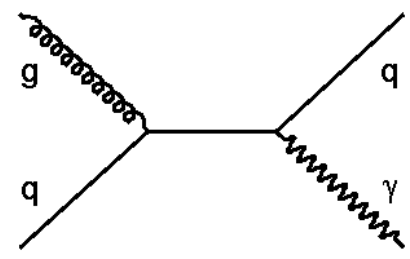
Direct Photons
and
Electrons

Direct Photons

Direct photons come from initial hot dense matter

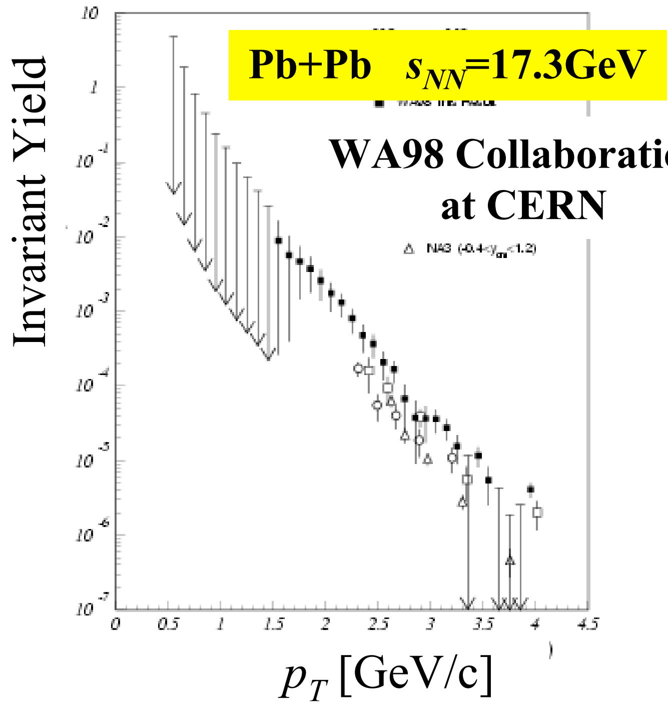
- Compton scattering of quarks and gluons: $q(\bar{q})g \rightarrow \gamma q(\bar{q})$
- Annihilation of quarks: $q\bar{q} \rightarrow \gamma g$
- Information on Thermo-dynamical state of medium
    - Initial temperature, Degree of freedom, etc.



Other sources of photons?

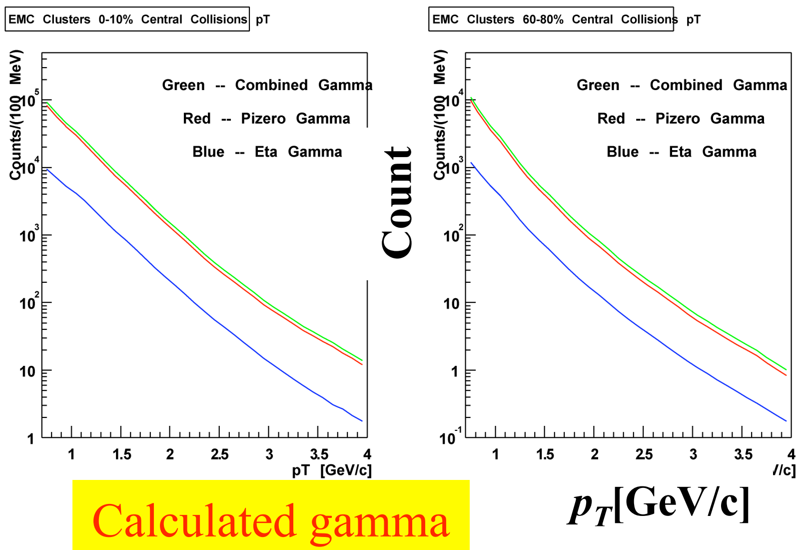
Decayed photons from hadronic sources

State	Mass (MeV/c^2)	$R_{X/\pi^0}(p_T \to \infty)$	Decay Branch	Branching Ratio
π^0	134.98		$\gamma\gamma$	98.798 %
			$e^+e^-\gamma$	1.198 %
η	547.3	0.55	$\gamma\gamma$	39.21 %
			$\pi^+\pi^-\gamma$	4.77 %
			$e^+e^-\gamma$	4.9×10^{-3}
			$\pi^0\gamma\gamma$	7.1×10^{-4}
			$\mu^+\mu^-\gamma$	3.1×10^{-4}
ρ^0	770.0	1.0	$\pi^+\pi^-\gamma$	9.9×10^{-3}
			$\pi^0\gamma$	7.9×10^{-4}
ω	781.9	1.0	$\pi^0\gamma$	8.5 %
			$\eta\gamma$	6.5×10^{-4}
η'	957.8	0.25	$\rho\gamma$	30.2 %
			$\omega\gamma$	3.01 %
			$\gamma\gamma$	2.11 %
K^0_s	497.7	0.4	$(\pi^0\pi^0)$	(31.39 %)
Σ^0	1192.6	1.0	$\Lambda\gamma$	100.0 %

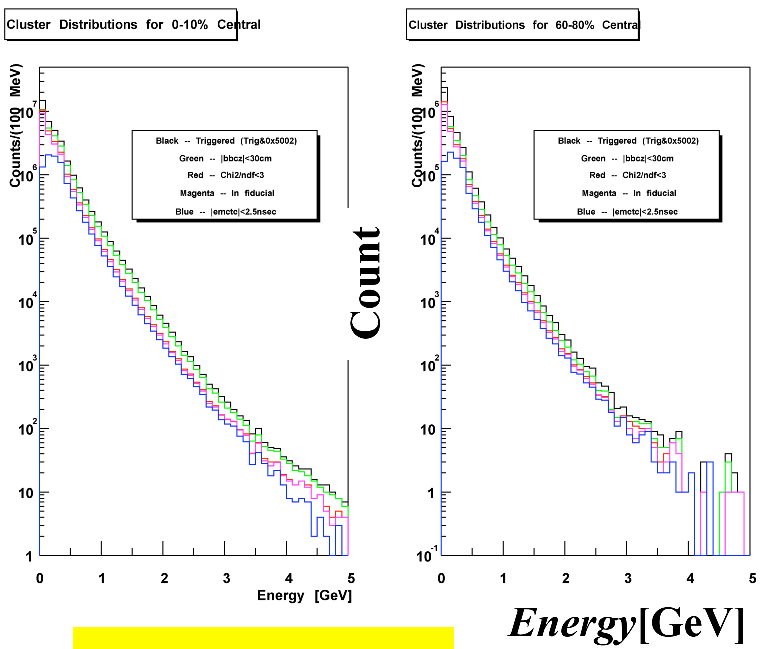


Phys. Rev. Lett. 85, 3595 (2000)

Analysis (s_{NN}=130GeV Au+Au)



Calculated gamma



Measured gamma

- Generate gammas from hadron sources
  - Take observed □^{0} p_T spectra
  - □, □□, □: m_T scaling of power-law fit to □^{0} is applied and estimated
  - Generate Flat rapidity of –0.5<y<0.5
  - Generate p_T measured or estimated
  - Decay hadrons into gammas
- Inclusive photon spectra
  - Efficiency and contamination estimated by comparing real data and simulation
- Systematic Error: Showing 1□ level

Correction or Systematics	Central	Errors to Total	Peripheral	Errors to Total
PID efficiency	88 %	±7.3 %	98.5 %	±7.3 %
Hadron Contam. (Incl. PID eff.)	10-50 %	±13.4 %	10-50 %	±7.4 %
Gamma Conversion loss	4 %	±2.0 %	4 %	±2.0 %
Nonvertex photons	6.0 %	±3.0 %	6.0 %	±3.0 %
η/π^0 ratio	0.55	±11.0 %	0.55	±11.0 %
Other hadron (η' and ω) contribution	0.4 %	±0.2 %	0.4 %	±0.2 %
η branching ratio	39.2 %	0	39.2 %	0
π^0 branching ratio	98.8 %	0	98.8 %	0
Total Systematic Errors	N/A	17.71 %	N/A	13.74 %

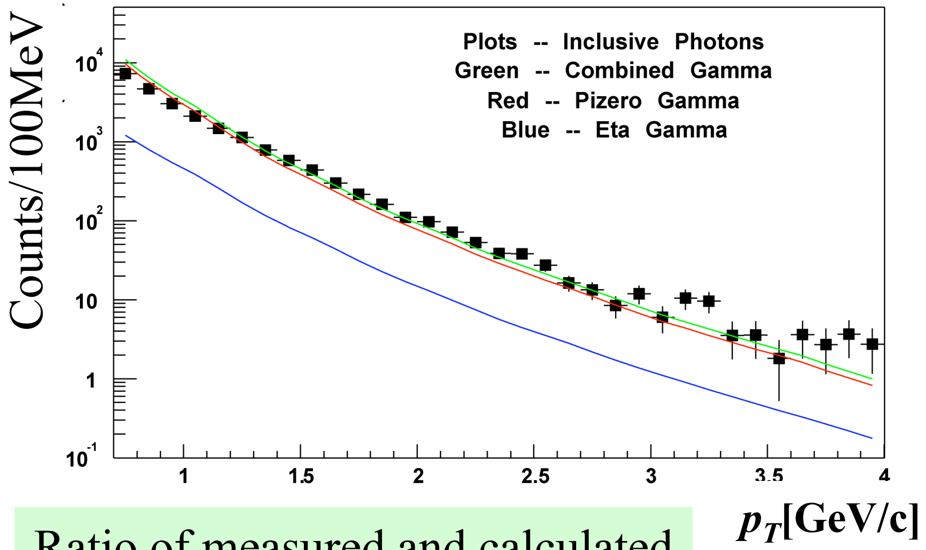
Comparison of Cluster Energy Distributions (I)

s_{NN}=130GeV Au+Au

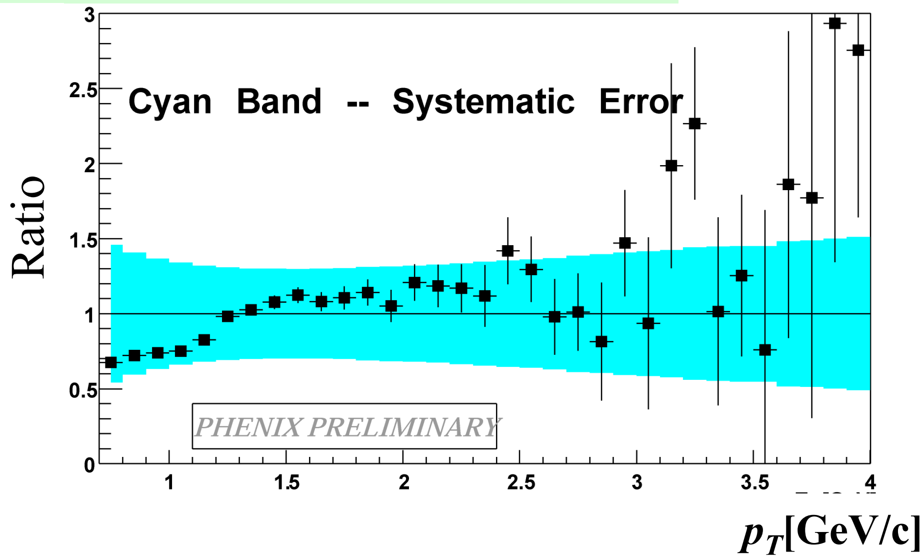
- <u>60-80% Central Events</u>
- Comparison between measured and calculated energy spectra
- Systematic error bans(Cyan)

Measured inclusive photons are consistent with contributions from known hadronic sources!

Comparison of measured and calculated



Ratio of measured and calculated

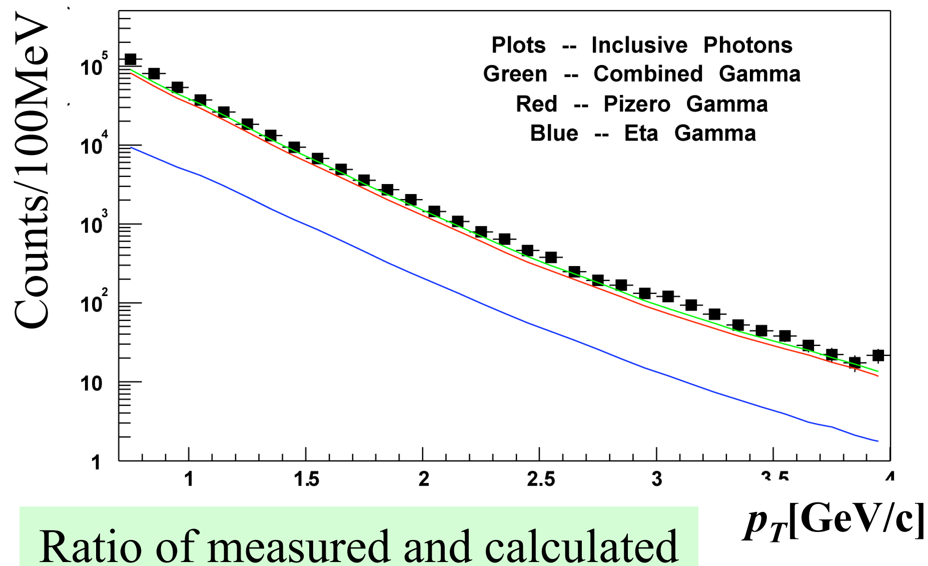


Comparison of Cluster Energy Distributions (II)

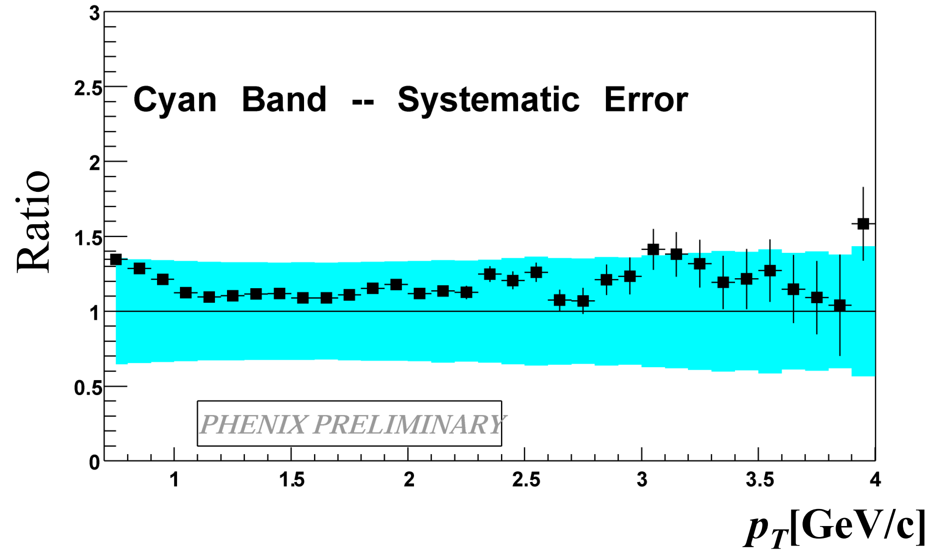
s_{NN}=130GeV Au+Au

- <u>0-10% Central Events</u>
- Systematic error bands (Cyan)

