Extracting the Gluon Piece of the Spin Puzzle

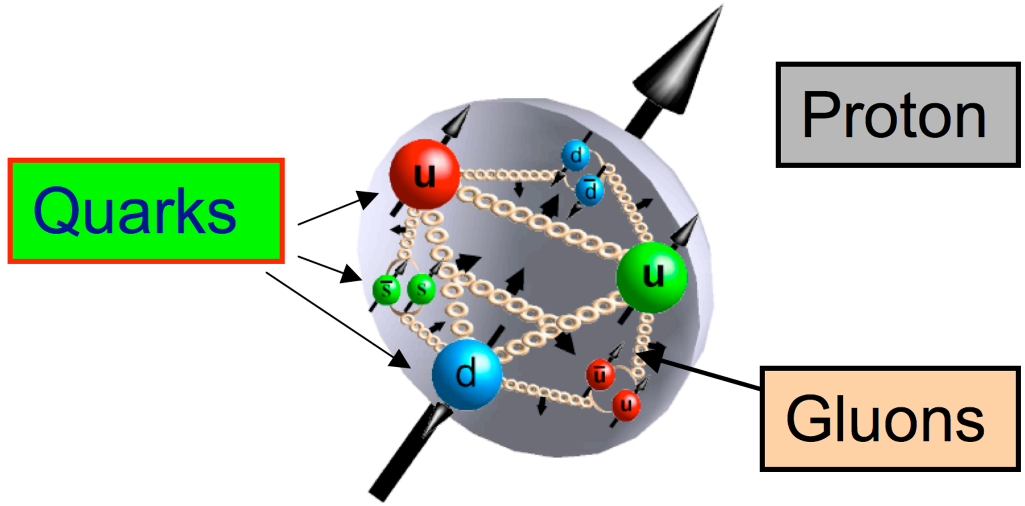
New Inclusive Jet Results From STAR

Renee Fatemi

University of Kentucky

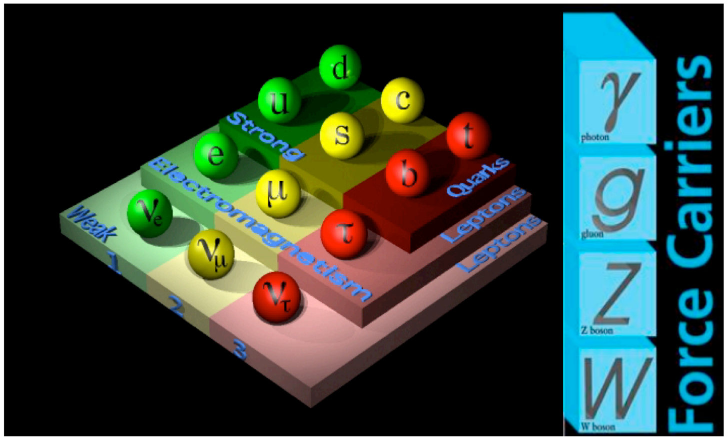
February 24th, 2009

Quick Historical Review of the Spin Puzzle



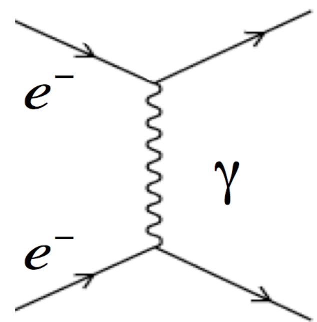
STAR Contributions to the Spin Puzzle

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



spin 1/2 spin 1

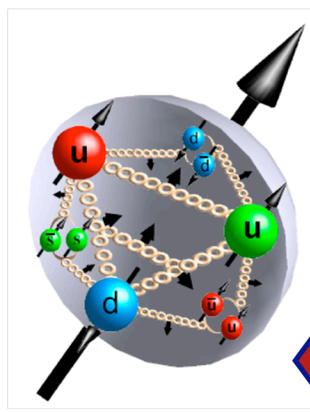
99.9% of mass of the visible universe composed of quarks and gluons - the building blocks of the nucleon



QED

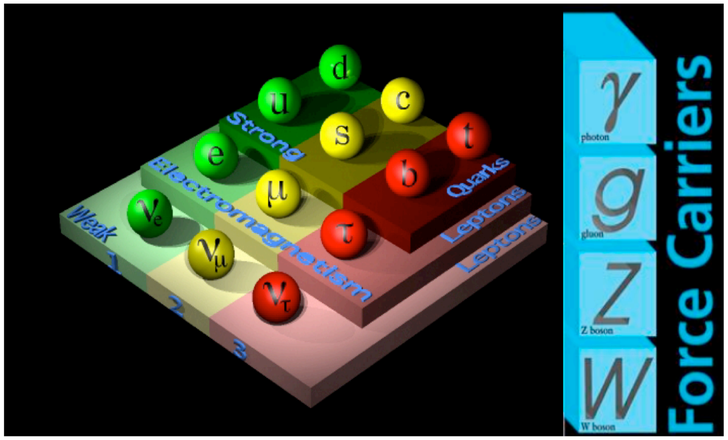
$$E \propto \frac{1}{r}$$

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



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

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



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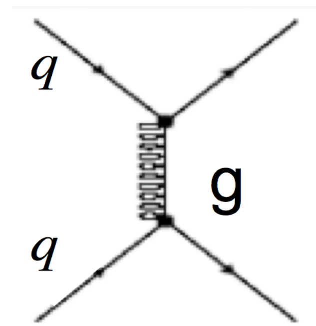

QCD

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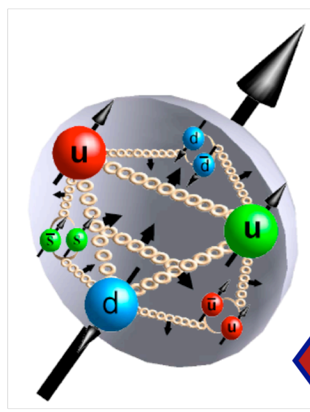

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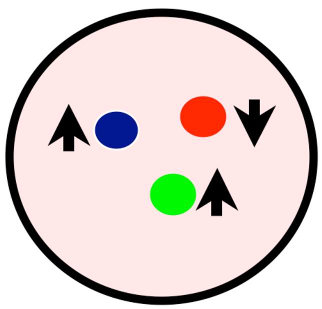
Initial (+30 years old now …) predictions for Parton Helicity Distributions:

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

Constituent Quark Model



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

100 % quarks

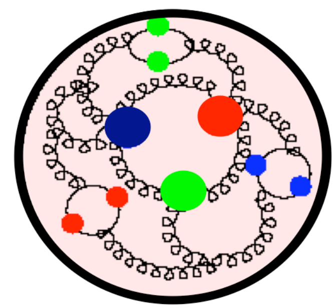
i. No gluon d.o.f

ii. $M_{quark} = 1/3\, M_{proton}$

iii. Assume S-state

iv. Relativistic Effect ~ 75%

Quark Parton Model



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

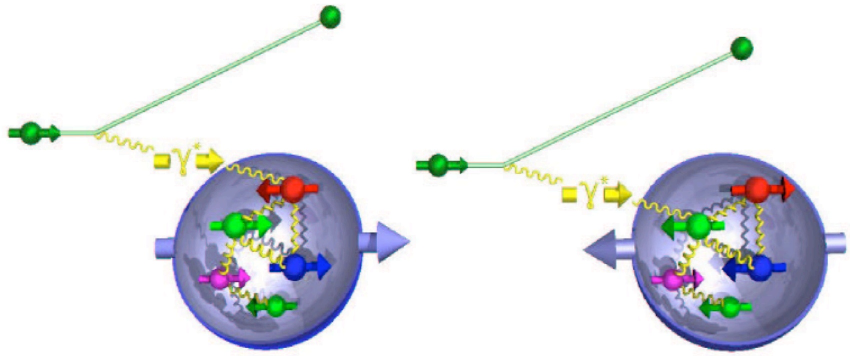
~60 % quarks

i. Allows massless gluons

ii. M_{quark} ~ 10's MeV

iii. Assume no strange sea constribution

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

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

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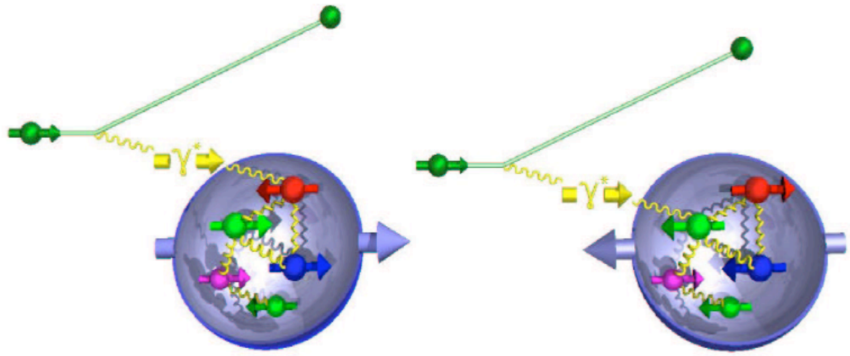

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Quark-Parton Model

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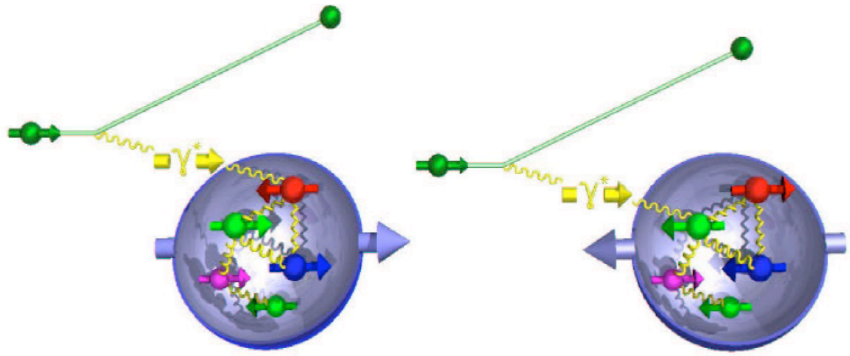

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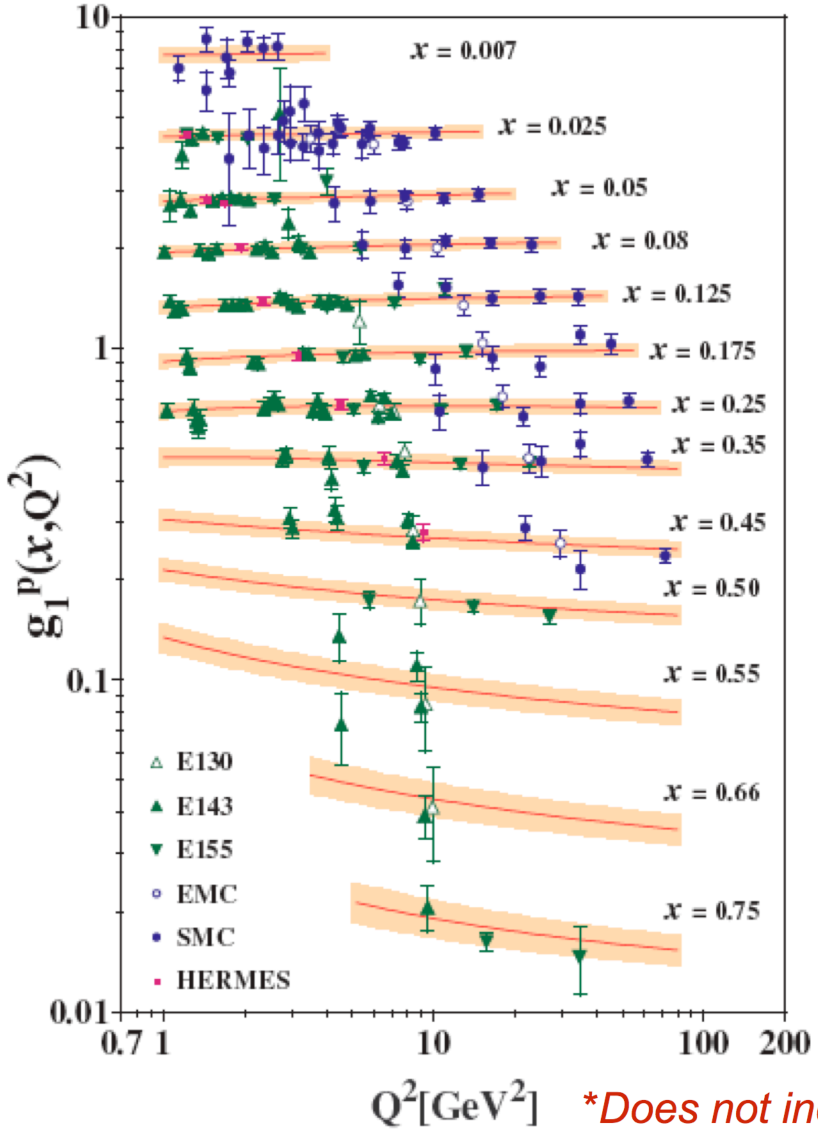
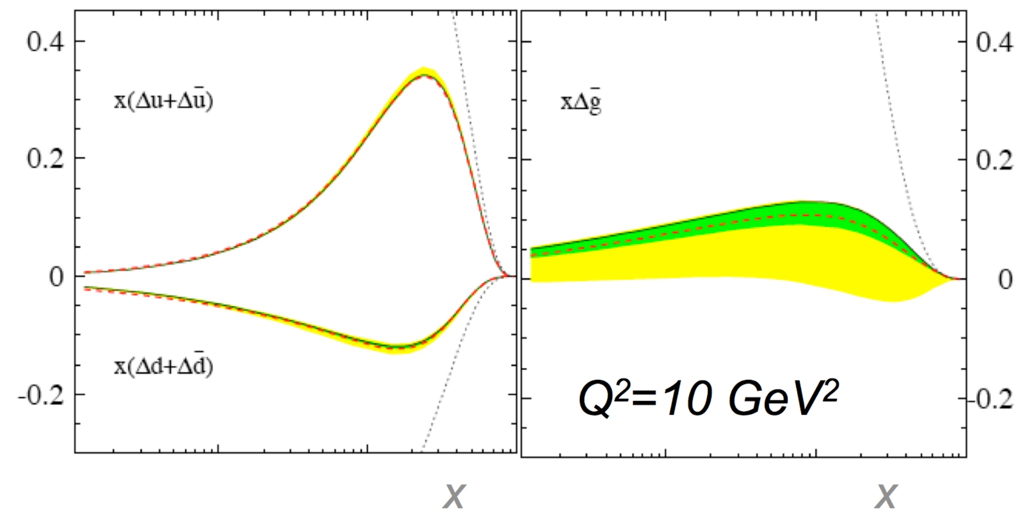
pQCD + OPE

$$A_{LL} \propto \int_0^1 g_1(x,Q^2)\,dx = C_1(\alpha_s,Q^2)[\frac{a_3}{12} + \frac{a_8}{12\sqrt{3}}] + C_2(\alpha_s,Q^2)\frac{a_0}{9}$$

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 $\Delta G(Q^2) = \int_{x=0}^{x=1} g(x,Q^2)dx$

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

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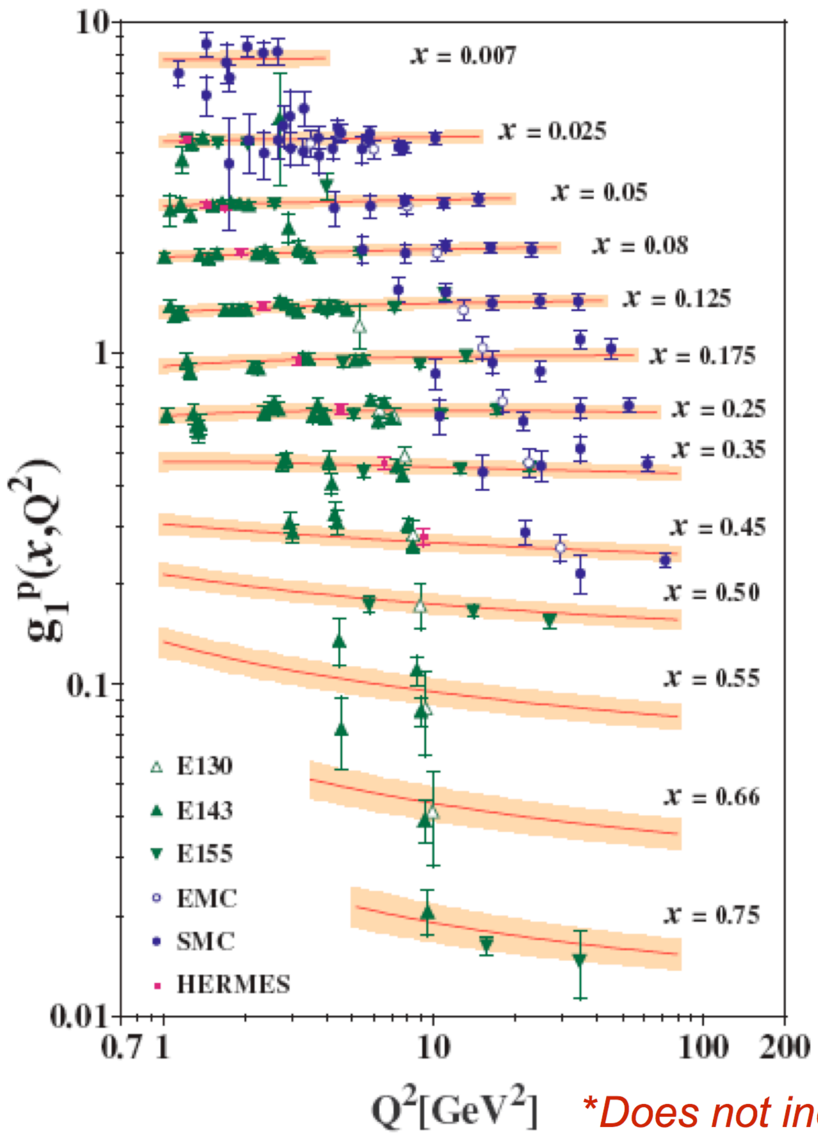
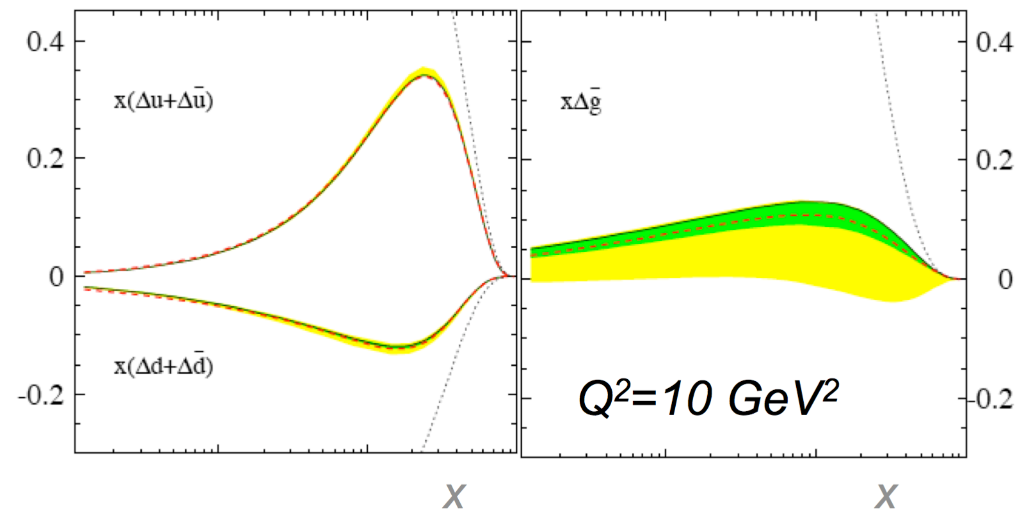


$$\Delta q(Q^2) = \int_{x=0}^{x=1} \left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right] dx$$



