Quarkonia photoproduction in Ultraperipheral A+A collisions at RHIC & LHC

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Overview

- Physics topics: $\gamma\gamma$, γ p collisions at e^+e^-, ep colliders
  $\gamma\gamma$, γ A collisions in UltraPeripheral A+A
- Experimental aspects: Ultraperipheral A+A collisions (signatures, brackgd, triggers, detectors, analysis cuts, ...)
- Results: Quarkonia γ–production in UPC @ RHIC (PHENIX)
- Prospects: Quarkonia γ–production in UPC @ LHC
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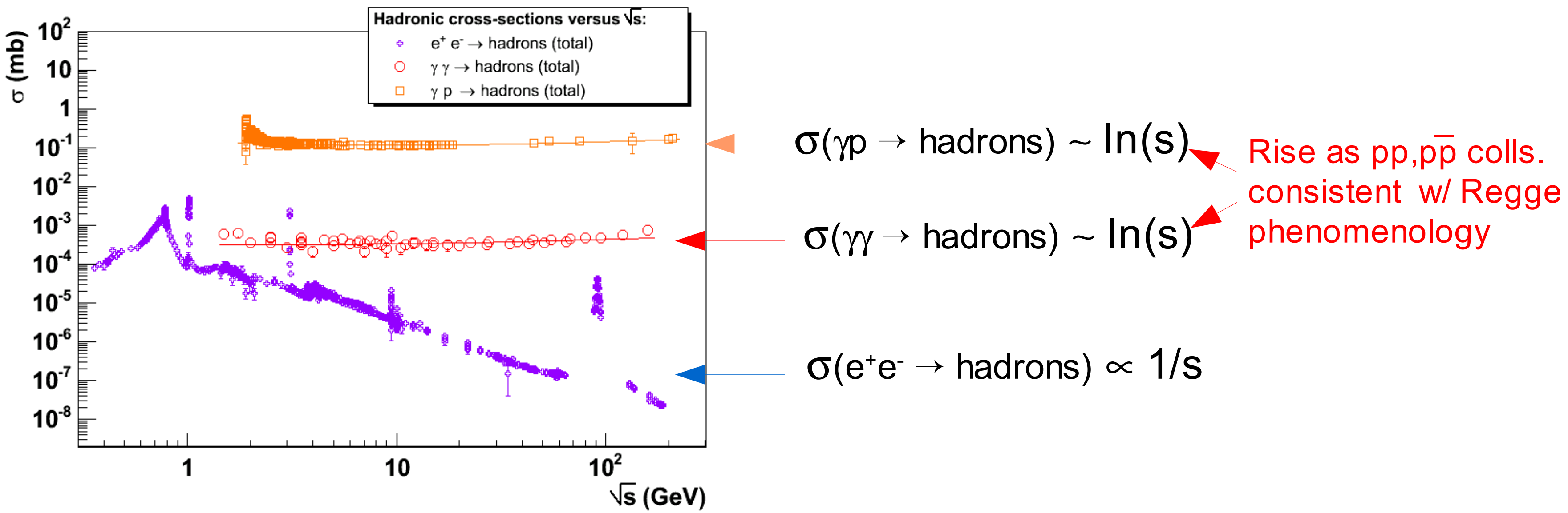
$\gamma\gamma$, γp collisions

- High-energy photon can interact point-like (e.g. Compton scatt.) or quantum fluctuating into fermion-antifermion or vector-meson ($J=1^{--}$):

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

- In practice: $\gamma \approx \gamma_0$, but $\gamma \rightarrow V,q\bar{q}$ fluctuations interact strongly and give largest contribution to $\gamma\gamma$ and γ p cross-sections:



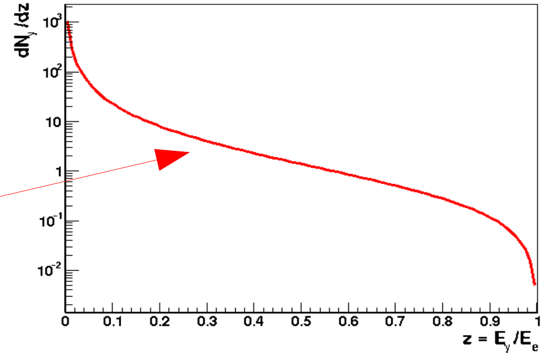
- High-energy $\gamma\gamma$, γp collisions complementary to more "conventional" e^+e^-, ep (DIS), pp, p$\bar{p}$ collisions to study QCD/QED (or even beyond-SM).

Equivalent γ beams at e^+e^-, ep colliders

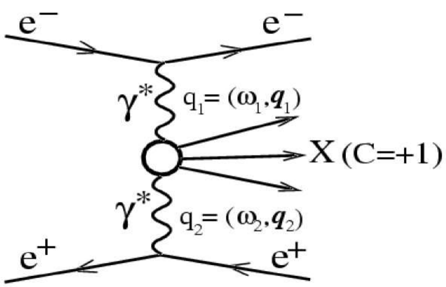
- EM field of relativistic charged particle = flux of "equivalent" photons.
  Weizsacker-Williams (EPA) formula for an e^{+-} beam:

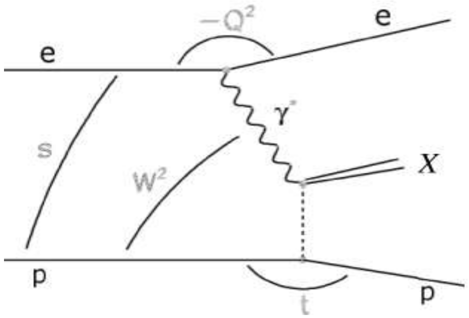
$$\frac{dN_\gamma}{dz} \approx \frac{\alpha_{em}}{2\pi} \frac{1}{z} [1+(1-z)^2] \ln \frac{Q^2_{max}}{Q^2_{min}} \;, \quad z = \omega / E_e$$

Soft bremsstrahlung γ spectrum



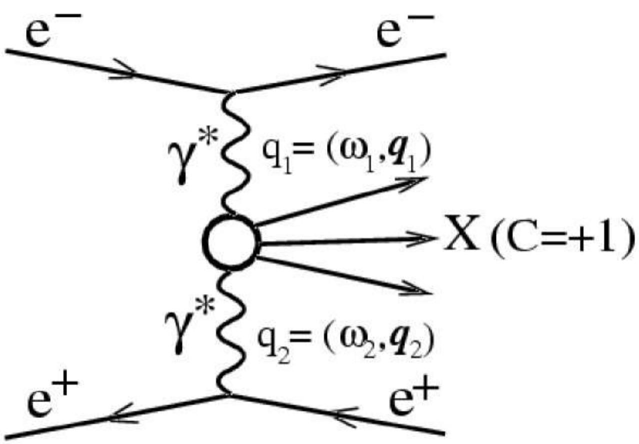
- Characteristics of γ-induced collisions at e^+e^- (LEP), ep (HERA) colliders:
  - Peaked at lower c.m. energies than parent beams: $0.1\sqrt{s} <\sim W_{\gamma\gamma,\gamma p} <\sim 0.5\sqrt{s}$
  - Quasi-real ($Q^2 \sim 0$) photons: parent $e^\pm$ scattered very close to beam, produced particles have low p_T.
- Schematic kinematics for $\gamma\gamma$ and γp:

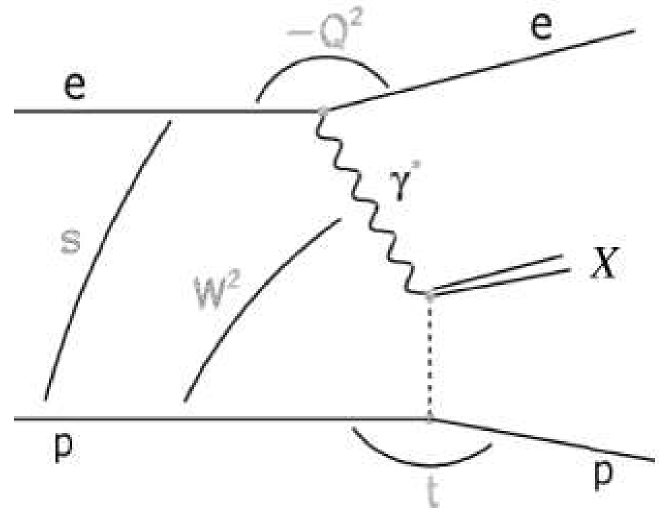




$\gamma\gamma$, γp physics at e^+e^-, ep colliders

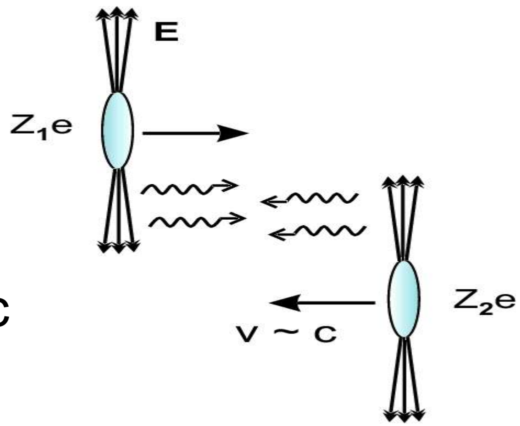
- Typical diagrams for $\gamma\gamma$ and γp collisions:





- Main interest of γ-induced collisions at LEP & HERA:
  - Precision QCD w/ low bckgd & simpler initial state than hadronic colls.
  - Measurements: σ(tot.had), $\Gamma_{\gamma\gamma}$ of $0^{-+}2^{++}$, VV production, γ structure function, hard photoproduction (Quarkonia, jets, heavy-Q), ...
  - Physics topics: Regge theory, low-energy q spectrosc., BFKL dynamics, hard scatt. factorization, G(x,Q^2) distribution, diffractive interactions, ...

