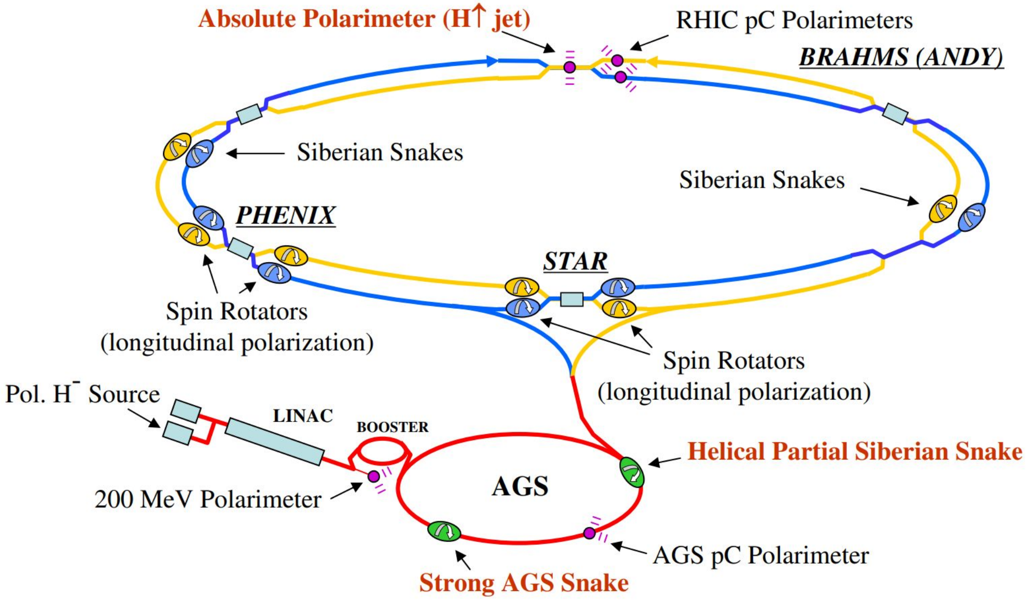
The forward η meson cross section and transverse single spin asymmetry at PHENIX

Devon Loomis for the PHENIX Collaboration

Polarized Physics Runs at PHENIX



Year	System	$\sqrt{s}$ (GeV)	Polarization Direction	Recorded Luminosity (pb^{-1})
2006	p+p	62.4	transverse	0.02
			longitudinal	0.08
		200	transverse	2.7
			longitudinal	7.5
2008	p+p	200	transverse	5.2
2009	p+p	200	longitudinal	16
		500		14
2011	p+p	500	longitudinal	18
2012	p+p	200	transverse	9.7
		510	longitudinal	32
2013	p+p	510	longitudinal	155
2015	p+p	200	transverse	60
	p+Au			1.27
	p+Al			3.97

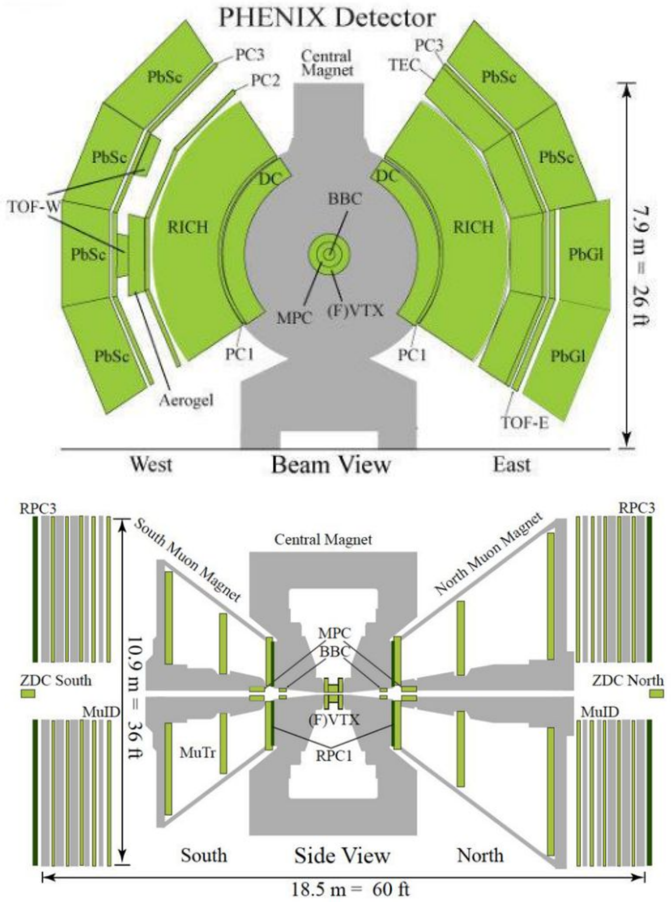
PHENIX Detector

Midrapidity

- ❑ $|\eta| < 0.35$
- ❑ Tracking: drift chamber (DC), pad chambers (PC)
- ❑ RICH
  - ❑ PID for electrons and charged pions
- ❑ TOF
  - ❑ PID for low momentum charged particles (pions,kaons,protons)
- ❑ EMCal
  - ❑ Energy deposits of photons and electrons

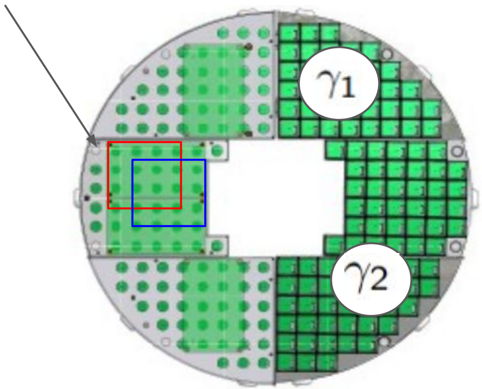
Forward rapidity

- ❑ Muon Piston Calorimeter (MPC)
  - ❑ π^0 and η identification through $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$
  - ❑ ~ $3.0 < |\eta| < 3.8$
- ❑ Beam-Beam Counter (BBC)
  - ❑ Collision vertex
  - ❑ Minimum bias trigger



Muon Piston Calorimeter

- Forward electromagnetic calorimeter
- MPC has 196 (220) towers of lead tungstate scintillating crystal in South (North) arm
- High energy photons are detected in MPC when they shower into electrons, positrons, and photons from a combination of pair production and bremsstrahlung
  - Clusters are formed from a central tower with local energy maximum and a group of surrounding towers containing some energy of the shower
- MPC dedicated trigger (MPC4x4)
  - Define groups of 4x4 towers as tiles (72 tiles in each arm)
  - MPC4x4 trigger fires when the ADC sum of towers in at least one tile exceeds threshold



