Center for Frontiers in Nuclear Science

Lecture 2: RHIC Spin: polarized glue, transverse spin and nuclear structure

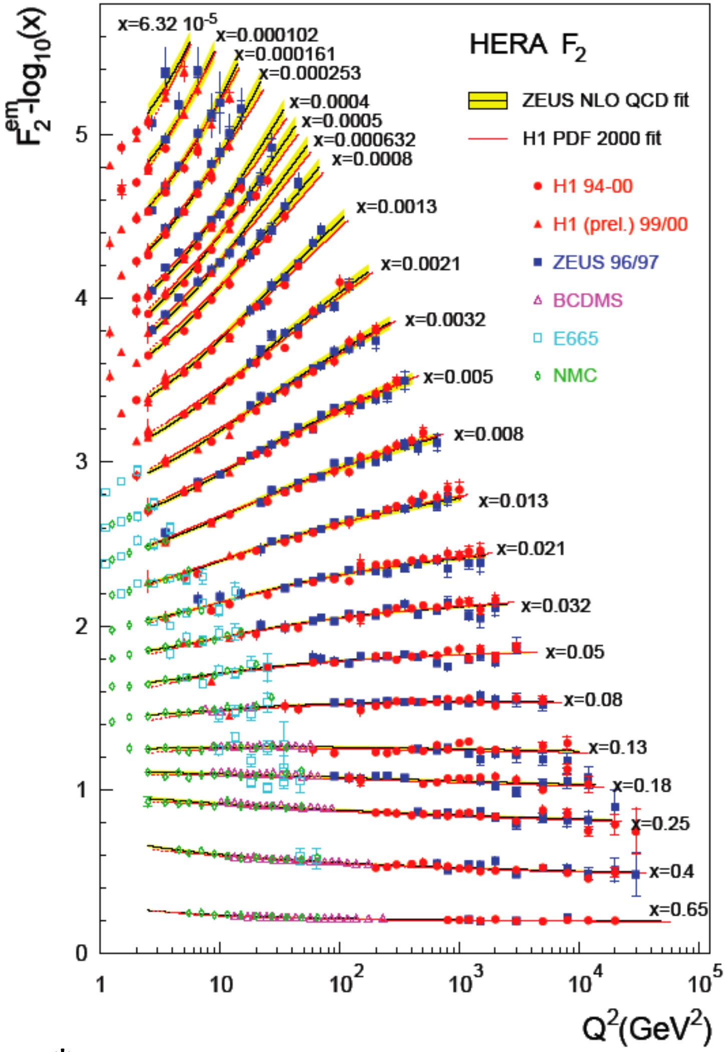
Abhay Deshpande

Measurement of unpolarized glue at HERA

F$_2$ Structure Function

Vs.

Q^2 mom. exchanged

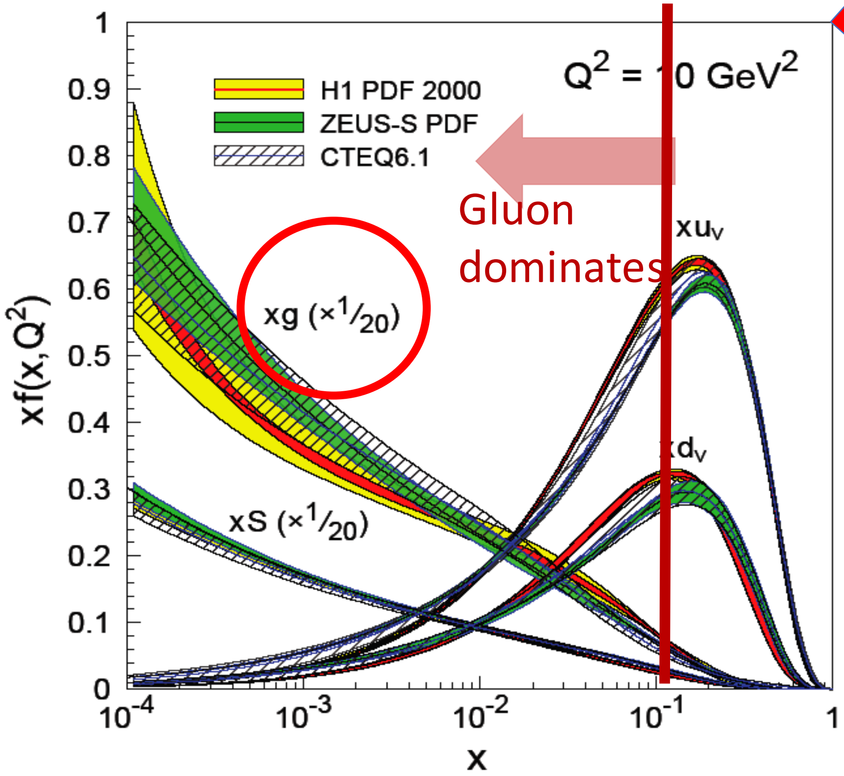


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

- Scaling violations of $F_2(x,Q^2)$

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

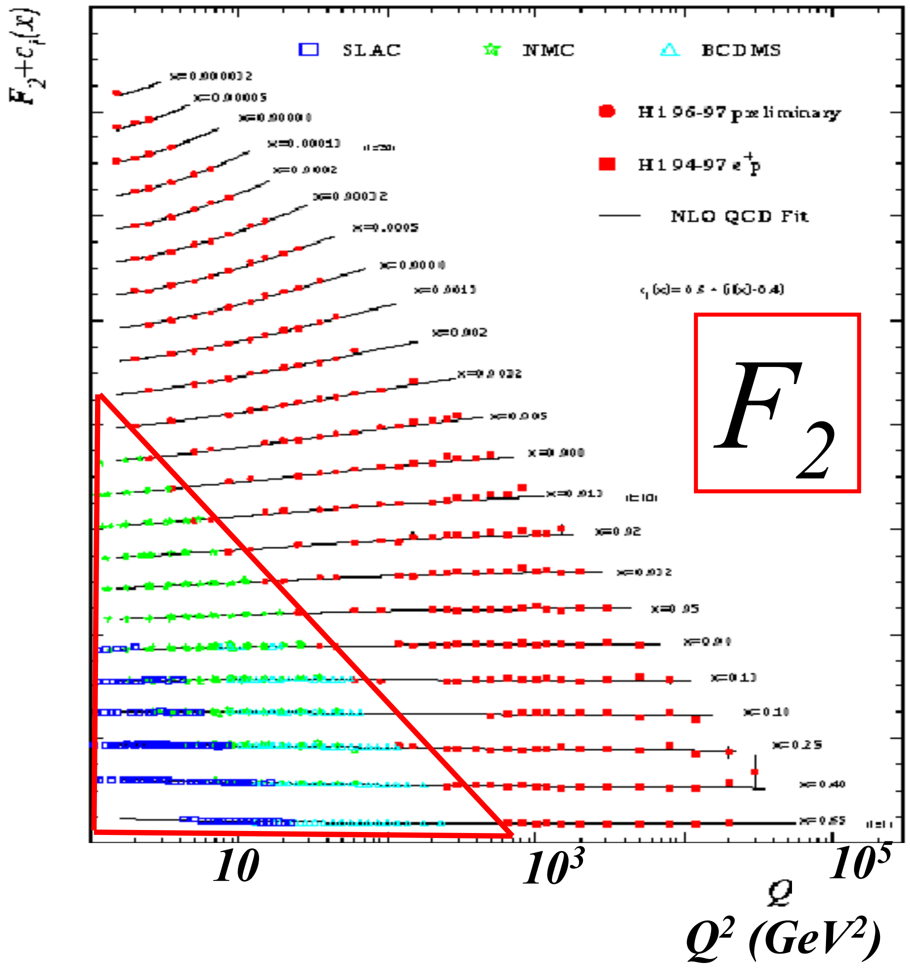
- NLO pQCD analyses: fits with **linear** DGLAP* equations



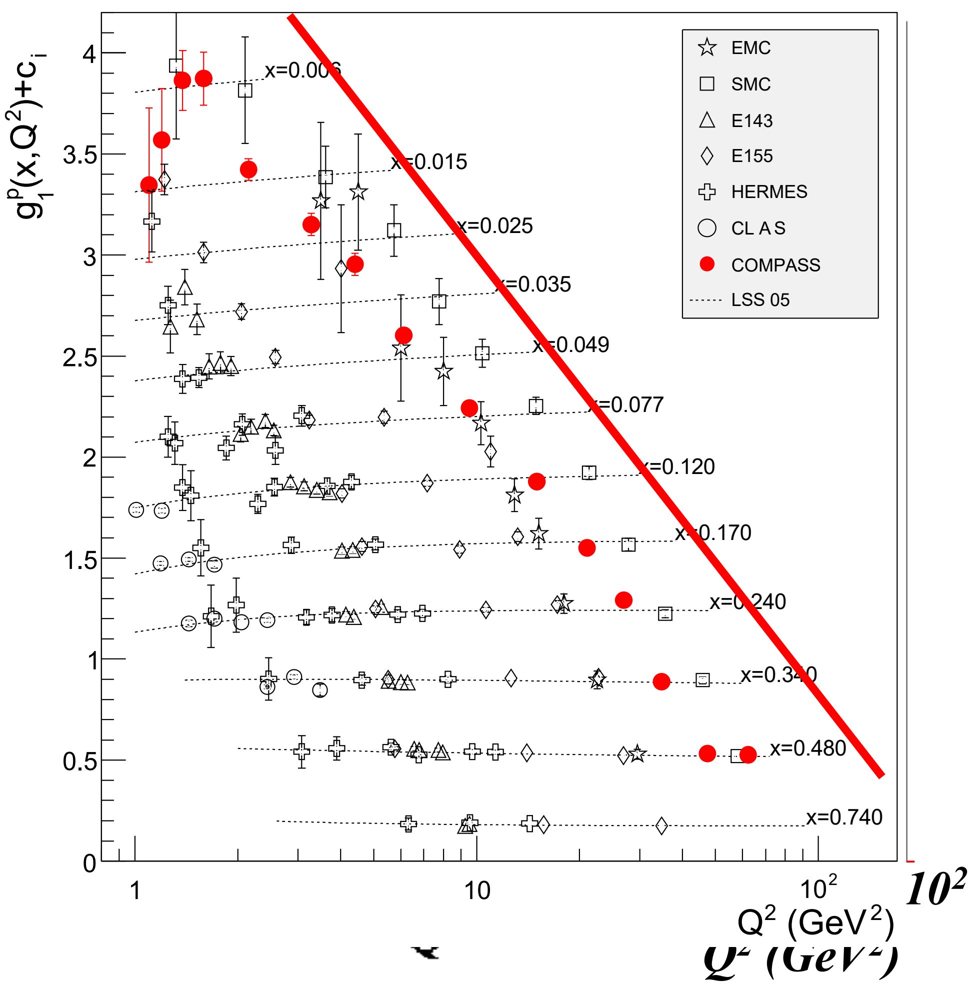
Can one do the same thing for spin structure function g_1?

Spin contribution of the gluon to the proton from scaling violation g_1 spin structure function?