Equivalent γ beams in UPC A+A collisions



- Heavy-ions (w/ charge Z) produce stronger electromagnetic fields than $e^{\pm}$ beams due to the coherent action of all proton charges.

- EPA formula for flux of photons in electromagnetic (i.e. ultraperipheral, $b>b_{min}\sim 2R_A$) A+A collisions:

$$\frac{dN_\gamma}{dz}(b>b_{min}) = \frac{\alpha_{em} Z^2}{\pi}\frac{1}{z}\left[2xK_0(x)K_1(x) - x^2\left(K_1^2(x)-K_0^2(x)\right)\right] \quad , \quad x = z\,m_A\,b_{min}$$

nucleus form factor dependence

- Characteristics of photon beams:

  - Flux ~ Z^2 (~$7\cdot 10^3$ for Pb) and $\sigma(\gamma\gamma)\sim Z^4$ (i.e. ~$4\cdot 10^7$) larger than $e^{\pm}$ beams !
  - "Coherence condition" : γ wavelength > nucleus size since all protons interact coherently ⇒ very low photon virtuality:

$$Q^2 = (\omega^2/\gamma^2 + q_\perp^2) \lesssim 1/R_A^2 \quad \text{(where } \gamma \text{ is the beam Lorentz factor)},$$

$$\omega < \omega_{max} \approx \frac{\gamma}{R} \quad \text{, and } q_\perp \lesssim \frac{1}{R} \approx 30\text{ MeV}.$$

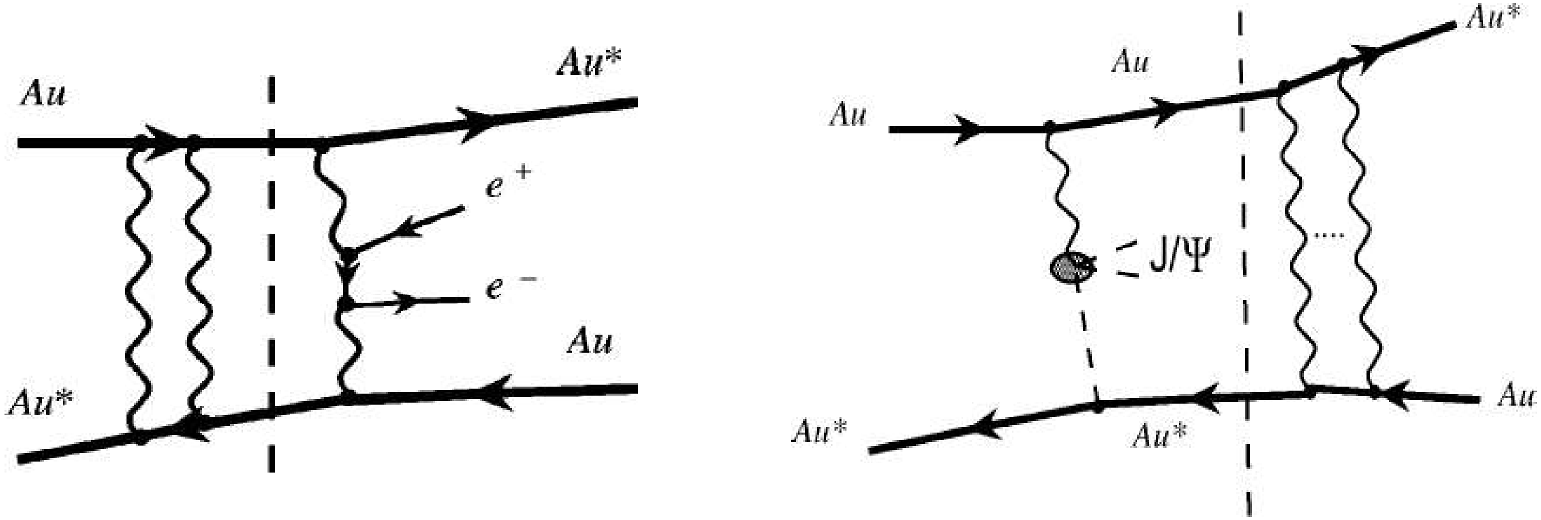
$E_{\gamma max}$ ~ 3 (80) GeV at RHIC (LHC)

$W_{\gamma\gamma}$ ~ 6 (160) GeV at RHIC (LHC)

$W_{\gamma A}$ ~ 30 (900) GeV at RHIC (LHC)

$\gamma\gamma$, γA physics in UPC A+A collisions

- Typical diagrams for $\gamma\gamma$ and γA collisions:

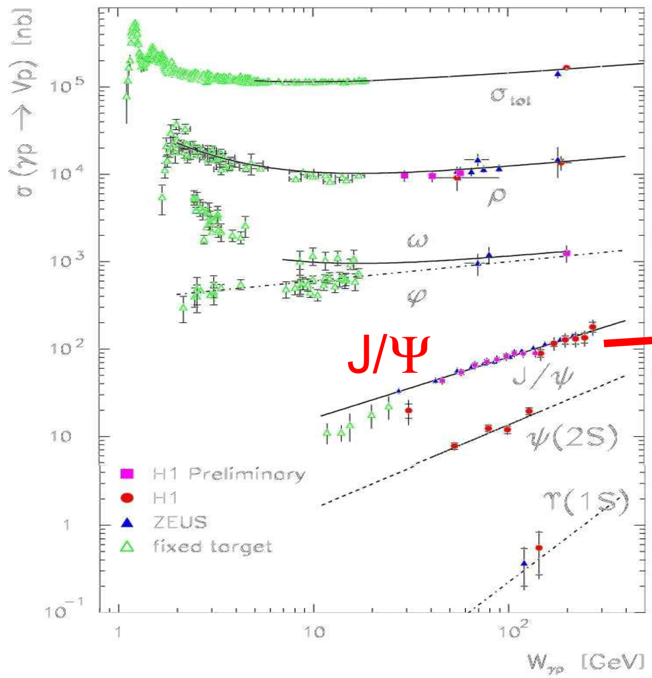


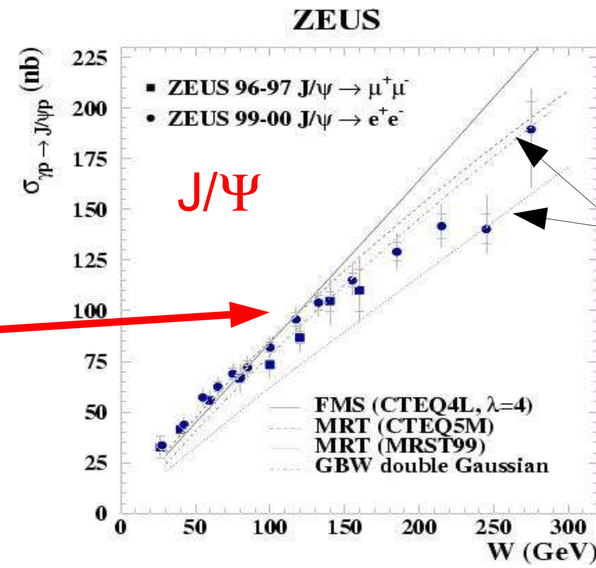
- Main interest of γ-induced collisions in UPC A+A collisions
  - Precision QCD: Low bckgd & simpler initial state than nuclear A+A colls.
  - Measurements: Dilepton pairs, hard photo-production (Quarkonia, jets, heavy-Q), ...
  - Physics topics: QED in strong regime ($Z\alpha_{em}$~1), nuclear $G_A(x,Q^2)$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

Quarkonia γ-production in UPC A+A

- HERA: $\gamma p \rightarrow Vp$ ($V = J/\Psi, \Upsilon$) very sensitive to gluon distrib. at small-x:

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





Discriminates diff. Ansätze & evolutions of $G(x,Q^2)$

Note: $\sqrt{s_{\gamma A}}$ (LHC) > 3--6·$\sqrt{s_{\gamma A}}$(HERA)

- Likewise RHIC,LHC: $\gamma + A \rightarrow V + A$ ($V = J/\Psi, \Upsilon$) in UPC A+A clean measurement of:
  - Nuclear $G_A(x,Q^2)$ at small-x: $x(J/\Psi) \sim 4\cdot 10^{-4}$, $x(\Upsilon) \sim 10^{-3}$ at LHC (y=0)
  - QQbar propagation in cold nuclear matter.

