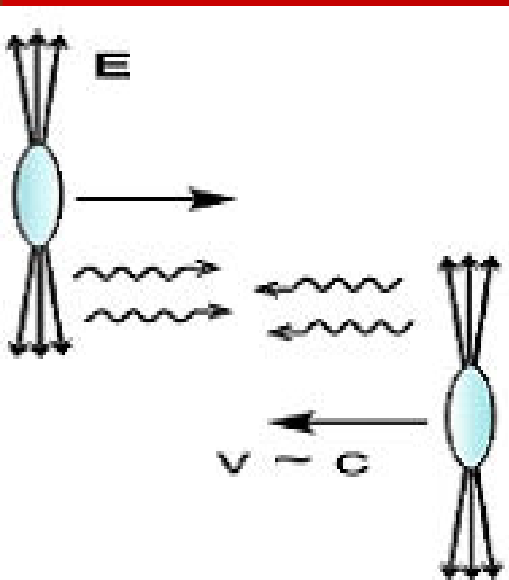


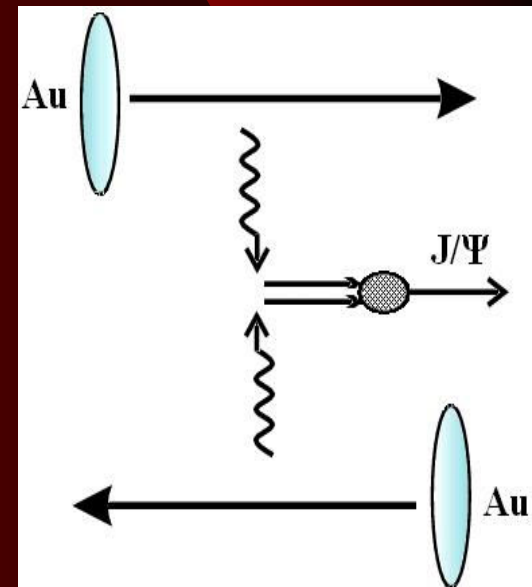
J/ Ψ photo-production in ultra-peripheral collisions

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Zimányi School on Heavy Ion Physics
Budapest, November 29 – December 4, 2009



- **UPC physics**
 - Photon-photon interactions
 - Photon beam in A+A
- **Measurements at RHIC**
 - Experimental signatures
 - Background
 - Results
- **LHC?**



Based on ...

- My previous talks on this subject ☺
- David d'Enterria for the PHENIX Coll.
Quark Matter 2005, nucl-ex/0601001
- Zaida Conesa del Valle for the PHENIX Coll.
Quark Matter 2009
- PHENIX publication (submitted to PLB)
arXiv: 0903.2041
- A lot of thanks...

Introduction

- **Nonlinear QCD dynamics at small x and Q^2 is one of the focal points of theoretical activity**

- Q^2 for coupling quarks even smaller, $\sim 1 \text{ GeV}^2$, black disk limit
- Mixing of perturbative and nonperturbative effects at small x and Q^2
- Interested in gluon distributions $G(x, Q^2)$

- **Photon to vectormeson processes: sensitivity to gluon distribution at small x , cross-section (with $Q^2 = M_V^2/4$, $x = M_V^2/W_{\gamma N}^2$):**

$$\left. \frac{d\sigma(\gamma N \rightarrow VN)}{dt} \right|_{t=0} \approx \frac{\alpha_s \Gamma_{ee}}{3\alpha_e M_V^5} 16\pi^3 \left(xG(x, Q^2) \right)^2$$

- **Photon-photon processes: tested in e^+e^- or ep (HERA)**

- Fermi 1924: The effect of the electromagnetic field of a relativistic particle is equivalent to a flux of photons with a continuous energy spectrum.

- **Possible new directions:**

- higher energies
- nuclear beams

Photon-photon interactions

- High-energy $\gamma\gamma$: complementary to "conventional" e^+e^- , ep (DIS), or pp collisions (to study QCD/QED, or even beyond-SM)
- High energy photon: point-like interaction or quantum-fluctuation into a vector meson or quark-pair

$$|\gamma\rangle = c_0 |\gamma_0\rangle + \sum_{V=\rho^0, \omega, \Phi, J/\Psi, \Upsilon} c_V |V\rangle + \sum_{q=u, d, s, c, b} c_q |q\bar{q}\rangle + \sum_{l=e, \mu, \tau} c_l |l\bar{l}\rangle$$

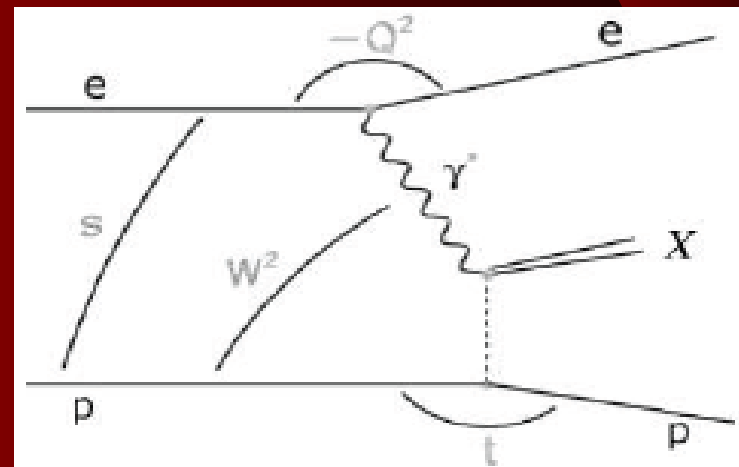
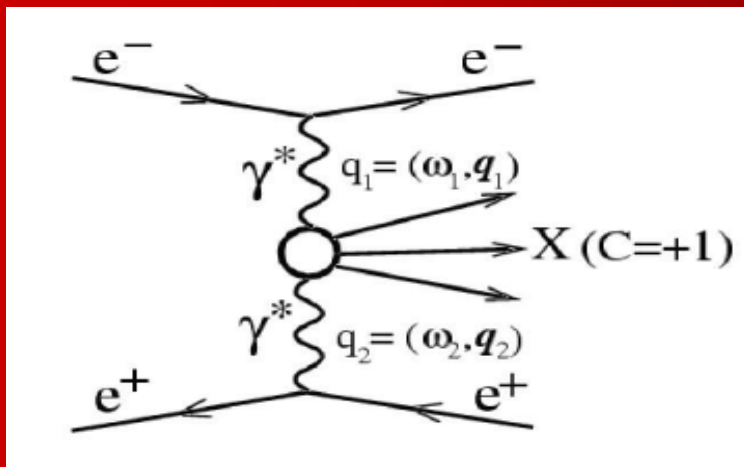
- γ_0 dominates, but $\gamma \rightarrow V, qq$ fluctuations interact strongly and give largest contribution to $\gamma\gamma$ cross-sections

How to make $\gamma\gamma$ collisions?

- EM field of relativistic charged particle = flux of “equivalent” photons.
- Weizsacker-Williams formula for γ -spectrum in an e^\pm beam (with $z=E_\gamma / E_e$):

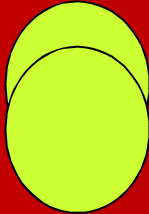
$$\frac{dN}{dz} \approx \frac{\alpha_{em}}{2\pi} \frac{1}{z} \left(1 + (1-z)^2 \right) \ln \frac{Q_{max}^2}{Q_{min}^2} \quad Q_{min}^2 = \frac{m_e^2 z^2}{1-z} \quad Q_{max}^2 = m_V^2 \text{ (e.g.)}$$

- Scattered beam close to parent beam (kinematics) \Rightarrow low p_t products & quasi-real photons ($Q^2 \sim 0$)

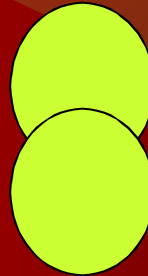


$\gamma\gamma$ in nucleon-nucleon collisions

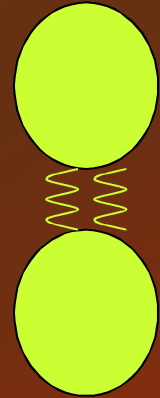
Central collision:



Peripheral collision:



Ultra-peripheral collision:



