Ultraperipheral Collisions (UPCs) at RHIC

What are Ultraperipheral Collisions (UPCs)?
Why are they interesting?
How do we study them?
What have we learned so far?

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Creighton University

EPSCoR Support

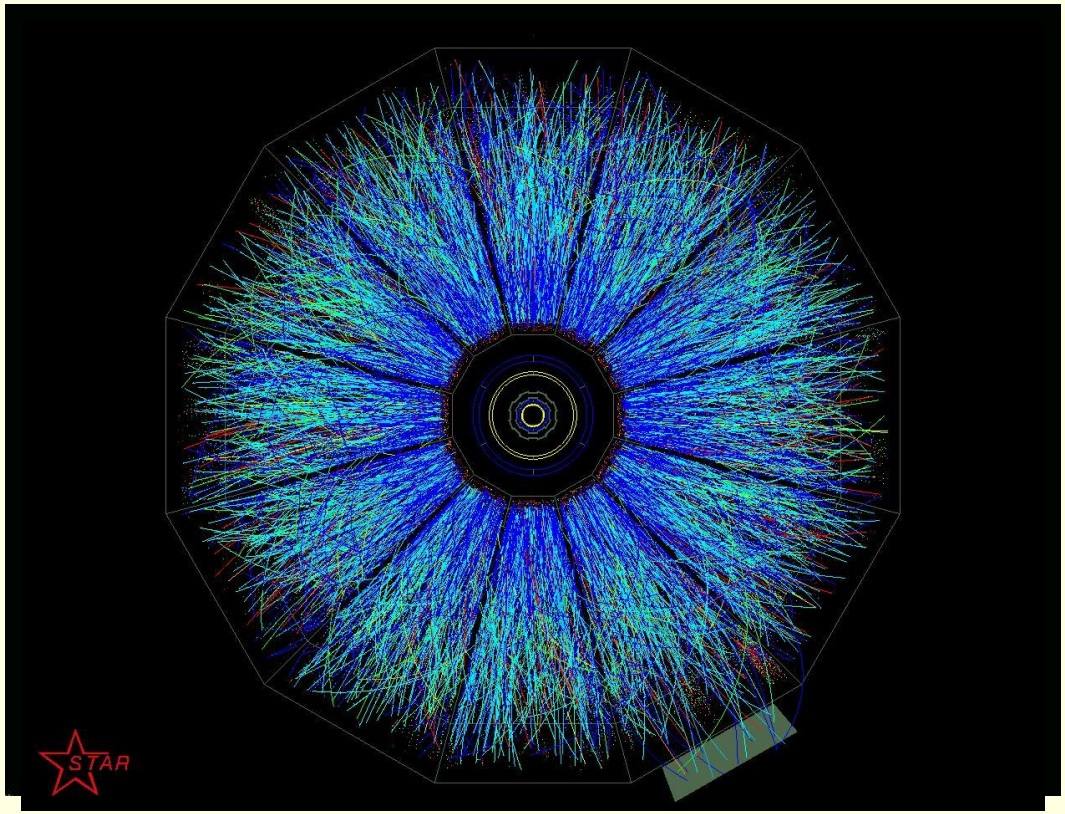
- Creighton University
  - Jesuit University in Omaha, NE
  - ~7000 students
  - Offers BS, MS in Physics
  - High-energy group: 3 faculty, 2 post-docs, students
  - Member of STAR collaboration at RHIC
    - Provide leadership to UPC Working Group within the collaboration
- EPSCoR funded UPC work at Creighton for 3 years
  - Dramatically improved productivity

55 Institutions

13 Countries(USA, Brazil, Britain, China, Croatia, Czech Republic, France, Germany, India, Korea, The Netherlands, Poland, Russia)

