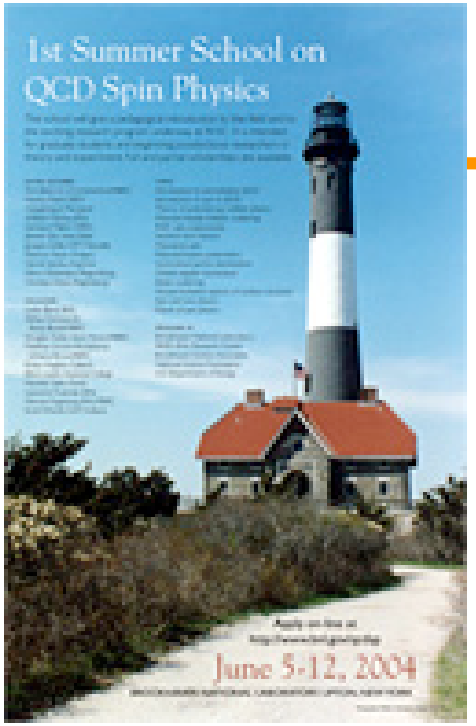


Future of Spin

Abhay Deshpande

Stony Brook & RBRC

June 12, 2004

1st QCD Spin Summer School at BNL

A very wise man once said:

" Predictions are always difficult, especially when they are about the future!"

A. Einstein

I will not try to predict the future, but give you a review of some spin related options

Some spin surprises:

- (1921) Stern & Gerlach Space quantization associated with direction
- (1926) Goudschmidt & Ulhenbeck: Atomic fine structure & electron spin magnetic moment
- (1933) Stern: Proton anomalous magnetic moment 2.79 m_N
- (1947) Kusch: Electron anomalous magnetic moment 1.00119m_0
- (1978) Prescott & Yale-SLAC Collaboration EW interference in polarized e-d DIS, parity non-conservation
- **(1988/89) European Muon Collaboration Spin Crisis/Puzzle**

- (1990s, 2000-Present) Transverse single spin asymmetries: E704, AGS pp scattering, HERMES (1990s) RHIC Spin (2001)
  - single spin neutron production (PHENIX) at 200 GeV Sqrt(s)
  - pion production (STAR) at 200 GeV Sqrt(S)
- Jefferson laboratory experiments hinting at the proton shape

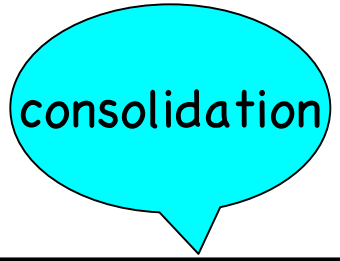
"Spin" has a high potential for surprises in future!

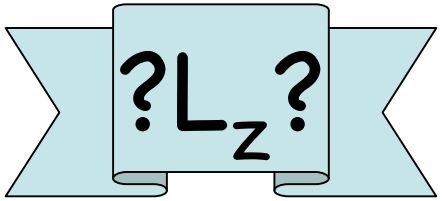
"Future of Spin"?

- Understand the nucleon spin in our conquest to understand nature of matter around us (QCD)
  - Where does "nucleon spin" come from?
  - What mount do quarks carry?
  - What role do the gluons play?
  - What about the orbital angular momentum?
  - **What experiments do we need?**
- Is that it?
  - Can we "use" spin to understand something *more* about physics?
- Is this only academic curiosity? Or can "spin" be more "useful"?

For students of nuclear-particle physics, its important to have on overview

Future of "Nucleon Spin"





Year --> Experiments	Pre-1980s & 1980s...	1990s	2000s	2010s	2020s
Fixed target	Yale-Slac EMC-CERN, E704	SMC SLAC HERMES	HERMES, COMPASS	Jlab-12	TESLA-N (?)
Collider p-p			RHIC-Spin →		Pol. LHC (?)
Collider e-p				eRHIC(?) →	ELIC(?)

When I grow up.. Will I have a job?

List of experimental facilities:

- COMPASS: Polarized muon-nucleon scattering fixed target experiment at CERN

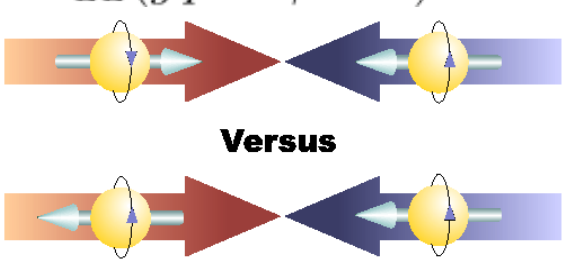
- RHIC Spin: Relativistic Heavy Ion Collider Spin
- eRHIC: electron beam facility + RHIC …
  - RHIC Facility Upgrade at BNL (add electron beam facility)

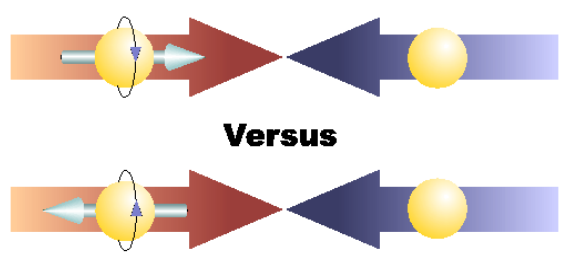
- ELIC: Electron Light Ion Beam
  - Jlab Electron beam facility upgrade (add hadron ring)

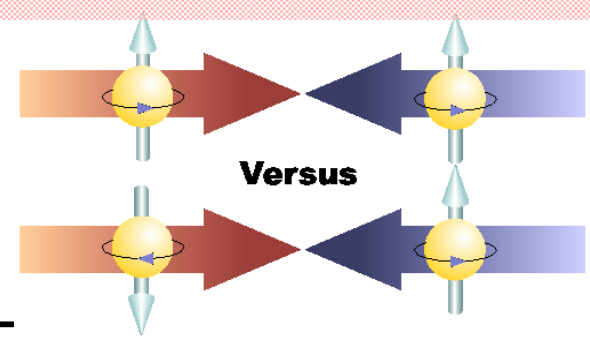
- Tesla-N: Tesla linear collider beam on fixed target
  - Future linear collider at DESY
- P-LHC: Polarized Large Hadron Collider
  - About 60 Siberian Snake magnets in each LHC ring

RHIC Spin Physics Program

Gluon Polarization	Flavor Decompsition	Transverse single/double spin physics
ΔG	$\frac{\Delta u}{u}, \frac{\Delta \overline{u}}{\overline{u}}, \frac{\Delta d}{d}, \frac{\Delta \overline{d}}{\overline{d}}$	
$\pi^{0,+,-}$ Production $A_{LL}(gg, gq \to \pi^{0,\pm} + X)$ Heavy Flavors $A_{LL}(gg \to c\overline{c}, b\overline{b} + X)$ Prompt Photon $A_{LL}(gq \to \gamma + X)$	W physics $A_L(u + \overline{d} \to W^+ \to l^+ + \nu_l)$ $A_L(\overline{u} + d \to W^- \to l^- + \overline{\nu_l})$ Longitudinal single spin physics	Transversity: Sivers vs. Collins effects & physics of higher twists; Pion interf. Fragmentation Transverse single spin physics Phenix-Local Polarimetry

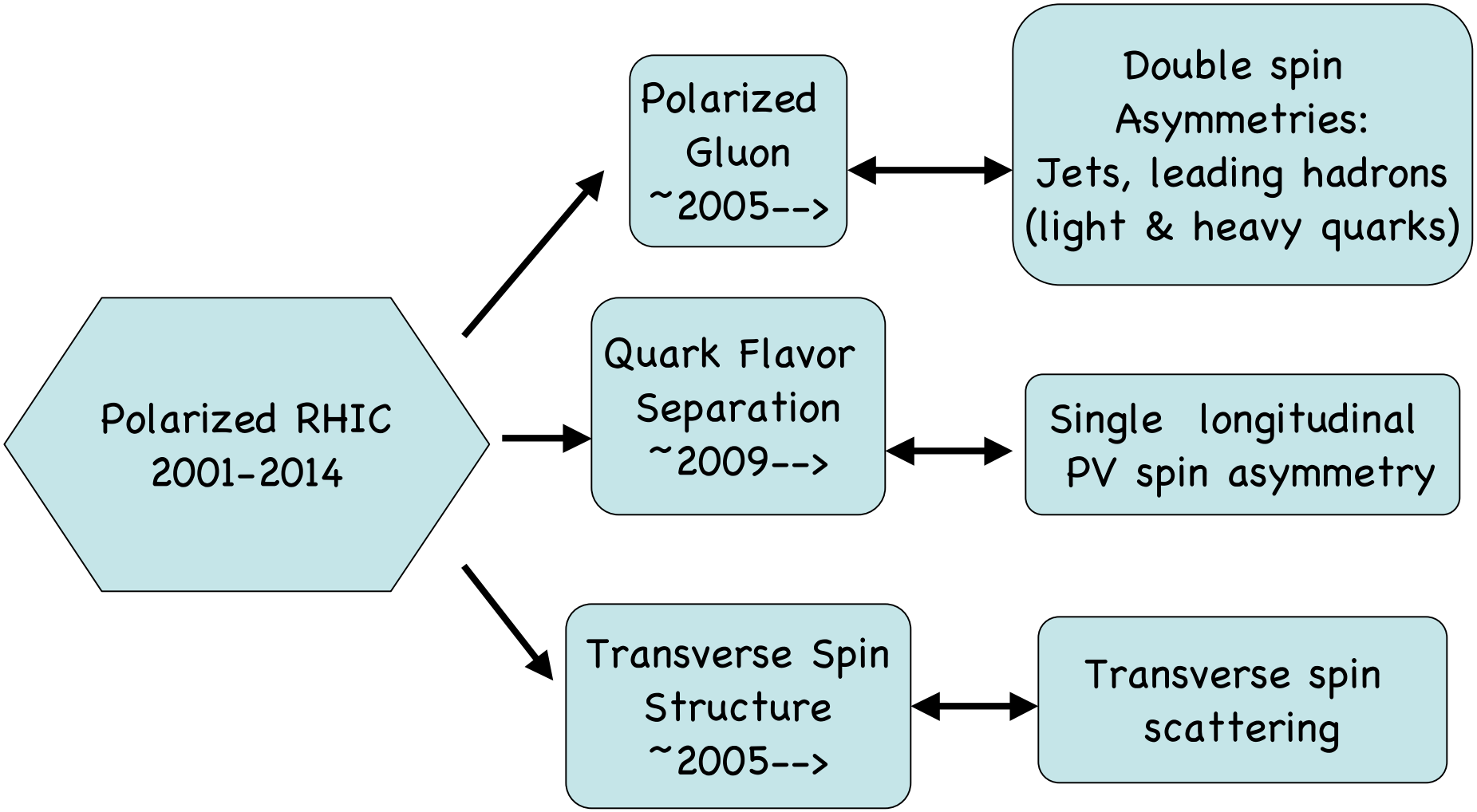




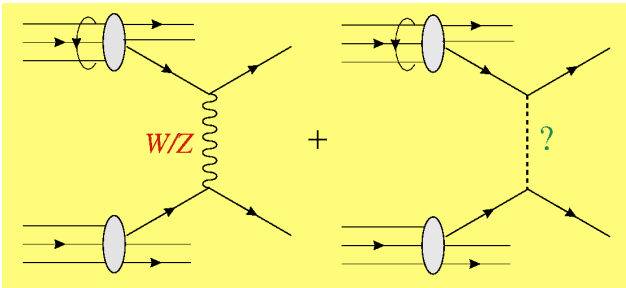


Understanding the nucleon spin….

RHIC Spin Program, PHENIX + STAR

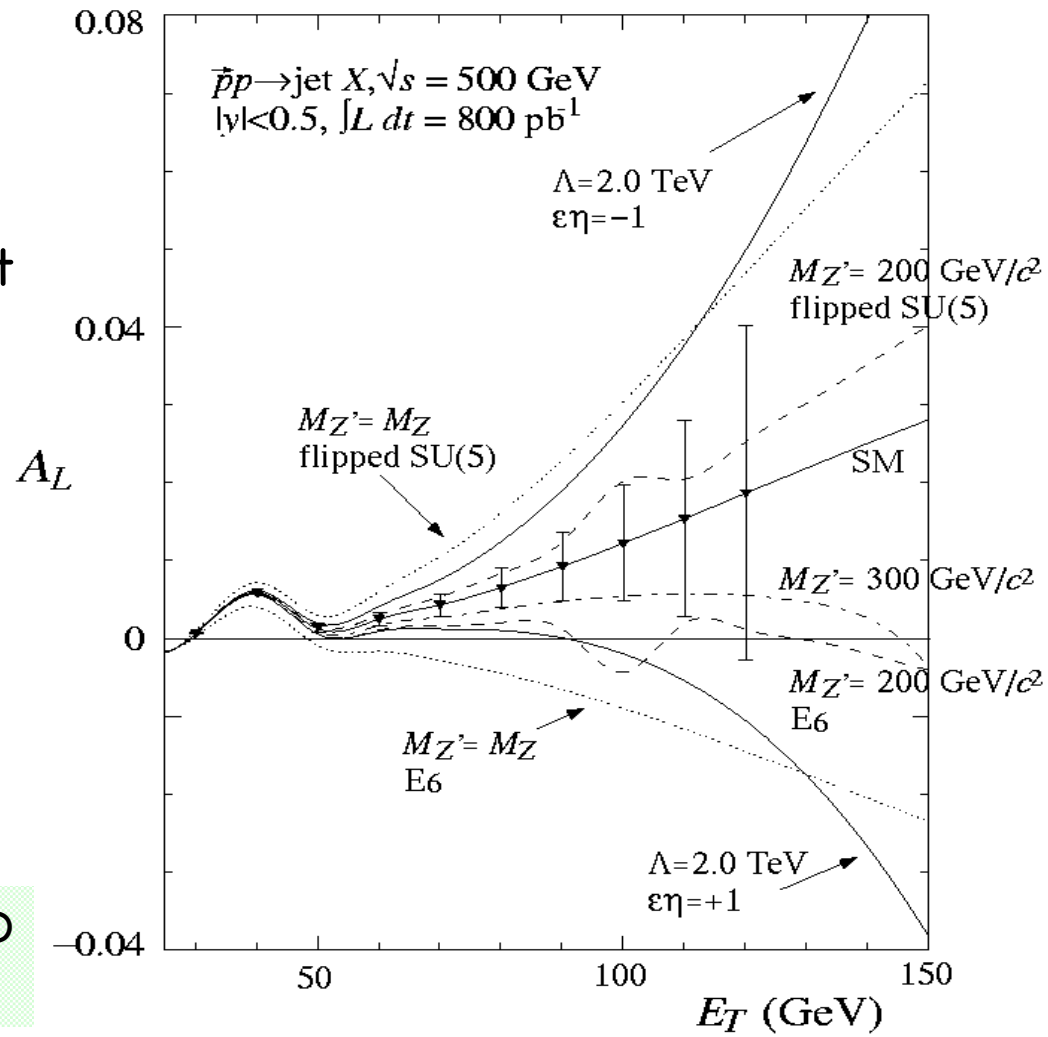


Searches for New Physics: RHIC II Spin(?)



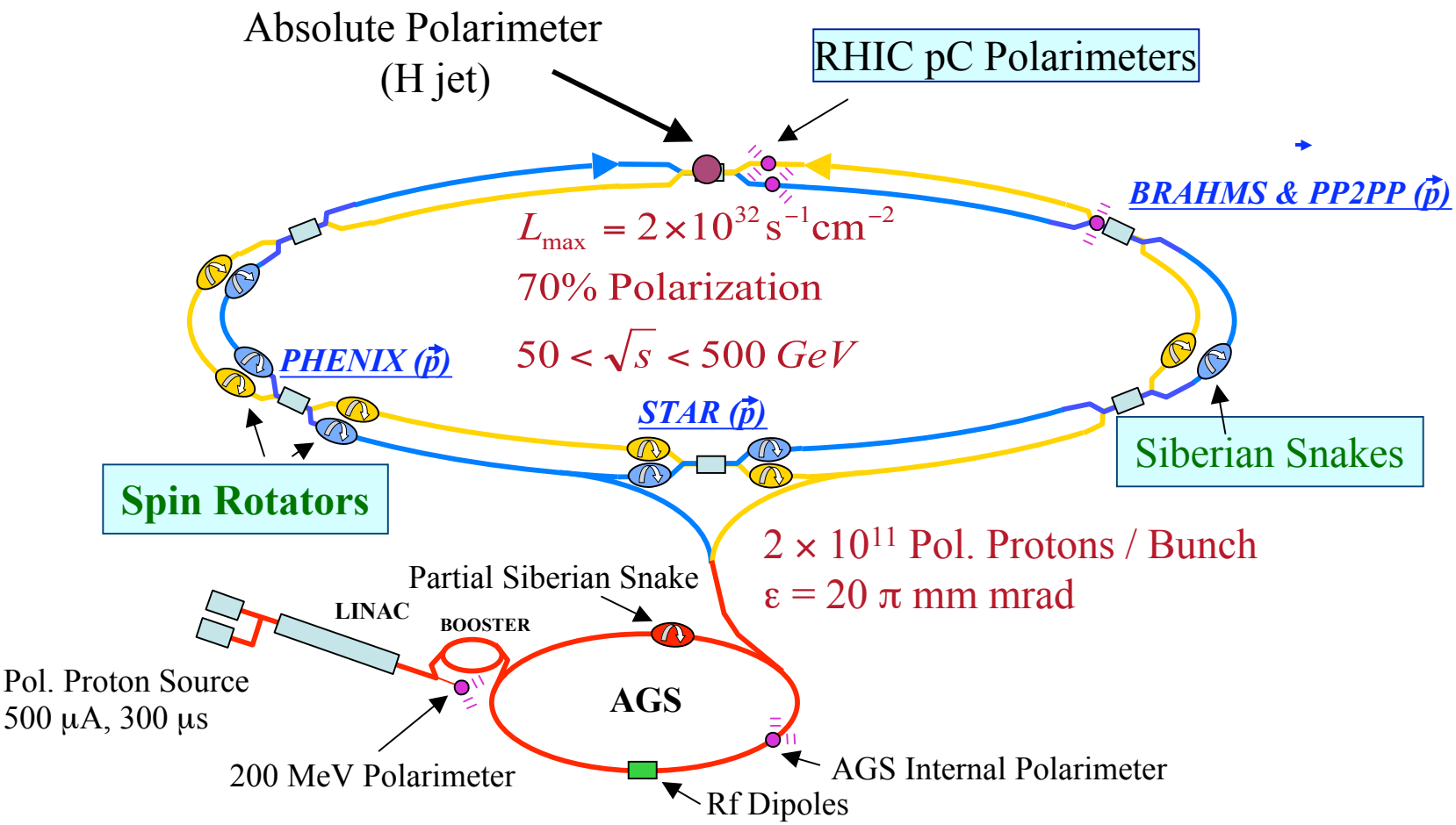
- Anomalous parity violation in jet production
  - Contact Interaction (Scale L)
    - CDF L>1.8 TeV
    - D0 L>2.4 TeV
    - RHIC Spin Reach L~3.3 TeV
  - New gauge boson Z'

P. Taxil & J-M. Virey, Phys. Rev. D (55) 2457 (1999)



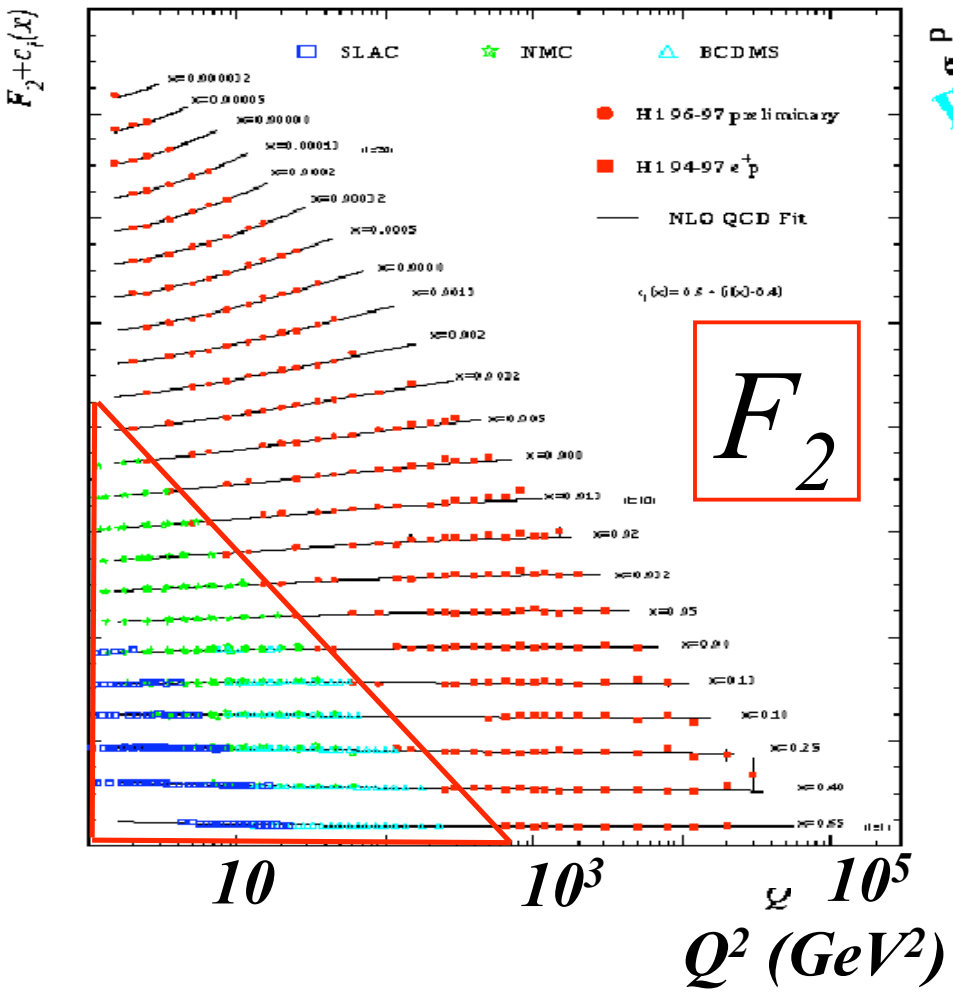
Ok, what after RHIC Spin at RHIC?

