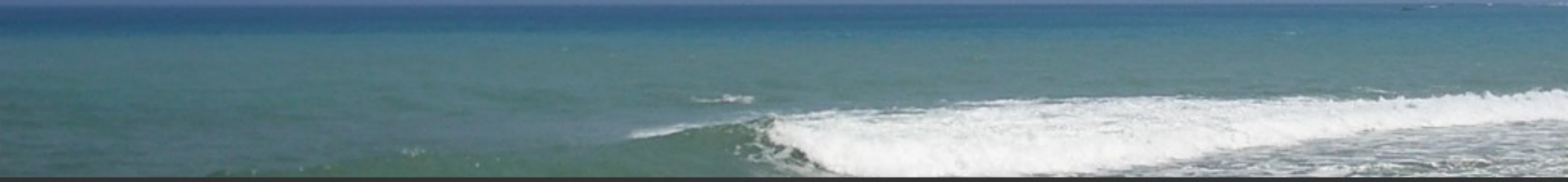
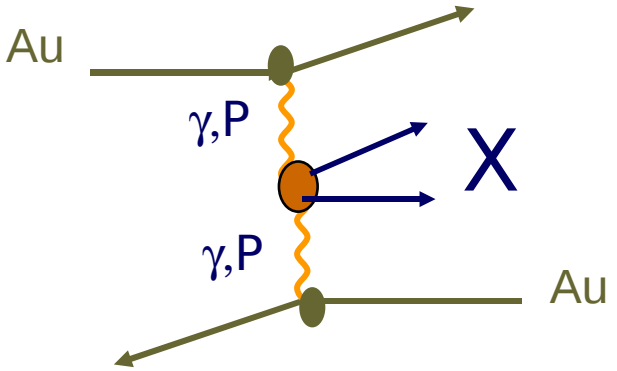
# Photoproduction in Ultra Peripheral Relativistic Heavy Ion Collisions with STAR

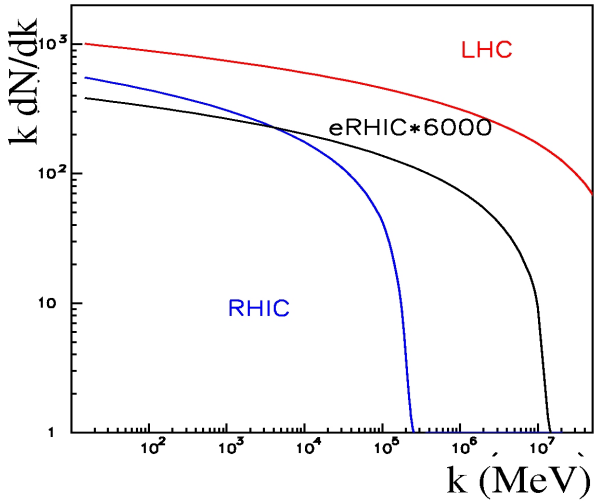
**Yury Gorbunov for the STAR collaboration**
Creighton University



# Ultra Peripheral Collisions

- Ultra Peripheral Collisions – nuclei miss each other and interact via long range fields
- Strong electromagnetic fields from heavy ions
  - Weizsacker-Williams: a field of almost-real photons
    - Virtuality $Q^2 < (h/R_A)^2$
- Photon $E_{max} \sim \gamma h/R_A$
  - 3 GeV with gold at RHIC
  - 80 GeV with Lead at the LHC
- Photon flux ~ $Z^2$
  - Higher intensity with heavy ions, higher probability of multi-photon interactions

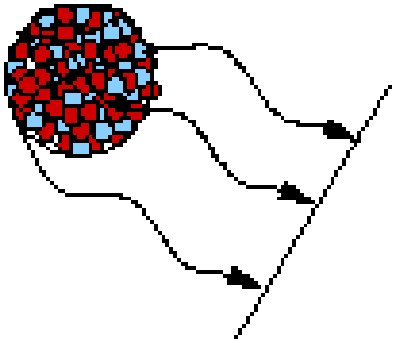


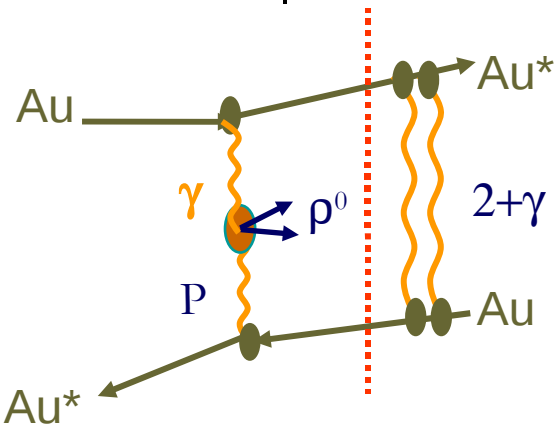




k is given in the rest frame of the nucleus

# Photonuclear and γγ Interactions

- Photonuclear interactions
  - γ-Pomeron/meson can be coherent
    - Coupling: $A^{4/3}$ (surface) to $A^2$ (volume)
- γγ interactions
  - QED process – proposed as luminosity monitor
- Strong coupling and multiple interactions
  - $Z^2\alpha \sim 0.6$ with gold/lead
    - Multi photon reactions
  - Mutual Coulomb excitation - event tag
  - Factorize as function of impact parameter
- Required $b > 2R_A$
  - No hadronic interactions
  - <b> ~ 20-60 fm at RHIC



