‘Photo-production’ of J/Ψ & high mass e^+e^- pairs in Ultra-Peripheral Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV in PHENIX

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for the PHENIX collaboration

La Londe-les-Maures, September 2008

Overview

- *Physics intro*: $\gamma\gamma$, γ A collisions in UltraPeripheral A+A

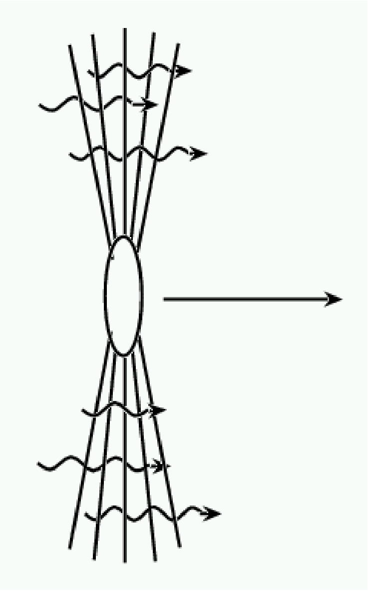
- *Experimental aspects*: Ultraperipheral A+A collisions

  (signatures, background, triggers, detectors, analysis cuts, ...)

- *Results*: Quarkonia and continuum γ– production in UPC @ RHIC (PHENIX)

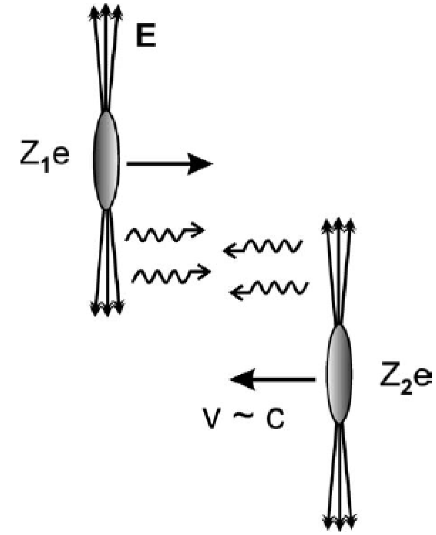
Electromagnetic Field of a Relativistic Charged Particle

Fermi 1924: *The effect of the electromagnetic field of a relativistic particle is equivalent to a flux of photons with a continous energy spectrum.* (hep-th/0205086)



Quantum Mechanical derivation 1935 by Weizsäcker,Williams.
$\Rightarrow$
Weizsäcker-Williams method

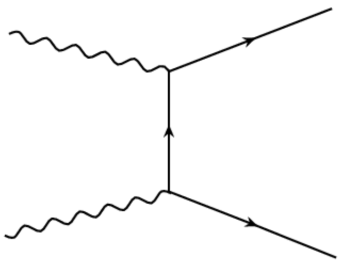
Ultra-peripheral collisions



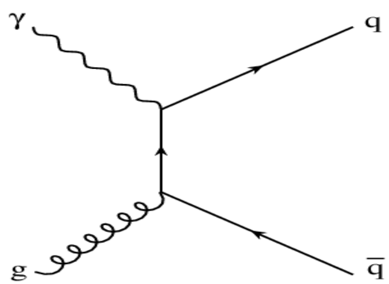
We study "collisions" with b > 2R..

The photons and nuclei can interact in several ways

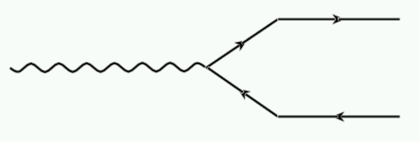
1. Electromagnetic interaction, two-photon



2. Direct photonuclear interaction, gamma+parton (γ+g→qq, γ+q→jet+jet)

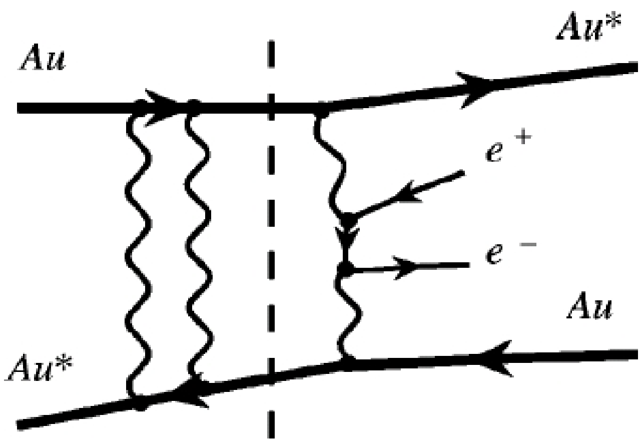


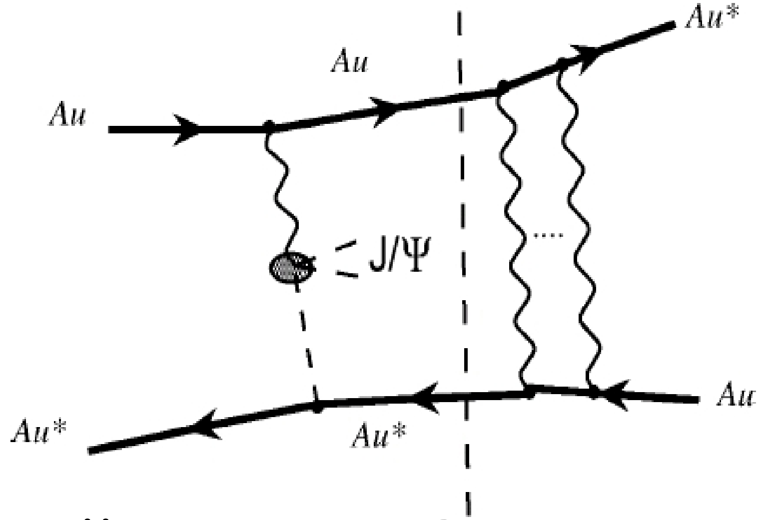
3. Resolved photonuclear interaction (VMD), elastic or inelastic



γγ, γA physics in UPC A+A collisions

➢ Typical diagrams for γγ and γA collisions:





➢ Main interest of γ-induced collisions in UPC A+A collisions

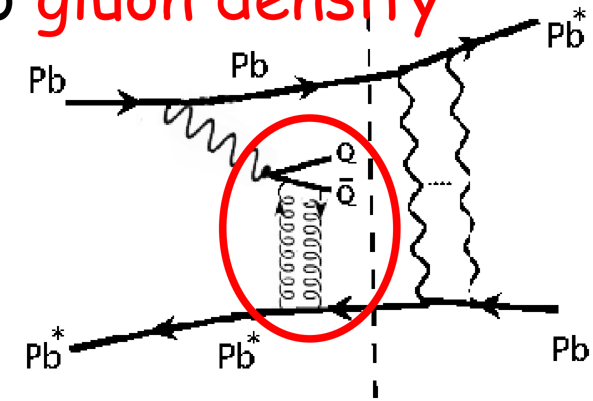
- ➢ Precision QCD: Low bkgd & simpler initial state than nuclear A+A colls.
- ➢ Measurements: Dilepton pairs, hard photo-production (Quarkonia, jets, heavy-Q), ...
- ➢ Physics topics: QED in strong regime ($Z\alpha_{em}$~1), nuclear $G_A(x,Q^2)$ function, small-x physics, QQbar dynamics in cold nuclear matter, ccbar (bbar) spectroscopy,. ..

$xG_A(x,Q^2)$ via diffractive $Q\bar{Q}$ γ-production (UPC)

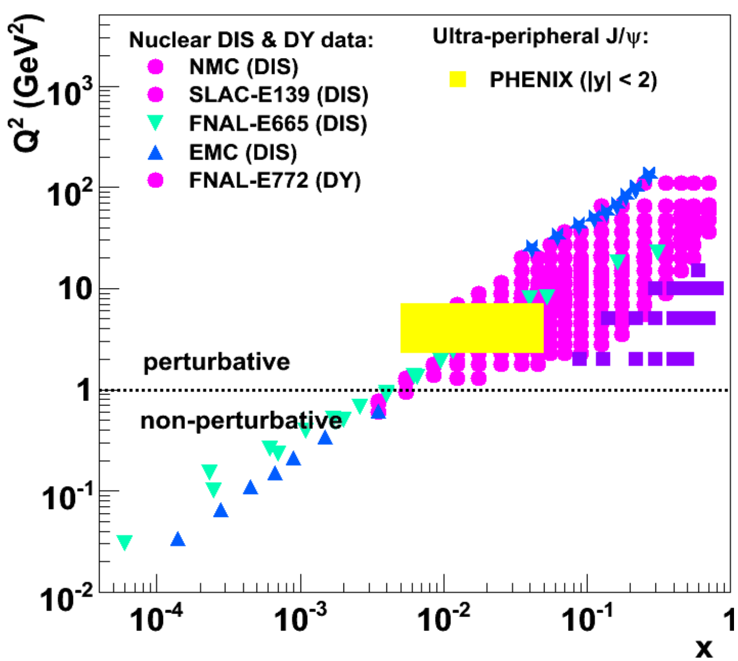
➢ γ+A->VM+A (VM=J/Ψ,ϒ) sensitive to gluon density squared:

$$\sigma_{\gamma A\to VA}(s_{\gamma N}) \sim \frac{d\sigma_{\gamma N\to VN}(s_{\gamma N})}{dt}\Big|_{t=t_{\min}} \left[\frac{G_A(x_1,x_2,t=0,Q^2_{\rm eff})}{AG_N(x_1,x_2,t=0,Q^2_{\rm eff})}\right]^2$$

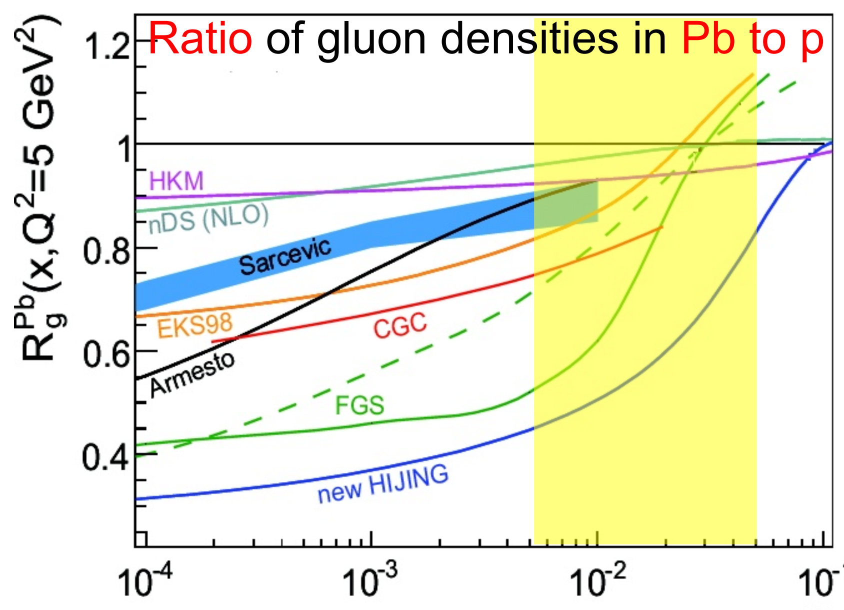
Strikman, Frankurt, Guzey, et al.



