Photoproduction of J/Ψ and high mass e^+e^- in ultra-peripheral Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with the PHENIX experiment

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«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

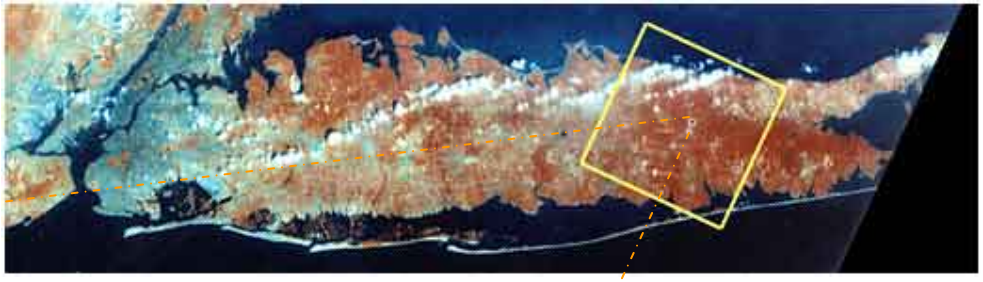
INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS

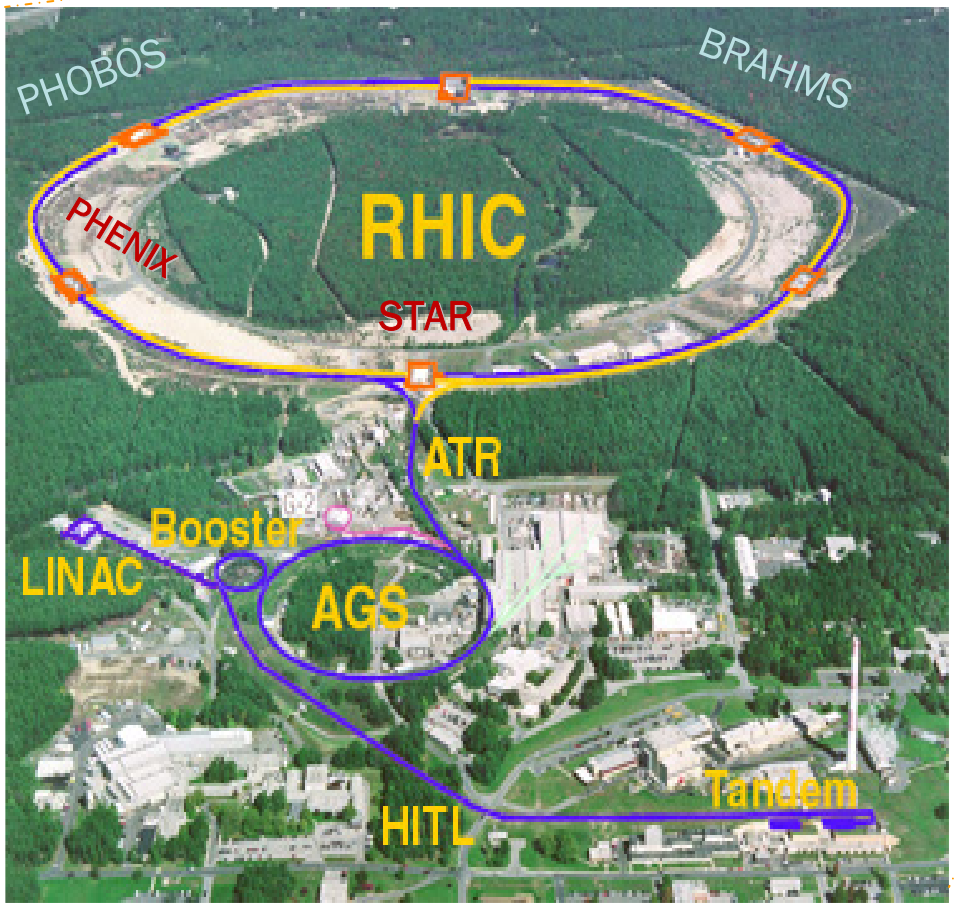
THE MOST UNEXPECTED AT LHC

AND THE STATUS OF HIGH ENERGY FRONTIER

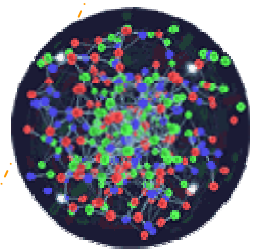
RHIC experimental facility

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

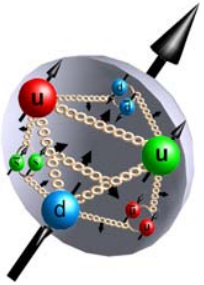




- Characteristics:
  - ~4km of circumference,
  - Polarized p to Au nuclei (soon U)
  - HIC: $\sqrt{s_{NN}}$ ~ 6-200 GeV
  - p+p: $\sqrt{s}$ ~ 6-500 GeV



Energy Density Frontier (QCD Matter Frontier)



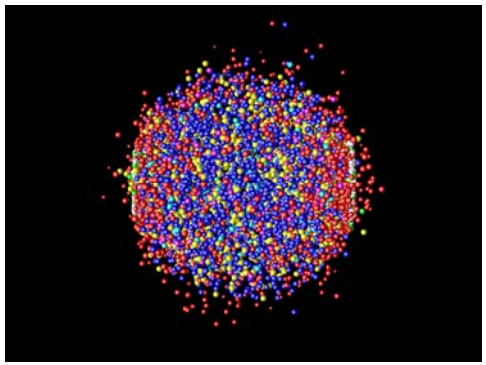
Spin Frontier

“Hadronic” Collider Processes

- **You’re probably familiar with the “Hadronic Interactions”**
- **But there are a lot more processes going on at a hadron collider**

Hadronic Interaction:

Au-Au --> X 6.8 barns



Hadronic Interaction

γ-γ:

AuAu --> AuAu + e^+e^- 33 kbarns

AuAu --> AuAu + 2(e^+e^-) 680 barns

AuAu --> AuAu + 3(e^+e^-) 50 barns

γ-N: L(γ-N)=10^{29} $cm^{-2}s^{-1}$ 2<Eγ<300GeV

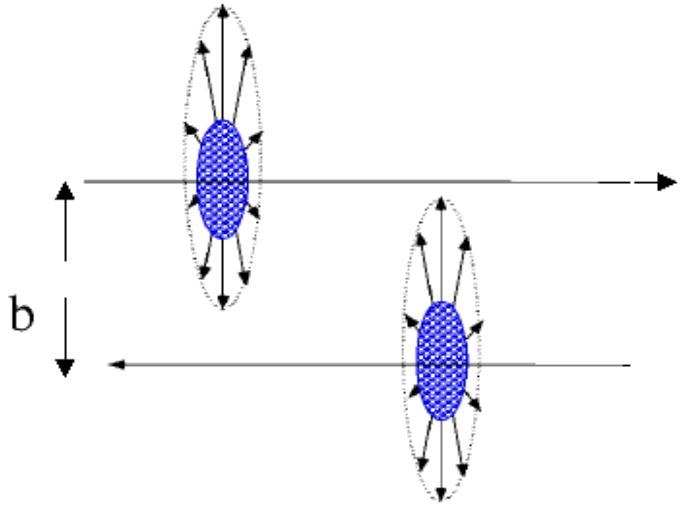
AuAu --> Au+Au* 92 barns

→ X+neutrons

AuAu --> Au*+Au* 3.67±0.26 barns

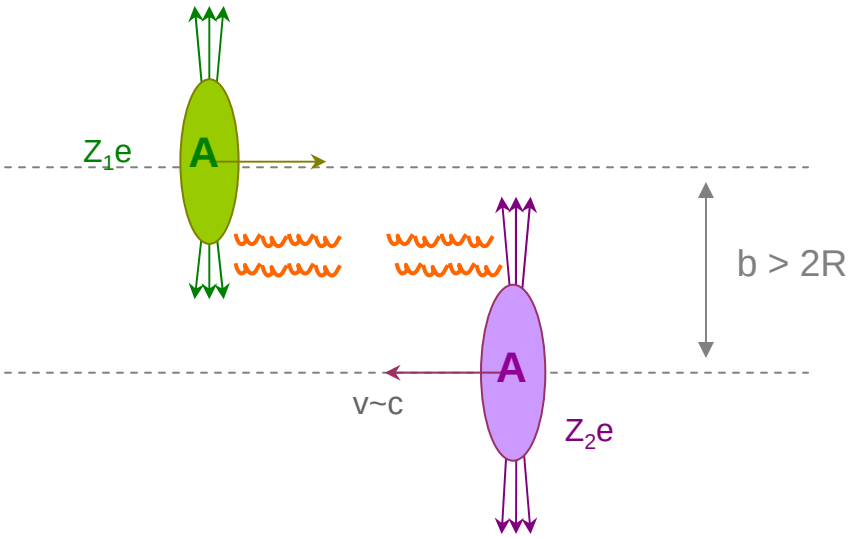
→ X+neutrons

→ Y+neutrons

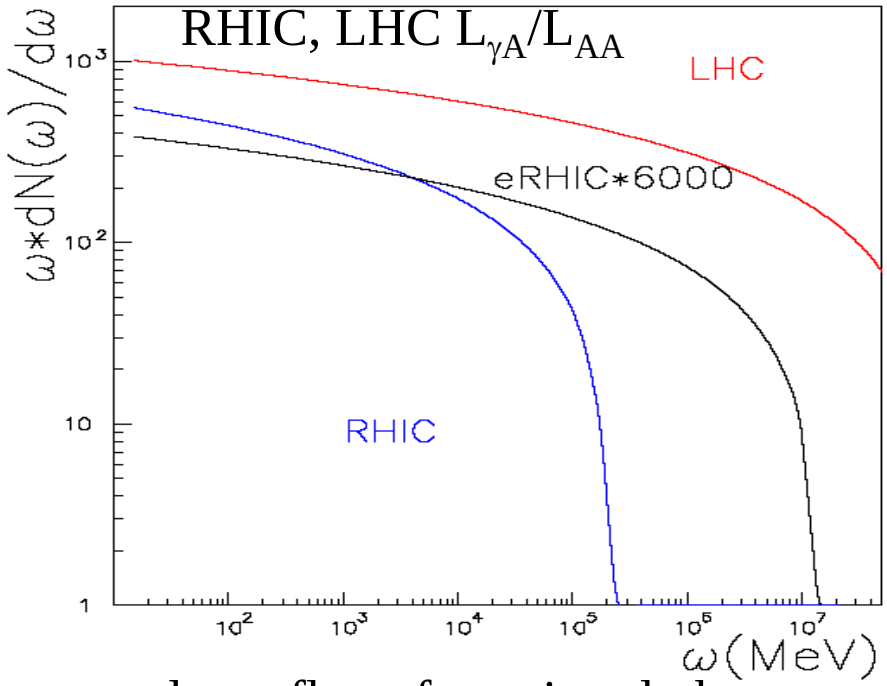


Peripheral Interaction

γ+γ and γ+A Luminosities



UPC A+A interaction



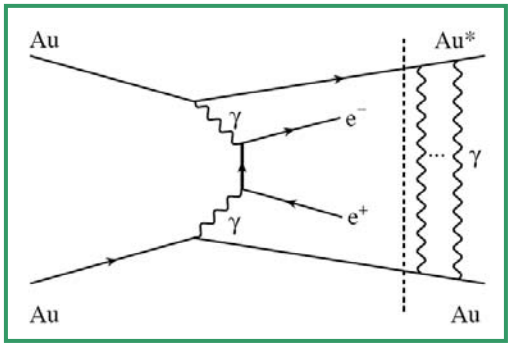
- The electromagnetic field is equivalent to a large flux of quasi-real photons, and can be calculated per (Fermi)-Weizsacker-Williams:

$$f_{\gamma/A}(z) = \frac{\alpha_{em} Z^2}{2\pi} \frac{1+(1-z)^2}{z} \int_{Q^2_{min}}^{\infty} \frac{Q^2 - Q^2_{min}}{Q^4} |F(Q^2)|^2 dQ^2$$

