Recent Results and Future Plans of the Longitudinal Spin Program at STAR

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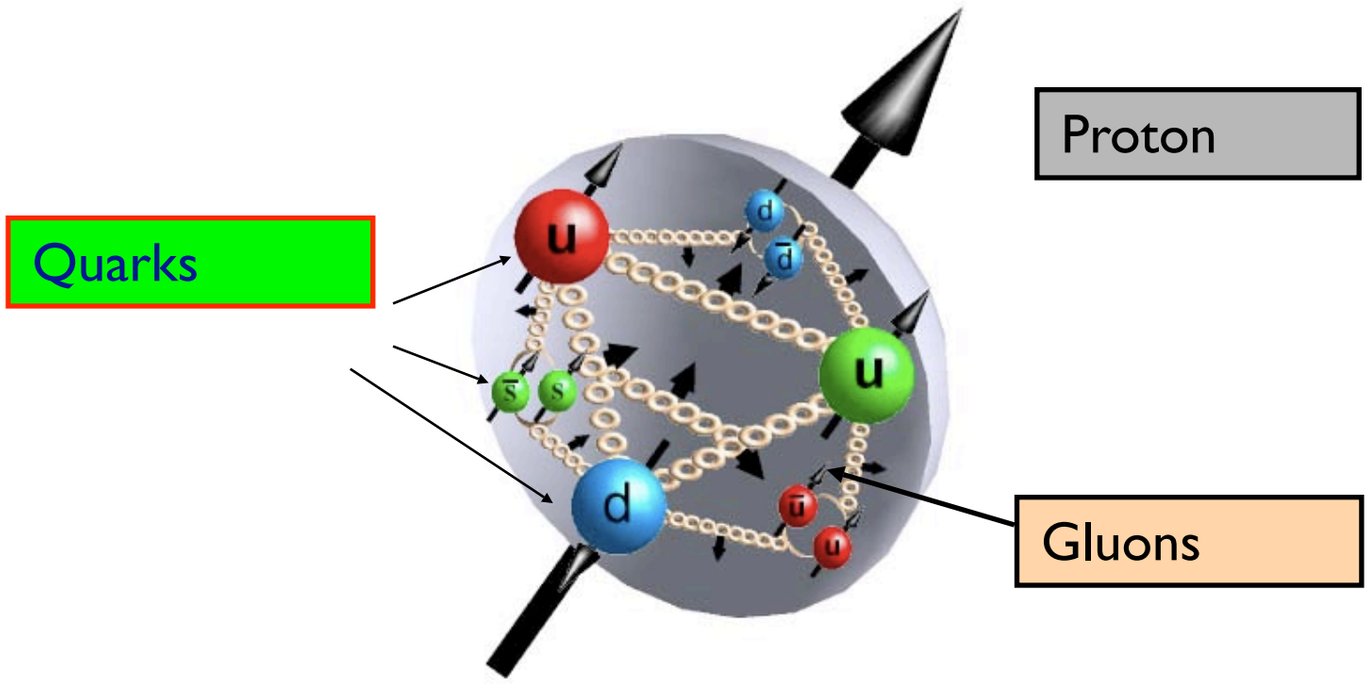
STAR

Excellence Cluster Universe

Motivation: The Spin Puzzle

- How do the quark and gluons combine to make up the exact 1/2 of the proton spin?



$$J_{PROTON} = \frac{1}{2} = \langle S_q \rangle + \langle S_G \rangle + \langle L_q \rangle + \langle L_g \rangle$$

Motivation: The Spin Puzzle

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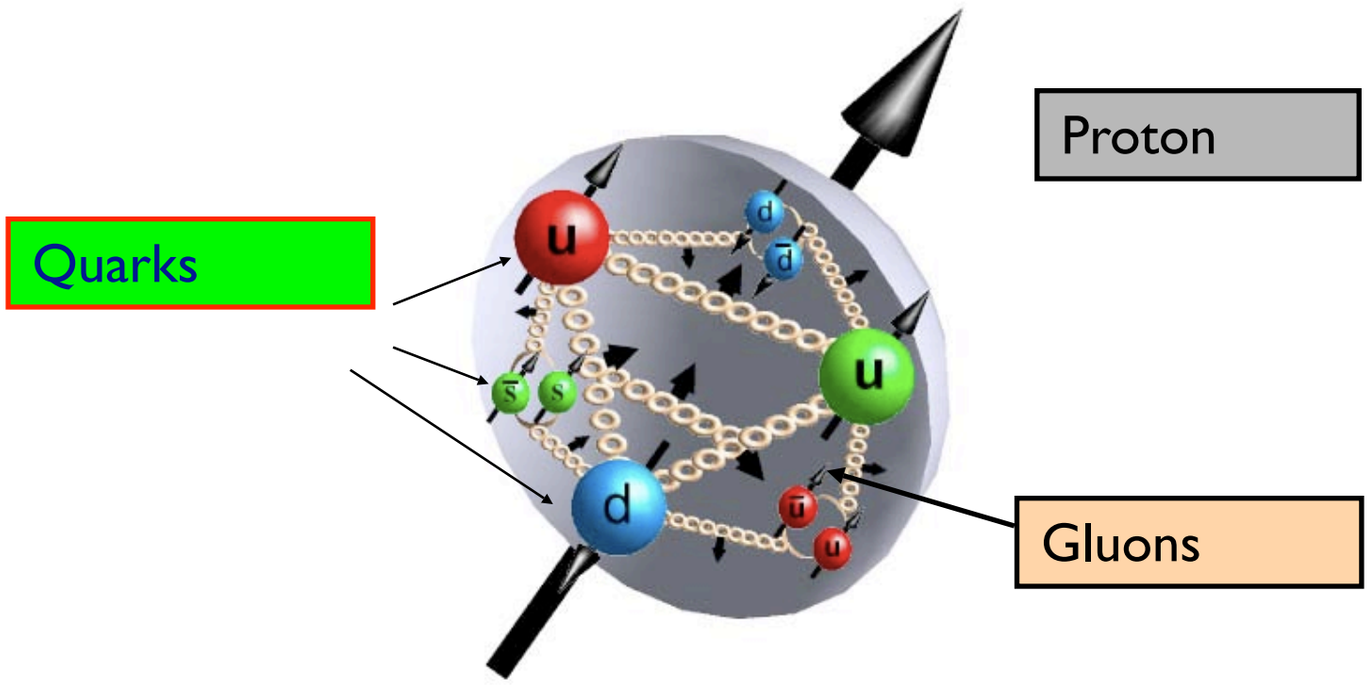
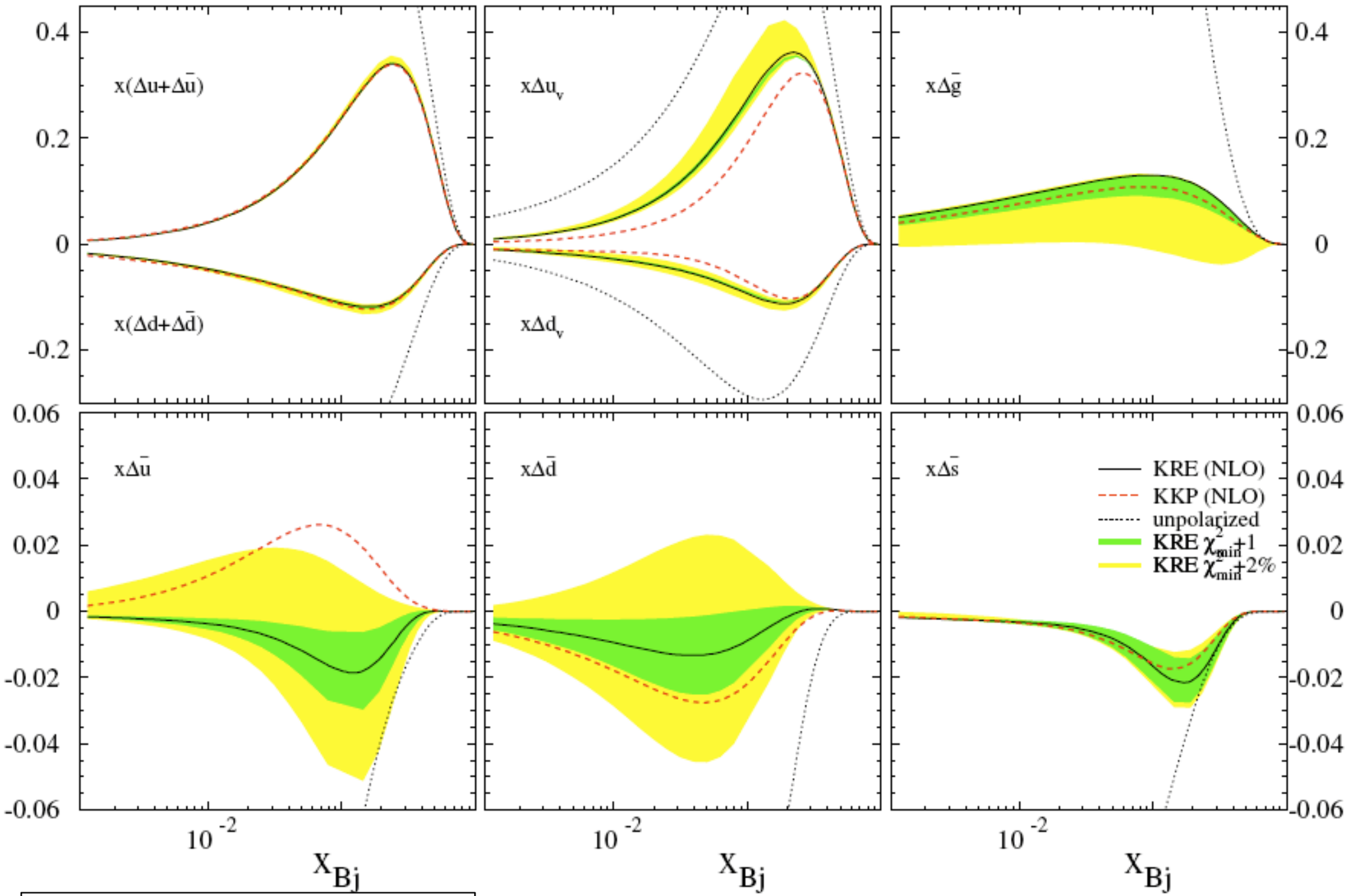


$$J_{PROTON} = \frac{1}{2} = \left\langle S_q \right\rangle + \left\langle S_G \right\rangle + \left\langle L_q \right\rangle + \left\langle L_g \right\rangle$$

only component known precisely to date, about 1/3 of total spin

Motivation: What do we know (before RHIC)?



D. de Florian et al. Phys. Rev. D71 094018 (2005)

Outline

1. Experimental Tools

- Polarized protons as a probe for the spin structure of the nucleon
- RHIC and the STAR experiment

2. Determining ΔG

- Accessing the gluon polarization in p+p collisions
- Inclusive probes at STAR: Jets, neutral and charged hadrons

3. Future Probes for ΔG

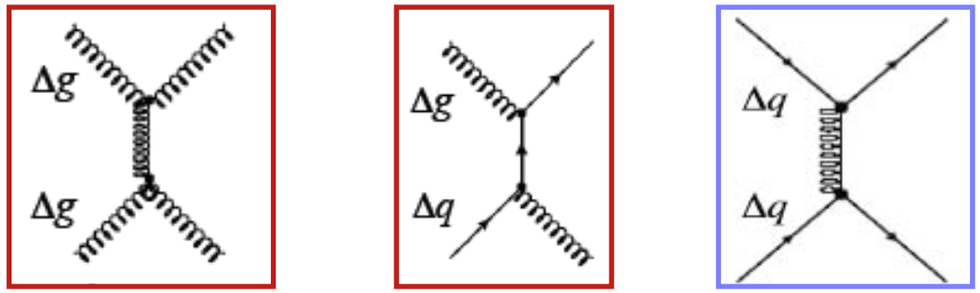
- Constraining distribution functions with correlation measurements

4. Accessing Quark Polarizations

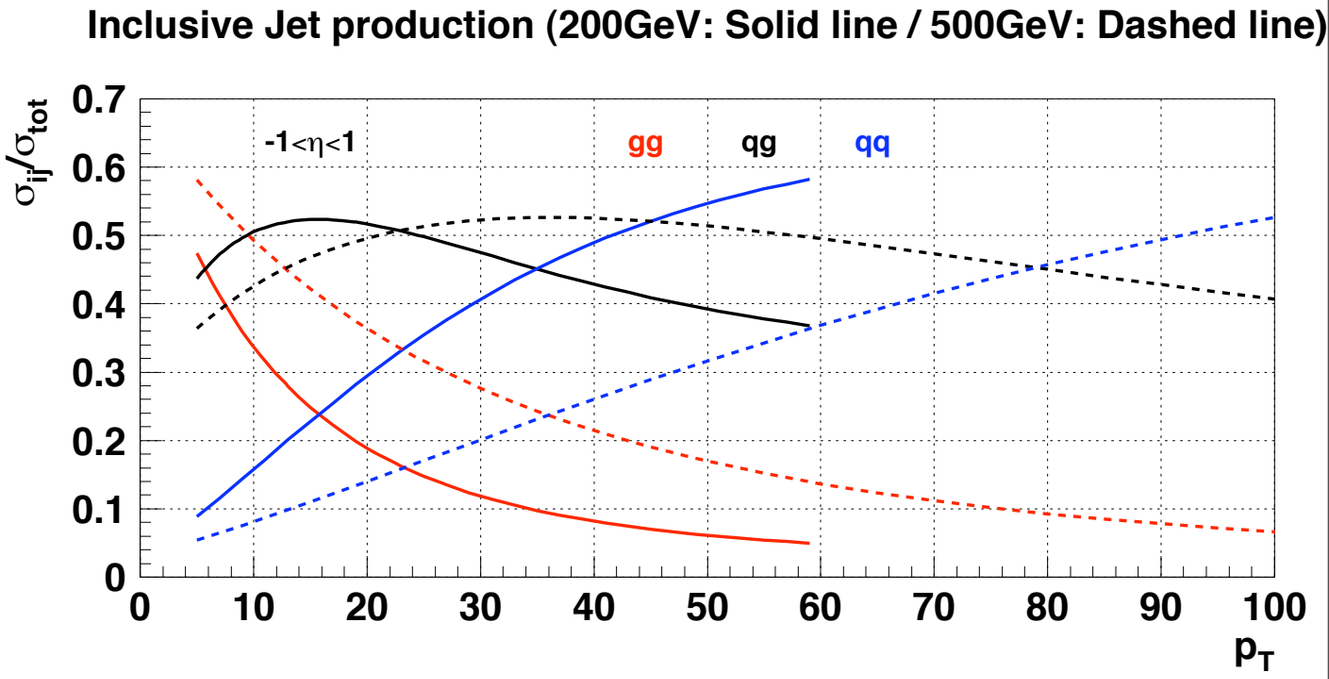
- W boson production at RHIC
- Forward tracking upgrade

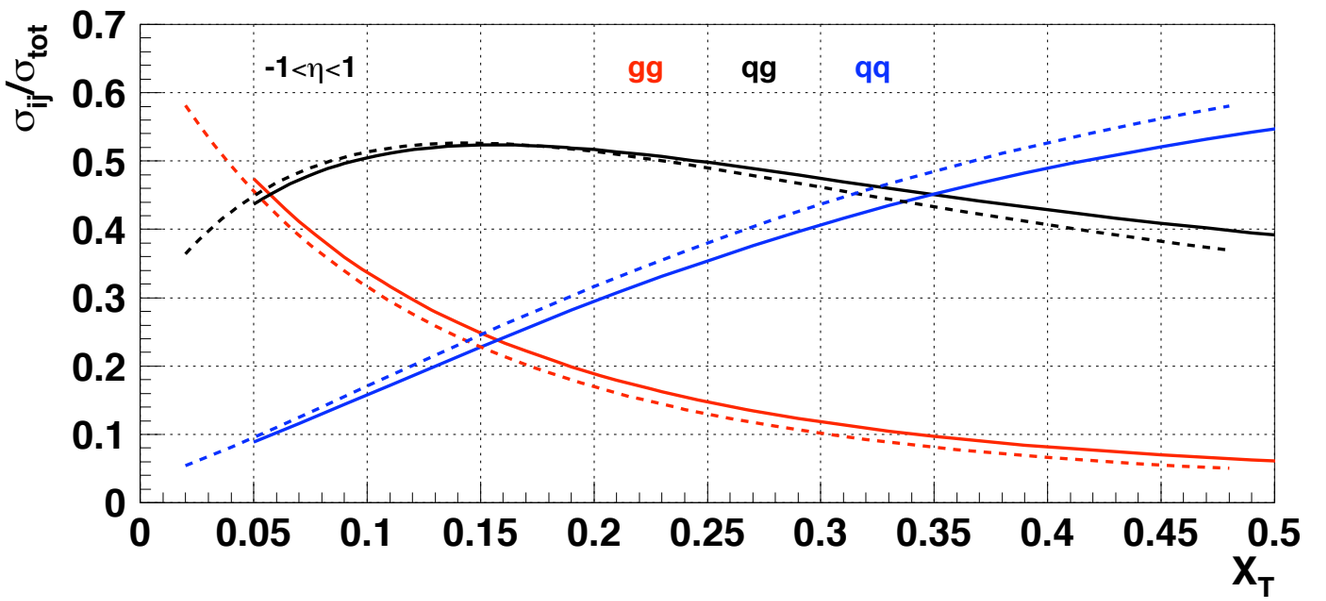
I. Experimental Tools

Polarized Protons to probe the Nucleon Spin Structure



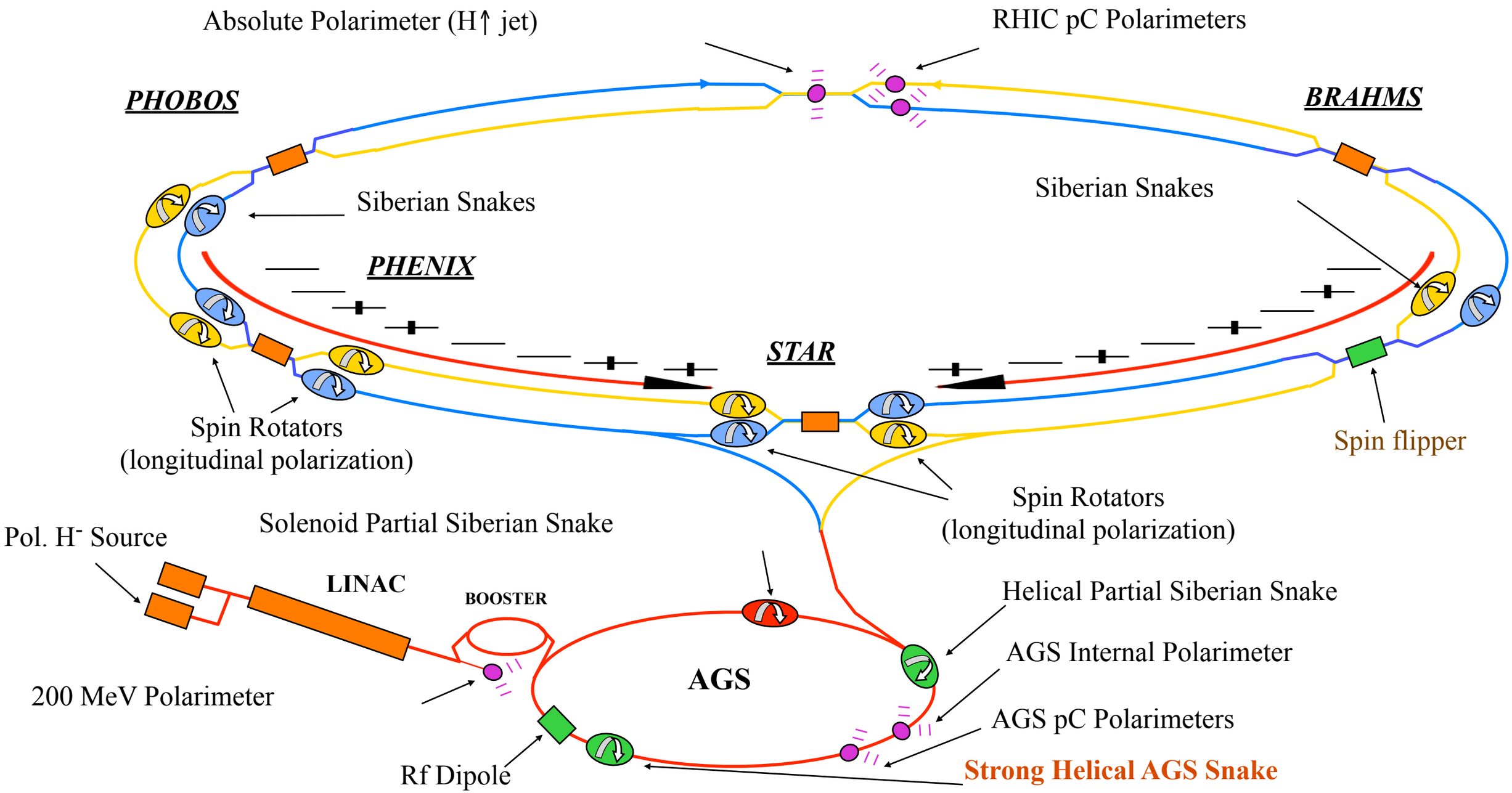
- At Leading Order
- Via g+g and q+g scattering
- Inclusive signals are diluted by q-q scattering, but relatively well studied in the kinematic regime.
- Underlying event complicates signal/ scale extraction
- Collider (theoretically) allows a wide range of CM energy scales
- Opposing strengths & weakness make pp and DIS complementary programs



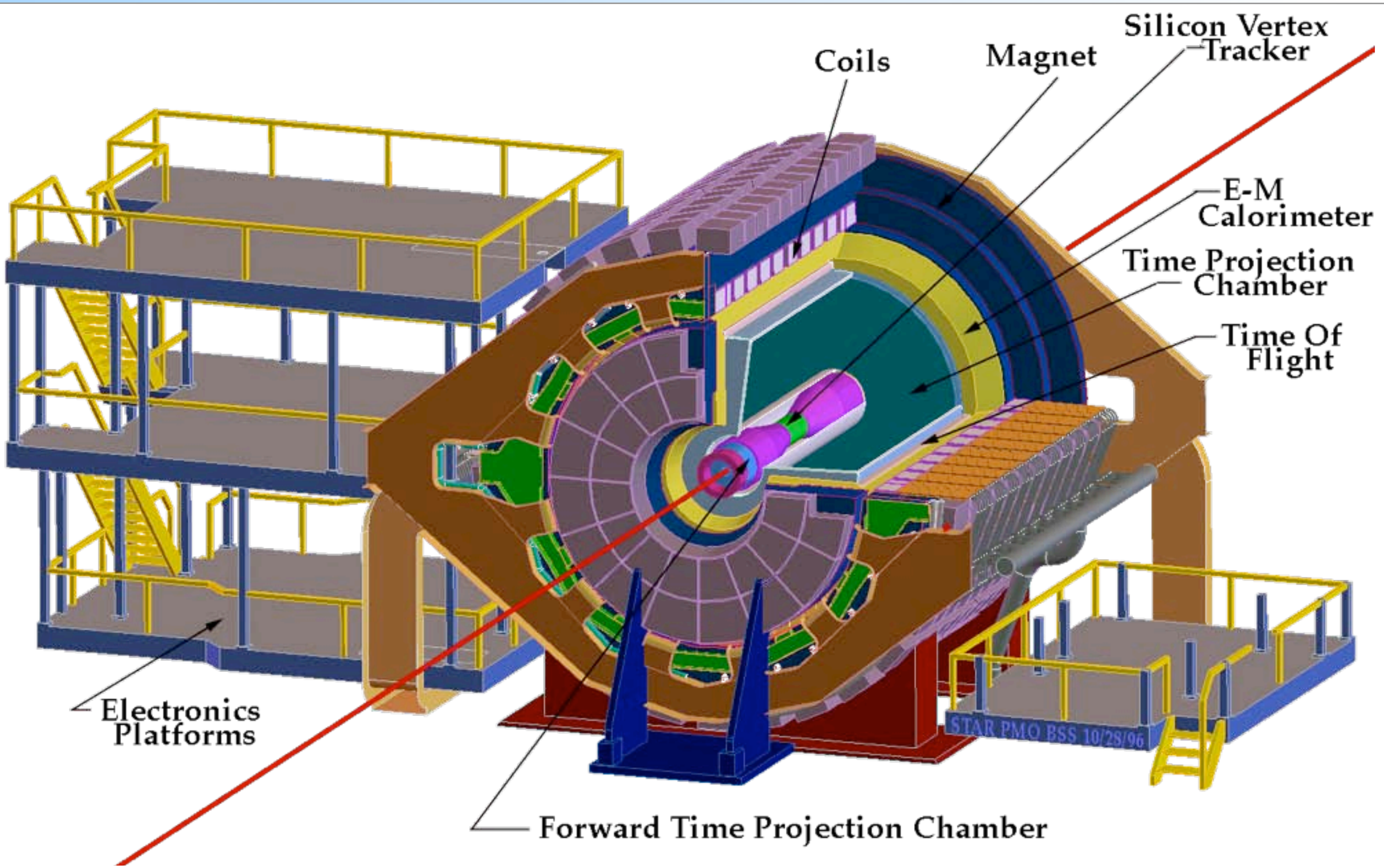


$$x_T = \frac{2\,p_T}{\sqrt{s}}$$

RHIC: The World's first Polarized p+p Collider

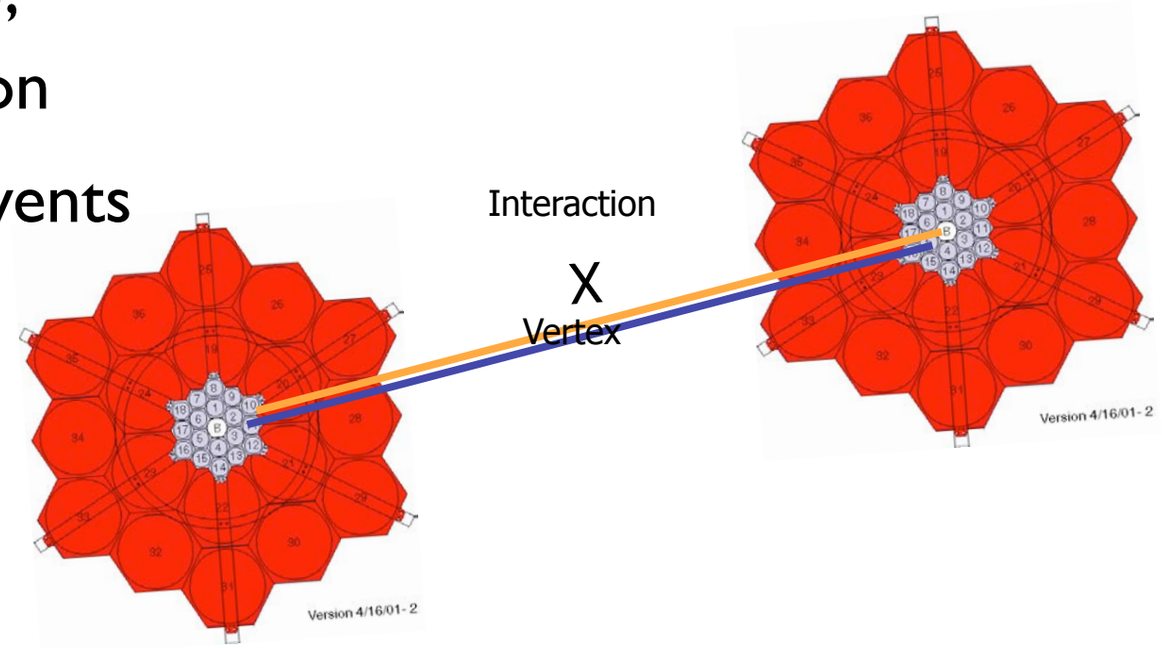


The STAR Detector

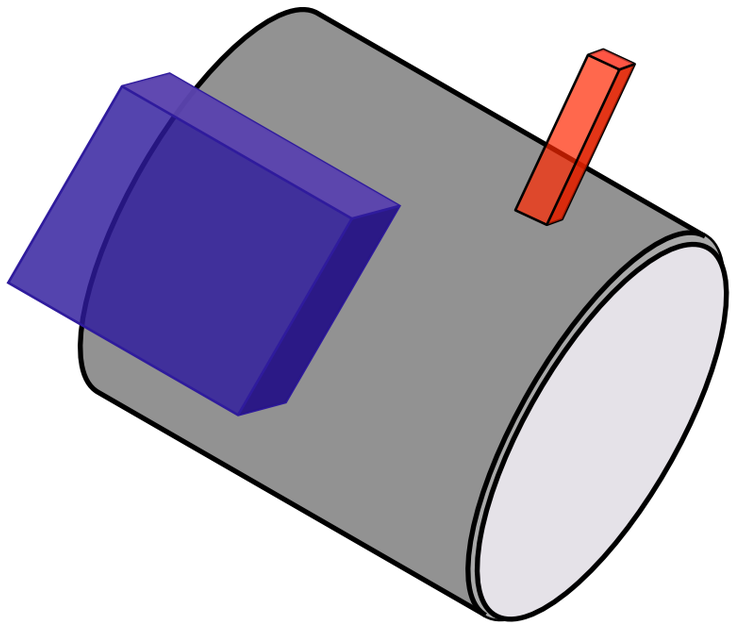


The STAR Trigger

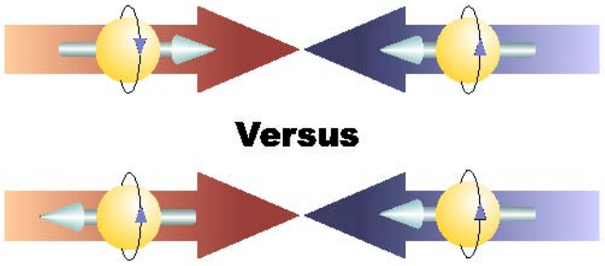
- Main trigger: Beam Beam Counters (BBC), coincidence of both sides of the interaction
- trigger on non singularly diffractive p+p events



- additional trigger on high electromagnetic energy deposit in the calorimeters
  - High tower trigger (HT): ($\Delta\eta x \Delta\varphi = 0.05 \times 0.05$)
  - Jet patch trigger (JP): ($\Delta\eta x \Delta\varphi = 1.0 \times 1.0$)
- + more sophisticated Level-2 triggers to select photon and pion candidates



Longitudinal Spin Physics: Asymmetry Measurements



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \times \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}, \text{FOM} \sim P_1^2 P_2^2 \cdot \int \mathcal{L} dt$$

Ingredients:

- Polarization: measured by RHIC polarimeters
- Relative Luminosity R measured with the STAR BBC & scaler system (relative luminosities for each bunch crossing available)

