The EIC project

Marco Radici

INFN - Pavia

INFN Istituto Nazionale di Fisica Nucleare

3DSPIN MAPPING THE PROTON IN 3D

erc European Research Council

Outline : the 5 W’s of journalism

You have to write about Who, What, Where, When, and Why. If you want to add something, ask for my permission!

the EIC project :

What ?

Why ?

Where ?

When ?

Who ?

What ?

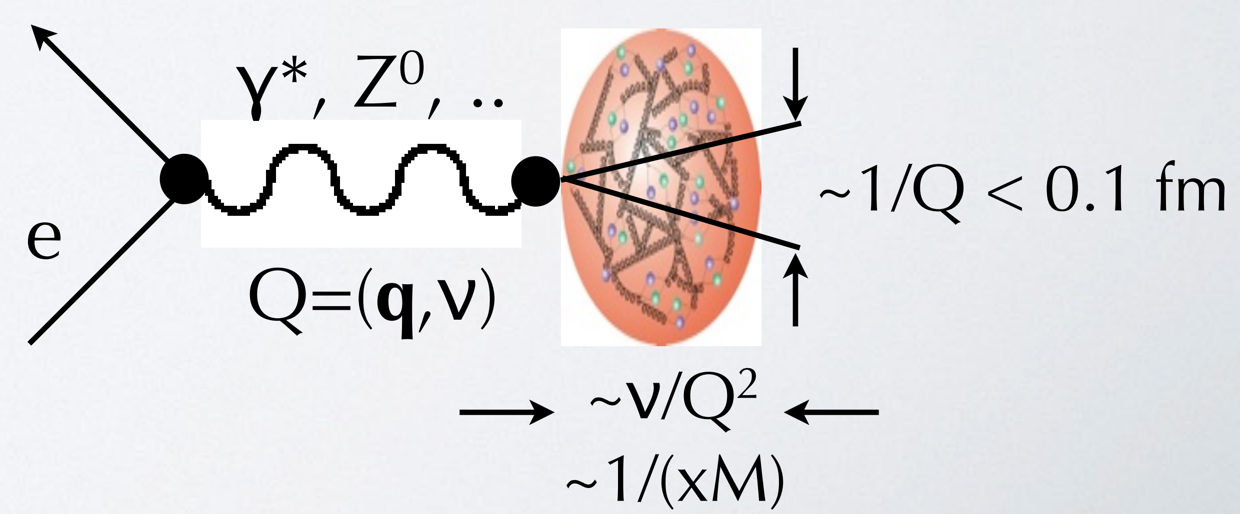
What is it all about ?

EIC = Electron - Ion Collider

machine parameters as identified in the
2015 Long Range Plan for Nuclear Science :

- **Ion beams** from protons, deuterons, to the heaviest stable nuclei
- **polarized** (~ 70%) electrons, protons, and light nuclei
- **variable c.m. energy** $\sqrt{s}$ ~20–100 GeV, upgradable to ~140 GeV
- **high** collision **luminosity** ~ $10^{33\text{-}34}$ cm^{-2} sec^{-1}
- possibly have more than one interaction region

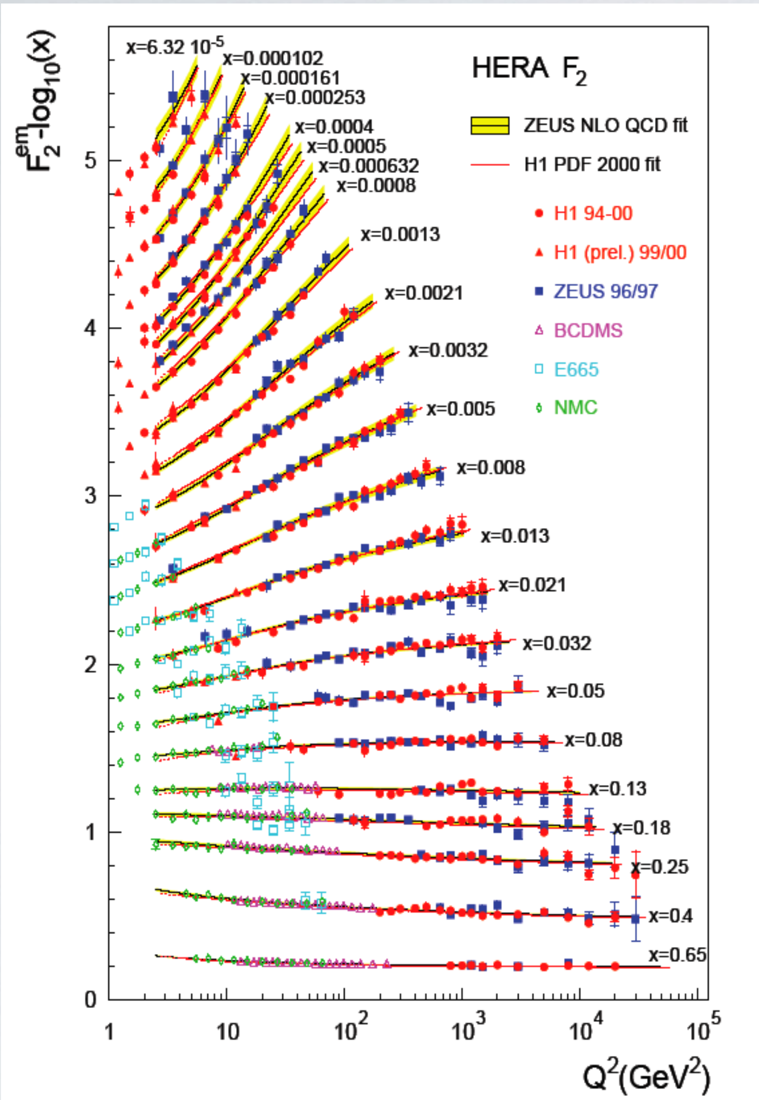
EIC = a high-resolution giant microscope



Why ?

the EIC Physics case ?

the EIC project : Why ?



from e–p collisions
@ 0.3 TeV (HERA)

(QCD)
- factorization
- evolution
- universality

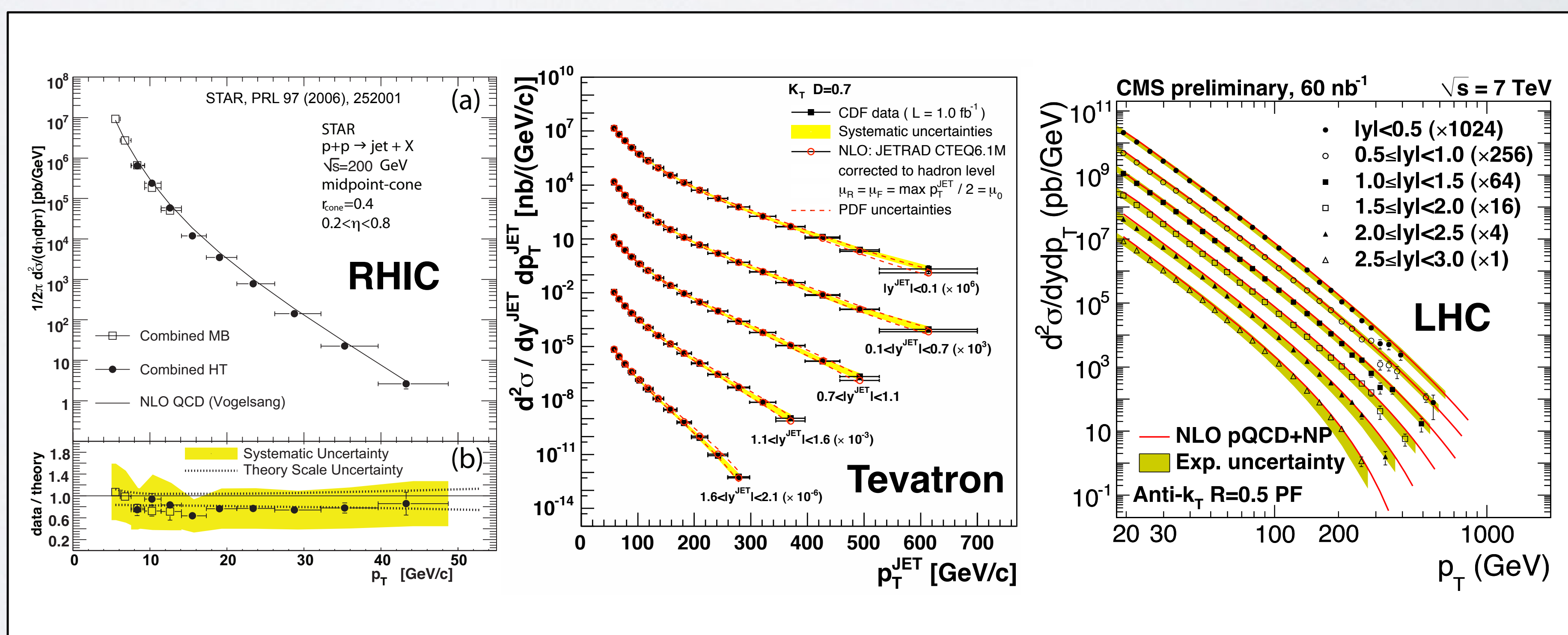
perturbative QCD

=

precision physics

works very well, but…

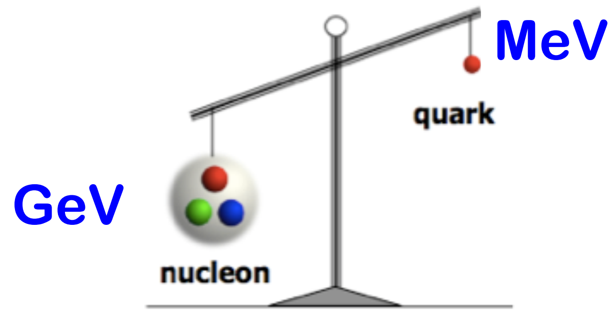
p–p, p–$\bar{p}$, jet cross section @ 0.2, 2, 7 TeV



the EIC project : Why ?

Hadron scale → non-perturbative QCD

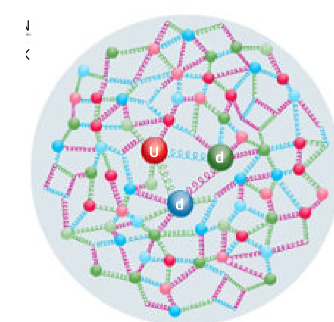
Why #1



The Higgs mechanism explains
only ~ 1% of visible matter,
which rather emerges as a result of
non-linear dynamics of QCD

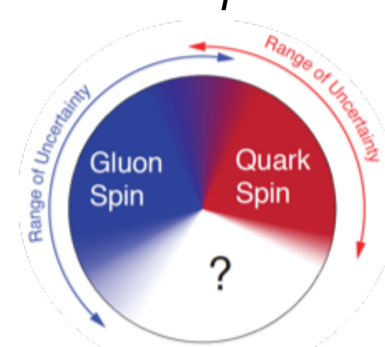
The US 2015 Long Range Plan
for Nuclear Science

".. the vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light.."

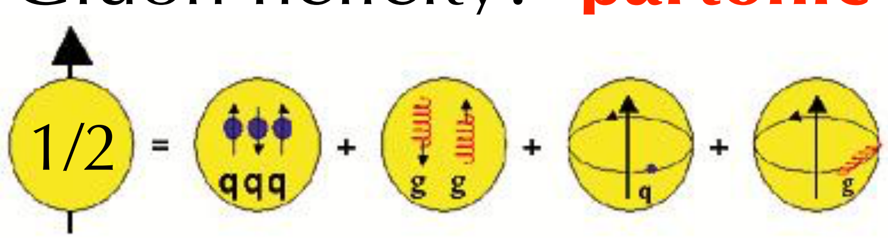


Why #2

proton spin 1/2 =



We know that quarks contribute only a fraction of nucleon's spin.
What about the rest? Gluon helicity? **partonic orbital motion ?**



the EIC project : Why ?

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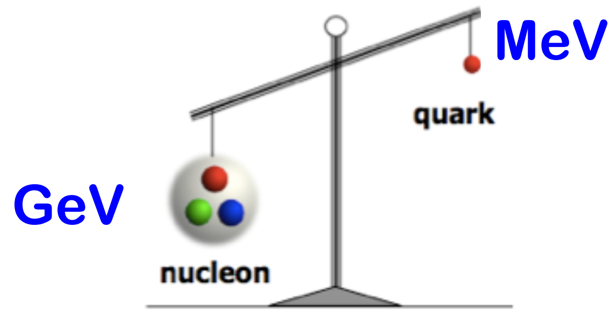
Why #1



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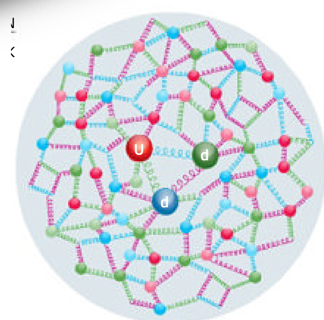
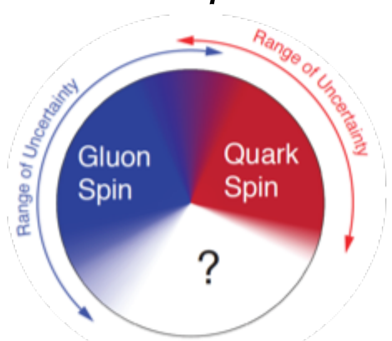


Big question:
how do the nucleon properties emerge from the non-linear QCD dynamics of confined partons?

Why # … …ton spin 1/2 =



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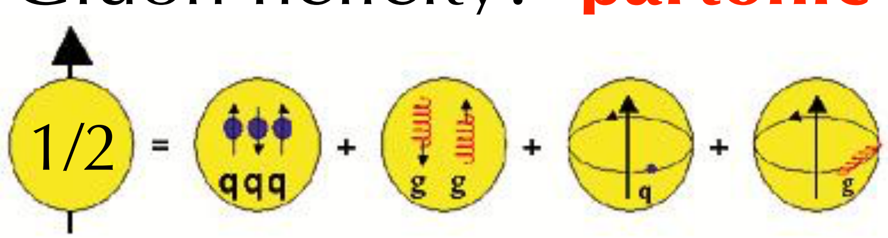
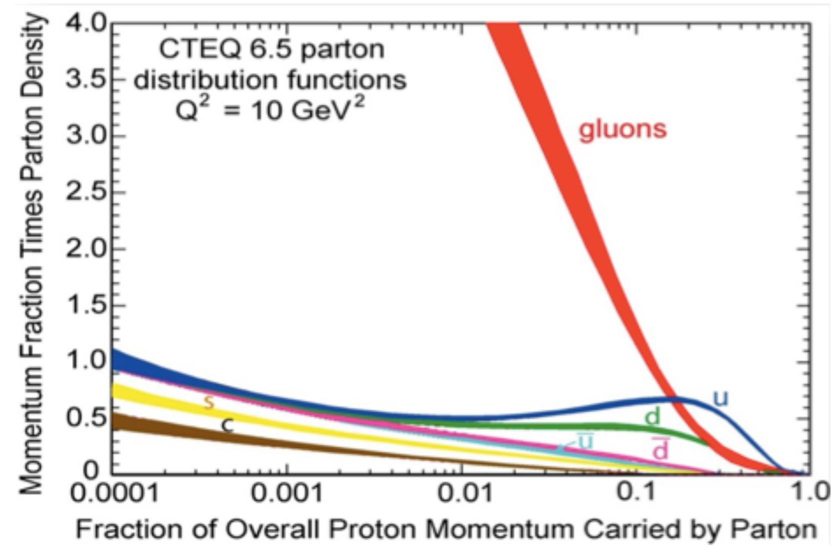
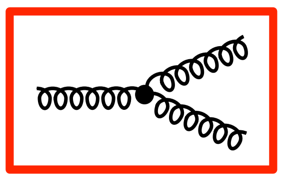


the EIC project : Why ?

