LES RENCONTRES DE PHYSIQUE DE LA VALLEE D'AOSTE
La Thuile, Aosta Valley
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Results and Perspectives in Particle Physics
Région Autonome Vallée d'Aoste Assessorat de l'Instruction Publique

"Heavy Ion Collider Physics"

(from Ultra-Peripheral Collisions to Hard Probes)

(~from very forward to y=0 @RHIC)

HI colliders are different from BEVALAC&AGS & SPS:

1) HI beams- a practical laboratory for □-A Interactions

2) Hard probes, jets emerge above the "soft physics" backgrounds

Sebastian White

BROOKHAVEN NATIONAL LABORATORY

<u>Heavy Ion stuff:</u>

•Luminosity determination easier than p-p:+/-5% @RHIC

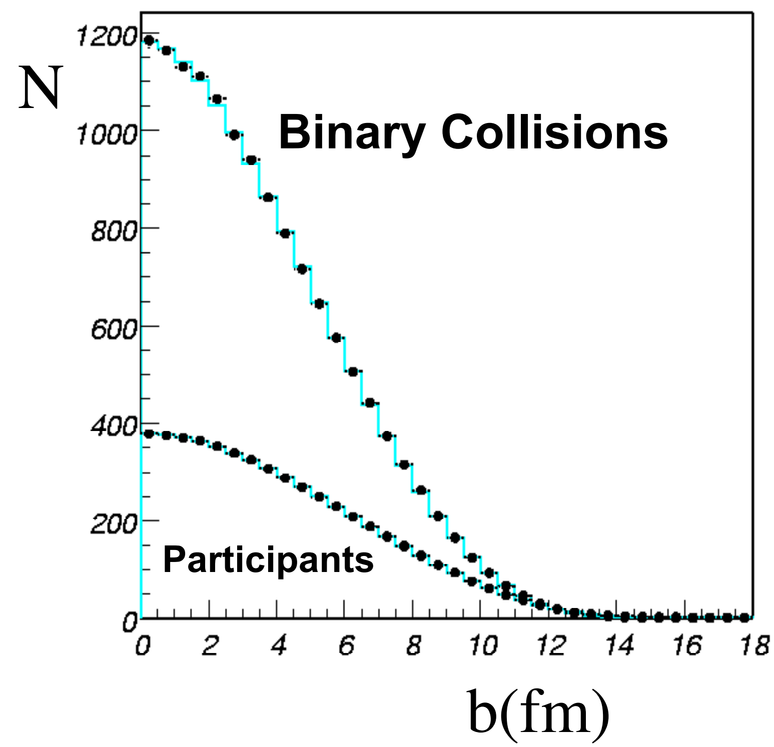
-> ~2% @LHC

•L~2*10^{26}(AuAu) vs ~10^{32}(pp)

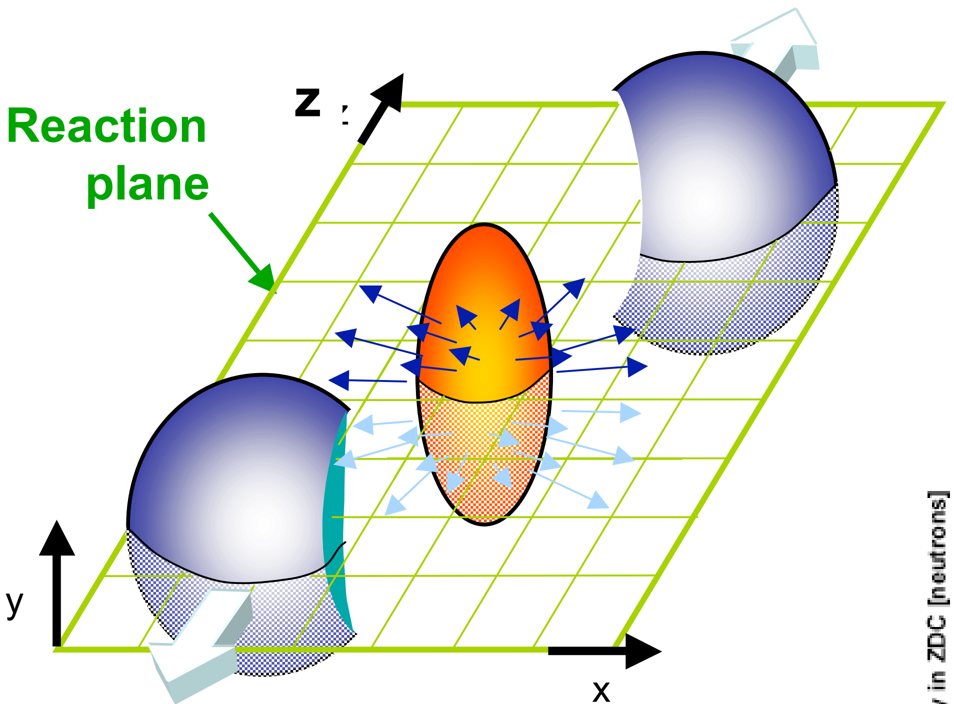
•L(b) vs. b known a priori

$$\frac{\int_0^b b'\,db'}{\int_0 b'\,db'} = \%Centrality$$

N_{part},N_{bin} from Glauber model



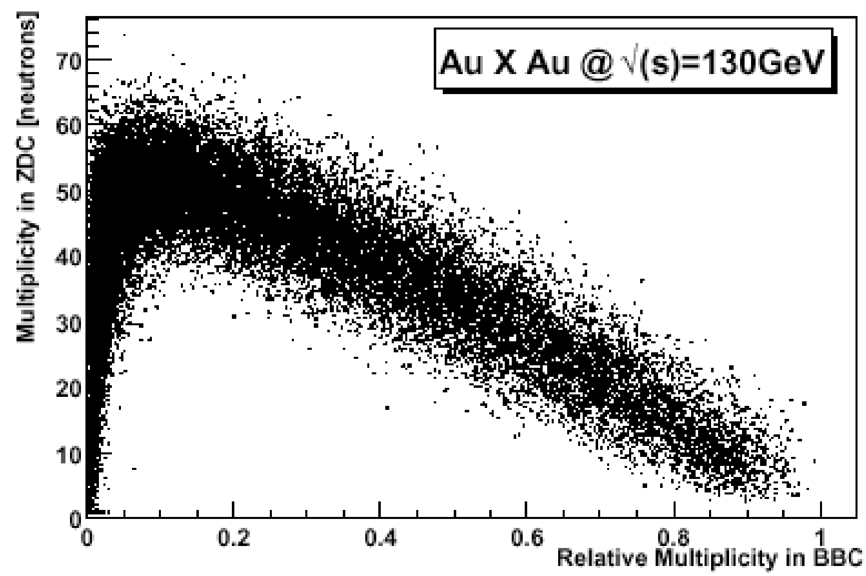
Event characterization with forward detectors(□>3)



Spectator neutrons
•measure centrality,
•Min_min_bias trigger

(Calorimeter@□<2mr.)

b direction from BBC
(3<□<4 hodoscope array)

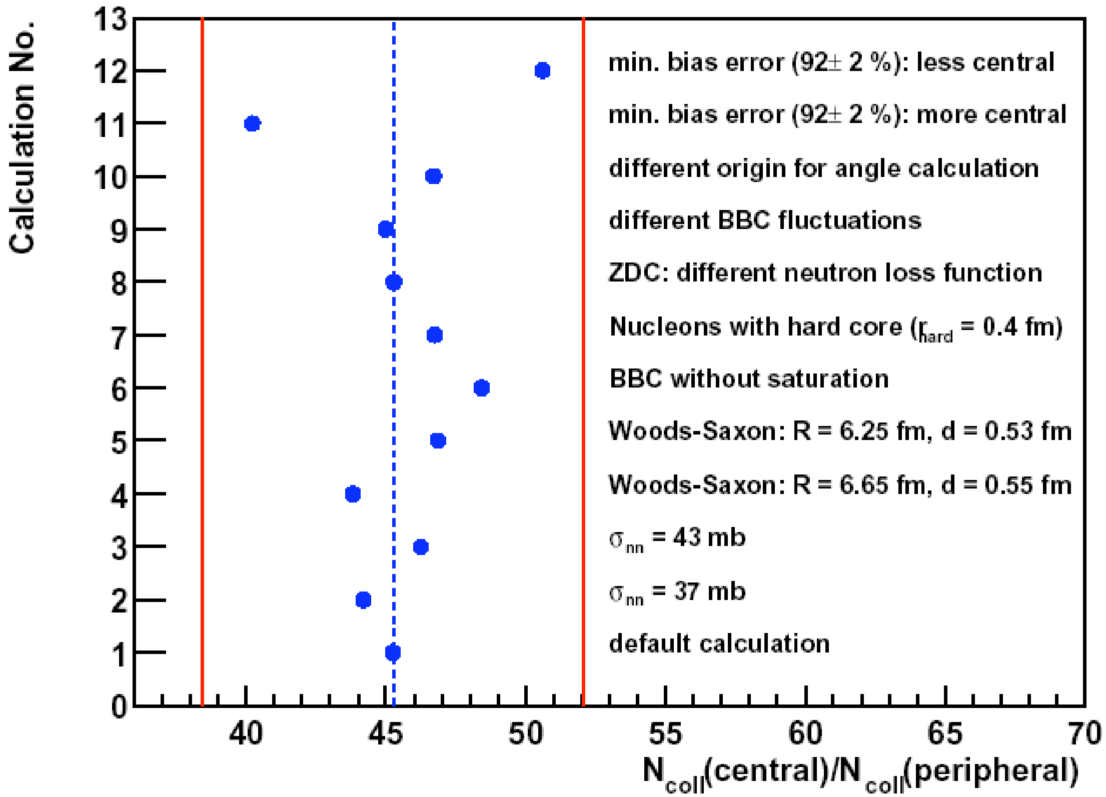


Beam-Beam Counter Mult/1000

AA cross-normalization with pp

1) From pp comparison data
   - Error from AA &pp Luminosity uncertainties and $_{\text{ncollision}}$

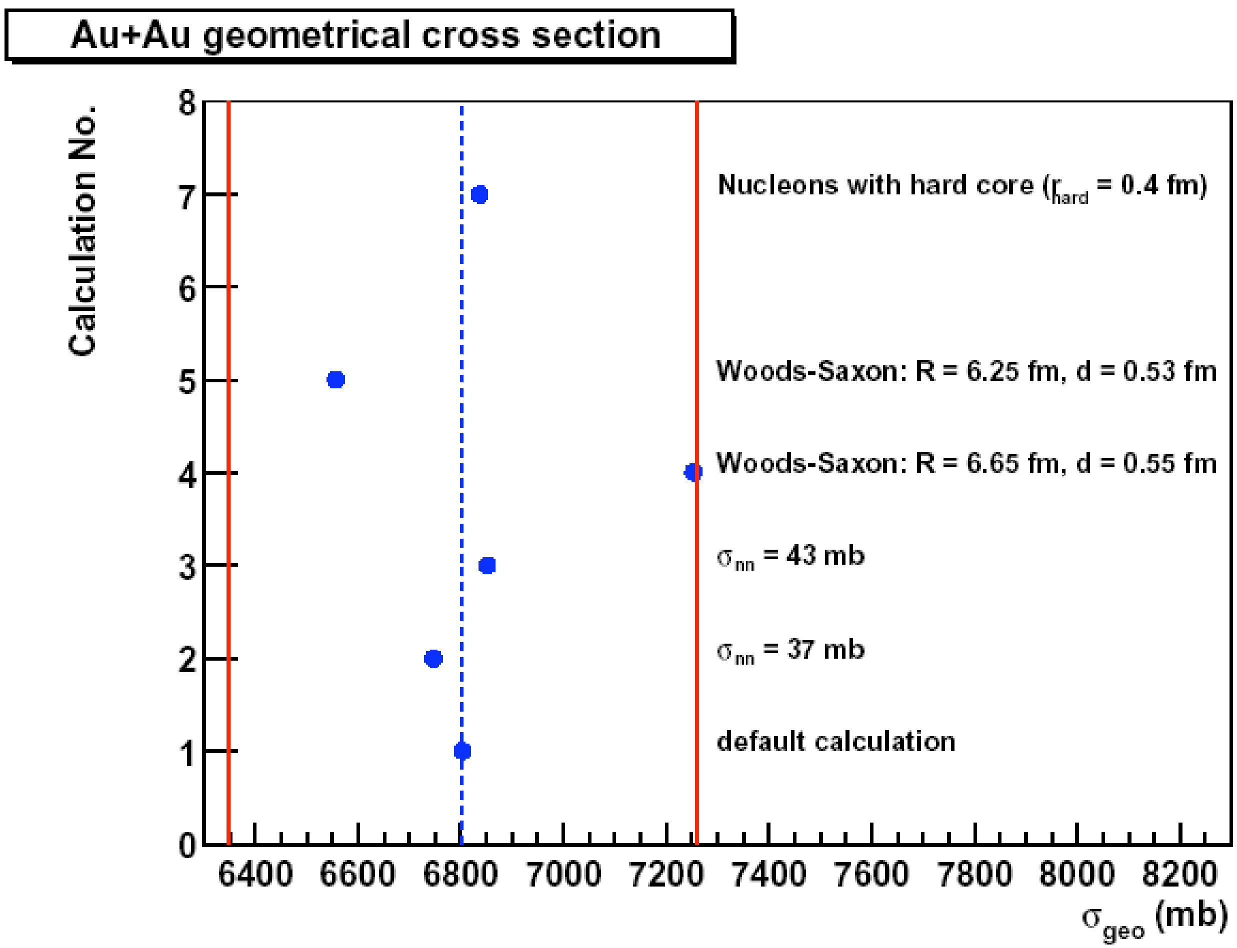
2) From central/peripheral
   - Error from determination of centrality classes



<- *Klaus Reygers, PHENIX internal note 7/01*

Total Inelastic Cross sections

Ion Geometric cross sections decouple from σ_{nn}



<- *ditto*

Electromagnetic Interactions of Heavy Ions:

