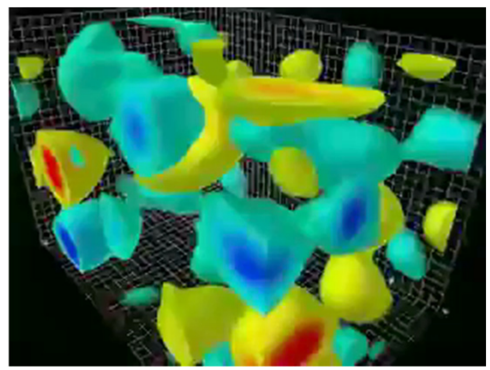
Accelerators in Nuclear Physics:

The Science of Electron Ion Colliders

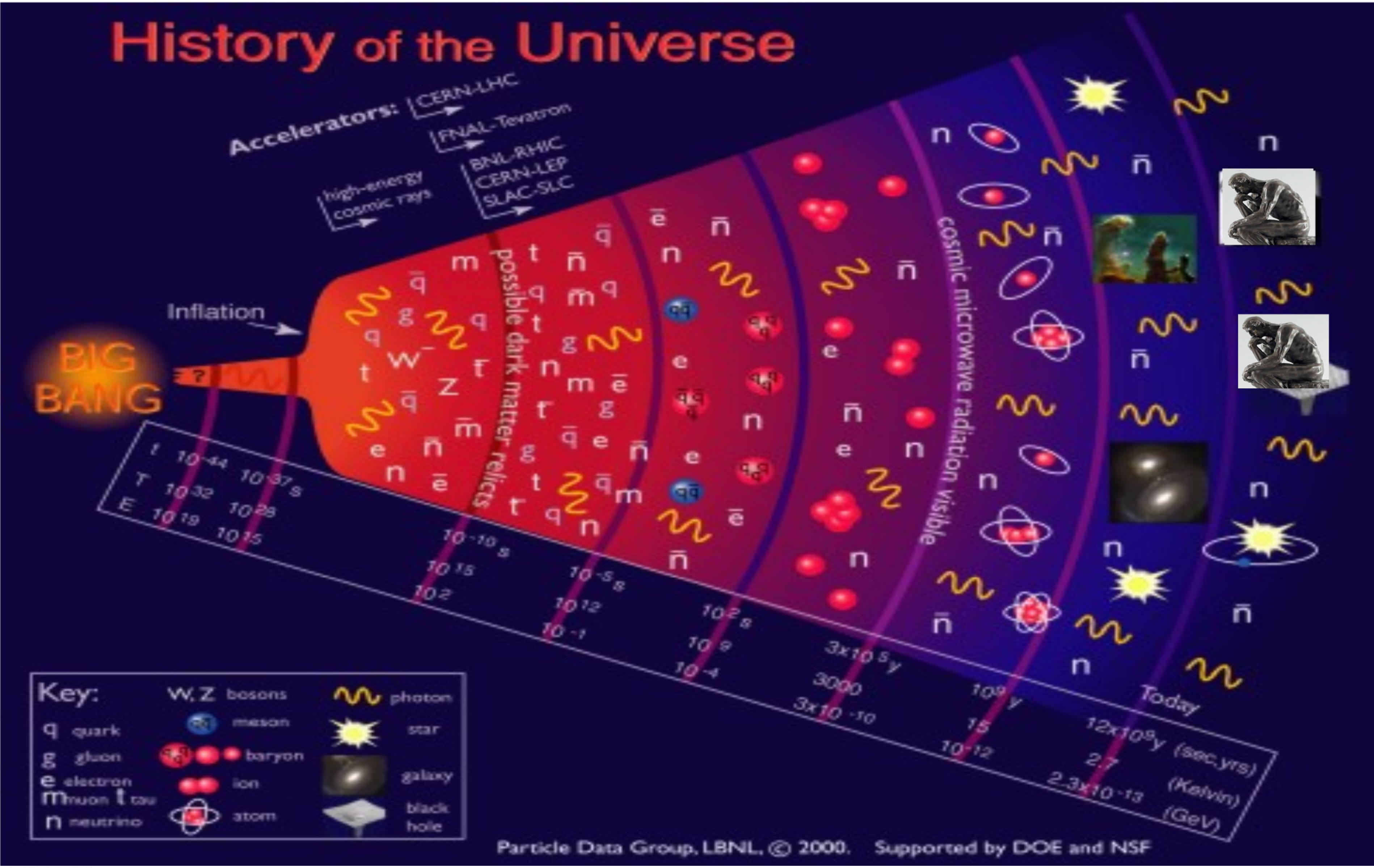


Leinweber et al.

Why EIC?

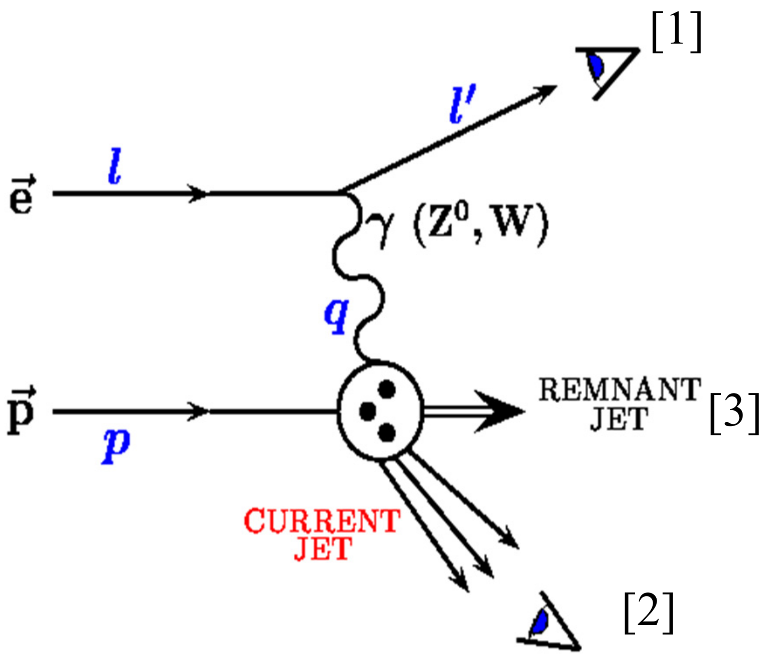
Precision study of the role of gluons in QCD

Accelerators: Time Machines!



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



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

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

Resolving power

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

Inelasticity

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

Mom. Frac. of struck quarks

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

Measurements:
Inclusive → Exclusive →
Low → high luminosity
Significant detector challenges

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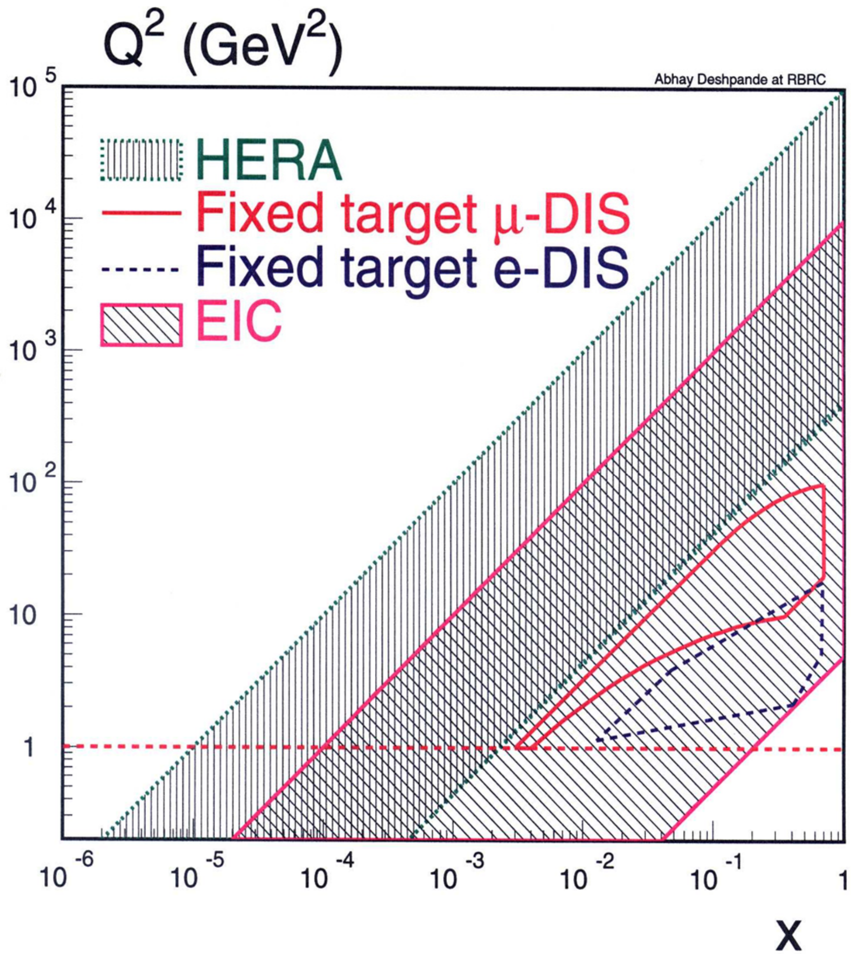
Four proposals…

- In United States:
  - ELectron Ion Collider (ELIC) at Jefferson Lab
    - Use 12 GeV CEBAF + a new hadron beam facility
  - eRHIC at Brookhaven National Laboratory
    - Use the RHIC + a new electron beam facility
  - Center of Mass Energy Range (Variable) 30-200 GeV

- In Europe:
  - LHeC at CERN
    - Use the LHC + a new electron beam facility
    - Center of Mass Energy 1.2 TeV
  - European Nucleon Collider (ENC) at FAIR
    - Use the HESR ring of GSI complex and PANDA detector
    - Center of Mass Energy 14 GeV

US EIC : Basic Parameters

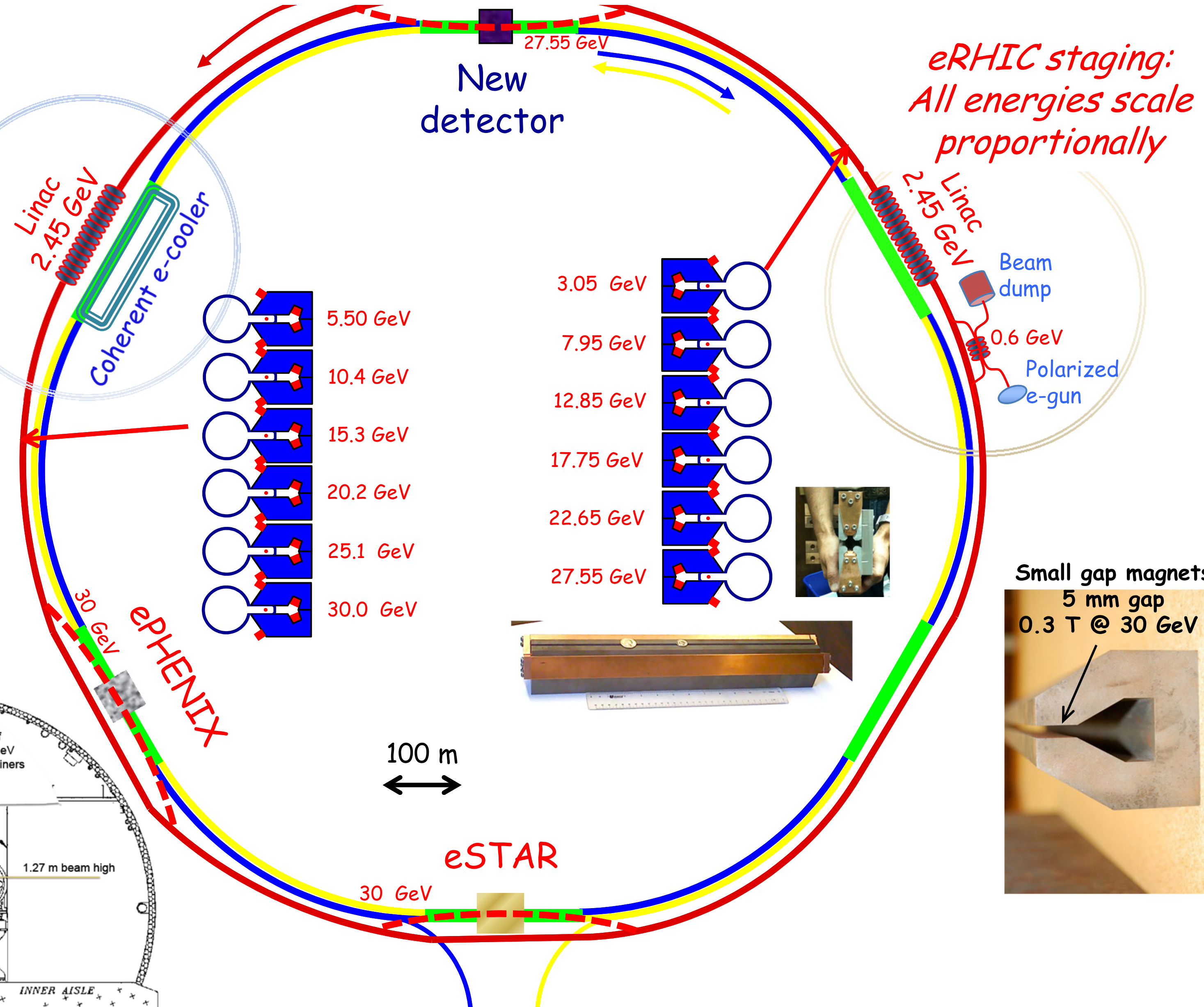


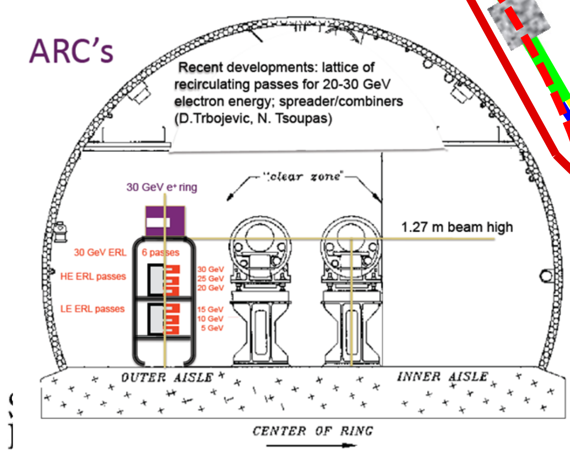
- E_e=10 GeV (5-30 GeV variable)
- E_p=250 GeV (50-325 GeV Variable)
- Sqrt(S_{ep}) = 100 (30-200) GeV
- $X_{min} = 10^{-4}$; $Q^2_{max} = 10^4$ GeV
- Beam polarization ~ 70% for e,p, d, He
- Luminosity L_{ep} = few x $\mathbf{10^{33\text{-}34}}$ cm^{-2}s^{-1}
- Minimum Integrated luminosity:
  - 50 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}**

