Photoproduction in ultra-peripheral ion collisions and at the EIC

Spencer Klein, LBNL/UC Berkeley

- Photoproduction: fixed target, eA and AA
- RHIC & Tevatron results – e^+e^- ρ, ρ', and the J/ψ
- High energy $\gamma\gamma/\gamma p$ at the LHC
- EIC prospects & comparison with other methods

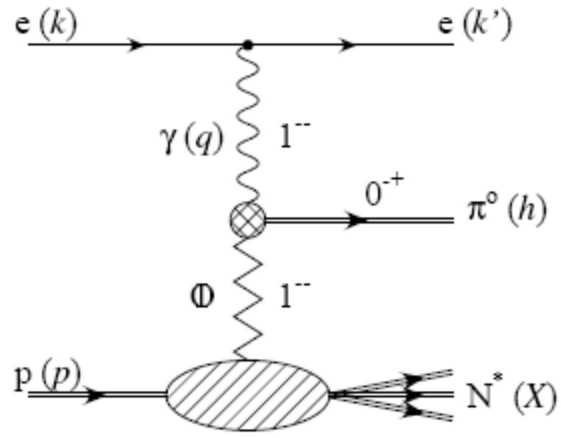
BERKELEY LAB

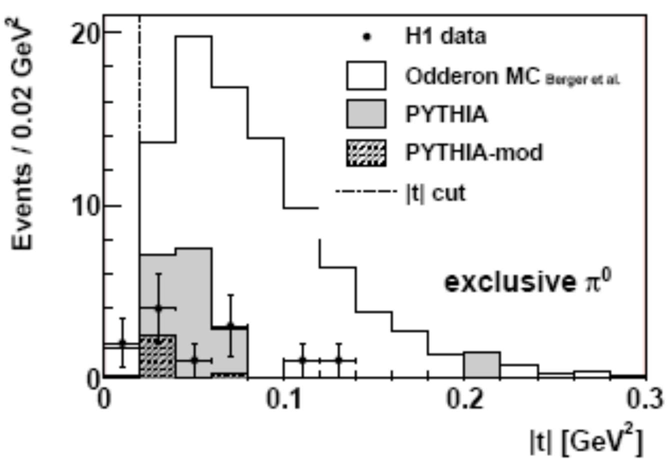
Fixed Target photoproduction

- 50+ year history
- Beams from MeV to ~ 400 GeV
  - From Coulomb excitation to $\sqrt{s_{\gamma n}}$~30 GeV
- Large Data samples
- Variety of nuclear targets
  - Very high effective luminosities
- Fully real photons
- Some Physics Foci
  - Vector Meson Dominance

Photoproduction:ep @ HERA

- Higher energy than fixed target
  - Similar topics
- Also, $\gamma\gamma$ reactions
- Some 'low energy' reactions
  - Search for photon Odderon --> π^0 or $f_2(1270)$
    - Odderon is spin 1, '3-gluon' counterpart of the Pomeron
      - Fundamental in QCD
    - Production rate
    - $\gamma\gamma$ and γO channels interfere
      - Angular distributions

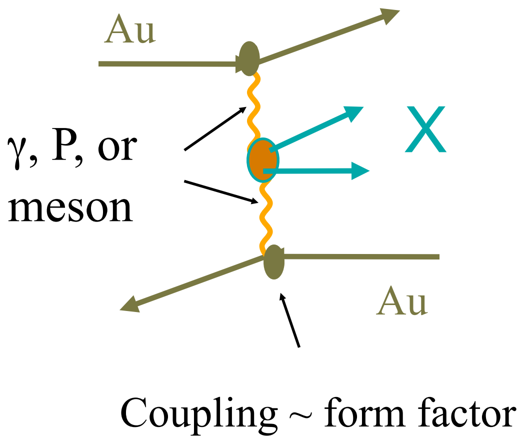




H1 Collab, Phys.Lett.B544, 35 (2002)

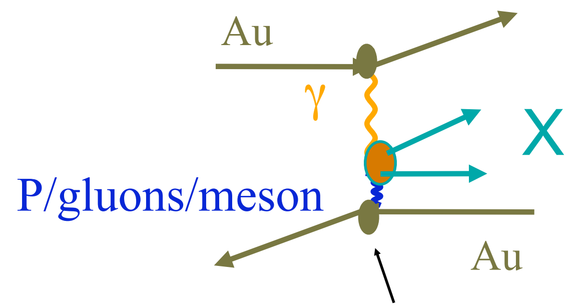
Photons from Hadrons

- Relativistic hadrons carry strong electromagnetic fields
  - Weizsacker-Wiliams: a field of almost-real photons
    - Virtuality $Q^2 < (h/R_A)^2$
      - Significant for e^+e^- production, and (maybe) with proton beams
- Photon $E_{max} \sim \gamma h/R_A$
  - 3 GeV with gold at RHIC
  - 80 GeV with Lead at the LHC
  - ~10%+ of proton energy at both machines
- Photon flux ~ Z^2
  - Higher intensity with heavy ions
    - Important for considering multiple interactions between a single ion pair
  - RHIC & LHC have higher luminosities for light ions --> often better overall rates
    - "Optimum" ion depends on the problem



Photonuclear Interactions

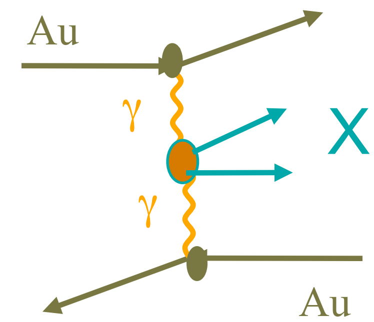
- Photon coupling $Z^2\alpha \sim 0.6$ for heavy ions
  - Multi-photon reactions common
- γ-gluon/Pomeron/meson interactions
- γ-Pomeron/meson can be coherent
  - Exclusive final states
  - Coupling ~ A^2 (bulk) $A^{4/3}$ (surface)
  - Large cross-sections for vector meson production
- Require $b > 2R_A$
  - no hadronic interactions
  - <b> ~ 20-60 fermi at RHIC
- Cross sections are huge
  - 5 barns for coherent ρ^0 production with lead at the LHC

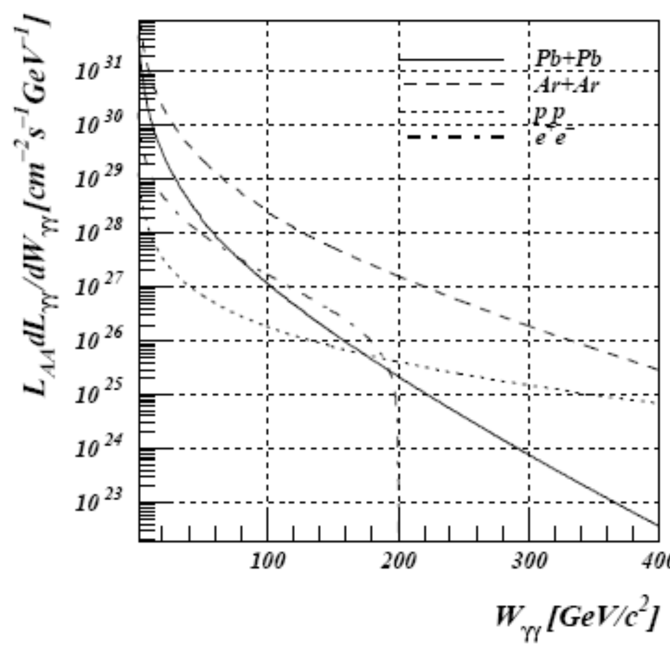


Coupling ~ form factor

$\gamma\gamma$ interactions

- Rate ~σ ~ Z^4
  - Rates to produce hadrons are much smaller than for photoproduction of vector mesons
- Prolific production of e^+e^- pairs
  - σ = 200,000 barns with lead at the LHC
  - QED process --> proposed as luminosity monitor.
- W_{max} ~ 2 k_{max}
  - 6 GeV with gold at RHIC