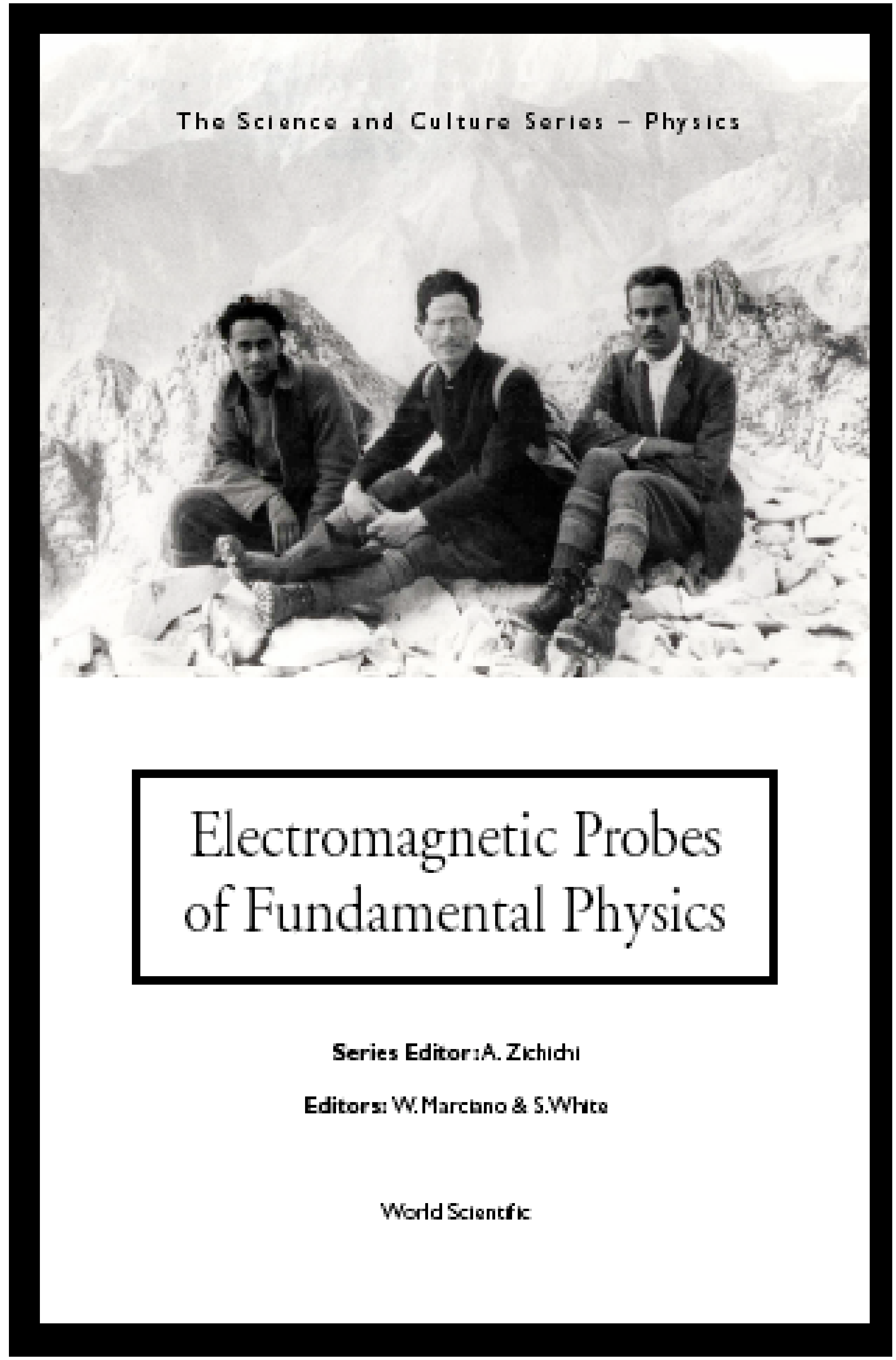
('24)-E.Fermi develops Equivalent γ approx for int of e^- and γ's with atoms

('33) -Weiszacker and Williams

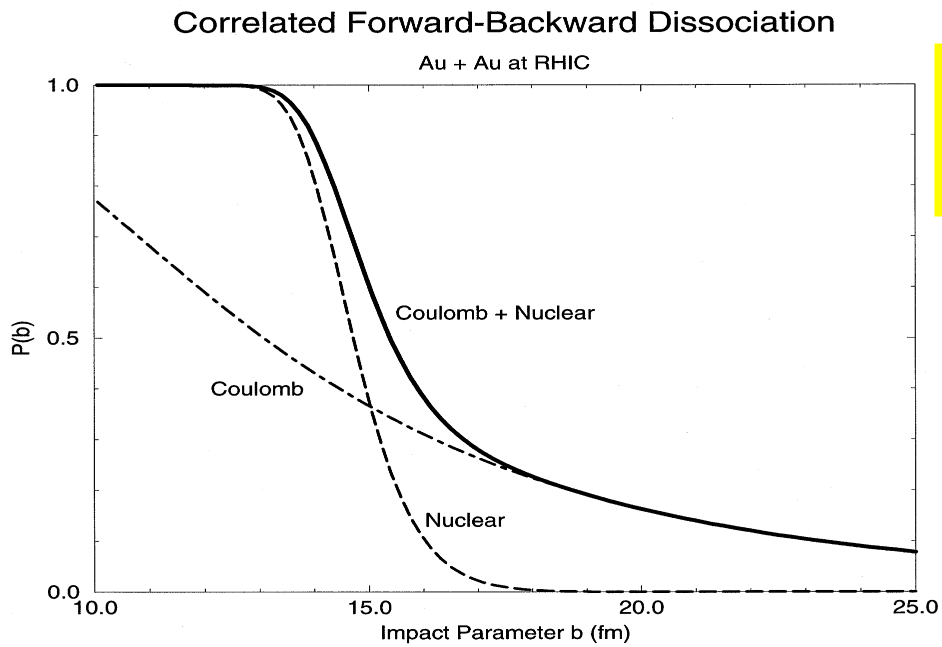
(50's) demonstration of EPA with interactions of ~500 MeV e^- with Nuclei- (Wilson, Panofsky et al. @ Stanford)

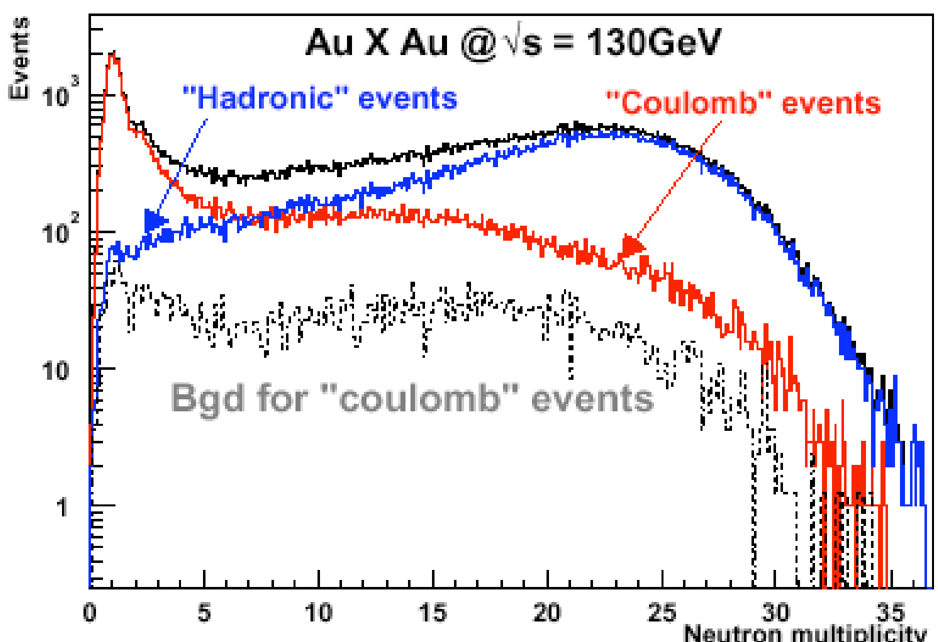
(80-90's) -first measurement of EM interaction using ion beams @Bevalac SPS and AGS

('03->)- "rapidity gap" physics w. Heavy Ions @ RHIC & LHC

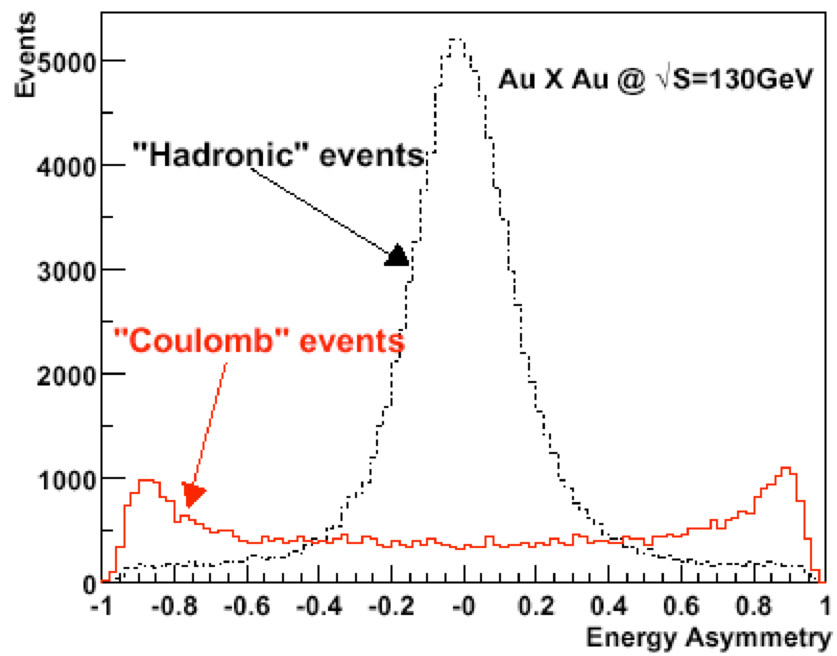


Large Ultra-Peripheral Cross Section from Coulomb Interactions





1 arm: calorimeter n multiplicity



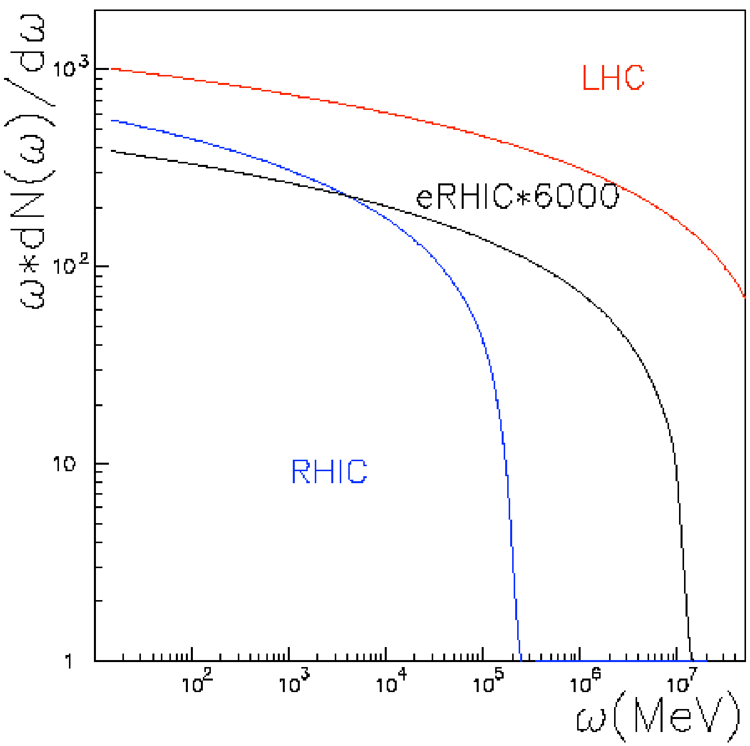
Difference: calorimeter n-mult

Cross sections from Run I in PRL

(1)Baltz & SNW
(2)Bondorff et al.
Meas.=Chiu et al.

TABLE I. Cross sections calculated and derived from the data. The errors quoted on measurements include the uncertainty of the BBC cross section [8]

Cross Section	Calculated Value(1)	Calculated Value(2)	Measured
σ_{tot}	10.83 ± 0.5Barns	$11.19 \pm$	N.A.
σ_{geom}	$7.09 \pm xx$	$7.29 \pm$ xx	N.A.
$\frac{\sigma_{geom}}{\sigma_{tot}}$	0.67	0.65	0.661 ± 0.014
electromagnetic			
$\frac{\sigma(1n,Xn)}{\sigma_{tot}}$	0.125	xx	$0.117 \pm 0.003 \pm 0.002$
$\frac{\sigma(1n,1n)}{\sigma_{1n,Xn}}$	0.329	xx	$0.345 \pm 0.01 \pm 0.006$
$\frac{\sigma(2n,Xn)}{\sigma_{1n,Xn}}$	xx	0.327	$0.345 \pm 0.011 \pm 0.01$



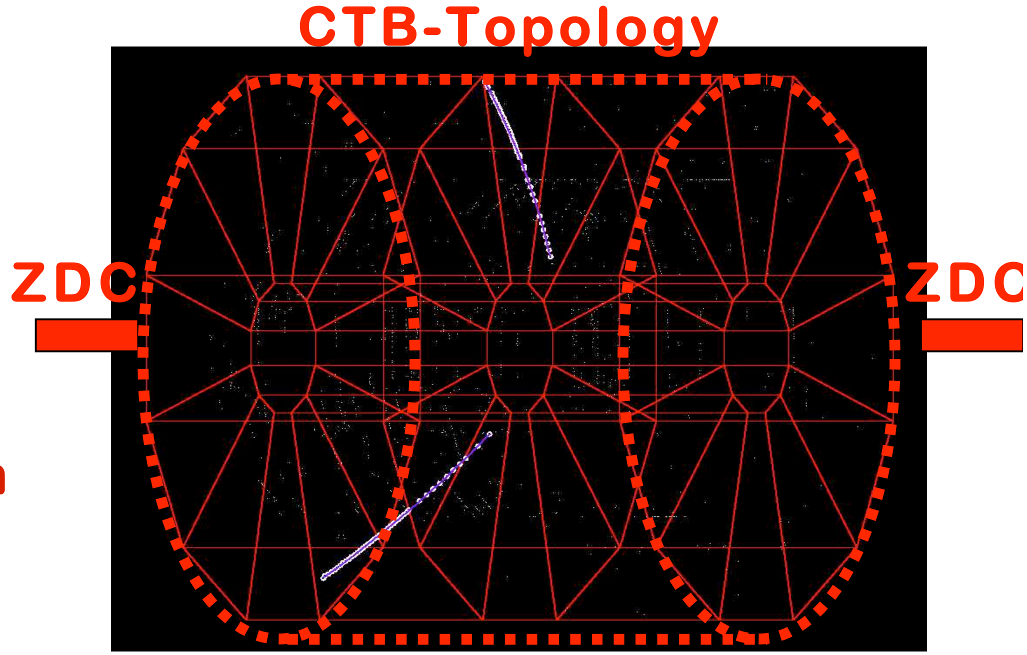
“Quasi-real” spectra compared to an e-hadron collider (target frame)

