Ultra-peripheral collisions in STAR
New results from dipions

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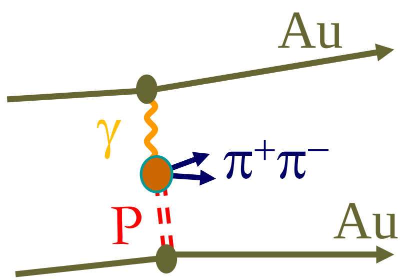
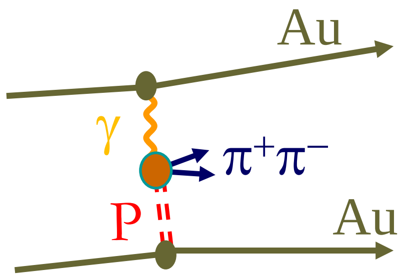
- UPC photoproduction
- The STAR detector
  - Trigger
- $\pi\pi$ around the ρ^0 mass
  - ρ, ω and direct $\pi\pi$ contributions
  - $d\sigma/dt$ and nuclear tomography
- A high mass $\pi\pi$ state

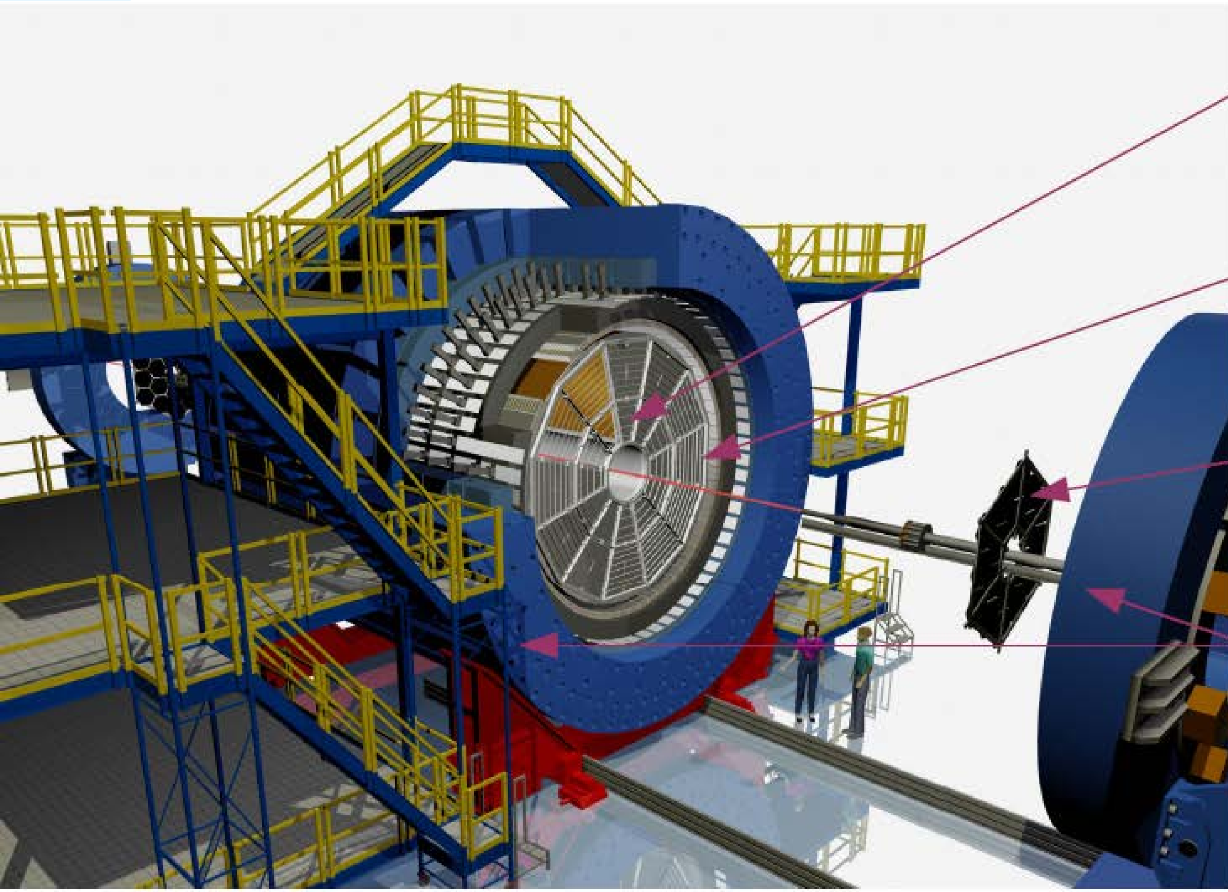


Ultra-peripheral photonuclear collisions



- Heavy nuclei carry intense photon fields
  - Perpendicular E and B fields -> photons
    - Weizsacker-Williams method
  - Flux ~ $Z^2\alpha$
- Large cross-sections for photonuclear interactions
  - 'photon-Pomeron' interactions
    - Pomeron = absorptive part of cross-section = gluon ladder (BFKL)
    - Couples equally to protons and neutrons
  - Some photon-meson interactions, at lower photon energies
- Vector meson dominance predicts mostly $J^{PC}=1^{--}$ states
  - $\pi\pi$ final state can come from ρ, ω, direct $\pi\pi$ production or higher excitations
    - $Br(\omega \to \pi^+\pi^-) \sim 1.5\%$ per PDG
    - Indistinguishable → interference -> add amplitudes