F_2 vs. g_1 structure function measurements



Aidala et al.1209.2803v2

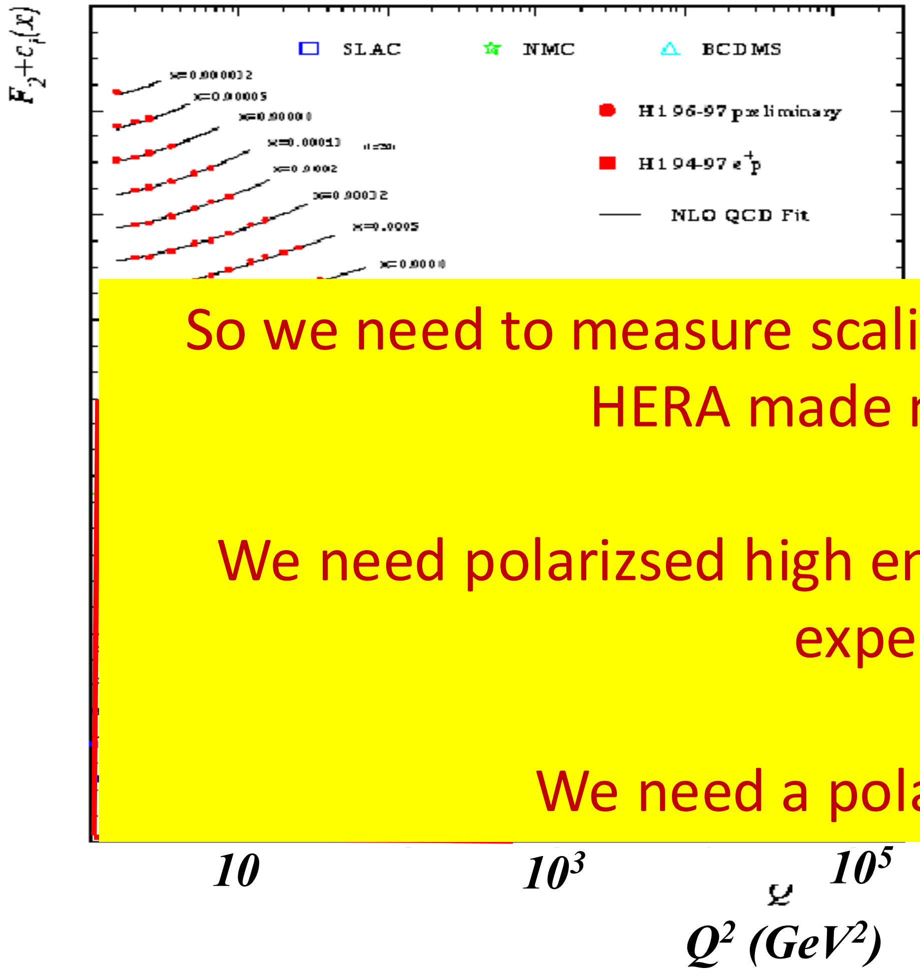


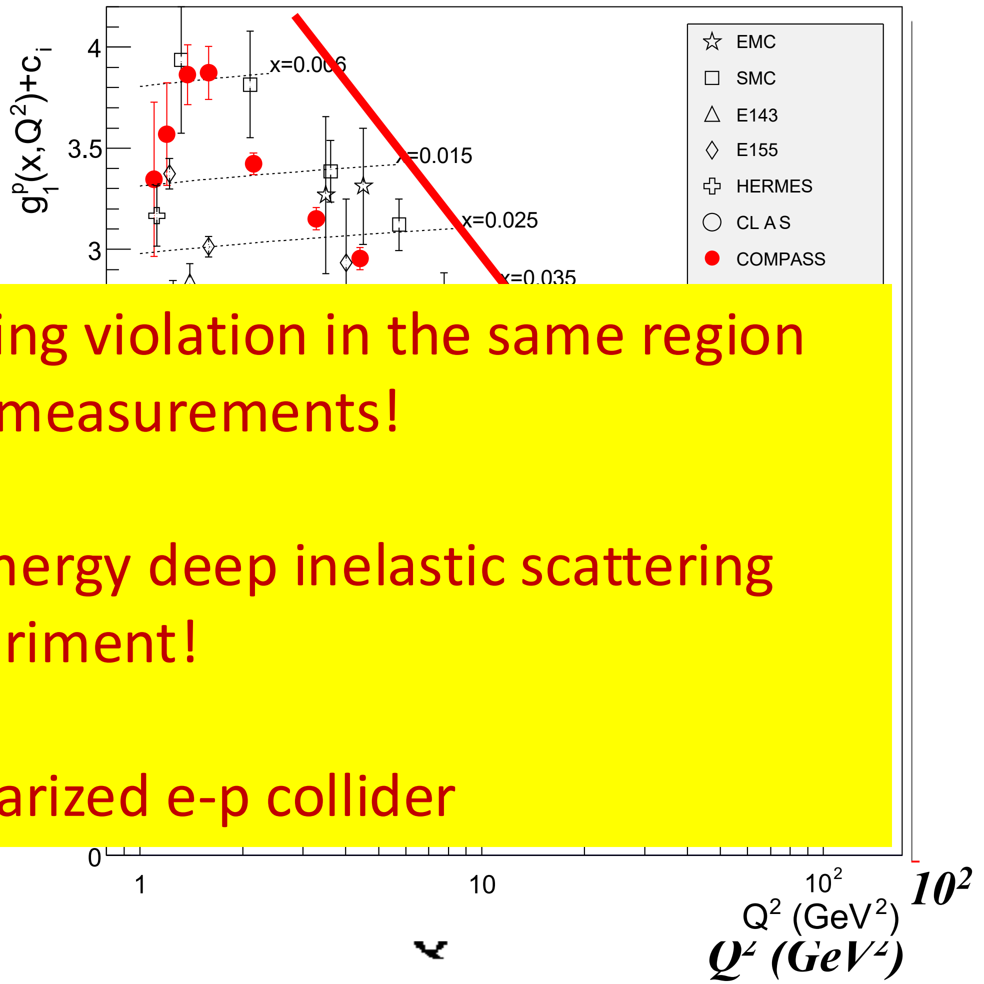
Large amount of polarized data since 1998… but not in NEW kinematic region!

Large uncertainty in gluon polarization (+/-1.5) results from lack of wide Q^2 arm

F_2 vs. g_1 structure function measurements

Aidala et al.1209.2803v2





So we need to measure scaling violation in the same region HERA made measurements!

We need polarizsed high energy deep inelastic scattering experiment!

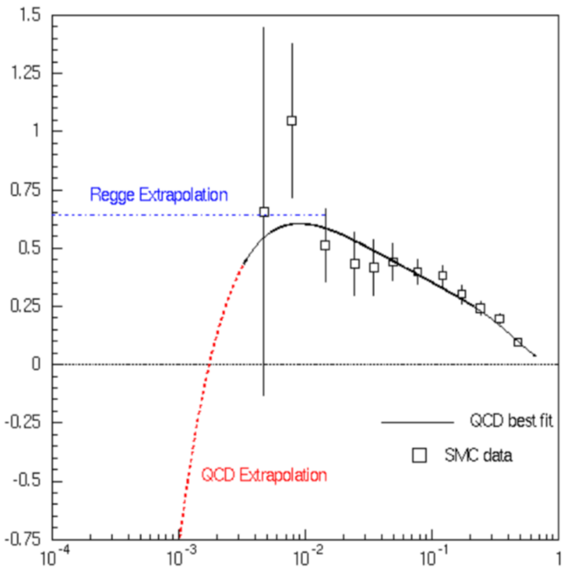
We need a polarized e-p collider

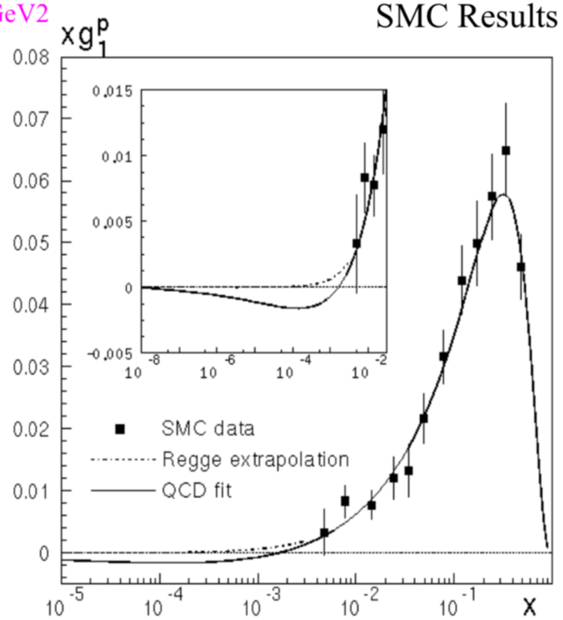
Large amount of polarized data since 1998… but not in NEW kinematic region!

Large uncertainty in gluon polarization (+/-1.5) results from lack of wide Q^2 arm

Lack of low x data… consequences

Q2 = 10 GeV2





- Regge extrapolation:

$$\int_0^{0.003} g_1^p(x, Q_0^2)dx = 0.002 \pm 0.002$$

- QCD fit extrapolation:

$$\int_0^{0.003} g_1^p(x, Q_0^2)dx = -0.011 \pm 0.011$$

$$g_1(x \to 0) \propto x^\alpha \quad \text{as } 0 < \alpha < 0.5$$

Regge/QCD

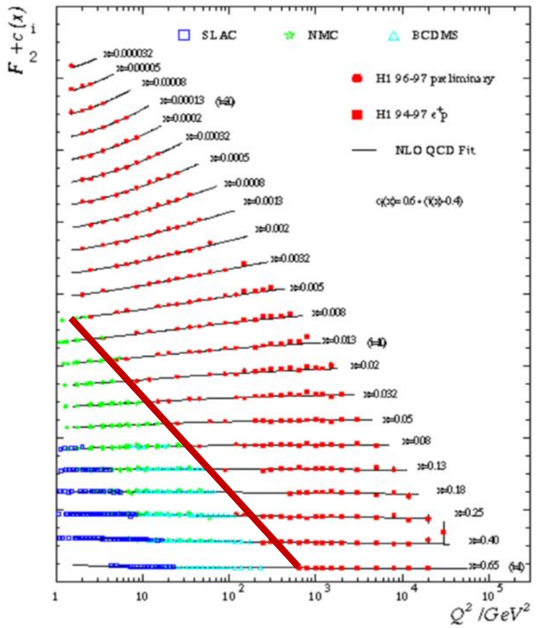
In these discussions, while many focused on the low-x Extrapolations.

SMC PRD98 (112002) 1998

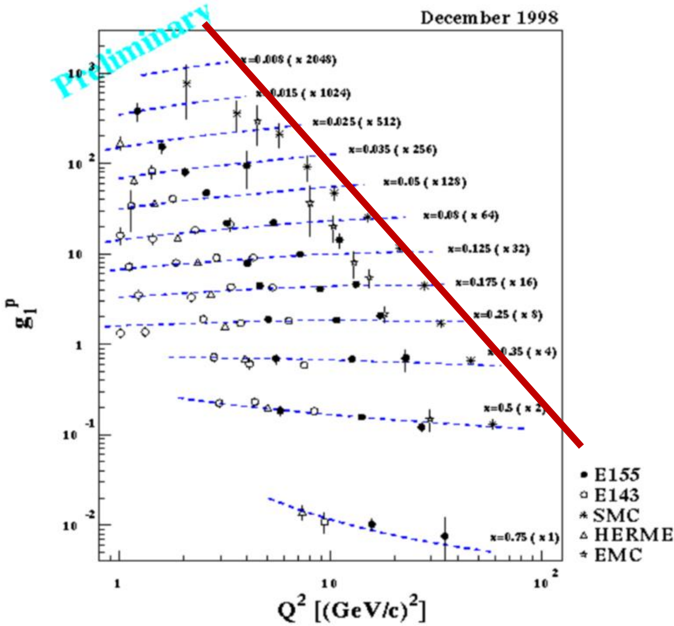
Seeds for a **polarized collider**

How far does polarized DIS have to go!

World data on F_1^p



World data on g_1^p



Consequence:

- Quark (+anti-quark) contribution to nucleon spin is small:

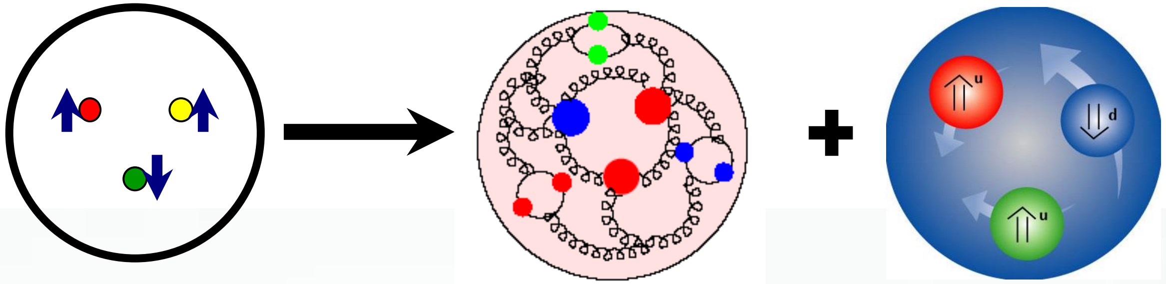
$\rightarrow \frac{1}{2}\Delta\Sigma = 0.15 \pm 0.03$ instead of the expected 0.5

  - Is this smallness due to some cancellation between quark & anti-quark polarization?

- Or does glue makes a very large contribution? $\Delta G = 1 \pm 1.5$

- Most Next to Leading Order (NLO) analyses by consistent with HIGH gluon contribution
  - Direct measurement of gluon spin with other probes warranted.
  - Seeded the RHIC Spin program

Our Understanding of Nucleon Spin Puzzle

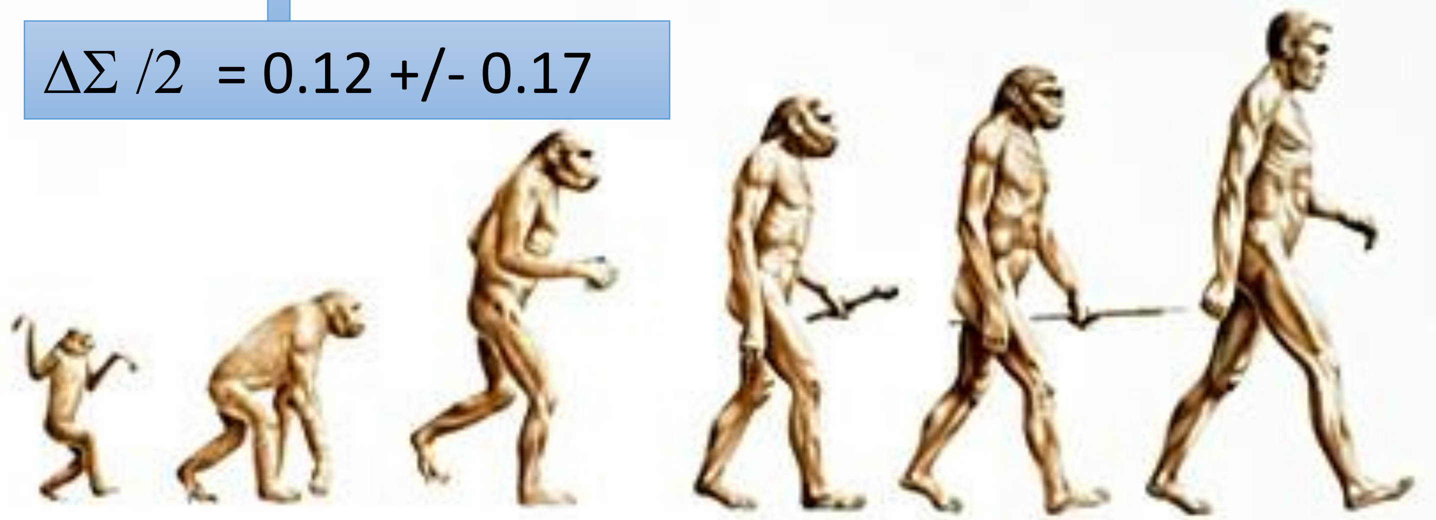


1980s

1990/2000s

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + \left[\Delta g + L_G\right]$$

