# Photoproduction of charged mesons in ultra-peripheral collisions

**Spencer Klein, LBNL**

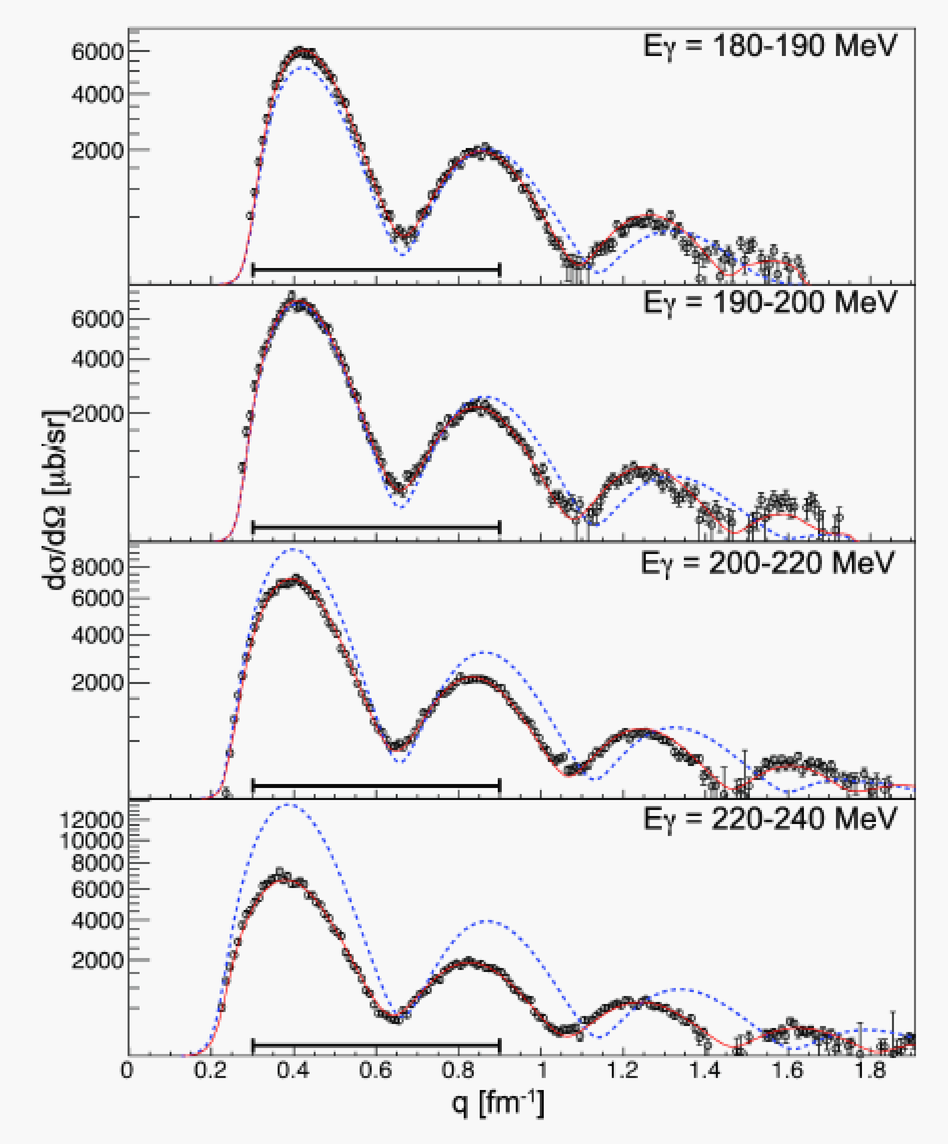
- Current UPC studies are focused on the exchange of neutral particle, i.e. Pomerons or neutral mesons
- What about the exchange of charged mesons?
- The $a_2(1320)$ meson
  - Measuring the neutron skin of heavy nuclei
- Rate estimates

# Does gold have a neutron shell?

- Expectation is that the neutron radius is ~ 0.25 fm larger than the proton radius
  - Proton radius well measured from electron scattering
- Data is limited, but most supports the idea of a neutron shell
  - Antiprotonic atoms
  - Atomic parity violation
  - Dipole polarizability of the nucleus
  - Coherent $\pi^0$ photoproduction
  - All of these methods have significant systematic uncertainties
- $a_2^+$ and $a_2^-$ photoproduction probe the neutron and proton radii of gold separately in the same experiment!
  - The systematics cancel

# Coherent $\pi^0$ photoproduction

- Low-energy (180-240 MeV) photons at MAMI
- Blue curve shows effect of including $\pi$-N interaction
- Measured
- $s = 0.15 \pm 0.03\,^{+0.00}_{-0.03}$ fm




C.M. Tarbert *et al.* (Crystal Ball Collab.), arXiv:1311.0168

# Coherence?

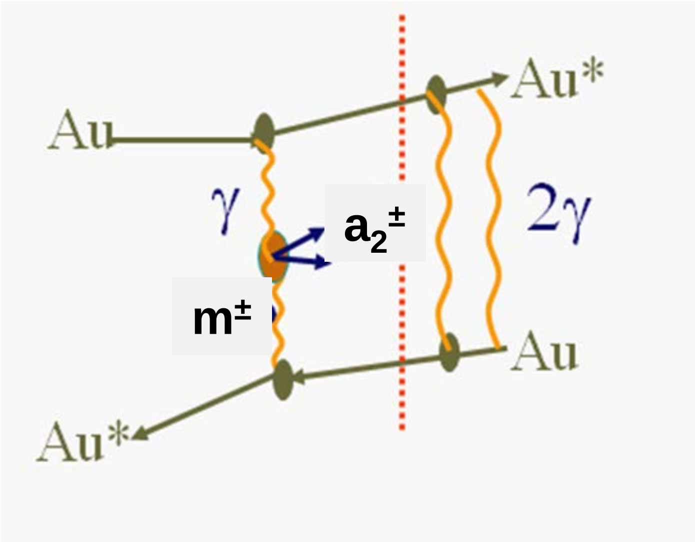
- Coherent production occurs when it is impossible to determine which nucleon the photon/Pomeron couples to.
  - Indistinguishable → add amplitudes
  - Amplitude ~ A so $\sigma \sim A^2$
    - Absorption can moderate Pomeron coupling, to $A^{4/3}$
- Conventional Wisdom: a charged intermediary will change protons into neutrons (or vice  versa), irredeemably marking them.
  - But…. Some theorists expected a similar loss of coherence in AuAu → $Au^*Au^*\rho^0$ because the final state nuclei are different from the initial state
- Alternate Wisdom: the created proton (neutron) is buried inside the nucleus, indistinguishable from the other protons (neutrons).
  - Coherent production remains possible, with $\sigma \sim Z^2$ or $(A-Z)^2$