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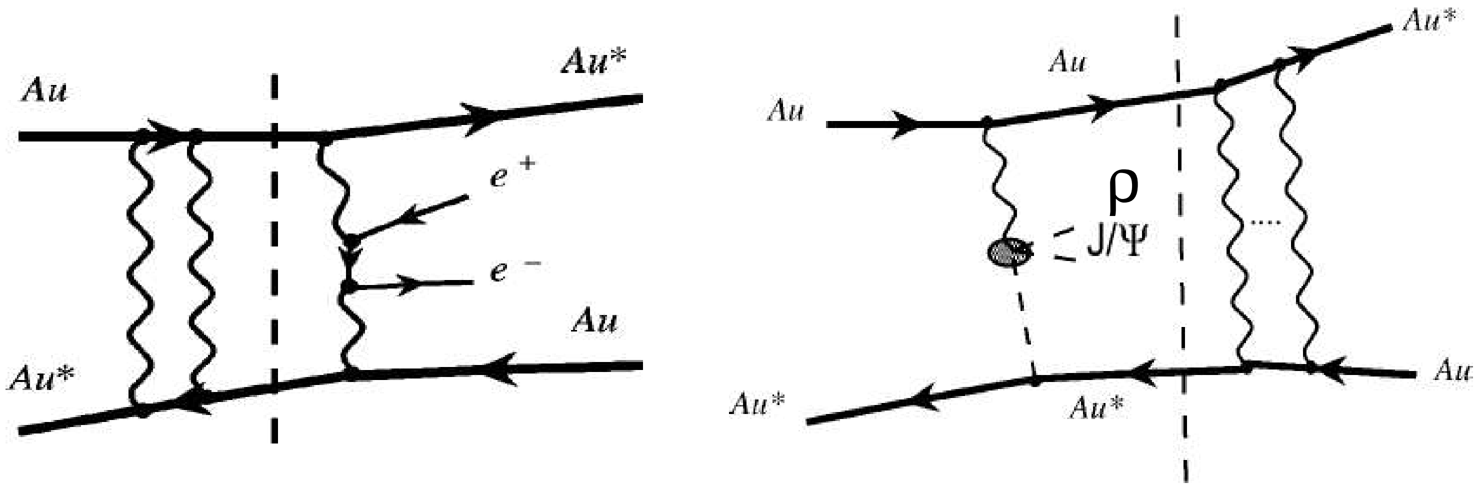
Existing $\gamma\gamma$, γA measurements @ RHIC

- **Measured processes** in A+A UPC collisions:



- **STAR:**

  (1) Coherent ρ production: γ+A → A*+ ρ (→ $\pi^+\pi^-$) PRL 89 272302 (02)

  (2) Dielectron continuum at low m_{inv}: γ +γ → (A*) + e^+e^- PRC 70 031902 (04)

- **PHENIX (Preliminary):**

  (1) Coherent J/Ψ production: γ+A → A*+ J/Ψ (→ e^+e^-)

  (2) Dielectron continuum at high m_{inv}: γ+γ → (A*) + e^+e^-

D.d'E, QM'05 poster
Proceeds. Acta Phys. Slovaka

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

$A + A \rightarrow A + A + \gamma \rightarrow A + A + X$ $(X = J/\Psi, ...)$

- Central rapidities:

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

(1) Low multiplicities: N<~15

(2) Low total transverse momentum ("coherence condition"):

$p_T < \sqrt{2}\ \hbar/R_A$ or $p_T \sim m_{inv}/\gamma$ ~ 30 – 50 MeV

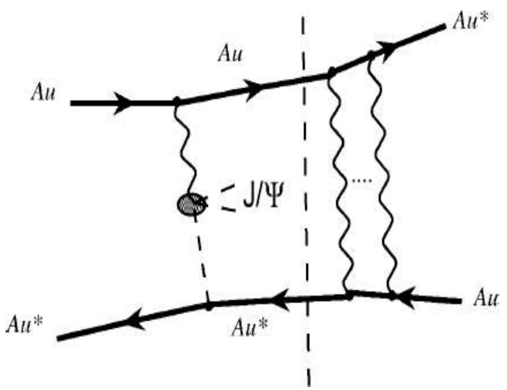
(3) Zero net charge: even # of charged tracks of opposite signs.

(4) Narrow dN/dy peaked at y=0 (narrower for larger m_{inv}).

- Forward rapidities:

Important for tagging/trigger purposes !

(5) 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).

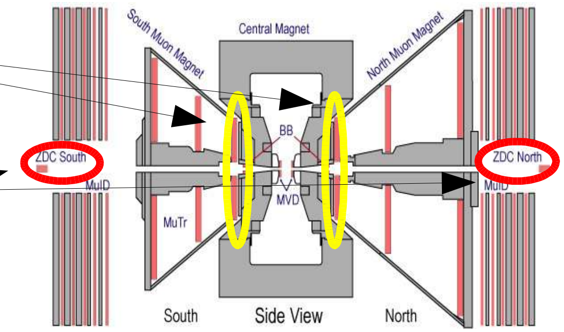


Note: Coulomb-dissoc. probab. factorizes
in UPC cross-section calculations

γ+A → J/Ψ+A : UPC trigger example

PHENIX Run-4 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]



- Definition: UPC: (ZDCN || ZDCS) && (!BBCLL1noVtx) && (ERT2x2)
  UPC-BBCSxorN : (ZDCLL1N || ZDCLL1S) && (BBCLL1S ^ BBCLL1N) && (ERT2x2)

- Events collected (~0.4% of MB trigger):

  UPC AuAu: 8.5 M
  MB AuAu (BBCLL1): 1122 M (equivalent $\int L = 120\ \mu b^{-1}$)

γ+A → J/Ψ+A : possible background sources

A + A → A + A + γ → A + A + J/Ψ

- "Non-physical":

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

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

- Physical processes:

  (3) Peripheral nuclear A+A: "large" multiplicity, large p_T

  (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 !) , $\gamma A \to$ jet(s)+A (lower cross-sections) ?

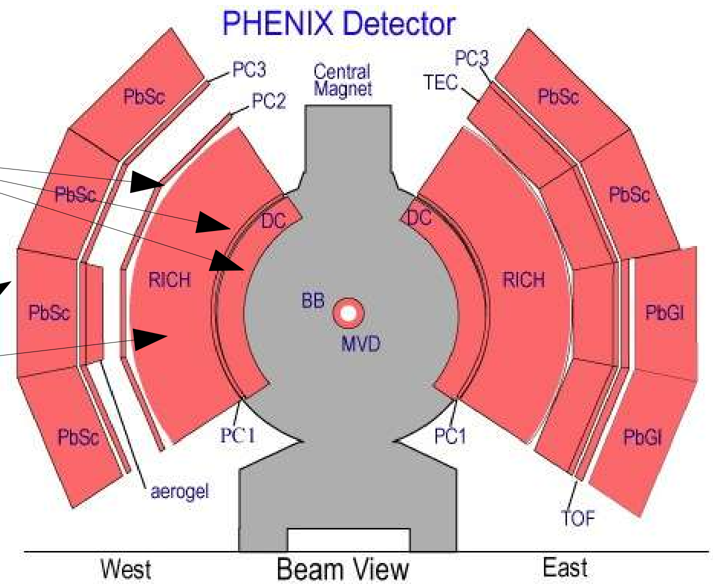
Trigger level [(1)–(4)]

Final signal [(4)–(6)]

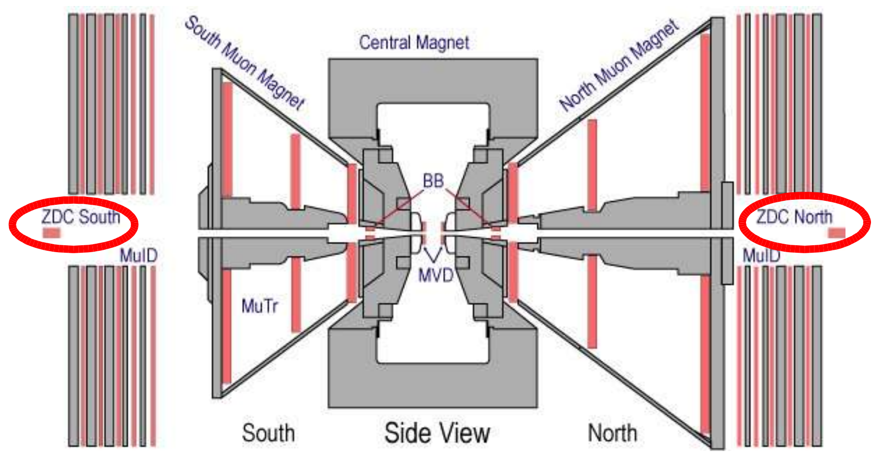
PHENIX UPC-measurement detectors

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

- RICH + EMCal: $e^{\pm}$ identification in central rapidity.



