Longitudinal Spin Transfer of Hyperons in Polarized Proton-Proton Collisions

Ernst Sichtermann (LBNL), *for the* STAR *Collaboration*

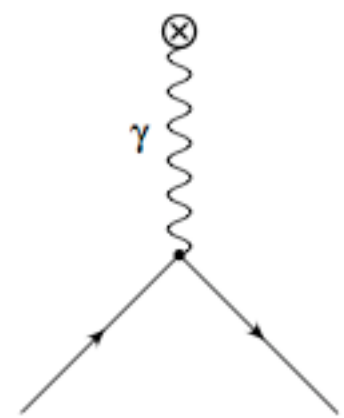
Outline:
- Introduction to Proton Spin Structure
- Gluon Polarization at RHIC
- Quark Polarization at RHIC
- Concluding Remarks

DNP 2008
Oakland, California

History - Magnetic Moment

- The magnetic moment $\vec{\mu}$ of a particle is related to its spin $\vec{S}$ according to:

$$\vec{\mu} = g \frac{e}{2mc} \vec{S}$$



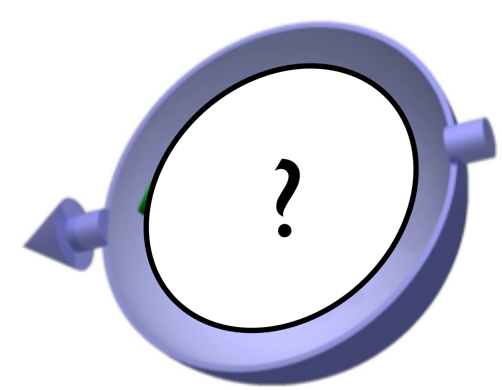
$g = 2$ for Dirac particles

- 1933 - Frisch and Stern:

$$\vec{\mu}_p = 5.8 \frac{e}{2mc} \vec{S}_p$$

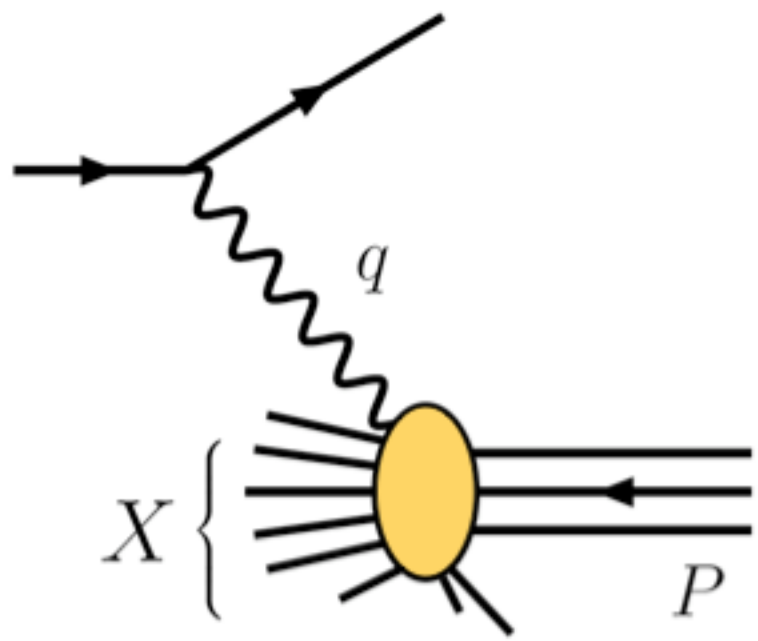
- *Proton has (spin-)substructure*

But, what is it?

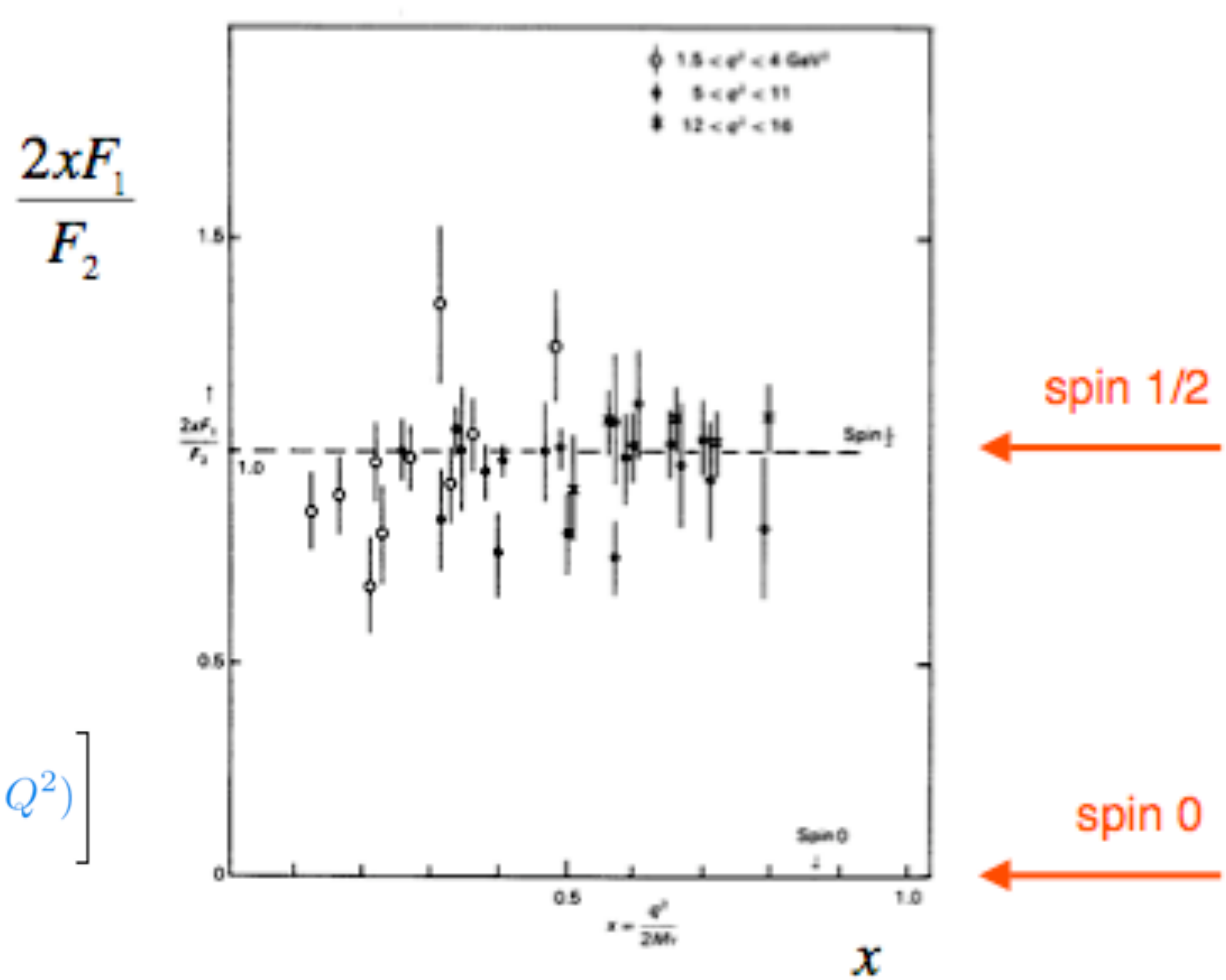


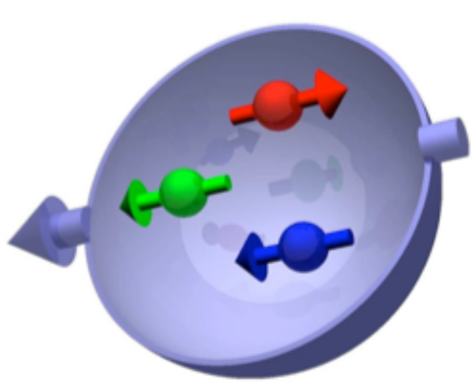
History - early DIS

Circa 1970 - Scaling and the Callan-Gross relation:



$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{Q^4 x}\left[xy^2\,F_1(x,Q^2) + (1-y)\,F_2(x,Q^2)\right]$$

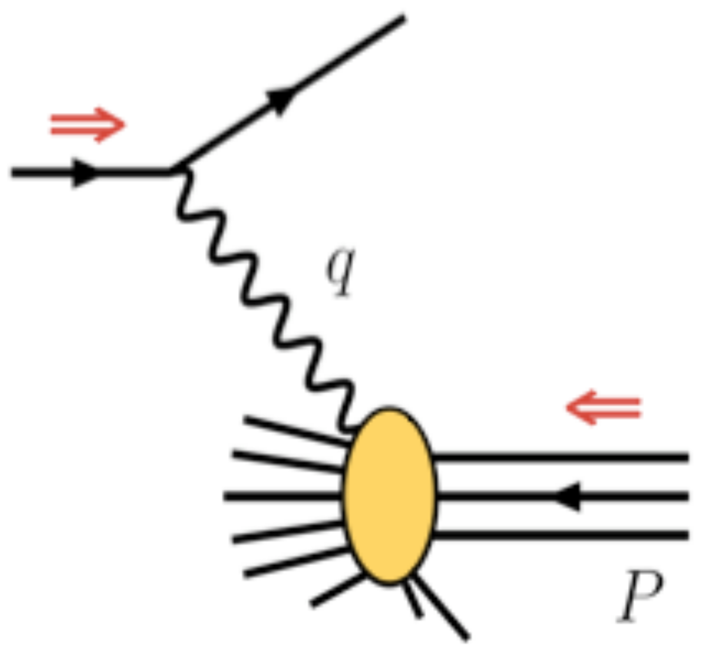




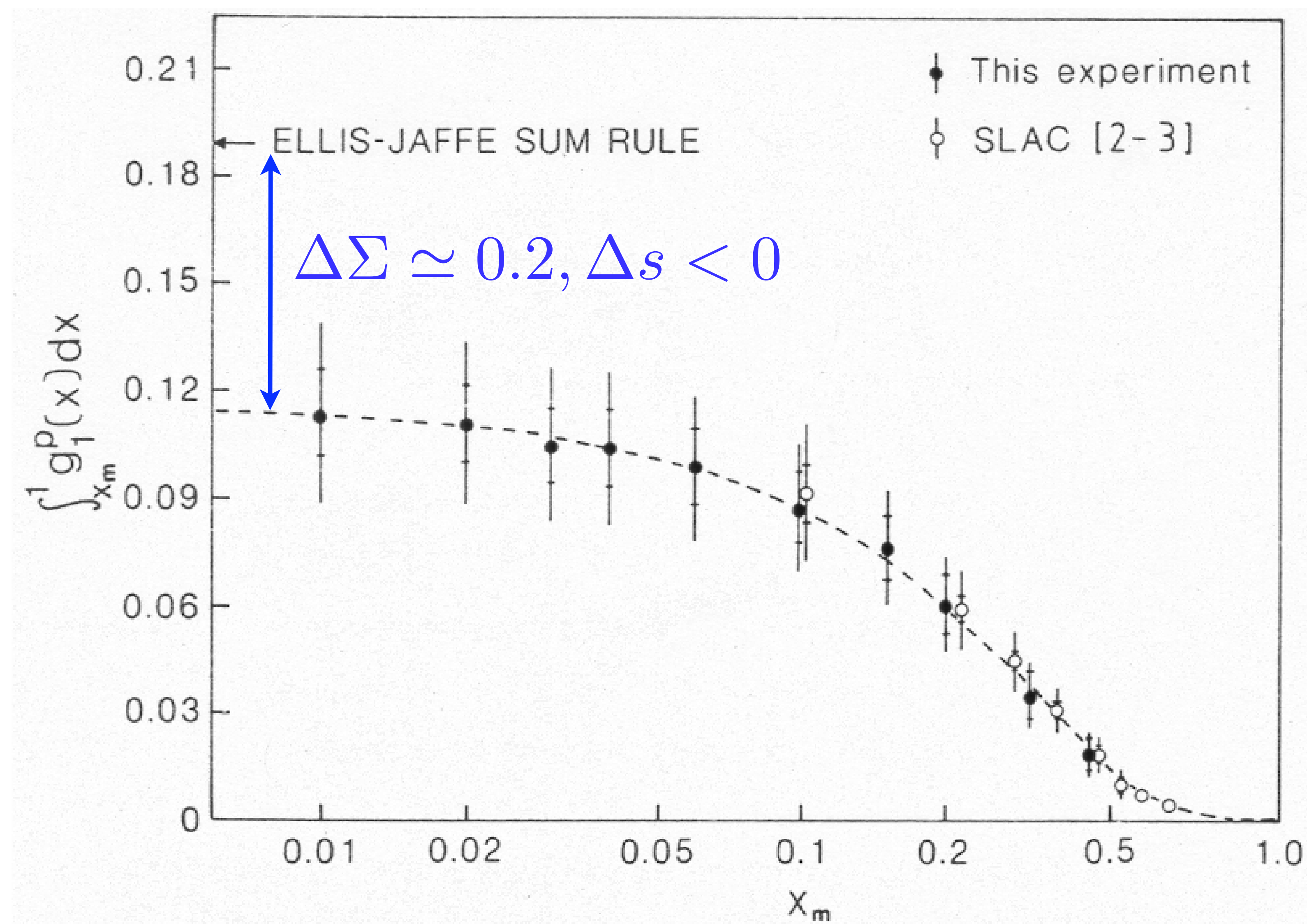
Quarks are spin-1/2

History - polarized DIS

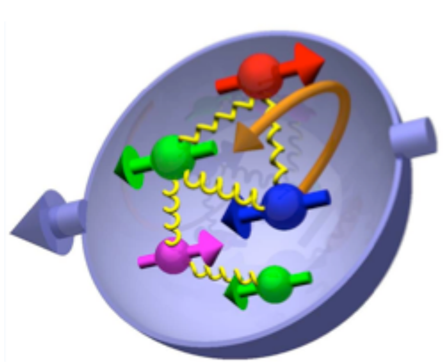
Circa 1985 - European Muon Collaboration:



$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x, Q^2)}$$



EMC: J.Ashman et al, Nucl. Phys. B328, 1 (1989)



The sum of Quark Spins contribute little to the proton spin,
Strange quarks are negatively polarized, $\Delta s < 0$

Nucleon Spin Structure - Present

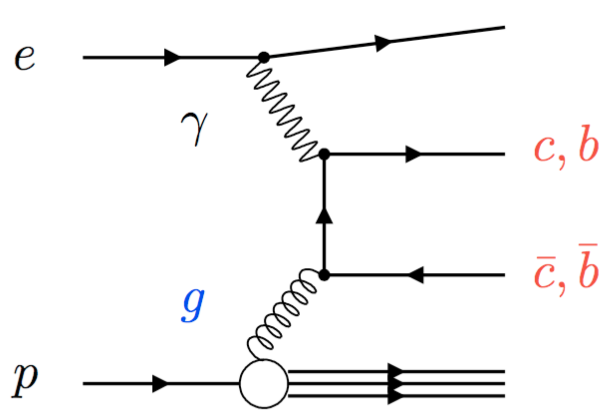
Frontier *questions* in nucleon spin structure,

- gluon polarization (gluons are numerous, $\alpha_s \Delta G \propto \mathrm{constant}$, ...)

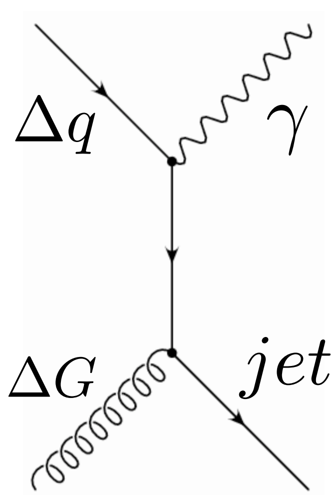
- flavor composition of quark spins ($\Delta s < 0$, cancellation, symmetries, ...),

- orbital momenta, $J_q(\infty) : J_g(\infty) \sim 1 : 1$ as for ordinary momenta, ...