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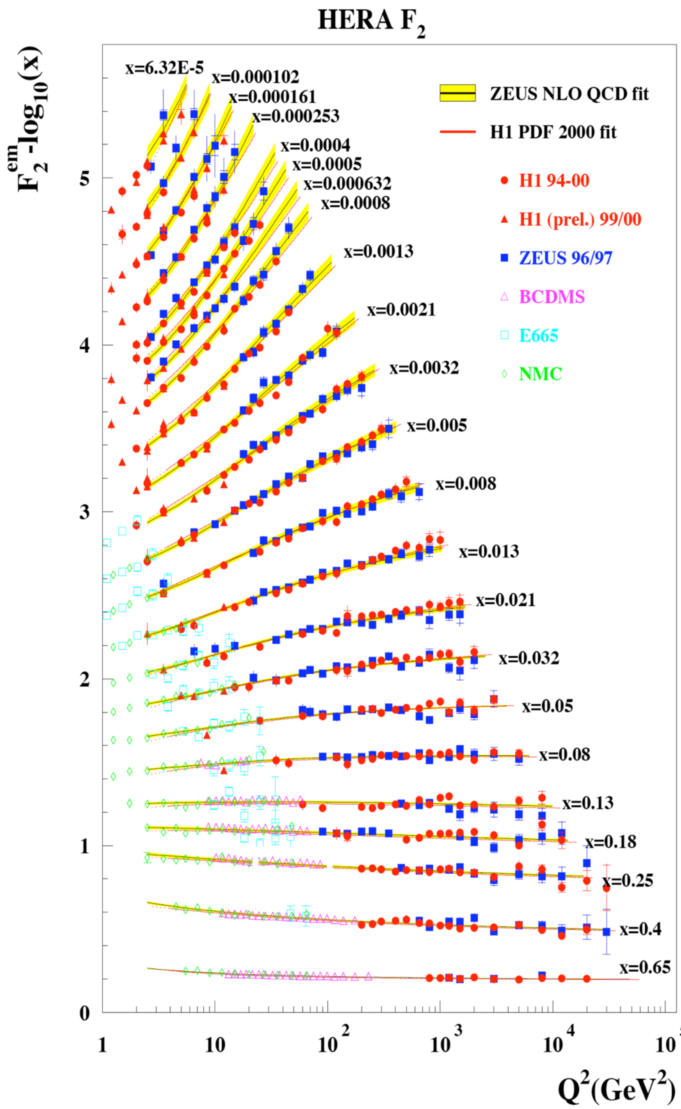
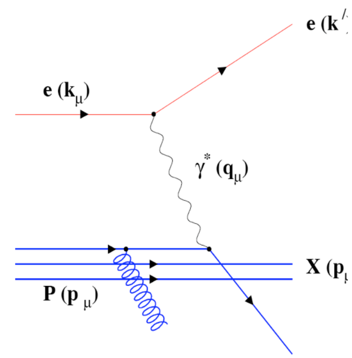
Momentum Parton Distribution Functions

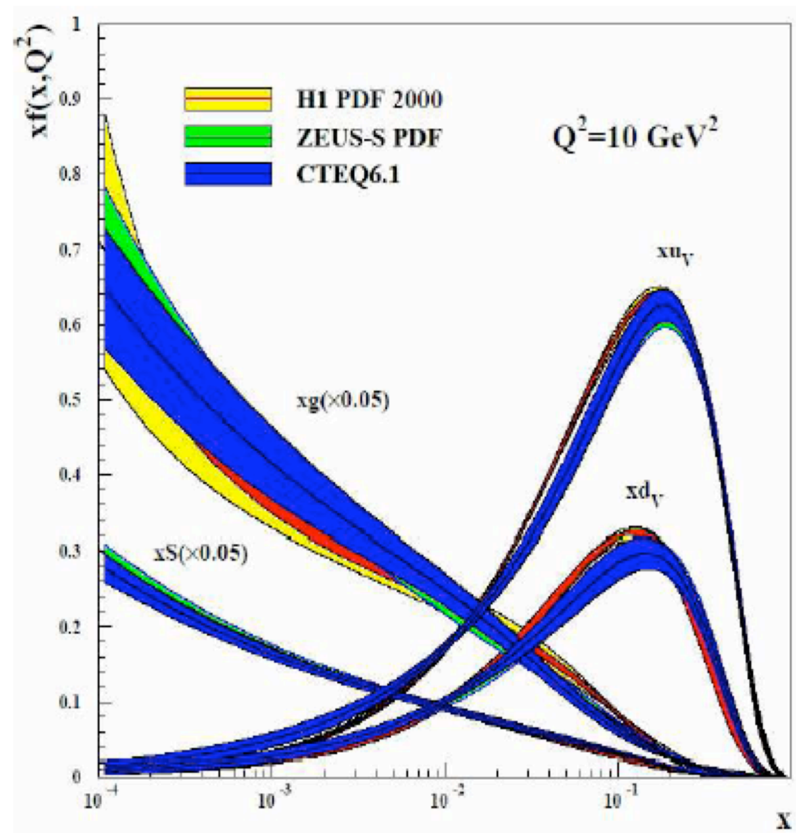
Motivation for Large gluon contribution?



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



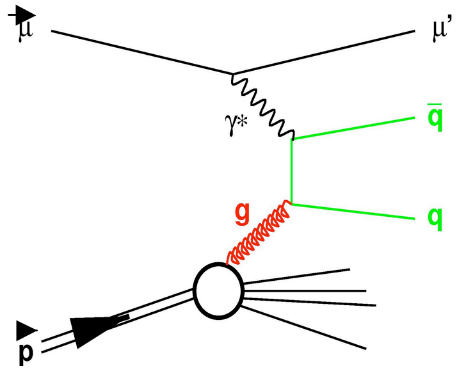
Contrary to: Low Q^2 high x!



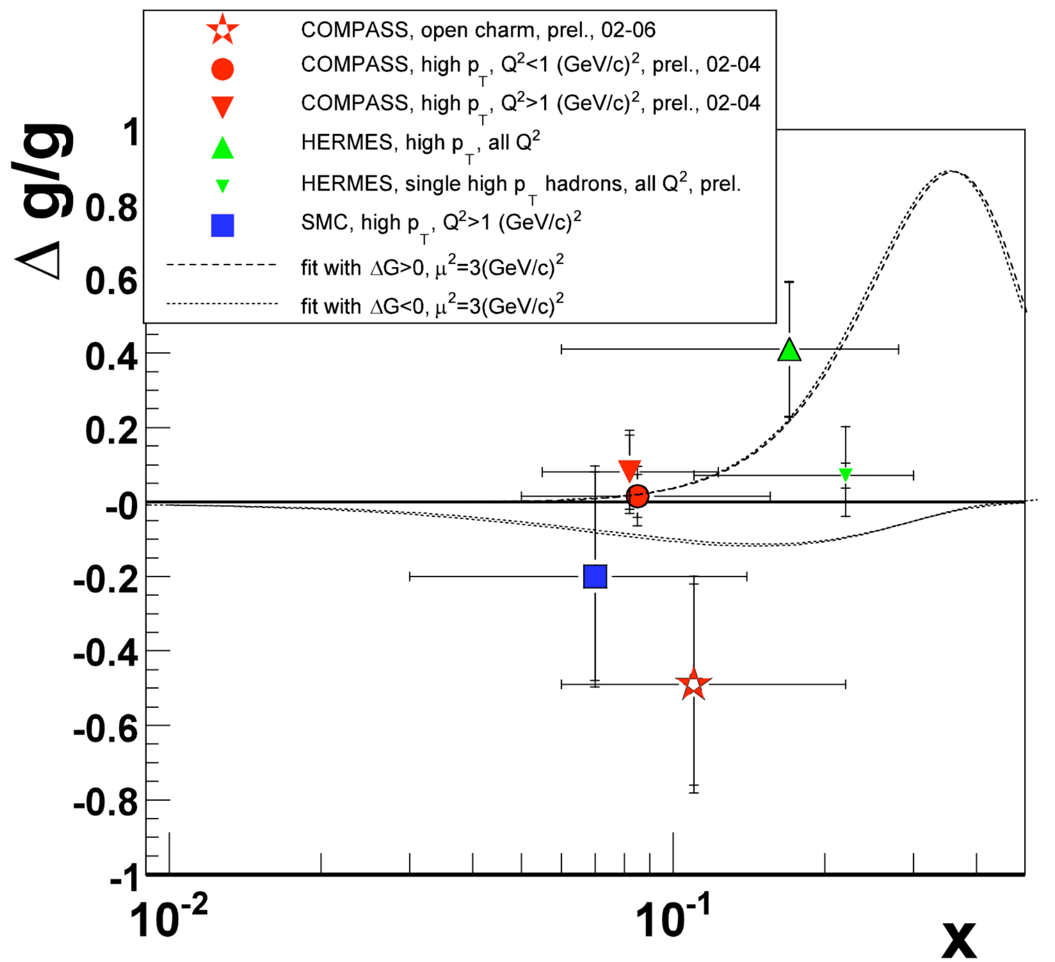
Note: g(x) scaled by 0.05! That means that at x = 0.1 there are more gluons than quarks!

Dedicated DIS ΔG Measurements

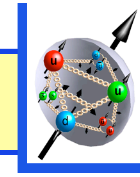
…from SPIN 2008



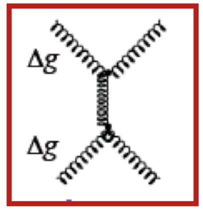
- PGF is access to ΔG in DIS
- Jet Proxy - high pT pairs
- Golden channel is Open Charm

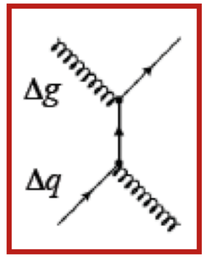


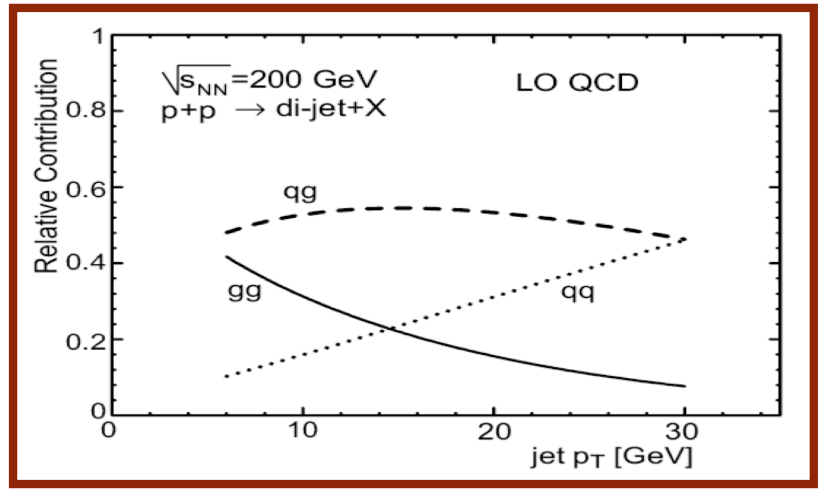
How do you access ΔG at a polarized $\vec{p}\vec{p}$ collider?



- ✓ 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 Deep Inelastic Scattering (DIS) programs very complementary







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

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

$$pp \to jet + X$$

$$pp \to jet + jet$$

At lower luminosities inclusive channels give most bang for the buck

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

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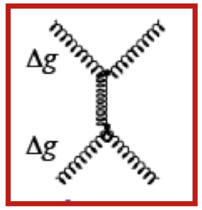

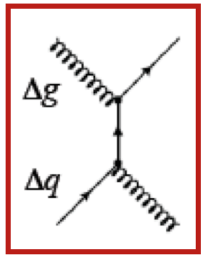

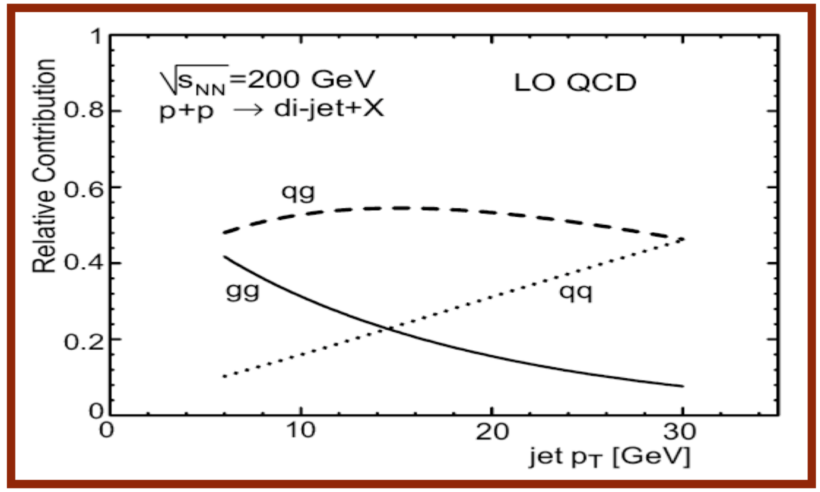

$pp \to \pi^{+/-} + X$ No trigger

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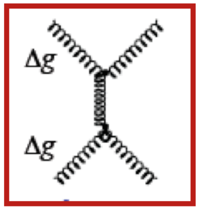

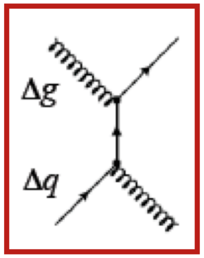

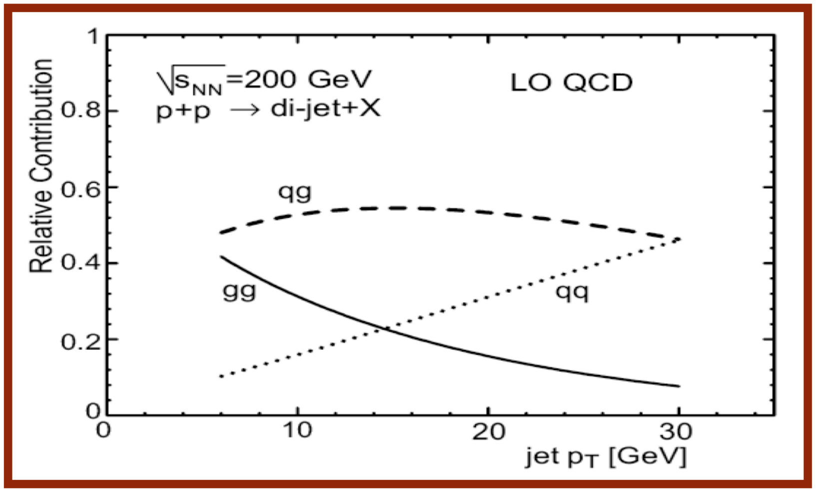

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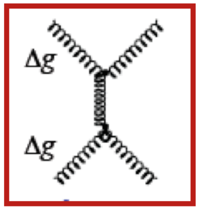

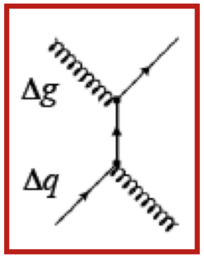

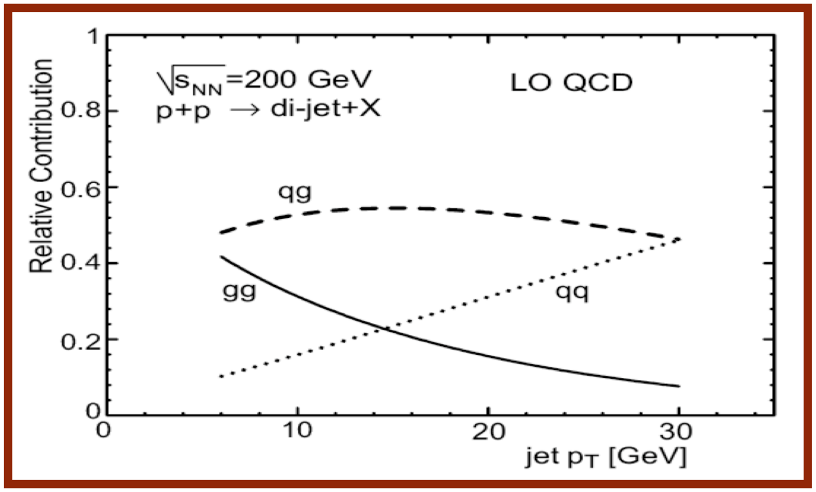

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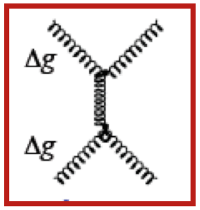

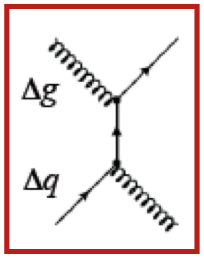

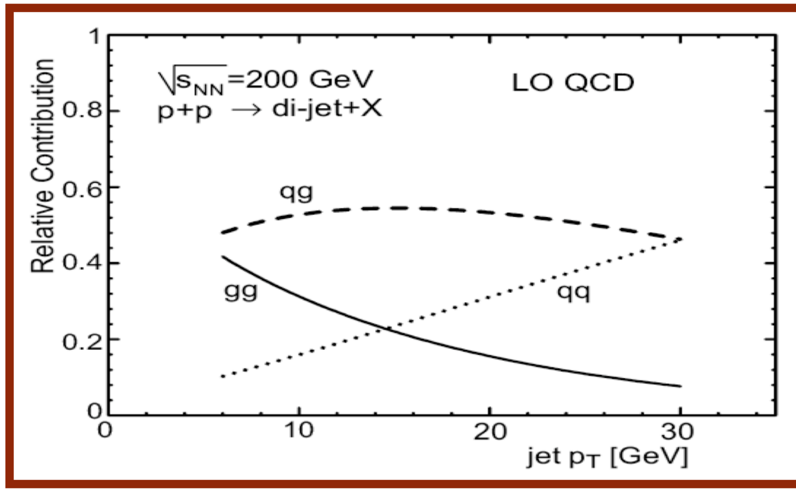

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$pp \rightarrow jet + X$	STAR does it better
$pp \rightarrow jet + jet$	Coming Soon!

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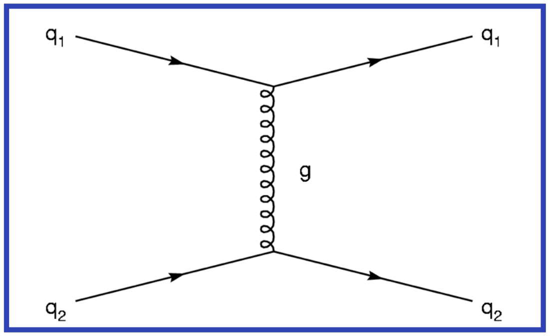
Color Confinement $\rightarrow$ Jets!