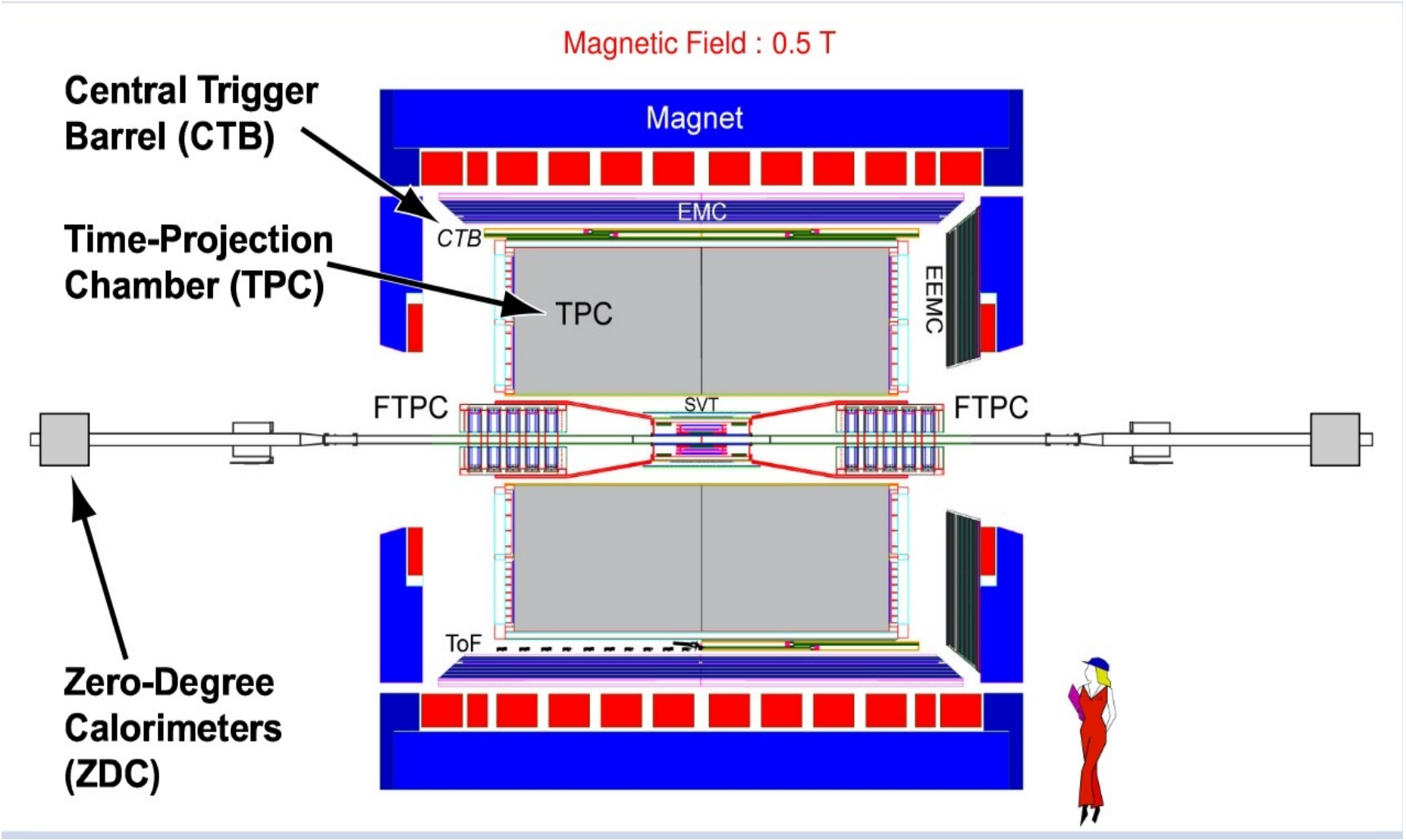



$$\sigma = \int d^2 b P_{2GDR}(b) P_{\rho^0}(b)$$

# Photoproduction Physics

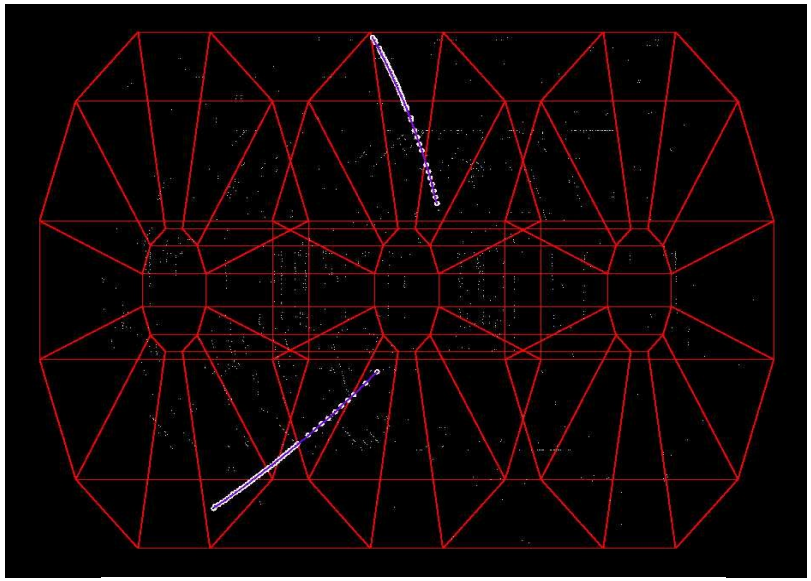
- Gluon structure function
  - $\gamma A \rightarrow J/\Psi$, cc(bar), dijets, etc
    - $\sigma_{J/\Psi} \sim g^2(x)$
    - $\sigma_{QQ,\ dijets} \sim g(x)$
- Meson spectroscopy
  - $\rho, \omega, \varphi$, excited states, etc
- Fundamental tests of Quantum Mechanics
  - Interference between non overlapping particles
- Diffractive phenomenon
  - Elastic and inelastic processes, spin dependence
- New physics
  - Glueballs, odderons, etc

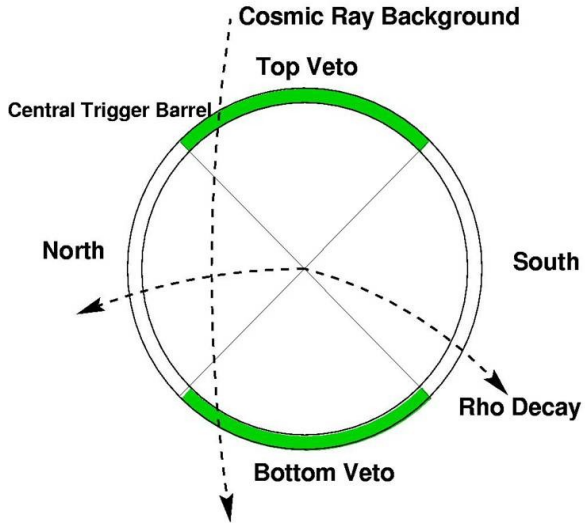
# STAR Detector



# Signatures & Triggering

- Signatures:
  - Coherent production dominates
  - $p_T \leq 2h/RA \approx 60$ MeV/c
  - Low multiplicity events with vertex
  - Events with nuclear breakup accompanied by forward neutrons
- Triggers:
  - “Minimum bias”
    - Low multiplicity
    - Neutrons in both ZDCs
  - “Topology”
    - Low multiplicity events
    - Coincidence of North and South
    - Top and Bottom veto cosmics

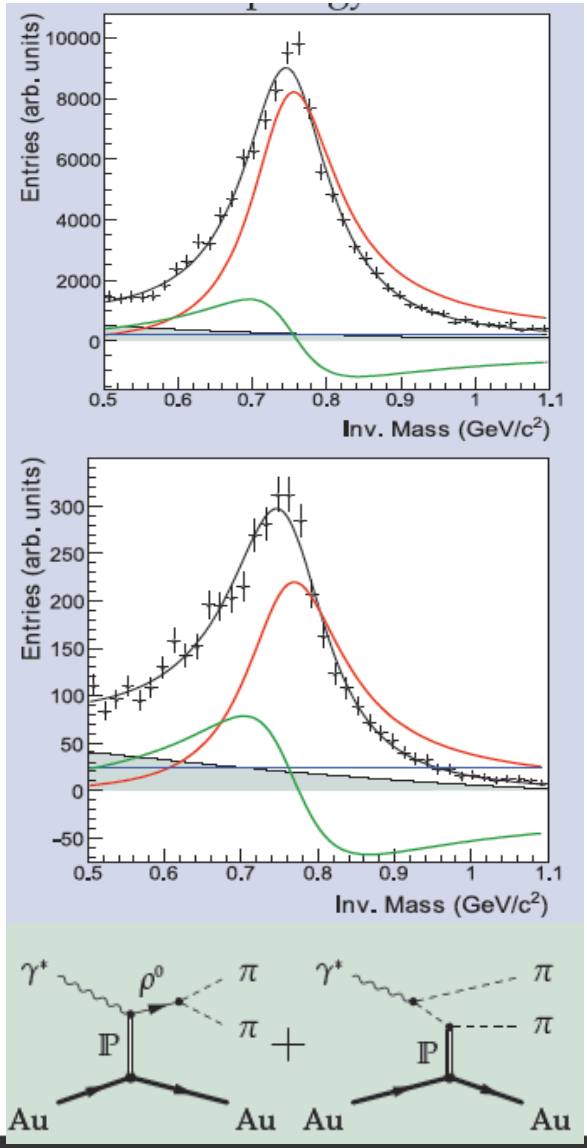




# $\rho^0$ Photoproduction at STAR

- Coherently produced events
  - Exclusive $\rho^0$ accomponied by mutual Coulomb excitation
  - $p_T$ < 150 MeV/c
  - Acceptance corrected
- Fit function:
  - Relativistic Breit-Wigner for $\rho^0$ signal
  - Mass independent direct $\pi^+\pi^-$ production amplitude
  - Söding term for the interference of the two

