Photoproduction in Ultra Peripheral Relativistic Heavy Ion Collisions

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Ultra Peripheral Collisions

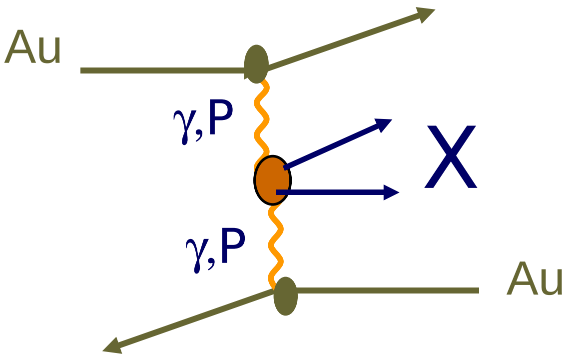
- Ultra Peripheral Collisions – nuclei miss each other and interact via long range fields
  - Electromagnetic fields can be treated as equivalent flux of photons
  - Weizsacker-Williams: a field of almost-real photons
    - Virtuality $Q^2 < (h/R_A)^2$
- Different particle production mechanism
  - Photon with certain probability can appear as qq(bar) pair
    - The wave function can be written as the Fock decomposition

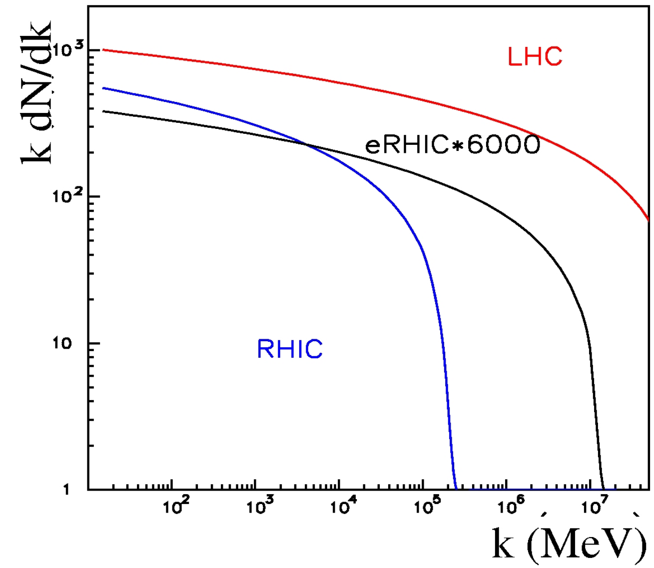
$$|\gamma\rangle = C_{bare} \, |\gamma_{bare}\rangle + C_\rho \, |\rho\rangle + C_\omega \, |\omega\rangle + C_\phi \, |\phi\rangle + \ldots + C_q \, |qq\rangle$$

  - Conservation of the quantum number (γ: $J^P = 1^-$)
  - Photon tends to fluctuate into vector meson ρ,ω,φ – Vector Meson Dominance

Ultra Peripheral Collisions

- 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
  - RHIC & LHC have higher luminosities for light ions --> often better overall rates





k is given in the rest frame of the nucleus

Production Rates

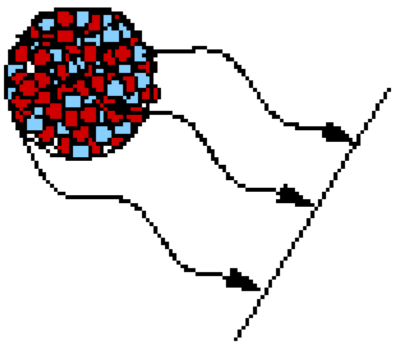
- Photonuclear vector meson production is the dominant coherent process
  - $\sigma(VMD) \approx 100 \times \sigma(\gamma\gamma)$
- At RHIC :
  - $\sigma(AuAu \rightarrow AuAu+\phi)$ = 39 mb photonuclear
  - $\sigma(AuAu \rightarrow AuAu+f_2(1270))$ = 0.54 mb $\gamma\gamma$
- Different types of reaction
  - Exclusive : nuclei stays in tact no other particles in the event
  - Coherent: fields couple to the entire nucleus with momentum transfer at the order of 1/R
  - Incoherent – scatters from the individual nucleon
- Uniques signatures of the events which can be used to identify the events

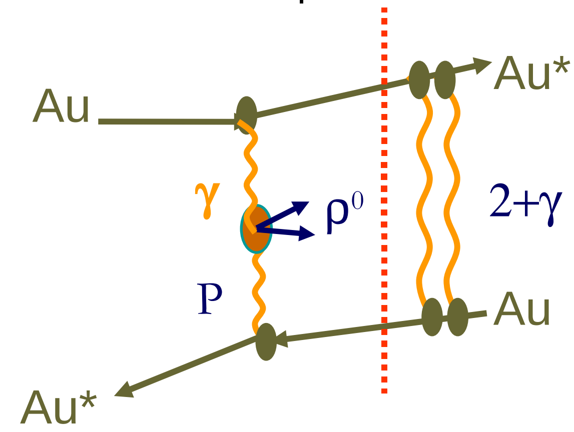
Cross sections at RHIC

	σ [mb]	(prod. rate)
ρ	590	(120 Hz)
ω	59	(12 Hz)
ϕ	39	(7.9 Hz)
J/ψ	0.29	(0.058 Hz)

Photonuclear and $\gamma\gamma$ Interactions

- Photonuclear interactions
  - γ-Pomeron/meson can be coherent
    - Coupling: $A^{4/3}$ (surface) to A^{2} (volume)
- $\gamma\gamma$ interactions
  - QED process – proposed as luminosity monitor
- Strong coupling and multiple interactions
  - $Z^2\alpha$ ~ 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





Factorization and Impact Parameter Tagging

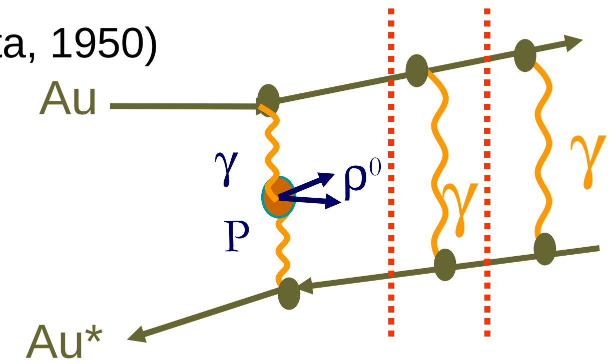
- Multiple photons are emitted independently (Gupta, 1950)
- To the lowest order, interactions are independent

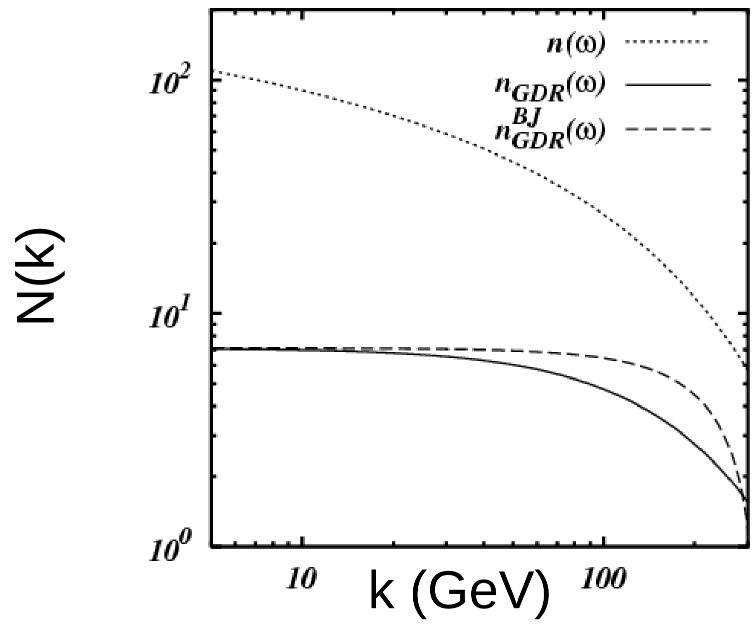
$$\sigma = \int d^2b P_1(b) P_2(b) \ldots$$

  - True for $\gamma\gamma$ + nuclear breakup for heavy io
- Nuclear excitation tags small b

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

- Multiple interactions are probable
  - P(2EXC, b=2R) ~ 30%





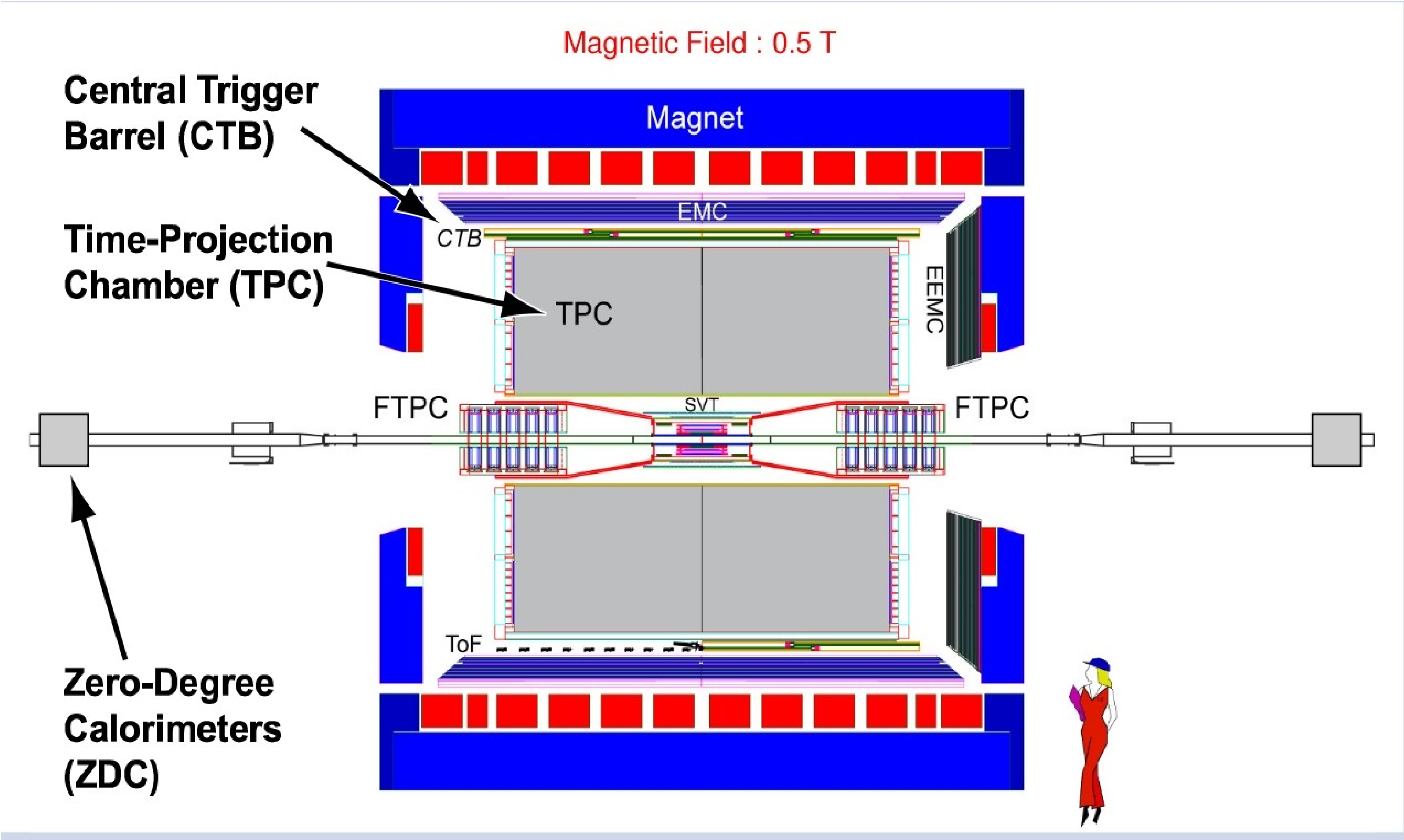
G. Baur et al, Nucl. Phys. A729, 787 (2003)

