Ultra-Peripheral Au+Au collisions at 200 GeV/A with the PHENIX experiment

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Outline: [PHENIX, arXiv: 0903.2041, submitted to PLB]

- ✓ Introduction
- ✓ J/ψ and e^+e^- measurement
- ✓ p_t^2 distributions
- ✓ Comparison with theoretical calculations

Elastic and Diffractive Scattering 2009

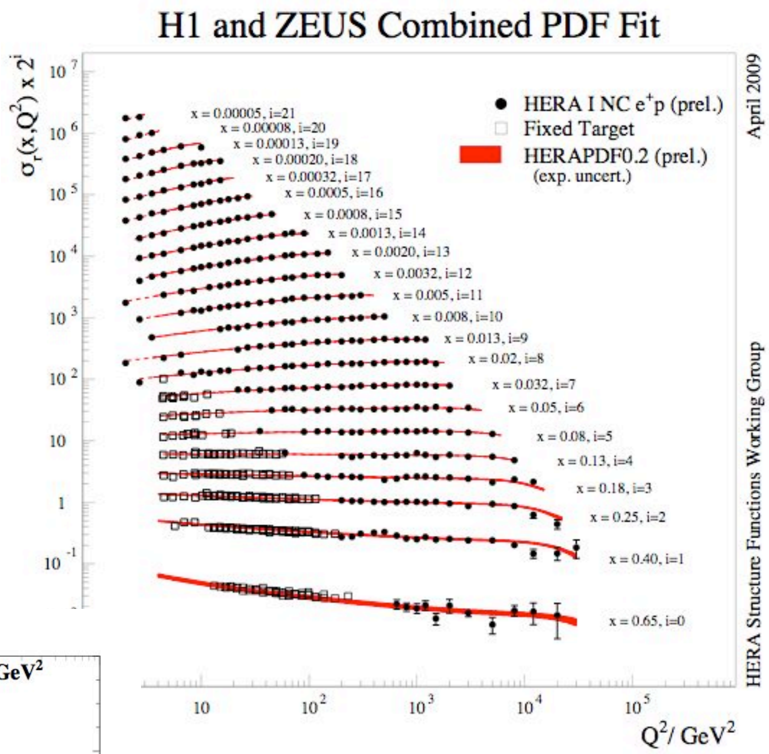
Parton Distribution Functions

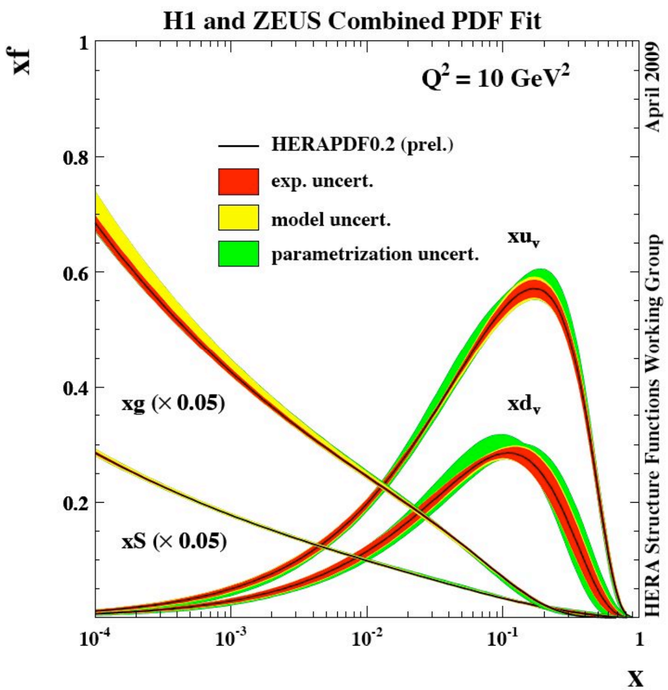
- QCD factorization theorem

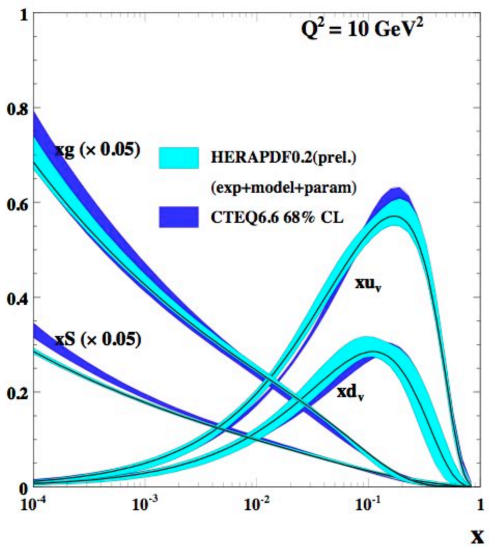
$$d\sigma_{AB} = \sum_{a,b} \int dx_a dx_b \, f_{a/A} \, f_{b/B} \, \widehat{\sigma}_{ab\to c} \, D_{c\to l}$$

- PDF measurements in ep DIS

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\,\alpha^2}{x\,Q^4}\left[2xy^2 F_1 + 2(1-y)F_2\right]$$







Probe smaller Bjorken-x at forward rapidities

$$x_{1,2} \sim \frac{Q}{\sqrt{s}} e^{\pm y}$$

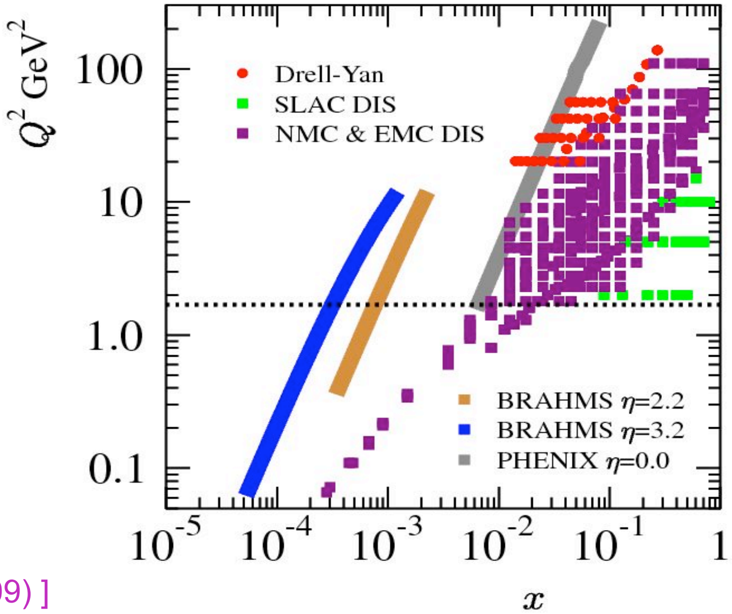
[Voica talk at DIS 2009]

Nuclear Parton Distributions

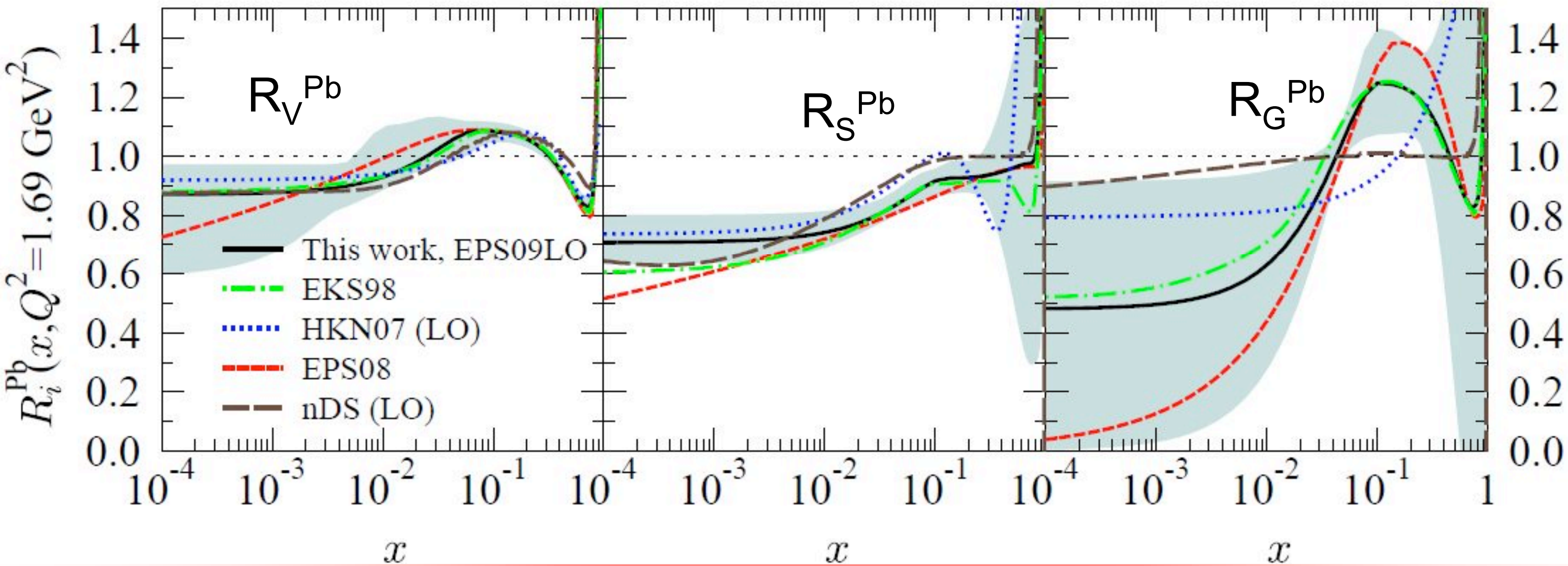
- In general, $\sigma^{\text{bound nucleon}} \neq \sigma^{\text{free nucleon}}$
- Proton and nucleus PDFs are related