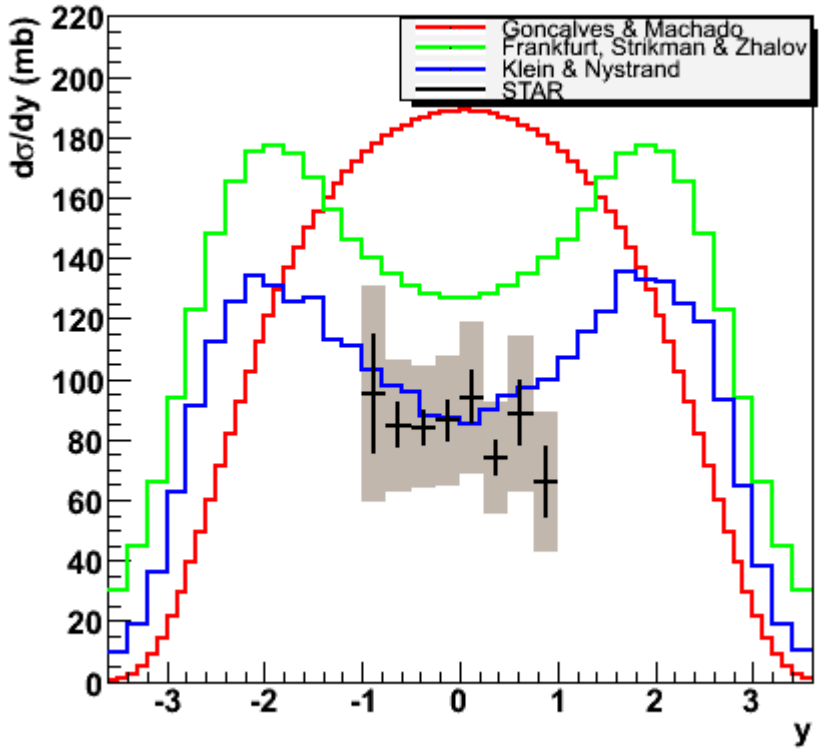
$$\frac{d\sigma}{dM_{\pi\pi}} = \left| A \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} + B \right|^2.$$




Phys. Rev. C77 34910 (2008)

# ρ Production Cross Section

- Goncalves & Machado (EPJ C29,2003)
  - QCD color dipole approach
  - Nuclear effects and parton saturation phenomena
- Frankfurt, Strikman & Zhalov (PRC67 034901 2003)
  - Generalized vector dominance (VDM)
  - QCD – Gribov-Glauber approach
- Klein & Nystrand (PR C60 014903, 1999)
  - VDM
  - Classical mechanical approach for scattering

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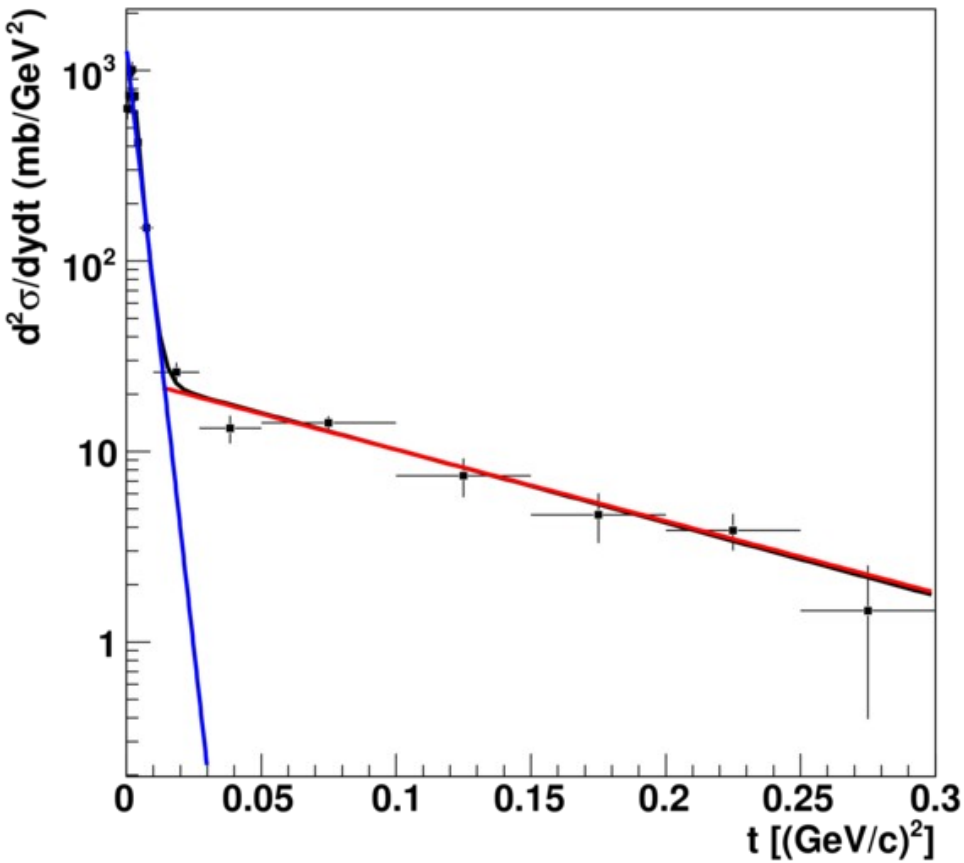
# Coherent and Incoherent Production of ρ

- Access to the coherent and incoherent form factor
  - Double exponential fit function
- Incoherent production – nucleon form factor
  - $b_N = 8.8 \pm 1.0\ GeV^{-2}$
- Coherent production
  - $b_{Au} = 388.4 \pm 24.8\ GeV^{-2}$
    - Data sensitive to hadronic radius of gold
      - ⋆ $b_{Au} \sim R_A^2$
- σ(incoh)/σ(coh)~ 0.29 ±0.03

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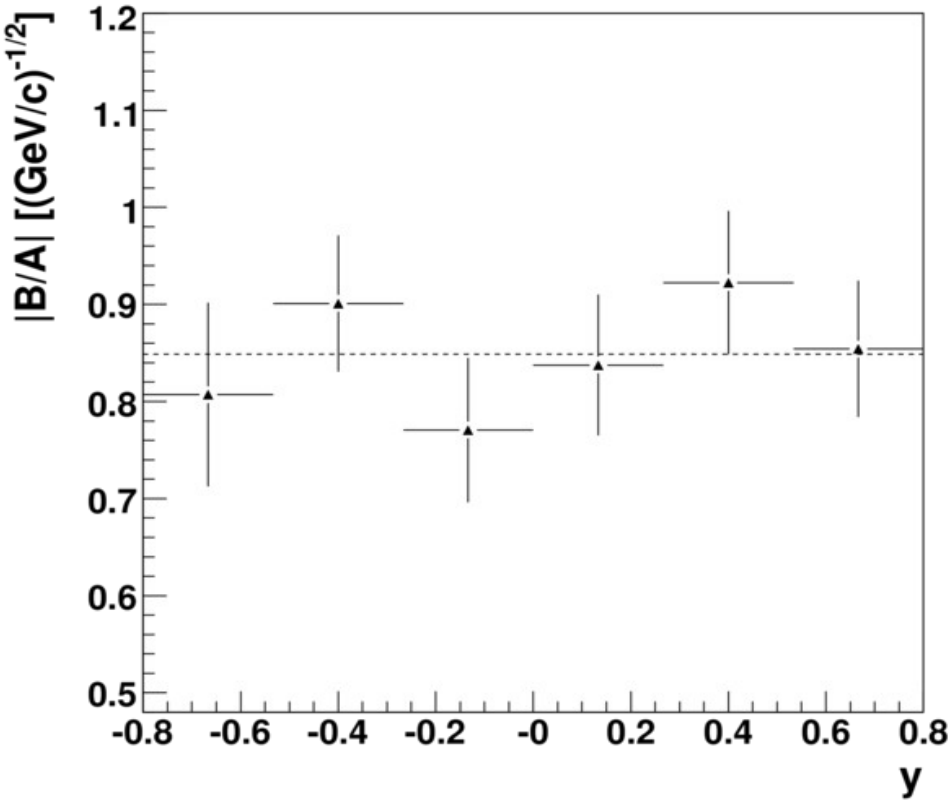
$$\frac{d\sigma}{dt} = a * \exp(-b_{Au} * t) + c * \exp(-b_N * t)$$

# Non resonant pion production

- Ratio of non-resonant to resonant pion production

$$\frac{d\sigma}{dM_{\pi\pi}} = \left| A \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} + B \right|^2 .$$