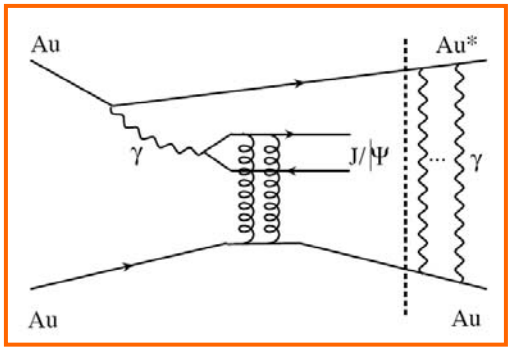
- Can get large flux due to the coherent effect of protons in nucleus (~Z^2)
- Two processes:
  1. photon-photon (coherent)
  2. photon-nucleon (incoherent,photoproduction)

γ+γ (Coherent) vs γ+A (Incoherent) Production

"Coherent"



"Incoherent"



RHIC max. CM energy

$W_{max},\gamma\gamma \sim 6$ GeV

$$\omega < \omega_{max} \approx \frac{\gamma}{R}$$

$W_{max},\gamma n \sim 34$ GeV

Max p_T

$p_T,\gamma\gamma < 1/R_{nuc} \sim 100$ MeV

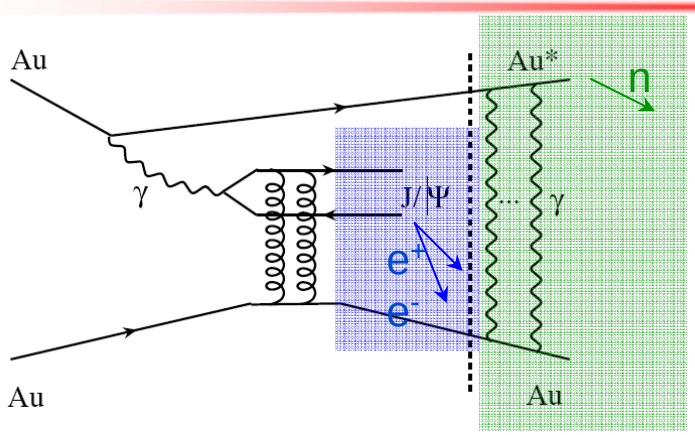
$p_T,\gamma n$ kin. limited

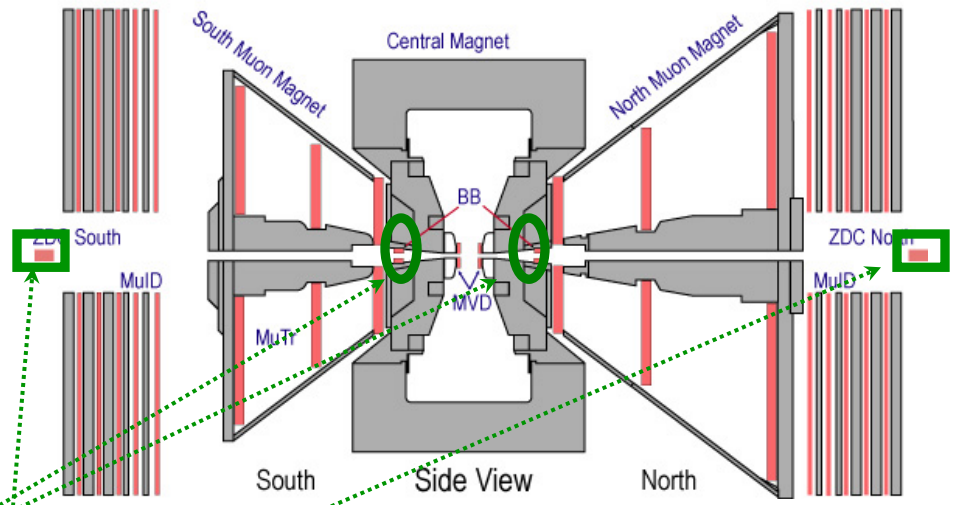
Luminosity

$\sigma(\gamma\gamma) \propto Z^4 \sim 4\cdot10^7$

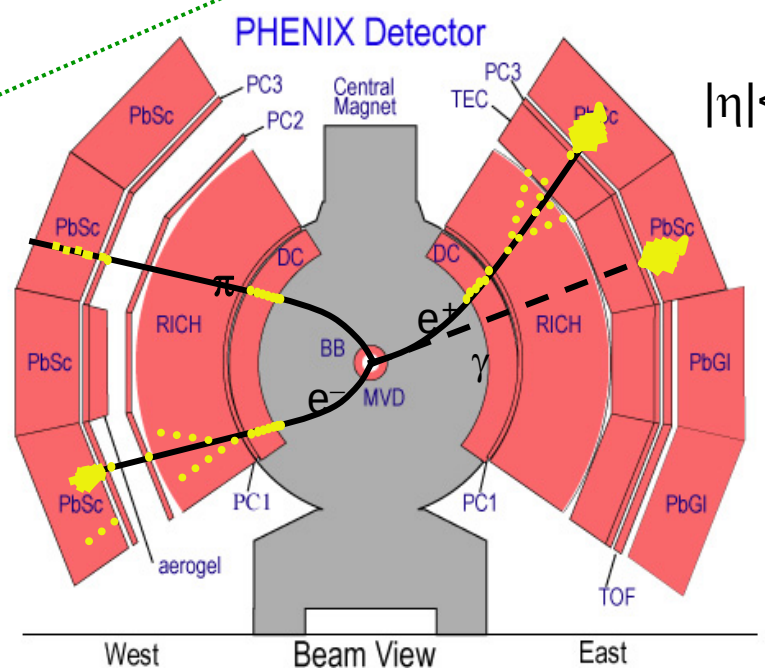
$\sigma(\gamma n) \propto Z^2 \sim 6\cdot10^3$