In Quantum Chromodynamics (QCD) two quarks feel an attractive force! The energy stored in the strong field between is:

$$E \propto r$$



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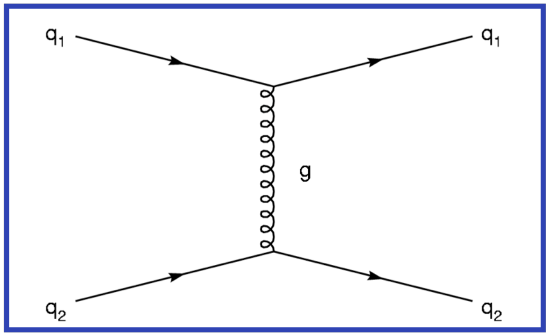

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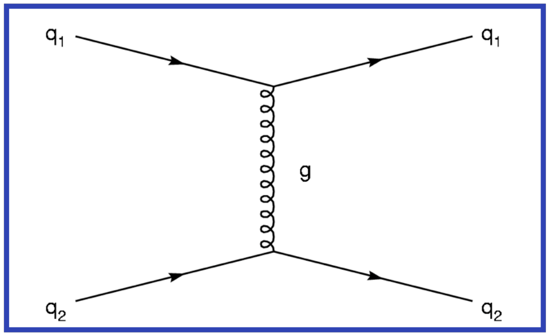

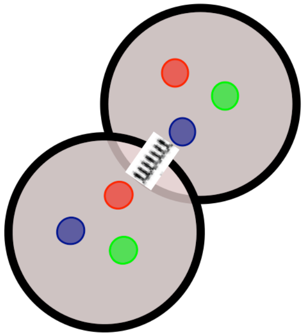

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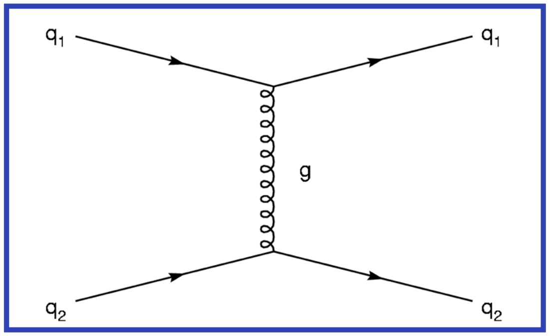

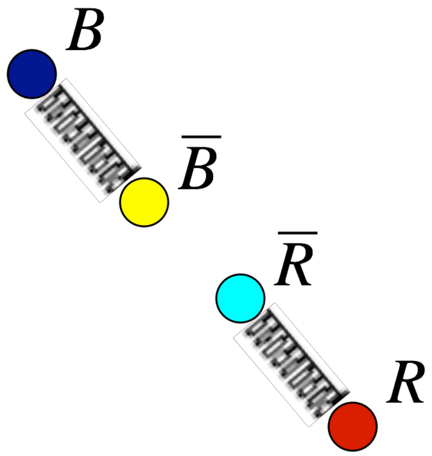

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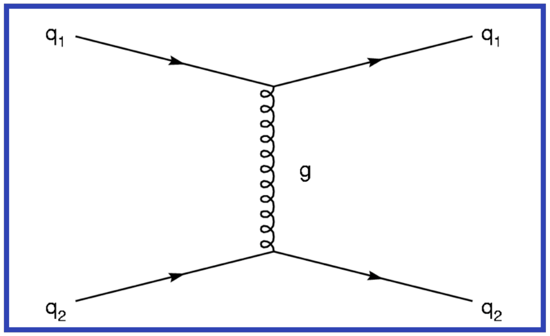

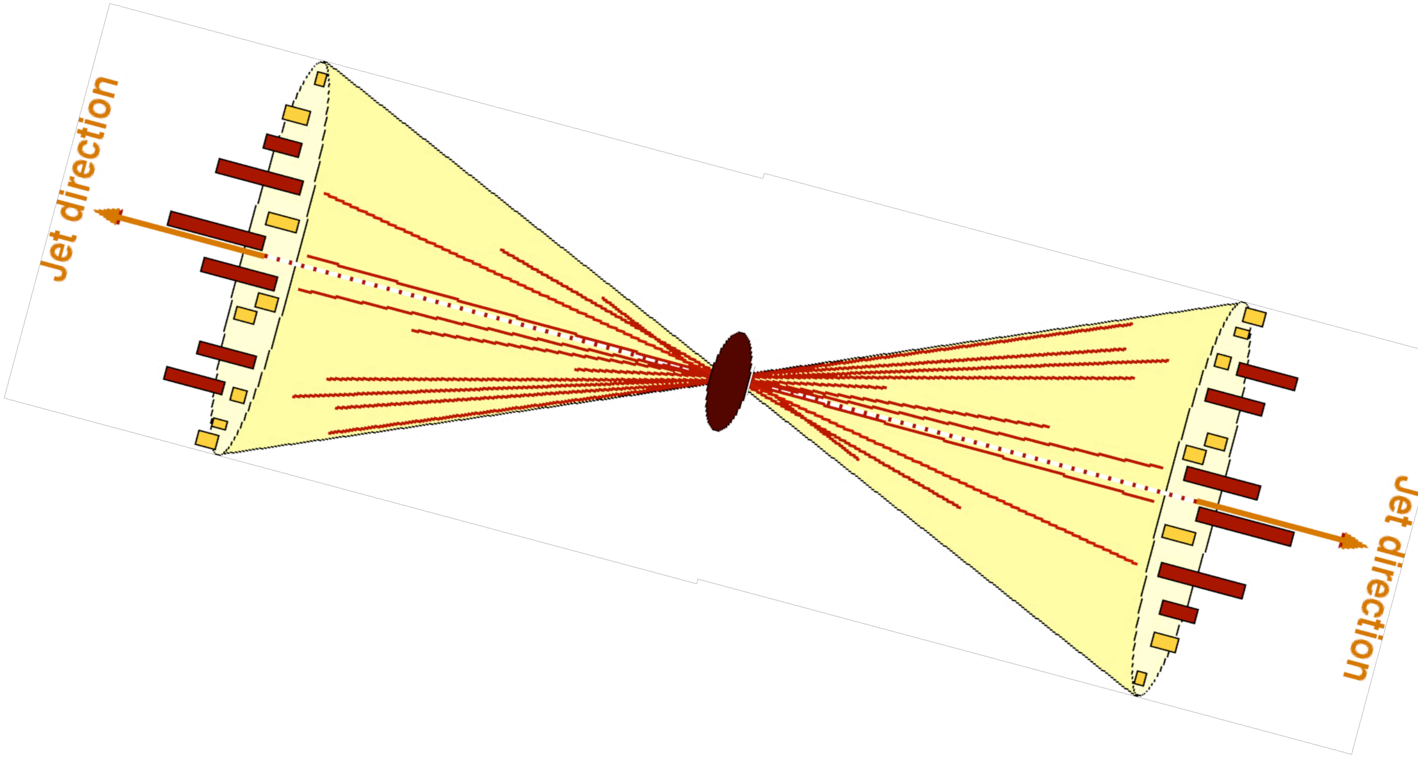

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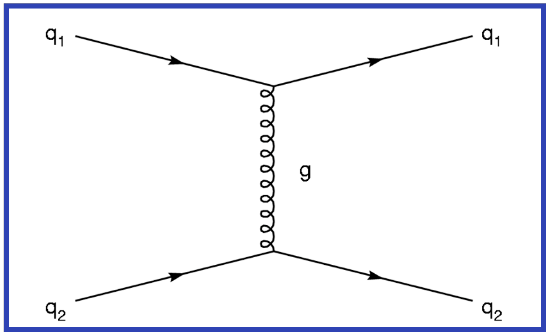

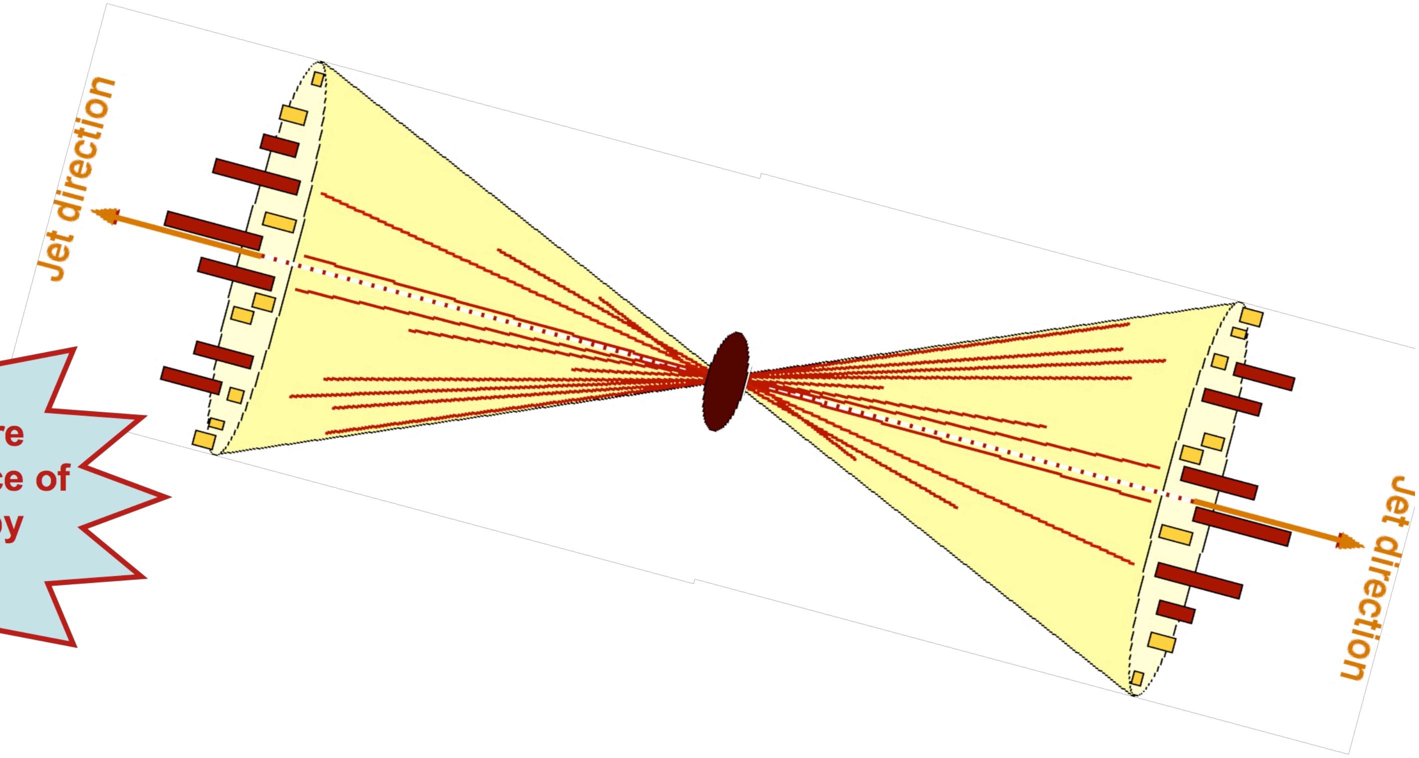

Three-jet events are first direct evidence of gluons observed by TASSO at DESY

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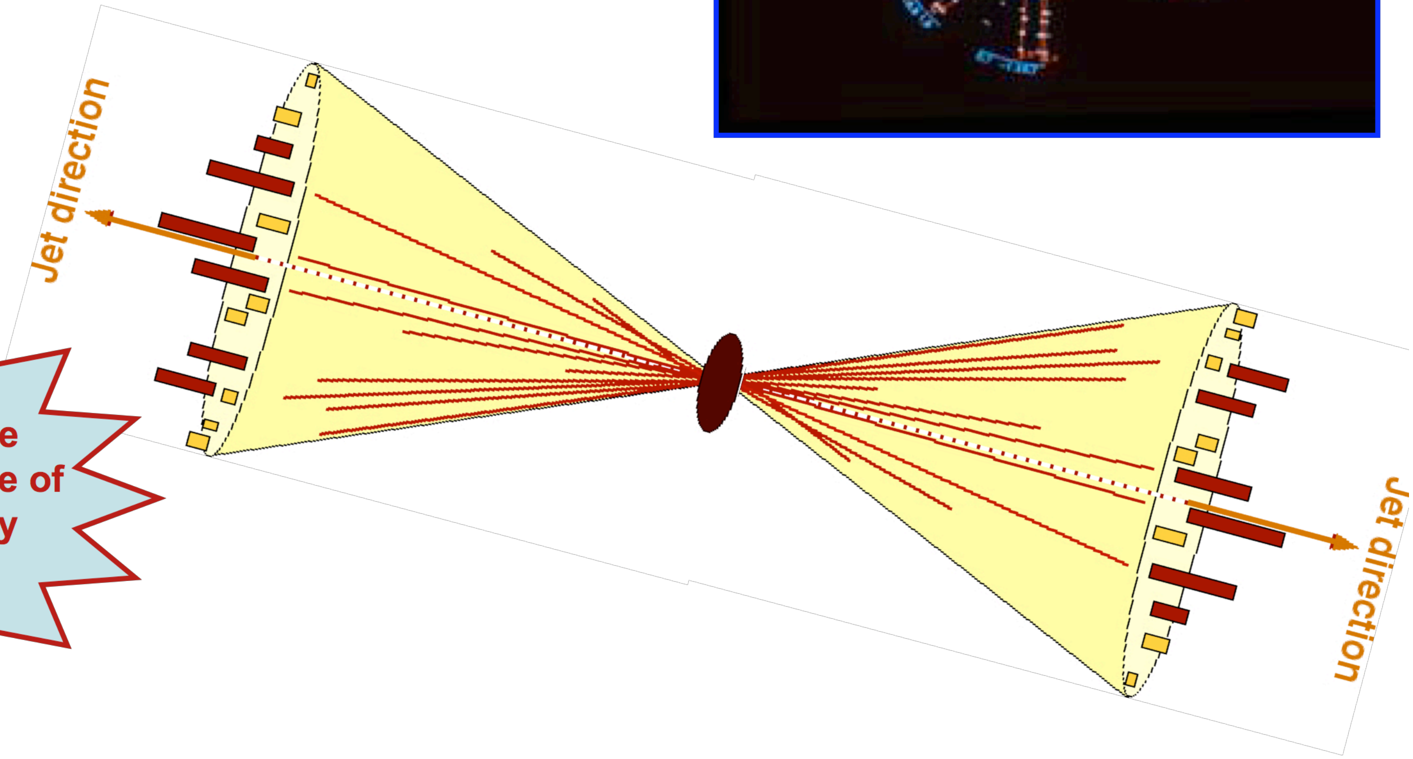
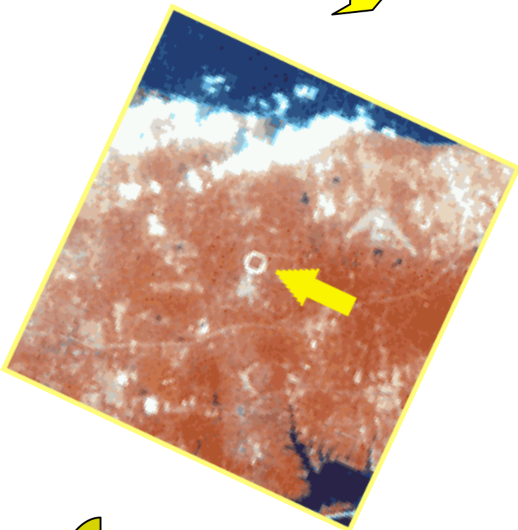
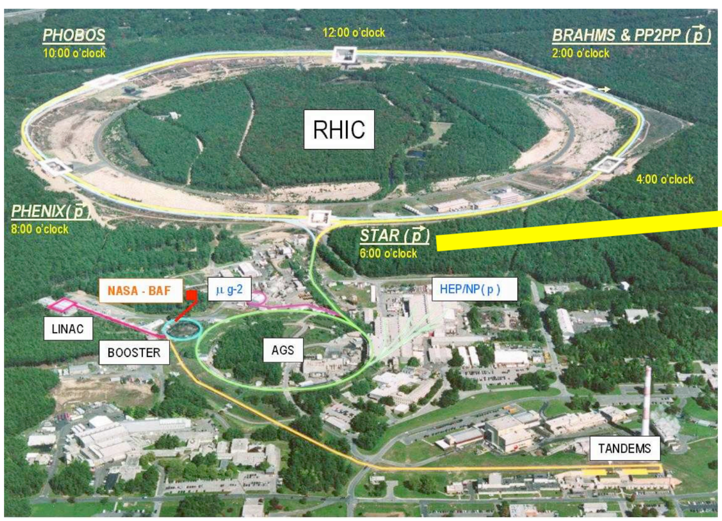
$$E \propto r$$

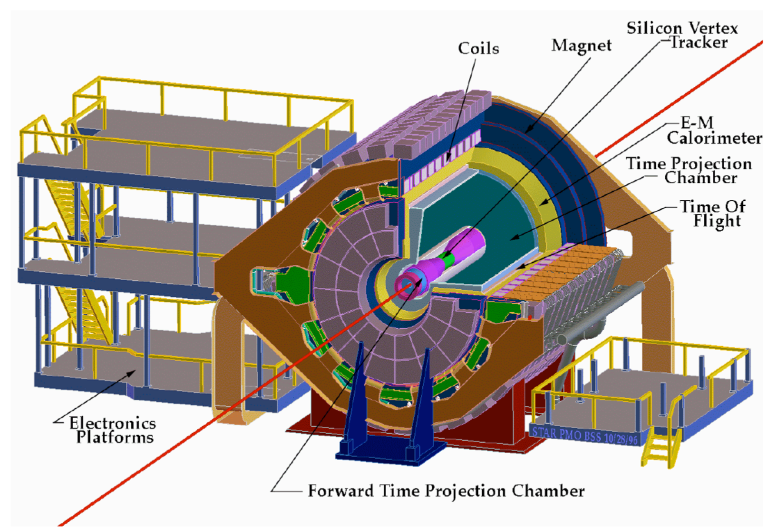


Three-jet events are first direct evidence of gluons observed by TASSO at DESY



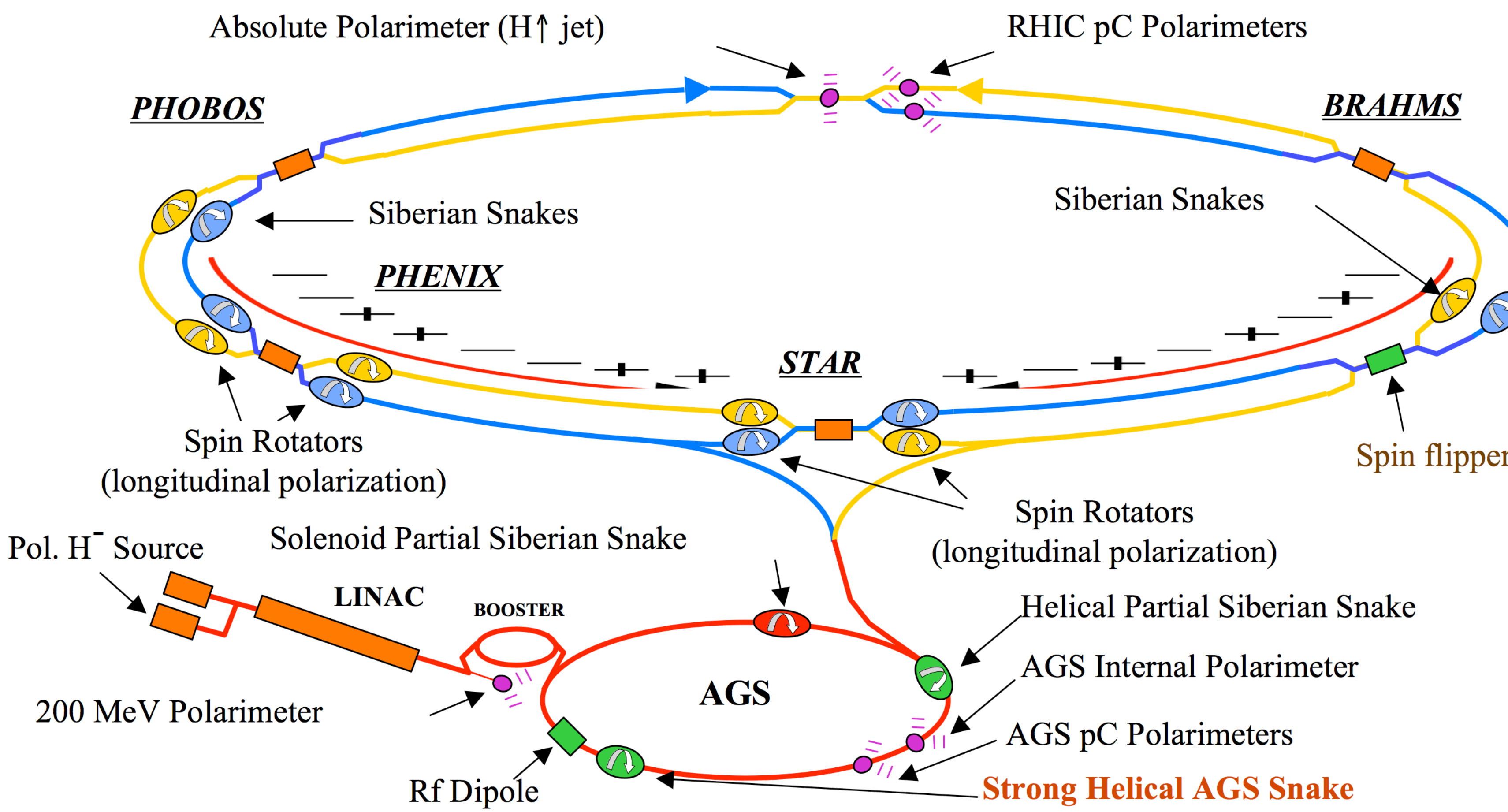
The Experiment





Relativistic Heavy Ion Collider

…worlds 1st $\vec{p}\vec{p}$ Collider



Annual Longitudinal $\vec{p}\vec{p}$ Data Summary for STAR

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	---	---

Annual Longitudinal $\vec{p}\vec{p}$ Data Summary for STAR

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	---	---

1st pp collisions

Annual Longitudinal $\vec{p}\vec{p}$ Data Summary for STAR

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	---	---

1st longitudinal

Annual Longitudinal $\vec{p}\vec{p}$ Data Summary for STAR

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	---	---

JP Trigger Tested

Annual Longitudinal $\vec{p}\vec{p}$ Data Summary for STAR

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	---	---

EEMC Complete

Annual Longitudinal $\vec{p}\vec{p}$ Data Summary for STAR

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	---	---

Shielding Installed (2006)

