Ultra-peripheral collisions with the STAR detector

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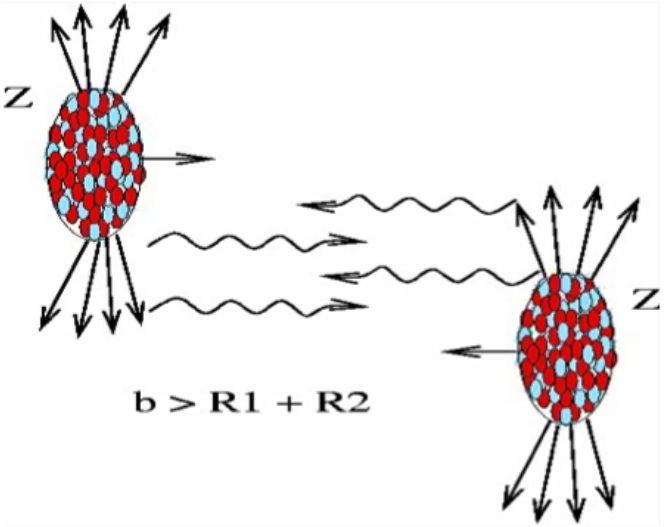
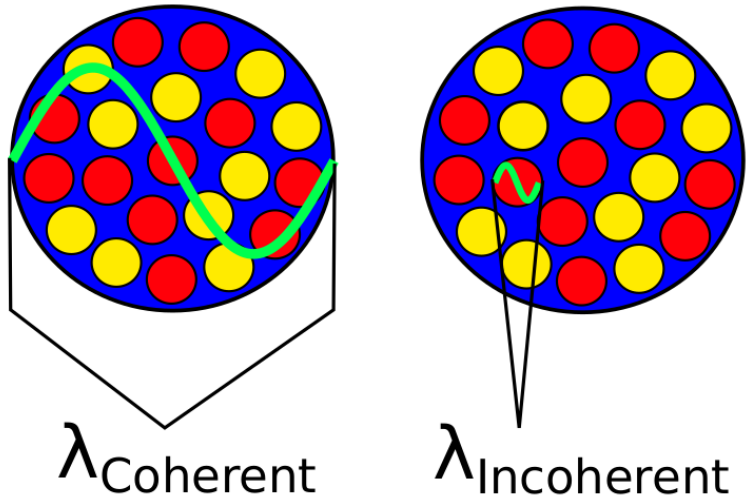
Probing QCD in Photon-Nucleus Interactions at RHIC and LHC: the Path to EIC
Institute for Nuclear Theory, University of Washington, Seattle

Ultra-peripheral collisions



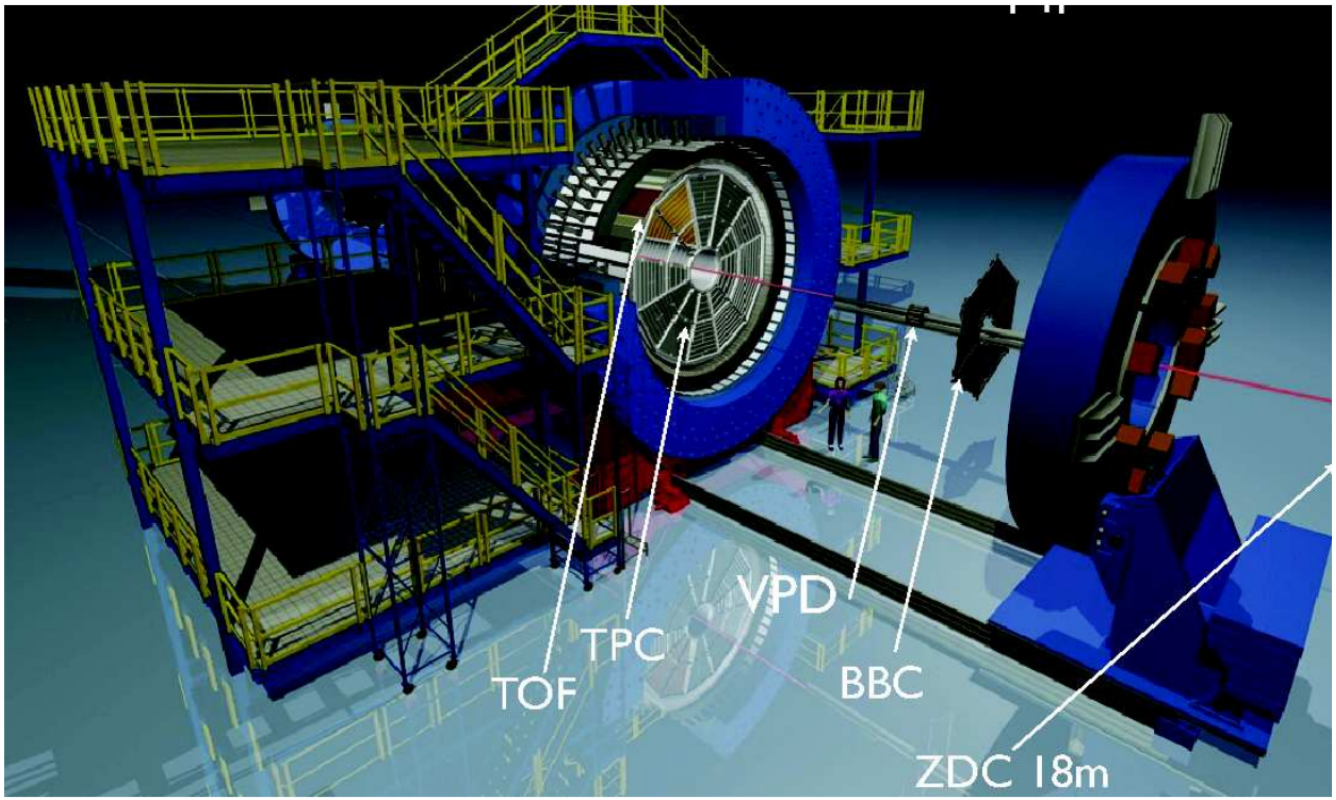
- A ultra-peripheral collision (UPC) is a collision of ions at impact parameter greater than the sum of the nuclear radii: $R1 + R2$
- It is mediated by electromagnetic forces and photon-Pomeron interactions
- It is possible to study photon-proton and photon-nucleus interactions

- Coherent photoproduction - photon interacts with whole nucleus
- Incoherent photoproduction - interaction on a single nucleon
- Coherent p_T is much lower than incoherent



The STAR Experiment

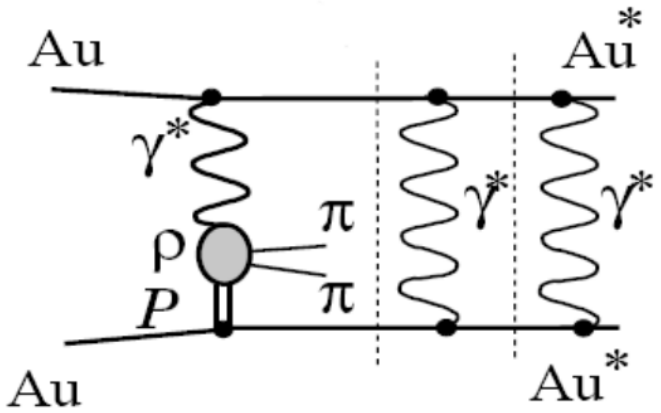
- Central tracking and particle identification, forward counters and neutron detection