- Two heavy nuclei not overlapping

- $b > b_{\min} \approx 2R$
- Ultra-Peripheral Collision (UPC)

- Emitting a quasi-real photon

- $z = E_\gamma / E_A$, $x = z m_A b_{\min}$, $K \dots$ Bessel functions

- flux:
$$\frac{dN_\gamma}{dz} \approx \frac{\alpha_{\text{em}} Z^2}{2\pi} \frac{1}{z} \left(2x K_0(x) - x^2 \left(K_1^2(x) - K_0^2(x) \right) \right)$$

- Interacts with the other nucleus

- Large photon cross-sections ($\sim Z^4$)

Where all this is done: BNL@RHIC

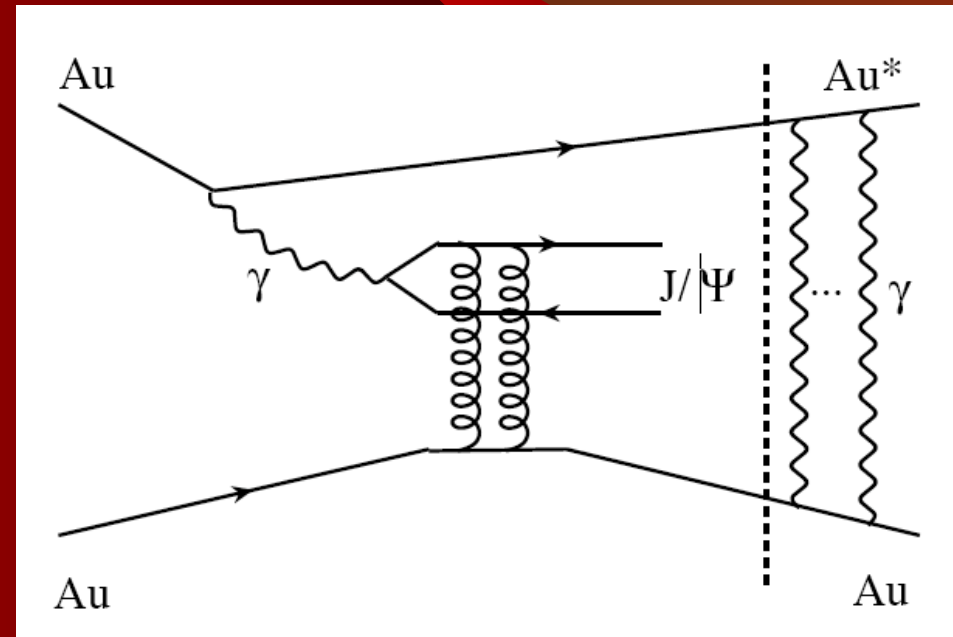
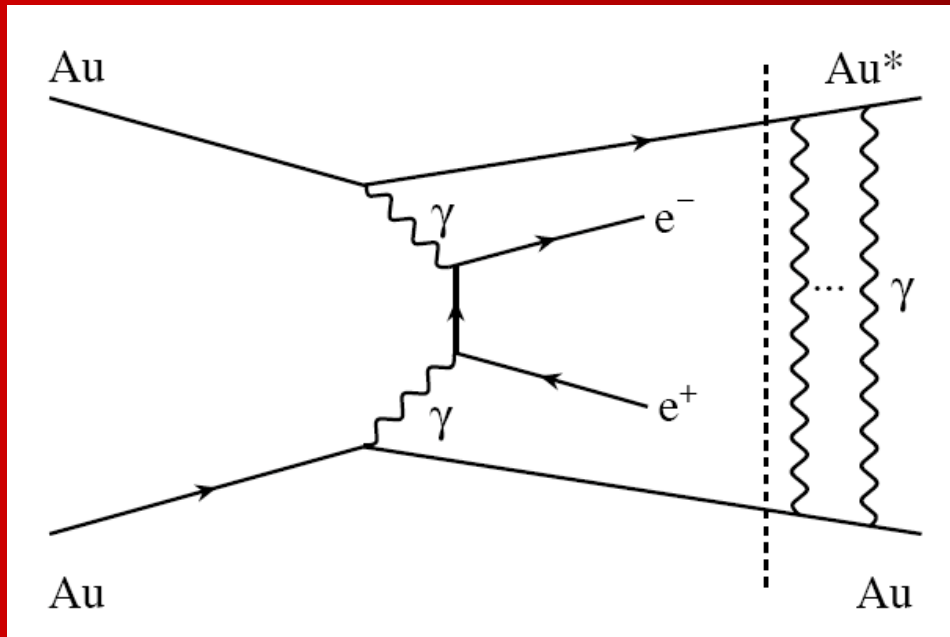
- **RHIC: Au+Au @ $E_{\text{cms}} = 200 \text{ GeV/nucleon} + \dots$**
 - Au+Au, Cu+Cu, pp+pp, d+Au collisions, up to 500 GeV/nucl.
 - 4 experimental collaborations:
BRAHMS, PHENIX, PHOBOS, STAR
- **PHENIX: several hundred scientist, a lot of topics**
- **See talks of David d'Enterria, John Koster, Raphael Granier de Cassagnac, Todd Kempel, Swadhin Taneja, Rachid Noucier, Yoshinori Fukao**



J/ Ψ production in UPC's

- Different type of processes

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



- Incoherent production (Coulomb-breakup):
 $\gamma + A \rightarrow A' + xN + J/\Psi (\rightarrow e^+ e^-)$, much larger p_t of the pair

Experimental signatures

- **Central rapidities:**

- Low multiplicities: $N < 15$ (well below 15)
- Low total p_t (large wavelength, “coherence condition”): $E_{\text{photon,max}} \sim \gamma/R \sim 3\text{GeV}$ (80GeV at LHC)
- Zero net charge
- Narrow dN/dy peaked at $y=0$ (tagging/triggering)

- **Forward rapidities:**

- Coulomb-excited A^* dissociation via (forward) neutron (Xn) emission

Measured processes in Au+Au UPC

STAR:

- PRL 89 272302 (02), Coherent ρ production,
 $\gamma+A \rightarrow A^* + \rho (\rightarrow \pi^+ \pi^-)$
- PRC 70 031902 (04), Dielectron continuum at low m_{inv} ,
 $\gamma + \gamma \rightarrow e^+ e^-$

• PHENIX:

- nucl-ex/0601001 (prelim.), 0903.2041 (final)
- J/ Ψ production: $\gamma + A \rightarrow A^* + J/\Psi (\rightarrow e^+ e^-)$
- Dielectron continuum at high m_{inv} : $\gamma + \gamma \rightarrow e^+ e^-$

Eliminating background sources

- **“Non-physical”:**

- Cosmic rays: no ZDC, no good vtx.
- Beam-gas collision: no good vertex, large multiplicity, asymmetric dN/dy

