Recent results and Future perspectives of the STAR high-energy polarized proton-proton program at RHIC

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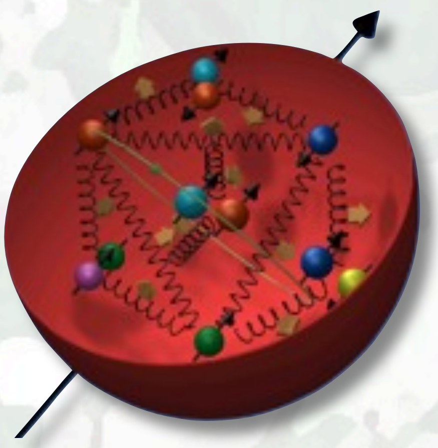
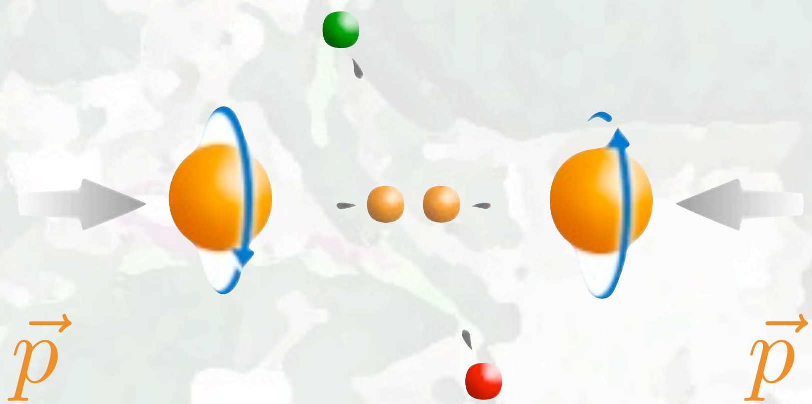


STAR India Collaboration Meeting at VECC
Kolkata, India, November 24, 2008

Outline

- Collider

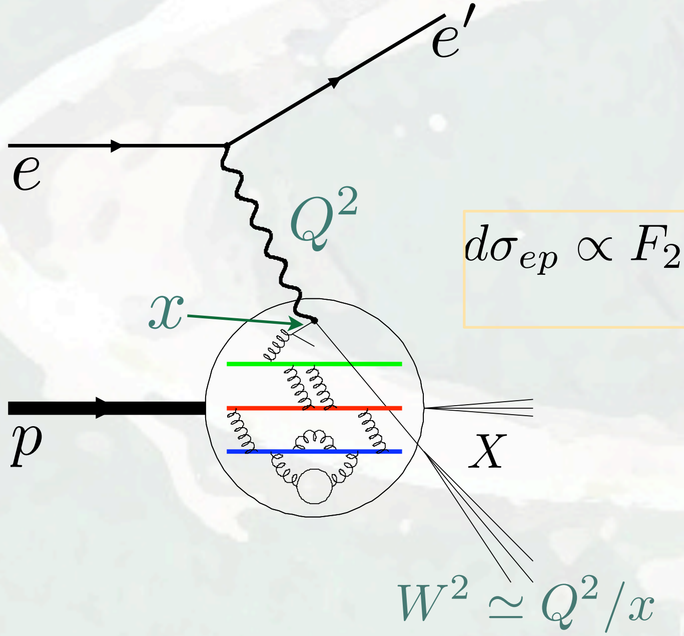
- Experiment
- Highlights of recent results and achievements
- Future polarized p-p physics program - FGT project
- Theoretical foundation



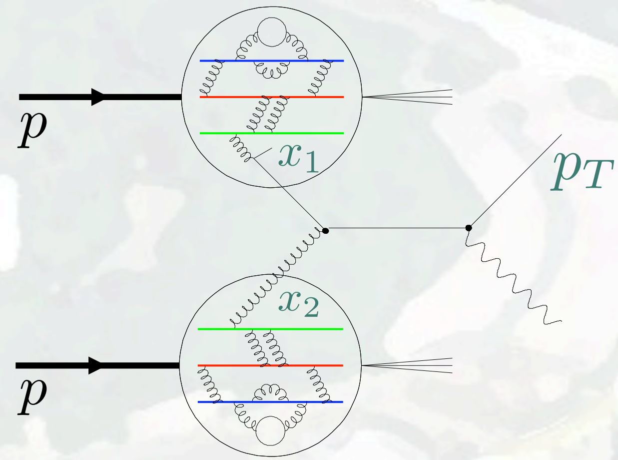
- Summary and Outlook

Theoretical foundation

- How do we probe the structure and dynamics of matter in ep / pp scattering?



$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$



Universality

$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$

Factorization

Momentum contribution

$$f(x) =$$

$$f^+(x) + f^-(x)$$

$$\Delta f(x) =$$

$$f^+(x) - f^-(x)$$

Spin contribution

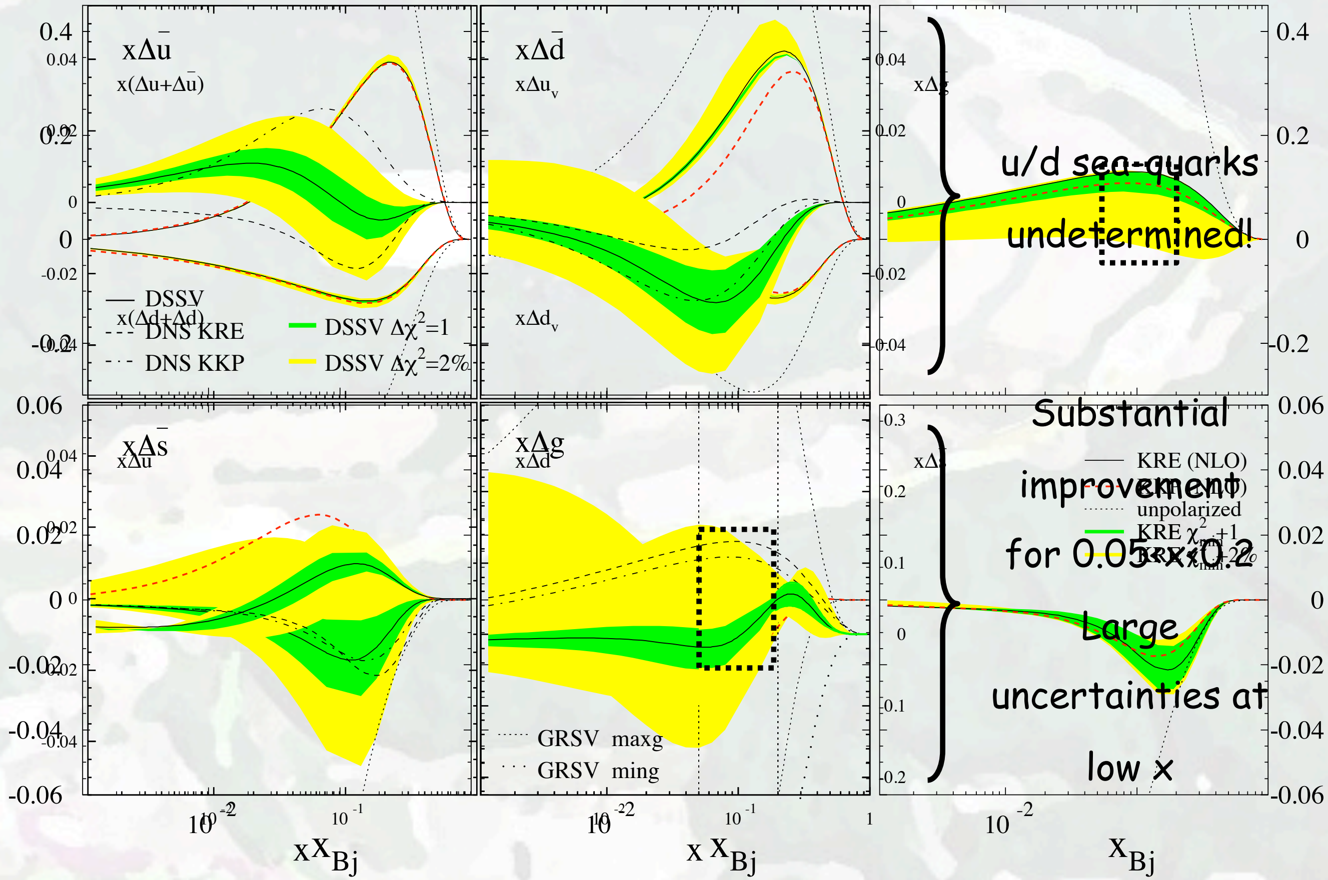
Theoretical foundation

- What do we know about the polarized quark and gluon distributions?
  - Spin carried by quarks is very small (ΔΣ ~ 0.4)!

$$\frac{1}{2} = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle$$

with $\langle S_q \rangle = \frac{1}{2}\Delta\Sigma$ and $\langle S_g \rangle = \Delta G$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$



D. de Florian et al., Phys. Rev. [illegible] 094018 (2005).

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

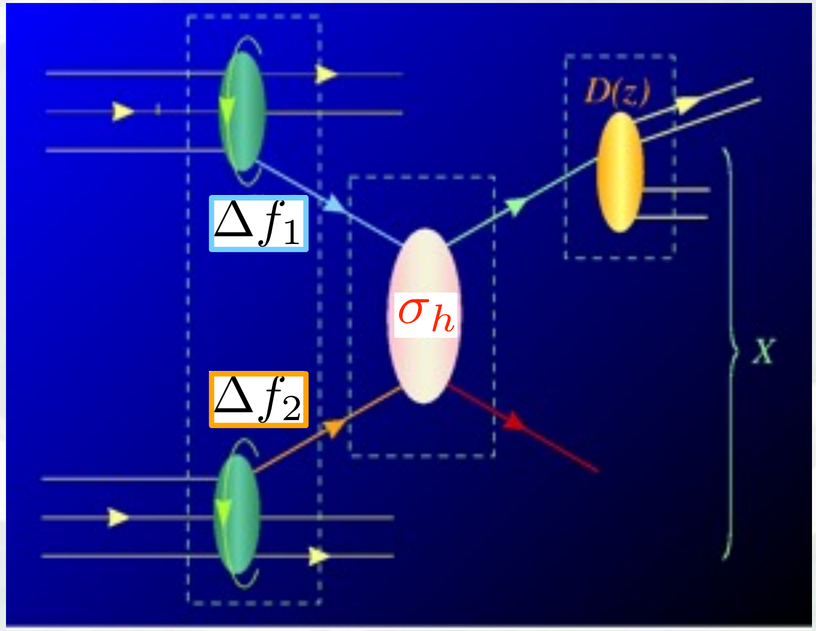
$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2)\,dx$$

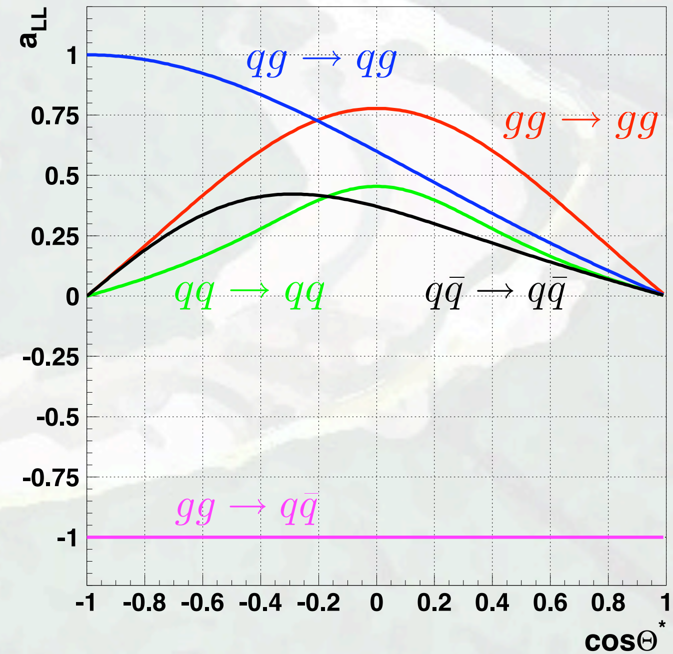
Theoretical foundation

- Gluon polarization - Extraction

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

Extract $\Delta g(x,Q^2)$ through Global Fit (Higher Order QCD analysis)!





long-range | short-range | long-range

$$A_{LL} = \frac{d\Delta\sigma}{d\sigma} \propto \frac{\Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h}{f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h}$$

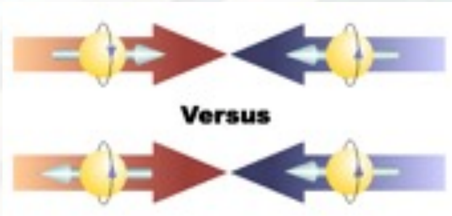
Δf_1, Δf_2

$$a_{LL} = \frac{\Delta \sigma_h}{\sigma_h}$$

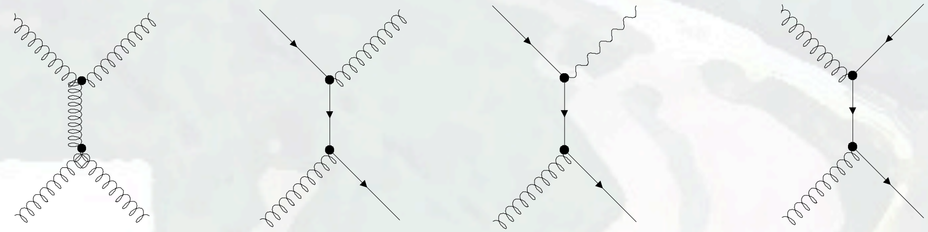
} Input

Theoretical foundation

- What is required experimentally to measure the gluon spin contribution?
  - Double longitudinal-spin asymmetry: A_{LL}



$$\vec{p} + \vec{p} \rightarrow$$



$\text{jets} + X$ $\quad \gamma + X \quad c\bar{c}\,(b\bar{b}) + X$

    - Study helicity dependent structure functions (Gluon polarization)!

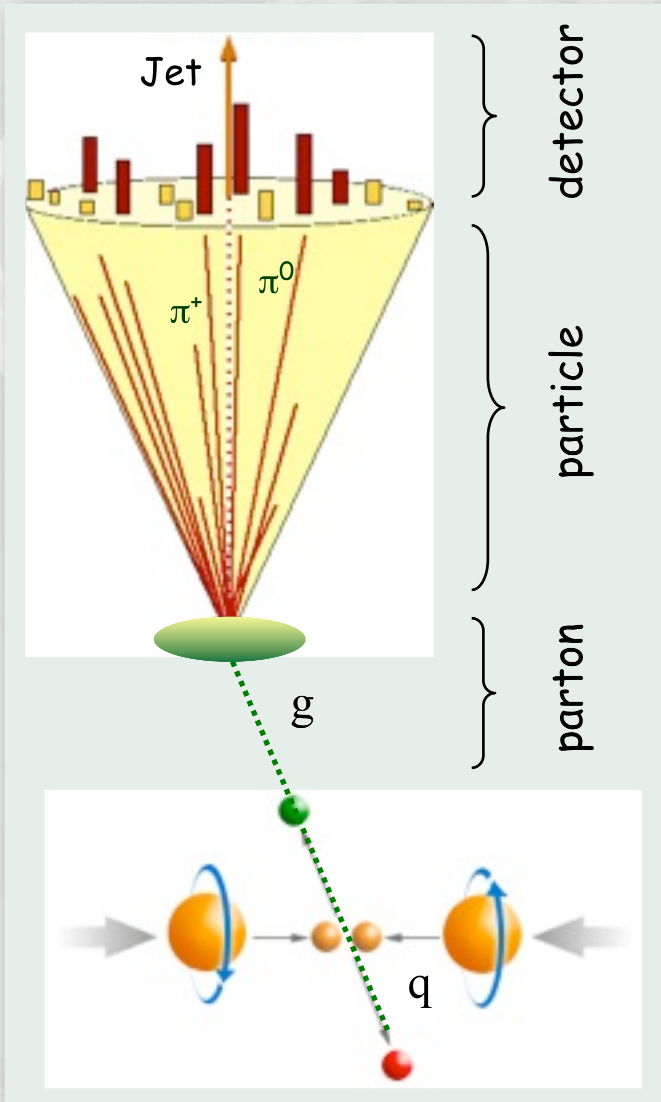
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

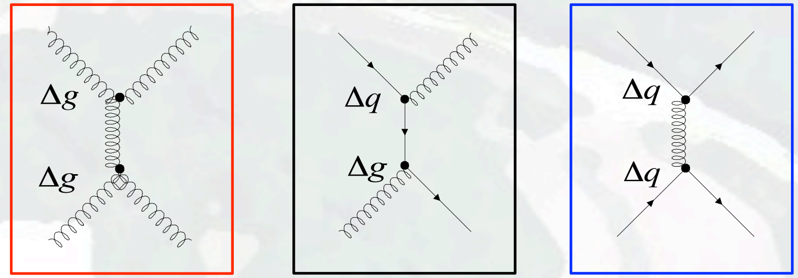
  - Require concurrent measurements:
    - Magnitude of beam polarization, $P_{1(2)}$ RHIC polarimeters — RHIC polarimeters
    - Direction of polarization vector
    - Relative luminosity of bunch crossings with different spin directions
    - Spin dependent yields of process of interest N_{ij}