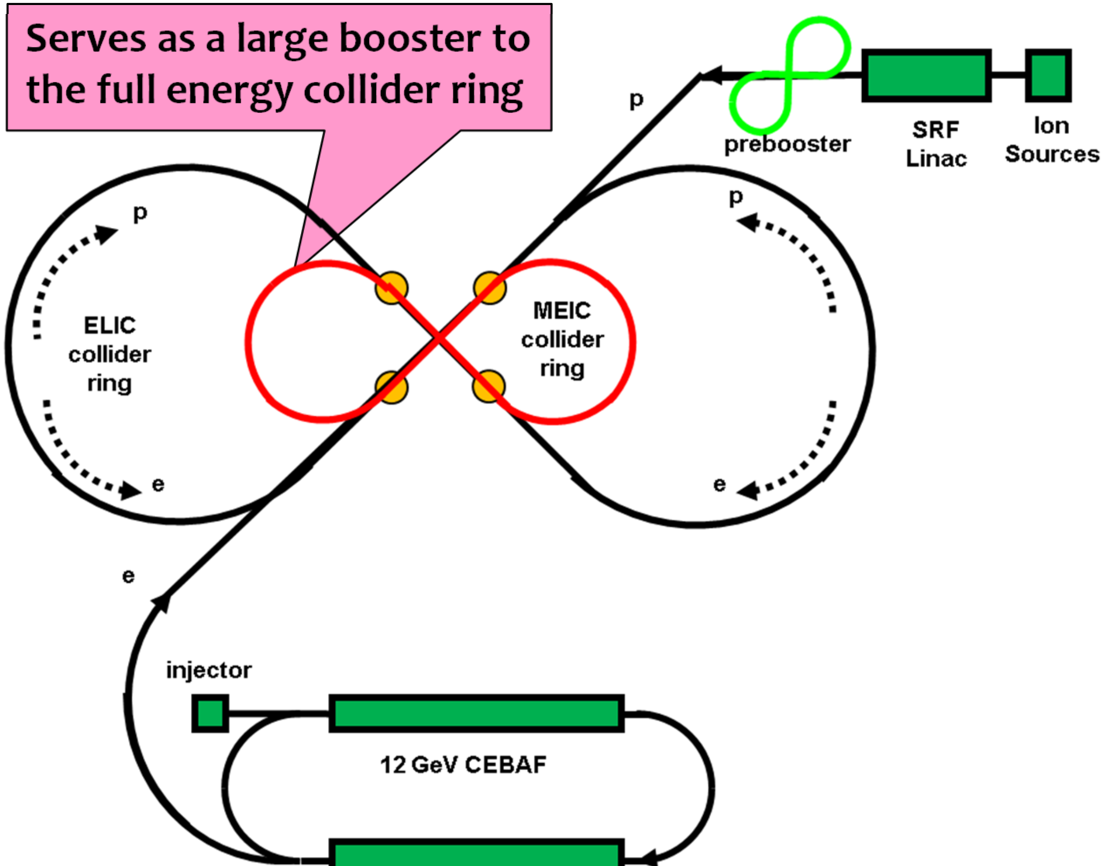
eRHIC: polarized electrons with $E_e \leq 30$ GeV will collide with either polarized protons with $E_e \leq 325$ GeV or heavy ions $E_A \leq 130$ GeV/u





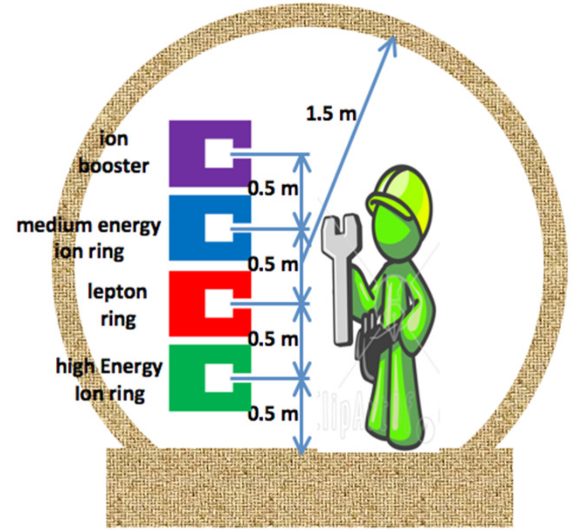
A. Hutton

ELIC: High Energy & Staging

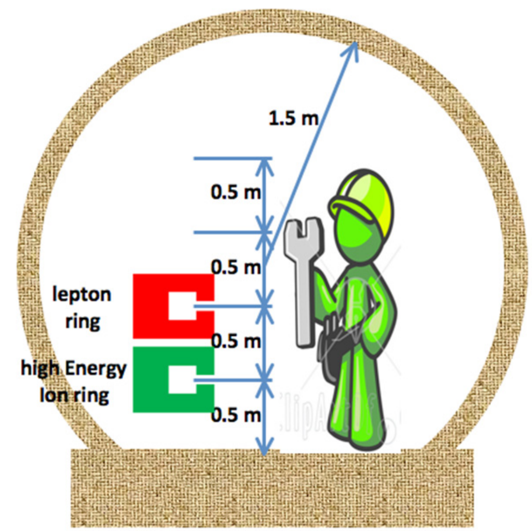


Stage	Max. Energy (GeV/c)		Ring Size (m)	Ring Type		IP #
	p	e		p	e	
Medium	96	11	1000	Cold	Warm	3
High	250	20	2500	Cold	Warm	4

Straight section



Arc



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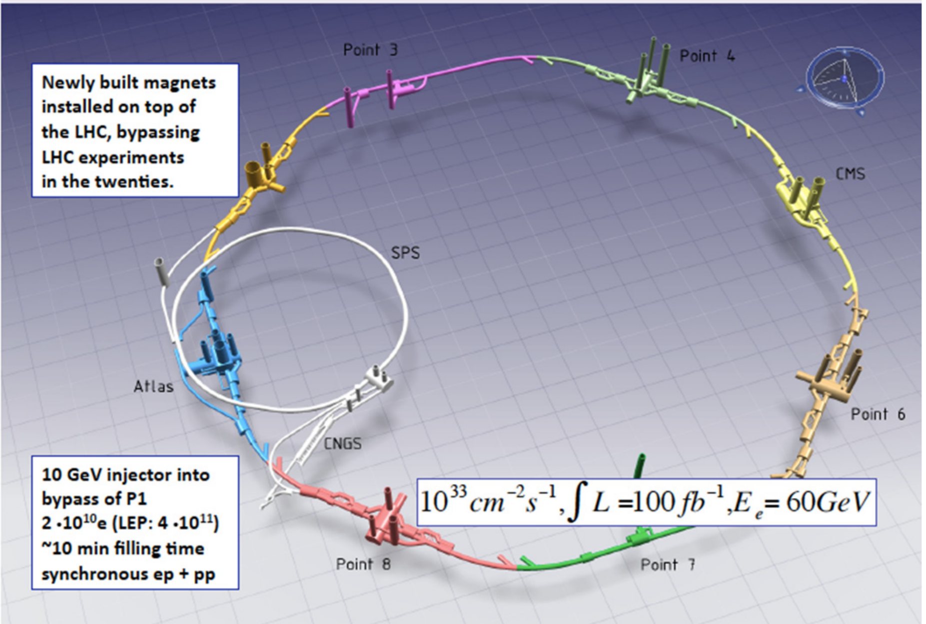
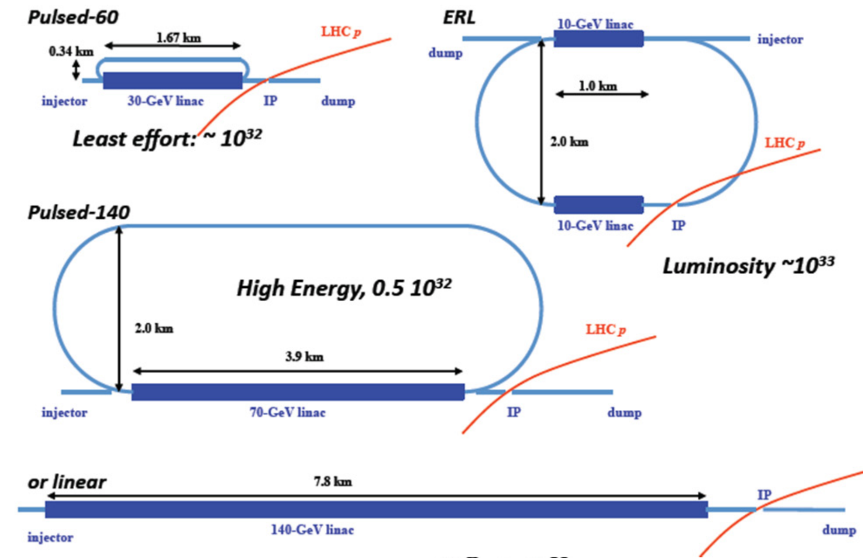
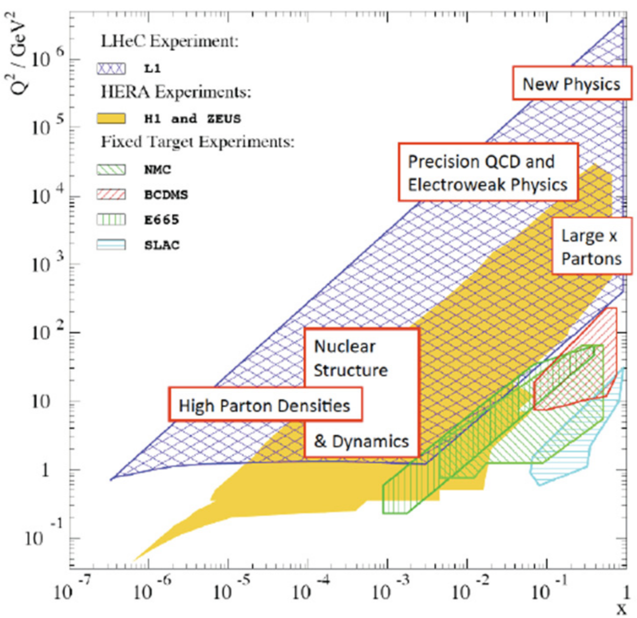
Ring-Ring configuration



Linac-Ring Configurations



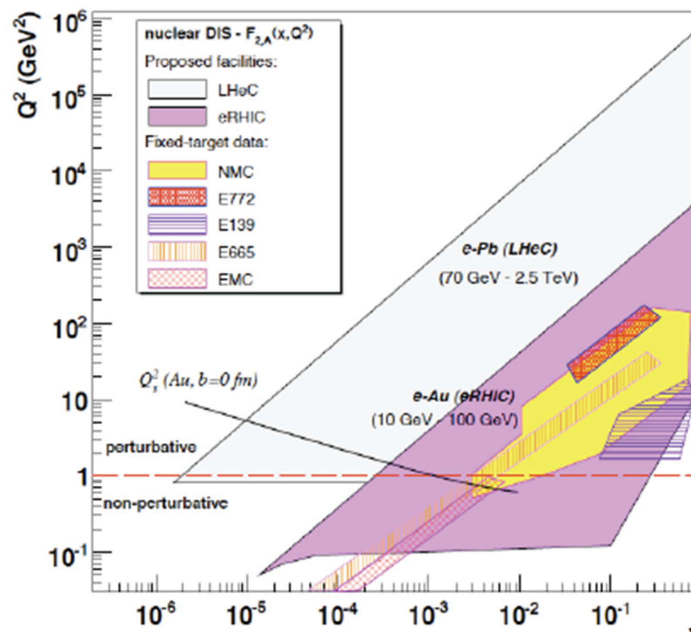
eA → eX



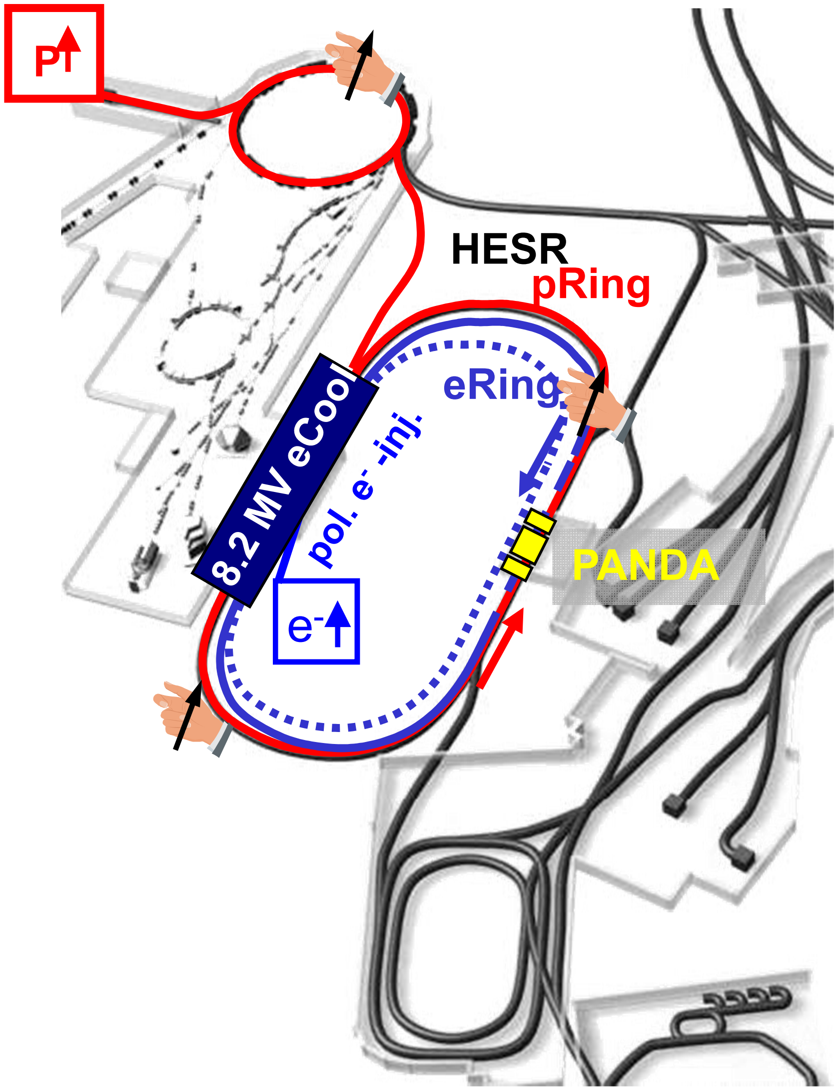
RR: 60 GeV e, 7 TeV p
LR: 140 GeV e, 7 TeV p

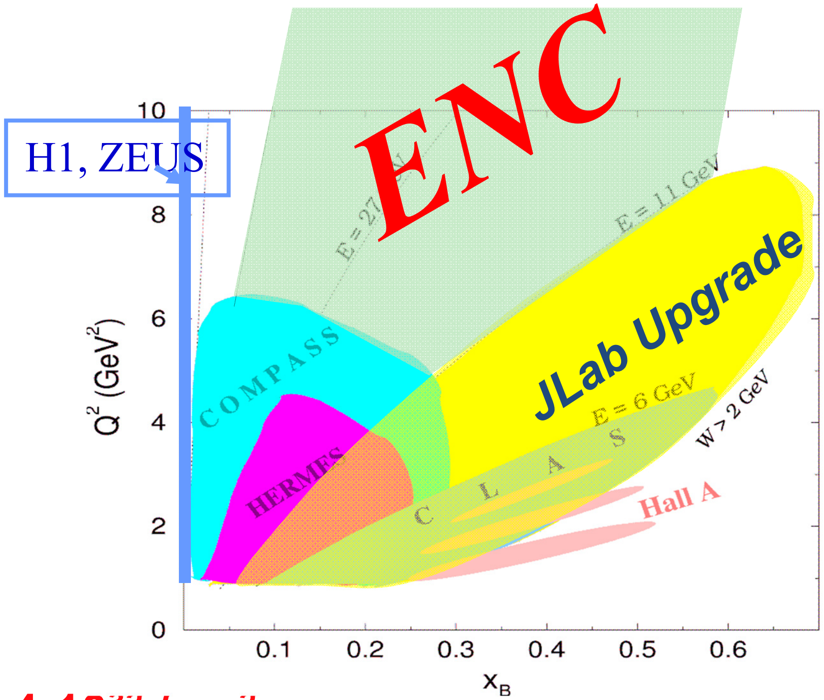
Physics:
Proton structure & QCD
Small x physics eP & eA

Electron-Quark systems
BSM: at 1 TeV scale
Search for new EW physics:
RH-W's, Contact Interactions



ENC at FAIR





L > 4·10³² /cm²s

s^1/2 > 10 GeV (3.3 GeV e⁻ ↔ 15 GeV p)

polarised e⁻ (80%)

↔

polarised p / d (80%)

(transversal + longitudinal)

Principle focus: Spin & 3D Imaging protons

GPDs and TMDs

EIC:

Why?