# The nuclear final state

- Quantum mechanics says that you add amplitudes if the final states are indistinguishable.
- Can one tell which proton is turned into which neutron?
- For RHIC:
  - $\gamma$ + $^{197}$Au -> $a_2^+$ + $^{197}$Pt ($\tau_{1/2}$ = 19 h)
  - $\gamma$ + $^{197}$Au -> $a_2^-$ + $^{197}$Hg ($\tau_{1/2}$ = 64 h)
  - Both nuclei also have excited states with shorter livetimes
- Since the nuclei will decay in the end, one could wait until after the decay; the nuclei will be ~ indistinguishable.

# Additional Photon exchange

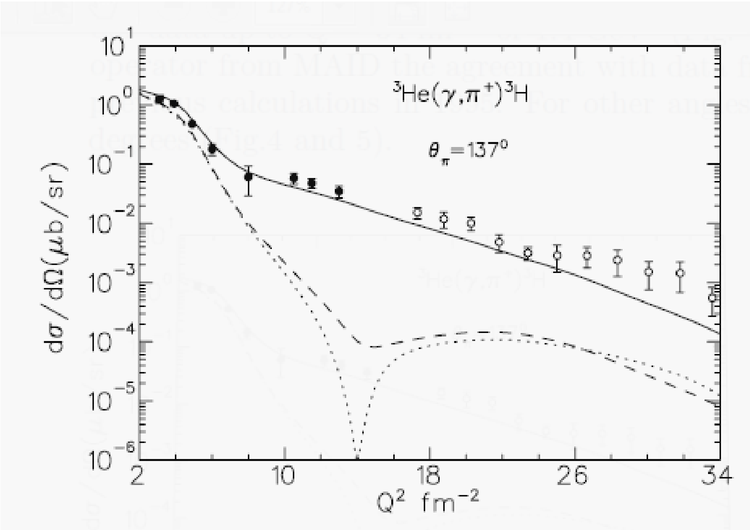
- $a_2$ photoproduction may be accompanied by mutual Coulomb excitation.
  - Key trigger for RHIC studies
  - GDR or higher excitation
- Independent photon exchange
  - $P(b) = \int P_{a2}(b) P_{Au1}(b) P_{Au2}(b)$
- The excited nucleus decays almost immediately
  - Information about nuclear shell states is partially or completely lost; no lingering nucleus




Baltz, Gorbunov, SK, Nystrand, PRL 89, 012301 (2002)
Baur, Hencken, Aste, Trautman, SK., Nucl. Phys. A729, 787 (2003)

# Two analogies

- This situation is similar to UPC coherent photoproduction accompanied by Coulomb excitation
  - The fact that the nucleus is excited and breaks up does not degrade the coherence.
    - Key to trigger for STAR, PHENIX… UPC program
- Coherent $\pi^0$ and $\pi^+$ photoproduction has been studied at fixed target accelerators.
- $\gamma^3He \rightarrow \pi^+\ ^3H$ fairly widely studied
  - @CLAS 0.55-1.50 GeV photons
  - Use same nuclear wave function for initial and final states, except for Coulomb corrections




Coherent Photoproduction of $\pi^+$ from $^3He$

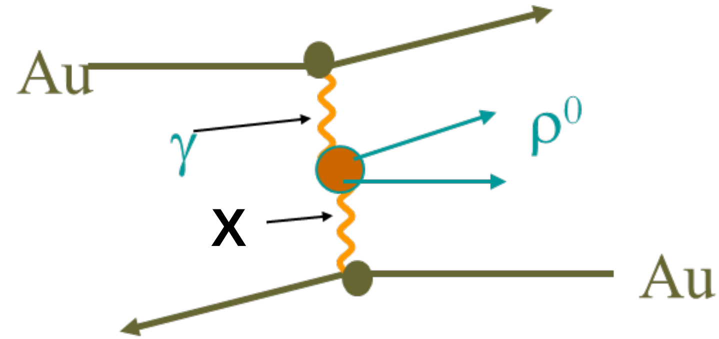
CLAS Collaboration, Phys. Rev. C83, 034001 (2011)