➢ Kinematical (x,Q^2) domains covered experimentally:



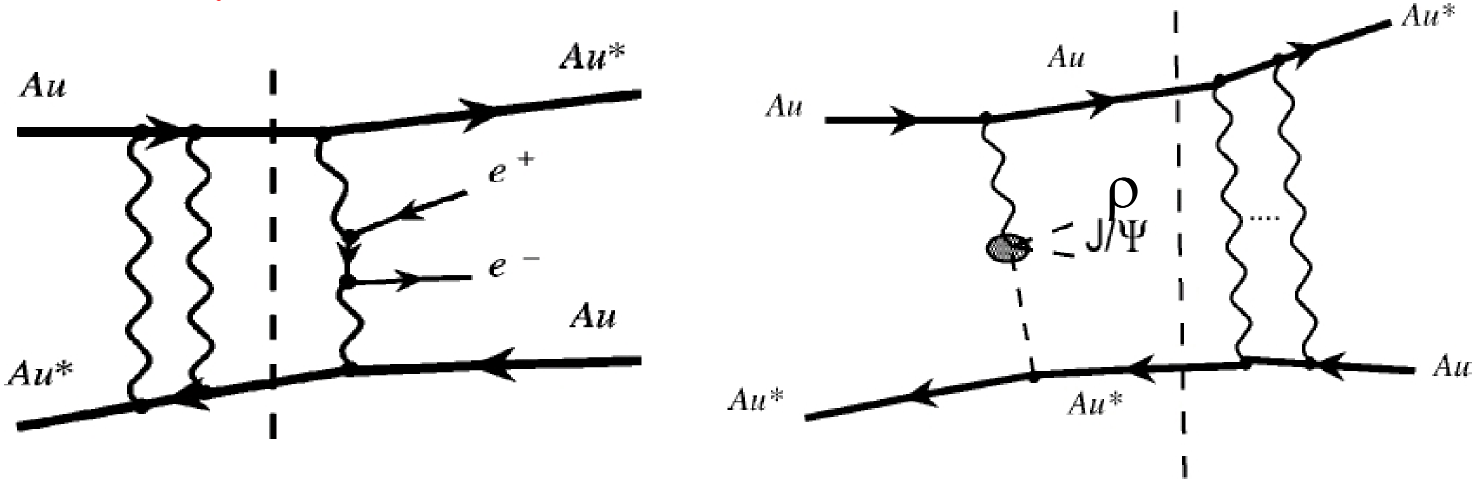
➢ Large uncertainties in $xG(x,Q^2)$ for $x<10^{-2}$!



Armesto, J.Phys.G32:R367 (2006)

Existing γ γ , γ A measurements @ RHIC

➢ Measured processes in A+A UPC collisions:



➢ STAR (published):

(1) Coherent ρ production: $\gamma + A \rightarrow A^* + \rho(\rightarrow \pi^+\pi^-)$

(2) Dielectron continuum at low m_{inv} : $\gamma + \gamma \rightarrow (A^*) + e^+e^-$

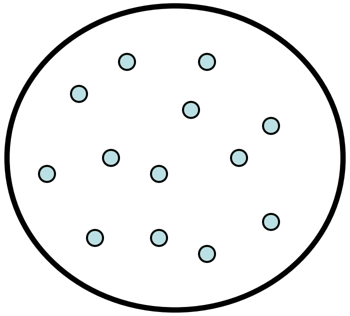
➢ PHENIX (preliminary):

(1) Coherent J/Ψ production: $\gamma + A \rightarrow A^* + J/\Psi(\rightarrow e^+e^-)$

(2) Dielectron continuum at high m_{inv} : $\gamma + \gamma \rightarrow (A^*) + e^+e^-$

Coherence

Photon flux: ~Z^2 (EPA; Fermi, WW)



Many scattering centra

Total scattering amplitude:

$$F(k,k') = \sum_{i=1}^{A} f_i(k,k') e^{iq\cdot xi} \longrightarrow \underbrace{\int \rho(x) e^{iq\cdot x} d^3x}_{A\cdot F(q)}$$

A·F(q)
F(q) – Nuclear Form Factor

$t = \mathbf{q}^2$; For small mom. transfers:

$$\left.\frac{d\sigma}{dt}\right|_{\gamma A} = A^2 \left.\frac{d\sigma}{dt}\right|_{\gamma p} |F(t)|^2$$

~ $4 \cdot 10^4$ for Au..
(assuming no shadowing)

$\rightarrow$ 0 for q > 1/R
1/R ~ 30 MeV/c for Au

Two-photon interactions (and any coherent process) will be significant only at high energies:

Max CM energies, W, at different heavy-ion accelerators, determined by the coherence requirement:

$$W \approx 2\,\gamma_{CM}\,(hc/R)$$

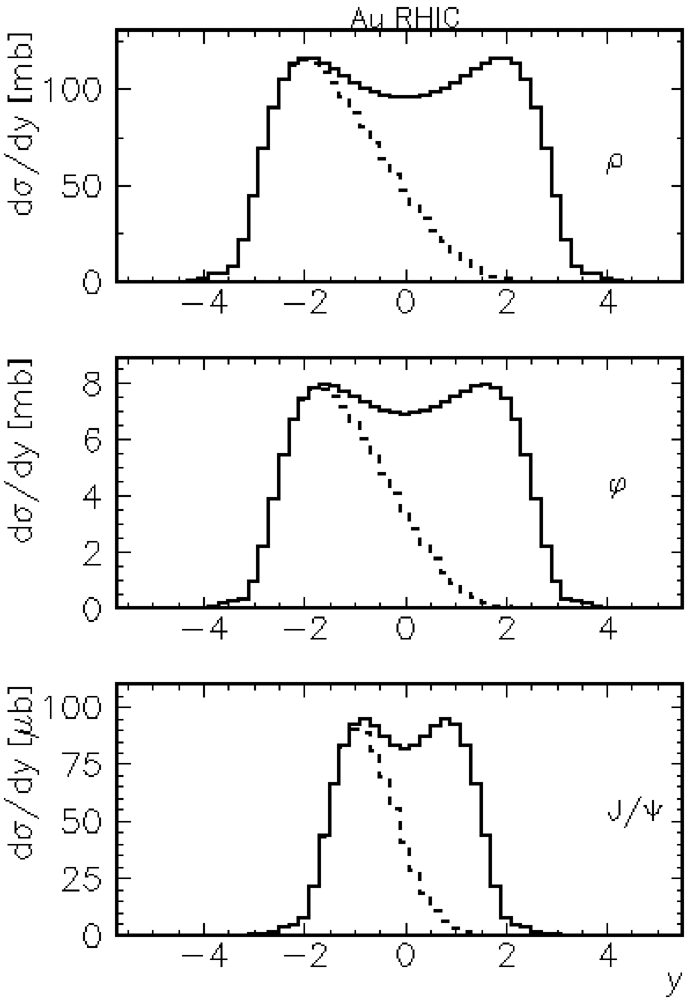
For Au/Pb

	γ_{CM}	W [GeV]
BNL AGS	3	0.1
CERN SPS	9	0.5
RHIC	100	6
LHC	2940	160

RHIC is the first heavy-ion accelerator where significant particle production can occur in ultra-peripheral collisions/ coherent interactions.
(cutoff not sharp though; and incoherent processes could contribute at e.g. SPS or CEBAF energies)

A model [STARLight] predicts cross sections, rapidity and p_T distributions of e.g. vector mesons.

For Au+Au 200 GeV at RHIC:



	σ [mb]	(req. Xn)
ρ	590	(170)
ω	59	(17)
φ	39	(13)
J/ψ	0.29	(0.16)

[Baltz, Klein, Nystrand: PRC 60(1999)014903, PRL 89(2002)012301]

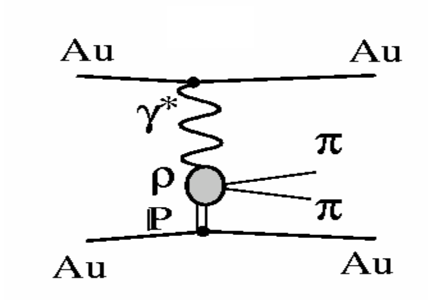
Cross sections in the 0.3-600 mb range! Requiring (Xn) neutron coinc. lowers σ by factor 1.8 – 3.5, but useful for trigger.