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



PHENIX UPC analysis cuts

- Global cuts:
  - Std. vtx. cut: | zvtx | < 30 cm
  - Multiplicity(tracks)<15 [removes non-UPC events]
- Loose PID e ± cuts (compared to std. AuAu-nuclear analysis):
  - RICH: n_0>=2 [# of photo-tubes within nominal ring radius]
  - CNT-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]

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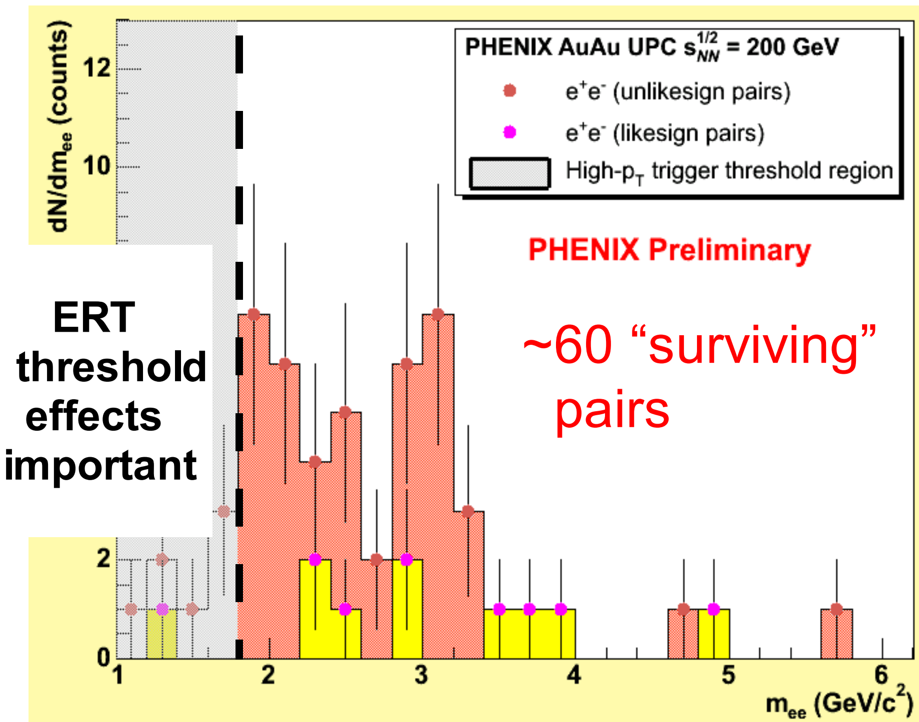
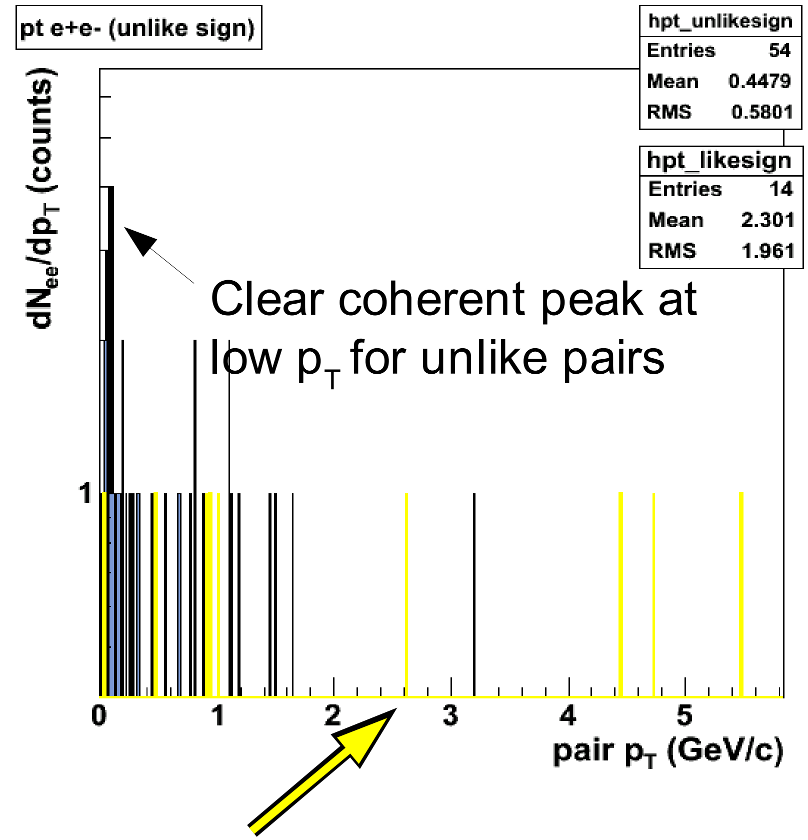
AuAu UPC results (I): dN/dm_{inv}, dN/dp_T ee pairs

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

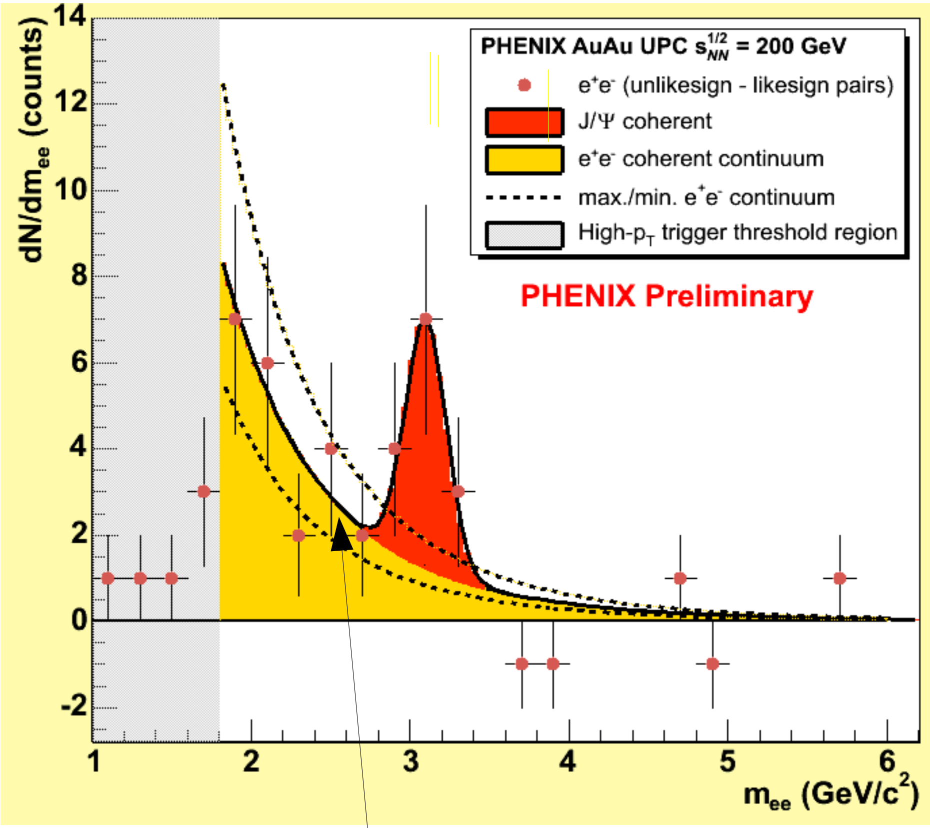




- Very small wrong-sign background (located in "non-coherent" high p_T region) well reproduced by MC.