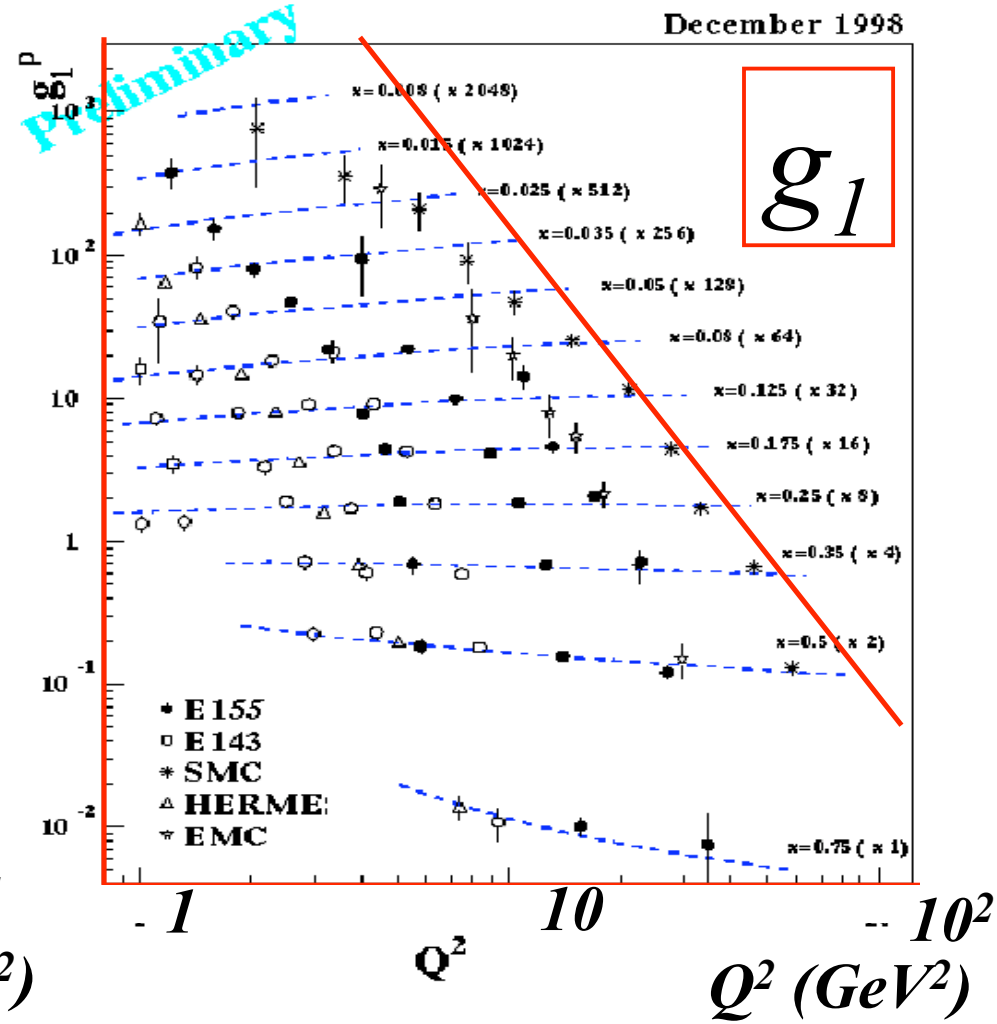
Relativistic Heavy Ion Collider



RHIC accelerates heavy ions to 100 GeV/A
and polarized protons to 250 GeV

Our Knowledge of Structure Functions





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

The Electron Ion Collider Proposals

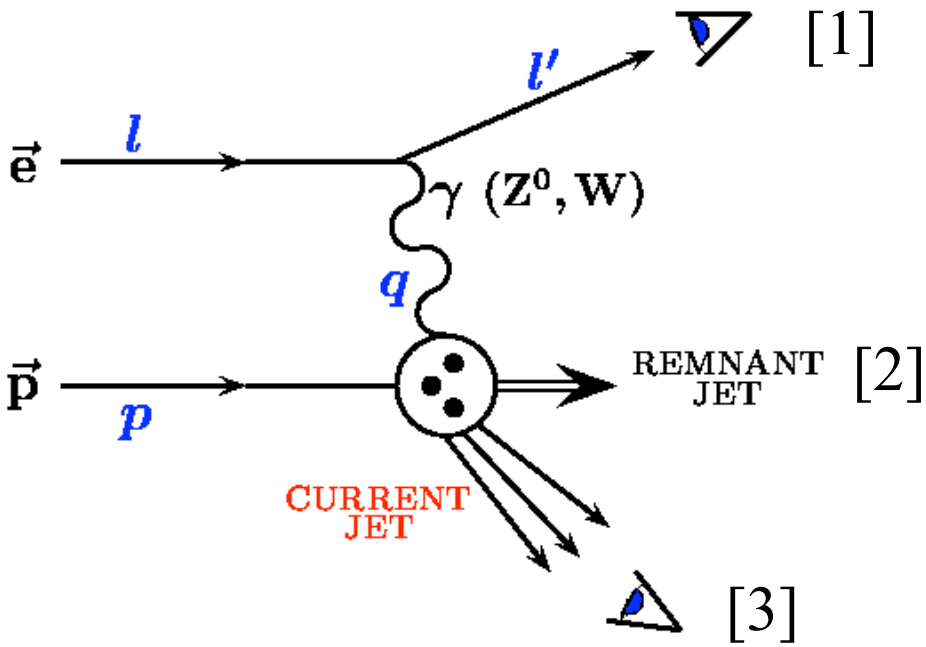
eRHIC at BNL

A high energy, high intensity polarized electron/positron beam facility at BNL to colliding with the existing heavy ion and polarized proton beam would significantly enhance RHIC's ability to probe fundamental and universal aspects of QCD

Jlab Upgrade II: CEBAF-II/ELIC

An electron-light-ion collider or/and a 25 GeV fixed target facility at Jlab will address the question of precision measurements of nucleon spin, including the issues related to generalized parton distributions with its large luminosity. The collider and fixed target facility will cover complementary kinematic regions.

Deep Inelastic Scattering



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot l}$$

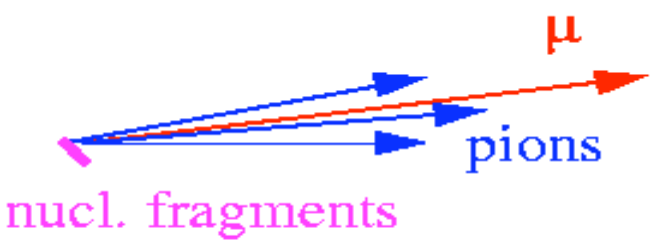
$$s = 4E_e E_p$$

$$W = (q+p)^2$$

- Observe scattered electron [1] inclusive measurement
- Observe [1] + current jet [2] semi-inclusive measurement
- Observe [1] + [2] + remnant jet [3] exclusive measurement
- Luminosity requirements from [1] (lowest)--> [2] --> [3](highest)
- Exclusive measurements also put demanding requirement on detectors, interaction region *and hence deliverable luminosity*

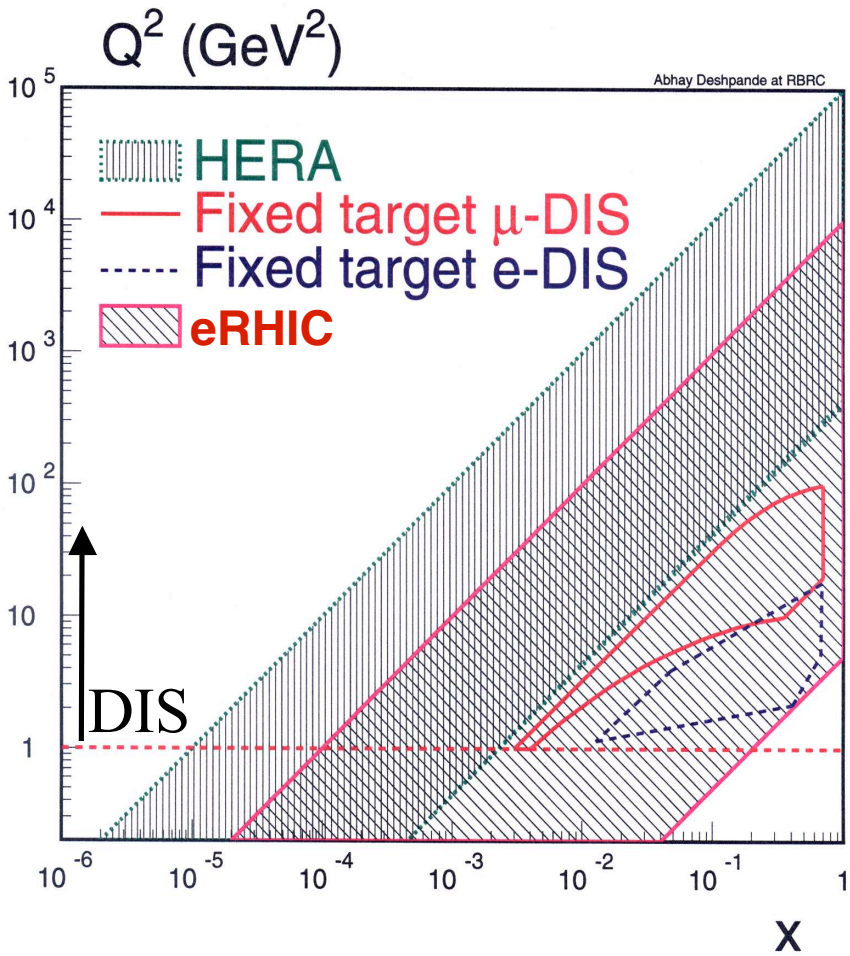
Why Collider In Future?

- Polarized DIS and e-A physics: in past only in fixed target mode
- Collider geometry--> distinct advantages (HERA Experience)



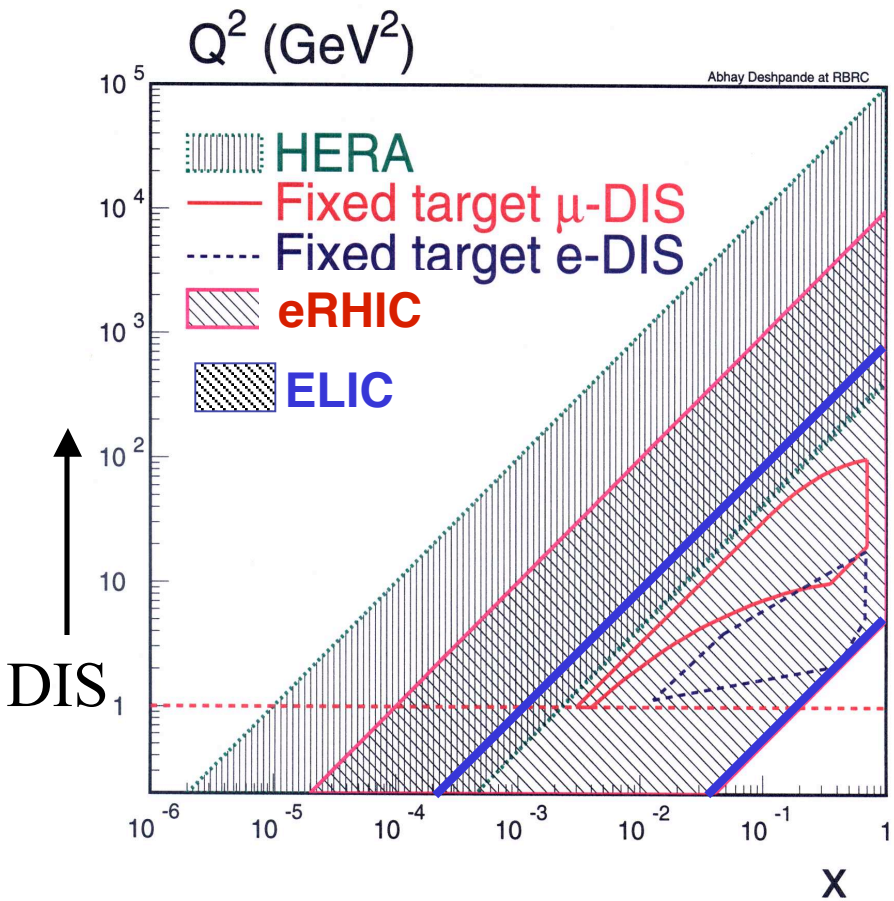
- Better angular resolution between beam and target fragments
  - Better separation of electromagnetic probe
  - Recognition of rapidity gap events (recent diffractive physics)
  - Better measurement of nuclear fragments
- Higher Center of Mass energies reachable
- **Tricky issues:** integration of interaction region and detector

eRHIC vs. Other DIS Facilities



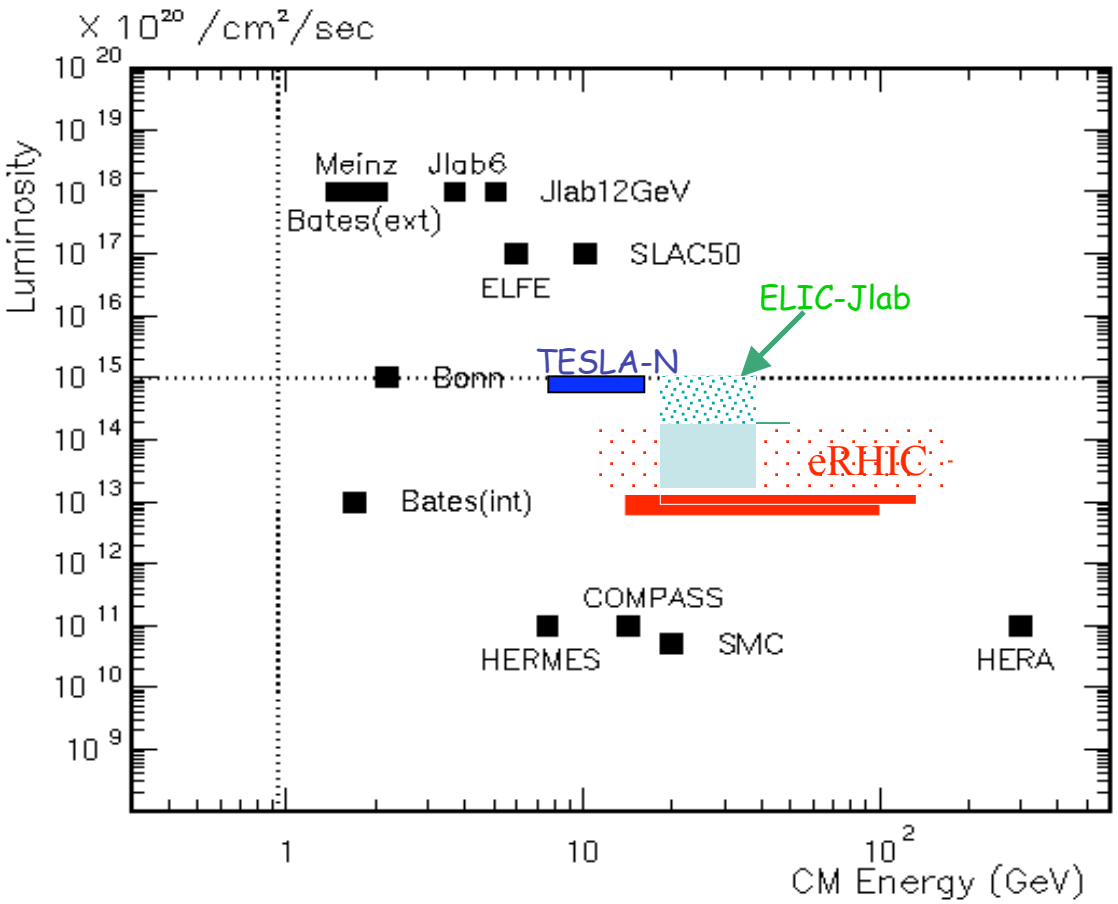
- New kinematic region
- E_e = 10 GeV (reducible to 5 GeV)
- E_p = 250 GeV (reducible to 50 GeV)
- EA= 100 GeV (reducible to 12 GeV)
- Sqrt[S_{ep}] = 30-100 GeV
- Sqrt[S_{eA}] = 63 GeV
  - Low x physics
- Kinematic reach of eRHIC:
  - X = 10^{-4} --> 0.7 (Q^2 > 1 GeV^2)
  - Q^2 = 0 --> 10^4 GeV^2
- Polarization of e,p and light ion beams at least ~ 70% or better
- Heavy ions of ALL species
  - High gluonic densities
- High Luminosity:
  - L(ep) ~10^{33-34} cm^{-2} sec^{-1}
  - L(eA) ~10^{31-32} cm^{-2} sec^{-1} N^{-1}