Photonuclear part dominates over γ+γ
The p_T distribution determined by the nuclear Form Factor, $p_T \sim 1/R$

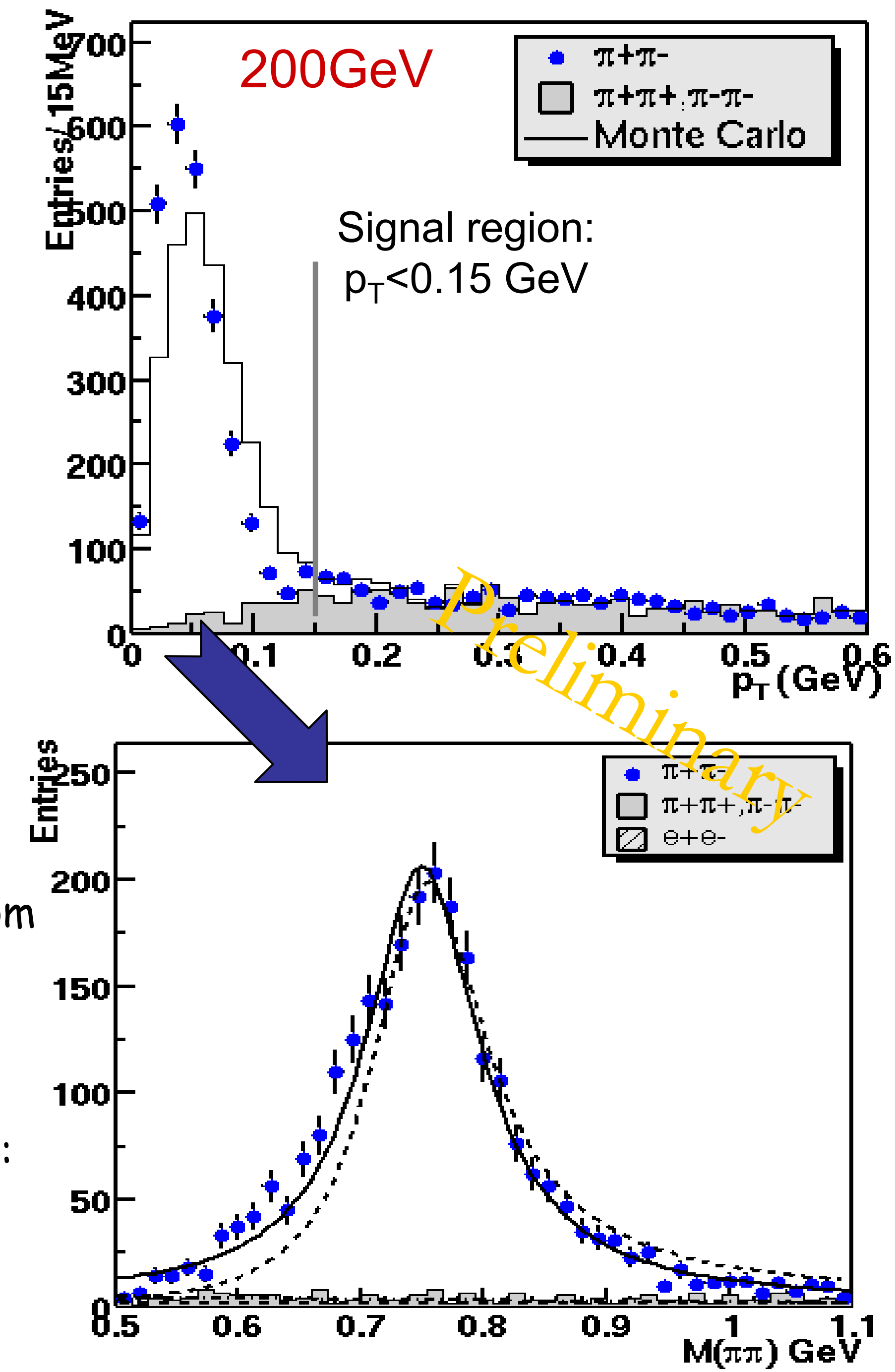
STAR Result

Topology Trigger

AuAu ⇨ AuAu ρ^0



- Peak at low pT ⇨
  coherent interaction



Cross-sections consistent with expectations from STARLight

[PRL 89(2002)272302 – result at 130 GeV;

also see e^+e^- low M_{inv} continuum result (52 pairs): PRC **70** (2004) 031902(R)]

$\gamma\gamma$, γA collisions: experimental signatures

$A + A \to A + A + \gamma \to A + A + X$ $(X = J/\Psi, \ldots)$

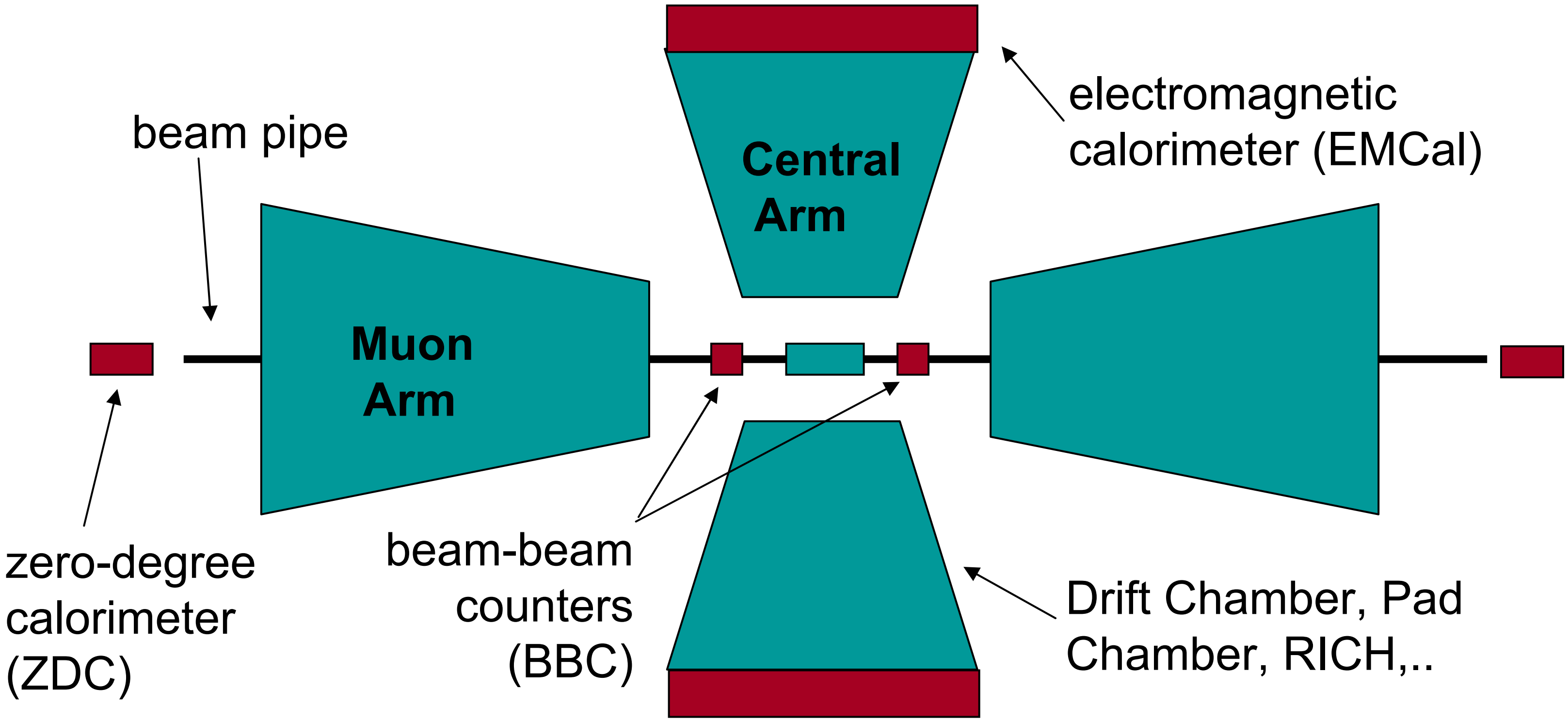
[All here also valid for: $A + A \to A + A + \gamma + \gamma \to A + A + X$]

- Central rapidities:
  (1) Low multiplicities: N <~ 10
  (2) Low total transverse momentum ("coherence condition"):
  $p_T < \sqrt{2}\,\hbar/R_A$ or $p_T \sim m_{inv}/\gamma \sim 30 - 50$ MeV
  (3) Zero net charge: even # of charged tracks of opposite signs.

- (Very) Forward rapidities:
  (4) Large probability of multiple e.m. interactions
  (3γ exch.): Mutual Coulomb excitation (GDR)
  leading to A* dissociation via (forward) neutron
  (Xn) emission: P~30-50% (J/Ψ).

Note: Coulomb-dissoc. probab. factorizes
in UPC cross-section calculations

PHENIX (bird's eye view)



Strengths and weaknesses:
+ Designed for lepton and photon detection, high rate and rare triggers.
- Limited acceptance
[2x90 deg. in phi, $|\eta|<0.35$ used here]

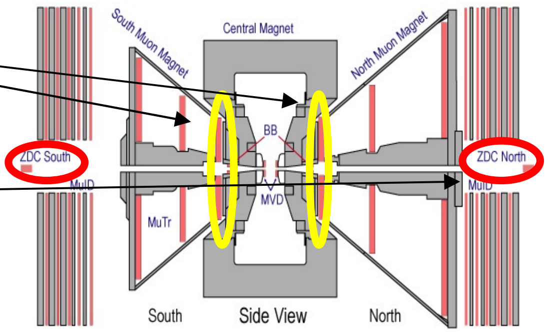
Goal [Run4 (2004)]:
Via electron channel, look for heavier vector meson (J/Ψ) and continuum at higher M_{inv}.