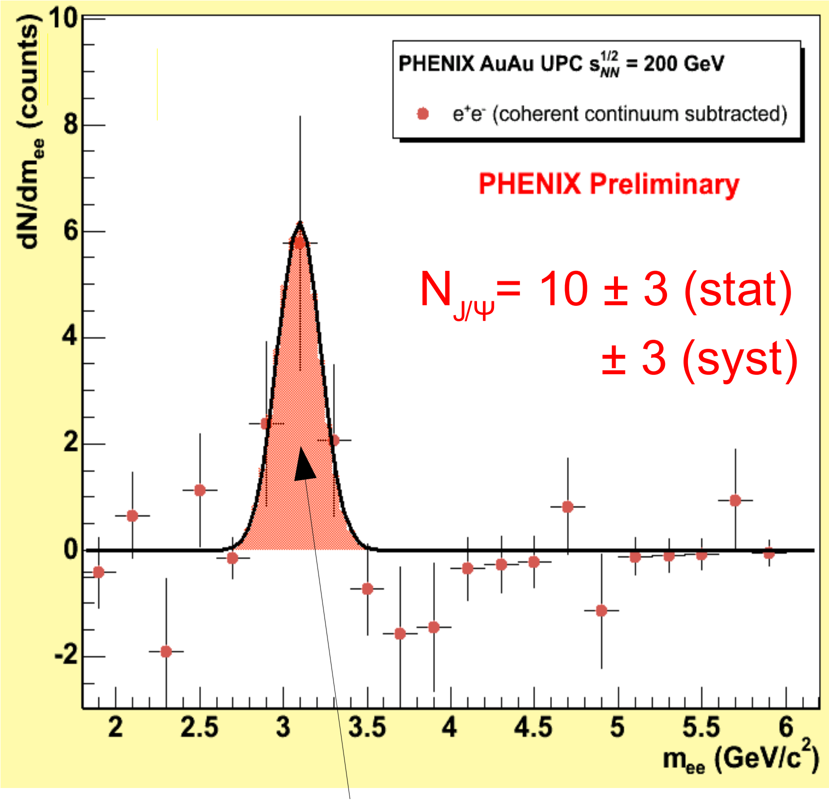
AuAu UPC results (II): dN/dm_{inv} e^+e^- pairs

- dN/dm_{inv} (backgd subtracted) & with 2 fits of expected e^+e^- continuum shape (normalized at m_{ee} = 1.8 – 2.2 GeV/c²)



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

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



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

$m_{J/\Psi}$ ~ 3.10 GeV ± 130 MeV

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

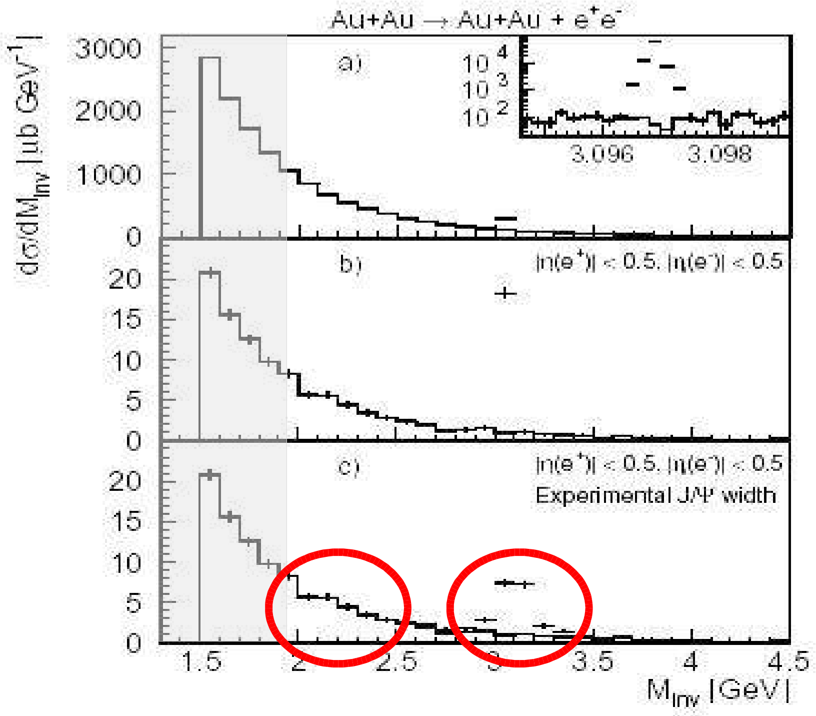
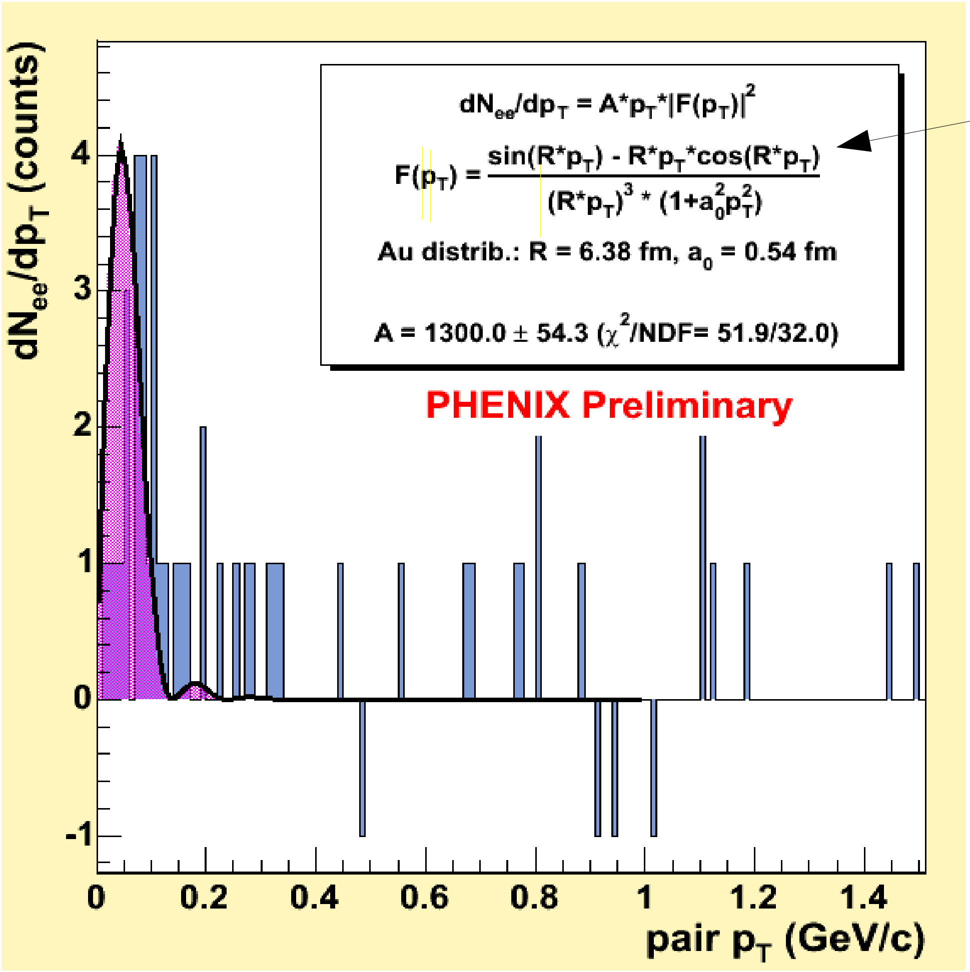


Figure 4. The differential cross section $d\sigma/dM_{inv}$ for dielectron production in ultra-peripheral Au+Au collisions at $\sqrt{s_{nn}} = 0.2$ TeV. The histograms show the two-photon contribution, and the bars or crosses show the sum of the two-photon and $J/\Psi \rightarrow e^+e^-$ contribution. 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}.

AuAu UPC 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.