- **Physical processes:**

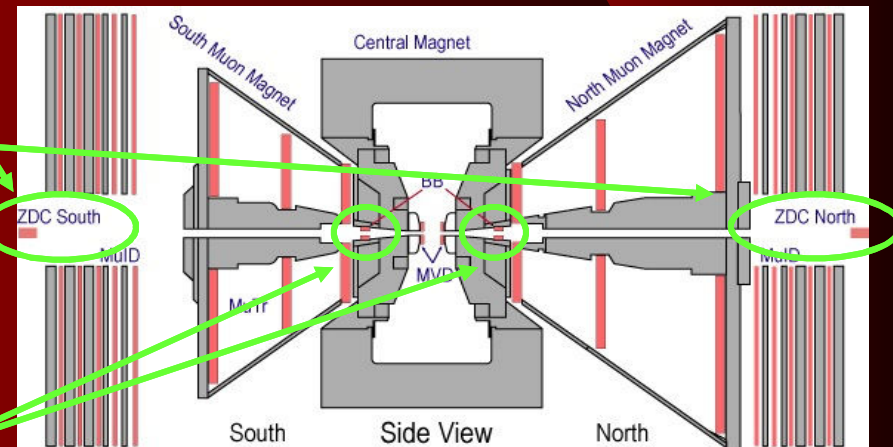
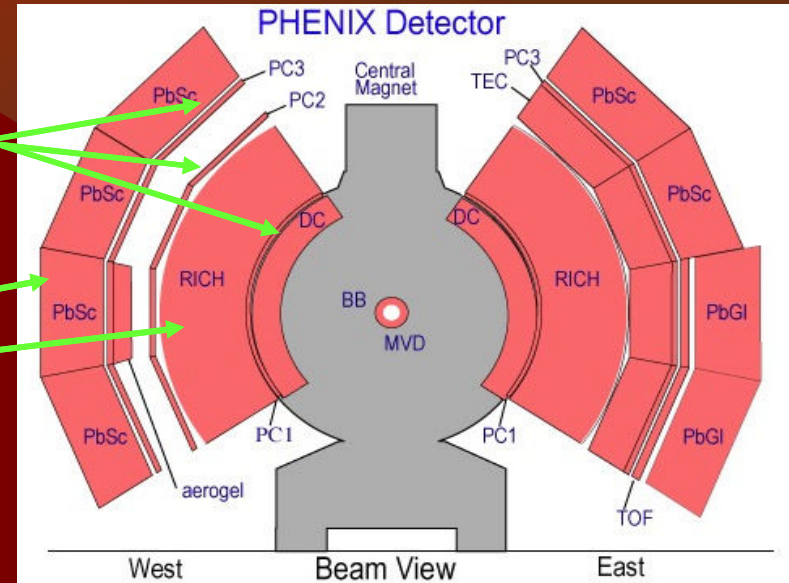
- Peripheral nuclear A+A: “large” multiplicity, large p_t
- Hadronic diffractive (Pomeron-Pomeron): forward proton emission, larger p_t : $p_t(\gamma\gamma) < p_t(PP)$, like-sign pairs. Hard-diffractive J/ Ψ production.
- Incoherent UPC $\gamma+n \rightarrow n+J/\Psi$: $p_t(\gamma\gamma) < p_t(\gamma P)$, wider & asymm. dN/dy , ≥ 2 neutrons (induced nuclear break-up) with same direction as J/ Ψ .
- Other coherent UPC processes: $\gamma\gamma \rightarrow e^+e^-$ (important , $\gamma A \rightarrow \text{jet}+A$ (lower cross-sections)

trigger level

final signal

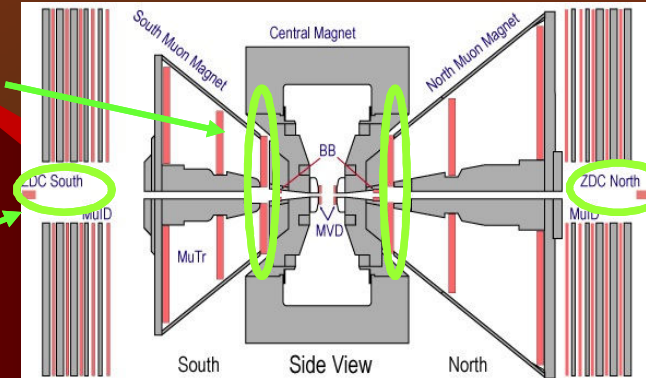
PHENIX detectors for UPC

- DC + PC's: Full central-arm charged tracking (e^\pm momentum).
- EMCal + RHIC: e^\pm identification in central rapidity.
- ZDC: Forward neutron detection (Au^* dissociation):
- BBC: charged tracks



Triggering on UPC's

- **PHENIX Run-4 AuAu UPC level-1 trigger:**
 - Sensitive to $\gamma + \text{Au} \rightarrow \text{Au}^* + \text{J}/\Psi (\rightarrow e^+e^-)$
- **Veto on coincident BBC ($|\eta| \sim 3-4$):**
 - avoid periph. nuclear, beam-gas colls.
- **Neutron in ZDC ($E > 30 \text{ GeV}$)**
 - sensitive to Au^* Coulomb dissociation
- **Large energy ($E > 0.8 \text{ GeV}$) cluster in EMCal:**
 - e^+e^- decay from J/Ψ
- **Trigger definition based on the above**
- **Events collected ($\sim 0.4\%$ of MB trigger):**
 - UPC AuAu: 8.5 M
 - MinBias AuAu (BBCLL1): 1122 M ($\int \mathcal{L} = 120 \mu\text{b}^{-1}$)

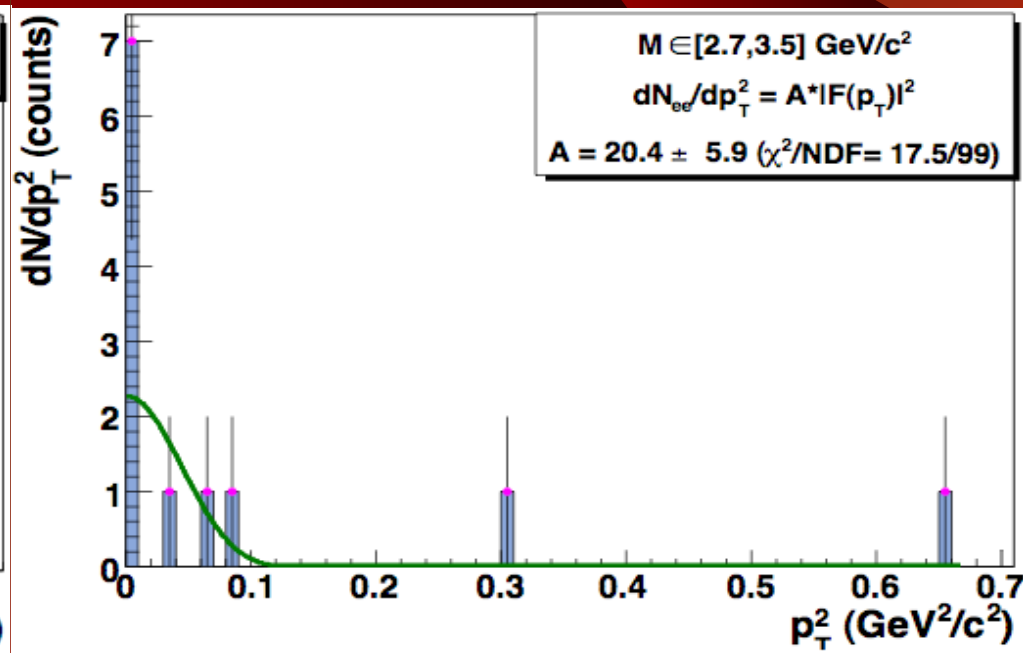
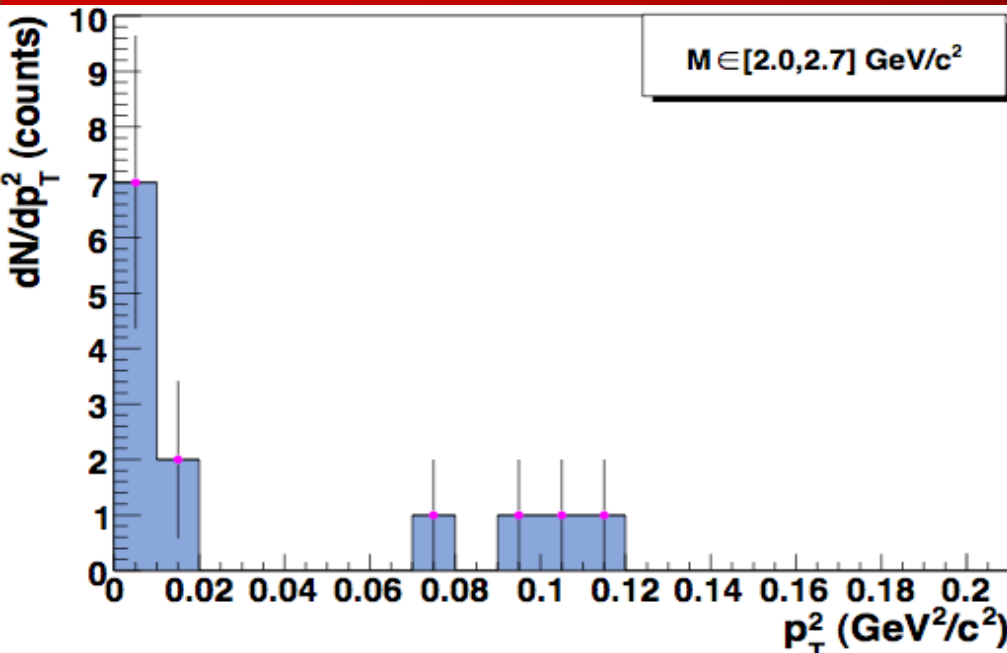
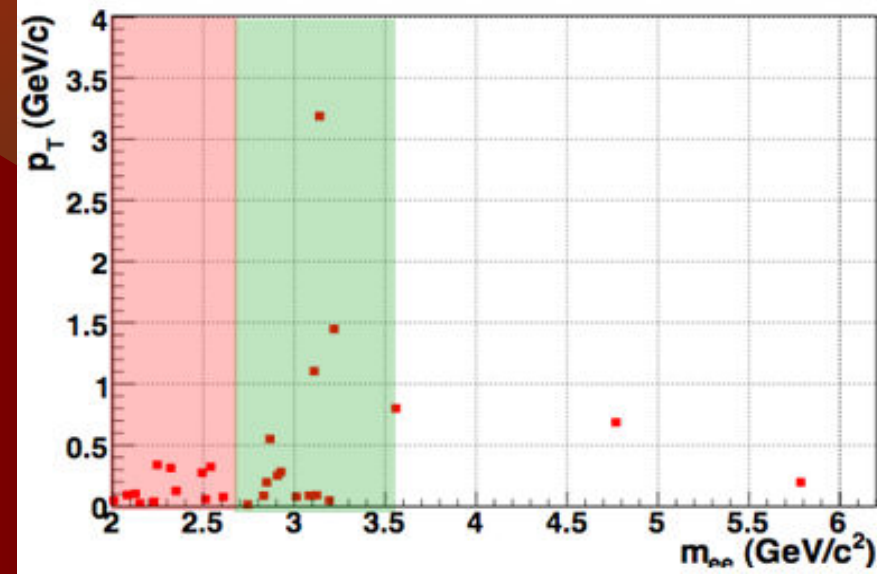


