Extracting the Gluon Piece of the Spin Puzzle

New Inclusive Jet Results From STAR

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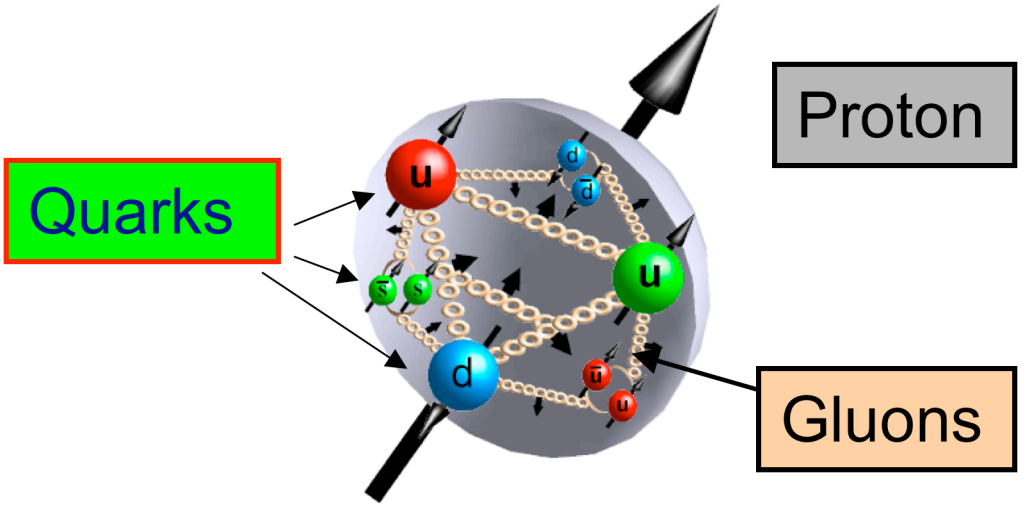
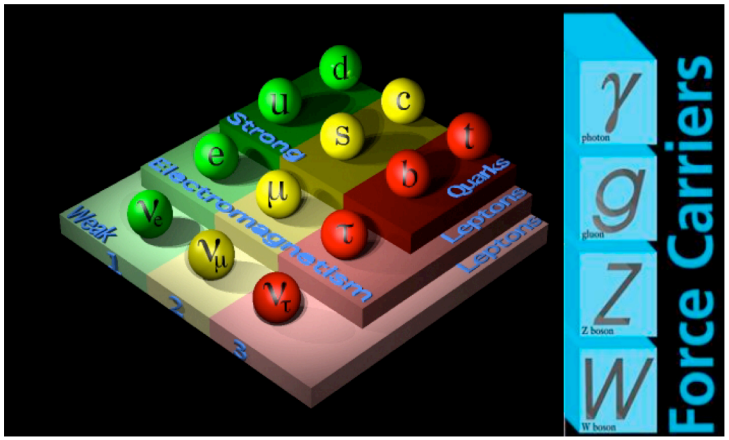
BROOKHAVEN NATIONAL LABORATORY

Quick Historical Review of the Spin Puzzle



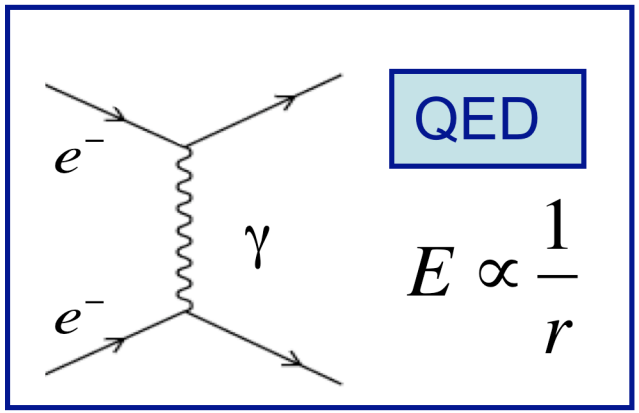
STAR Contributions to the Spin Puzzle

The Spin Puzzle → Key Question in **Standard Model QCD**

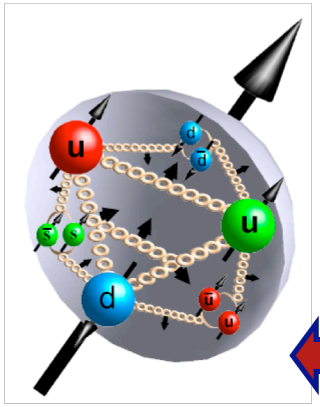


spin 1/2 spin 1

99.9% of mass of the visible universe composed of quarks and gluons - the building blocks of the nucleon

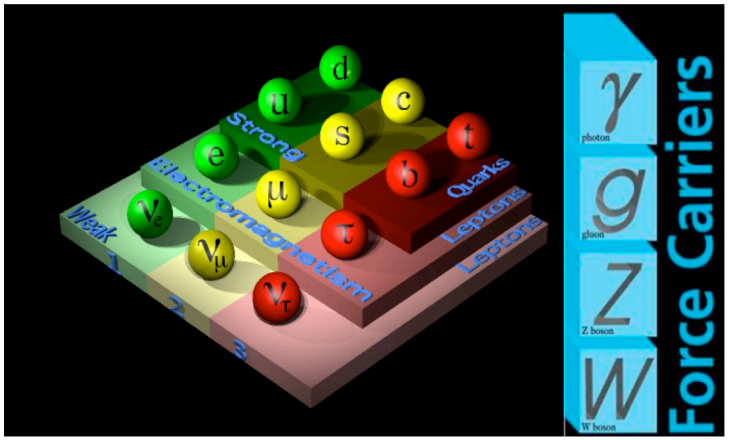


How do partonic degrees of freedom - mass, charge, color, **SPIN** - manifest as the nucleon degrees of freedom?



No access to free partons due to confinement! The proton is a stable and abundant source of partons

The Spin Puzzle → Key Question in **Standard Model QCD**



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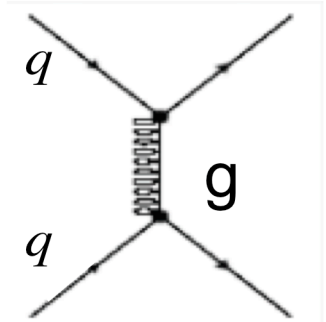
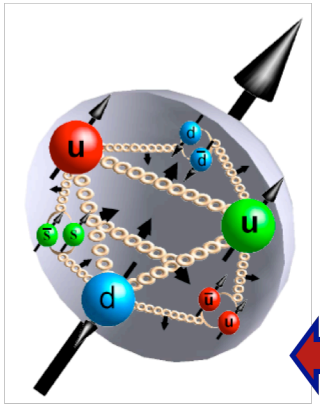


QCD

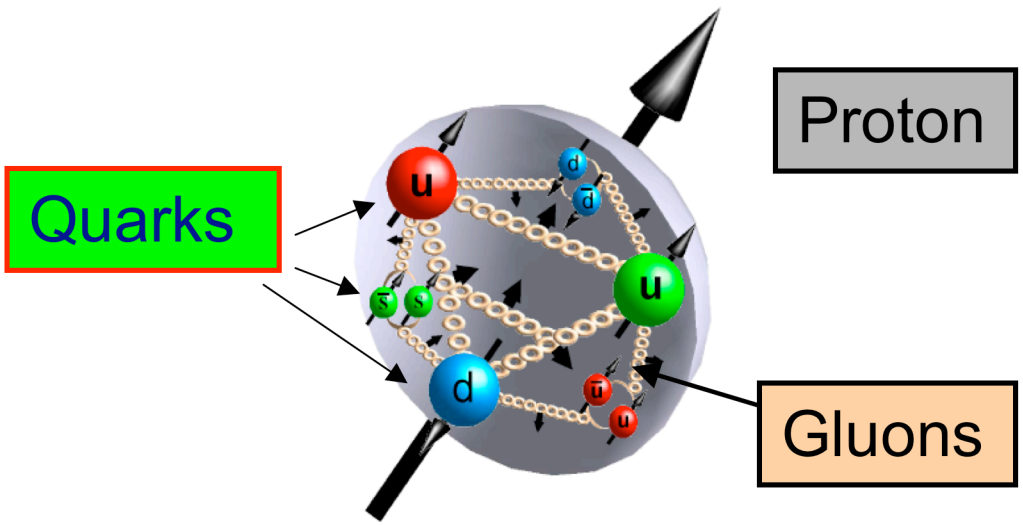
$E \propto r$

How do partonic degrees of freedom - mass, charge, color, **SPIN** - manifest as the nucleon degrees of freedom?



No access to free partons due to confinement! The proton is a stable and abundant source of partons

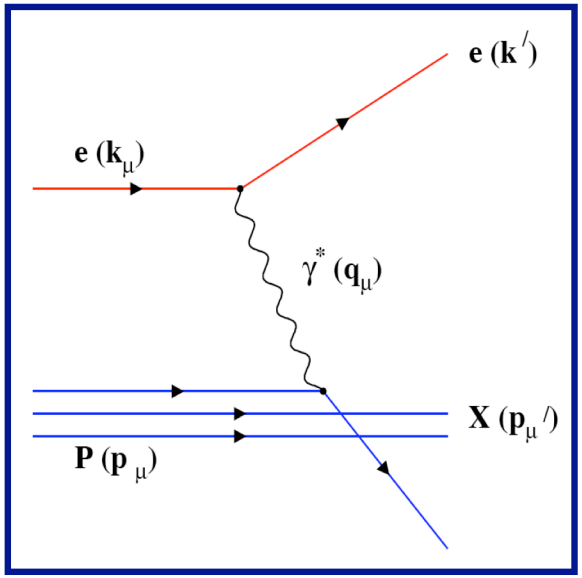
Color Confinement forbids the isolation of free quarks and gluons. The stable and abundant **Proton** is an excellent "partonic laboratory"



The Proton is "**bag**" of 3 spin 1/2 quarks which are constantly interacting via spin 1 gluons. Gluons also interact with each other and produce quark + anti-quark pairs which make up the "**sea**".

Question: How do the quarks and gluons combine to form the quantum numbers of the hadrons which form **99%** of the visible universe?

Deep Inelastic Scattering



λ = Resolution

Increased E_γ means increased resolution

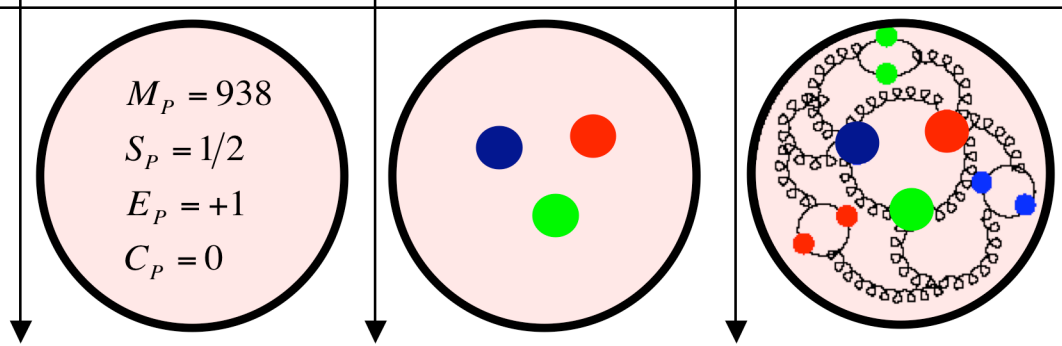
$$E_\gamma = \frac{hc}{\lambda}$$

Δt = lifetime

Increased E_γ means shorter interaction time

$$\Delta E_\gamma \Delta t \propto \frac{h}{2}$$

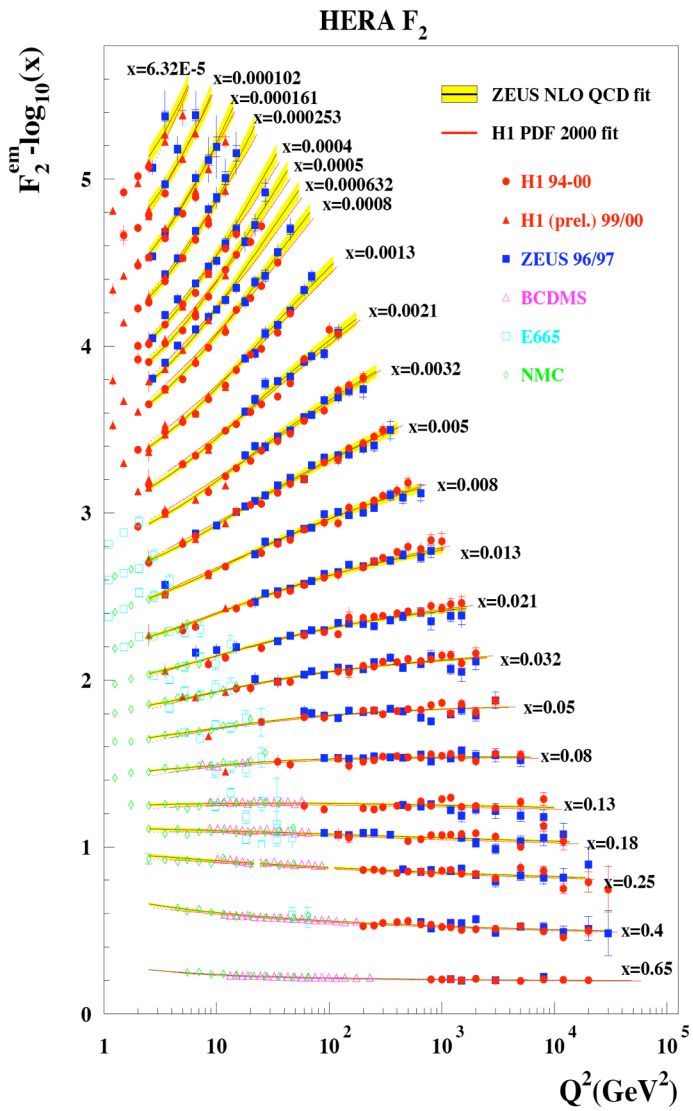
λ (fm)	1	0.2	0.05
Q^2 (GeV^2)	0.04	1	10



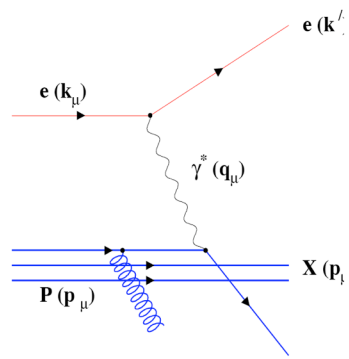
$$Q^2 = 2 m_P x_B E_\gamma$$

$$x_B = \frac{P_{parton}}{P_{proton}}$$

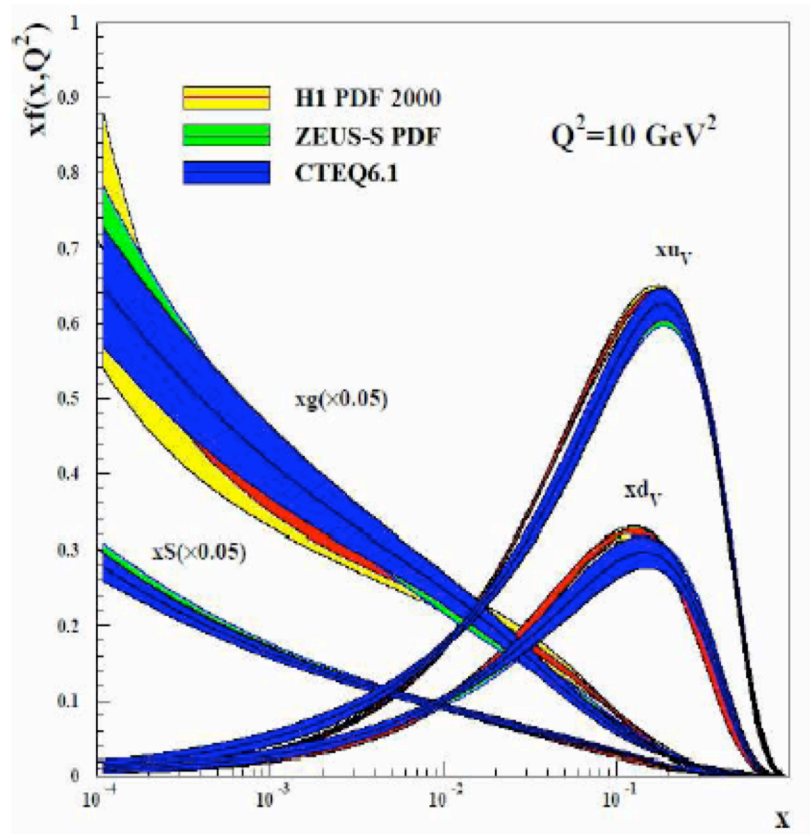
Momentum Parton Distribution Functions



Strong violation of scaling at low x and high Q^2



Contrary to: Low Q^2 high x!