Photon spectra at RHIC

Photoproduction Physics

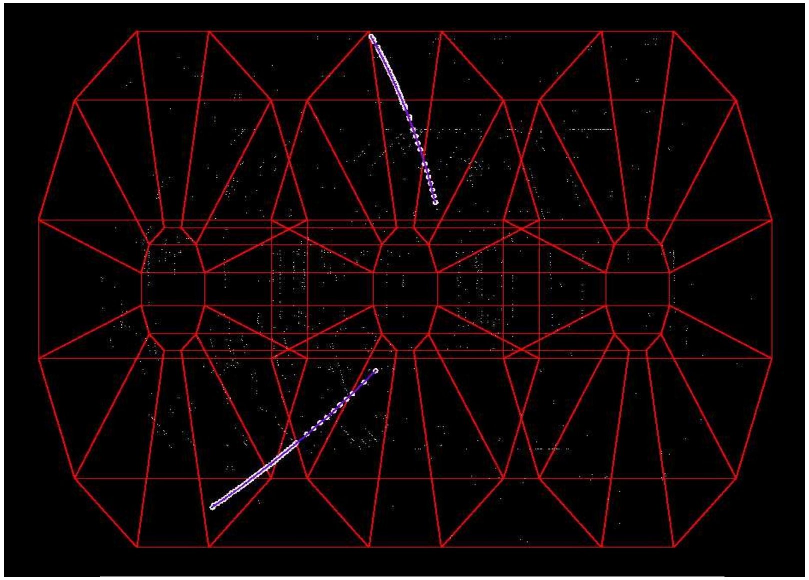
- Gluon structure function
  - γA -> J/Ψ, cc(bar), dijets, etc
    - $\sigma_{J/\Psi} \sim g^2(x)$
    - $\sigma_{QQ,\ dijets} \sim g(x)$
- Meson spectroscopy
  - ρ,ω,φ, excited states, etc
    - ρ' state which believed to consist of ρ(1450) and ρ(1700)
    - $\sigma(\gamma p \rightarrow \rho p)$ and $\sigma(\gamma A \rightarrow \rho A)$ of the two components should scale differently with A due to shadowing
- Transition from soft physics (ρ,ω,φ) to pQCD (J/Ψ, Y)
- Fundamental tests of Quantum Mechanics
  - Interference between non overlapping particles
- Multiple production
  - Unitarization of the strong fields leads to production of multiple VM in a single event

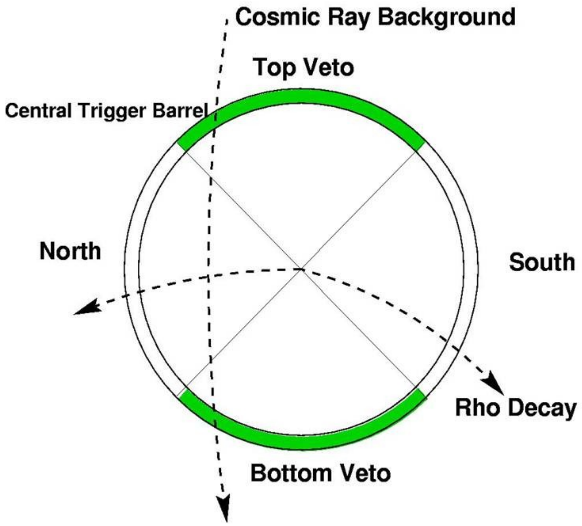
STAR Detector

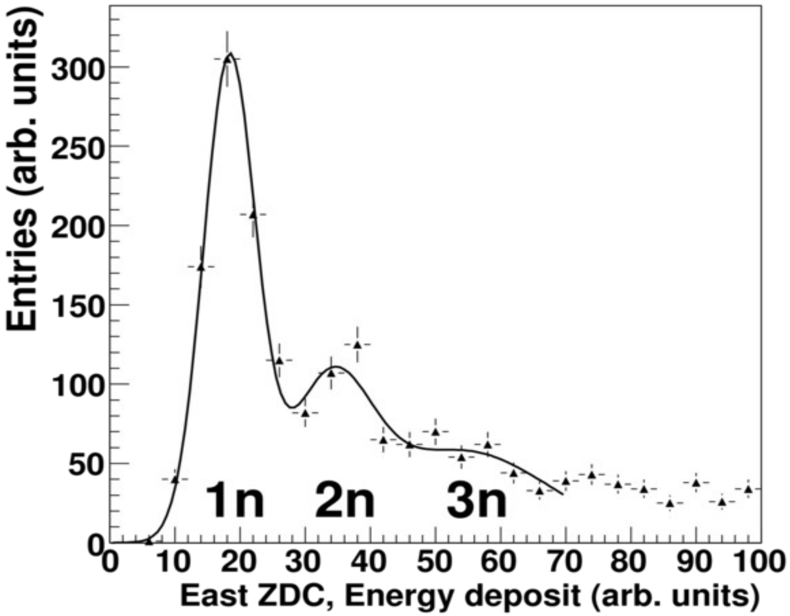


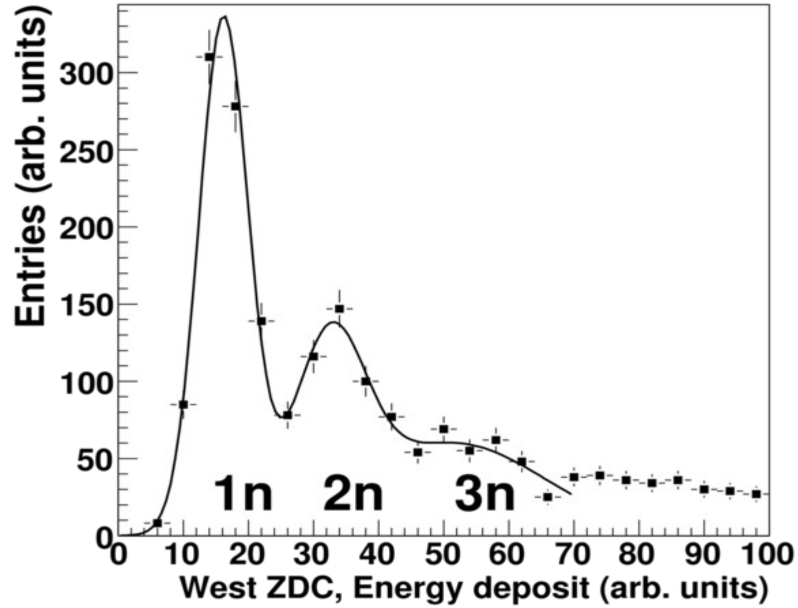
Signatures & Triggering

- 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









- Acceptance of the ZDCs is close to 1
- Good resolution , allows to select different excited states
- Neutron tag allows to select different median <b>

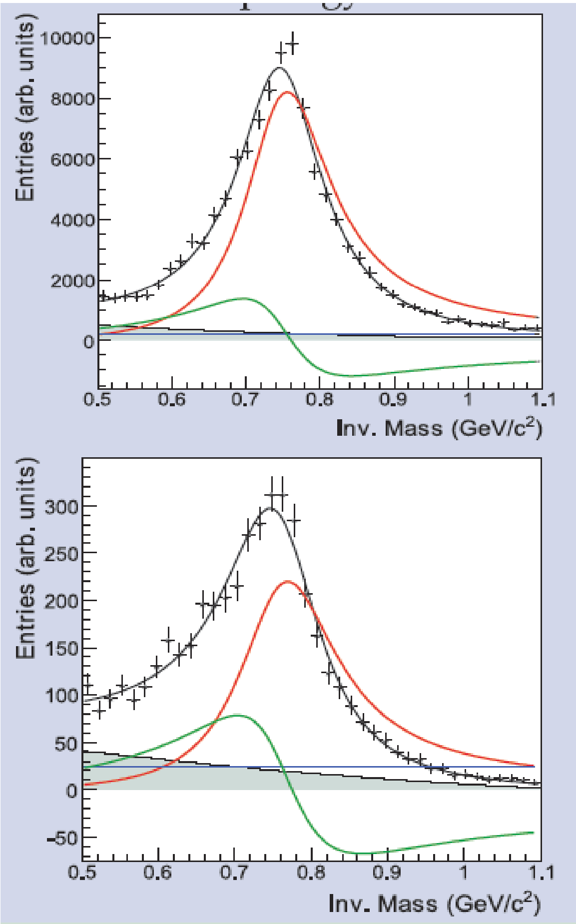
Background and its Reduction

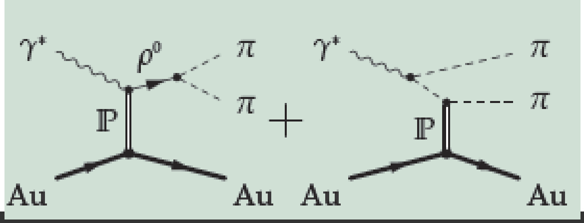
- Beam Gas Interactions
  - Requiring low track multiplicity
  - Limiting primary vertex position
- Peripheral hadronic interactions
  - Requiring low track multiplicity
  - Selecting low p_T
- Pile up events
  - Low track multiplicity
  - Limiting primary vertex position
- Cosmic Rays
  - Minimum bias trigge: ZDC neutron tag
  - Topology trigger : excluding events around |y| =0

ρ^0 Photoproduction at STAR

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

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

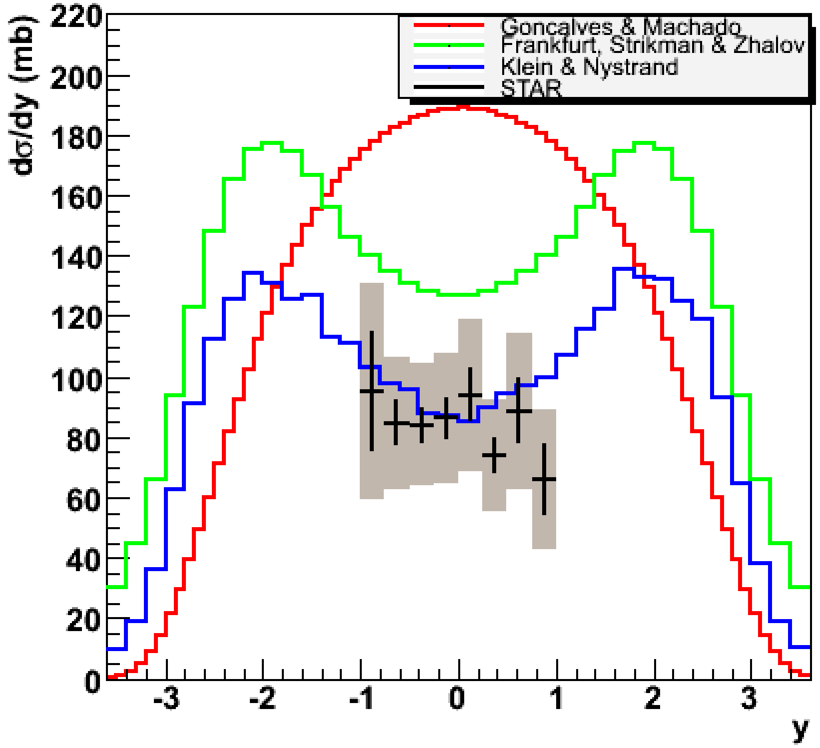




Phys. Rev. C77 34910 (2008)