ELIC vs. Other DIS Facilities



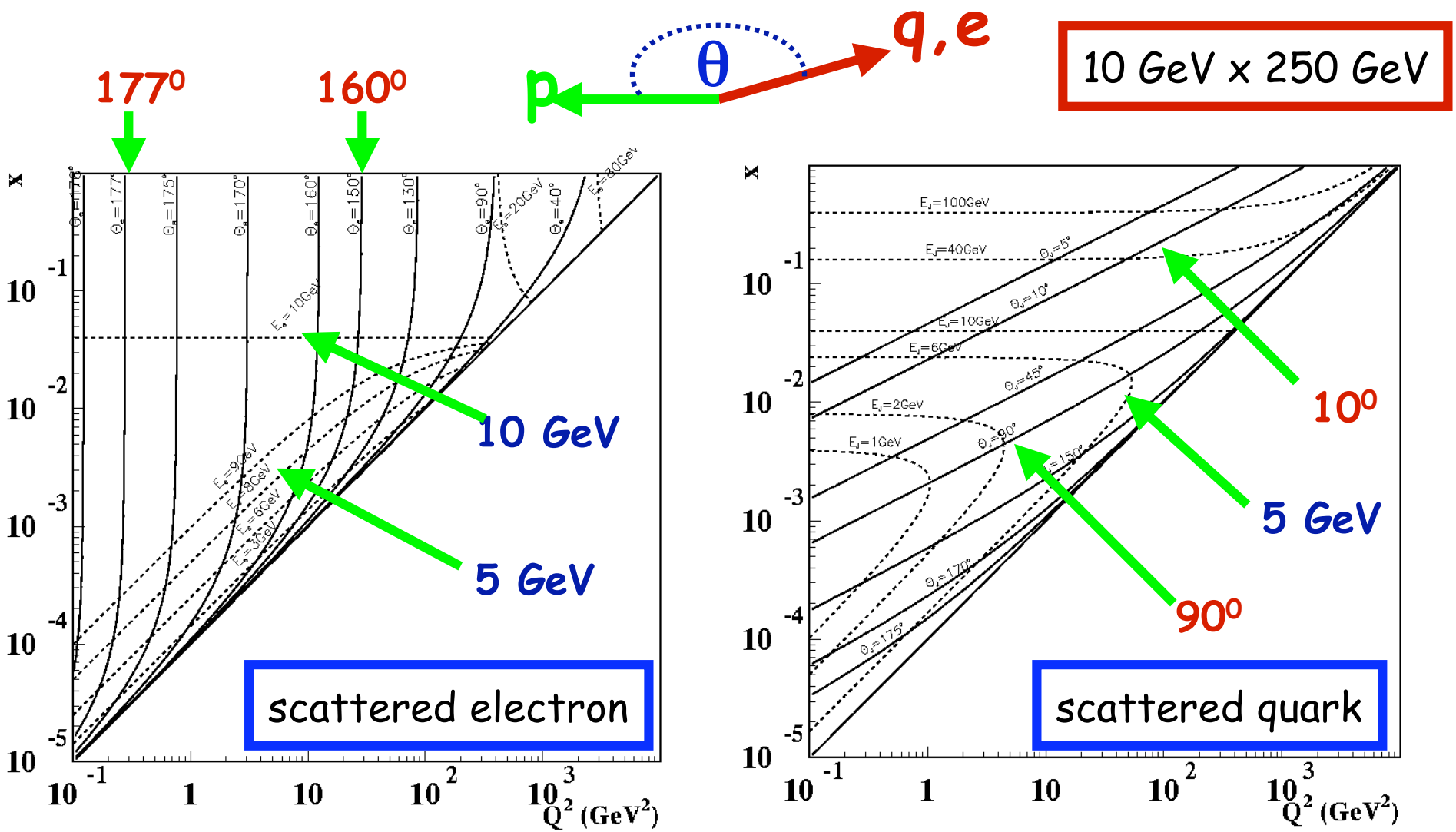
- Physics of Exclusive measurements
- Ee = 3-7 GeV
- Ep = 30-100 (150) GeV
- Sqrt[S_ep] = 20-45 (65) GeV
- Kinematic reach of ELIC
  - $X = 10^{-3}$ --> 0.8 ($Q^2 > 1$ GeV^2)
  - $Q^2 = 0$ --> 10^3 GeV^2
- Polarization of e, p & light ion beams ~ 70%
- High luminosity:
  - L_(ep) ~10^{33-35} cm^{-2} sec^{-1}
  - Staged increase in luminosity

CM vs. Luminosity

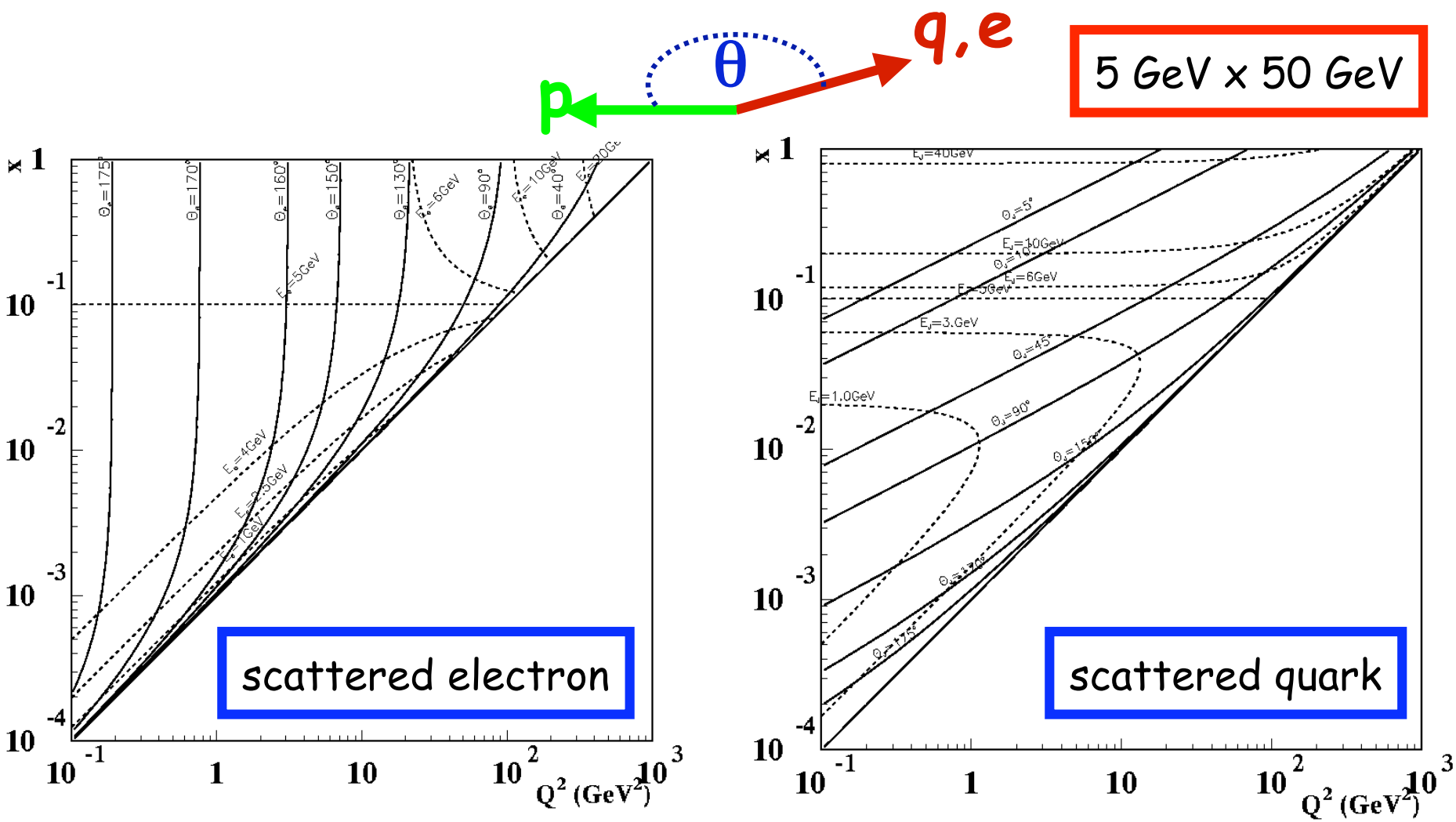


- **eRHIC**
  - Variable beam energy
  - P-U ion beams
  - Light ion poalrization
  - Large luminosity
- **ELIC**
  - Variable beam energy
  - Light ion polarization
  - Huge luminosity

Where do electrons and quarks go?



Electron, Quark Kinematics



A Detector for eRHIC → A 4π Detector

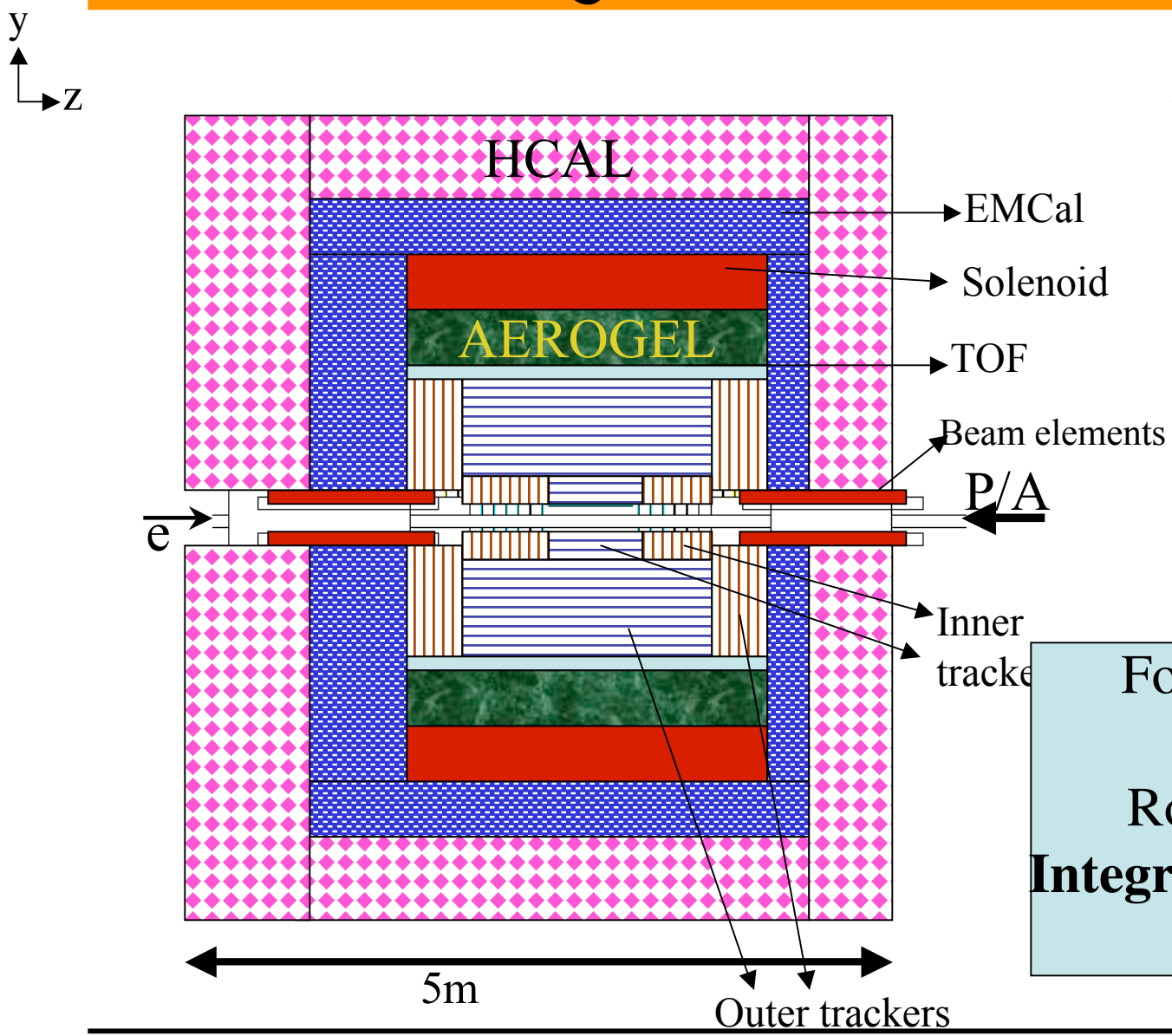
- Scattered electrons to measure kinematics of DIS
- Scattered electrons at small (~zero degrees) to tag photo production
- Central hadronic final state for kinematics, jet measurements, quark flavor tagging, fragmentation studies, particle ID
- Central hard photon and particle/vector detection (DVCS)
- ~Zero angle photon measurement to control radiative corrections and in e-A physics to tag nuclear de-excitations
- Missing E_T for neutrino final states (W decays)
- Forward tagging for 1) nuclear fragments, 2) diffractive physics

- ***Lot of experience from HERA… use it!***
  - What was good about HERA detectors?
  - What was bad? How/What can we improve?

- eRHIC will provide: 1) Variable beam energies 2) different hadronic species, some of them polarization, 3) high luminosity

B. Surrow, N. Smirnov, A. D.

Detector Design HERA like…+ PID



(Not to scale)

A HERA like Detector with dedicated PID:
>>Time of flight
>>Aerogel Ckov

AND

Forward detectors including Roman Pots etc…
Integrated in to the beam Elements!

Scientific Frontiers Open to EICs

eRHIC

- Nucleon structure, role of quarks and gluons in the nucleons
  - Unpolarized quark and gluon distributions, confinement in nucleons
  - Polarized quark and gluon distributions
  - Correlations between partons
    - Exclusive processes--> Generalized Parton Distributions
  - Understanding confinement with low x/lowQ^2 measurements
- Meson Structure:
  - Goldstone bosons and play a fundamental role in QCD
- Nuclear Structure, role of partons in nuclei
  - Confinement in nuclei through comparison e-p/e-A scattering
- Hadronization in nucleons and nuclei & effect of nuclear media
  - How do knocked off partons evolve in to colorless hadrons
- Partonic matter under extreme conditions
  - For various A, compare e-p/e-A

ELIC

Light nuclei

Unpolarized e-p at The eRHIC

- Although large kinematic region already covered at HERA, additional studies with high luminosities desirable

- Unique features: high luminosity, variable CM energy, He beams, *and improved detectors and interaction regions*

- *Precision Measurements:*
  - With d, He beams, neutron structure [1]
  - strong coupling constant and its evolution [1]
  - photo-production physics at high energies [1]
  - gluon distribution [1]
  - F_L structure function [1]
  - slopes of F_2 structure function exploring confinement [1]
  - Diffractive physics [1]
  - Semi-inclusive and exclusive reactions [1,2]
  - Nuclear fragmentation region [2,3]

Polarized DIS at eRHIC

- Spin structure functions g_1 (p,n) at low x, high precision [1]
  -- g_1(p-n): Bjorken Spin sum rule better than 1% accuracy
- Polarized gluon distribution function $\Delta G(x,Q^2)$ [1]
  -- at least three different experimental methods
- Precision measurement of $\alpha_S(Q2)$ from g_1 scaling violations [1]
- Polarized s.f. of the photon from photo-production [1]
- Electroweak s. f. g_5 via $W^{+/-}$ production [1,2]
- Flavor separation of PDFs through semi-inclusive DIS [1]
- Deeply Virtual Compton Scattering (DVCS) ELIC [1,2]
  >> Generalized Parton Distributions (GPDs) [3]
- Transversity [1]
- Drell-Hern-Gerasimov spin sum rule test at high ν [1]
- Target/Current fragmentation studies ELIC [2,3]
- … etc….

Luminosity Requirement

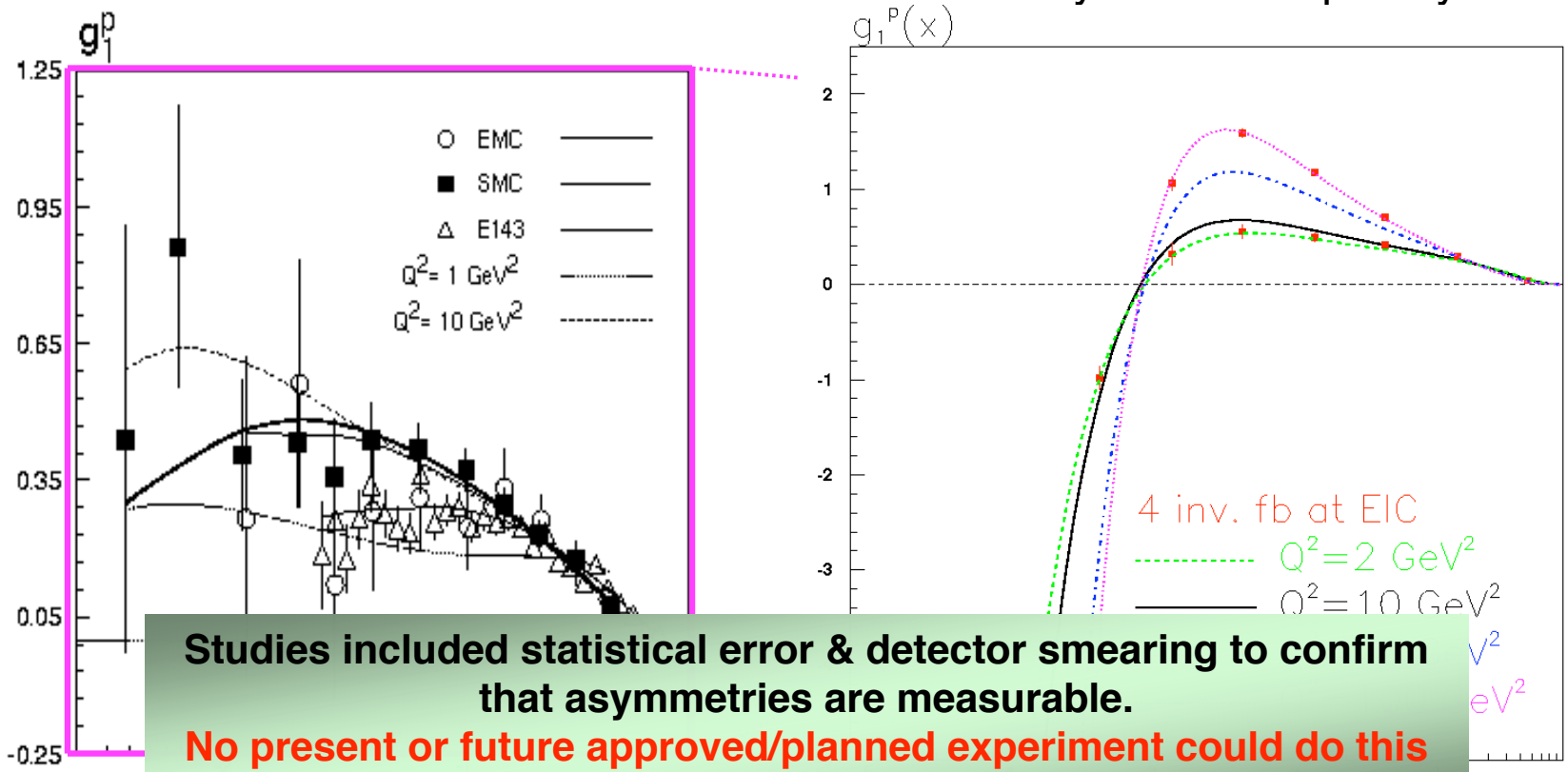
Proton Spin Structure at Low x

Fixed target experiments

1989 – 1999 Data

eRHIC 250 x 10 GeV

Luminosity = ~85 inv. pb/day



Studies included statistical error & detector smearing to confirm that asymmetries are measurable.

No present or future approved/planned experiment could do this measurement!

