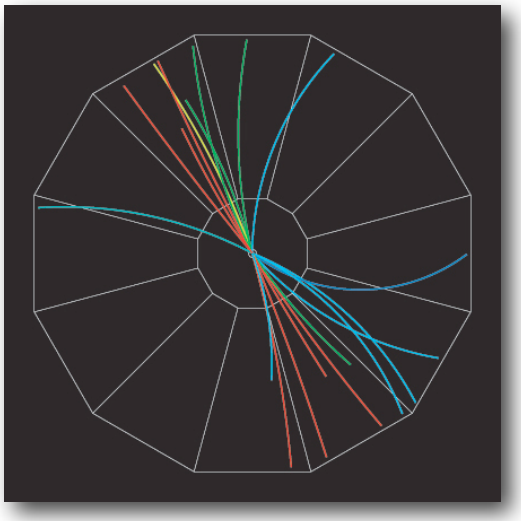
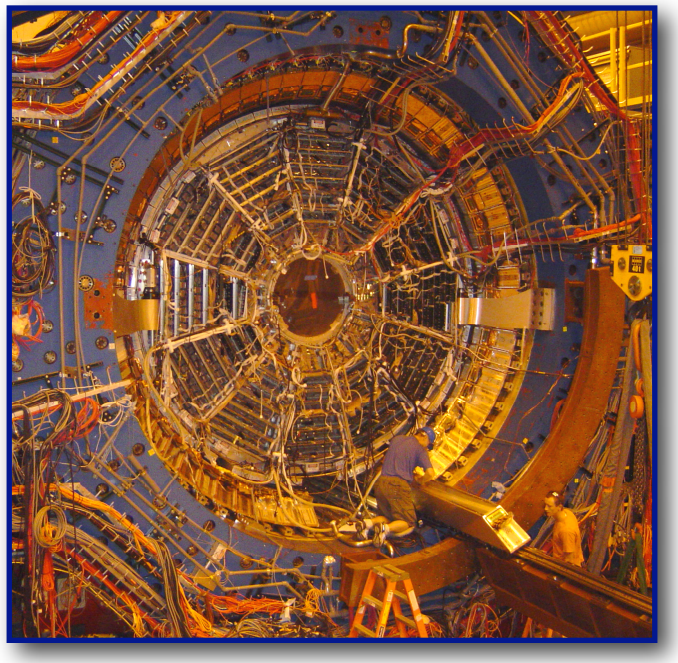
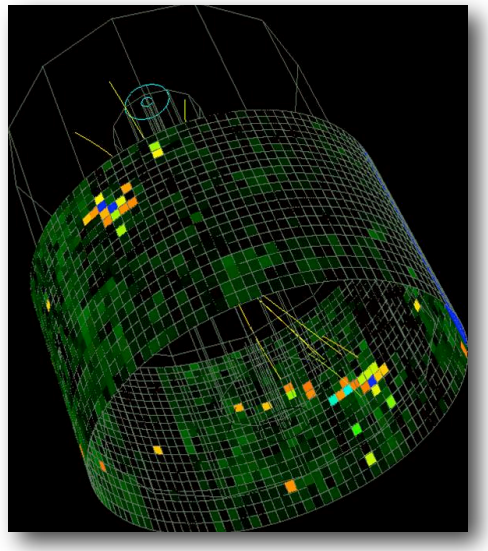
Closing in on the spinning glue



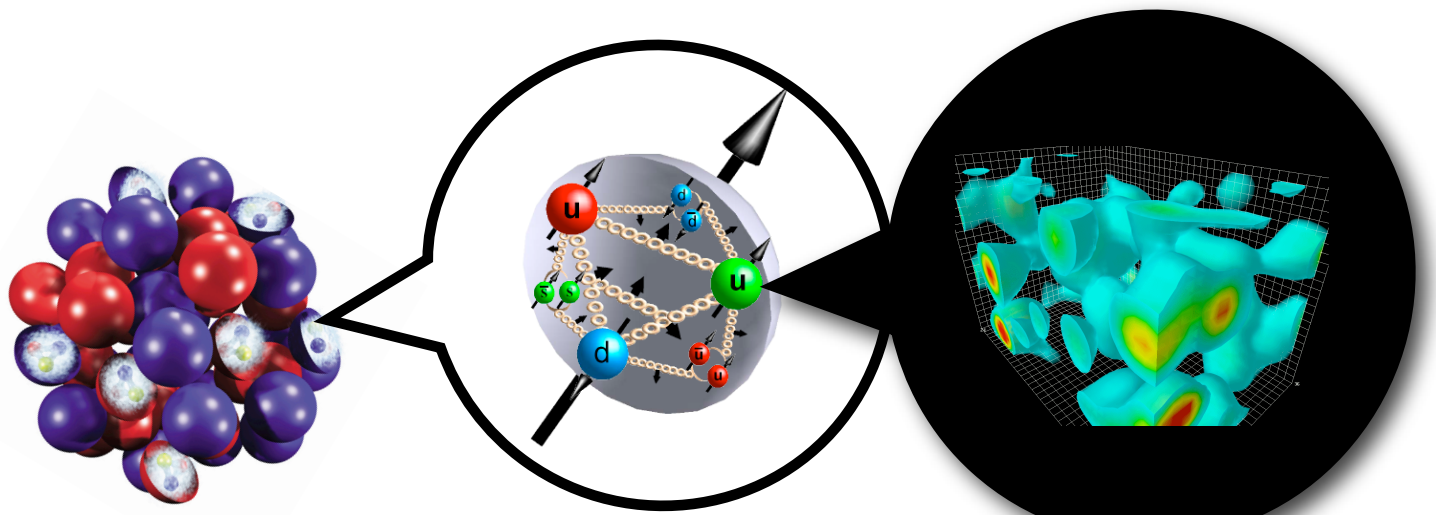




Mike Miller
MIT

From symmetry emerges rich phenomena

$$[i\hbar c\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - mc^{2}\bar{\psi}\psi] - \frac{1}{16}F^{\mu\nu}F_{\mu\nu} - (q\bar{\psi}\gamma^{\mu}\lambda\psi)A_{\mu}$$



parton dist. functions

Hadrons and Exotica

Lattice

Quark Gluon Plasma

Spin structure

How do those fit together?

WHY STUDY QCD?
WHY IS IT A CHALLENGE?

- The only example we know of a strongly interacting gauge theory.
- We understand the theory at short distances
- The quasiparticles – the excitations of the vacuum – are hadrons, which do not look at all like the short distance quark gluon degrees of freedom

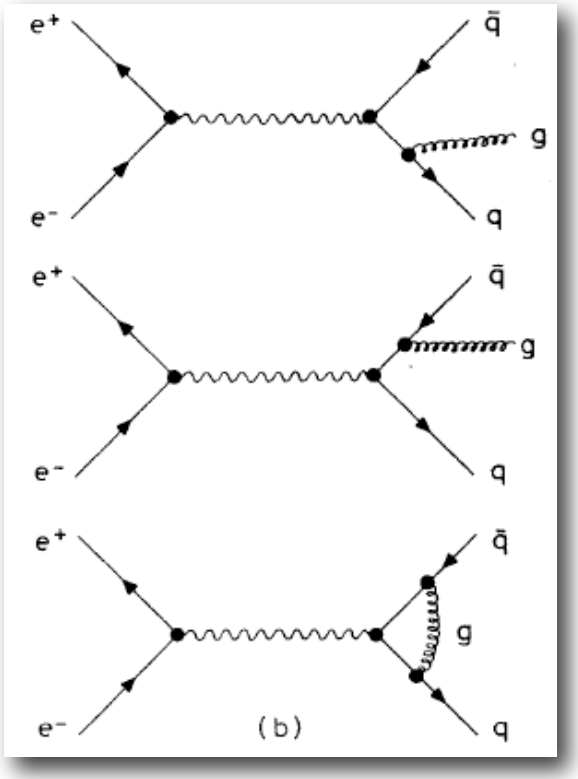
Krishna Rajagopal
MIT

HOW DO WE RESPOND TO THE CHALLENGE?

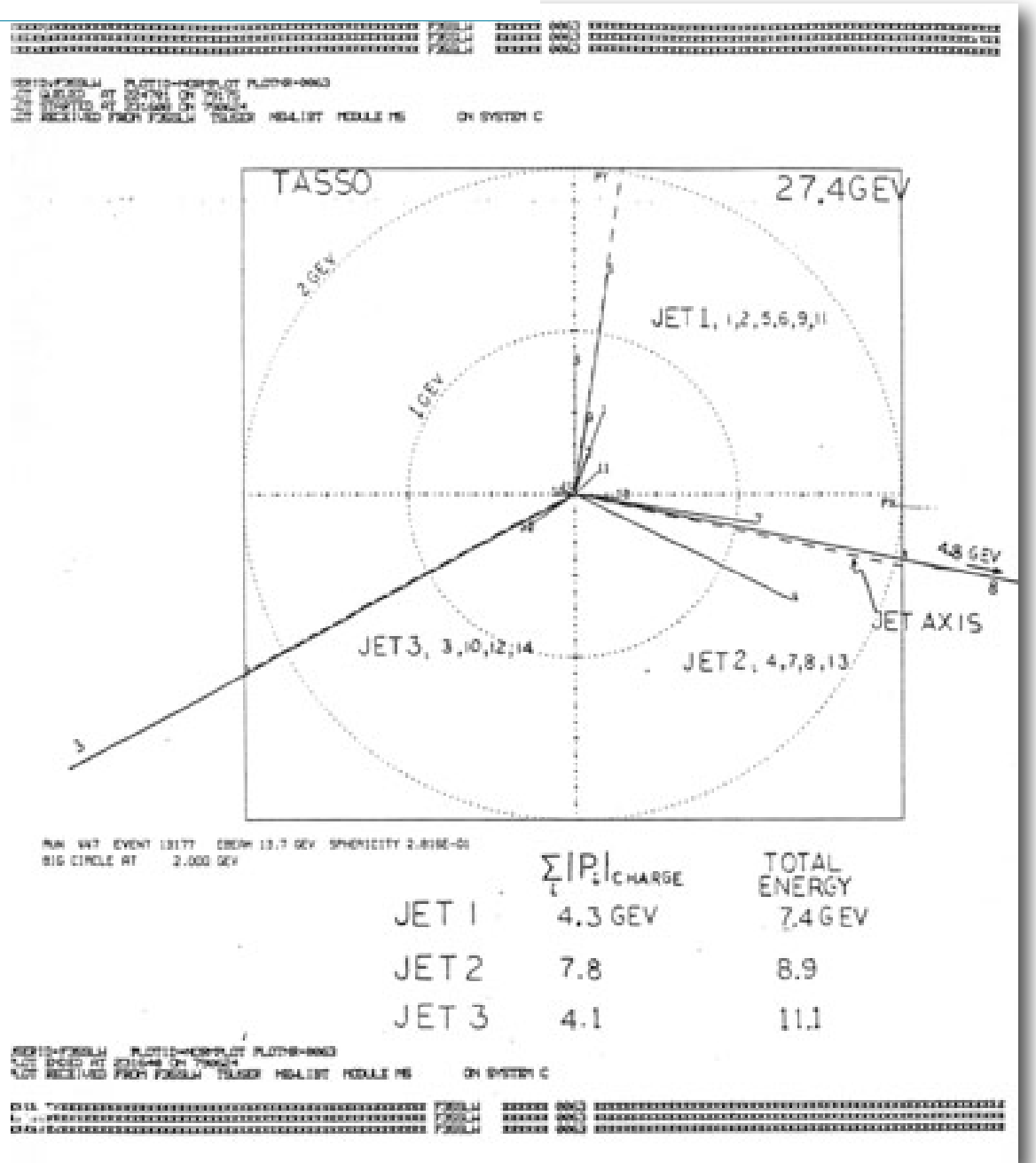
- Study the spectrum, properties, and structure of the hadrons.
- Get away from the vacuum. Understand other phases of QCD, and their quasiparticles. Map the QCD phase diagram.

➡ gluon

Gluon physics: then and now



logbook: gluon discovery



Gluon contriubtion to momentum, mass, spin?

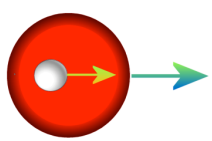
The proton spin budget

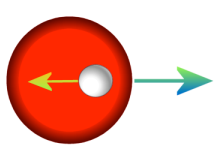
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + \Delta g(Q^2) + L_q(Q^2) + L_g(Q^2)$$

The proton spin budget

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + \Delta g(Q^2) + L_q(Q^2) + L_g(Q^2)$$

$$\Delta g(x, Q^2) = g^+(x, Q^2) - g^-(x, Q^2)$$

g^+ : 

g^- : 

The proton spin budget

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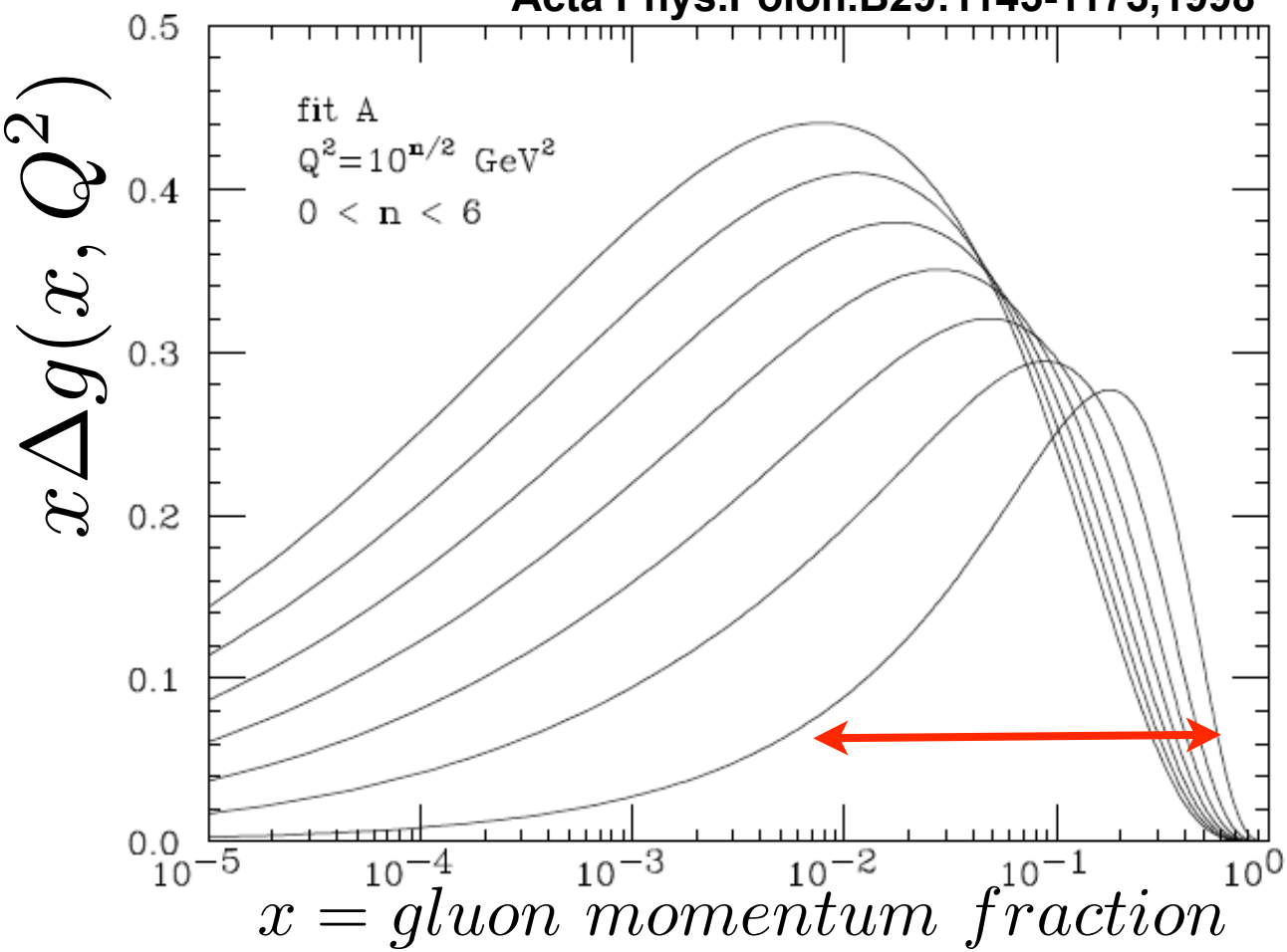
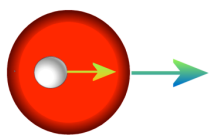
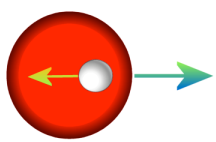
Acta Phys.Polon.B29:1145-1173,1998



g^+ :



g^- :