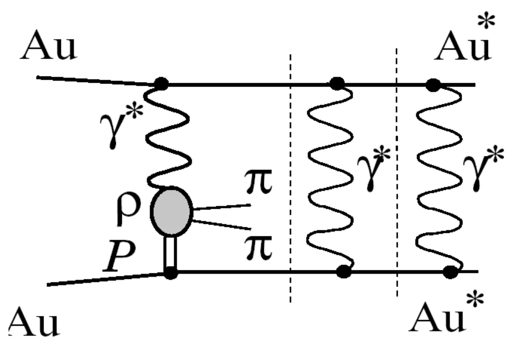
->100 TeV @ LHC

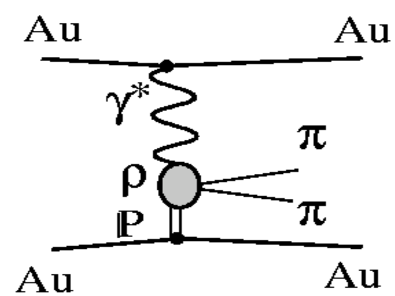
Experimental Signature of UPC

- Two oppositely charged tracks with vertex
- Low total p_T
- Back-to-back in transverse plane

STAR peripheral production
F.Meissner, LBNL





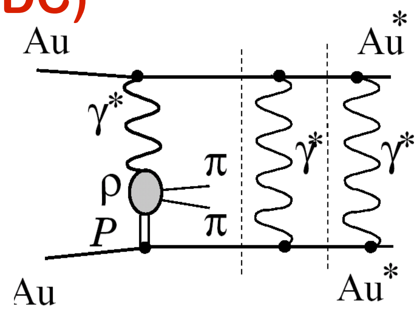


Coincident signals from nucl. Breakup in zero degree calorimeters (ZDC)

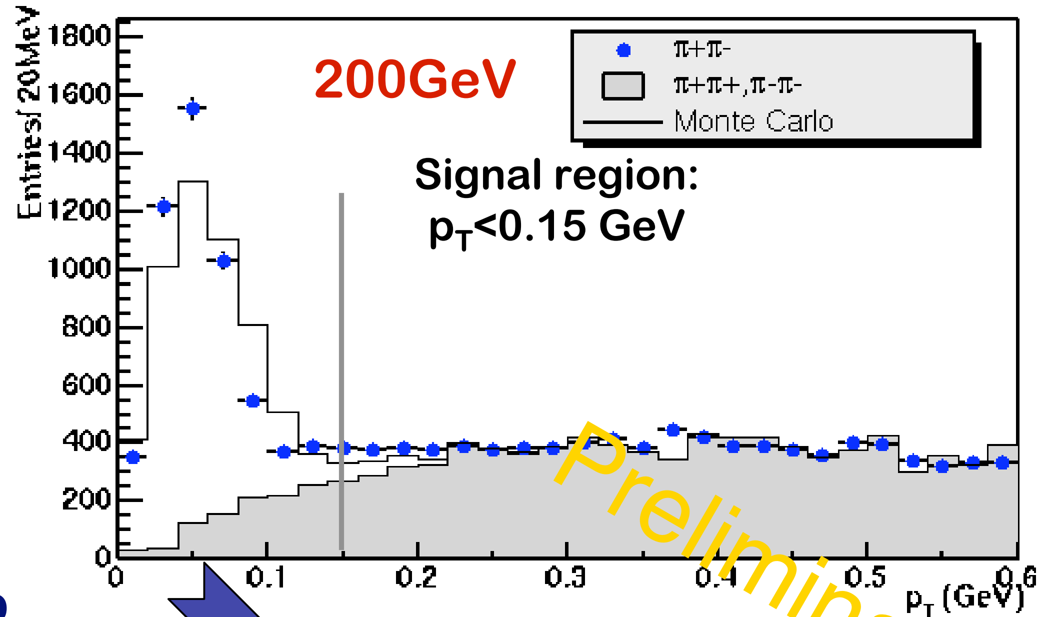
Topology requirements in central trigger barrel (CTB)

Meson Production with Nuclear Break-up

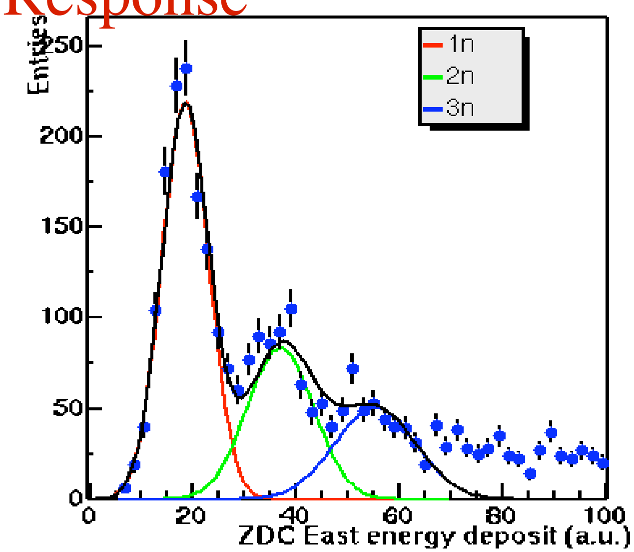
Minimum Bias (ZDC) Trigger AuAu
□Au*Au*□^{0}

