

# RHIC実験のまとめと

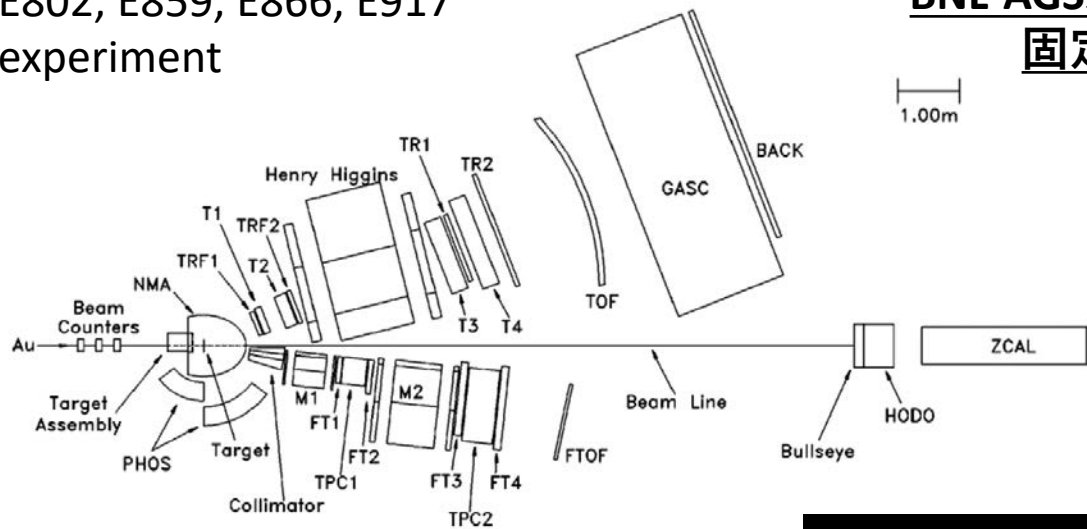
## RHIC衝突ビーム・エネルギー走査実験による AGS・SPSエネルギー領域での再挑戦

### ～高密度領域のQCD相図の理解へ向けて～

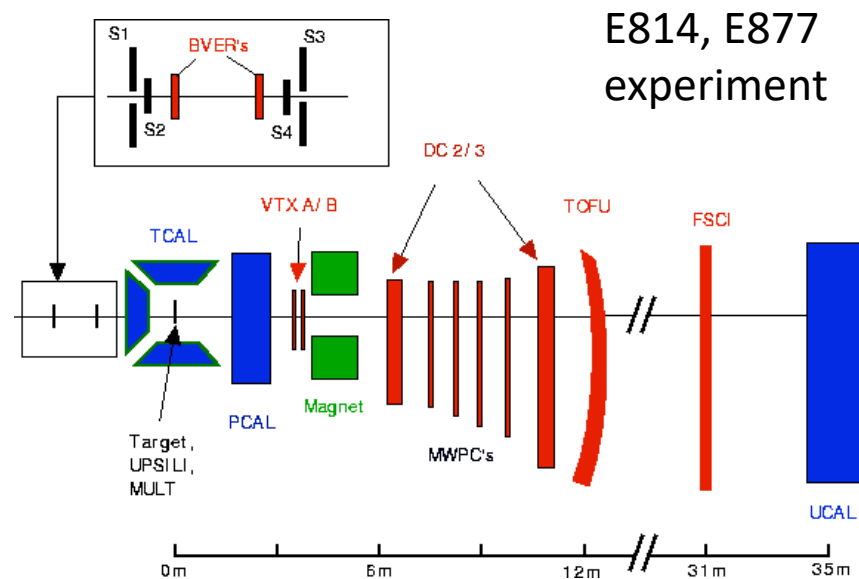
AGS・SPS実験のおさらい  
RHIC実験のまとめ  
RHIC-BES実験の結果  
次へのステップ

筑波大学 数理物質系 物理学域  
宇宙史研究センター(TCHoU) クォーク・核物質(QNM)  
高エネルギー原子核実験グループ  
江角 晋一

E802, E859, E866, E917  
experiment

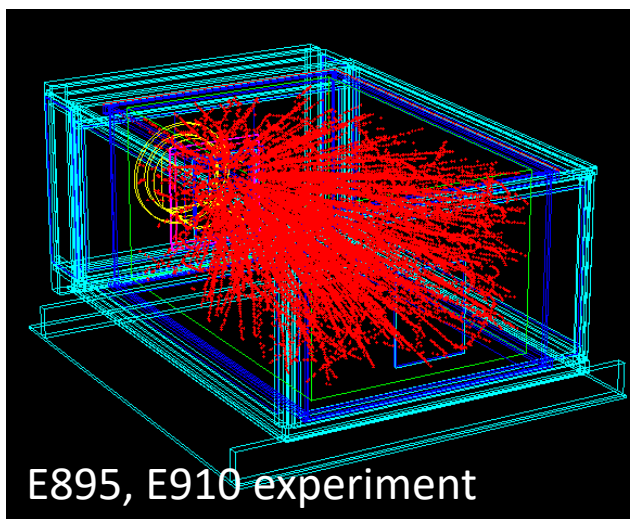
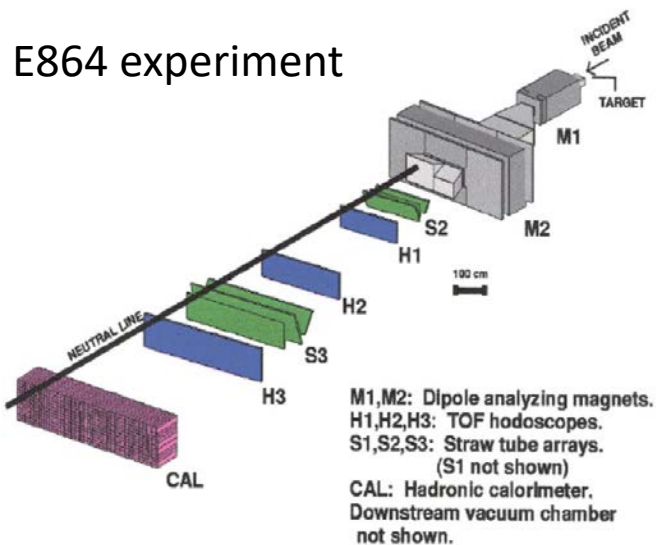


**BNL-AGS加速器を用いた  
固定標的実験**



E814, E877  
experiment

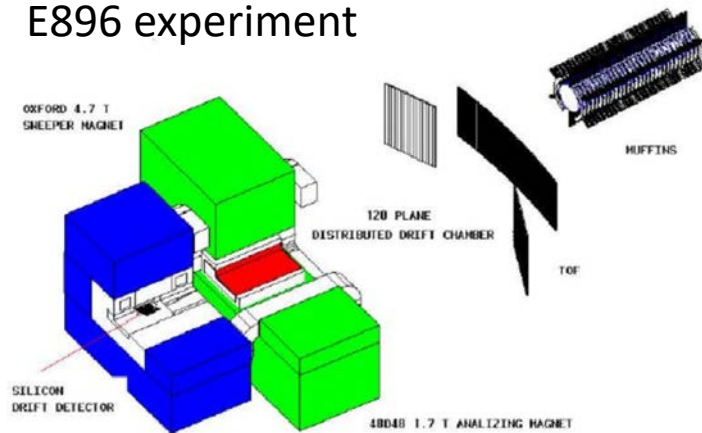
E864 experiment



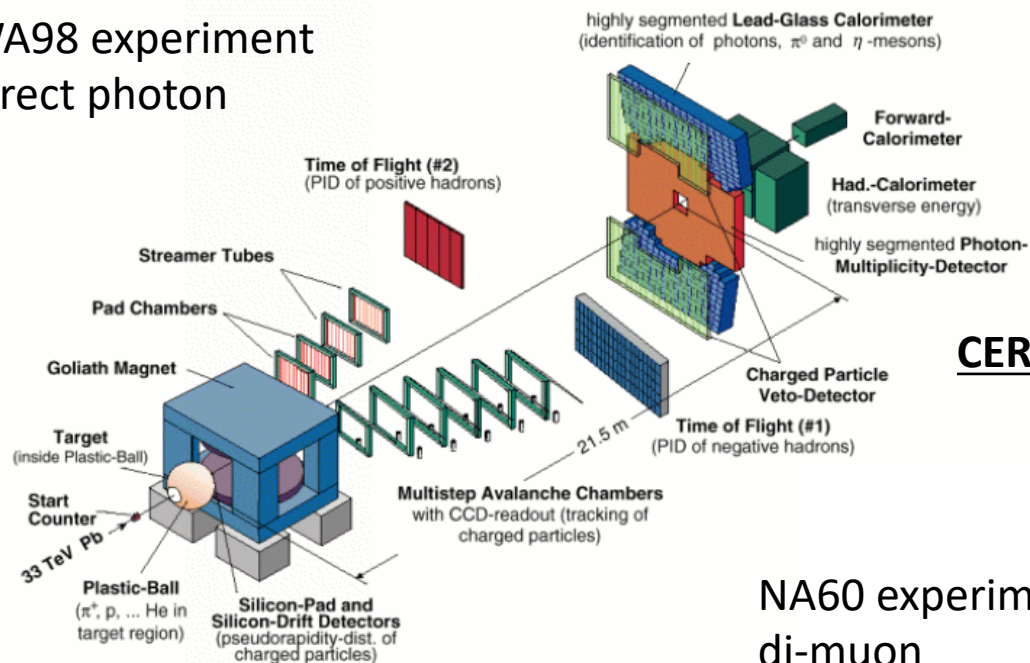
E895, E910 experiment

**RHIC-BES2 (FXT)エネルギー領域**

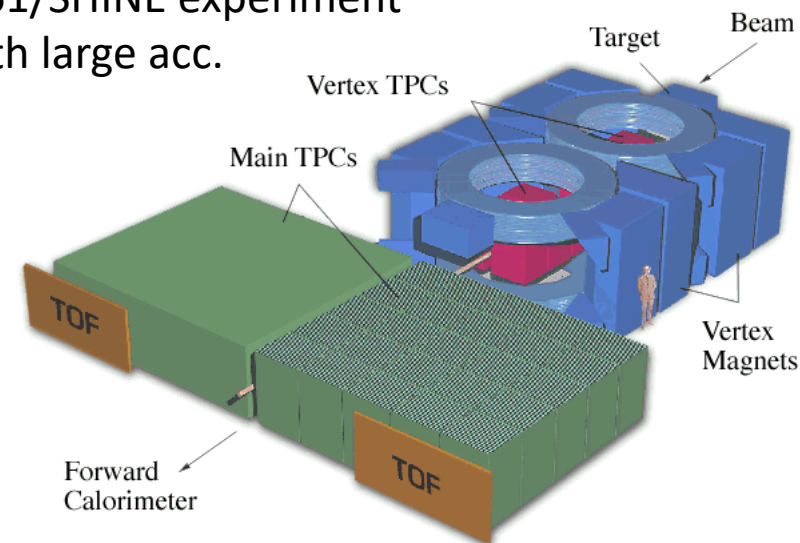
E896 experiment



WA98 experiment  
direct photon

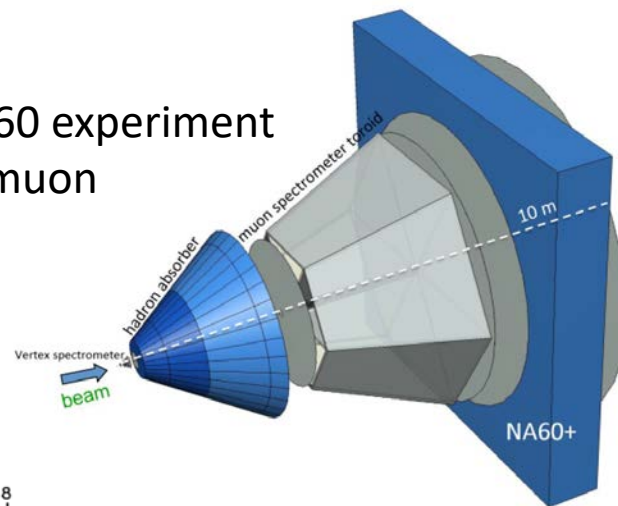


NA49, NA61/SHINE experiment  
hadron with large acc.

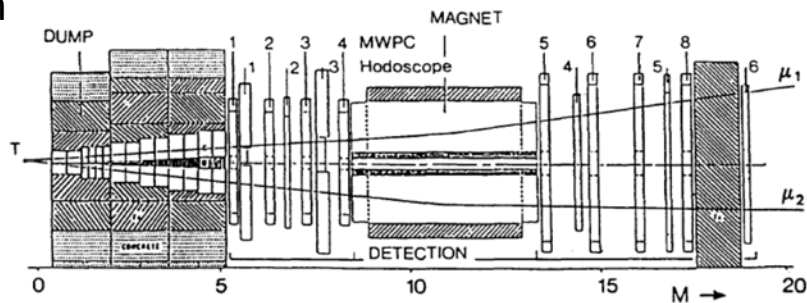


CERN-SPS加速器を用いた  
固定標的実験

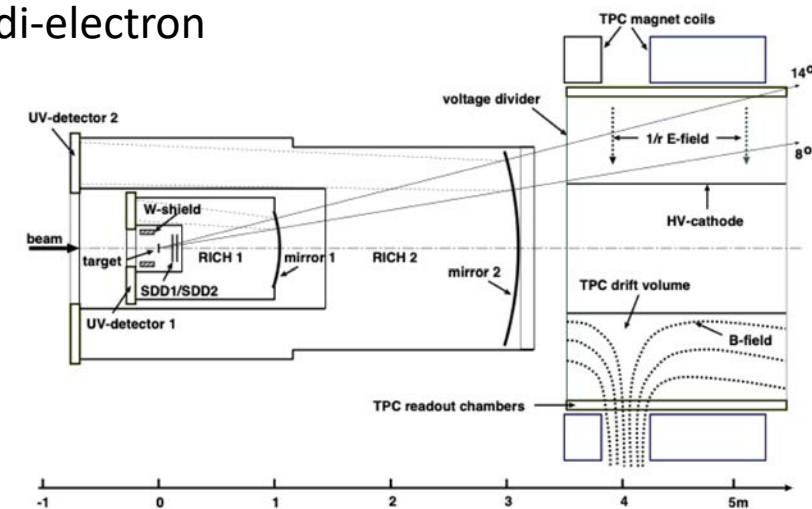
NA60 experiment  
di-muon



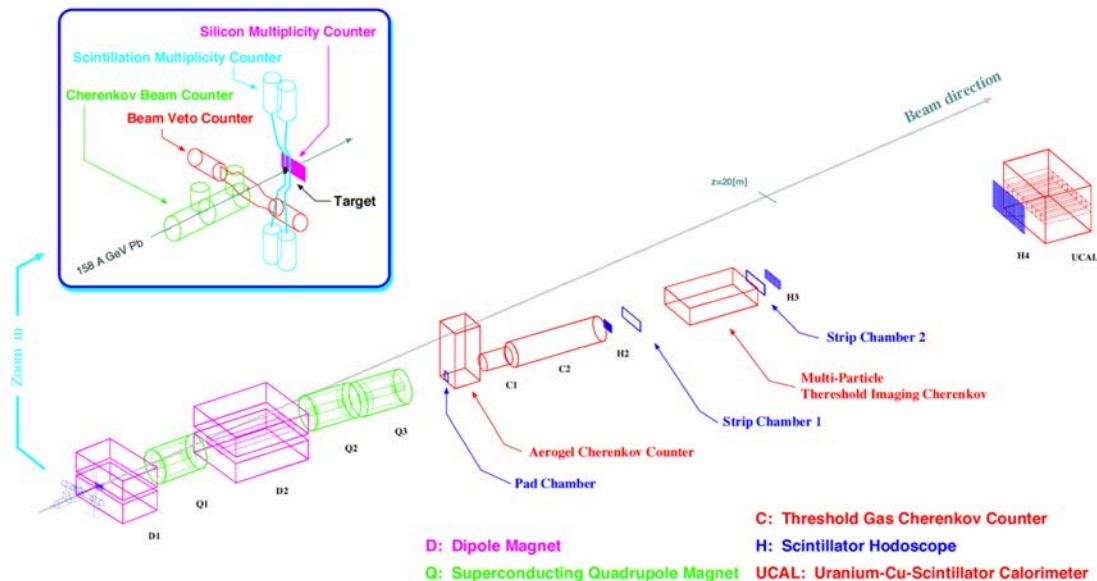
NA38, NA50, NA51 experiment  
di-muon



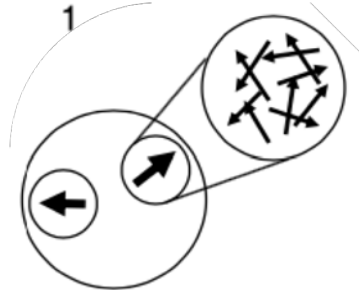
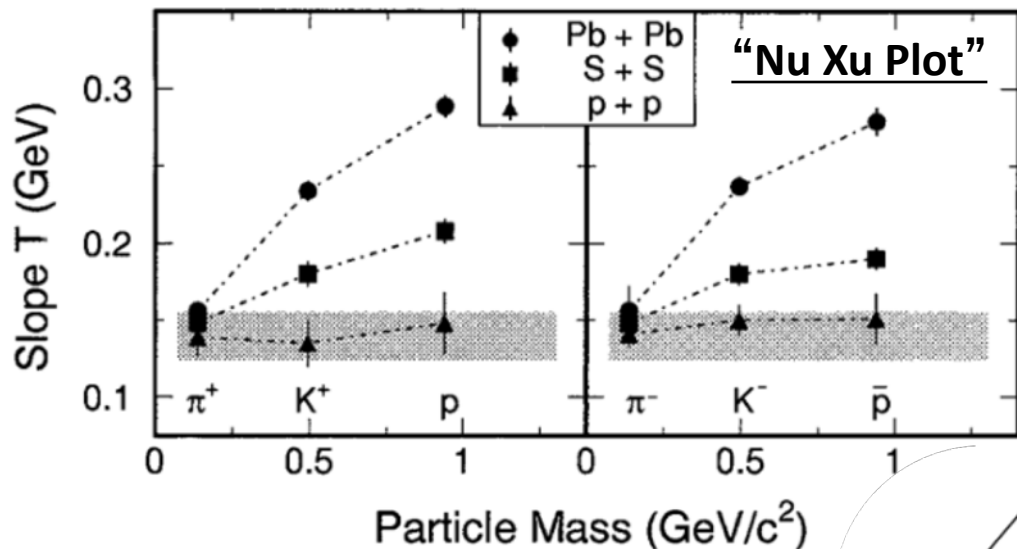
NA45/CERES experiment  
di-electron