$$f_i^A(x,Q^2) \equiv R_i^A(x,Q^2)\, f_i^p(x,Q^2)$$

- Low-x PDF measurements
  - pp, pA: DY, prompt-γ, di-jets, heavy-Q
  - γp, γA: heavy-Q, $Q\bar{Q}$
  - ep DIS

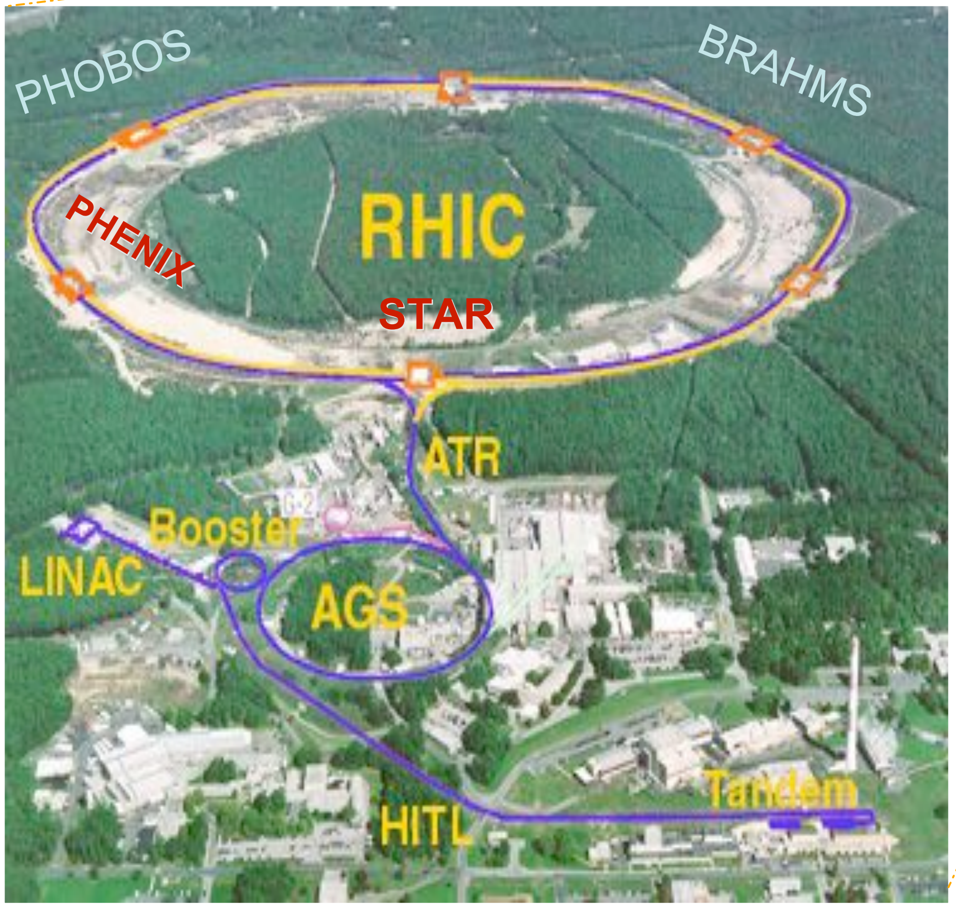


[Paukkunen et al, talk at DIS 2009; JHEP 0904:065 (2009)]



RHIC experimental facility

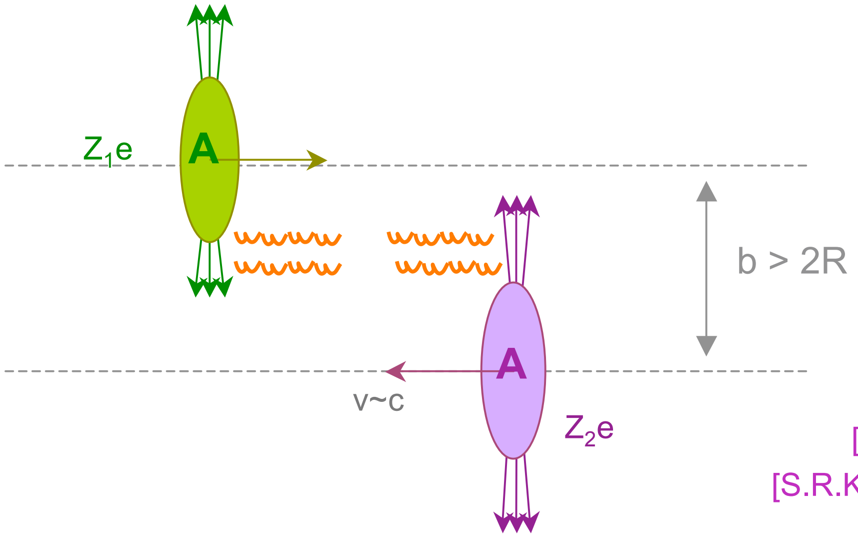
Relativistic Heavy Ion Collider, at the Brookhaven National Laboratory (NY,USA)



- Characteristics:
  - ~4km of circumference,
  - from p to Au nuclei,
  - center-of-mass energies of 62-200 GeV.
- Originally 4-experiments, now only PHENIX & STAR

Ultra-peripheral collisions

- Weizsacker-Williams (EPA):
  - Electromagnetic field of an ultra-relativistic particle ≈ photon flux with continuous energy
- Characteristics of ultra-peripheral collisions (UPC)
  - **b > 2 R**
  - Nuclei do not collide, possibility to study **γ - induced reactions**
  - γ - flux is $\sigma(\gamma X) \propto Z^2$ ~ $6 \cdot 10^3$ & $\sigma(\gamma\gamma) \propto Z^4$ ~ $4 \cdot 10^7$ ⇒ **larger than e-beams**
  - Coherence condition:
    γ wavelength > nucleus size ⇒ very low photon virtuality
  - RHIC max. center of mass energies: $W_{max,\gamma n}$~ 34 GeV & $W_{max,\gamma\gamma}$~ 6 GeV

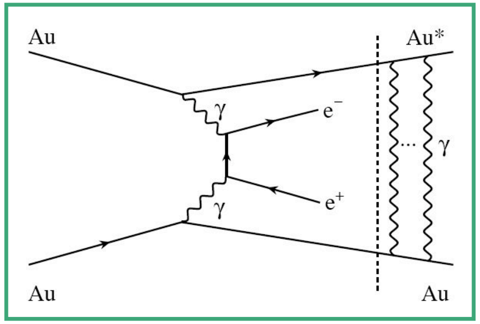


[J.Nystrand, NPA752 (2005) 470]
[Balz et al P.R.L.89 012301 (2002)]
[S.R.Klein, J.Nystrand; PRC60 (1999) 014903]
[Baur et al, N.P.A729 787 (2003)]

Physics processes of interest

[Baur et al, N.P.A729 787 (2003)]
[M. G. Ryskin, Z. Phys. C 57 (1993) 89]

- Dilepton:
  - test QED on a strongly interacting regime ($Z\alpha_{em}$ ~ 1)