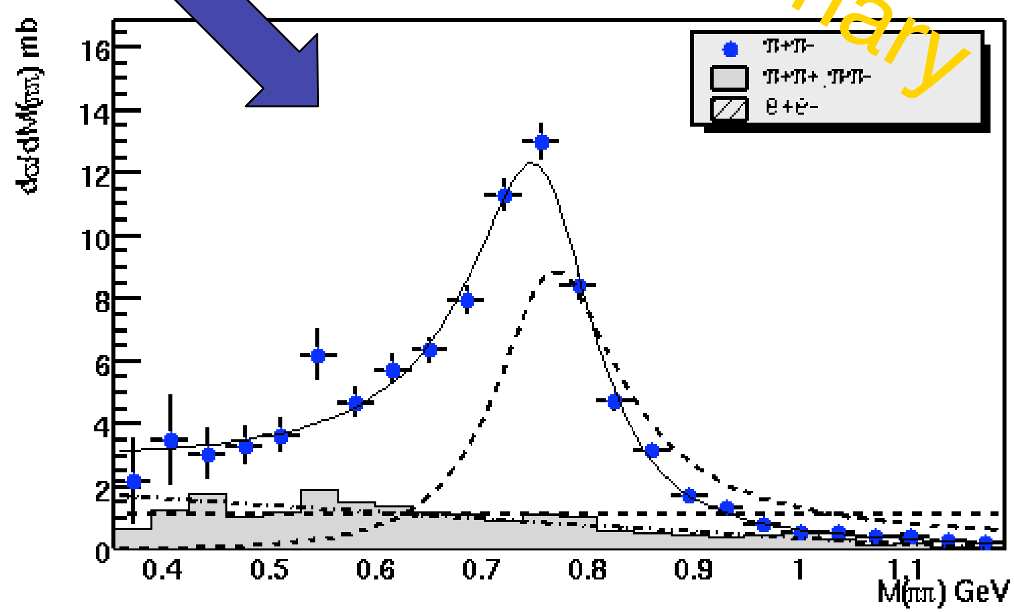


- **2000: ~400k triggers L~60/mb**
- **2001: ~1.7M triggers L~250/mb**

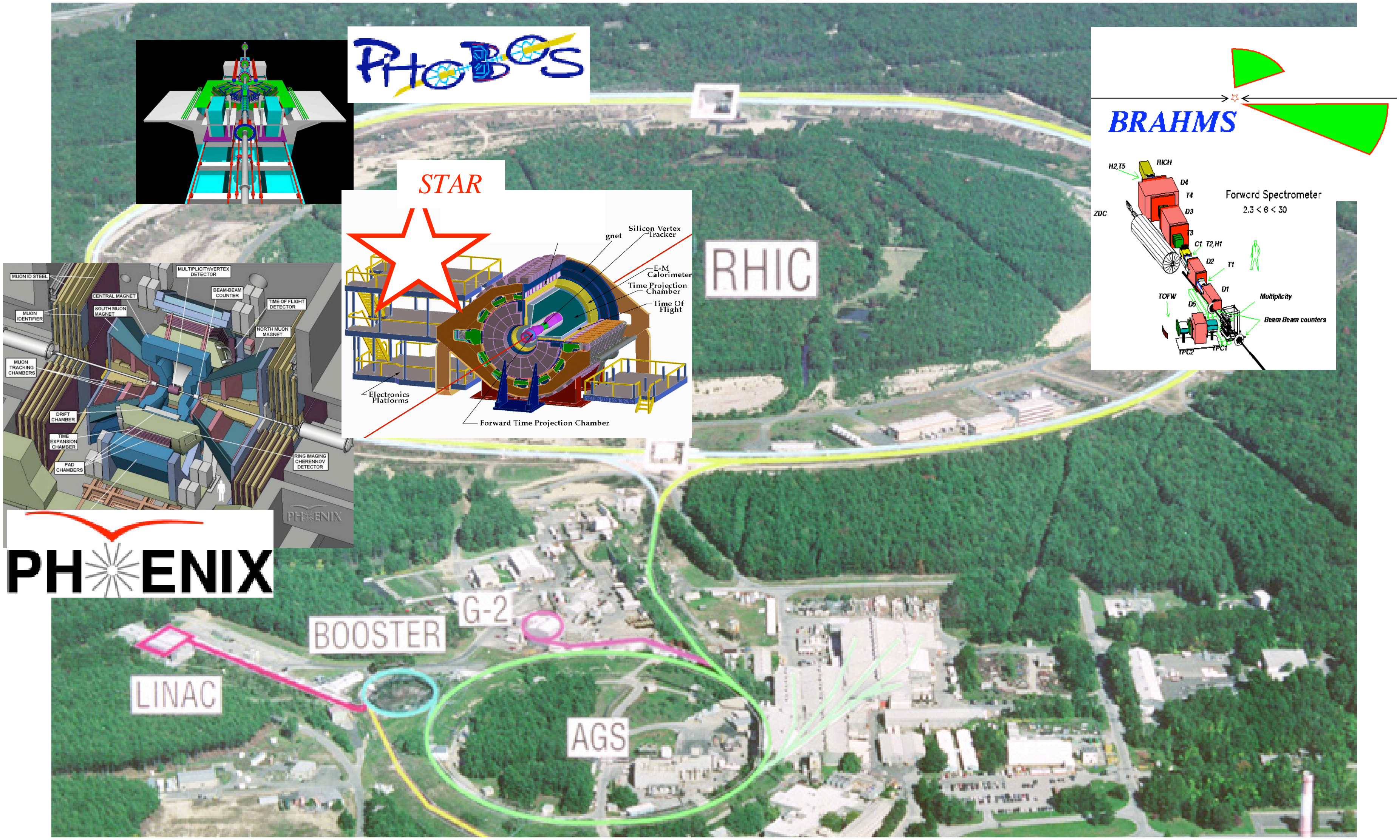


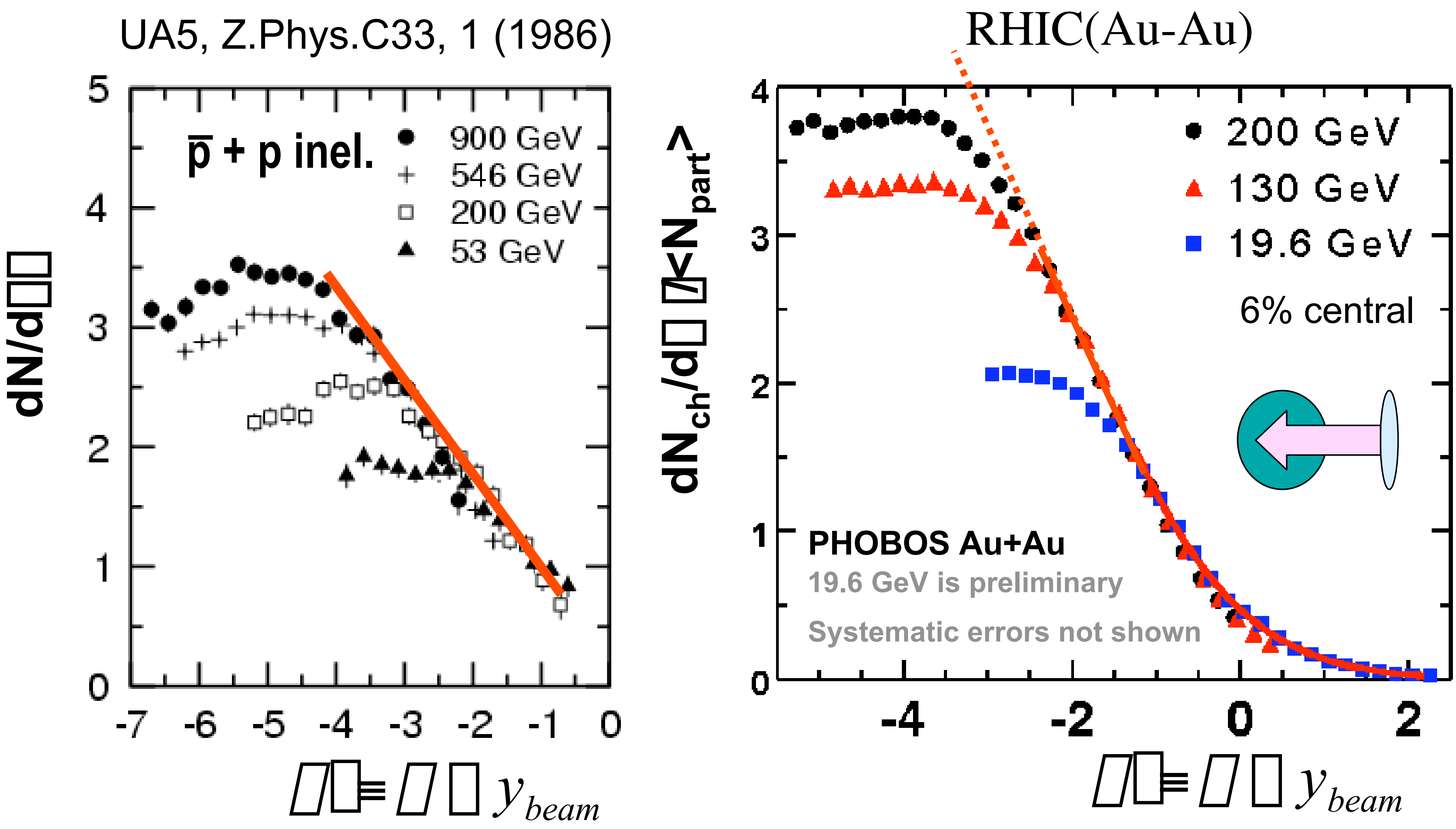
ZDC Response





The Four RHIC Experiments

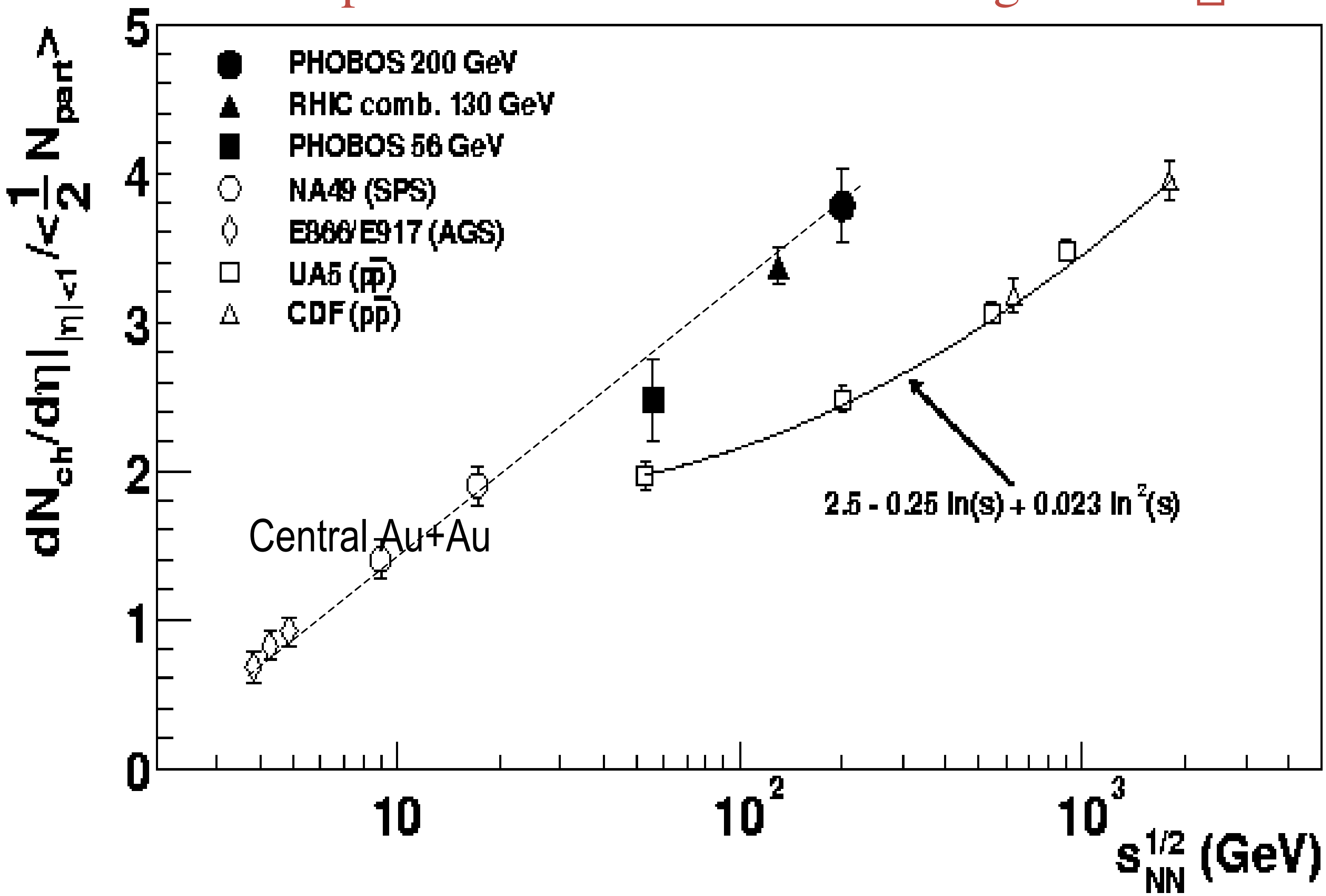




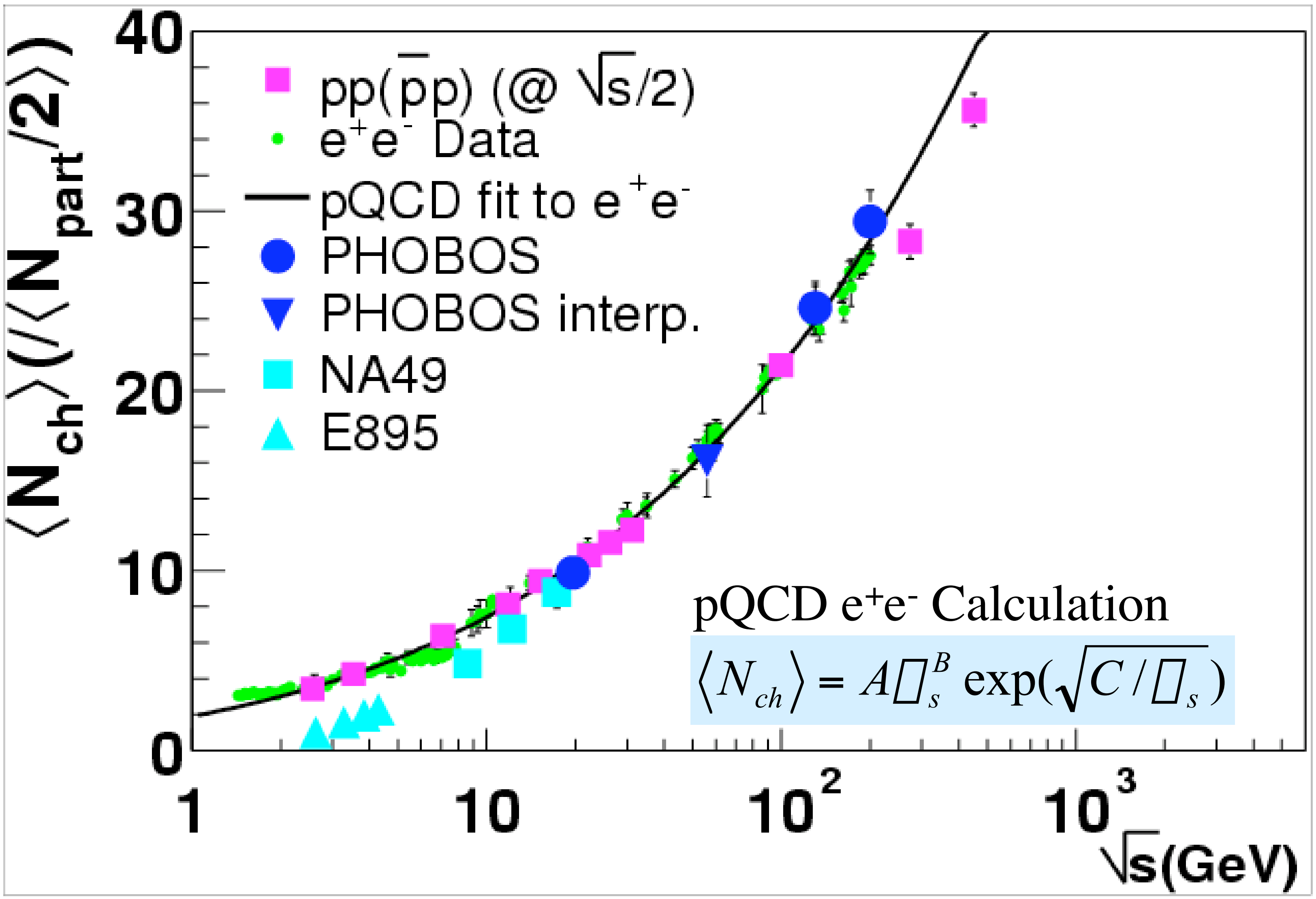
“forward-edge” of charged multiplicity distribution relative to y_{beam}

Highlights from Run 1(&2): Multiplicity distributions (PHOBOS et al.)

Extrapolation to LHC ~1/4 of "design" dN/d



Comparison of ⟨N_{ch}⟩ vs. Energy



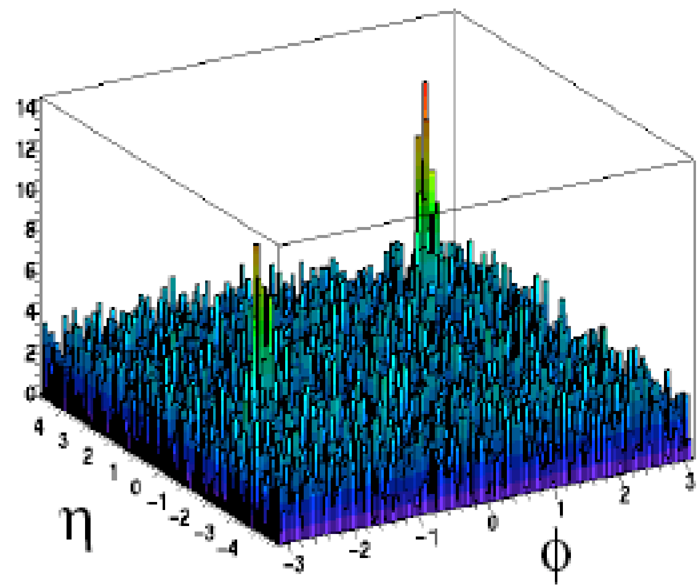
$$\langle N_{ch} \rangle = A \alpha_s^B \exp(\sqrt{C/\alpha_s})$$

P.Steinberg, BNL(PHOBOS)

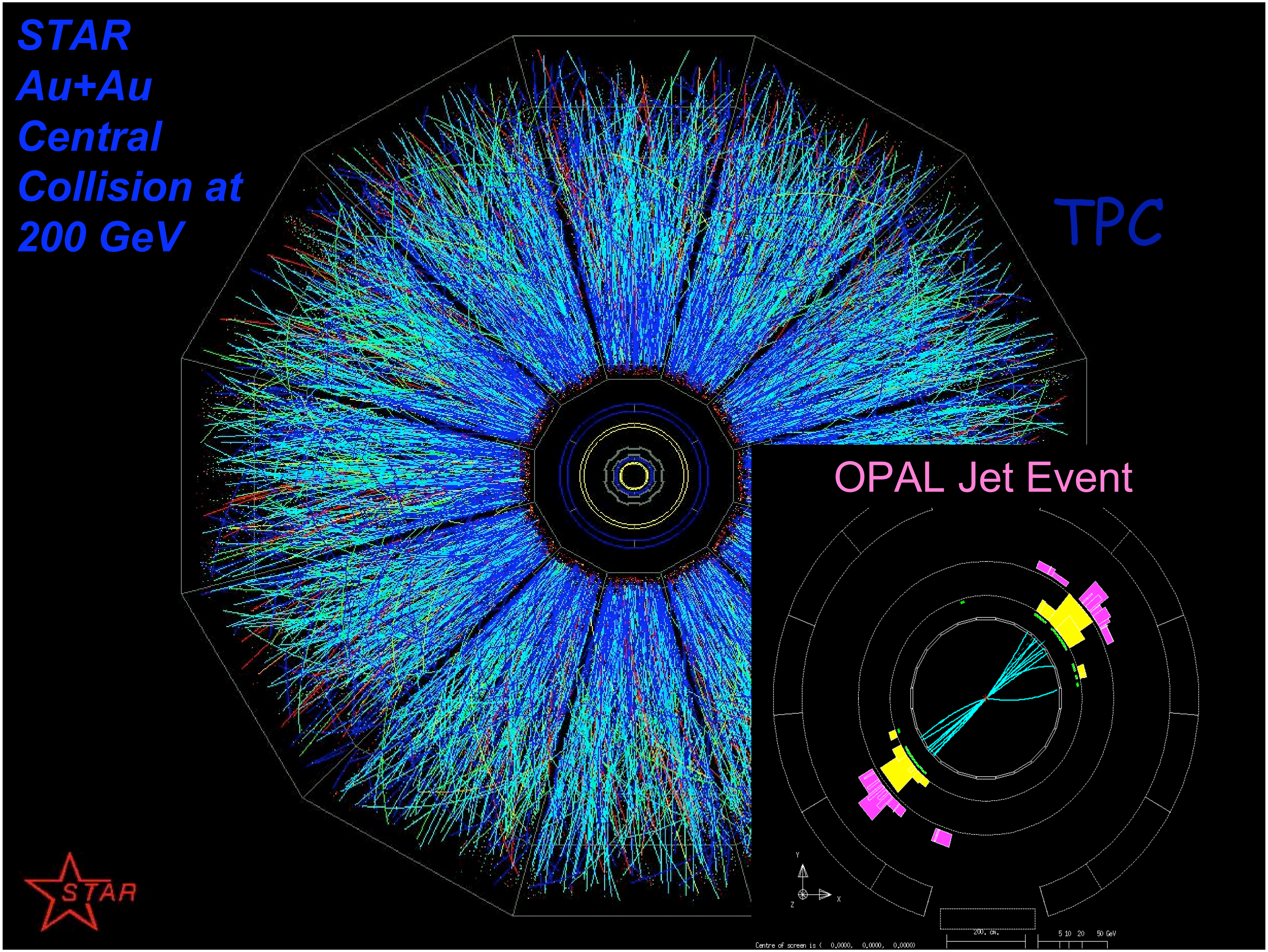
How to measure jets @ RHIC?