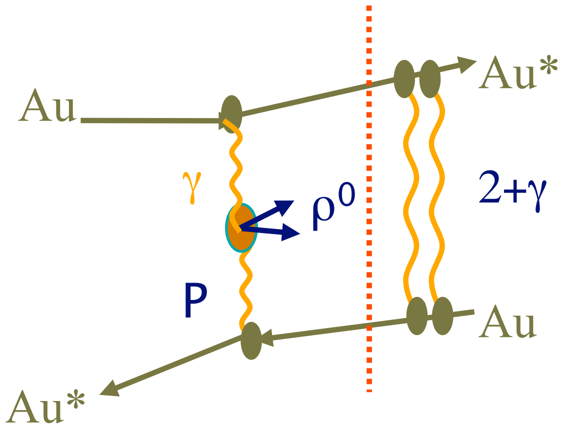


$\gamma\gamma$ Luminosity

Unique Possibilities with ion-ion collisions

- Symmetric initial state
  - Quantum interference
- Highly charged photon emitters
  - Multi-photon interactions
    - Impact parameter tagging
- Ion interactions
  - Pair production with capture

Strong Coupling/ Multiple Interactions

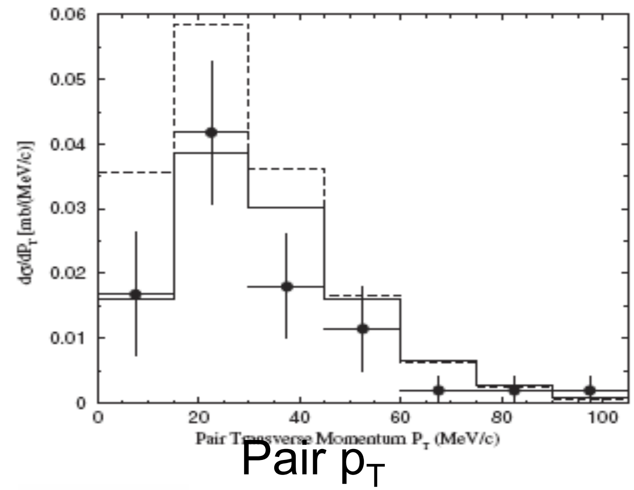


- $Z^2\alpha$ ~ 0.6 with gold/lead
  - ‘Extra’ photons are cheap
- Higher order diagrams could be important
- Multi-photon reactions are important
  - They factorize
- Mutual Coulomb excitation of colliding nuclei is a useful tag
  - Simple experimental trigger
  - Selects events with small impact parameters

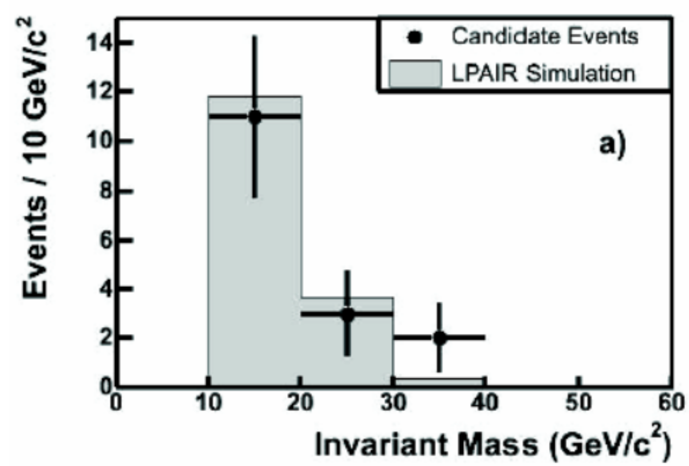
$$\sigma = \int d^2b P_{2EXC}(b) P_{\rho^0}(b)$$

e^+e^- production w/ STAR & CDF

- With Coulomb excitation in 200 GeV gold-on-gold collisions
  - STAR finds 52 events
    - M_{ee} > 140 MeV/c^2, $|Y_{ee}|$< 1
  - Highest order corrections needed to fit data
    - Lowest order σ is 30% higher in STAR acceptance
  - Equivalent photon method fails miserably for pair p_T spectrum
    - Photon virtuality is important

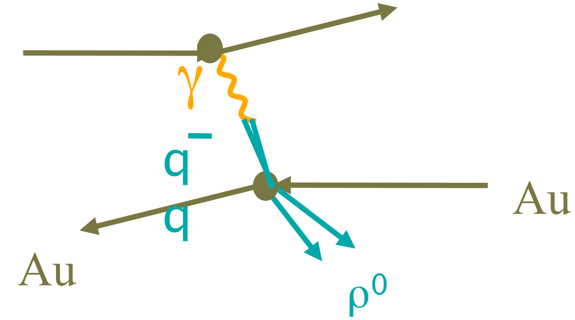


STAR data, calcs by A. Baltz
PRL 100, 062302 (2007)

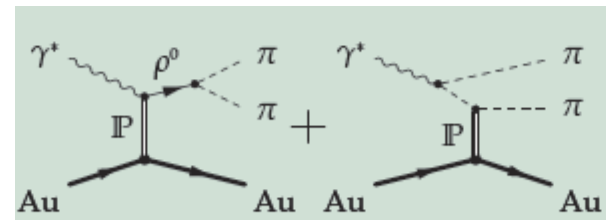


CDF, PRL 98,112001 (2007)