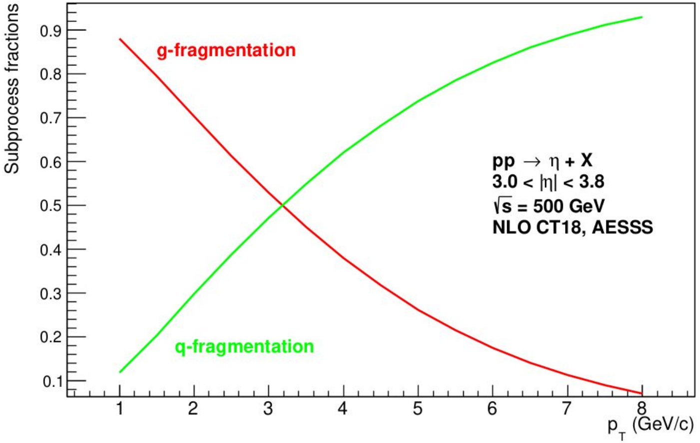
Run-09 (2009) Forward η meson Cross Section

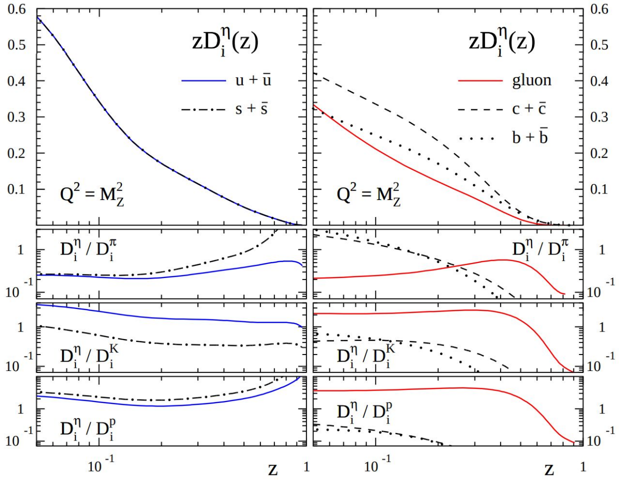
Accessing collinear η FFs with forward cross section

- In p+p collisions, inclusive hadronic cross sections directly access quark <u>and gluon</u> fragmentation

$$d\sigma_{pp} \propto f_a(x_a) f_b(x_b) d\sigma^{ab\to cX} D_c^h(z_c)$$

- Only one existing set of η meson fragmentation functions (FFs)





PRD. 83 034002 (2011)

$$\delta D^{\eta}_{u,d} = ^{+30\%}_{-20\%}$$

$$\delta D^{\eta}_{g} = \pm 15\%$$

New inputs for a potential updated η FF analysis

Experiment	*Observable*	$\sqrt{s}$ *(TeV)*	*Pseudorapidity*	
PHENIX	$d\sigma_{pp\to\eta X}$	0.2	Forward	PRD 90 072008 (2014)
PHENIX	$d\sigma_{pp\to\eta X}$	0.5	Forward	
PHENIX	$d\sigma_{pp\to\eta X}$	0.2	Midrapidity	PRD 83 032001 (2011)
PHENIX	$d\sigma_{pp\to\eta X}$	0.51	Midrapidity	In progress
ALICE	$d\sigma_{pp\to\eta X}$	2.76	Midrapidity	Eur. Phys. J.C (2017) 77:339
ALICE	$d\sigma_{pp\to\eta X}$	7	Midrapidity	Phys. Lett. B717 (2012) 162
ALICE	$d\sigma_{pp\to\eta X}$	8	Midrapidity	Eur. Phys. J.C (2018) 78:263
STAR	η/π^0	0.2	Midrapidity	PRC 81 064904 (2010)

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Forward η meson cross section

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\mathcal{L}}\frac{1}{\mathcal{BR}_{\eta\to\gamma\gamma}}\frac{1}{2\pi p_T}\frac{\Delta N^{meas}}{\epsilon_{trig}\epsilon_{reco}\Delta p_T \Delta\eta}$$

- Cross section is binned in p_T and integrated over pseudorapidity ($3.0 < |\eta| < 3.8$)
  - Minimum Bias p_T : 1-4.5 GeV/c
  - MPC4x4 trigger p_T : 3.5-6.5 GeV/c
- Measured independently for each MPC Arm
- 5 inputs into cross section
  - $BR_{\eta\to\gamma\gamma} = 0.3941 \pm 0.002$
  - Integrated Luminosity: $\mathcal{L}_{MB} = 5.52\ nb^{-1}$ $\mathcal{L}_{4x4A} = 9.26\ pb^{-1}$
  - Yields
  - Reconstruction efficiency
  - Trigger Efficiency

Forward η meson cross section

Yields

- $\eta \rightarrow \gamma\gamma$ reconstructed as pairs of photon clusters in the MPC
- Invariant mass given by