Need for *complementary* methods/techniques,



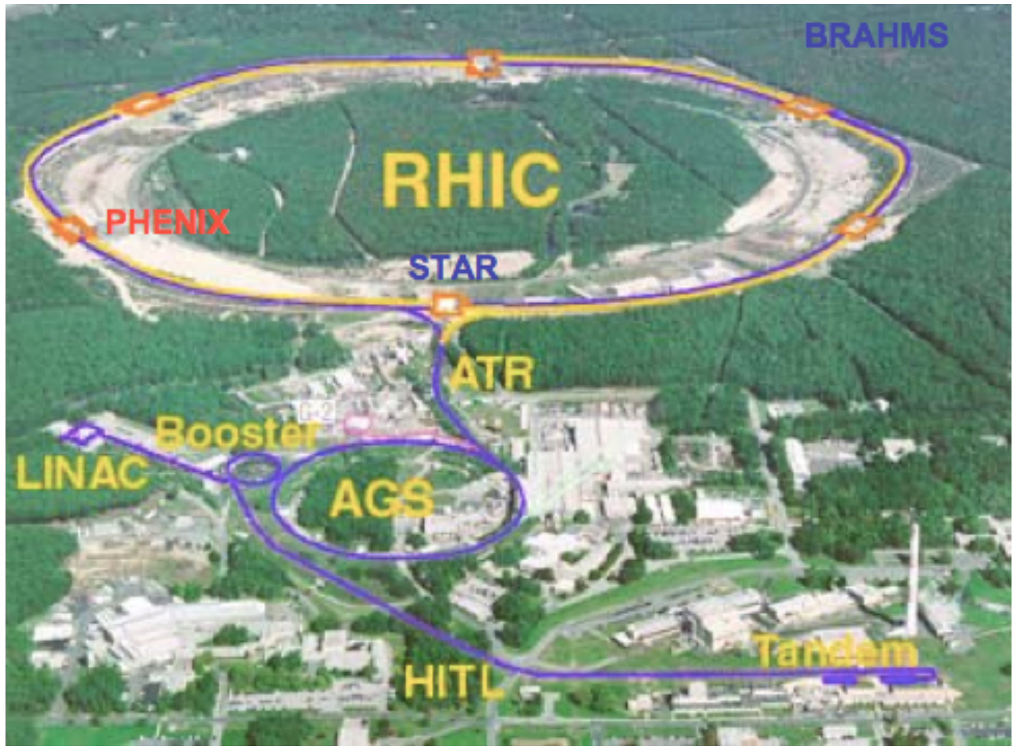
and



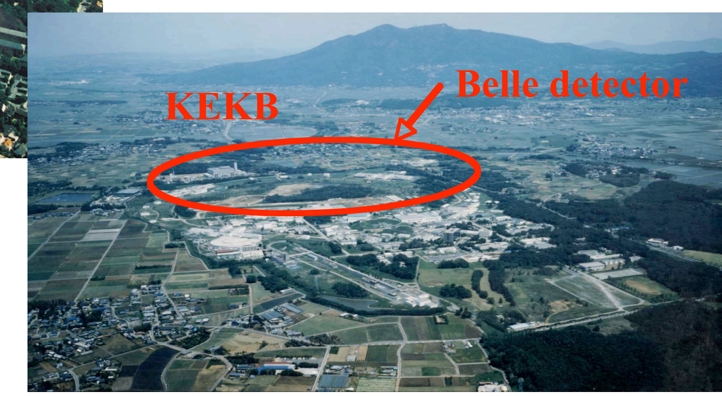
and ...

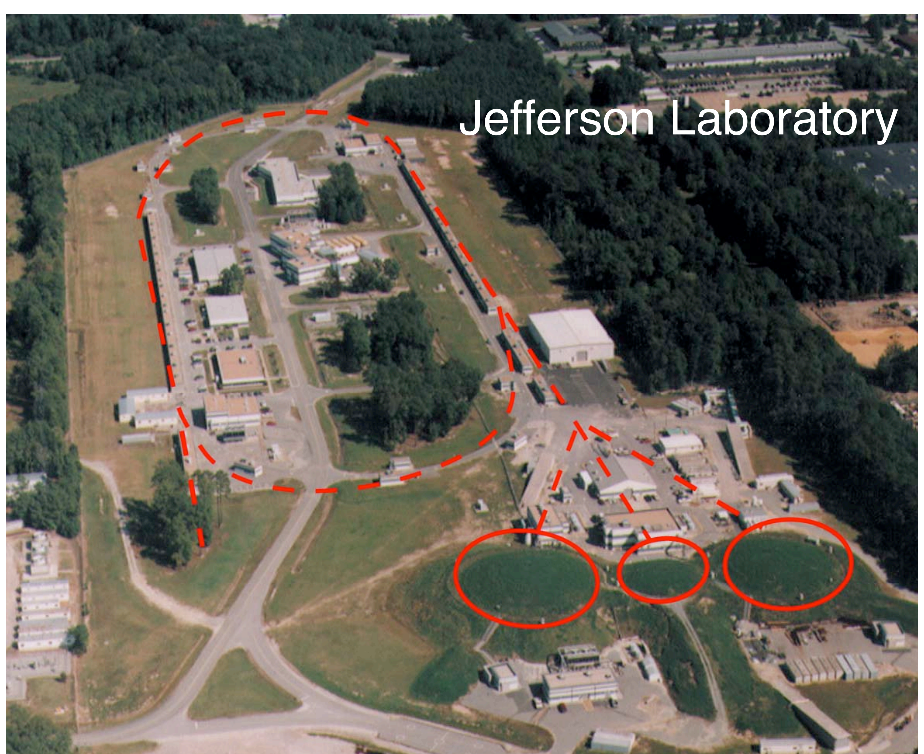
semi-inclusive DIS *proton-proton* *EIC, neutrino-nucleon, ...*

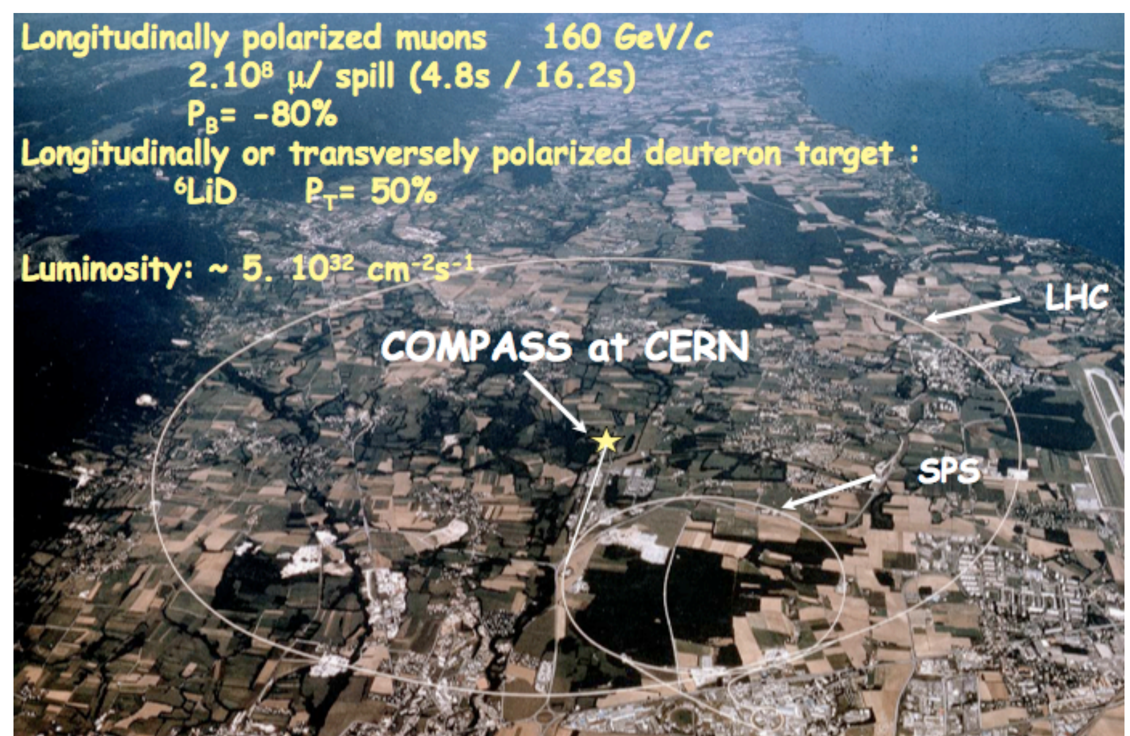
World-wide Quest



27 GeV e$^+$/e$^-$ beam of HERA ep collider

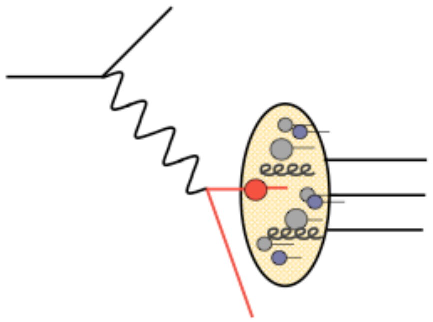


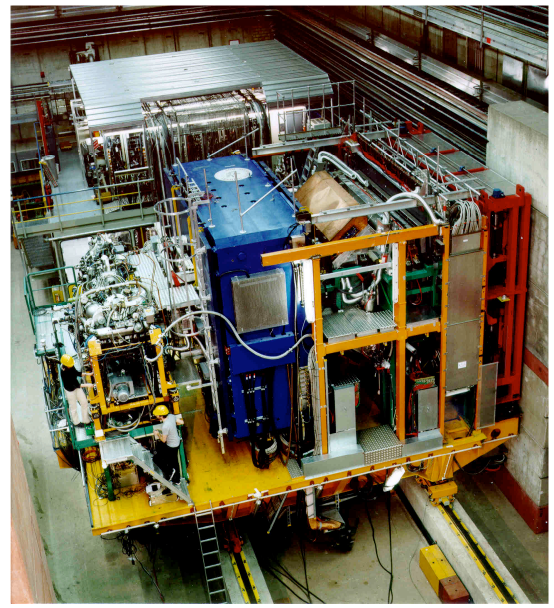


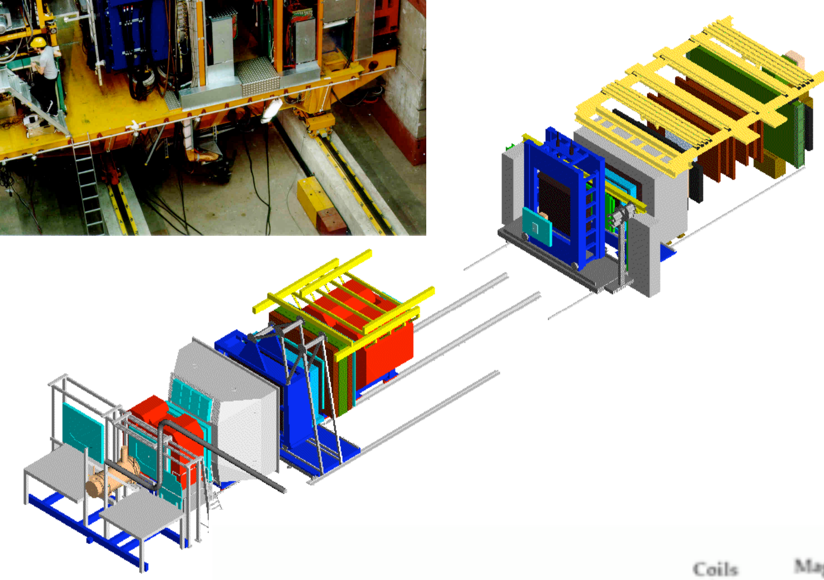


World-wide Quest

DIS





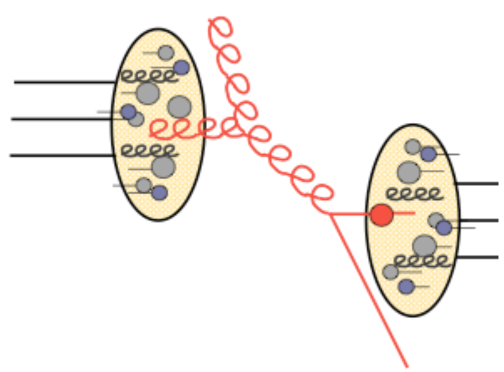


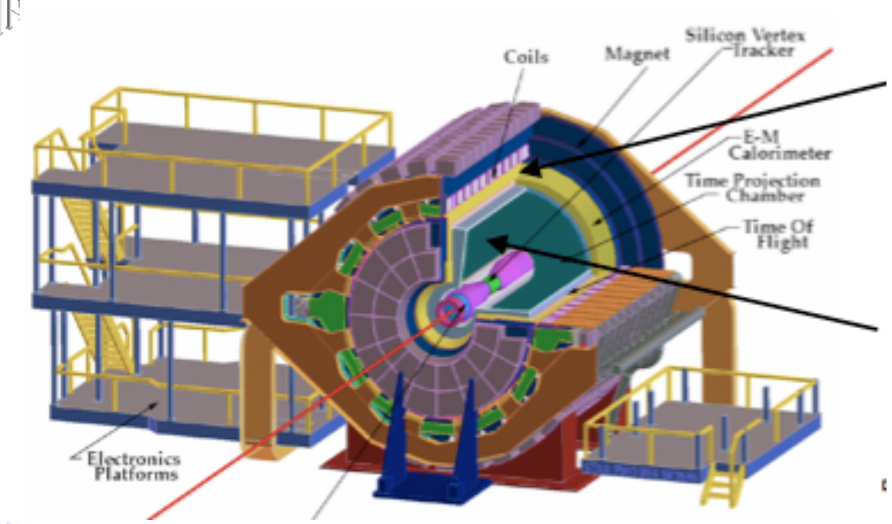
HERMES at DESY:
- 27 GeV electron beam,
- fixed target,
- PID

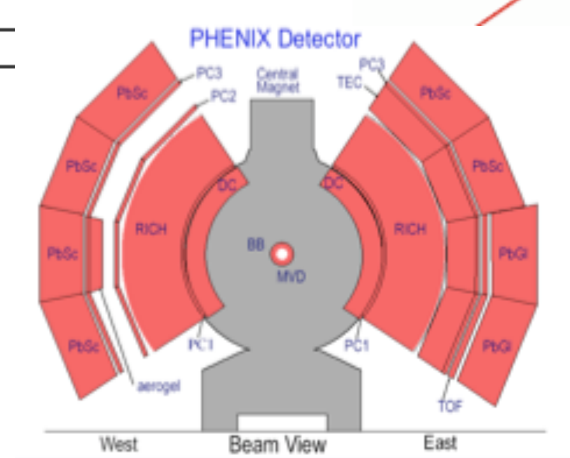
COMPASS at CERN:
- 160 GeV muon beam,
- fixed target,
- open spectrometer

JLAB:
- 6-12 GeV el. beam,
- fixed target
- very high intensity

pp







STAR at RHIC:
- 200-500 GeV E_{cms},
- large acceptance

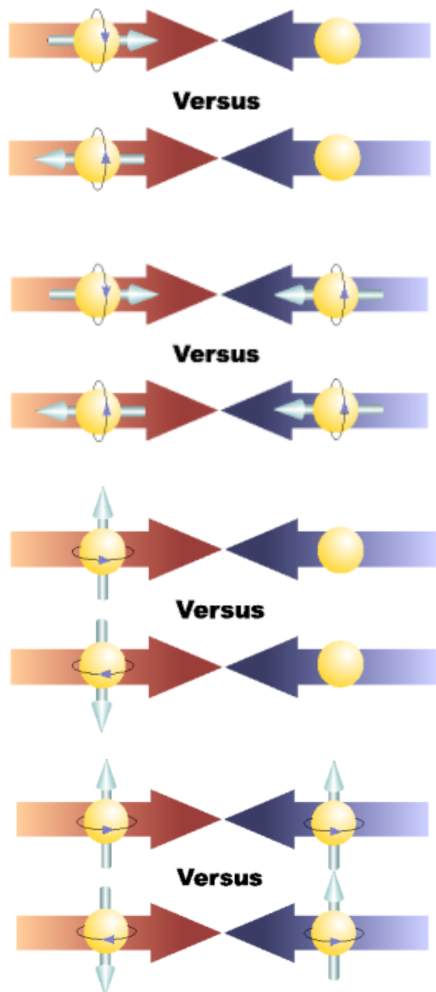
PHENIX at RHIC:
- high resolution,
- high rate

