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

Supported in part by the U.S. Department of Energy Office of Science

Creighton University

STAR

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FOR THE STAR COLLABORATION

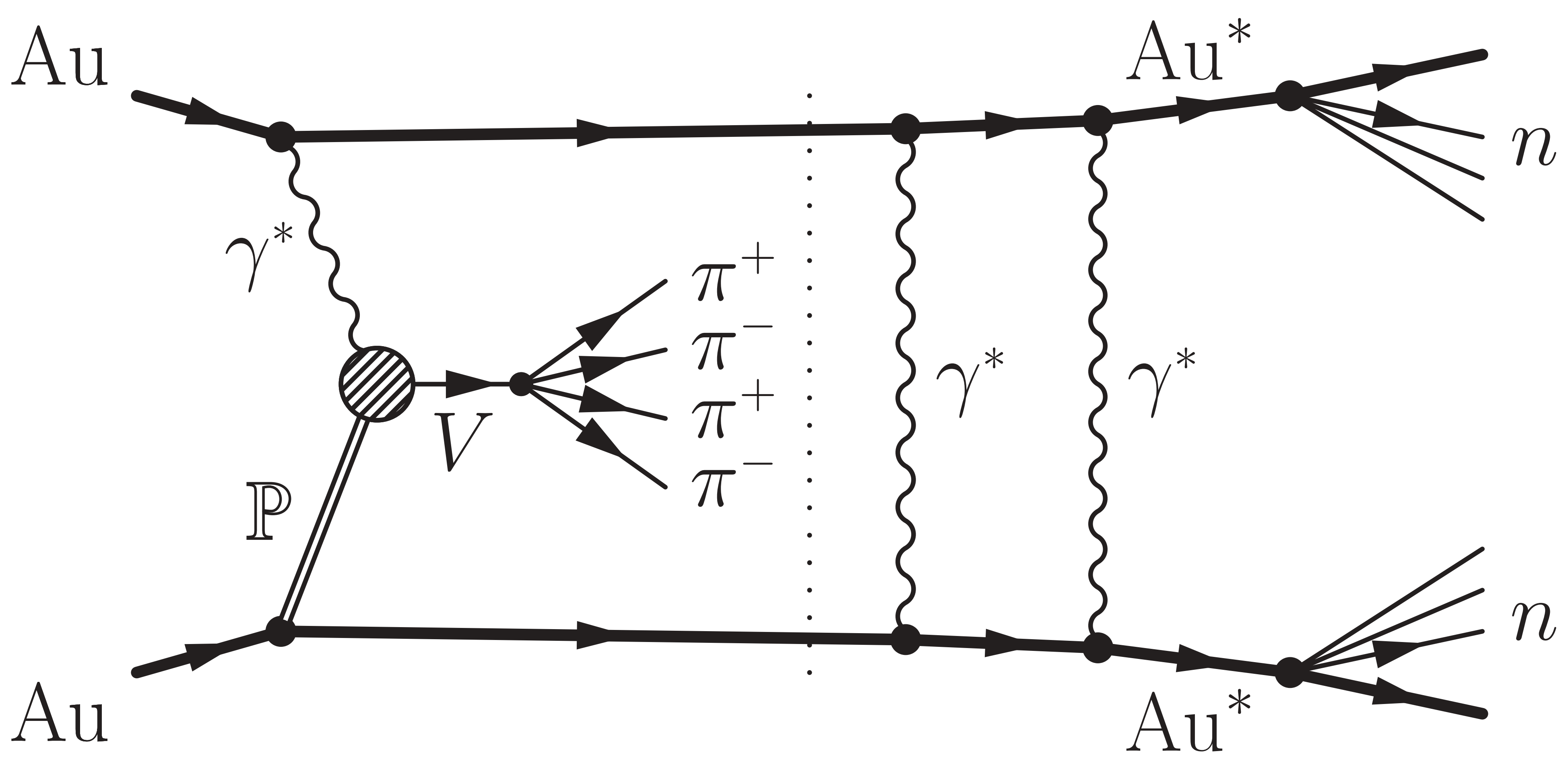
OBSERVATION OF $\pi^+\pi^-\pi^+\pi^-$ AND $\pi^+\pi^-$ FINAL STATE PHOTO PRODUCTION IN UPC AT $\sqrt{S_{NN}} = 200$ GEV AT THE STAR DETECTOR

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 [PDG - 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 $\rho(2150)$

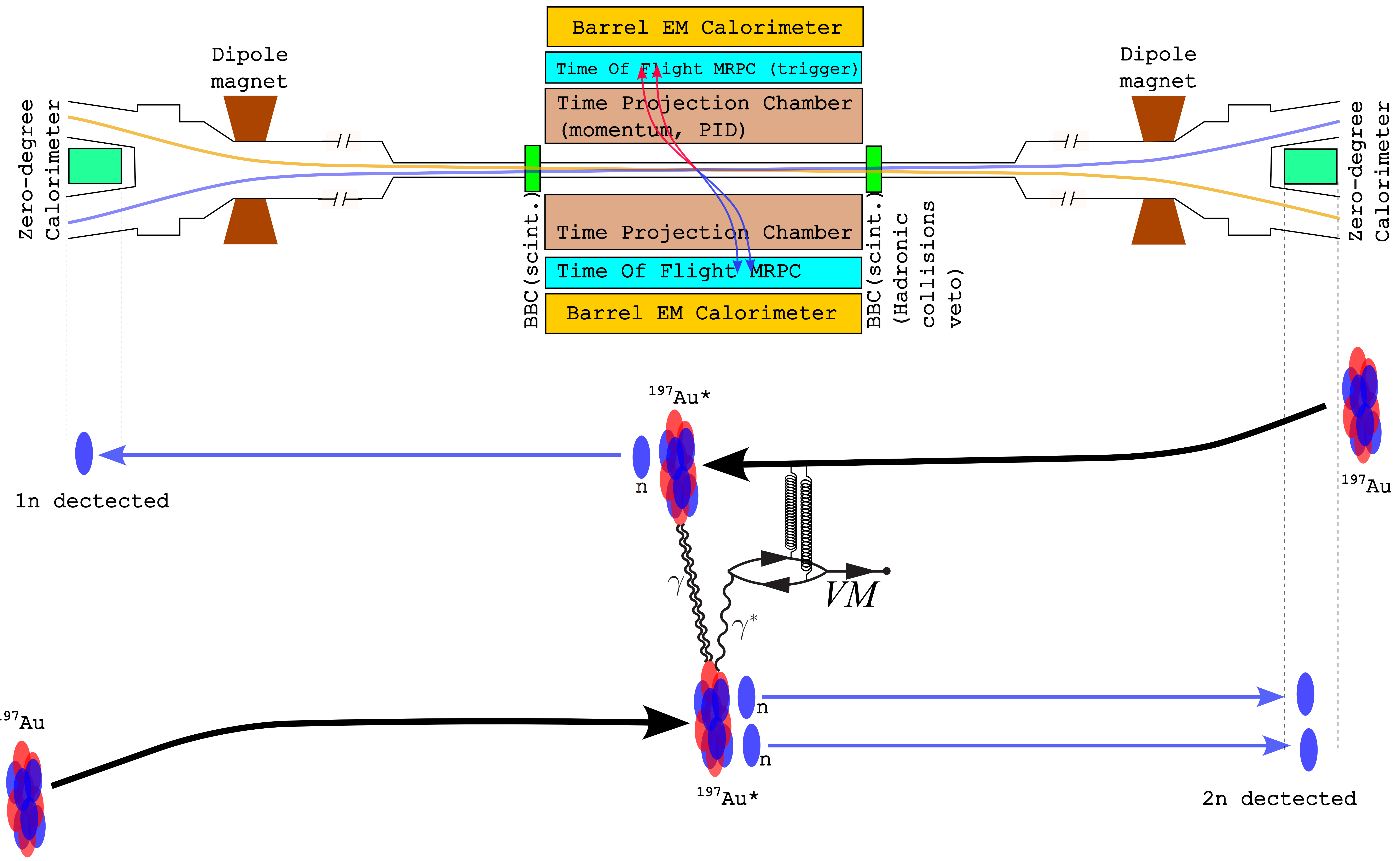
UPC AS A GREAT PRODUCTION TOOL

- 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
  - $(-1,1) \xrightarrow{2019} (-1.5,1.5)$
- neutron tagging
- charged hadrons PID
  - plus electron calorimetry including decay topology
- veto particles in the UPCs rapidity gap regions



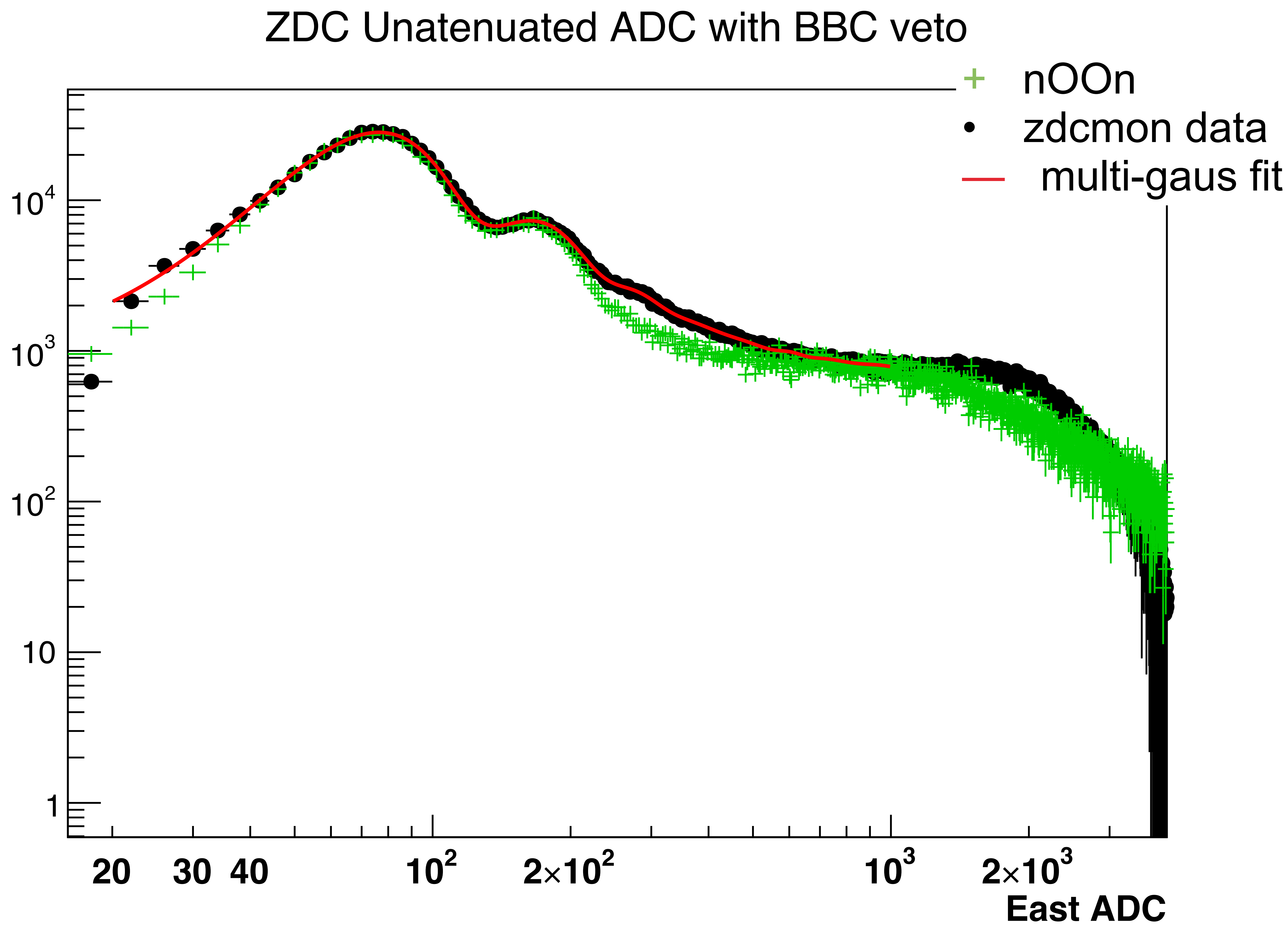
DATASETS, LUMINOSITIES AND EVENT SELECTION

- 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 $\lvert v_z \rvert$<130	0.664	0.813	0.764

σTRIGGER → σNN.

