Recent Spin Measurements at PHENIX

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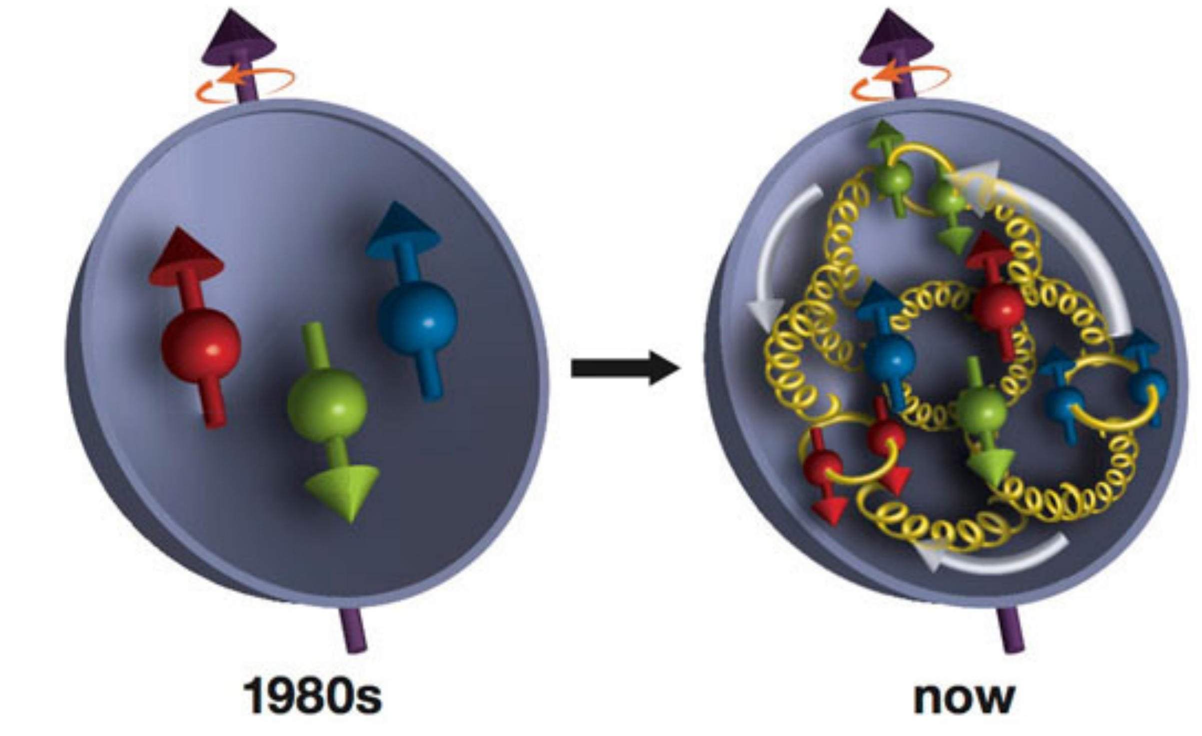
Understanding Proton Spin

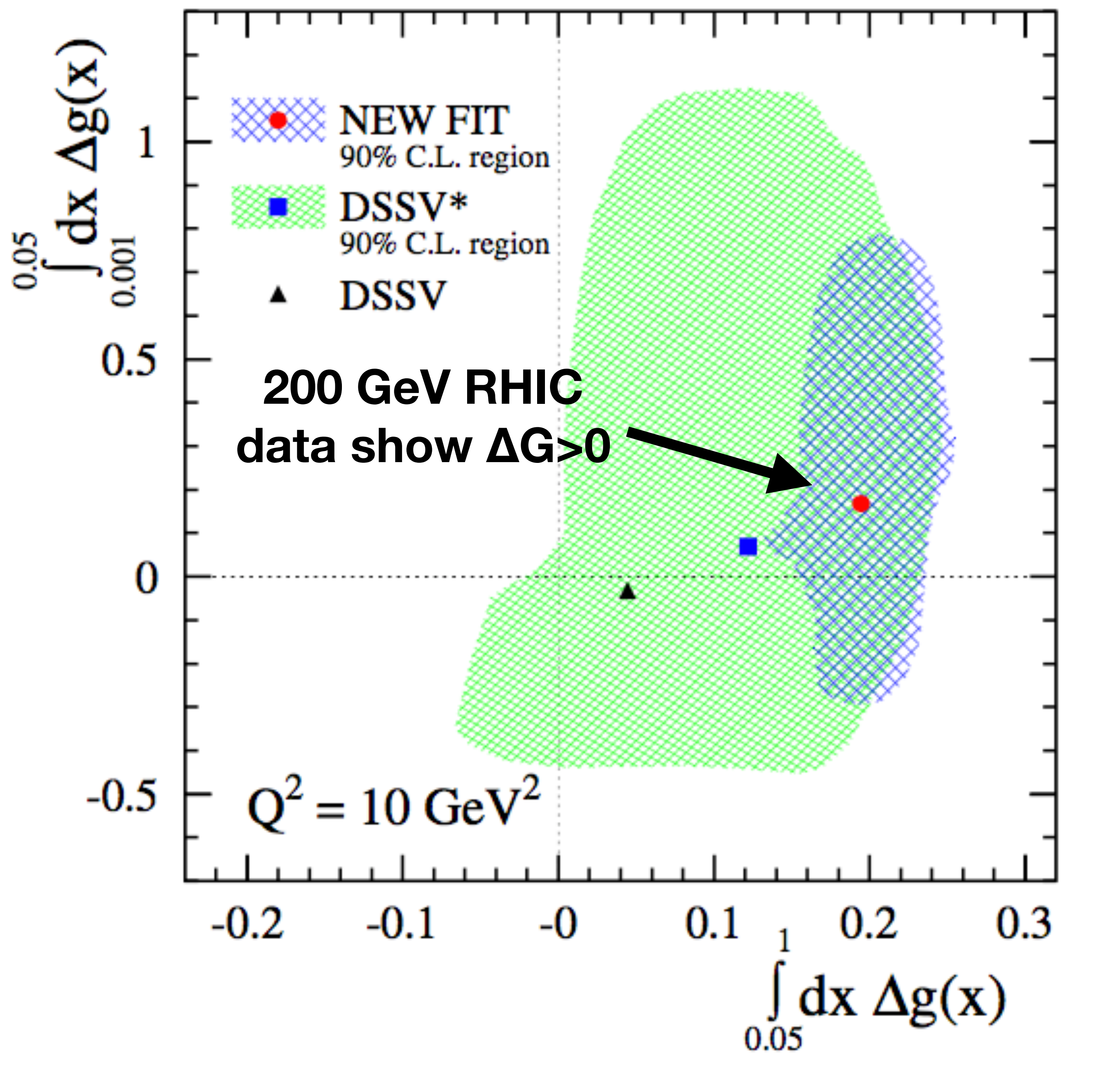
- Valence quarks do not carry all the spin. More complex dynamics are at hand:

$$\frac{1}{2} = \frac{1}{2}\sum_q \Delta Q + \Delta G + L_q + L_g$$

quarks | gluons | orbital motion

- **Longitudinal** -- how do partons polarize wrt the proton?
- **Transverse** -- how are proton spin and parton transverse momentum and spin correlated?





arxiv:1404.4293 : PRL 113, 012001 (2014)

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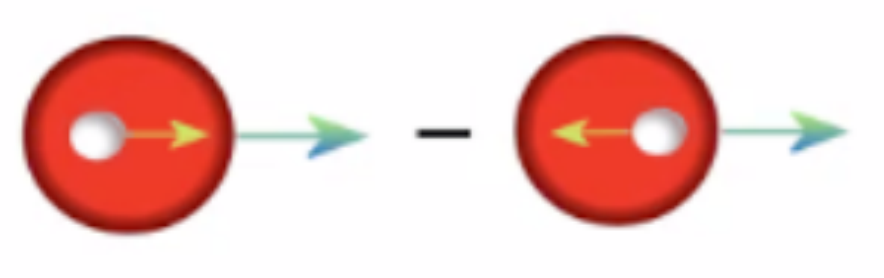
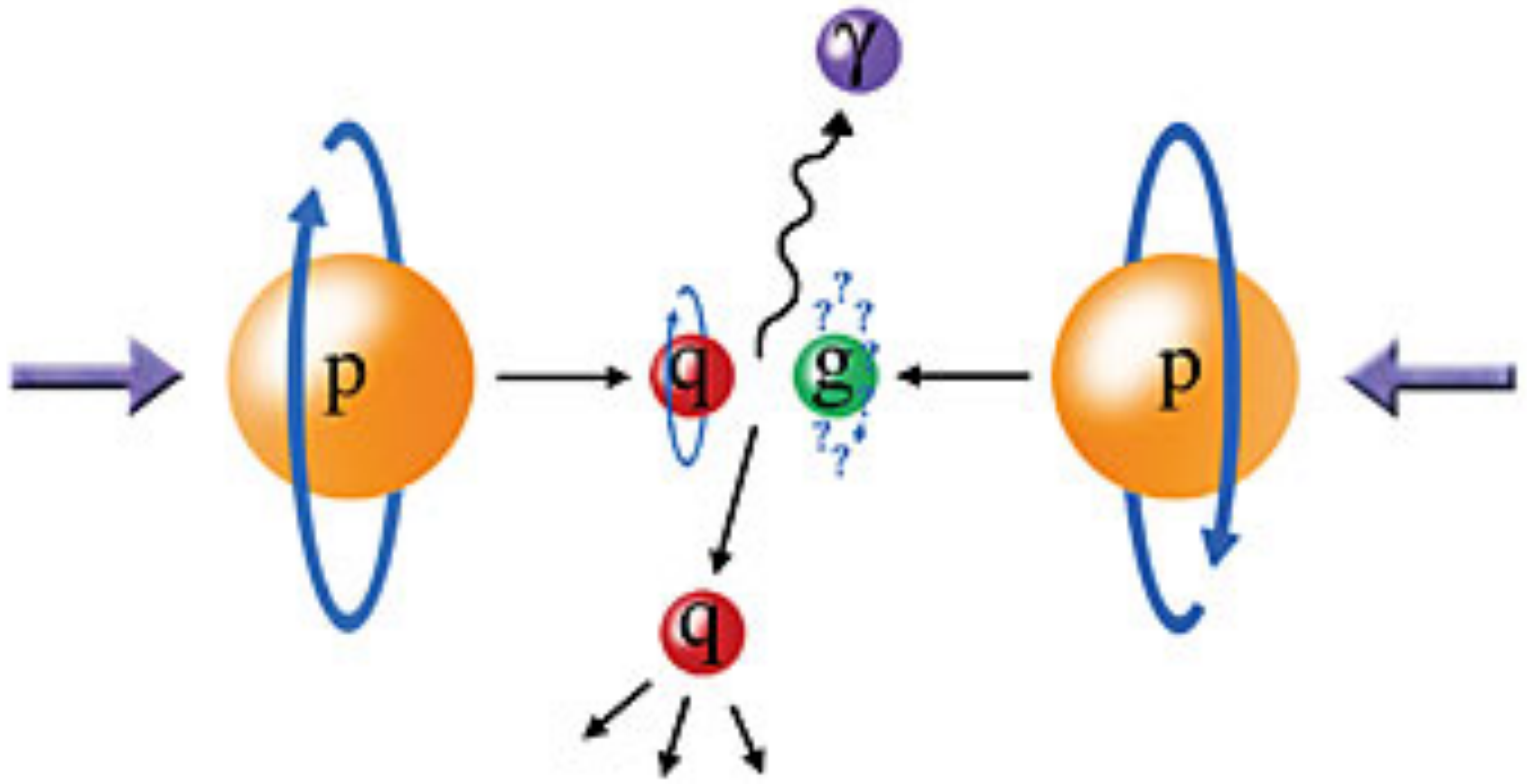
Longitudinal Asymmetries

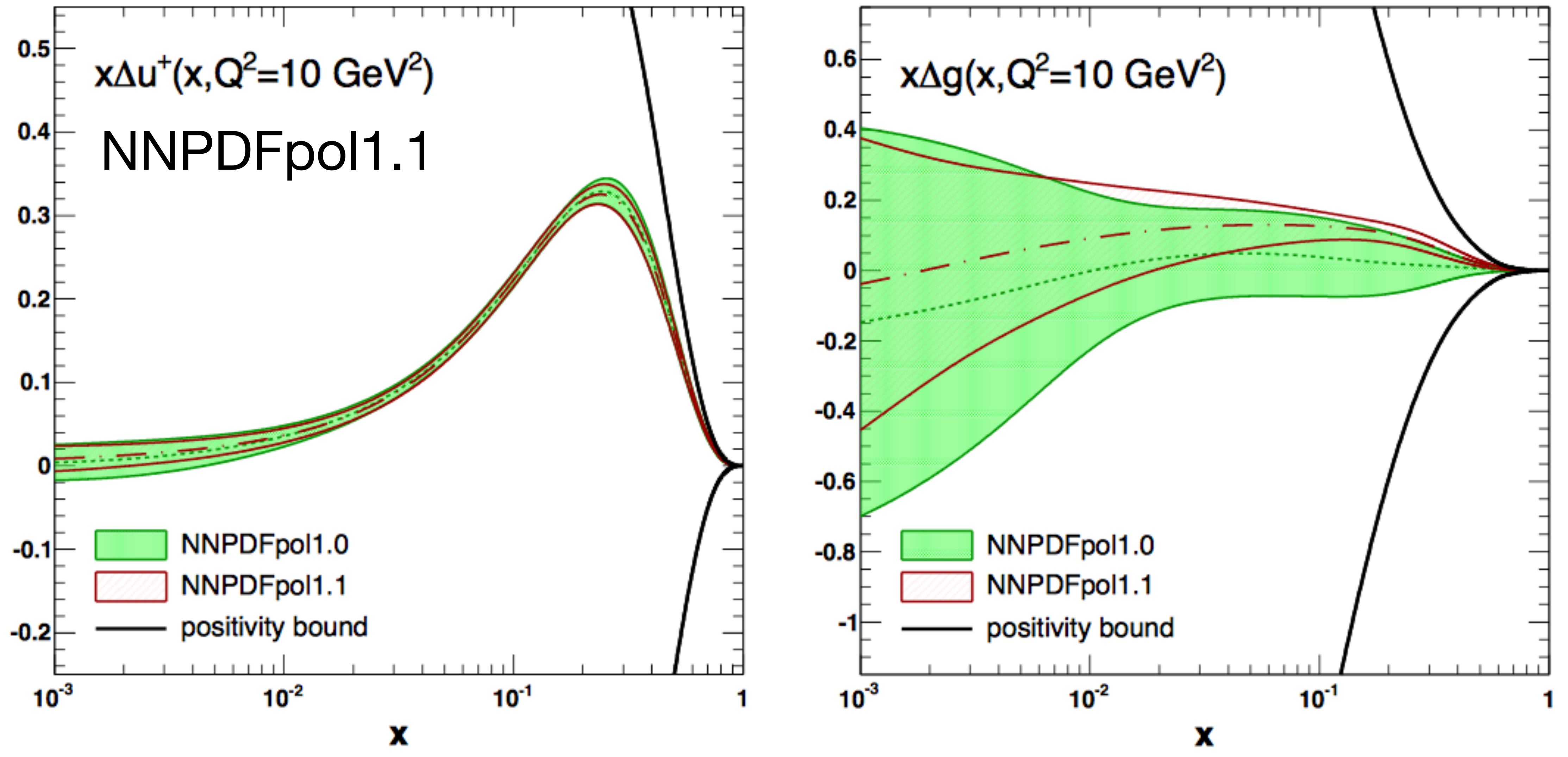
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\Delta\sigma}{\sigma}$$

$$\Delta\sigma = \sum_{a,b} \Delta f_{a/A} \otimes \Delta f_{b/B} \otimes \Delta\sigma_{ab}$$

$\Delta q(x) =$ 



- Partonic asymmetries can be large
- Multiple initial states contribute to each final state observable
- Combine different final states to extract underlying pPDFs via global fit



arxiv:1406.5539 : Nucl.Phys.B 887, 276 (2014)