$\Delta\Sigma/2$ = 0.12 +/- 0.17



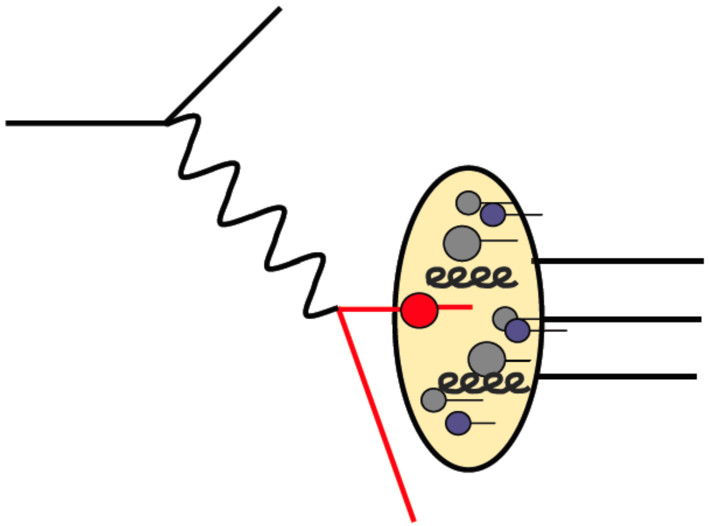
Need information about transverse dimensions of the proton

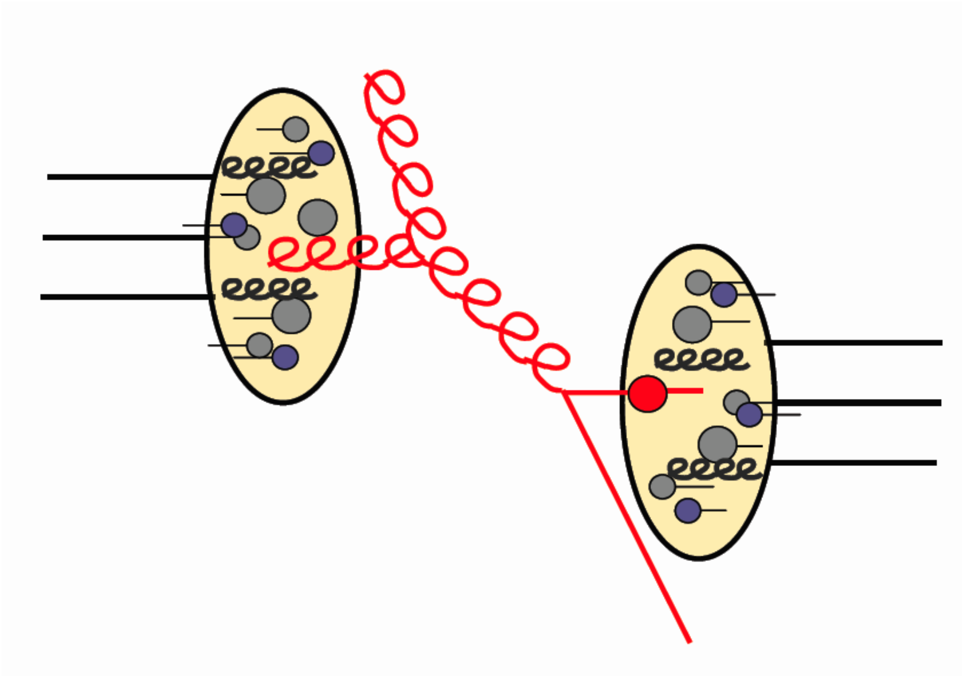
Spin discovered a problem…. What now? Need precision and investigations of gluons….

RHIC Spin program: a polarized collider

Pre-cursor to a polarized e-p --- Electron Ion Collider

Complementary techniques





Photons colorless: forced to interact at NLO with gluons

Can't distinguish between quarks and anti-quarks either

Why not use polarized quarks and gluons abundantly available in protons as probes ?

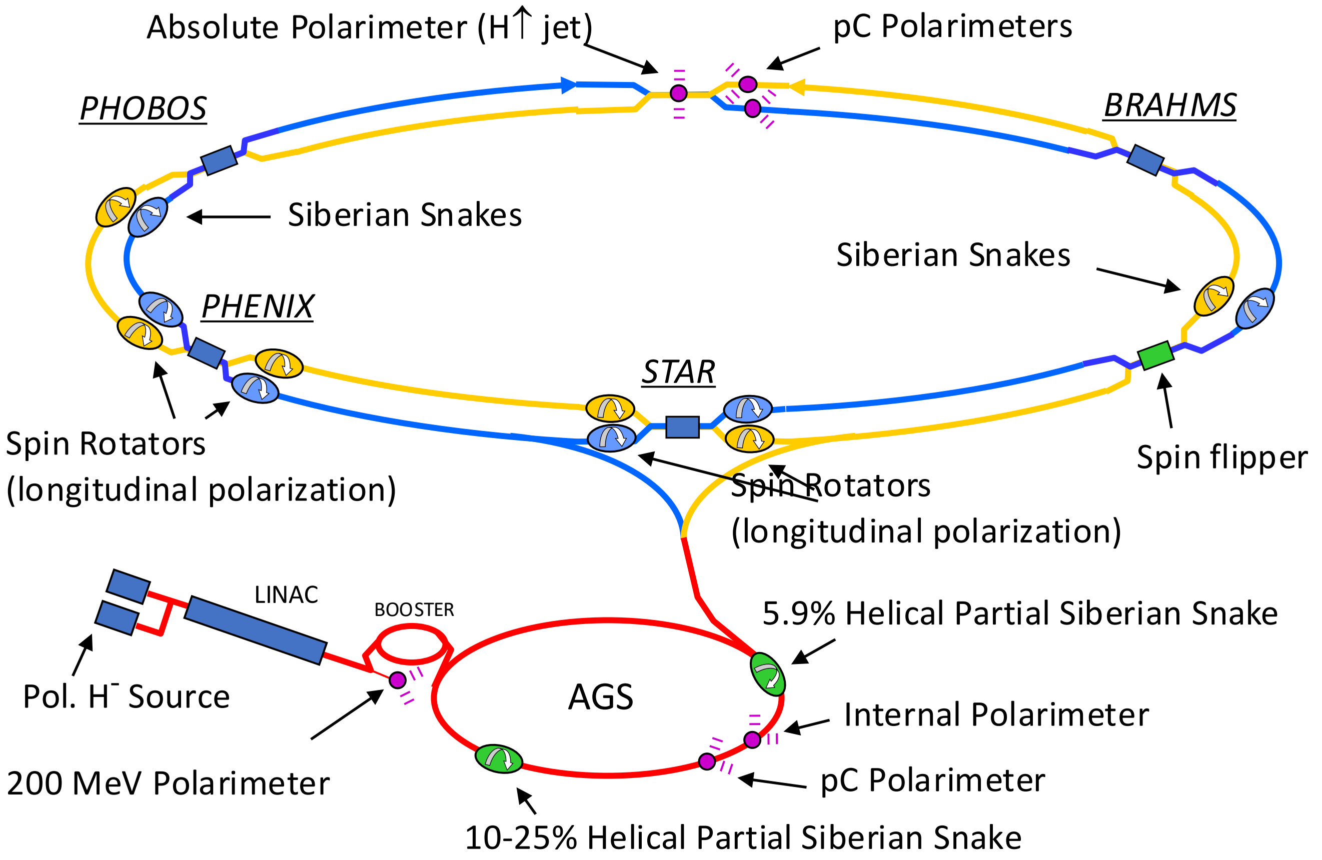
Seeds for RHIC Spin program:

If one wants to study gluon's spin contribution to proton's spin, ***why not directly explore the gluon spin with polarized proton p-p collisions?***

Curious and bothersome transverse spin asymmetries in p-p scattering persistent in every experiment performed…. US physicists heavily involved… decided to investigate further at high energy

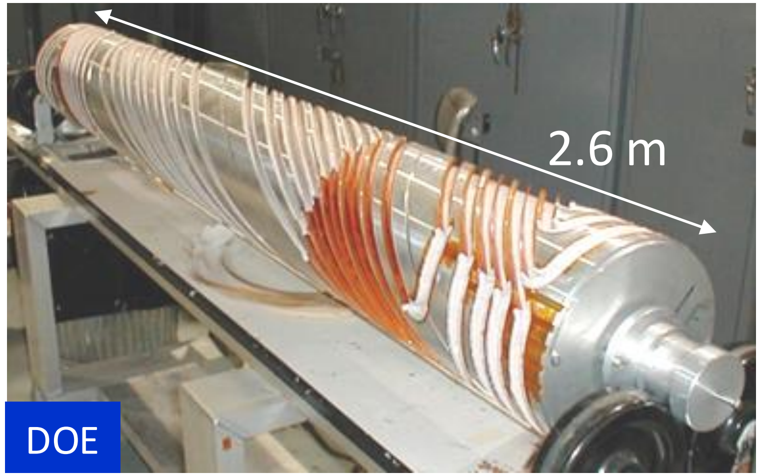
Technical know-how of polarizing proton beams at high energy became available in the mid-late 1990's

RHIC as a Polarized Proton Collider

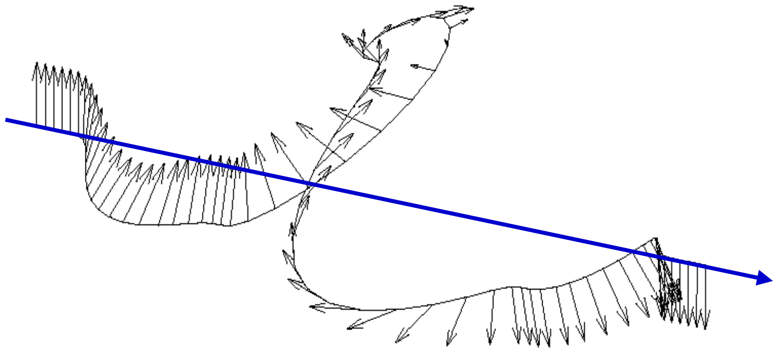


Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79$ E/m → ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½$ → no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

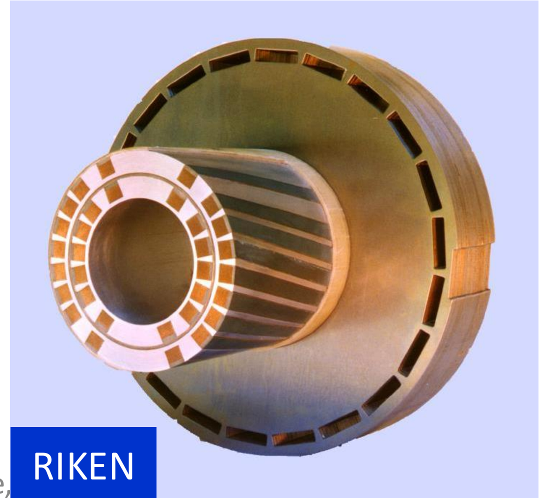
Siberian Snakes



- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist



Courtesy of A. Luccio



$A_{measured} = A_{LL}$
Double Longitudinal Spin asymmetry

REMEMBER?

$$A_{measured} = \frac{N^{\rightarrow\leftarrow} - N^{\rightarrow\rightarrow}}{N^{\rightarrow\leftarrow} + N^{\rightarrow\rightarrow}}$$

$$N^{\leftarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\leftarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

If all other things are equal,

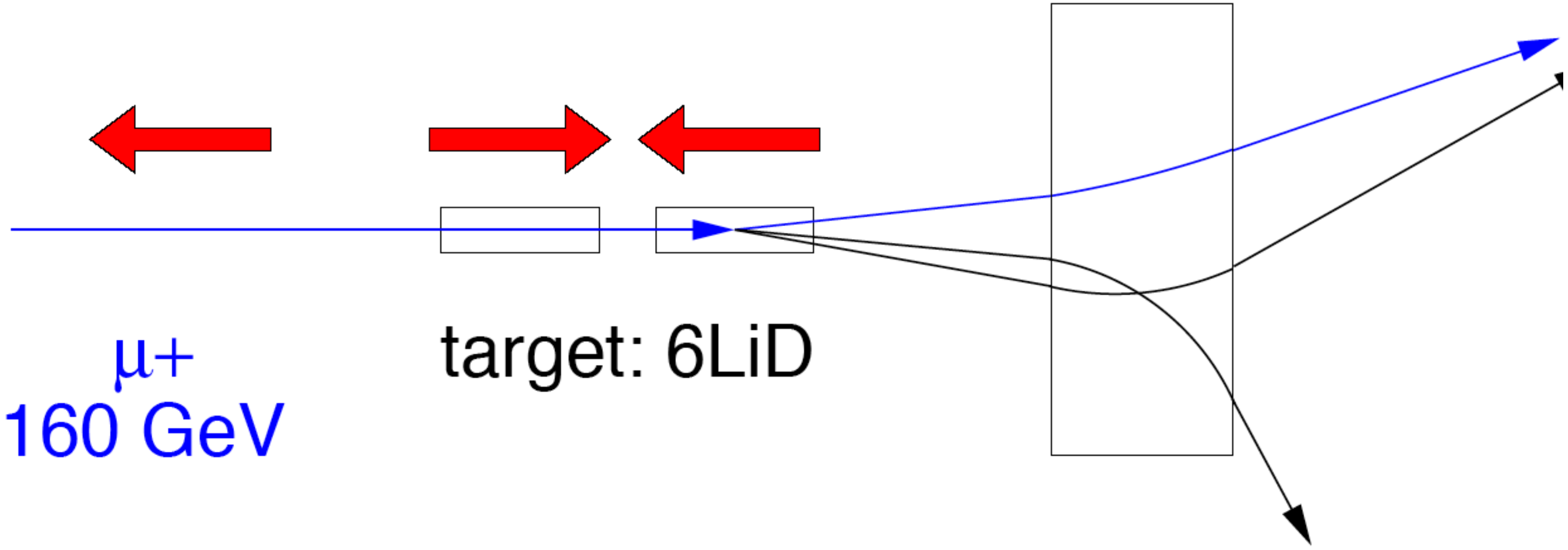
they cancel in the ratio

$$A_{measured} = \frac{\sigma^{\rightarrow\leftarrow} - \sigma^{\rightarrow\rightarrow}}{\sigma^{\rightarrow\leftarrow} + \sigma^{\rightarrow\rightarrow}}$$

A Typical Setup

REMEMBER?