The STAR Detector



Time Projection Chamber
Tracking, PID (dE/dx), vertexing
multiplicity

Time-Of-Flight detector
PID (time-of-flight)

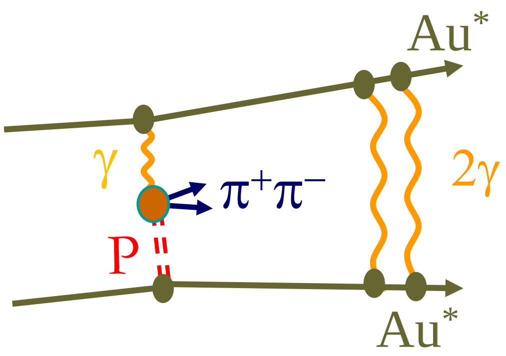
Beam-Beam Counter
Min-bias trigger

Magnet

Zero Degree Calorimeters (18 m upstream & downstream)

UPC Triggering: ZDCs, TOF and BBC veto
UPC Reconstruction: TPC, TOF

Triggering



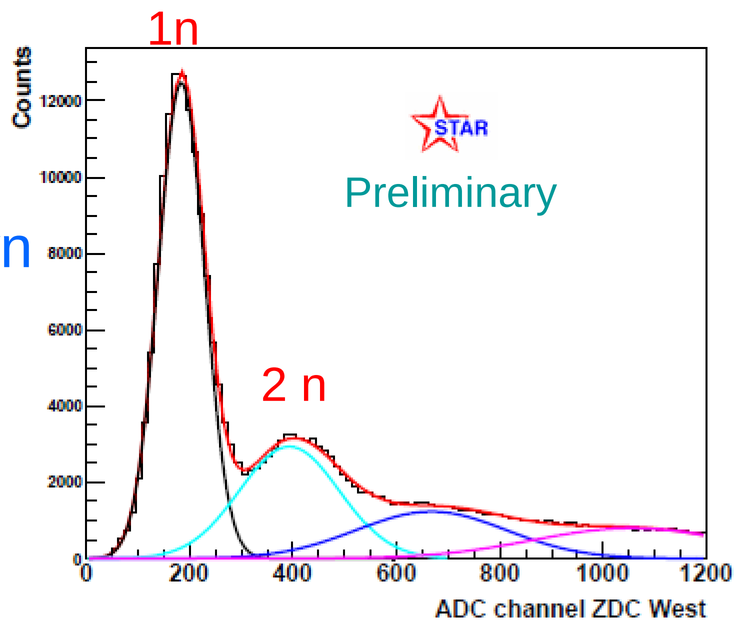
- Triggering on low-multiplicity final states is hard for STAR
  - Beam gas and cosmic-ray backgrounds
- Use the presence of additional photon exchange (mutual Coulomb exchange) to 'tag' UPCs at low impact parameters
  - Individual cross-sections factorize

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

- Require 1-5 neutrons in each zero degree calorimeter
  - We lose some events with more neutrons
- Require low multiplicity in time-of-flight system, and veto events with hits in beam-beam counters
- 38 million triggers recorded in 2010 data

Neutron Spectrum

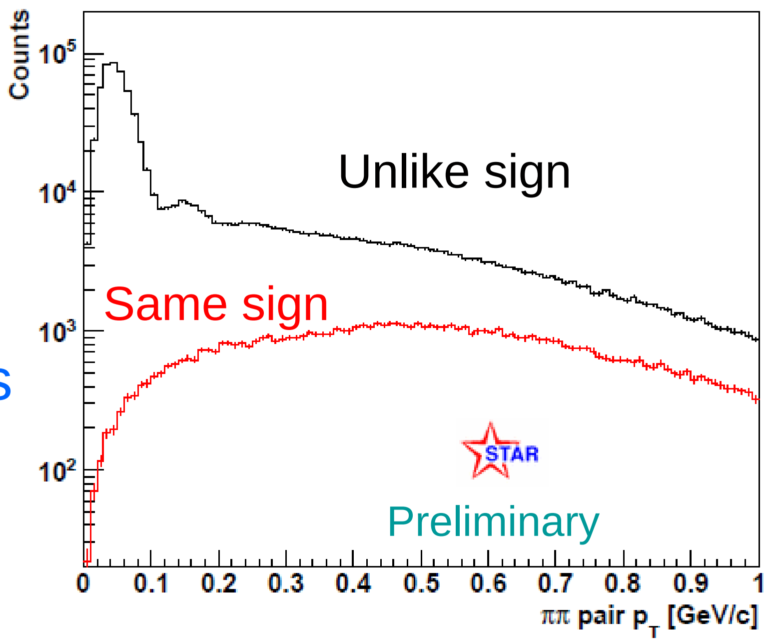
- A prominent 1n and smaller 2n peaks are visible in the zero degree calorimeter ADC spectra
  - 1n excitation occurs primarily via Giant Dipole Resonance excitation
  - ZDC cut acceptance in number of neutrons is not well known
- Use 1n1n events for overall cross-section normalization
  - the 1n1n cross-section is well known



ADC Counts in West ZDC

Pion pair selection

- Select well-reconstructed tracks
  - 14 hits in TPC (our of 45 normally possible)
  - Associated with a hit in the time-of-flight system
    - |Track pseudrapidity|< 1
    - Eliminates out-of-time tracks
  - Specific dE/dx within 3σ of pion expectation
- Like sign pairs are a background measure, and are subtracted.
- Efficiency corrections done with STARlight Monte Carlo events embedded in zero-bias data.
  - STARlight matches the kinematics for UPC photoproduction well.