(similar to ISR-era with pp)

- -focus on measurement of high-p_T hadrons
  - → Dominated by fragmentation of hard-scattered partons.
- -also angular / p_T correlations between hadrons
  - → Indirectly sensitive to jet properties
  - → And to di-jets

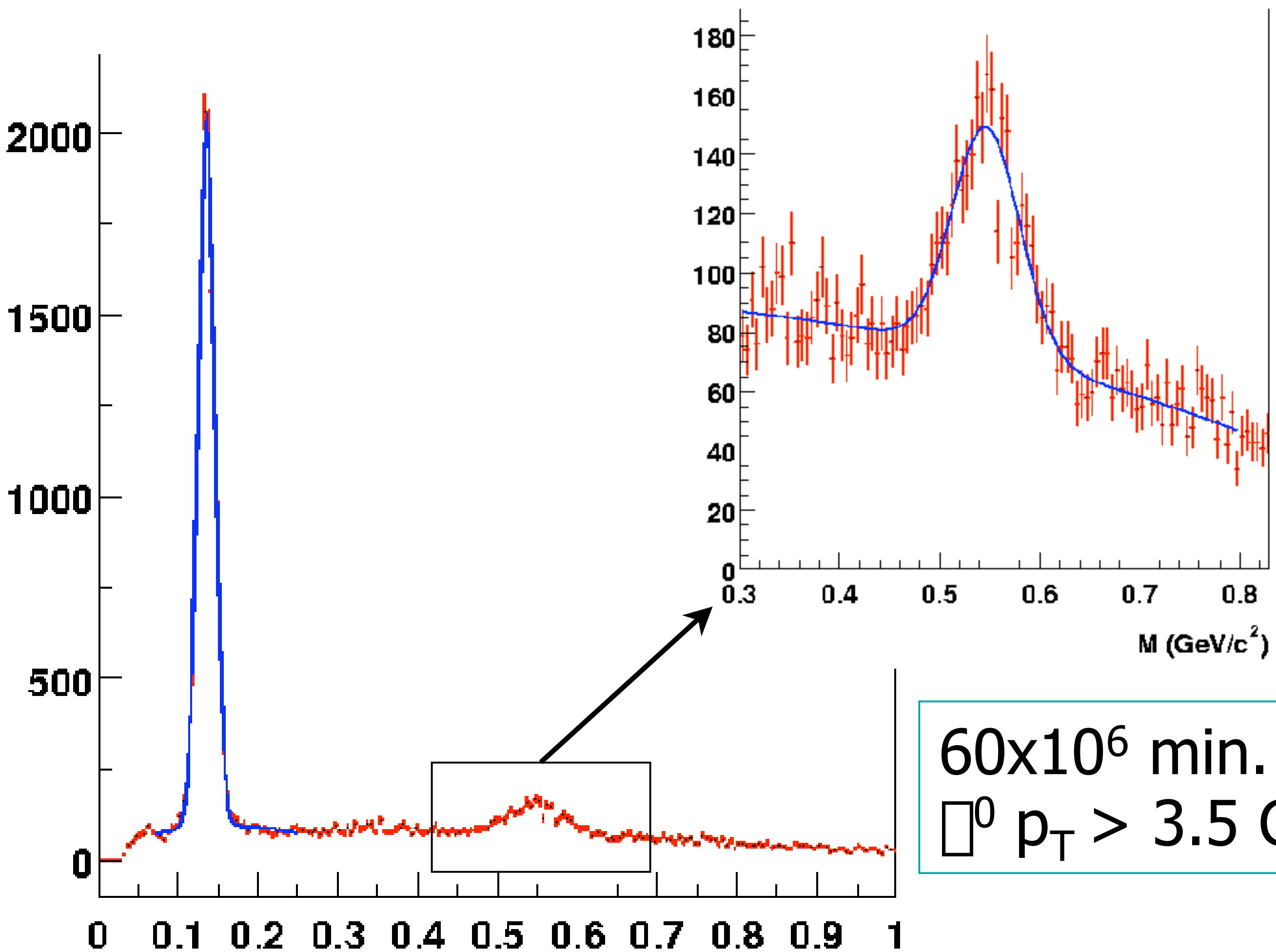


200 GeV jet overlay on central Pb-Pb event with ATLAS calorimter segmentation


STAR
Au+Au
Central
Collision at
200 GeV
TPC
OPAL Jet Event
STAR
200. cm.
5 10 20 50 GeV
Centre of screen is (0.0000, 0.0000, 0.0000)

PHENIX EMC

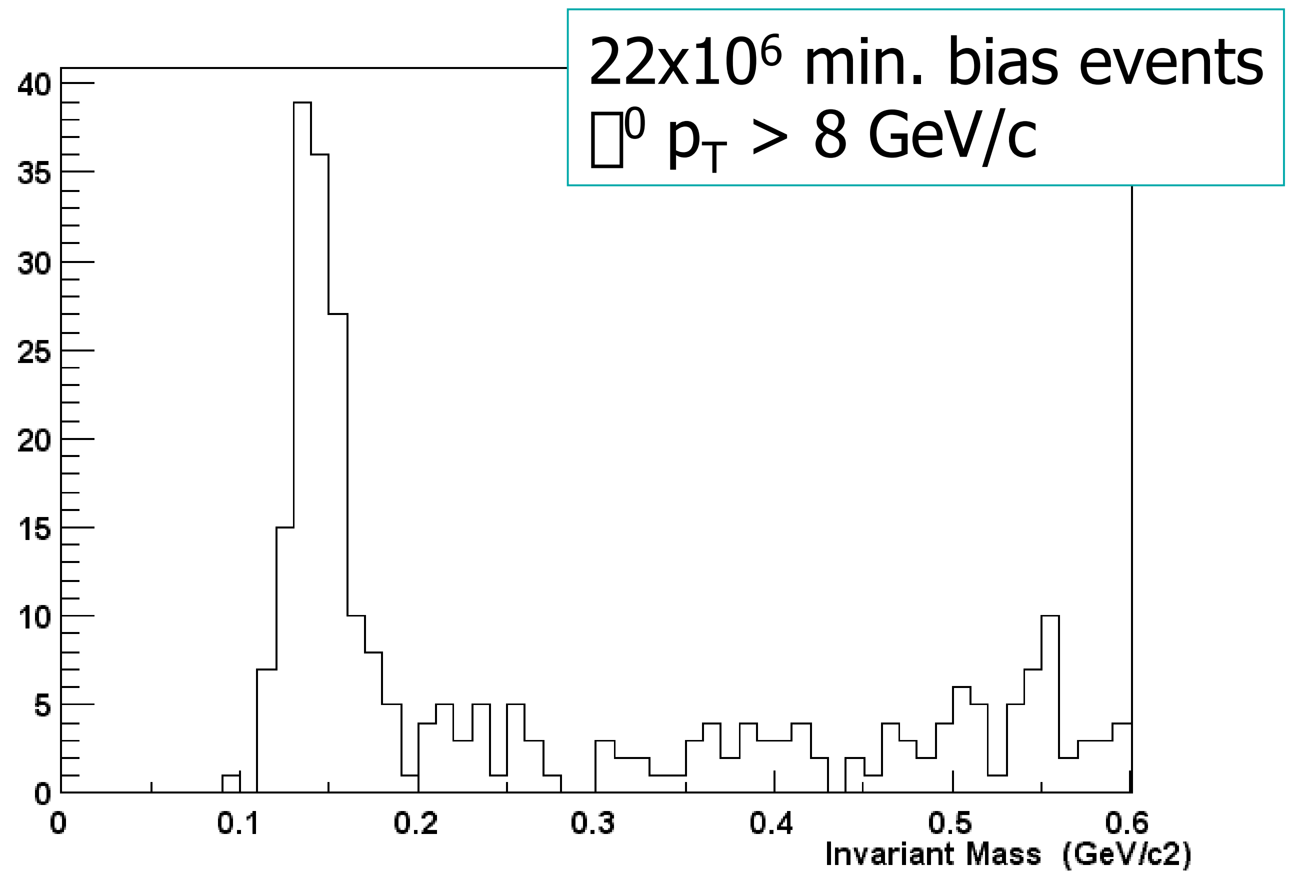
π^0 in p+p at $\sqrt{s}$ = 200 GeV



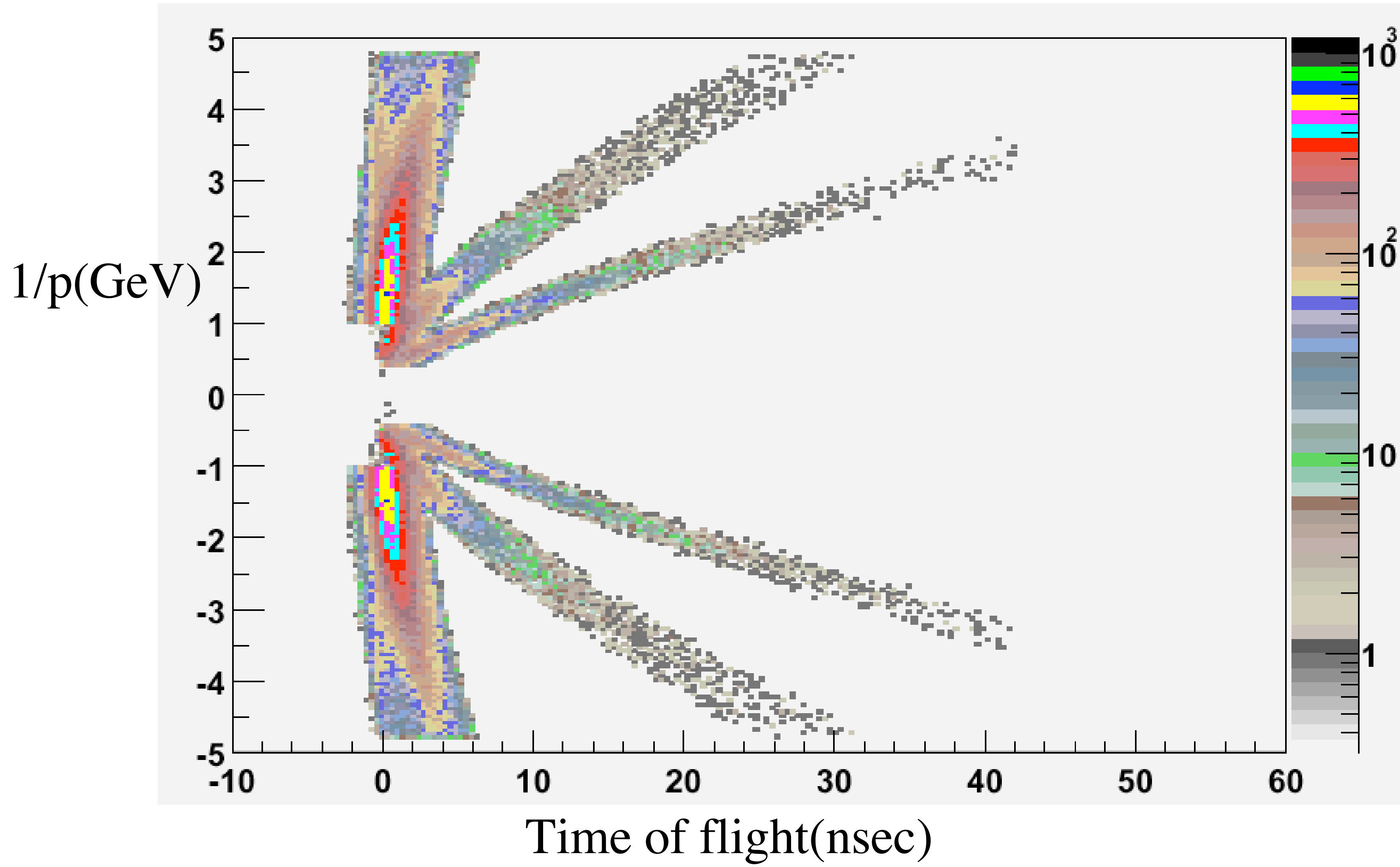
60×10^6 min. bias events
π^0 p_T > 3.5 GeV/c

PHENIX EMC

high p_T π^0 full energy Au+Au



Particle id w. PHENIX Pb/Sc EMCAL t.o.f.



RHIC Measurements at High p_T

0. Foreword: " high p_T" _ $p_T > 2.0$ GeV/c @ mid-rapidity (except $y \approx 2$ BRAHMS $□^-$)

1. Unidentified charged-particles:
   - 130 GeV ($p_T^{max} \approx 5$ GeV/c)
   - 200 GeV ($p_T^{max} \approx 12$ GeV/c)
2. Identified baryons – protons, lambdas:
   - 130 GeV ($p_T^{max} \approx 3.5$ GeV/c)
   - 200 GeV ($p_T^{max} \approx 4 - 5$ GeV/c)
3. Identified mesons – $□^0$, $□^\pm$:
   - 130 GeV ($p_T^{max} \approx 4$ GeV/c)
   - 200 GeV ($p_T^{max} \approx 10$ GeV/c for Au+Au, 13 GeV/c for p+p)
4. Particles ratios:
   - 130 GeV ($p_T^{max} \approx 3.5$ GeV/c)
   - 200 GeV ($p_T^{max} \approx 4$ GeV/c)

