UPC 2025: The Second International Workshop on the Physics of Ultra Peripheral Collisions

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Creighton UNIVERSITY

STAR

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FOR THE STAR COLLABORATION

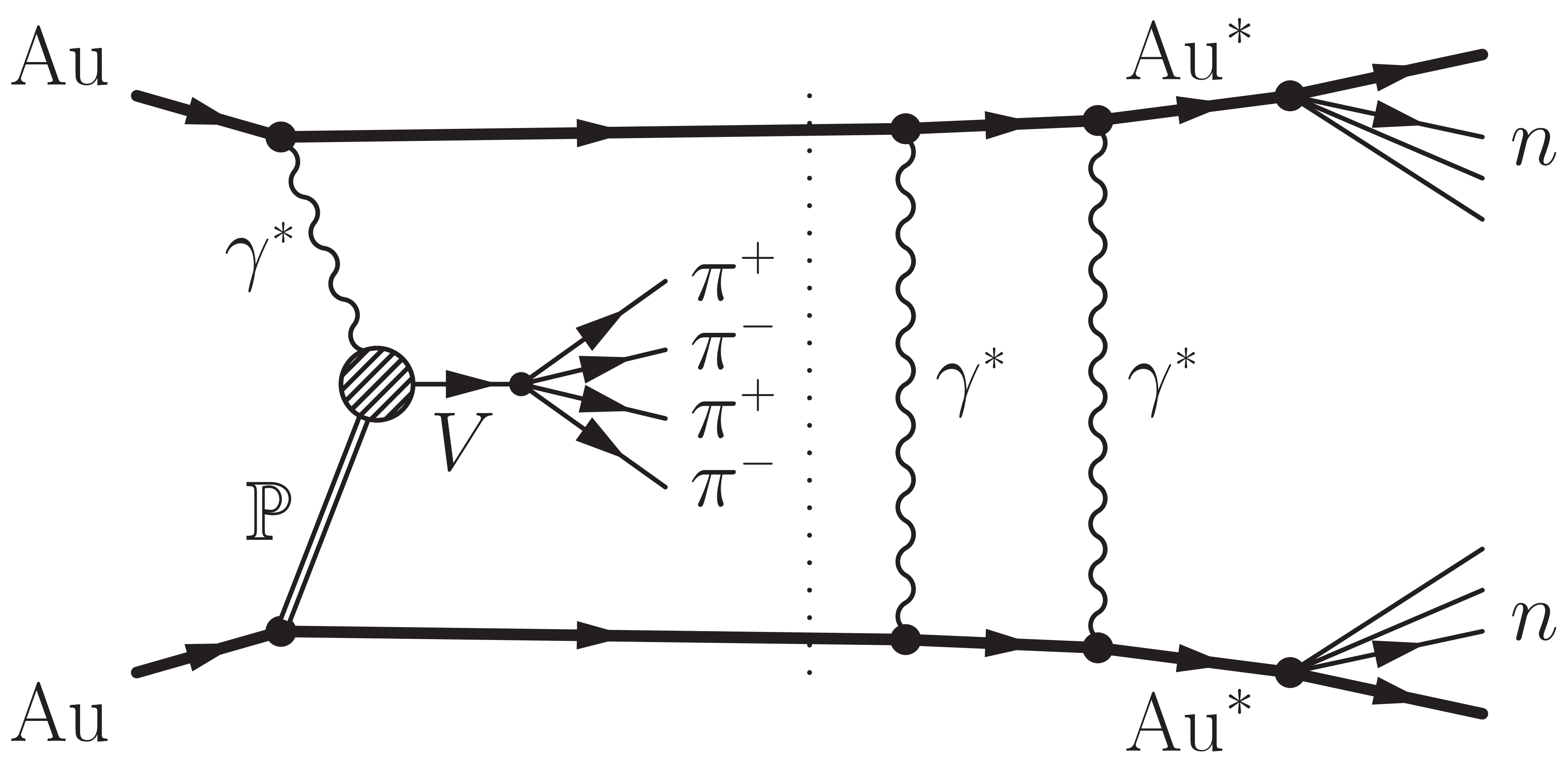
OBSERVATION OF $\pi^+\pi^-\pi^+\pi^-$ AND $\pi^+\pi^-$ FINAL STATE PHOTO PRODUCTION IN UPC AT $\sqrt{S_{NN}} = 200$ GEV AT THE STAR DETECTOR

MOTIVATION

- The first radial excitation 2^3S_1 of ρ_0 is considered to be the ρ_{1450} [PRD 110 030001], but decays suggest it is a hybrid state [PRD 56 1584]
- ρ_{1700} is assigned to 1^3D_1 state - there is need for precise measurement of mass and width to clarify its nature [PRD 110 030001]
- Questions of the ρ_{1450} relation to the ρ_{1700} have been raised
- The relativistic quark model [PRD 32 189] predicts 2^3D^1 state $J^{PC} = 1^{--}$ at 2.15 GeV which can be identified with the $\rho(2150)$

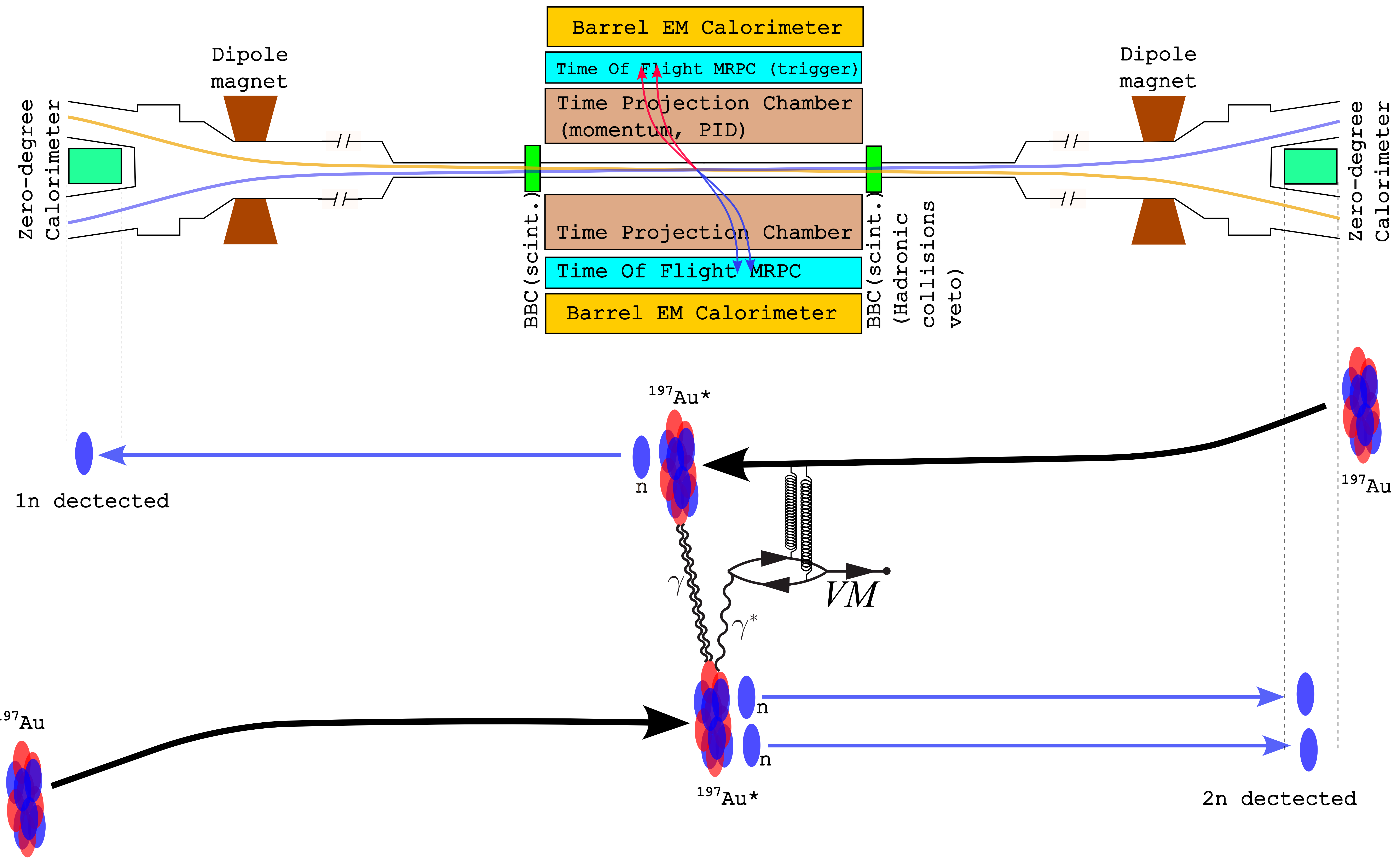
UPC AS A GREAT PRODUCTION TOOL

- Heavy Ion Collisions - large charge => large photon flux => large production cross section, accompanied by Coulomb excitation of the beam particles which emit neutrons => easy to trigger
- coherent (on nucleus) and incoherent (on nucleons)
- coherent photo production
  - final state is exclusive
  - easy to separate the signal from background



STAR EXPERIMENTAL SETUP (UPC RELEVANT DETECTORS ONLY)

- Solenoidal Tracker At RHIC
- central rapidity coverage
  - $(-1,1) \overset{2019}{\overbrace{\longrightarrow}} (-1.5,1.5)$
- neutron tagging
- charged hadrons PID
  - plus electron calorimetry including decay topology
- veto particles in the UPCs rapidity gap regions



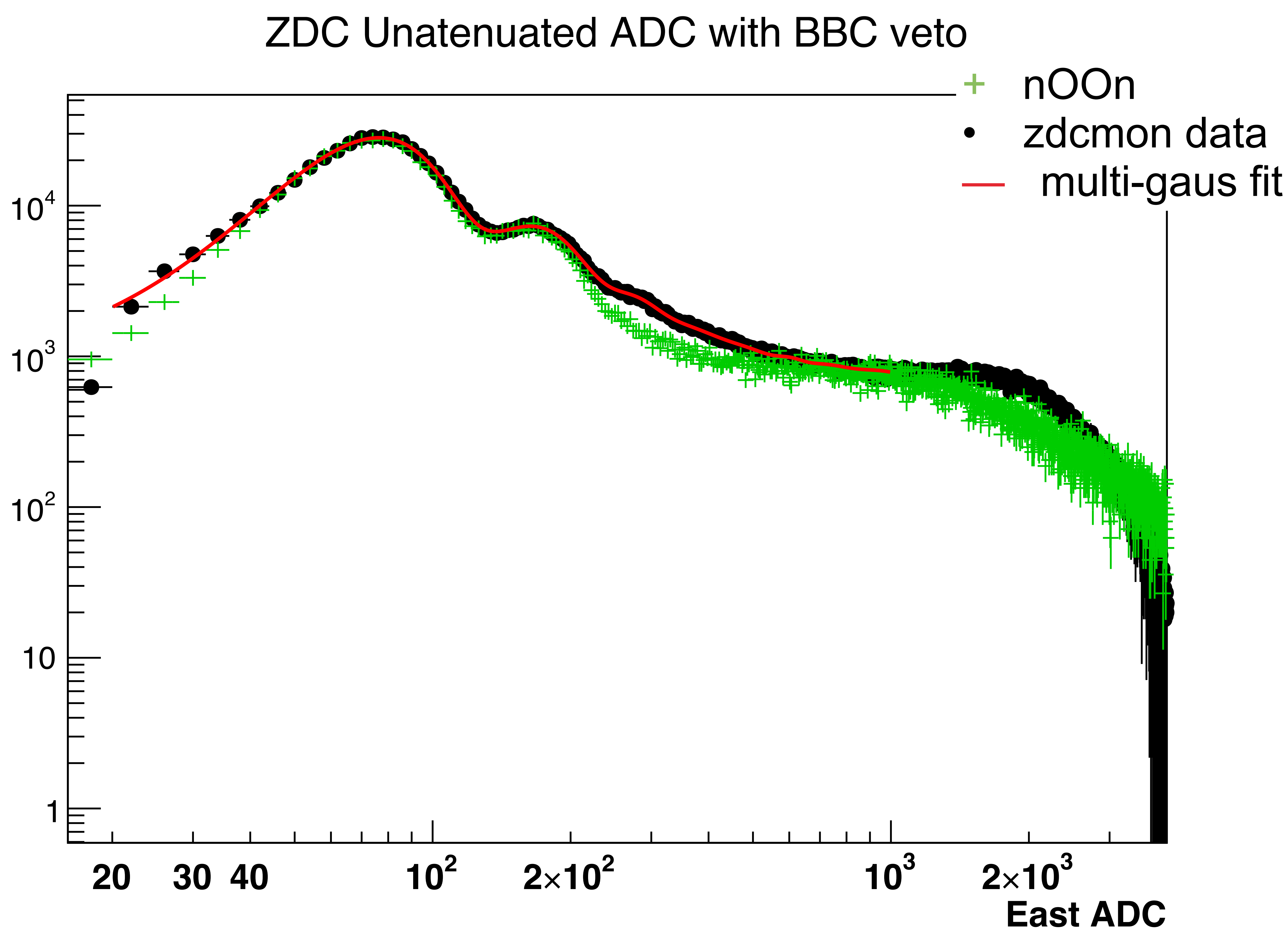
DATASETS, LUMINOSITIES AND EVENT SELECTION