- TPC: tracking in $|\eta| < 1$, particle identification by $\mathrm{d}E/\mathrm{d}x$
- TOF: multiplicity trigger and pile-up track removal
- BBC: forward counter in $2.1 < \eta < 5.2$
- ZDC: detection of very forward neutrons

Trigger using forward neutrons

- Mutual Coulomb excitation
- Process independent of vector meson photoproduction
- Excited nuclei emit neutrons

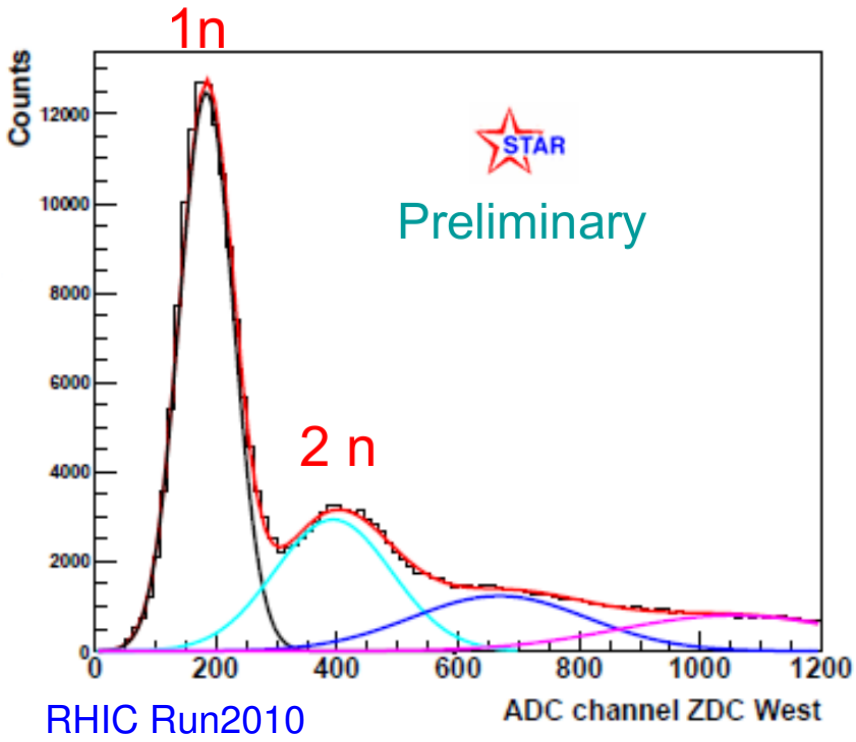


- Convenient to trigger for UPC events at STAR
- Would be problematic otherwise due to cosmic and beam-gas background
- Events with one neutron in each side (1n1n) used to normalize cross sections

Requirement for 1-5 neutrons in each ZDC together with exclusivity selection for UPC events

Neutron spectrum

- Spectrum of Analog-to-Digital counts from ZDC



- Excitation leading to one emitted neutron is a result of Giant Dipole Resonance
- Peaks of one and two neutrons clearly visible
- Distribution of number of neutrons not well known, therefore 1n1n events are used for normalization

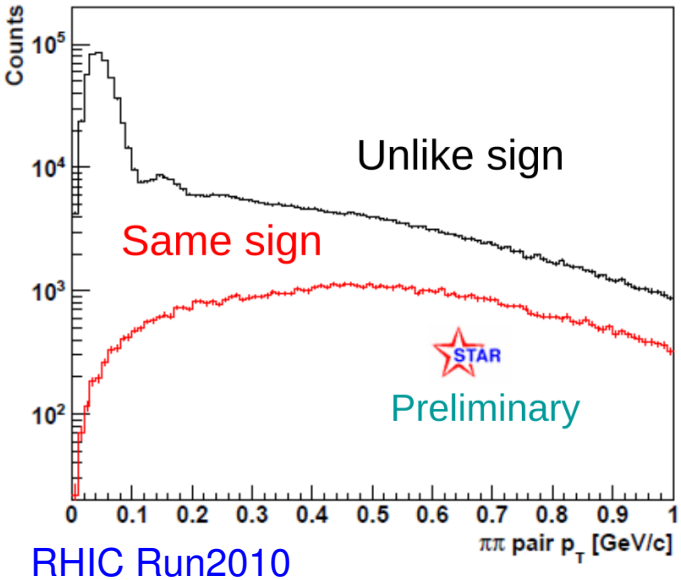
Photoproduction of $\pi^+\pi^-$ pairs

Au+Au @ $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV

Selection criteria for $\pi^+\pi^-$ pairs

- Transverse momentum of selected $\pi^+\pi^-$ candidates:

- Requirements for tracks:
  - Pseudorapidity $|\eta| < 1$
  - At least 14 hits in TPC (out of 45 possible)
  - TPC $\mathrm{d}E/\mathrm{d}x$ consistent with pions within 3σ
  - Both tracks need a hit in TOF to select those from a given bunch crossing



RHIC Run2010

- Like-sign $\pi^\pm\pi^\pm$ pairs provide background sample, which is subtracted
- Efficiency is obtained using STARLIGHT embedded in unbiased data

STARLIGHT: Comp. Phys. Comm. 212C (2017) 258, https://starlight.hepforge.org/

Description of $\pi^+\pi^-$ invariant mass spectrum

- Selection criteria take 384 000 $\pi^+\pi^-$ pairs
- Contributions by ρ^0, ω^0 and direct $\pi^+\pi^-$ pairs
- Processes can not be distinguished on event basis, fit by added amplitudes:

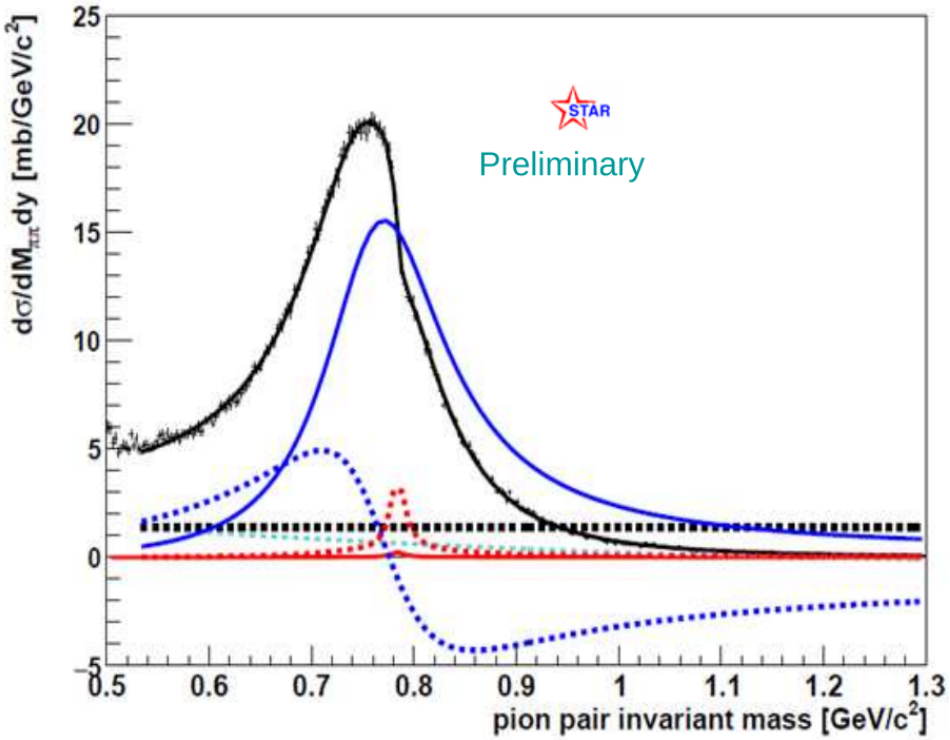
$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{\pi^+\pi^-}} \propto \left| A_\rho \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} + B_{\pi\pi} + C_\omega e^{i\phi_\omega} \frac{\sqrt{M_{\pi\pi} M_\omega \Gamma_\omega}}{M_{\pi\pi}^2 - M_\omega^2 + i M_\omega \Gamma_\omega} \right|^2 + f_p$$

- Parameters of the fit:
  - ρ^0 mass and width
  - ω^0 mass and width
  - Amplitudes of ρ^0, ω^0 and direct $\pi^+\pi^-$
  - Quadratic polynomial to handle remaining background

Fit to $\pi^+\pi^-$ invariant mass

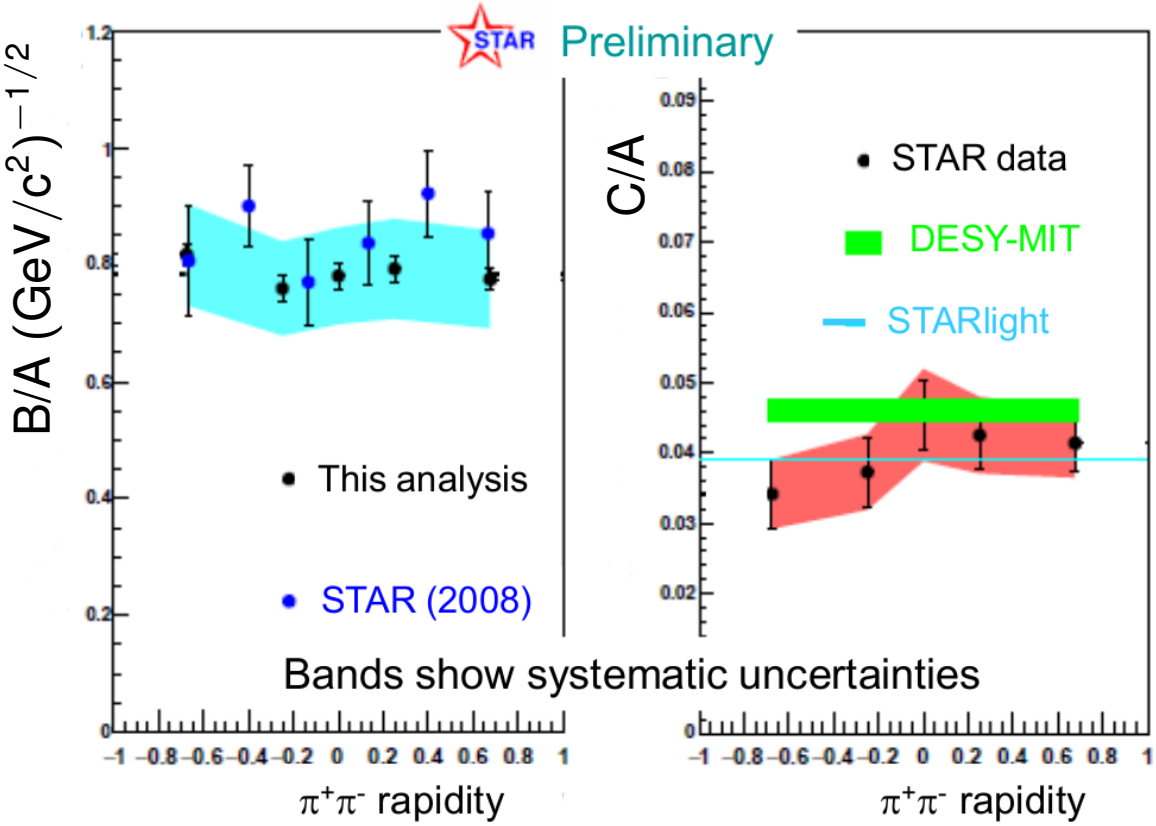
- Fit in 320 bins per 2.5 MeV, χ^2/NDF = 314/297

- Components:
  - Solid blue: ρ^0
  - Dotted blue: $\rho^0/\pi^+\pi^-$ interference
  - Solid red: ω^0
  - Dotted red: ω^0/ρ^0 interference
  - Dotted black: direct $\pi^+\pi^-$



- Mass and width of ρ^0 consistent with PDG
- Contribution from ω^0 is needed for good χ^2/NDF