$$M = \sqrt{4E_1E_2}\sin\frac{\theta}{2}$$

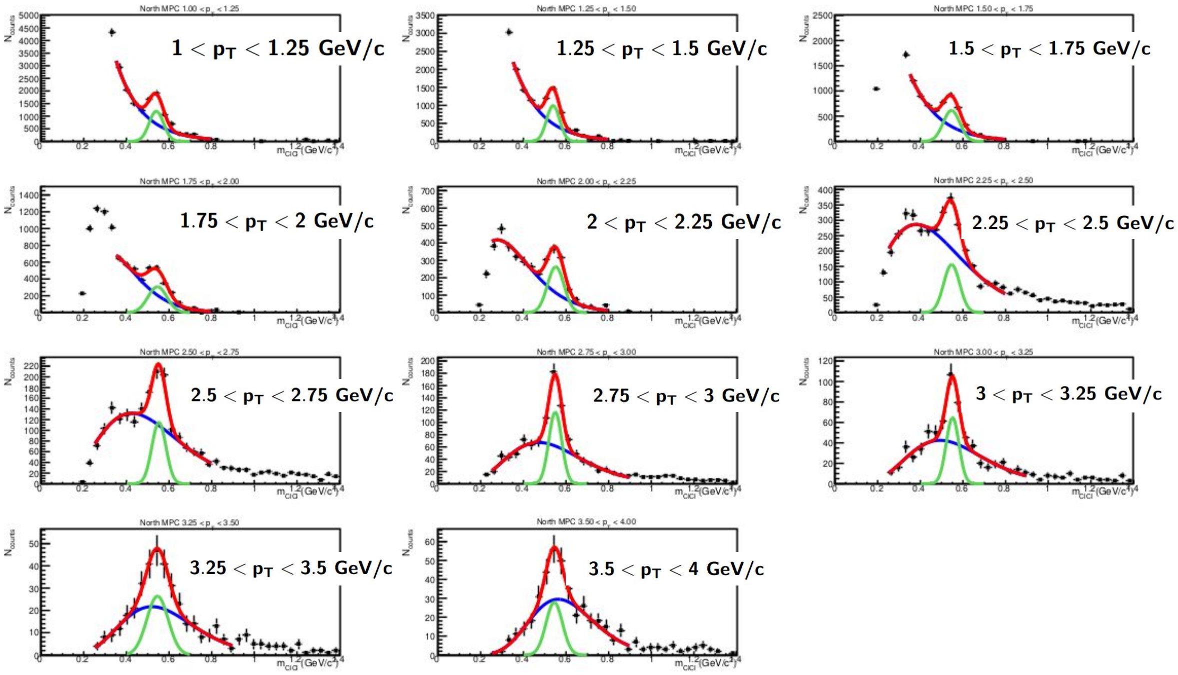
- Fit invariant mass distributions by

$$\Phi(x) = \boxed{af(x;\alpha,\beta)} + \boxed{\frac{N}{\sqrt{2\pi\sigma^2}}\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]}$$

Gamma distribution background   Gaussian signal

$$f(x;\alpha,\beta) = \frac{x^{\alpha-1}e^{\beta x}\beta^{\alpha}}{\Gamma(\alpha)}$$

- Background also estimated using Gaussian Process Regression
  - Systematic uncertainty from difference in yields between methods



Forward η meson cross section

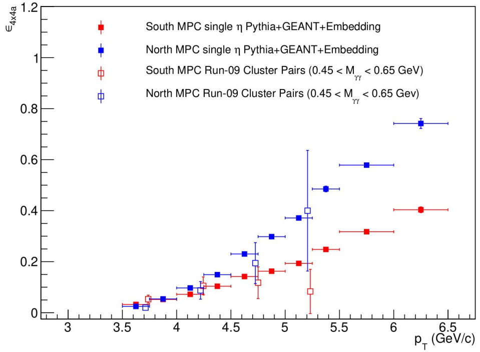
Corrections

Trigger Efficiency

- Minimum Bias
  - Data driven using MPC triggered dataset $\epsilon^{MB}_{trig} = \frac{N^{\eta}_{MB \wedge MPC}}{N^{\eta}_{MPC}}$ = 0.92 ± 0.04 (uniform in p_T)
- MPC4x4 trigger
  - Find MPC4x4 ADC sum threshold by matching the single cluster efficiencies of data and full event simulations
  - Use ADC sum threshold on single η meson simulations to find trigger efficiency vs. p_T

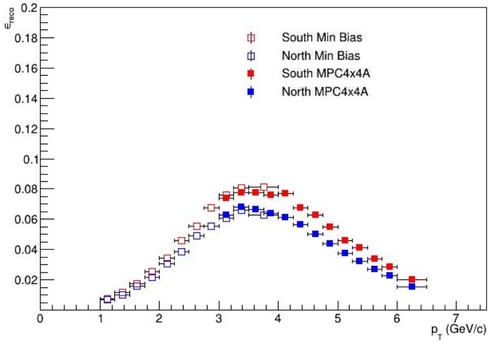
$$\epsilon^{\eta}_{4x4a}(p_T^{reco},\Theta) = \frac{\sum N^{reco}(p_T^{reco}) \times \Theta(\theta_{cl1,4x4id=(i,j,k,l)}(ADC), \theta_{cl2,4x4id=(i,j,k,l)}(ADC))}{\sum N^{reco}(p_T^{reco})}$$

$$\theta_{cl,i} = \begin{cases} 1 & \text{if } ADC_{cl,i} > ADC(\epsilon_{thresh}) \\ 0 & \text{if } ADC_{cl,i} < ADC(\epsilon_{thresh}) \end{cases}$$



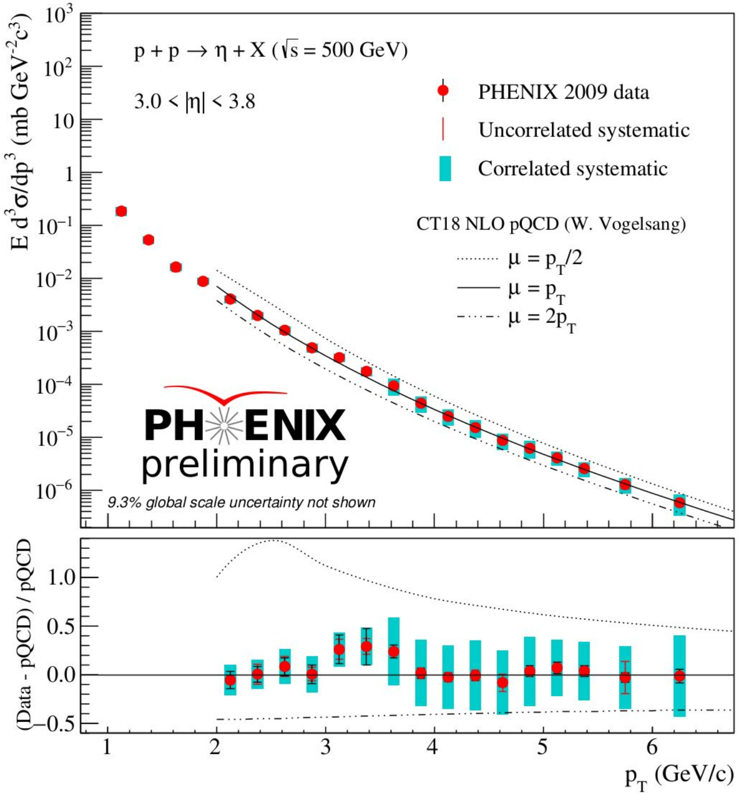
Reconstruction Efficiency

- Pythia + GEANT simulations of single η mesons
- Iteratively weighted to match the flat p_T , pseudorapidity distributions to data