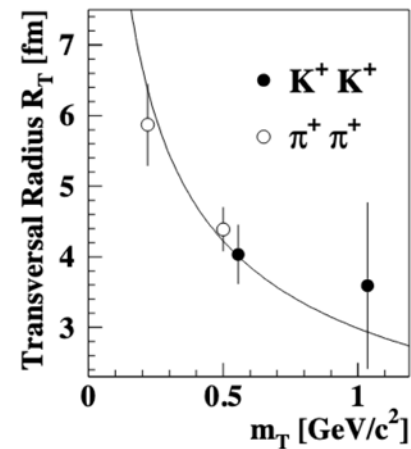
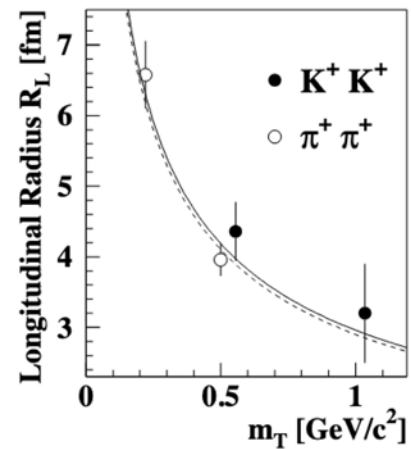
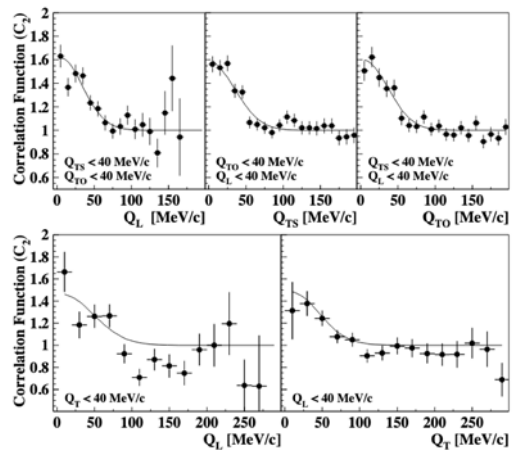
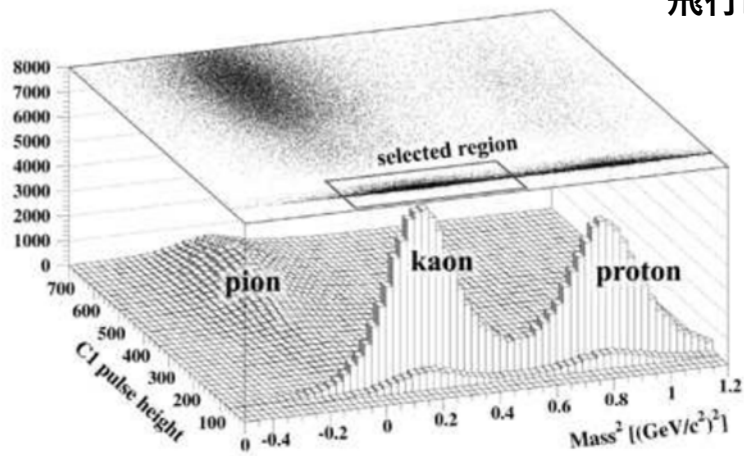
**RHIC-BES2 (COL)  
エネルギー領域**

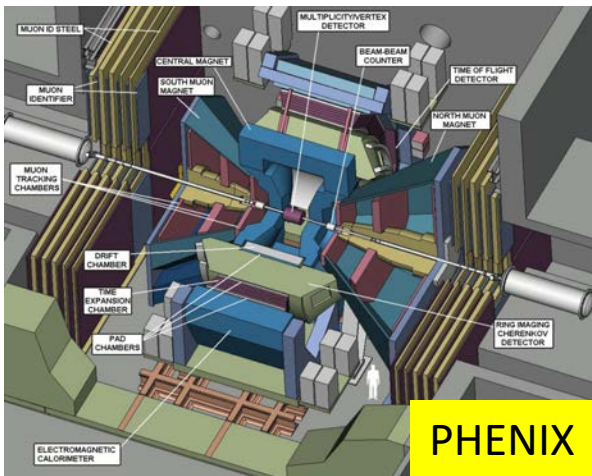


熱力学的凍結温度と半径方向膨張

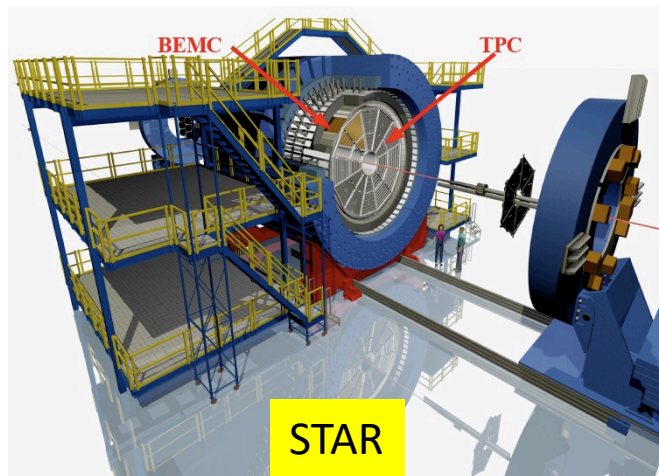


飛行時間測定 + チェレンコフ光による粒子識別とHBT測定

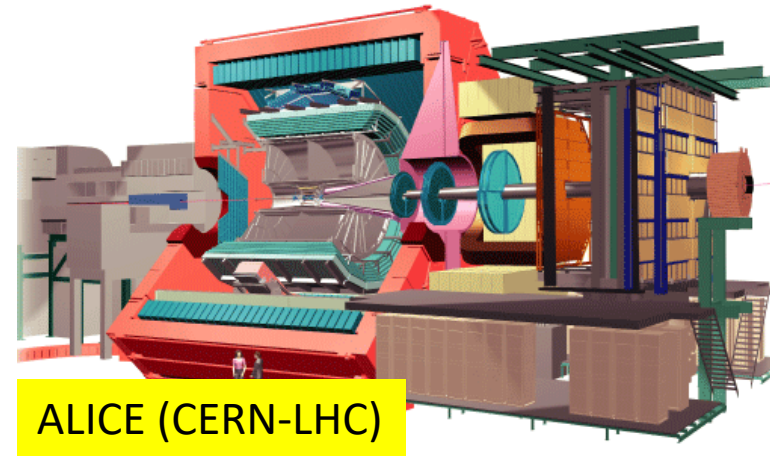




PHENIX



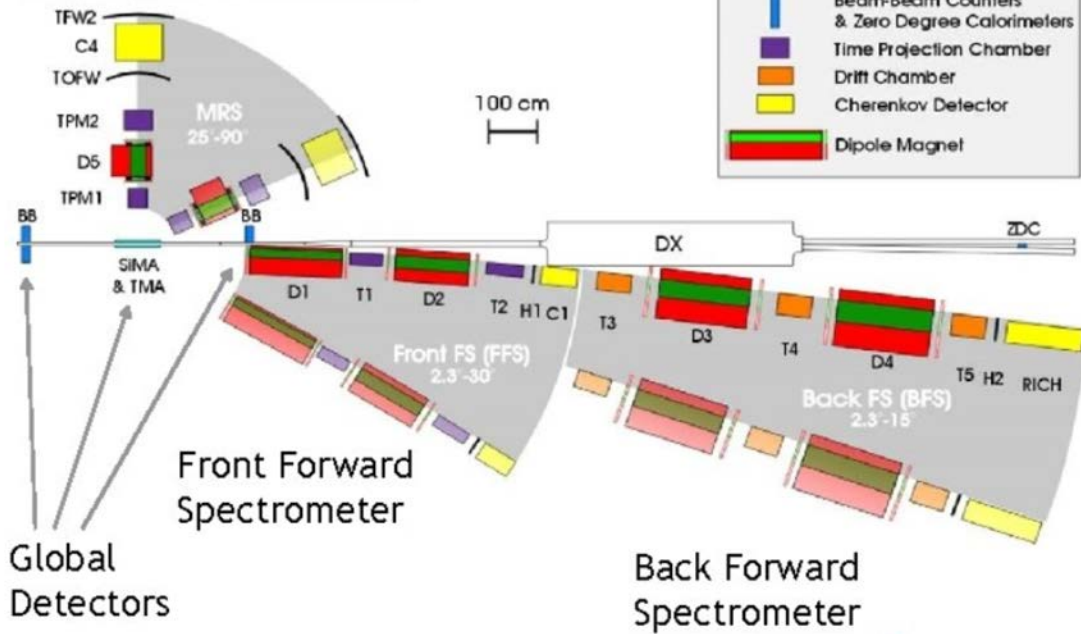
STAR



ALICE (CERN-LHC)

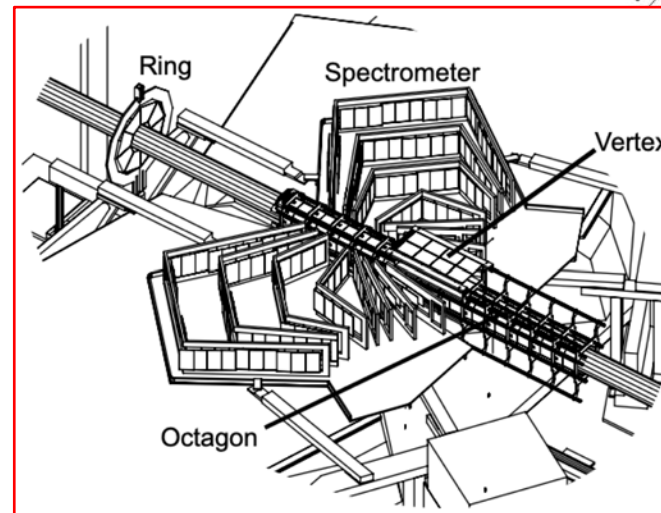
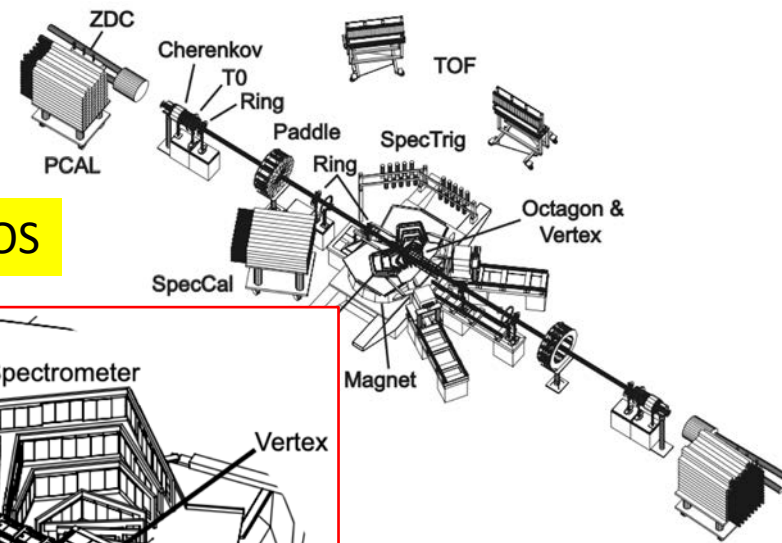
### BRAHMS Experimental Setup

#### Mid Rapidity Spectrometer



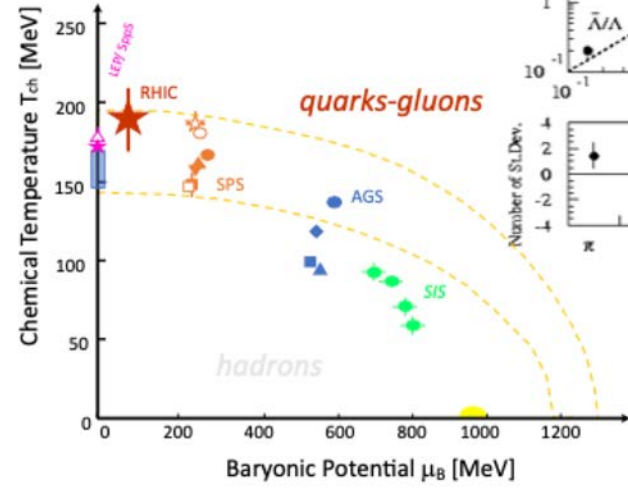
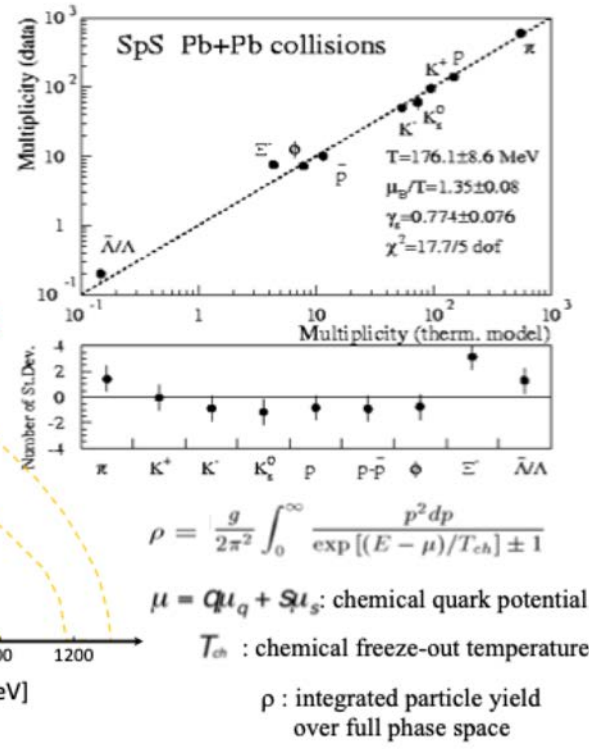
### BNL-RHIC加速器での初期四実験

PHOBOS



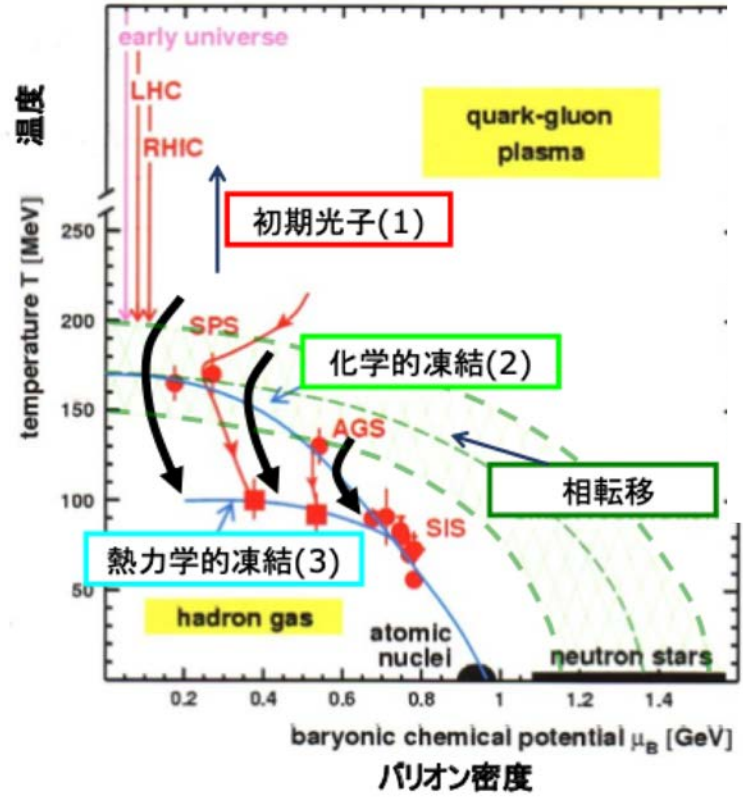
# 化学的凍結

the end of inelastic interactions



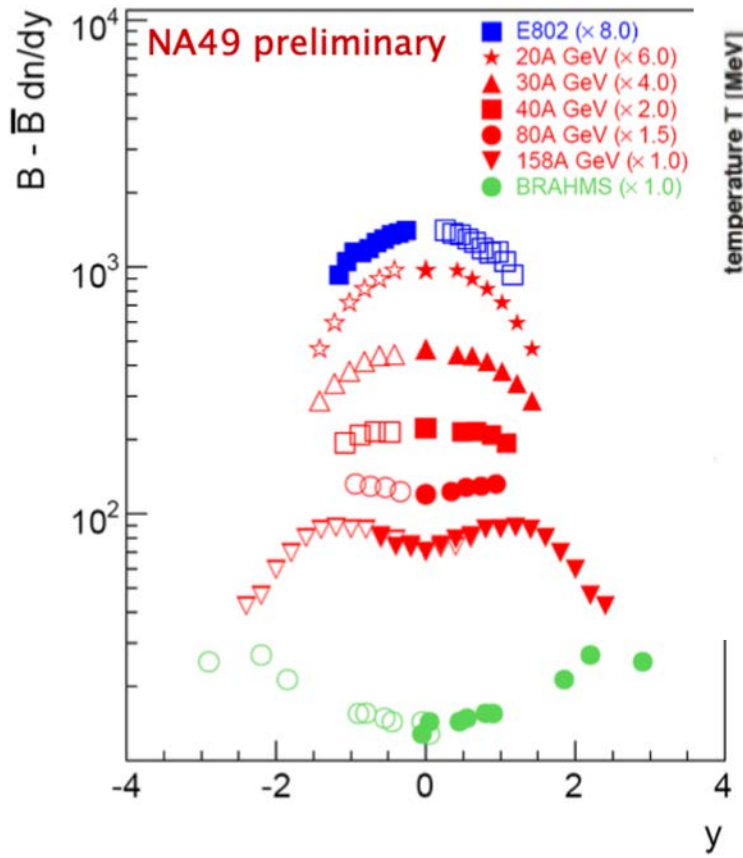
## 粒子収量・比でみる化学的凍結温度 (SPSにおけるQGP証拠1)