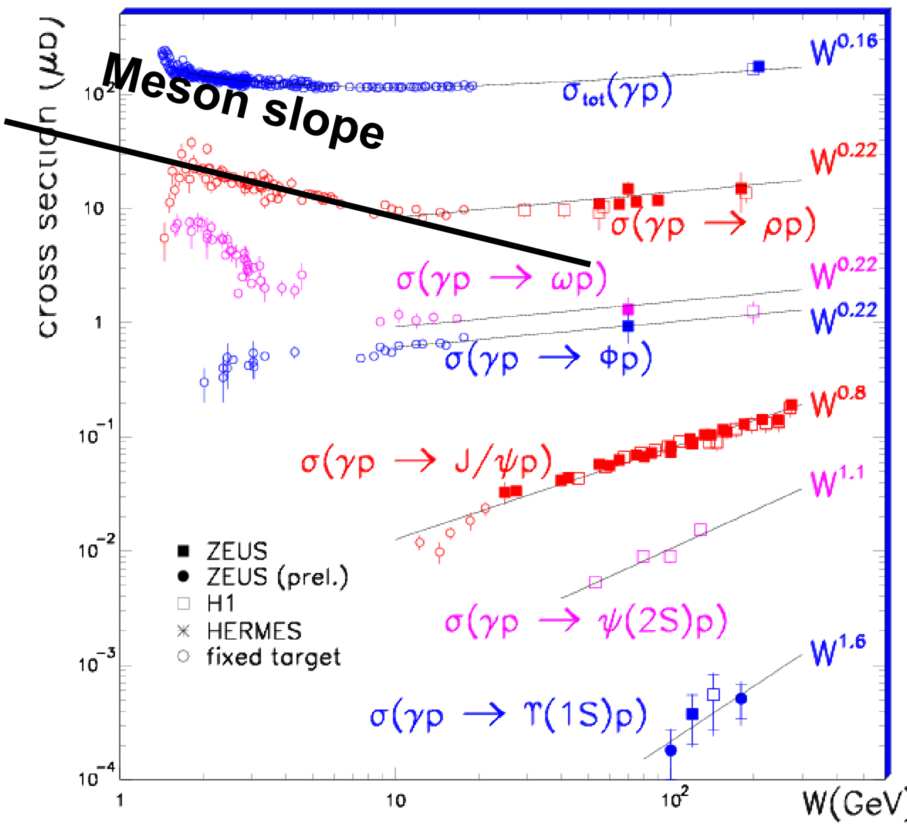
# The nuclear final state

- $\gamma^3He \rightarrow \pi^+ \, ^3H$ is a special case: ppn -> pnn
  - 2 proton targets, leading to a final state neutron
    - Protons are identical except for spin.
- For other nuclei, $a_2$ photoproduction may create a hole in a shell, and produce a nucleon with a position & momentum that are a poor fit for the lowest lying open shell. Depending on the initial and final nucleon quantum numbers, the produced nucleus may be in an excited state.
  - Nuclear matrix elements are probably < 1, not yet reflected here.
  - If the final state nucleus is excited, it may visibly de-excite
- If the nucleus is also Coulomb excited into a Giant Dipole Resonance or higher excitation, likely making details of the final state moot.

# Meson Couplings

- Neutral particle exchange is mostly Pomeron & meson…
  - The meson exchange decreases with increasing $W_{\gamma p}$, but is not negligible at STAR energies.
- At $W_{\gamma p}$ = 14 GeV, the meson coupling is only a few times weaker than the Pomeron coupling
  - $\gamma_{500\ \mathrm{MeV}} + P_{500\ \mathrm{MeV}} \rightarrow \phi$
  - At midrapidity $W_{\gamma p}$ = 14 GeV
- Within current UPC range



# The $a_2(1320)$

- Decays primarily to $(\pi\pi\pi)^{\pm}$
- M= 1320 MeV
  - $\Gamma$=100 MeV
  - $J^{PC}=2^{++}$
  - Decay to $\rho^0\pi$ (70%) , $f_2(1270)\pi$, $\rho(1450$
    - * $\rho(1450)\pi$ is subthreshold
- Photoproduced at SLAC
  - $\gamma p \rightarrow (\pi\pi\pi)^{\pm}$ n
  - $a_2(1320)$ prominent at low $p_T$
  - Consistent with one particle exchange model
    - In agreement with theory calculations assuming 1 $\pi$ exchange

Y. Eisenberg *et al.,* PRD 5, 15 (1972)
Y. Huang et al., arXiv:1308.3382

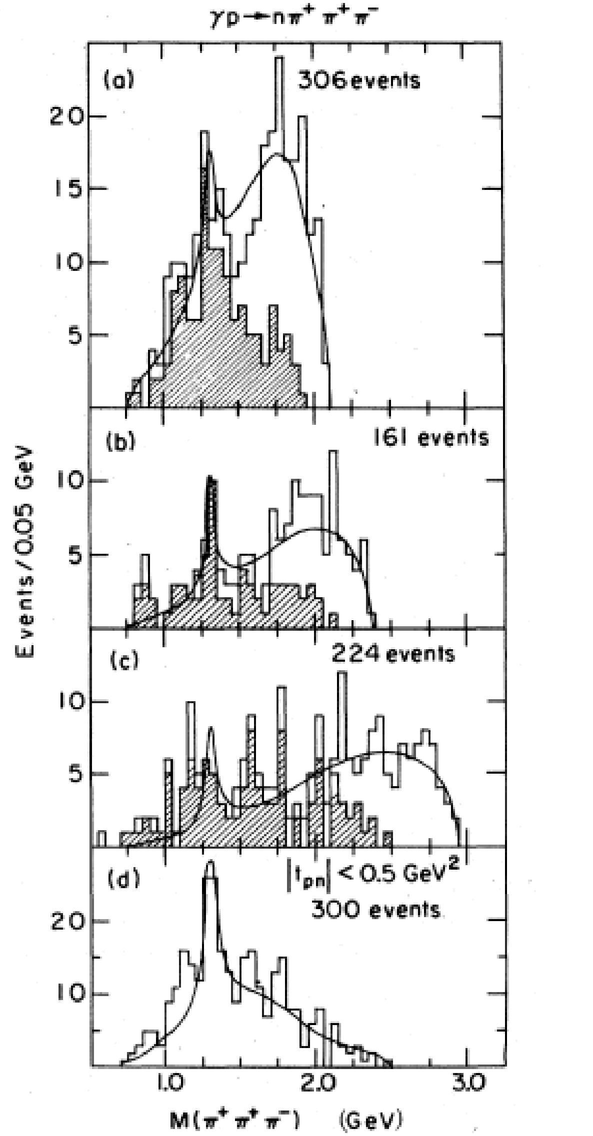
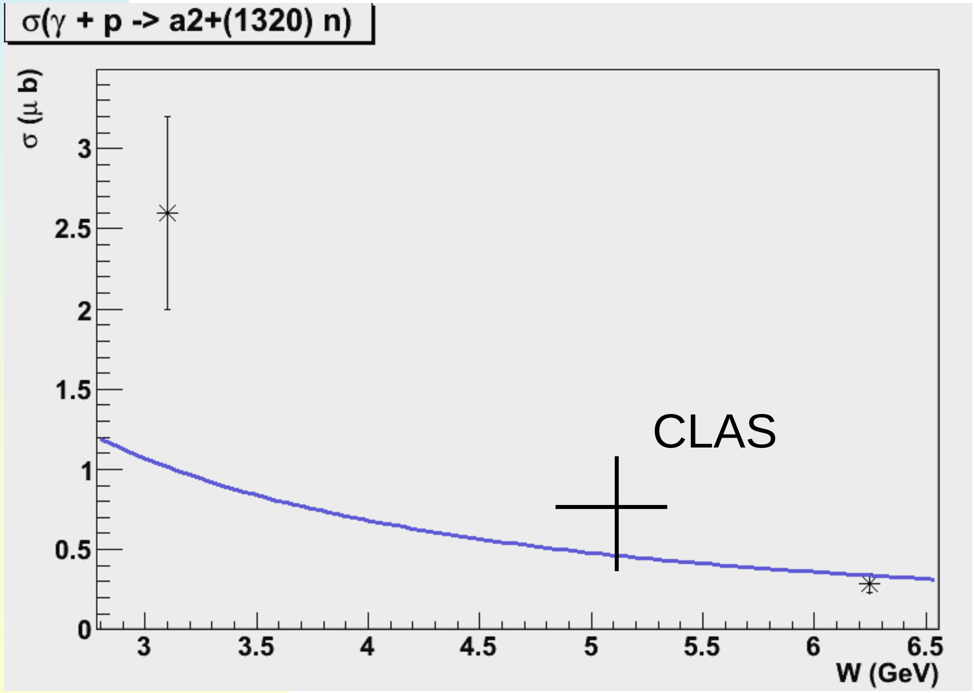