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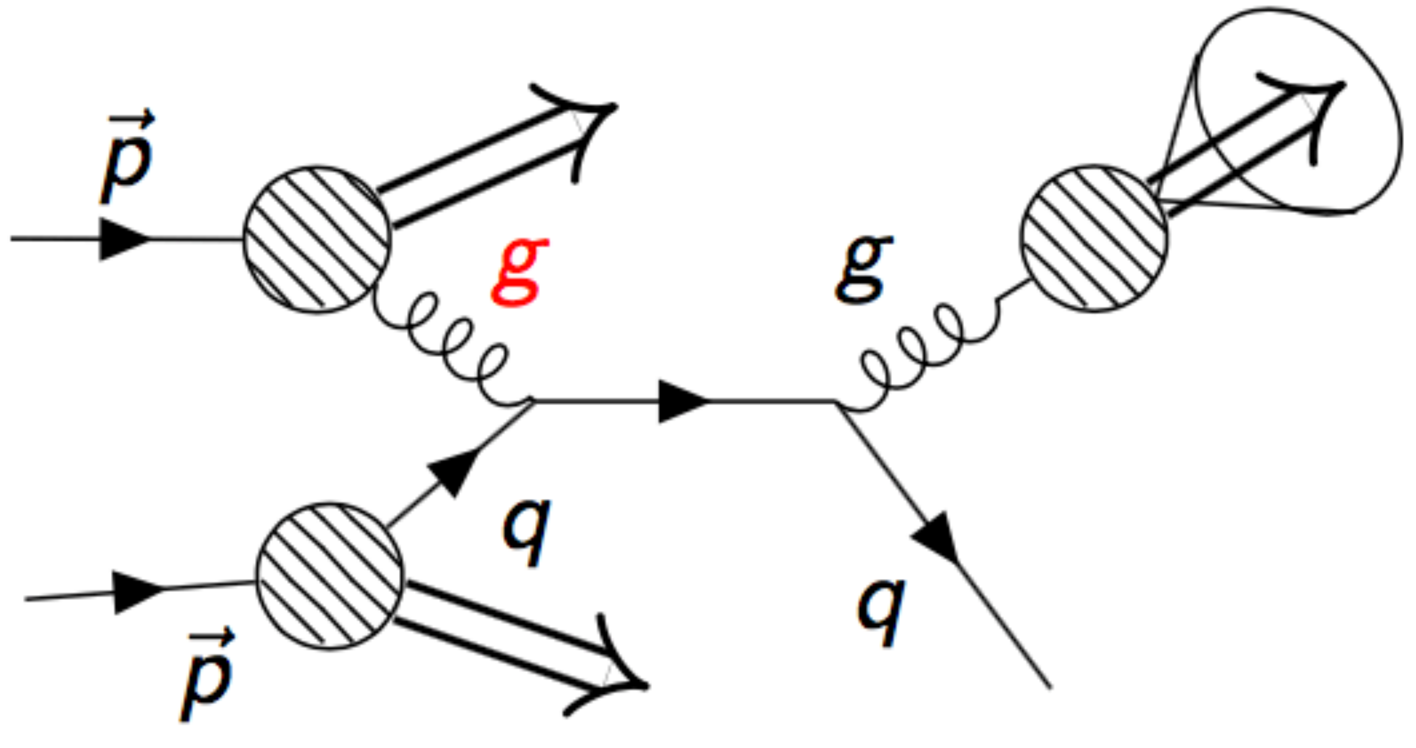
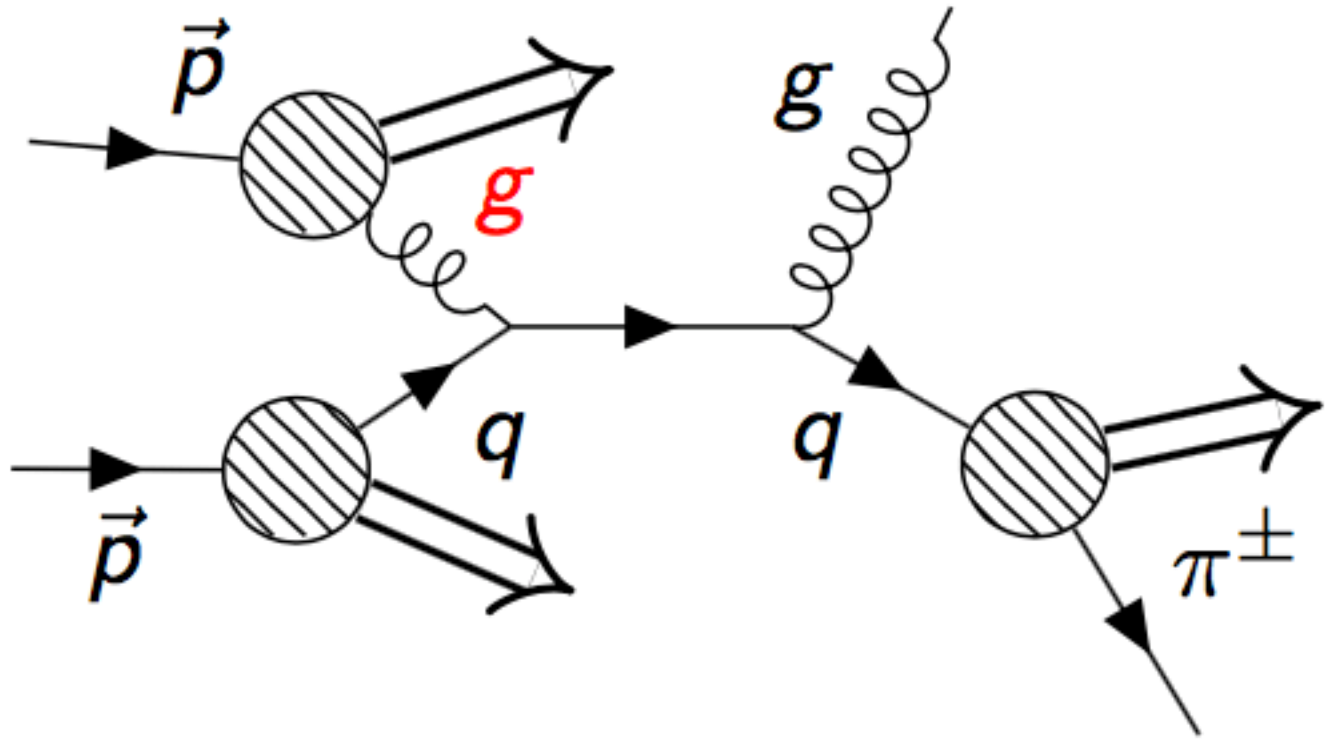
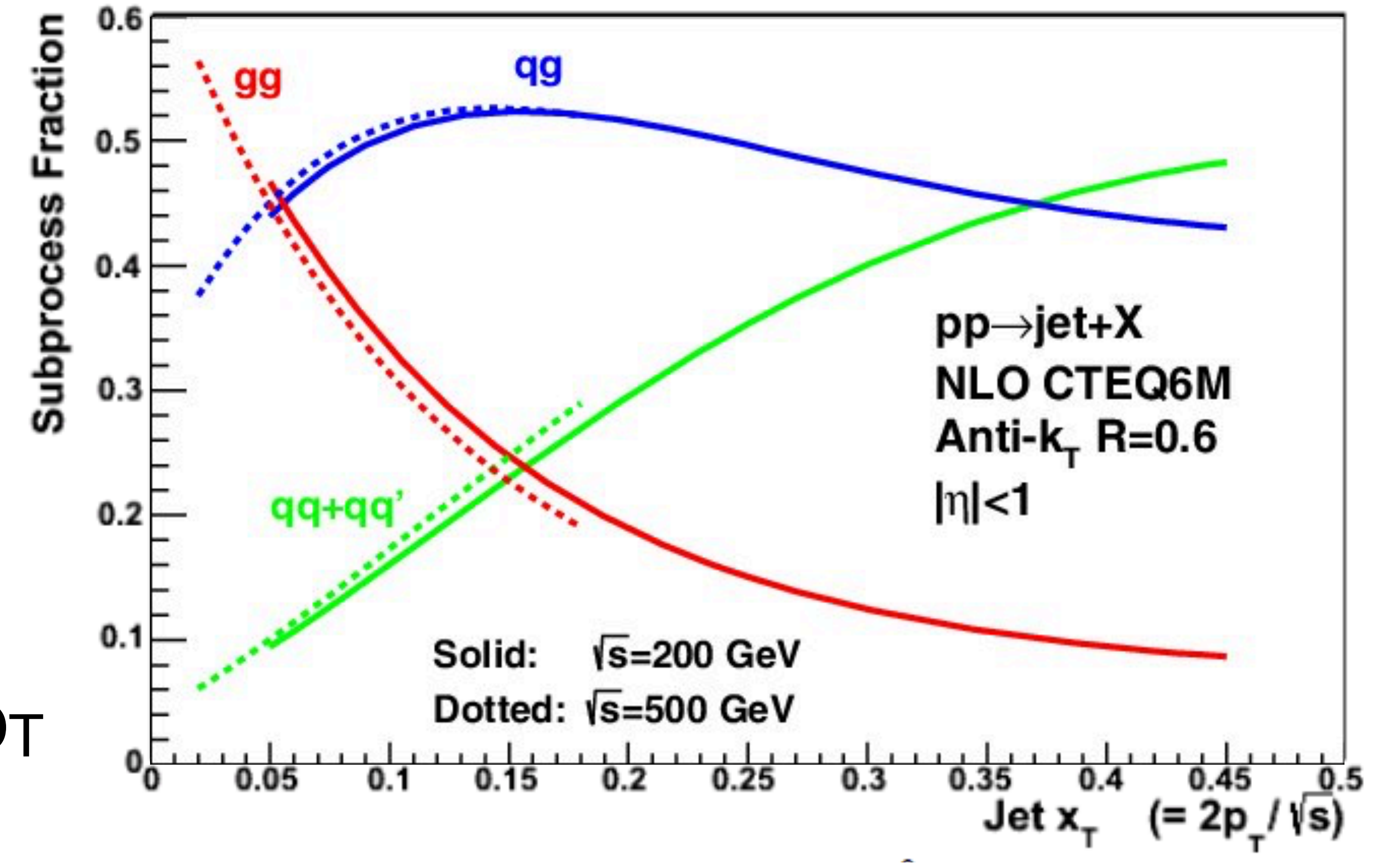
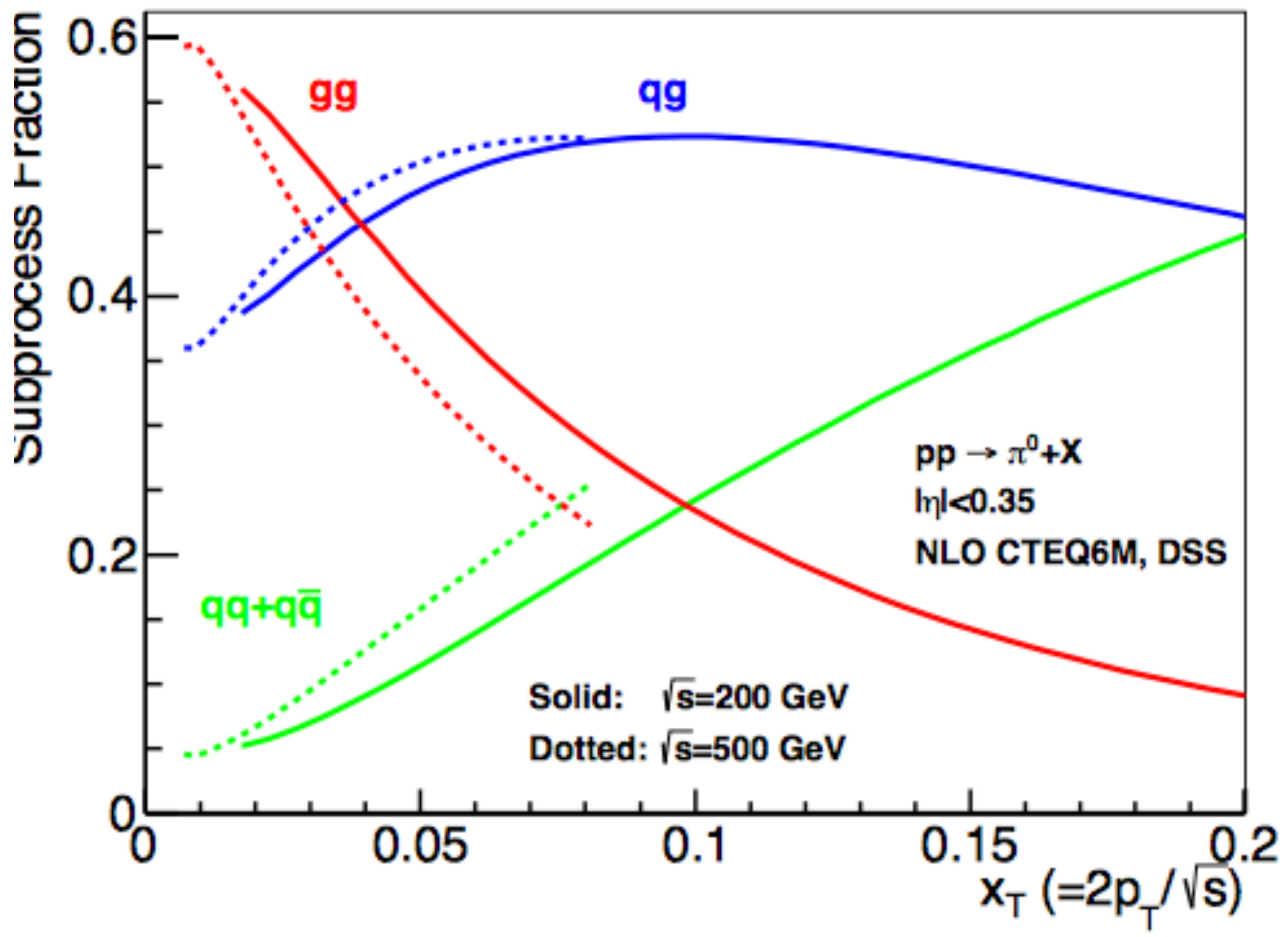
Accessing Δg

- No free gluons in the final state -- extract pPDFs via global fits of multiple observables
- Models predict how much each subprocess contributes to a final state:
- **Jets**: Copious, gg and qg dominate at RHIC
- **Pions**: Same processes, some discrimination of initial state for $\pi^{\pm}$
- **Photons**: no final state effects, qg compton scattering dominates at RHIC
- Some lever arm by changing collision energy: access lower Bjorken x at same p_T



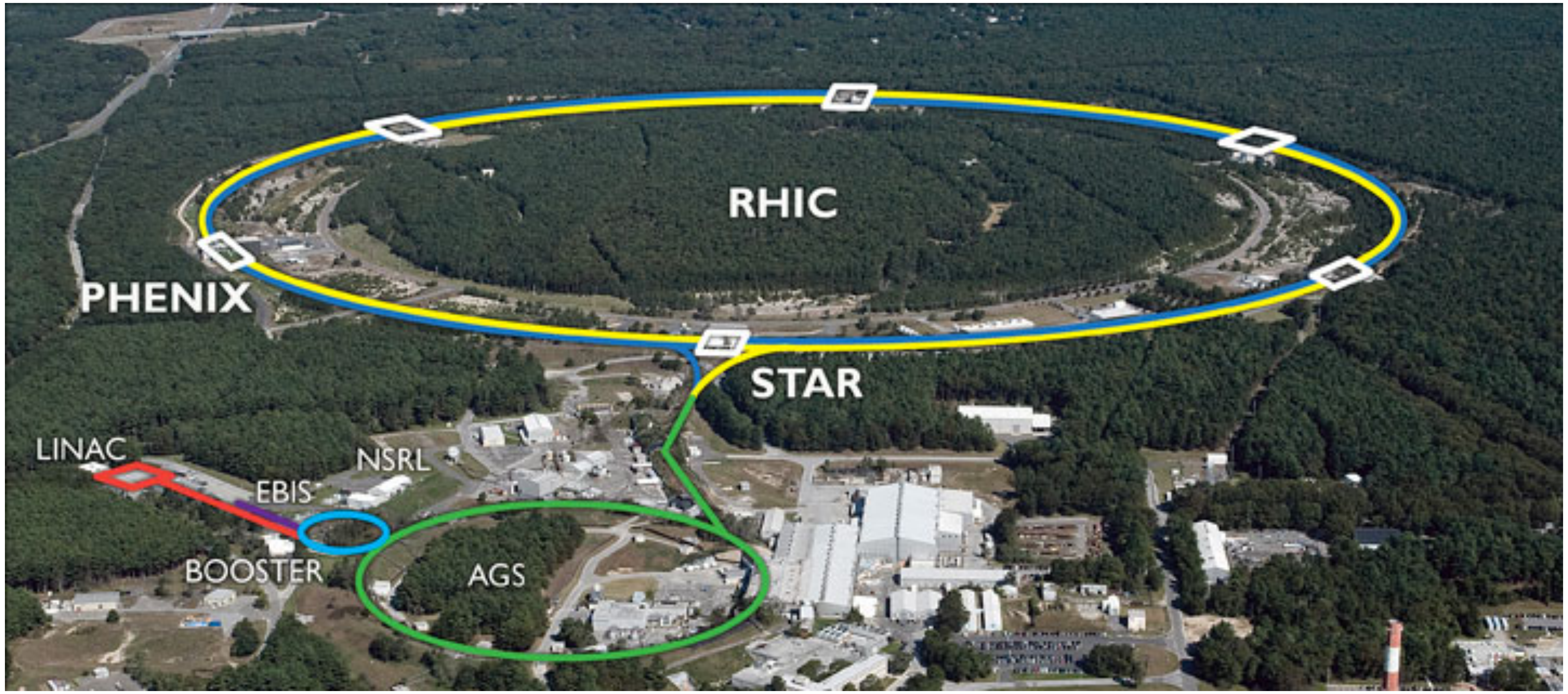




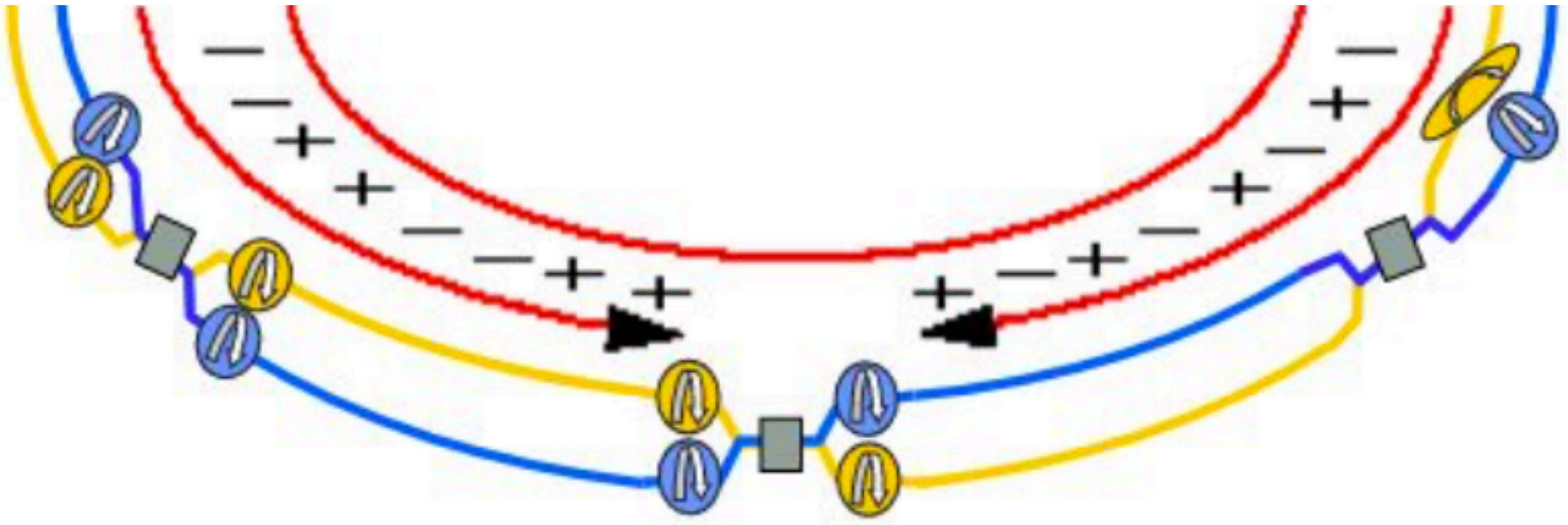


Probing Spin at RHIC

- World's only polarized p+p collider*
  *** also p↑He, p↑Al, p↑Au,...**
- Operational 2000 - (y_{EIC})
- STAR and PHENIX general-purpose detectors

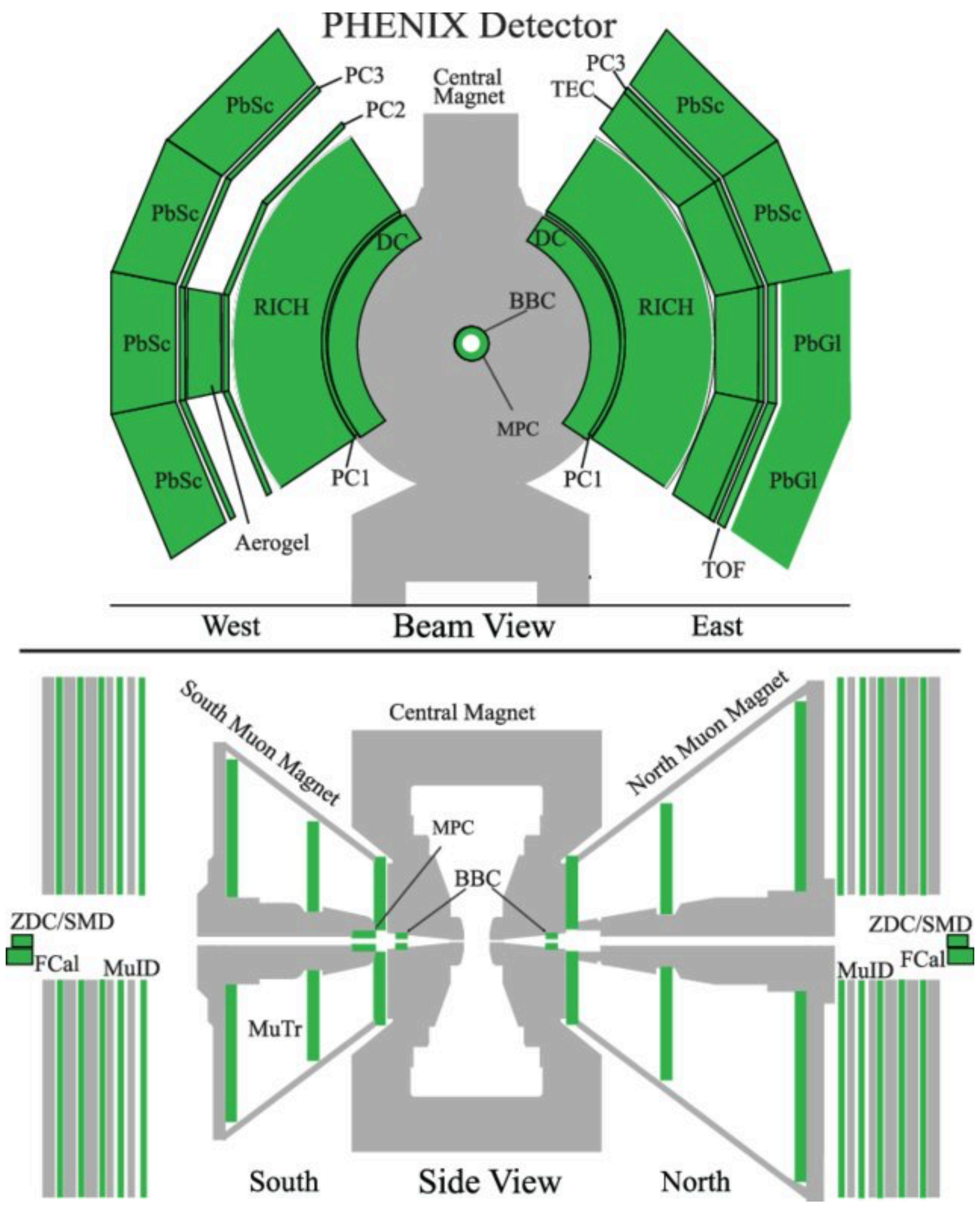


- Siberian snakes, spin rotators to control polarized beams.
- Alternating spin pattern bunch-by-bunch



PHENIX Detector

- Took data until 2016 (==>sPHENIX)
- Wide variety of probes:
  - Central: π^0, $\pi^{\pm}$, η, γ, jets, ...
  - Forward: π^0, η, ***n***, ...
- At mid rapidities ($|\eta|<0.35$):
  - Charged particle tracks from Pad+ Drift chambers
  - pID from RICH ($\pi^{\pm}$ >4.9GeV, $e^{\pm}$ > 20 GeV)
  - Energy and trigger with EMCal



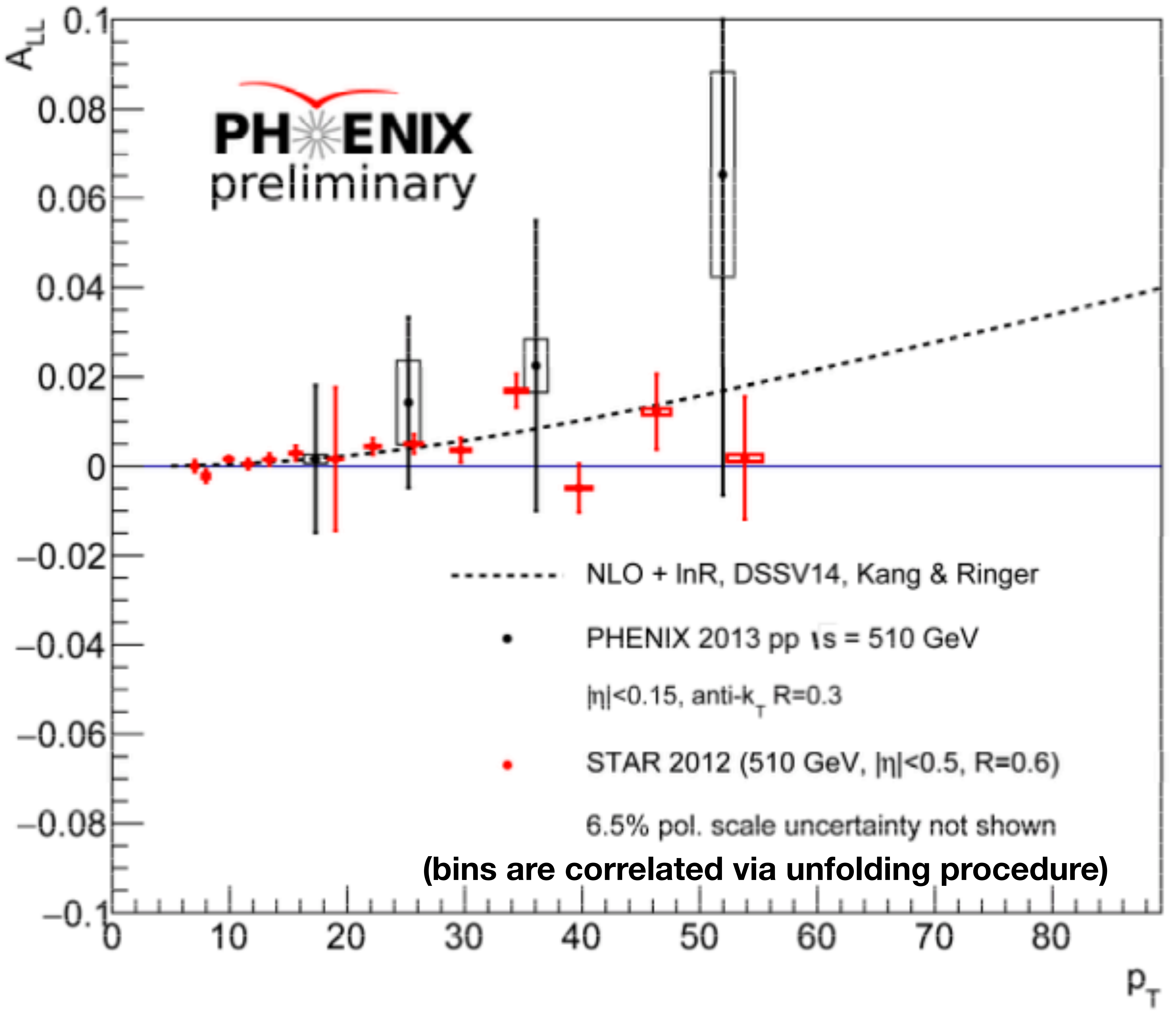
Jet A_{LL} @ 510

PHENIX

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$$= \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

- Main systematics from fidelity of detector simulation in unfolding studies
- Jet Radius of 0.3. Wider not practical for PHENIX acceptance
- Asymmetry consistent with STAR result and theoretical prediction