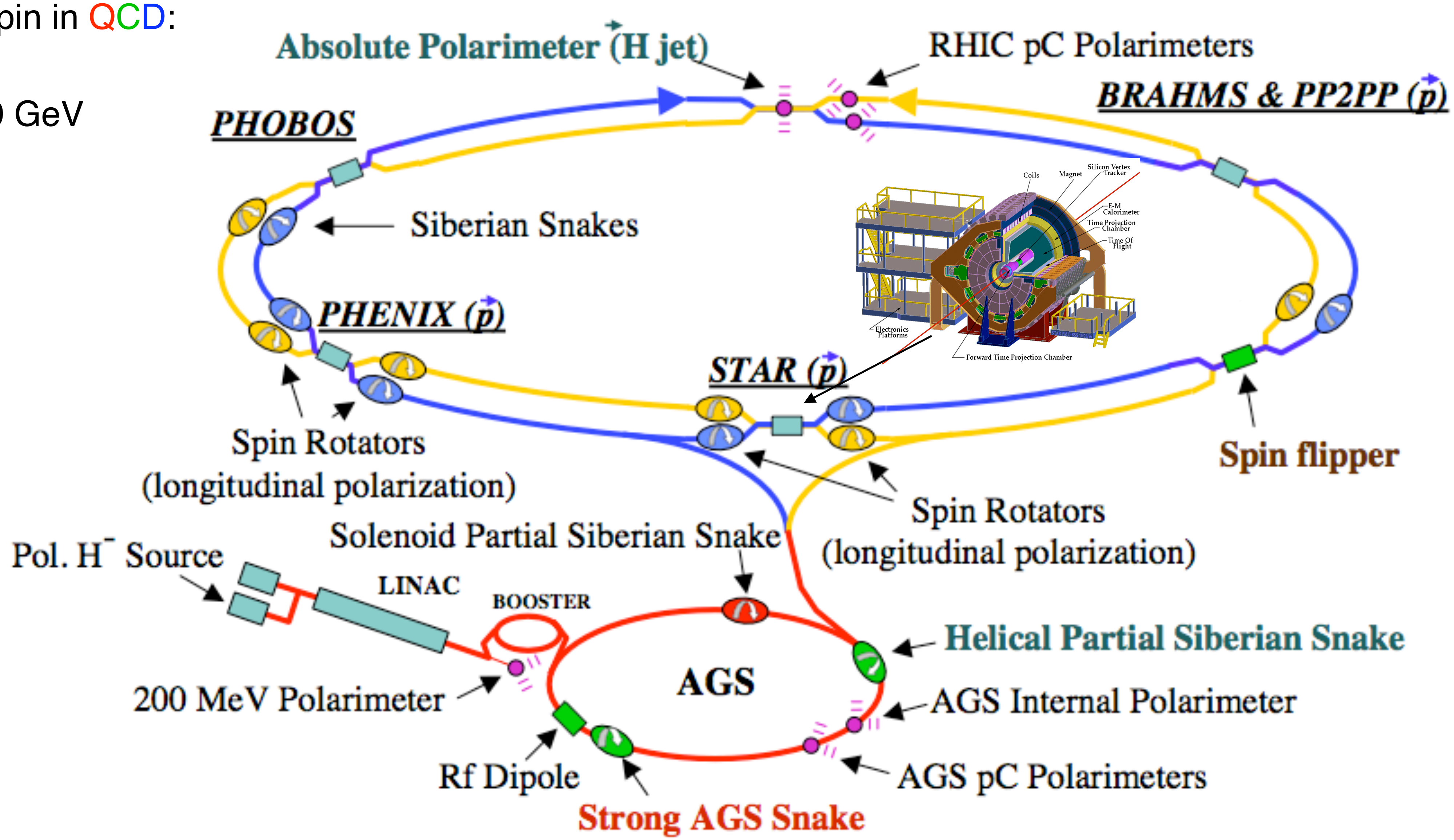
BRAHMS at RHIC:
- spectrometer + PID

RHIC - Polarized Proton-Proton Collider

Unique opportunities to study spin in QCD:

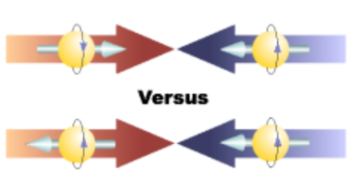
$\sqrt{s}$ = 62, 200, and (future) 500 GeV





at hard (perturbative) scales with good systematic controls, e.g. bunch pattern:

Longitudinal performance (STAR recorded):

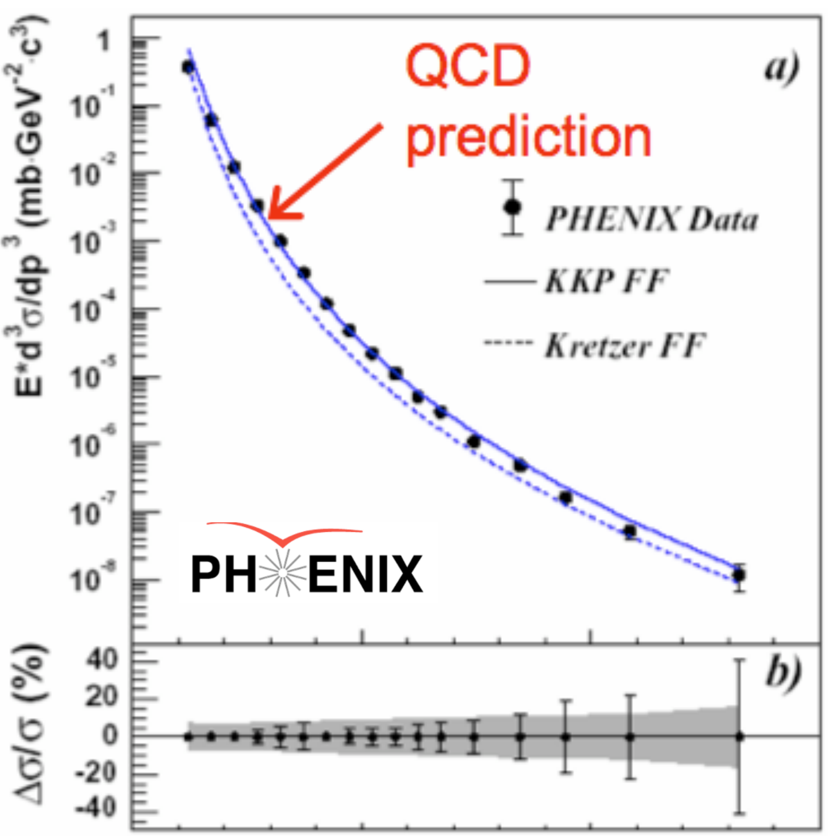


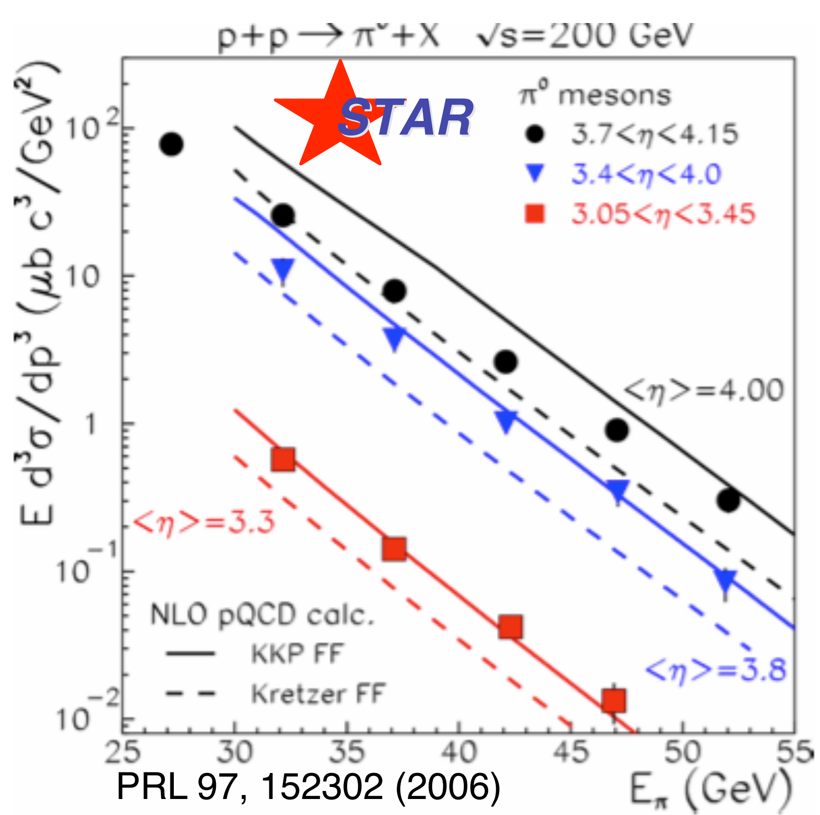
	2003-2004	2005	2006	2009 (request)	
$\sqrt{s}$ = 200 GeV	0.3 pb^{-1}	2 pb^{-1}	5 pb^{-1}	50 pb^{-1}	Luminosity
	30-45%	50%	~55%	60%	Polarization
	0.01 pb^{-1}	0.1 pb^{-1}	0.5 pb^{-1}	6 pb^{-1}	FoM

RHIC - Inclusive Cross Sections

pions

PRL 91, 241803 (2003)

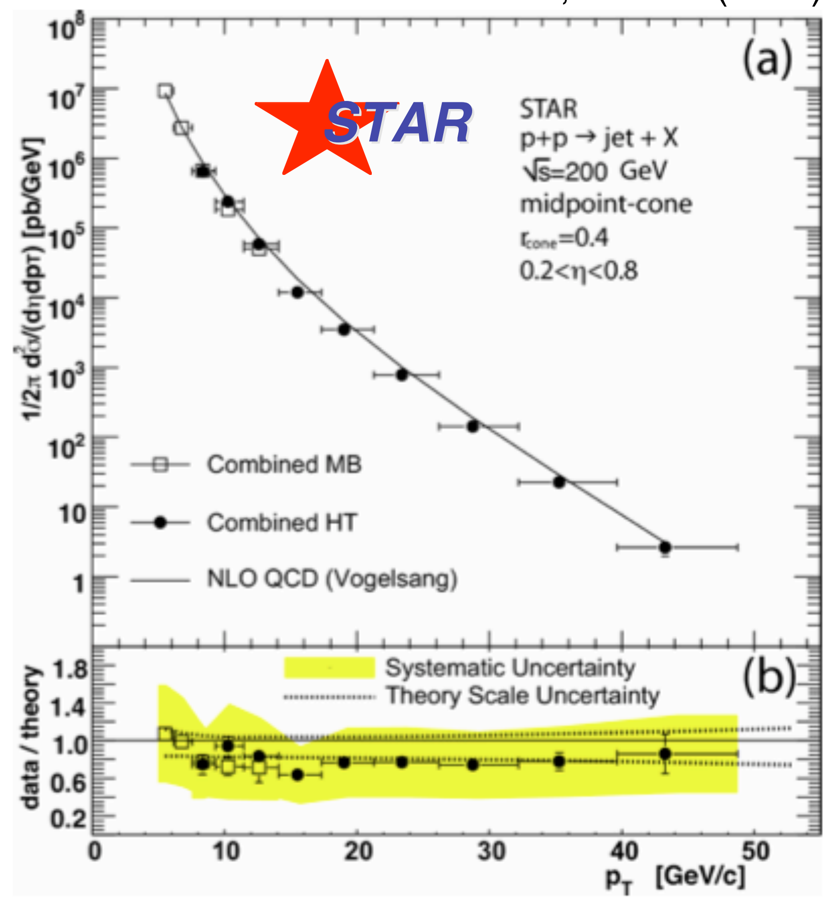




PRL 97, 152302 (2006)

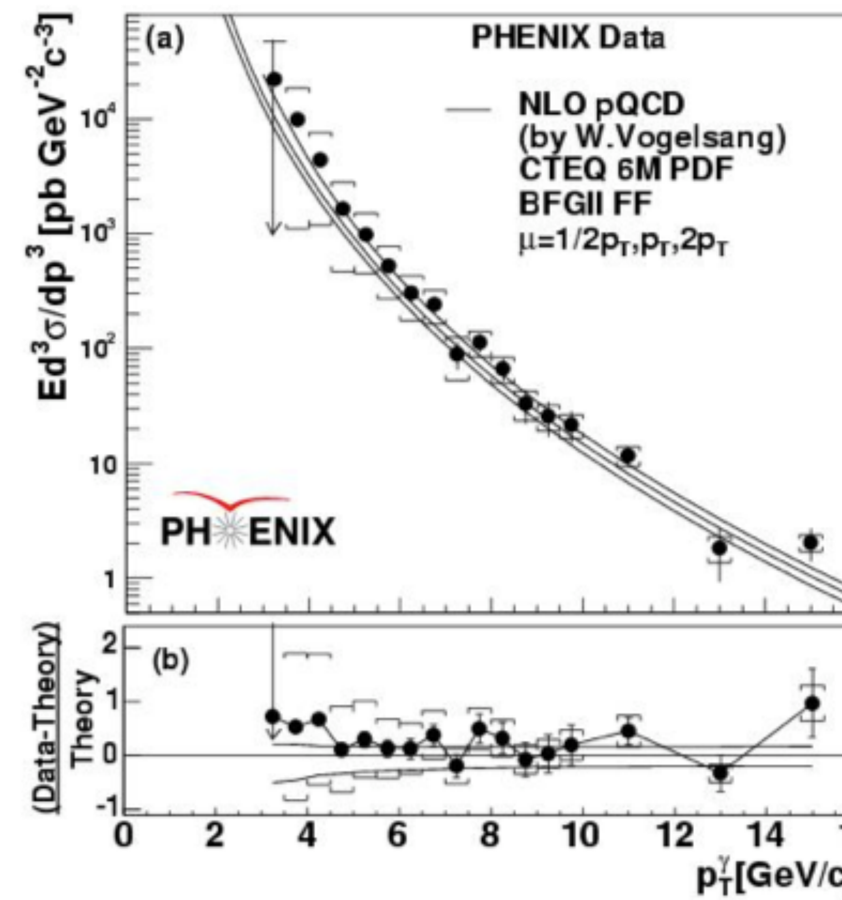
jets

PRL 97, 252001 (2006)



photons

PRL 98, 012002 (2007)



Good agreement between data and theory (pQCD @NLO) for mid-rapidity pions, jets, and photons;

⟶ interpretable measurements!

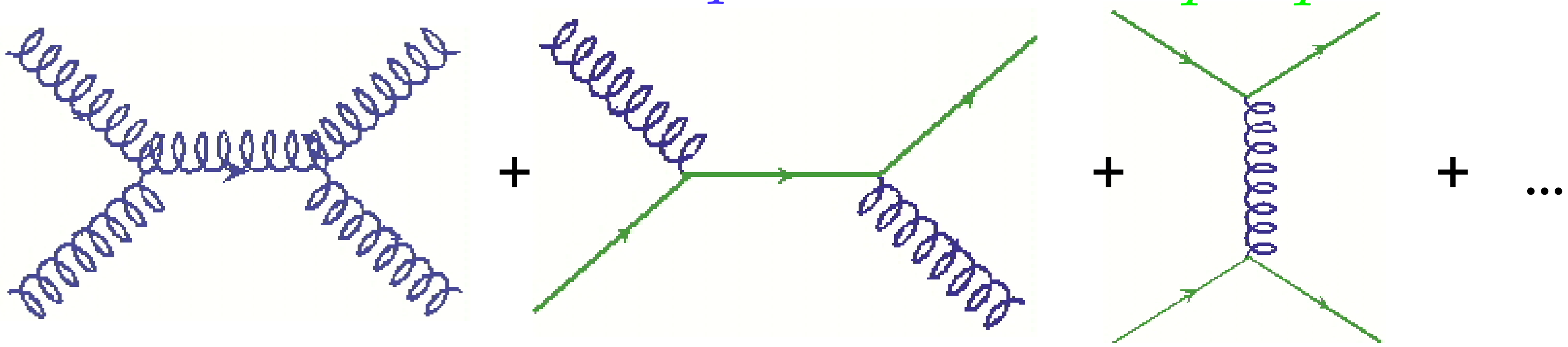
Start to see a break-down at very forward rapidities.

Other examples exist, more to come!

