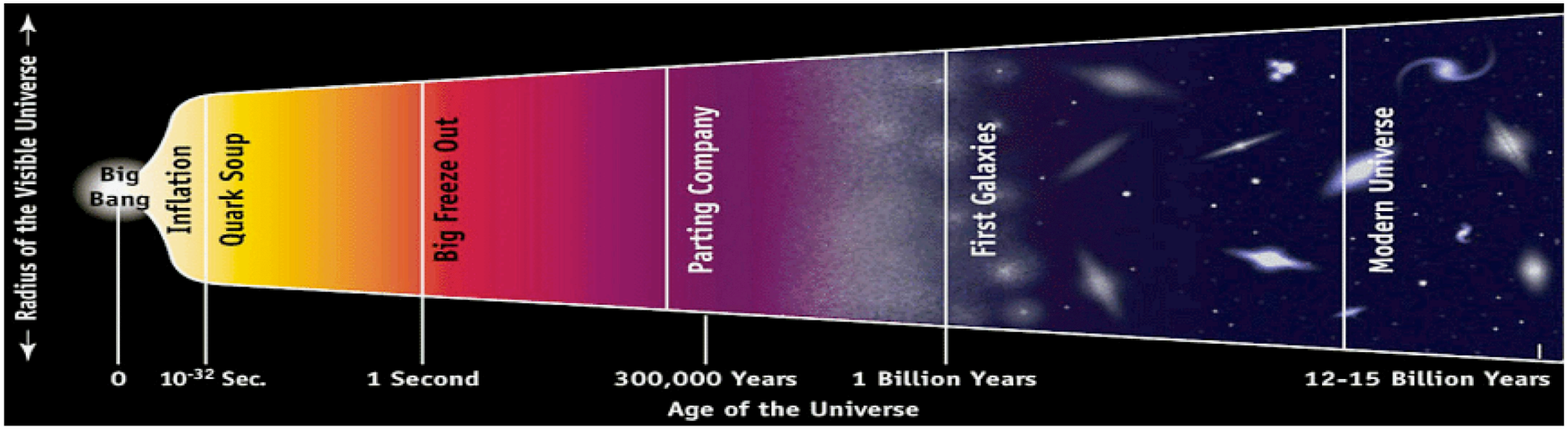
QGP生成のプローブとしての
中間横運動量領域のハドロン物理



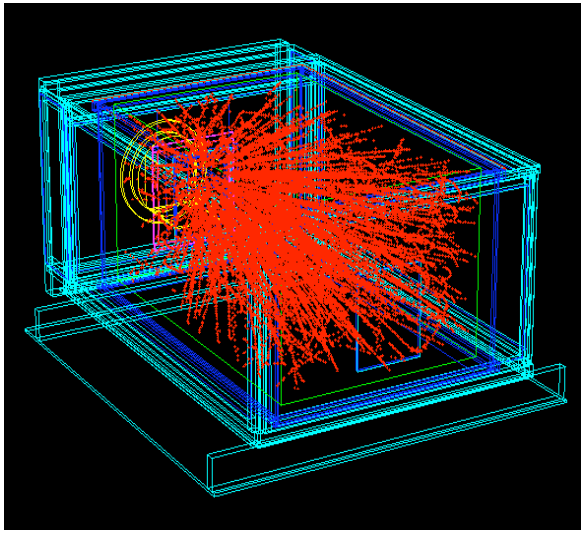
中條 達也

Vanderbilt Univ.

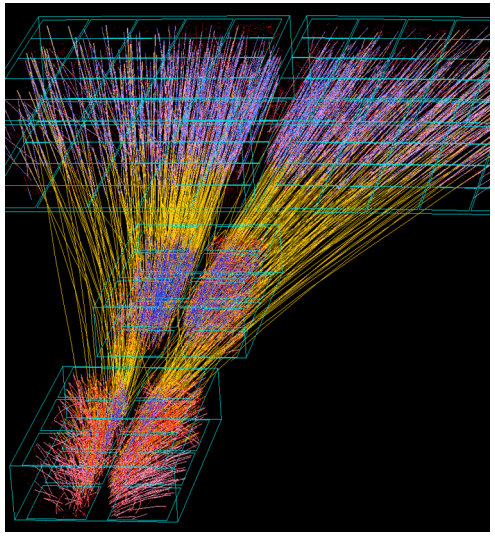
はじめに

- ８０年代から精力的に研究が続けられている高エネルギー重イオン反応。
  - 衝突エネルギーを上げながら、精密、系統的な測定を行う。
- ２０００年、RHIC (the Relativistic Heavy Ion Collider) を用いての金原子核衝突実験開始。
- RHICで４年目の物理測定ランが終了、実験の論文数：99 (2004. 8 月現在、e-print 含)
- 低～中間横運動量領域でのハドロン生成で何がわかったのか？

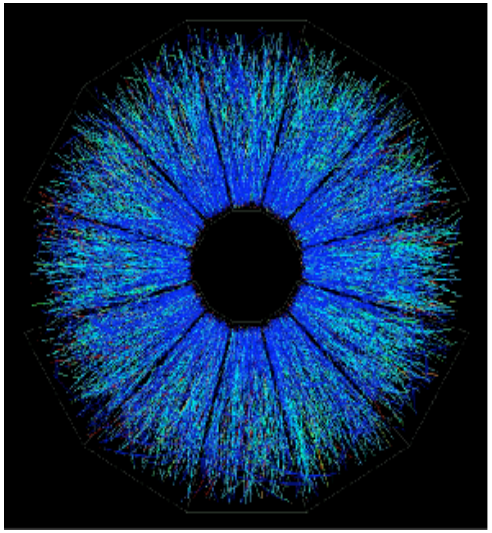
AGS ($\sqrt{s_{NN}}$ = 5 GeV)



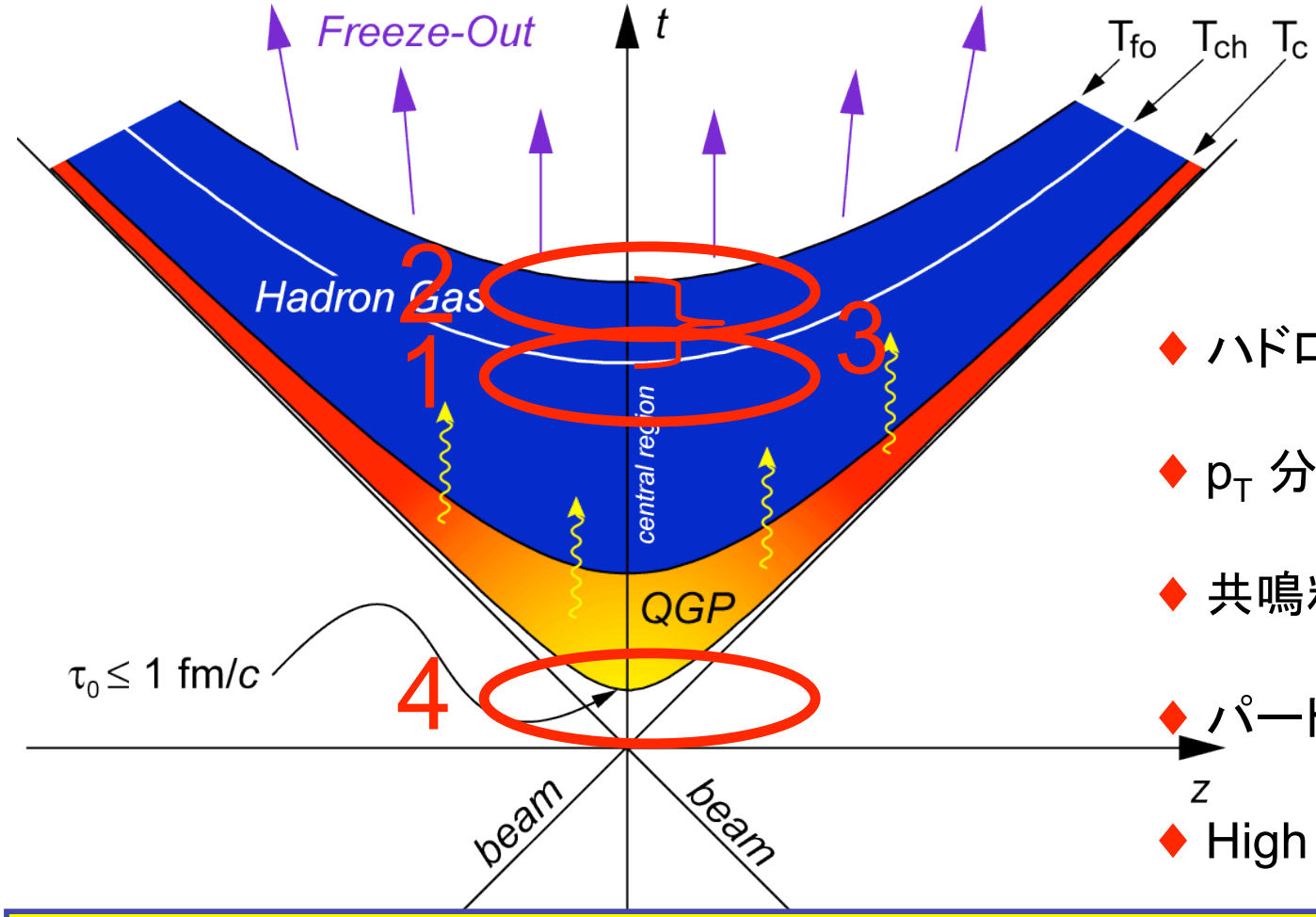
SPS ($\sqrt{s_{NN}}$ = 17 GeV)

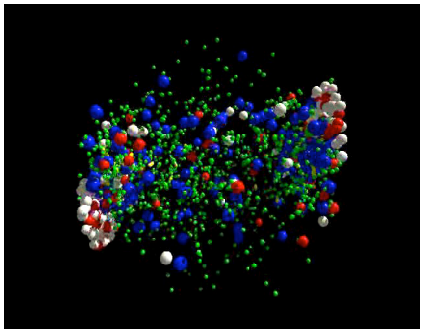


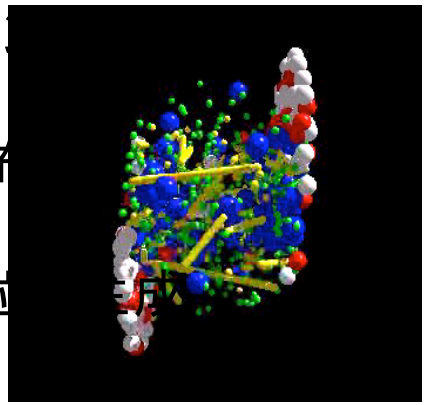
RHIC ($\sqrt{s_{NN}}$ = 200 GeV)

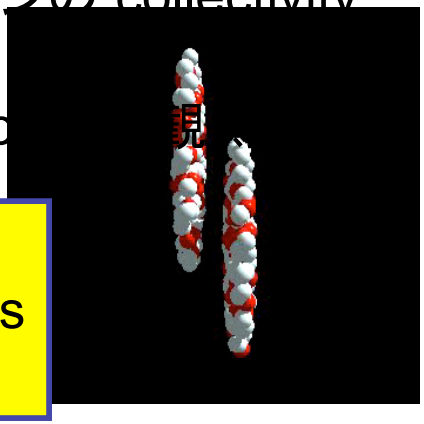


衝突の時空発展





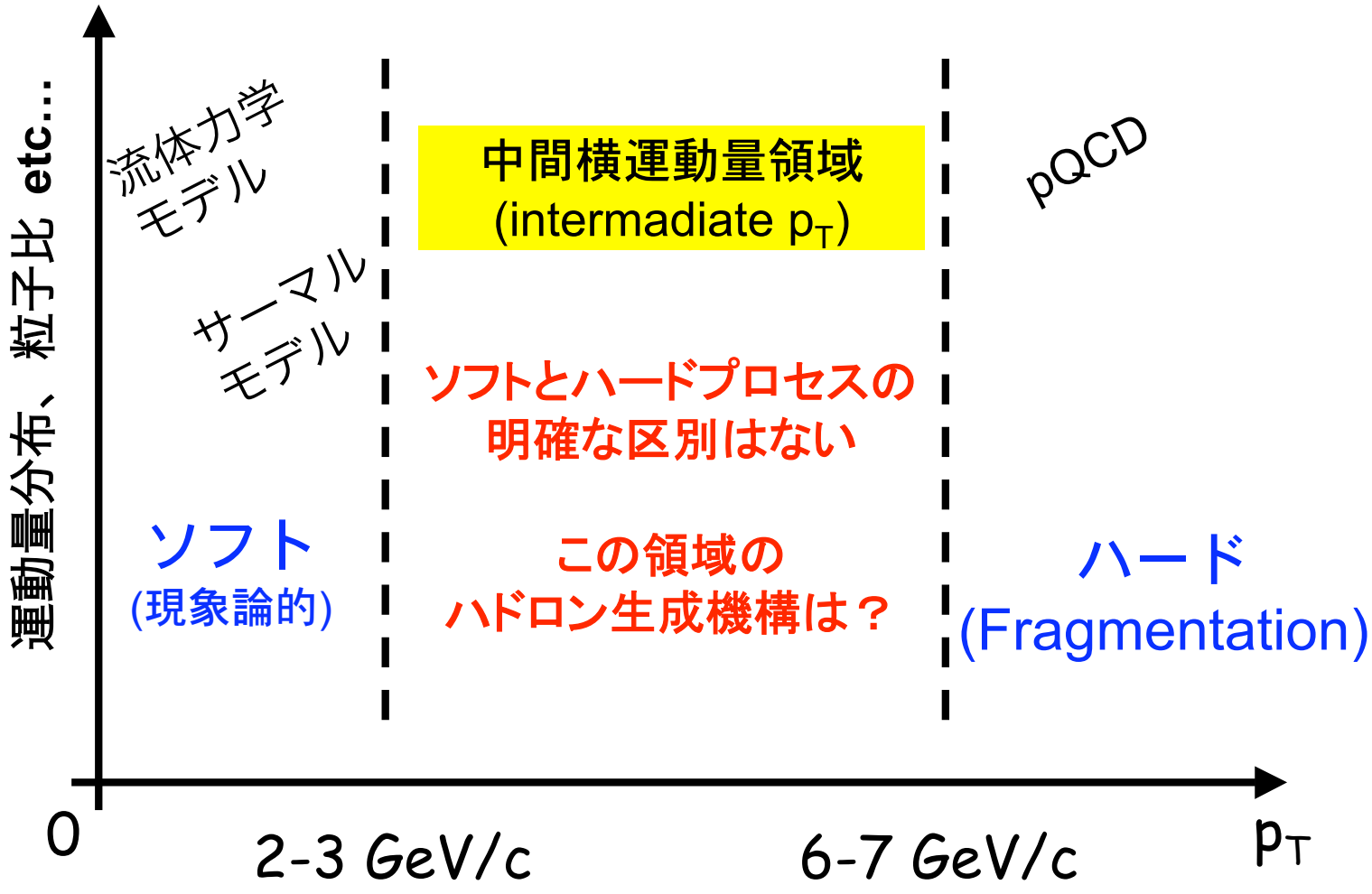




- ハドロ
- p_T 分布
- 共鳴粒 生成
- パートンの collectivity
- High p 現

T_c – Critical temperature for transition to QGP
T_{ch}– Chemical freeze-out ($T_{ch} \leq T_c$) : inelastic scattering stops
T_{fo} – Kinetic freeze-out ($T_{fo} \leq T_{ch}$): elastic scattering stops