612 Collaborators

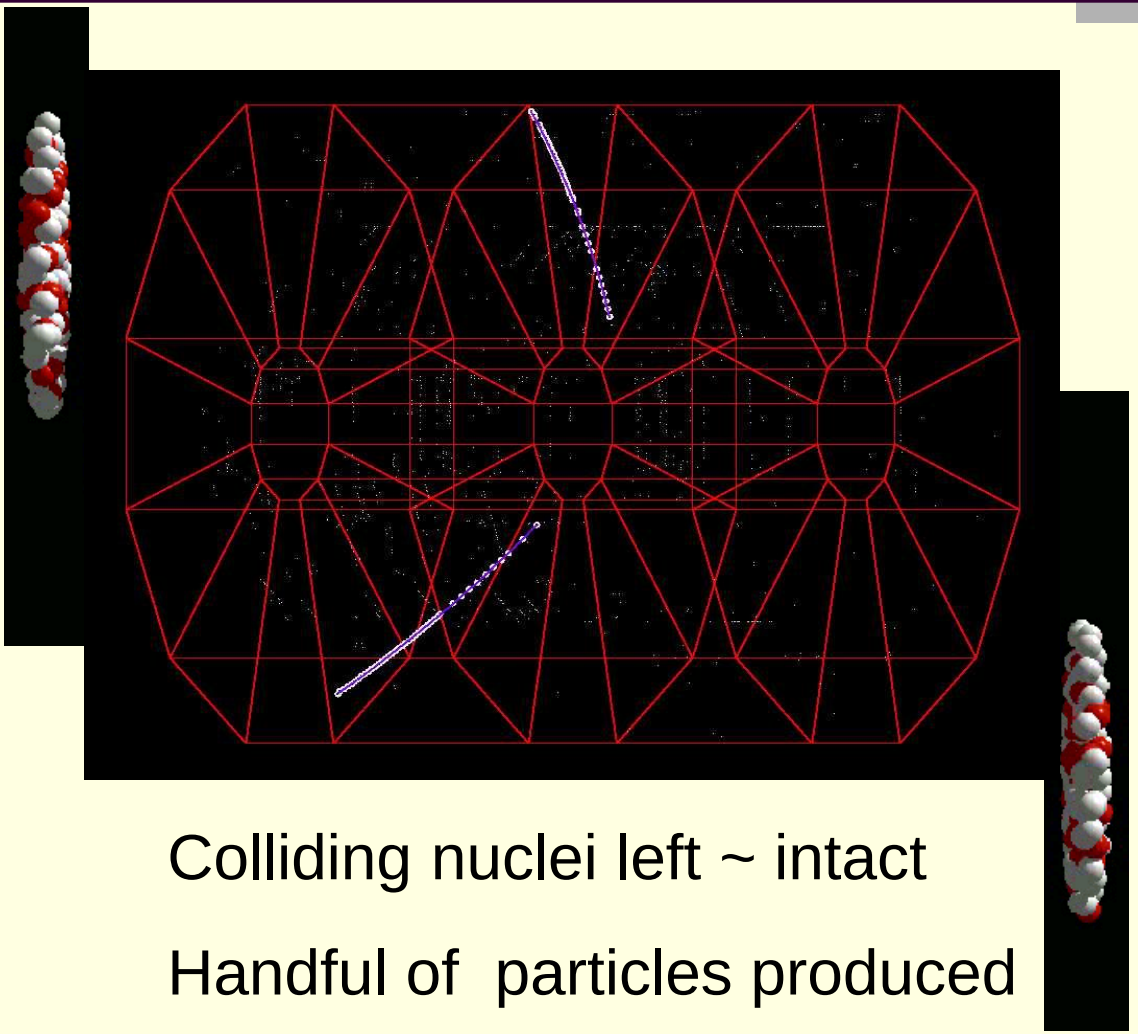
Central Collisions at RHIC



Complete disintegration of colliding nuclei

Thousands of particles produced

Ultraperipheral Collisions at RHIC

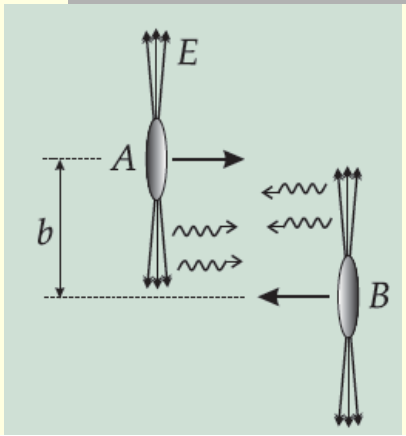


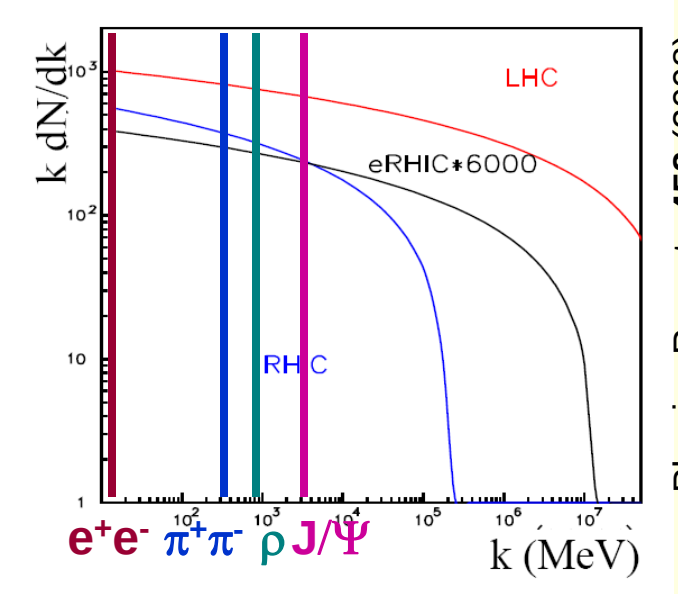
Colliding nuclei left ~ intact

Handful of particles produced

Large impact parameter → long-range electromagnetic interaction only

- Colliding nuclei surrounded by cloud of quasi-real virtual photons
- Fast-moving heavy ions produce intense photon flux
  - Described by Weizsäcker-Williams approximation
  - Photon flux ~ Z^2
- Single photons energetic enough to create particles
- Can have multiple photons exchanged in a single "collision"



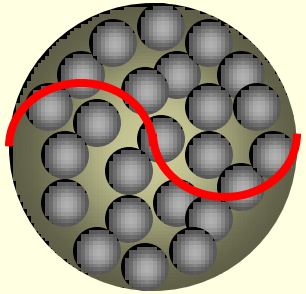


Physics Reports **458** (2008)

RHIC is a "nuclear flashlight"

Momentum of exchanged photons

- Depends on size of emitter!
- In rest frame of emitting nucleus, momentum of emitted photon is $$p = \frac{h}{\lambda} \approx \frac{h}{2R_A}$$
  - Coherent emission → photon emitted by nucleus as a whole (only in UPCs!)
  - R_A ~ 7 fm for gold → p □ 90 MeV/c
- In the lab frame, the *transverse* component retains this limit: p_T □ 90 MeV/c



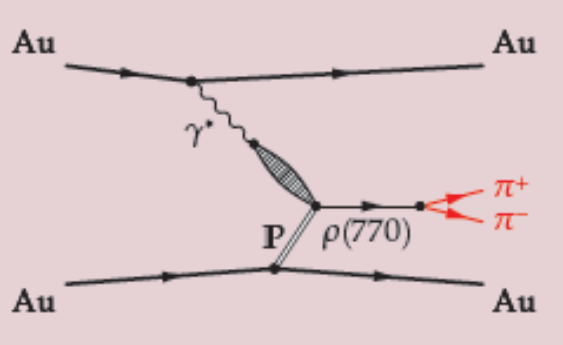
Photons with very low transverse momentum are a "smoking gun" that an ultraperipheral collision occurred!

