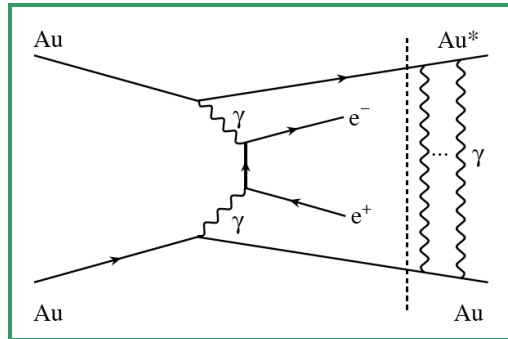


Photoproduction of J/Ψ and
high mass lepton pairs in ultra-
peripheral Au+Au collisions at
 $\sqrt{s_{NN}} = 200$ GeV with the -----
PHENIX experiment

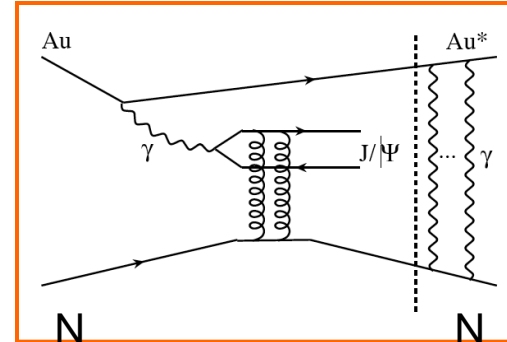
Mickey Chiu
BROOKHAVEN
NATIONAL LABORATORY

$\gamma+\gamma$ (Coherent) vs $\gamma+A$ (Incoherent) Production

“Coherent”



“Incoherent”



RHIC max. CM energy

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

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

$$W_{\max, \gamma N} \sim 34 \text{ GeV}$$

Max p_T

$$p_{T, \gamma\gamma} < 1/R_{\text{nuc}} \sim 100 \text{ MeV}$$

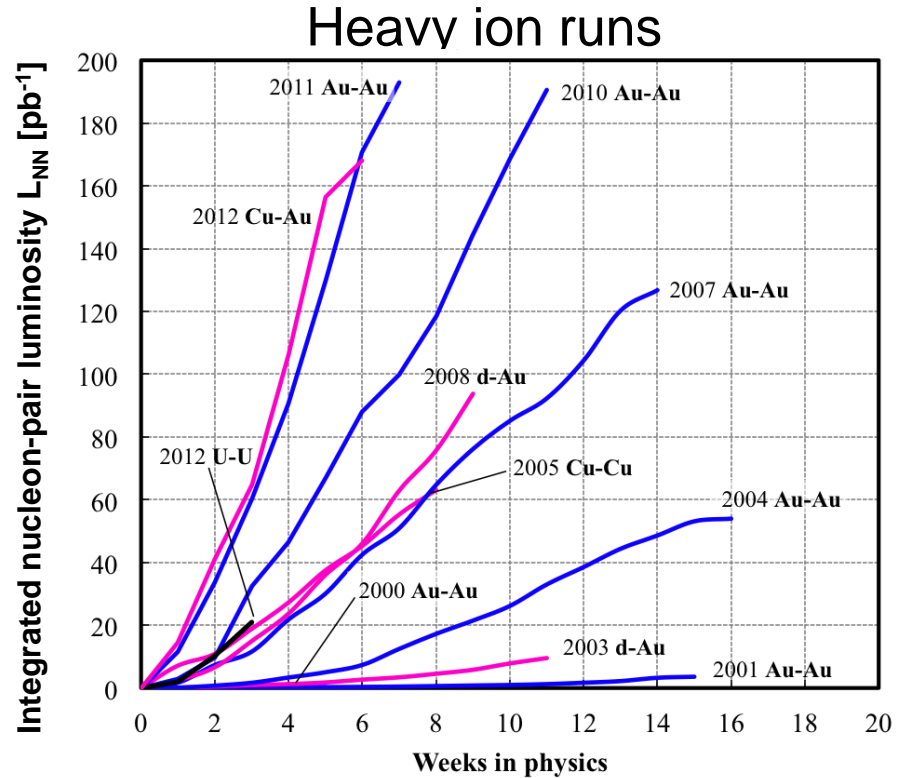
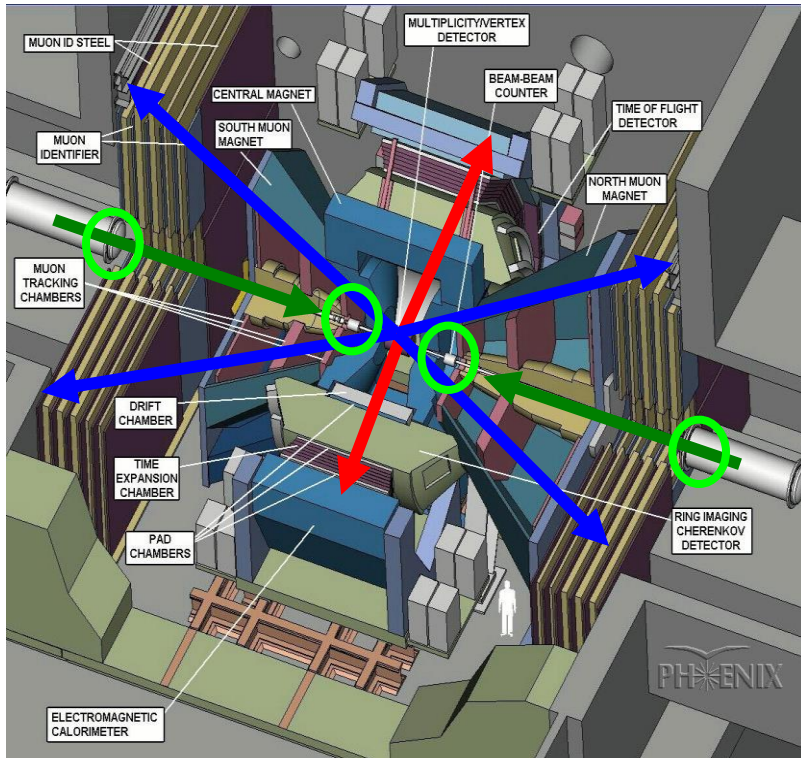
$p_{T, \gamma N}$ kin. limited

Luminosity

$$\sigma(\gamma\gamma) \propto Z^4 \sim 4 \cdot 10^7$$

$$\sigma(\gamma N) \propto Z^2 \sim 6 \cdot 10^3$$

PHENIX UPC Data-sets



2004-RUN

- $|y| < 0.35$
- Au+Au
- 200GeV
- $\sim 100/\mu\text{b}$

2007-RUN

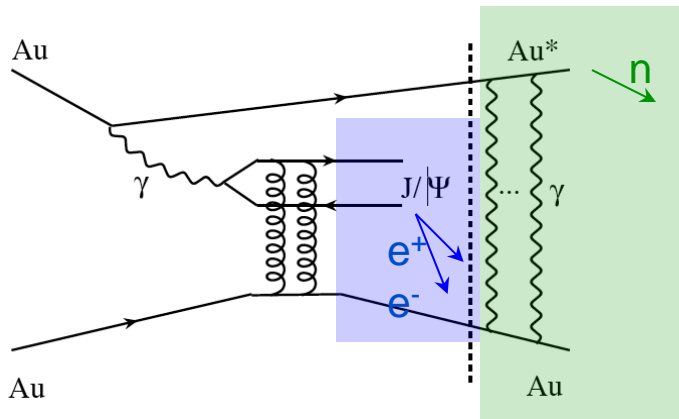
- $|y| < 0.35$
- Au+Au
- 200GeV
- $\sim 530/\mu\text{b}$