- |B/A| - ratio of non-resonant to resonant $\pi^+\pi^-$ production
  - 200 GeV: |B/A| = 0.84 ± 0.11 GeV $^{-1/2}$
  - 130 GeV: |B/A| = 0.81 ± 0.28 GeV $^{-1/2}$
  - No angular dependence or rapidity dependence
  - In agreement with previous HERA experiments
    - EPJ C2 247 (1998)

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# S-channel Helicity

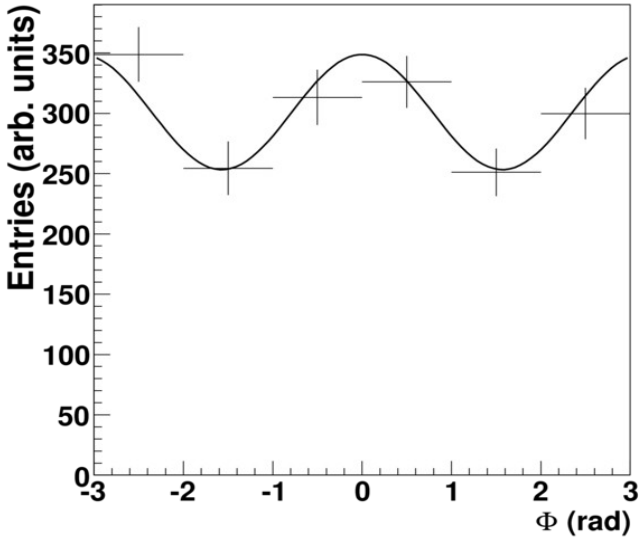
- S-channel helicity conservation
  - Produced vector meson retains helicity of the initial photon

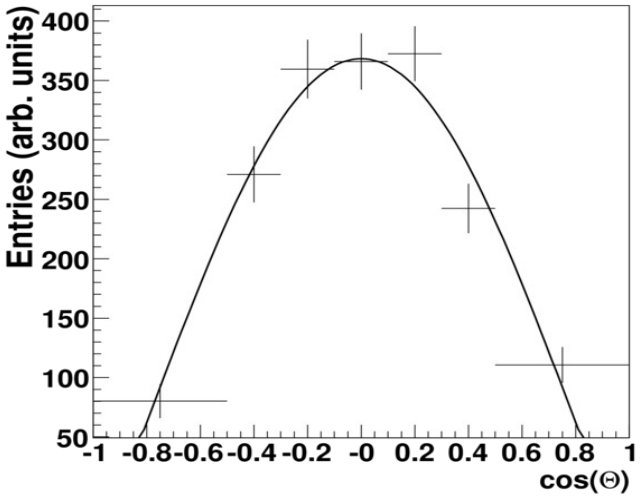
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos(\Theta_h)d\Phi_h} = \frac{3}{4\pi}[\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2(\Theta_h)$$
$$-\sqrt{2}\Re e[r^{04}_{10}]\sin(2\Theta_h)\cos(\Phi_h) - r^{04}_{1-1}\sin^2(\Theta_h)\cos(2\Phi_h)]$$

    - Θ is angle between polar angle between the beam direction and the direction of the $\pi^+$
    - Φ is angle between ρ decay and production plane
  - Spin density elements close to zero – s-channel helicity conservation

| Parameter | STAR | ZEUS |
|---|---|---|
| $r^{04}_{00}$ | $-0.03 \pm 0.03_{stat.} \pm 0.06_{syst.}$ | $0.01 \pm 0.01_{stat.} \pm 0.02_{syst.}$ |
| $\Re e[r^{04}_{10}]$ | — | $0.01 \pm 0.01_{stat.} \pm 0.01_{syst.}$ |
| $r^{04}_{1-1}$ | $-0.01 \pm 0.03_{stat.} \pm 0.05_{syst.}$ | $-0.01 \pm 0.01_{stat.} \pm 0.01_{syst.}$ |

    - The fit function describes different states: non-flip, single and double flip and their combination
      - Not able to measure interference between non flip and single flip due to production plane ambiguity

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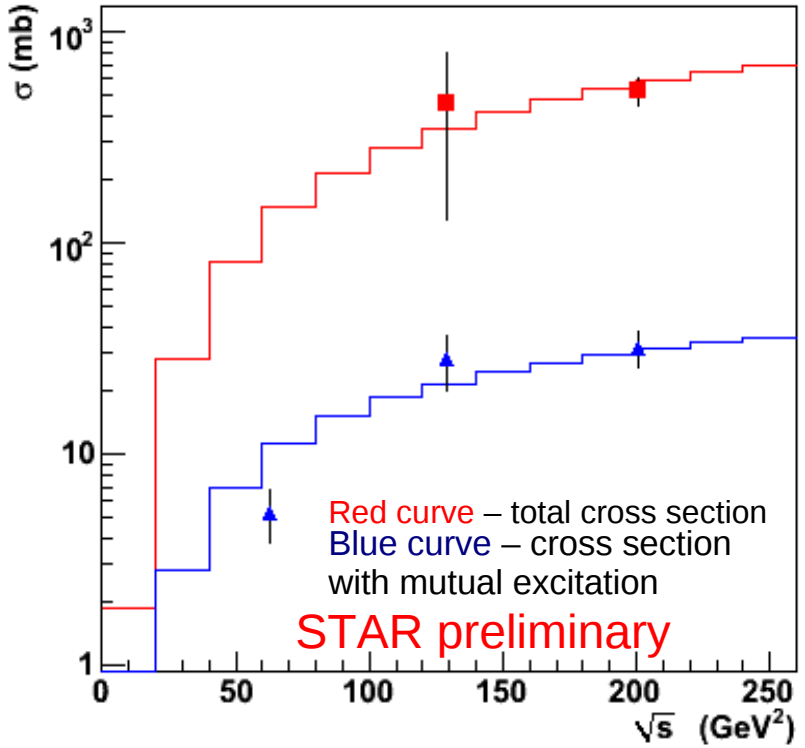
# ρ Production Cross Section

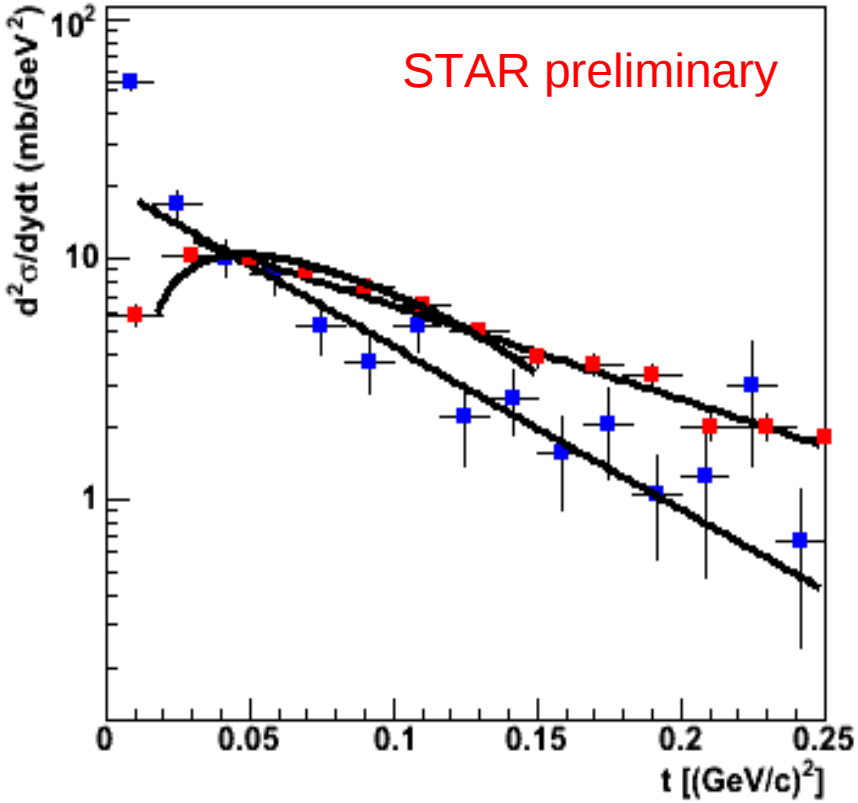
- Several data sets:
  - AuAu √s=62 GeV — In progress
  - AuAu √s=130 GeV — PRL89 272302 (2002)
  - AuAu √s=200 GeV — PRC77 34910 (2008)
  - dAu √s=200 GeV — In progress