STARlight: PRC C60, 014903 (1999)
& PRL 84, 2330 (2000)

$\pi^+\pi^-$ final state

- 384,000 reconstructed pairs with $p_T < 100$ MeV/c
- 3 sources: ρ^0, ω^0 (small B.R.), direct $\pi^+\pi^-$
  - Indistinguishable-> add amplitudes in fit

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

- Fit parameters
  - ρ^0 mass and width
  - ω mass and width
  - ρ,ω and direct $\pi\pi$ amplitudes, and ω phase
  - Quadratic polynomial for remaining backgrounds
    - N. b. remaining background is small; includes e^+e^- pairs…

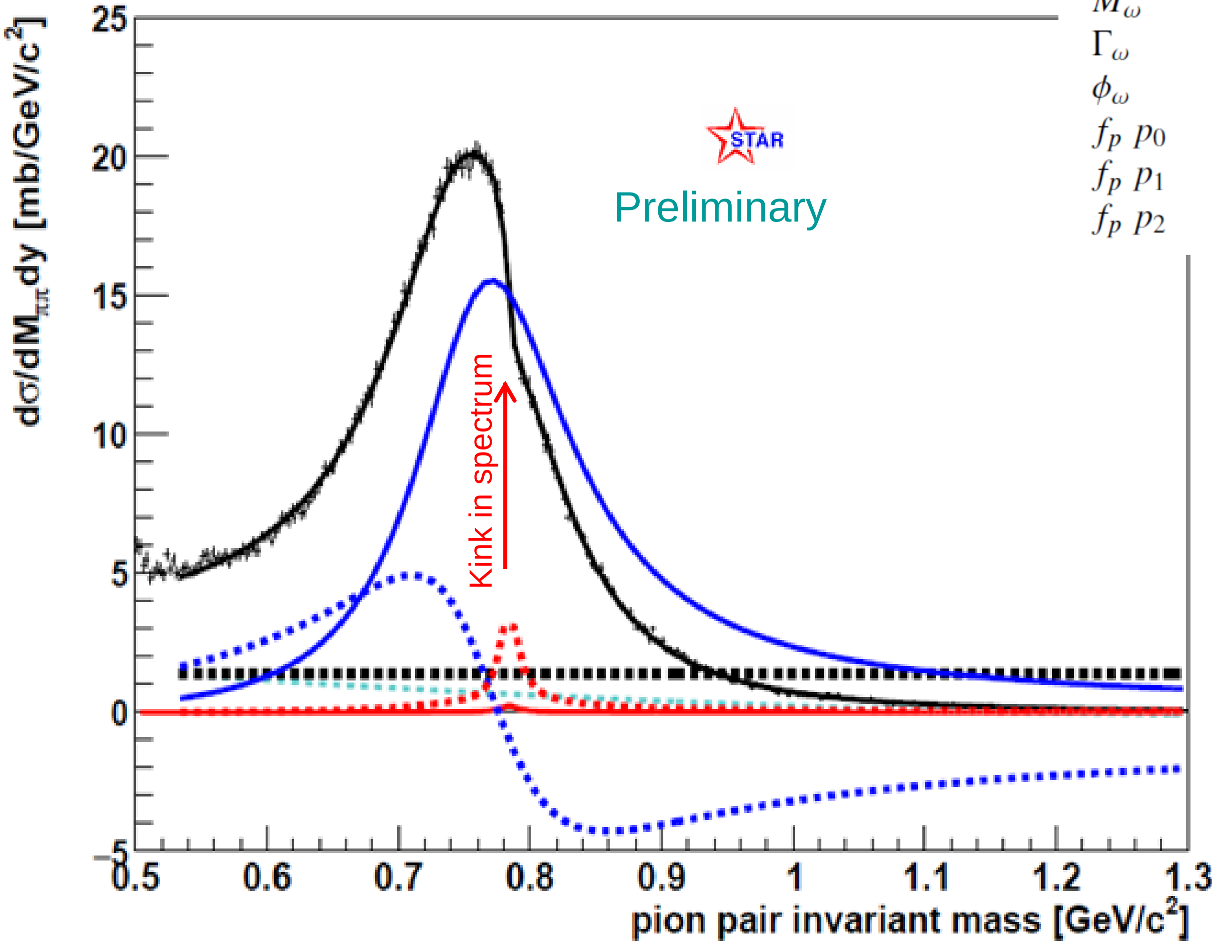
$\pi^+\pi^-$ fit

320 bins, 2.5 MeV wide

χ^2/DOF =314/297

Fit Parameter	value	units
M_ρ	0.7757 ± 0.0006	GeV/c^2
Γ_ρ	0.1475 ± 0.0014	GeV/c^2
A_ρ	1.511 ± 0.005	
$B_{\pi\pi}$	-1.176 ± 0.016	$(\mathrm{GeV/c^2})^{-1/2}$
C_ω	0.0626 ± 0.004	
M_ω	0.7838 ± 0.0009	GeV/c^2
Γ_ω	0.0163 ± 0.0017	GeV/c^2
ϕ_ω	1.73 ± 0.13	radians
$f_p\ p_0$	3.566 ± 0.304	
$f_p\ p_1$	-5.084 ± 0.53	
$f_p\ p_2$	1.743 ± 0.24	