Annual Longitudinal $\vec{p}\vec{p}$ Data Summary for STAR

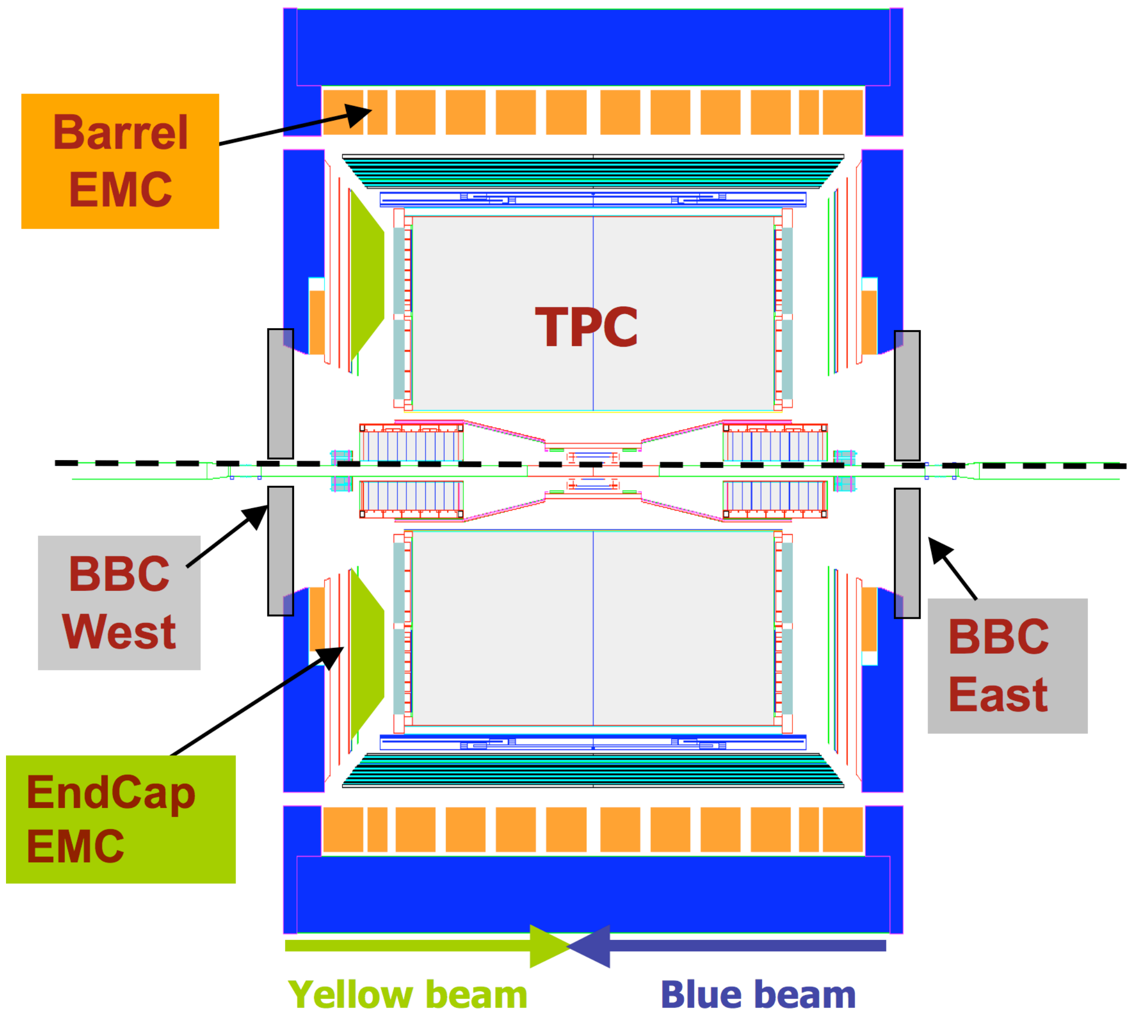
year	<*pol*>	Sampled (pb^{-1})	Analyzed (pb^{-1})
2002	15	---	----
2003	30	0.3	0.18
2004	45	0.4	0.12
2005	50	3.1	2.1
2006	60	6.8	5.5
2007	----	---	---
2008	45	---	---

BEMC Complete

Annual Longitudinal $\vec{p}\vec{p}$ Data Summary for STAR

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	---	---

STAR Detector components used in jet reconstruction



TPC |η|<1.4	Charged particle momentum
BEMC |η|<1.0	Neutral Energy High pT Trigger
EEMC 1<η<2	Neutral Energy High pT Trigger
BBC 3.4<η<5	MinBias Trigger Relative Lumi

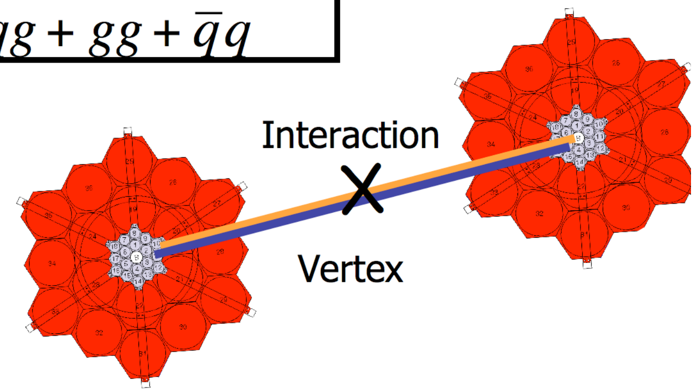
$$\eta = -\ln[\tan(\Theta/2)]$$

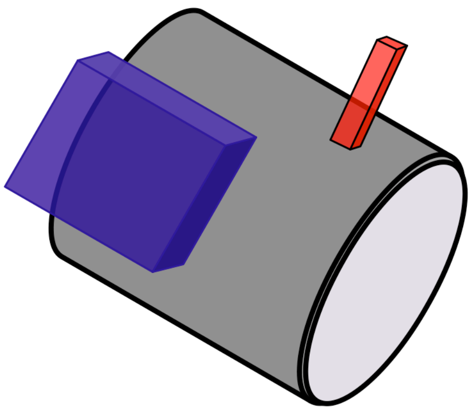
STAR Trigger

Composition of $\vec{p}\vec{p}$ 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

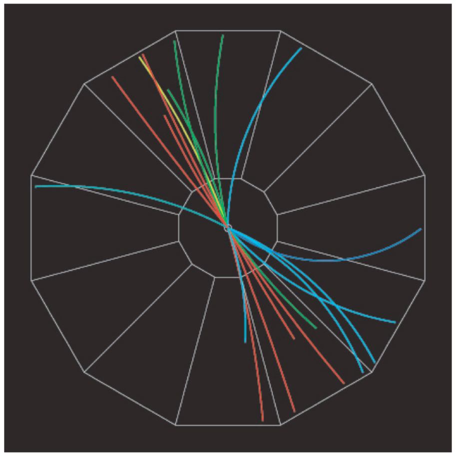


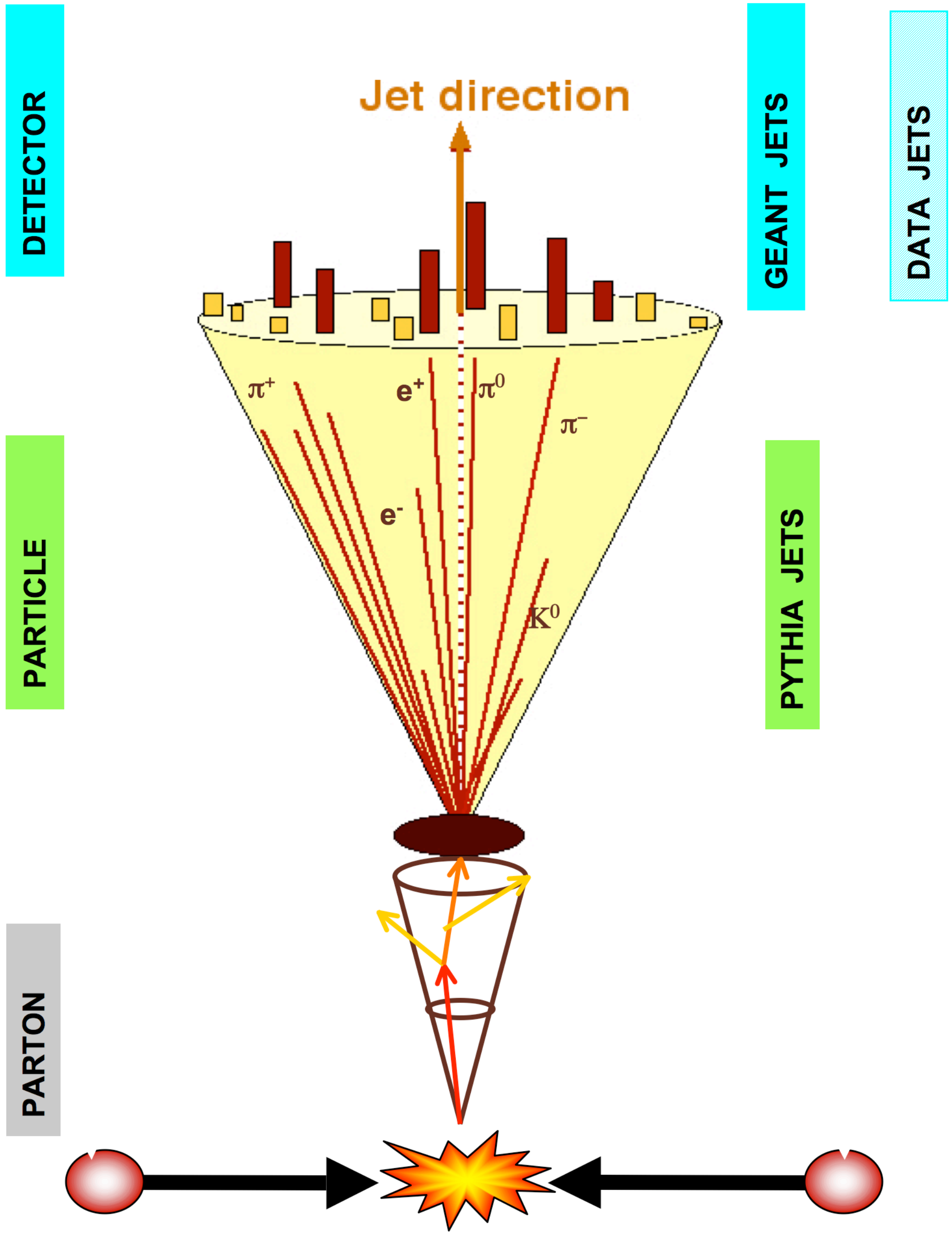


High Tower	1 tower $(\Delta\eta = \Delta\phi = 0.05)$ above threshold Requires hard neutral fragmentation
Jet Patch (2005/6 only)	400 localized towers $(\Delta\eta = \Delta\phi = 1)$ above threshold. Allows for cluster of softer fragmentation

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

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

What do STAR jets look like?

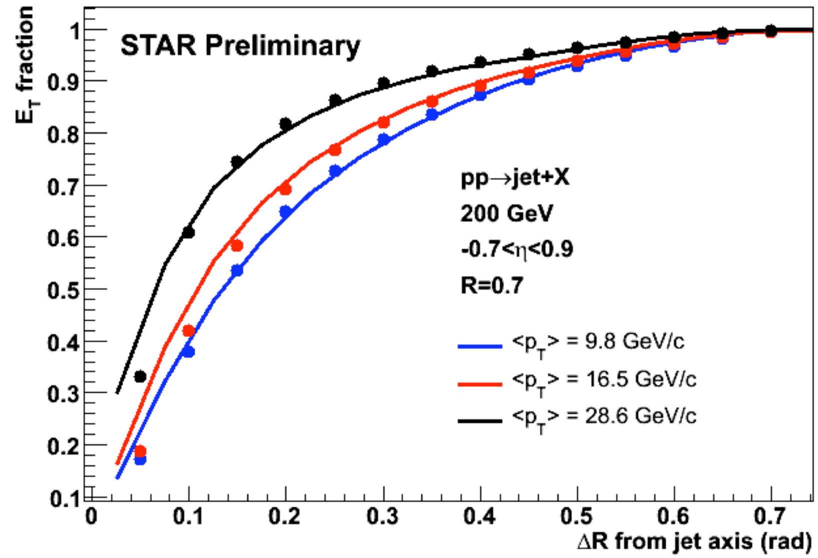
Midpoint cone algorithm
(Adapted from Tevatron II - hep-ex/0005012)

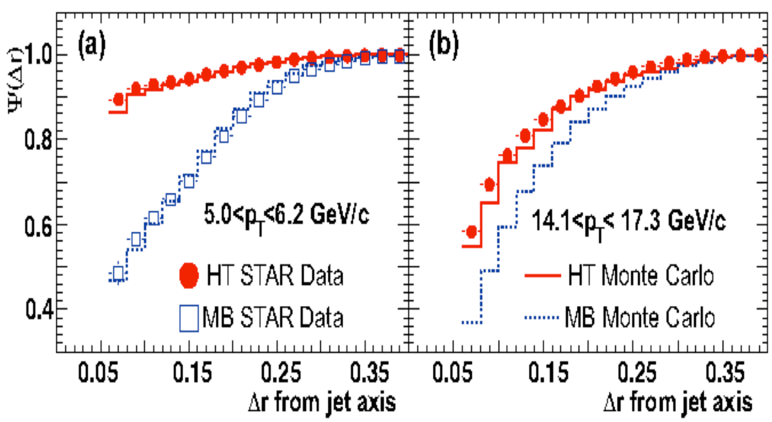
Seed energy = 0.5 GeV

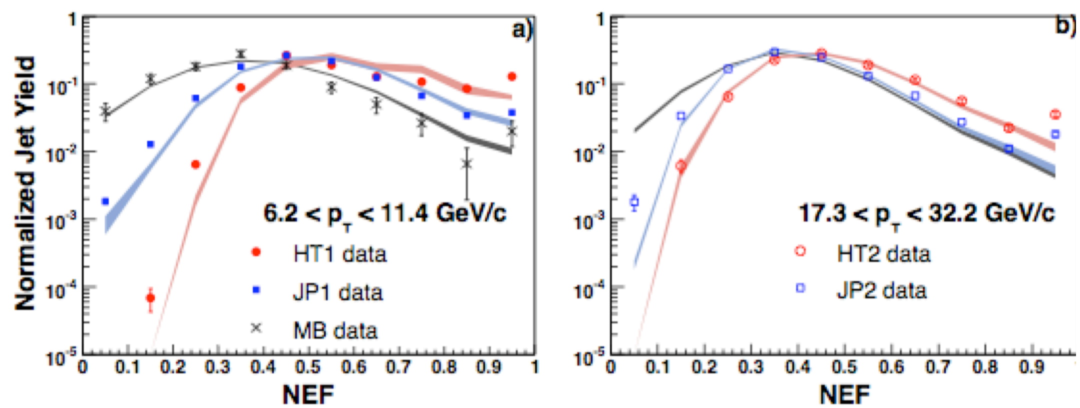
Cone radius in η-ϕ
R=0.4 with 0.2 < η < 0.8 (2003-2005)
R=0.7 with -0.7 < η < 0.9 (2006)

Splitting/merging fraction f=0.5

2006



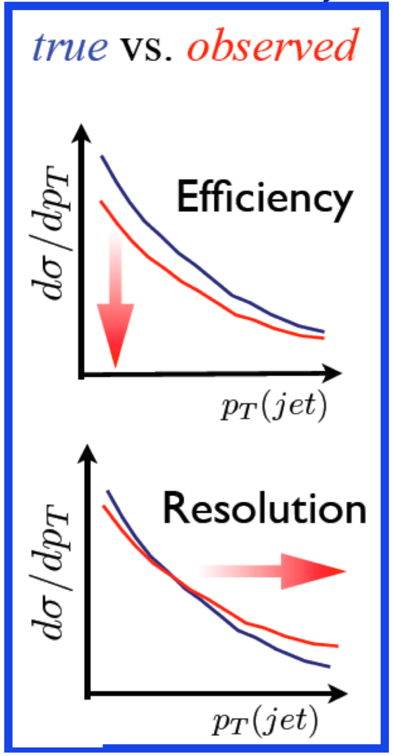


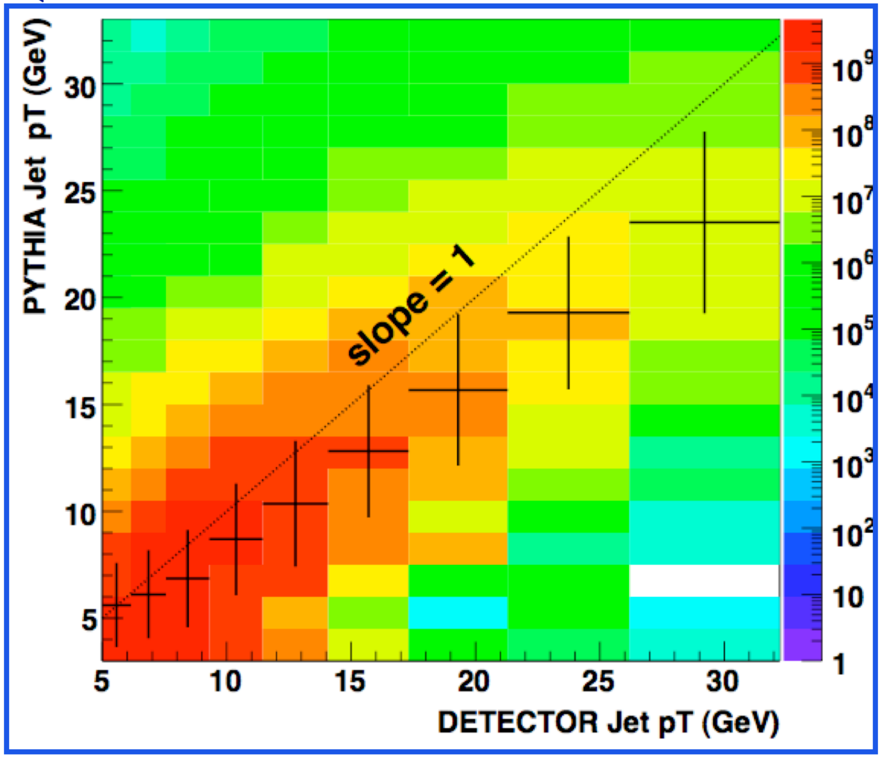


2004

2005

STAR Jet p_T Scale Corrections & Systematics





TYPE of JET	Scale
Beam Pile Up	5/50 MeV
Beam Backgrounds	---
Trigger	----
Detector Resolution	0.2-10 GeV
Detector Efficiency & Fiducial Cuts	
Particle (Hadronization + Underlying Event)	+4% sys
Beyond NLO (Fragmentation)	
NLO	μ

