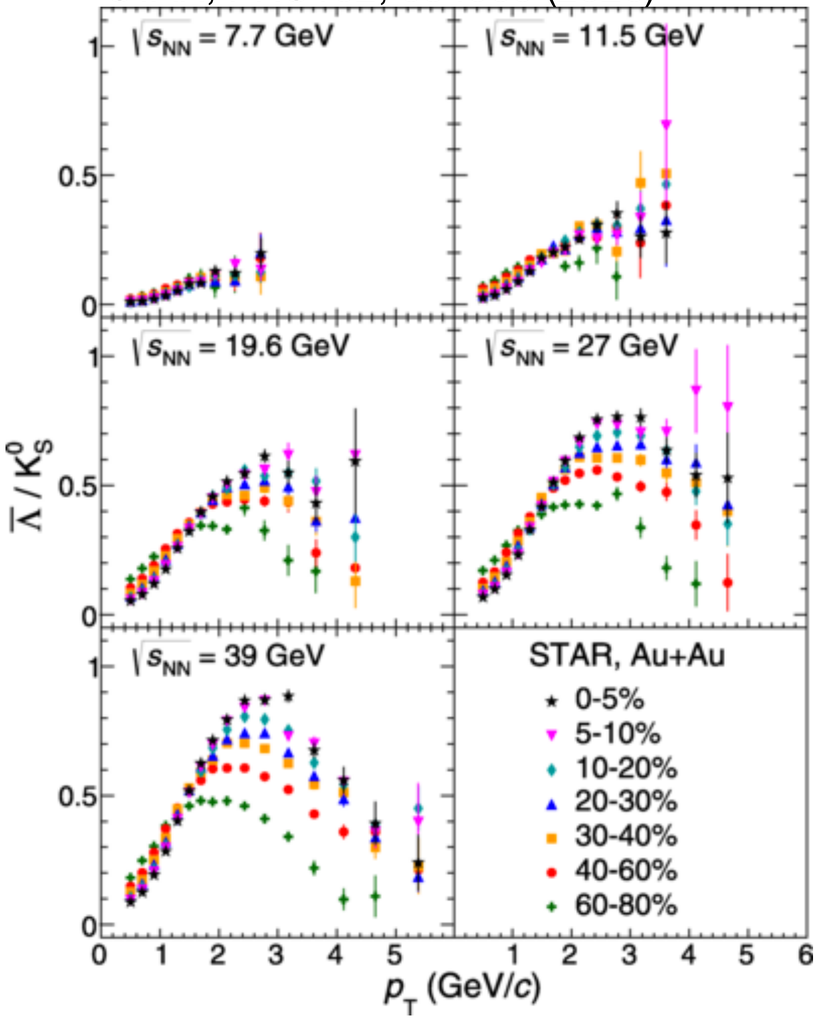
Enhancement at intermediate p_T at $\sqrt{s_{NN}}$ >= 19.6
-> hadronization through quark coalescence

Fast increase with p_T at 3 GeV

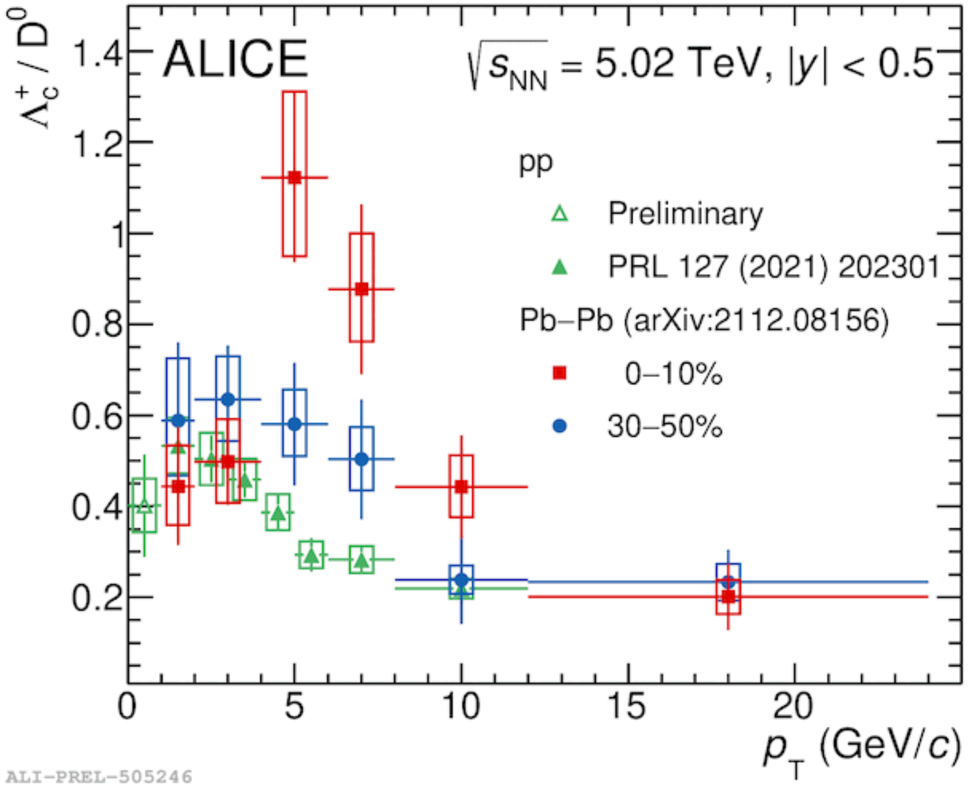
Baryon-to-meson ratio

Talk by M. Puccio (ALICE)

STAR, PRC102, 034909 (2020)



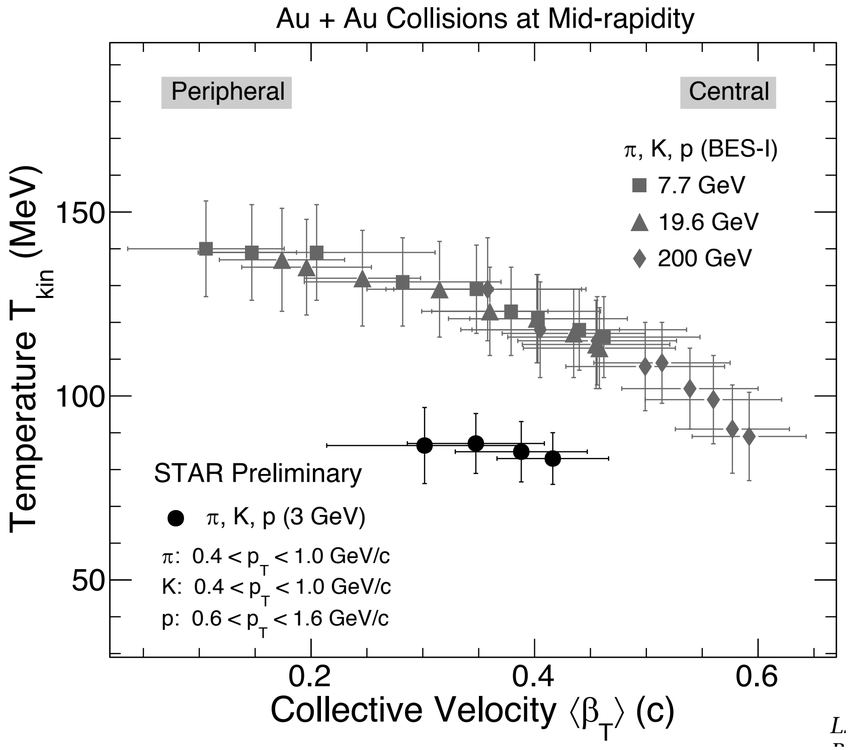
ALICE, arXiv:2112.08156

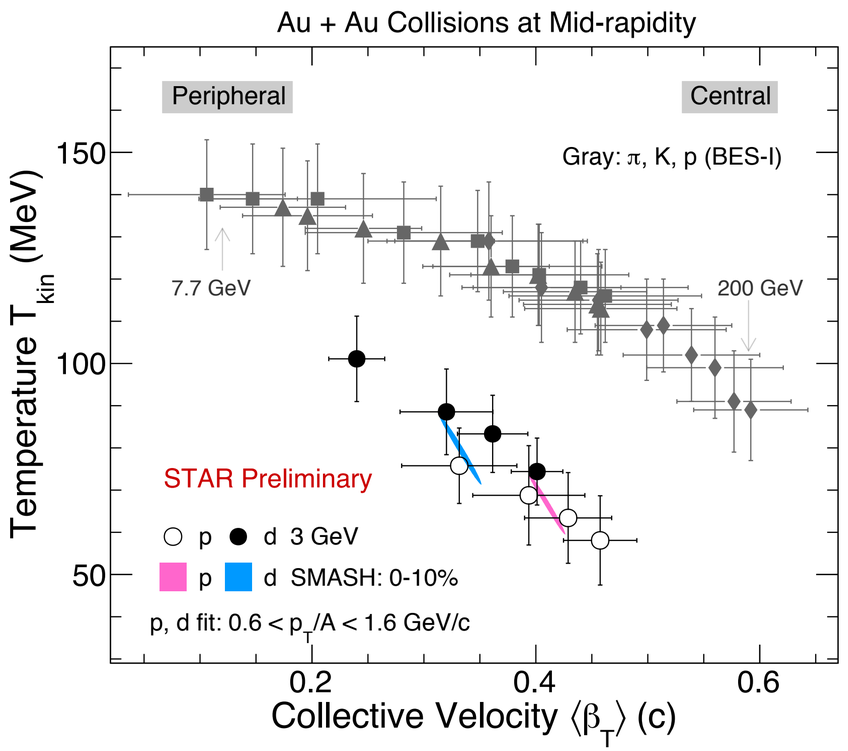


Enhancement at intermediate p_T at $\sqrt{s_{NN}}$ >= 19.6
-> hadronization through quark coalescence

Similar enhancement in charm sector
-> charm recombination?