Statistical errors only



Black: data points & fit

Solid blue: – ρ^0

Dotted blue: ρ^0/direct $\pi\pi$ interference

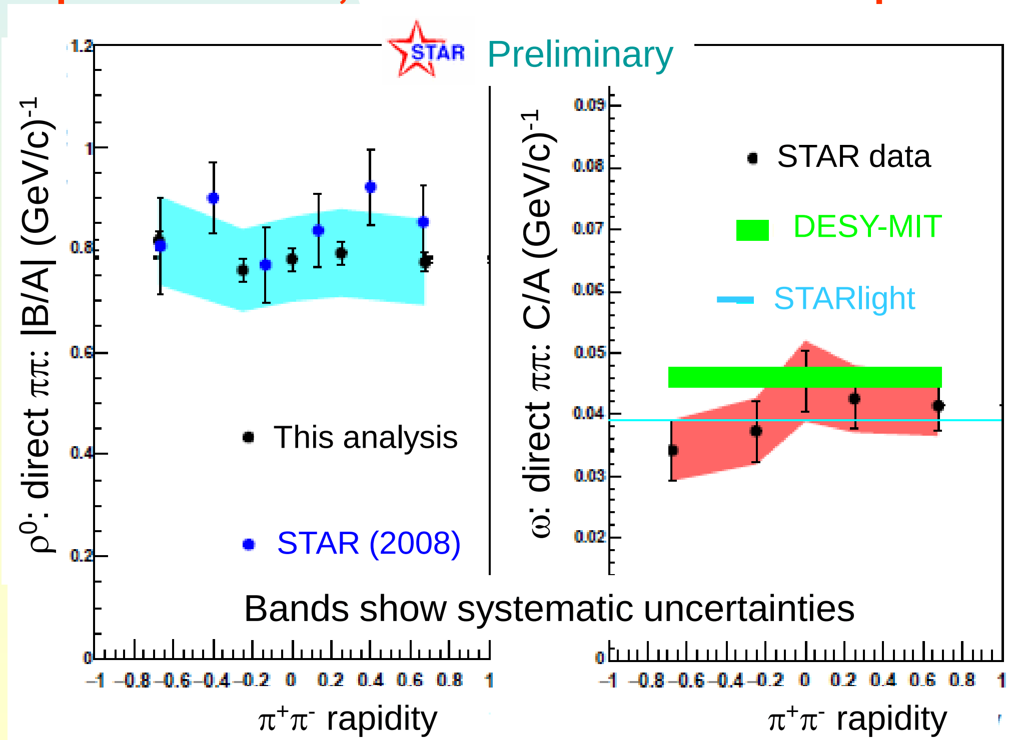
Solid red: ω

Dotted red: ω/ρ interference

The ω is needed; χ^2 quadruples without it!

Relative amplitudes: ρ:ππ and ρ:ω ratio

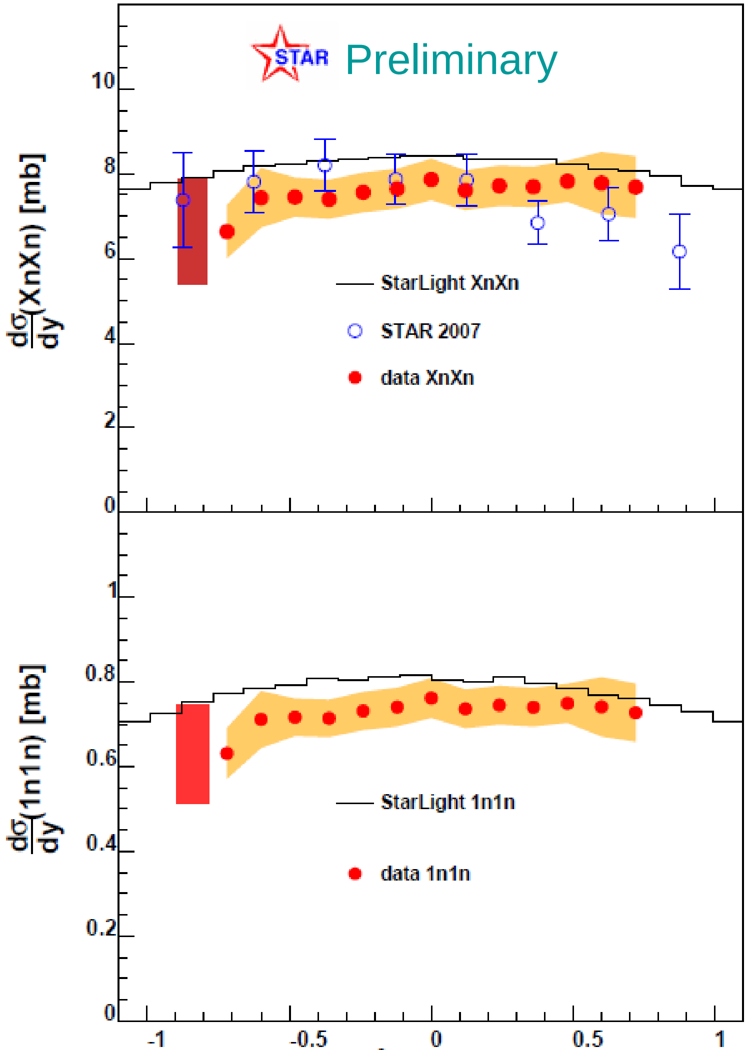
- ρ:ππ ratio is consistent with previous STAR & ALICE results, & also consistent with HERA results (on proton targets)
- ρ:ω ratio is consistent with measured γπ->ωp cross-section, Glauber calculation, via STARlight) and measured (per PDG) $Br(\omega\to\pi^+\pi^-)=0.015 \pm 0.001$ & with DESY fixed-target data
- ω phase ≠ 0; is consistent with previous DESY results