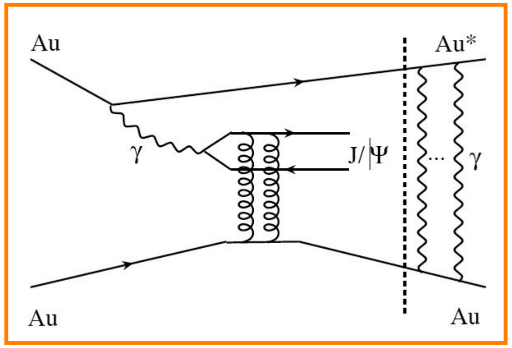


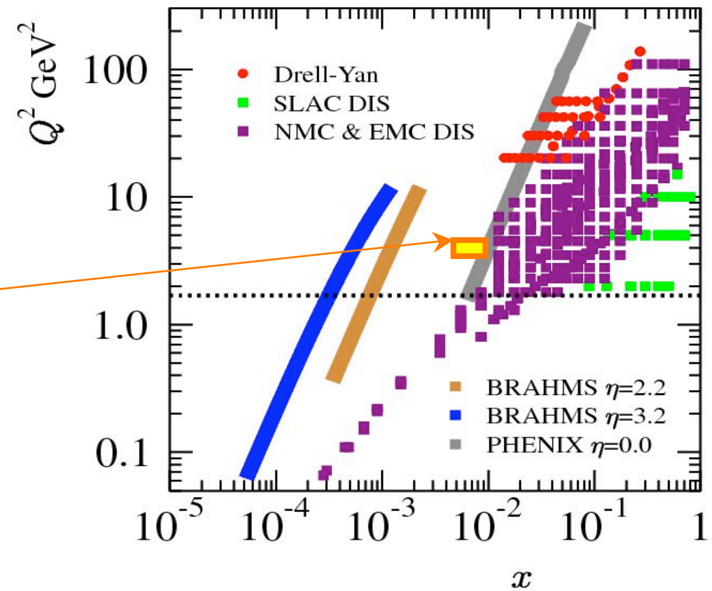
- Vector meson:

$$\frac{d\sigma(\gamma p \to J/\psi + p)}{dt} = [F_N^{2G}(t)]^2 \frac{\alpha_s^2 \Gamma_{ee}^J m_J^3}{3\alpha_{em}} \pi^3 \times \left[\bar{x} G(\bar{x}, \bar{q}^2) \frac{2\bar{q}^2 - |q_1^J|^2}{(2\bar{q}^2)^3} \right]^2$$

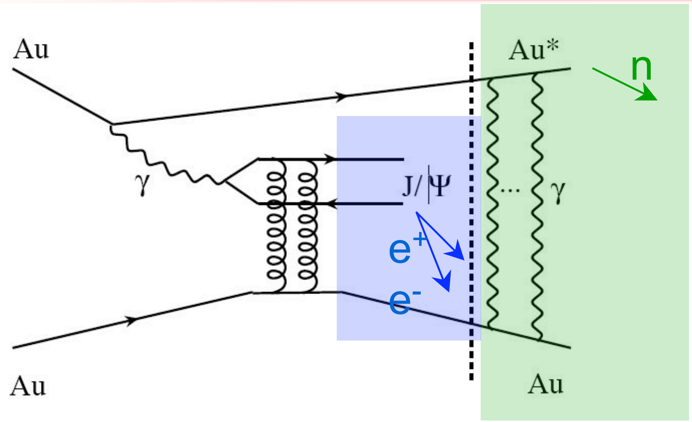
  - Low-x (10^{-2}) gluon PDFs, $x=(m_{VM}/W_{\gamma A})^2$
  - $Q\bar{Q}$ propagation in Cold Nuclear Matter (shadowing, absorption)

[J.Nystrand, NPA752 (2005) 470]
[Armesto, J.Phys.G32:R367,2006]

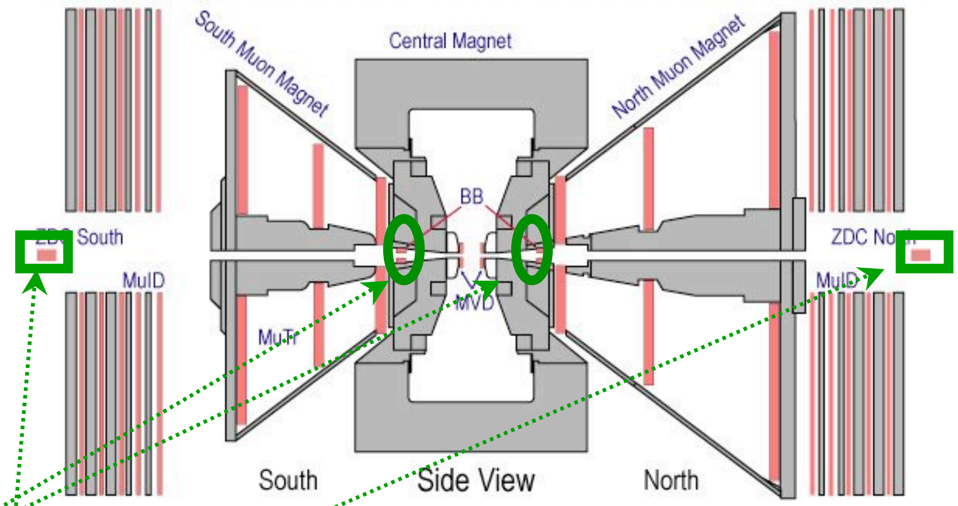


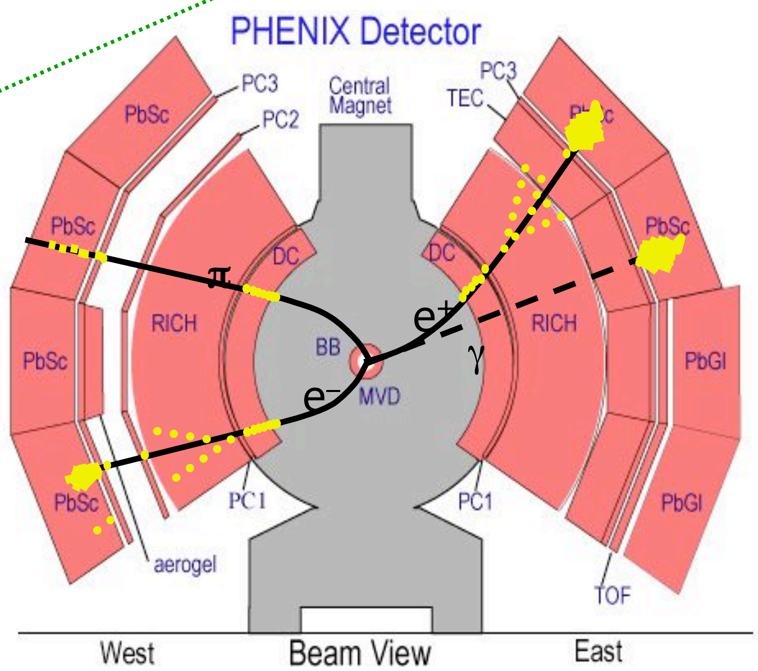


γ Au $\rightarrow$ J/ψ Au* measurement in PHENIX



- UPC dedicated trigger
  - Rapidity gap $3<|\eta|<4 \Rightarrow$ MB interaction veto (BBC veto)
  - Large probability to exchange additional photons by GDR $\Rightarrow$ 1 or 2 ZDC trigger
  - Enrich electron sample $\Rightarrow$ EmCal trigger (E<0.8GeV)

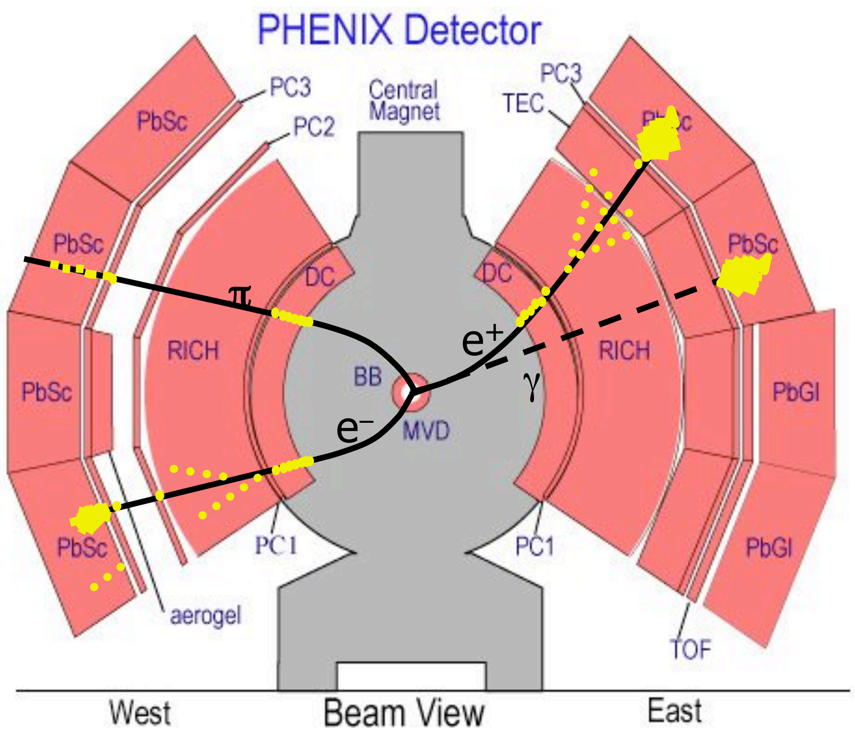




- γ Au $\rightarrow$ J/ψ ($\rightarrow e^+e^-$) Au*
  - DC & PC tracking detectors
  - RICH & EmCal electron identification devices