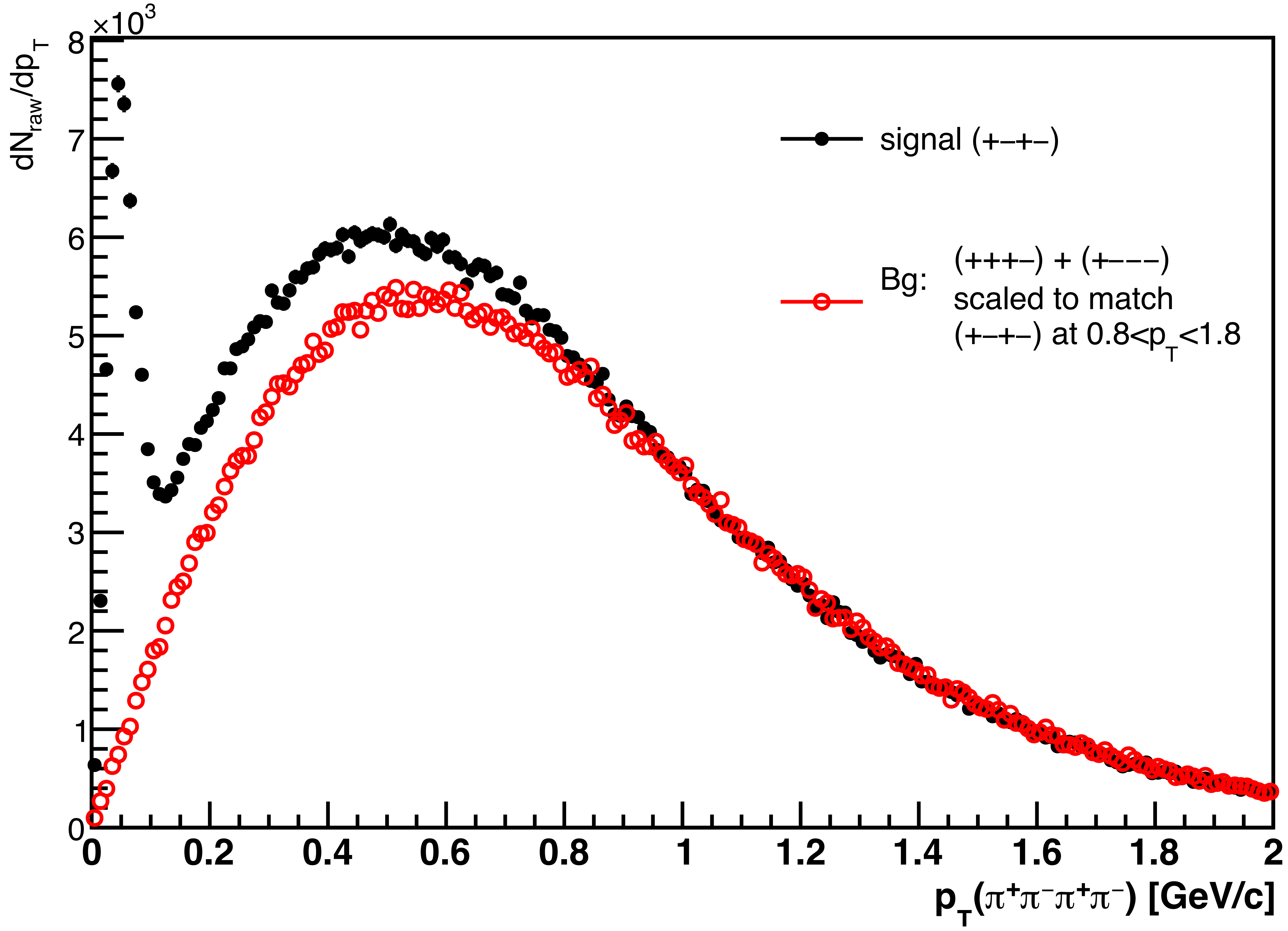
- UPC_main trigger does not see whole σ_{nn}
- STAR added a special trigger in Run14 called "zdcmon" that was just ZDC coincidence (no cut on ADC, no hadron veto)
  - we analyzed these data and compare with UPC_main to what fraction of σnn the UPC_main trigger "see" in each year.
- nOOn model [CPC 253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

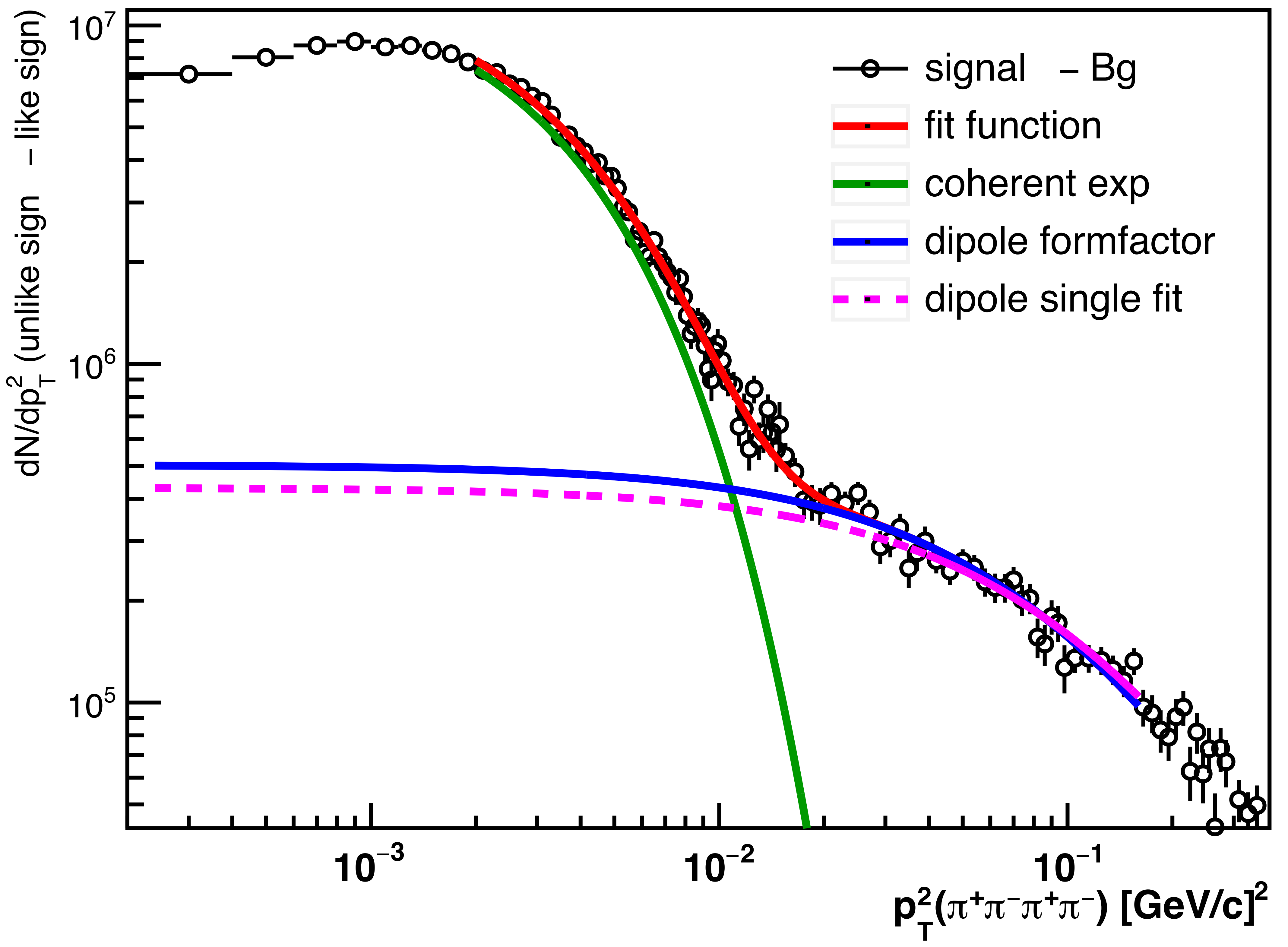


	Run14	Run11	Run10
UPC_main trigger	1-11n	1-3.5n	1-4.5n
fraction from zdcmon data	56.74%	37.72%	41.58%
fraction from nOOn	63.16%	39.52%	43.52%

we used average of zdcmon data and nOOn

INCOHERENT CONTRIBUTION IN $P_T < 0.15$ RANGE





fit function $= f_{coh} + f_{incoh}$

$$f_{coh} = \exp(a + bp_T^2)$$

$$f_{incoh} = \frac{c}{d(1 + p_T^2/d)^2}$$ (dipole form factor)

