From Parity Violation to Hadron Structure & more

Opportunities in Electroweak Physics at a future e-A Collider

The Science and Status of Electron Ion Collider in the US

Why an Electron Ion Collider (EIC)?
Role of Glue in QCD:
Structure & Dynamics of partons
in nuclei & nucleons

Electron Ion Collider Proposals:
Machine and Detector Concepts

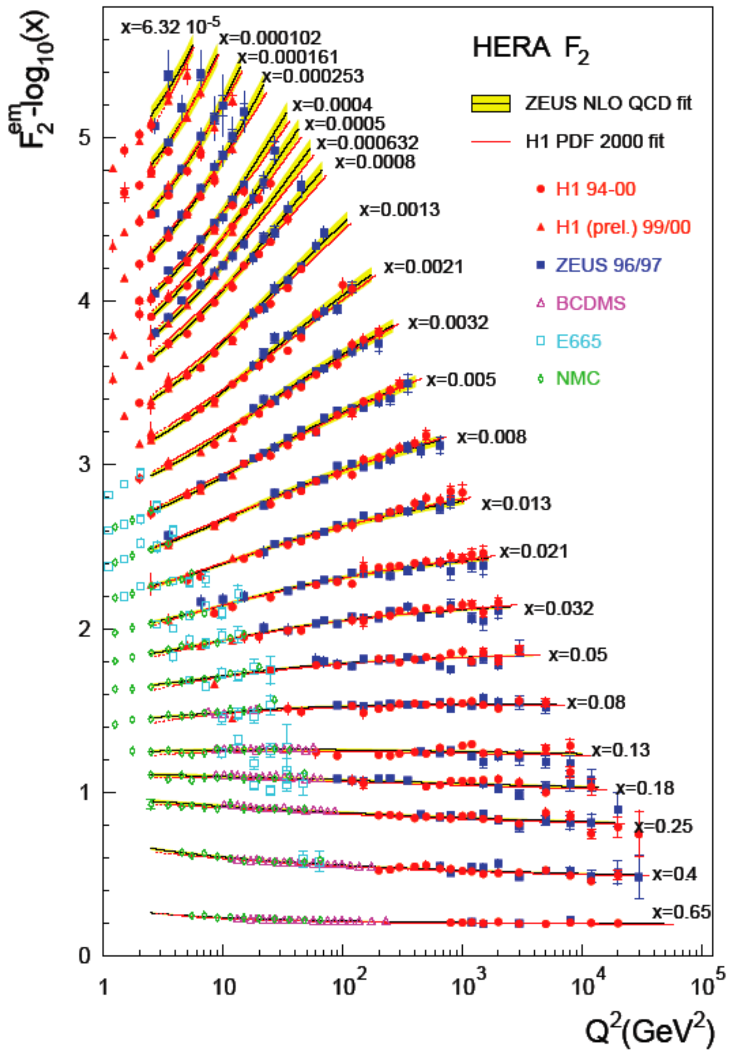
Abhay Deshpande
Stony Brook University

Early studies and possibilities of EW, BSM

What is the role of gluons at high energy?

HOW WELL DO WE UNDERSTAND GLUONS?

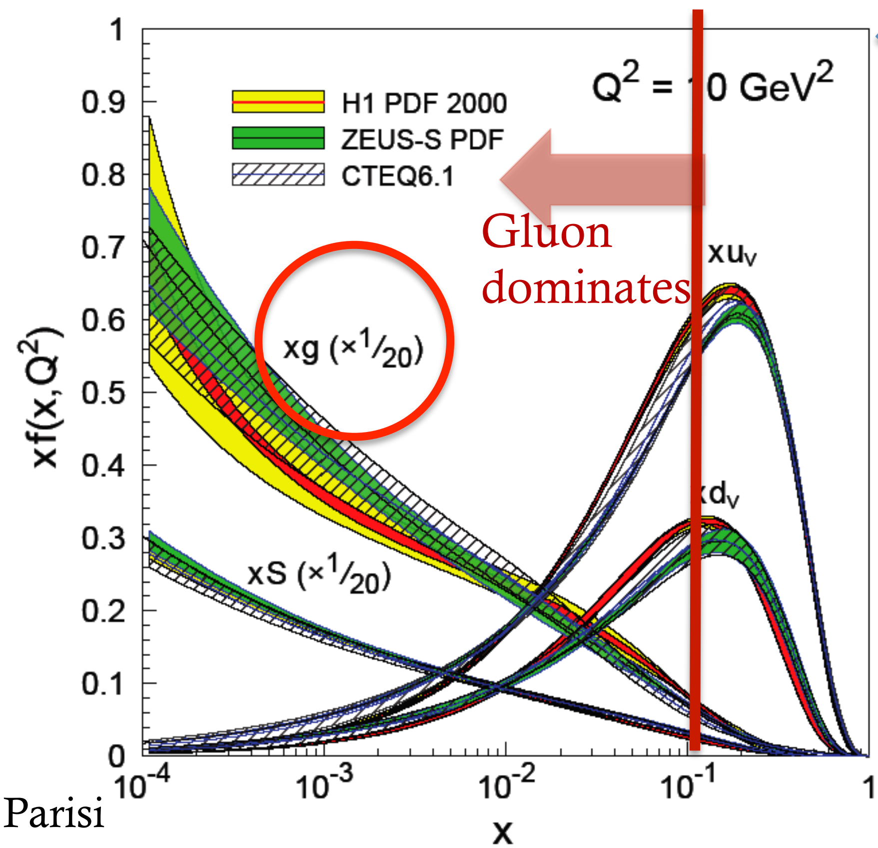
Measurement of Glue at HERA



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

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

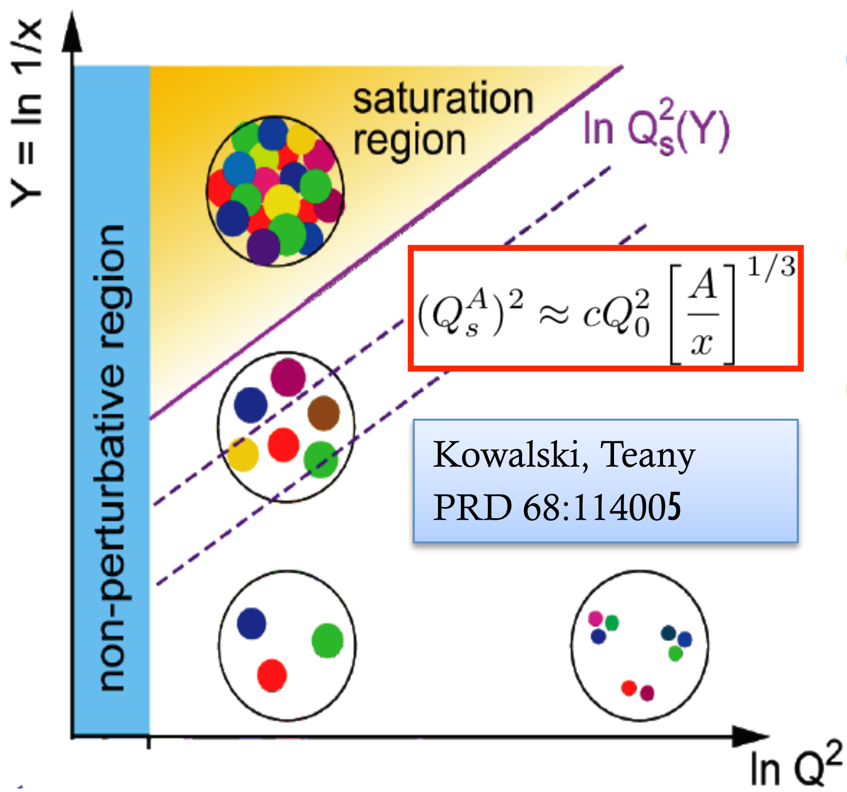
- NLO pQCD analyses: fits with **<u>linear</u>** DGLAP* equations

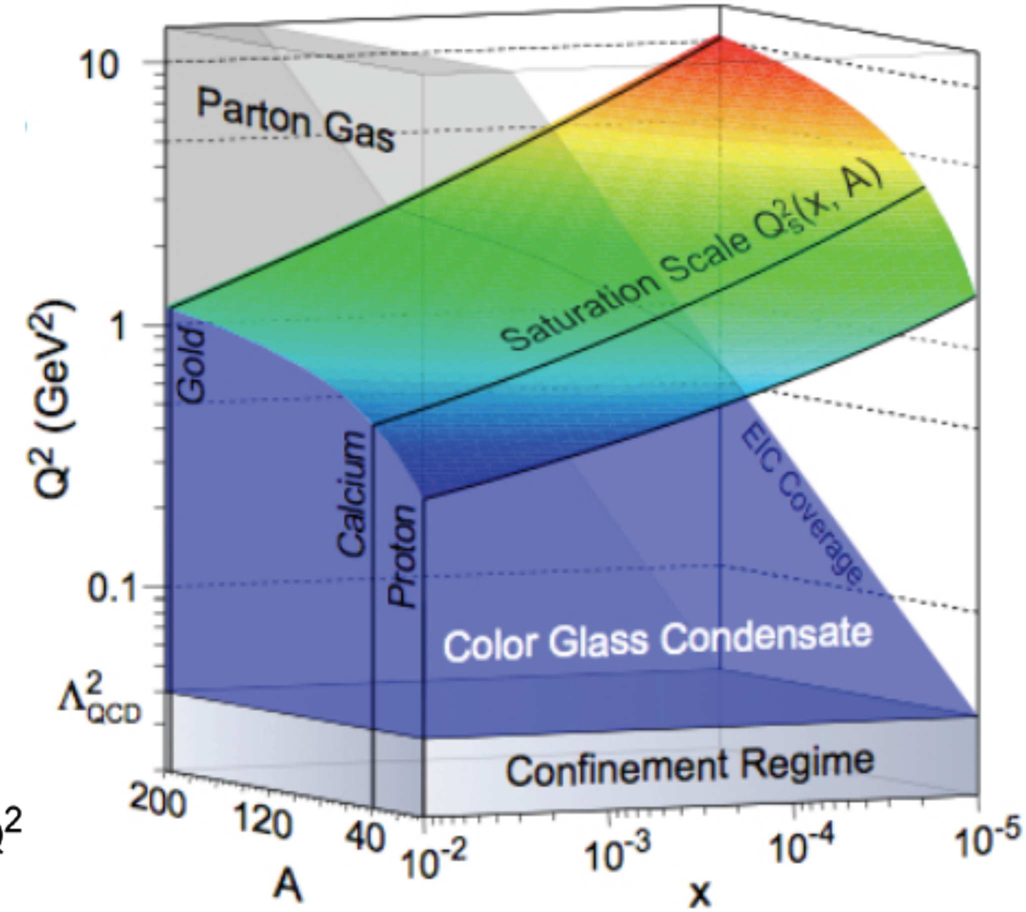


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Gluons at Low x: Color Glass Condensate(?)