$\Rightarrow$ BJORKEN SUMRULE $\int_0^1 dx(g_1^p - g_1^n)(x, Q^2)$ ~ 1-2% precision at eRHIC

Consequence of Precision Bj SR

$$\int_0^1 g_1^p - g_1^n dx = \frac{1}{6}\frac{g_A}{g_V} C_{NS}(O^4(\alpha_s))$$

$\alpha_s(M_Z)$ has been determined from Bj spin sum rule by:

1. J. Ellis & M. Karliner, Phys. Lett. B341, 387 (1995)
2. G. Altarelli et al., Nucl. Phys. B496, 337 (1997)
3. B. Adeva et al. SMC Collaboration, Phys. Rev. D58 (1998) 112002

Values range from 0.114-119 with uncertainties:

+/- 0.004 (experimental)

+/- 0.010 (theory/ low x extrapolation)

Particle Data Book (2002), Extended version:

"Theoretically, this sum rule is better for determining α_s because perturbative QCD result is known to higher order ($o(\alpha_s^4)$), and these terms are important at low Q^2....

Should data at lower x become available, so that the low x extrapolation is more tightly constrained, the ***Bj sum rule method could give the best determination of α_s***"

Fits of $g_1(x,Q^2)$+jets

J. Lichtenstadt
AD, A.De Roeck,V. Hughes, G.Radel

Constrain better the shape and the first moment

ΔG determined from the Scaling violations of g1

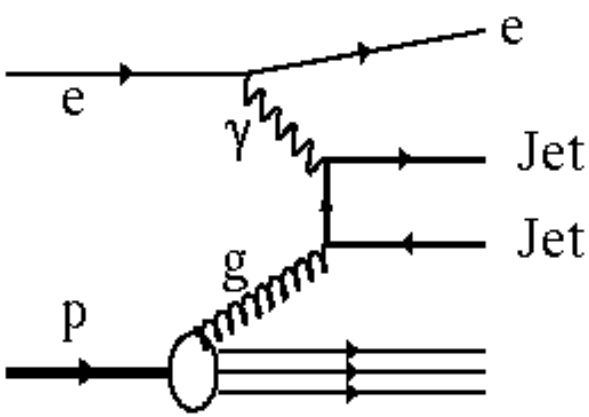
SMC Published 1998: First Moment of $\Delta G(x)$

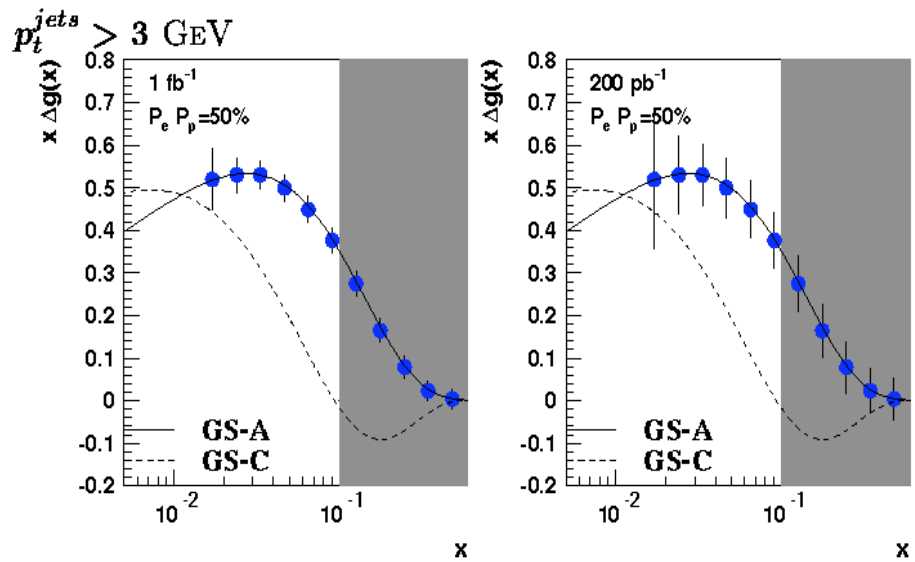
$\int \Delta G(x)dx =$ 1.0 +/- 1.0 (stat) +/- 0.4 (exp.syst) +/- 1.4 (theory)

-- one week eRHIC reduces statistical & theory errors by ~5

-- low x --> strong coupling, functional form at low -x, renorm. & fact. scales

Di-Jet at eRHIC:



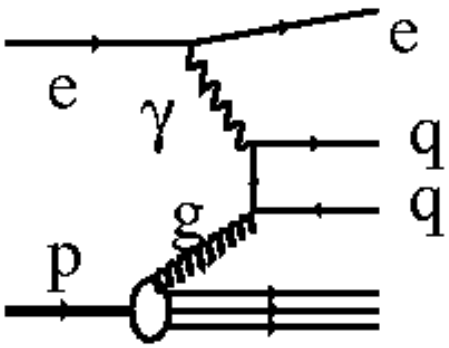


M. Stratmann, W. Vogelsang

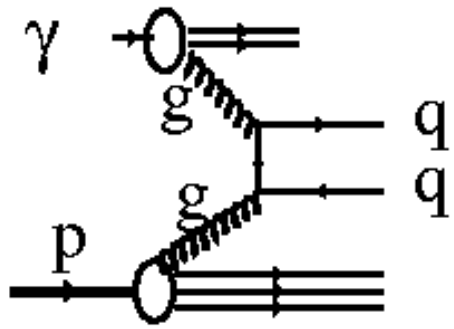
Polarized PDFs of the Photons

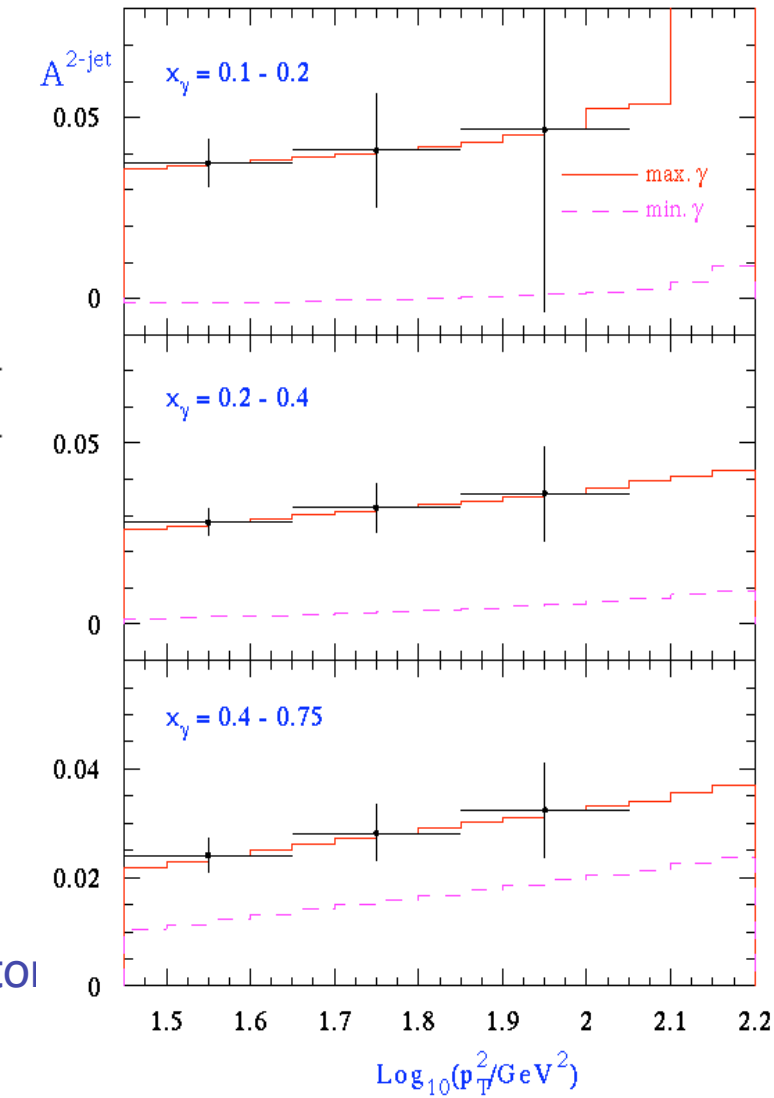
- Photo-production studies with single and di-jet

Direct Photon



Resolved Photon

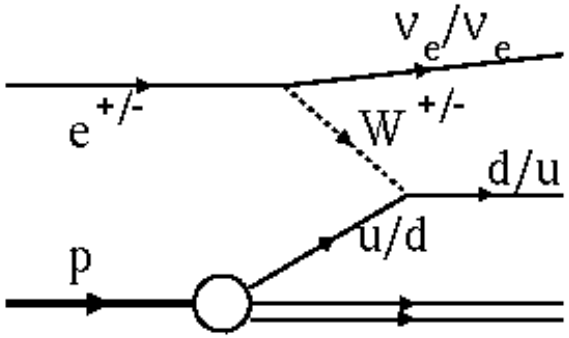




- Photon Gluon Fusion or Gluon Gluon Fusion (Photon resolves in to its partonic contents)
- Resolved photon asymmetries result in measurements of spin structure of the photon
- 1 fb-1 (~3 weeks) data, ZEUS acceptance: ample data to explore the QCD/spin structure of the photo

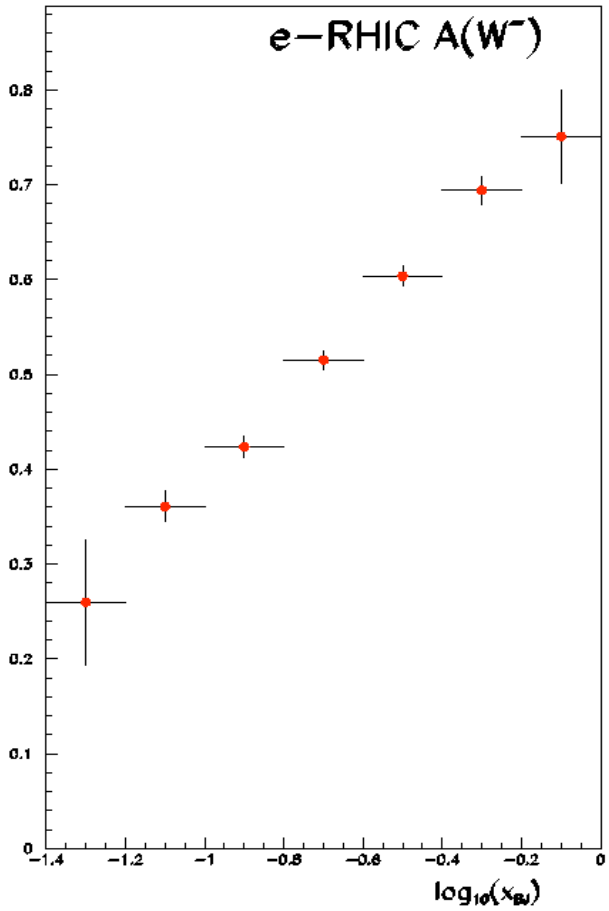
J. Contreras, A. De Roeck

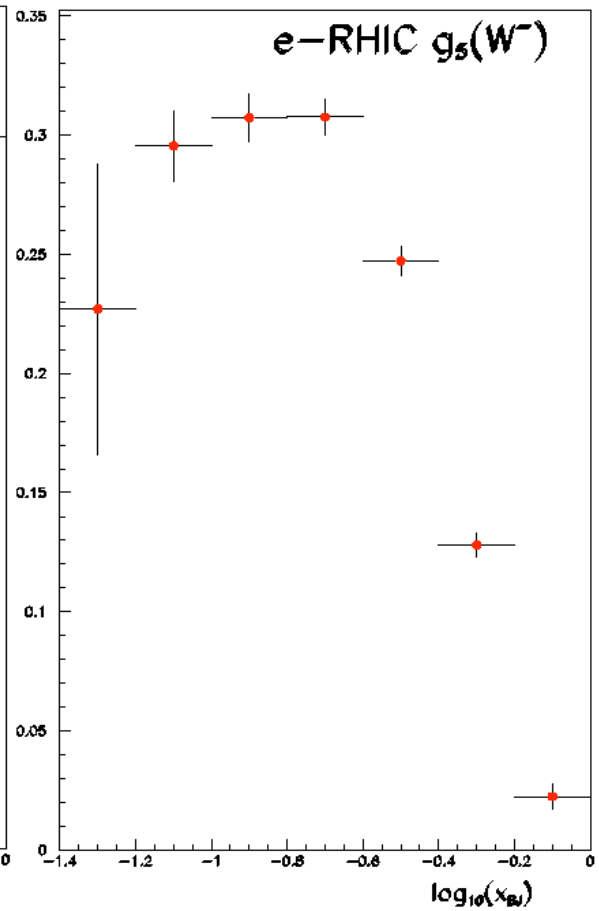
Measurement Accuracy PV g_5 at eRHIC



$$g_5^{W-} = \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}$$
$$g_5^{W+} = \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c}$$

Need hermetic detector like ZEUS/H1





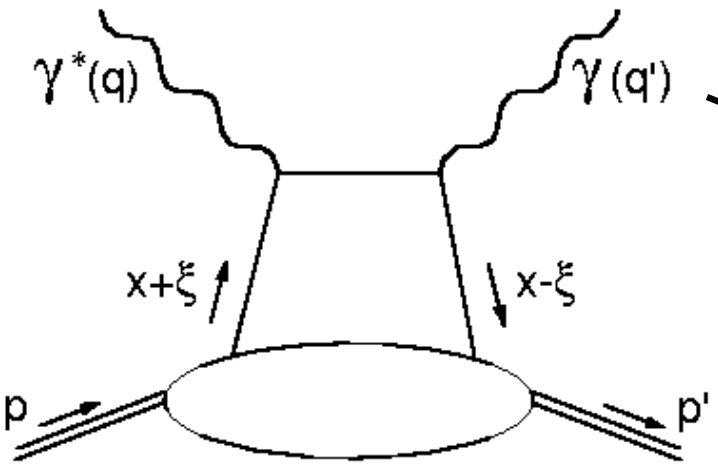
Assumes:

1. Input GS Pol. PDfs
2. xF_3 measured
3. 4 fb^{-1} luminosity

Positrons & Electrons in eRHIC ➔ $g_5(+)$

>> reason for keeping the option of positrons in eRHIC

DVCS/Vector Meson Production



- Hard Exclusive DIS process
- g (default) but also vector mesons possible
- Remove a parton & put another back in!

  ➔ Microsurgery of Baryons!

- Claim: Possible access to skewed or off forward PDFs?
  Polarized structure: Access to quark orbital angular momentum?

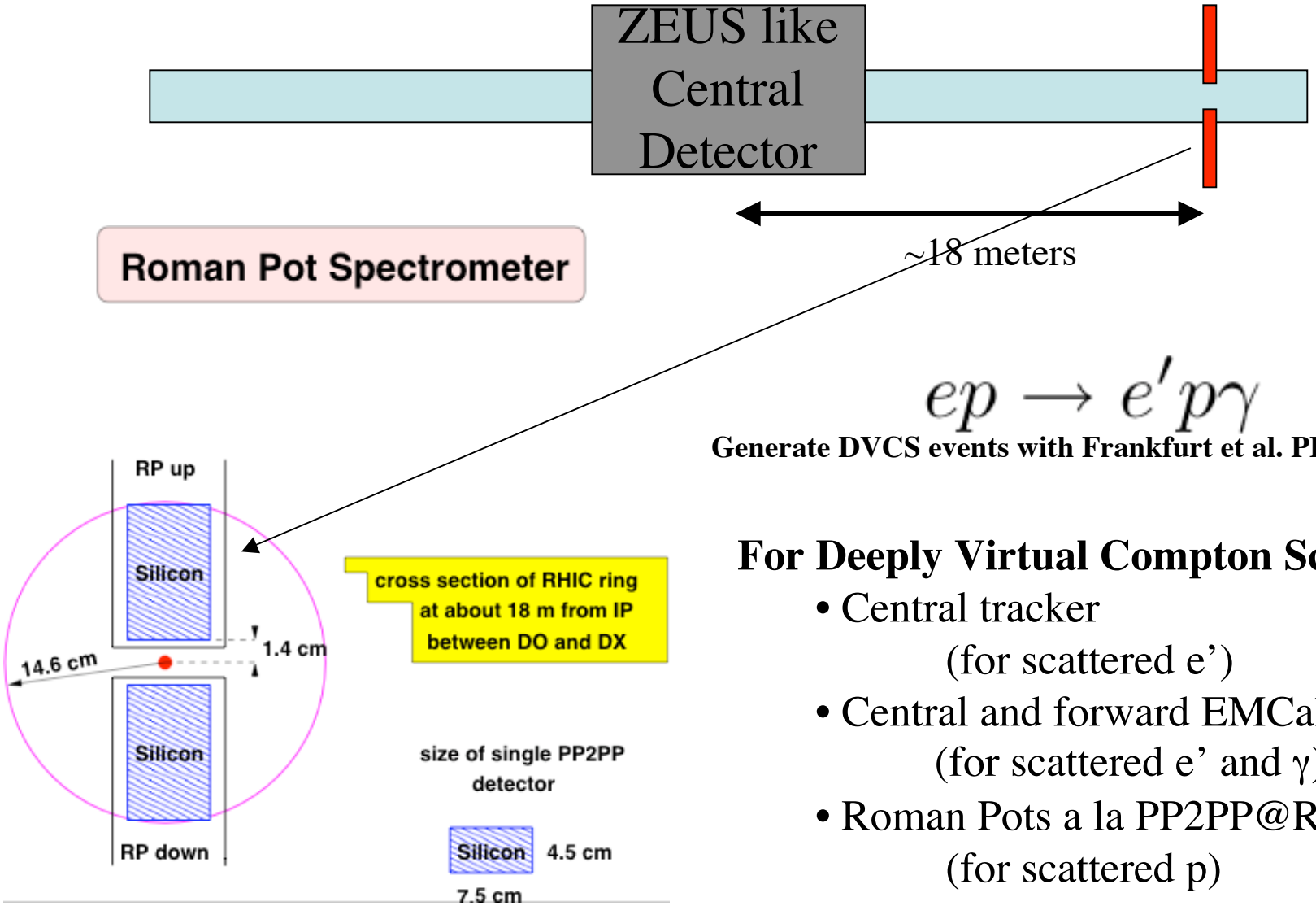
$$\int x dx [H(x,t,\xi) + E(x,t,\xi)] = 2J_{quark} = \Sigma + 2L_q$$

On going theoretical debate… experimental effort just beginning…

--A. Sandacz et al.