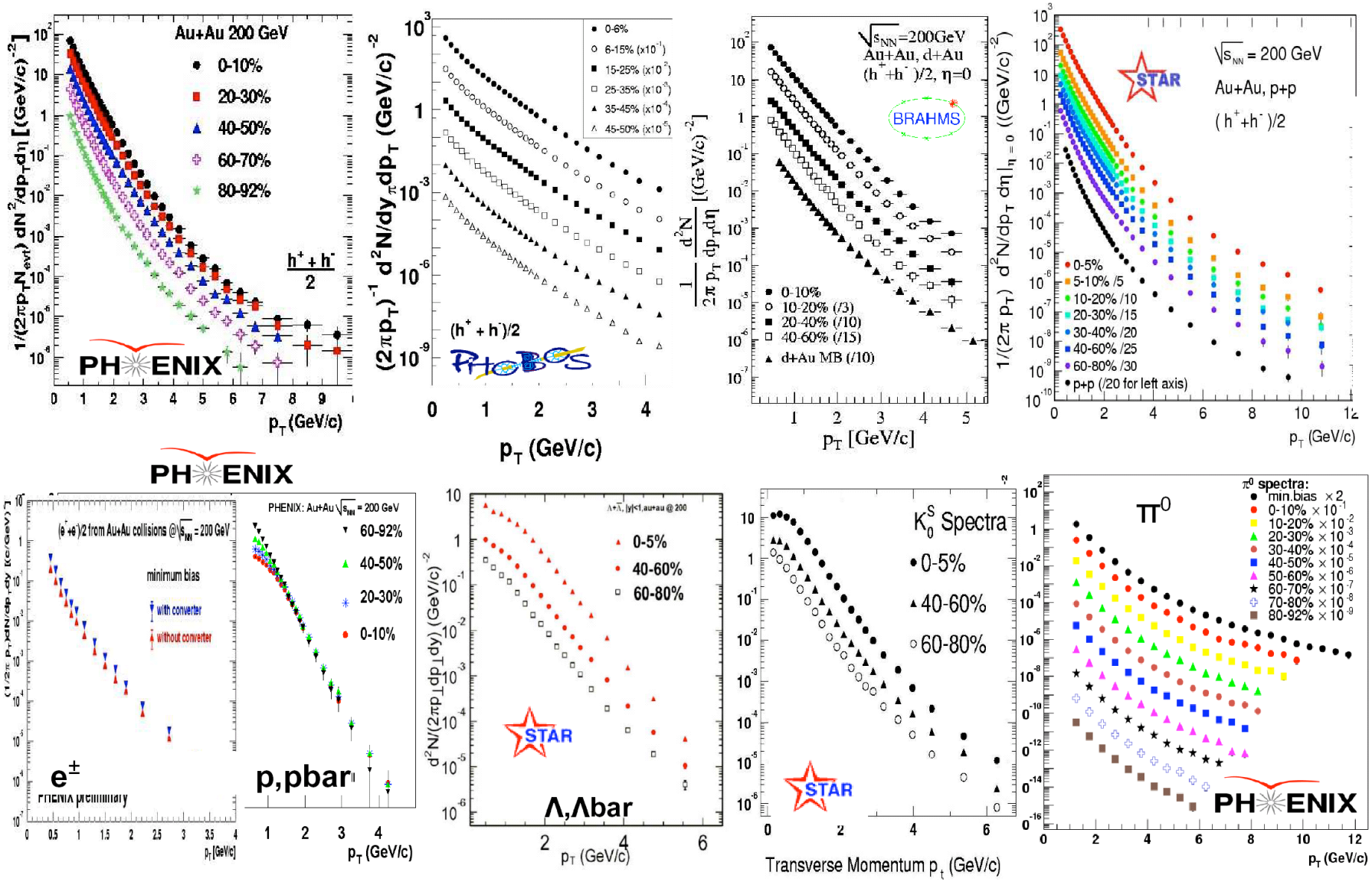
p_T 領域とハドロン生成



本講演では…

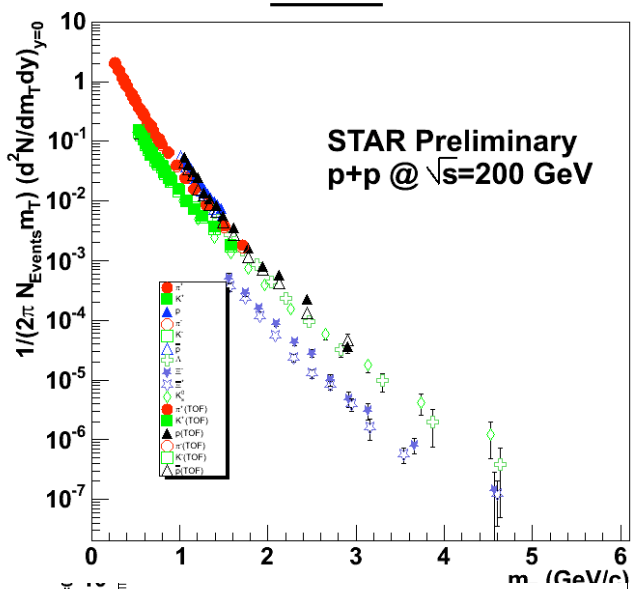
1. 横運動量分布（運動学的フリーズアウト, 粒子の等方的集団運動)
2. 粒子比 (化学平衡、サーマルモデル)
3. 中間 p_T 領域の物理
4. 新しい結果から（62 GeV Au+Au データ）
5. まとめ

RHIC で測定された横運動量(p_T)分布（一部）

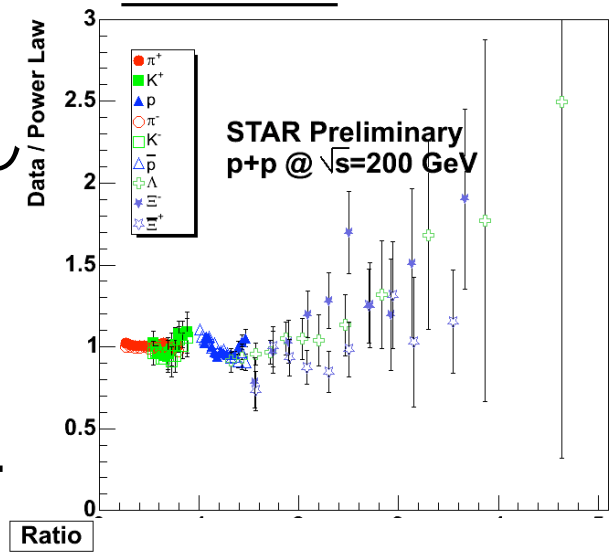


p+p と Au+Au

Data



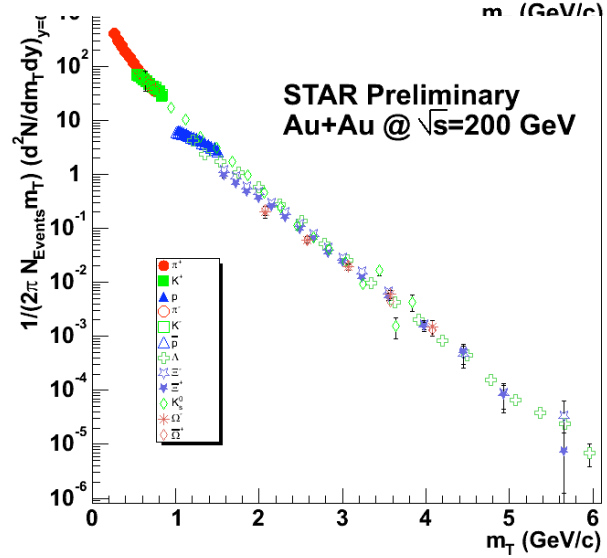
Data /Fit



絶対値での
m_T scaling なし

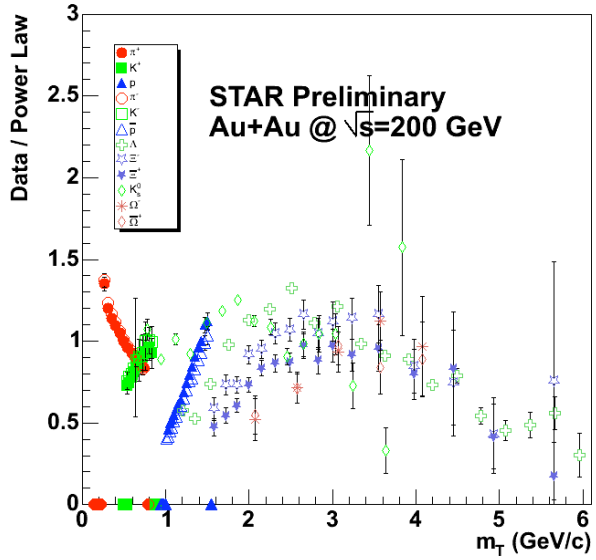
← p+p →

しかし、y軸を
スケールすると…



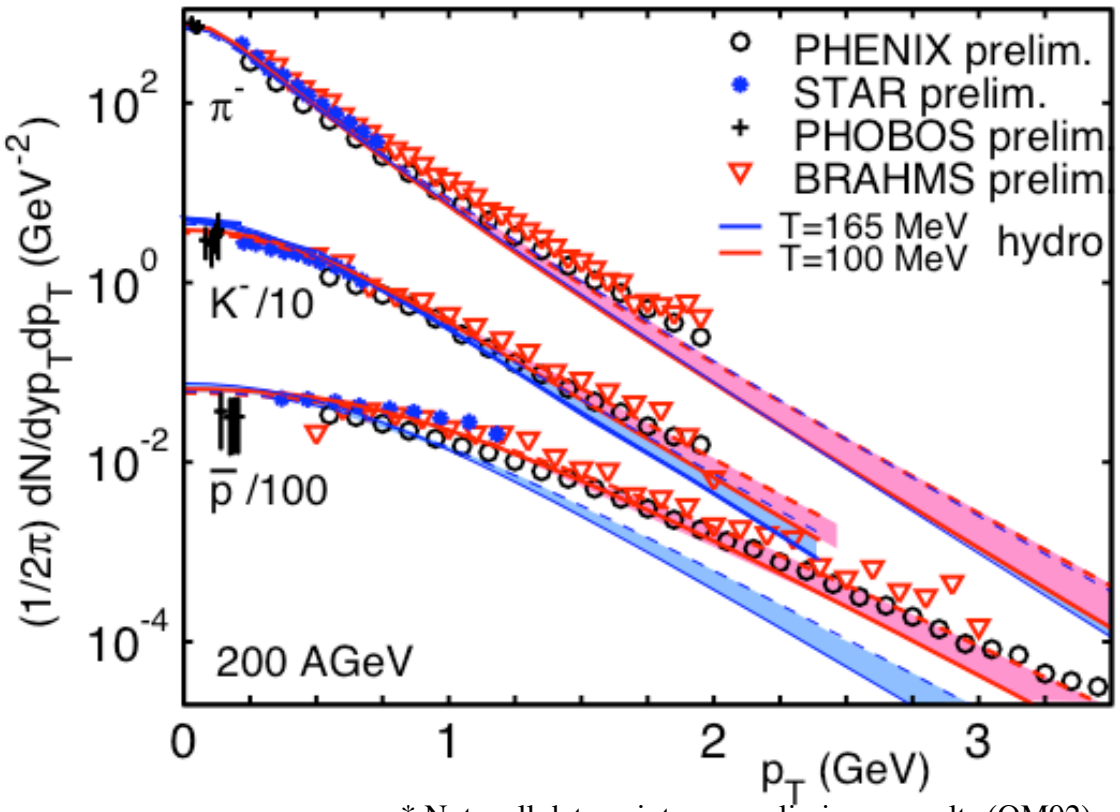
← Au+Au →

スケーリングなし



横運動量分布と流体力学計算

Hydro-calculations including chemical potentials: P.Kolb and R. Rapp, Phys. Rev. C 67 (03) 044903



* Note: all data points are preliminary results (QM02).

横運動量(p_T)分布：
終状態における系の運動学的な温度や膨張の度合いを反映

流体計算との比較：
(初期条件)
QGPタイプの状態方程式
衝突初期の圧力が非常に高い
ハドロン相へ急激に転移
(~10 fm/c)

QGPを仮定した流体力学計算は $p_T < 2$ GeV/c 以下のすべて粒子のp_T分布をよく記述する。

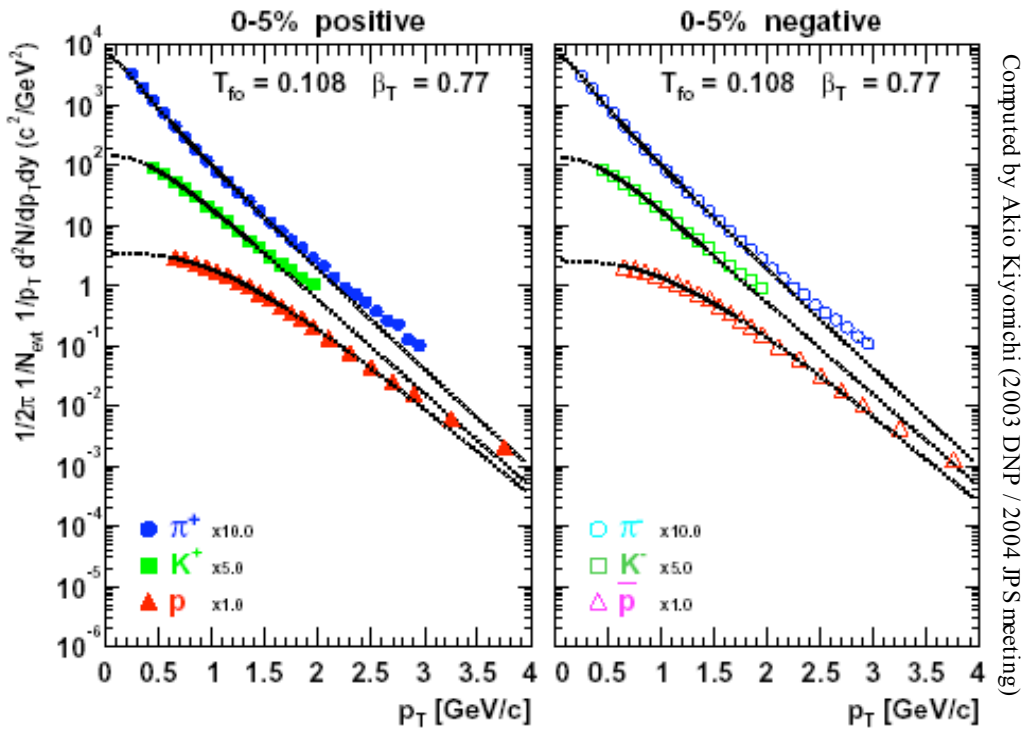
サーマル分布と集団的運動 (collective flow)

- 粒子の質量によって異なる p_T 分布の形（金原子核中心衝突）
  → **強い集団的運動を示唆**

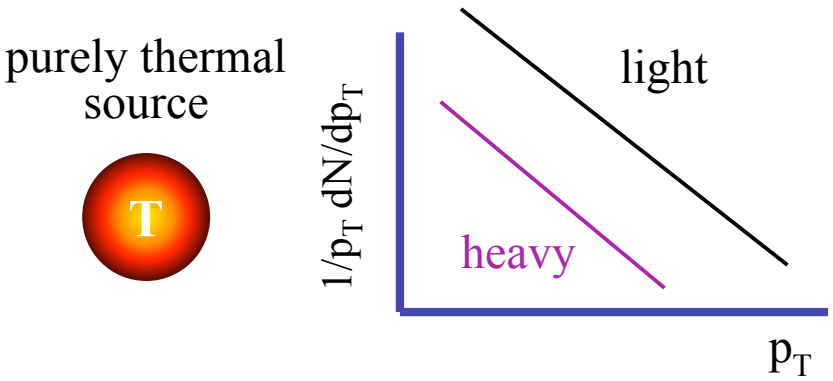
- p_T 分布は単純な温度指標パラメータ "T" だけでは記述できず、集団運動をになうパラメータ "β_T "の導入が必要

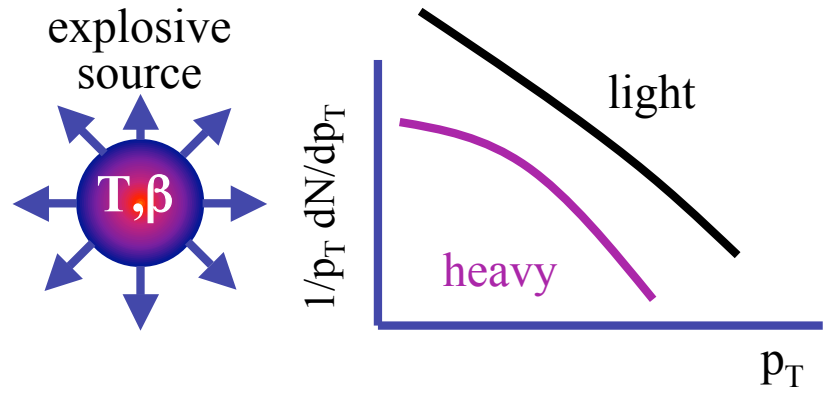
- **π, K, p のp_T 分布を同時フィットし、T, β_T をχ^2最小にするパラメータを求める**