Kinetic freeze-out parameters





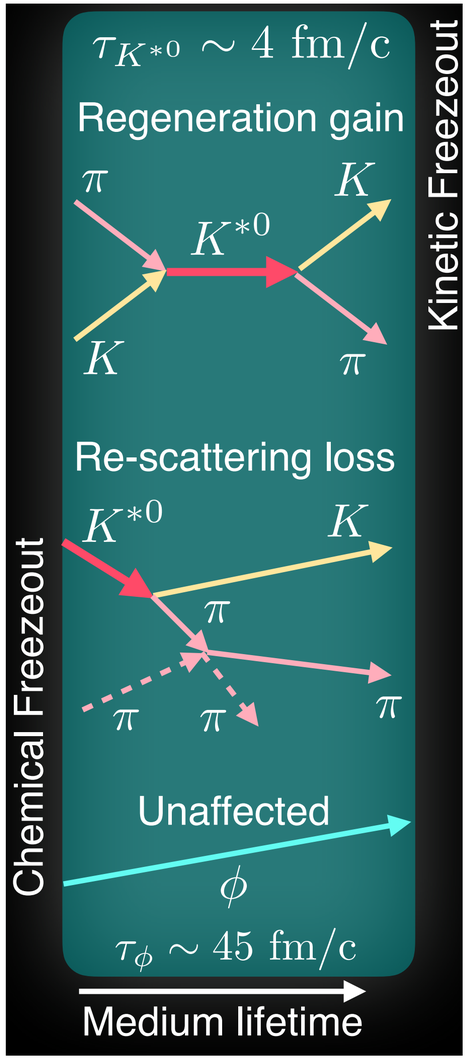
Different trend of kinetic freeze-out temperature (T_{kin}) and and radial flow velocity (β) at 3 GeV (applicability of blast-wave model at this lower energy?)

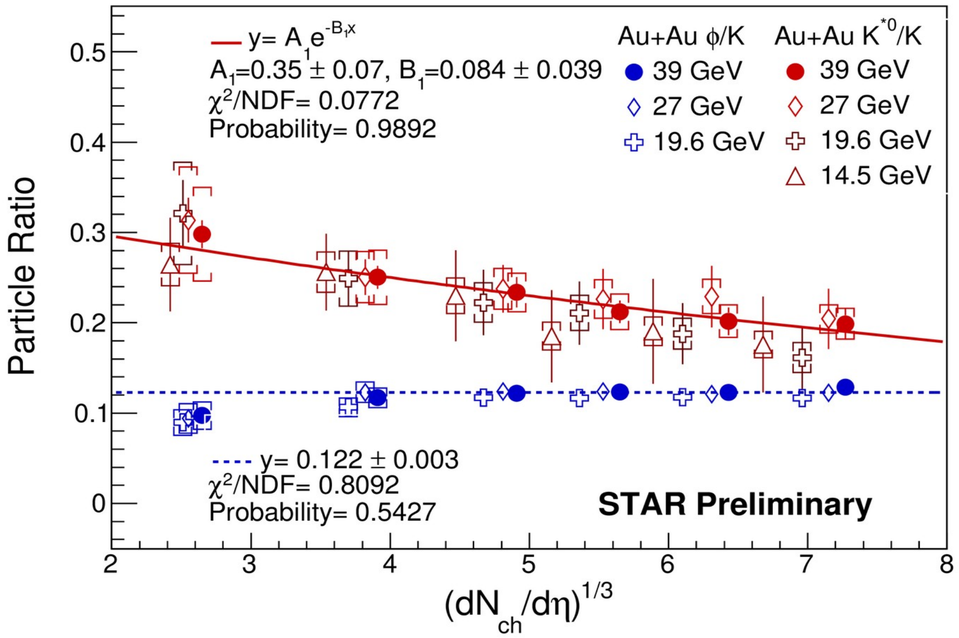
3 GeVにおけるT_{kin}は、7.7-200 GeVと比較して低い。

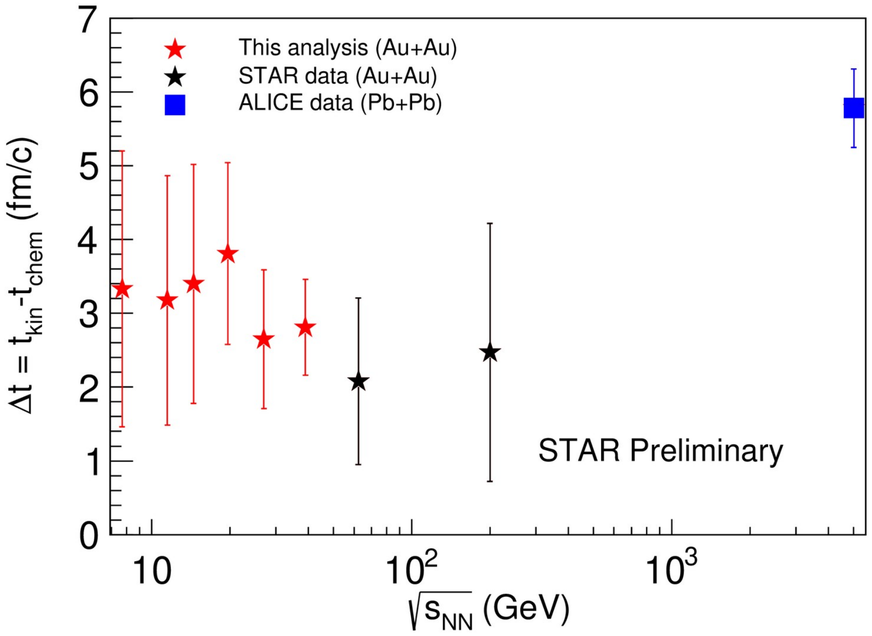
$T_{kin}(d) > T_{kin}(p)$: pよりもdの方が早くfreeze-outする?

Probing hadronic-phase lifetime by K*0/K

Talk by A. Sahoo (STAR)







短寿命の共鳴粒子は、hadronic phase lifetimeに敏感な量。

rescattering (減少)とregeneration (増加)の兼ね合い。

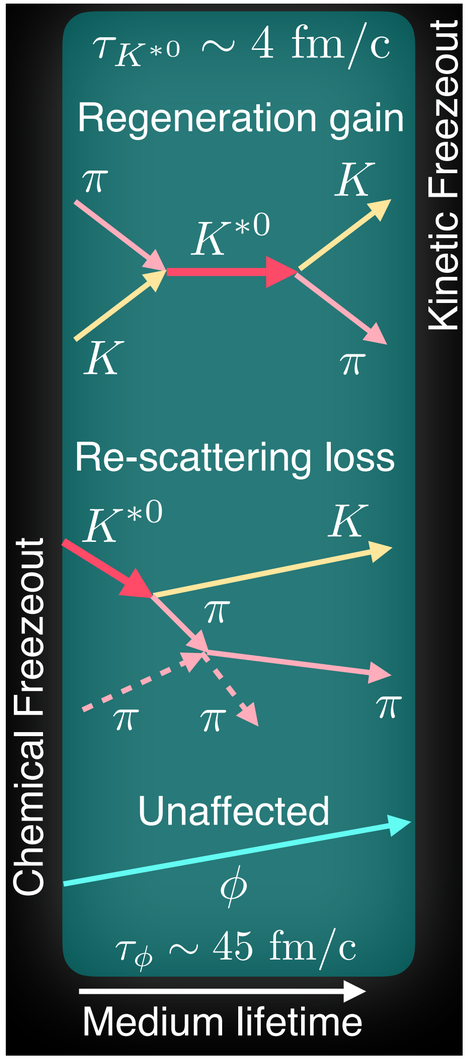
- 中心衝突におけるrescattering loss
- LHCでは、regenerationの影響が大きい and/or hadronic phaseが長い

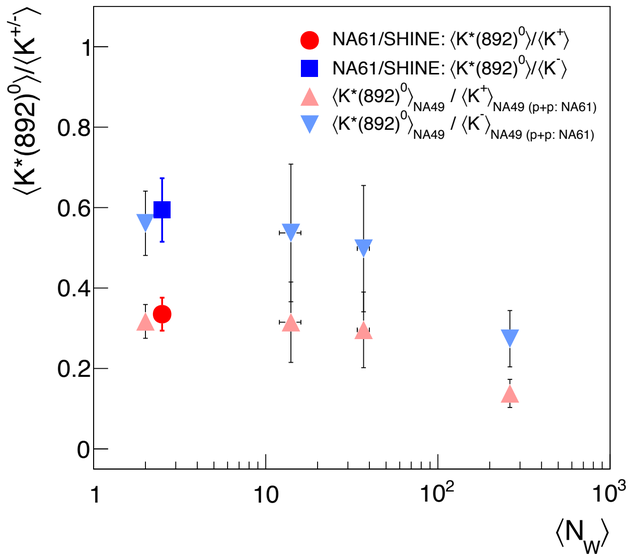
$(K^{*0}/K)_{kin} = (K^{*0}/K)_{chem} \times e^{-\Delta t/\tau}$

$(K^{*0}/K)_{kin} \approx (K^{*0}/K)_{AA}$

$(K^{*0}/K)_{chem} \approx (K^{*0}/K)_{pp}$

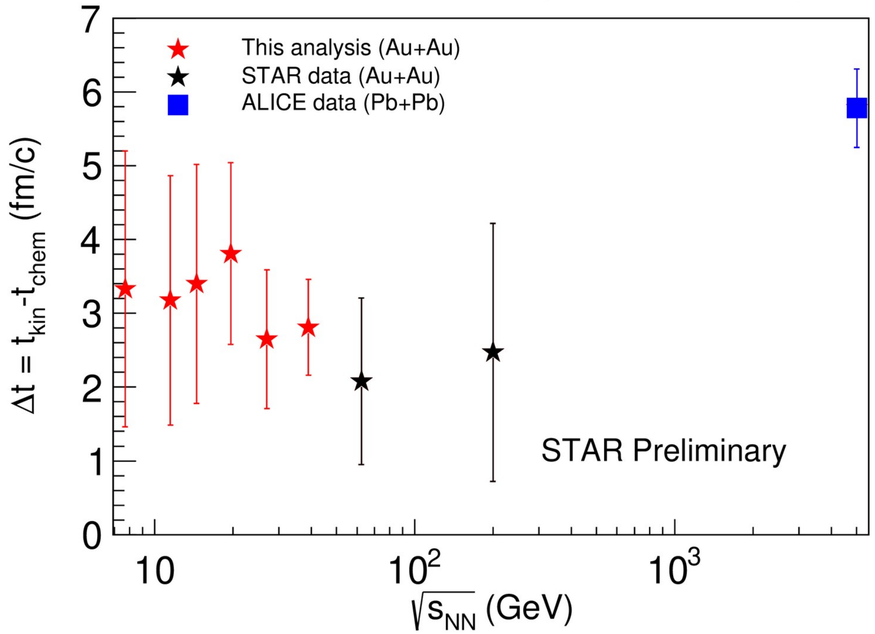
Probing hadronic-phase lifetime by K*0/K





- 5.3 fm/c for $K^*(892)^0/K^+$
- 4.6 fm/c for $K^*(892)^0/K^-$

Talk by A. Sahoo (STAR)
Talk by M. Lewicki (HADES)



短寿命の共鳴粒子は、hadronic phase lifetimeに敏感な量。

ただし、rescattering (減少)とregeneration (増加)の兼ね合い。

- 中心衝突におけるrescattering loss
- $\Delta t_{RHIC} < \Delta t_{LHC}$: LHCでhadronic phaseが長いことを示唆？
- $\Delta t_{SPS} > \Delta t_{RHIC}$: RHICにおけるregenerationの影響？

CP search with fluctuations

Talk by T. Nonaka

Why do we want to study fluctuations of conserved charges?