    (Direction of polarization vector, relative luminosity, spin dependent yields:) STAR experiment

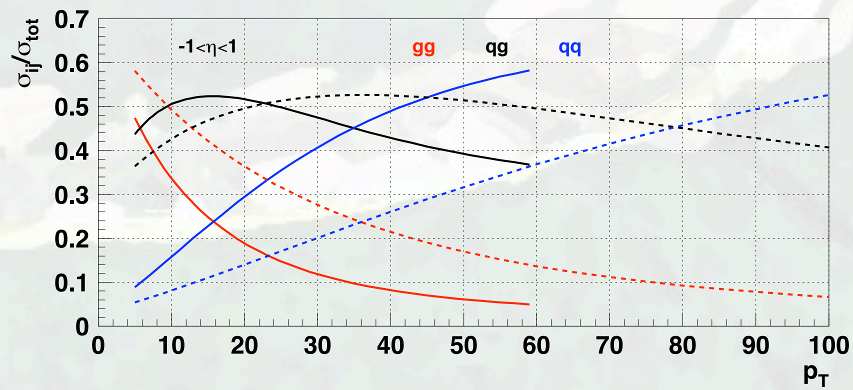
Theoretical foundation

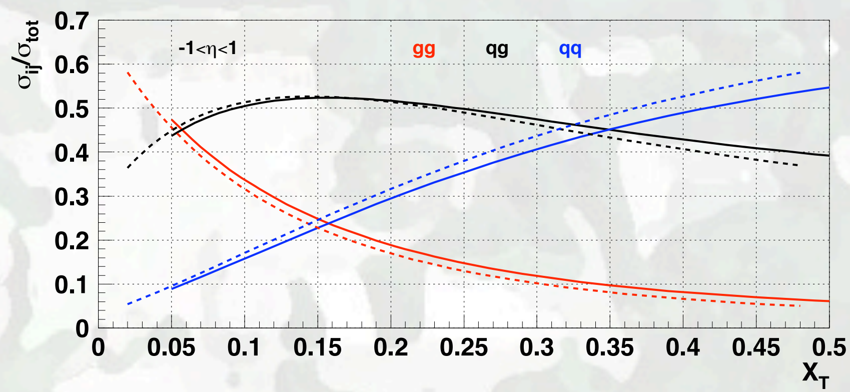
Gluon polarization - Inclusive Measurements





Inclusive Jet production (200GeV: Solid line / 500GeV: Dashed line)



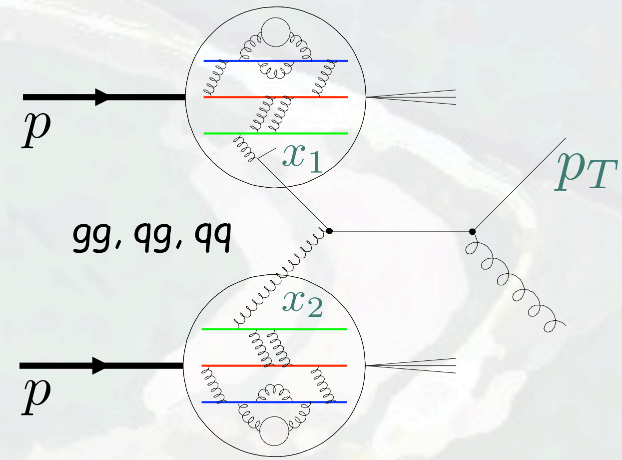


$$x_T = 2p_T/\sqrt{s}$$

Theoretical foundation

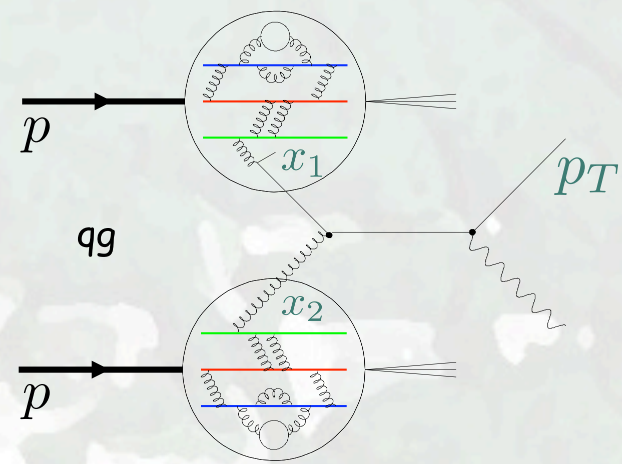
- Gluon polarization - Correlation Measurements
  - Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production

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



Di-Jet production

  - Di-Jet production / Photon-Jet production
    - Di-Jets: All three (LO) QCD-type processes contribute: gg, qg and qq with relative contribution dependent on topological coverage
    - Photon-Jet: One dominant underlying (LO) process with large partonic a_{LL} at forward rapidity
    - Larger cross-section for di-jet production compared to photon related measurements
    - Photon reconstruction more challenging than jet reconstruction
    - Full NLO framework exists ⇒ Input to Global analysis



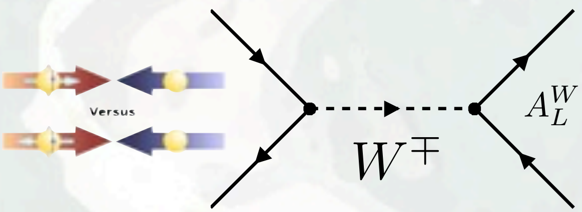
Photon-Jet production

Theoretical foundation

Quark / Anti-Quark Polarization - W production

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

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

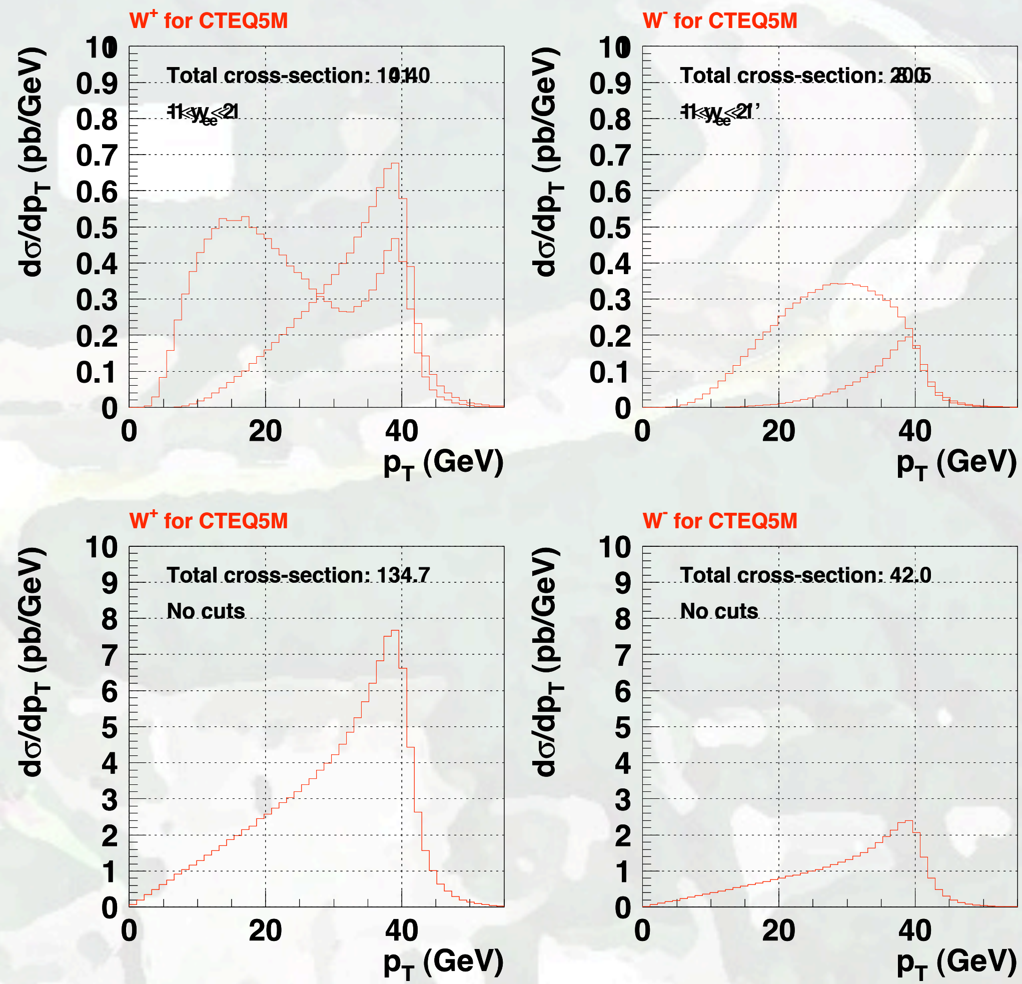


$$A_L^W = \frac{1}{P}\frac{N^+(W) - N^-(W)}{N^+(W) - N^-(W)}$$

$$W^+ \rightarrow e^+ + \nu_e$$

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

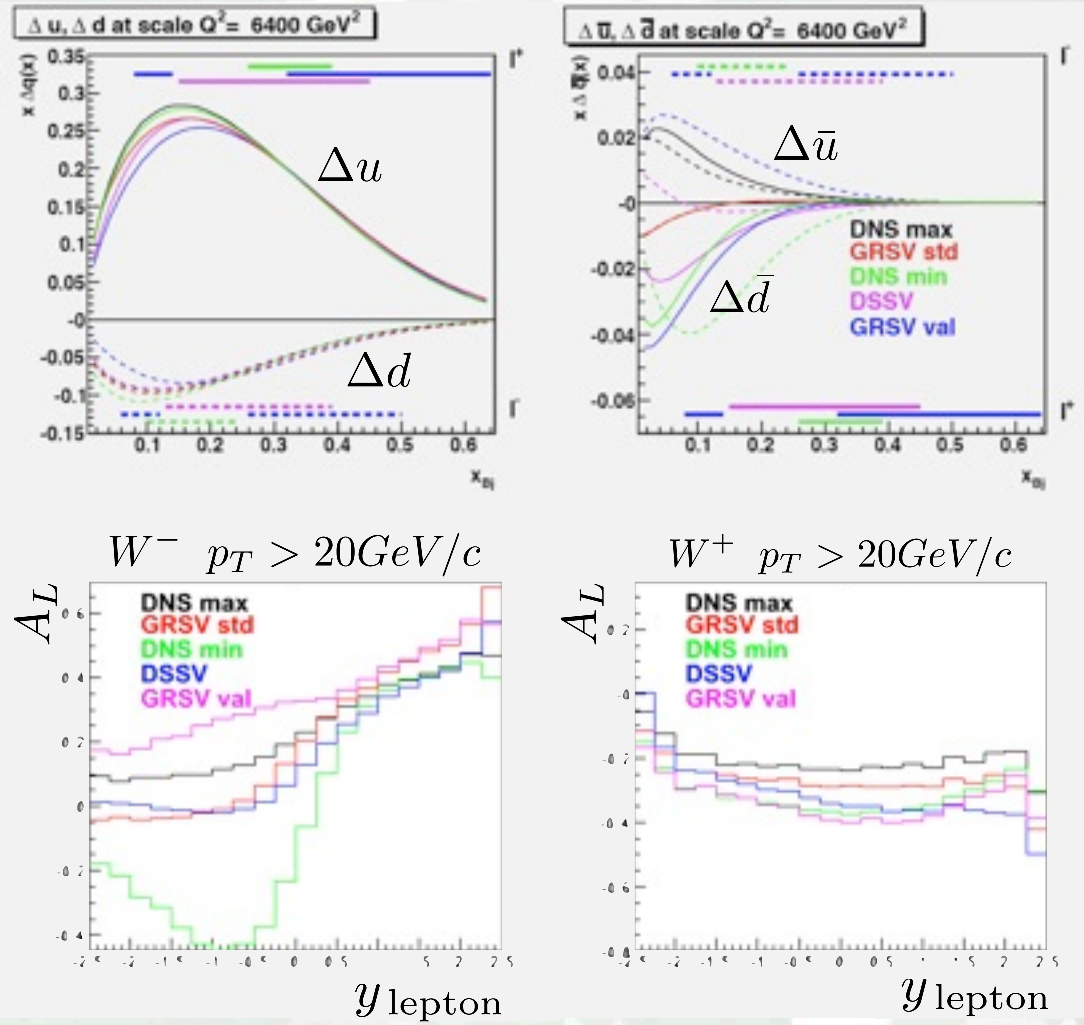
RHICBOS W simulation at 500GeV CME



- Key signature: High p_T lepton (e^-/e^+ or μ^-/μ^+) (Max. $M_W/2$) - Selection of W^-/W^+ : Charge sign discrimination of high p_T lepton
- Required: Lepton/Hadron discrimination

Theoretical foundation

Quark / Anti-Quark Polarization - Sensitivity in W production



- Theoretical framework for leptonic asymmetries exists (RHICBOS) ⇒ Basis for input to global analysis!
- Reconstruction of W-rapidity only possible in approximative way in forward direction
- Important contribution from forward and mid-rapidity region

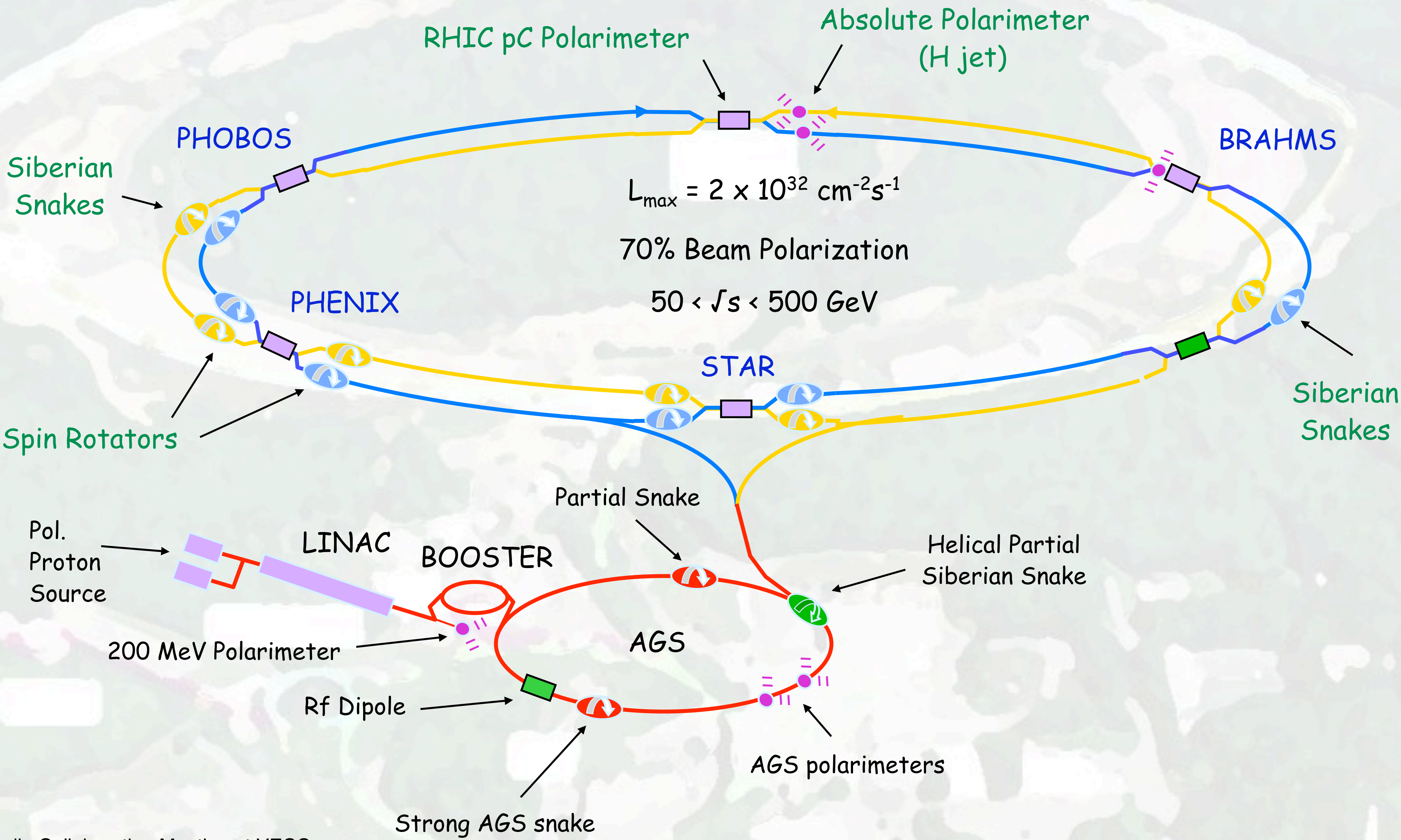
$$A_L^{W^-} = -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W} \qquad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

- Large uncertainties for polarized anti-quarks reflected in leptonic asymmetries!