FIG. 18. $M(\pi^+\pi^+\pi^-)$ distribution in the reaction $\gamma p \to n\pi^+\pi^+\pi^-$ at (a) 4.3 GeV, (b) 5.25 GeV and (c) 7.5 GeV. The shaded areas represent events with $|t(p,n)| \leq 0.5$ GeV$^2$. (d) Mass distribution combining the three energies for above $t$ cut. The curves are best fits to $A_2$ resonance [$M(A_2) = 1.30$ GeV, $\Gamma(A_2) = 0.1$ GeV] and phase space (see Table VIII).

# Cross-section for $\gamma p \rightarrow a_2^+(1320)\, n$

- Data from fixed two fixed target experiments
- Fit based on Condo et al.
  - Fit is mediocre, but so is the data…
- Assume $\sigma(\gamma n \rightarrow a_2^-(1320)p)$ is the same




G. T. Condo et al., PRD 38, 3045 (1993); CLAS Collab.arXiv:0805.4438,

# Glauber formalism for $a_2^{\pm}$ production?

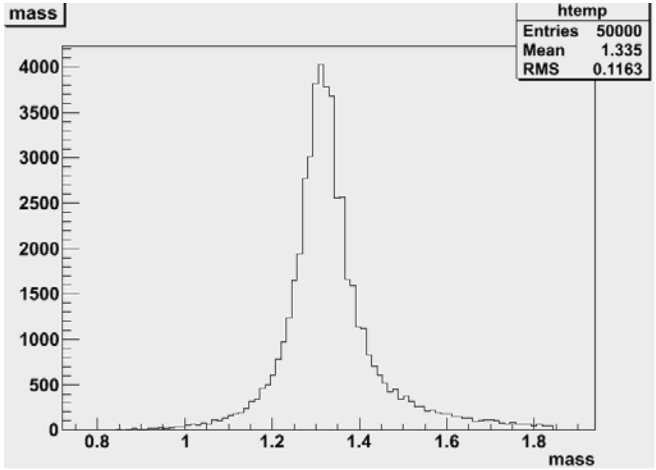
$$\frac{d\sigma^{(c)}}{dt} = \left(\frac{d\sigma_0}{dt}\right)_{t=0} \frac{4}{(\sigma_1 - \sigma_2)^2} \left| \int J_0(qb) \left[ \underbrace{e^{-\frac{1}{2}\sigma_1 T(b)}}_{=1} - e^{-\frac{1}{2}\sigma_2 T(b)} \right] d^2b \right|^2 .$$

- $\sigma_1$ & $\sigma_2$ are total particle-nucleon cross-sections for incident & outgoing particle
  - In VM photoproduction, take $\sigma_1=0$, $\sigma_2 \sim \sigma_{VM} \sim 24$ mb (for $\rho$)
    - Take $\sigma_{a2} = 24$ mb
  - Successful for UPC & fixed target photoproduction
- $d\sigma_0/dt$ is the cross-section for $a_2^{\pm}$ photoproduction
- Separate T(b) for protons and neutrons
- Assume full coherence ($J_0(qb)=1$)
- OK for the $a_2^{\pm}$?
  - Interaction is not just $q\bar{q}$ dipole elastic scattering
  - At high energies, incident particle is a $q\bar{q}$ dipole