PHENIX UPC analysis cuts

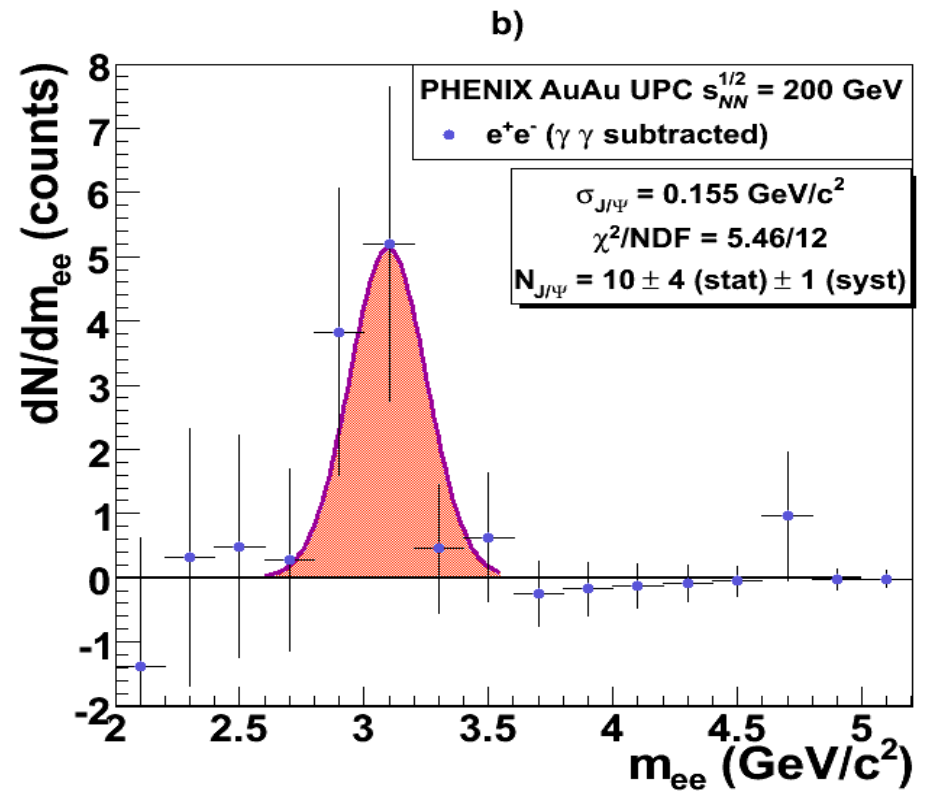
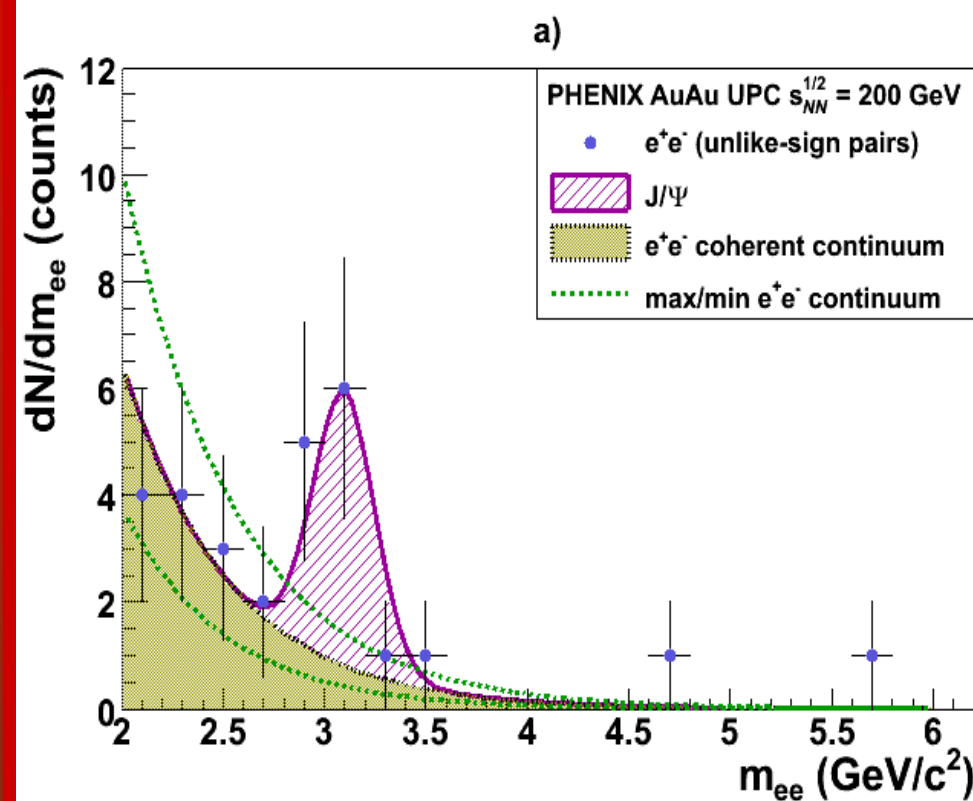
- Cuts made on the 8.5M UPC triggered events
- Global cuts:
 - Standard vertex cut: $|z_{\text{vtx}}| < 30$ cm
 - Multiplicity (number of tracks) = 2, removes non-UPC
- Electron ID cuts:
 - RICH: # of photo-tubes within nominal ring radius > 2
 - Electrons: $E_1 > 1$ GeV or $E_2 > 1$ GeV, high- p_t trigger threshold
- Pair cuts:
 - Dielectrons back-to-back (low sum p_t)
- Residual background subtraction:
 - unlike-sign pairs – like-sign pairs
- Result: 28 unlike-sign pairs and no like-sign pairs of $m_{ee} > 2$ GeV/c²: clean sample with 0 net charge

Transverse momentum distribution

- J/Ψ : low p_t region consistent with Au form factor fit
- High p_t region: also an incoherent component
- Continuum: coherent nature