Forward η meson cross section

- First measurement of η meson cross section at forward rapidity at 500 GeV
- Cross checks
  - North and South MPC cross sections agree
  - Minimum bias and MPC4x4 triggered cross sections agree in overlap region ($3.5 < p_T < 4.5$ GeV/c)
- Systematic uncertainties
  - Uncorrelated: yield extraction, mixed event background subtraction
  - Correlated: MPC energy scale, trigger efficiency, reconstruction efficiency, cluster merging
- Consistent with NLO pQCD using CT18 PDFs and AESSS η meson fragmentation functions



Run-12 (2012) Forward η meson A_N

Transverse Single Spin Asymmetries (A_N)

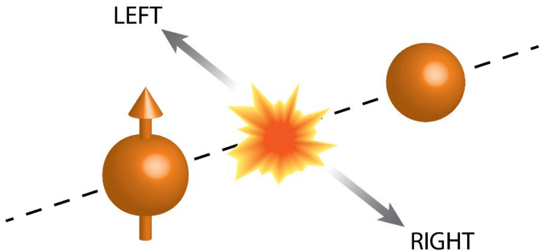
- In transversely polarized p+p collisions, the cross section is modified by an azimuthal modulation

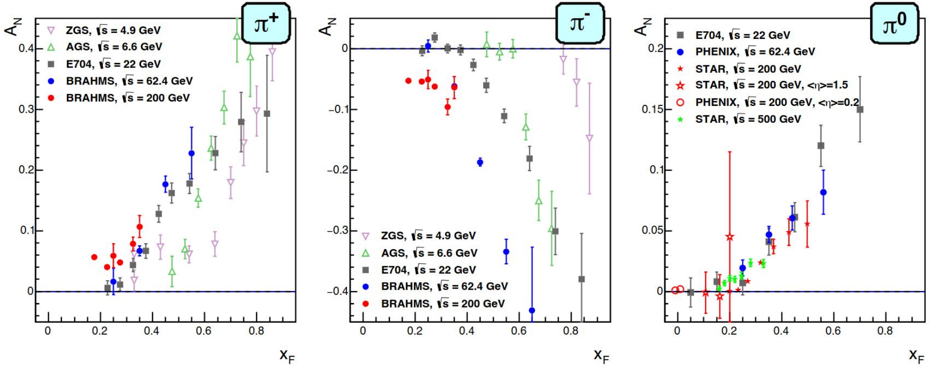
$$d\sigma = (d\sigma)_0 \left[1 + \epsilon(\phi)\right], \quad \epsilon(\phi) = P_Y A_N \cos\phi$$

- Transverse single spin asymmetries quantify this modulation as a left-right asymmetry in particle production

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \sim \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$

- Many measurements have shown strikingly large A_N (up to 40%) that can't be described by leading twist collinear factorization
- To describe large A_N, one must go to sub-leading twist or introduce the transverse momentum dependent (TMD) formalism





$$x_F = 2p_z/\sqrt{s}$$

arXiv:1602.03922 [nucl-ex]

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Beyond leading twist collinear factorization

- Transverse momentum dependent (TMD) distributions
  - Nonperturbative transverse momentum dependence in the leading twist PDFs or FFs
  - TMD PDFs describe the spin-momentum correlations of the initial state proton and a constituent parton
  - TMD FFs describe the spin-momentum correlations of the final state hadron and the fragmenting parton
- Twist-3 collinear factorization
  - Interference between the leading twist process and a process with an additional gluon connecting the hard scattering to a nonperturbative region

$$A_N \propto \sum_{a,b,c} \phi^{(3)}_{a/A}(x_1, x_2, \vec{s_\perp}) \otimes \phi_{b/B}(x') \otimes \hat{\sigma} \otimes D_{c\to C}(z)$$

Sivers like

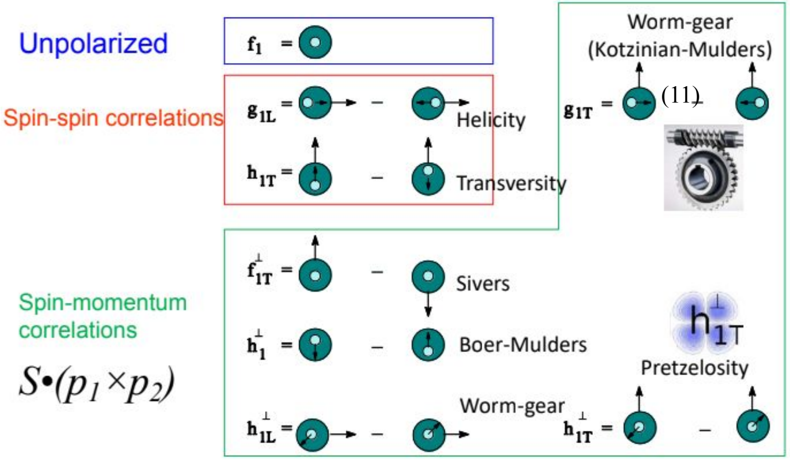
$$+ \sum_{a,b,c} \delta q_{a/A}(x, \vec{s_\perp}) \otimes \phi^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}' \otimes D_{c\to C}(z)$$

Boer-Mulders like

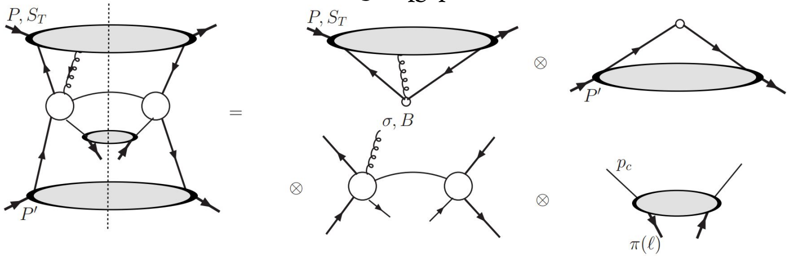
$$+ \sum_{a,b,c} \delta q_{a/A}(x, \vec{s_\perp}) \otimes \phi_{b/B}(x') \otimes \hat{\sigma}'' \otimes D^{(3)}_{c\to C}(z_1, z_2)$$

Collins like

TMD PDFs



Twist-3 ETQS (qgq) function

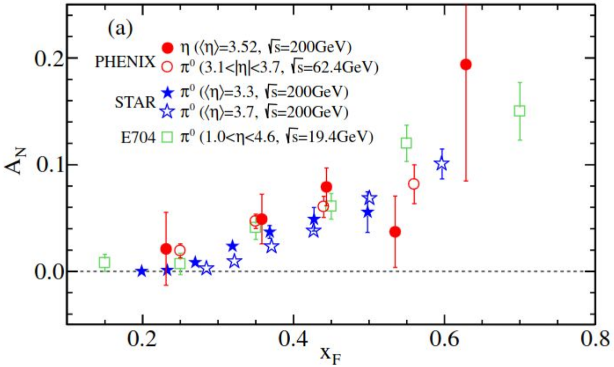


PRD. 74 114013 (2006)