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

ρ^0 rapidity distribution

- Rapidity distribution is in good agreement with STARlight
- 1n,1n cross-section is consistent with STARlight
  - ~10% below prediction
    - < $1\sigma_{syst}$.
- XnXn cross-section is scaled from 1n,1n using STARlight
  - The distribution of the number of neutrons is not well known.

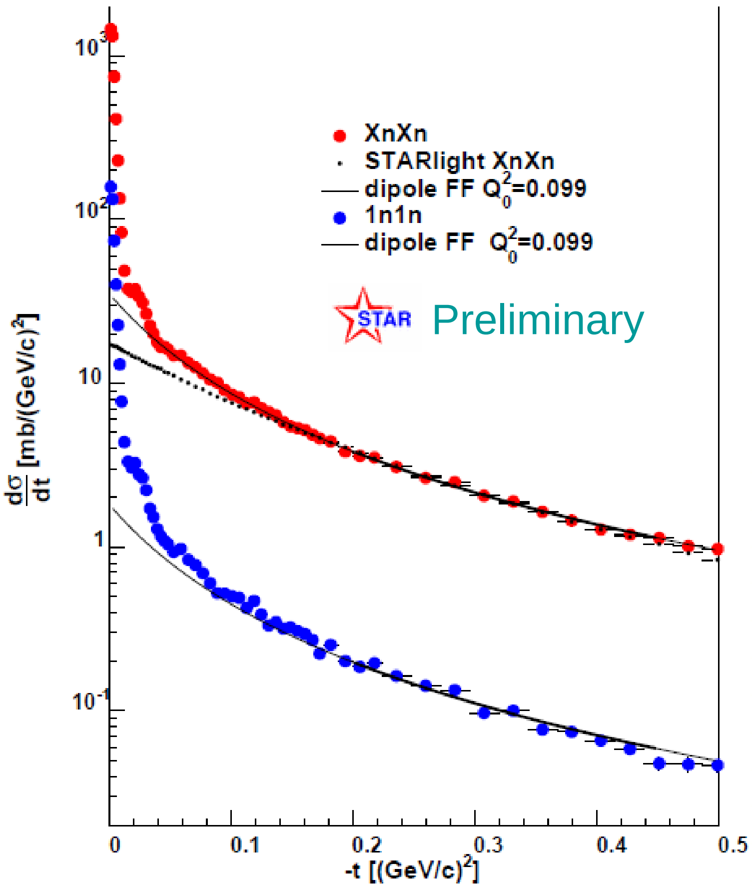


Bands show systematic uncertainties

ρ^0 Rapidity

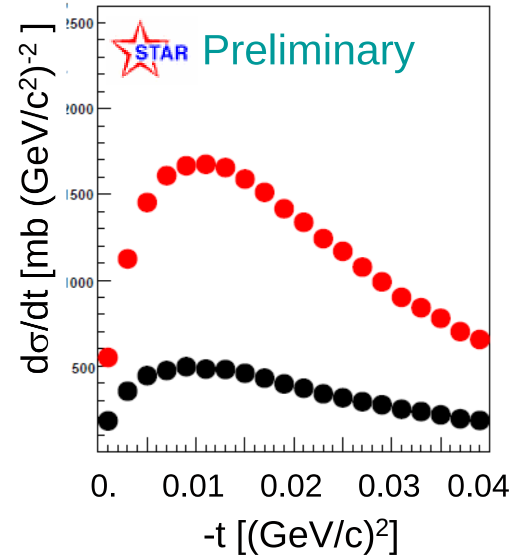
dσ/dt

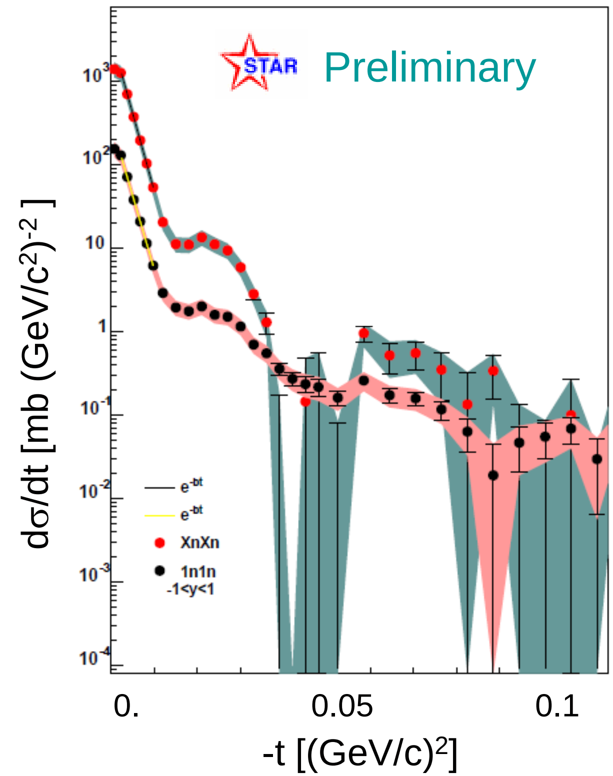
- Coherent (over the entire nucleus) + incoherent (off a single nucleon) production both occur
  - Incoherent -> often cause neutron emission or nuclear breakup
    - Because of trigger, cannot observe neutrons from nuclear breakup
  - Find coherent spectrum by subtracting incoherent
- Fit incoherent region, $|t|>0.2\ GeV^2$ region to a dipole form factor
  - $F(t)=A/(Q_0^2+|t|^2)$
  - $Q_0^2 = 0.099\ GeV^2$
  - Separate fits for 1n,1n and Xn,Xn



Coherent production

- Multiple diffraction dips visible
  - Expected as nucleus approaches ‘black disk’
    - Slightly washed out because of photon p_T
- Downturn for $|t|<10^{-3}$ GeV^2 due to interference between the two production targets (nuclei)
  - $S=|A_1-A_2\exp^{(ikb)}|^2$
  - A_1, A_2 are amplitudes for the two nuclear targets