Relative amplitudes

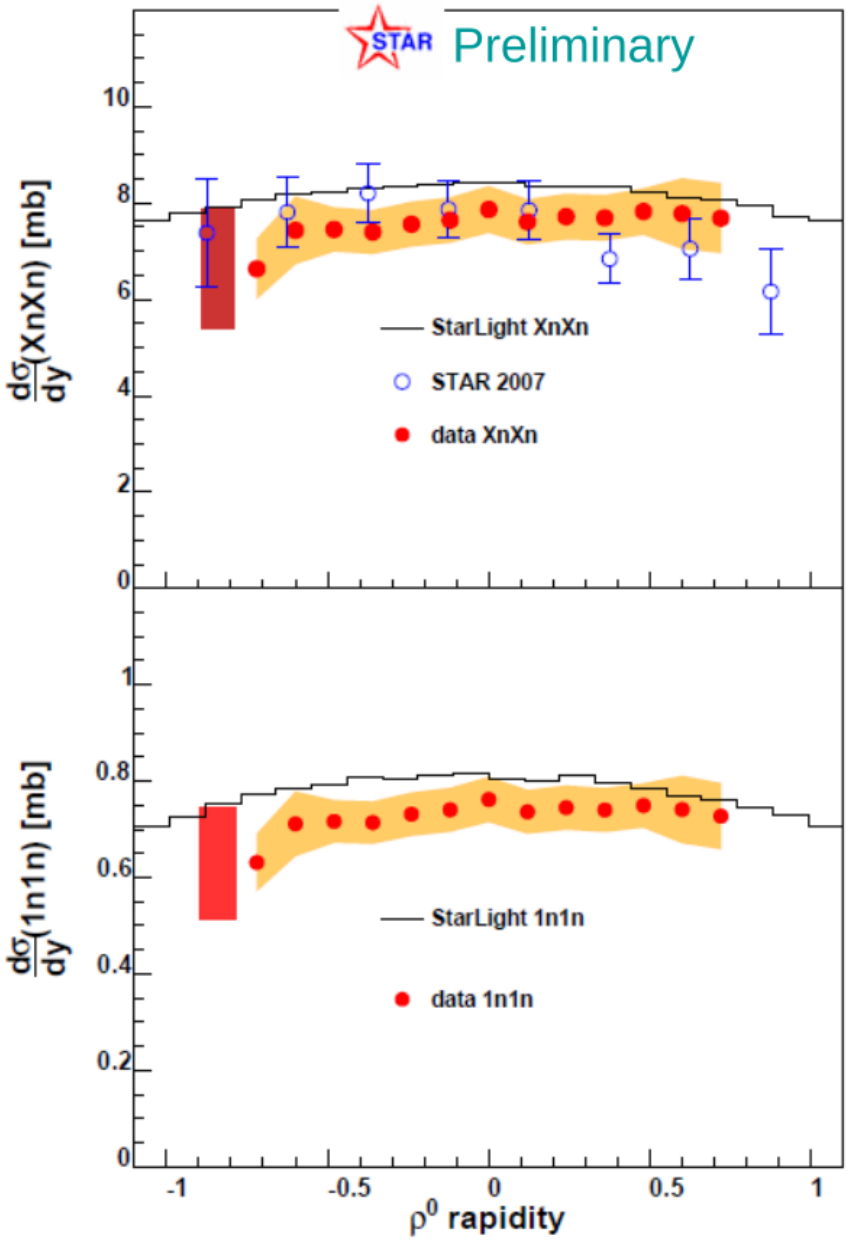


- $\pi^+\pi^-/\rho^0$ (B/A) consistent with previous results by STAR, ALICE and also HERA
- ω^0/ρ^0 (C/A) consistent with experimental cross section $\gamma\pi \to \omega p$, STARLIGHT(Glauber approach), PDG BR($\omega^0 \to \pi^+\pi^-$) and DESY
- The only previous data on ρ^0-ω^0 interference are from much lower photon energies 5-7 GeV (DESY-MIT, fixed target)
- Observe nonzero phase of ω^0 consistent with DESY experiments

STAR 2008: PRC 77, 034910 (2008), ALICE: JHEP 1509, 095 (2015), DESY-MIT: PRL 27, 888 (1971)

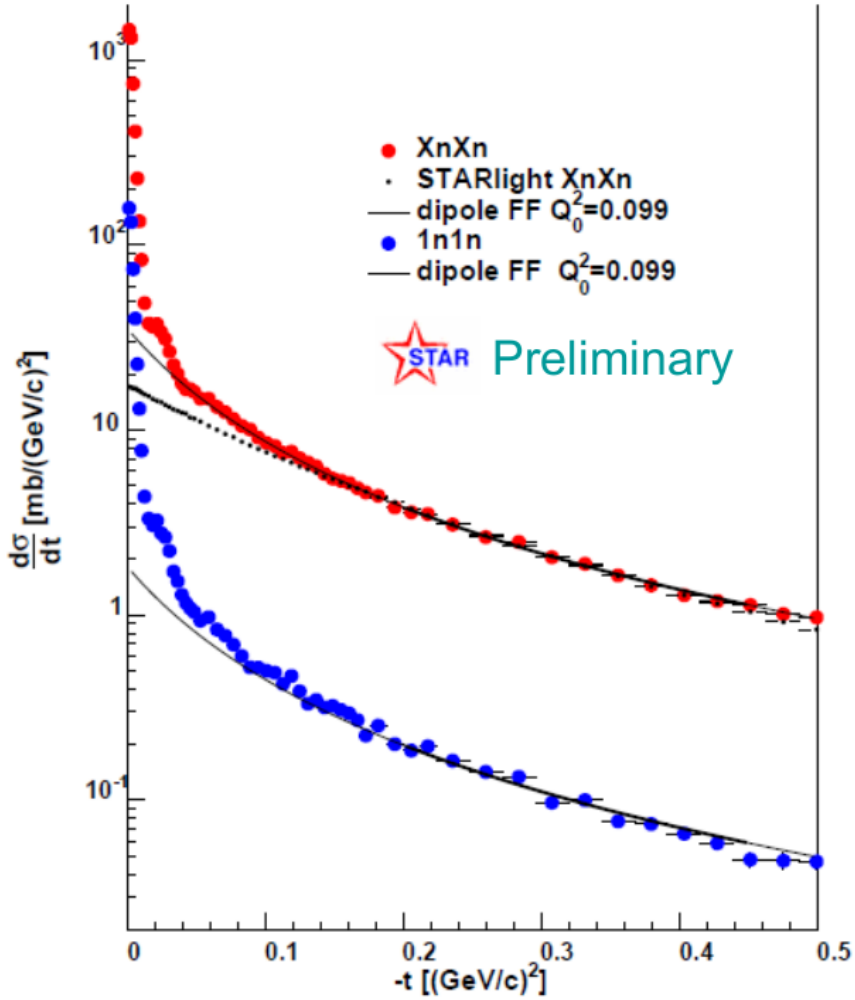
ρ^0 cross section as a function of rapidity

- STARLIGHT is in good agreement with the data
- 1n1n cross section is compatible with STARLIGHT within systematic uncertainties
- XnXn cross section is scaled from 1n1n using STARLIGHT
- Scaling is necessary because distribution in number of neutrons is not well known



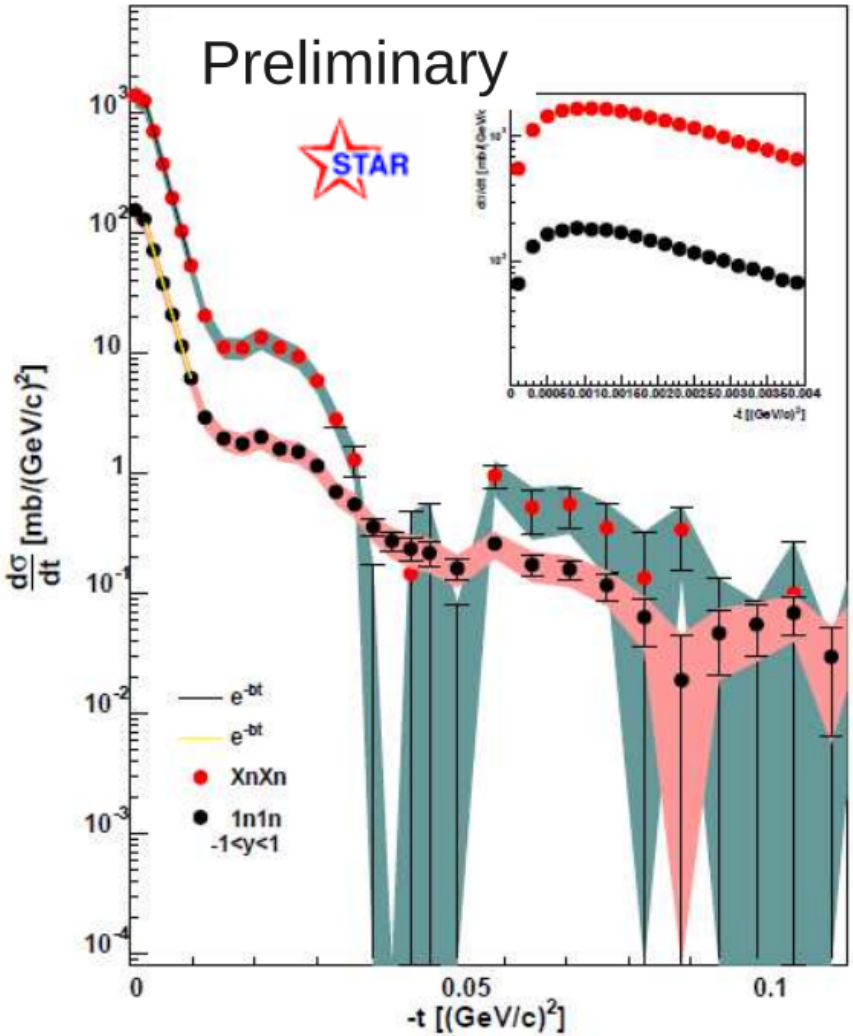
t-dependence of ρ^0 cross section ($-t \simeq p_T^2$)