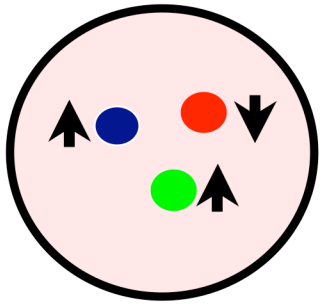


Note: g(x) scaled by 0.05!

Initial Predictions for Polarized PDF's:

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

Constituent Quark Model

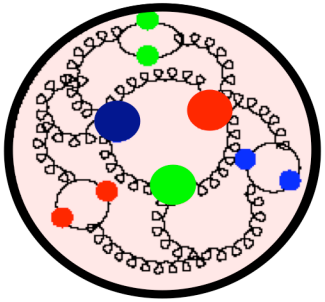


i. No gluon d.o.f
ii. $M_{quark} = 1/3\ M_{proton}$
iii. Assume S-state
iv. Relativistic Effect ~ 75%

$$\sum S_Z^{quarks} = \frac{1}{2}$$

100 % from quarks

Quark Parton Model

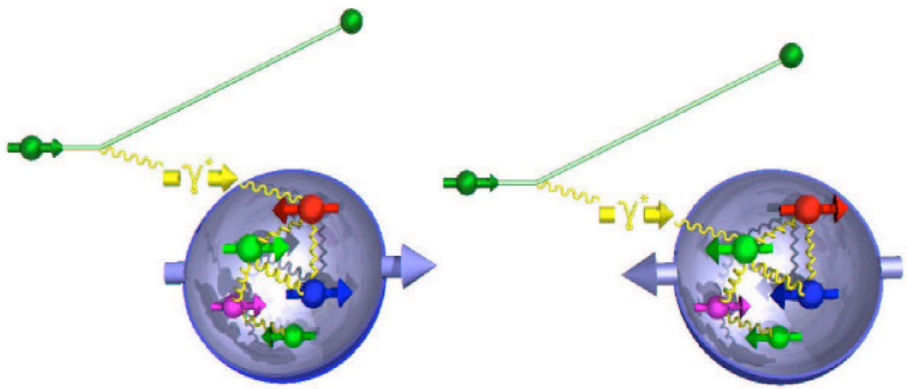


i. Allows massless gluons
ii. M_{quark} ~ 10's MeV
iii. Assume no strange sea constribution

$$\sum S_Z^{quarks} = 0.58 \bullet \frac{1}{2}$$

~60 % from quarks

Recipe for Measuring Quark Spins in Polarized DIS

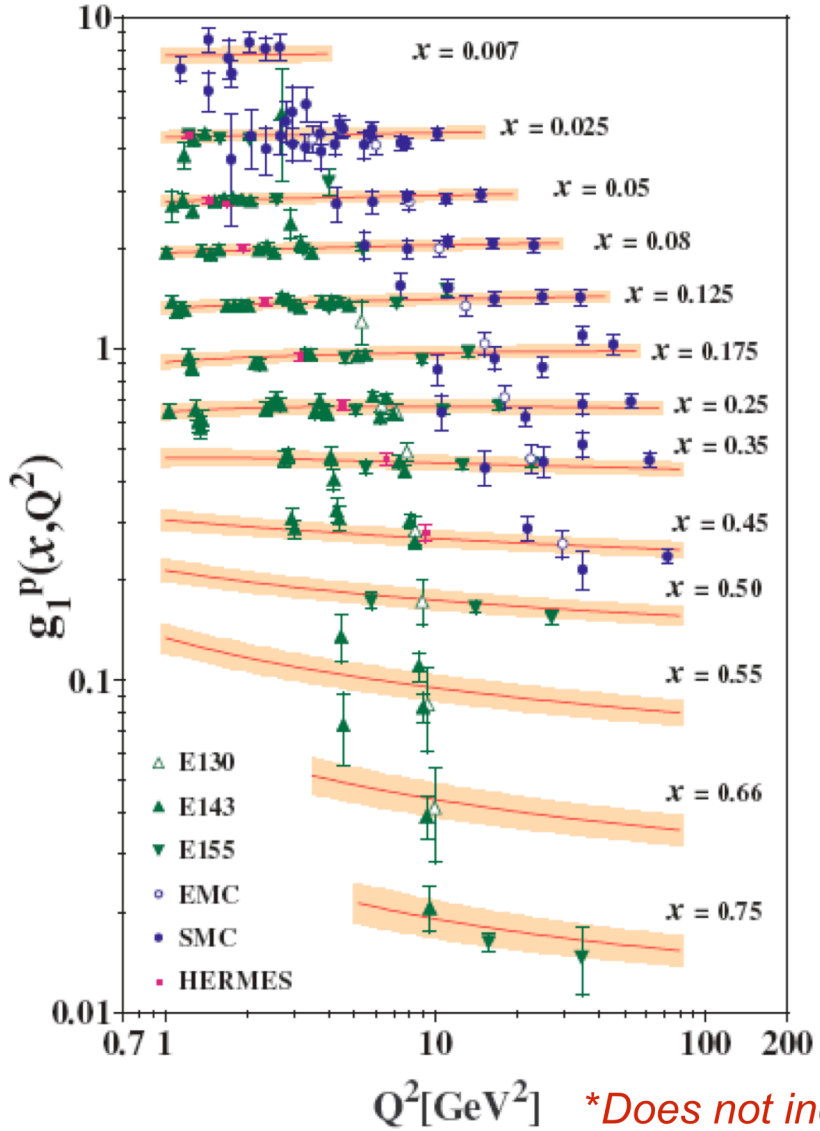


1. Take one lepton beam with it's spin aligned with it's momentum
2. Scatter from proton target whose spin is (anti)aligned with the lepton spin
3. Count # scattered leptons with spin (anti) aligned with target

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

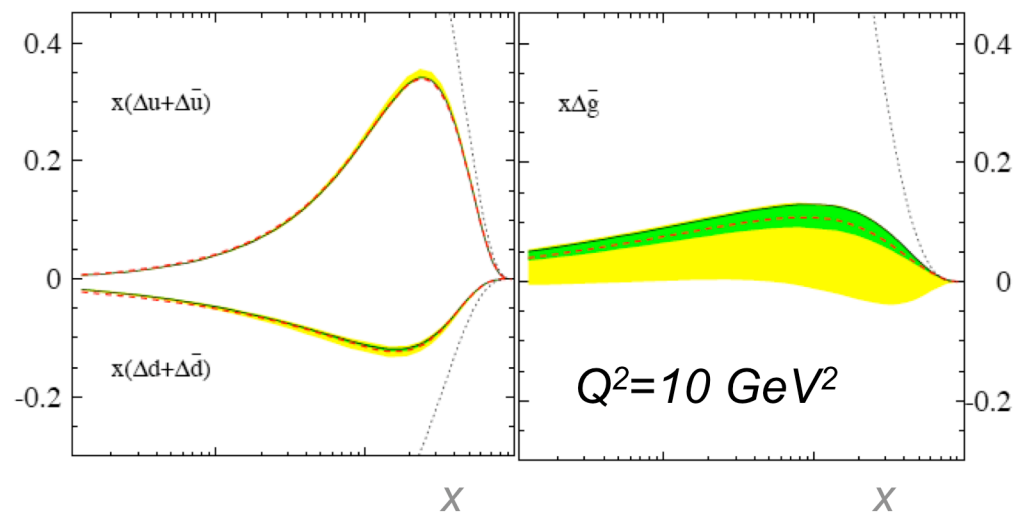
$$A_{LL} \propto g_1(x) \rightarrow \langle S_q \rangle = \frac{1}{2}(\Delta u + \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s})$$

30 Years of Polarized DIS Experiments Yield…



Quark Spin ~20-30% of proton!

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

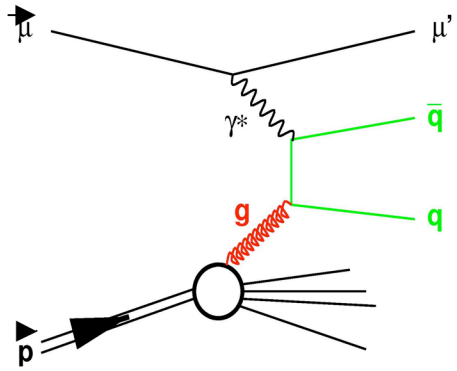


Unlike unpolarized case, reduced CM Energy, allows **limited** constraint on Δg

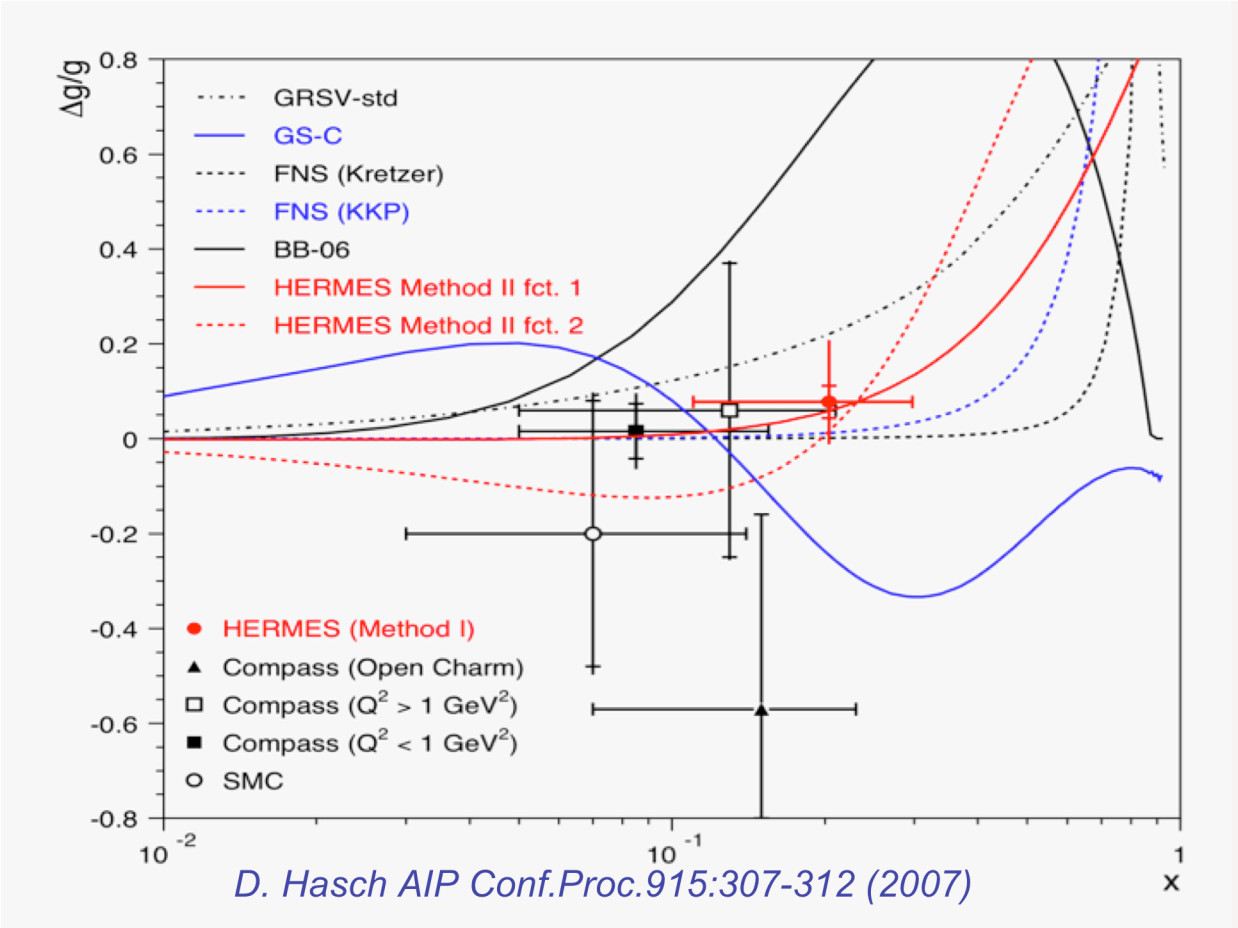
**Does not include most recent 2007 Hermes/SMC g_1 results*

Dedicated DIS ΔG Measurements

…from SPIN 2006



- PGF is access to ΔG in DIS
- Jet Proxy - high pT pairs
- Golden channel is Open Charm

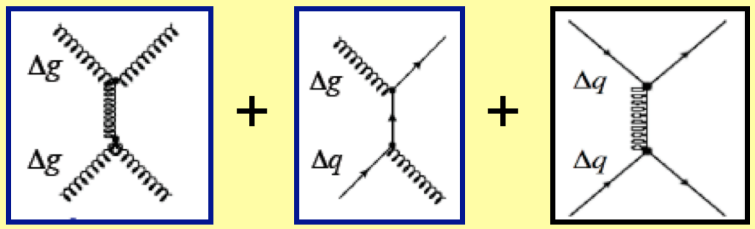


D. Hasch AIP Conf.Proc.915:307-312 (2007)

Disfavors maximal scenario but cannot determine sign

Accessing ΔG at STAR

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



$pp \to \pi^{+/-} + X$
$pp \to \pi^{0} + X$

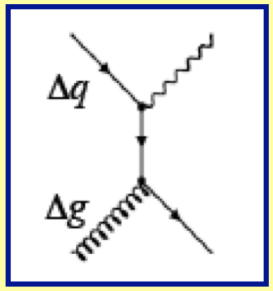
Requires D_{AB}^{π} for partonic kinematics

$pp \to jet + X$

No FF! Average over partonic kinematics

$pp \to jet + jet$

No FF! Reconstruct partonic kinematics. Statistically limited until 2006.