Collider: The First polarized p+p collider at BNL

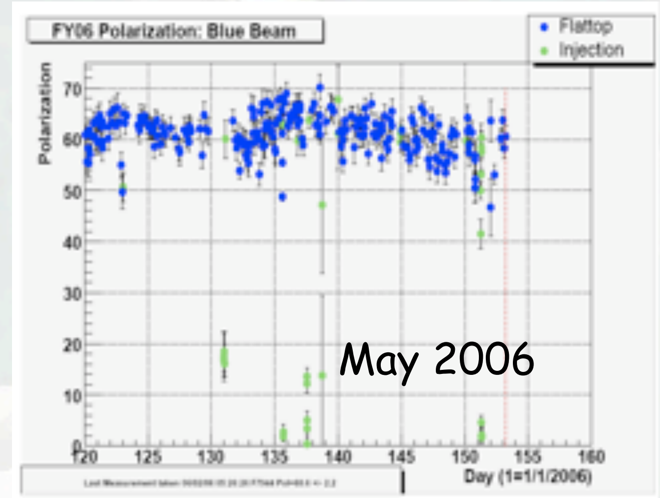
- Overview of collider complex

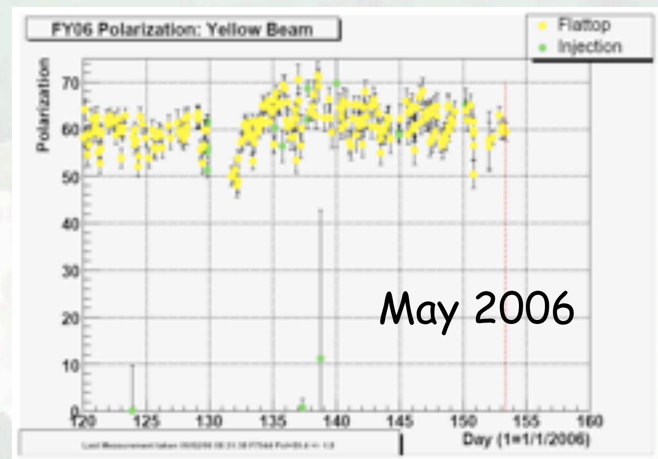


Collider: The First polarized p+p collider at BNL

- RHIC collider aspects: p-p - Performance

RHIC RUN	s [GeV]	$L_{recorded}$ [pb^{-1}] (transverse)	$L_{recorded}$ [pb^{-1}] (longitudinal)	Polarization[%]
RUN 2	200	0.15	0.3	15
RUN 3	200	0.25	0.3	30
RUN 4	200	0	0.4	45
RUN 5	200	0.4	3.1	50
RUN 6	200	3.4/6.8	8.5	60





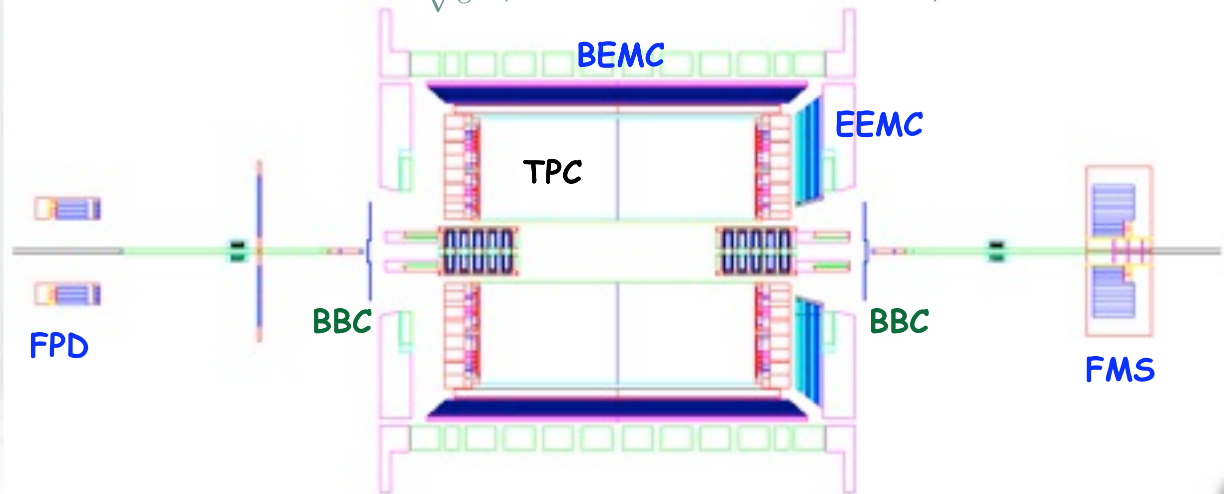
- All RHIC polarized pp accelerator components are in place!
- 2006 performance (√=200GeV): ~60% polarization (70% design) and ~1pb^{-1}/day (~3pb^{-1}/day design) delivered luminosity

The STAR Experiment

- Overview

- Wide rapidity coverage of STAR calorimetry (Jets /Neutral Pions / Photons) system:
  - FPD: -4.1 < η < 3.3
  - BEMC: -1.0 < η < 1.0
  - EEMC: 1.09 < η < 2.0
  - FMS: 2.5 < η < 4.0

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

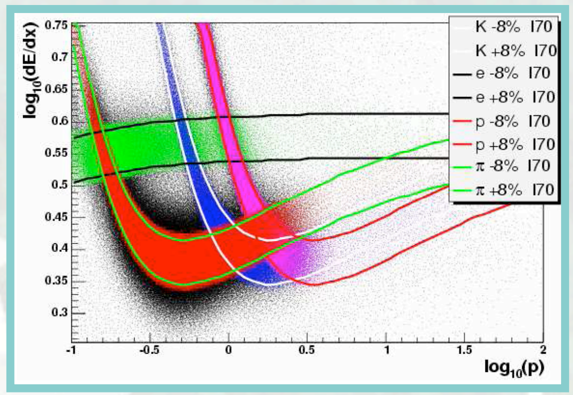


- BBC: Relative luminosity and Minimum bias trigger

Key elements for STAR Δg(x) program:

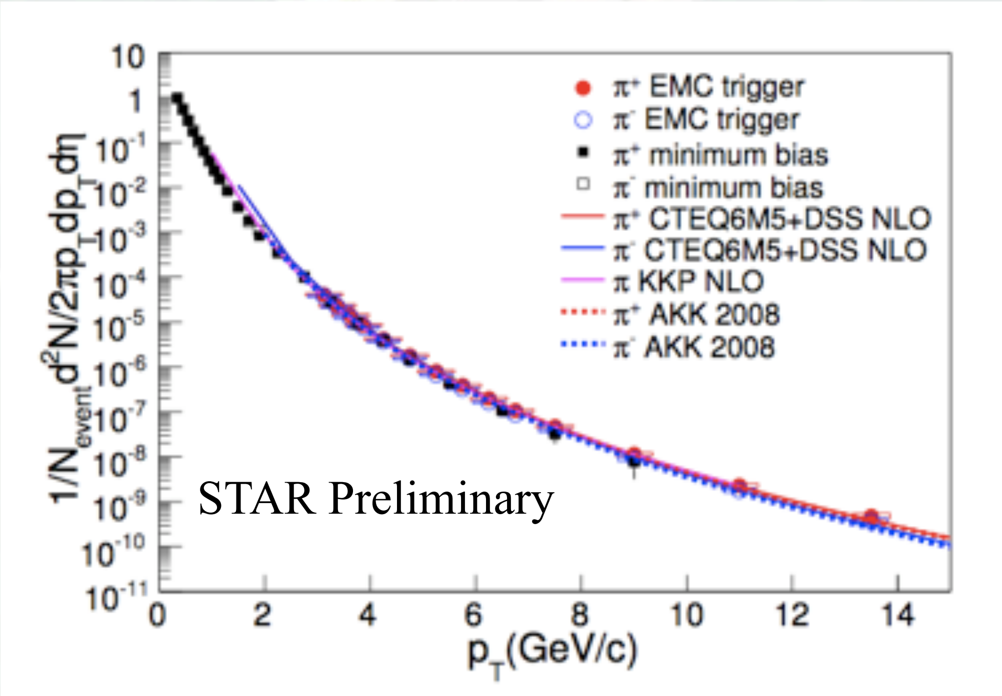
- Higher precision on Δg(x) : Luminosity / DAQ upgrade (DAQ 1000)
- Sensitivity to shape of Δg(x): Correlation measurements
- Low-x region of Δg(x): 500GeV program / Asymmetric collisions (Forward calorimetry)

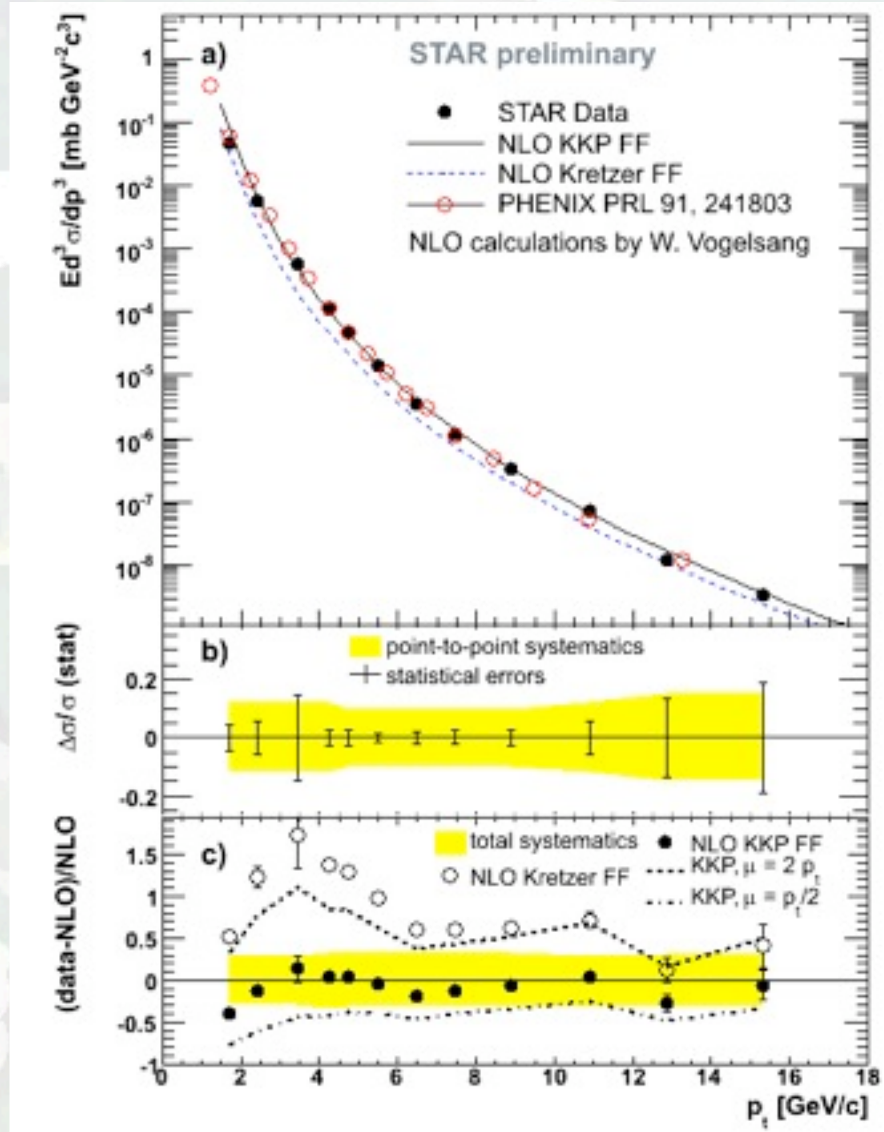
- TPC: Tracking and PID using dE/dx for |η| < 1.3 and p_T < 15 GeV/c



Highlights of recent results and achievements

- STAR Run 5 Cross-section results: Mid-rapidity charged and neutral pion production

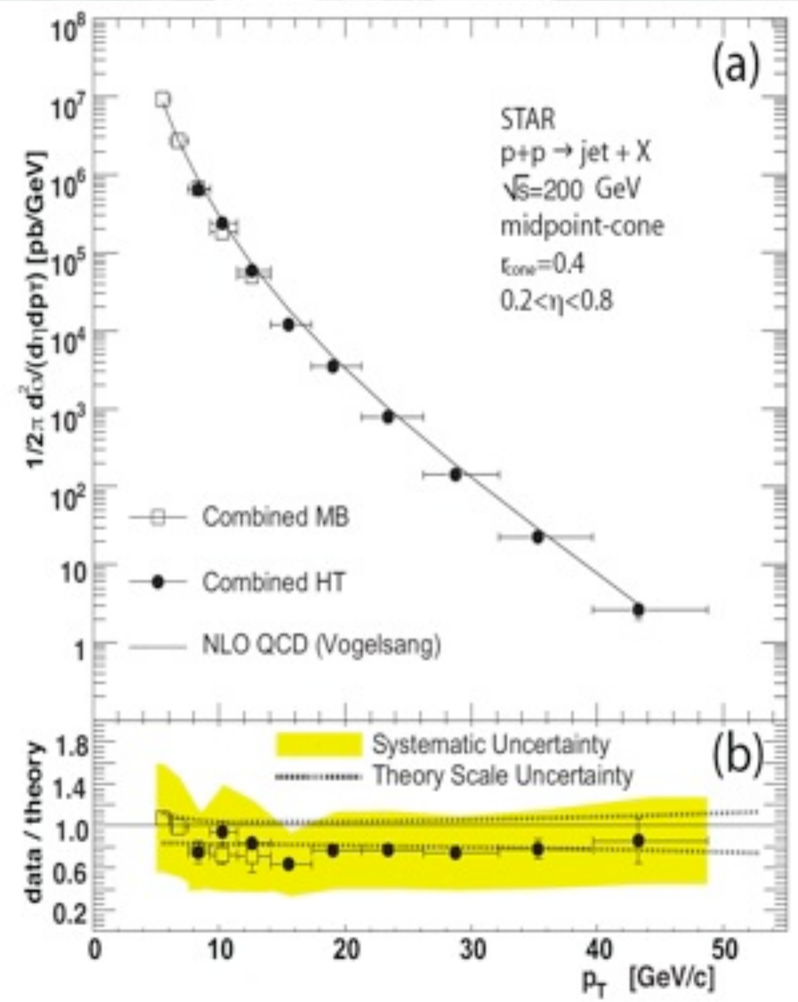


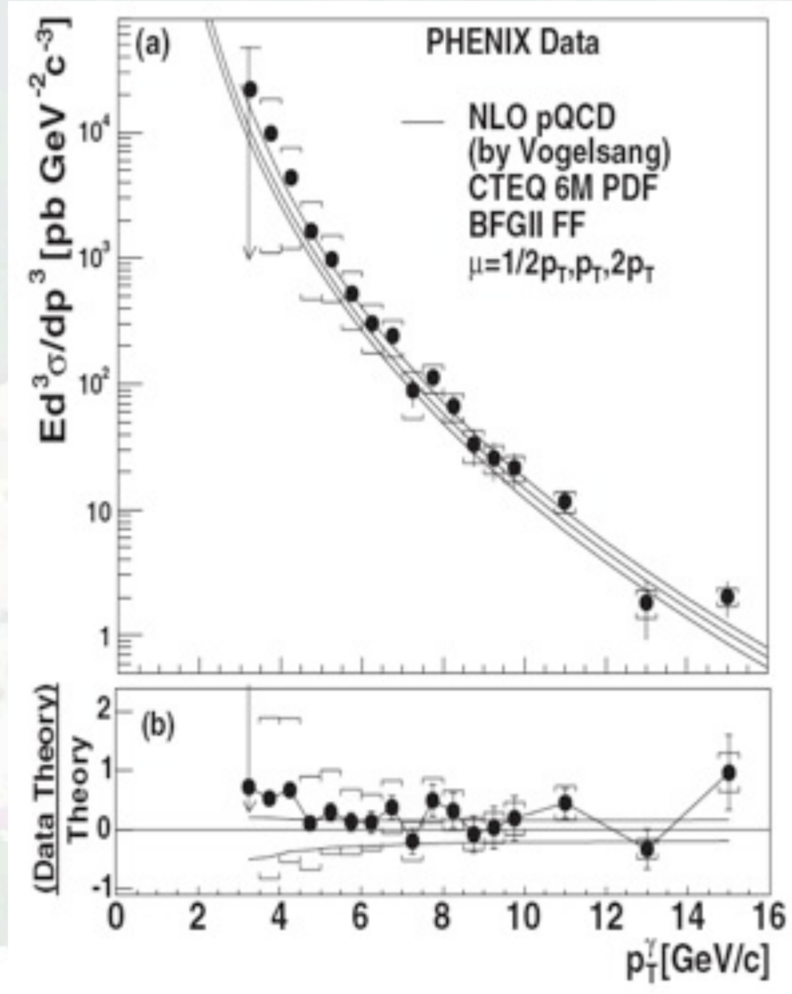


- Sophisticated TPC (dE/dx) calibrations improve precision at high p_T (arXiv:0807.4303-physics)
- Good agreement between data and NLO calculations for charged and neutral pion production

Highlights of recent results and achievements

- STAR Run 3/4 Cross-section results: Mid-rapidity Jet and Prompt Photon production