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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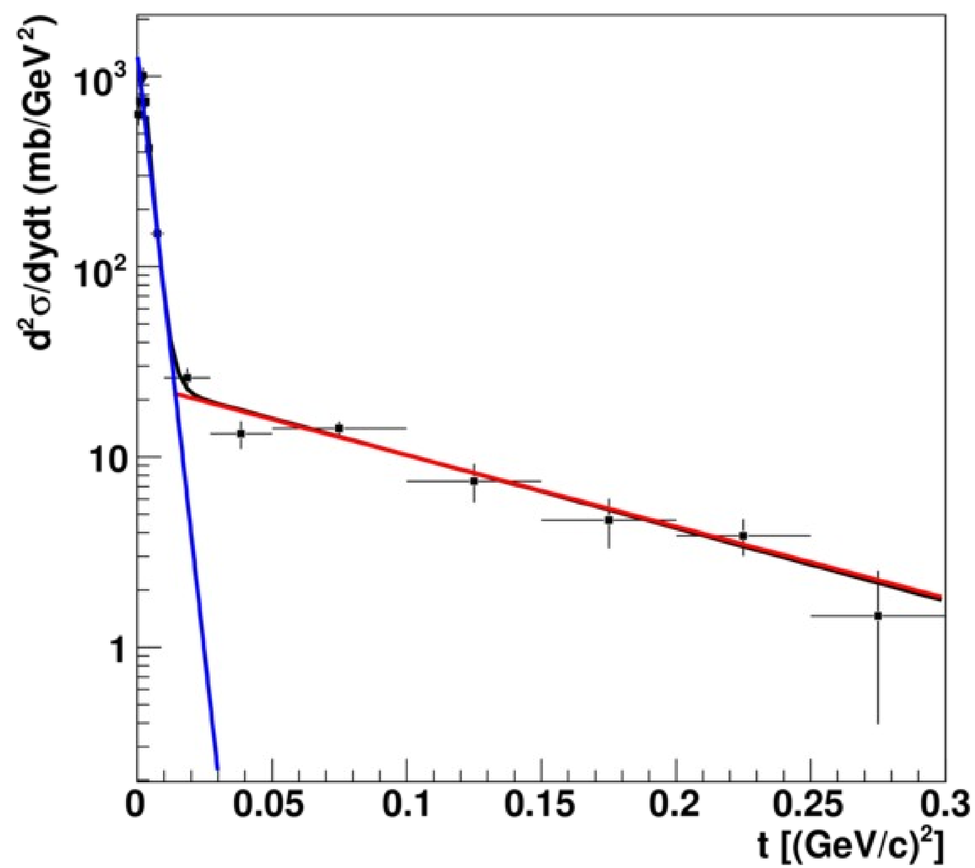
Coherent and Incoherent Production of ρ

- 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
      - $b_{Au} \sim R_A^2$
- $\sigma(incoh)/\sigma(coh) \sim 0.29 \pm 0.03$



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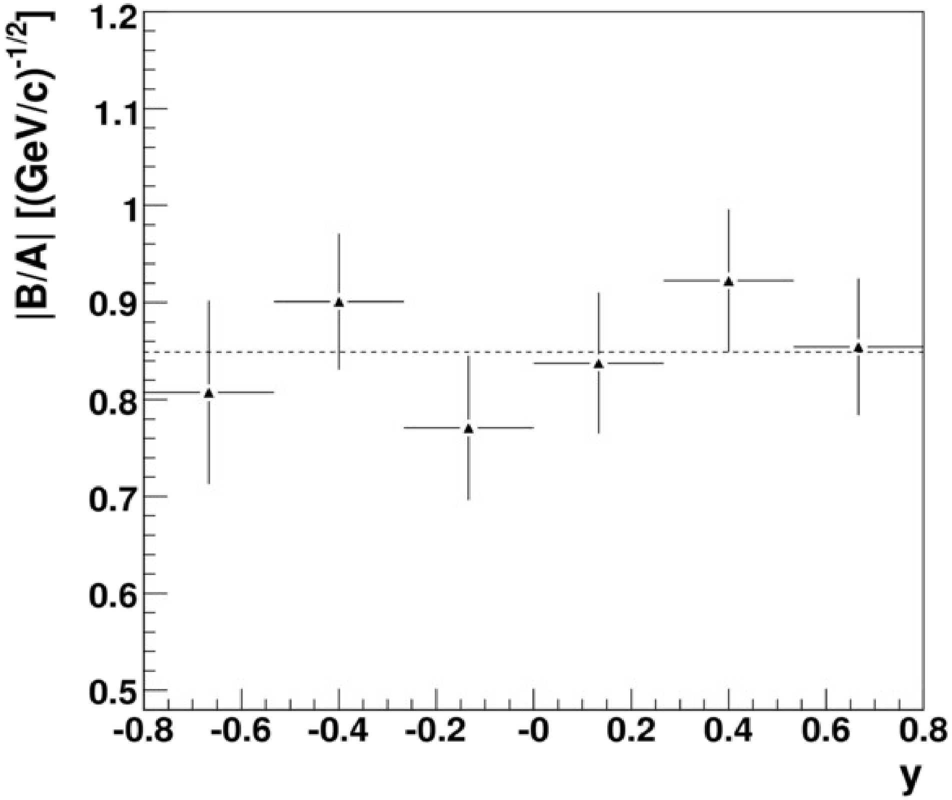
$$\frac{d\sigma}{dt} = a * \exp(-b_{Au} * t) + c * \exp(-b_N * t)$$

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

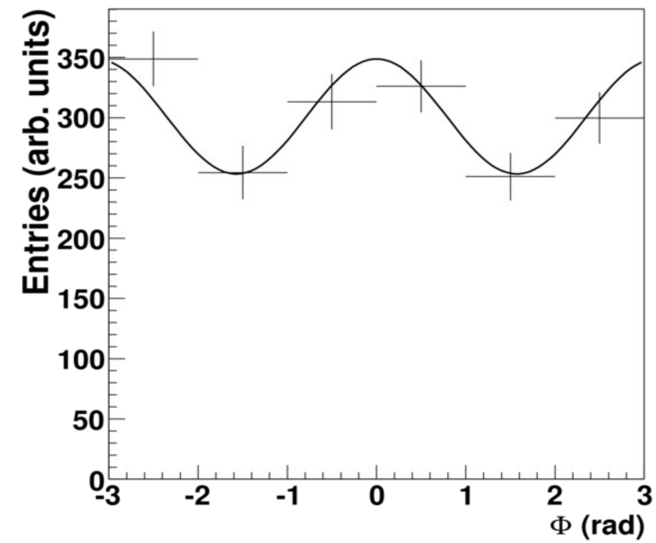
- S-channel helicity conservation
  - Produced vector meson retains helicity of the initial photon

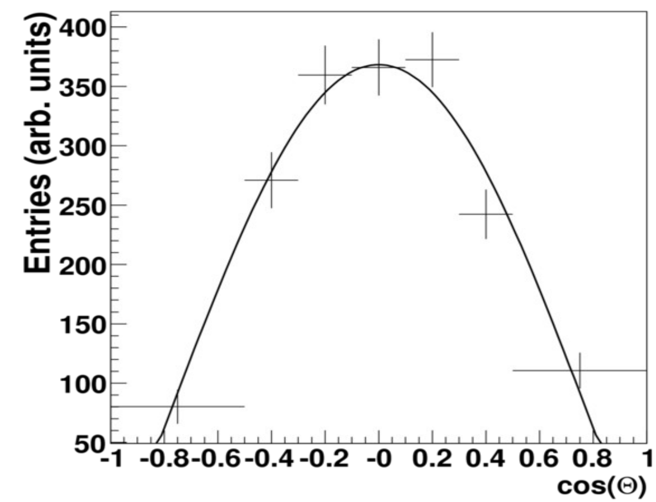
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos(\Theta_h)d\Phi_h} = \frac{3}{4\pi}[\frac{1}{2}(1-r_{00}^{04}) + \frac{1}{2}(3r_{00}^{04}-1)\cos^2(\Theta_h)$$
$$-\sqrt{2}\Re e[r_{10}^{04}]\sin(2\Theta_h)\cos(\Phi_h) - r_{1-1}^{04}\sin^2(\Theta_h)\cos(2\Phi_h)]$$

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

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

    - 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

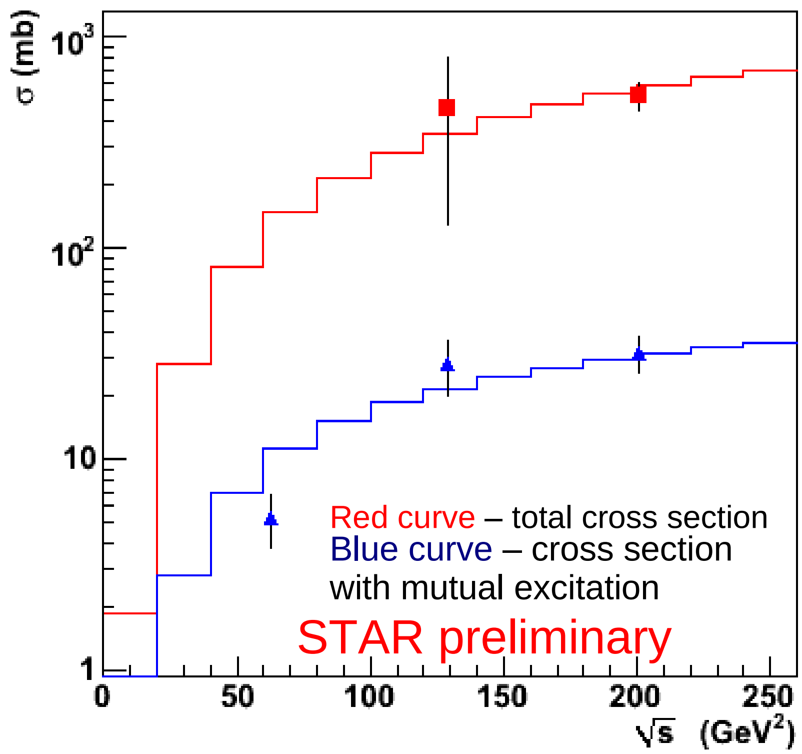




Phys. Rev. C77 34910 (2008)

ρ Production Cross Section

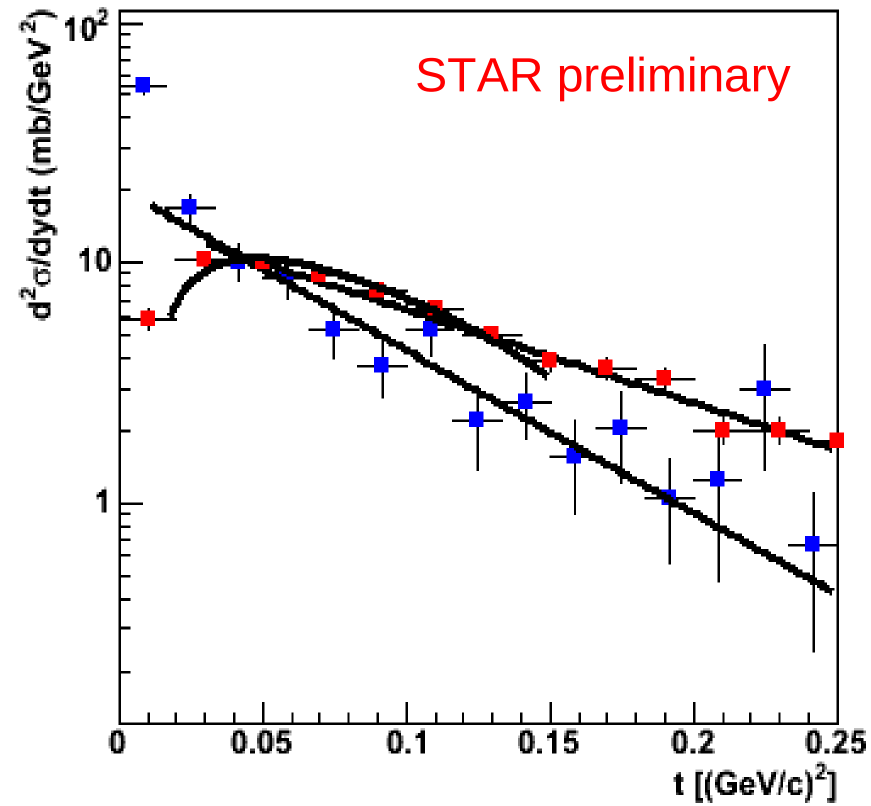
- Several data sets:
  - AuAu √s=62 GeV In progress
  - AuAu √s=130 GeV PRL89 272302 (2002)
  - AuAu √s=200 GeV PRC77 34910 (2008)
  - dAu √s=200 GeV In progress



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

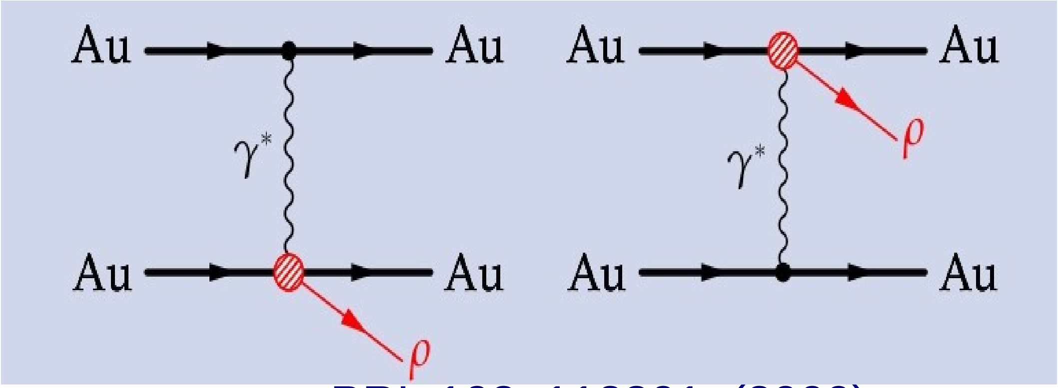


Red – incoherent production
Blue – coherent production

Interference in ρ Production

- Impossible to distinguish source of γ and target
  - VM are short lived - Decay points are separated in space-time
    - No interference

