Recent Results on Electromagnetic Measurements at RHIC

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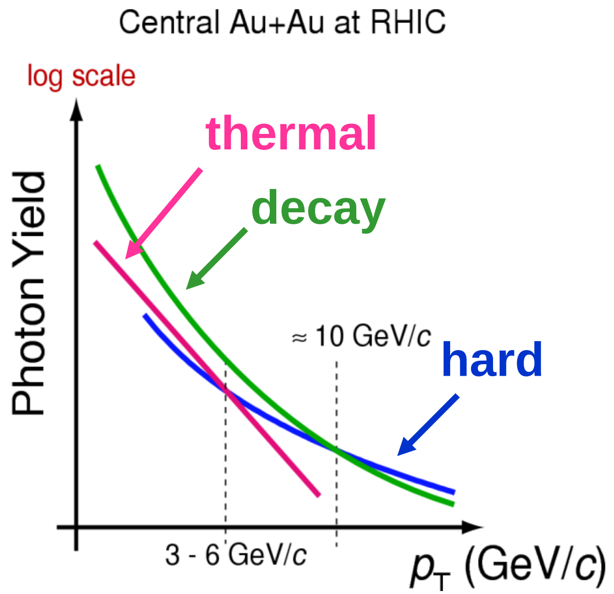
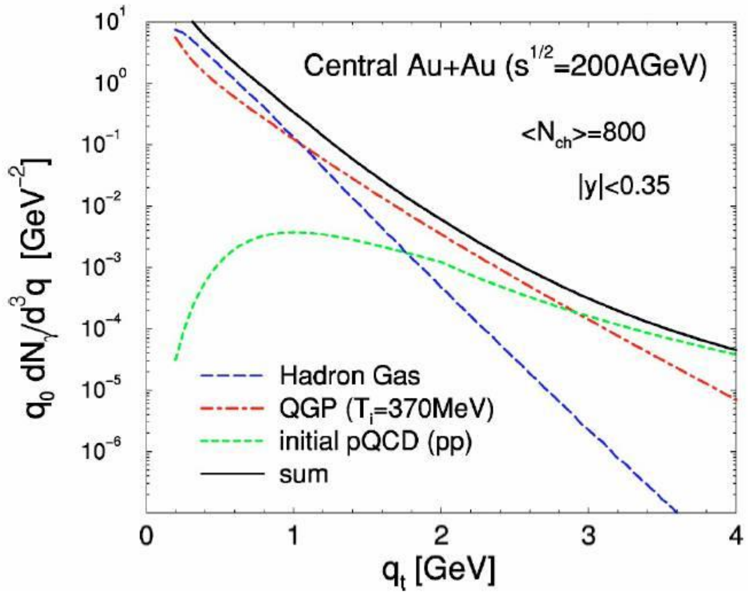
Outline of My Talk

- Photon measurements
  - Medium to High pT region — T. Isobe
  - Low pT region — Y. Yamagachi
- Single electron measurement
  - R_{AA} in p+p and Au+Au — F. Kajihara
  - b/(c+b) in p+p collisions — Y. Morino
- J/ψ measurement
  - J/ψ in Au + Au collisions — T. Gunji
  - χ_c in p+p collisions — S. Oda
- Summary and Outlook
  - Special thanks to the memebers of my group; F. Kajihara, (T. Isobe,) T. Gunji, S.X. Oda, Y. Morino, Y. Yamaguchi

Various Photon Sources

- Measurement of direct photons is very HARD, due to severe background from hadron decays
- Hard photons were seen in A-A collisions at RHIC
  - strong suppression of high pT hadrons helps to improve the S/N ratio
- Thermal photon is difficult
  - a window for QGP thermal photons at pT = 1 ~ 3 GeV/c at RHIC

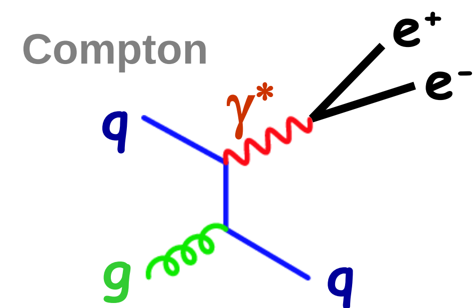


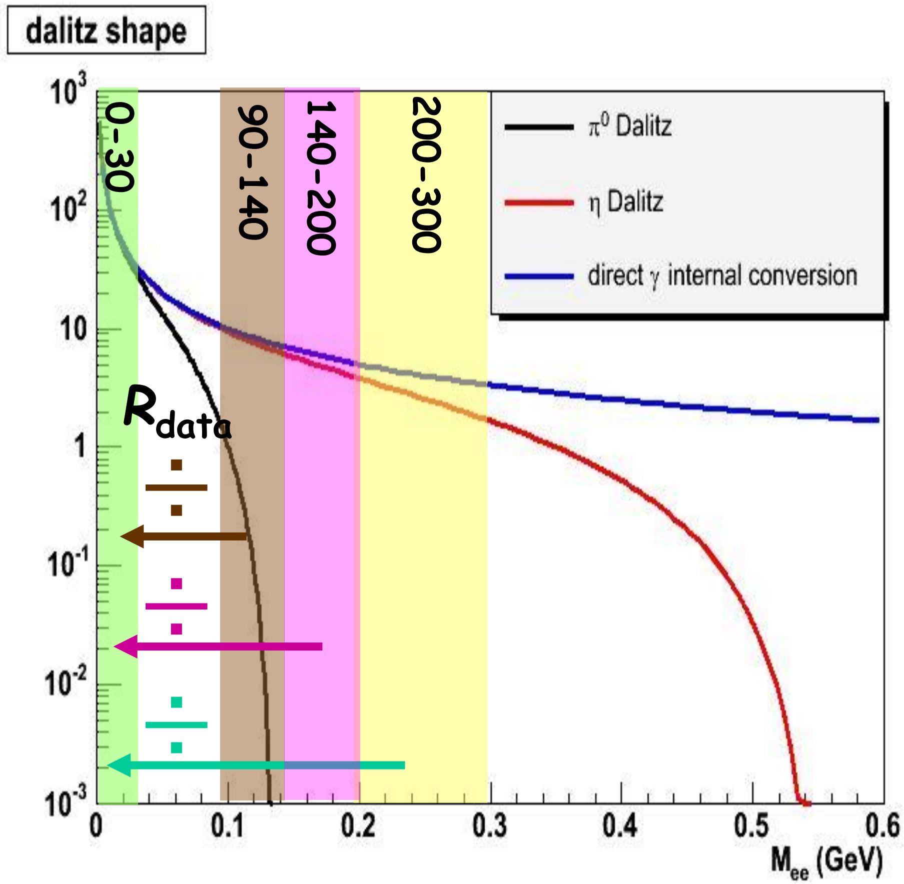


Internal-Conversion Method

Kroll-Wada Formula

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)\frac{1}{m_{ee}}\left|F(m_{ee}^2)\right|^2\left(1-\frac{m_{ee}^2}{M^2}\right)^3$$





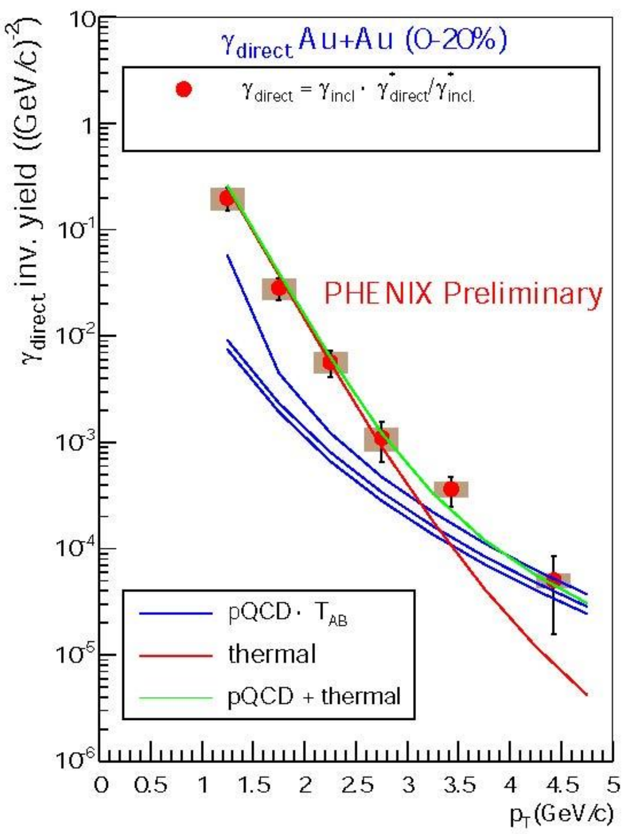
- Measure virtual photons with very low invariant mass
- yield ratio:

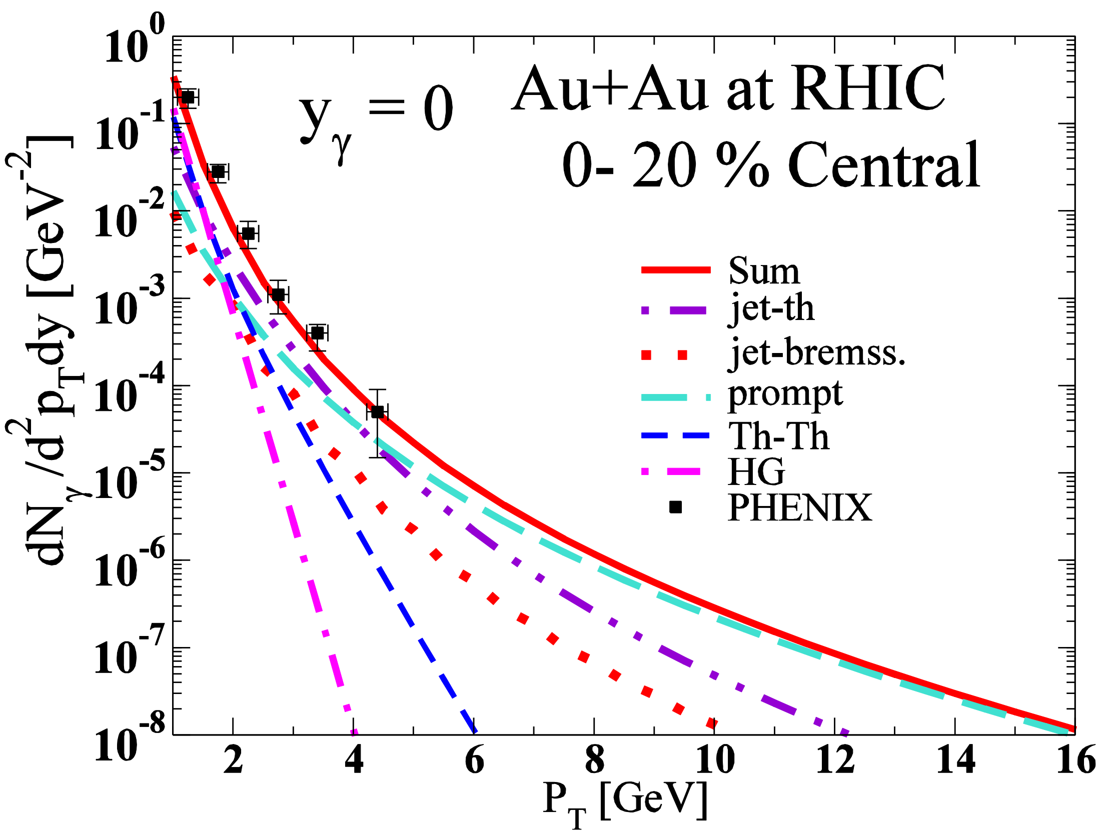
  R(M1:M2)=N(M1:M2)/N(0:30)
- Excess of R(M1:M2) over Dalitz decay -> direct photons.

Comparison with Theoretical Calculations

D'Enterria, Peressounko nucl-th/0503054
τ_0 = 0.15 fm/c, T = 570 MeV

Turbide, Rapp, Gale PRC 69 014903 (2004)
τ_0 = 0.33 fm/c, T = 370 MeV



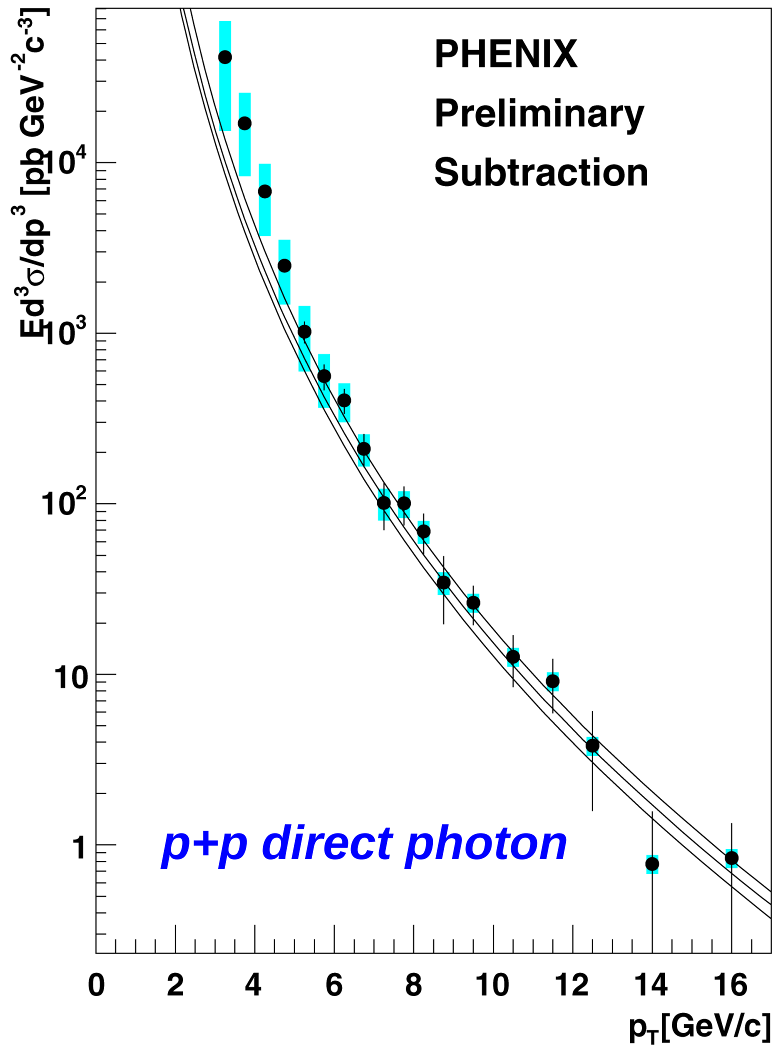


- very interesting, but we have to recall that …

That ...