- Data: mixture of coherent (whole nucleus) and incoherent (single nucleon) ρ^0
- Coherent ρ^0 obtained by subtracting incoherent contribution
- Fit over incoherent region $|t| > 0.2$ GeV^2
  - Fit formula: $F(t) = A/(Q_0^2 + |t|^2)$
  - $Q_0^2 = 0.099$ GeV^2
  - Separate fits done for 1n1n and XnXn



Coherent ρ^0 cross section

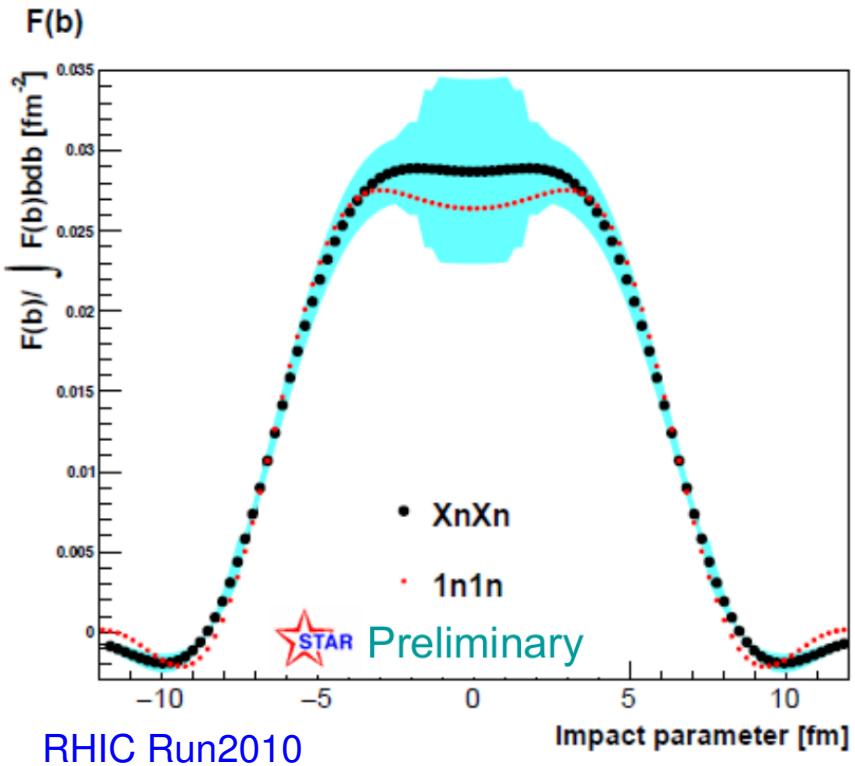
- Characteristic diffraction dips visible, positions:
  - 1^{st} : $-t = 0.018 \pm 0.005$ GeV^{-2}
  - 2^{nd} : $-t = 0.043 \pm 0.01$ GeV^{-2}
- Expected when approaching black disk limit
- Partially washed out due to photon p_T distribution and detector resolution
- Consistent with Normalized nuclear form factor, mVMD-GGM lower by $\sim 1\sigma$
- Interference between the two production nuclei makes downturn at $|t| < 10^{-3}$ GeV^2



Norm nucl form factor: Atom. Data Nucl. Data Tabl. 36, 495 (1987), mVMD-GGM: Phys. Lett. B 752, 51 (2016), calculations: arXiv:1611.05471

From ρ^0 cross section to nuclear spatial distribution

- Fourier 2-D (Hankel) transformation relates $\mathrm{d}^2\sigma/\mathrm{d}y\mathrm{d}t$ to the spacial distribution in target Au nucleus integrated over z



RHIC Run2010

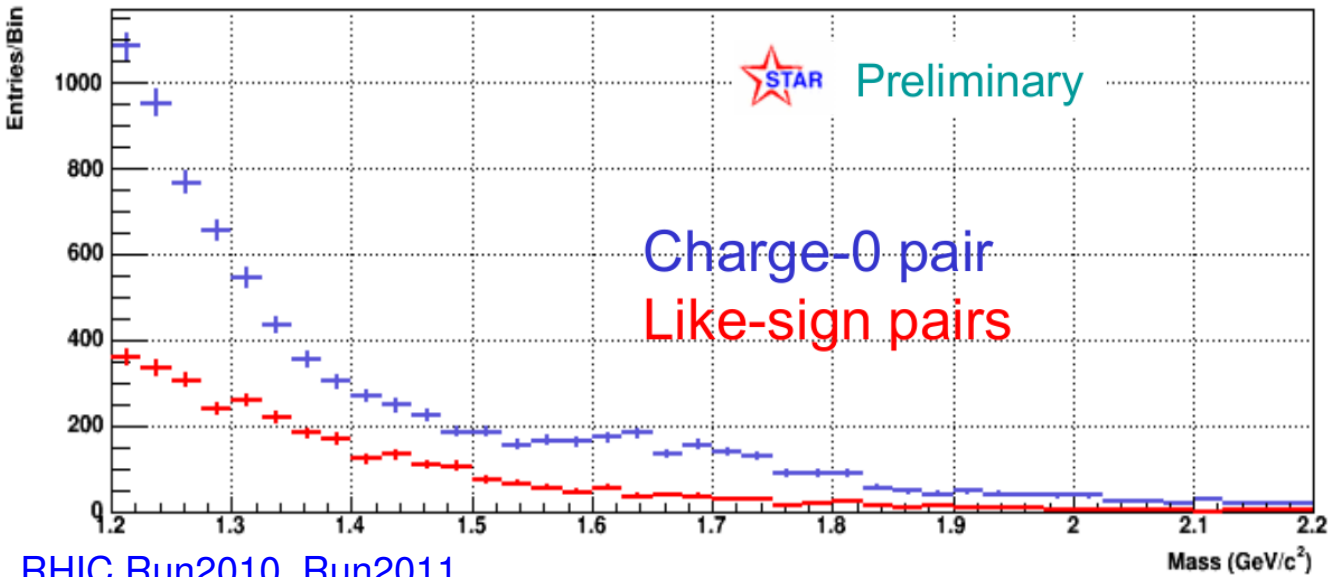
- Transformation prescription:

$$F(b) \propto \frac{1}{2\pi} \int_0^\infty \mathrm{d}p_T \, p_T J_0(bp_T) \sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$