Why #3

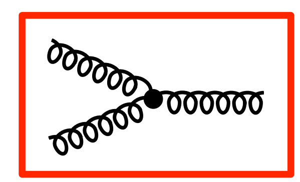
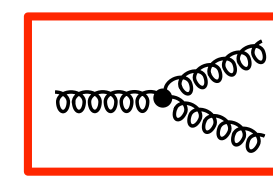


x



gluon self-interaction → proliferation of # gluons
dramatic rise of gluon density @ low fractional momenta x

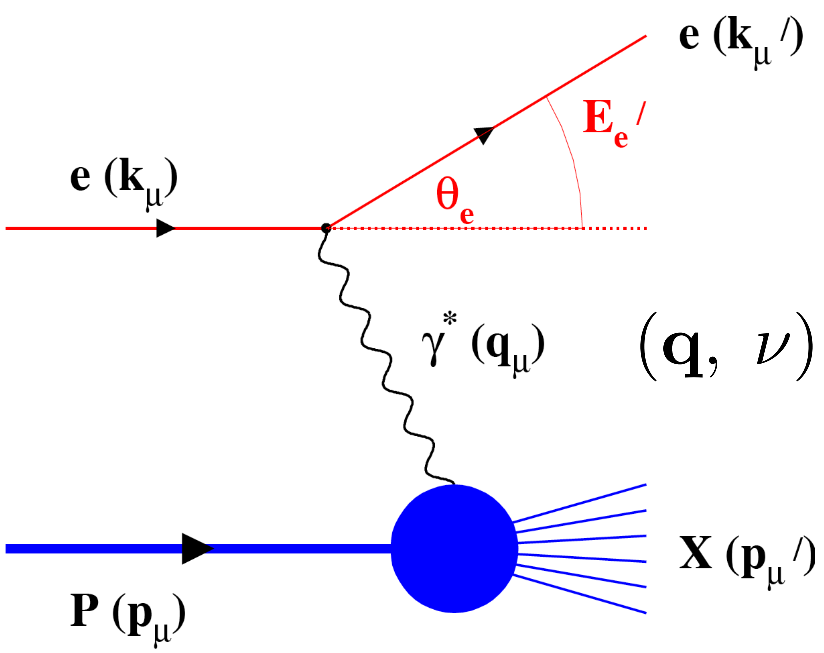
unitarity → gluons must recombine to balance splitting (saturation)

 = 

Where does saturation set in? Never clearly seen before.
Is there a universal gluonic matter at high density?
How does nuclear matter affect quark & gluon interactions?

the EIC project

Electron-Ion Collider : a multi-purpose microscope



$$y = \frac{P\cdot q}{P\cdot k} = \frac{\nu}{E_e} = 1 - \frac{E_e'}{E_e}\cos^2\frac{\theta_e}{2}$$ measure of inelasticity

$$Q^2 = \mathbf{q}^2 - \nu^2 = 2E_e\,E_e'\,(1-\cos\theta_e)$$ measure of resolution

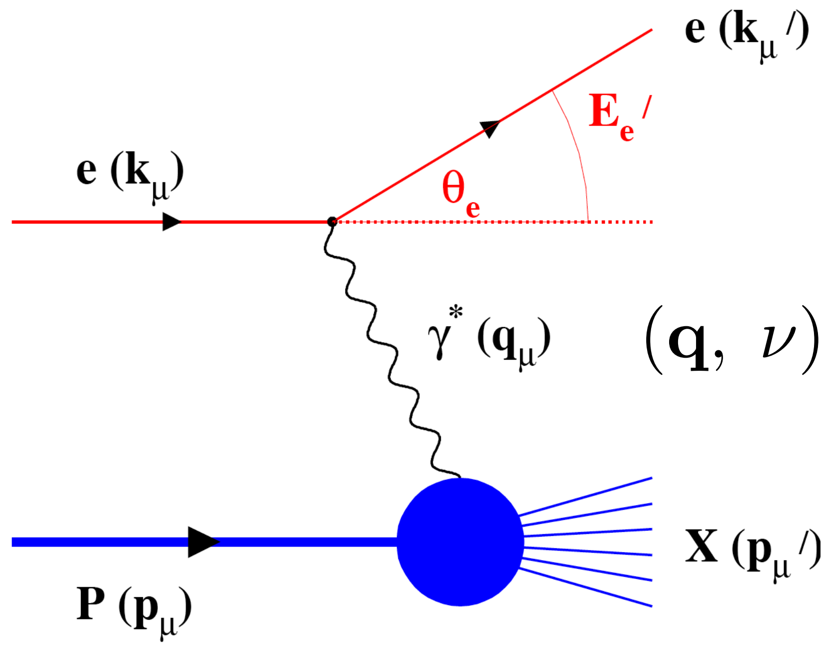
$$x = \frac{Q^2}{2P\cdot q}$$ fractional momentum of struck parton

$$\sqrt{s} = 2\sqrt{E_e\,E_P}$$ c.m. energy

e + p/A → e′	+ X	**inclusive**
→ e′ + h (π, K, p, jet)	+ X	**semi-inclusive**
→ e′ + h (π, K, p, jet)	+ p′/A′	**exclusive**

very good PID capability required !

Electron-Ion Collider : a multi-purpose microscope



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→ e′ + h (π, K, p, jet) + p′/A′ **exclusive**

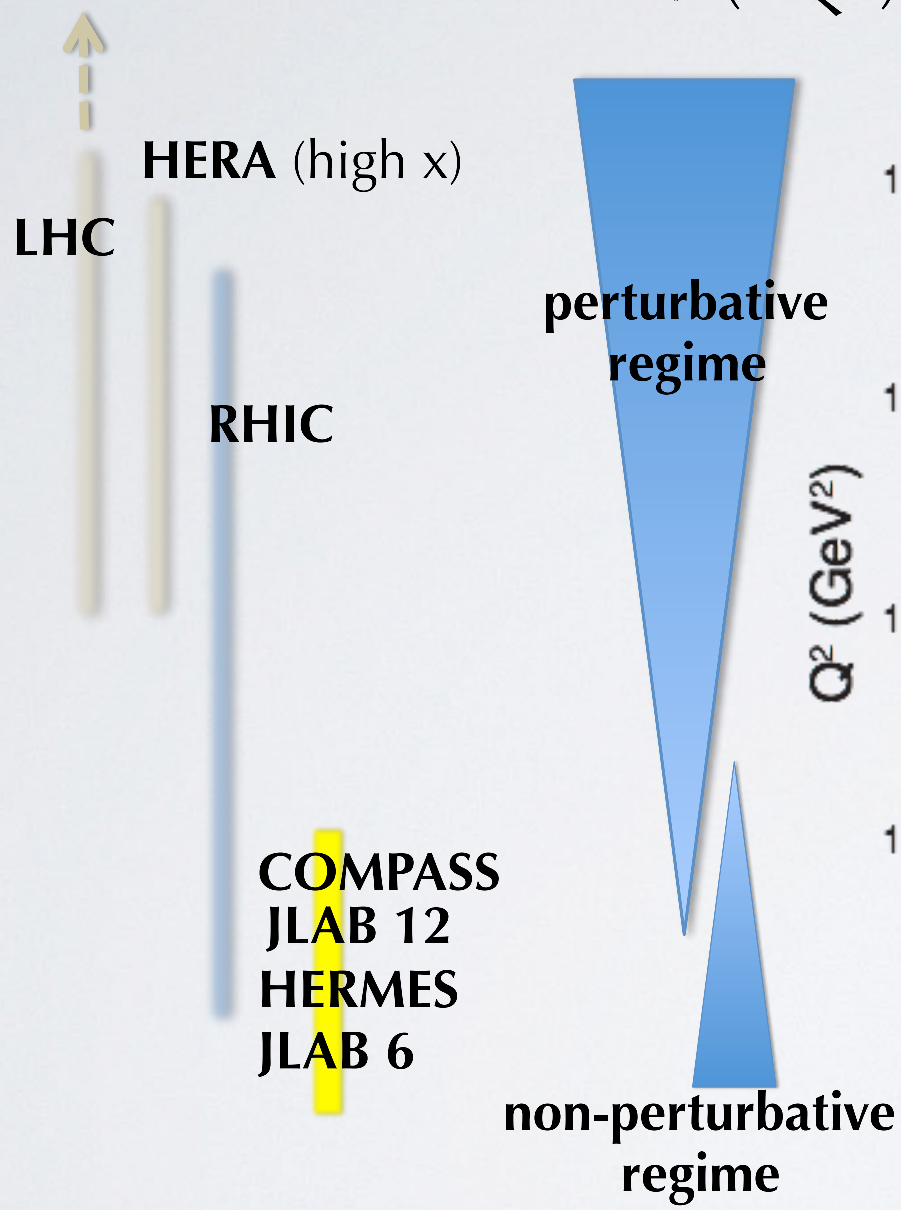
very good PID capability required !