# 実験結果でみる相図



1. 直接光子でみる初期温度
2. 粒子比でみる化学的凍結温度 (相転移温度)
3. 運動量分布でみる熱力学的凍結温度

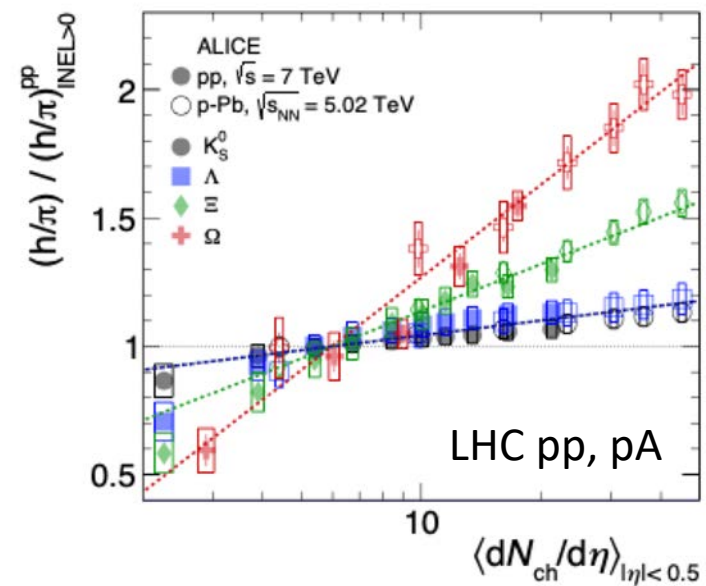
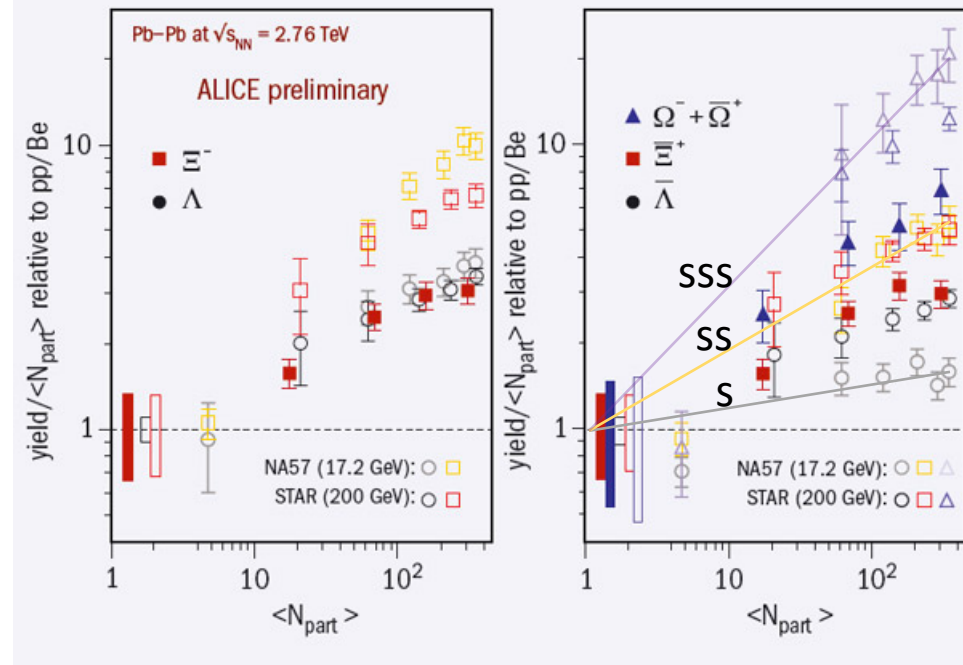
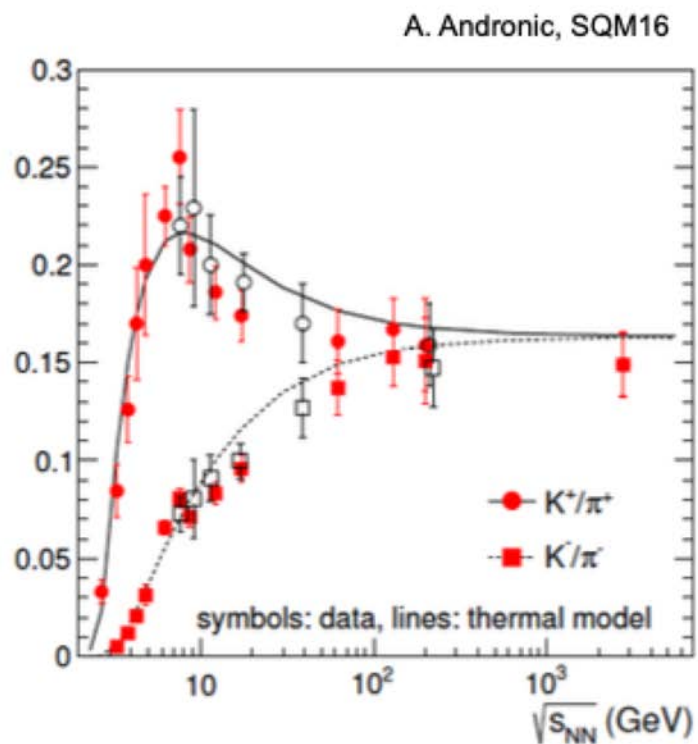
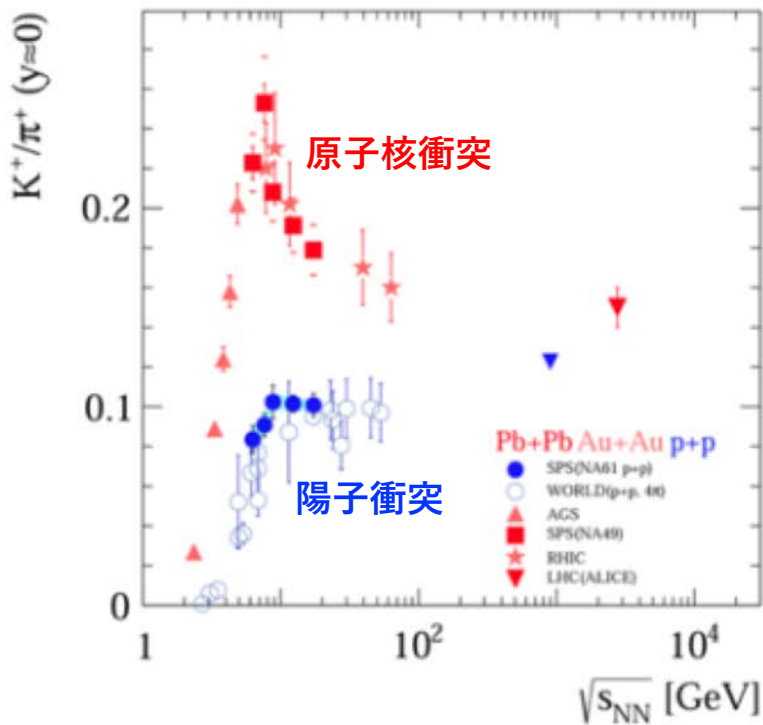
# バリオンのStopping



# ストレンジネスの増大 (SPSにおけるQGP証拠2)

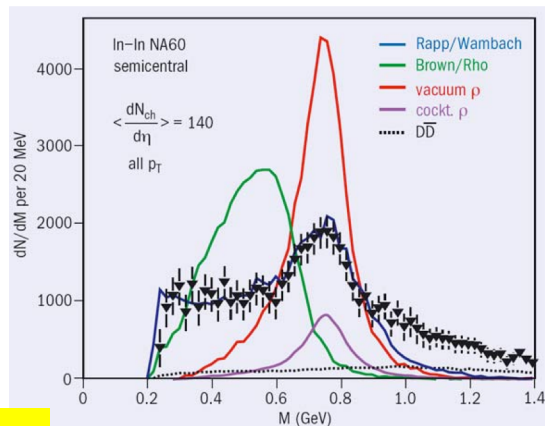
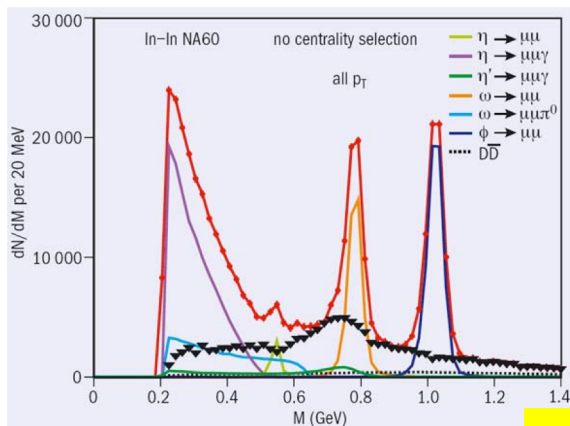
u,d,s クォーク質量  
QGP相転移温度  
c,b,t クォーク質量

K/pi hornは、相転移か？

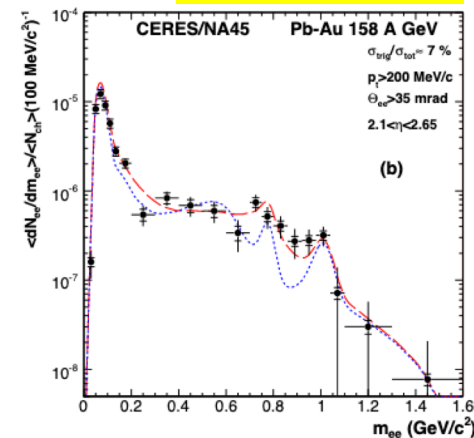
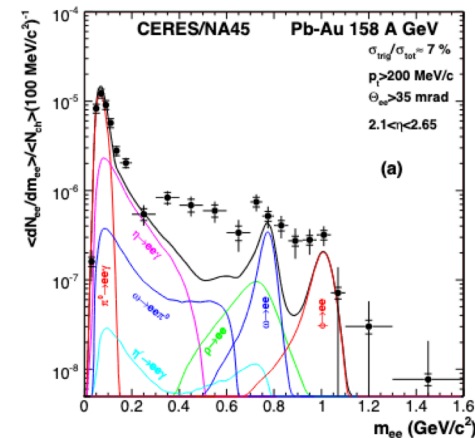


# di-muon $M_{inv}$ 分布, di-electron $M_{inv}$ 分布 (SPSにおけるQGP証拠3)

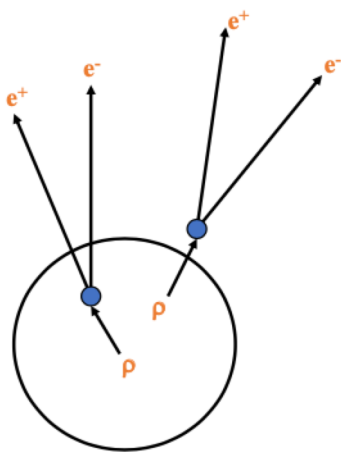
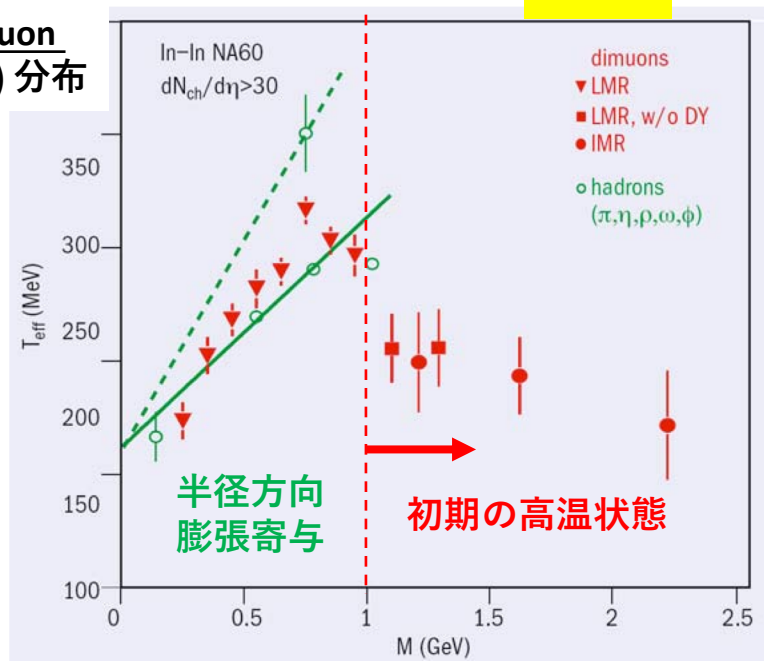
CERES/NA45



NA60

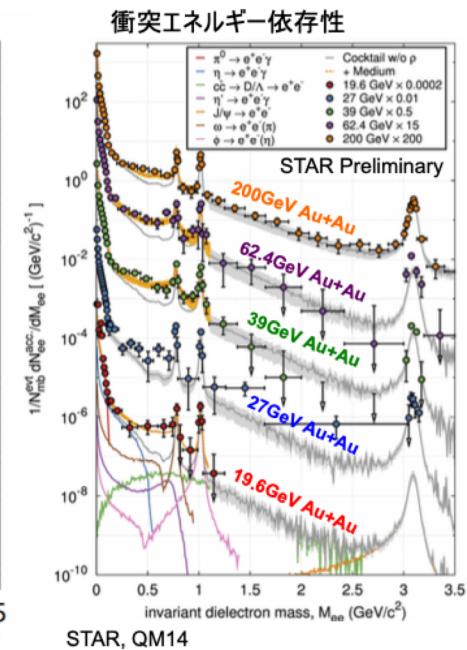
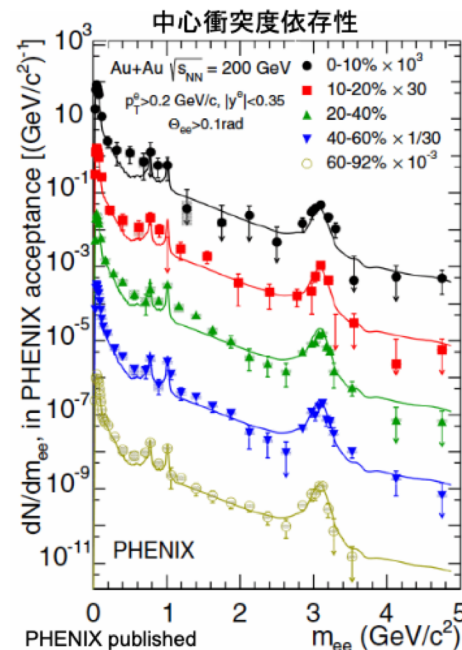