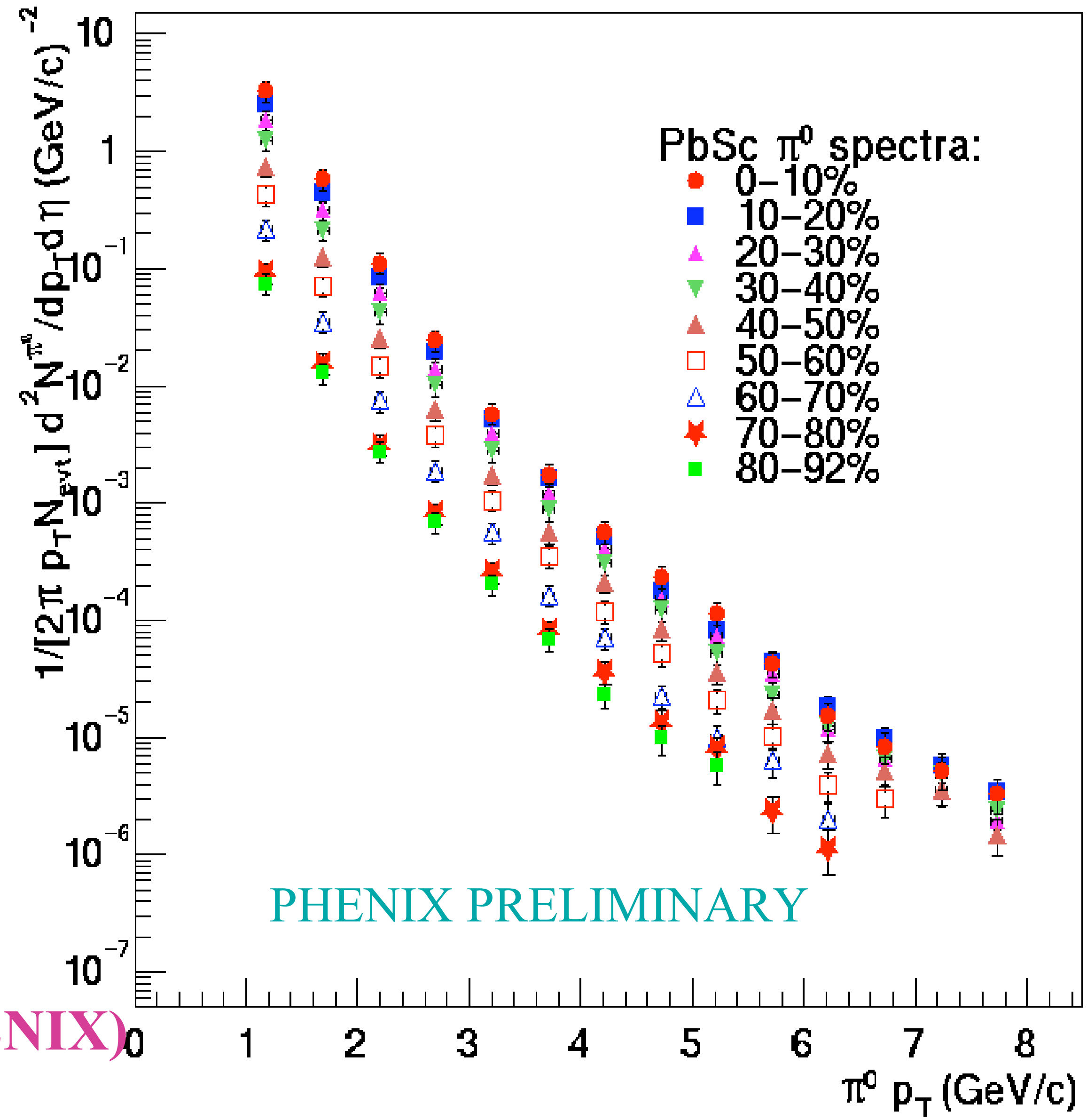
5. Two-particle correlations

π^0 yields measured in Au+Au collisions for all centralities

- "Invariant yields" vs. centrality
- Most central 0-10%

vs.

- Most peripheral 80-92%: like p+p collision
- also compare to pp (PHENIX data and SppS)



S. Mioduszewski,BNL(PHENIX)

If no nuclear enhancement/suppression expect:

$$\frac{\text{Yield}_{AA}}{\text{Yield}_{pp}} = \text{number of Nucleon - Nucleon binary collisions}$$

$$= \langle N_{binary} \rangle \quad \text{for the AA centrality class}$$

- Define :

$$R_{AA}(p_T) = \frac{1/N_{events}\, d^2N^{AA}/dp_T d\eta}{\langle N_{binary} \rangle (d^2\sigma_{pp}/dp_T d\eta / \sigma^{pp}_{inelastic})} = \frac{\text{Yield}_{central} / \langle N_{binary} \rangle_{central}}{\text{Yield}_{pp}}$$

$$= \frac{\text{Yield}_{central} / \langle N_{binary} \rangle_{central}}{\text{Yield}_{peripheral} / \langle N_{binary} \rangle_{peripheral}}$$

Expectations in nuclear collisions

- In the absence of nuclear effects, these ratios are expected to be 1 at high p_T

- Departures from 1, measure nuclear effects

  Previously observed effects (at lower energies):
  - Shadowing
  - "Cronin effect" (p_T broadening)

  Possible new effect:
  - Parton energy loss in dense medium

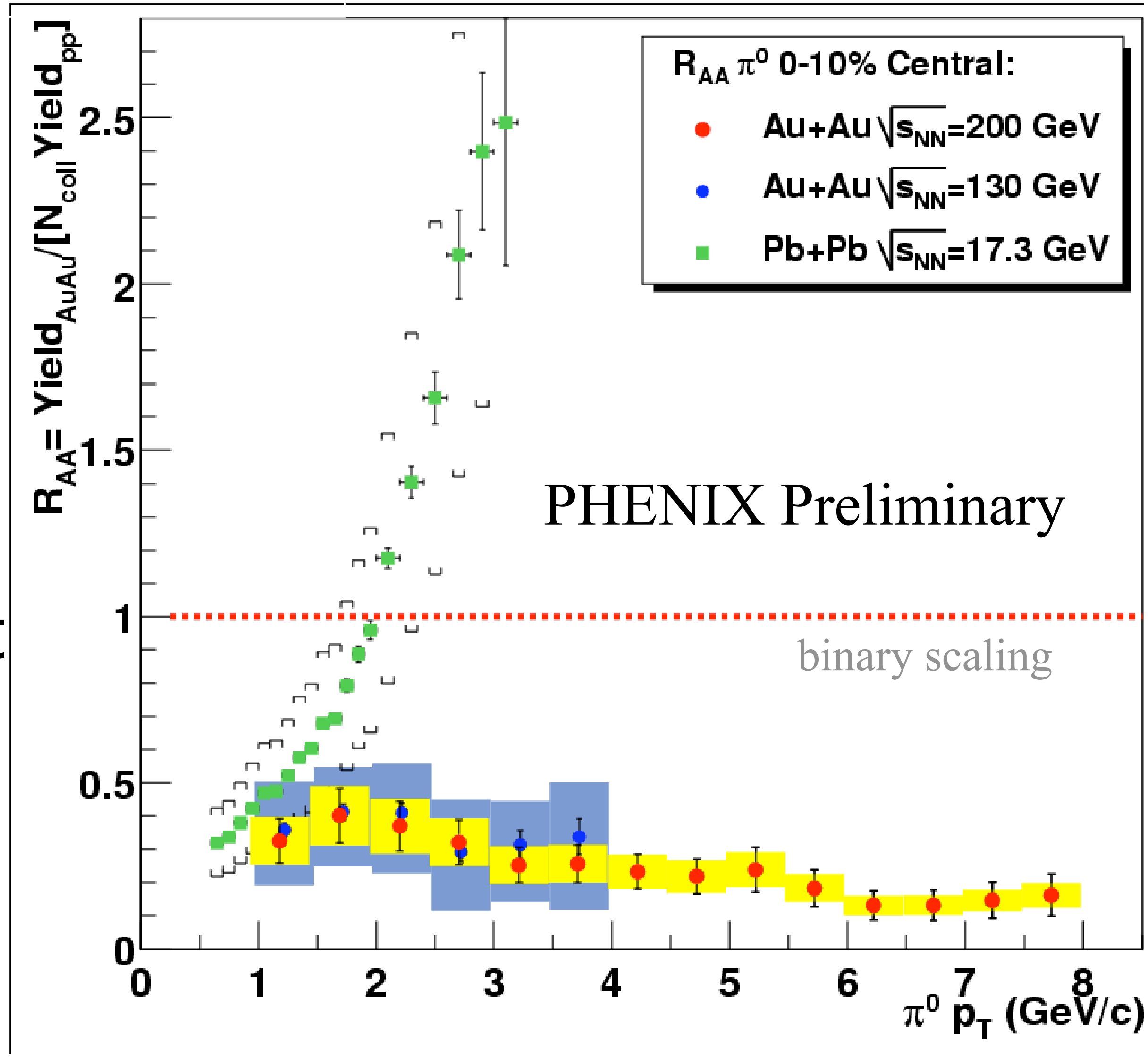
Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{1/N_{events}\ d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle (d^2\sigma_{pp}/dp_T d\eta / \sigma^{pp}_{inelastic})} =$$

$$\frac{Yield_{central} / \langle N_{binary}\rangle_{central}}{Yield_{pp}}$$

SPS – "Cronin" effect

RHIC - suppression



Nuclear Modification Factor

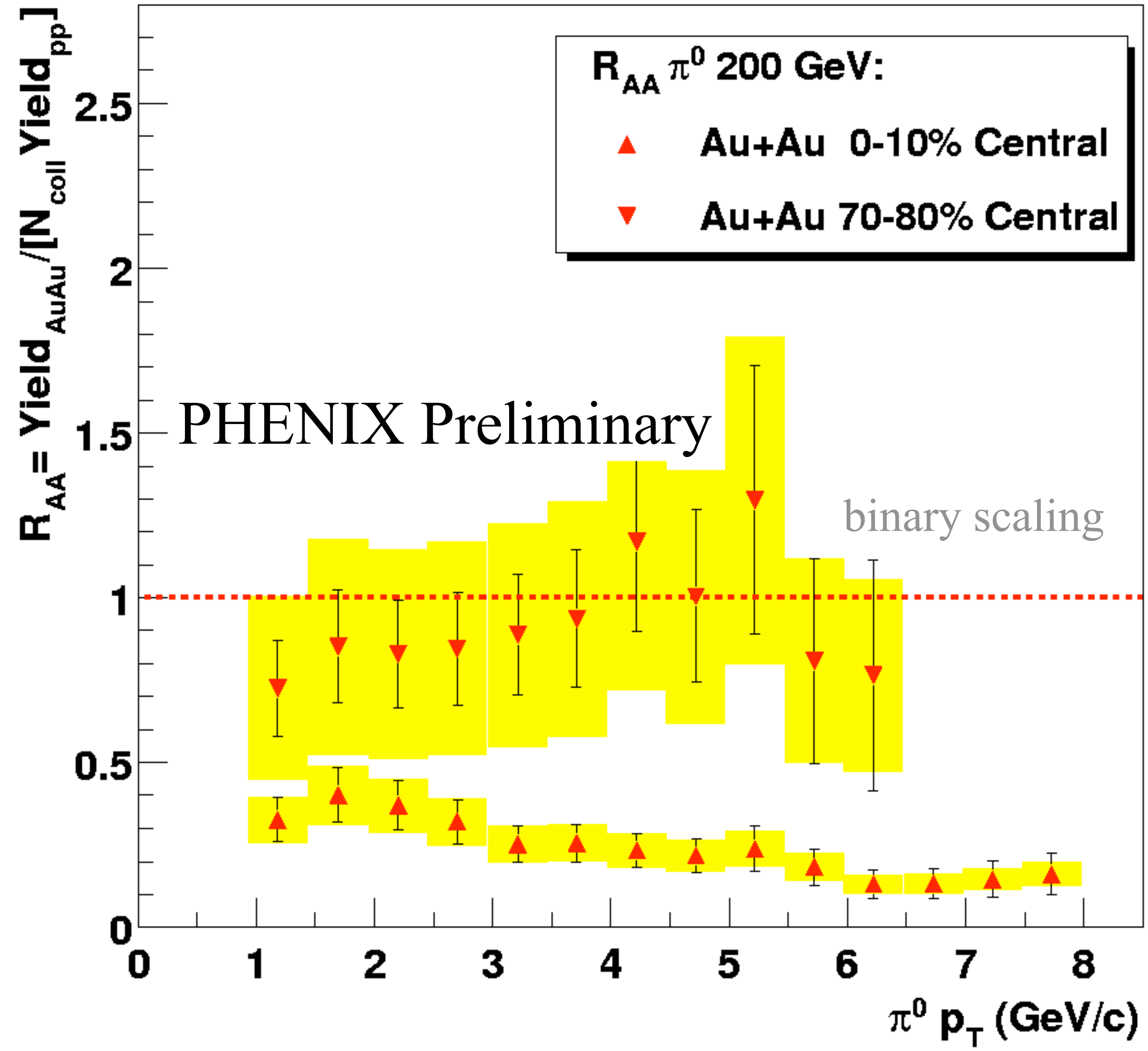
$$R_{AA}(p_T) = \frac{1/N_{events}\, d^2N^{AA}/dp_T d\eta}{\langle N_{binary}\rangle (d^2\sigma_{pp}/dp_T d\eta/\sigma^{pp}_{inelastic})} = \frac{Yield_{peripheral}/\langle N_{binary}\rangle_{peripheral}}{Yield_{pp}}$$

Comparison of peripheral to central

RHIC 200 GeV

central - Suppression

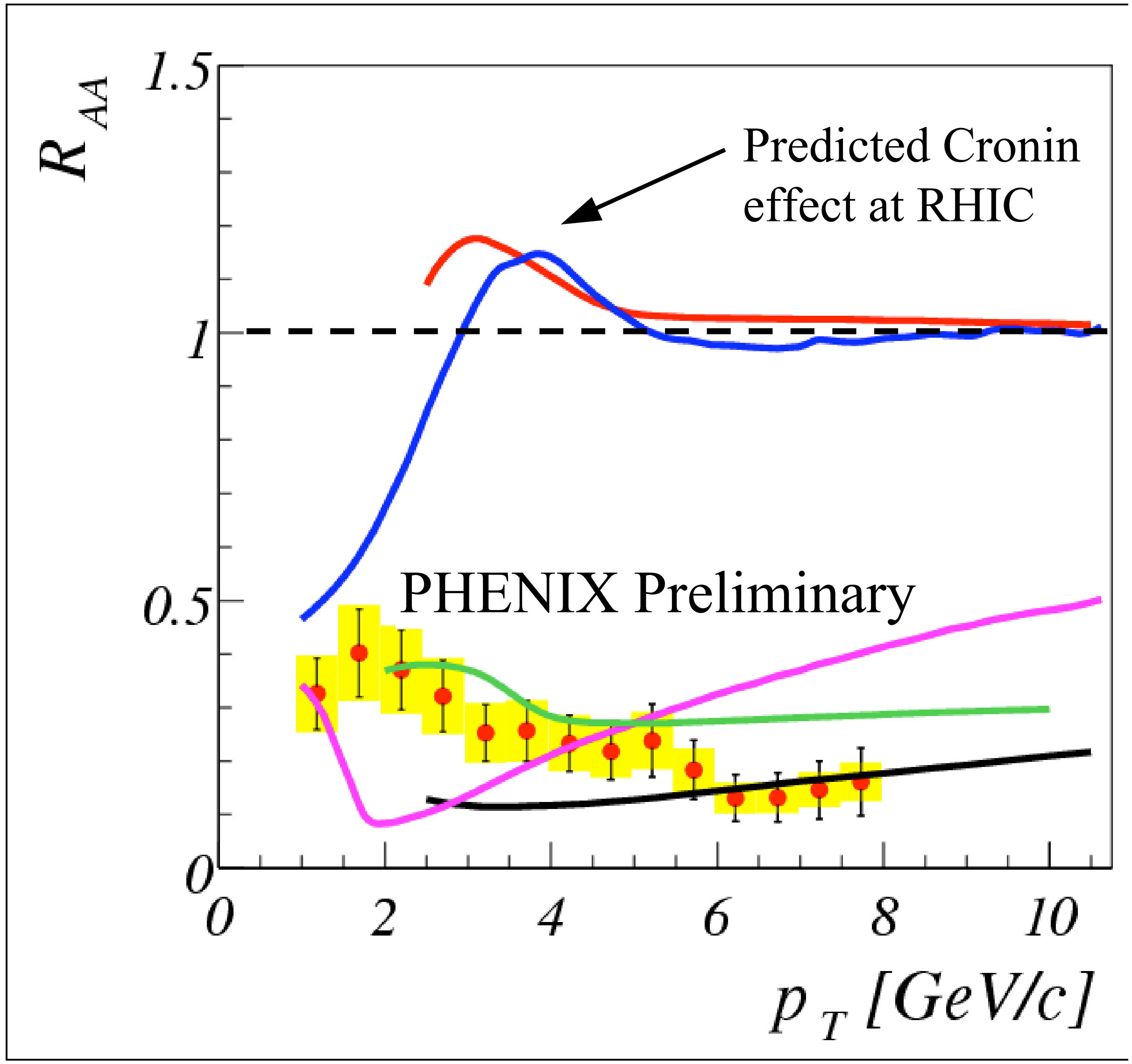
peripheral – N_{binary} scaling



Theory Comparisons for R_{AA}

- Wang dE/dx = 0
- dE/dx ≈ 0.25 GeV/fm (expanding)