2010-RUN

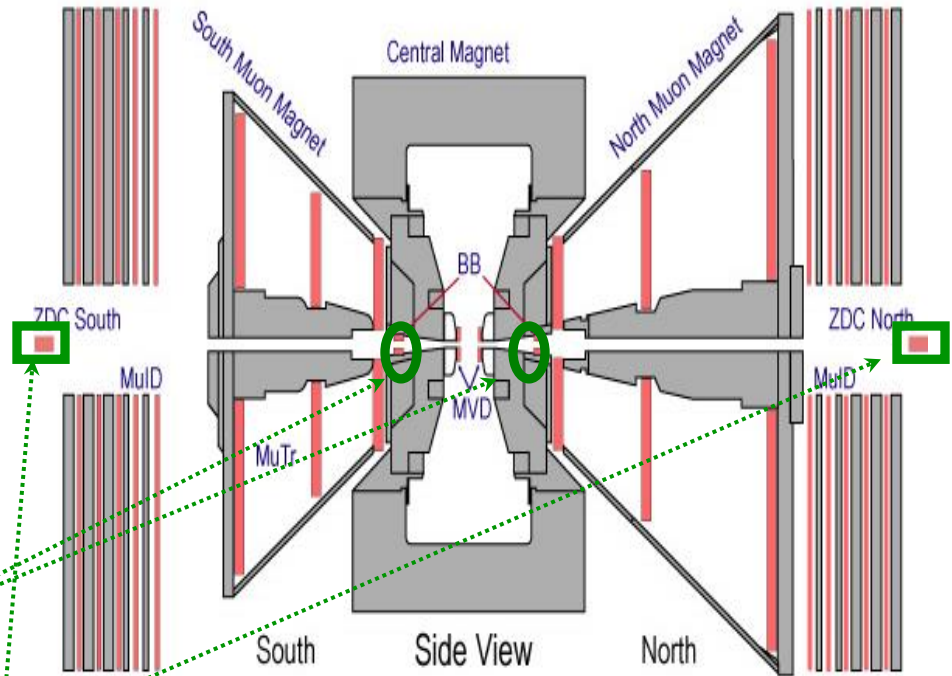
- $|y| < 0.35$ AND $1.2 < |y| < 2.2$
- Au+Au
- 200GeV
- $\sim 800/\mu\text{b}$

Runs 2011 and 2014 Au+Au data still to be analyzed ($\sim 2500/\text{ub}$)

γ Au \rightarrow J/ ψ Au* Triggers in PHENIX



- UPC dedicated triggers
 - Rapidity gap $3 < |\eta| < 3.9 \Rightarrow$ MB interaction veto (**BBC veto**)
 - Large probability to exchange additional photons by GDR \Rightarrow 1 or 2 **ZDC** trigger
 - Electron sample \Rightarrow **EmCal** trigger, $E < 0.8$ (2004) or 1.0 GeV (2007)
 - Muon sample \Rightarrow MUID 2D trigger



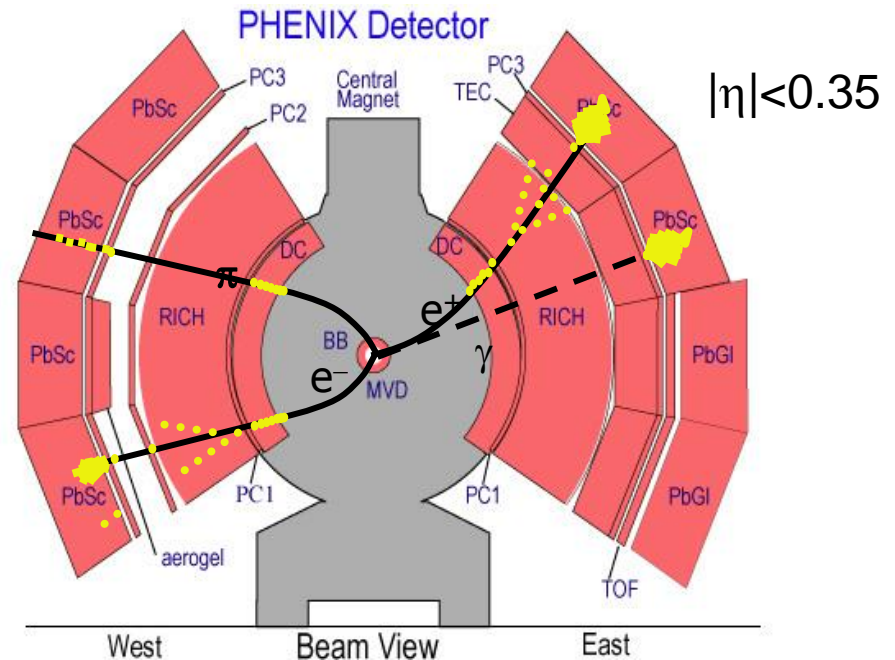
PHENIX MB: 4kHz
 PHENIX ERT2x2(EMcal): 8kHz
 PHENIX MUID2D: O(100) Hz

To reduce trigger rate,
 ZDC was required...

Mid-Rapidity $J/\psi + Xn$, $|\eta| < 0.35$

$$\gamma \text{ Au} \rightarrow J/\psi (\rightarrow e^+e^-) \text{ Au}^*$$

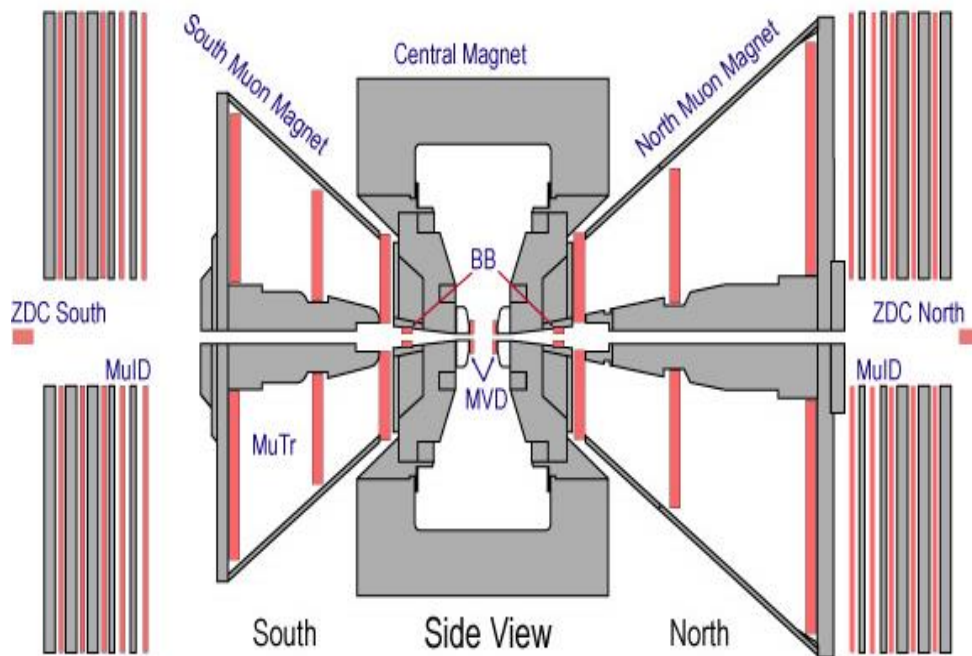
DC & PC tracking detectors
RICH & EmCal electron identification devices



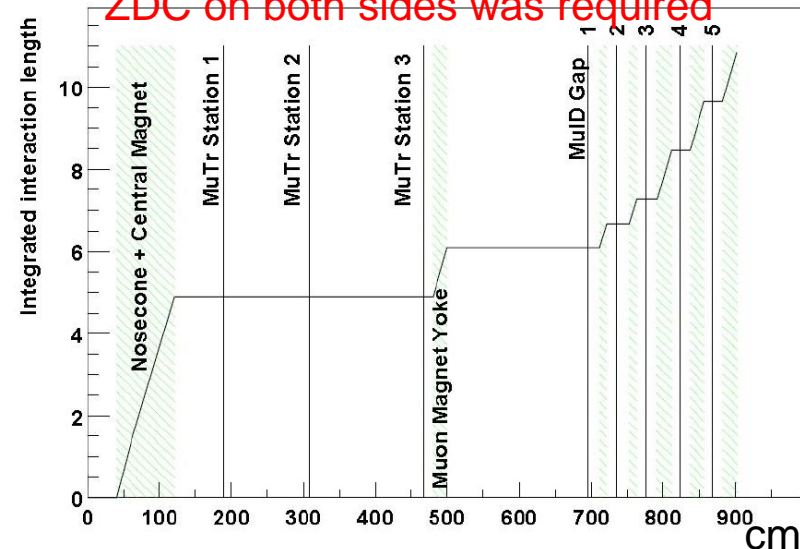
Offline analysis cuts

1. **|collision vertex determined from tracks reconstructed in the PAD chambers| < 30cm**
2. Number of tracks==2
3. North or south BBC charge==0
4. Energy deposit of ZDC>30GeV