## di-muon $p_T$ ( $m_T$ ) 分布



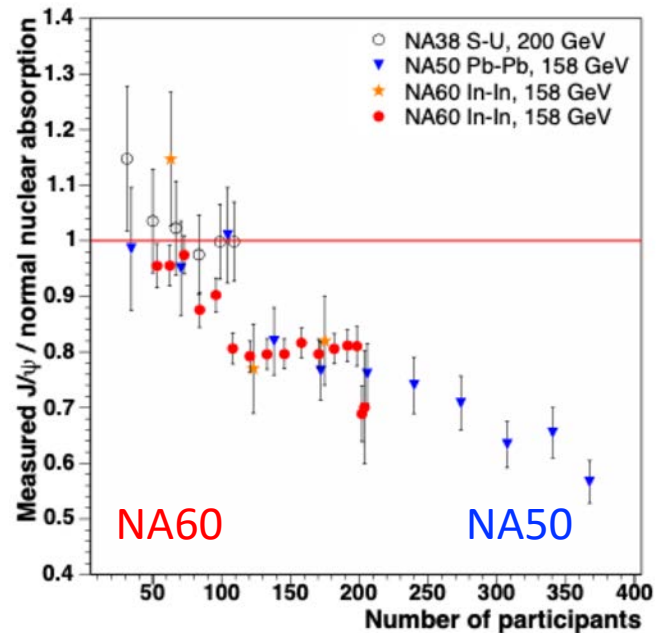
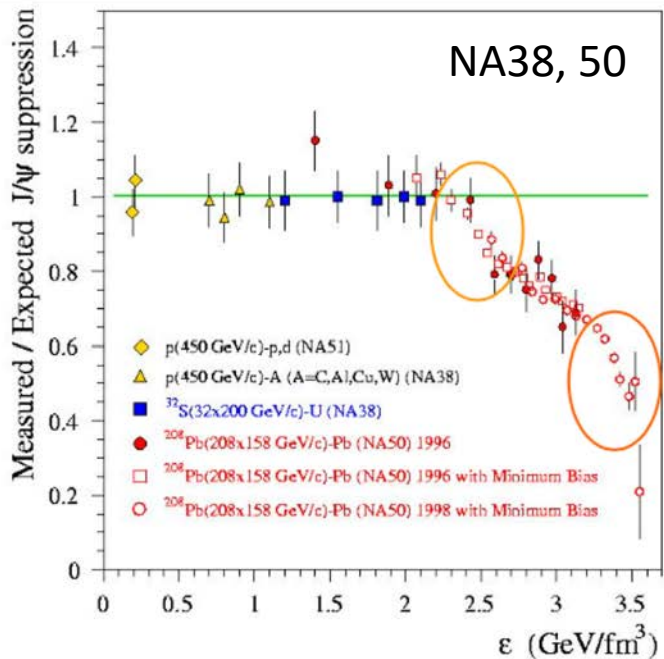
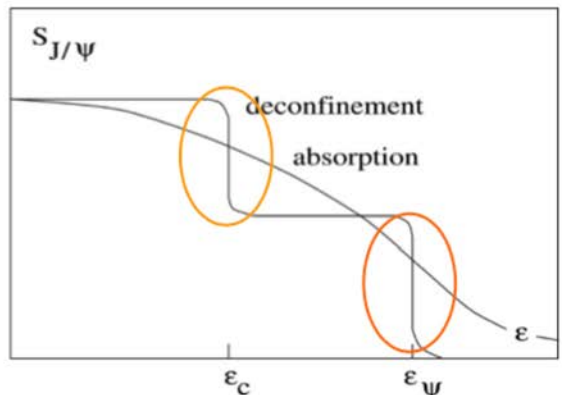
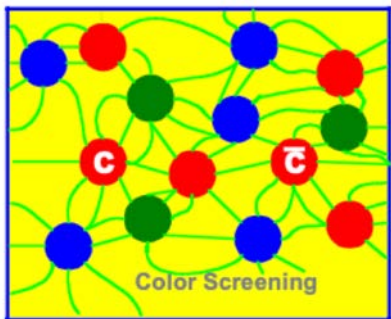
質量変化系の寿命熱光子

PHENIX STAR

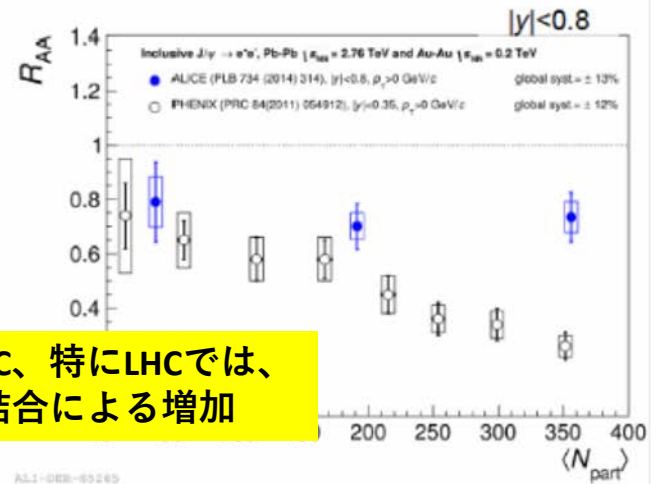
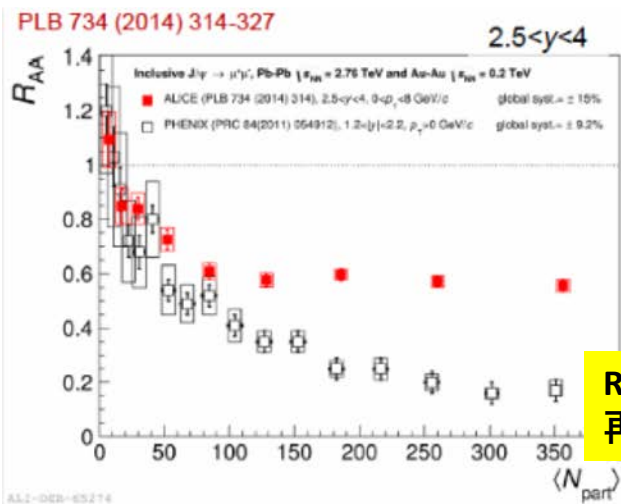
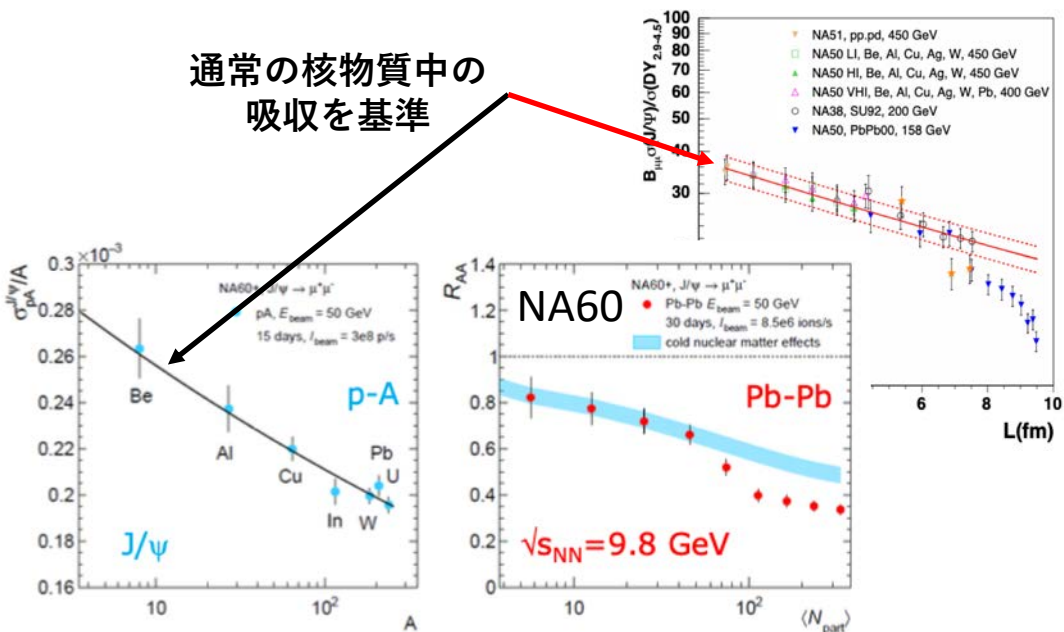




J/ψの消滅 (QGP中でのカラー遮蔽)



通常の核物質中の  
吸収を基準

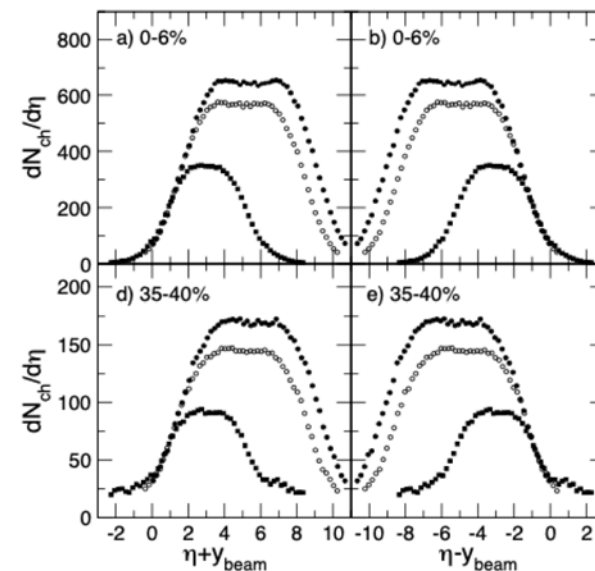
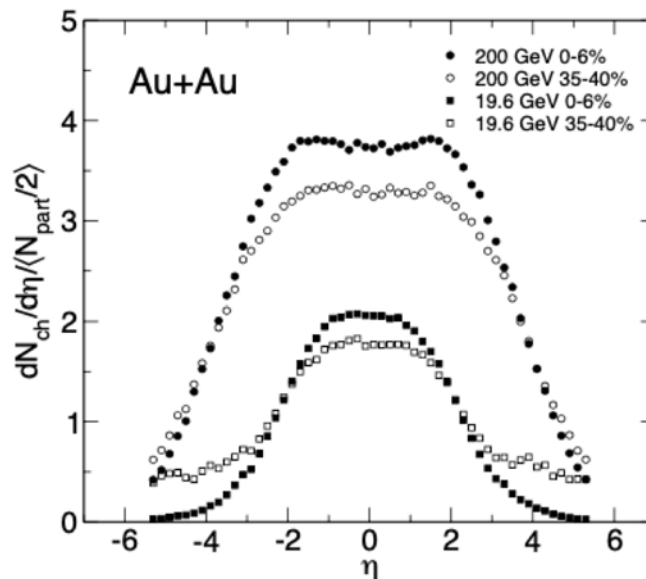
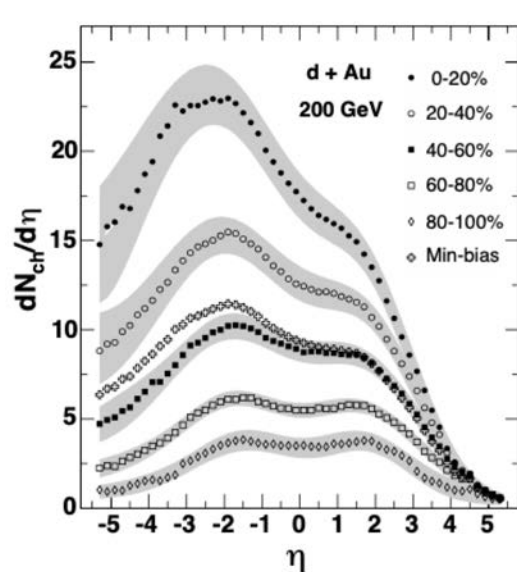


RHIC、特にLHCでは、  
再結合による増加

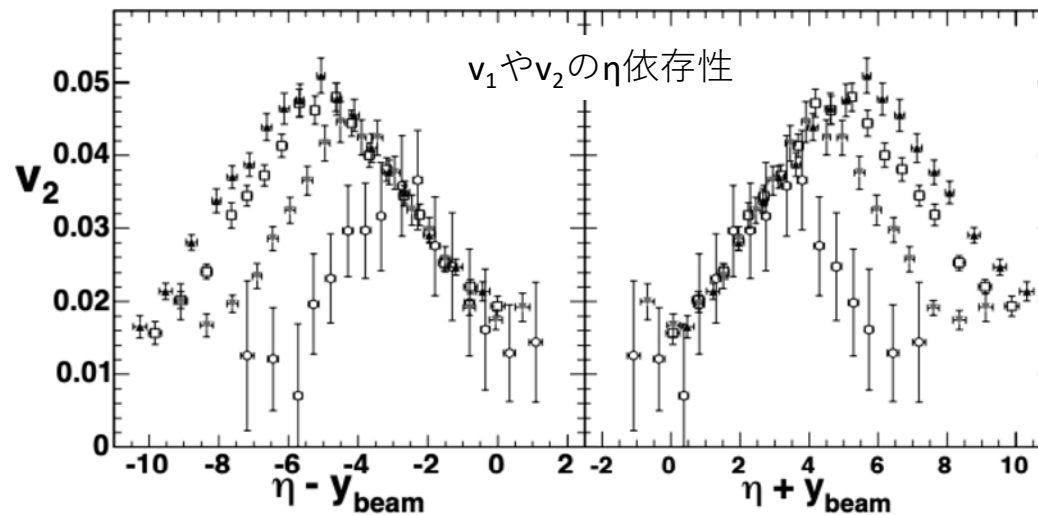
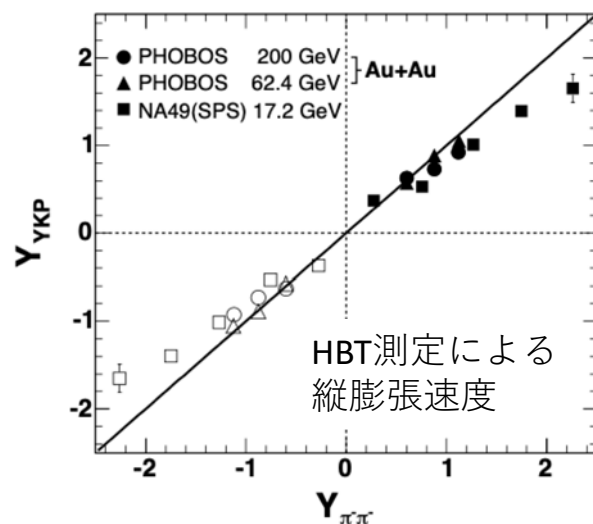
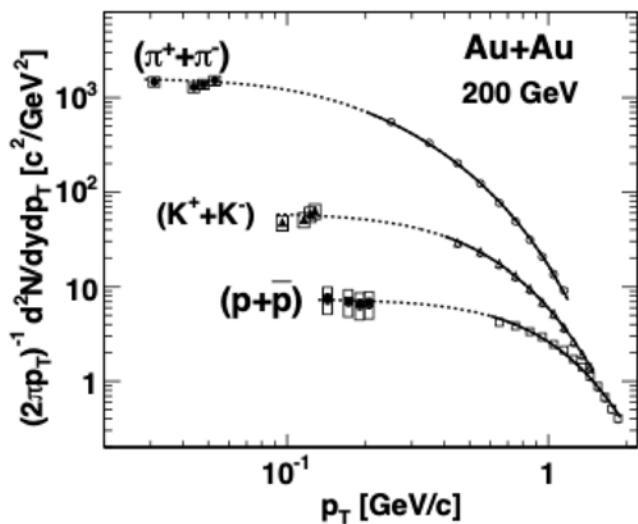
# $dN/d\eta$ 分布 (d+Au 200 GeV, Au+Au 20~200 GeV)

## RHIC-PHOBOS 実験の強み

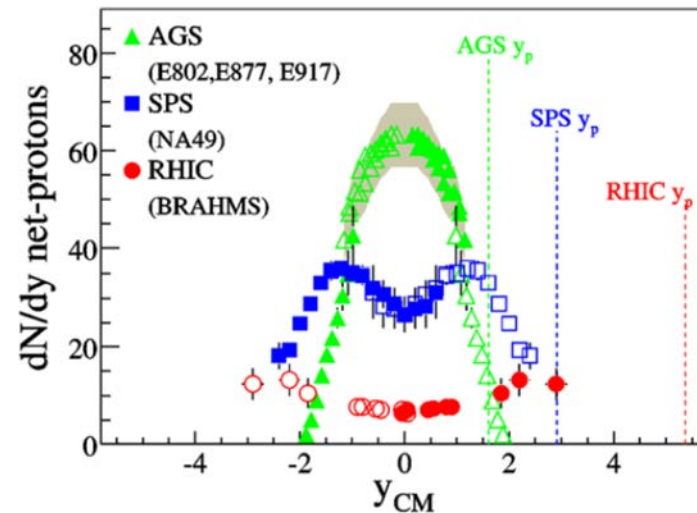
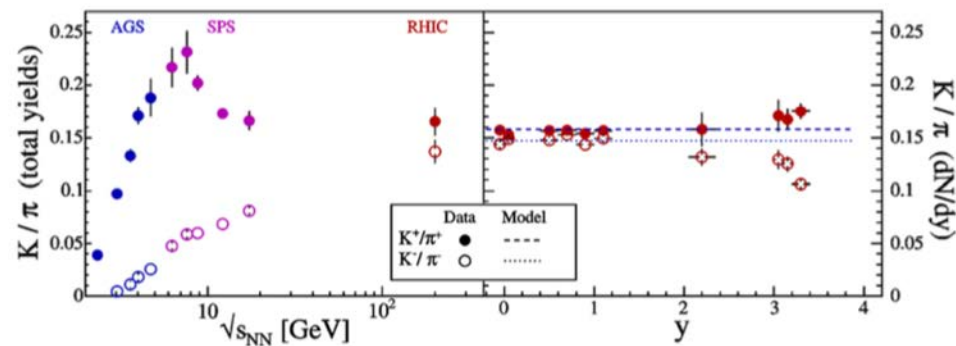
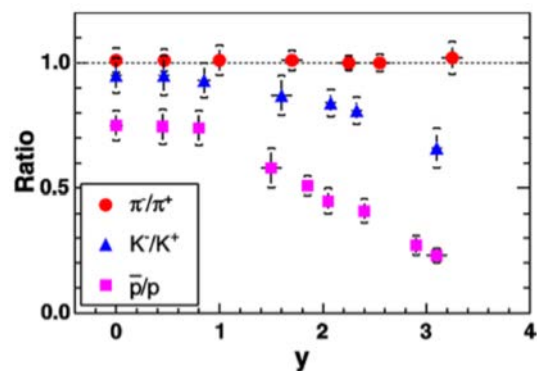
(全 $\eta$ 領域にわたる  
荷電粒子測定)