Fit range : m_T-mass < 1 GeV/c^2

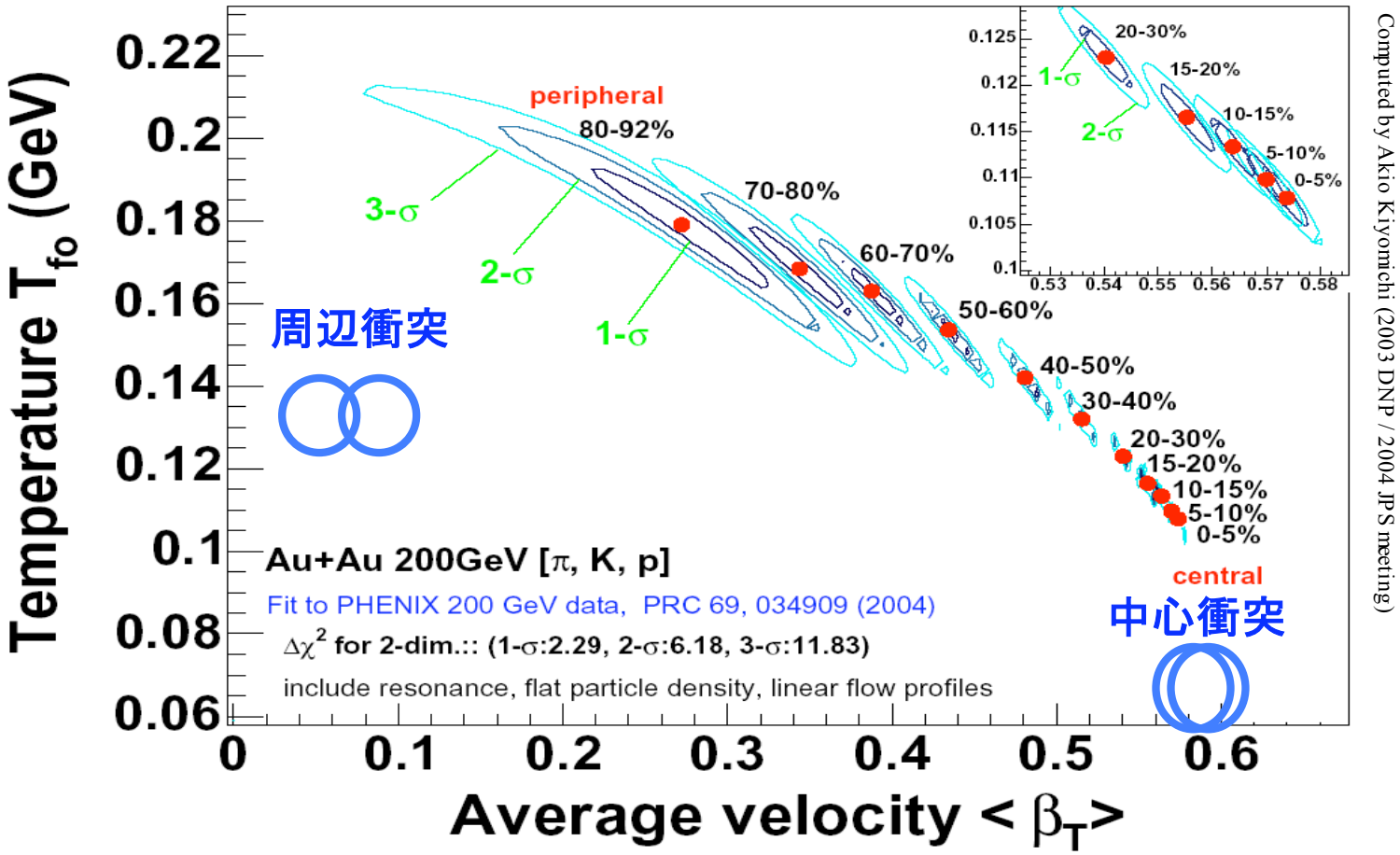


Computed by Akio Kiyomichi (2003 DNP / 2004 JPS meeting)





フィットの結果



強い中心衝突度依存性を観測

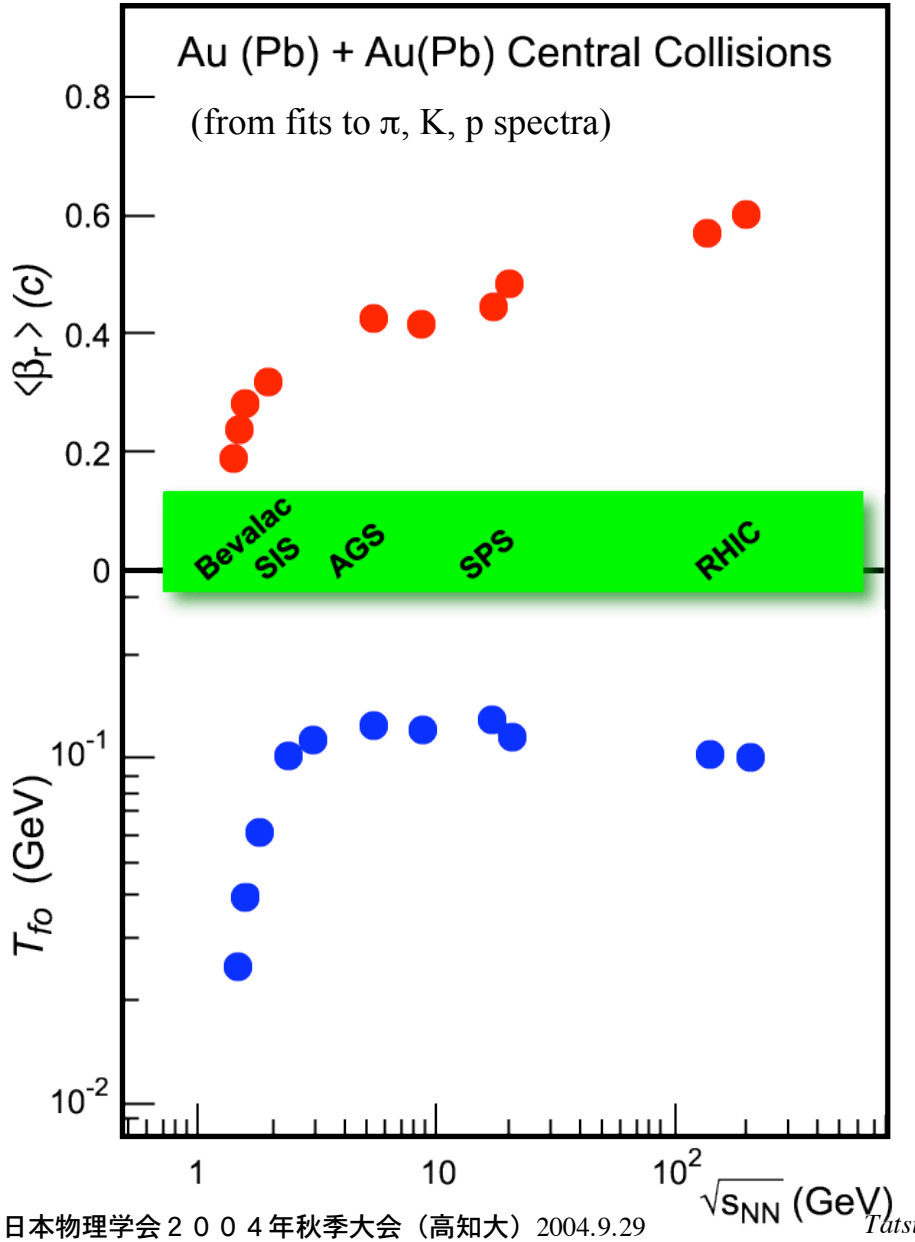
PHENIX Au+Au 200 GeV

(中心衝突)

- T_{fo} = 108MeV

- $<\beta_T>$ = 0.57 c

ビームエネルギー依存性



- $<\beta_T>$
  - ビームエネルギーとともに増加
- T_{fo}
  - AGS 領域で saturate

RHIC エネルギーにおいて最も強い等方的集団運動を観測
- 圧力勾配大
- 再散乱確率の増加
- 熱平行状態？

統計的サーマルモデル

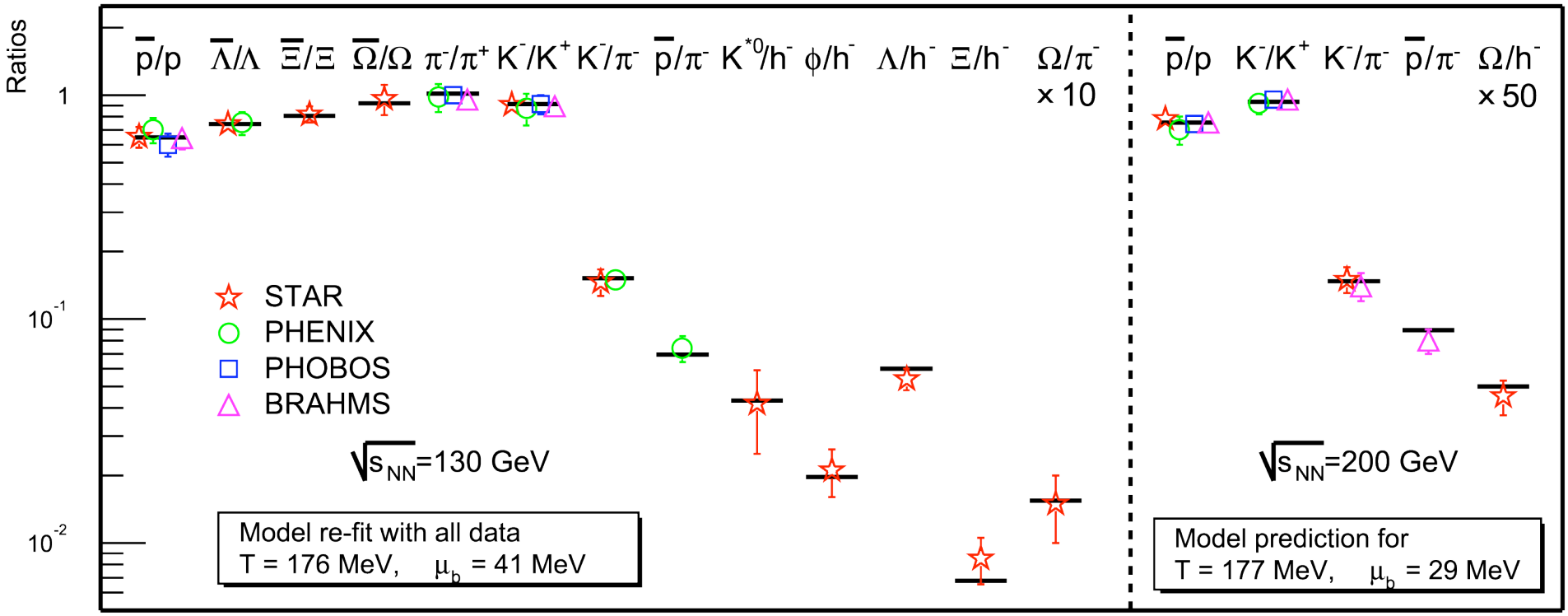
- 局所的熱平衡 (T_{ch}一定) と 化学平衡(n_i一定) を仮定 (@ chemical freeze-out)
- 系の中での共鳴粒子の影響も考慮
- システムサイズを仮定（HBT２粒子相関測定より）
- T_{ch} ,μ ‘s (+ system size)より 粒子多重度 n_i が決定される(grand canonical ensemble)

$$n_i = \frac{g}{2\pi^2}\int_0^\infty \frac{p^2 dp}{e^{(E_i(p)-\mu_i)/T} \pm 1}, \quad E_i = \sqrt{p^2 + m_i^2}$$

- 保存則： バリオン数、ストレンジネス、アイソスピン

計算値と実験での粒子比の差を最小化 → T_{ch}, μ_B

データ vs. 統計的サーマルモデル (RHIC)



Braun-Munzinger et al., PLB 518 (2001) 41

D. Magestro (updated July 22, 2002)

サーマルモデルは様々な粒子比を再現

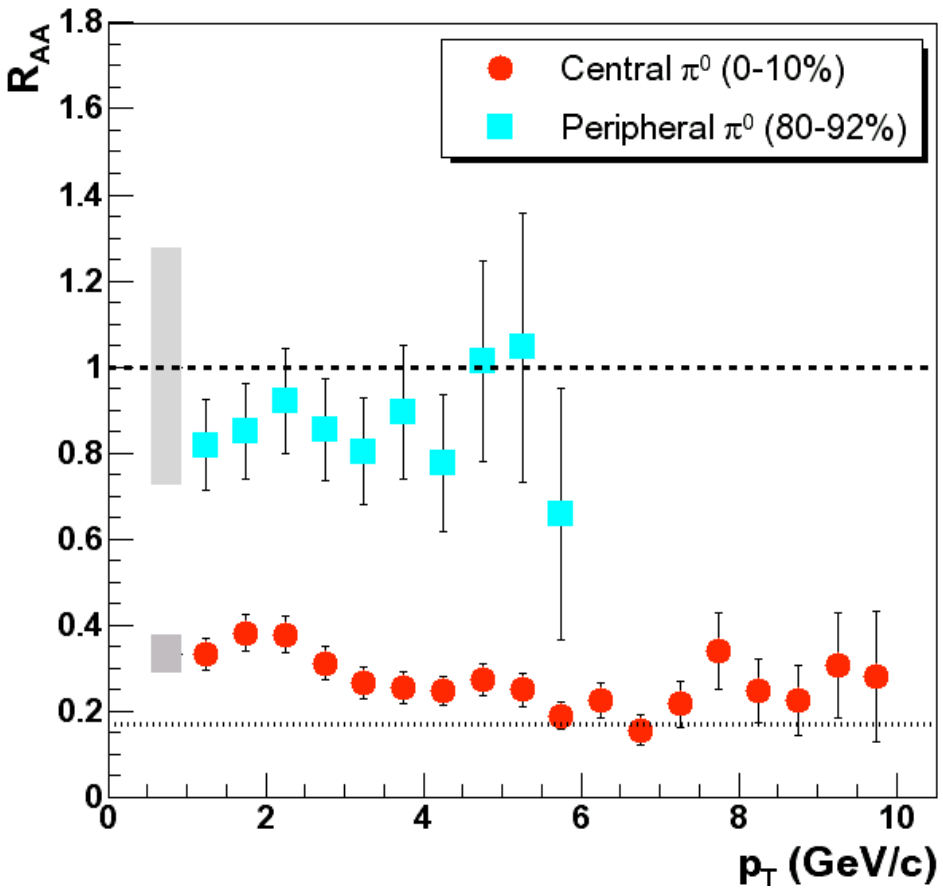
低いp_T 領域から中高 p_T 領域へ
(p_T > 3 GeV/c)