UPC $J/\psi + X_n(y > 0) + Y_n(y < 0)$, $1.2 < |y| < 2.2$



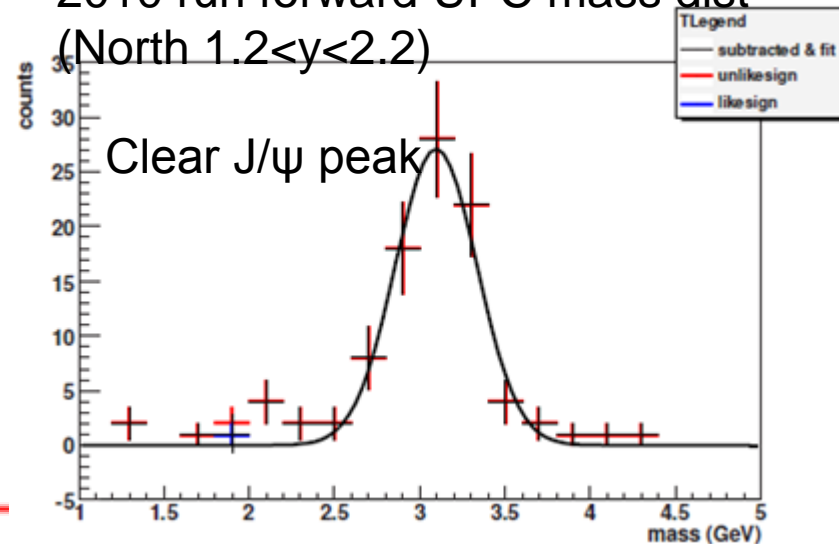
5 interaction lengths \rightarrow
to get vertex information,
ZDC on both sides was required



Offline analysis cuts

1. **|vertex determined from ZDC| < 30 cm**
2. Number of tracks == 2
3. North or south BBC charge == 0
4. Both RXNP charge < 1000 a.u.
5. energy deposit of ZDC > 30 GeV

2010 run forward UPC mass dist
(North $1.2 < y < 2.2$)

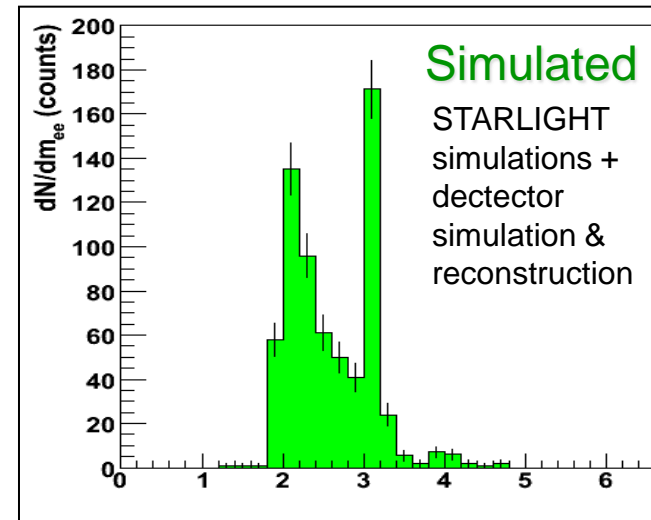
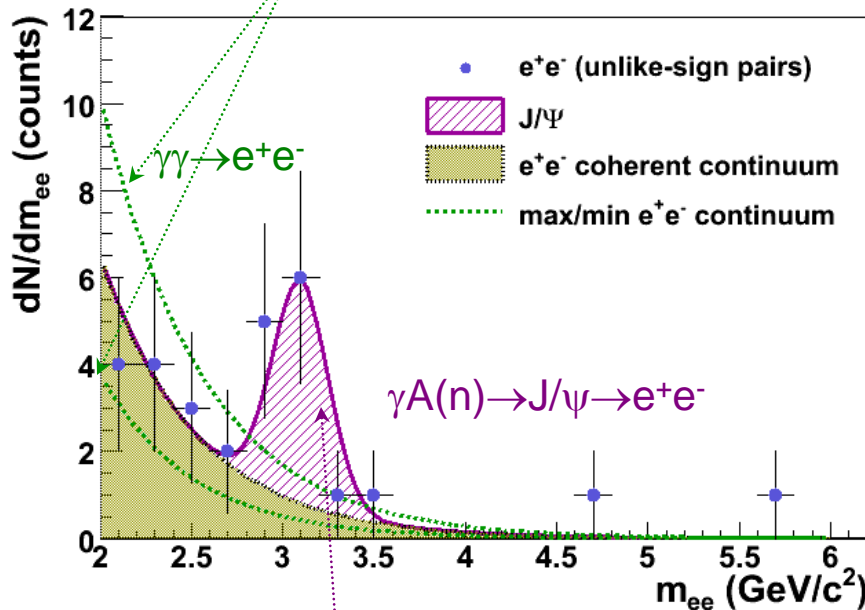


First Result: Run2004 measured invariant mass

PLB 679 (2009) 321-329

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

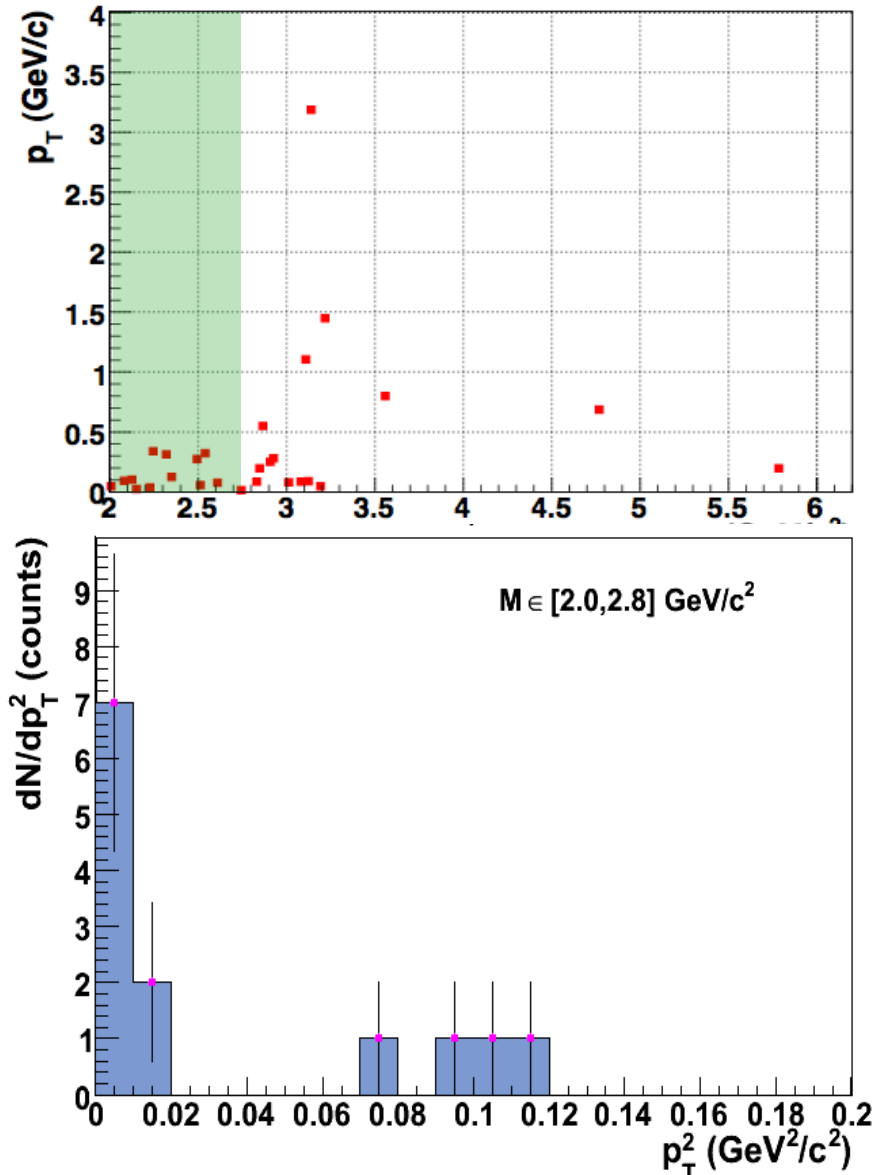
$$dN/dm_{e^+e^-} = A \cdot \exp(c m_{e^+e^-});$$



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

$$N(J/\psi) = 9.9 \pm 4.1 \text{ (stat)} \pm 1.0 \text{ (syst)}$$

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



- $N(e^+e^-) = 13.7 \pm 3.7 \pm 1.0$
 $m_{ee} \in [2.0, 2.8] \text{ GeV}/c^2$
- Slicing in mass
 - $N(e^+e^-) = 7.4 \pm 2.7 \pm 1.0$
 $m_{ee} \in [2.0, 2.3] \text{ GeV}/c^2$
 - $N(e^+e^-) = 6.2 \pm 2.5 \pm 1.0$
 $m_{ee} \in [2.3, 2.8] \text{ GeV}/c^2$
- $\gamma\gamma \rightarrow e^+e^-$ spectra is peaked at very low p_T

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

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

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

$m_{e^+e^-}$ [GeV/c ²]	$d^2\sigma/dm_{e^+e^-}dy _{y=0}$ [$\mu\text{b}/(\text{GeV}/c^2)$]	
	data	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