Physics topics for UPCs

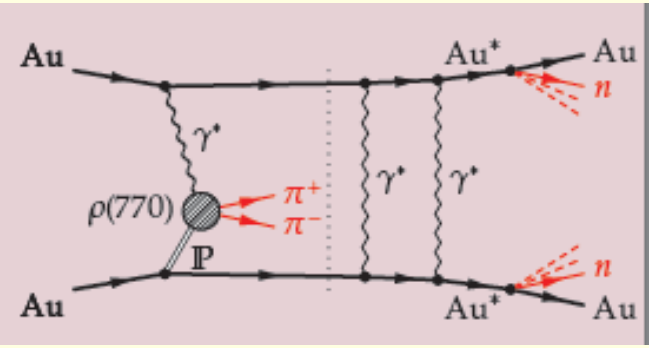
- Light meson spectroscopy
  - ρ, ω, ϕ, excited states, etc
  - Non-perturbative QCD, described by “soft” Pomeron
- Fundamental tests of Quantum Mechanics
  - Interference between non-overlapping particles
- Heavy vector mesons (J/Ψ, Ψ', Υ…)
  - Described by perturbative QCD
  - Probe nuclear structure at short distance scales
  - Gluon distributions important and not well understood

Light vector meson production

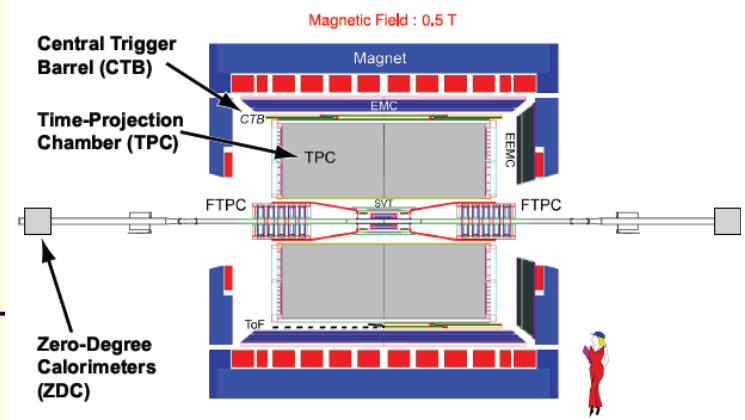
- **Exclusive production**
  - $\gamma*$ from "source" nucleus fluctuates into $q\bar{q}$-pair
  - $q\bar{q}$-pair scatters off "target" nucleus into real vector meson

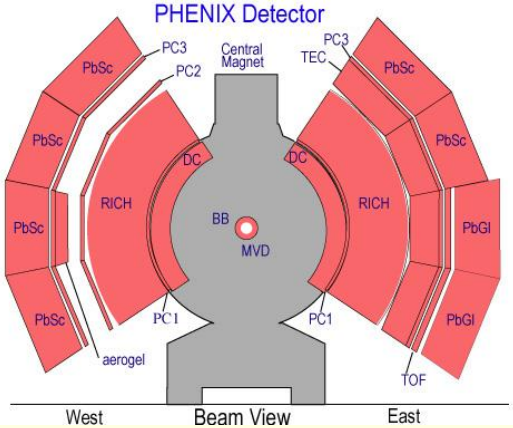


- **Production accompanied by mutual nuclear breakup**
  - Additional independent photons exchanged
  - Predominantly Coulomb excitation of Giant Dipole Resonances
    - decay via forward neutron emission → distinctive signature

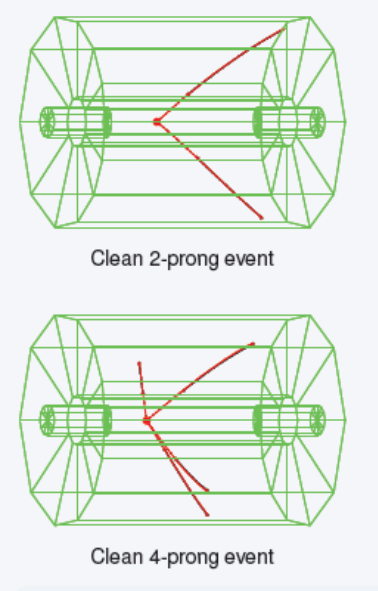


To study UPCs





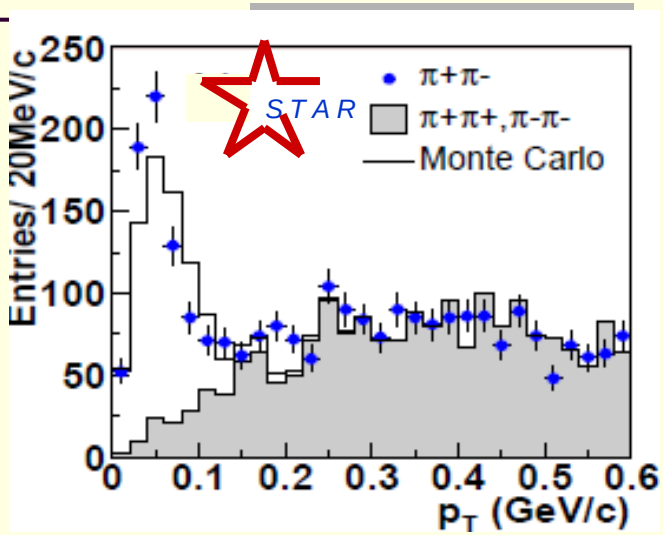
- **Trigger on events with very low multiplicity**
  - **Can also trigger on forward neutrons from GDR decay**
- **Select events with**
  - **Track vertex near collision point**
  - **Total charge = 0**
  - **Total transverse momentum p_T □ 100 MeV**