- Blue band provides effect of varying $|t|_{\max}$
- Negative values on the sides are attributed to interference between the two production nuclei

Production of $\pi^+\pi^-$ pairs at higher masses

- High mass tail of the ρ^0 distribution
- Data from 2010+2011, slightly modified selection criteria
- Rejection at $|y_{\pi^+\pi^-}| < 0.04$ against cosmic ray background

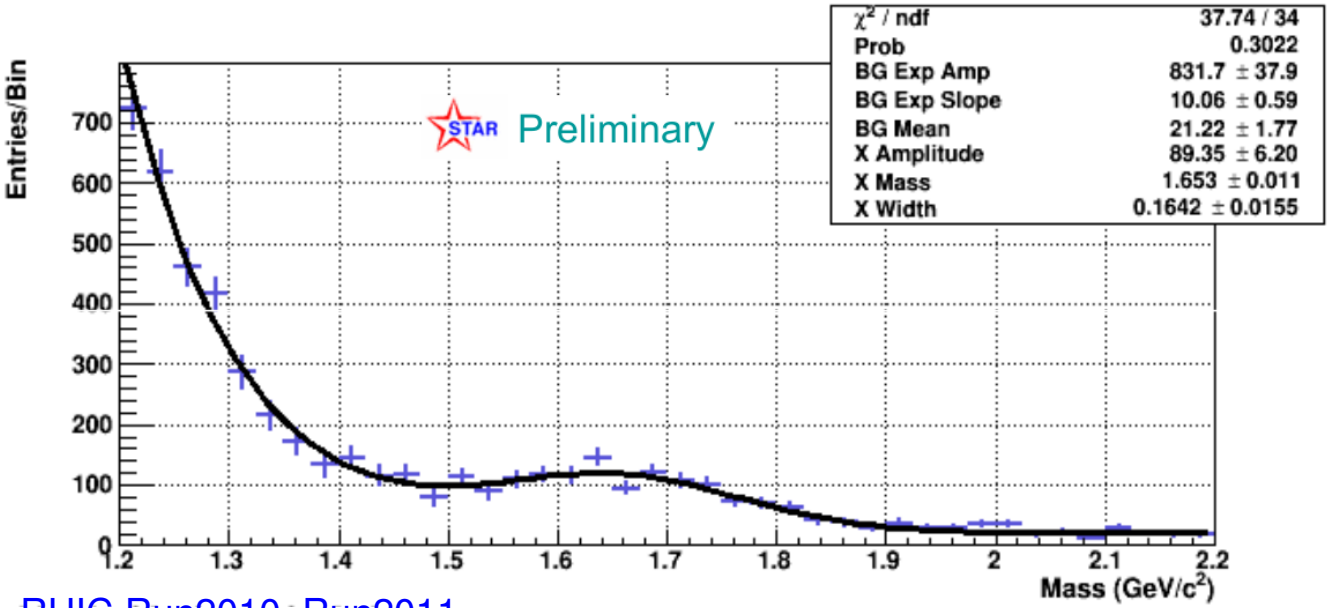


RHIC Run2010, Run2011

- Description by fit to ρ^0 high mass tail, Gaussian peak and flat background

Fit to $\pi^+\pi^-$ at higher masses

- Like-sign background subtracted
- Mass and width of Gaussian peak: $M_X = 1653 \pm 10$ MeV, $\Gamma_X = 164 \pm 15$ MeV (stat only)



RHIC Run2010, Run2011

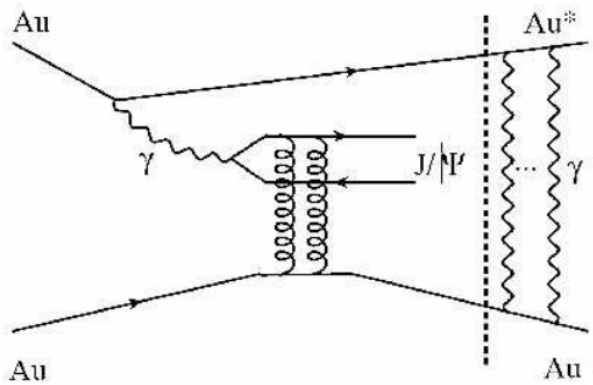
- χ^2/NDF = 37.7/34
- Cross section consistent (to order-of-magnitude) with one previous measurement of $\rho_3(1690)$

Photoproduction of J/ψ

Au+Au @ $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV

Photoproduction of J/ψ and selection criteria

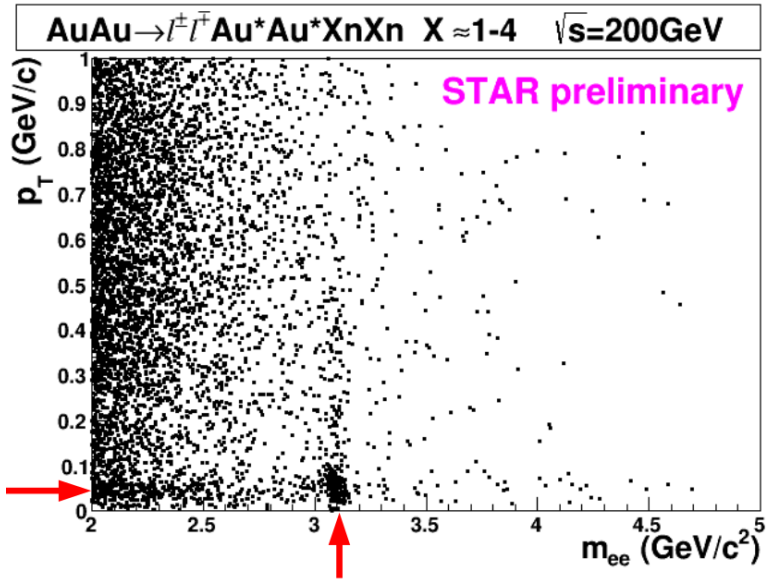
- 2-gluon exchange
- Scale given by mass of J/ψ
- Sensitivity to gluon distribution at $x \approx 0.01$
- Independent mutual Coulomb excitation