STARLIGHT:
WW approx. in
impact parameter
space with Breit-
Wheeler (LO) eqn

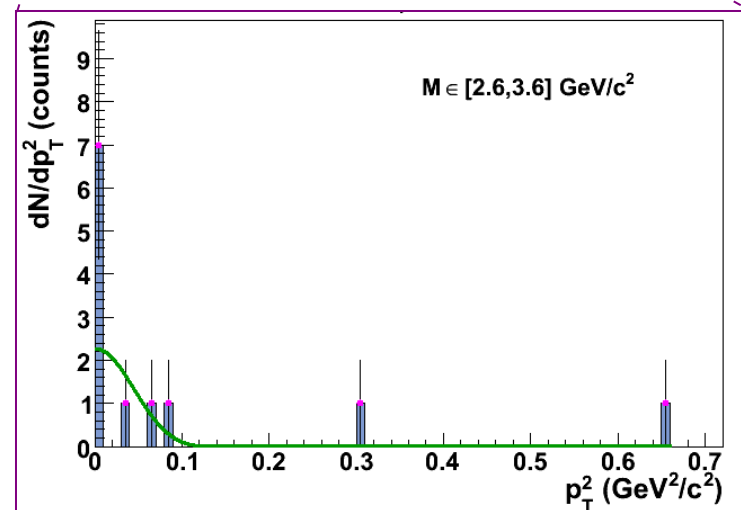
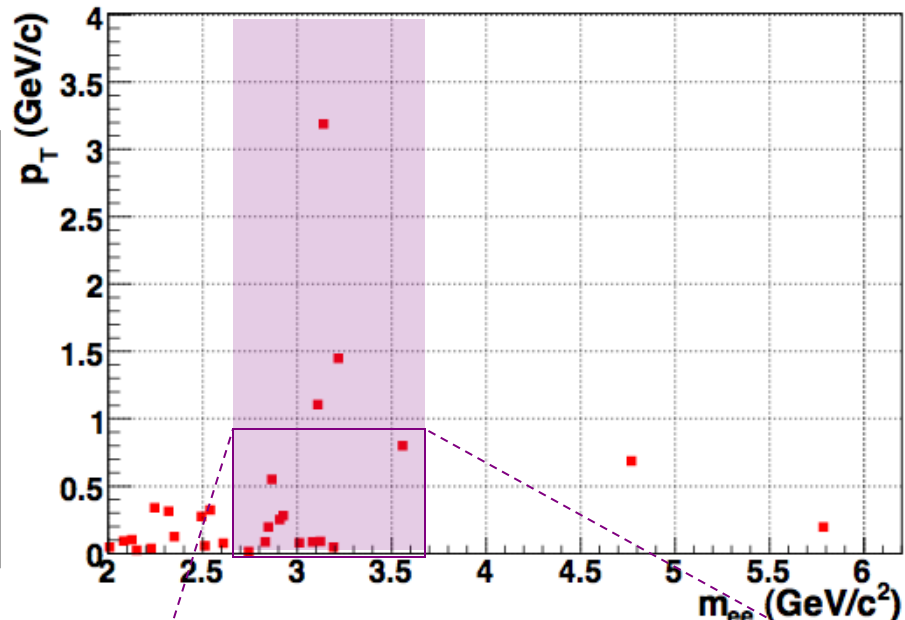
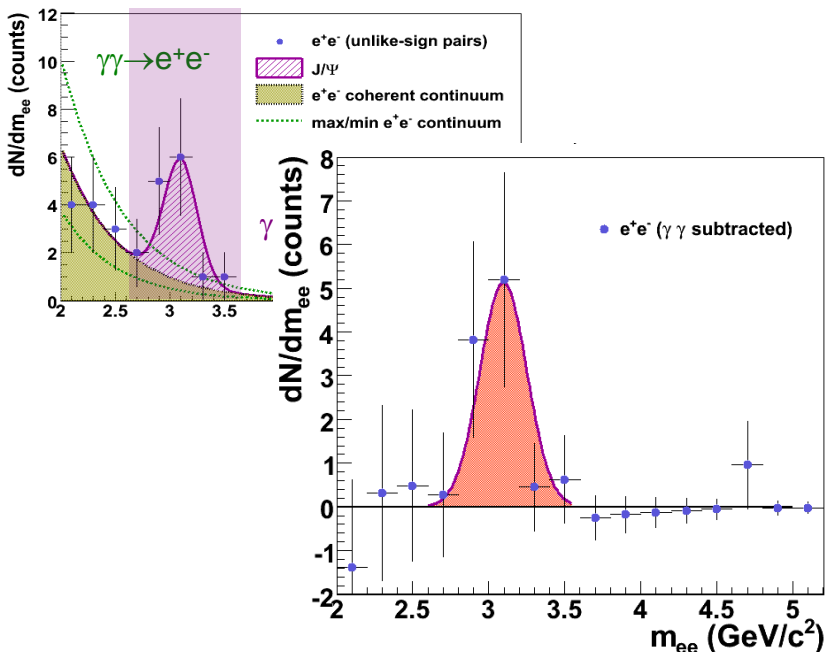
★ Results consistent with QED theoretical (STARLIGHT) calculations

Caveat:

Baltz, PRL 100 (2008) 062302

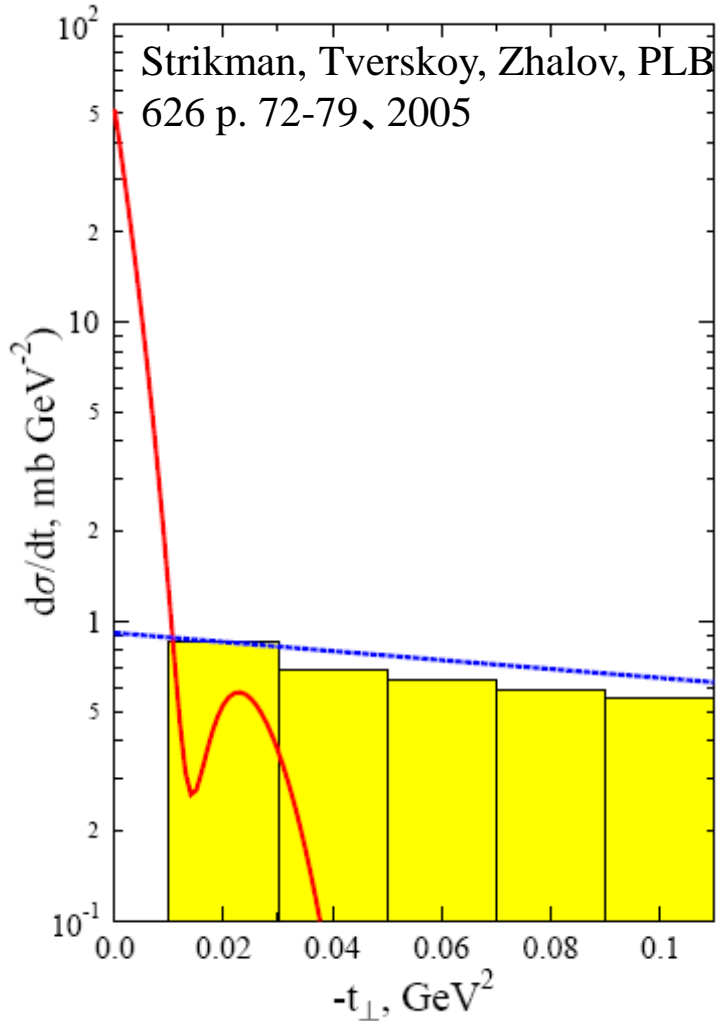
- NLO calculations seem to suggest that **higher order corrections** would suppress the e^+e^- cross-section by $\sim 20\%$
- $\alpha \sim Z\alpha_{EM} \sim 0.6$
- $E_{\max} \sim \frac{Zey}{b^2} \sim E_{crit} Z\alpha\gamma$ for $b \sim 1/\lambda_e$ (Compton wavelength)
 - $E_{crit} = m^2 c^3 / \hbar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

J/ψ \square transverse momentum distribution

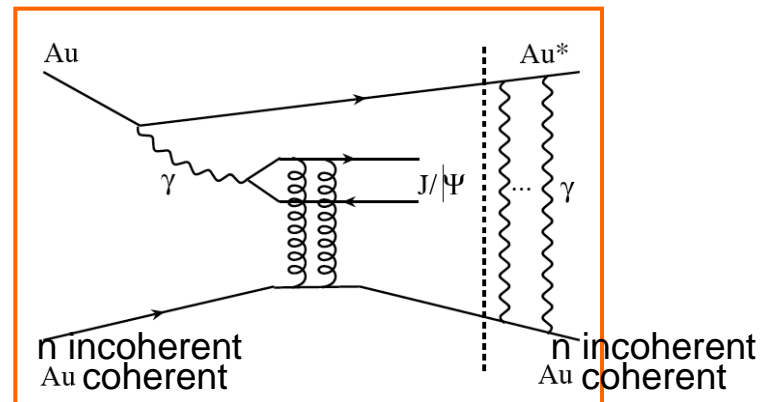


- The low p_T J/ψ consistent with the Au nuclear form factor F
 $dN_{ee} / dp_T = A \cdot p_T \cdot |F(p_T)|^2$
 \Rightarrow coherent ($\gamma\gamma$) J/ψ production
- But there seems to be also an incoherent (γn) J/ψ component
- ★ Hints of both coherent & incoherent J/ψ production in 2004 data