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Incoherent fraction for 0.9 < M(4π) < 4.0 GeV : (18.7 ± 1.2)%
Incoherent fraction for 1.5 < M(4π) < 2.5 GeV : (16.1 ± 1.3)%
Incoherent fraction for 0.6 < M(2π) < 2.8 GeV : (8.35 ± 0.52)%
Incoherent fraction for 1.5 < M(2π) < 2.5 GeV : (26.8 ± 0.8)%
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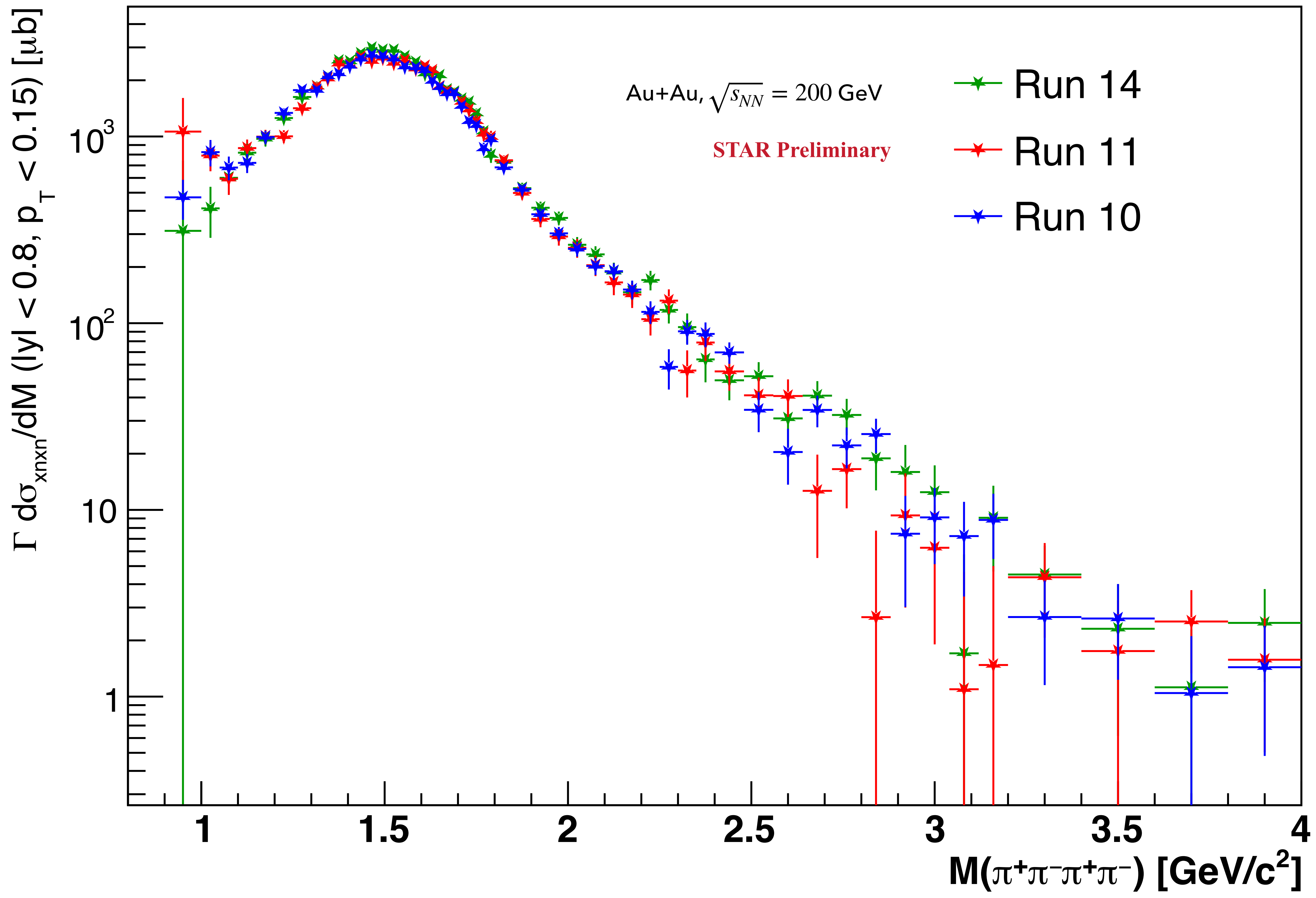
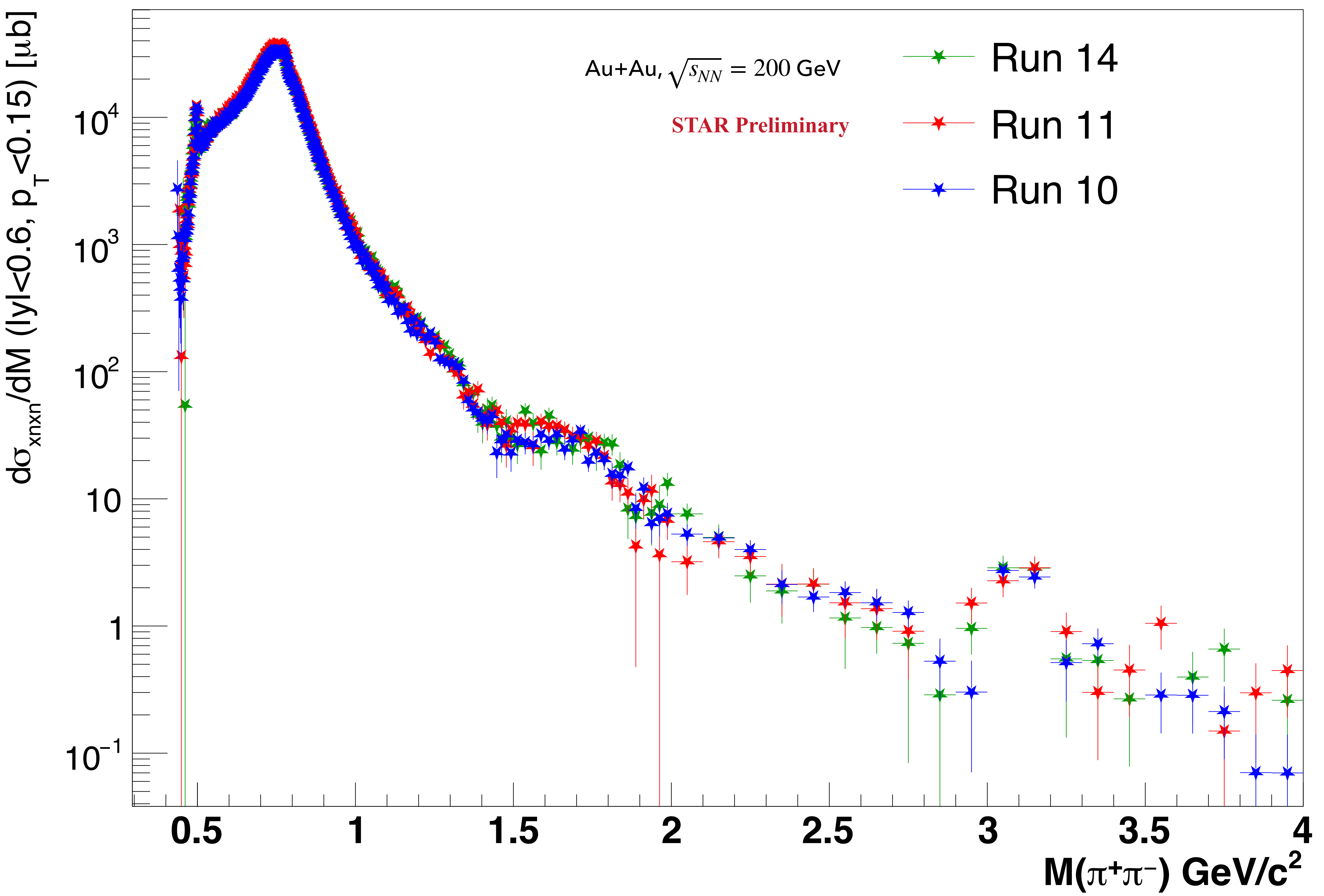
MASS SPECTRA OF $\pi^+\pi^-$ AND $\pi^+\pi^-\pi^+\pi^-$ (BOTH $P_T < 0.15$ GEV/C)





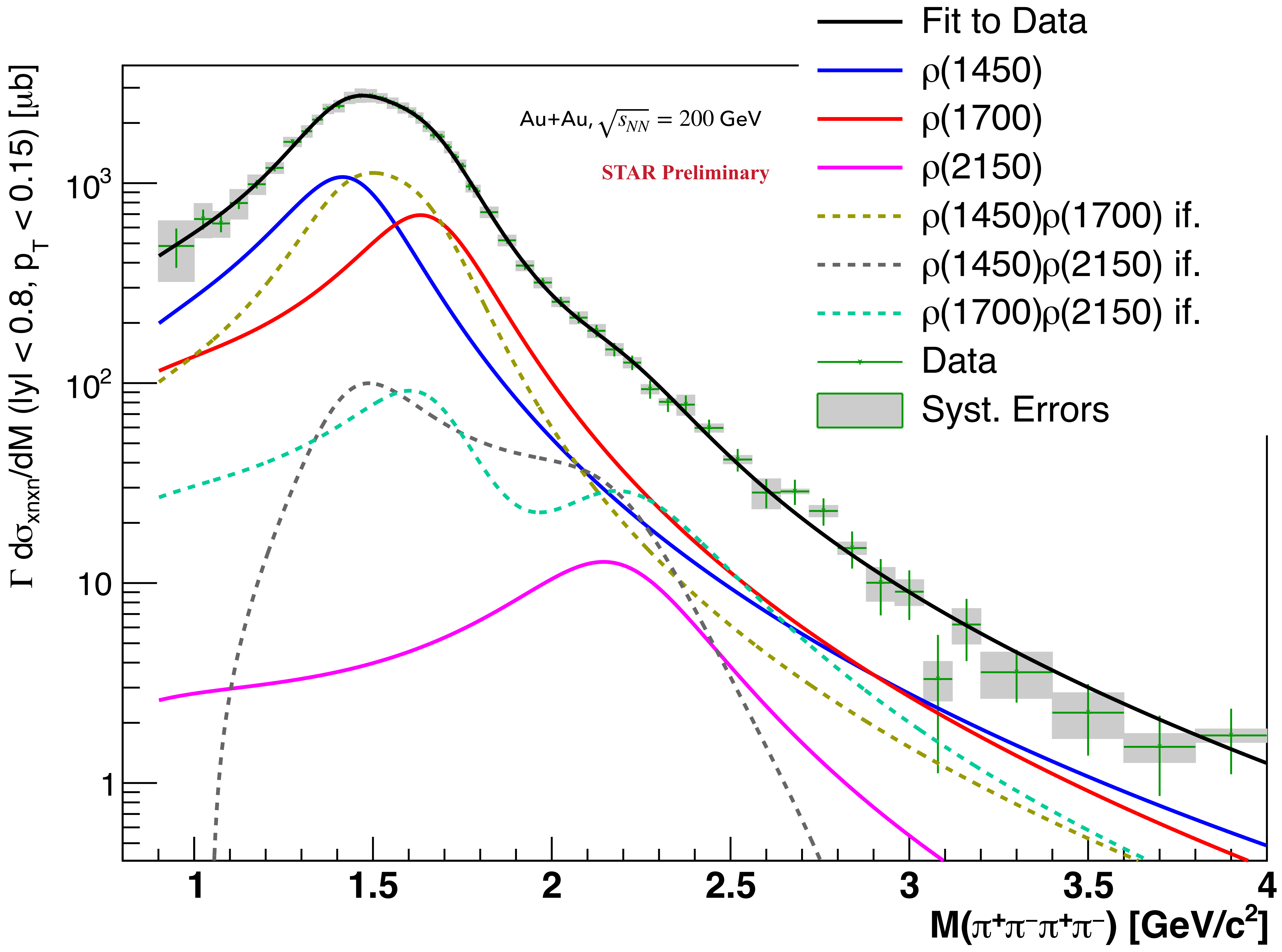
- Main "sanity check" - cross section consistent between datasets

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	PDG
Mass ρ(1450)	1486	20.3	1465± 25
Width ρ(1450)	400.3	30	400± 60
RSP1	2.17	0.27	
Mass ρ(1700)	1701	15.4	1720± 20
Width ρ(1700)	399.6	34.5	250±100
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	

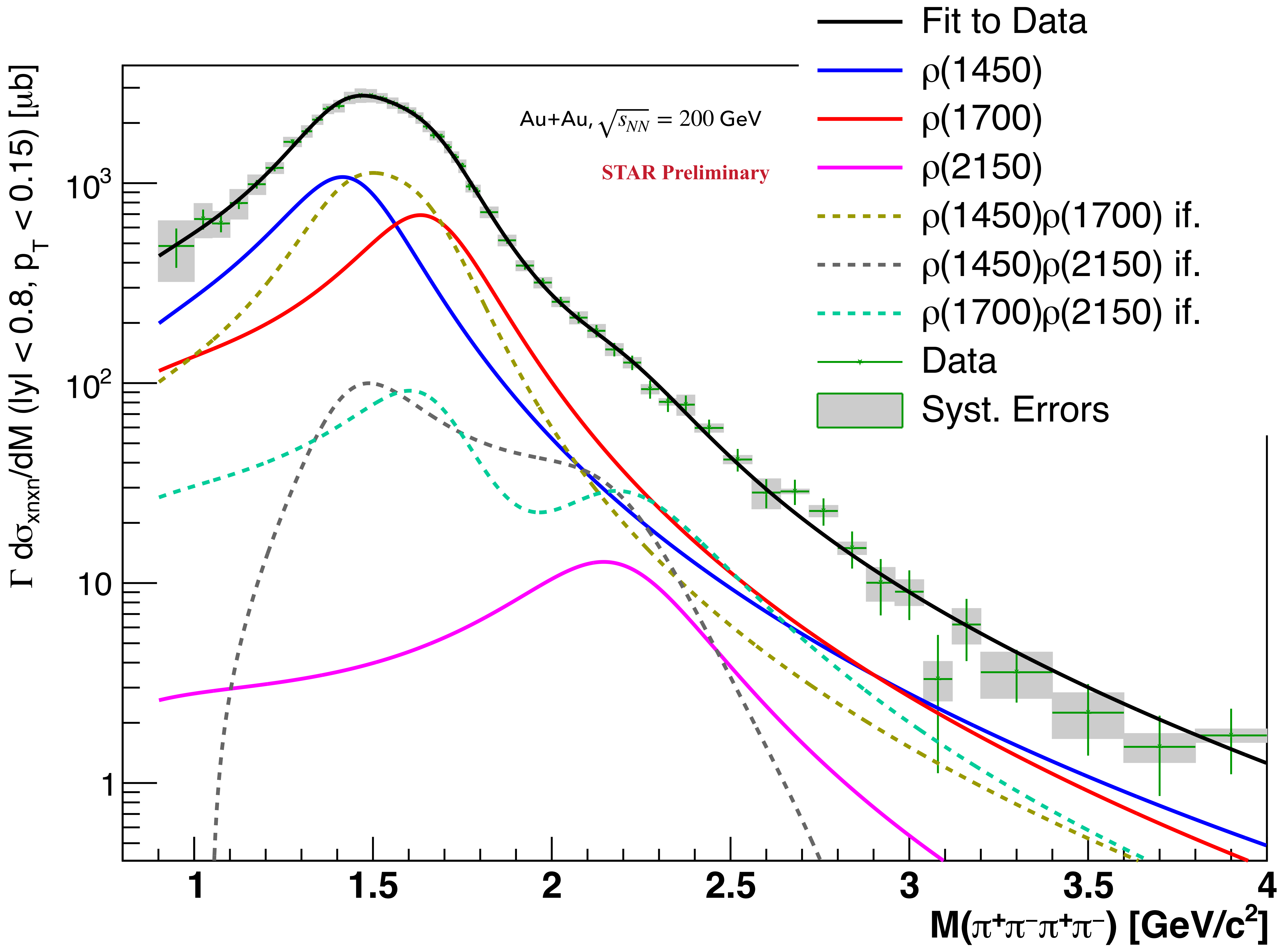
Chi2/ndf 33.0882/41

[PDG - PRD 110 030001]