- pQCD calculation is not reliable at low pT
- Reference data from p+p is not available, because of large systematic error for pT < 5 GeV with the real photon measurement

=> Virtual photon analysis in p+p is crucial

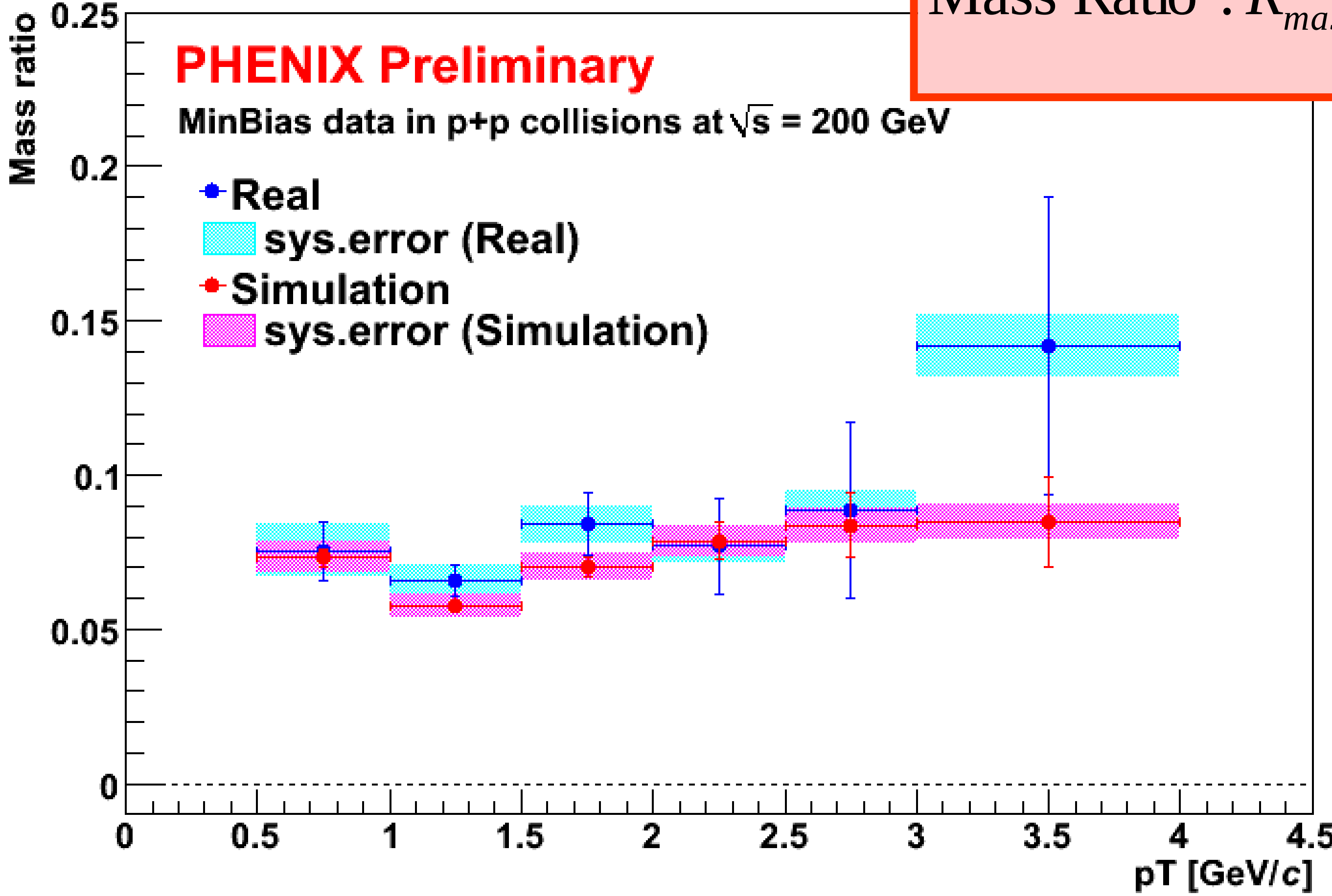


NLO pQCD: L.E.Gordon and W. Vogelsang, PRD48(1993)3136

Yield Ratio of the Two Mass Bins

- For Real Data & Simulation

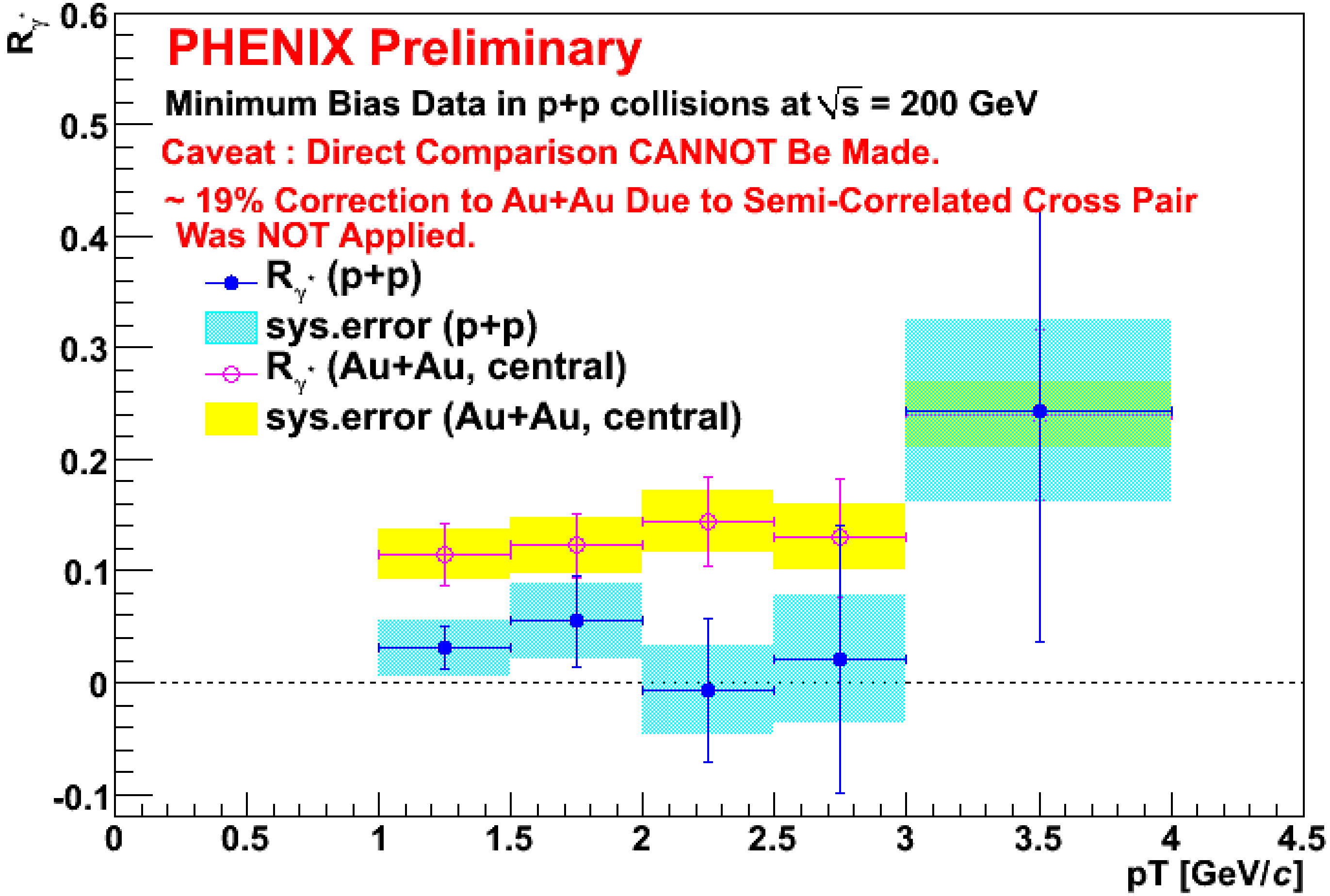
$$\text{Mass Ratio} : R_{mass} = \frac{N_{90-300}}{N_{0-30}}$$



Virtual Photon Ratio in p-p

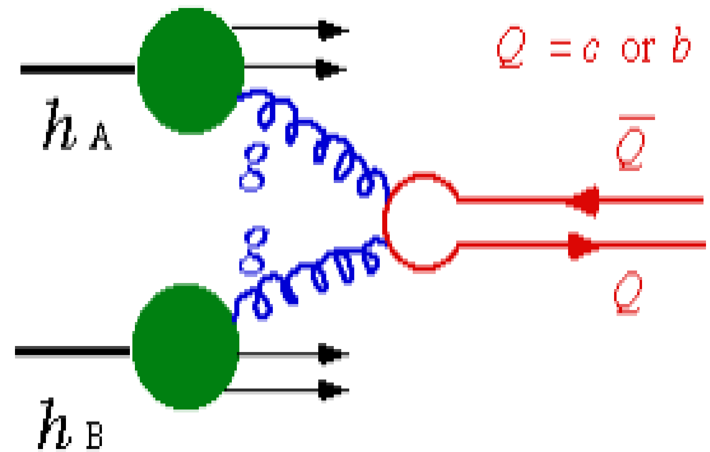
$$R_{\gamma^*} = \frac{N_{0-30}^{direct}}{N_{0-30}^{all}} = \frac{R_{mass}^{real} - R_{mass}^{hadron}}{R_{mass}^{direct} - R_{mass}^{hadron}}$$

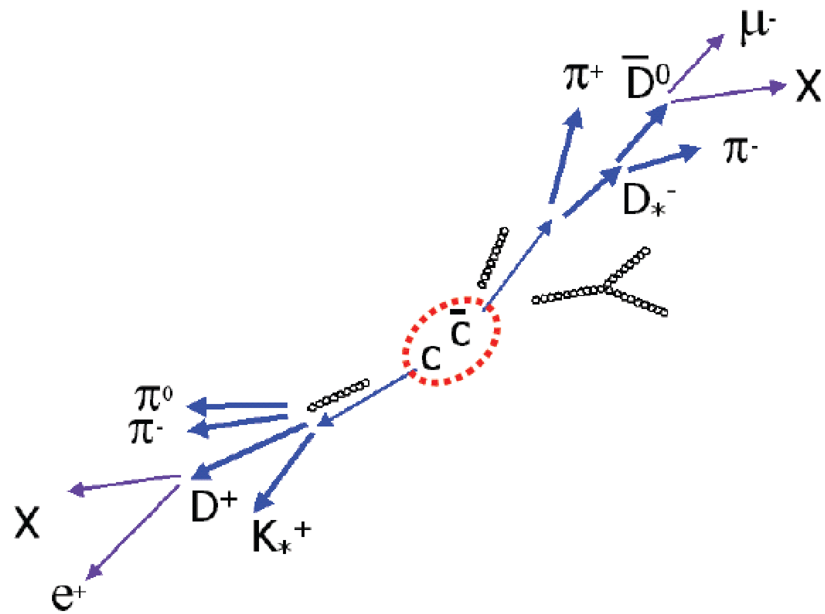
- More statistics will come soon.