- Experiment setup (EMC, SMC, COMPASS@CERN)

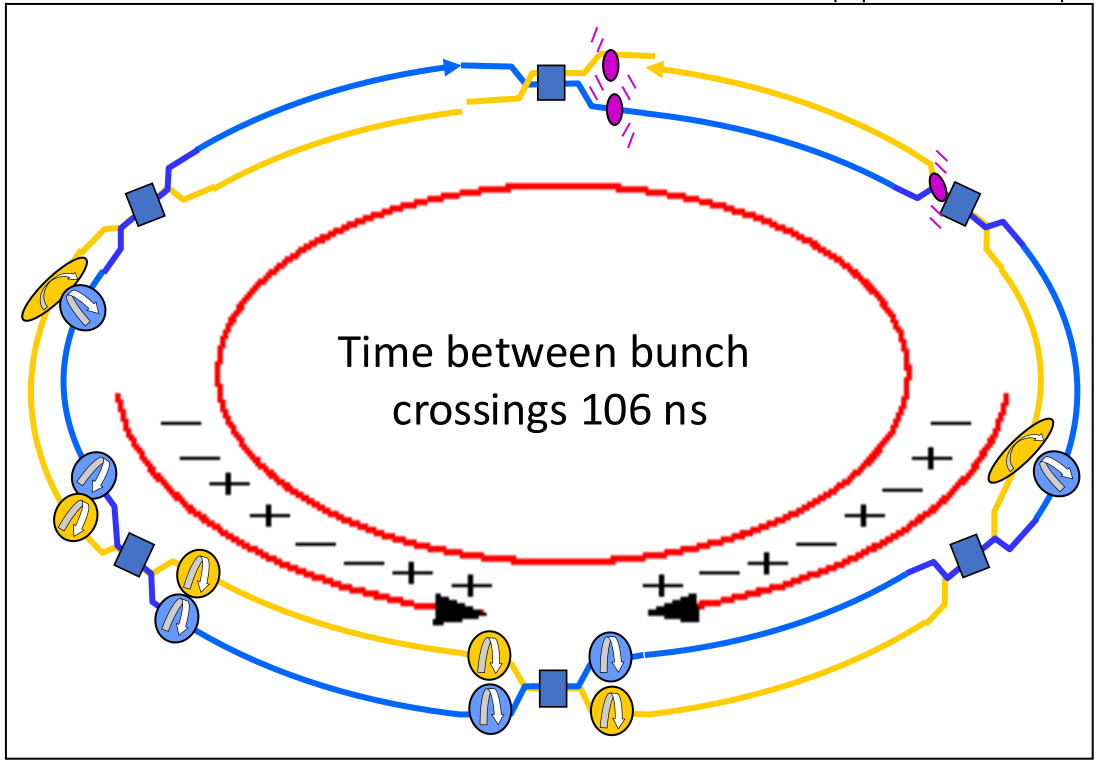


- Target polarization direction reversed every 6-8 hrs
- Typically experiments try to limit false asymmetries to be about 10 times smaller than the physics asymmetry of interest

Measuring A_{LL}

Longitudinal Spin Asymmetry using polarized proton bunches in the RHIC ring

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$



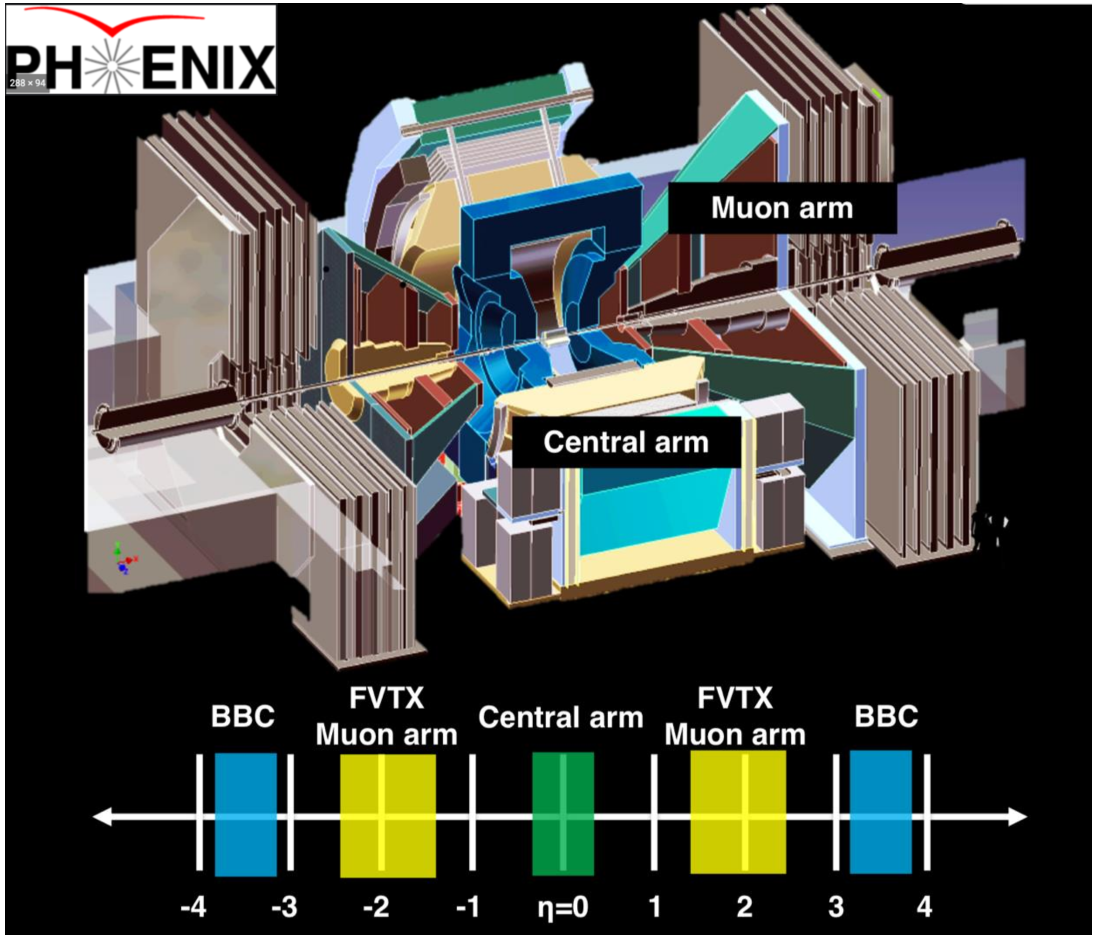
(N) Yield
(R) Relative Luminosity
(P) Polarization

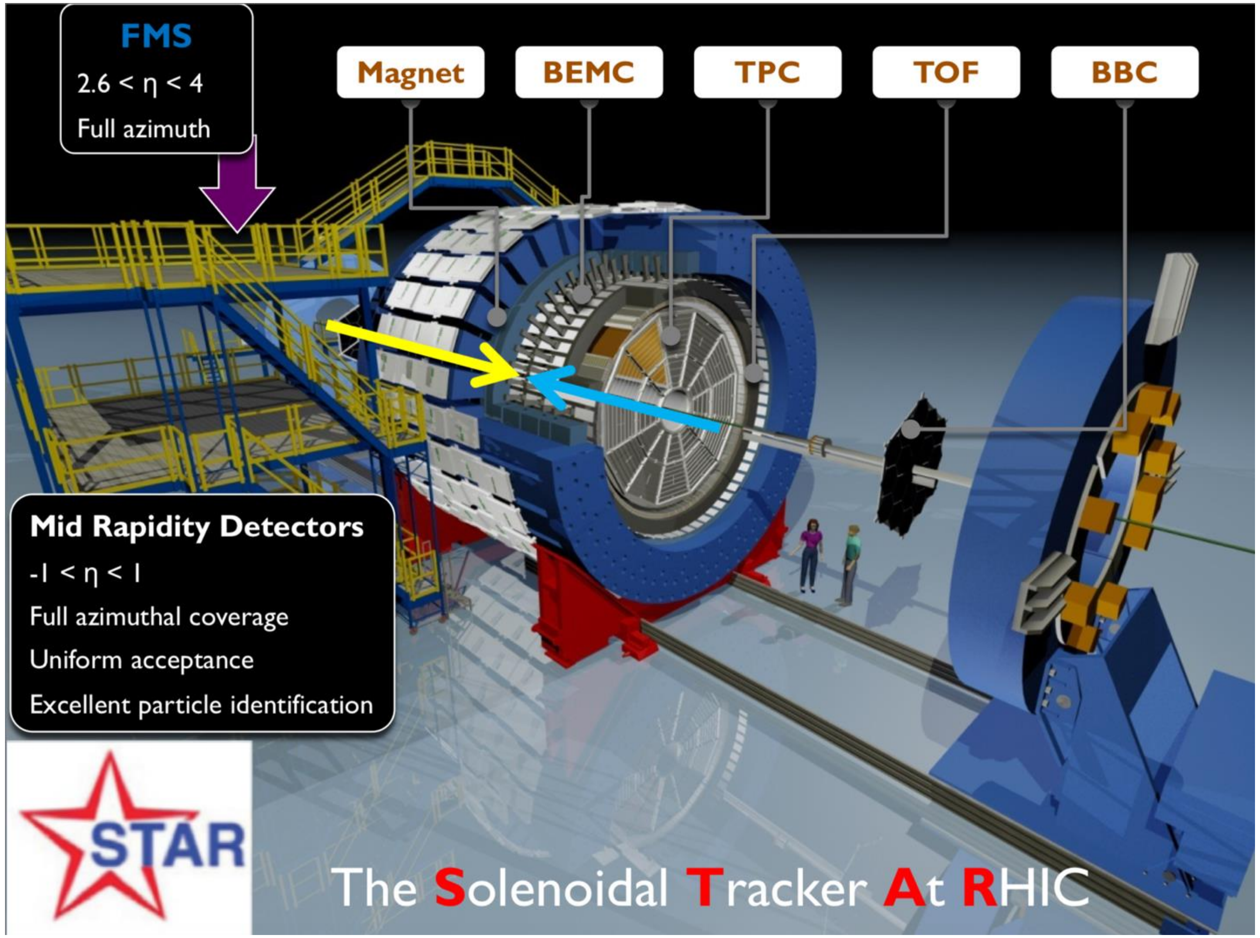
Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

- ✓ Bunch spin configuration alternates every 106 ns
- ✓ Data for all bunch spin configurations are collected at the same time