A. Sandacz, A.D.

Roman Pots for eRHIC



$$ep \rightarrow e' p \gamma$$

Generate DVCS events with Frankfurt et al. PRD58 (1998)

For Deeply Virtual Compton Scattering:

- Central tracker
  (for scattered e')
- Central and forward EMCal
  (for scattered e' and γ)
- Roman Pots a la PP2PP@RHIC
  (for scattered p)

Study DVCS acceptance

Central Detector Acceptance

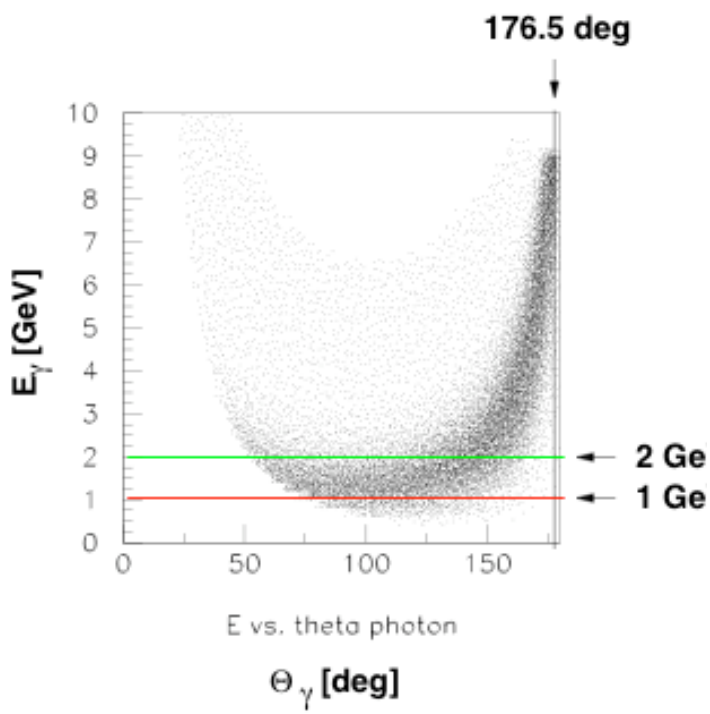
$2.2 < \Theta_{e'} < 176.5$ deg

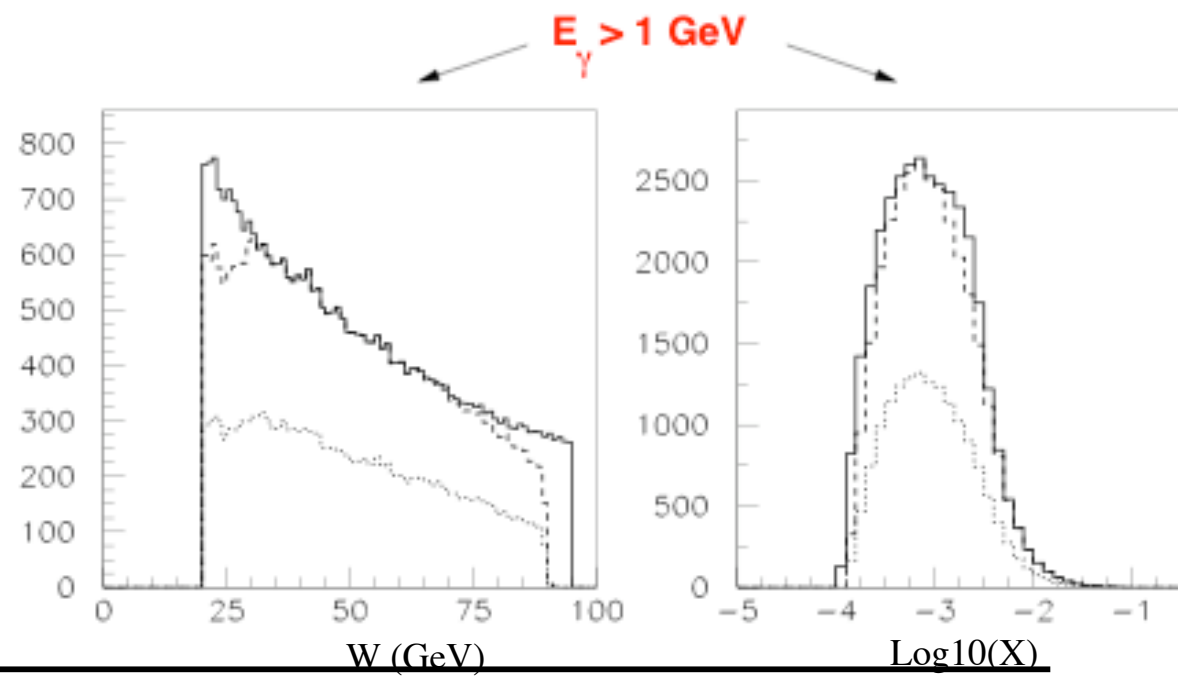
$2.2 < \Theta_{\gamma} < 176.5$ deg

$\Theta_{e'\gamma} > 3.1$ deg

$E_{e'} > 2$ GeV

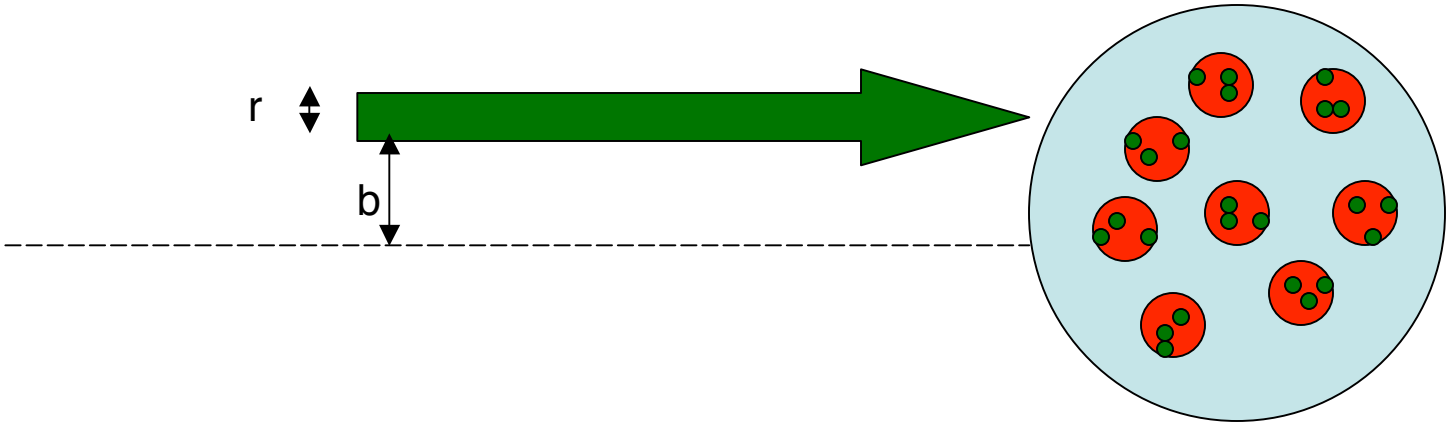
$E_{\gamma} > 1$ GeV





Precision eA measurements

- Enhancement of possible nonlinear effects (saturation)



At small x, the scattering is coherent over nucleus, so the diquark sees much larger # of partons:

$xg(x_{eff},Q^2) = A^{1/3}\, xg(x,Q^2)$, at small-x, $xg \propto x^{-\lambda}$, so

$x_{eff}^{-\lambda} = A^{1/3} x^{-\lambda}$ so $x_{eff} \approx xA^{-1/3\,\lambda} = xA^{-3}\ (Q^2 < 1\ \mathrm{GeV}^2)$

$= xA^{-1}\ (Q^2 \approx 100\ \mathrm{GeV}^2)$

Highlights of e-A Physics at eRHIC

- Study of e-A physics in Collider mode for the first time
- QCD in a different environment

- Clarify & reinforce physics studied so far in fixed target e-A & μ-A experiments including target fragmentation

  QCD in: $x > [1/(2m_N R_N)] \sim 0.1$ (high x)

  QCD in: $[1/(2m_N R_A)] < x < [1/(2m_N R_N)] \sim 0.1$ (medium x)

  Quark/Gluon shadowing

  Nuclear medium dependence of hadronization

- …. And extend in to a very low x region to explore:

  saturation effects or high density partonic matter also called the Color Glass Condensate (CGC)

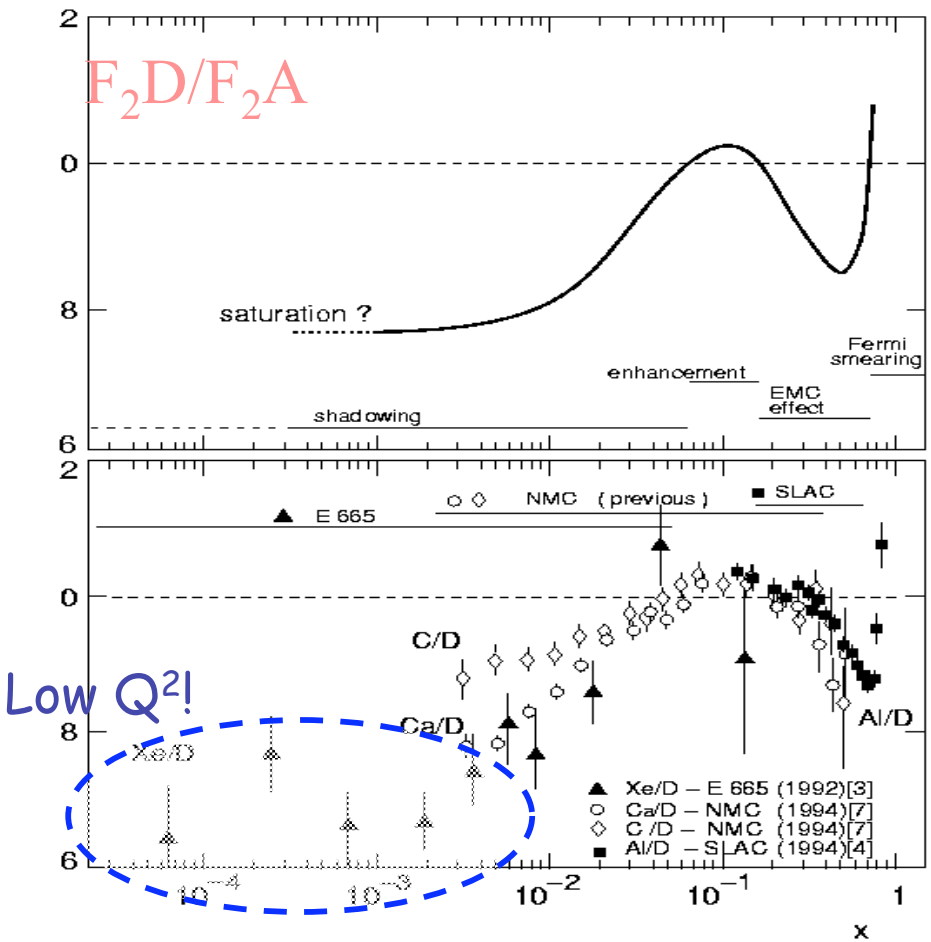
  QCD in: $x < [1/(2m_N R_A)] \sim 0.01$ (low x)

Recent interest in eRHIC from HERA

- Proposals for HERA-III have presently an uncertain future
- Physics of strong interaction, main motivation for HERA-III
  - **Understanding the radiation processes in QCD at small and large distances:**
    - Small distance scales: explores parton splitting (DGLAP, BFKL, CCFM...)
    - Large distance scales: transition from pQCD to non-pQCD regime
- Needs specially designed detector to look in to very very forward directions, unprecedented so far at HERA

- Early indications are that eRHIC energies would be sufficient to study this physics... if a specially designed detector is installed in eRHIC.

DIS in Nuclei is Different!



Regions of:

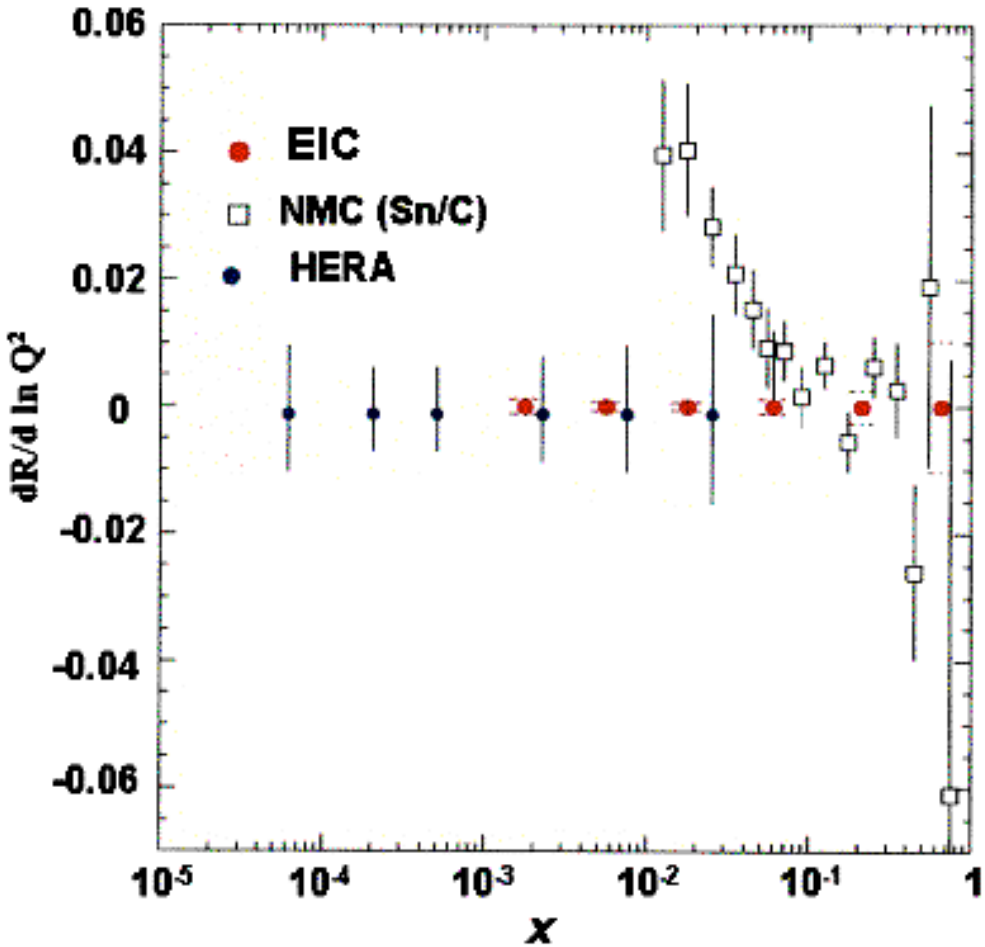
- Fermi smearing
- EMC effect
- Enhancement
- Shadowing
- Saturation?

Regions of shadowing and saturation mostly around Q^2 ~1 GeV^2

An e-A collision at eRHIC can be at significantly higher Q^2

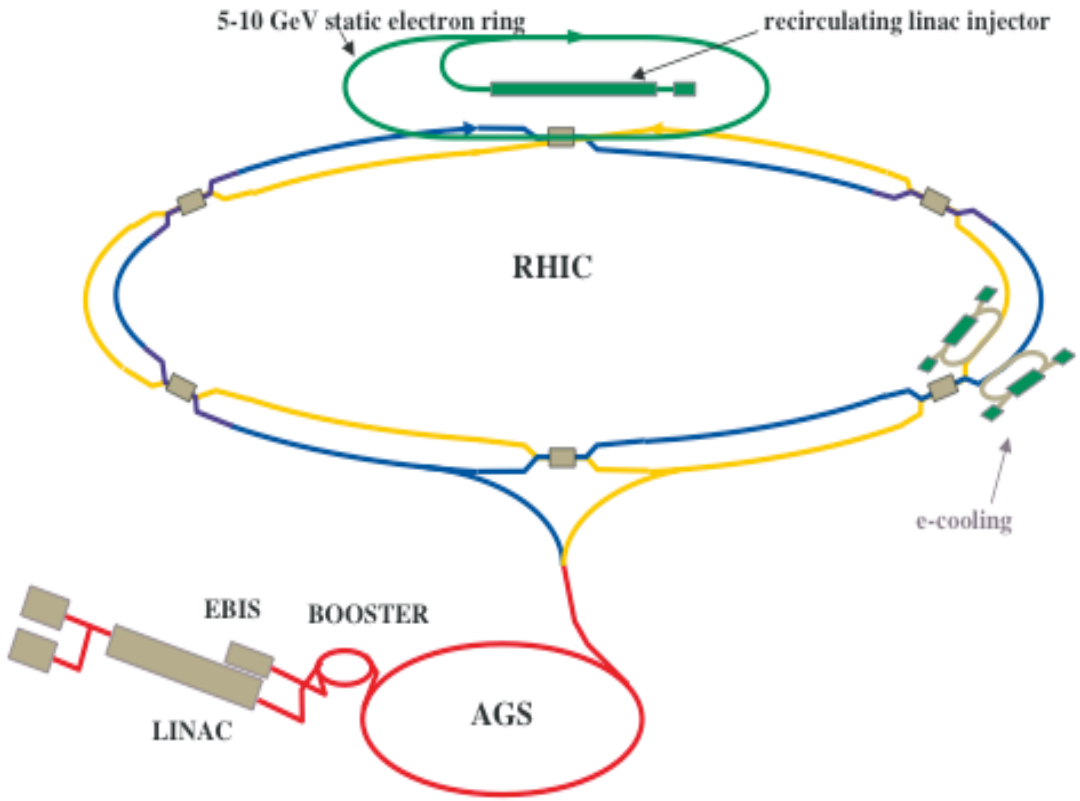
T. Sloan

Statistical Precision at eRHIC for e-A



- High precision at EIC shown statistical errors for 1 pb^{-1}
- Recall: eRHIC will ~85 pb^{-1} per day
- NMC data F_2(Sn/D)
- EIC's Q^2 range between 1 and 10 GeV^2
- Will explore saturation region!

The eRHIC Ring-Ring Lay Out & Plans



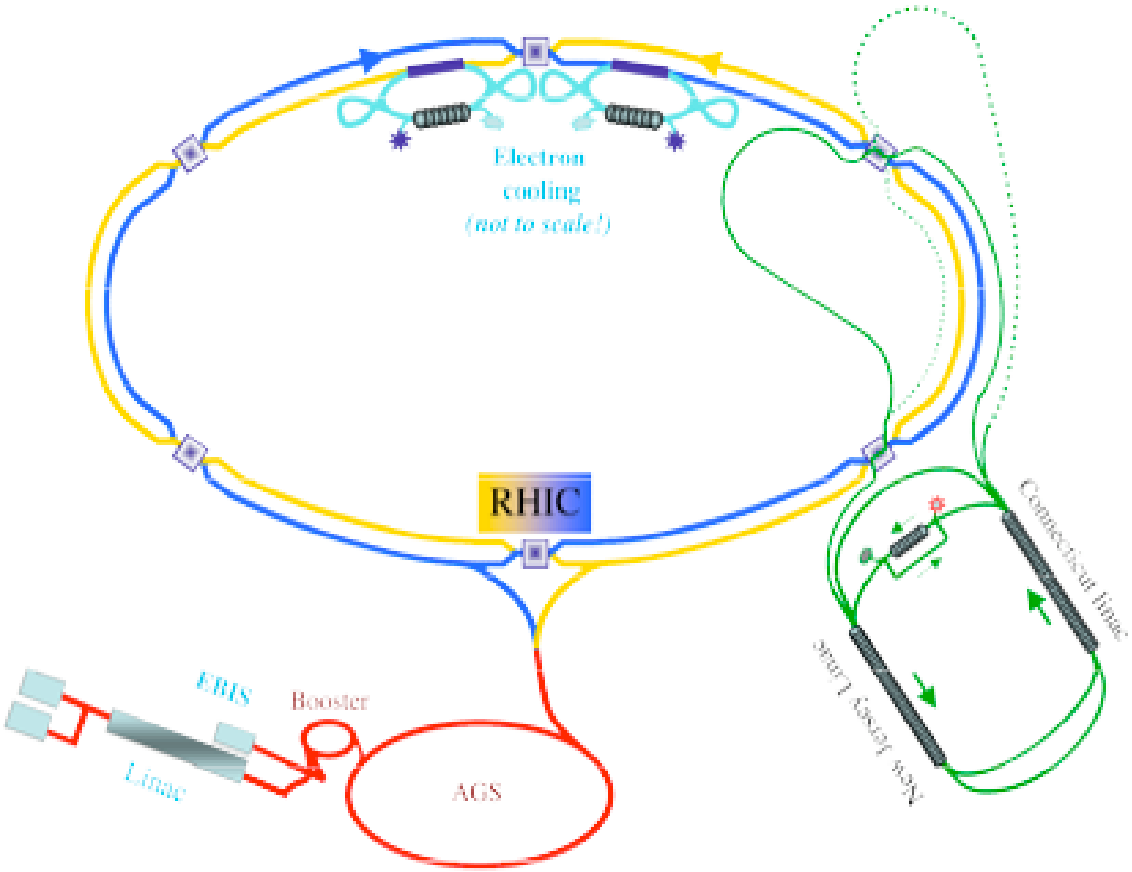
- Full energy injection
- Polarized e- source & unpolarized e+ --> (polarization via synchrotron radiation)
- 10 GeV main design but up to 5 GeV reduction possible with **minimal polarization loss**
- Fill in bunch spacing 35ns

Present conservative estimates L_(ep)~ 4 x 10^{32} cm^{-2} sec^{-1} **work on luminosity enhancement continues.**

Advantages: both positrons/electrons positrons.....