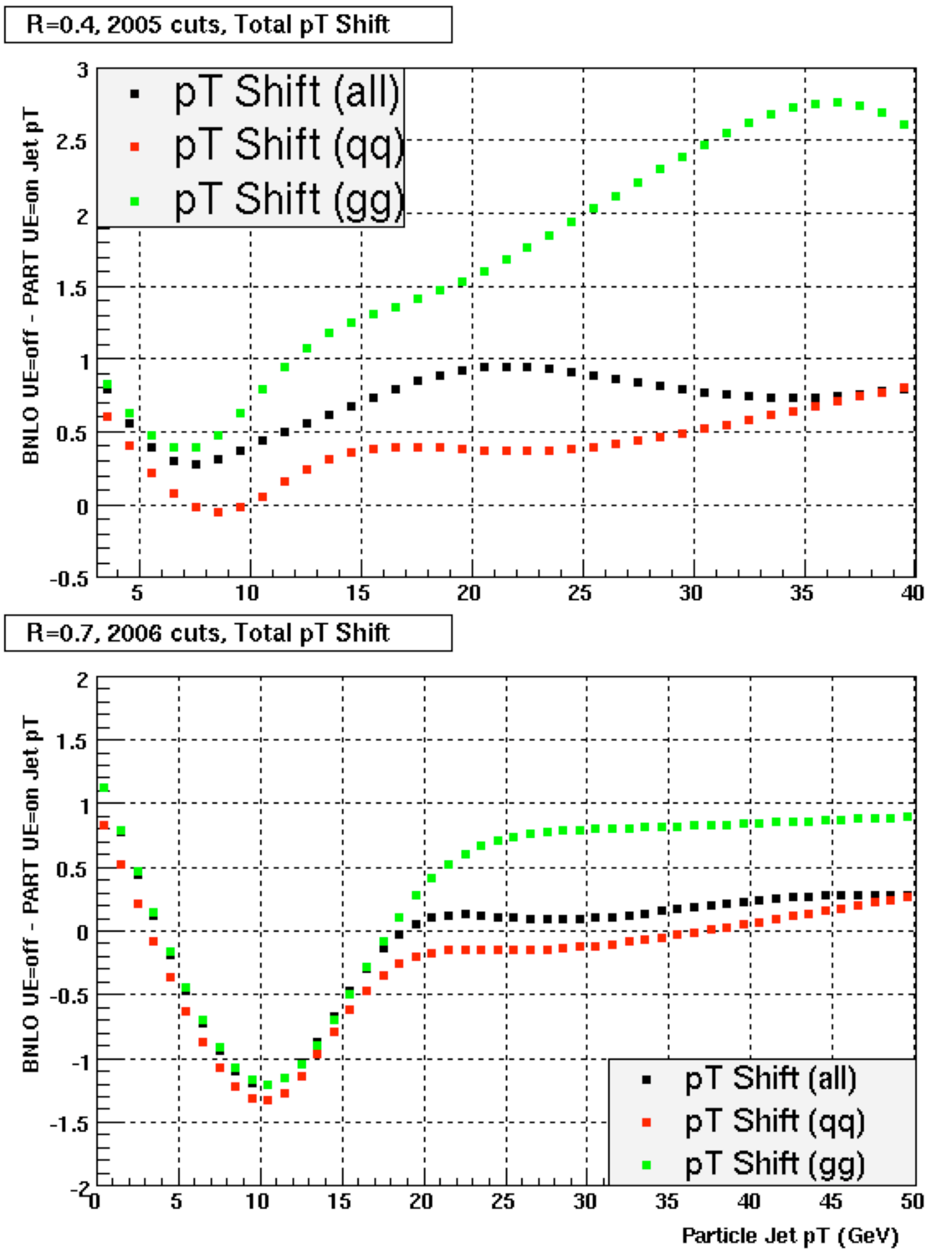
Largest effects are Detector Related:

Resolution: ~25% + Inefficiency: ~10%

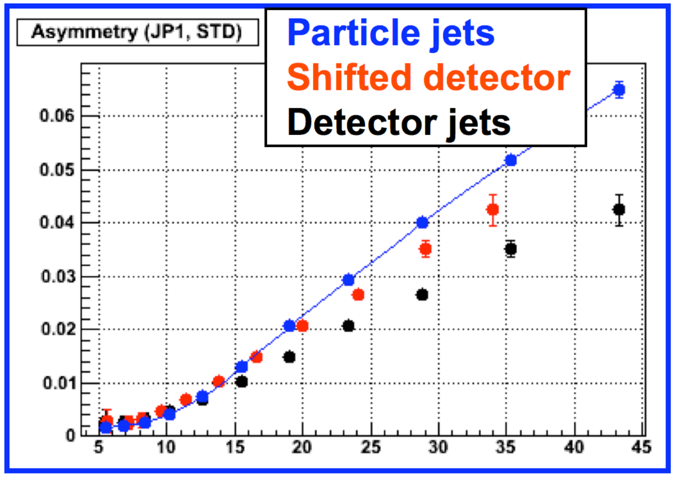
CORRECTIONS made to final pT distributions using STAR PYTHIA+ GEANT simulations.

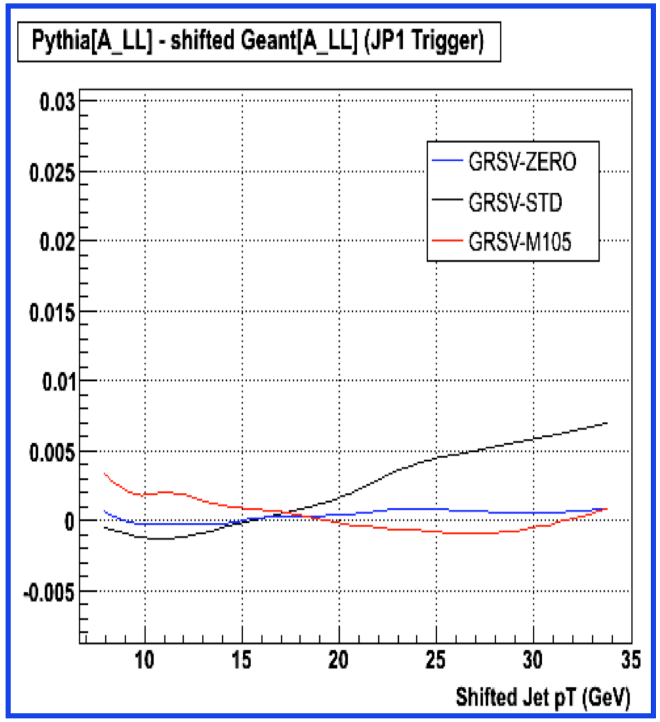
Hadronization and Underlying Event Systematic

1. Estimated completely from generator level Monte Carlo (PYTHIA)
2. Uses same jet algorithm as used in data and GEANT simulations
3. Compare jets found at the particle level with UE+HAD on to jets found at the parton level with UE+HAD off.
4. Hadronization causes energy to fall out of the cone. Effect is larger for R=0.4 than R=0.7
5. Underlying event contributes energy to the cone for both R=0.4 and R=0.7
6. Unfortunately there is a subprocess dependence



Trigger Bias Dominates the Asymmetry Systematics

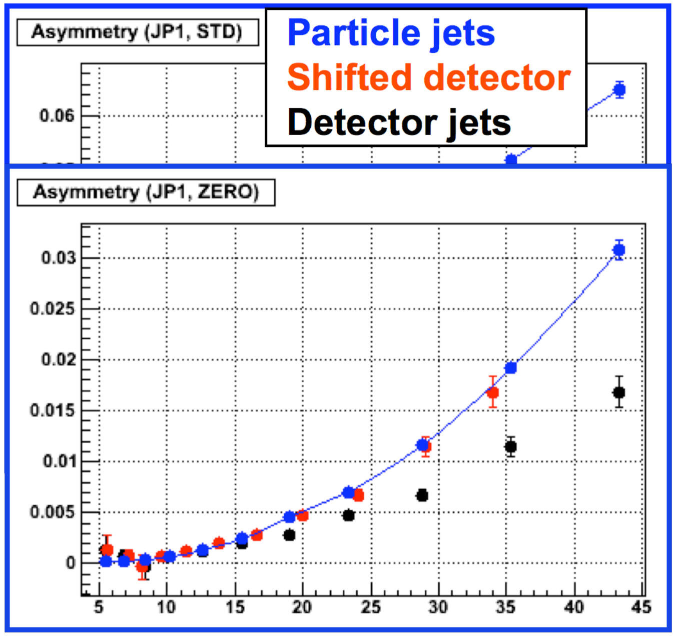


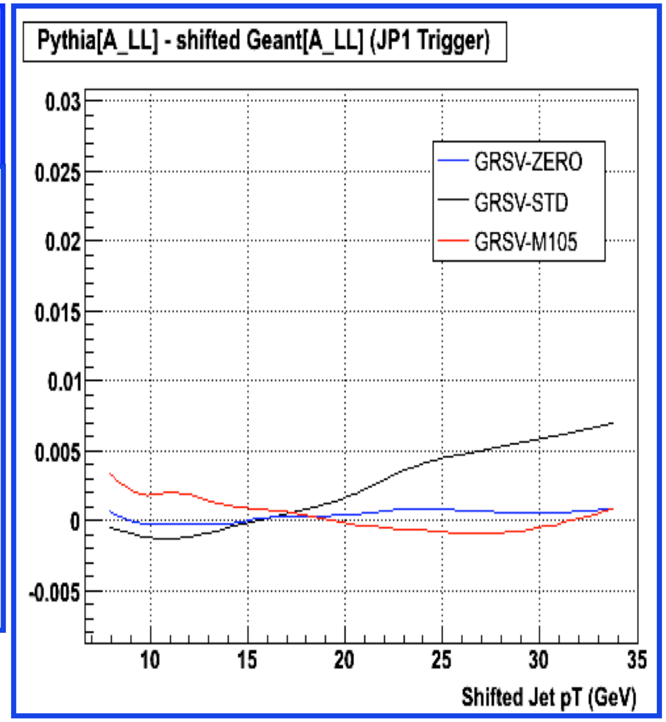


TYPE of JET	SPIN
Beam Pile Up	---
Beam Backgrounds	0.7 $\times 10^{-3}$
Trigger	2-5 or -1-3 $\times 10^{-3}$ p_T dep
Detector Resolution	
Detector Efficiency & Fiducial Cuts	
Particle (Hadronization + Underlying Event)	small Inc. in p_T sys.
Beyond NLO (Fragmentation)	
NLO	a_{LL}

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

Trigger Bias Dominates the Asymmetry Systematics





TYPE of JET	SPIN
Beam Pile Up	---
Beam Backgrounds	0.7 $\times 10^{-3}$
Trigger	2-5 or -1-3 $\times 10^{-3}$ p_T dep
Detector Resolution	
Detector Efficiency & Fiducial Cuts	
Particle (Hadronization + Underlying Event)	small Inc. in p_T sys.
Beyond NLO (Fragmentation)	
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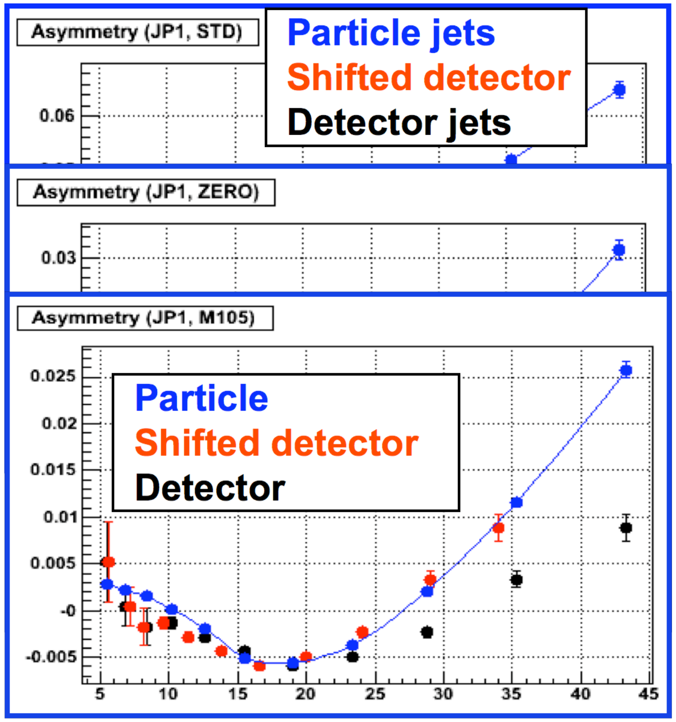
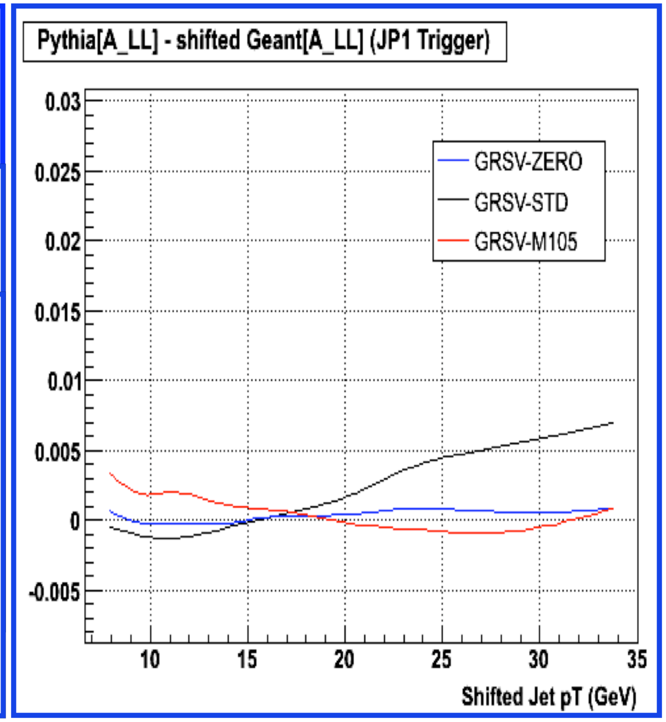
Trigger Bias Dominates the Asymmetry Systematics

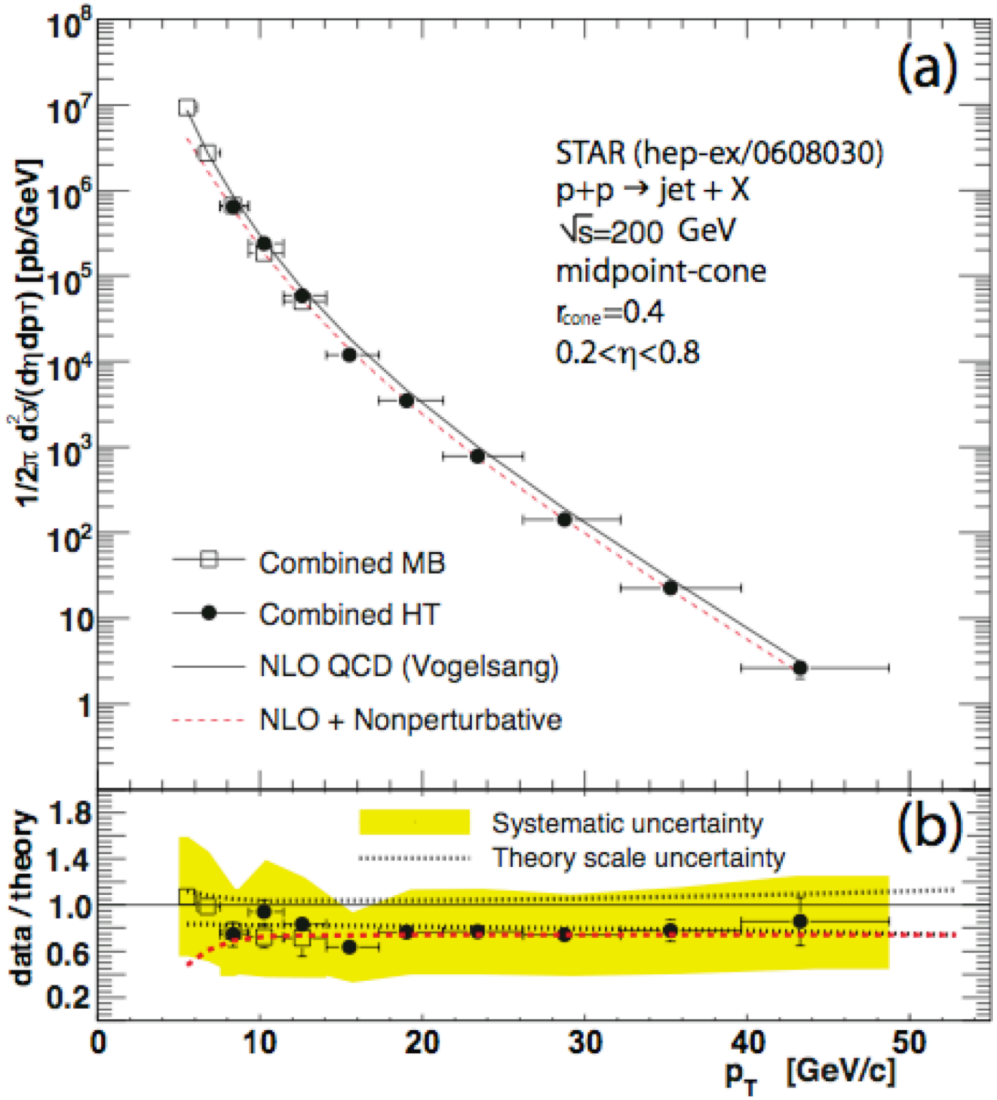




TYPE of JET	SPIN
Beam Pile Up	---
Beam Backgrounds	0.7 $\times 10^{-3}$
Trigger	2-5 or -1-3 $\times 10^{-3}$ p_T dep
Detector Resolution	
Detector Efficiency & Fiducial Cuts	
Particle (Hadronization + Underlying Event)	small Inc. in p_T sys.
Beyond NLO (Fragmentation)	
NLO	a_{LL}

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

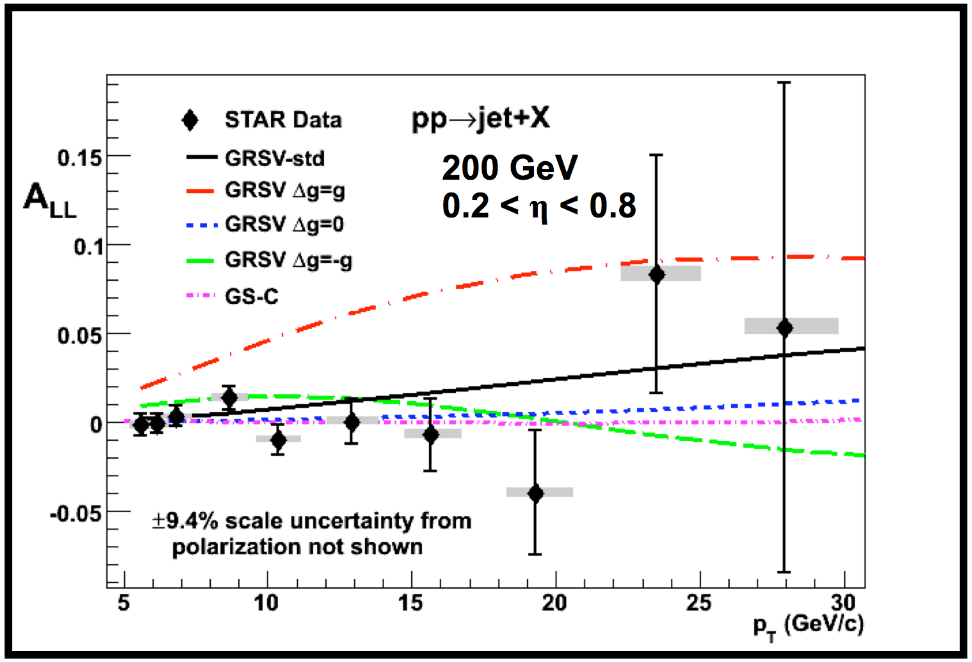
2003/2004 Inclusive Jet Cross-Section Results