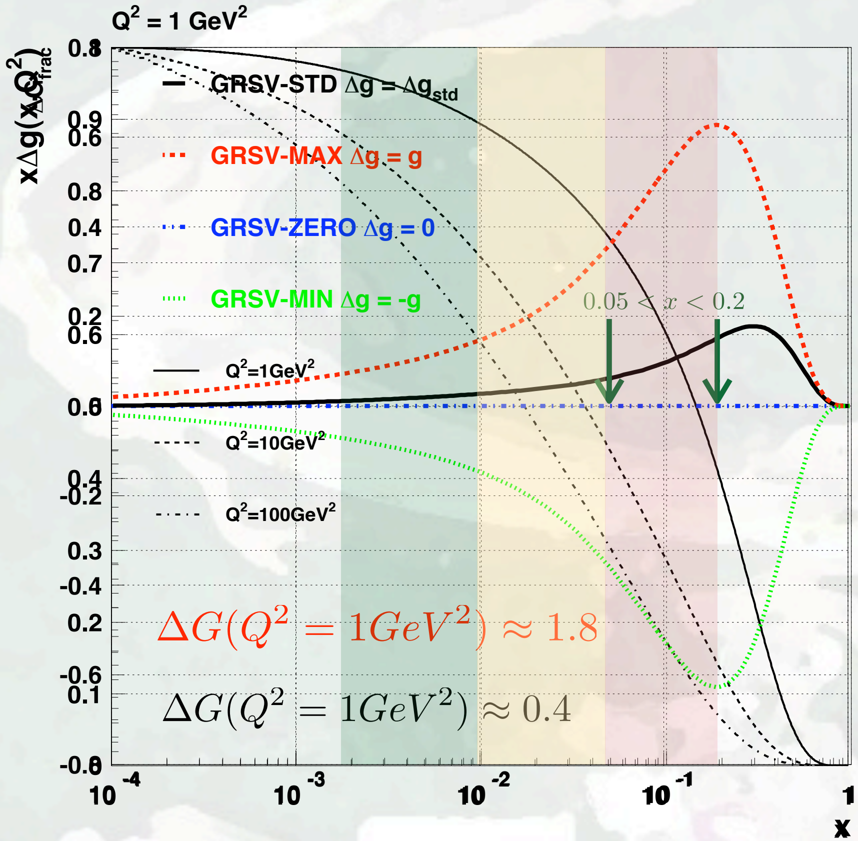


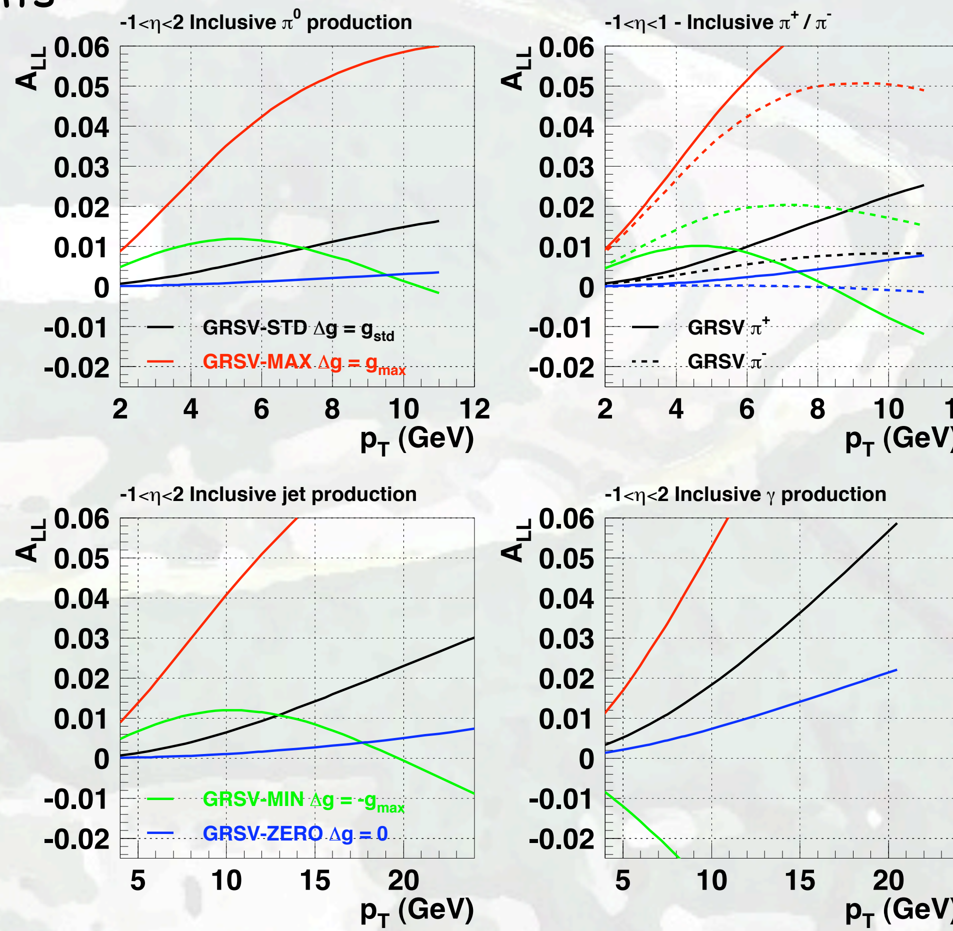


- Good agreement between data and NLO calculations for jet production and prompt photon production at central rapidity

Highlights of recent results and achievements

Gluon polarization - Inclusive Measurements





- Examine wide range in Δg: $-g < \Delta g < +g$

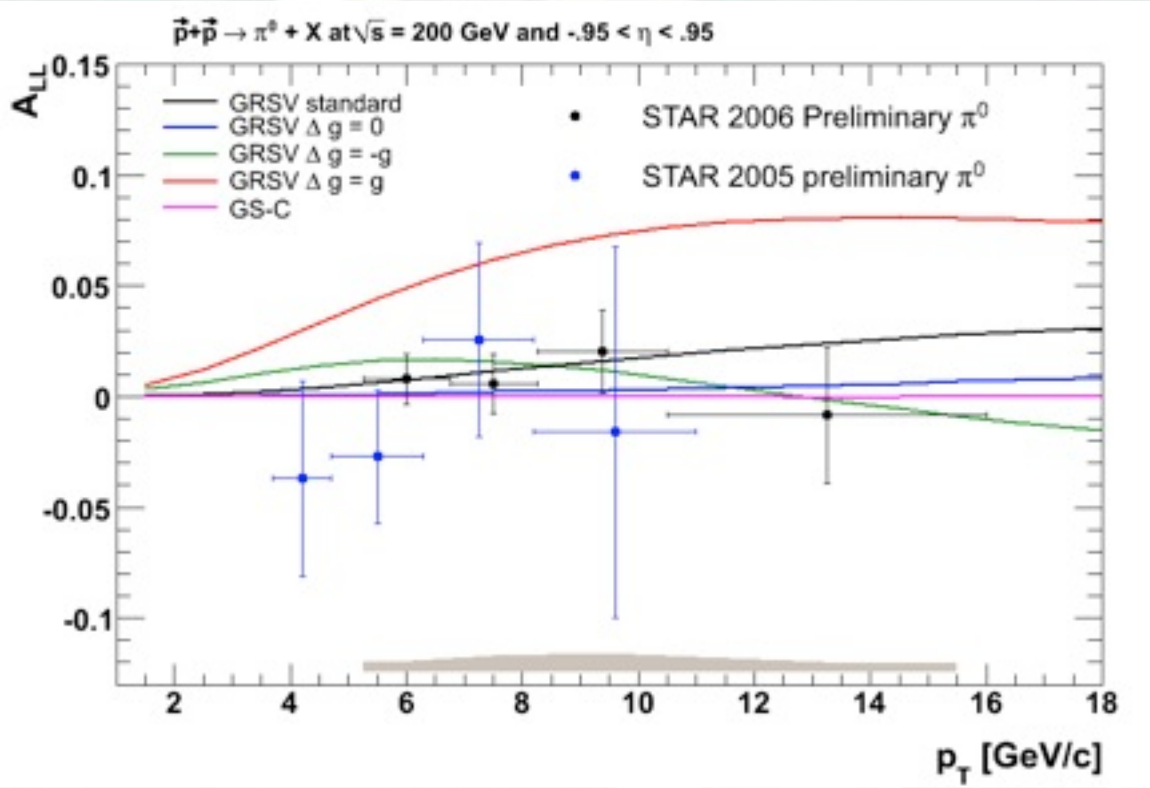
$$x_{\mathrm{parton}} \simeq 2p_T/\sqrt{s}$$

- GRSV-STD: Higher order QCD analysis of polarized DIS experiments!

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

Highlights of recent results and achievements

- STAR Run 5 / 6 A_{LL} result: Mid-rapidity neutral pion production



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

$$\Delta G(Q^2 = 1GeV^2) \approx 1.8$$

$$\Delta G(Q^2 = 1GeV^2) \approx 0.4$$

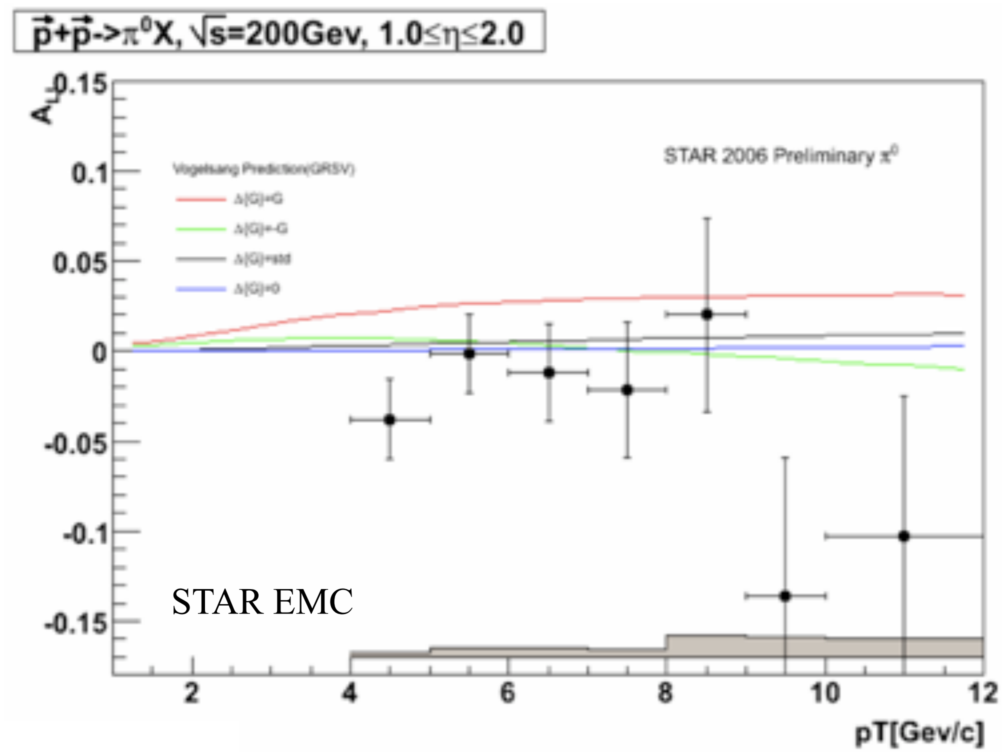
$$\Delta G(Q^2 = 1GeV^2) \approx 1.0$$

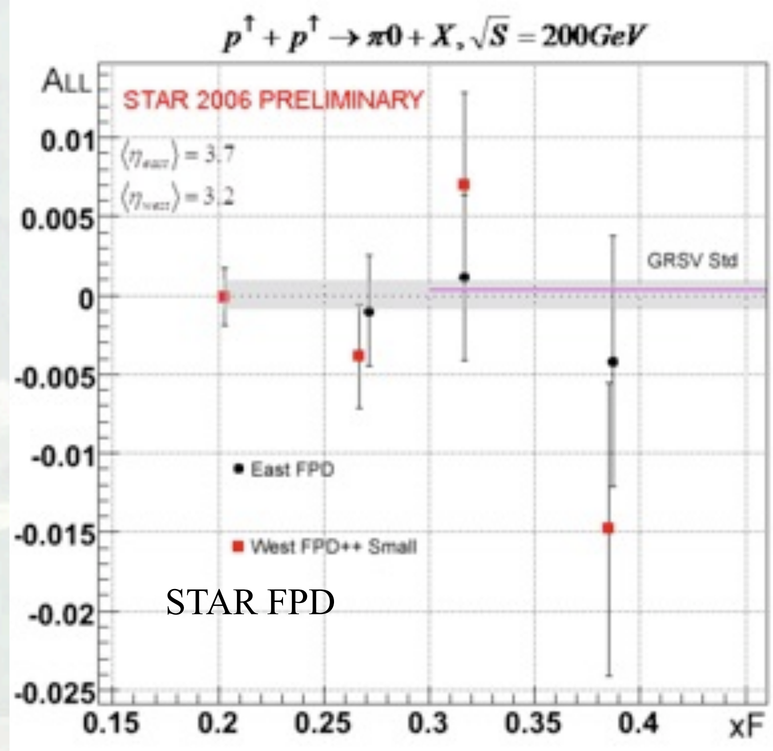
p_T range [GeV/c]	A_{LL} ± Stat. ± Sys.
5.2 - 6.75	0.0080 ± 0.0115 ± 0.002
6.75 - 8.25	0.0058 ± 0.0136 ± 0.004
8.25 - 10.5	0.0203 ± 0.0189 ± 0.004
10.5 - 16.0	-0.0084 ± 0.0306 ± 0.002

- RUN 6 results: GRSV-MAX ruled out
- Significant increase in statistical precision as well as greater p_T reach compared to previous Run 5 Neutral Pion result

Highlights of recent results and achievements

- STAR Run 6 A_{LL} result: Forward rapidity (FPD/EEMC) neutral pion production

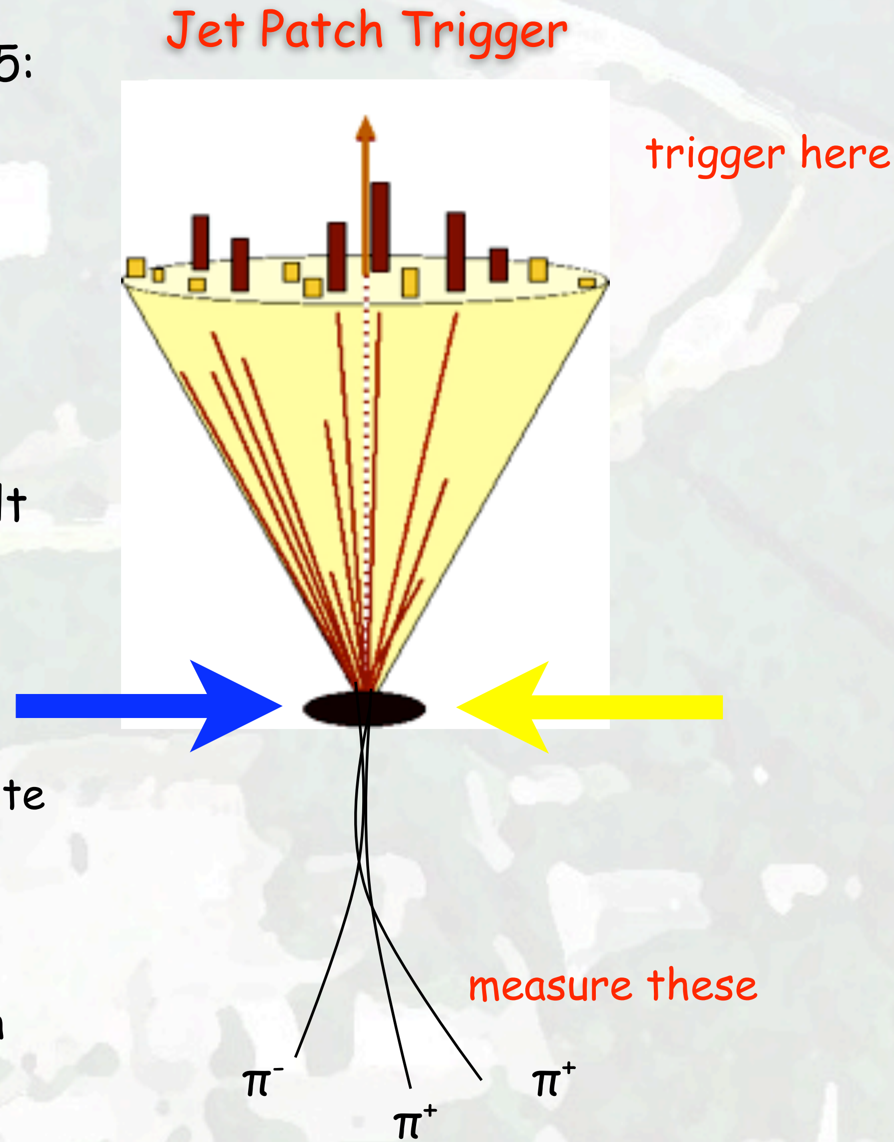




- First A_{LL} measurements at forward rapidity (STAR EEMC / STAR FPD)
- Probe small-x region (Probe smaller $\Delta g(x)$ ⇒ Smaller A_{LL} consistent with theoretical predictions)
- Important baseline measurements for STAR inclusive γ and γ-jet program

Highlights of recent results and achievements

- STAR Run 6 A_{LL} result: Mid-rapidity charged pion production
  - Significant improvements compared to Run 5:
    - 50% ⇒ 60% beam polarization
    - 1.6 pb^{-1} ⇒ 5.4 pb^{-1}
    - BEMC η acceptance [0,1] ⇒ [-1,1]
  - But ... increased JP trigger thresholds result in strong fragmentation bias for charged pions in trigger jet
    - Limit bias by measuring charged pions opposite a trigger jet
    - Plot asymmetry versus $z \equiv p_T(\pi) / p_T(\text{trigger jet})$ to cleanly isolate favored fragmentation