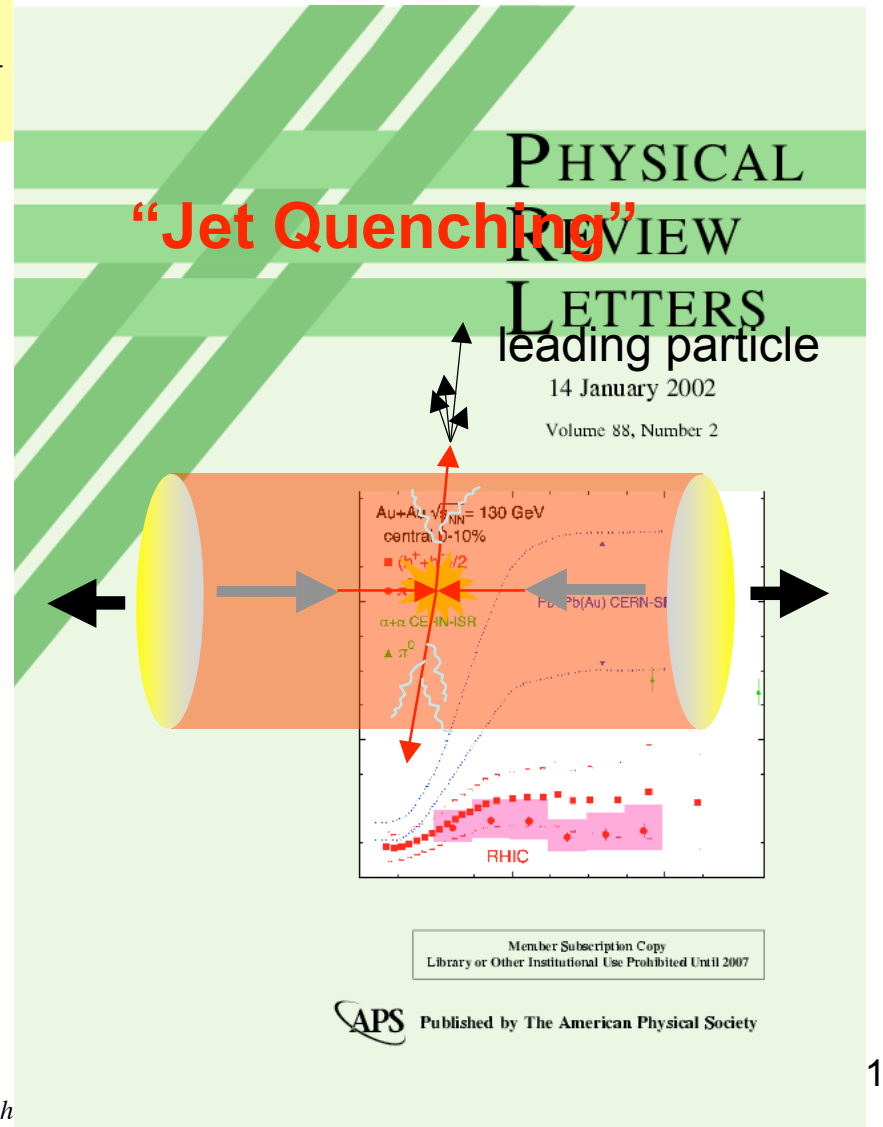
High p_T 収量抑制効果@RHIC

PRL91, 072301(2003)

PHENIX

$$R_{AA} = \frac{Yield_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{Yield_{pp}}$$



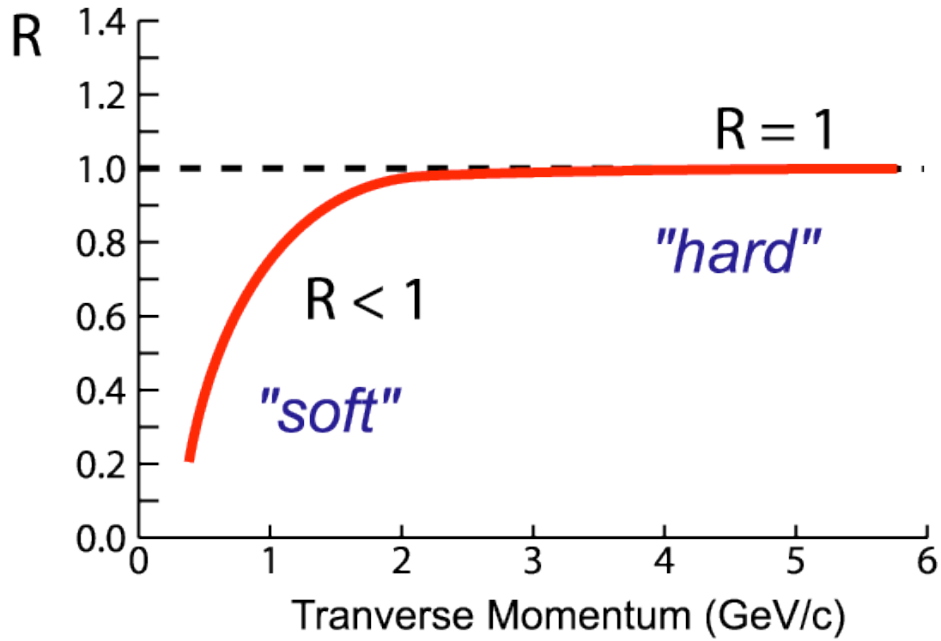


Nuclear Modification Factor R_{AA}/R_{CP}

p+pから予測される振る舞いからのずれで定量化

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta} \approx R_{CP}(p_T) = \frac{Yield_{central}/\langle N_{bin}^{central}\rangle}{Yield_{peripheral}/\langle N_{bin}^{peripheral}\rangle}$$

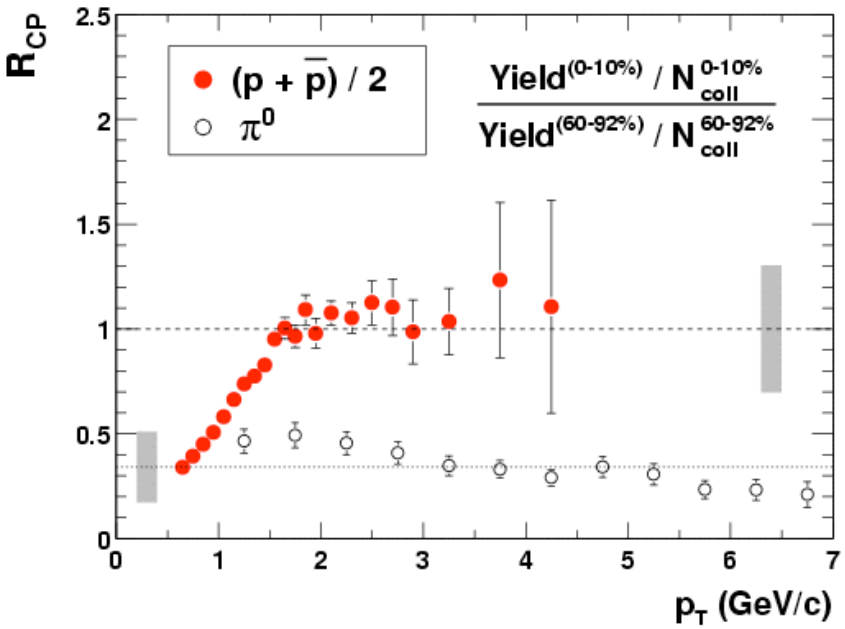
$\langle N_{binary}\rangle / \sigma_{inel}^{p+p}$

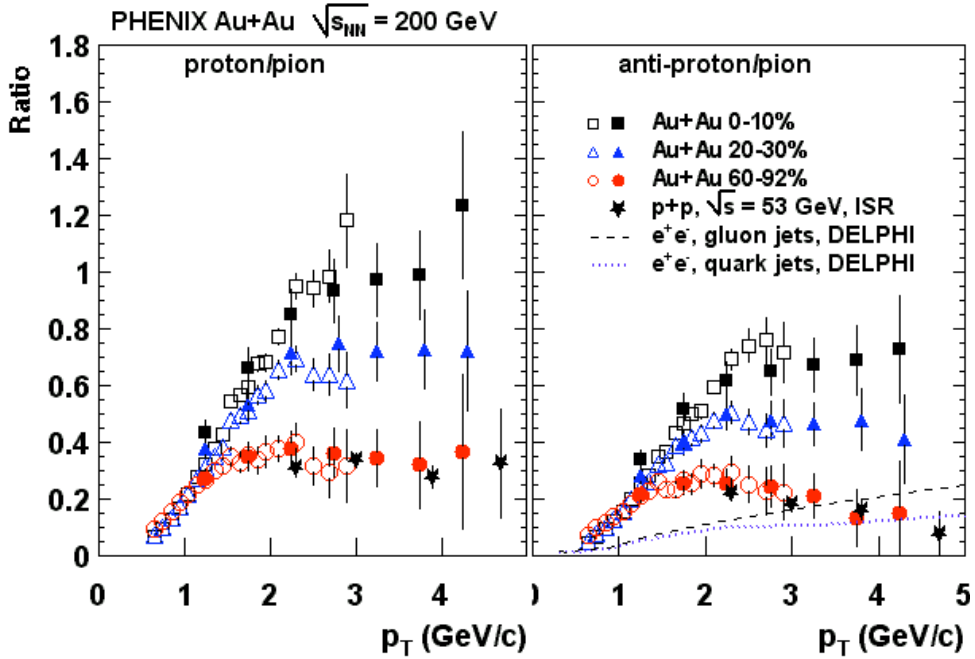


R < 1:収量抑制効果 (p_T>3GeV/c)
R = 1:ppの重ね合わせ (hard scattering) で記述

RHICでのバリオン生成

PHENIX: PRL 91, 172301 (2003), PRC 69, 034909 (2004)



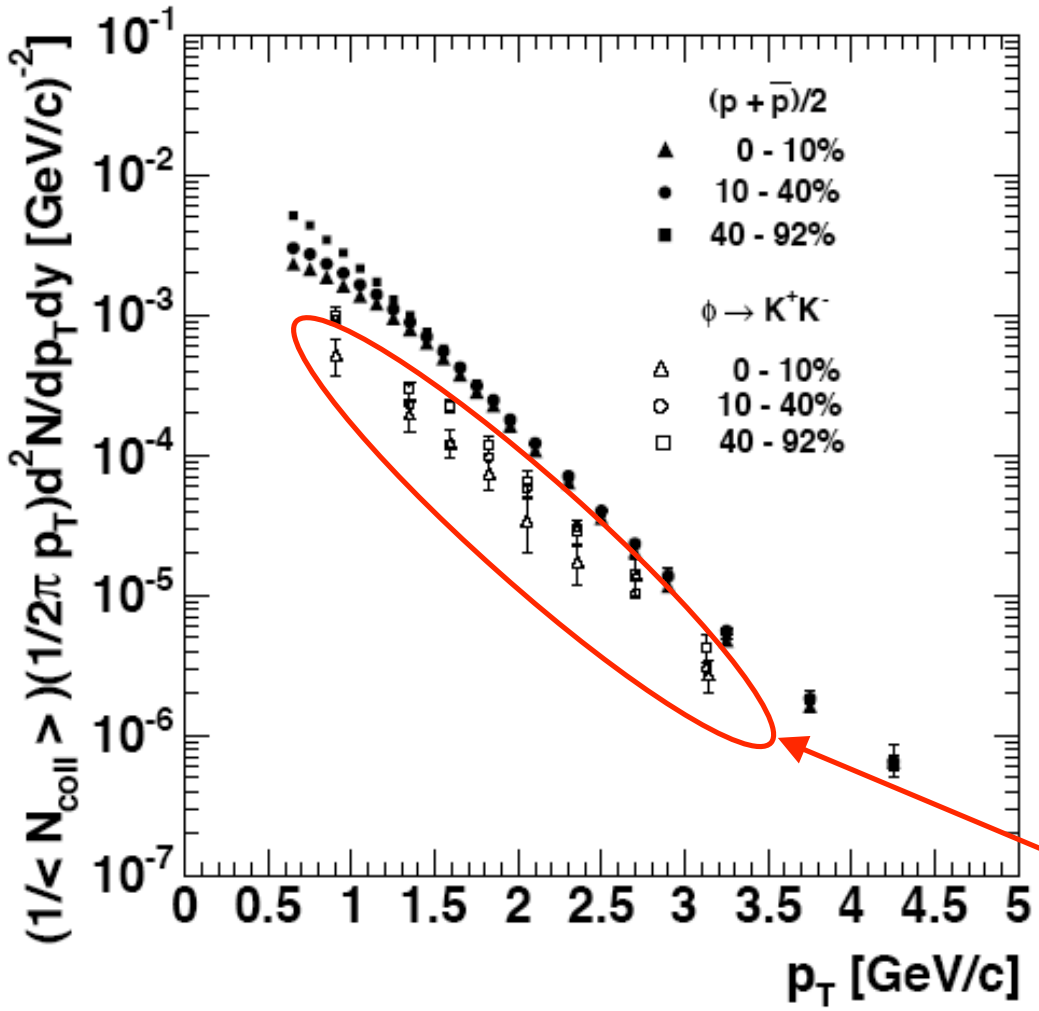


陽子、反陽子：
収量抑制効果見られず
N_{coll} scaling @ 1.5 GeV - 4.5 GeV
π^0: 強い抑制効果

- **中心衝突: p/π と pbar/π 比が周辺衝突や陽子・陽子から約3倍の増加（中間p_T領域）**
- 周辺衝突: gluon/quark jet fragmentation と IRS データと矛盾しない

φ(1020)メソンの場合は？

proton, pbar: PHENIX: PRL 91, 172301 (2003), PRC 69, 034909 (2004)
φ: PHENIX final data, will be submitted to PRC.



φ 中間子:

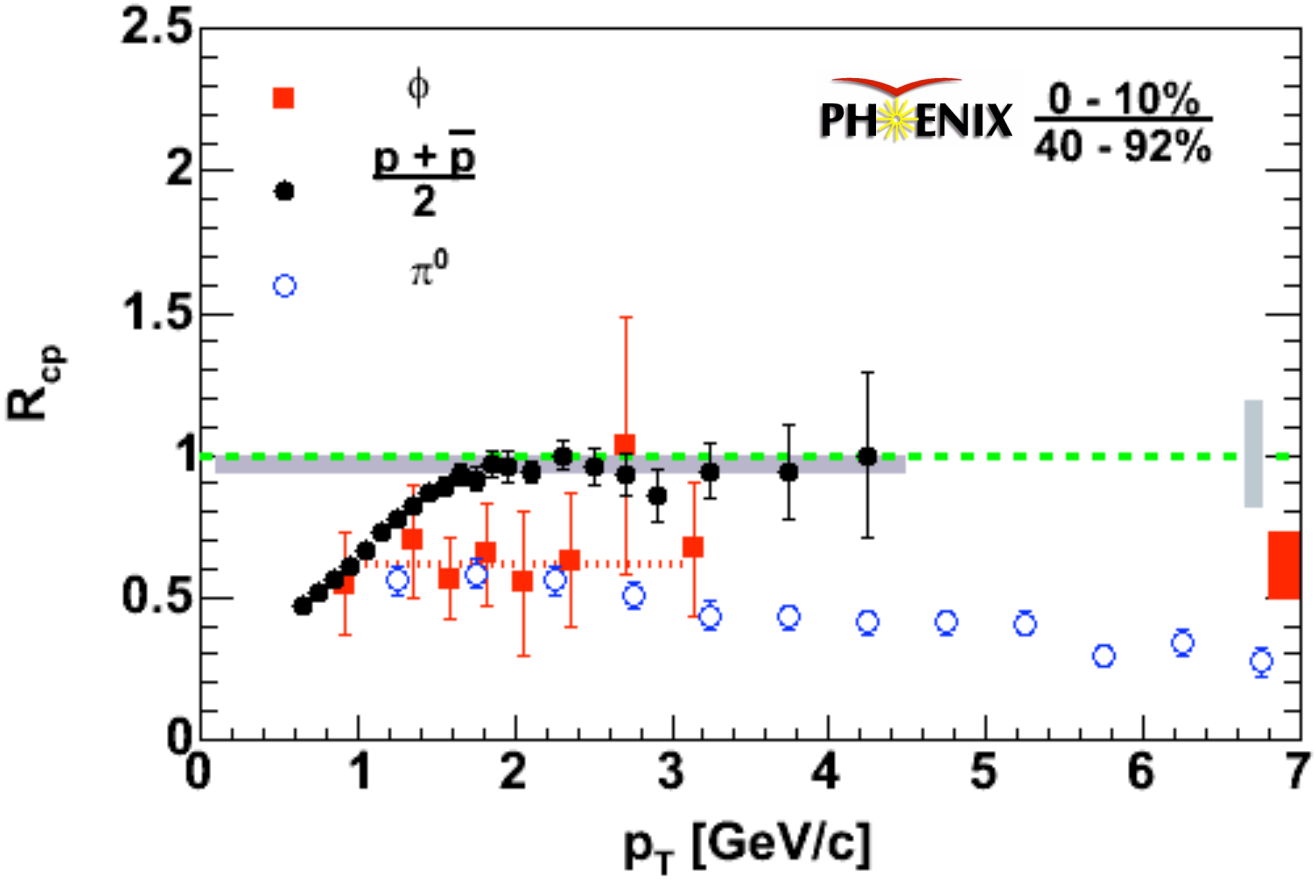
- 陽子と同程度の質量を持つメソン。

-> 観測されたバリオンの振る舞いが単なる粒子の質量（collective flow）の効果かどうかを見るのに理想的なテスト粒子。

陽子・反陽子:

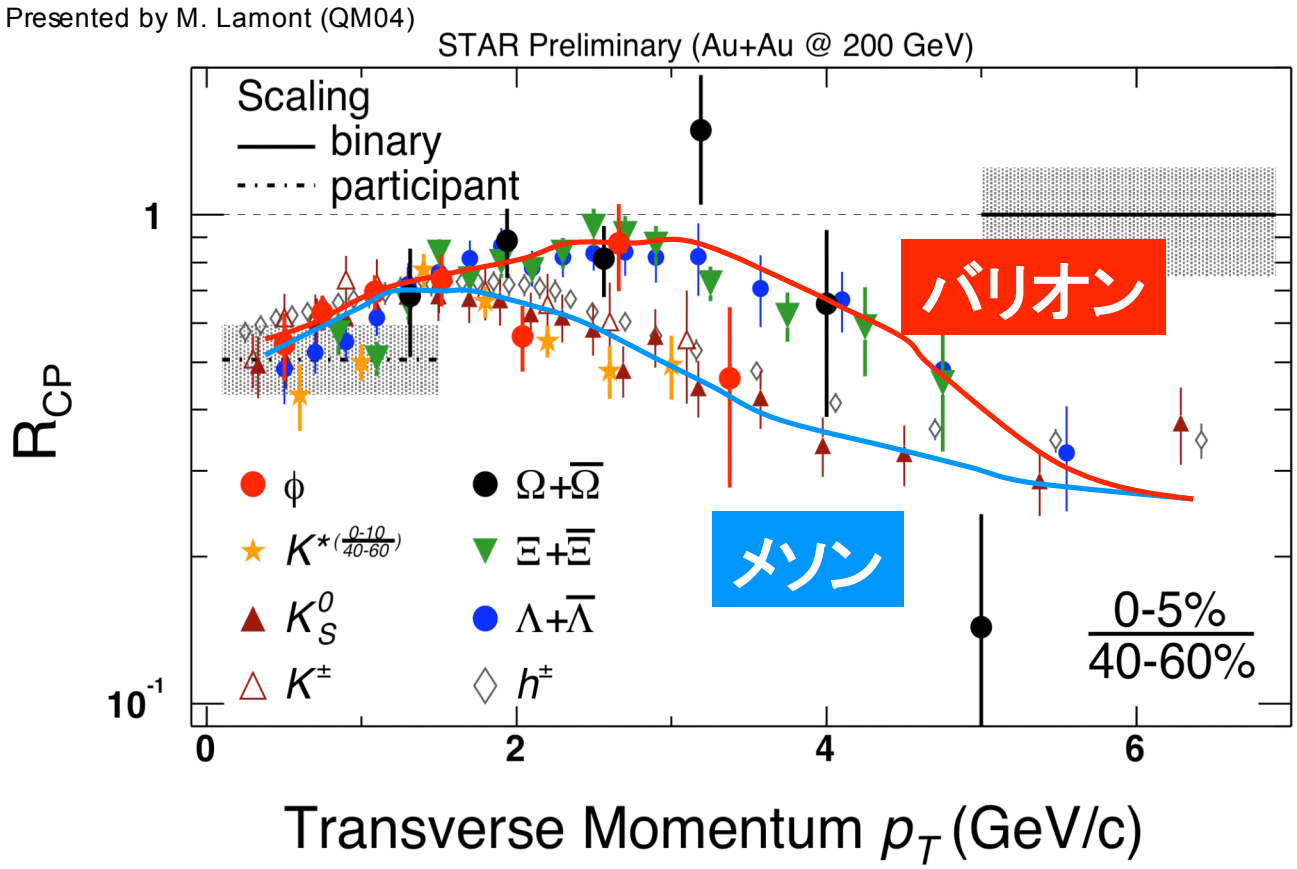
低い p_T (< 1.5 GeV/c): 集団運動の効果により異なる分布
中間 p_T: Ncoll でスケール
φ: N_{coll} でスケールしない

φ メソンの R_{cp}



- 陽子ではなく、π^0 のデータポイントと同じ傾向
- 陽子の中間 p_T領域で抑制効果が見えないのは、質量効果では"ない"ことを示唆。

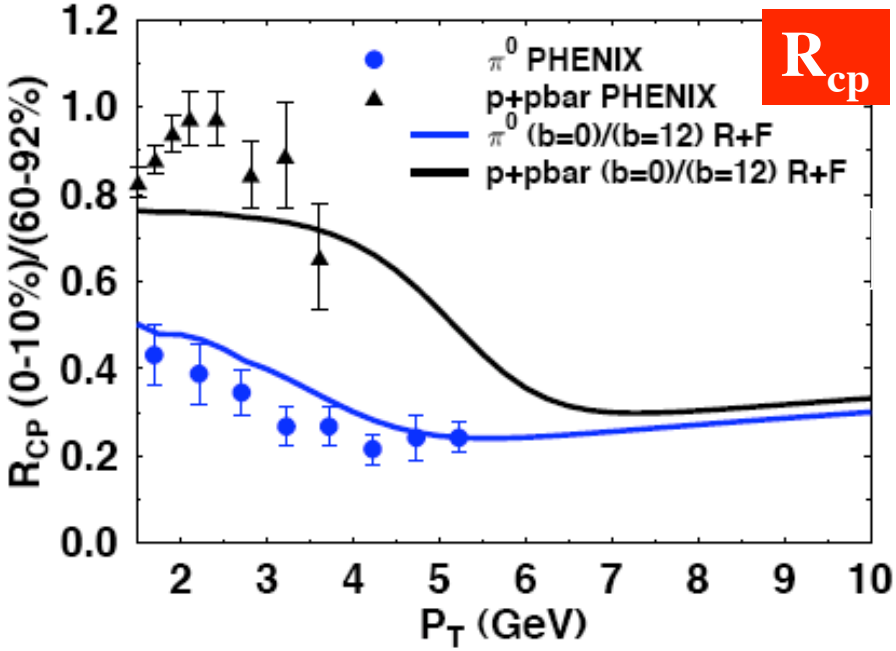
Compilation on R_{cp} from STAR

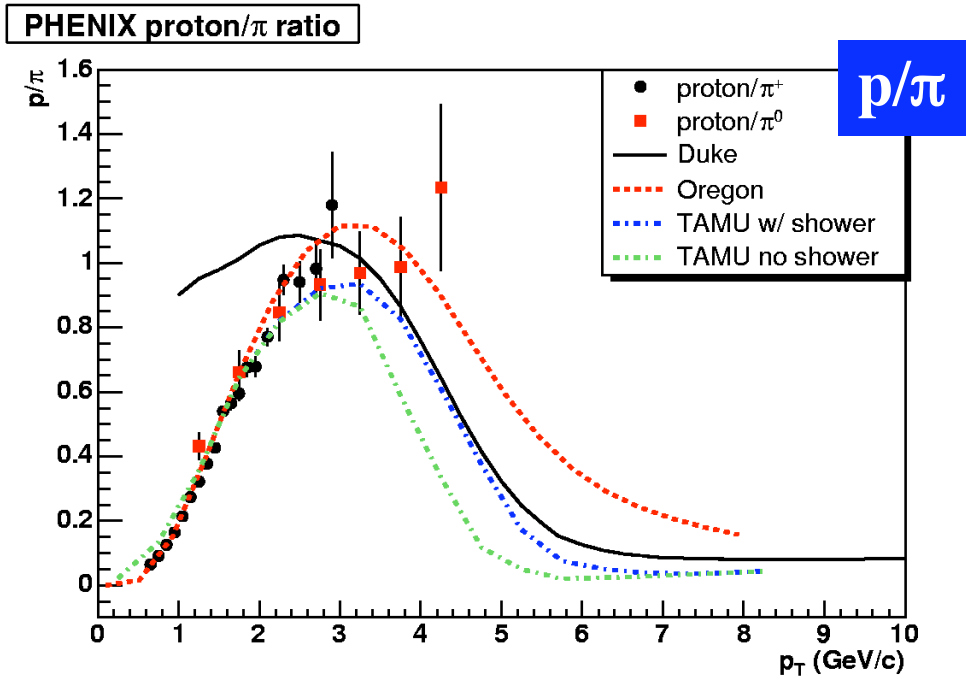


R_{cp}:2つのグループ、すなわちメソンとバリオンに分かれる。粒子の質量では分かれていない。

p_T ~ 2 GeV/c でわかれ、5 GeV/cで再び交わる.

Recombination モデル





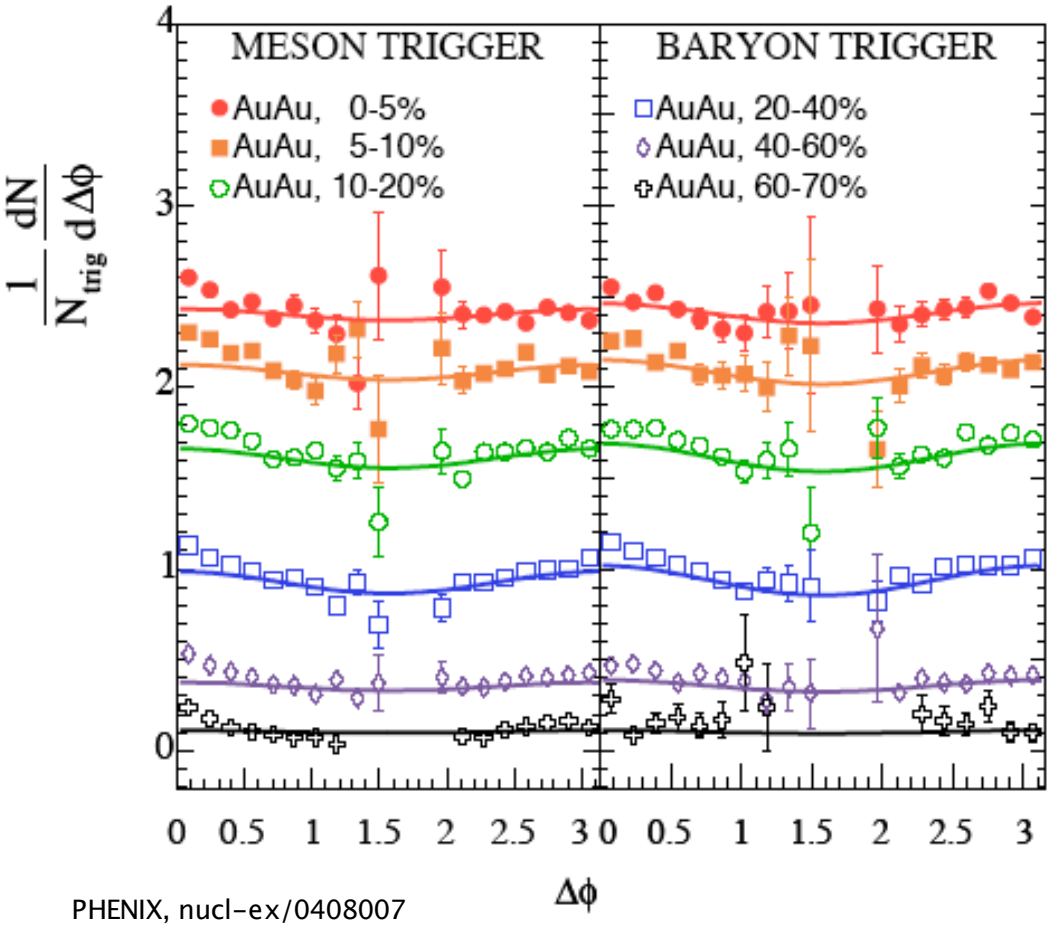
- R_{cp} (陽子＋反陽子) :モデルと定量的一致
- もし (thermal - hard) の寄与を加えるとより良い一致があるように見える
- Recombinationモデル:集団運動はパートンレベルで発展することを仮定 (partonic flow,β_T~0.55c at T=T_c).

中間p_T領域の陽子・反陽子生成の起源は?

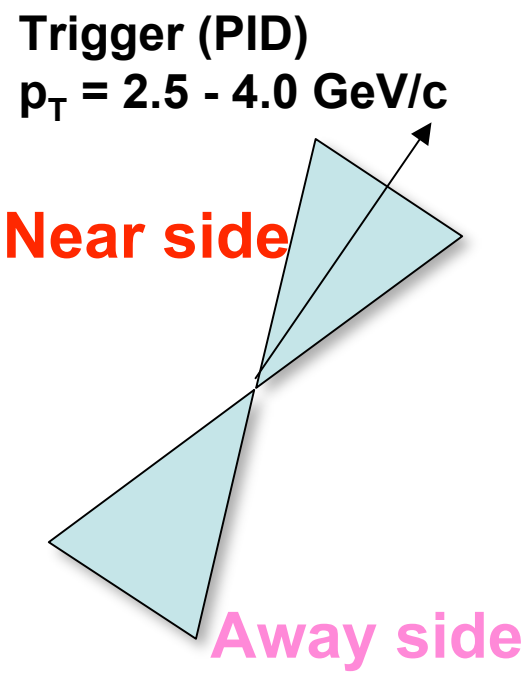
- 中間p_T 領域はソフトからハードプロセスへの移行領域であるが、その間に明確な区別があるわけではない。
- 中間 p_T 領域での陽子、反陽子生成の生成メカニズムは？

→ 粒子識別トリガー (p+pbar, π+K)を使ってジェット相関を測定（in Au+Au, d+Au）

PID triggerでみたジェット相関



PHENIX, nucl-ex/0408007

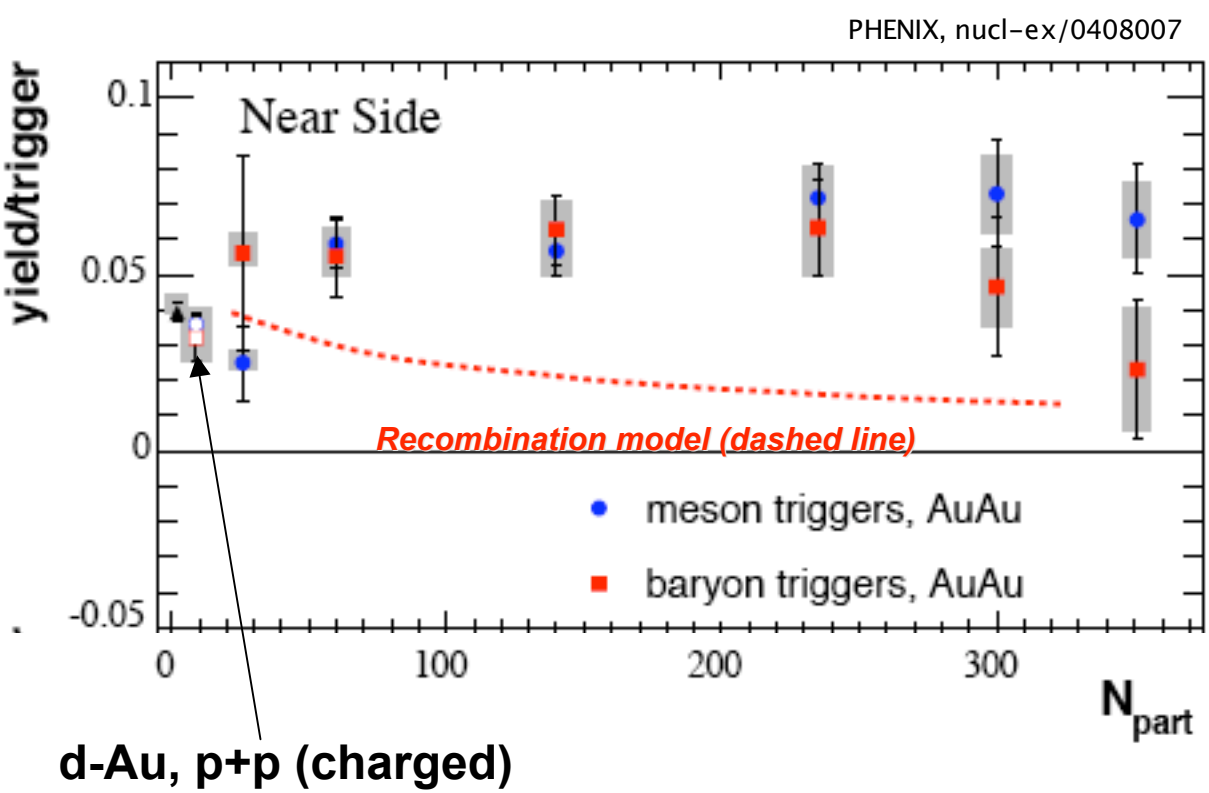


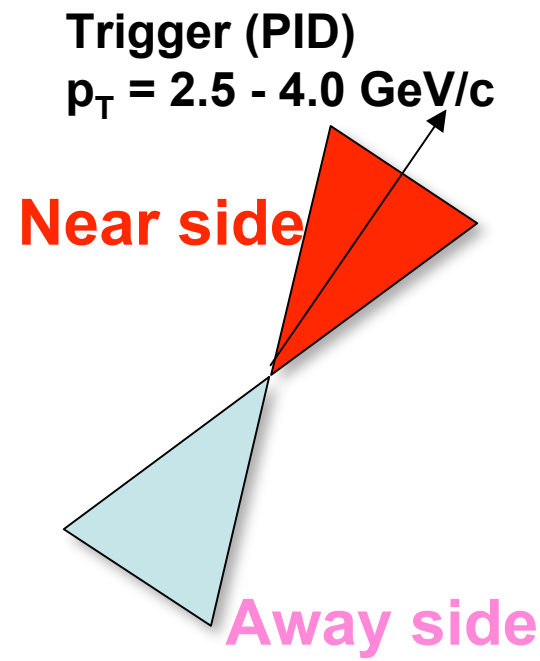
*Line: calculated combinatorial BG modulated by the measured v_2.