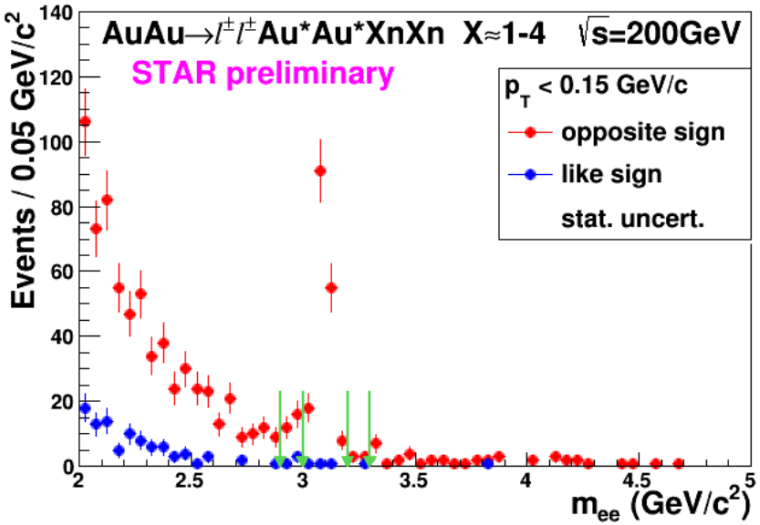


- Trigger:
  - 2 – 6 hits in TOF
  - 1 – 4 neutrons in each ZDC
  - Empty BBC
- Selection criteria for the J/ψ:
  - At least 15 points in TPC (out of 45 possible)
  - Both tracks have a corresponding hit in TOF
  - Vertex in STAR center formed out of 2 or 3 tracks
  - Rejection at rapidity $|y| < 0.02$ to prevent cosmic background

Mass and p_T distribution of selected candidates

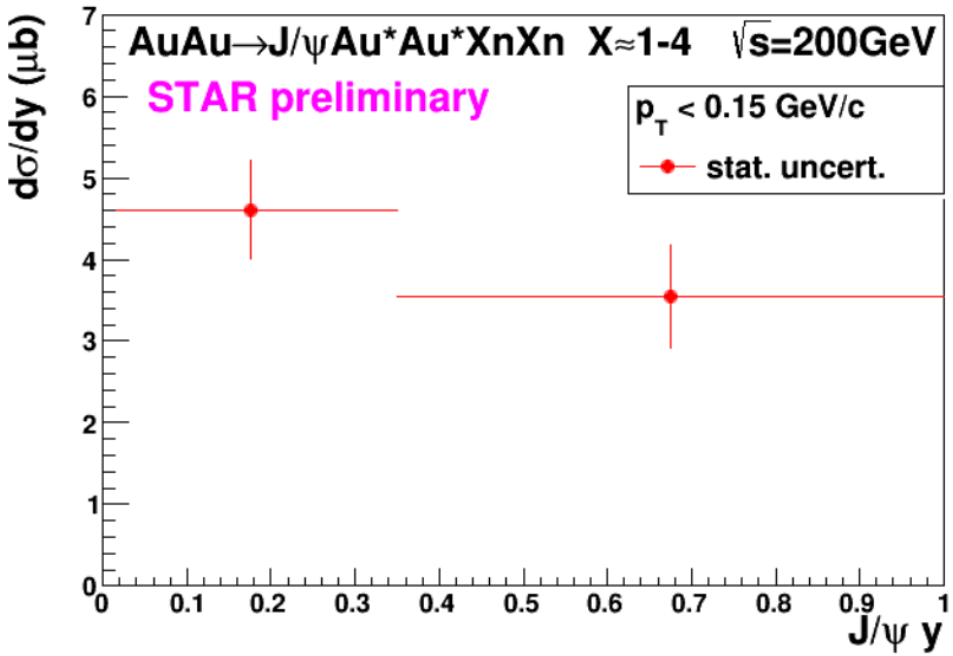
- Band around mass of the J/ψ and low p_T
- Sign of incoherent J/ψ at $p_T > 0.1$ GeV
- Band of dielectrons at lower masses and p_T
- Clear peak of the J/ψ
- Signal extracted by subtracting like sign background and side bands off the peak



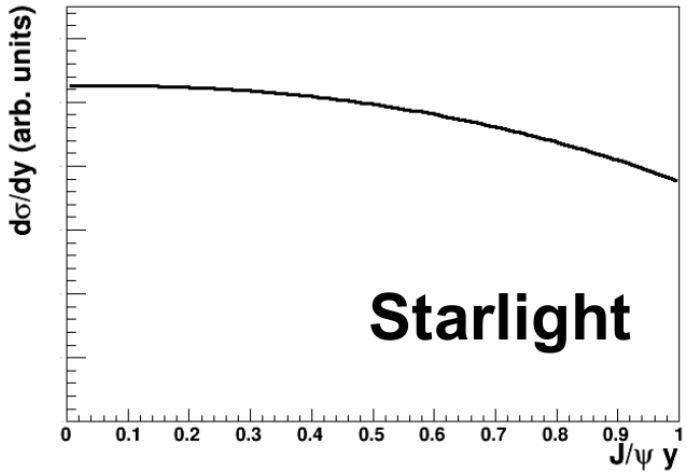


Coherent J/ψ cross section

- Cross section decreases away from mid-rapidity as described by STARLIGHT

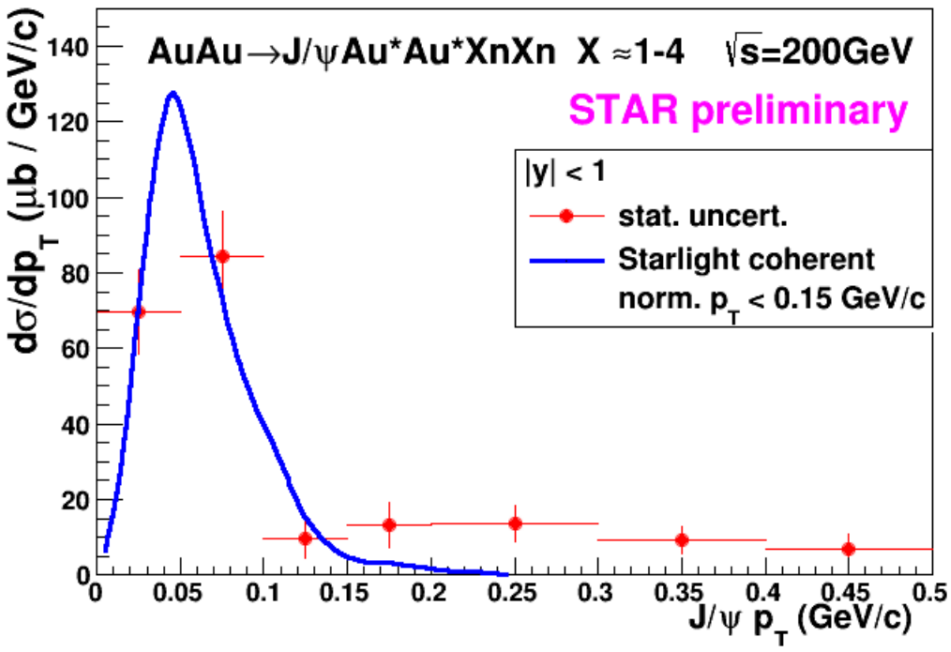


- Normalization uncertainties:
  - Uncertainties in neutron spectra by RELDIS (electromagnetic dissociation of heavy ions, estimates of number of neutrons distribution)
  - Uncertainties in Coulomb excitation in STARLIGHT