STAR - ρ^0 Photoproduction

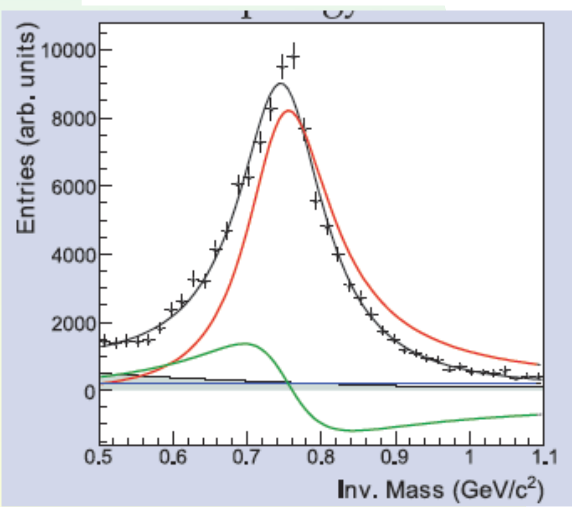


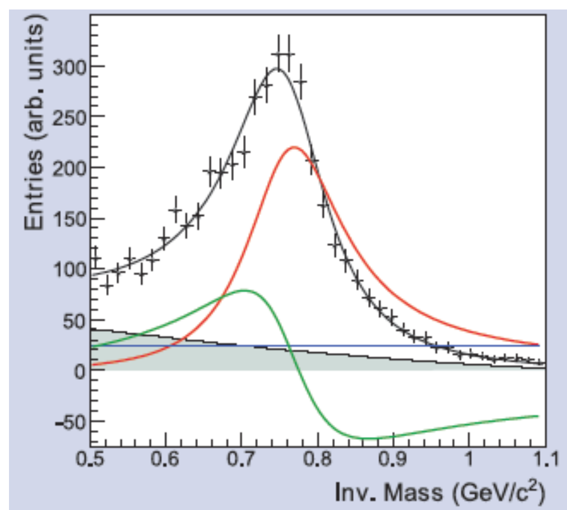
- Coherent production events
  - $p_T < \sim 150$ MeV/c
- $M_{\pi\pi}$ fit to ρ^0 + direct $\pi^+\pi^-$ spectrum
  - Relativistic Breit-Wigner w/ phase space
  - ρ^0:direct $\pi^+\pi^-$ ratio same as γp @ HERA



- Exclusive ρ^0 and with mutual Coulomb excitation

Mass spectra for coherent ($p_T < 150$ MeV/c) production





ρ^0

ρ^0:$\pi\pi$ interference

Gray -background

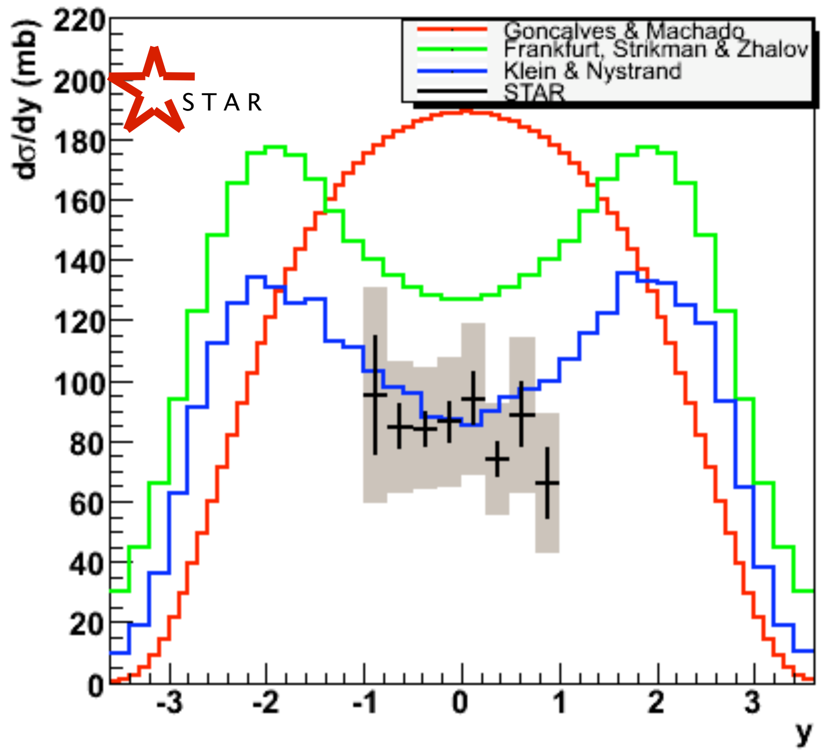
STAR, Phys. Rev. C77, 34910 (2008)

Exclusive ρ^0

ρ^0 + Mutual Coulomb Excitation

ρ^0 rapidity distribution

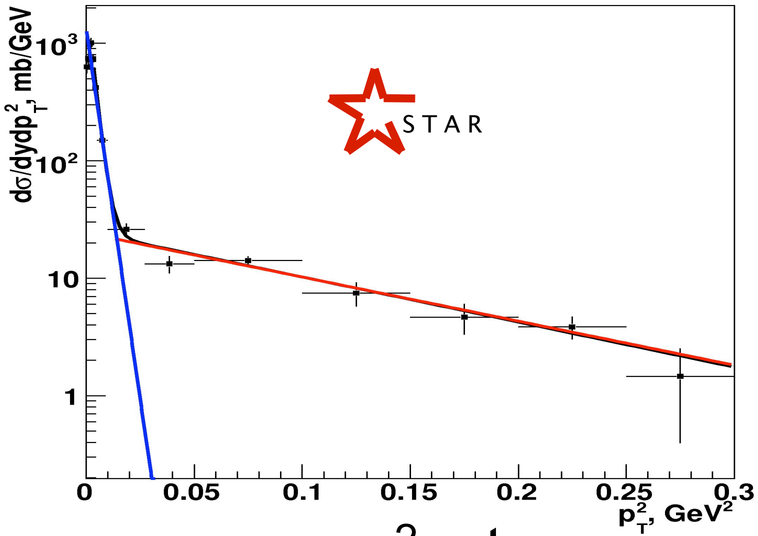
- ρ^0 w/ mutual Coulomb excitation
- Photon energy
  - $k = M_v/2 \exp(y)$
  - 2-fold directional ambiguity leads to symmetric distributions
- Cross-section depends on $\sigma_{qq\text{-}N}$, which depends on the hadronic model
  - Saturation models of Goncalves & Machado is ruled out



STAR, Phys. Rev. C77, 34910 (2008)

ρ^0 p_T spectra

- Coherent + Incoherent form factors
  - Fit to dual exponential
- Incoherent production
  - $b_N = 8.8 \pm 1.0$ GeV^{-2}
    - nucleon form factor
- Coherent production
  - $b_{Au} = 388.4 \pm 24.8$ GeV^{-2}
    - $b_{Au} \sim R_A^2$
    - Data sensitive to R_A
    - Measure hadronic radius of gold
      - 3% statistical uncertainty
      - Significant theoretical corrections/ uncertainty
- $\sigma(incoh)/\sigma(coh) \sim 0.29 \pm 0.03$