Production cross section with mutual Coulomb excitation as a function of ion gamma
Solid line – simulation based on Klein & Nystrand

# ρ Production in dAu collisions

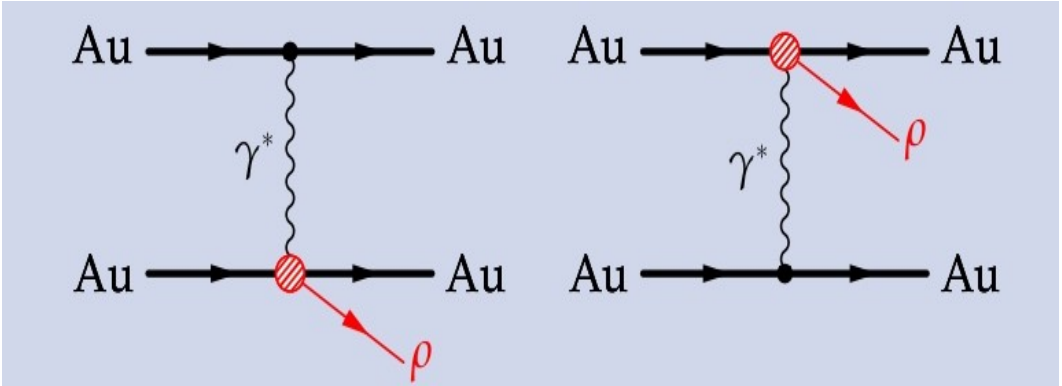
- Asymmetric collision
  - The photon is almost always emitted by the gold nucleus, avoiding the two-fold ambiguity.
- Two fit functions
  - Single exponential
  - Fit function based on the Glauber prediction from Eisenberg et al, NP B104, 61 1976
- Downturn at low t , not enough energy for the d dissociation
  - Similar behavior observed by SLAC experiment at 4.3 GeV Eisenberg et al, NP B104, 61 1976




Red – incoherent production
Blue – coherent production

# Interference in ρ Production

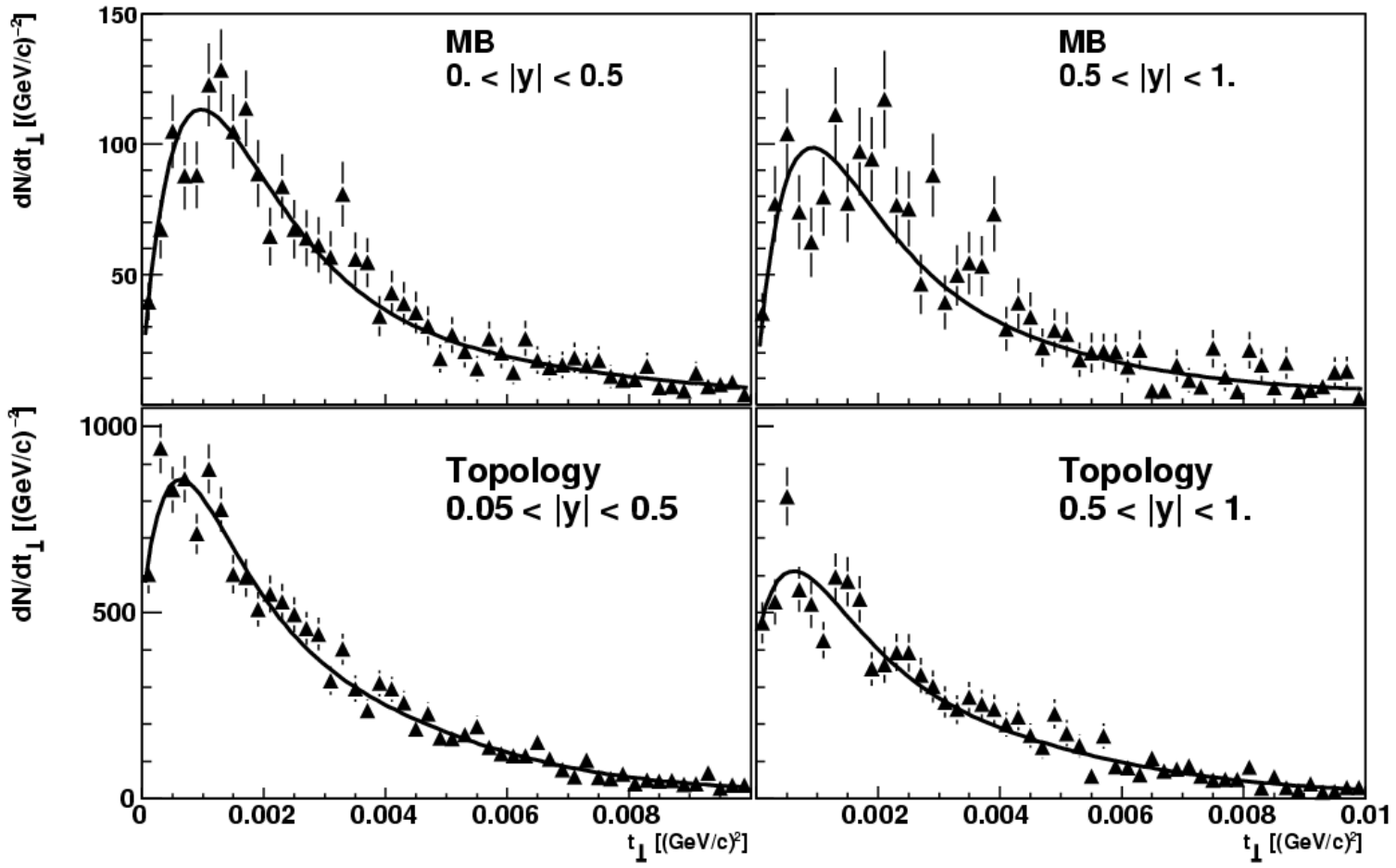
- Impossible to distinguish source of γ and target
  - Interference
  - Entangled final state ππ wave function




nucl-ex/0402007

- ρ,ω, ϕ, J/ψ are $J^{PC} = 1^{--}$
  - $\sigma \sim |A_{1(b,y)} - A_{2(b,-y)} e^{ip \cdot b}|^2$ where b is impact parameter
  - Suppression at low $p_T \leq h/\langle b \rangle$
- Different triggers provide access to different median impact parameter
  - Topology data : median b ≈ 46 fm
  - Minimum bias : median b ≈ 18 fm (extends interference effects to larger $p_T$)
- Photon energy dependence of the ρ production amplitudes leads to the decrease of the interference at large rapidities