Heavy flavor production

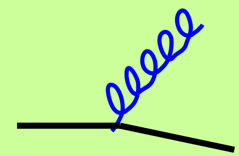
- Charm (& bottom) production = hard process
  - leading order at low x = "gluon fusion"
  - Ncoll scaling should hold, with known nuclear effects; nuclear shadowing and kT broadening
- A good probe of
  - partonic energy loss
  - thermalization & Flow
- How to measure
  - "exclusive" is favorable, but
  - semi-leptonic decay → measure electrons/muons





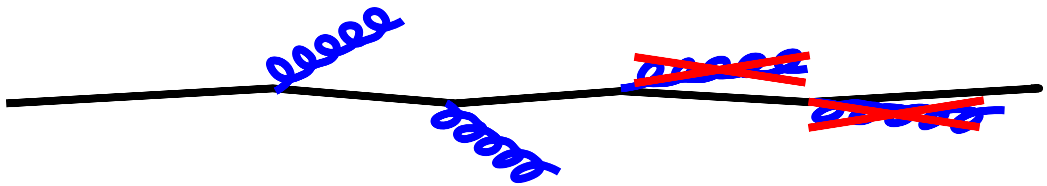
Energy Loss of Heavy Quark

- Dead cone effect: gluon bremsstrahlung is suppressed at forward angles; $\theta < m_Q/E_Q$



$$\propto \frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$

Q

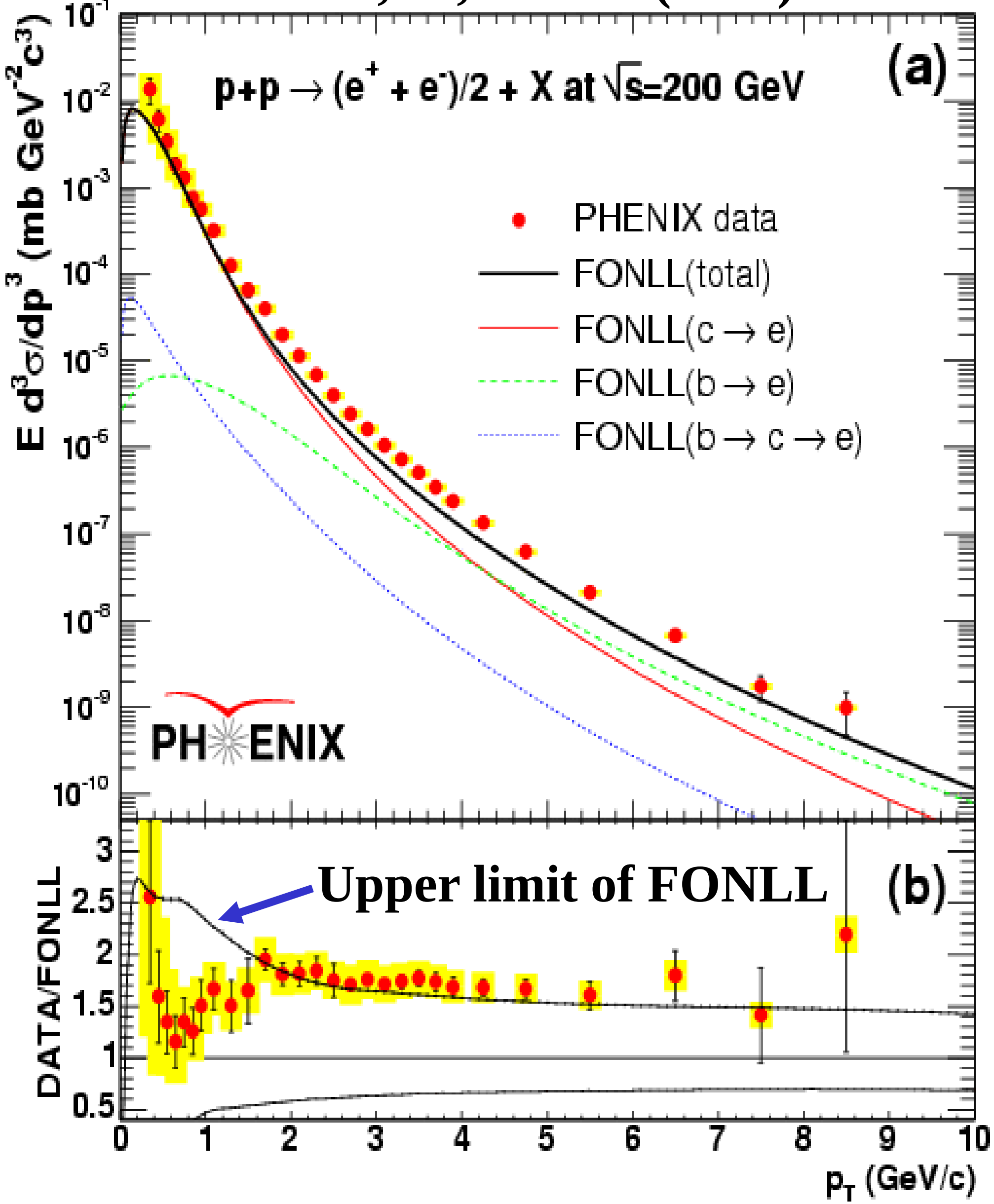


$$\omega \frac{dI}{d\omega}\bigg|_{HEAVY} = \omega \frac{dI}{d\omega}\bigg|_{LIGHT} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

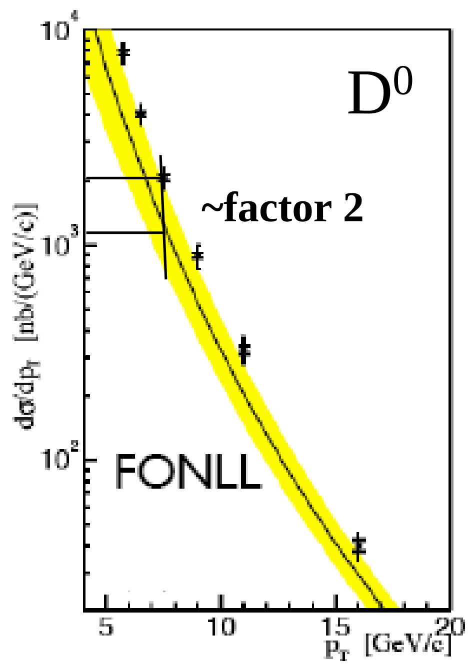
Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

Result of p+p at √s = 200 GeV

PRL, 97, 252002 (2006)



- Heavy flavor electron compared to FONLL
- Data/FONLL = 1.71 +/- 0.019 (stat) +/- 0.18 (sys)
- Experimental result at Tevatron



CDF, PRL 91, 241804 (2003)

ts a

Hamagaki

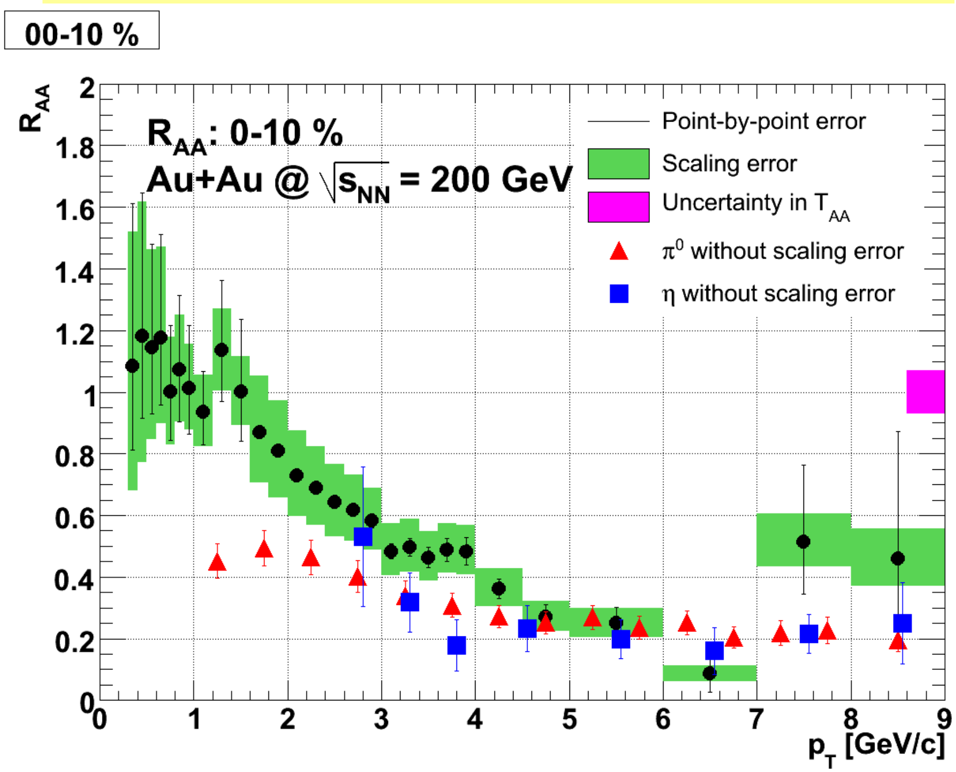
R_{AA} in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

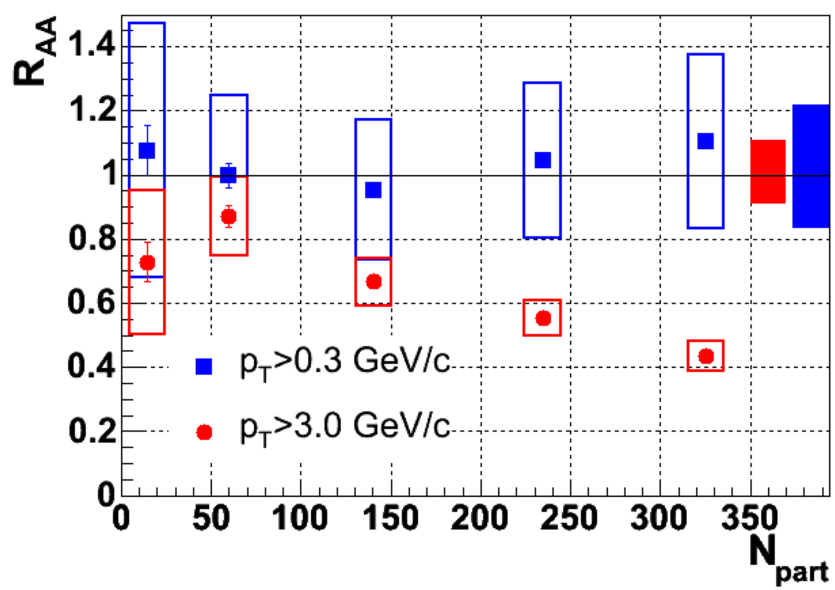
$$R_{\mathrm{AuAu}}(p_{\mathrm{T}}) = \frac{dN^{e}_{\mathrm{AuAu}}/dp_{\mathrm{T}}}{N_{\mathrm{col}} \cdot dN^{e}_{\mathrm{pp}}/dp_{\mathrm{T}}}$$

Suppression level is the almost same as p^0 and h in high p_T region

$$R_{\mathrm{AuAu}}(N_{\mathrm{part}}) = \frac{\int_{p'_{\mathrm{T}}}^{9.0} \frac{dN^{e}_{\mathrm{AuAu}}}{dp_{\mathrm{T}}} dp_{\mathrm{T}}}{N_{\mathrm{col}} \cdot \int_{p'_{\mathrm{T}}}^{9.0} \frac{dN^{e}_{\mathrm{pp}}}{dp_{\mathrm{T}}} dp_{\mathrm{T}}}$$

Binary scaling works well for integrated yield for p'_T > 0.3 GeV/c

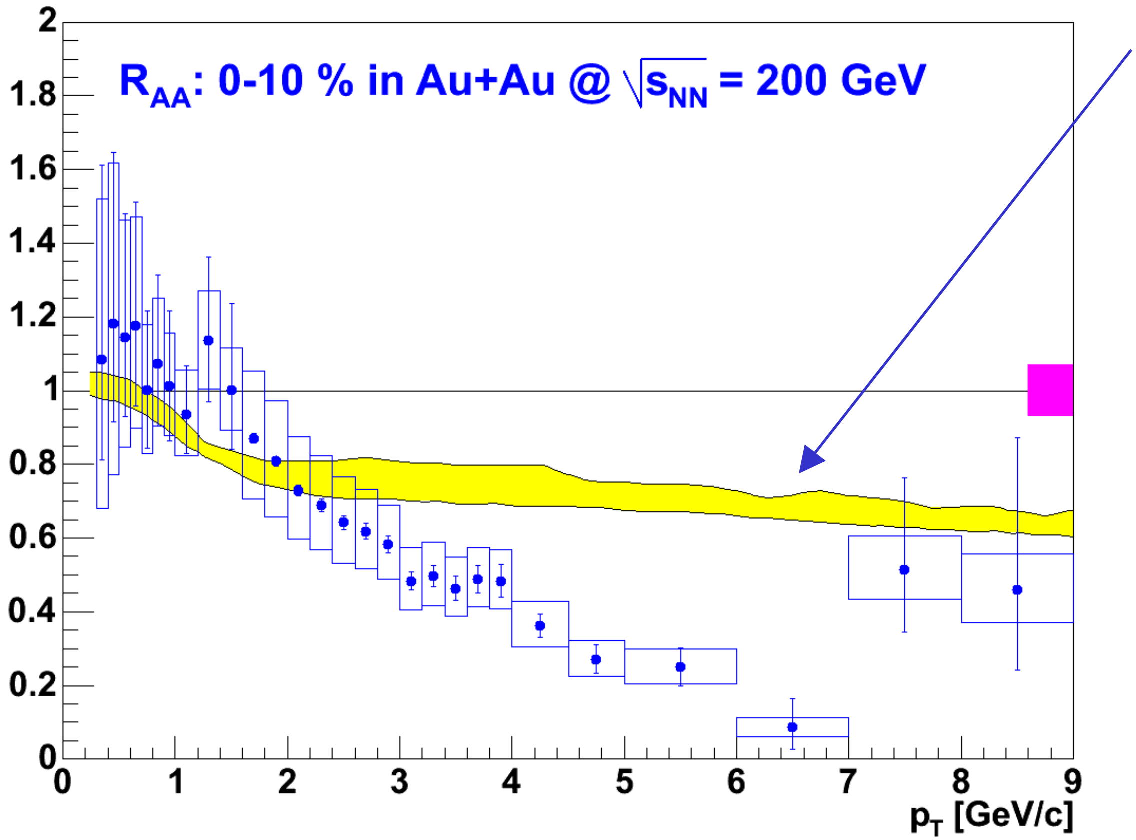




Radiative Energy Loss

- Radiative energy loss with reasonable gluon densities does NOT explain the observed suppression

Djordjevic, Phys. Lett. B632 81 (2006)
Armesto, Phys. Lett. B637 362 (2006)