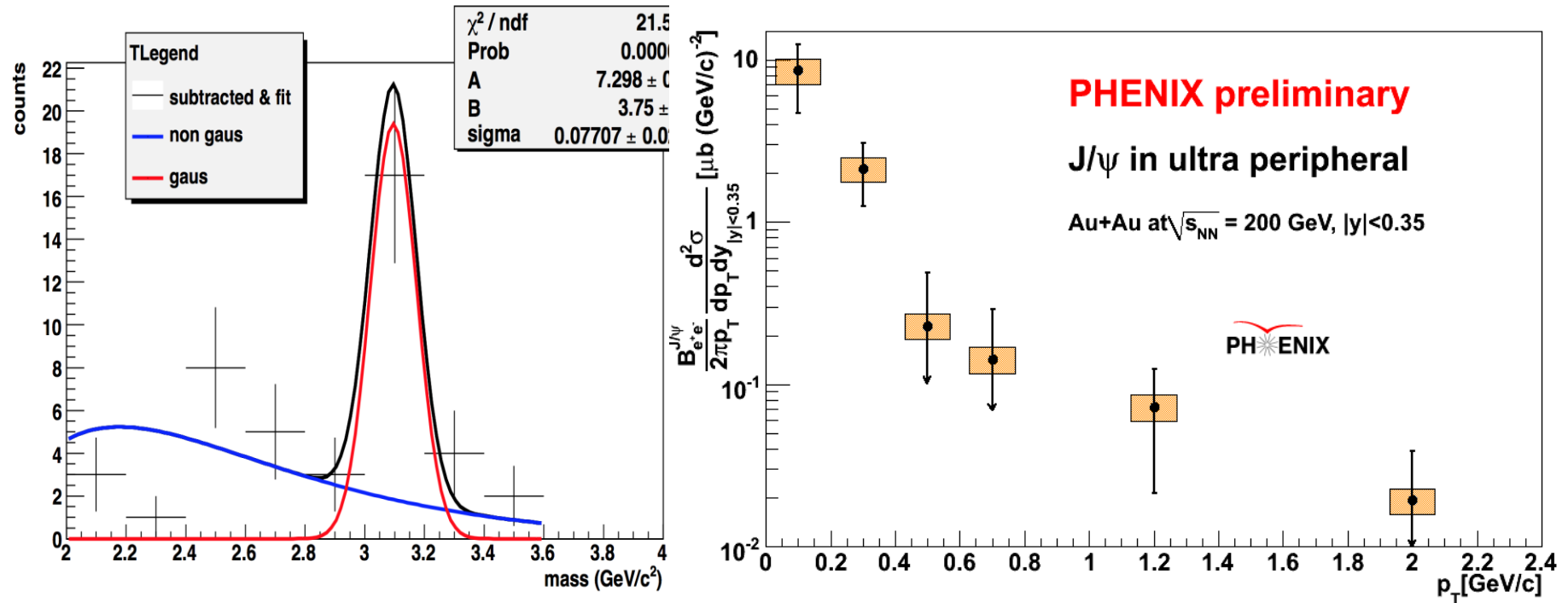
coherent and incoherent distribution



- Strikman et al calculate that quasi-elastic (incoherent) J/ψ cross-section comparable to coherent production at mid-rapidity
- Incoherent J/ψ produced from photo-nucleon interaction
 - Much larger t distribution expected for incoherent
- Both process emit only J/ψ and nucleons. p_T distribution is important to divide them, as well as directionality of neutrons.
- Strikman's predictions say at central rapidity, coherent process is dominant, but at forward rapidity, incoherent process is dominant at PHENIX

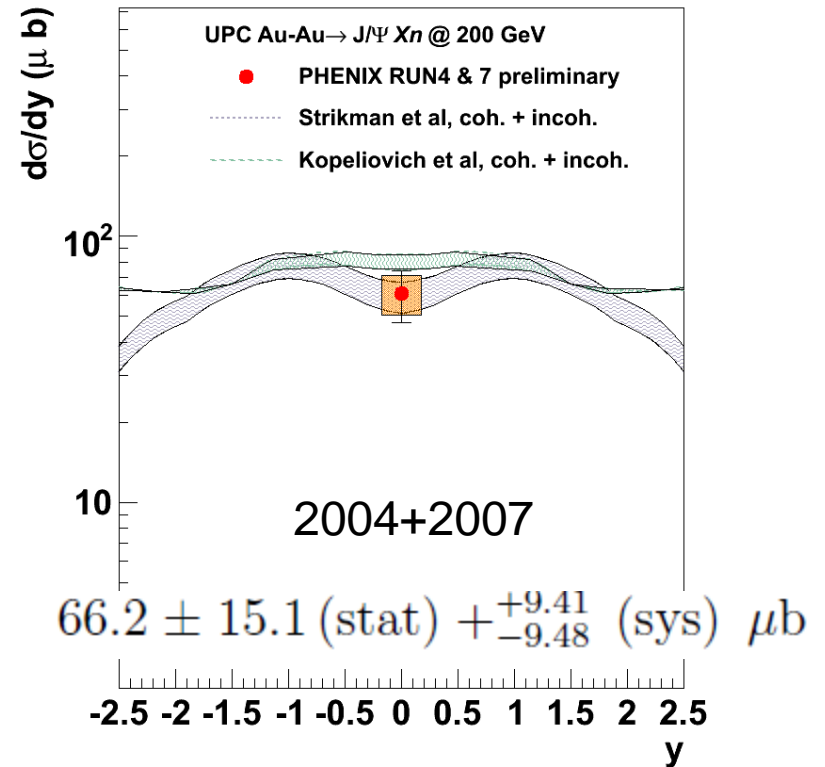
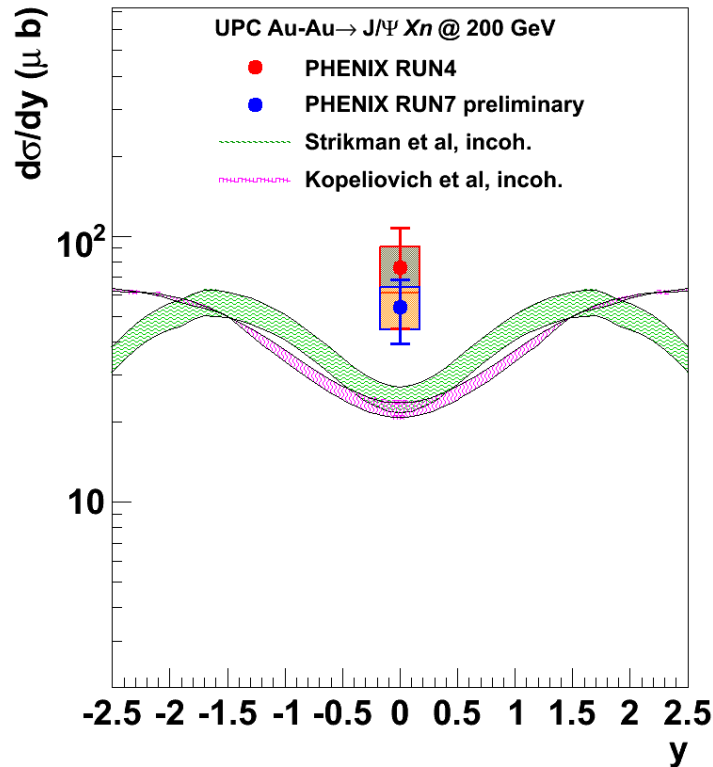


Run 2007 Central Arm Results ($|y| < 0.35$)



- Clear J/ψ peak
- Only unlike-sign pairs over 1 GeV
- Clear Coherent (low p_T) peak and incoherent distribution
- $46.7 \pm 13 \mu\text{b}$ for $p_T < 0.4 \text{ GeV}$ (upper limit of coherent)
 - compatible with suppression (shadowing) of gluons at low x