Comparison of measured and calculated



Ratio of measured and calculated

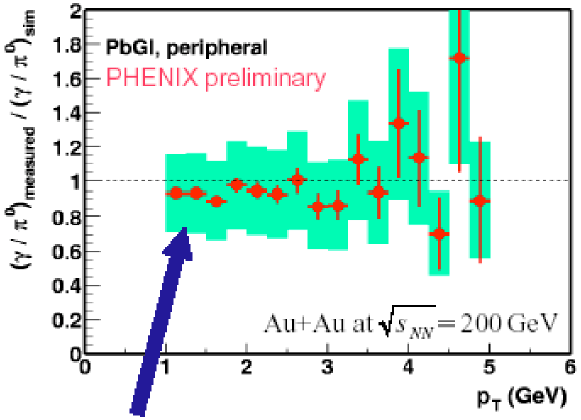


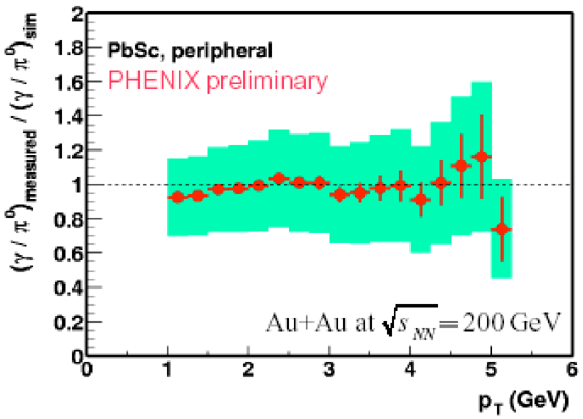
Measured inclusive photons are yet not inconsistent with contributions from known hadronic sources within current systematic errors

Photon Result - Au+Au- s_{NN}=200GeV

- Plotted are ratios of photons to π^0
- Denominator:
  - Photons calculated from hadronic sources
- Numerator:
  - Inclusive photons measured

$(\gamma/\pi^0)_{measured}$ / $(\gamma/\pi^0)_{simulated}$: Peripheral

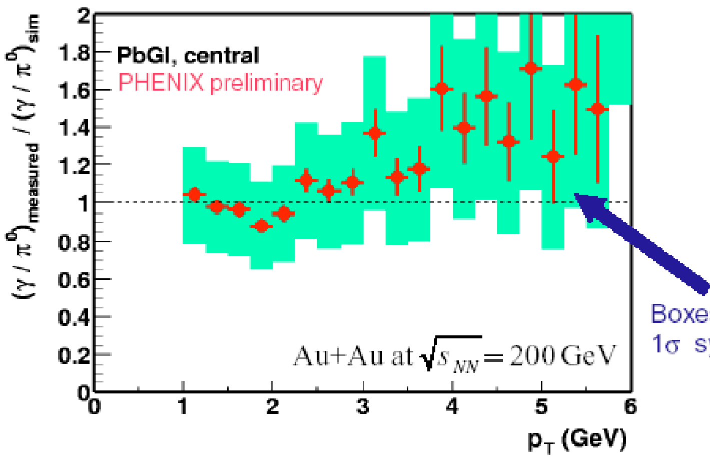




Boxes: 1σ systematic error

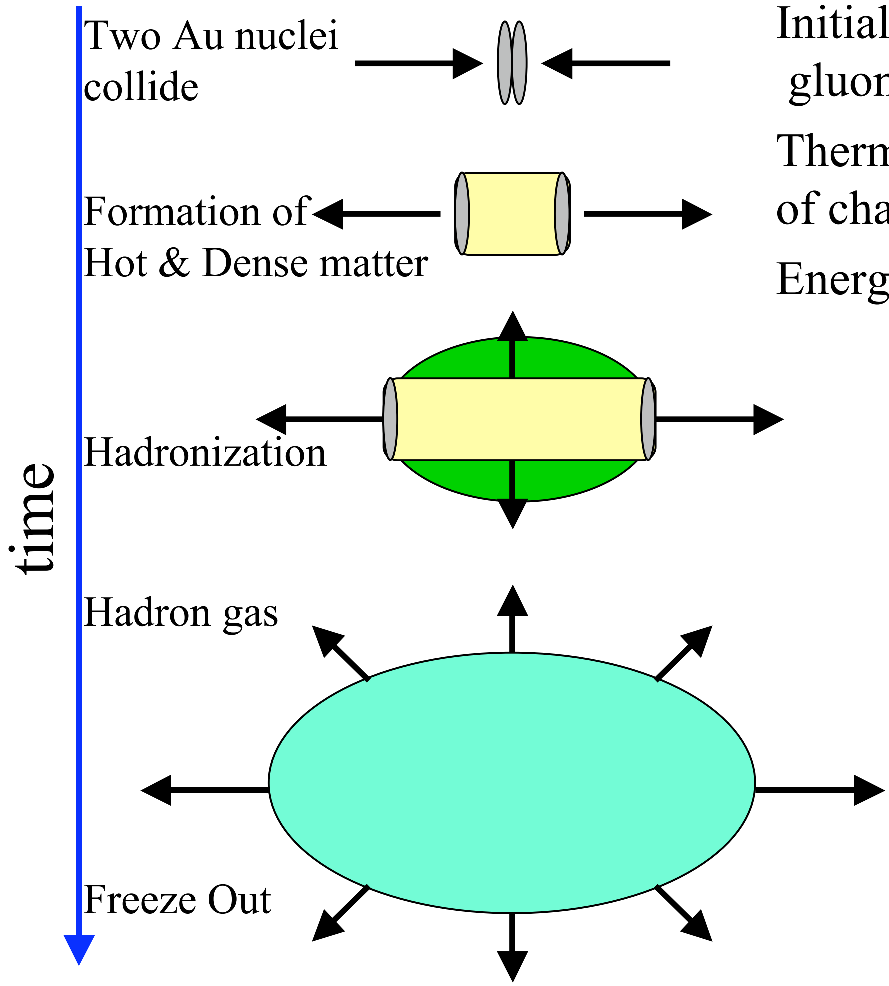
$(\gamma/\pi^0)_{measured}$ / $(\gamma/\pi^0)_{simulated}$: Central

Measured inclusive photons are yet not inconsistent within current systematic errors..



Boxes:
1σ systematic errors

Single electron and Charm



Initial gluon density ⟷ Charm cross section

gluon shadowing? ⟷ Charm suppression?

Thermal production of charm ⟷ Charm enhancement?

Energy loss of charm ⟷ Charm pt distribution

Charm is a very good probe of initial stage of heavy ion collisions.

Open charm measurement is important to understand J/ψ production

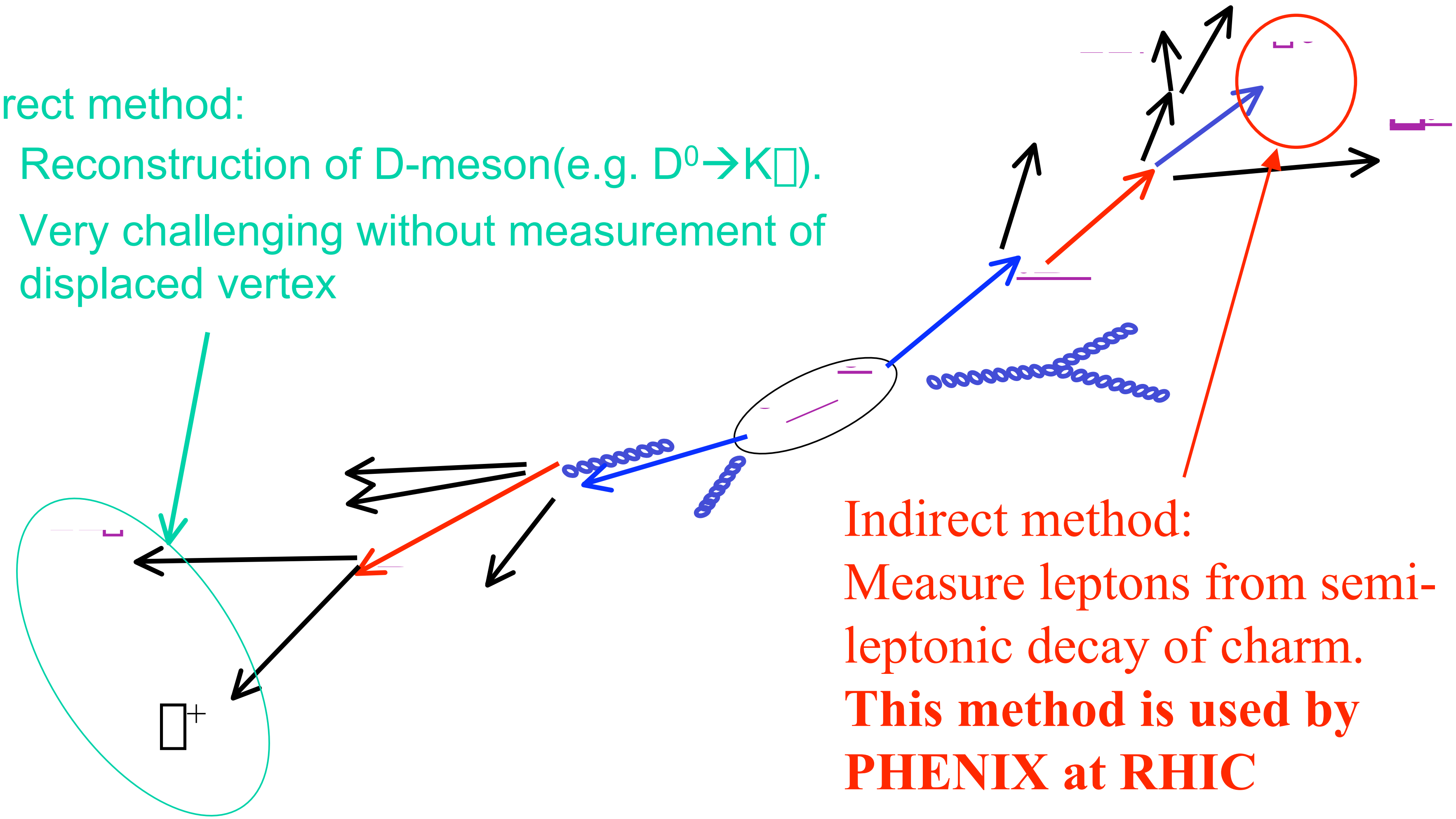
Charm production at RHIC can be studied from its decay to single electrons

Charm measurement

Direct method:

Reconstruction of D-meson(e.g. $D^0 \rightarrow K$□).

Very challenging without measurement of displaced vertex

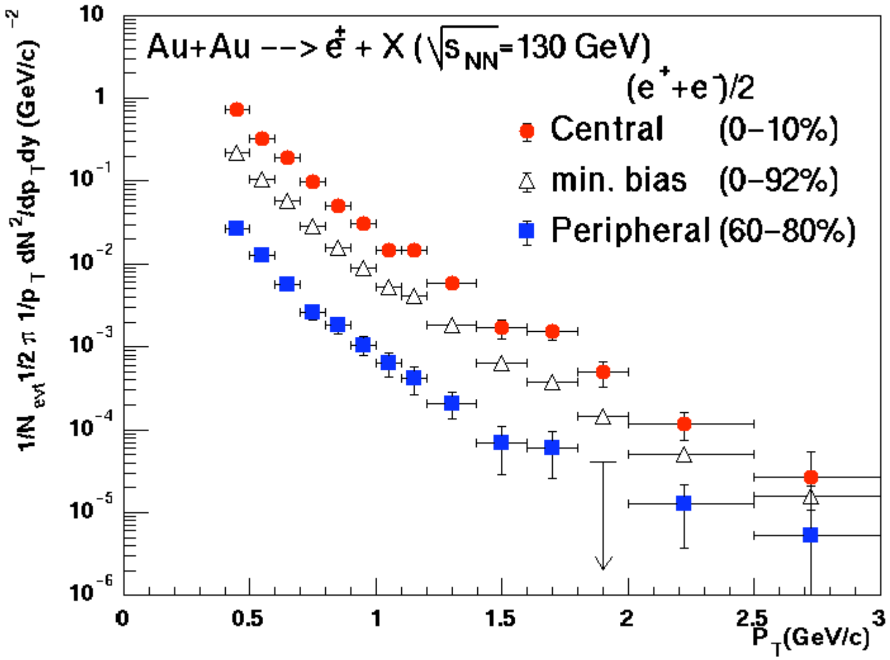


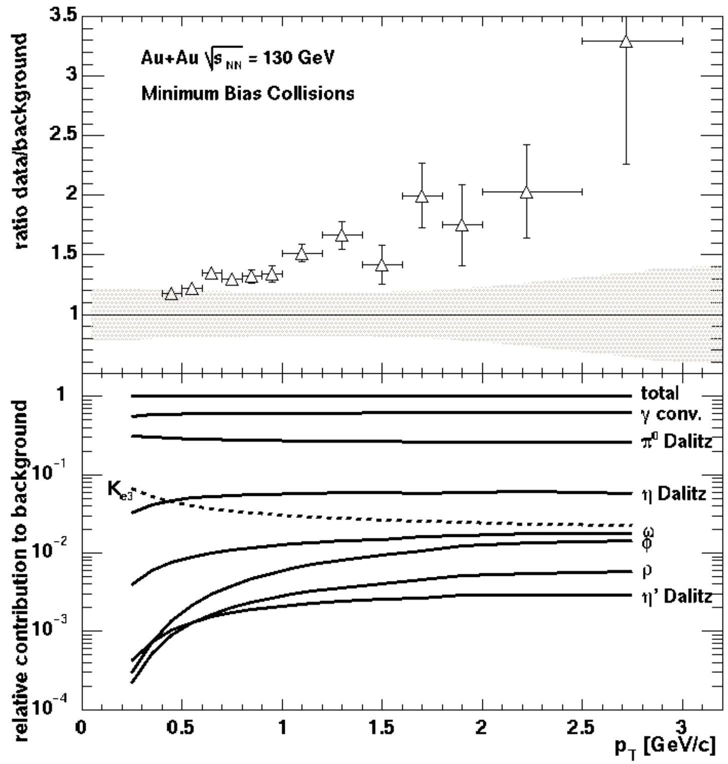
Indirect method:

Measure leptons from semi-leptonic decay of charm.