A surprise in the budget

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + \Delta g(Q^2) + L_q(Q^2) + L_g(Q^2)$$

A surprise in the budget

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- Non. Relativistic quark model
  - $\Delta\Sigma = 1$ (*a la* Griffiths)
- Relativistic quark model
  - $\Delta\Sigma \approx 0.75$
- Ellis-Jaffe sum rule
  - $\Delta\Sigma \approx 0.60$

A surprise in the budget

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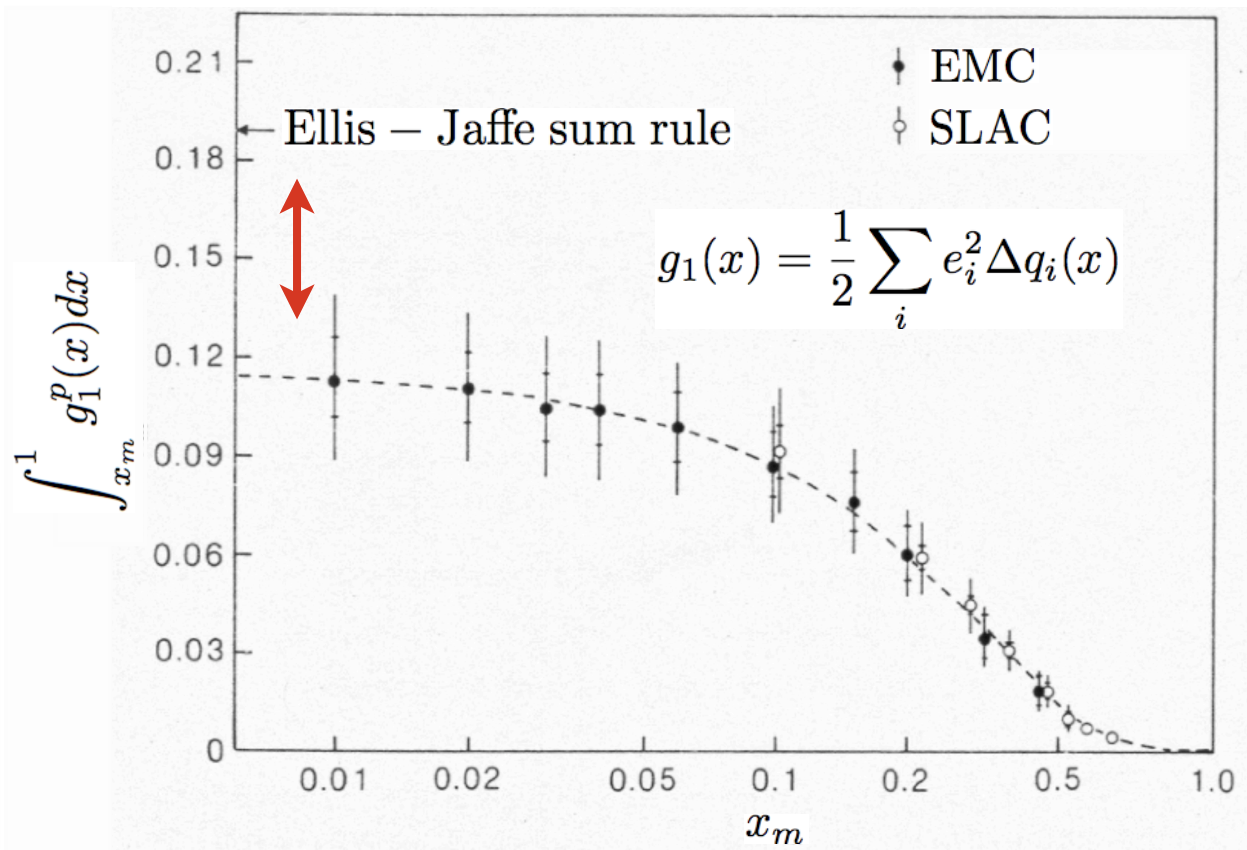
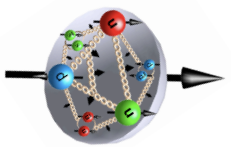
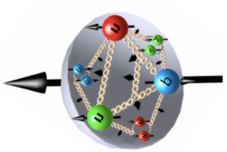


- quarks: 30% of 1/2 (?!)
  - u: +70%
  - d: -40%
- Sea quarks? *L ?*
- ***⇒ gluons***

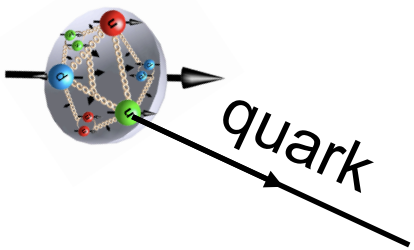
Picking gluons from the Partonic tree

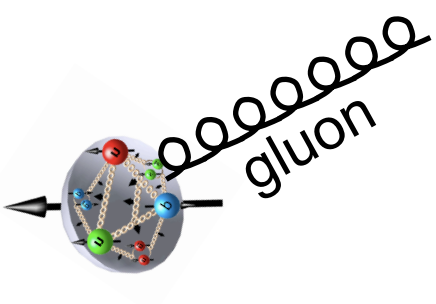




time

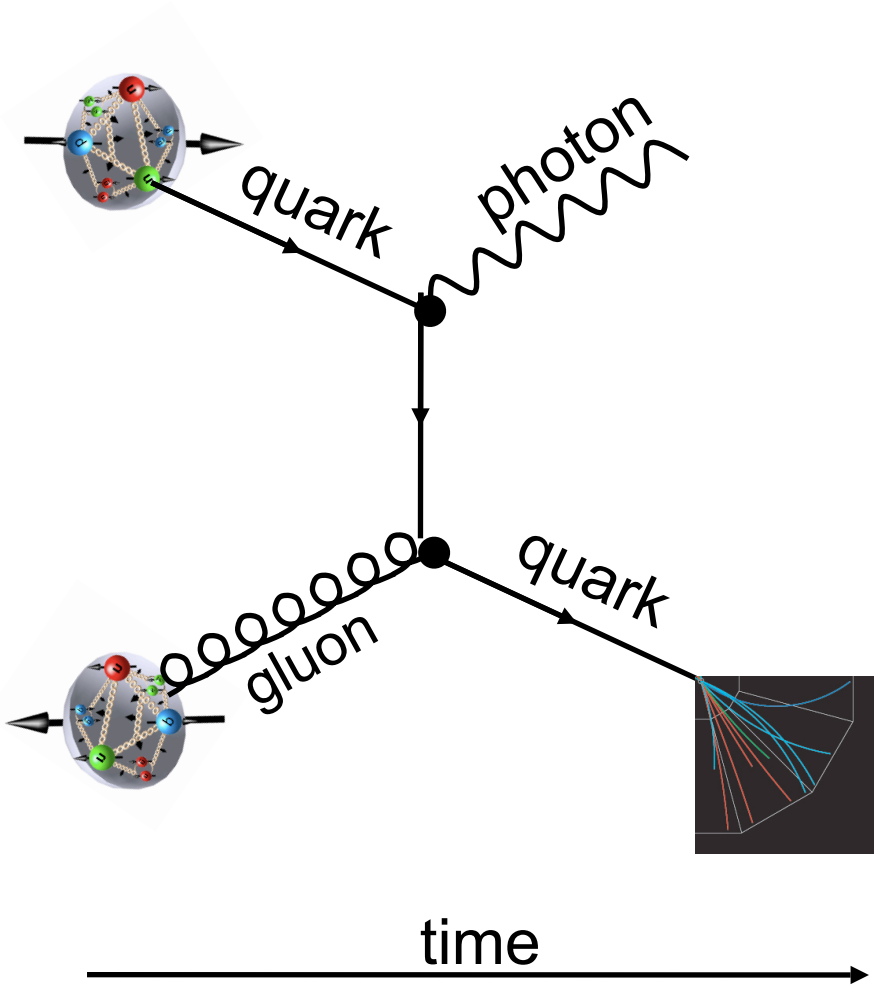
Picking gluons from the Partonic tree



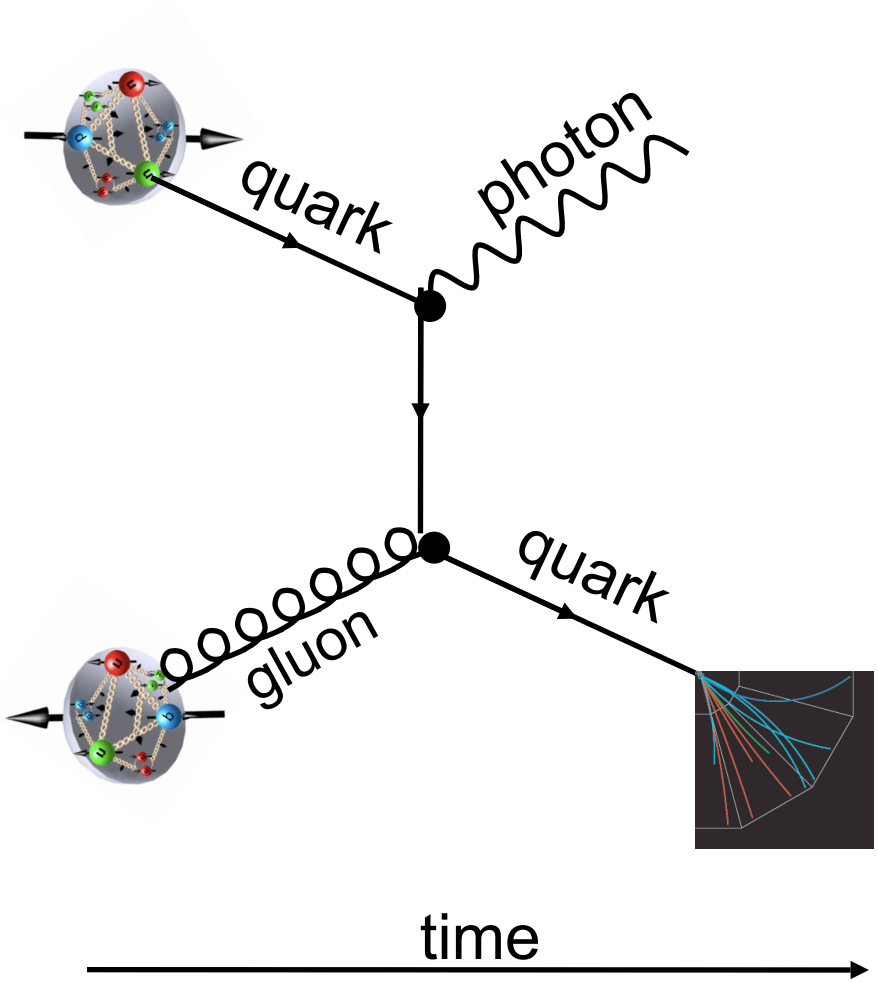


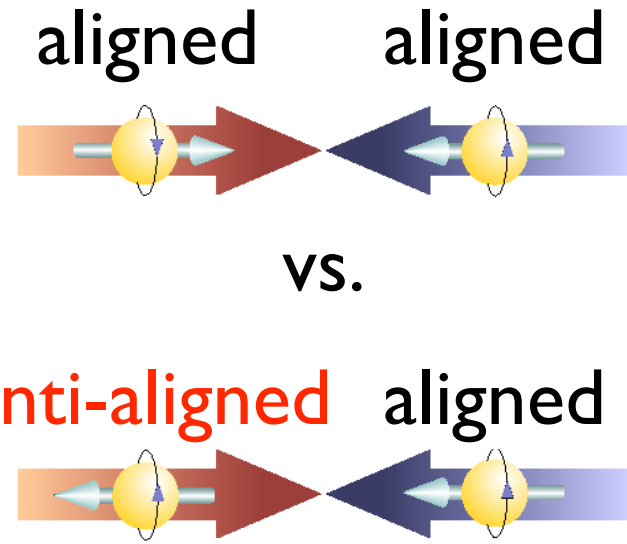
time

Picking gluons from the Partonic tree



Picking gluons from the Partonic tree

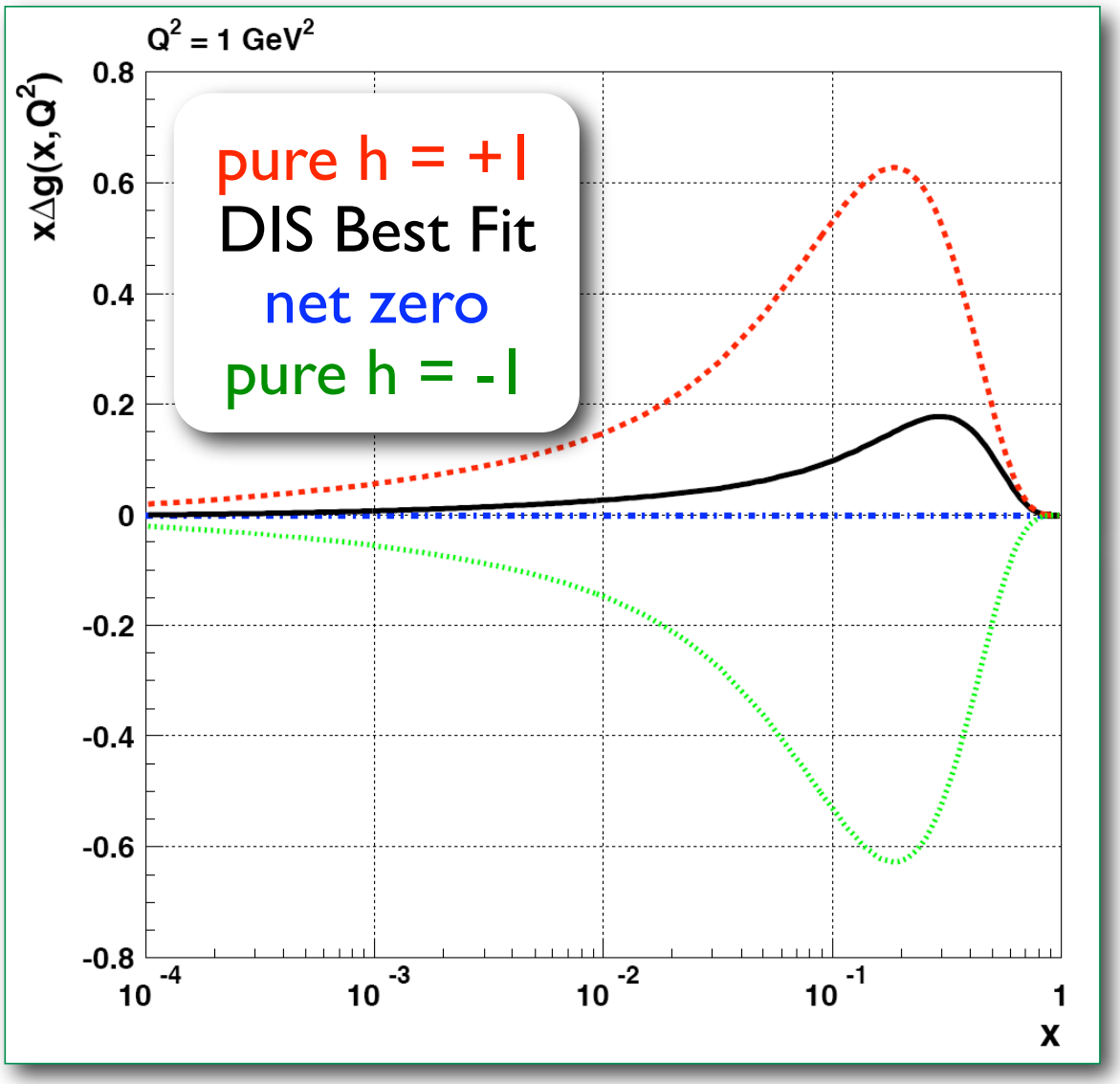




Ratio of cross sections "aligned" vs. "anti-aligned" probes how gluons are spinning in the proton