The experimental signatures, the analysis

- Signatures:
  - Low particle multiplicities
  - Low transverse momentum : coherence condition
    $p_T < 2\hbar/R$ or $p \sim m_{ee}/\gamma \sim$ 30-50 MeV
  - Zero net charge ($N_{e+} = N_{e-}$)



- Analysis:
  - |vertex| < 30 cm
    (Select events centered on the detector fiducial area)
  - N. charged tracks == 2
    (Selective diffractive criteria)
  - Electron identification
    - RICH signal, $n_0 \geq 2$
    - Track-EmCal matching with no dead/noisy tower
    - $E_1 > 1$ GeV || $E_2 > 1$GeV select electrons above the ERT trigger turn on curve
  - Back-to-back electrons

Possible signal and background sources

- Non-physical sources: [D. D'Enterria et al., nucl-ex/0601001 (2005)]
  - Cosmic rays:
    - no vertex,
    - no ZDC.
  - Beam gas interactions:
    - no vertex,
    - large multiplicities.
  - ⇒ Trigger criterion gets rid of those

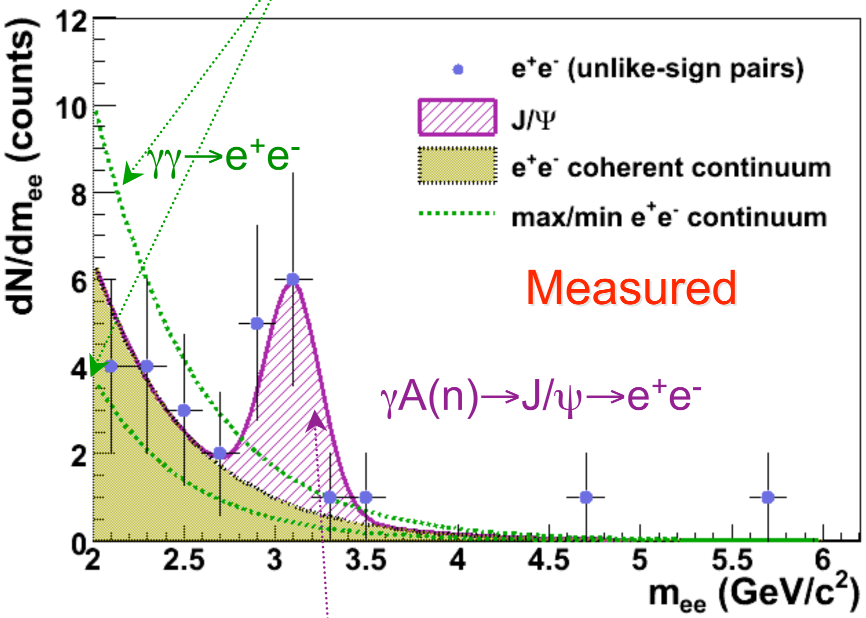
- Physical sources:
  - Peripheral nuclear A+A collisions:
    - large multiplicities,
    - large p_T.
  - Hadronic diffractive (Pomeron-Pomeron, rapidity gap):
    - forward proton emission,
    - larger p_T: $p_T(\gamma\gamma) < p_T(PP)$,
    - expect like-sign pairs too.
  - ⇒ Analysis cuts gets rid of them
  - ✓ Incoherent UPC: $\gamma + n \rightarrow n + J/\psi$
    - wider p_T: $p_T(\gamma\gamma) < p_T(\gamma P)$,
    - asymmetry dN/dy,
    - >2 neutrons (induced nuclear break-up) w/ same direction as J/Ψ.
  - ✓ Coherent UPC: $\gamma+\gamma \rightarrow e^+e^-$, $\gamma + A \rightarrow X + J/\psi$, $\gamma + A \rightarrow$ jet(s)+A

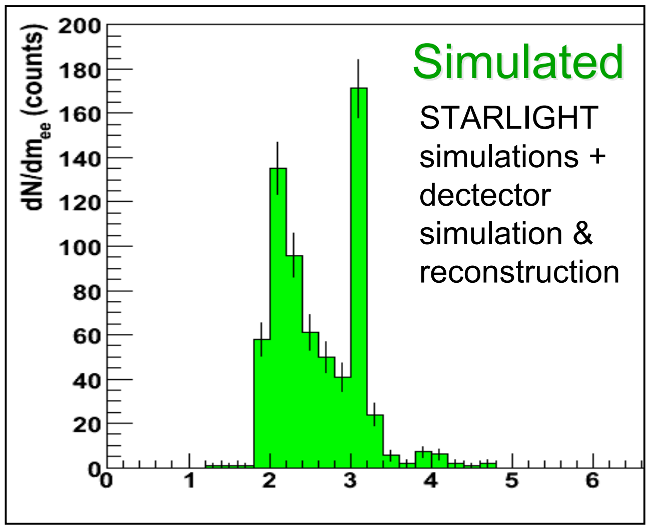
★ We are sensitive to coherent and incoherent UPC !

The measured invariant mass

- 28 unlike-sign pairs and no like-sign pairs of m_{ee} > 2 GeV/c^2
  ⇒ Clean sample, with zero net charge !
- Invariant mass fit input:
  - Coherent continuum shape derived from theoretical STARLIGHT-MC input + full detector simulation and reconstruction

    $dN/dm_{e+e-} = A \cdot \exp(c\, m_{e+e-})$;

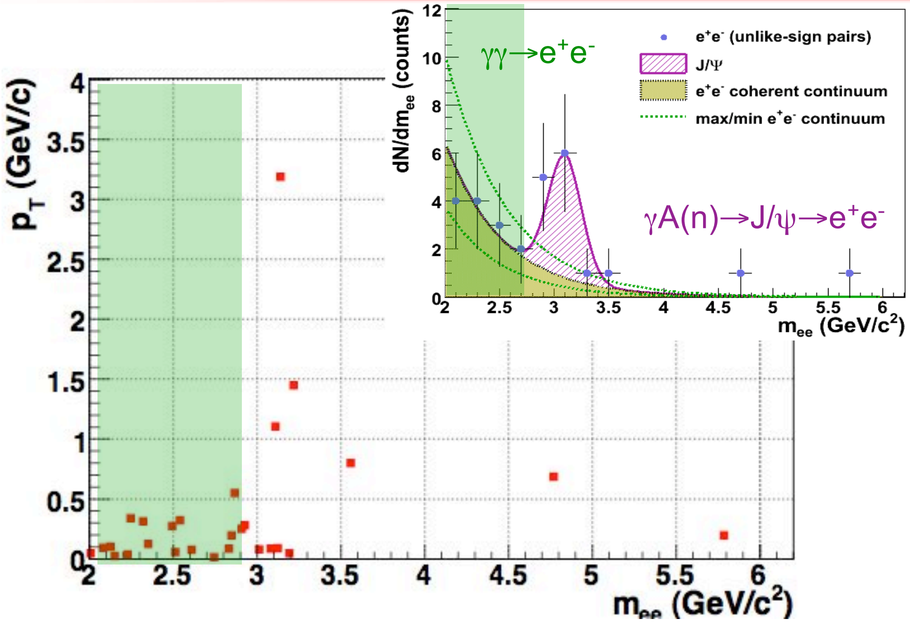




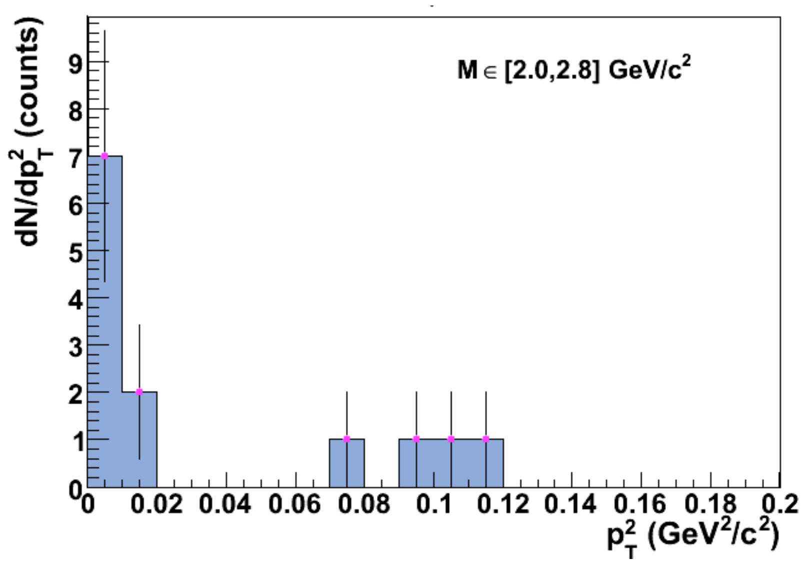
  - J/ψ Gaussian fit shape ⇒ width 155 MeV/c^2 consistent with MC