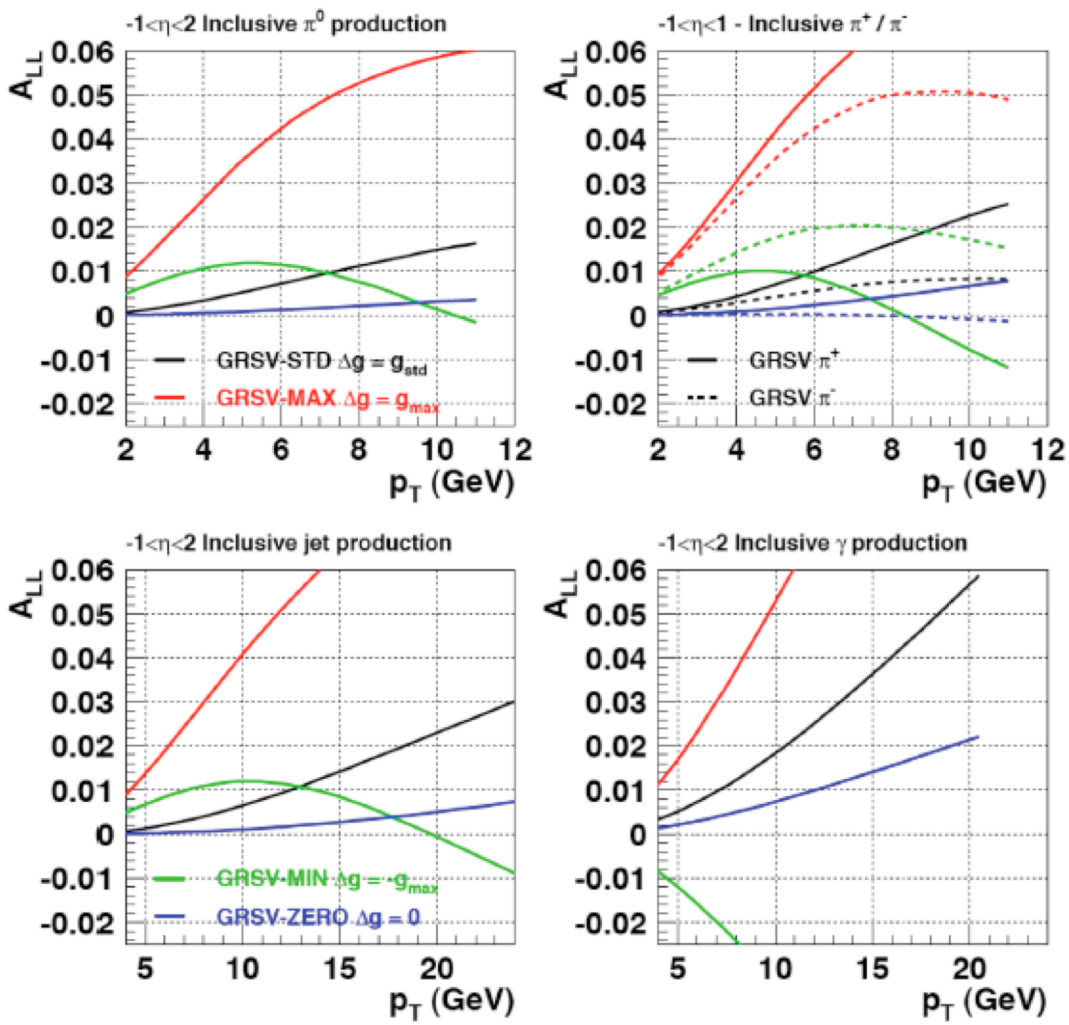


$pp \to jet + \gamma$

$pp \to \gamma + X$

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

Observable Sensitivity to ΔG

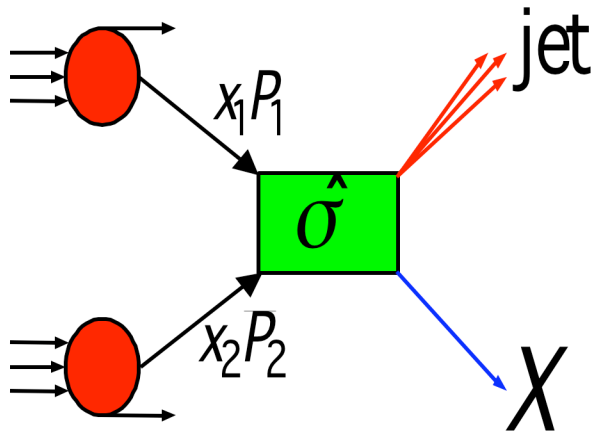


- Max Sensitivity in Inclusive γ but Xsec suppressed
- Inclusive Jets provide sensitivity in high pT region where curves diverge
- Pions are less sensitive due to limited pT reach
- For qg processess, ALL(p+) - ALL(p-) tracks **sign** of ΔG
- <x> range = 0.01-0.1 over measured pT range for jets and hadrons

STAR Analysis Plan

I. Cross-sections

- Establish validity of Next to Leading Order perturbative QCD for RHIC kinematics.
- Test understanding of detector, measured observable and quality of simulations

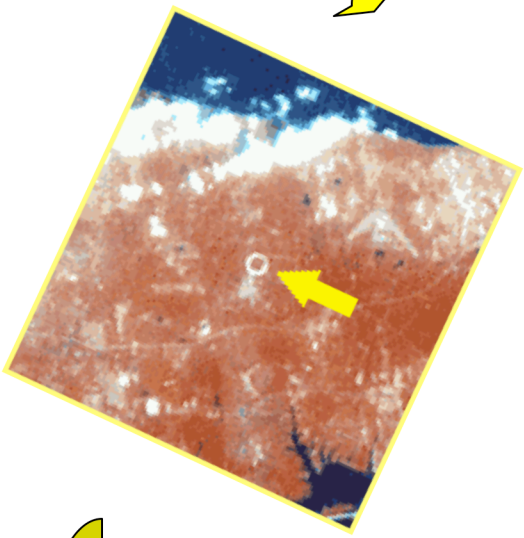


II. Asymmetries

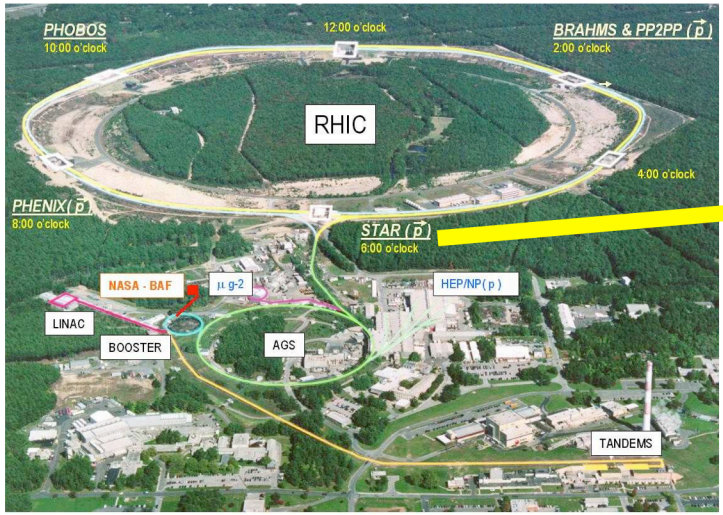
- Provide access to polarized parton distributions

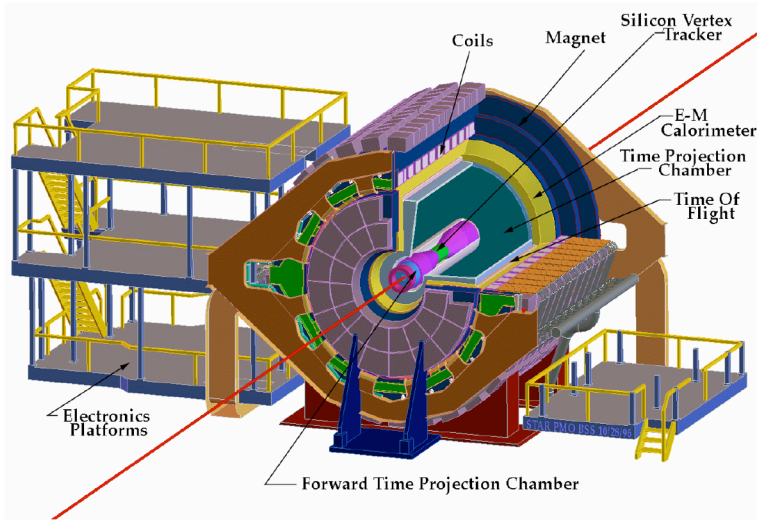
$$A_{LL} = \frac{1}{P_Y P_B} \frac{N^{parallel} - R \cdot N^{antiparallel}}{N^{parallel} + R \cdot N^{antiparallel}}$$

N: Spin Yields
P: Beam Pol.
R: Relative Lumi.



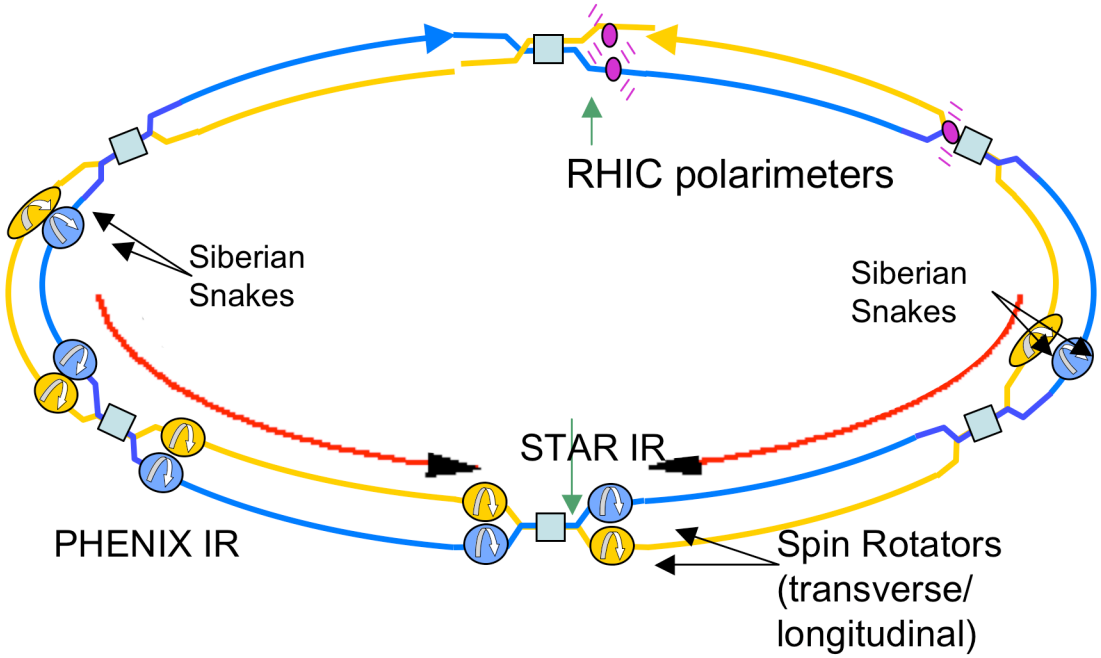
The Experiment





Relativistic Heavy Ion Collider

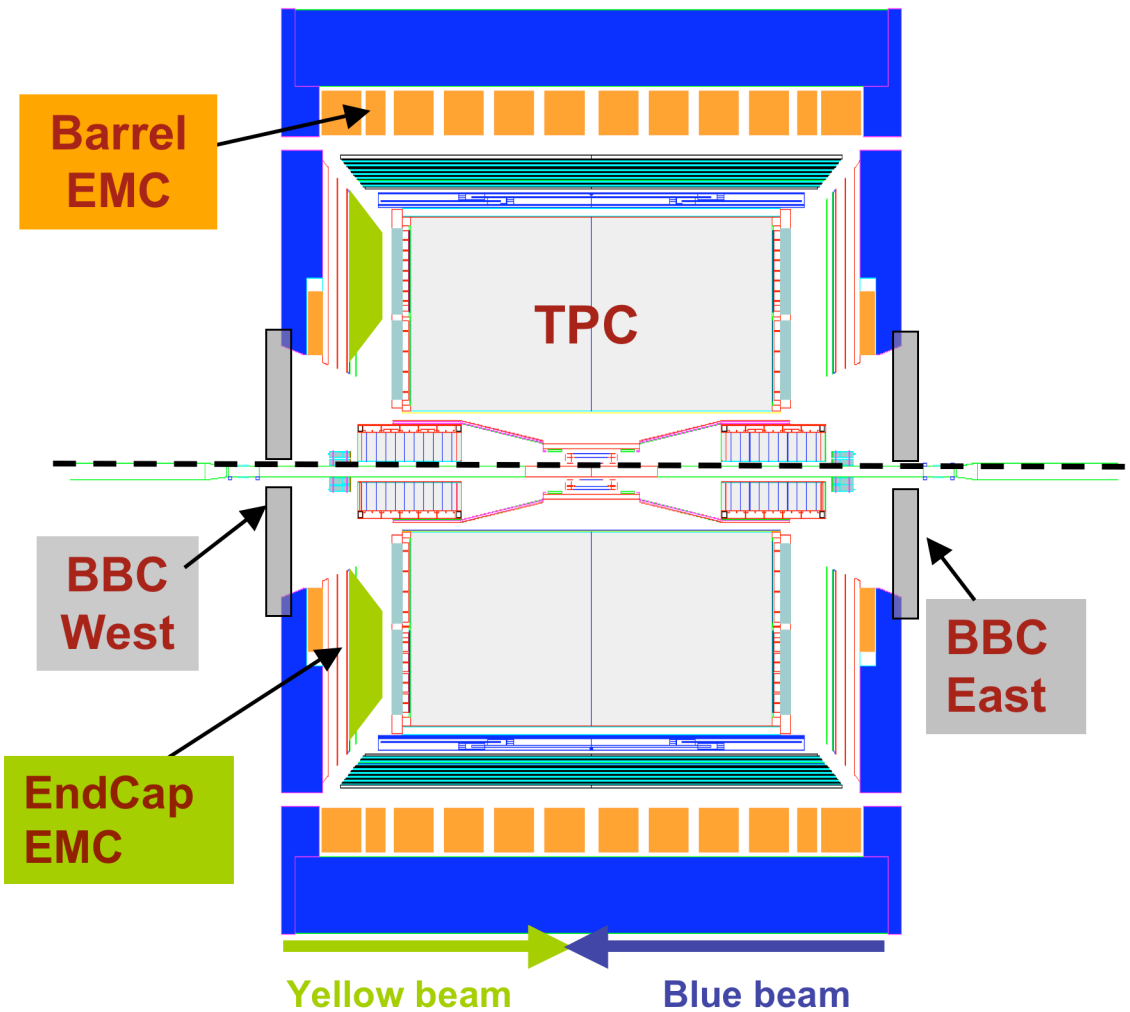
…worlds 1st *pp* Collider



- 100 GeV beam proton beams
- Each bunch filled with a distinct polarization state
- Spin Rotators at STAR IR allow for transverse and longitudinal spin orientation
- Bunch Xings every 100-200ns
- CNI polarimeters + Hydrogen Jet target provide run by run & absolute polarization

pp Run Year	2002	2003	2004	2005	2006
< Polarization> %	15	30	40-45	45-50	60
L_{max} [10^{30} $s^{-1}cm^{-2}$]	2	6	6	16	30
L_{int} [pb^{-1}] at STAR (L/T)	0 / 0.3	0.3 / 0.25	0.4 / 0	3.1 / 0.1	8.5 / 10.2