Cross-section, $J/\psi + Xn$ Central 2004 & 2007



2004 PHENIX

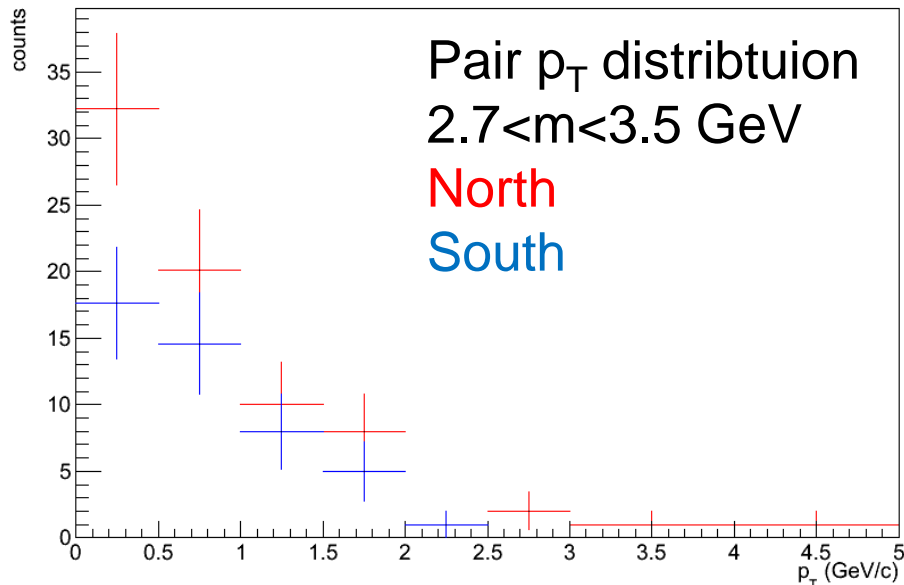
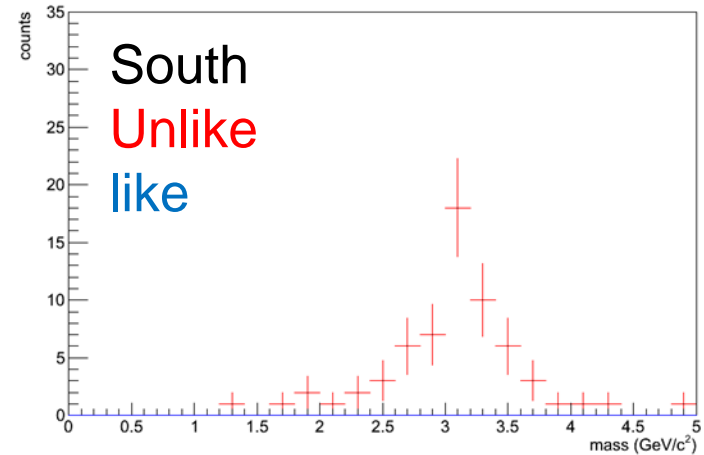
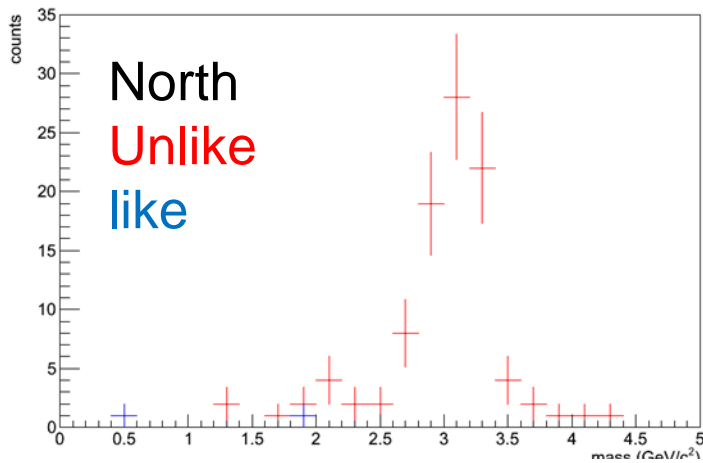
76 ± 31 (stat) ± 15 (syst) μb

2007 PHENIX

61.8 ± 17 (stat) $+8.7$ -8.8 (sys) μb

J. Nystrand, Nucl. Phys. A 752(2005)470c; A.J. Baltz, S.R. Klein, J. Nystrand, PRL 89(2002)012301; S.R. Klein, J. Nystrand, Phys. Rev. C 60(1999)014903
 M. Strikman, M. Tverskoy and M. Zhalov, Phys. Lett. B 626 72 (2005)
 V. P. Goncalves and M. V. T. Machado, arXiv:0706.2810 (2007).
 Yu. P. Ivanov, B. Z. Kopeliovich and I. Schmidt, arXiv:0706.1532 (2007).

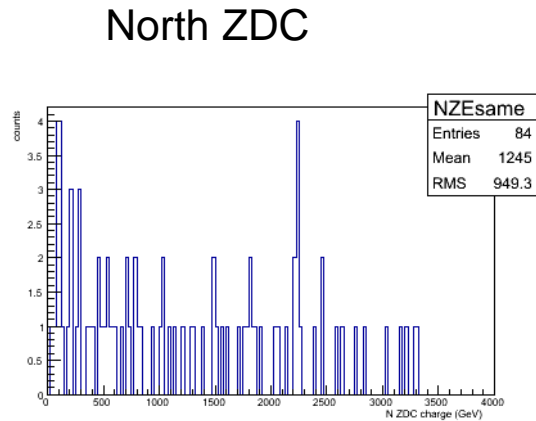
Run2010 di-muons ($1.2 < |y| < 2.2$)



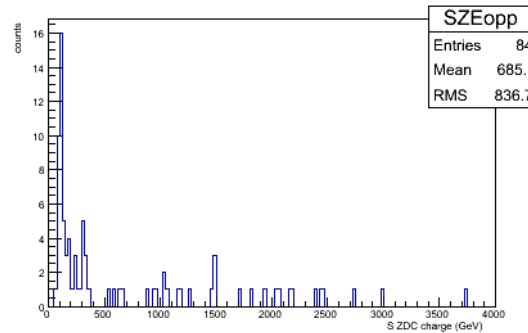
- Clear J/ψ peak
- Only unlike sign pair ($2 \text{ GeV} > \text{mass}$)
- Coherent (low p_T) peak is not so clear
 - But still 0 p_T peak

Neutron emission for dimuon J/ψ

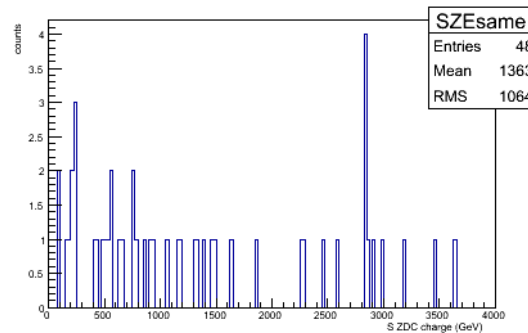
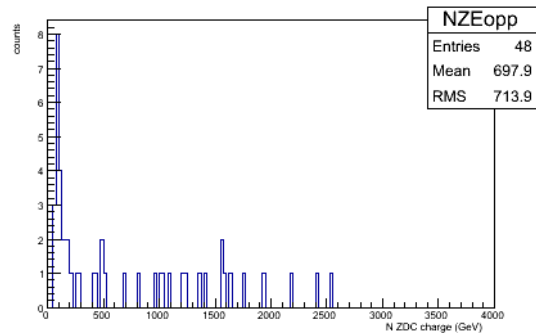
Dimuon
North



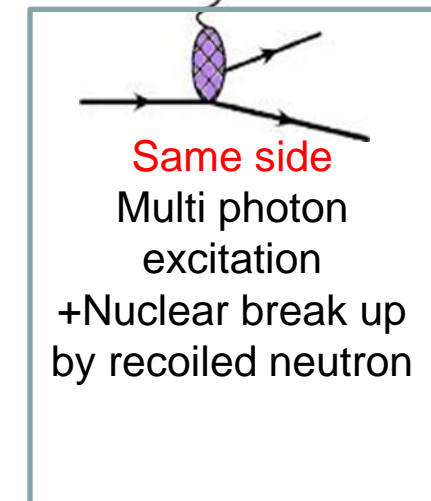
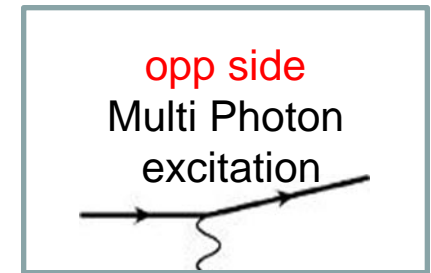
South ZDC