Kolbig and Margolis, Nucl. Phys. B6, 85 (1968); Mark Strikman

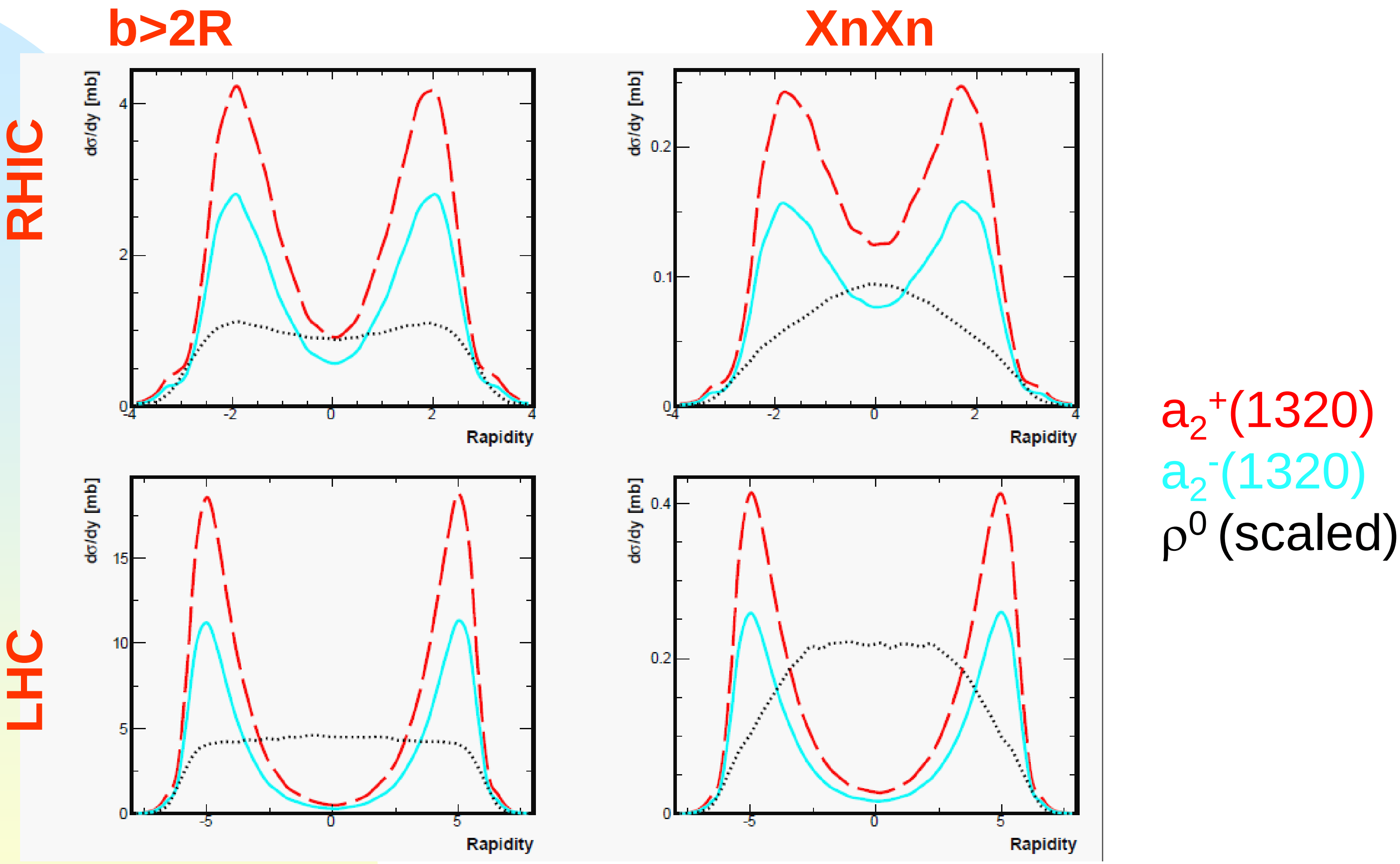
# $a_2$(1320) production in STARlight

- So far (private version)
- Assume a Breit-Wigner line shape
- Quantum Glauber calculation
- Coupling to number of protons/neutrons
  - Use Woods-Saxon parameters for $a_2^+$
  - Add 0.25 fm to radius for $a_2^-$
    - No 100% consistent way to back-fit
      - Larger neutron radius will change b>2R & other nuclear breakup criteria for all reactions
      - For now, alter form factor, but not radius for nuclear breakup criteria
- Assume $a_2$(1320) -> $\rho^0\pi^+$ decay
  - Phase space corrections to width
  - Not terribly important




Produced mass – from STARlight

# dσ/dy




$a_2^+$ and $a_2^-$ rapidity distributions are essentially identical

The $a_2$ is produced primarily at larger rapidity than the $\rho^0$, since most production involves relatively low photon energies.

# Cross-sections with gold at RHIC

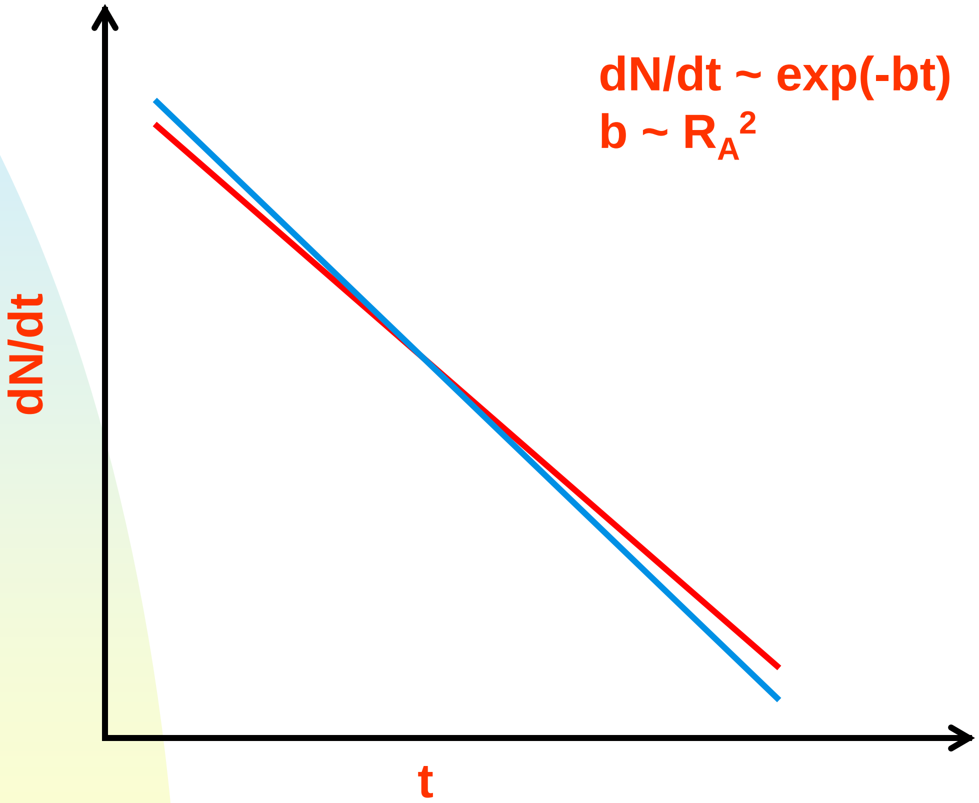
| | **B>2R** | **XnXn** |
|---|---|---|
| $\rho^0$ (no direct $\pi\pi$) | 590 mb | 39 mb |
| $a_2^+$ | 9.6 mb | 0.63 mb |
| $a_2^-$ | 14.5 mb | 0.98 mb |

Classical Glauber for $\rho^0$, QM for $a_2$

Total $a_2$ cross-section is 4% of the $\rho$ cross-section
60 times larger than for the J/$\psi$

XnXn $a_2$ cross-section is also 4% of the $\rho$ XnXn cross-section
36 times larger than for the J/$\psi$