McLerran, Venugopalan… See Review: F. Gelis et al., , arXiv:1002.0333)





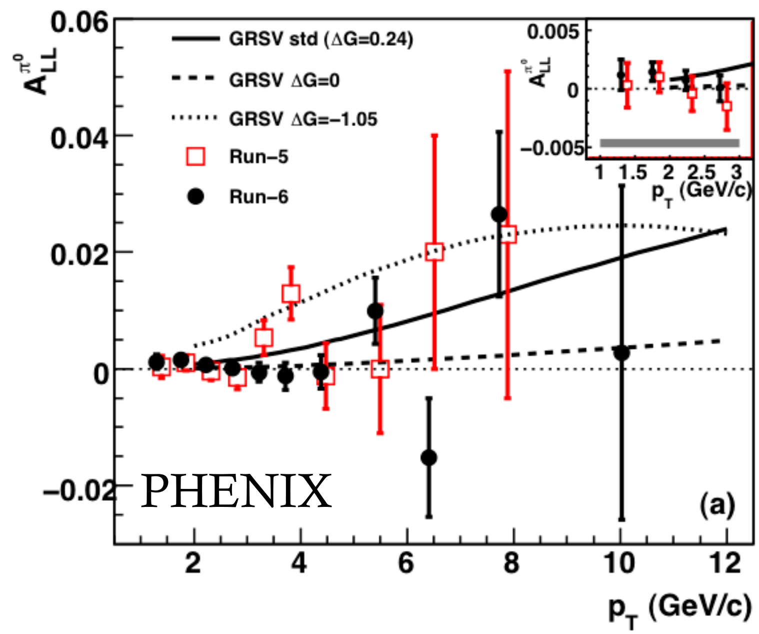
Could be explored cleanly in future with a high energy electron-Nucleus Collider

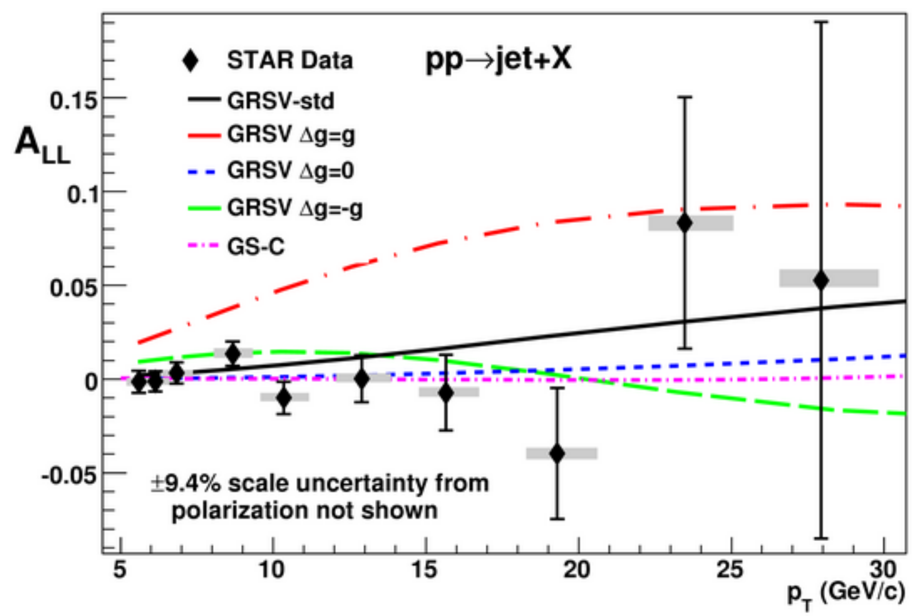
UNDERSTANDING NUCLEON SPIN:
WHAT ROLE DO GLUONS PLAY?

Status of "Nucleon Spin ~~Crisis~~ Puzzle"

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

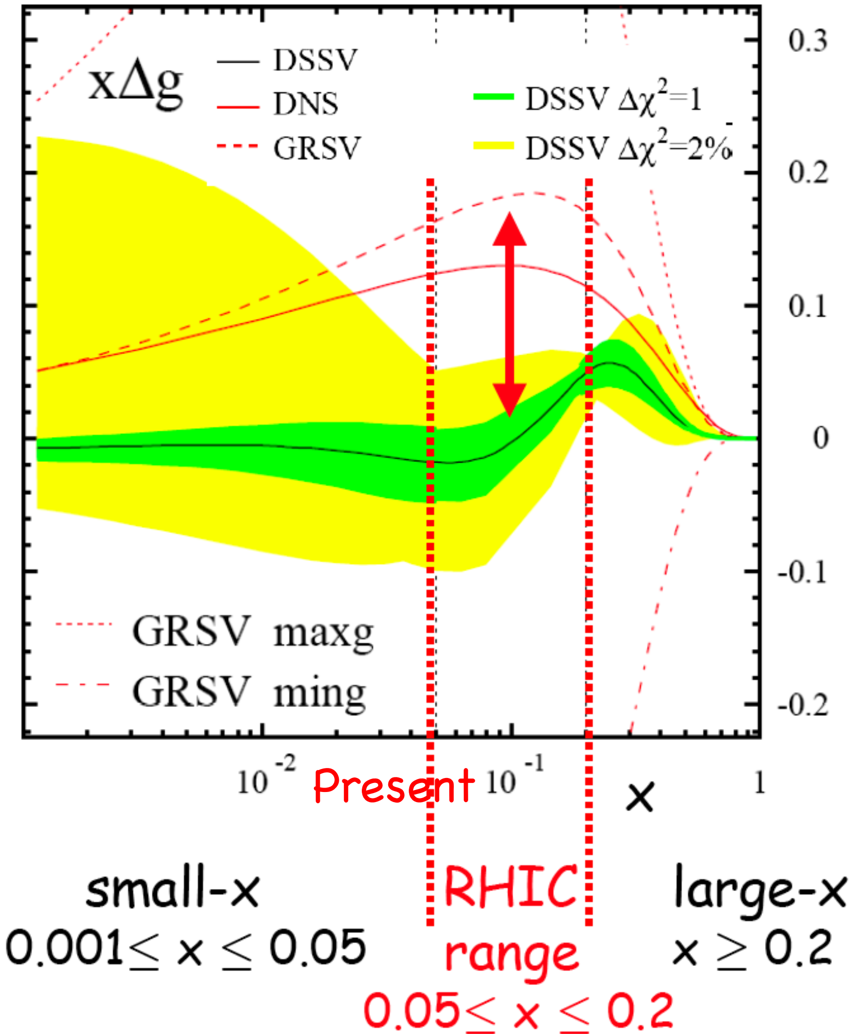
- We know how to determine $\Delta\Sigma$ and Δg precisely: data+pQCD
  - ½ ($\Delta\Sigma$) ~ 0.15 : From fixed target pol. DIS experiments
  - RHIC-Spin: Δg *not large* as anticipated in the 1990s, but *measurements & precision needed at low & high x*





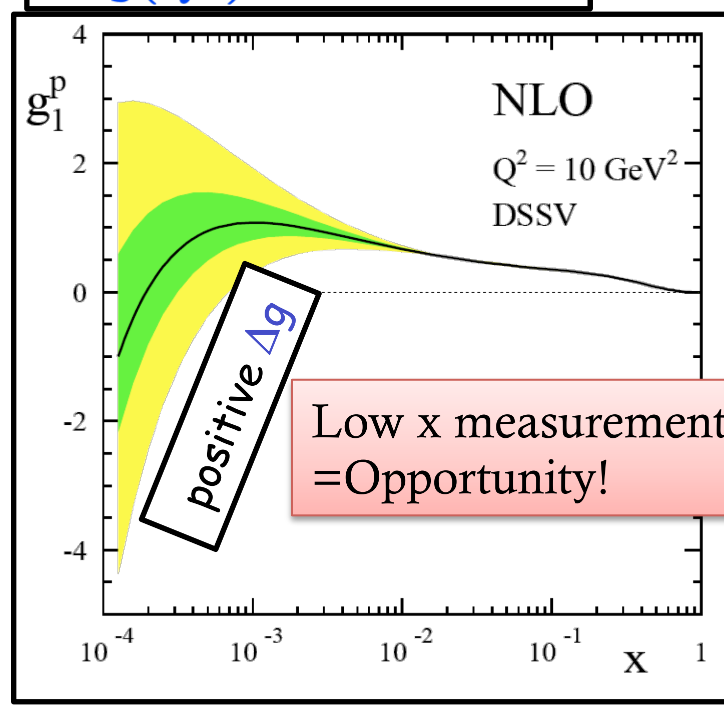
$\Delta g(x)$ @ Q^2=10 GeV^2

de Florian, Sassot, Stratmann & Vogelsang



- **Global analysis: DIS, SIDIS, RHIC-Spin**
- **Uncertainly on ΔG large at low x**

$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$



Low x measurements =Opportunity!

Status of "Nucleon Spin ~~Crisis~~ Puzzle"

$$\frac{1}{2} = \boxed{J_q} + J_g = \boxed{\frac{1}{2}\Delta\Sigma + L_q} + \Delta g + L_g$$

- We know how to measure ΔΣ and ΔG precisely using pQCD
  - ½ (ΔΣ) ~ 0.15 : From fixed target pol. DIS experiments
  - RHIC-Spin: ΔG *not large* as anticipated in the 1990s, but *measurements & precision needed at low & high x*

- Generalized Parton Distributions: H,E,E',H' → Connection to partonic OAM
  - Quark GPDs → J_q: 12GeV@JLab & COMPASS@CERN
  - Gluons @ low x → J_g → will need the future EIC!
- (2+1)D tomographic image of the proton…. Transverse Mom. Distributions
  - **2: x,y position and +1:momentum in z direction**

Towards Full understanding of transverse and longitudinal hadron structure including spin!

Do we really "understand" QCD?

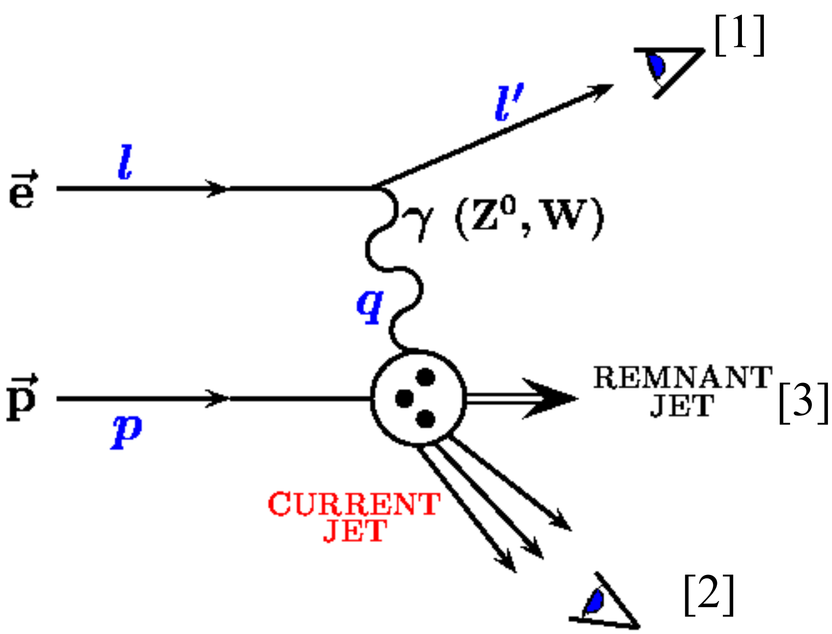
While there is no reason to doubt QCD, our level of understanding of QCD remains extremely unsatisfactory: both at low & high energy

- Can we explain basic properties of hadrons such as mass and spin from the QCD degrees of freedom at low energy?
- What ***are*** the effective degrees of freedom at high energy?
- How do these degrees of freedom interact with each other and with other hard probes?
- What can we learn from them about confinement & universal features of the theory of QCD?

After ~20+ yrs of experimental & theoretical progress, we are only *beginning to understand* the many body dynamics of QCD

The Proposal:

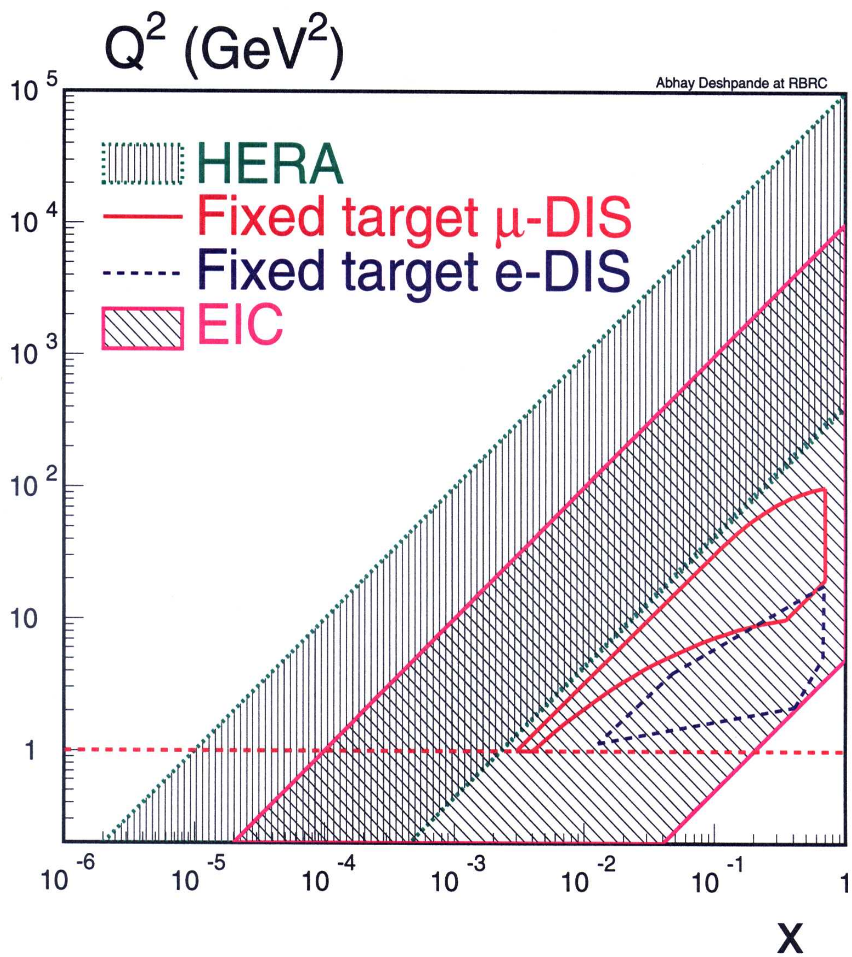
Future DIS experiment at an Electron Ion Collider: A high energy, high luminosity (polarized) *ep* and eA collider and a suitably designed detector