Dimuon
South



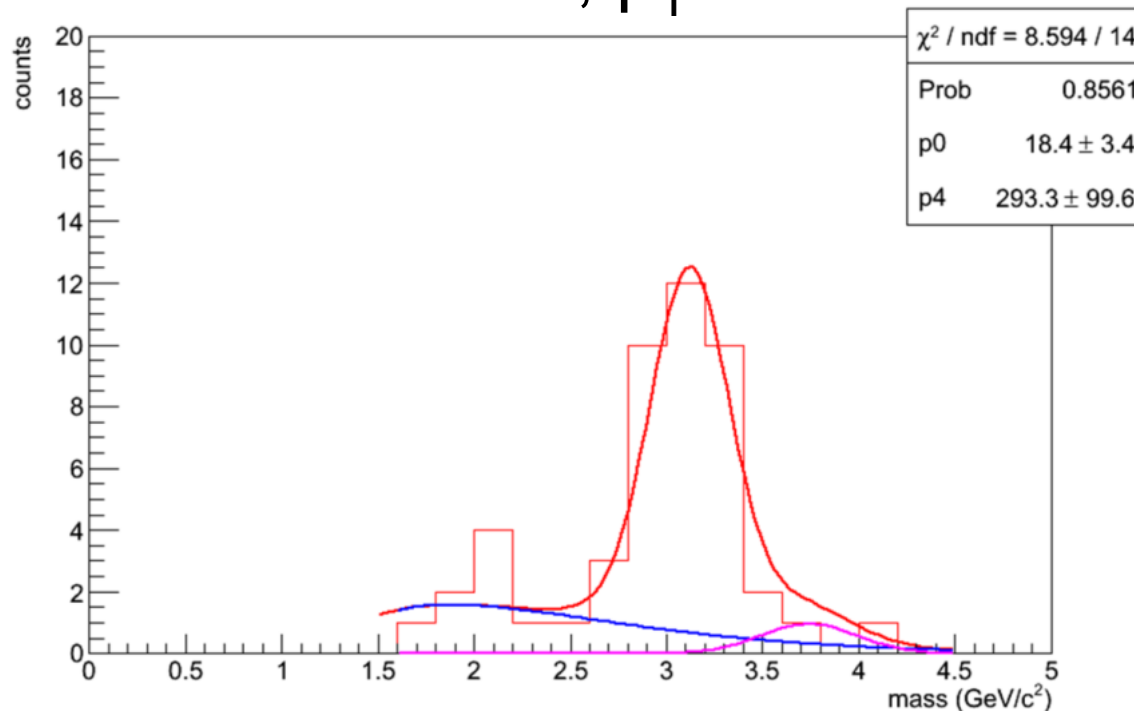
- Same side: 1300 GeV
- Opp side : 700 GeV



- If this was a nuclear hadronic collision, the asymmetry can't be explained
- Consistent with UPC (incoherent) process

Continuum for dimuon ($1.2 < |y| < 2.2$)

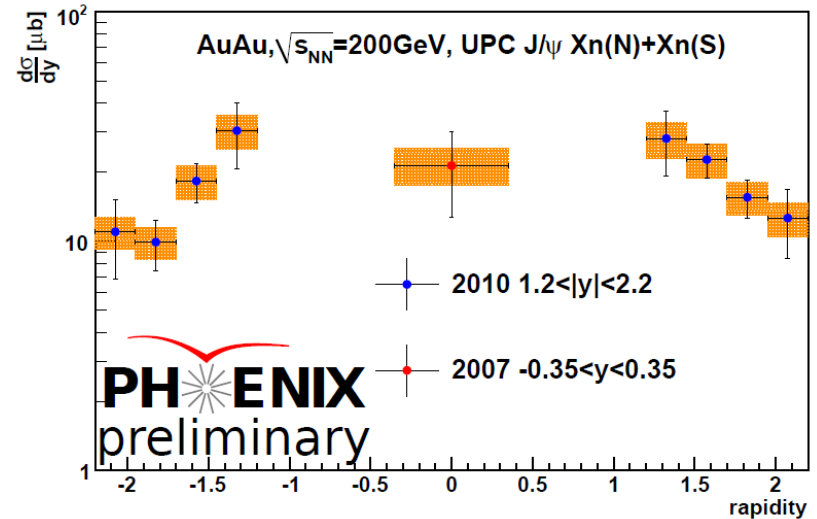
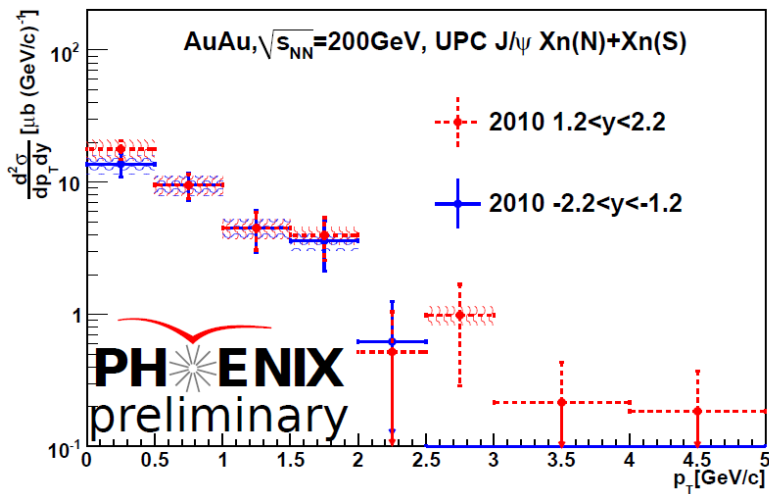
North dimuons, $p_T < 0.5 \text{ GeV}/c$



Background by UPC process are suggested

- $\gamma\gamma \rightarrow \mu^+\mu^-$ continuum?
- UPC $c\text{-}\bar{c}$?
- $\gamma\text{Au} \rightarrow \text{dipion} \rightarrow \text{dimuon}$?

Run 2010 J/ ψ +Xn(y>0)Yn(y<0), Muon Arms



- The p_T distributions at forward rapidity shows that incoherent process is very visible at forward ($1.2 < |y| < 2.2$)
 - Can't easily see coherent peak
- There are no theoretical predictions with XnYn condition

Possible 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):

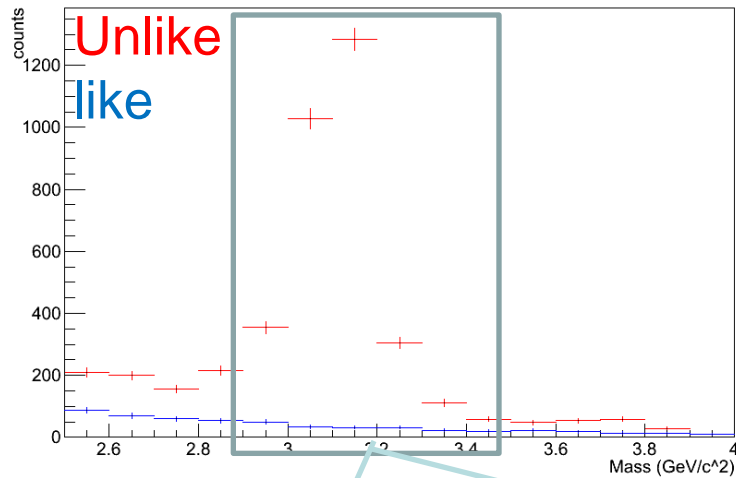
- ☐ forward proton emission, ☐ larger p_T : $p_T(\gamma\gamma) <$
 $p_T(PP)$,

- ☐ expect like-sign pairs too.

⇒ Analysis cuts gets rid of them

Comparison with p+p for dielectron

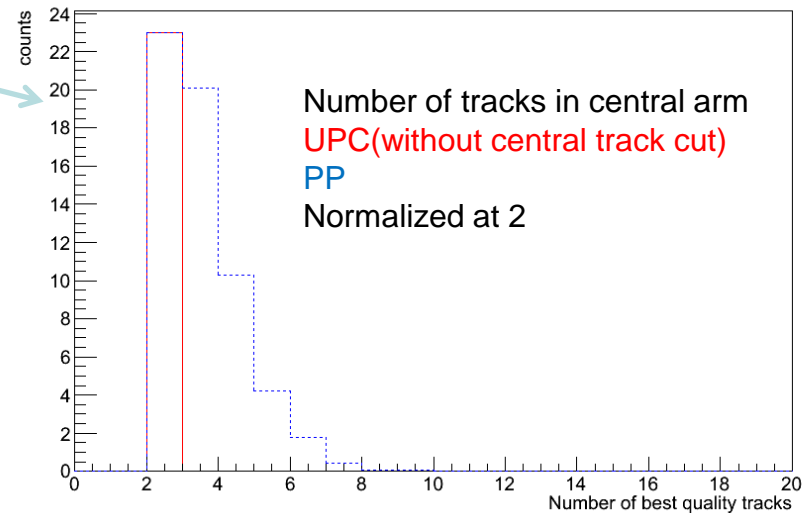
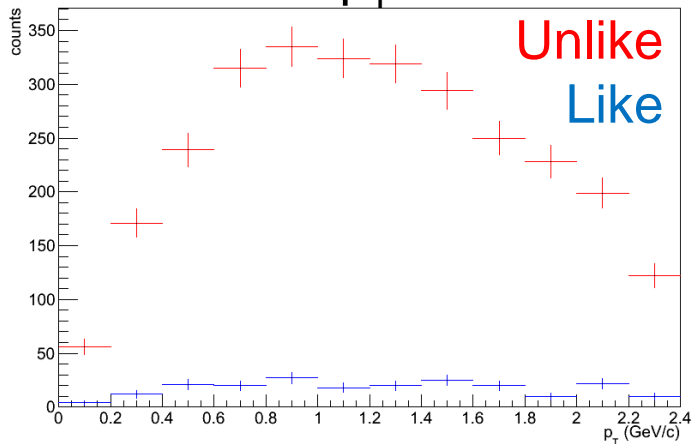
Mass distribution