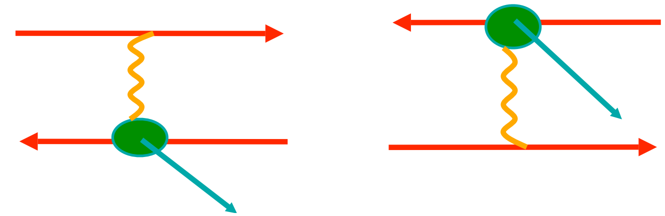


$p_T^2 \sim t$

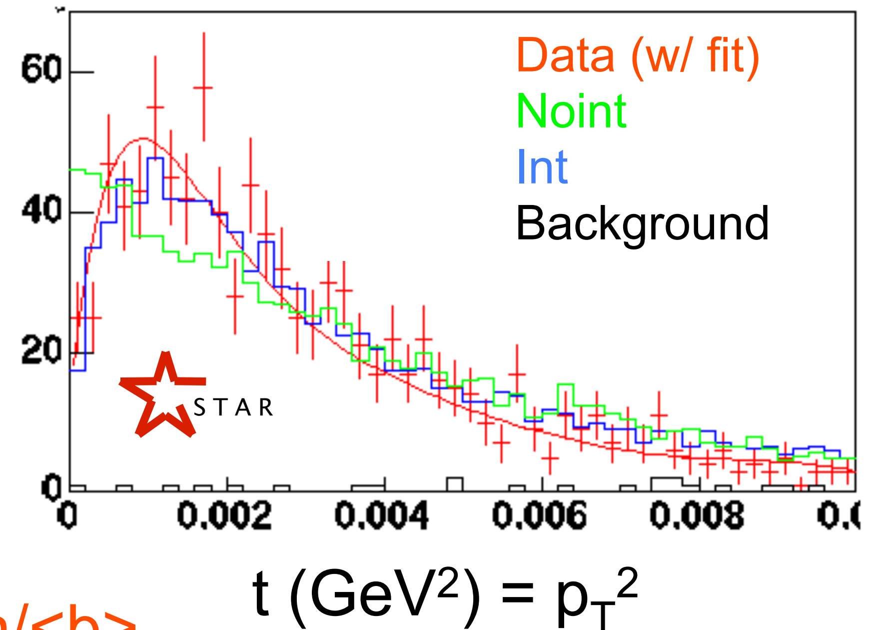
$$\frac{d\sigma}{dt} = a * \exp(-b_{Au} * t) + c * \exp(-b_N * t)$$

STAR, Phys. Rev. C77, 34910 (2008)

ρ^0 at small p_T - interference



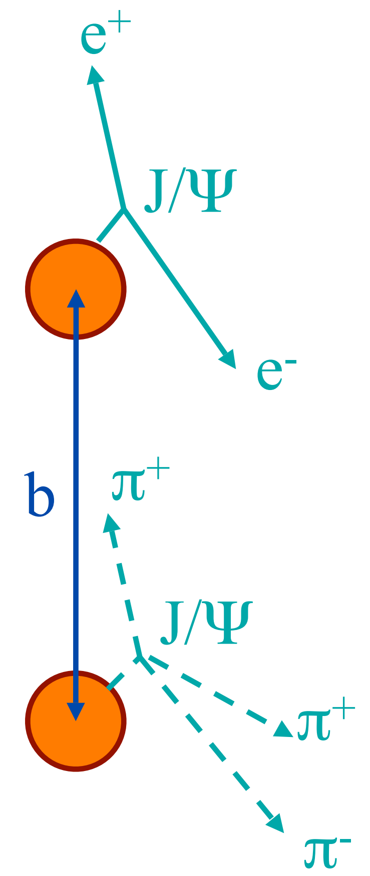
- 2 indistinguishable possibilities
  - Interference!!
- No dipole moment, so
  - no dipole radiation
- $\rho, \omega, \phi, J/\psi$ are $J^{PC} = 1^{--}$
  - $\sigma \sim |A_1 - A_2 e^{ip\cdot b}|^2$ for pp, AuAu…
    - b is impact parameter
    - $\sigma \sim |A_1 + A_2 e^{ip\cdot b}|^2$ for pbarp
- Production suppressed for $p_T < h/<b>$
  - $p_T < 30$ MeV/c for ρ^0 + Mut. Coul. Exc.
- STAR measures this dip at 87 ± 5 (stat.) ± 8 (syst.)% of the expected level



STAR Collaboration, arXiv:0812.1063

Interferometry with short-lived particles

- ρ^0 have $c\tau$ ~ 1 fm << <b>
  - Decay points are separated in space-time
    - no interference
  - **OR**
    - the wave functions retain amplitudes for all possible decays, long after the decay occurs
- Non-local wave function
  - **non-factorizable**: $\Psi_{\pi+\,\pi-} \neq \Psi_{\pi+}\,\Psi_{\pi-}$
- We measure π momenta. Could instead have measured the π positions shortly after

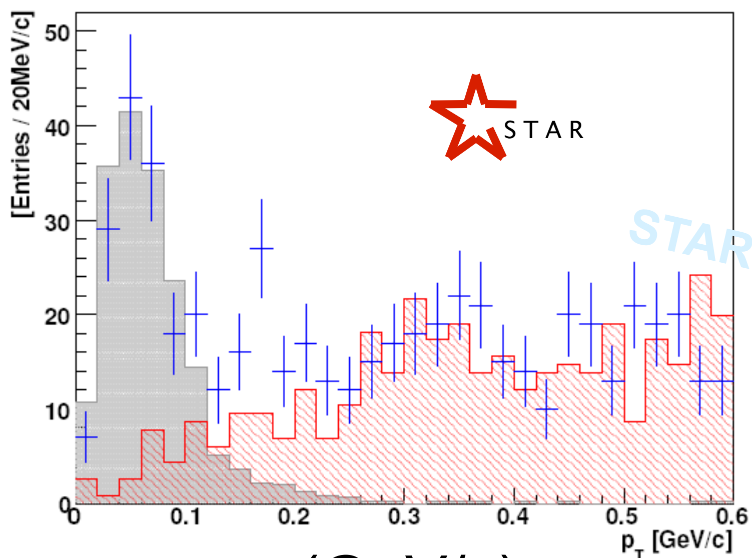


(transverse view)

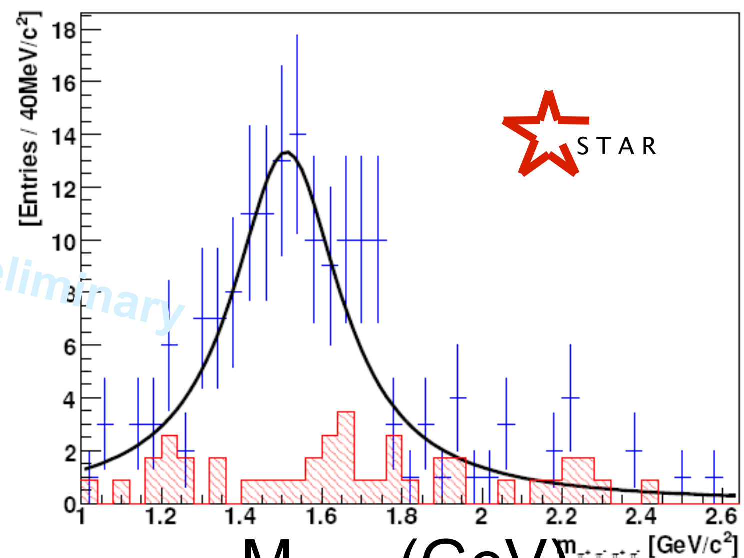
SK, J. Nystrand., Phys. Lett. A308, 323 (2003).