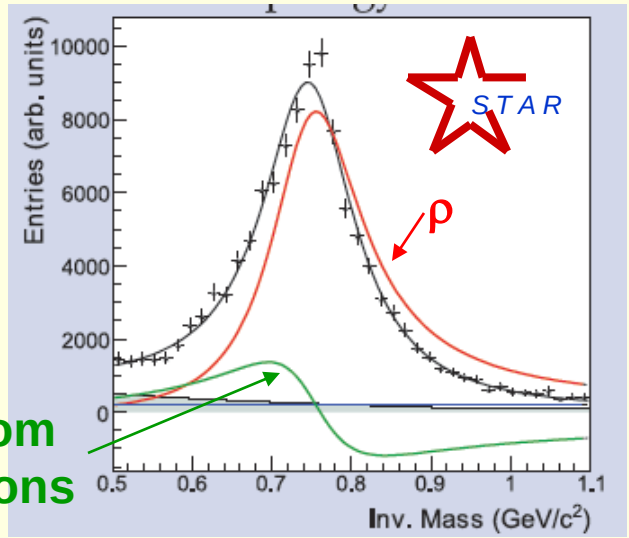
UPC events reconstructed in STAR detector

Observed ρ meson production

- ρ not observed directly
  - Electrically neutral→ not tracked in detector
  - Decays almost instantaneously into $\pi^+\pi^-$
- ρ-meson reconstructed from the observed decay products
  - Signal at low p_T → coherent production
- Pion pairs can be produced directly, as well as through ρ-decay
  - Experimentally indistinguishable



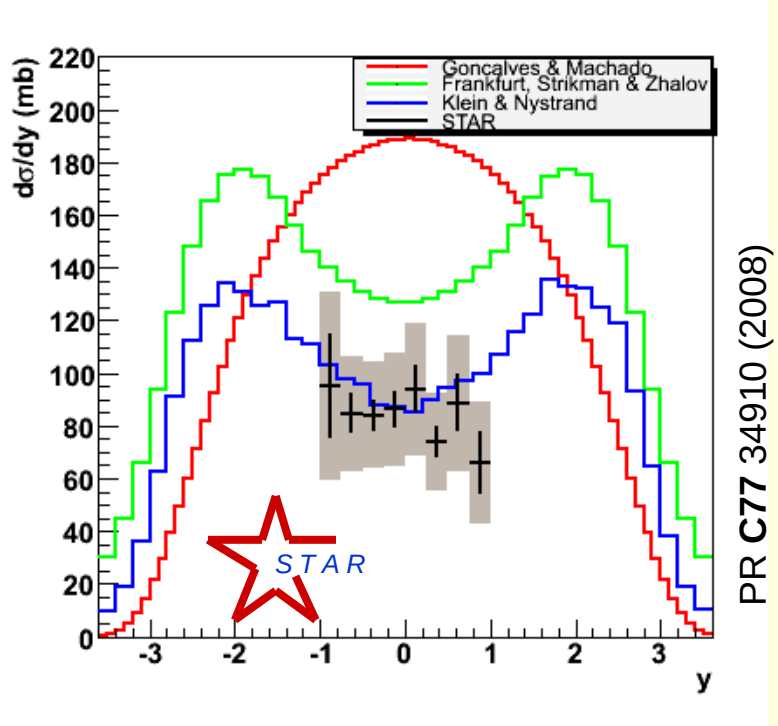
PRL **89**, 272302 (2002)



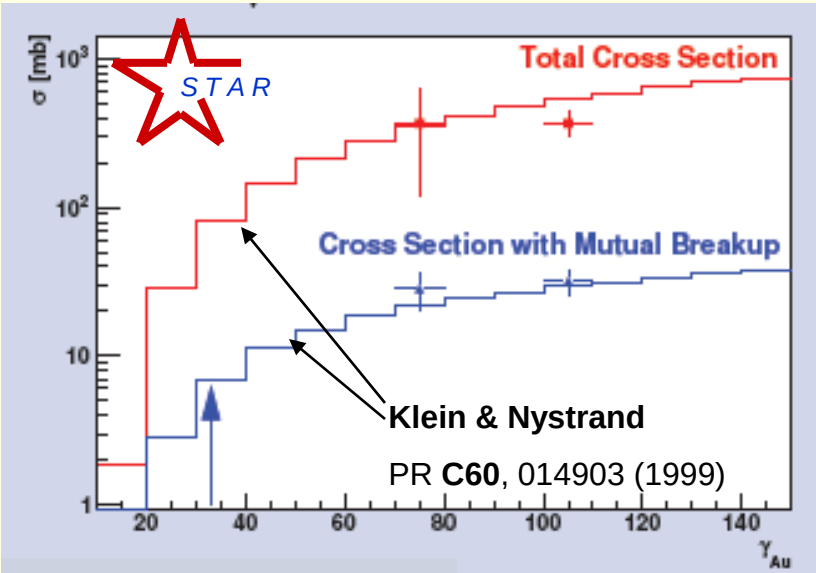
Interf. from direct pions

PR **C77**, 034910 (2008)

Reasonable theoretical understanding of light-meson production



PR **C77** 34910 (2008)



PRL **89**, 272302 (2002),
PR **C77**, 034910 (2008)

Magnitude ~ right at mid-rapidity

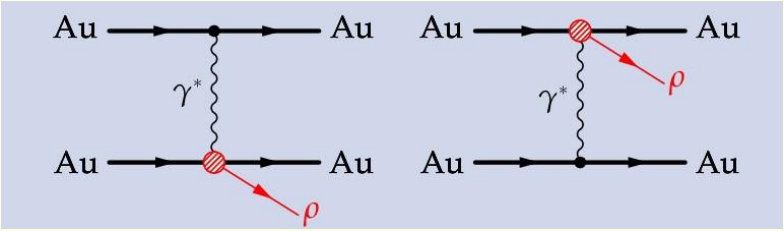
Need wider range in rapidity to determine shape of distribution