- Online Event Selection (“UPC_main” trigger)
  - number of neutrons on each side
    - 1 - 4.5 (Run 10)
    - 1 - 3.5 (Run 11)
    - 1 - 11 (Run 14)
  - 2 ≦ Track Multiplicity ≦ 6
  - UPC Rapidity Gap Veto
- Offline Event Selection (analysis)
  - | Z-Pos. of collision vertex | < 130 cm from acceptance center
  - Track DCA to the vertex < 3cm
  - TPC PID using dE/dx: normalized $|\sigma_\pi| < 3$
  - #TPC track hits > 15
  - $p_T(\pi^+\pi^-) < 0.15$ GeV/c or $p_T(\pi^+\pi^-\pi^+\pi^-) < 0.15$ GeV/c

	Run14	Run11	Run10
L^{-1} [μb^{-1}]	787	523	926
L^{-1} fraction in $\|v_z\|<130$	0.664	0.813	0.764

$\sigma_{TRIGGER} \rightarrow \sigma_{NN.}$

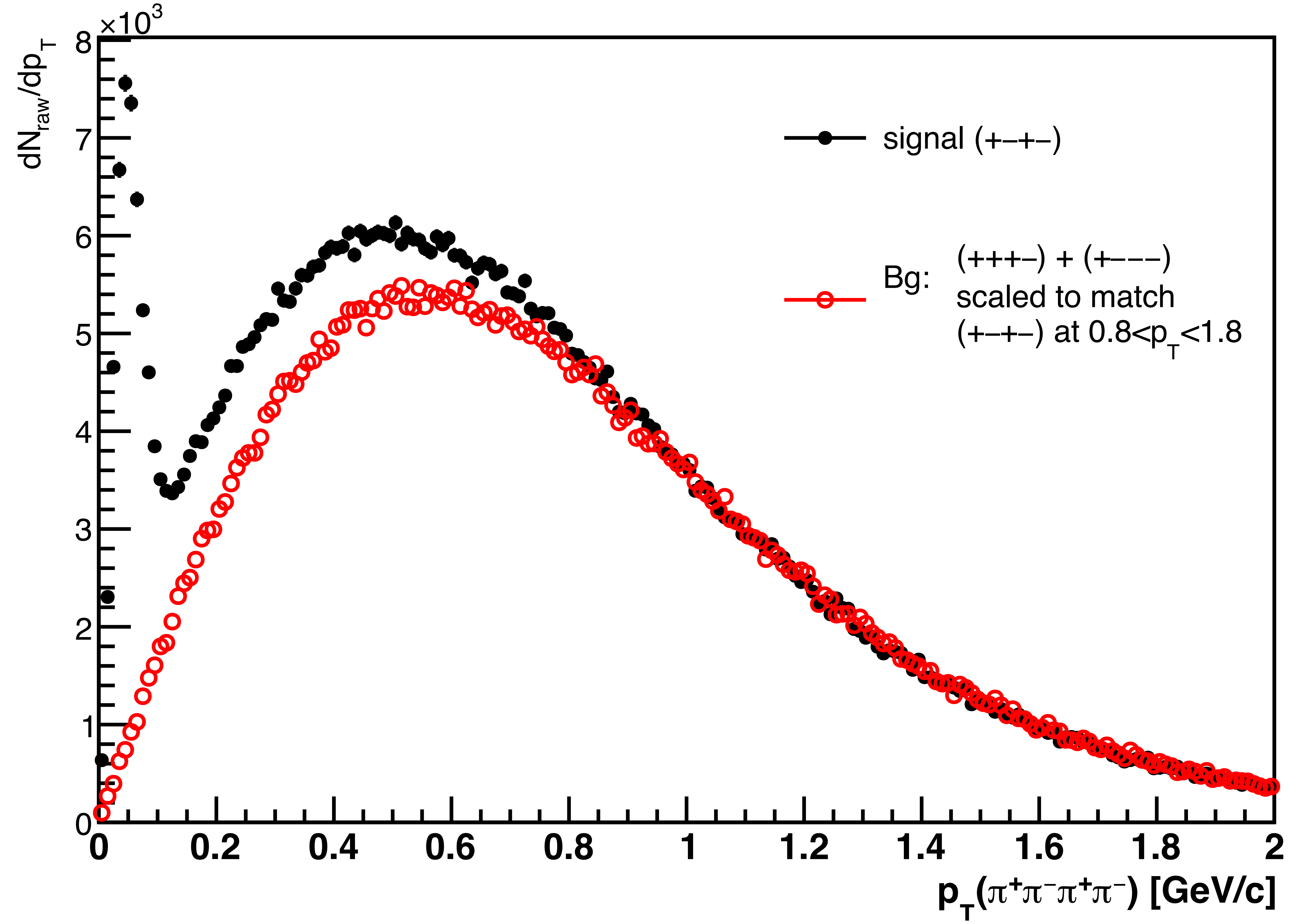
- UPC_main trigger does not see whole σ_{nn}
- STAR added a special trigger in Run14 called "zdcmon" that was just ZDC coincidence (no cut on ADC, no hadron veto)
  - we analyzed these data and compare with UPC_main to what fraction of σnn the UPC_main trigger "see" in each year.
- nOOn model [CPC 253 107181] of neutron production can predict neutron distribution in heavy ion collisions

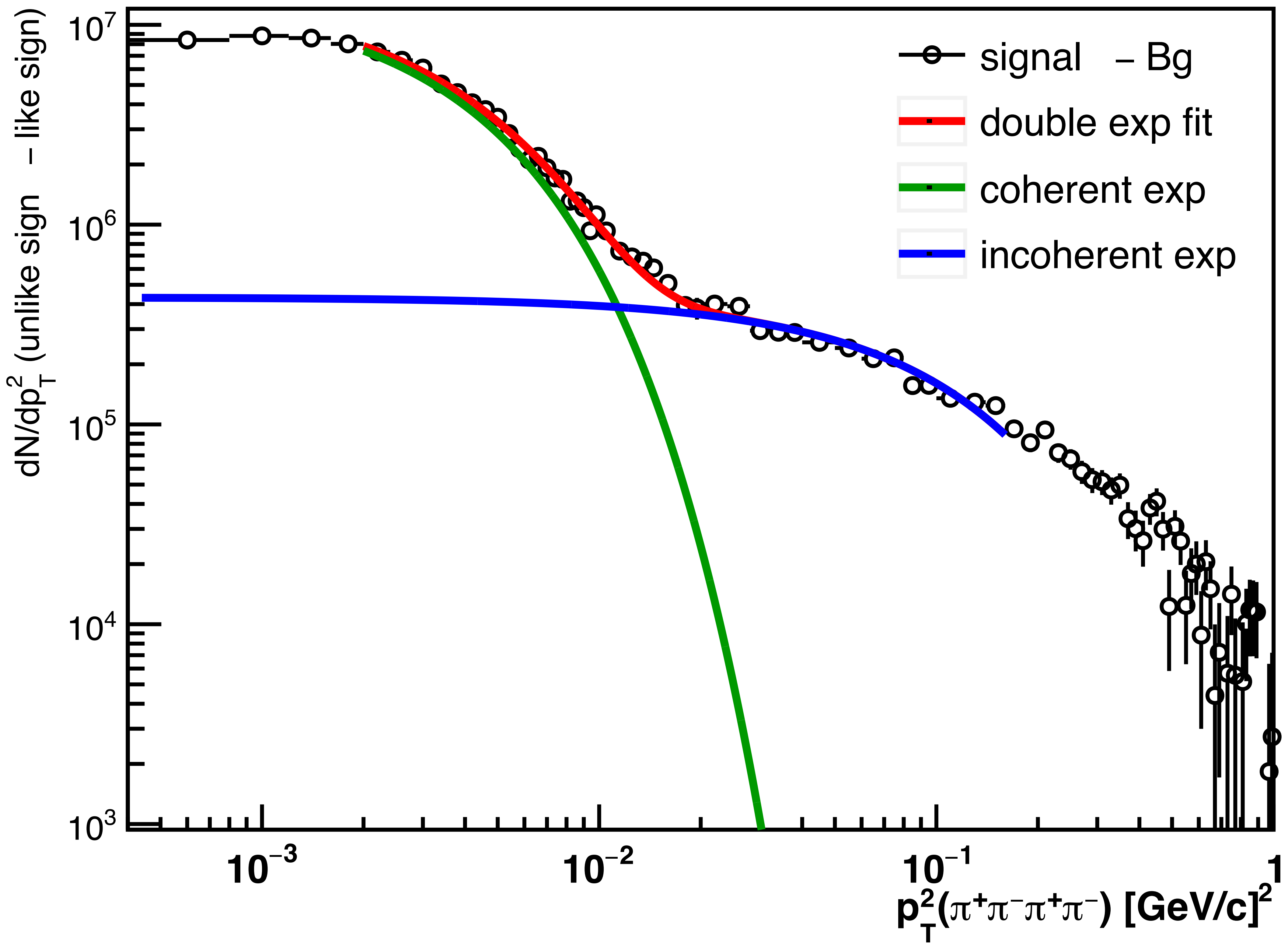


	Run14	Run11	Run10
UPC_main trigger	1-11n	1-3.5n	1-4.5n
fraction from zdcmon data	56.74%	37.72%	41.58%
fraction from nOOn	63.16%	39.52%	43.52%