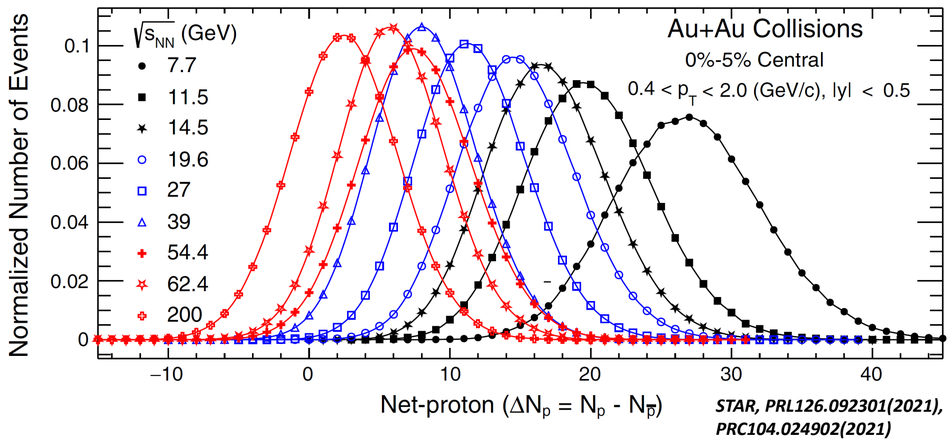
- Critical pointでは、（無限に大きな系では）相関長が発散する
- 保存量の揺らぎ相関長ξに敏感で、揺らぎはキュムラントCnで定量化

$$C_1 = \langle N \rangle, \; C_2 = \left\langle (\delta N)^2 \right\rangle \quad \delta N = N - \langle N \rangle$$
$$C_3 = \left\langle (\delta N)^3 \right\rangle \; C_4 = \left\langle (\delta N)^4 \right\rangle - 3 \left\langle (\delta N)^2 \right\rangle^2$$

$$C_2 =< (\delta N)^2 >_c \approx \xi^2$$
$$C_3 =< (\delta N)^3 >_c \approx \xi^{4.5}$$
$$C_4 =< (\delta N)^4 >_c \approx \xi^7$$

M. Stephanov, PRL102.032301 (2009)
M. Asakawa et al., PRL103.262301(2009)

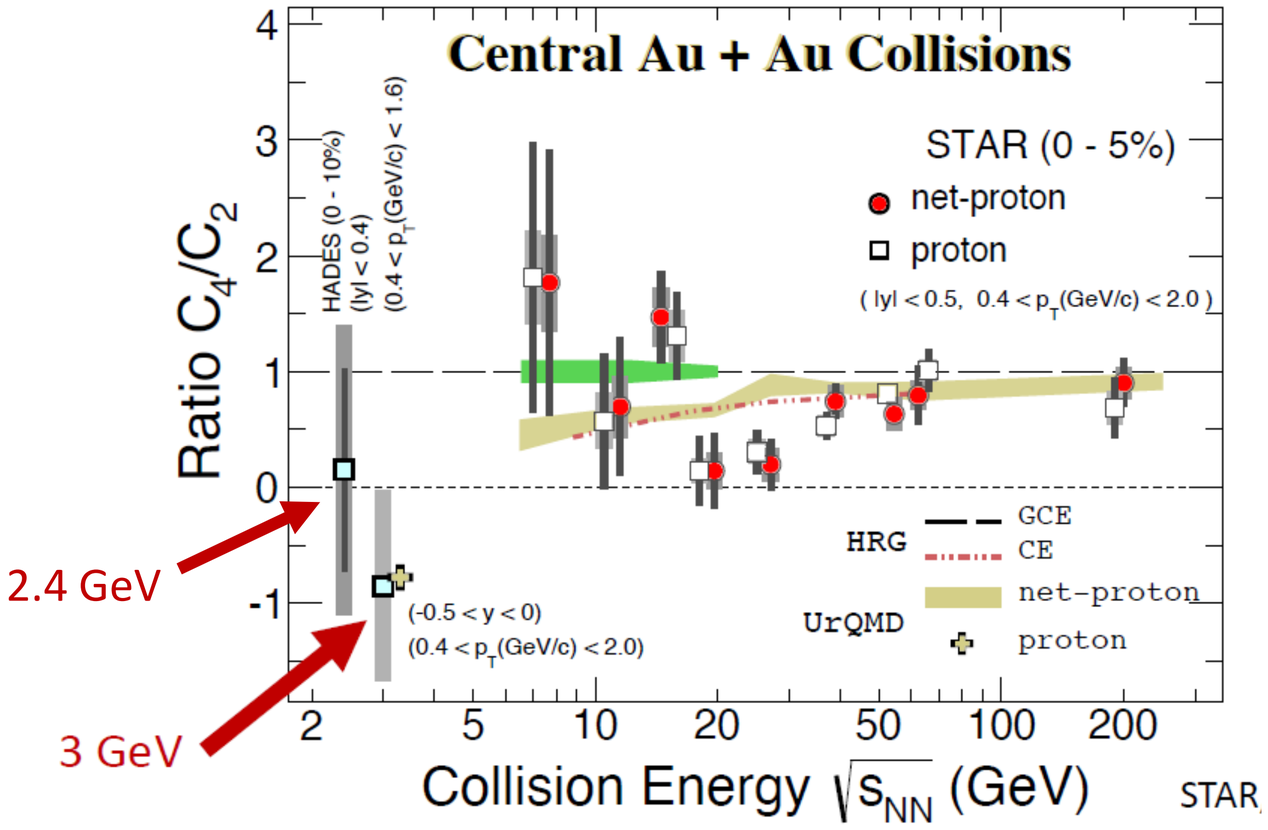
- 体積効果をキャンセルするために、キュムラント比が測定量
- net-baryonは測定できないので、net-protonを用いる

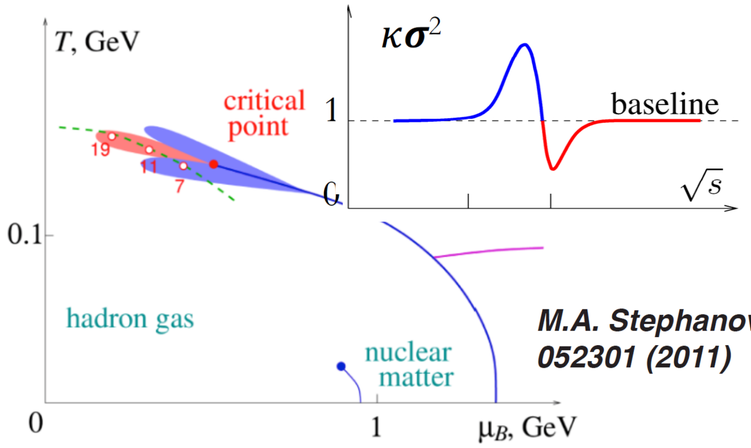


STAR, PRL126.092301(2021), PRC104.024902(2021)

Net-proton C_4/C_2

Talks by T. Nonaka, Yu Zhang (STAR)





M.A. Stephanov, PRL107, 052301 (2011)

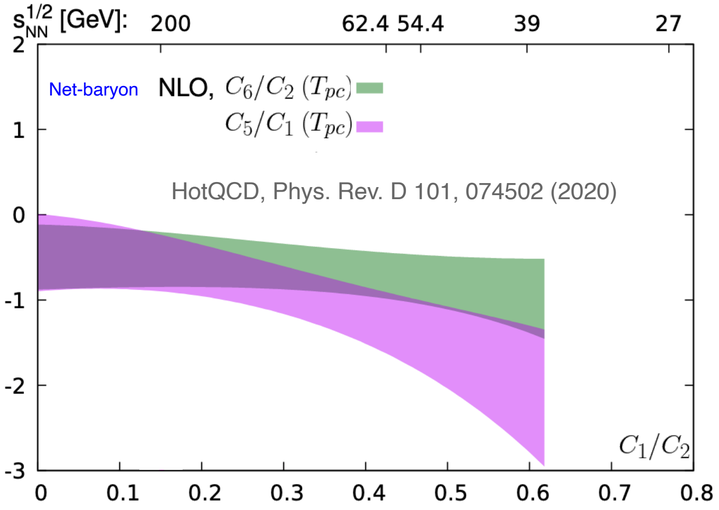
HADESの2.4 GeV、STARの3 GeVのC_4/C_2は、
ゼロもしくは負の値になる
→ baryon conservation (UrQMD)で説明できる

CPから予測されるピーク構造は、3 GeV以上にありそう
→ BES-IIの高統計に期待

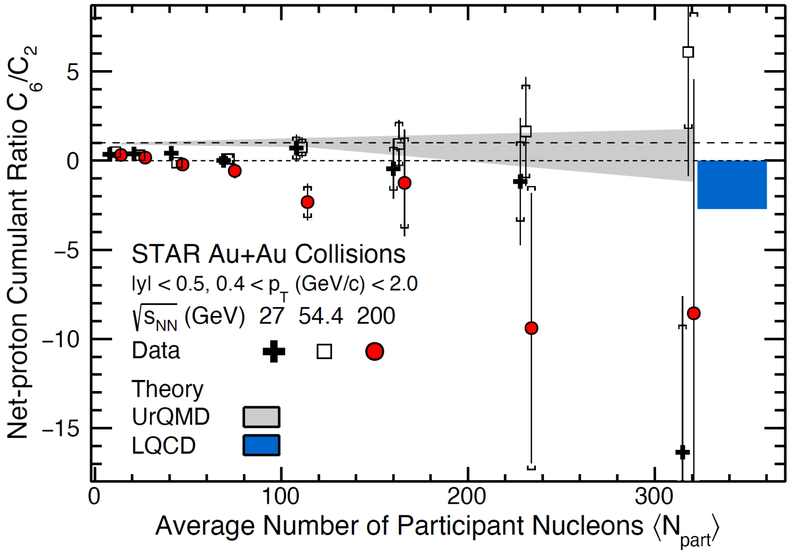
STAR, arXiv:2112.00240
HADES, PRC102.024914 (2020)