Highlights of recent results and achievements

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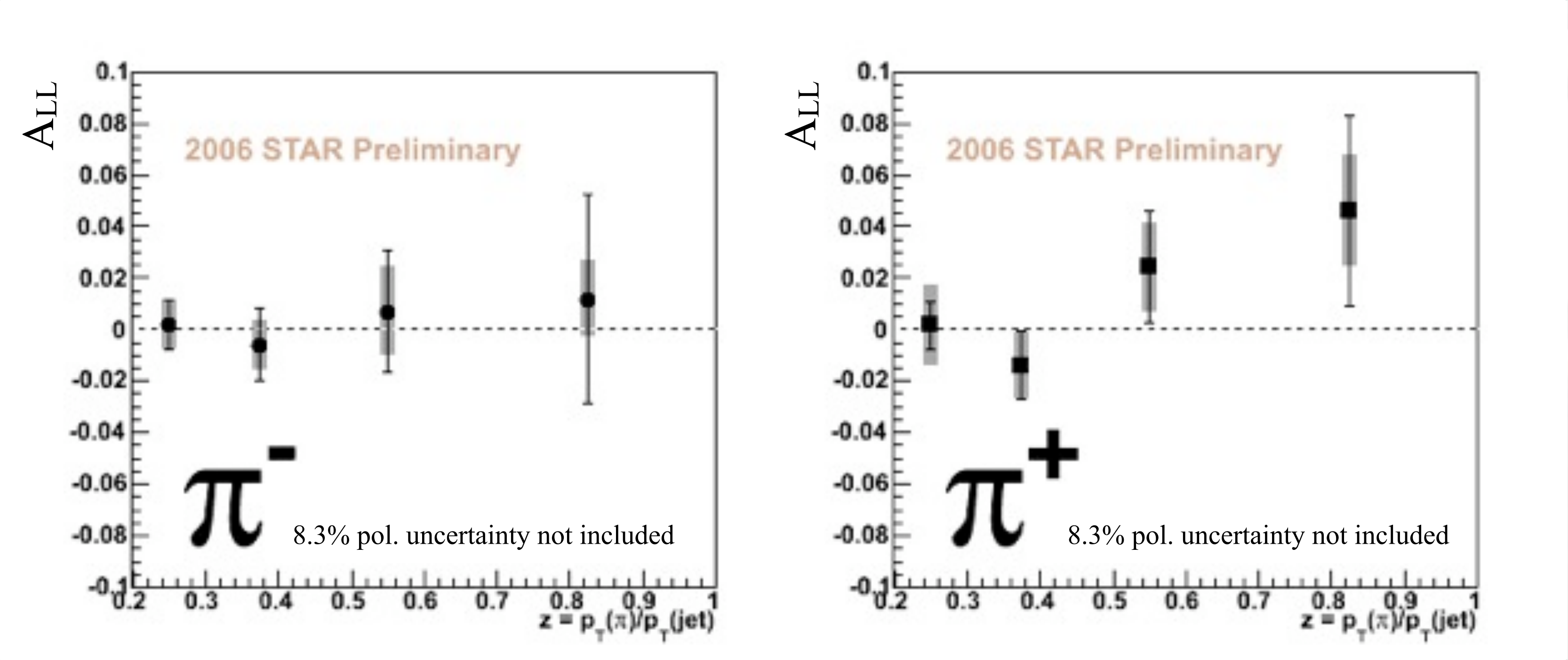
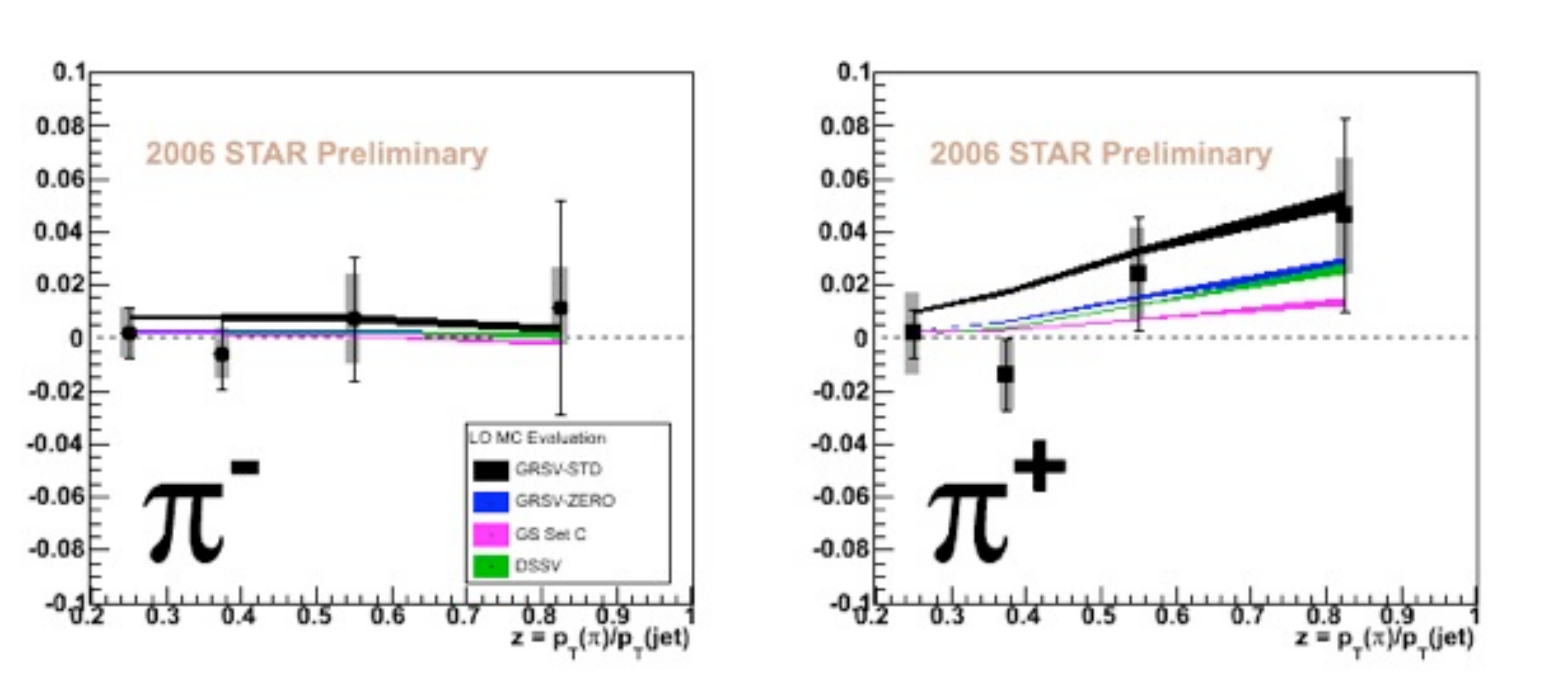


- Conservative systematic uncertainties are evaluated for:
  - Trigger bias: 6 - 15 x 10^{-3}
  - PID background contamination: 2 - 10 x 10^{-3}
  - Uncertainty on the jet p_T shift: 3 - 16 x 10^{-3}
  - Non-longitudinal components, relative luminosity: small

Highlights of recent results and achievements

- STAR Run 6 A_{LL} result: Mid-rapidity charged pion production

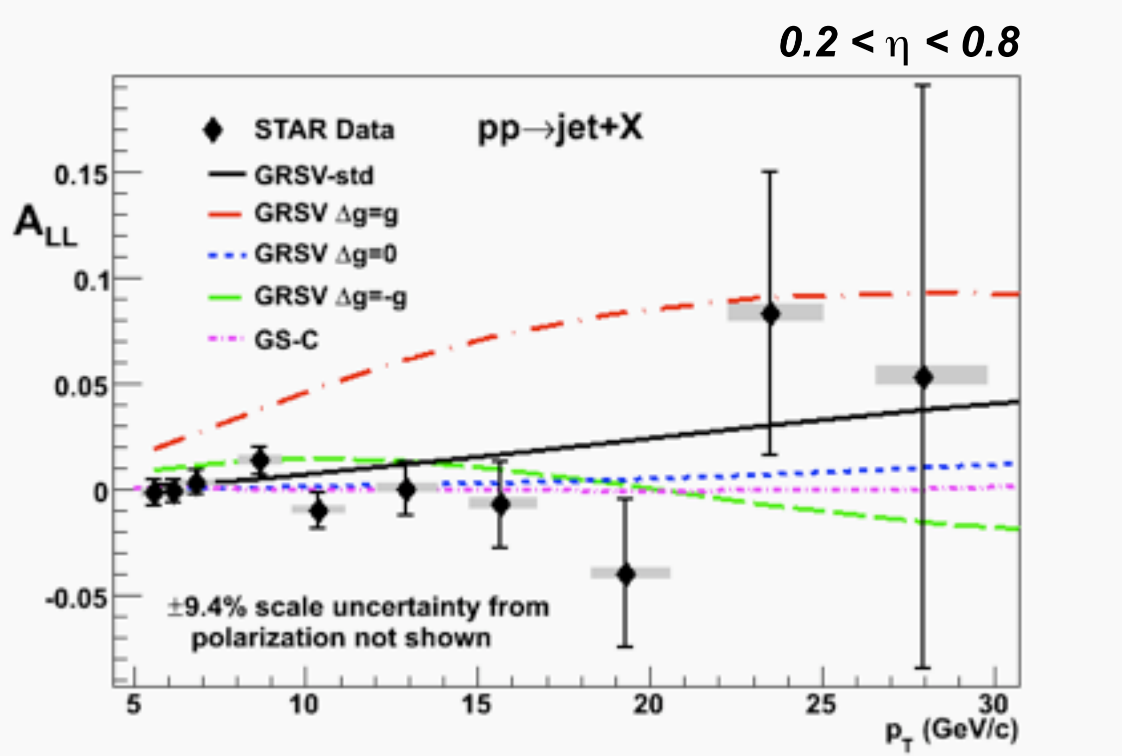


  - Full NLO pQCD predictions are not yet available for this measurement, but started!
  - These curves generated by sampling a_{LL} and parton distribution functions at kinematics of PYTHIA event.
  - π^{+} offers significant sensitivity at high z

Highlights of recent results and achievements

- A_{LL} Inclusive Jet 2005 result - STAR

STAR Collaboration, PRL **100**, 232003 (2008).



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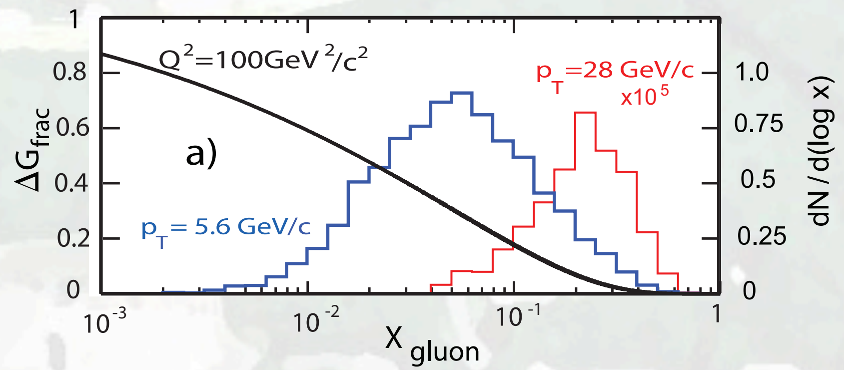
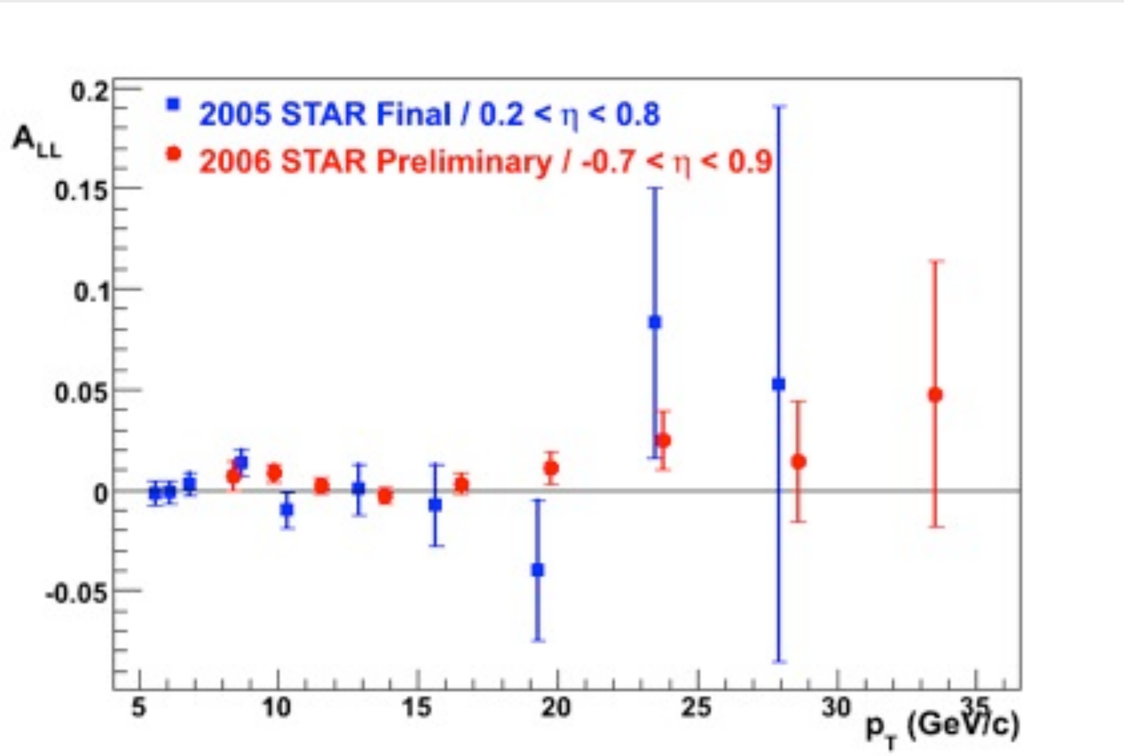


- Maximum gluon polarization scenario (GRSV-MAX) ruled out
- A_{LL} inclusive jet result (Run 5) consistent with previous Run 3/4 result

STAR Collaboration, PRL **97**, 252001 (2006).

Highlights of recent results and achievements

- A_{LL} Inclusive Jet 2006 result - STAR



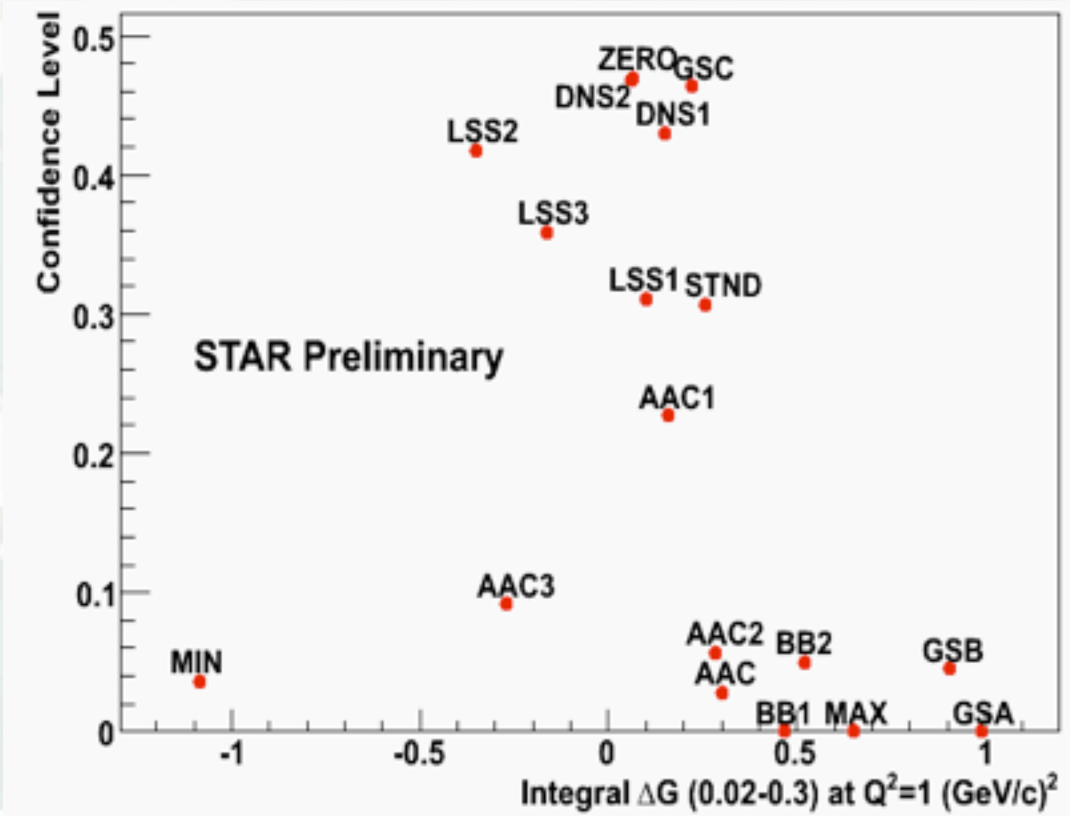
A_{LL} systematics	(x 10^{-3})
Reconstruction + Trigger Bias	[-1,+3] (p_T dep)
Non-longitudinal Polarization	~ 0.03 (p_T dep)
Relative Luminosity	0.94
Backgrounds	1st bin ~ 0.5 else ~ 0.1

p_T systematic	± 6.7%

- RUN 6 results: GRSV-MAX / GRSV-MIN ruled out - A_{LL} result favor a gluon polarization in the measured x-region which falls in-between GRSV-STD and GRSV-ZERO
- Consistent with RUN 5 result (Factor 3-4 improved statistical precision for p_T>13GeV/c)