⇒ Possibility for false asymmetries are greatly reduced

Two main detectors for spin studies

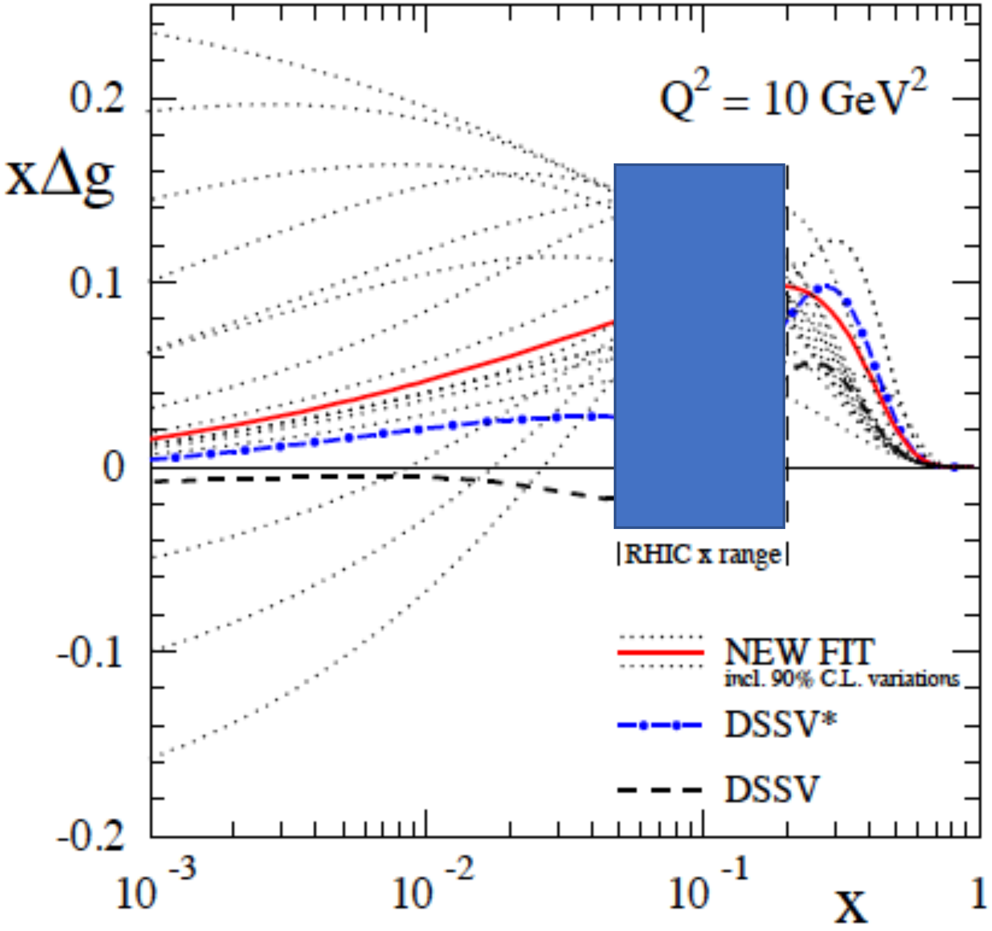




Recent global analysis: DSSV

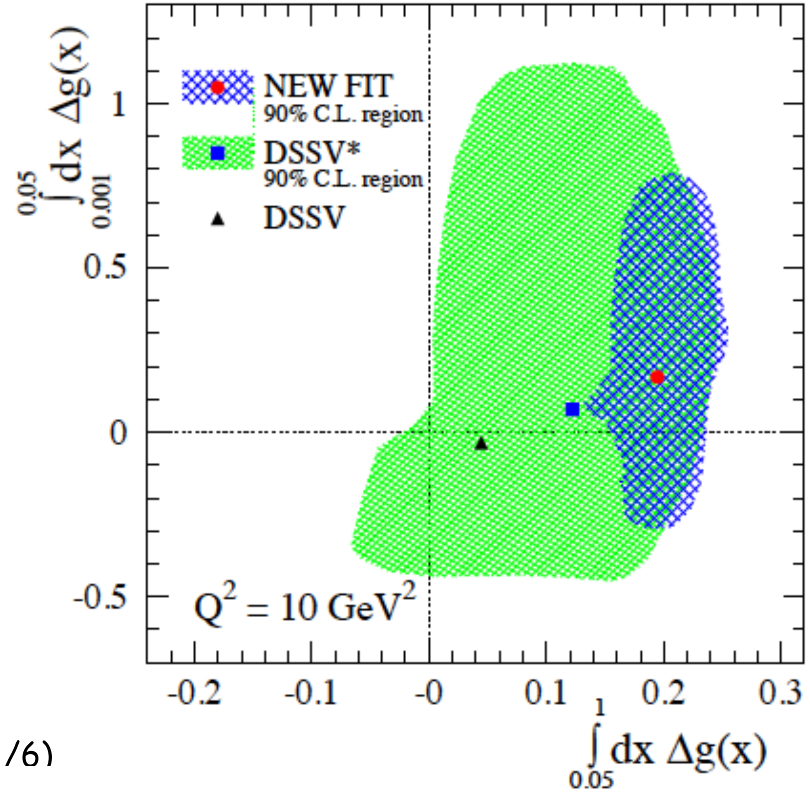
D. deFlorian et al., arXiv:1404.4293

Wide spread at low x (x<0.05) of alternative fits consistent within 90% of C.L.



/6)

$\Delta G = 0.2$ +/- 0.02 +/- 0.5



While RHIC made a huge impact on ΔG

large uncertainties remain in the low-x unmeasured region!

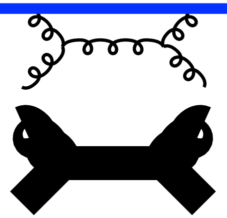
2009 RHIC data established non-zero ΔG

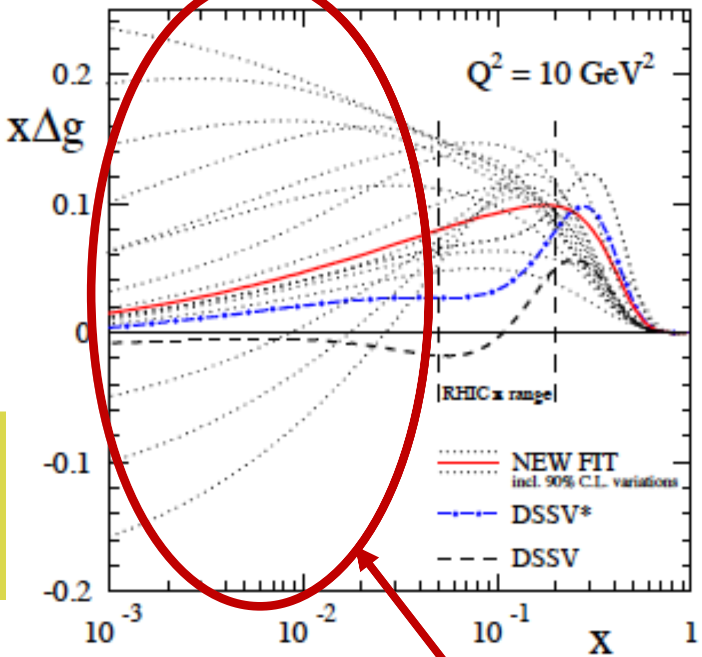
-- PHENIX 2005-9, PRD 90, 12007 (2014)

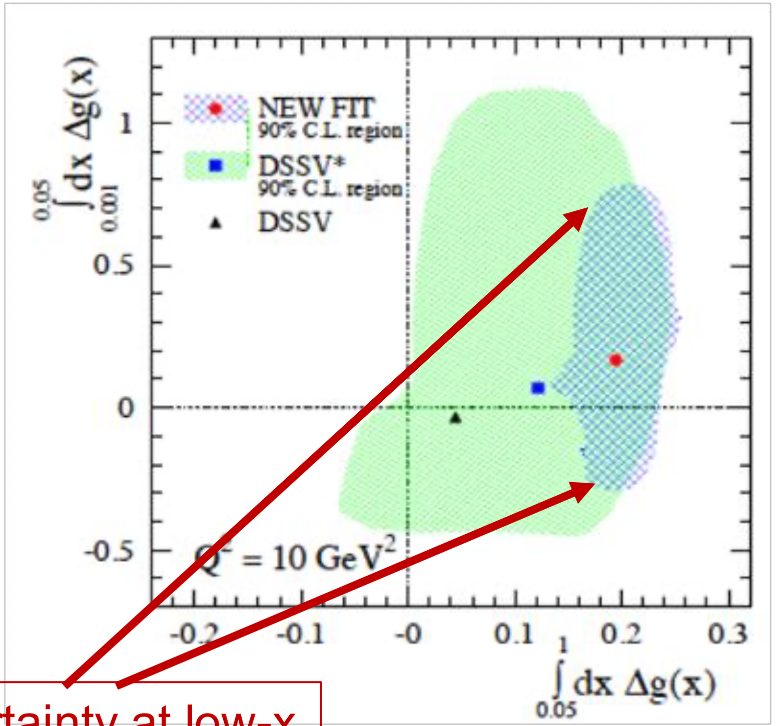
-- STAR 2009, PRL 115 (2015) 92002

-- DSSV PRL (113) 12001 (2014)

$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} \text{ @ } 10 \text{ GeV}^2$$

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)

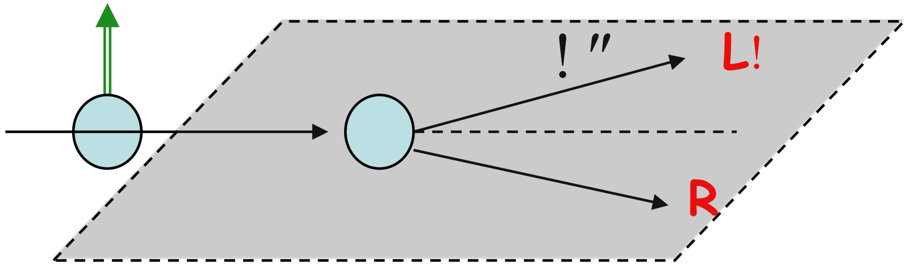




Large uncertainty at low-x

Transverse Spin effects in p-p observed but ignored for 40+ years

Transverse spin introduction



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

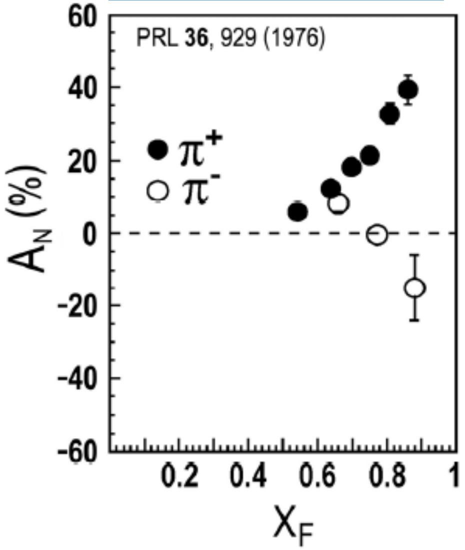
$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

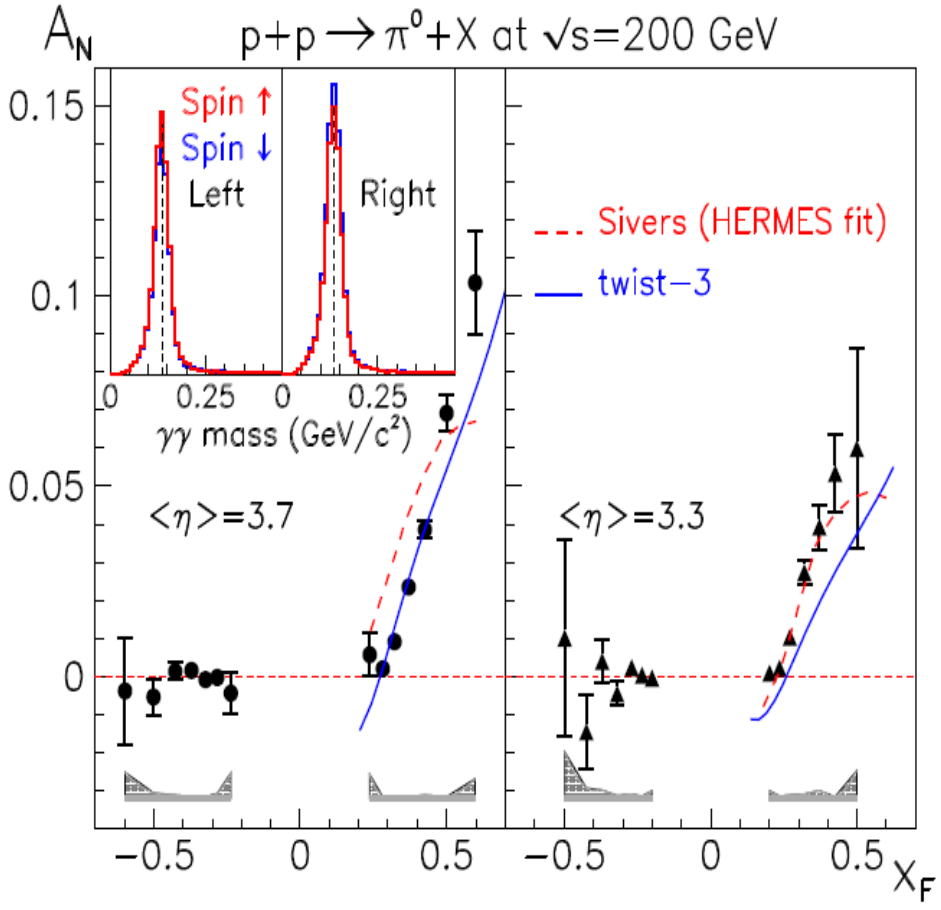
Kane, Pumplin and Repko
PRL 41 1689 (1978)

- Since people focused at high p_T to interpret them in pQCD frameworks, this (expected small effect) was “neglected However….
- Pion production in single transverse spin collisions showed us something different….

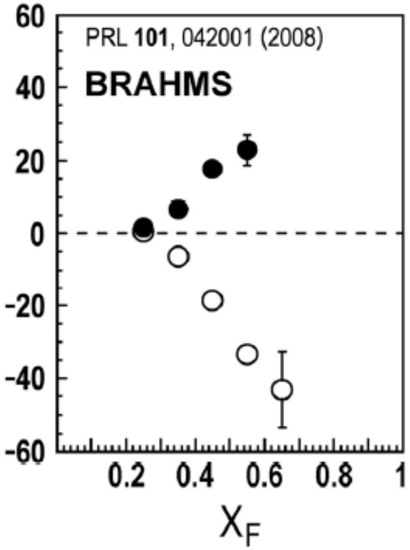
Pion asymmetries: at broad range in CM energies!