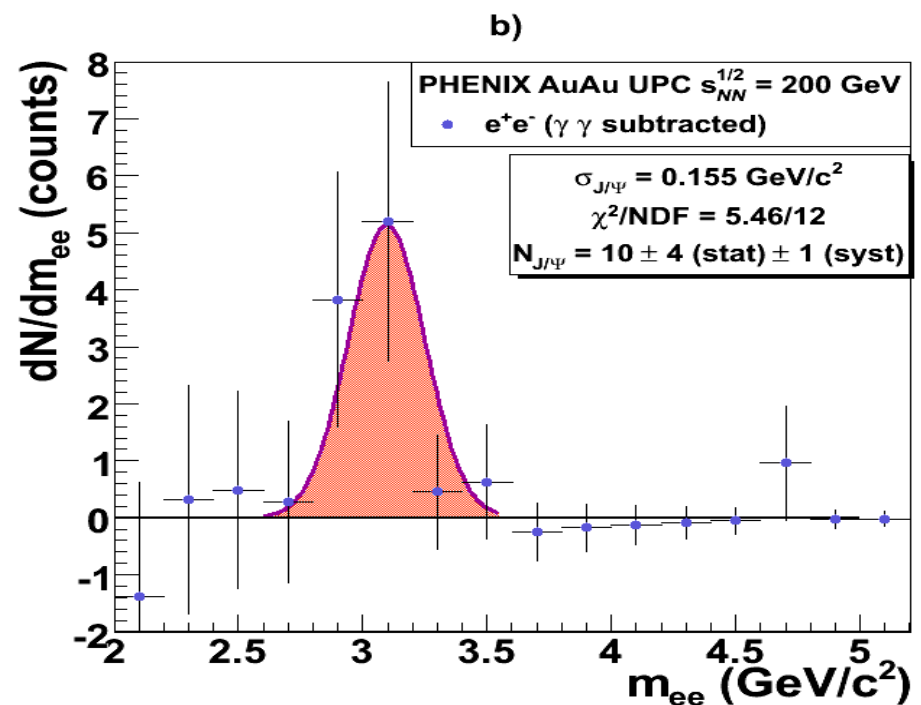
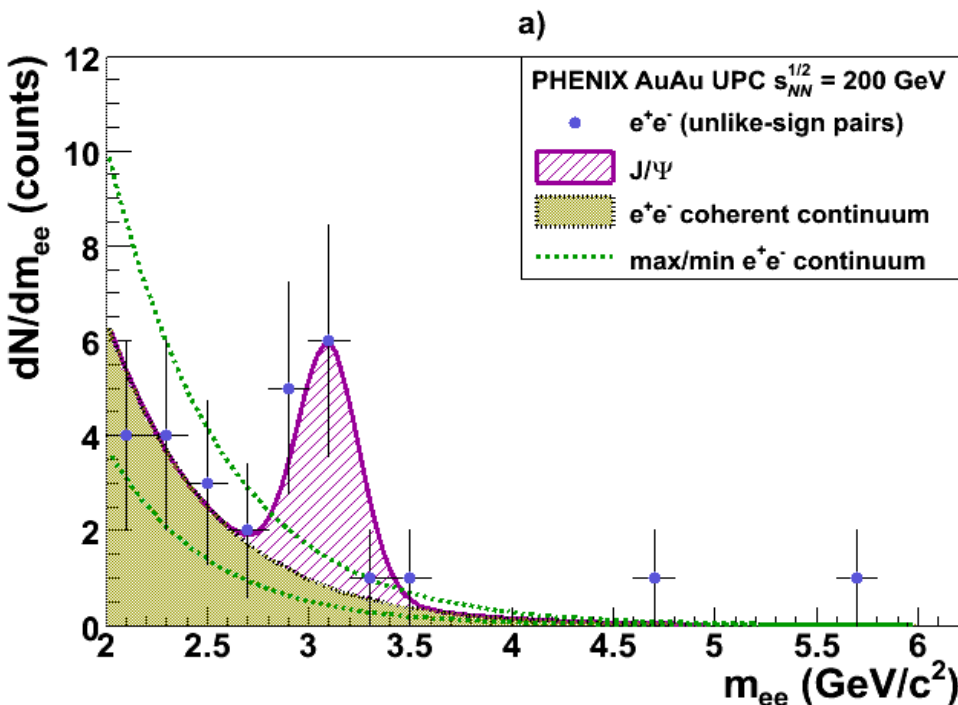
Invariant mass distributions



- Continuum in good agreement with theoretical input
- J/ Ψ peak & width also (theoretical input + full MC resp.+reco)

Yields

Sample, $m_{e^+e^-}$ [GeV/c ²]	Yield
J/ Ψ [2.7,3.5]	9.9 ± 4.1 (stat) ± 1.0 (syst)
e^+e^- continuum [2.0,2.8]	13.7 ± 3.7 (stat) ± 1.0 (syst)
e^+e^- continuum [2.0,2.3]	7.4 ± 2.7 (stat) ± 1.0 (syst)
e^+e^- continuum [2.3,2.8]	6.2 ± 2.5 (stat) ± 1.0 (syst)



Continuum cross-sections

$$\left. \frac{d^2\sigma_{e^+e^- \rightarrow Xn}}{dy dm_{ee}} \right|_{|y| < 0.35, \Delta m_{ee}} = \frac{N_{e^+e^-}}{\text{Acc} \cdot \varepsilon \cdot \varepsilon_{\text{trigg}}} \cdot \frac{1}{L} \cdot \frac{1}{\Delta y \Delta m_{ee}}$$

- **Cross-sections after efficiency corrections:**

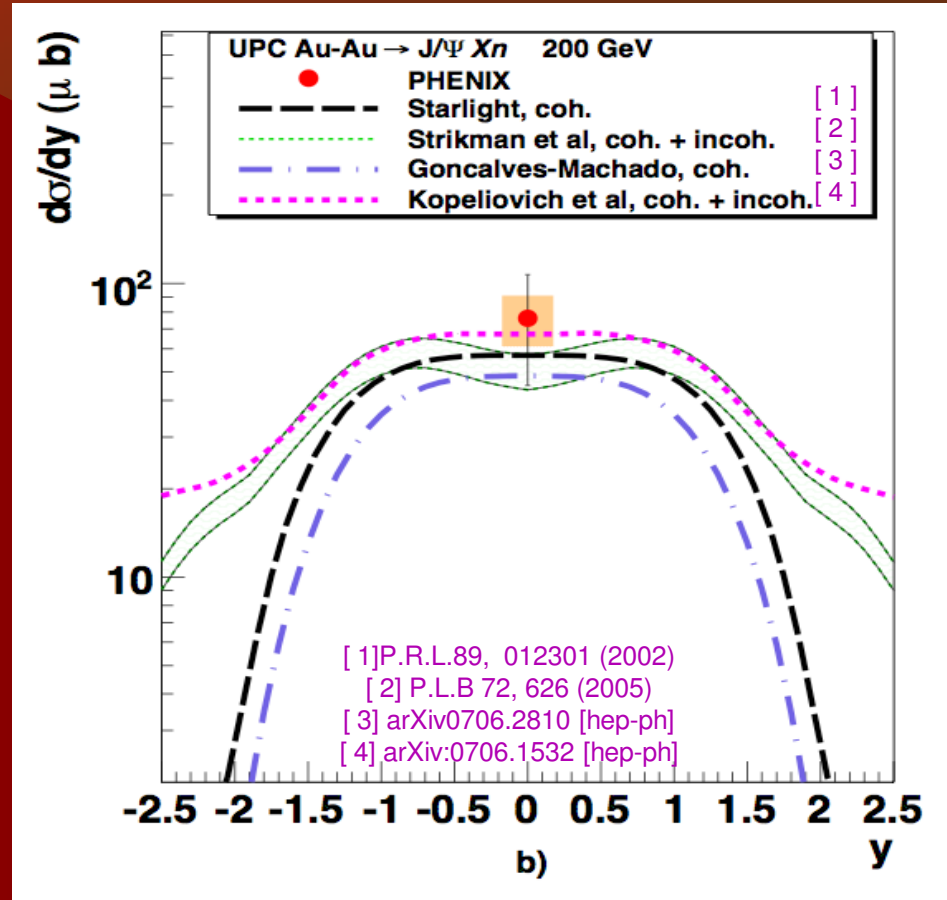
$m_{e^+e^-}$ interval [GeV/c ²]	$d^2\sigma/dm_{ee} dy _{y=0}$ [$\mu\text{b c}^2/\text{GeV}$]	STARLIGHT
e^+e^- continuum [2.0,2.8]	86 ± 23 (stat) ± 16 (syst)	90
e^+e^- continuum [2.0,2.3]	129 ± 47 (stat) ± 28 (syst)	138
e^+e^- continuum [2.3,2.8]	60 ± 24 (stat) ± 14 (syst)	61