(i) ***High Energy*** collisions of (ii) ***polarized protons*** and (iii) a world class ***detector***

The observable and expectations



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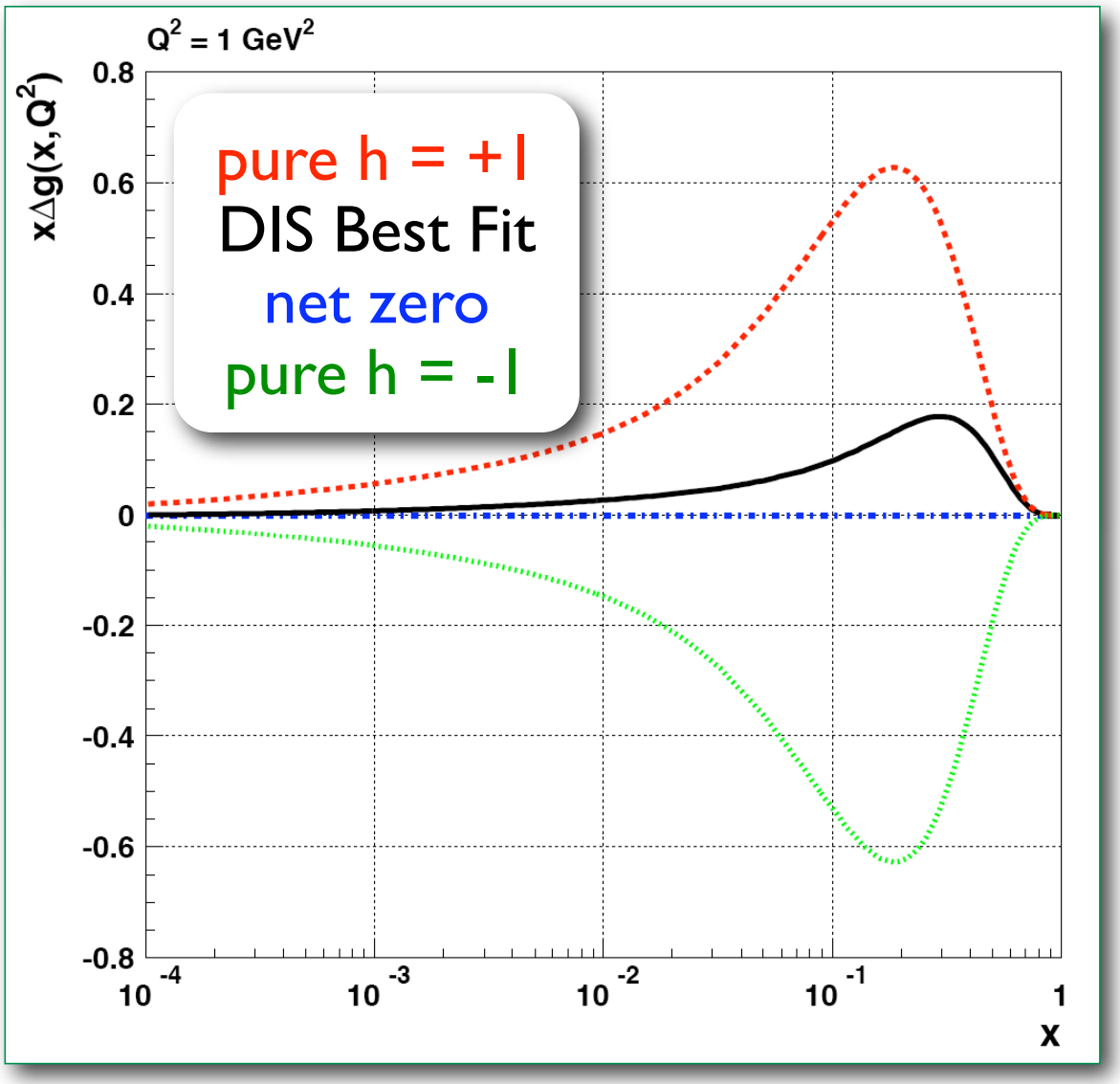
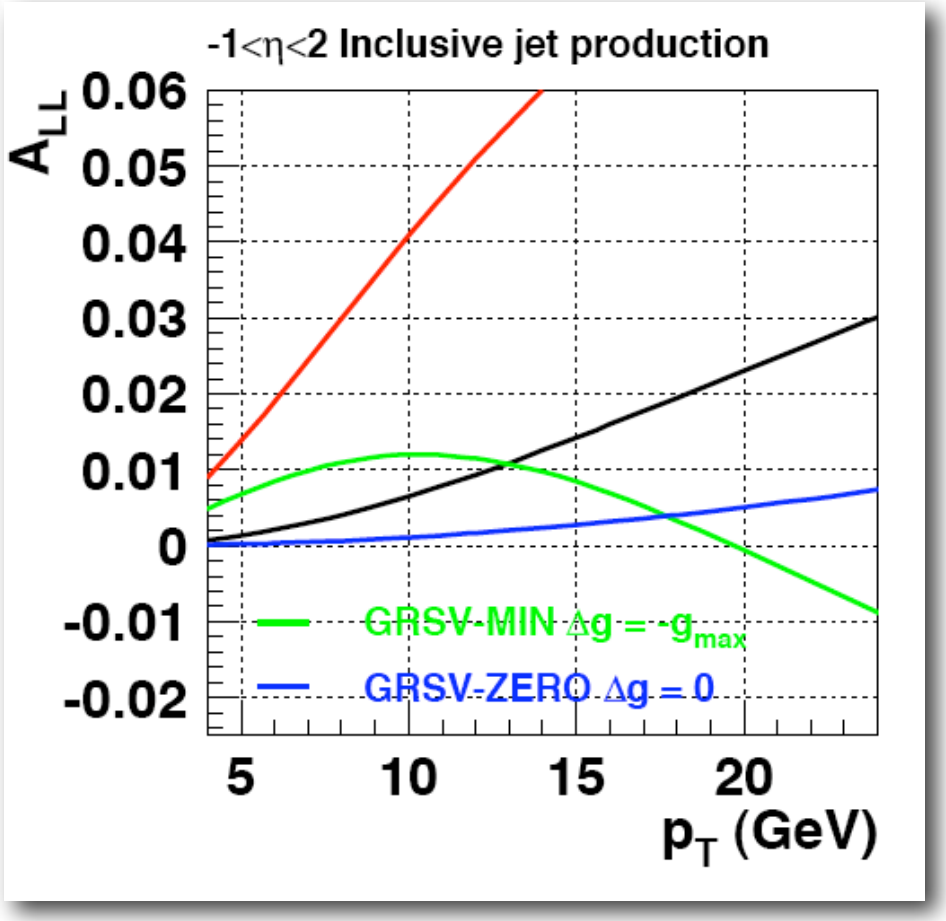


$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$



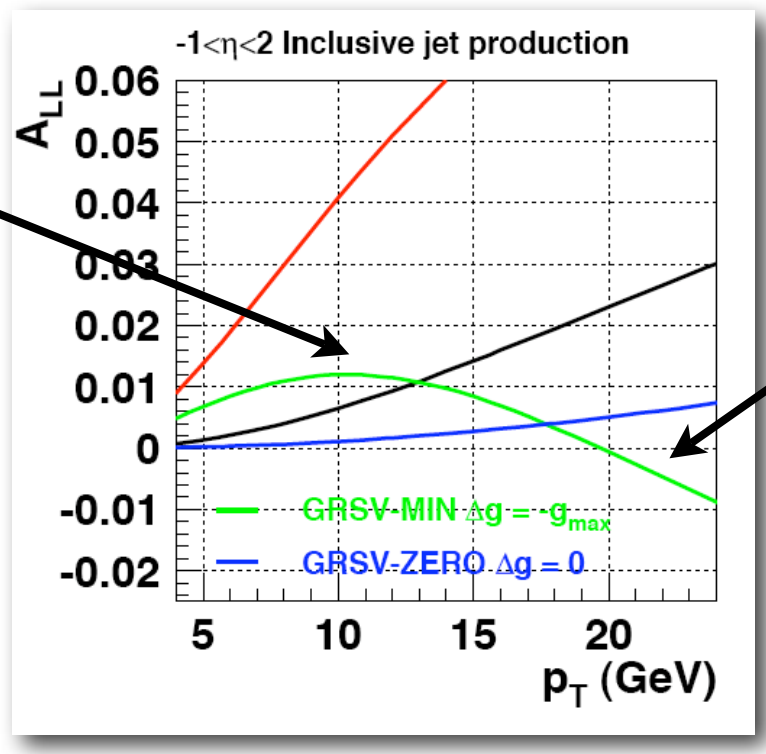
gluon hypothesis + pQCD => Asymmetrty Prediction

The observable and expectations

$$A_{LL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{d\Delta\sigma}{d\sigma}$$

$$\frac{d\Delta\sigma}{d\sigma} \sim \frac{\Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}_{ab\to cd}\hat{a}_{LL}^{ab\to cd}}{f_1 \otimes f_2 \otimes d\hat{\sigma}_{ab\to cd}}$$

g-g dominated



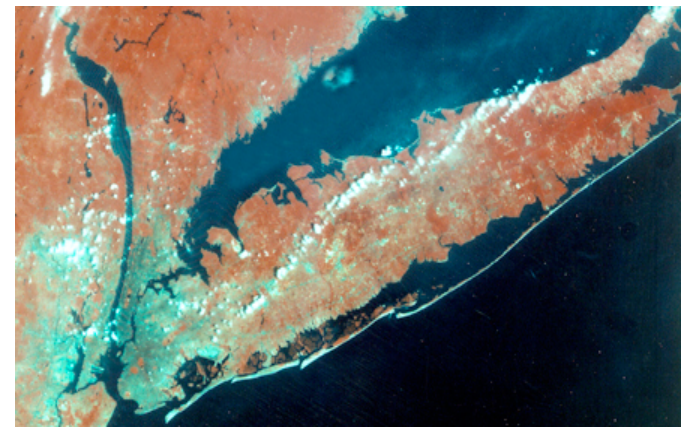
q-g dominated

Preparing for the hunt

- **Measure quark, gluon contribution to proton spin**
  - q well constrained by previous DIS measurements
  - g wide open and requires a new approach: p+p, DIS++
- **Staged analysis of various channels**
  - p+p → jets
  - p+p → γ + jet
  - p+p → charm, bottom

- **First measure cross sections**
  - under control experimentally *and* theoretically at NLO
- **Then measure asymmetries**
  - NLO QCD + phenomenology → extract Δg, ΔΣ

The RHIC Complex



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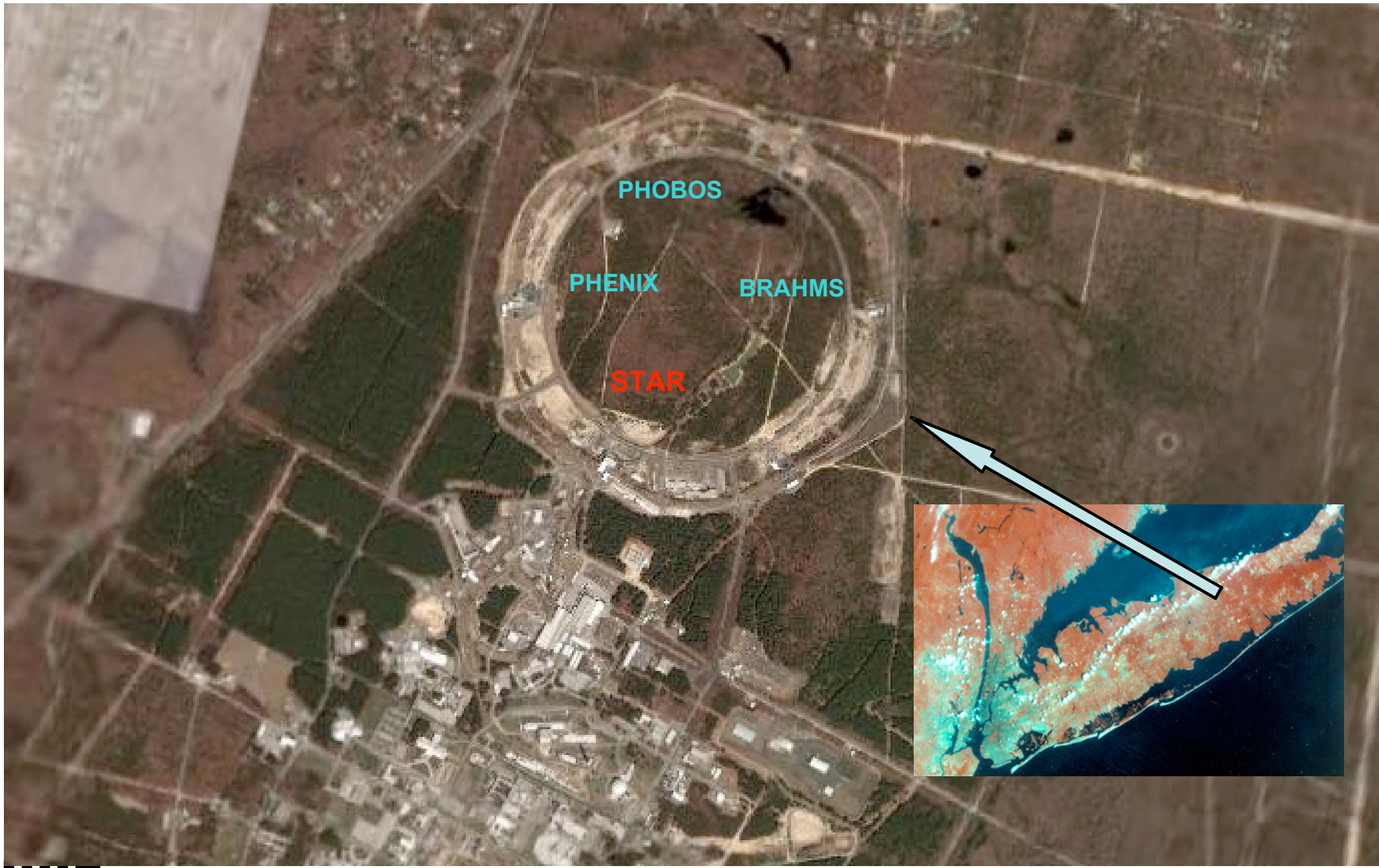