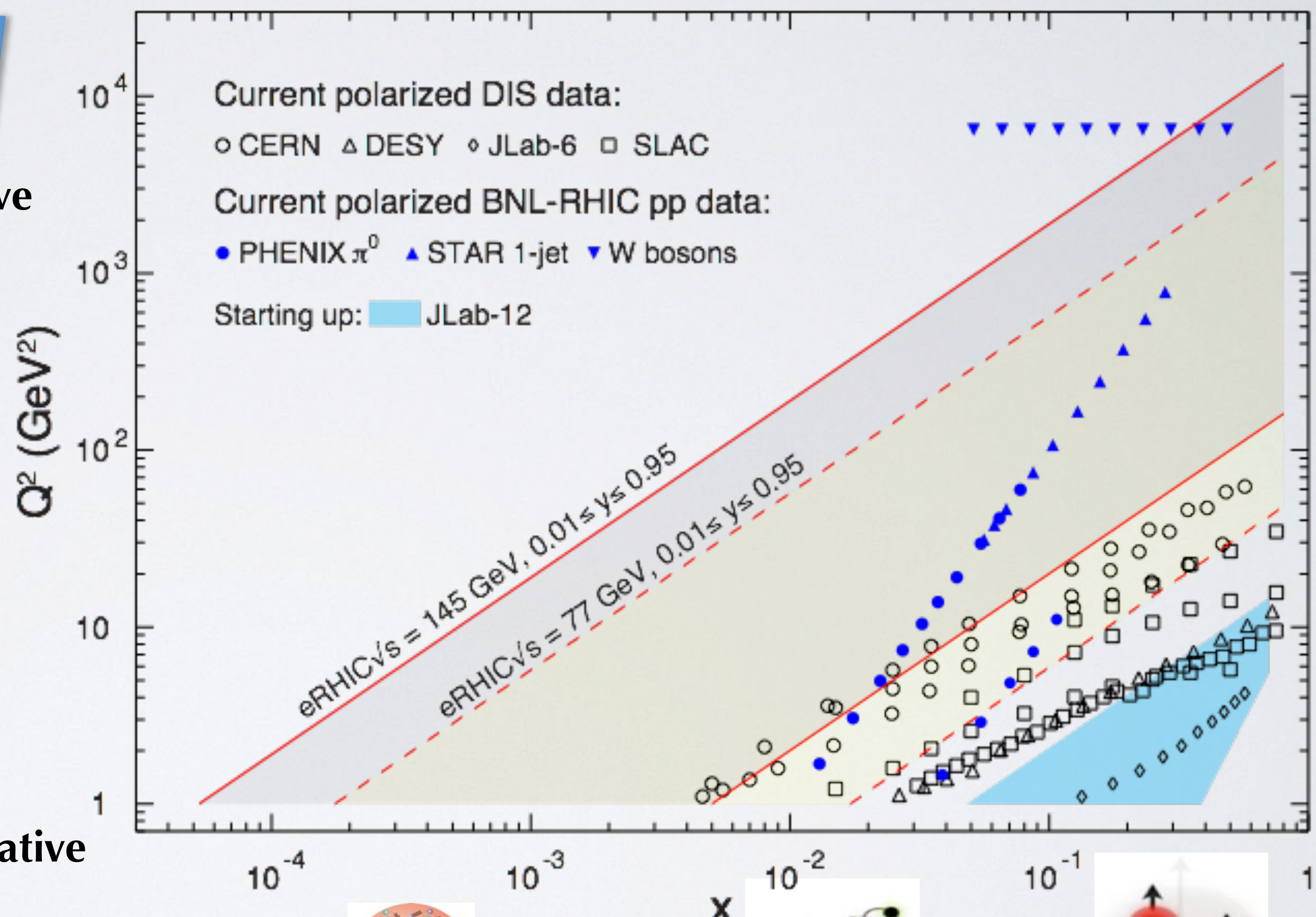
$$Q^2 = s \; x \; y$$

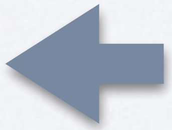
the EIC project

$Q^2 = s\,x\,y$ the larger the energy the larger the coverage, but

$\sigma \sim 1/(xQ^4)$ and detector resolution $\Rightarrow y > y_{min}$

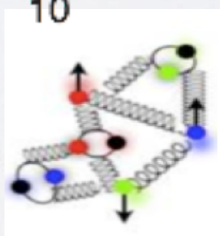




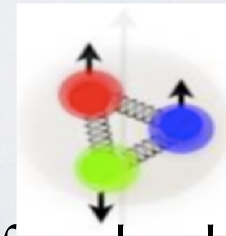


saturation regime

collective regime



many-body regime

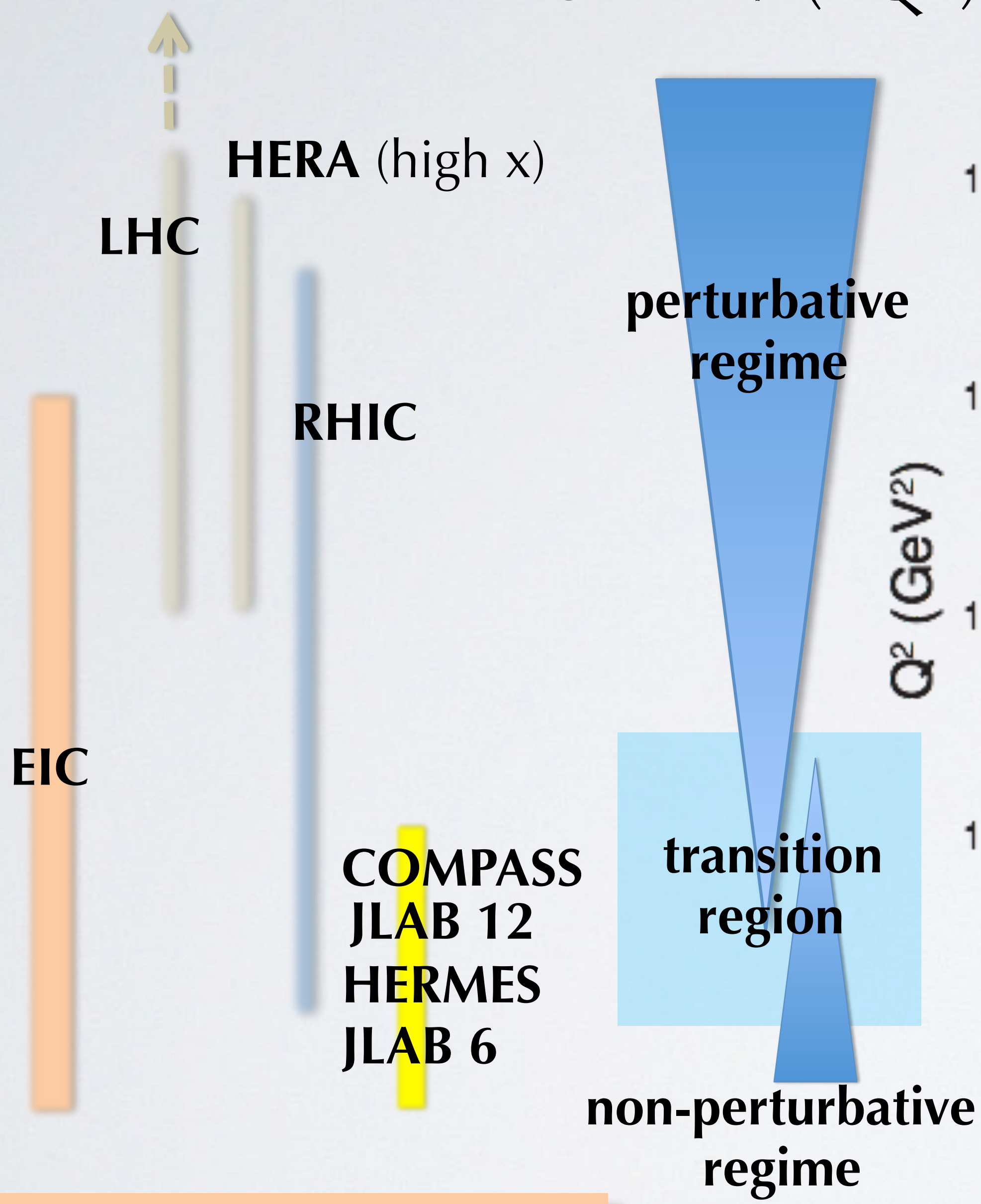


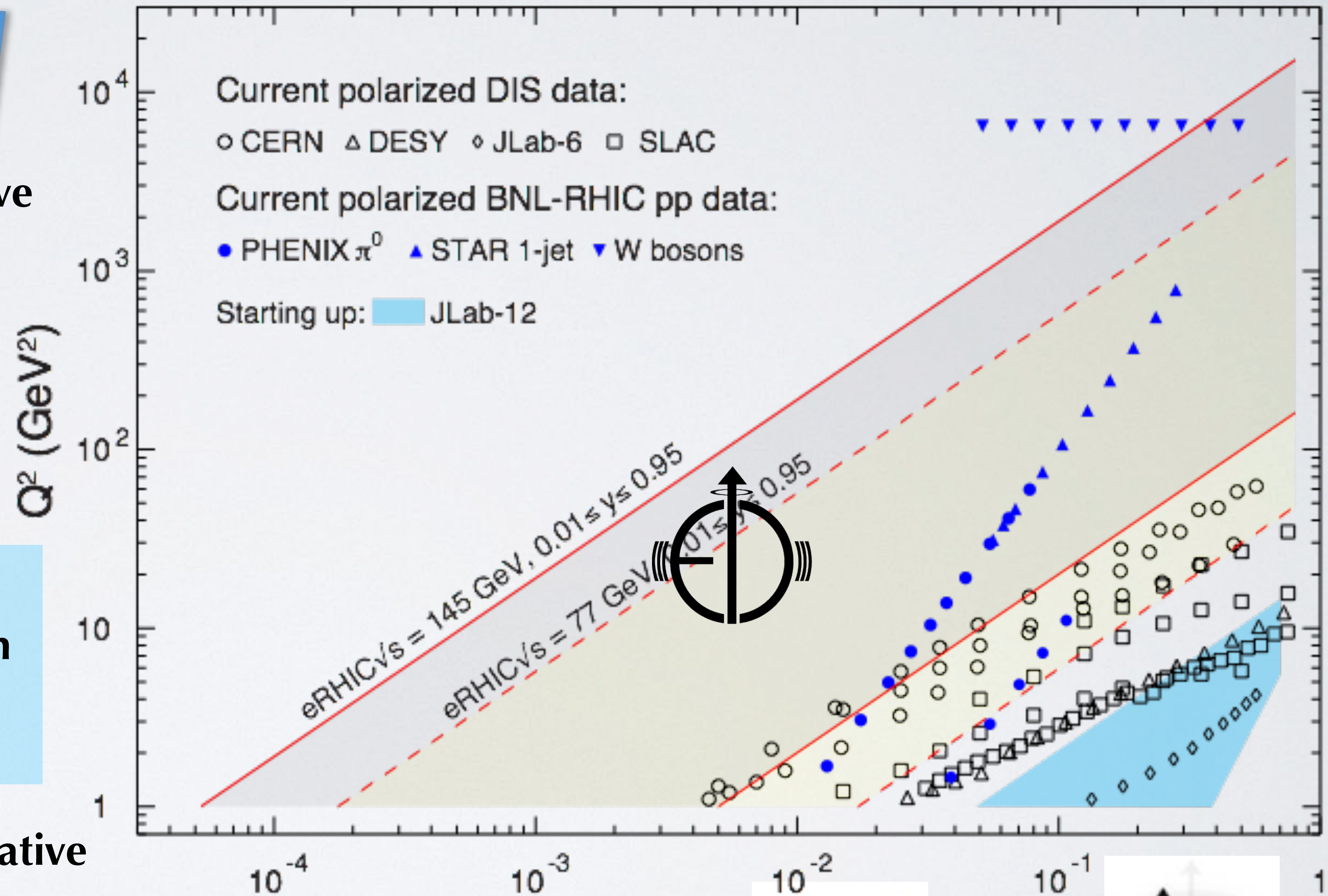
few-body regime (JLab12)