N(J/ψ) = 9.9 ± 4.1 (stat) ± 1.0 (syst)

Continuum component ($\gamma\gamma \rightarrow e^+e^-$) characteristics



- $N(e^+e^-) = 13.7 \pm 3.7 \pm 1.0$ $m_{ee} \in [2.0, 2.8]$ GeV/c^2
- Slicing in mass
  - $N(e^+e^-) = 7.4 \pm 2.7 \pm 1.0$ $m_{ee} \in [2.0, 2.3]$ GeV/c^2
  - $N(e^+e^-) = 6.2 \pm 2.5 \pm 1.0$ $m_{ee} \in [2.3, 2.8]$ GeV/c^2



- $\gamma\gamma \rightarrow e^+e^-$ spectra is peaked at very low pt ($p_T \leq 100$ MeV/c^2)

★ Evidence of the $\gamma\gamma \rightarrow e^+e^-$ coherent nature !

Coherent di-electron ($\gamma\gamma \to e^+e^-$) cross section

- Cross section

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

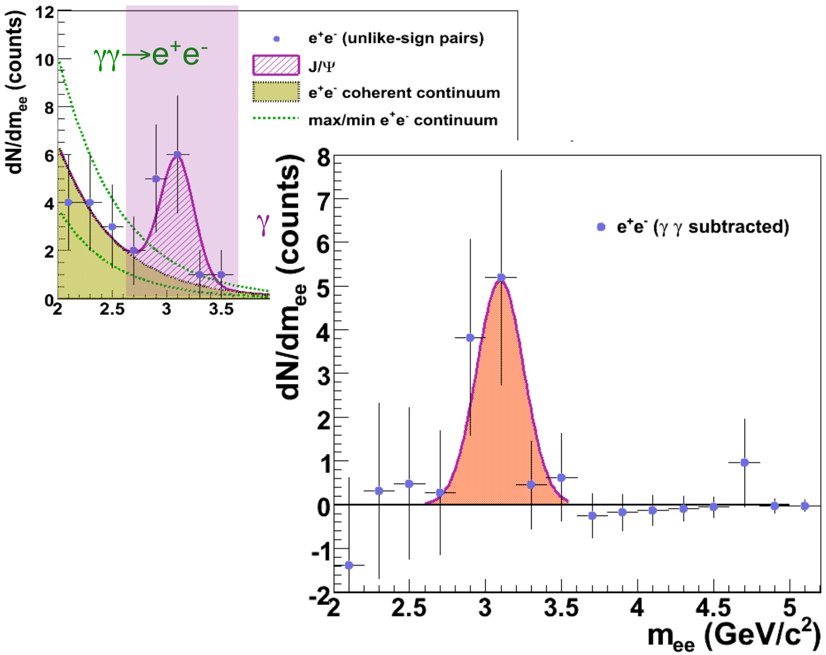
$m_{e^+e^-}$ [GeV/c²]	$d^2\sigma/dm_{e^+e^-}dy\|_{y=0}$ [μb/(GeV/c²)] data	STARLIGHT
e^+e^- continuum [2.0,2.8]	$86 \pm 23\,(\text{stat}) \pm 16\,(\text{syst})$	90
e^+e^- continuum [2.0,2.3]	$129 \pm 47\,(\text{stat}) \pm 28\,(\text{syst})$	138
e^+e^- continuum [2.3,2.8]	$60 \pm 24\,(\text{stat}) \pm 14\,(\text{syst})$	61

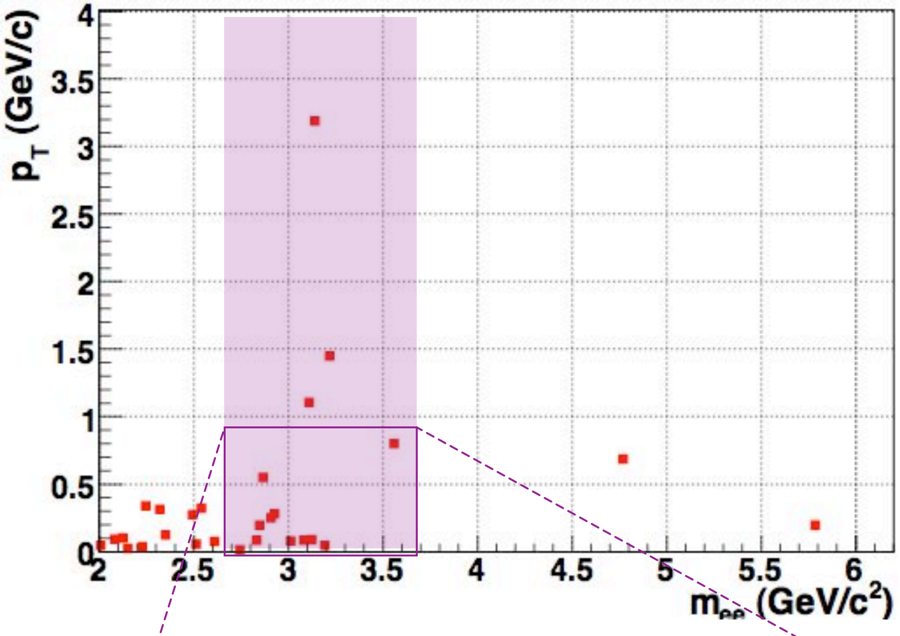
STARLIGHT:
WW approx. in
impact parameter
space at LO

★ Results agree with QED theoretical (STARLIGHT) calculations even though we are in a strongly interacting regime !

- Caveats / leftovers:
  - Lacking of other model comparisons on this kinematical region… input from theorists is most welcome !
  - Recent calculations seem to suggest that higher order corrections would suppress the e^+e^- cross-section [Baltz, Phys.Rev.Lett. 100 (2008) 062302]

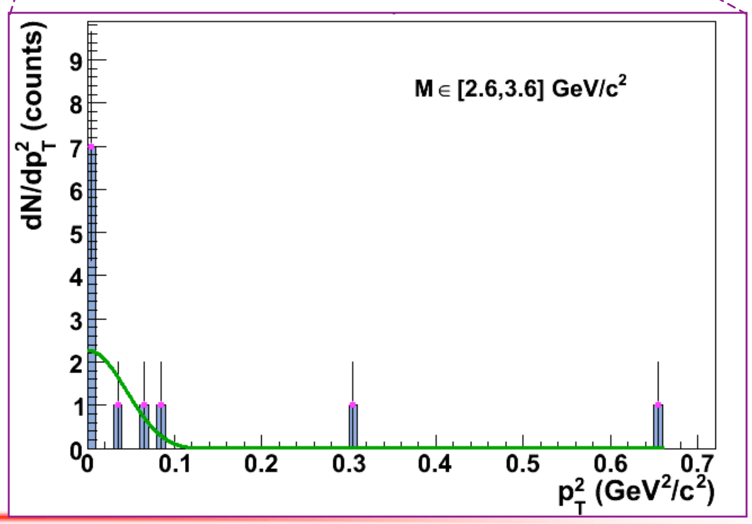
J/ψ transverse momentum distribution





- The low p_T J/ψ consistent with the Au nuclear form factor F $dN_{ee} / dp_T = A \cdot p_T \cdot |F(p_T)|^2$ ⇒ coherent (γA) J/ψ production
- But there seems to be also an incoherent (γn) J/ψ component