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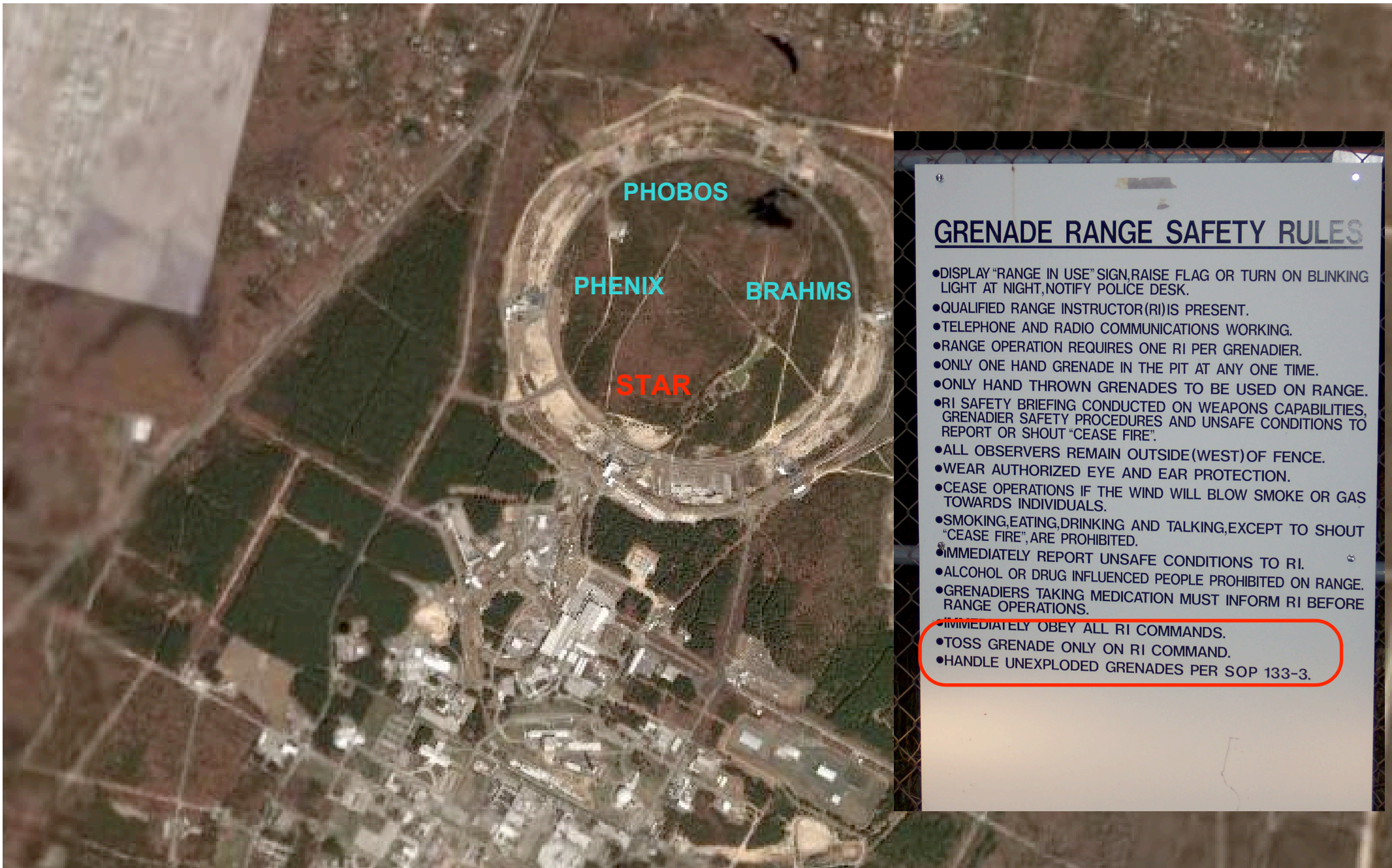

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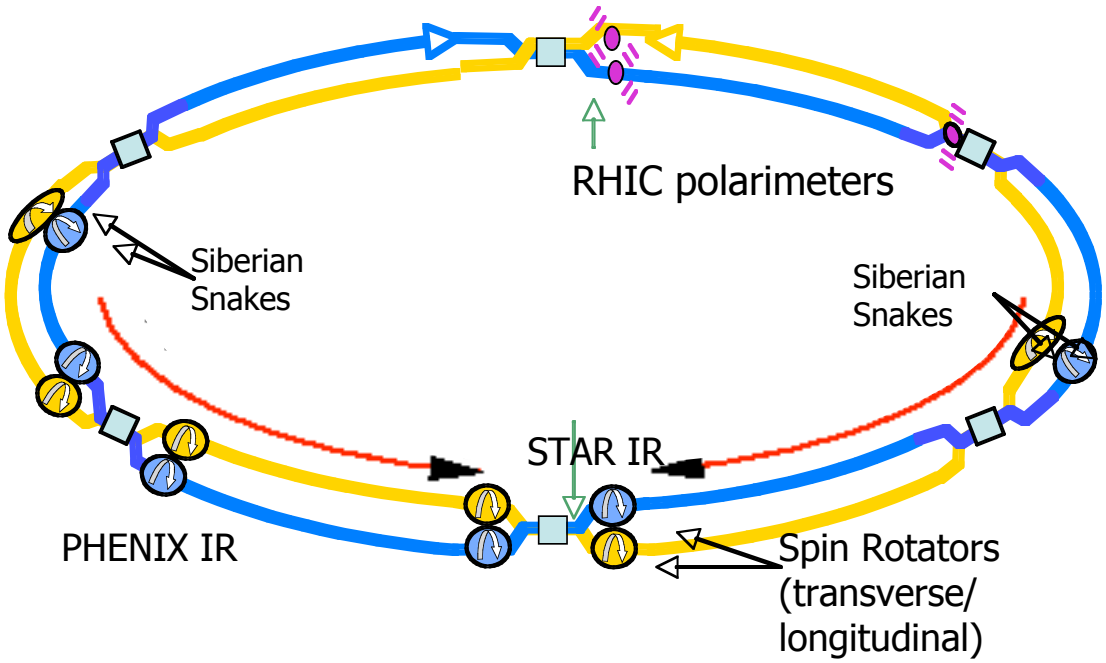
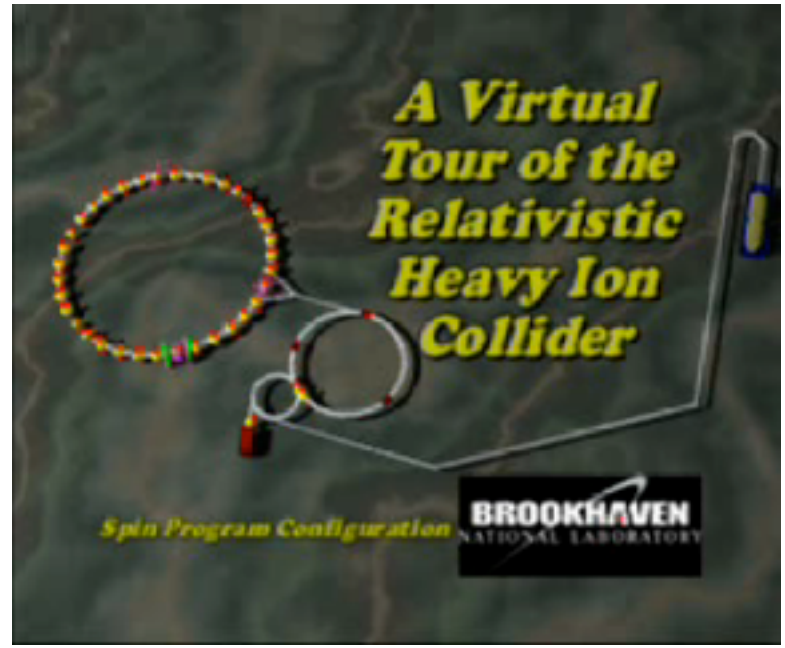
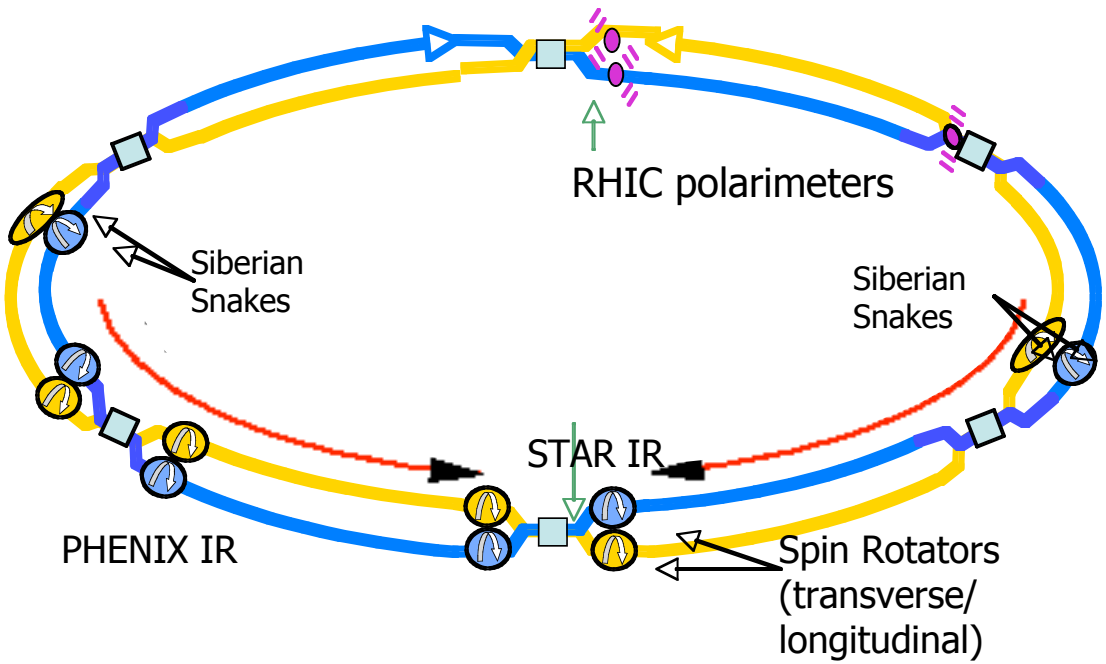
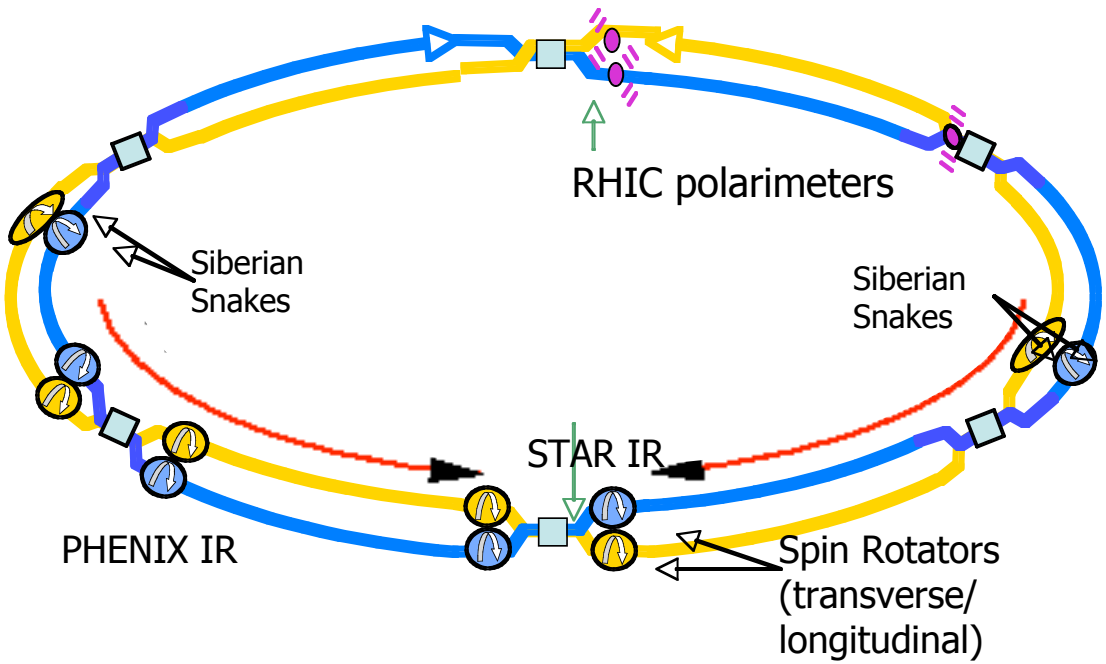




The RHIC complex



The RHIC complex

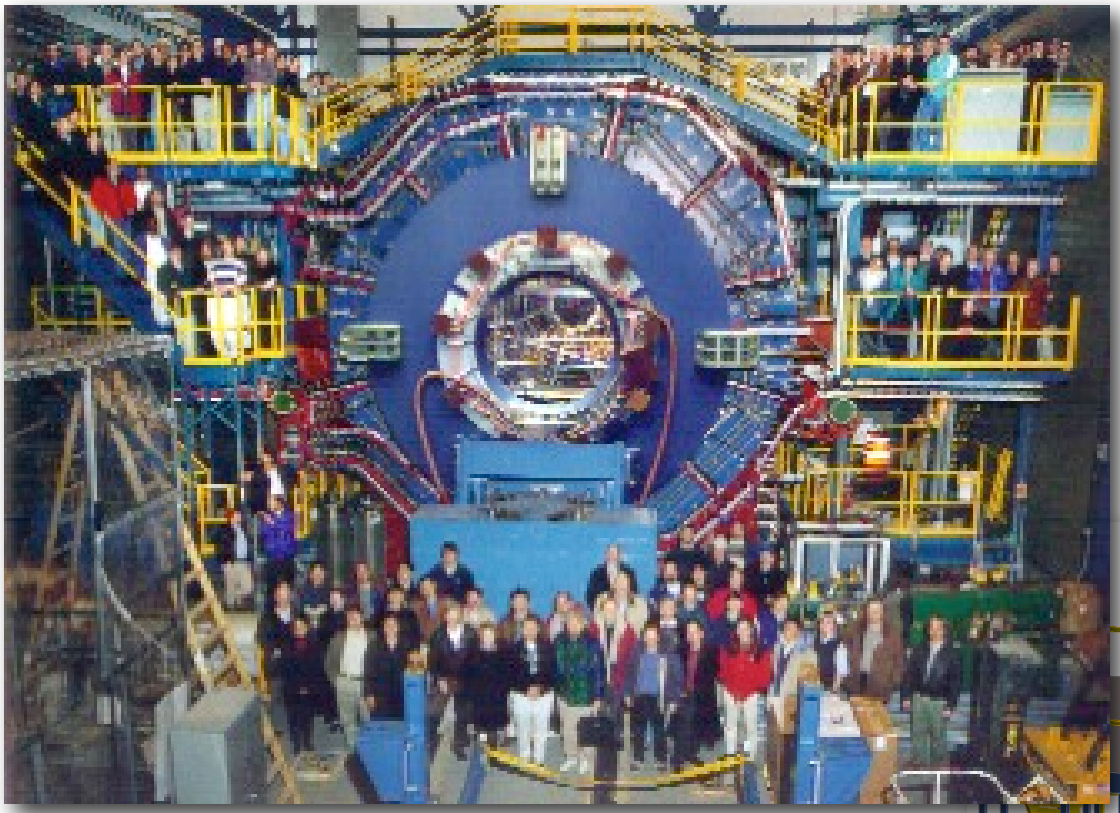


- 100 GeV proton beams
- Each bunch filled with a distinct polarization state
- Spin Rotators at STAR IR allow for transverse and longitudinal spin orientation
- Bunch Xings every 120 ns
- CNI polarimeters + Hydrogen Jet =>run by run polarization