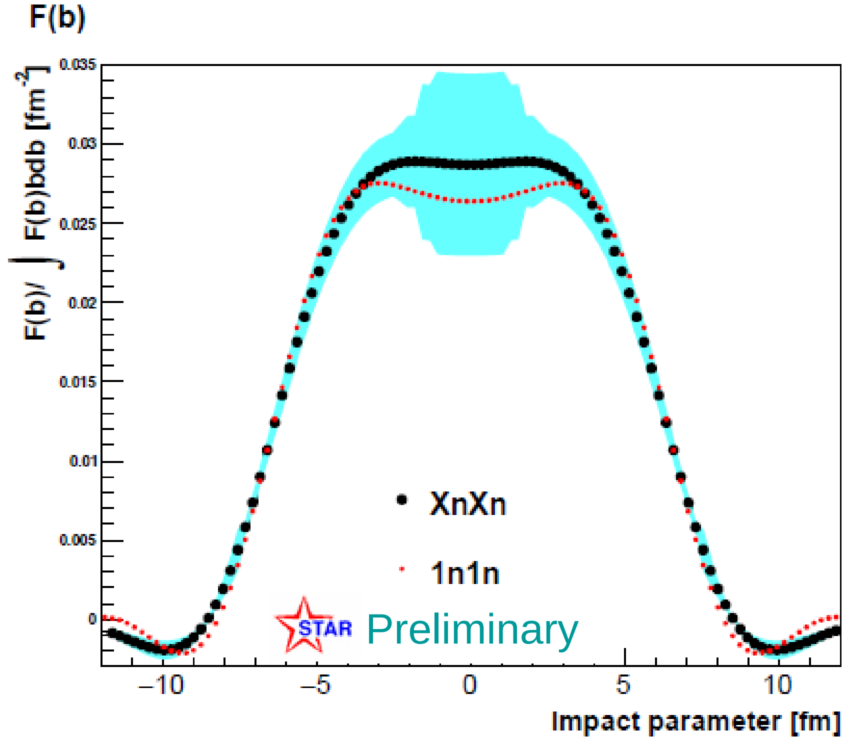




"Imaging" the nucleus

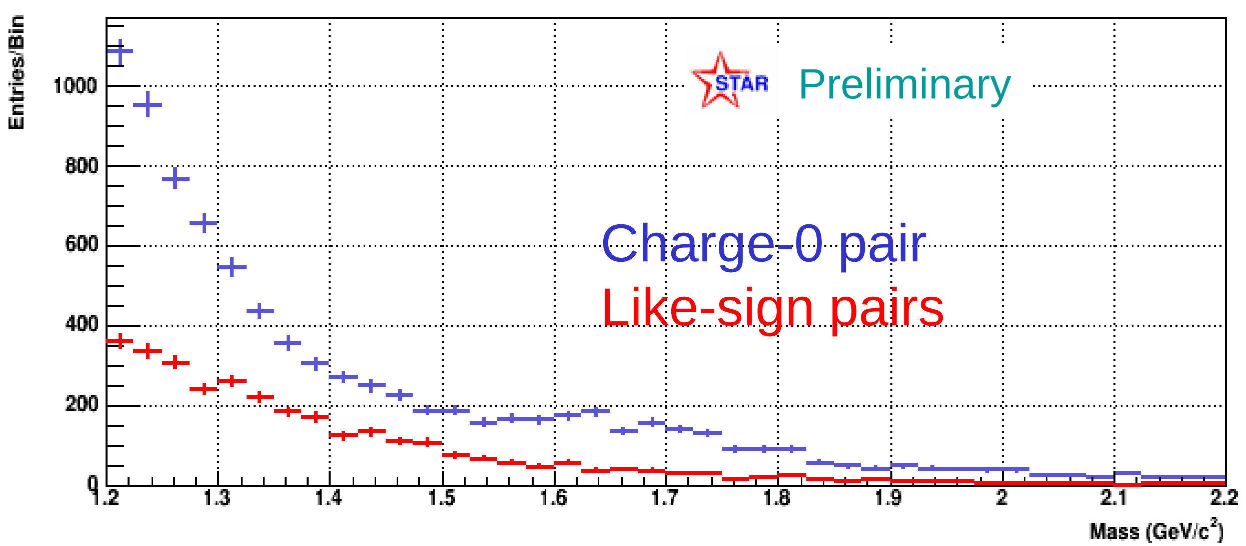
- Target (gluons?) density is the Fourier transform of dσ/dt
- $|t|_{max}$ = 0.06 GeV^2
- 2-d Fourier (Hanckel) tranform
  - Targets, integrated over z
- Blue band shows effect of varying $|t|_{max}$ from 0.05 - 0.09 GeV^2
  - Variation at small |b| may be due to windowing (finite t range)
- Negative wings at large |b| are likely from interference