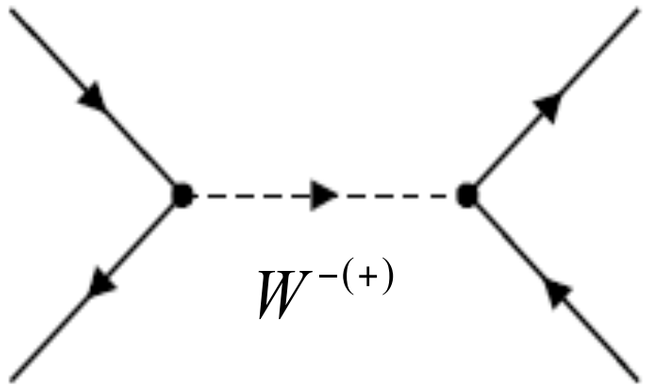
$$R = \frac{L_{++}}{L_{+-}}$$

- Spin dependent yields N_{++}, N_{+-} : number of detected particles for a given combination of beam polarization directions

Flavor Structure of the Proton Spin

- Flavor structure of the proton sea can be probed via $W^{\pm}$ production: flavor separation possible

$$d + \bar{u} \rightarrow W^-$$
$$\bar{d} + u \rightarrow W^+$$



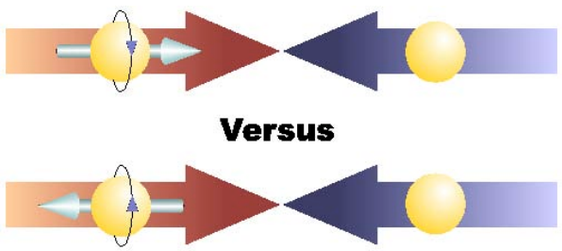
$$W^- \rightarrow e^- + \bar{\nu}_e$$
$$W^+ \rightarrow e^+ + \nu_e$$

RHIC: 500 GeV CME in p+p collisions

⇨the quark is usually a valence quark (large x)

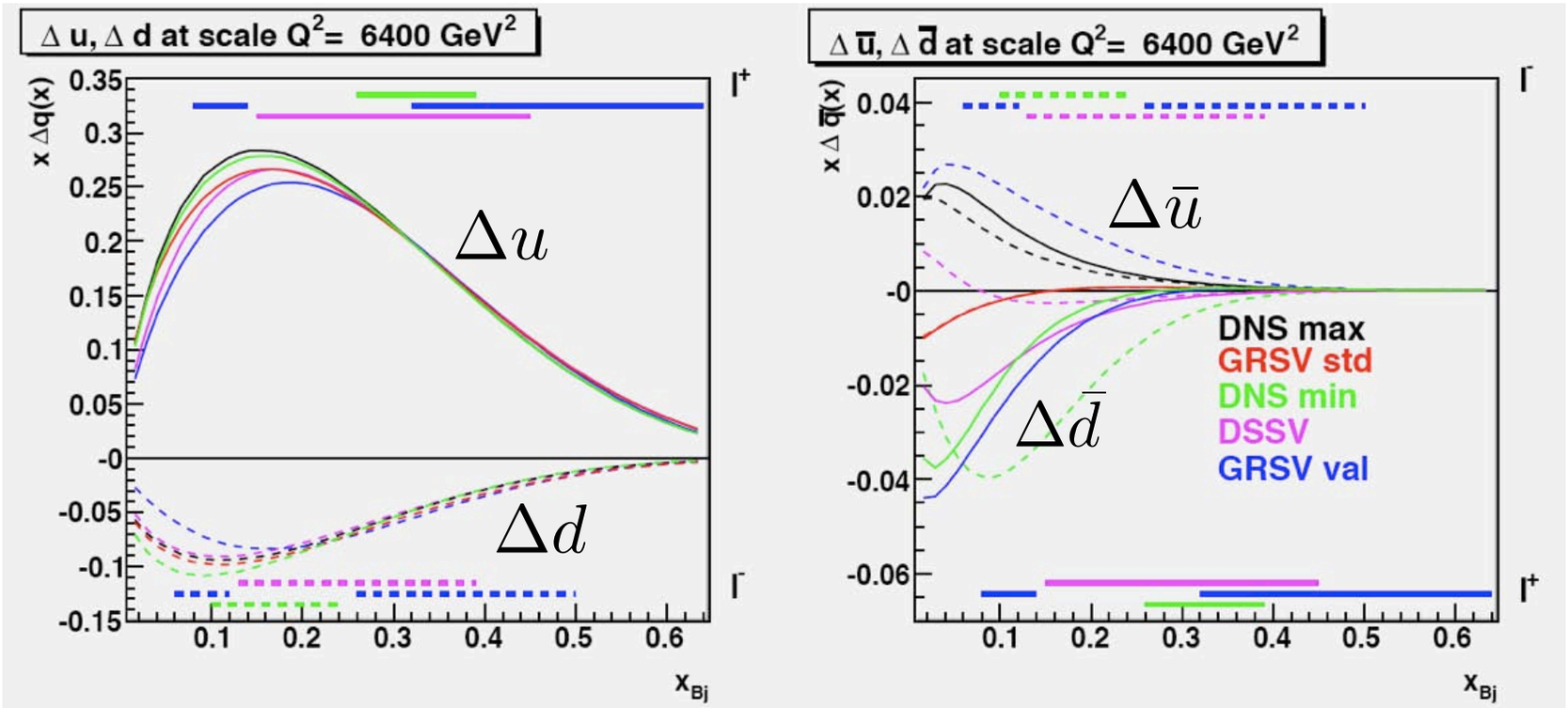
⇨contributions from s, c quarks are small

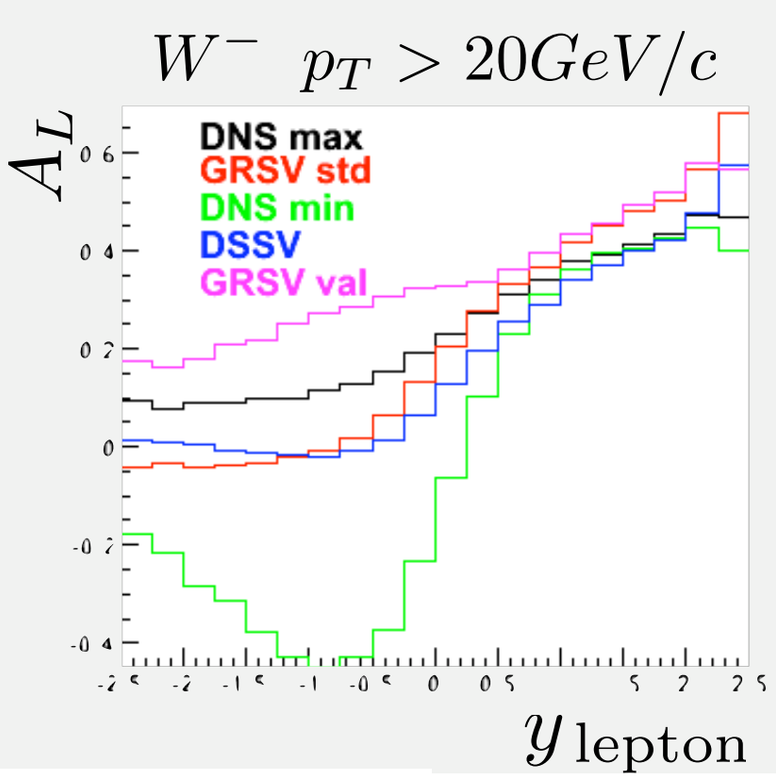
- Measure parity-violating single spin asymmetries:

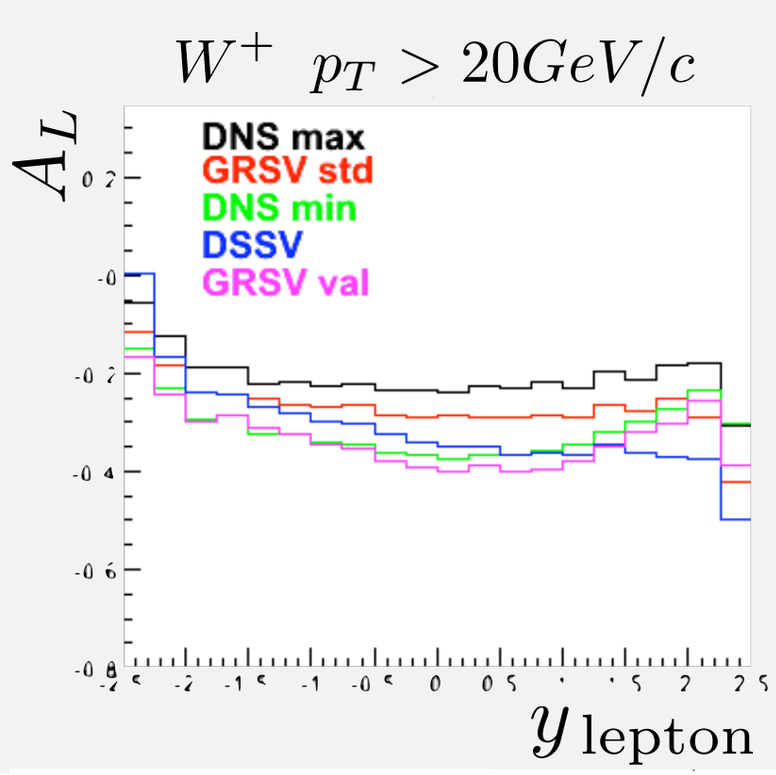


$$A_L^{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Quark / Anti-Quark Polarizations





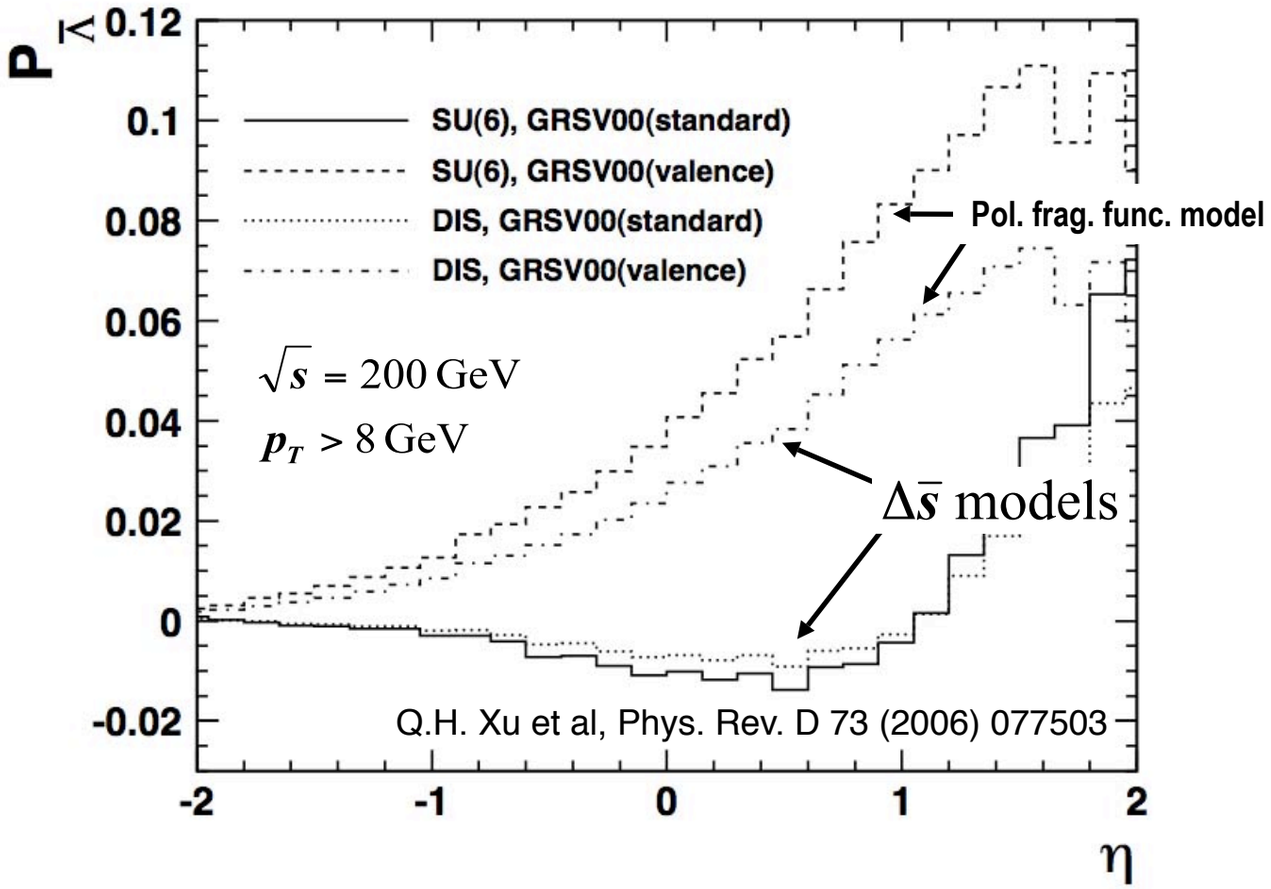


- Valence Quark polarizations well determined
- Large uncertainties for sea quarks: reflected in anti-quark polarizations

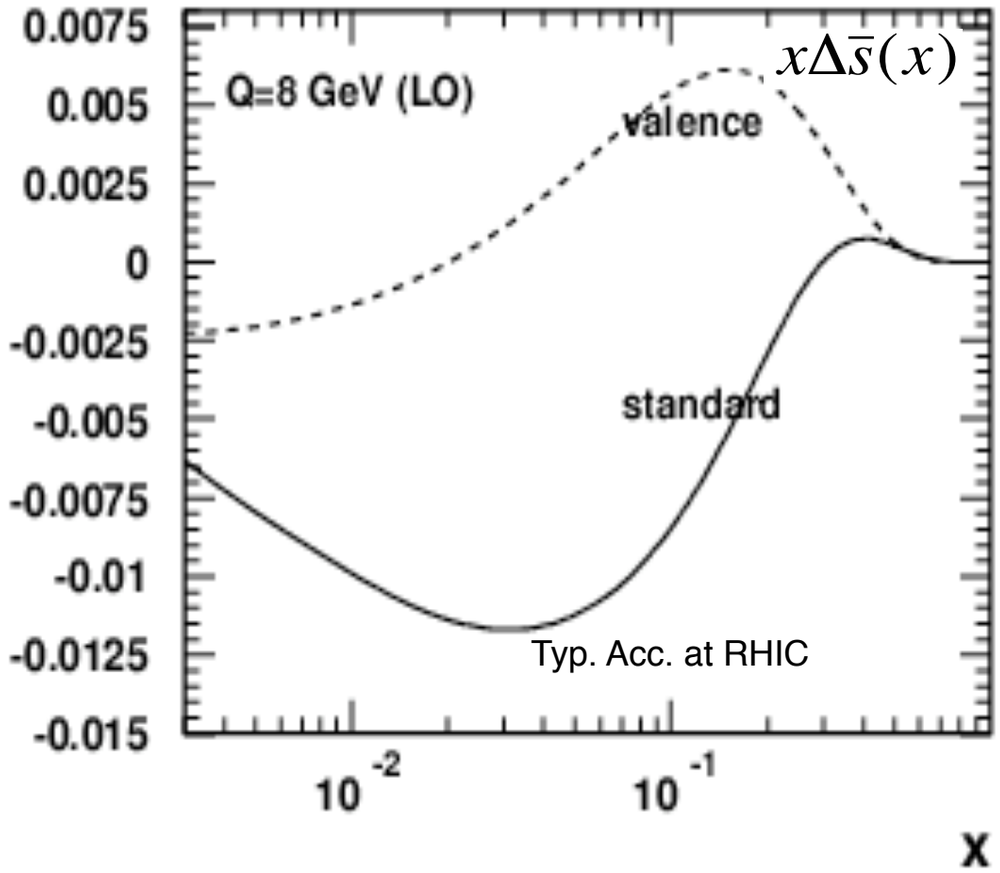
- Particularly good discrimination between models at forward (or backward) rapidities

Strange Quark Polarizations

- The polarization of anti-strange quarks in the proton can be probed via the polarization of Anti-Lambdas



GRSV00 - M. Glück et al Phys.Rev.D63 (2001) 094005



- Measurement: Longitudinal Spin transfer D_{LL}, the Lambda polarization for a given beam helicity
  - Lambda polarization measured from angular distribution of decay into p π

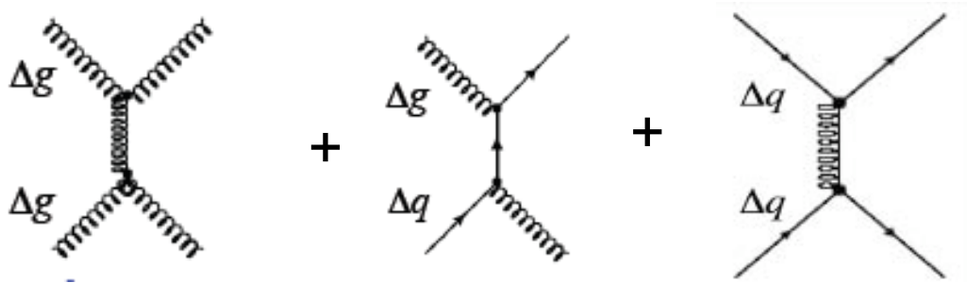
II. Determining ΔG

Accessing Δg at a Proton Collider

longitudinal spin asymmetry

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \sum_{f_A f_B} \frac{\Delta f_A \Delta f_B \times \Delta\sigma_{AB\to CX} \times D_C}{f_A f_B \times \sigma_{AB\to CX} \times D_C}$$

Phase 1

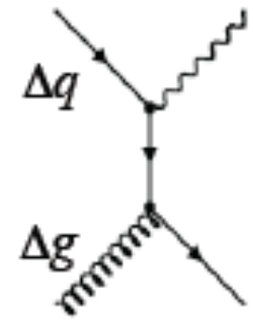


$\vec{p}\vec{p} \to \pi^{+/-} + X$
$\vec{p}\vec{p} \to \pi^{0} + X$
Requires D_{AB}^{π} for interpretation

$\vec{p}\vec{p} \to jet + X$
No FF! Average over partonic kinematics

$\vec{p}\vec{p} \to jet + jet$
No FF! Reconstruct partonic kinematics. Statistically limited until 2006.

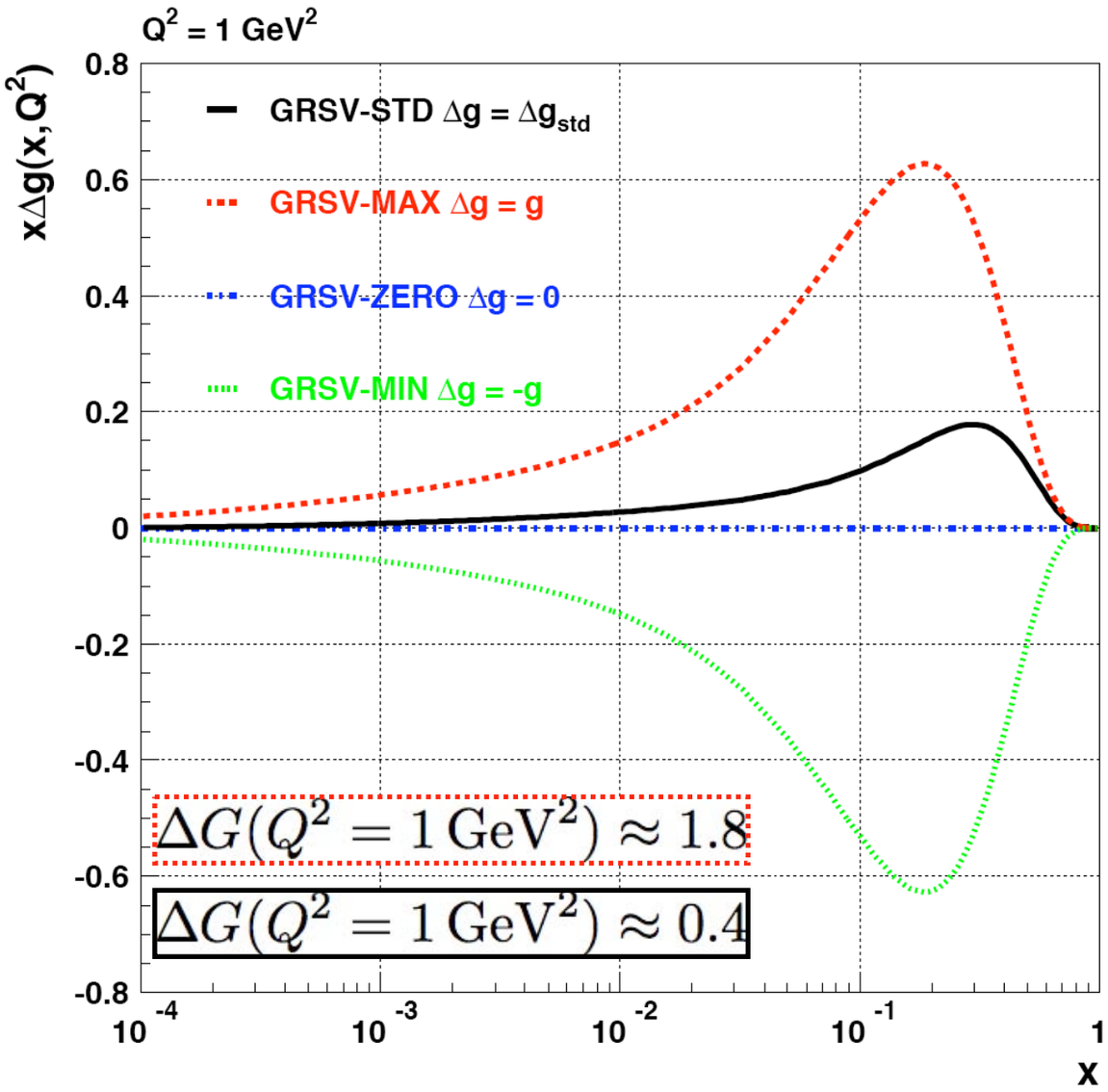
Phase 2



$\vec{p}\vec{p} \to jet + \gamma$
$\vec{p}\vec{p} \to \gamma + X$

- Reconstruction of partonic kinematics
- Statistically limited - requires high luminosity
- challenging pion background subtraction

Models for the Gluon Polarisation I

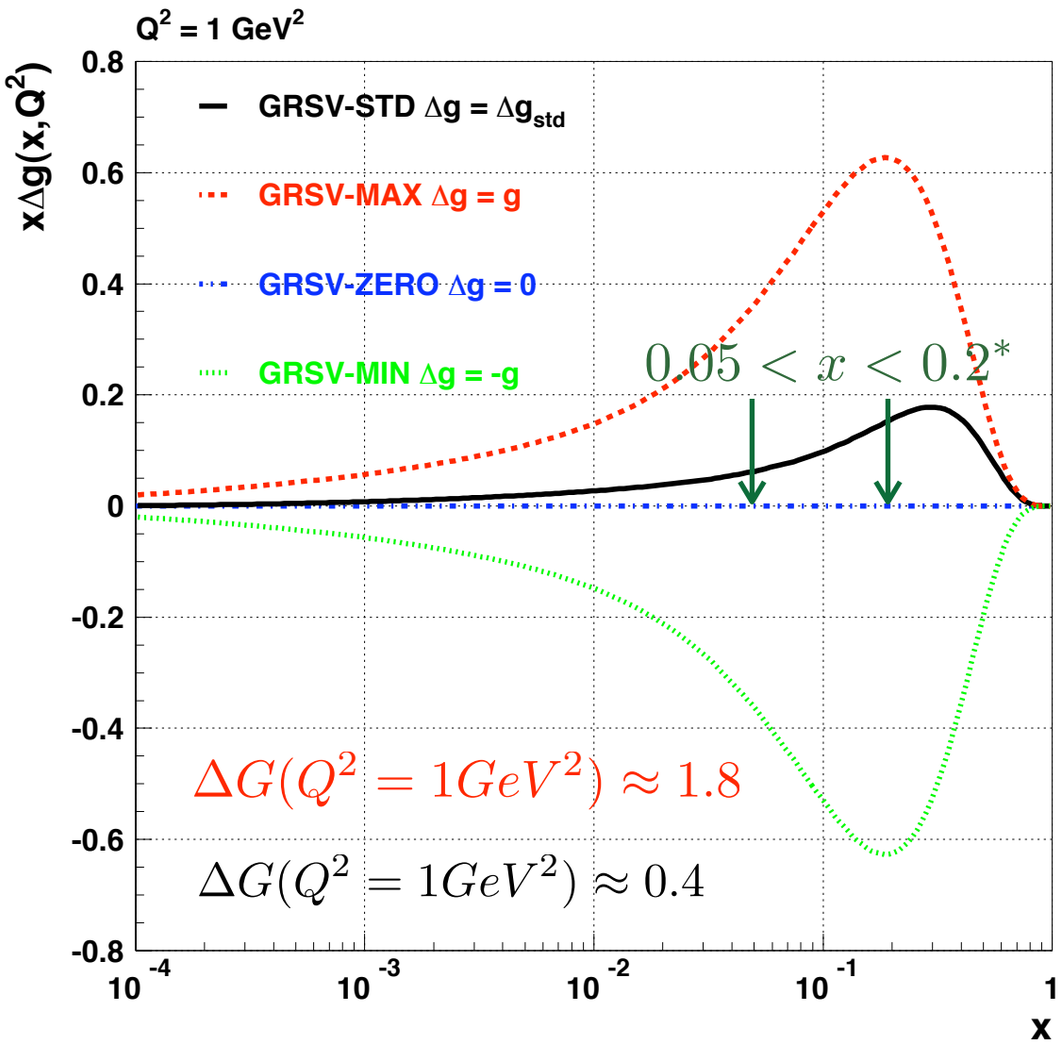


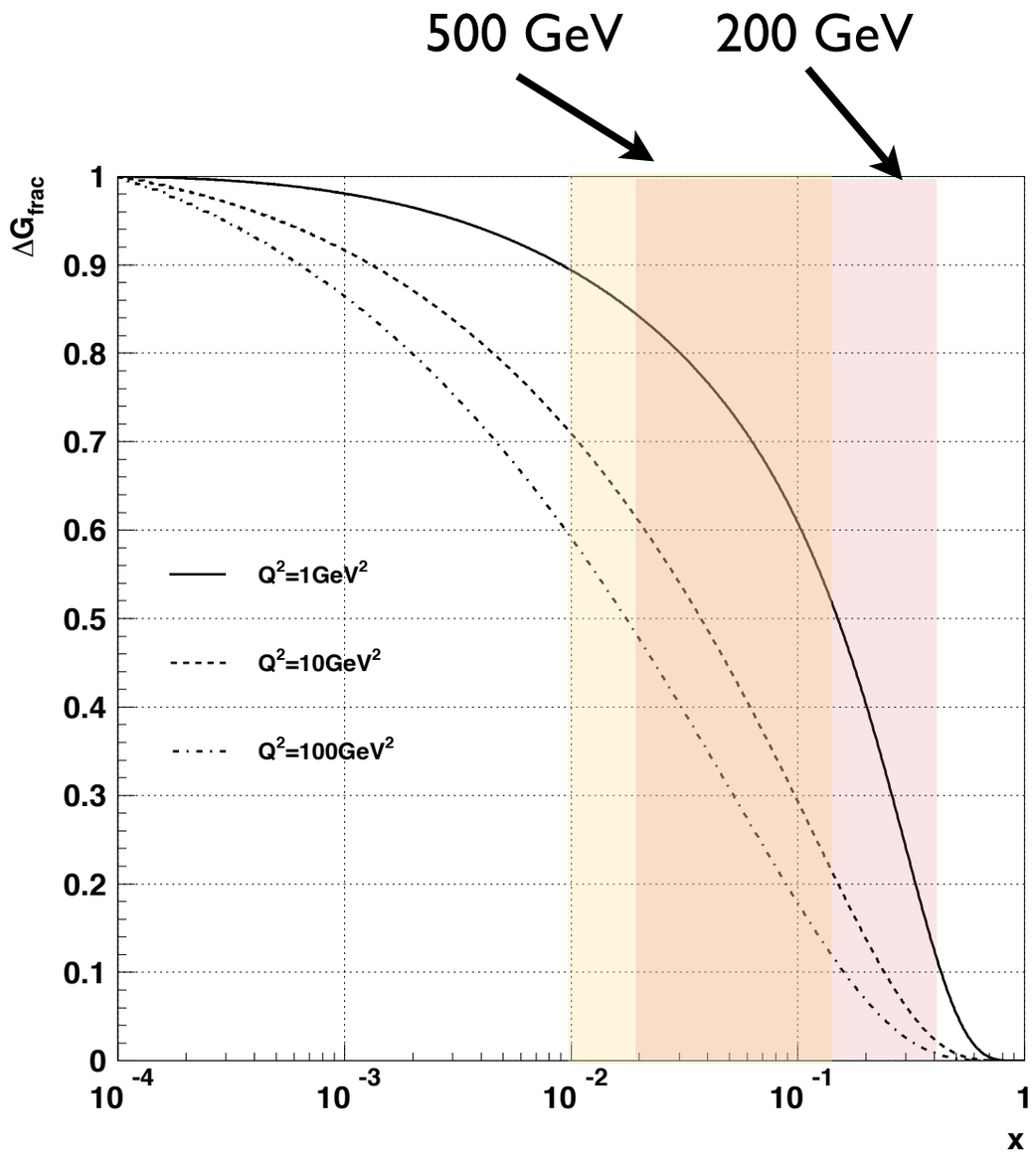
$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$

- For comparisons of data to theory four scenarios are used:
  (PRD63, 094005 (2001)
  PRD70, 034010 (2004))
  - GRSV-STD: Best fit to DIS data
  - GRSV-ZERO: No gluon polarization
  - GRSV-MAX: Maximal positive gluon polarization
  - GRSV-MIN: Maximal negative gluon polarization