Count associated low p_T particles with PID mid-p_T trigger

- **Near side: Number of jet associated particles from same jet.**
- **Away side: Number of fragments from opposing jet.**

Jet correlation: near side

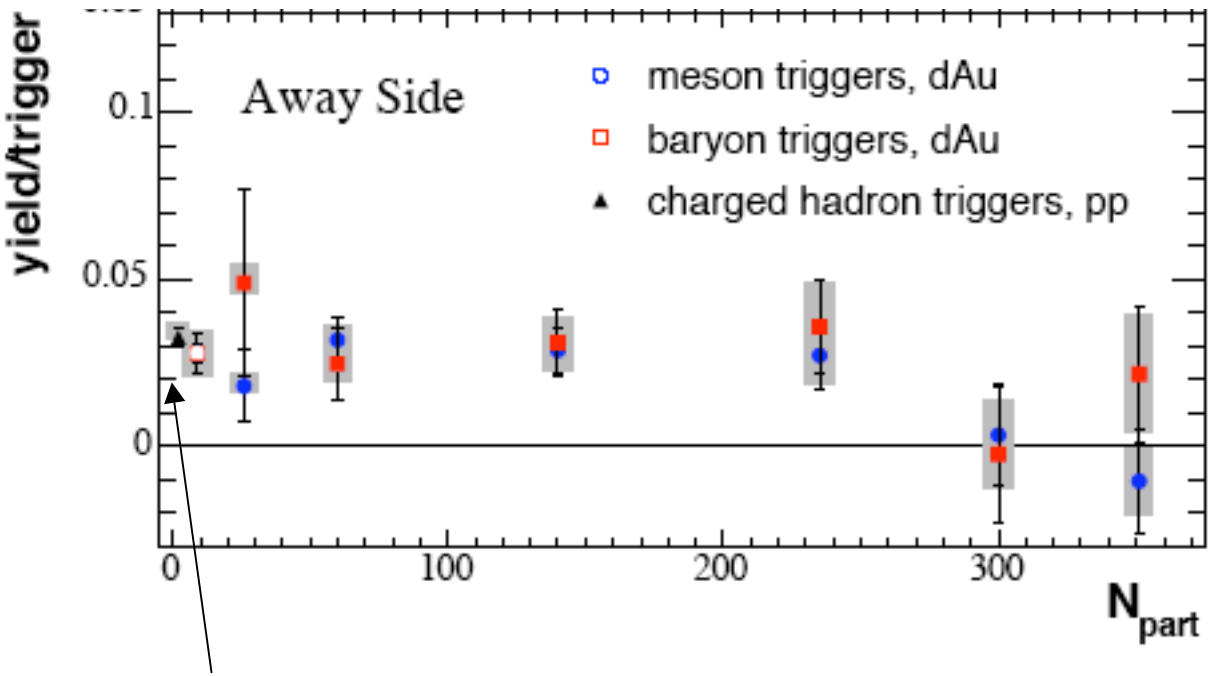




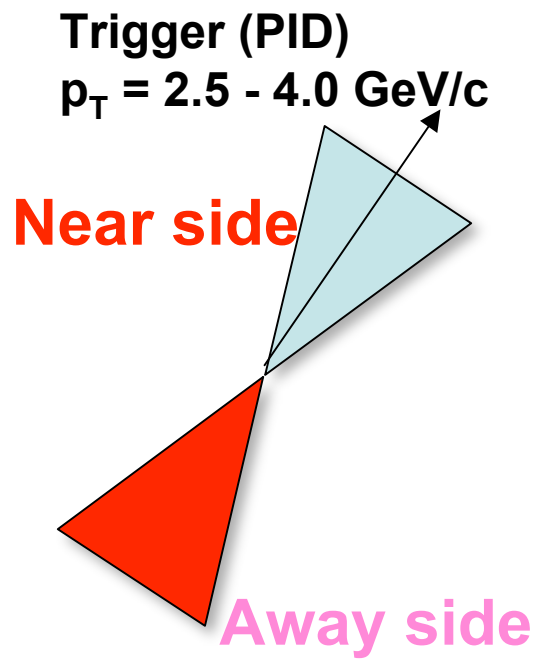
- **No apparent difference on jet partner yield between trigger baryons and mesons, perhaps except most central Au+Au for baryons.**
- **Suggested intermediate p_T baryon arises from a fragmentation from jet.**

Jet correlation: away side

PHENIX, nucl-ex/0408007



d-Au, p+p (charged)



- **Meson and baryon are comparable and decreasing at most central Au+Au collisions.**
- **In agreement with the disappearance/ broadening of back-to-back jet correlation in central Au+Au.**

Au+Au $\sqrt{s_{NN}}$ = 62.4 GeV での陽子・反陽子生成

なぜ 62.4 GeV?

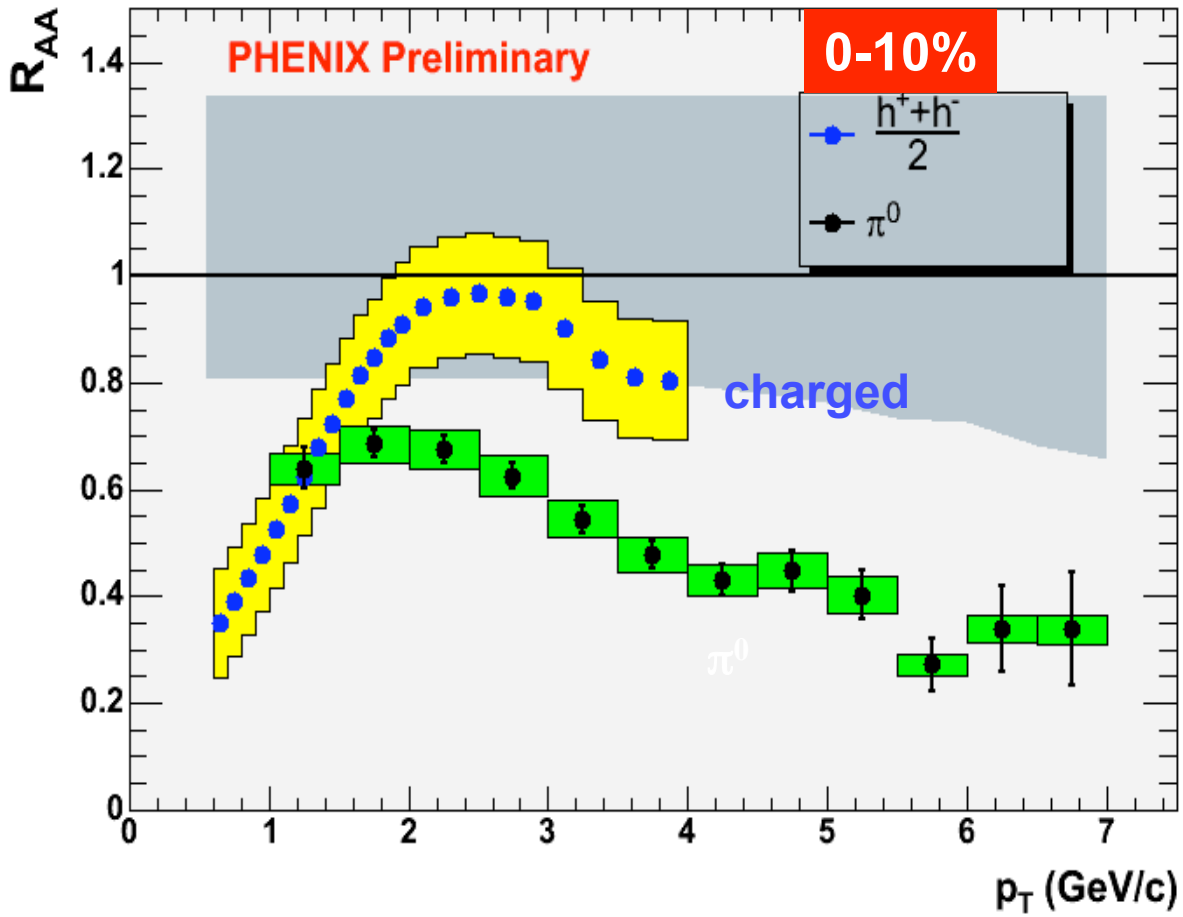
1)Located in the middle between SPS(17GeV) and RHIC top energy (200 GeV) in $\sqrt{s_{NN}}$.

2)Many reference data from ISR.

3)Provide a constraint on jet quenching model.

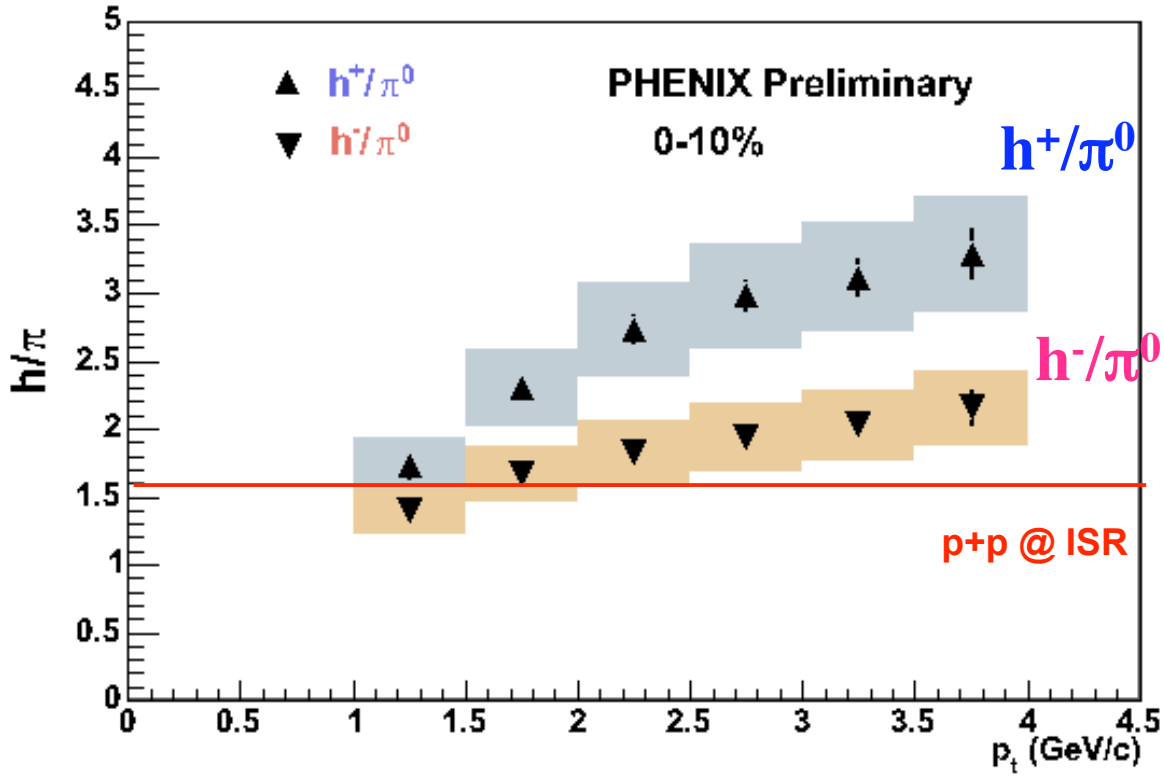
4)Allow to study the excitation function of baryon production/transport, further constrain on various models for hadron production at intermediate p_T.

R_{AA} @ 62.4 GeV : Charged hadron and π^0



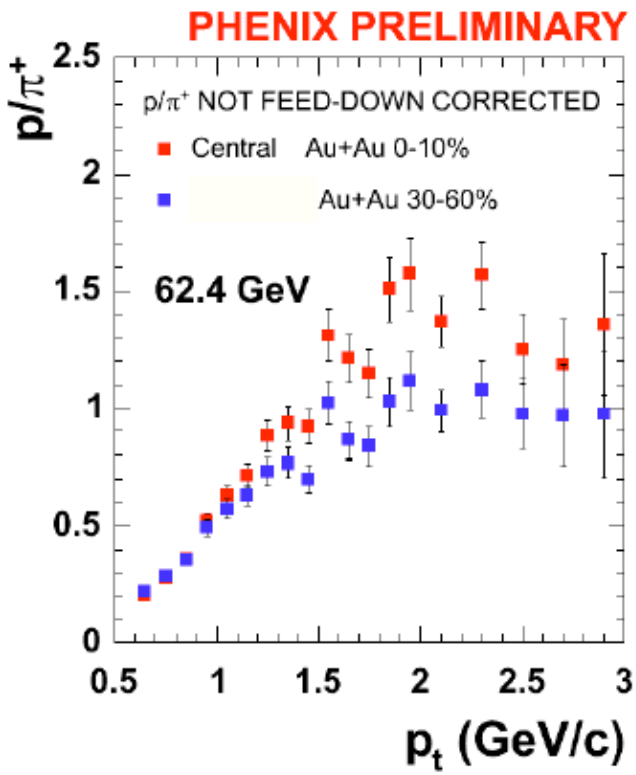
- Common reference p+p→charged+X is used (instead of ISR π^0 reference).
- **Clear difference between charged and π^0 at intermediate p_T up to 4 GeV/c.**
- Suggests a large proton contribution in this p_T region, as seen in 200 GeV data.