This method is used by PHENIX at RHIC

Single electron in RUN-1(130GeV)

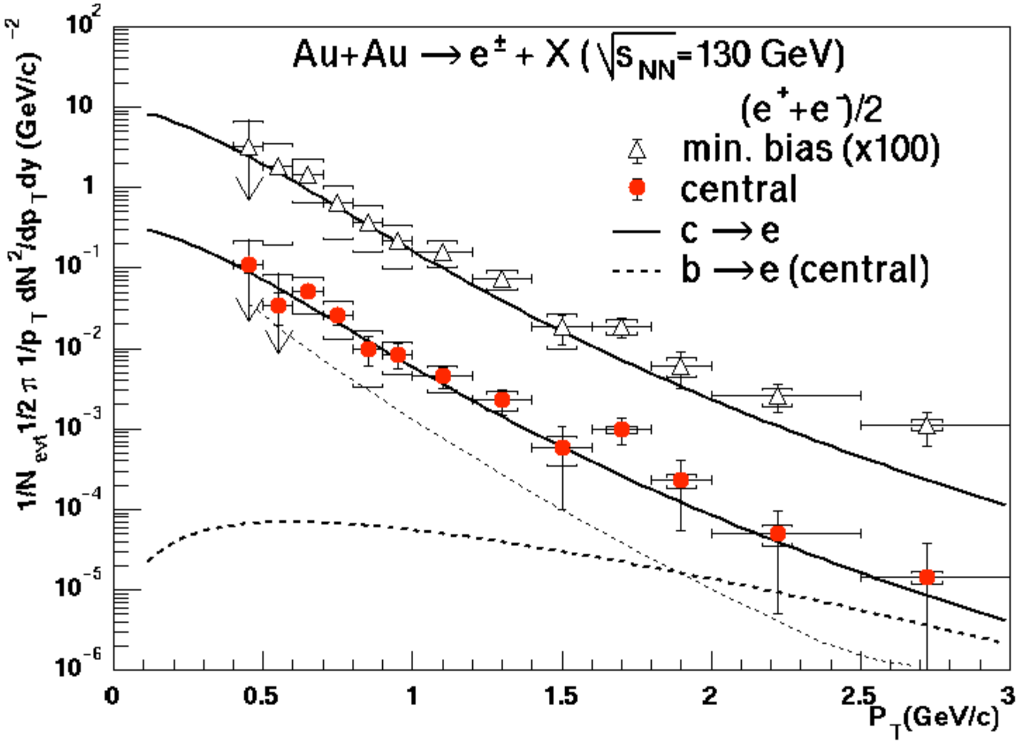




- Inclusive electron spectra are measured at y=0
- The background from π^0 Dalitz, photon conversions, etc are estimated and subtracted.
- Observe excess over background in pt>0.8 GeV/c

PRL 88, 192303

Background-subtracted single electron spectra



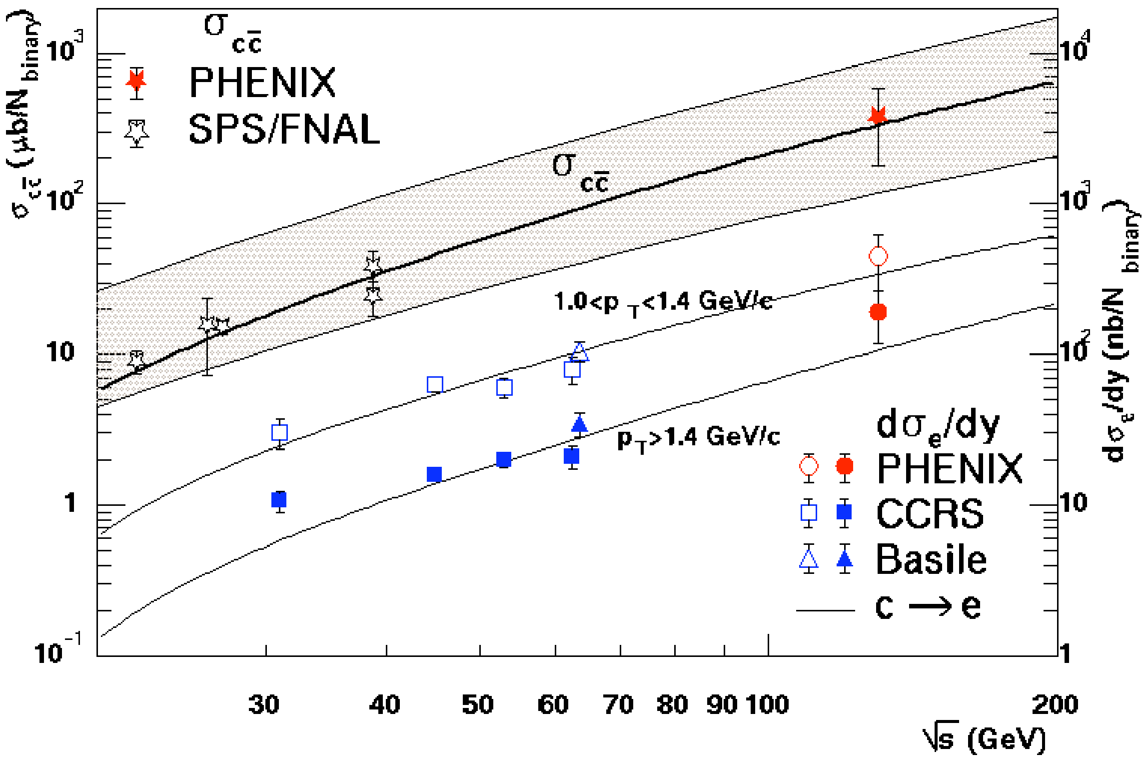
- Background subtracted electron spectra are compared with the charm decay contribution.
- Charm decay contribution is calculated as

  $EdN_e/dp^3 = T_{AA} Ed\sigma/dp^3$
  - T_{AA}: nuclear overlap integral
  - $Ed\sigma/dp^3$: electron spectrum from charm decay calculated using PYTHIA
- From the single electron yield in pt>0.8 GeV/c, charm cross section per binary collision is obtained as

  σ_{cc} = 380±60±200 μb

PRL 88, 192303

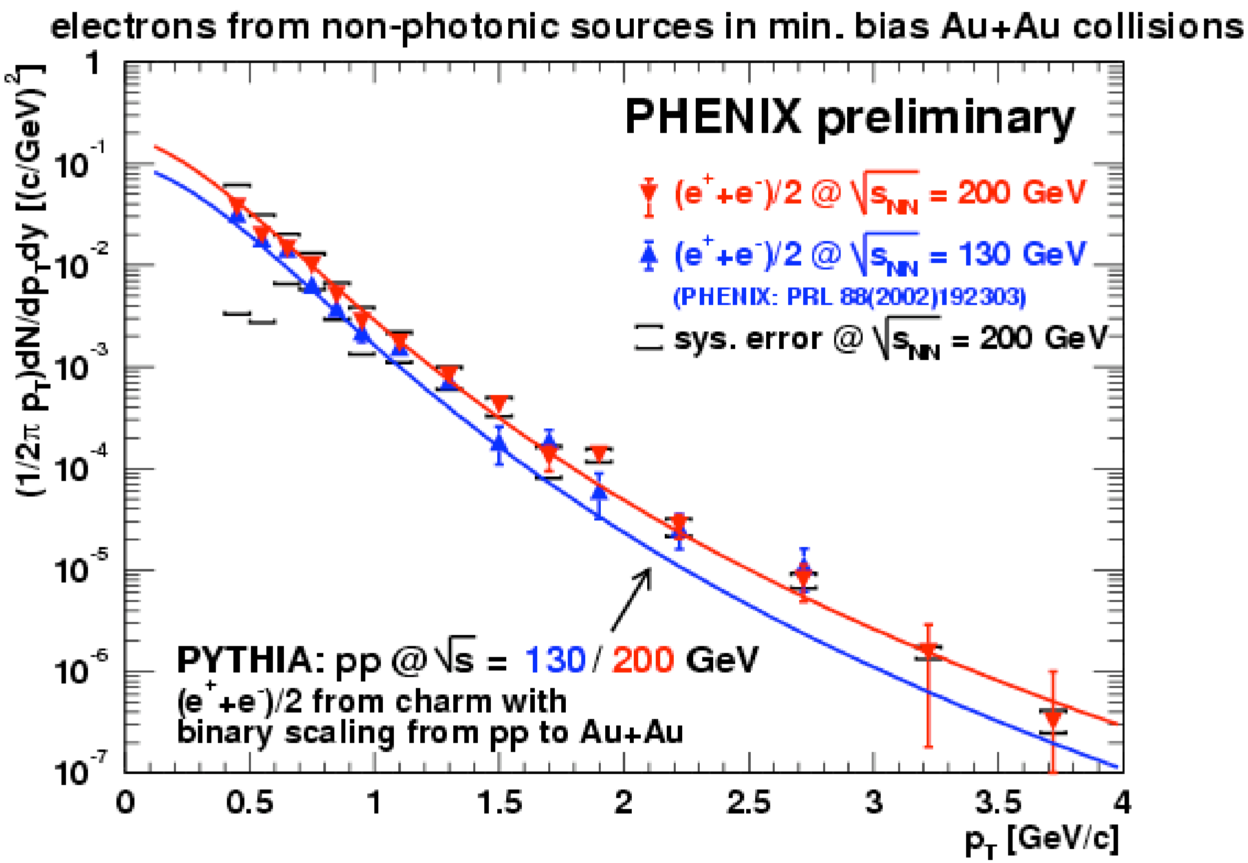
Comparison with other experiments



- PHENIX single electron cross section is compared with the ISR data
- Charm cross section derived from the electron data is compared with fixed target charm data
- Solid curves:
  PYTHIA
- Shaded band:
  NLO pQCD

PRL 88, 192303

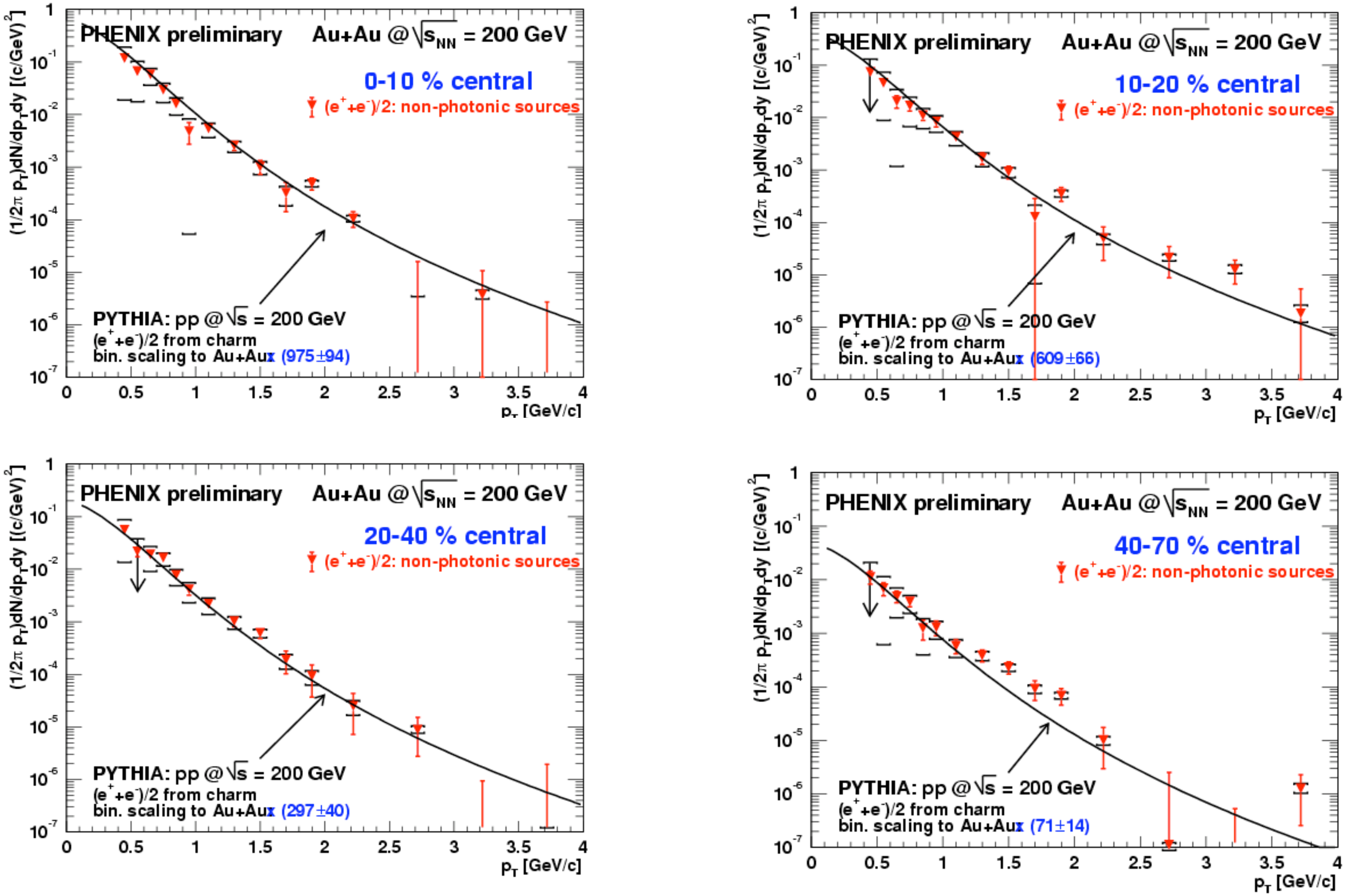
RUN2 single electron result



- The yield of non-photonic electron at 200 GeV is higher than 130 GeV
- The increase is consistent with PYTHIA charm calculation (σ_{cc}(130GeV)=330 μb → σ_{cc}(200GeV)=650 μb)

nucl-ex/0209016

Centrality Dependence

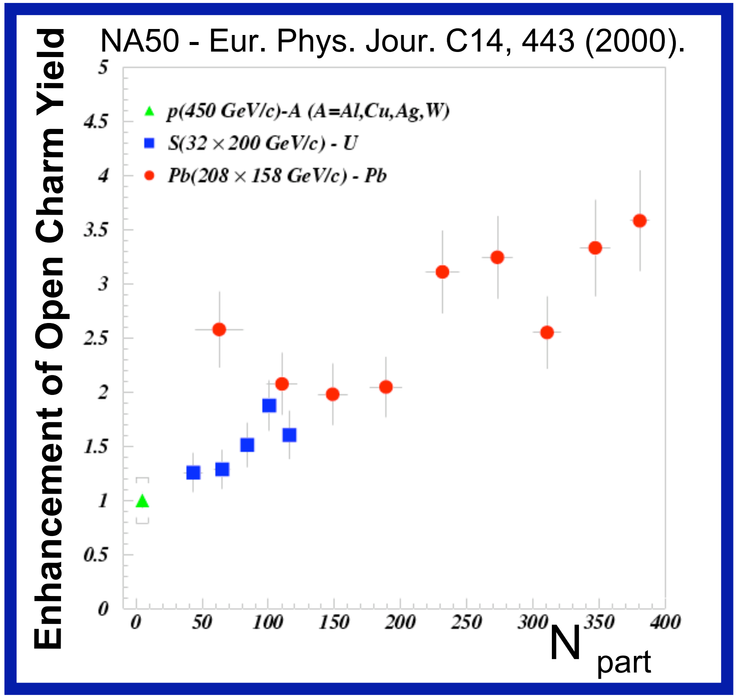


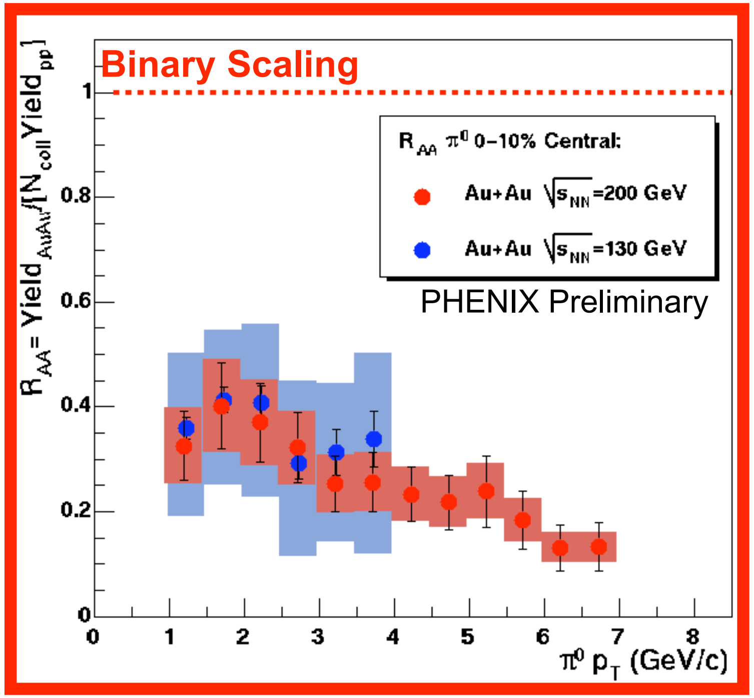
In all 4 centralities, the data are consistent with N_{coll} scaled charm decay contribution calculated by PYTHIA.