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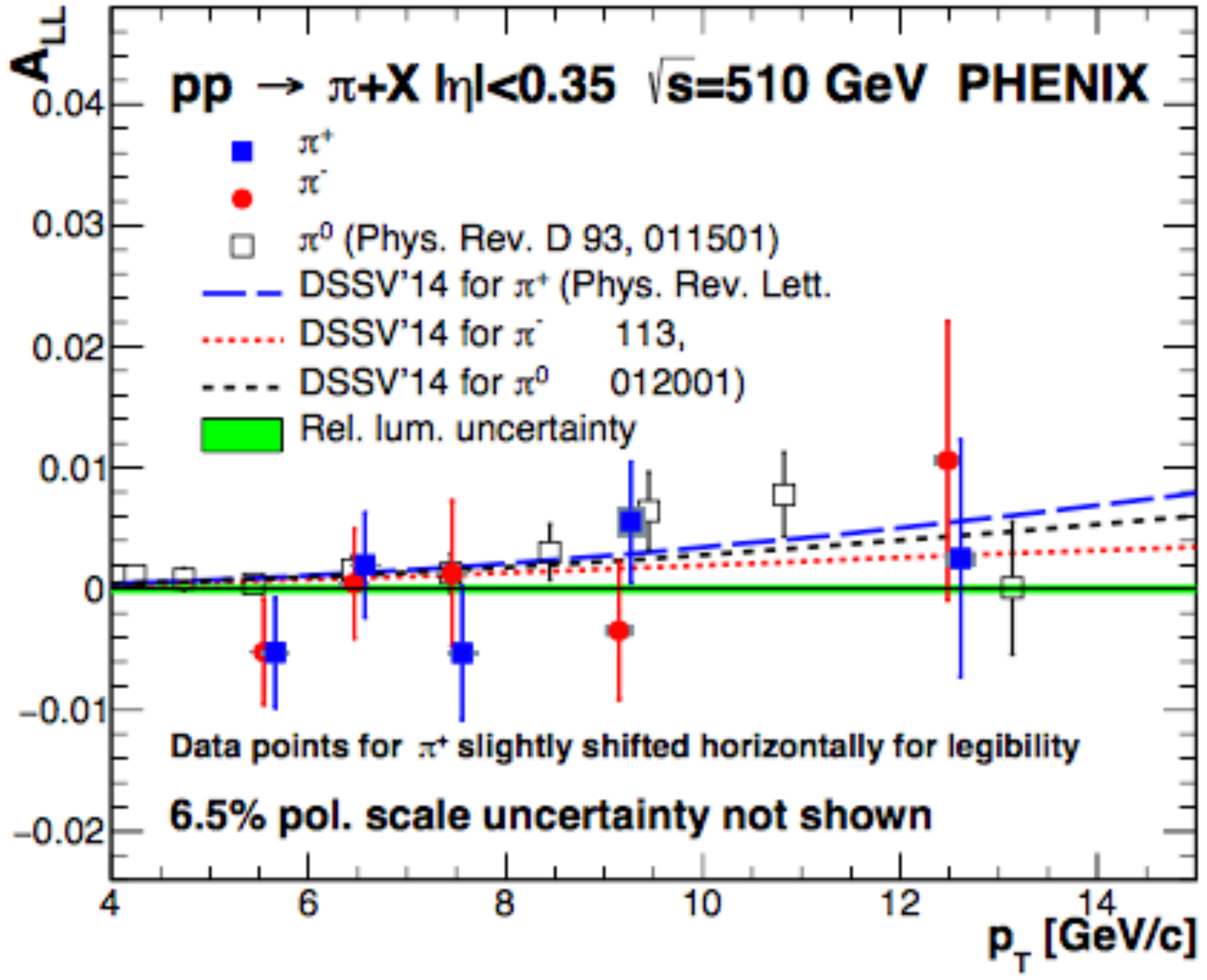
Charged Pion A_{LL} @ 510

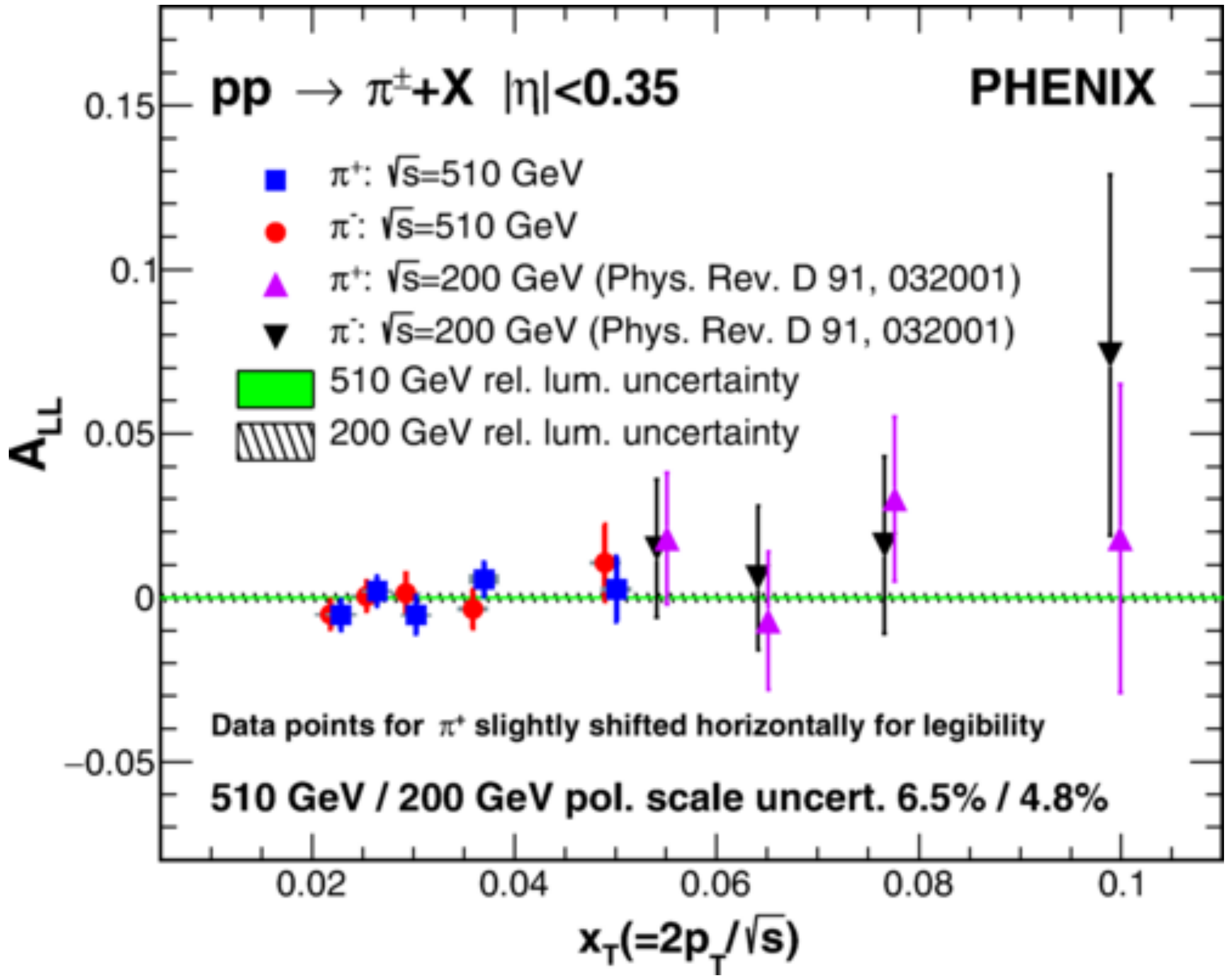
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$$= \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

$$A_{LL}^{tot} = (1 - \Sigma r_i) A_{LL}^{\pi} + \Sigma (r_i A_{LL}^{i})$$

$\pi^{\pm}$ A_{LL} @ 510





- Background asymmetry consistent with zero, fraction also small
- Consistent with DSSV fits of 200 GeV data: positive gluon polarization
- Complementary x_T range, corresponds to $0.04 \lesssim x_B \lesssim 0.09$

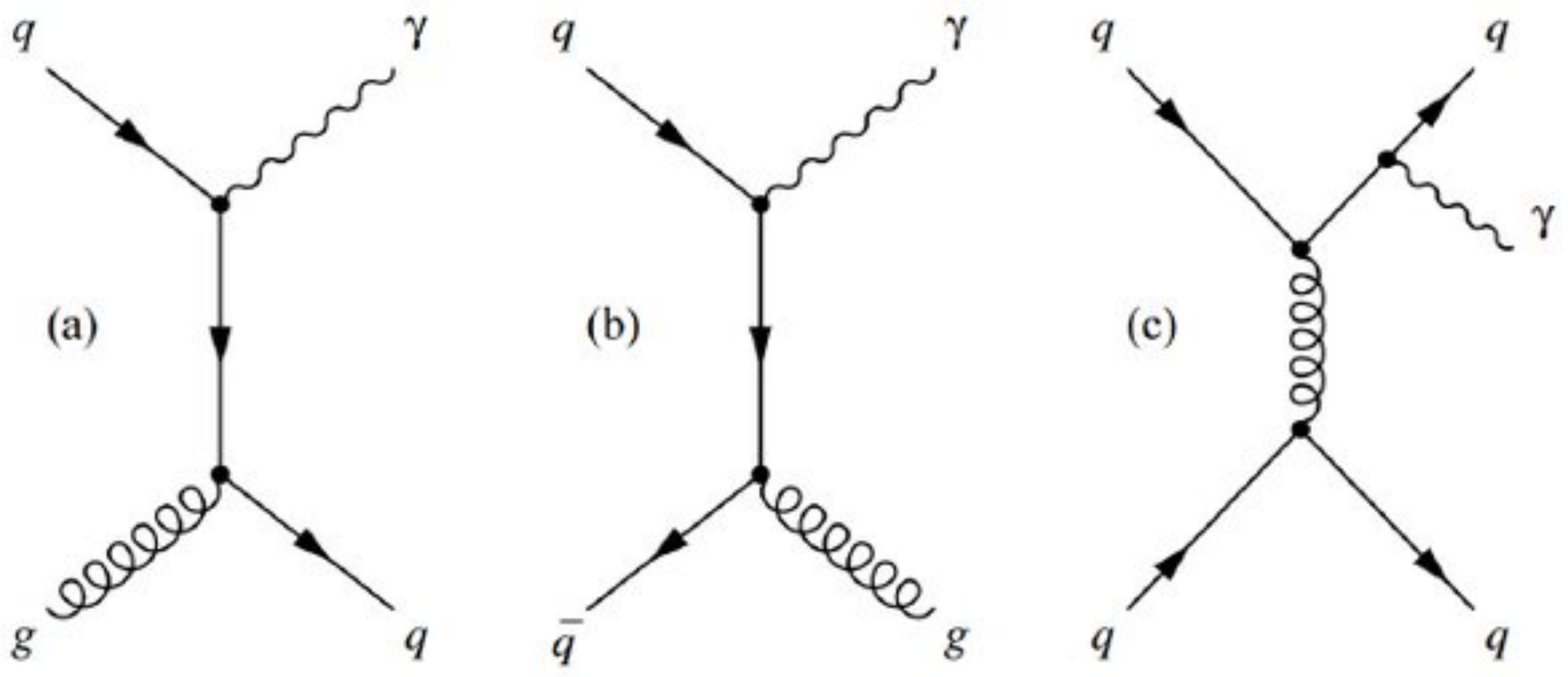
arXiv:2004.02681
Phys.Rev.D102, 032001 (2020)

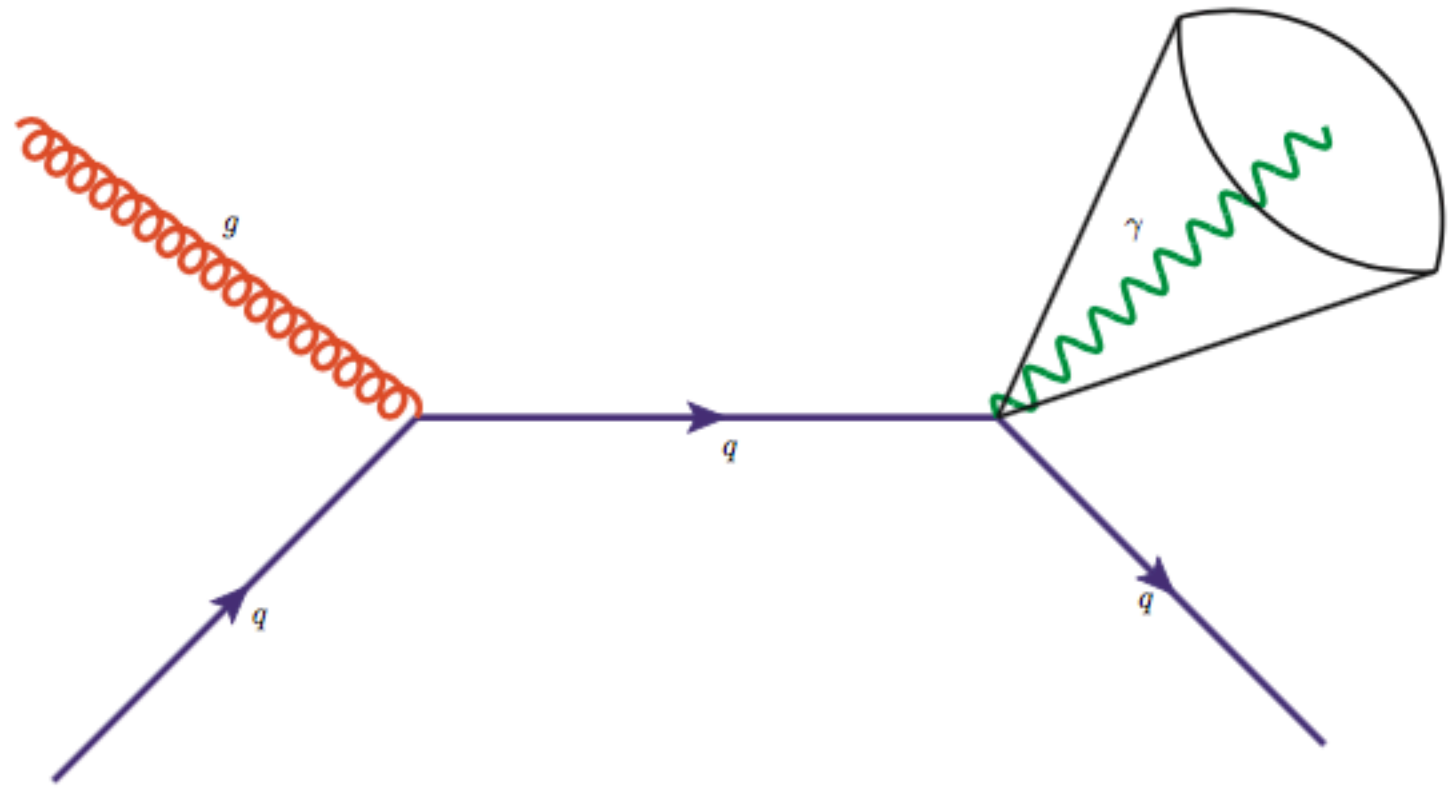
Direct Photons

- *No final state effects*
- Directly sensitive to gluon pPDFs via:

$$q + g \rightarrow q + \gamma$$

- But challenging to remove background from hadronic decays
- Can impose isolation criterion:





$r = \sqrt{(\delta\eta)^2 + (\delta\phi)^2} = 0.5$

Isolation cut requirement:
$\sum E_{neutral} + \sum E_{charged} < 0.1 E_{\gamma}$

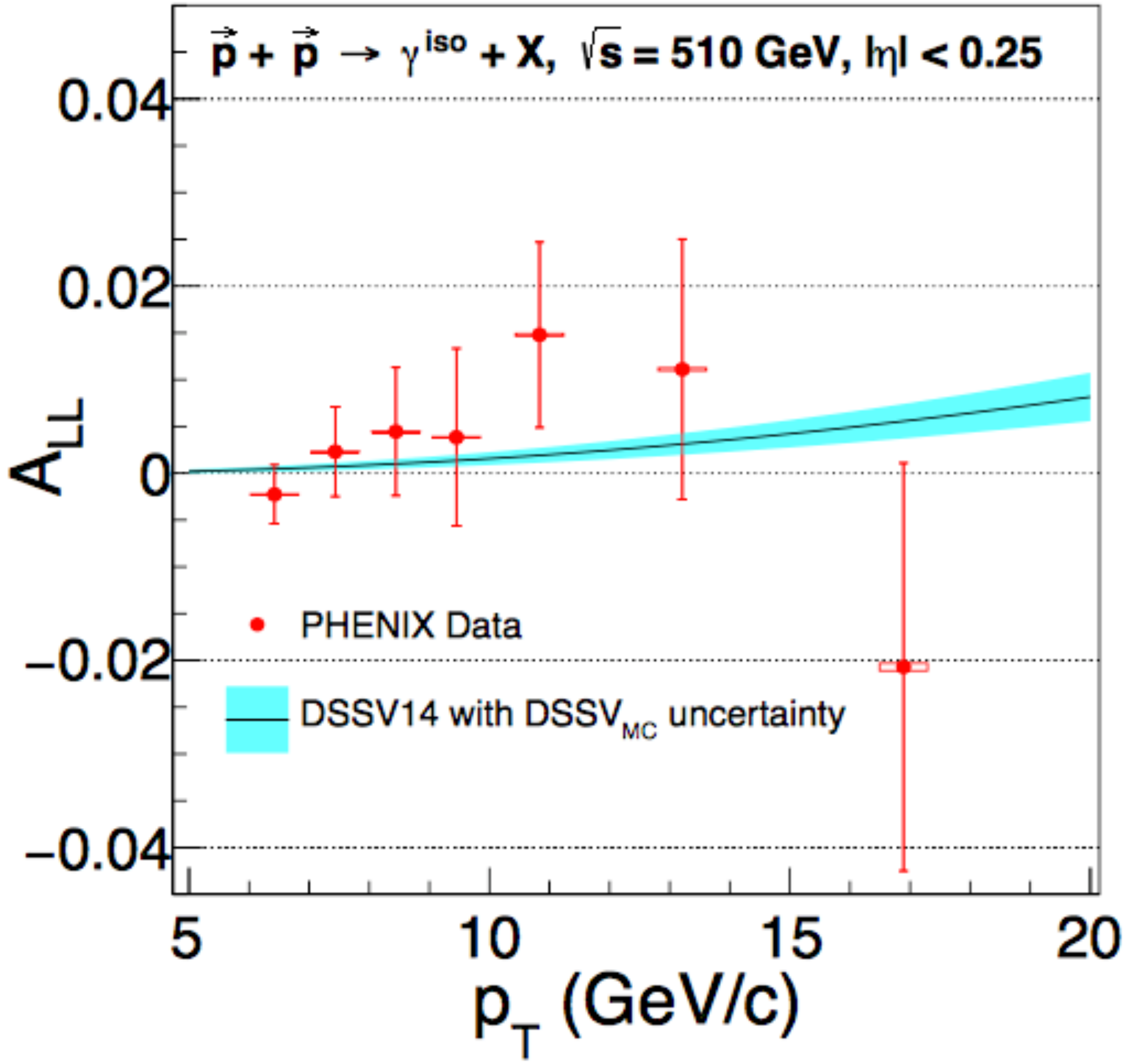
Direct Photon A_{LL} @ 510

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$$= \frac{1}{P_B P_Y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

- First direct photon analysis for gluon polarization
- Large sample ($155 pb^{-1}$) will help constrain Δg through global fit

Isolated Direct Photons A_{LL} @ 510



arXiv:2202.08158
(submitted to PRL)