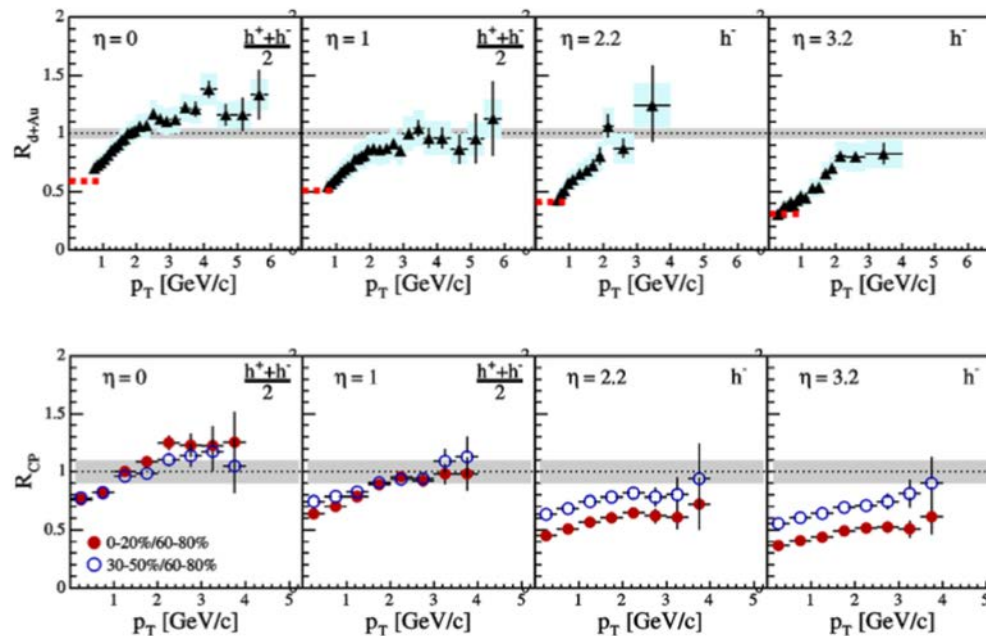
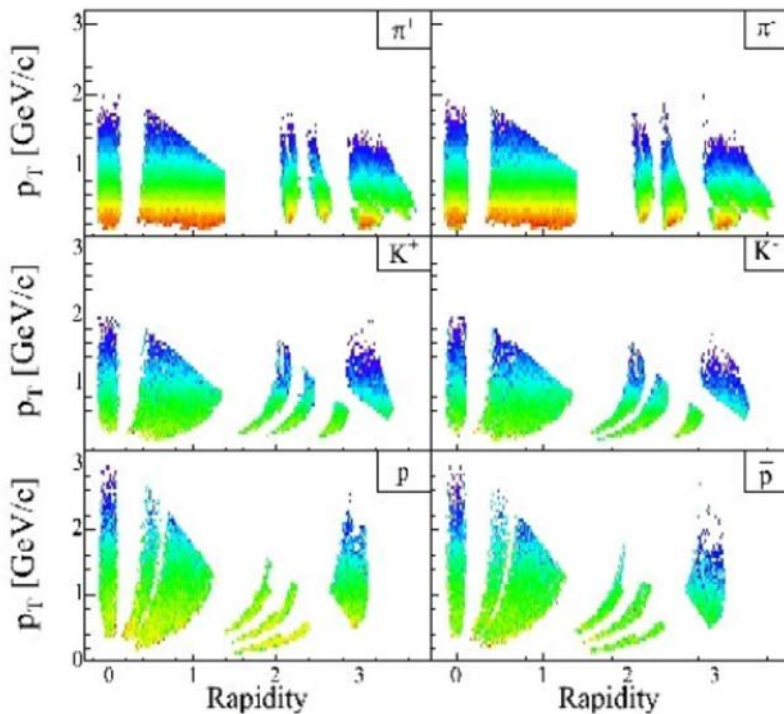
シリコン検出器の $dE/dx$ によるPID



# RHIC-BRAHMA実験の強み (広いrapidity領域にわたるハドロン粒子識別)

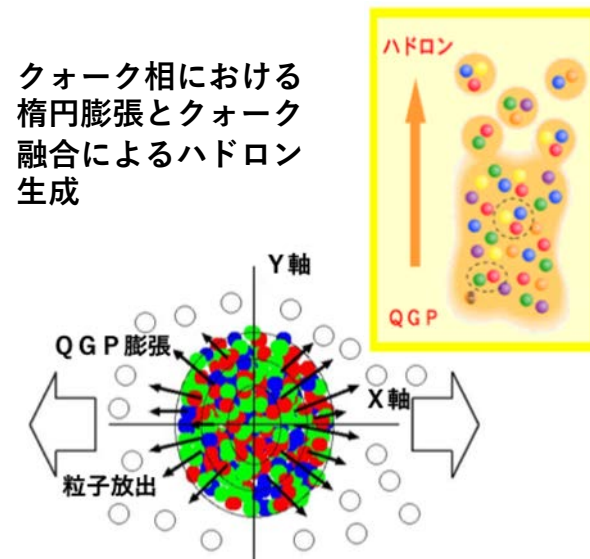
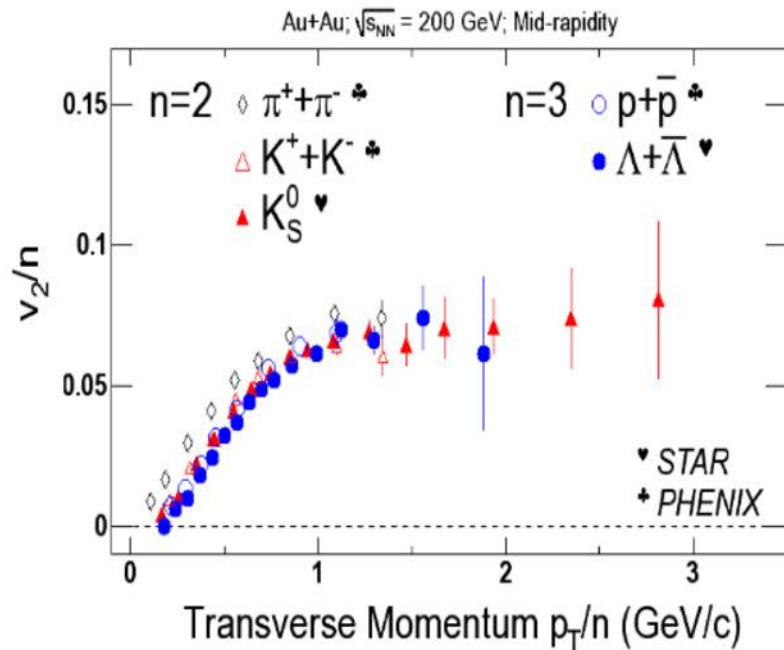
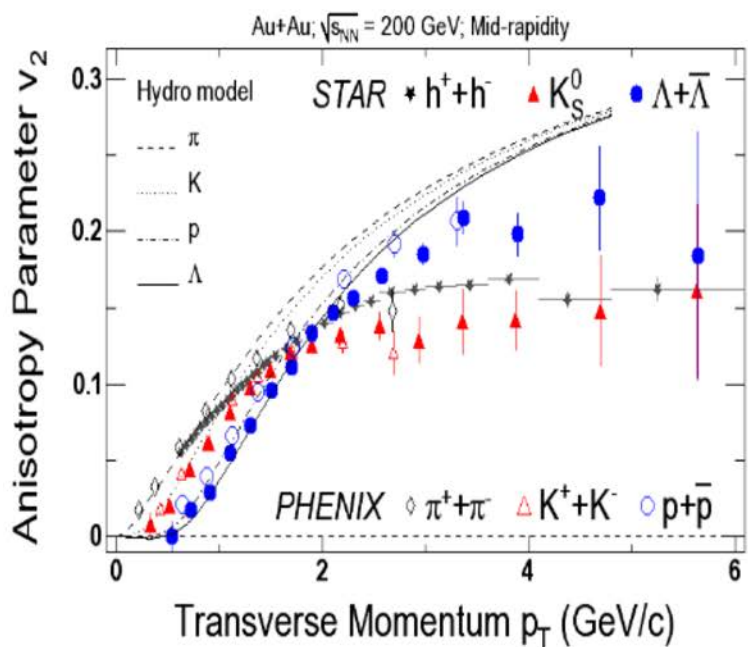
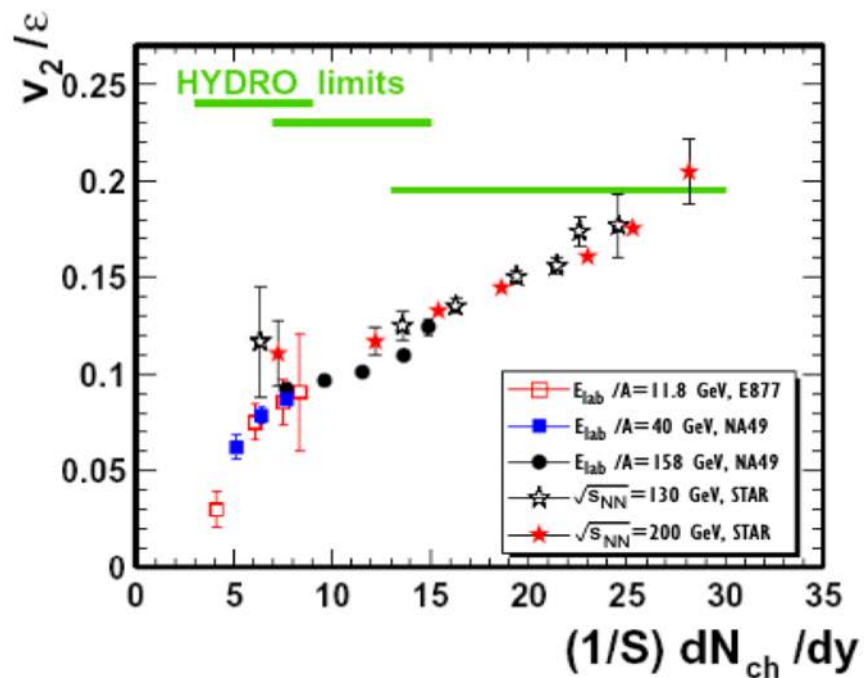
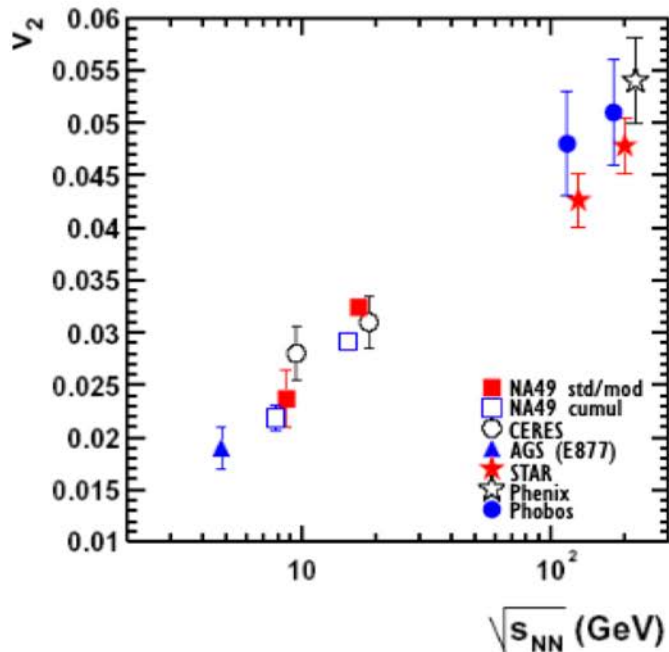
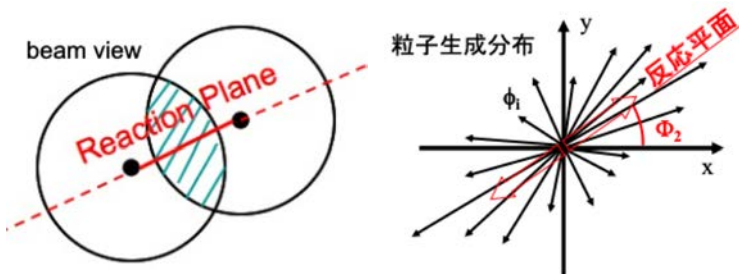


可動型スペクトロ  
メーターによる  
アクセプタンス



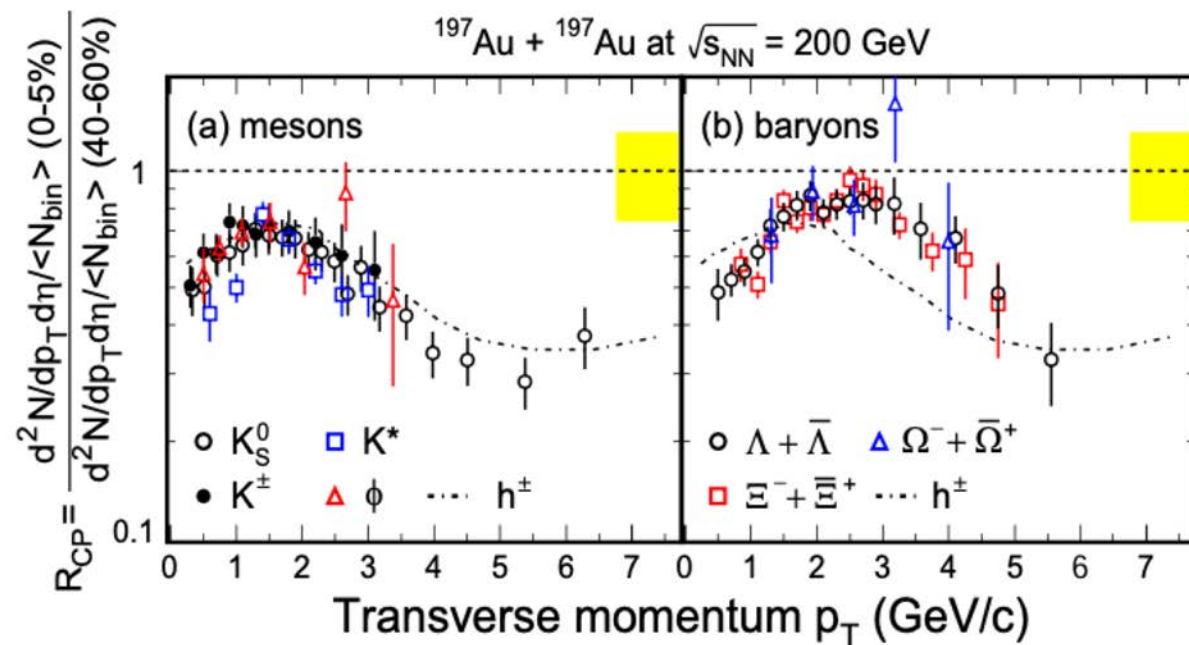
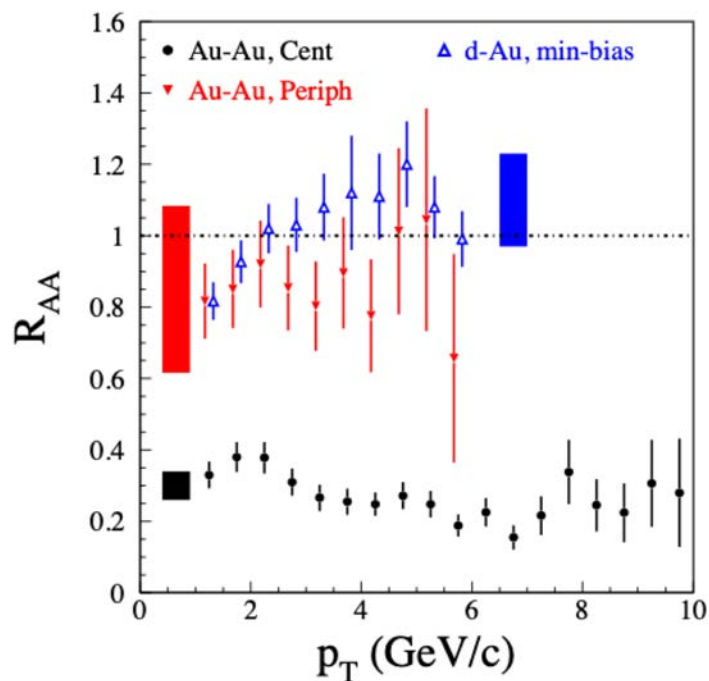
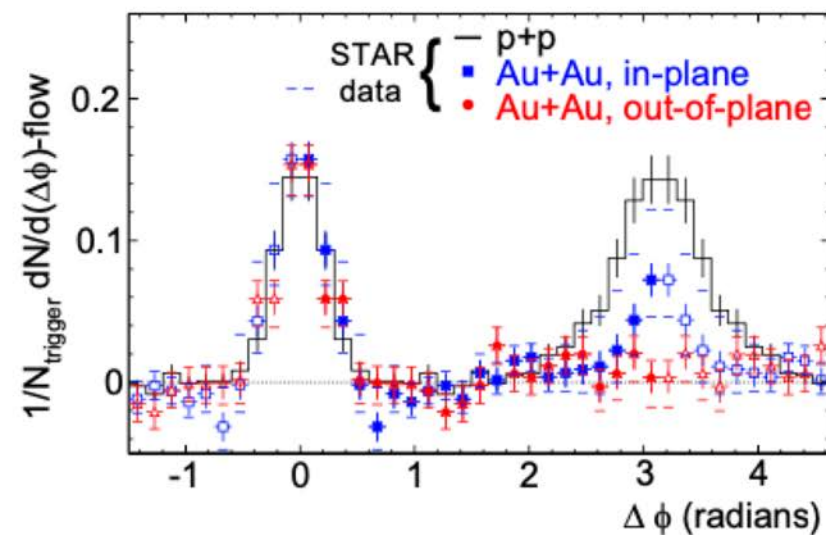
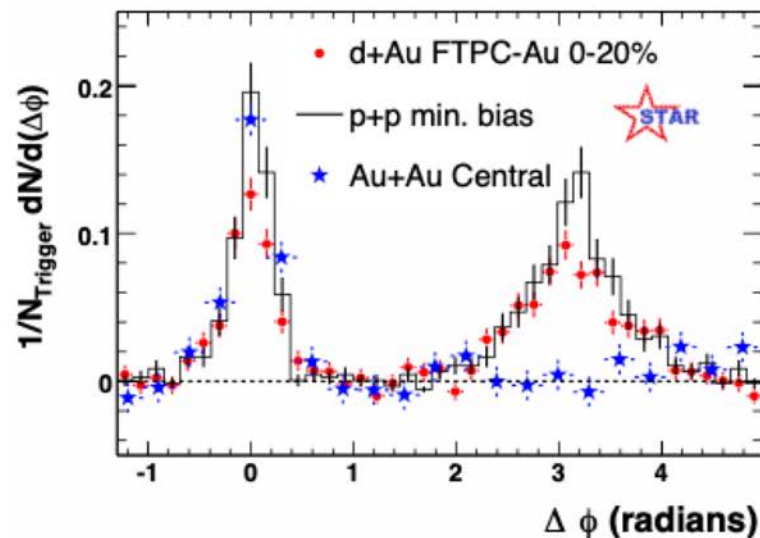
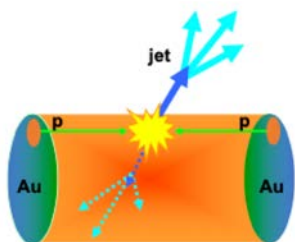
# 流体極限に迫る楕円フローとクォーク数によるスケーリング則