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





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



|η|<0.35

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

Possible signal and background sources

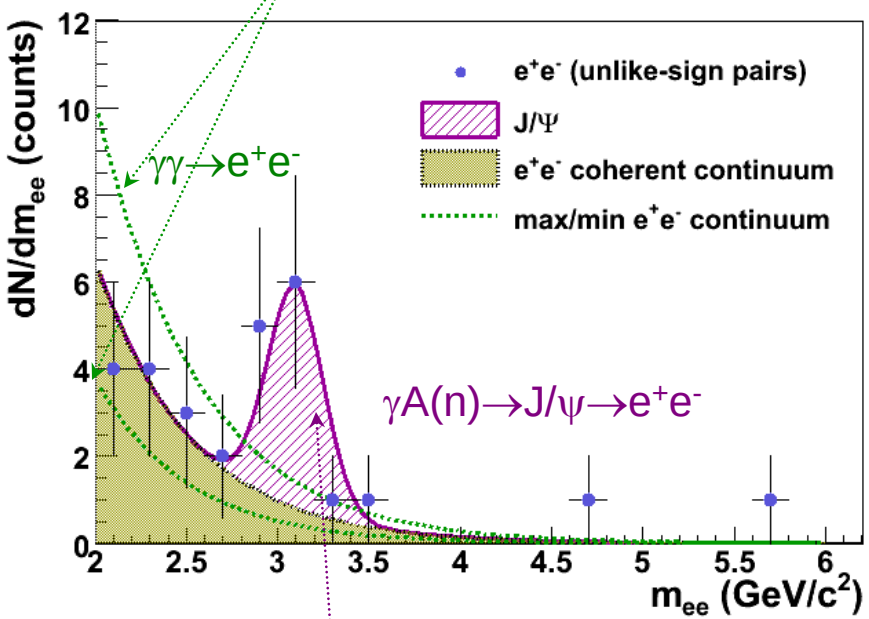
- Non-physical sources:
  - ✗ Cosmic rays:
    - ☐ no vertex, ☐ no ZDC.
  - ✗ Beam gas interactions:
    - ☐ no vertex, ☐ large multiplicities.
  - ⇒ Trigger criterion gets rid of those
- Physical sources:
  - ✗ Peripheral nuclear A+A collisions:
    - ☐ large multiplicities, ☐ large p_T.
  - ✗ Hadronic 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

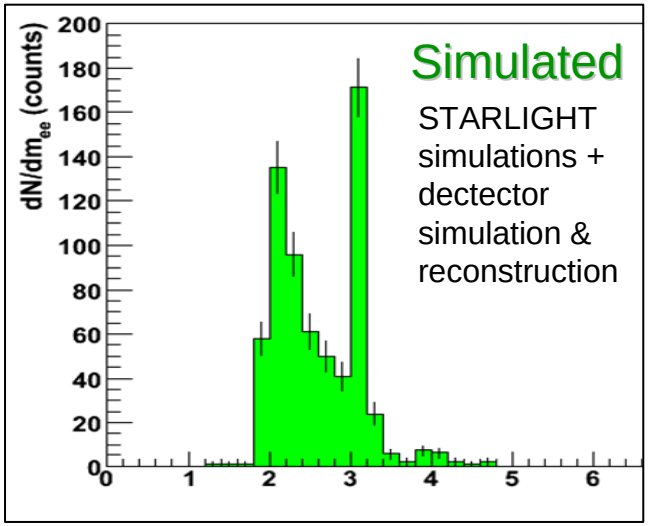
Sensitive to coherent and incoherent UPC

The measured invariant mass

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

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

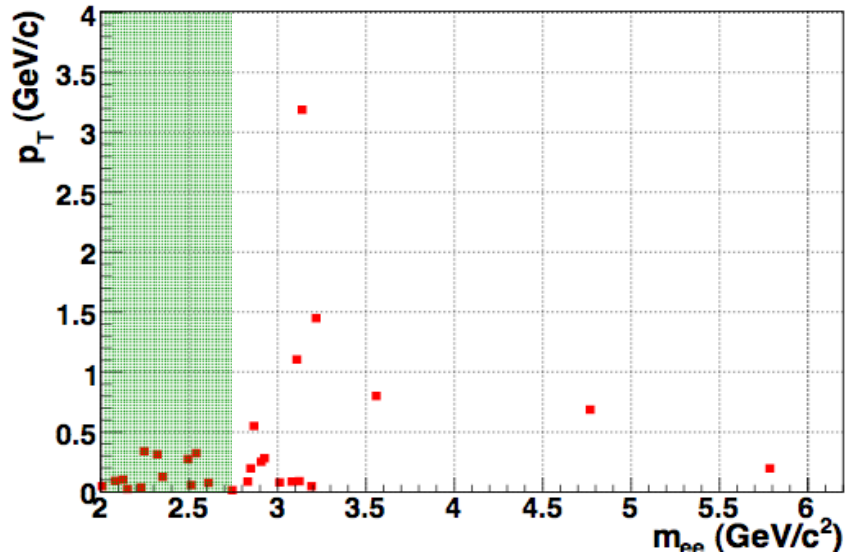


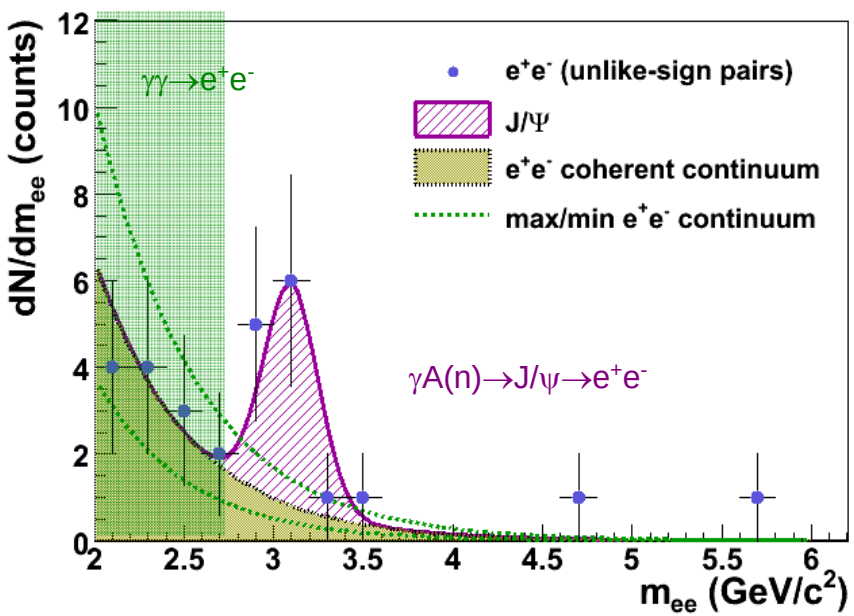


- J/ψ Gaussian fit shape $\Rightarrow$ width 155 MeV/c^2 consistent with MC

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 dist consistent w/ constraint of nucleus form factor $\rightarrow$ Evidence of continuum e^+e^- coherent nature