γ +A -> J/Ψ+A : UPC trigger example

PHENIX Run-4 (2004) AuAu UPC trigger:
Sensitive to $\gamma + Au \rightarrow Au^{*} + J/\Psi(\rightarrow e^{+}e^{-})$

➢ L1 UltraPeripheral Trigger:

- Veto on coincident BBC (|y| ~3-4):
  [avoid periph. nuclear, beam-gas colls.]
- Neutron(s) in at least one ZDC (E>30 GeV)
  [sensitive to Au* Coulomb dissociation]
- Large energy (E > 0.8 GeV) cluster in EMCal:
  [e+e- decay from J/Ψ]



➢ Events collected (~0.4% of MinBias (BBC) trigger)

PHENIX UPC analysis cuts

- Global cuts:
  - Std. vtx. cut: | zvtx | < 30 cm
  - Multiplicity(tracks)<15 [removes non-UPC events]
- Loose PID $e^{\pm}$ cuts (compared to std. AuAu-nuclear analysis):
  - RICH: n_0>=2 [# of photo-tubes within nominal ring radius]
  - Track-EMCal matching (plus no dead tower within 2x2).
  - E_1 > 1 GeV || E_2 > 1 GeV [offline high-p_T trigger threshold]
- Pair cuts:
  arm1 != arm2 [back-to-back di-electrons from J/ψ ~at rest]
- Residual background subtraction:
  m_{inv}[unlike-sign ee pairs] – m_{inv}[like-sign ee pairs]

γ +A -> J/Ψ+A : possible background sources (I)

A + A -> A + A + γ -> A + A + J/Ψ

➢ "Non-physical":

Trigger level

(1) Cosmic rays: no ZDC, no good vtx.

(2) Beam-gas: no good vtx., large multiplicity, asymmetric dN/dy

γ +A -> J/Ψ+A : possible background sources (II)

Physical processes (possibly affecting final signal):

(3) Peripheral nuclear A+A: "large" multiplicity, large p_T (~2 GeV/c)

(4) Hadronic diffractive (Pomeron-Pomeron, rapidity gap evt.): forward proton emission, larger p_T: $p_T(\gamma\gamma) < p_T(PP)$, like-sign pairs. Hard-diffractive J/Ψ production.

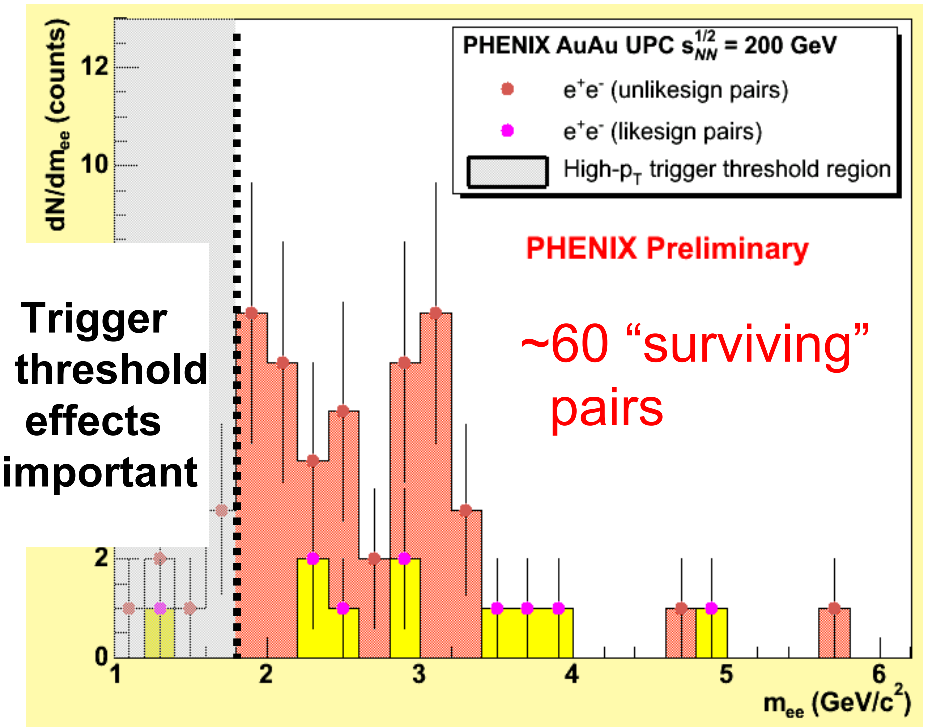
(5) Incoherent UPC γ+n -> n+J/Ψ: $p_T(\gamma\gamma) < p_T(\gamma P)$, wider & asymm. dN/dy ≥2 neutrons (induced nuclear break-up) w/ same direction as J/Ψ.

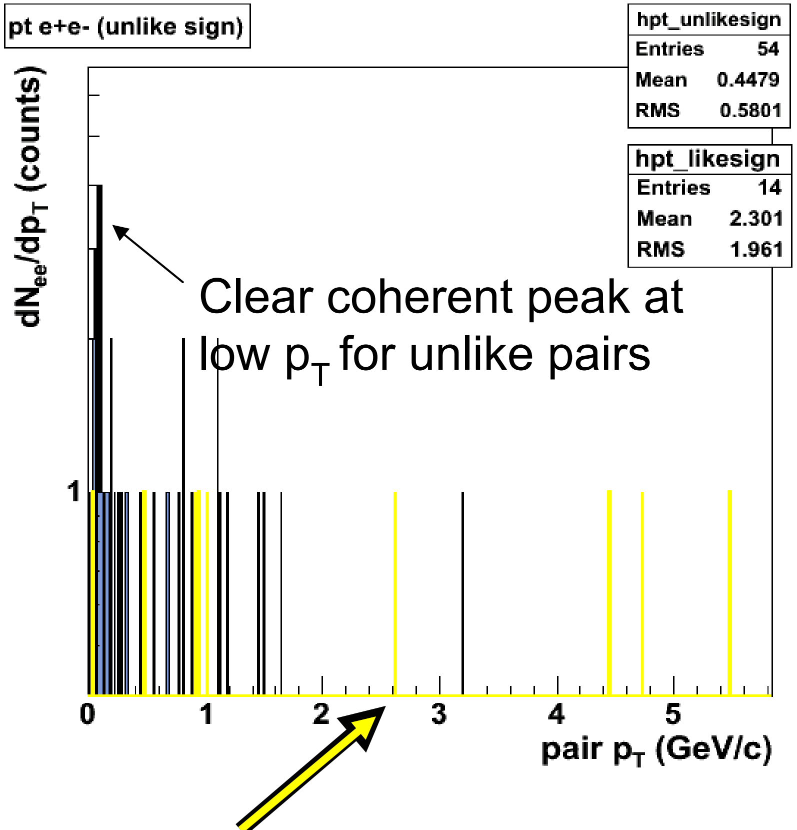
(6) Other coherent UPC processes: $\gamma\gamma \to e^+e^-$ (Important !) , γA -> jet(s)+A (lower cross-sections) ?

PHENIX UPC Preliminary Results

AuAu UPC preliminary results (I): dN/dm_{inv}, dN/dp_T ee pairs

➢ dN/dm_{inv} ,dN/dp_T distributions after QA, global-, single- & pair- cuts for unlike-sign (red) and like-sign (yellow) pairs:



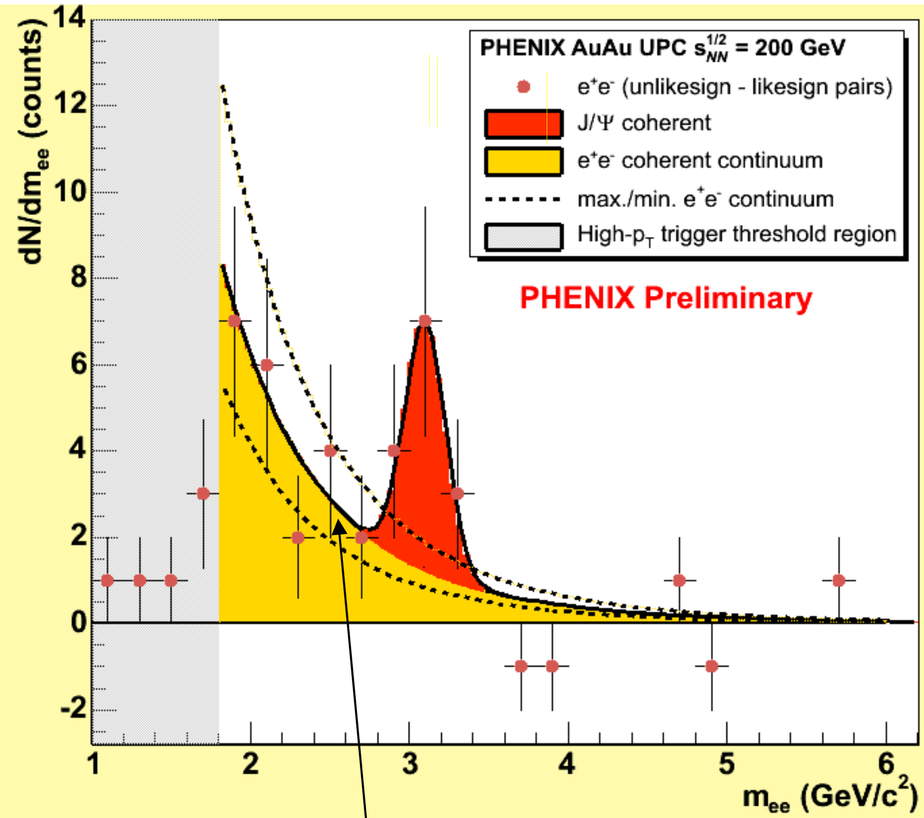


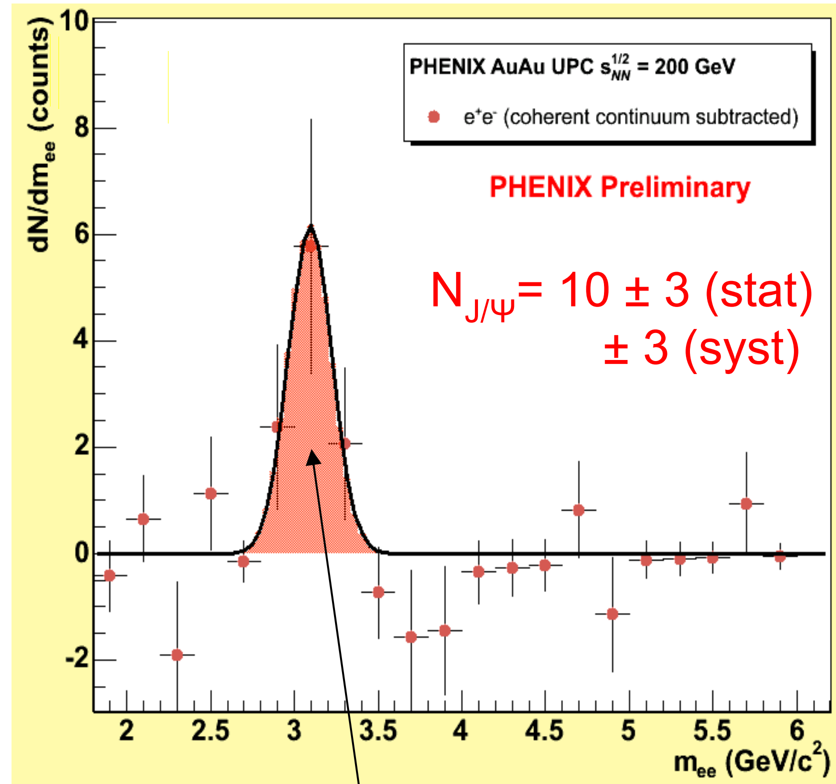
➢ Very small wrong-sign background (located in “non-coherent” high p_T region) well reproduced by MC.
-Can be removed by tighter eID (E/p) cuts that were however not used in preliminary analysis shown here.