## (RHICにおけるQGP証拠1)

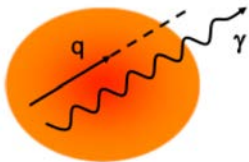


# QGP中でのエネルギー損失による ジェット・クエンチング

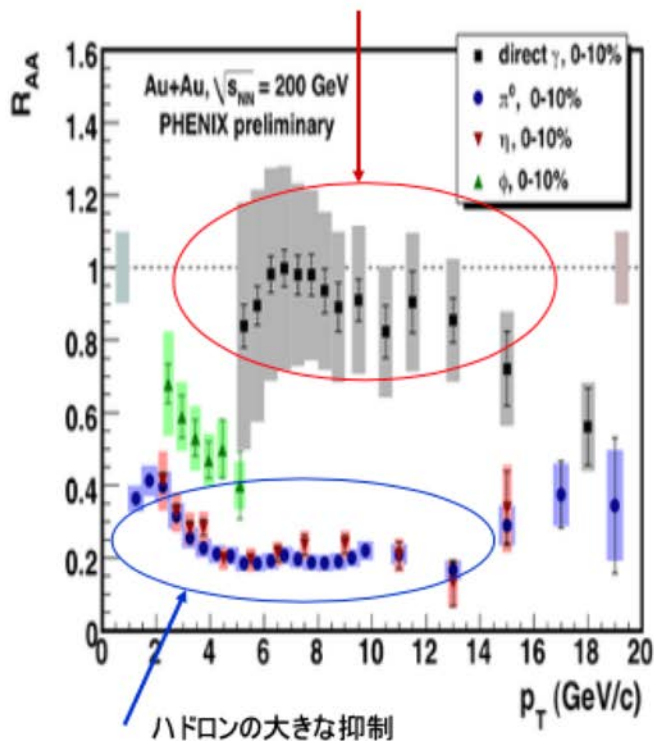
(RHICにおけるQGP証拠2)



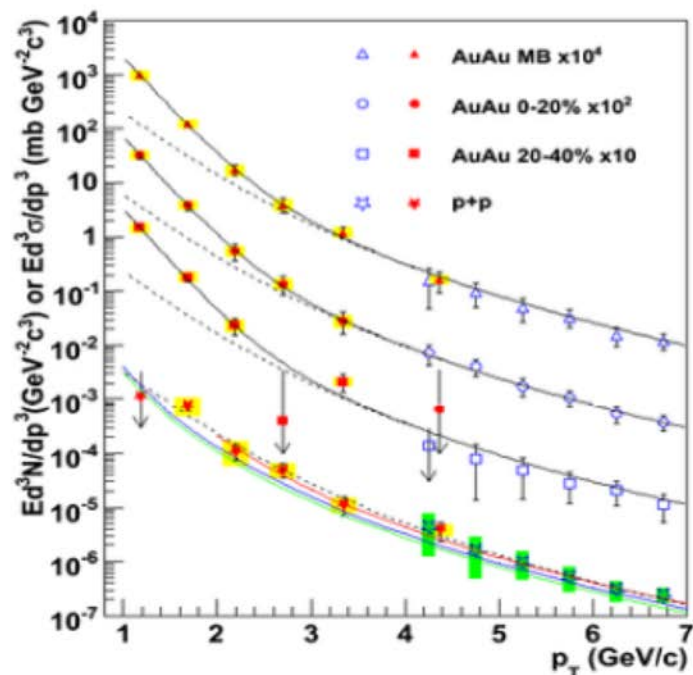
# 初期光子の非抑制 ( $p_T > 5 \text{ GeV}/c$ )、熱光子の発見 ( $p_T < 3 \text{ GeV}/c$ )、大きな熱光子 $v_2$ (光子パズル)



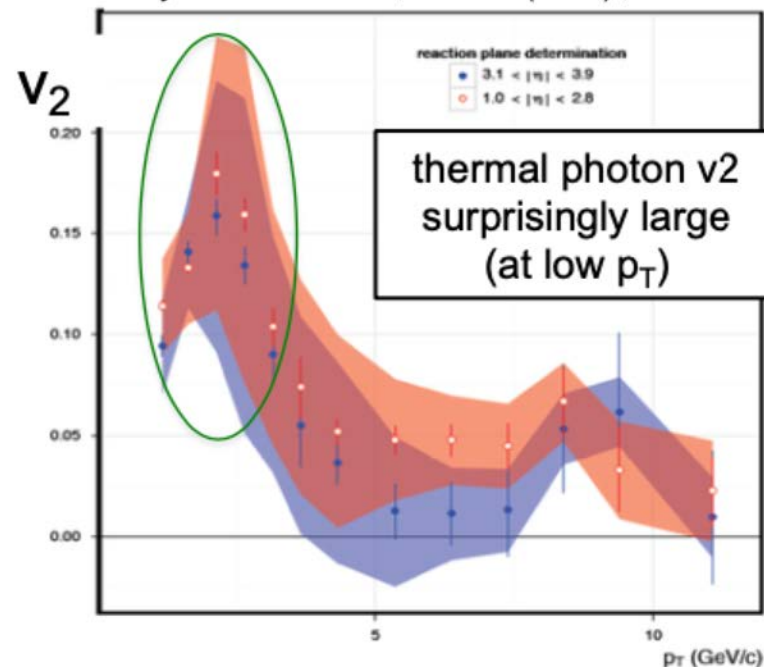
直接光子の非抑制



高温QGP相からの  
熱光子による温度測定

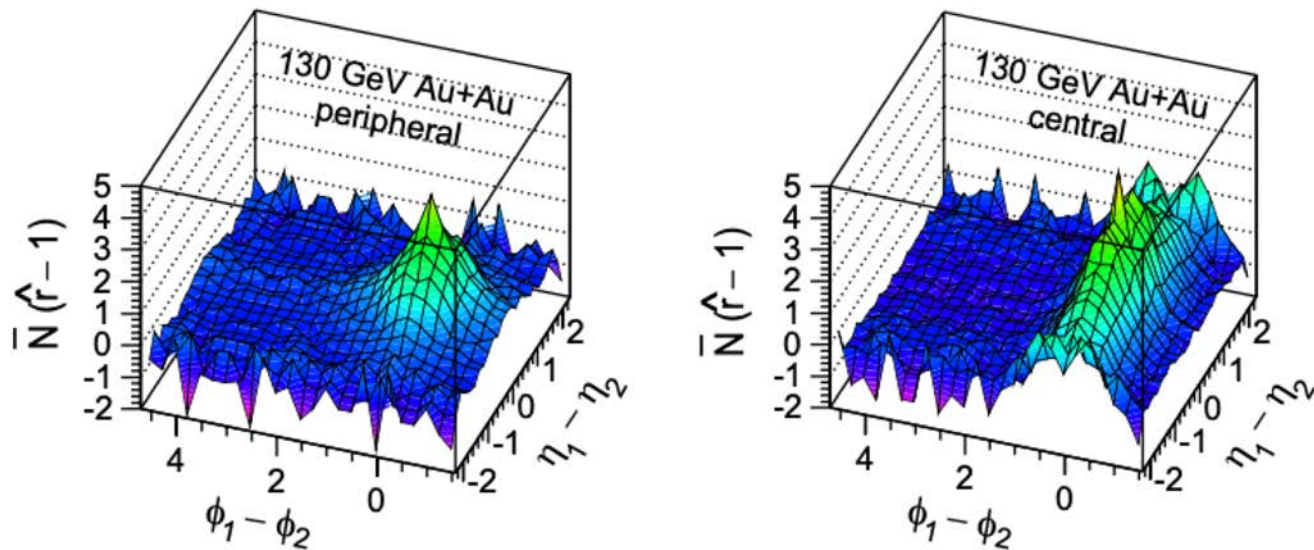
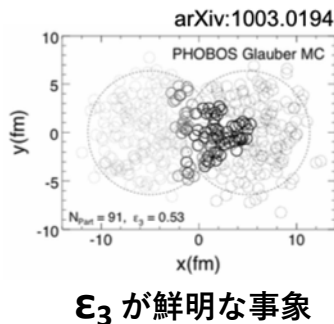


Phys. Rev. Lett. 109, 122302 (2012), PHENIX

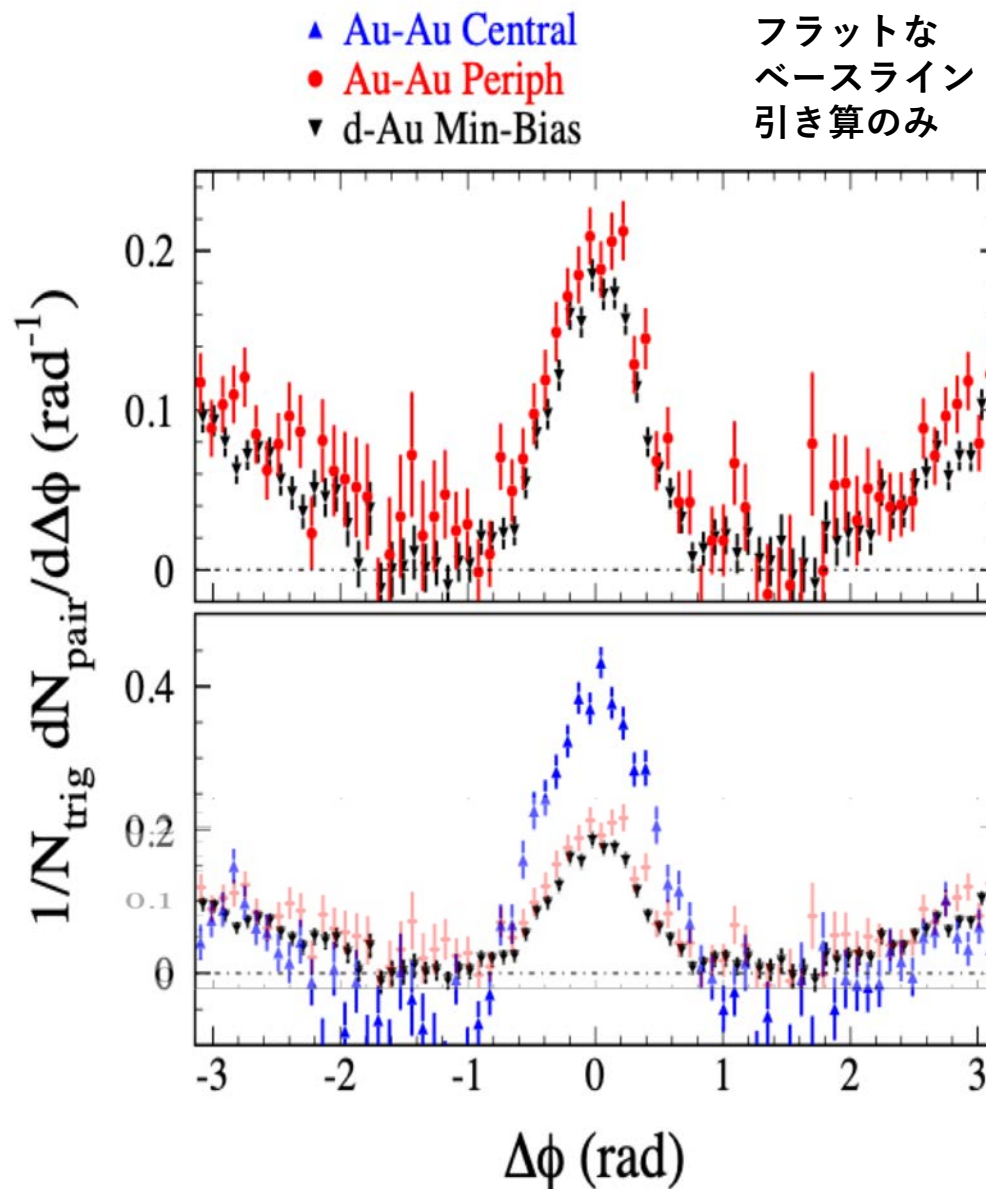


# Ridge発見、Mach-cone 発見 (誤報)

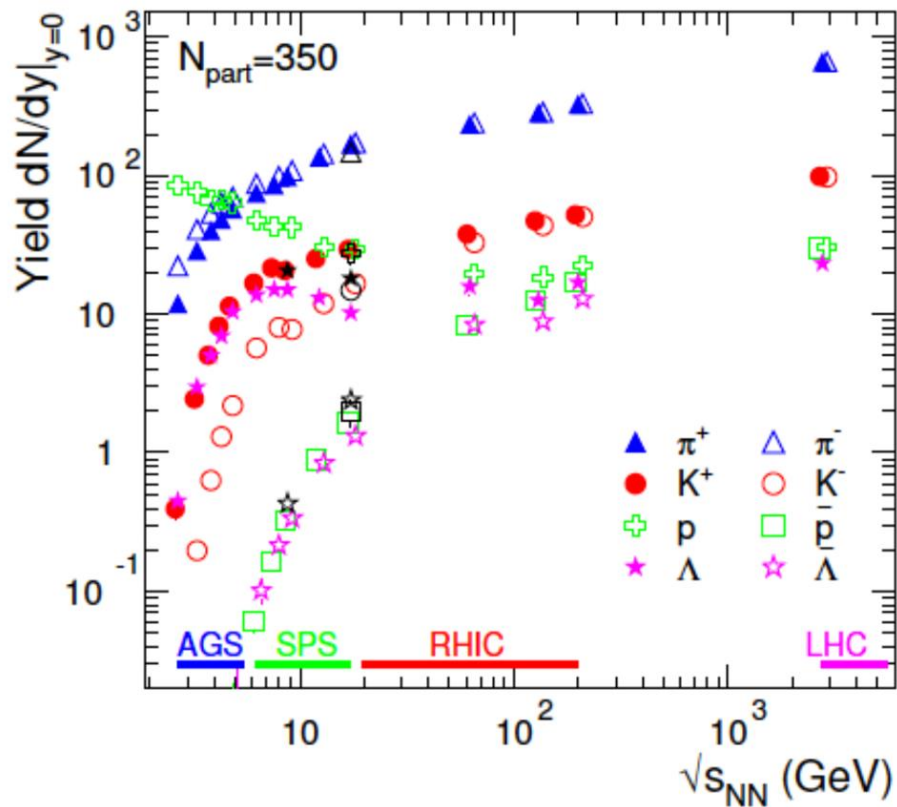
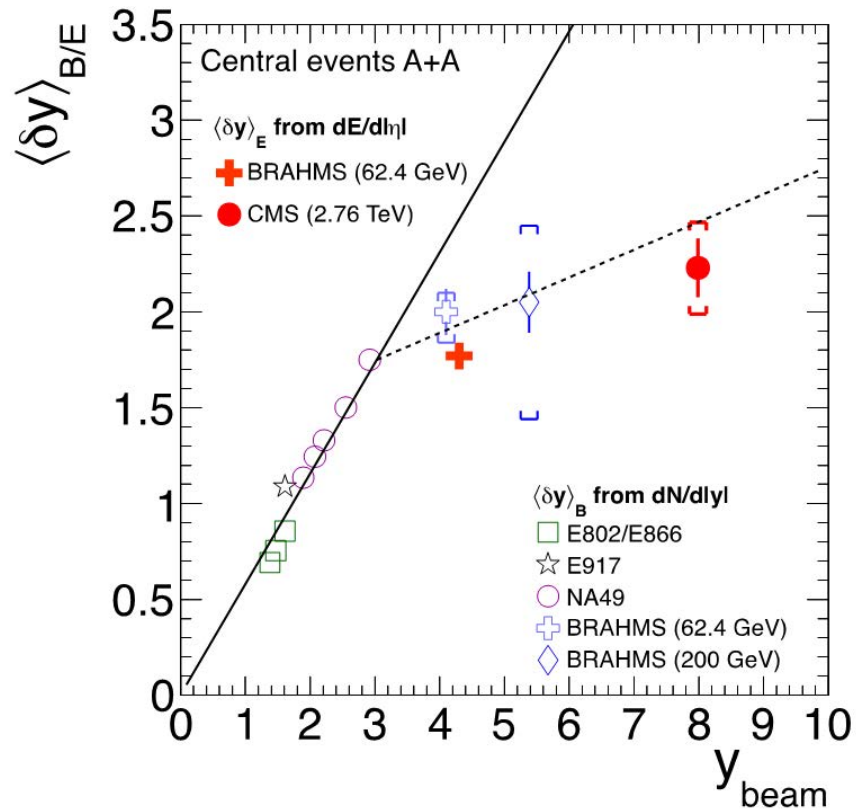
初期異方性ゆらぎ起源の高次フロー  $v_n$  ( $n>2$ )  
 楕円率も  $\epsilon$ (Standard)から、 $\epsilon$ (Participant)へ