Crossover search

Talk by T. Nonaka,
Talk by H.-S. Ko (STAR)

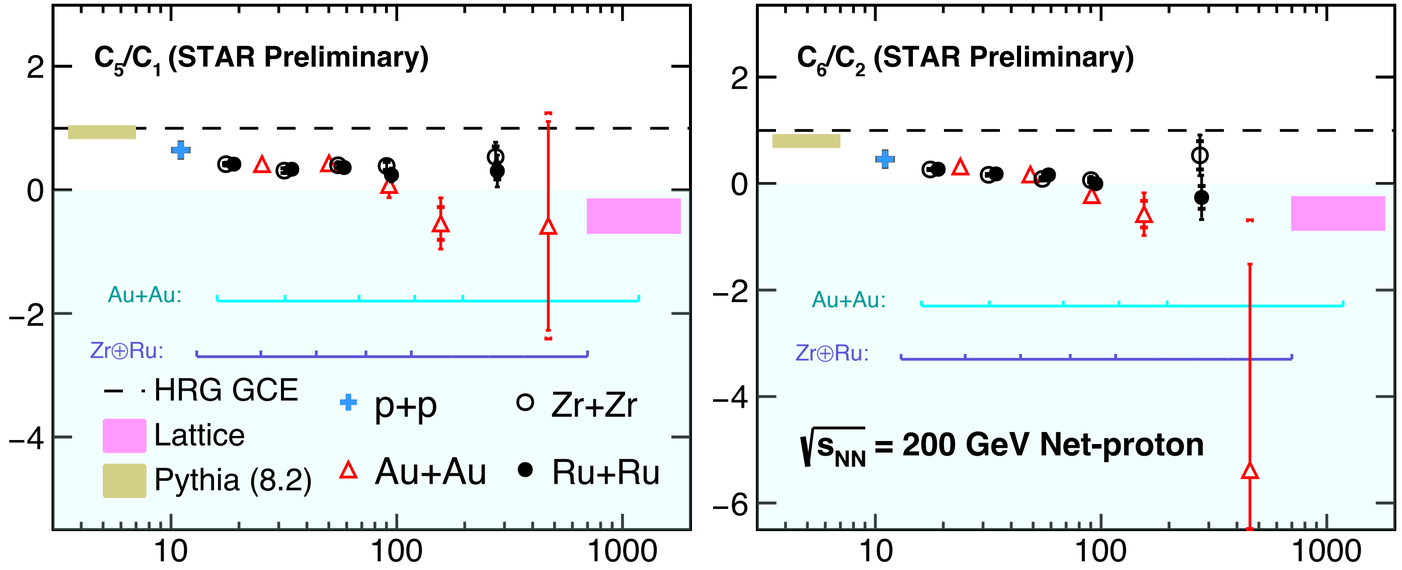


STAR, PRL127.262301 (2021)



LQCD predicts $C_6/C_2<0$ and $C_5/C_1<0$

- In 200 GeV Au+Au, C_6/C_2 changes the sign to be negative when going from peripheral to central collisions
- Isobar results follow the trend of multiplicity dependence from Au+Au and p+p at 200 GeV



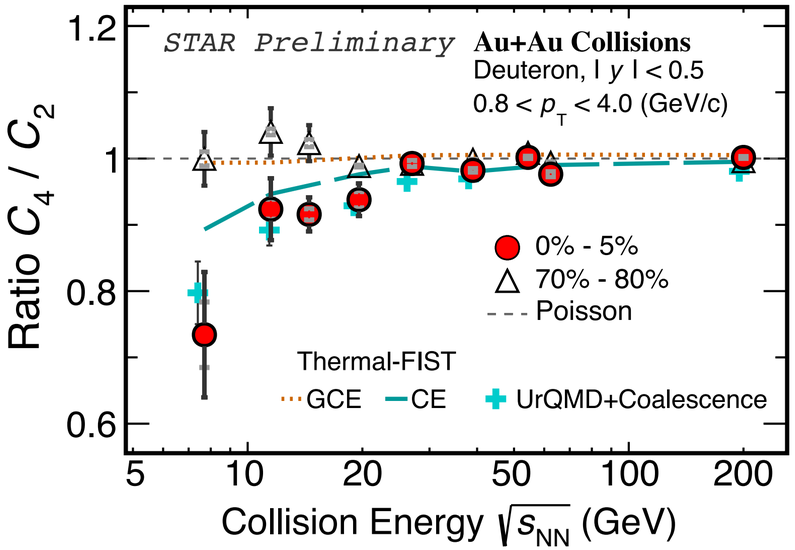
(Efficiency uncorrected x-axis)

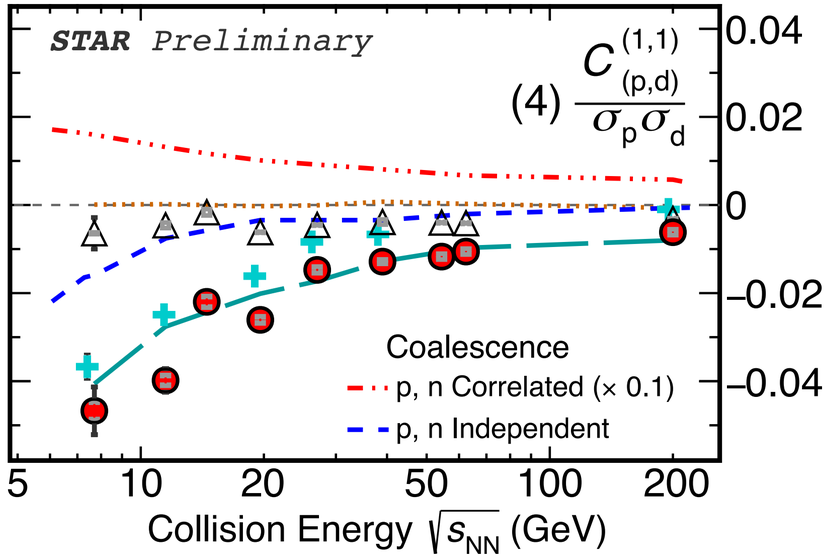
Poster by Ashish Pandav (S1 T07_1)

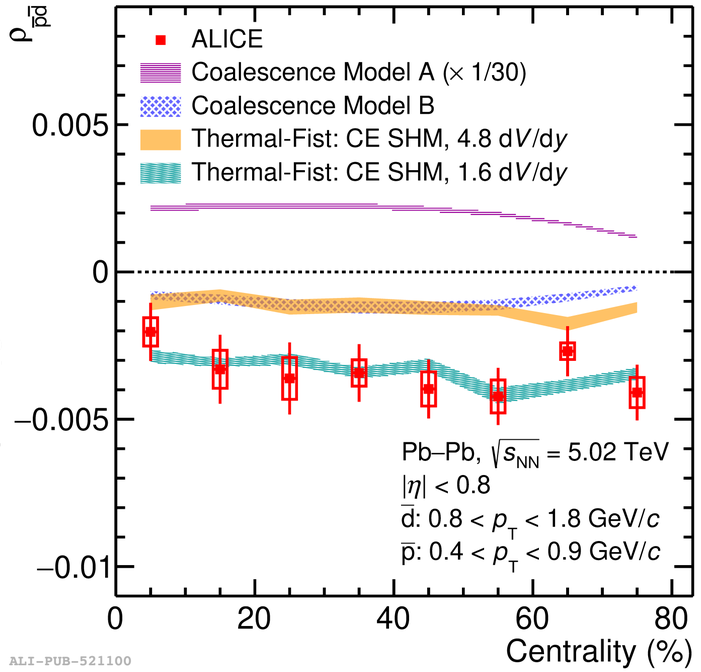
deuteron-proton correlation

Talk by D. Mallick (STAR)
Talk by S. Kundu (ALICE)

$$\rho(n_p, n_d) = \frac{\langle (n_p - \langle n_p \rangle)(n_d - \langle n_d \rangle) \rangle}{\sigma_p \sigma_d}$$





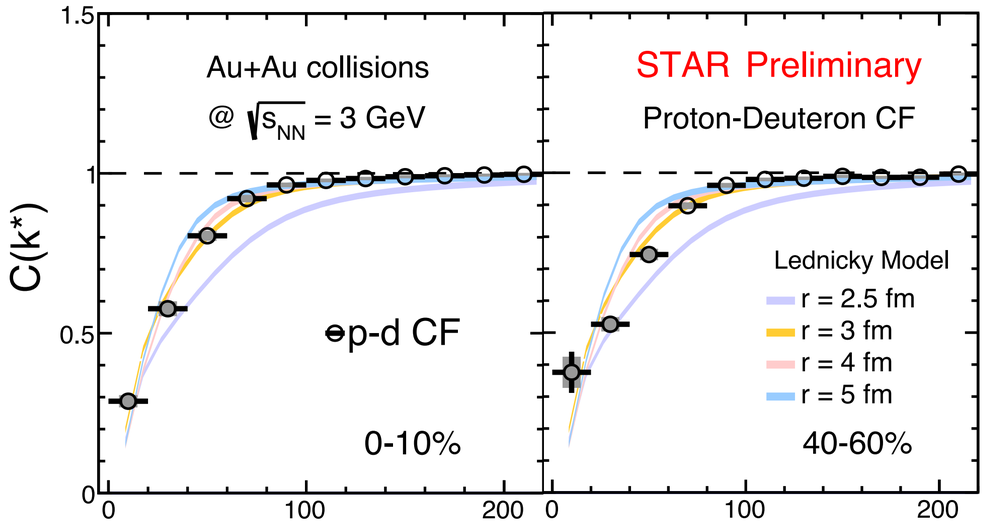


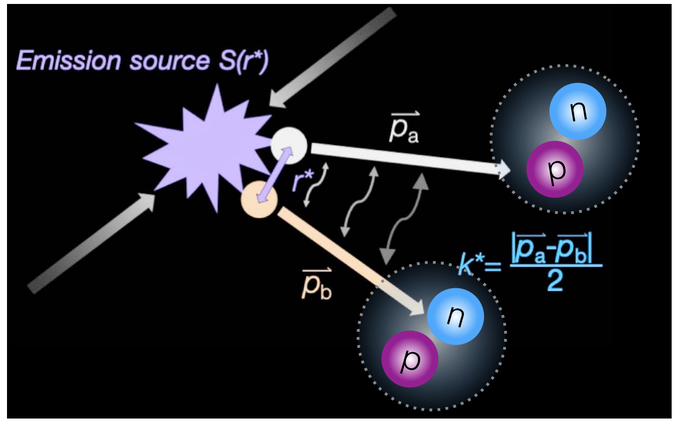
Monotonic energy dependence of deuteron (B=2) fluctuations