Measurements:
[1] → Inclusive
[1] and [2] **or** [3] →Semi-Inclusiv
[1] and [2] **and** [3] →Exclusive

Inclusive → Exclusive
Low → High Luminosity
Demanding Detector capabilities

EIC : Basic Parameters



- E_e=10 GeV (5-30 GeV variable)
- E_p=250 GeV (50-325 GeV Variable)
- Sqrt(S_{ep}) = 100 (30-200) GeV
- $X_{min} = 10^{-4}$; $Q^2_{max} = 10^4$ GeV
- Beam pol. ~ 70% for e,p,D,^{3}He
- Luminosity $L_{ep} = 10^{33\text{-}34}$ $cm^{-2}s^{-1}$
- Minimum Integrated luminosity:
  - 50 fb^{-1} in 10 yrs (100 x HERA)
  - Possible with 10^{33} $cm^{-2}s^{-1}$
  - Recent projections *much higher*

Nuclei:

- **p->U; E_A=20-100 (140) GeV/N**
- **Sqrt(S_{eA}) = 12-63 (75) GeV**
- **$L_{eA}/N = 10^{33}$ $cm^{-2}s^{-1}$**

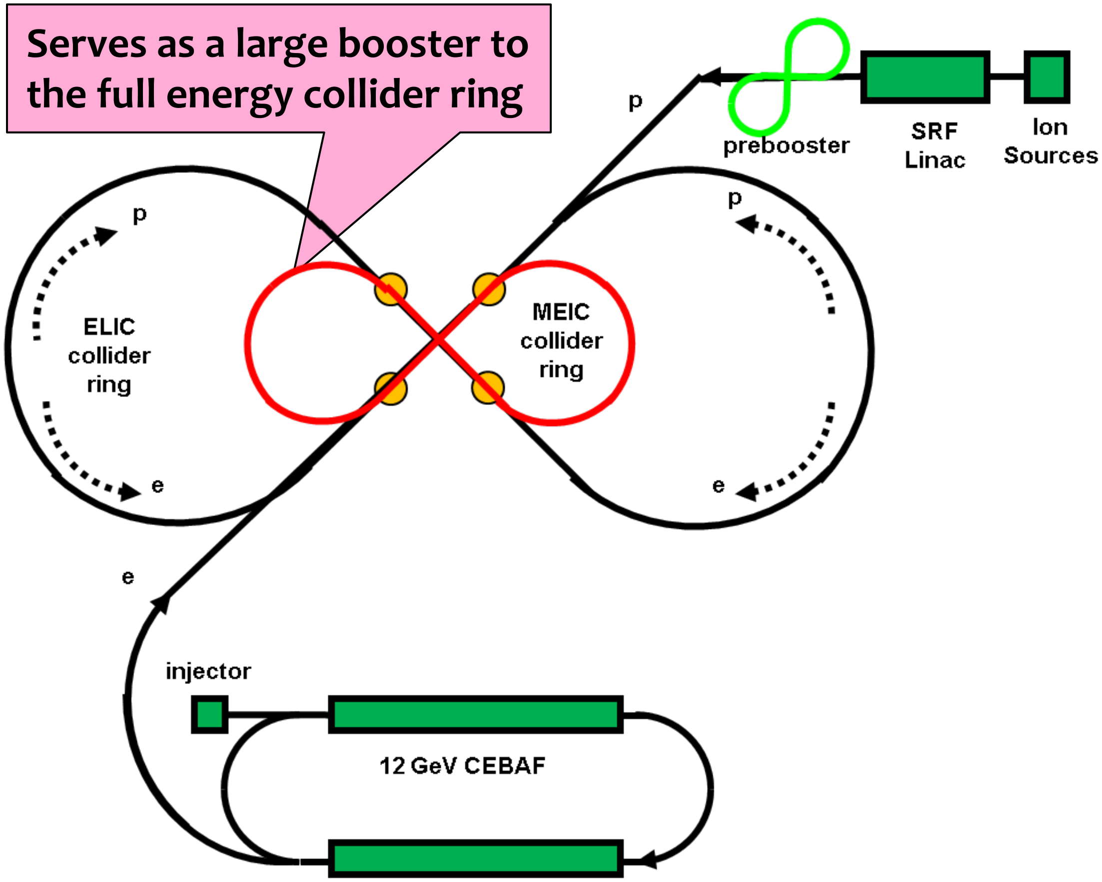
Machine Designs

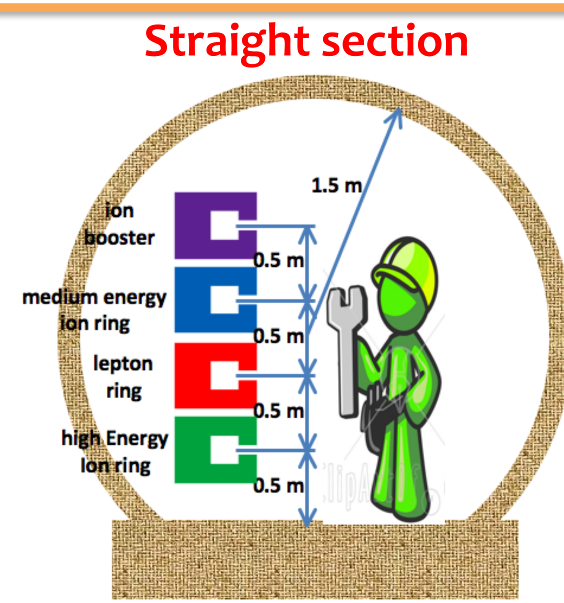
eRHIC at Brookhaven National Laboratory
using the existing RHIC complex

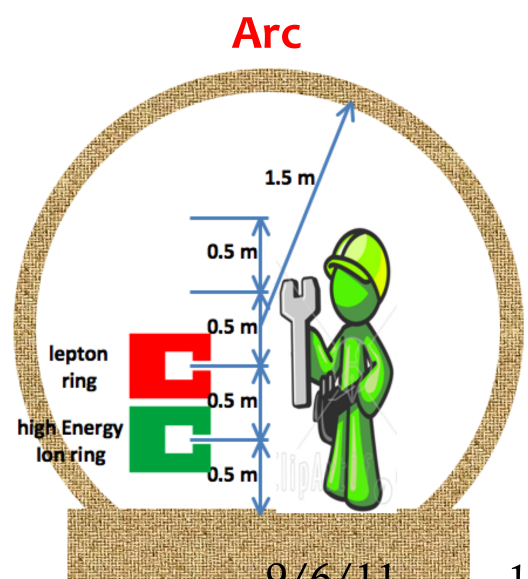
ELIC at Jefferson Laboratory using the
Upgraded 12GeV CEBAF

Both planned to be STAGED

ELIC: High Energy & Staging

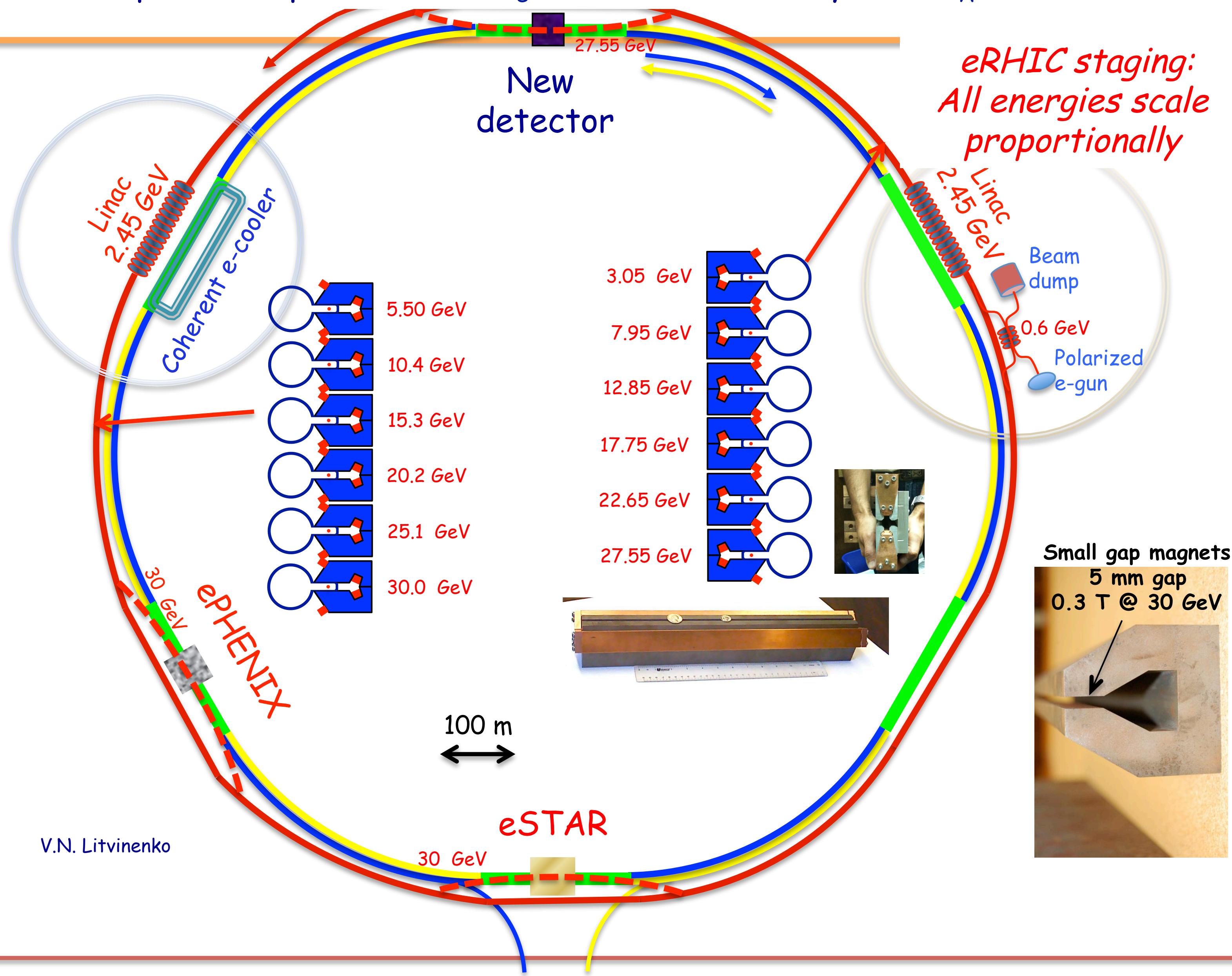






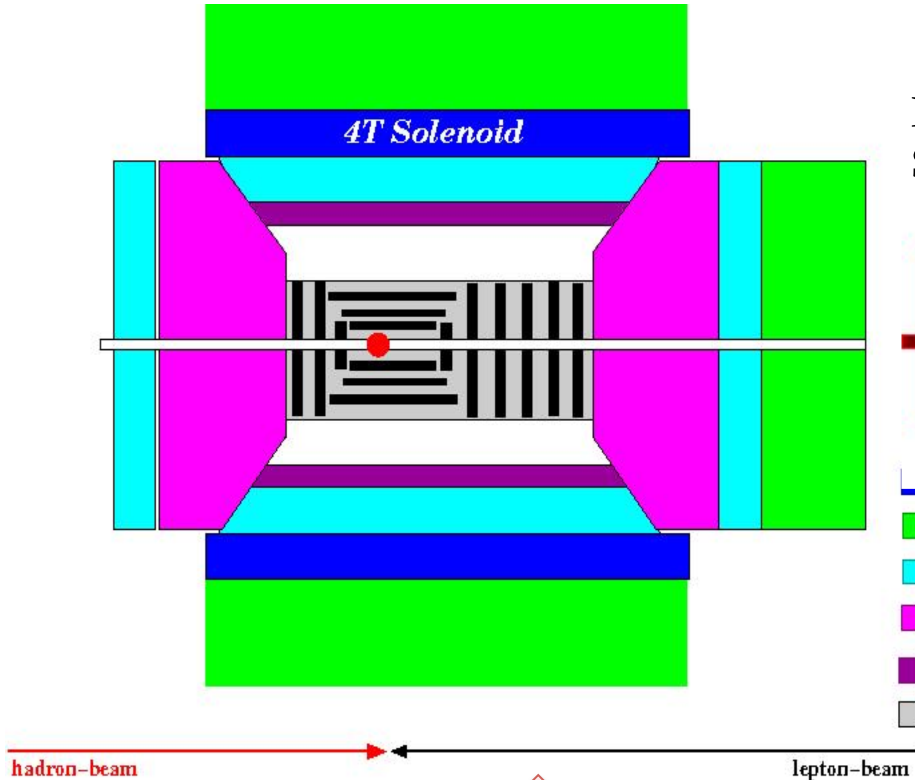
Stage	Max. Energy (GeV/c)		Ring Size (m)	Ring Type		IP #
	p	e		p	e	
Medium	96	11	1000	Cold	Warm	3
High	250	20	2500	Cold	Warm	4

eRHIC: polarized electrons with $E_e \leq 30$ GeV will collide with either polarized protons with $E_e \leq 325$ GeV or heavy ions $E_A \leq 130$ GeV/u