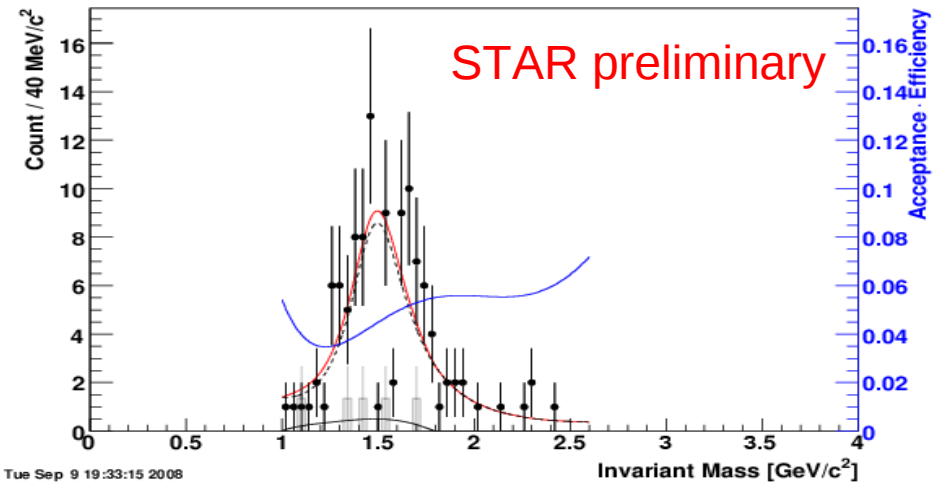
# Interference in coherent ρ Production

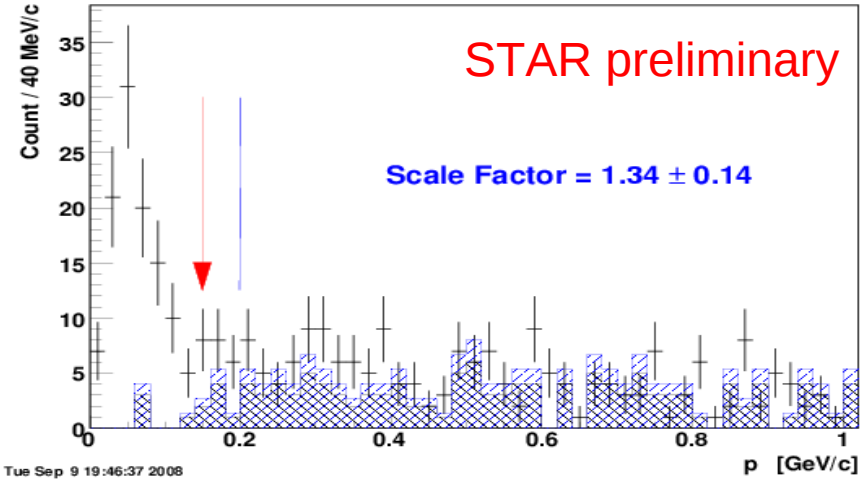



- Measured level of interference at 87 ±5 (stat.) ±8 (syst.)% from the expected level (arXiv:0812.1063)

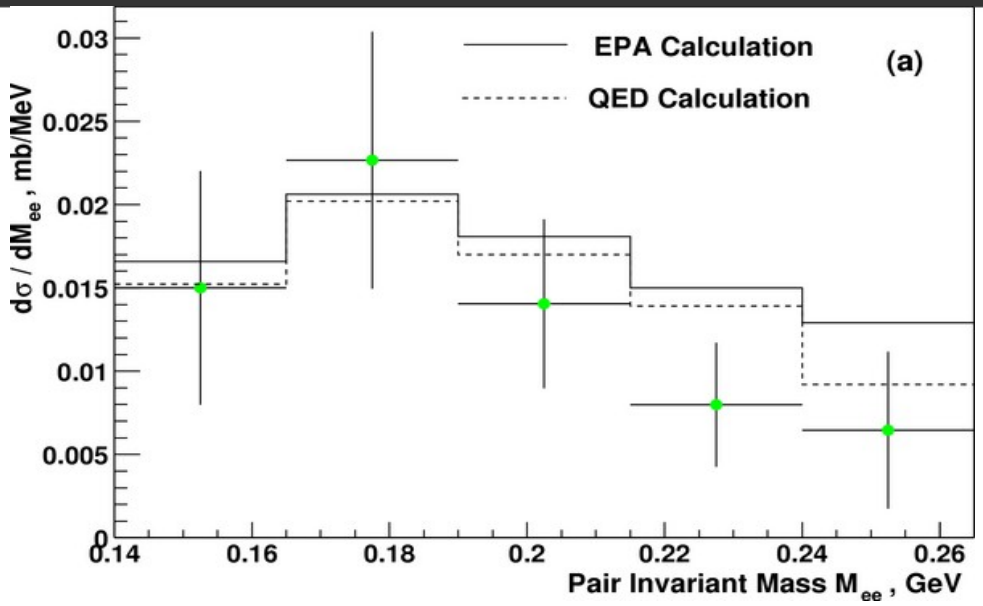
# Photoproduction of $\pi^+\pi^-\pi^+\pi^-$

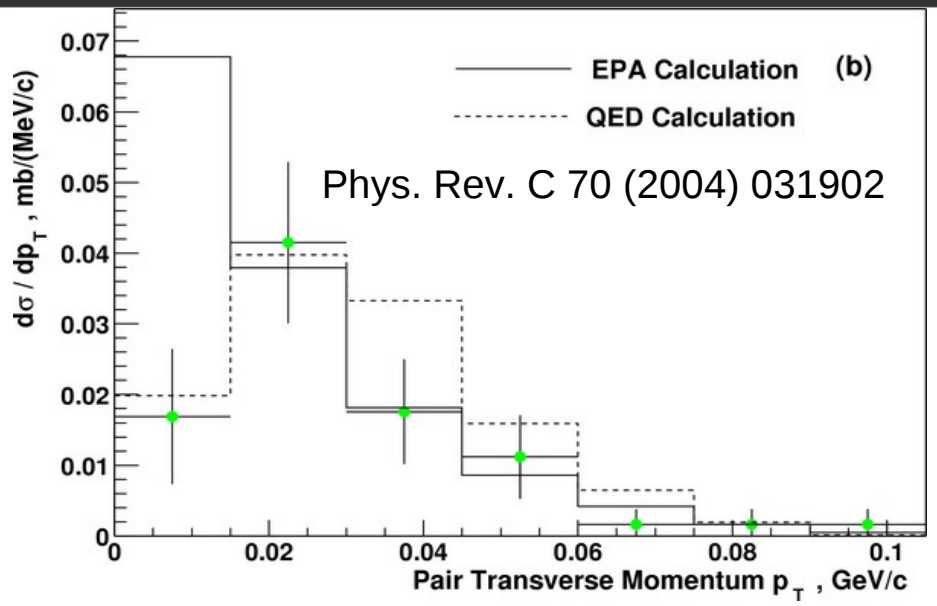
- Expected to be largely through a radially excited ρ
  - Could be ρ(1450) and/or ρ(1700)
- Peaks at low $p_T$ due to the coherent production
- Mass spectra similar to γp collisions
- Studies of the substructure showed low mass pion pairs accompanied by ρ(770)