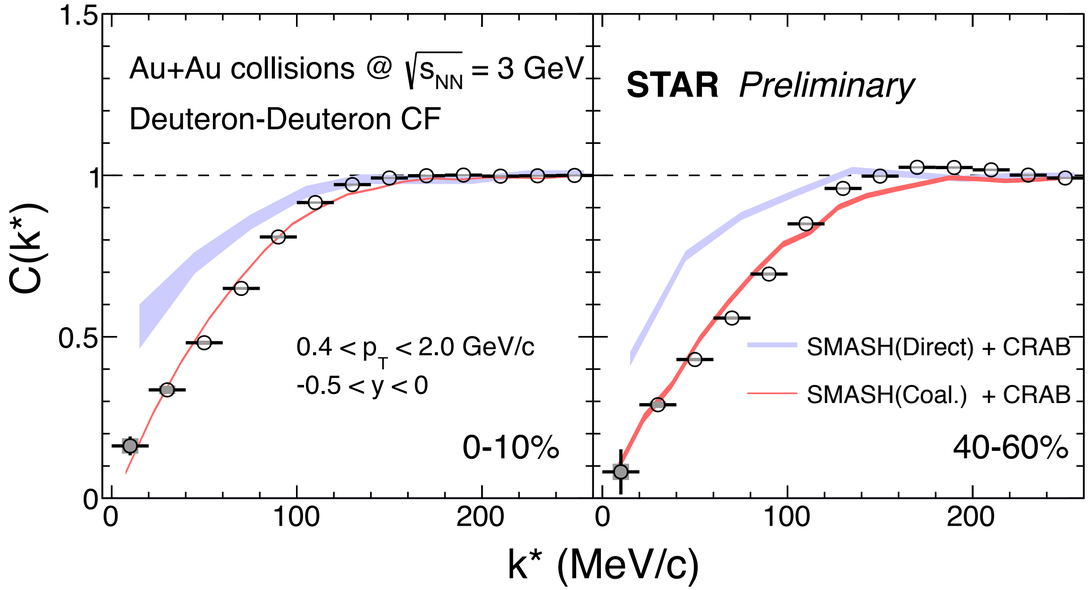
- p and d numbers are anti-correlated in both STAR BES and ALICE
- Data favors coalescence with independent p and n fluctuations

femtoscopic deuteron-proton correlation

Talk by K. Mi (STAR)
& P. Tribedy (STAR)



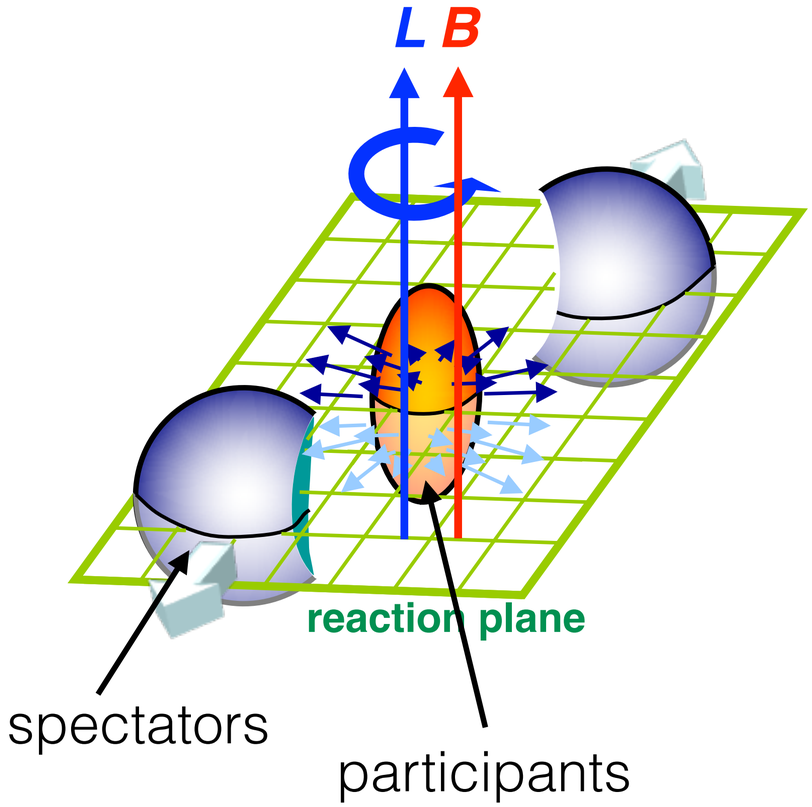


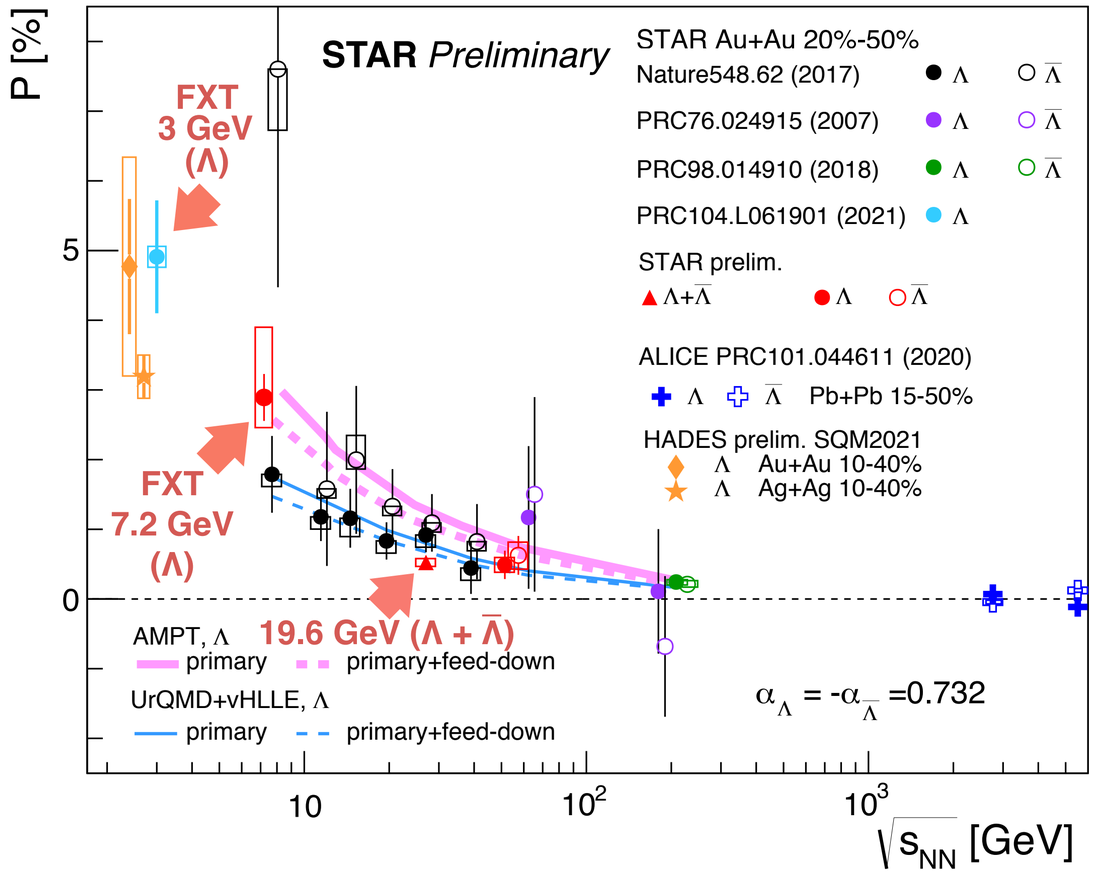


- p-d and d-d correlations show anti-correlation
- p-d CF is described well by Lednicky model
- d-d CF is described better by transport model (SMASH) with coalescence

Vorticity and polarization

Talk by J. Adams (STAR)
Poster by K. Okubo (STAR)