- Based on NLO pQCD Calculations

Kinematic Coverage



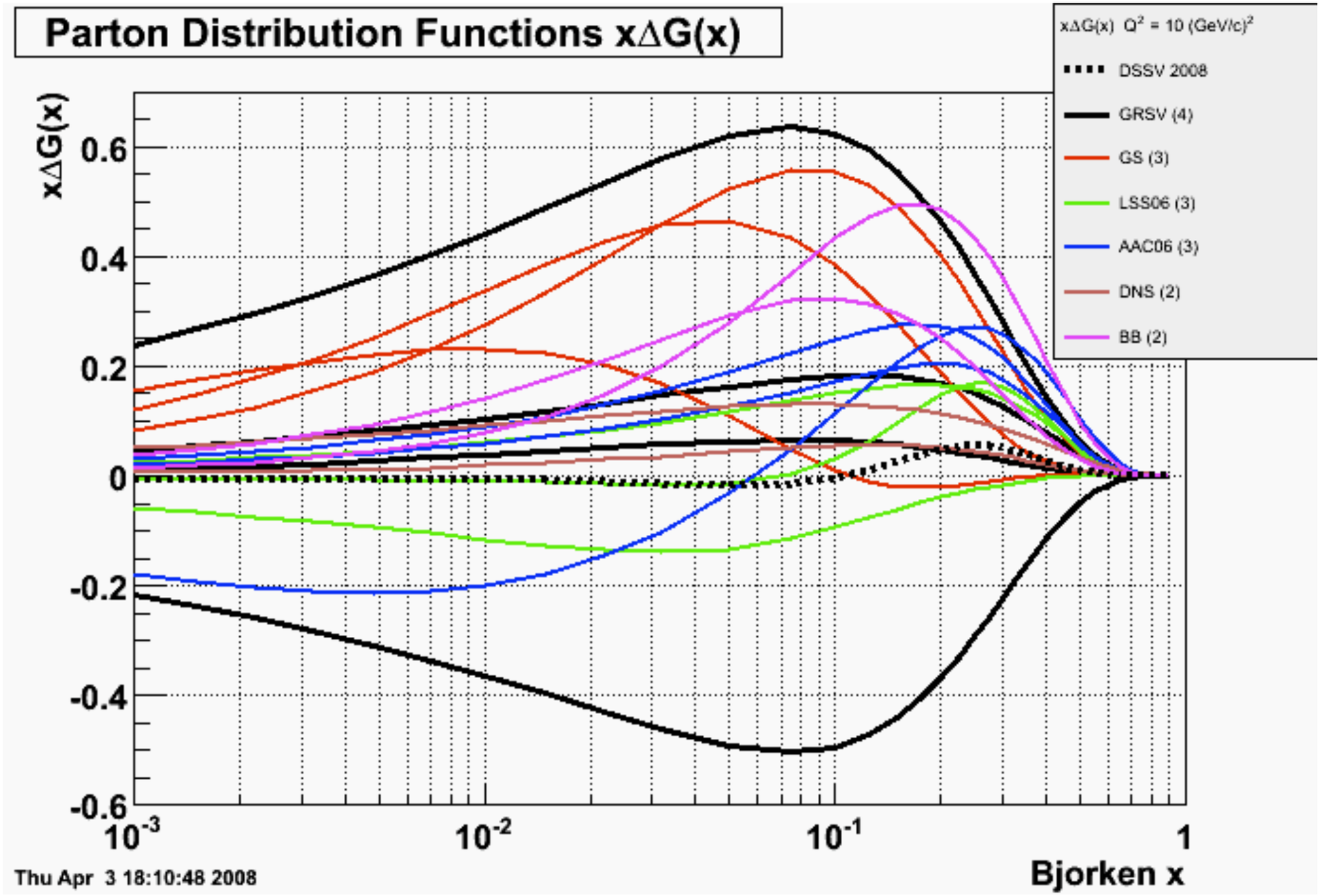


* used in global analysis

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$$

- Different center of mass energies allow to explore a wide kinematic region in x

Models for the Gluon Polarization II



- A large variety of global analyses of polarized DIS data, one including RHIC results (DSSV 2008)

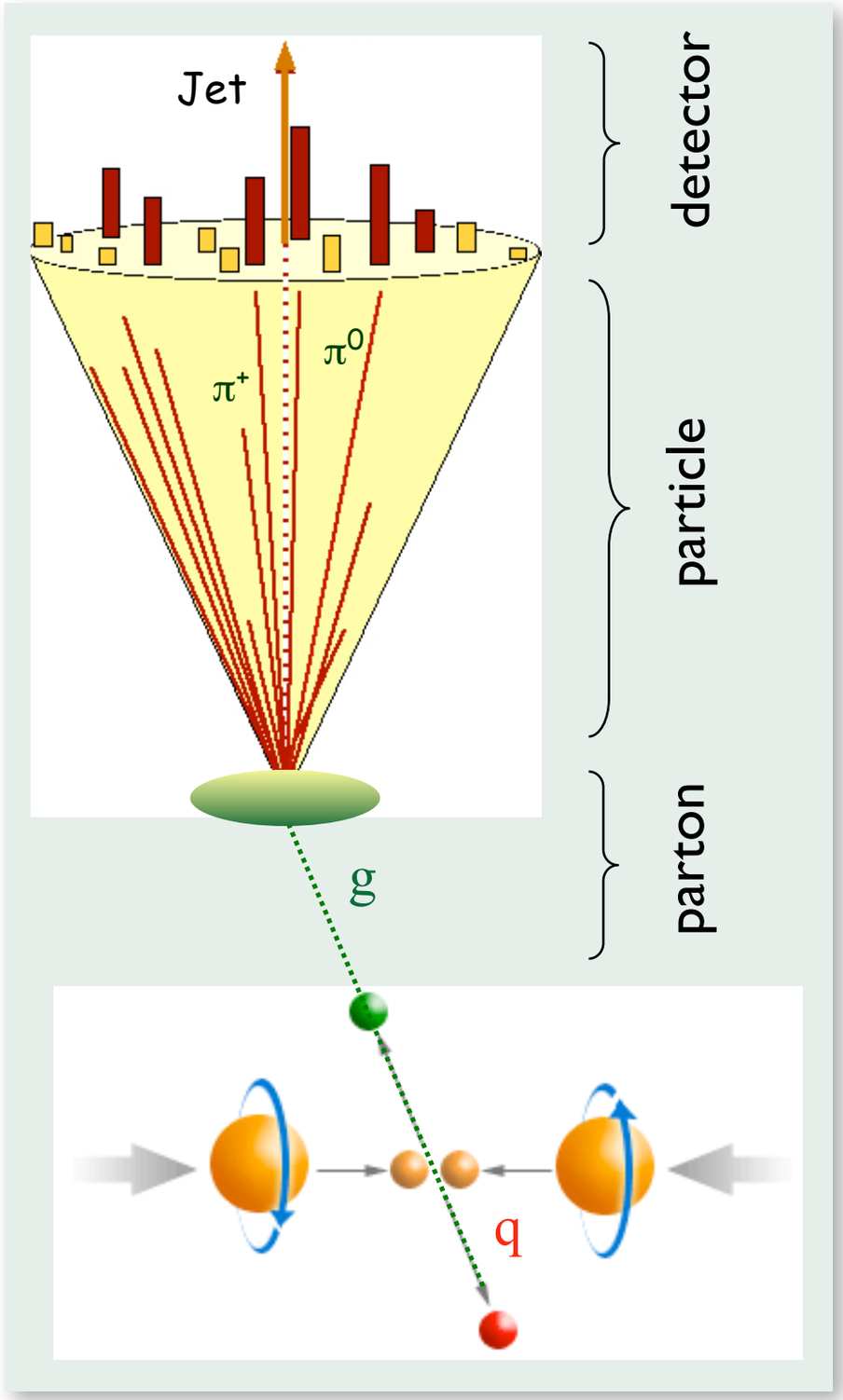
Probes for ΔG @ STAR

- Flagship Measurement: Inclusive Jets
  - Uses STAR main TPC, Electromagnetic Calorimetry
- Inclusive Hadrons:
  - Neutral Pions, identified with the electromagnetic calorimeters (both barrel and endcap)
  - Charged Pions, identified via specific energy loss in the main TPC

- Connection to gluon polarization:
  - through comparison with NLO pQCD calculations with fixed ΔG
  - global analysis allows to extract ΔG

- All probes use the same underlying processes
- Different systematics in each measurement

Jet Finding in STAR



Midpoint Cone Algorithm (hep-ex/0005012)

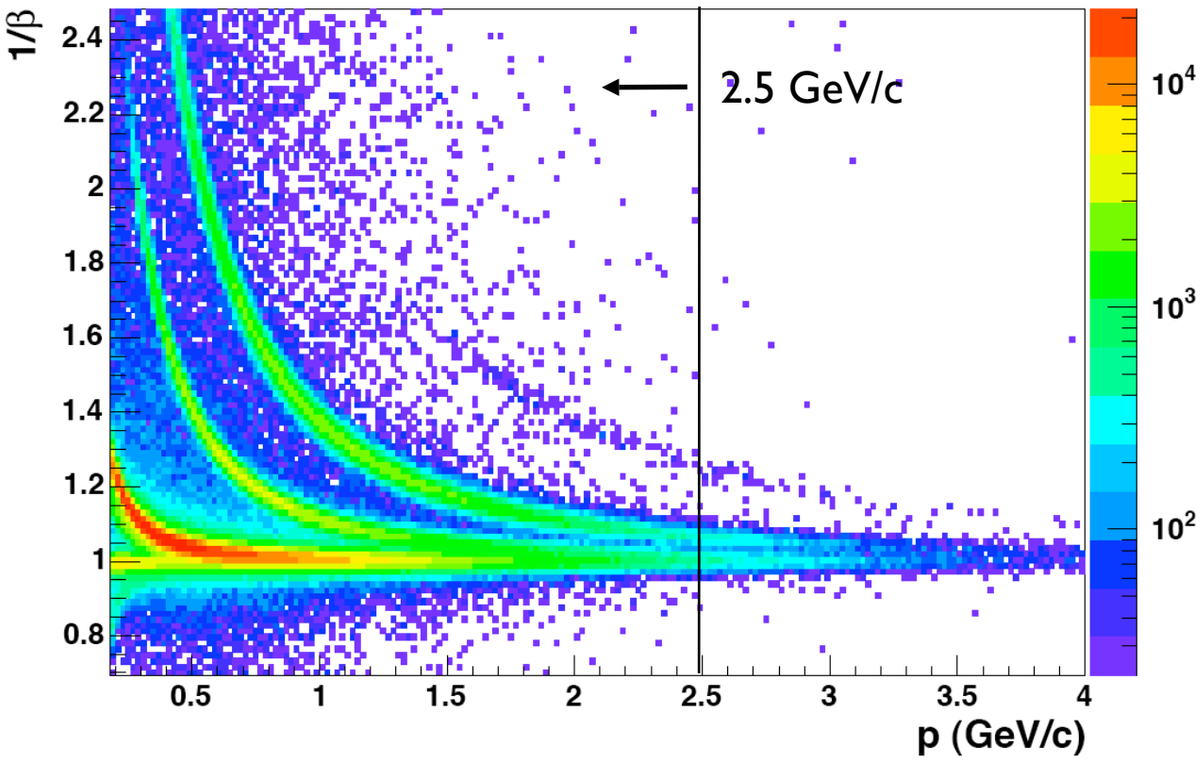
- Collinear and infrared safe -

- Jet Cone Radius = 0.4 / 0.7 (from 2006 on)
- Split/Merge = 0.5
- Neutral Energy Cut R < 0.8(0.9) to remove backgrounds
- Use Simulation (MC) to provide correction to RAW jet yield
  PYTHIA 6.205 (CDF Tune A) + GEANT (Geisha)

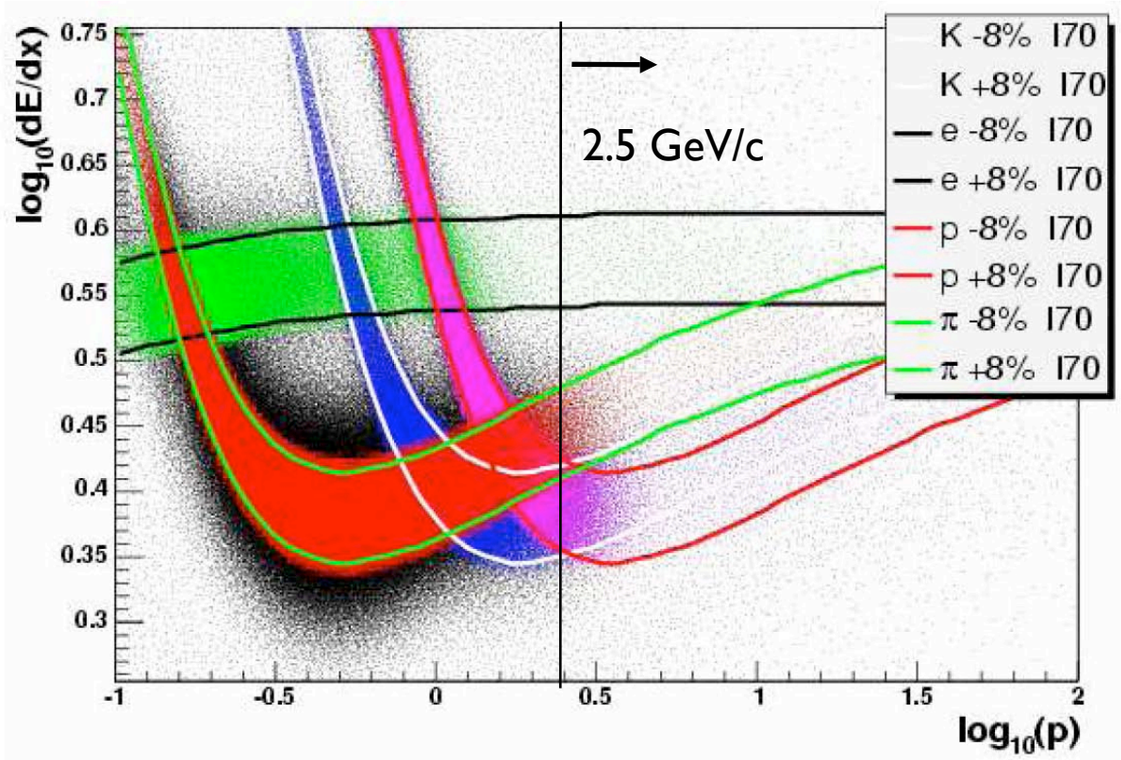
$$\text{Corrected Jet Yield} = \text{DATA JETS} \times \frac{\text{PYTHIA JETS}}{\text{GEANT JETS}}$$

Charged Pions: Extraction

low p_t: particle ID via TOF

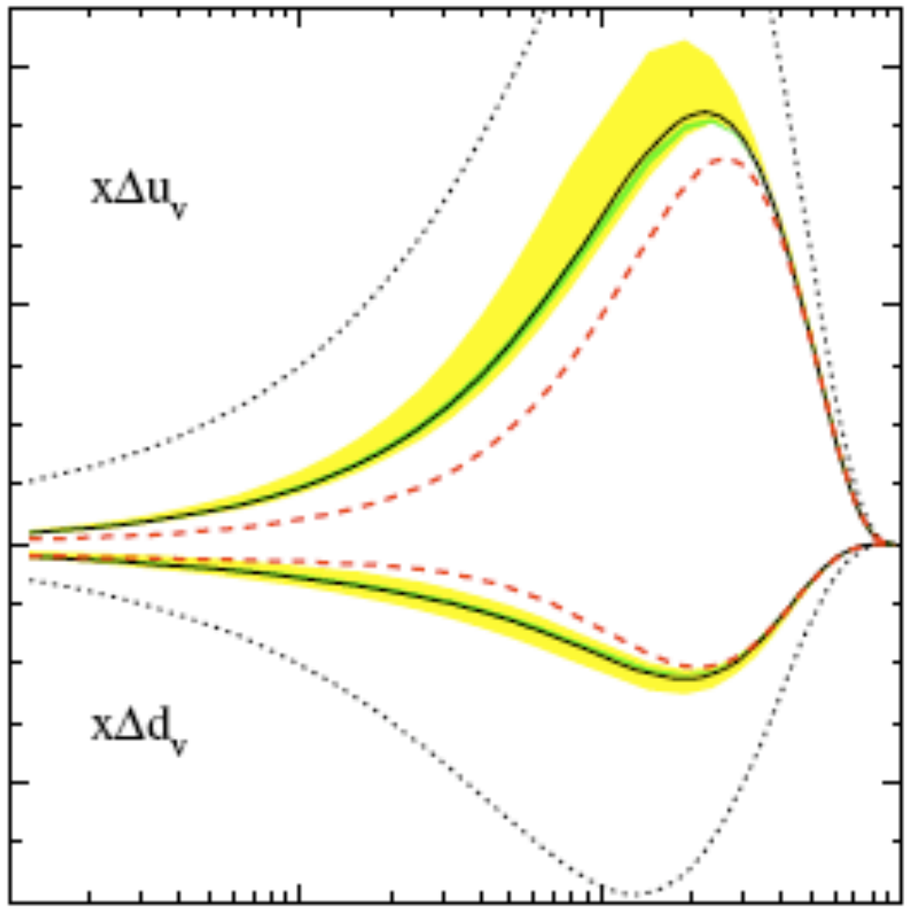


high p_t: particle ID via TPC dE/dx



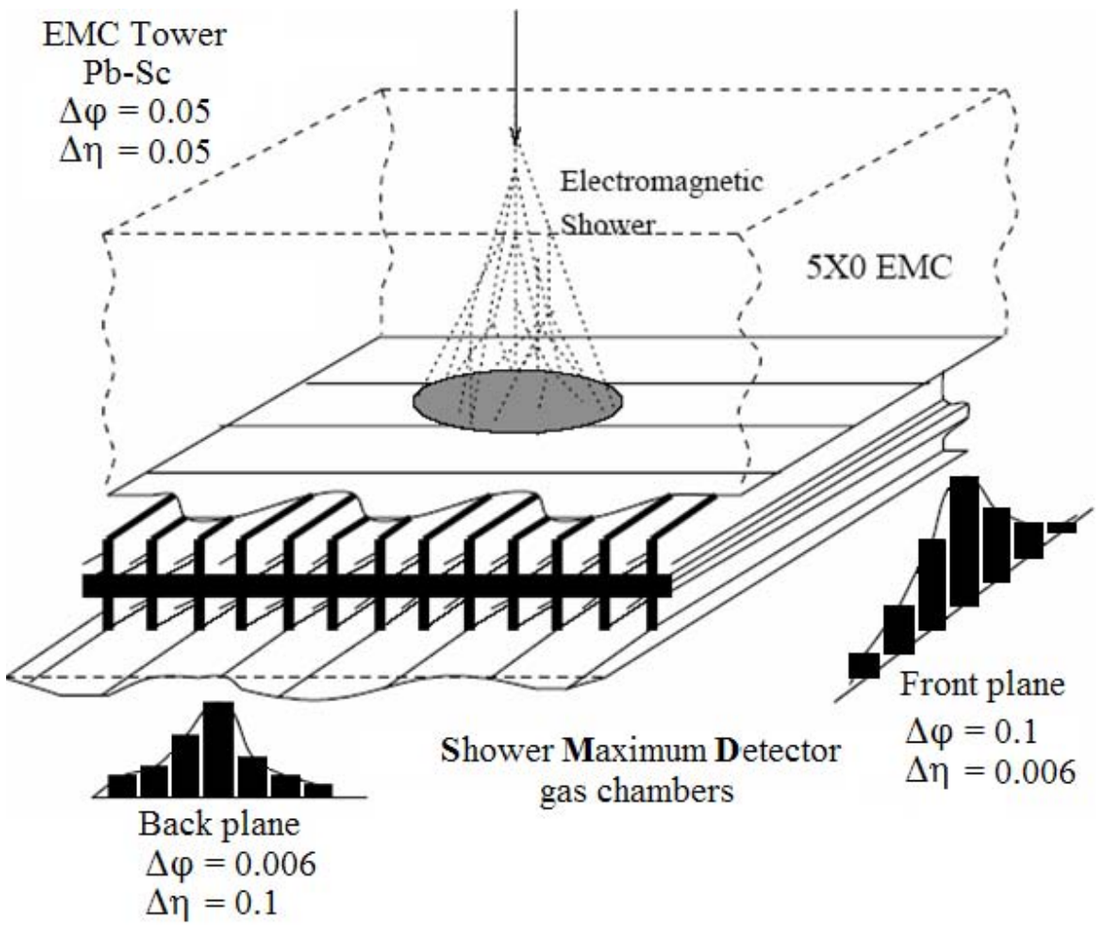
- Time of flight measurement used to separate π, K, p at low p_t (< 2.5 GeV/c), limited by time resolution
- Specific energy loss in the TPC can be used at high p_t to provide π, K, p separation (pt > 2.5 GeV/c) since the π dE/dx is higher than that for K and p in the relativistic rise region

Charged Pions: Sensitivity to the Sign of ΔG



- Opposite sign for polarization of valence u and d quarks
- Charged pion production in q g scattering is sensitive to the sign of ΔG

Neutral Pion Reconstruction



Barrel EMC:

tower size (Δφ x Δη)0.05 x 0.05

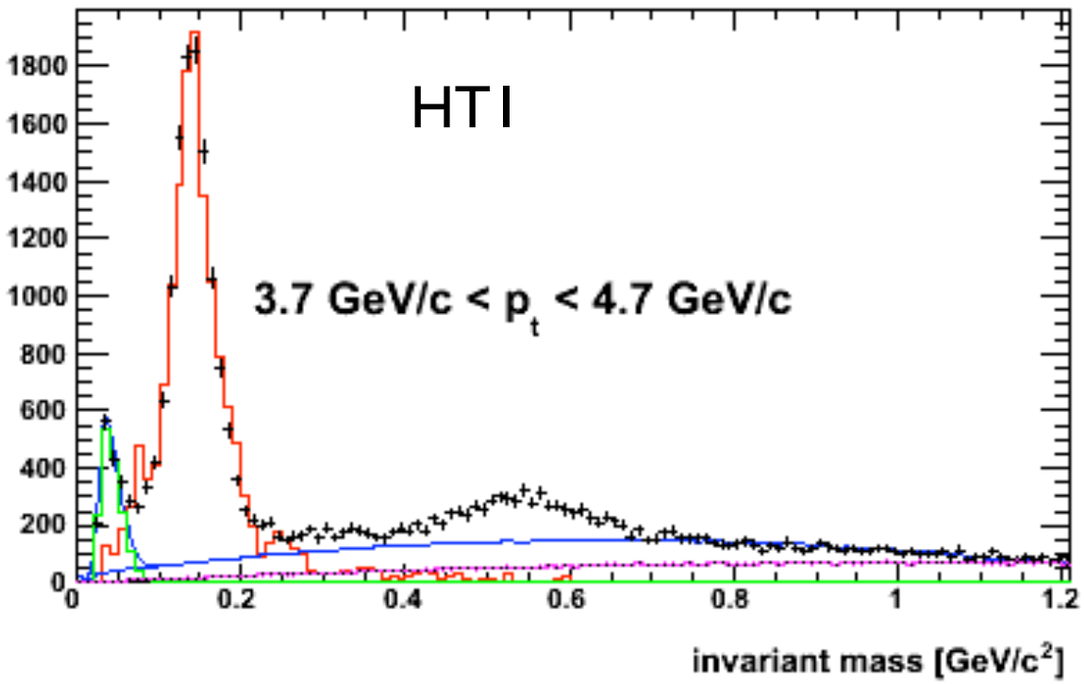
π^0 invariant mass: $m_{inv}^2 = 2E_1E_2(1-\cos\theta)$

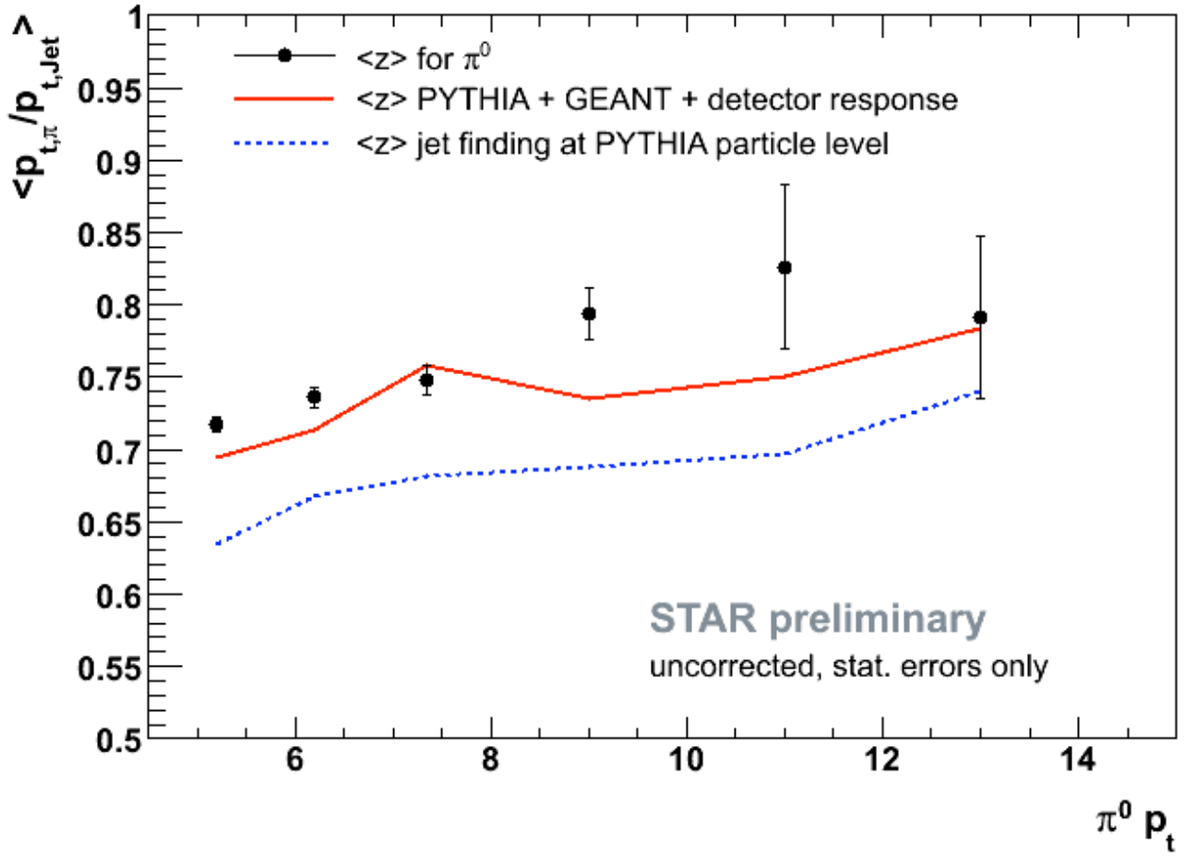
⇨ SMD becomes crucial for π^0 reconstruction for p_t ~ 5 GeV/c (photon separation equal to tower size)

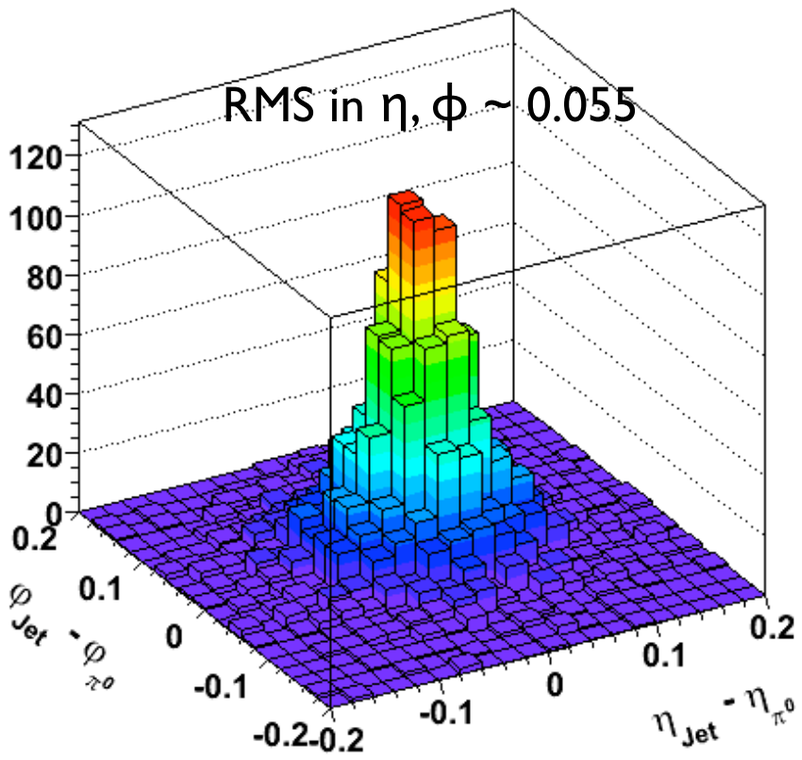
veto calorimeter hits that have a charged track leading to them

- π^0 candidates accepted for 0.1 < y < 0.9 (2006: -0.9 < y < 0.9)
- π^0 has to be able to fire the trigger (but does not have to be the triggering particle)
- rejection of beam background found with pattern recognition code