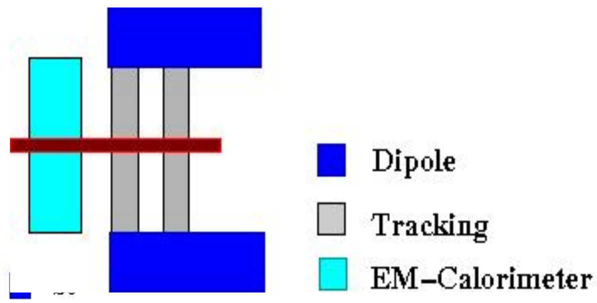


Detector Concepts

Similar!

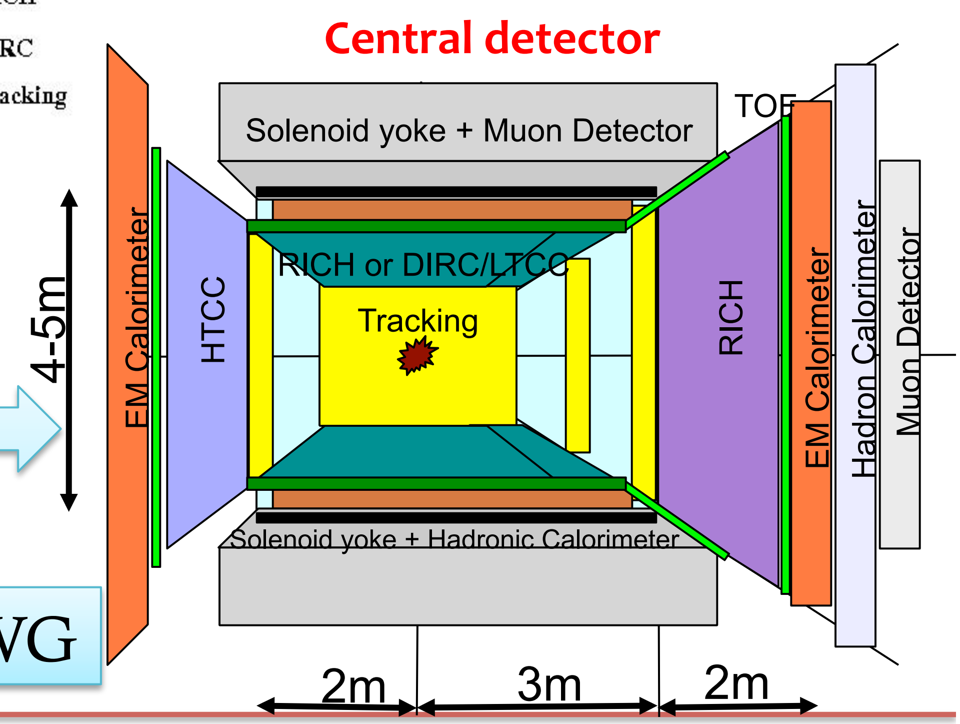


Forward / Backward Spectrometers:



BNL EIC Task Force

(not to scale)



JLab EIC WG

Science of EIC:

Institute of Nuclear Theory (INT) Program at U. of Washington: Sep-Nov 2010

Organizers: D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang

Impact of EIC….

"golden measurements"

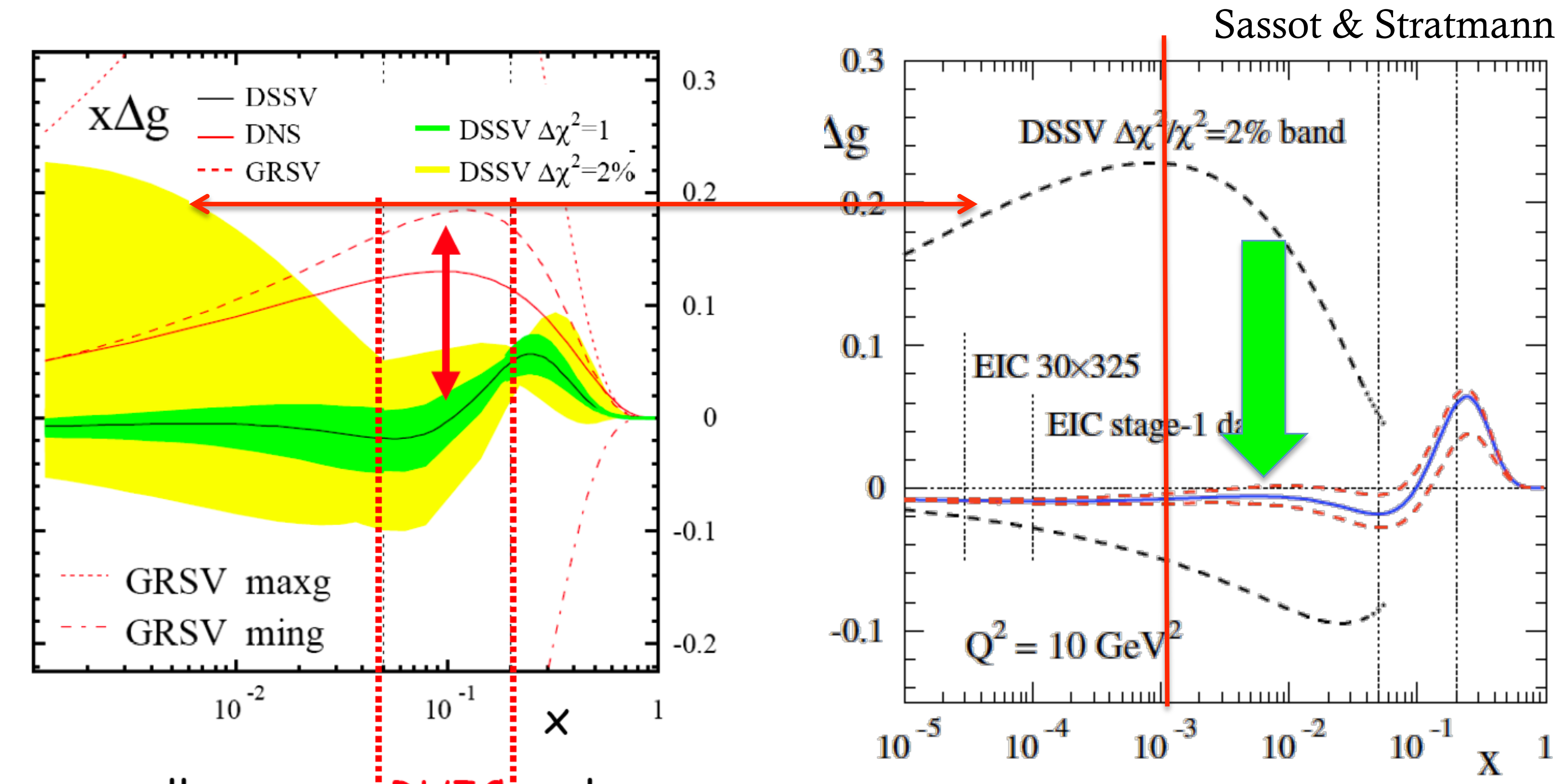
See the INT workshop for details of all studies

http://www.int.washington.edu/PROGRAMS/10-3/

INT Workshop Write-up: arXiv: 0295324 [nucl-th] 5 August 2011

http://skipper.physics.sunysb.edu/~abhay/2011/EICINTReport/

Nucleon Spin: Precision measurement of ΔG



small-x
$0.001 \leq x \leq 0.05$

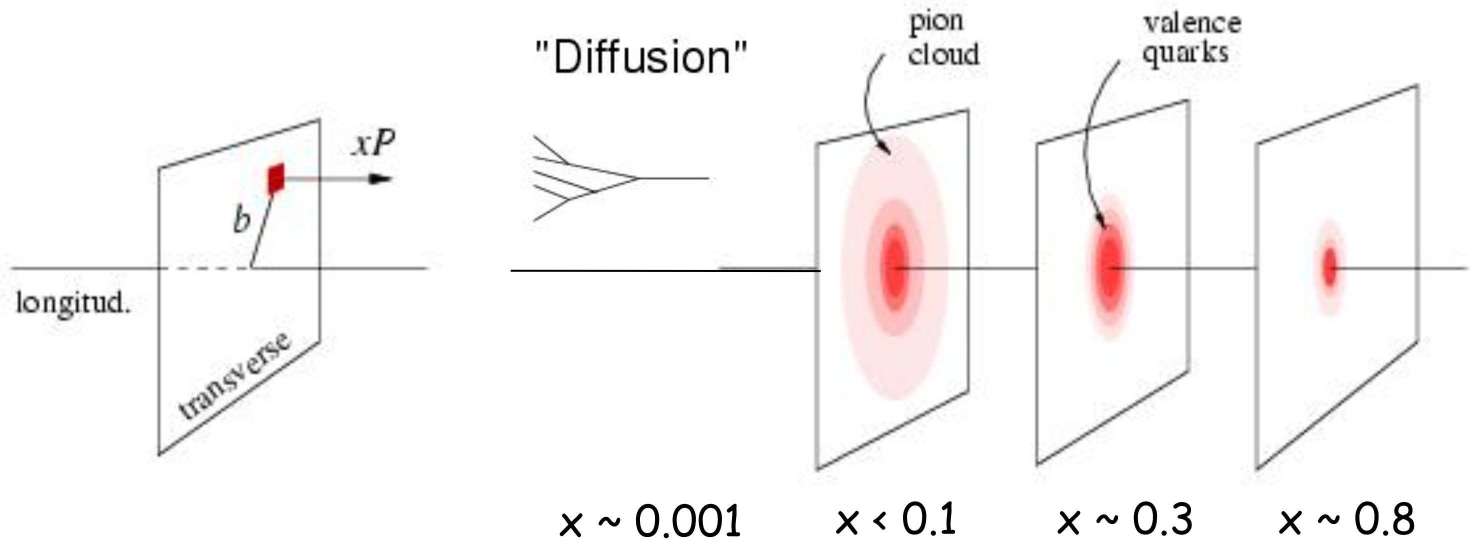
RHIC range
$0.05 \leq x \leq 0.2$

large-x
$x \geq 0.2$

Yellow band (left) reduces to the band shown with **red dashed line** (right)