Photoproduction of $\pi\pi\pi\pi$

- Expected to be largely through a radially excited ρ
  - $\rho(1450)$ and/or $\rho(1700)$
- Peak at low p_T from coherent enhancement
- Studies of resonant substructure are in progress



p_T (GeV/c)



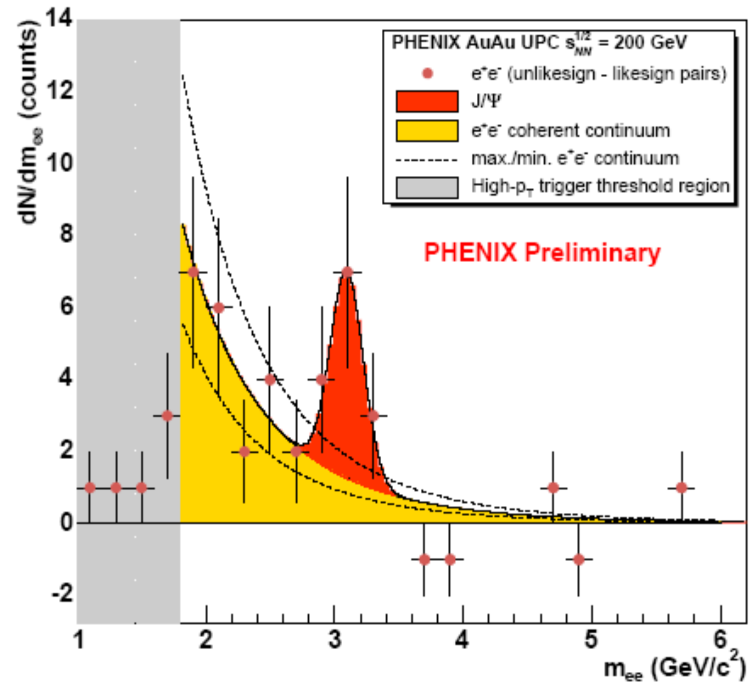
$M_{\pi\pi\pi\pi}$ (GeV)

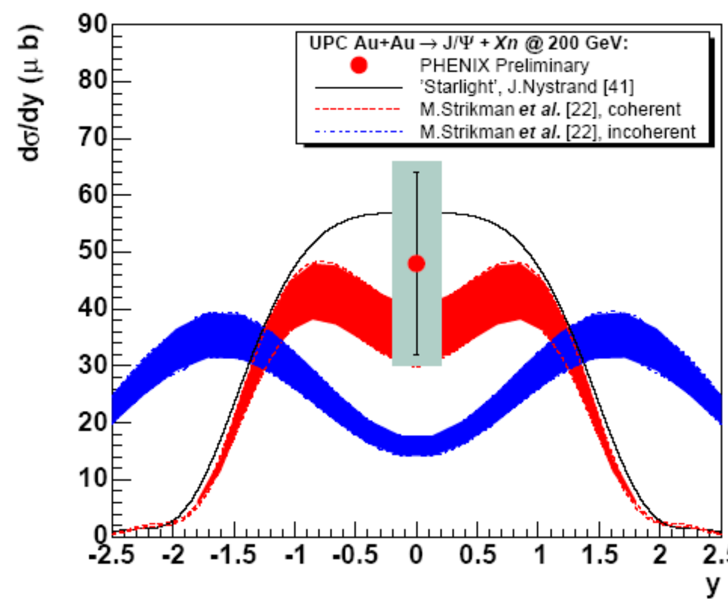
B. Grube, Wkshp. on HE Photon Collisions at the LHC

J/ψ photoproduction at RHIC

- e^+e^- pair + 1 nucleus breakup
  - Nuclear breakup needed for trigger
  - J/ψ + continuum γγ --> e^+e^-
  - ~ 12 events in peak
- Cross sections for both J/ψ and continuum e^+e^- ~ as expected

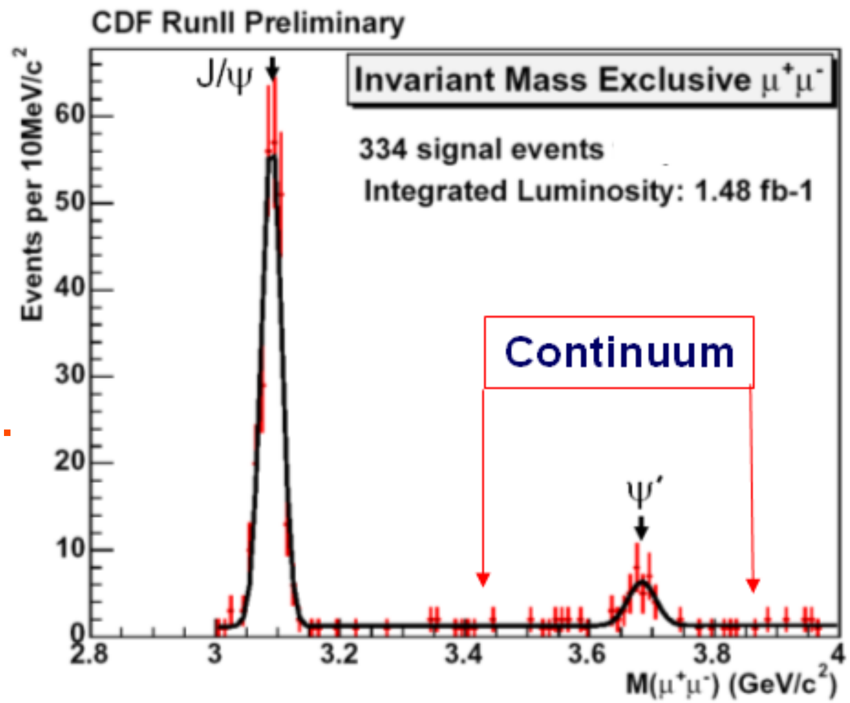
D'Enterria, PHENIX, nucl-ex/0601001





J/ψ photoproduction at the Tevatron

- CDF selects exclusive J/ψ photoproduction is sensitive to gluon structure of nuclei
  - $\sigma \sim |g(x,M_V^2/4)|^2$
- 334 exclusive $\mu^+\mu^-$ signal events.
  - "Background" from double Pomeron production
    - $\chi_c \to \gamma J/\psi$
  - Some ψ'
- Cross section determination in



$M(\mu\mu)$ (GeV/c^2)

J. Pinfold, Wkshp. on HE Photon Collisions at the LHC; M. Albrow, arXiv: 0812.0612

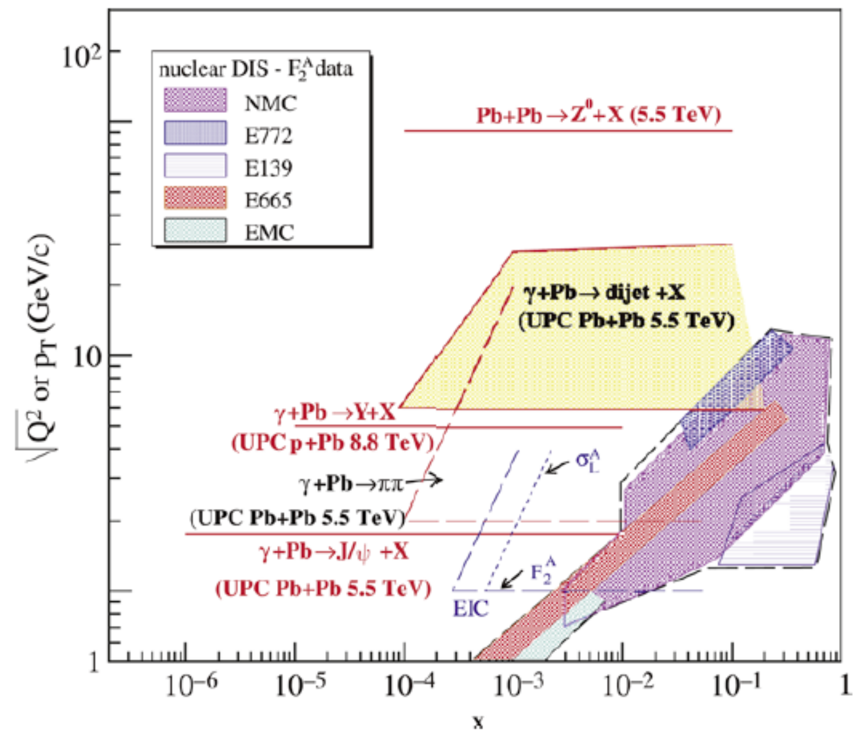
UPCs at the LHC

- CMS, ALICE and ATLAS plan programs
- "Yellow Book" gives physics case
  - K. Hencken et al., Phys. Rept. **458**, 1 (2008).