we used average of zdcmon data and nOOn

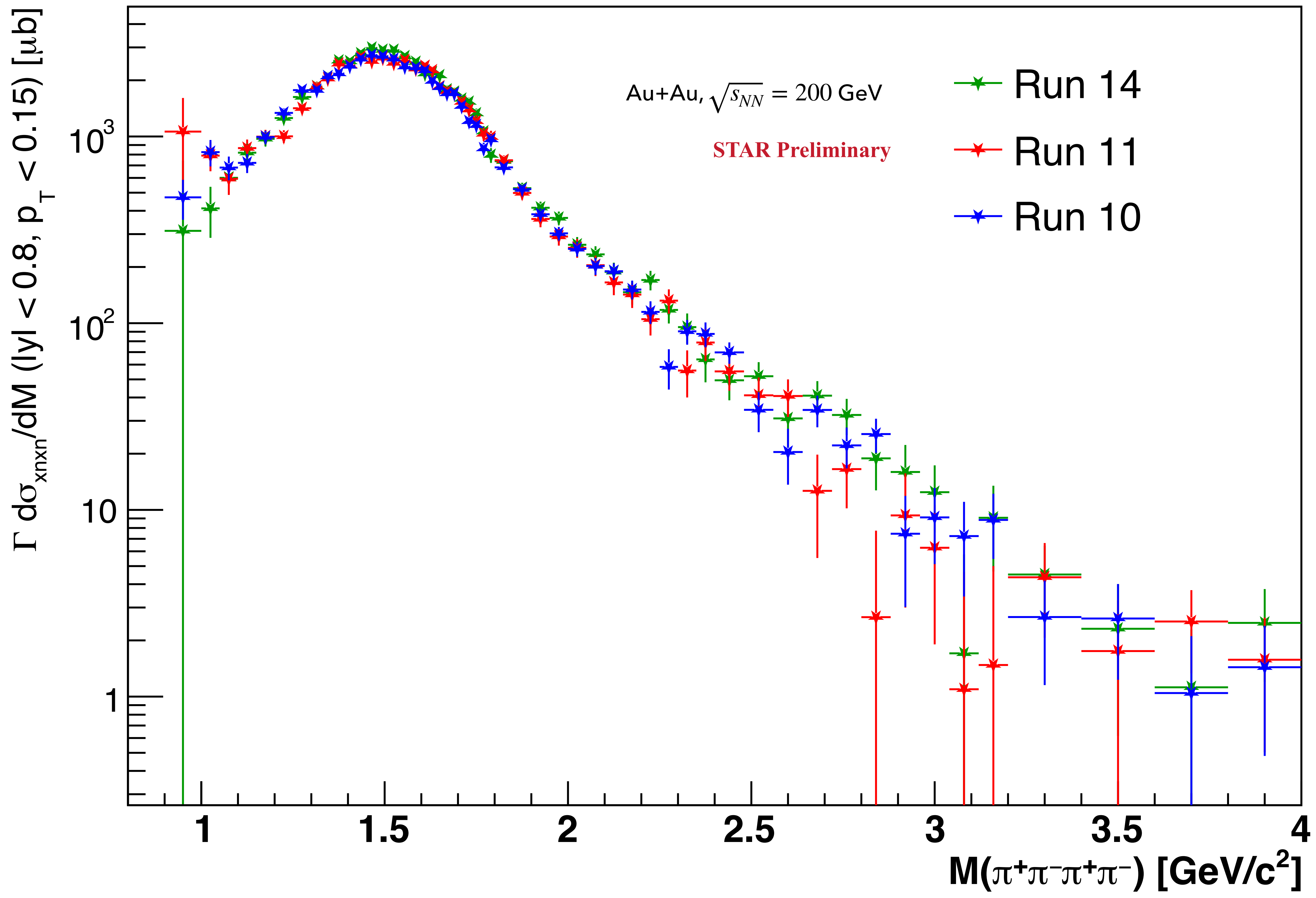
INCOHERENT CONTRIBUTION IN P_T<0.15 RANGE

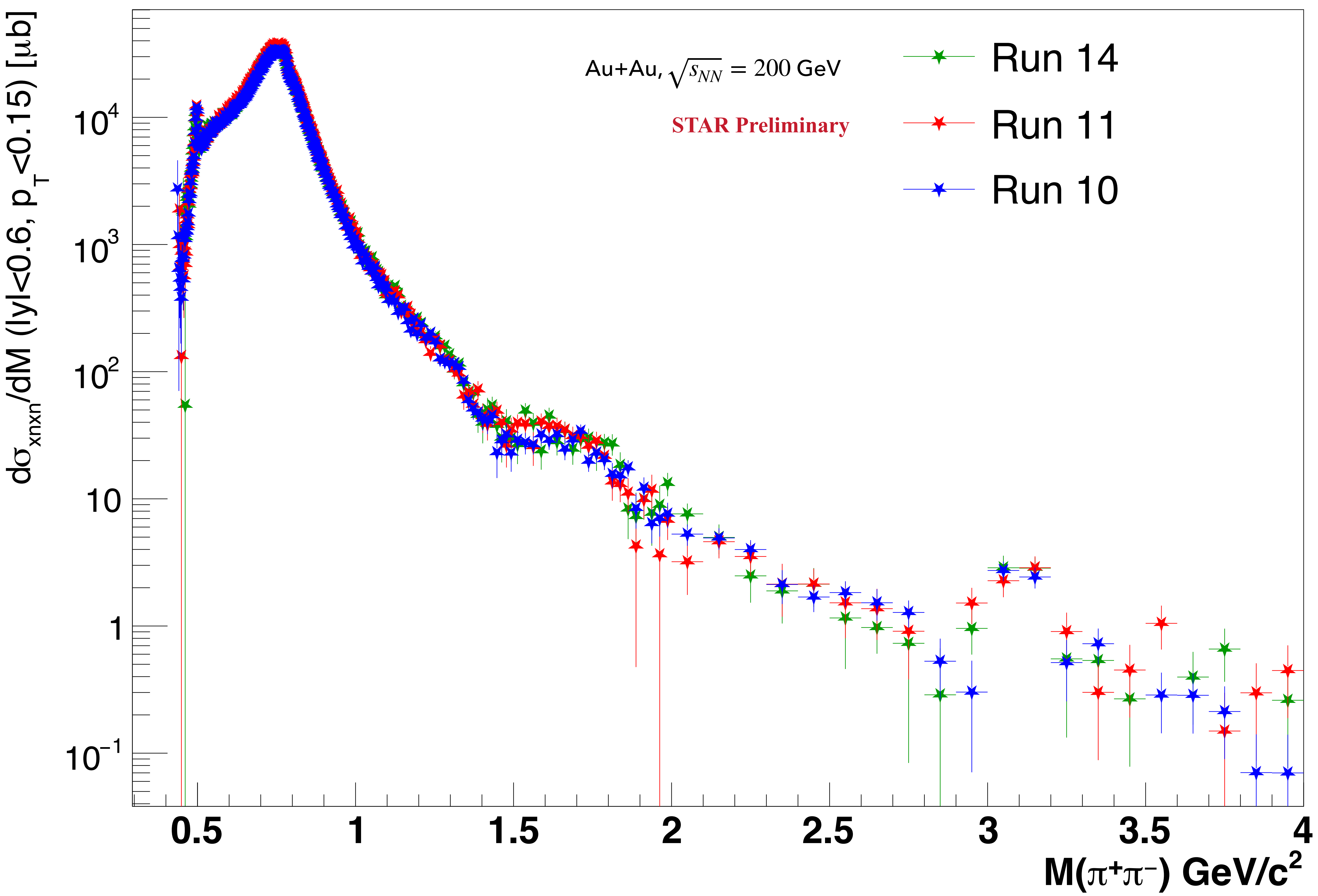




Incoherent fraction for 0.9 < M(4π) < 4.0 GeV : 0.181
Incoherent fraction for 1.5 < M(4π) < 2.5 GeV : 0.160
Incoherent fraction for 0.6 < M(2π) < 2.8 GeV : 0.064
Incoherent fraction for 1.5 < M(2π) < 2.5 GeV : 0.252

MASS SPECTRA OF $\pi^+\pi^-$ AND $\pi^+\pi^-\pi^+\pi^-$ (BOTH P_T < 0.15 GEV/C)



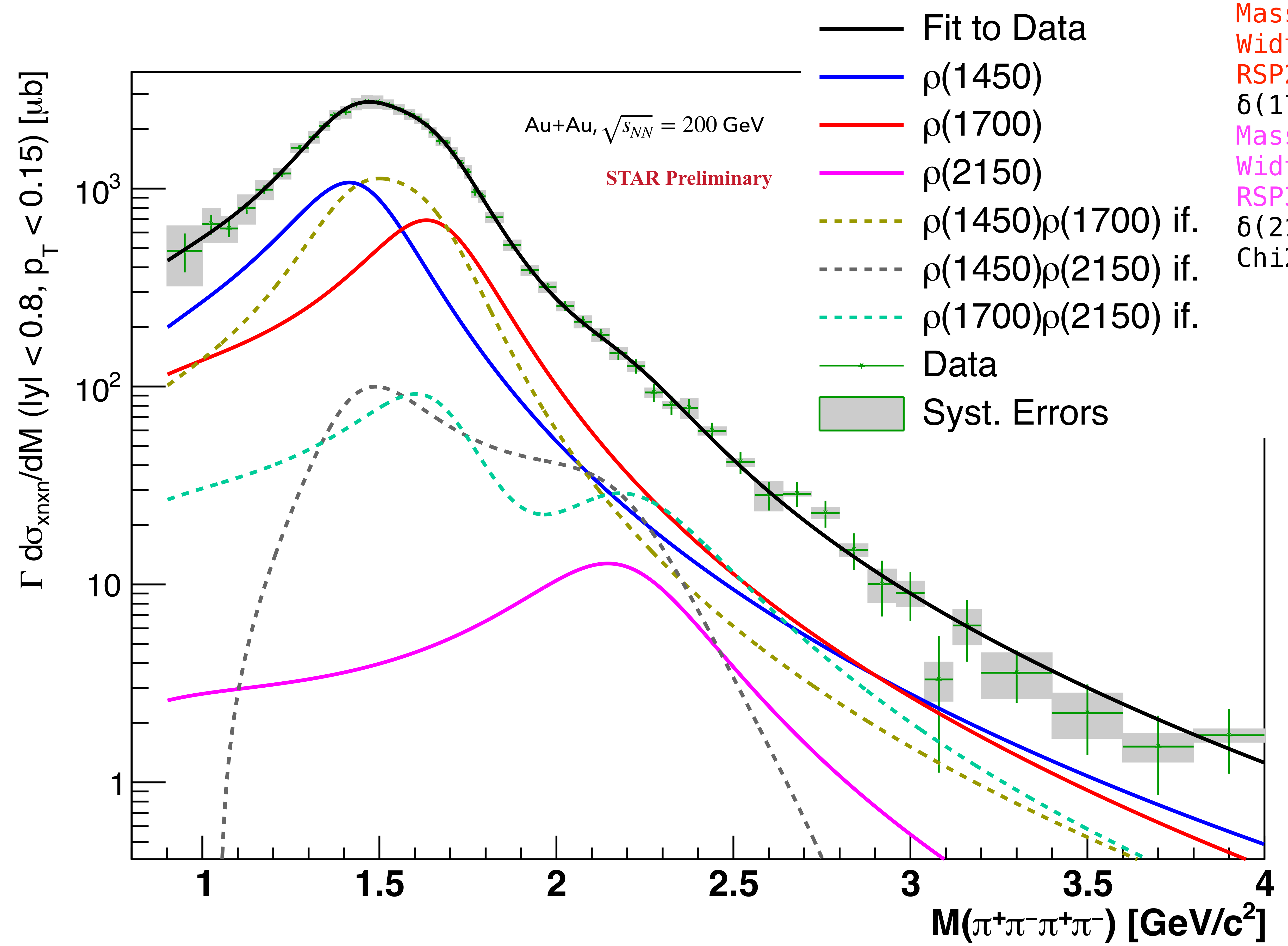


- Main “sanity check” - cross section consistent between datasets

MASS($\pi^+\pi^-\pi^+\pi^-$) AND RAPIDITY COMBINED FROM ALL RUNS

$$\Gamma\frac{d\sigma}{dM} = A^2|BW(\rho_{1450})|^2 + B^2|BW(\rho_{1700})|^2 + C^2|BW(\rho_{2150})|^2 + 2\sqrt{AB}\,\Re\left[BW^*(\rho_{1450})BW(\rho_{1700})e^{i\delta(1700)}\right] + 2\sqrt{BC}\,\Re\left[BW^*(\rho_{1700})BW(\rho_{2150})e^{i\delta(2150)}\right] + 2\sqrt{AC}\,\Re\left[BW^*(\rho_{1450})BW(\rho_{2150})e^{i(\delta(1700)+\delta(2150))}\right]$$

$$BW(\rho) \equiv \left(\frac{M_\rho}{M}\right)^{RSP}\frac{\sqrt{WM_\rho}}{M^2 - M_\rho^2 + iM_\rho W}, \quad W = W_\rho\frac{M_\rho}{M}\left(\frac{M^2 - 16m_\pi^2}{M_\rho^2 - 16m_\pi^2}\right)^{3/2}$$