Highlights of recent results and achievements

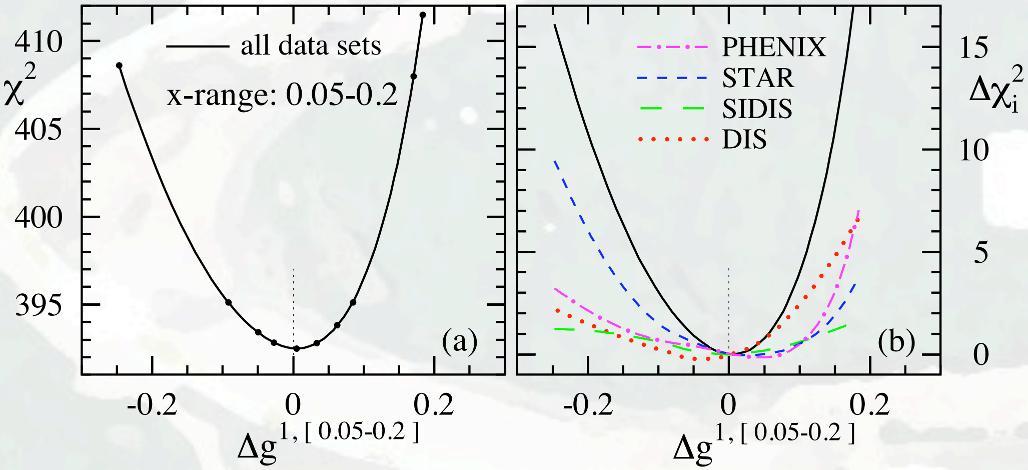
- Quantify theory comparison of measured A_{LL} for 2006 inclusive jet result

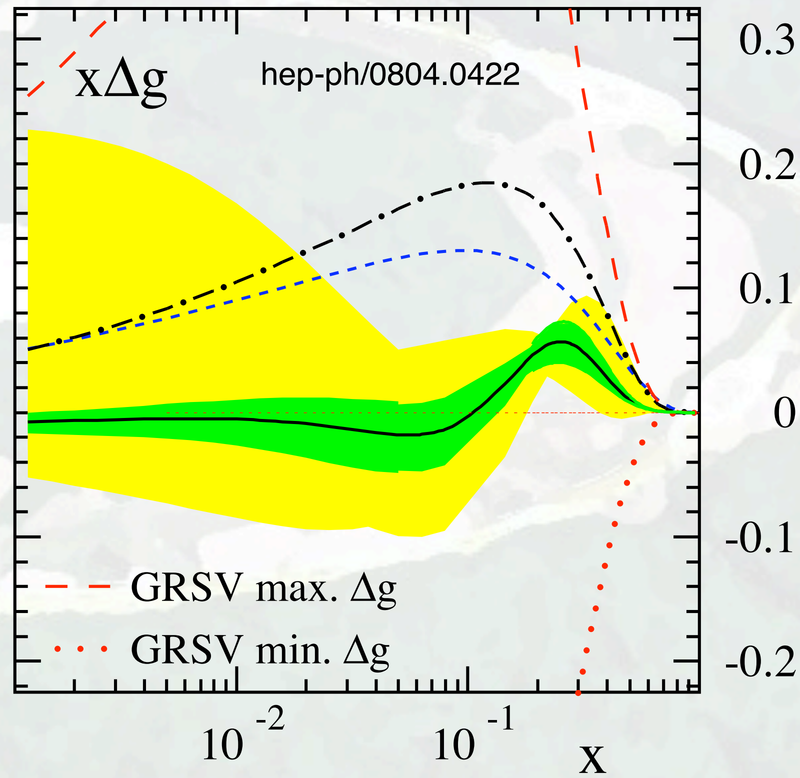


  - The STAR data exclude a broad range of global fit results that have a larger first moment (ΔG) than that in GRSV-STD
  - Counterexample is GS-C: Large and positive at low x and negative at high x (Note at x ~ 0.1)

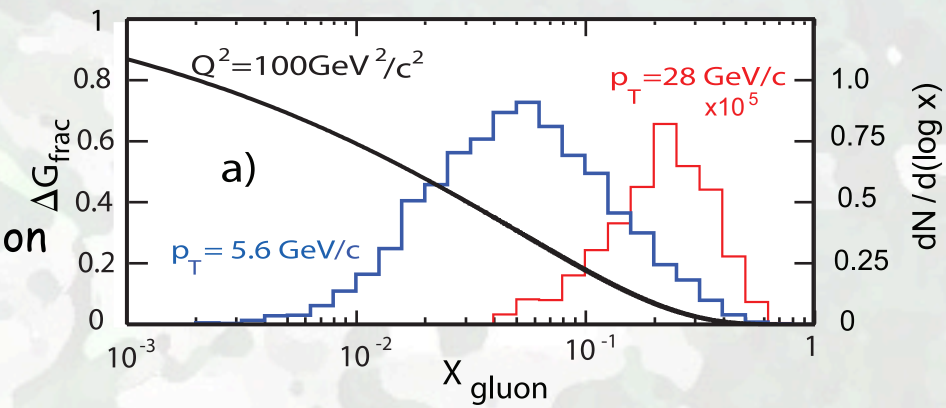
Highlights of recent results and achievements

- Global analysis incl. RHIC pp data





- Strong constraint on the size of Δg from RHIC data for $0.05<x<0.2$
- Evidence for a small gluon polarization over a limited region of momentum fraction
- Important: Mapping x-dependence and extension of x-coverage needed!



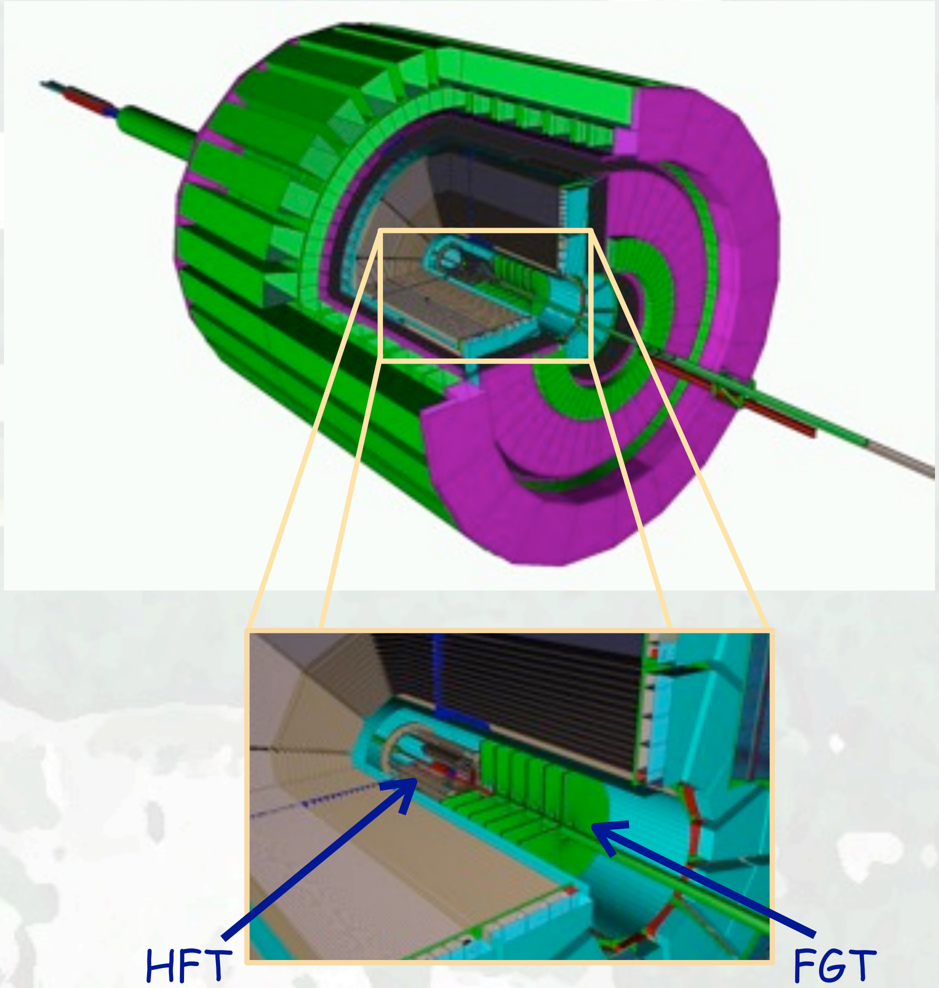
Future polarized p-p physics program - FGT

- Quark / Anti-Quark polarization program at STAR

Forward GEM Tracker: FGT

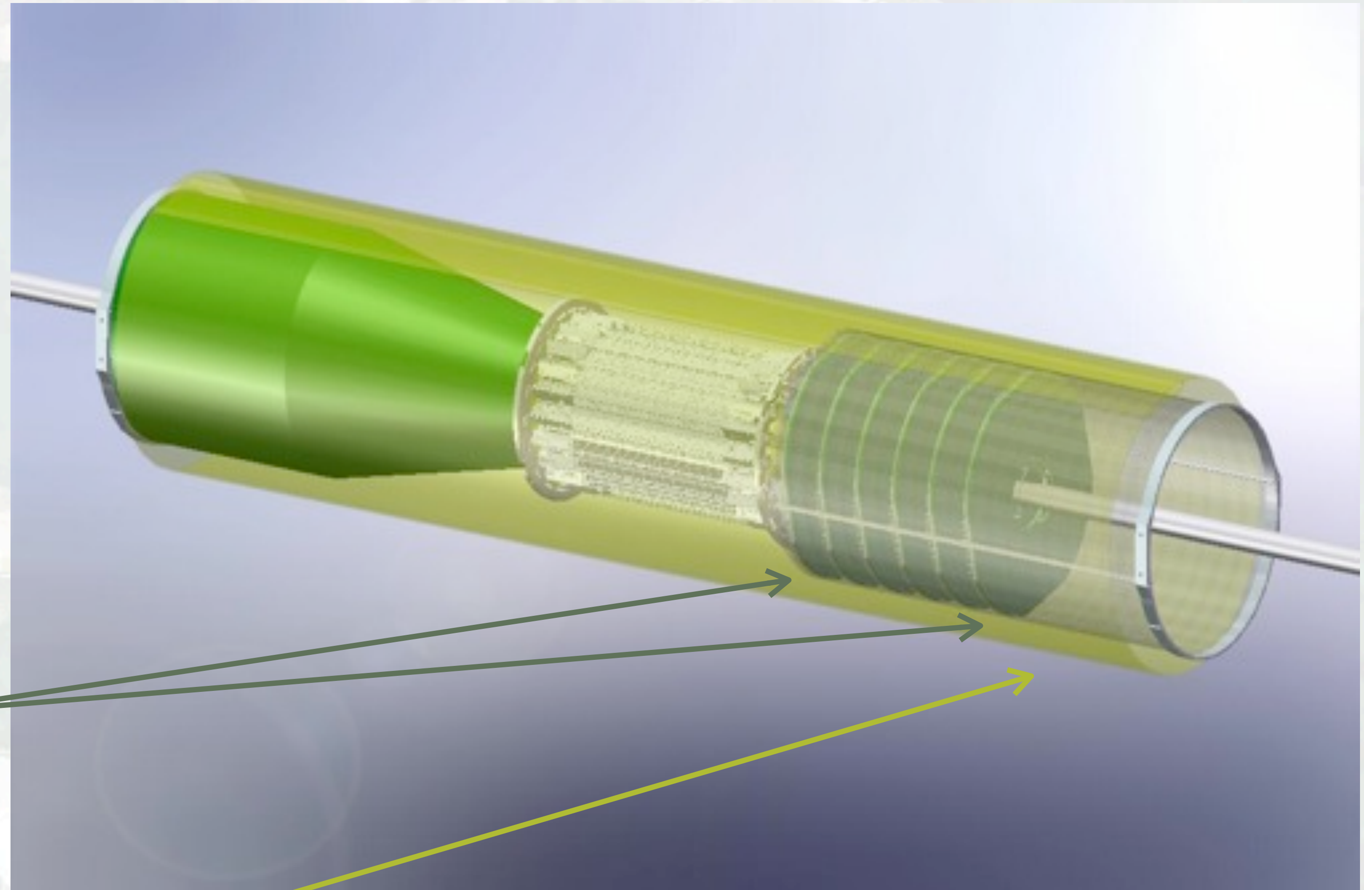
- Charge sign identification for high momentum electrons from $W^{\pm}$ decay (Energy determined with EEMC)
- Triple-GEM technology
- FGT project:

  ANL, IUCF, LBL, MIT, MPI Munich, University of Kentucky, Valparaiso University, Yale
- Successful project review (Capital equipment funding): January 2008
- Expected installation: Summer 2010



Future polarized p-p physics program - FGT

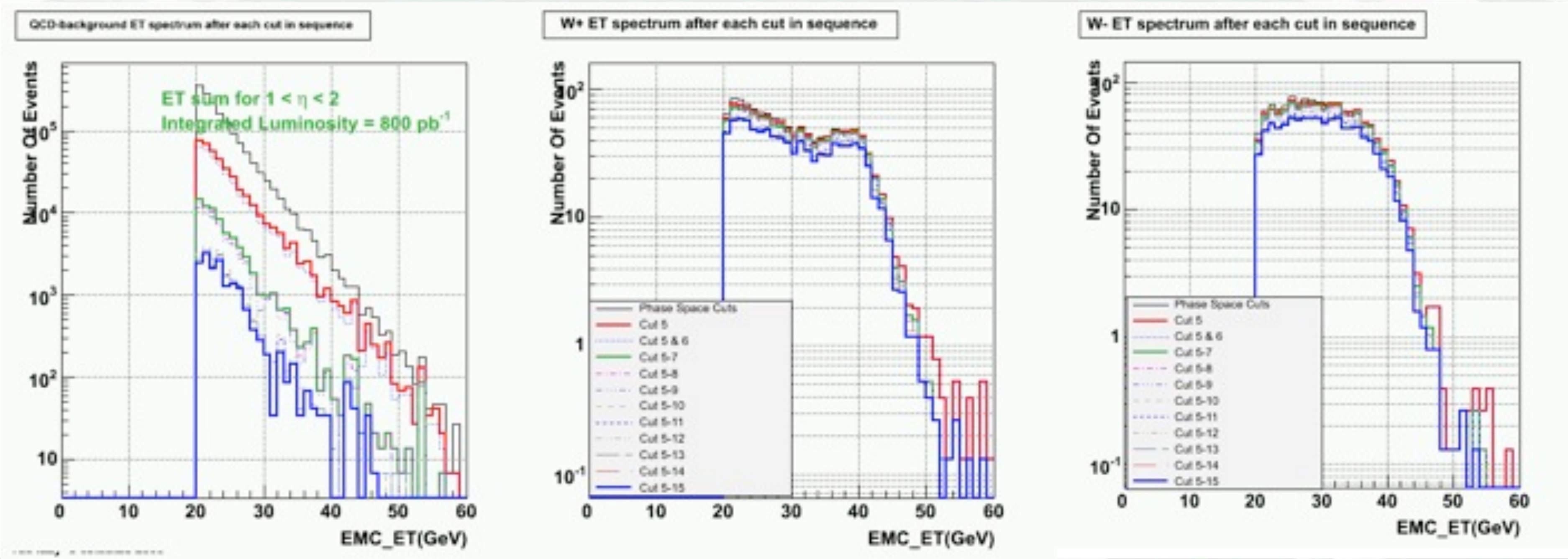
- Layout



  - FGT: 6 light-weight triple-GEM disks - WEST side of STAR
  - New mechanical support structure

Future polarized p-p physics program - FGT

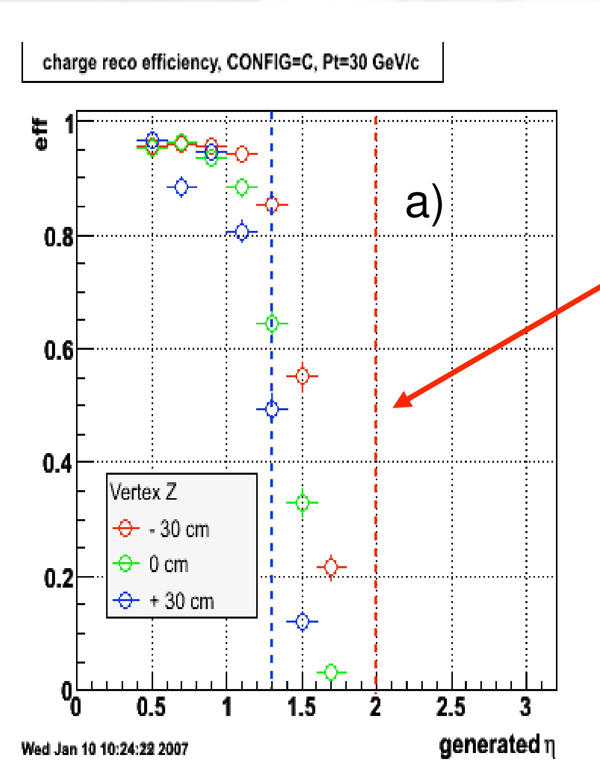
- Quark / Anti-Quark polarization program at STAR - e/h separation
  - Full PYTHIA QCD background and W signal sample including detector effects