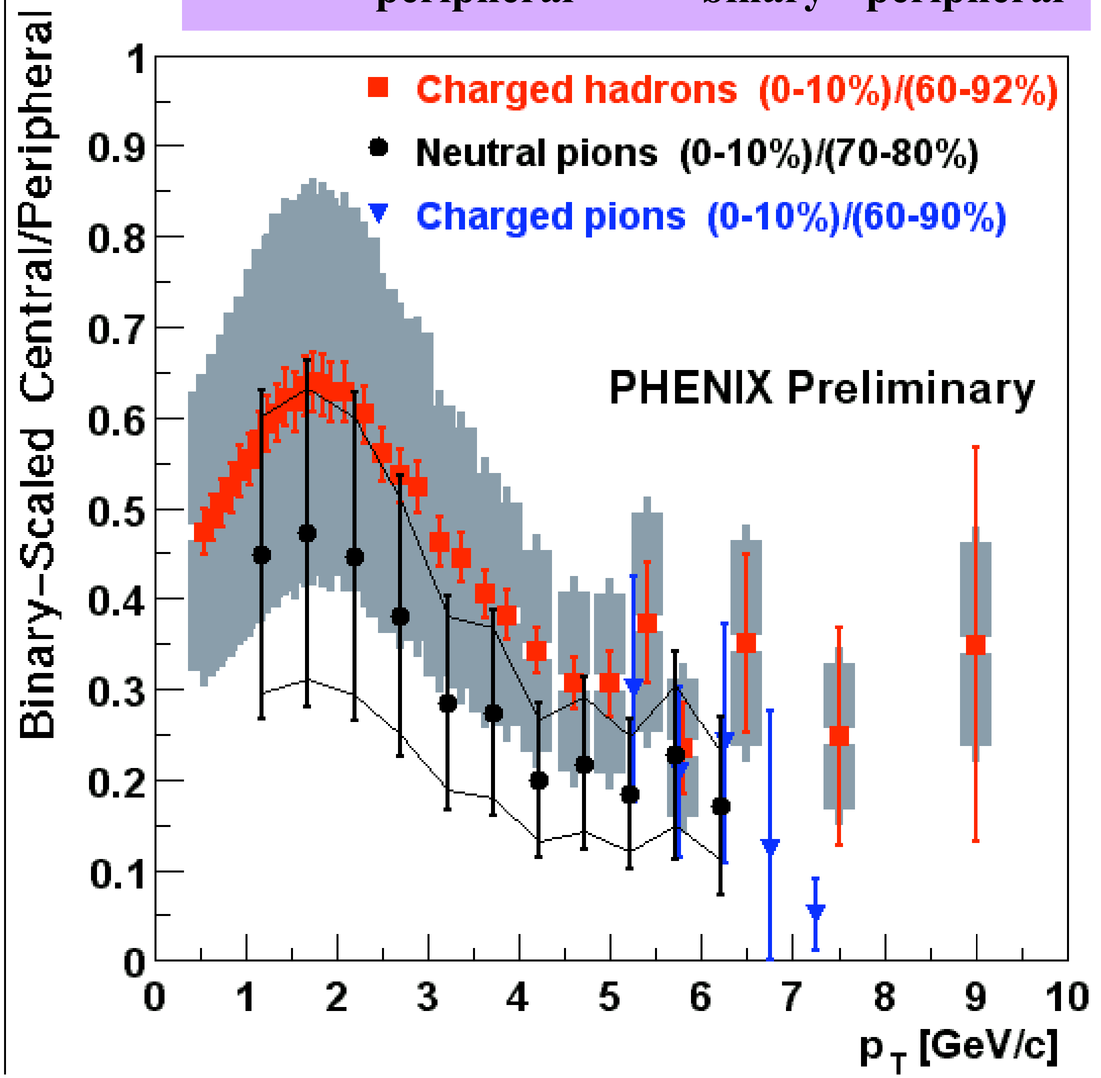
  dE/dx|$_{eff}$ ≈ 7 GeV/fm (static source)
- X.N. Wang, Phys. Rev. C61, 064910 (2000).
- Levai L/□ = 0
- L/□ = 4
- Gyulassy, Levai, Vitev: P.Levai, Nuclear Physics A698 (2002) 631.
- Vitev dN^g/dy = 900
- GLV, Nucl. Phys. B 594, p. 371 (2001).



Central to Peripheral Ratio

$$\frac{\text{Yield}_{central} / \langle N_{binary} \rangle_{central}}{\text{Yield}_{peripheral} / \langle N_{binary} \rangle_{peripheral}}$$

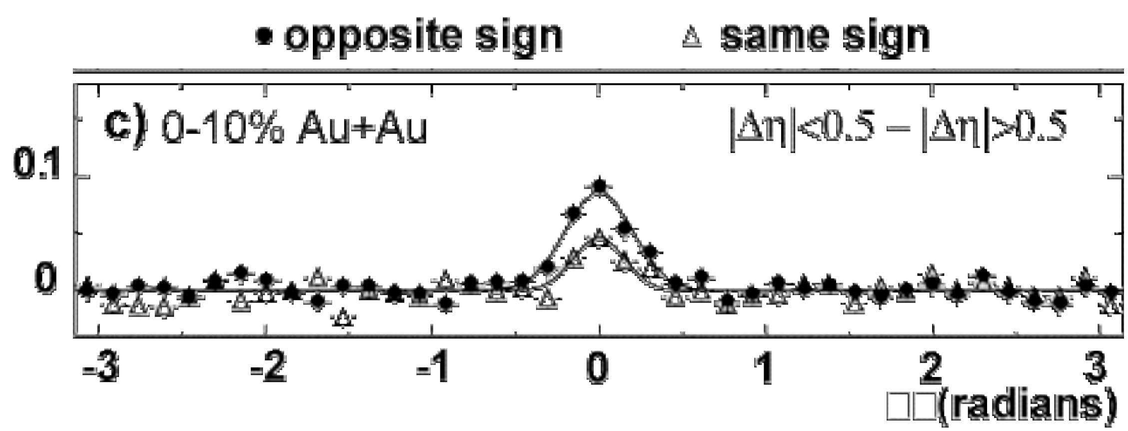
- Suppression seen in 3 independent measurements



Sources of azimuthal correlations

- Au+Au
  - flow
- p+p and Au+Au collisions:
  - di-jets
  - combinatorial background
  - jets
  - resonances

} Small □□



STAR nucl-ex/0210033

→ Subtracting the correlations for large □□ from those for small □□ leaves correlations only due to jets and/or resonances

Summary so far:

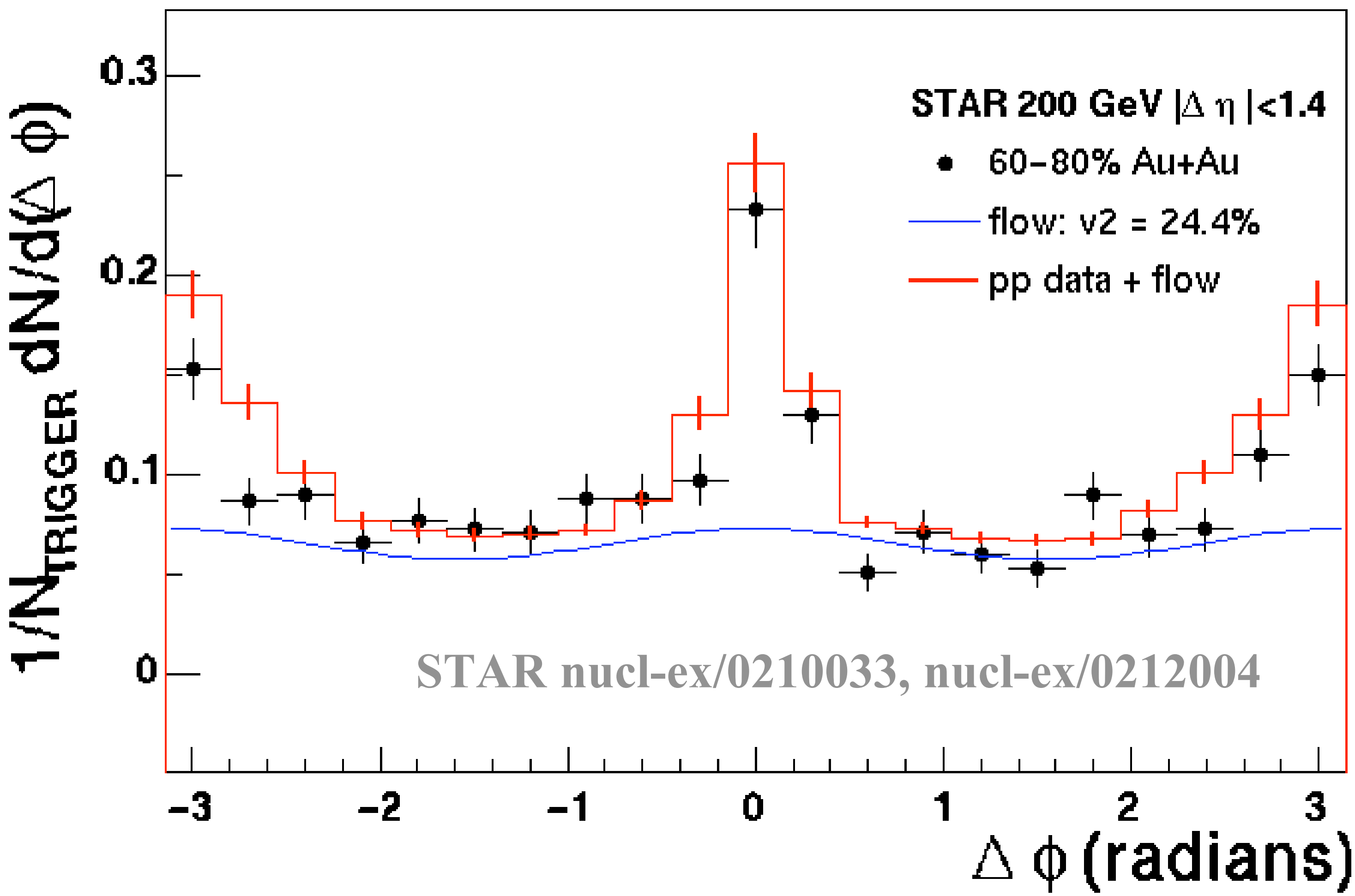
- Hadron spectra show suppression ~2-10 GeV/c
- Hadrons with $p_T > 4$ GeV have significant jet contributions

→ Suppression is occurring in a region where hadrons have contributions from jet fragmentation

(Similar analysis by PHENIX experiment for leading photon, mostly from π^0, with energy greater than 2.5 GeV/c supports this conclusion)