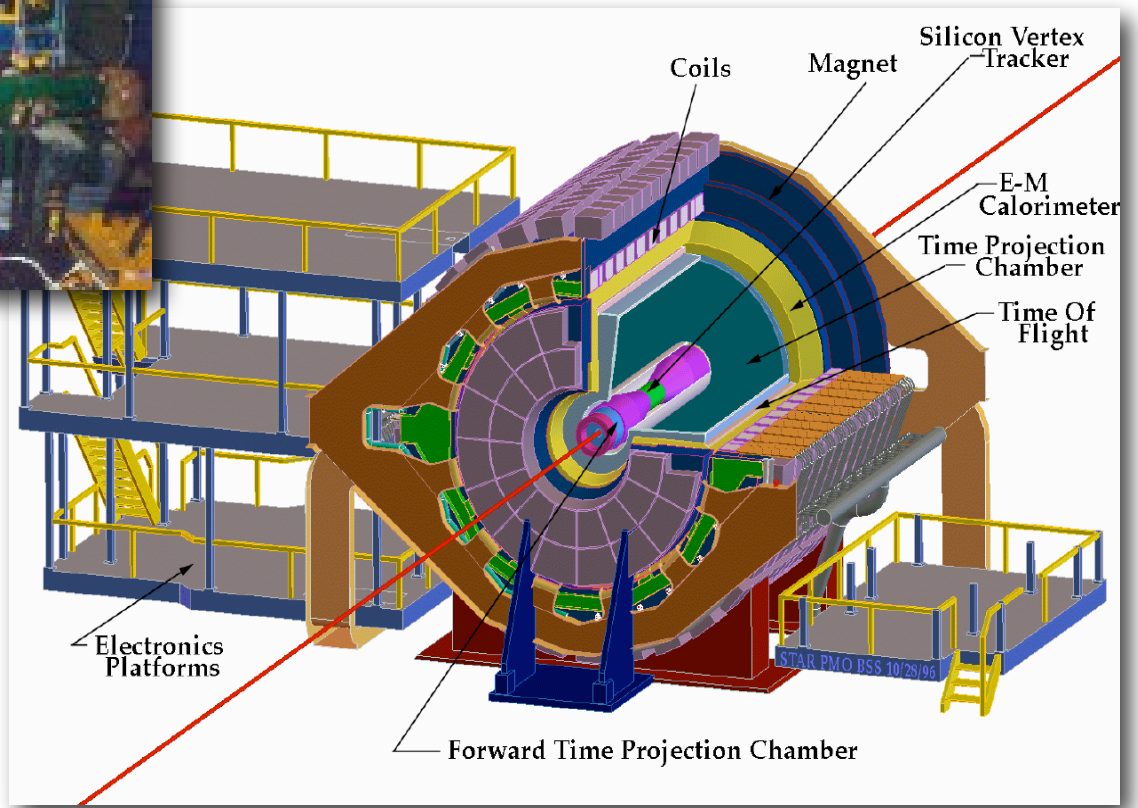
pp Run Year	2002	2003	2004	2005	2006
< Polarization> %	15	30	40-45	45-50	60
L_{max} [10^{30} $s^{-1}cm^{-2}$]	2	6	6	16	30
L_{int} [pb^{-1}] at STAR (L/T)	0 / 0.3	0.3 / 0.25	0.4 / 0	3.1 / 0.1	8.5 / 10.2

Jim Simons

The STAR collaboration



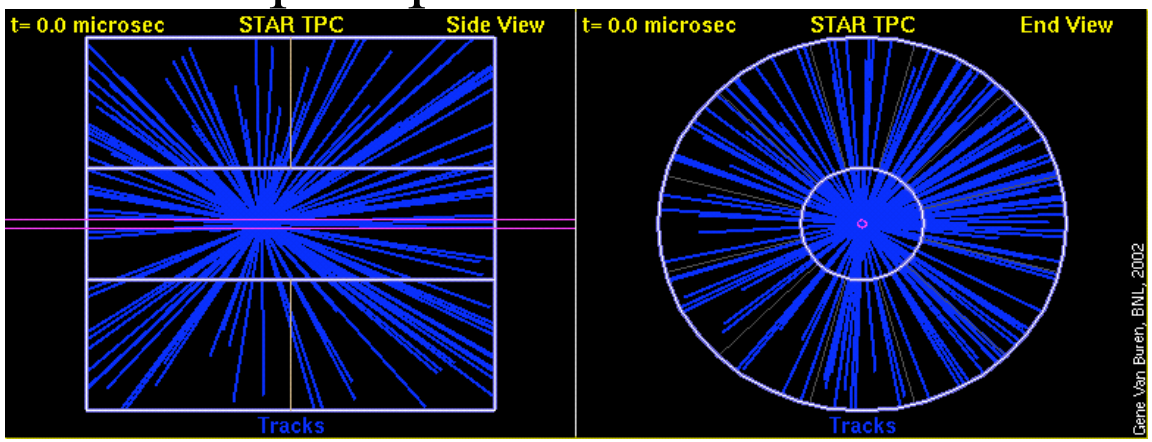
~500 people
~15 nations



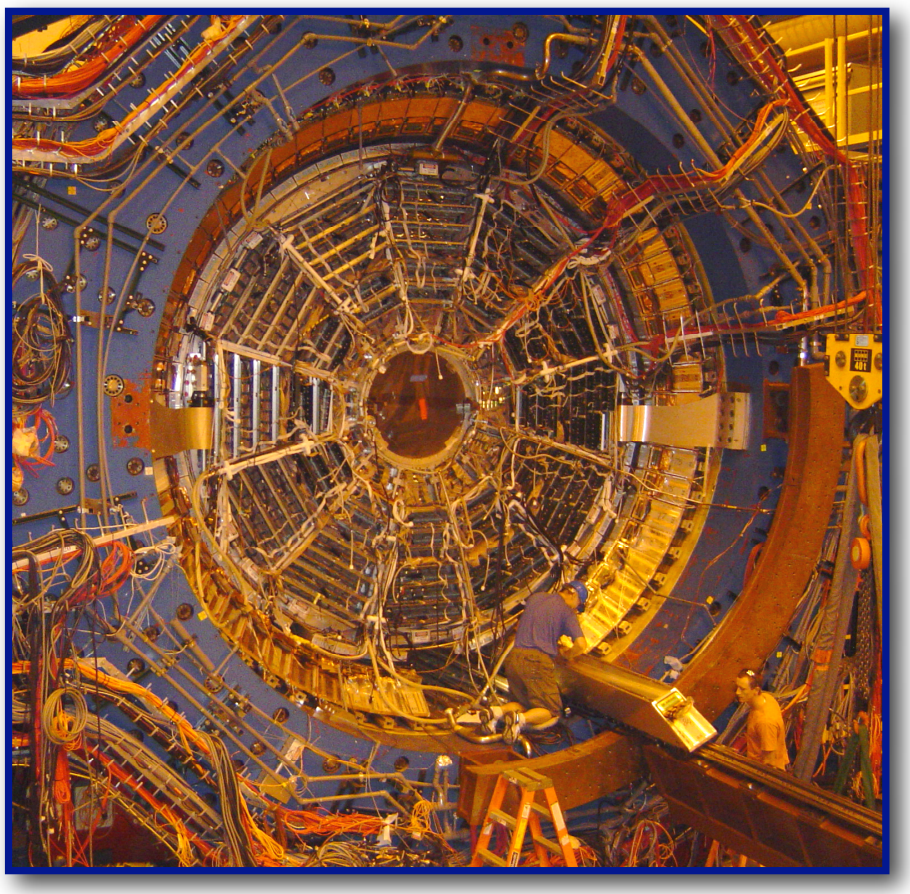
gluon spin:
30-40 FTEs

A taste of the challenges

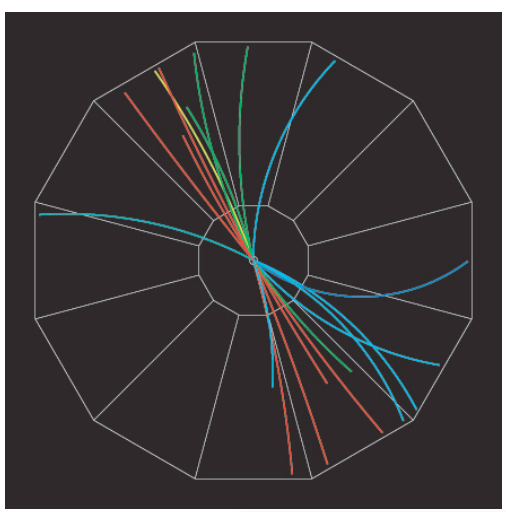
TPC readout 40 μs & 107 ns crossing⇒ massive pileup



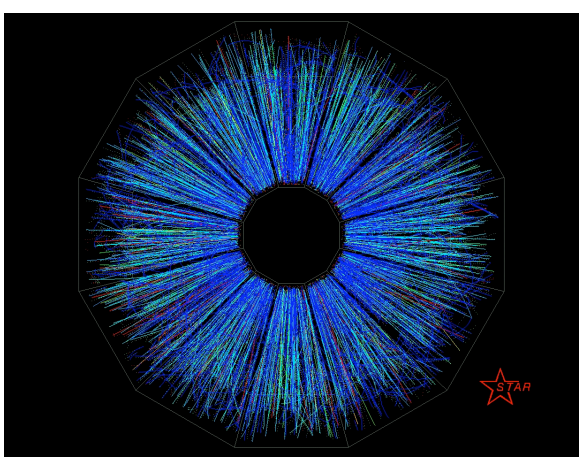
- Steady lumi progess
- EMCal late addition
- No HCal