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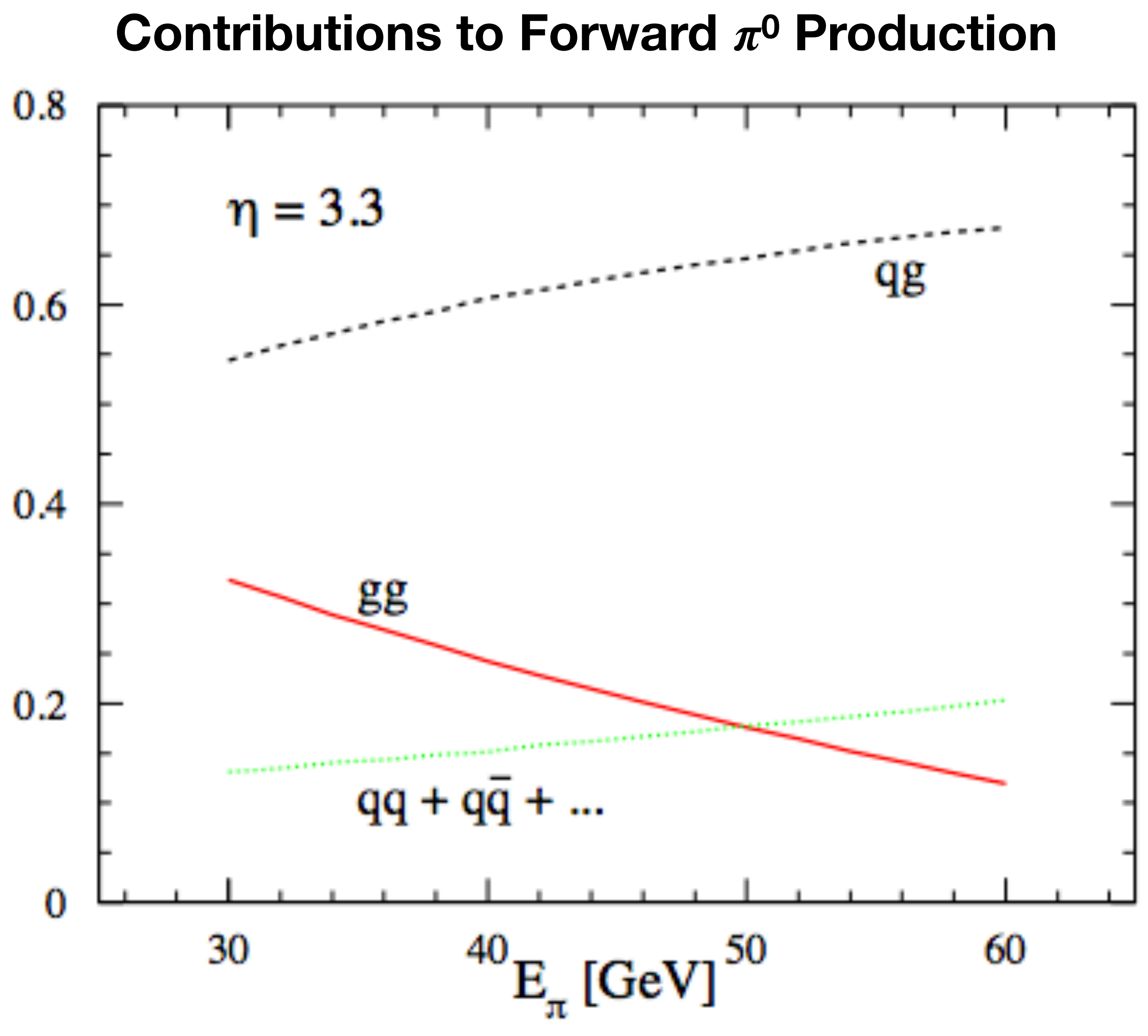
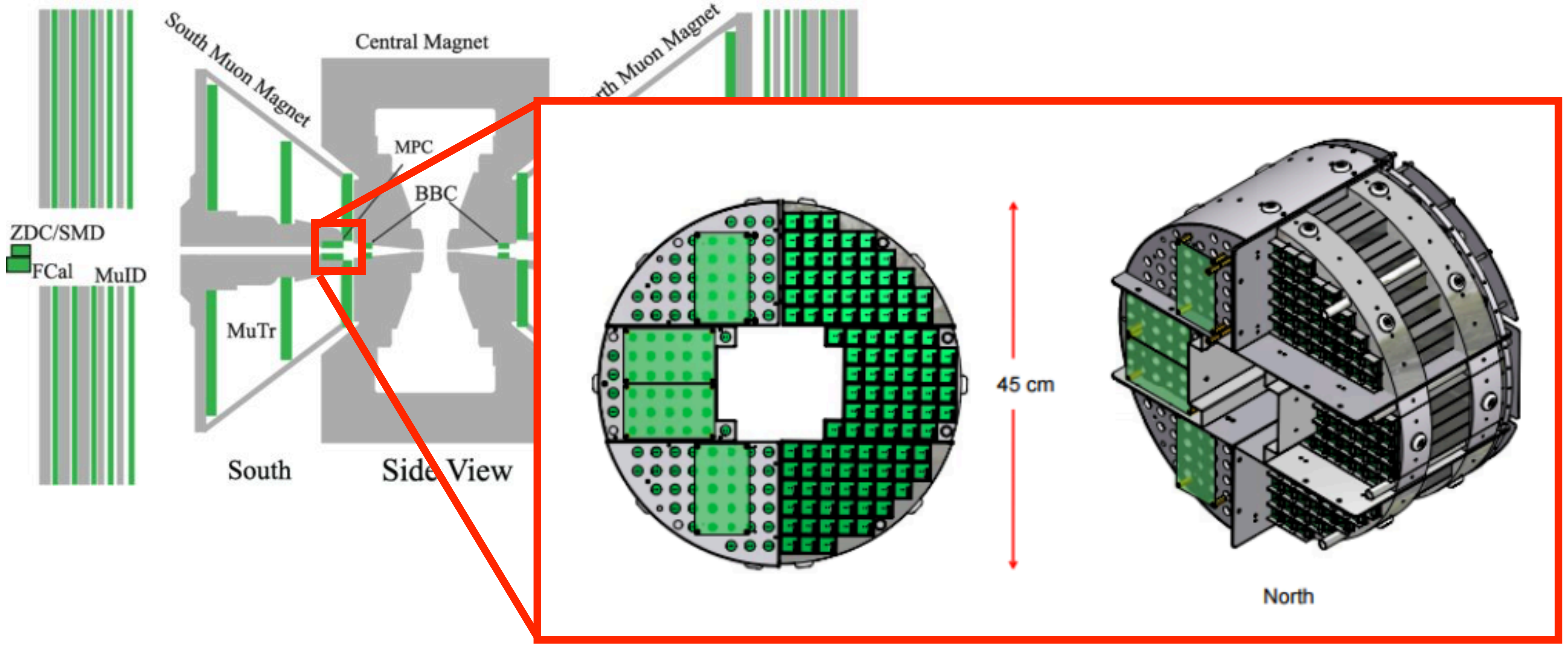
Pions Going Forward





- *qg* subprocess increasingly dominates at forward angles and larger energies
- PHENIX Muon Piston Calorimeter covers 3.1<η<3.9(3.7) North(South)
- Most likely: high-*x* valence quark, low-*x* gluon ==> ΔG down to *x*~0.001
- Analysis of √s=510GeV (Run13) data in progress

Transverse Asymmetries

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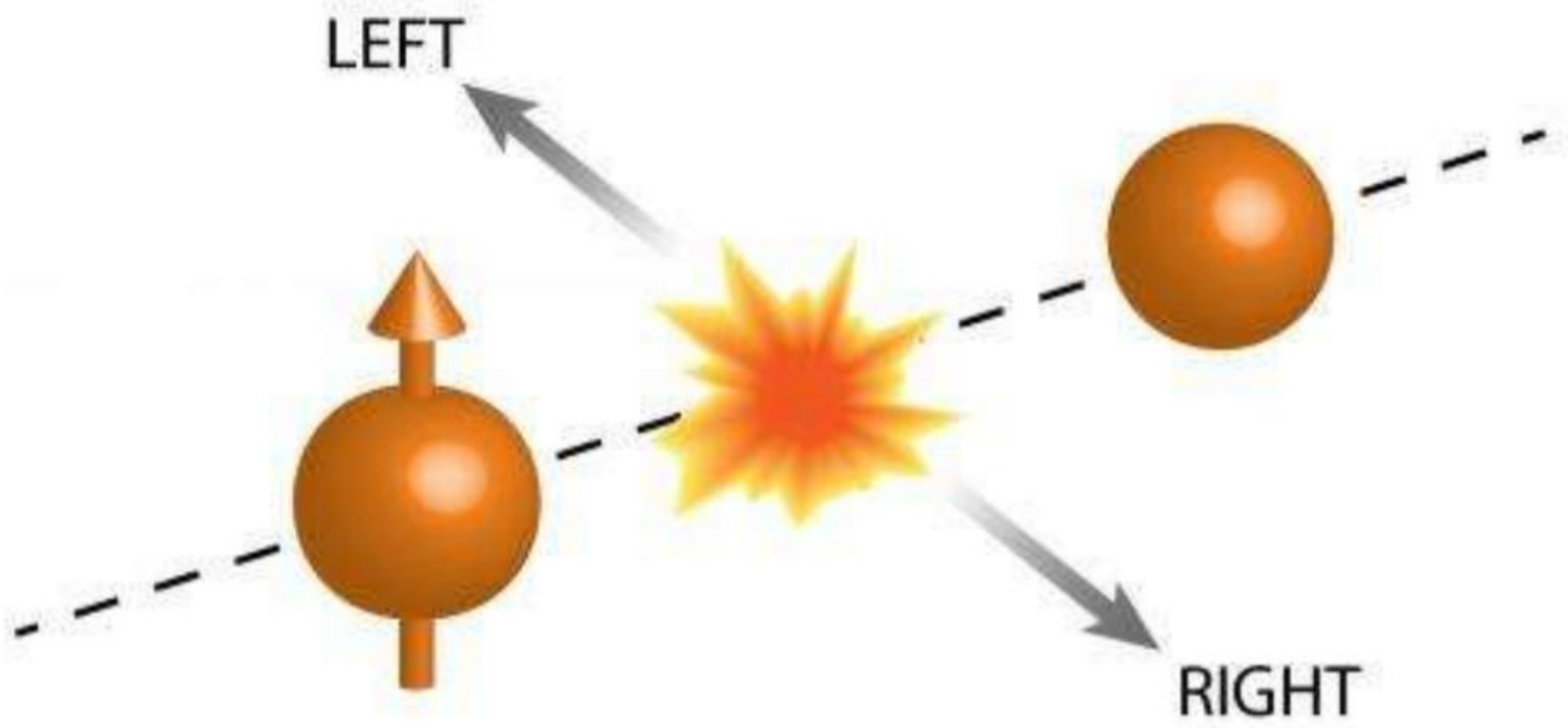
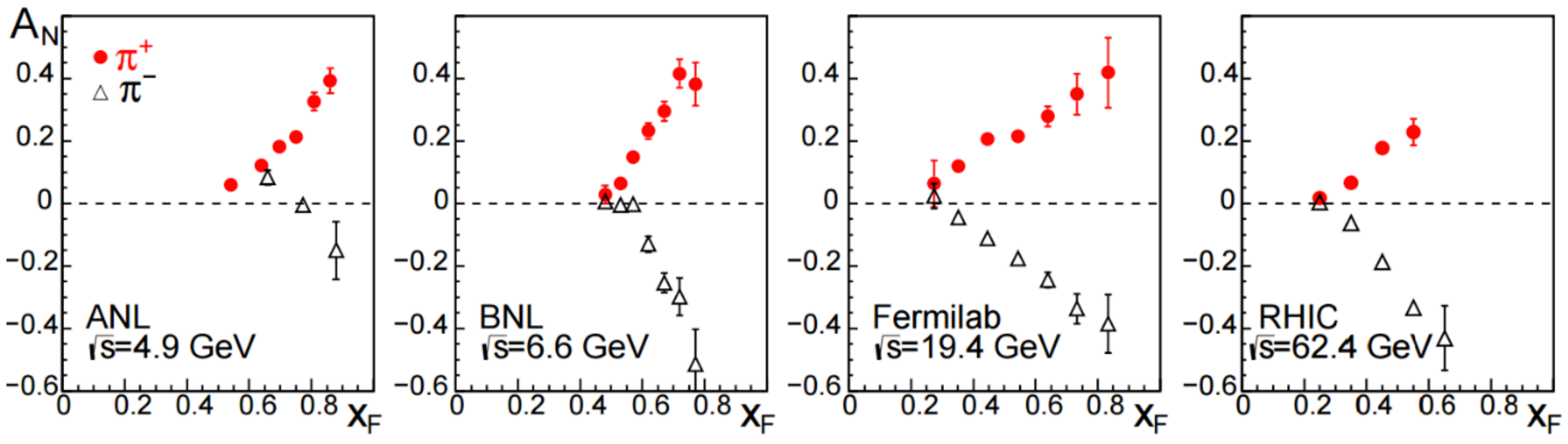
Transverse Single Spin Asymmetry (TSSA)

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

- Hard scatter pQCD predicted small A_N (Kane, 1978)
- ...but measured to be large
- Initial state effects ~ scattered quark interacts with fragment of parent nucleon?
- Final state effects ~ scattered quark interacts with fragment of other nucleon?
- Interpret with interference between two- and three-parton interactions (eg Efremov, Teryaev, Qiu, Sterman)





$$x_F = 2P_{hz}/\sqrt{s}$$

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arxiv:1209.2803
Rev.Mod.Phys. 85 (2013)

Direct Photons A_N in $p^{\uparrow}$+p @ 200

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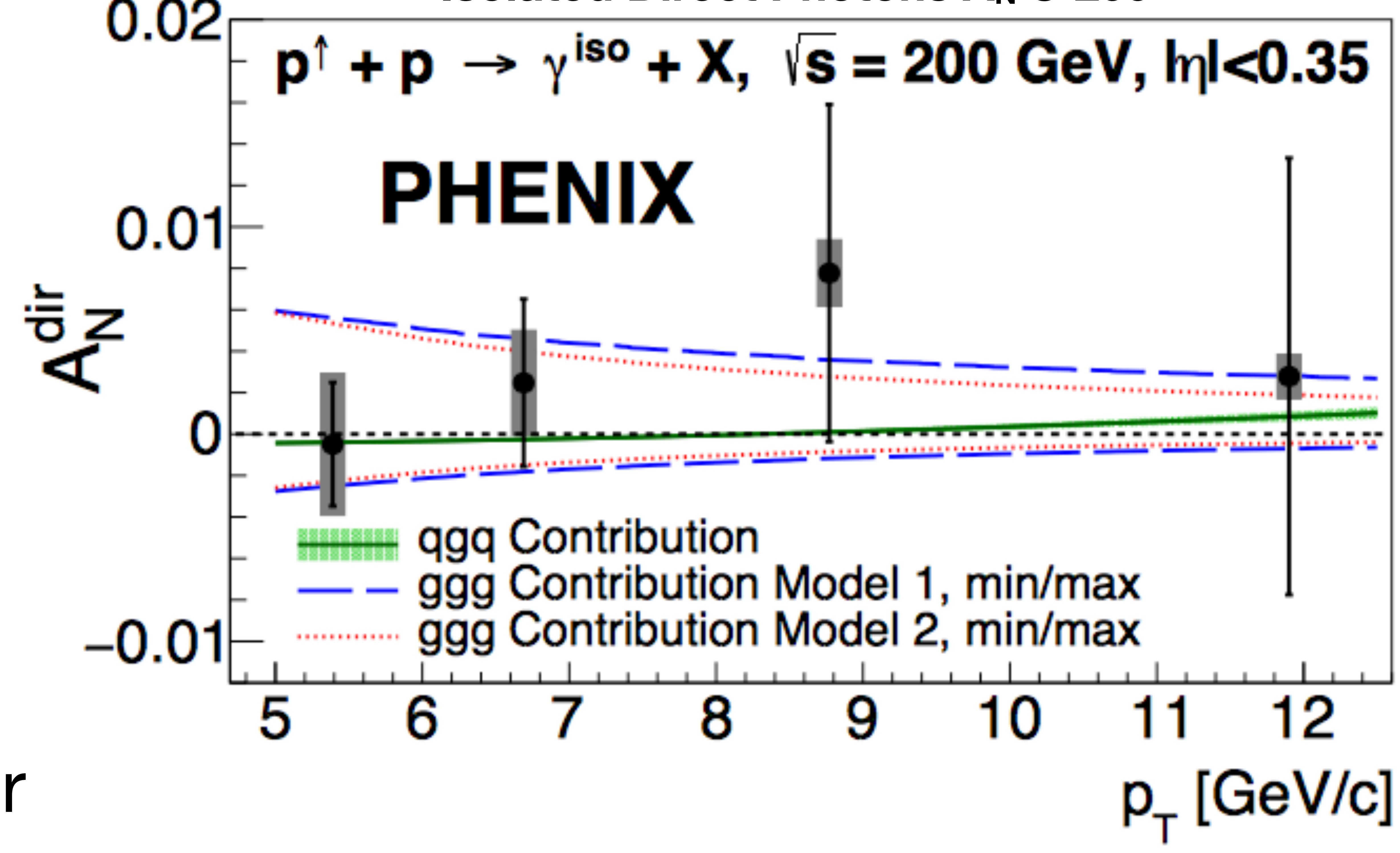
$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{1}{P \langle \cos(\phi) \rangle} \frac{N^{\uparrow} - \mathcal{R} N^{\downarrow}}{N^{\uparrow} + \mathcal{R} N^{\downarrow}}$$

Isolated Direct Photons A_N @ 200



- First RHIC measurement of direct photon A_N
- Improves constraints on ggg correlator in transversely polarized proton

arxiv:2102.13585
Phys. Rev. Lett. 127, 162001

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$\pi^{+(-)}$ A_N in $p^{\uparrow}+p$

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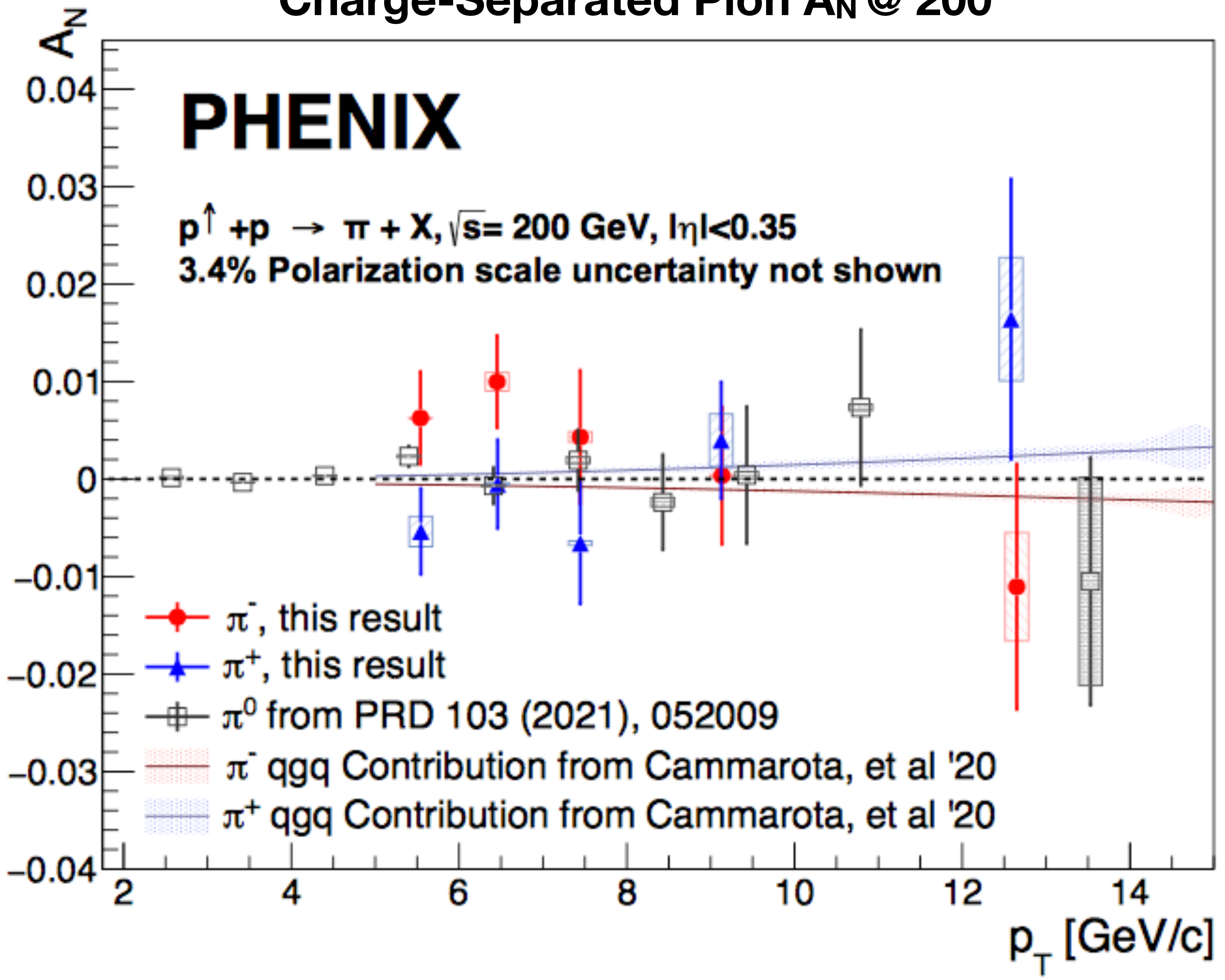
- Expect to be dominated by qgq contribution at high pT
- Combined, consistent with π^0
- Separated, some indication of charge-dependence -- possible flavor dependence in underlying process?
- Sivers and Collins effects expect to see this flavor dependence

Charge-Separated Pion A_N @ 200



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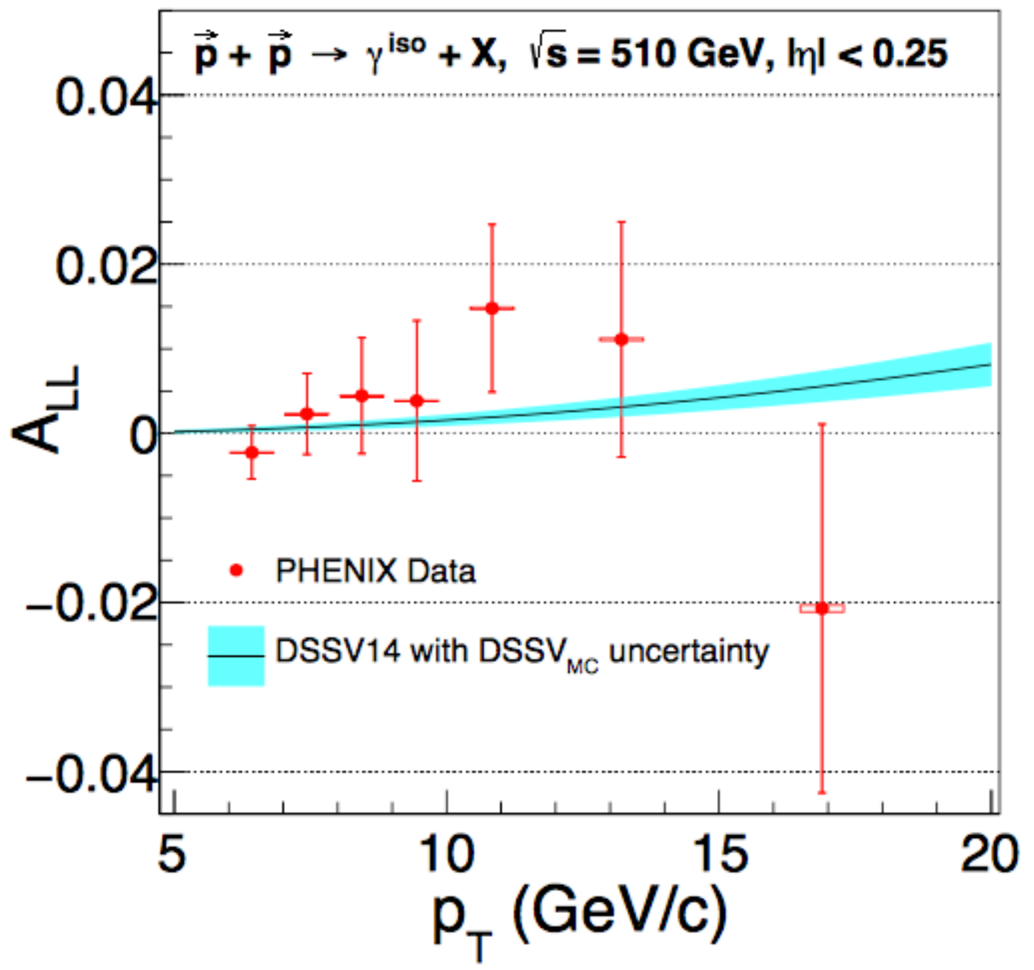
arxiv:2112.05680
Phys. Rev. D 105, 032003 (2022)