Detector components used in jet reconstruction



TPC $\lvert\eta\rvert<1.4$	Charged particle momentum
BEMC $\lvert\eta\rvert<1.0$	Neutral Energy High pT Trigger
EEMC $1<\eta<2$	Neutral Energy High pT Trigger
BBC $3.4<\eta<5$	MinBias Trigger Relative Lumi

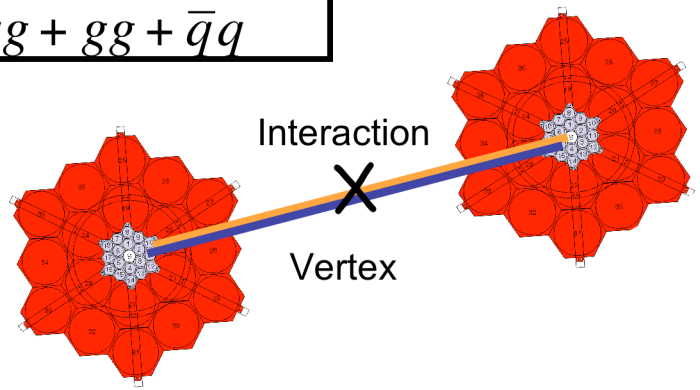
$\eta = -\ln[\tan(\Theta/2)]$

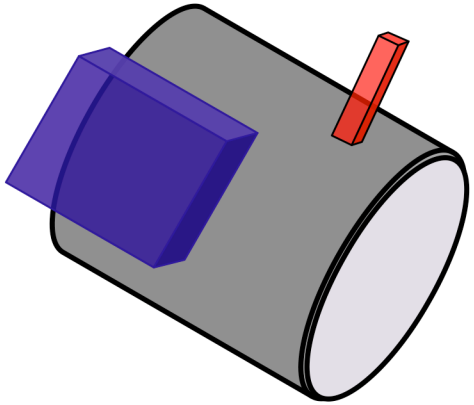
STAR Trigger

Composition of $\bar{p}p$ Events

Mother Nature	Elastic, single+doubly diffractive, hard scattering $\rightarrow qq + qg + gg + \bar{q}q$

Minimum Bias	Requires in-time hit in ExW Very little change in hard scattering process mix

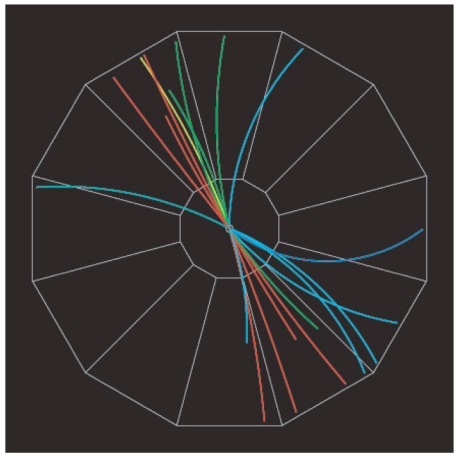




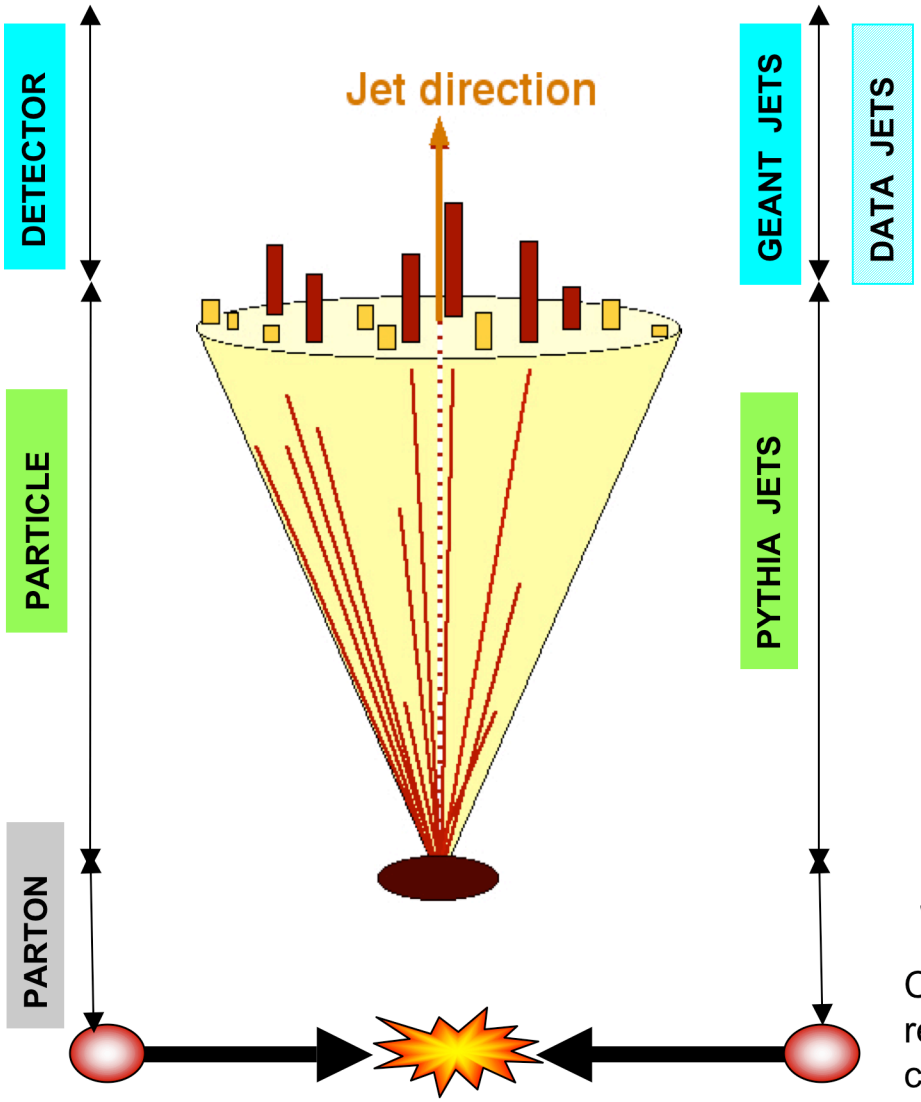
High Tower	1 tower $(\Delta\eta = \Delta\phi = 0.05)$ above threshold Requires hard neutral fragmentation
Jet Patch (2005/6 only)	400 localized towers $(\Delta\eta = \Delta\phi = 1)$ above threshold. Allows for cluster of softer fragmentation

The study of how the calorimeter triggers change the sub-process fraction is major contribution to the systematic error

STAR Inclusive Jet Analysis



STAR Jet Algorithm



Midpoint Cone Algorithm (hep-ex/0005012)

- Collinear and infrared safe -

i. P^{μ} of TPC track, EMC tower OR particle used as seed for cluster formation

ii. Cluster P^{μ} around seed inside Jet Cone Radius = 0.4 (2003-2005) or 0.7 (2006)

iii. Look for additional stable clusters at "midpoint" between two clusters

iv. Merge jets if Energy overlap > 50%

v. Sum of P^{μ} in each stable cluster forms jet

vi. Require Jet pT > 5 GeV

vii. Same algorithm used for DATA, GEANT and PYTHIA jets

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

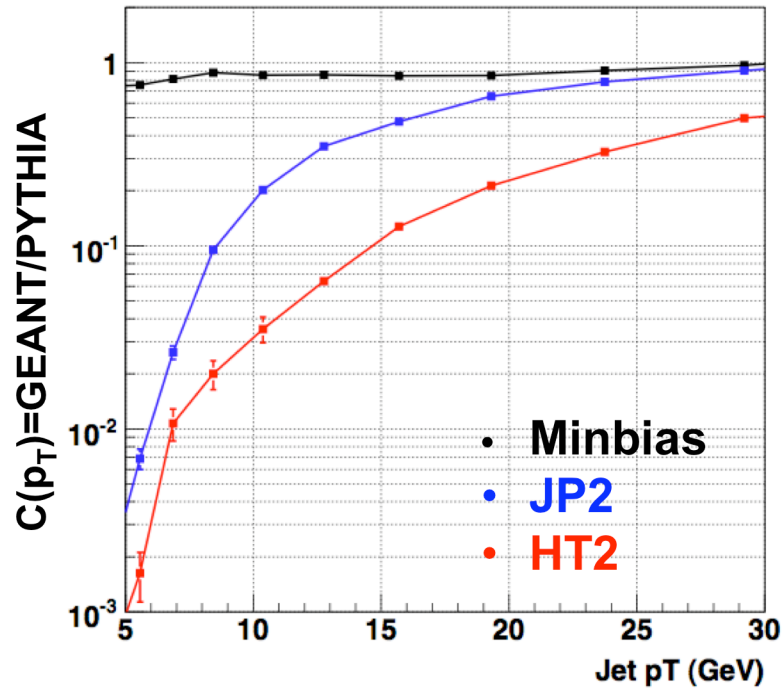
Correction factor incorporates detector resolution, and energy losses due to fiducial cuts and undetected neutral energy

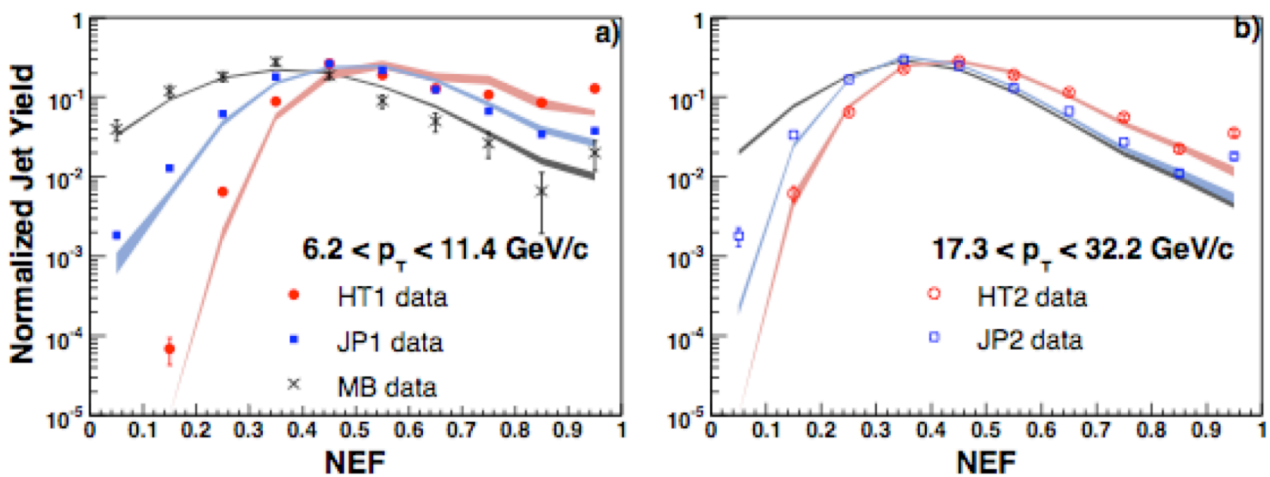
Inclusive Jet Cross-Section Analysis

Use Simulation (MC) to provide correction to RAW jet yield

- trigger and jet inefficiencies
- jet resolution & bin migration
- undetected particles (n + ν)
- PYTHIA 6.205 CDF Tune A
- GEANT (Geisha)

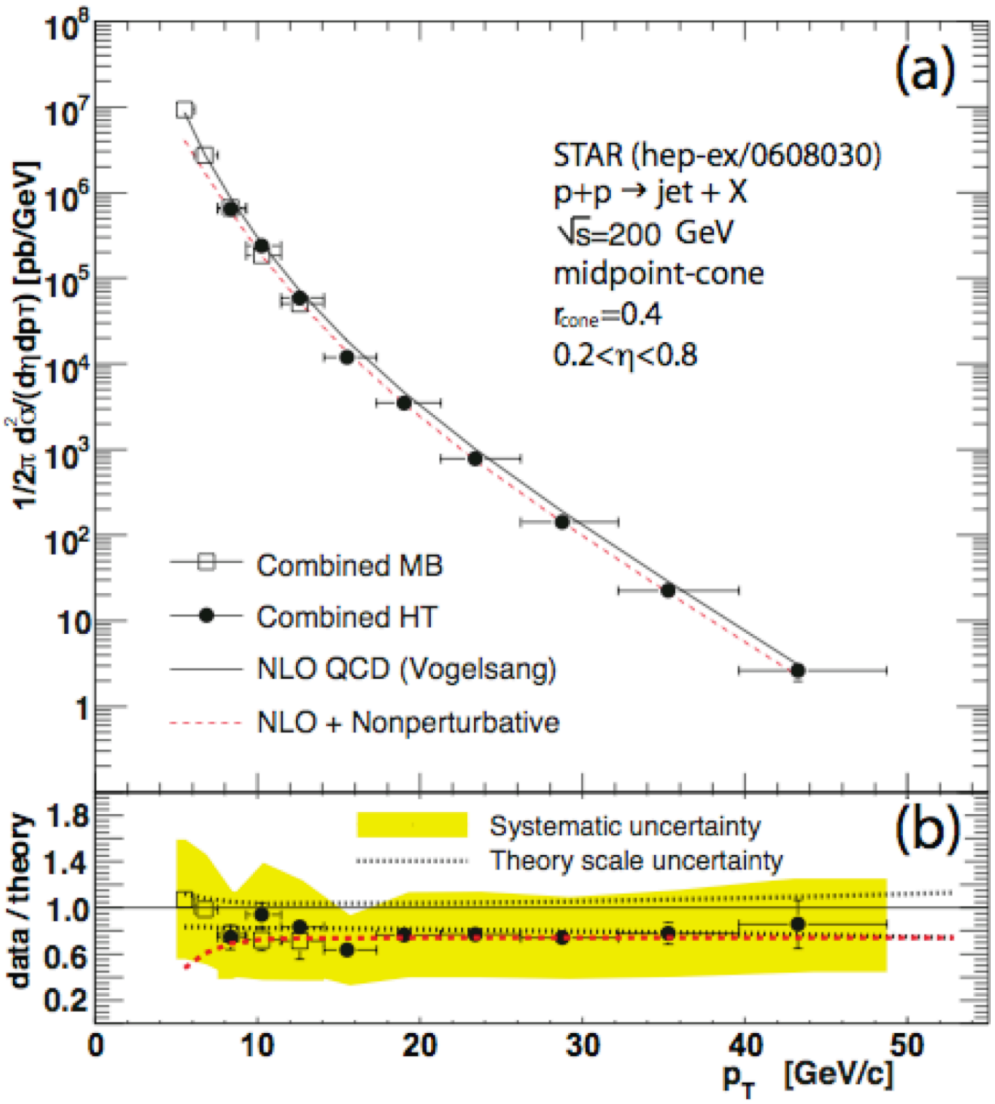
Verification of DATA/MC agreement essential





The shape of the Fraction of Neutral Energy in the Jet (EMF) is sensitive to the trigger bias as well as contributions from beam background.