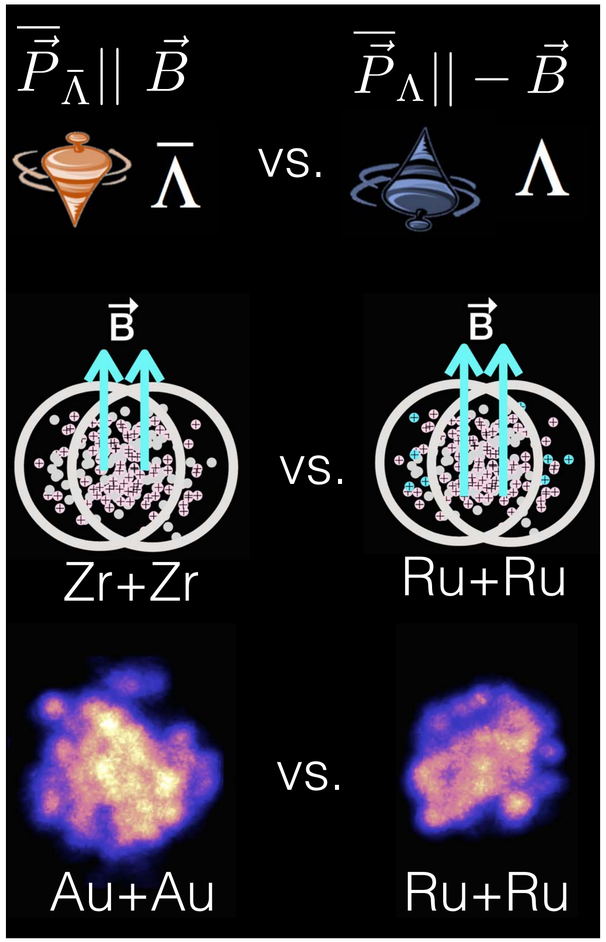


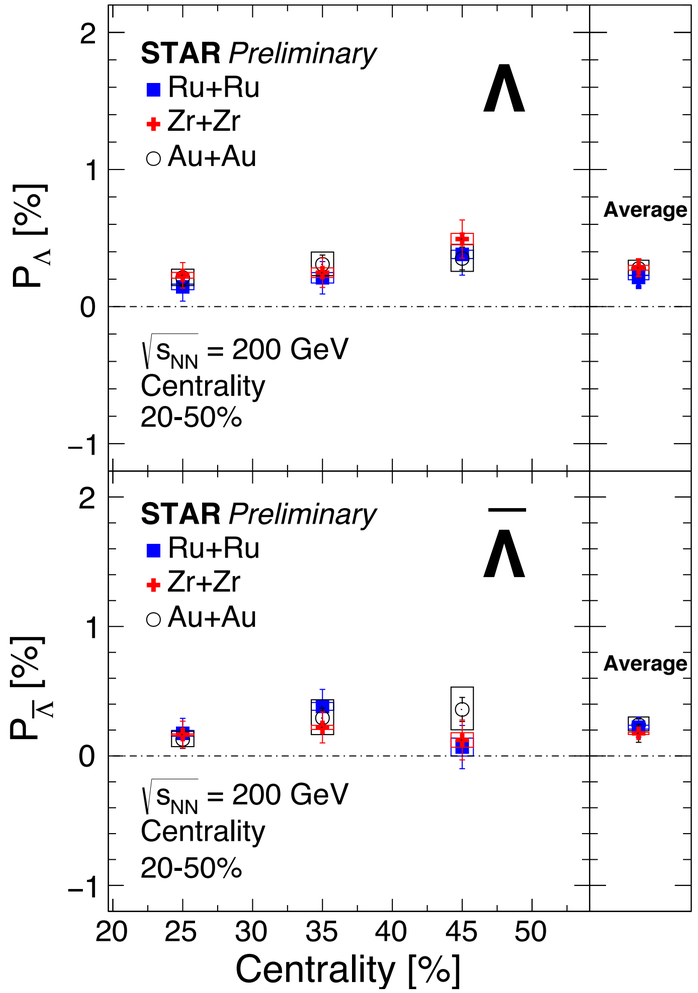
- 初期の軌道角運動量→反応平面垂直方向に粒子のスピンが偏極
- weak decayするΛハイペロンを用いた測定
  （ΞやΩの偏極測定もされている）

More precise results from BES-II are coming

Global polarization in isobar collisions

Talk by J. Adams (STAR)
Poster by X. Gou (STAR)





$$^{197}\mathrm{Au} > {}^{96}_{44}\mathrm{Ru},\ {}^{96}_{40}\mathrm{Zr} > {}^{63}\mathrm{Cu} > {}^{16}\mathrm{O}$$

Isobarでは、初期の磁場 (B^2)が10-15%異なるので

$P_{\text{anti-}\Lambda} > P_{\Lambda}$ の関係は見られるか？

小さい衝突系のほうが大きな偏極とモデルは予想しているが、その関係は見られるか？ $P_{\Lambda}^{Au} > P_{\Lambda}^{Ru/Zr}$

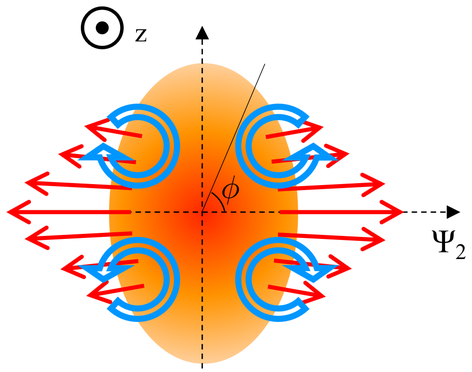
S. Shi et al., PLB788 (2019) 409
S. Alzhrani et al., arXiv:2203.15718

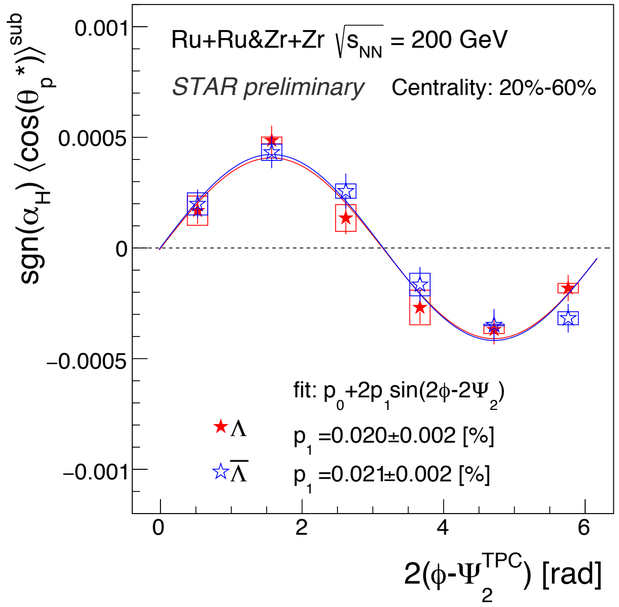
→ Λとanit-Λに有意な差はなさそう。

& 衝突系の違いは見られない。O+O?

Local polarization in isobar collisions

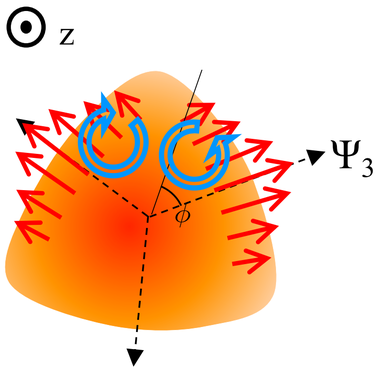
Talk by J. Adams (STAR)
Poster by T. Niida (STAR)

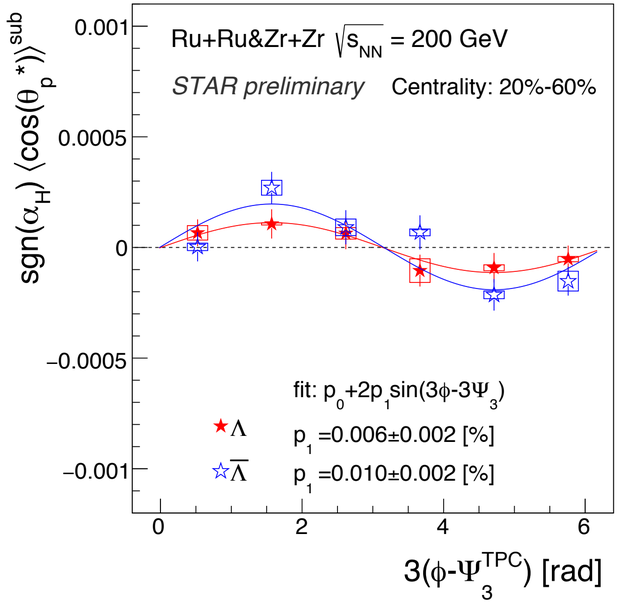


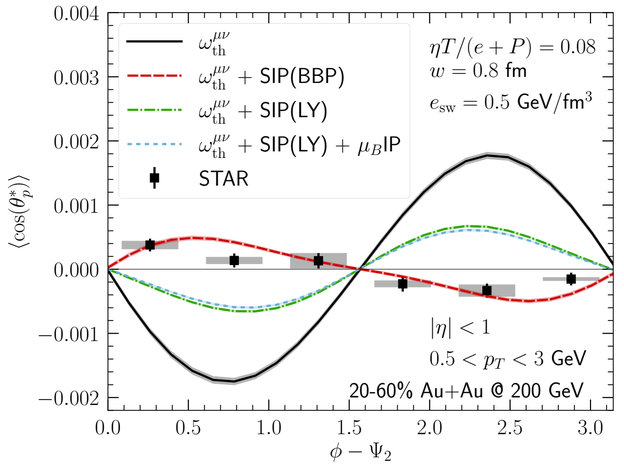


Flowによって、ビーム軸を回転軸とするような渦が生まれ、それが偏極に繋がる。

- Au+Au 200 GeV同様、isobarでもv_2-drivenな偏極を観測
- ２次同様、３次平面に対する依存性も観測！
  →v_3-drivenな渦＆偏極を示唆
- shear termを入れることで“spin puzzle”は、一応解決しそう







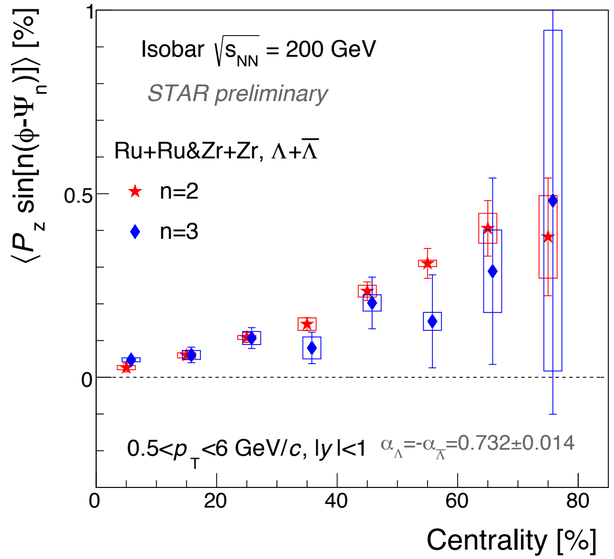
vorticity: $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$

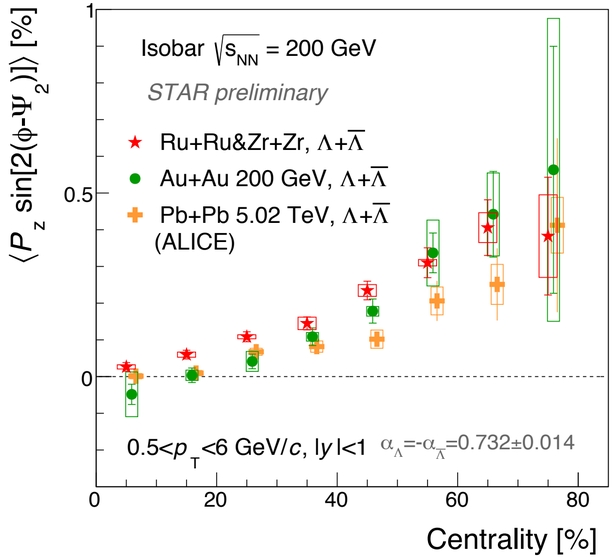
shear: $\Xi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho + \partial_\rho u_\sigma)$