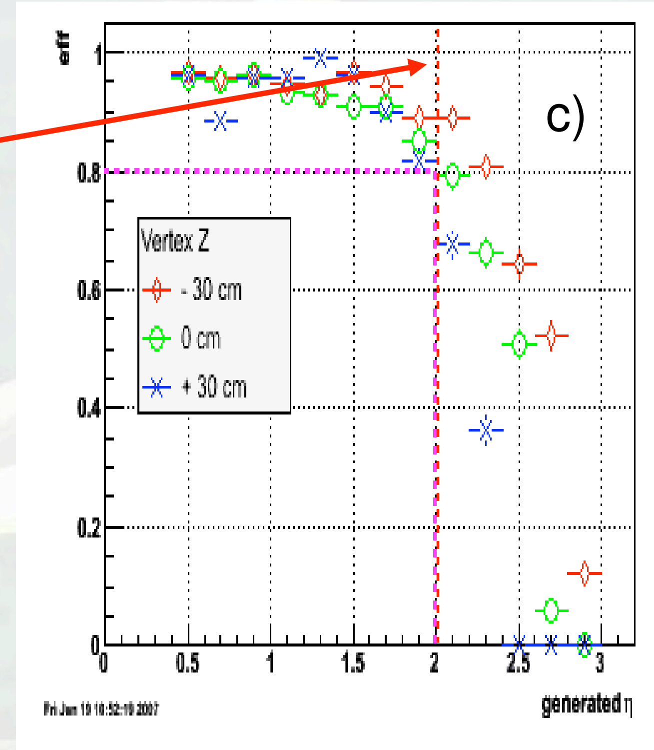
  - e/h separation based on global cuts (isolation/missing E_T) and EEMC specific cuts as
  - With current algorithm: E_T > 25GeV yields S/B > 1 (For E_T < 25GeV S/B ~ 1/5) used for A_L uncertainty estimates

Future polarized p-p physics program - FGT

- Quark / Anti-Quark polarization program at STAR - e^+/e^- separation



Reach of EEMC Acceptance



TPC + FGT Tracking, p_T = 30 GeV/c

Conclusion:

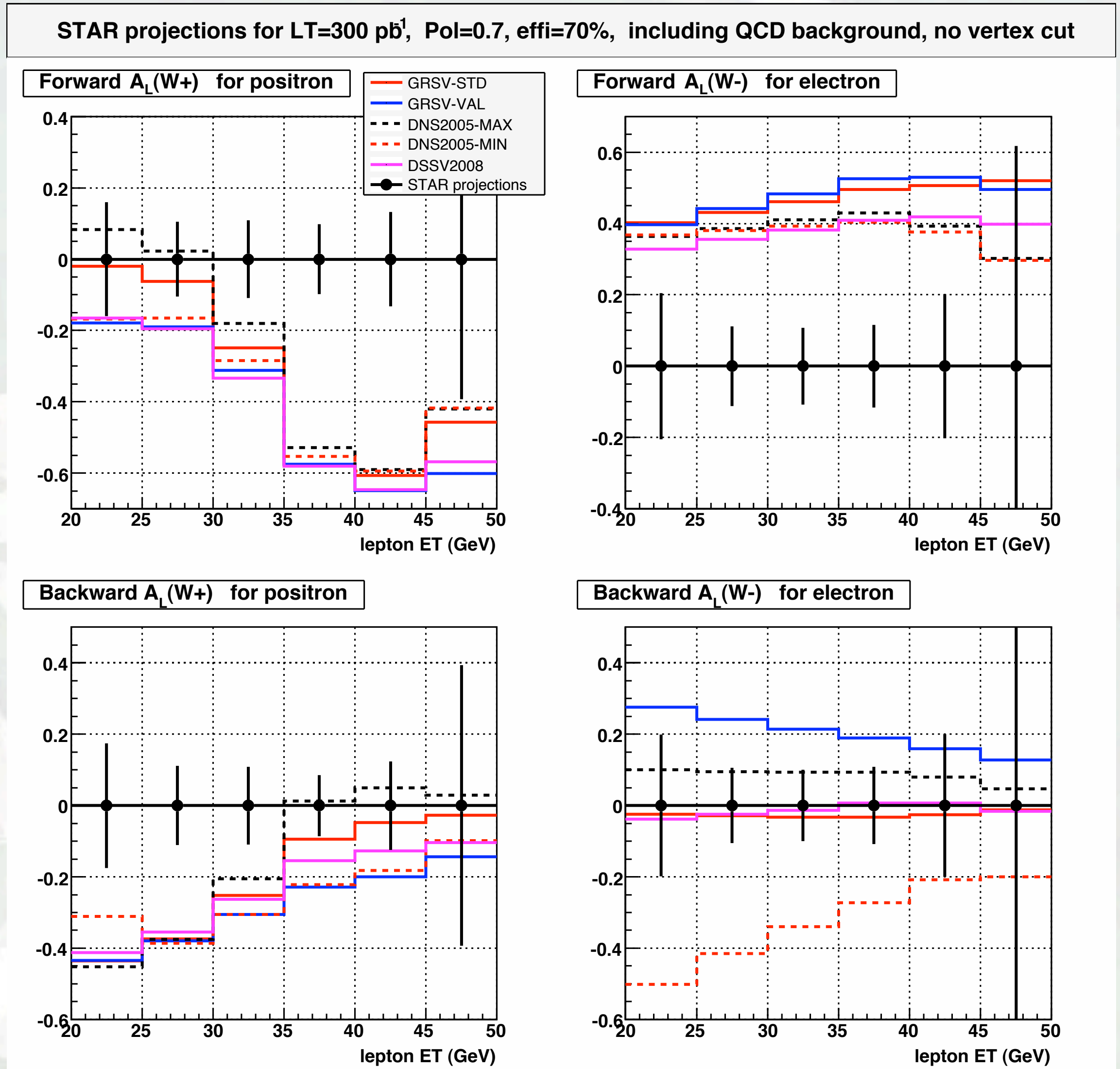
Charge sign reconstruction impossible beyond η = ~1.3

6 triple-GEM disks, assumed spatial resolution 60μm in x and y (Fairly insensitive for 60-100μm)

Charge sign reconstruction probability above 90% for 30 GeV p_T over the full acceptance of the EEMC for the full vertex spread

Future polarized p-p physics program - FGT

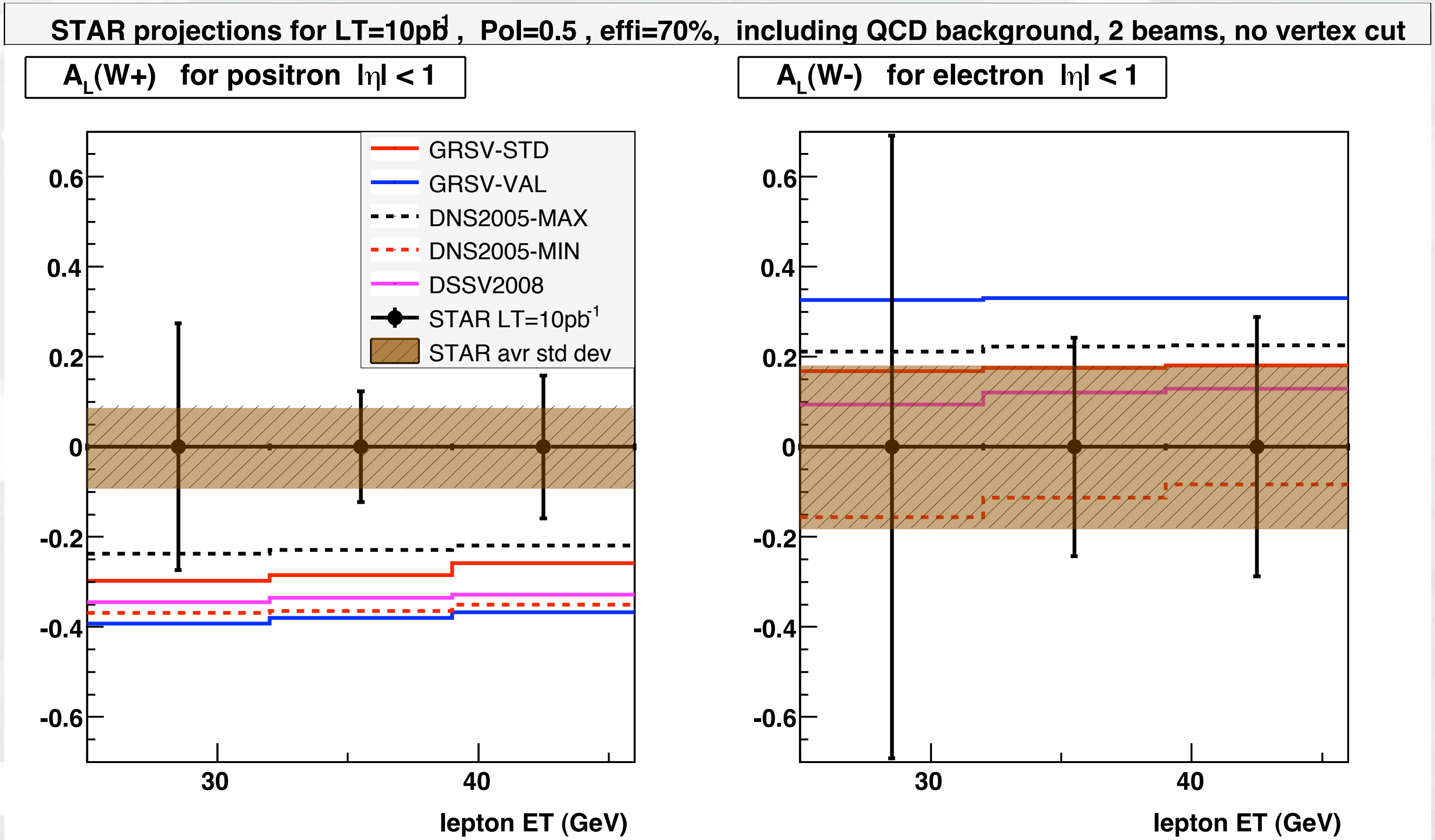
- Quark / Anti-Quark polarization program at STAR (Forward rapidity)
  - Large asymmetries dominated by quark polarization - Important consistency check to existing DIS data with 100pb^{-1} (Phase I)
  - Strong impact constraining unknown antiquark polarization requires luminosity sample at the level of 300pb^{-1} for 70% beam polarization (Phase II)



Future polarized p-p physics program

- Quark / Anti-Quark polarization program at STAR (Mid-rapidity)

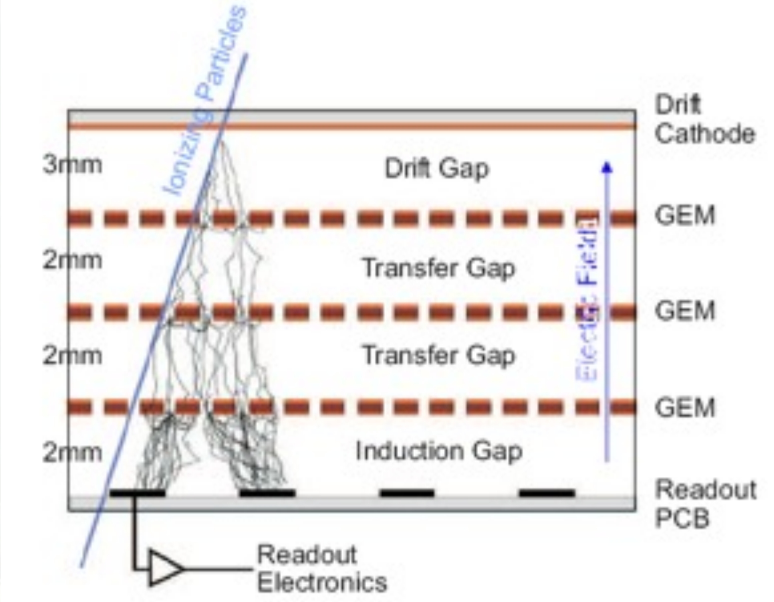
  - Polarization = 50%
  - Luminosity: $10pb^{-1}$



- 500 GeV running in Run 9 focus at mid-rapidity integrated [-1,+1]
- Demonstrate W production at mid-rapidity and first A_L measurement at STAR

Future polarized p-p physics program - FGT

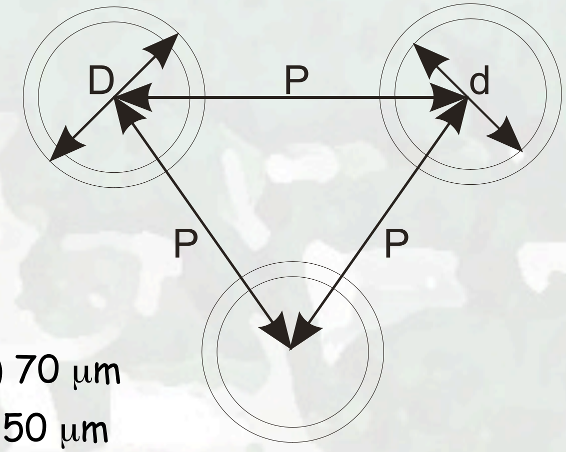
- GEM technology
  - Example: Triple-GEM application at COMPASS
  - Advantages:
    - Reliable (COMPASS, multi-year experience)
    - High gas amplification (Multiple GEMs: up to ~10^6)
    - Fast (< 20 ns FWHM, rate capability up to 10^5 Hz/mm)
    - Low mass (50μm Kapton + 10μm Cu; Thin low Z read-out plane)
    - Good spacial resolution (1D and 2D) (~60μm)
    - Simple construction and in-expensive



F. Sauli, Nucl Instr. and Meth. A386 (1997) 531.

C. Altunbas et al., Nucl Instr. and Meth. A490 (2002) 177.

Standard layout:
- Pitch (P) 140 μm
- Outer diameter (D) 70 μm
- Inner diameter (d) 50 μm



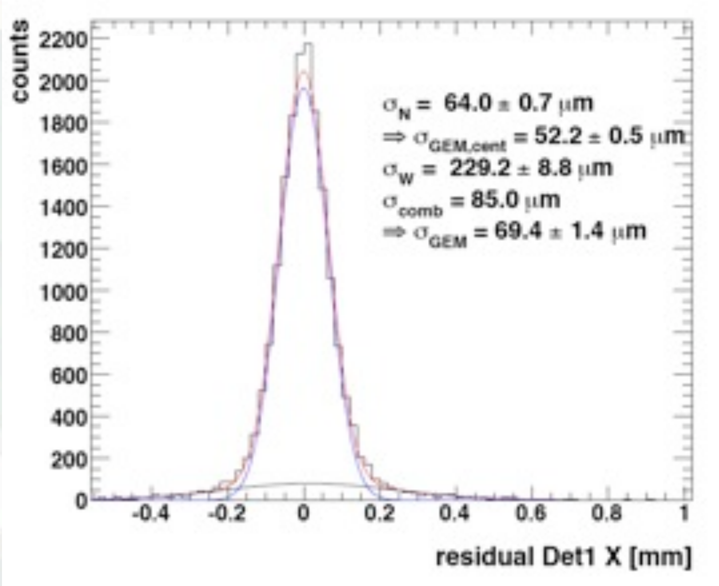
Future polarized p-p physics program - FGT

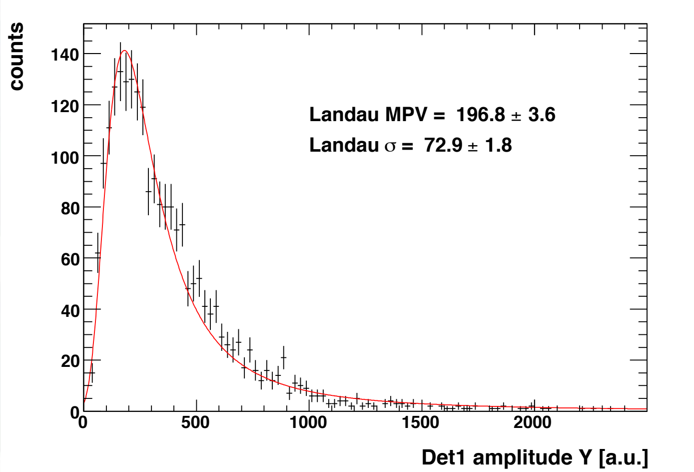
- GEM technology development

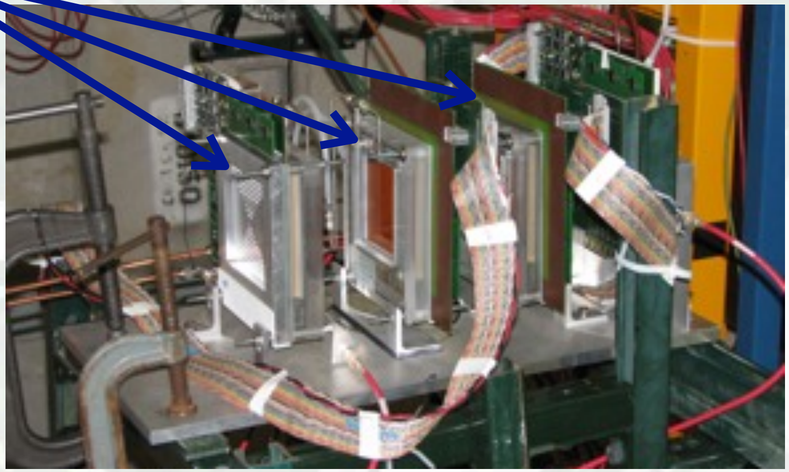
  - SBIR proposal (Phase I/II): Established commercial GEM foil source (Tech-Etch Inc.)