    OR
    - The wave function retains amplitudes for all possible decays, long after decay occurs
  - Non-local wave function - Non factorizable $\Psi_{\pi+\pi-} = \Psi_{\pi+}\Psi_{\pi-}$

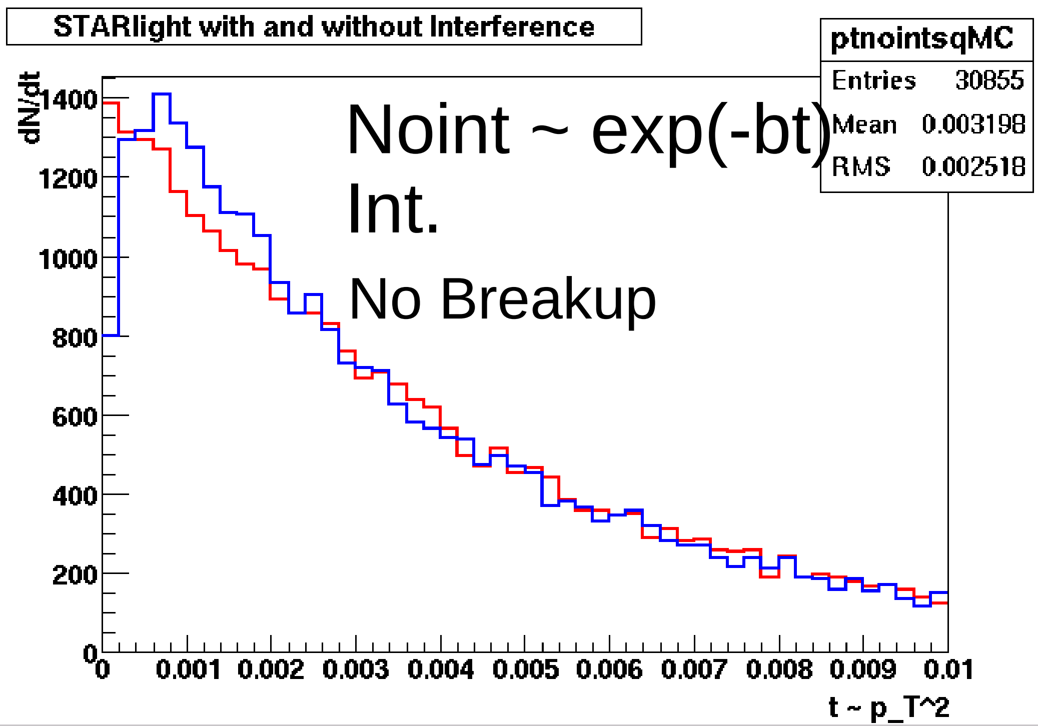


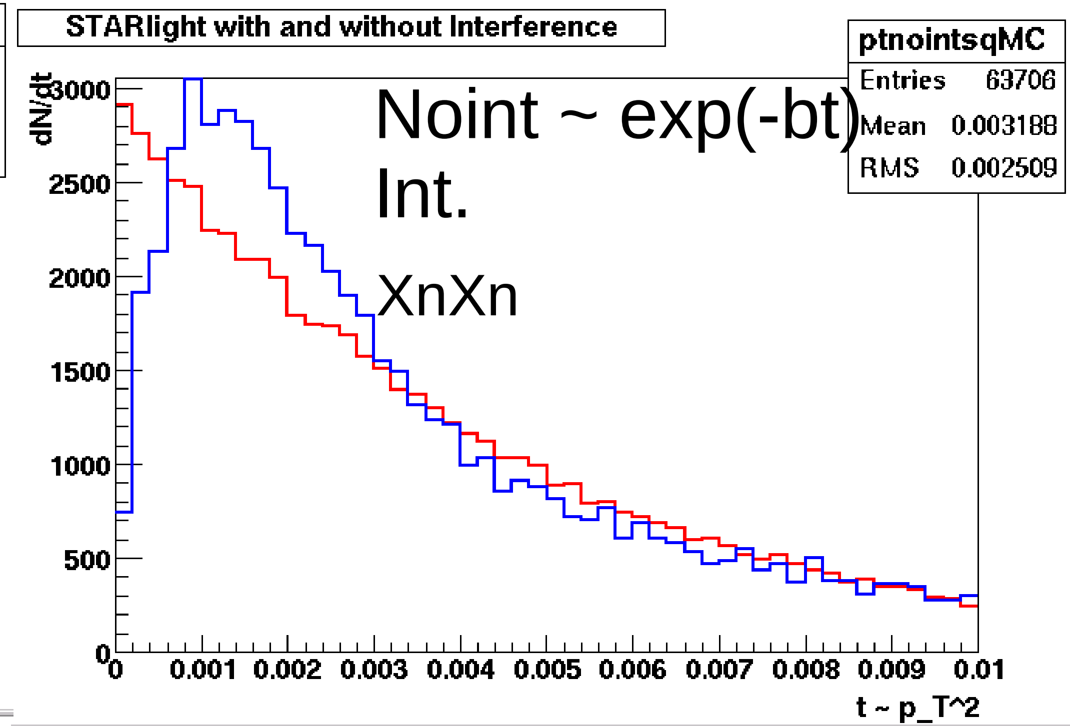
PRL 102, 112301 (2009)

- 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 and Nuclear Excitation

- Smaller <b> -> interference at higher $\langle p_T \rangle$
  - Suppression for $\langle p_T \rangle < h/b$

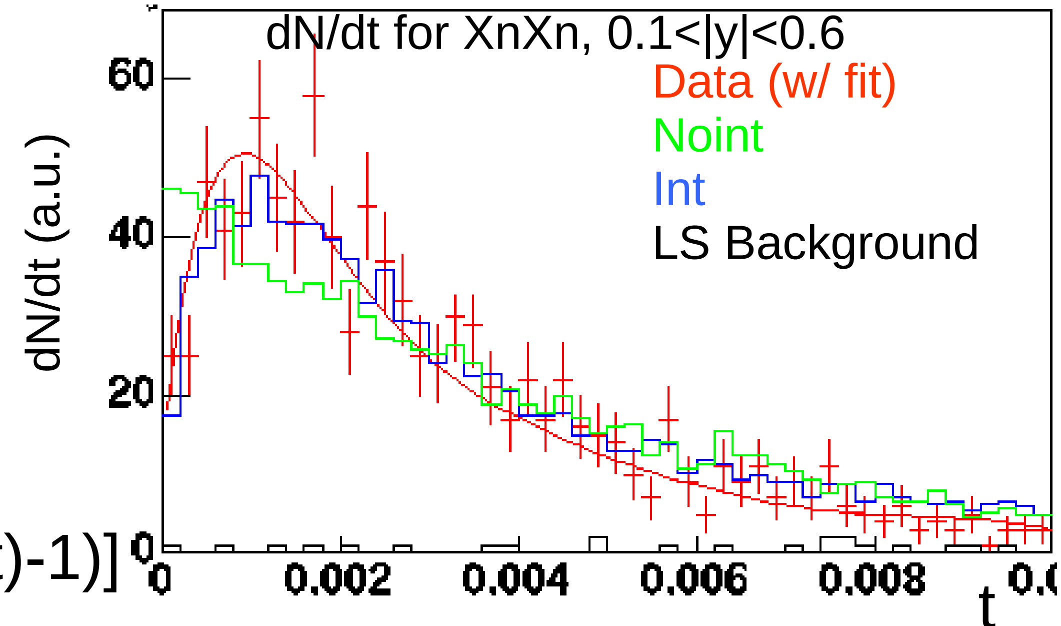


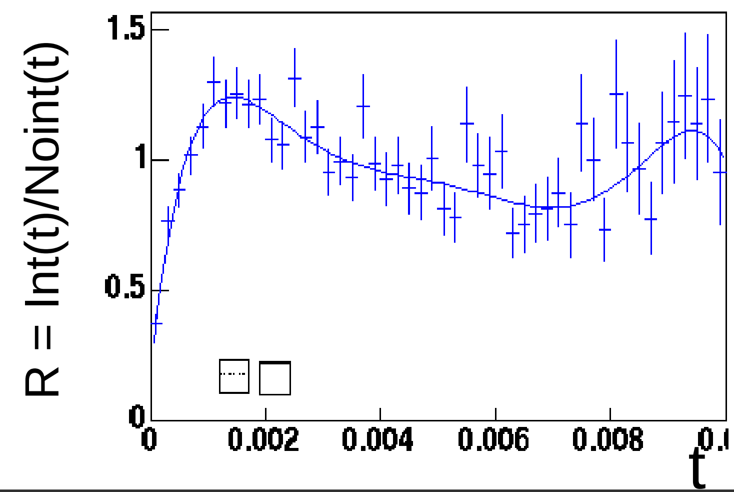


Interference Analysis

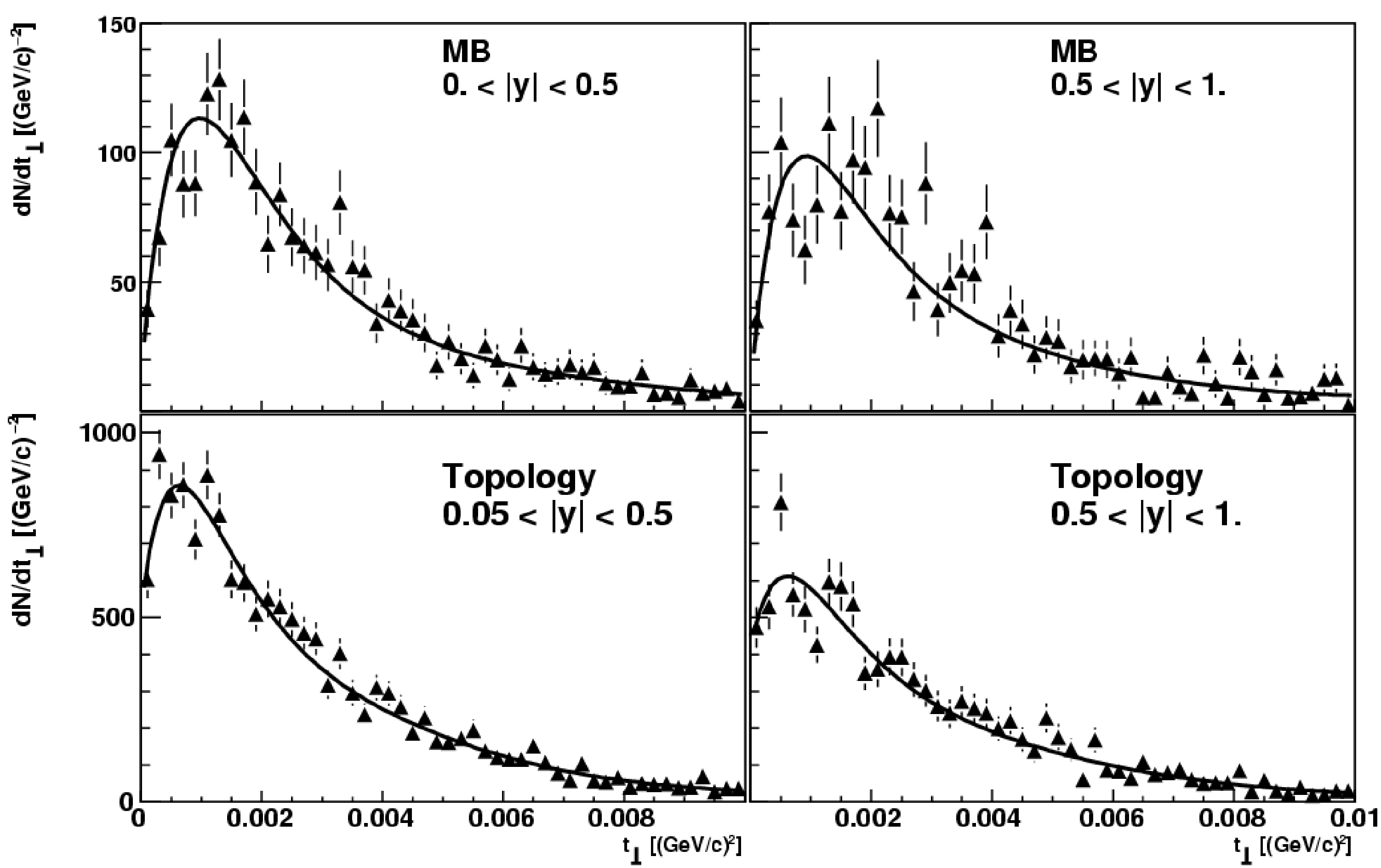
- Topology (multiplicity) trigger for exclusive ρ^0
- Neutron in both ZDCs to select events with mutual Coulomb excitation
- Tight selection cuts
  - Exactly 2 tracks
  - 1 vertex with Q=0
  - $0.52 < M\pi\pi < 0.92$ GeV
- Fit dN/dt spectra
  - Require clean dN/dt w/o interference
  - Efficiency independent in t
    - Momentum smearing affects two low t bins
      - Included in MC
- Maximum interference at |y| =0 and decreases with rise of y
  - Two rapidity bins : 0.05<|y|<0.5 and 0.5<|y|<1.0