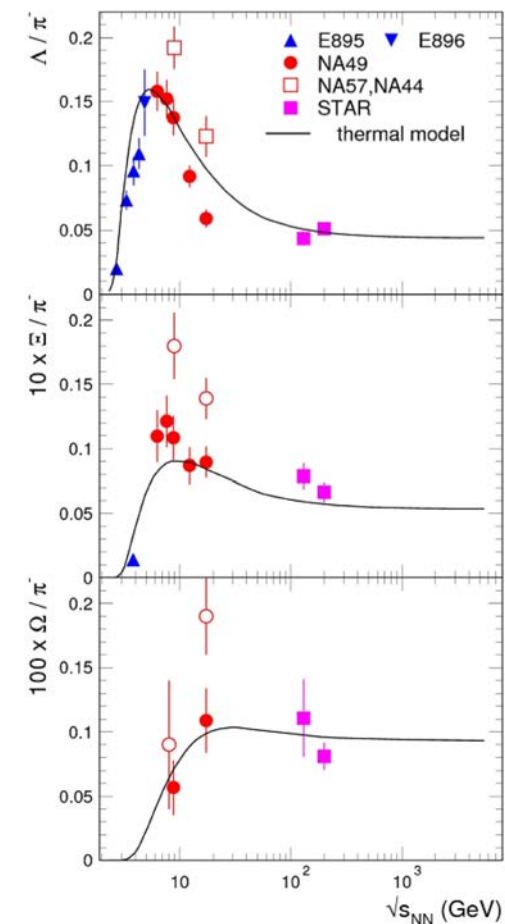
$v_2$ によるBG寄与を引いている



# 広いエネルギー領域にわたるバリオンStopping、ハドロン収量



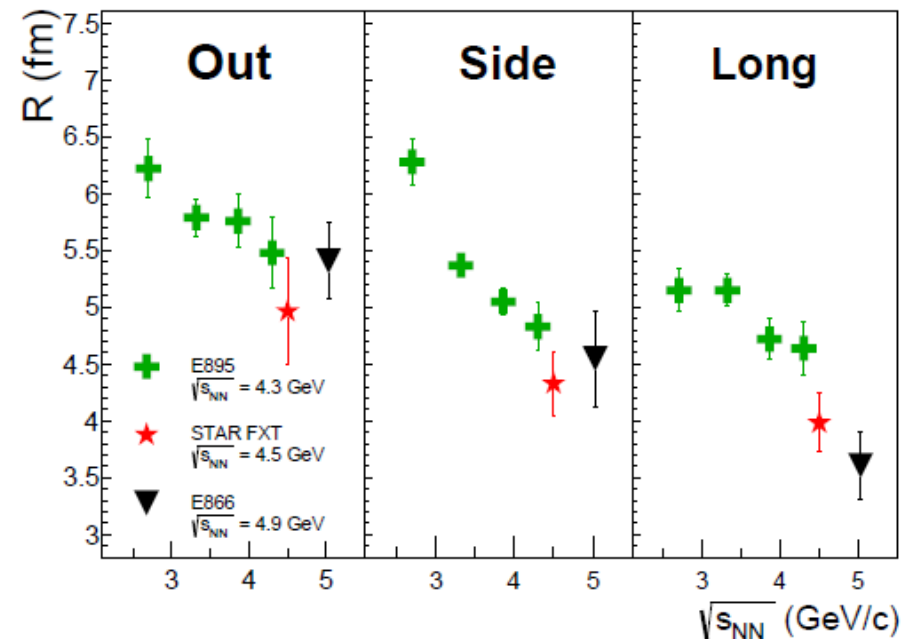
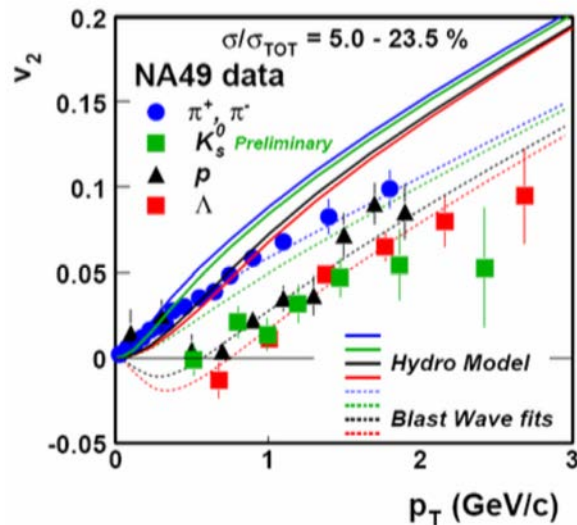
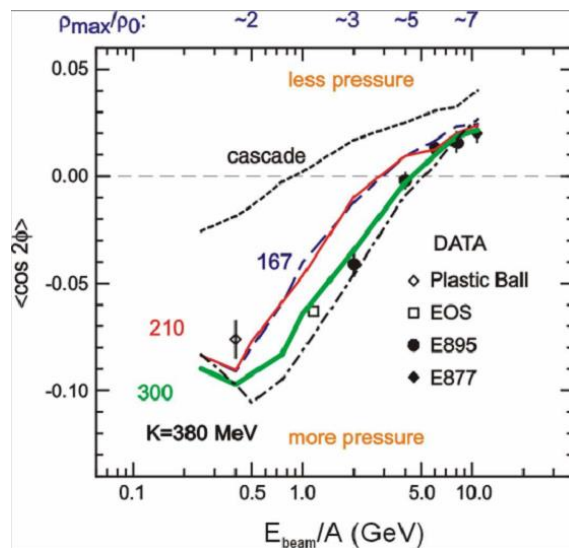
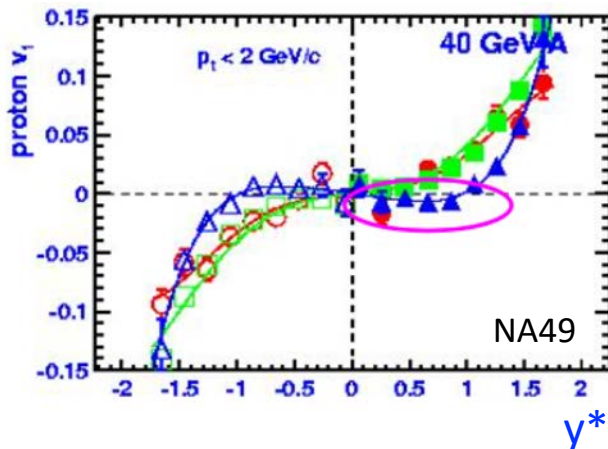
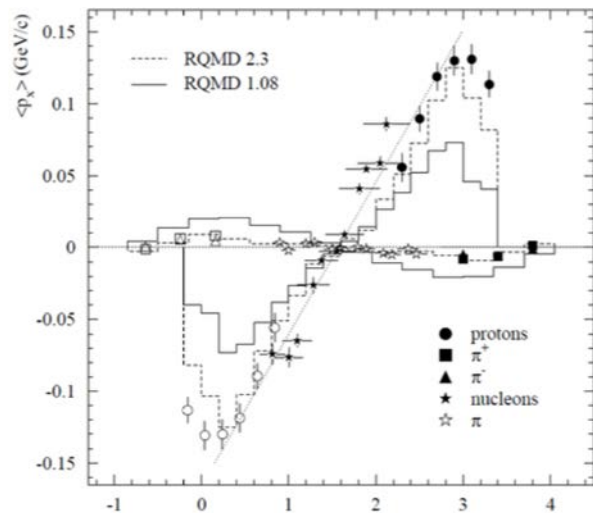
## K/pi hornの検証





# AGSエネルギー領域における 方位角異方的なフロー測定やHBT測定

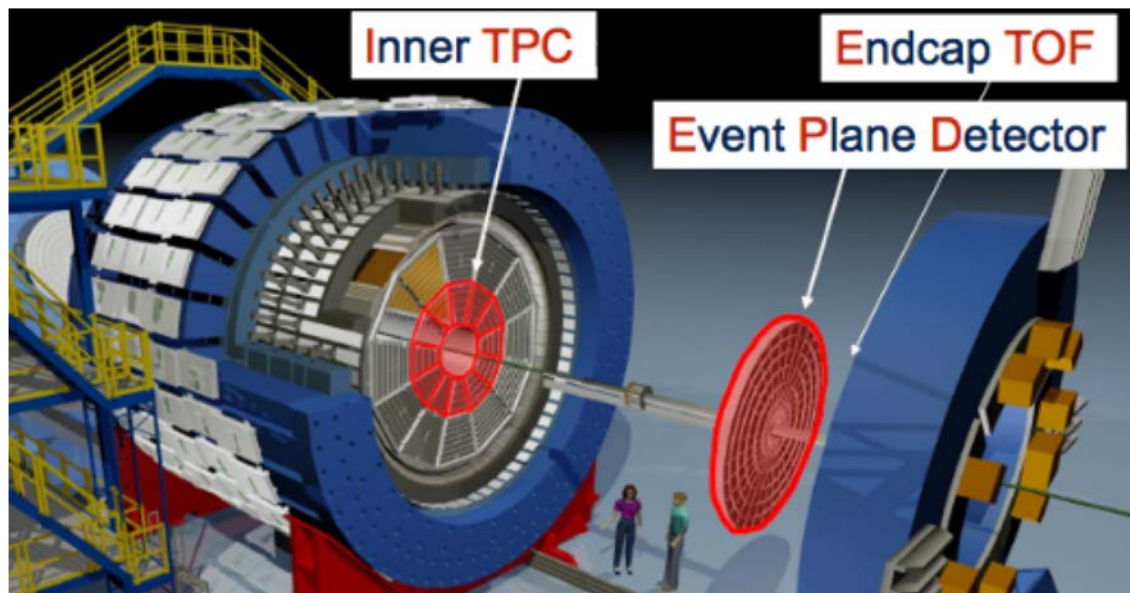
E877 PRC56(1997)3254



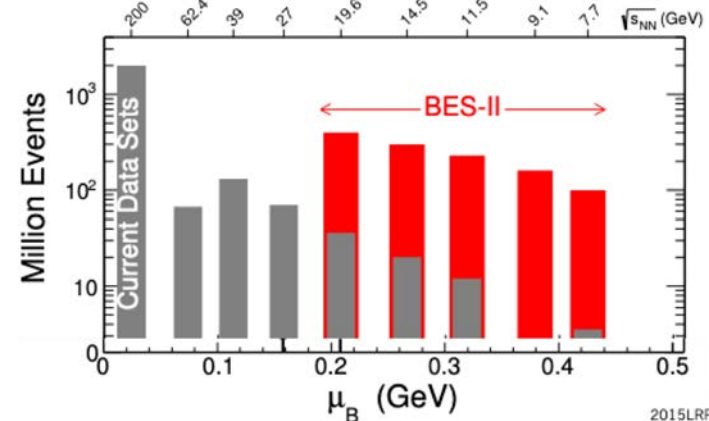
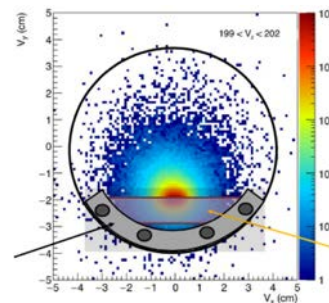
高統計のRHIC, LHCエネルギー領域データの方位角異方性測定、粒子相関測定、揺らぎ測定などに対する基準を与えるAGS, SPSエネルギー領域のデータが不十分。

BNL-RHIC-BES1, BES2 (FXT)  
GSI-FAIR-CBM, NICA, HIAF, J-PARC-Heavy-Ion

# RHIC ビームエネルギー走査実験 (BES-I, BES-II, FXT)



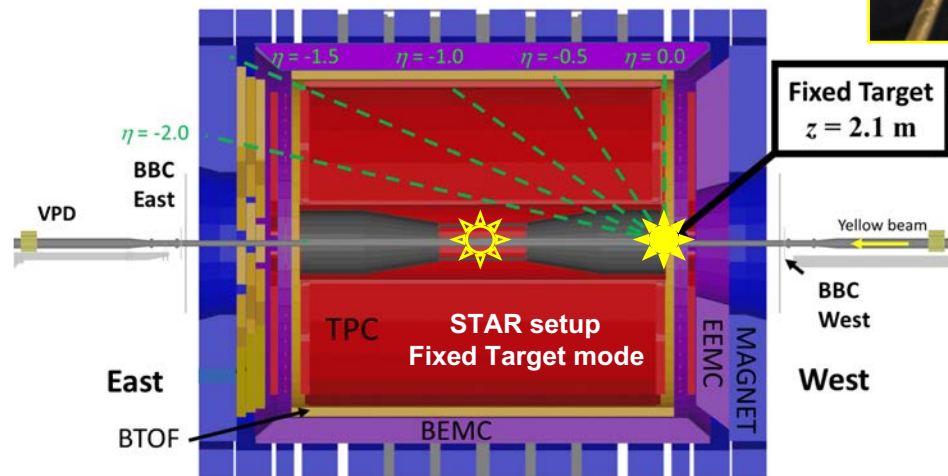
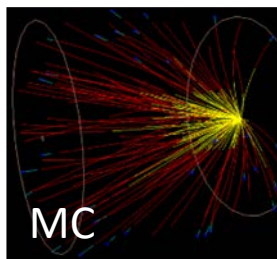
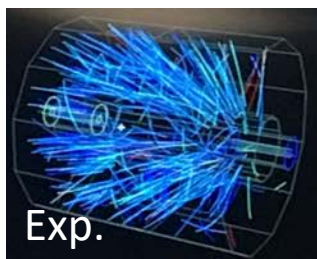
- Collider mode :  
down to 7.7 GeV
- Fixed target mode :  
down to 3 GeV



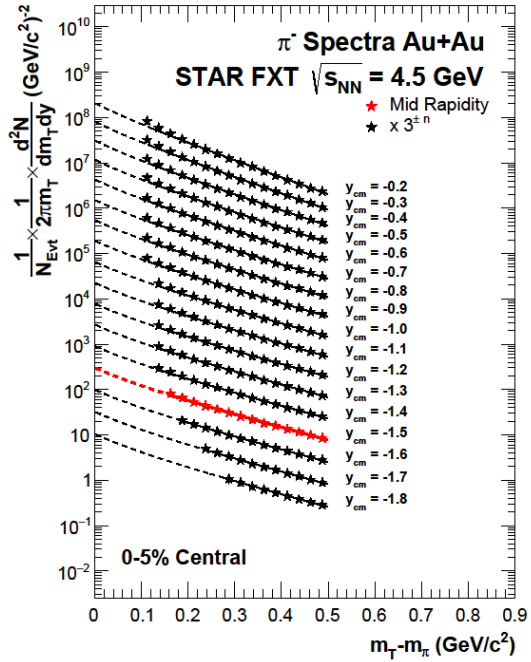
2015LRP

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	Year(s) of mass	$\mu^B$ (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