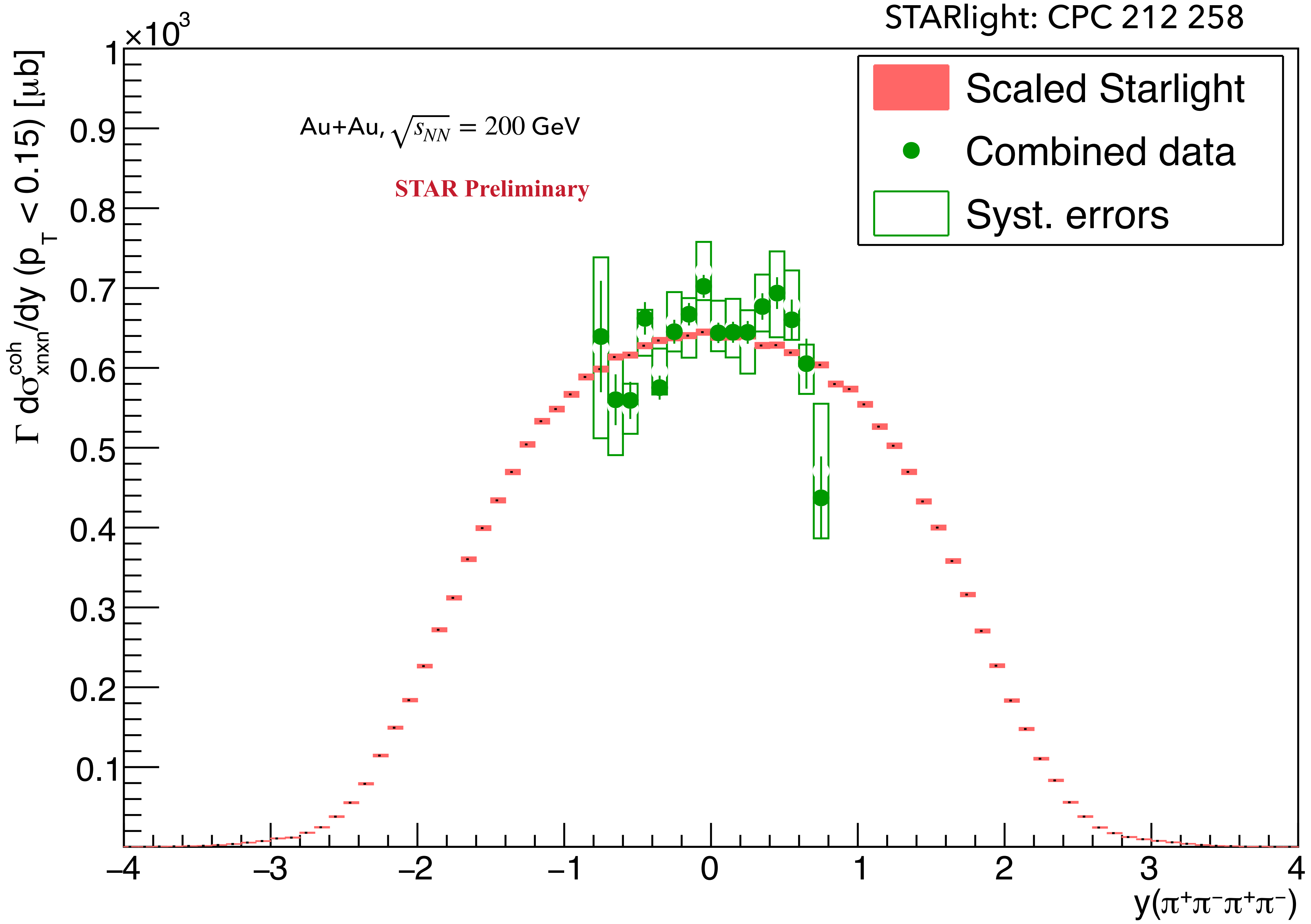
MASS($\pi^+\pi^-\pi^+\pi^-$) AND RAPIDITY COMBINED FROM ALL RUNS

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

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



STARlight: CPC 212 258



$$\sigma^{\mathrm{coh}}_{4\pi,xn,xn}(|y|<0.8) = 1336 \pm 15_{\mathrm{stat.}} \pm 26_{\mathrm{syst.}} \pm 160_{\mathrm{norm.}}$$

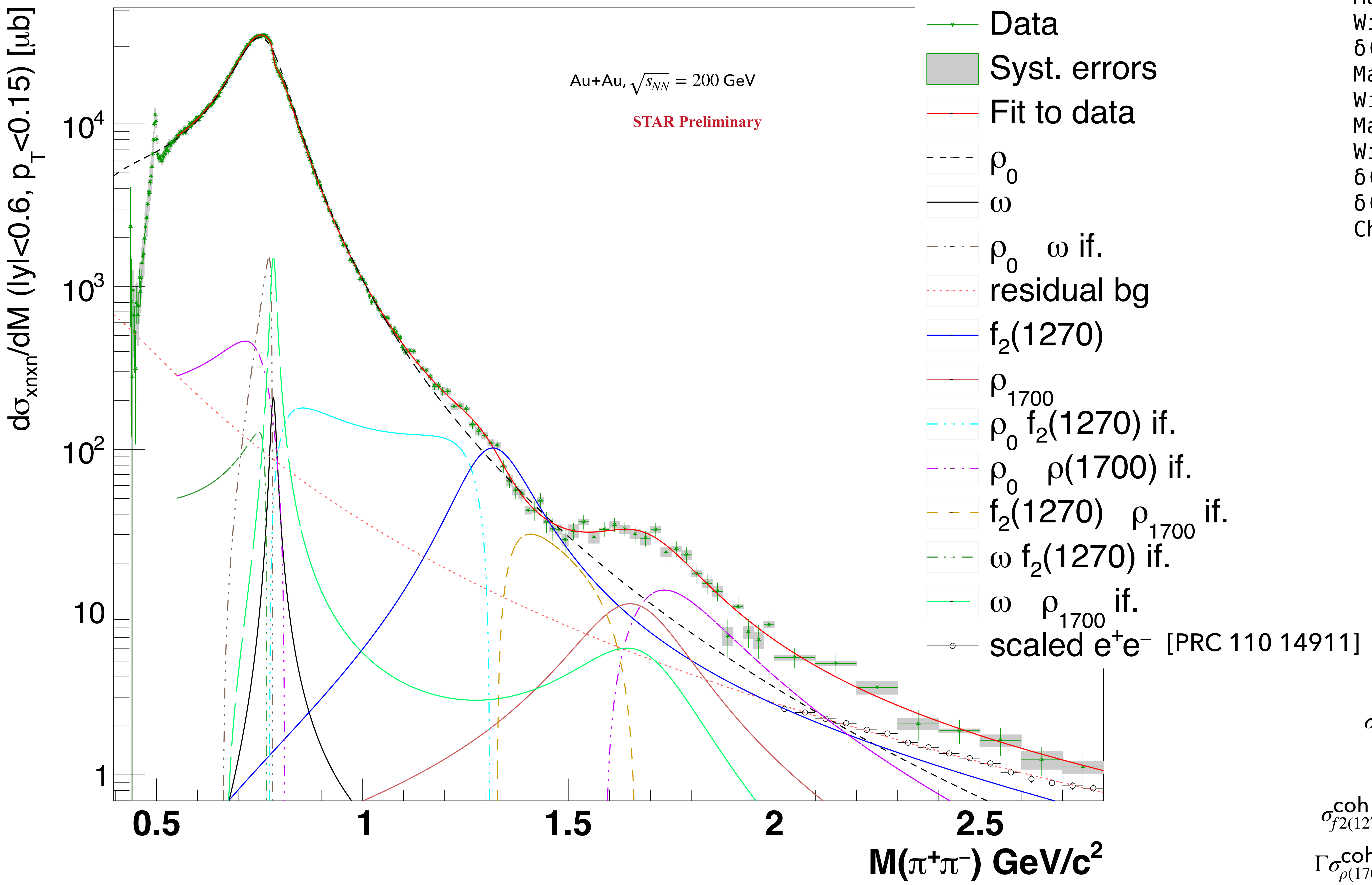
$$\Gamma\sigma^{\mathrm{coh}}_{\rho1450,xn,xn}(|y|<0.8) = 450 \pm 172_{\mathrm{stat.}} \pm 214_{\mathrm{syst.}} \pm 54_{\mathrm{norm.}}$$

$$\Gamma\sigma^{\mathrm{coh}}_{\rho1700,xn,xn}(|y|<0.8) = 325 \pm 160_{\mathrm{stat.}} \pm 170_{\mathrm{syst.}} \pm 39_{\mathrm{norm.}}$$

$$\Gamma\sigma^{\mathrm{coh}}_{\rho2150,xn,xn}(|y|<0.8) = 9.3 \pm 7.7_{\mathrm{stat.}} \pm 2.4_{\mathrm{syst.}} \pm 1.1_{\mathrm{norm.}}$$