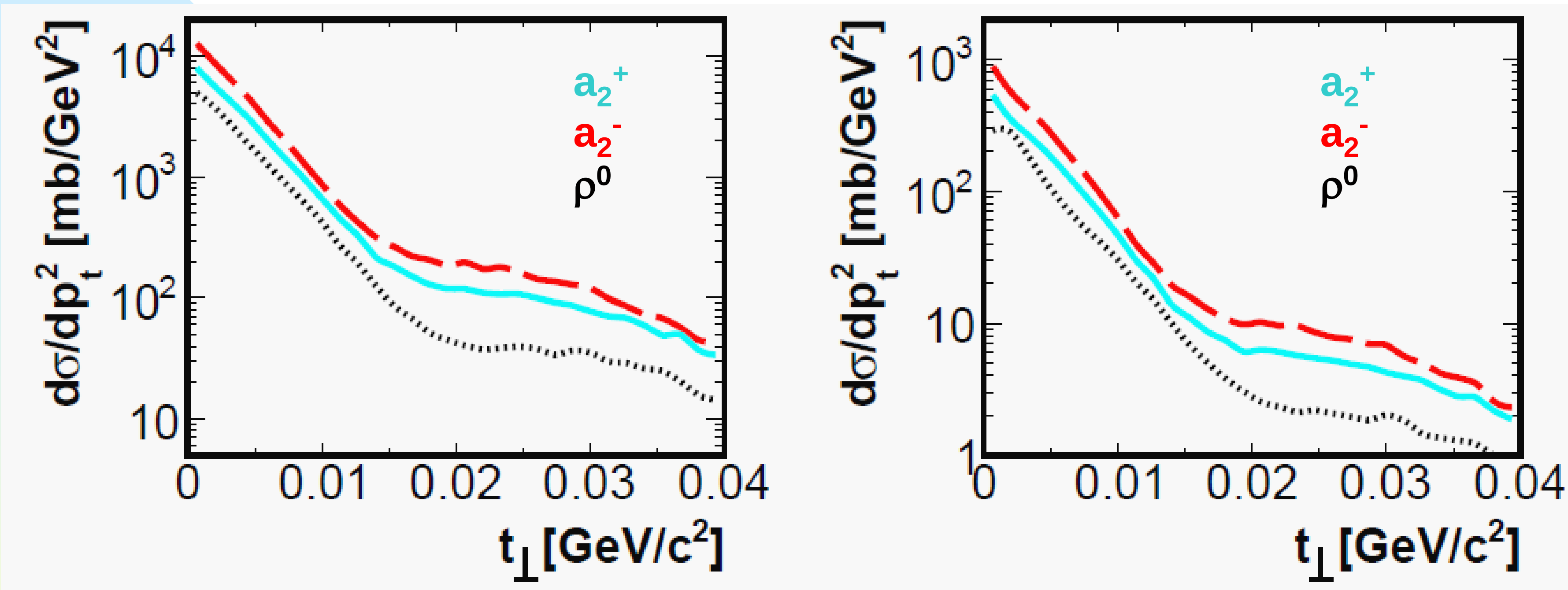
# $d\sigma/dp_T$ and the neutron radius of gold




n.b. In the late 1960s, Sam Ting & collaborators used this method with $\rho^0$ photoproduction to measure the hadronic radius of heavy nuclei (with limited statistical accuracy)

# t-spectra

**No hadronic Breakup** **XnXn**

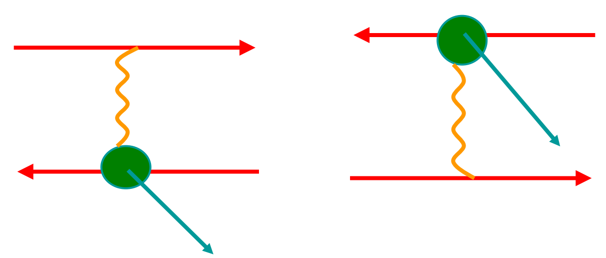



**Preliminary!!**

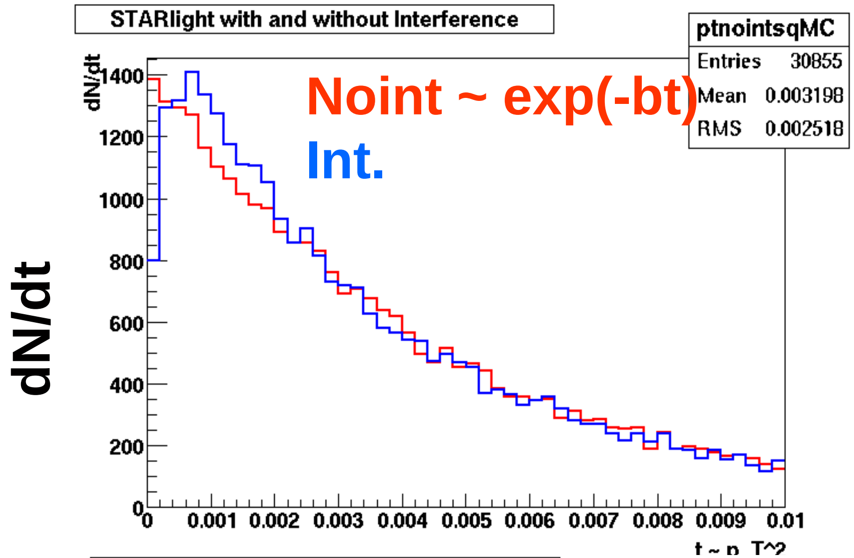
$t = p_T^2$

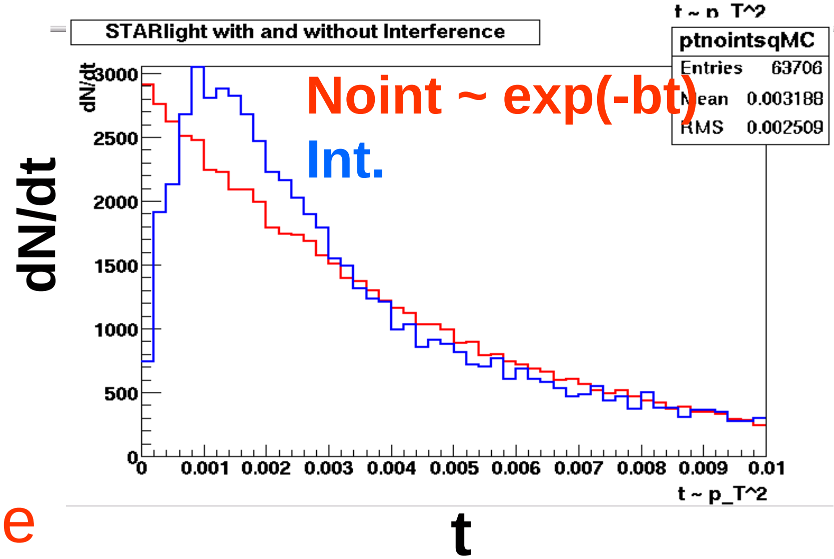
Clear difference visible (n. b. Some y dependence!)
Slope changes and 2nd diffraction peak moves
n.b. neutron skin should also be present for $\rho^0$, but there is no
No-neutron' standard for comparison