nucl-ex/0209016

Observations

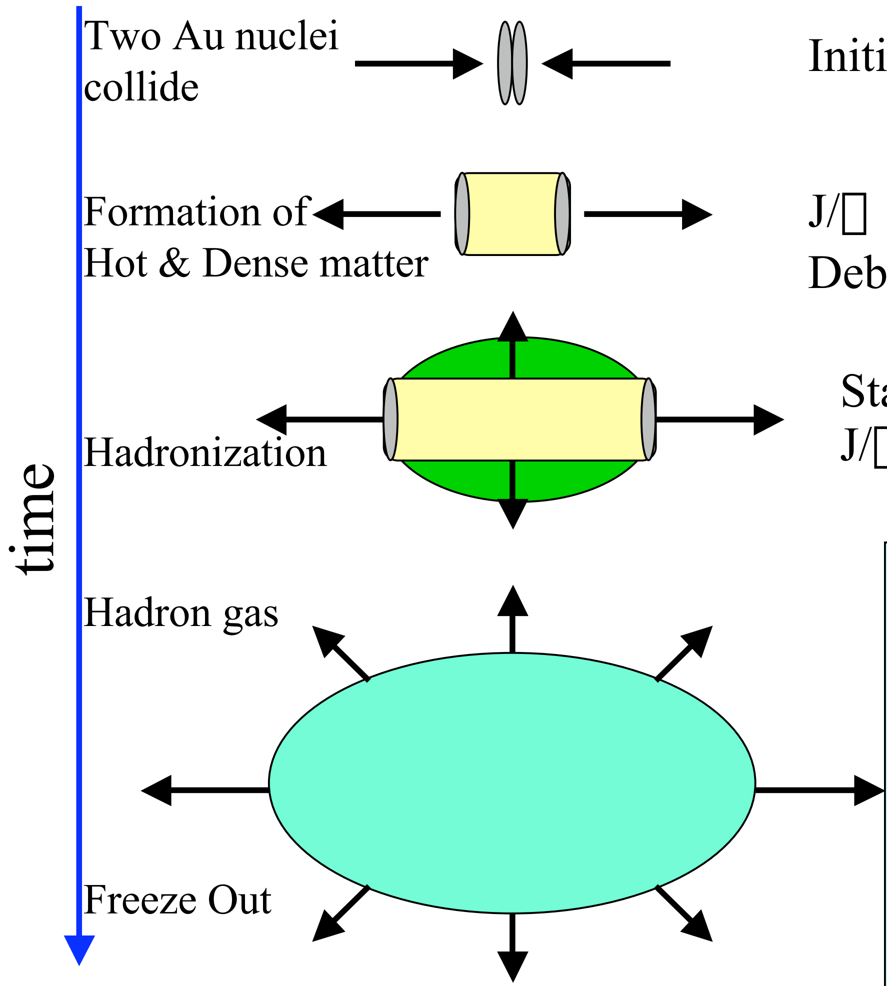
- PHENIX single electron data are consistent with *binary scaling* within current statistical and systematic errors.
    - Both errors will be much reduced in final RUN-2 result
- NA50 has inferred a factor of ~3 charm *enhancement* at lower energy. We do not see this large effect at RHIC.
- PHENIX observes a factor of ~3-5 *suppression* in high p_T π^0 relative to binary scaling. We do not see this large effect in the single electrons.
    - Initial state high pt suppression is excluded?
    - smaller energy loss for heavy quark ? (dead cone effect)





J/ψ Suppression

J/ψ measurement



Initial ccbar production

J/ψ can not form due to Debye Screening in QGP ⇨ J/ψ suppression

Statistical formation of J/ψ from ccbar pair ⇨ J/ψ enhancement at RHIC?!

J/ψ suppression, predicted by Matsui and Satz and observed by NA50 at SPS, is considered as one of the strongest evidence of QGP formation.

If J/ψ suppression is due to QGP formation, much stronger suppression is expected at RHIC.

New theory of J/ψ formation predicts J/ψ enhancement at RHIC energy by statistical formation of J/ψ at hadronizatoin

Do we observe J/ψ *suppression* or *enhancement* at RHIC?

ベクトル中間子（Vector Meson）

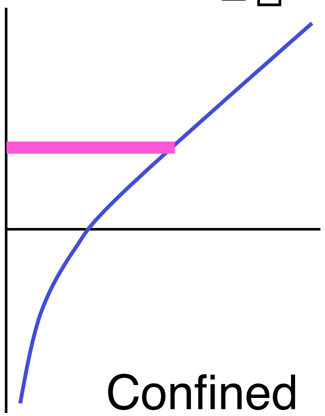
- スピン = 1、パリティ = -1 : 光子と同じ量子数
- クォーク・反クォーク -- ポジトロニウムと似た系
- 重いクォーク　→　古典的

$$V_C = -\frac{q}{4\pi r}$$

$$V_{linear} = \kappa r$$

$$H = \frac{p^2}{2m} - \frac{\alpha_{eff}}{r} + \kappa r$$

$$\alpha_{eff} = \frac{q^2}{4\pi} = \frac{4}{3}\alpha_s \qquad q^2 = \frac{4}{3}g^2$$



Charmoniumのパラメーターセット

α_{eff} = 0.52, κ = 0.926 GeV/fm, m_c = 1.84 GeV

α_{eff} = 0.30, κ = 1.18 GeV/fm, m_c = 1.65 GeV

重い vector mesons

	J/ψ	ψ’	Υ
composition	$c\bar{c}$	$c\bar{c}$	$b\bar{b}$
Mass (GeV)	3.10	3.69	9.46
Γ (keV)	87	277	53
Γ_{ee} (keV)	5.26	2.14	1.32
r (fm)	0.29	0.56	0.13

QGP中での Charmonium

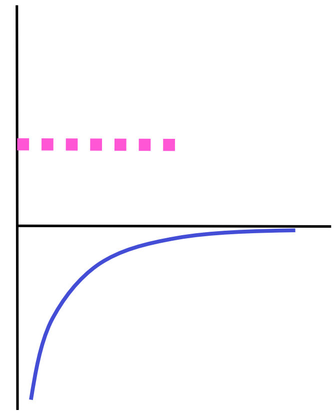
閉じ込めポテンシャルが消滅

Debye screening → 湯川型の ポテンシャル

$$V(r) = \frac{q}{4\pi r} e^{-r/\lambda_D}$$

λ_D : Debye screening length

$m = \lambda_D^{-1}$: Debye screening mass



$$H = \frac{p^2}{2\mu} - \frac{\alpha_{eff}}{r} e^{-r/\lambda_D}$$

$$\langle p^2 \rangle = 1/r^2$$

$$E(r) = \frac{1}{2\mu r^2} - \frac{\alpha_{eff}}{r} e^{-r/\lambda_D}$$

$$\frac{dE(r)}{dr} = 0 \rightarrow \frac{r}{\lambda_D}\left(1 + \frac{r}{\lambda_D}\right) e^{-r/\lambda_D} = \frac{1}{\alpha_{eff}\mu\lambda_D}$$

$$f(x) = x(1+x)e^{-x} : f(x)|_{max} = 0.840 \text{ at } x = 1.62$$

$1/(\alpha_{eff}\ \mu\ \lambda_D) > 0.84$ では束縛状態が存在しない

$r_{Bohr} = 1 / \alpha_{eff}\ \mu$ ($\lambda_D = \infty$: クーロンポテンシャルでのBohr半径)

$1.19\ r_{Bohr} > \lambda_D$

$$\lambda_D(PQCD) = \frac{1}{T}\frac{1}{\sqrt{\left(\frac{N_C}{3}+\frac{N_f}{6}\right)g^2}} = \sqrt{\frac{2}{3}}\frac{1}{gT} \quad (N_c = 3,\ N_f = 3)$$

$$= 0.36\ \mathrm{fm\ at\ T = 200\ MeV : g^2} = 4\pi\alpha_{eff}, \alpha_{eff} = 0.52$$

$$\lambda_D(\mathrm{Lattice\text{-}QCD}) \sim 0.5\lambda_D(PQCD), \quad r_{Bohr} = \frac{1}{\alpha_{eff}\mu} \sim 0.4\ \mathrm{fm} : \mu = 1840/2\ \mathrm{MeV}$$

$$\boxed{T_X = \frac{\mu}{0.840}\sqrt{\frac{2\alpha_{eff}}{9\pi}} = 0.291\sqrt{\alpha_{eff}}\ (\mathrm{GeV})}$$

charm: α_{eff} = 0.30 → Tx = 143 MeV

α_{eff} = 0.52 → Tx = 209 MeV

bottom: Tx = (4.73/1.84) x 143 = 368 MeV

- J/ψは100～200MeV程度で溶解する
- ψ' はJ/ψよりも低い温度で溶解する（半径が大）
- Y の溶解温度は非常に高い
- ρ, ω, φ（質量が小さい）はQGPでは存在し得ない

J/ψの最初の測定

CERN-SPS NA38 (NA50)

muon 対の測定

200 AGeV O, S + A

J/ψ vs E_T

E_T ：横放出エネルギー

＝中心衝突の度合い

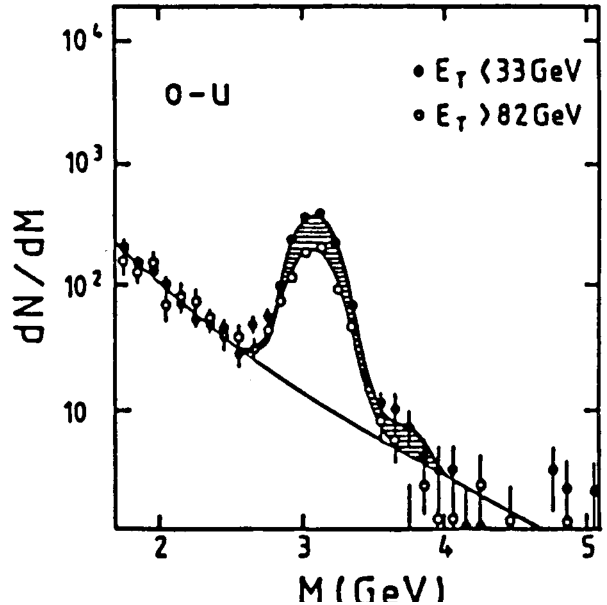
強い J/ψ ψ’ suppressionが

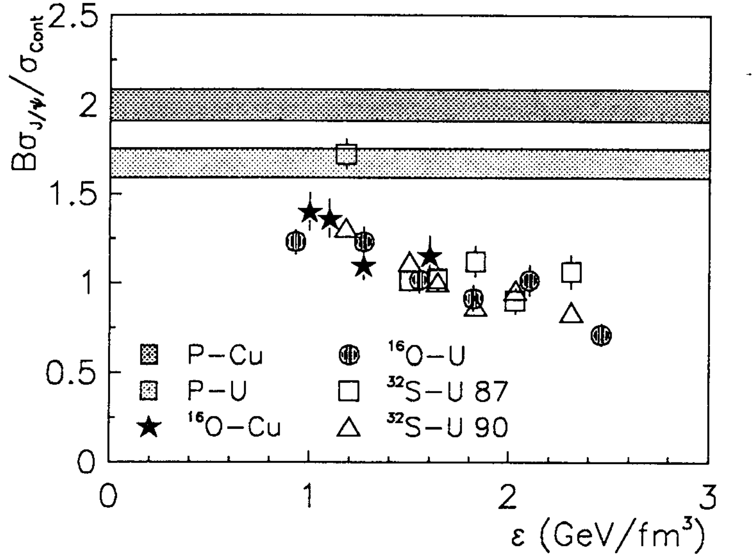
大きな E_T で観測された

J/ψ と連続スペクトルの収量比は

エネルギー密度 εの増加とともに減少

$\varepsilon = E / V \sim (dE_T/dy)/(\pi r_0^2 A^{2/3} \tau_0)$



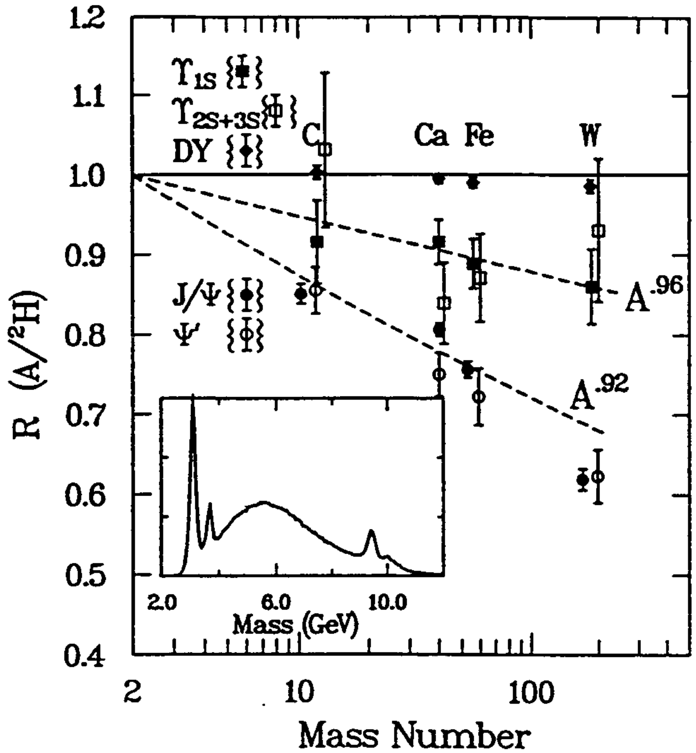


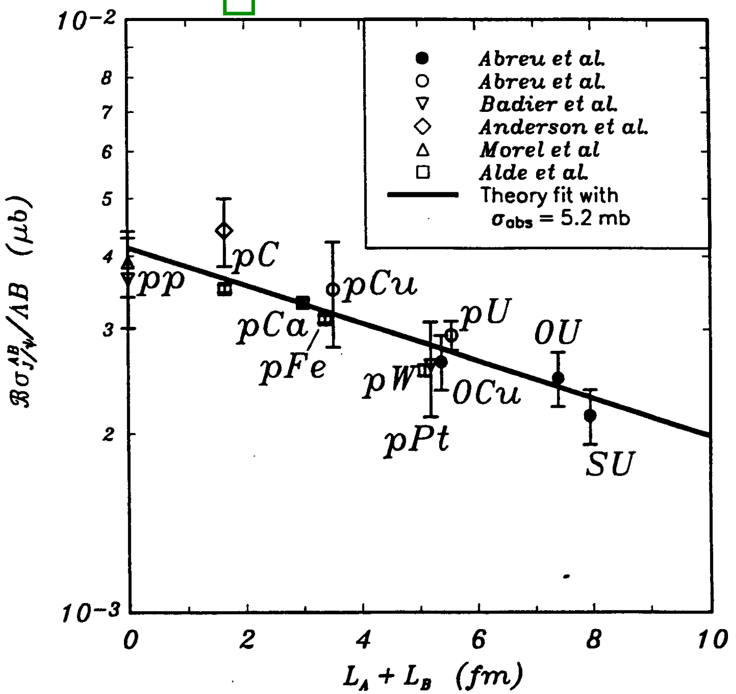
p + A、A + A衝突での質量依存性

Fermi-Lab E772 実験

ターゲット質量数 (A) 依存性： A^{α}

- Drell-Yan (DY) α = 1
- J/ψ, ψ’ α = 0.92
- Υ α = 0.96





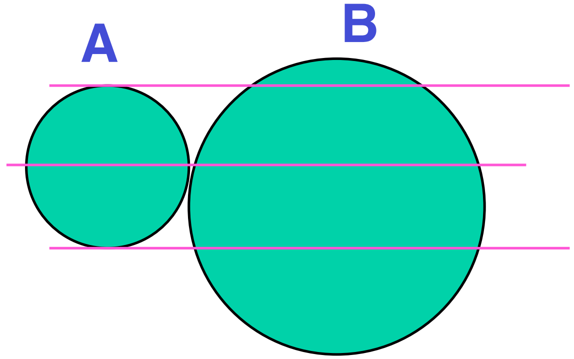
p+A, A + A で同一のスケーリング

- p + A 衝突で QGP が生成されている？
  ありそうも無い
- ハドロンとの衝突・反応が原因？

J/ψ suppression の“ハドロン”描像

- ハドロンとの衝突によって、これる

  J/ψ + h → D + $\bar{D}$ + X



- 幾何学的な計算

  $B\sigma_{J/\psi}^{AB}/AB = 4.1 \exp[-\rho_0 \sigma_{abs} (L_A + L_B)]$ mb

  $\rho_0 = 0.14$ fm^{-3}

  $\sigma_{abs} = 5.2$ mb

  $L_A + L_B$: 良い scaling パラメーター

  - 実効的なパス長（幾何平均）

J/ψ suppression は核子のみによる?