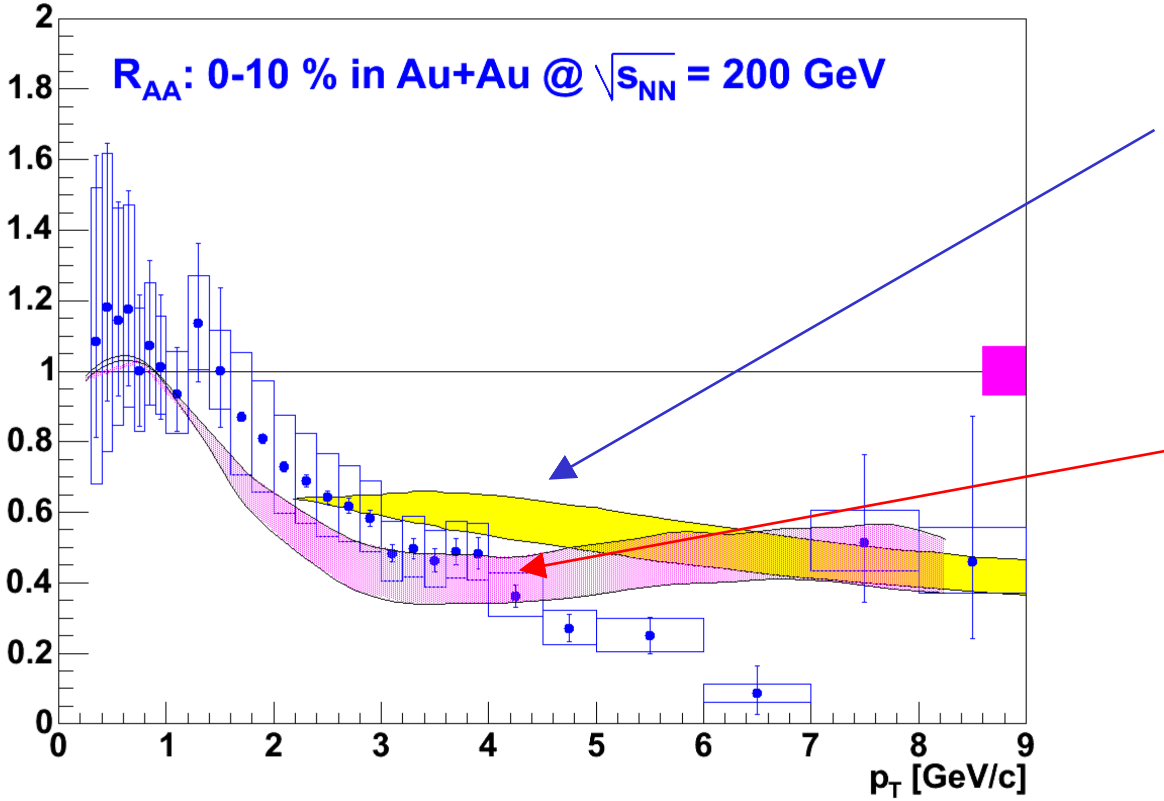


DGLV model; radiative energy loss with $dN_g/dy = 1000$

Collisional Energy Loss

- Inclusion of collisional energy loss seems to improve the situation

S. Wicks et al., NPA784:426-442,2007 (nucl-th/0512076)
F. van Hess et al., PRC73 034913 (2006)



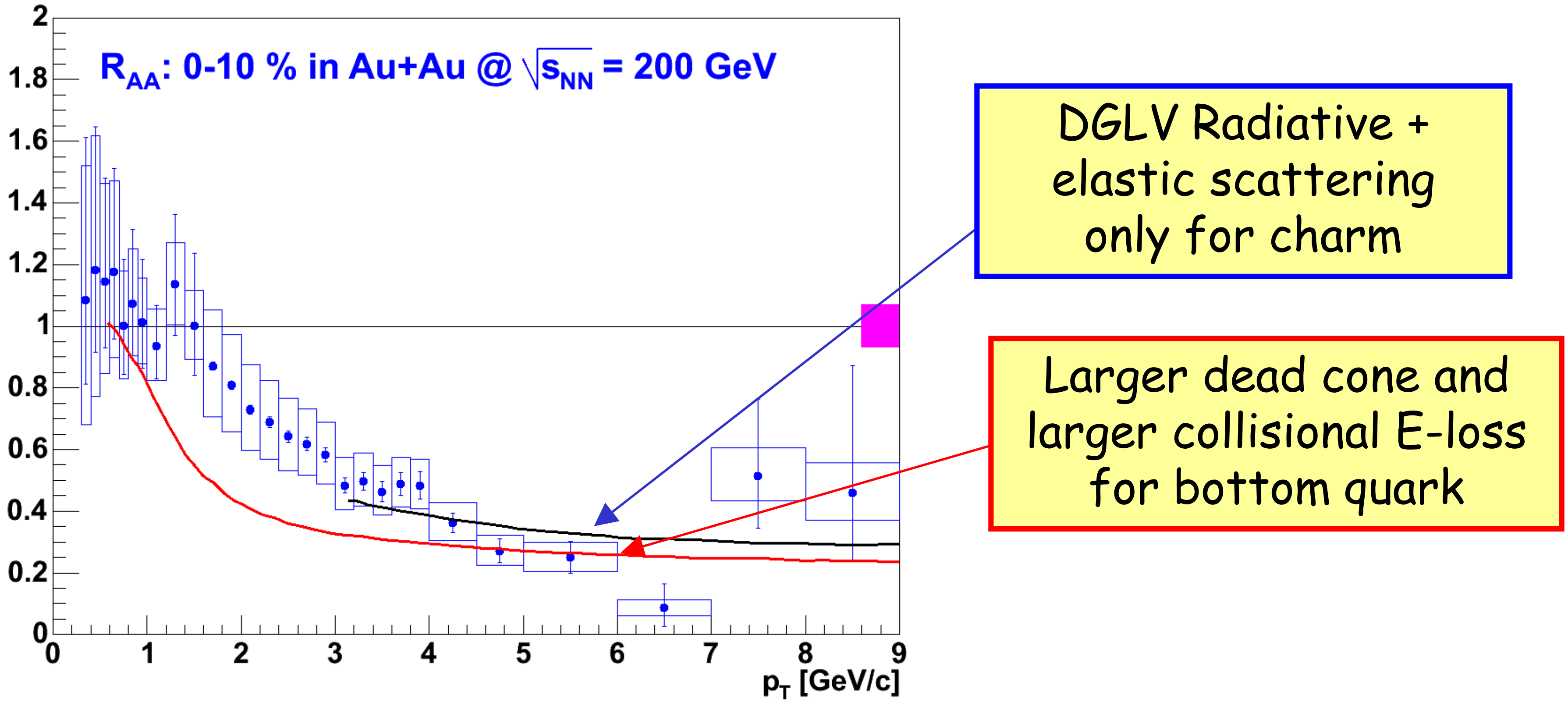
DGLV Radiative + Elastic Scattering $dN_g/dy = 1000$

van Hees et al: Elastic Scattering

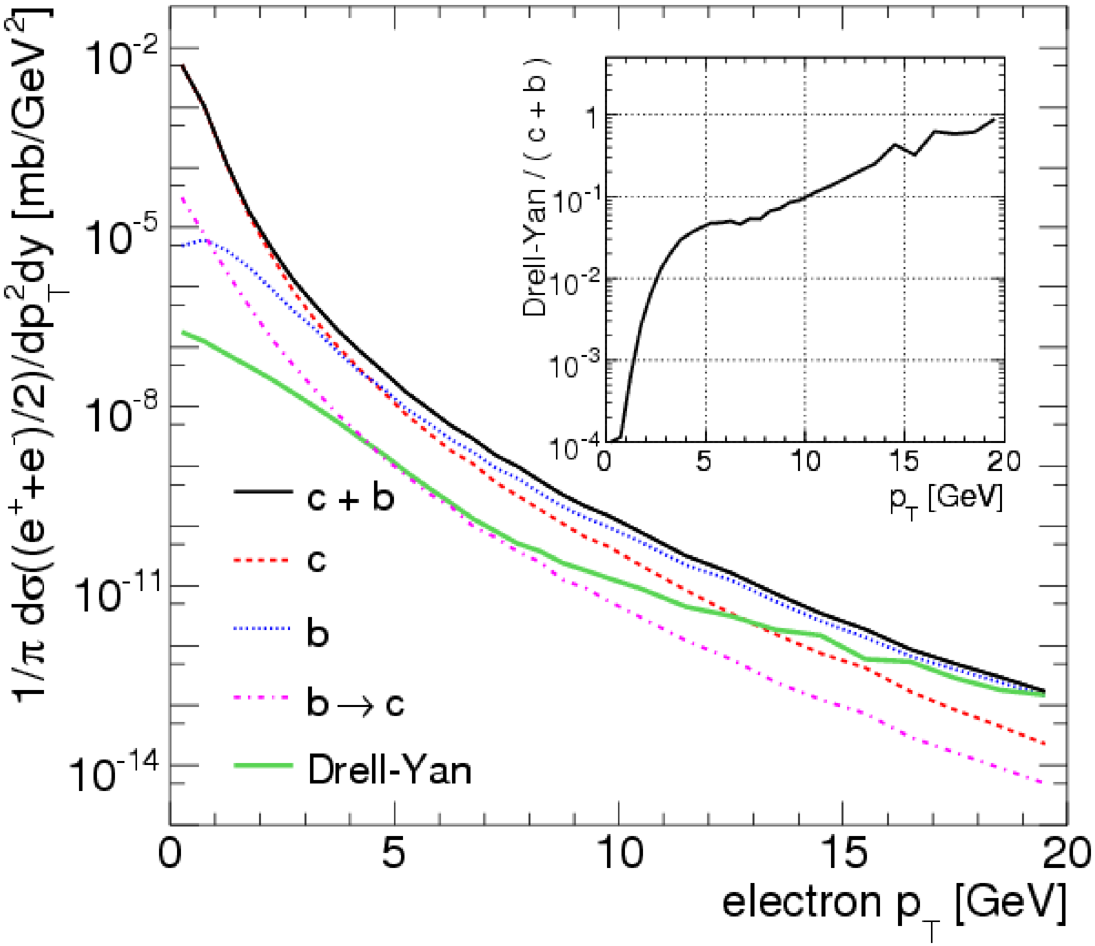
Other models

- charm and bottom will behave differently, because of mass dependence of dead cone & collisional E-loss.

-> fraction of c and b at each pT region is needed.



Electrons from Various Sources; FONLL Prediction

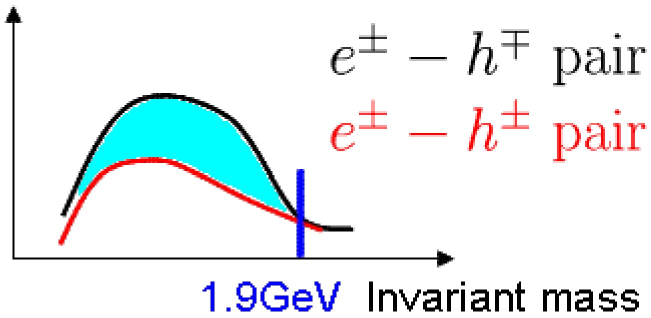


- FONLL predicts; ~50% c + ~50% b for 3 < p_T < 8 GeV
- Drell-Yan component is less than 10% up to 10 GeV

FONLL calculation: Cacciari, Nason, Vogt, PRL95 (2005) 122001
Drell-Yan from: Gavin et al., hep-ph/9502372
Comparison: Armesto, Cacciari, Dainese, Salgado, Wiedemann, hep-ph/0511257

The Ratio b/(c+b) in p + p Collisions

- D → e K ν; measure e & h (K) coincidence
- How to obtain the ratio



subtraction of like-sign pair from unlike-sign pair

$N_{tag} = N_{unlike} - N_{like}$

From experimental data:

$$\epsilon_{data} \equiv \frac{N_{tag}}{N_{e(non-photonic)}} = \frac{N_{c\to tag} + N_{b\to tag}}{N_{c\to e} + N_{b\to e}}$$

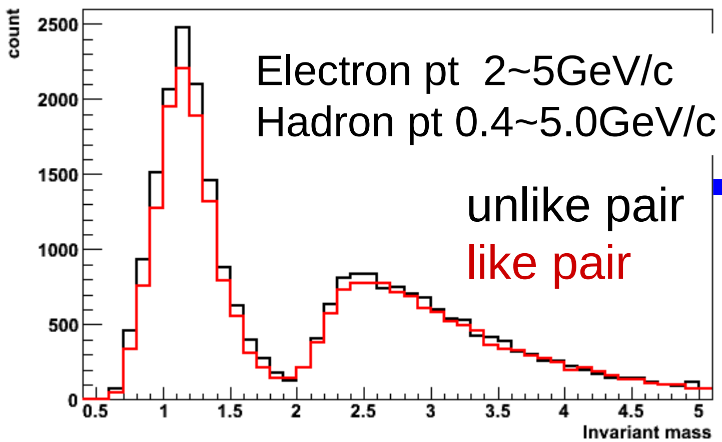
From PYTHIA simulation:

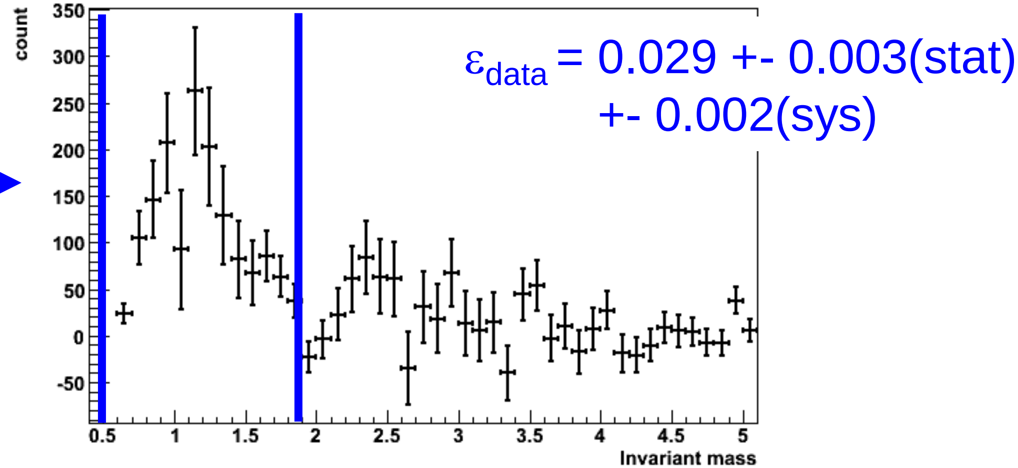
$$\epsilon_c \equiv \frac{N_{c\to tag}}{N_{c\to e}}, \epsilon_b \equiv \frac{N_{b\to tag}}{N_{b\to e}}$$

$$\frac{N_{b\to e}}{N_{c\to e} + N_{b\to e}} = \frac{\epsilon_c - \epsilon_{data}}{\epsilon_c - \epsilon_b}$$