- **Results agree with QED theoretical (STARLIGHT) calculations even though we are in a strongly interacting regime !**
- **Lacking of other model comparisons on this kinematical region... input from theorists is most welcome !**

J/ Ψ cross-sections

$$\left. \frac{d\sigma_{J/\Psi}}{dy} \right|_{|y| < 0.35} \equiv \frac{1}{BR} \frac{N_{J/\Psi}}{Acc \cdot \varepsilon \cdot \varepsilon_{trigg}} \cdot \frac{1}{L \Delta y}$$

- Agreement with theoretical results
- But: coherent + incoherent production
- Main systematic error: coherent continuum
- Statistical errors: larger luminosity
- Present status: detailed study of $G_A(x, Q^2)$, J/ Ψ absorption in cold nuclear matter not possible

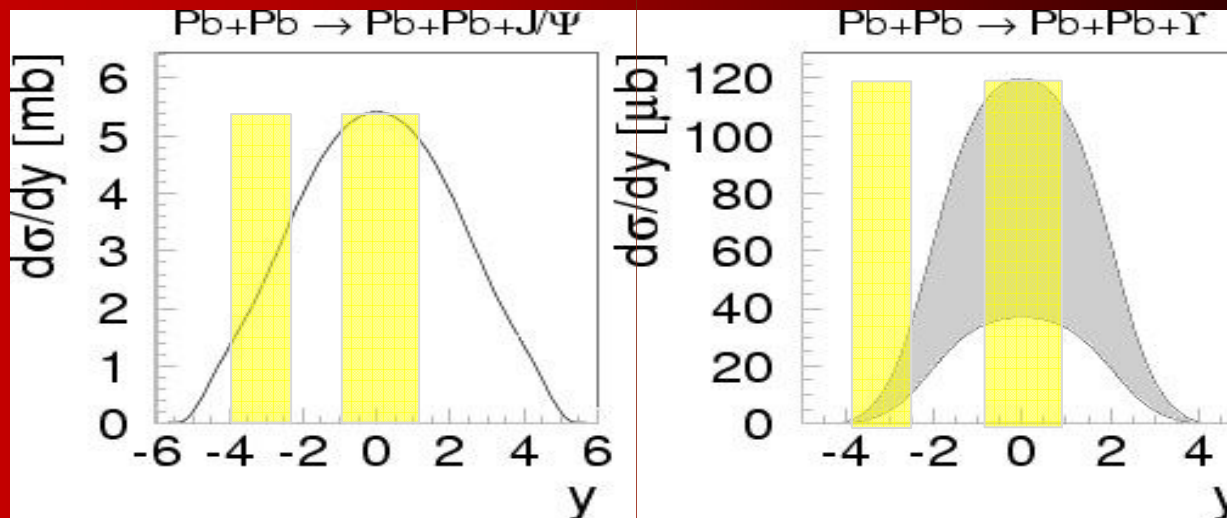


LHC prospects

Cross-sections from J. Nystrand, hep-ph/0412096, NPA752(2005)470

Accelerator	Hadroproduction $p + p \rightarrow V + X$	Photoproduction $p + p \rightarrow p + p + V$
RHIC $\sqrt{s} = 0.2$ TeV, $V = J/\Psi$	$4.0 \pm 0.9 \mu\text{b}$	3.0 nb
LHC $\sqrt{s} = 5.5$ TeV, $V = J/\Psi$	19-48 μb	54 nb
LHC $\sqrt{s} = 5.5$ TeV, $V = \Upsilon(1S)$	190-280 nb	720 pb

Accelerator	Hadroproduction $A + A \rightarrow V + X$	Photoproduction $A + A \rightarrow A + A + V$
RHIC $\sqrt{s_{nn}} = 0.2$ TeV, $V = J/\Psi$	160 mb	290 μb
LHC $\sqrt{s_{nn}} = 5.5$ TeV, $V = J/\Psi$	820-2100 mb	32 mb
LHC $\sqrt{s_{nn}} = 5.5$ TeV, $V = \Upsilon(1S)$	8-12 mb	170 μb

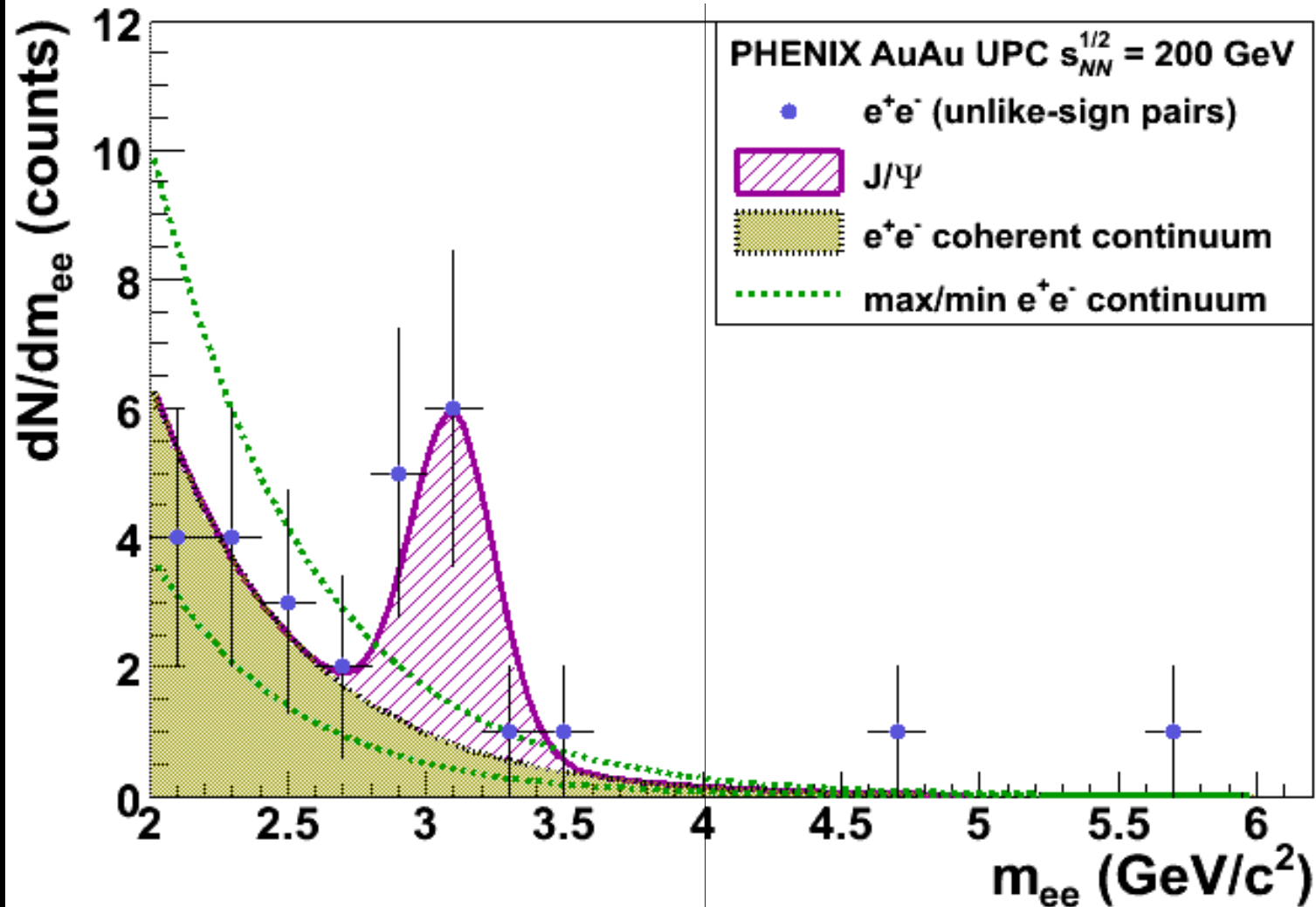


Summary

- **UPC collisions: high energy photon beam**
- **Precision QCD**
 - Low background, simple initial state
 - Complimentary to conventional e^+e^- or ep
- **First results from RHIC**
 - Efficient trigger, simple analysis
 - Good theoretical description
 - Main systematic uncertainty: dielectrons
 - No strong constraint on model ingredients yet
- **To be continued at LHC**
 - Incoherent processes, continuum cross-section
 - Higher rates and energies