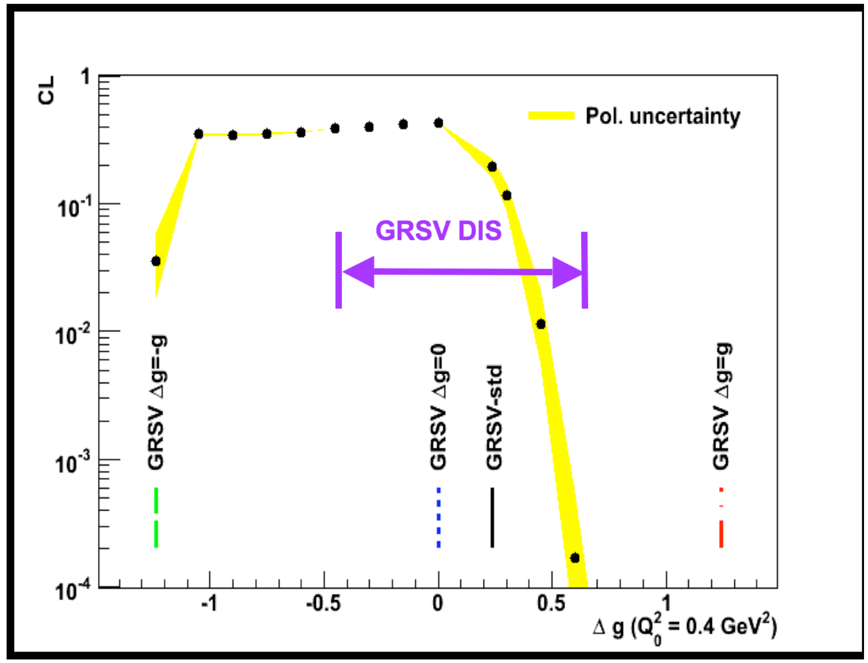


$$\frac{1}{2\pi}\frac{d^2\sigma}{d\eta dp_T} = \frac{1}{2\pi}\cdot\frac{N_{Jets}}{\Delta\eta\Delta p_T}\cdot\frac{1}{\int Ldt}\cdot\frac{1}{c(p_T)}$$

- 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!**

Inclusive Jet Asymmetries (2005) *PRL 100:23, 2008*



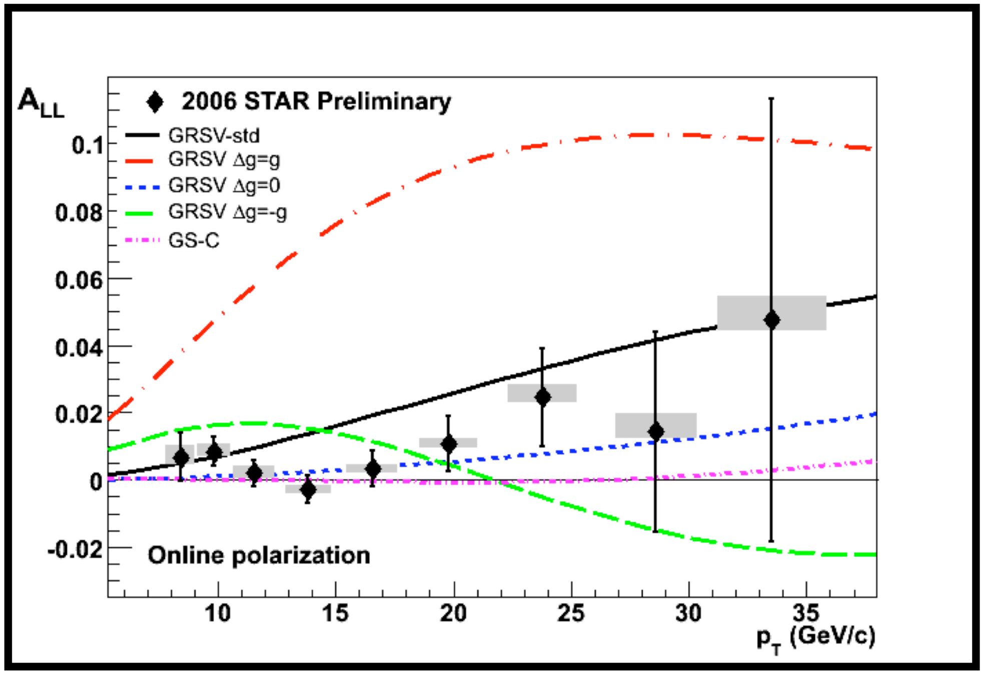


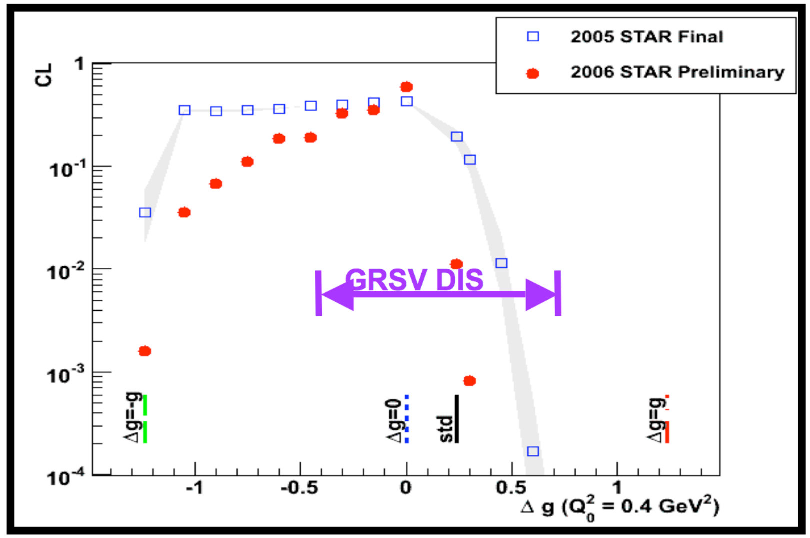
A_{LL} systematics	(x 10^{-3})
Reconstruction + Trigger Bias	2-5 (p_T dep)
Non-longitudinal Polarization	0.1-0.8 (p_T dep)
Relative Luminosity	0.94
Backgrounds	0.70
p_T systematic	[-5.4%,+6.7%]

Quantifies the effects from non-longitudinal components of spin in the colliding protons. Includes a measurement of A_Σ in transverse.

Quantifies the limitations in measuring the luminosity associated with each spin state. Based on BBC-ZDC comparisons.

Inclusive Jet Asymmetries (2006) provide significant new constraints on ΔG!



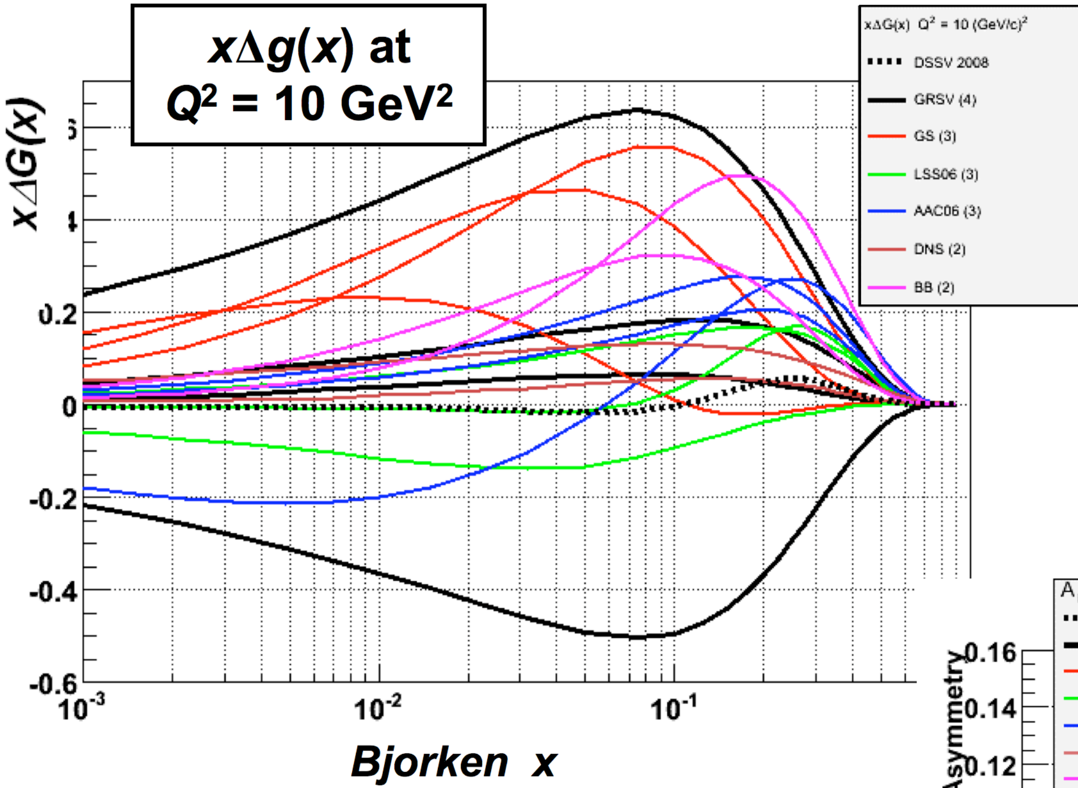


2006 Improvements:

- Full BEMC
- Jet finder extends into EEMC
- Cone radius enlarged to 0.7
- Increases in luminosity and polarization
- Statistical uncertainties are 3x-4x smaller for high pT (pT > 13 GeV).

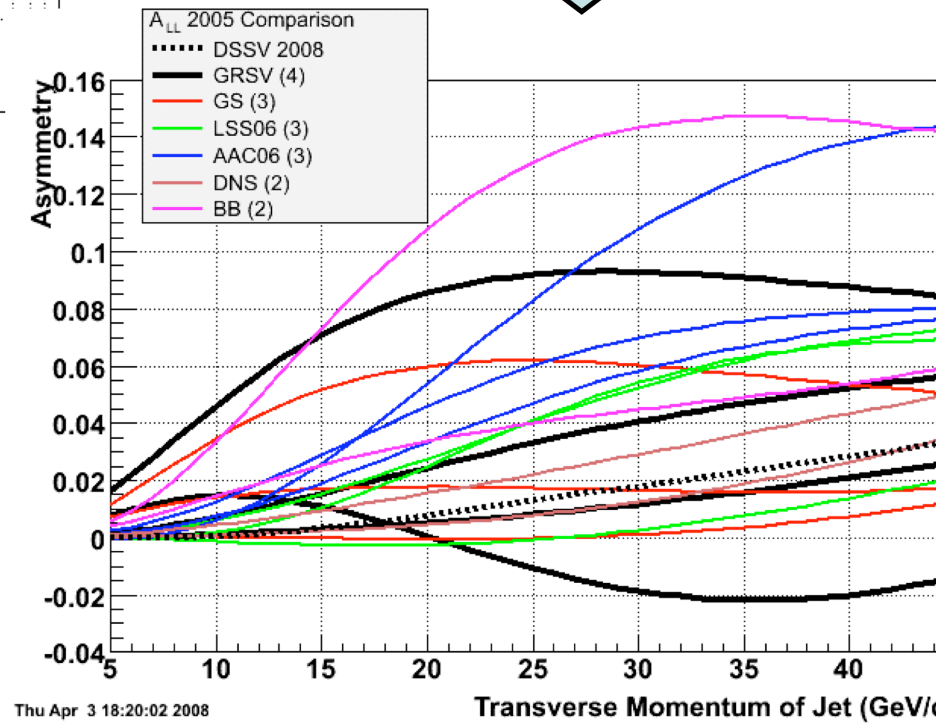
A_{LL} systematics	(x 10^{-3})
Reconstruction + Trigger Bias	[-1,+3] (p_T dep)
Non-longitudinal Polarization	~ 0.03 (p_T dep)
Relative Luminosity	0.94
Backgrounds	1st bin ~ 0.5 all others ~ 0.1

p_T systematic	±6.7%

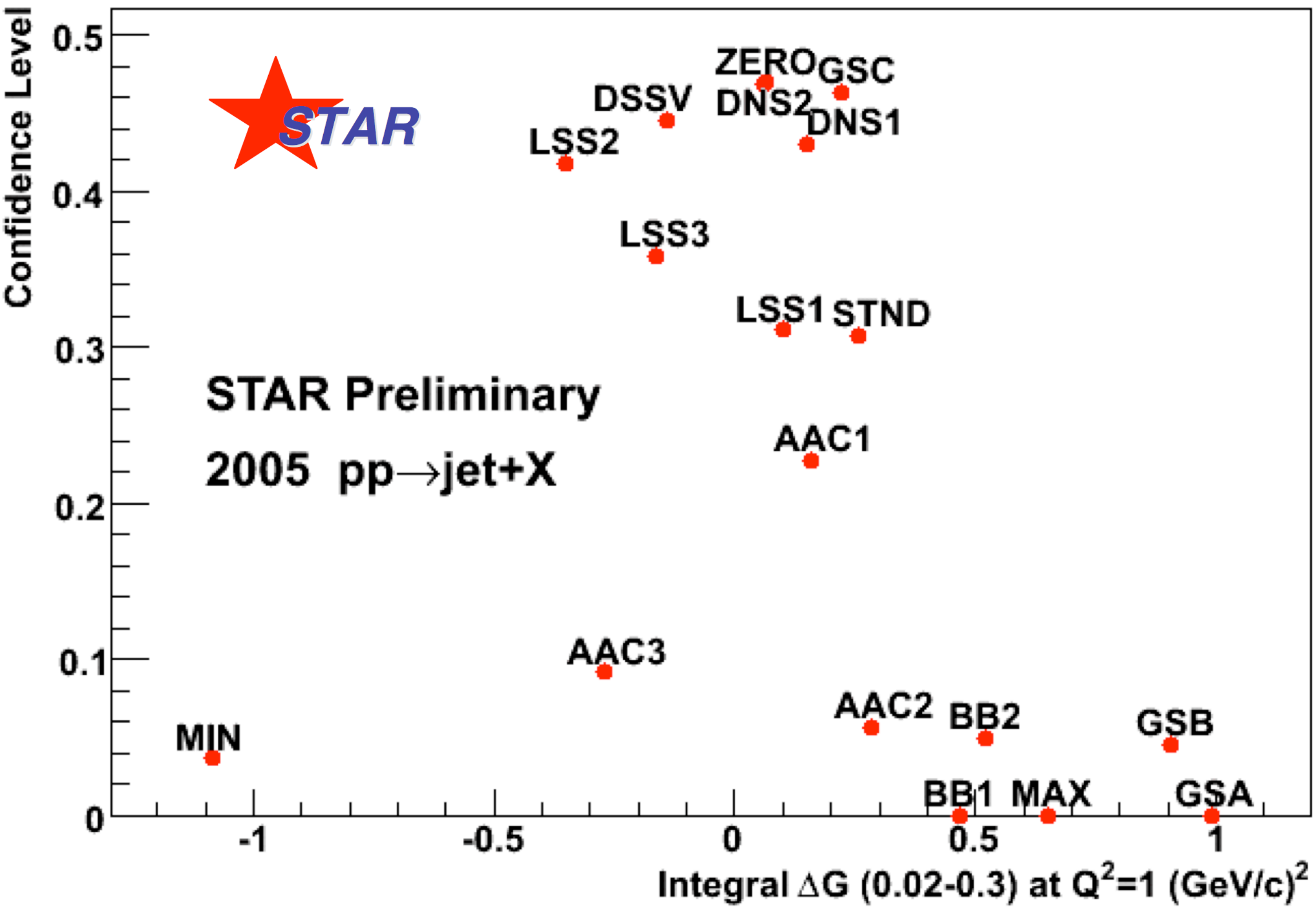


There are many predictions for $\Delta g(x)$ vs x which can be translated into predictions for A_{LL} vs. jet p_T

Sensitivity to GRSV is not unique! STAR data constrain several models



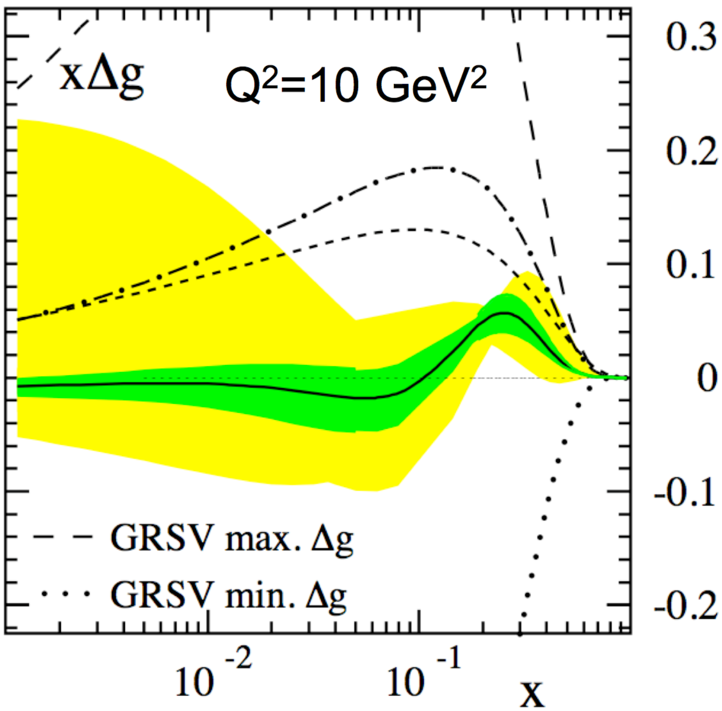
Comparison to other global analyses

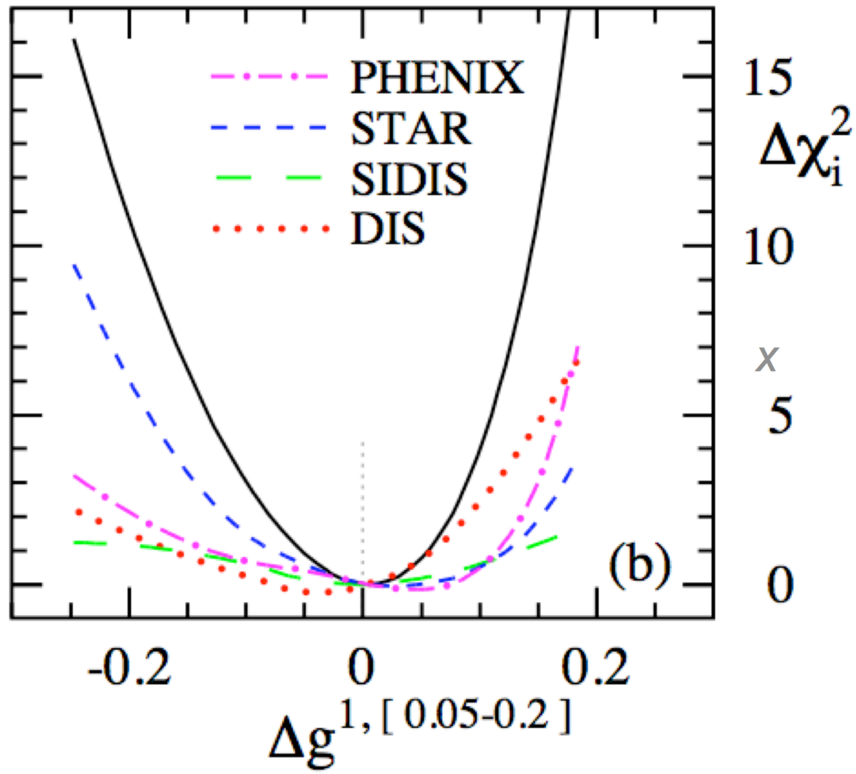


1. *The STAR data exclude a broad range of models that have ΔG larger than that in GRSV-std*
2. *The counterexample is GS-C, which is negative at large x, has a node near x ~ 0.1, and has a large first moment at small x*

New Global Analysis with all World Data - including RHIC Results!