~~How?~~

~~When?~~

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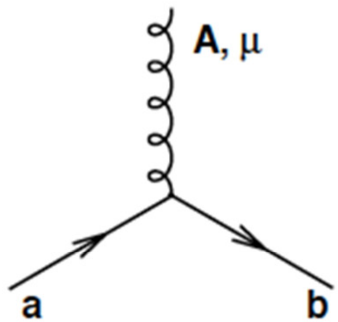
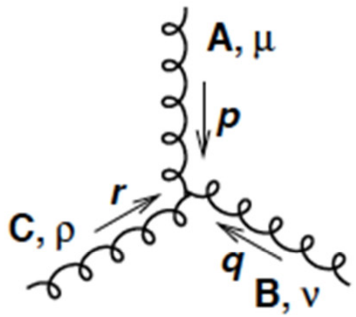
What distinguishes QCD from QED?

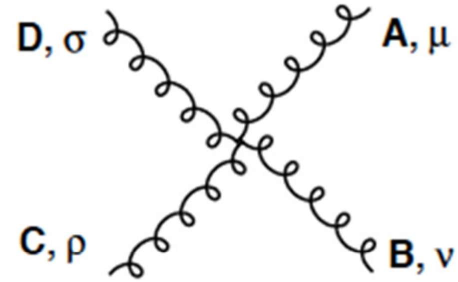
QED is mediated by photons γ which are charge-less
QCD is mediated by gluons g which *ARE* colored!

In QCD &
g → γ in QED

Only in QCD



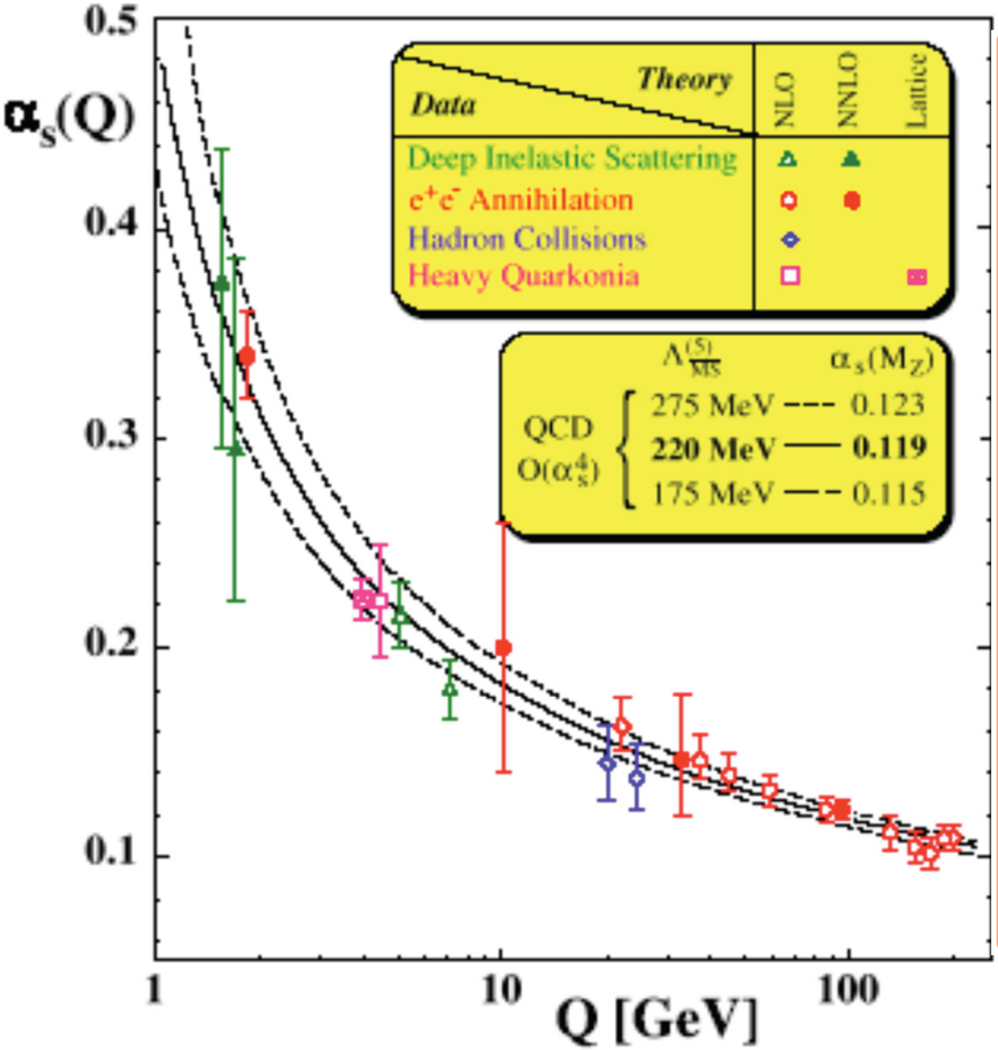




$$F_{QED} \propto \frac{1}{r^2}$$

$$F_{QCD} \propto r$$

What distinguishes QCD from QED?



Asymptotic Freedom ⇔ antiscreening

$$\text{QCD: } \frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) < 0$$

Compare

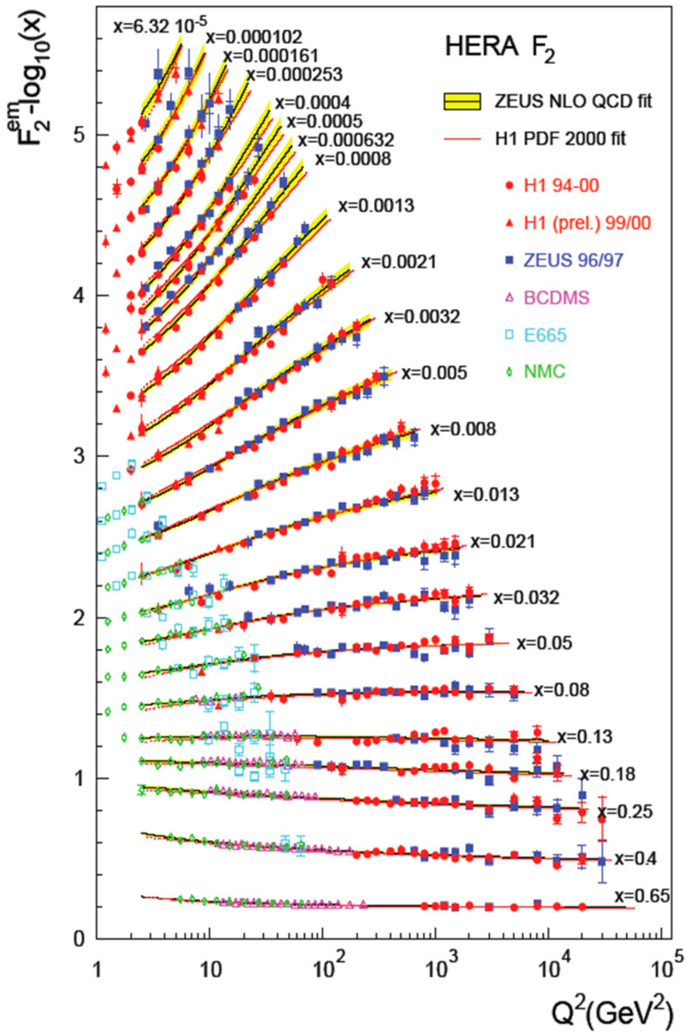
$$\text{QED: } \frac{\partial \alpha_{EM}(Q^2)}{\partial \ln Q^2} = \beta(\alpha_{EM}) > 0$$

D.Gross, F.Willczek, Phys.Rev.Lett 30, (1973)
H.Politzer, Phys.Rev.Lett. 30, (1973)

2004 Nobel Prize in Physics

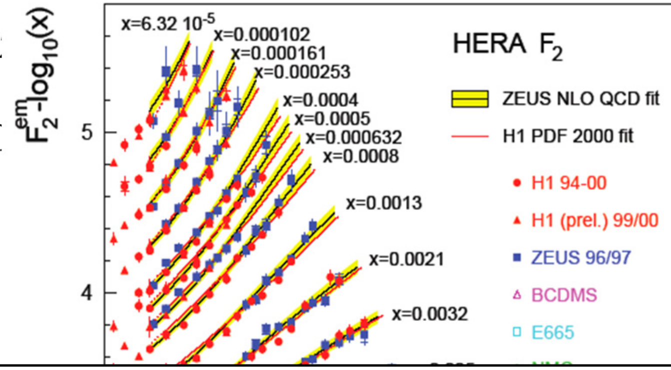
Success of pQCD at High Q: Jet Cross section

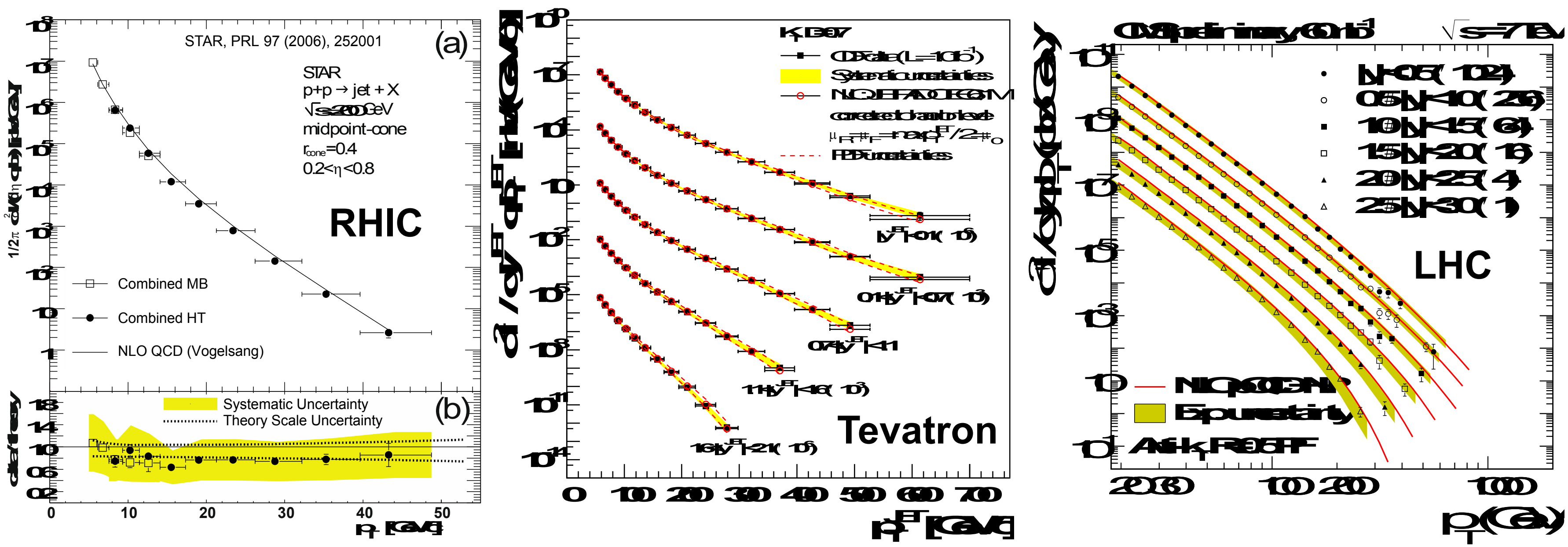
- Input:
  - F_2(x,Q
  - Next tc … D



Success of pQCD at High Q: Jet Cross section

- Input:
  - $F_2(x,Q$
  - Next tc … D



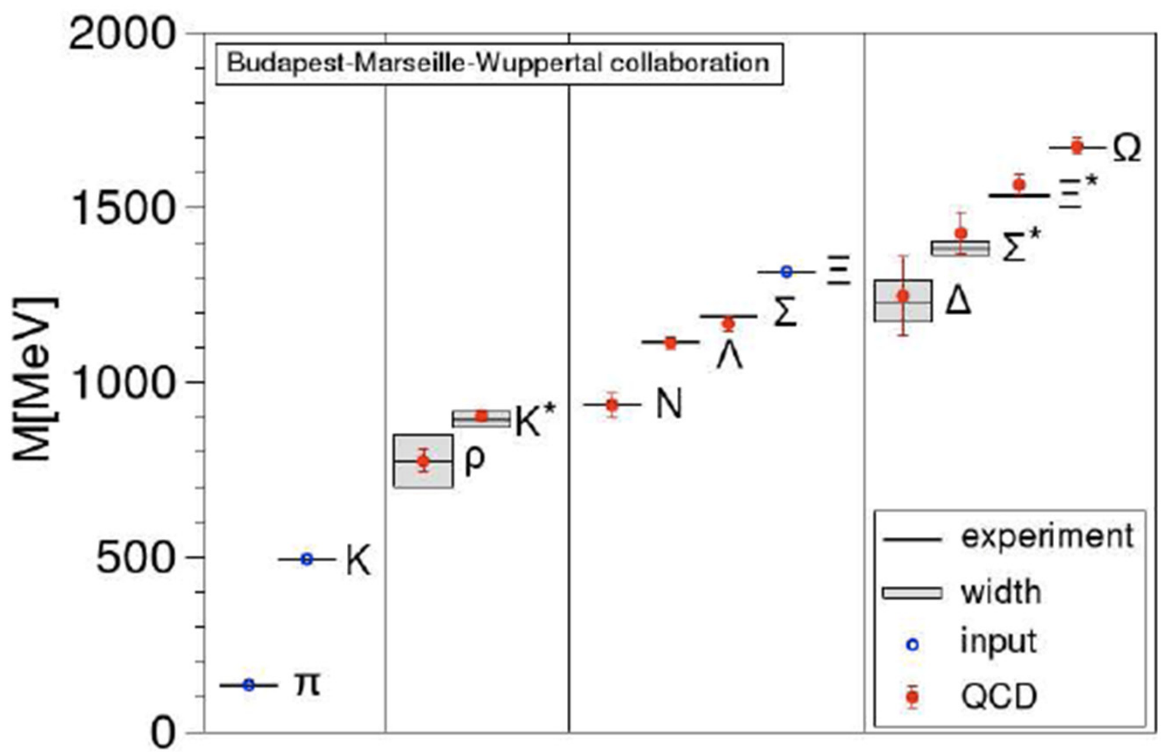


Compilation: J. Putschke

QCD definitely correct, but…

Lattice QCD

- Starting with QCD Lagrangian → Static properties of hadrons: hadron mass spectrum



Durr et al '08

No guidance on partonic dynamics

QCD: The SM of Strong Interactions

"Folks, we need to stop "testing" QCD
and start <u>understanding</u> it"

Yuri Dokshitzer

1998, ICHEP Vancouver, BC , Conference Summary Talk

2004 For the discovery of asymptotic freedom in QCD





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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

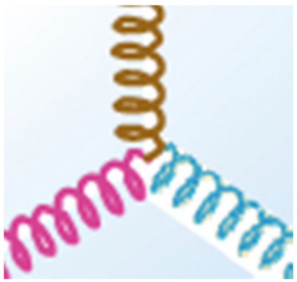
- Can we explain basic properties of hadrons such as mass and spin from the QCD degrees of freedom (partons) at low energy?