Obtain Tagging Efficiency

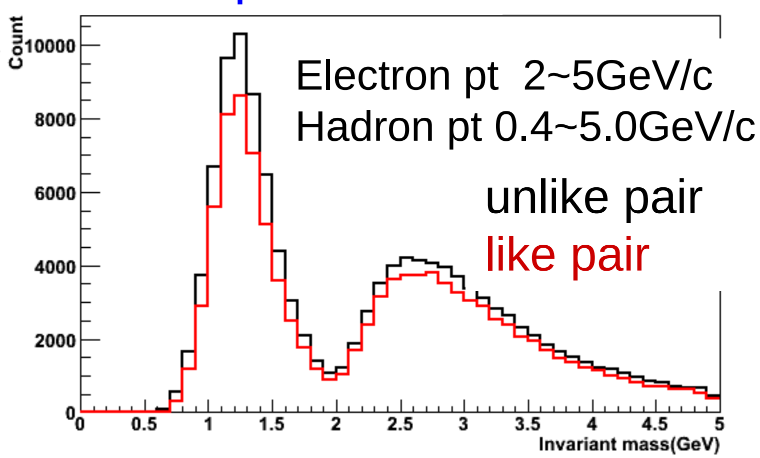
- Real data



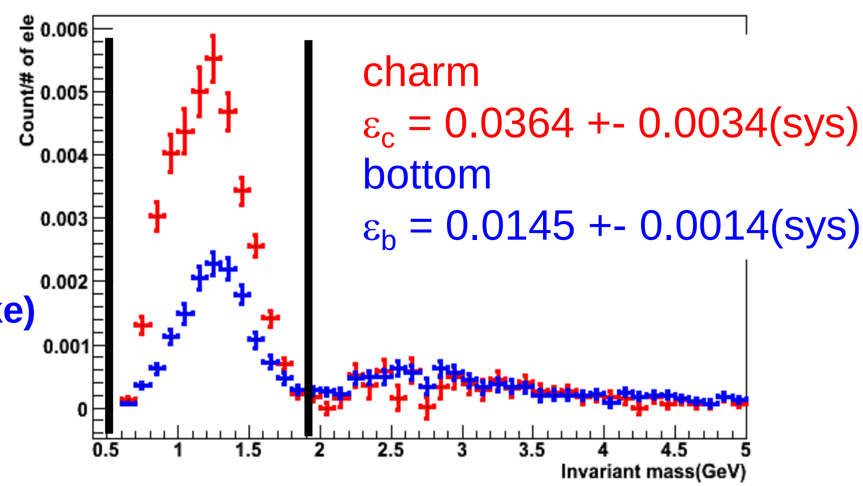


- Simulation (PYTHIA and EvtGen)

bottom production



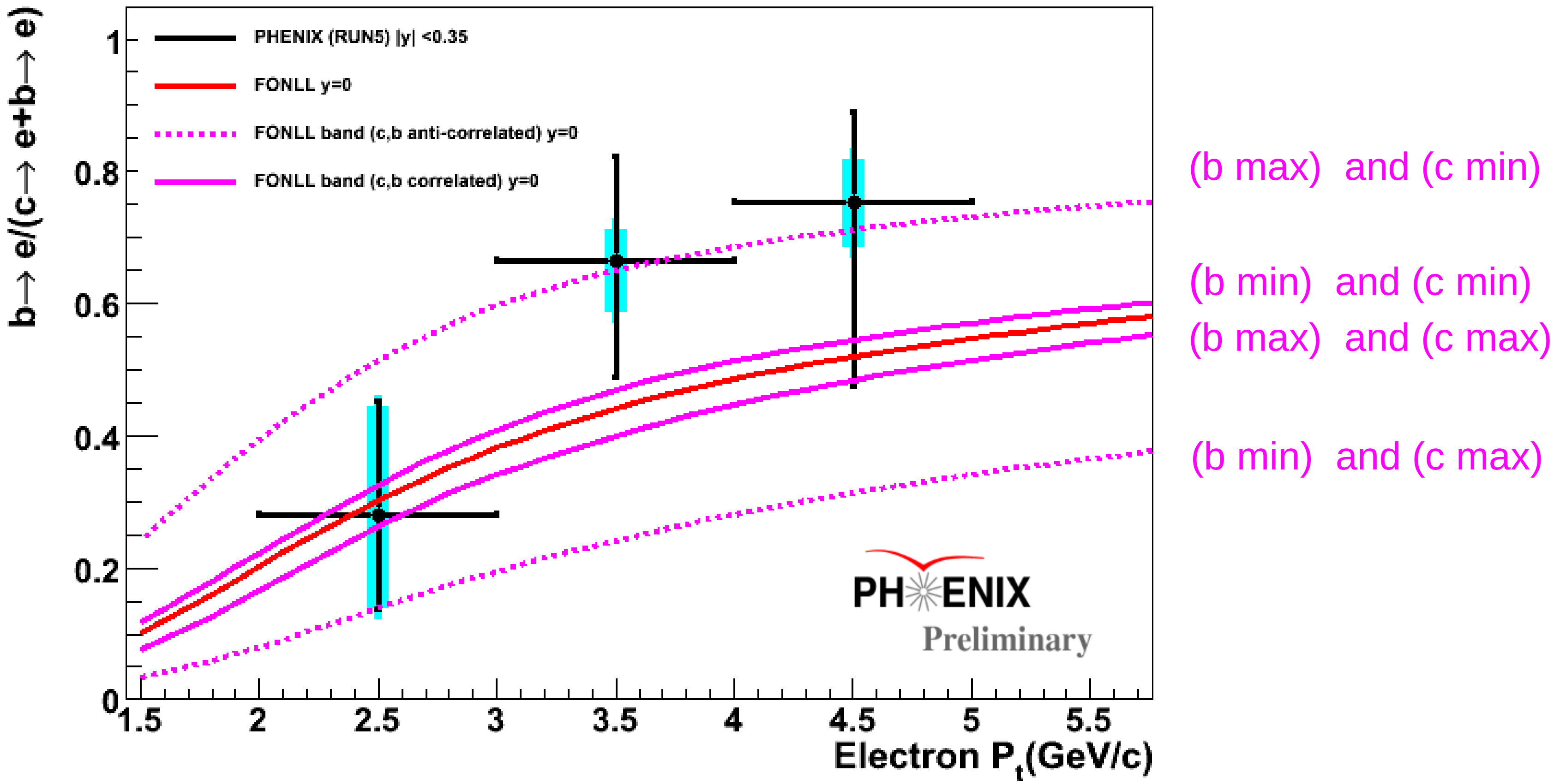
(unlike-like)
/# of ele



[b->e]/([c->e]+[b->e]) Ratio

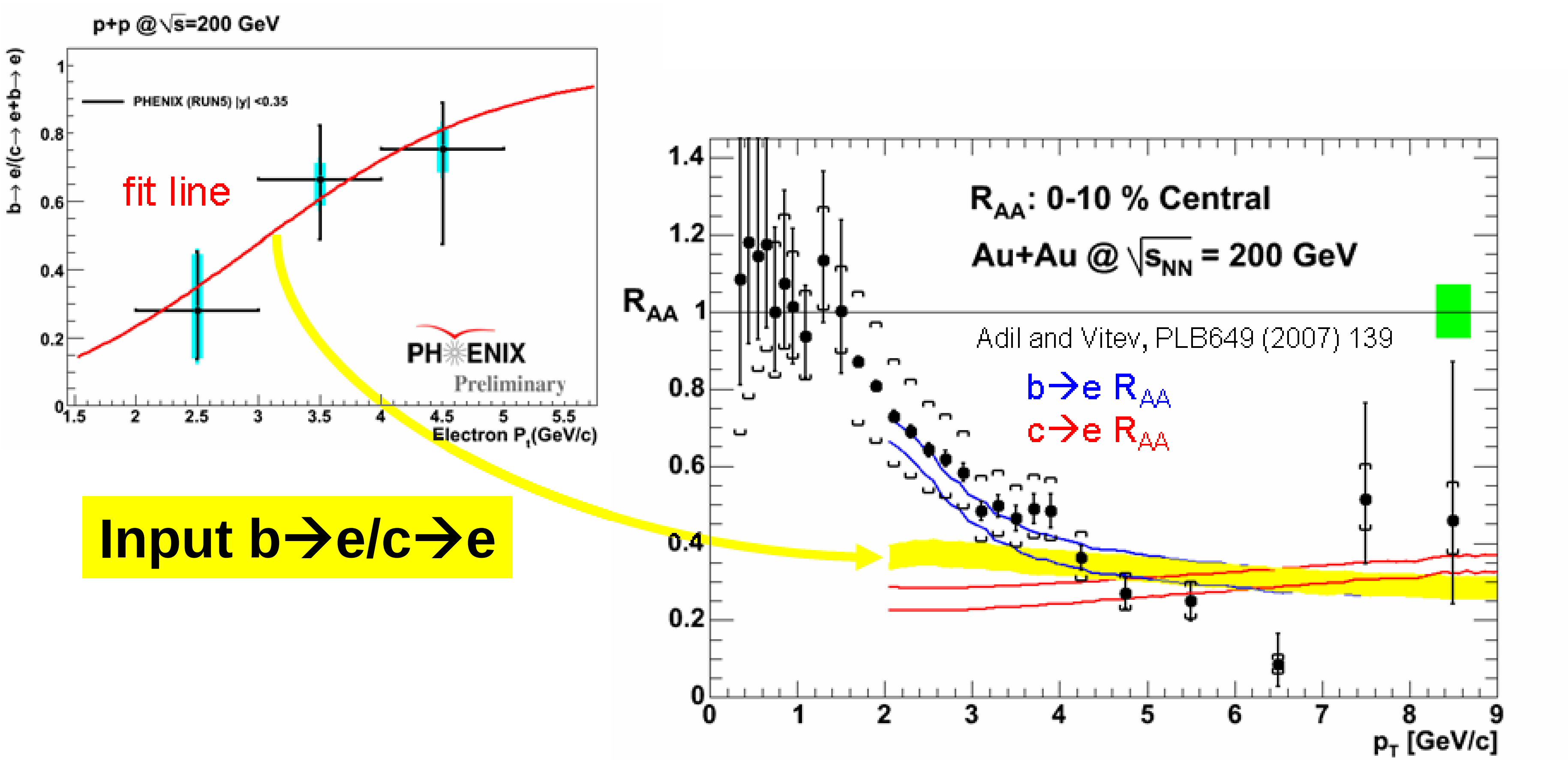
- The ratio as a function of electron pt
  - Compared with FONLL: Fixed Order plus Next to Leading Log pQCD calculation

p+p @ $\sqrt{s}$=200 GeV



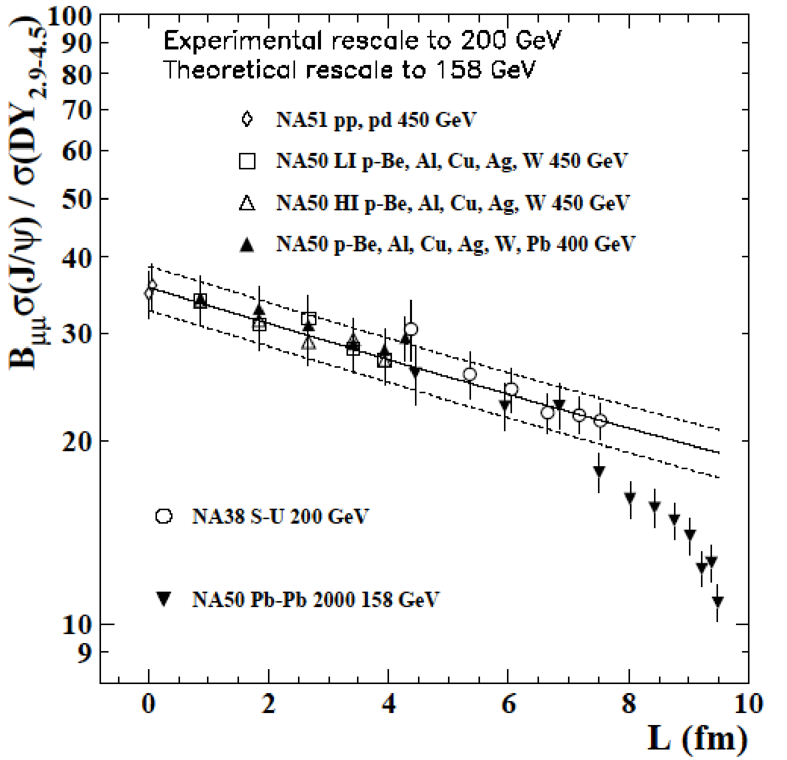
How to utilize the b/c ratio

- Collisional dissociation model (by Adil and Vitev) = heavy quarks form mesons inside the medium, and are suppressed by dissociation