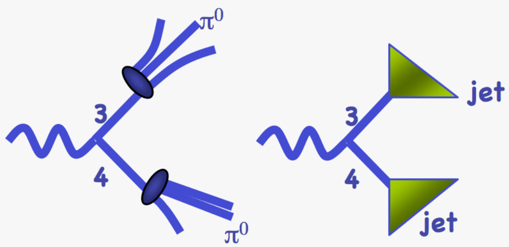
DeFlorian, Sassot, Stratmann and Vogelsang, Phys.Rev.Lett. 101:072001, 2008



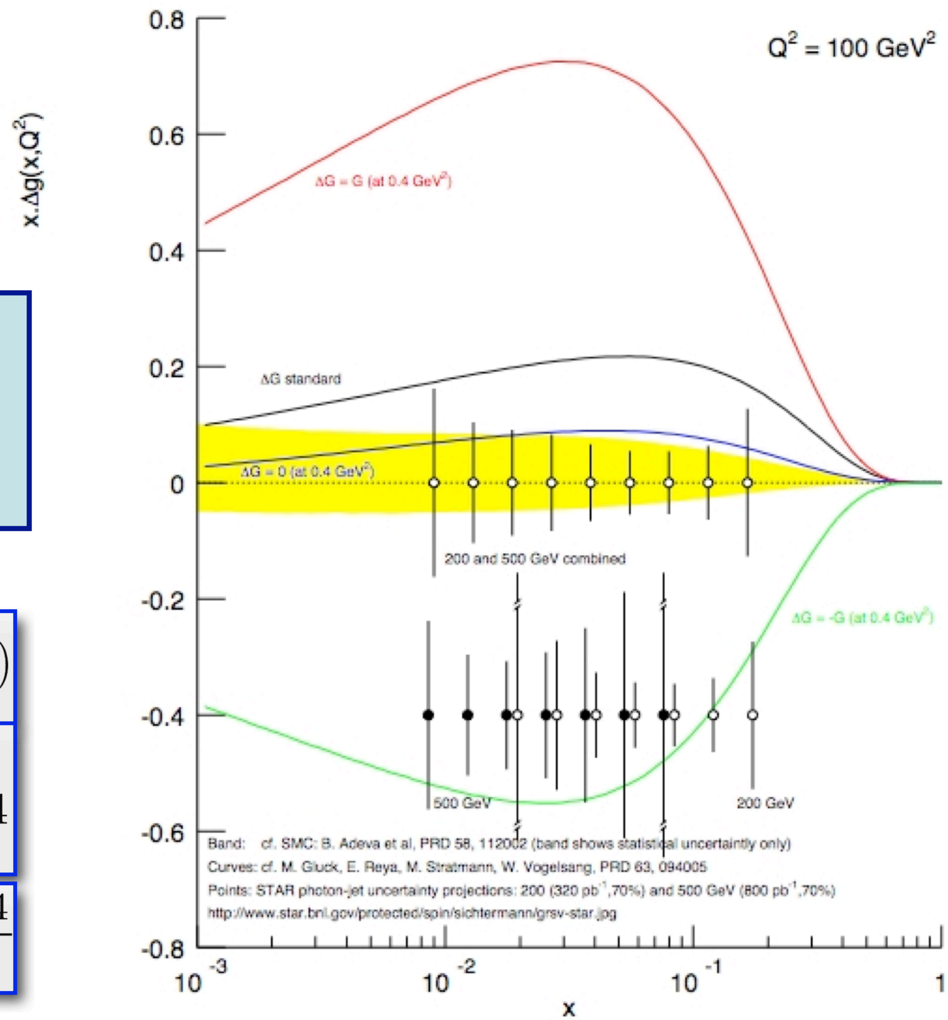


Final States

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



Sample a different <x> range with 500 GeV running



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

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

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

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

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 jet measurements rule out substantial phase space compared to DIS, but cannot be translated easily into a direct ΔG value.

• A recent Global Analysis of all DIS, SIDIS, STAR and PHENIX data has indicated ΔG is small and doesn't appear to provide remaining spin of proton.

• This initial conclusion needs to be verified by probing the lower x region of the integral - where the gluon density increases rapidly.

• 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.

BACKUP

RHIC and JLAB → Diverging Paths?

Ji:

Measured in DVCS

$$\frac{1}{2} = L_q + \frac{1}{2}\Delta\Sigma + J_g$$

Jaffe:

Measured in DIS+RHIC

$$\frac{1}{2} = l_q + l_g \frac{1}{2}\Delta\Sigma + \Delta G$$

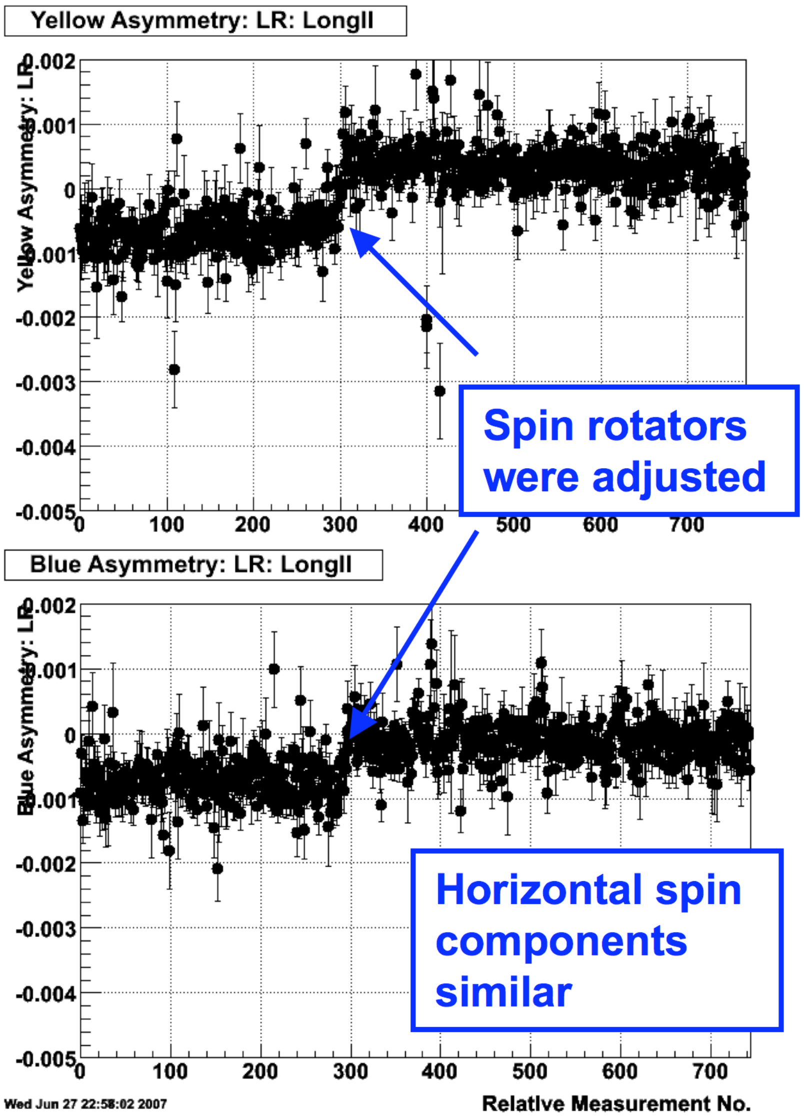
L_q, 1/2 ΔΣ and J_g terms are each gauge invariant. But the separate gluon spin and OAM terms are NOT gauge invariant.

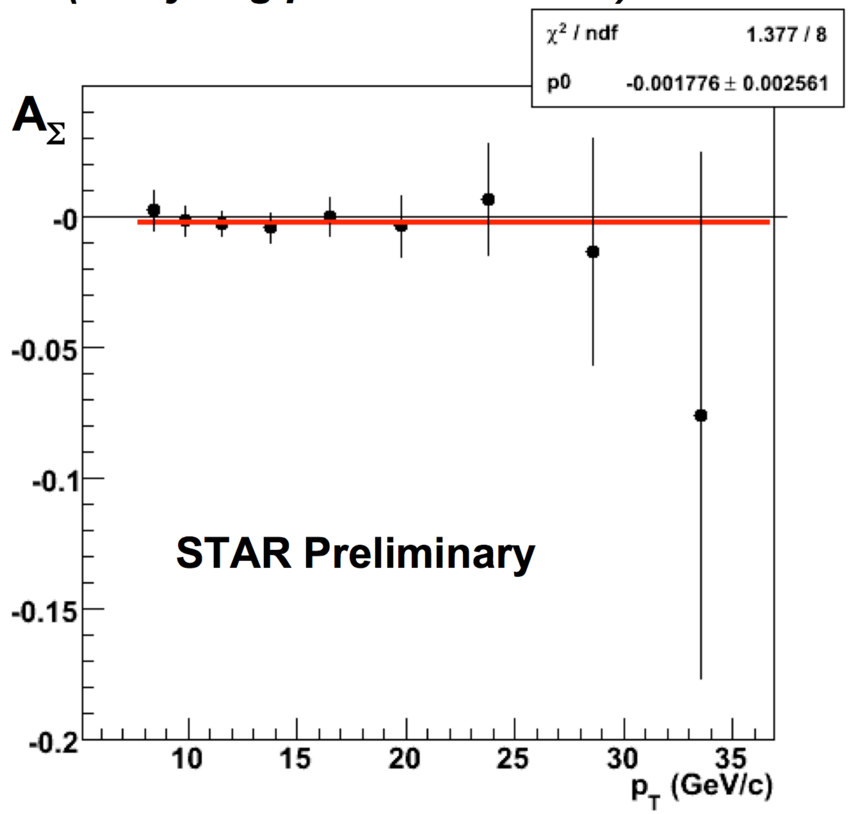
$$J_g \neq l_g + \Delta G$$

l_g, l_q, 1/2 ΔΣ, ΔG terms are gauge invariant. But no clear experimental way to measure l_g or l_q yet!

Residual Transverse Polarization Systematic

BBC measures blue and yellow residual transverse components during longitudinal run (analyzing power 6~7 x 10^{-3})



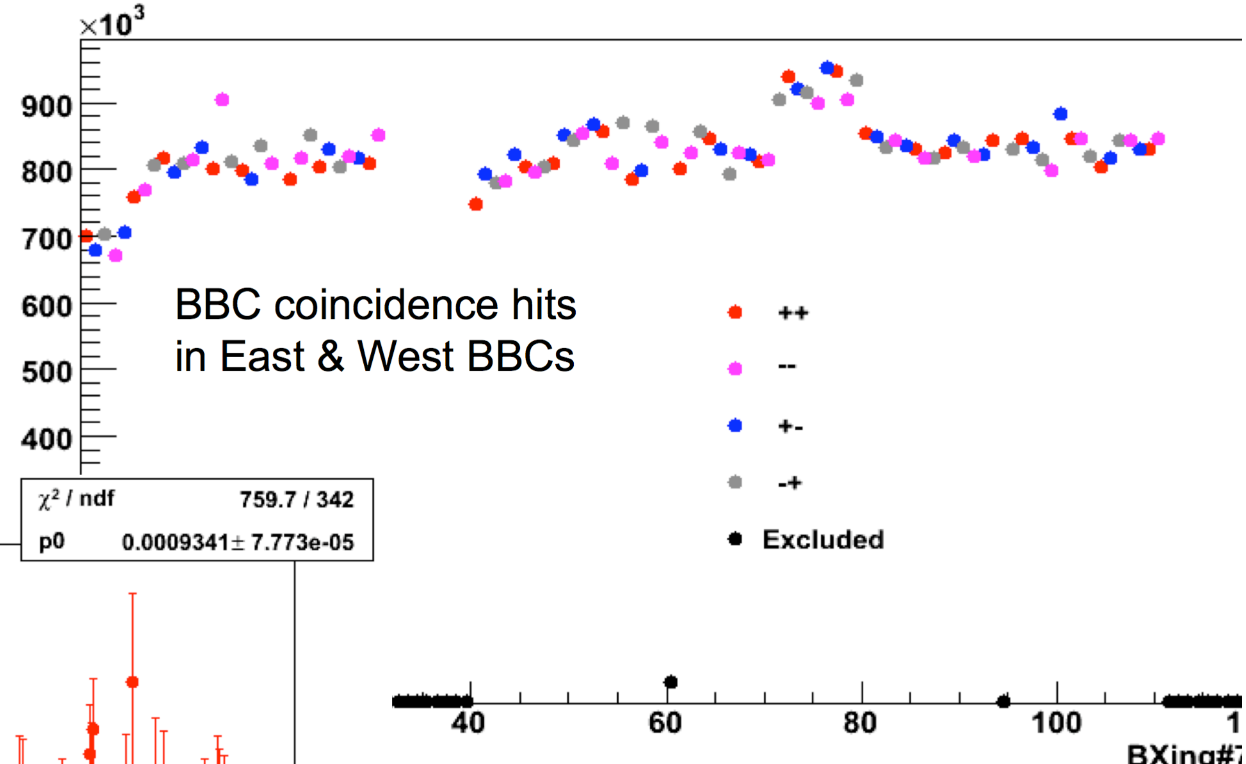


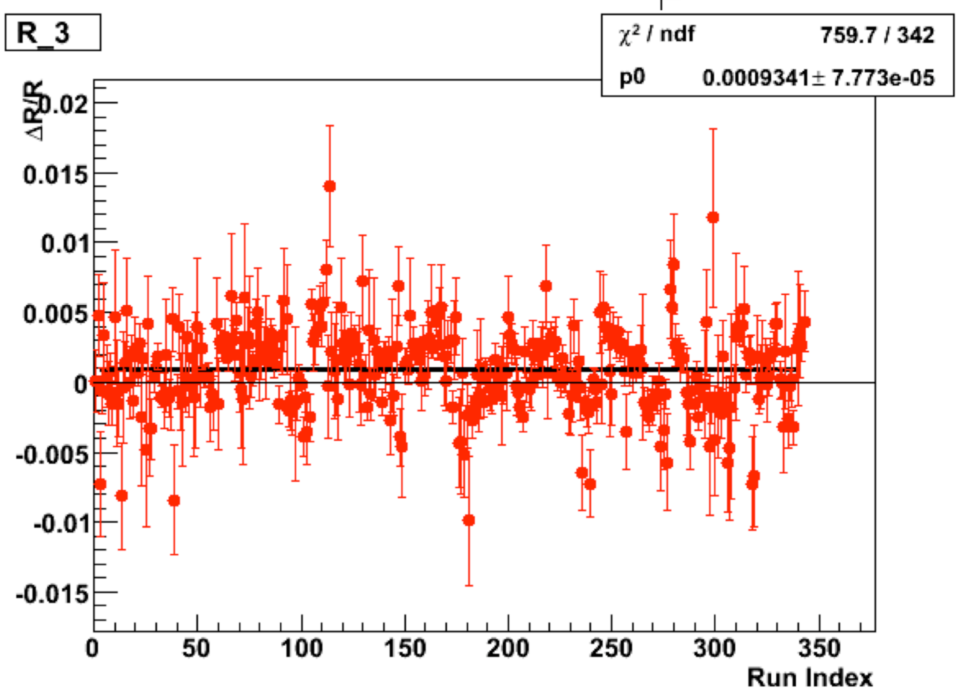
Measure A_Σ in transverse running. Combine with transverse components to set an upper limit on the contribution to the A_{LL} measurement from non-longitudinal polarization components

Relative Luminosity Systematic

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

ΔA_{LL} (BBC&ZDC) ~ 9.4×10^{-3}

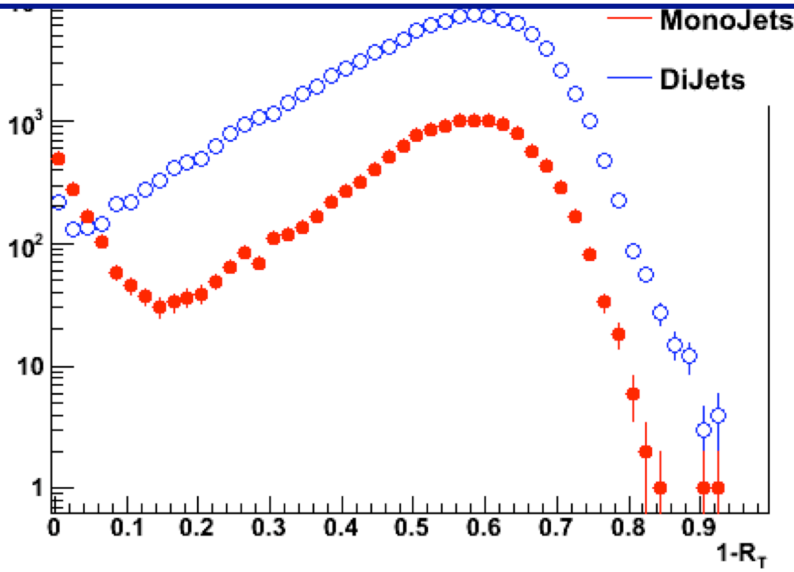




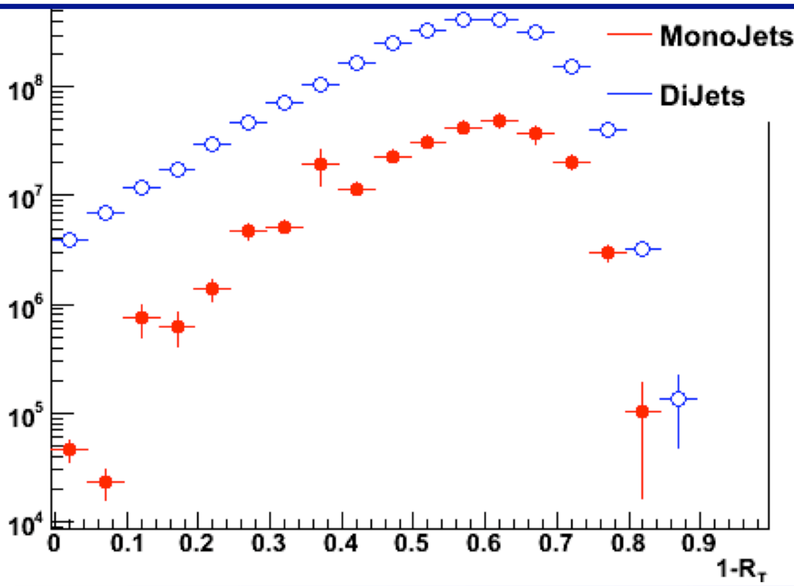
Relative luminosity systematic calculated from BBC and ZDC asymmetry comparison

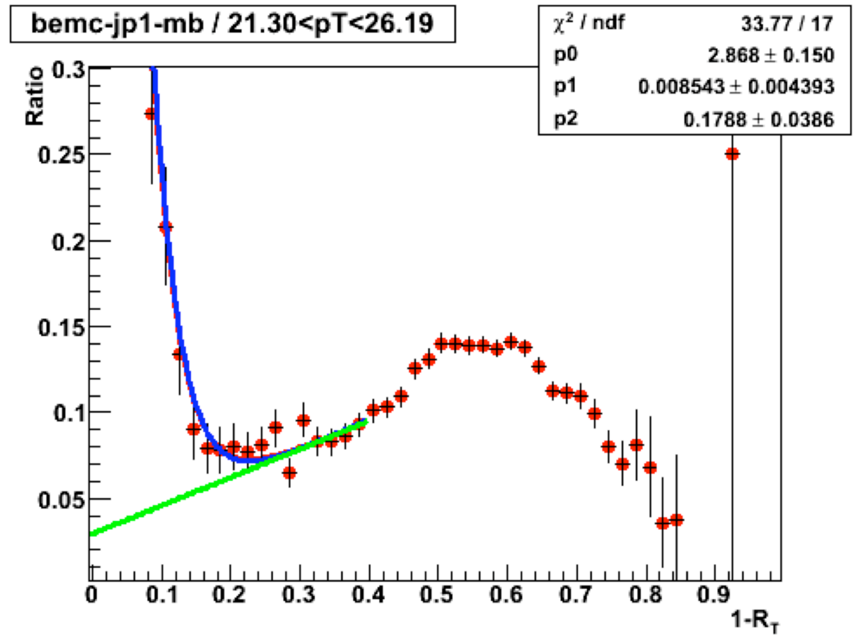
Beam Gas Background

JP1 Data (21.30< pT<26.19)