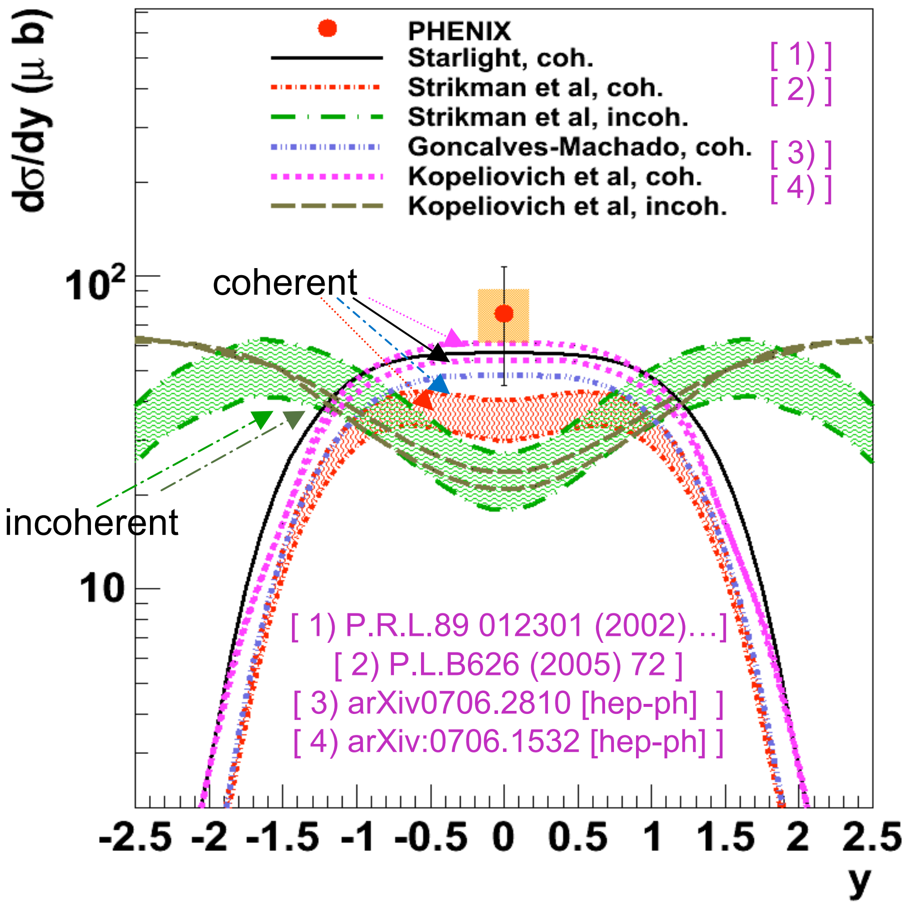
★ Observe both coherent (γA) & incoherent (γn) J/ψ production !



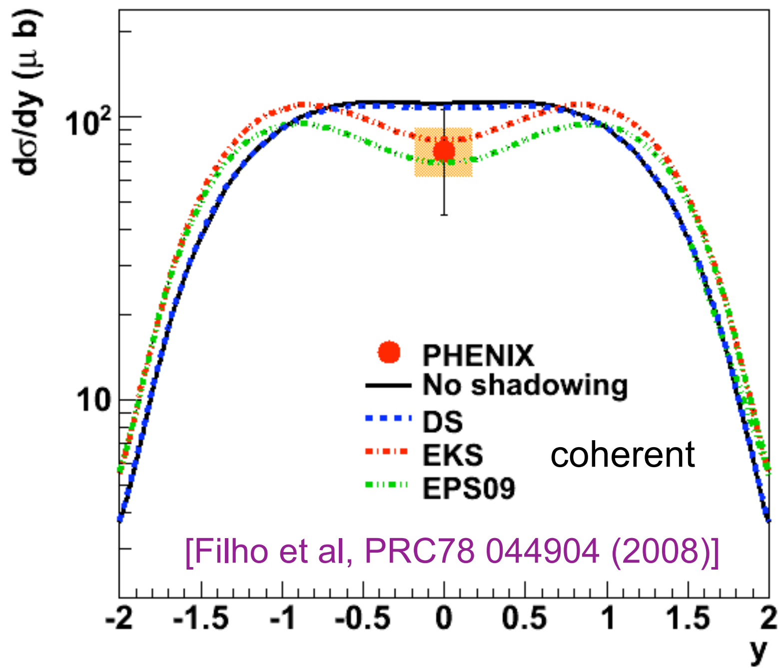
J/ψ cross section vs theoretical calculations I

$$\left.\frac{d\sigma_{J/\psi+Xn}}{dy}\right|_{|y|<0.35} = \frac{1}{BR} \cdot \frac{N_{J/\psi}}{Acc \cdot \varepsilon \cdot \varepsilon_{trigg} \cdot \mathcal{L}_{int}} \cdot \frac{1}{\Delta y}$$

⇒ $d\sigma/dy|_{y=0} = 76 \pm 31$ (stat) ± 15 (syst) μb

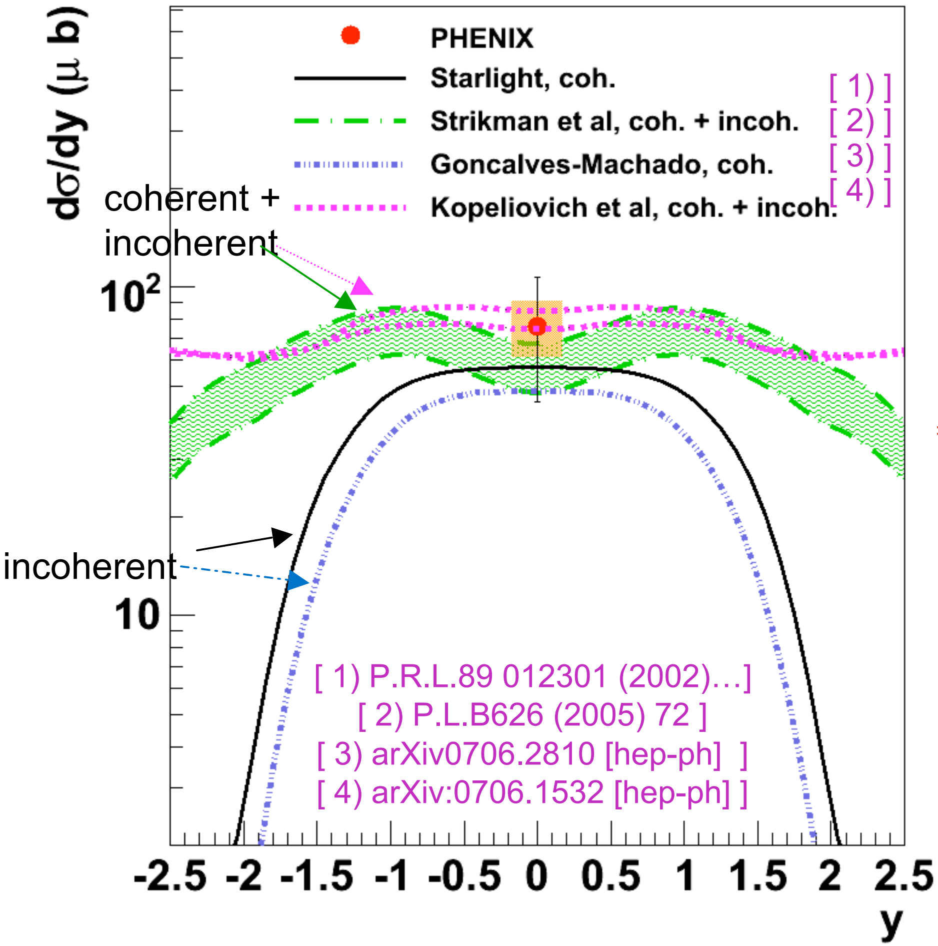


- Compatible with coherent predictions,
- Sensitive to the shadowing parameterizations,
- but... measured p_t spectra suggests both coherent (γA) and incoherent (γN) J/ψ production



J/ψ cross section vs theoretical calculations II

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

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

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

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

- ➢ Similar comparison with STAR ρ measurement gives $\alpha_{coh} = 0.75 \pm 0.02$, 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]

Summary

- First measurement of $J/\psi \rightarrow e^+e^-$ photo-production and of two-photon production of high-mass e^+e^- in nucleus-nucleus interactions !
- Efficient trigger & clean sample with no like-sign pairs, and ~ 10 J/ψ.
- Their p_T spectrum is peaked at low p_T~90MeV as expected for coherent photo-production.

- $\gamma\gamma \rightarrow e^+e^-$ cross-section at mid-rapidity is in good agreement with QED theoretical calculations.