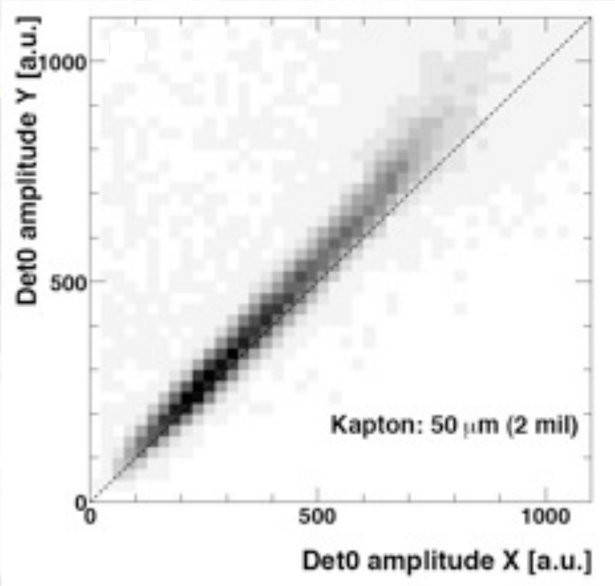
  - FNAL testbeam of three prototype triple-GEM chambers including APV25 chip readout

  - Performance meets requirements!





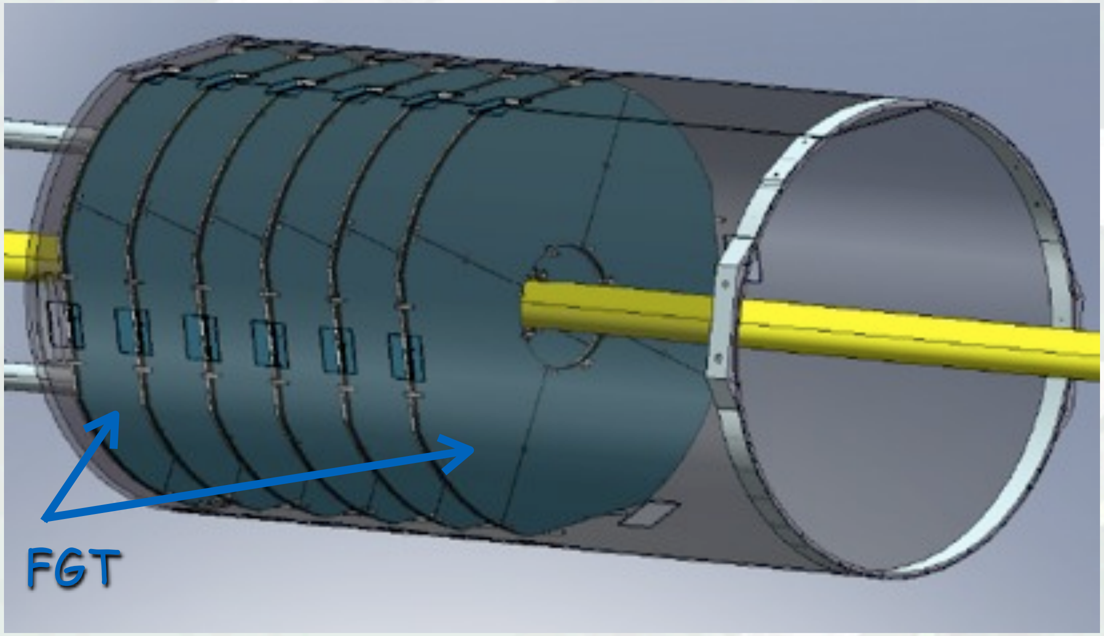


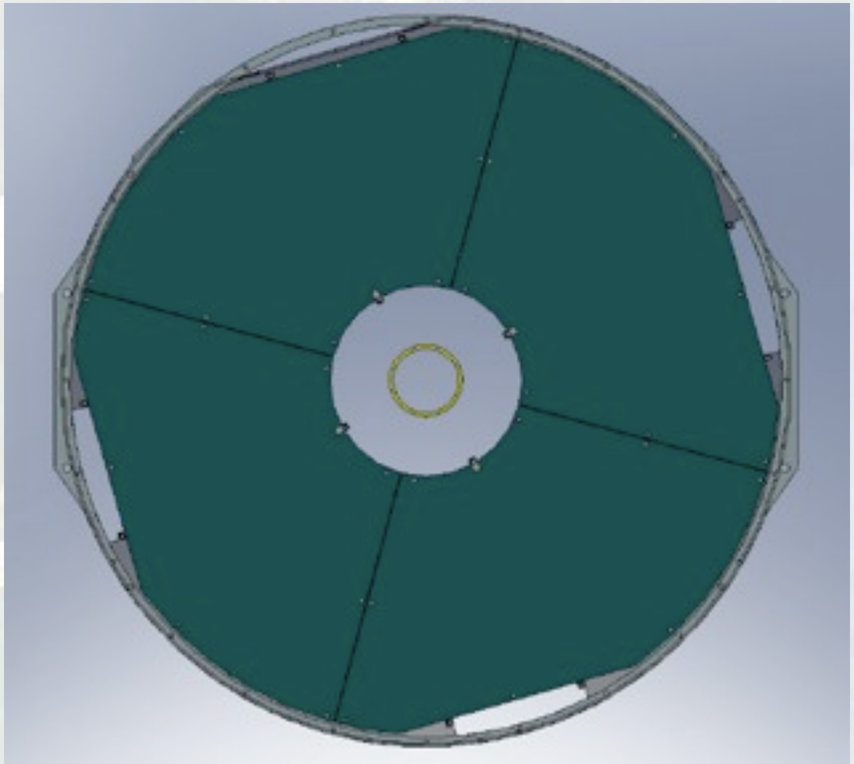


- Good charge sharing!

Future polarized p-p physics program - FGT

- Mechanical design

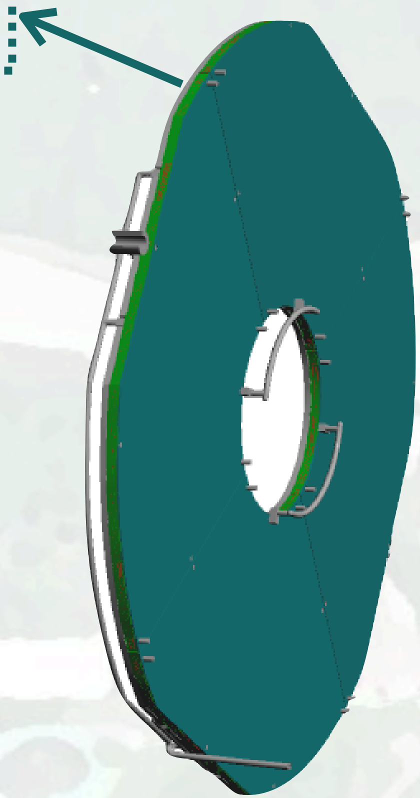




- FGT: 6 light-weight disks
- Each disk consists of 4 triple-GEM chambers (Quarter sections)
- Procurement and assembly of full quarter section prototype in preparation

Future polarized p-p physics program - FGT

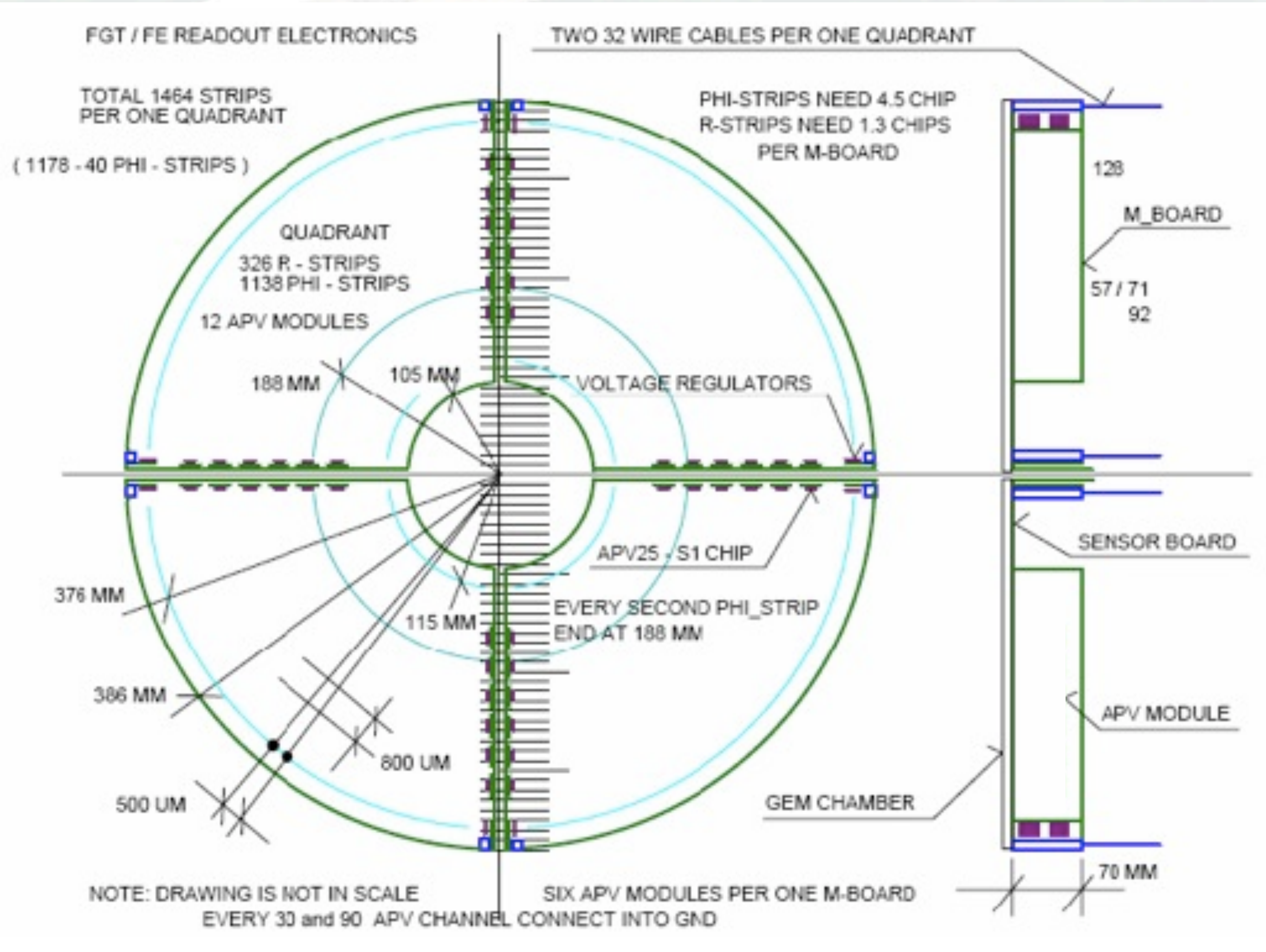
- Triple-GEM detectors - Quarter section

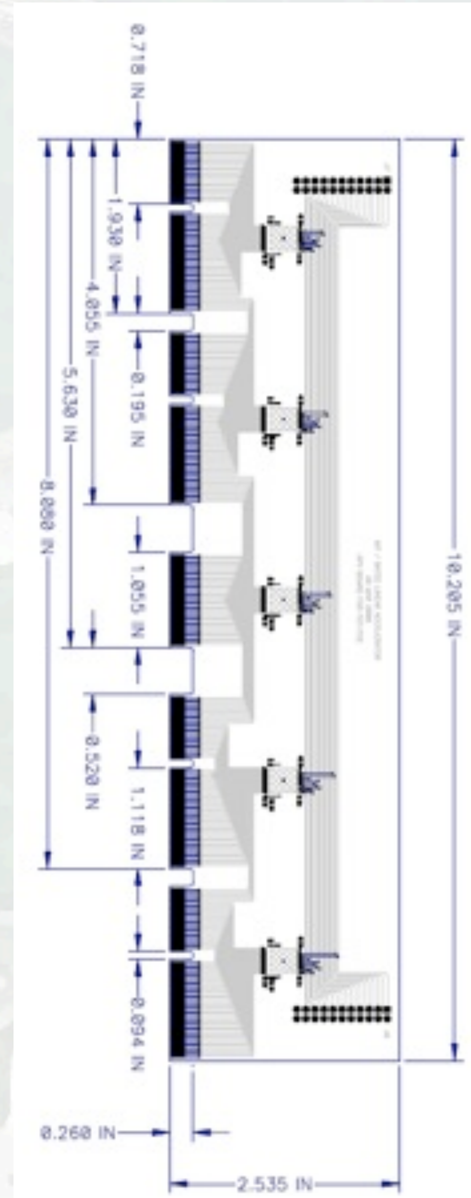


Component	Material	Radiation Length [%]
Support plate	5 mm Nomex	0.040
	2x250 μm FR4	0.257
HV layer	5 μm Cu	0.035
	50 μm Kapton	0.017
GEM foils	6x5 μm Cu (70%)	0.147
	3x50 μm Kapton (70%)	0.036
Readout	5 μm Cu (20%)	0.007
	50 μm Kapton (20%)	0.003
	5 μm Cu (88%)	0.031
	50 μm Kapton	0.017
	5 μm Cu (10%)	0.004
	0.125 mm FR4	0.064
	5 μm Cu (10%)	0.004
Drift gas	10 mm CO_2 (30%)	0.002
	10 mm Ar (70%)	0.006
Total		0.670

Future polarized p-p physics program - FGT

- 2D readout board and Front-End Electronics



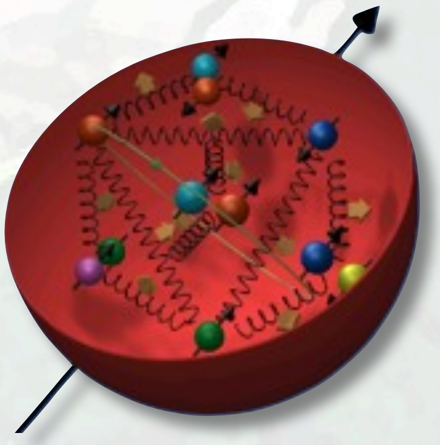


Future polarized p-p physics program - FGT

- Overview - Planing
  - Goal: Installation in summer 2010 ⇒ Ready for anticipated first long 500GeV polarized pp run in FY11 consistent with STAR 5-year Beam Use Request
  - Review: Successful review January 2008 / Beginning of construction funds FY08
  - Cost estimate and planing relies on the R&D and pre-design work:
    - Triple-GEM Detector: Complete prototype tested on the bench and during FNAL testbeam experiment with extensive experience in mechanical design work (MIT-Bates) and assembly including previous experience at COMPASS
    - Front-End Electronics (FEE) System: Complete prototype tested on the bench and during FNAL testbeam experiment based on existing APV25-S1 readout chip (MIT-Bates)
    - Data Acquisition (DAQ) System: Conceptual layout is based on similar DAQ sub-detector systems with extensive experience (ANL/IUCF)
    - GEM foil development: Successful development of industrially produced GEM foils through SBIR proposal in collaboration with Tech-Etch Inc. (BNL, MIT, Yale University)

Summary and Outlook

- Summary - RHIC-SPIN
  - Successful polarized proton collisions at high energies at RHIC at Brookhaven National Laboratory
  - QCD: Critical role to interpret measured asymmetries - First global analysis
  - Strong constraint on the size of Δg from RHIC data for $0.05 < x < 0.2$
  - Evidence for a small gluon polarization over a limited region of momentum fraction ($0.05 < x < 0.2$)
  - Important: Mapping x-dependence and extension of x-coverage needed - Critical to reduce large uncertainties on first moment of Δg
  - Next critical step: Improved precision and Measurements to constrain shape of Δg (Di-Jet production and Photon-Jet production)



Summary and Outlook

- Outlook - RHIC SPIN
  - Three key elements:
    - Gluon polarization
    - Quark / Anti-Quark Polarization
    - Transverse spin dynamics
  - Critical:

Recorded Luminosity	Main physics Objective	Remarks
~50pb^{-1}	Gluon polarization using di-jets and precision inclusive measurements	200 GeV
~100pb^{-1}	W production (Important consistency check to DIS results - Phase I) Gluon polarization (Di-Jets / Photon-Jets)	500 GeV
~300pb^{-1}	W production (Constrain antiquark polarization - Phase II) Gluon polarization (Di-Jets / Photon-Jets)	500 GeV
~30pb^{-1}	Transverse spin gamma-jet	200 GeV
~250pb^{-1}	Transverse spin Drell-Yan (Long term)	200 GeV

- Beam polarization: 70% / Narrow vertex region / Spin flipper for high precision asymmetry measurements
- Critical: Sufficient running time!

http://spin.riken.bnl.gov/rsc/