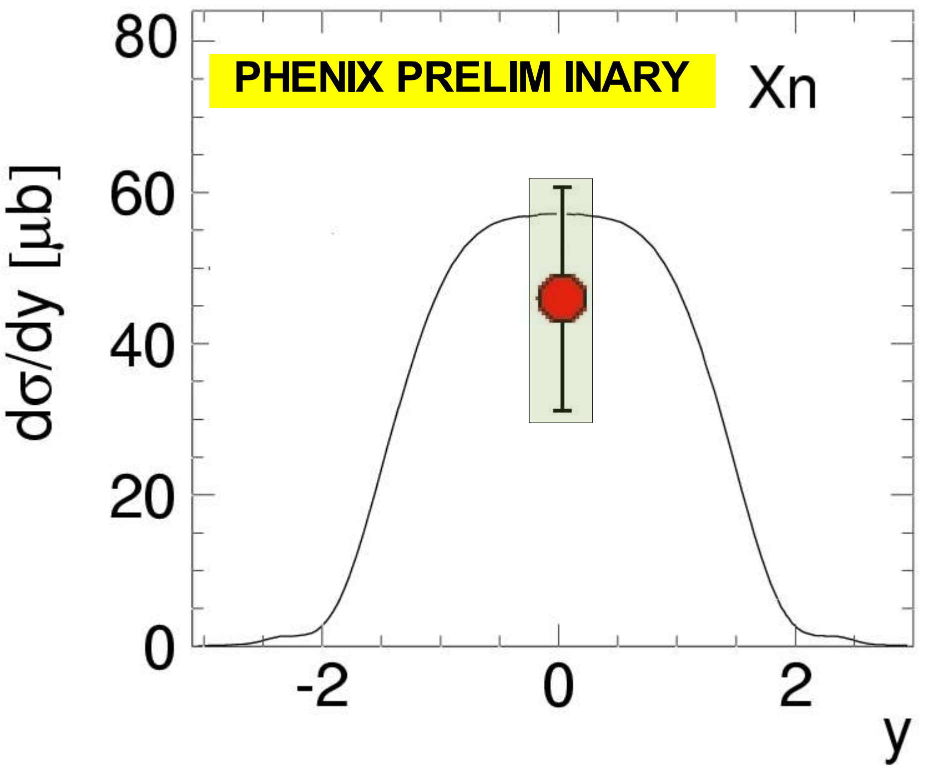
Good detailed agreement w/ theoretical expectations [*]

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

$d\sigma_{J/\Psi}/dy|_{y=0}$ = 1/BR × 1/(Acc$|_{y=0}$·ε) × 1/ε_{trig} × 1/L_{int} × $N_{J/\Psi}/\Delta y$ =

= 1/(5.9%)×1/(5.7%·56.4%)×1/(90%)×1/120 μb^{-1}×(10 ± 3± 3) =

= 48. ± 16. (stat) ± 18. (syst) μb



- Measured J/Ψ yield at y=0 consistent w/ theoret. calcs. [1,2]
- Main 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)

[1] Starlight: J.Nystrand, S. Klein NPA 752(2005)470
[2] Strikman et al., hep-ph/0505023

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Quarkonia γ-production in UPC A+A @ LHC (I)

Most results from UPC Chapter ALICE PPR II [J.Nystrand et al.]

- Some key figures:

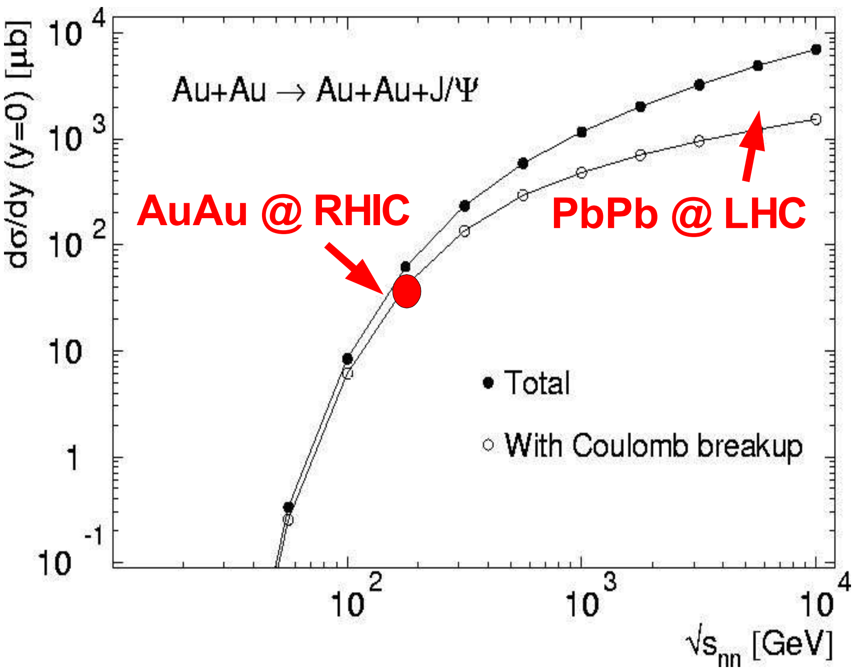
• Max. $\sqrt{s_{\gamma A}}$(LHC) ≈ 900 GeV > 3 – 5×$\sqrt{s_{\gamma p}}$(HERA)

• Max. $\sqrt{s_{\gamma\gamma}}$ (LHC) ≈ 160 GeV ≈ $\sqrt{s_{\gamma\gamma}}$ (LEP)

• LHC (y=0): x(J/Ψ) ~$4\cdot10^{-4}$, x(ϒ)~10^{-3}

• LHC (y=3): x(J/Ψ) ~ $2\cdot10^{-5}$, x(ϒ)~10^{-4}

- $\gamma+A \rightarrow J/\Psi + A$
  in UPC A+A versus $\sqrt{s_{NN}}$:



- LHC QQbar cross-sections:

  σ_{QQbar} (LHC) ~ 40 – 100×σ_{QQbar}(RHIC)

- (first time ϒ measurable in UPC)

Quarkonia γ-production in UPC A+A @ LHC (II)

Most results from UPC Chapter ALICE PPR II [J.Nystrand et al.]

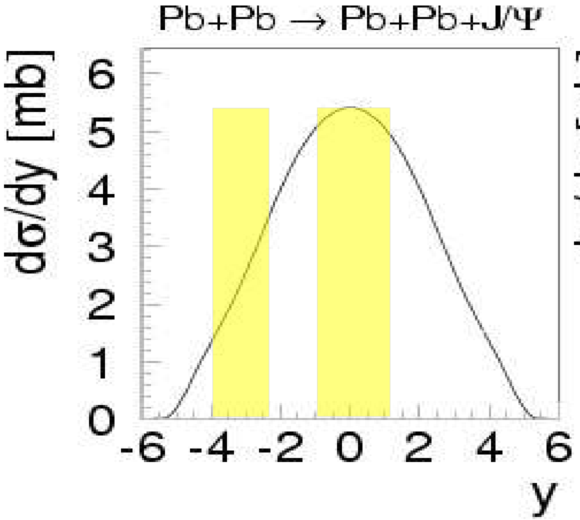
- **Cross-sections, rates:**

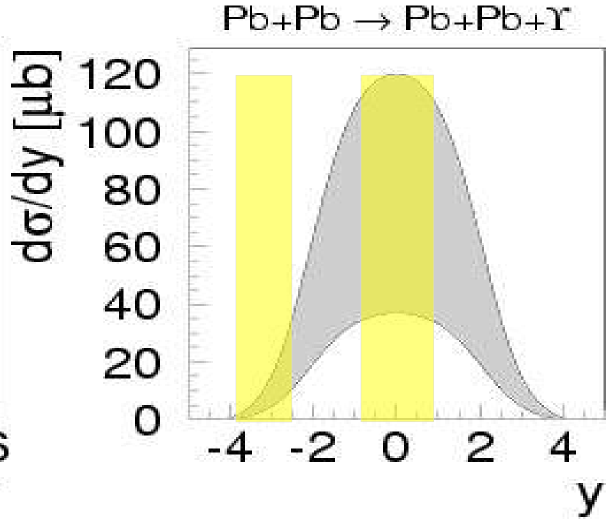
ALICE Pb+Pb $\rightarrow J/\psi, \Upsilon(1S) \rightarrow e^+e^-$, $\gamma = 2750$

Final state	σ_{LTA}	$\sigma_{W\delta}$	$\sigma_{impulse}$	BR	Acc.	rate (per 10^6 s)
J/ψ	15 mb	32 mb	70 mb	5.93%	16.4%	150000
$\Upsilon(1S)$	78 μb	150 – 500 μb	133 μb	2.38%	23.6%	400 – 1400

High sensitivity to different $G(x,Q^2)$ [~30% reduction of $G(x,Q^2) \Rightarrow 0.5\cdot\sigma_{J/\Psi,\Upsilon}$)

- **Rapidity distrib. γ+A→ J/Ψ,ϒ +A in UPC A+A:**





μμ decay (ALICE μ-spectrom.) ~1/2 – 1/5 less rates than ee mode at y=0

Summary

- UPC A+A collisions generate high-energy γ beams for "non-QGP" studies: $\gamma+\gamma$, γ+A physics at $\sqrt{s}_{\gamma\gamma,\gamma A}$ larger than LEP & HERA.
- Main motivation: Precision QCD studies w/ low bckgd environment & simpler initial state than pp,A+A collisions.
- 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: $\gamma+\gamma \to 0^{+-}2^{++}$ states, ...
- Lessons from RHIC:
  - 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)
  - Main source of syst. uncertainty: coherent $\gamma+\gamma \to e^+e^-$ physics background
- Prospects for LHC:
  - Unexplored kinematic regime (max. energies ever, small-x, $\gamma+A \to \Upsilon$, ...)
  - Expected rates ~1000 higher than at RHIC.
  - High sensitivity to nuclear $G_A(x,Q^2)$ at small-x