2003/2004 Inclusive Jet Cross-Section Results



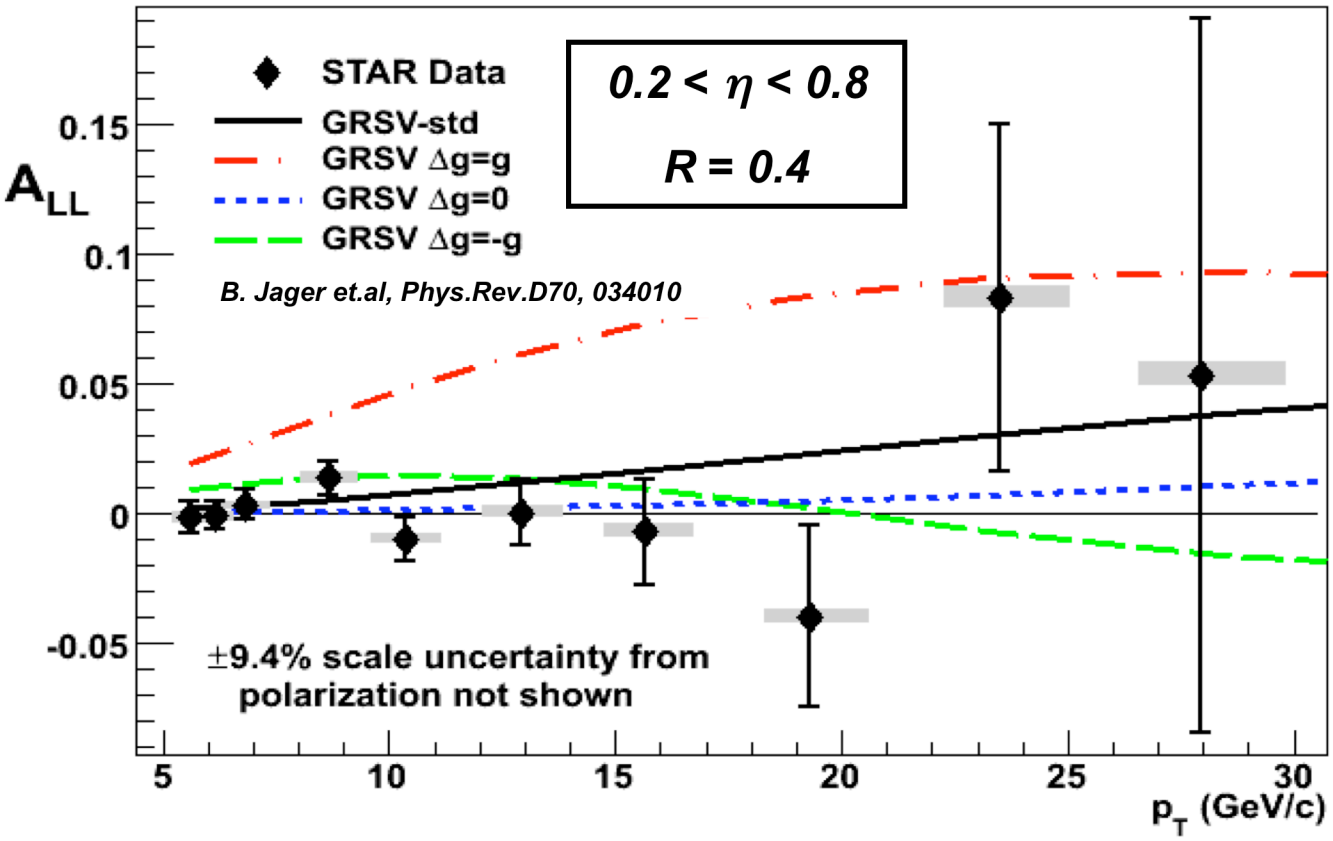
$$\frac{1}{2\pi}\frac{d^2\sigma}{d\eta dp_T} = \frac{1}{2\pi}\cdot\frac{N_{Jets}}{\Delta\eta\Delta p_T}\cdot\frac{1}{\int Ldt}\cdot\frac{1}{c(p_T)}$$

- 3 point overlap between HT and MINB show good agreement.
- 50% systematic shown in yellow band comes from uncertainty in jet energy scale. Need π^0 or gamma-jet to reduce this error.
- Application of hadronization correction removes systematic offset from NLO and data
- **Agreement -within-systematics over 7 orders of magnitude!**

2005 Inclusive Jet A_{LL}

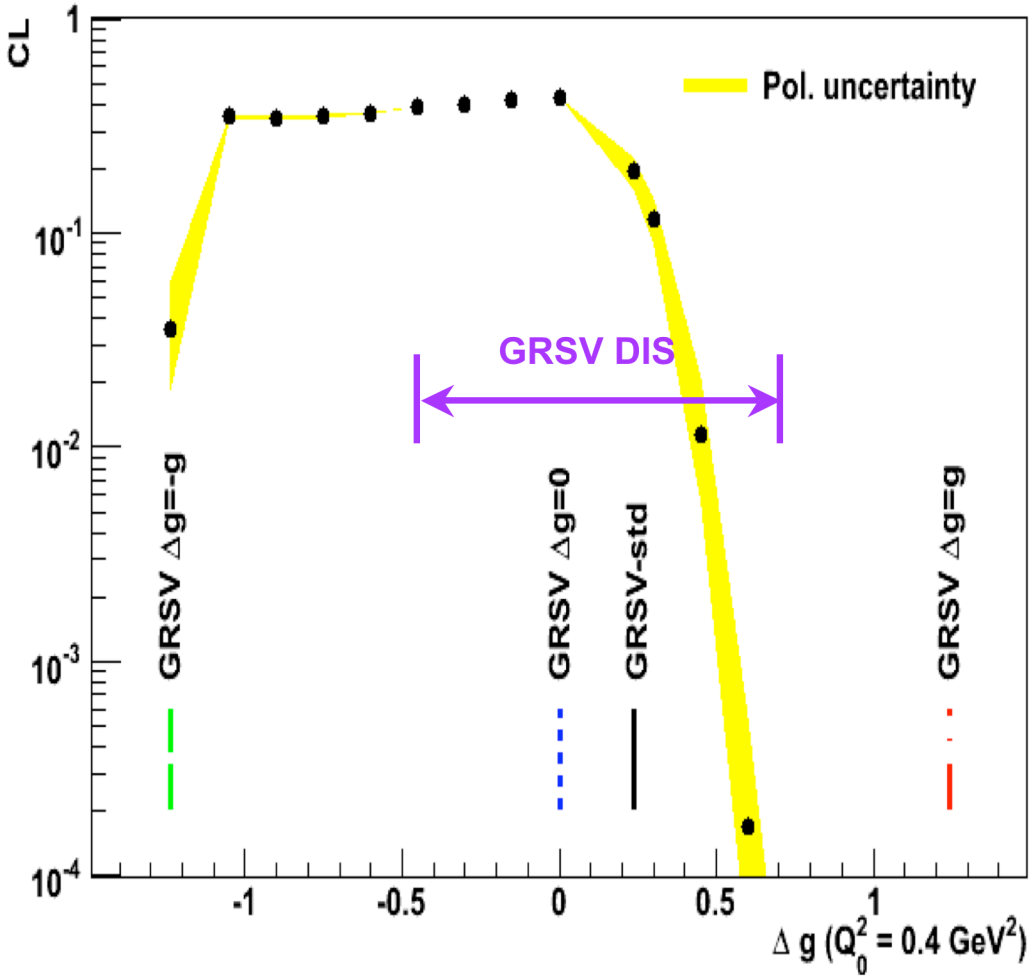
$$\frac{1}{P_Y P_B}\frac{N^{parallel} - R\cdot N^{antiparallel}}{N^{parallel} + R\cdot N^{antiparallel}}$$

Systematics	(x 10^{-3})
Reconstruction + Trigger Bias	2–5 (p_T dep)
Non-longitudinal Polarization	0.1–0.8 (p_T dep)
Relative Luminosity	0.94
Backgrounds	0.70
p_T systematic	−5.4% +6.7%



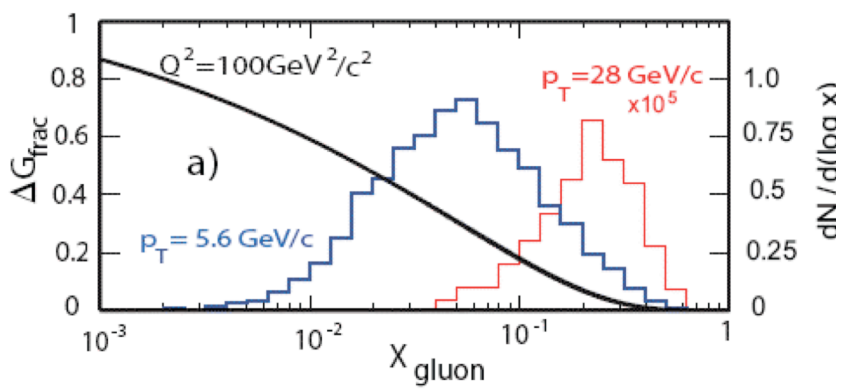
Submitted to PRL arXiv:0710.2048

2005 Confidence Levels



Theory (GRSV)	CL
Δg = -g	***0.06***
Δg = 0.33	***0.10***
Δg = g	***~10^{-13}***

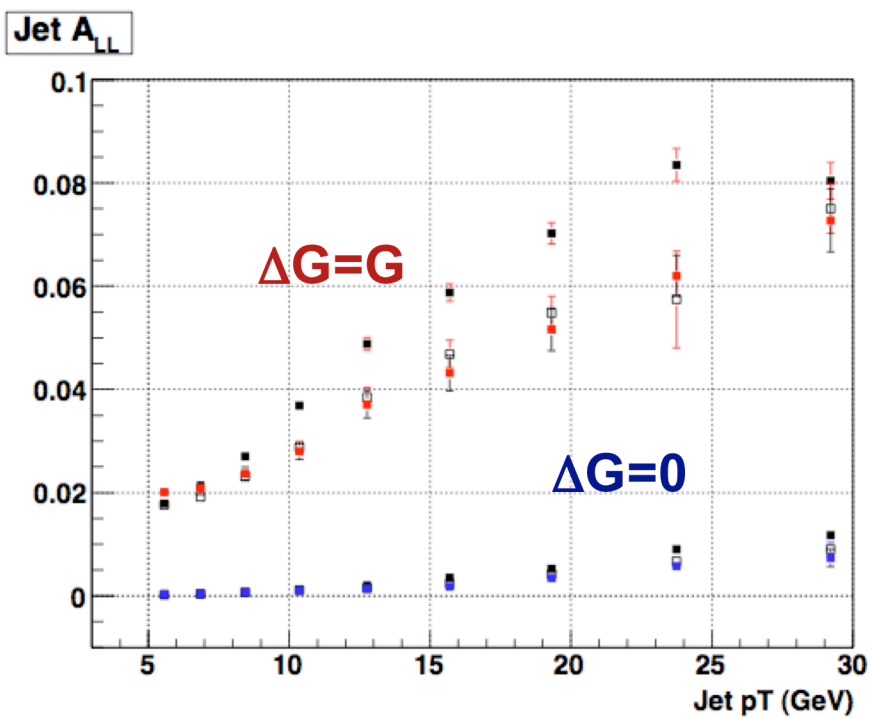
Data covers ~50% of GRSV total integral

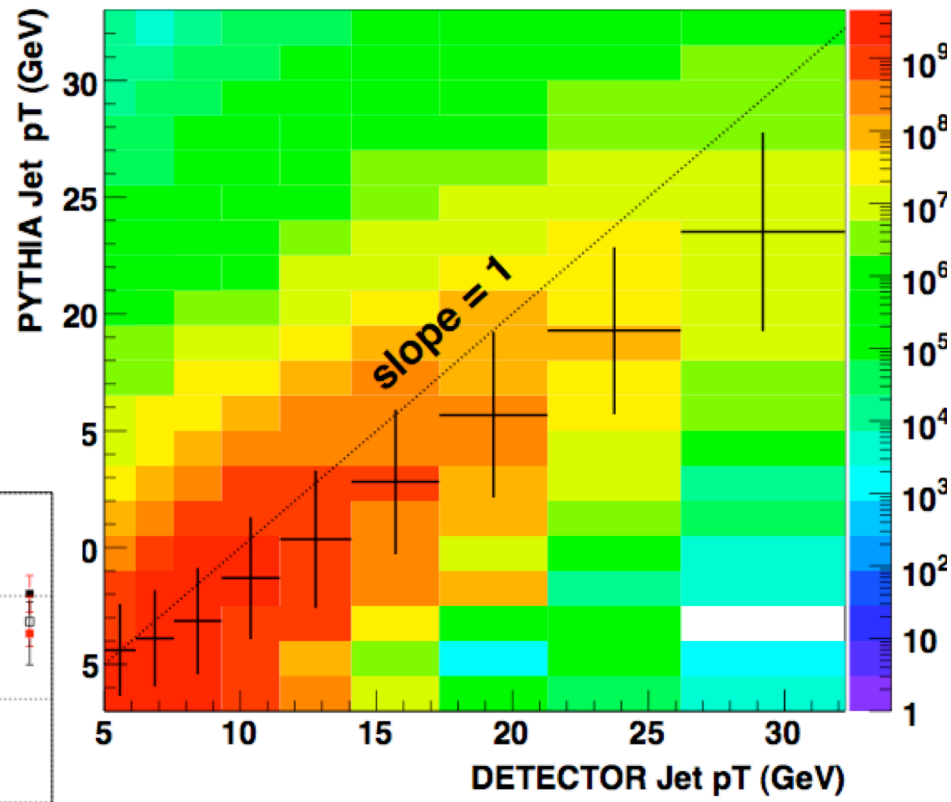


Jet A_{LL} Systematics: Jet Reconstruction Bias

On average PARTICLE Jets are reconstructed in the DETECTOR with **20% increase in pT**!