RELDIS: PRC C64, 024903 (2001) & PPN 42, 215 (2011)

J/ψ cross section as a function of p_T



- Coherent peak and incoherent tail falling to zero
- STARLIGHT normalized to the data in region of $p_T < 0.15$ GeV/c
- Width of coherent peak consistent with the data

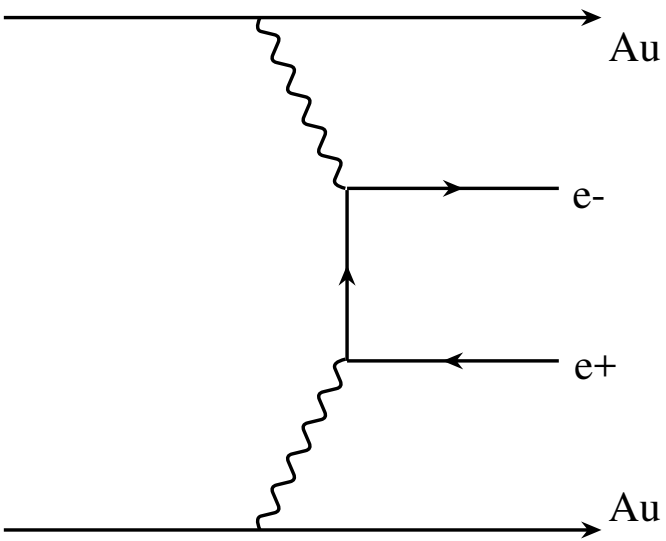
Outlook for J/ψ measurements

- RHIC Run 2014: trigger from EM calorimeter for $J/\psi \to e^+e^-$
- RHIC Run 2016:
  - Drop of neutron ZDC requirement
  - Data sample larger by factor of 30-50
  - Measurement with and without Coulomb dissociation
- J/ψ photoproduction on polarized protons
  - p+A and p+p
  - J/ψ transverse asymmetry
  - Roman Pot system to tag scattered protons
  - Data on J/ψ to measure Generalized Parton Distributions

Photoproduction of e^+e^- pairs

Au+Au @ $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV

Two-photon production of electron-positron pairs



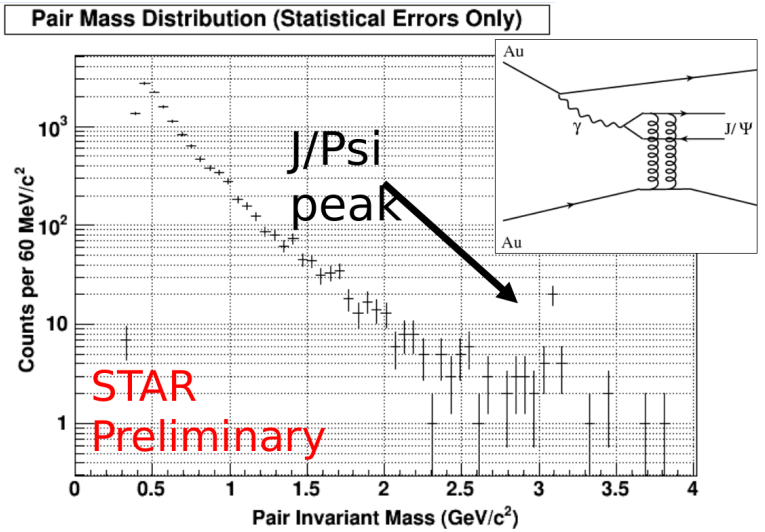
- Test of QED using ultra-peripheral collisions
- Enhanced in Au+Au by high photon fluxes ($\sim Z^2$)
- Measured at mid-rapidity using trigger from TOF, BBC and ZDC
- Cross section for pair at mass W is given by Breit-Wheeler formula:*

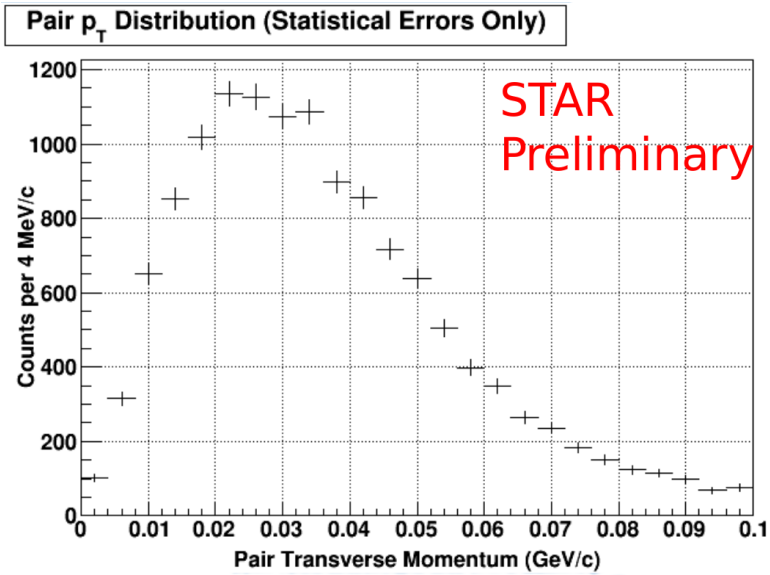
$$\sigma(\gamma\gamma \to l^+ l^-) = \frac{4\pi\alpha^2}{W^2}\left\{\left(2 + \frac{8m^2}{W^2} - \frac{16m^4}{W^4}\right)\ln\left[\frac{W+\sqrt{W^2-4m^2}}{2m}\right] - \sqrt{1-\frac{4m^2}{W^2}}\left(1+\frac{4m^2}{W^2}\right)\right\}$$

* Phys. Rev. D4, 1532 (1971)

Selection criteria for e^+e^- pairs and performance

- Selection criteria for e^+e^- pairs:
  - Two tracks in vertex
  - Both tracks have a corresponding hit in TOF
  - $|z_{\text{vertex}}| < 30$ cm
  - Pair $p_T < 0.1$ GeV/c and $|y| < 0.8$
  - Pair TPC $\mathrm{d}E/\mathrm{d}x$ in 2σ for electron (tracks added in quadratures)
- Summary on selected candidates:
  - $\sim 13\,000$ e^+e^- candidates
  - ~ 10 like-sign pairs
  - Shape of p_T distribution matches expectation for $\gamma\gamma \to e^+e^-$





RHIC Run2010, Run2011

Conclusions

- High statistics sample of photoproduced $\pi^+\pi^-$ pairs
- Observation of ρ^0, ω^0 and direct $\pi^+\pi^-$
- Diffraction pattern in cross section t-dependence
- Fourier 2-D transform for spacial image of nucleus

- Measurement of coherent J/ψ
- Clear coherent and incoherent contributions
- Data sample 30-50 times larger now in progress
- Upcoming measurement on polarized protons

- Data on $\gamma\gamma \to e^+e^-$ pairs
- Work in progress towards the cross section