- Gluon structure Functions at low-x
  - Including saturation tests
- The 'black disc' regime of QCD
- Search for exotica/new physics
  - $\gamma\gamma$ --> Higgs, Magnetic monoples, etc.

Structure Functions at the LHC

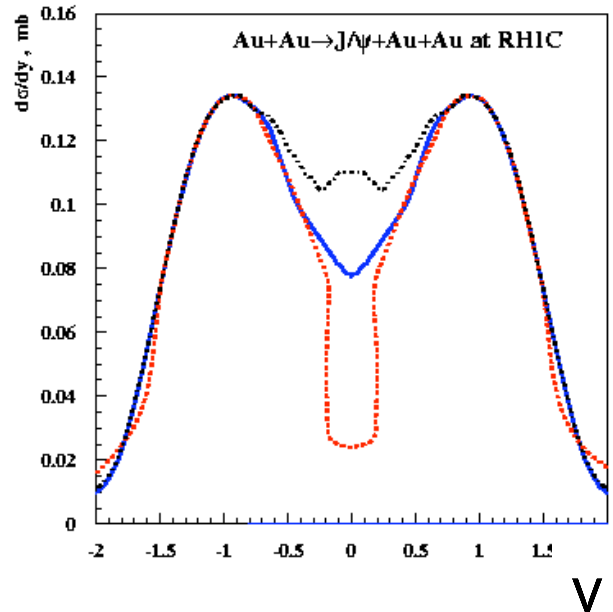
- Many photoproduction reactions probe structure functions
  - $\gamma \to q\bar{q}$; the quarks interact with target gluons
  - $Q^2 \sim (M_{\text{final state}}/2)^2$
  - $x \sim 10^{-4}$ at midrapidity
  - $x \sim 10^{-6}$ in forward regions
- J/ψ, ψ', Υ states
- Open charm/bottom/top?
- Dijets
- The twofold ambiguity can be

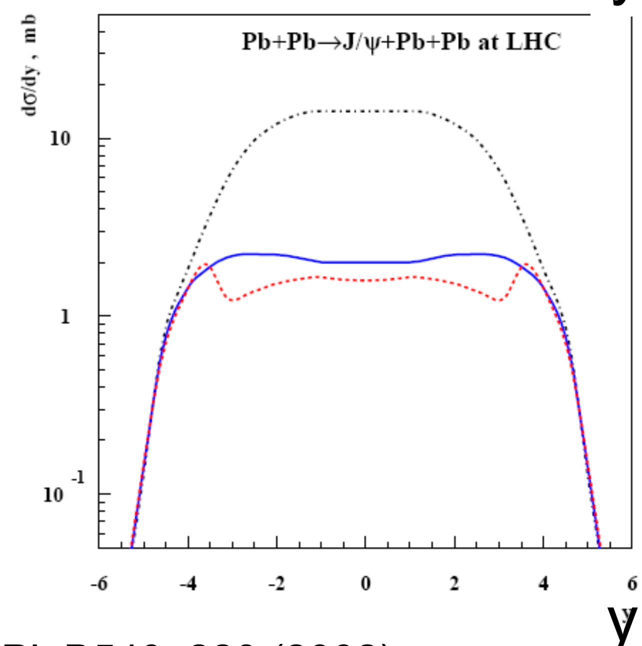


These techniques also apply at EIC, but the x,Q^2 range is limited

J/ψ photoproduction

- $\sigma \sim g(x,Q^2)^2$
  - $x \sim$ few 10^{-4} for J/ψ@ the LHC
  - $x \sim$ few 10^{-2} for J/ψ@ RHIC
  - $Q^2 \sim M_V{}^2/4$
- Coherent production
  - $p_T < h/R_A$
- High rates
  - 3.2 Hz production with Pb
- Detection is easy

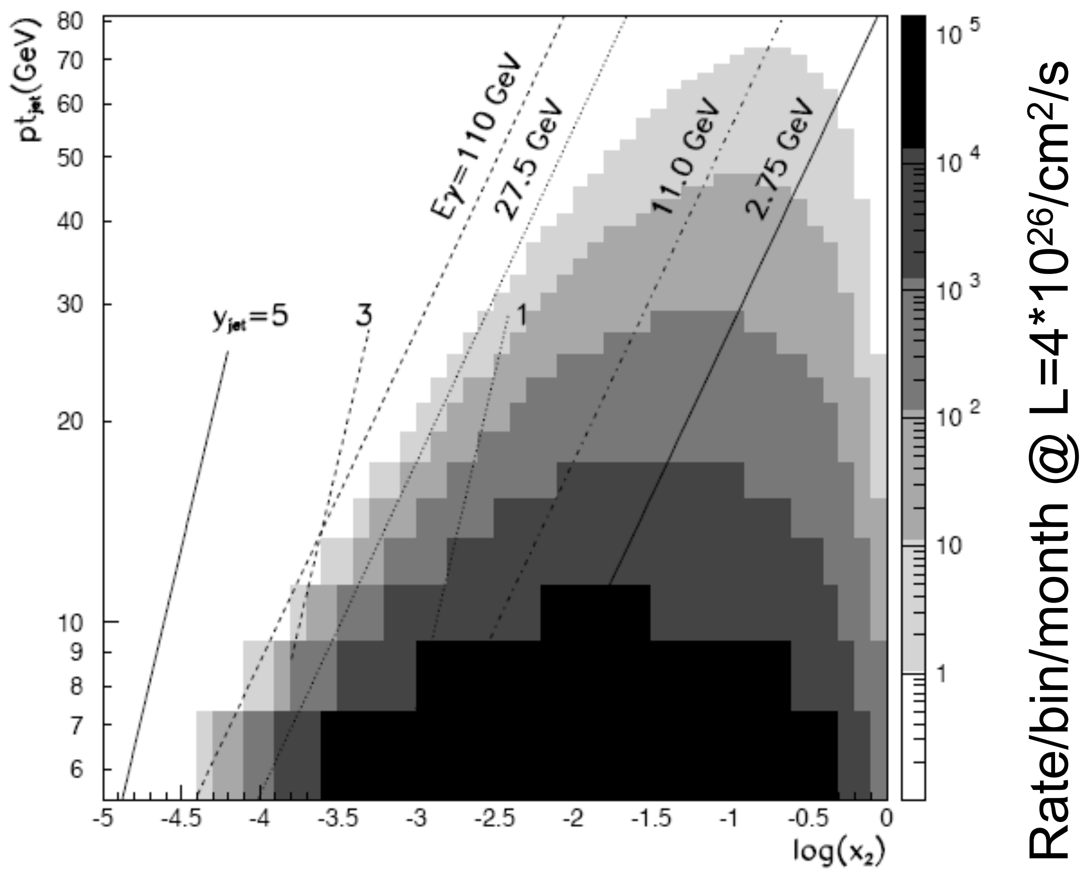




M. Strikman, F. Strikman and M. Zhalov, PL B540, 220 (2002)

Dijets

- With calorimetery to |y|<3, probe down to $x \sim 10^{-4}$ in 1 month
- Use standard jet triggers