p+p (ncoll=1 limit),

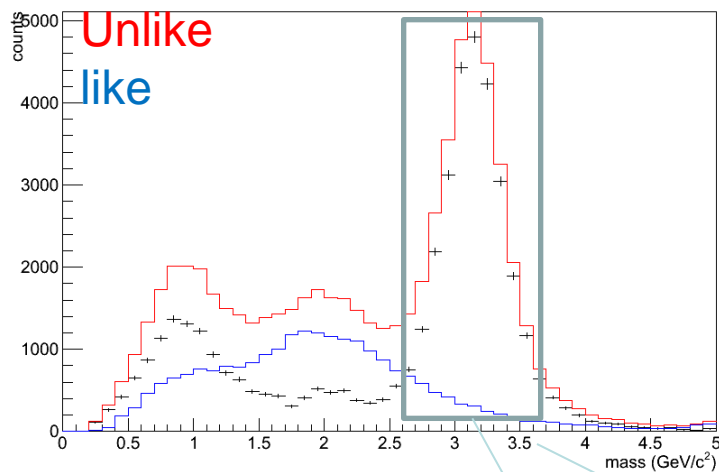
- J/ψ events are associated with additional tracks
- At $p_T \sim 2.5$ GeV/c, unlike/like ~ 2
- UPC and PP J/ψ p_T distribution is different

p_T distribution



Comparison with pp for dimuon

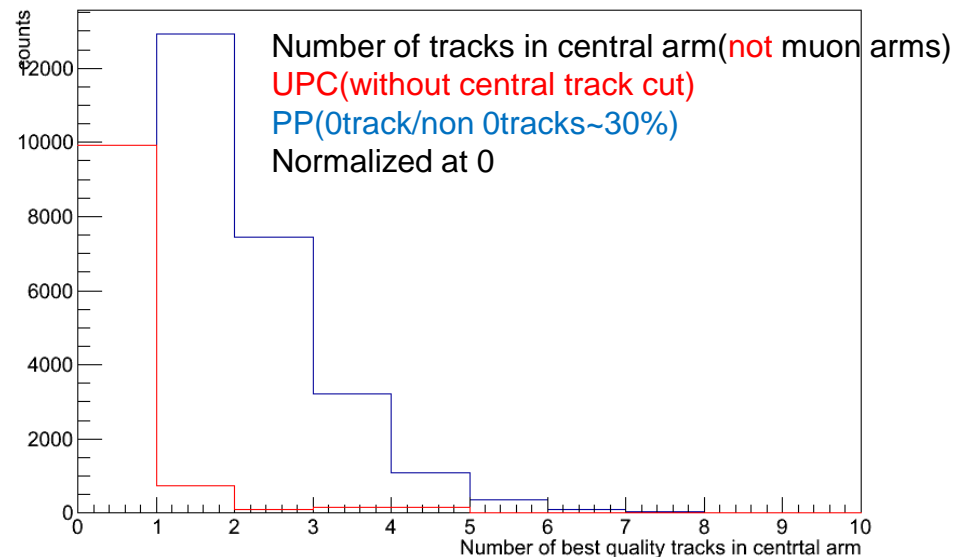
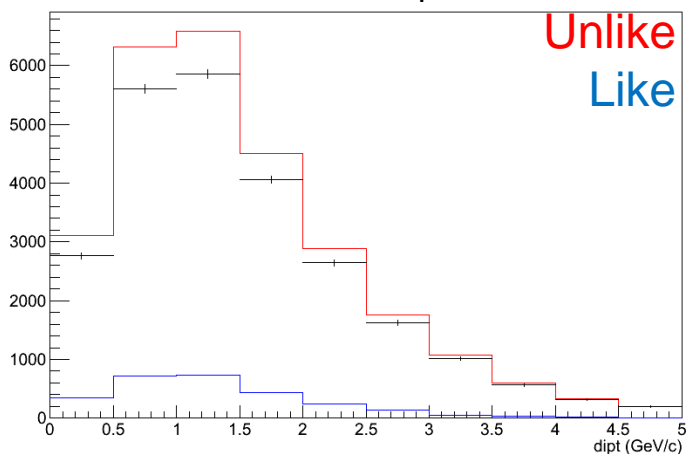
Mass distribution



Even pp (ncoll=1 limit),

- J/ψ events are associated with additional tracks
- At $p_T \sim 2.5$ GeV/c, unlike/like ~ 2
- UPC and PP J/ψ p_T distribution is different
- Central multiplicity distribution suggest little most peripheral contamination
 - About 3 J/ψ per arm.

p_T distribution

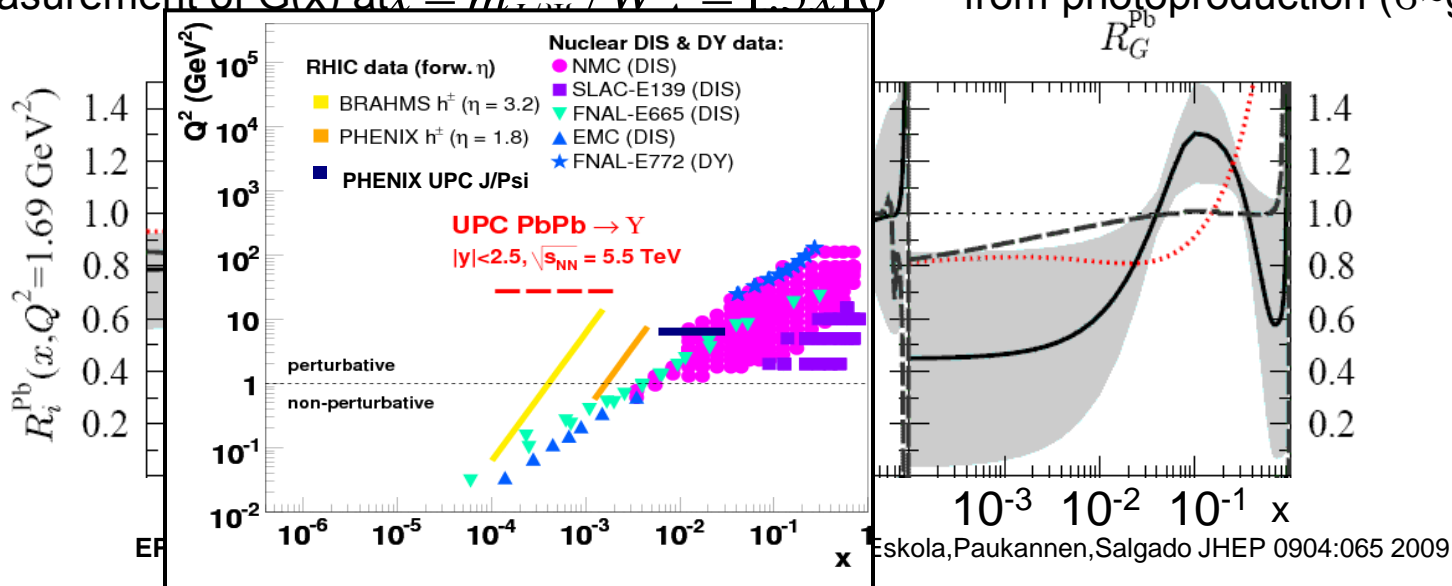


$\gamma+\gamma, \gamma+p, \gamma+A$ “Applications”

- 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 $x \equiv m_{J/\Psi}^2 / W^2 \equiv 1.5 \times 10^{-2}$ from photoproduction ($\sigma \sim g^2(x)$)



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

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($J/\Psi, \Psi' \dots$), STAR (ρ), LHC
- Testing of our understanding of these processes
 - Strong QED (continuum at mid-rapidity)
 - Coherent vs Incoherent Processes
 - 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, EIC diffractive J/ψ
 - Understanding J/Ψ propagation through nuclear matter?
 - Tests of EM in strong coupling regime – Reaches Schwinger Limit
- Future: VTX/FVTX (charm), sPHENIX