JP1 Simulation (21.30< pT<26.19)





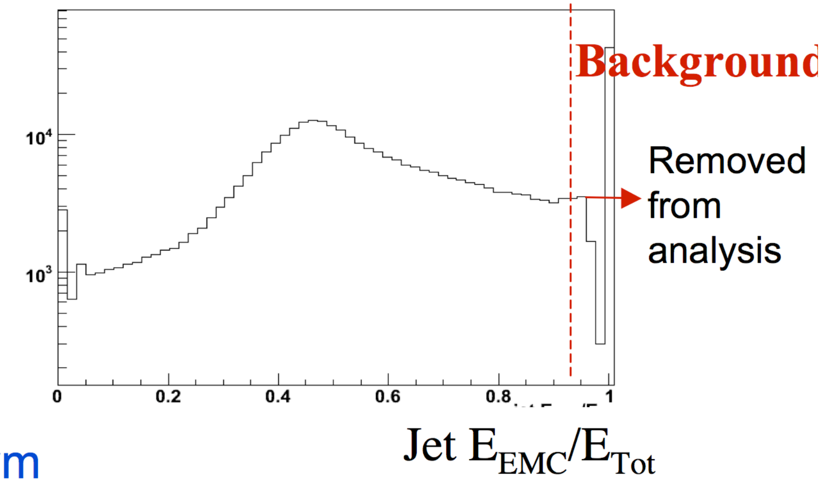
1. Measure Background A_{LL} in monojets (R_T>0.95)
2. Determine fraction background/signal

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

A_{LL} Systematics: 2005 Background Estimate

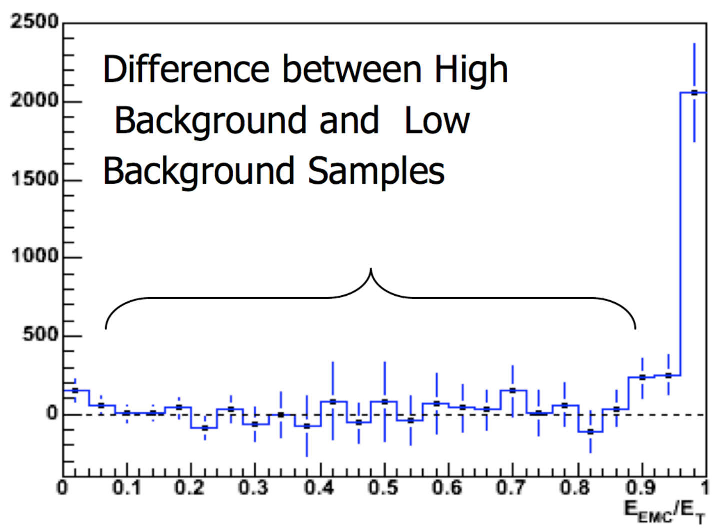
Background manifests itself as jets with large neutral energy deposit

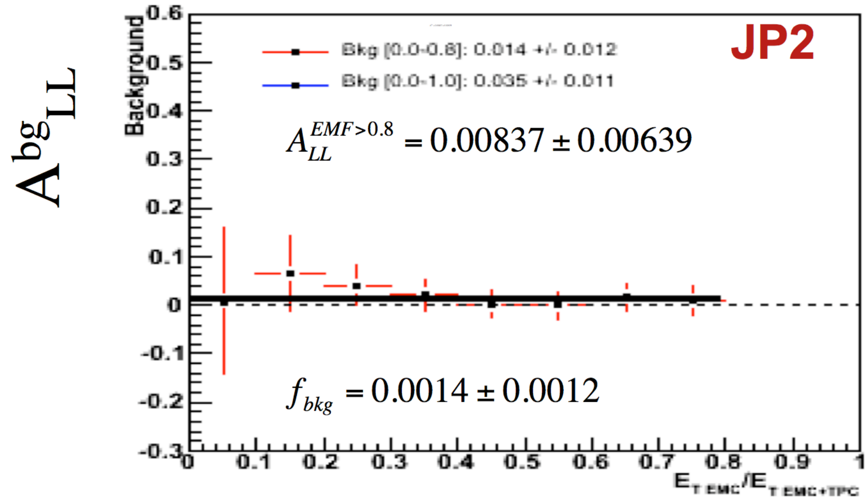
$$A_{LL}^{meas}(p_T) = \frac{A_{LL}(p_T) + f_{bg}(p_T) \times A_{LL}^{bg}(p_T)}{1 + f_{bg}(p_T)}$$



Background Fraction

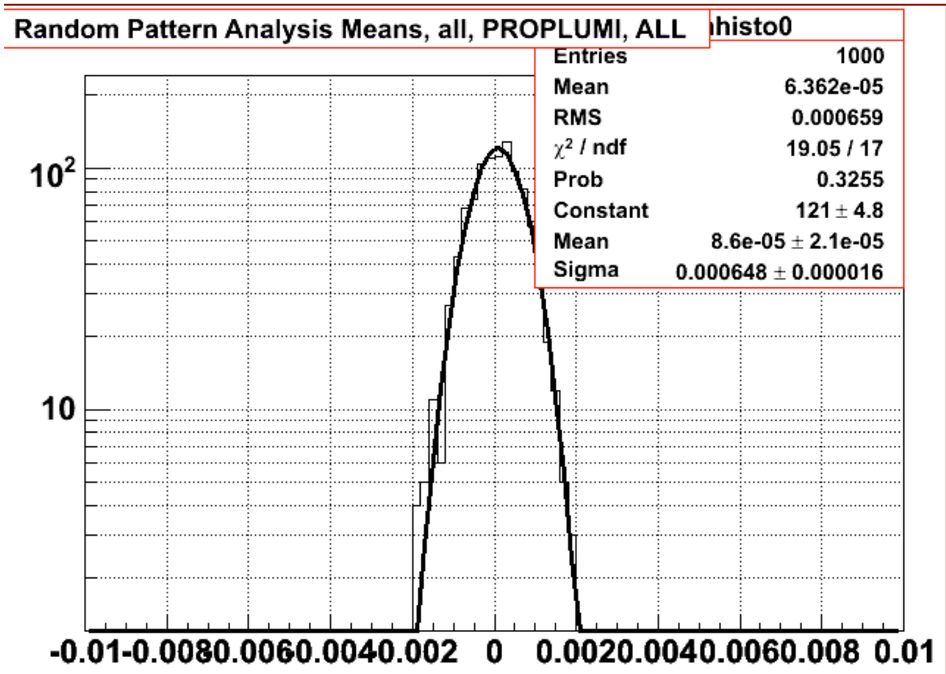
Background Asym

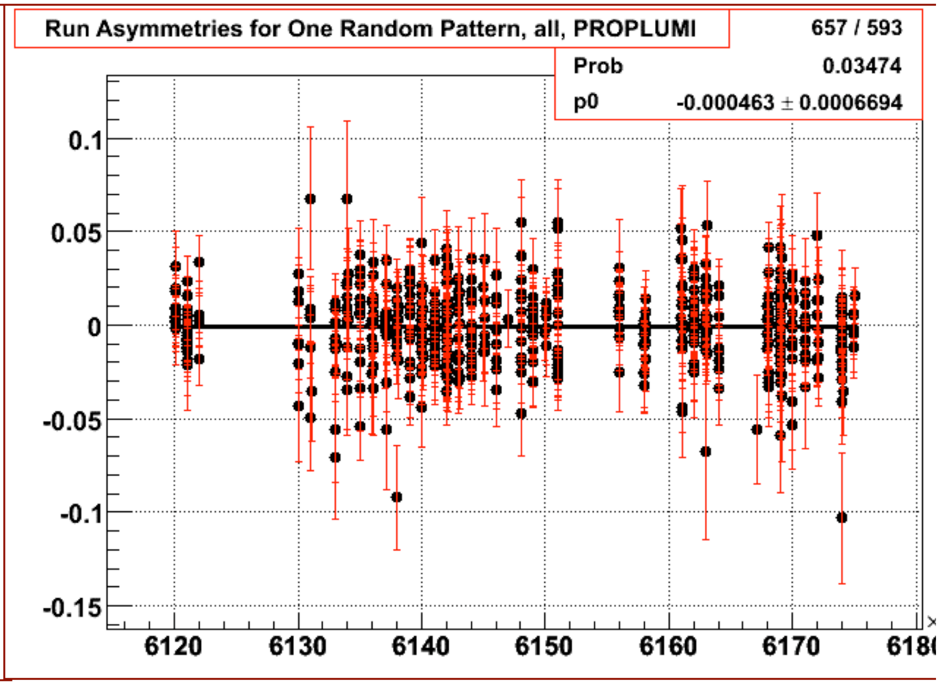




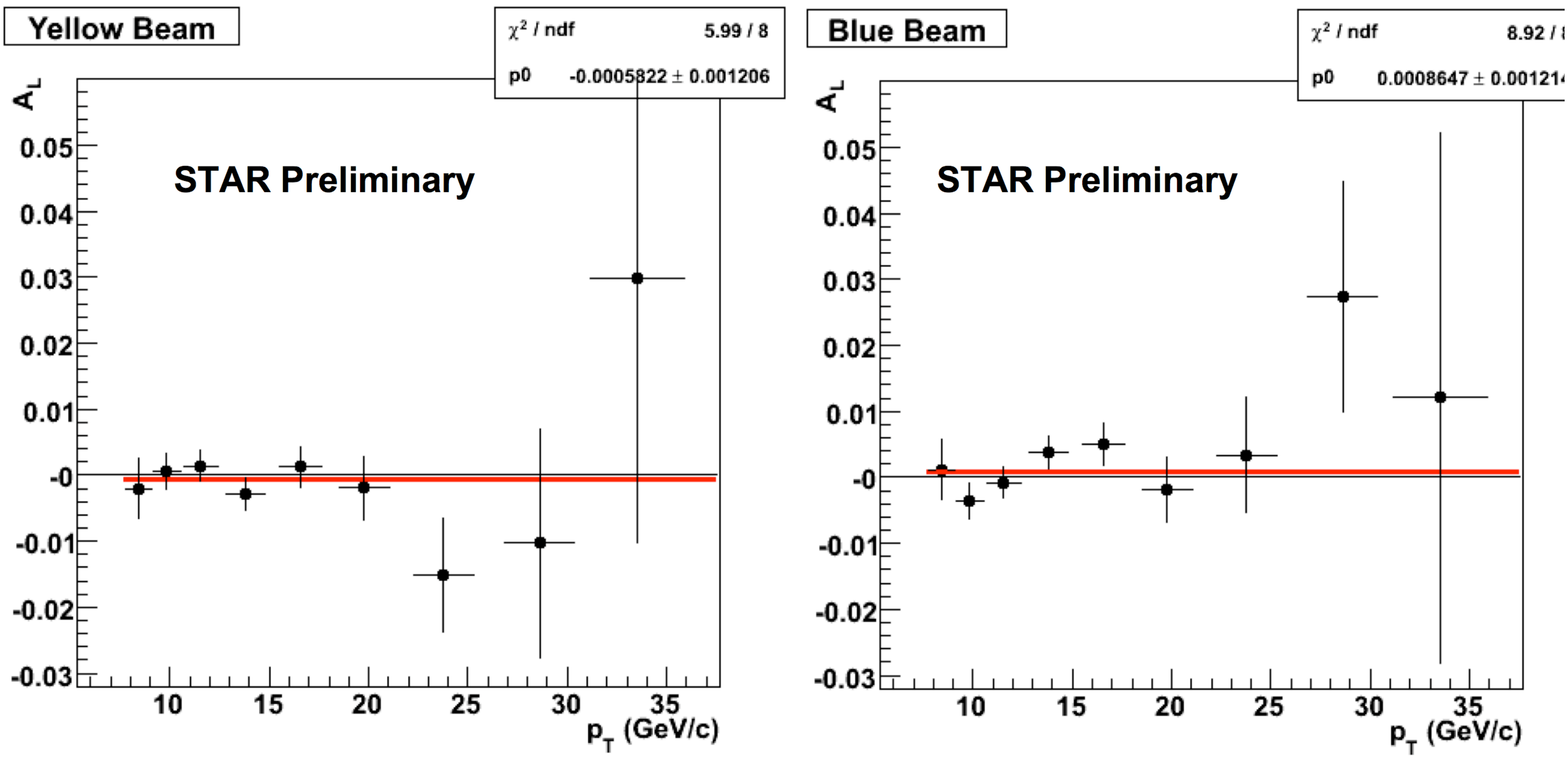
A_{LL} Systematics: Random Pattern Analysis

The random pattern analysis randomly creates new spin states for every run. 1000 random patterns were used. The RMS of the distribution of the ε_{LL}s is smaller (within error) than the statistical error, so the systematic error from bunch-dependent correlations is zero.





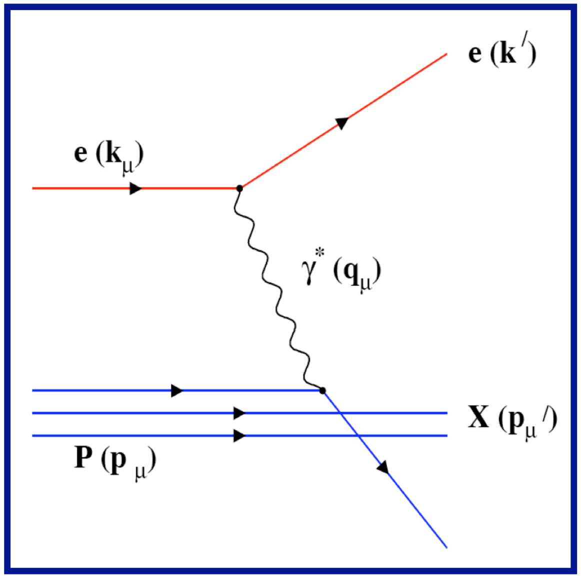
False Asymmetry Systematic Check



How RHIC works for $\vec{p}\vec{p}$

1. Optically pumped Polarized H- source
2. H- source is stripped and pumped into Booster - a fast cycling cyclotron
3. Injected into Alternating Gradient Synchrotron at 2.35 GeV and accelerated to 24.3 GeV
4. Injected into RHIC ring at 24.3 GeV and accelerated to 100 GeV
5. The H- jet target was installed in 2004 to calibrate the CNI polarimeter
6. Two Siberian Snakes are used to preserve polarization of beams
7. Challenge for the future is to overcome expected resonances and preserve polarization beyond beam energies of 100 GeV.
8. CNI provides 10% error
9. Absolute normalization from Jet Target provides 20 % error per beam.

Deep Inelastic Scattering



λ = Resolution

Increased E_γ means increased resolution

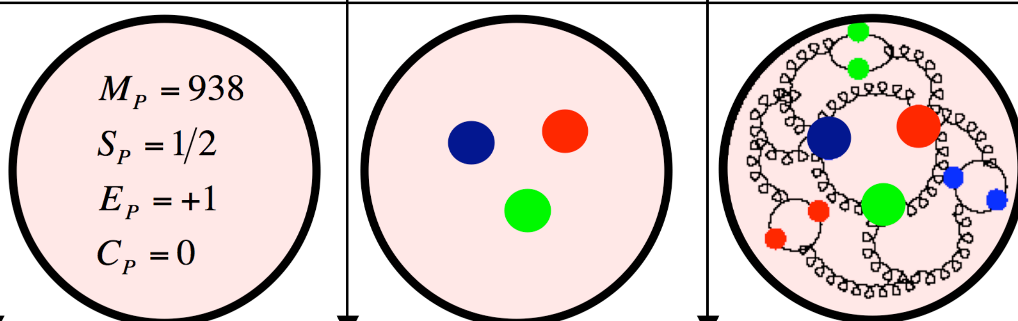
$$E_\gamma = \frac{\hbar c}{\lambda}$$

Δt = lifetime

Increased E_γ means shorter interaction time

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

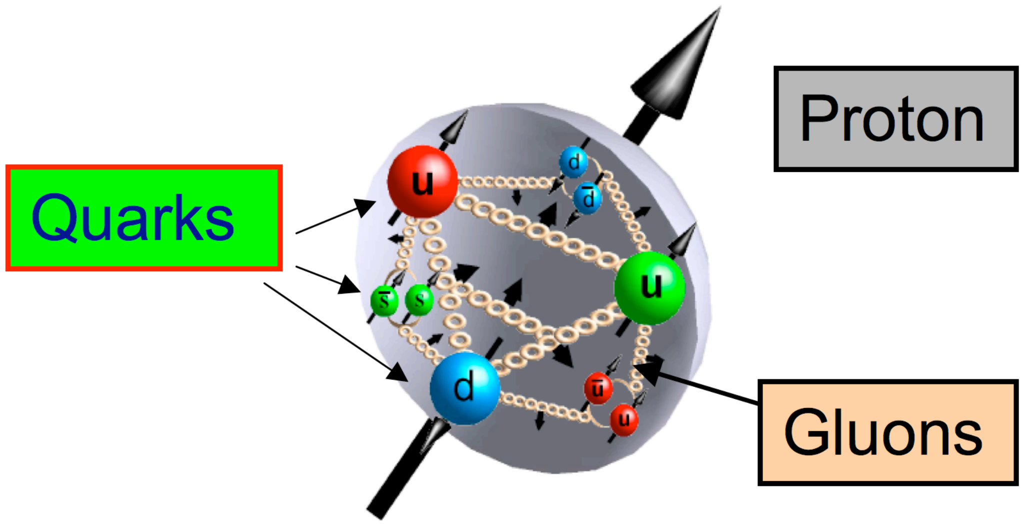
λ (fm)	1	0.2	0.05
Q^2 (GeV^2)	0.04	1	10



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

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

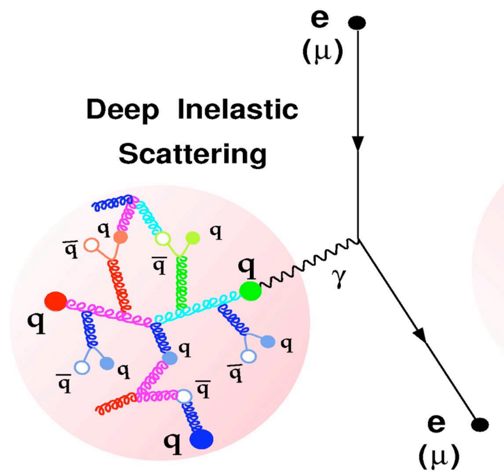
Color Confinement forbids the isolation of free quarks and gluons. The stable and abundant **Proton** is an excellent "partonic laboratory"



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?

A Quick Review of Nucleon Spin Structure Physics



Longitudinally polarized lepton-nucleon scattering probes spin structure of the nucleon

→ $g_1(x,Q^2)$

X = % Nucleon Momentum carried by Parton

Q^2 = Momentum Transfer of γ !Resolution!

If $Q^2 >> M_N$ then γ interacts with only 1 "free" quark with spin anti-aligned with that of the photon

Quark Parton Model →

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta q(x) + \Delta\bar{q}(x)\right]$$

$a_0 = \Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$

Measured in n and hyperon decay

pQCD +OPE →

$$\Gamma_1(Q^2) \equiv \int_0^1 dx g_1(x,Q^2) = C_1(\alpha_s,Q^2)\left[\frac{a_3}{12} + \frac{a_8}{12\sqrt{3}}\right] + C_2(\alpha_s,Q^2)\frac{a_0}{9}$$