the EIC project

$Q^2 = s\,x\,y$ the larger the energy the larger the coverage, but

$\sigma \sim 1 / (xQ^4)$ and detector resolution $\Rightarrow y > y_{min}$

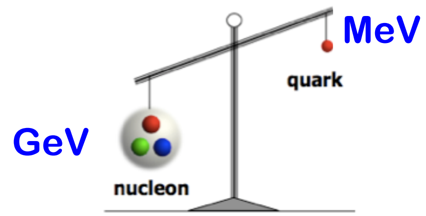




- large lever arm in Q^2 (evolution)
- disentangle non-pert./pert. regimes

NP QCD: from Discovery to Precision

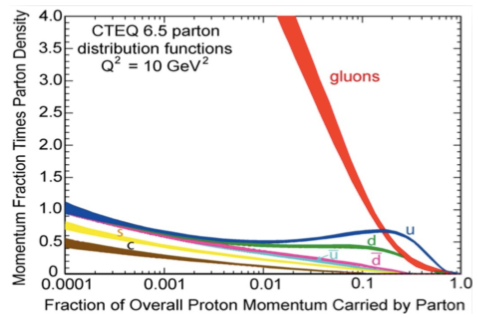
Why #1



Why #2

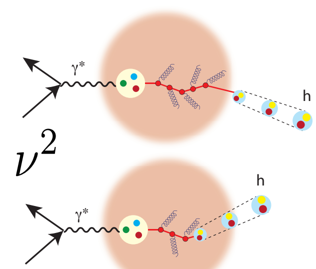
proton
spin 1/2

Why #3

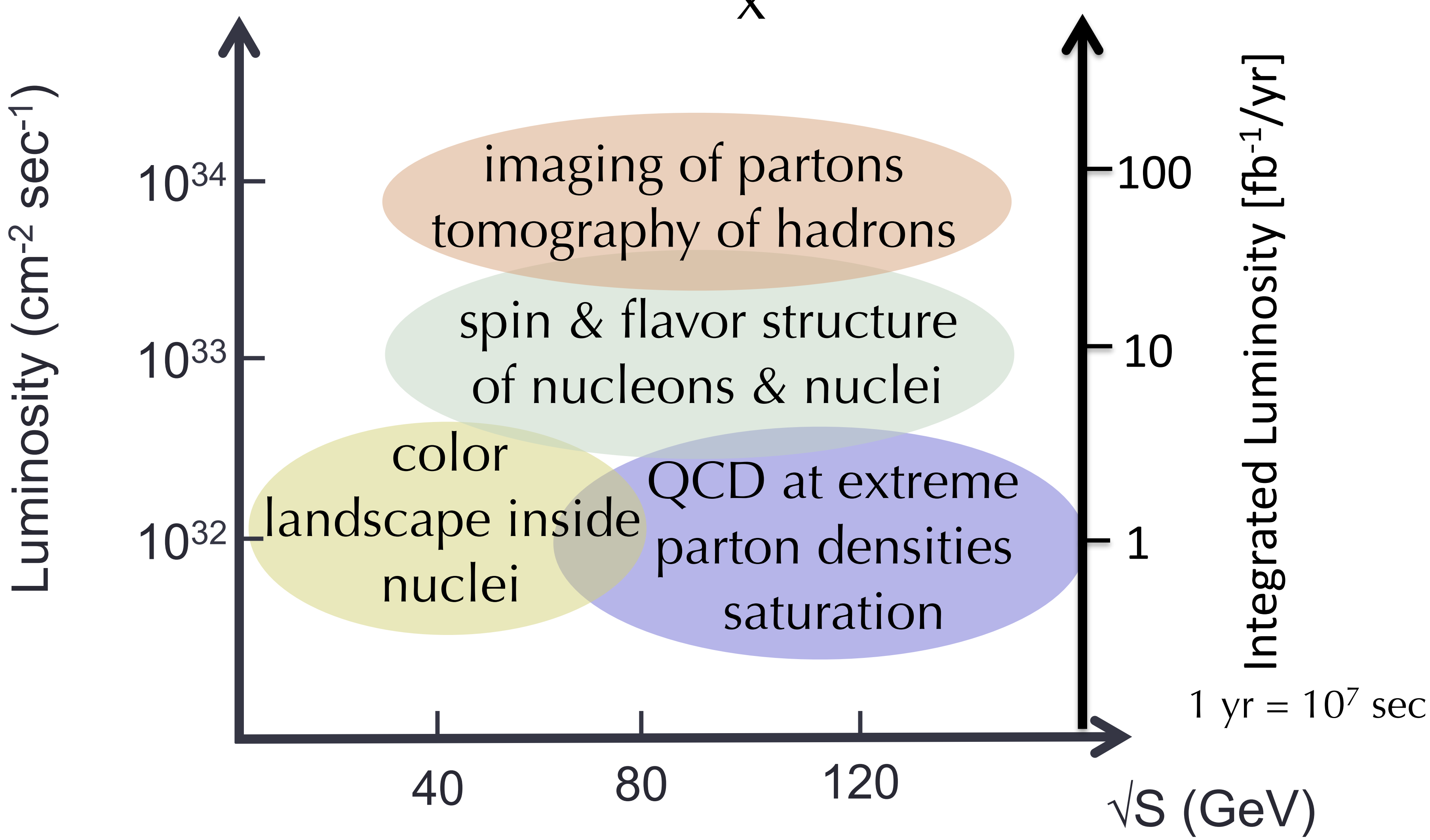


x

$$Q^2 = \mathbf{q}^2 - \nu^2$$



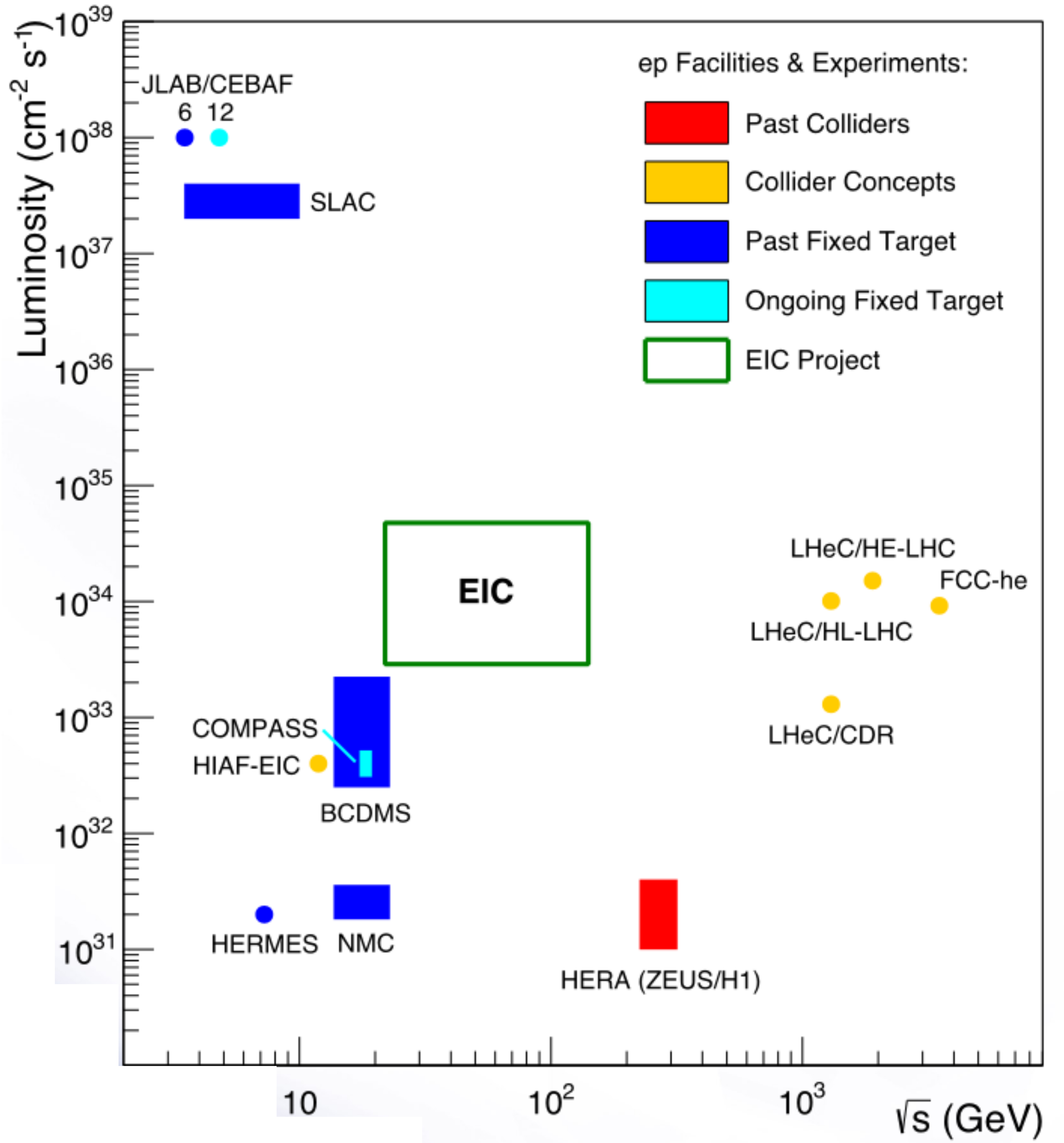
$$\frac{\nu}{Q^2} = \frac{1}{2xM}$$



high luminosity
and polarization

wide range of
c.m. energies and
nuclear probes

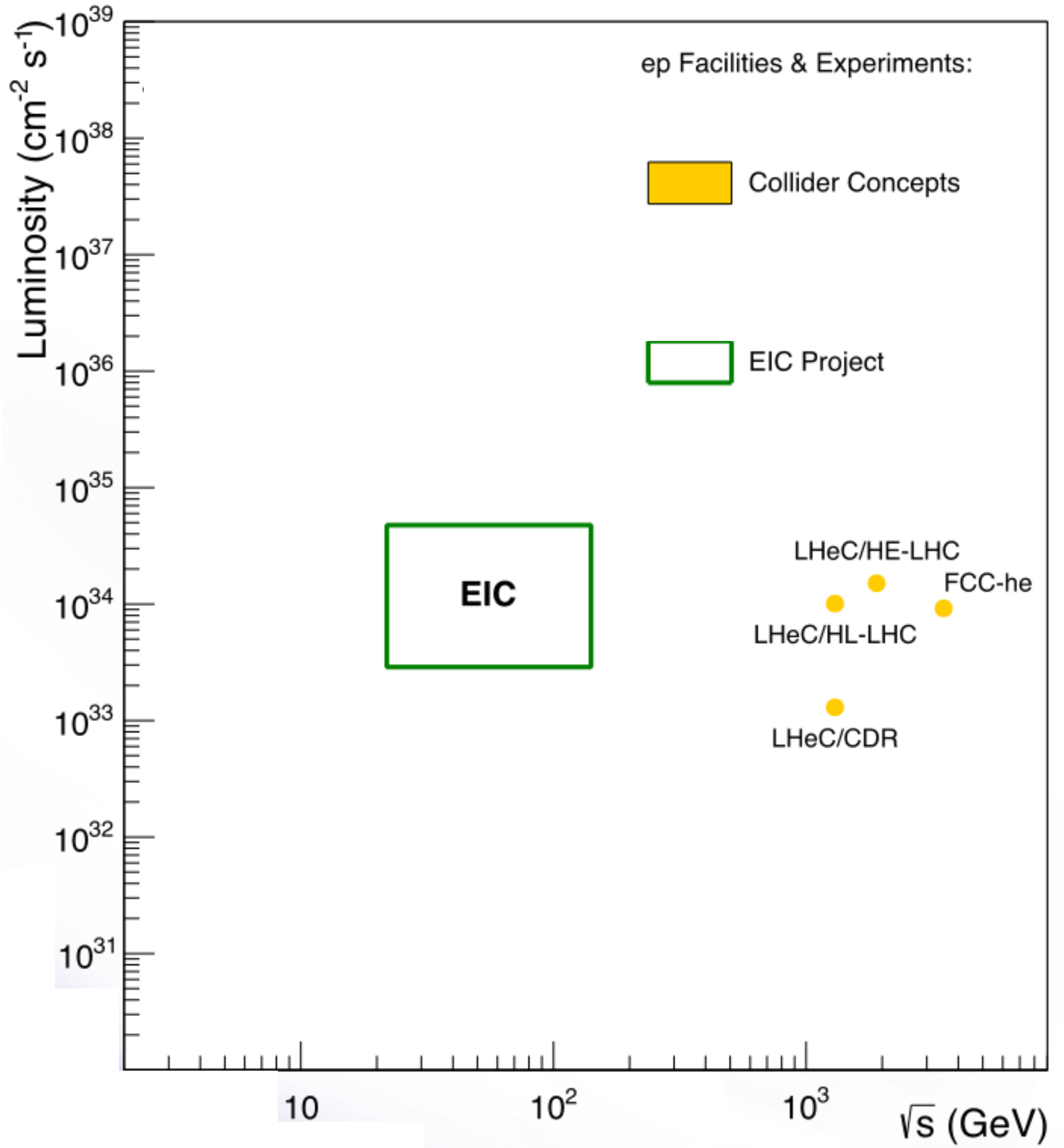
Uniqueness of EIC



All DIS facilities in the world

However, if we ask for…

Uniqueness of EIC



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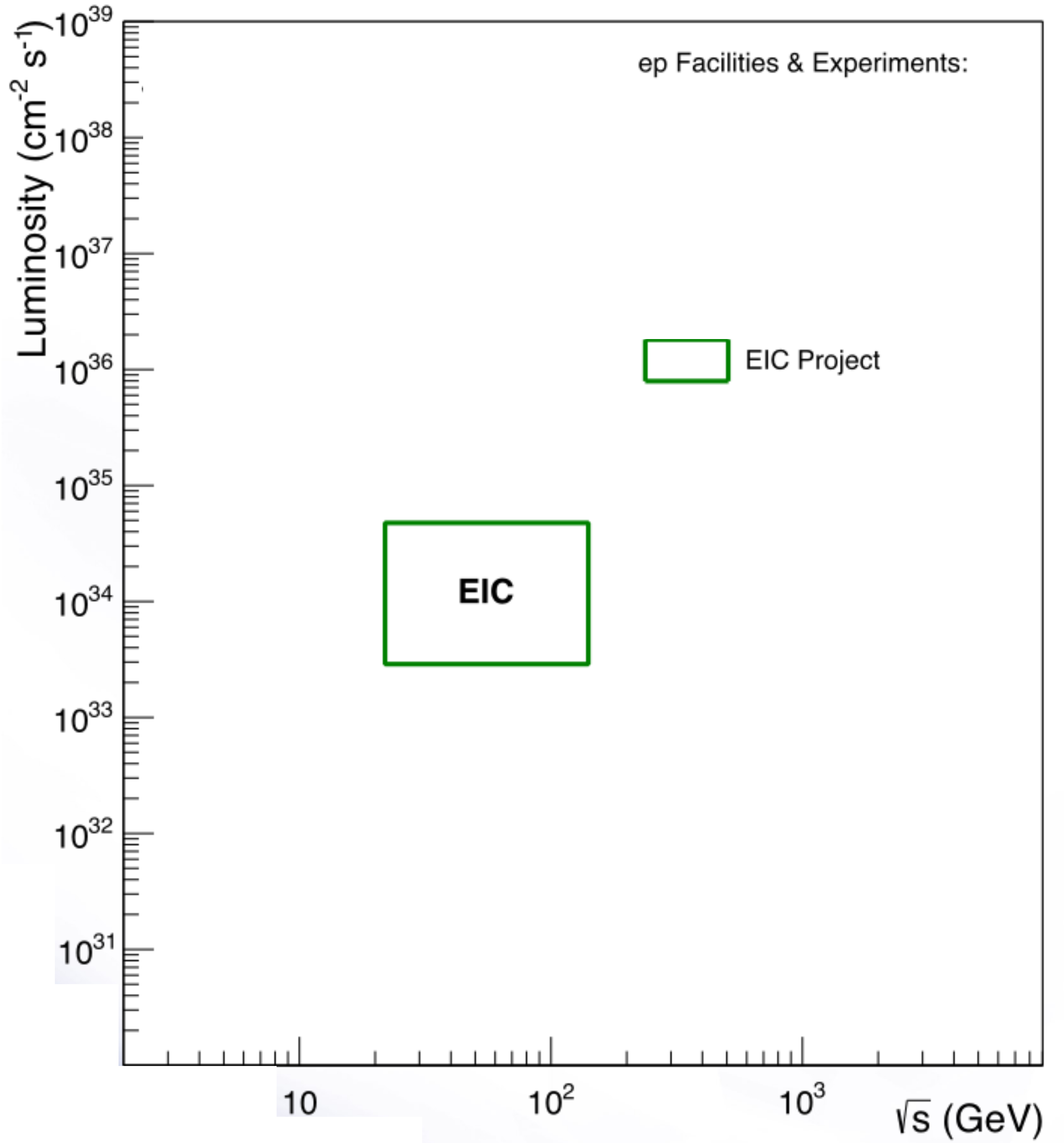
However, if we ask for…

- high luminosity and wide reach in $\sqrt{s}$

Uniqueness of EIC



All DIS facilities in the world

However, if we ask for…

- high luminosity and wide reach in $\sqrt{s}$
- polarized lepton & hadron beams
- nuclear beams

EIC stands out as unique facility

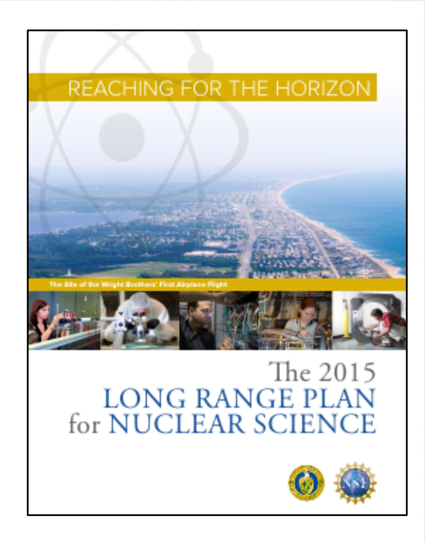
Potential of EIC

A glimpse of
the expected performance of EIC
about some "observables" related to
the issues raised by Why's

details in

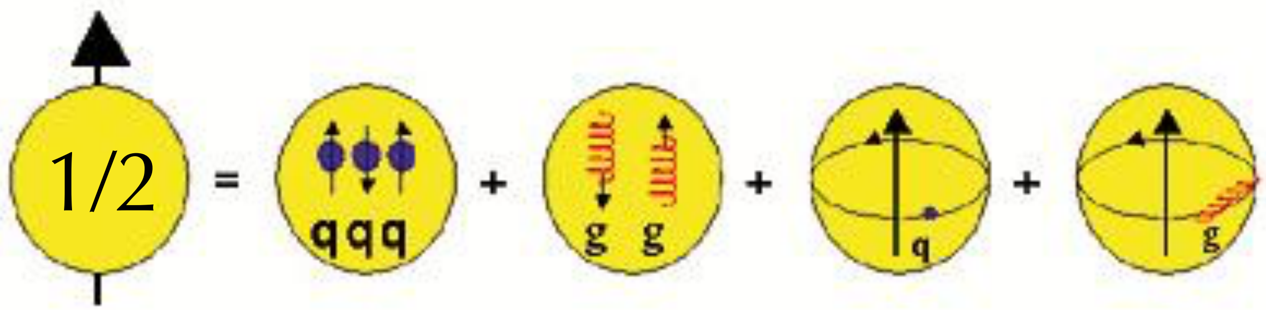
INT 2010
arXiv:1108.1713

White Paper
*EPJ **A52** (16) 268, arXiv:1212.1701*



The Nucleon Spin Puzzle

Why #2 : How does QCD generate the Nucleon's spin ?



sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + \sum_q L^{q+\bar{q}} + L^g \Big|_{Q^2}$$

1st step:
the parton helicities

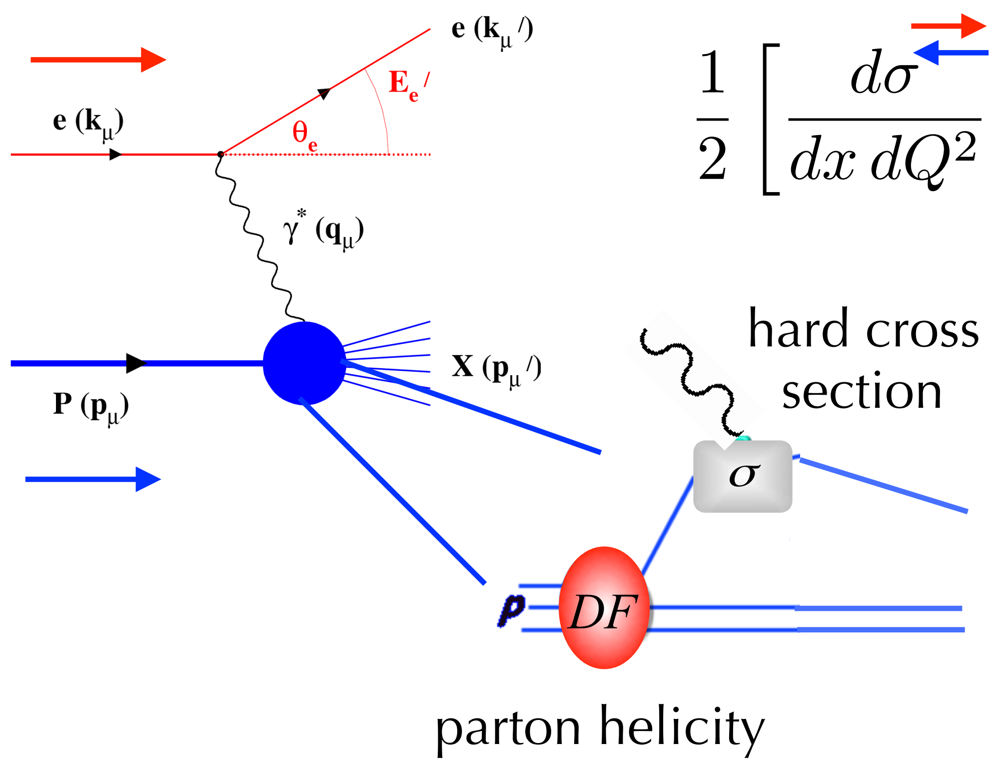
quark $\Delta\Sigma(Q^2) = \sum_q [\,\Delta q(Q^2) + \Delta\bar{q}(Q^2)\,]$

gluon $\Delta g(Q^2)$

where do they come from?

The Nucleon Spin Puzzle

polarized Deep-Inelastic Scattering (DIS)



$$\frac{1}{2}\left[\frac{d\sigma^{\rightleftarrows}}{dx\,dQ^2} - \frac{d\sigma^{\rightrightarrows}}{dx\,dQ^2}\right] \simeq \frac{4\pi\alpha^2}{Q^4}\; y\,(2-y)\; g_1(x,Q^2) + \mathcal{O}\left(\frac{M^2}{Q^2}\right)$$

factorization theorem:

connect nucleon (g_1) to parton (Δq, Δg)