B. Fu et al., PRL127, 142301 (2021)
F. Becattini et al., PRL127, 272302 (2021)
S. Alzharani et al., arXiv:2203.15718

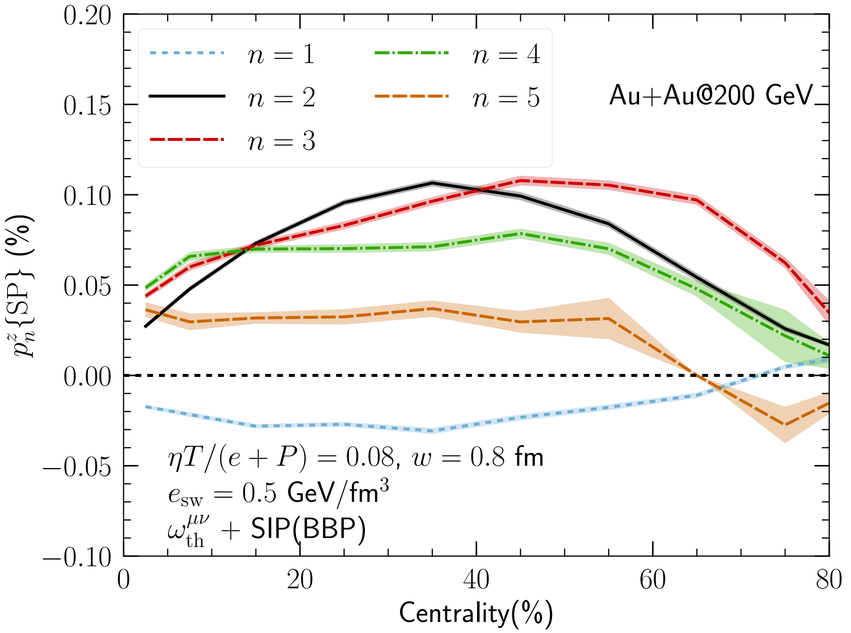
Local polarization in isobar collisions

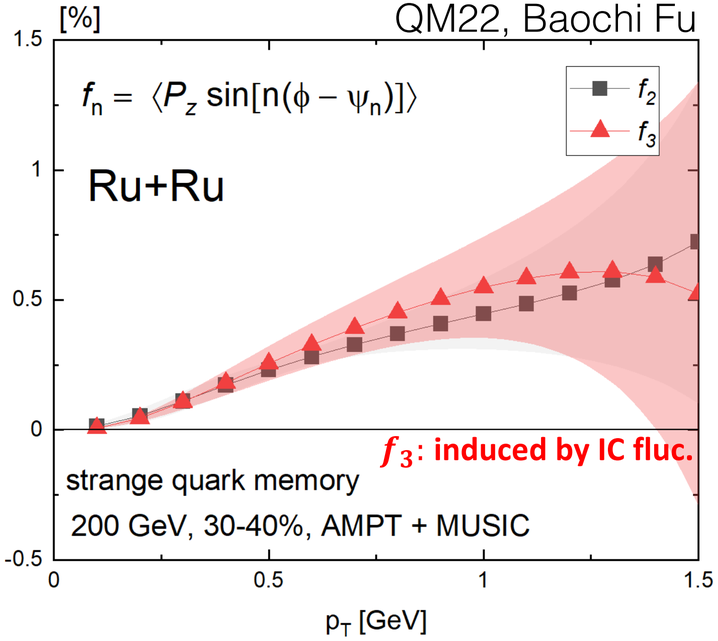
Posters by T. Niida (STAR), S. Ryu
Talk by B. Fu





S. Alzharani, S. Ryu, and C. Shen, arXiv:2203.15718





- Shearを取り入れた流体計算は、２次＆3次とも定性的に再現（符号と強度）
- 理想流体ではP$_z$がゼロになるという点で、addional constraint on η/s

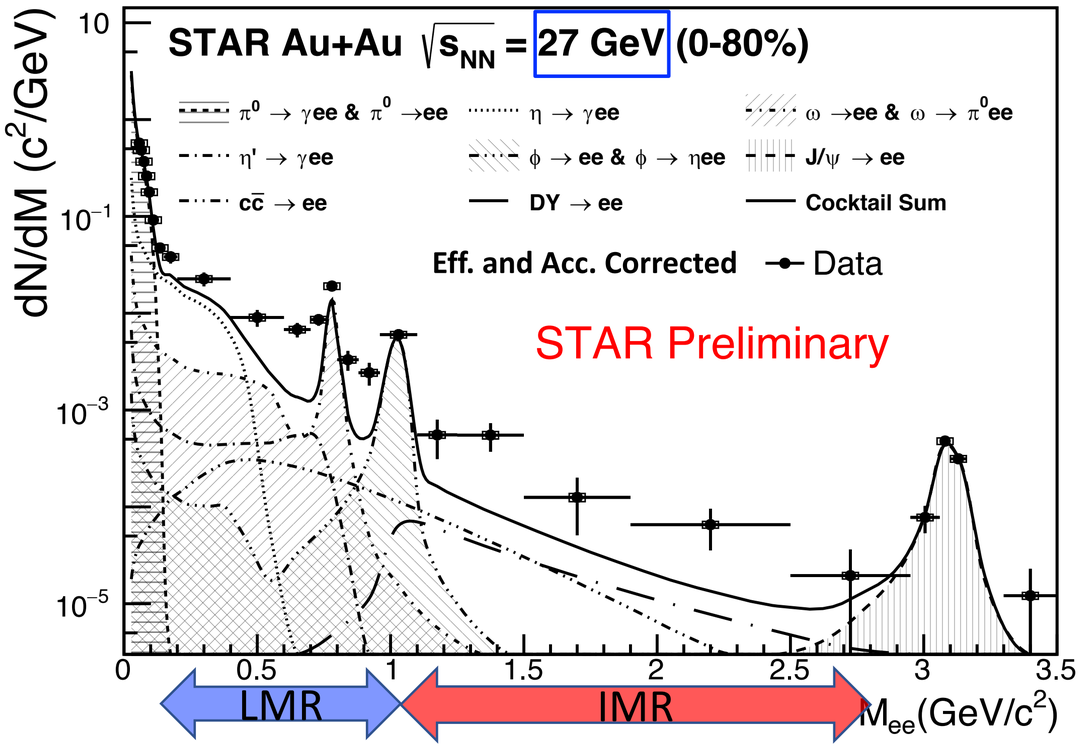
Medium temperature with dileptons

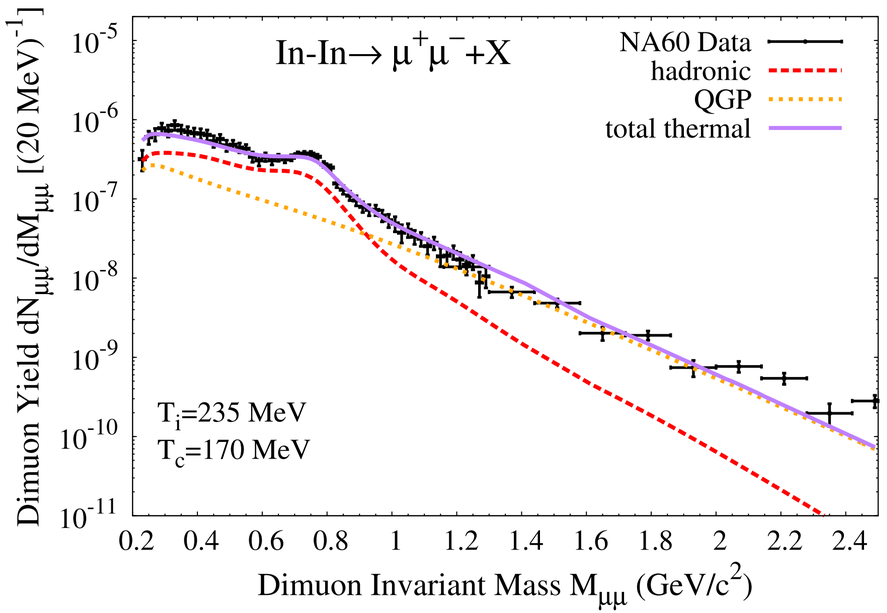
Talk by Z. Ye (STAR)

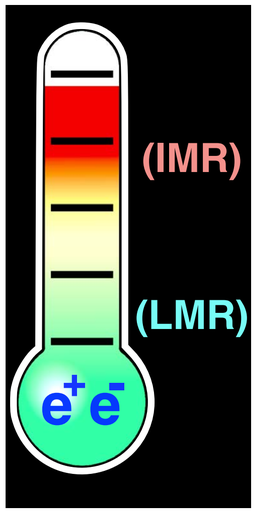
"invariant" mass分布のfitから、 radial flowによるblue-shit freeな温度測定

$$\mathrm{d}R_{ll}/\mathrm{d}M \propto (MT)^{3/2}\exp(-M/T)\ ,$$

Rapp and Hess, PLB753(2016)586





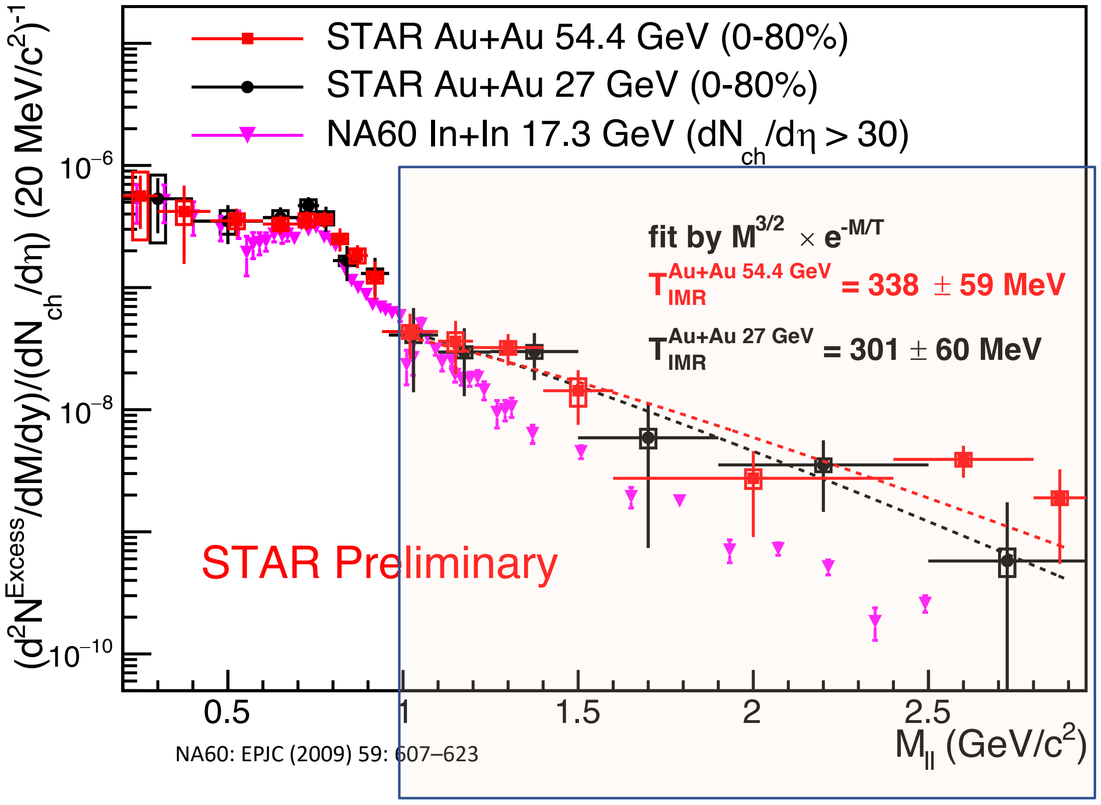


LMR (low mass region): $M_{ee}<M_\phi$
IMR (intermediate mass region): $M_\phi<M_{ee}<M_{J/\psi}$