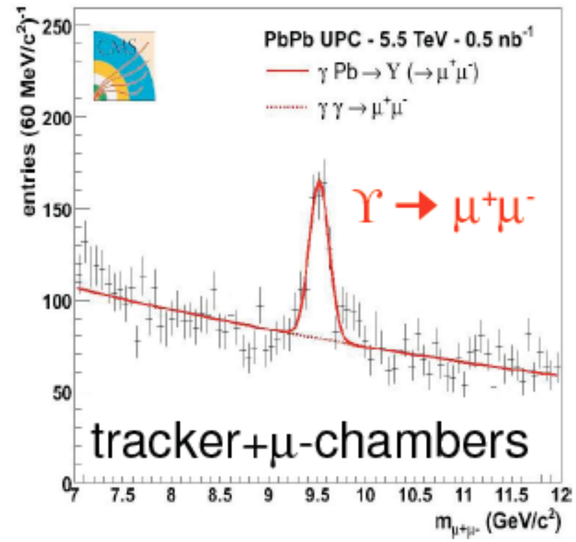


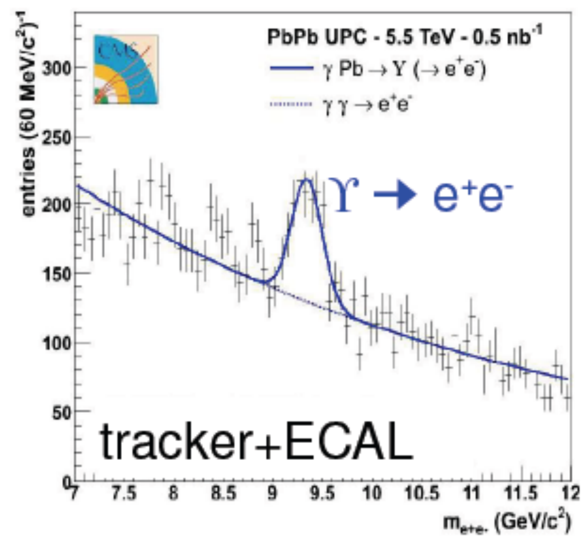
M. Strikman, R. Vogt and S. White, PRL86, 082001 (2006)

LHC – Plans & Issues

Dd'E, hep-ex/0703024

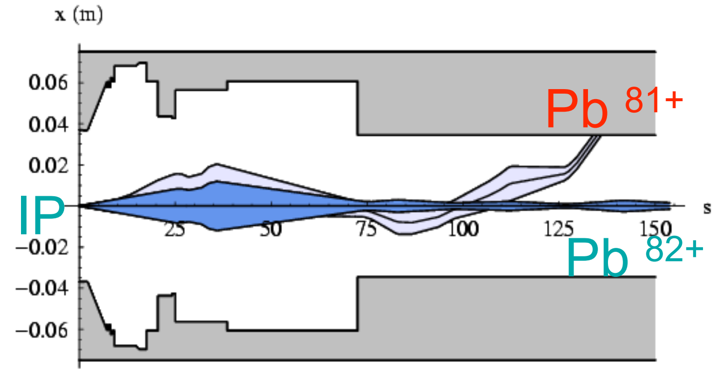
- J/ψ,ψ', Υ --> leptons is relatively easy
  - CMS, ALICE, ATLAS are pursuing
- Di-jets
  - ATLAS is pursuing
- e^+e^- pairs
  - Interest by ALICE
    - Untriggered?
- Triggering is problematic
  - ZDC coincidences might help with backgrounds

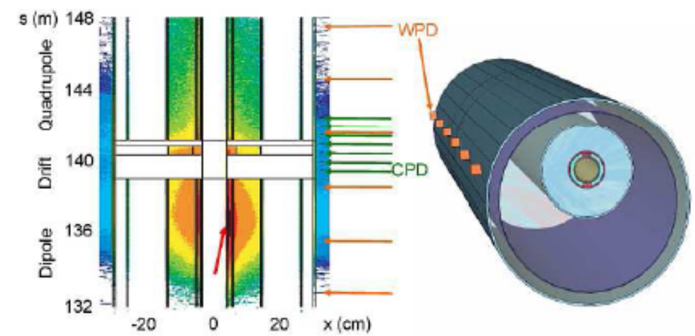


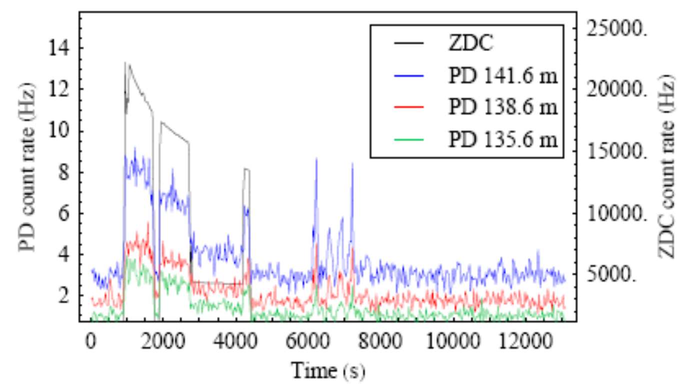


Bound Free Pair Production

- A + A --> A + Ae$^-$ + e$^+$
  - 1e$^-$ atom has lower Z/A
    - Less bending in dipoles
  - Momentum ~ unchanged --> beam
- σ ~ 280 barns w/ lead at the LHC
  - 280,000 ions/s at L = 10^{27}/cm^2/s
    - 28 watts!
  - Hits beampipe ~ 136 m from the IP
    - Enough energy to quench superconducting magnets?
- Limits LHC luminosity w/ heavy ions
- Observed with copper beams at RHIC
    - σ ~ 200 mb