AuAu UPC preliminary results (II): dN/dm_{inv} e^+e^- pairs

- dN/dm_{inv} (backgd subtracted) & with 2 fits of expected e^+e^- continuum shape (normalized at m_{ee} = 1.8 – 2.2 GeV/c^2)

- dN/dm_{inv} after e^+e^- continuum subtraction





Shape of e^+e^- continuum in good agreement w/ theoretical input + full-MC resp.+ reco

J/Ψ peak & width in good agreement w/ theoretical input + full MC resp.+reco

Peak ~ 3.10 GeV/c^2; Width ~ 130 MeV/c^2

Monte Carlo: dN/dm_{inv} J/Ψ & e^+e^- continuum

➢ Good agreement with expected signals from "Starlight" MC

J. Nystrand / Nuclear Physics A 752 (2005) 470c–479c

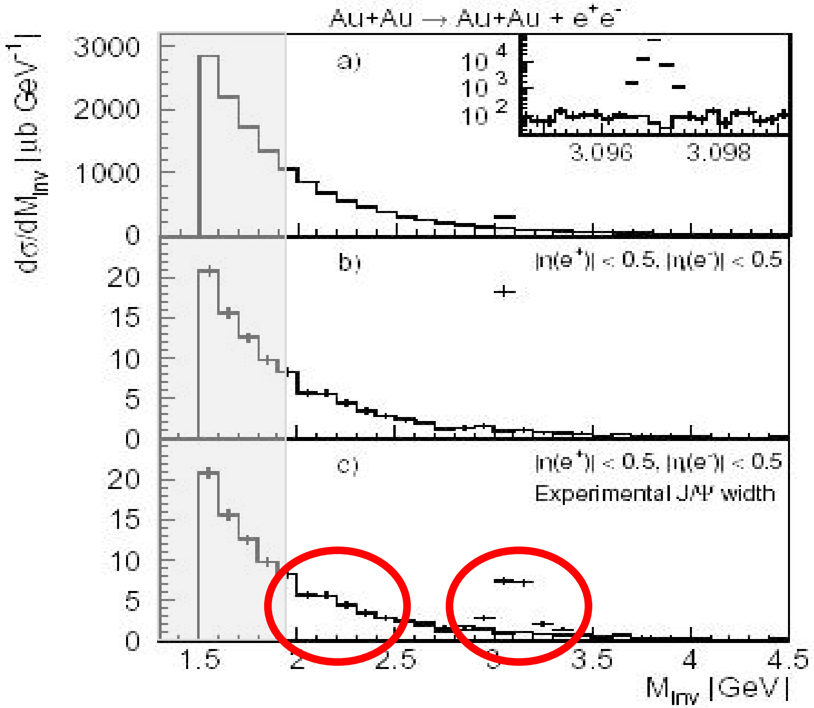


Figure 4. The differential cross section $d\sigma/dM_{inv}$ for dielectron production in ultra-peripheral Au+Au collisions at $\sqrt{s_{nn}} = 0.2$ TeV. The histograms show the two-photon contribution, and the bars or crosses show the sum of the two-photon and $J/\Psi \rightarrow e^+e^-$ contribution. The inset in a) has an expanded M_{inv} scale. The distributions have been calculated from a Monte Carlo simulation. 700k e^+e^--pairs with $M_{inv} > 1.5$ GeV have been generated, corresponding to an intergrated luminosity of 500 μb^{-1}.

Continuum Cross sections

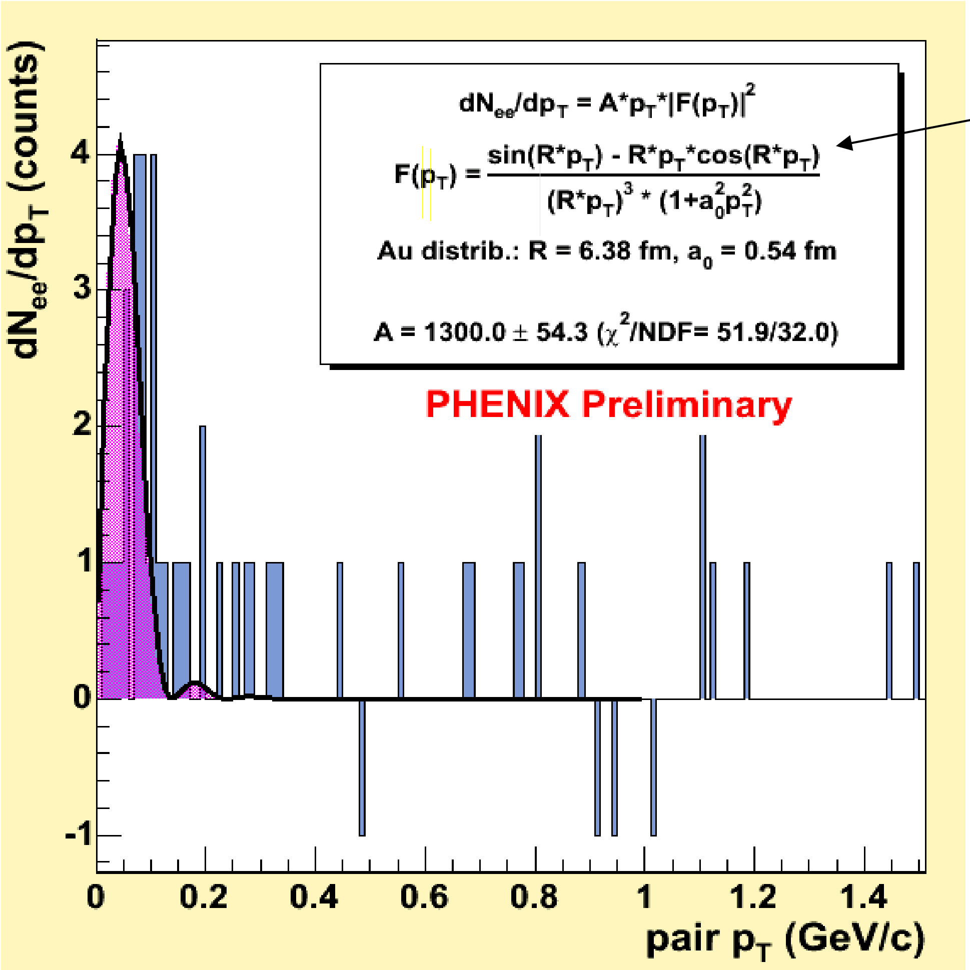
Total, Au+Au → Au+Au+e+e- : 32000 b
(Alscher-Hencken-Trautmann-Baur, PRA 55(1997)396)

With minv cut:

	Total	Xn-fragmentation
Minv > 1.5 GeV	1.4 mb	0.61 mb
Minv > 3.0 GeV	45 µb	25 µb
Minv > 6.0 GeV	450 nb	300 nb

Xn-fragmentation = Coulomb break-up of one or both nuclei.

AuAu UPC preliminary results (III): dN/dp_T e^+e^- pairs



[*] Nuclear form factor fit from J.Nystrand, nucl-th/0112055

- dN_{ee}/dp_T peaked at low p_T~90 MeV/c as expected for coherent production.