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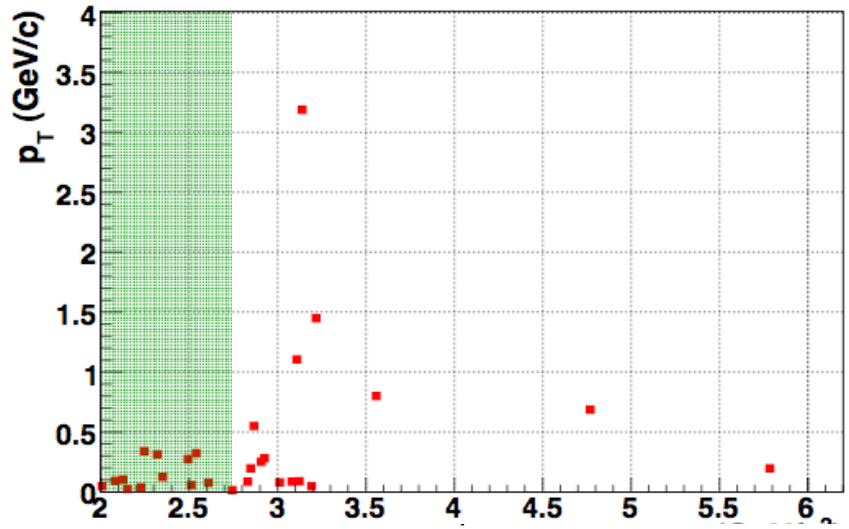

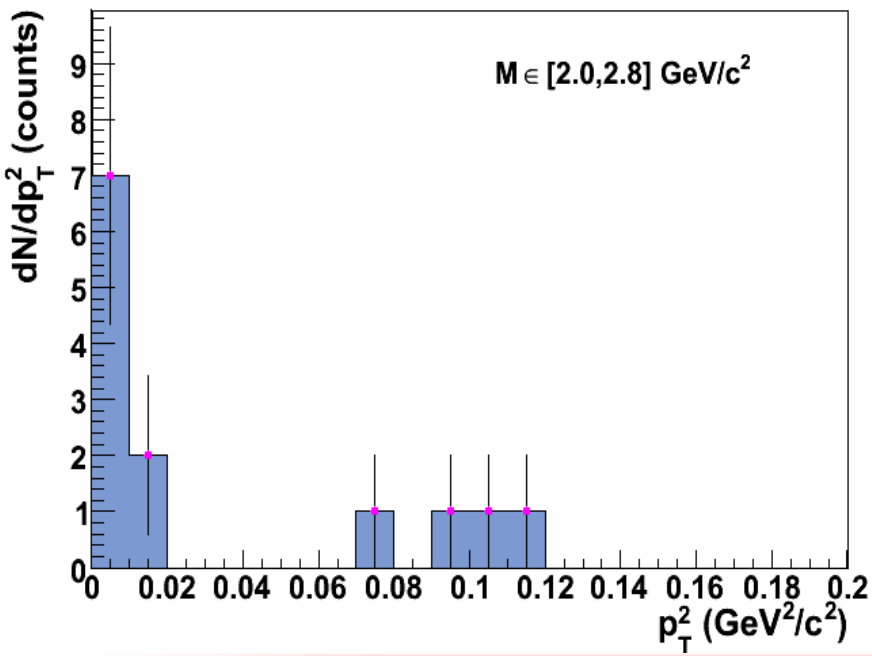

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Coherent di-electron ($\gamma\,\gamma \rightarrow e^+e^-$) cross section

- 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/c^2]	$d^2\sigma/dm_{e^+e^-}dy\|_{y=0}$ [μb/(GeV/c^2)]	
	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 with Breit-Wheeler (LO) eqn

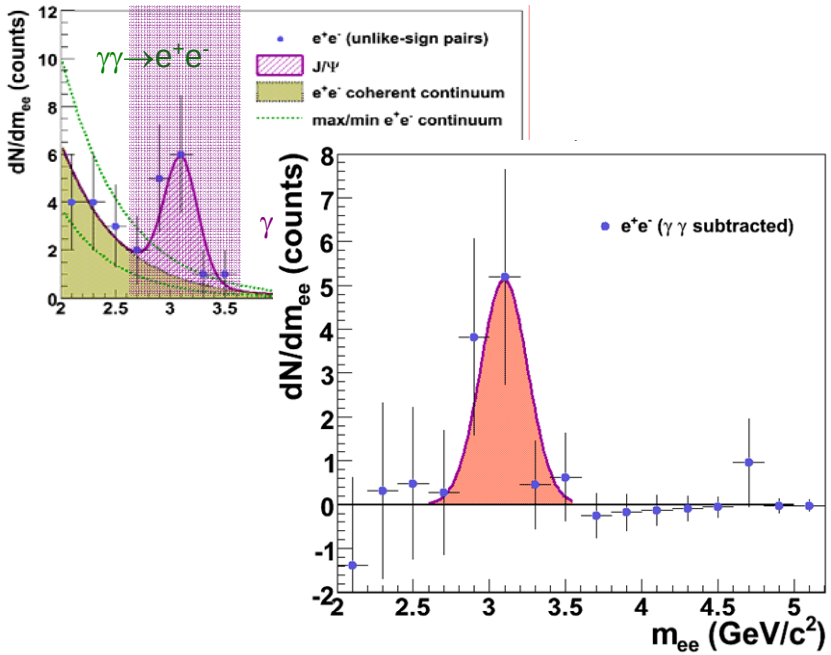
★ Results consistent with QED theoretical (STARLIGHT) calculations