Find this

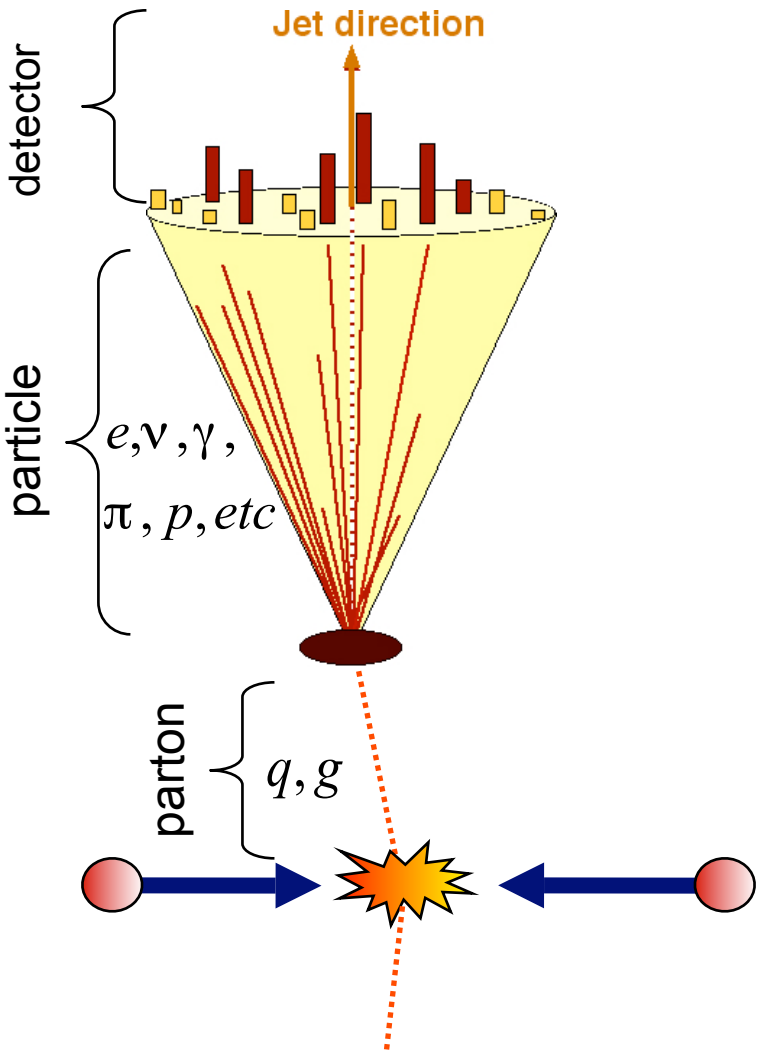


In something like this

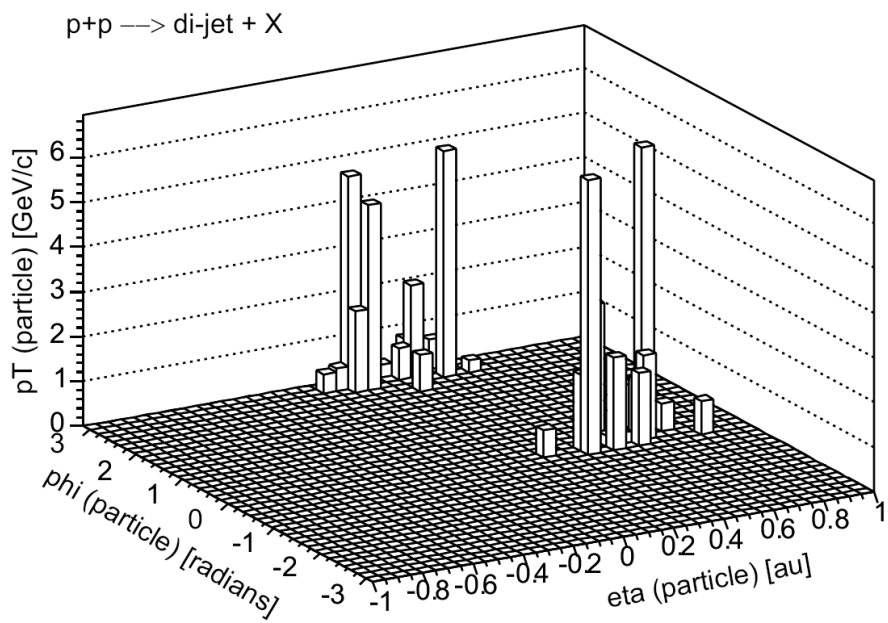


Significant challenges to overcome, MIT key player

Jet Reconstruction at STAR

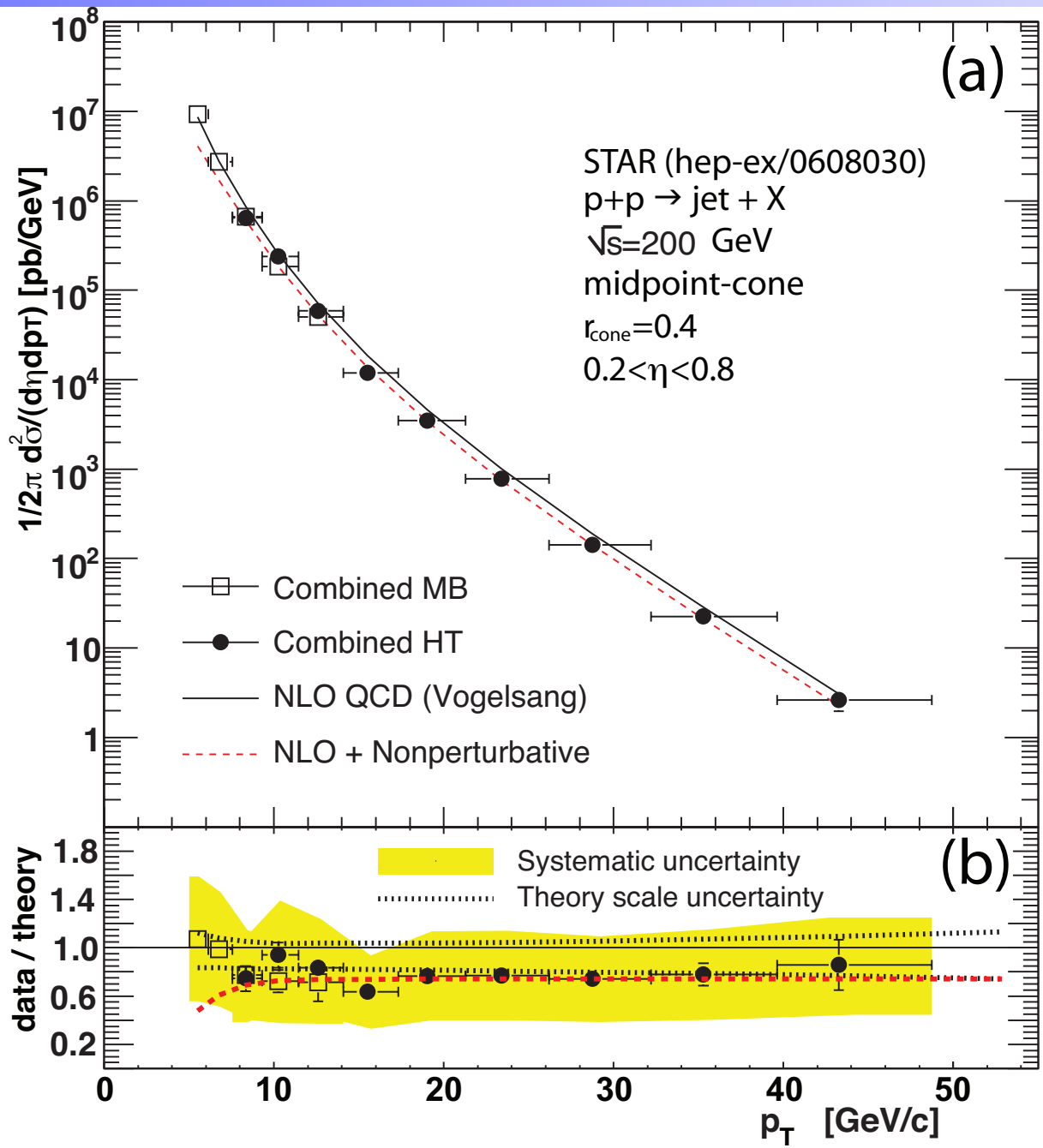


- charged tracks + EMCal
- "particle-flow" - like
- midpoint-cone algorithm
- detailed corrections for non-perturbative effects



Corrections to measured jets critical for physics bottom line

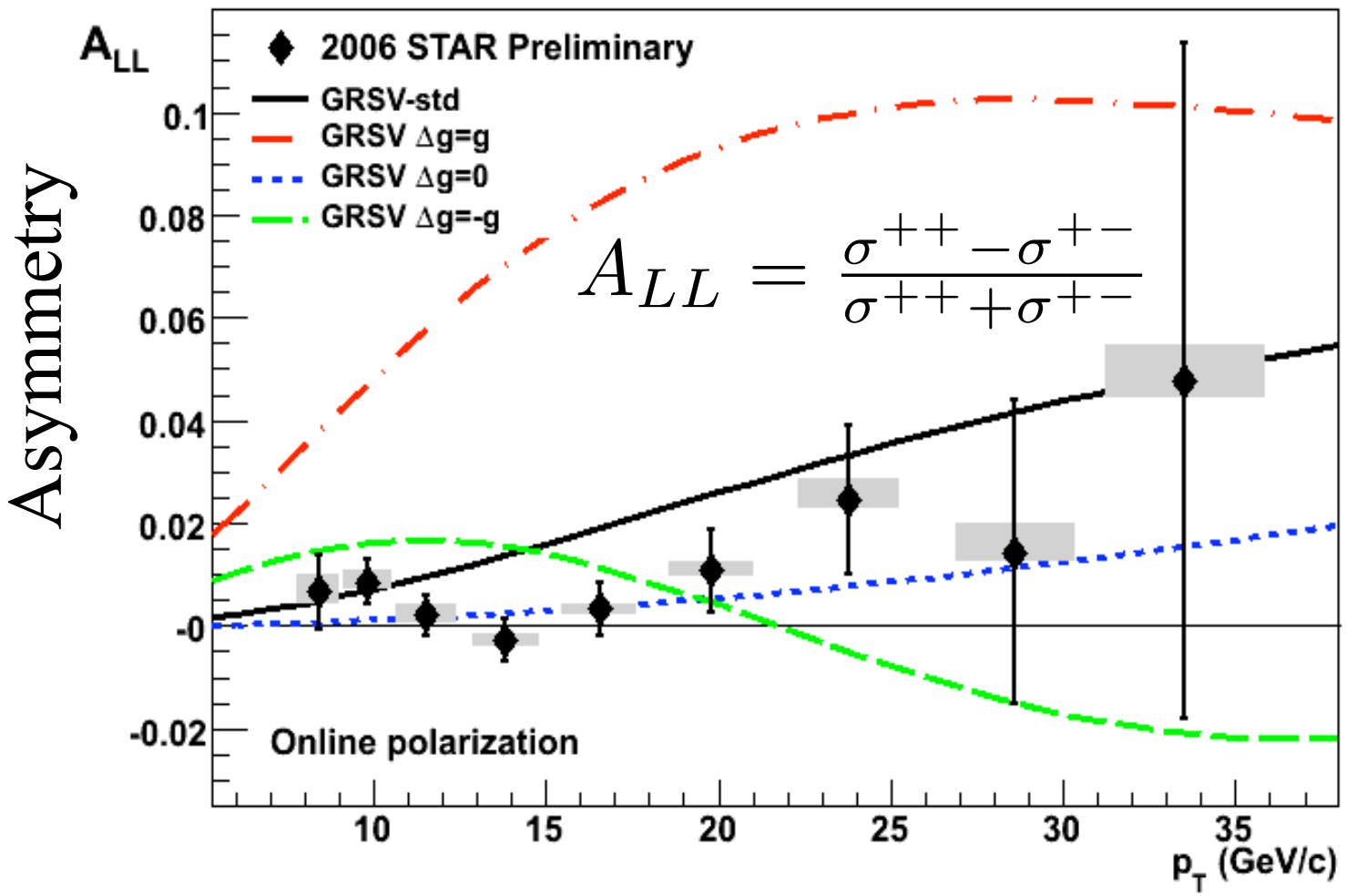
Unpolarized inclusive jet cross section



- ☑ Excellent agreement with theory
- ➡ Robust measurement
- ➡ Data analyzable via perturbative QCD

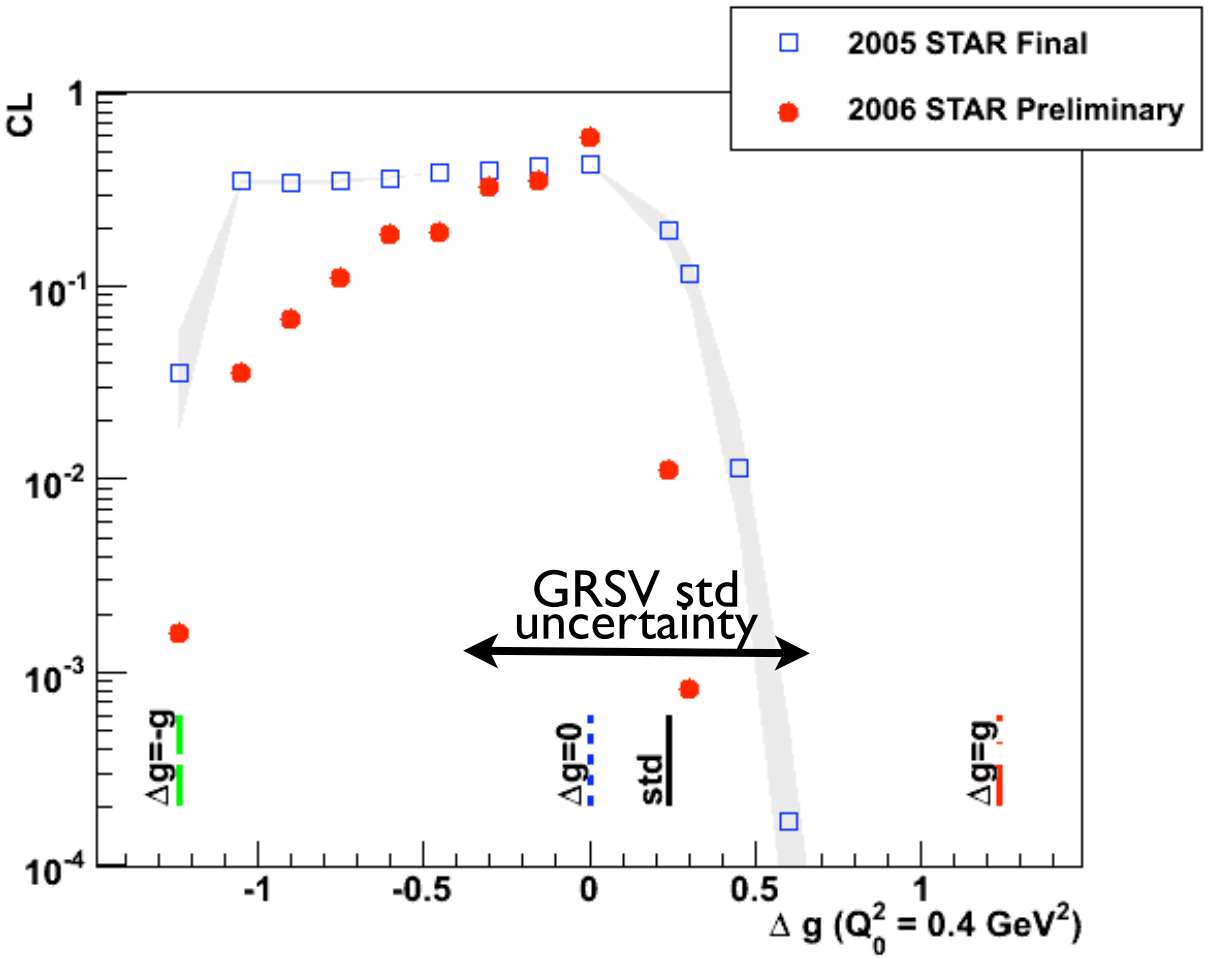
Our best asymmetry measurement yet

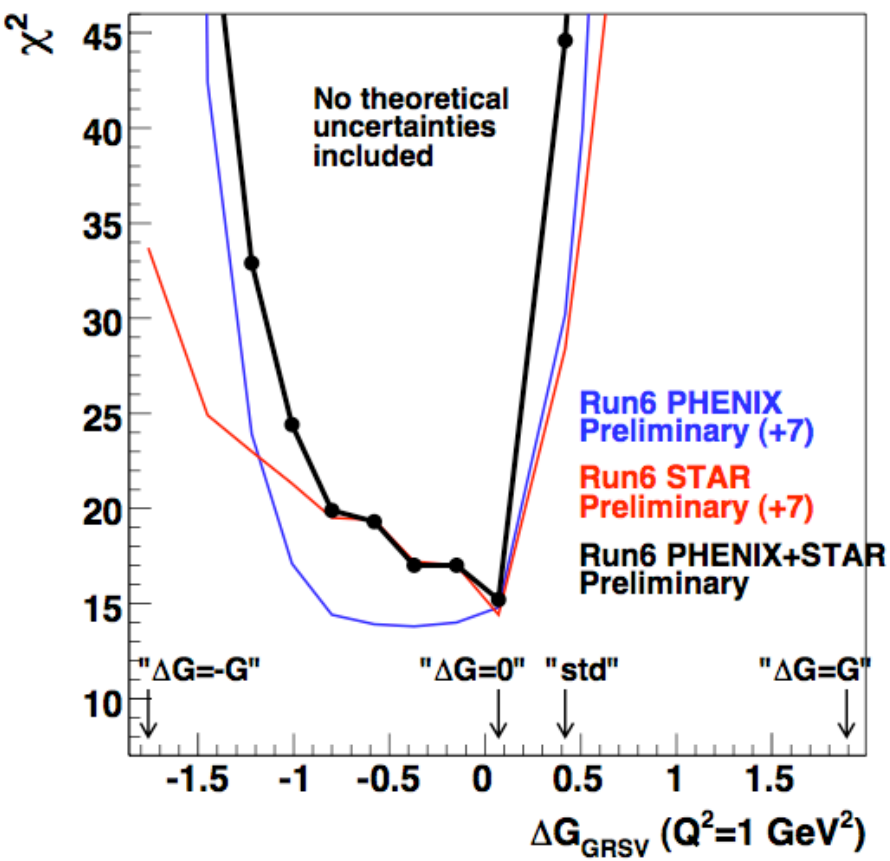
$$\vec{p} + \vec{p} \rightarrow \text{jet} + X$$



- Precision asymmetry measurements at a *polarized* hadron collider using jets
- Systematics 1-5 x10^{-3} => still statistically limited
- NLO pQCD with different assumptions for spinning glue

Closing in on the spinning glue





- Previously ruled out large and positive (DIS + early RHIC)
- Now clearly rule out large and negative
- Now rule out "GRSV-std" at 99% CL
- Reject $\Delta G < -0.7$ with 90% CL

So what would this mean?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + \Delta g(Q^2) + L_q(Q^2) + L_g(Q^2)$$

- At Q^2 = 1 GeV^2
  - seems that gluon does not make large contribution
- What are theoretical uncertainties?
  - e.g., assumption on shape of gluon distribution
  - => di-jet (RHIC 2008), photon-jet, heavy flavor (RHIC++)
- If this holds, focus shifts to quark angular momentum
  - natural in relativistic quark model
  - calculable on the lattice
  - can be measured in e+p scattering

So what would this mean?