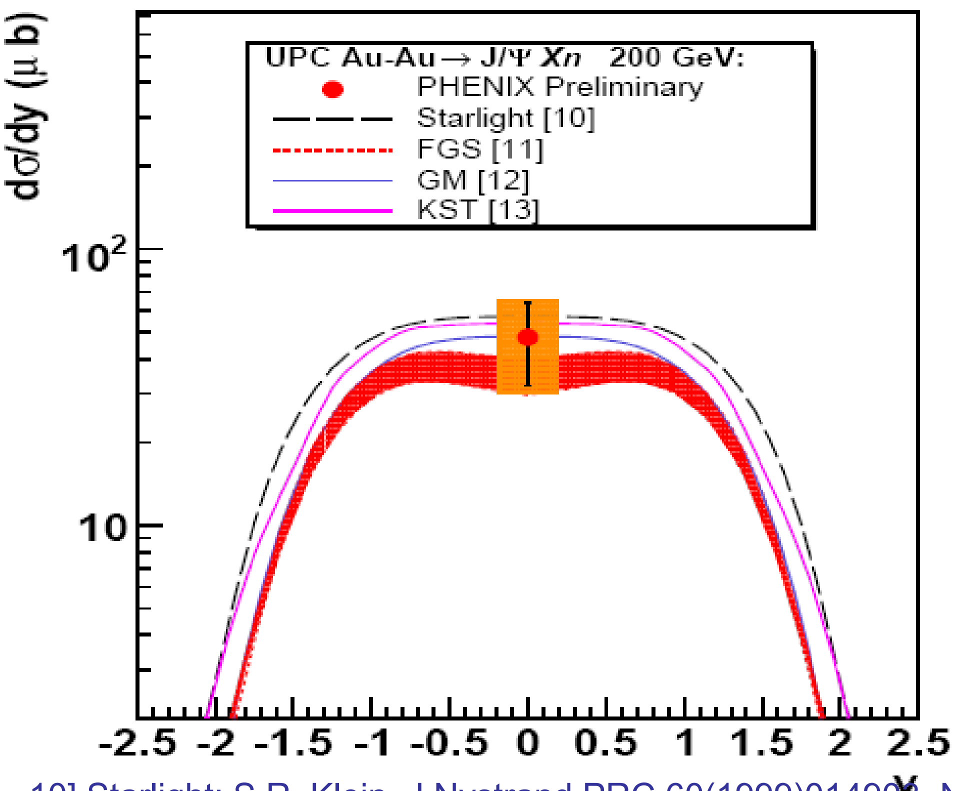
Good detailed agreement w/ theoretical expectations [*]

AuAu UPC preliminary results (IV): J/Ψ cross-section

$d\sigma_{J/\Psi}/dy|_{y=0}$ = $1/BR \times 1/(Acc|_{y=0} \cdot \varepsilon) \times 1/\varepsilon_{trig} \times 1/L_{int} \times N_{J/\Psi}/\Delta y$ =

= $1/(5.9\%) \times 1/(5.7\% \cdot 56.4\%) \times 1/(90\%) \times 1/120\ \mu b^{-1} \times (10 \pm 3 \pm 3)$ =

= 48. ± 16. (stat) ± 18. (syst) μb



- Measured J/Ψ yield at y=0 consistent w/ theoret. calcs.
- Syst. uncertainty: coherent e^+e^- continuum under J/Ψ (*work in progress*).
- Reduction of stat. errors need larger luminosity.
- Current uncertainties preclude yet detailed study of crucial model ingredients:

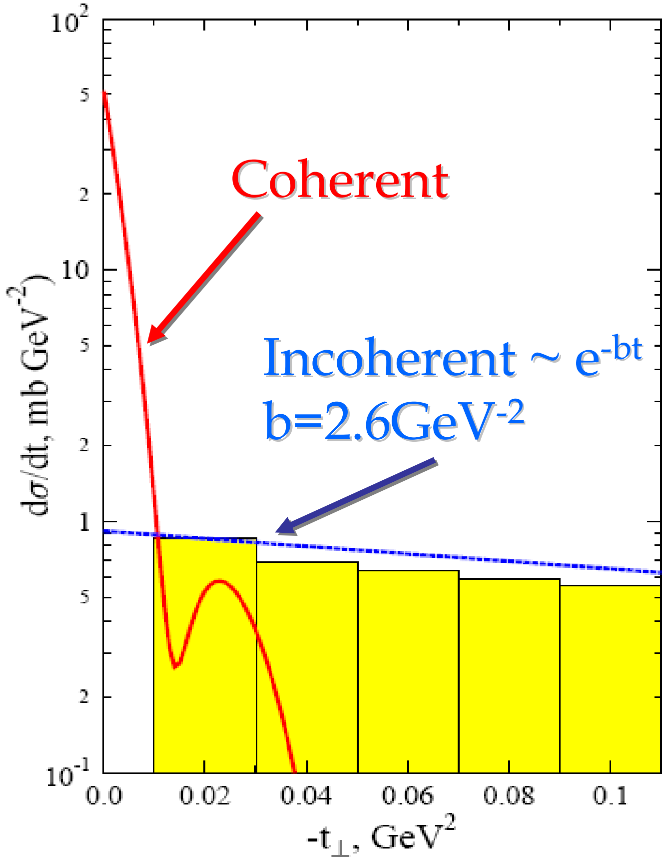
  $G_A(x,Q^2)$, σ(J/Ψ absorption)

10] Starlight: S.R. Klein, J.Nystrand PRC 60(1999)014903, NPA 752(2005)470.
[11] M. Strikman, M. Tverskoy, M. Zhalov, PLB 626(2005)72.
[12] V. P. Goncalves and M. V. T. Machado,arXiv:0706.2810 (2007).
[13] Yu. P. Ivanov, B. Z. Kopeliovich and I. Schmidt, arXiv:0706.1532 (2007).

Incoherent J/Ψ production

- How to separate incoherent from the coherent?

Via t distribution , $t=p_T^2$



Study yield as a function of cuts in t, and compare with cut expectations.

Eg. a la
Tight cut:
N1 = 0.9*C + 0.05*I [below]
N2 = 0.1*C + 0.95*I [above]

Looser cut:
N3 = 0.95*C + 0.3*I [below]
N4 = 0.05*C + 0.7*I [above]

Looking Forward

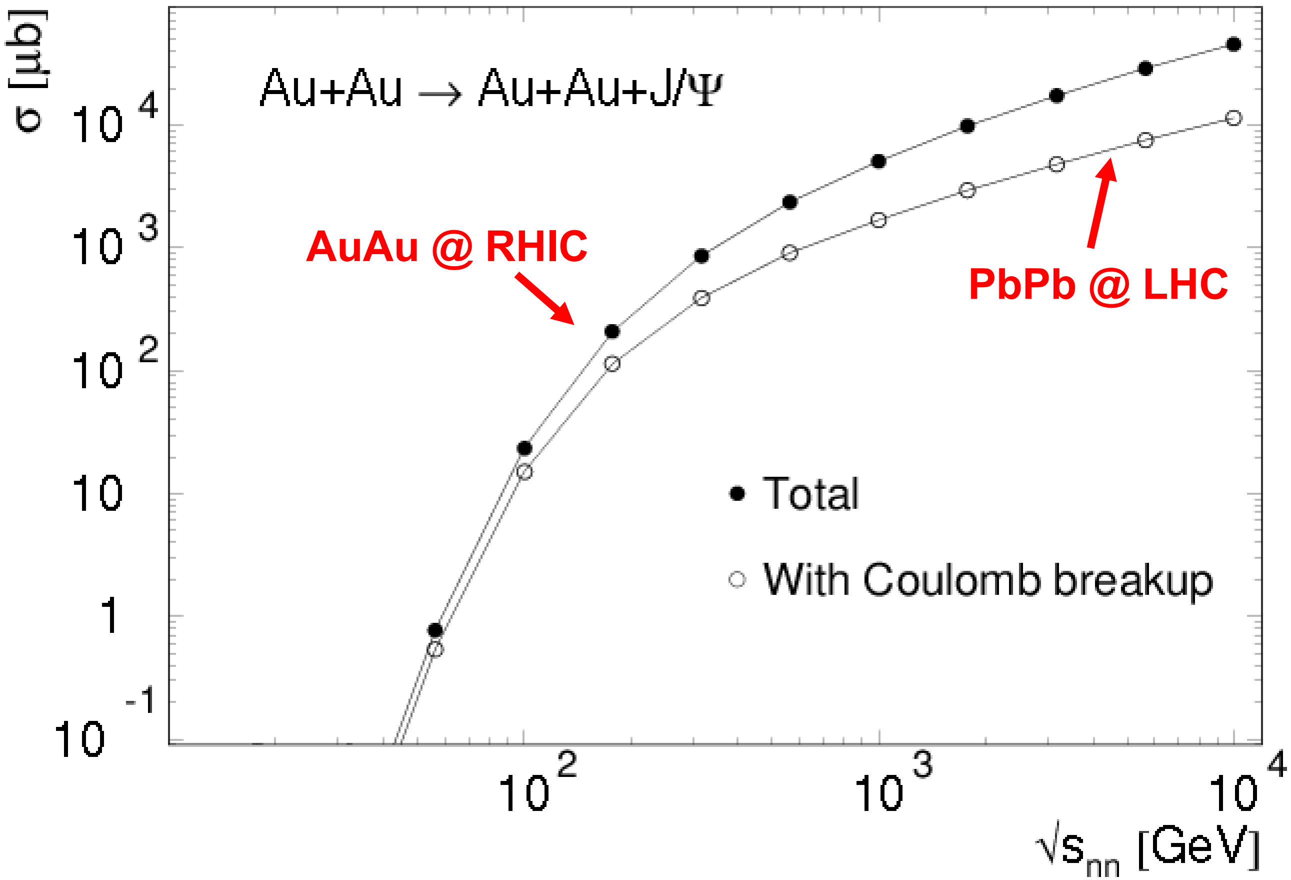
Goal: Publish the Run4 (2004) results
[turn preliminary into final results a.s.a.p.]

Increased luminosity in later runs should allow for a more significant result.

[Side note: Longer term future at RHIC includes eRHIC, whose program is being defined now – input from this community is most welcomed.]

And then there is also the LHC..

J/Ψ Excitation Function



Changes from RHIC→ LHC:

ρ:	RHIC 590mb	→ LHC 5200mb	factor 9
J/ψ	RHIC 0.3 mb	→ LHC 32mb	factor 100!

Summary

- UPC A+A collisions generate high-energy γ beams for "non-QGP" studies: $\gamma+\gamma$, γ+A physics
- Physics topics in UPC quarkonia photo-production:
  - Nuclear $G_A(x,Q^2)$ at small-x [Gluon saturation, CGC, ...], QQbar propagation in cold nuclear matter, QQbar spectroscopy: $\gamma+\gamma$ -> $0^{+-}2^{++}$ states, ...
- Lessons from RHIC (STAR and PHENIX):
  - Efficient trigger w/ forward neutron tagging (A* dissoc.) + high-p_T at y=0
  - Physics signal accessible w/ relative "simple" cuts & analysis
  - Good theoretical description of **J/Ψ** (pQCD) & high-mass e^+e^- (QED)
  - Large source of syst. uncertainty for J/Ψ: coherent $\gamma+\gamma$ -> e^+e^- physics background
  - Run-7 (2007): expected x3 stat. improvement for more significant result
- Prospects for LHC:
  - Unexplored kinematic regime (max. energies ever, small-x, γ+A -> Υ , ...)
  - Expected rates orders of magnitude higher than at RHIC; triggering is a key issue.