to extrapolate to full rapidity - multiply by 2.18

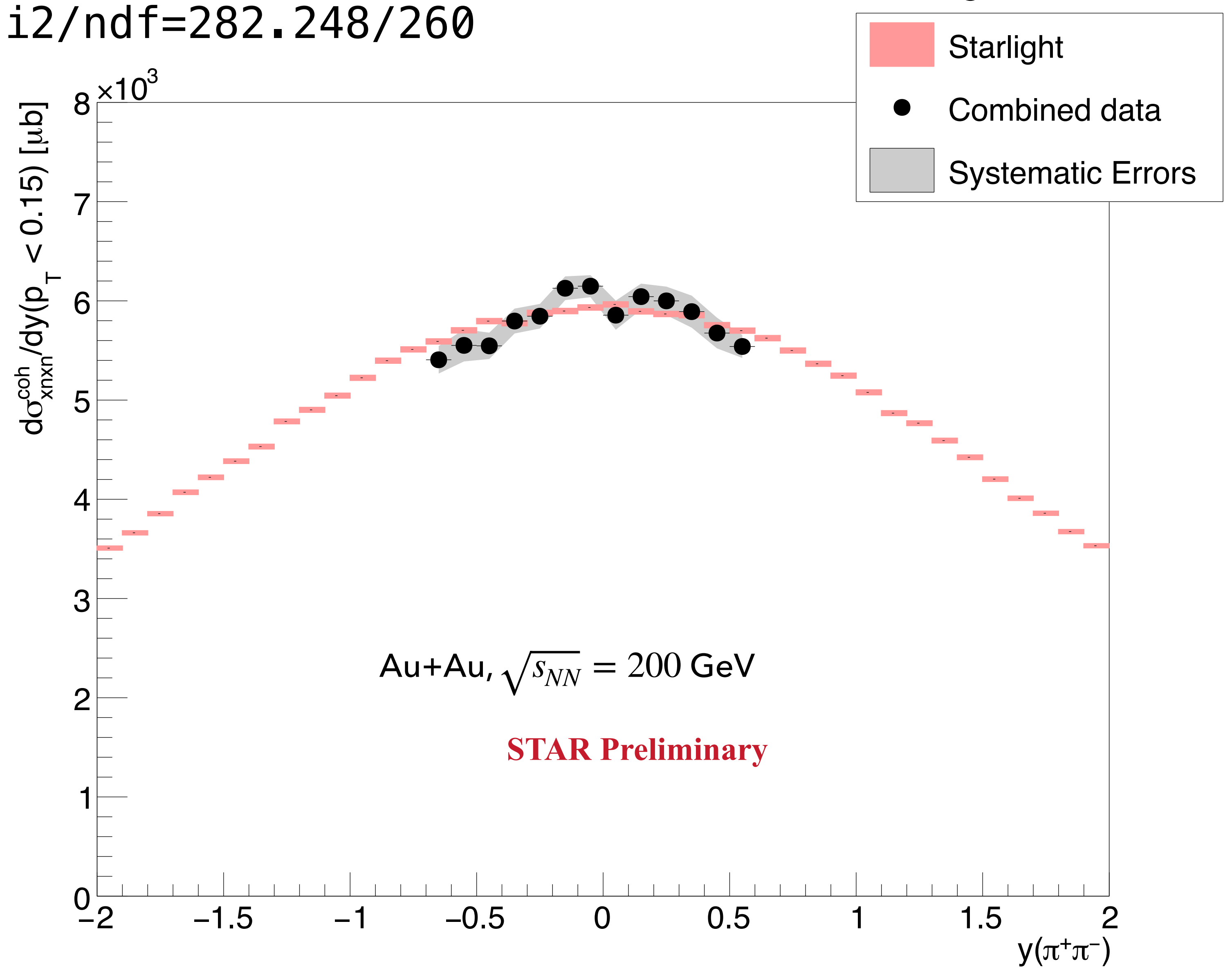
MASS OF $\pi^+\pi^-$ COMBINED FROM ALL RUNS



PARAMETER	VALUE	ERROR	PDG
Mass ρ_0	774.83	0.30	775.26±0.23
Width ρ_0	146.39	0.57	147.40±0.80
RSP ρ_0	2.76	0.02	
Mass ω	783.82	0.50	782.66±0.13
Width ω	16.13	0.85	8.68±0.13
δ(ω)	1.97	0.17	
Mass f_2	1339.26	19.63	1275.4±0.8
Width f_2	210.35	38.30	185.8±2.8
Mass ρ_{1700}.	1700.65	22.71	1720 ± 20
Width ρ_{1700}	317.79	46.75	250 ± 100
δ(f_2)	3.12	0.18	
δ(ρ_{1700})	0.38	0.18	

Chi2/ndf=282.248/260

[PDG - PRD 110 030001]
STARlight: CPC 212 258



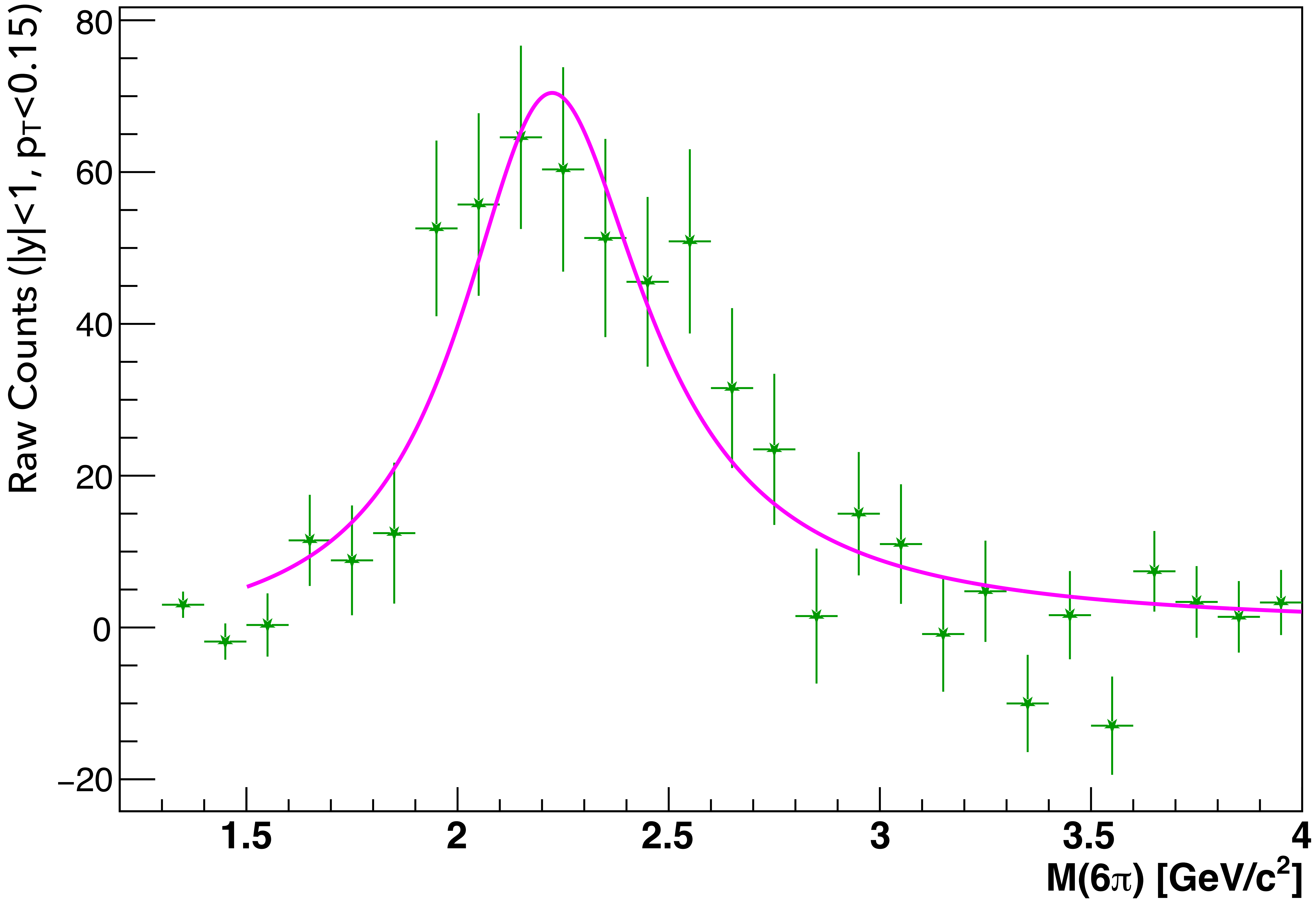
$$\sigma^{coh}_{\rho 0,xn,xn}(|y|<0.6) = 7069 \pm 28_{stat.} \pm 76_{syst.} \pm 848_{norm.}$$

$$\sigma^{coh}_{\rho 0,xn,xn} = 25883 \pm 102_{stat.} \pm 279_{syst.} \pm 3106_{norm.}$$

$$\sigma^{coh}_{f2(1270),xn,xn}(|y|<0.6) = 20.9 \pm 12.1_{stat.} \pm 12.8_{syst.} \pm 2.5_{norm.}$$

$$\Gamma\sigma^{coh}_{\rho(1700),xn,xn}(|y|<0.6) = 3.35 \pm 1.02_{stat.} \pm 1.47_{syst.} \pm 0.40_{norm.}$$

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		

Resonance with consistent

mass and width in 4π

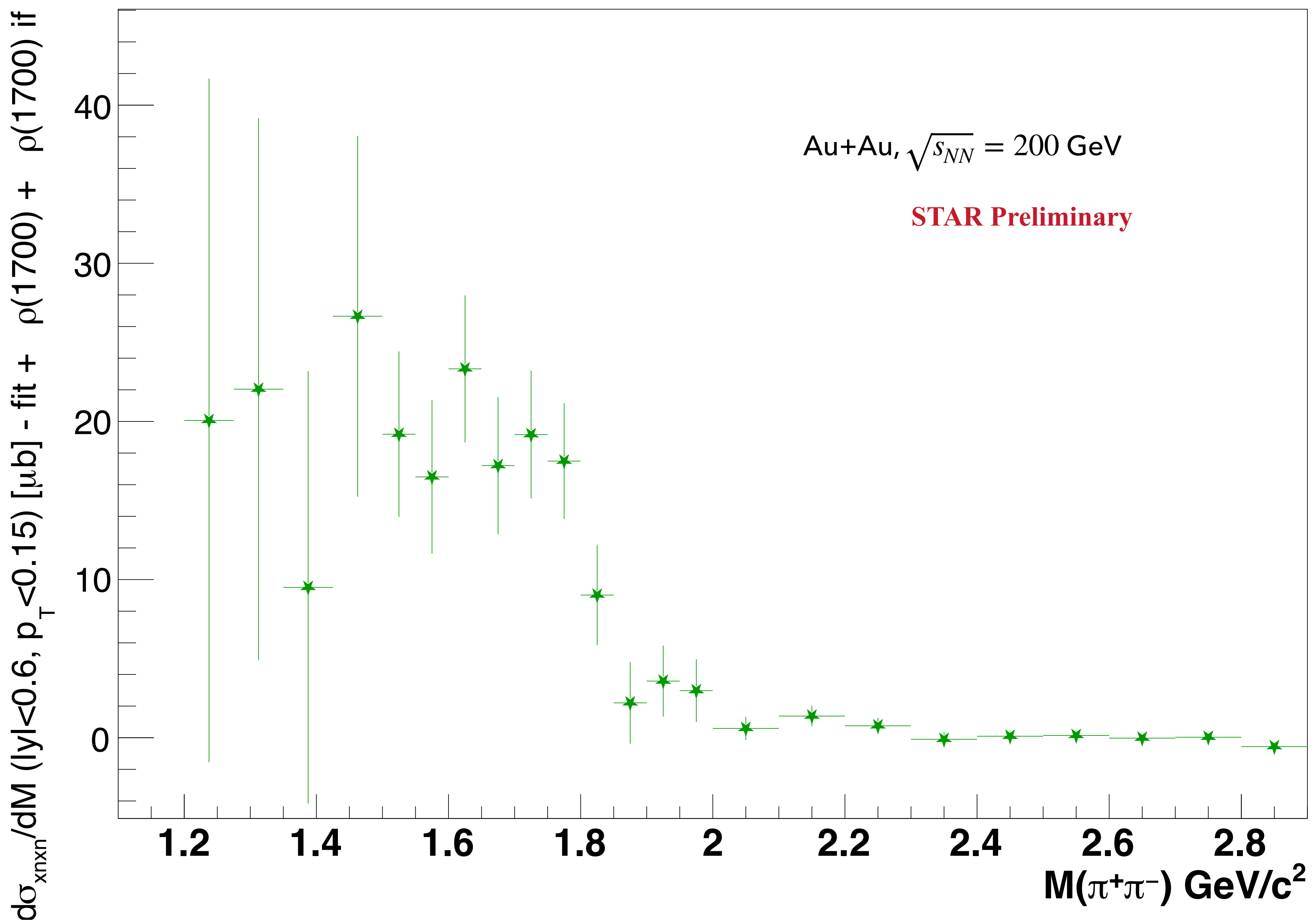
Could be ρ(2150)