- 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

Generation of Mass – Gluons in QCD

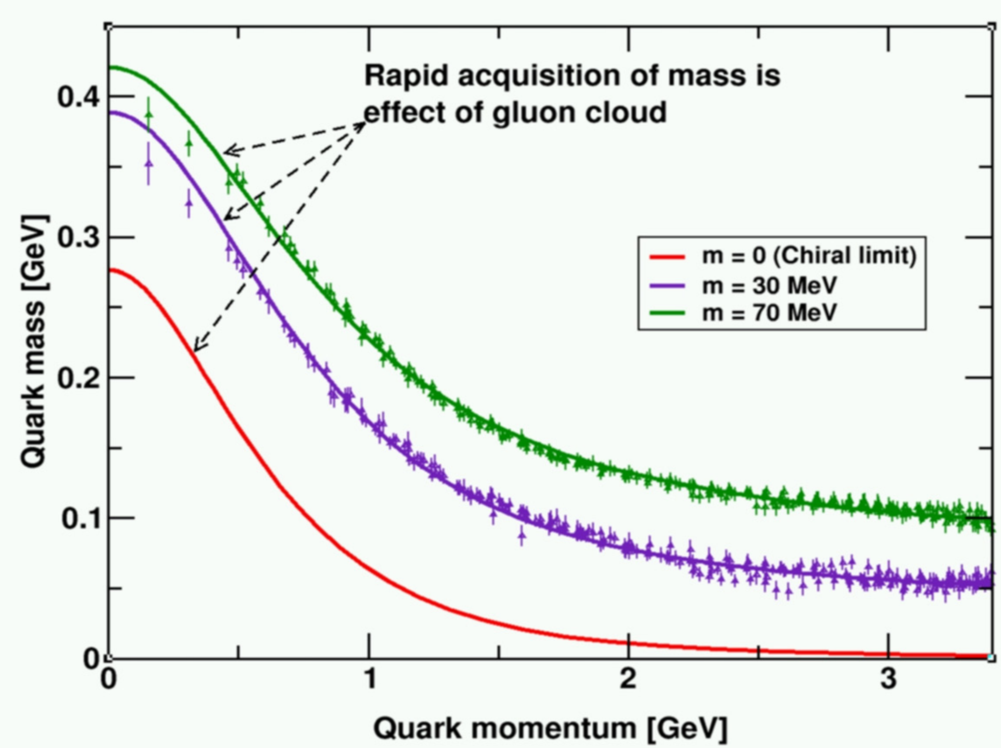
- Protons and neutrons form most of the mass of the **visible universe**
- 99% of the nucleon mass is due to **self generated gluon fields (E=mc^2)**
  - **Similarity** between p, n mass indicates that **gluon dynamics is identical** & overwhelmingly important

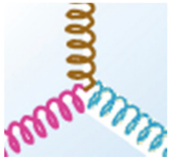


- Lattice QCD supports this

Higgs Mechanism, often credited with mass generation, is of no consequence

Bhagwat et al.





Gluon self-interaction in QCD

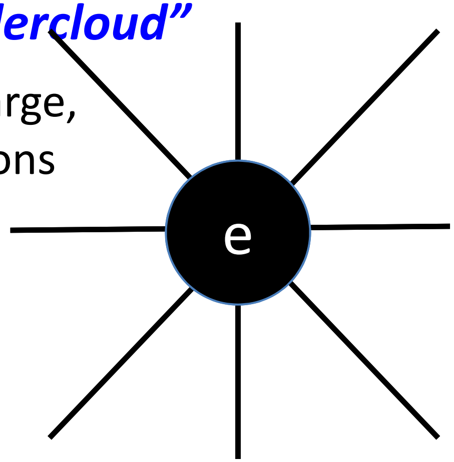
Dynamical generation & self-regulation of hadron masses

F. Wilczek in "Origin of Mass"

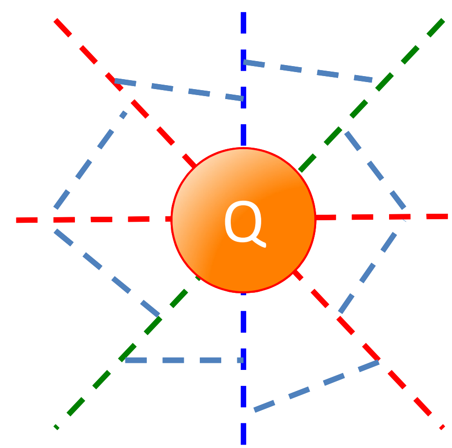
*Its enhanced coupling to soft radiation… means that a 'bare" color charge, inserted in to empty space will start to surround itself with a cloud of virtual color gluons. These color gluon fields themselves carry color charge, so they are sources of additional soft radiation. The result is a self-catalyzing enhancement that leads to a **runaway growth**. A small color charge, in isolation builds up a big color thundercloud…*

theoretically the energy of the quark in isolation is infinite… having only a finite amount of energy to work with, nature always finds a way to short cut the ultimate thundercloud"

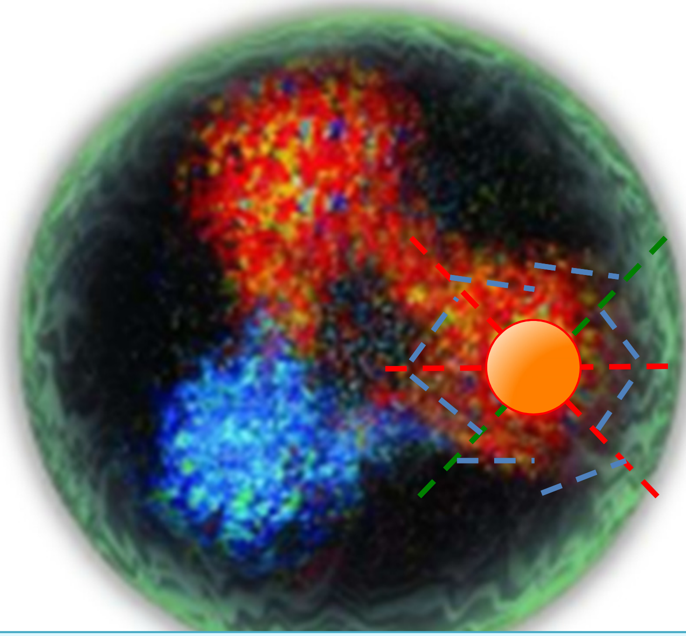
Electric charge,
lines: photons



Color charge
gluons



What limits the "thundercloud"?



- Partial cancellation of quark-color-charge in color neutral finite size of the hadron (confinement) is responsible, ***but***
- **Saturation of gluon densities due to gg→ g (gluon recombination) must also play a critical role regulating the hadron mass**

Need to experimentally explore and study ***many body dynamics***
a) regions of ***quark-hadron transition*** and
b) non-linear QCD regions of extreme ***high gluon density***

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HOW WELL DO WE KNOW GLUONS?

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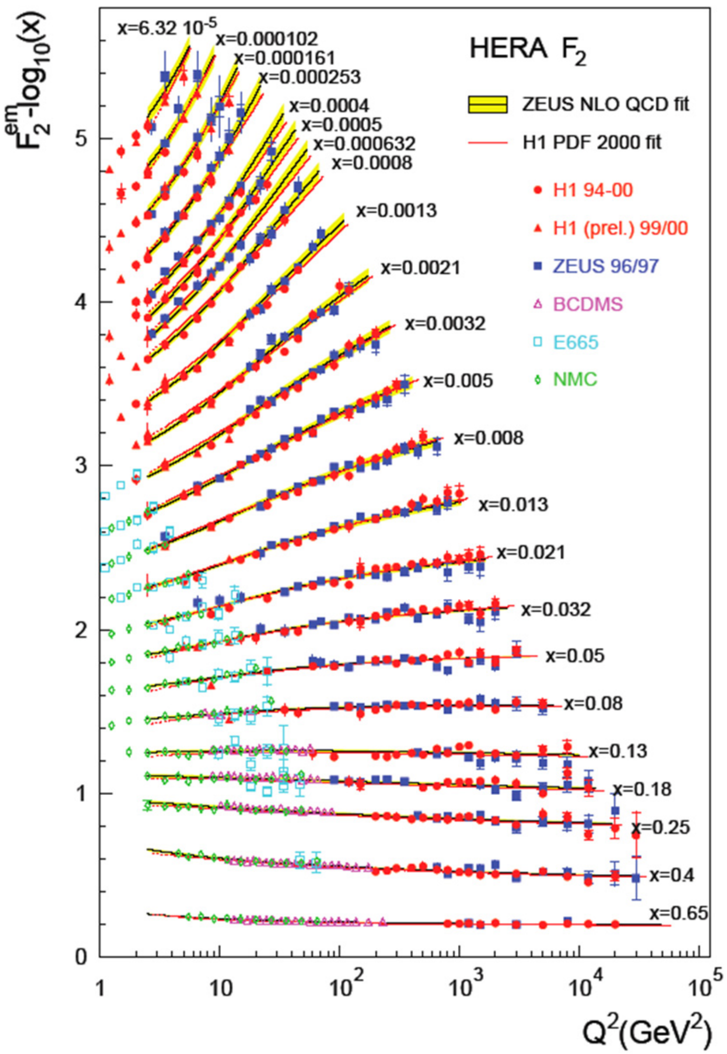
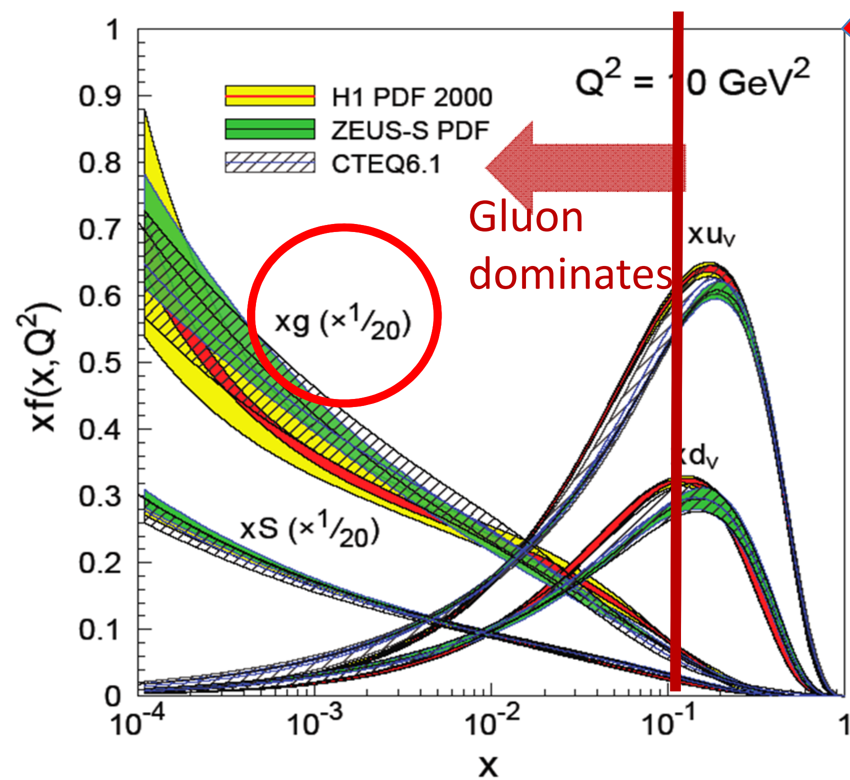
Measurement of Glue at HERA



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

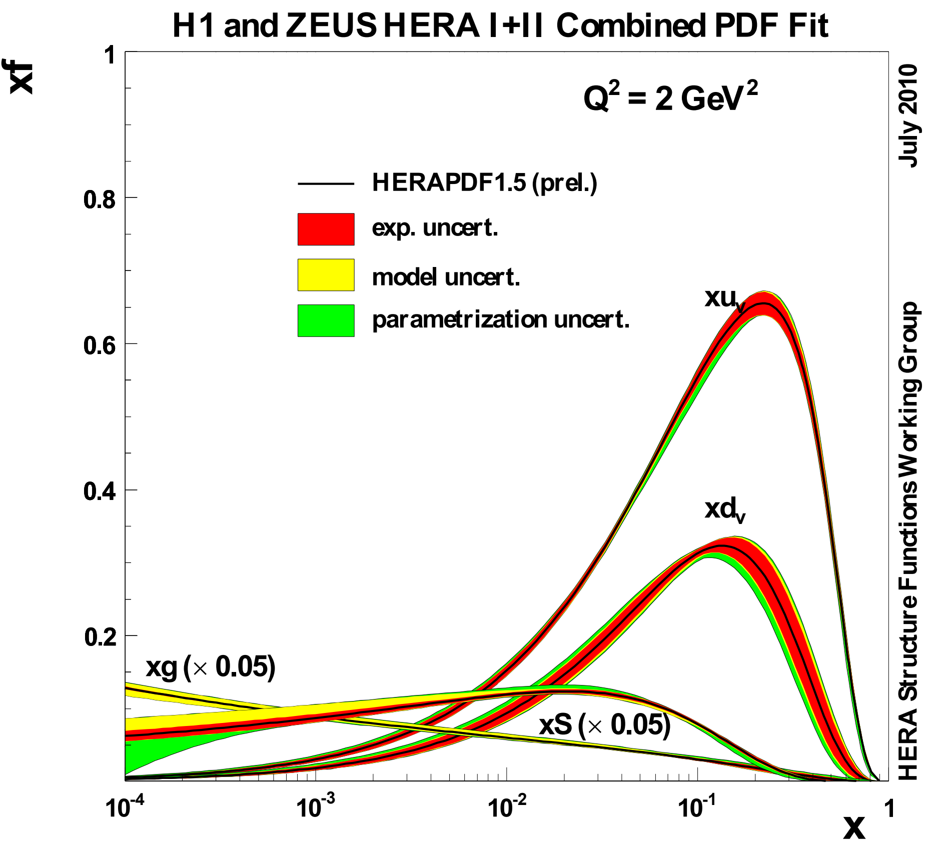
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

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

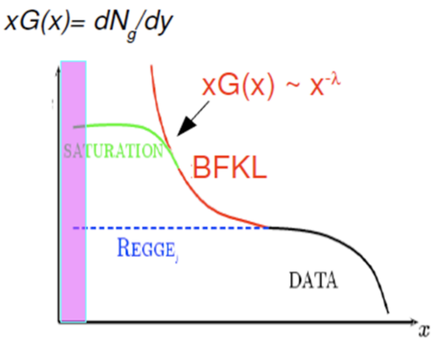


*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Gluon distribution at low-x understood?