- J/ψ measured p_T distribution suggests both coherent (γA) and incoherent (γn) J/ψ photo-production in accordance with predictions,
- J/ψ photo-production cross-section at mid-rapidity is consistent with different model predictions (pQCD) and with HERA data but precludes yet any detailed conclusion on the gluon-shadowing and J/ψ nuclear absorption.

- Looking forward the increased statistics at RHIC and the future eRHIC & LHC programs.

Backup slides

Comparison with HERA data

- Rough comparison with HERA e-p data, if coherent incoherent ratio is 50% - 50%

$$\sigma(\gamma\, A \to J/\psi\, A) = \frac{d\sigma(A\,A \to J/\psi\, A\,A)}{dy} \cdot \frac{1}{2\omega \frac{dN_\gamma}{d\omega}}$$

$$2N_\gamma = 6.7\,(10.5) \text{ for coherent (incoherent) at } \langle W_{\gamma p}\rangle = 24\,\text{GeV}$$

$$\sigma(\gamma\, Au \to J/\psi\, Au) = 5.7 \pm 2.3 \pm 1.2\,\mu b \text{ for coherent}$$

$$\sigma(\gamma\, Au \to J/\psi\, Au) = 3.6 \pm 1.4 \pm 0.7\,\mu b \text{ for incoherent}$$

- HERA (H1 & ZEUS) input

$$\sigma(\gamma\, p \to J/\psi\, p) = 30.5 \pm 2.7\, nb \text{ at } \langle W_{\gamma p}\rangle = 24\,\text{GeV}$$

$$\frac{\sigma(\gamma\, Au \to J/\psi\, Au)}{\sigma(\gamma\, p \to J/\psi\, p)} = 186 \pm 88\ (118 \pm 54) \text{ for coherent (incoherent)}$$

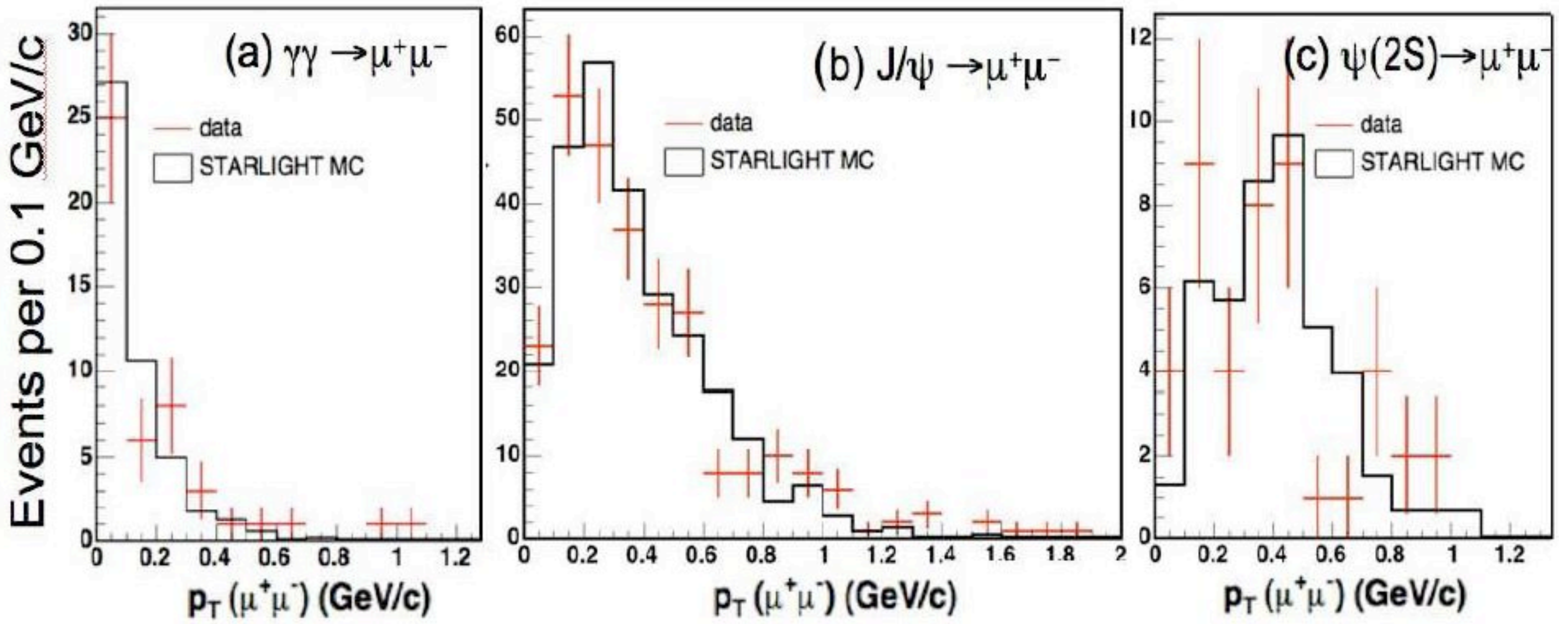
$$\sigma(\gamma\, Au \to J/\psi) = A^\alpha\, \sigma(\gamma\, p \to J/\psi)$$

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

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

J/ψ photo-production at CDF

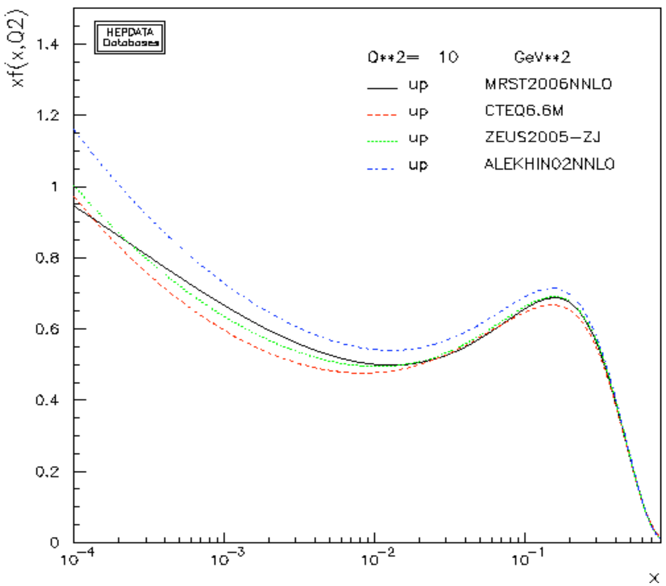
[CDF, arXiv: 0902.1271, 7 Feb 2009]

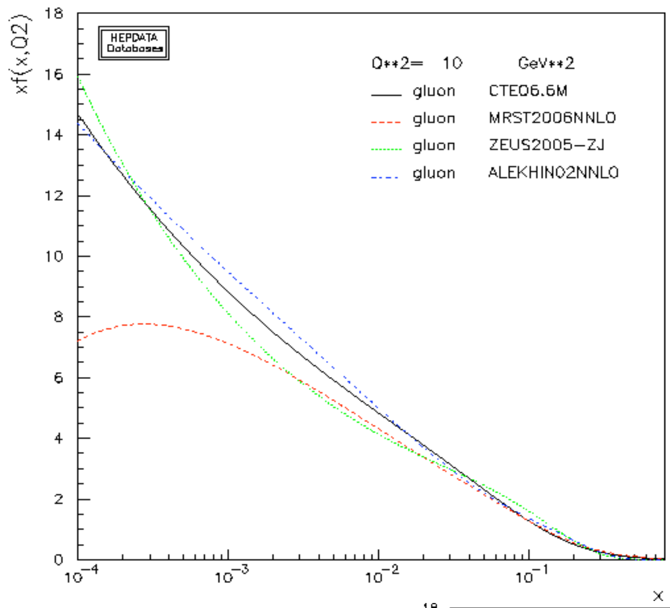


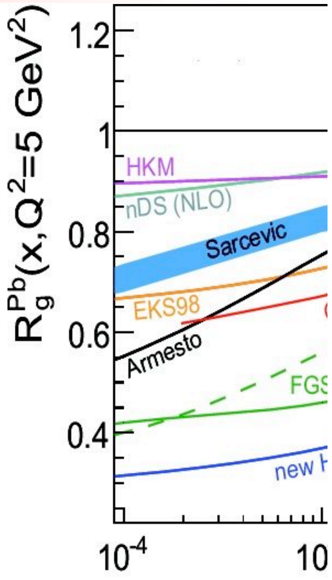
Knowledge on PDFs and nuclear modifications