GPDs and transverse parton imaging

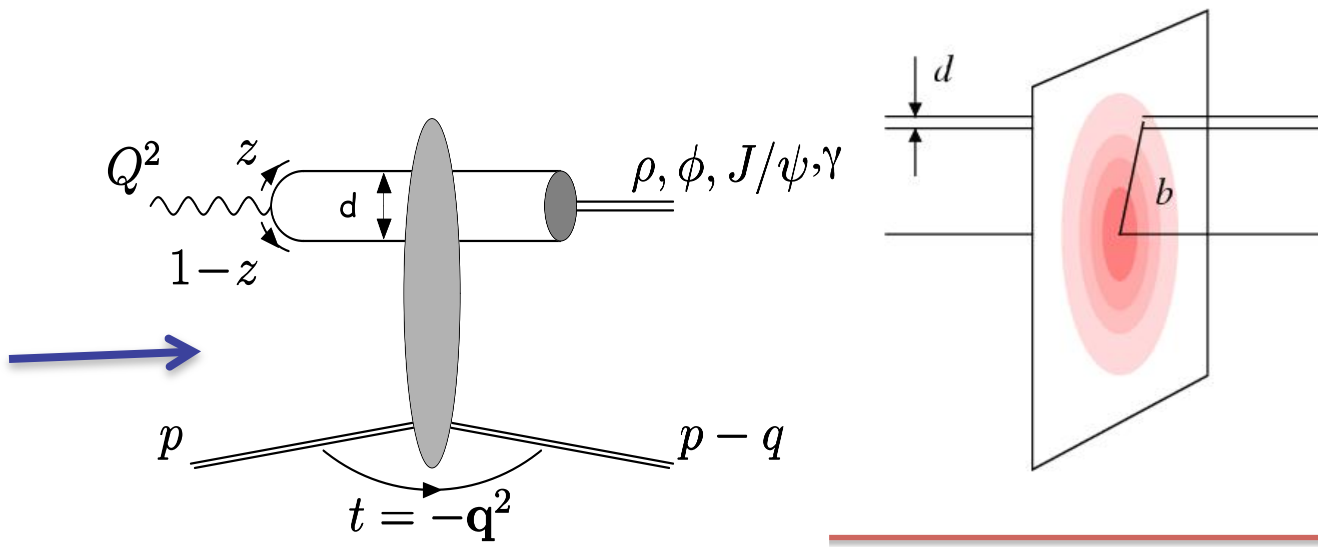
Fourier transform in momentum transfer



EIC:

1) x < 0.1: gluons!

2) ξ ~ 0 → the "take out" and "put back" gluons act coherently.



Some measurements considered so far for the EIC:

- Push the luminosity requirements ~ 10^{34} $cm^{-2}s^{-1}$
  - Recall that although lower in luminosity than fixed target experiments, the collider is at (high) 100-200 GeV in CM Energy
- Push the polarimetry and beam quality requirements to the extreme:
  - (dPol/Pol) ~ 1%
  - Ultra low beam divergence for DVCS/Diffraction…

Why not consider using this machine for precision EW-Physics measurements?

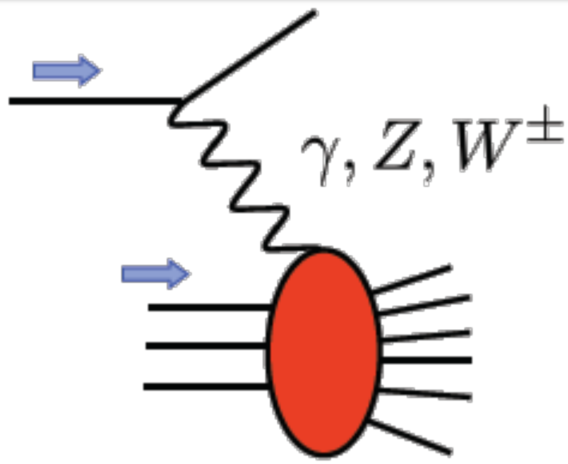
Electroweak & beyond….(?)

BNL LDRD: Deshpande, Marciano, Kumar & Vogelsang

- High energy collisions of polarized electrons and protons and nuclei afford a unique opportunity to study electro-weak deep inelastic scattering
  - **Electroweak structure functions (including spin)**
  - Significant contributions from W and Z bosons which have different couplings with ***quarks and anti-quarks***
- **Parity violating DIS**: a probe of beyond TeV scale physics
  - Measurements at higher Q^2 than the PV DIS 12 GeV at Jlab
  - Precision measurement of $\mathrm{Sin}^2\Theta_W$
- **New window for physics beyond SM?**
  - Lepton flavor violation search $e^- + p \rightarrow \tau^- + X$

arXiv: 006.5063v1 [hep-ph]
M. Gonderinger et al.

main objective / why interesting



at high enough Q^2 electroweak probes become relevant

- **neutral currents** (γ, Z exchange, γZ interference)
- **charged currents** (W exchange)

parameterized by new structure functions which probe combinations of PDFs different from photon exchange
--> **flavor decomposition without SIDIS, e-w couplings**

hadron-spin averaged case: studied to some extent at HERA (limited statistics)

hadron-spin difference:

contains e-w propagators and couplings

Wray; Derman; Weber, MS, Vogelsang; Anselmino, Gambino, Kalinowski; Blumlein, Kochelev; Forte, Mangano, Ridolfi; ...

$$\frac{d\Delta\sigma^{e^{\mp},i}}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\left[\pm y(2-y)x\hat{g}_1^i - (1-y)\hat{g}_4^i - y^2 x\hat{g}_5^i\right] \quad \mathrm{i = NC, CC}$$

unexplored so far – unique opportunity for an EIC

what can be learned

in the parton model (for simplicity)

NC:

$$\left[g_1^{\gamma}, g_1^{\gamma Z}, g_1^{Z}\right] = \frac{1}{2}\sum_q \left[e_q^2, 2e_q g_V^q, (g_V^q)^2 + (g_A^q)^2\right](\Delta q + \Delta\bar{q})$$

$$\left[g_5^{\gamma}, g_5^{\gamma Z}, g_5^{Z}\right] = \frac{1}{2}\sum_q \left[0, e_q g_A^q, g_V^q g_A^q\right](\Delta q - \Delta\bar{q})$$

CC:

$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c)$$
$$g_1^{W^+} = (\Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c})$$
$$g_5^{W^+} = (\Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c})$$
$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c)$$

requires a positron beam

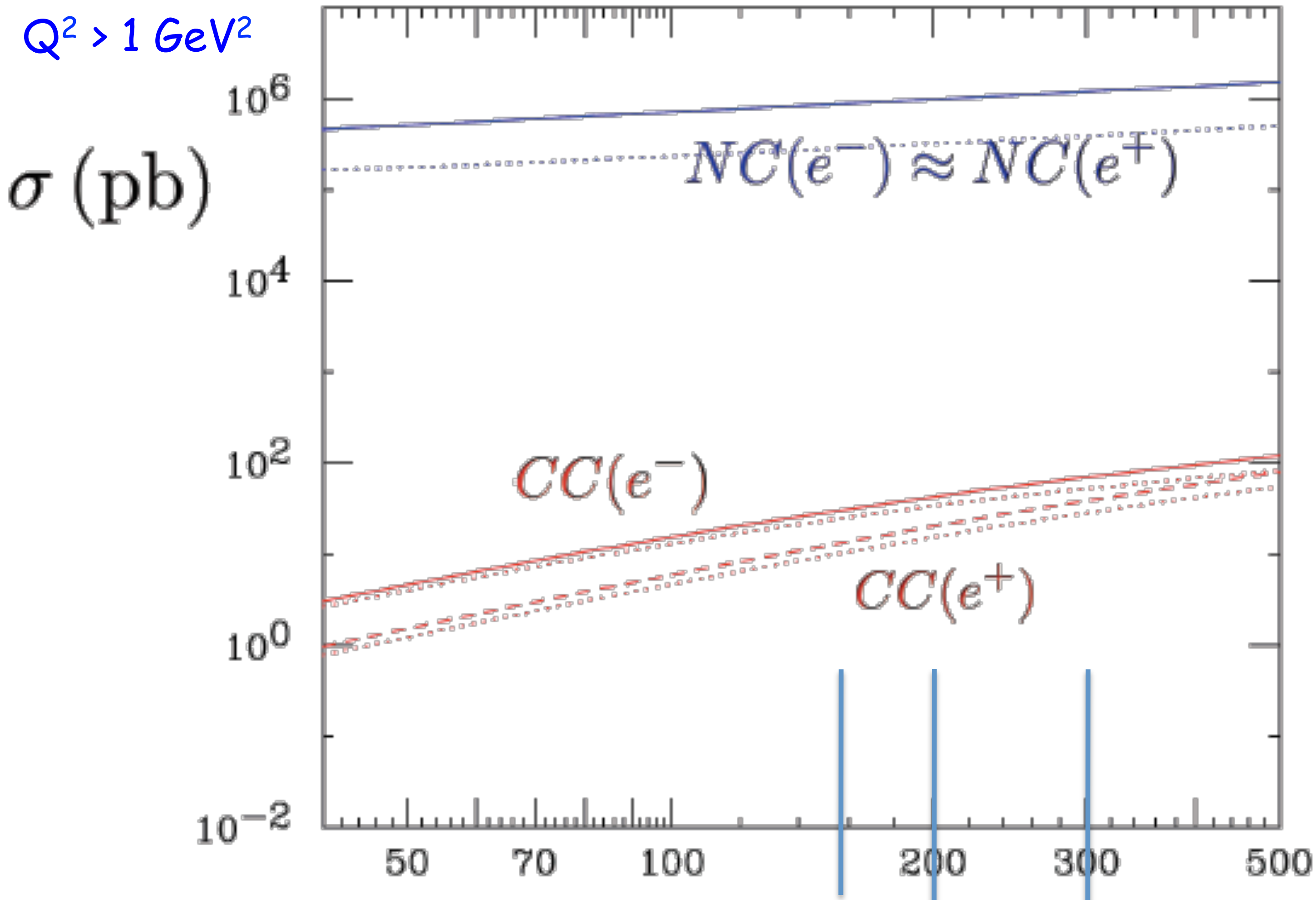
- NLO QCD corrections all available
- can be easily put into global QCD analysis
- enough combinations for a flavor separation (no fragmentation)

de Florian, Sassot; MS, Vogelsang, Weber;
van Neerven, Zijlstra; Moch, Vermaseren, Vogt