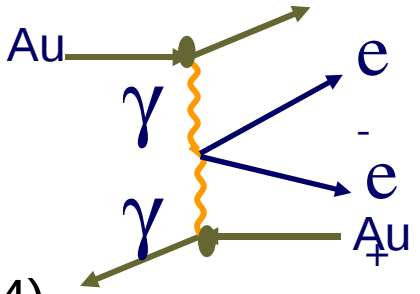



# $e^+e^-$ Production at STAR in AuAu at √s=200GeV



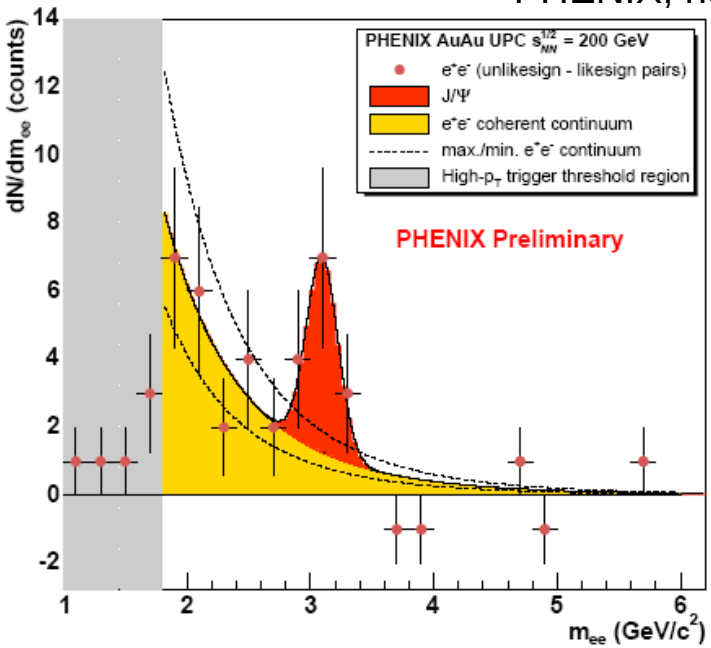



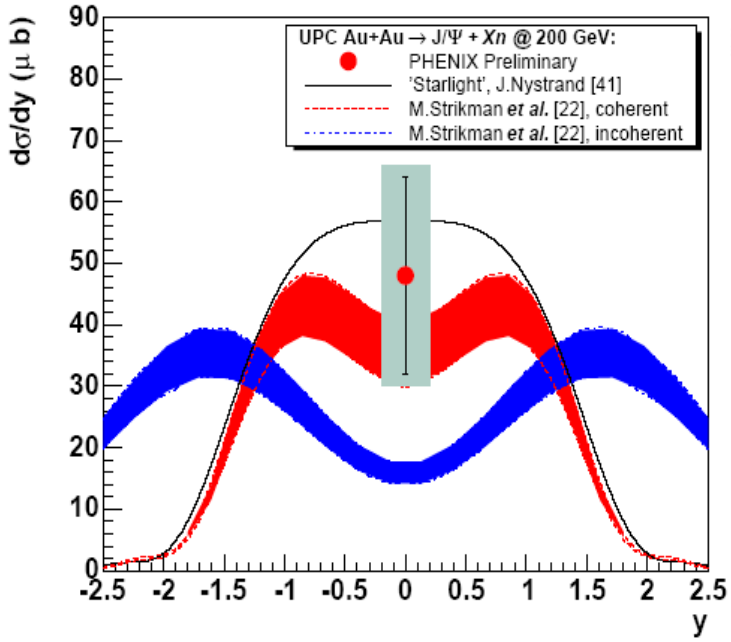

- Compared with two models
  - EPA(equivalent photon approach)
    - Treats γ as real photon
  - QED – lowest order QED calculation based on GDR only with correction for higher states Hencken PR C69 054902 (2004)
- New calculation by Baltz PRL 100, 062302 (2007)
  - Realistic phenomenological treatment of nuclear breakup

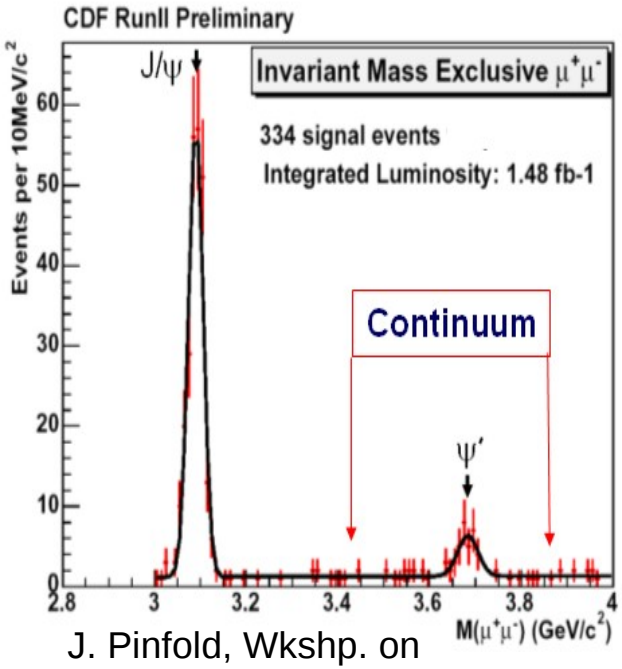


# J/ψ Production at RHIC

PHENIX, nucl-ex/0601001




J. Pinfold, Wkshp. on HE Photon Collisions at the LHC

- Trigger
  - $e^+e^-$ pair + 1 nucleus breakup
- Signal: 12 events
- Cross section at expected level, big errors

334 exclusive $\mu^+\mu^-$ events
Paper draft in collaboration

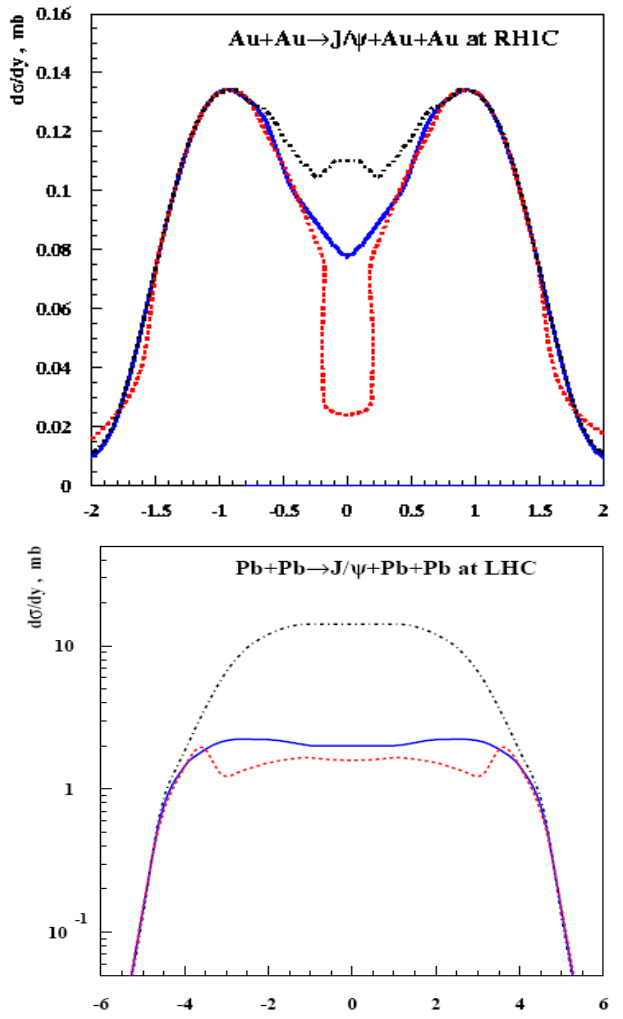
# J/Ψ Photoproduction

- J/ψ sensitive to gluon distribution in the nucleus
  - $\sigma \sim g(x,Q^2)^2$
    - X ~ few $10^{-4}$ for J/ψ at LHC
    - X ~ few $10^{-2}$ for J/ψ at RHIC
- Clear shadowing effect
  - Several factor difference in cross section at LHC