Forward η meson A_N

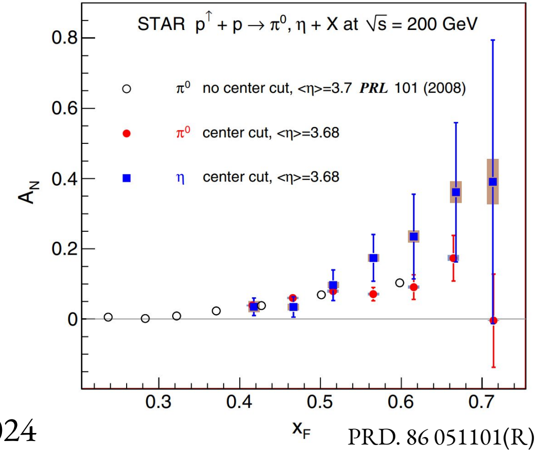
- $p^{\uparrow} + p \rightarrow h + X$ at forward rapidity accesses high x_F region where large nonzero asymmetries have been measured
  - Single scale process dominated by valence quark interactions -> probe of twist-3 ETQS qgq correlator
  - Recent phenomenological work suggests that A_N for inclusive pions is dominated by Collins-like twist-3 fragmentation term [PRD 89, 111501(R) (2014)]
- Comparing to forward π^0 A_N can highlight potential contribution from strange quarks
  - Previous measurements hint that η A_N could be larger than π^0 A_N

PHENIX 2008



PRD. 90 072008 (2014)

STAR 2012



PRD. 86 051101(R) (2012)

Forward η meson A_N

Raw asymmetries

$$A_N \cos\phi = \frac{1}{P_Y}\epsilon(\phi)$$

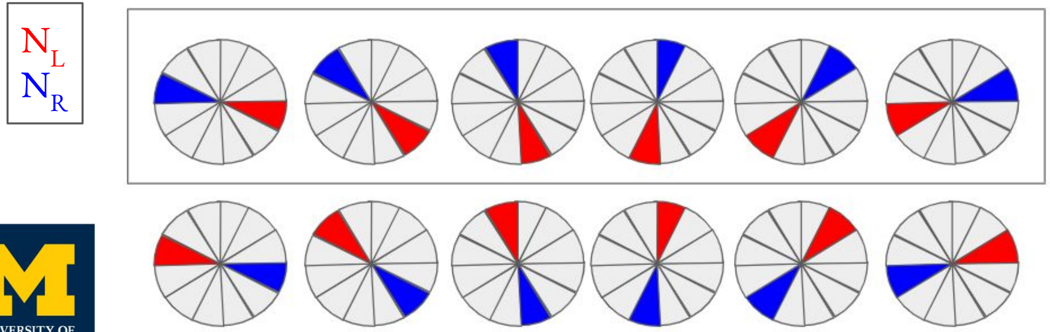
- Square root method (geometric mean between left and right side of detector)

$$\epsilon_{sqrt}(\phi) = \frac{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} - \sqrt{N_L^{\downarrow}N_R^{\uparrow}}}{\sqrt{N_L^{\uparrow}N_R^{\downarrow}} + \sqrt{N_L^{\downarrow}N_R^{\uparrow}}}$$

- Relative luminosity method

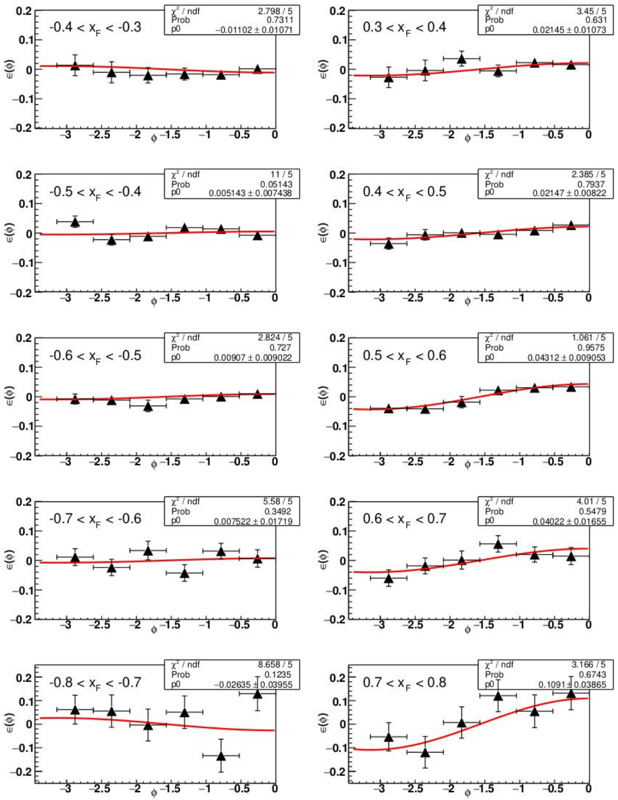
$$\epsilon_{pol}(\phi) = \frac{N_L^{\uparrow} - \mathcal{R}N_L^{\downarrow}}{N_L^{\uparrow} + \mathcal{R}N_L^{\downarrow}}$$