Theory matches energy dependence so far;
STAR has 62 GeV point coming

Starlight: Monte Carlo simulation for UPCs

- Based on successful Klein-Nystrand model
- Models
  - Photonuclear interactions
  - Photon-photon interactions
  - Symmetric (Au-Au, etc.) or asymmetric collisions (d-Au, etc.)
  - Interference effects
- Matches observed data well
- Used by experiments at RHIC and LHC
- Newest upgrade (by Creighton student, Joey Butterworth) available on SourceForge (http://upcstarlight.sourceforge.net)

QM interference in ρ photoproduction



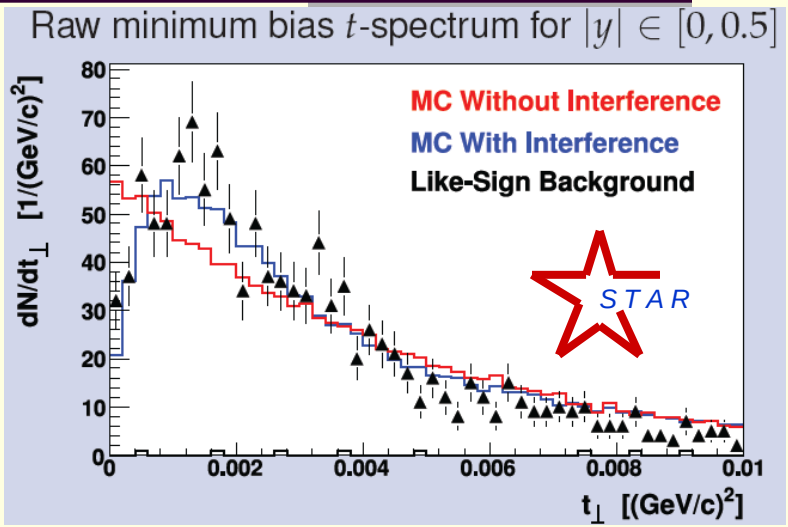
- Cannot distinguish between "source" and "target" of γ^*
- ρ production occurs close to target nucleus (d ~ 1 fm)
  - Two indistinguishable processes related by parity transformation
    - ρ has negative parity → amplitudes subtract

$$\sigma = \left| A(p_T, b, y) - A(p_T, b, -y) e^{i\vec{p}_T \cdot \vec{b}} \right|^2$$

    - At mid-rapidity, $\sigma(p_T, b, 0) = 2\left|A(p_T, b, 0)\right|^2 \left[1 - \cos(\vec{p}_T \cdot \vec{b})\right]$
  - System acts like two-slit interferometer with slit separation b

Interference observed

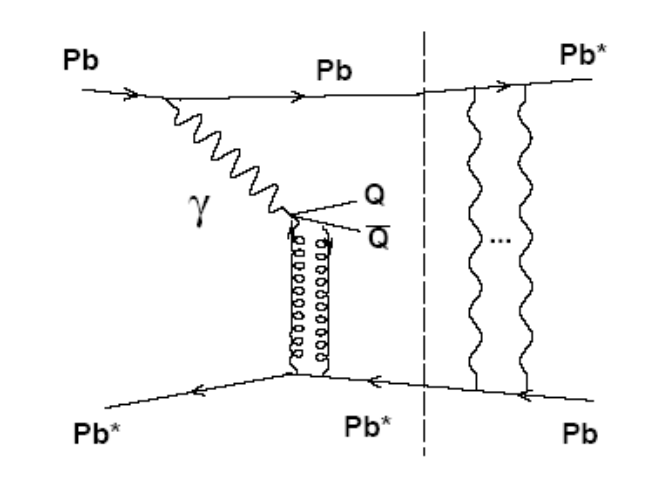
- QM interference suppresses ρ production for p_T □ □/⟨b⟩
- Observed t (≈ p_T^2) spectrum roughly exponential with significant downturn for t < 0.0015 GeV^2
  - Consistent with Monte-Carlo including interference effect
- Since $\beta\gamma c\tau$ □ <b>, produced ρ decay at two points well separated in space-time
  - Two amplitudes overlap and interfere only after decay
  - Interference must involve $\pi^+\pi^-$ final state
  - Interference only possible for entangled final state $\pi^+\pi^-$ wave function that is not factorizable into separate π wave functions
  - Example of Einstein-Podolsky-Rosen paradox with continuous variables momentum and position



PRL 102, 112301 (2009)