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PHENIX

14 Countries; 69 Institutions

600+ Collaborators

600+ MByte/s peak

600+ TByte/run (year)

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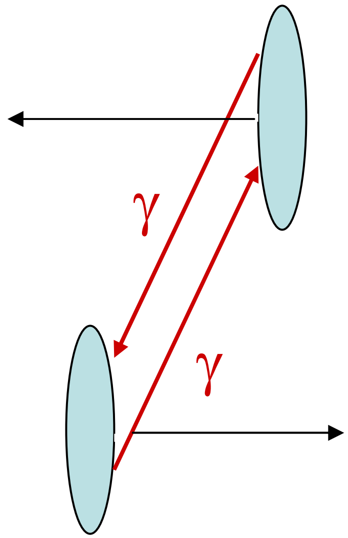
Backup slides

Electromagnetic interactions in heavy-ion interactions vs. in e^+e^- and ep (eA)

- Directional symmetry. Both beams (nuclei) can act as photon emitter or target.
- Away from y=0, the different photon emitter/target combinations give different contributions.
- Strong fields lead to high probability for emission of multiple photons.



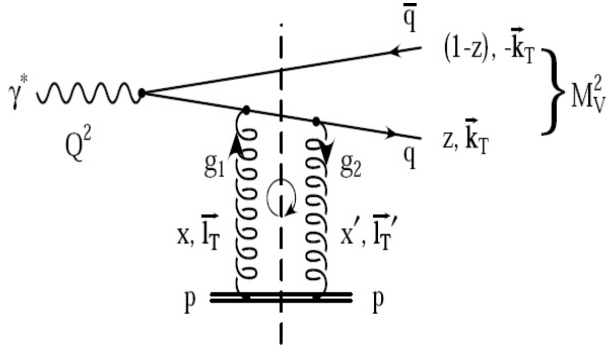
$xG(x,Q^2)$ via diffractive $Q\bar{Q}$ γ-production (HERA)

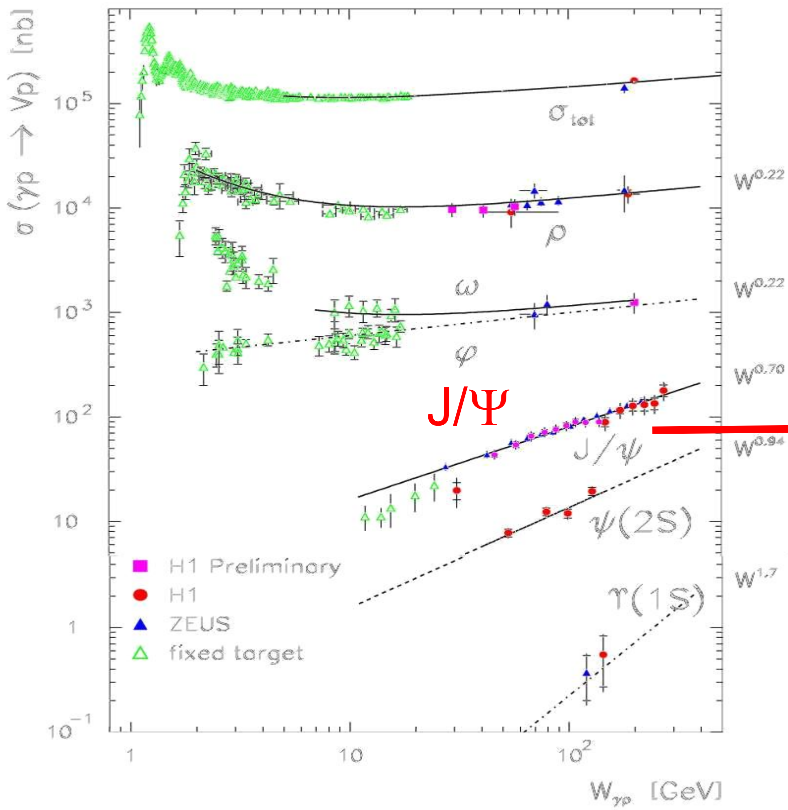
➢ $\gamma + p \rightarrow VM + p$ ($VM = J/\Psi, \Upsilon$) sensitive to gluon density squared:

$$\left.\frac{d\sigma(\gamma p \to V p)}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 \left[xG(x,Q^2)\right]^2, \text{ with } Q^2 = M_V^2/4$$

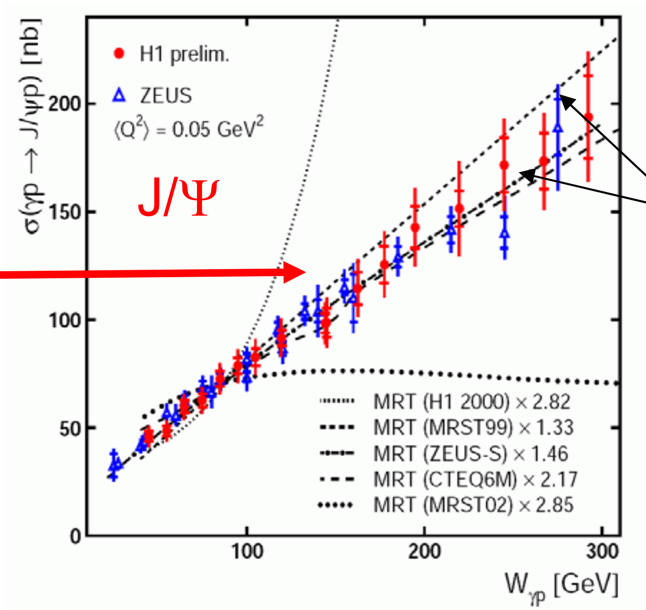
$$x = M_V^2 / W_{\gamma p}^2$$

Ryskin et al. ZPC 76 (1997)231





perturbative QCD calculations available:



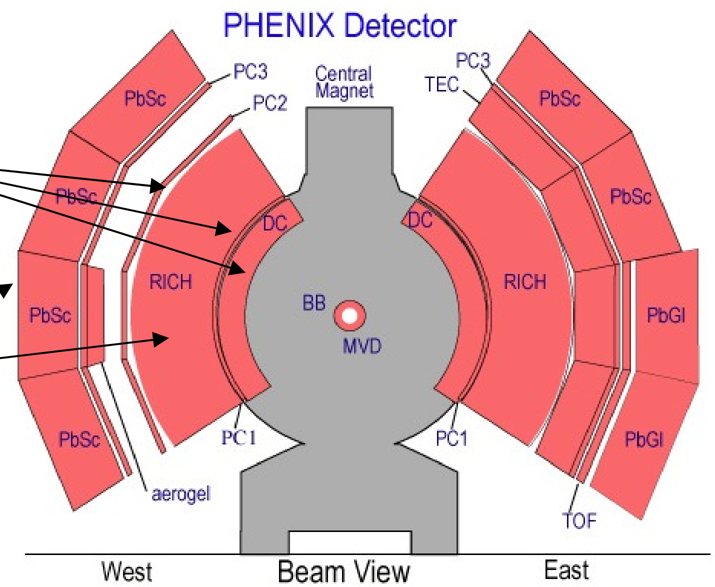
Discriminates different Ansätze of $xG(x,Q^2)$

Fleischmann,Teubner DIS07

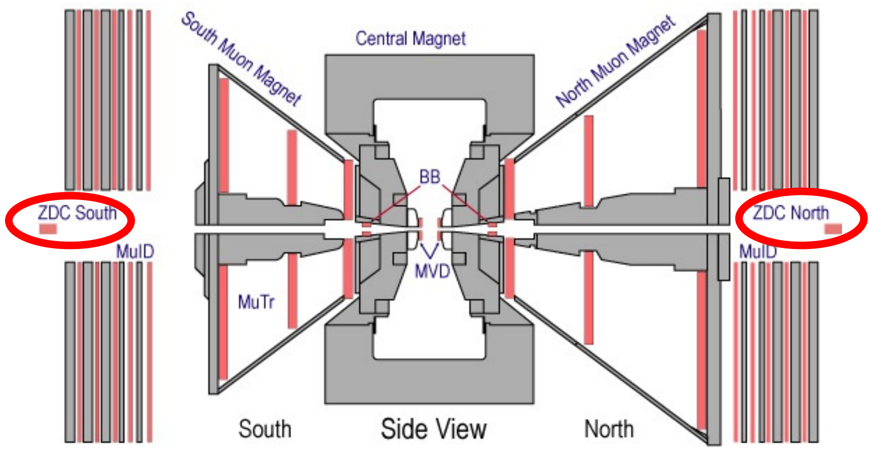
PHENIX UPC- key measurement detectors

➢ DC + PCs: Full central-arm charged tracking ($e^{\pm}$ momentum).