Resolution of the Proton Spin Problem

F. Myhrer[a] and A.W. Thomas[b,c]

hep-ph/0709.4067

These three pieces of physics, tested in many independent ways, all have the effect of converting quark spin to orbital angular momentum. ....

.... Altogether, these effects reduce the fraction of the proton spin carried by its quarks to about one third, in very good agreement with the data.

Experiment		Theory
$14 \pm 9 \pm 21\%$	time ↓	$\Sigma \simeq 0.65$
$\Sigma_{\rm inv} = 0.33 \pm 0.03({\rm stat.}) \pm 0.05({\rm syst.})$,		between 0.35 and 0.40

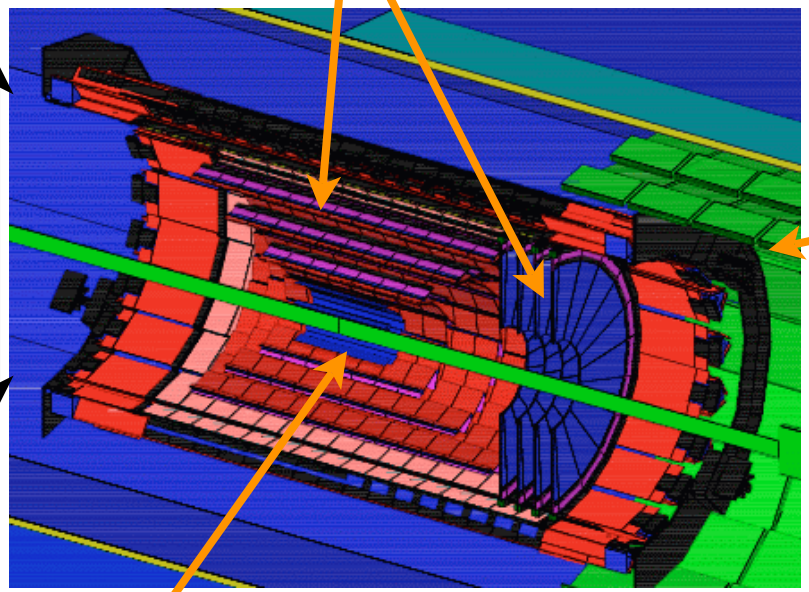
The next steps

- polarized p+p@RHIC → staged attack on the gluon
  1. Directly constrained Δg via jets, di-jets
  2. Map x-dependence of Δg
  3. Precision measurement with photon + jet
- Now beginning new era of phenomenology/calculation
  - global fits @NLO using
  - preliminary lattice calculations
- RHIC++ era → precision attack on Δg and $\Delta\Sigma$
  - 0.5 TeV running
  - Electroweak channels
  - Potential Beyond SM physics
- But experiment is pushing this field forward!

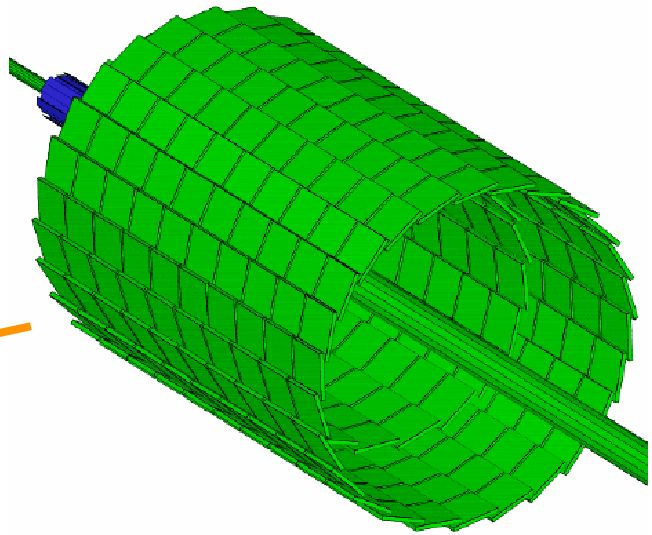
Future directions: Tracking Upgrade

Si Strips + APV25
(MIT)

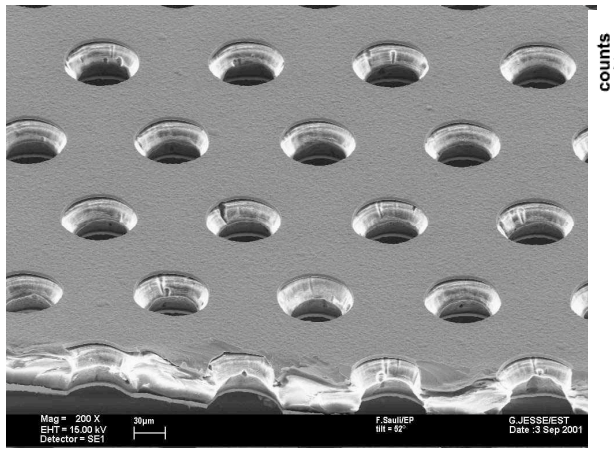
~30 cm

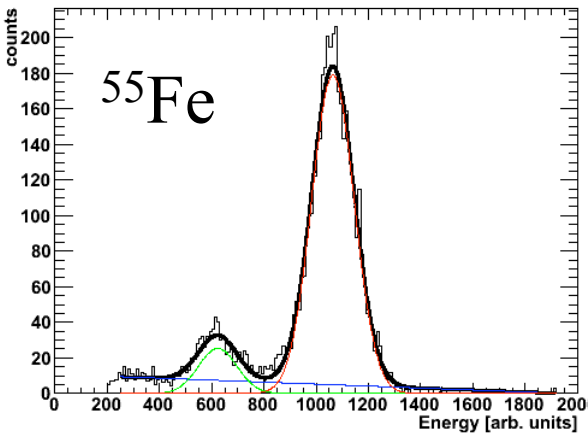


GEM + APV25
(MIT, Yale, ANL)

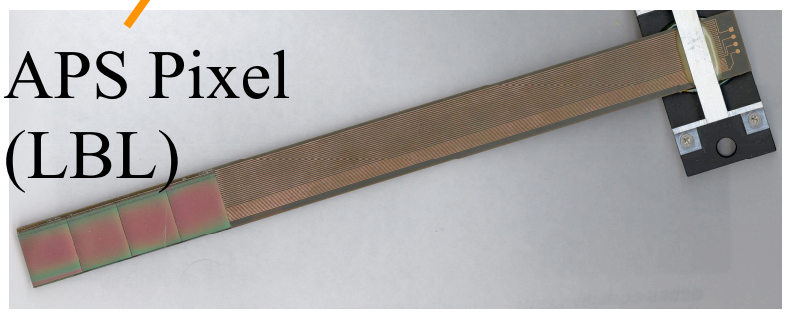


~70 μm holes
SBIR(II) Tech Etch Inc. / MIT

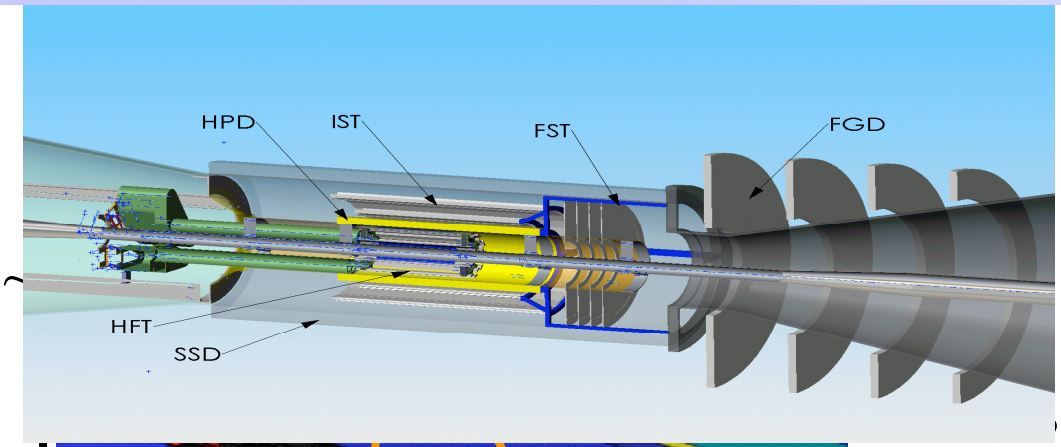




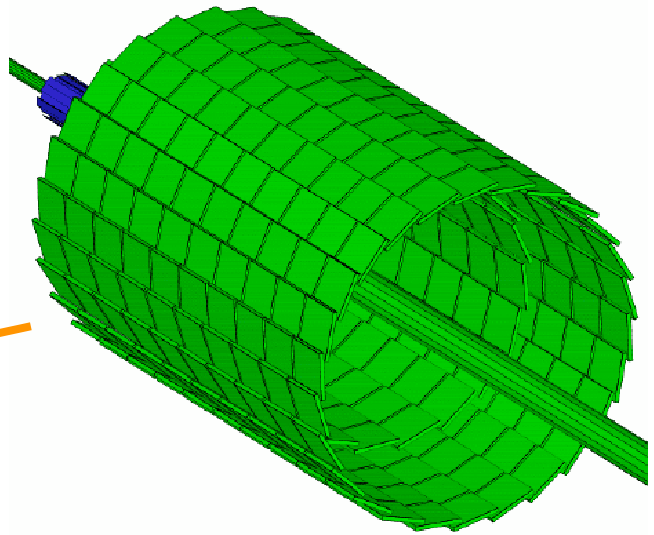
APS Pixel
(LBL)

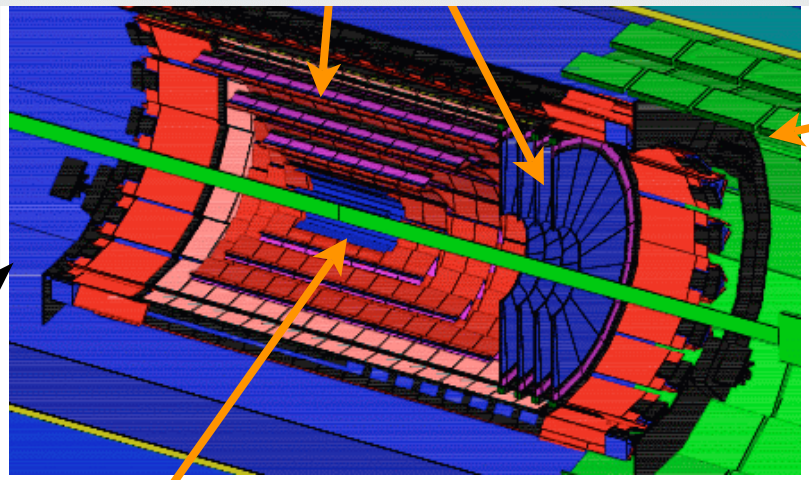


Future directions: Tracking Upgrade



+ APV25
Yale, ANL)





~70 μm holes
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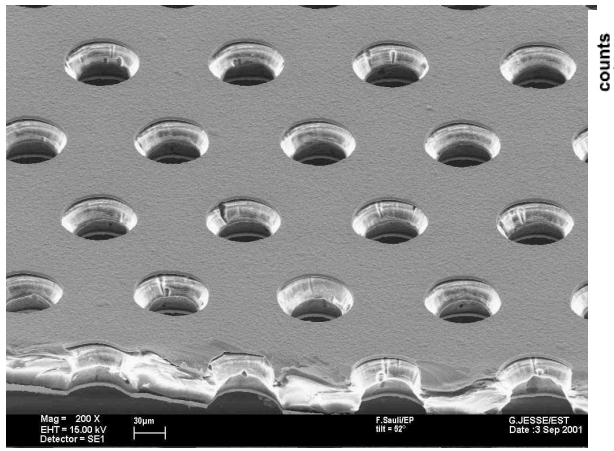

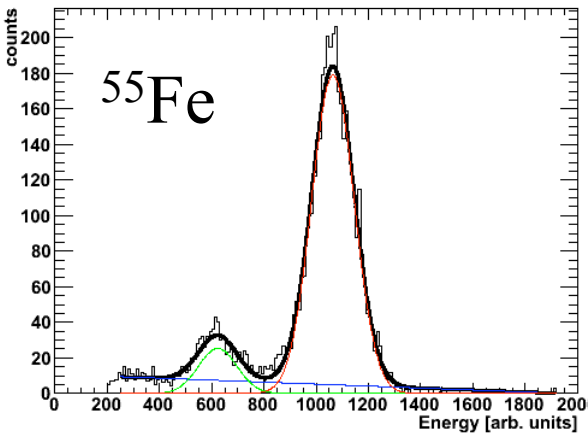

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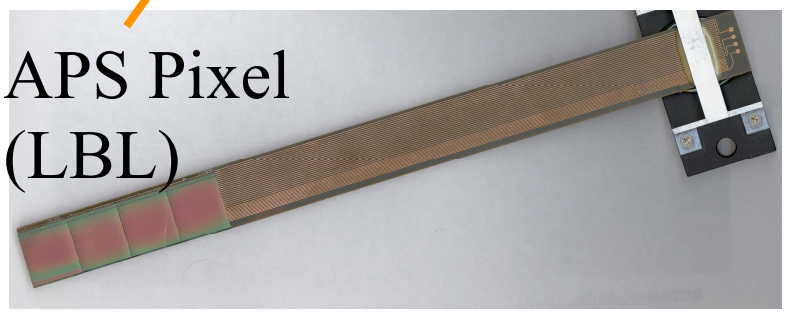