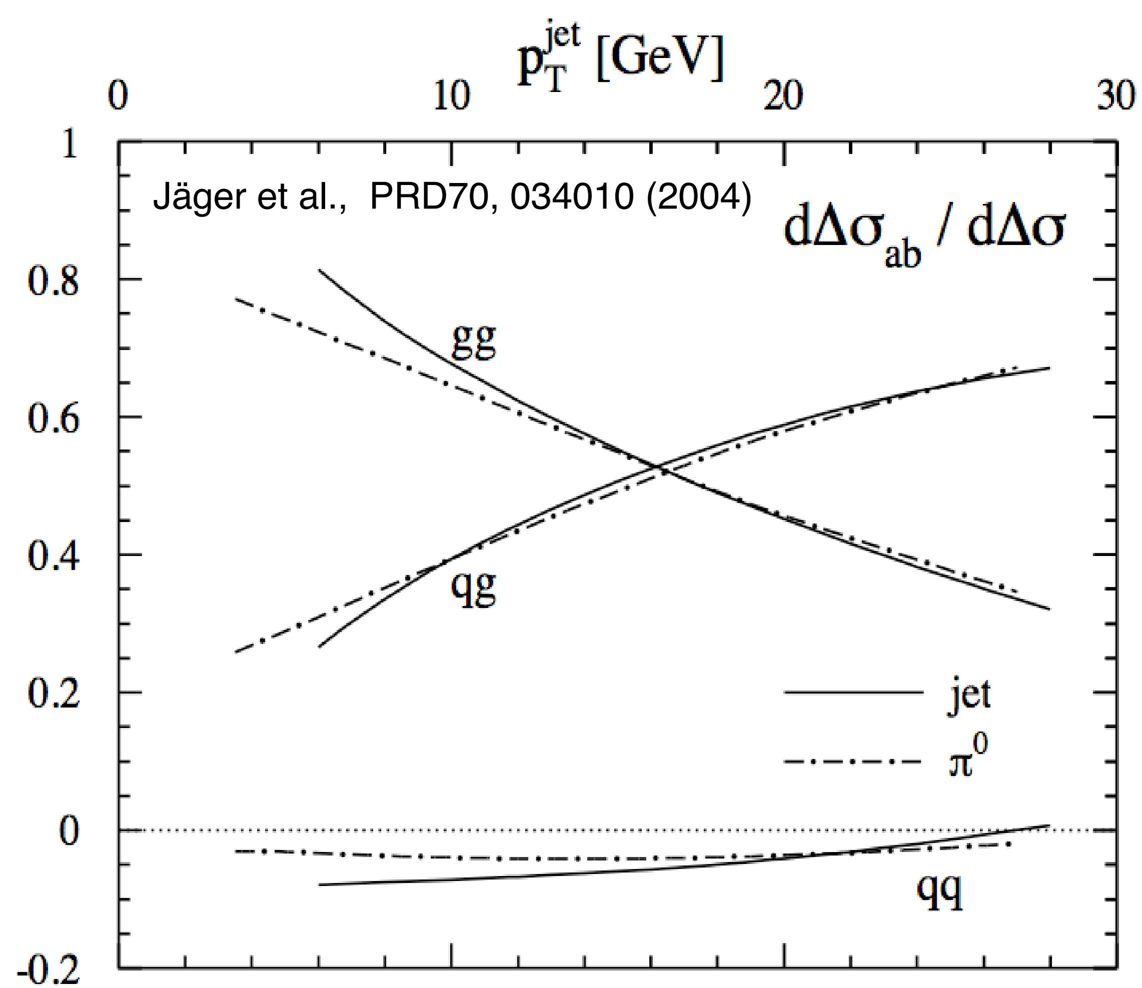
Longitudinal Spin Asymmetries and Inclusive Channels (jets, pions)

Sensitivity to:

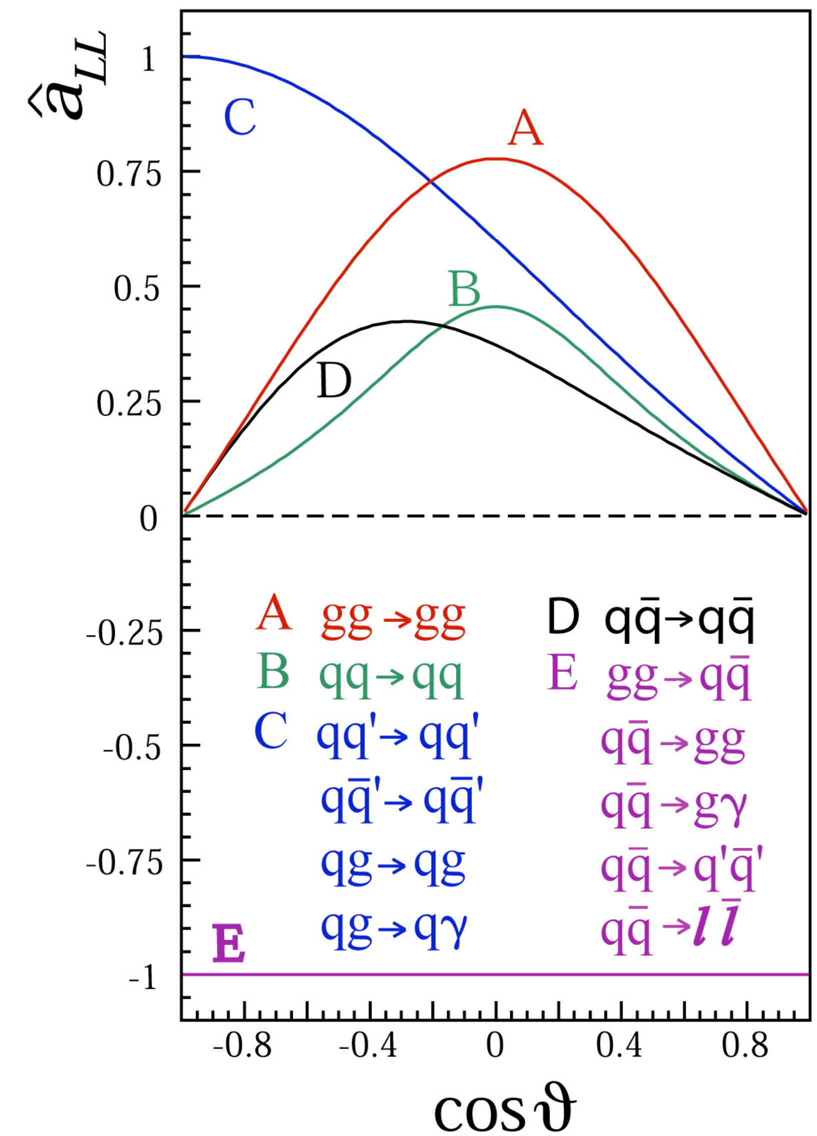
$\frac{\Delta G}{G}\frac{\Delta G}{G}$ $\frac{\Delta q}{q}\frac{\Delta G}{G}$ $\frac{\Delta q}{q}\frac{\Delta q}{q}$



with large contributions from gluon-gluon and quark-gluon scattering,



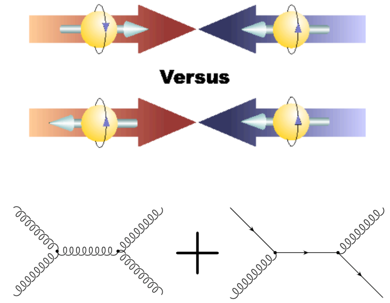
with large partonic asymmetries at 'midrapidity',



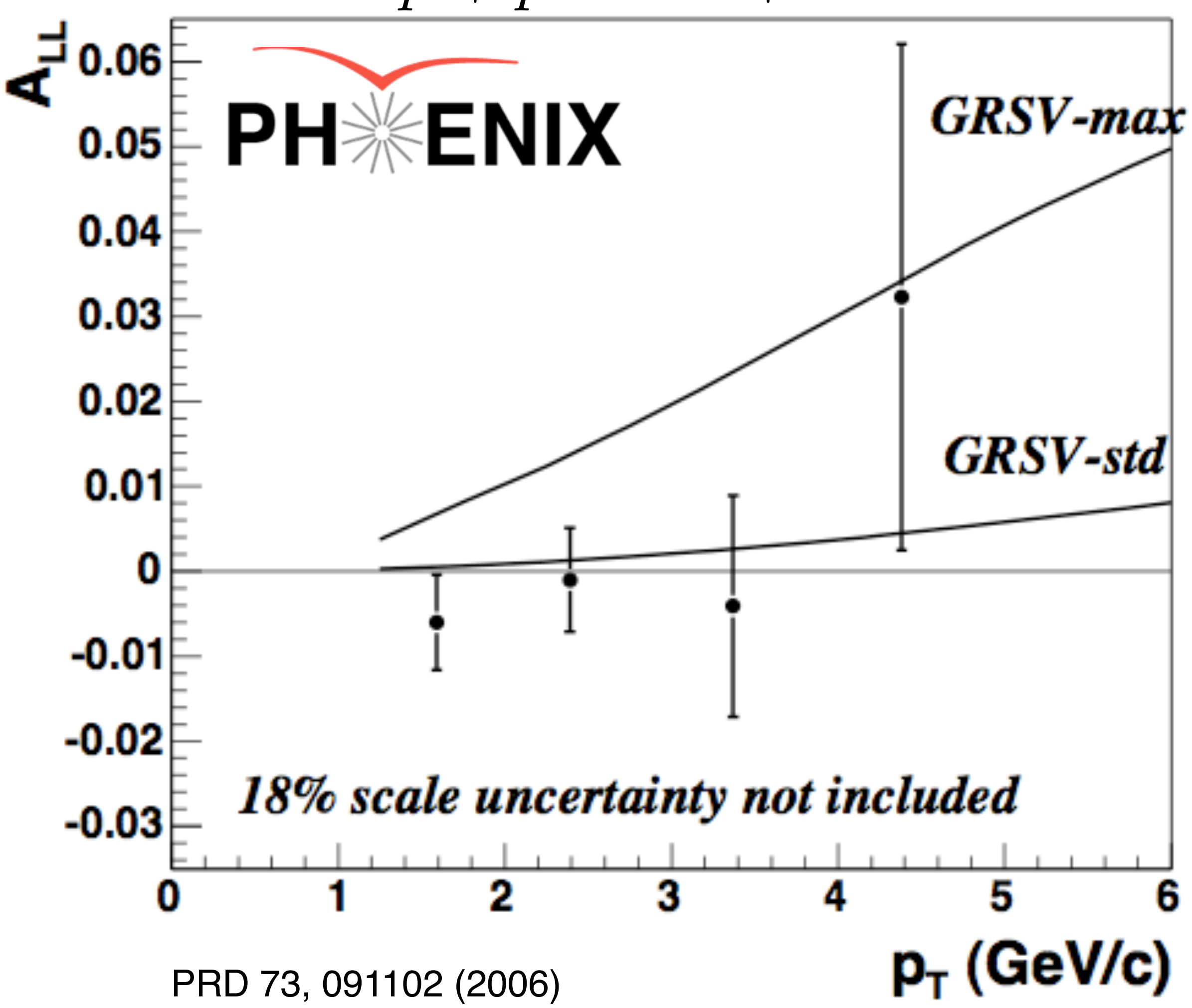
and, in the case of (unbiassed) jets, without fragmentation uncertainties,

$$A_{LL} \propto \frac{\Delta f_a}{f_a}\frac{\Delta f_b}{f_b}\hat{a}_{LL}$$

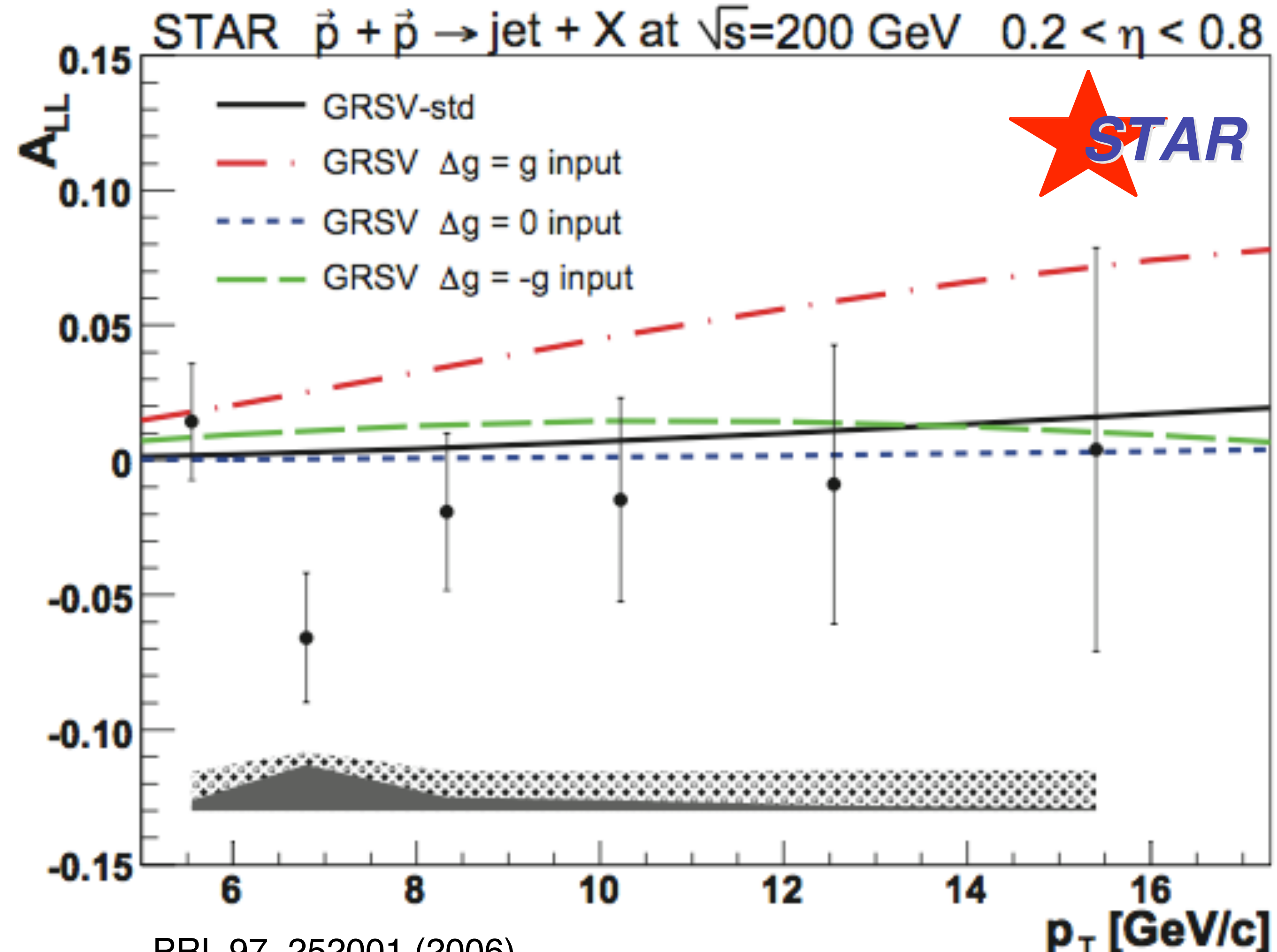
RHIC - First Gluon Asymmetries



$$\vec{p} + \vec{p} \rightarrow \pi^0 + X$$



PRD 73, 091102 (2006)

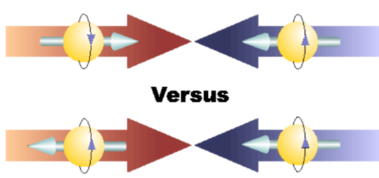


PRL 97, 252001 (2006)

Disfavor maximal gluon polarization

RHIC - From First Gluon Asymmetries to Physics Answers

Measure double longitudinal spin asymmetries and establish the factorized framework,

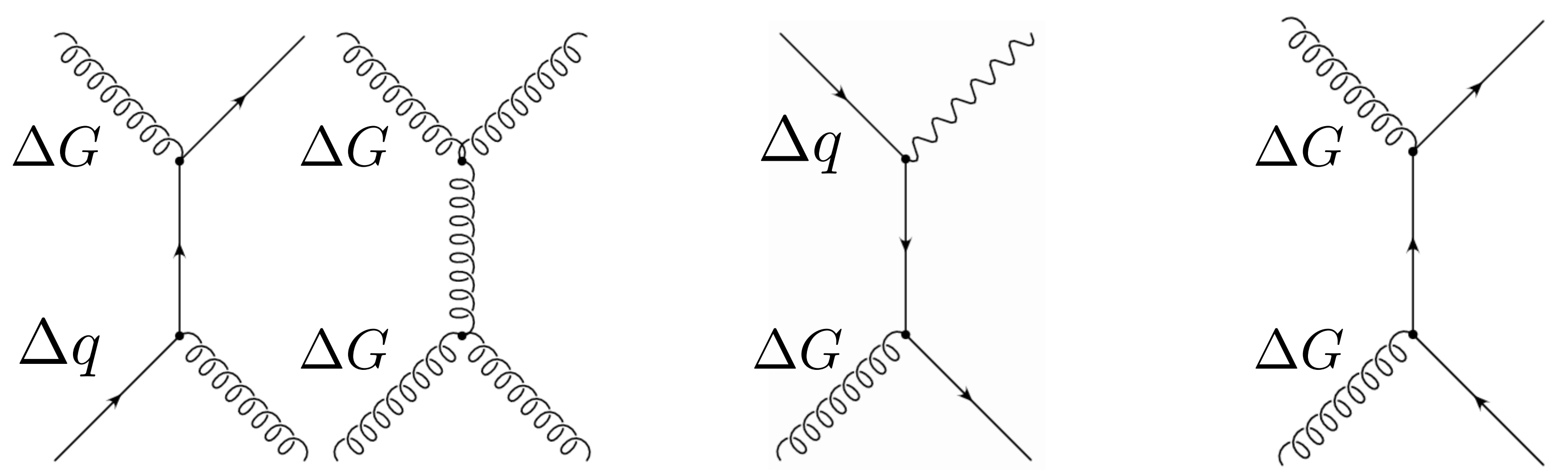


$$A_{LL} \equiv \frac{\sigma^{\uparrow\uparrow} - \sigma^{\downarrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow}} \stackrel{!}{=} \sum \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \hat{a}_{LL} \otimes (\text{fragmentation functions})$$

Start with abundantly produced jets at mid-rapidity, where the partonic asymmetries are sizable.