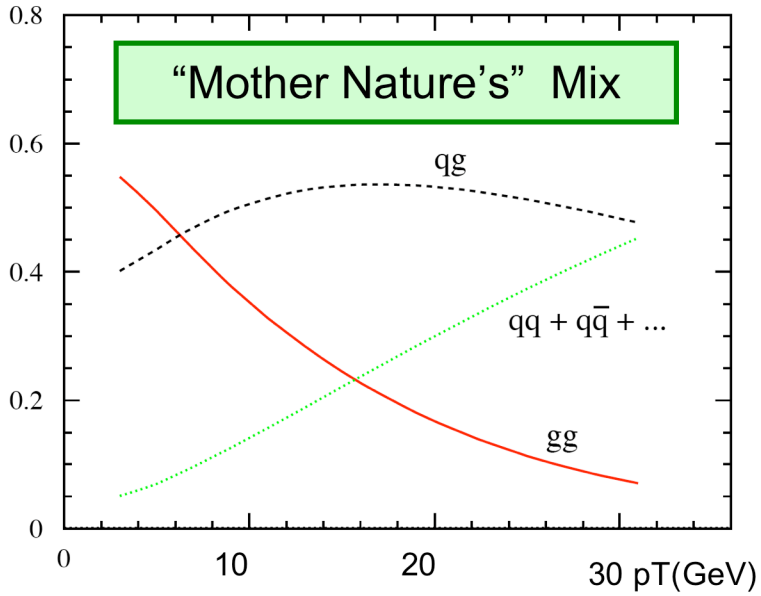
REASON: 25% Jet Resolution + Steeply falling jet pT distribution





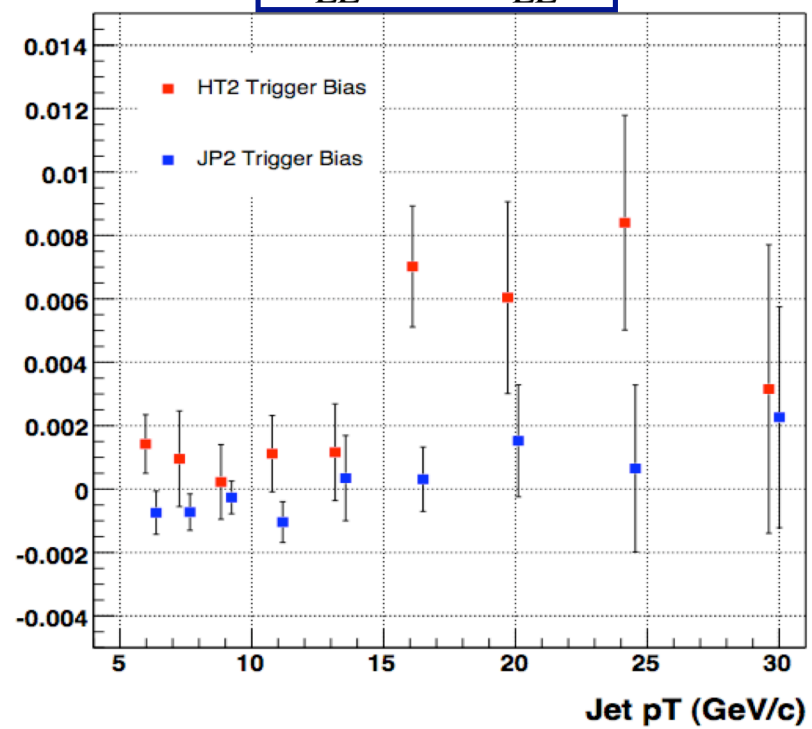
Systematic offsets in pT cause dilutions of the jet asymmetry which depend on the size of the asymmetry!

Jet A_{LL} Systematics: Trigger Bias



The trigger biases jets toward higher neutral energy. This may change nature's mix of qq+qg+gg and therefore change the asymmetries

$$A_{LL}^{DET} - A_{LL}^{TRIG}$$



Trigger Bias:

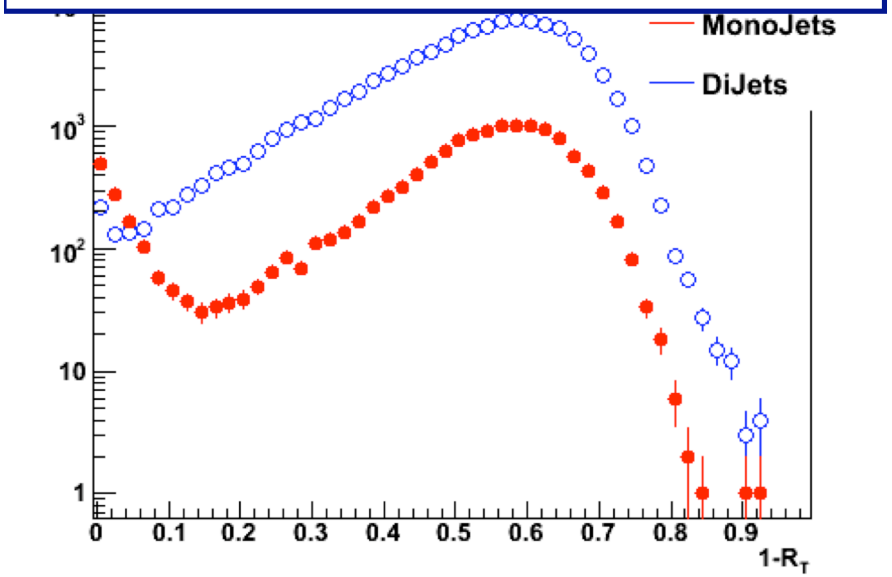
- JP << HT
- $\Delta A_{LL}/A_{LL} \rightarrow$ larger at low pT

Total Systematic:

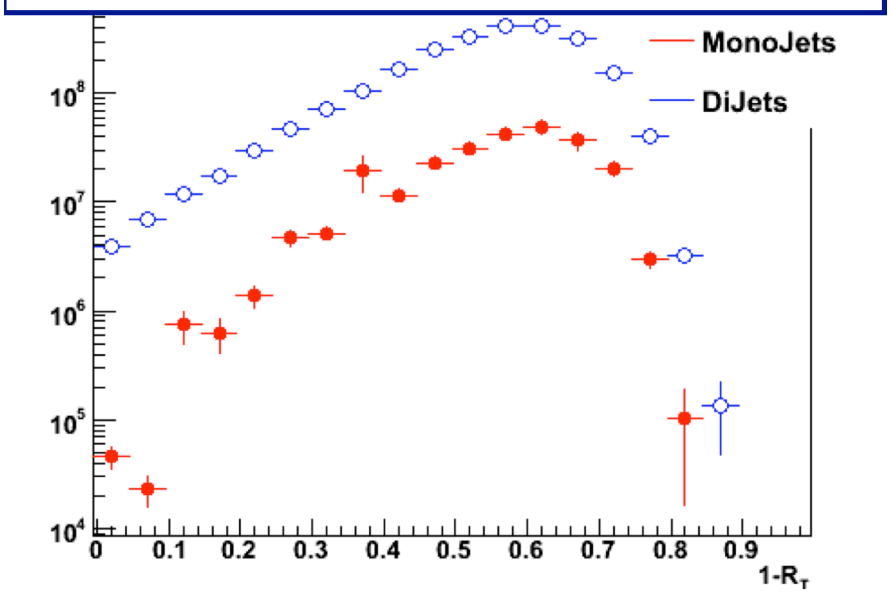
1. Shift pT from Particle to Detector
2. $\delta A_{LL} = A_{LL}^{DETECTOR} - A_{LL}^{TRIGGER}$

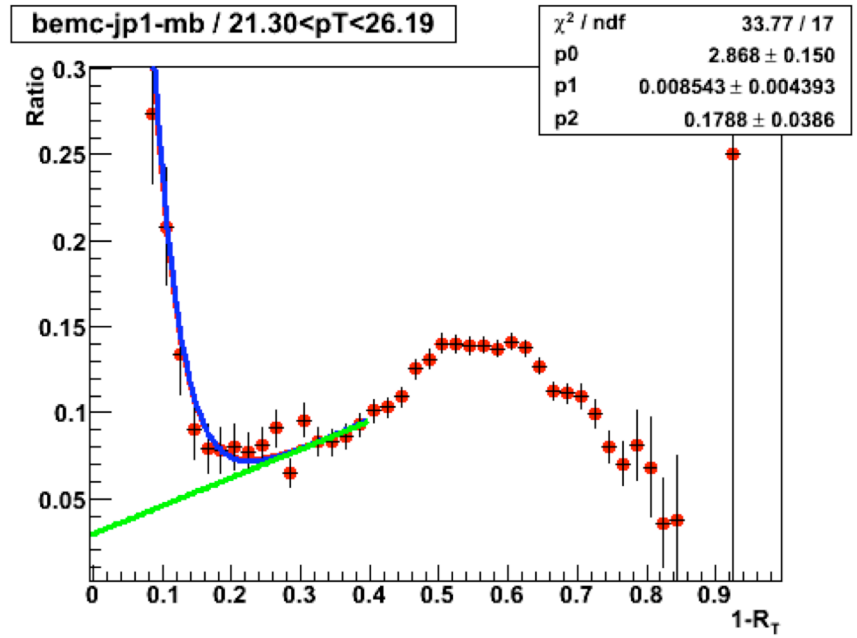
Beam Gas Background

JP1 Data (21.30< pT<26.19)



JP1 Simulation (21.30< pT<26.19)

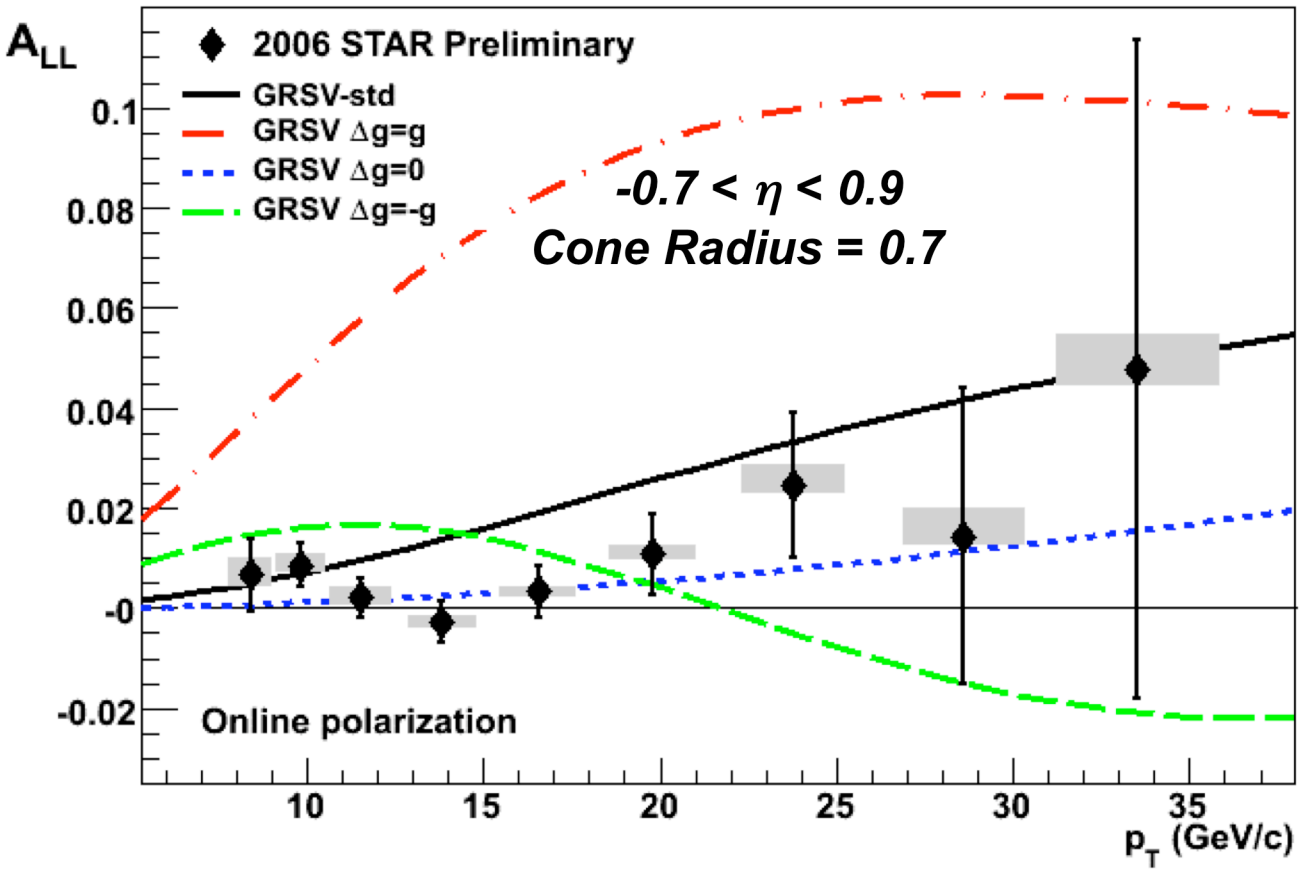




1. Measure Background A_{LL} in monojets (R_T>0.95)
2. Determine fraction background/signal

$$\delta A_{LL}^{bkg} = \frac{f^{bkg} \times \left(\Delta A_{LL}^{bkg} + f^{sig} \Delta A_{LL}^{sig}\right)}{(1 - f^{sig})}$$

NEW! 2006 Inclusive Jet A_{LL}



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	0.5 – 0.1
p_T systematic	±6.7%

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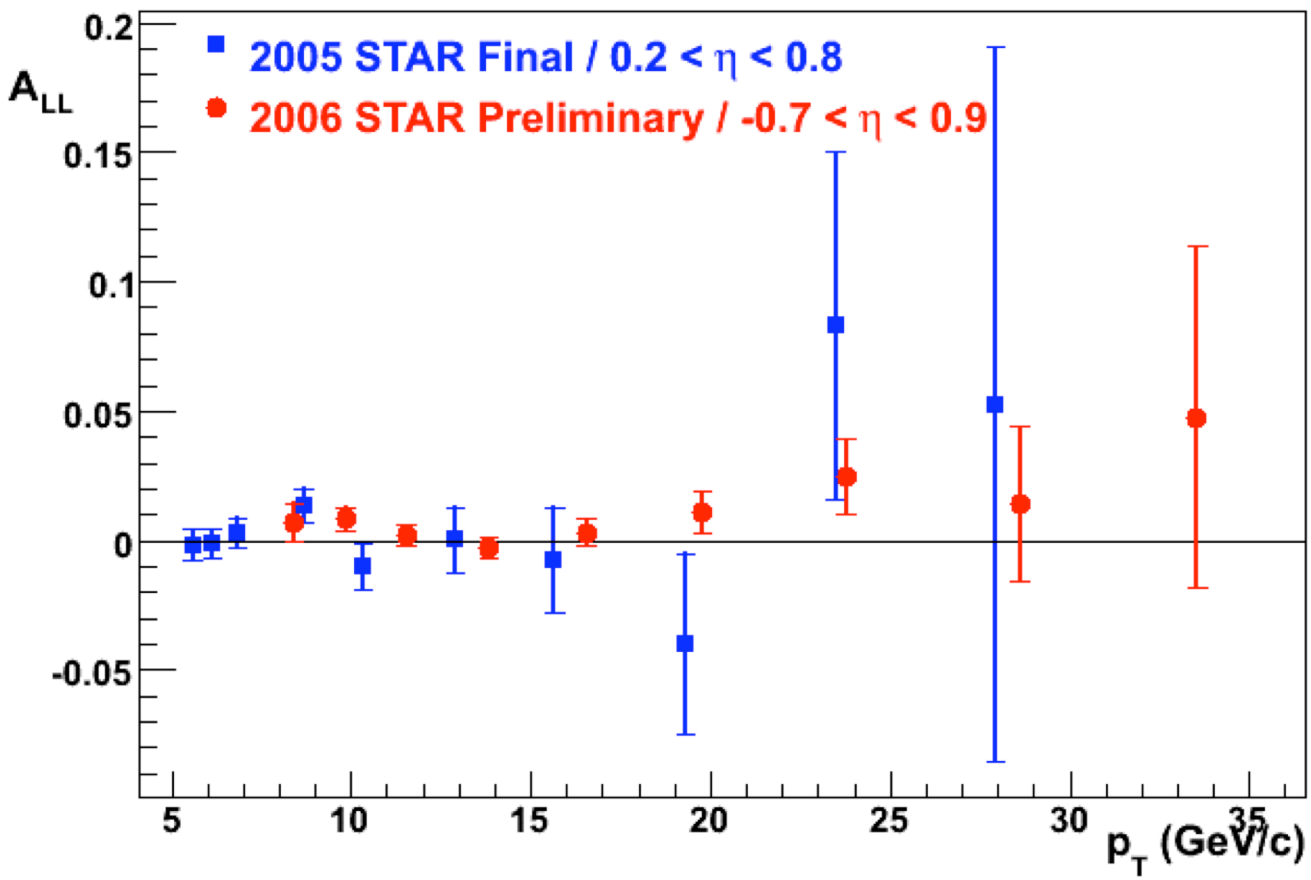