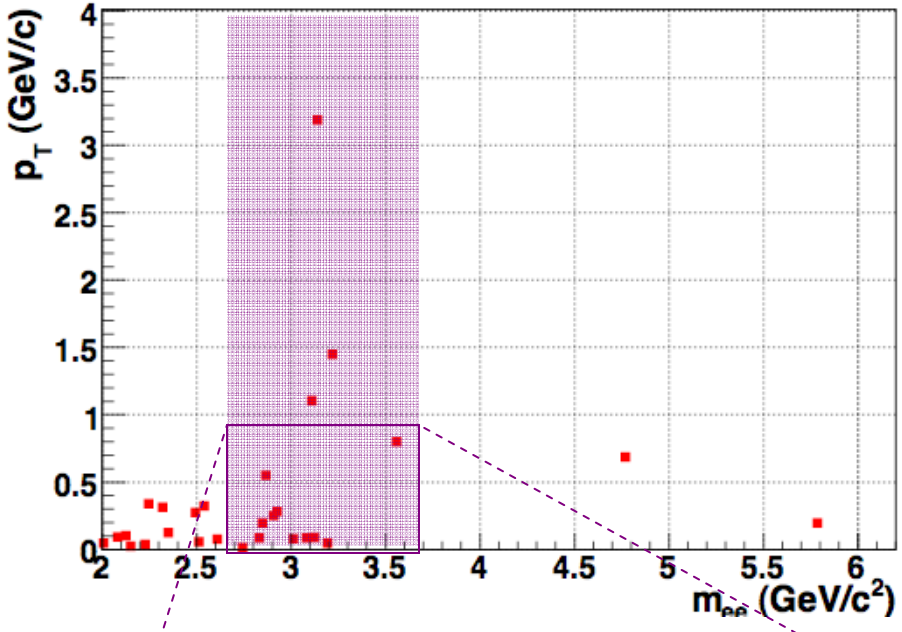
- Caveat:

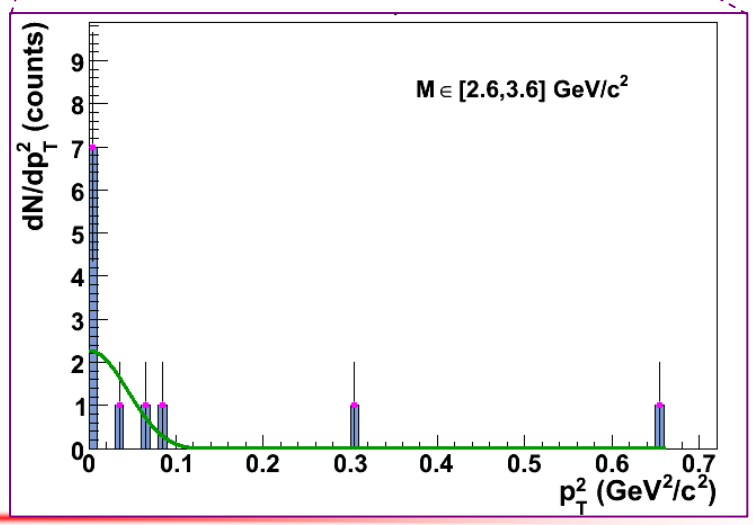
Baltz, PRL 100 (2008) 062302

  - Recent NLO calculations seem to suggest that higher order corrections would suppress the e^+e^- cross-section by ~20%
  - $\alpha \sim Z\alpha_{EM} \sim 0.6$
  - $E_{\max} \sim \frac{Ze\gamma}{b^2} \sim E_{crit} Z\alpha\gamma$ for $b \sim 1/\lambda_e$ (Compton wavelength)
    - $E_{crit} = m^2c^3/\hbar e$ Schwinger critical field strength (1.5×10^{16} V/cm)

J/ψ | transverse momentum distribution







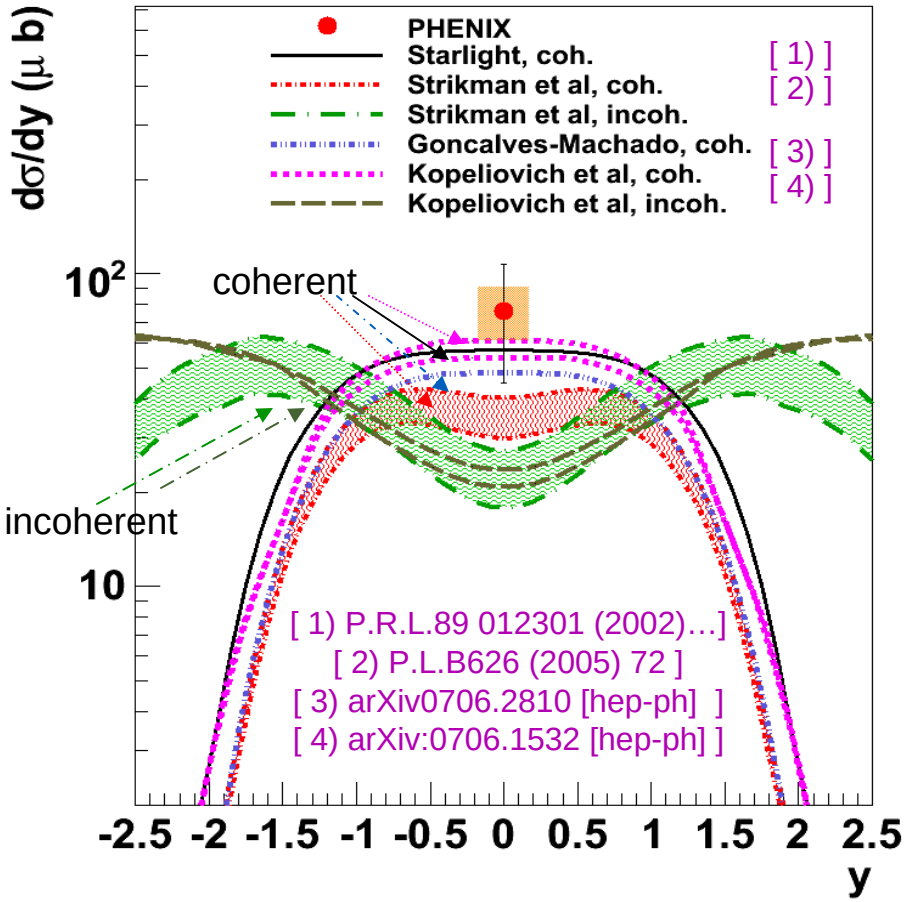
- The low p_T J/ψ consistent with the Au nuclear form factor F
  $dN_{ee} / dp_T = A \cdot p_T \cdot |F(p_T)|^2$
  ⇒ coherent (γγ) J/ψ production
- But there seems to be also an incoherent (γn) J/ψ component