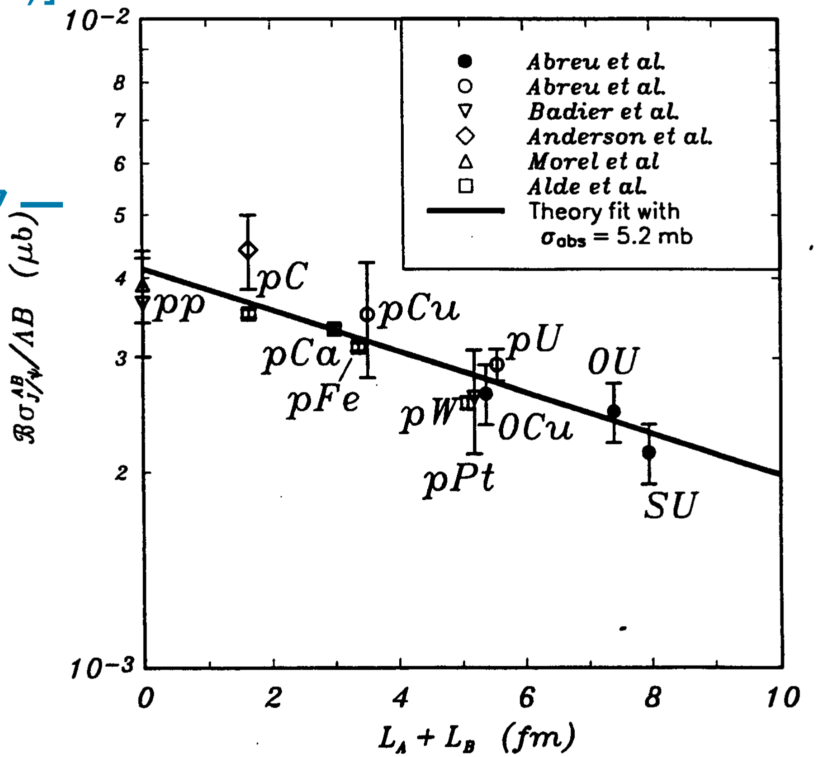
$\sigma_{tot}^{J/\psi\text{-}N} = 2.2\ (0.7)$ mb

(J.J. Aubert et al., Nucl. Phys. B213 (1983) 1)

$\sigma_{quasi\text{-}elastic}^{J/\psi\text{-}N} = 0.79\ (0.12)$ mb

(R.L. Anderson, SLAC-Pub 1741 (1976))

$\sigma_{abs}^{J/\psi\text{-}N} = 1.4$ mb

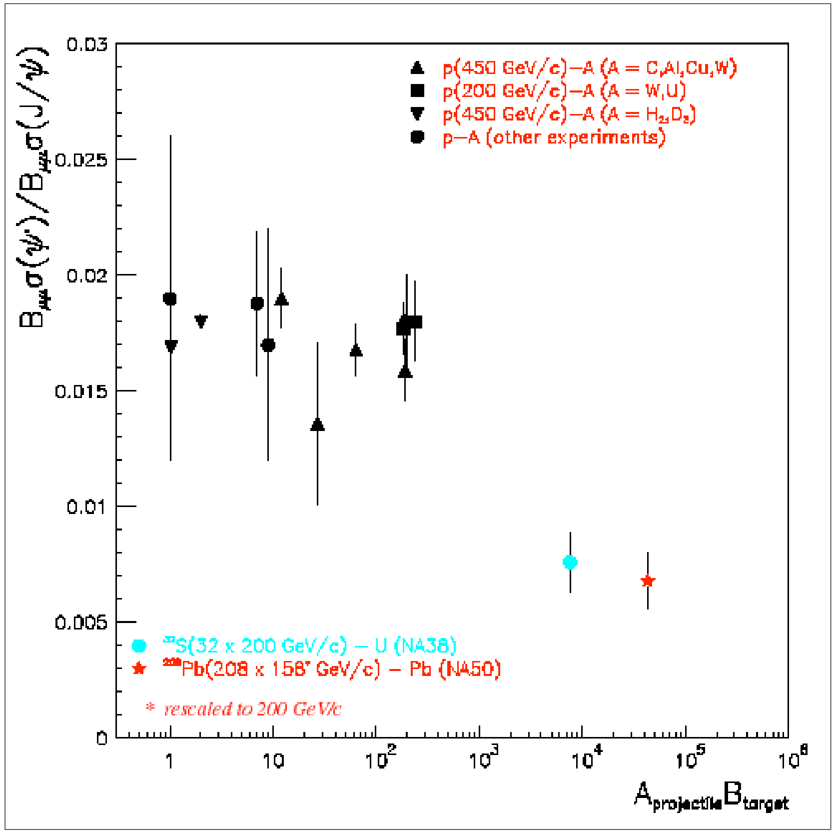


□ ’ 収量の変な振る舞い

□ ’ - J/□ ratio

□ ’ と J/□ の振る舞い

- p + A ではよく似ている
- S + A, Pb + Pb では、 J/□ に比べて□ ’ 収量は大きく suppress される

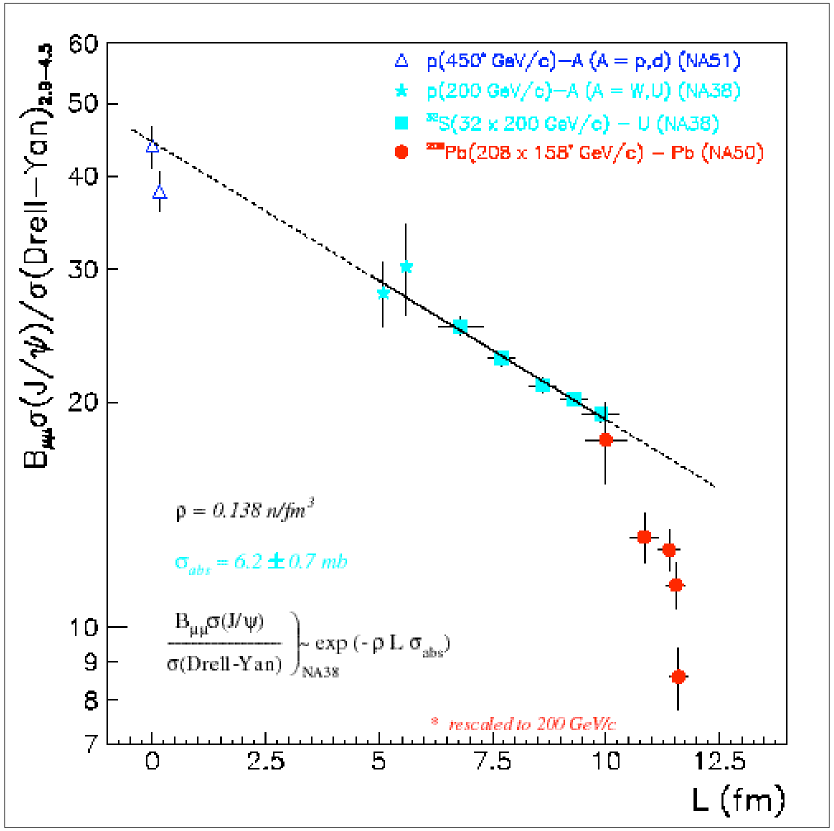


Pb + Pb 衝突での J/ψ Suppression

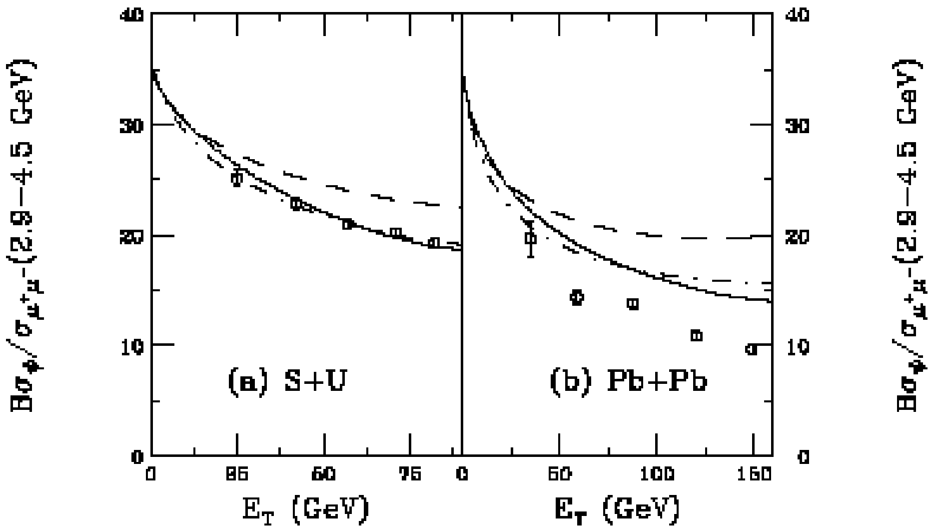
強い suppression

- p+A、S+Aで見られた幾何学的な系統性から大きくずれる

J/ψ - Drell-Yan ratio



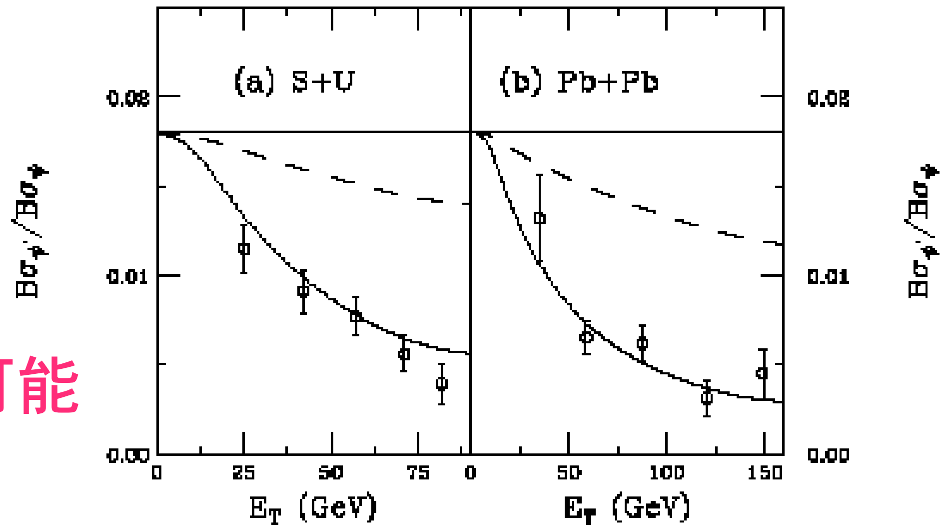
Co-mover モデルに基づく計算：S+U Pb+Pb



□□co = 3.2 mb
if corss section scales with (radius)^2
□□'co = 3.8 □□co
□□co = 2.4 □□co

Solid line: □□co = 3.2 mb,
□□'co = 25 mb,
n_{co} =0.8/fm^3
dashed line: □□'co = 3.8 □□co
n_{co} =0.5/fm^3
a parameter set with feeding to J/□ from □ and □' included

Solid line: □□□ = 4.8 mb,
□□co = 3.2 mb,
n_{co} =0.8/fm^3
dashed line: □□□ = 4.8 mb
dot-dashed line: □□□ = 7.3 mb



同じパラメーターセットで
同時にフィットすることは不可能

二つのパズルを解く

- □’ の S+U での振る舞い
- J/□ の Pb + Pb での振る舞い

ひとつの解釈

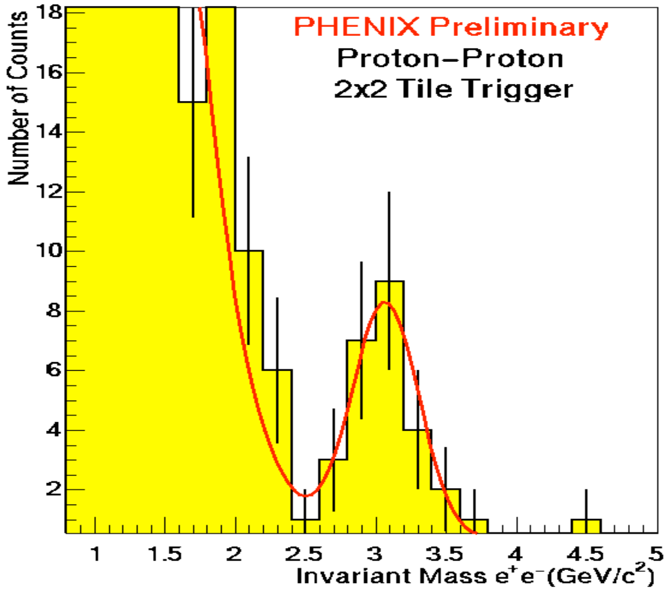
- □’ は比較的低い温度で溶解する
  - S+Uで既に溶解
- J/□ はPb + Pbで溶解：
  → Pb+Pbで温度が上がる