**Black → Impulse Approx.**

**Red → gluon diffractive density**

**Blue → H1 Gluon density**



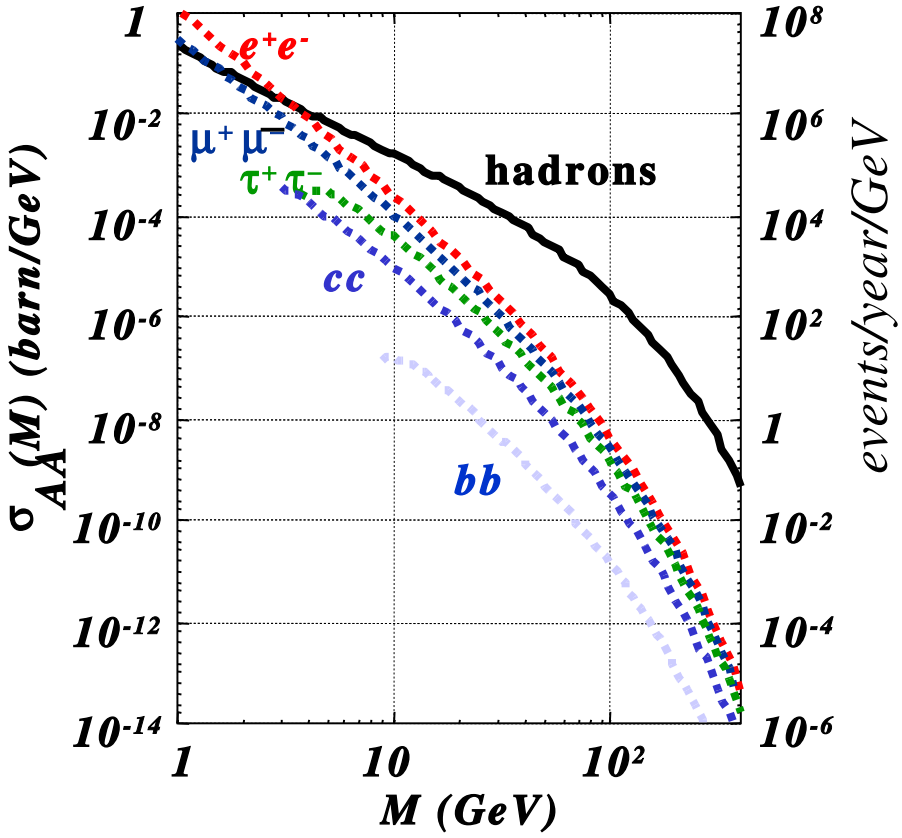

M. Strikman, F. Strikman and M. Zhalov, PL B540, 220 (2002)

# Why UPC is interesting at LHC

- Maximum mass given by the coherence production conditions: $M_{max} = \gamma \ h/R_{nucleus}$
  - Mass of accessible final states increase from 2- 3 GeV to 100 GeV

| Final State | Acceptance | Rate/$10^6$ s |
|---|---|---|
| $\rho^0 \to \pi^+\pi^-$ | central barrel | $2 \times 10^8$ |
| $J/\psi \to e^+e^-$ | central barrel | $1.50 \times 10^5$ |
| $\Upsilon(1S) \to e^+e^-$ | central barrel | 400 – 1400 |
| $e^+e^-, M > 1.5$ GeV/$c^2$ | central barrel, $p_T > 0.15$ GeV/$c$ | $7 \times 10^5$ |
| $e^+e^-, M > 1.5$ GeV/$c^2$ | central barrel, $p_T > 3$ GeV/$c$ | $1.4 \times 10^4$ |
| $\mu^+\mu^-, M > 1.5$ GeV/$c^2$ | muon spectrometer, $p_T > 1$ GeV/$c$ | $6 \times 10^4$ |

Yields in PbPb UPC collisions in ALICE acceptance
Alice collaboration JP G 32 1295



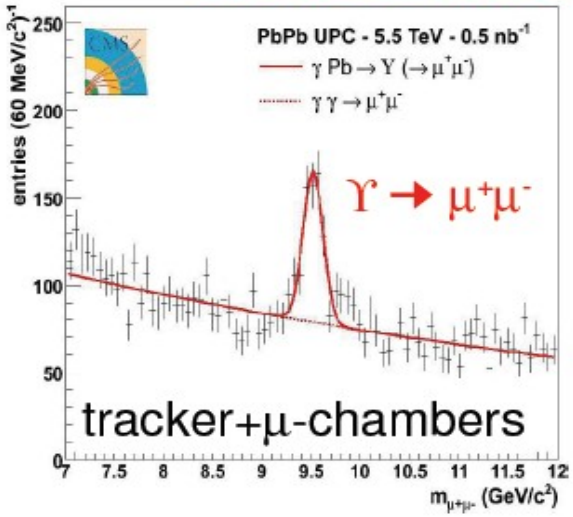
# Program at LHC

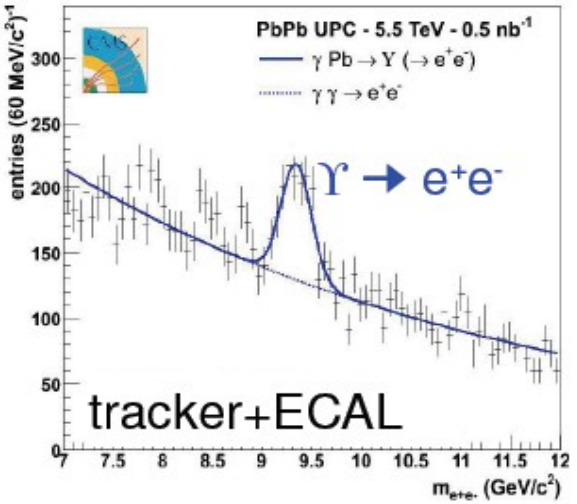
- CMS, ALICE, ATLAS, FP420, TOTEM & other forward detectors planed programs
- “Yellow Book” gives physics case
  - K. Hencken et al., Phys. Rept. **458**, 1 (2008).
- Gluon structure Functions at low-x
  - Nuclear gluon distributions can be measured by studying photo-production of heavy quarks
    - $\sigma_{J/\Psi} \sim g^2(x)$
    - $\sigma_{QQ,\ dijets} \sim g(x)$
- The ‘black disc’ regime of QCD
- Search for exotica/new physics
  - $\gamma\gamma$ --> Higgs, Magnetic monoples, etc.
- Diffractive phenomenon
  - Roman pots useful for pp

# Plans at LHC

- J/ψ,ψ', Υ in lepton channel
  - CMS, ATLAS, Alice
    - γ+A →J/Ψ +A
      - expected prod rate ~ 1x10$^7$/ year
    - γ+A →Υ +A
      - expected prod rate ~ 1x10$^5$/ year
- Photonuclear production of heavy quarks
  - γ+g→cc
- Di-jets
  - ATLAS
    - Photonuclear jet production; photon+parton→jet+jet; e.g. γ+g → q+q
- Triggering is challenging
  - ZDC signal may help reduce background; not always available at Level 0

Dd'E, hep-ex/0703024



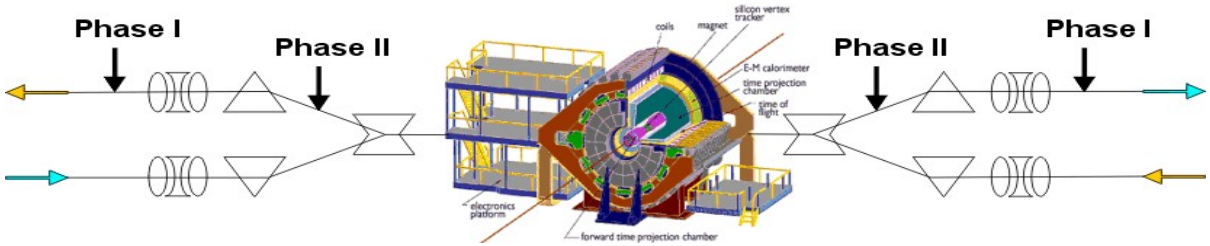



# Summary

- Hadron collider is unique tool to study photoproduction reaction
  - At RHIC STAR & Phenix have studied several topics
    - Published new measurement of $\rho^0$ production cross section at $\sqrt{s}$=200 GeV
      - Good agreement with theoretical predictions
    - Paper about interference effect has been submitted to the PRL and is likely being published
    - Ongoing analysis
      - dAu at 200 GeV and AuAu at 62 GeV data sets are currently analyzed
      - Resonant production of $\pi\pi\pi\pi$ at $\sqrt{s}$ = 200 GeV
        - At very advanced stage, manuscript is being prepared

# Outlook

- Several new detector are being commissioned right now
  - Central Trigger Barrel is being replaced by the TOF system
    - Improved triggering performance
  - New data acquisition system
    - Readout at 1kHz with low dead time




  - Roman pots system has been installed
    - Dedicated three day run this year
      - Phase I – elastic scattering and particle production in Double Pomeron Exchange (DPE)
      - Phase II - increased data set for elastic scattering and particle production in DPE
- RHIC is a good place to study diffractive and electromagnetic processes in heavy ion collisions

# Physics Outlook

- New DAQ 1000 system should increase available statistic by factor 10
  - Studies of J/Ψ, etc
    - Gluon shadowing
  - Substructure in 4 pion state
  - Meson spectroscopy : $\rho^*, \rho^0\rho^0, \omega, \varphi$, etc
- Roman pots system
  - Elastic and inelastic diffractive processes and spin dependence
  - Exotic