Pursue *precision*, *coverage*, sensitivity to *initial kinematics*, and *selective probes*,

$\vec{p} + \vec{p} \rightarrow \text{jet(s)} + X$ $\quad$ $\vec{p} + \vec{p} \rightarrow \gamma + \text{jet}$ $\quad$ $\vec{p} + \vec{p} \rightarrow c\bar{c}, b\bar{b} + X$



$$\mathcal{L} \simeq 3 - 8 \cdot 10^2\,\text{pb}^{-1}, \quad P = 0.4 - 0.7, \quad \sqrt{s} = 200 - 500\,\text{GeV}$$

time

Best knowledge from global analyses of *complementary* data

Covered in the next talks, e.g.

precision:
Jacobs, Grebenyuk - jets, π^0

initial kinematics through di-jets
Sowinski,

selectivity through heavy flavor,
Kurnadi, Wang

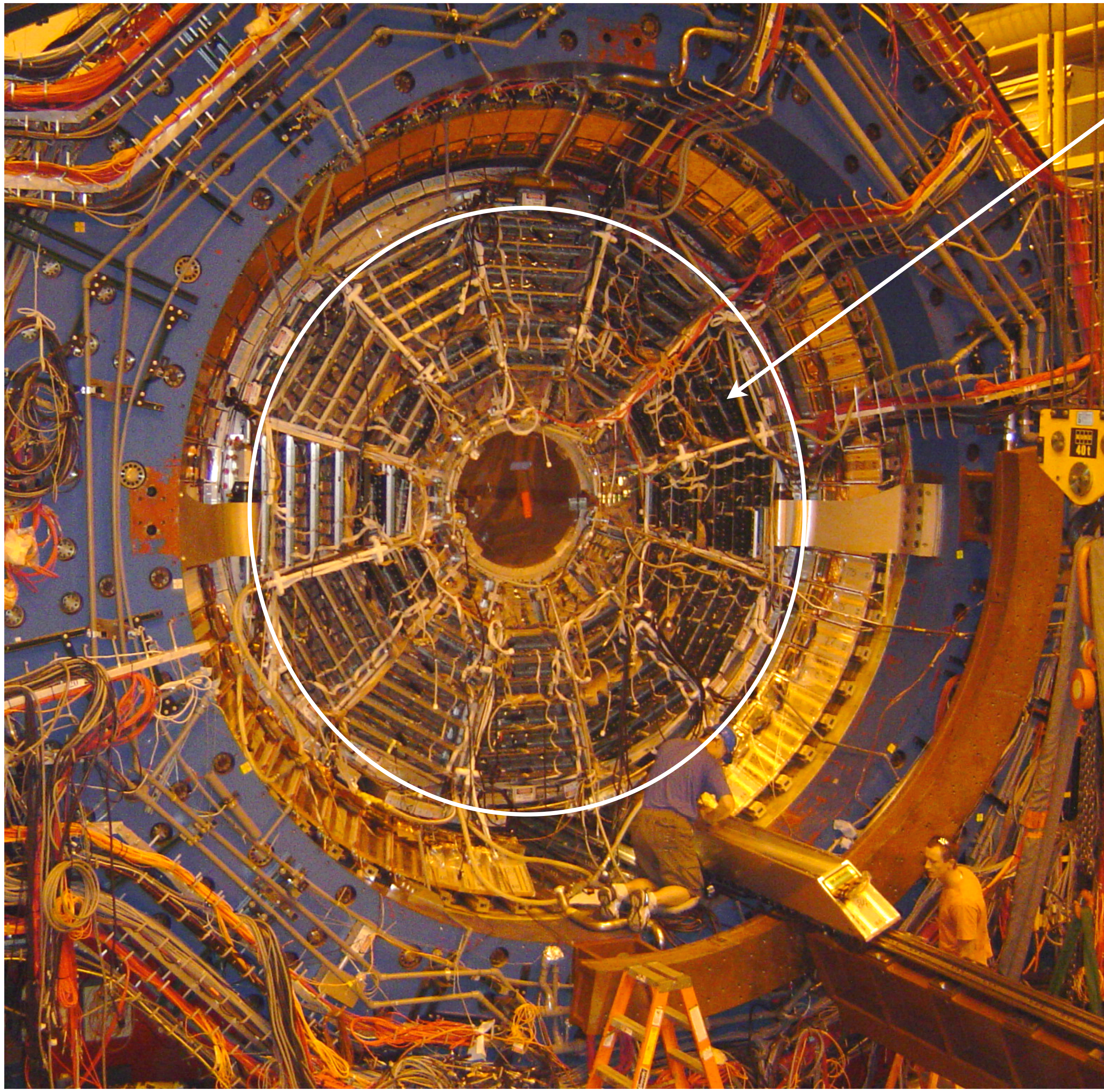
Current State of the Art:
De Florian et al, *PRL 101, 072001*

RHIC - Possibilities to Access Quark Polarization

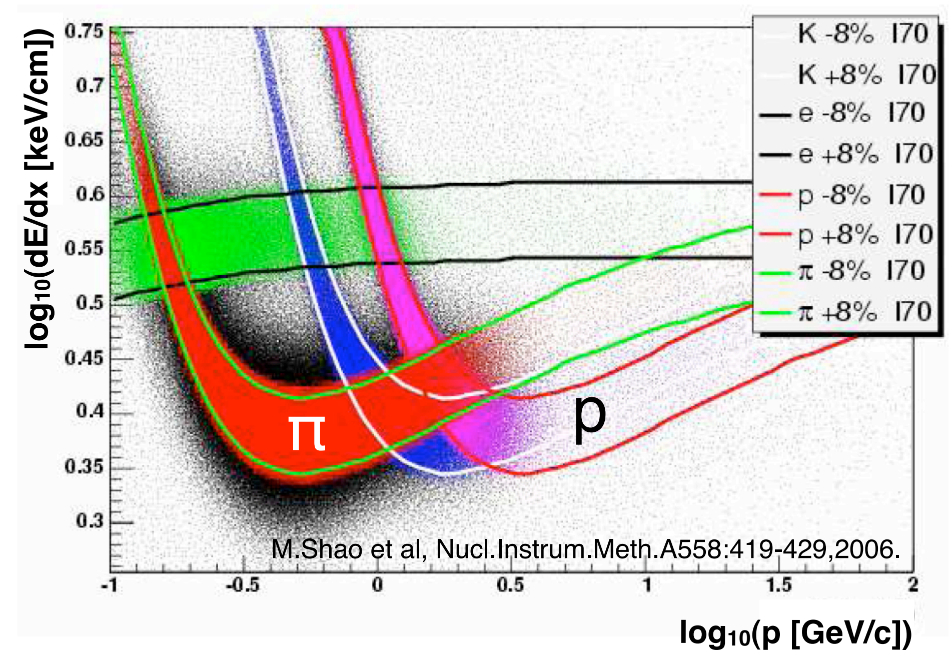
$\sqrt{s} = 500\,\mathrm{GeV}$ use W-bosons as quark polarimeters,

$\sqrt{s} = 200\,\mathrm{GeV}$ Hyperon polarization measurements?

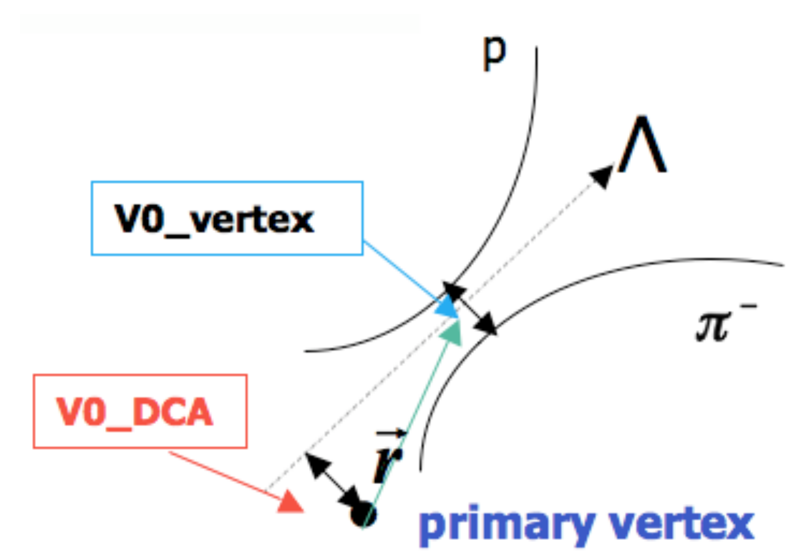
Lambda and anti-Lambda Hyperons in STAR



Time Projection Chamber enables PID,

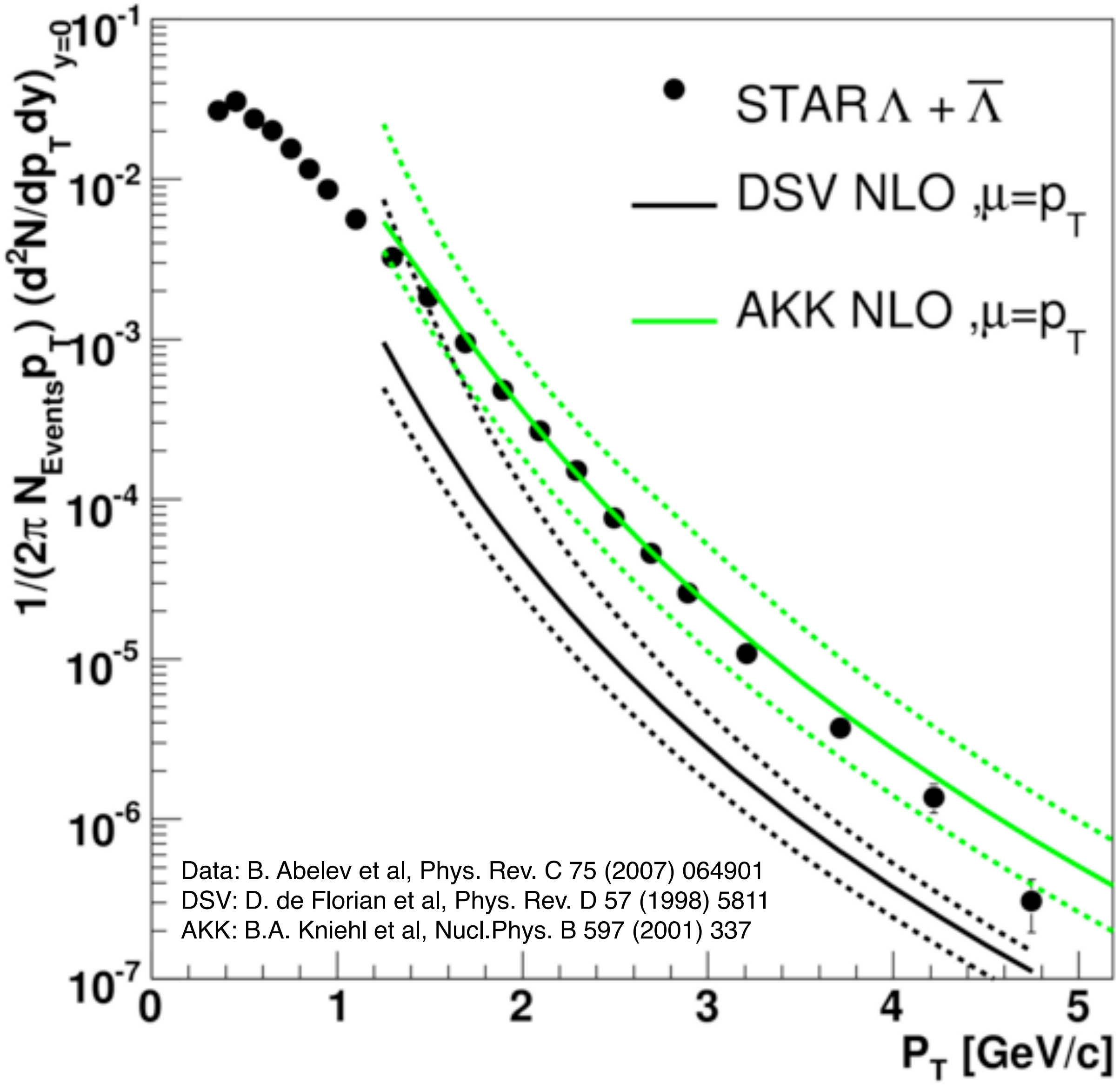


and topological reconstruction,

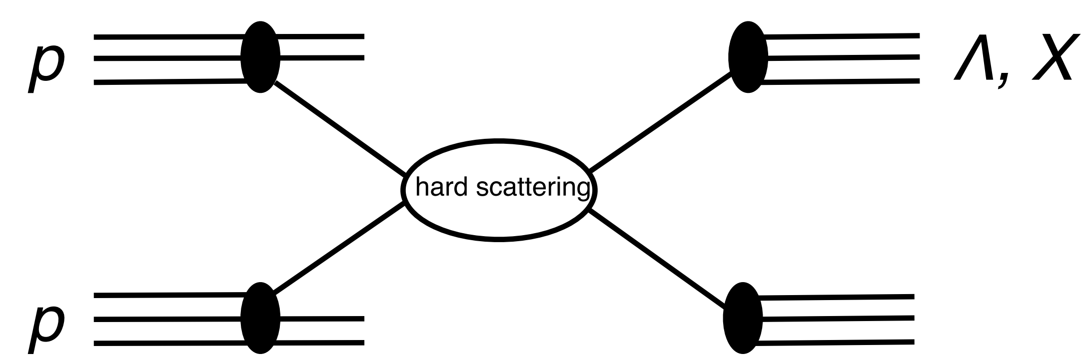


for $|\eta| \leq \sim 1.3$

Differential Cross Section



Factorized framework,



$$f,\ \Delta f \quad \otimes \quad \hat{\sigma},\ \Delta\hat{\sigma} \quad \otimes \quad D,\ \Delta D$$

enables perturbative description.

Agreement of STAR data and theory, for a suitable choice of *D*, is a necessary condition for interpretation.

D_{LL} - Longitudinal Spin Transfer

At RHIC,

$$D_{LL}^{\Lambda} \equiv \frac{\sigma_{p^+p\to\Lambda^+X} - \sigma_{p^+p\to\Lambda^-X}}{\sigma_{p^+p\to\Lambda^+X} + \sigma_{p^+p\to\Lambda^-X}} = P_{\Lambda}^{+}$$

that is, the longitudinal polarization of the Λ for a specific beam-helicity configuration.

This polarization can be determined in the usual way,

$$\frac{dN}{d\Omega} \propto A(\cos\theta^*)(1 + \alpha P_{\Lambda}\cos\theta^*)$$

from the angular distribution of the $p + \pi$ decay mode with B.R. ~64%.