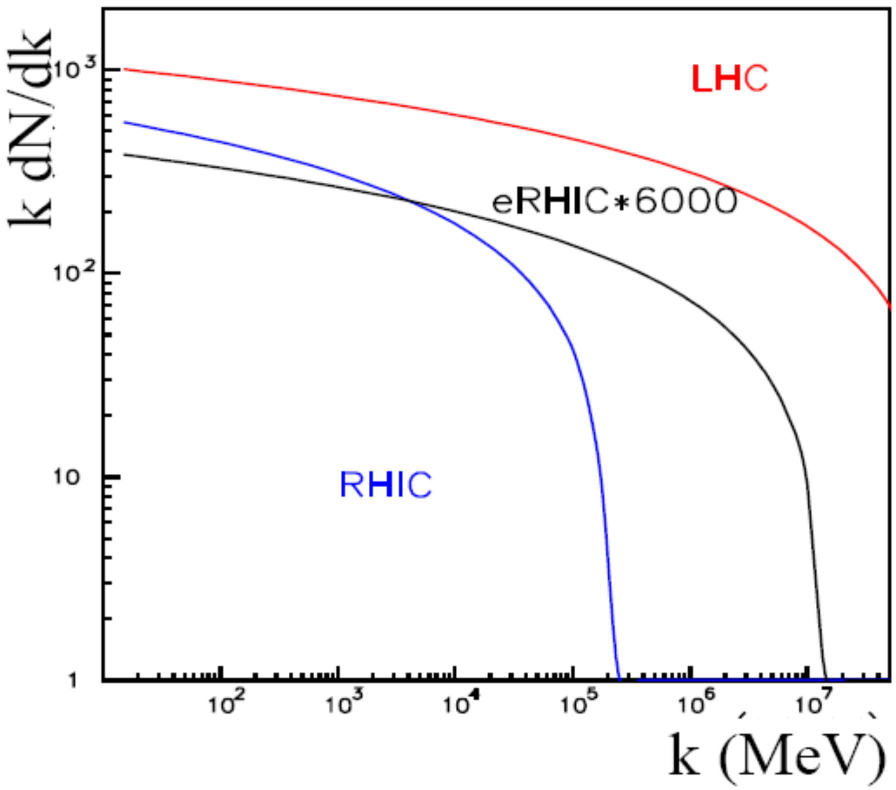






SK, NIM **A459**, 51 (2001); R. Bruce et al. PRL **99**, 144801 (2007)

EIC vs. UPCs: Comparison plot



RHIC: AuAu
$10^{26}/cm^2/s$

LHC: AuAu
$10^{27}/cm^2/s$

eRHIC: eAu
Luminosity circa 2003

S. N. White, 2003

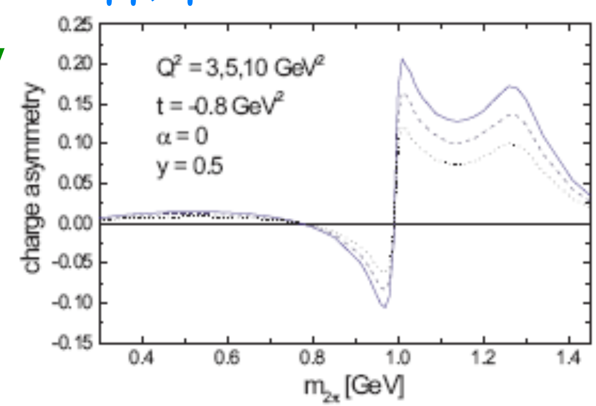
Theory faces reality

- The luminosities are huge, but what can a ‘real’ experiment actually measure?
  - Triggers
  - Backgrounds
  - Detection of scattered hadrons
    - Roman pots for p or d?
      - Also relevant for ep @ EIC
    - Otherwise, kinematics are less constrained
  - CMS and ATLAS have limited capabilities for low p_T particles & ALICE has limited trigger capabilities for low multiplicity interactions.

"UPC-ish" Odderon searches that could be studied at the EIC

- Odderon ==Spin-1, 3-gluon counterpart of the Pomeron
  - Fundamental in QCD
- Pomeron + Odderon --> J/ψ
  - Different p_T spectrum from γP
- $\gamma\gamma$ + γPomeron + γOdderon --> $\pi^+\pi^-$
  - γP through ρ^0 intermediary, direct $\pi\pi$ pairs
  - $\gamma\gamma$, γO through $f_2(1270)$ intermediary
  - γP has different final state spin/parity from $\gamma\gamma$, γO
    - In ep/eA, forward backward asymmetry

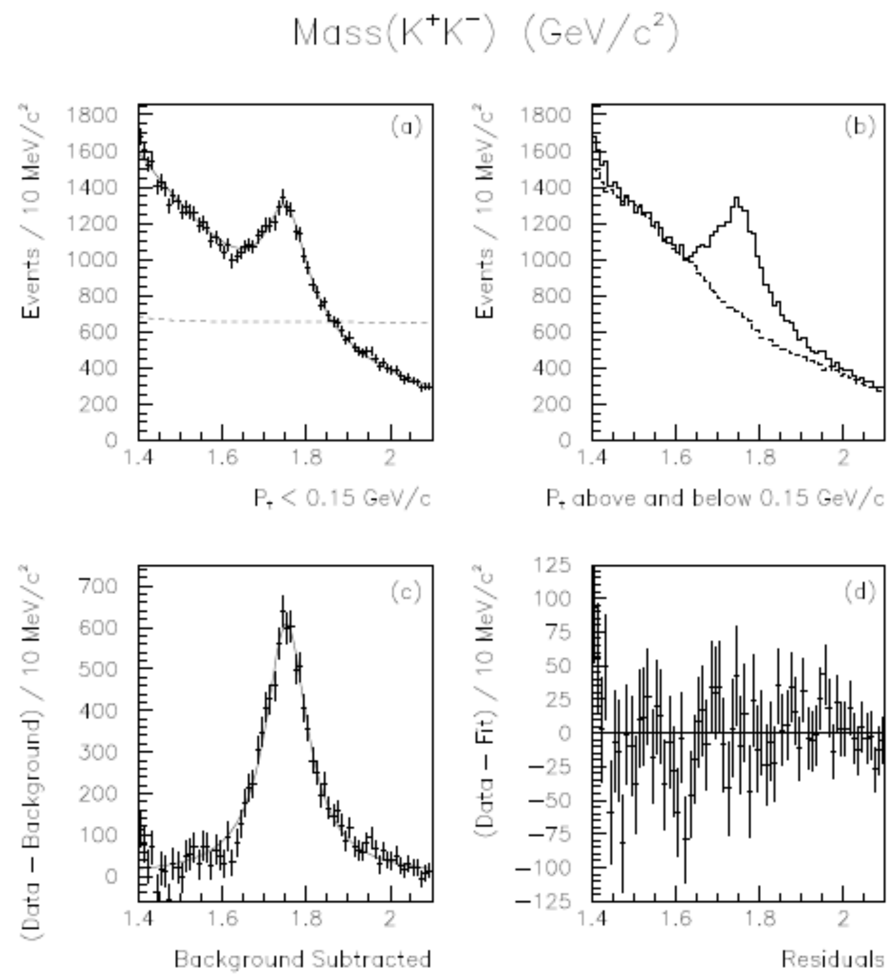
$$\frac{\sum\limits_{\lambda=+,-} \int \cos\theta \, d\sigma(s, Q^2, t, m_{2\pi}^2, y, \alpha, \theta, \lambda)}{\sum\limits_{\lambda=+,-} \int d\sigma(s, Q^2, t, m_{2\pi}^2, y, \alpha, \theta, \lambda)}$$



Hagler et al, hep-ph/0310068

$X(1750) \rightarrow K^+K^-$

- Diffractively photoproduced?
  - seen by FOCUS
- $p_T < 0.15$ GeV/c, compatible w/ coherent γP or $\gamma\gamma$ production
  - Angular analysis shows probably $J^{PC}=2^{++}$
    - $\gamma\gamma$ production?
  - Too heavy to be $\phi(1680)$
- Upper limit on UPC production in STAR masters thesis
- What is it?



Conclusions

- Photonic reactions can be studied in many venues.
- The LHC will produce the highest energy $\gamma p/\gamma A$ and $\gamma\gamma$ collisions in the world.
  - These collisions occur at very high luminosity.
- The study of many of these reactions is limited by the detector triggers, limited acceptance, and/or inability to observe the scattered nuclei.
- Some photonic reactions are unique to heavy-ion colliders
  - Interference between production sites