- FWHM=2*(6.17±0.12 fm)

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



The high-mass region

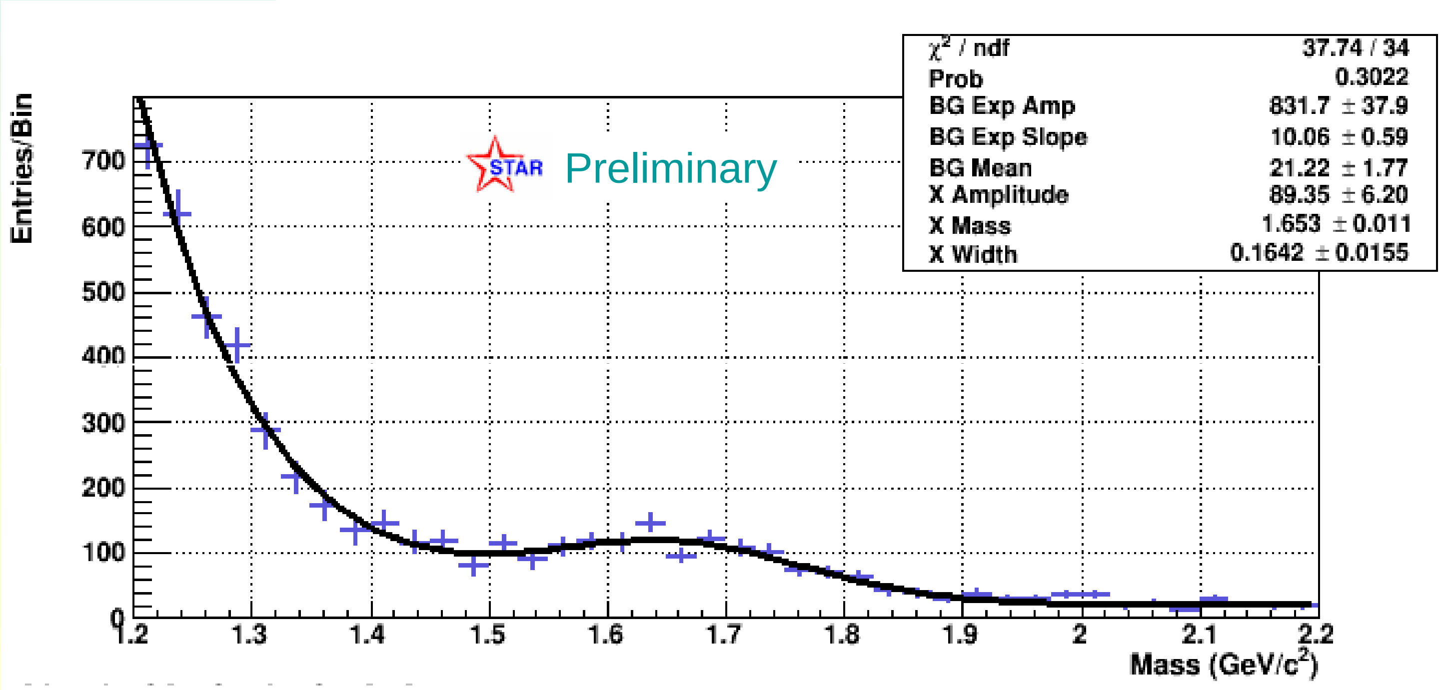
- 2 years (2010+2011) data w/ slightly different cuts
  - Cut $|y_{\pi\pi}|>0.04$ reduces cosmic-ray background
  - Twice as much data total
- The high-mass tail of the $\pi\pi$ mass distribution
- Fit to exponential tail of ρ^0, flat background & Gaussian peak
  - Simple, provides good description w/ 6 parameters total