# Interference in UPC photoproduction



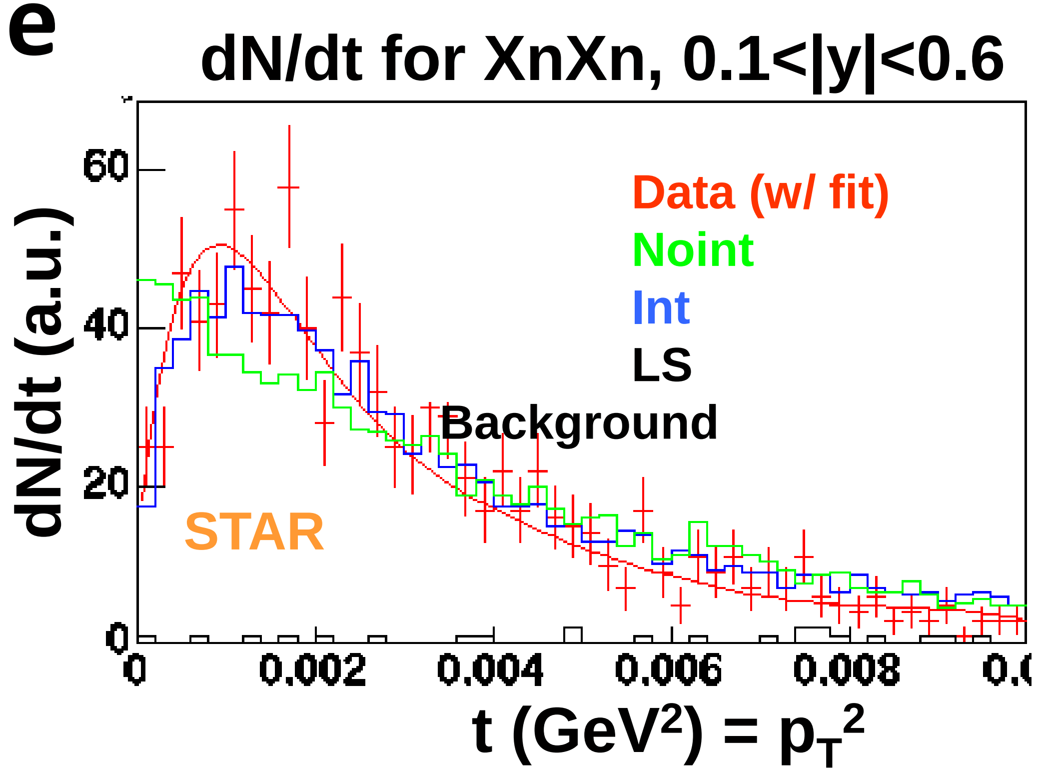
- 2 indistinguishable possibilities
  - Interference!!
- Similar to pp bremsstrahlung
  - no dipole moment, so
  - no dipole radiation
- 2-source interferometer
  - separation b
- $\rho,\omega,\ \phi$, $J/\psi$ are $J^{PC} = 1^{--}$
- Amplitudes have opposite signs
- $\sigma \sim |A_1 - A_2 e^{ip\cdot b}|^2$
- b is unknown
  - For $p_T << 1/<b>$
    - destructive interference
- $\rho^0$+XnXn has much smaller $<b>$, so inteference is much more visible

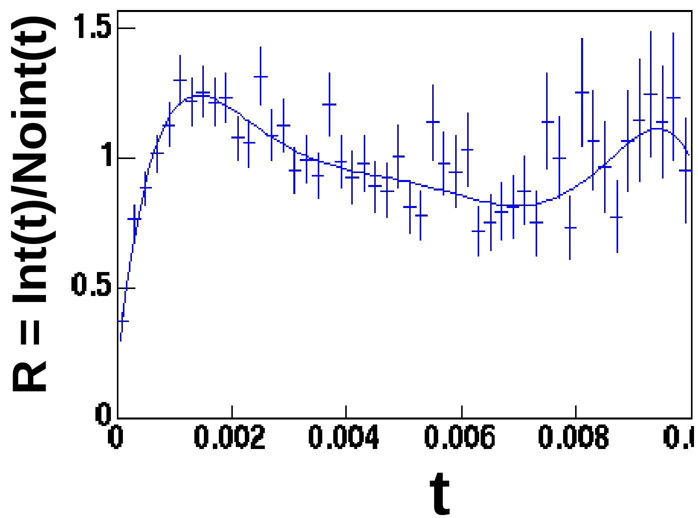


# Analysis Technique

- Select clean events
  - tight cuts
- 2 Monte Carlo samples:
  - Interference
  - No interference
  - w/ detector simulation
    - Detector Effects Small
- 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 interference




STAR, Phys. Rev. Lett. 102 (2009) 112301

# What about the $a_2$?

- The a2 is positive parity
  - Constructive Interference!
- Interference is largest near |y|=0, where the amplitudes for the two photon directions are ~~ equal
  - $d\sigma/dy$ for the $a_2$ is small around y=0
  - Interference is less important