Quarkonium

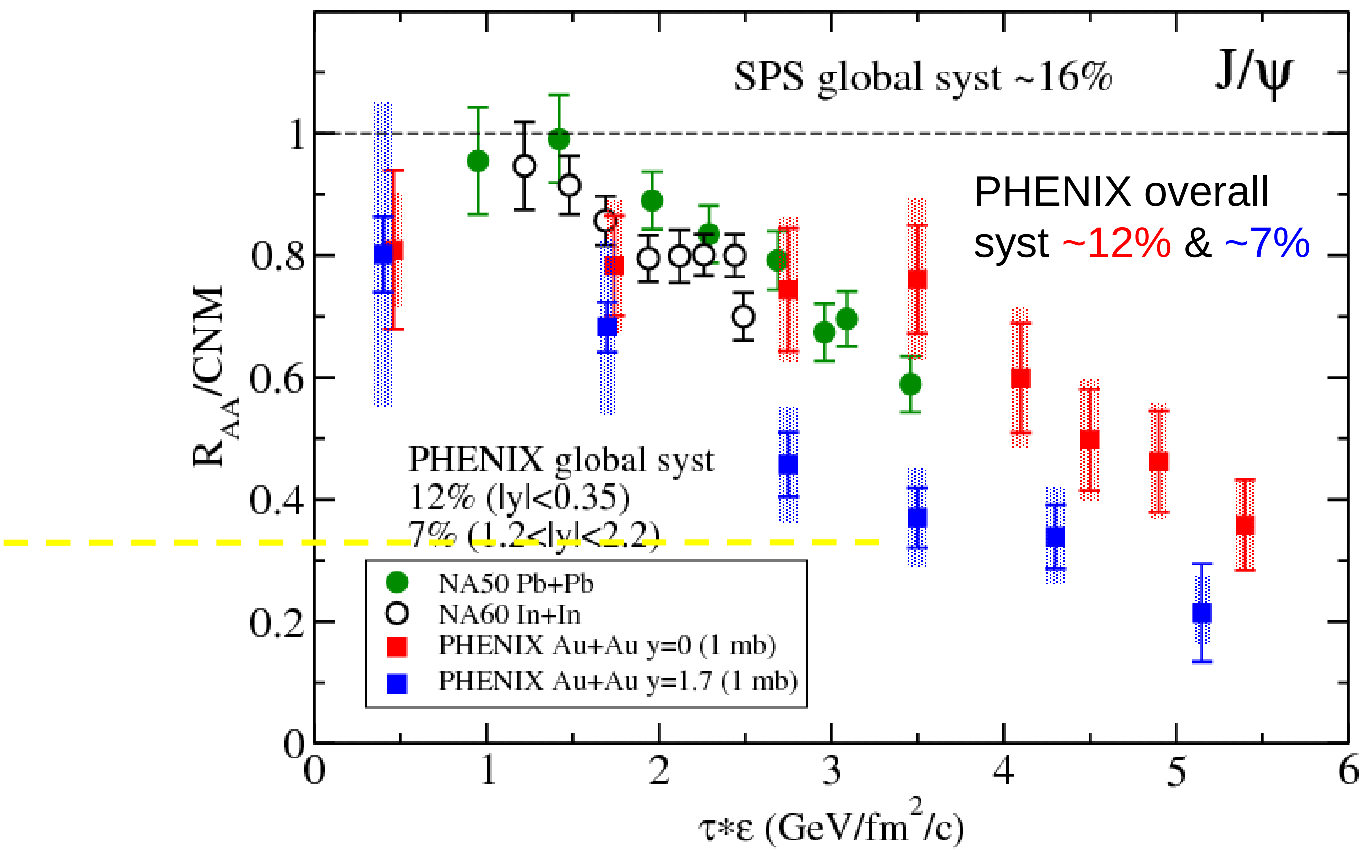
- Idea of J/ψ suppression
  - proposed by Matsui and Satz (1986; before experimental results), as a good probe of deconfinement
    - suppresion due to Debye screening in the deconfined phase



- History at SPS in Brief
  - suppression in S + A
    - → turned out to be similar to p + A
  - anomalous suppression observed in Pb + Pb

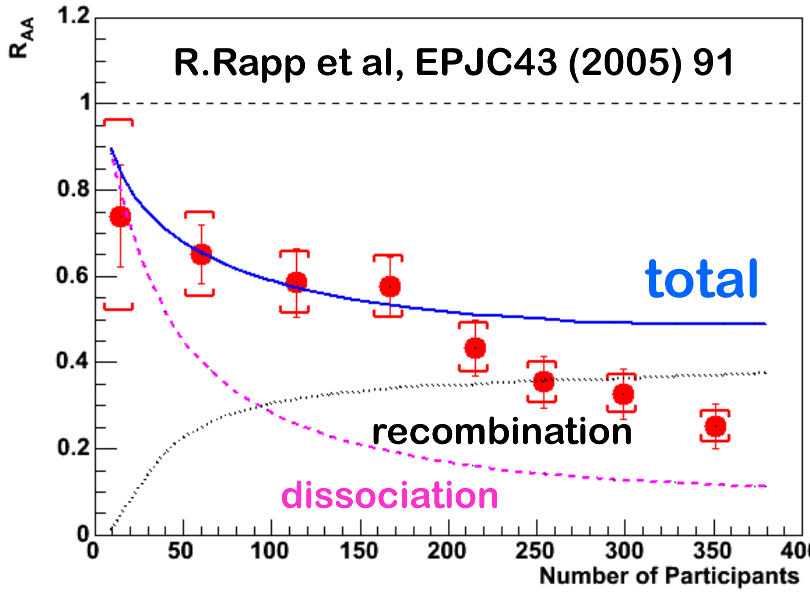
J/ψ Suppression at RHIC

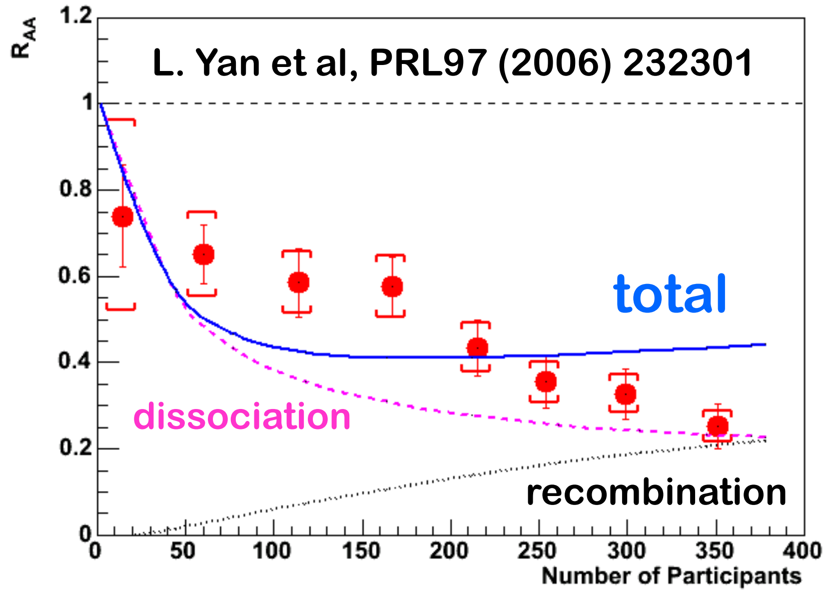
- Larger suppression at forward angle at RHIC
- Suppression seems to be larger at RHIC, after CNM (cold nuclear matter) effect is corrected



Dissociation + Recombination

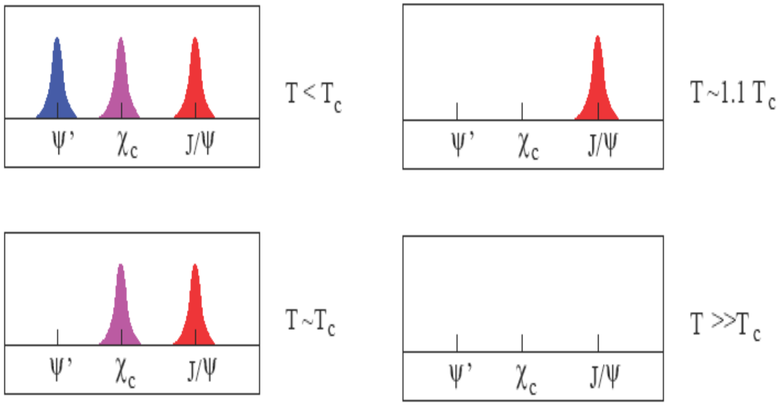
- Gluon dissociation + recombination
  - Dissociation by thermal gluons supplemented by the regeneration of J/ψ from c-cbar coalescence
    - R. Rapp et al. [EPJC34, 91 (2005)], L. Yan et al. [PRL97,232301 (2006)], R. Thews [NPA783 301(2007)], A.Andronic et al.[nucl-th/0701079], etc
- Magnitude is OK, but the trend cannot be reproduced
  - trend = decrease of R_{AA} starting at Npar ~ 150



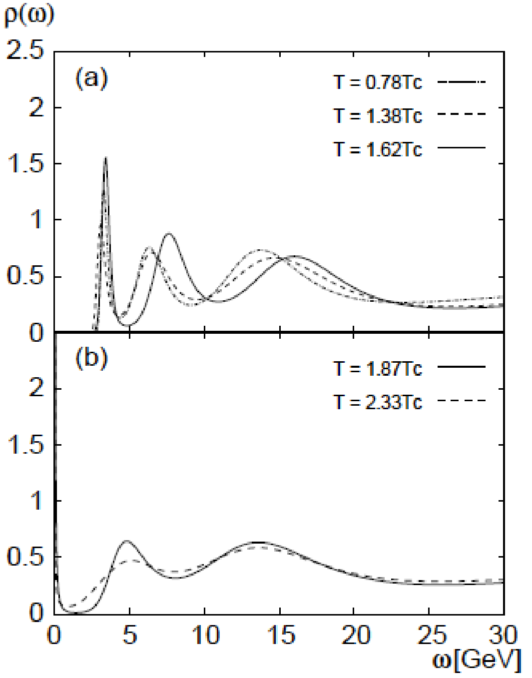


Idea of "Thermometer"

H. Satz, J. Phys. **G32**, R25 (2006)



- Color Debye Screening
  - Different T_{diss} for different quarkonia.
  - The quarkonium suppression pattern may be used as a QGP thermometer.
- Recent Lattice QCD results
  - J/ψ may survive above T_c

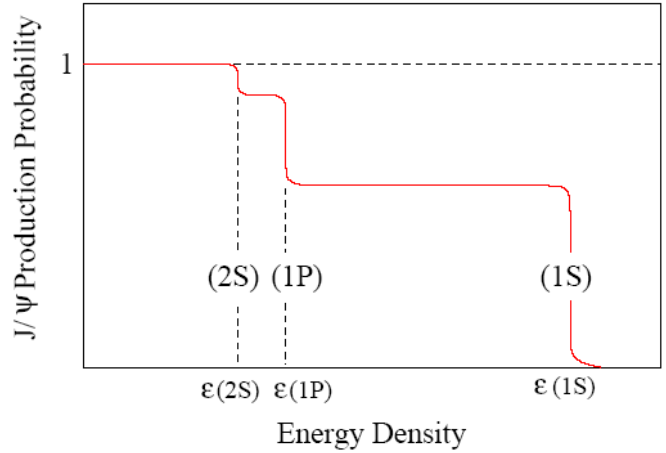


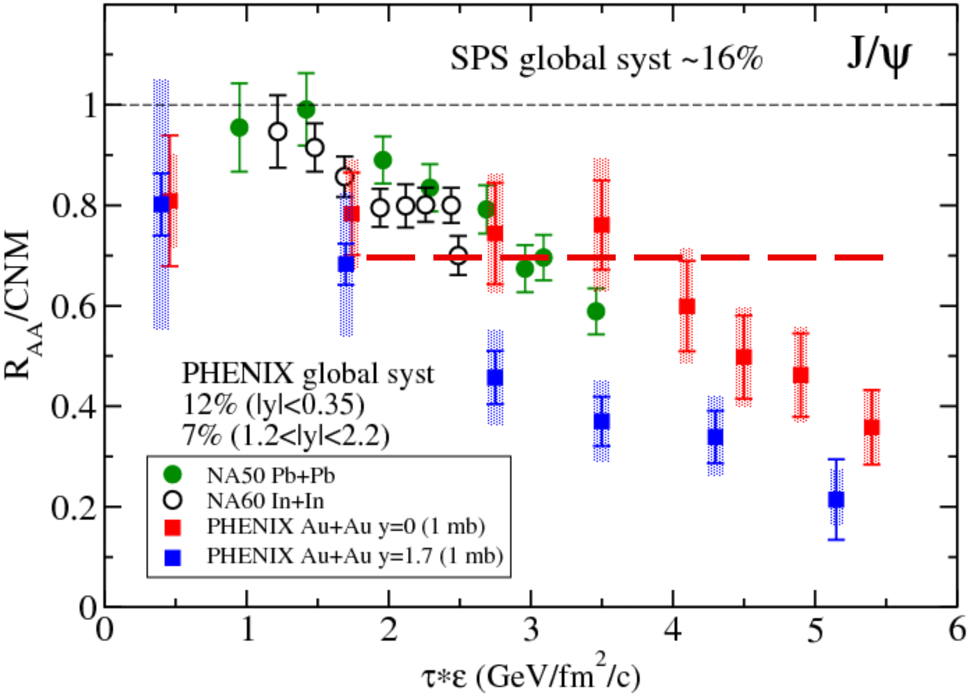
* M. Asakawa, T. Hatsuda; Phys. Rev. Lett. 92 (2004) 012001
* Datta & al, hep-lat/0409147. * Alberico & al, hep-ph/0507084
* Wong, hep-ph/0408020 ← Satz, hep-ph/0512217