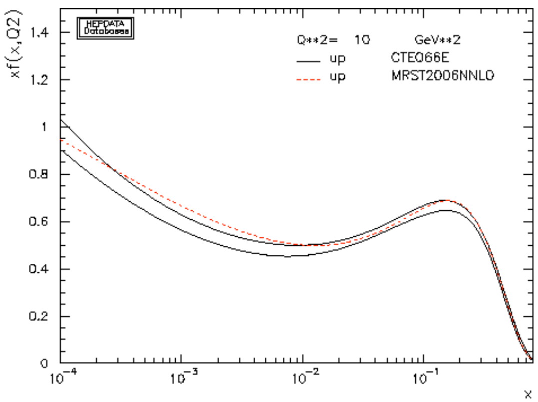
- DIS ep collisions probe the proton PDFs

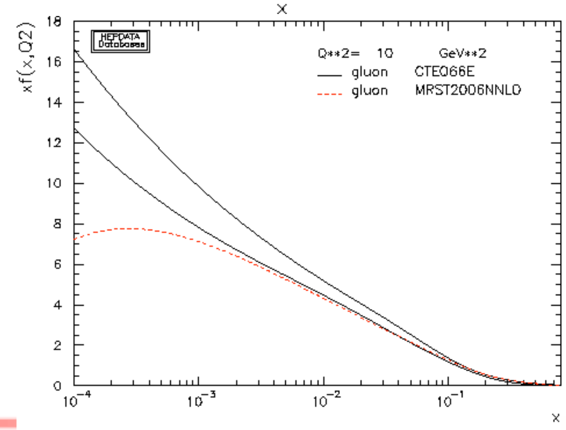
$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\,\alpha^2}{x\,Q^4}[2xy^2F_1 + 2(1-y)F_2]$$





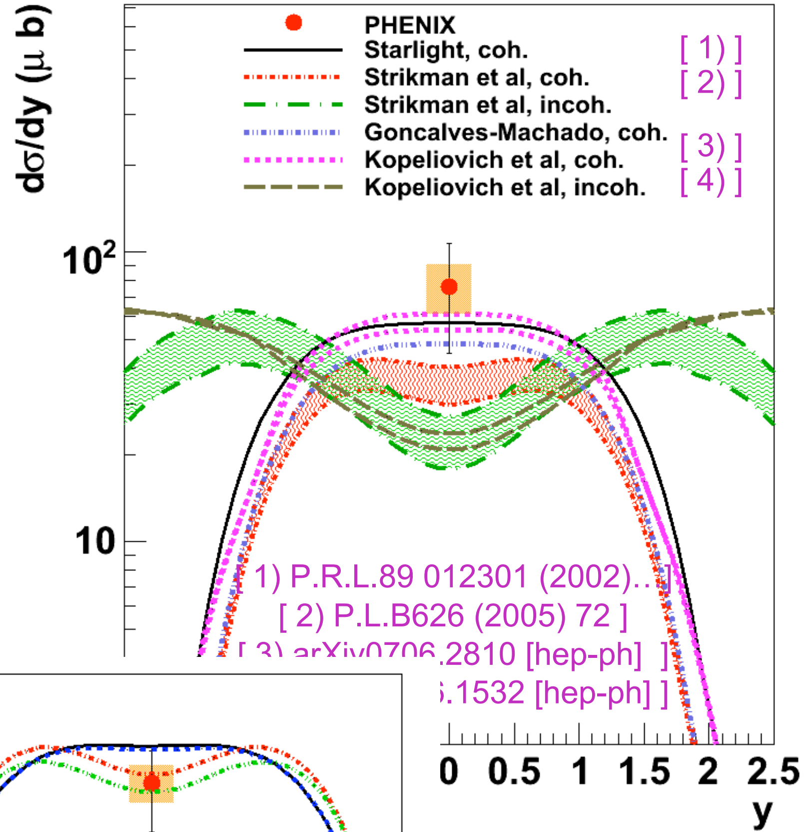


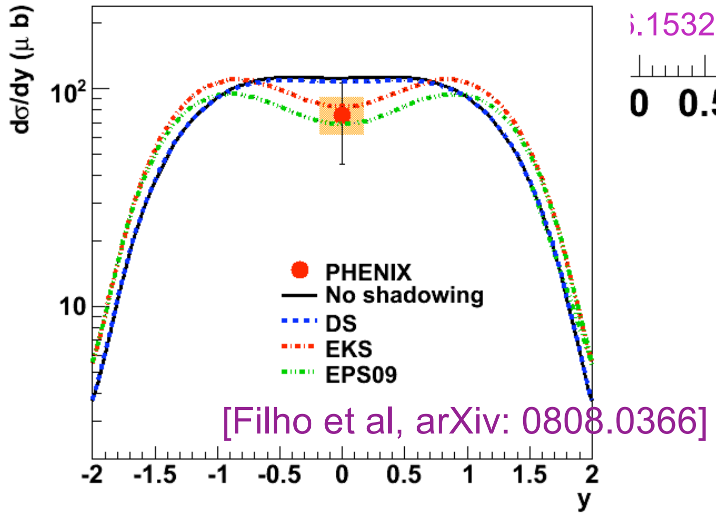




J/ψ cross section theoretical calculations

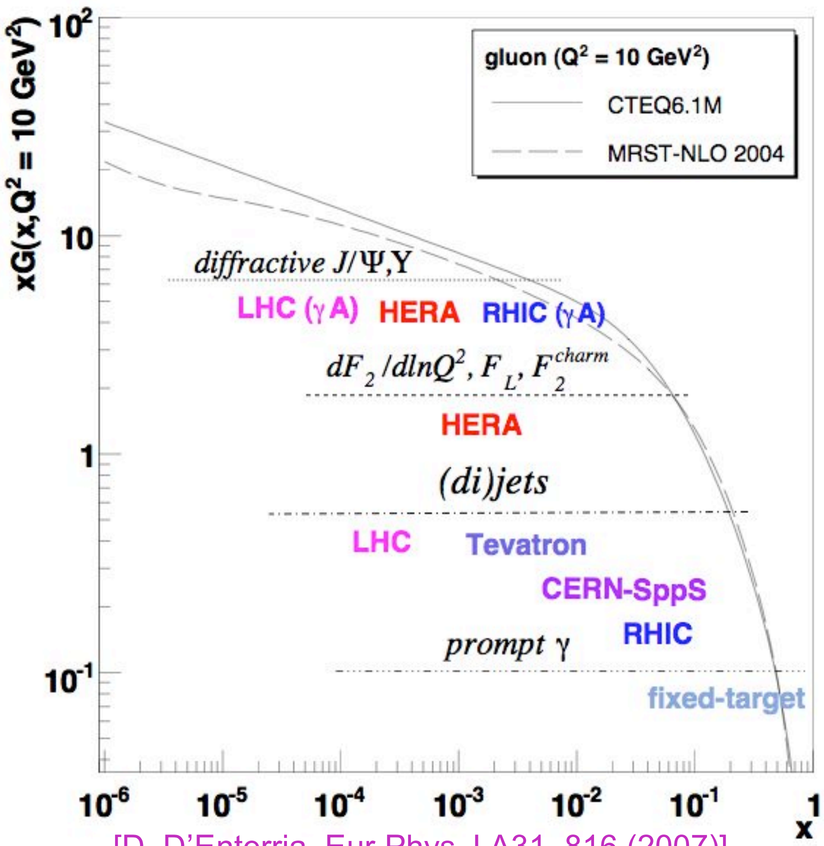
- Model predictions drawn
  - Starlight:
    coherent only,
    parameterization of HERA data
  - Strikman et al:
    coherent & incoherent
    color-dipole + $\sigma_{J/\psi N}$ = 3mb
  - Gonçalves-Machado:
    coherent only
    color-dipole + Glauber-Gribov shad.
  - Kopeliovich et al:
    coherent & incoherent
    color-dipole + gluon saturation
  - Filho, Gonçalves, Griep:
    coherent
    parameterization of HERA data
    different shadowing schemes





What is next ? Looking forward…

- Collected data on 2007 ~ 3 x statistics on 2004
  - Increased statistics:
    - Improve the statistical uncertainties
    - May allow to separate coherent & incoherent J/ψ components
  - Forward rapidity measurements become possible.
    Models predict distinct rapidity dependences depending on the nuclear shadowing scheme



[D. D'Enterria, Eur.Phys,J.A31, 816 (2007)]

- Further future plans may include the eRHIC program ?

- The LHC, new insights
  - Unexplored kinematic regime
  - J/ψ at x~5·10^{-4} at y~0
  - Υ UPC studies will be possible