Here,

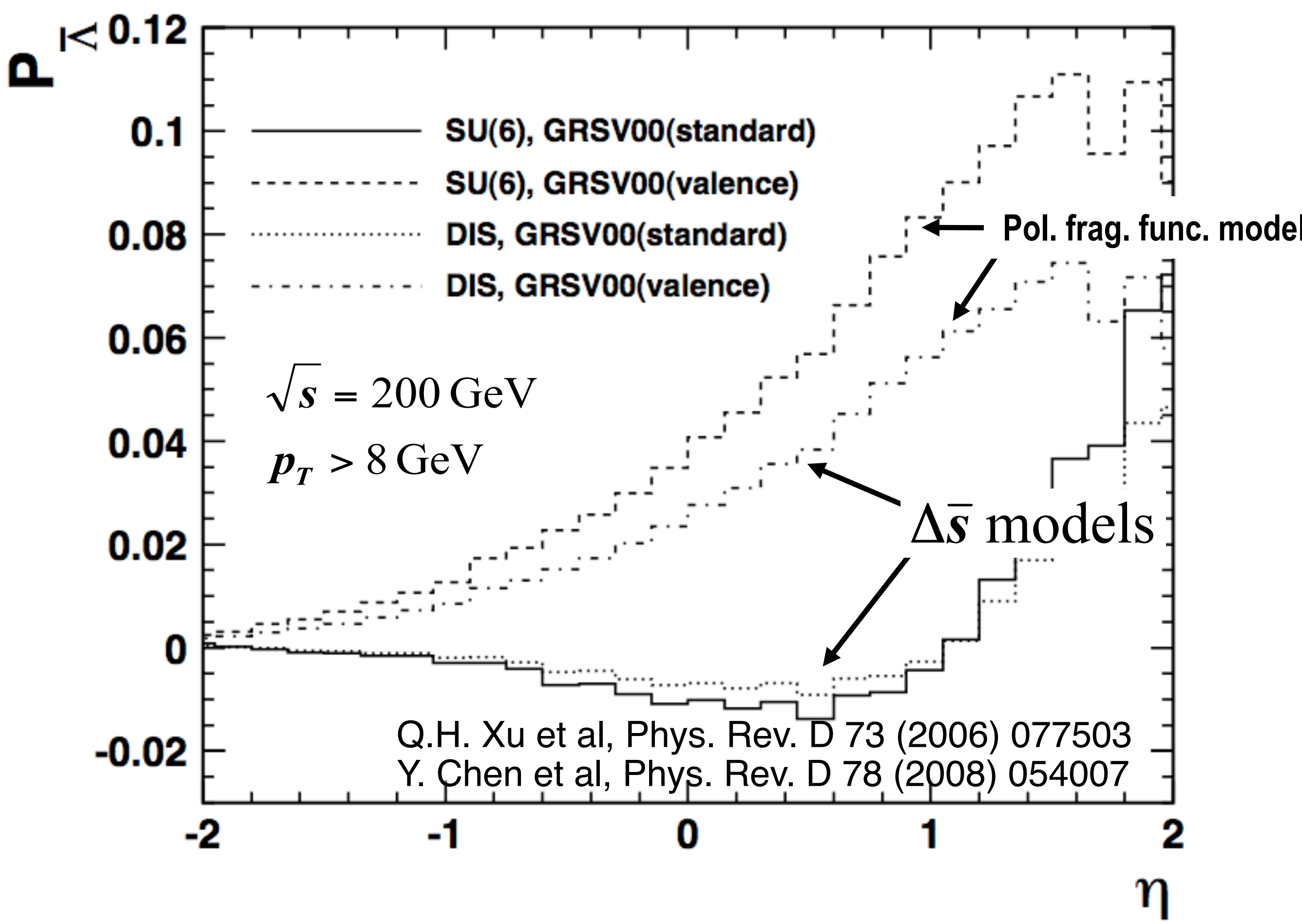
A is the detector acceptance,

θ^* is the angle defined by the Λ momentum and the p direction in the Λ rest frame,

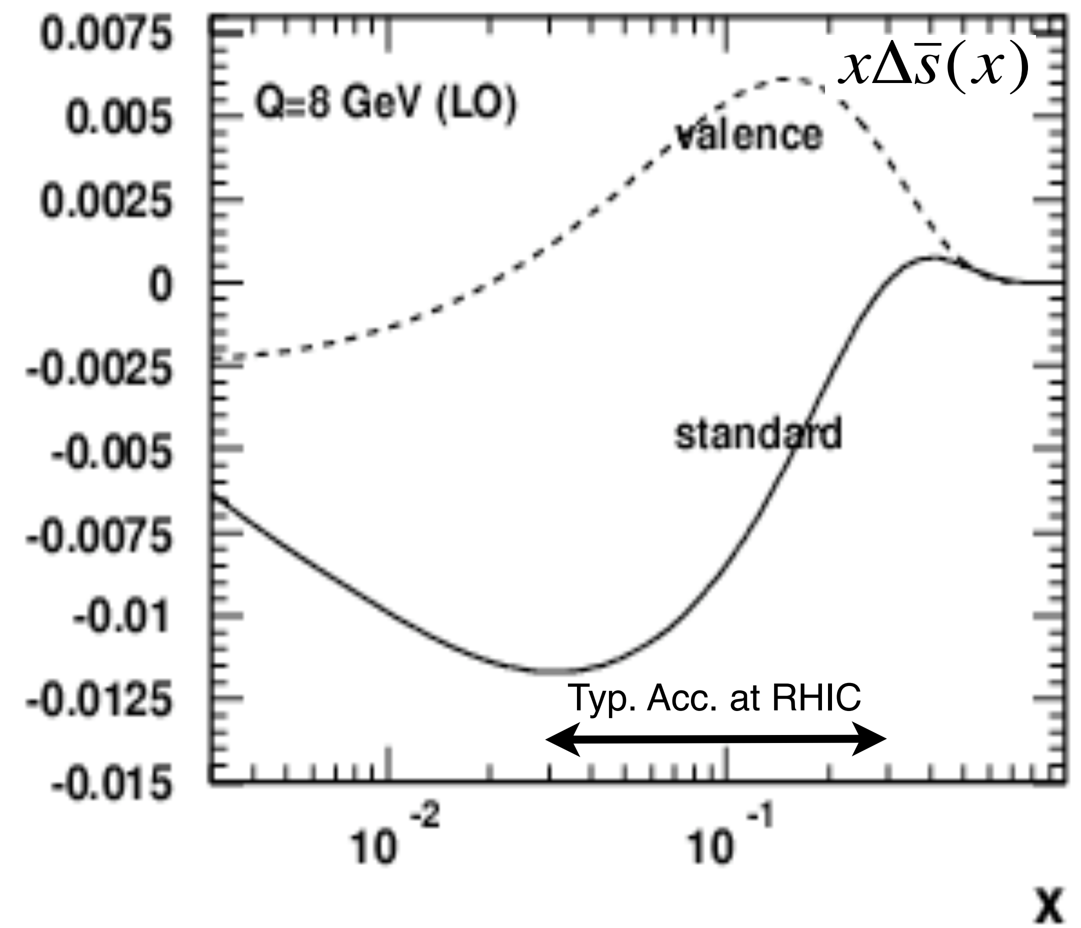
$\alpha = 0.642 \pm 0.013$ is the decay parameter.

D_{LL} - Longitudinal Spin Transfer

Expectations at LO show sensitivity of D_{LL} for the $\bar{\Lambda}$ to the $\bar{s}$ helicity distribution, $\Delta\bar{s}$,



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



more so than to the fragmentation in this model.

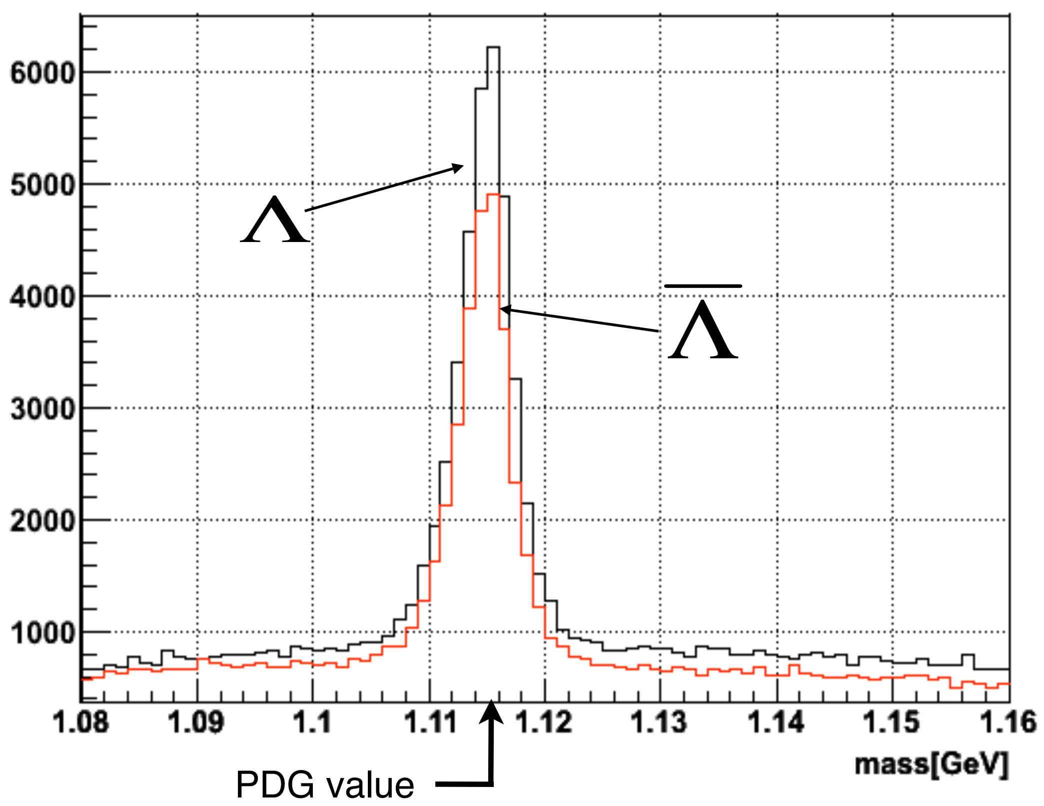
The Λ D_{LL} is less sensitive to Δs, partly due to larger *u* and *d* quark fragmentation contributions.

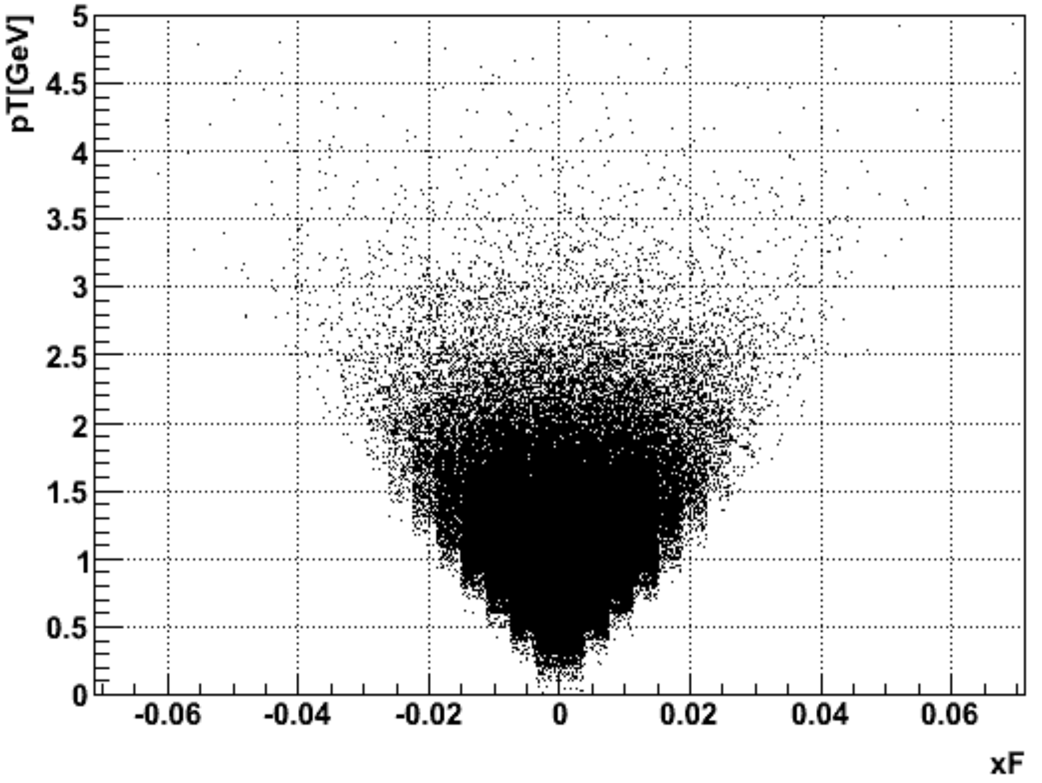
Promising measurement: neither the role of (anti-)strange quarks nor polarized fragmentation is well known/understood - effects are potentially large enough to be observed.

Note: predictions include decay contributions, e.g. $\Sigma \rightarrow \Lambda$

STAR Data - 2005

~3.10^6 events collected with a beam-collision trigger (minimum bias, bandwidth limited),





~ 30.10^3 Λ candidates,

~ 25.10^3 $\bar{\Lambda}$

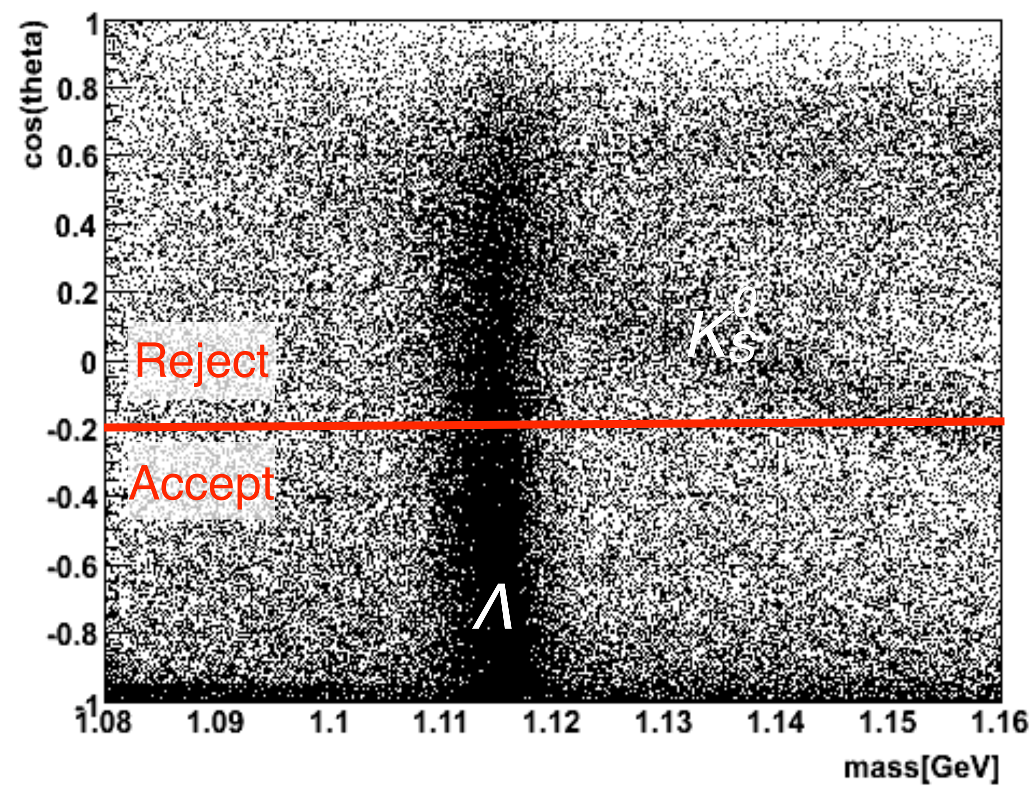
$\langle p_T \rangle \approx 1.3$ GeV/c

$\langle |x_F| \rangle \approx 0.008$

Analysis Features

Uses the $\Lambda \rightarrow p + \pi$ weak decay mode,

$$\frac{dN}{d\Omega} \propto A(\cos\theta^*)(1 + \alpha P_\Lambda \cos\theta^*)$$



Restrict $\cos\theta^*$ to eliminate K_S^0 background caused by misidentified π (cuts ~40%).