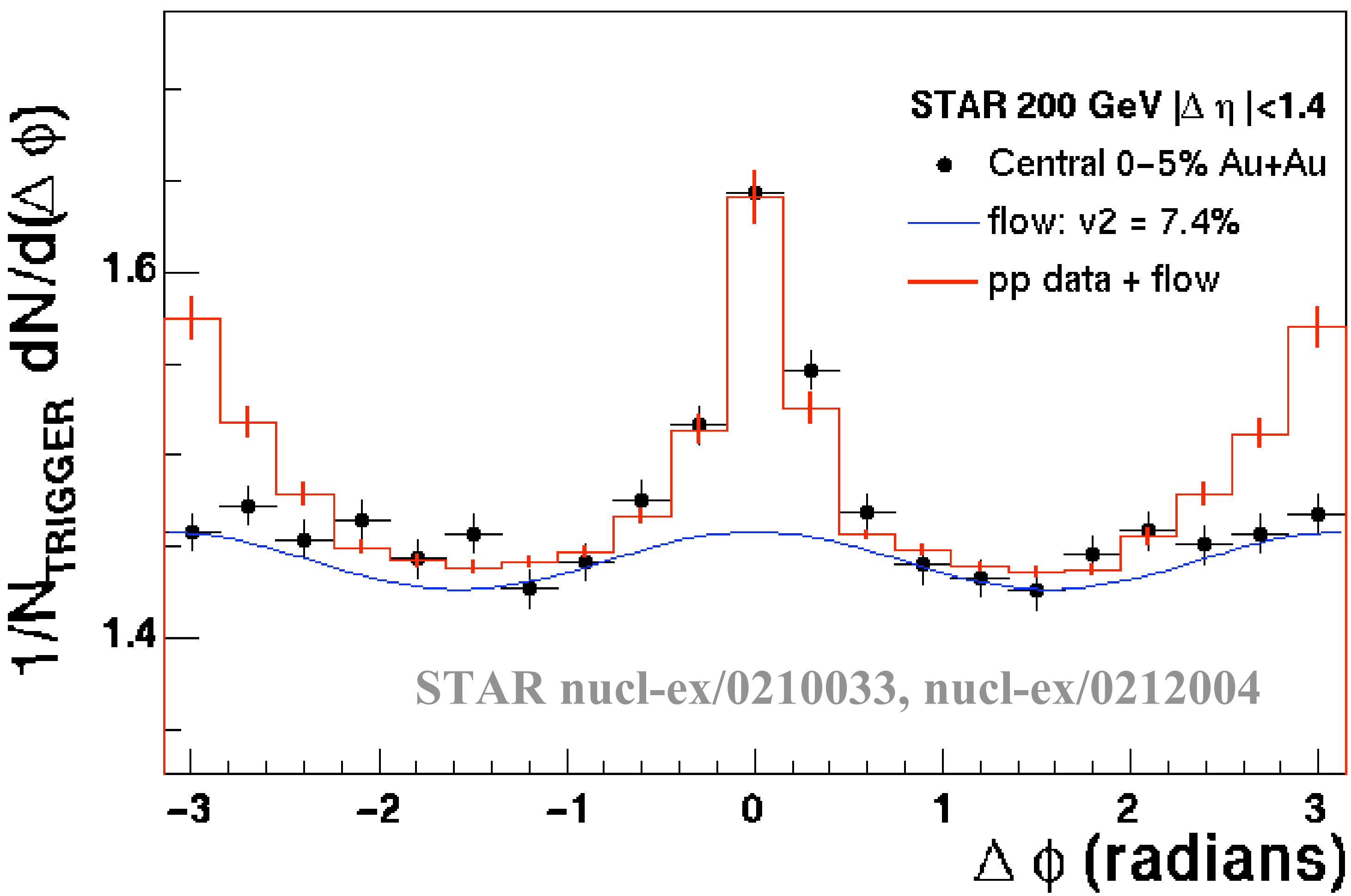
Peripheral Au+Au data vs. pp+flow

$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$

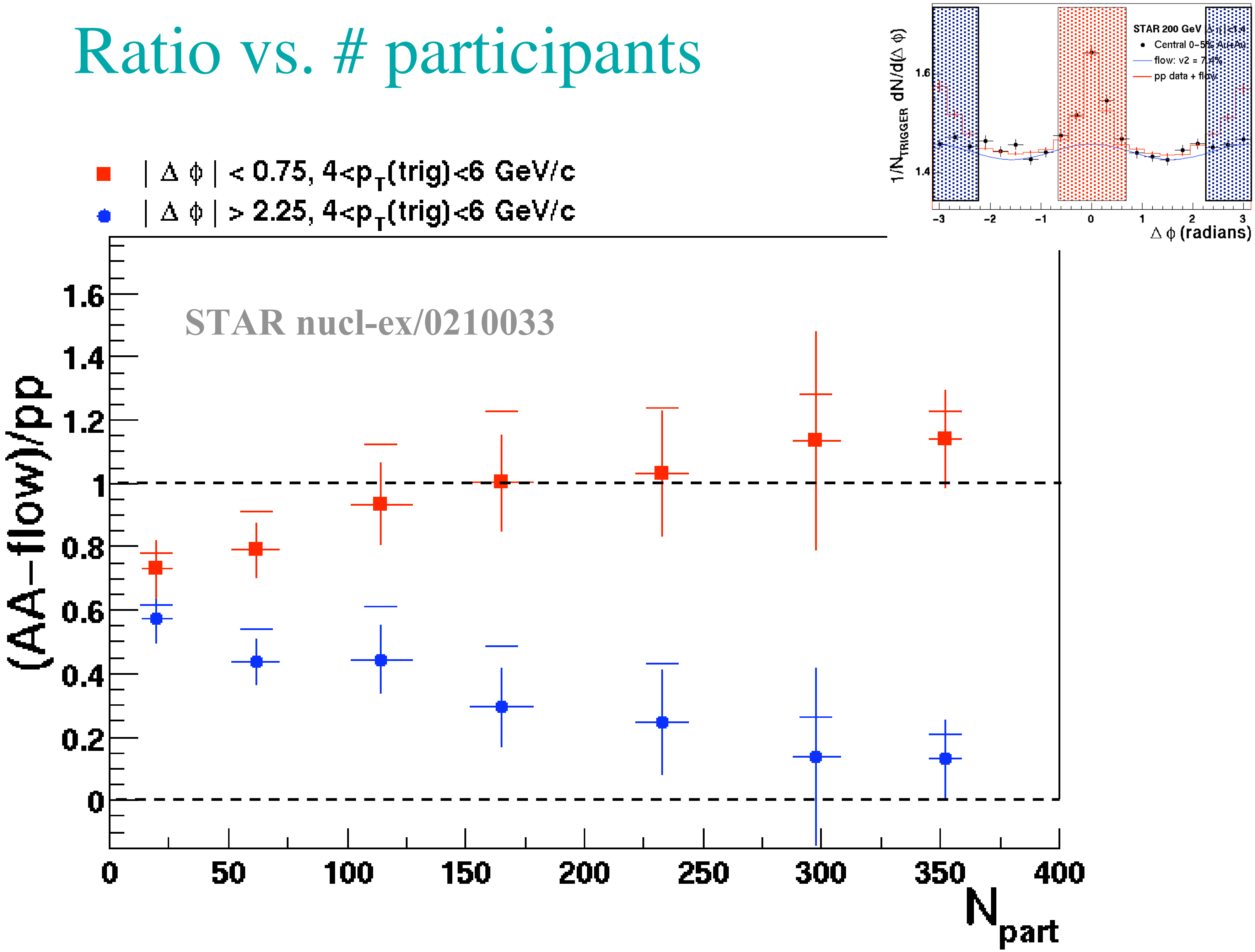


Central Au+Au data vs. pp+flow

$$C_2(Au + Au) = C_2(p + p) + A * (1 + 2v_2^2 \cos(2\Delta\phi))$$



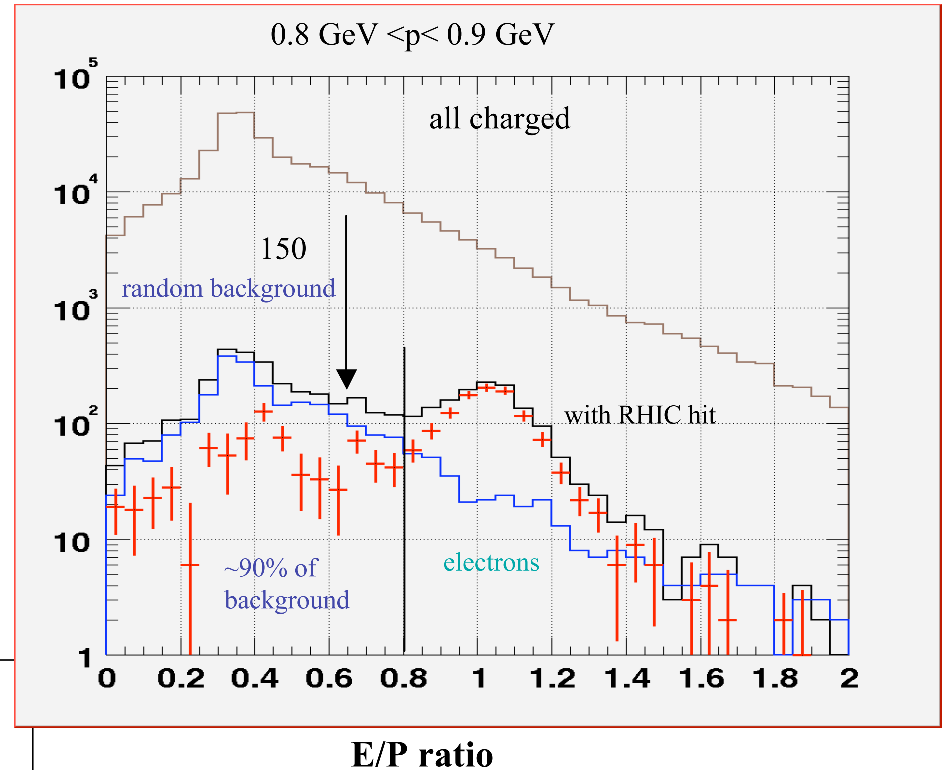
Ratio vs. # participants



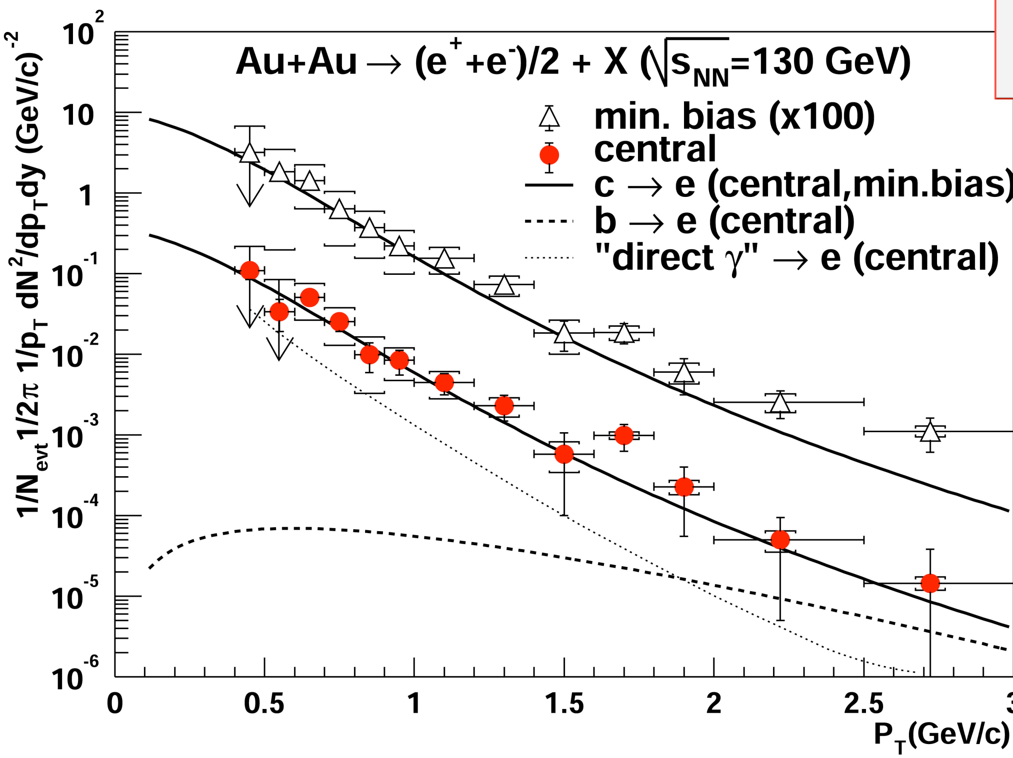
More on this from RHIC soon.

- Inclusive spectra in d-A collisions
- Enhanced if source is parton energy loss(GLV et al)
- Suppressed if saturation of gluon pdf
- Inclusive spectra for p,pbar, hyperons
- Is there a suppression of heavy flavor spectra(c,b-jets)? PHENIX

Electron id using Momentum and Ecal + RICH



PHENIX electrons



data are well described using PYTHIA cross-section multiplied by number of binary collisions obtained from nuclear thickness function, T_{AB} (i.e., a Glauber model).

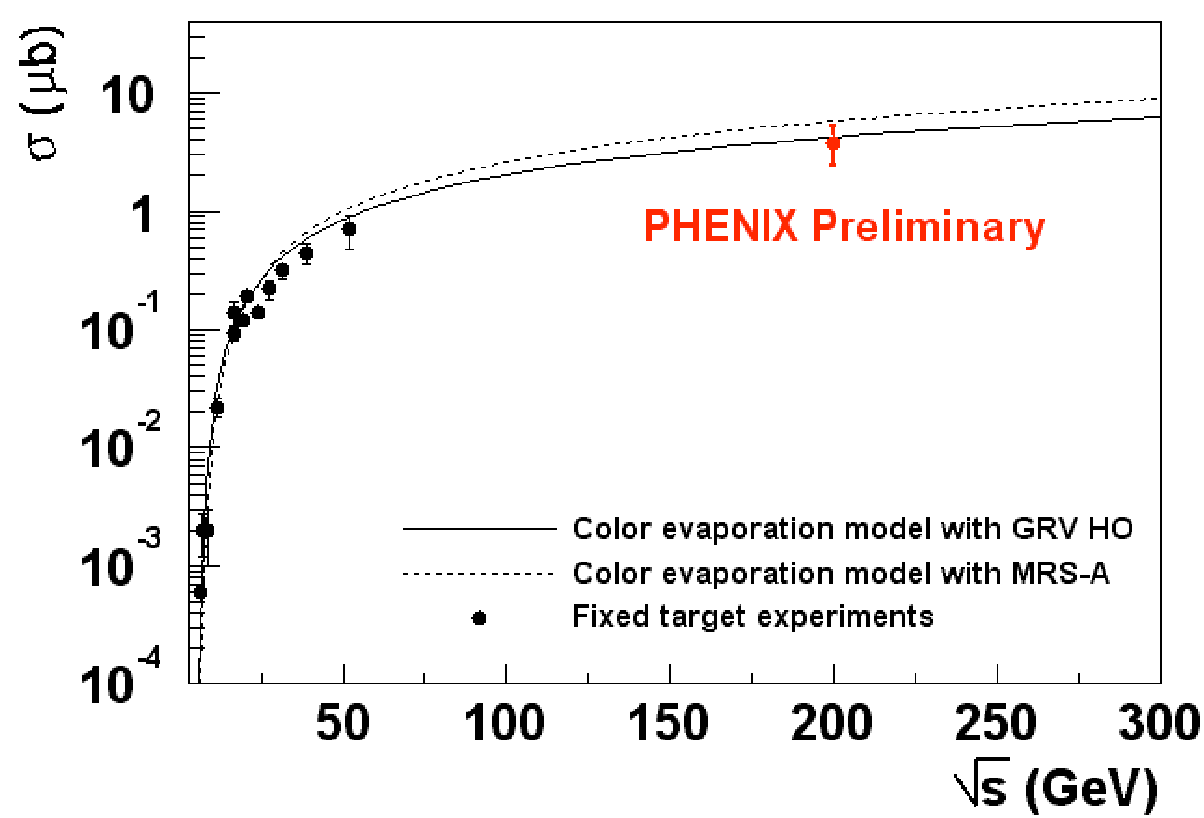
$$\sigma_{c\bar{c}}(0-10\%) = 380 \pm 60 \pm 200\,\mu b$$

$$\sigma_{c\bar{c}}(0-92\%) = 420 \pm 33 \pm 250\,\mu b$$

Charmonia in pp data(Run II)

PHENIX preliminary

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



I already gave my perspective.

I think it will get better.