Disadvantages: Multiple detectors or/and Interaction Regions?

eRHIC: Linac-Ring Option



Features:

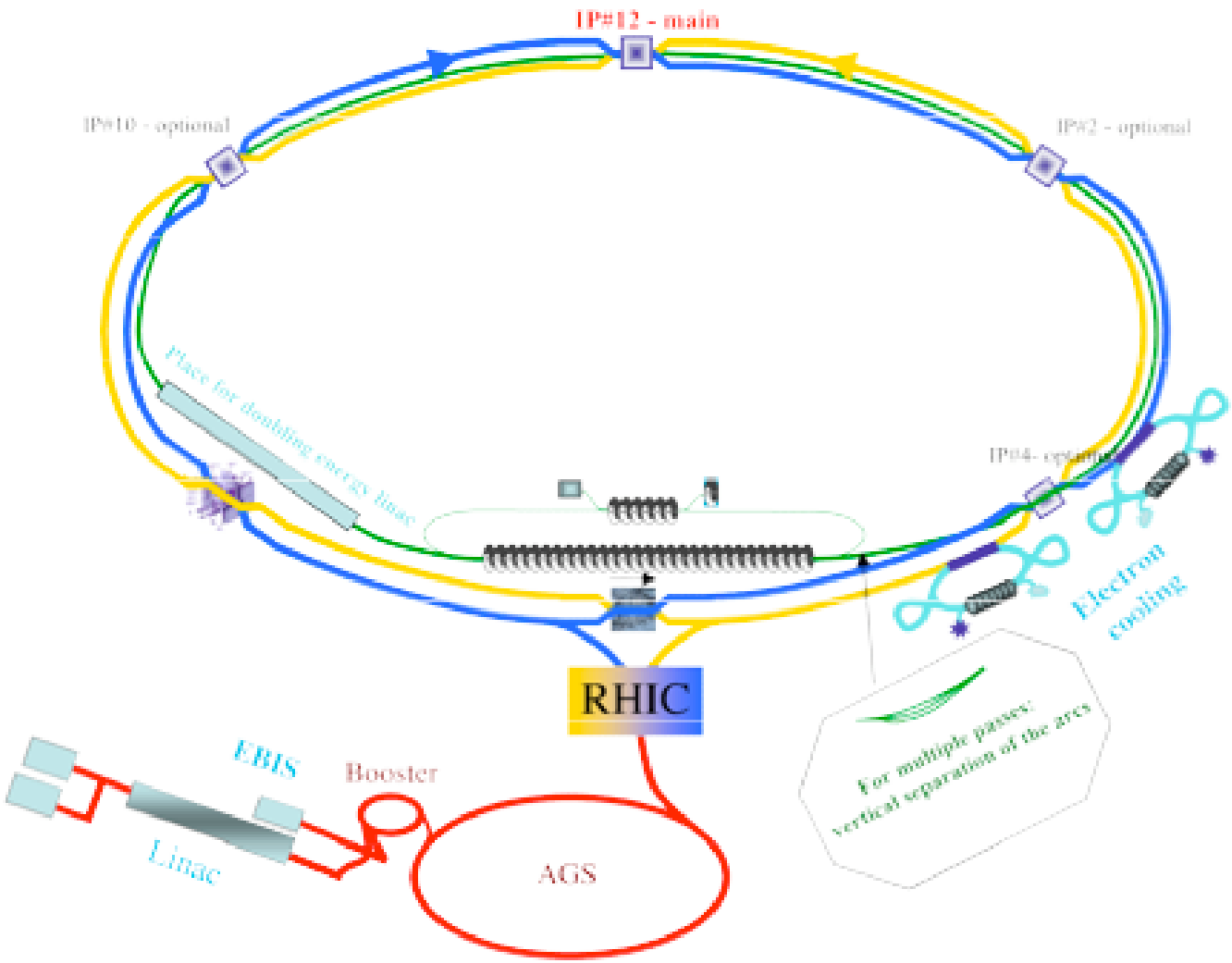
- Up to L(ep) ~10^{34} $cm^{-2}sec^{-1}$
- Polarization transparency at all energies
- Multiple IRs and detectors
  - Long element free regions
- STAR & PHENIX still run
- Full range of CM Energies
- Future upgrades to 20 GeV seem straightforward

Limitations:

Positron beams not possible

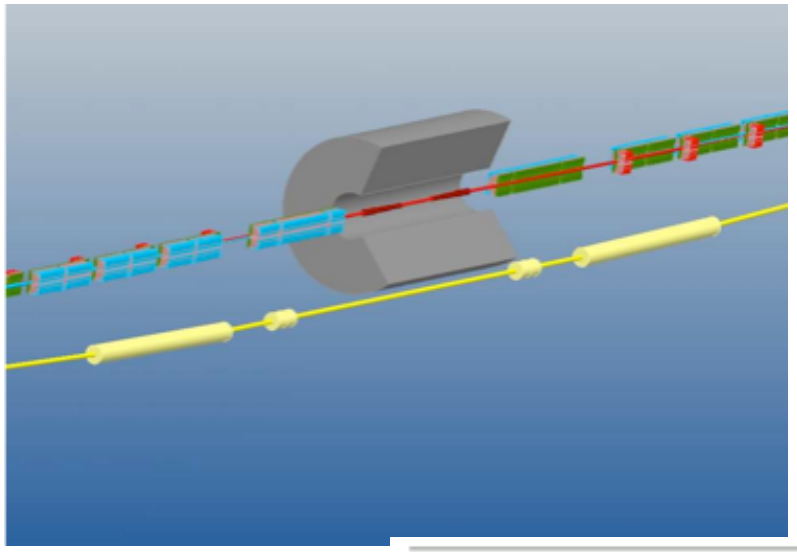
Physics implications?

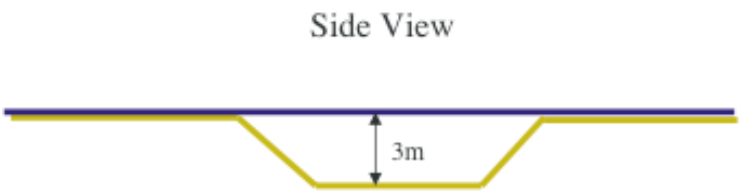
eRHIC Linac-Ring….. The Cadilac!

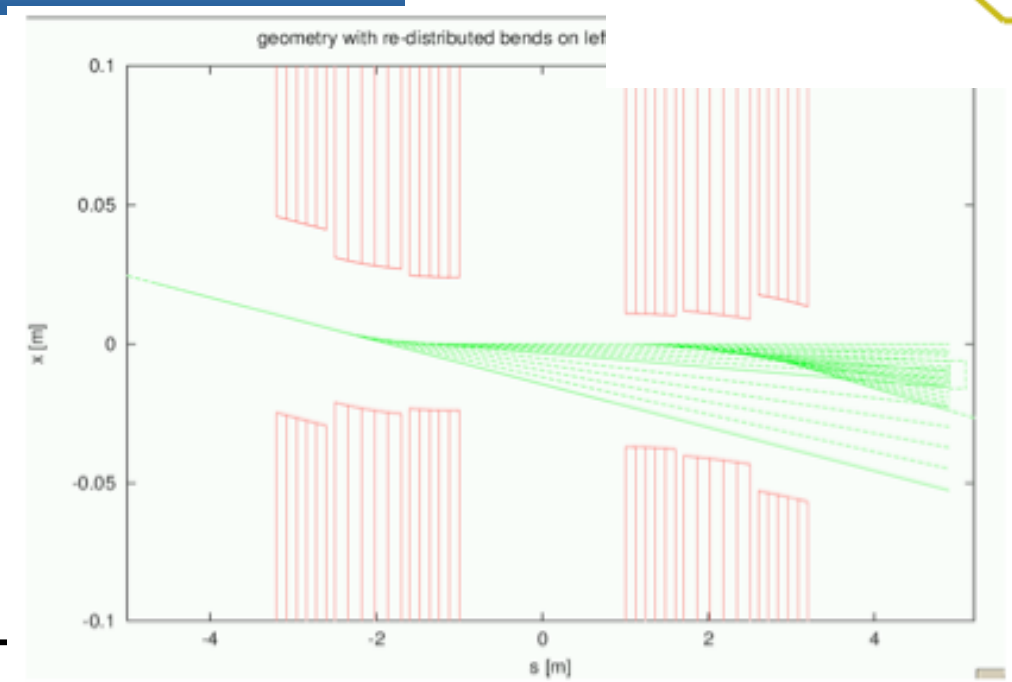


Up to 4 Irs
Up to 20 GeV
Electron beams

IR, Synchrotron Radiation, other Hadron Beam Modification



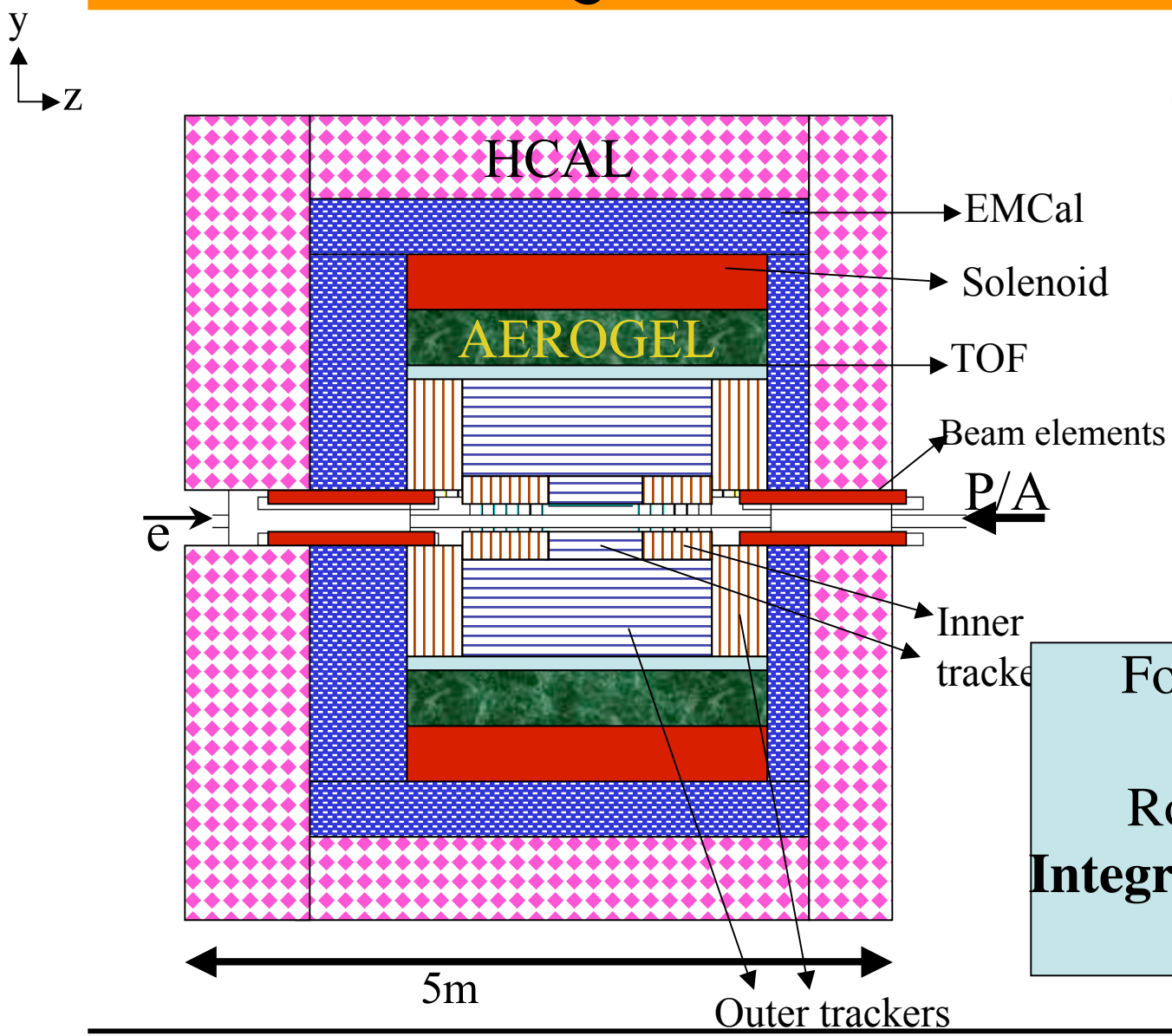




Abhay Deshpande, Stony Brook/RBRC

B. Surrow, N. Smirnov, A. D.

Detector Design HERA like…+ PID



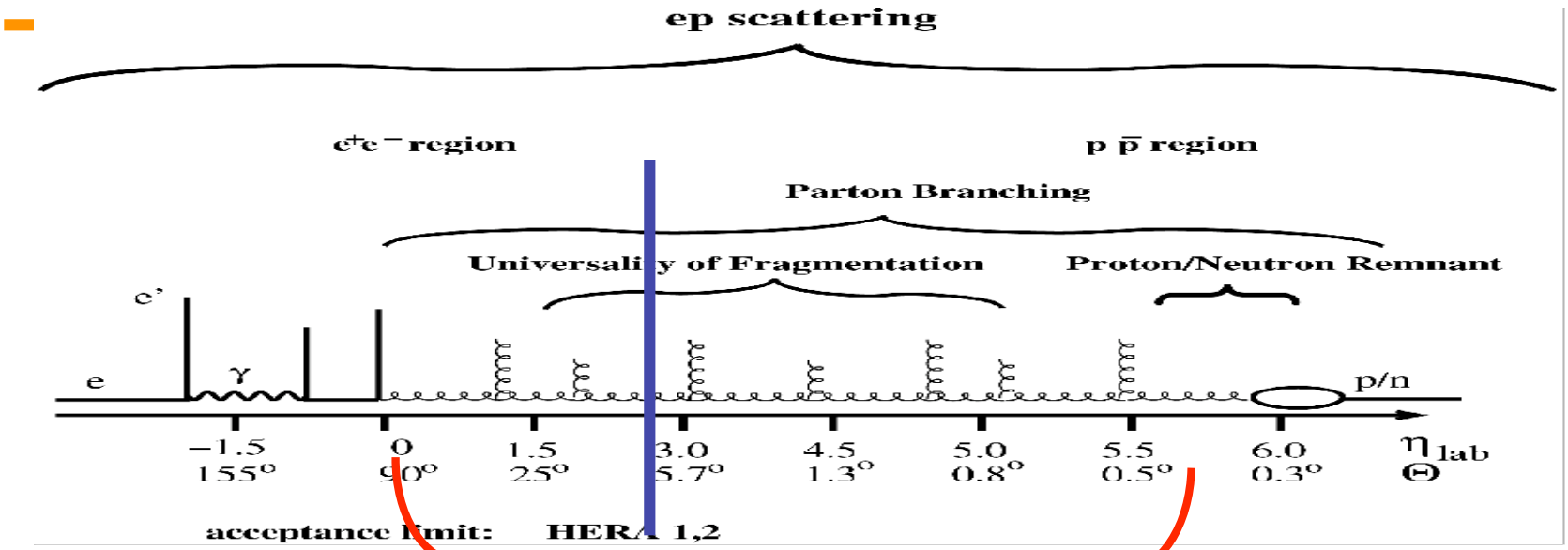
(Not to scale)

A HERA like Detector with dedicated PID:
>>Time of flight
>>Aerogel Ckov

AND

Forward detectors including Roman Pots etc…
Integrated in to the beam Elements!

More detailed tests of radiation in QCD: forward jets



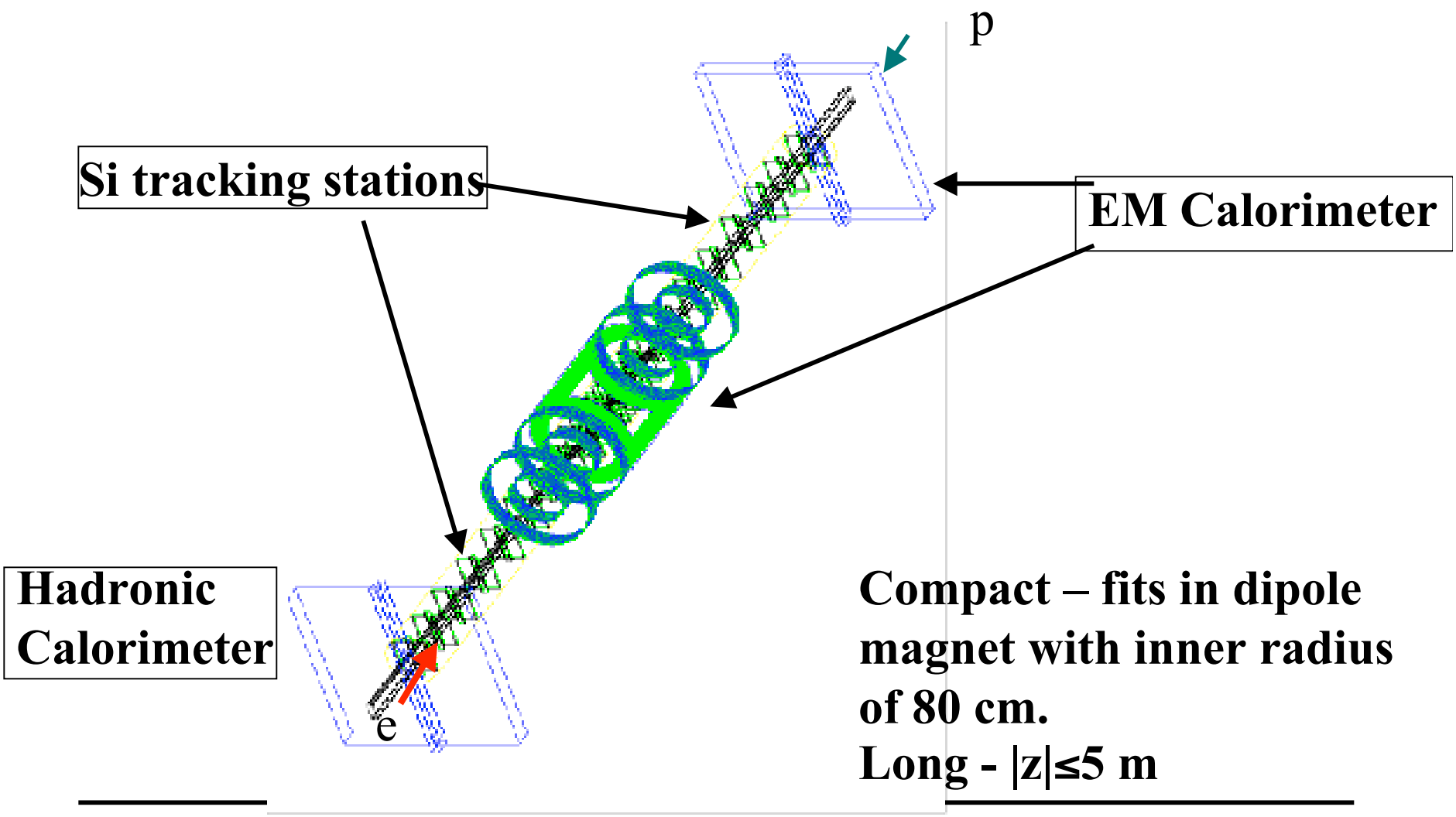
Investigate this region

Large effects are expected in Forward jet cross sections at high rapidities (also for forward particle production (strange, charm, …)