# Rate Estimates in STAR at RHIC

- Scale from $\rho^0$
  - Assume 500,000 observed $\rho^0$ in 2010 dataset
- Cross-section is 4% of $\rho^0$
- $a_2$ are produced at larger rapidity
  - Lose a factor of 3 due to rapidity distribution
- Three prong vs. 2 prong
  - Assume factor of 2 loss of efficiency
- Expect to observe 3,300 $a_2^{\pm}$ in 2010 data
  - Factor of 2 uncertainty in input cross-sections
  - Enough to measure cross-section, rapidity and $p_T$ distributions, study decay modes (Dalitz plot), etc.
  - May be enough to measure radius difference
    - 2007 STAR $\rho^0$ paper used the similar sized 2004 data sample to measure t-slopes to 6% (3% in nuclear radius)
- Later data sets will add more data

# Other/future venues

- UPCs are not the only place to study photoproduction
- JLAB Hall D offers very high photon rates
  - But, longitudinal coherence is incomplete
    - $L_f = 2\hbar k/M_a^2 < R_A$ for k< 28 GeV
  - Moderate/modest complication
- An electron-ion collider offers higher photon energies
  - Can select events with $Q^2 \sim 0$, or even scan in $Q^2$
  - Track outgoing electron; subtract off photon $p_T$
- F(t) is Fourier transform of r(radius); in principle, one could independently probe the proton and neutron densities
- Single $\pi^{\pm}$ production might be used for the same purpose?
  - Seems experimentally difficult

# Conclusions

- The charged $a_2^{\pm}(1320)$ should be produced by photon-meson fusion in UPCs at RHIC
- The rate is estimated using fixed target photonproduction data to find the $\gamma p \to a_2 p$ cross section, and a Glauber calculation to find the AuAu cross-section.
- The summed cross-section for the $a_2^+$ and $a_2^-$ are about 4% of the $\rho^0$ cross-section.
- An expected difference in proton and neutron radii for nuclei will lead to different t-slopes for the $a_2^+$ and $a_2^-$
- After corrections for relative acceptance, STAR could see about 3,300 $a_2^{\pm}$ in the 2010 data set.
- In the long run, can use detailed studies to measure the proton and neutron distributions, not just radii

# Final states?

- Single $\pi^{\pm}$
  - Seen at HERA photoproducton in $\gamma p \rightarrow n\pi^{\pm}$, but experimentally very hard
- $(\pi\pi\pi)^{\pm}$
  - Seen at SLAC in $\gamma p \rightarrow (\pi\pi\pi)^{\pm} n$
  - For k= 10 GeV, $\sigma \sim 1/3$ of $\sigma(\rho^0)$
  - $a_2(1320)$ prominent at low $p_T$
    - M= 1320 MeV
    - $\Gamma$=100 MeV
    - $J^{PC}=2^{++}$
    - Decay to $\rho^0\pi$, $f_2(1270)\pi$, $\rho(1450)\pi$
      - * $\rho(1450)\pi$ is subthreshold

Y. Eisenberg et al, Phys. Rev. D5, 15 (1972)

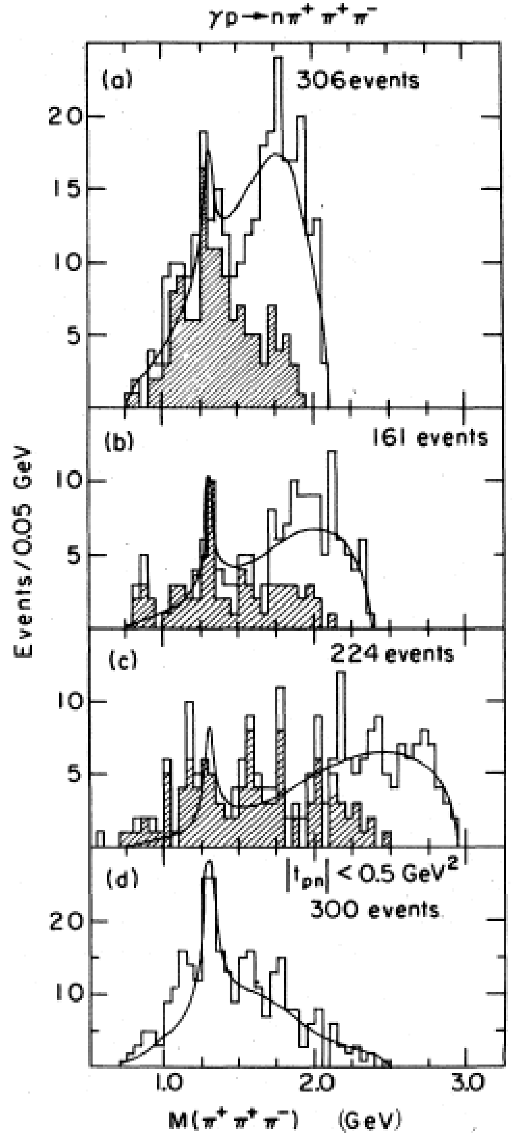



FIG. 18. $M(\pi^+\pi^+\pi^-)$ distribution in the reaction $\gamma p \rightarrow n\pi^+\pi^+\pi^-$ at (a) 4.3 GeV, (b) 5.25 GeV and (c) 7.5 GeV. The shaded areas represent events with $|t(p,n)| \leq 0.5$ GeV$^2$. (d) Mass distribution combining the three energies for above $t$ cut. The curves are best fits to $A_2$ resonance [$M(A_2) = 1.30$ GeV, $\Gamma(A_2) = 0.1$ GeV] and phase space (see Table VIII).

# Cross-sections

- Scaled to $\rho^0$
  - $\sigma(a_2)$ ~ 2% of $\rho^0$ for k = 8 GeV
  - From the SLAC paper, so includes a $\rightarrow 3\pi$ branching ratio
- Scaling to k = 14 GeV
  - Assume $a_2$ is dominated by meson exchange.
  - $\sigma(a_2)$ ~ 0.5% of $\rho^0$ for k = 14 GeV
- Assuming Coherence
  - For $\rho^0$, $\sigma \sim A^{4/3}$
  - For $\gamma p \to a_2^+ n$: $\sigma \sim Z^{4/3}$
  - For $\gamma n \to a_2^- p$: $\sigma \sim (A-Z)^{4/3}$
    - If gold has a neutron skin, $a_1^+$ and $a_1^-$ have different form factors
  - Factor of ~ 0.3
- $N(a_2)/N(\rho)$ ~1/1,000
  - Well within STAR's sensitivity range.