PARAMETER	VALUE	ERROR
Mass ρ(1450)	1486	20.3
Width ρ(1450)	400.3	30
RSP1	2.17	0.27
Mass ρ(1700)	1701	15.4
Width ρ(1700)	399.6	34.5
RSP2	2.39	0.37
δ(1700)	1.22	0.38
Mass ρ(2150)	2247	91.2
Width ρ(2150)	570	fixed
RSP3	2.36	2.50
δ(2150)	0.50	0.48
Chi2/ndf 33.0882/41		

$\sigma^{coh}_{4\pi,xn,xn}(|y| < 0.8) = 1348 \pm 16_{stat.} \pm 20_{syst.} \pm 162_{norm.}$

$\sigma^{coh}_{4\pi,xn,xn} = 2941 \pm 34_{stat.} \pm 45_{syst.} \pm 352_{norm.}$

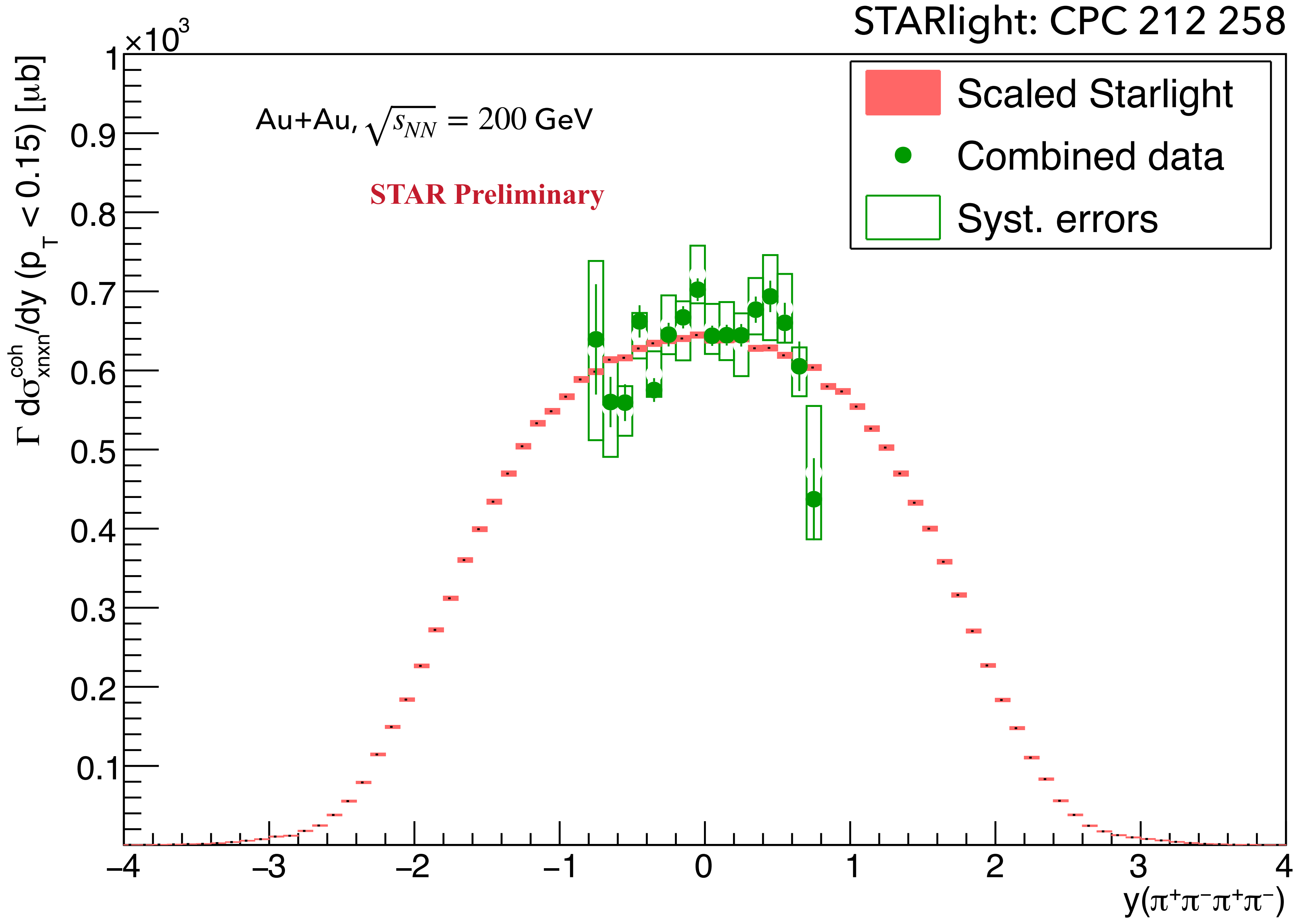
$\Gamma\sigma^{coh}_{\rho1450,xn,xn}(|y| < 0.8) = 426 \pm 162_{stat.} \pm 202_{syst.} \pm 51_{norm.}$

$\Gamma\sigma^{coh}_{\rho1700,xn,xn}(|y| < 0.8) = 310 \pm 148_{stat.} \pm 169_{syst.} \pm 37_{norm.}$

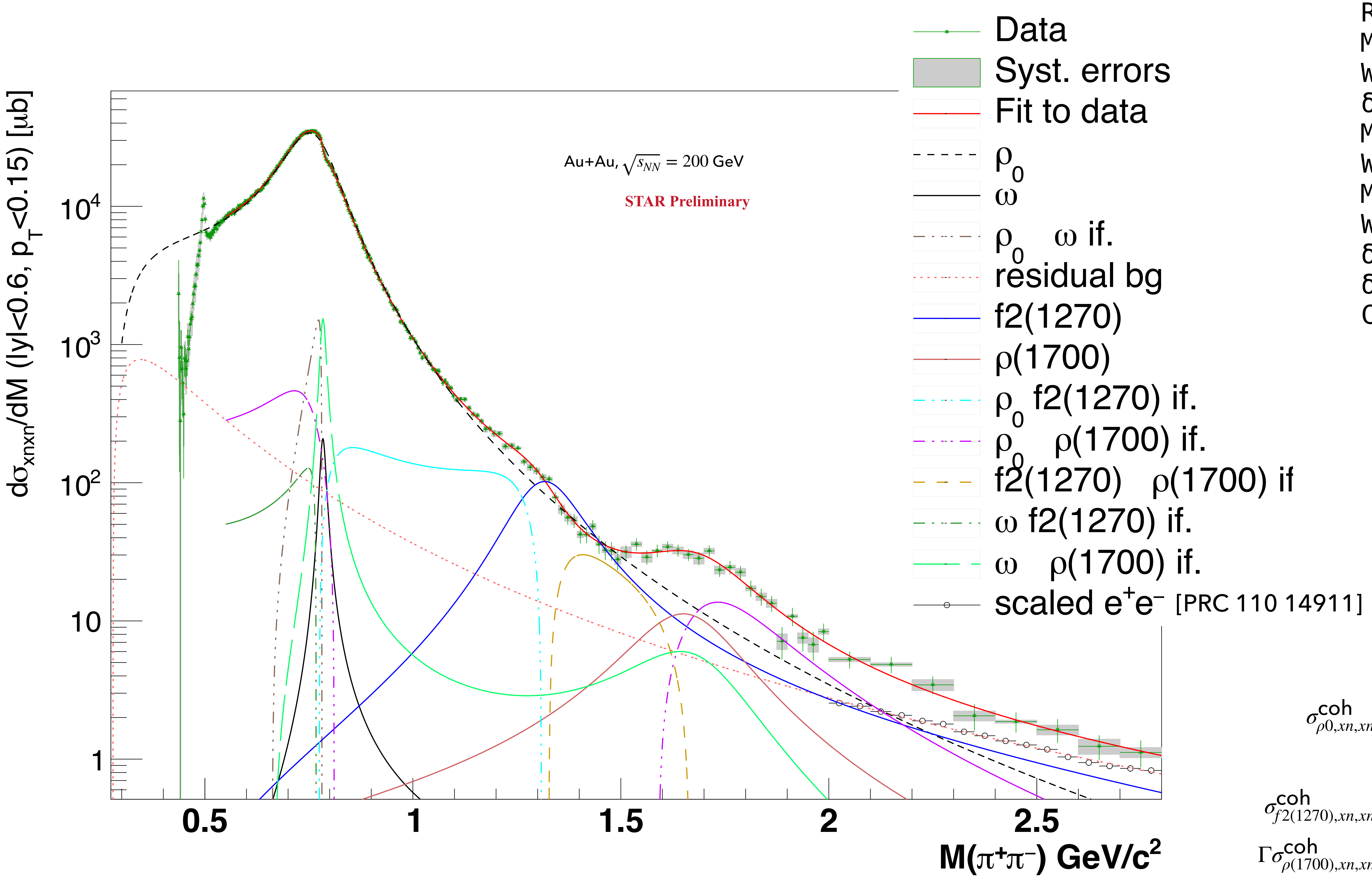
$\Gamma\sigma^{coh}_{\rho2150,xn,xn}(|y| < 0.8) = 8.9 \pm 6.1_{stat.} \pm 1.3_{syst.} \pm 1.1_{norm.}$