Neutral Pions: Identified Particles within Jets



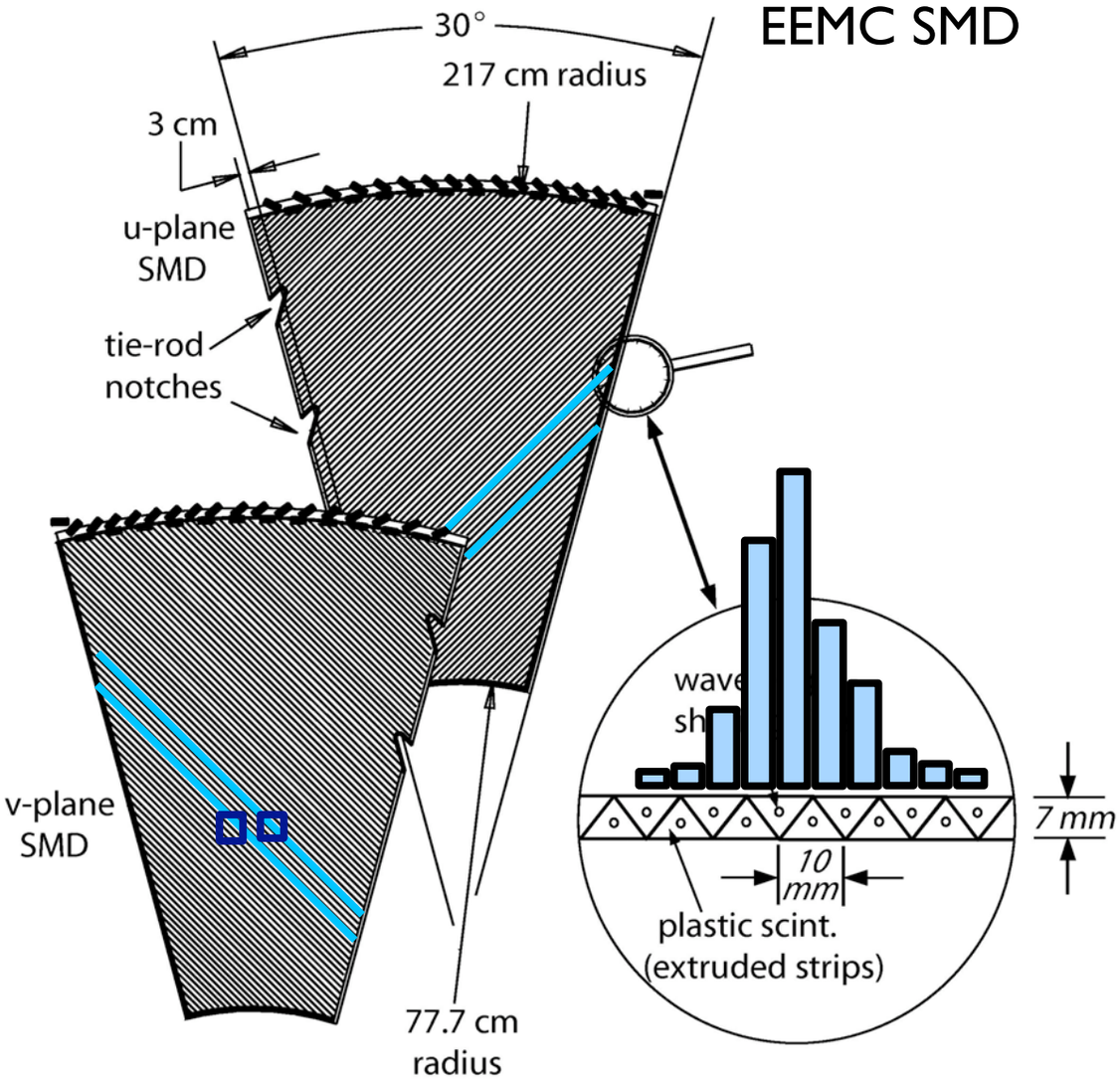


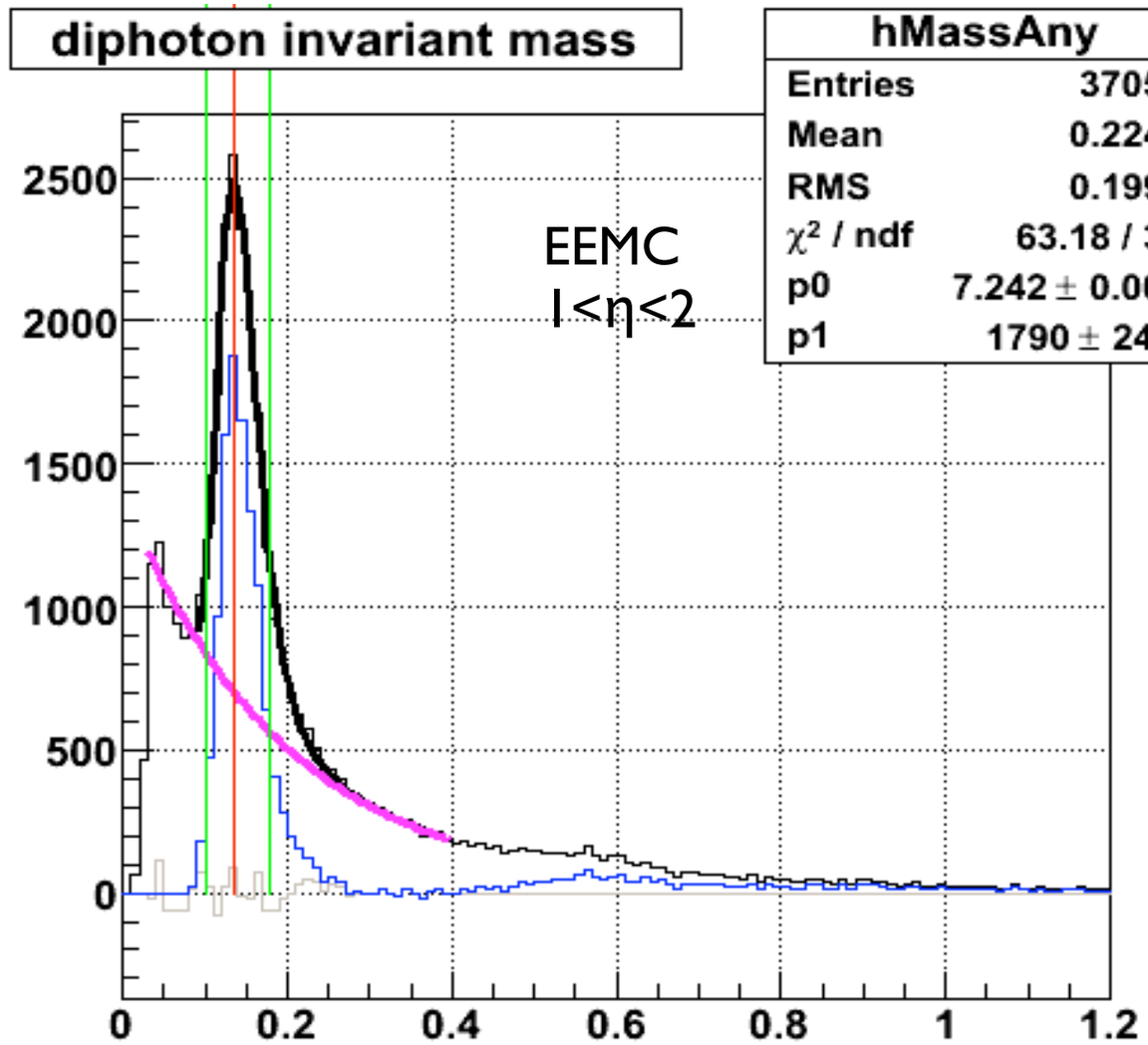


- γγ invariant mass spectrum well understood
- High - energy π^0 direction correlates well with jet axis -> leading particles
- <z> consistent with PYTHIA expectations

$$\langle z \rangle = \left\langle \frac{p_t^{\pi^0}}{p_t^{jet}} \right\rangle$$

Extended Coverage: Neutral Pions in the EEMC





- EEMC invariant mass spectrum: well described by phenomenological fits to signal + background
  - Higher background contributions compared to BEMC

STAR Longitudinal Data Summary

year	<*pol*>	Sampled (pb^{-1})	Analyzed (pb^{-1})
2002	15	---	----
2003	30	0.3	0.18
2004	45	0.4	0.12
2005	50	3.1	2.1
2006	60	6.8	5.5
2007	----	---	---
2008	45	transverse spin, high L development	

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1st pp collisions

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1st longitudinal

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JP Trigger Tested

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EEMC Complete

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Shielding, full BEMC

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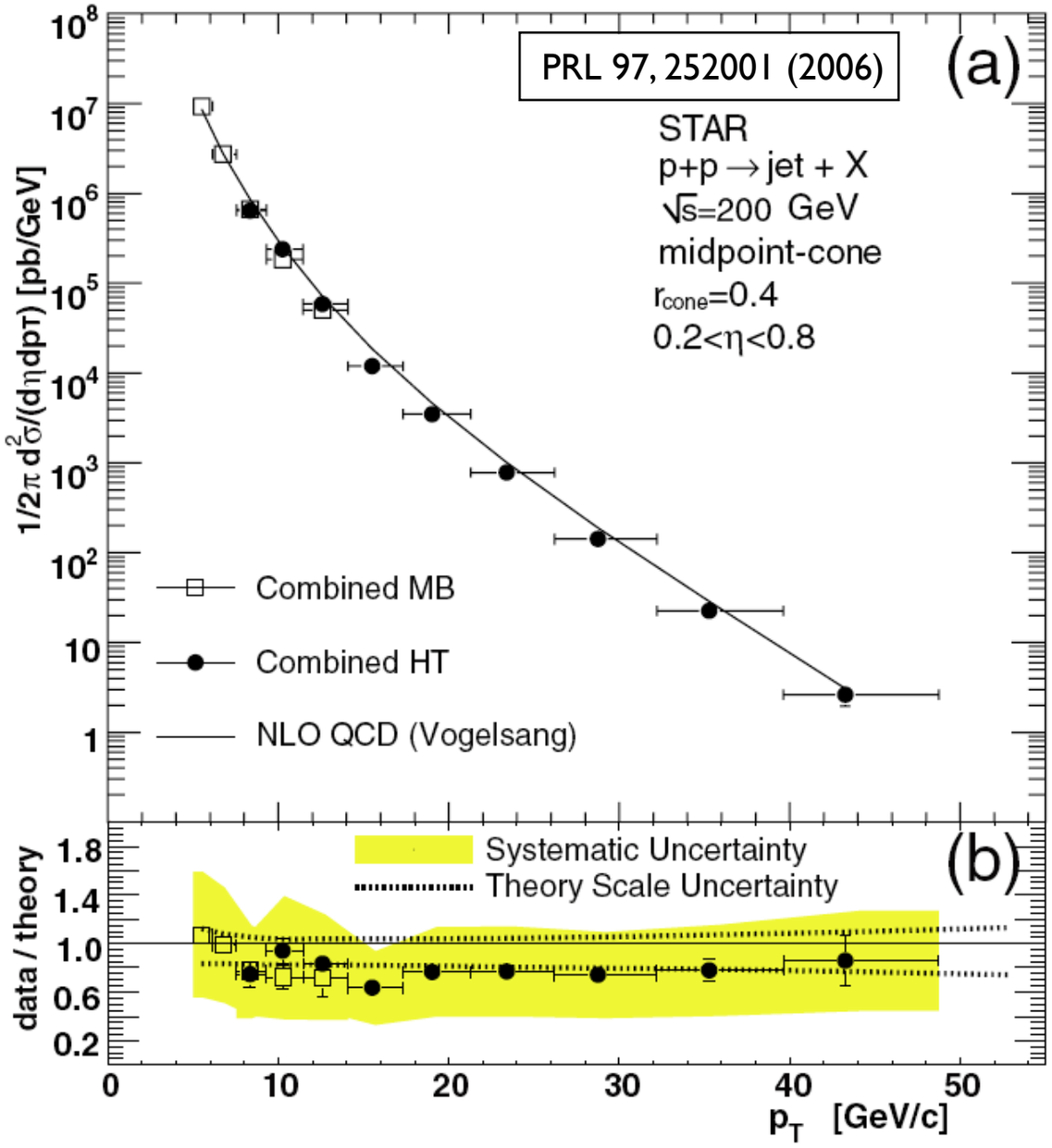
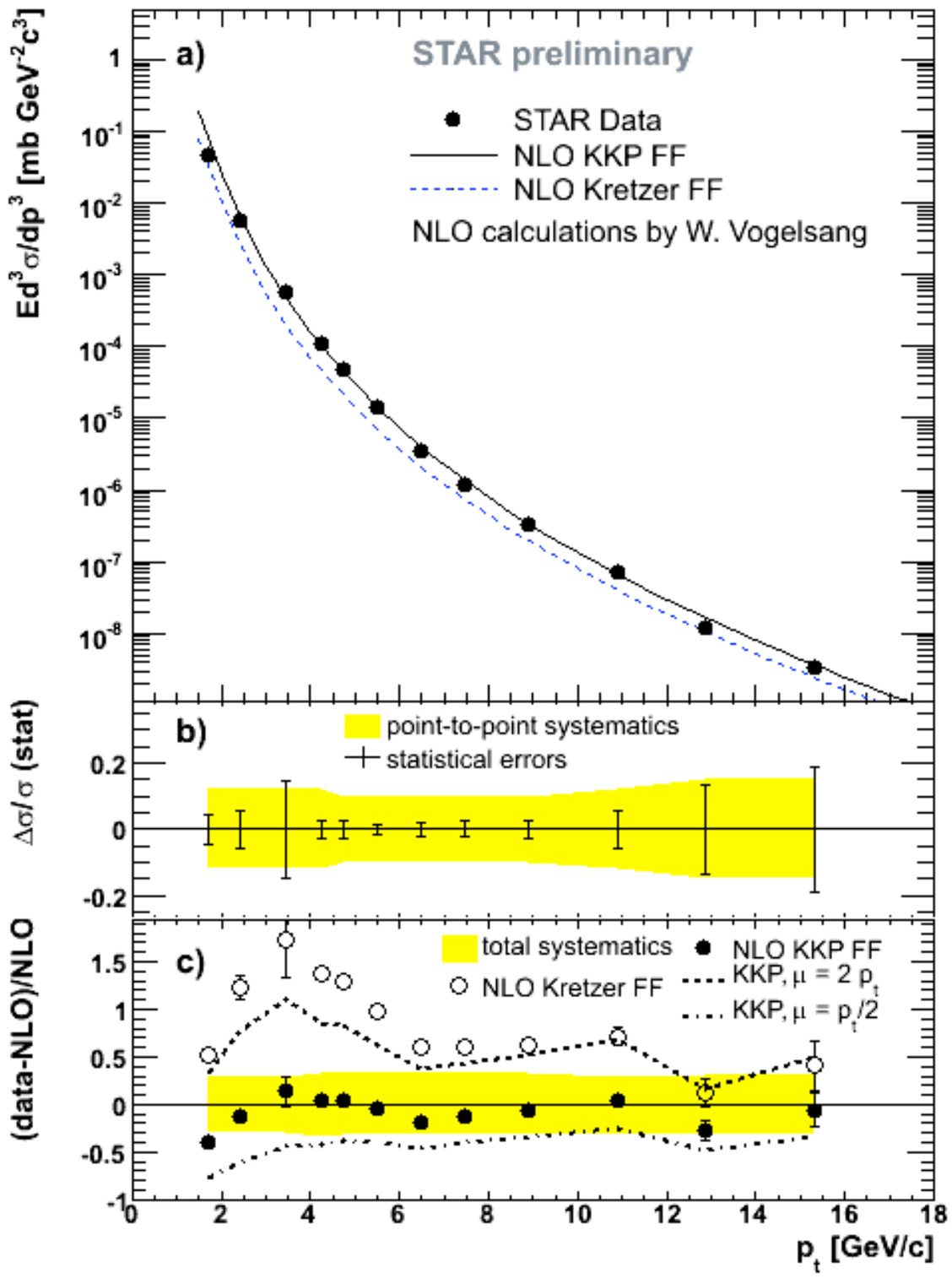
pQCD works: Cross Sections





- Inclusive jet and π^0 cross section
- Good agreement with pQCD over 7 orders of magnitude

Asymmetry Measurements: Systematics

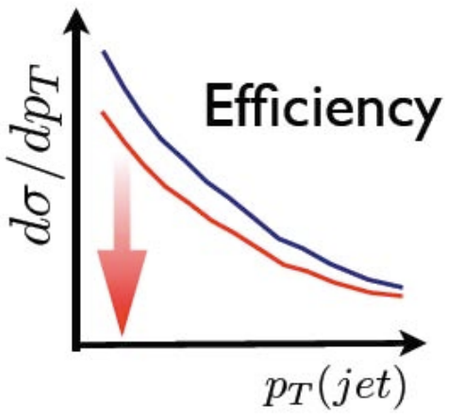
- Common Systematics:
  - Polarization (obtained from RHIC CNI Polarimeters, overall scale uncertainty)
  - Relative luminosities (at the level of 10^{-3})
  - Non-longitudinal polarization component (at the level of a few times 10^{-4})

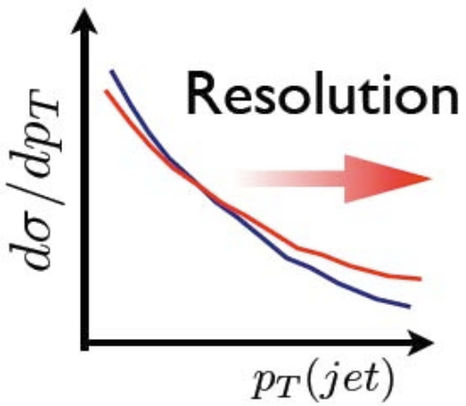
- Analysis Specific Systematics:
  - Trigger and reconstruction bias (jets, charged pions)
  - Beam background (all)
  - p_T scale (jets)
  - Yield extraction, particle identification (neutral and charged pions)

- Different systematic effects in each measurement, global analysis of all observables very powerful
- Determination of systematics often limited by statistics

Jet Systematics: Resolution & Reconstruction

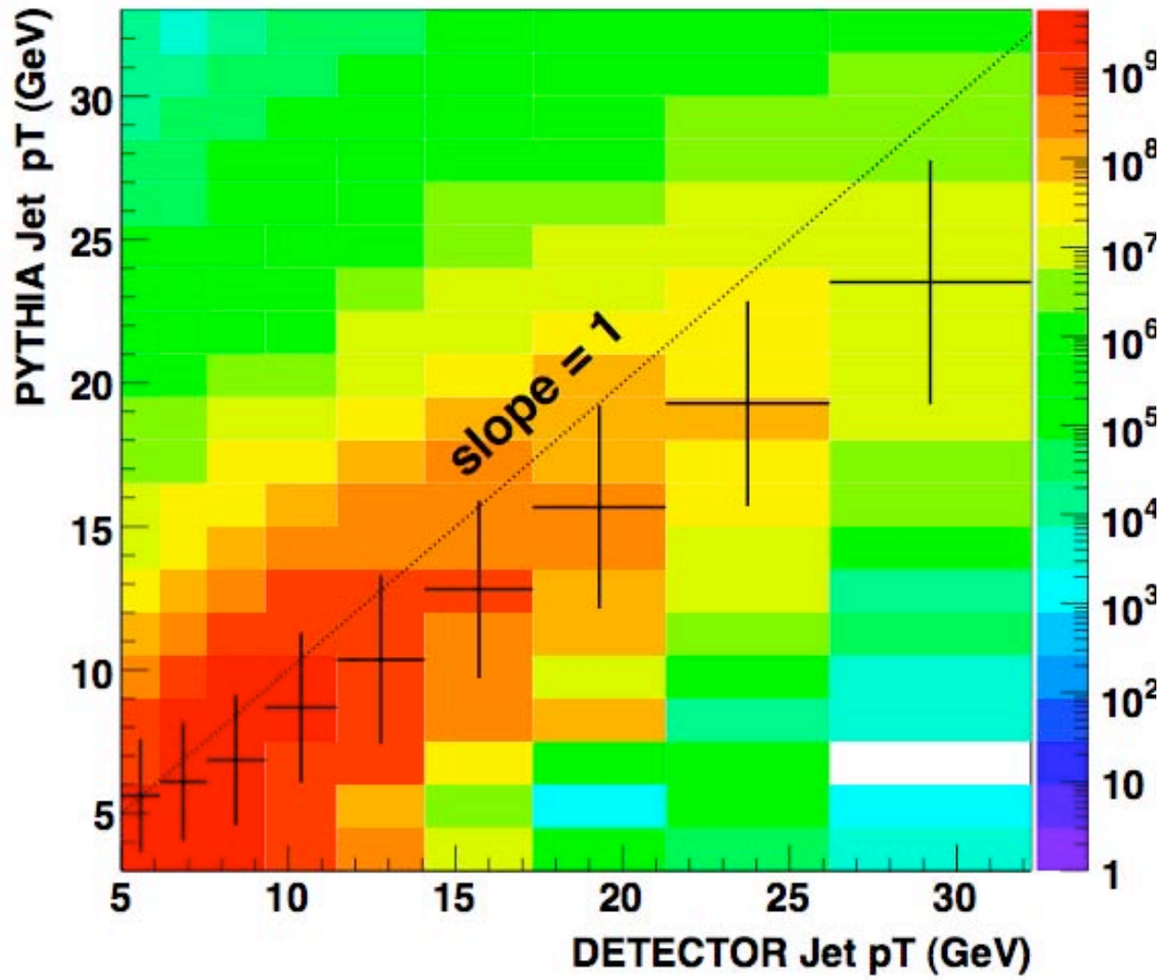
true vs. *observed*





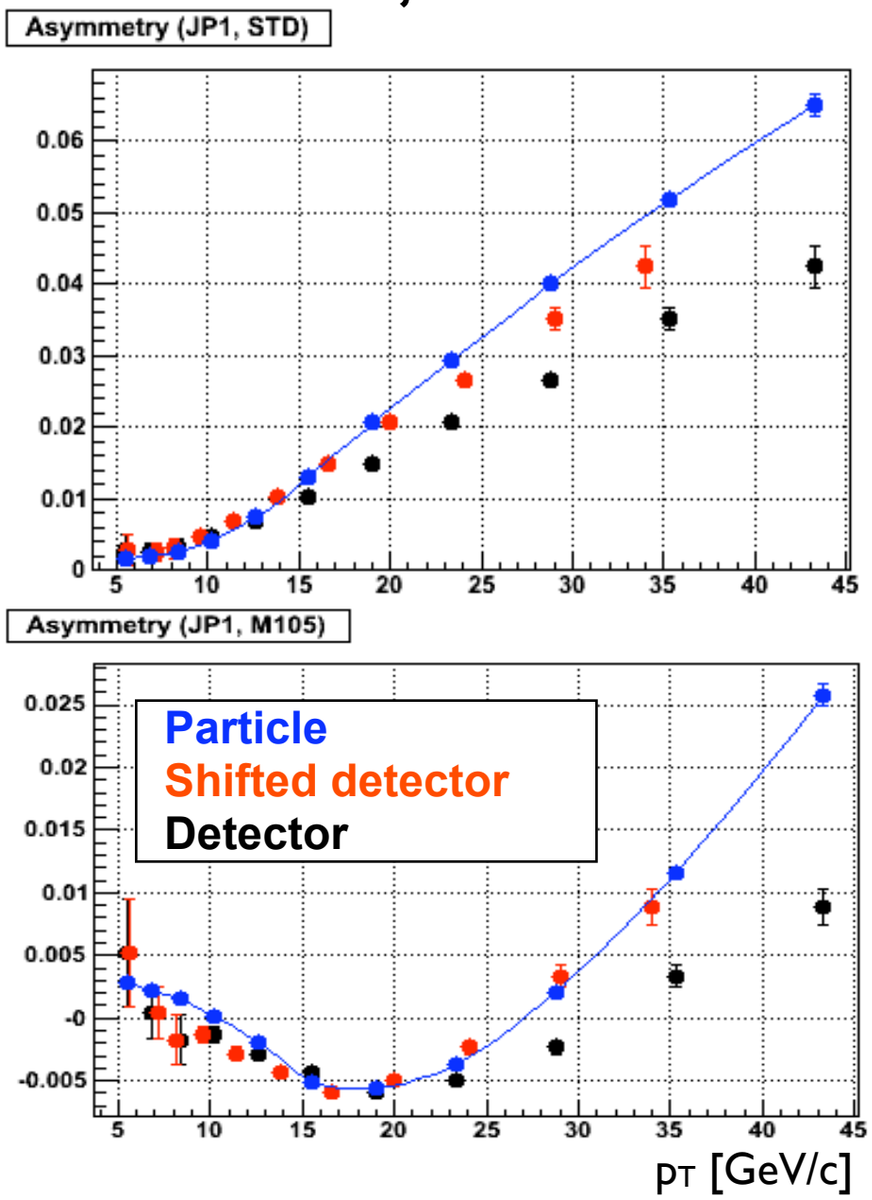
- Finite momentum resolution and reconstruction efficiency together with steeply falling cross section affects reconstructed jet p_T
- Changes sub-process contributions!

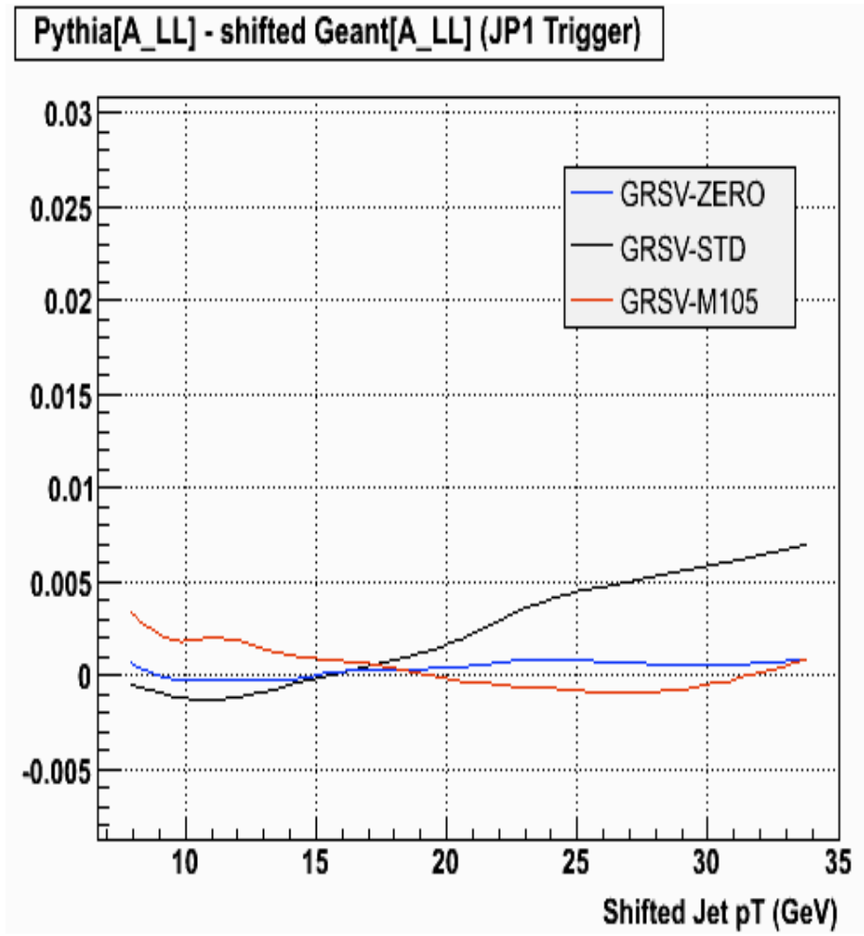
- Large Detector-related effects: Resolution ~ 25%, Efficiency ~ 10%
- Corrections made to final p_T distributions using PYTHIA + GEANT



Jet Systematics: Trigger Bias

- STAR triggers on localized electromagnetic energy deposit in the calorimeters
- can lead to a bias by changing the subprocess contributions (gg, qg, qq):
  - quark jets tend to fragment harder and tend to contain more energy in a narrow cone around jet axis



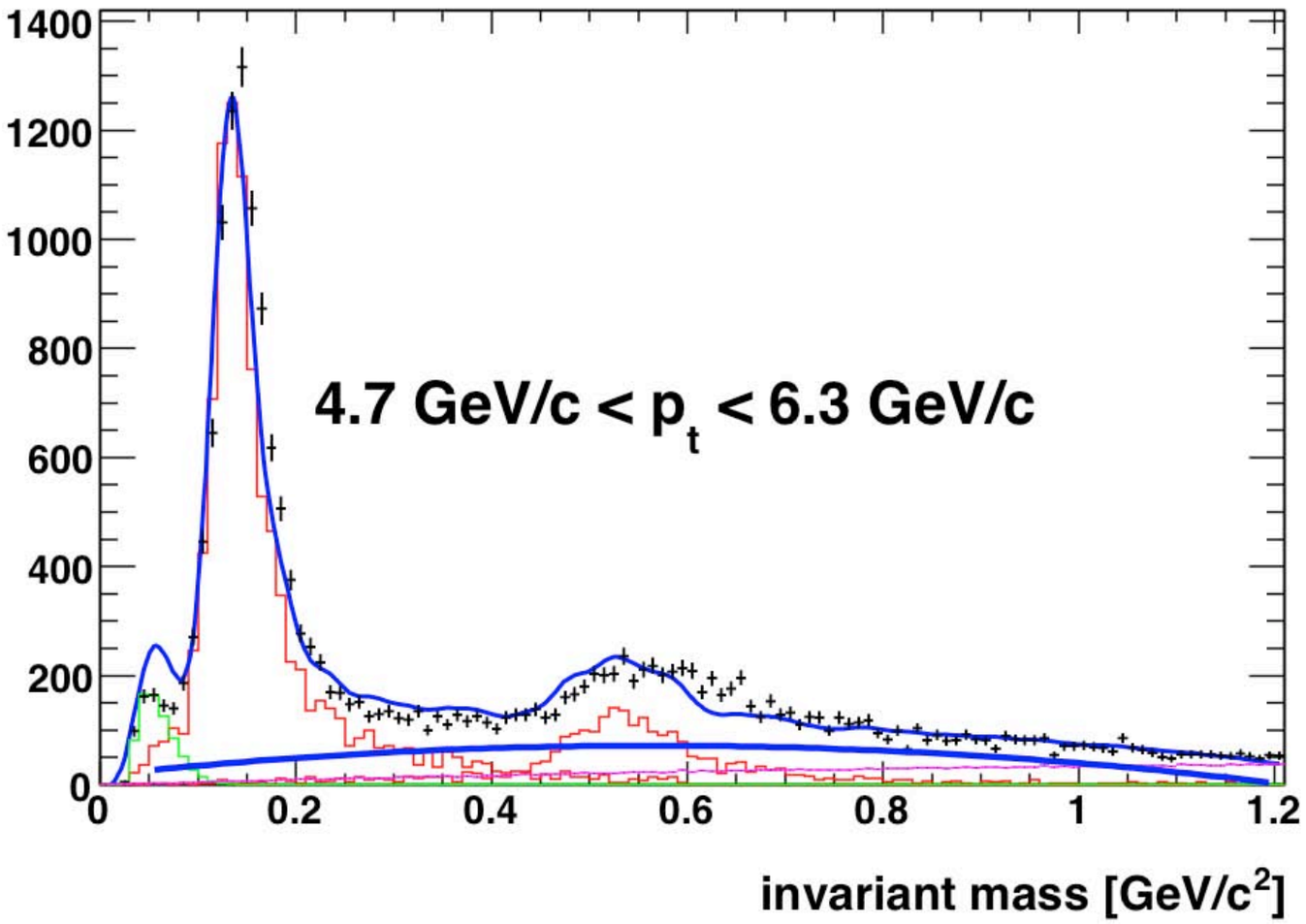


1. Calculate MC Asymmetries for Particle and Triggered Detector jets using various GRSV ΔG scenarios
2. Shift p_T of the Detector Jets
3. Maximum difference in asymmetry of detector jet and particle jet is the systematic.