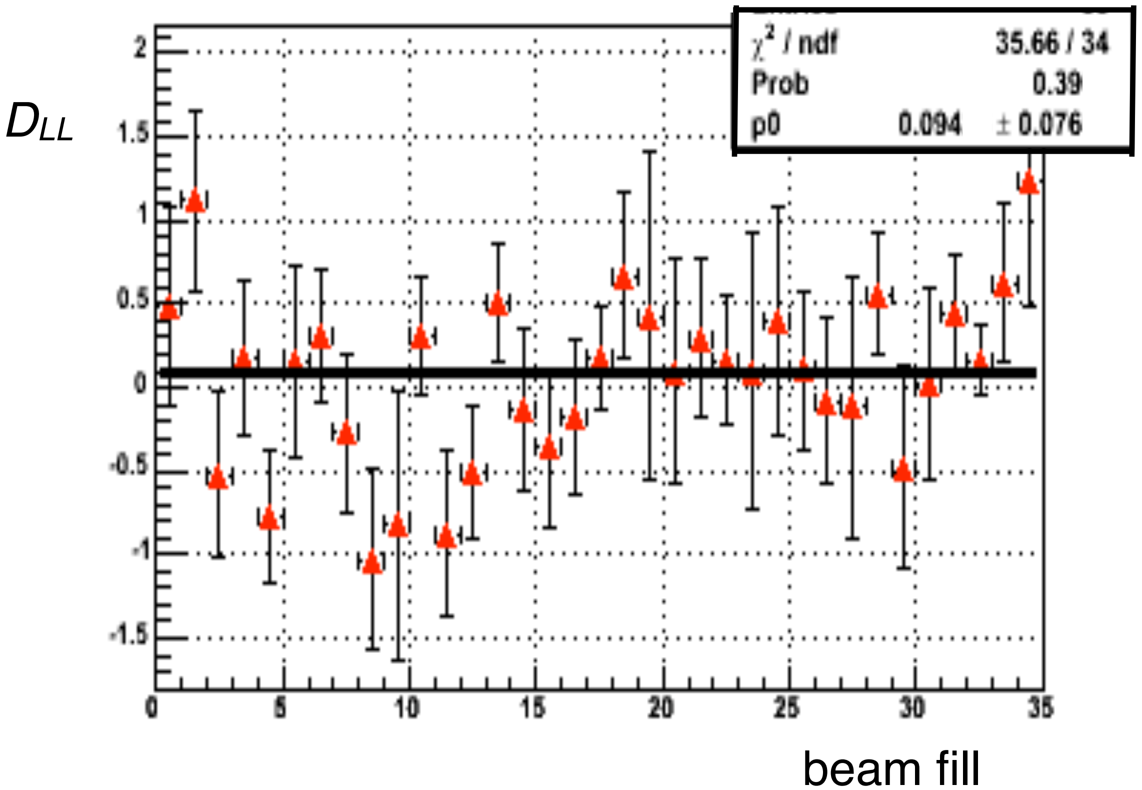
Use beam spin configurations and symmetries to (largely) cancel *A(cosθ*)* and extract,

$$D_{LL}^{\Lambda} = \frac{1}{\alpha \cdot P_b \cdot \langle \cos\theta^* \rangle} \cdot \frac{N_\Lambda^+ - N_\Lambda^-}{N_\Lambda^+ + N_\Lambda^-}$$

in small *cosθ** intervals. Here, $N_\Lambda^+ = N_\Lambda^{++} \cdot \frac{\mathcal{L}^{--}}{\mathcal{L}^{++}} + N_\Lambda^{+-} \cdot \frac{\mathcal{L}^{--}}{\mathcal{L}^{+-}}$ and $N_\Lambda^- = N_\Lambda^{-+} \cdot \frac{\mathcal{L}^{--}}{\mathcal{L}^{-+}} + N_\Lambda^{--}$

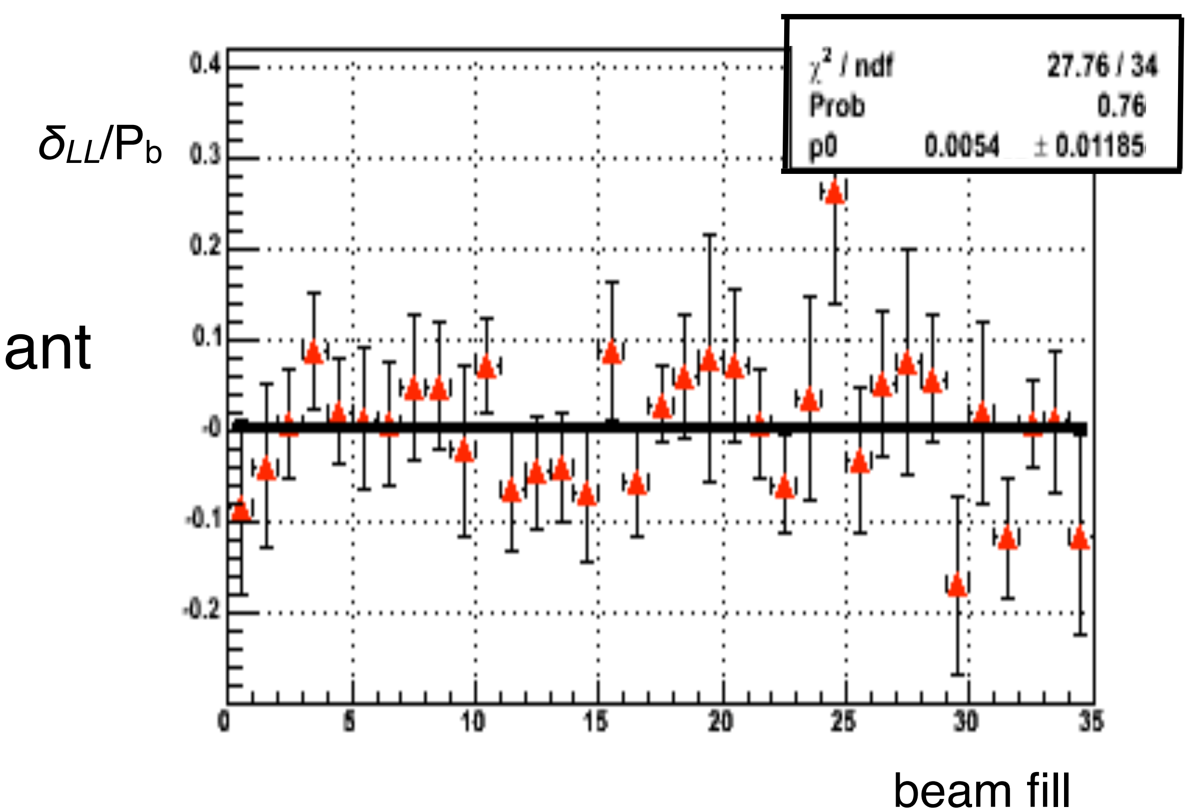
The luminosity ratios are measured at STAR and beam polarization in RHIC.

Analysis (continued)

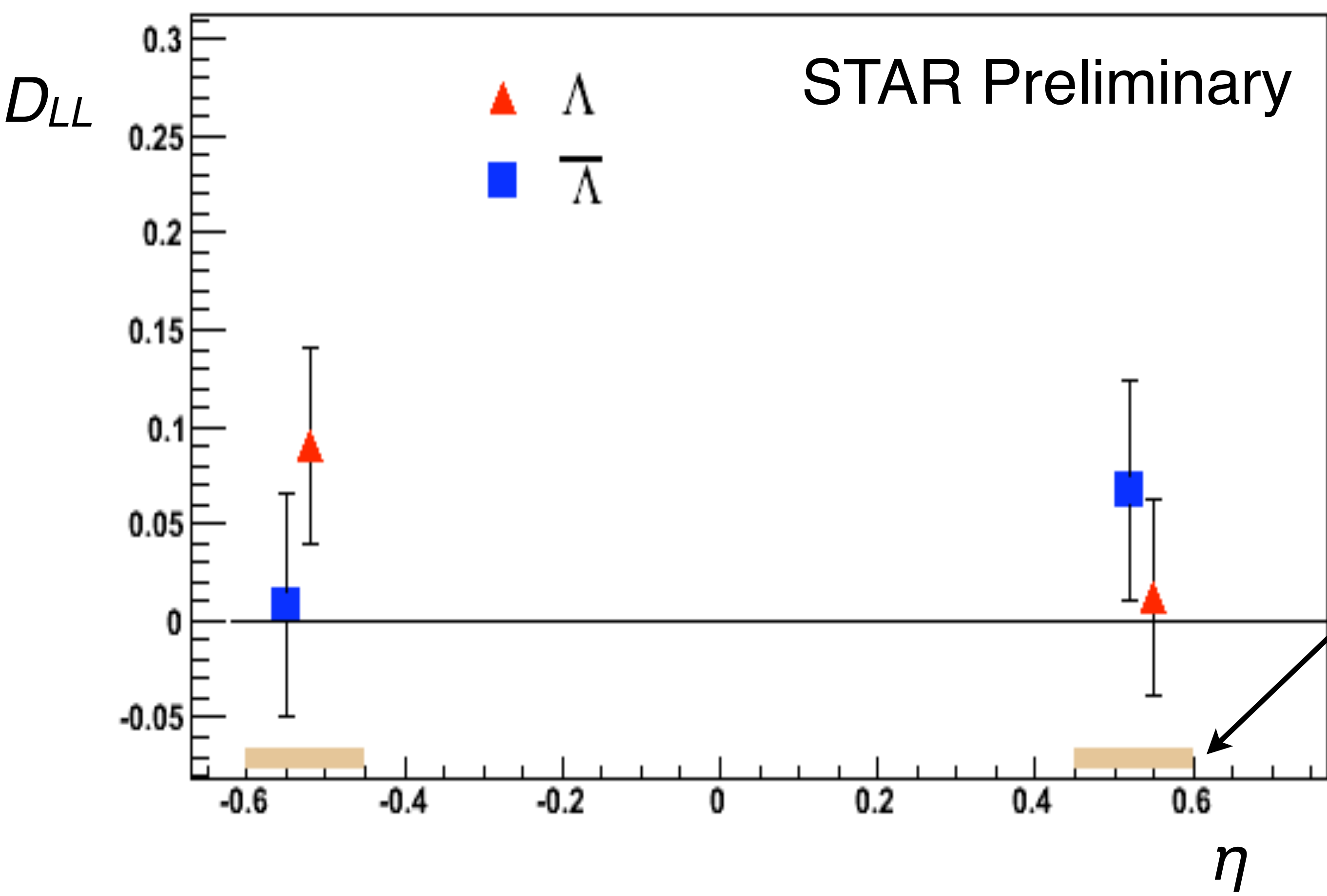


The extracted D_{LL} exhibits the expected statistical variation with time.

Control-measurement with the more abundant and spin-less K_S^0 shows no evidence for experiment systematics larger than ~0.01.



First Spin Transfer Results at RHIC



First D_{LL} from RHIC,

Statistics limited,

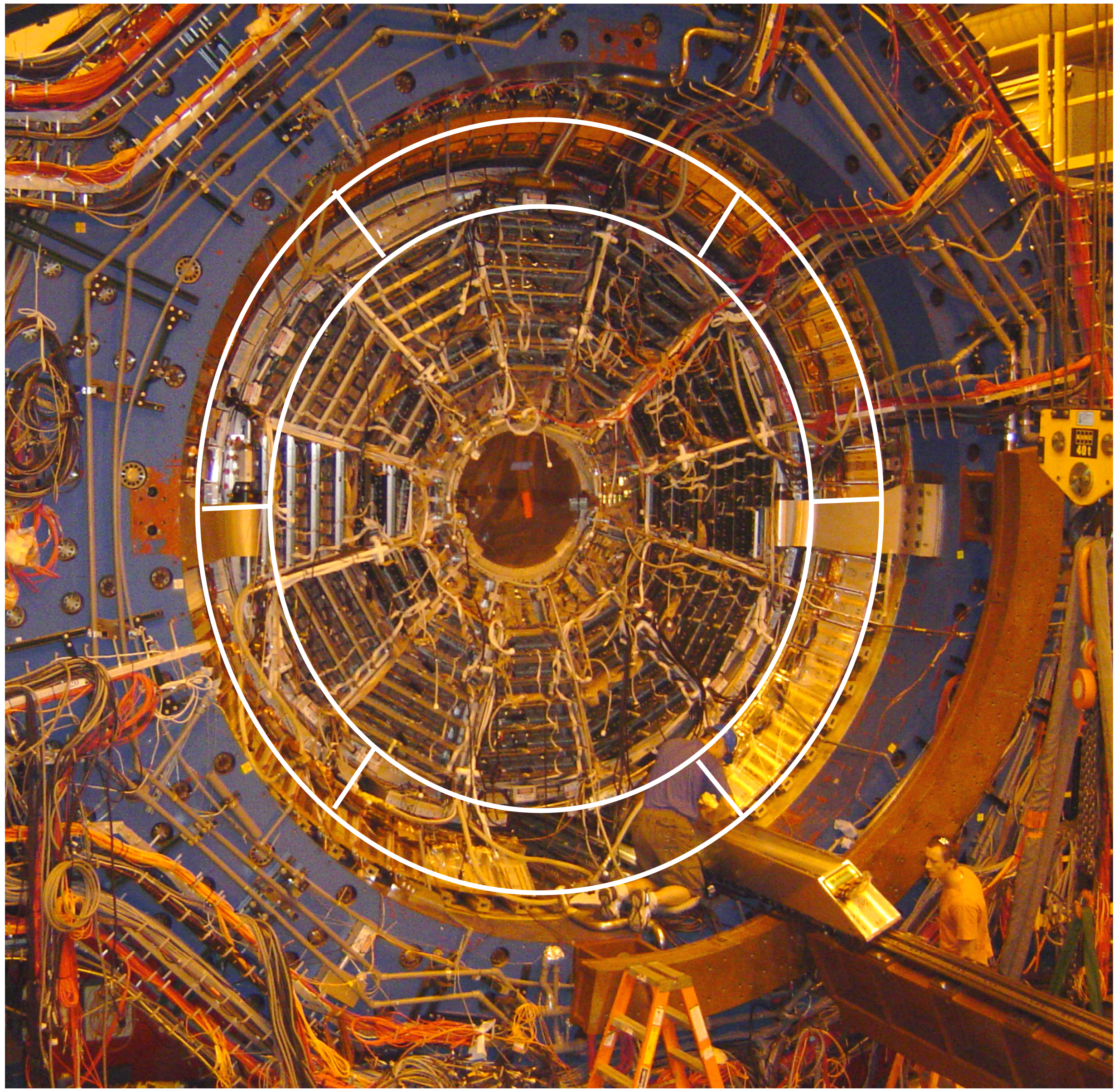
Systematics under control,

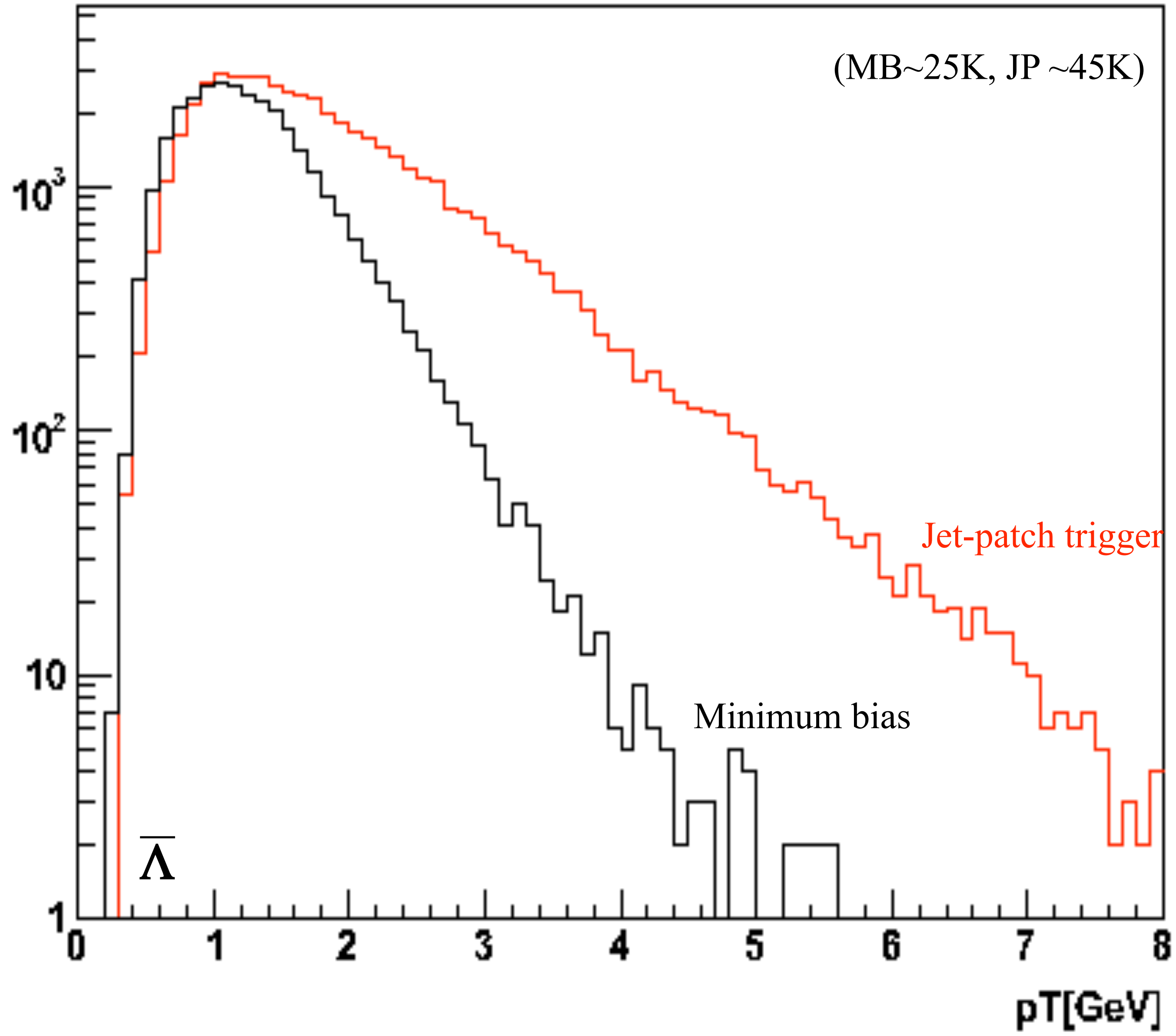
$\langle p_T \rangle \approx 1.3$ GeV/c, $\langle |x_F| \rangle \approx 0.008$