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

- comparison of yields directly from Breit-Wigner functions
  - $\Gamma_{2\pi}\sigma^{\text{coh}}_{\rho1700,xn,xn} = 4.42 \pm 1.34_{\text{stat.}} \pm 1.67_{\text{syst.}}$ in |y|<0.8 from $\pi^+\pi^-$
  - $\Gamma_{4\pi}\sigma^{\text{coh}}_{\rho1700,xn,xn} = 325 \pm 160_{\text{stat.}} \pm 170_{\text{syst.}}$ in |y|<0.8 from $\pi^+\pi^-\pi^+\pi^-$

$$\Gamma_{2\pi}/\Gamma_{4\pi}(\rho_{1700}) = 1.36 \pm 0.79_{\text{stat.}} \pm 0.88_{\text{syst.}} \,\%$$

- 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 = $6.56 \pm 0.60_{\text{stat.}} \pm 0.32_{\text{syst.}}$

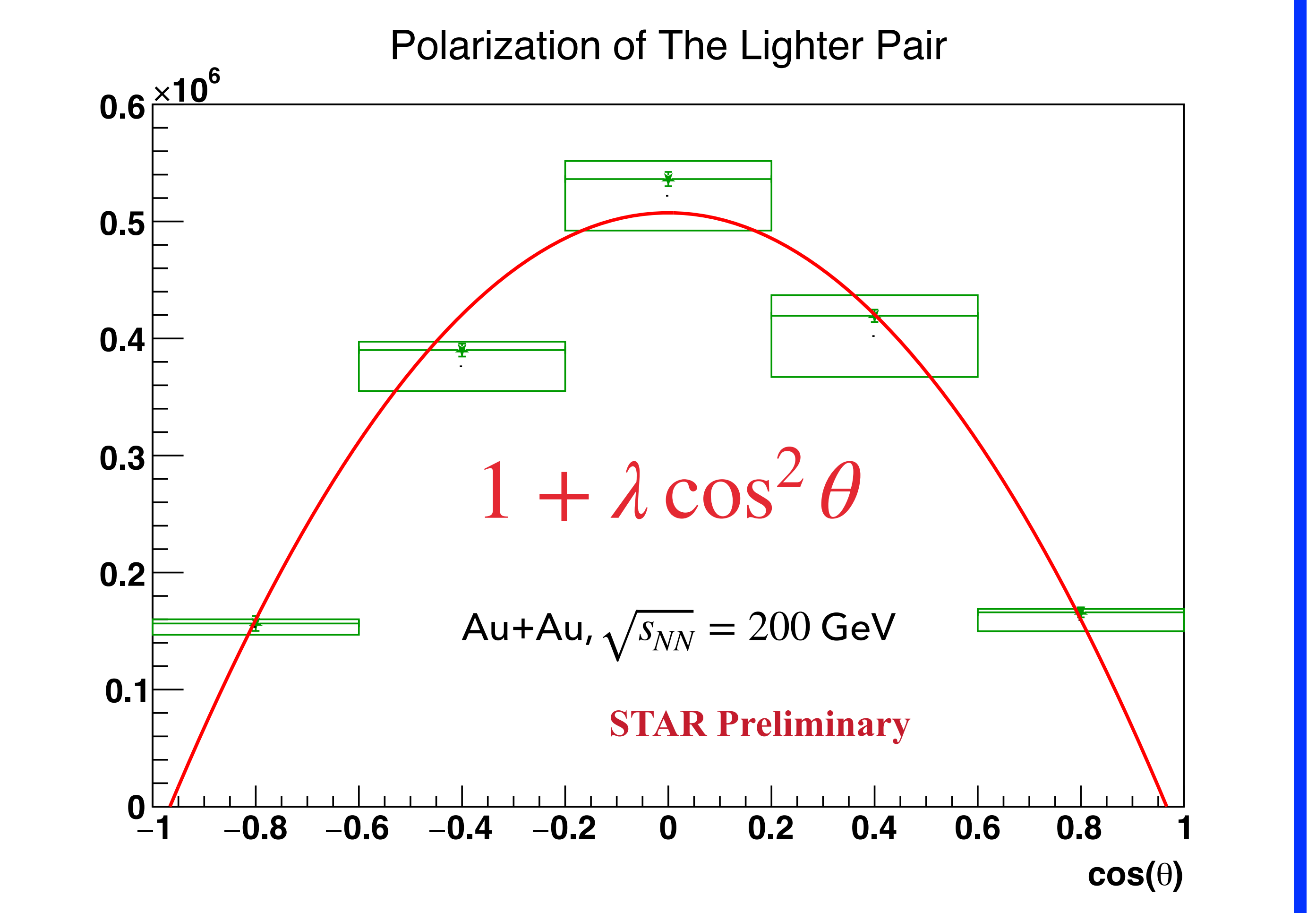
$$\sigma^{\text{coh}}_{4\pi,xn,xn}(|y| < 0.8,\ 1.5 < M < 2.5) = 612 \pm 8_{\text{stat.}} \pm 21_{\text{syst.}}$$

$$\Gamma_{2\pi}/\Gamma_{4\pi}(|y| < 0.8,\ 1.5 < M < 2.5) = 1.07 \pm 0.10_{\text{stat.}} \pm 0.06_{\text{syst.}} \,\%$$

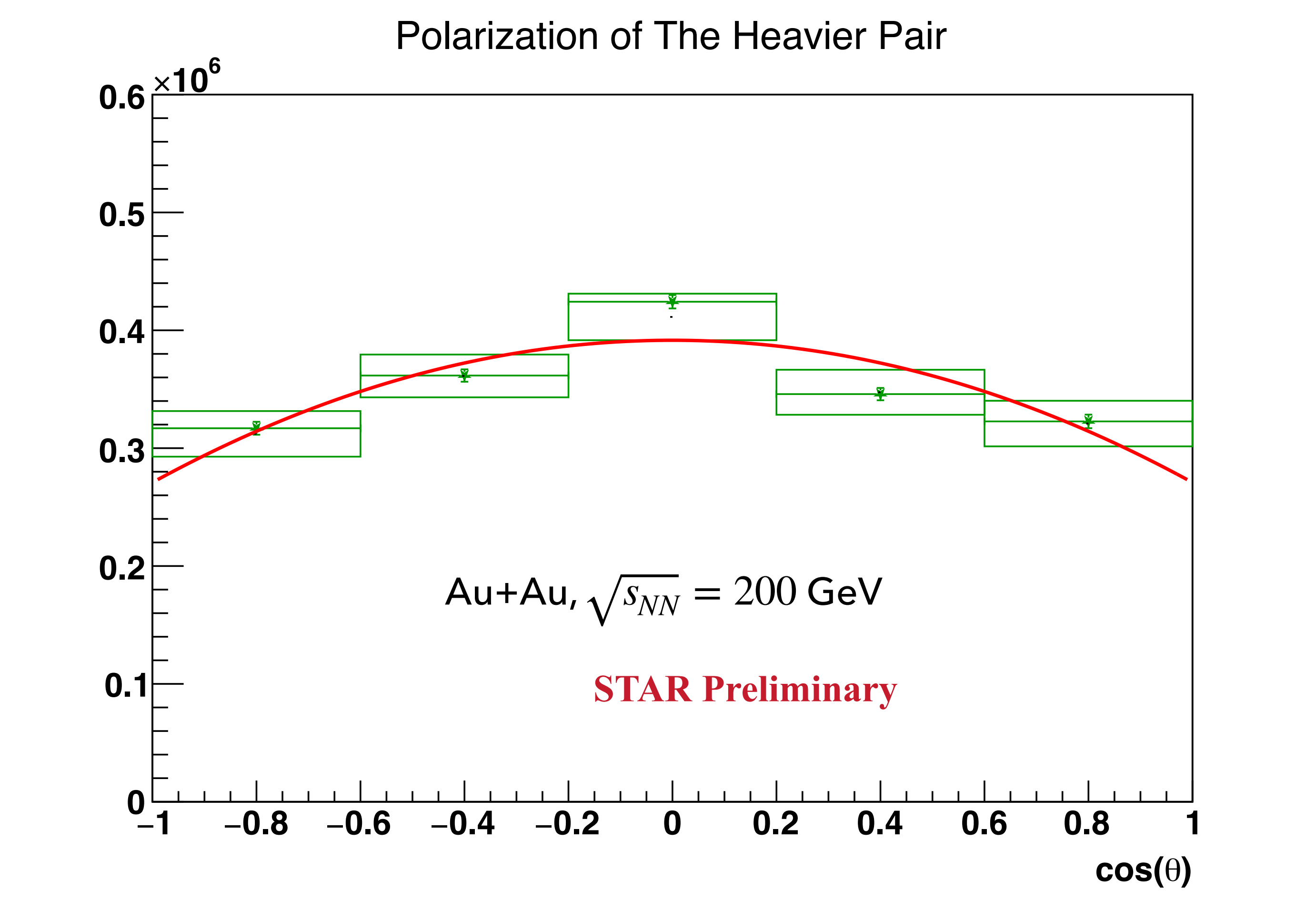
	PRC 81 044901
$\sigma^{\text{coh}}_{4\pi,xn,xn}/\sigma^{\text{coh}}_{\rho0,xn,xn}(\lvert y\rvert < 0.8) = 14.1 \pm 0.4_{\text{stat.}} \pm 0.5_{\text{sys.}} \,\%$	$16.4 \pm 1.0_{\text{stat}} \pm 5.2_{\text{syst}}\%$
$\sigma^{\text{coh}}_{4\pi,xn,xn}/\sigma^{\text{coh}}_{\rho0,xn,xn} = 11.1 \pm 0.3_{\text{stat.}} \pm 0.4_{\text{sys.}} \,\%$	$13.4 \pm 0.8_{\text{stat}} \pm 4.4_{\text{syst}}\%$