- p_T dependent systematic on A_{LL} of up to 5×10^{-3}

Systematics: Neutral Pions

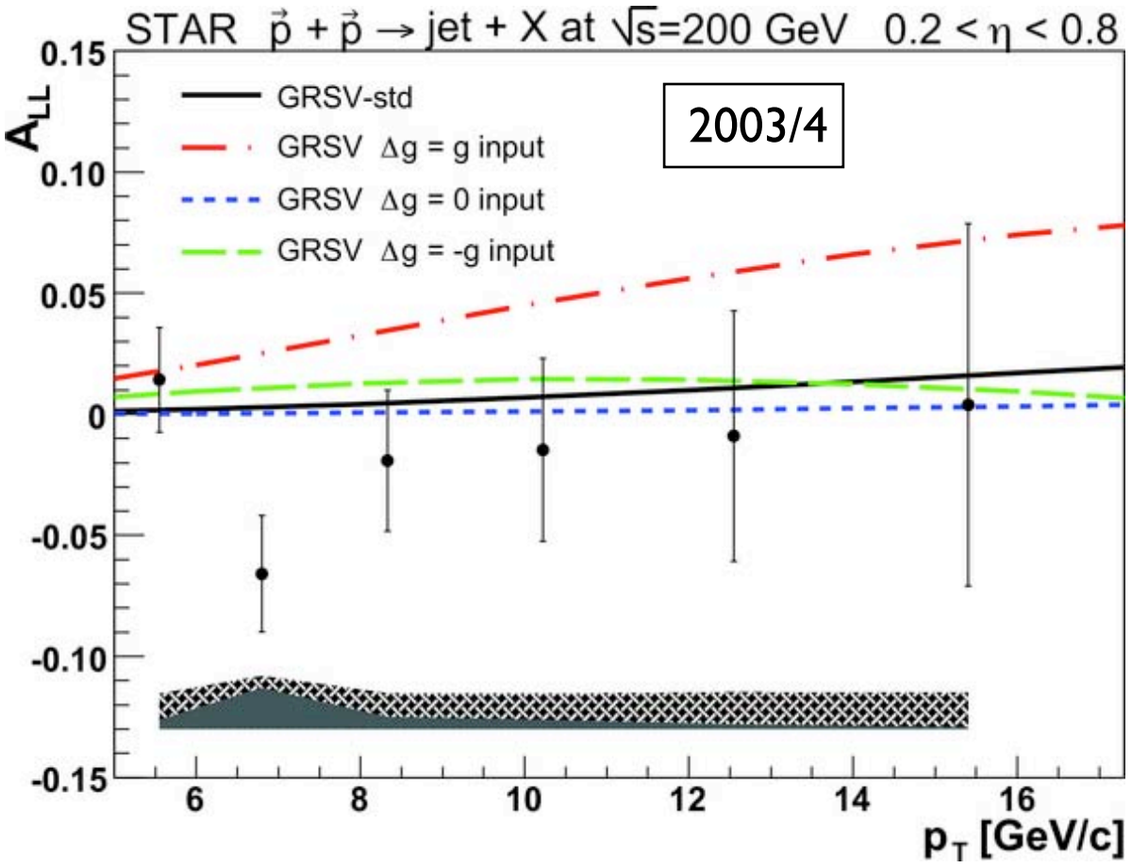
- No trigger bias, since π^0 are directly triggered on
  - fragmentation uncertainties are hidden in the fragmentation functions



- Leading systematic: Background in invariant mass spectrum
  - Low mass background from cluster splitting
  - combinatoric background
  - additional background contributions (combinatorics within parent jets, ...)
- Systematic on A_{LL} evaluated by studying asymmetries outside the π^0 mass region (statistics limited)

Systematic error on A_{LL} from background: up to ~0.01

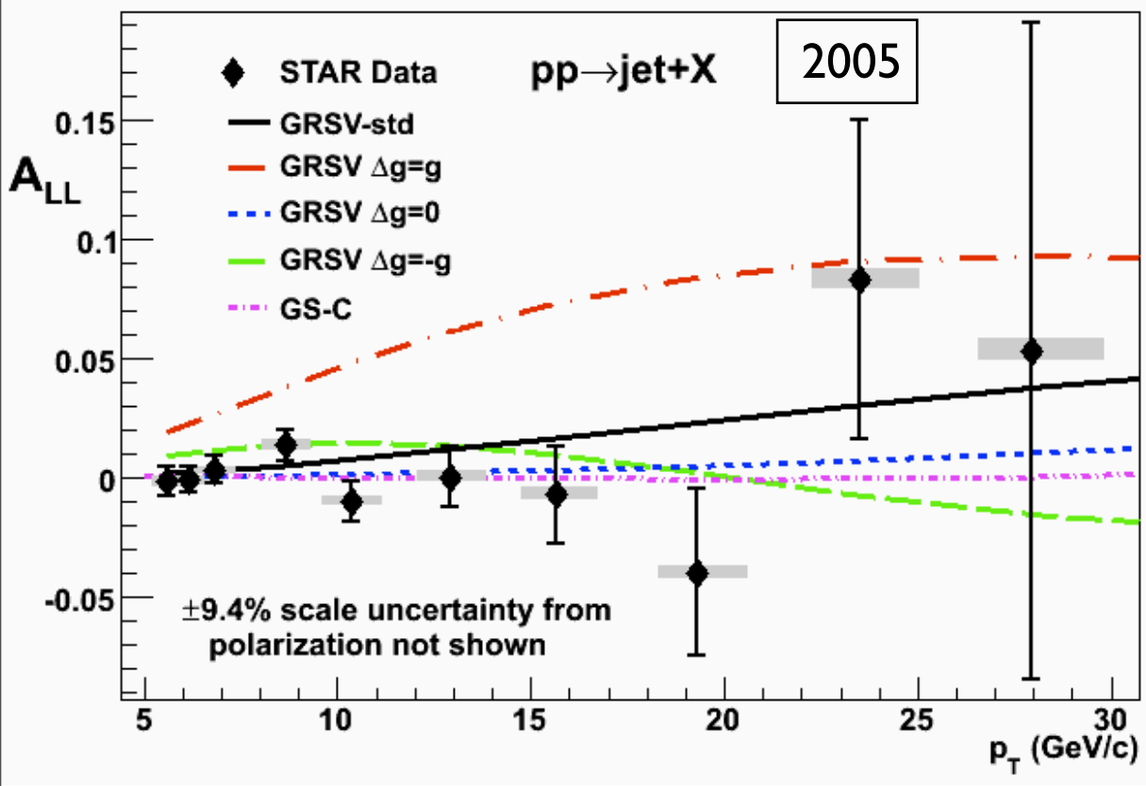
Jet Longitudinal Asymmetry A_{LL}



PRL 97, 252001 (2006)

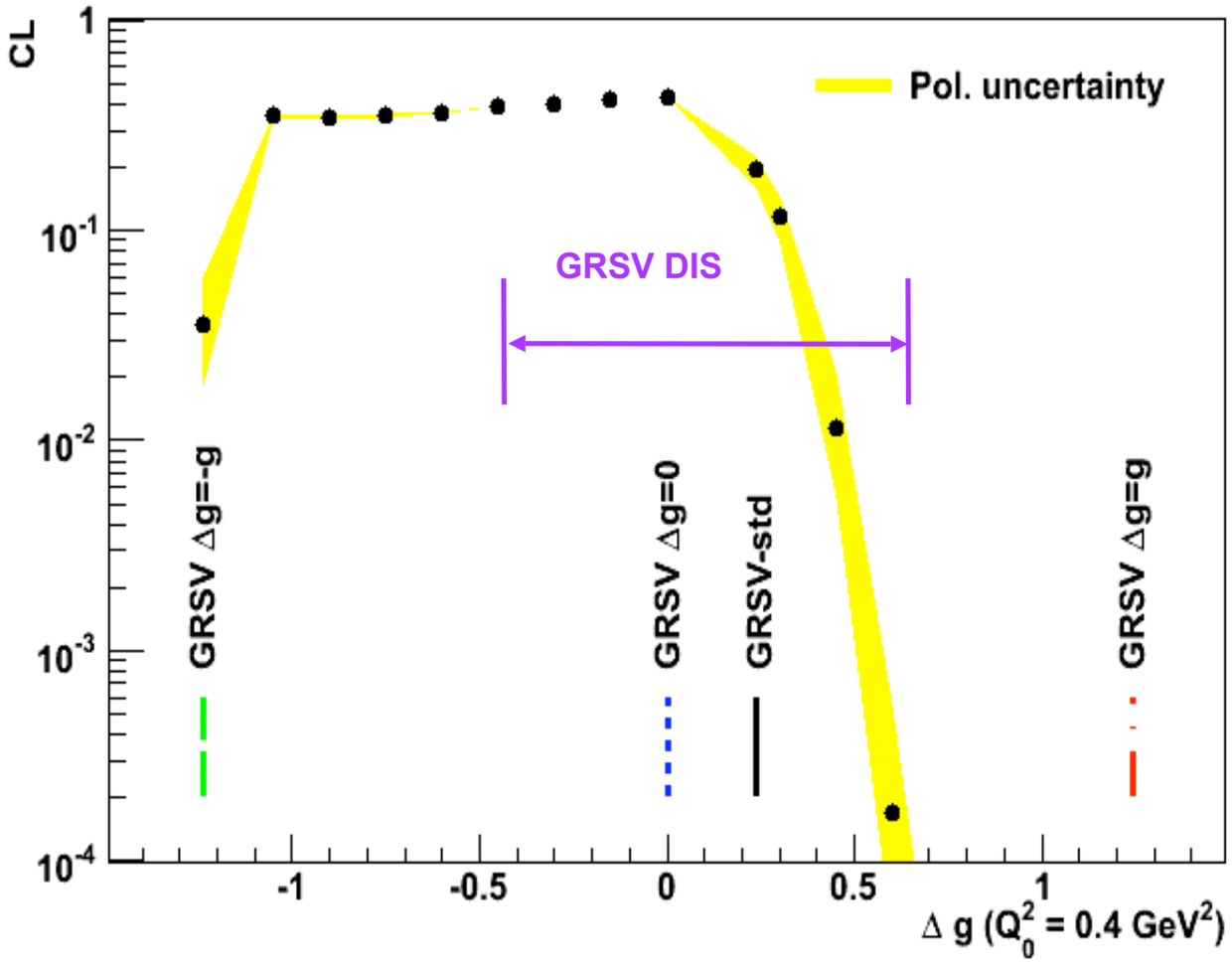
- A_{LL} for inclusive jet production, compared to predictions based on GRSV parameterizations for polarized gluon distributions

Jet Longitudinal Asymmetry A_{LL}



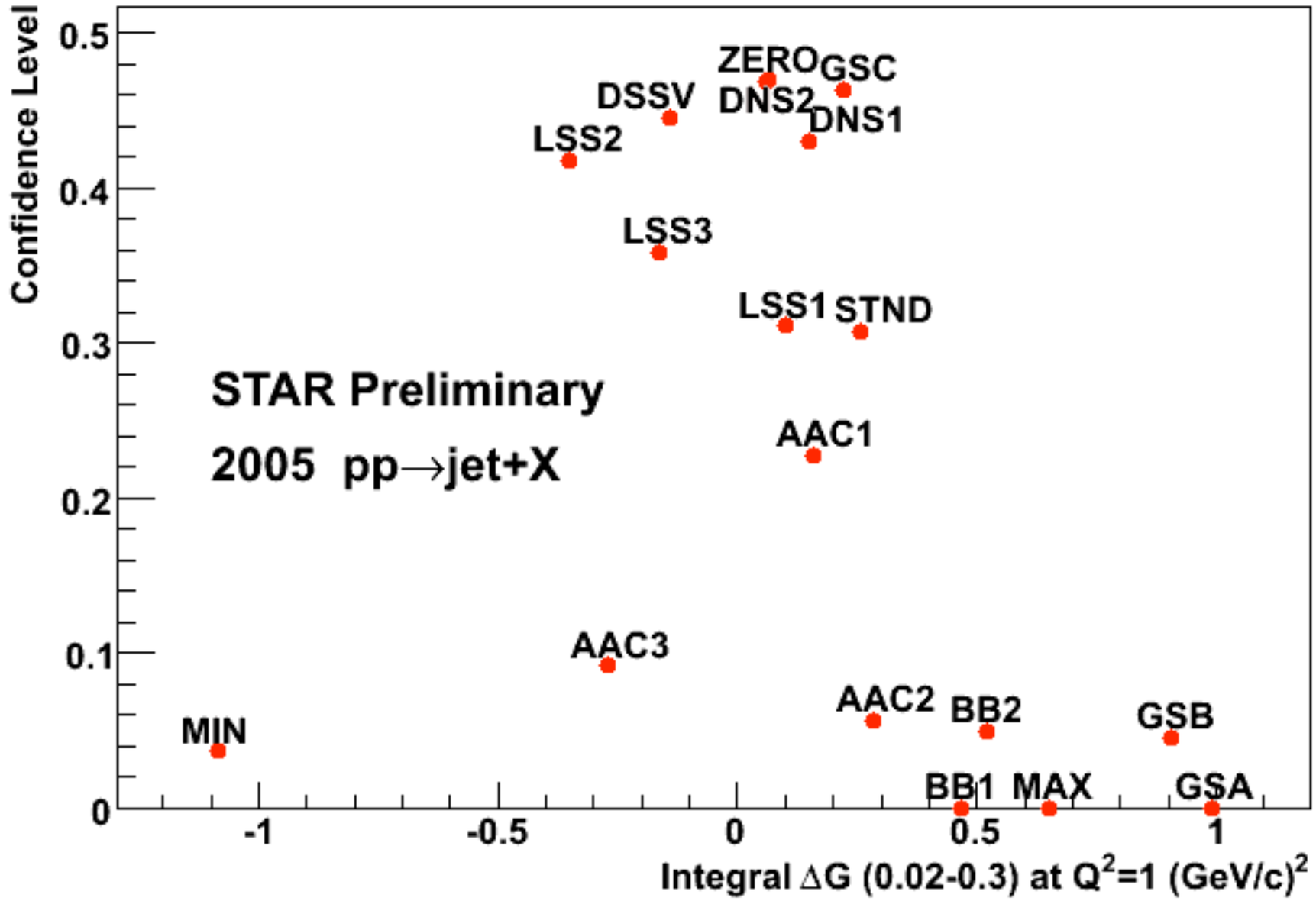
PRL 100, 232003 (2008)

- A_{LL} for inclusive jet production, compared to predictions based on GRSV parameterizations for polarized gluon distributions



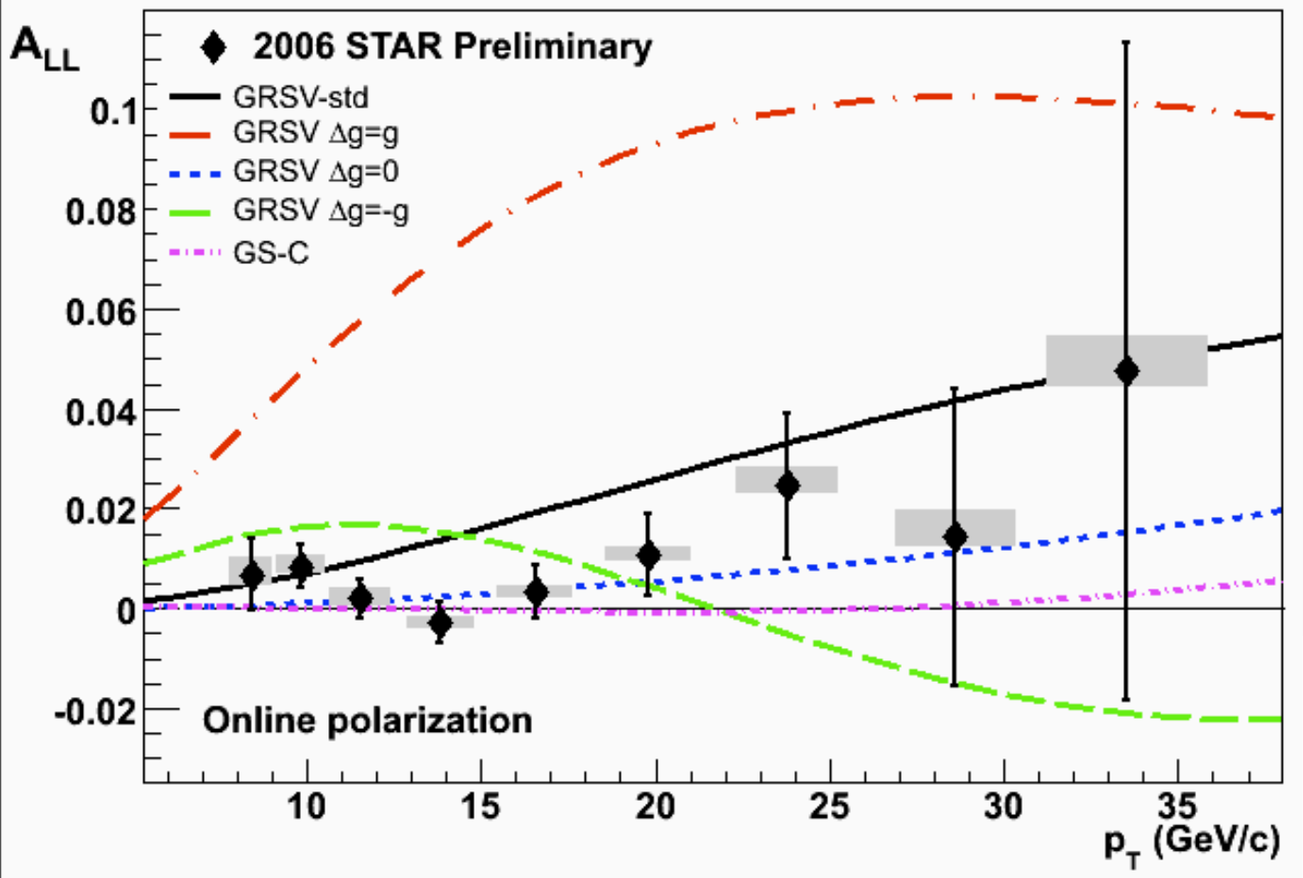
- Confidence level calculated wrt GRSV predictions for different ΔG:
  - Positive values beyond GRSV-std (best fit to DIS) are clearly disfavored

Comparison to other Global Analyses



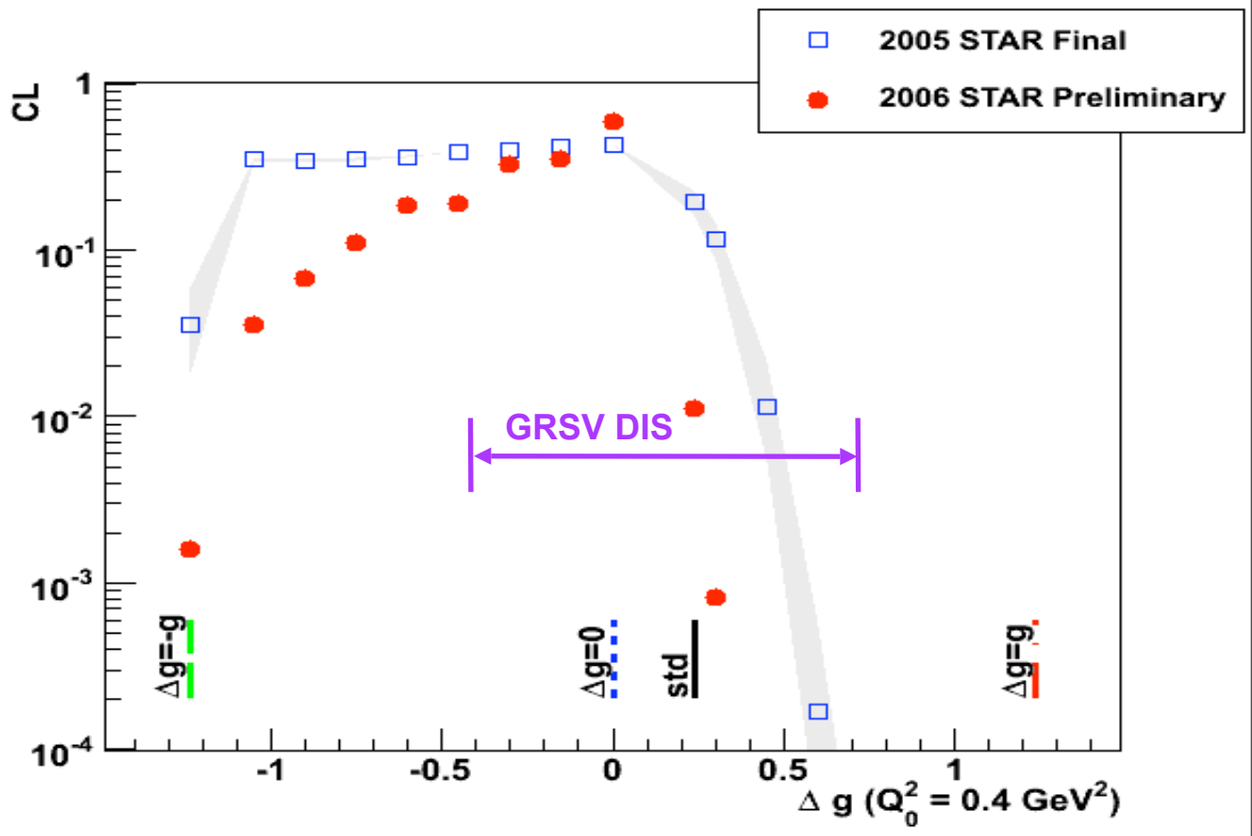
- The 2005 STAR data exclude a broad range of models with ΔG larger than GRSV-std
- Counterexample GSC: node at x ~ 0.1, large first moment at small x

Jet A_{LL}: Improvements with 2006 Data

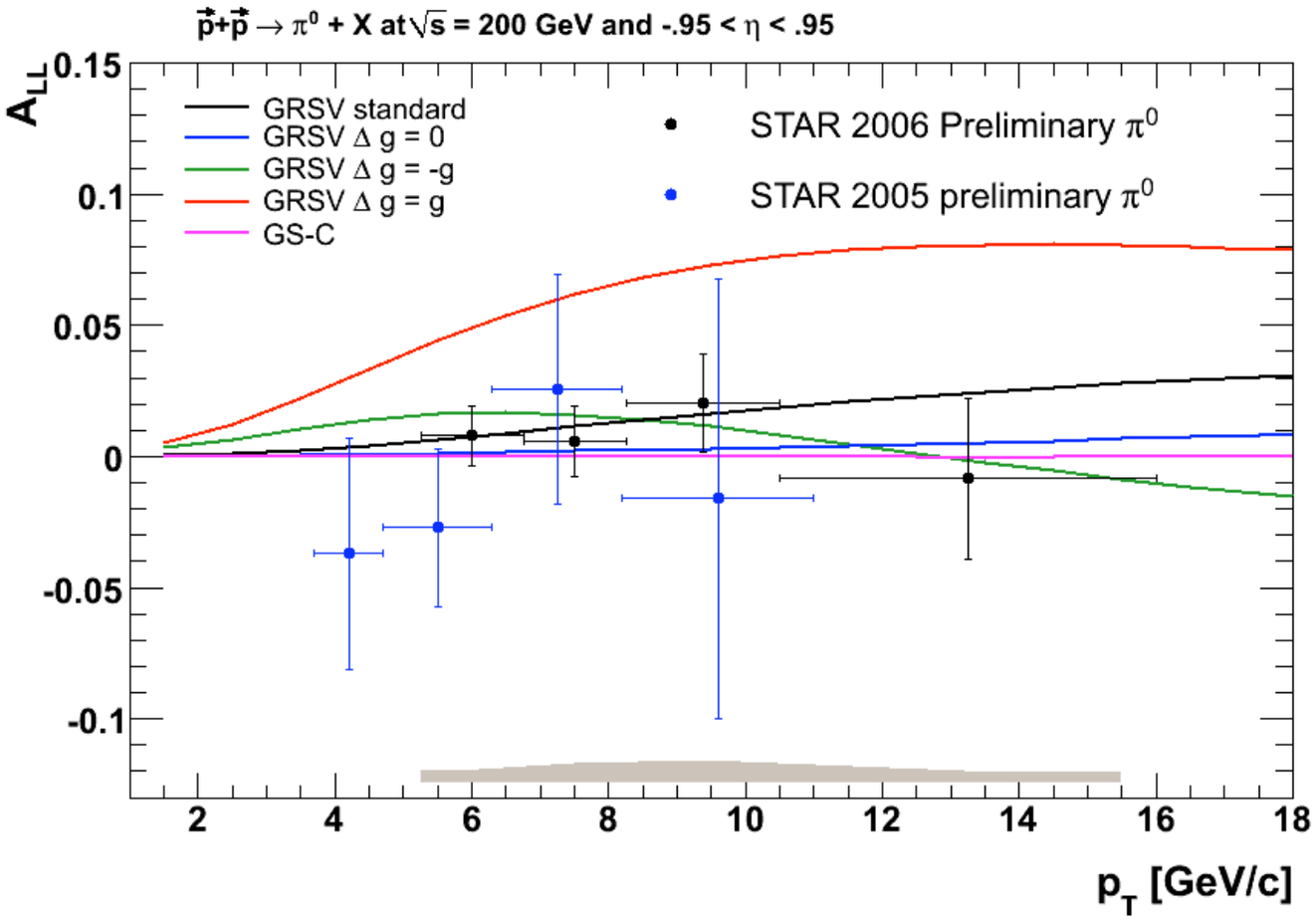


- Significant improvements with 2006 Data:
  - Full BEMC, Jet Finder extends into EEMC: Acceptance increased
  - Increase in luminosity and polarization
  - Jet cone radius increased to 0.7

- Decrease of statistical errors by a factor of 3 - 4 (for p_T > 13 GeV)
- Corresponding increase of sensitivity to models

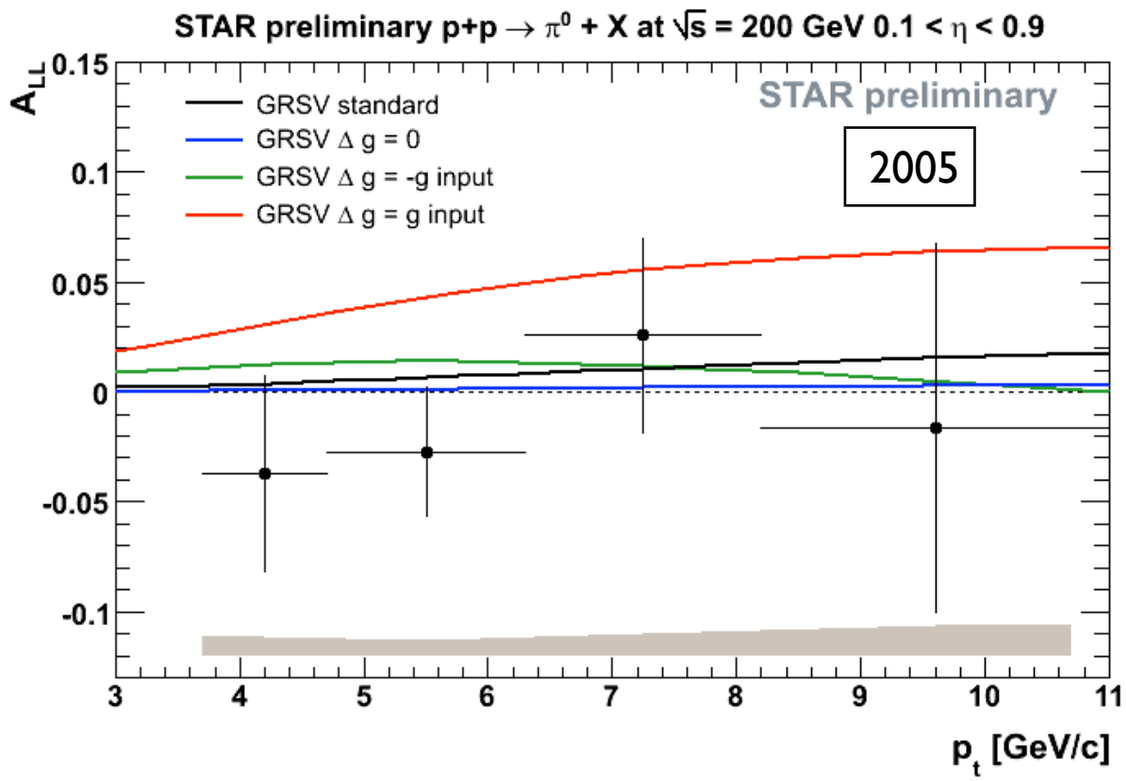


Neutral Pions: Mid-rapidity

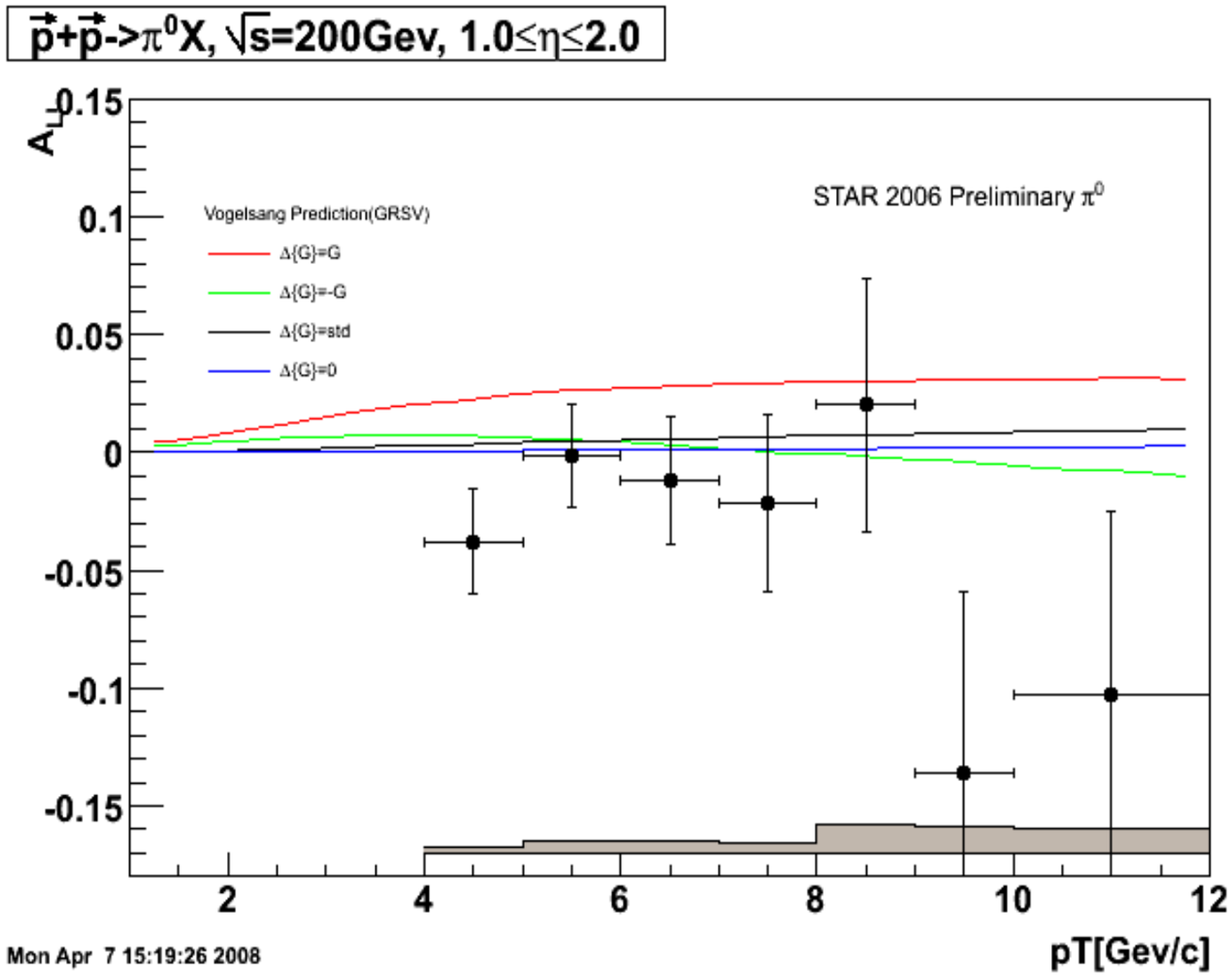


- GRSV scenarios with large positive ΔG excluded
  - 2006 χ^2/ndf: ~11.4 (max), ~0.3 (std)
- Significantly smaller statistics than jet measurement

- Preliminary results for 2005 and 2006
- acceptance increased by ~ 2.4 due to completion of BEMC