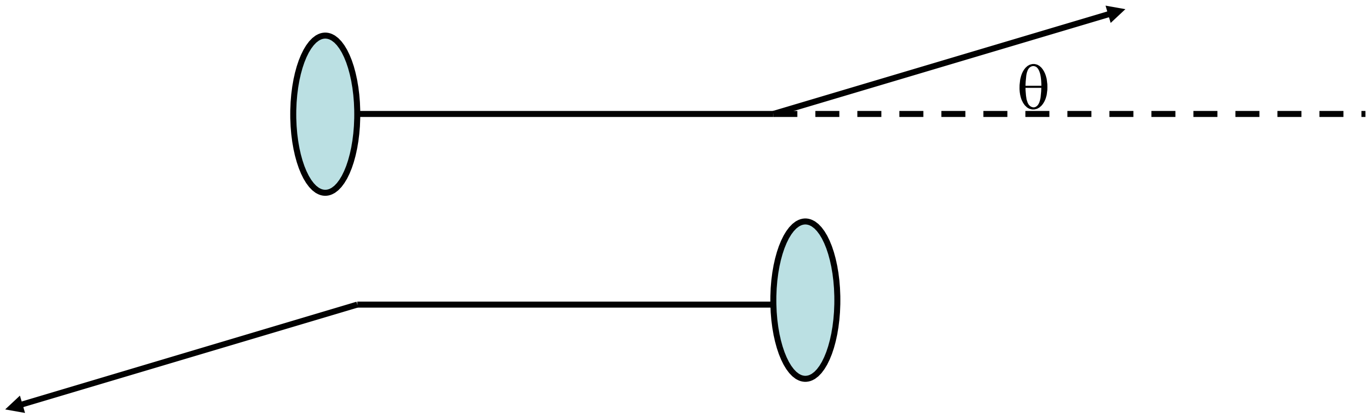
➢ RICH + EMCal: $e^{\pm}$ identification in central rapidity, and triggering (ERT)



➢ ZDC: Forward neutron detection (Au* dissociation):



No tagging of the nuclei



The coherence requirement limits the angular deflection to

$$\theta \sim 0.175 / (\gamma \cdot A^{4/3})$$

At RHIC

Au	A=197	θ ~ 1 μrad
Si	A=28	θ ~ 17 μrad

At LHC

Pb	A=208	θ ~ 0.05 μrad
Ar	A=40	θ ~ 0.3 μrad

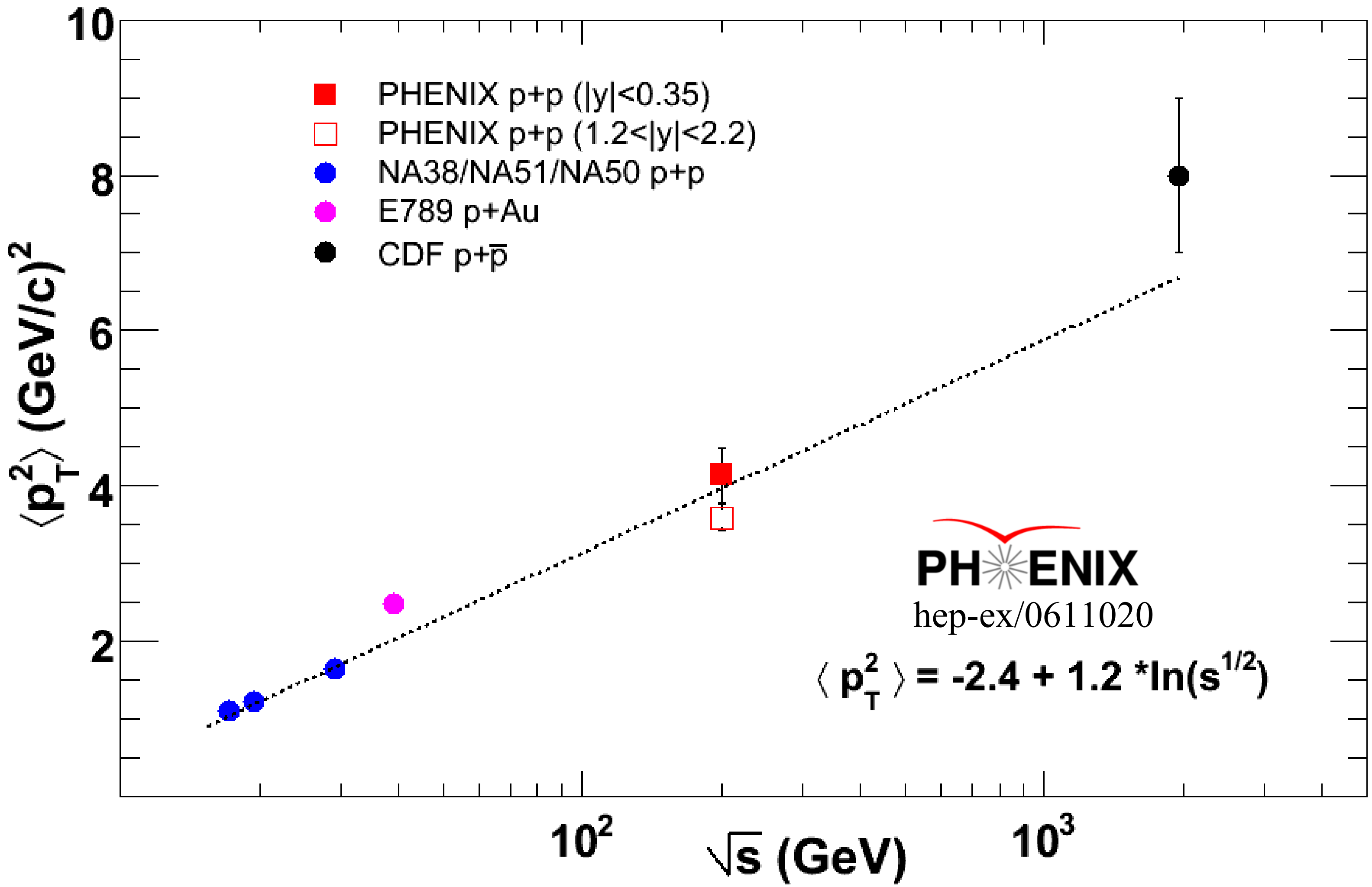
⇒Not possible to tag the outgoing nuclei. Might be possible with protons.

Experimental method: Rapidity gaps, reconstruct the entire event, signal of coherence from low p_T.

Intermission: ‘Normal’ J/psi distr.

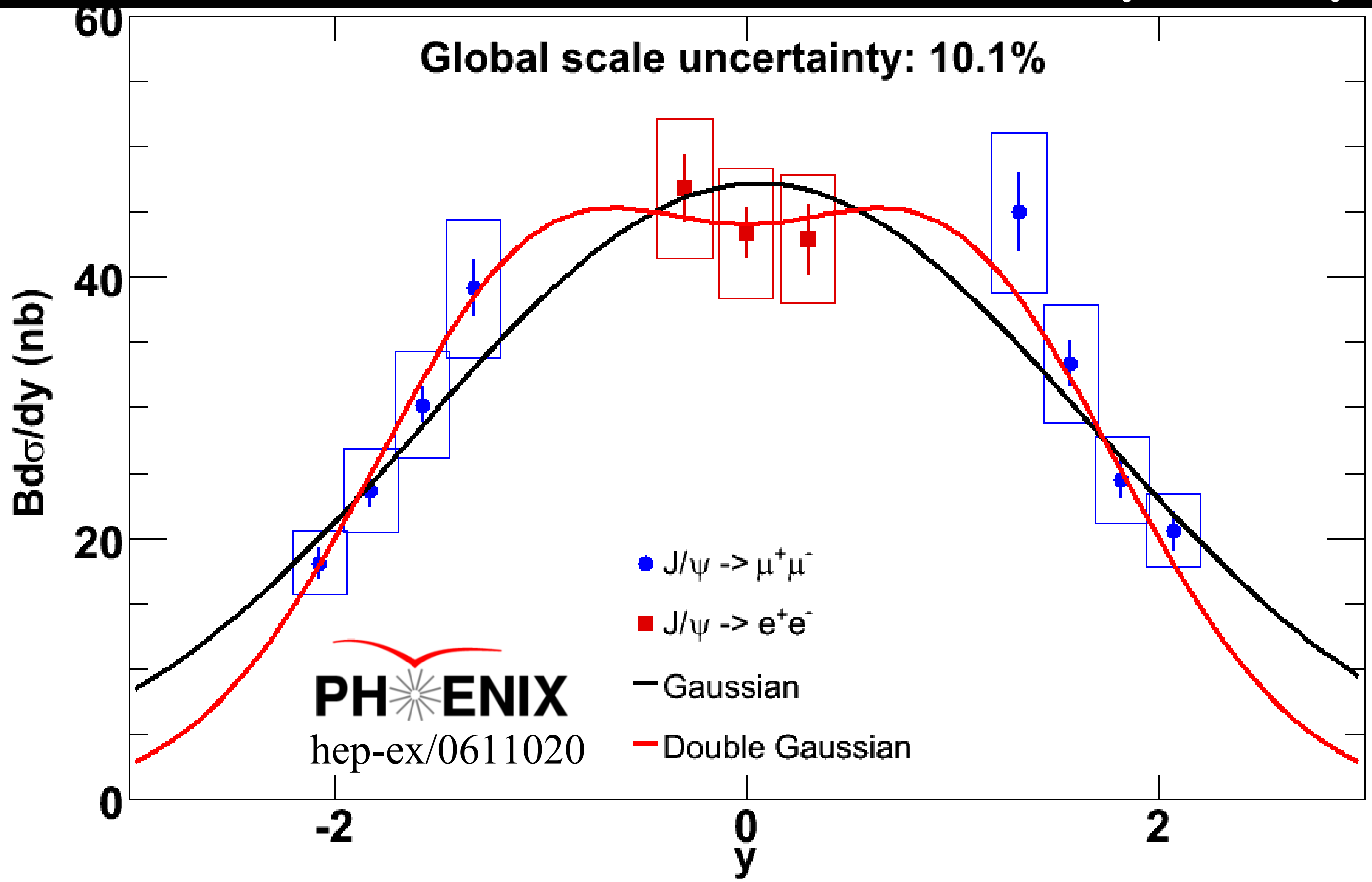
Results from regular p+p interactions shown for comparison..

$\langle p_T^2 \rangle$ vs Collision Energy



PHENIX $\langle p_T^2 \rangle$ measurements compared to measurements at other energies.
As a function of collision energy approx. a linear dependence on the $\ln(\sqrt{s})$.
- Significantly larger p_T values than for coherent interactions.

J/ψ Cross Section vs Rapidity



- The statistics available are large enough to allow eleven rapidity bins!
- p+p data now limited by systematic error not statistics
- The data slightly favor a flat distribution over the rapidity range |y|<1.5

But!

- Remember the systematic errors on the mid and forward rapidity points are independent ∴ a narrower distribution is not excluded.

Even with this very good stat., the shape is not unambiguosly defined..