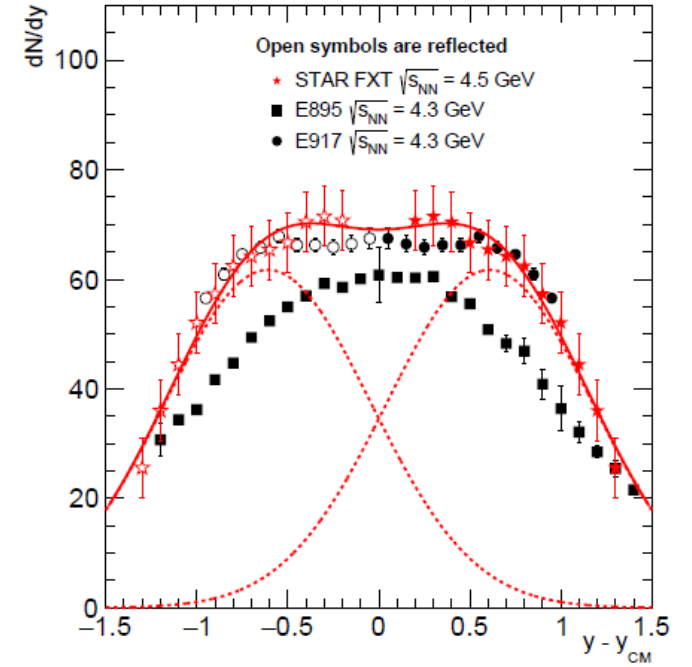
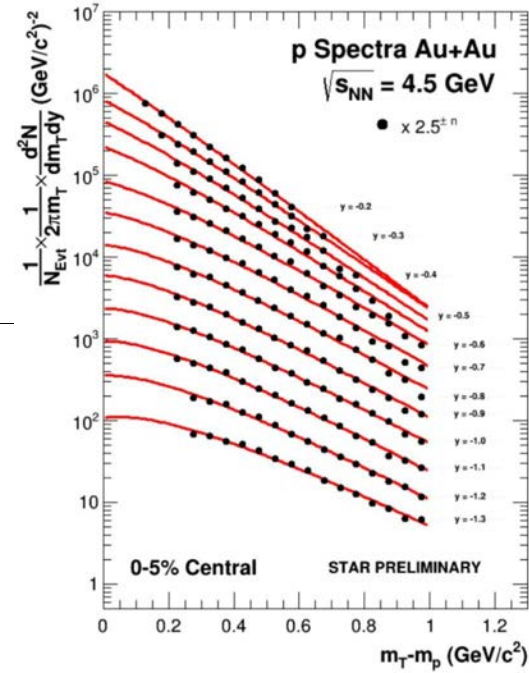
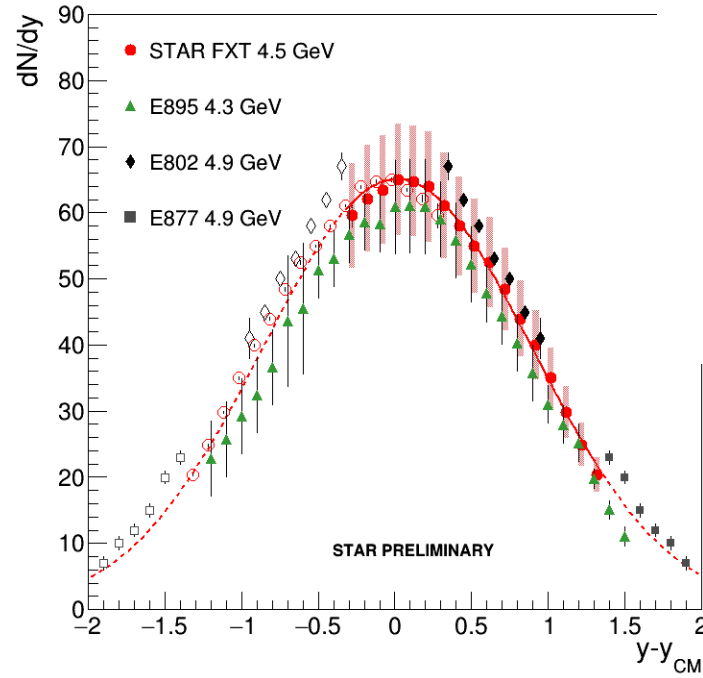
200GeV d+Au, 200GeV O+O during run21



# STAR-FXT 固定標的実験 4.5GeV $\pi^-$ 中間子、陽子の $p_T$ , rapidity分布



$\pi^-$  Rapidity Density



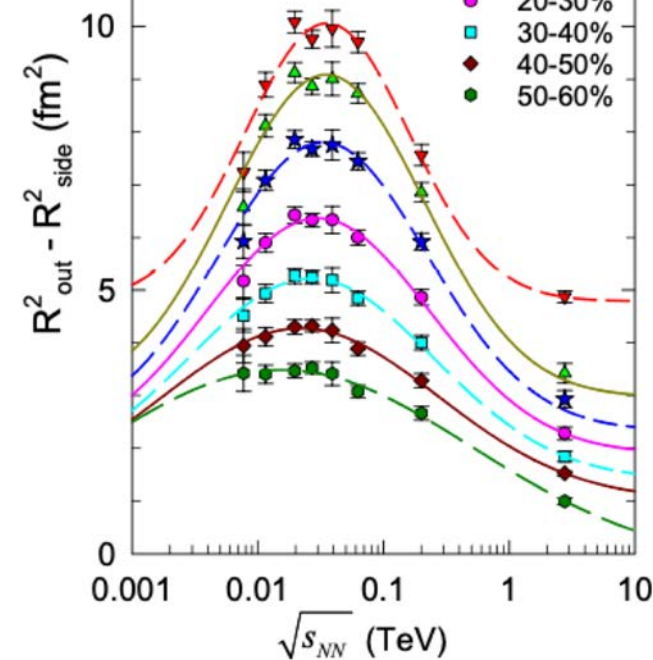
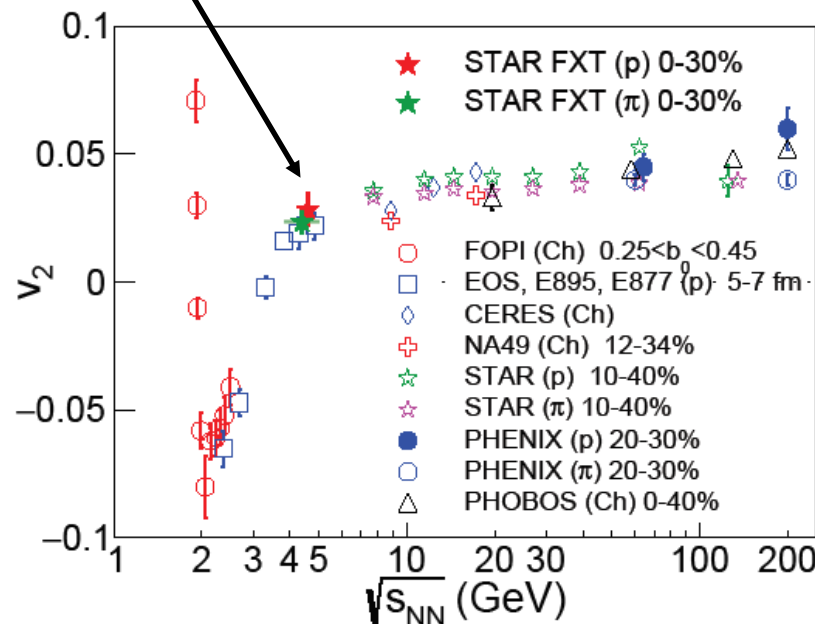
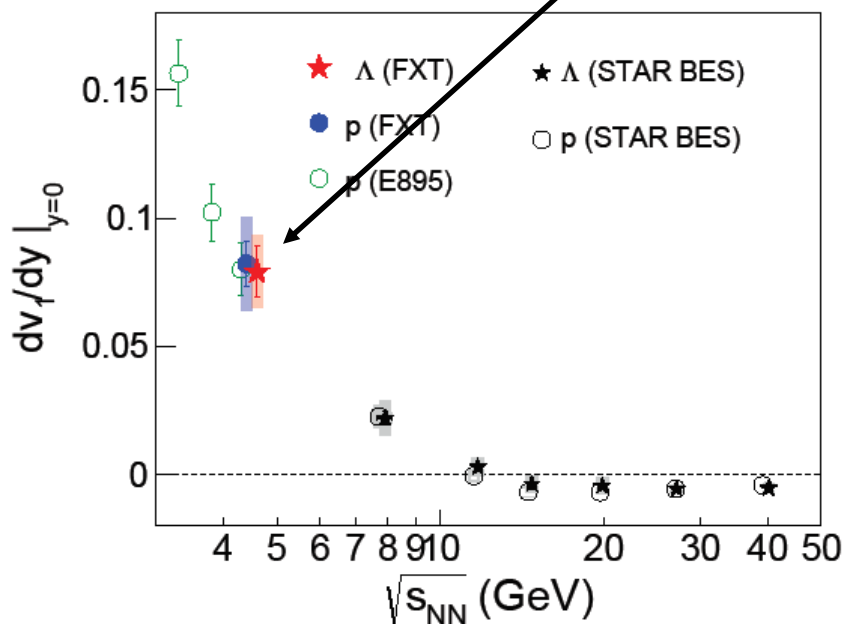
Rapidity loss 測定:  
 $\Delta y = Y_{\text{Gaussian Peak}} - Y_{\text{Beam}}$

# STAR-BES-I / FXT エネルギー走査実験 方位角異方的なフロー測定、HBT測定



Phys. Rev. Lett. 114, 142301 (2015)

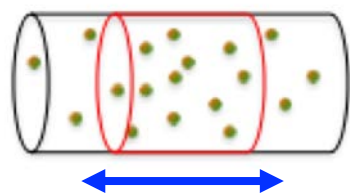
## STAR-FXT 固定標的実験 4.5GeV



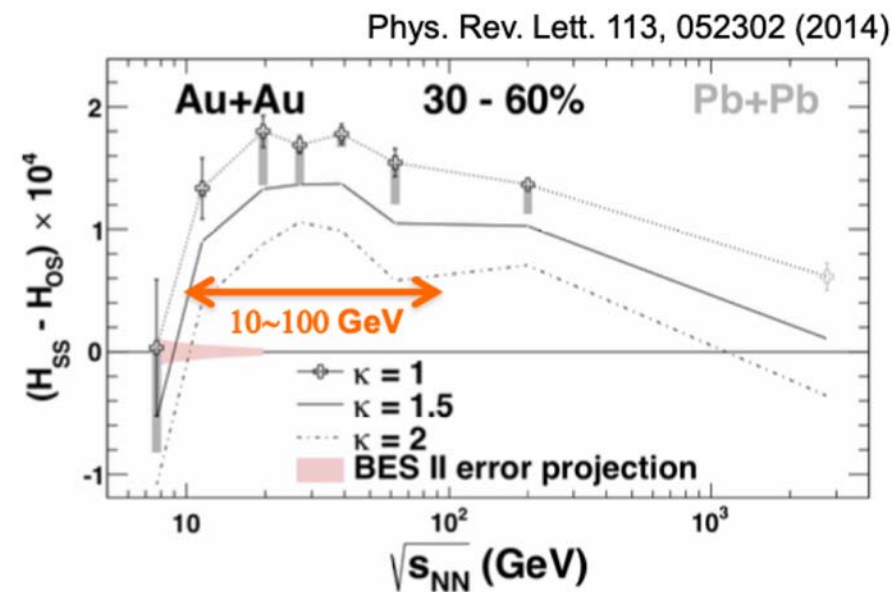
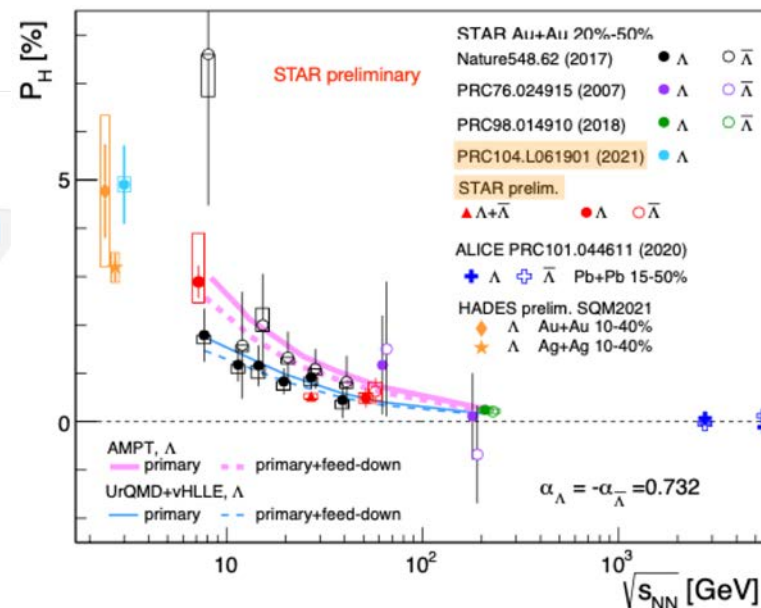
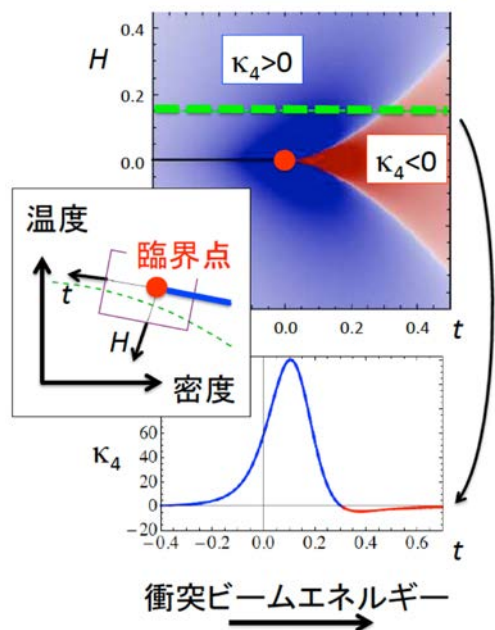
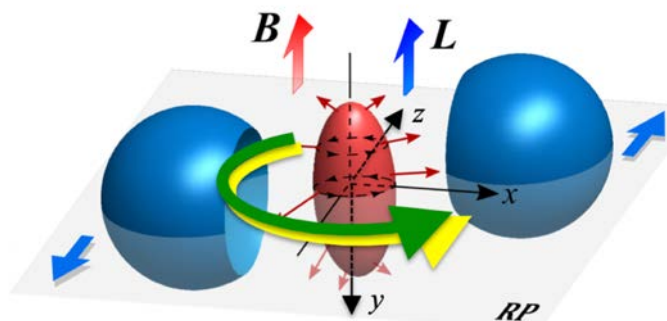
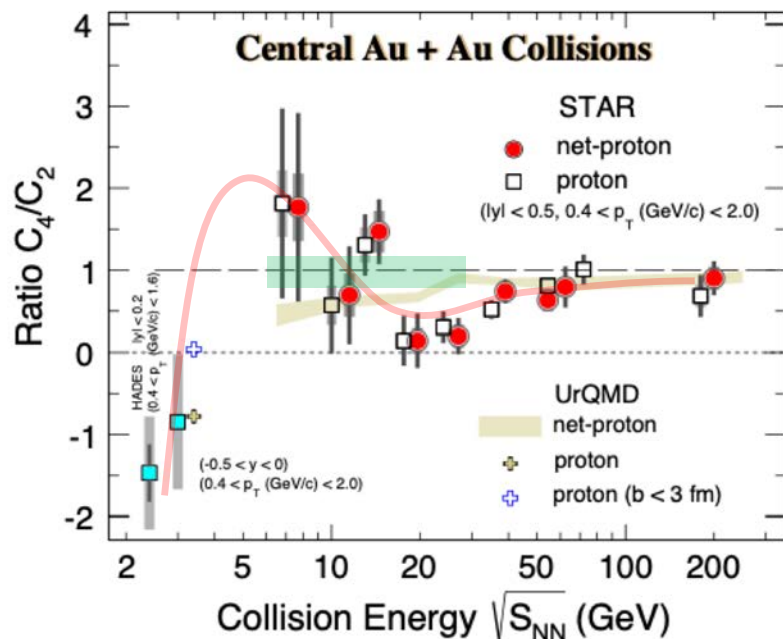
more differential studies to come, including energy, centrality, rapidity,  $p_T$  dependences, and especially charge/charge dependence to look for initial fields with  $v_1$  more recently

$p_T$ ,  $m_T$ , rapidity dep.  
 azimuthal  $\Psi_1$ ,  $\Psi_2$  dep.  
 as a function of  $\sqrt{s}$

# STAR-BES-I / FXT エネルギー走査実験 保存量ゆらぎ測定、渦・CME測定

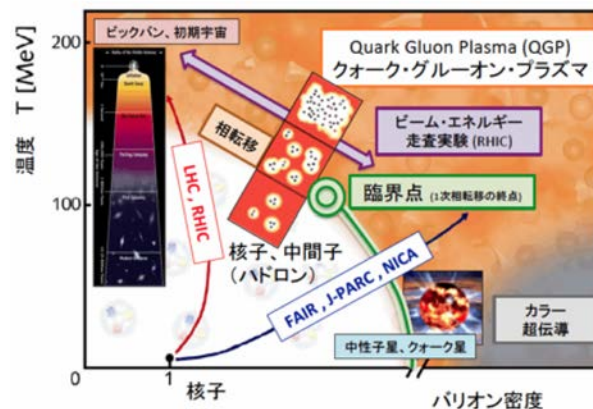


相転移や臨界点付近で  
Beam軸(rapidity方向)の  
相関長の変化



# まとめと今後

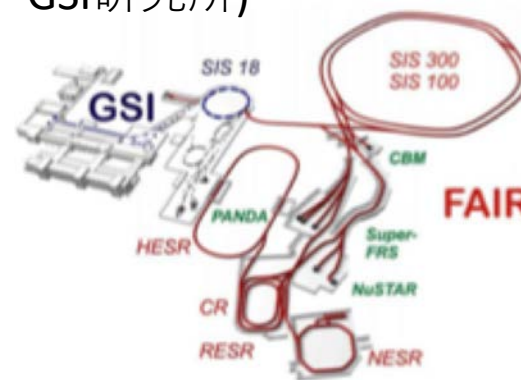
AGS・SPS実験のおさらい、RHIC実験のまとめ  
 RHIC-BES実験の現状、次へのステップ  
 BNL-RHIC-BES1, BES2 (FXT)  
 GSI-FAIR-CBM, NICA, HIAF  
 J-PARC-Heavy-Ion



NICA (ロシア)

HIAF (中国)

FAIR-CBM実験 (ドイツ、GSI研究所)



J-PARC (日本、茨城県東海村)