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17

Idea of Sequential Melting

- ~40% of J/ψ come from ψ′ and χ_c (= feed down)
  - J/ψ ~ 0.6 J/ψ + 0.3χ_c + 0.1ψ′
    - HERA-B exp. PLB561 (2003)
  - J/ψ suppression pattern may provide information on the melting of ψ′/χ_c.
- J/ψ suppression at SPS may be described by feed down effect
  - claimed by Karsch, Kharzeev & Satz: PLB637(2006)75





Hydro+J/ψ Model

- By T. Gunji, T. Hirano, T. Hatsuda, H.H.
- Incorporate J/ψ, χ_c and ψ' into a hot matter, described by the (3+1)-D relativistic hydrodynamics
  - T. Hirano and Y. Nara, PRL 91, 082301, (2003)
  - T. Hirano and Y. Nara, PRC 69, 034908, (2003)
  - T. Hirano and K. Tsuda, PRC 66, 054905, (2002)

- J/ψ, χ_c and ψ': traversing through the matter

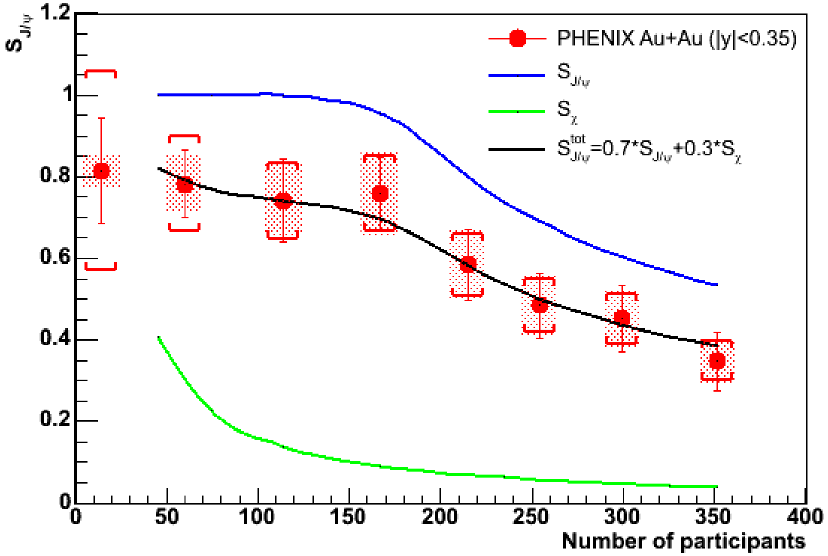
$$S_{J/\psi}^{tot} = (1 - f_{FD}) \times S_{J/\psi} + f_{FD} \times S_{\chi,\psi'}$$

$$S_{J/\psi}\left(\vec{x}_{J/\psi}(\tau)\right) = \exp\left[-\int_{\tau_0}^{\tau} \Gamma_{dis}\left(T(\vec{x}_{J/\psi}(\tau'))\right) d\tau'\right]$$

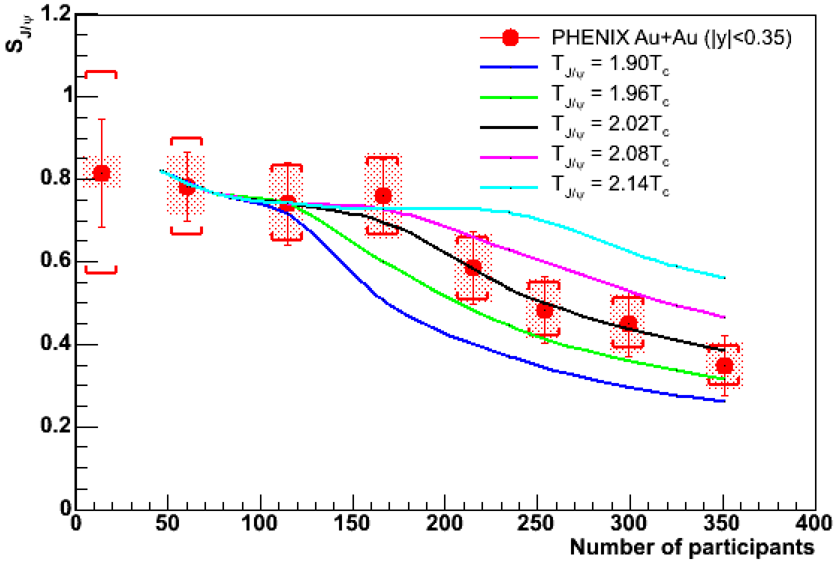
$$\Gamma_{dis}(T) = \infty(T > T_{J/\psi}),\ 0(T < T_{J/\psi})$$

Model Calculations

- Good fit to the experimental $S_{J/\psi}{}^{tot}$ ($=R_{AA}/CNM$).
  - Min. χ^2 at $(T_{J/\psi}, T_\chi, f_{FD})$ = $(2.02T_c, 1.22T_c, 30\%)$



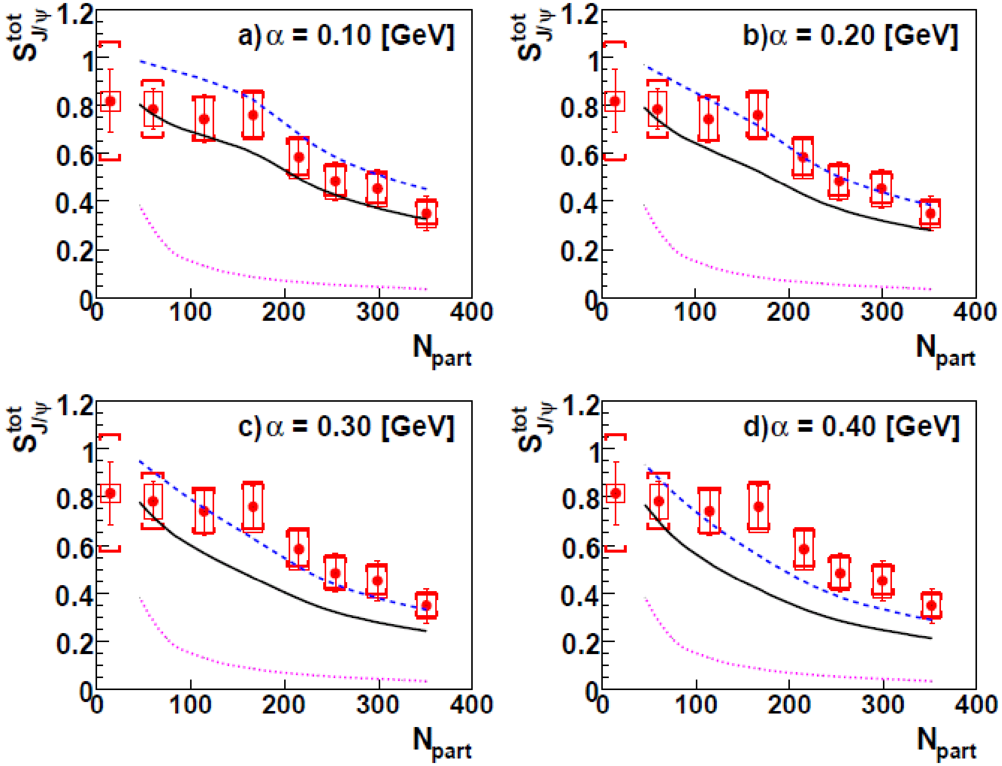
- Sensitivity to $T_{J/\psi}$
  - $T_{J/\psi}/T_c$ = 1.9, 1.96, 2.02, 2.08, 2.14
  - $T_c = 1.22T_c$ and $f_{FD} = 30\%$



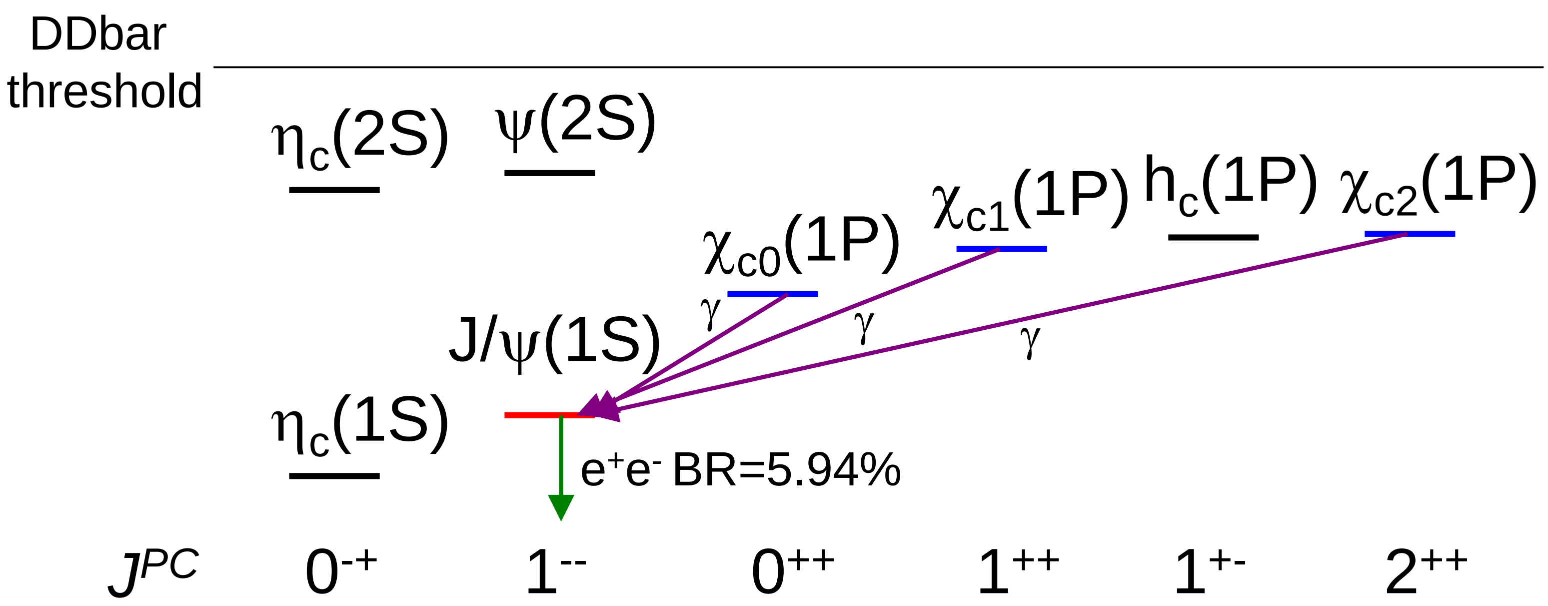
New Results

- $\Gamma_{dis}(T<T_{J/\psi}) = 0$ -> Include dissociation by thermal gluons
  - $\Gamma_{dis}(T<T_{J/\psi}) = \alpha(T/T_C-1)^2$
    - NLO calculation by Y. Park, K-L. Kim, T. Song, S.H. Lee and C-Y. Wong, arXiv:0704.3770 [hep-ph].

- Large α value (α > 0.2 GeV) is not favored.