$\phi = -\pi$ $\phi = 0$



$\phi = \pi$

Square root method



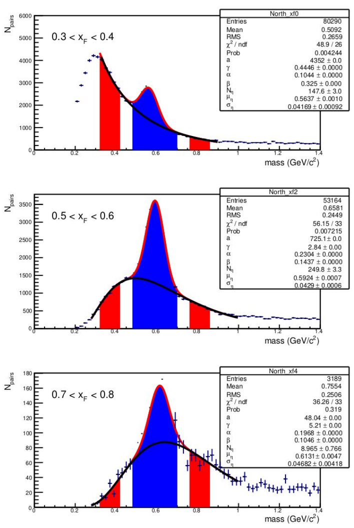
Forward η meson A_N

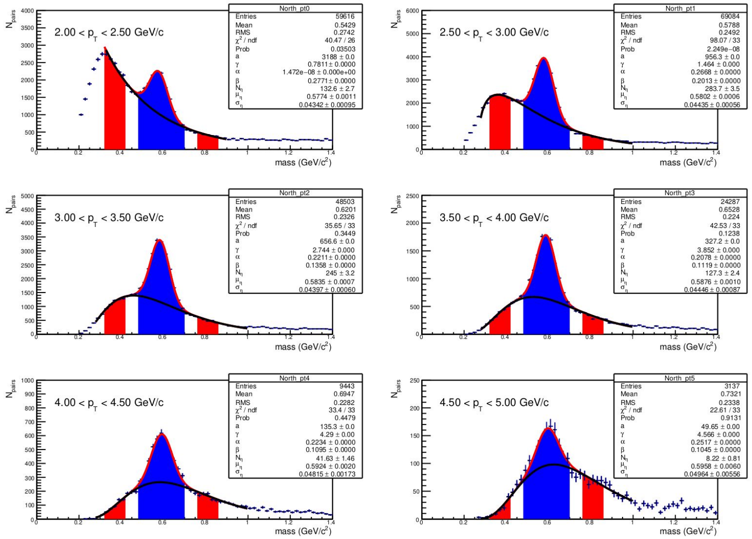
Background correction

- Backgrounds underneath the eta meson peak are corrected by

$$A_N = \frac{A_N^{peak} - r A_N^{bkg}}{1 - r}$$

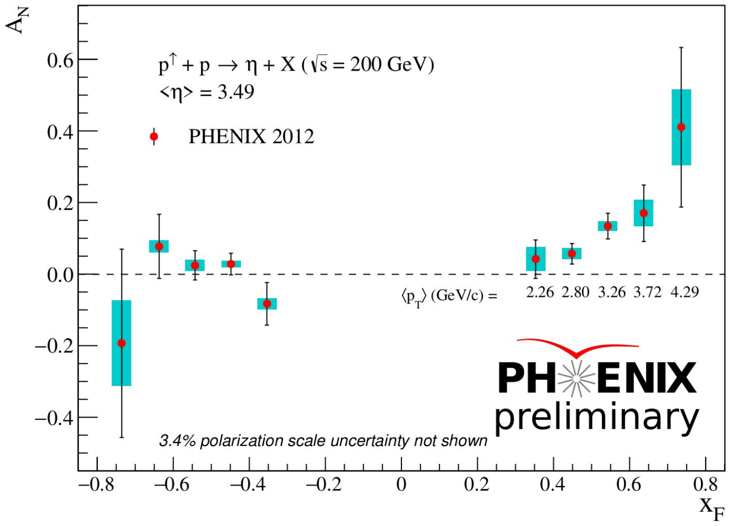
- Background fraction r is determined by fits to the invariant mass distributions and the background asymmetries are the weighted mean of the asymmetries in the low mass and high mass sidebands

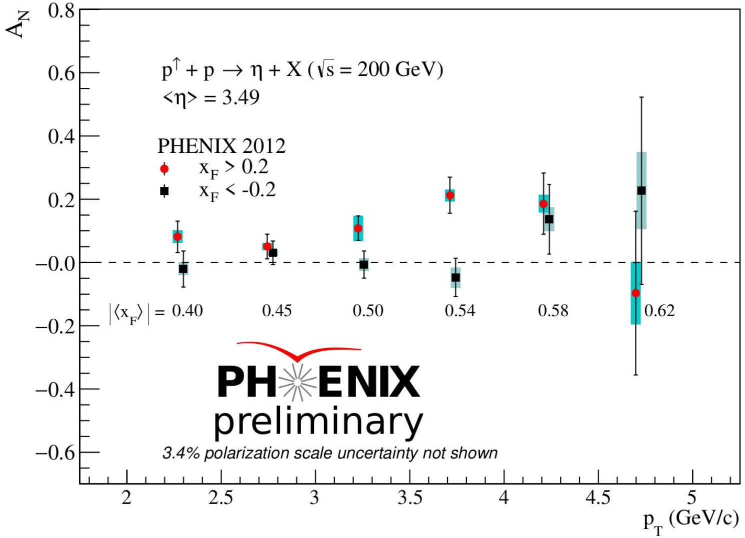




Forward η meson A_N

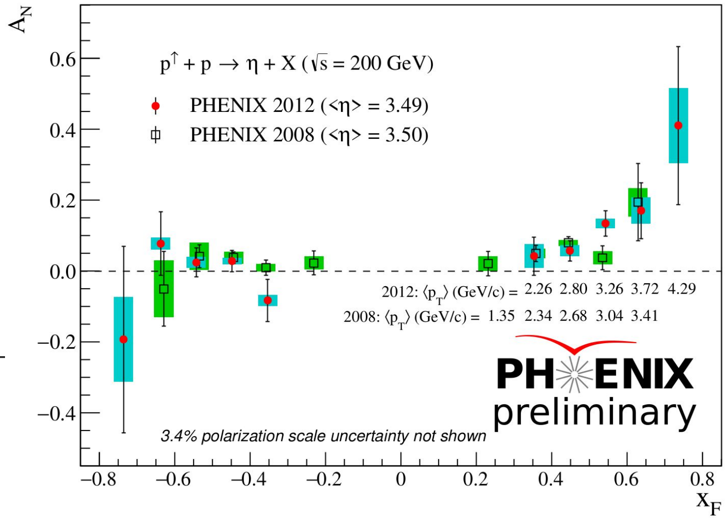
- Large asymmetries up to 40% at high x_F
- Asymmetries consistent with zero at negative x_F
- Increase in A_N from low to intermediate p_T and flattening out at high p_T

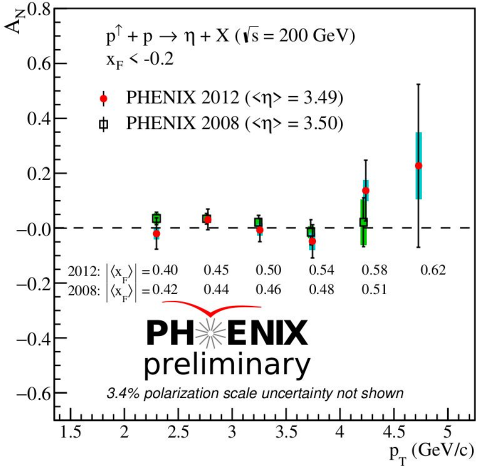


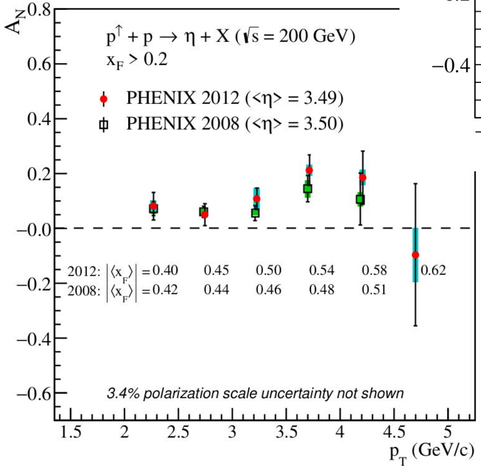


Forward η meson A_N

- Agreement between 2008 and 2012 PHENIX data within statistical and systematic uncertainties
- This additional statistically independent measurement should improve the existing statistical uncertainties of the overall PHENIX η A_N by ~√2