- 2 Monte Carlo samples
  - Interference
  - No interference
  - Including detector effects
- Data matches int
- Inconsistent with noint
- Fit to dN/dt = A exp(-kt)* [1+c(R(t)-1)]
  - Exponential for nuclear form factor
  - R = Int(t)/NoInt(t)
  - Separates nuclear form factor (exponential) & interference





Interference in coherent ρ Production



- Efficiency corrected spectra
- MB – top row , Topology bottom row
  - Cut at 0.05 rapidity to remove cosmics

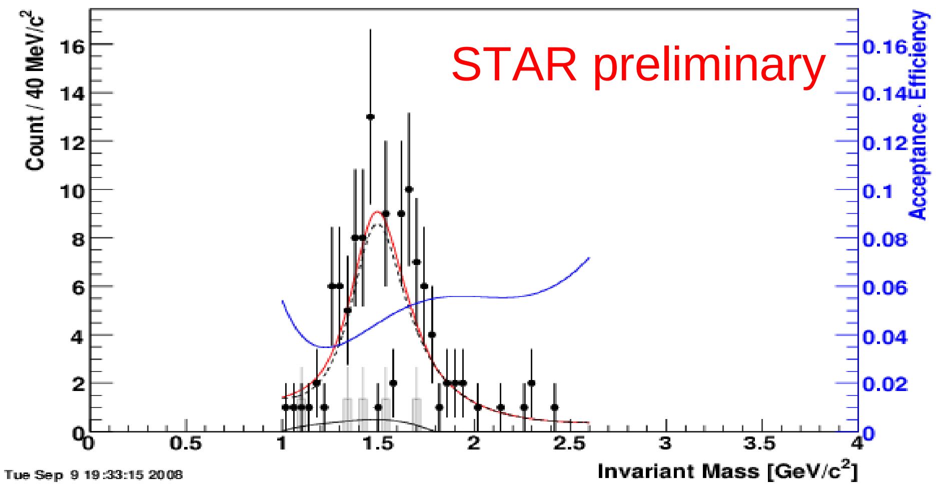
Results

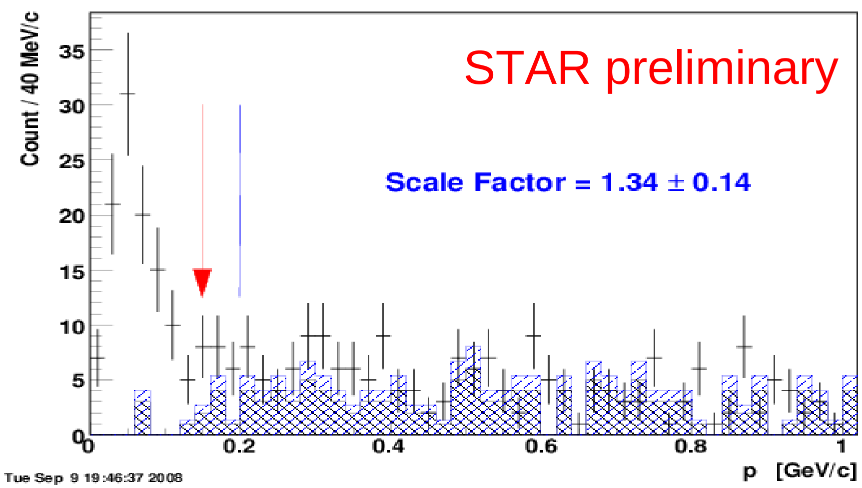
Dataset	A	k (GeV^{-2})	c	$\chi^2/$ DOF
MB, $\|y\| < 0.5$	$6,471 \pm 301$	299 ± 12	0.92 ± 0.07	$45/47$
MB, $0.5 < \|y\| < 1.0$	$5,605 \pm 330$	303 ± 15	0.92 ± 0.09	$76/47$
T, $0.05 < \|y\| < 0.5$	$11,070 \pm 311$	350 ± 8	0.73 ± 0.10	$53/47$
T, $0.5 < \|y\| < 1.0$	$12,060 \pm 471$	333 ± 11	0.77 ± 0.18	$64/47$

- χ^2/DOF > 1 for 2 samples
  - Scale errors by $\sqrt{\chi^2/\mathrm{DOF}}$ (PDG prescription)
- Systematic errors due to trigger (10% for topology), other detector effects (4%), background (1%), fitting & nuclear radius(4%), theoretical uncertanties (5%)
- Combined measured interference c=0.87 ± 0.05 (stat.) ± 8 (syst.)%

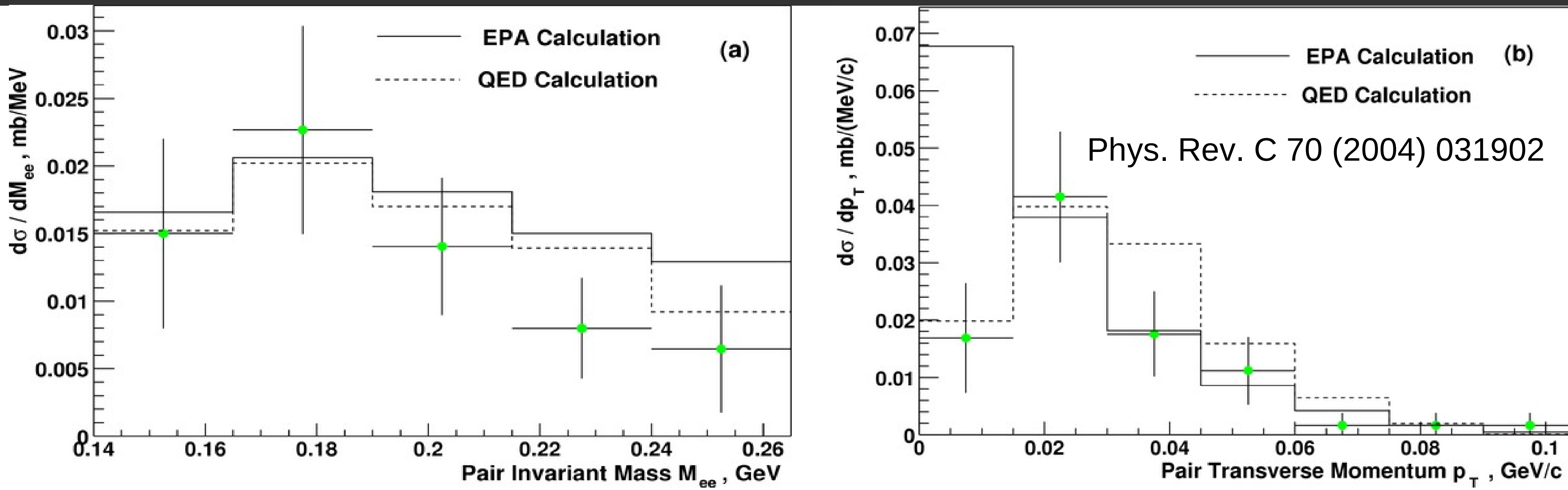
Photoproduction of $\pi^+\pi^-\pi^+\pi^-$

- 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)

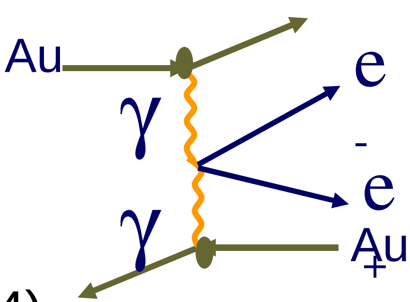




e^+e^- Production at STAR in AuAu at $\sqrt{s}$=200GeV

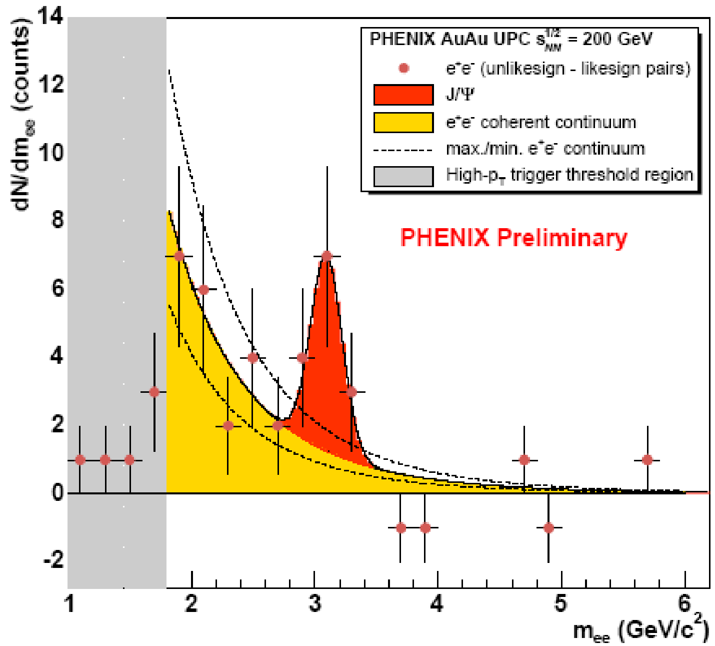


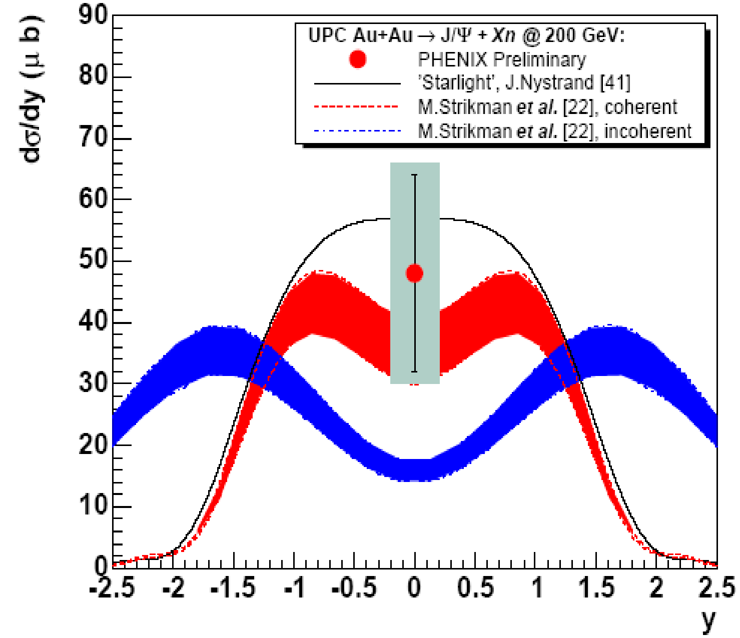
- Compared with two models
  - EPA(equivalent photon approach)
    - Treats γ as real photon
  - QED – lowest order QED calculation based on GDR only with correction for higher states Hencken PR C69 054902 (2004)



- New calculation by Baltz PRL 100, 062302 (2007)
  - Realistic phenomenological treatment of nuclear breakup