- Indefinite rise:
  - Could this be an **artifact** of using of **linear** DGLAP in gluon extraction?
  - Infinite high energy hadron cross section?



Either build a HIGHER energy e-p collider than HERA! → "LHeC"

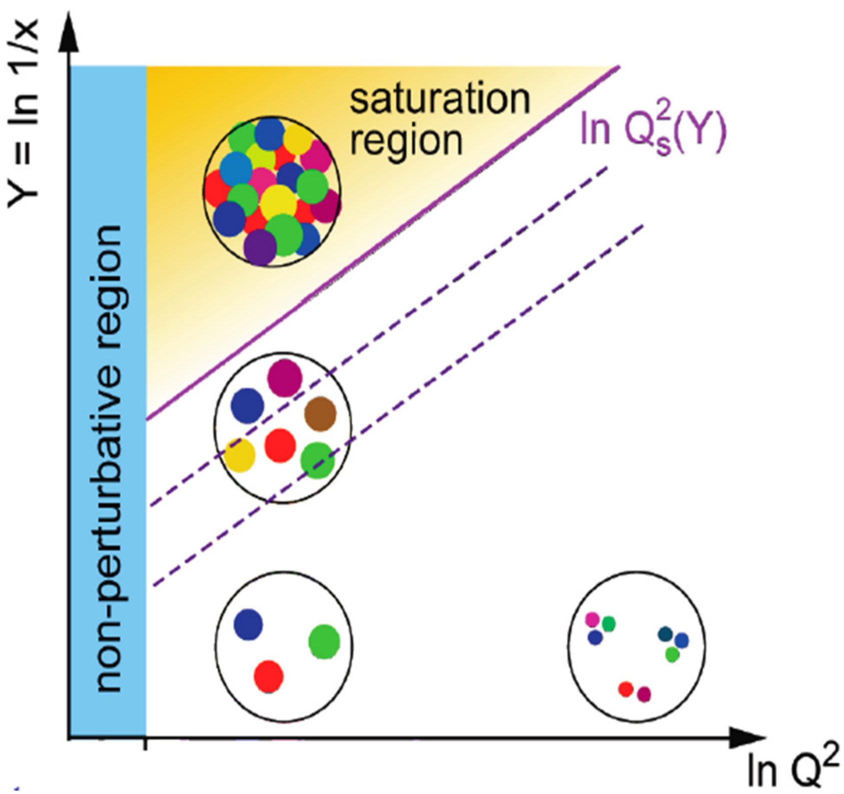
OR:

Why not do NUCLEAR DIS at highest possible energy? → "US EIC, LHeC"

Nuclei, naturally enhance the densities of partonic matter

Low-x, higher twist & Color Glass Condensate

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



Method of including **non-linear** effects in DGLAP equation developed →
Small coupling, high gluon densities
→ Some form of saturation
Color Glass Condensate an exotic form of gluonic matter is predicted

Saturation Scale $\mathbf{Q_S(x,Q^2,A)}$

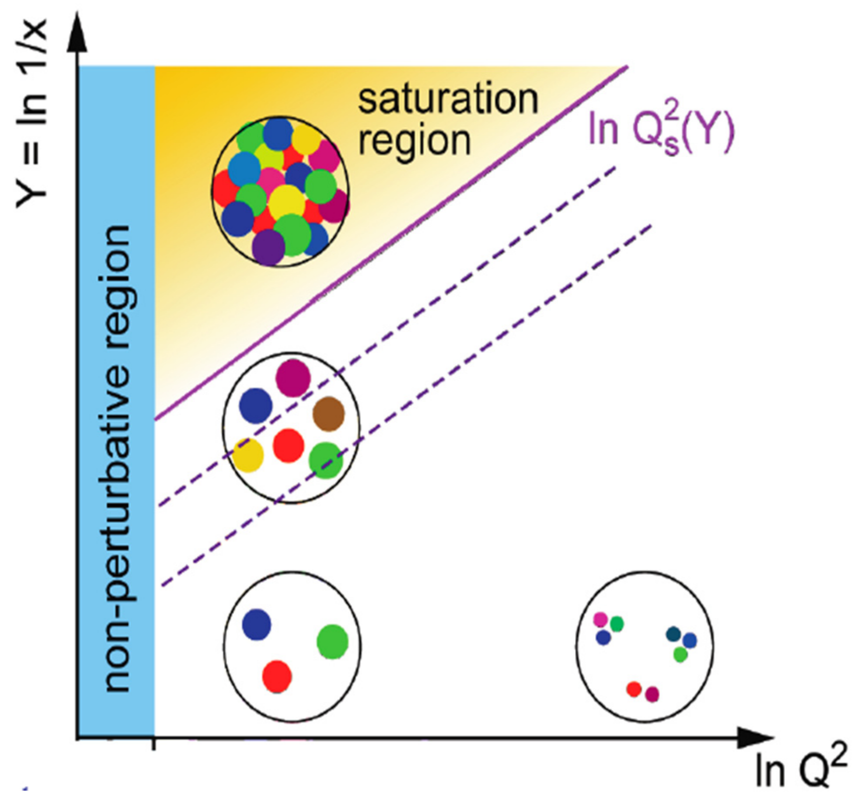
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

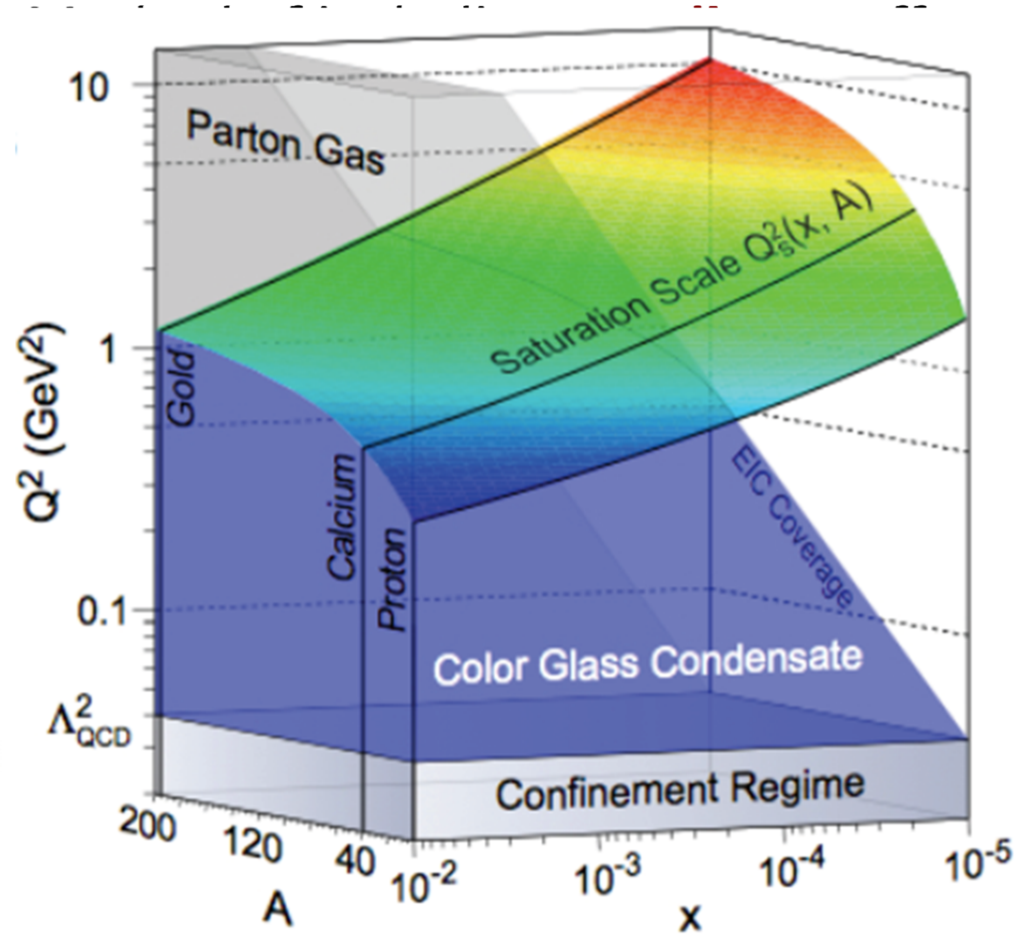
Kowalski
Teany
PRD 68:114005

No unambiguous experimental evidence yet, but many smoking guns (HERA, RHIC & now LHC!)

Low-x, higher twist & Color Glass Condensate

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





Could be explored cleanly in future with a highest energy electron-Proton/Nucleus Collider

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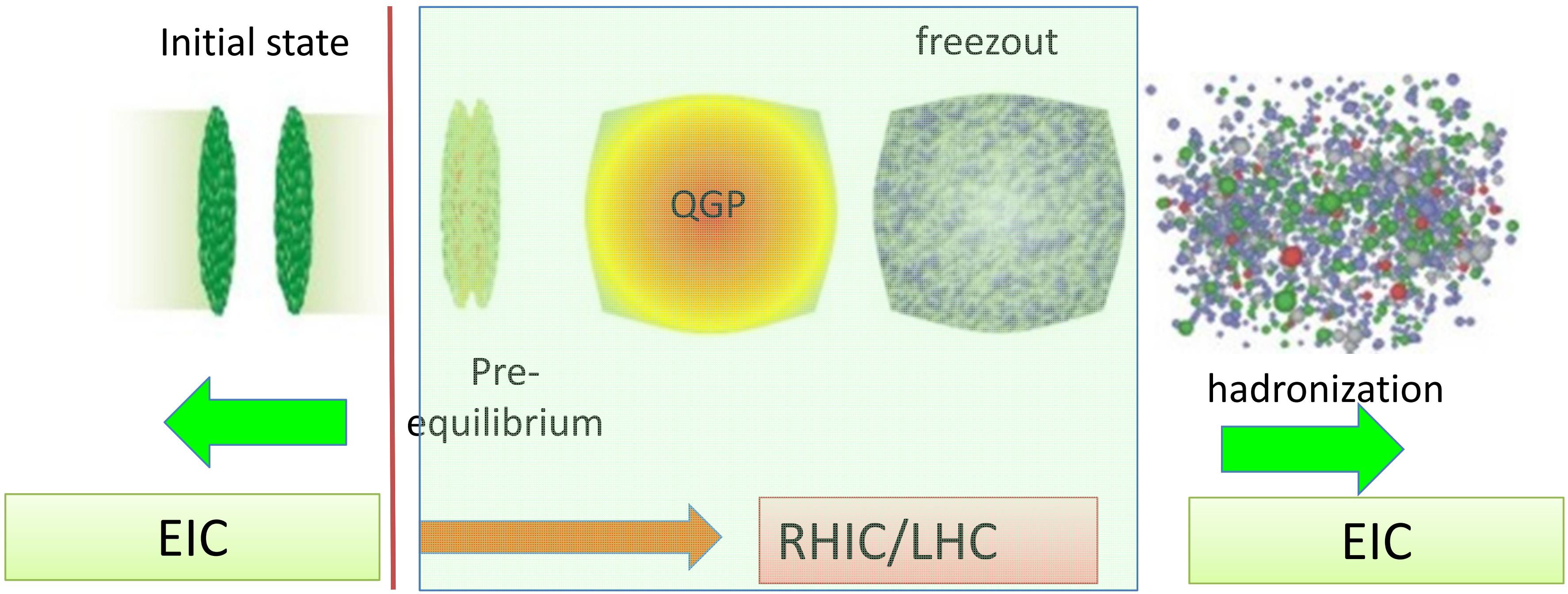
EIC and RHIC/LHC (Heavy Ion)



A decadal plan is being launched to characterize the "QGP"

To understand "QGP" fully, we need to understand:

The initial state i.e. the nucleus & hadronization

Deeper Connection: many body interactions of parton in QC

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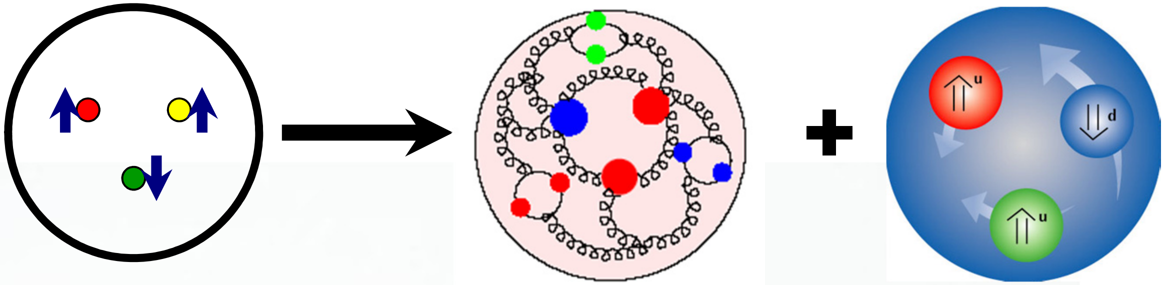
UNDERSTANDING NUCLEON SPIN:

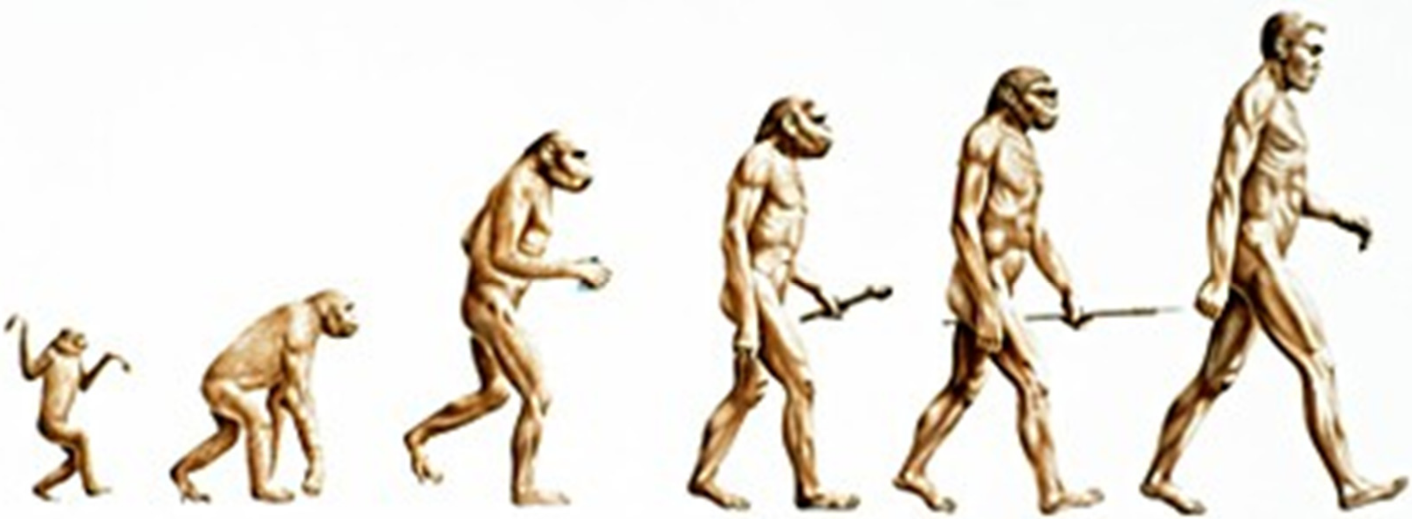
WHAT ROLE DO GLUONS PLAY?