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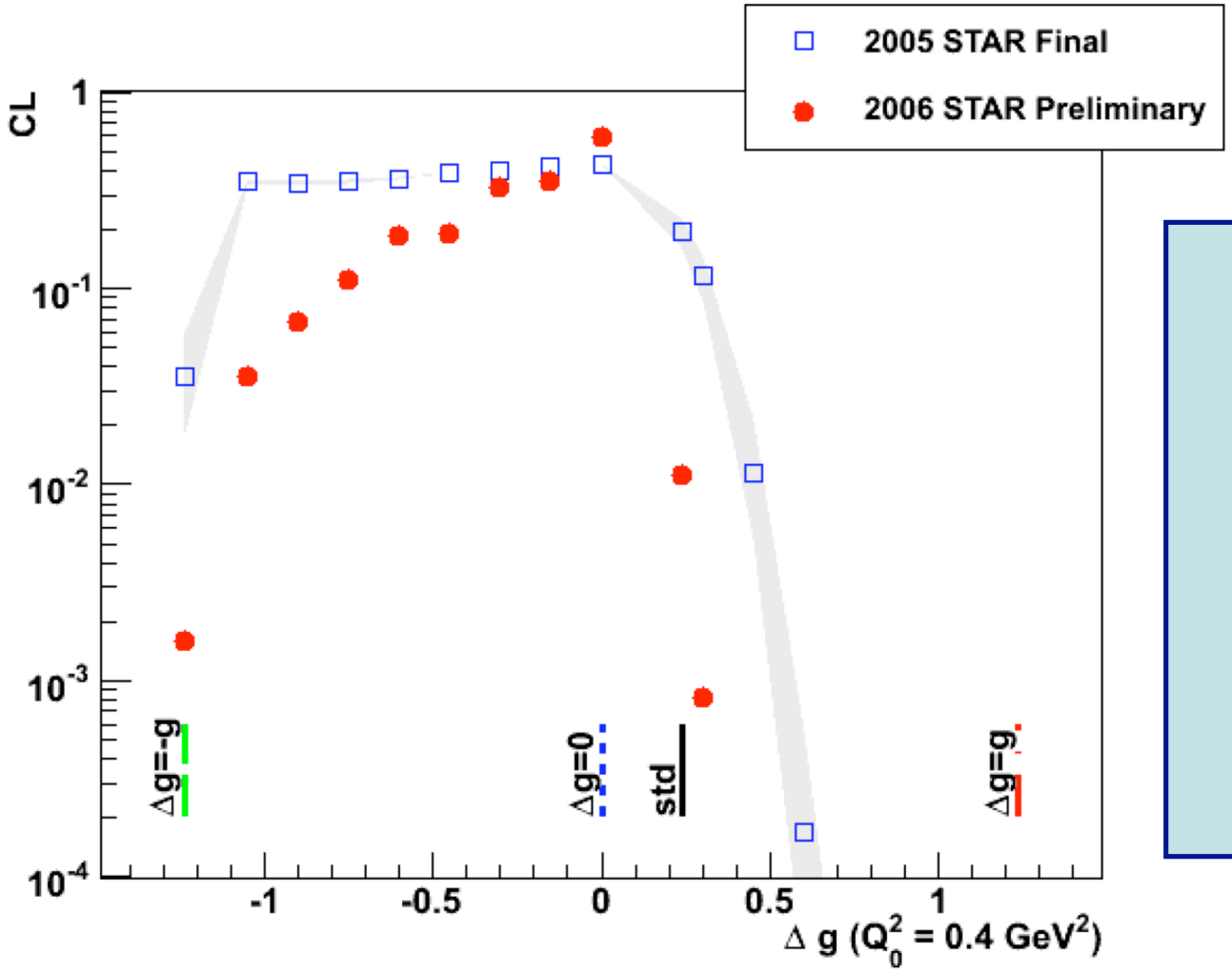
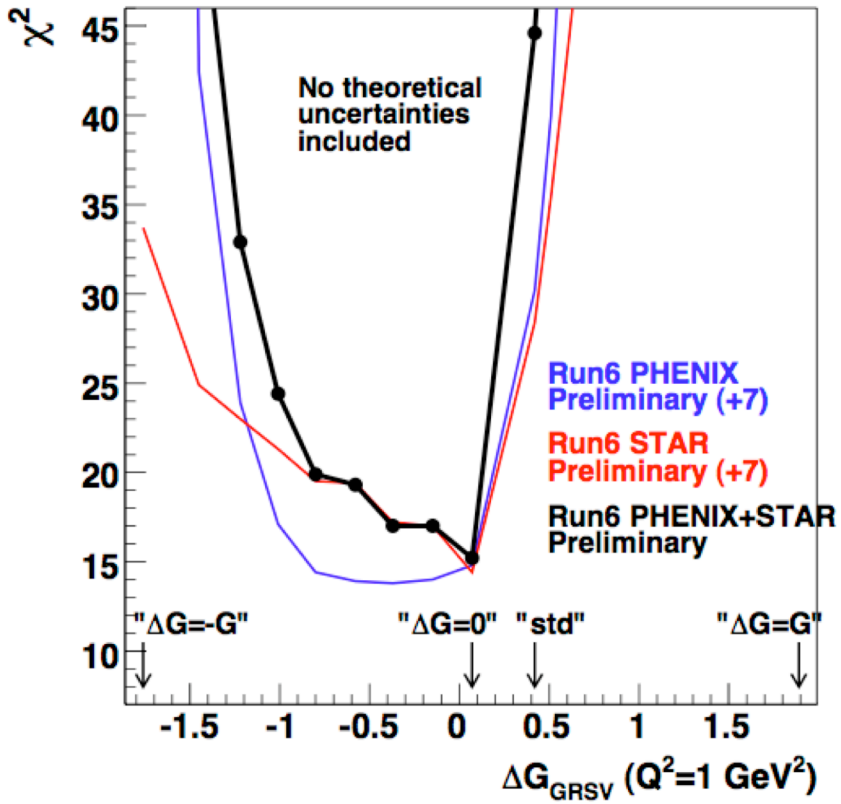
2006 Confidence Levels



Within GRSV framework:

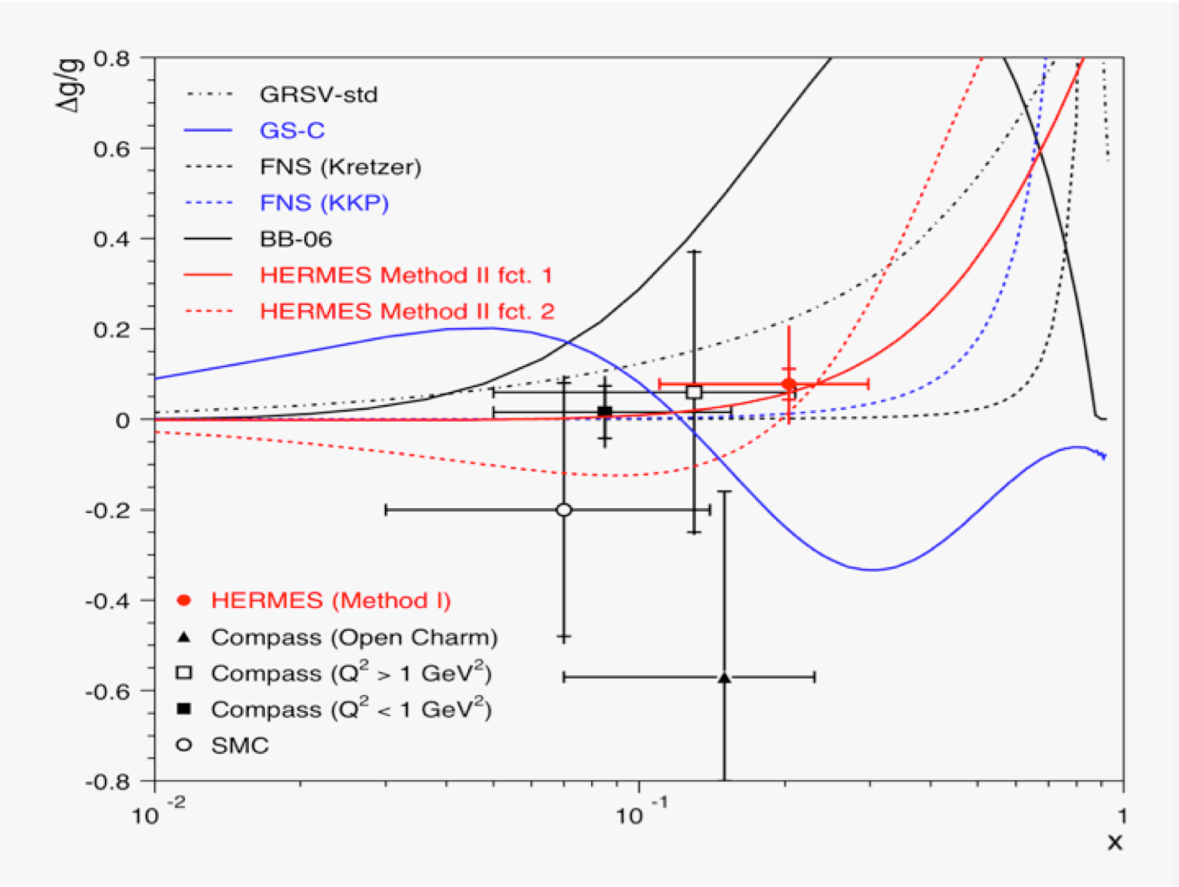
- ***Δg_STD*** excluded with ***99% CL***
- ***Δg<-0.7*** excluded with ***90% CL***

χ^2 comparison with PHENIX



1. STAR and PHENIX are in good agreement
2. Within GRSV framework, at 0.4 GeV^2/c^2, the total gluon contribution is nearly zero or negative.

But beware…conclusions are model dependent!



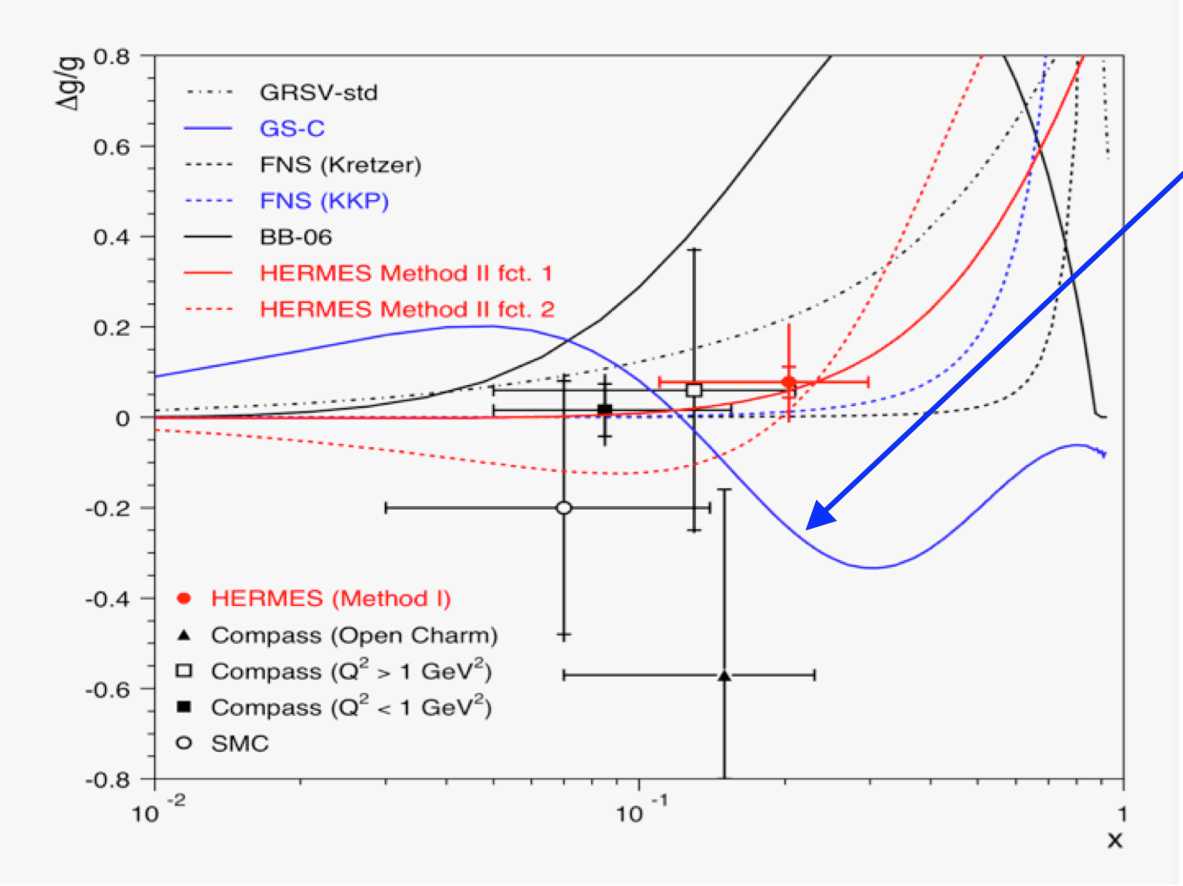
Total integral is larger for GSC

$$\int_0^1 \Delta g(x)dx$$

BUT sampled fraction is LARGER for GRSV

$$\int_{0.02}^{0.3} \Delta g(x)dx$$

But beware…conclusions are model dependent!