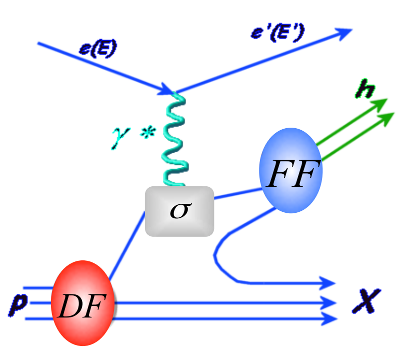
$$\int_0^1 dx\; g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2\,[\,\Delta q(Q^2) + \Delta\bar{q}(Q^2)]$$

at leading order (LO)

$$\int_0^1 dx\; \frac{dg_1}{d\log Q^2} \longrightarrow \Delta g(Q^2)$$

scaling violations at NLO

Semi-Inclusive DIS

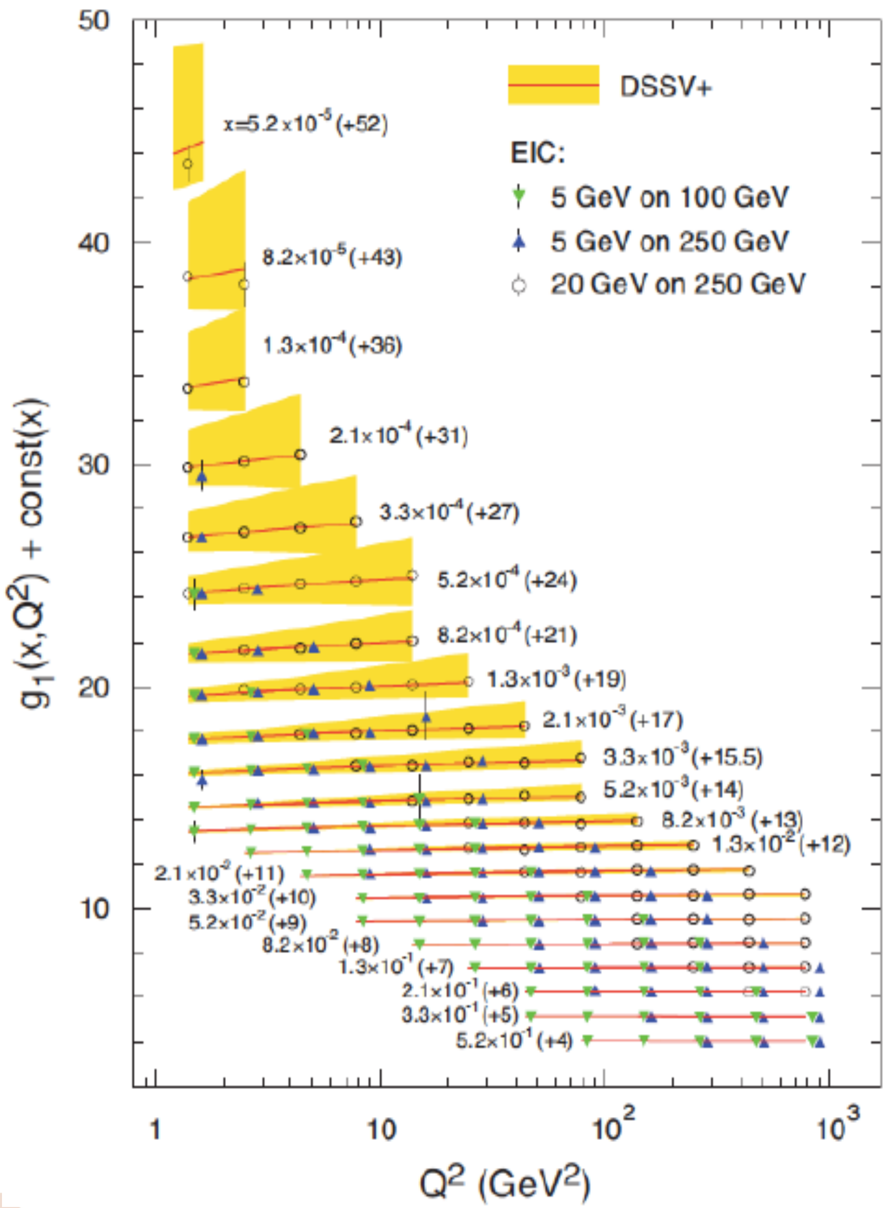


$$\int_0^1 dx\; g_1^h(x,Q^2,z) = \frac{1}{2}\sum_q e_q^2\,[\,\Delta q(Q^2)\,D_q^h(Q^2) + \Delta\bar{q}(Q^2)\,D_{\bar{q}}^h(Q^2)]$$

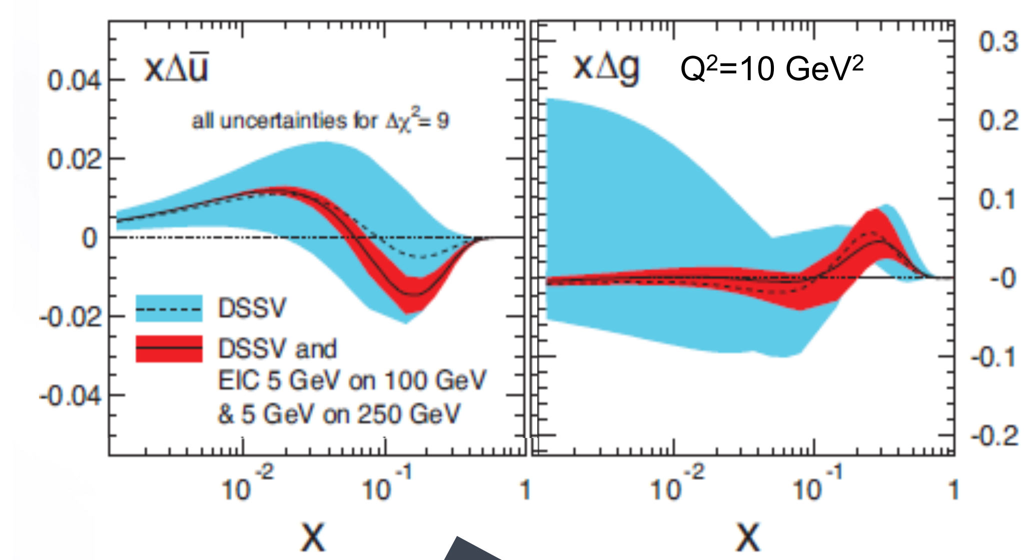
separate various flavors

The Nucleon Spin Puzzle

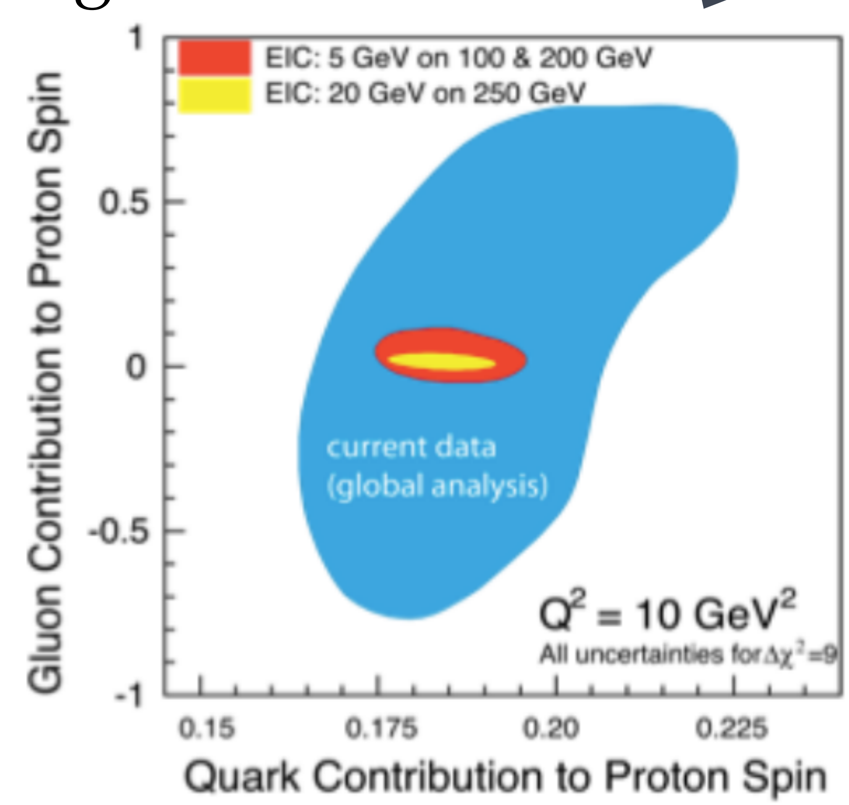
generate pseudo-data



fit → g_1^q, $g_1^{\bar{q}}$, g_1^g



Δg

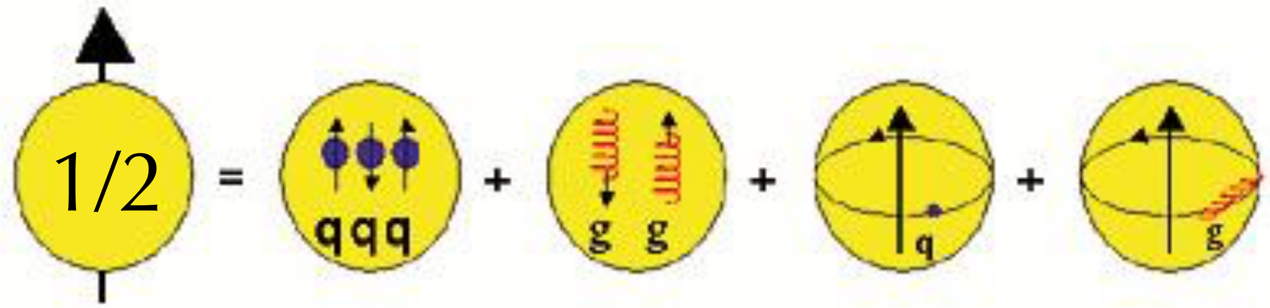


ΔΣ /2

huge impact from EIC !

the first polarized electron-proton collider

The Nucleon Spin Puzzle



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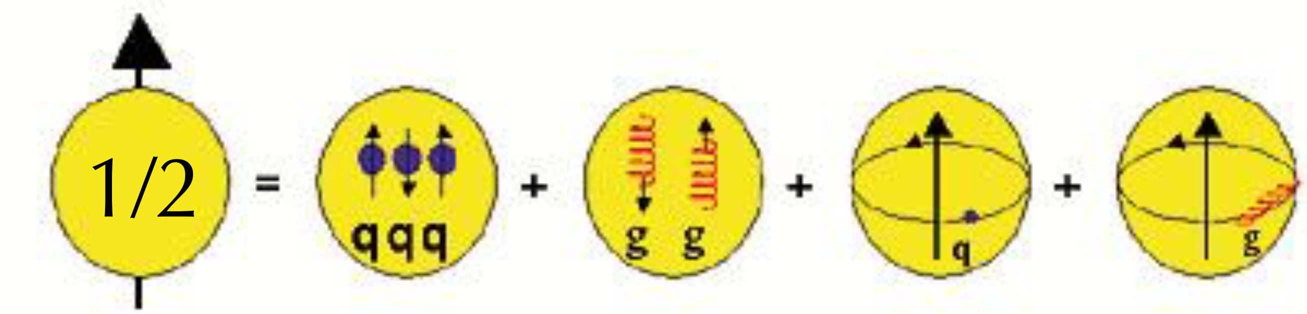
2nd step:

precise knowledge ➡ clear idea of size of Orbital Angular Mom. (OAM)

The Nucleon Spin Puzzle



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2nd step: precise knowledge ➡ clear idea of size of Orbital Angular Mom. (OAM)

<u>Present situation is not so clear…</u>

- new data from RHIC → new fit DSSV14 → **Δg larger → no room for OAM** **but data only in x ∈ [0.02,0.4]**

STAR *P.R.L.* ***115*** *(15) 092002*

PHENIX *P.R.* ***D90*** *(14) 012007*

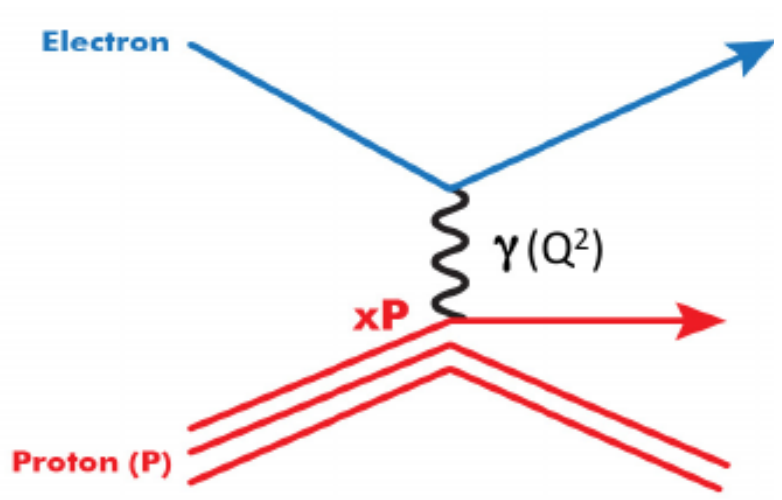
De Florian et al.,
P.R.L. ***113*** *(14) 012001*

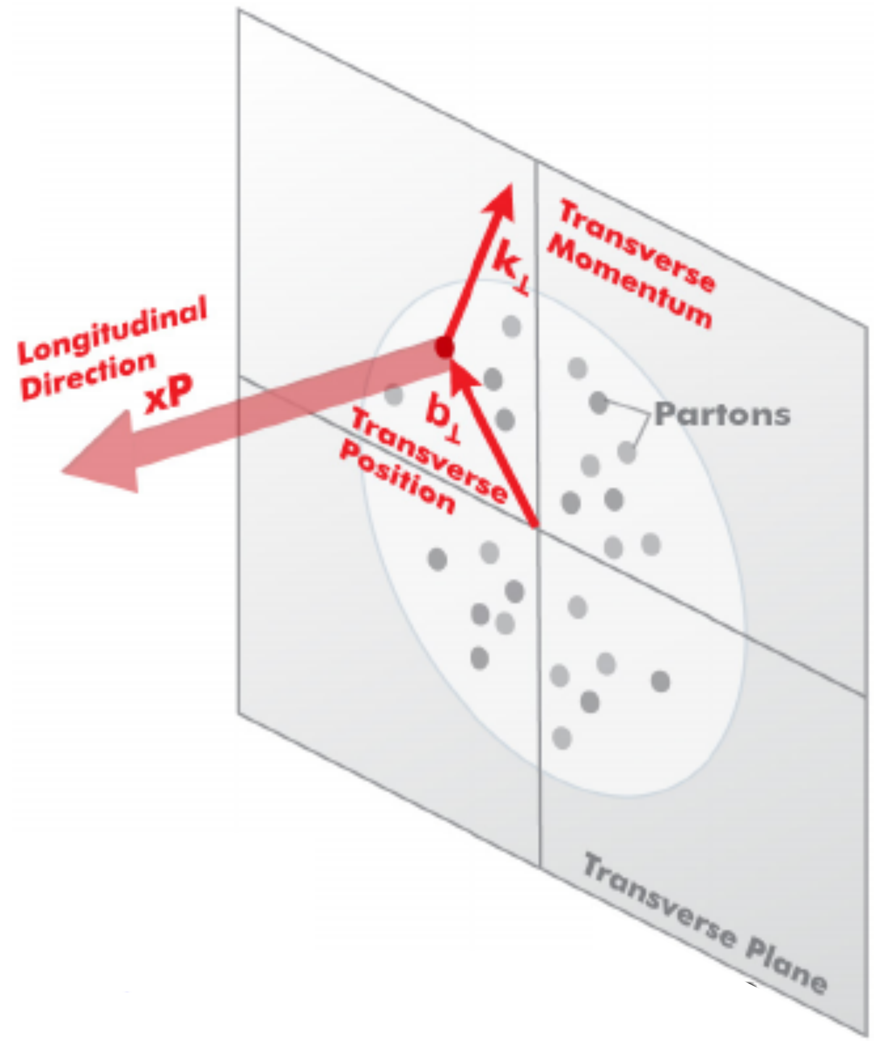
- recent lattice calculations from χQCD Collab. → direct $S^g \sim 50\% \pm 10\%$ *P.R.L.* ***118*** *(17) 102001*
  → **sea quark OAM** = $J^q - \Delta\Sigma/2$ **~ 50% ± 10%**
  P.R. ***D91*** *(15) 014505*

$S^g \leftrightarrow \Delta g$?
disconnected diagrams ?

3Dim Imaging of Partons

In order to directly explore the orbital motion of partons, we need to extend our view **from 1Dim to 3Dim pictures**





need two scales $Q \gg Q_0$:

- hard scale Q to localize the probe and see partons as particles

- soft scale $Q_0 \sim k_\perp \sim 1/b_\perp \sim \Lambda_{QCD}$ to be sensitive to confinement scale

high luminosity required !