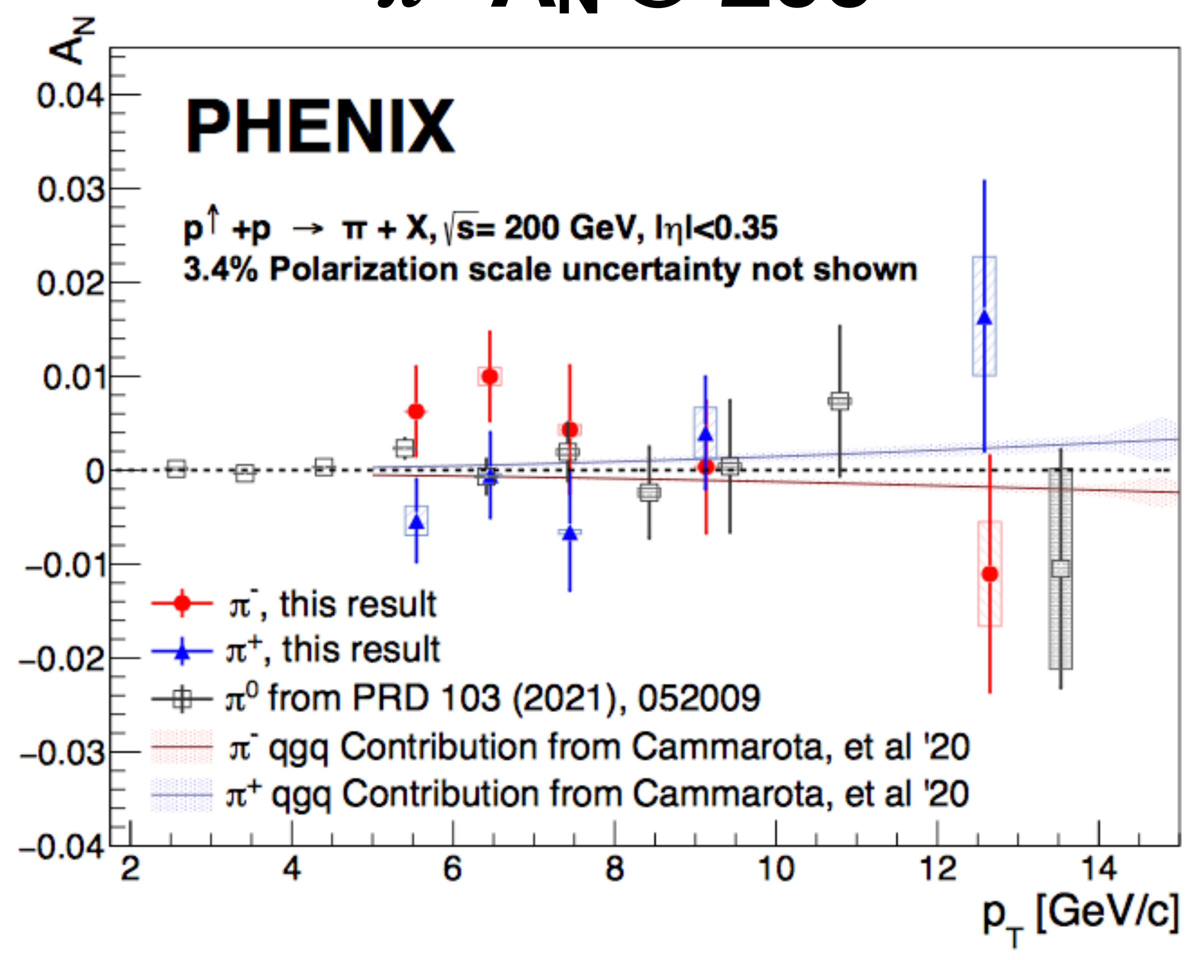
Summary and Outlook

- PHENIX jet, $\pi^{\pm}$, γ A_{LL} measurements at 510 GeV further corroborate ΔG>0
- TSSAs beginning to differentiate extremal ggg correlator models

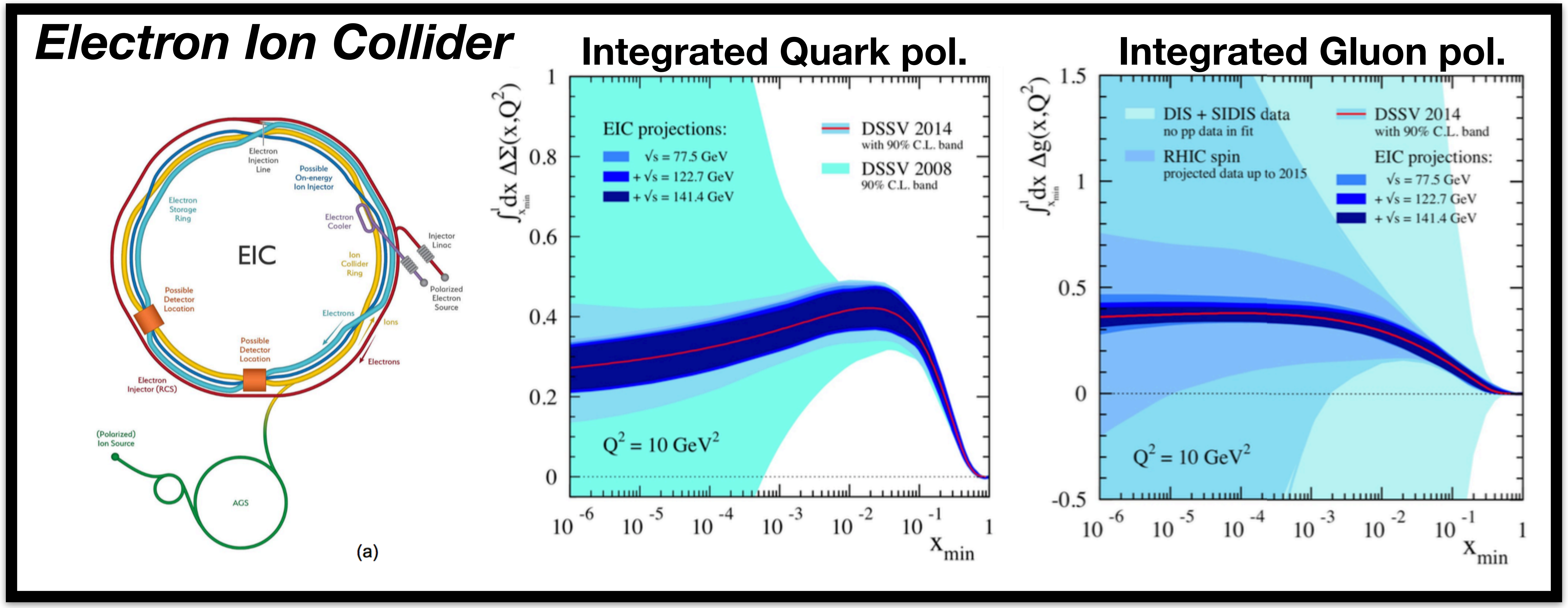
γ_{iso} A_{LL} @ 510



$\pi^{\pm}$ A_N @ 200



- Now: Transition to sPHENIX, improved statistics for mid-x
- Soon(ish): EIC, and significantly improved access to small x



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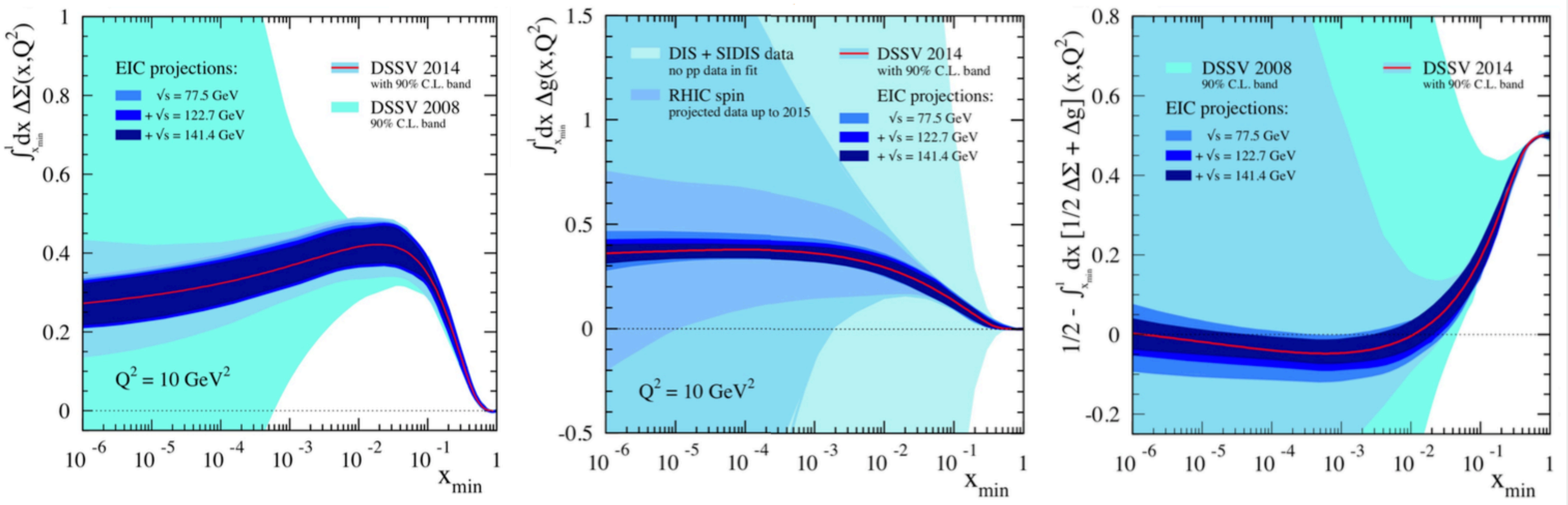
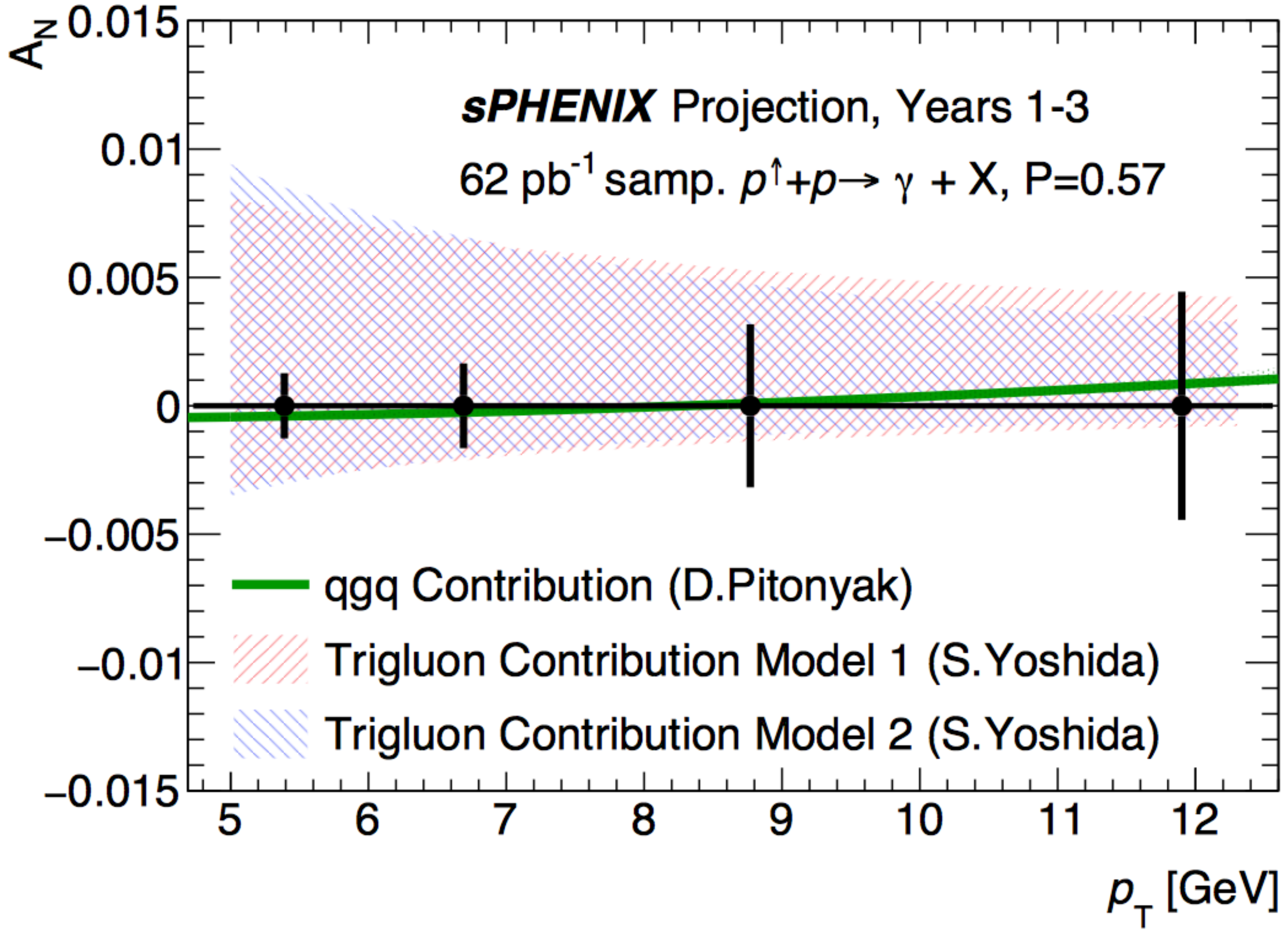
EIC projections



TSSAs at sPHENIX

- Assuming sufficient transverse running, sPHENIX projected statistics can strongly constrain ggg correlators



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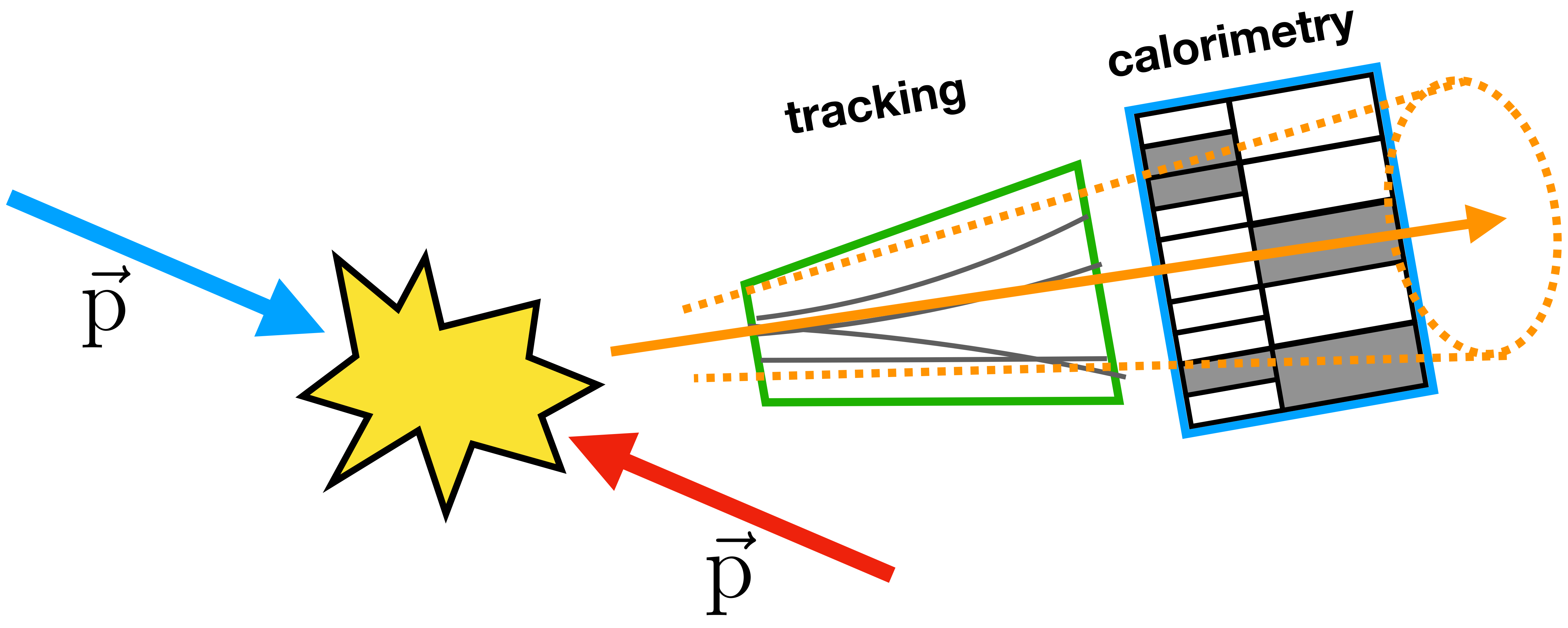
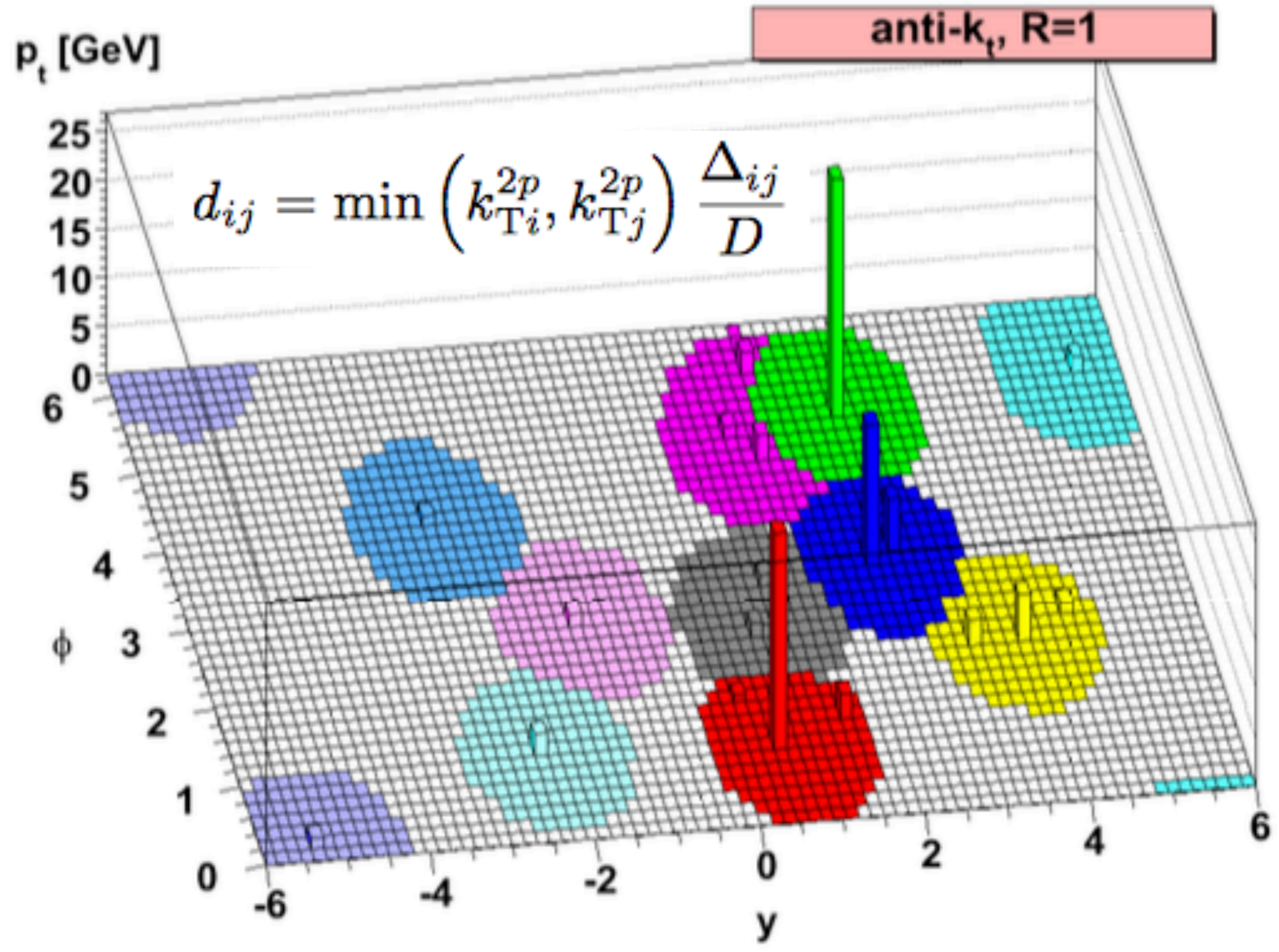
Reconstructing Jets

PHENIX

- Select tracks with pT>0.5GeV, EMCal clusters with E>0.5GeV
- FastJet Anti-kT algorithm produces detector jets (R=0.3)
- Control noise with cuts on measured jet pT, charge fraction, number of constituents
- Cut on jet axis |η|<0.15 to minimize jet energy lost outside acceptance

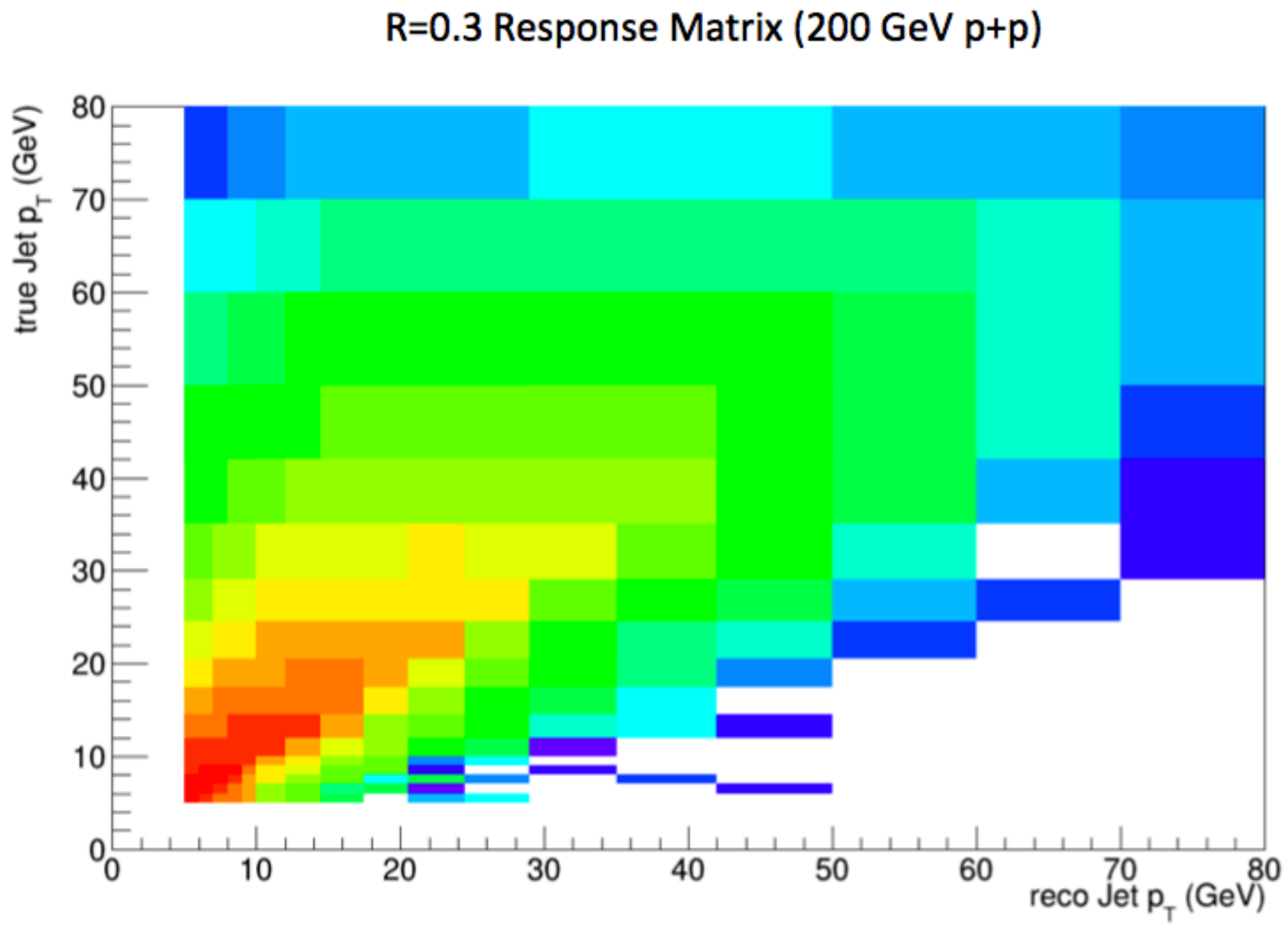




arxiv:0802.1189 JHEP 0804:063, 2008

Correcting Jet Energy

- True jet energy is distorted by
  - Missing energy (punch-through / acceptance)
  - Bin migration (resolution)
  - Trigger efficiency
  - Underlying event
- Pythia events generated and studied to produce response matrix.
- RooUnfold Bayesian unfolding procedure (2 iterations)