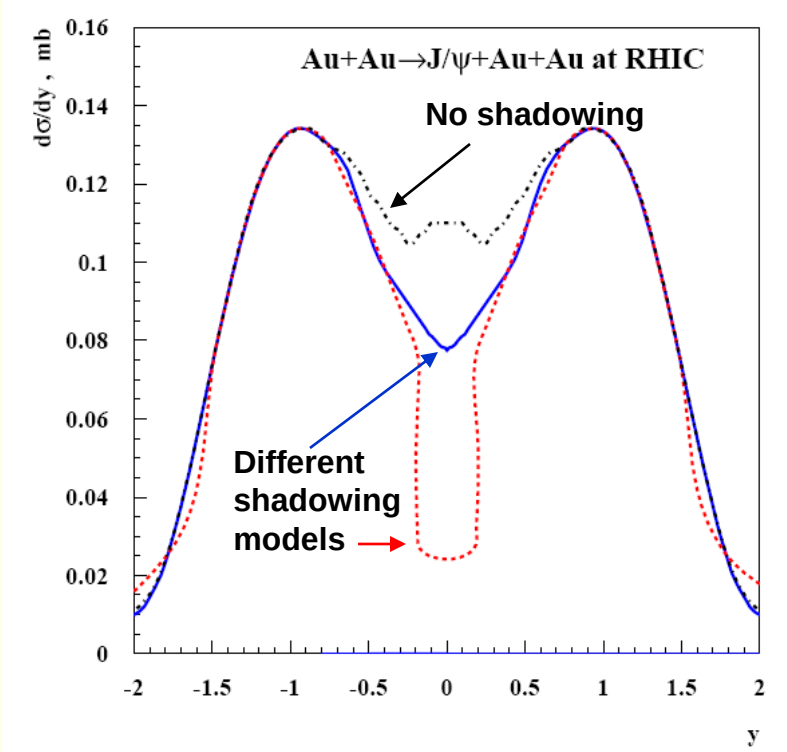
Heavy Vector Mesons

- Contain charm, bottom, top quarks
- Described by perturbative QCD (2-gluon exchange)
- Cross sections are sensitive to gluon distribution function
  - $\sigma(VM) \sim |g(x,Q^2)|^2$



Gluon shadowing alters rapidity dist.

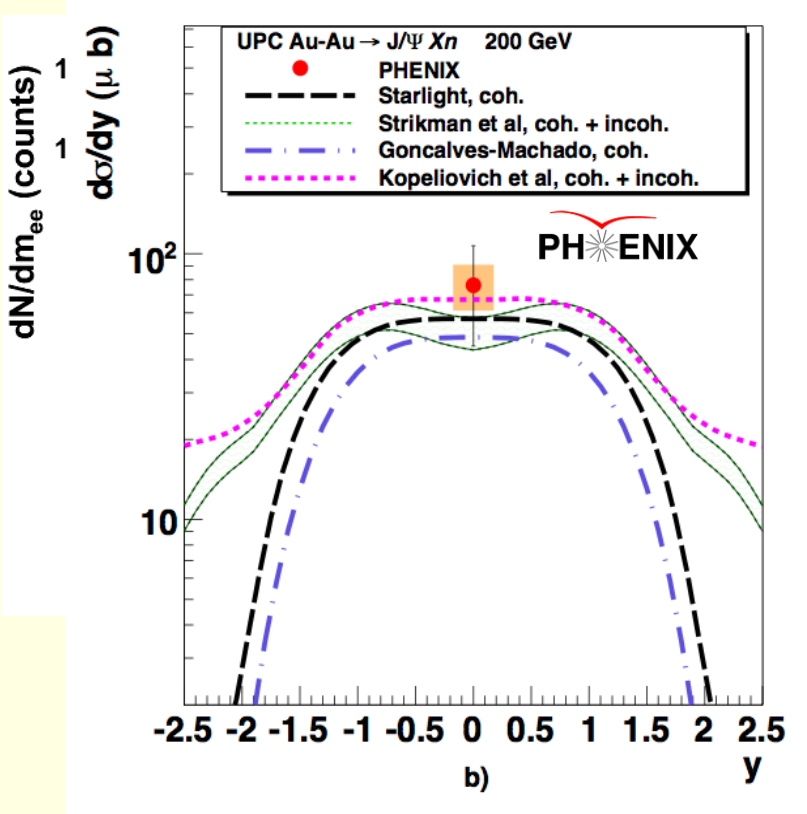
- Shadowing reduces cross section at mid-rapidity
  - Where detector acceptance is best!
  - A colored glass condensate could have a larger effect
- UPCs are a "clean" environment to test theory



FSZ, Phys Lett B540

J/Ψ observed in UPCs at RHIC

- PHENIX detected J/Ψ → e^+e^- channel
- Fit J/Ψ peak on top of continuum of directly produced e^+e^- pairs
- Signal of ~ 10 J/Ψ
- Not enough data yet to distinguish between different models



arXiv:0903.2041v1

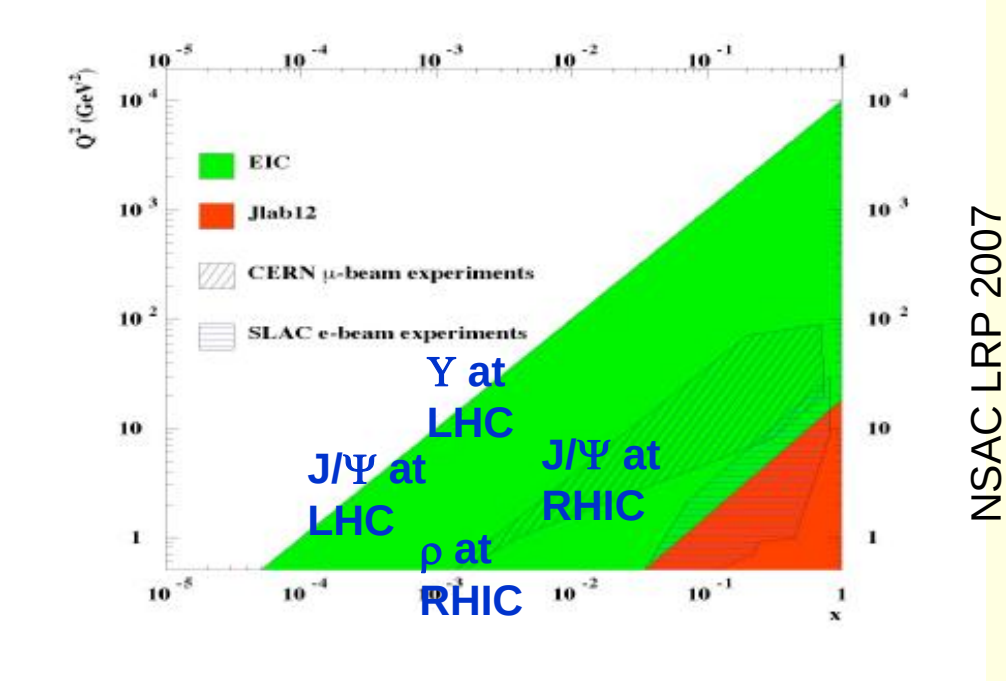
Future outlook

- Detector upgrades will improve statistics for
  - J/Ψ
  - Meson spectroscopy : $\rho^*, \rho^0\rho^0, \omega, \phi$, etc
  - Exotics
- Roman Pots added to STAR will allow measurement of forward particles
  - Elastic and inelastic diffractive processes, spin dependence
- At the LHC,
  - J/Ψ produced at high rates
  - Υ UPC studies will be possible
- Further future plans may include eRHIC?