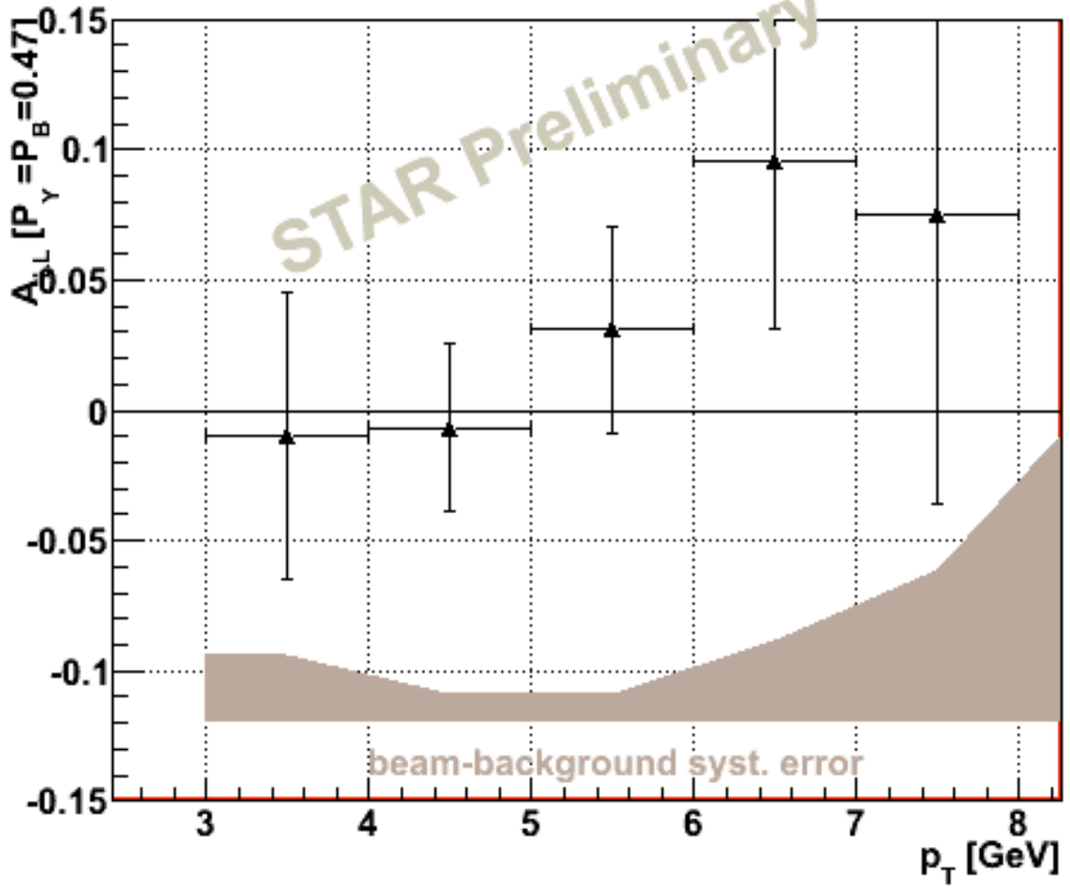
Neutral Pions: Forward Rapidity



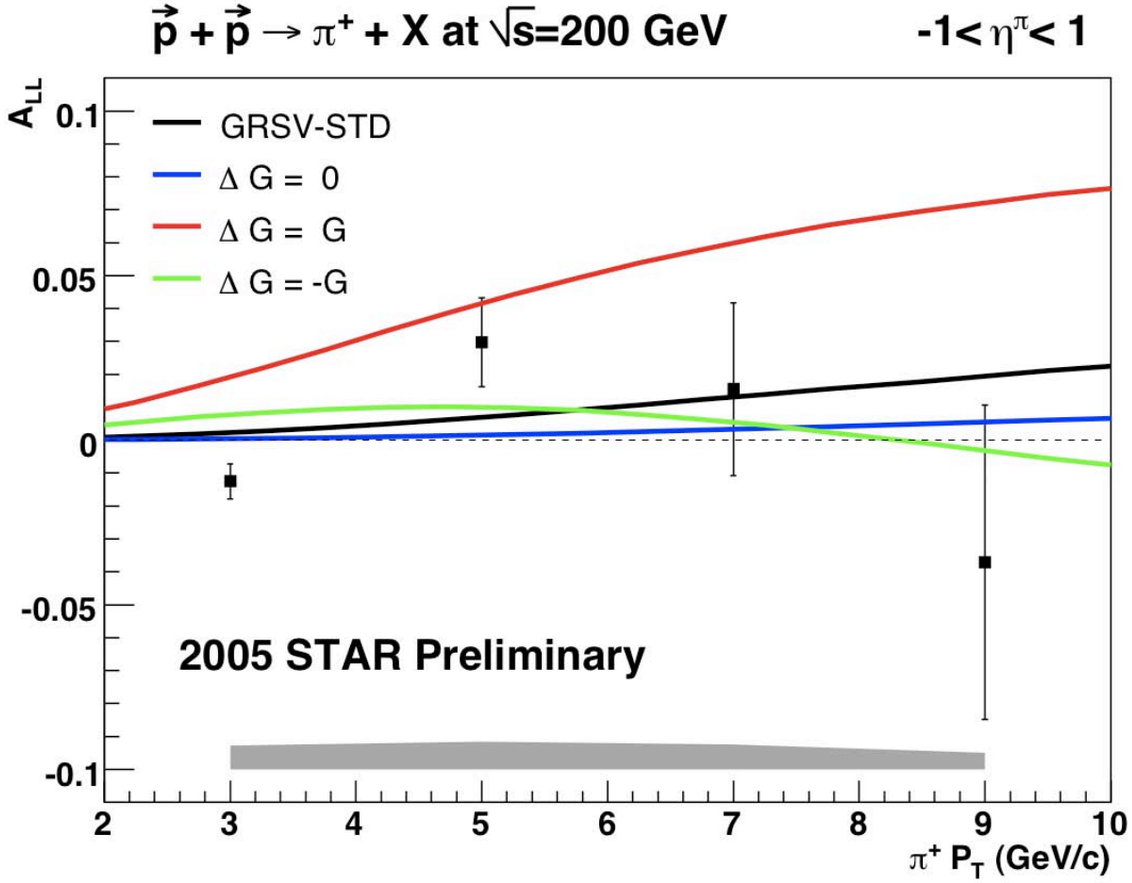
- Statistical precision comparable to mid-rapidity results
- Smaller sensitivity to ΔG due to smaller asymmetries

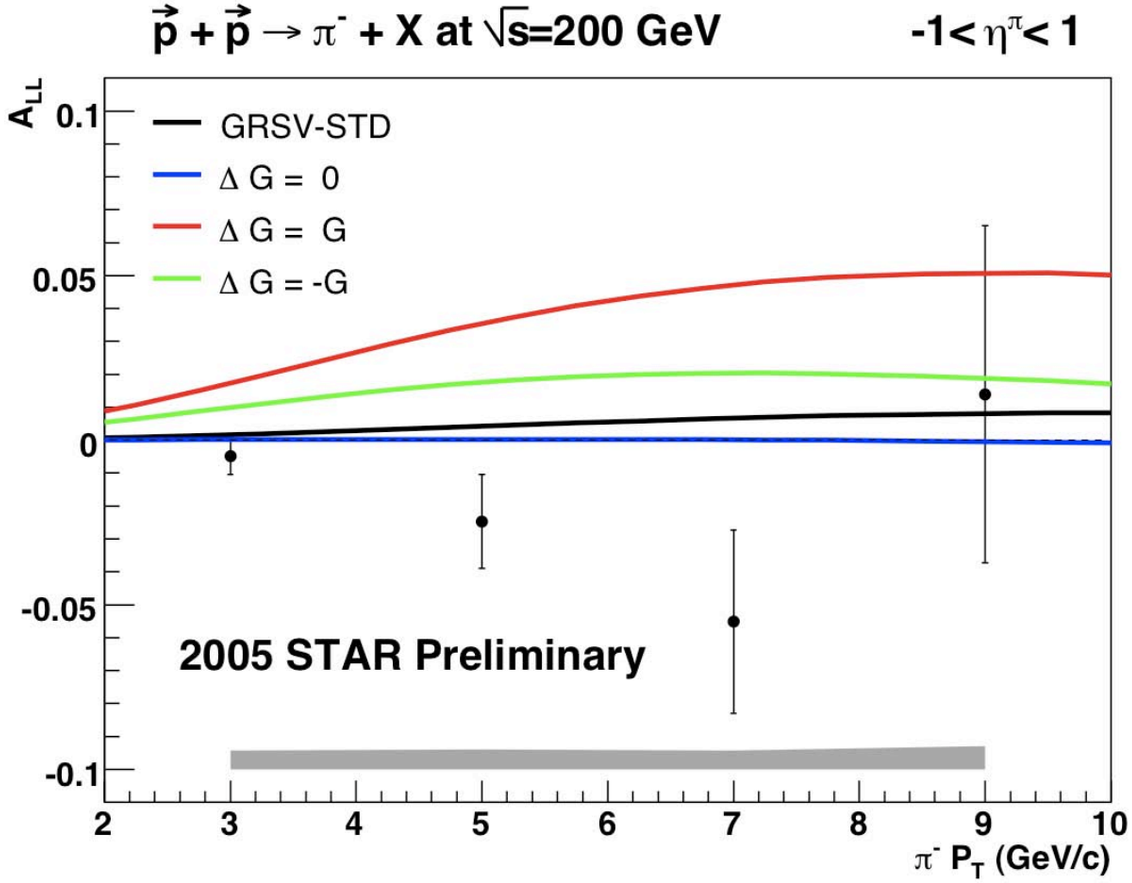
- Preliminary results for 2005 and 2006
- Extension of acceptance
- Significant reduction of background in 2006 through additional shielding in accelerator tunnel

2005: beam background dominant sytematic

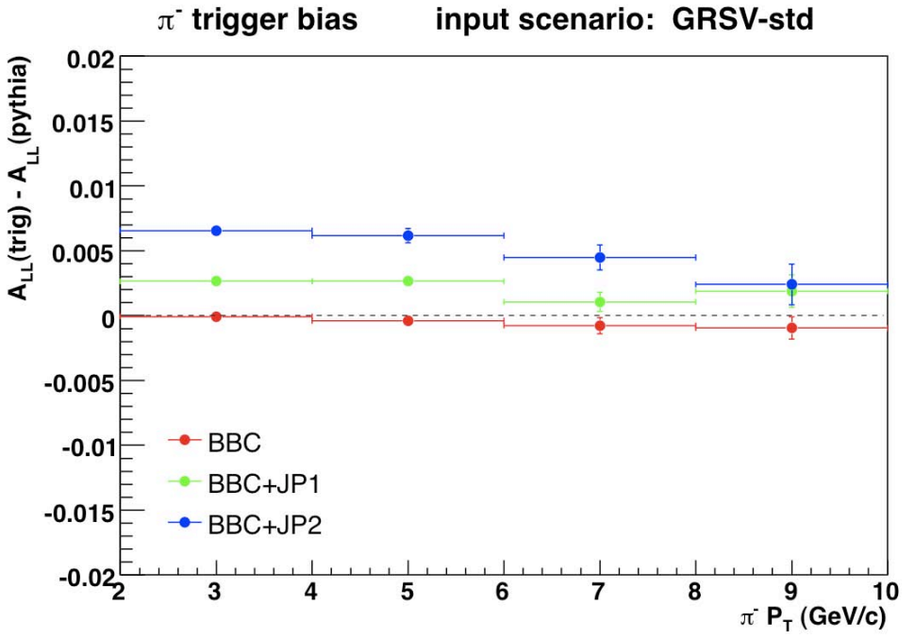


Charged Pions



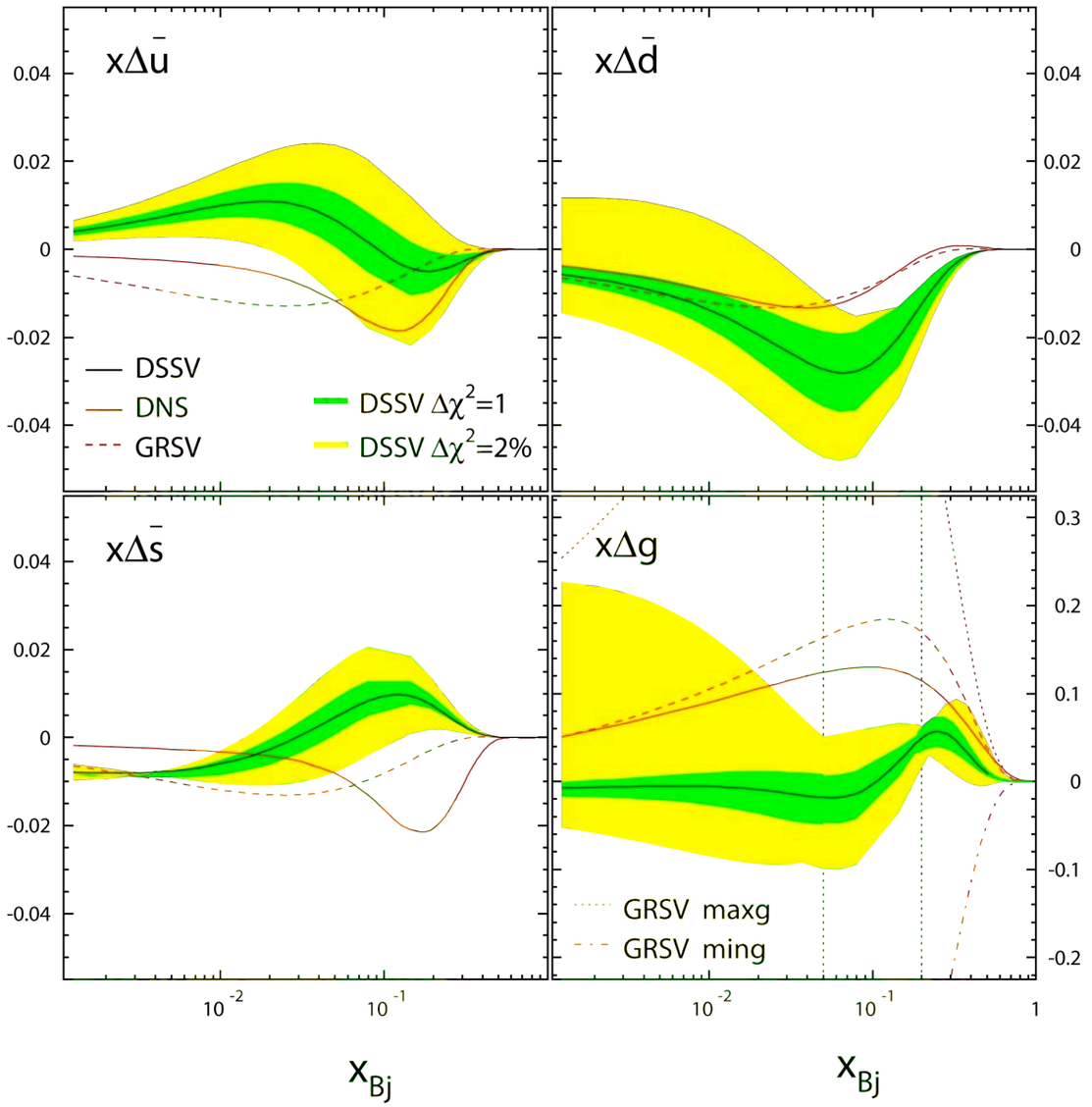


- Consistent with neutral pions
- trigger bias is the largest systematic:
  - most charged pions are subleading particles due to the calorimeter trigger
  - away-side asymmetries (less bias) consistent with near-side
- 2006 Analysis ongoing

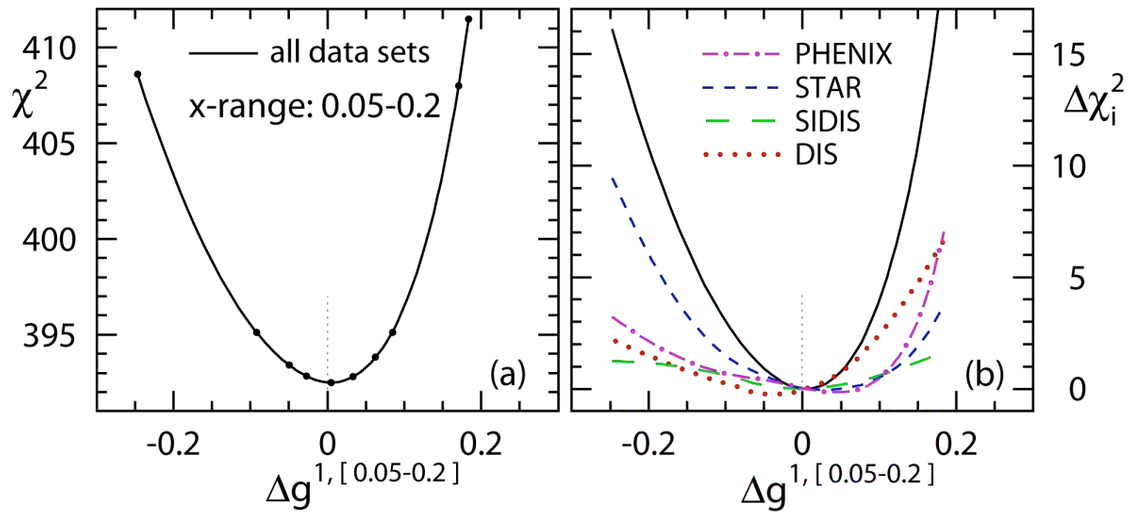


III. Future Probes for ΔG

Impact of Inclusive measurements

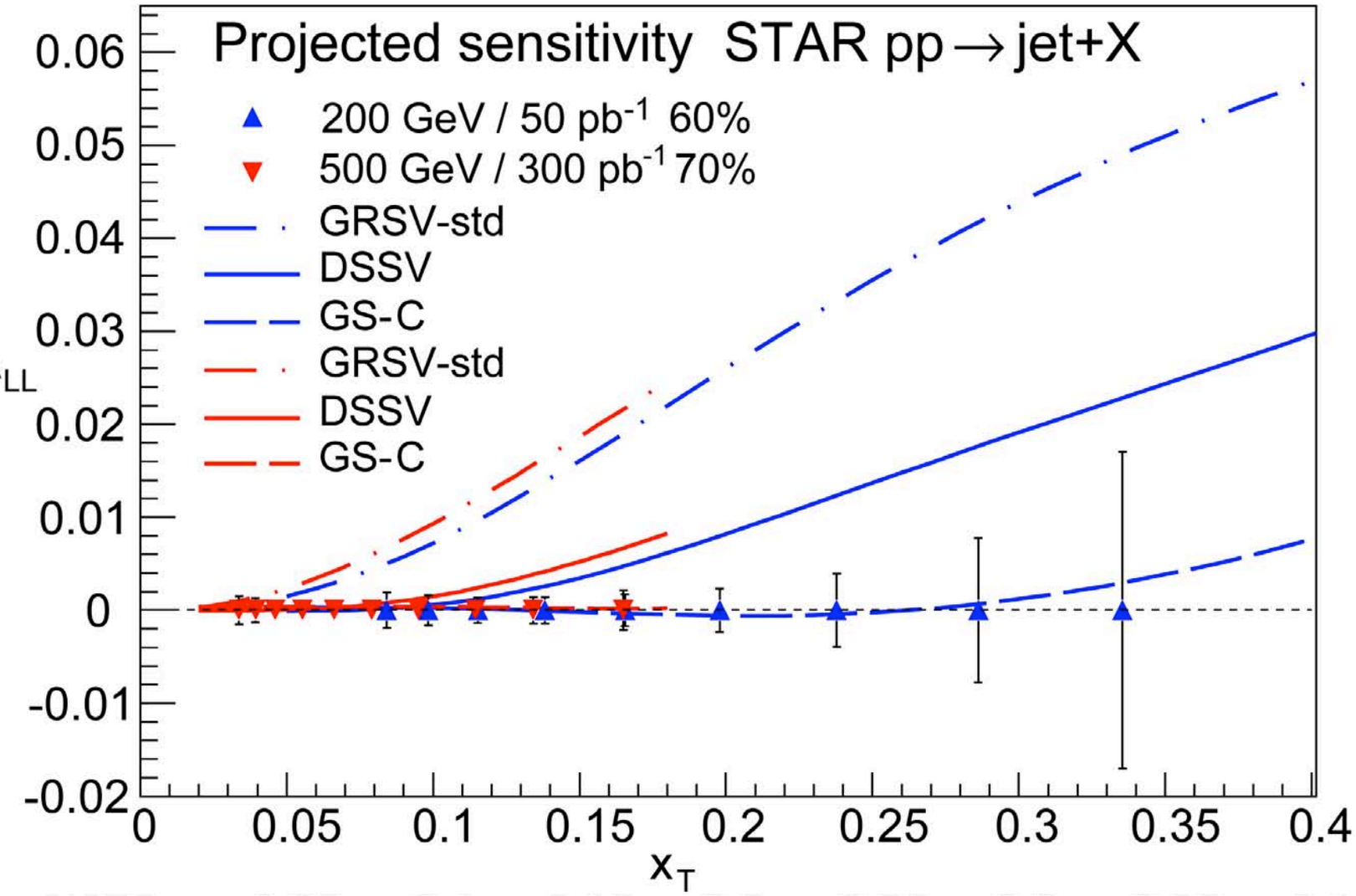


de Florian, Sassot, Stratmann, Vogelsang
arXiv: 0804.0422



- Early RHIC data (2005, 2006 preliminary) used in a global analysis together with DIS and SIDIS data
- evidence for a small gluon polarization over a limited region of momentum fraction ($0.05 < x < 0.2$)

Inclusive Measurements: Increasing Precision

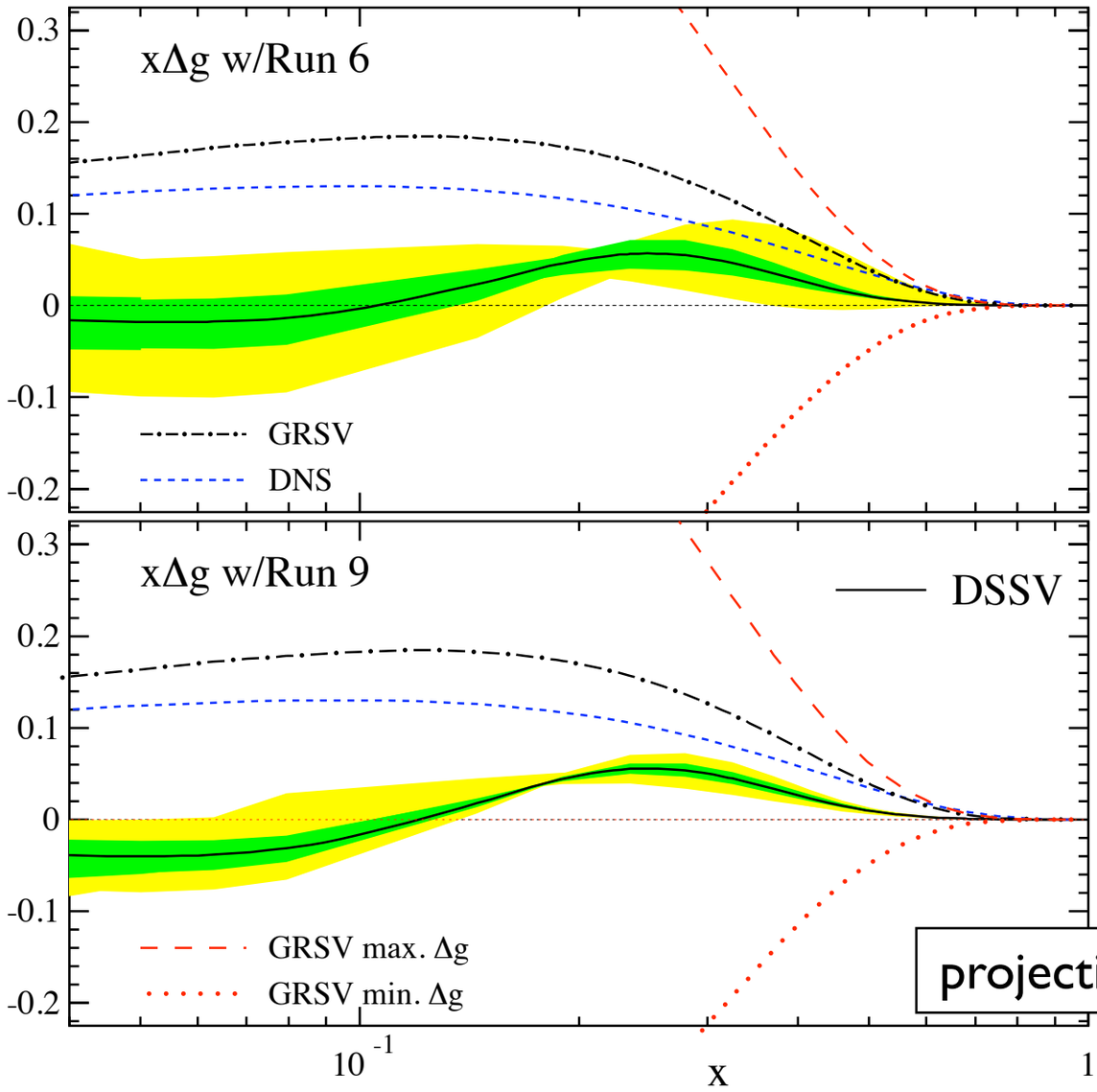


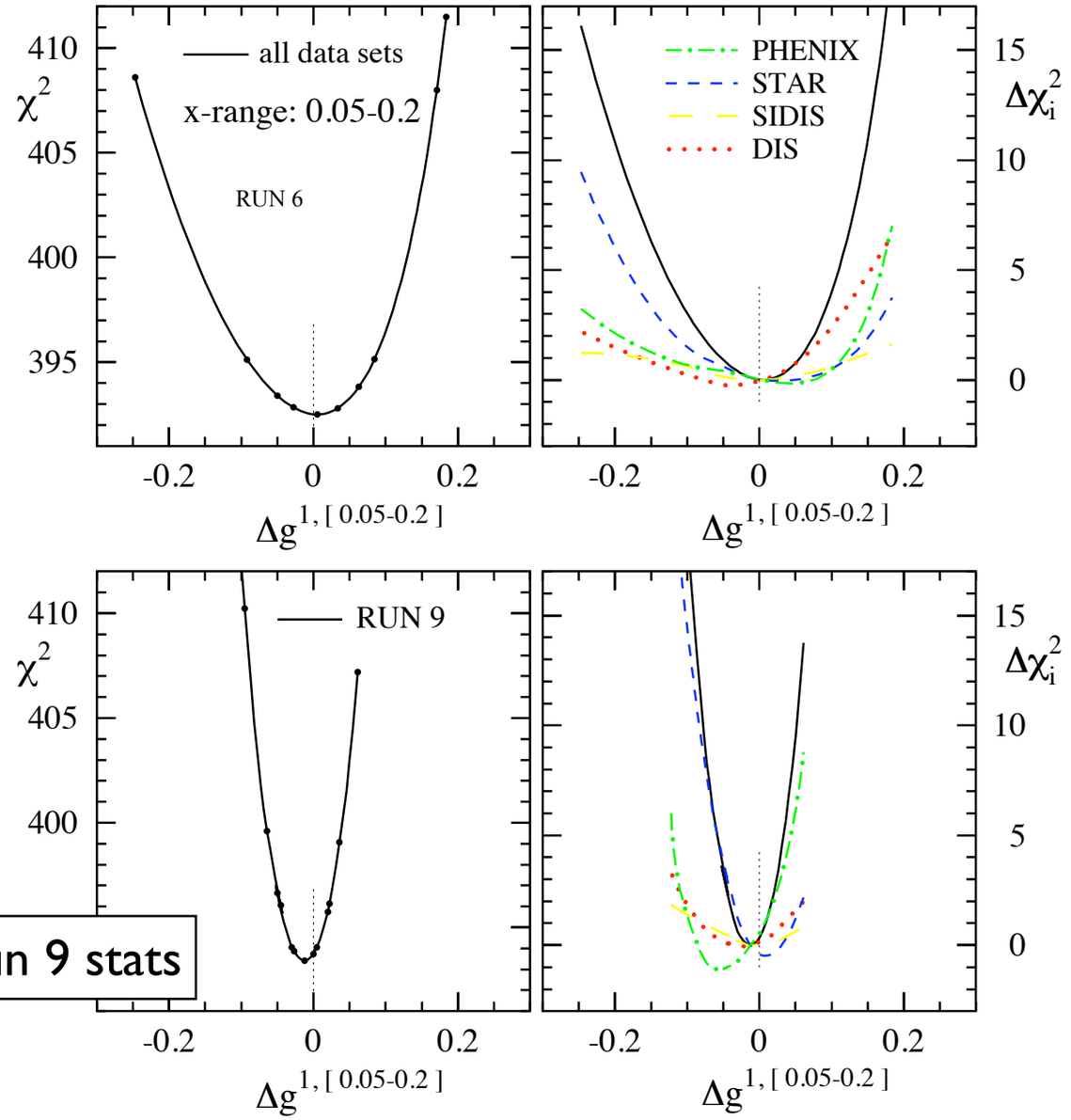
$$x_T = \frac{2\,p_T}{\sqrt{s}}$$

projected statistics based on measured yields and syst. error floors

- Substantial increase in integrated luminosity expected for 2009 run
- 500 GeV running for W program will also yield a large inclusive dataset
  - Higher energy at same p_T gives lower x_g, x_q
  - less quark polarization, but higher statistics