J=1 TRANSFER TO COSθ ANISOTROPY

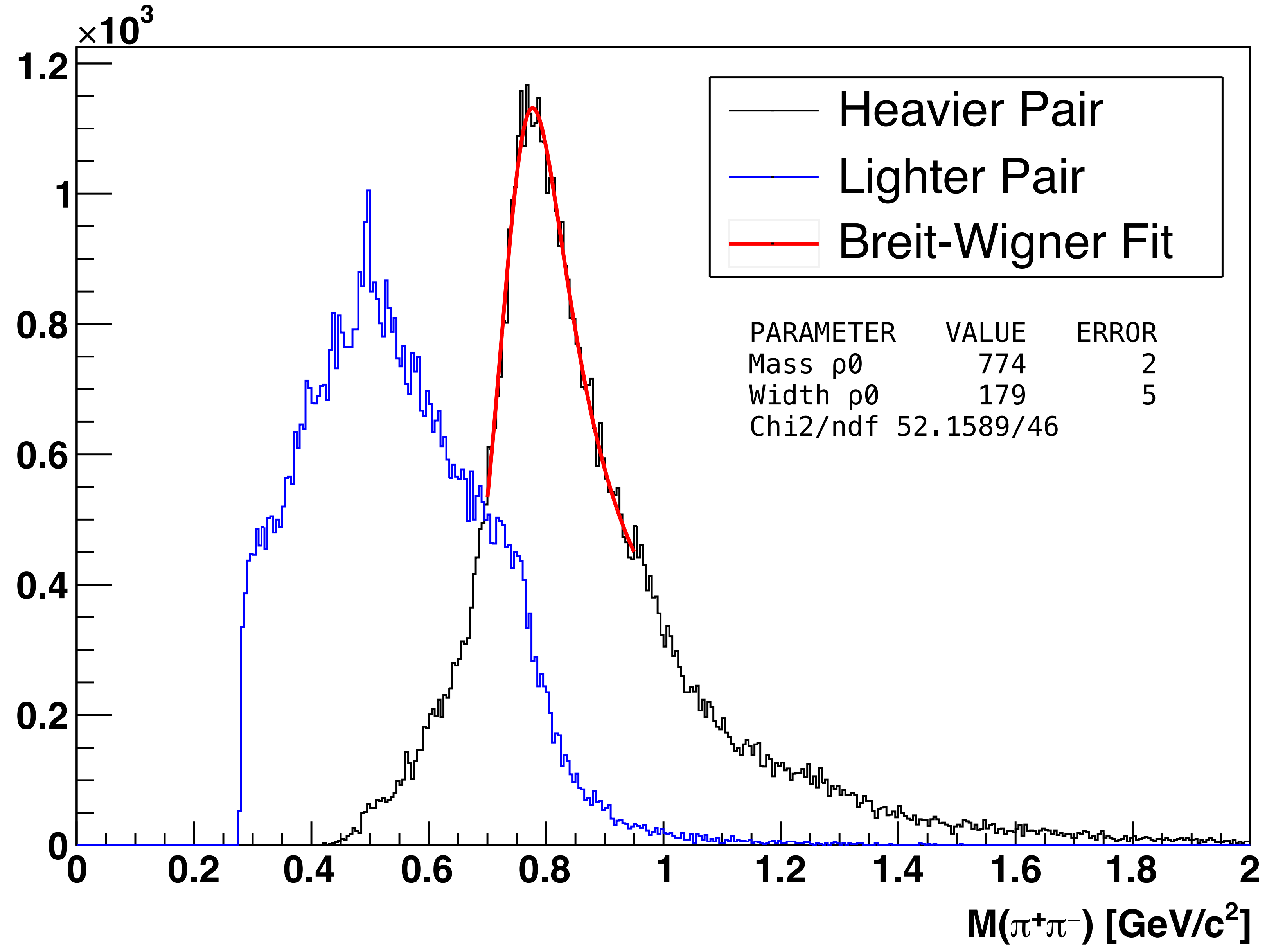
$$\rho(1450) + \rho(1700) \rightarrow (\pi^+\pi^-)_{\text{heavy}} + (\pi^+\pi^-)_{\text{light}} \rightarrow \pi^+\pi^-\pi^+\pi^-$$



$\lambda = -1.062 \pm 0.076$



$\lambda = -0.303 \pm 0.084$



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

- 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?
  - $f_2(1270)$ and ρ_{1700} observed in $\pi^+\pi^-$ mass spectrum
    - $f_2(1270)$ 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
  - $(\rho_{1700} \to \pi^+\pi^-)/(\rho_{1700} \to \pi^+\pi^-\pi^+\pi^-) = 1.07 \pm 0.10_{\text{stat.}} \pm 0.06_{\text{syst.}}$ % 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 $f_0(500)$, 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

$$\frac{d\sigma}{dM} = \sigma_1 |BW_1|^2 + \sigma_2 |BW_2|^2 + 2\sqrt{\sigma_1\sigma_2}\Re\left[BW_1^* BW_2 e^{i\phi}\right]$$

$$BW(\rho) \equiv \left(\frac{M_\rho}{M}\right)^n \frac{\sqrt{\Gamma_\rho M_\rho}}{M^2 - M_\rho^2 + iM_\rho\Gamma_\rho}$$

$$|BW_1|^2 = BW_1 BW_1^* = \left(\frac{M_1}{M}\right)^{2n} \frac{\Gamma_1 M_1}{\underbrace{(M^2 - M_1^2)}_{\mu_1}{}^2 + M_1^2\Gamma_1^2}$$

To get the real part which contributes to the cross section, one needs to get the complex term to $\Re(z) + \Im(z)$ form. So first, we need to expand the fraction so there are imaginary terms only in the nominator.

$$BW_1(e^{i\phi}BW_2)^* = \left(\frac{M_1}{M}\right)^{n_1}\left(\frac{M_2}{M}\right)^{n_2} \underbrace{\frac{e^{-i\phi}\sqrt{\Gamma_1 M_1 \Gamma_2 M_2}}{(\mu_1 + iM_1\Gamma_1)(\mu_2 - iM_2\Gamma_2)}}_{z}$$

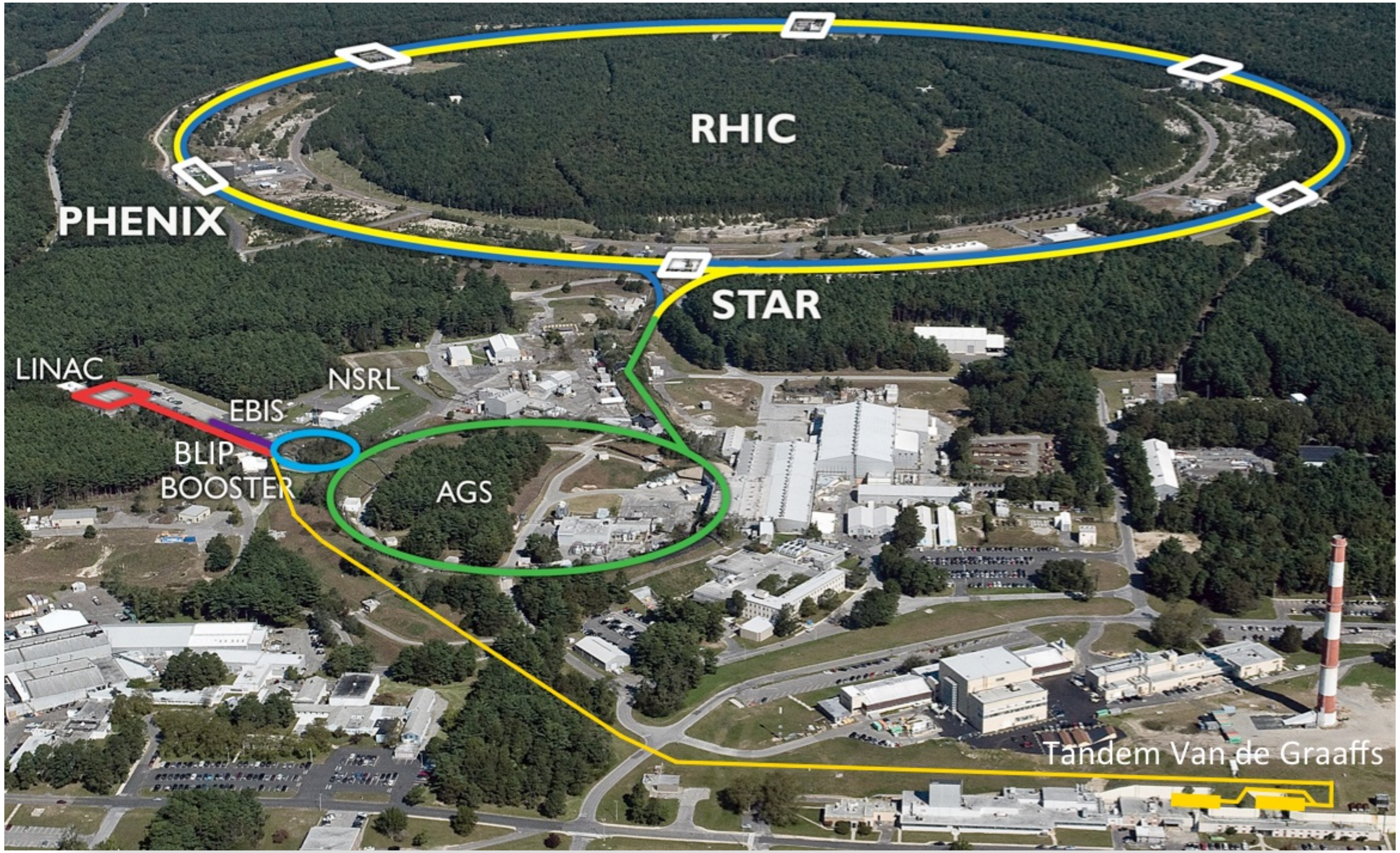
$$z \cdot \frac{(\mu_1 - iM_1\Gamma_1)(\mu_2 + iM_2\Gamma_2)}{(\mu_1 - iM_1\Gamma_1)(\mu_2 + iM_2\Gamma_2)} = \sqrt{\Gamma_1 M_1 \Gamma_2 M_2}\frac{(\cos\phi - i\sin\phi)(\mu_1 - iM_1\Gamma_1)(\mu_2 + iM_2\Gamma_2)}{\mu_1^2\mu_2^2 + \mu_1^2 M_2^2\Gamma_2^2 + \mu_2^2 M_1^2\Gamma_1^2 + M_1^2\Gamma_1^2 M_2^2\Gamma_2^2}$$

$$\Re(z) = \sqrt{\Gamma_1 M_1 \Gamma_2 M_2}\frac{\cos\phi(\mu_1\mu_2 + M_1\Gamma_1 M_2\Gamma_2) + \sin\phi(M_2\Gamma_2\mu_1 - M_1\Gamma_1\mu_2)}{\mu_1^2\mu_2^2 + \mu_1^2 M_2^2\Gamma_2^2 + \mu_2^2 M_1^2\Gamma_1^2 + M_1^2\Gamma_1^2 M_2^2\Gamma_2^2}$$

$2\sqrt{\sigma_1\sigma_2}\Re(z)$ is then the interference term, ϕ is the phase shift between the resonances