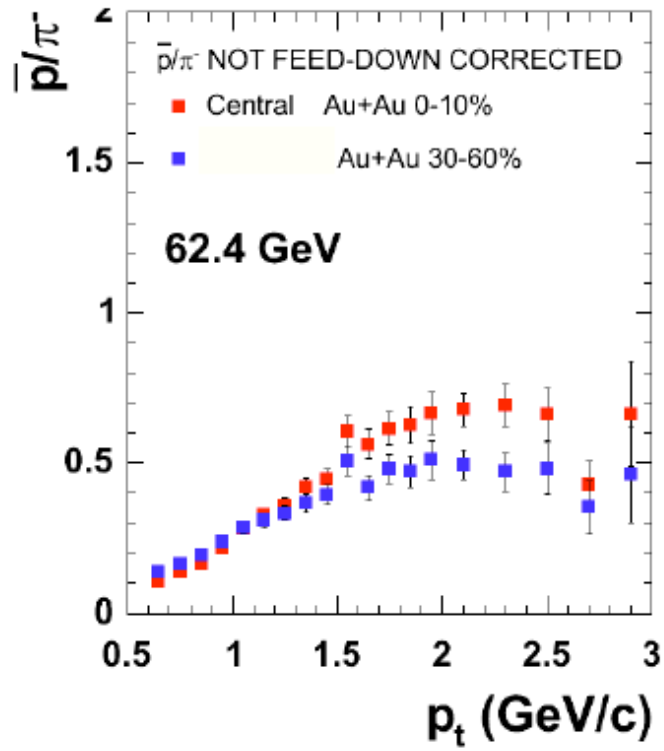
h^+/π^0 and h^-/π^0 ratios @ 62 GeV



- Monotonic increase for both ratios at measured p_T, starting from 1.6.
- **Difference between negative and positive hadron to π^0 ratio.**

p/π^+, $pbar/\pi^-$ ratios @ 62 GeV

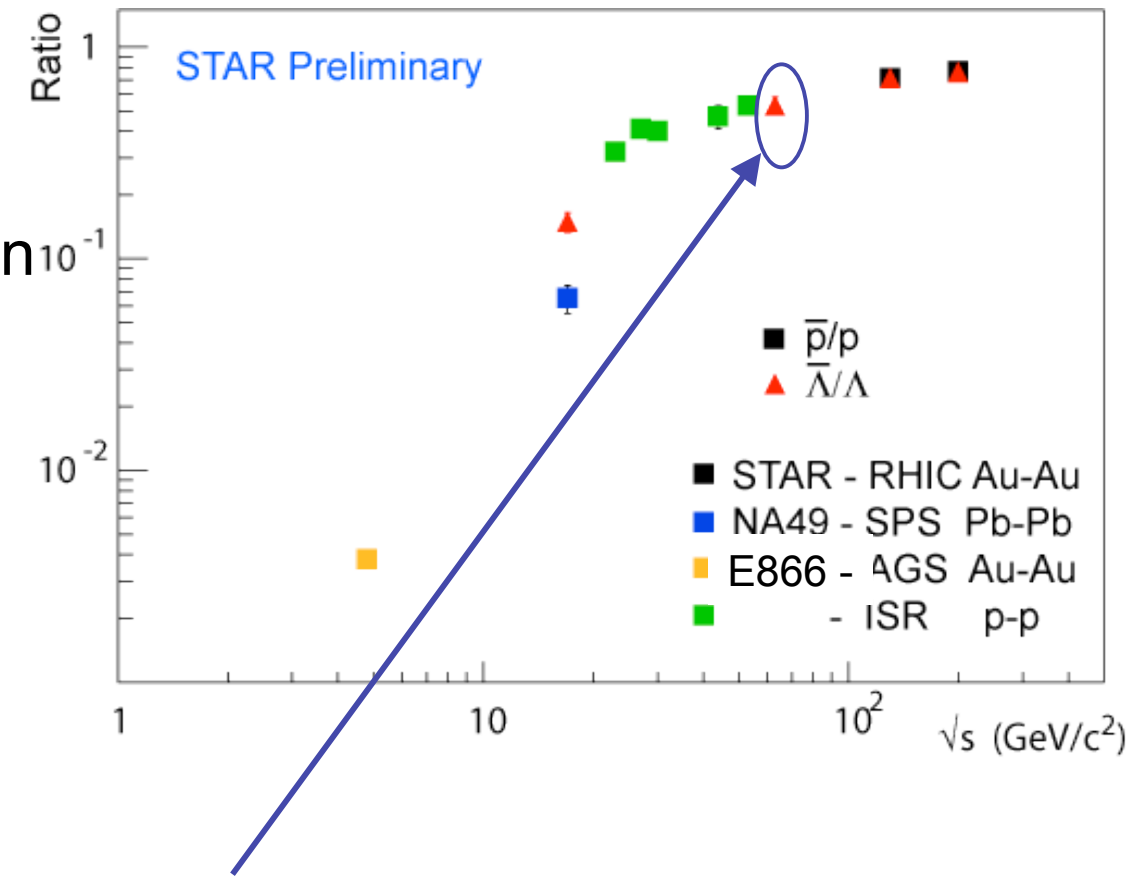




- **Large proton contribution** at intermediate p_T 62.4 GeV (too).
- **Less antiproton** in central collisions at 62.4 GeV than 130/200 GeV.
- **Indicating more baryon transport and less p-pbar pair production at 62 GeV than 200 GeV.**
- The 62 GeV p_T spectra will tell us more about the excitation function of chemical properties, scaling and radial flow at RHIC (stay tuned!).

Baryon transport to mid-rapidity

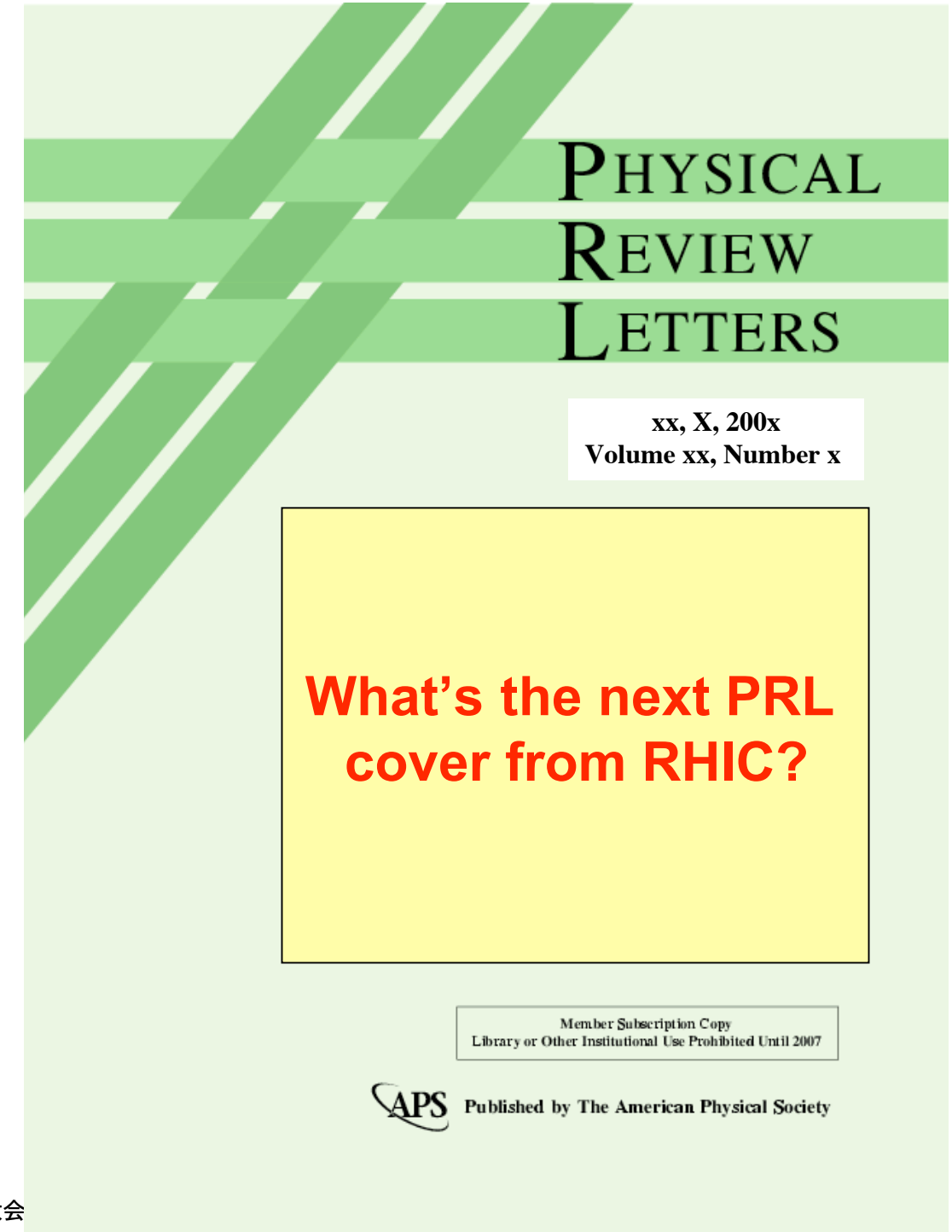
- Clear systematic trend with collision energy
- Very similar trend between heavy ion and p-p



62.4 GeV data fits into pattern

まとめ

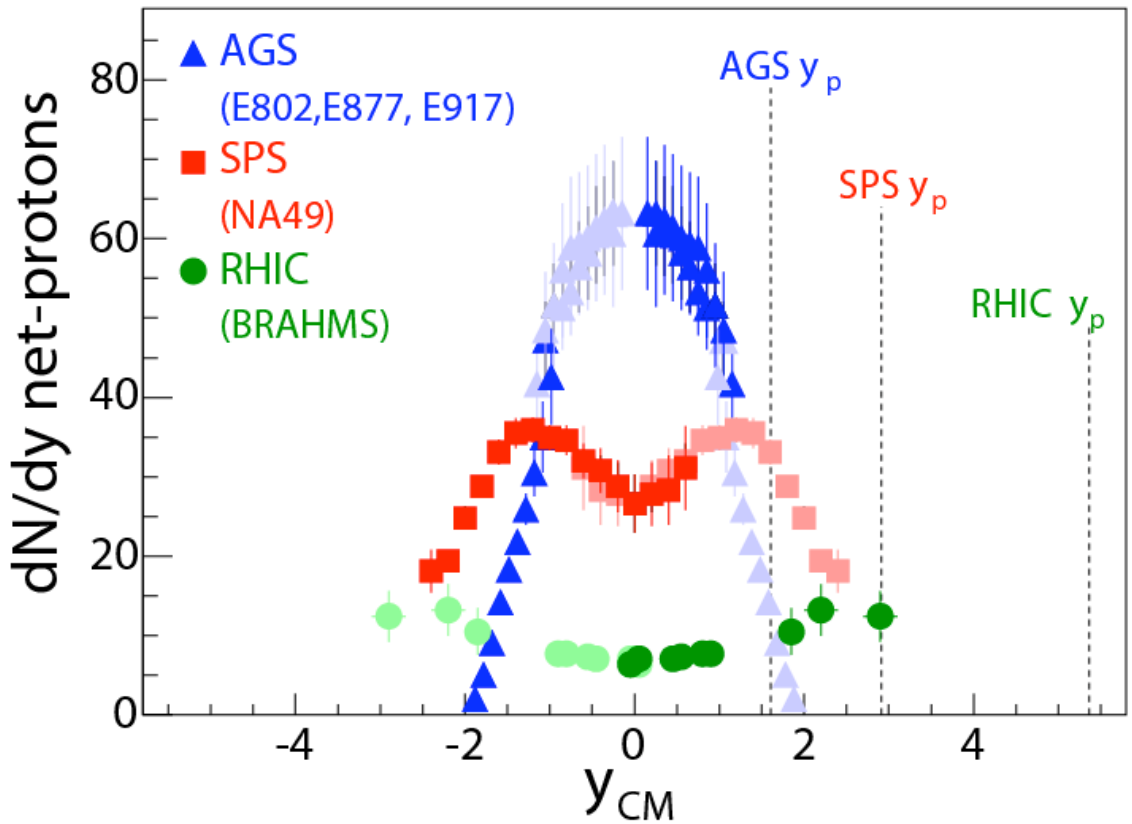
- 過去４年の測定で RHIC から数多く興味深い論文が発表されている。
- 強い等方的集団運動
- 統計的サーマルモデルで粒子比を再現
- 中間 p_T 領域では、リーコンビネーションモデルが有効なハドロン生成であることを示唆。
  - パートンレベルでの集団運動 (not hadronic flow)
  - Fragmentation の寄与の重要性
- 62 GeV の新しい結果
- 今後の方向
  - さらに高い p_T領域での粒子識別(< 10 GeV/c, fragmentation regionの物理)
  - 系統的測定（軽イオン衝突、エネルギースキャン）


PHYSICAL
REVIEW
LETTERS
xx, X, 200x
Volume xx, Number x
What's the next PRL cover from RHIC?
Member Subscription Copy
Library or Other Institutional Use Prohibited Until 2007
APS
Published by The American Physical Society

おわり

Backup Slides

Energy Dependence of Net-Protons

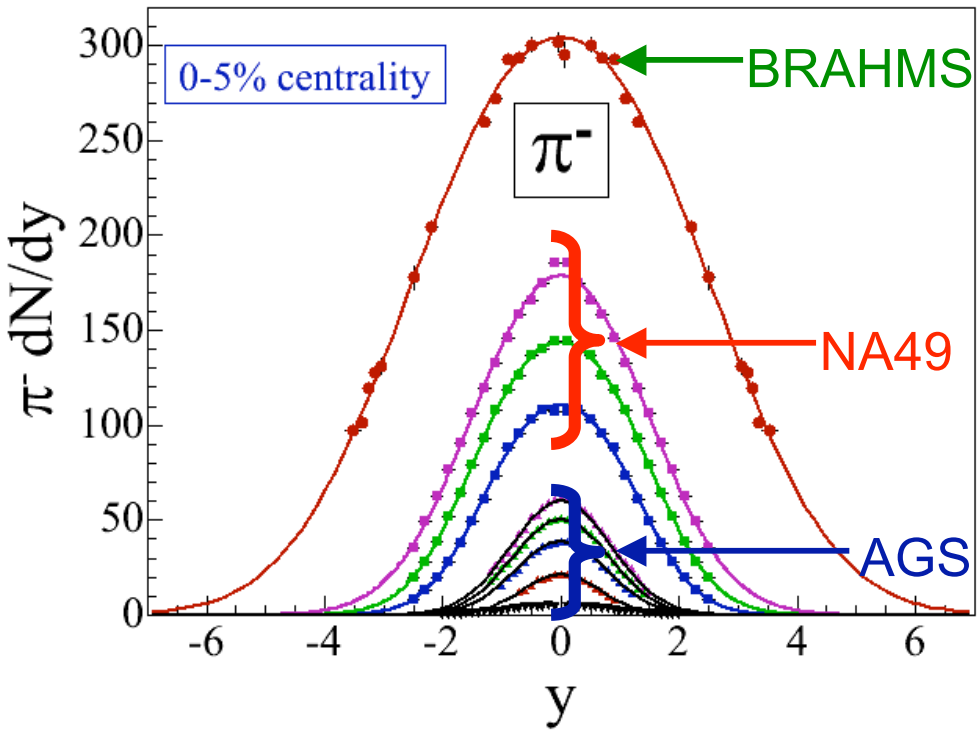


The shape of the distributions changes dramatically with energy

BRAHMS, nucl-ex/0313023

AGS: baryonic system ↔ RHIC: mesonic system
→ Large implications in the hadronic sector

Rapidity Distributions (Pions)



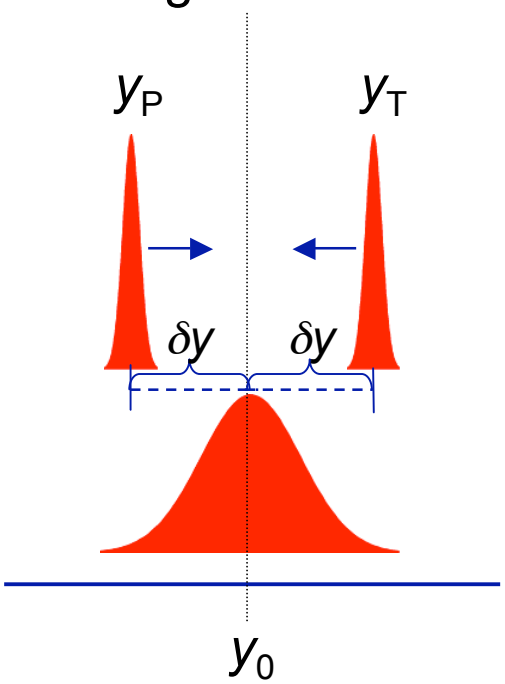
Pion rapidity distributions fit perfectly to Gaussians at all energies

D. Ouerdane, QM04

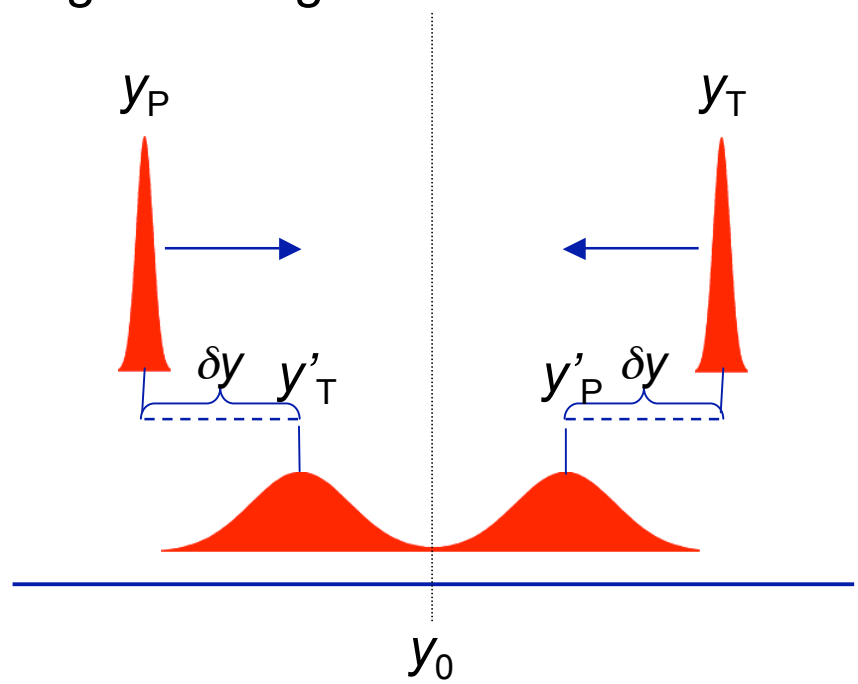
Boost invariance of particle production?