to extrapolate to full rapidity - multiply by 2.18

STARlight: CPC 212 258

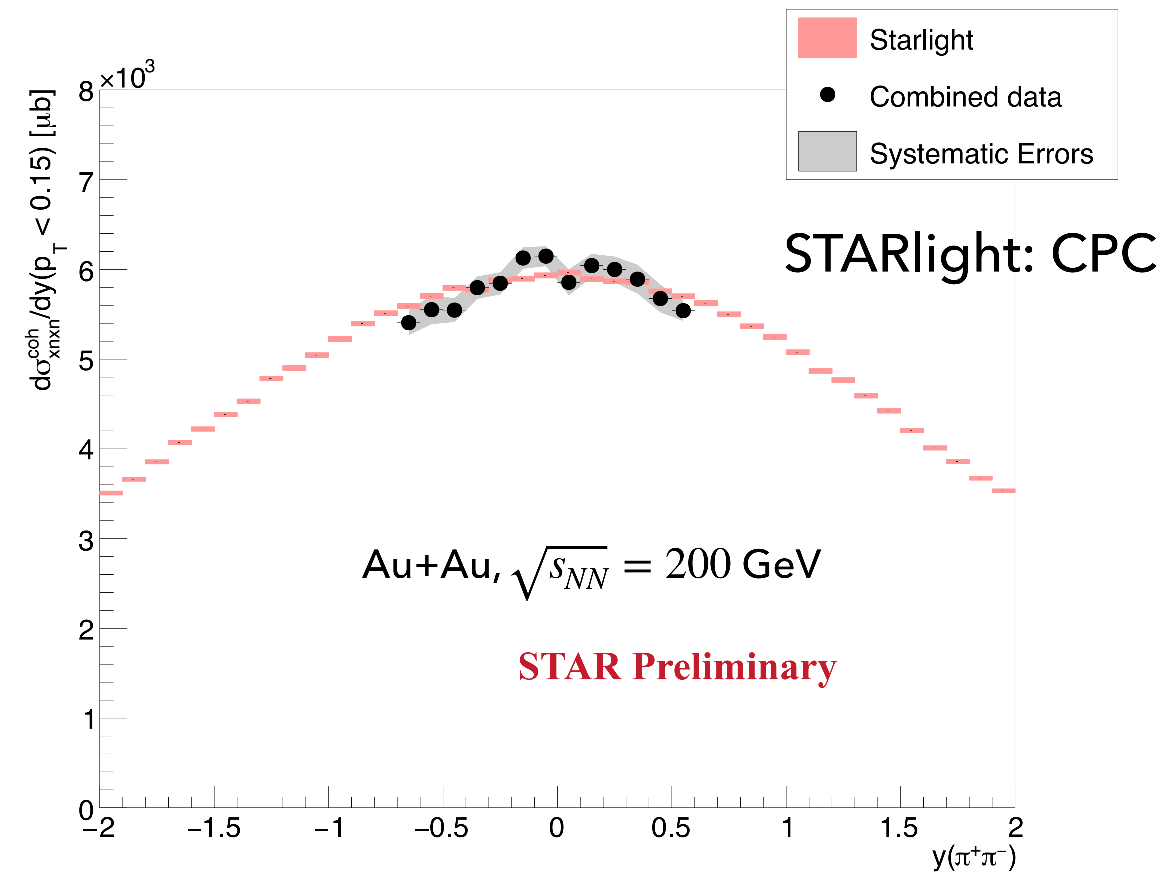


MASS OF $\pi^+\pi^-$ COMBINED FROM ALL RUNS



PARAMETER	VALUE	ERROR
Mass ρ0	774.83	0.30
Width ρ0	146.39	0.57
RSP ρ0	2.76	0.02
Mass ω	783.82	0.50
Width ω	16.13	0.85
δ(ω)	1.97	0.17
Mass f2	1339.26	19.63
Width f2	210.35	38.30
Mass ρ(1700)	1700.65	22.71
Width ρ(1700)	317.79	46.75
δ(f2)	3.12	0.18
δ(1700)	0.38	0.18

Chi2/ndf=282.248/260



STARlight: CPC 212 258

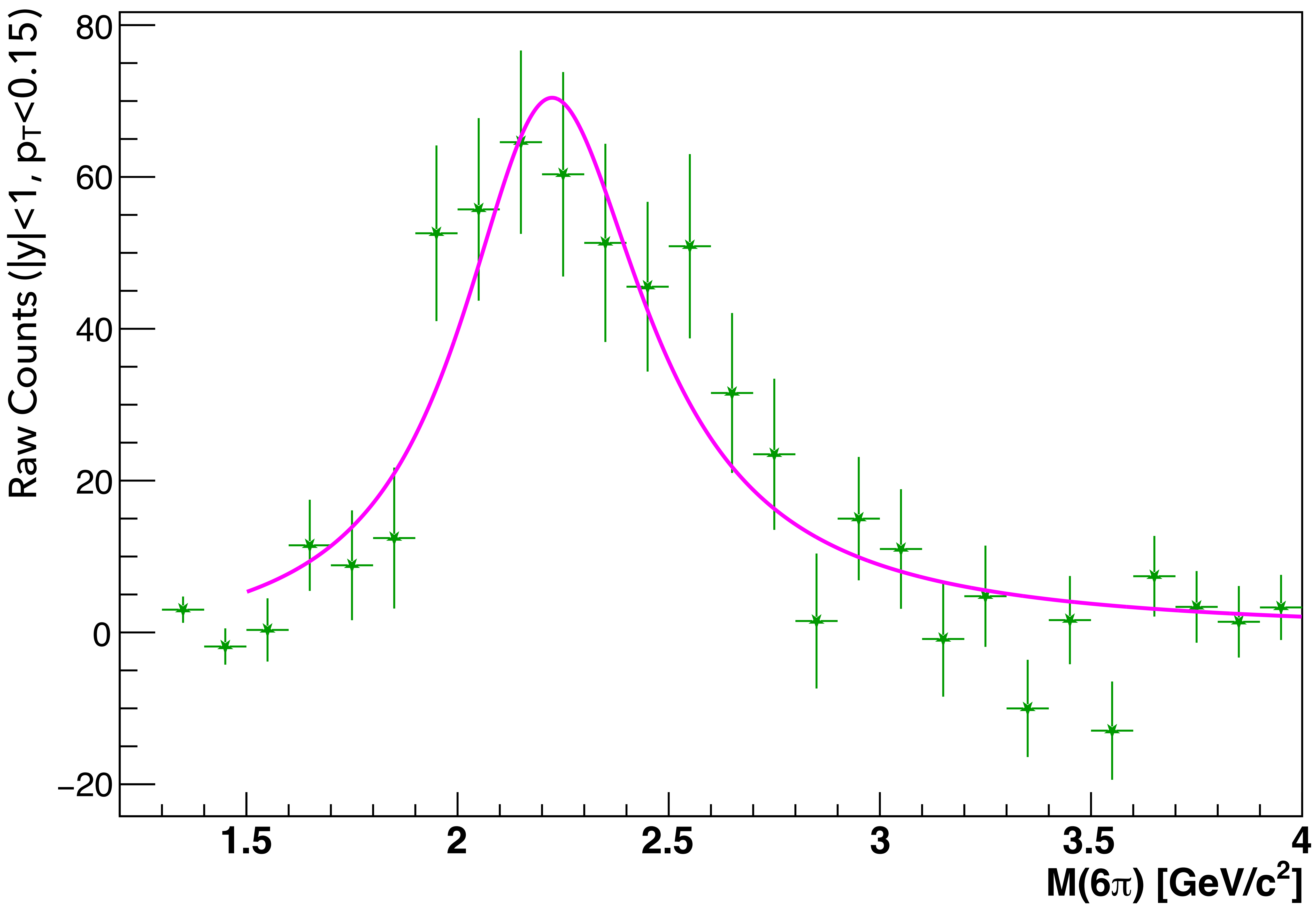
$$\sigma^{coh}_{\rho 0,xn,xn}(|y|<0.6) = 7219 \pm 28_{stat.} \pm 70_{syst.} \pm 866_{norm.}$$

$$\sigma^{coh}_{\rho 0,xn,xn} = 26422 \pm 102_{stat.} \pm 256_{syst.} \pm 3170_{norm.}$$

$$\sigma^{coh}_{f2(1270),xn,xn}(|y|<0.6) = 25.4 \pm 14.7_{stat.} \pm 12.8_{syst.} \pm 3.1_{norm.}$$

$$\Gamma\sigma^{coh}_{\rho(1700),xn,xn}(|y|<0.6) = 3.43 \pm 1.05_{stat.} \pm 1.47_{syst.} \pm 0.41_{norm.}$$

6π PHOTO PRODUCTION RESULTS



PARAMETER	VALUE	ERROR
Mass ρ(2150)	2276	57.8
Width ρ(2150)	573	84.5
RSP ρ(2150)	0.82	0.42
Chi2/ndf 27.9946/21		

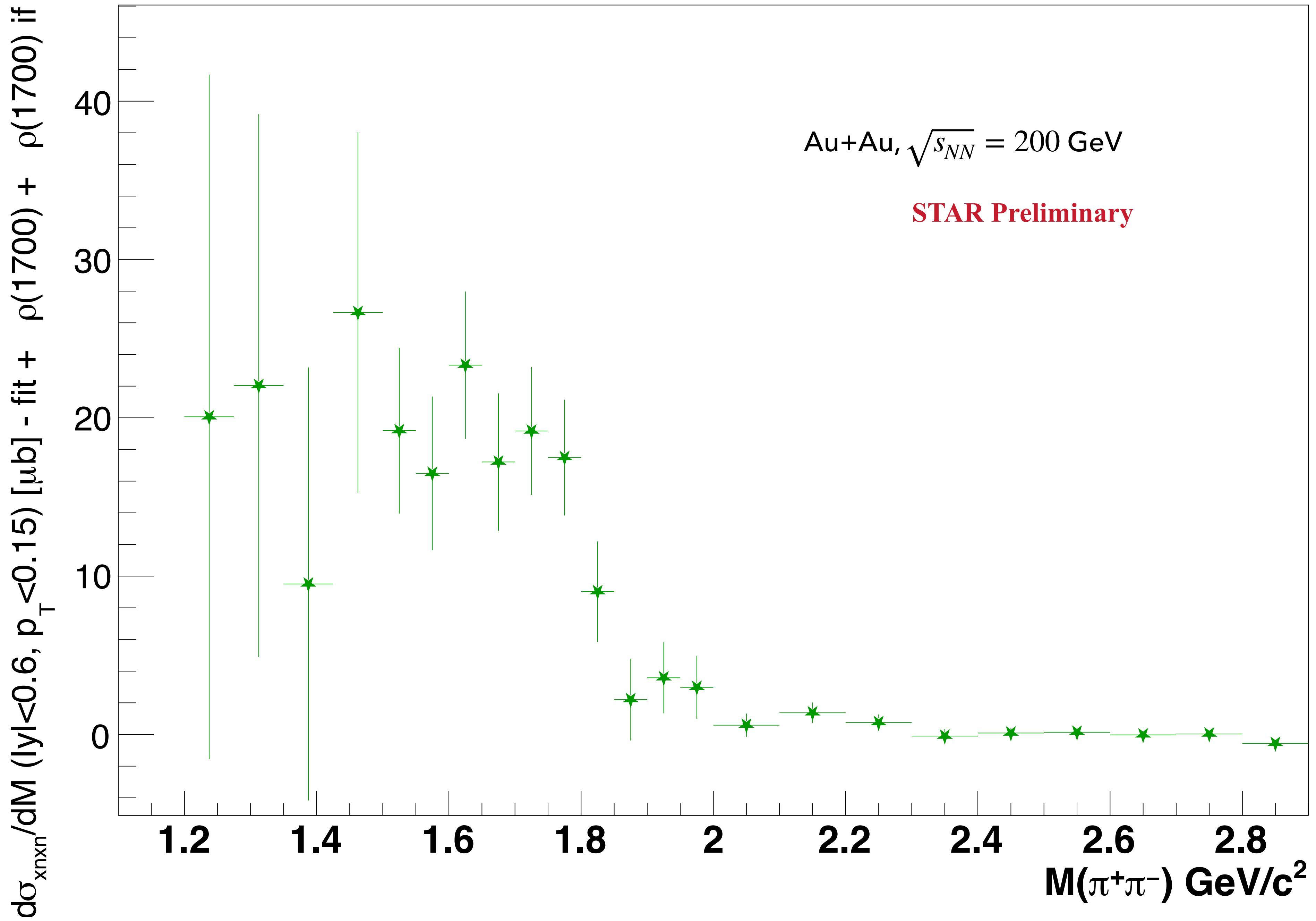
First observation at STAR

RATIO OF THE BRANCHING FRACTIONS OF THE RHO1700 TO 2PI AND 4PI

- comparison of yields directly from Breit-Wigner functions
  - $\Gamma_{2\pi}\sigma^{\text{coh}}_{\rho 1700,xn,xn} = 4.53 \pm 1.38_{\text{stat.}} \pm 1.93_{\text{syst.}}$ in $|y|<0.8$ from $\pi^+\pi^-$
  - $\Gamma_{4\pi}\sigma^{\text{coh}}_{\rho 1700,xn,xn} = 328 \pm 161_{\text{stat.}} \pm 178_{\text{syst.}}$ in $|y|<0.8$ from $\pi^+\pi^-\pi^+\pi^-$

$$\Gamma_{2\pi}/\Gamma_{4\pi}(\rho_{1700}) = 1.38 \pm 0.80_{\text{stat.}} \pm 0.95_{\text{syst.}}\ \%$$