ZGS/ANL
√s=4.9 GeV





RHIC
√s=62.4 GeV

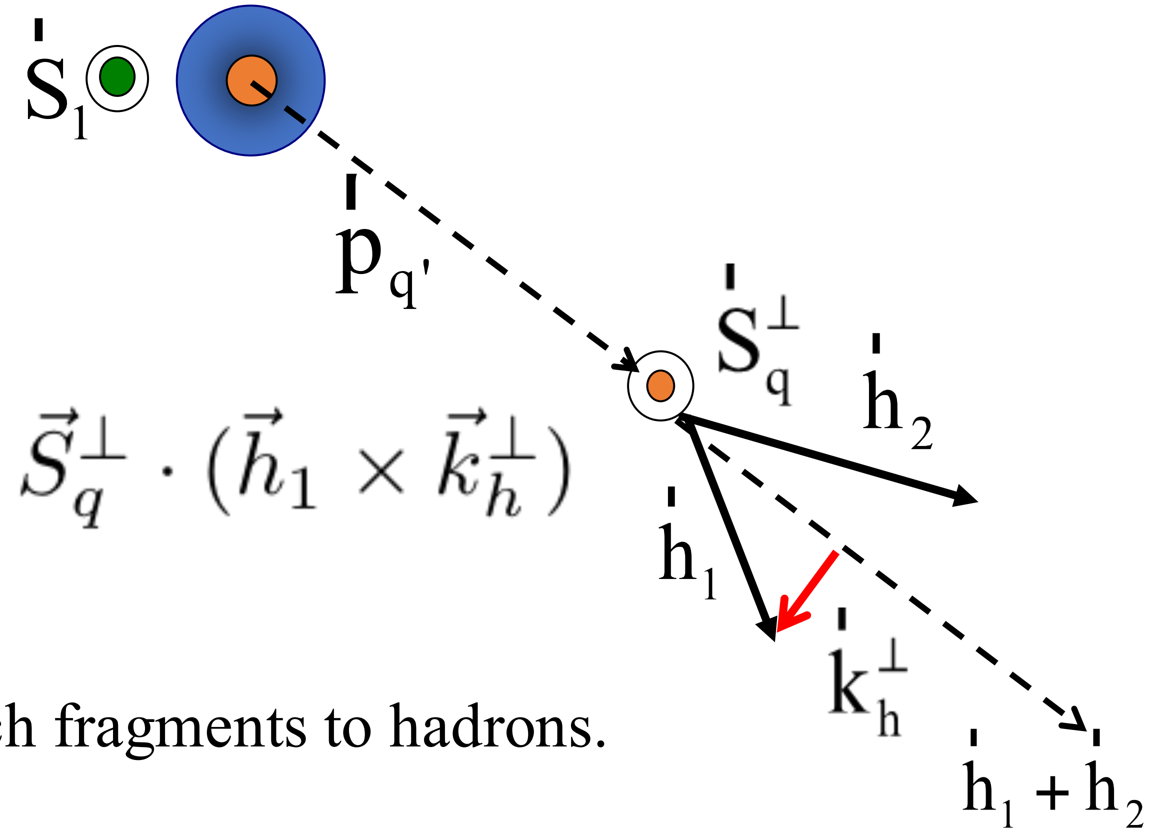


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well ➔ **0.001 expected 0.2-0.6 observed at all Center of Mass Energies**

What could be the origin of such effect?
Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

Example: $p^{\uparrow} + p \to h_1 + h_2 + X$

Nucl Phys B396 (1993) 161,
Nucl Phys B420 (1994) 565

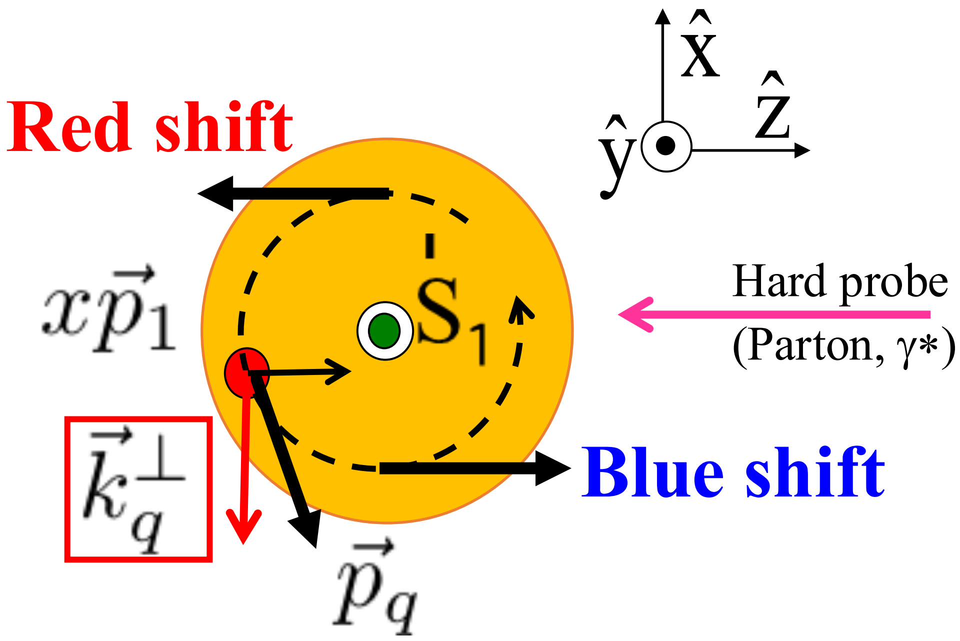


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

Polarization of struck quark which fragments to hadrons.

Other possibility: What does "Sivers effect" probe?

Top view, Breit frame



Quarks orbital motion adds/ subtracts longitudinal momentum for negative/positive $\hat{x}$.

PRD66 (2002) 114005

Parton **D**istribution **F**unctions rapidly fall in longitudinal momentum fraction x.

Final **S**tate **I**nteraction between outgoing quark and target spectator.

Sivers function

$$f_{1T}^{\perp}(x, \vec{k}_q^{\perp})$$

hep-ph/ 0703176

Quark Orbital angular momentum

Generalized **P**arton **D**istribution **F**unctions

PRD59 (1999) 014013

Lessons learned:

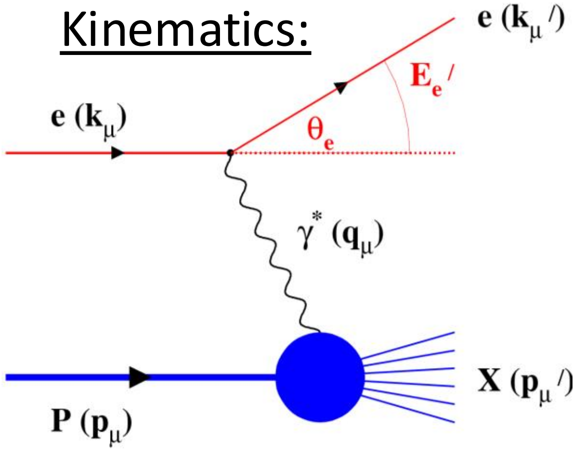
- Proton and neutrons spin *not just* alignment of quarks and gluons….
  - Proton's spin is complex: alignment of quarks + **gluons and orbital motion**
- To fully understand proton structure (including the above partonic dynamics)
  - one needs to explore over a **broader x-Q2 range** (not in fixed target but in collider experiment) Low-x behavior of gluons in proton also needed
  - Need *polarized* protons and electrons in colliders

- Low x behavior of partons in Nuclei essential to complete our understanding of structure of matter…
- To understand the nuclear fragments – target fragment – one needs to measure e-A in a collider geometry

We need a new high-luminosity polarized **e-p/A** collider….

Deep Inelastic Scattering: Precision and control

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k_\mu')^2$$

$$Q^2 = 2E_e E_e'(1-\cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E_e'}{E_e}\cos^2\left(\frac{\theta_e'}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu};\ p_t$$

with respect to γ^*

$$s = 4E_h E_e$$

High lumi & acceptance

Exclusive DIS
detect & identify *everything* e+p/A → e'+h(π,K,p,jet)+…

Semi-inclusive events:
e+p/A → e'+h(π,K,p,jet)+X
detect the scattered lepton in coincidence with identified hadrons/jets

Inclusive events:
e+p/A → e'+X
detect *only the scattered lepton* in the detector

Low lumi & acceptance

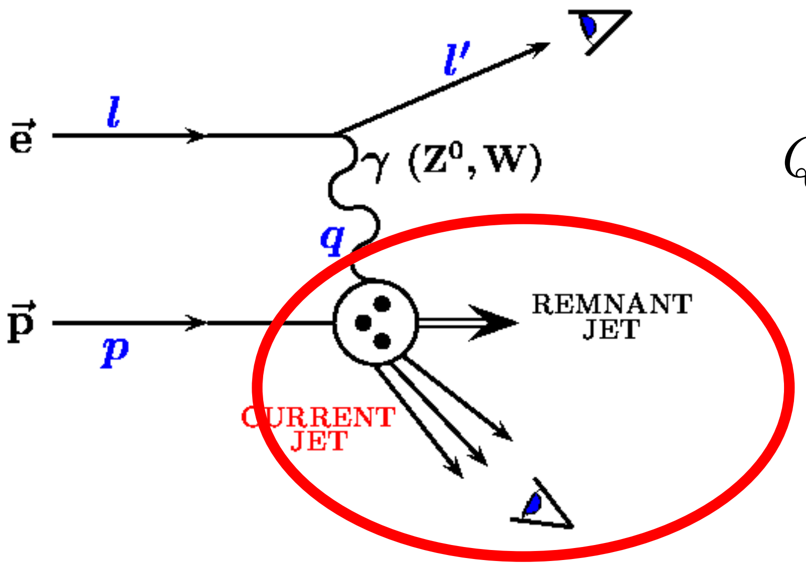
Some times scattered electron can't be measured….

Reason:

1) Scattering angle so small that it is too close to the beam pipe

2) Radiative correction too large, i.e. electron lost its energy due to Initial State Radiation or Brehmstrahlung through material -- So the kinematic reconstruction unreliable.

What to do? Then see if we can reconstruct the hadronic final state?



$$y = \frac{E_j}{2E_e}(1 - cos\theta_j)$$

$$Q^2 = E_j^2 sin^2\theta_j/(1 - y)$$

$$x = \frac{E_j}{2E_p}(1 + cos\theta_j)/(1 - y)$$

$$E_j = yE_e + x(1 - y)E_p$$

$$cos\theta_j = \frac{-yE_e + (1-y)xE_p}{y\,E_e + (1-y)xE_p}$$

$$E_j^2 sin^2\theta_j = 4\,xy(1-y)E_eE_p = Q^2\,(1-y)$$

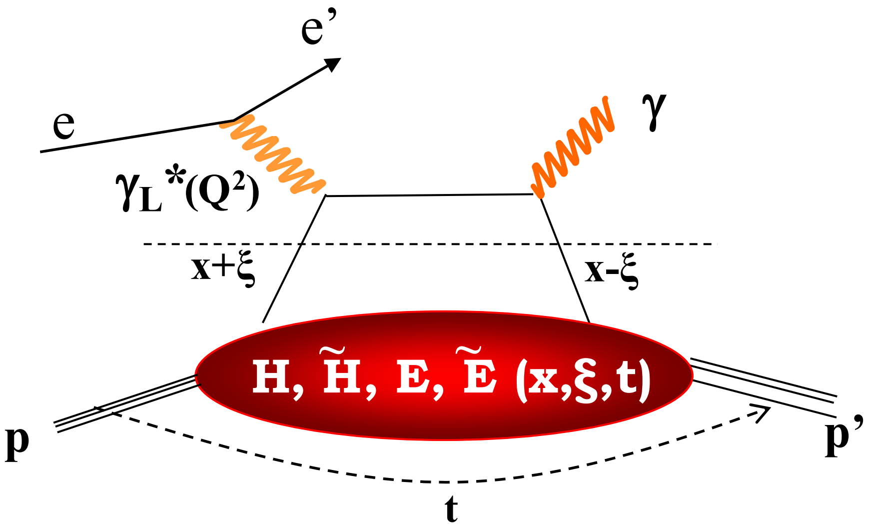
$$y_{JB} = \frac{1}{2E_e}\sum_h(E_h - p_{Zh})$$

$$Q^2_{JB} = \frac{(\sum_h p_{Xh})^2 + (\sum_h p_{Yh})^2}{1 - y_{JB}}$$

$$x_{JB} = Q^2_{JB}/(y_{JB}s)$$

Deep Inelastic Scattering: Deeply Virtual Compton Scattering

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

Measure of resolution power

$$Q^2 = 2E_e E'_e(1-\cos\Theta_{e'})$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x_B = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

$$t = (p-p')^2, \xi = \frac{x_B}{2-x_B}$$

Exclusive measurement:

e + **(p/A)** → e'+ **(p'/A')**+ γ / J/ψ / ρ / ϕ

detect **all** event products in the detector

Special sub-event category rapidity gap events

e + **(p/A)** → e' + γ / J/ψ / ρ / ϕ / jet

Don't detect **(p'/A') in final state**

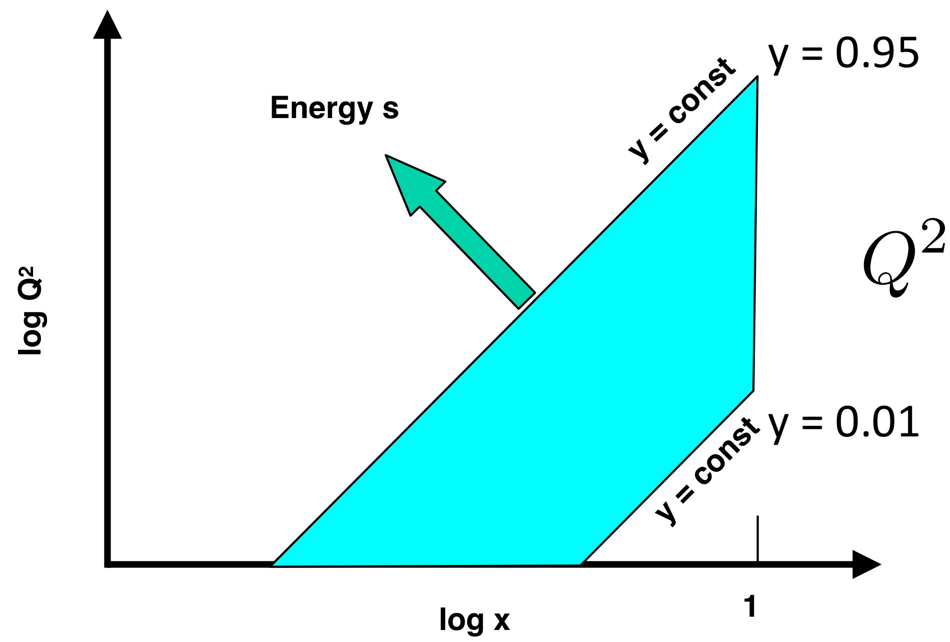
Complete set of variables for DIS e-p:

https://core.ac.uk/download/pdf/25211047.pdf

We will use some of these more often than others, you should know them all.