★ Hints of both coherent & incoherent J/ψ production

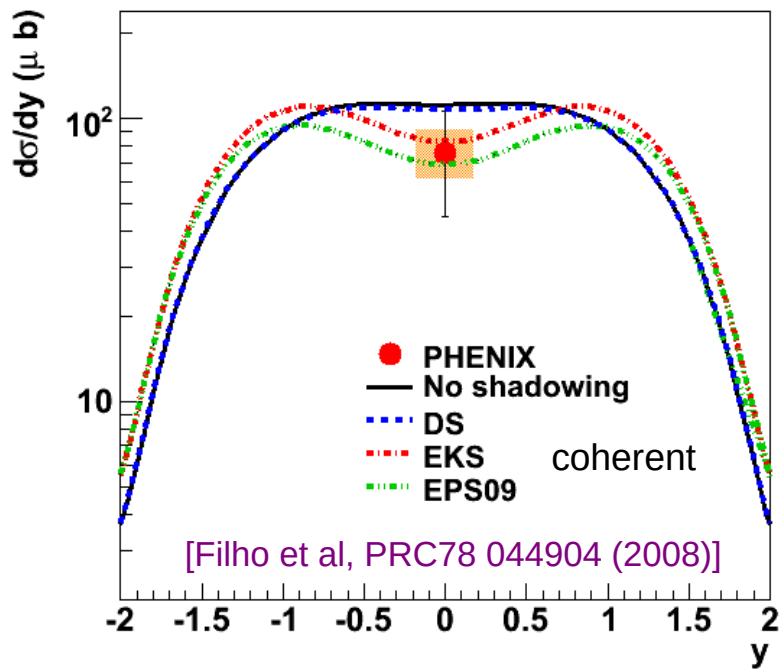
J/ψ cross section vs theoretical calculations

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

⇒ $d\sigma/dy\,|_{y=0}$ = 76 ± 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



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

[ZEUS, Eur.Phys.J. C24 (2002) 345]
[H1, Eur.Phys.J. C46 (2006) 585]

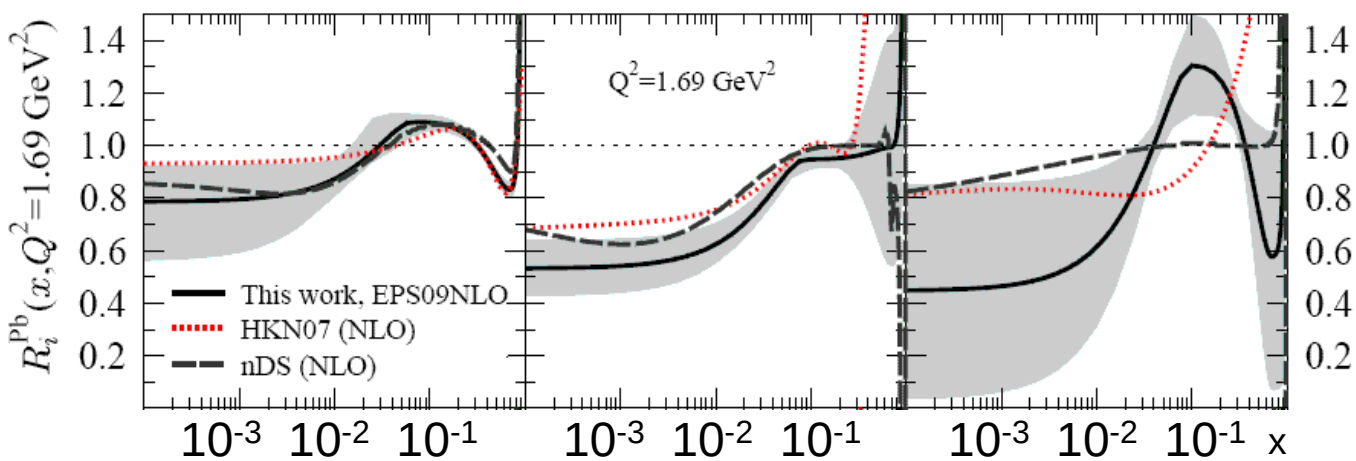
$\Rightarrow$ $\alpha \sim 1$, good agreement with HERA data hard probes scaling

$\gamma+\gamma$, $\gamma+p$, $\gamma+A$ "Applications"

- Higgs as well as many SUSY ptcls should be produced at the LHC in $\gamma+\gamma$ and $\gamma+p$ ($\gamma+A$)
  - *High energy photon interactions at the LHC*, de Jeneret et al, arXiv:0908.2020
    - FP220, FP420
  - *Observation of exclusive charmonium production and gamma+gamma to mu+mu- in p+pbar collisions at sqrt{s} = 1.96 TeV*, CDF, PRL102:242001,2009

Nucleus-Nucleus Interactions

- Direct measurement of G(x) at $x = m_{J/\Psi}^2 / W_{\gamma A}^2 = 1.5x10^{-2}$ from photoproduction ($\sigma \sim g^2(x)$)



EPS09: A New Generation of NLO and LO Nuclear PDF's, Eskola,Paukannen,Salgado JHEP 0904:065 2009

- Possibly study dynamics of J/Ψ propagation through nuclear matter
  - Feature or Bug?
- Test of QED in strong-coupling regime?: $\alpha = Z\alpha_{EM} \sim 0.6$