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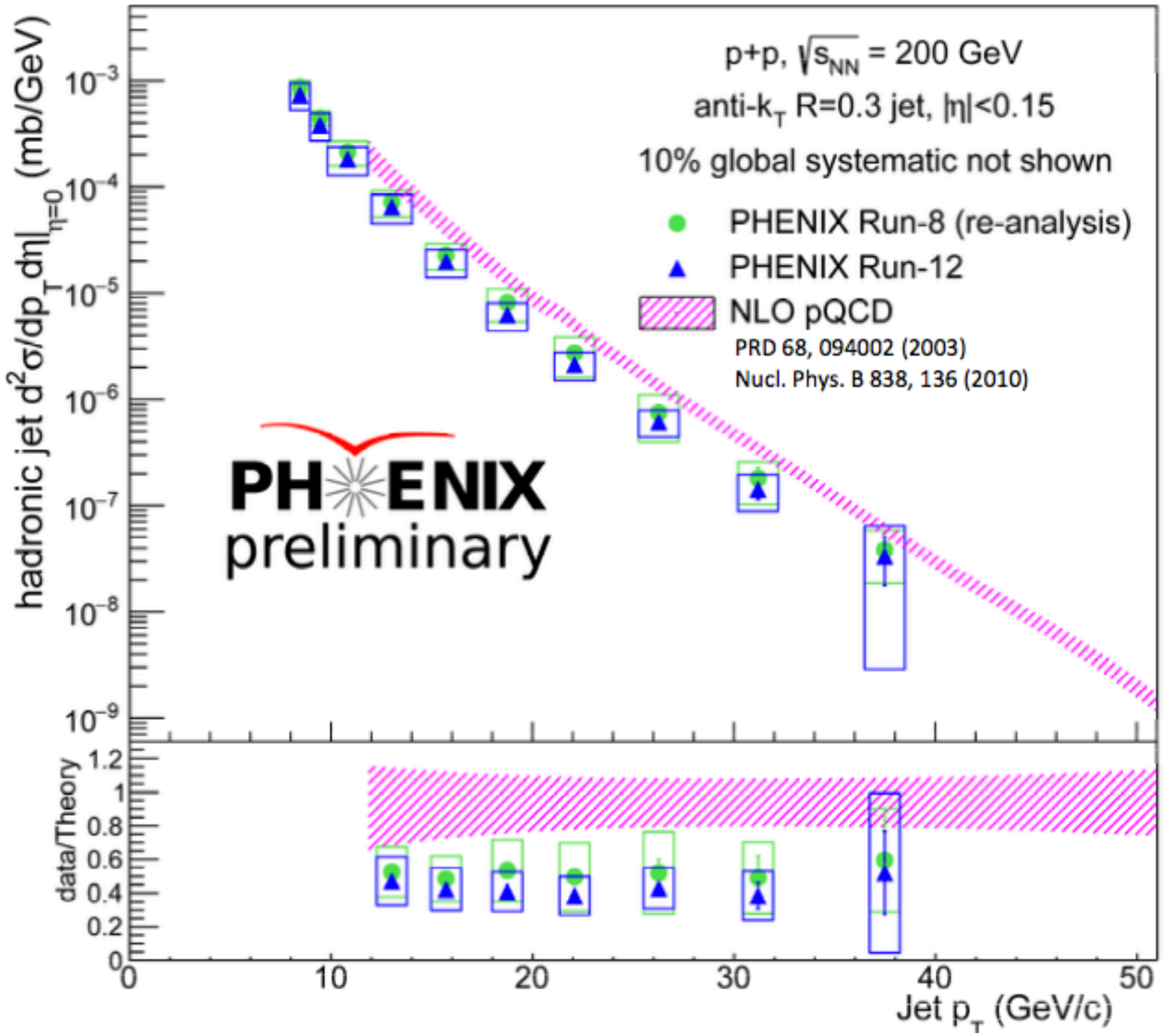
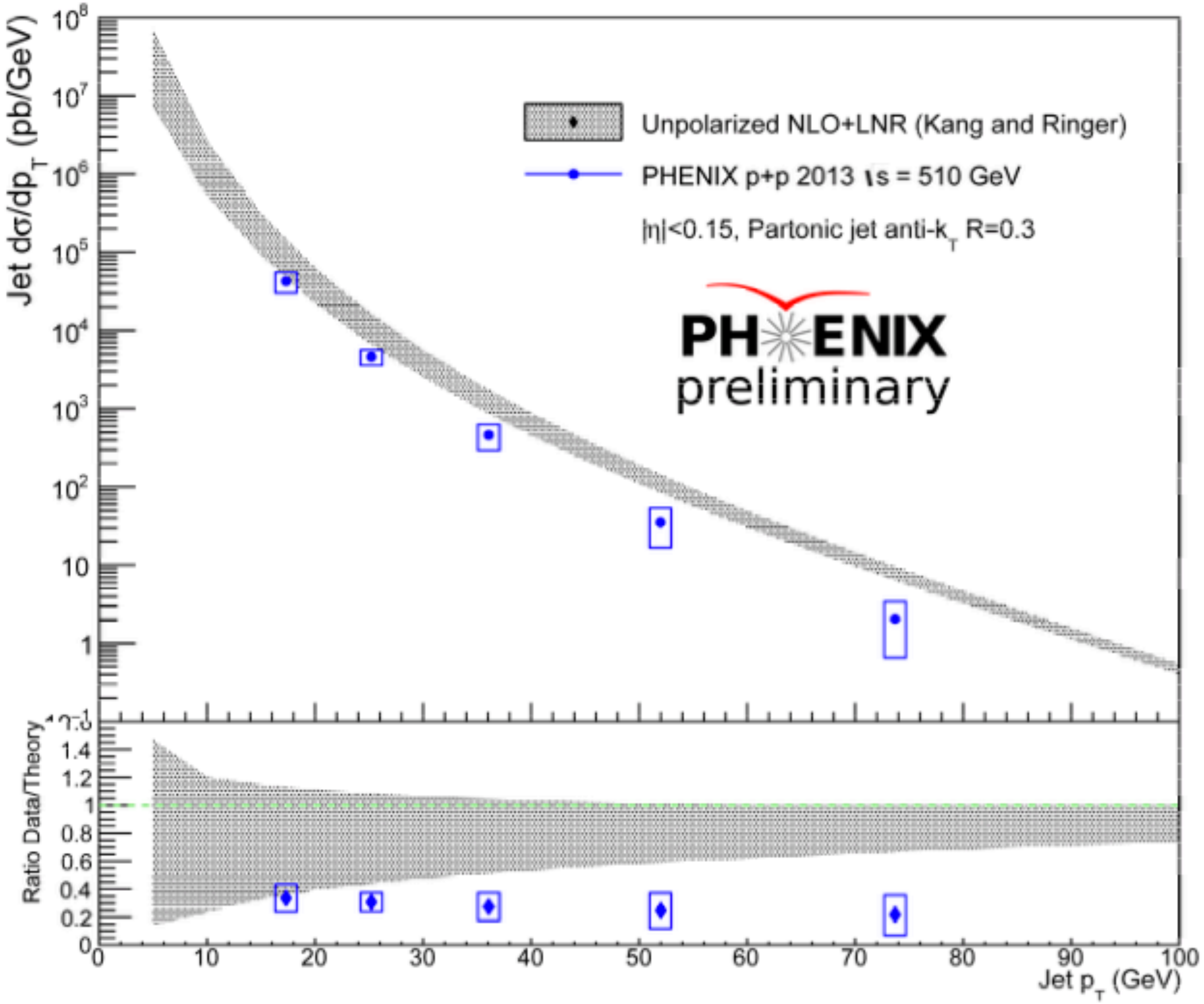
Jet Cross Section @ 200

- After unfolding, jet cross section can be plotted with 'real' jet pT
- Results are systematically lower than NLO predictions (also seen at small R in CMS)
- suggests shape of NLO jets is narrower than in data
- Wider jet radius not practical for PHENIX acceptance



Jet Cross Section @ 510

- Similar trend at 510 GeV



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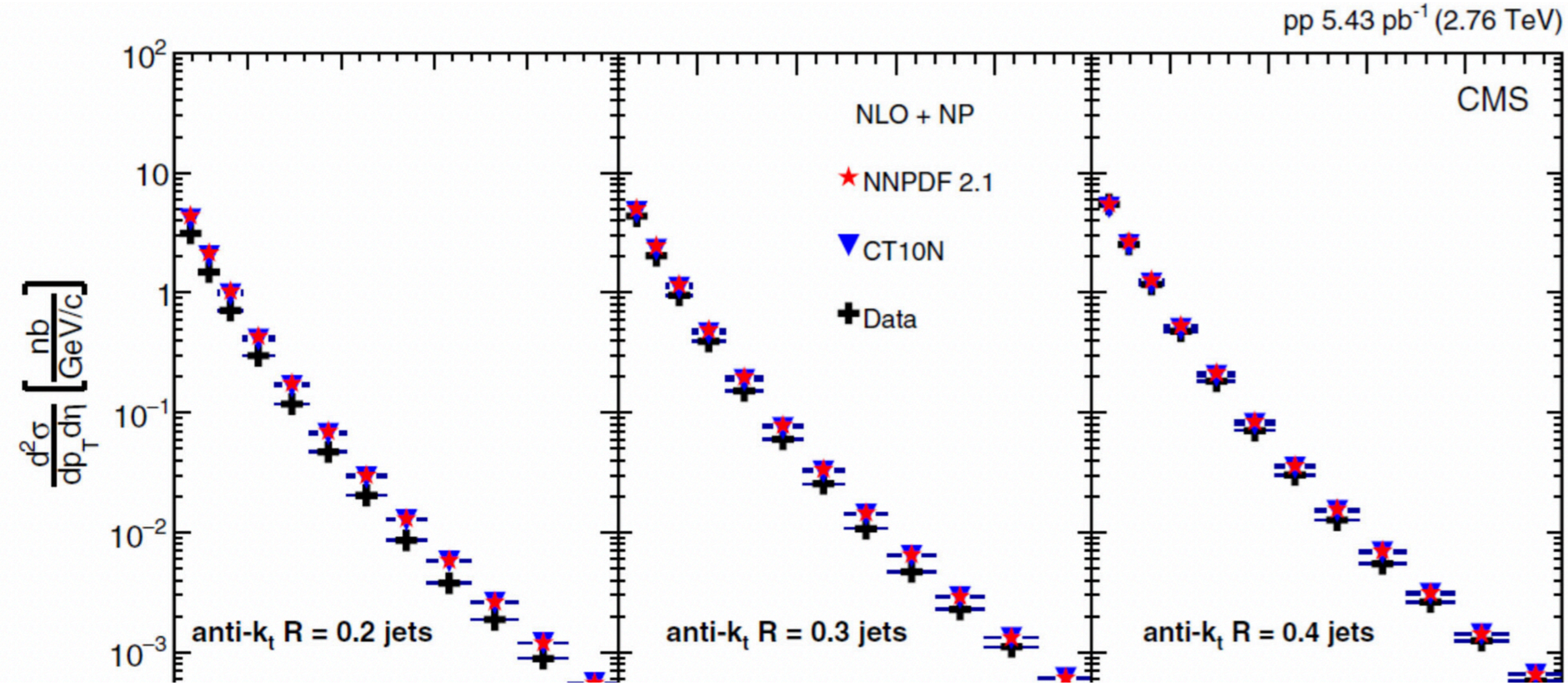
NLO Jets at CMS



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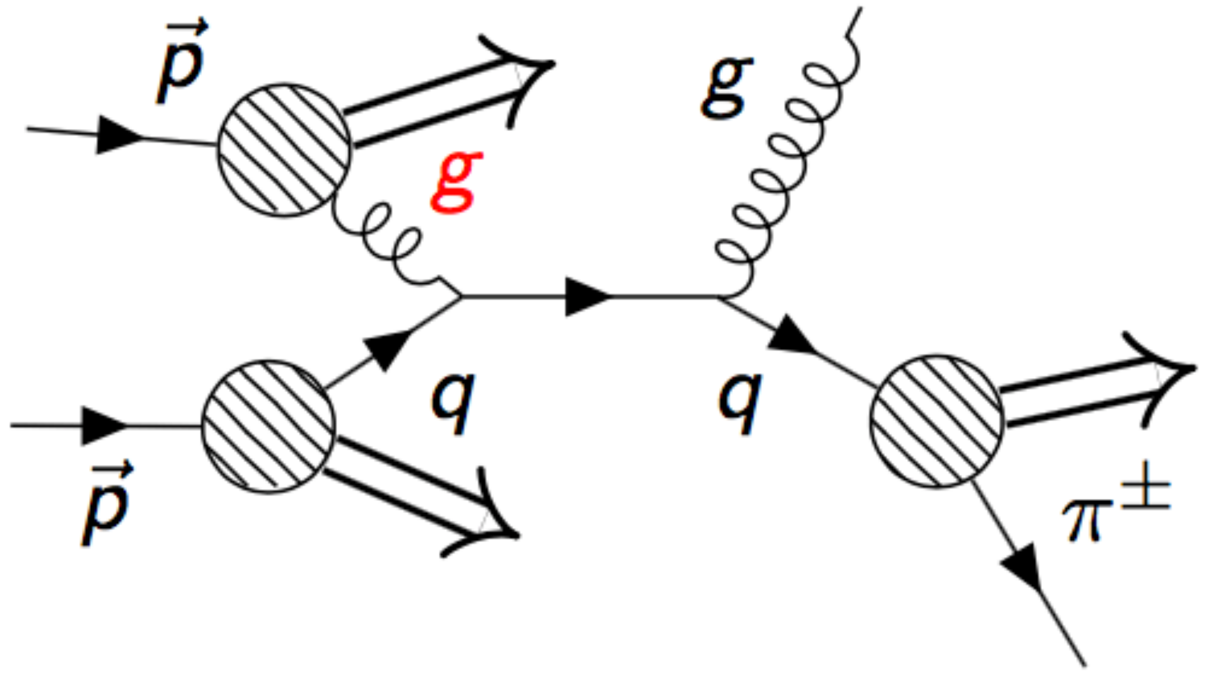
Pions and Favored Fragmentation

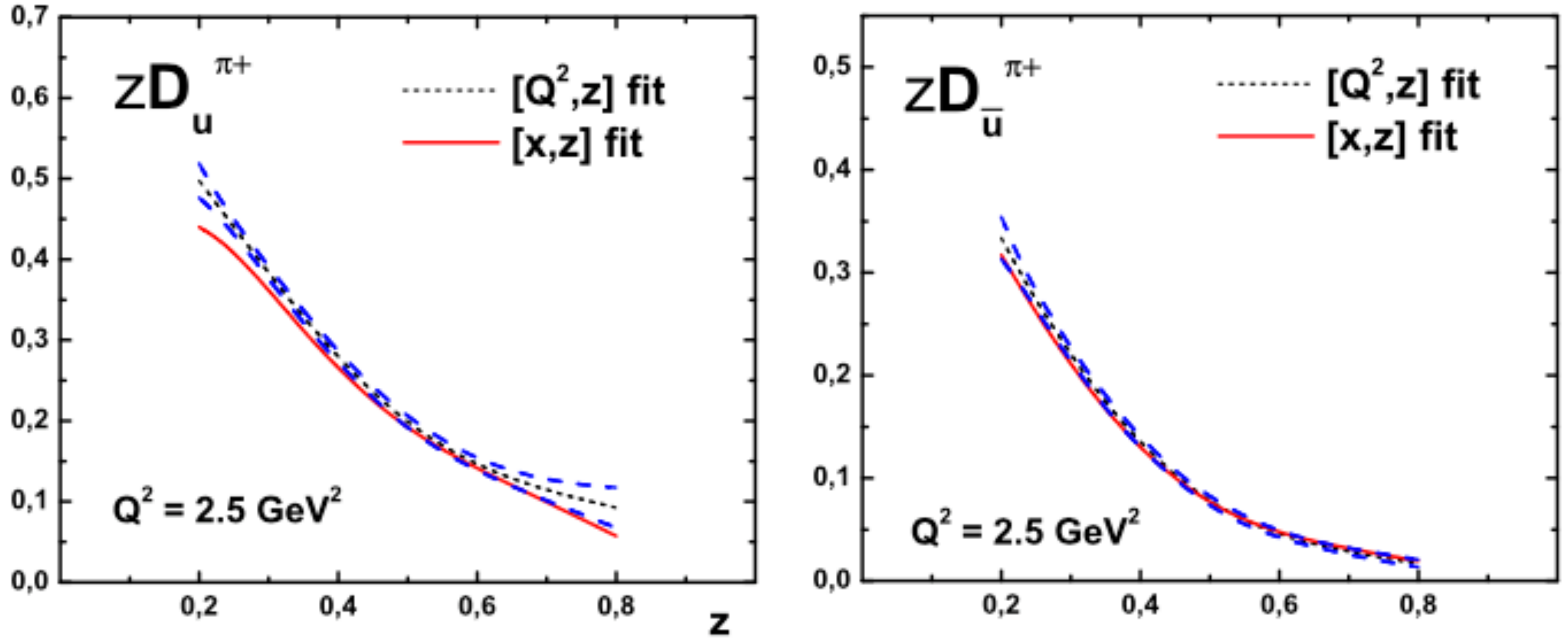
- Select π candidates with RICH, E/p, shower shape, subtract data-driven and geant background models



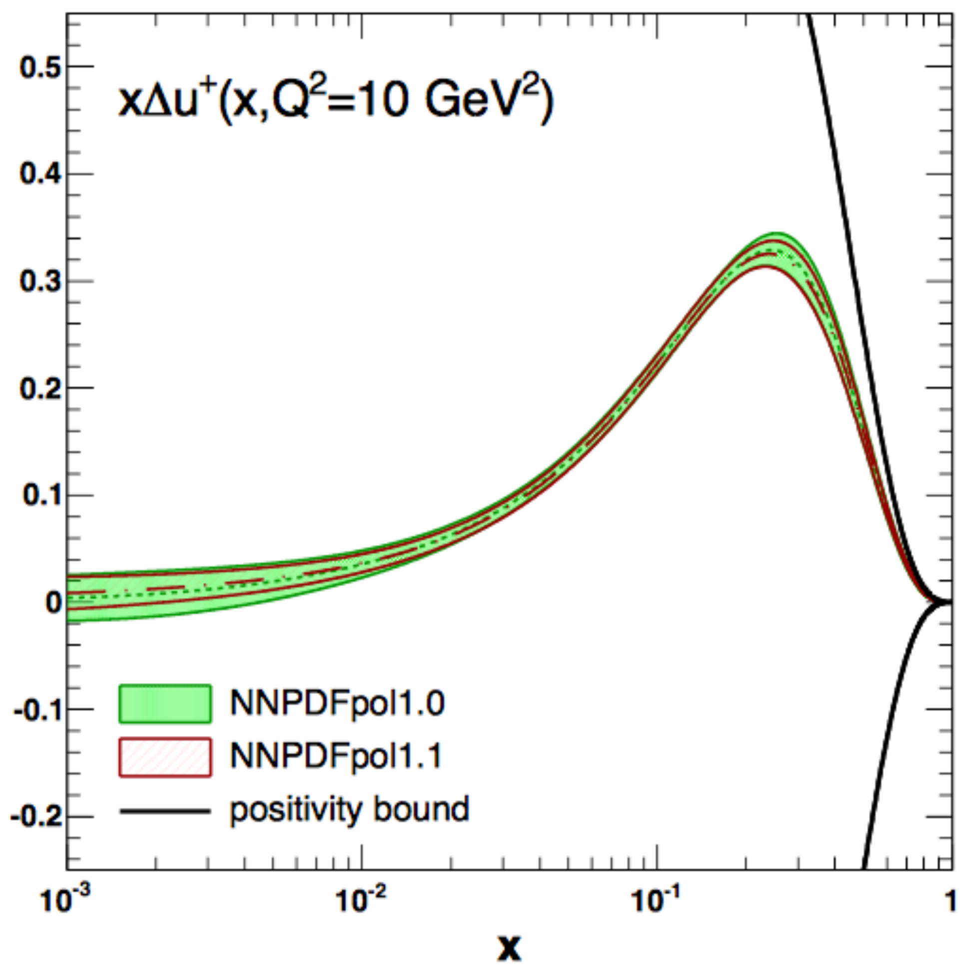
- Single particle signal reduces acceptance issues
- Pion production in jets *favors* sign that matches the hard-scatter quark
- Existing knowledge of Δu and Δd gives a lever arm to look at Δg