Backup slides

PHENIX UPC analysis

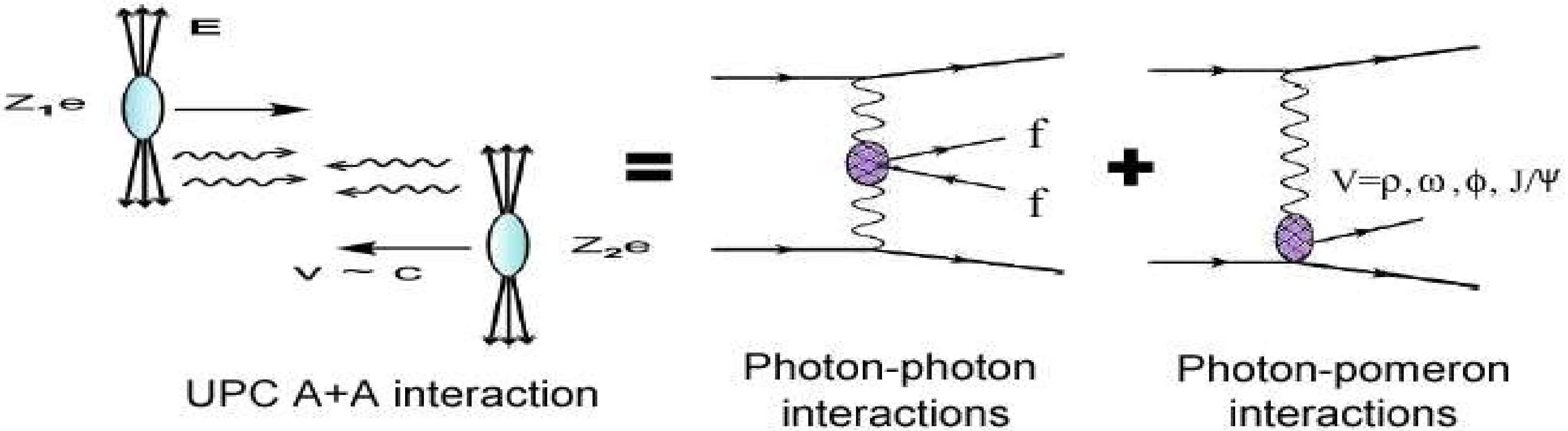
- UPC- Events collected & integrated luminosity

Total equivalent sampled luminosity:

$L_{int} = \sigma_{AuAu}$ /BBCLL1 x ε_{BBC} x ε_{loss} = $1122 \cdot 10^6/(6.9\ b) \times 0.92 \times 0.79 = 120\ \mu b^{-1}$

ε_{loss} accounts for # runs excluded (6.7 Mevts instead of 8.5 Mevts)

Total data set: 1352 PRDFFs * 0.8 GB/file ~ 1.04 TB



Theoretical input distribution: J/Ψ

10^5 J/Ψ generated (EXODUS)

Realistic input dN/dy and dN/dp_T distributions ("StarLight" model)

474c J. Nystrand / Nuclear Physics A 752 (2005) 470c–479c

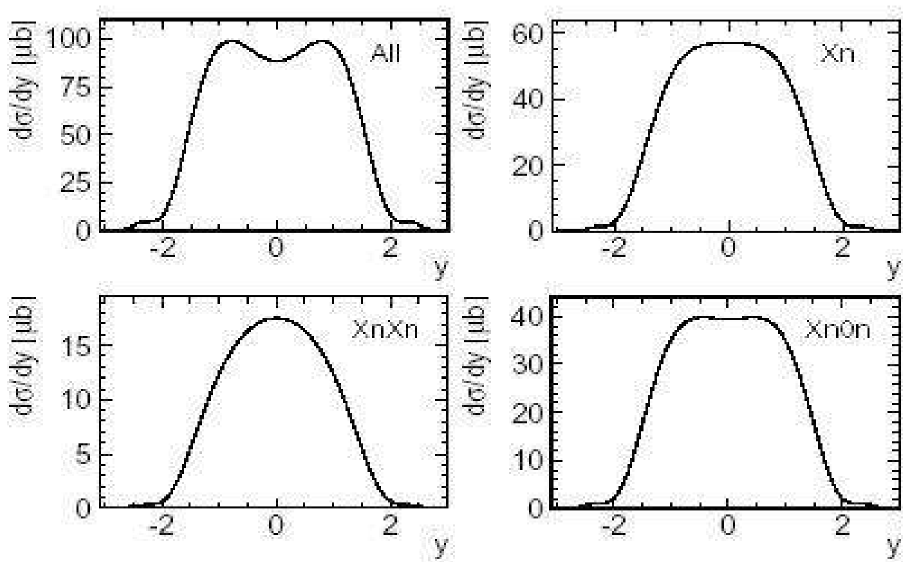


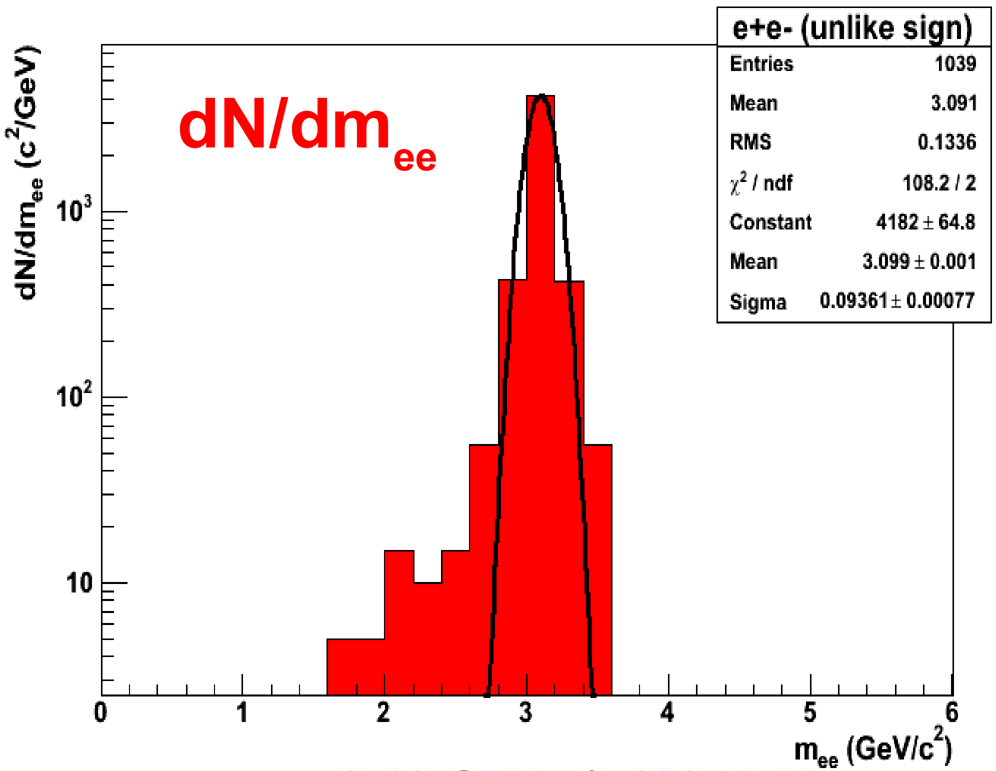
Figure 3. Differential cross sections for $Au + Au \rightarrow Au + Au + J/\Psi$ at $\sqrt{s} = 0.2$ TeV for different Coulomb breakup modes. "All" is the total coherent cross section. "Xn" corresponds to J/Ψ production in coincidence with Coulomb breakup of at least one of the nuclei. This sample is divided into the cases where both nuclei break up ("XnXn") and where only one of them breaks up ("Xn0n"). The total cross sections, integrated over all rapidities, are 290 μb ("All"), 159 μb ("Xn"), 115 μb ("Xn0n"), and 44 μb ("XnXn").