  - an alternative method using an excessive yield in $\pi^+\pi^-$ and yield in $\pi^+\pi^-\pi^+\pi^-$ in the mass window from 1.5 to 2.5 GeV/c^2 - a good proxy for ρ_{1700}
  - the excessive yield in $\pi^+\pi^-$ can be calculated as $\pi^+\pi^-$ data – components of the fit function excluding ρ_{1700} Breit-Wigner and its interference



Excess in 1.5 < Mass < 2.5 |y|<0.8 = 6.72 ± 0.61$_{\text{stat.}}$± 0.33$_{\text{syst.}}$

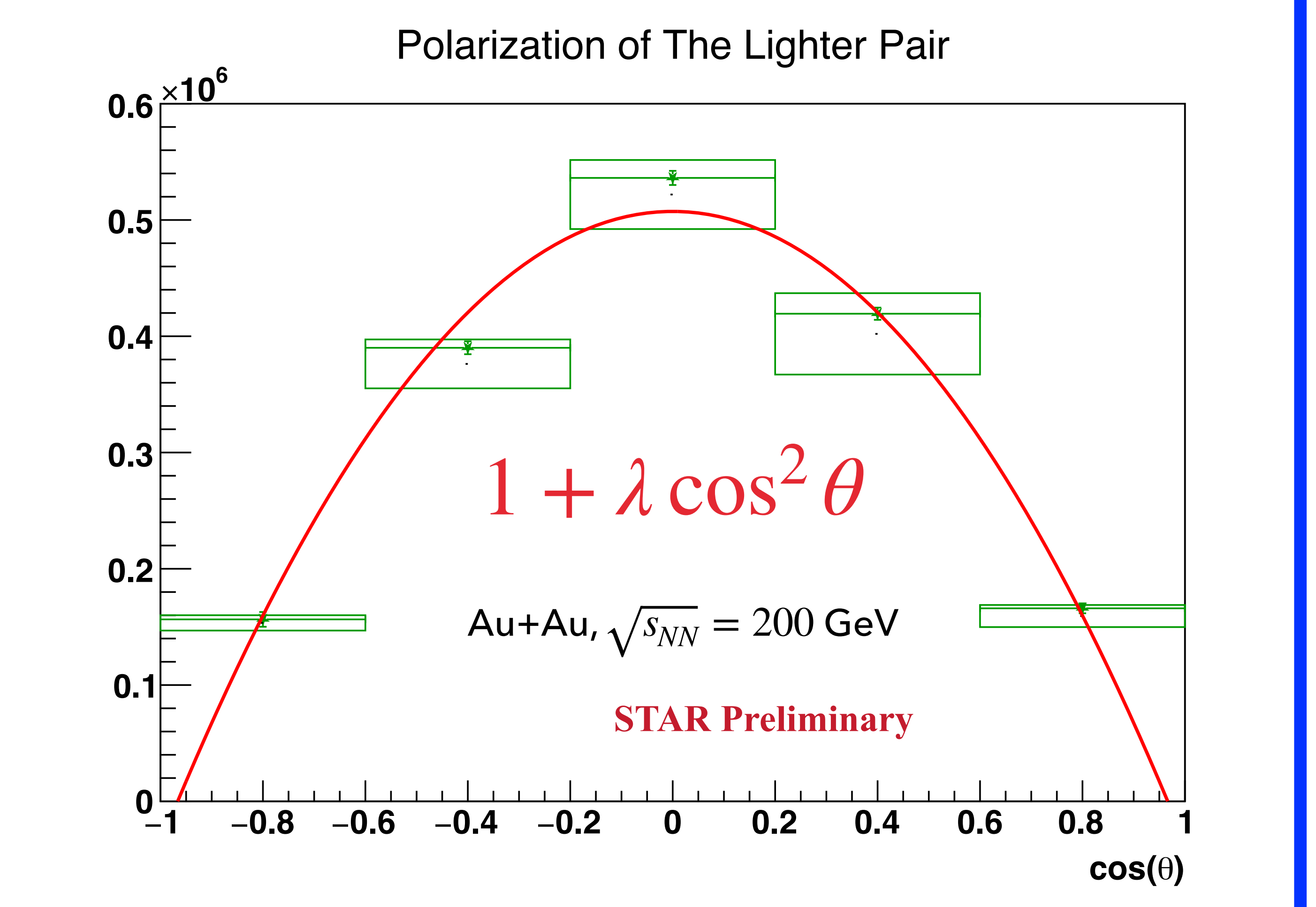
$$\sigma^{\text{coh}}_{4\pi,xn,xn}(|y| < 0.8,\ 1.5 < M < 2.5) = 612 \pm 8_{\text{stat.}} \pm 17_{\text{syst.}}$$

$$\Gamma_{2\pi}/\Gamma_{4\pi}(|y| < 0.8,\ 1.5 < M < 2.5) = 1.10 \pm 0.10_{\text{stat.}} \pm 0.06_{\text{syst.}}\ \%$$

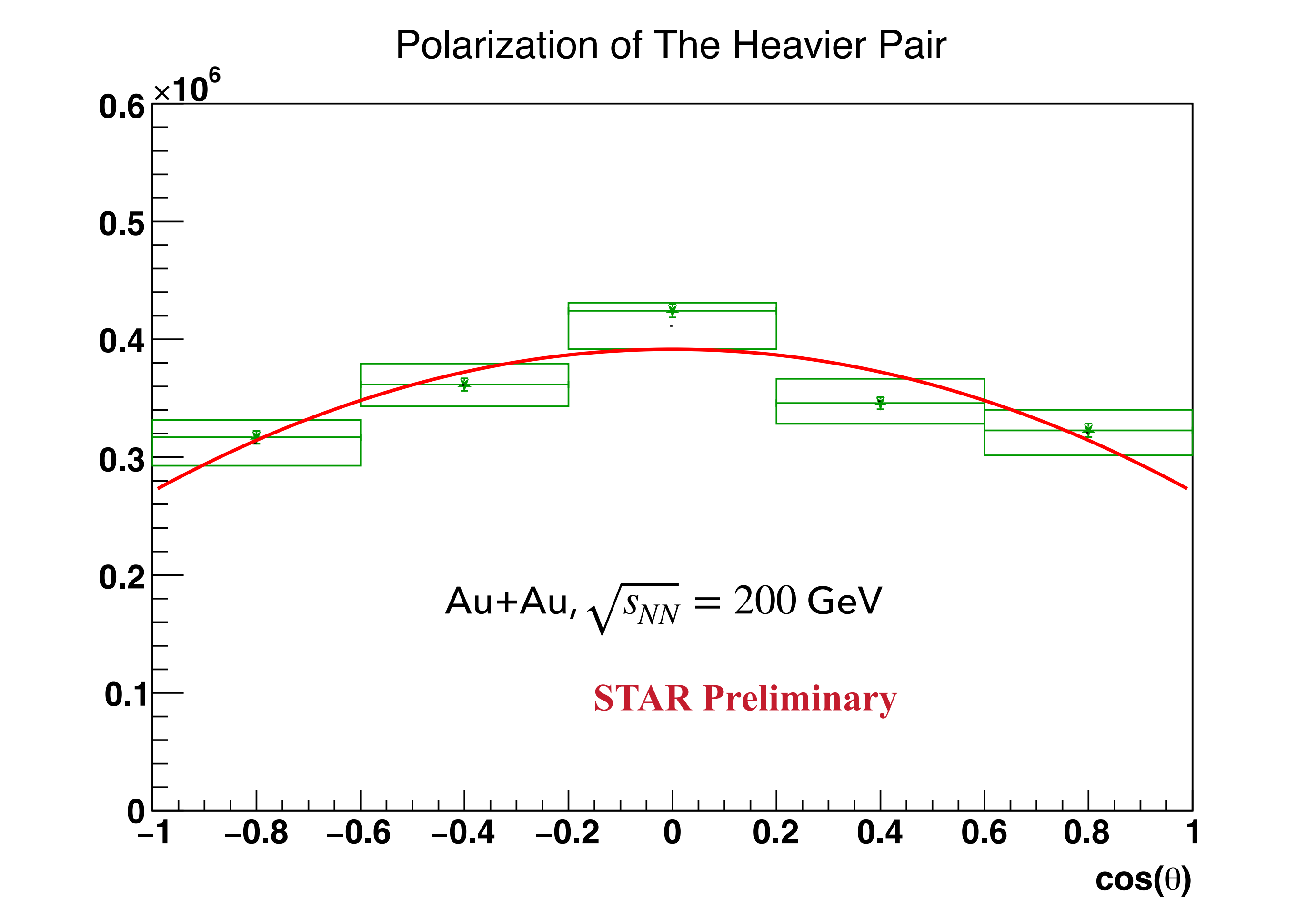
	PRC 81 044901
$\sigma^{\text{coh}}_{4\pi,xn,xn}/\sigma^{\text{coh}}_{\rho 0,xn,xn}(\lvert y\rvert < 0.8) = 14.1 \pm 0.4_{\text{stat.}} \pm 0.5_{\text{sys.}}\ \%$	$16.4 \pm 1.0_{\text{stat}} \pm 5.2_{\text{syst}}\%$
$\sigma^{\text{coh}}_{4\pi,xn,xn}/\sigma^{\text{coh}}_{\rho 0,xn,xn} = 11.1 \pm 0.3_{\text{stat.}} \pm 0.4_{\text{sys.}}\ \%$	$13.4 \pm 0.8_{\text{stat}} \pm 4.4_{\text{syst}}\%$