Need better precision and higher p_T

STAR Triggered Data - 2005

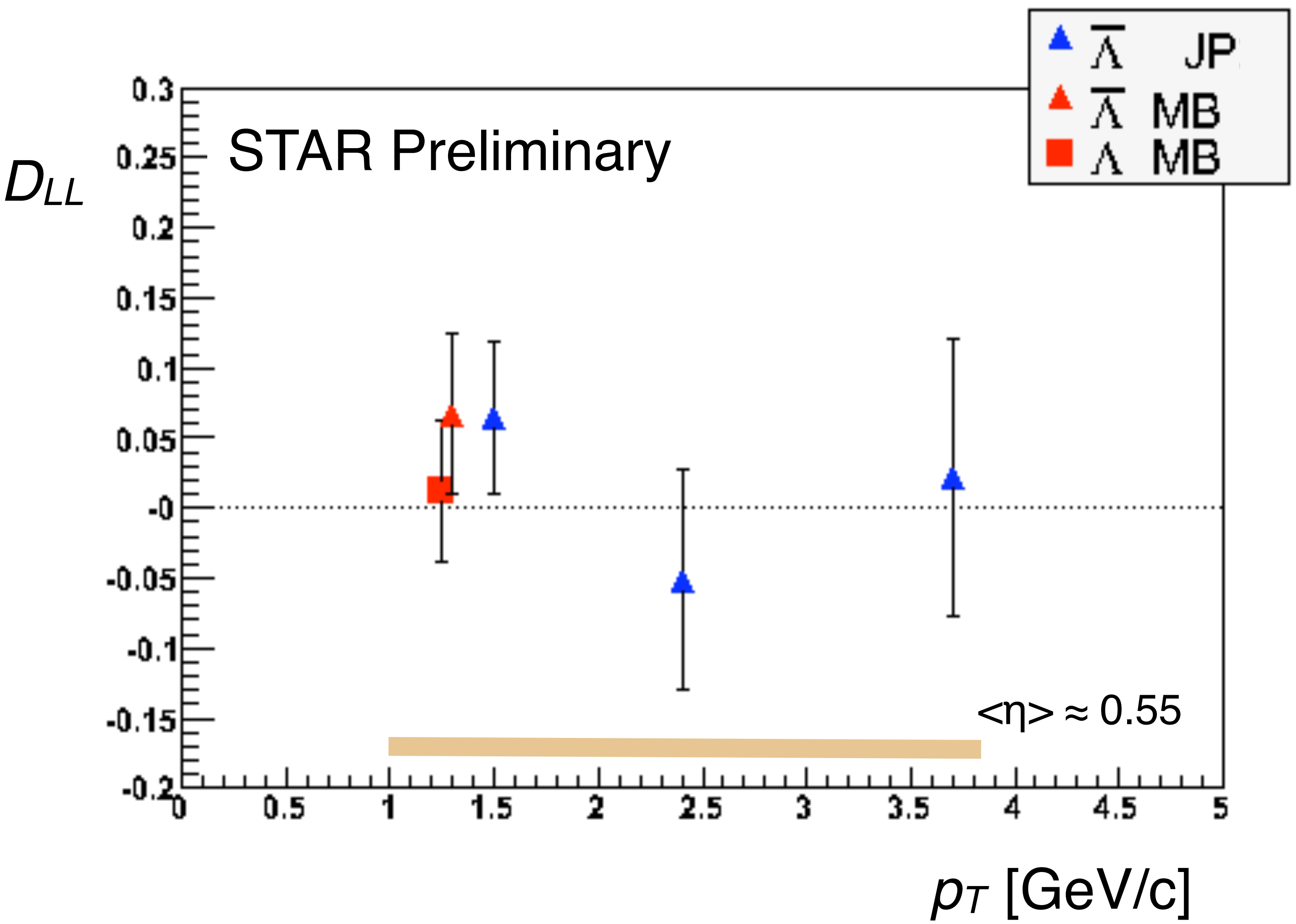
STAR was triggered on energy deposits in jet-patches of the Barrel E.M. Calorimeter,





Although this is <u>not</u> a “Hyperon Trigger”, it did record a (biased) sample of Λ and $\overline{\Lambda}$ candidates with considerably higher p_T; focus on $\overline{\Lambda}$ here.

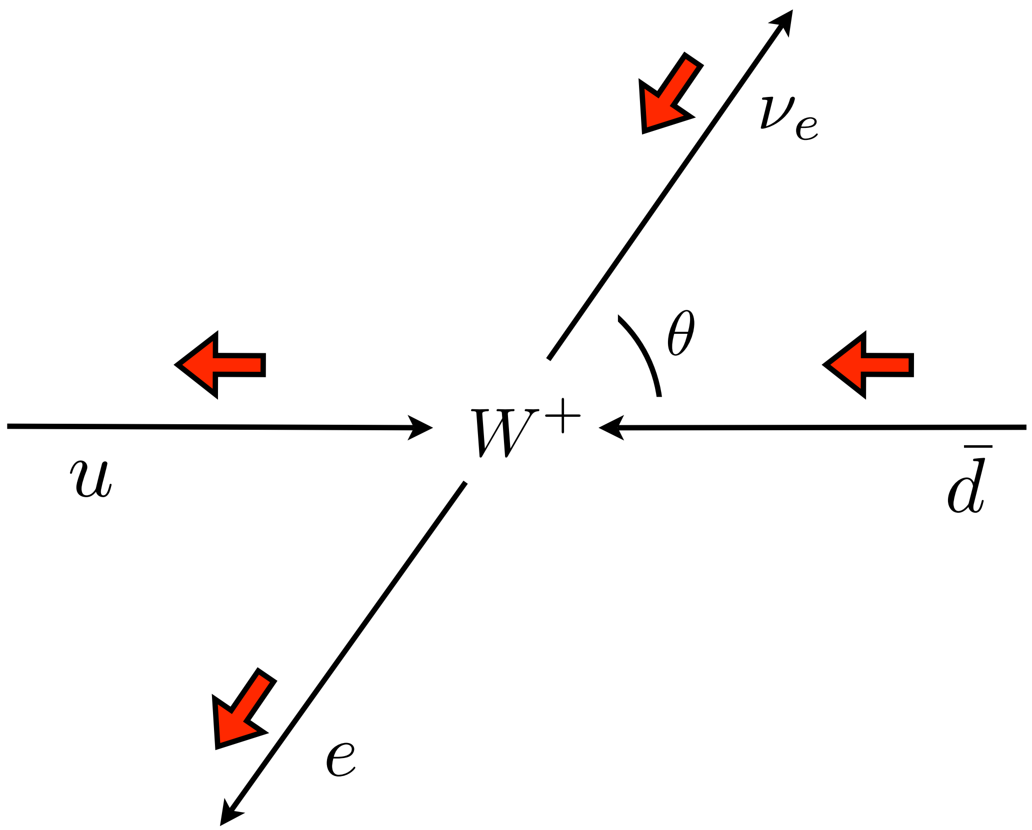
First Spin Transfer Results at RHIC



Systematic Uncertainty Estimates:

5% RHIC measurement of P_b,
2% residual transverse pol. at STAR,
2% decay parameter *α*,
< 0.01 relative luminosity measmnt,
< 4% event pile-up in TPC,
< 5% background,
<15% trigger bias (MC simulation).

RHIC - W-boson Polarimetry to access Quark Polarizations



Experiment Signature:
large p_T lepton, missing E_T

$$\Delta\sigma^{\text{Born}}(\vec{p}p \to W^+ \to e^+\nu_e) \propto -\Delta u(x_a)\bar{d}(x_b)(1+\cos\theta)^2 + \Delta\bar{d}(x_a)u(x_b)(1-\cos\theta)^2$$

Spin Measurements:

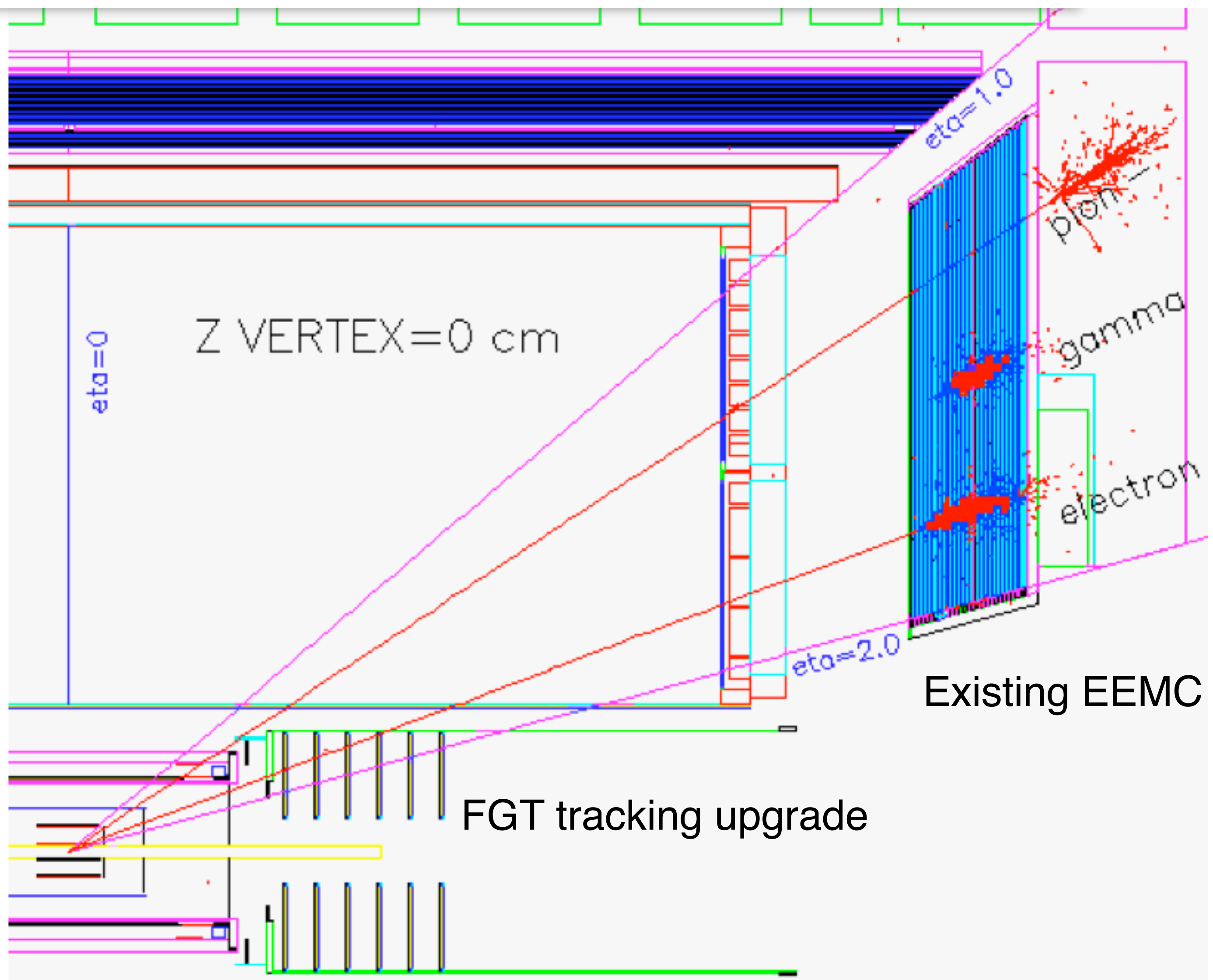
$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\dfrac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \to 1 \end{cases}$$

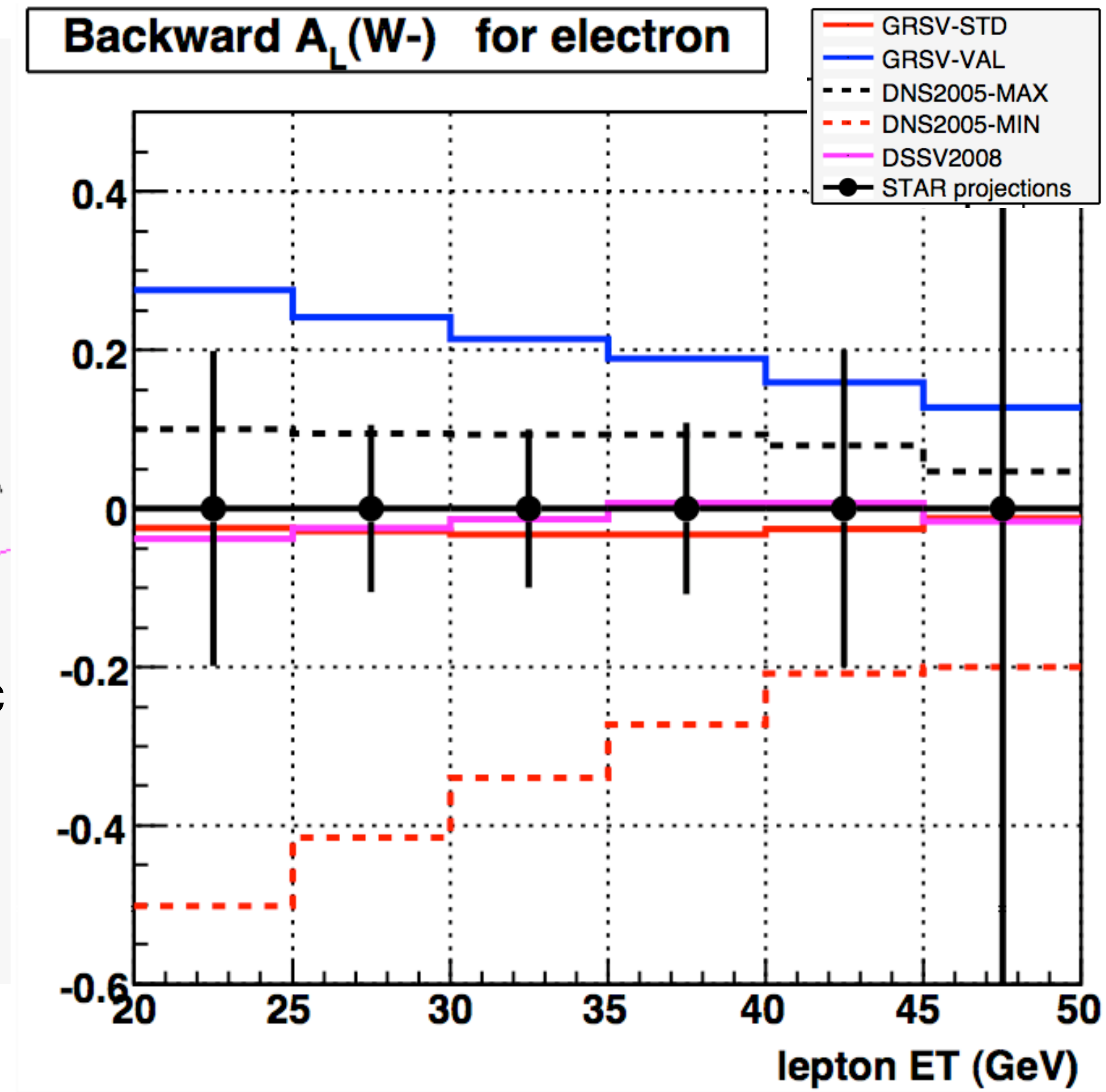
$$A_L(W^-) = \begin{cases} -\dfrac{\Delta d(x_a)}{d(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{u}(x_a)}{\bar{u}(x_a)}, & x_b \to 1 \end{cases}$$

Experiment Challenges:
- charge-ID at large |rapidity|
- electron/hadron discrimination
- luminosity hungry!

Talks by:
Balewski, CF00006
Page, HG00003

STAR - W-boson Polarimetry to access Quark Polarizations





Talks by:
Balewski,CF00006
Page, HG00003

300pb-1, 70% pol., includes expected det. resp. and bg.

Illustrates sensitivity to $\Delta\bar{u}$

Concluding Remarks

- RHIC-spin is fully online,
- Cross sections for jets and other “workhorse” probes are well reproduced in NLO-pQCD over many orders of magnitude,
- Initial longitudinal spin results with 0.01 pb^{-1} FoM disfavor maximal ΔG,
- Data from up to ~5 pb^{-1} FoM have been analyzed,
  - result in greatly improved precision and p_T coverage,
  - enable a *start* with more selective, but less abundant, probes and processes,

    e.g. Λ-D_{LL} - sensitive to Δs and polarized fragmentation at ~10^{-2} level,
    STAR has performed a proof-of-principle measurement;
    find consistency with DIS-based expectations, but
    the data do not (yet) discriminate between quark polarization scenarios,
  - are still not sufficient to resolve the kinematic dependence $\Delta G(x)$ via 2-jet events,

  } *next talks in this session*
- Clear need for ~50 pb-1 FoM - STAR beam-use-request for upcoming beam-period,
- Eagerly anticipate also 500 GeV center-of-mass energy.