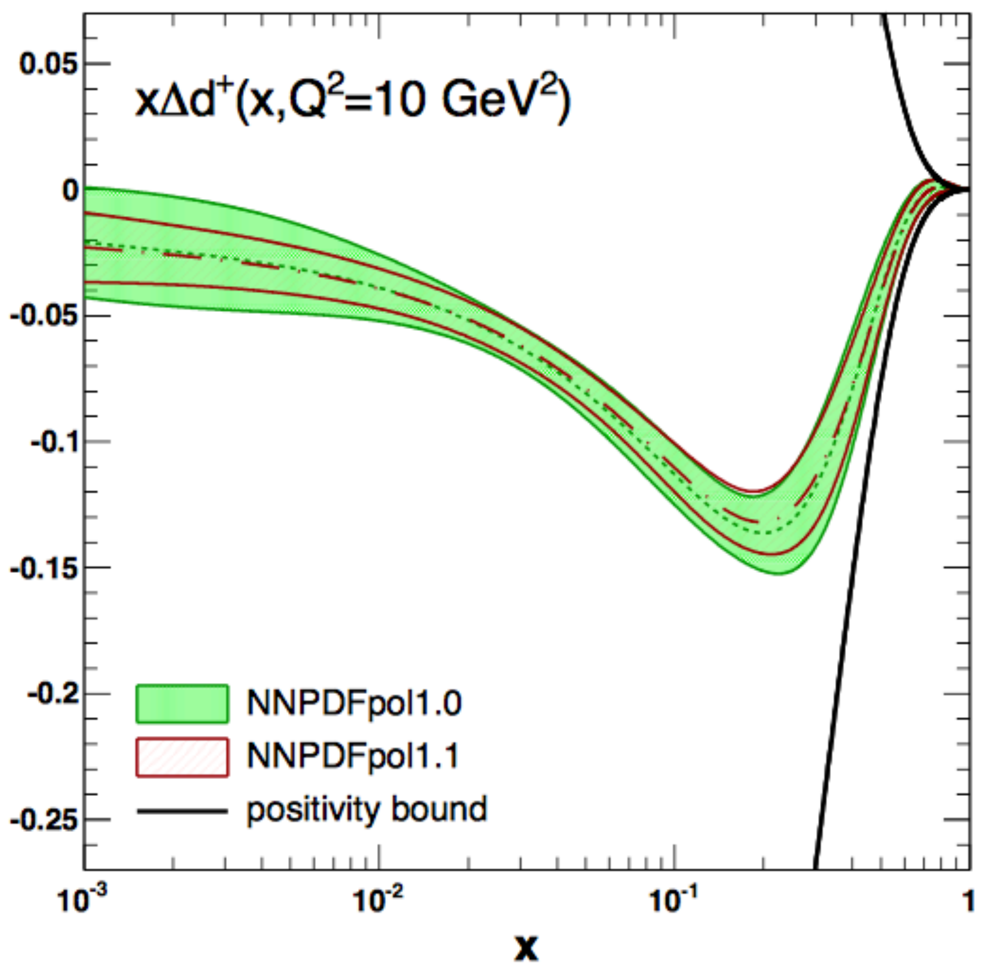
Favored

Unfavored



arxiv:1506.06381 Phys. Rev. D 93, 074026 (2016)





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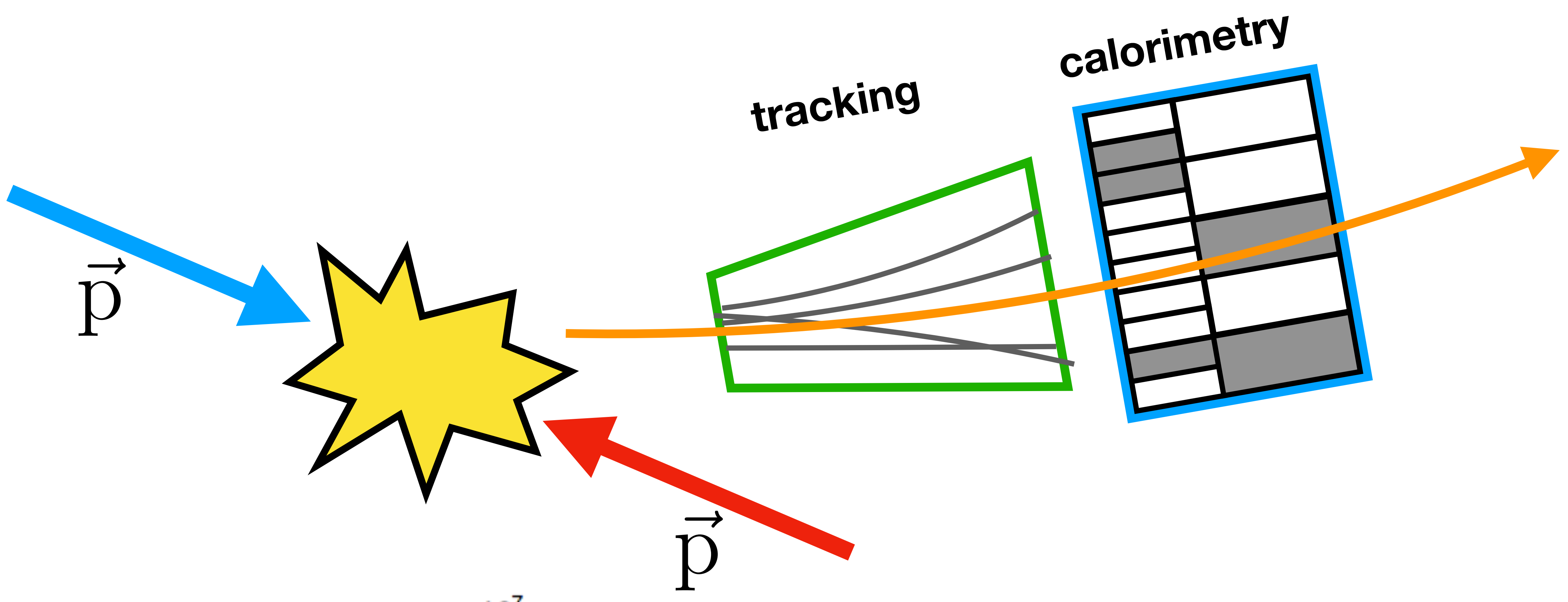
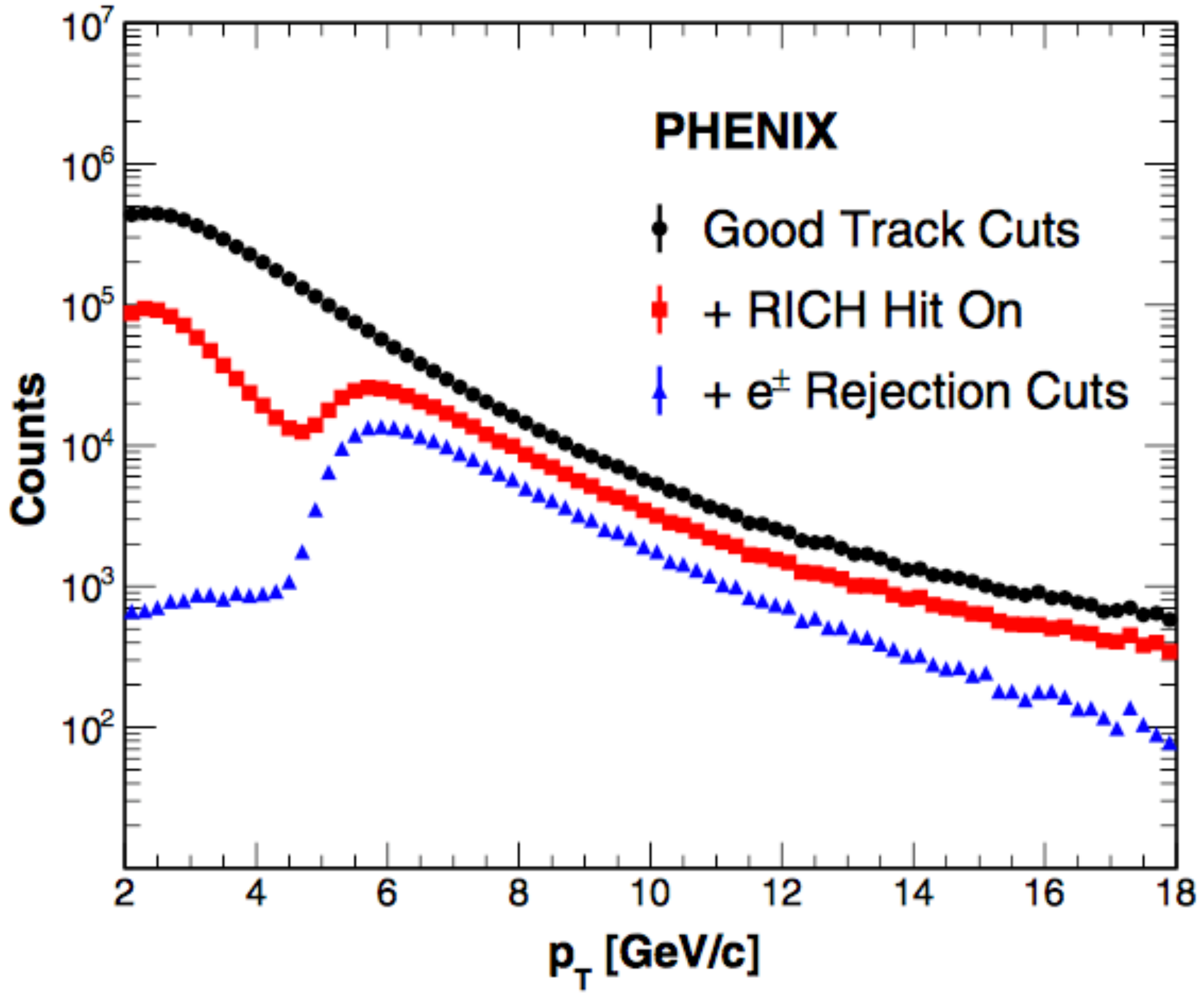
Reconstructing Charged Pions

- Trigger on EMCal energy, candidate track must match to tower
- Challenge: ~50% of pions have significant EMCal punch-through
- Pion ID:
    - >1 PMT in RICH must fire (4.9- 17.3GeV fires only for pions and electrons)
    - 0.2<E/p<0.8 -- punchthrough to disfavor electrons
    - Require bad match to EM shower shape
- Remaining BG studied in PYTHIA+GEANT





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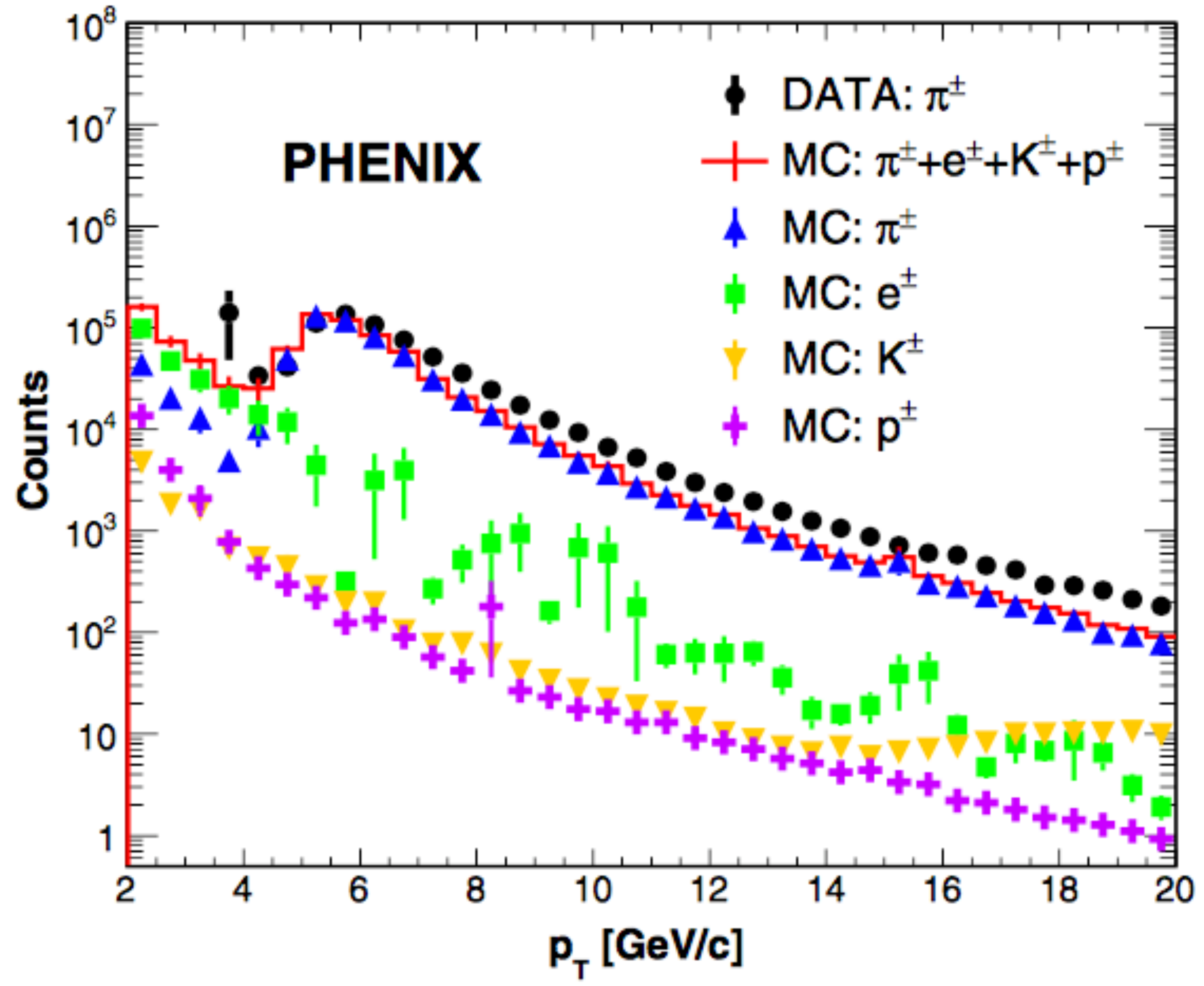
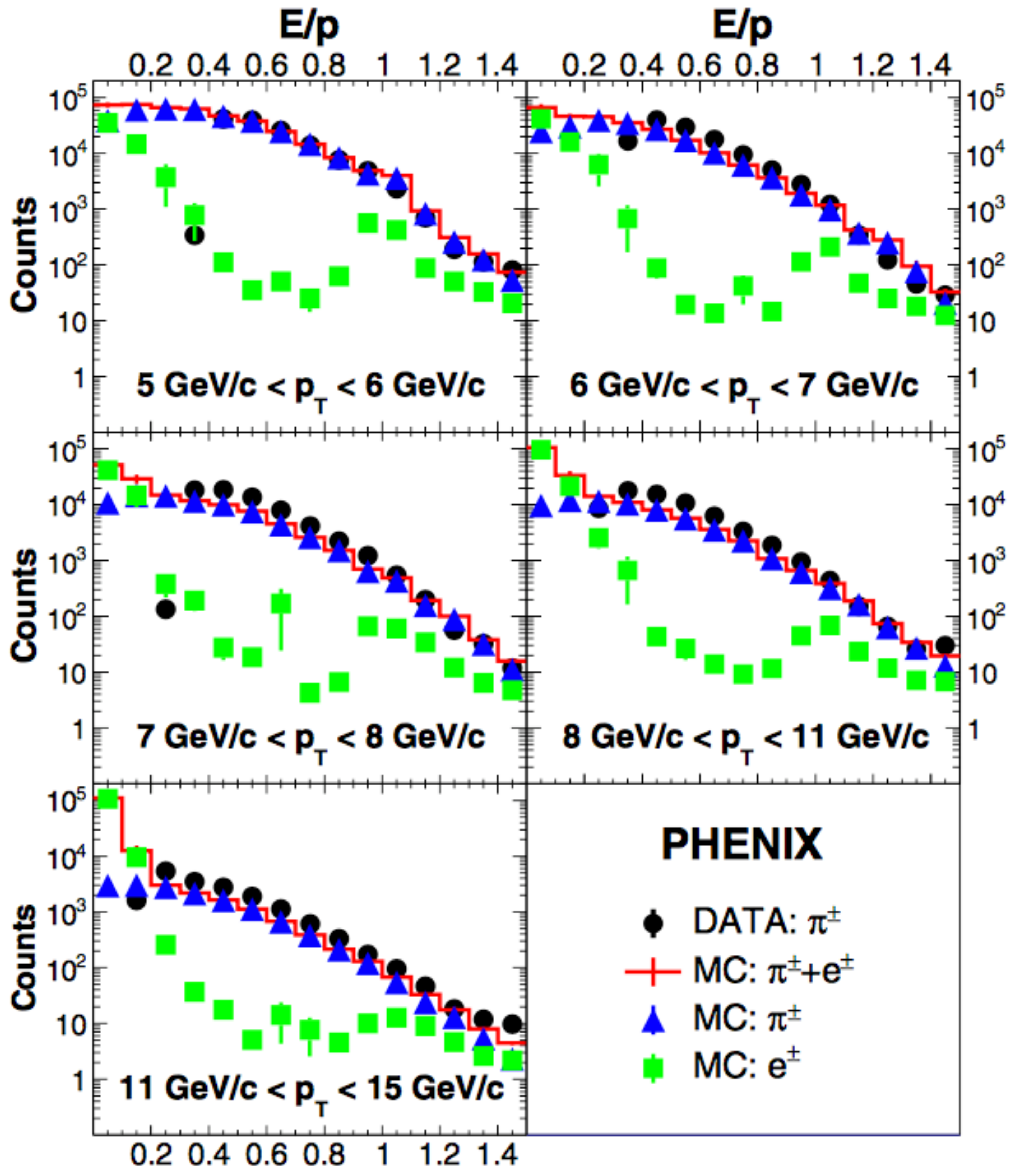
Pion Background Studies





- MC studies show electrons dominate:
  - below threshold and until kaons can fire the RICH
  - at high E/p (EM shower fully captured)
  - at low E/p (late conversion)

Describing Large TSSAs

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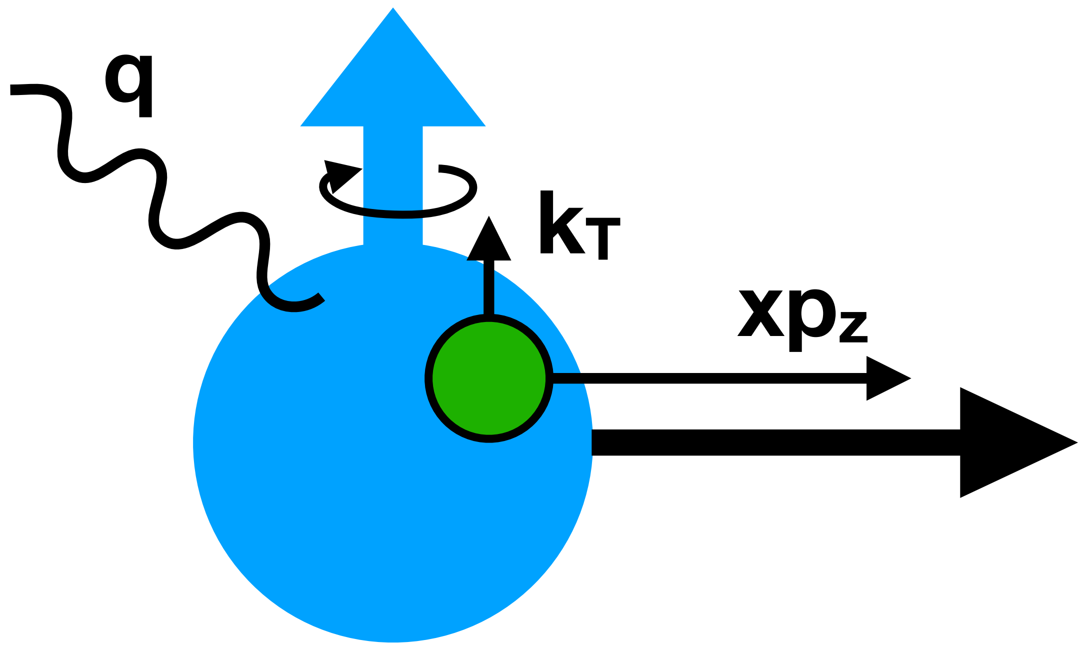
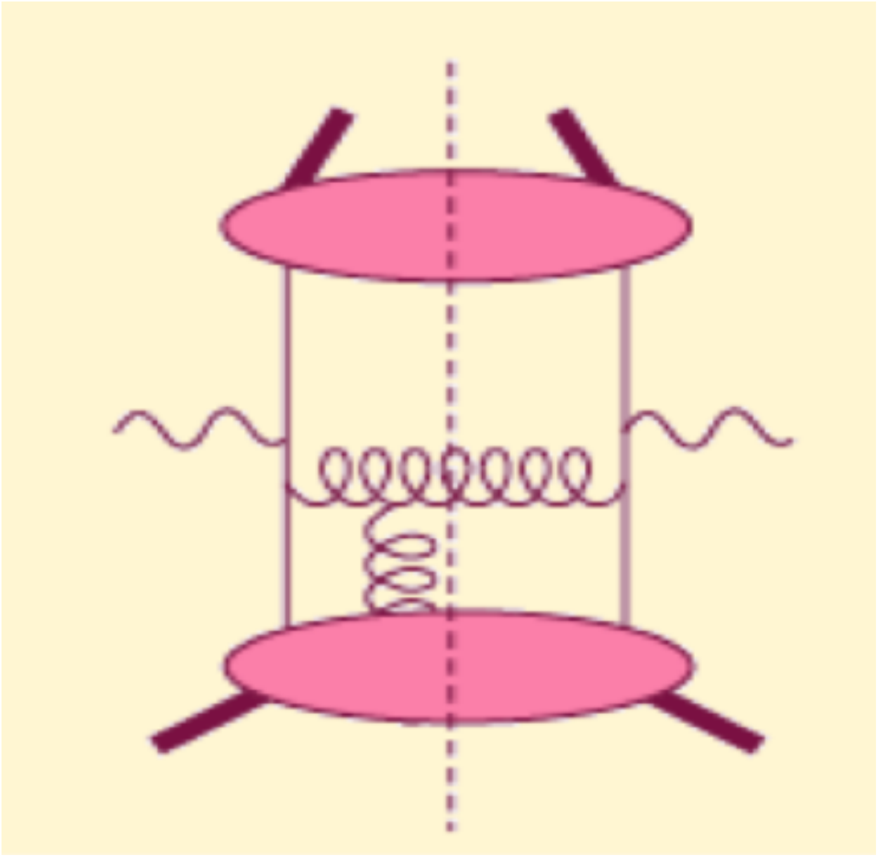
- Two frameworks to describe large TSSAs:
  1. nonperturbative Transverse Momentum Dependent Functions:
     - explicit dependence on k_T
     - need access to both Q *and* k_T in observables
  2. Higher-twist effects:
     - Collinear: Single hard scale, pT
     - Twist-3: ~'NLO'. Matrix Element contains interference between two- parton and three-parton interactions.
       (eg Efremov, Teryaev, Qiu, Sterman)