E_p	proton beam energy
E_e	electron beam energy
$p = (0, 0, E_p, E_p)$	four momentum of incoming proton with mass m_p
$e = (0, 0, -E_e, E_e)$	four momentum of incoming electron
$e' = (E'_e sin\theta'_e, 0, E'_e cos\theta'_e, E'_e)$	four momentum of scattered electron
$s = (e + p)^2 = 4E_pE_e$	square of total ep c.m. energy
$q^2 = (e - e')^2 = -Q^2$	mass squared of exchanged current J
	= square of four momentum transfer
$\nu = q \cdot p/m_p$	energy transfer by J in p rest system
$\nu_{max} = s/(2m_p)$	maximum energy transfer
$y = (q \cdot p)/(e \cdot p) = \nu/\nu_{max}$	fraction of energy transfer
$x = Q^2/(2q \cdot p) = Q^2/(ys)$	Bjorken scaling variable
$q_c = x \cdot p + (e - e')$	four momentum of current quark
$M^2 = (e' + q_c)^2 = x \cdot s$	mass squared of electron - current quark system.

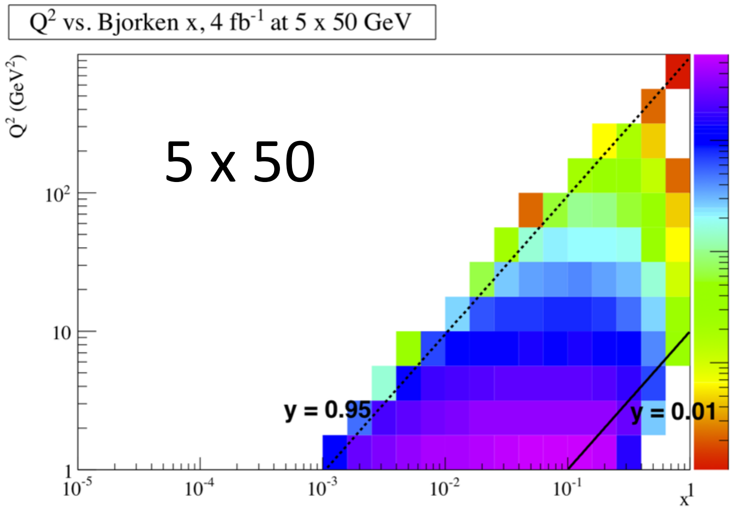
The x-Q^2 plane…

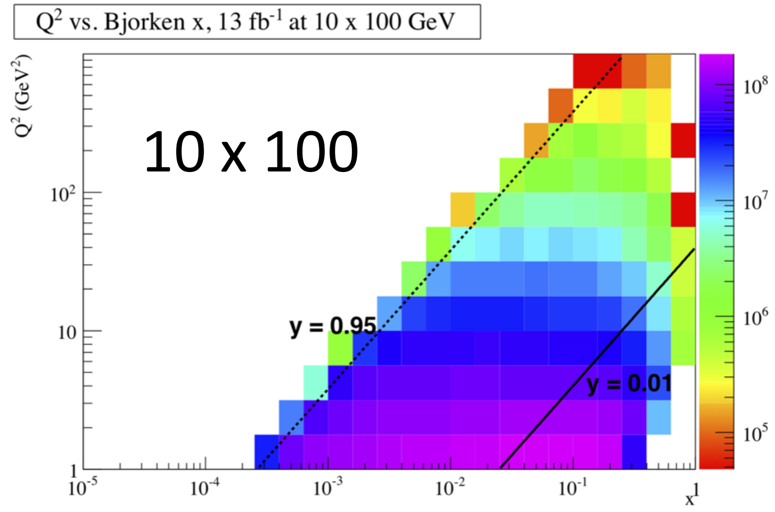


$$Q^2 \approx s \cdot x \cdot y$$

- Low-x reach requires large $\sqrt{s}$
- Large-Q^2 reach requires large $\sqrt{s}$
- *y* at colliders typically limited to 0.95 < y < 0.01

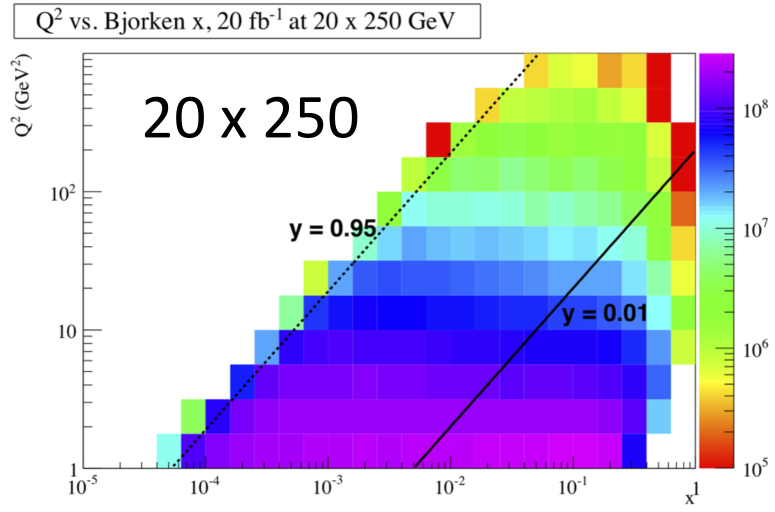
Kinematic coverage as a function of energy of collisions





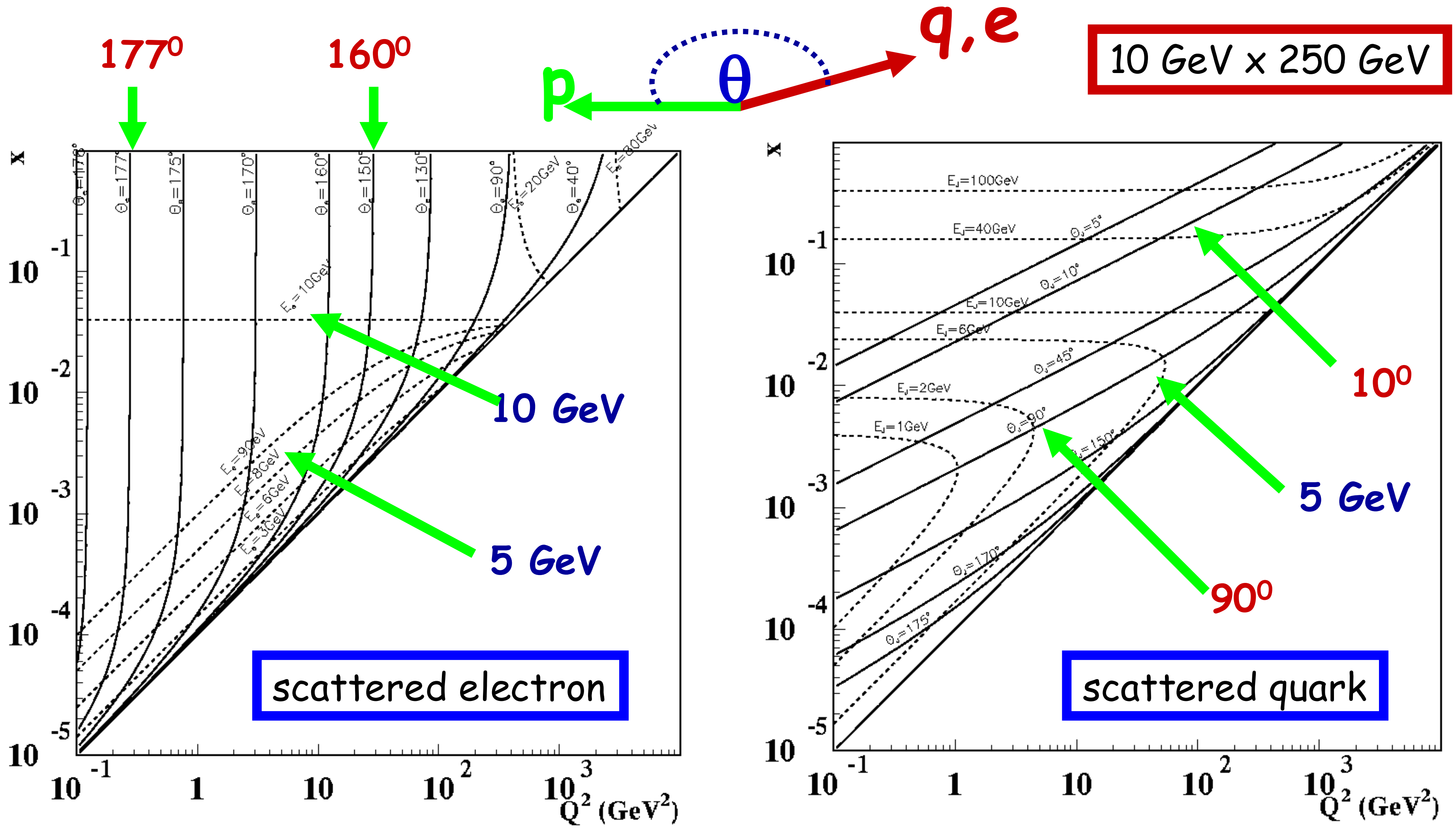
As beam energies increase, so does the x, Q^2 coverage of the collider: 5, 10 and 20 GeV electrons colliding with 50, 100 and 250 GeV protons

y = 0.95 and 0.01 are shown on all plots (they too shift as function of energy of collisions)

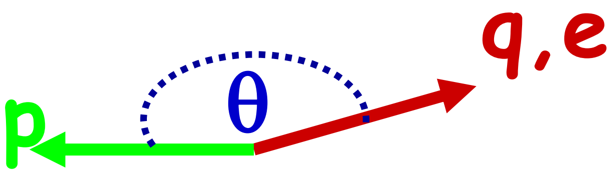


Home Work: Where do electrons and quarks go?