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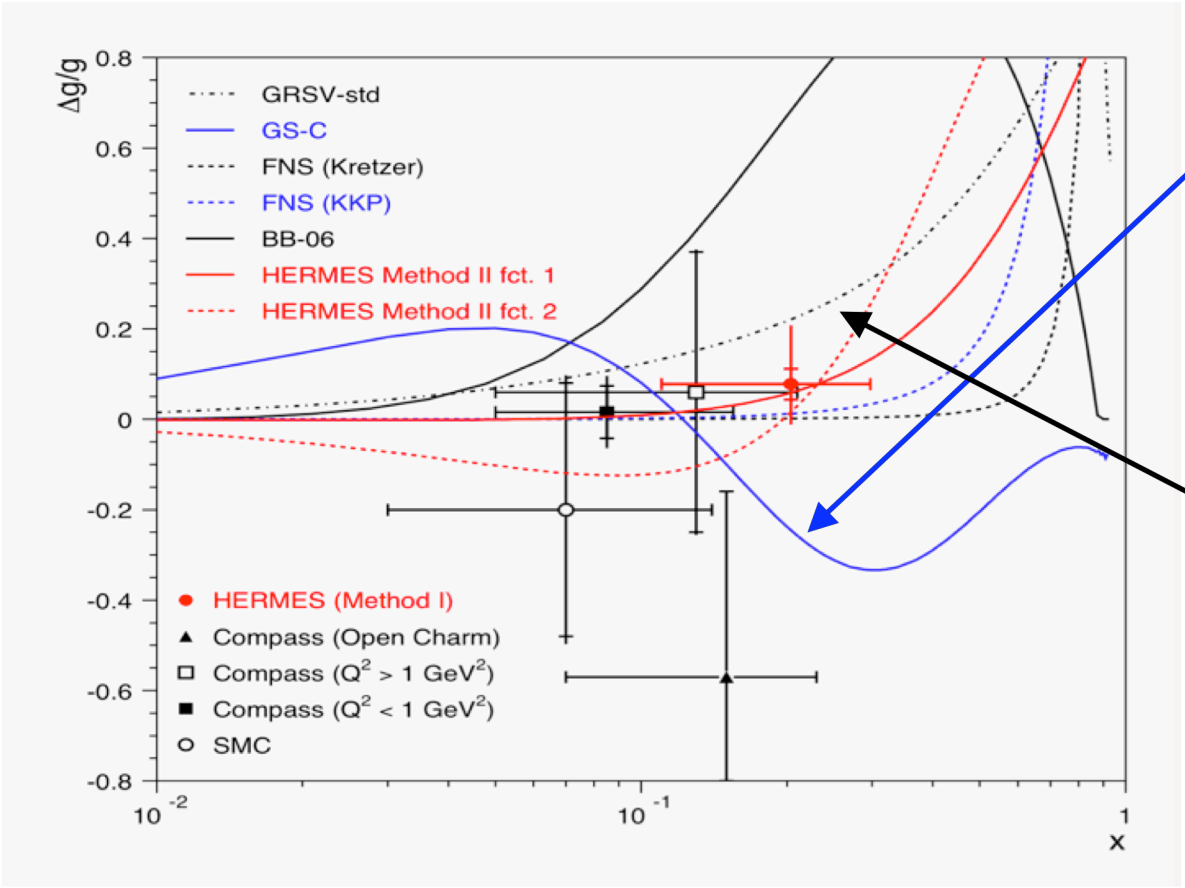

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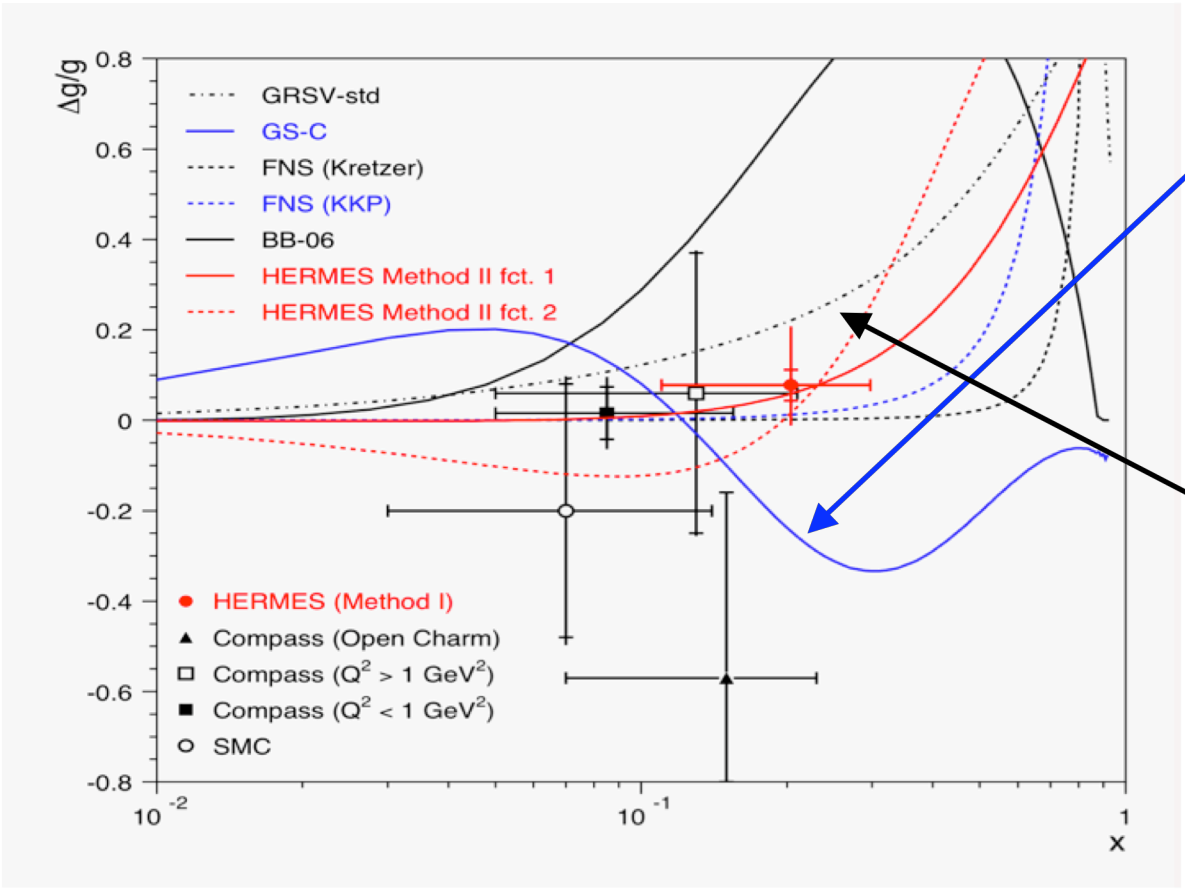

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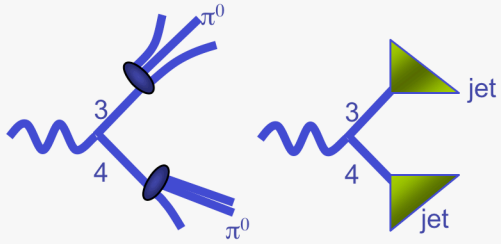
Really need global analysis + x sensitive measurements!

Final States

$$p_T \; E_T \; \eta \; \varphi$$



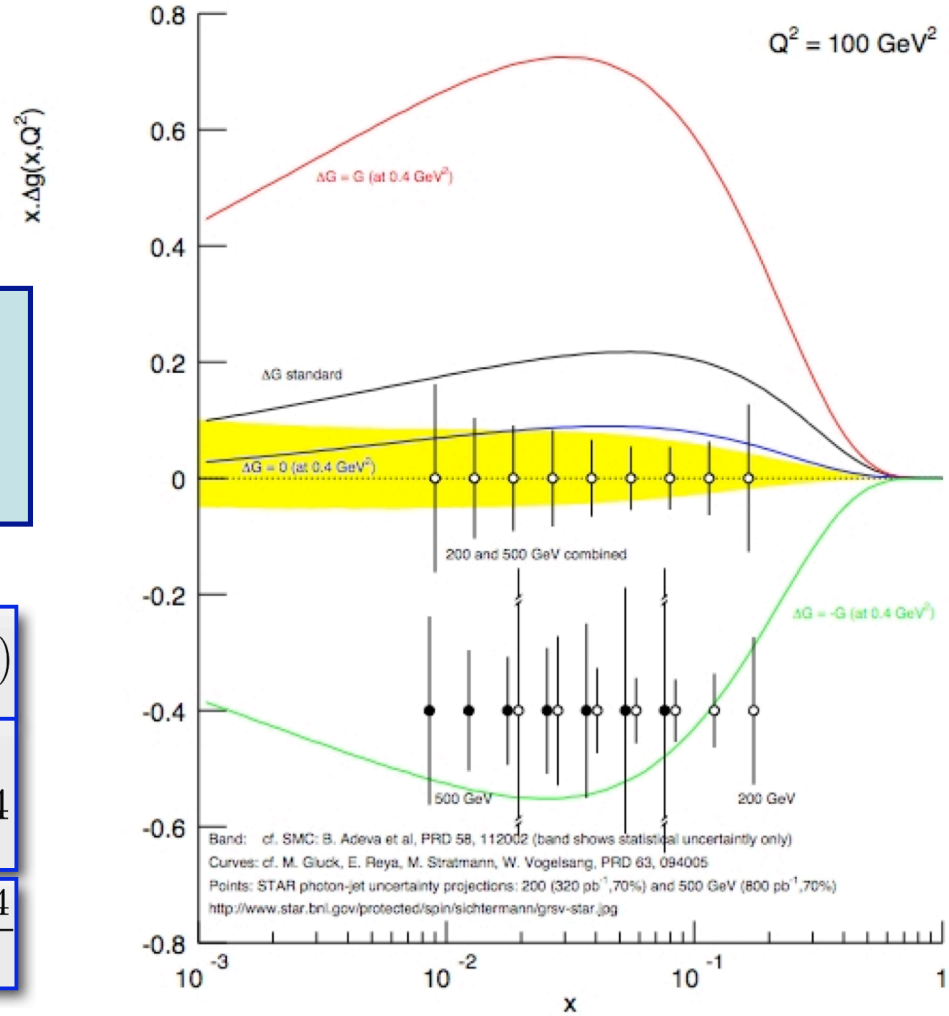
Sample a different <x> range with 500 GeV running

Access partonic kinematics via Di-jet and photon-jet
Provides mapping of Δg(x)

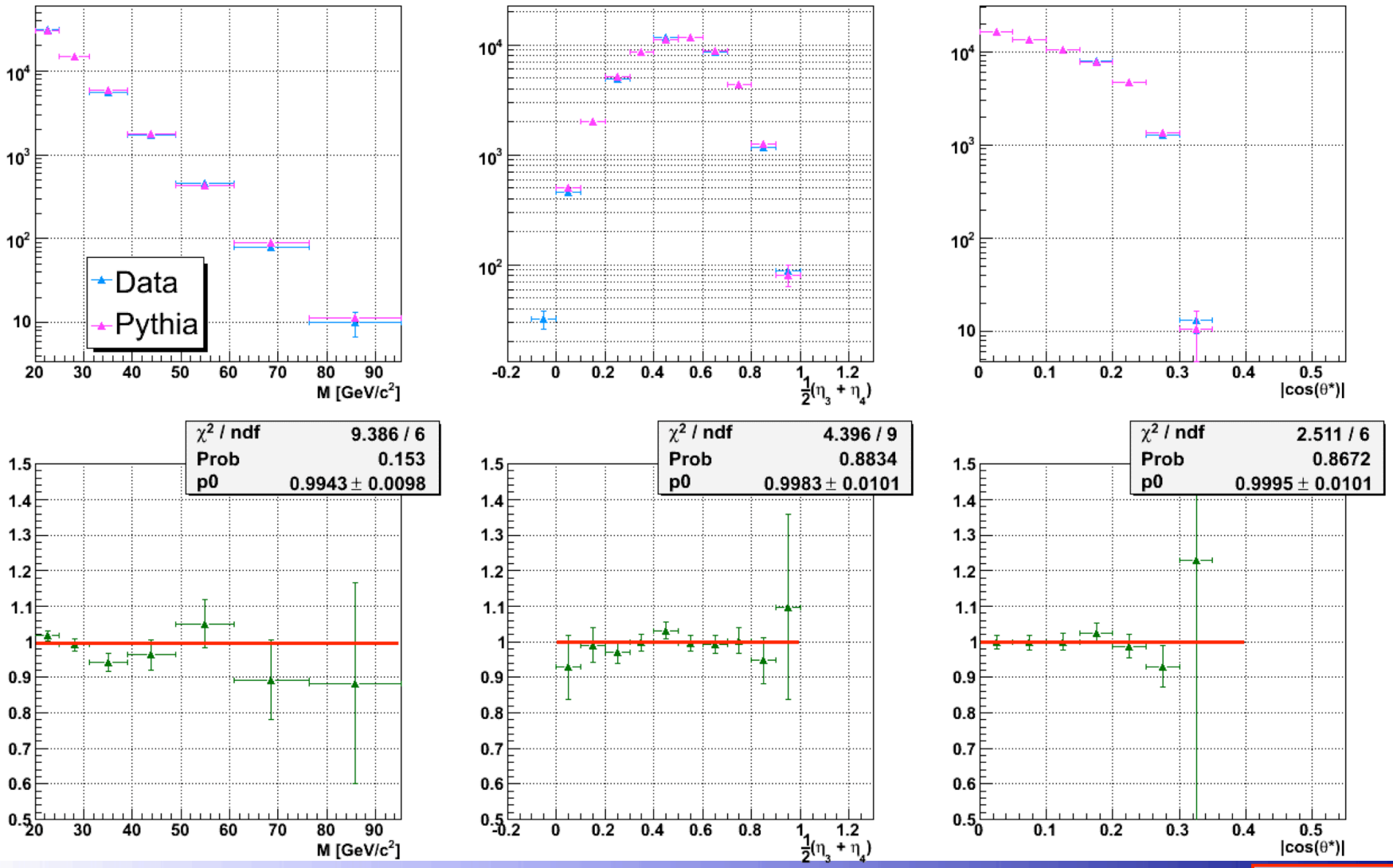
$$x_2 = \frac{1}{\sqrt{s}}(p_{T3}e^{-\eta 3} + p_{T4}e^{-\eta 4})$$

$$\frac{1}{2}\log\frac{x_1}{x_2} = \eta_3 + \eta_4$$

$$\cos\theta^* = \tanh\frac{\eta_3 - \eta_4}{2}$$



2005 Dijet distributions are well described by MC - Xsec close!



Summary

- From DIS: QUARKS = 20-30% of total proton spin, while the gluon spin is poorly constrained.
- The RHIC spin program aims to access ΔG directly
- STAR inclusive Jets rule out substantial phase space compared to DIS, but cannot be translated easily into a direct ΔG value.
- The STAR Spin program is entering a very rich phase of correlation and direct photon measurements, while continuing to expand the p_T reach of the inclusive channels.
- A Global Analysis incorporating the world dataset, along with future precision measurements in x space, are needed to provide a complete and definitive answer.