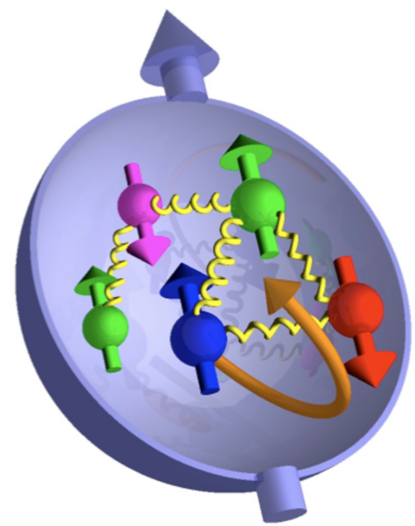
Evolution: Our Understanding of Nucleon Spin



1980s

1990/2000s



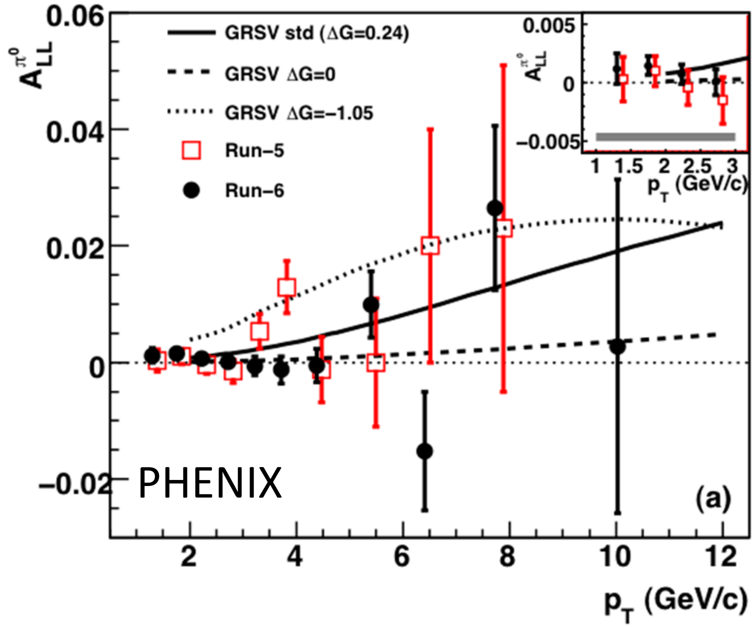


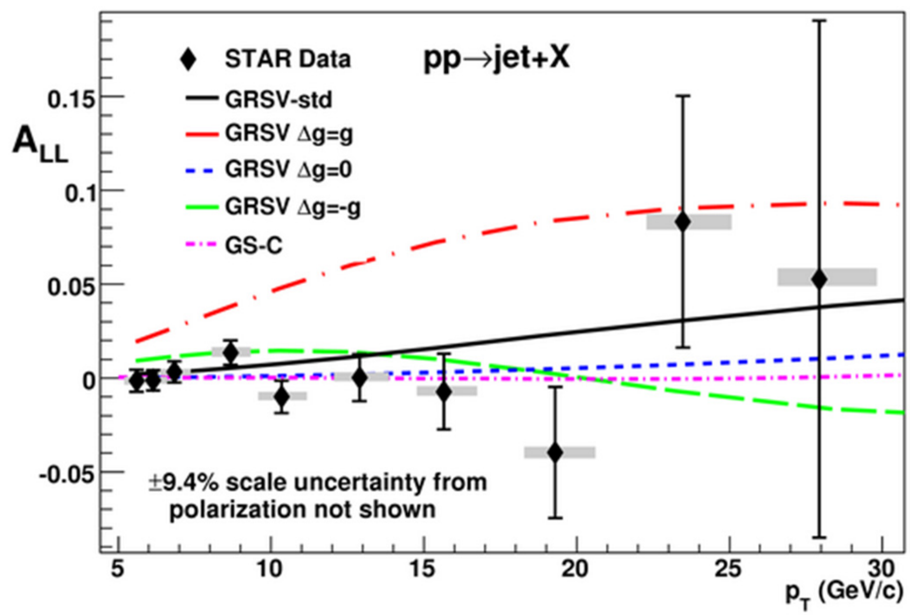
We have come a long way, but do we understand nucleon spin?

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

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

- We know how to determine ΔΣ and Δg precisely: data+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*

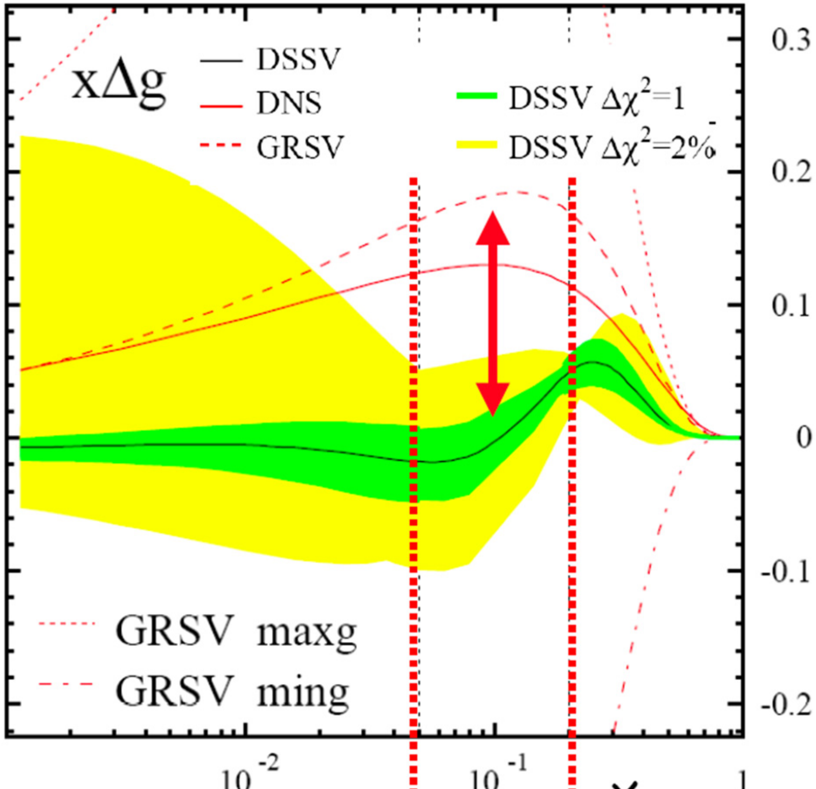




$\Delta g(x)$ @ Q^2=10 GeV^2

Now

de Florian, Sassot, Stratmann & Vogelsang



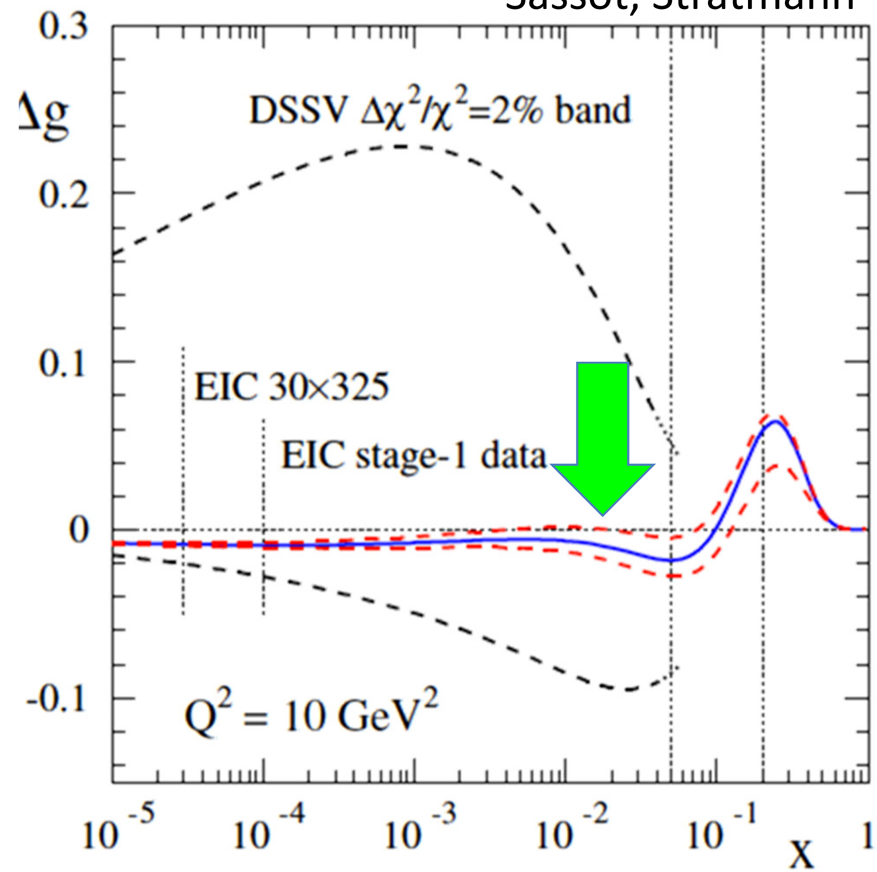
Present RHIC range $0.05 \leq x \leq 0.2$

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

large-x $x \geq 0.2$

With polarized EIC

Sassot, Stratmann



Yellow Error band ➔ Red Dotted

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

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- 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*
- **Would it not be great to have a (2+1)D tomographic image of the proton…. (2: x,y position and +1:momentum in z direction)?**
  - Explore transverse & longitudinal hadron structure including spin!
  - Orbital angular momenta: Generalized Parton Distributions (GPDs)
  - Quark GPDs: 12GeV@JLab & COMPASS@CERN
  - Gluons @ low x → J_G → will need the future EIC

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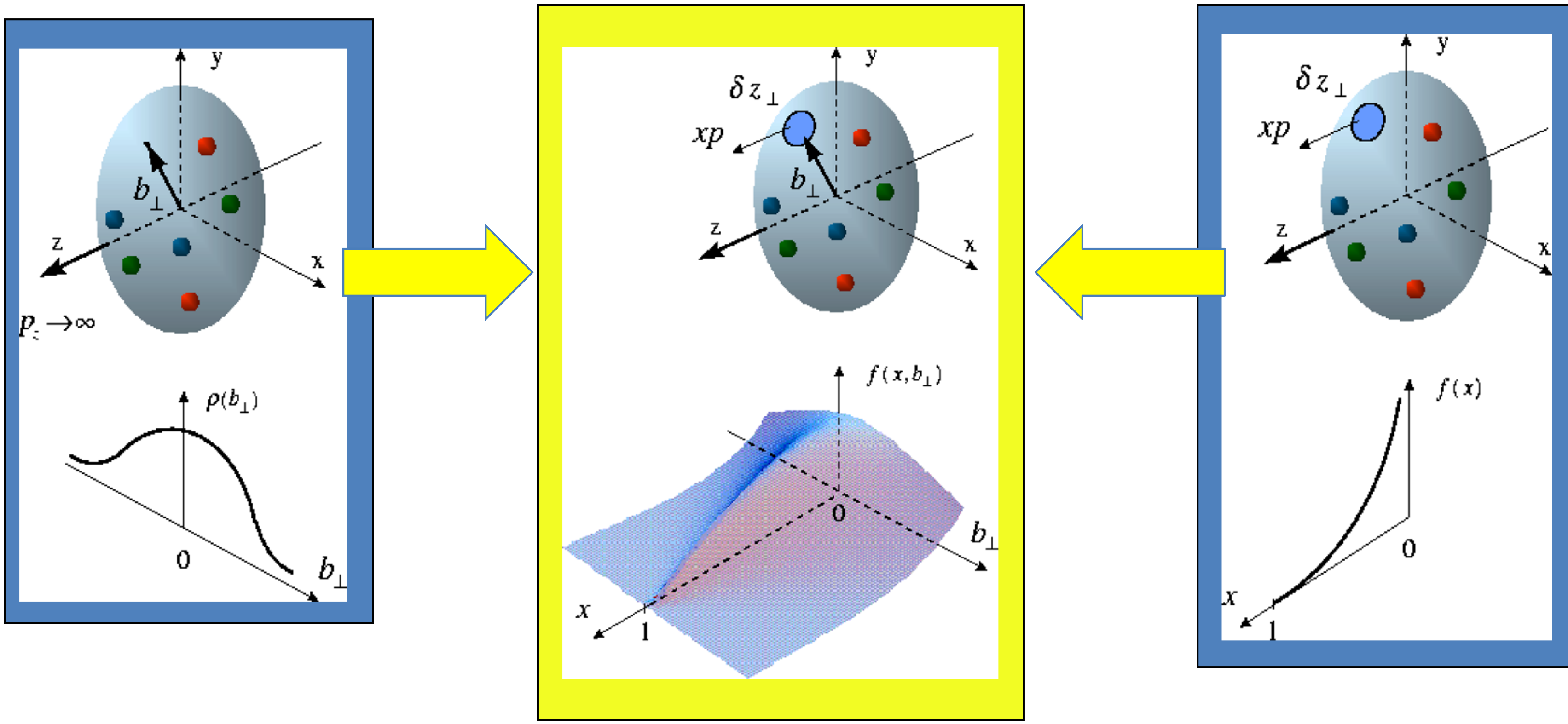
Beyond form factors and quark distributions

Generalized Parton Distributions

X. Ji, D. Mueller, A. Radyushkin (1994-1997)

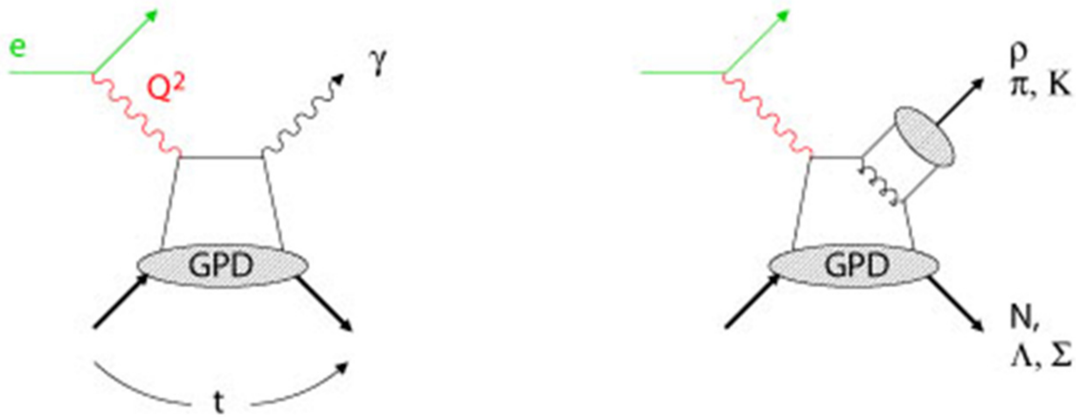


Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Proton Tomography: GPDs → OAM