J=1 TRANSFER TO COSθ ANISOTROPY

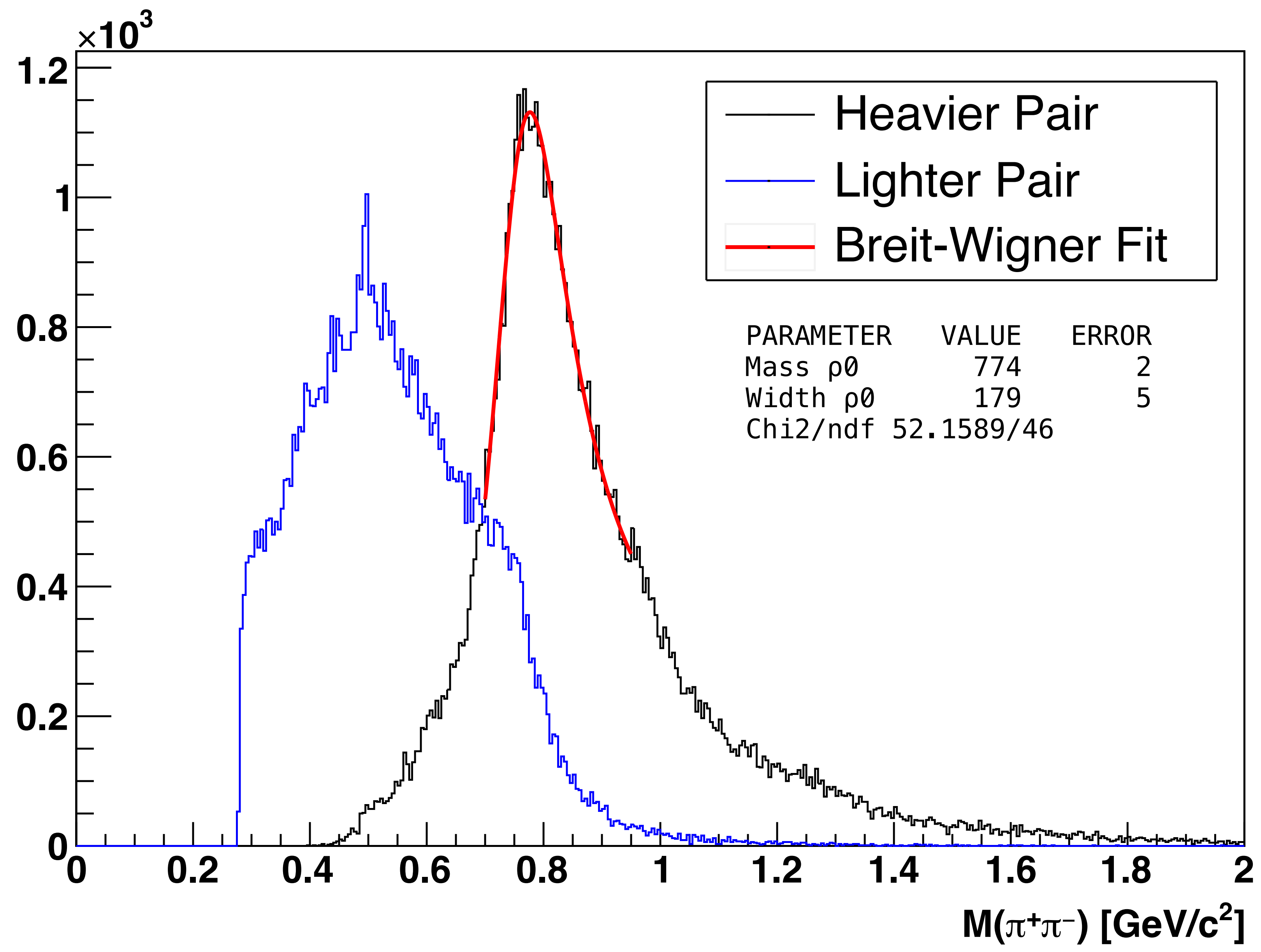
$$\rho(1450) + \rho(1700) \rightarrow (\pi^+\pi^-)_{\text{heavy}} + (\pi^+\pi^-)_{\text{light}} \rightarrow \pi^+\pi^-\pi^+\pi^-$$



$\lambda = -1.062 \pm 0.076$



$\lambda = -0.303 \pm 0.084$



$$\cos\theta = \frac{\overrightarrow{P_{\pi^+\pi^-}} \cdot \overrightarrow{p_\pi{}^*}}{\|\overrightarrow{P_{\pi^+\pi^-}}\|\|\overrightarrow{p_\pi{}^*}\|}$$

- Breit-Wigner fit to the heavier pair mass point to ρ_0 meson.
- Heavy pair polarized, but not fully
- Light pair likely contains $f_0(500)$ resonance. But this resonance is supposed to be a scalar meson while its polarization indicates vector meson.

SUMMARY

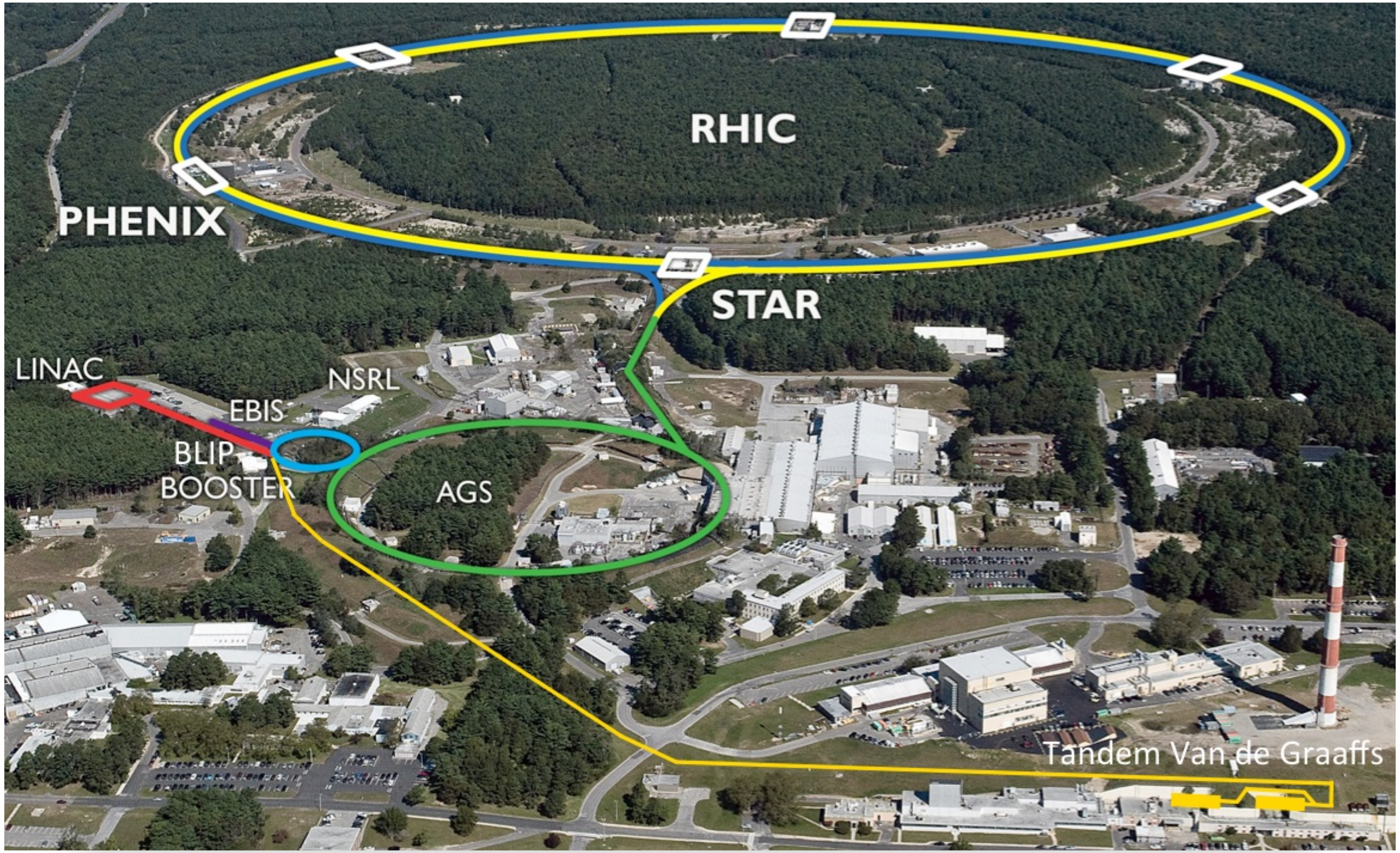
- STAR presented a precise measurement of $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-$ photo-production in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
  - ρ_{1450} (2^3S_1), ρ_{1700} (1^3D_1) clearly and ρ_{2150} (2^3D_1) likely observed in $\pi^+\pi^-\pi^+\pi^-$ mass spectrum
    - ρ_{1450} mass and width consistent with the world average
    - ρ_{1700} mass consistent with the world average, but width larger => more decays modes possible, hybrid state indication?
  - f2(1250) and ρ_{1700} observed in $\pi^+\pi^-$ mass spectrum
    - f2(1250) mass larger - might contain ρ_{1450}, but we can't separate these states
    - ρ_{1700} mass and width consistent with the world average, width lower than in $\pi^+\pi^-\pi^+\pi^-$ => existence of intermediate states in decay
  - ρ_{2150} (2^3D_1) observed in $\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$ mass spectrum - first time at STAR
  - $(\rho_{1700} \to \pi^+\pi^-)/(\rho_{1700} \to \pi^+\pi^-\pi^+\pi^-) = 1.10 \pm 0.10_{\text{stat.}} \pm 0.06_{\text{syst.}}\,\%$ in mid rapidity and
  - $\sigma^{\text{coh}}_{4\pi,xn,xn}/\sigma^{\text{coh}}_{\rho0,xn,xn} = 14.1 \pm 0.4_{\text{stat.}} \pm 0.5_{\text{sys.}}\,\%$ in mid and $11.1 \pm 0.3_{\text{stat.}} \pm 0.4_{\text{sys.}}\,\%$ in full rapidity
- $\pi^+\pi^-\pi^+\pi^-$ states' (all supposed to have J=1) decay can be separated to 2 $\pi^+\pi^-$ pairs by their mass
  - the lighter pair which likely contains f0(500), a scalar meson, decays like fully polarized particle ($\lambda = -1$)
  - the heavier pair whose mass spectrum resembles ρ_0 is partially polarized ($\lambda = -0.3$)

THANK YOU

BACKUP SLIDES

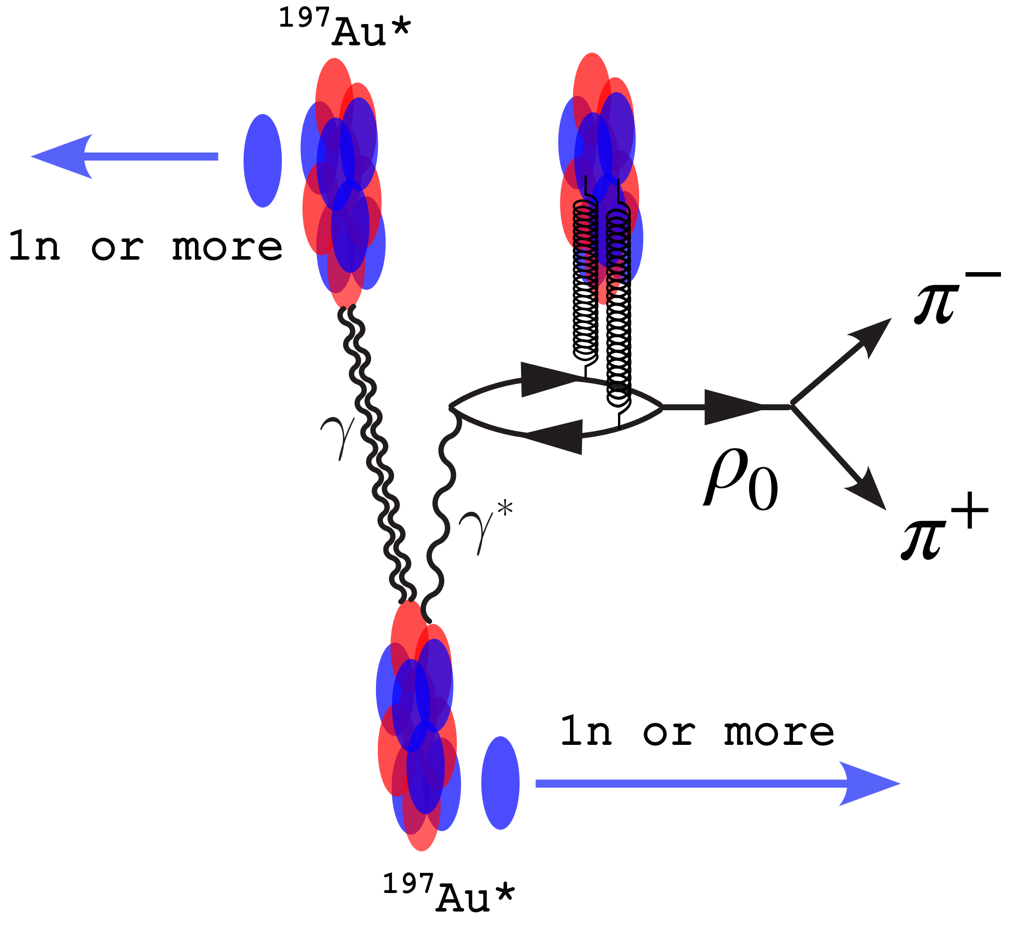
UTRA-PERIPHERAL COLLISIONS AT RHIC

- Relativistic Heavy Ion Collider
  - located in Brookhaven National Laboratory (Long Island, USA)
- different species, energy, and proton polarization