RHICでは

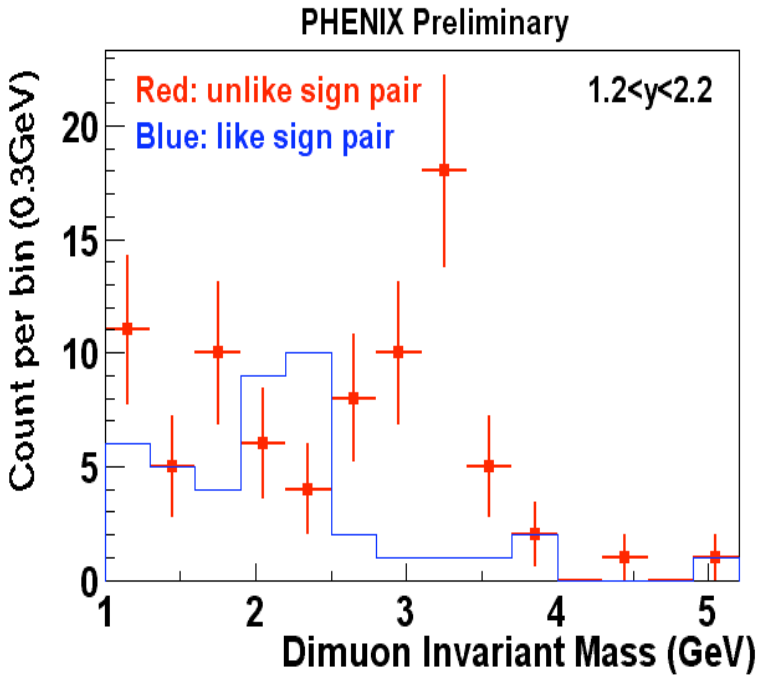
- より高い温度状態が期待される
- SPSではできなかった □ の測定が可能
  → よりはっきりした結論

pp→J/ψ at 200 GeV

pp → e^+e^- X (|y|<0.35)



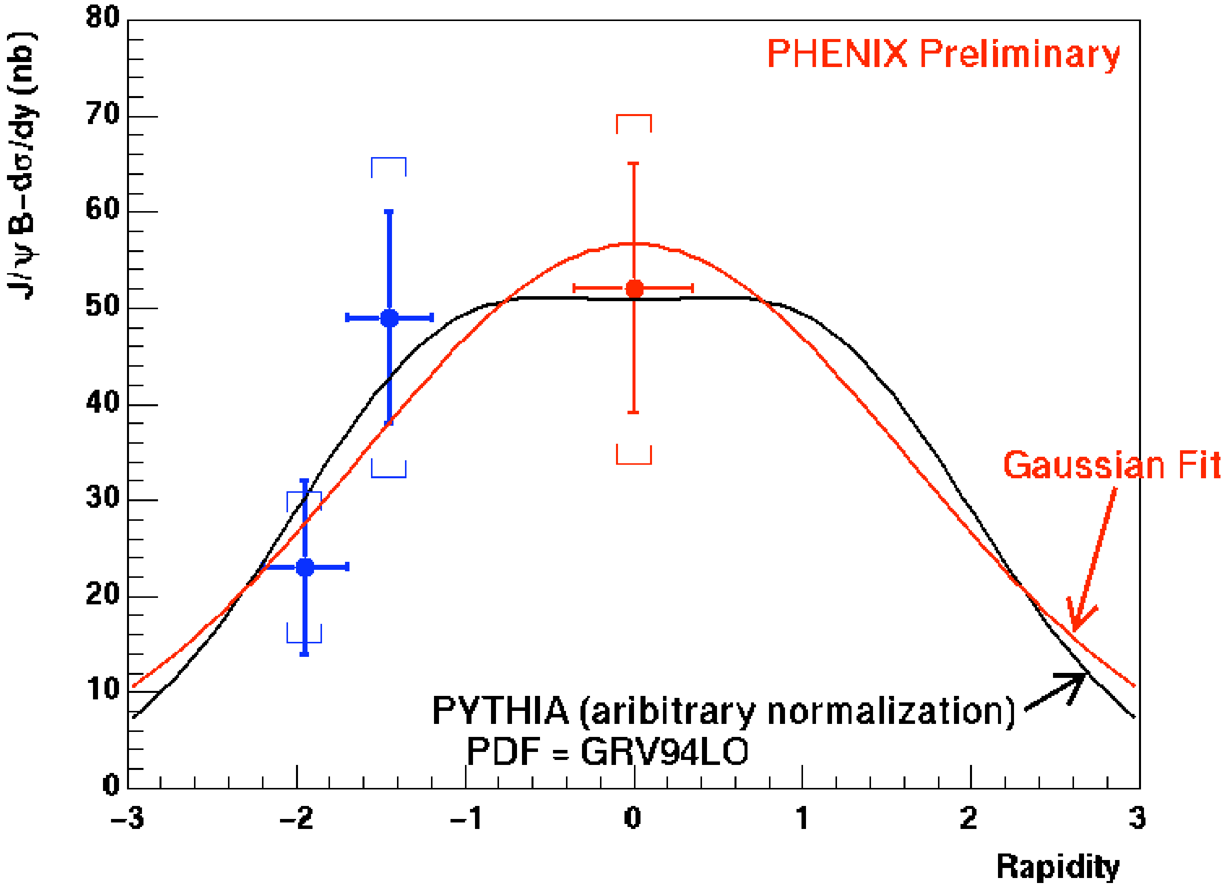
pp → $\mu^+\mu^-$ X (1.2<y<2.2)



- pp→J/ψ is measured both in ee and in μμ

nucl-ex/0210013

J/ψ Bdσ/dy in p+p(200GeV)



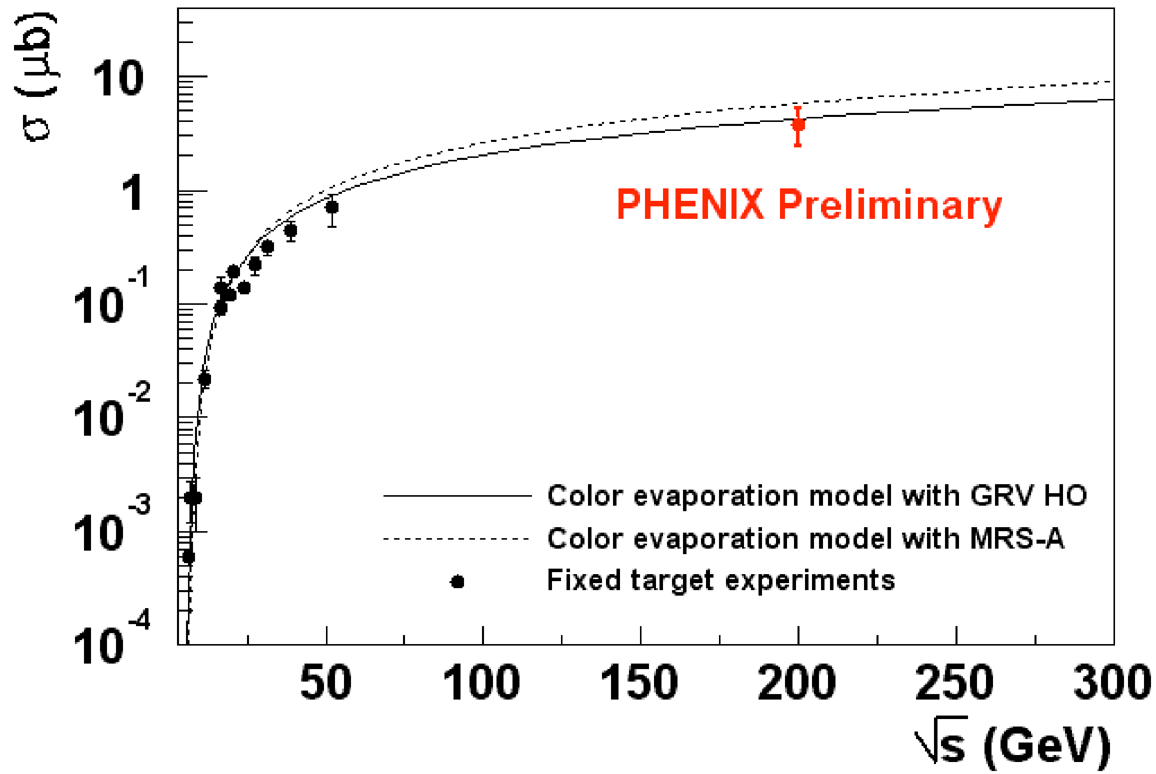
$$B\cdot\sigma(pp\to J/\psi+X)=226\pm36(stat)\pm79(sys)\ \text{nb}$$
$$\sigma(pp\to J/\psi+X)=3.8\pm0.6(stat)\pm1.3(sys)\ \mu\text{b}$$

nucl-ex/0210013

Comparison with lower energy

PHENIX preliminary

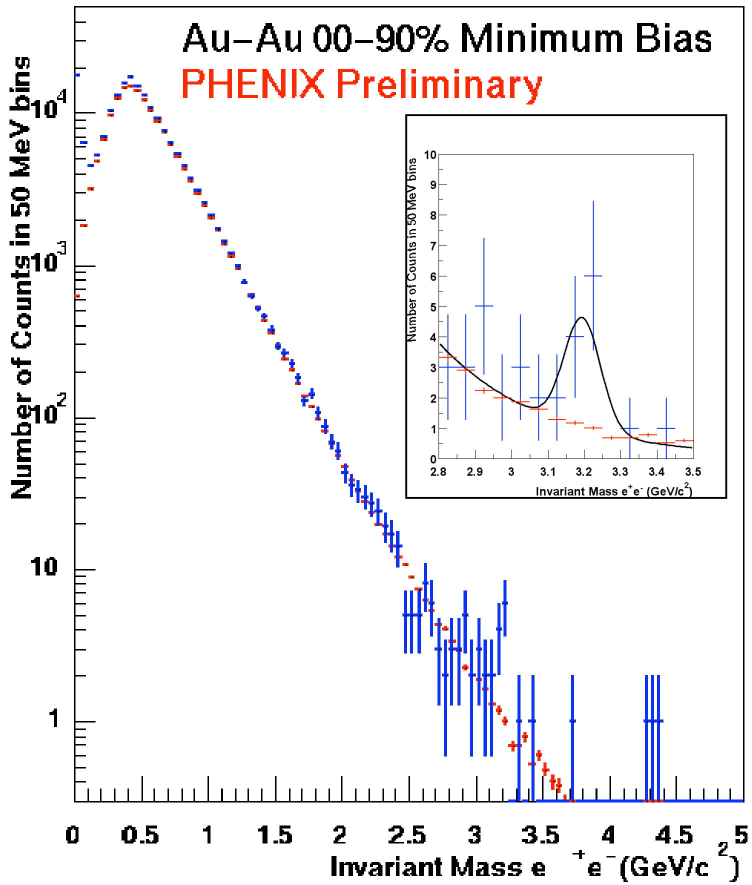
$$\sigma(pp \rightarrow J/\psi + X) = 3.8 \pm 0.6(stat) \pm 1.3(sys)\ \mu\text{b}$$



Color evapolation model prediction is consistent with PHENIX data at $s^{1/2}$=200 GeV

J/ψ → e^+e^- in Gold-Gold

- **From 26 M min. bias Au+Au collision @ 200 GeV (1/2 – 1/3 of all data)**
- **$N_{J/\psi}$ in 3 centrality bins.**
  - **0-20%:**
    5.9 ± 2.4(stat) ± 0.7(sys)
  - **20-40%:**
    4.5 ± 2.1(stat) ± 0.5(sys)
  - **40-90%:**
    3.5 ± 1.9 (stat)± 0.5(sys)



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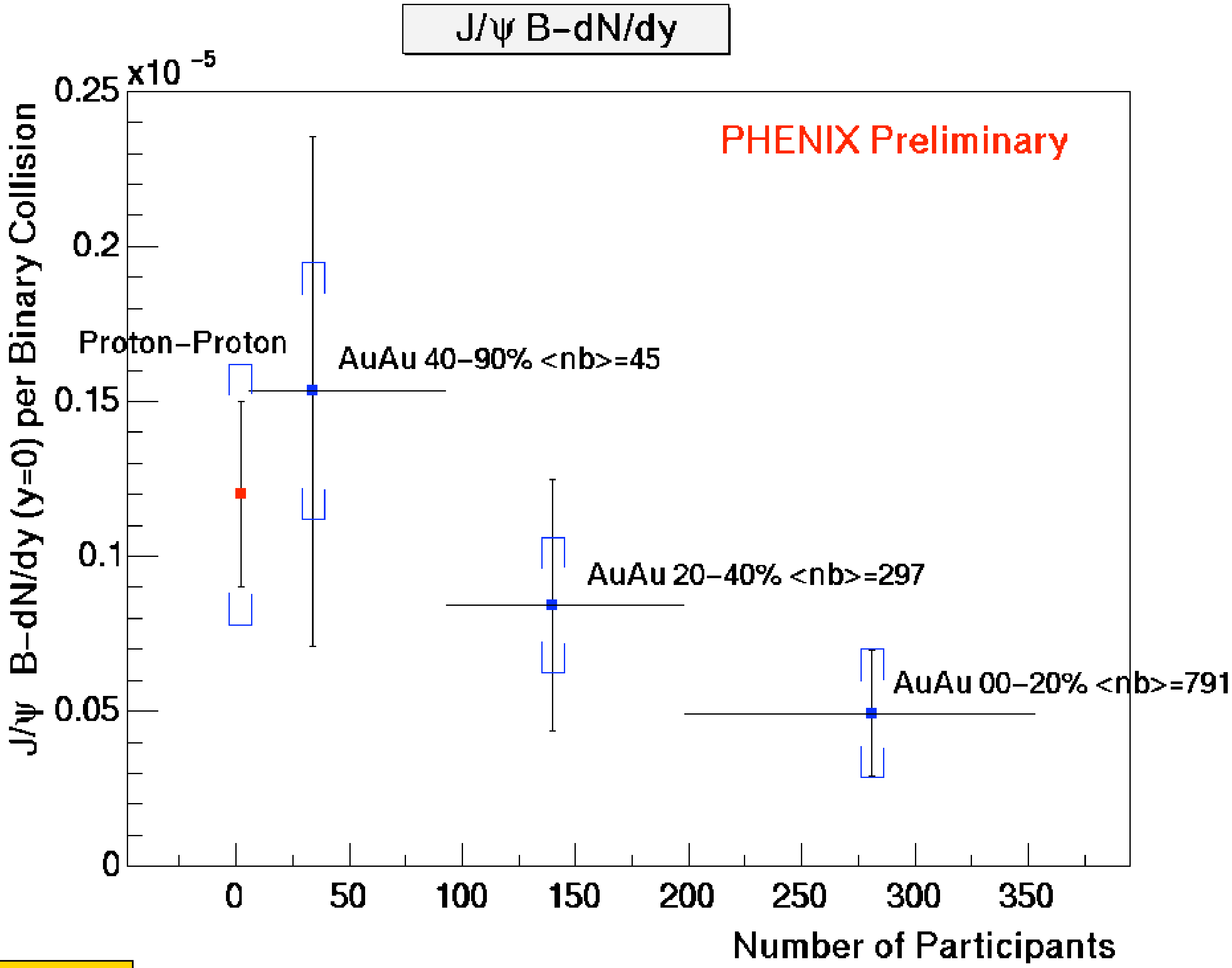
J/ψ B-dN/dy per binary collision