Impact on Global Analysis



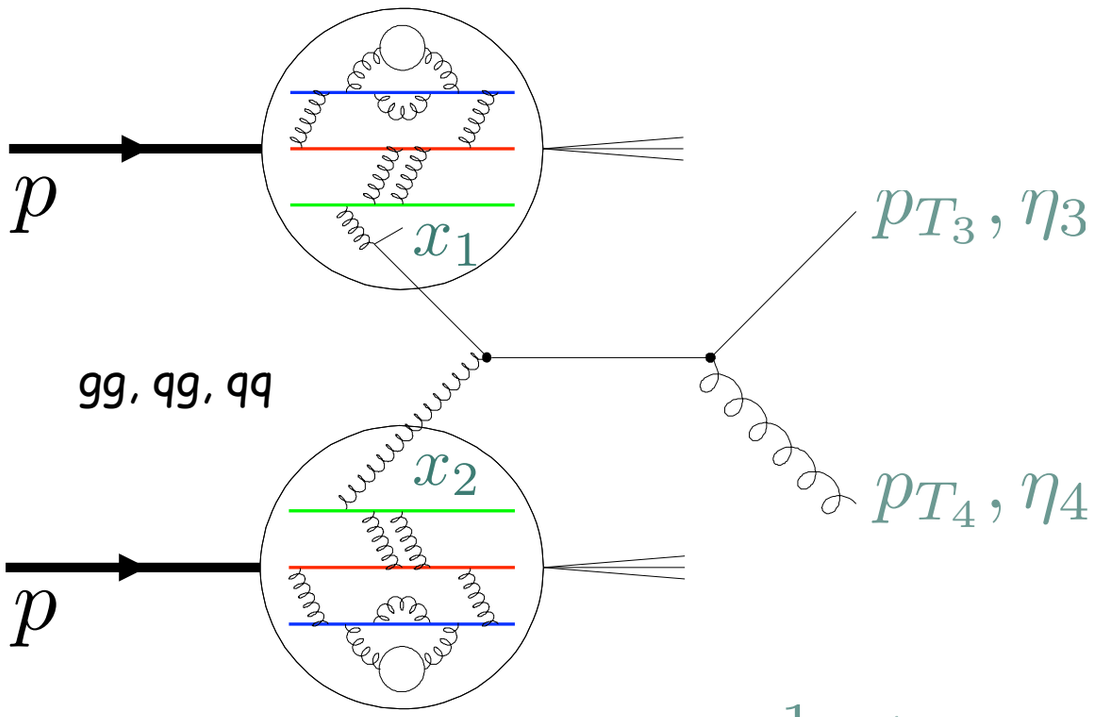


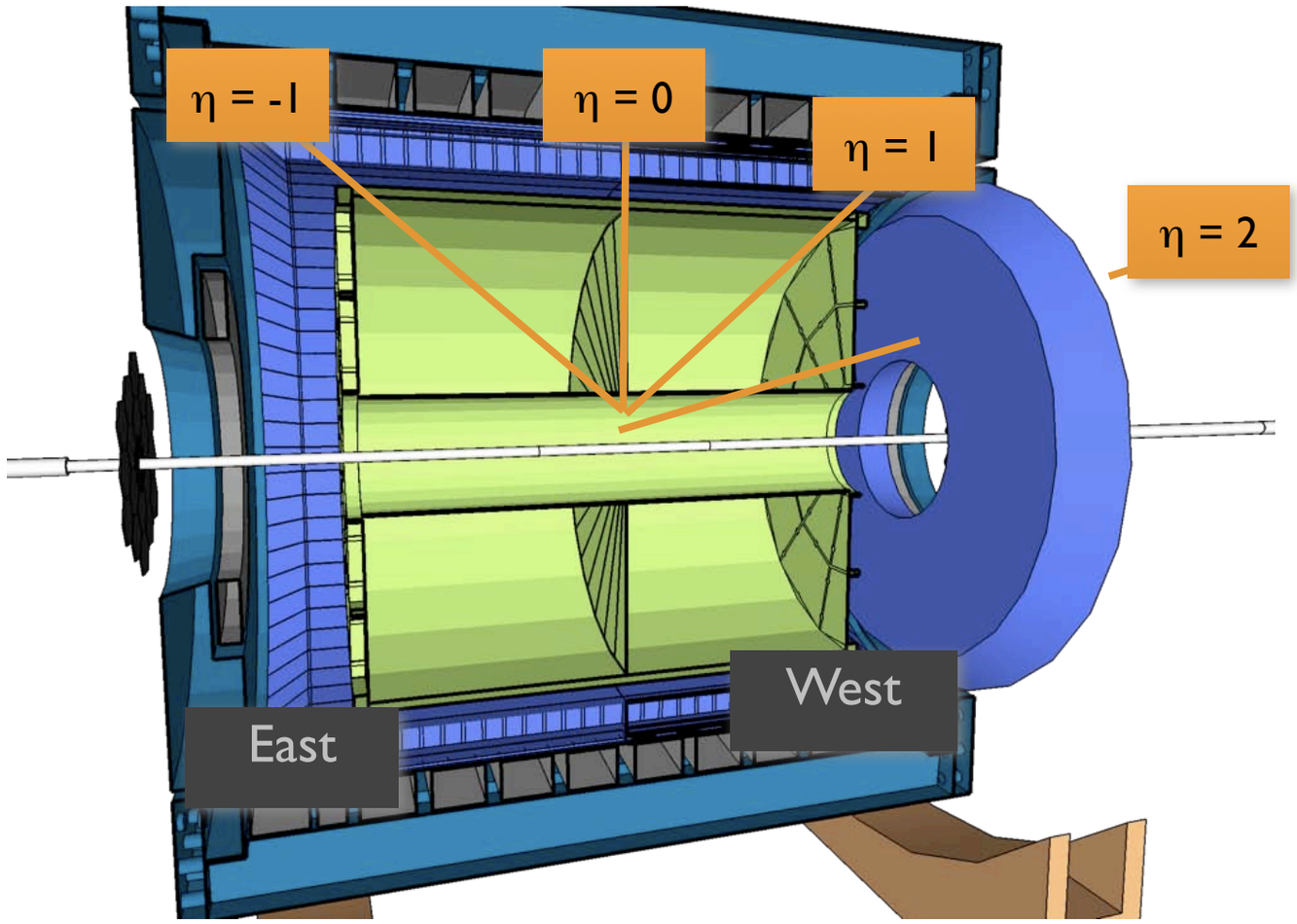
projection for run 9 stats

- Significant increase in precision expected with a global analysis of the anticipated 2009 data

Correlation Measurements

- Gluon polarization - Correlation Measurements:
  - access to partonic kinematics through
    Di-Jet/Di-Hadron production
    Photon-Jet production





$$x_{1\,(2)} = \frac{1}{\sqrt{s}}\left(p_{T_3} e^{\eta_3(-\eta_3)} + p_{T_4} e^{\eta_4(-\eta_4)}\right)$$

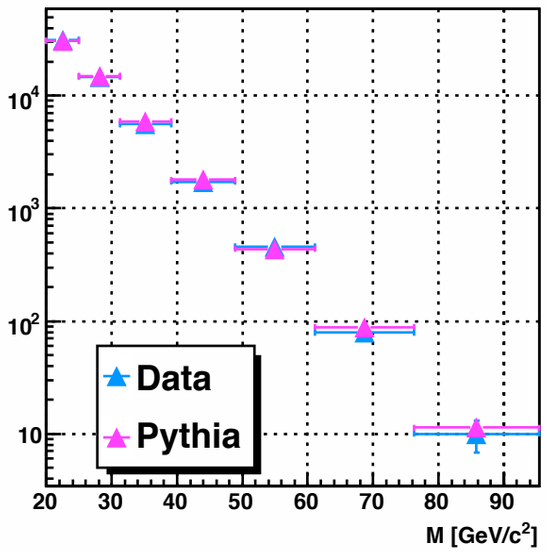
$$M = \sqrt{x_1 x_2 s}$$

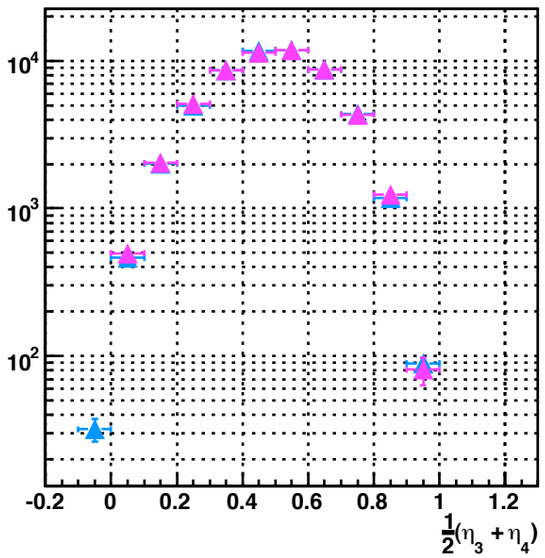
$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

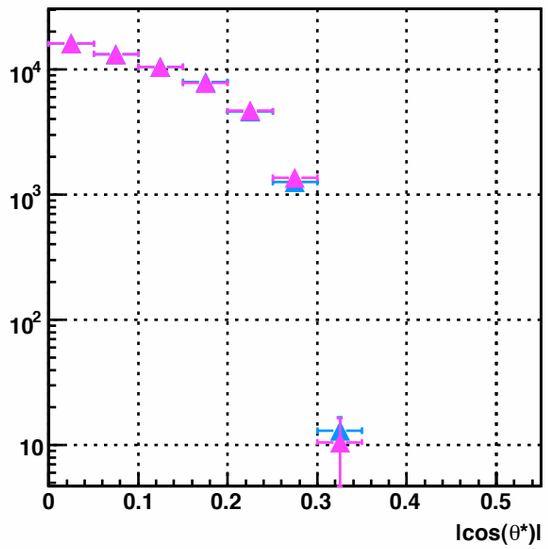
$$\cos\theta^* = \tanh\left(\frac{\eta_3 - \eta_4}{2}\right)$$

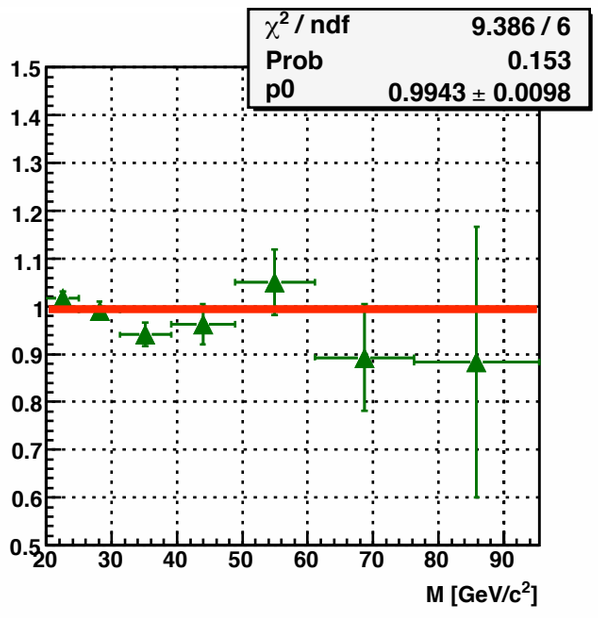
Di-Jets: Data Understanding

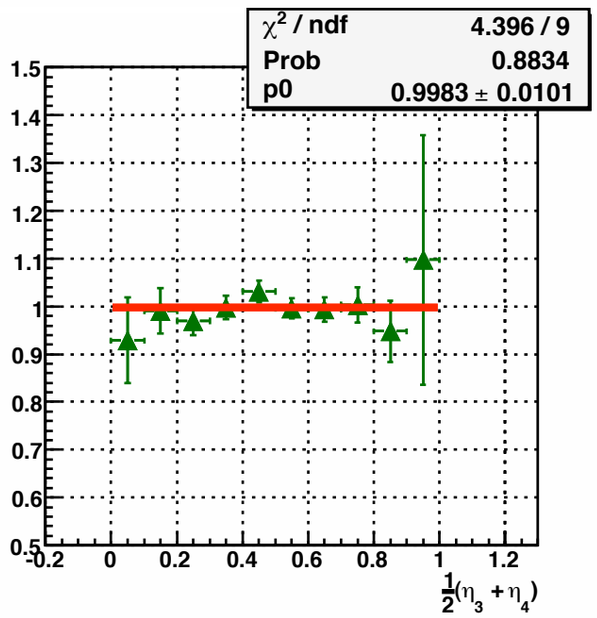
- 2005: Data / MC comparison shows very good agreement over many variables

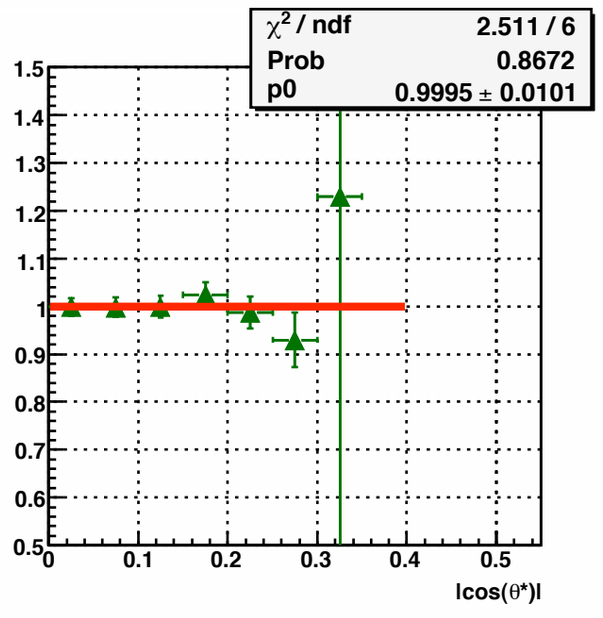












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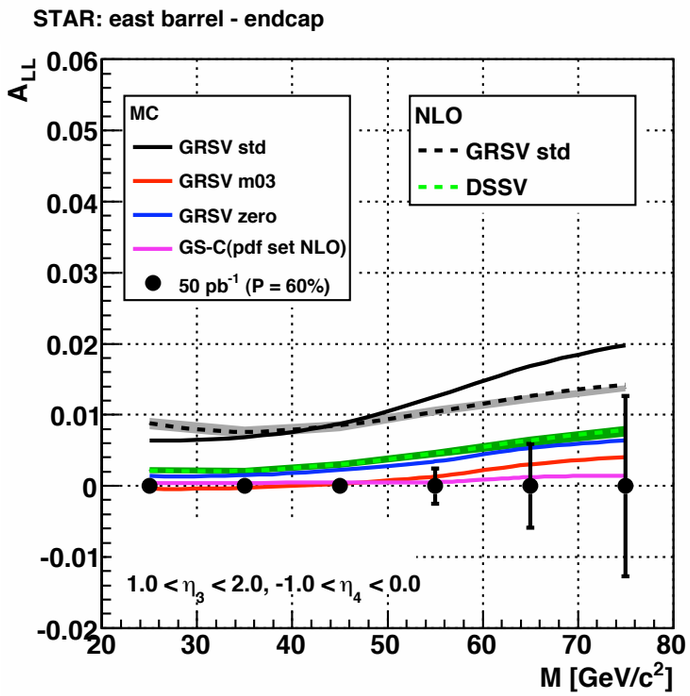
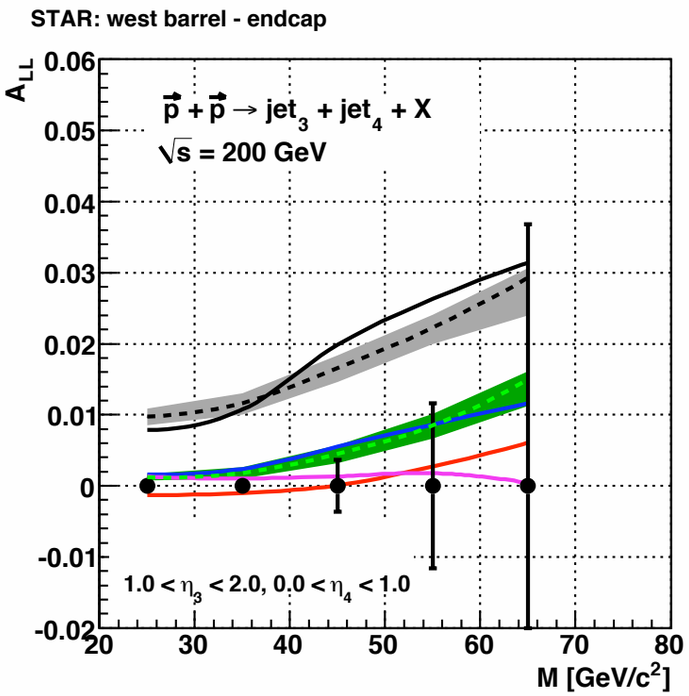
Di-Jets: Upcoming Measurements

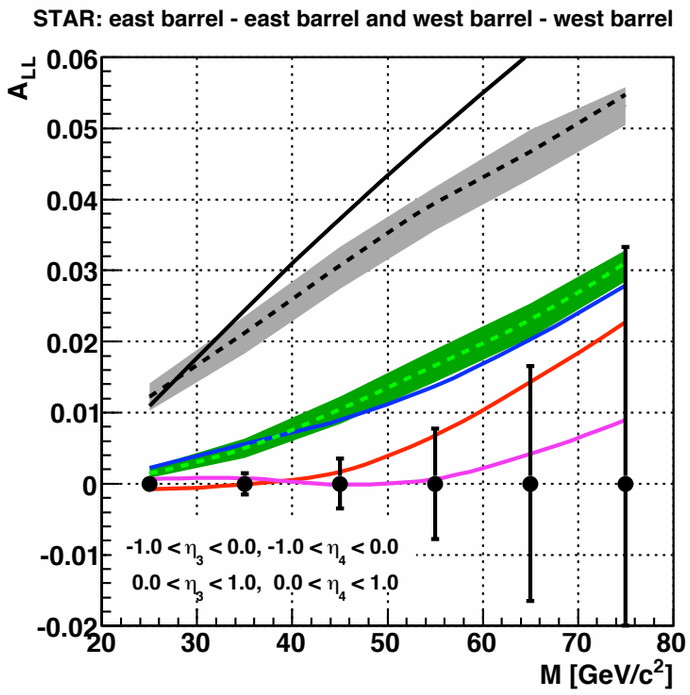
- High sensitivity to gluon polarization with anticipated 50 pb^{-1}
  - NLO calculations and MC based on PYTHIA with an evaluation of partonic asymmetries at leading order available

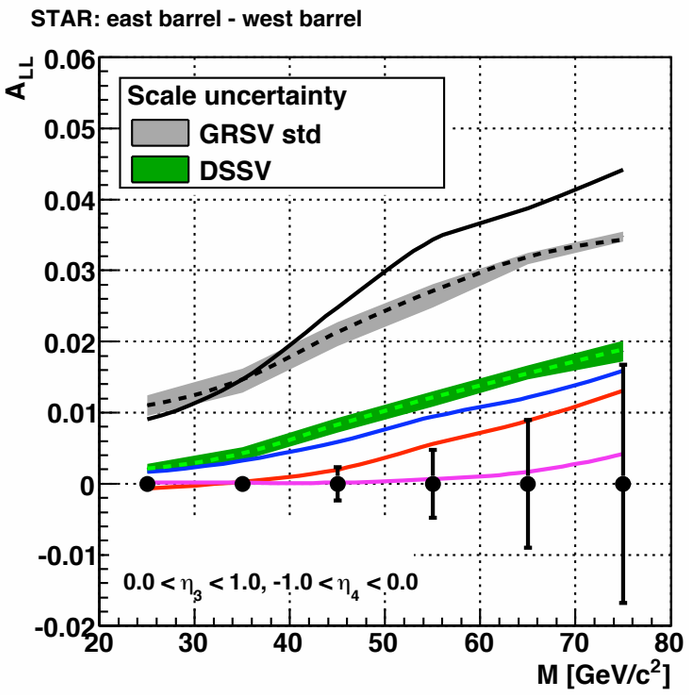




- Combination of different STAR regions provides access to different x regions

$$M = \sqrt{x_1 x_2 s} \qquad \eta_3 + \eta_4 = \ln \frac{x_1}{x_2}$$





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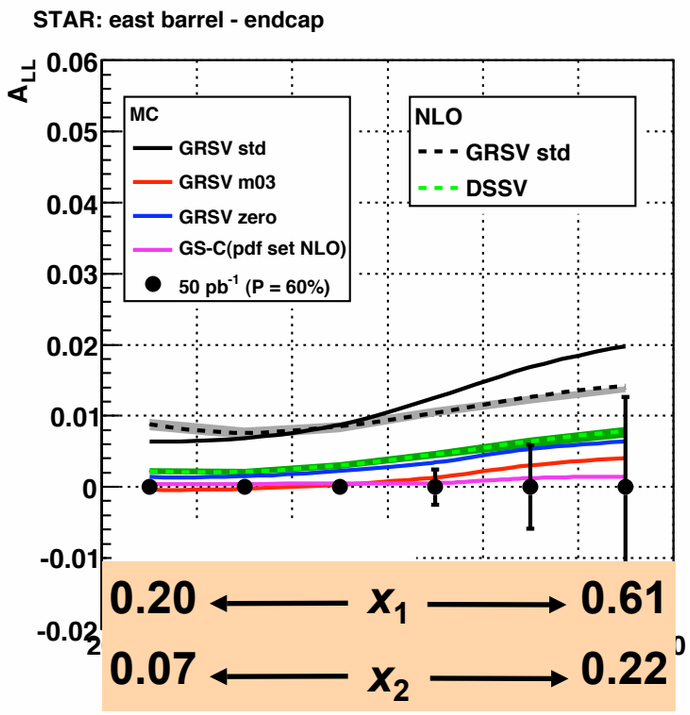
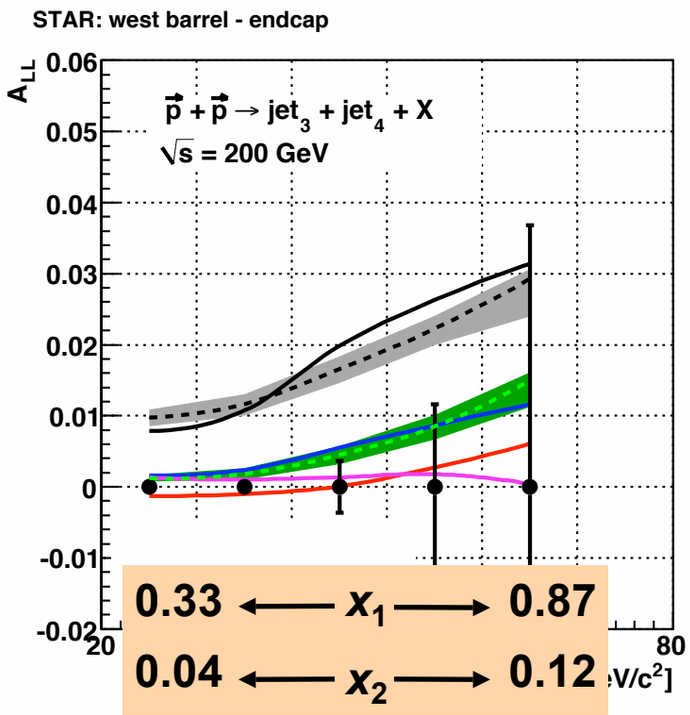
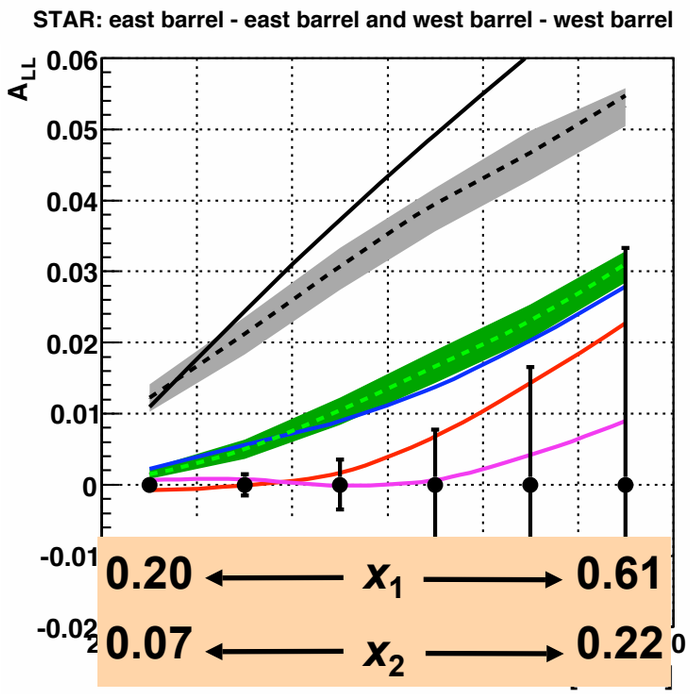
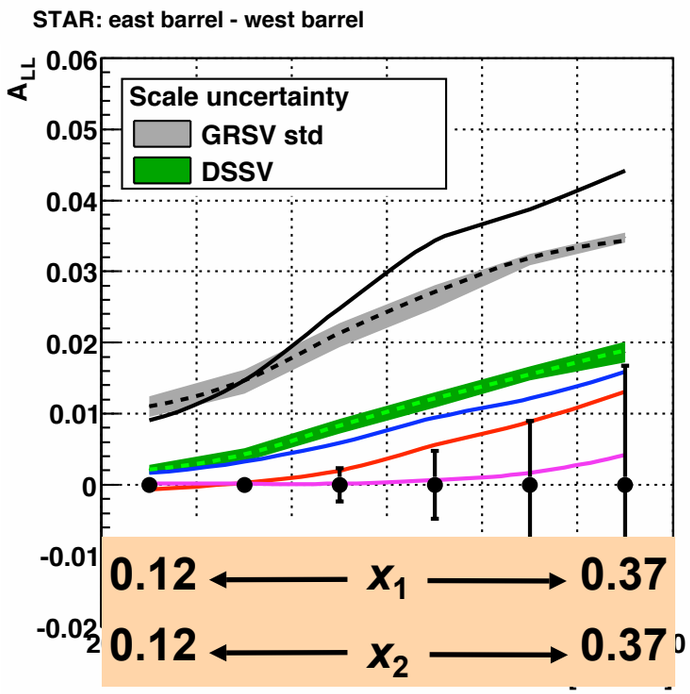


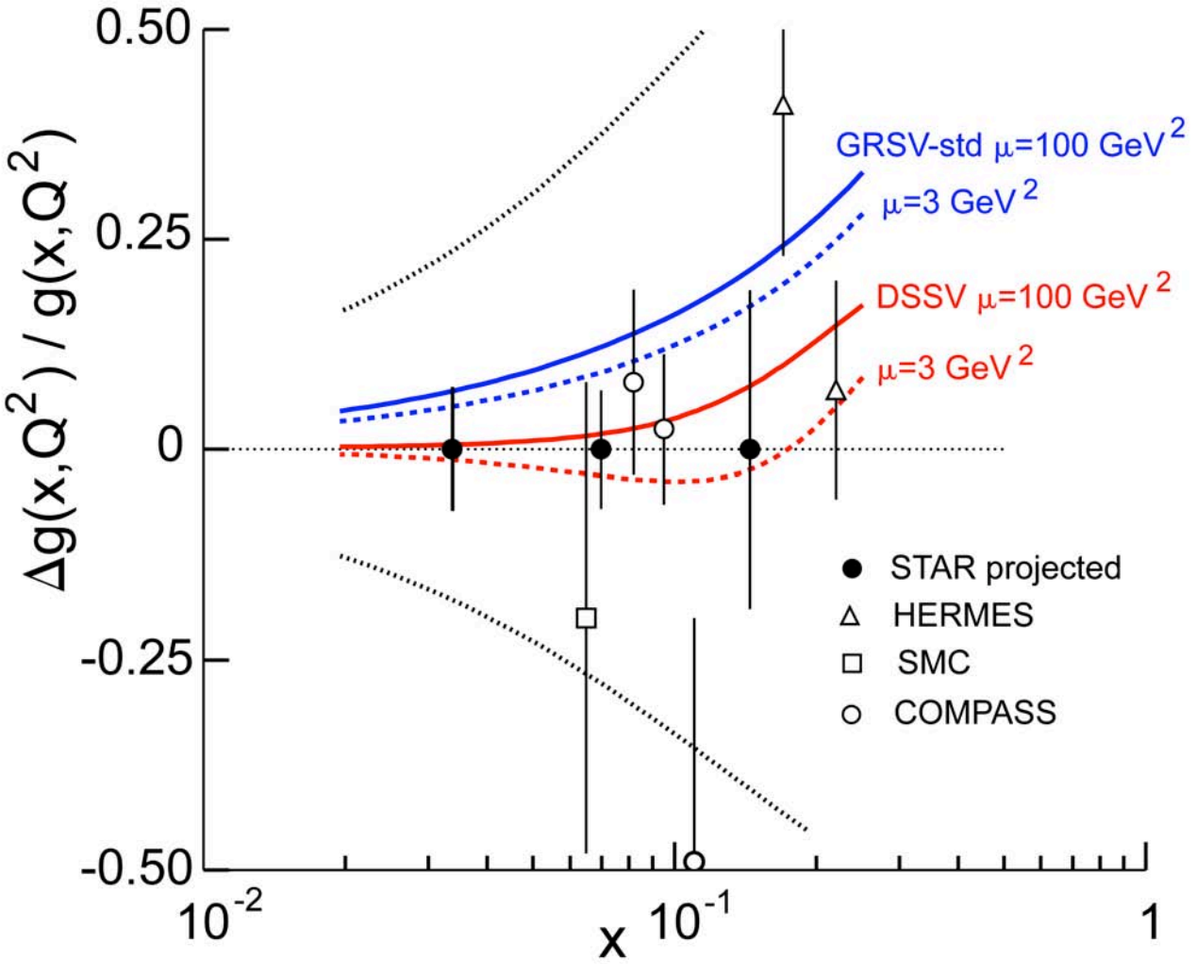




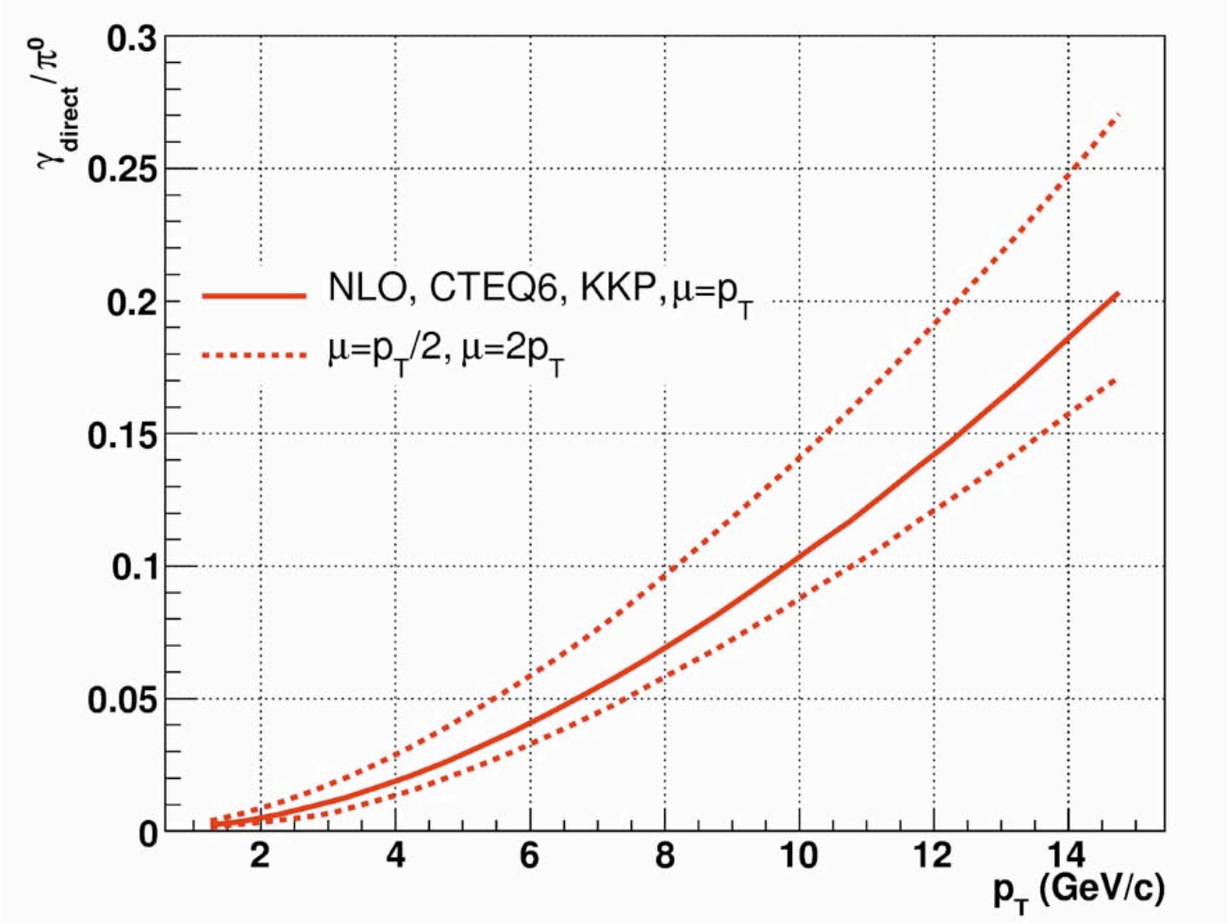


Direct Photon - Jet Correlations

- Direkt γ - Jet dominated by qg - Compton process: 90% from qg



- LO estimate of statistical uncertainties for 50 pb^{-1} with 100 % efficiency and no background, p_T > 10 GeV
  - Significantly more stats at lower p_T