Some of the new MIT faces in QCD














experiments are dedicated to a direct determination of the spin-dependent gluon distribution $\Delta g(x, Q^2)$,

$$\Delta g(x, Q^2) \equiv g^+(x, Q^2) - g^-(x, Q^2) \,, \tag{2}$$

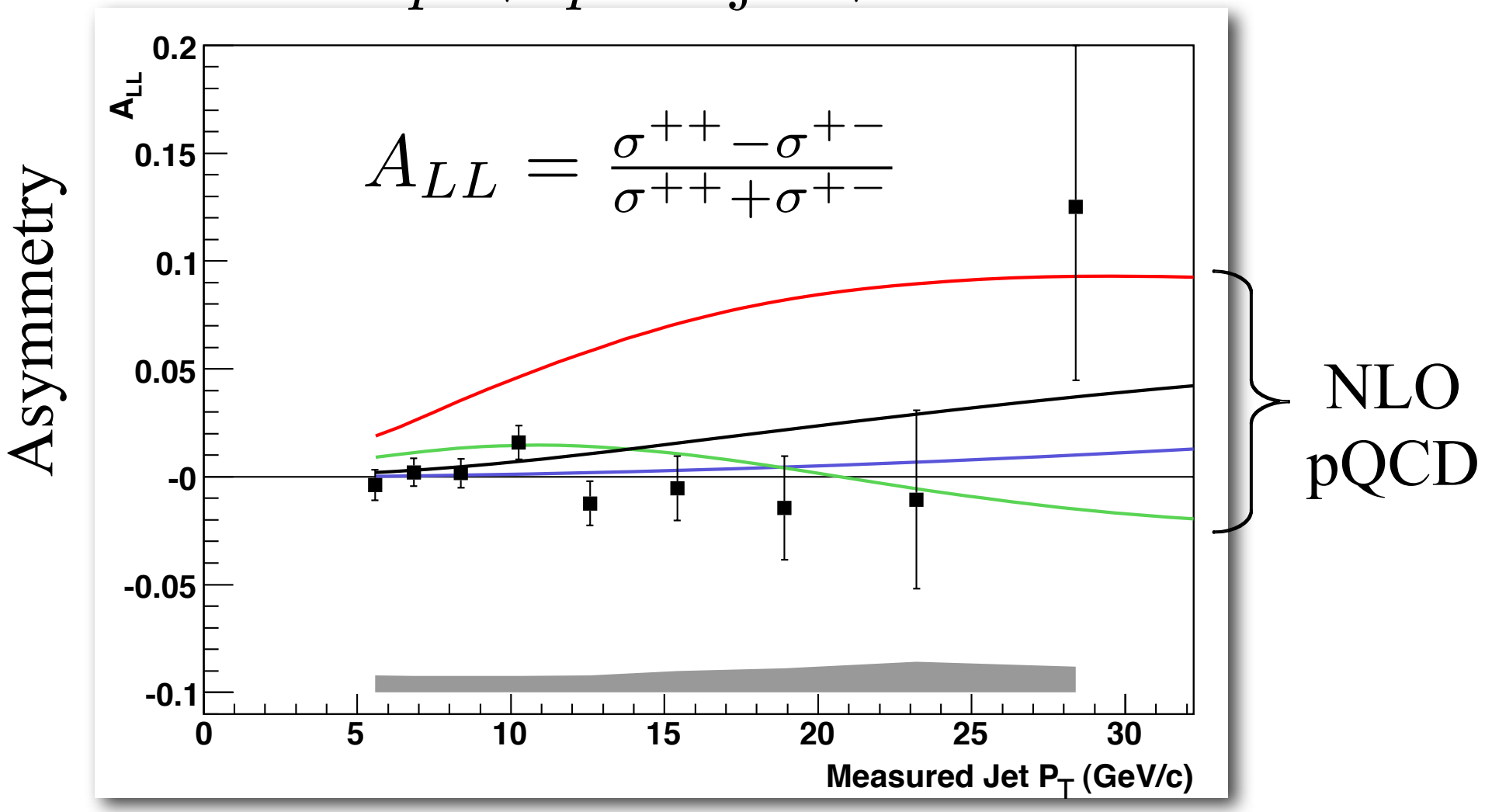
where g^+ (g^-) denotes the number density of gluons in a longitudinally polarized proton with same (opposite) sign of helicity as the proton's, and where x is the gluon's light-cone momentum fraction. The field-theoretic definition of Δg is

$$\Delta g(x, Q^2) = \frac{i}{4\pi\, x\, P^+} \int d\lambda\, \mathrm{e}^{i\lambda x P^+} \, \langle P, S | G^{+\nu}(0)\, \tilde{G}^+{}_{\nu}(\lambda n) | P, S \rangle \Big|_{Q^2} \,, \tag{3}$$

written in $A^+ = 0$ gauge. $G^{\mu\nu}$ is the QCD field strength tensor, and $\tilde{G}^{\mu\nu}$ its dual. The integral of $\Delta g(x, Q^2)$ over all momentum fractions x becomes a local operator only in $A^+ = 0$ gauge and then coincides with $\Delta G(Q^2)$ [2, 7]. The COMPASS experiment at CERN and the HERMES experiment at DESY attempt to access $\Delta g(x, Q^2)$ in charm- or high-p_T hadron final states in photon-gluon fusion $\gamma^* g \to q\bar{q}$. A new milestone has been reached with the advent of the first polarized proton-proton collider, RHIC at BNL [8, 9]. RHIC will provide precise and detailed information on Δg, over a wide range of x and Q^2, and from a variety of probes.

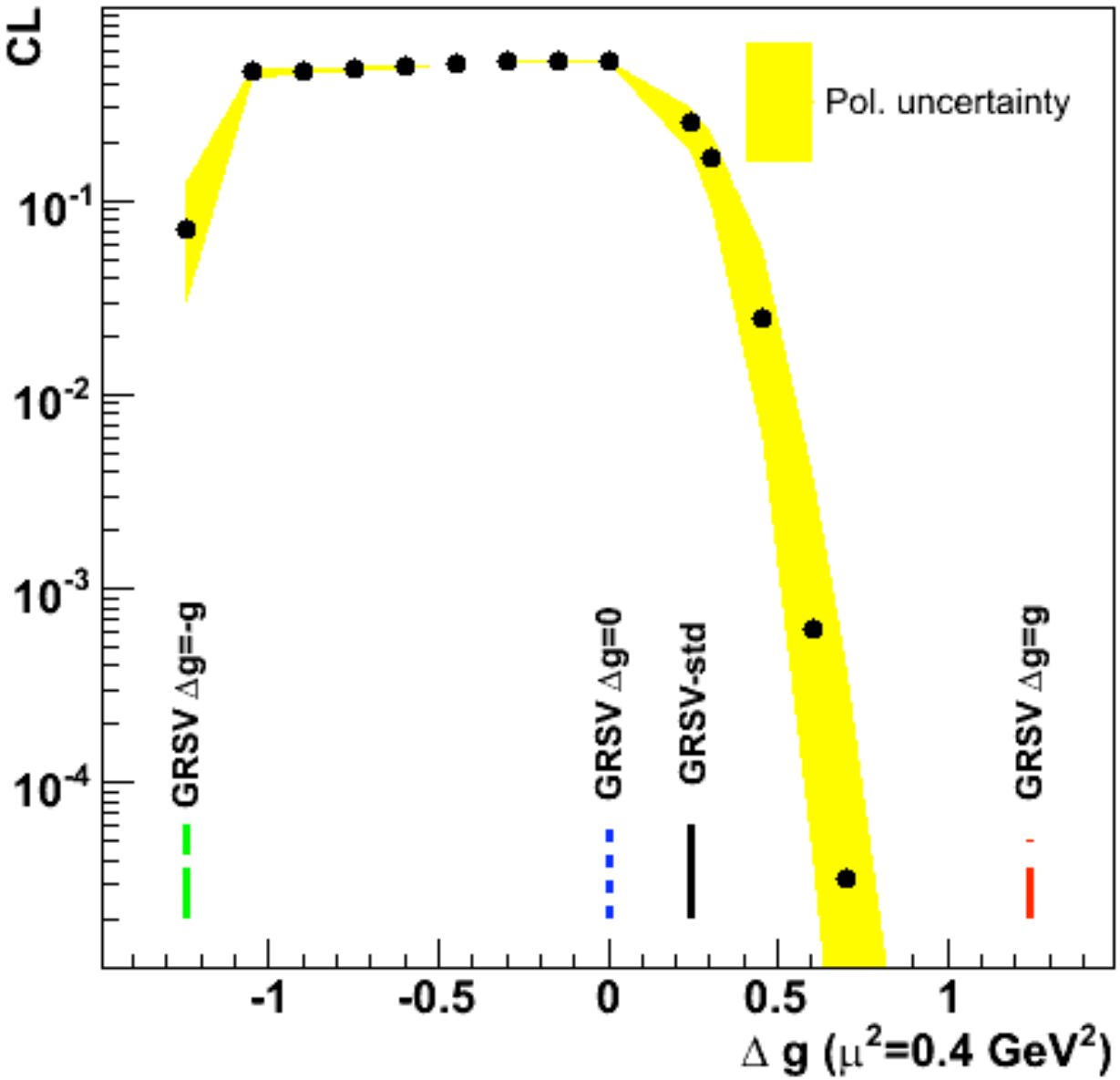
Our best asymmetry measurement yet

$$\vec{p} + \vec{p} \rightarrow \text{jet} + X$$



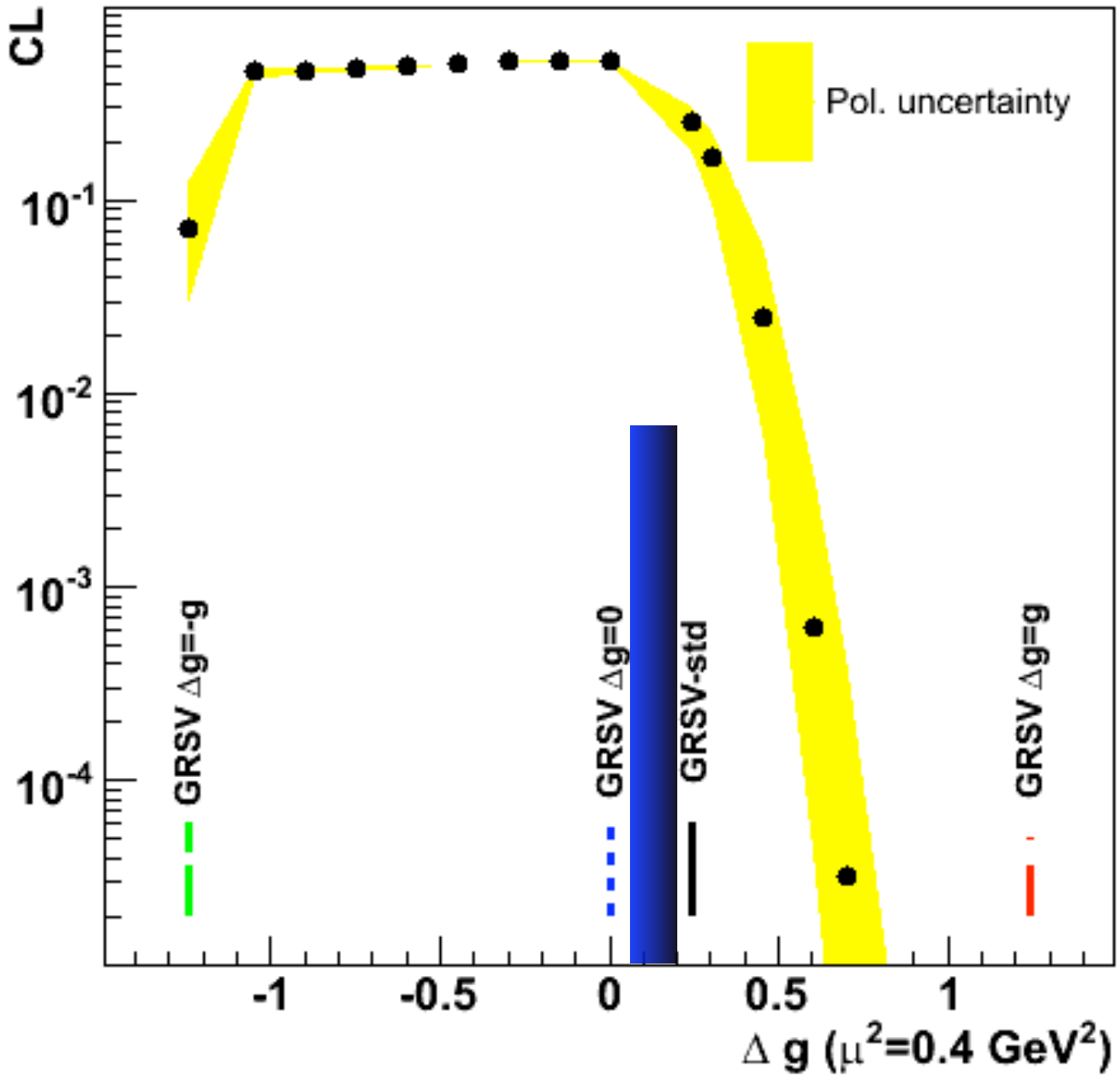
- Precision asymmetry measurements at a *polarized* hadron collider
- NLO pQCD with different assumptions for spinning glue

Translated to confidence levels



Models of large positive gluon helicity clearly ruled out

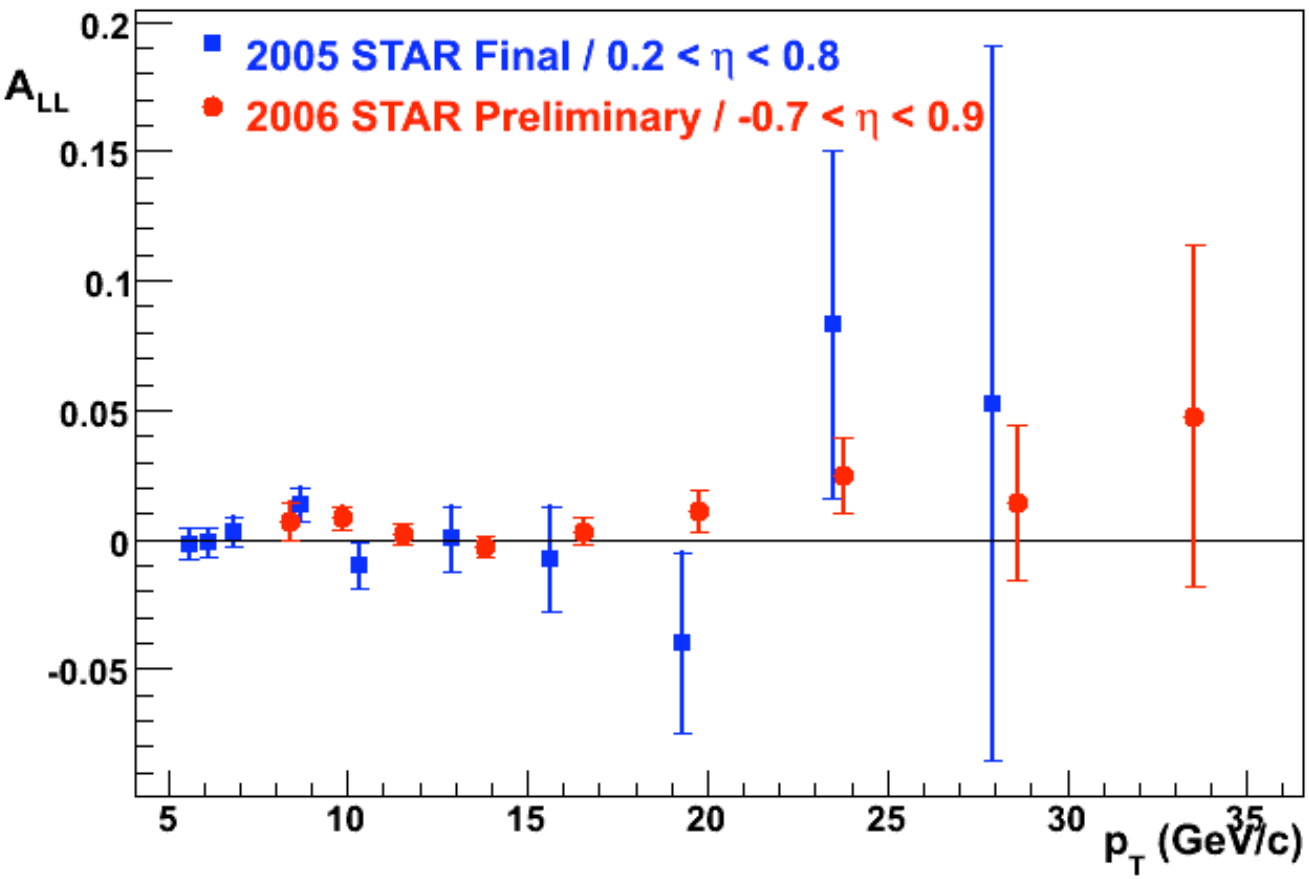
Translated to confidence levels



- Suppose best value between blue and black line

➡ At Q^2=1 GeV^2, spin budget closed by quarks, gluons

Models of large positive gluon helicity clearly ruled out



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%