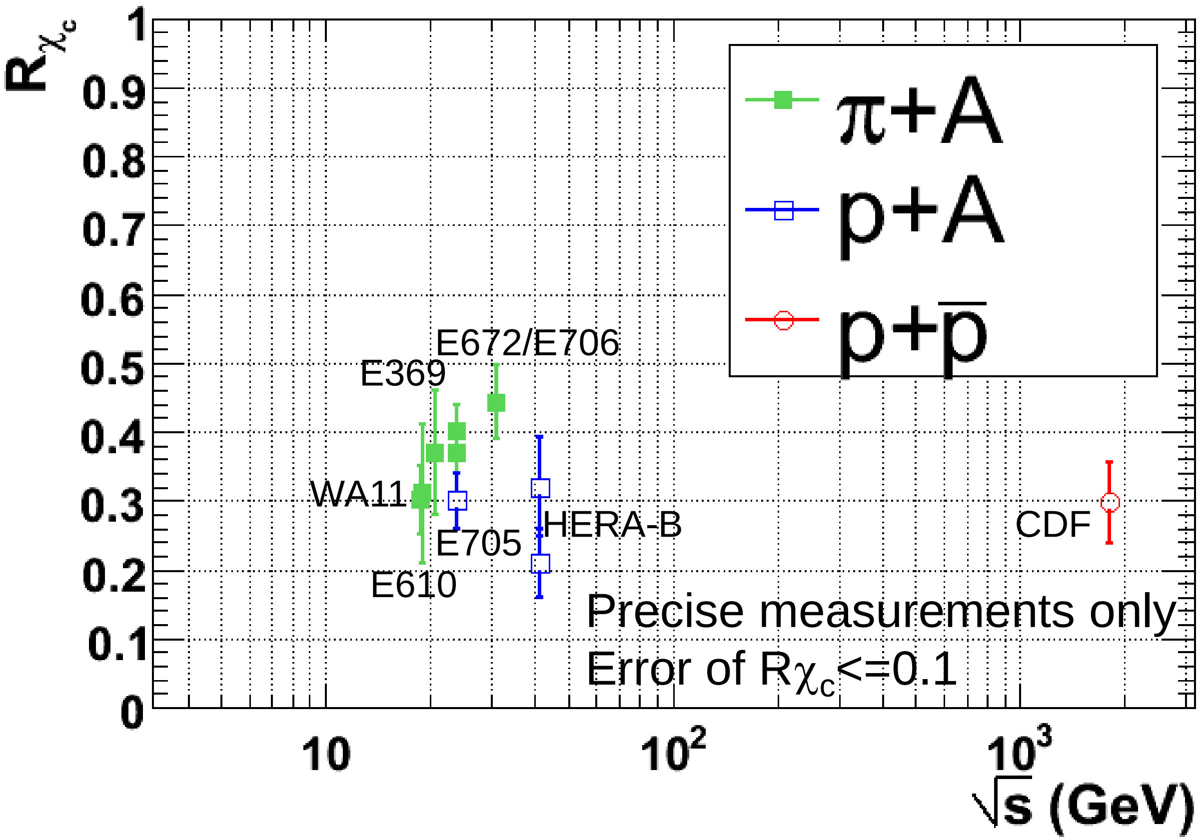
Charmonium system



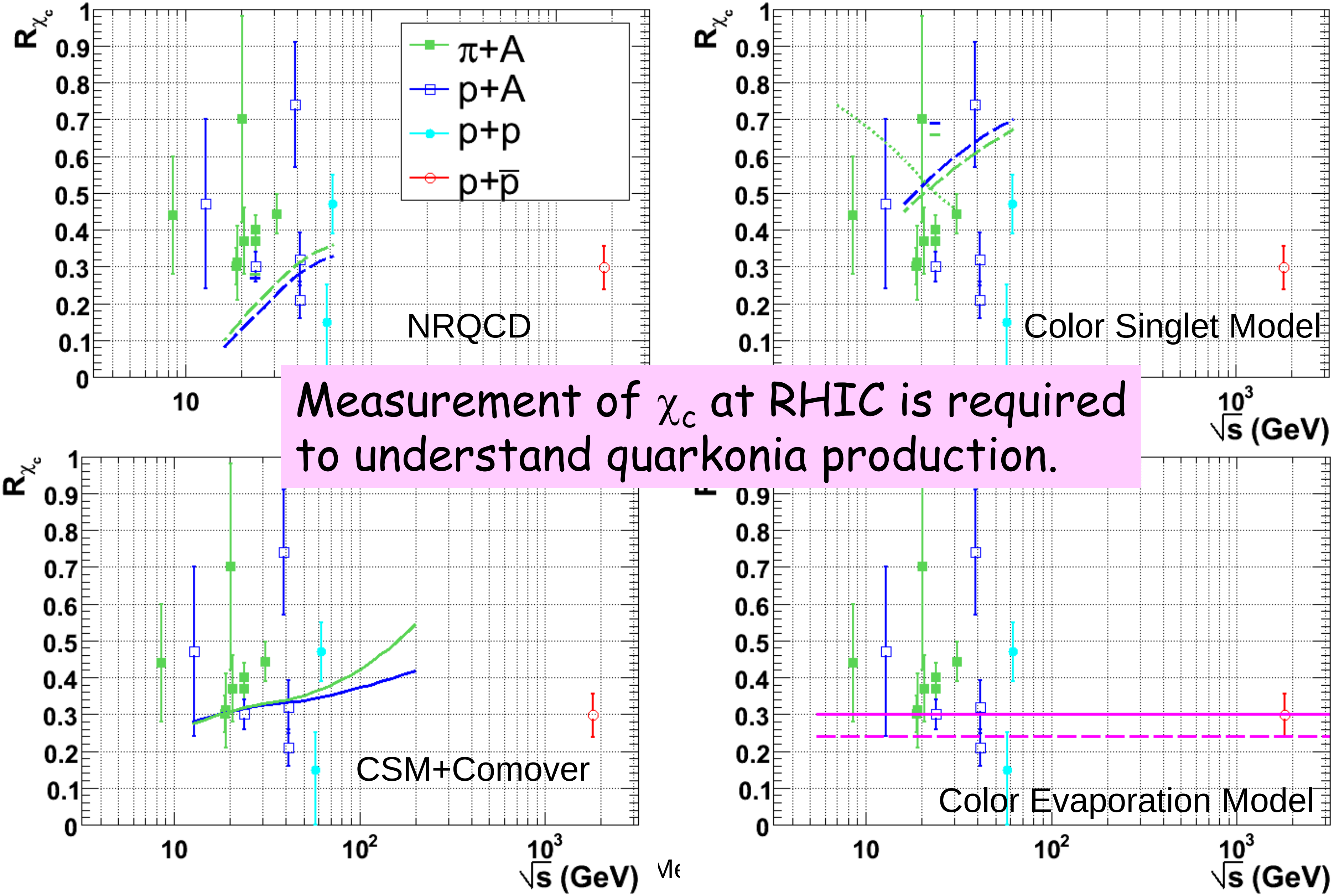
Particle	Mass (MeV/c^2)	Width (MeV/c^2)	Mass difference from J/ψ (MeV/c^2)	$BR(\chi_c \rightarrow J/\psi\gamma)$
$J/\psi(1S)$	3096.916 ± 0.011	0.0934 ± 0.0021	–	–
$\chi_{c0}(1P)$	3414.76 ± 0.35	10.4 ± 0.7	318	$1.30 \pm 0.11\%$
$\chi_{c1}(1P)$	3510.66 ± 0.07	0.89 ± 0.05	414	$35.6 \pm 1.9\%$
$\chi_{c2}(1P)$	3556.20 ± 0.09	2.06 ± 0.12	459	$20.2 \pm 1.0\%$

Fraction of J/ψ from χ_c decay

$$R_{\chi_c} = \frac{1}{\sigma(J/\psi)} \sum_{J=0}^{2} \sigma(\chi_{cJ}) BR(\chi_{cJ} \to J/\psi\, \gamma)$$



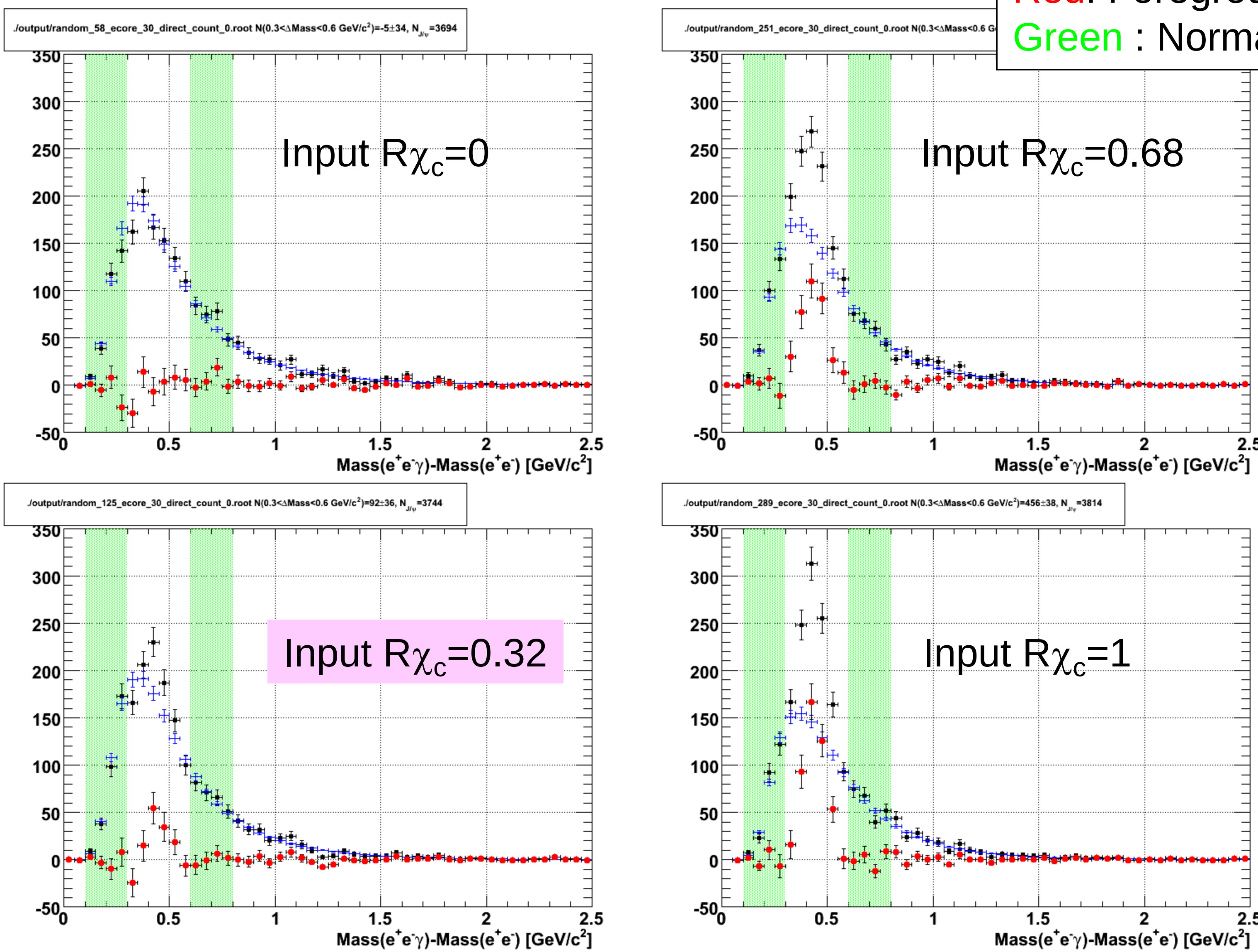
Theoretical Model Predictions



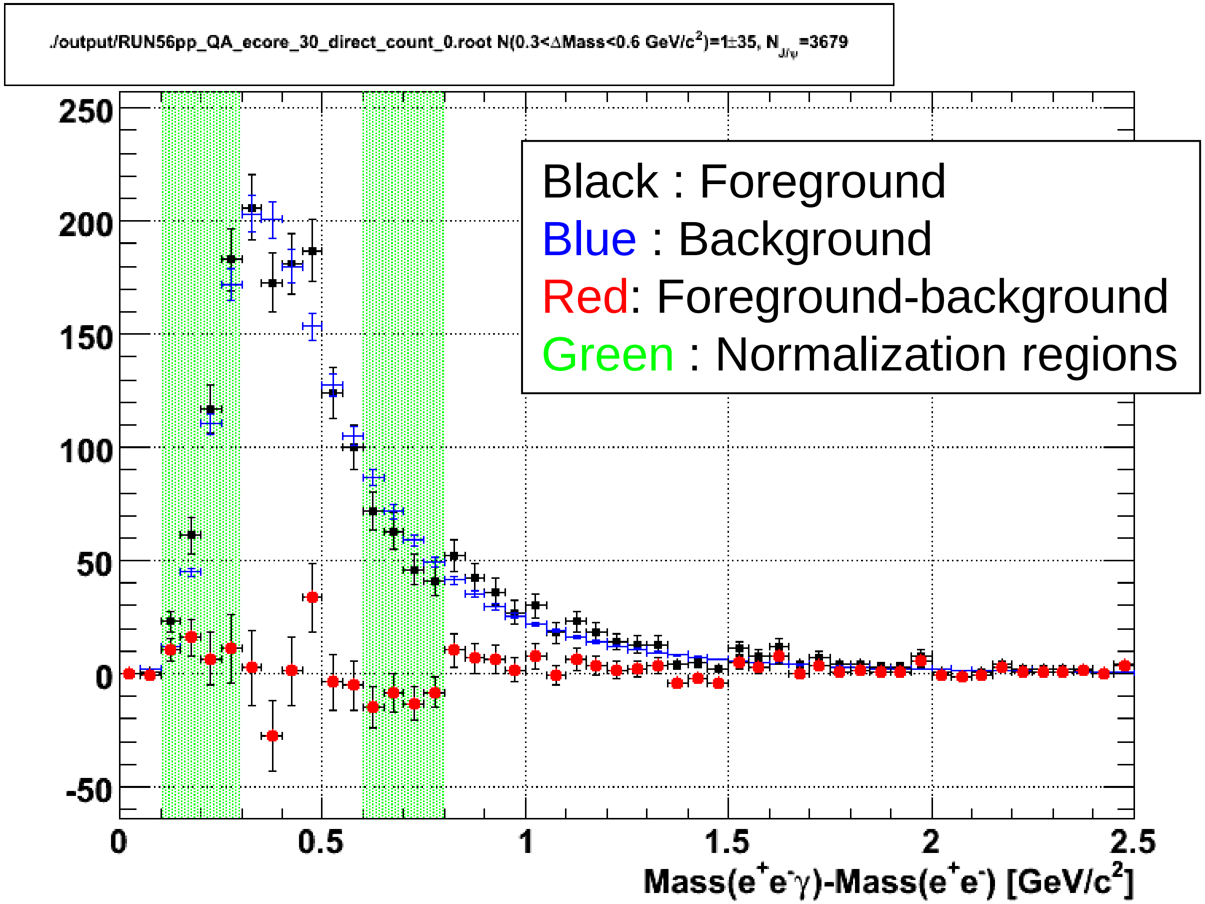
Measurement of χ_c at RHIC is required to understand quarkonia production.

Feasibility Study Using Simulation

Black : Foreground
Blue : Background
Red: Foreground-background
Green : Normalization regions



Data Analysis is in Progress



- The fraction of J/ψ from χ_c feed down (Rχ_c) seems to be small.

Summary

- Direct photons
  - A new preliminary result; photons at low pT in p-p collisions
- Single electrons
  - large suppression at high pT in Au-Au central collisions
    - gluon bremsstrahlung is not enough
  - A new preliminary result; b/(c+b) in p-p collisions
- J/ψ
  - a sequential melting model seems quite reasonable to explain J/ψ suppression Au-Au
  - Analysis of feed down from χ_c is in progress

Outlook

- Not covered in this talk
  - high pT photons
  - large enhancement of low-mass electron pair

- In near future, new findings are expected with higher statistics data for p-p, d-Au, Au-Au (& Cu-Cu) collisions.

- New results soon to come from LHC should provide a different viewpoint to the RHIC results.