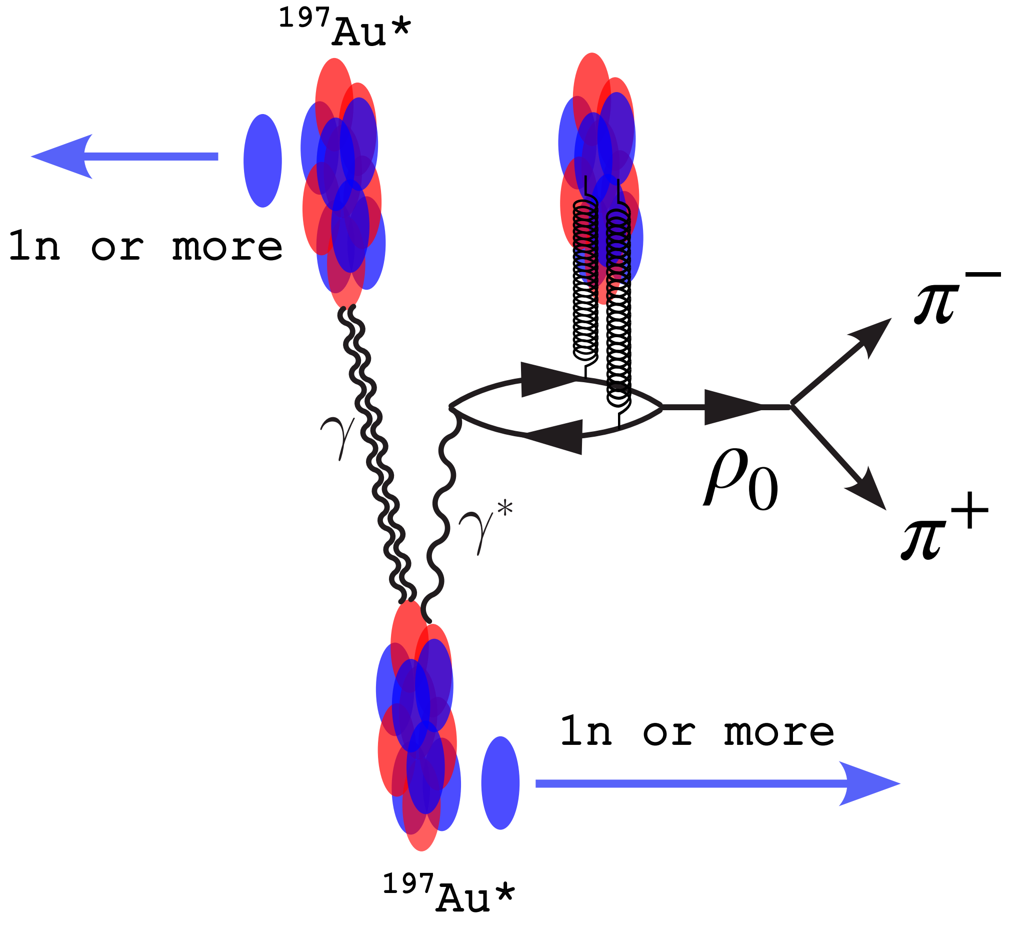
UTRA-PERIPHERAL COLLISIONS AT RHIC

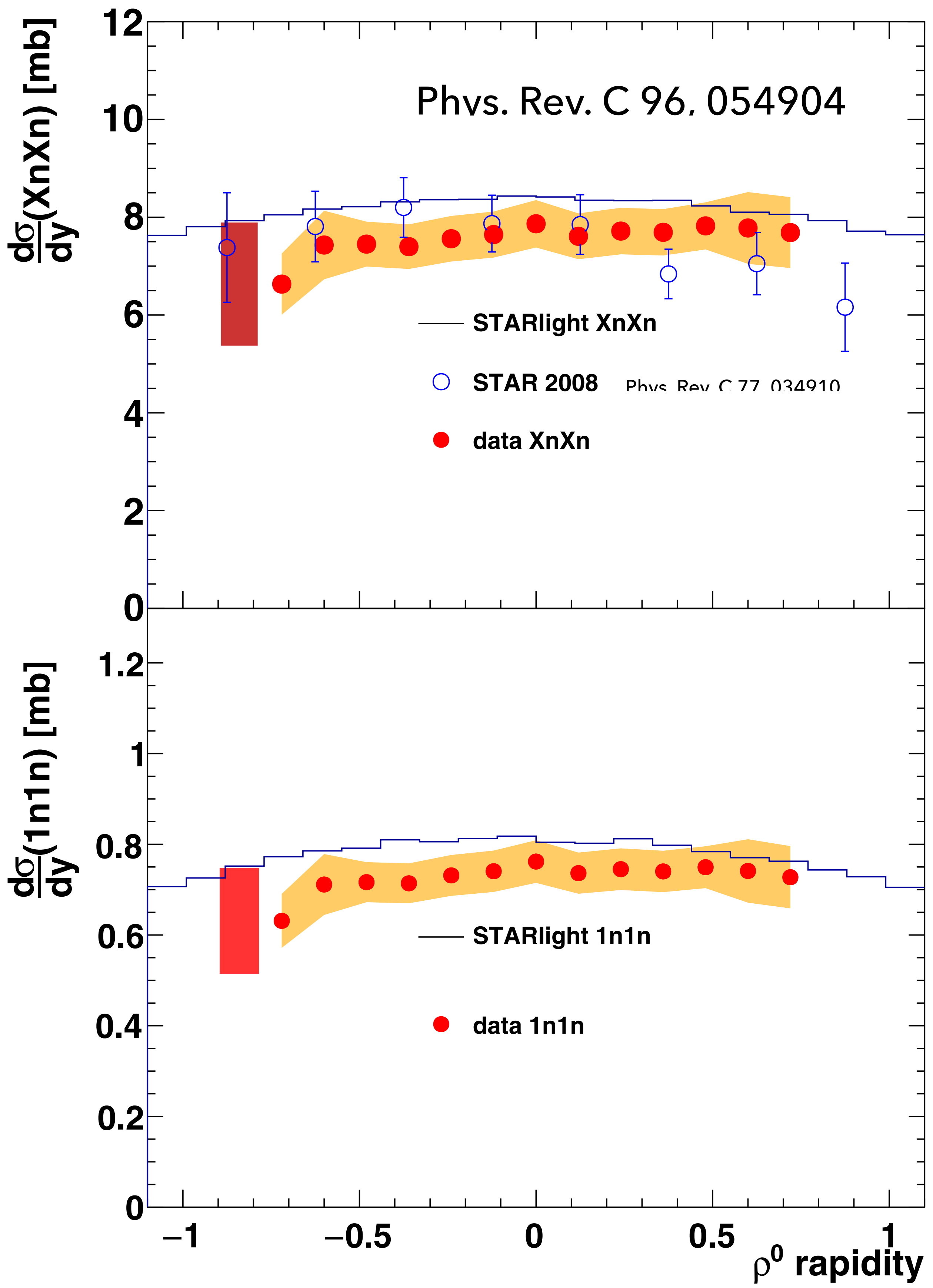
- Relativistic Heavy Ion Collider
  - located in Brookhaven National Laboratory (Long Island, USA)
- different species, energy, and proton polarization

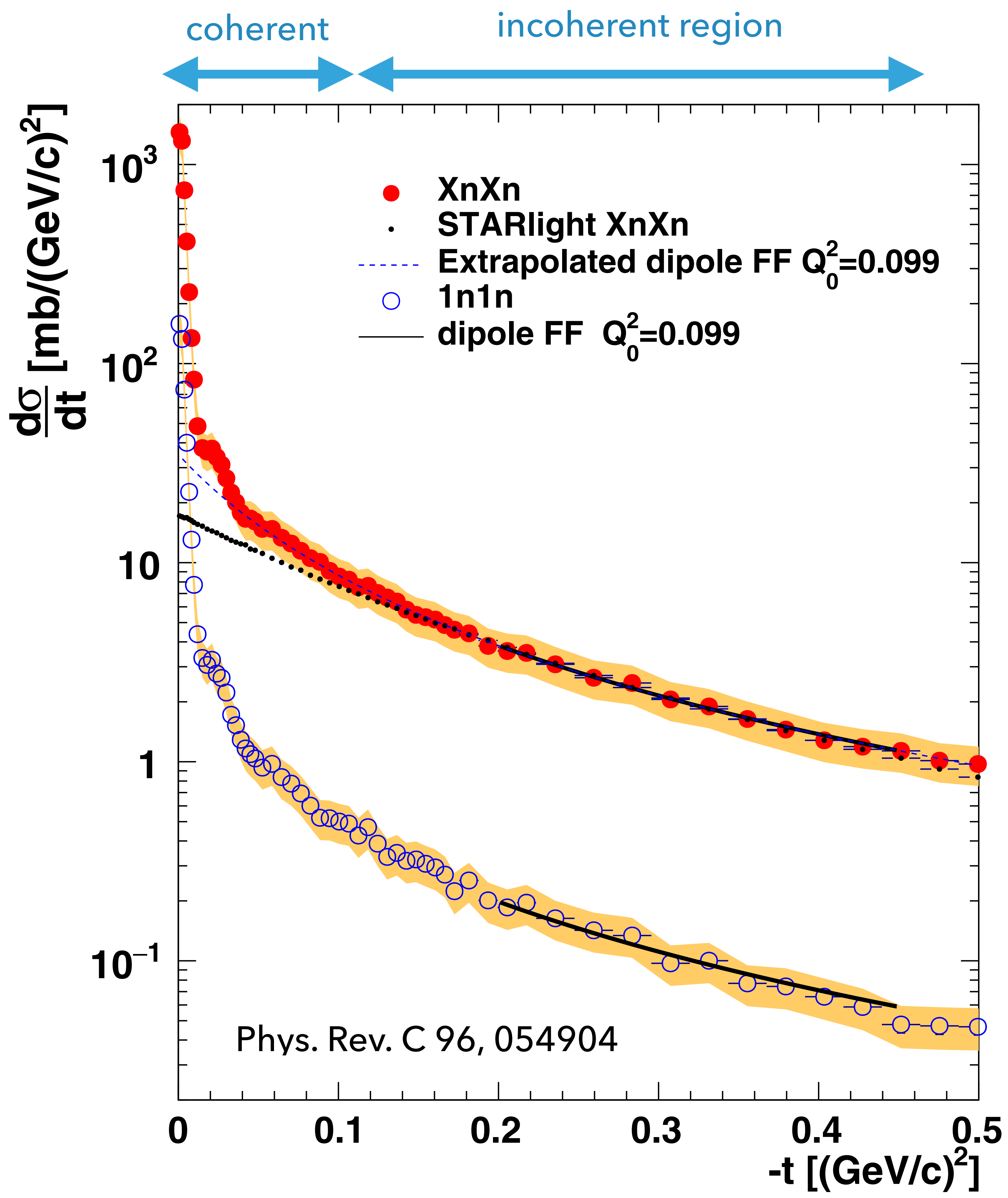


U^{238}, Au^{197}, Zr^{96} , Ru^{96}, d^2 at 200 GeV and *pp* at 510 GeV

ρ_0 CROSS SECTION





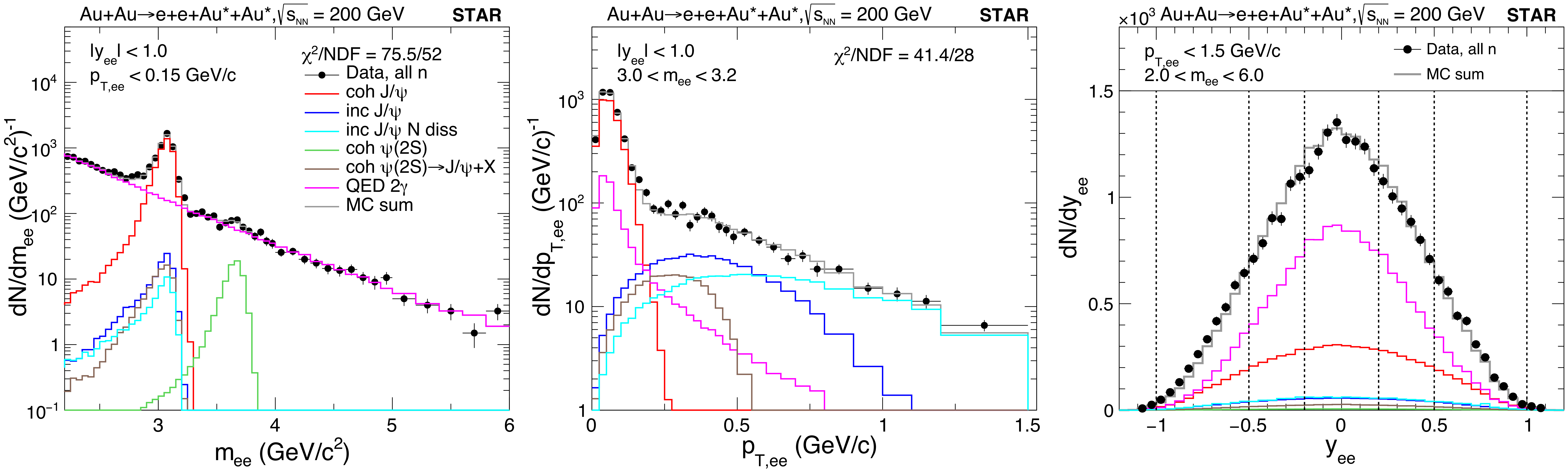


- integrated luminosity of 1100±100 μb−1 of data collected in 2010
- XnXn extrapolated from 1n1n using STARlight
- incoherent components in $d\sigma/dt$ are fit in range $-t = (0.2, 0.45)$
  - σ_{incoh} are integrals of the fits

Parameter	$XnXn$	$1n1n$
$\sigma_{coh.}$	6.49 ± 0.01 (stat.) $\pm$ 1.18 (syst.) mb	0.770 ± 0.004 (stat.) $\pm$ 0.140 (syst.) mb
$\sigma_{incoh.}$	2.89 ± 0.02 (stat.) $\pm$ 0.54 (syst.) mb	0.162 ± 0.010 (stat.) $\pm$ 0.029 (syst.) mb
$\sigma_{incoh.}/\sigma_{coh.}$	0.445 ± 0.015 (stat.) $\pm$ 0.005 (syst.)	0.233 ± 0.007 (stat.) $\pm$ 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 $(t \sim p_T^2)$