New Tools

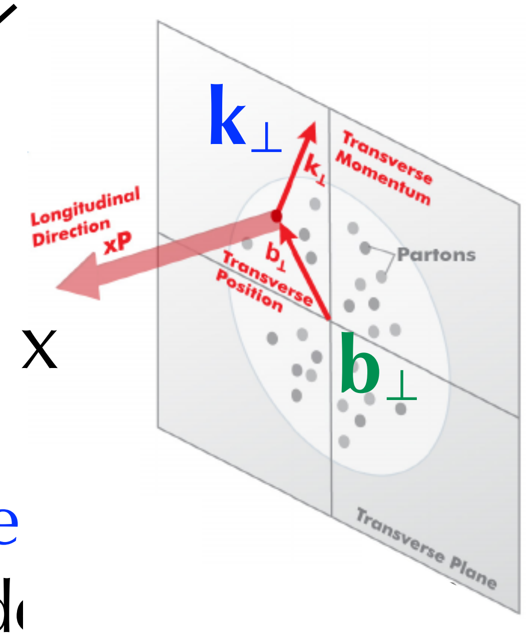
Useful tool for 3Dim imaging of partons: **Wigner distributions**

$W(x, \mathbf{k}_\perp, \mathbf{b}_\perp)$

momentum space

$\int d\mathbf{b}_\perp$

$q(x, \mathbf{k}_\perp)$



coordinate space

$\int d\mathbf{k}_\perp$

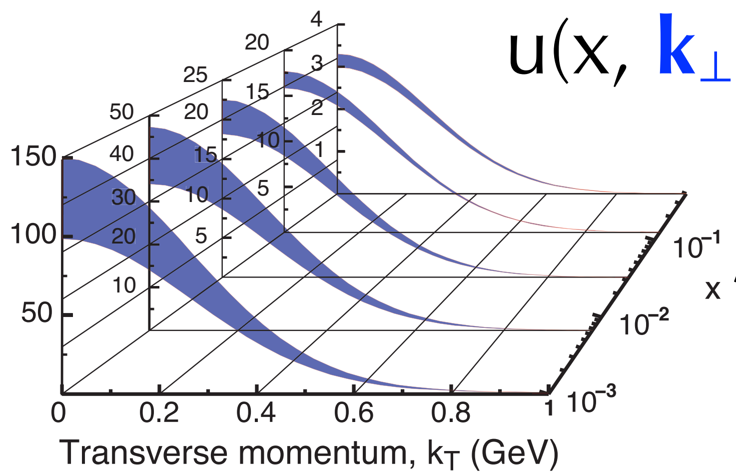
$q(x, \mathbf{b}_\perp)$

3Dim images in mom. space
Transverse-Momentum Dependent
distribution functions
TMD's
SIDIS: factor. th. if $\mathbf{k}_\perp \ll Q$

2 + 1 Dim images
$\perp$ coord. space + x long. mom.
Fourier Transformed ($\mathbf{b}_\perp \leftrightarrow \mathbf{q}$) of
Generalized Parton Distributions
GPD's
exclusive processes: factor. th. if $-\mathbf{q}^2 \ll Q^2$

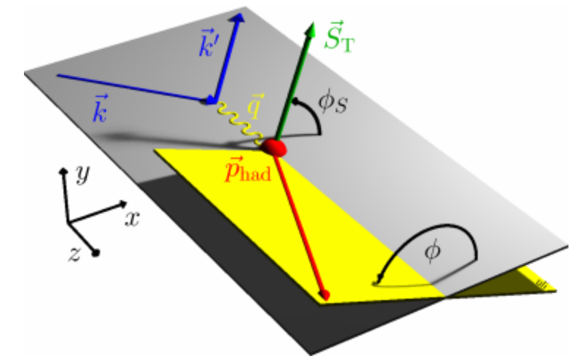
$\mathbf{k}_\perp \not\leftrightarrow \mathbf{b}_\perp$

TMD : the Sivers function



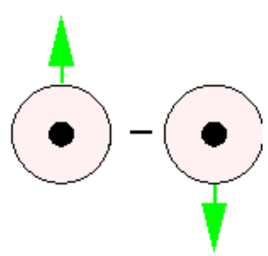
u(x, $\mathbf{k}_\perp$)

SIDIS : e + N → e′ + h + X



the "TMD zoo" at leading twist

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ -
	L		$g_1 =$ -	$h_{1L}^\perp =$ -
	T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

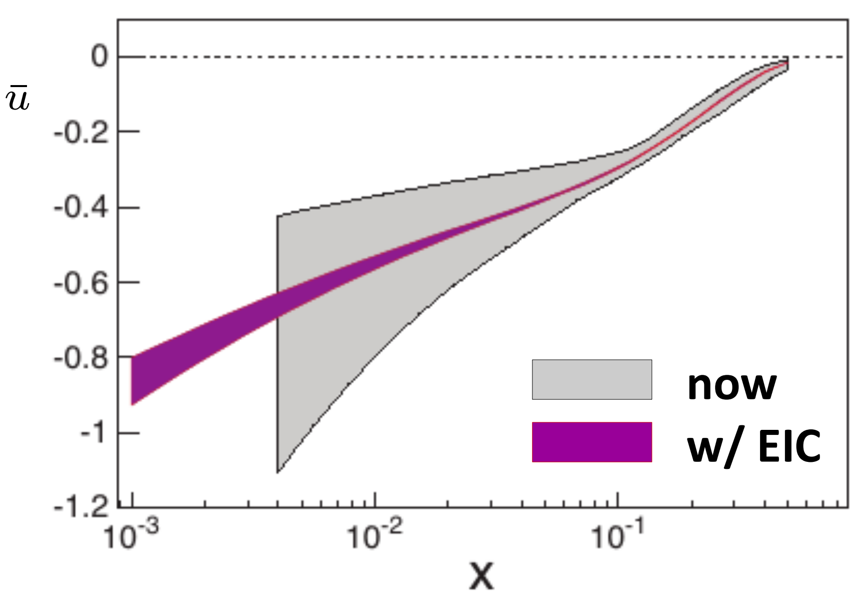


Sivers function

distortion of q distribution because of N↑ polarization

*Sivers, P.R. D **41** (90) 83*

$$\int dk_\perp^2 \, \frac{k_\perp^2}{2M^2} \, f_{1T}^{\perp\, u-\bar{u}}$$



Saturation at high nuclear density

Why #3 : Is there a universal gluon matter at high density?

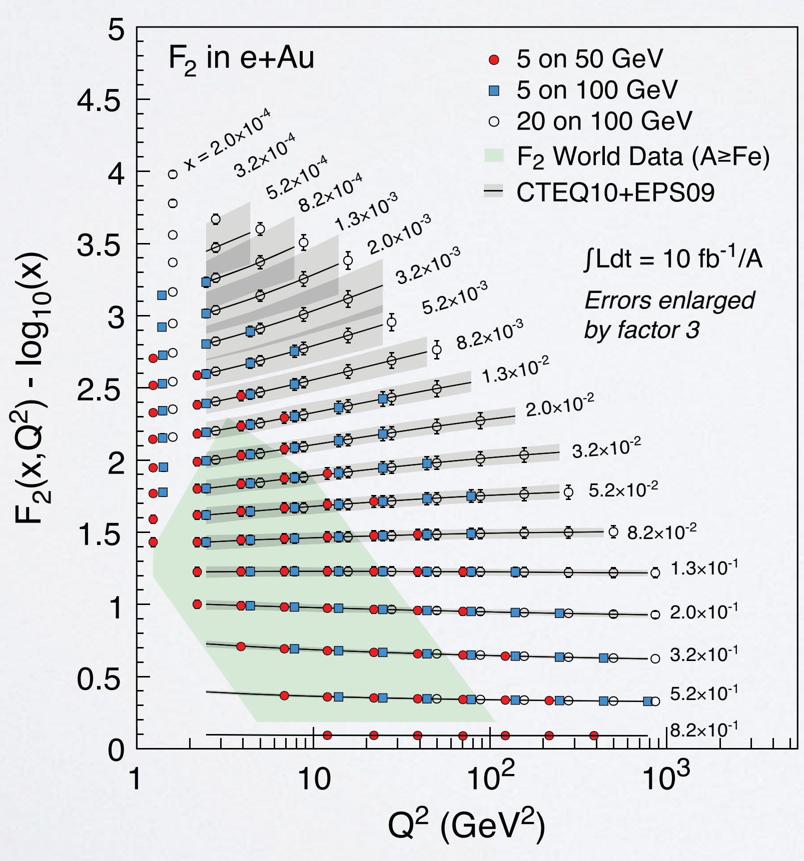
First of all, how well do we know nuclear nPDF?

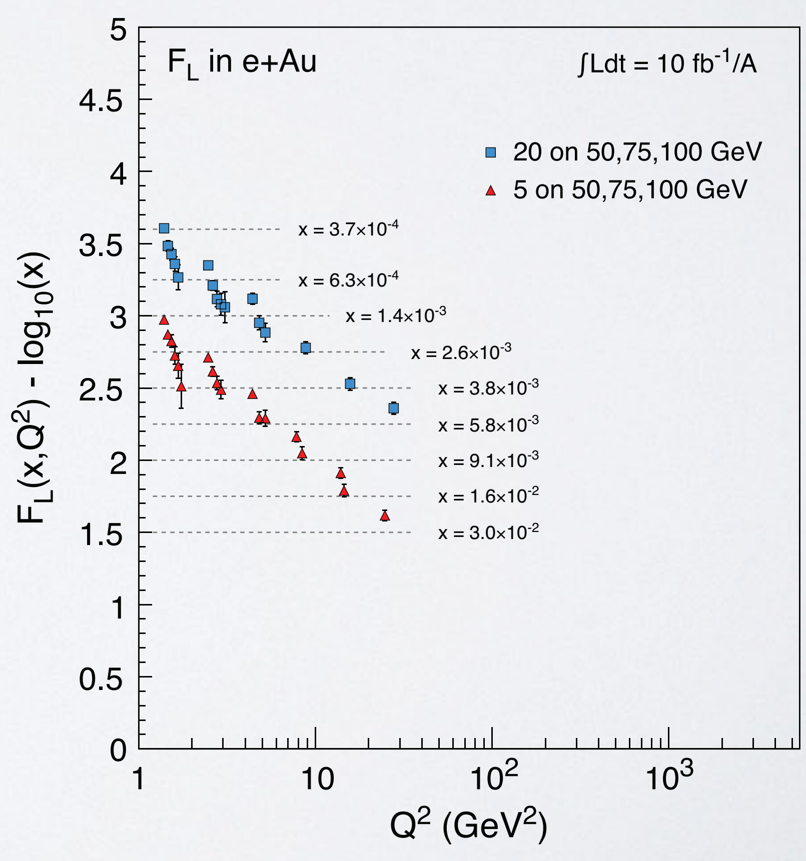
DIS $$\frac{d\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right) F_2(x,Q^2) - \frac{y^2}{2} F_L(x,Q^2)\right]$$

$q + \bar{q}$ mom. distributions

gluon mom. distribution

generate pseudo-data

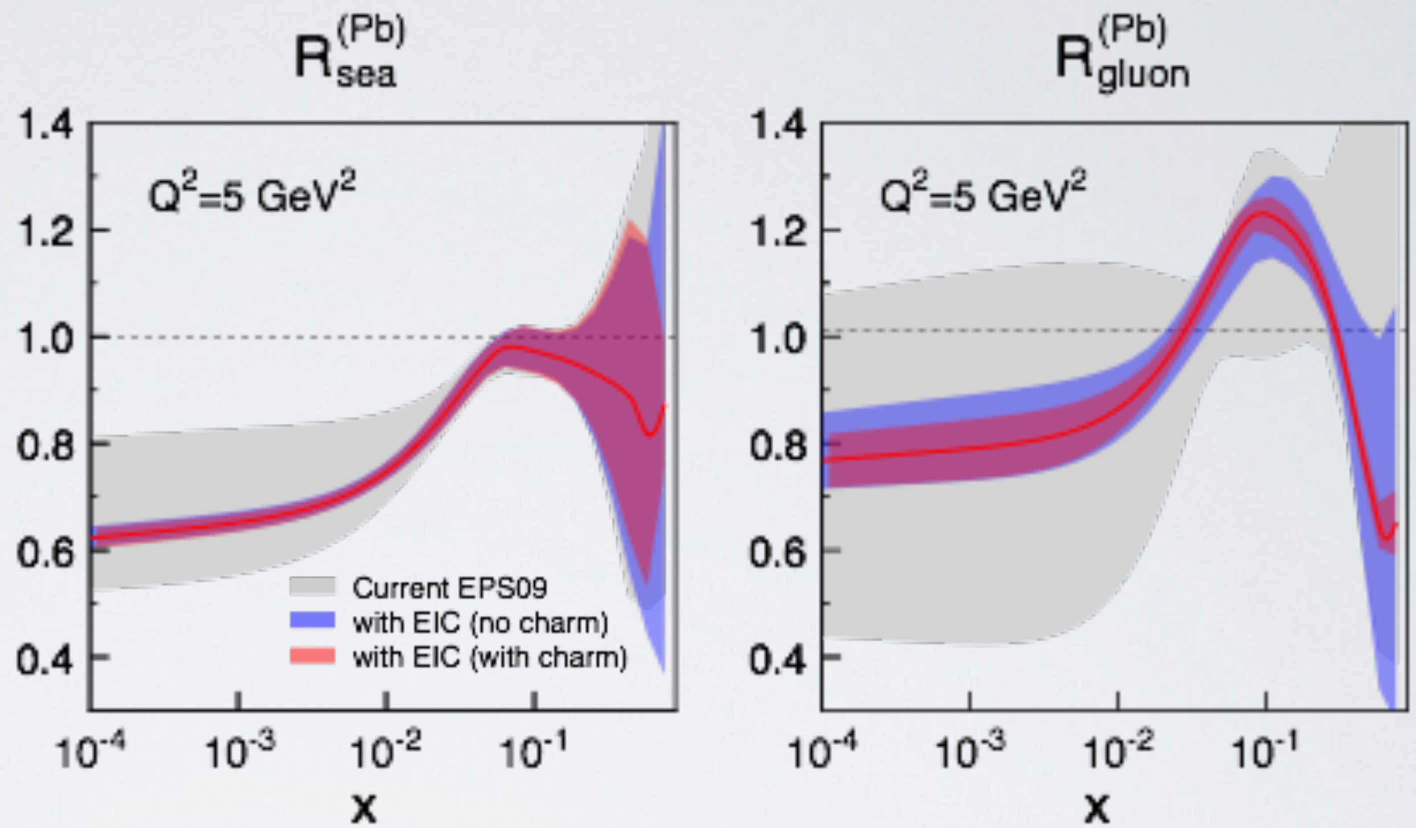




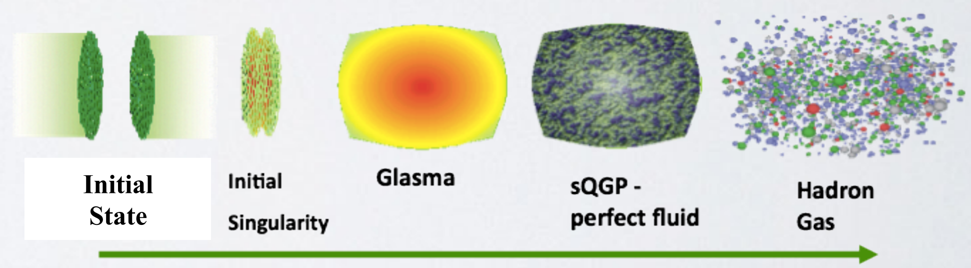
nuclear PDF

$$R = \frac{\text{PDF (Pb)}}{\text{PDF (p)}}$$

nuclear modification factor for partons



- EIC: better precision at small x; adding charm pseudo-data, also at high x
- complementary to LHC data: + test universality of nPDF
  + reduce QCD uncertainties in BSM searches
- impact on Heavy Ion Physics: initial state cleanly disentangled