A. Caldwell et al.

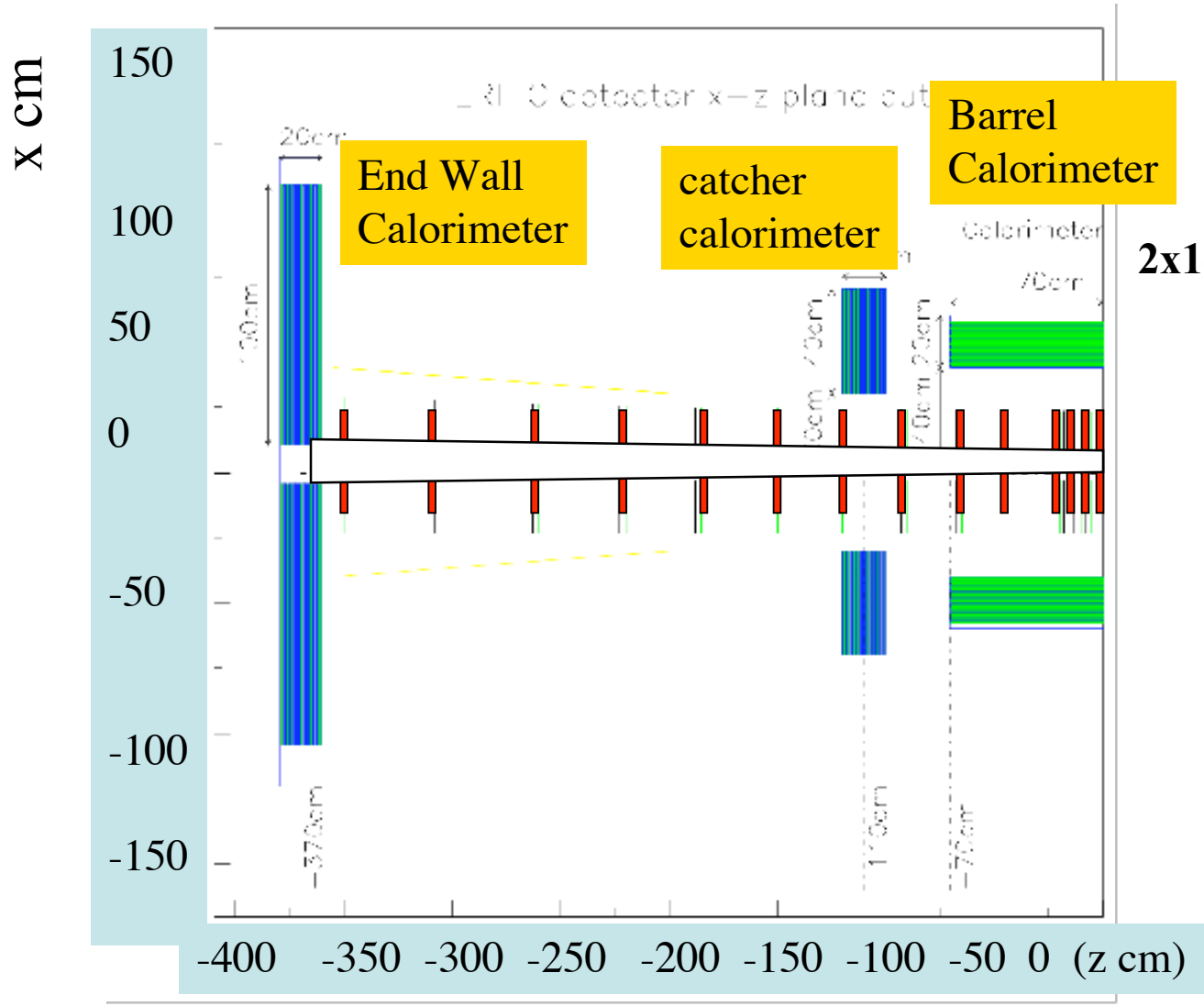
A new detector to study strong interaction physics

A. Caldwell et al.



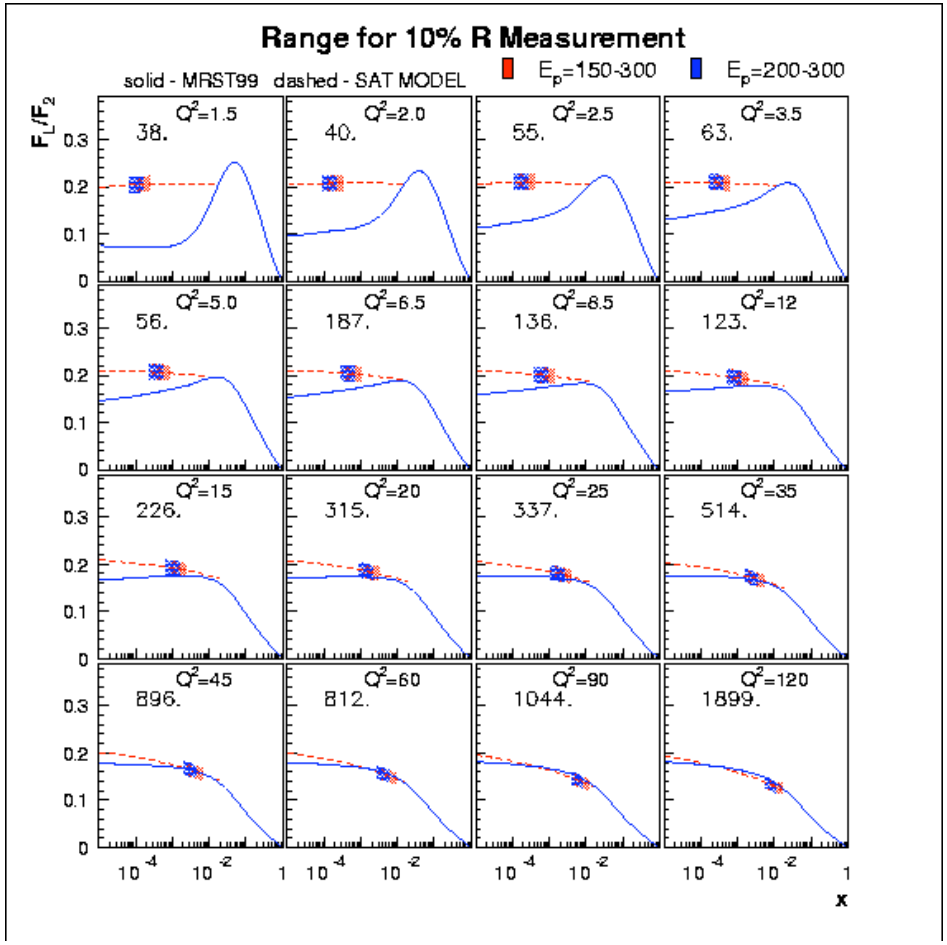
Compact – fits in dipole magnet with inner radius of 80 cm.
Long - |z|≤5 m

Low x Detector studies for eRHIC



2x14 Si tracking stations

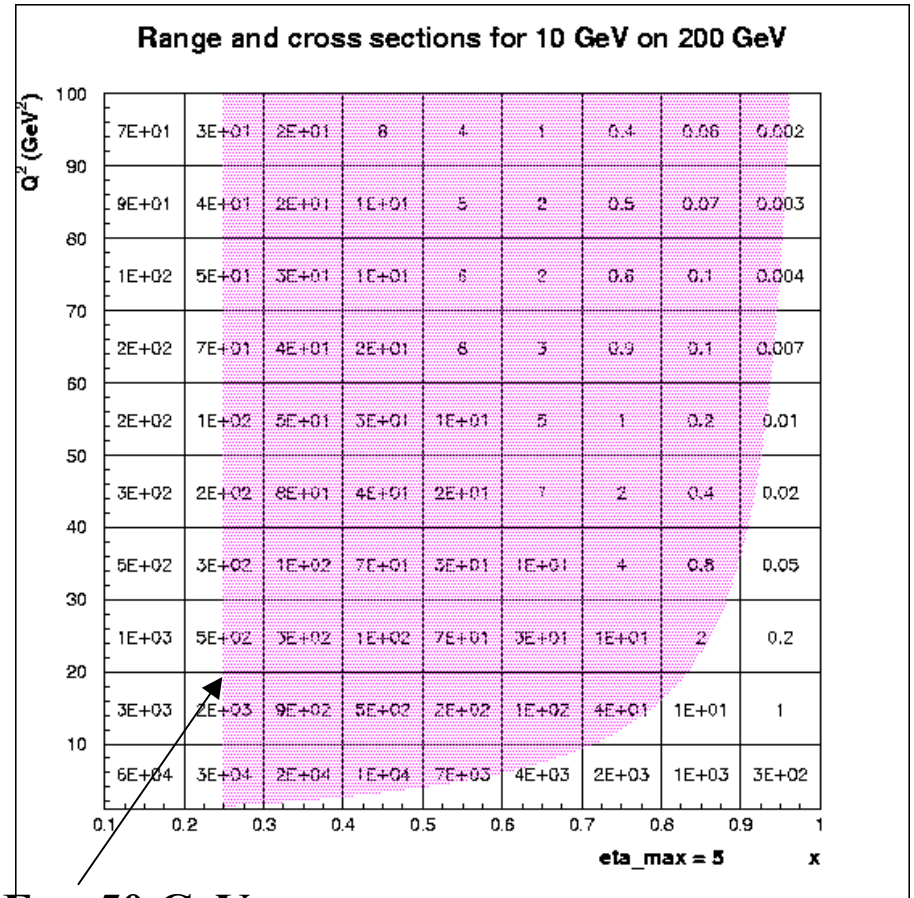
F_L/F_2 vs. x for different Q^2



High x measurement

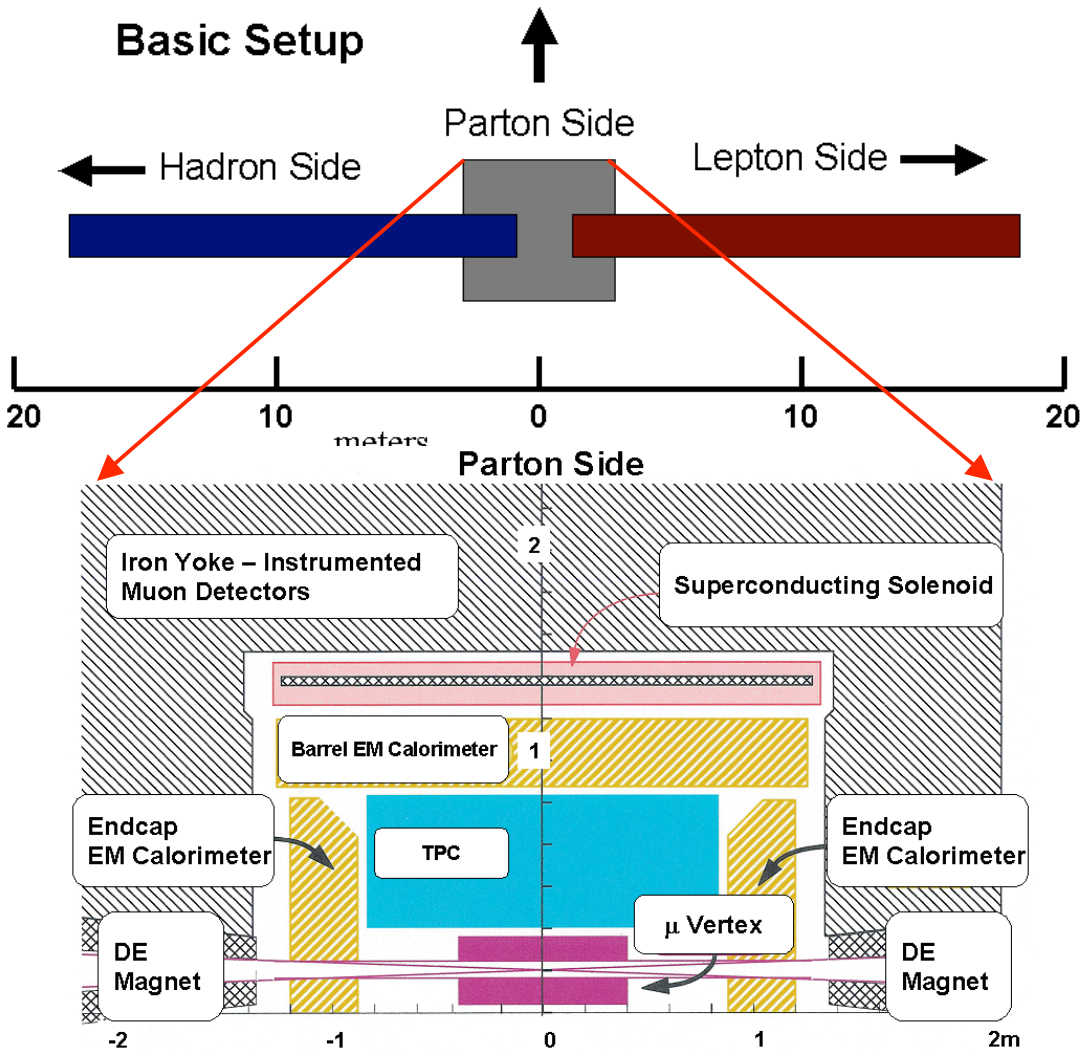
W^2>5 GeV^2

Cross sections in pb

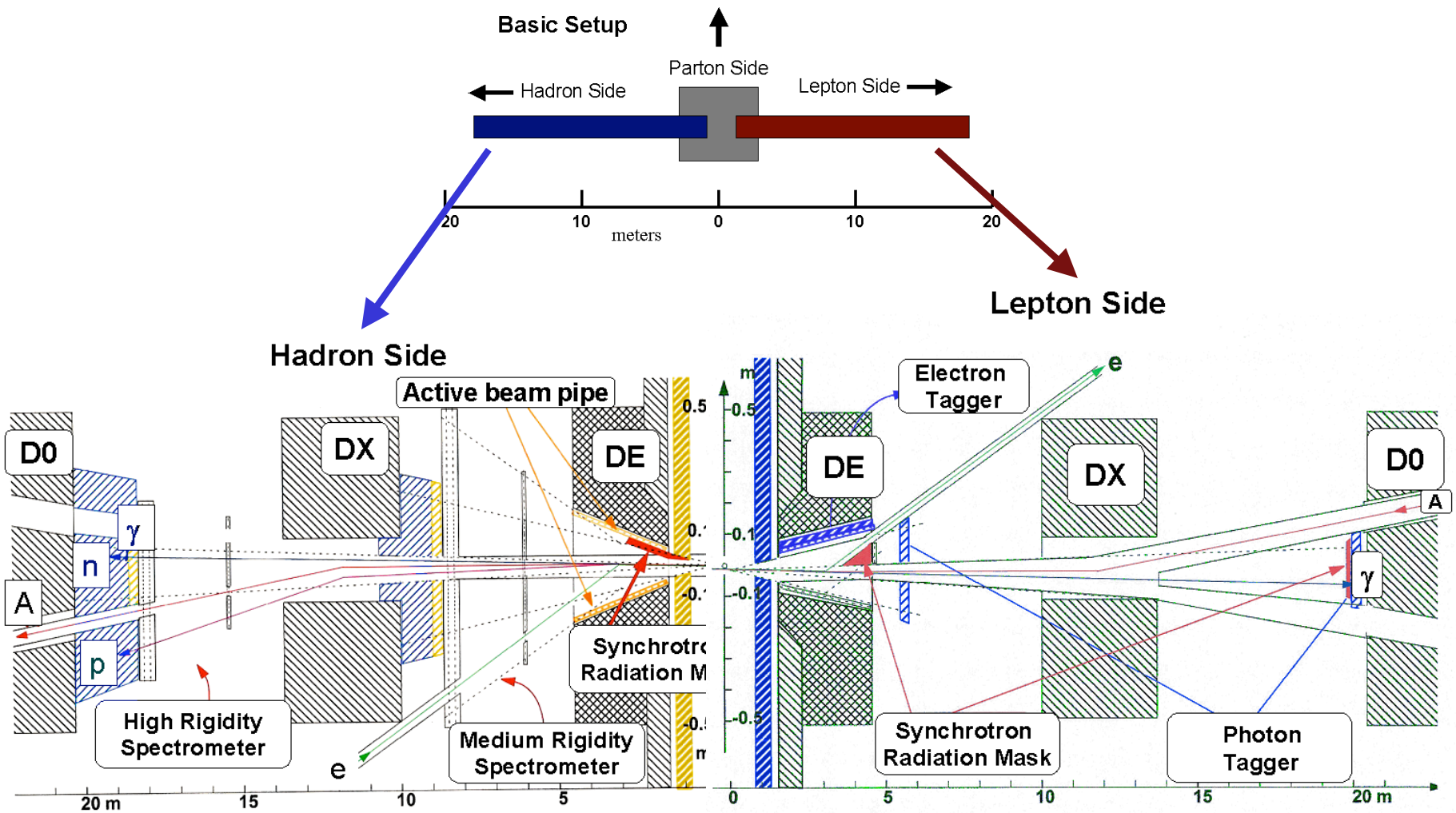


E_{jet}>50 GeV

Detector Design….



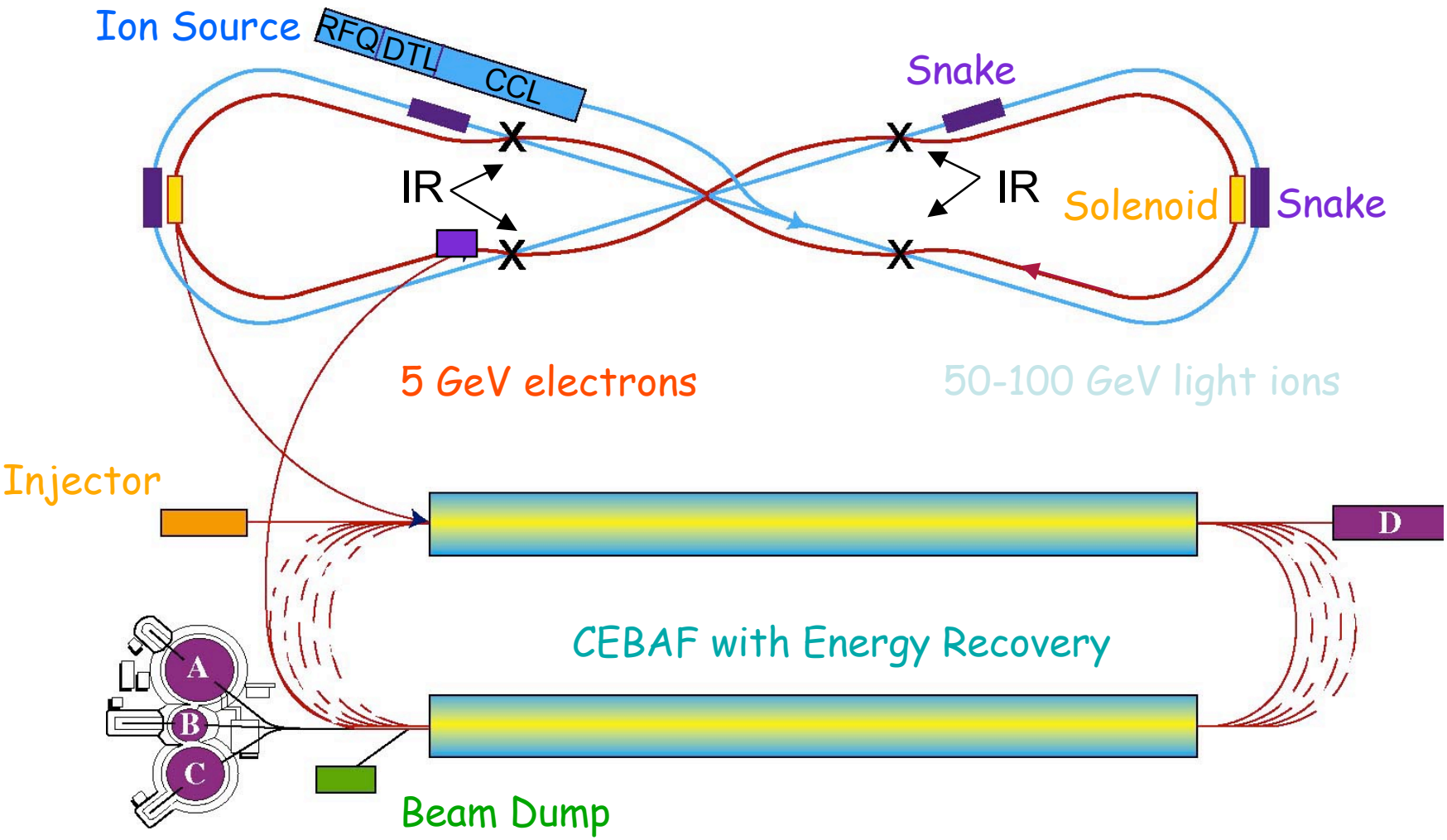
Detector Design ....