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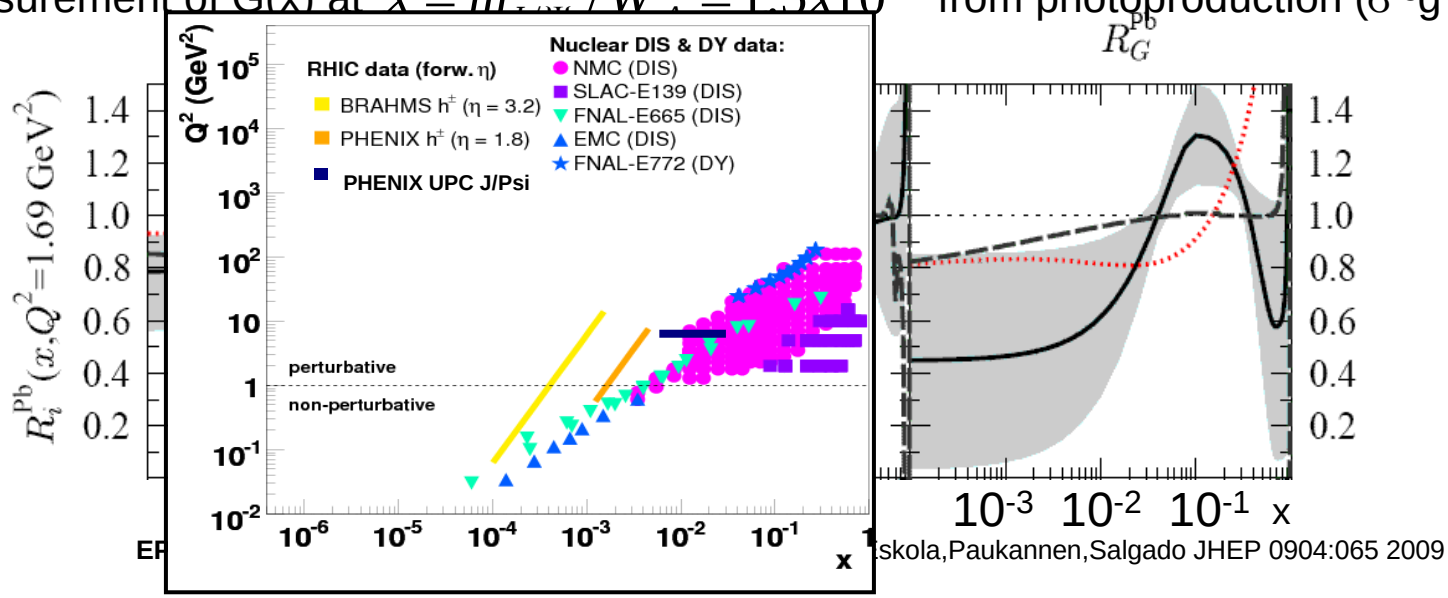

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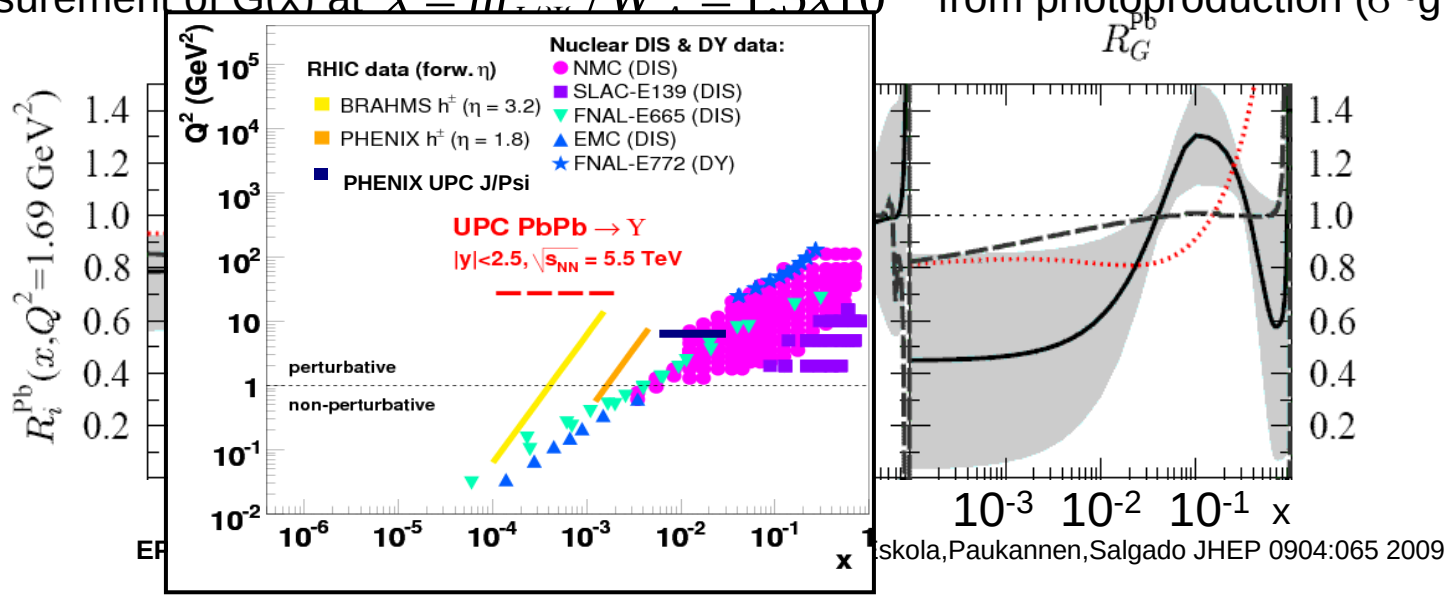

EP … skola,Paukannen,Salgado JHEP 0904:065 2009

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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
  - Other hadron collider measurements: CDF(J/Ψ,Ψ'…), STAR (ρ)
- Testing of our understanding of these processes
  - Coherent vs Incoherent
  - Does DESY experience translate to hadron-hadron colliders?
    - Indications are that it does
  - How to trigger (experimental issues)
    - Good progress on this issue
- Important for
  - Future searches for new physics in diffractive p+p and Pb+Pb at LHC
    - Can reach mass at TeV scales – good sensitivity to Higgs and SUSY
  - Constraints on QCD background to above searches by measurement of g(x) and $g_A(x)$ at low x
    - Gluon Saturation
  - Understanding J/Ψ propagation through nuclear matter?
  - Tests of EM in strong coupling regime – Reaches Schwinger Limit