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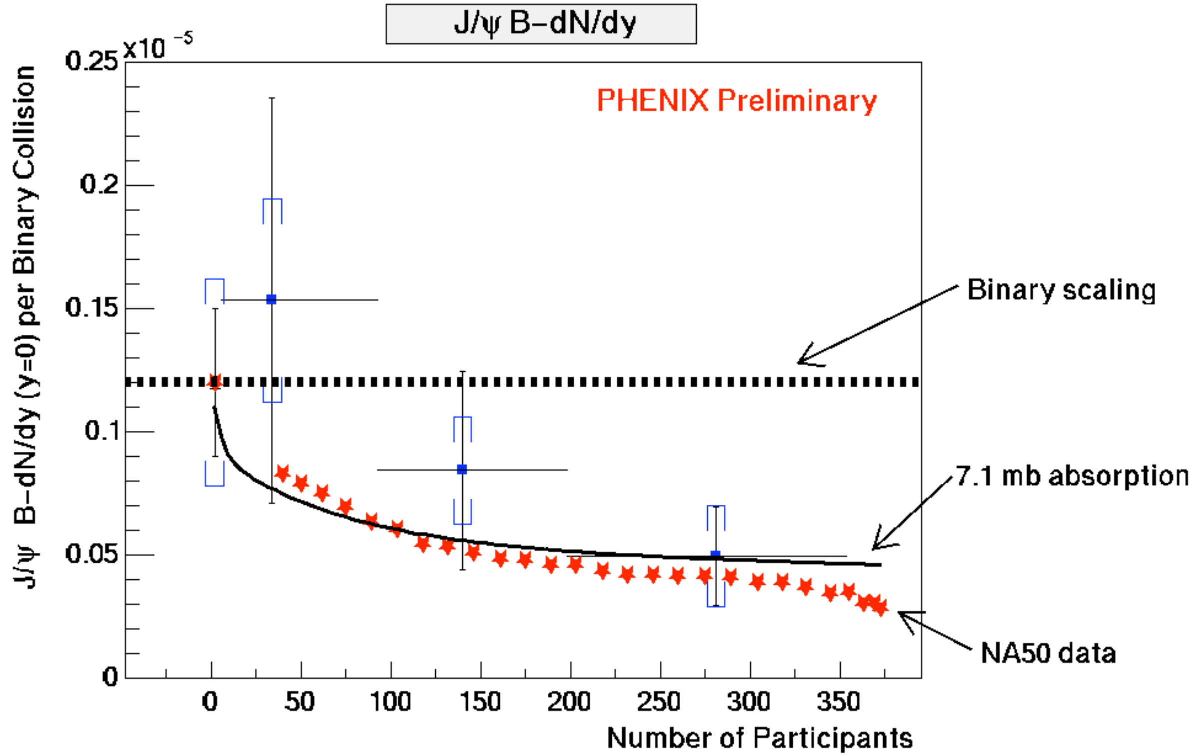
Model Comparisons (1)



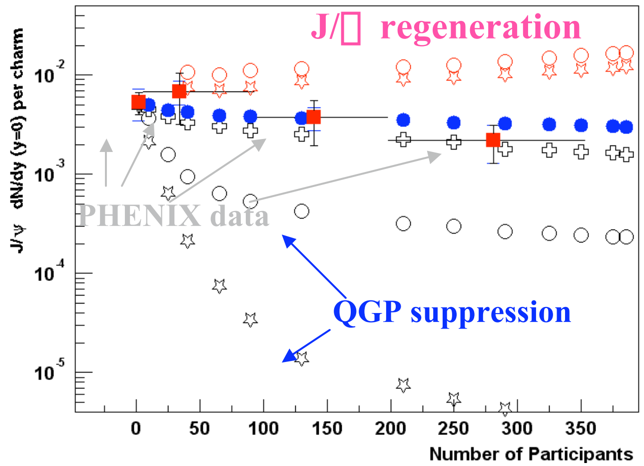
(1) J/ψ scale with the number of binary collisions
(2) J/ψ follow normal nuclear absorption with $\sigma_{J\text{-}N}$=7.1 mb
(3) J/ψ follow same pattern as NA50 (J/ψ / DY(mb))[1]

Due to low statistics, our data are compatible all of these models.

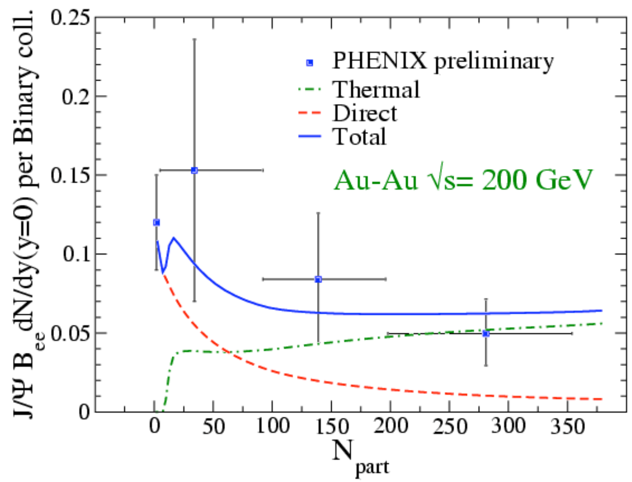
nucl-ex/0209015

Model comparion(2)
J/ψ re-generation models

Theory curve from R. L Thews, PRC63,054905



L. Grandchamp and R. Rapp, hep-ph/0209141



- At RHIC, about 10 ccbar pairs produced in central event.
- They can recombine to form J/ψ. Those models that assume formation of J/ψ inside of QGP predict enhanced production of J/ψ in Au+Au.

  PHENIX data does not favor a large enhancement.
- In QGP suppression model, very strong J/ψ suppression at RHIC is expected.

  PHENIX data does not favor a very strong suppression.
- Models of statistical generation of J/ψ at hadronization stage predict that J/ψ yield in central Au+Au is about half of that of pp.

  A much larger statistics is required to test those models. (→RUN4)

カイラル対称性

- カイラル対称性とは
- 実験研究

QCD真空の性質

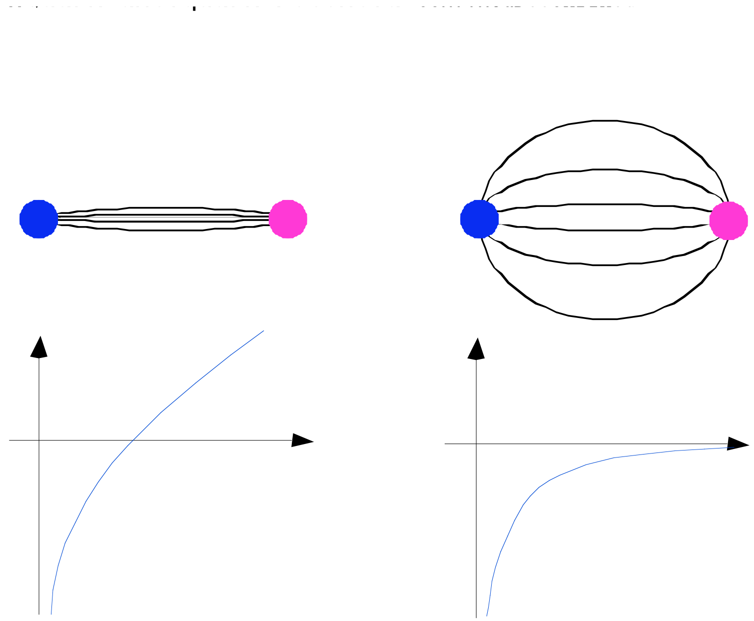
QCD真空は完全反誘電性

$$\varepsilon(k) \sim 1 - \frac{C}{\ln\left(k^2/\Lambda^2\right)} \qquad (k^2 \to \infty)$$

$$\sim \frac{k^2}{m_L^2} \qquad (k^2 \to 0)$$

D = εE

外場Eをかけても内部場D=0



真空凝縮

$$\langle \bar{q}q \rangle_0 = -\frac{f_\pi^2 m_\pi^2}{2m_q} = (-225 \pm 25\ \mathrm{MeV})^3$$

$$\left\langle \frac{\alpha_s}{\pi} G^a_{\mu\nu} G_a^{\mu\nu} \right\rangle_0 = (350 \pm 30\ \mathrm{MeV})^4$$

真空凝縮

QCD真空は、あたかも物性（多体系）の特別な状態

- 強磁性体：ハミルトニアン $H = -g\sum s_i \cdot s_j$ は回転対称性を持つが、基底状態では対称性が破れている。臨界温度T_Cで復活。
- 超伝導体：Cooper pair の凝縮 $\langle \psi_\uparrow \psi_\downarrow \rangle \neq 0$で、Lagrangian L の対称性が破れる。高温、高磁場で復活。

L_{BCS}は、$\psi \to e^{i\theta}\psi$ に対して不変

pair のオペレーター $\psi_\uparrow \psi_\downarrow$: $\psi_\uparrow \psi_\downarrow \to \psi_\uparrow e^{2i\theta} \psi_\downarrow$

L の持つ対称性を持たない operator = order parameter

order parameter の真空期待値：真空の対称性の判定基準

- QCD真空：$\bar{q}q$ の pairing による凝縮、高温、高密度で回復。
  カイラル対称性が破れている。

L_{QCD}は、$\psi \to e^{i\gamma_5\theta}\psi$ に対して不変

pair のオペレーター $\bar{\psi}\psi$: $\bar{\psi}\psi \to \bar{\psi} e^{2i\gamma_5\theta} \psi$

order parameter

カイラル対称性の Order Parameter

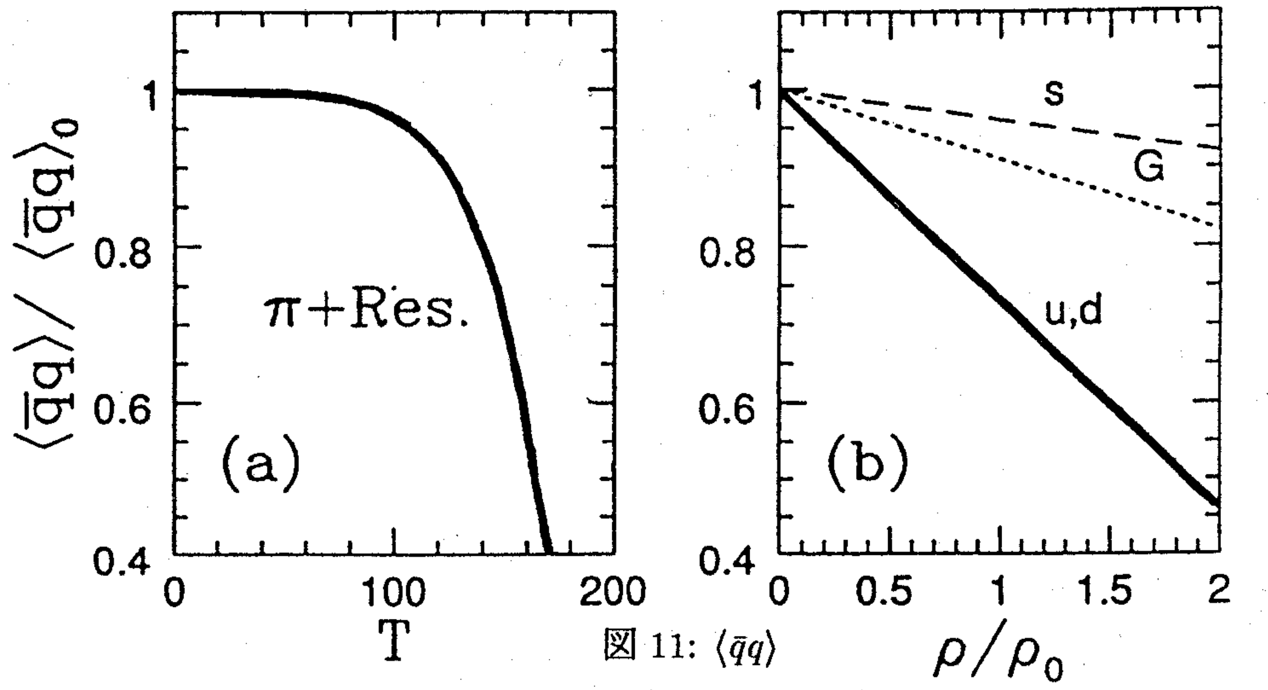


図 11: $\langle \bar{q}q \rangle$

ハドロンの質量

QCD真空の対称性の破れにより動的に形成

高温、高密度

→真空状態が変化

→ハドロンの性質に影響

「カイラル対称性の回復」研究の方法

ハドロンの媒質効果

- 高温、高バリオン密度状態の物質中に置かれたハドロンの性質の変化を調べる

注目：low-mass ベクターメソン □^{0} □ □

- 質量がカイラル対称性のオーダーパラメータに比例 $m \quad \langle \bar{q}q \rangle$

- レプトン対崩壊
  - 分岐比は小さい
  - メディアの影響小

「カイラル対称性回復」の実験的研究

原子核中での媒質効果

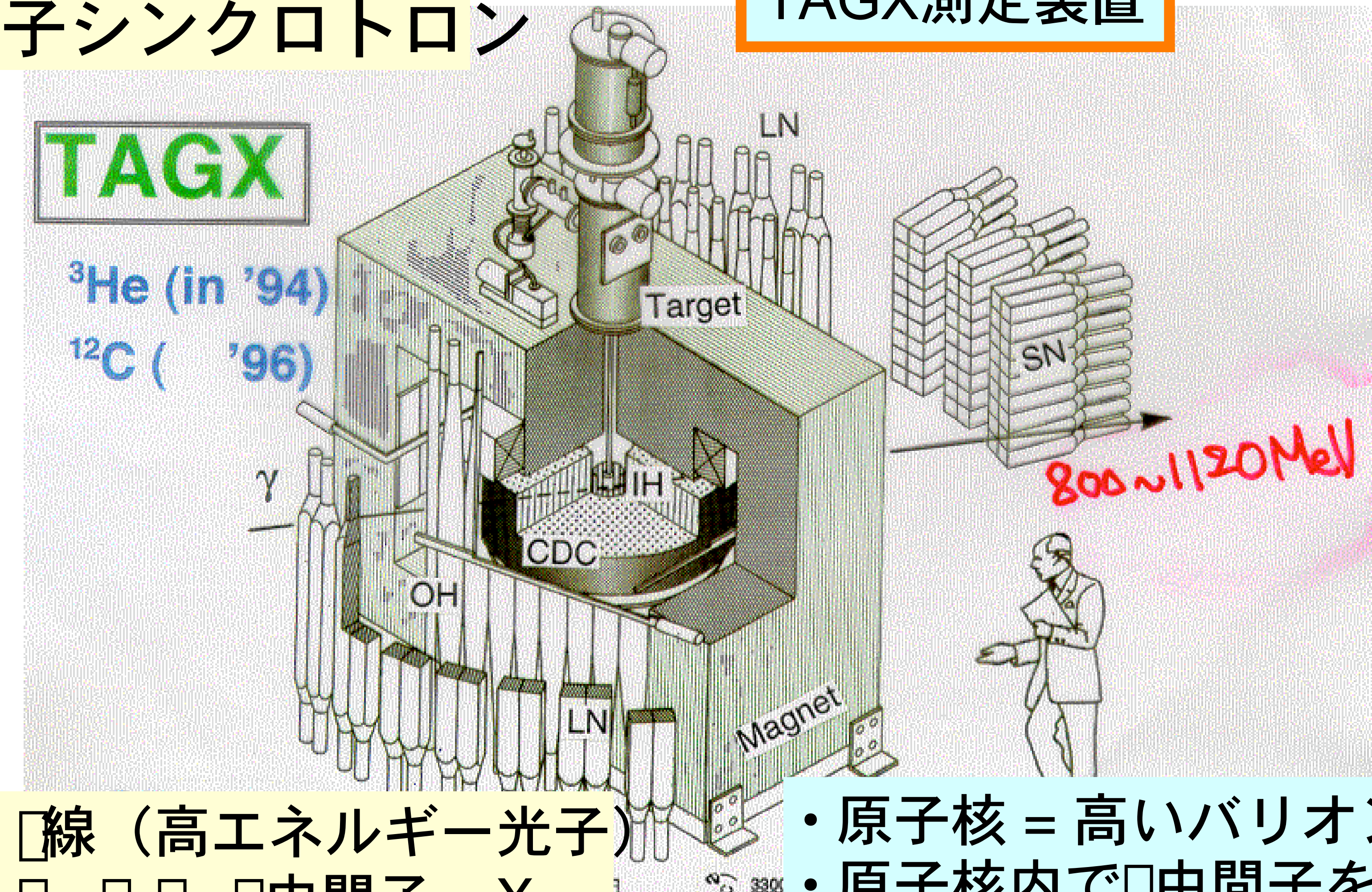
- KEK－PS：□→ e^+e^-、K^+K^-
- （旧）INS－ES： □→ □$^+$ □$^-$
- Spring-8： □ □→ e^+e^-
- GSI： □→ e^+e^-