nuclear PDF

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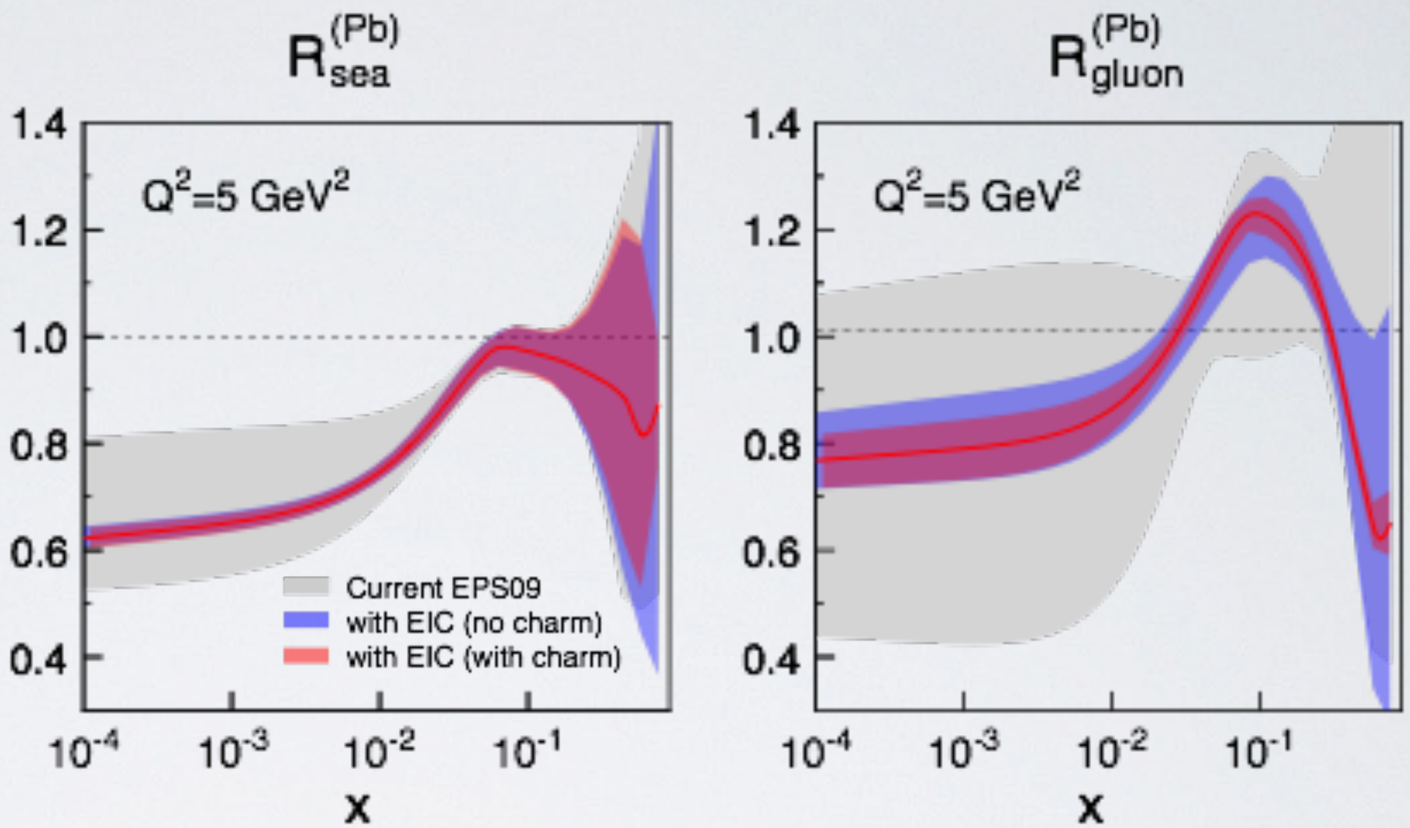
nuclear modification factor for partons



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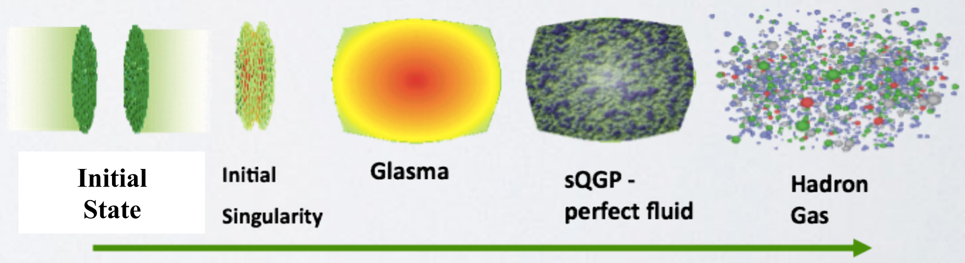
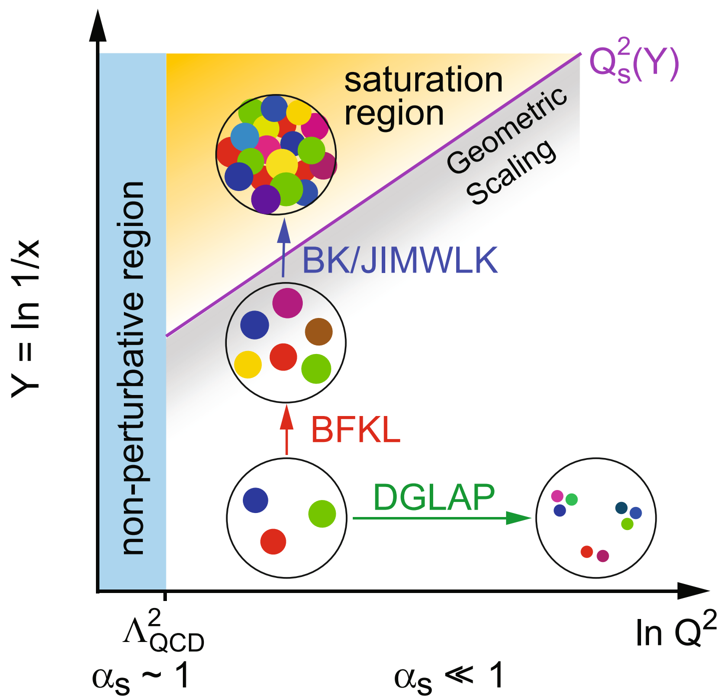


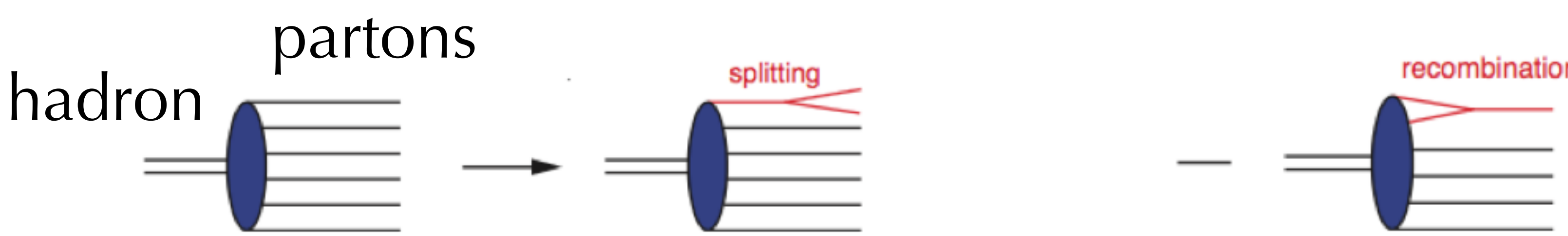
What happens at very low x?

(implications for astronomical objects like neutron stars)

Saturation at high nuclear density

Where is onset of high-density regime? Look at evolution eq.'s

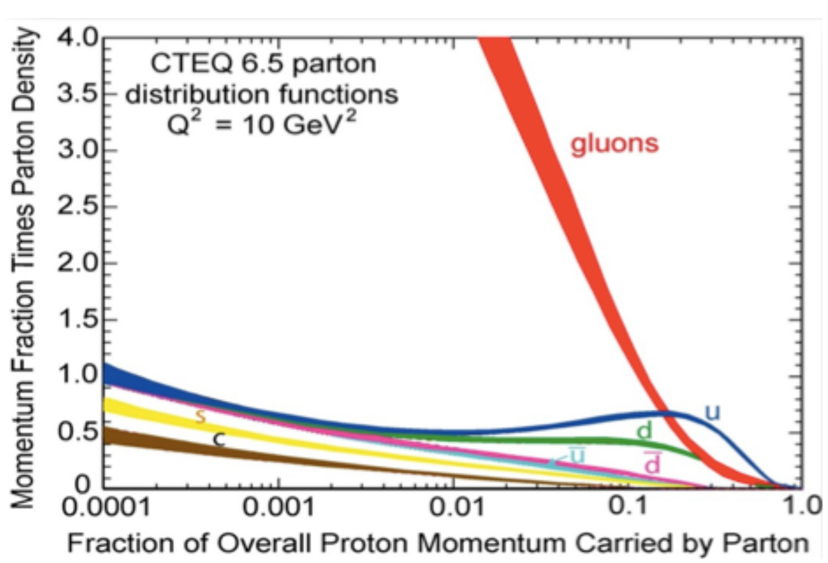




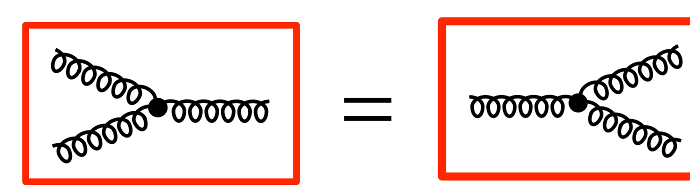
BFKL evolution | BK / JIMWLK evo

$$\frac{\partial N_g(x,1/Q)}{\partial \log(1/x)} = \alpha_s\; K_{\rm BFKL} \otimes N_g(x,1/Q) \quad -\alpha_s\;[N_g(x,1/Q)]^2$$

unlimited rise of gluon density
$N_g \sim 1/x^\lambda$
($\sigma \sim s^\lambda$)
seen at HERA



unitarity
↓
Froissart bound $\sigma \sim \log^2 s$
↓
saturation, i.e.



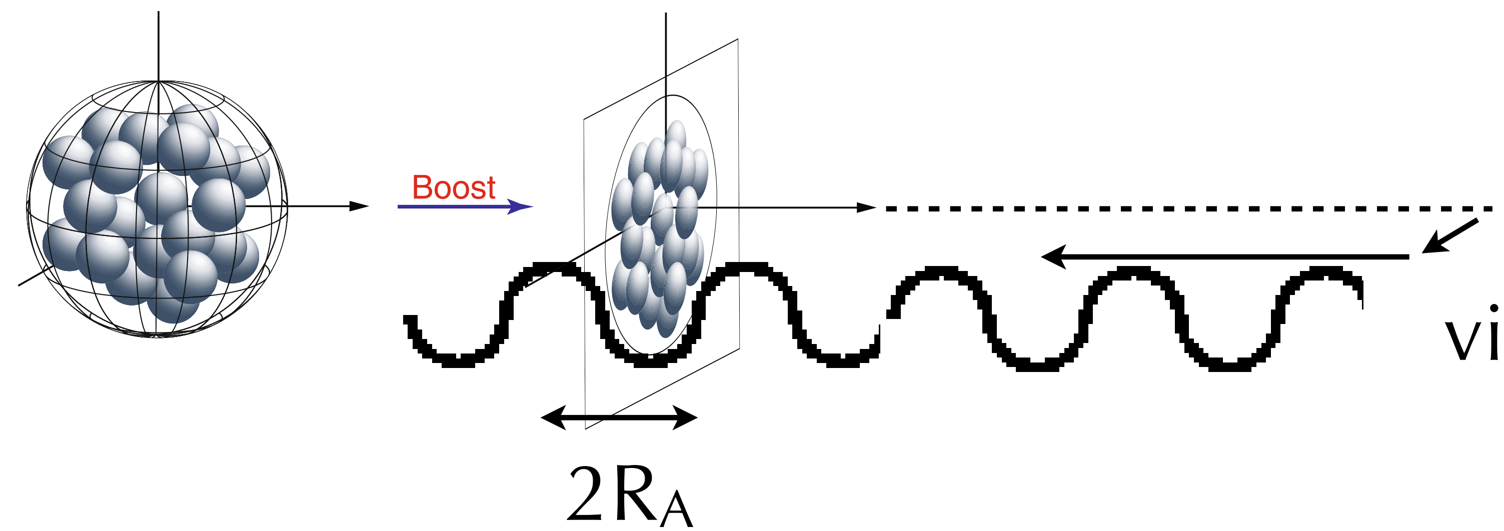
at some scale
$Q_s(x,A) \gg \Lambda_{QCD}$

the Color Glass Condensate (CGC)

Iancu, Leonidov, McLerran, P.L. ***B510*** *(01) 133*

Universal gluonic matter (CGC) ?

Nucleus
A



virtual photon has wave length L ~ 1/x » $2R_A$ ~ $A^{1/3}$ boosted nucleus size
lepton probes coherently all gluons inside nucleus at given b

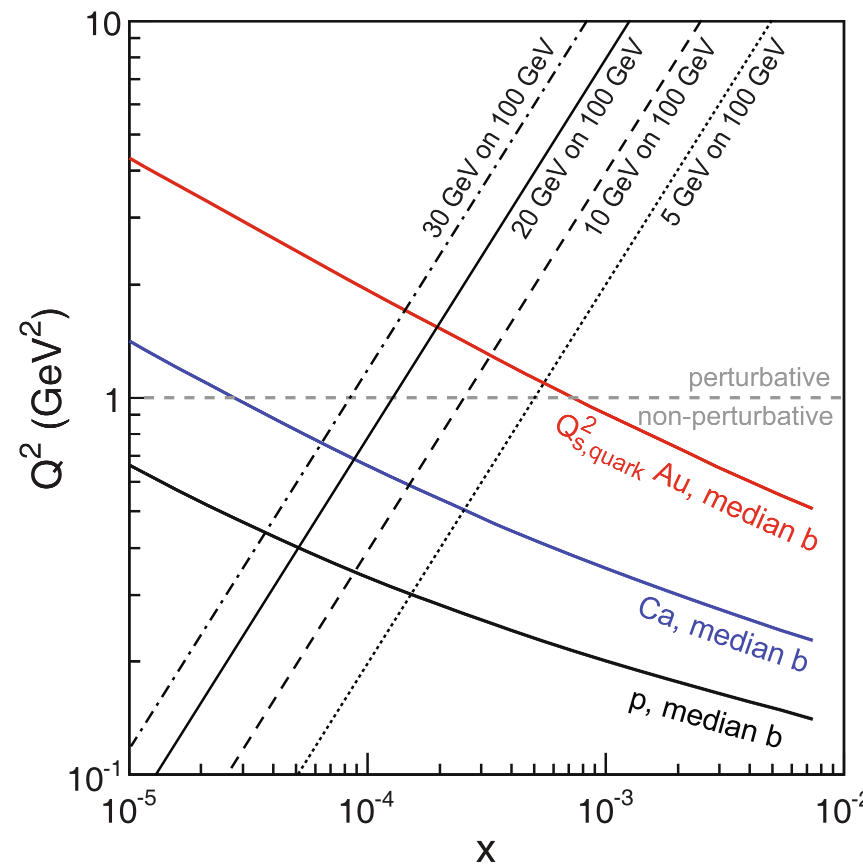
Saturation scale

$$[Q_s(x,A)]^2 \sim \left(\frac{A}{x}\right)^{\frac{1}{3}}$$

(maximum at b=0)