J/ψ Production at RHIC



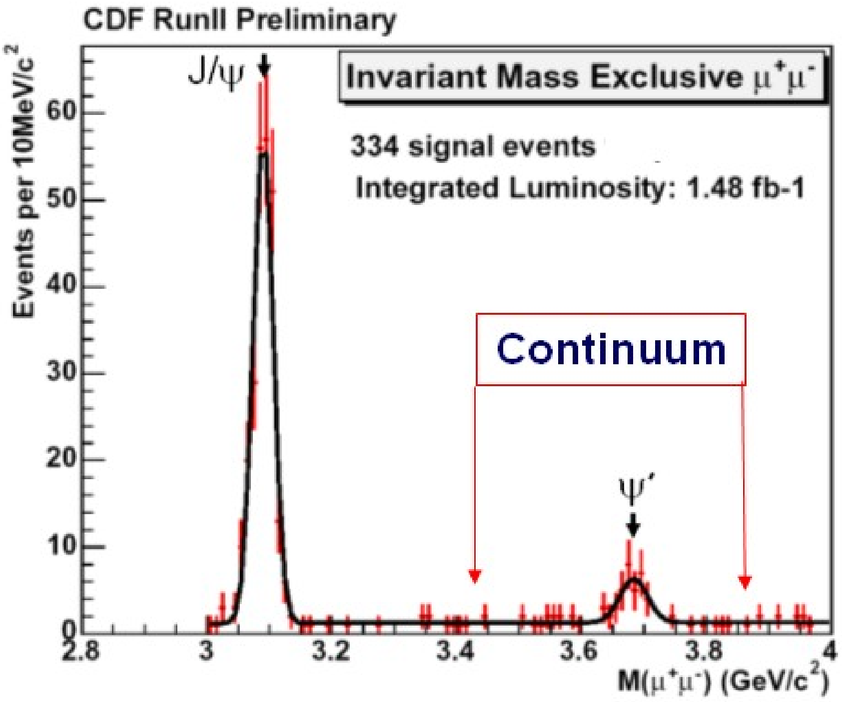


PHENIX, nucl-ex/0601001

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

J/ψ Production at Tevatron

- CDF collected an exclusive J/ψ data sample which is sensitive to the gluon structure of nuclei
  - $\sigma \sim |g(x,M_V^2/4)|^2$
- 334 exclusive $\mu^+\mu^-$ signal events
  - Background from $\chi_c \to \gamma J/\psi$
  - Some ψ' is present
- No final numbers on cross section yet

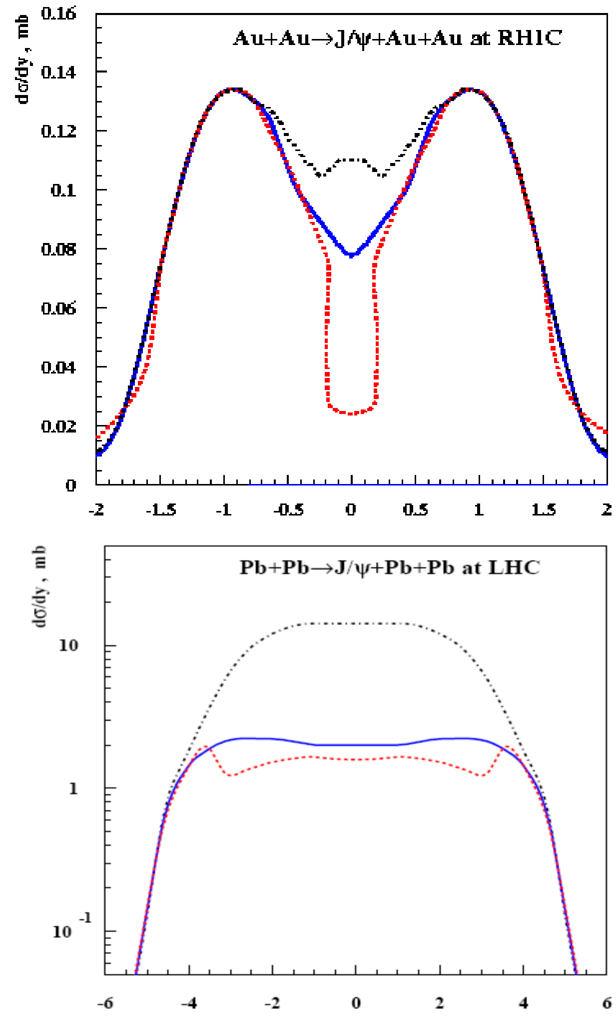


- J/ψ sensitive to gluon distribution in the nucleus
  - $\sigma \sim g(x,Q^2)^2$
    - X ~ few 10^{-4} for J/ψ at LHC
    - X ~ few 10^{-2} for J/ψ at RHIC
- Clear shadowing effect
  - Several factor difference in cross section at LHC

Black → Impulse Approx.

Red → gluon diffractive density

Blue → H1 Gluon density



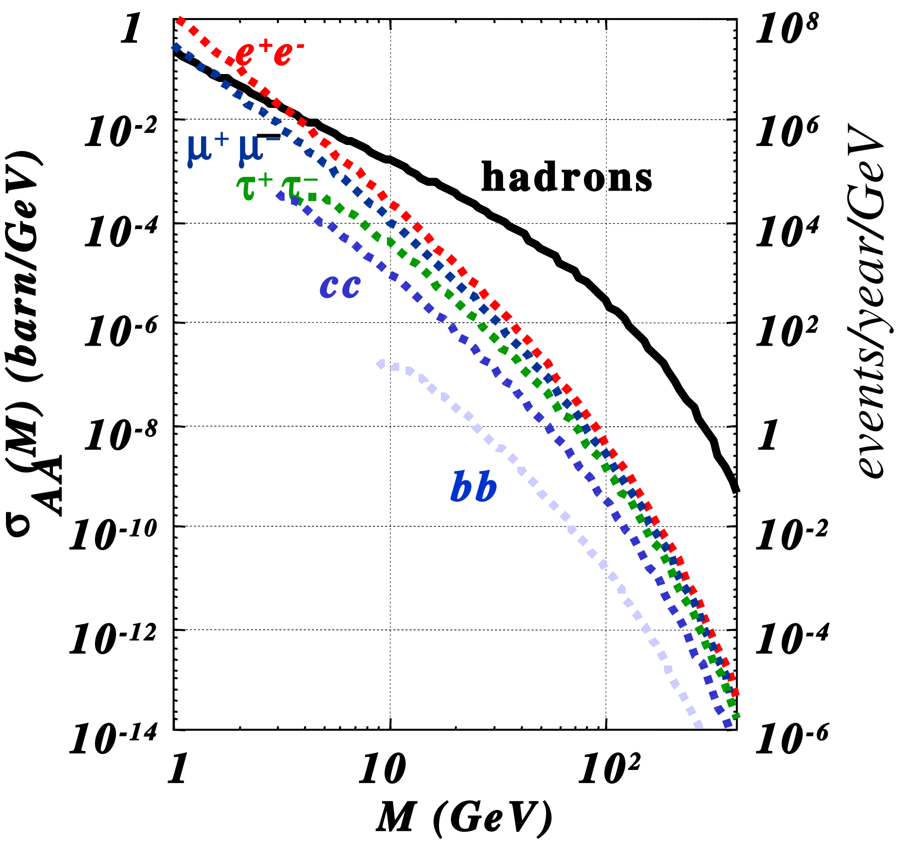
M. Strikman, F. Strikman and M. Zhalov, PL B540, 220 (2002)

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	2×10^8
$J/\psi \to e^+e^-$	central barrel	1.50×10^5
$\Upsilon(1S) \to e^+e^-$	central barrel	400 – 1400
$e^+e^-, M > 1.5$ GeV/c^2	central barrel, $p_T > 0.15$ GeV/c	7×10^5
$e^+e^-, M > 1.5$ GeV/c^2	central barrel, $p_T > 3$ GeV/c	1.4×10^4
$\mu^+\mu^-, M > 1.5$ GeV/c^2	muon spectrometer, $p_T > 1$ GeV/c	6×10^4

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

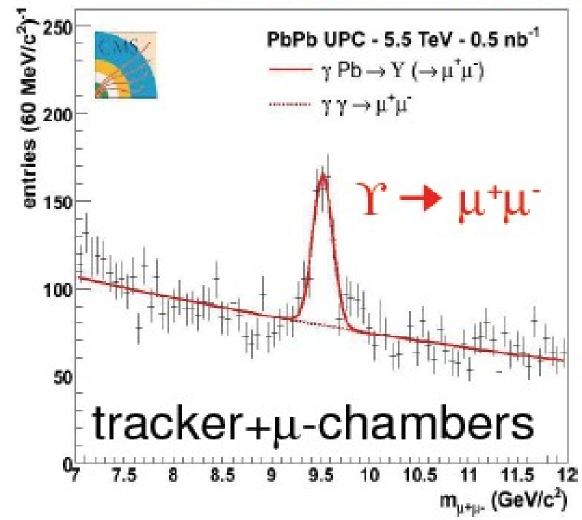


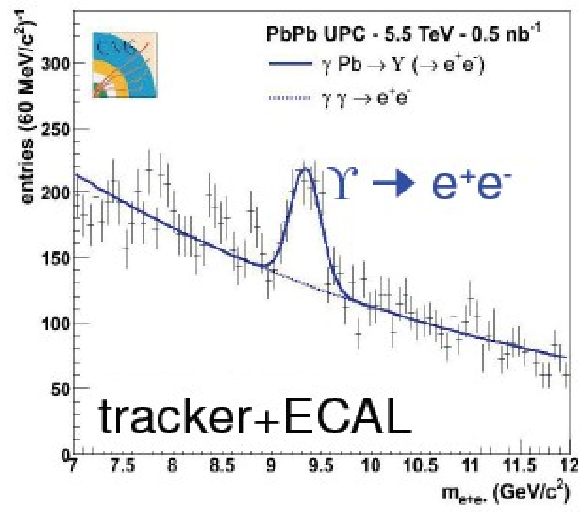
Program at LHC

- 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
    - $\sigma_{J/\Psi} \sim g^2(x)$
    - $\sigma_{QQ,\ dijets} \sim g^2(x)$
- The 'black disc' regime of QCD
- Search for exotica/new physics
  - $\gamma\gamma$ --> Higgs, Magnetic monoples, etc.
- Diffractive phenomenon
  - Roman pots useful for pp

- J/ψ,ψ', ϒ in lepton channel
  - CMS, ATLAS, Alice
    - γ+A →J/Ψ +A
      - expected prod rate ~ 1×10^7/ year
    - γ+A →ϒ +A
      - expected prod rate ~ 1×10^5/ 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

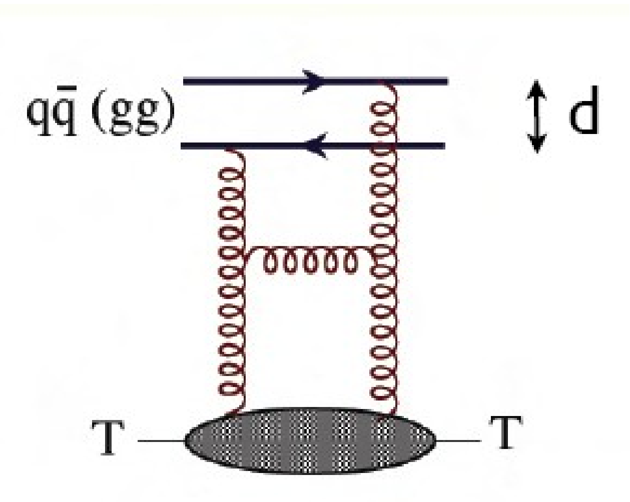
Dd'E, hep-ex/0703024





"Black Disk" Regime

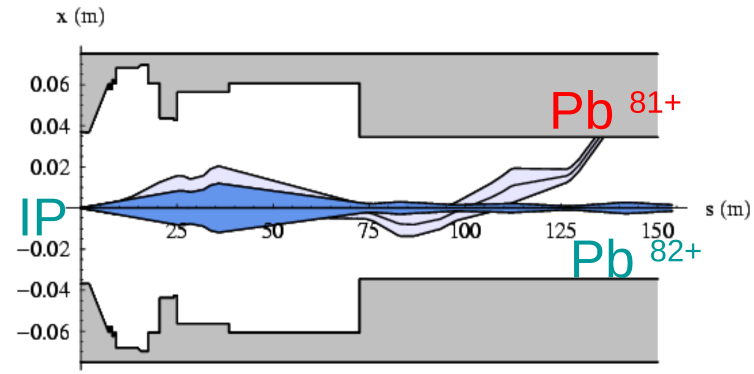
- At high energy (low *x*) nuclei *look like a black (absorptive) disk*
  - Based on the results from HERA the regime should be visible at $Q^2 < 4\ \text{GeV}^2$
- Photon fluctuates into qq dipoles with separation d
  - $\sigma_{\text{dipole-target}} \sim \pi d^2$
  - Photons contain many dipoles which leads to the increase of the number of interactions and rise of corresponding $\sigma_{tot}(\gamma p)$
  - Increase in high pt interactions
  - Fraction of the diffractive events increases