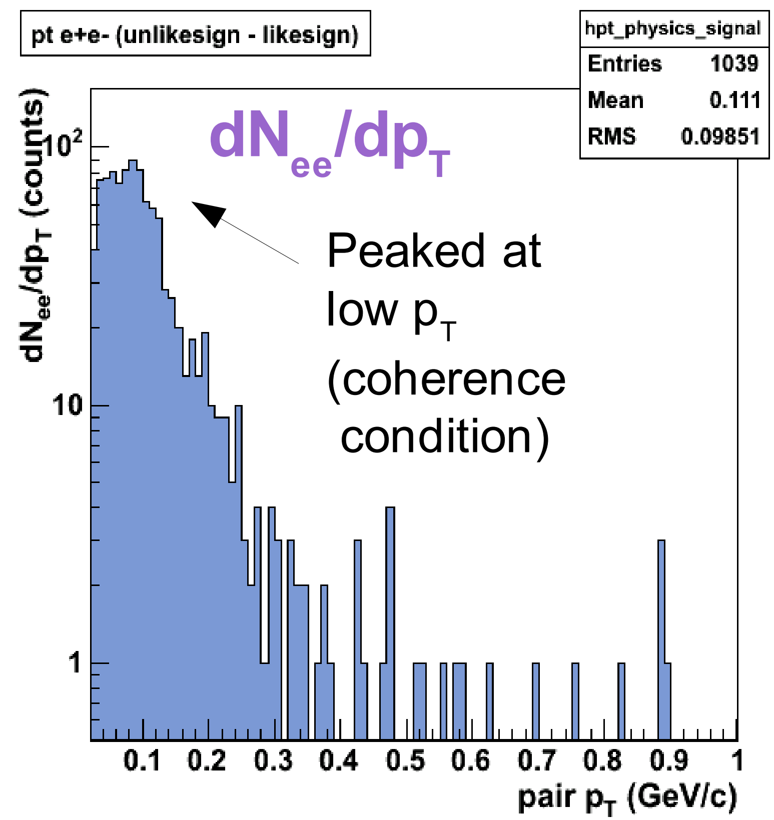
Full MC simulation: J/Ψ

Input: 10^5 J/Ψ with realistic $d^2\sigma/dydp_T$ from "Starlight" [J.Nystrand, S.Klein]
PISA production & reco. w/ the same analysis code as for real data

Losses:
- (Branching ratio: 5.93%)
- Acceptance & vtx & multiplicity cut: ~5.0%
- Efficiency loss single & pair cuts: ~ 56.4%
- Unlike-sign background: 0

Accep. x Effic x BR ~ $2 \cdot 10^{-3}$





$m_{J/\Psi}$ ~ 3.10 GeV +/- 100 MeV

Full MC simulation: e+e- continuum

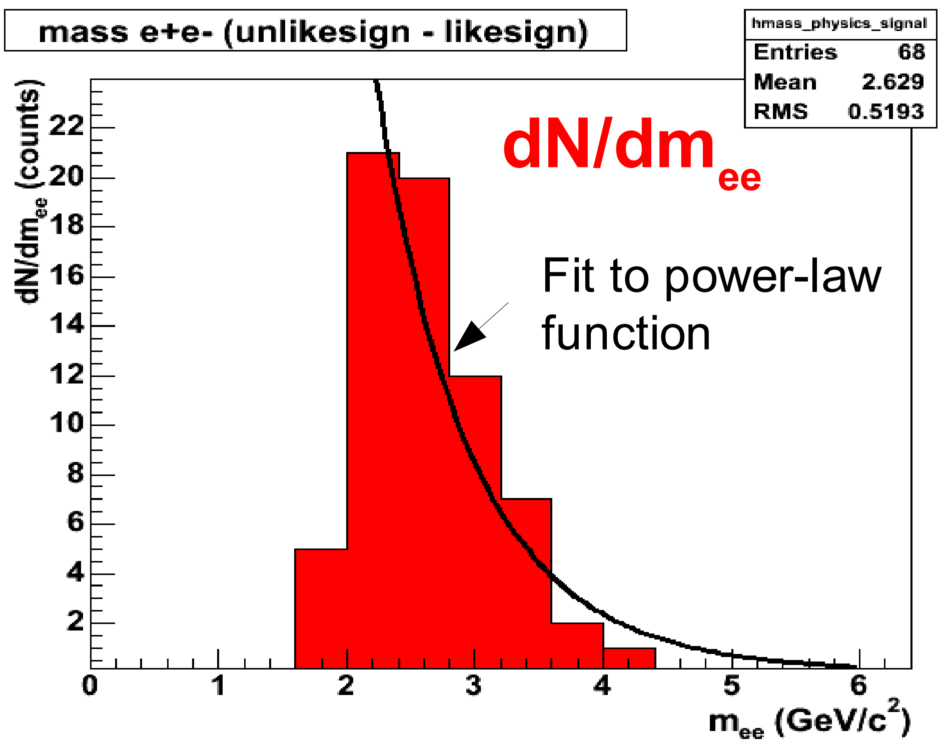
Input: $2\cdot10^5$ pairs with realistic $d^2\sigma/dydp_T$ from "Starlight" [J.Nystrand, S.Klein]

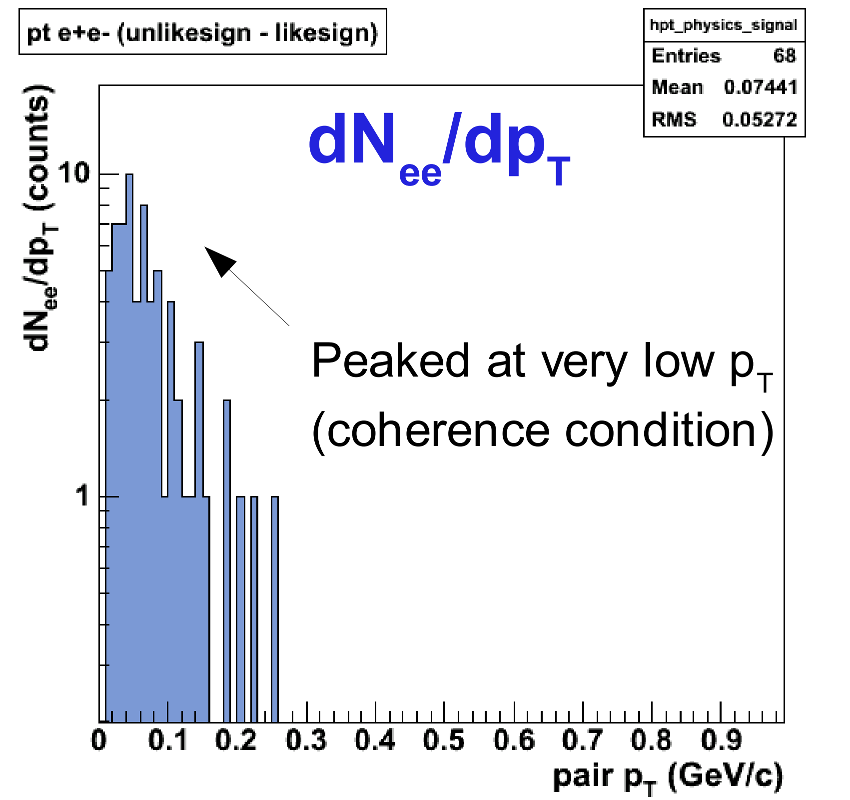
Full PISA production & reco. w/ the same analysis code as for real data

Losses:

- Acceptance & vtx & multiplicity cut: ~2.1%
- Efficiency loss single & pair cuts: ~ 5.5%
- Unlike-sign background: 0

Accep. x Effic: $\sim10^{-3}$





Summary

- Analysis of all statistics of Run-4 AuAu UPC triggered data.
- Previous results shown as "work in progress" last DNP'04.
- New PRDFF → nDST repass of UPC data at ORNL (pro.66.upc)
- New reco analysis (pro.70) w/ official Run-4 (re)calibrators and electron-based afterburners. New set of analysis cuts.
- Full PISA MonteCarlo production & reconstruction with realistic input distributions for UPC J/ψ and di-electron continuum.

- Clear indications of J/ψ & high mass di-lepton continuum from UPC AuAu collisions (Run-4).
- Dielectron continuum: dN/dm_{ee} and dN_{ee}/dp_T in god agreement with coherent production (very low pair p_T, m_{ee} spectral shape)
- J/ψ signal: dN/dm_{ee} peak at 3.1 GeV/c^2 w/ 130 MeV width (good agreement with full PISA MC with realistic input). J/ψ dN/dp_T peaked at very low p_T as expected for UPC events.
- N= 10 ± 3 counts: $dN_{J/\psi}|_{y=0}$= 44. ± 16. (stat) ± 18. (syst) μb
- 4 plots requested PHENIX-PRELIMINARY for QM'05 (poster)

Motivation (cont'd)

- Large cross-sections expected at RHIC due to:

  (i) Large Au charge ($\sigma_{AA} = Z_1^2 Z_2^2\, \sigma_{NN} \sim 4 \cdot 10^5 \sigma_{NN}$)

  (ii) High $\sqrt{s}$ (mass: $w \sim 2\, \gamma_{CM}(hc/R) \sim 6$ GeV for $\gamma_{CM} = 100$)

- Some predictions:

(Coulomb) Excited Au* emits X neutrons → (req. Xn)

STAR measurement → ρ

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

J/ψ: Highest mass vector meson accessible in UPC colls. at RHIC

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