Deeply virtual Compton scattering

Deeply virtual meson production

$$\text{Nucleon Spin} = \frac{1}{2} = J_{\text{quark}} + J_{\text{gluons}}$$

$$J_q = \frac{1}{2}\Delta\Sigma + L_q \qquad GPDs : H, E, \tilde{H}, \tilde{E}$$

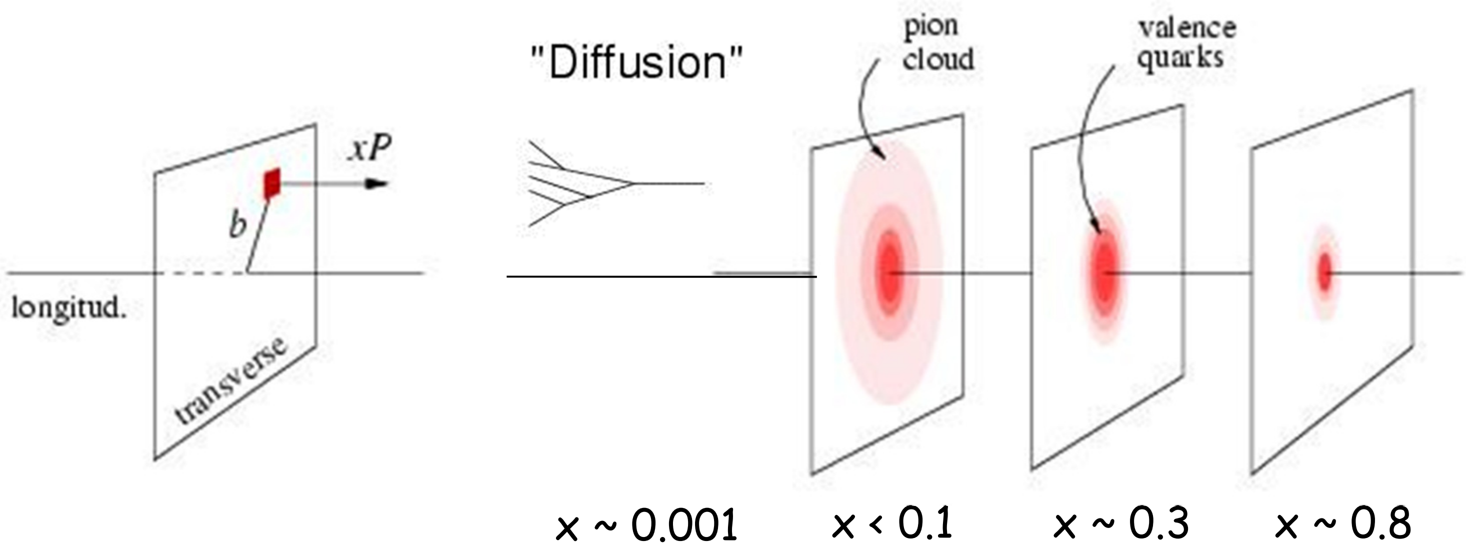
$$J_q = \frac{1}{2}\int_0^1 x dx \left[H(x,t,\zeta) + E(x,t,\zeta)\right]$$

Similar expression for gluon J_g total spin contribution through DVVM

Needs measurements over a wide range in each of the variables & large luminosity

GPDs and transverse parton imaging

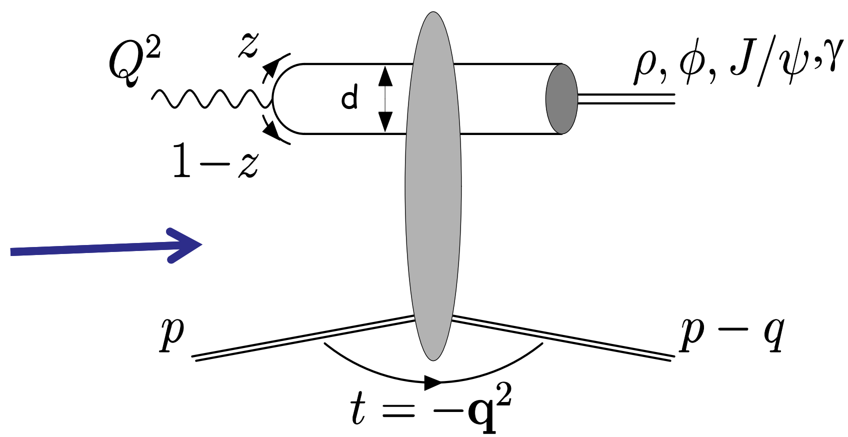
Fourier transform in momentum transfer

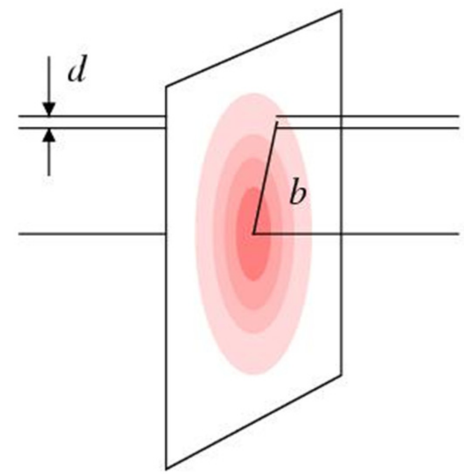


EIC:

1) x < 0.1: gluons!

2) $\xi \sim 0$ → the "take out" and "put back" gluons act coherently.





Summary: Science of EIC: Precise Investigations of the "Glue"

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

- Study **of extreme high gluon density medium** systematic study with a wide range of nuclei at highest possible energies

- Precision measurements of Gluon's Spin: high energy, spin
- Measurement of **(gluon)** GPDs: **high luminosity, spin**
  - (2+1) D momentum and position (correlations)
  - *Possibly* leading to gluon's orbital angular momentum

- With **highest energy or/and luminosity**, electron beam polarization, and a hermatic detector: Possible access to Electro-Weak and Beyond the SM Physics….

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Summary

Science Case for EIC: → "Understand QCD" *a la* Dokshitzer

Understand: Role of gluons in QCD

Many body dynamics (a la Condense Matter) in QCD

Structure of hadrons, dynamics of partons in them

At the highest energy an EIC (LHeC) will enable EW & Beyond the Standard Model Physics (not discussed today) complimentary to LHC.

- For US EIC in the US this will make high luminosity & hermetic detector an absolute necessity

The US-EIC, the LHeC and the ENC collaborations are moving forward towards realization of this projects

Ingenious ideas and innovations from accelerator physicists of today & tomorrow are absolutely crucial!

Look! Purple mountains! Spacious skies! Fruited plains!

Look! Glue in hadrons, nuclei…..

Lets explore and understand it…. With the Electron Ion Collider….

Complementarity of future proposals: US-EICs, LHeC, ENC

- Understanding QCD of high gluon density: High an energy essential
  - LHeC with eP & eA
  - US EIC with eA

- QCD Nucleon spin 3D structure: Polarized hadron beams essential
  - US EIC proposals: x << 0. 1 Gluon, & Quark GPDs (high energy)
  - ENC at FAIR: x ~ 0.1 Quark GPDs

- EW & BSM Physics: High energy or/and luminosity
  - LHeC with e-beam polarization
  - US EIC with e & p/n beam polarization (BSM?)

"Many body" interactions….

- QED: understanding the interactions of electric & magnetic charges + including quantum mechanics + relativity
  - Condense Matter Physics is "Many Body QED"
    - Complicated, but extremely important and rich!

- QCD: understanding the interactions of color charge leading to fundamental understanding of strong interactions….
  - *Heavy Ion Physics and the physics EIC are essential components for the next step: MANY BODY SYSTEMS IN QCD*
    - *"Condense Matter Physics equivalence of QCD"*

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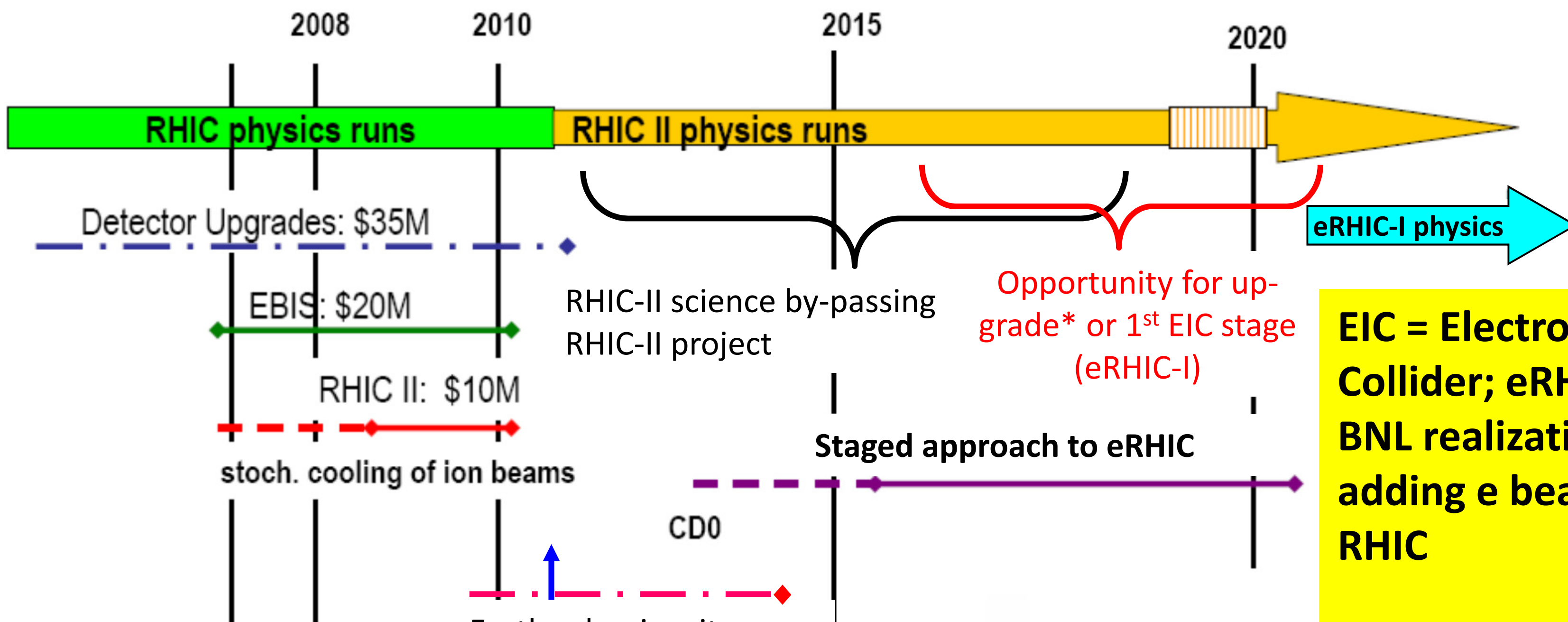
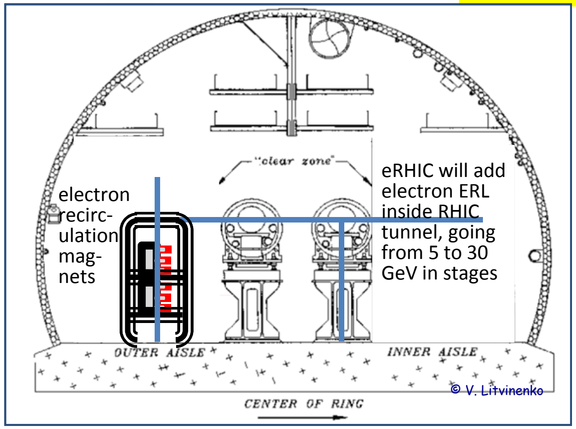
A Long Term (Evolving) Strategic View for RHIC



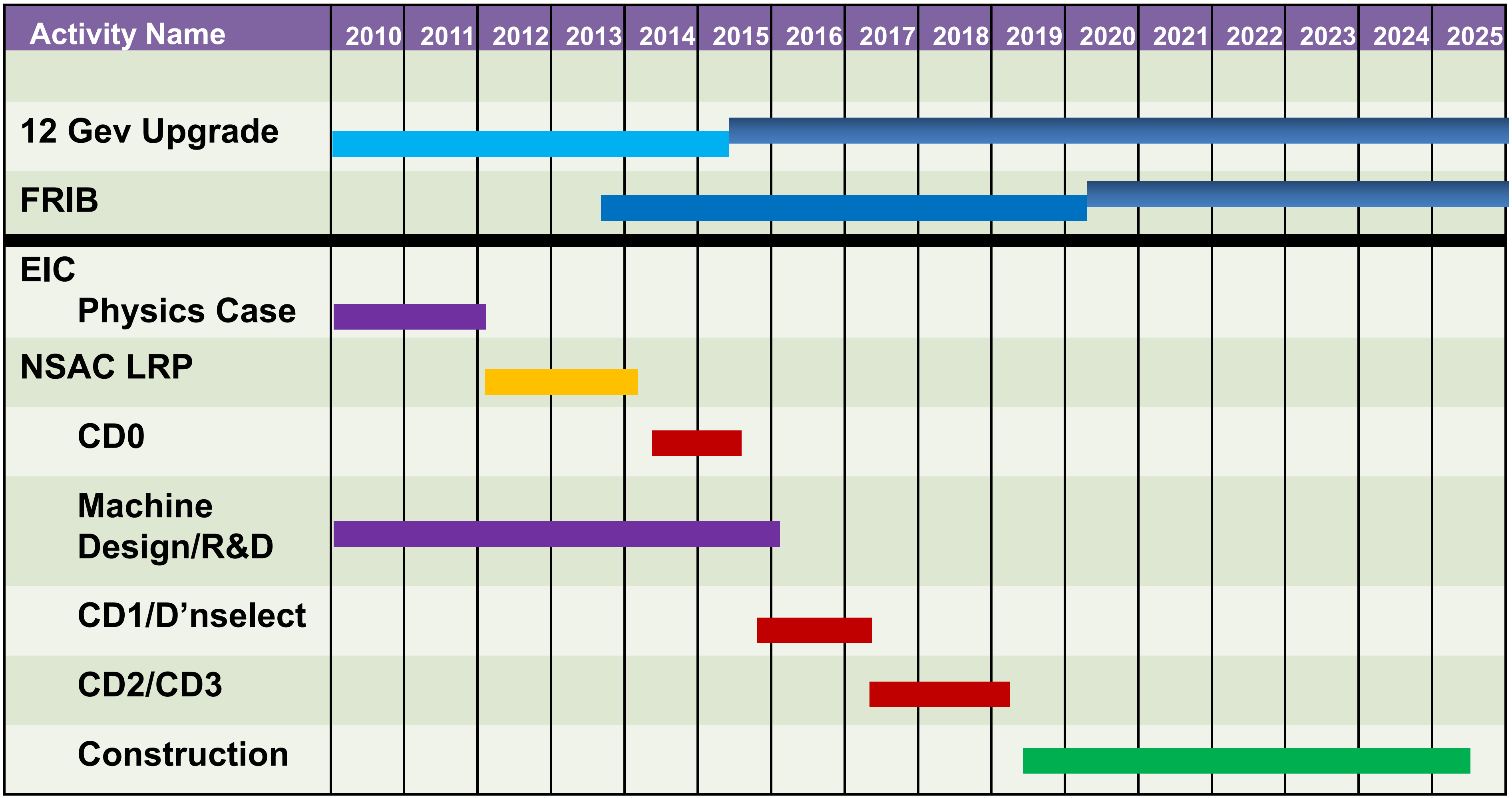
EIC = Electron-Ion Collider; eRHIC = BNL realization by adding e beam to RHIC



* New PHENIX and STAR Decadal Plans provide options for this period. Dedicated storage ring for novel charged-particle EDM measurements another option.