IMR is dominated by QGP thermal radiation

Medium temperature with dileptons

Talk by Z. Ye (STAR)

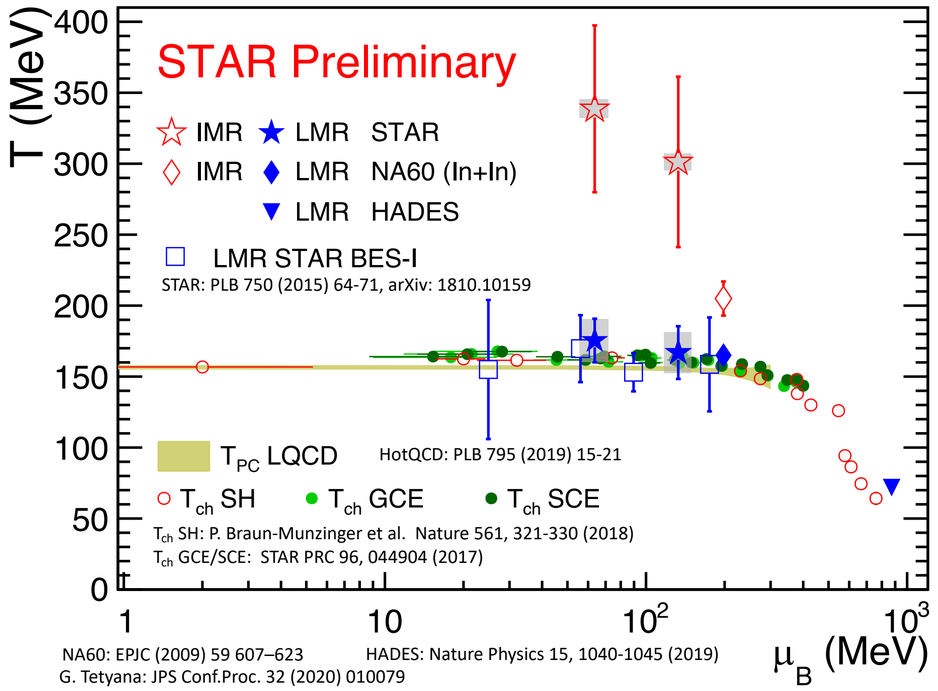


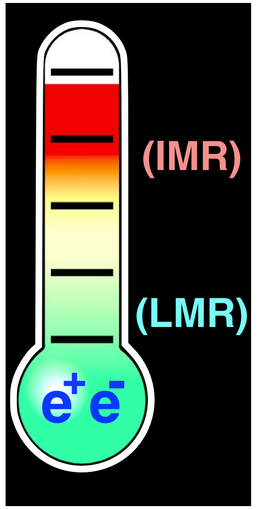
Excess dilepton mass spectra from STAR BES, comparing to NA60 dimuon result

"invariant" mass分布のfitから、 radial flowによるblue-shit freeな温度測定

$$\mathrm{d}R_{ll}/\mathrm{d}M \propto (MT)^{3/2}\exp(-M/T)\ ,$$

Rapp and Hess, PLB753(2016)586



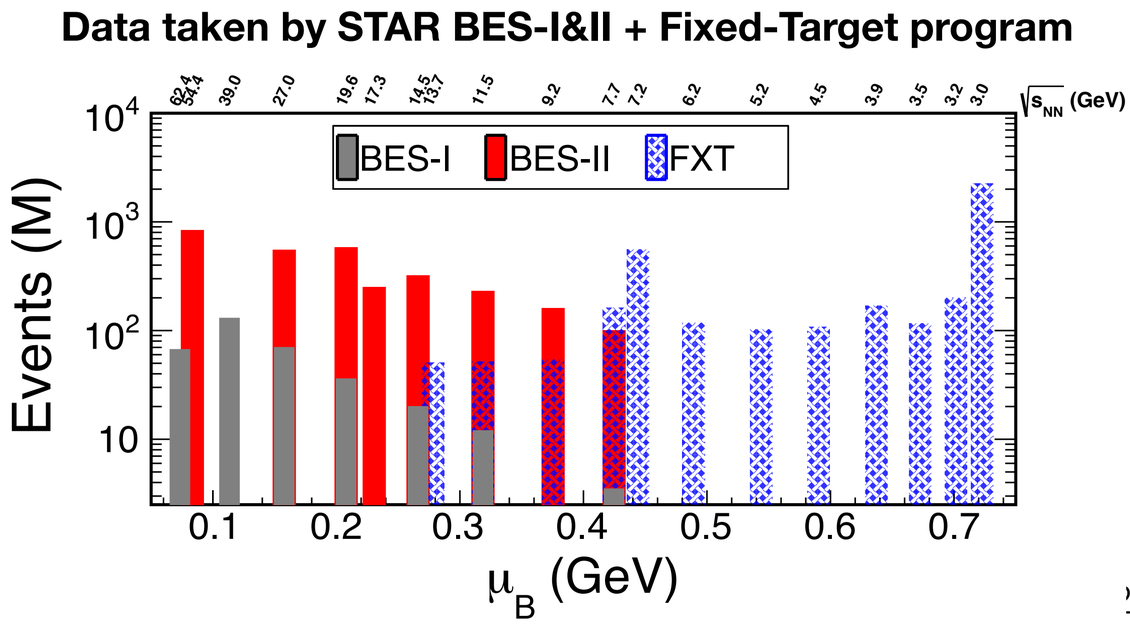


SPSよりもRHICの方がmediumの温度が高い

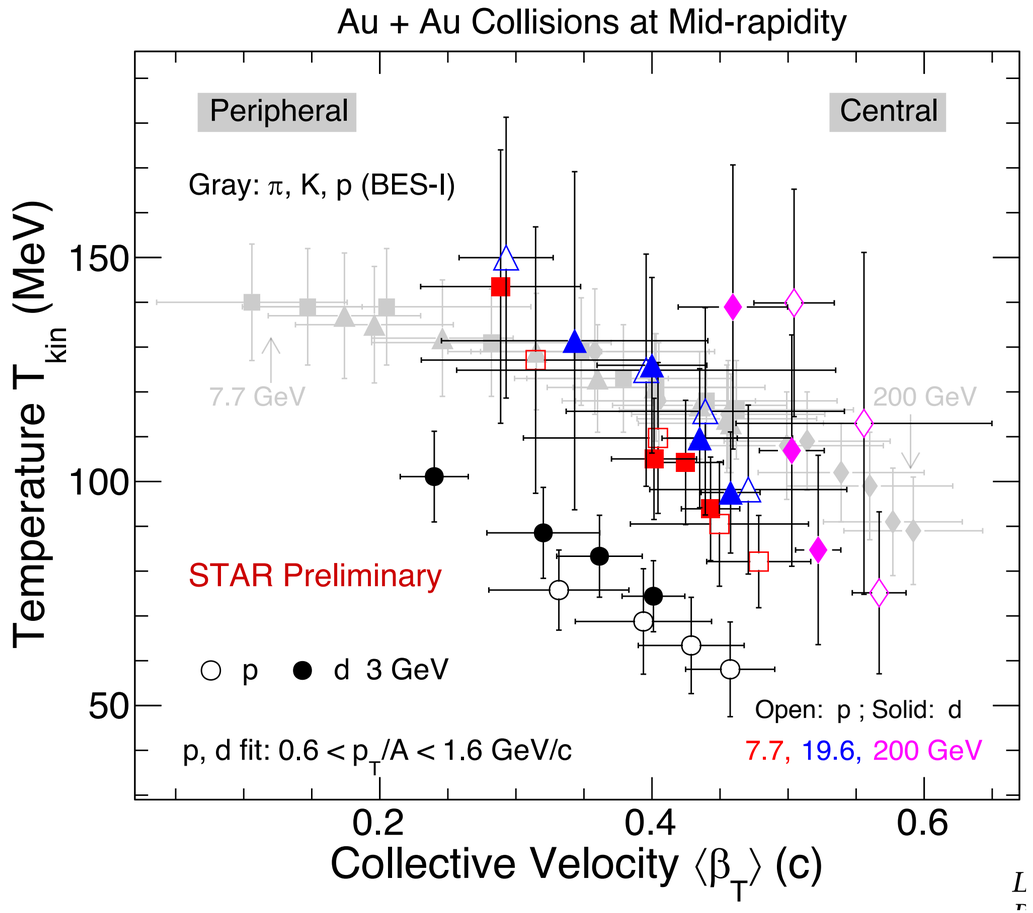
(27-54GeVにしては)高すぎるかもしれない (ただし誤差も大きい)

Summary

- Search for CP/crossover/1st-order phase transition is ongoing
  - No conclusive result/signature so far (in my opinion)
- New results at lower energies (~3 GeV) where baryon-rich medium is created
- Data taking of BES-II just completed,
  so more interesting results will come soon.



Backup


Au + Au Collisions at Mid-rapidity
Peripheral
Central
Gray: π, K, p (BES-I)
7.7 GeV
200 GeV
STAR Preliminary
p d 3 GeV
Open: p ; Solid: d
7.7, 19.6, 200 GeV
p, d fit: 0.6 < p_T/A < 1.6 GeV/c
Temperature T_kin (MeV)
150
100
50
0.2
0.4
0.6
Collective Velocity ⟨β_T⟩ (c)