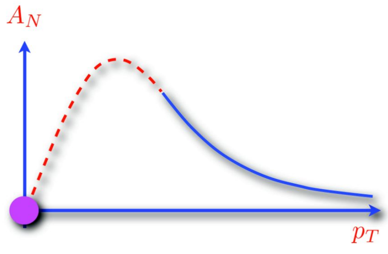






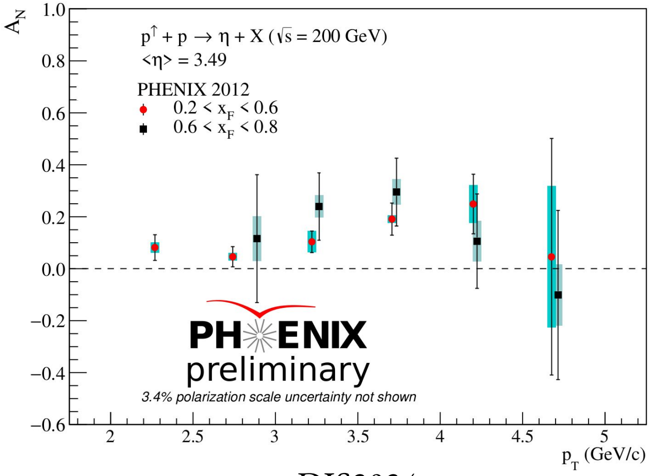
Forward η meson A_N

- Twist-3 calculations predict decrease in A_N of inclusive light hadrons at high x_F + high p_T
  - PRD 83, 114024 (2011)
  - PRD 89, 111501(R) (2014)



TMD region
Twist-3 region

- A potential hint of this decrease can be seen when separating the η A_N vs. p_T into intermediate x_F ($0.2 < x_F < 0.6$) and high x_F ($0.6 < x_F < 0.8$) regions



DIS2024

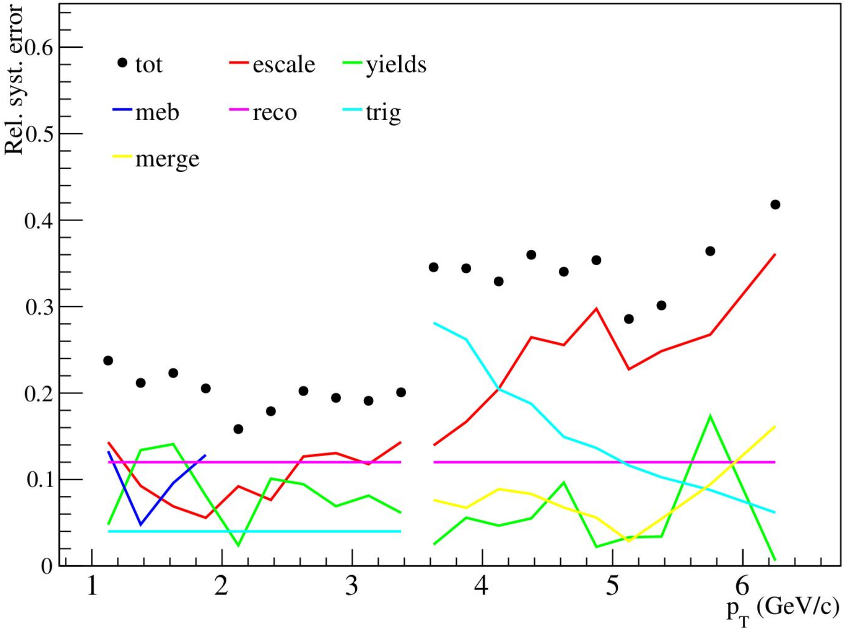
Summary

- The forward η meson cross section and transverse single spin asymmetry measurements probe the unpolarized and polarized structure of the proton
- The recent measurement of the PHENIX Run 9 forward η meson cross section can be used in a future improved global fit to the η meson fragmentation functions
- The PHENIX Run 12 forward η meson A_N should reduce the existing PHENIX η meson A_N statistical uncertainty by a factor of $\sim\sqrt{2}$
  - Explore the differences between the η and π^0 A_N
  - Access to twist-3 correlators

Backup

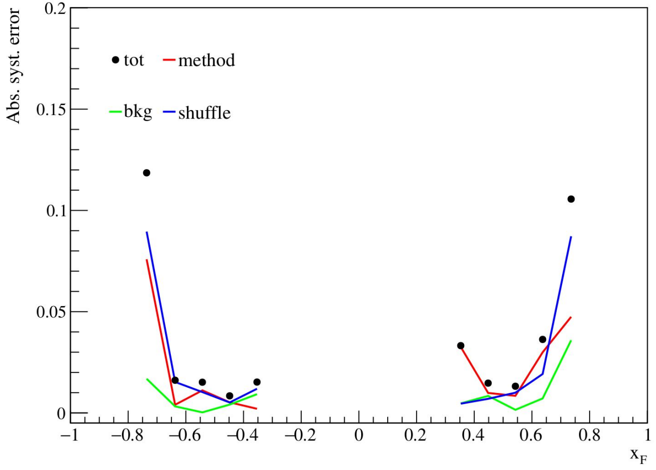
Systematics for forward η meson cross section

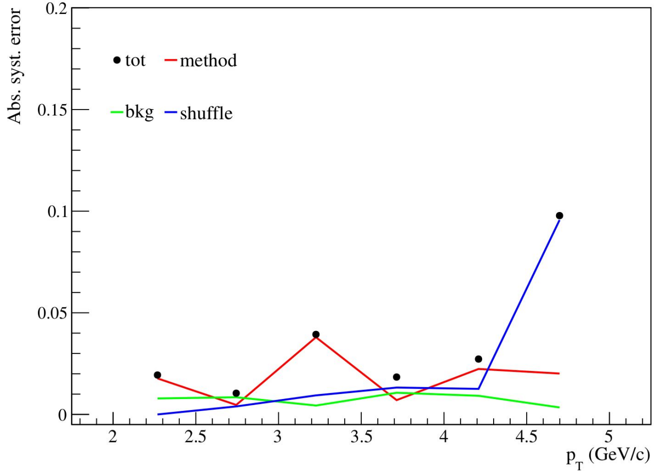
- MPC energy scale
- Yield fits to invariant mass distributions
- Mixed event background subtraction
- Reconstruction efficiency GEANT
- Trigger efficiencies
- Cluster merging at high p_T