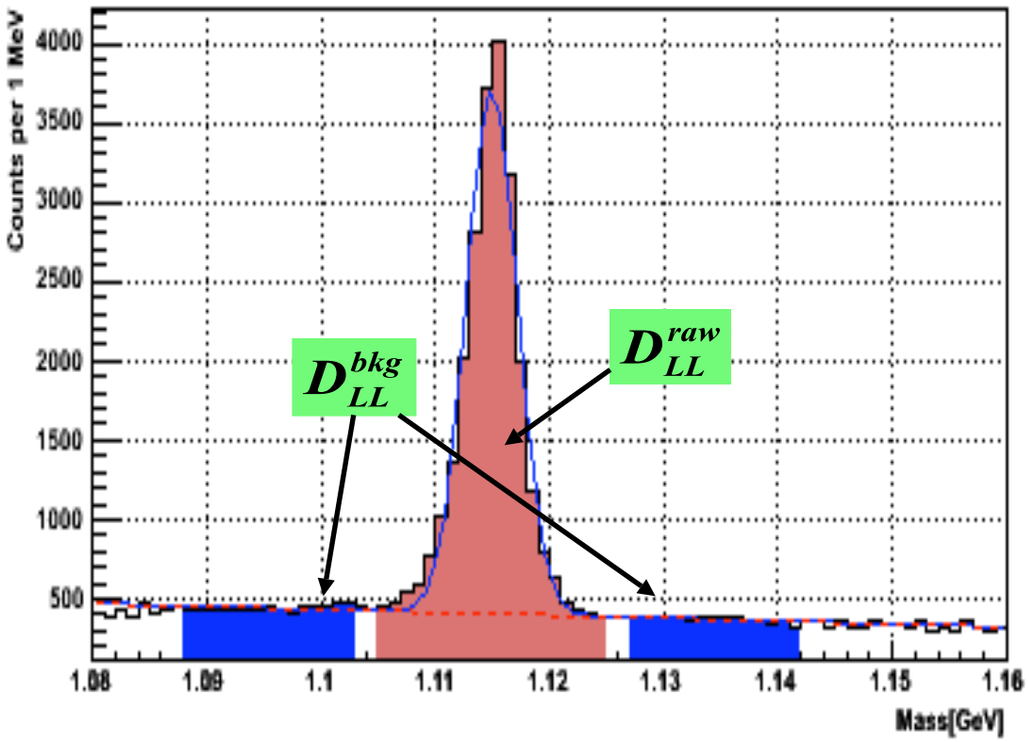


- γ/π^0 ratio at mid-rapidity
  - Challenging background from inclusive hadron channels

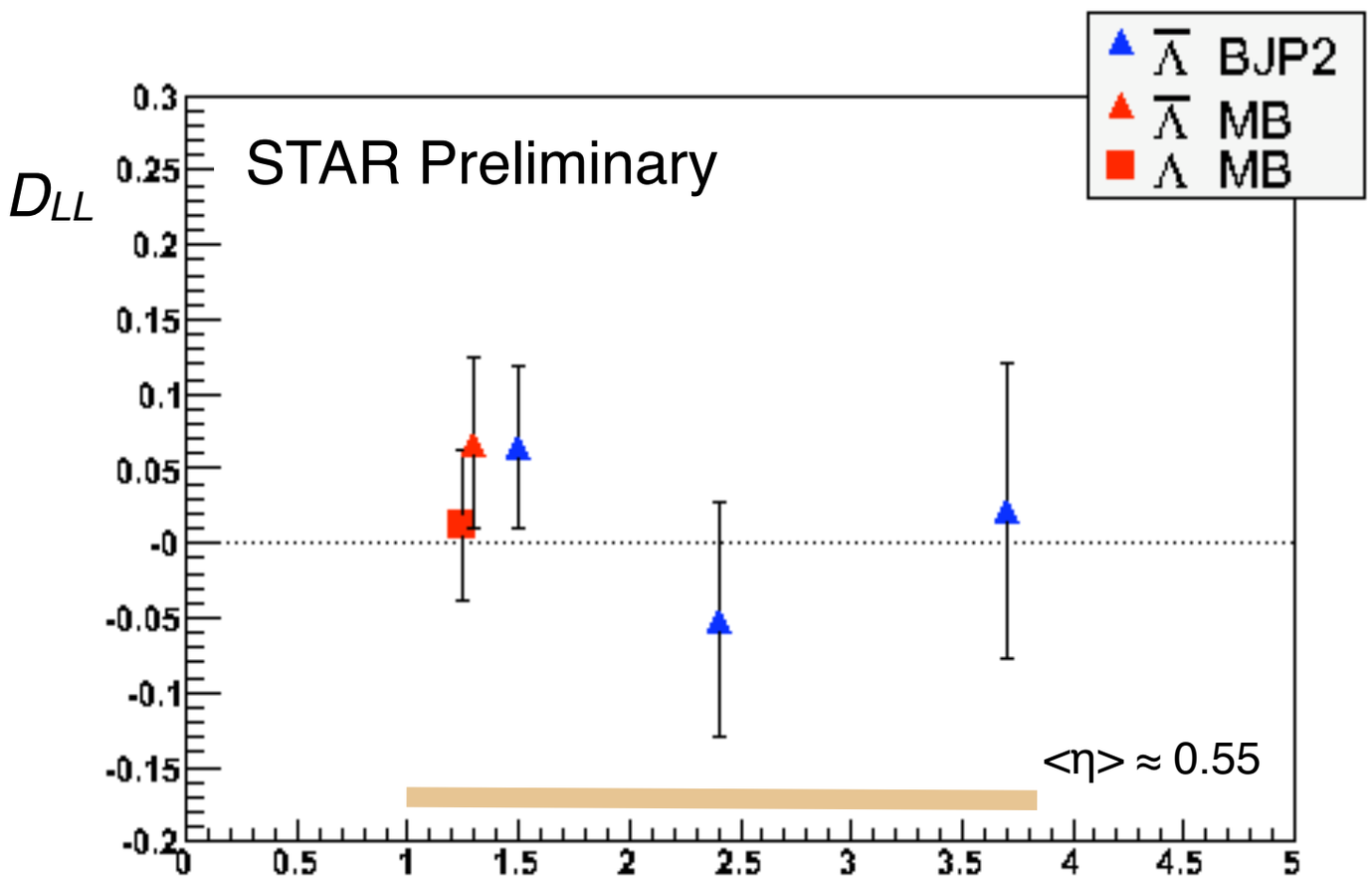
Studies ongoing!

IV. Accessing Quark Polarizations

Longitudinal Spin Transfer

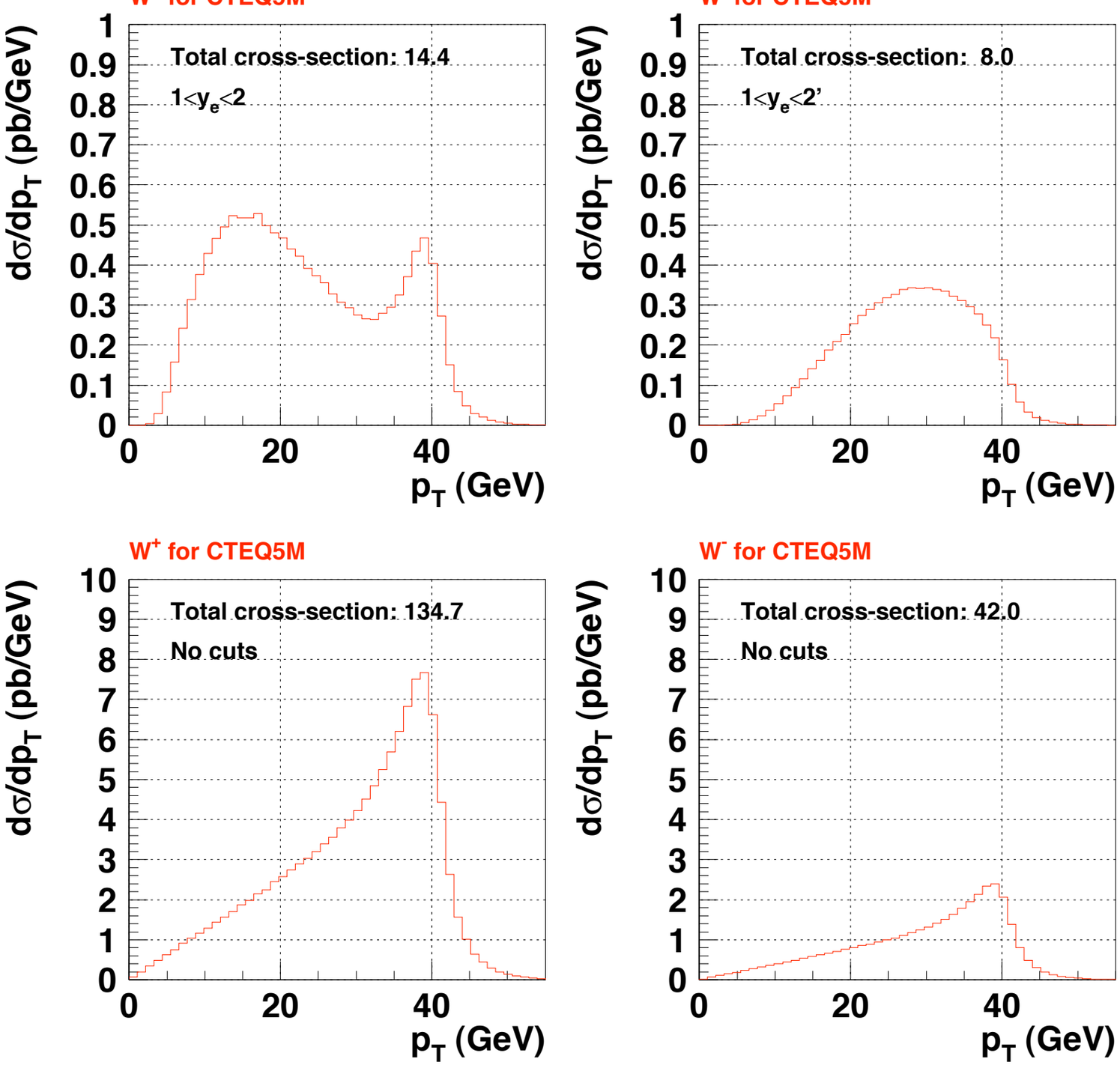


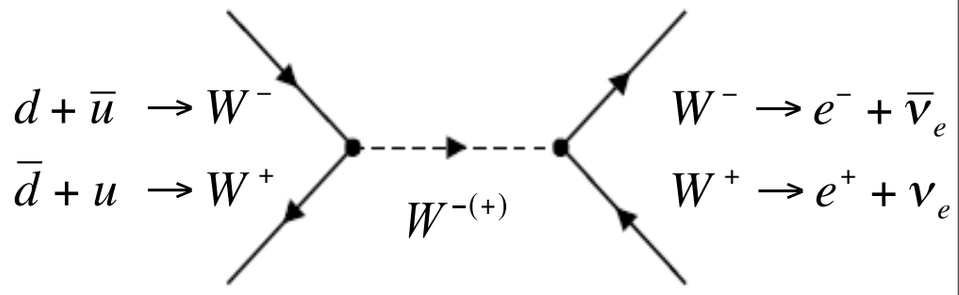
- Lambdas reconstructed from decay into proton and pion in the main TPC



- Proof of principle measurement
  - Extension to higher p_T and possibilities for triggering are being explored

W Bosons at Forward Rapidity: The Challenge

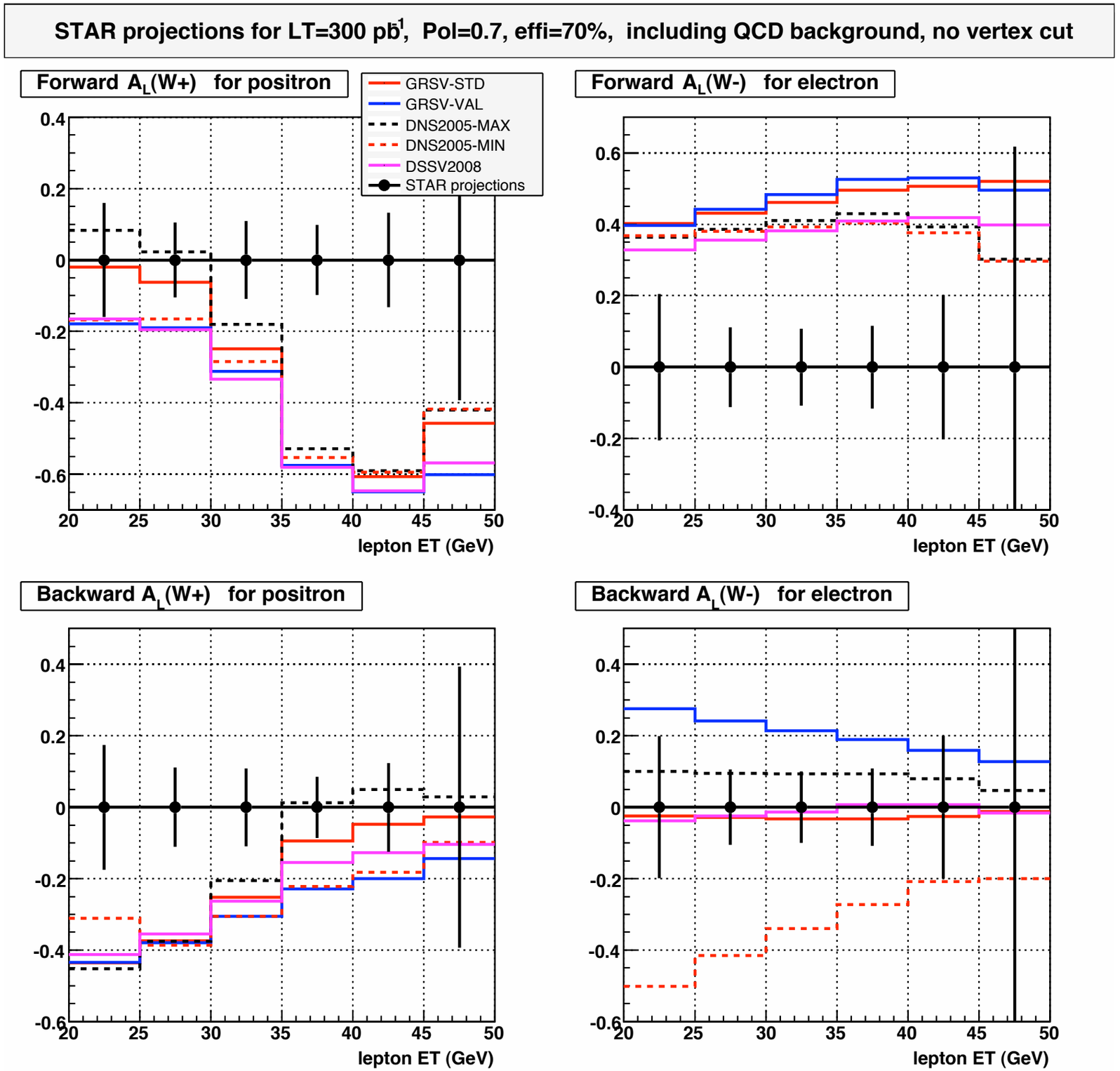




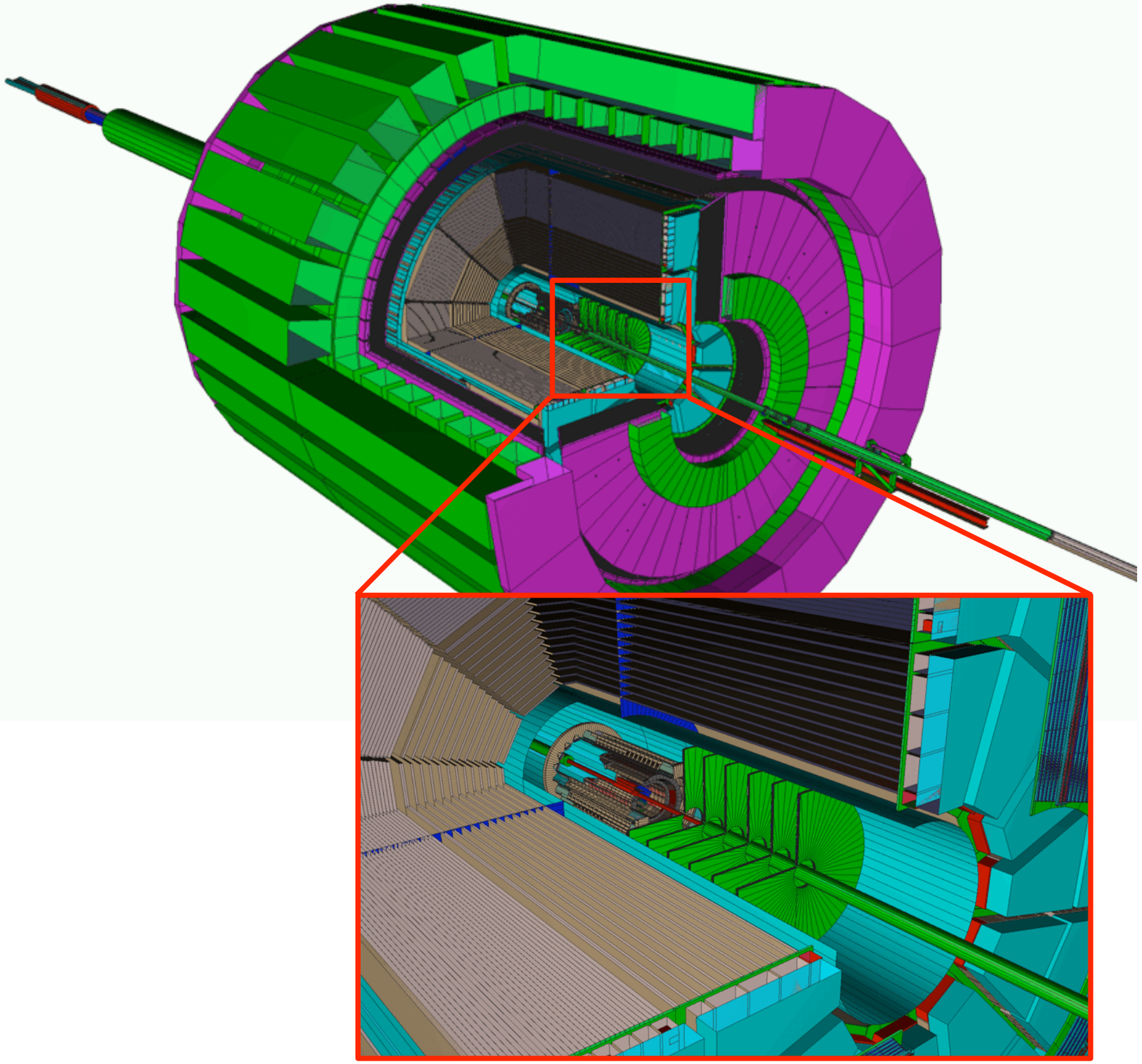
- W identified from their leptonic decay
- Good electron - hadron separation in the EEMC
- Charge-sign identification for high p_T electrons in the EEMC acceptance
  - Precision tracking at forward rapidity
    $1 < \eta < 2$

W Measurement: Sensitivity

- Large asymmetries dominated by quark polarizations: Consistency check with DIS data, 100 pb^{-1}
- With 300 pb^{-1} a strong impact constraining the unknown sea quark polarizations

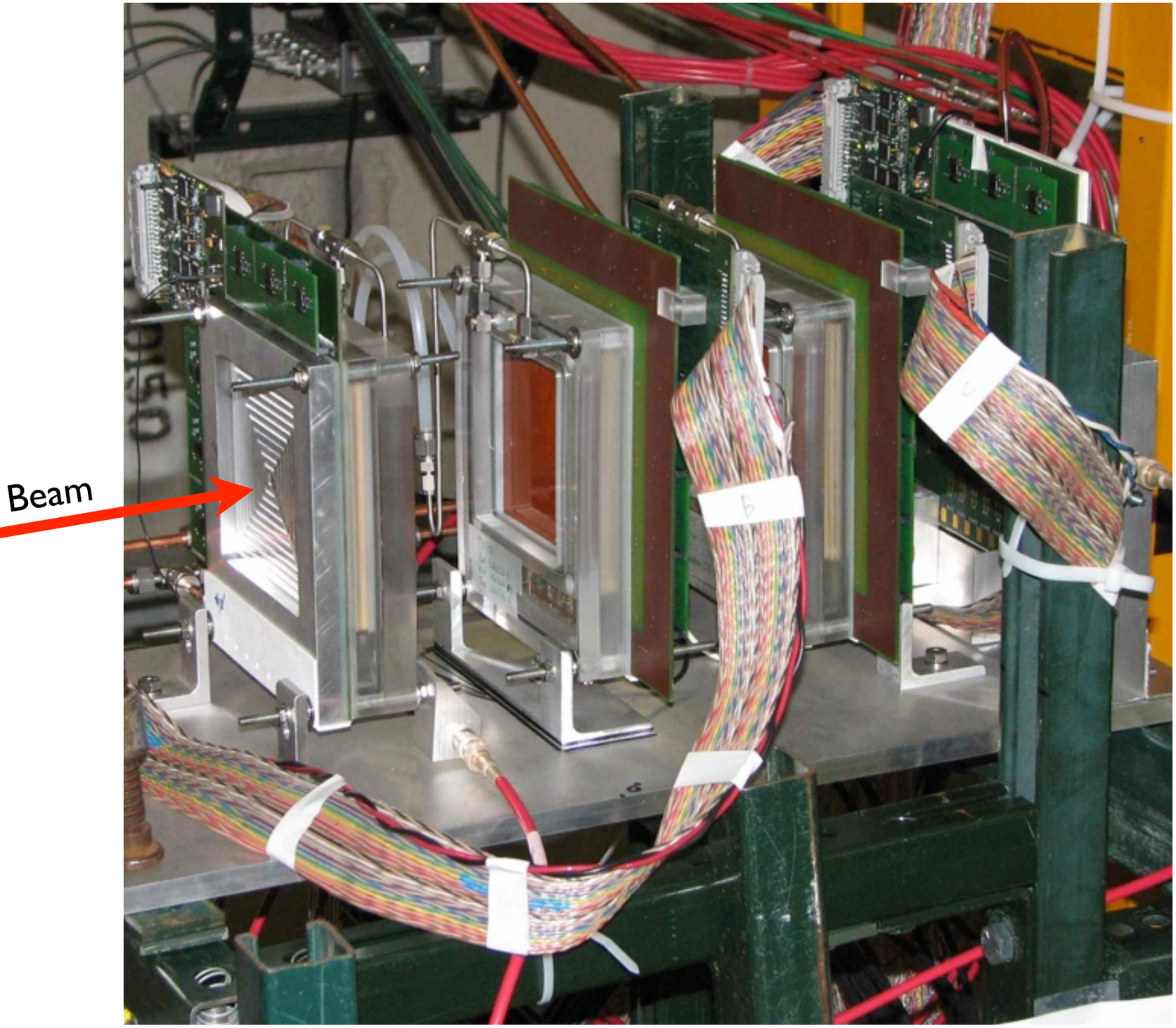


The STAR Forward GEM Tracker: FGT



- 6 Triple-GEM disks, subdivided into quarter sections
- provide coverage of EEMC acceptance over the full extend of the interaction diamond in 500 GeV collisions
- spatial resolution ~ 70 μm, demonstrated with prototypes in beam tests
- expected installation in Summer 2010

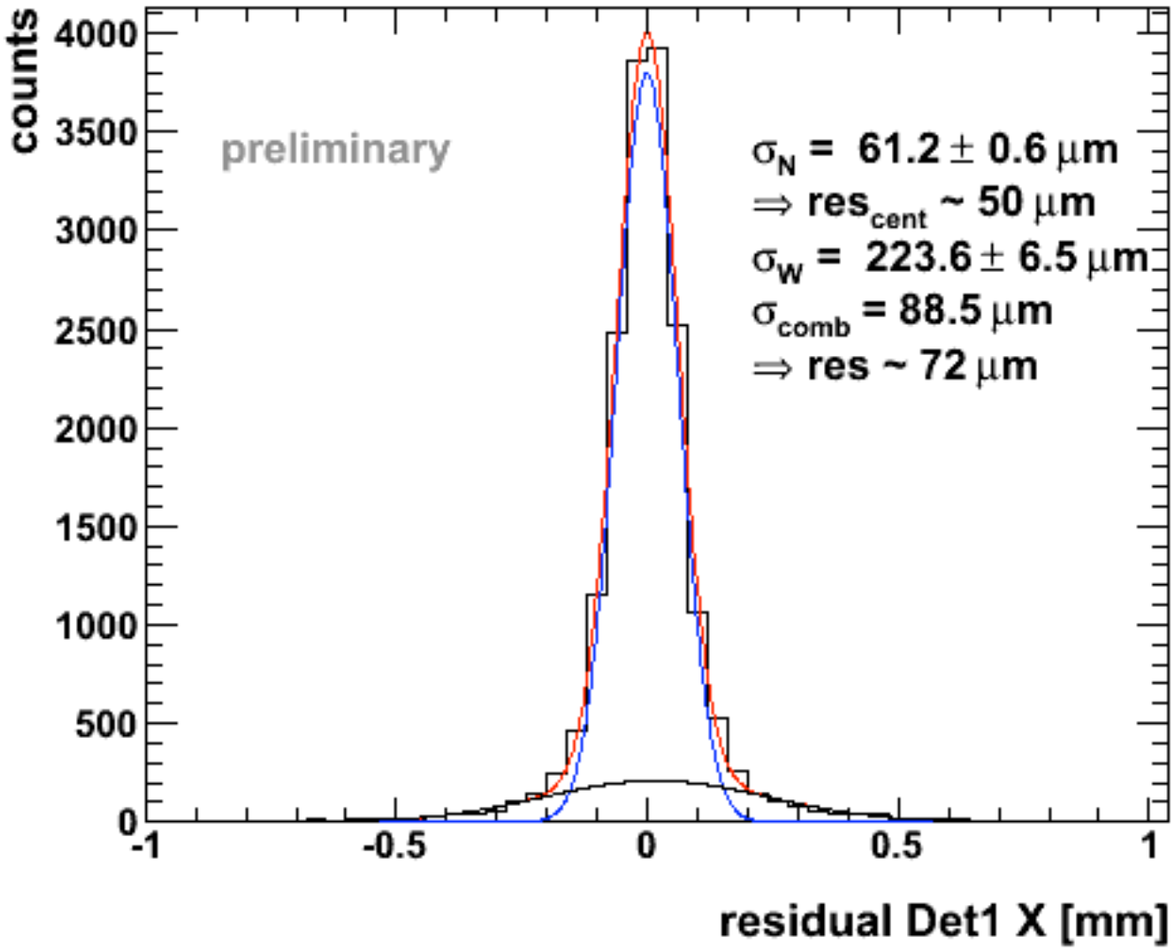
Prototype Beam Test



- Test of 3 triple - GEM detectors with orthogonal 2D strip readout at FNAL
  - GEM foils manufactured by TechEtch
  - APV25S1 readout electronics

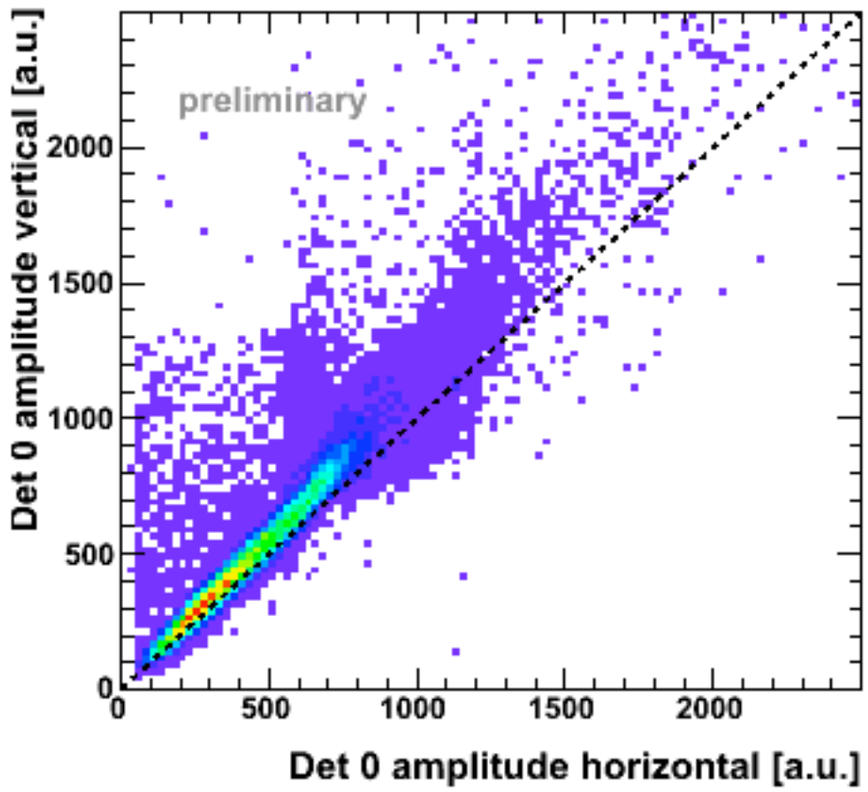
Beam Test Results

- Test detectors use larger readout strip pitch than final FGT design



- Spatial resolution of ~ 70 μm demonstrated, central distribution of good events yields ~ 50 μm

- Good charge sharing between readout coordinates achieved



Conclusion

- STAR has established a diverse program to explore the spin structure of the proton in longitudinally polarized p+p collisions
- Currently inclusive probes, with jets as the flagship measurement, are providing constraints on the gluon polarization ΔG
  - First RHIC measurements have been used successfully in a global analysis, providing new constraints on the polarized gluon distribution
- In the near future:
  - increased statistics and different CM energies for inclusive probes will yield additional constraints
  - correlation measurements (di-jet, di-hadron, γ-jet) will provide better resolution in x
- With 500 GeV collisions, the study of (anti-) quark polarizations becomes possible through W boson production
  - STAR FGT will allow W identification at forward rapidities

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Vibrant transverse spin program, too! See next talk by Mirko Planinic