feasibility – 1st exploratory studies

Ringer, Vogelsang

$Q^2 > 1\ GeV^2$



no y cut
y > 0.1

20×250
30×325
HERA

2nd indep. study: Kumar, Riordan, Deshpande, Taneja, Paschke

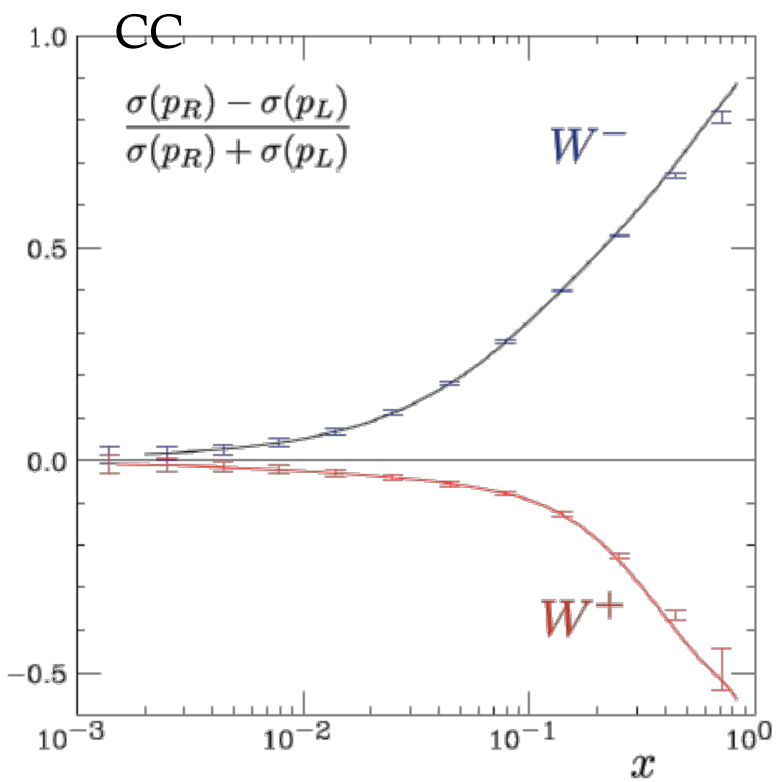
Charged & Neutral Currents…

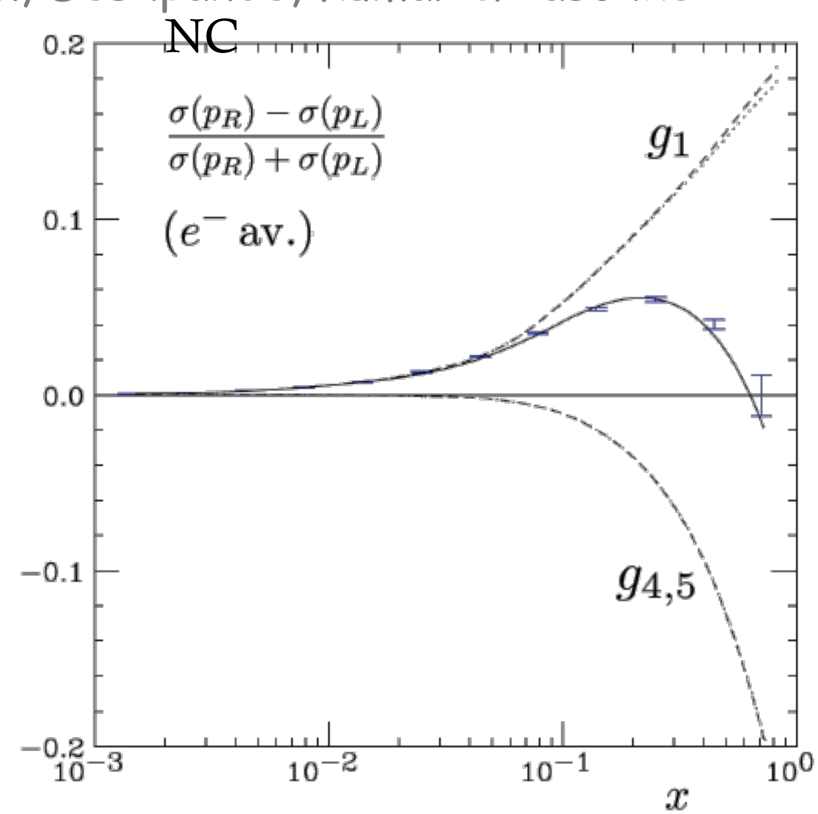
20 × 250 GeV, $Q^2 > 1$ GeV^2, $0.1 < y < 0.9$, **10 fb^{-1}**, DSSV PDFs

(Could begin the program with 5x250 GeV)

Two studies: (1) Ringer & Vogelsang (these figures),

(2) Taneja, Riordin, Deshpande, Kumar & Paschke



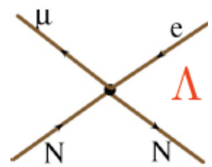


Experimental Studies of LFV

- Lepton flavor violation searches have predominantly been in 1st, and 2nd generation leptons (μ,e) → "LFV(1,2)"

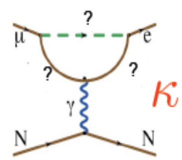
$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\sum \bar{q}_L\gamma^\mu q_L\right)$$

- SINDRUM (μ→3e)
- SINDRUM II (μ→e)

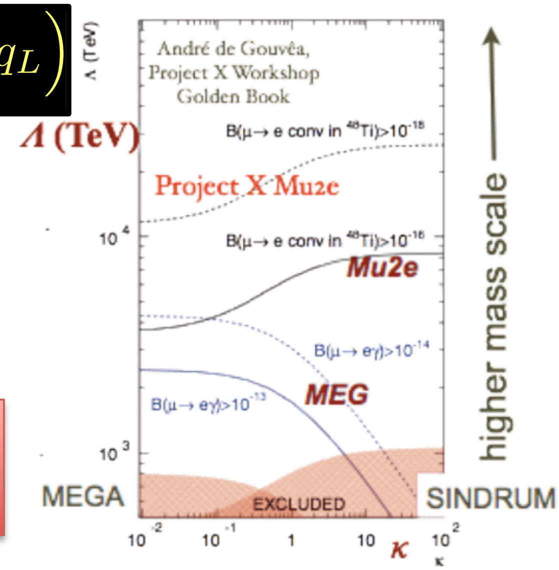


Contact Interactions

- MEGA (μ→eγ)



SUSY & heavy neutrinos



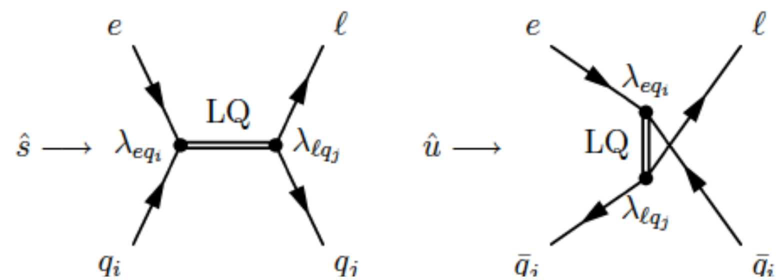
Project X

- LFV(1,3) limits few orders of magnitudes weaker than LVF(1,2)
  - BaBar (τ→eγ)
  - BELLE (τ→3e)
- Future measurements at Mu2e@FNAL, MEG@PSI also focus on LFV(1,2)

Opportunity for EIC

- Limits on **LFV(1,3)** experimental searches are significantly worse than those for LFV(1,2)
- Especially if there are BSM models which specifically allow and enhance LFV(1,3) over LFV(1,2)
  - Minimal Super-symmetric Seesaw model
    - J. Ellis et al. Phys. Rev. D66 115013 (2002)
  - SU(5) GUT with leptoquarks
    - I. Dorsner et al., Nucl. Phys. B723 53 (2005)
    - P. Fileviez Perez et al., Nucl. Phys. B819 139 (2009)
- M. Gonderinger & M.Ramsey Musolf, JHEP 1011 (045) (2010); arXive: 1006.5063 [hep-ph]
- Clearly there is an opportunity for EIC: if a search can be effectively launched with it's planned (high luminosity) and large large acceptance detector suitable for the GPD/Exclusive physics program

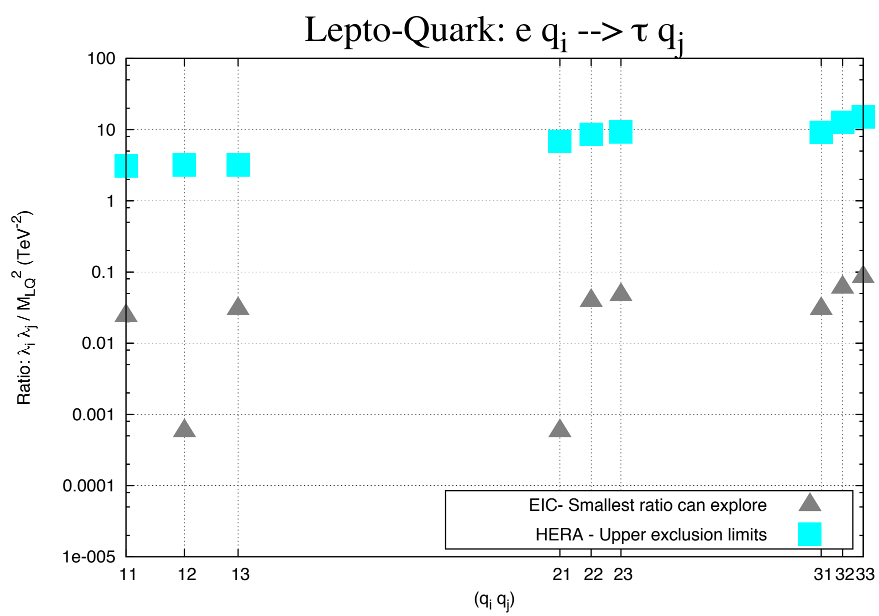
LFV phenomenology



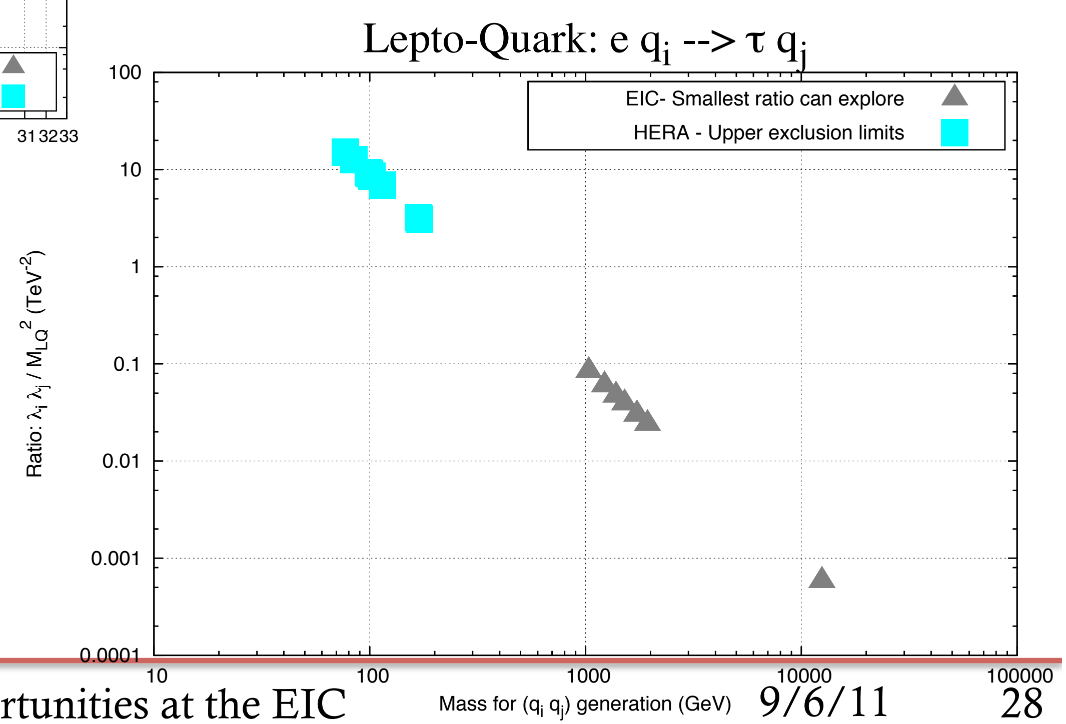
$$\frac{d^2\sigma_s}{dxdy} = \underbrace{\frac{1}{32\pi\hat{s}}}_{\text{phase space}} \cdot \underbrace{\frac{\lambda_{eq}^2\lambda_{\ell q}^2\hat{s}^2}{(\hat{s}^2 - m_{\mathrm{LQ}}^2)^2 + m_{\mathrm{LQ}}^2\Gamma_{\mathrm{LQ}}^2}}_{\text{Breit-Wigner LQ propagator term}} \cdot \underbrace{q_i(x,\hat{s})}_{\text{parton density}} \times \begin{cases} \frac{1}{2} & \text{scalar LQ} \\ 2(1-y)^2 & \text{vector LQ} \end{cases}$$

- LPQ event topologies studied with:
  - LFV MC generator: LQGENEP (L. Bellagamba, Comp. Phys. Comm. 141, 83 (2001)
  - LQ generator for e-p processes using BRW effective model
- To increase efficiency of calculations: BW-LO propagator replaced with a constant.
  - m_{LQ} = 200 GeV, λ = 0.3 (for example one particular LQ…)
  - **Then go over various values of M_{LQ} i.e. ratios: z = $\lambda i \lambda j / M_{LQ}^2$**

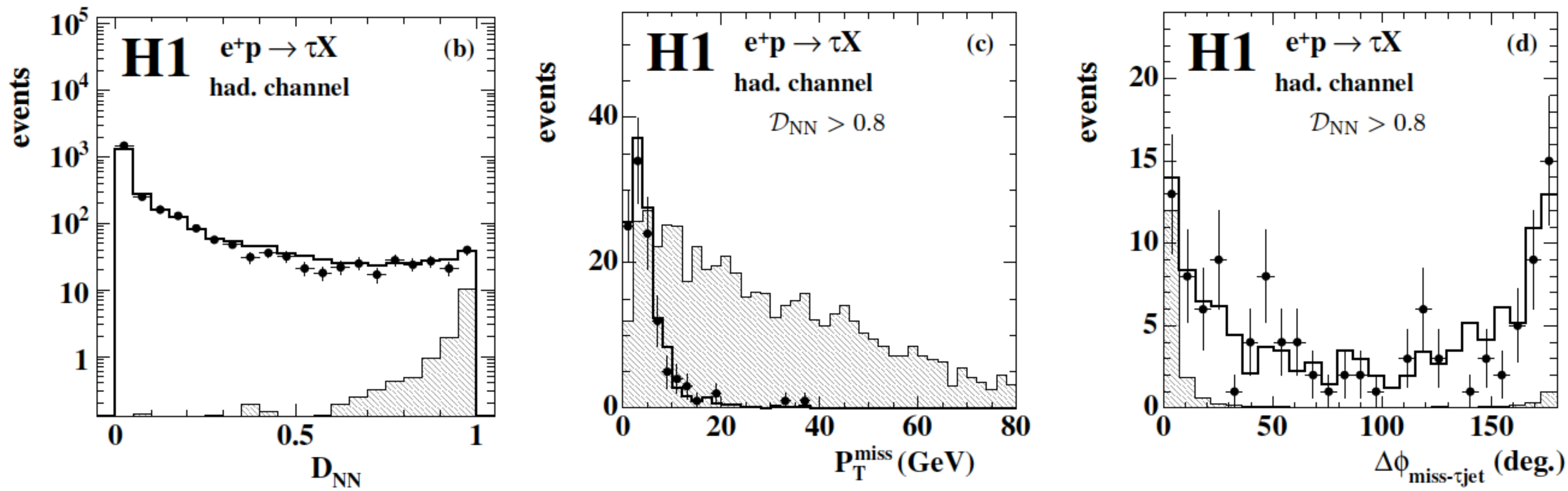
How does EIC compare with HERA?