ストッピング　Rapidty Shift δy

Baryon number distributions at lower energies:



higher energies:



Determines the energy available in the produced fireball

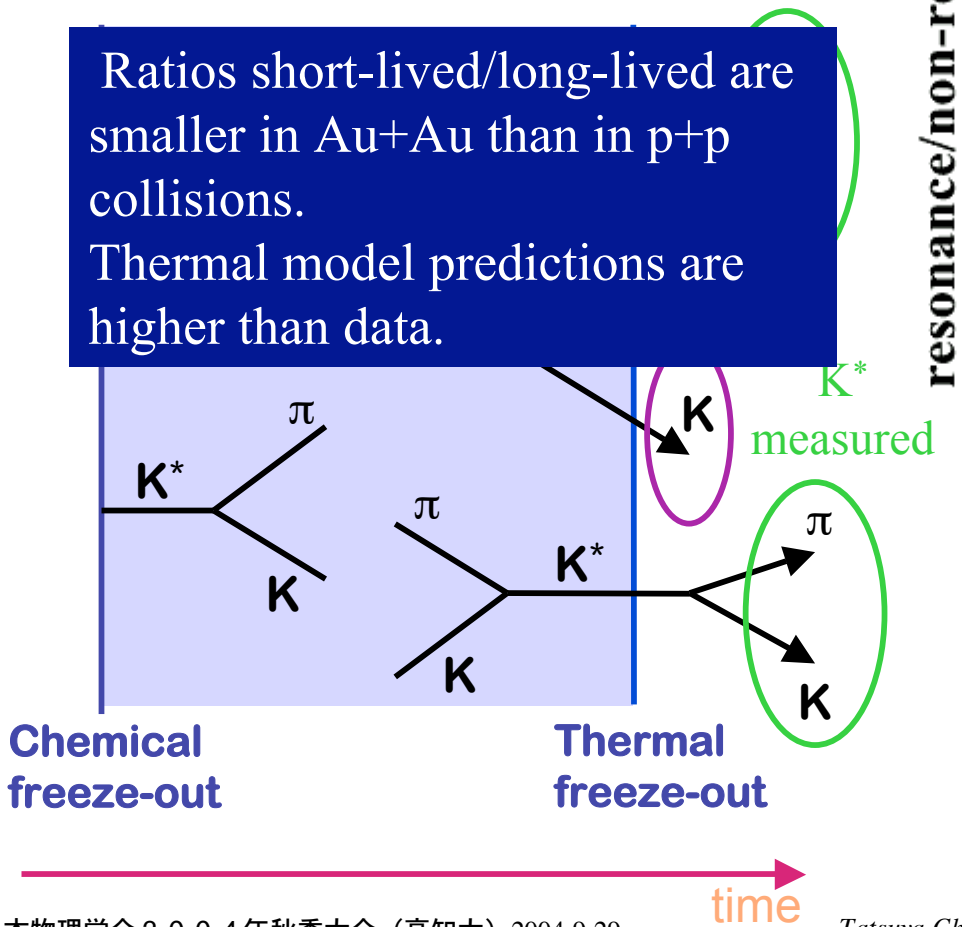
How does the rapidity shift δy evolve with beam energy?

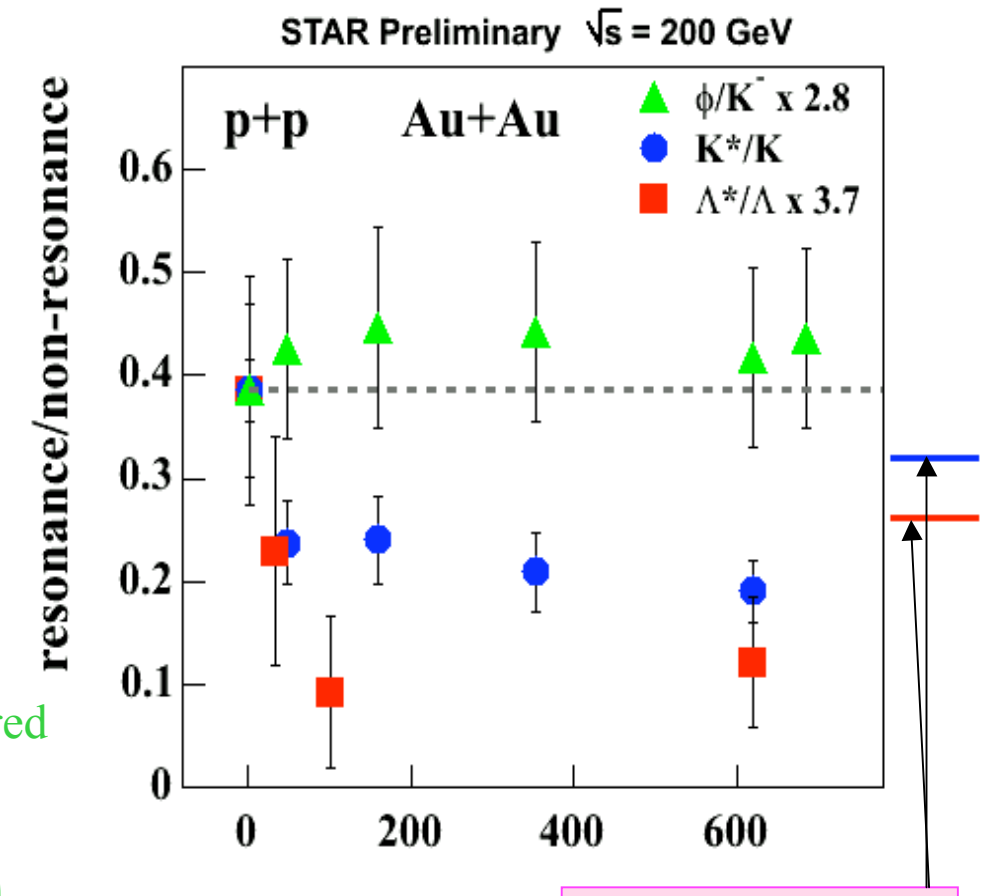
例外も… (short-lived resonance)

Produced short lived resonances (K*, ρ)

- rescattering of daughters
- regeneration effect

Ratios short-lived/long-lived are smaller in Au+Au than in p+p collisions.
Thermal model predictions are higher than data.

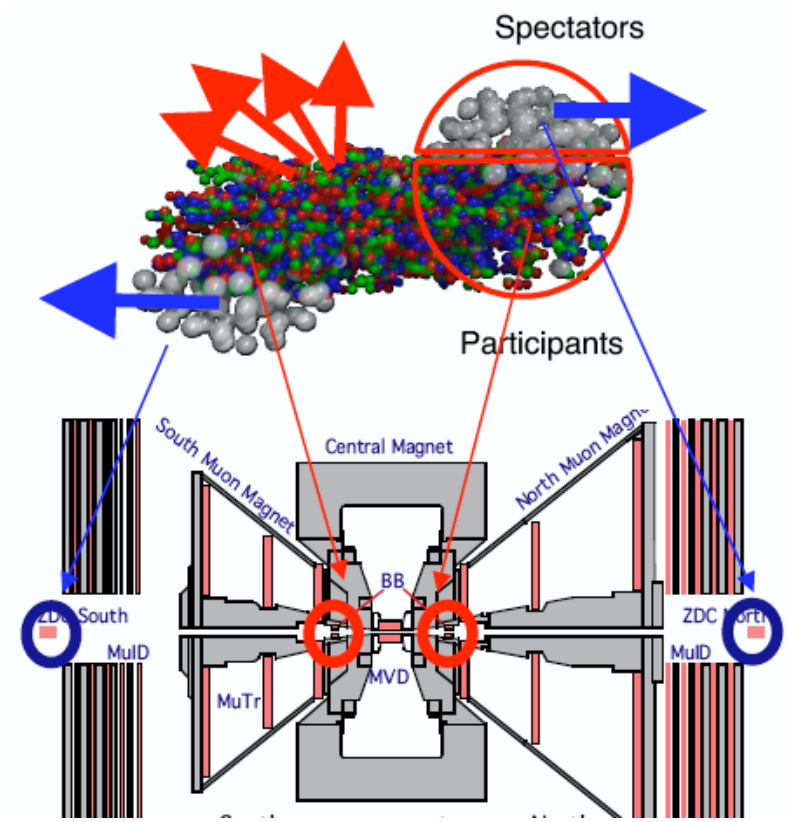


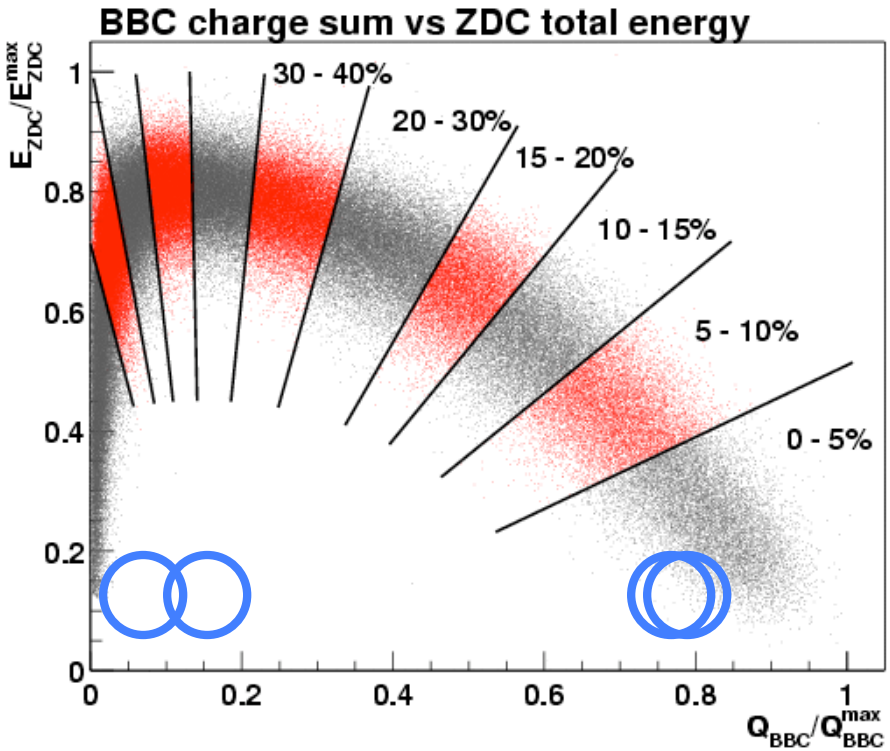


Life time:
ϕ (1020) = 40 fm/c
L(1520) = 13 fm/c
K(892) = 4 fm/c

Thermal model [1]:
T = 177 MeV
μ_B = 29 MeV

衝突イベントの選別





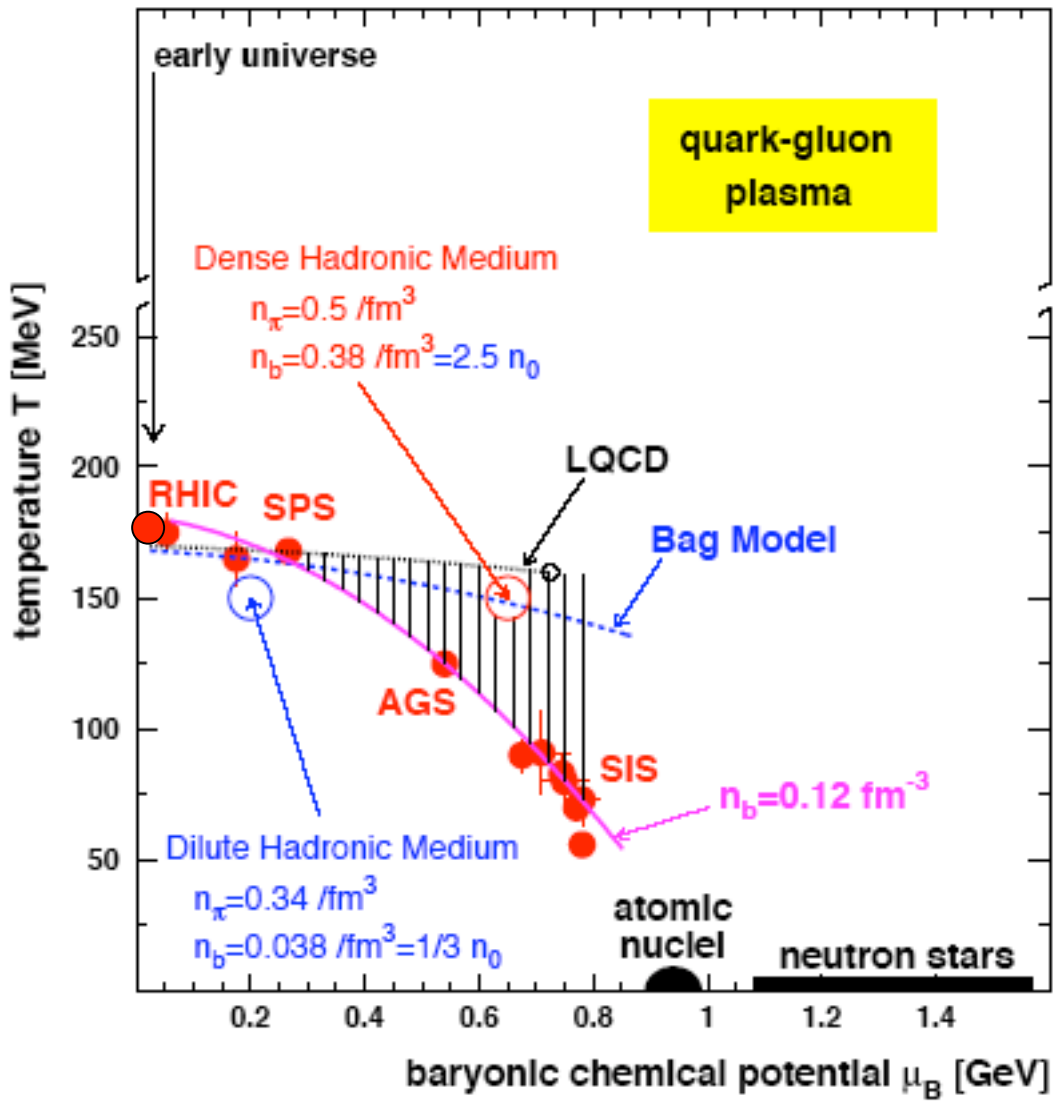
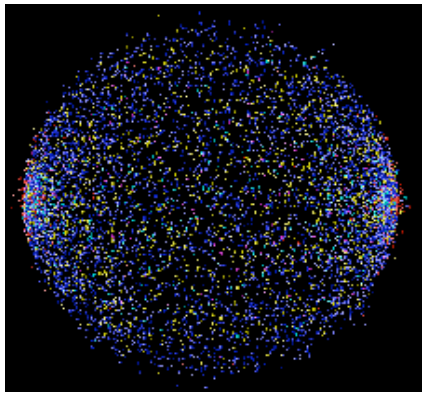
周辺衝突 → 中心衝突

- 重イオン衝突では衝突のジオメトリーを決定することが必須。
- ビームカウンター (**BBC**)の荷電粒子数とゼロ度方向カロリメータ(**ZDC**) の中性子がおとしたエネルギー相関によって中心衝突度を測定。

粒子比からわかる相図

PBM, J. Stachel, nucl-th/0112051, J. Phys. G28, 1971 (2002)

•統計的熱力学モデル

$$\rho_i = \frac{g_i}{2\pi}\int \frac{p^2 dp}{\exp(E_i - \mu_i/T_{ch}) \pm 1}$$

• RHIC と SPS のデータは格子QCDの phase boundary と非常に近い