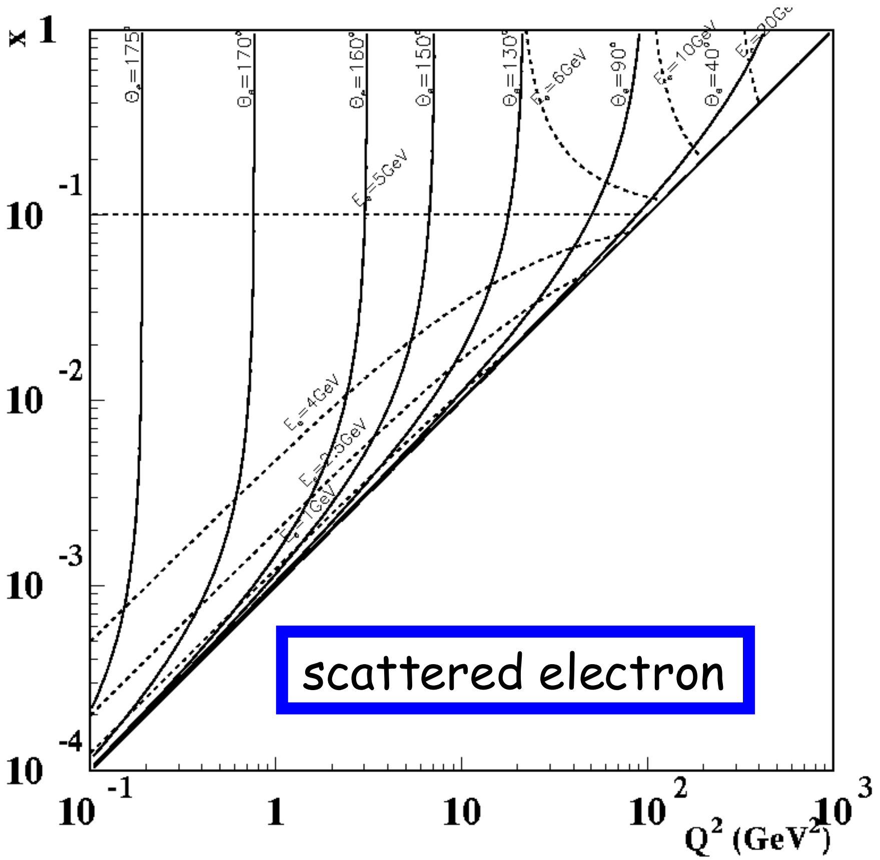
Angles measured w.r.t. proton direction

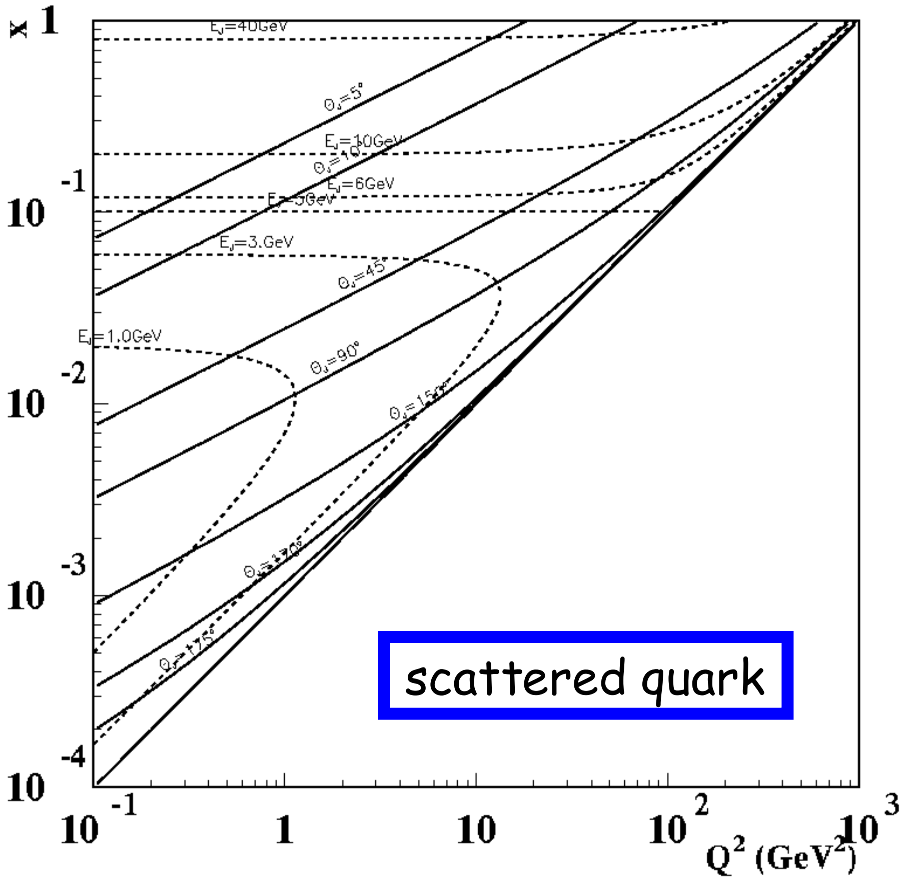


Electron, Quark Kinematics



5 GeV x 50 GeV

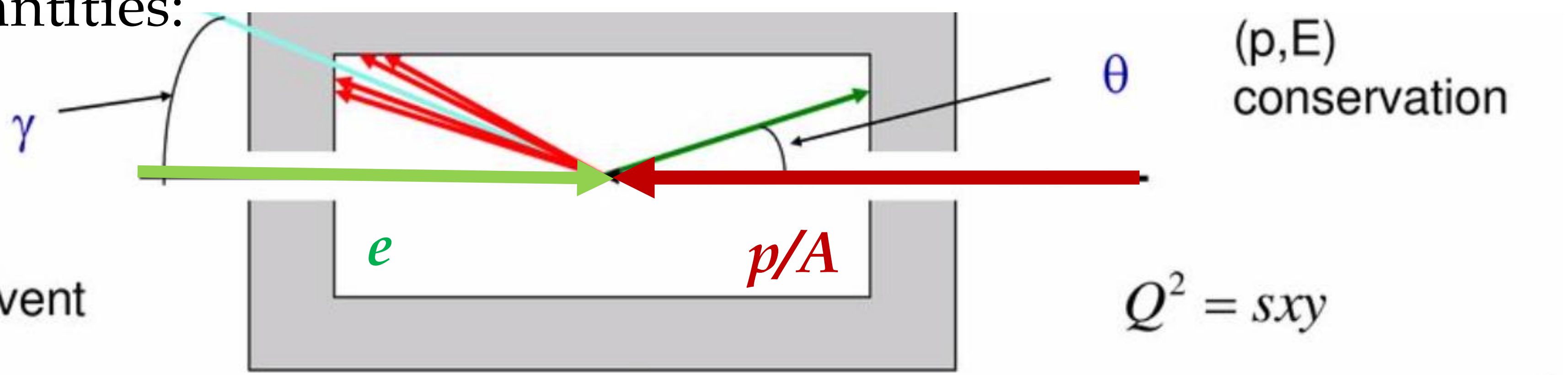




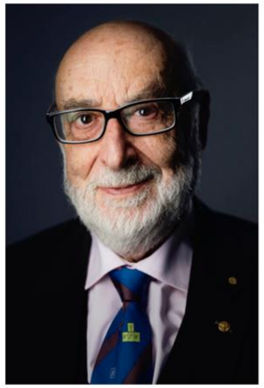
There are multiple ways to reconstruct events:

Four measured quantities:

$$E'_e, \theta, E_h, \gamma$$



Proton mass puzzle



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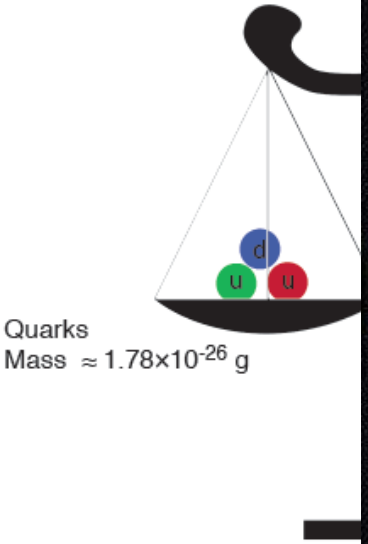
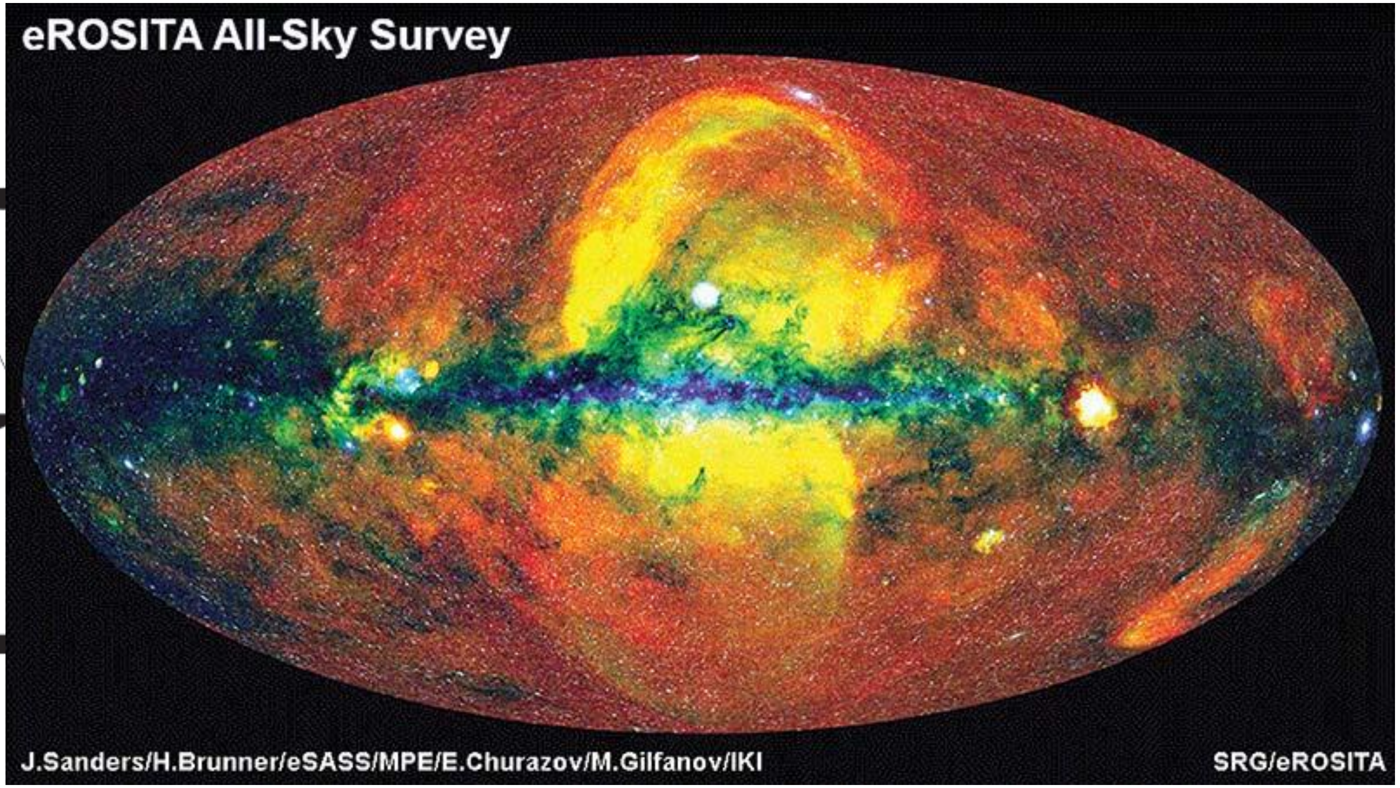
Peter W. Higgs

Nobel 2013 With
Francois Englert
"Higgs Boson" that gives mass to quarks, electrons,….



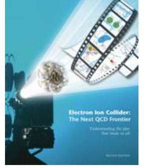


Add the masses of the quarks (HIGGS mechanism) together 1.78 x 10^{-26} grams

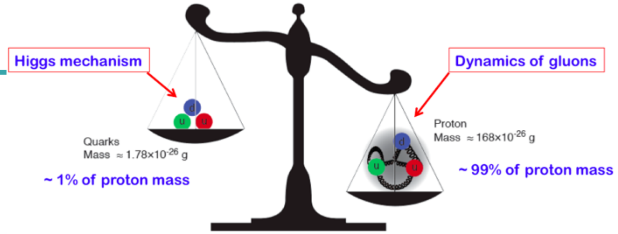
But the proton's mass is 168 x 10^{-26} grams

→ **only 1% of the mass of the protons (neutrons)** → Hence the Universe

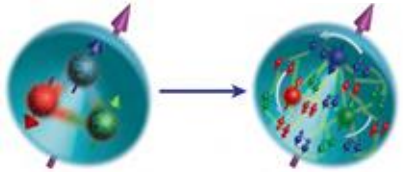
→ Where does the rest of the mass come from?

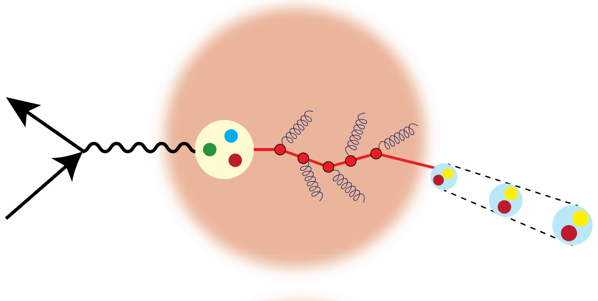


A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

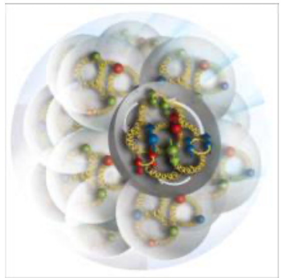


How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties (spin, mass) emerge from them and their interactions?





How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

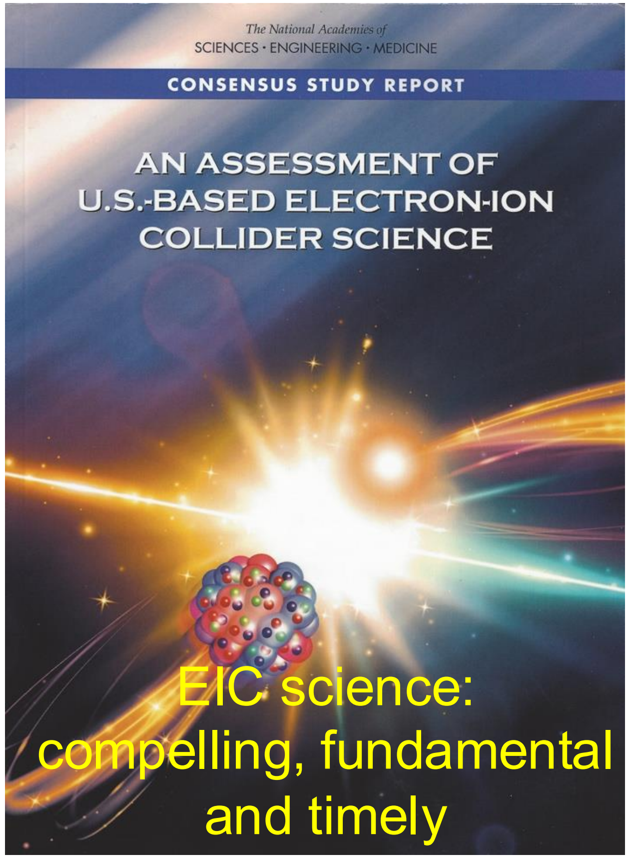


What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

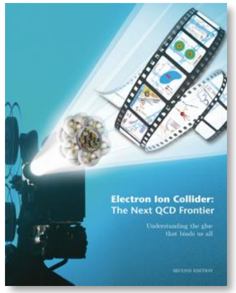
gluon emission

gluon recombination

EIC proposal and the US National Academy's Assessment



EIC science:
compelling, fundamental
and timely



Machine Design Parameters:

- High luminosity: up to 10^{33}-10^{34} $cm^{-2}sec^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-100 GeV upgradable to 140 GeV
- Polarized beams e-, p, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors well-integrated detector(s) into the machine lattice