Heavy ion colliders like RHIC are a great place to study electromagnetic processes!

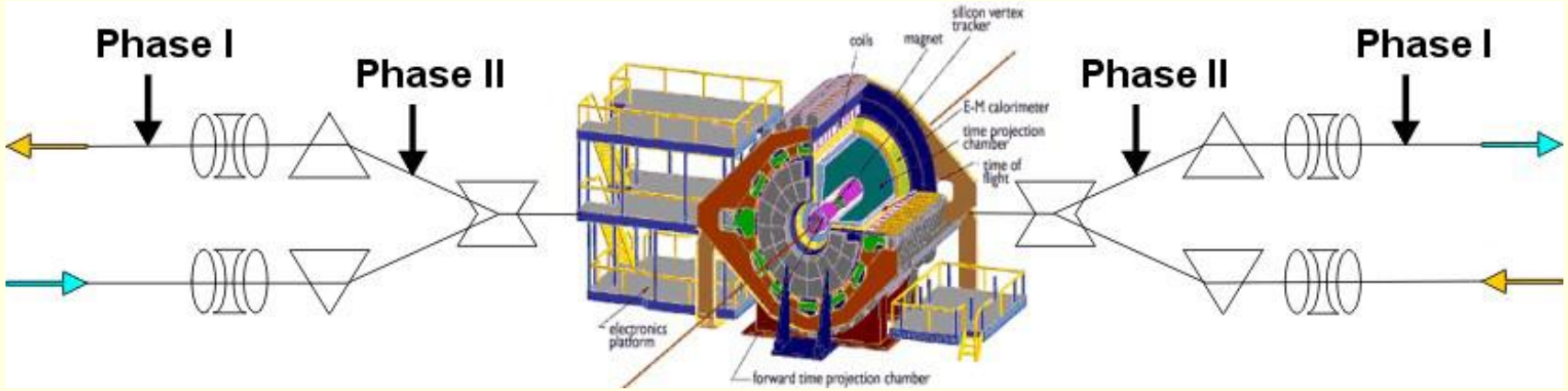
Kinematic range of UPCs

- UPCs sensitive to gluon distribution at
  - $x = M_V/2\gamma m_p\, e^{\pm y}$
  - $Q^2 \sim M_V^2$
  - Low-mass states at high rapidity probe low x



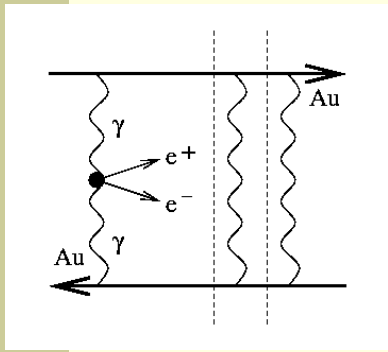
NSAC LRP 2007

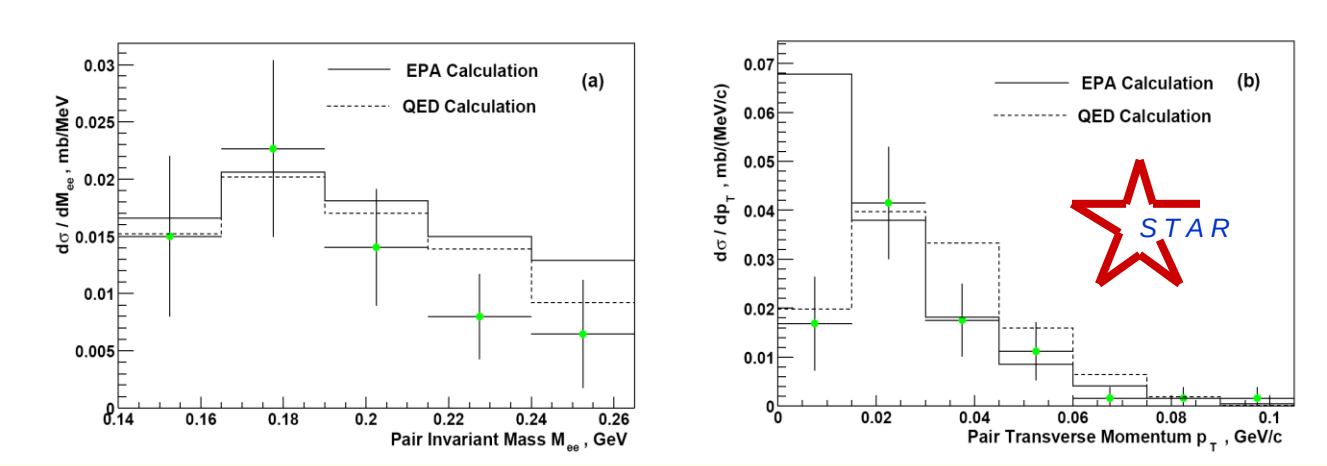
Diffractive physics coming at STAR



- Roman pots system has been installed at STAR
  - 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