Bound Free Pair Production

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

- A + A --> A + Ae^- + e^+
  - e^- is captured by one of the nuclei
  - $1e^-$ atom has lower Z/A
    - Less bending in the dipole
- Estimated cross section is ~ 280 barns at LHC
  - 280,000 ions/s at $L = 10^{27}/cm^2/s$ result in 28 watts
  - Hits the beam pipe ~ 136 m from the interaction point
    - Possible can effect the performance of the magnet and limit heavy ion luminosity at LHC



R. Bruce et al. PRL **99**, 144801 (2007)

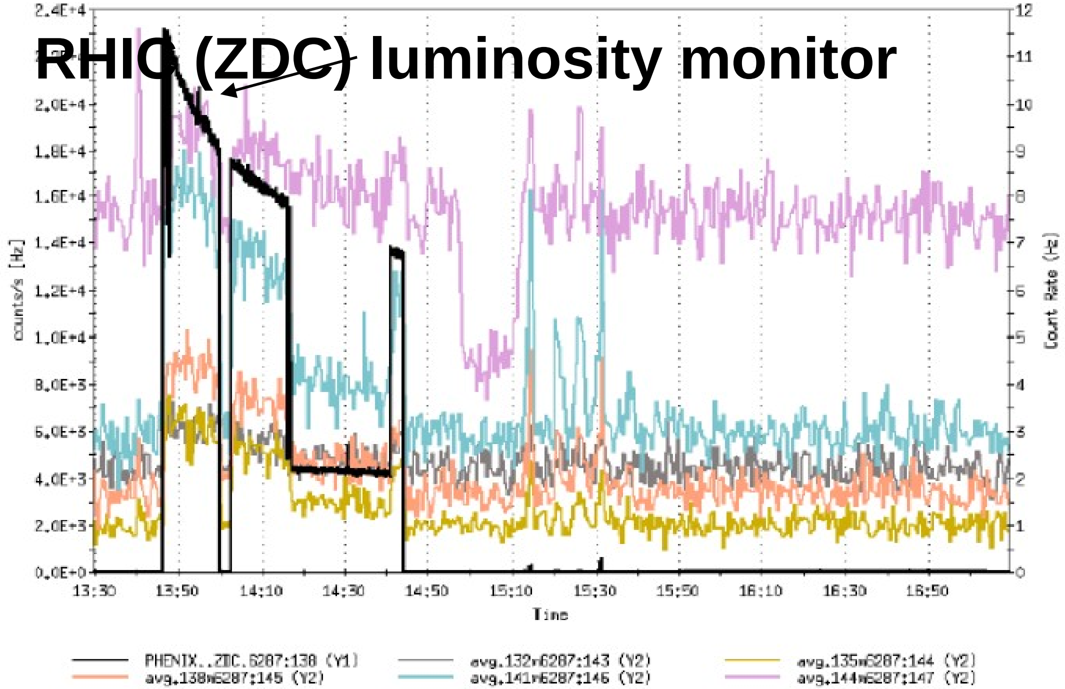
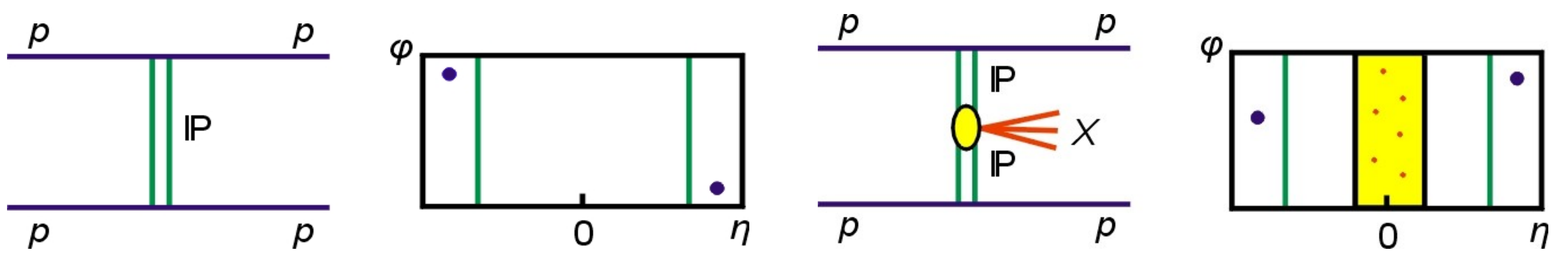


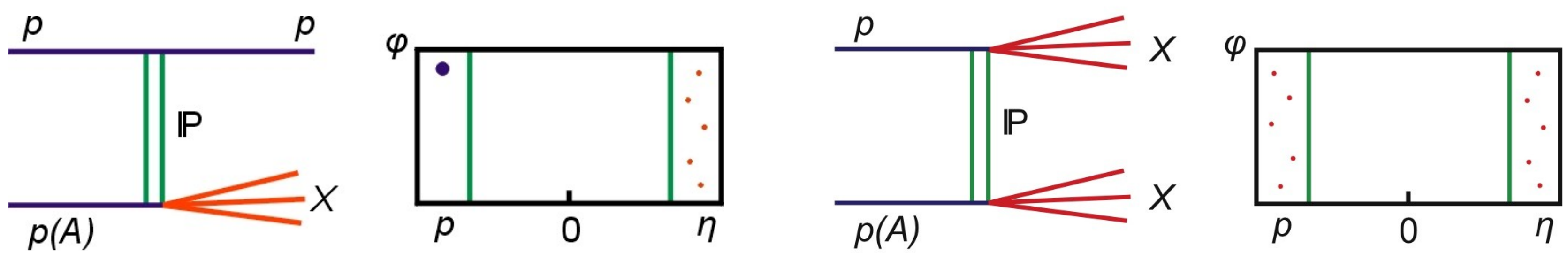
Figure 3: Count rates measured on the ZDC luminosity monitors (black, left scale) and PDs (colours, right scale) during a store in which beams were put into collision just after 13:45 with PDs in the wide configuration.

- Can be observed by looking for showers with PIN diodes
  - Correlation between luminosity and PIN diodes rates

- p + p → p + p



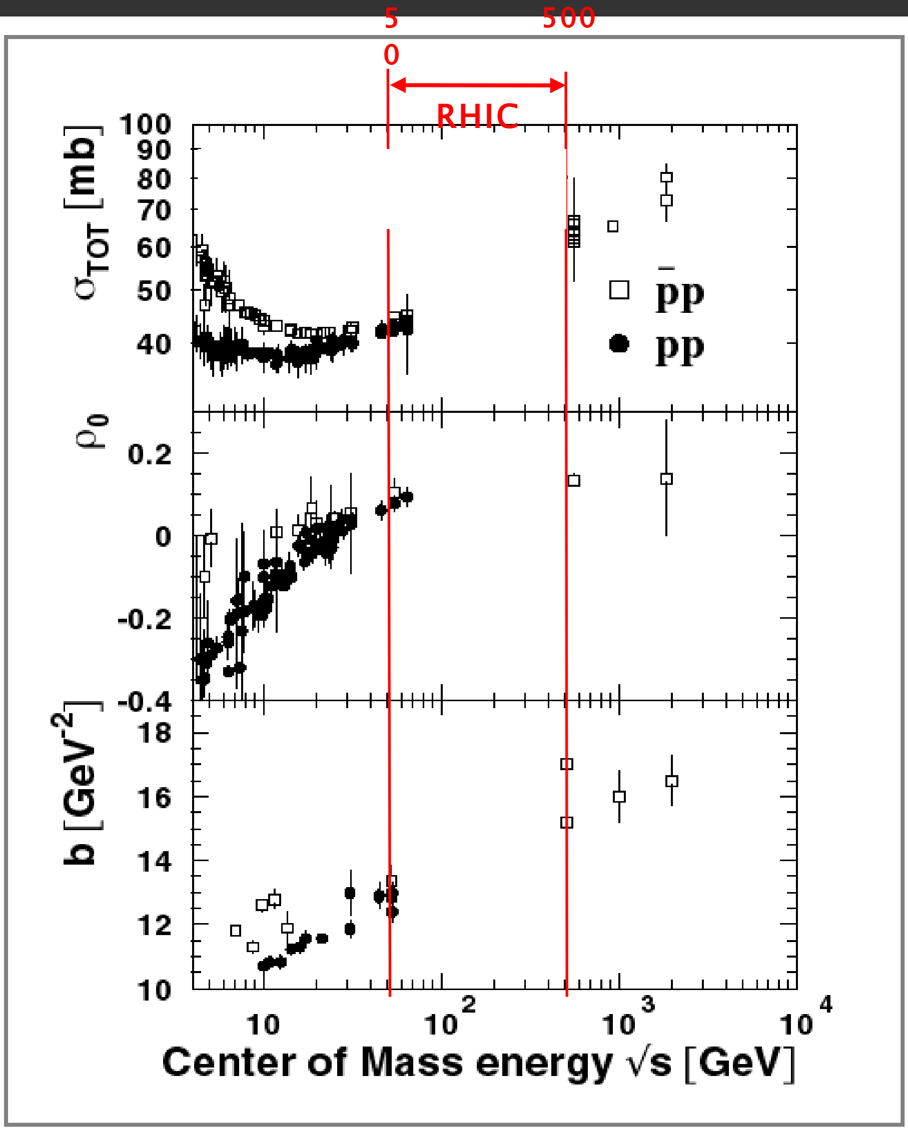
- p + p → p +X+ p ; X = particles, jets,...



Physics with Tagged Forward Protons

- Study standard hadron diffraction both elastic and inelastic and its spin dependence in unexplored t and $\sqrt{s}$ range;
- Study the structure of color singlet exchange in the non-perturbative regime of QCD.
  - Pomeron exchange consists of the exchange of a color singlet combination of gluons - triggering on forward protons at high energies predominantly selects exchanges mediated by gluonic matter
- Search for central production of light and massive systems in double Pomeron exchange process (glueballs)
  - Pomeron is made from two gluons – natural place to look for gluon bound state
- Search for an Odderon - an eigenstate of CGC
  - Odderon (C=1) is the counterpart of the pomeron with C= -1

Existing Elastic Data



- Elastic scattering in the energy range not measure before - unique measurement in wide t range with polarized beam
  - Highest energy so far
    - pp 62 GeV ISR
    - p(b)p 1.8 TeV Tevatron
  - RHIC energy
    - RHIC energy range:

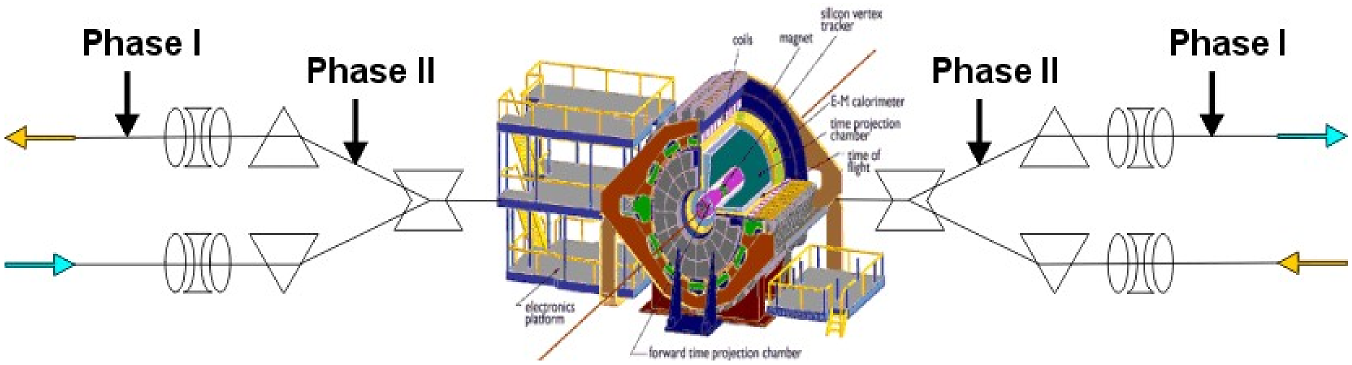
      50 GeV $\leq \sqrt{s} \leq$ 500 GeV
    - RHIC $|t|$-range:

      (at $\sqrt{s}$ = 500 GeV)

      $4 \cdot 10^{-4}$ GeV$^2 \leq |t| \leq$ 1.3 GeV^2

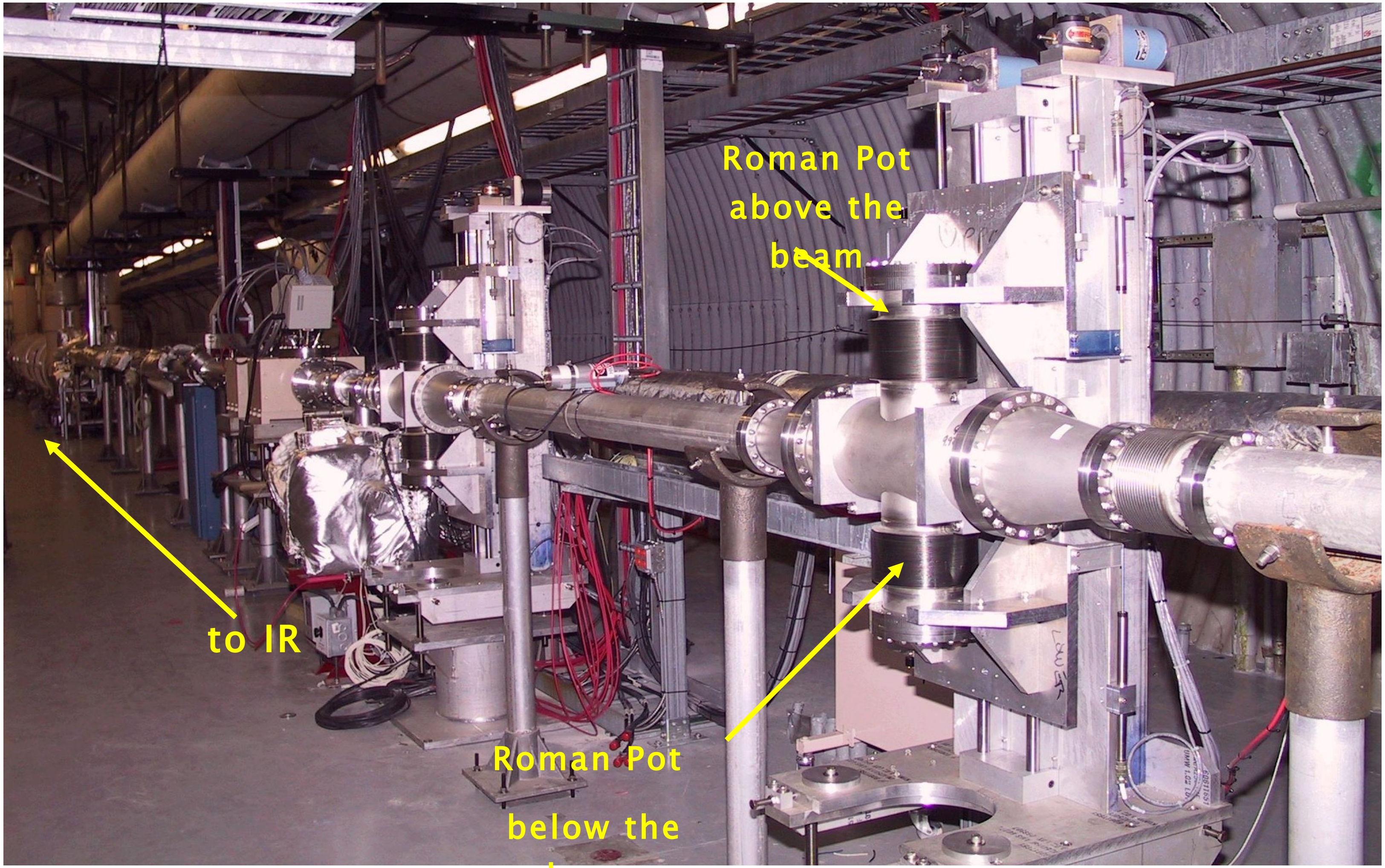
Detector

- Roman pots to measure forward protons : small t (four-momentum transfer) and **$\xi = \Delta p/p$, M_x** invariant mass
- Detector with good acceptance and particle Id for measurement of the centrally produced systems - STAR!



Roman Pots from pp2pp experiment has been installed at STAR

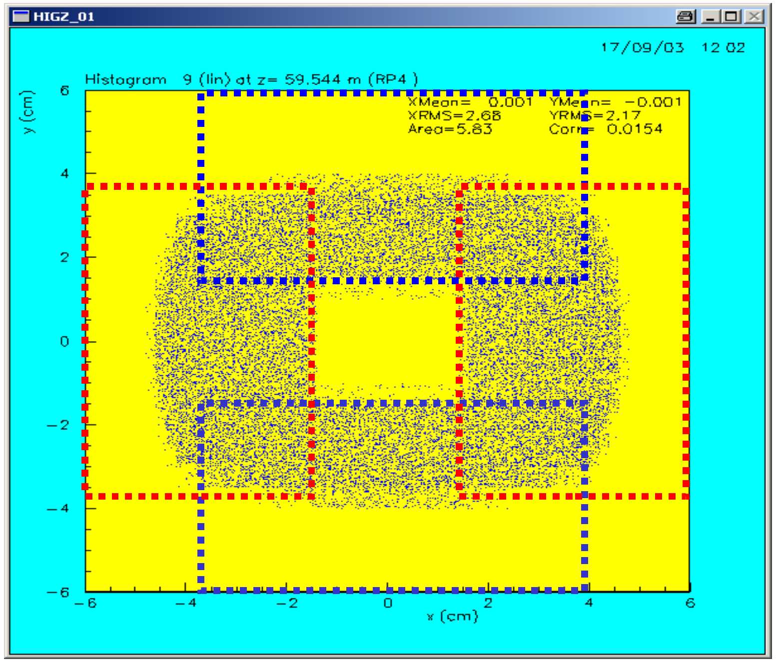
Roman Pots



Phase I and II

- Phase I: 8 roman pots at ~ ±60 m away from IP
  - Requires a special beam tuning parameters
  - Commissioning is in progress , the program is focused on $0.002 < |t| < 0.03$ GeV^2
- Phase II : roman pots at ~ 12 m from IP
  - Planned to be available 2011-12
  - Does not require any special beam conditions (great benefit for central production studies)

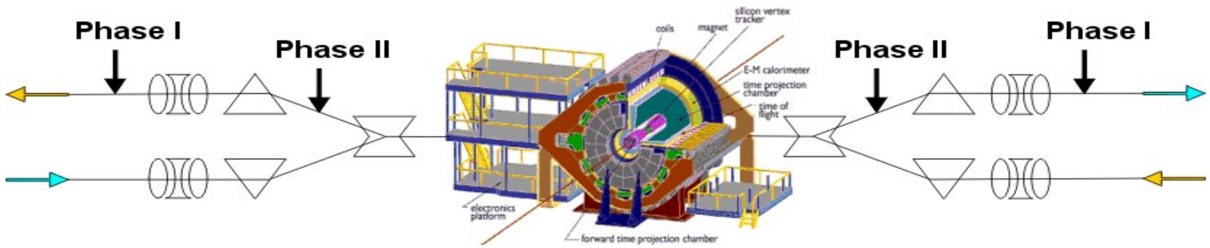
x-y



Summary

- Hadron collider is unique tool to study photoproduction reaction
  - At RHIC STAR & Phenix have studied several topics
    - Published new measurement of ρ^0 production cross section at $\sqrt{s}$=200 GeV
      - Good agreement with theoretical predictions
    - Interference effect - PRL 102, 112301 (2009)
    - 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

- 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

- 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

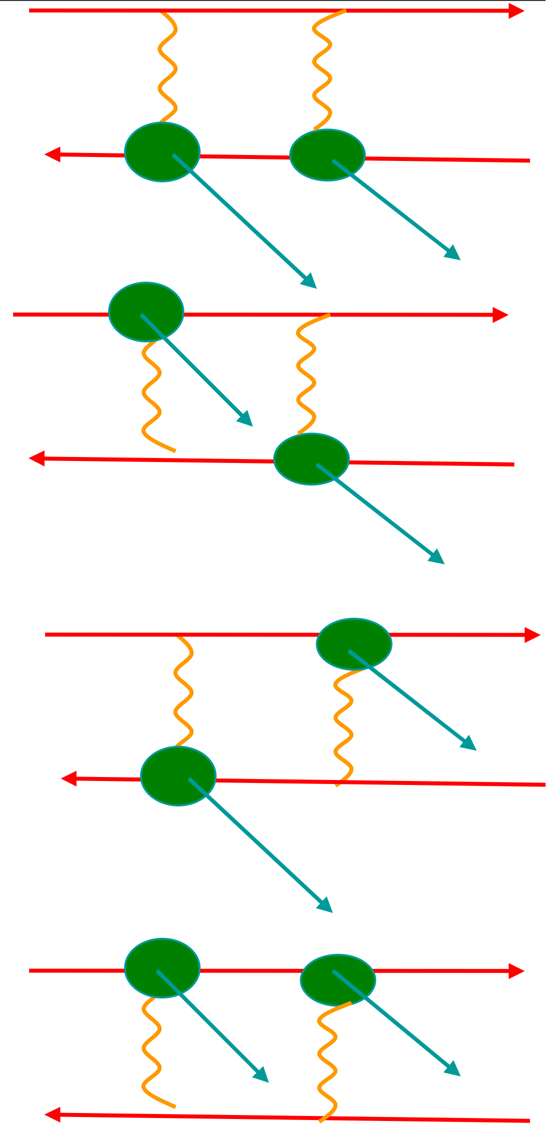
- 4 diagrams interfere

$$Amp \sim A^2(y)e^{i(p_{T1}x_1+p_{T2}x_1)} + A^2(-y)e^{i(p_{T1}x_2+p_{T2}x_2)}$$
$$- A(y)A(-y)[e^{i(\vec{p}_{T1}\vec{x}_1+\vec{p}_{T2}\vec{x}_2)} - e^{i(\vec{p}_{T1}\vec{x}_2+\vec{p}_{T2}\vec{x}_1)}]$$

- Away from y = 0, top and bottom diagrams dominate

$$A \sim \cos([p_{T1} + p_{T2}]\cdot b)$$

  - Stimulated emission at low p_T
  - Possibility to look for the stimulated decays
- Issues
  - More luminosity
  - Rejection of ρ'



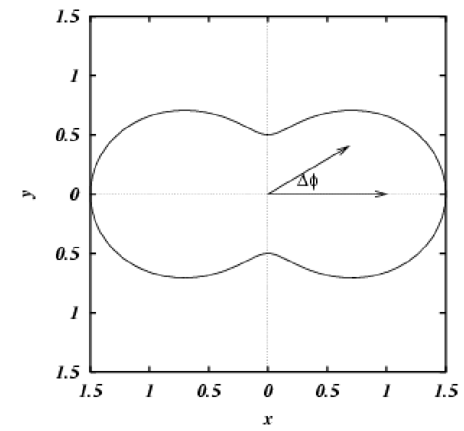
Correlations in $\rho^0\rho^0$ & mutual nuclear excitation to GDR

- any states decaying via a vector decay
- In linearly polarized ρ^0 decays, the angle

between the ρ^0 polarization and the π^+/π^-

p_T (wrt the direction of motion) follows $\cos(\phi)$

  - π^+/π^- direction acts as an analyzer



- The ρ^0 polarization follows the γ polarization
- The angle between the π^+/π^- p_T in $\rho^0\rho^0$ decays is the convolution of the two $\cos(\phi)$ distributions
  - $C(\Delta\phi) = 1 + 1/2\cos(2\Delta\phi)$
- Possible way to study linear polarization

G. Baur et al.,Nucl. Phys. A729, 787 (2003)