Lets see the "other collider concept" Electron Light Ion Collider (ELIC) at Jlab

L. Merminga

Jlab Upgrade II: ELIC Layout



One accelerating & one decelerating pass through CEBAF

NSAC Subcommittee Evaluation March 03: 1 Science, 3 for Readiness

L. Merminga

JLAB/ELIC Aggressive R& D Launched

- **Conceptual development:**
  - Circulator ring → to reduce the high current polarized photo-injector and ERL requirement
  - Highest luminosity limits

- **Analysis and simulations:**
  - electron cooling and short bunches
  - beam-beam physics
  - energy recovery linac physics

- **Experimental research effort:**
  - CEBAF-ERL to address ERL issues in large scale systems
  - JLAB FEL (10mA), Cornell/JLAB Prototypes (100 mA), BNL Cooling Prototype (100mA) to address high current ERL issues.

Concluding thoughts….on future colliders

- The case for a future ep/eA collider is very strong already and is being continuously improved

- eRHIC at BNL, **ZDR is now ready**; will seek approval from NSAC in the next LRP (2005-2006) and prepare the CD0
  - **Advanced accelerator designs** integrating IR and Detector issues will be ready by that time after a few more iterations with the experimental physicists

- ELIC design will solidify in the next few years and a dedicated R&D program will lead and decide the details of luminosity and interaction region issues

- Prospects of precision studies of nucleon spin with colliders looks very bright!

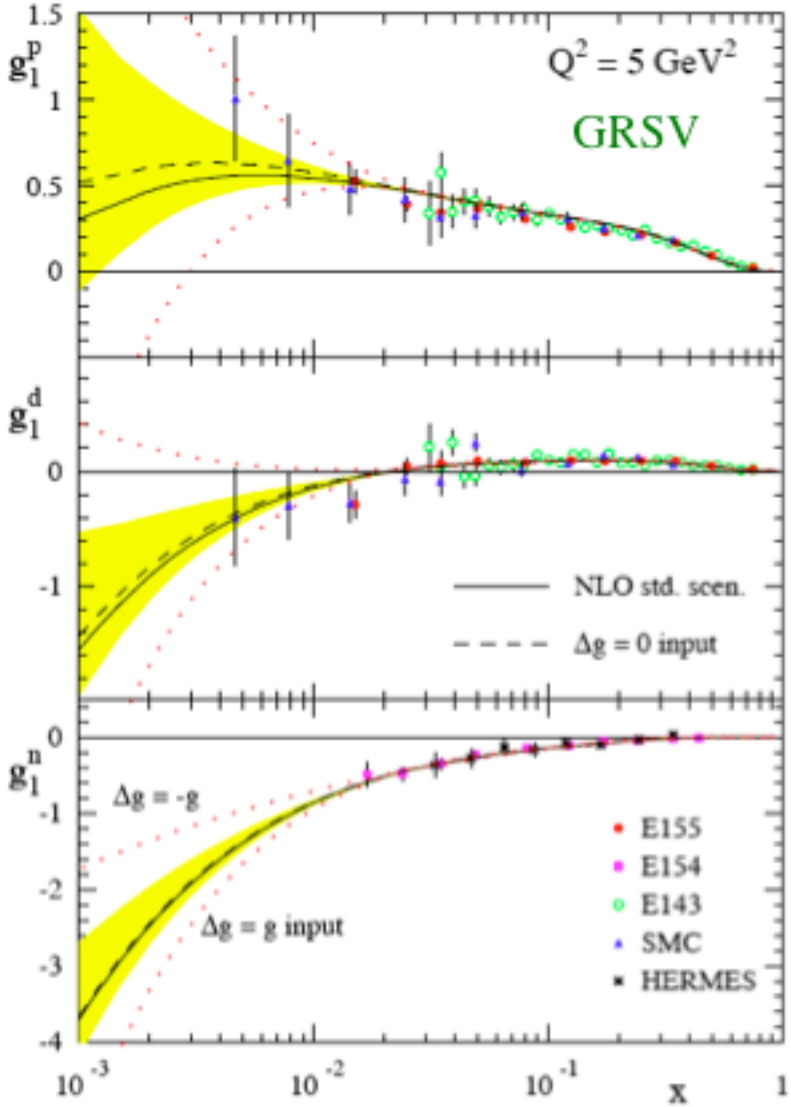
And now for something completely different!

(Monte Python's Flying Circus)

Are studies of spin just academic curiosity?

Understanding fundamental structure of matter?

Data: g1 and uncertainties



Data collected over the last Two and a half decades

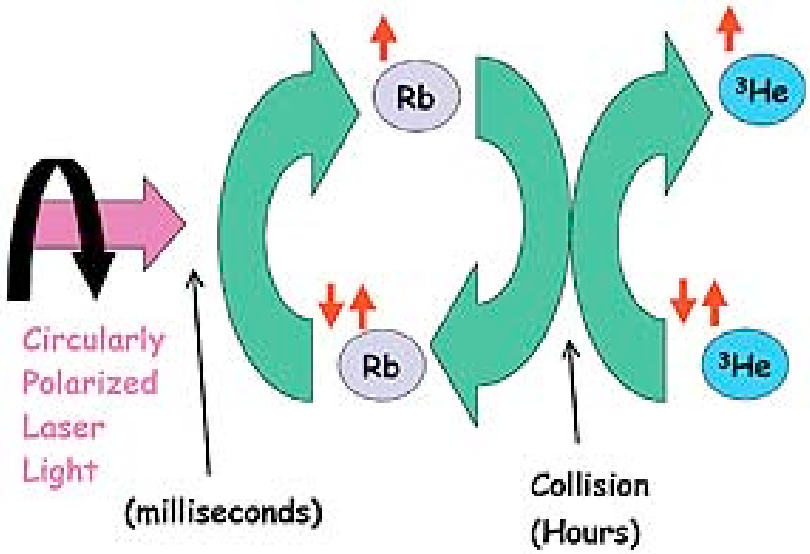
Fixed target lepton nucleon Scattering

Targets:
Proton: Amonia or butanol
Deuteron: deuterated butenol or deuterated amonia
--> Subtract proton and get neutron
Neutron: Helium 3 targets
Effort led by SLAC-Experiment Collaborators. (Princeton->UVa, SLAC->Caltech and others)

Large quantities of polarized ^{3}He

G. Cates et al., E. Hughes et al.

- Polarized ^{3}He:
  - Does NOT decay just like ^{4}He
  - Noble gas… "innert", does not react with anything
  - Only difference from ^{4}He is: one less neutron
    - When polarized two protons spin anti-aligned and neutron imparts the ^{3}He its spin!
- Before SLAC experiments (1990s) largets amounts of polarized ^{3}He produced was "cubic cms" --> E142/E143/E154 needed "litres"
- Atomic physicists got involved
  - heat rubidium
  - impinge with circularly pol. laser light
  - let it stay with 3He after hours (~1 litre/24hrs)



What "else" with polarized ^{3}He?

- Safe to take in to the body!
- High polarization (50%) gives good control over large number of spins so as to produce large signals

- Combine this with Magnetic Resonance Imaging (MRI) technique
- Inhale and look at your lungs!

Normal MRI:

- put yourself in to large superconducting magnets with high fields
- the signals normally comes from water in the body: spinning protons in hydrogen nuclei act like tiny magnets
- higher the field, larger the signal but you have only very few polarizable hydrogens (10^{-4})... You could increase this by lowering the body temperature of liquid nitrogen/helium but that may not be such a good idea for the person!

^{3}He: Although lower in density 50% polarization vs. 0.0001 makes significant difference

Problem:

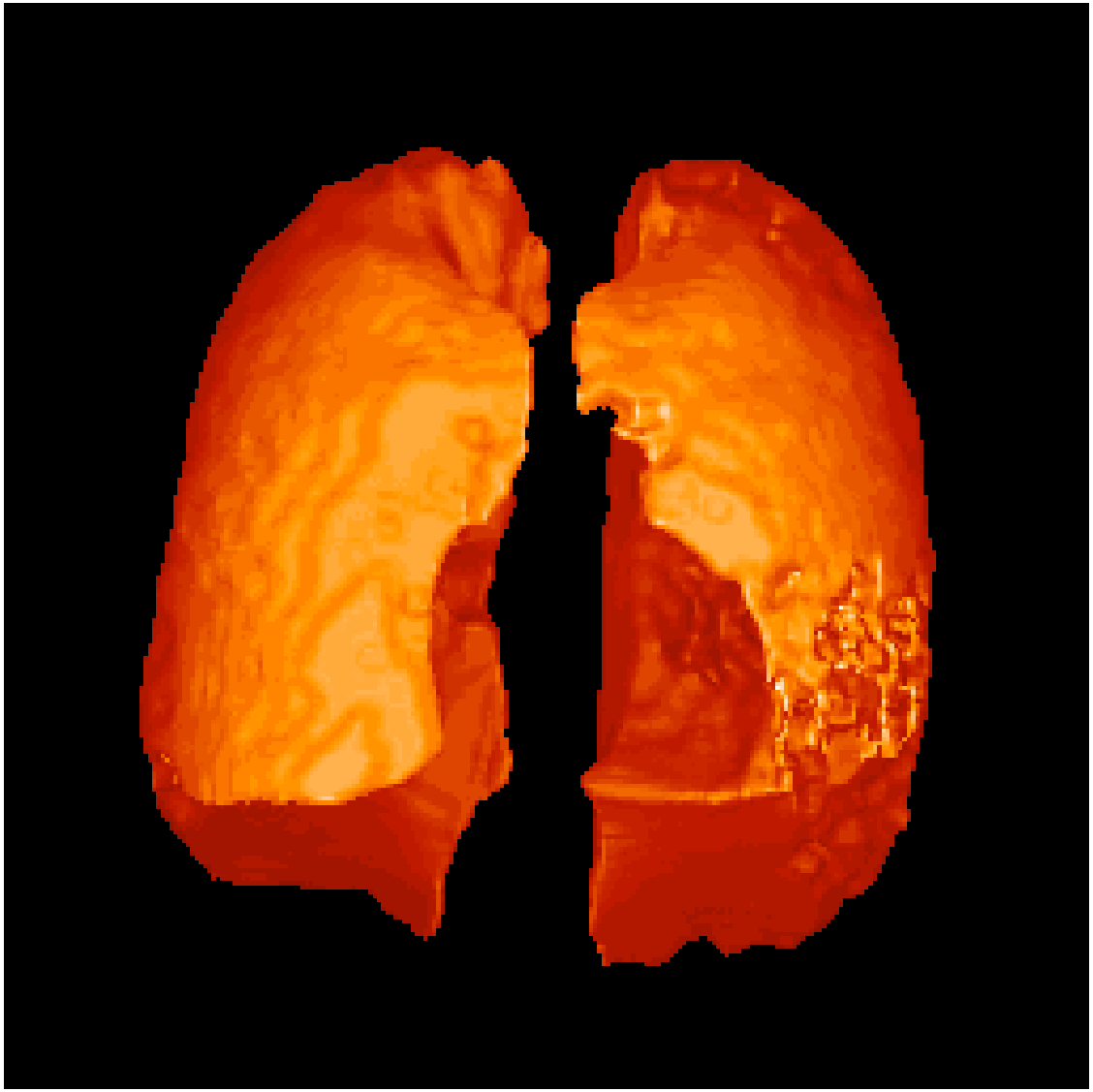
^{3}He is produced in Weapons program! --> $300/bottle

If you have lots of tritium price of 3He goes down.
Tritium is used in nuclear bombs.
Tritium (a radio-active isotope of hydrogen, with two neutrons and one proton) decays in to ^{3}He (two protons and one neutron)

Solution (?): Xenon: ^{129}Xe --> $10/bottle

Has even number - 54 - protons & 75 number of neutrons!
Also has spin 1/2
Not radioactive
Safe to inhale
Difference: inhale helium your voice becomes high!
inhale Xenon it will become **low (speed of sound dependent on the mas of the gas nuclei)**

Lungs seen through the ^{3}He lense



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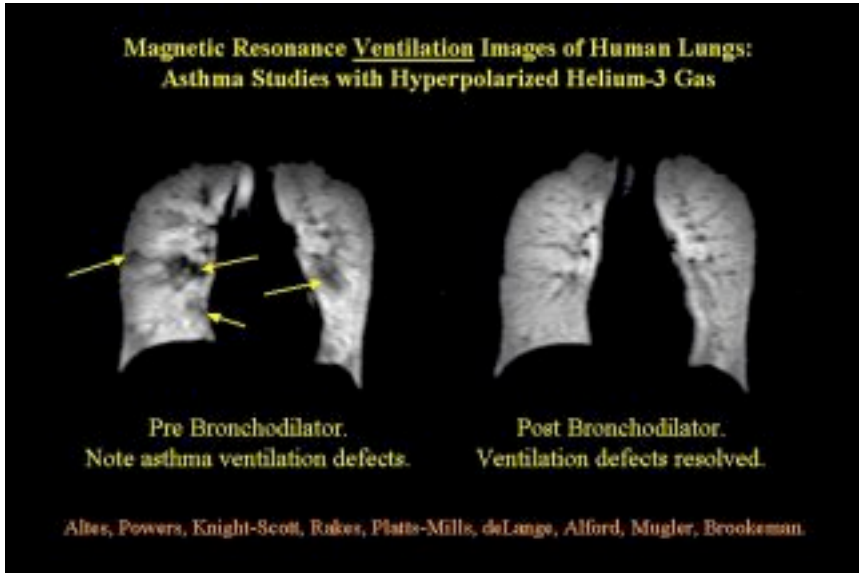
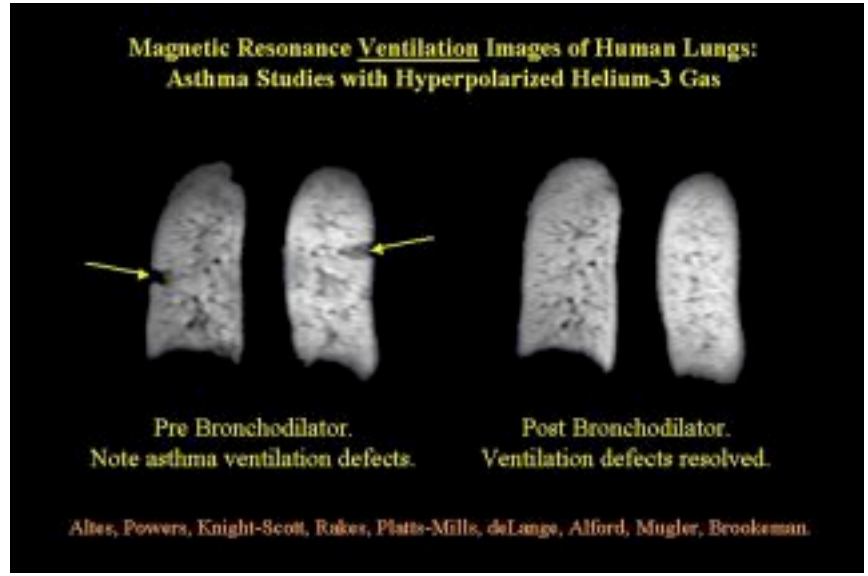
Asthema before symptoms appear!





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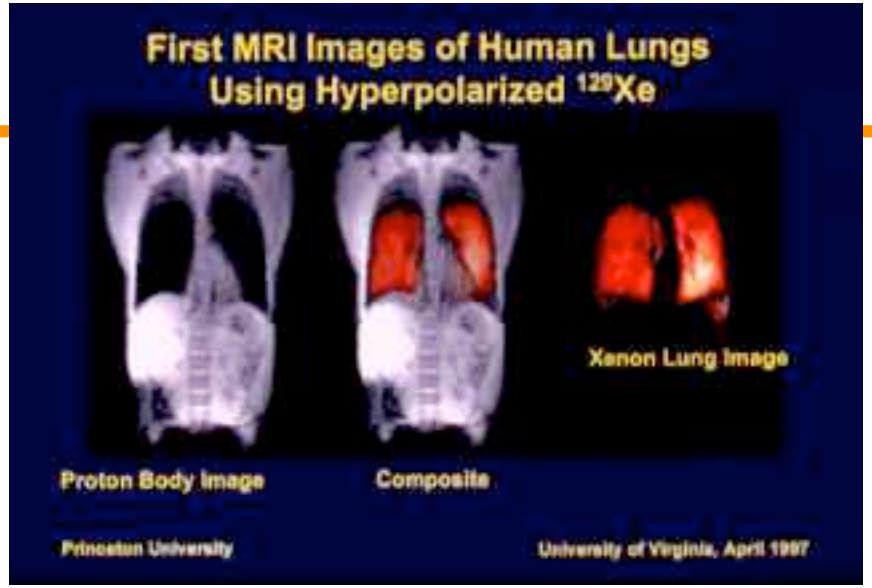
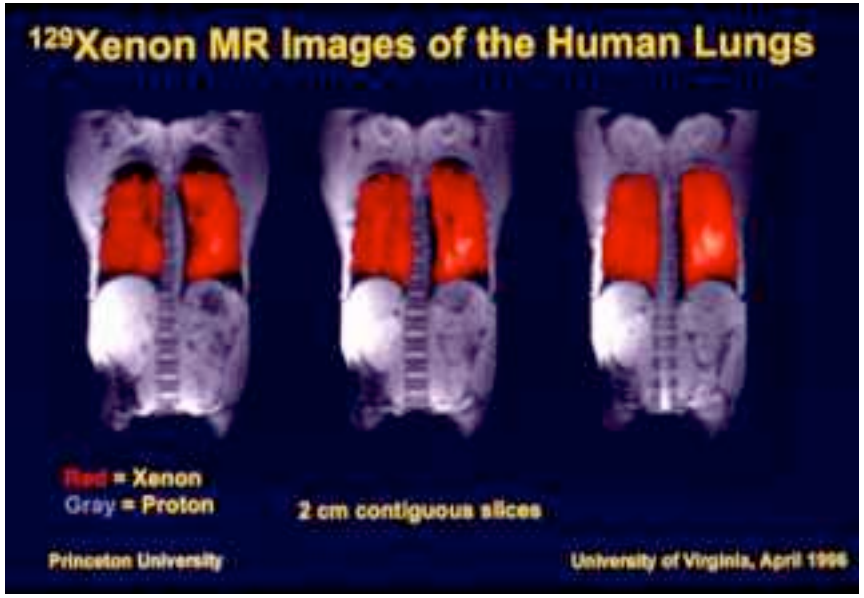
Xenon





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Our Message to You:

Spin is a very interesting and exciting property of matter

Nucleon spin is still a "Puzzle" but its on the border line of being "crisis" (Elliot Leader, ~1989)

RHIC Spin is a new technique to address the spin puzzle
eRHIC will follow up with many new and exciting measurements

Spin also tends to have many spin offs which might be of particular interest to some of you!

Good luck, and hope to spin with you in future!