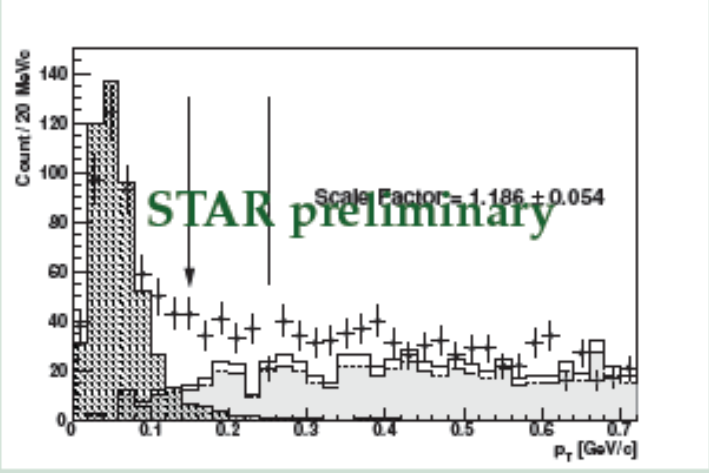
Coherent production of e^+e^- pairs

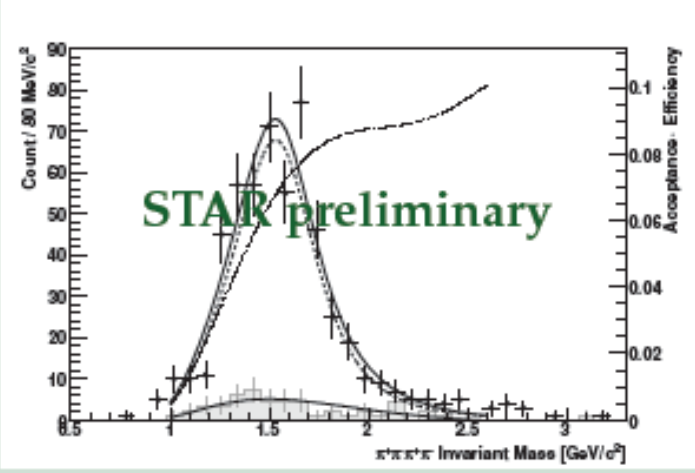




- Differential cross sections compared with two models
  - equivalent photons (photon virtuality ignored) Klein, Nystrand
  - lowest order QED Hencken, Baur, Trautman
- Photon virtuality required to describe p_T distribution

Photoproduction of 4-pion state: $\pi^+\pi^-\pi^+\pi^-$

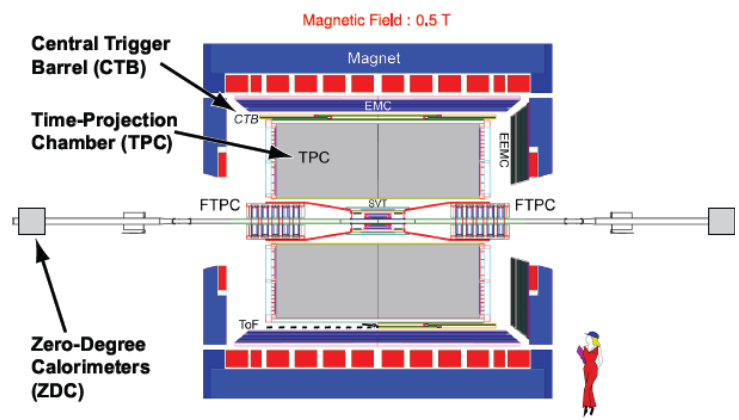


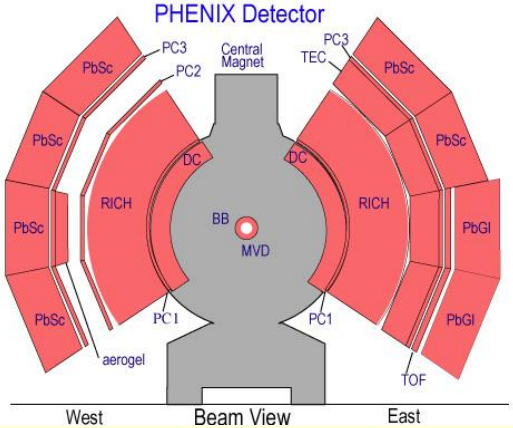


Boris Grube, EDS 2009

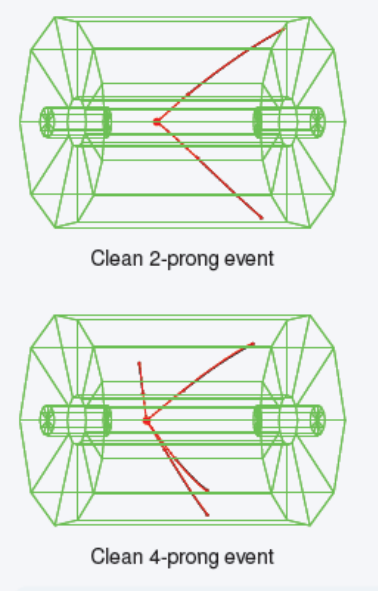
- Peak at low p_T → coherent production
- Mass spectra similar to γp collisions
  - Expected to be produced largely through a radially excited ρ
  - Could be $\rho(1450)$ and/or $\rho(1700)$

To study UPCs





- **Trigger on events with very low multiplicity**
  - **Can also trigger on forward neutrons from GDR decay**
- **Select events with**
  - **Track vertex near collision point**
  - **Total charge = 0**
  - **Total transverse momentum p_T □ 100 MeV**
- **Backgrounds**
  - **Cosmic rays** ← Remove w/ neutron trigger or rapidity cut
  - **Beam-gas events** ← Remove w/ vertex cut
  - **Pile-up** ← Remove w/ vertex cut
  - **Incoherent events** ← Remove w/ p_T cut



UPC events reconstructed in STAR detector