Systematics for forward η meson A_N

- Square root vs. relative luminosity method
- Background fraction fits to invariant mass distributions
- Bunch shuffling



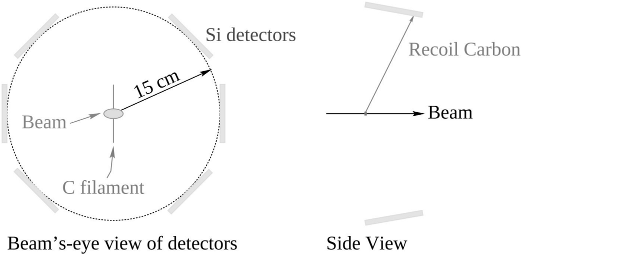


Polarimetry at RHIC

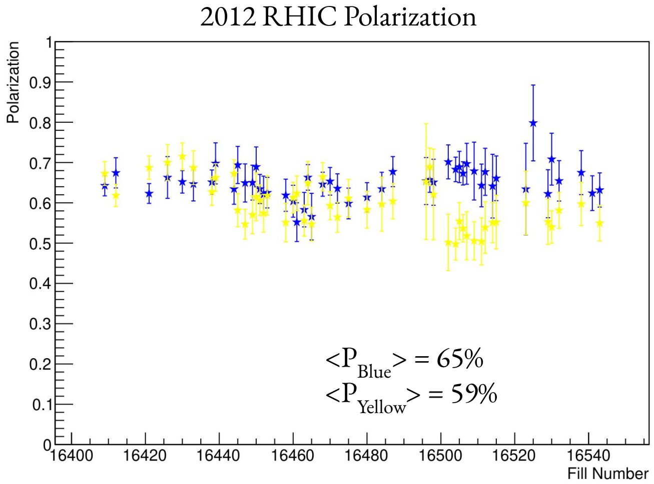
- pC polarimeters
  - Proton-carbon elastic scattering in the Coulomb-nuclear interference region
  - Sizable A_N in process with large cross section and weak √s dependence
  - Beam polarization measurements several times per fill

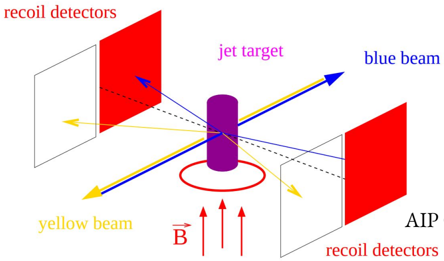
$$P_B = \frac{1}{A_N}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Absolute H-jet polarimeter
  - Polarized hydrogen gas jet target
  - Requires data taking across multiple fills due to limited statistics from small cross section
  - Accuracy to a few percent for CNI elastic A_N
    - Used for calibration of the fast pC CNI polarimeters



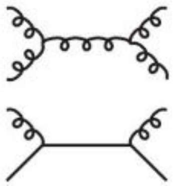
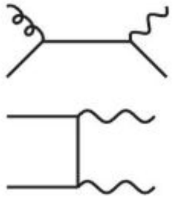
NIMA 499 (2003) 392-414





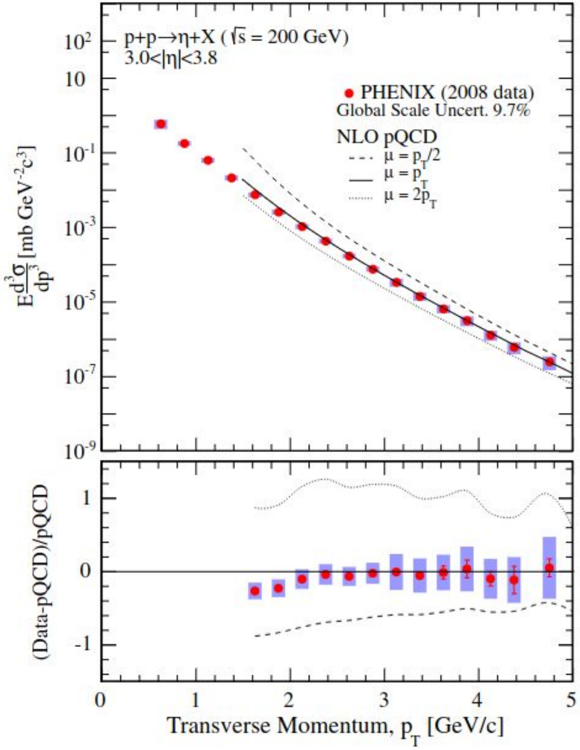
AIP Conf. Proc. 675, 830-835 (2003)

Dominant partonic processes at PHENIX

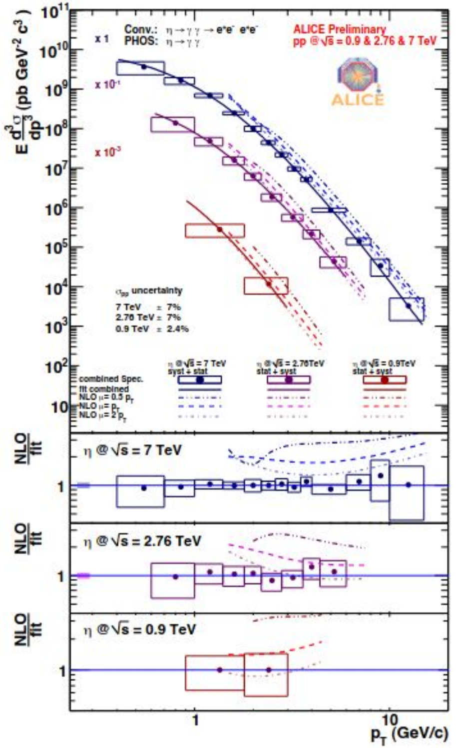
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	

η meson cross sections

- 200 GeV forward η cross section from PHENIX consistent with NLO pQCD
- NLO pQCD agrees with 900 GeV ALICE midrapidity η cross section but overestimates cross section at 7 TeV and 8 TeV



PRD 90, 072008 (2014)



J. Phys. G: Nucl. Part. Phys. 38 124076 (2011)