Private communications: M. Gonderinger



Tau Jet identifiers and selections



- Reconstructed D_{NN} variable for Tau into hadronic channel
- $P_{T(miss)}$ distribution
- $\Delta\phi_{miss\text{-}TauJet}$

MC generator level studies…. So far

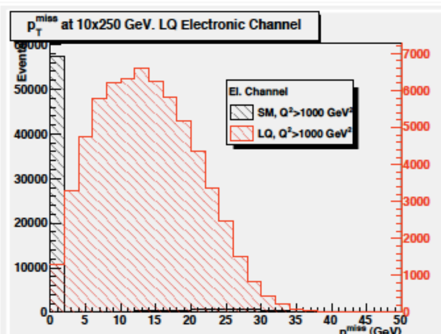
- **Standard model backgrounds generated**: Neutral & Charged current DIS, photo-production, lepton-pair production & W production…. *Compare event topologies* with the LQ events
- τ has a clean signature: repeated similar set of analyses as performed for such analyses in H1 and ZEUS analyses at HERA: **Established that: Clean identification of Tau is certainly possible both for**
  - Leptonic Decays of τ
  - Hadronic Decays: Narrow "pencil" like jets with 1-3 pions
- Very clear differences in topologies of SM and LQ events established. Realistic (GEANT) detector simulations now underway.

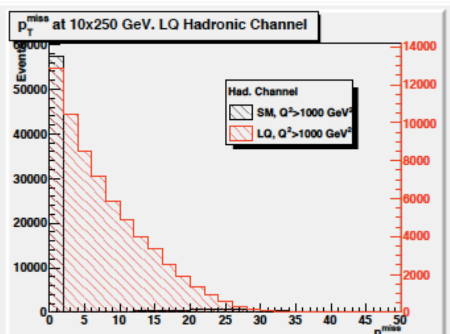
SM vs. LPQ

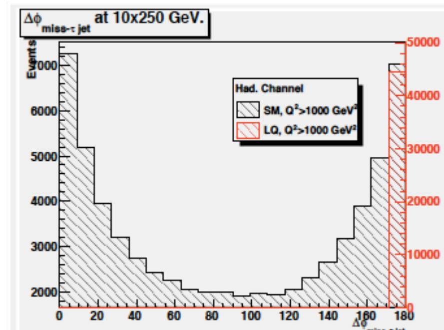
$$p_T^{miss} = \sqrt{(\sum P_{x,i})^2 + (\sum P_{y,i})^2}$$

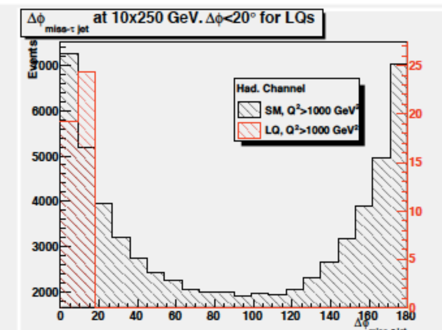
Acoplanarity: $\Delta\phi_{miss}\text{-}\tau_{jet}$

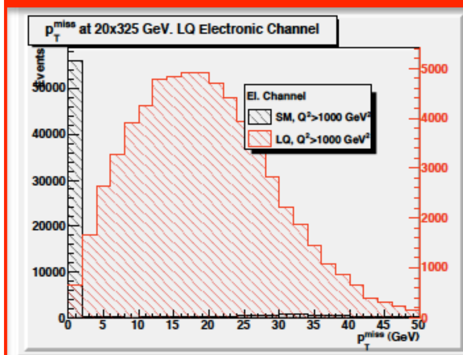
10 x 250

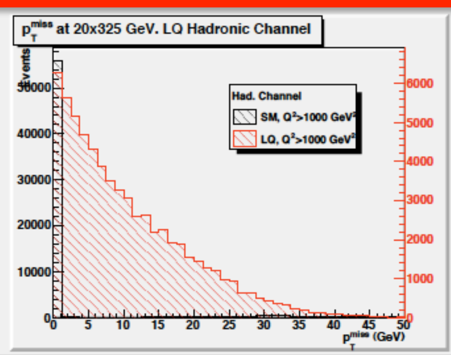


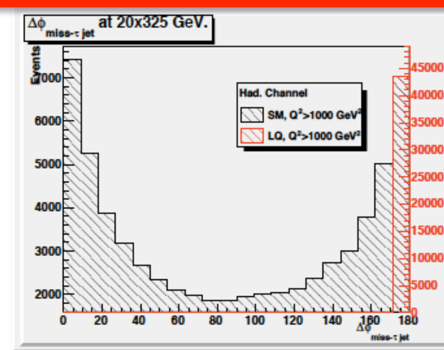


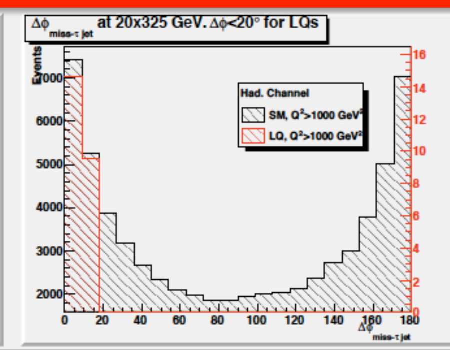






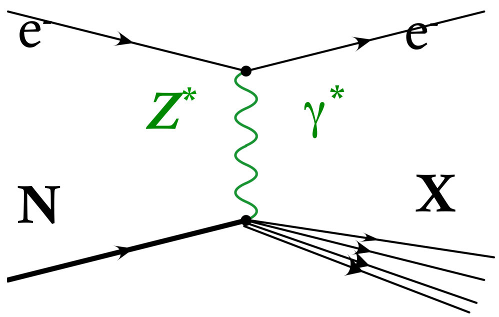






20 x 325

A_{PV} in Deep Inelastic Scattering



A_{PV} in e-N DIS:

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

For a ^{2}H target, assuming charge symmetry, structure functions largely cancel in the ratio

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots$$

$$b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

$$C_{1u} = (1 - 8\sin^2\theta_W/3)/2 \sim 0.20 \text{ Hadronic}$$
$$C_{1d} = (1 - 4\sin^2\theta_W/3)/2 \sim -0.32 \text{ Hadronic}$$
$$C_{2u} = (1 - 4\sin^2\theta_W)/2 \sim 0.04 \text{ Leptonc}$$
$$C_{2d} = -(1 - 4\sin^2\theta_W)/2 \sim -0.04 \text{ Leptonc}$$

C_{2q} sensitive to RC & New Physics

Measure A_{PV} (C_{2q}) to better than 0.5% (1-2%) ?

Prospects: near and far future….

Jefferson Laboratory:

- 6 GeV DIS eD→ eX proceeding
- 12 GeV DIS eD in future (after 2015)
  - Measure C_{2q}'s New Physics, Charge Symmetry violation
  - Effective luminosity (fixed target) 10^{38} $cm^{-2}sec^{-1}$

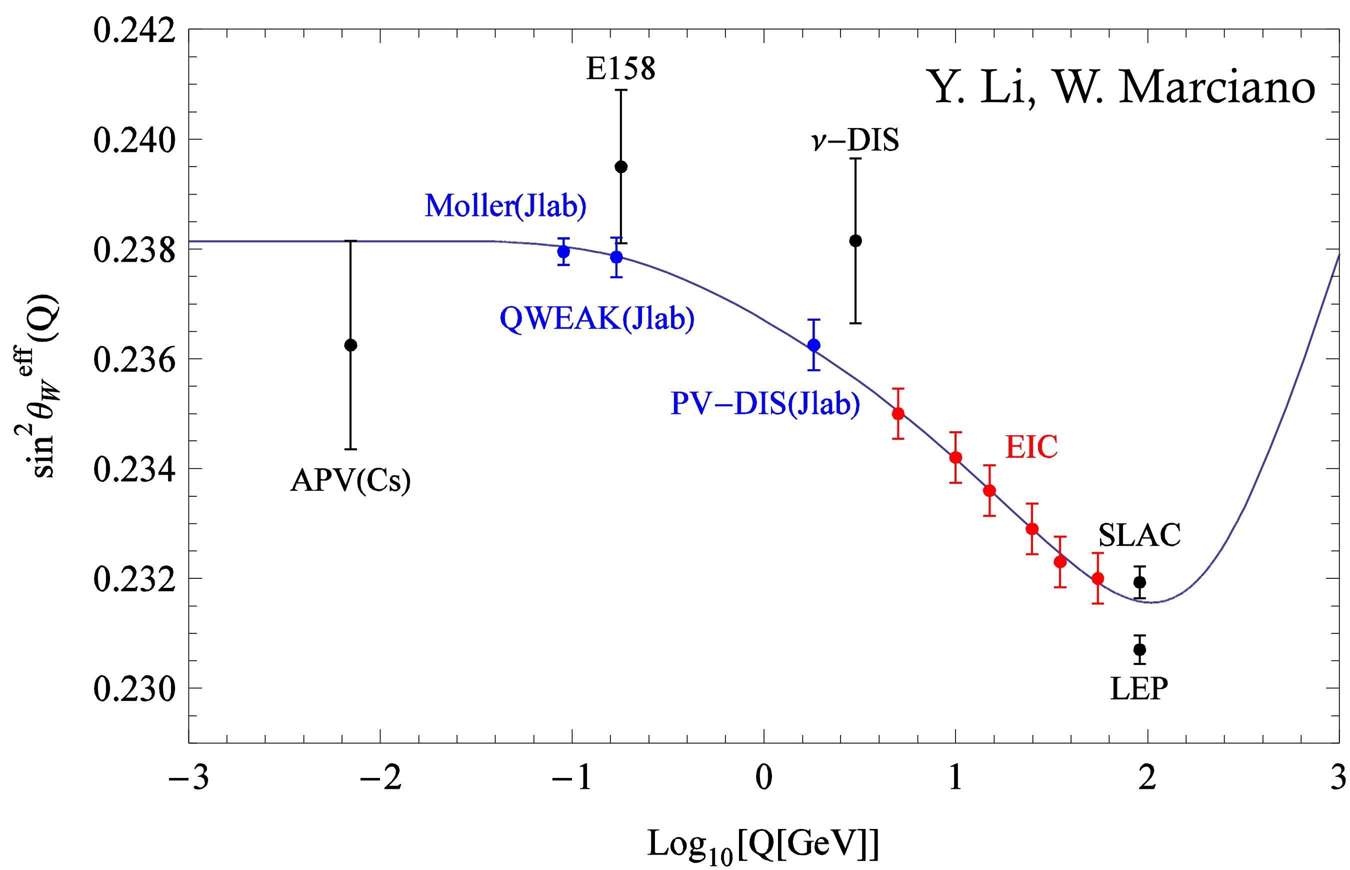
Future ep, eD collider:

- Asymmetry: FOM ~ A^2N; **$A \sim Q^2$ & $N \sim 1/Q^2$,** Acceptance
- **Collider: higher Q^2 but luminosity(?)**
- **Need accumulate > 100 fb^{-1} (possible with 10^{34} $cm^{-2}sec^{-1}$)**

Y. Li & W. Marciano studied this at Sqrt(s) = 140 GeV (ep or eD)

$Sin^2\Theta_W$ with the EIC

- Deviation from the "curve" may be hints of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, E_6/Z' based extensions of the SM



EIC Project status and plans

- A "collaboration" of highly motivated people/groups intends to take this project to realization:
  - EIC Collaboration **Web Page:** **http://web.mit.edu/eicc/**
  - 100+ dedicated physicists from 20+ institutes
  - Details of many recent studies: Recent Workshop @ INT at U. of Washington**:** **http://www.int.washington.edu/PROGRAMS/10-3/**
  - **INT Workshop Write-up: arXiv: 0295324 [nucl-th] 5 August**
  - Working groups/Task Forces at BNL and at Jefferson Laboratory
  - Steering Committee (coordinators: A. Deshpande & R. Milner)

- International Advisory Committee formed by the BNL & Jlab Management to steer this project to realization: *W. Henning (ANL, Chair), J. Bartels (DESY),A. Caldwell (MPI, Munich) A. De Roeck (CERN), R. Gerig (ANL), D. Hetrzog (U of W), X. Ji (Maryland), R. Klanner (Hamburg), A. Mueller (Columbia), S. Nagaitsev (FNAL), N. Saito (J-PARC), Robert Tribble (Texas A&M), U. Wienands (SLAC), V. Shiltev (FNAL)*

A White Paper for NSAC Long Range Plan 2012/2013 to be produced by early 2012

Co-Chairs: J. Qiu, Z.E. Meziani & A. Deshpande

Senior Advisors: A. Mueller, R. Holt

Writing Group: E; Aschenauer, M. Diehl, H. Gao, A. Hutton, T. Horn, K. Kumar, Y. Kovchegov, M. Ramsey-Musolf, T. Roser, F. Sabatie, E. Sichtermann, T. Ullrich, W. Vogelsang, F. Yuan

Summary

Science Case for EIC: → "Understand QCD"

"Precision study of the role of gluons & sea quarks in QCD"

Many body dynamics in QCD is an essential focus of this study

Exciting new possibilities are also emergent on the EW and BSM front, if at highest levels of EIC luminosities and energies and accuracy of polarization can be achieved.

The Collaboration & the BNL+Jlab managements are moving ***(together)*** towards realization: ***NSAC approval 2013 → Next Milestone***

- Machine R&D, detector discussions, simulation studies towards making the final case including detailed detector design and cost considerations

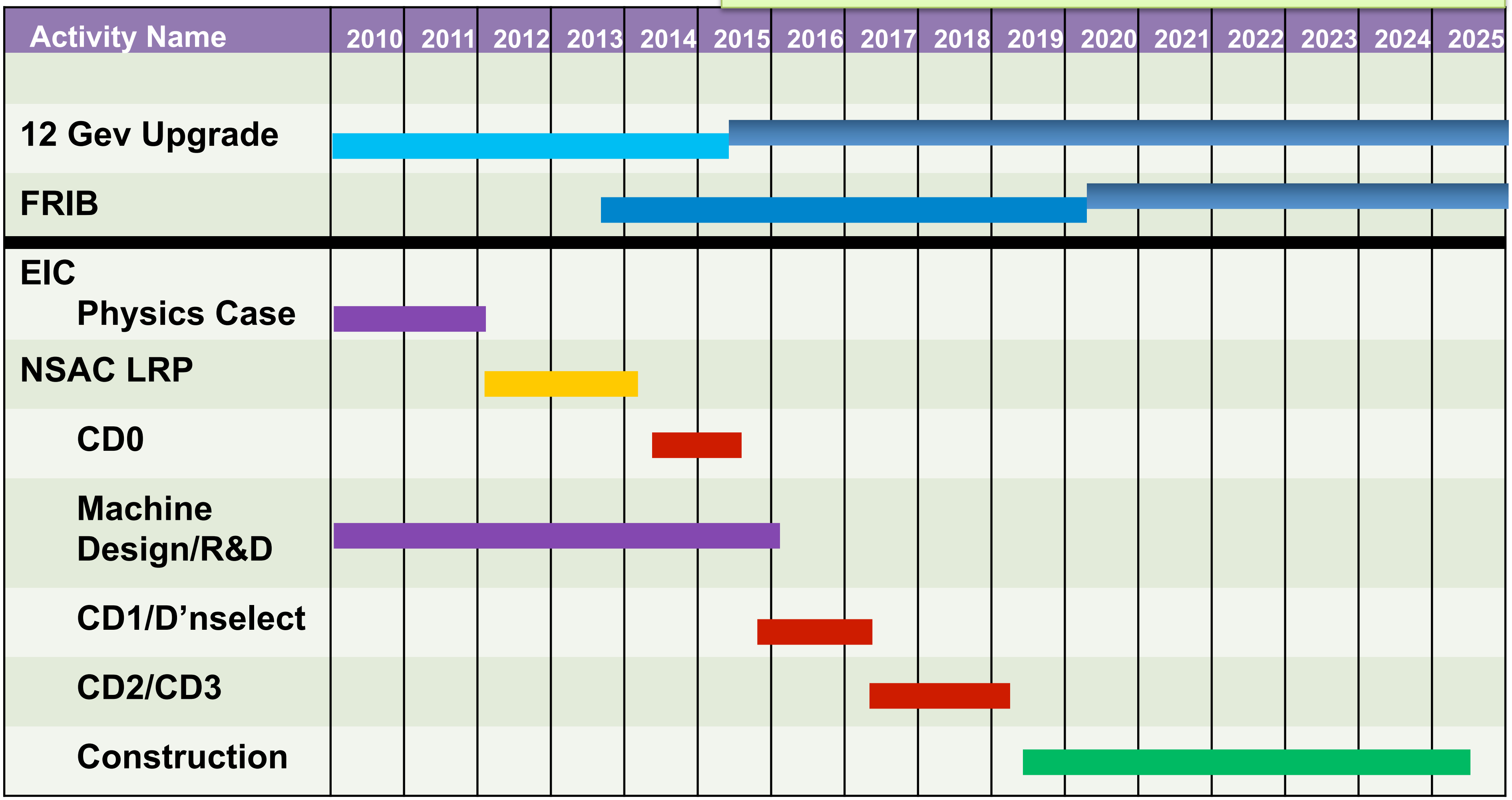
INVITATION: Ample opportunities to ***get involved and influence*** the design of this machine according to ***your own physics interests*** and participate in this exciting quest.

Thank You!

H. Montgomery, Jeff. Laboratory Director

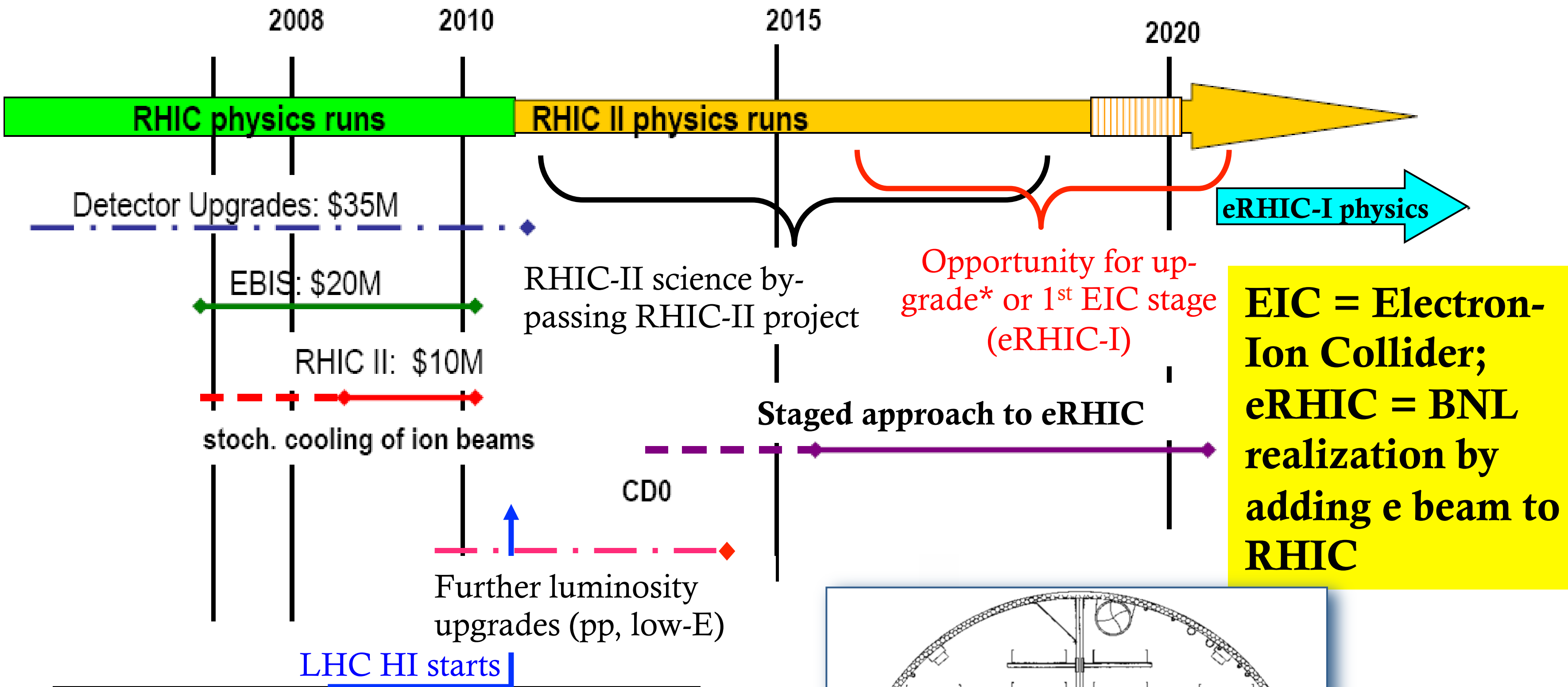
EIC at JLab Realization Imagined

Time line at BNL not ***too*** different



S. Vigdor, BNL Associate Director

A Long Term (Evolving) Strategic View for RHIC



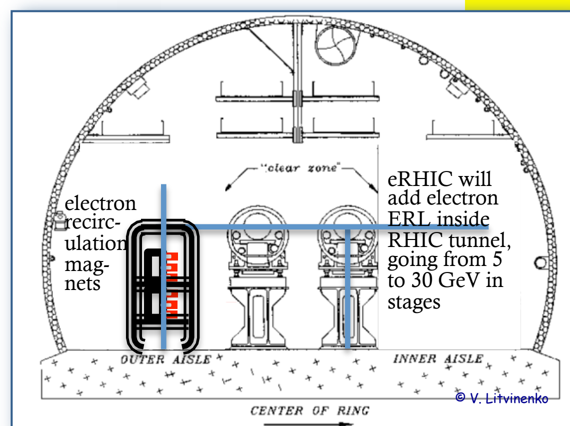
Legend:

- - - - - - - - *R&D*

◆———◆ *Construction*

— · — · — · → *Multiple small projects*

CD0: DOE Critical Decision, mission need

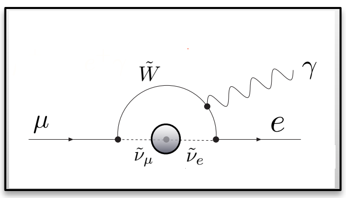


* New PHENIX and STAR Decadal Plans provide options for this period.

Why search for Lepton Flavor Violation?

- Every conservation law in the SM of Physics is anticipated to have a "symmetry" associated with it
- We have no knowledge of a symmetry that asserts Lepton Flavor Conservation, and yet its violation has not been seen

Although neutrino oscillation implies charged lepton flavor violation within the SM, observation of processes such as μ→eγ, very challenging due to smallness of neutrino mass



$$\mathrm{BR}(\mu \to \mathrm{e}\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$

Many models of physics beyond the SM predict rates of charged LFV larger than those within the SM and within reach of existing and near-future experiments.

LVF is hence considered an important probe of physics beyond the Standard model