H. Montgomery, Jeff. Laboratory Director

EIC at JLab Realization Imagined



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**
  - Working groups/ Task Forces at BNL and at Jefferson Laboratory
  - Steering Group, co-chairs/contact: R. Milner (MIT) & AD (SBU)

- 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), D. Hetrzog (U of W), X. Ji (Maryland), R. Klanner (Hamburg), A. Mueller (Columbia), K. Oide (KEK), N. Saito (J-PARC), U. Wienands (SLAC)*

- Plan to go to the NSAC Long Range Plan (2012/13) with the science case & machine/detector designs (including costs & realization plans)

Summary (US Collider)

Science Case for EIC: → "Understand QCD" *a la* Dokshitzer

"Precision study of the role of gluons in QCD"

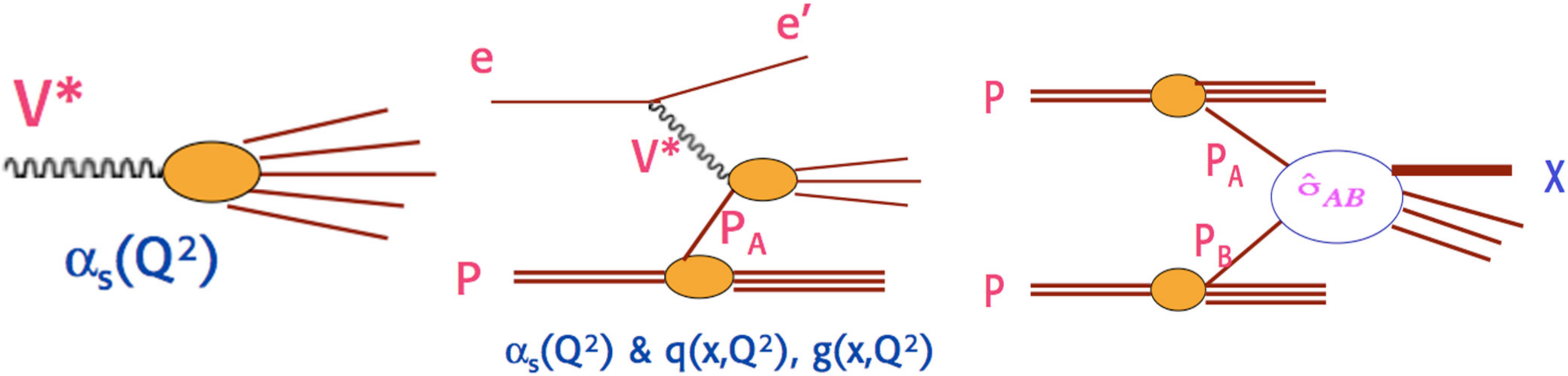
Many body dynamics in QCD is an essential part of this study

Will enable us to understanding the nucleon & nuclei at high energy including possibly (EW probes of hadron structure & beyond… *not emphasized today*)

In the US: The EIC Collaboration & the BNL+Jlab managements are moving 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 the exciting quest for understanding of QCD!

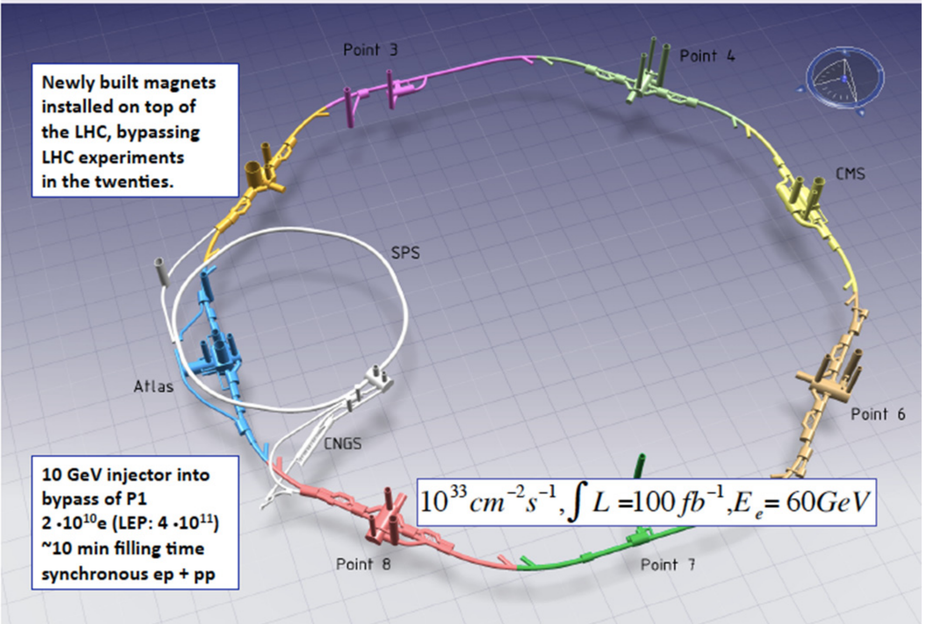


- Experimental tools of high energy physics:
  - e-e (ho hadron: LEP, BELLE, BaBar), e-p (one hadron: HERA), p-p (two hadrons: SppS, Tevatron… now at LHC)

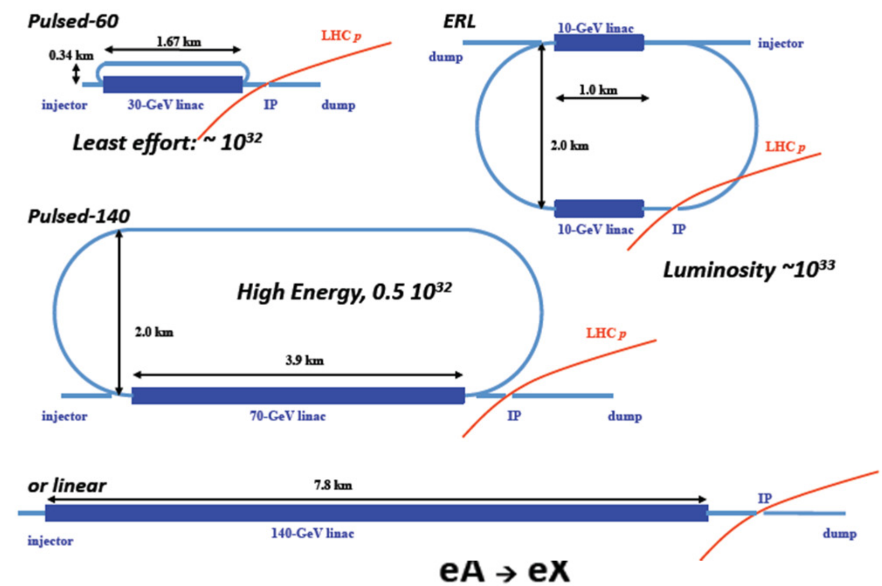
Progress in physics needed continuous interplay amongst different techniques to take the full advantage of their complementarity

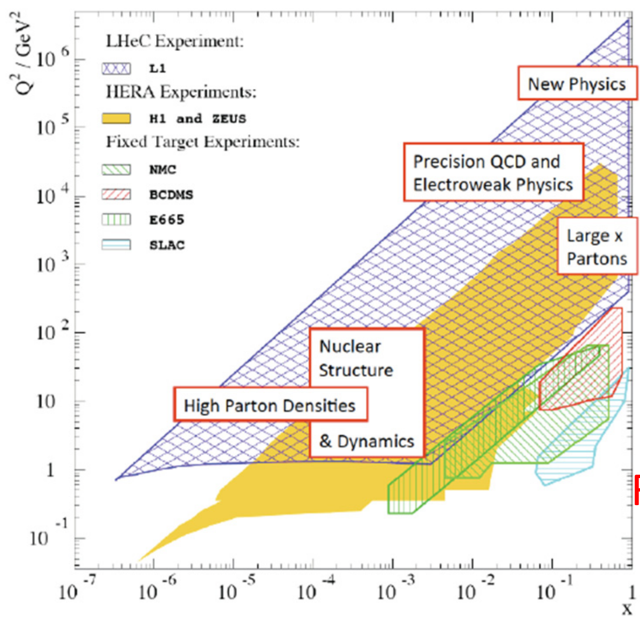
EIC promises to include nuclei in this game!

Ring-Ring configuration



Linac-Ring Configurations





Physics:

Proton structure & QCD

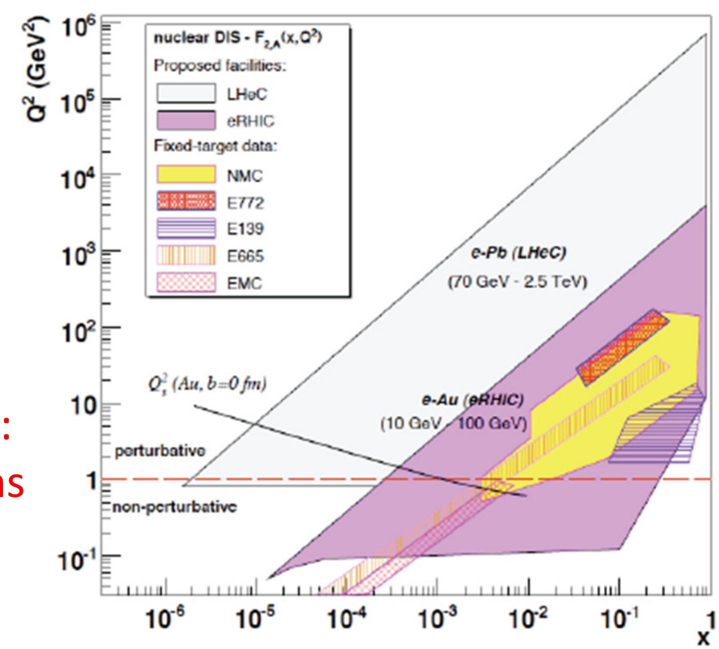
Small x physics eP & eA

Electron-Quark systems

BSM: at 1 TeV scale

Search for new EW physics:

RH-W's, Contact Interactions



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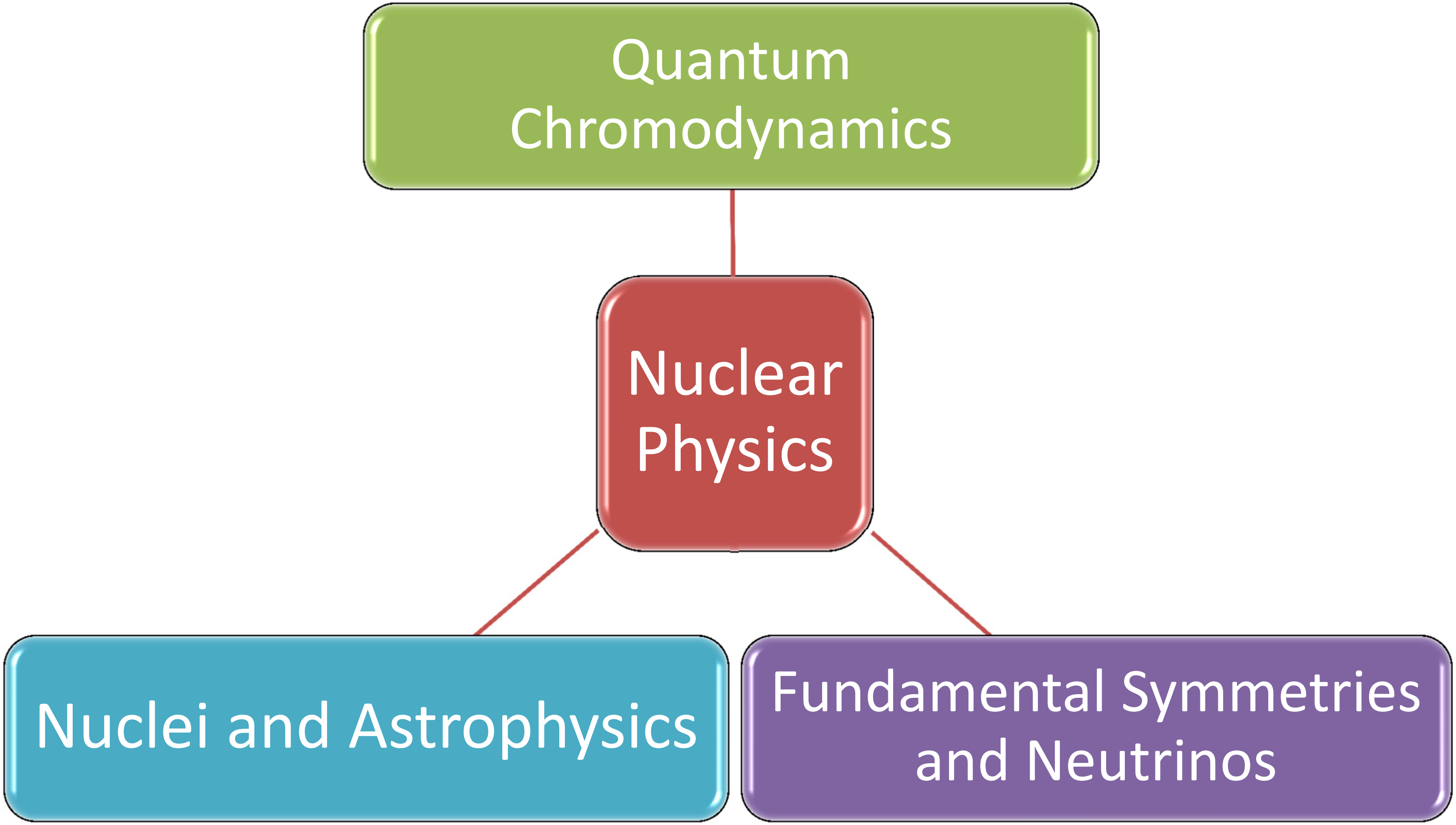
Electroweak & beyond….(?)

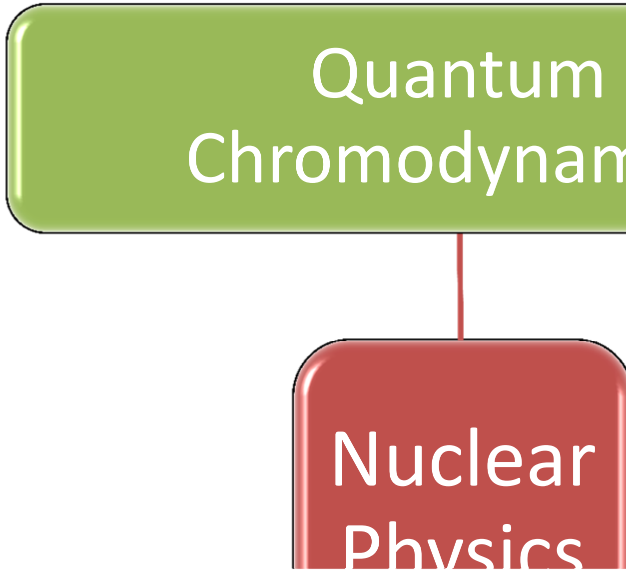
- High energy collisions of polarized electrons and protons and nuclei afford a unique opportunity to study electro-weak deep inelastic scattering
  - **Electroweak structure functions (including spin)**
  - Significant contributions from W and Z bosons which have different couplings with ***heavy quarks 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

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

$$e^- + p \rightarrow \tau^- + X$$



Accelerators are ***critical*** tools in all three of these subfields!



Session: Others (special and plenary)

ABSTRACT: There is substantial international interest in construction of an Electron Ion Collider. Such a collider could explore physics ranging from discovery of a new state of matter in QCD to probing physics beyond the standard model. The speaker will review the physics goals for a proposed Electron Ion Collider, and review relevant performance of existing proposals for such a facility.

Because titles can occasionally be ambiguous, the abstract is provided for your guidance as to the program committee's intentions for the subject matter. If you accept this invitation, you will be given ownership of the

Accelerators are ***critical*** tools in all three of these subfields!