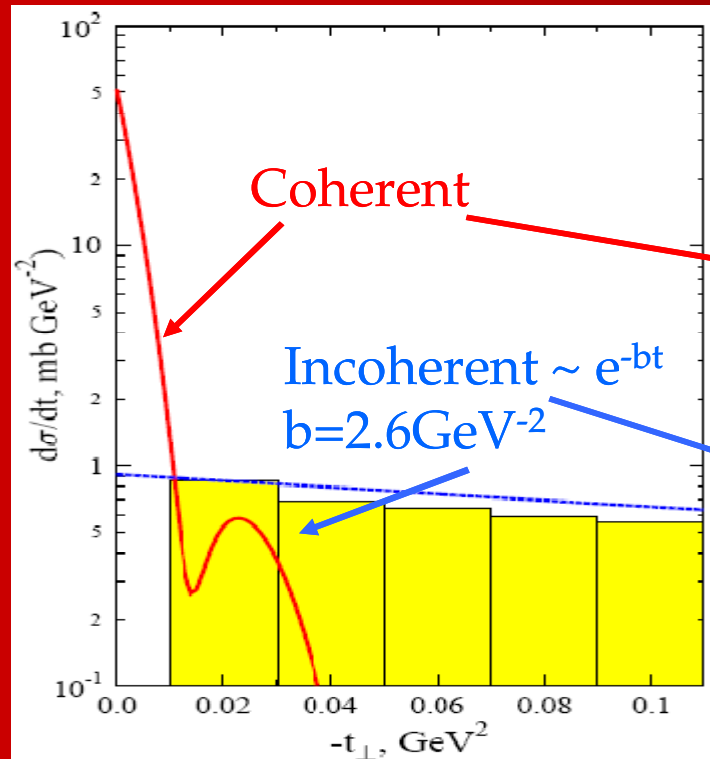
Thank you for the attention!

arXiv: 0903.2041

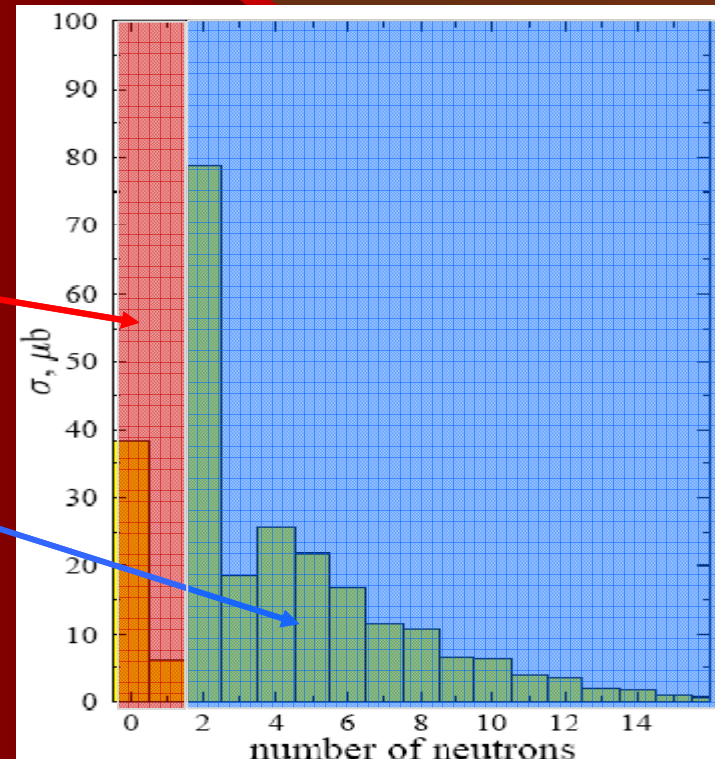


Incoherent J/Ψ production

- Via Coulomb-breakup
- How to separate from the coherent? Strikman:
Via t distribution



Via neutron tagging



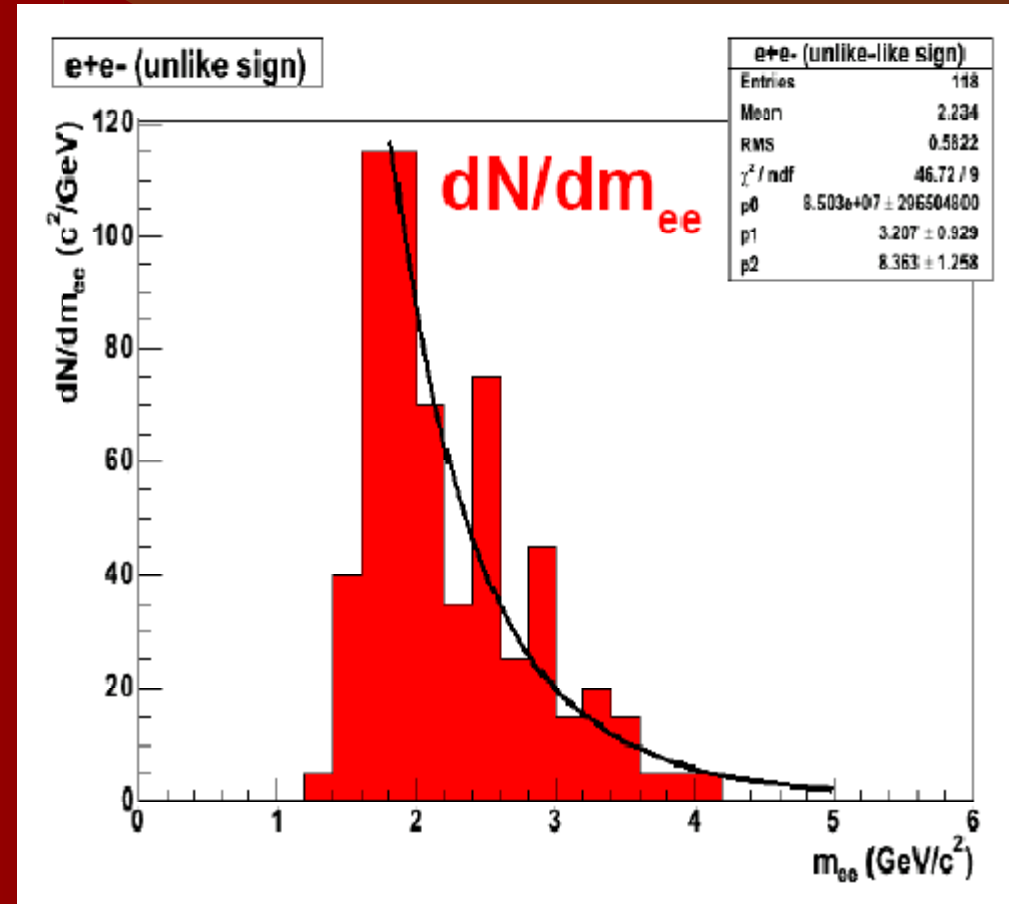
Strikman et al., hep-ph/0505023

- Limited statistics ...