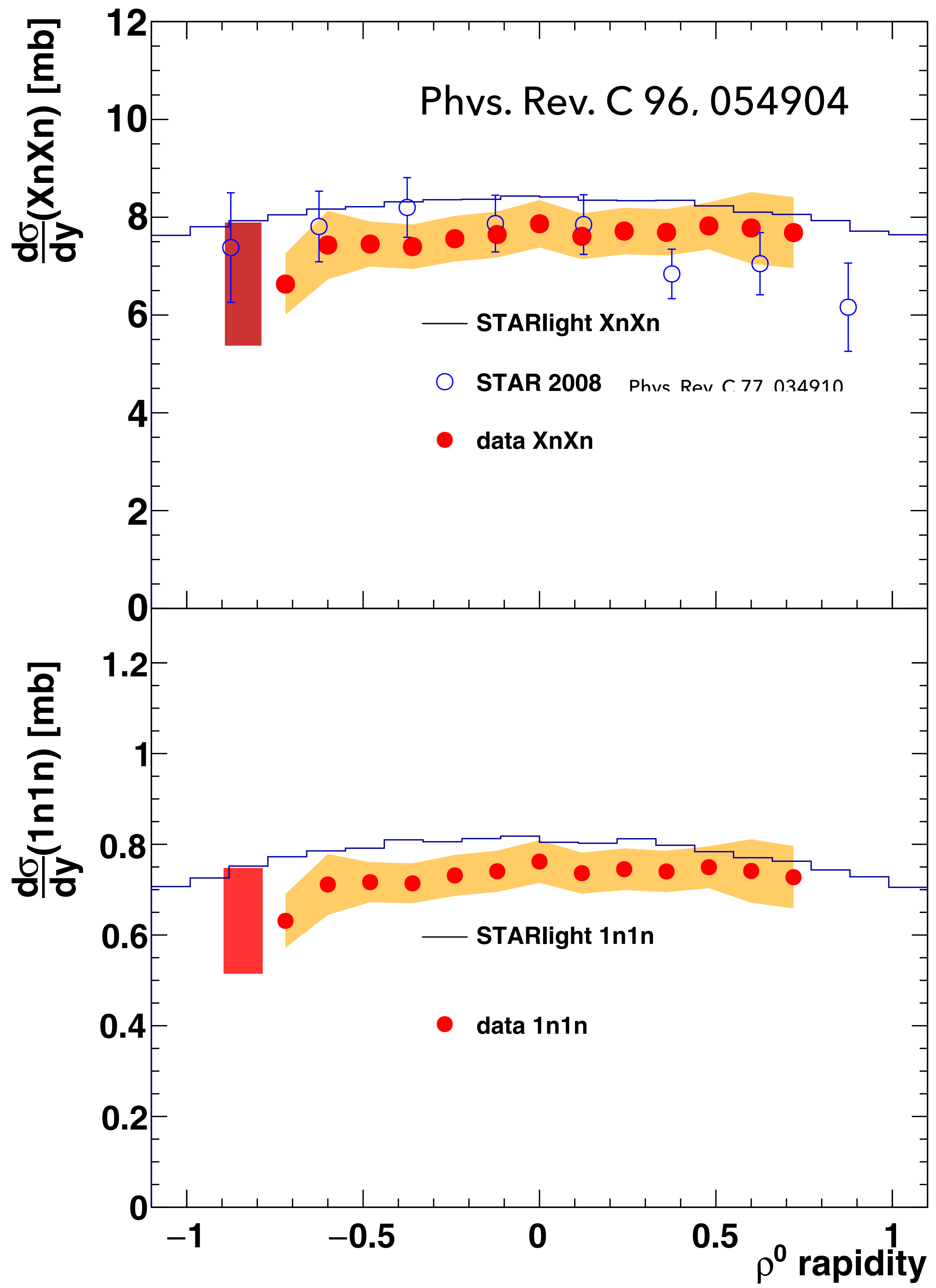


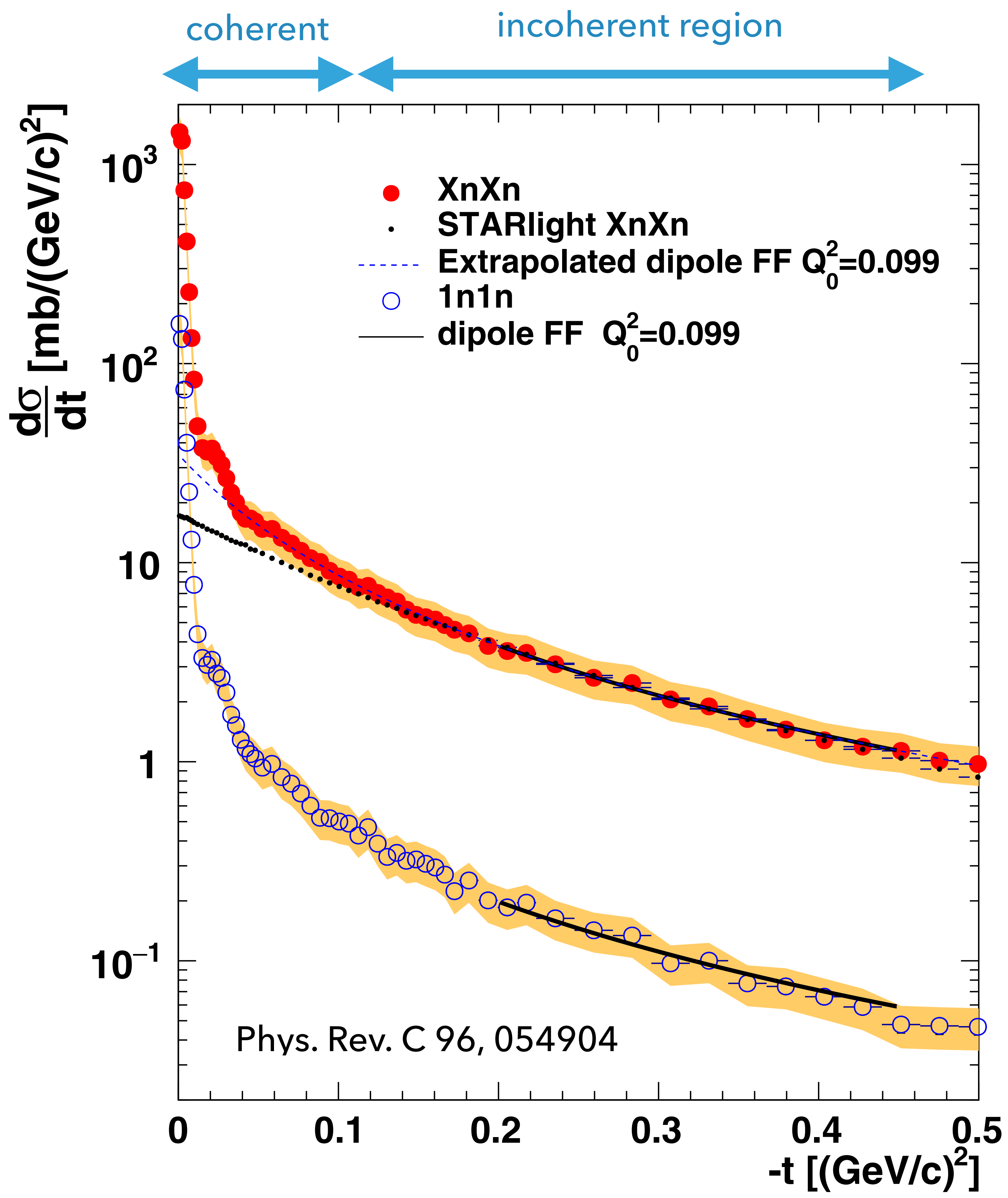
U^{238}, Au^{197}, Zr^{96} , Ru^{96}, d^2 at 200 GeV and *pp* at 510 GeV

ρ_0 CROSS SECTION



- integrated luminosity of 1100±100 μb−1 of data collected in 2010
- XnXn extrapolated from 1n1n using STARlight
- incoherent components in $d\sigma/dt$ are fit in range $-t = (0.2,0.45)$
  - σ_{incoh} are integrals of the fits

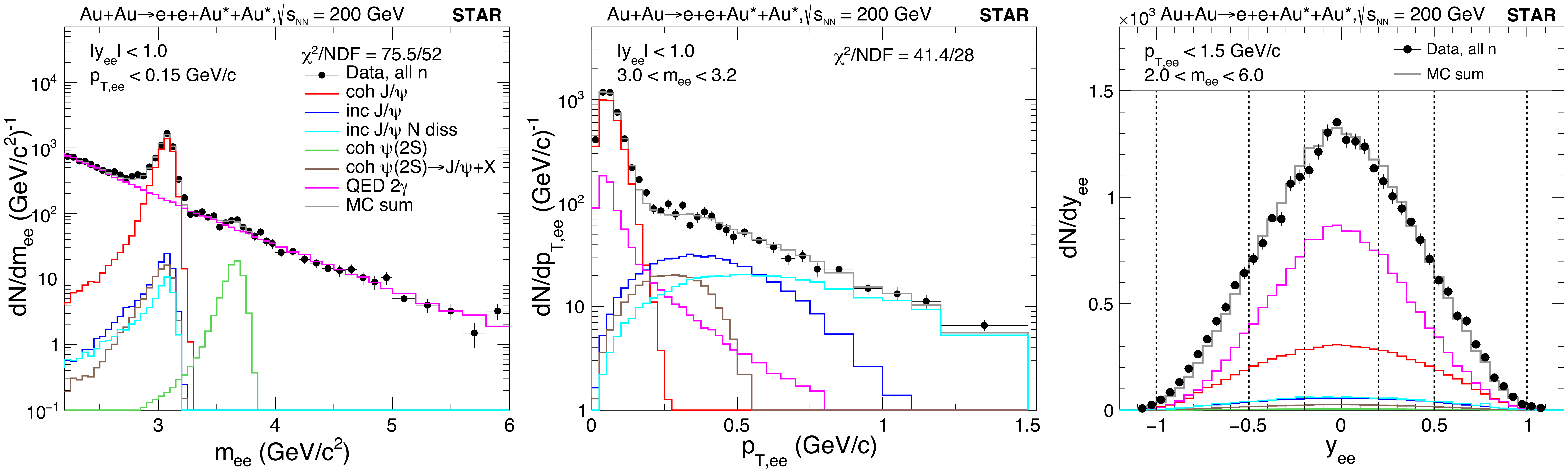




Parameter	$XnXn$	$1n1n$
$\sigma_{\mathrm{coh.}}$	6.49 ± 0.01 (stat.) ± 1.18 (syst.) mb	0.770 ± 0.004 (stat.) ± 0.140 (syst.) mb
$\sigma_{\mathrm{incoh.}}$	2.89 ± 0.02 (stat.) ± 0.54 (syst.) mb	0.162 ± 0.010 (stat.) ± 0.029 (syst.) mb
$\sigma_{\mathrm{incoh.}}/\sigma_{\mathrm{coh.}}$	0.445 ± 0.015 (stat.) ± 0.005 (syst.)	0.233 ± 0.007 (stat.) ± 0.007 (syst.)

Nuclear excitation and ρ_0 photo production are not completely independent

J/ψ PHOTOPRODUCTION IN AU+AU UPC EVENTS AT 200 GEV



- when $Q^2 \sim 0$, p_T of J/ψ is directly related to momentum transfer $(t \sim p_T^2)$