n.b. $\gamma\gamma$->f_2(1270)->$\pi\pi$ is not clearly visible

A high mass state

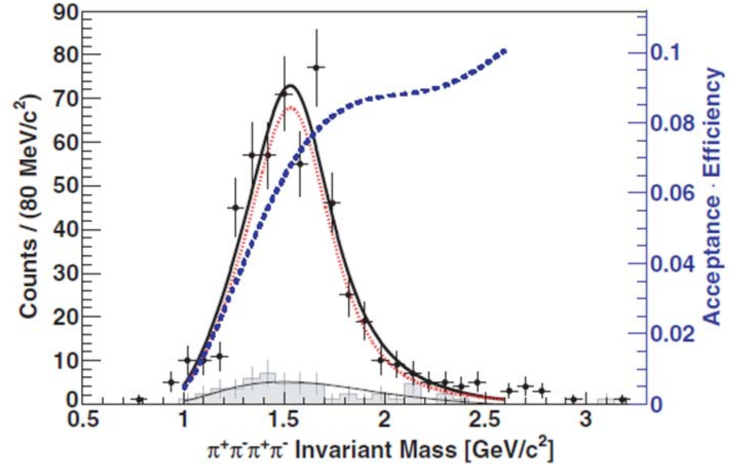
- $N = a * exp^{-(b[Mpp-1.2\ GeV])} + c + d\ exp(-[M_{\pi\pi}-M_X]^2/\sigma^2)$
  - χ^2/DOF= 37.7/34
  - χ^2/DOF increases to 252/35 w/o X resonance
- M_X = 1653 ± 10 MeV, Γ(X)=164+/- 15 MeV (stat. only)
- $N(M_X)$=1034 ± 71: 15 σ significance (stat. only)

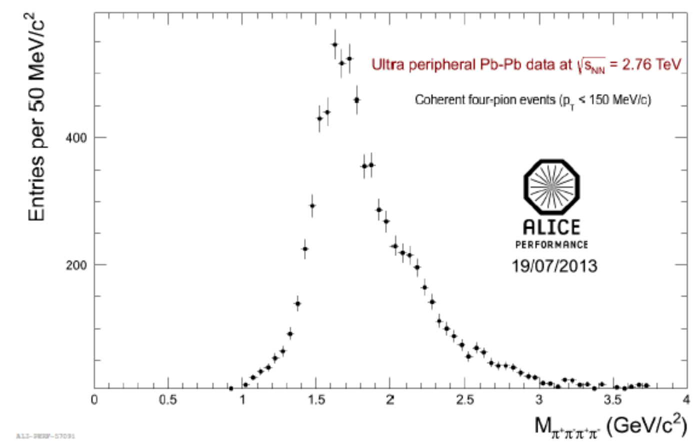


What is this state?

- Heavier and much narrower than previous STAR, ALICE observations of $\pi\pi\pi\pi$ final state
  - $\pi\pi\pi\pi$ was likely mixture of $\rho'(1450)$ & ρ' (1700)
- Heavier than the $\rho'(1450)$
- ~ lighter & narrower than the $\rho'(1700)$
  - Br ($\rho'(1700)$ -> $\pi\pi$) likely small: "seen"
- Consistent w/ ρ_3 (1690)
  - M= 1690 & Γ= 161 MeV
  - Br(ρ_3 -> $\pi^+\pi^-$) = 23.6 ± 1.3 %
  - N(ρ_3)/Br(ρ^0) ~~ 1/750
    - consistent w/ Br(ρ_3->$\pi^+\pi^-$) & previous γp-> ρ_3 -> $\eta\pi^+\pi^-$ data

STAR $\pi\pi\pi\pi$ mass
PRC81, 044901 (2010)





ALICE $\pi\pi\pi\pi$ mass
C. Mayer, 2014 CERN UPC wkshp

γp –> ρ_3 -> $\eta\pi^+\pi^-$ from OMEGA photon collaboration: Z Phys. **C30**, 531 (1986)

Conclusions

- STAR has made a high-statistics study of photoproduced $\pi\pi$ in ultra-peripheral collisions.
  - We observe the ρ, direct $\pi\pi$ and ω photoproduction.
    - The ω is observed through its interference with the ρ^0.
    - The ω amplitude is consistent with the measured ω photoproduction cross-section and branching ratio to $\pi^+\pi^-$.
    - The ω phase angle is non-zero, and consistent with previous studies.
- We see 2 diffraction minima in $d\sigma/dt$ for ρ^0 photoproduction
  - By Fourier transforming the coherent portion of $d\sigma/dt$, we can 'image' the nucleus, forming a 2-dimensional picture of the photoproduction targets.
- We observe an excited state with a mass of 1653 MeV and width of 164 MeV. The closest match in the particle data book is the $\rho_3(1690)$.
  - The cross-section is consistent with a previous photoproduction measurement.

Bill Schmidke will present STAR J/ψ photoproduction results this afternoon.