Background subtraction

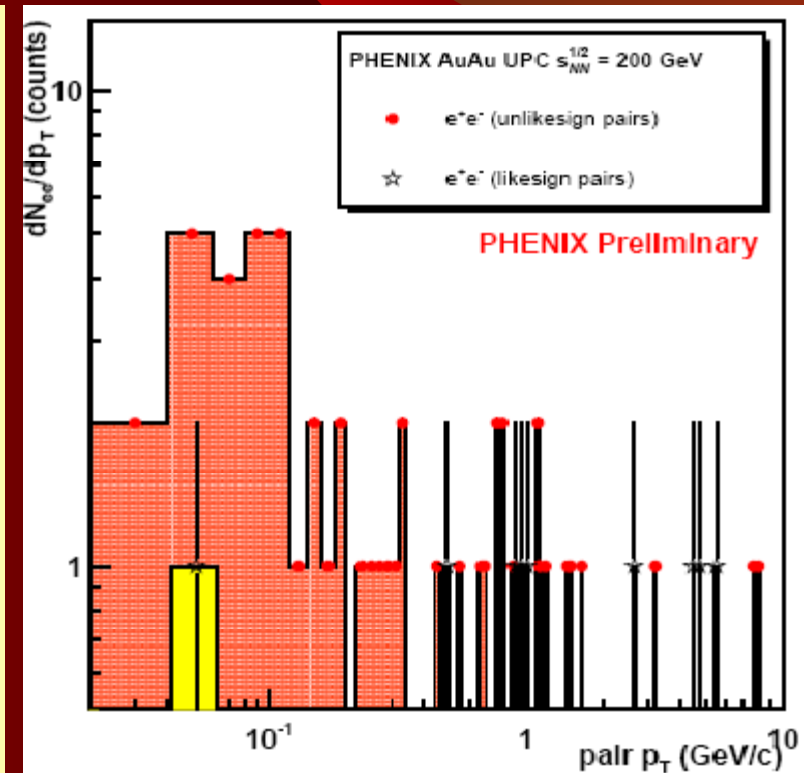
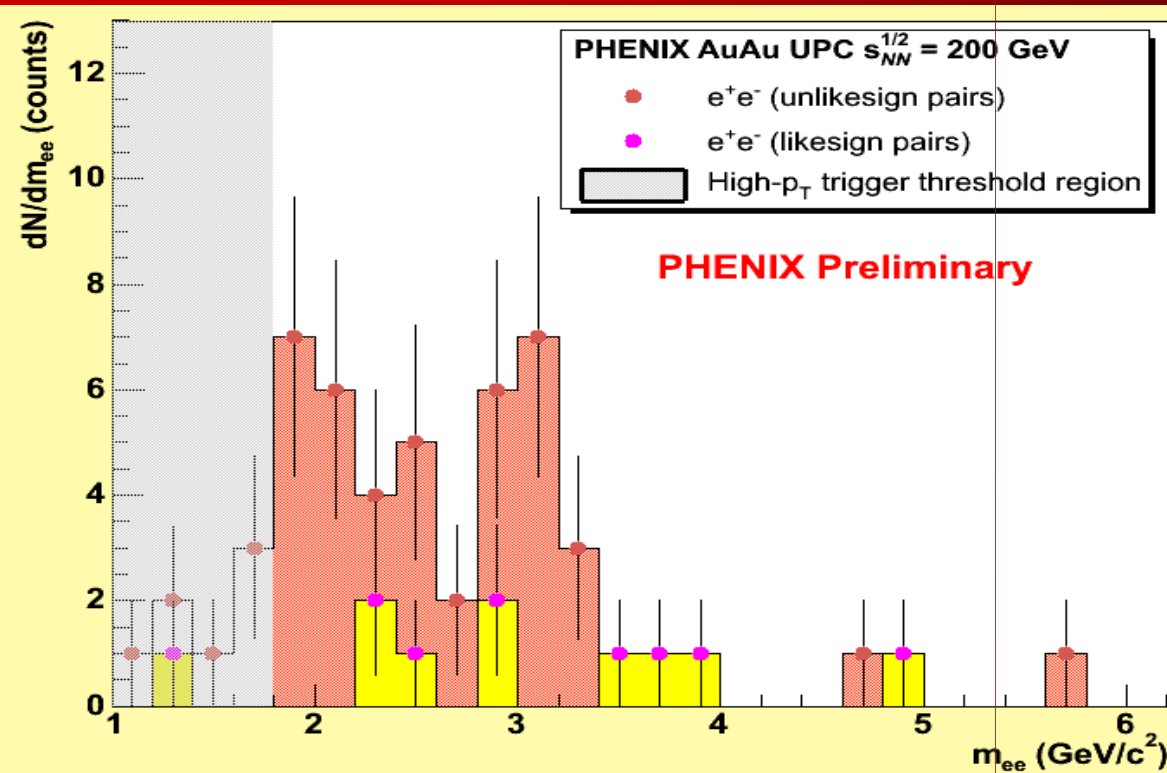
J. Nystrand, hep-ph/0412096, NPA752(2005)470

- Starlight Monte Carlo simulation
- Determine continuum shape
- 700k e^+e^- pairs with $m_{inv} > 1.5$ GeV, $500 \mu\text{b}^{-1}$



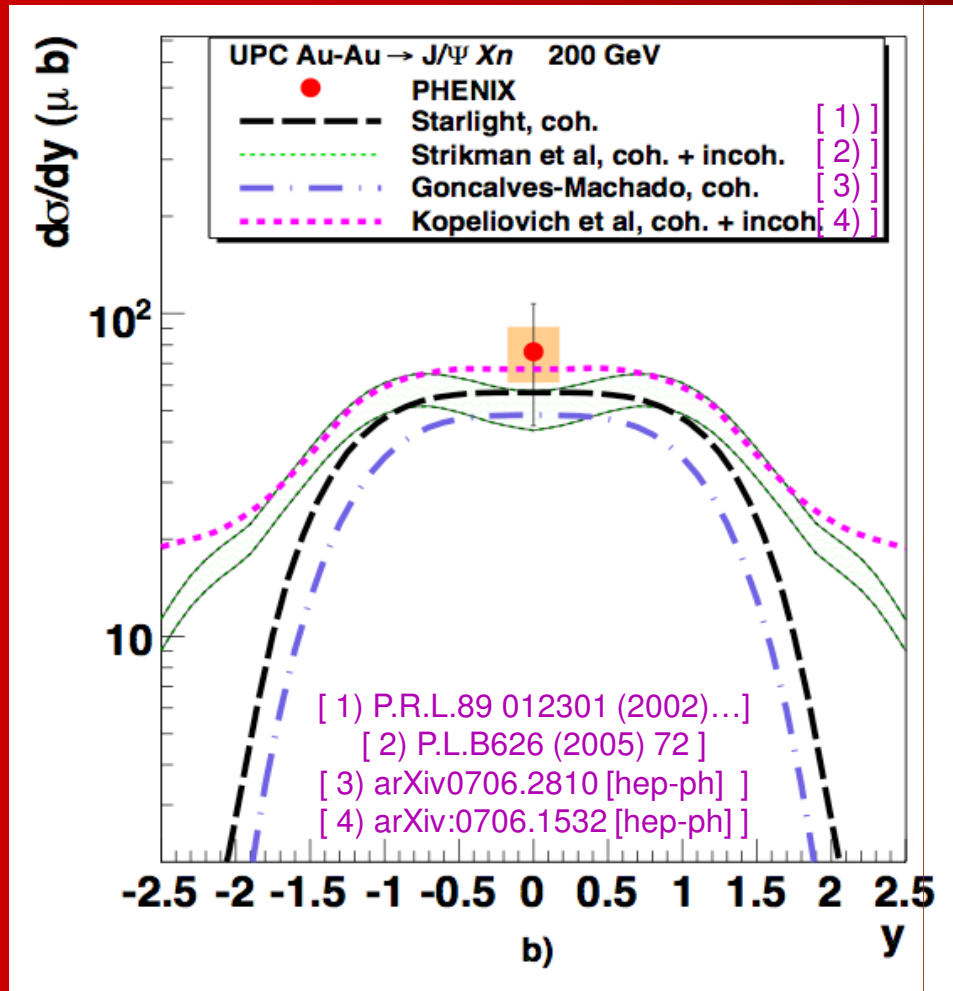
Resulting distributions

- Invariant mass distribution with continuum background
- Pair transverse momentum distribution
- Unlike-sign (red) and like-sign (yellow) pairs



Theoretical calculations

- Cross-section is consistent with different model predictions
- ... though current precision precludes yet any detailed conclusion on the basic ingredients: shadowing and nuclear absorption



Rough comparison with HERA

e-p data, $\sigma_{\gamma p} = A^\alpha \sigma_{\gamma A}$

If coh. incoh. ratio is 50% - 50%

- $\alpha_{\text{coh}} = 1.01 \pm 0.07$
- $\alpha_{\text{incoh}} = 0.92 \pm 0.08$

$\Rightarrow \alpha \sim 1$, good agreement with HERA data hard probes scaling!

- Similar comparison with STAR ρ measurement gives

$\alpha_{\text{coh}} = 0.75 \pm 0.02$,
closer to $A^{2/3}$ soft scaling

[ZEUS, Eur.Phys.J. C24 (2002) 345]

[H1, Eur.Phys.J. C46 (2006) 585]

[STAR, Phys.Rev.C77 (2008) 034910]