- Some success relating these two approaches:

$$-\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{SIDIS} = T_{q,F}(x,x)$$

Sivers TMD <==> ETQS

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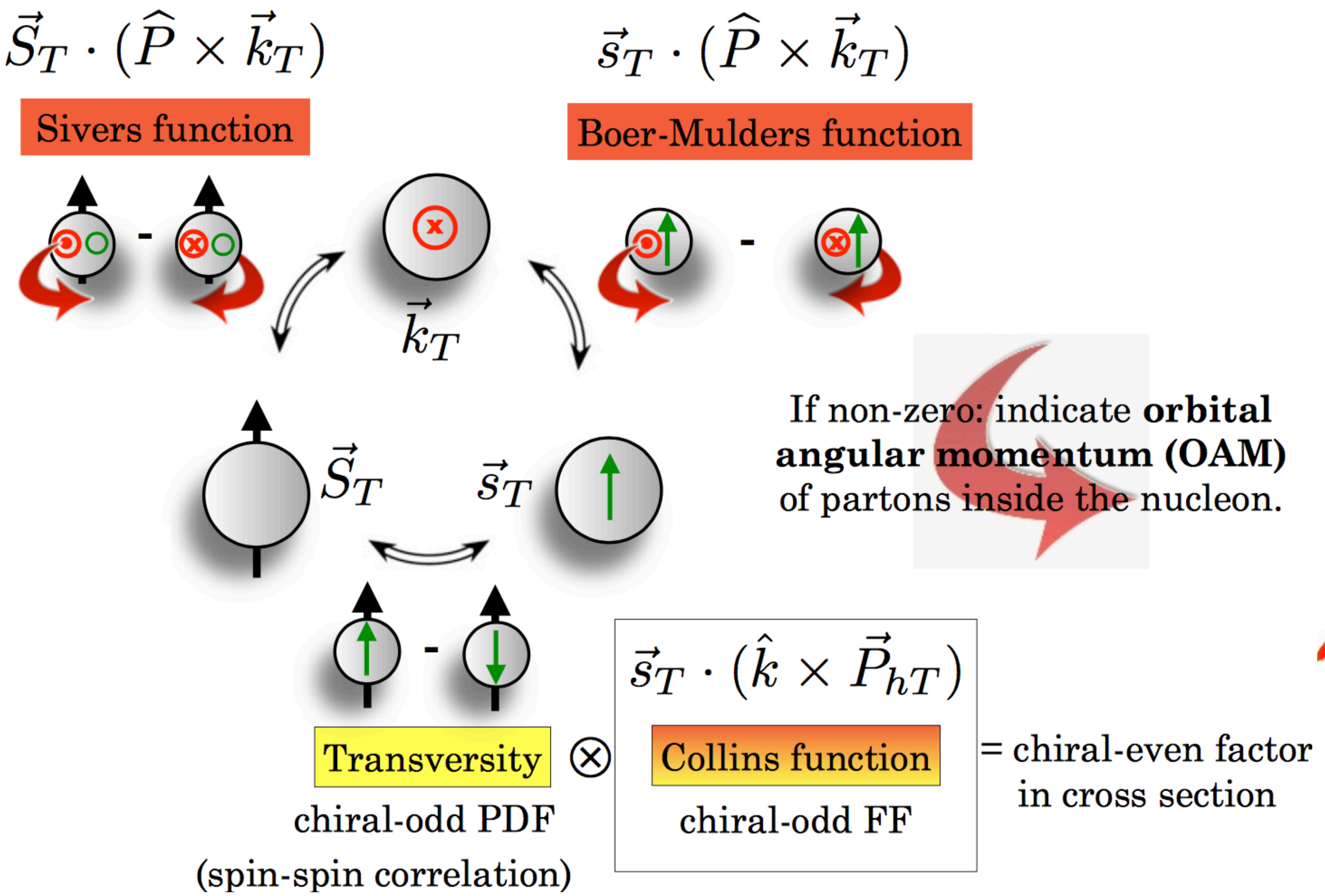
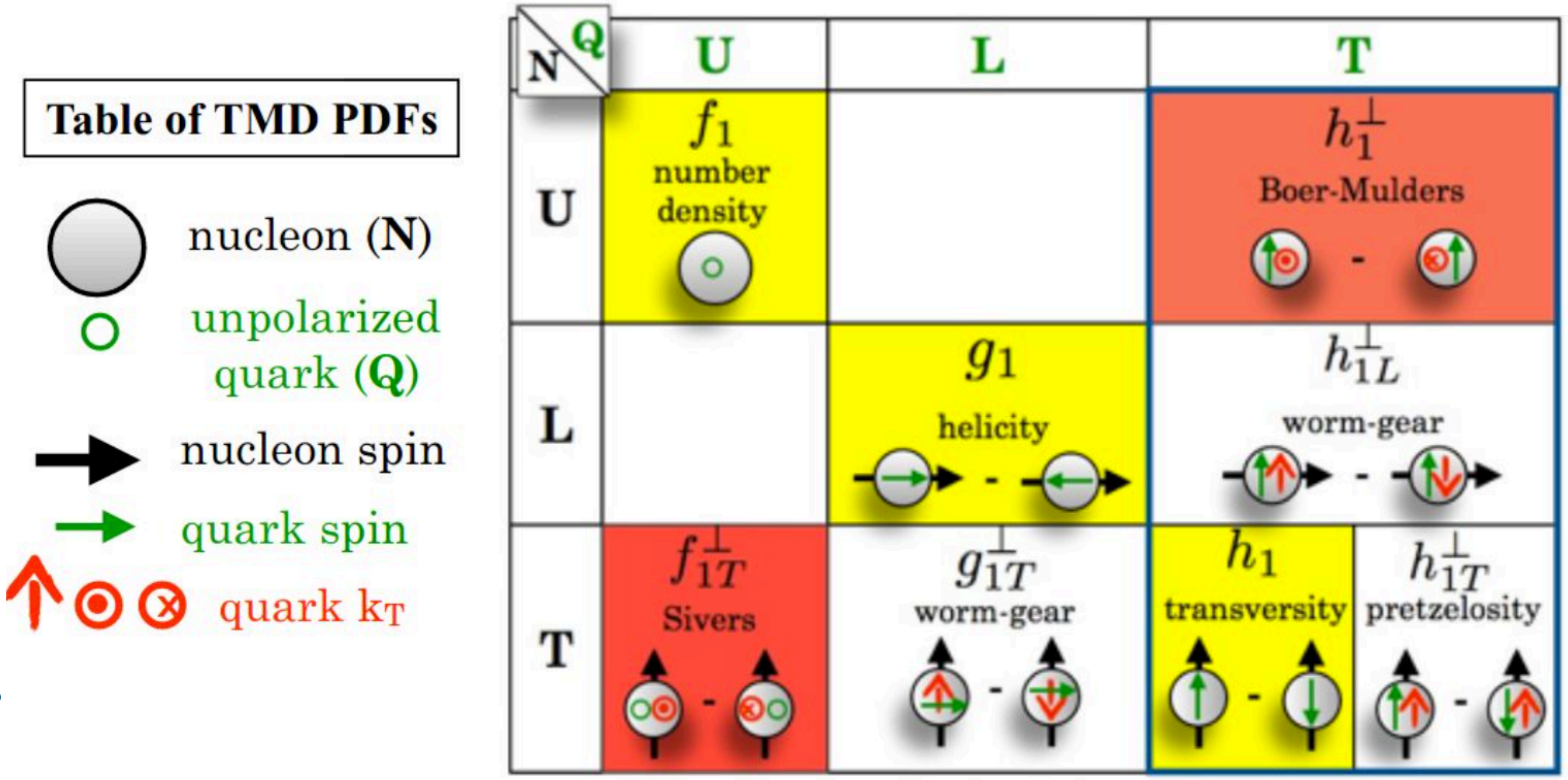
TMDs



If non-zero: indicate **orbital angular momentum (OAM)** of partons inside the nucleon.

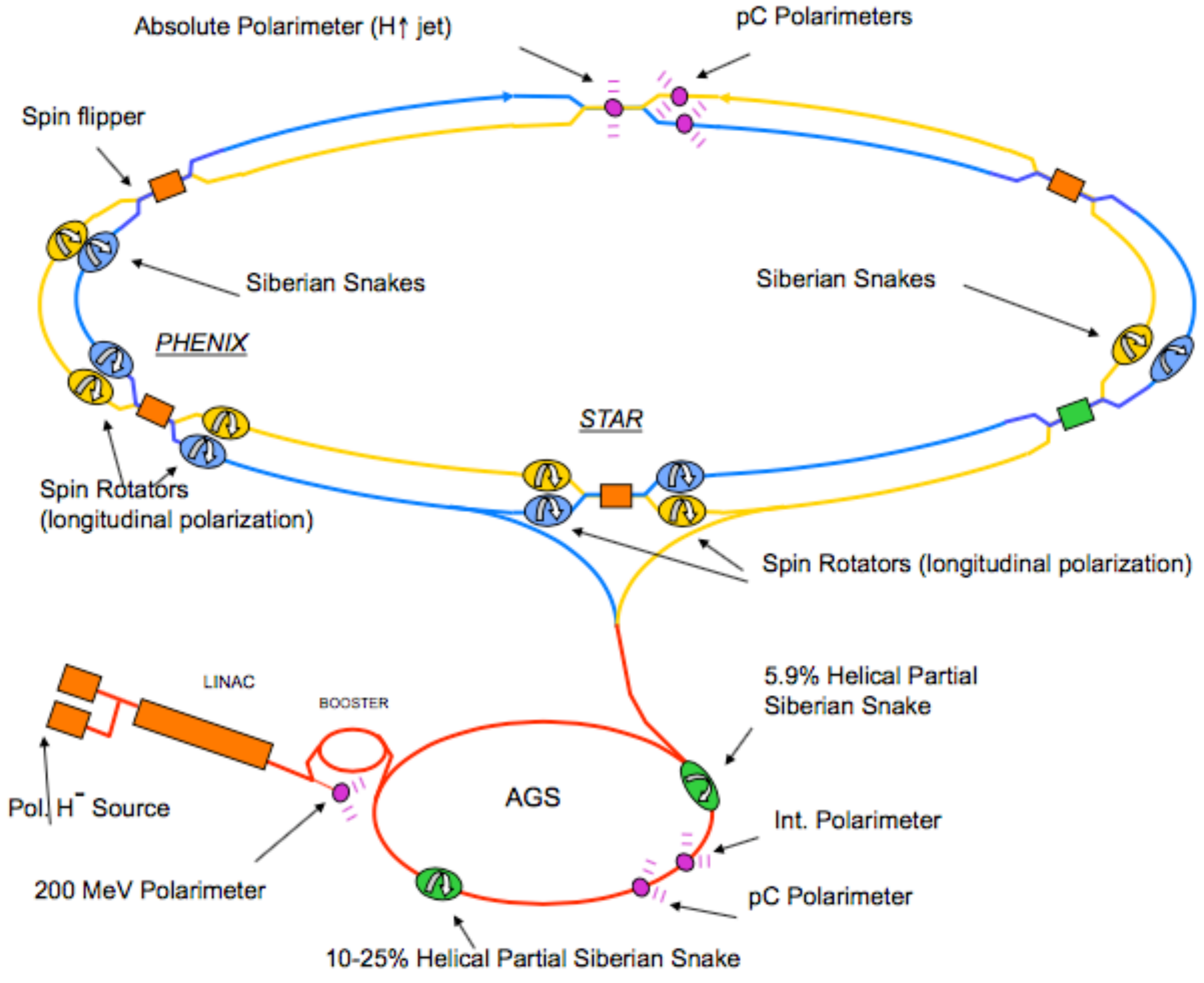


N \ Q	U	L	T	
U	f_1 number density		$h_1^\perp$ Boer-Mulders	
L		g_1 helicity	$h_{1L}^\perp$ worm-gear	
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ worm-gear	h_1 transversity	$h_{1T}^\perp$ pretzelosity

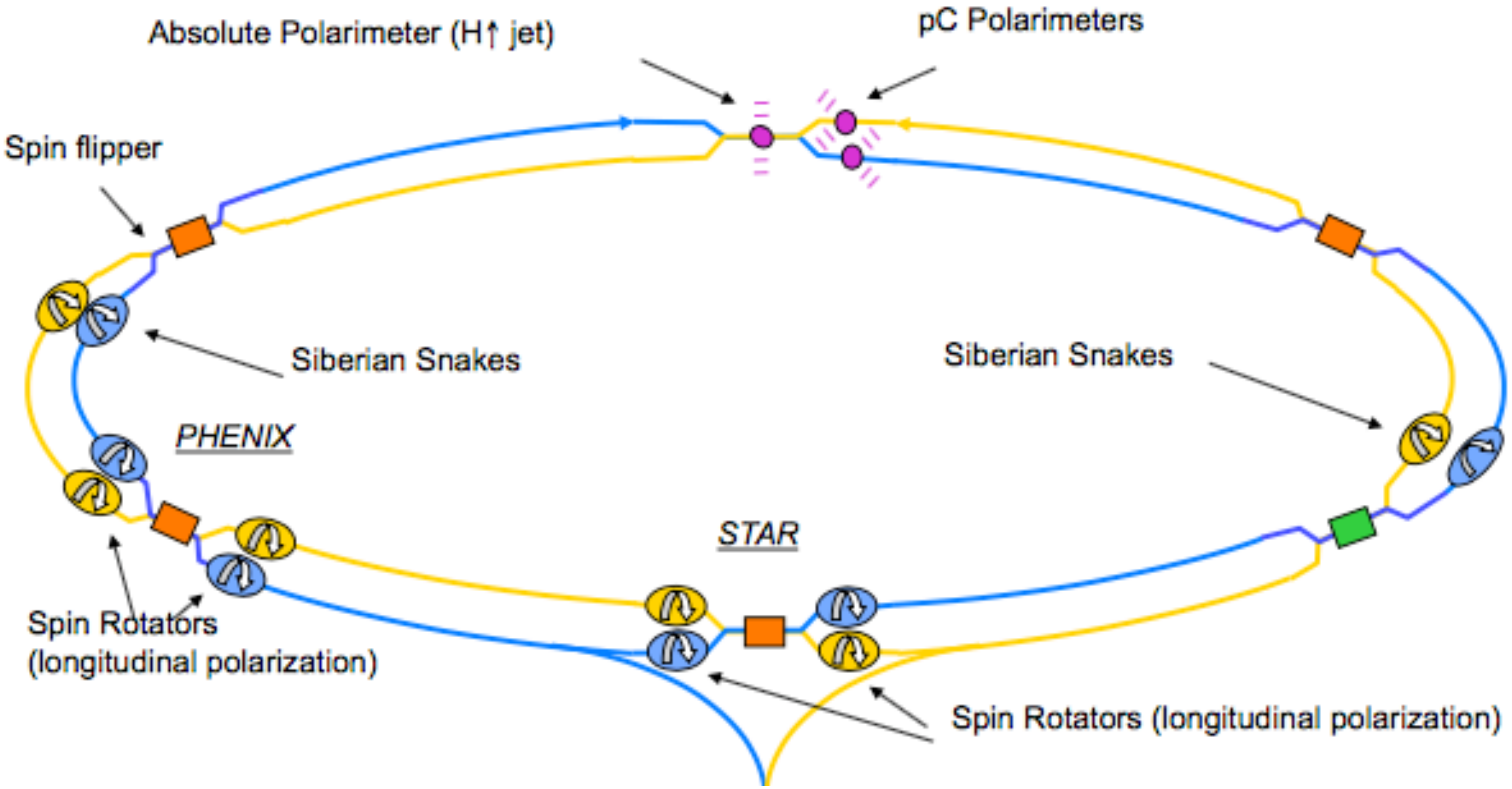
Graphics from Caroline Riedl's APS 2016 Talk

TSSAs in pA

RHIC Ring



Absolute Polarimeter (H↑ jet)
pC Polarimeters
Spin flipper
Siberian Snakes
Siberian Snakes
PHENIX
STAR
Spin Rotators
(longitudinal polarization)
Spin Rotators (longitudinal polarization)
LINAC
BOOSTER
5.9% Helical Partial
Siberian Snake
Pol. H⁻ Source
AGS
Int. Polarimeter
200 MeV Polarimeter
pC Polarimeter
10-25% Helical Partial Siberian Snake



Absolute Polarimeter (H↑ jet)
pC Polarimeters
Spin flipper
Siberian Snakes
Siberian Snakes
PHENIX
STAR
Spin Rotators
(longitudinal polarization)
Spin Rotators (longitudinal polarization)

RHIC Runs

PHENIX

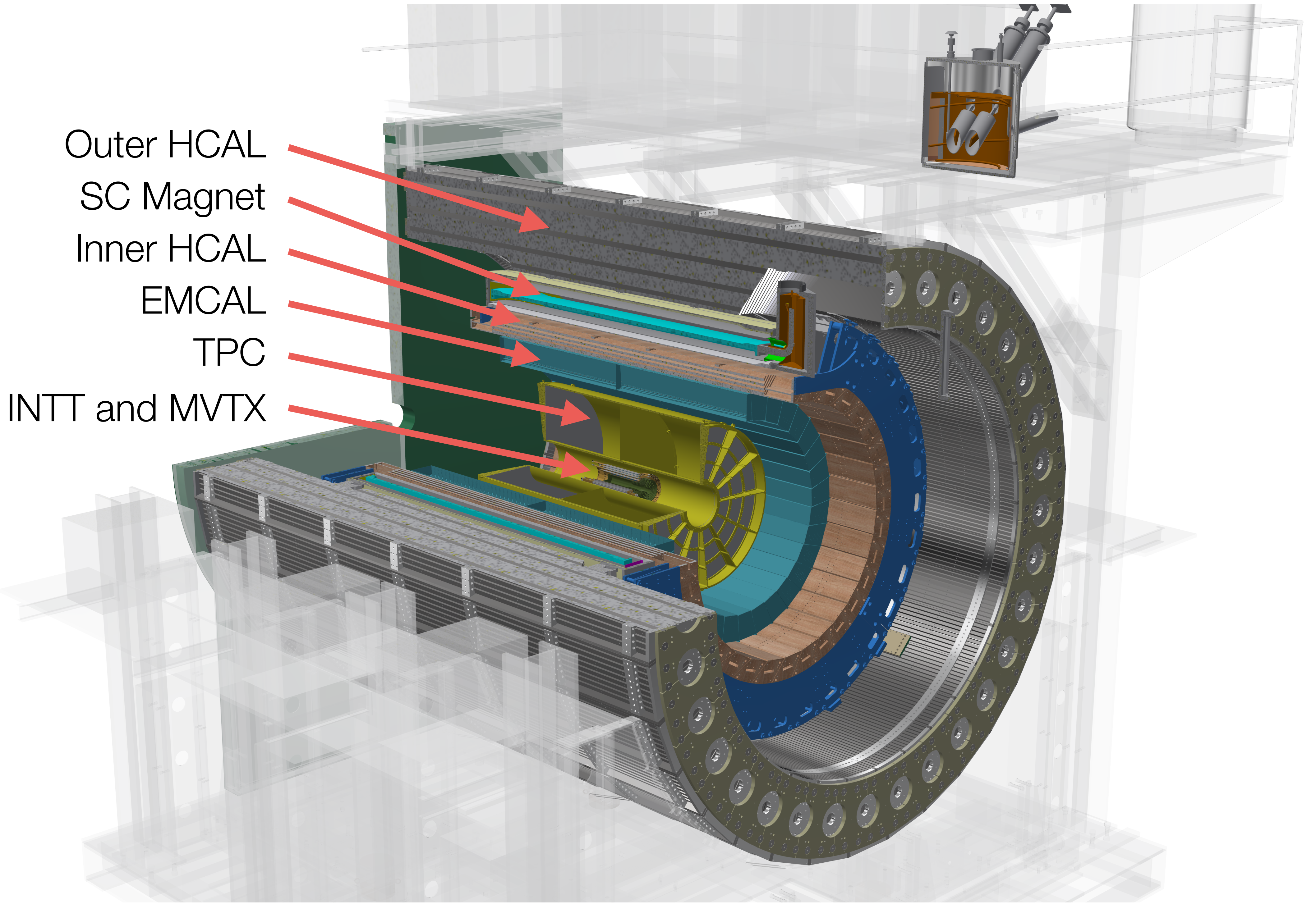
- Large datasets available in longitudinal and transverse polarizations
- Run 13:
  long 510GeV run
- Run 15:
  first p↑ on nuclei
- (Heavy Ion not shown)

Year	$\sqrt{s}$ (GeV)	Recorded Luminosity for longitudinally / transverse polarized p+p STAR	Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX	<P> in %
2006	62.4 200	-- pb^{-1} / 0.2 pb^{-1} 6.8 pb^{-1} / 8.5 pb^{-1}	0.08 pb^{-1} / 0.02 pb^{-1} 7.5 pb^{-1} / 2.7 pb^{-1}	48 57
2008	200	-- pb^{-1} / 7.8 pb^{-1}	-- pb^{-1} / 5.2 pb^{-1}	45
2009	200 500	25 pb^{-1} / -- pb^{-1} 10 pb^{-1} / -- pb^{-1}	16 pb^{-1} / -- pb^{-1} 14 pb^{-1} / -- pb^{-1}	55 39
2011	500	12 pb^{-1} / 25 pb^{-1}	18 pb^{-1} / -- pb^{-1}	48
2012	200 510	-- pb^{-1} / 22 pb^{-1} 82 pb^{-1} / -- pb^{-1}	-- pb^{-1} / 9.7 pb^{-1} 32 pb^{-1} / -- pb^{-1}	61/56 50/53
2013	510	300 pb^{-1} / -- pb^{-1}	155 pb^{-1}/ -- pb^{-1}	51/52
2015	200	52 pb^{-1} / 52 pb^{-1}	-- pb^{-1}/ 60 pb^{-1}	53/57
2015	200 *p* Au	total delivered Luminosity = 1.27 pb^{-1}		60
2015	200 *p* Al	total delivered Luminosity = 3.97 pb^{-1}		54

= Transversely polarized

sPHENIX

- 2π symmetric tracking and EM+H calorimetry at 15kHz readout



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