高温状態での媒質効果

- CERN-SPS CERES実験：□ □ → e^+e^-
- RHIC PHENIX
  - □→ e^+e^-、K^+K^-
  - □ □→ e^+e^-

KEK-田無分室
電子シンクロトロン

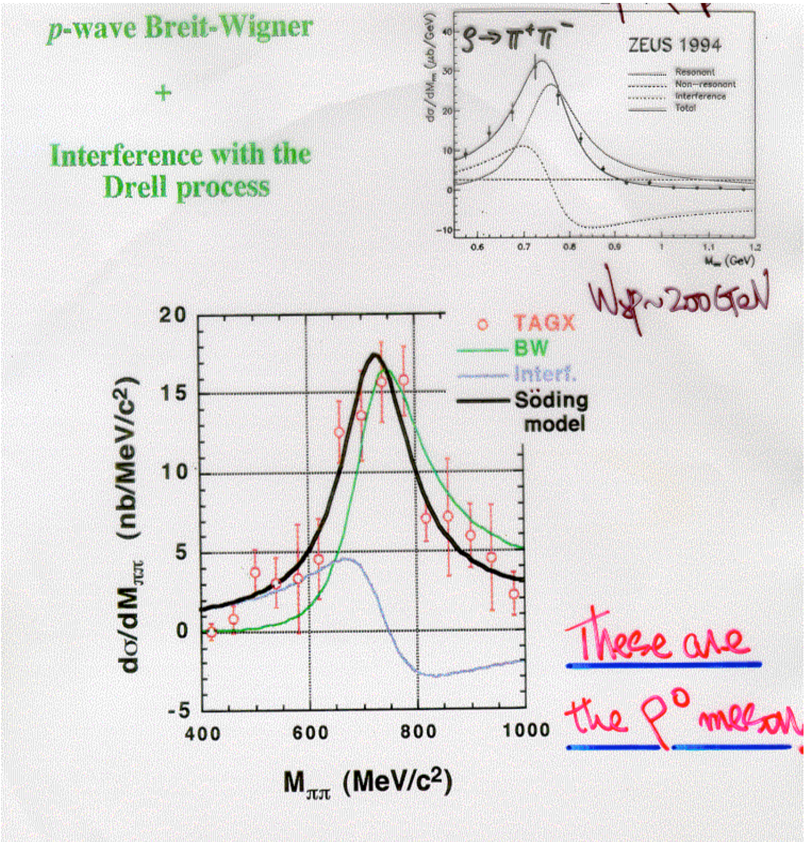
TAGX測定装置



□線（高エネルギー光子）
□+ □ □> □中間子 + X
□中間子 □> □$^{+}$ + □$^{□}$

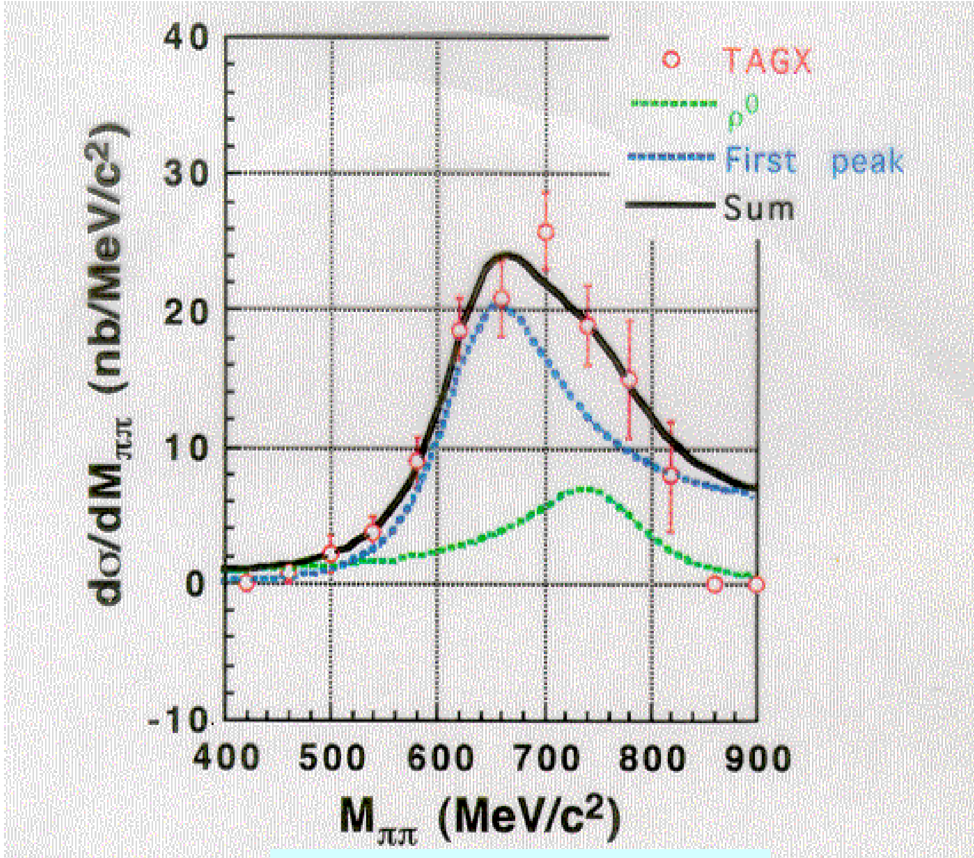
- 原子核 = 高いバリオン密度
- 原子核内で□中間子を生成

原子核の外で生成された場合



$\pi^+ + \pi^-$の不変質量

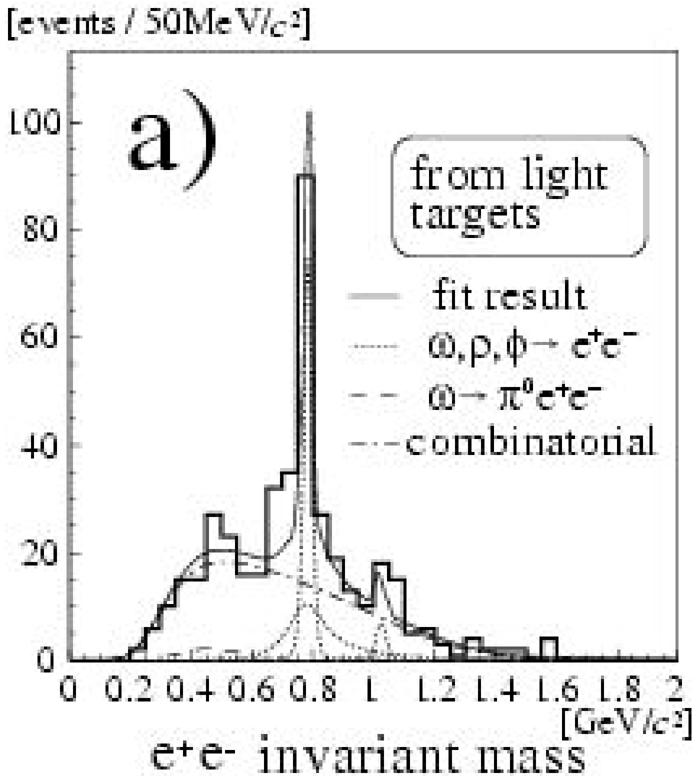
原子核の内部で生成された場合

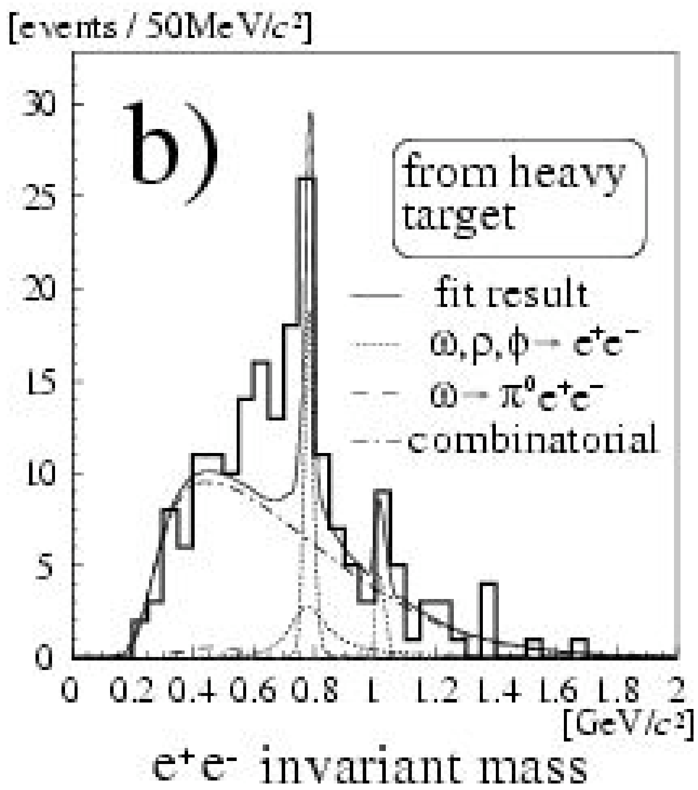


$\pi^+ + \pi^-$の不変質量

KEK-PSでの実験

- p+A 反応における生成電子対の測定
- 軽いターゲットと重いターゲットで、不変質量分布に顕著な差



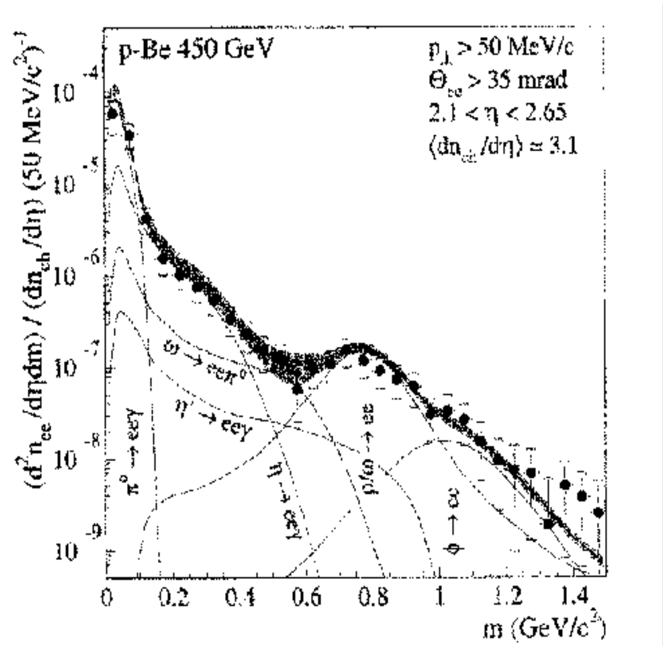


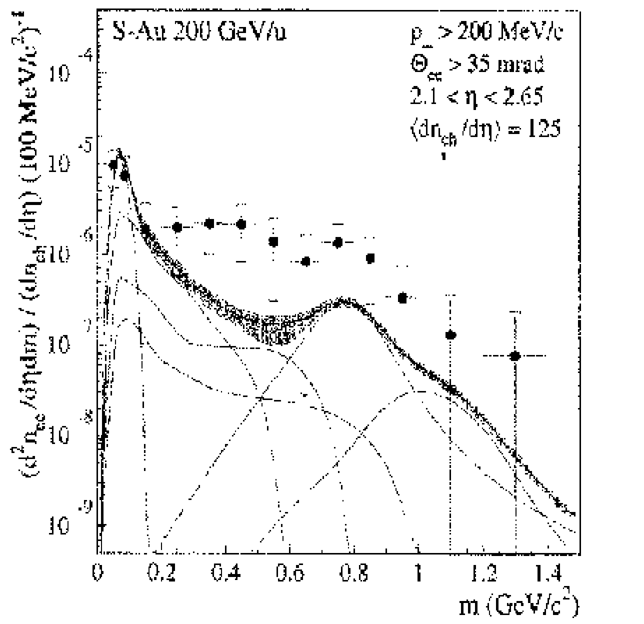
CERN-SPS CERES 実験

ひとつの説明：□ メソンのカイラル対称性復活

□^{0} → e+e- 収量が重イオン衝突で増加
短い寿命（〜1.3 fm）→ 高温状態で熱平衡

□^{0} □ □$^+$□$^□$
N(□^{0} □ $e^+e^□$) □t(系の持続時間)





ベクターメソンの収量

- 高温熱平衡状態 → 持続時間 ΔT の後に freeze-out
- ベクターメソン V
  - 寿命 = τ、　e+e- 分岐比 = B
  - 熱平衡: 個数 N_V 一定（崩壊分は直ちに補われる）

$$n\left(V \to e^+e^-\right) \sim \int_0^{\Delta T} \frac{BN_V}{\tau} dt + \int_{\Delta T}^{\infty} \frac{BN_V}{\tau} e^{-(t-\Delta T)/\tau} dt$$

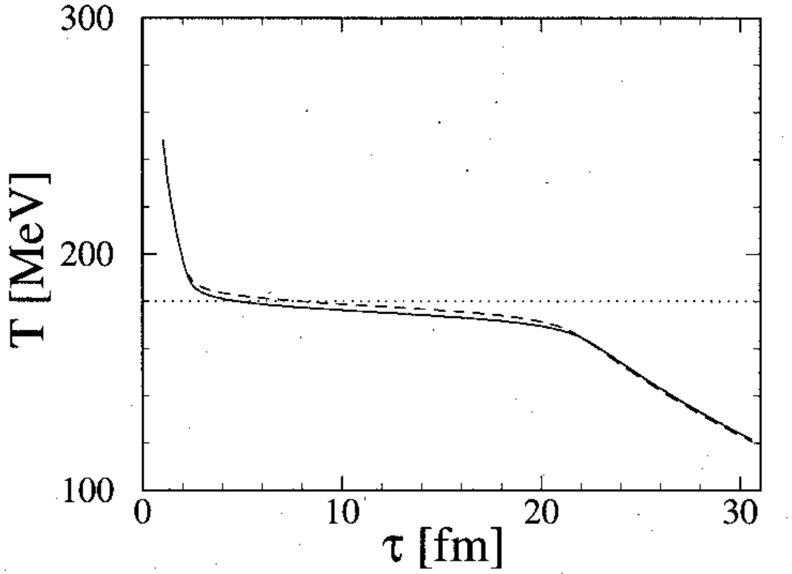
$$= \frac{\Delta T}{\tau} BN_V + BN_V = BN_V \left(1 + \frac{\Delta T}{\tau}\right)$$

τ >> ΔT → n ～ BN_V

τ << ΔT → n ～ $BN_V \Delta T/\tau$

RHIC-PHENIX 実験での計画

□→ e^+e^-、K^+K^-
□ □ → e^+e^-



ＱＧＰ相 → ハドロン相

自由度がミスマッチ
エントロピー密度が十分下がるまで
系はほぼ一定温度で膨張を続ける

□がダブルピーク！