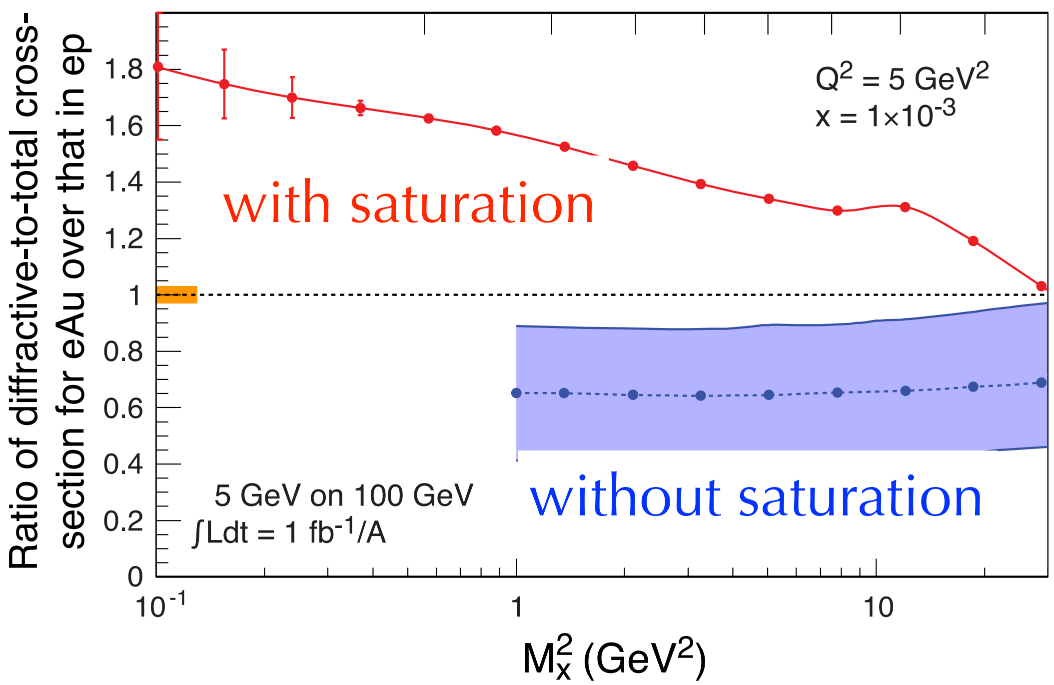
Advantage of having ion beams

same Q_s reached at (A × larger) x
hence, at (1/√A × smaller) energy √s



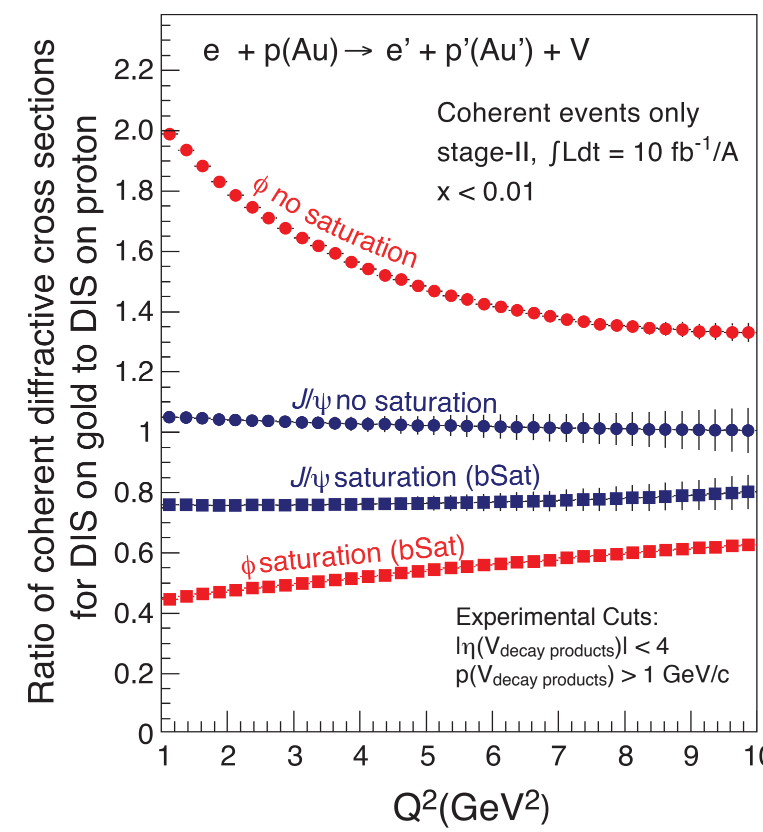
Importance of diffraction

Diffraction: a powerful probe of onset of QCD
non-linear dynamics in saturation



$$\frac{\sigma_{diff}\ (e\text{-}Au)}{\sigma_{tot}\ (e\text{-}Au)} \Big/ \frac{\sigma_{diff}\ (e\text{-}p)}{\sigma_{tot}\ (e\text{-}p)}$$

coherent destructive interf. in $\sigma_{diff} \ll \sigma_{tot}$



diffractive vector meson production
$\sigma_{diff}^V\ (Au)\ /\ \sigma_{diff}^V\ (p)$
Q^2 dependence of saturation

Diffractive di-jet production: access gluon Wigner distribution ?

Zheng et al.,
*P.R. D**89** (14) 074037*

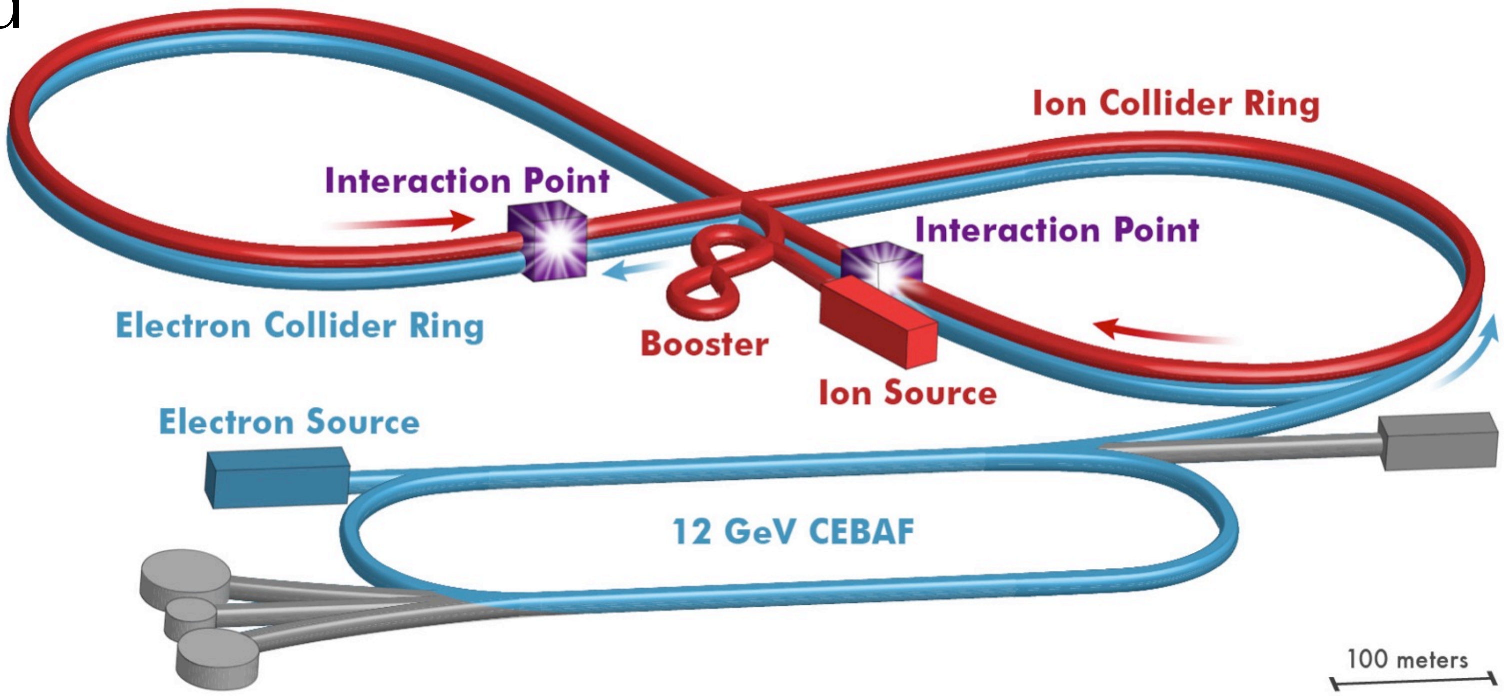
Where ?

Where can this facility become real ?

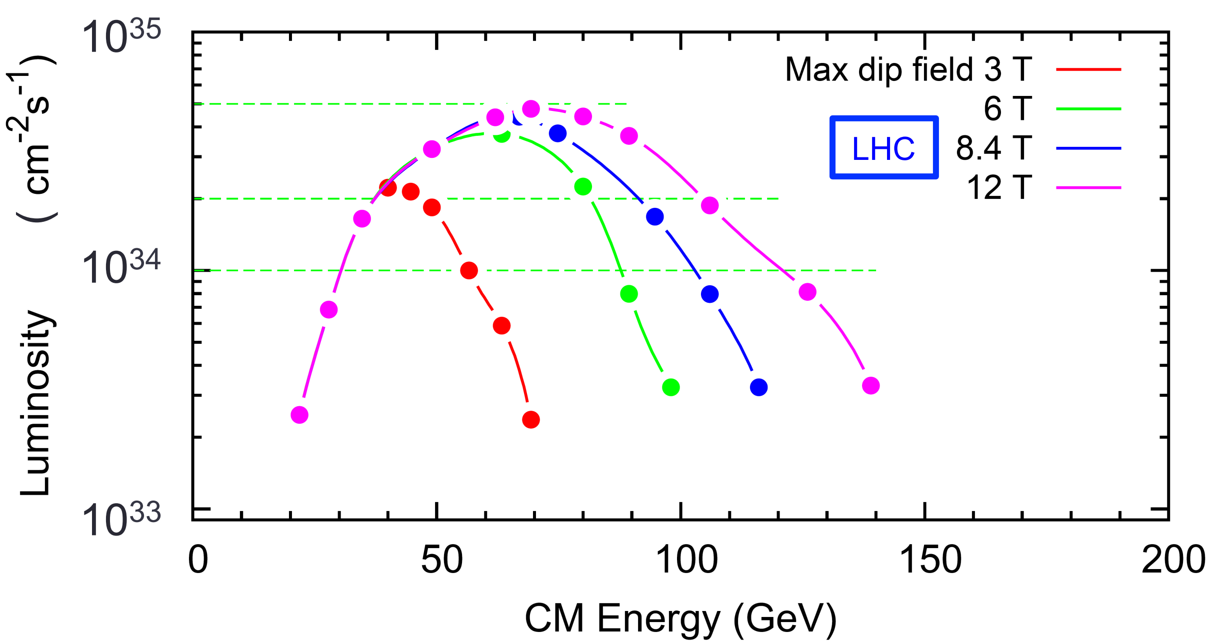
the EIC project : Where ?

the JLEIC project

- "figure 8" layout optimized for high ion polarization



- fully integrated detector/IR
- use existing CEBAF for polarized e^- injector
- energy range $\sqrt{s}$: 20 → 65 - 140 GeV (depending on magnet tech.)
- JLEIC achieves initial high Lumi; choice of magnet technology determines initial / upgraded energy reach

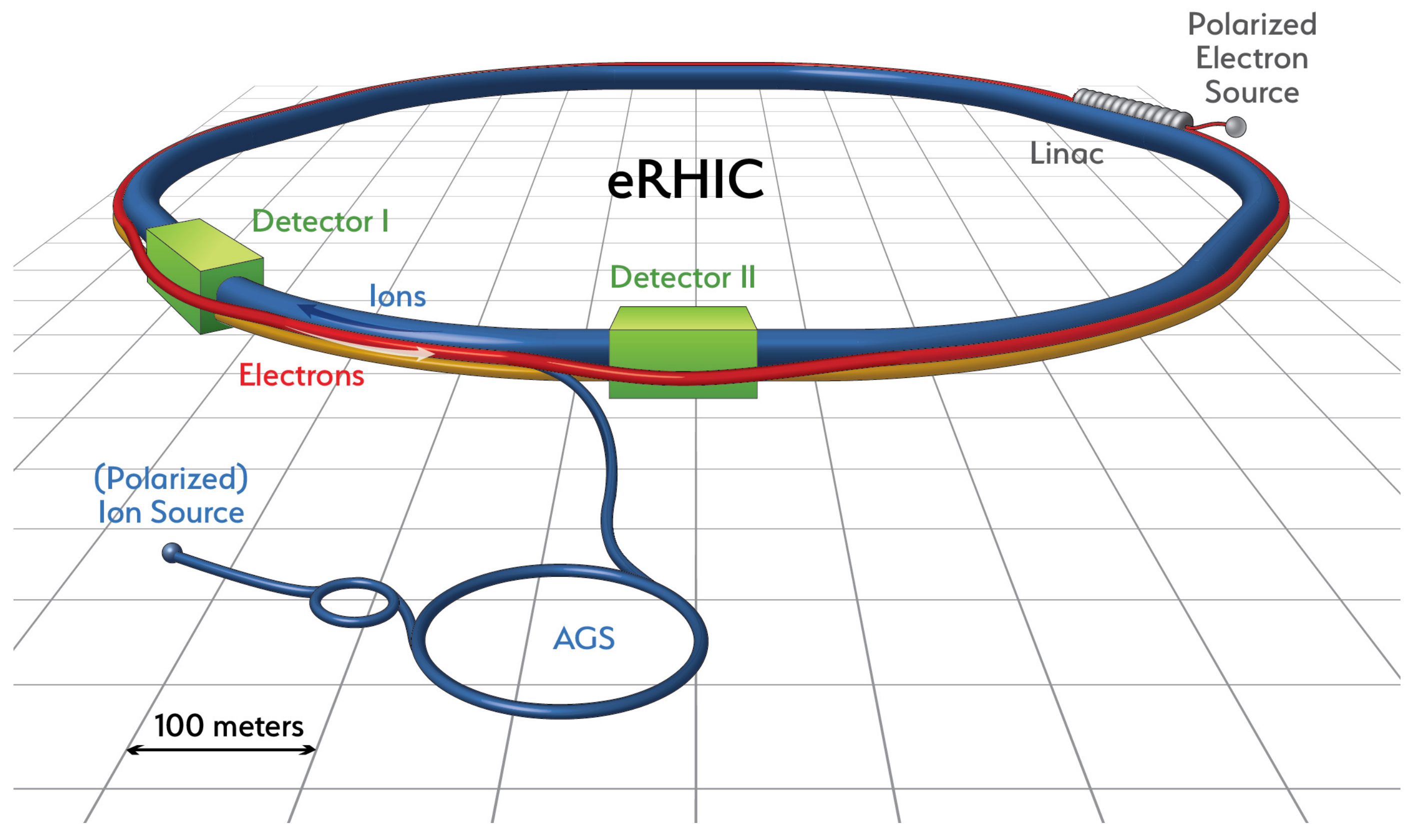


the eRHIC project

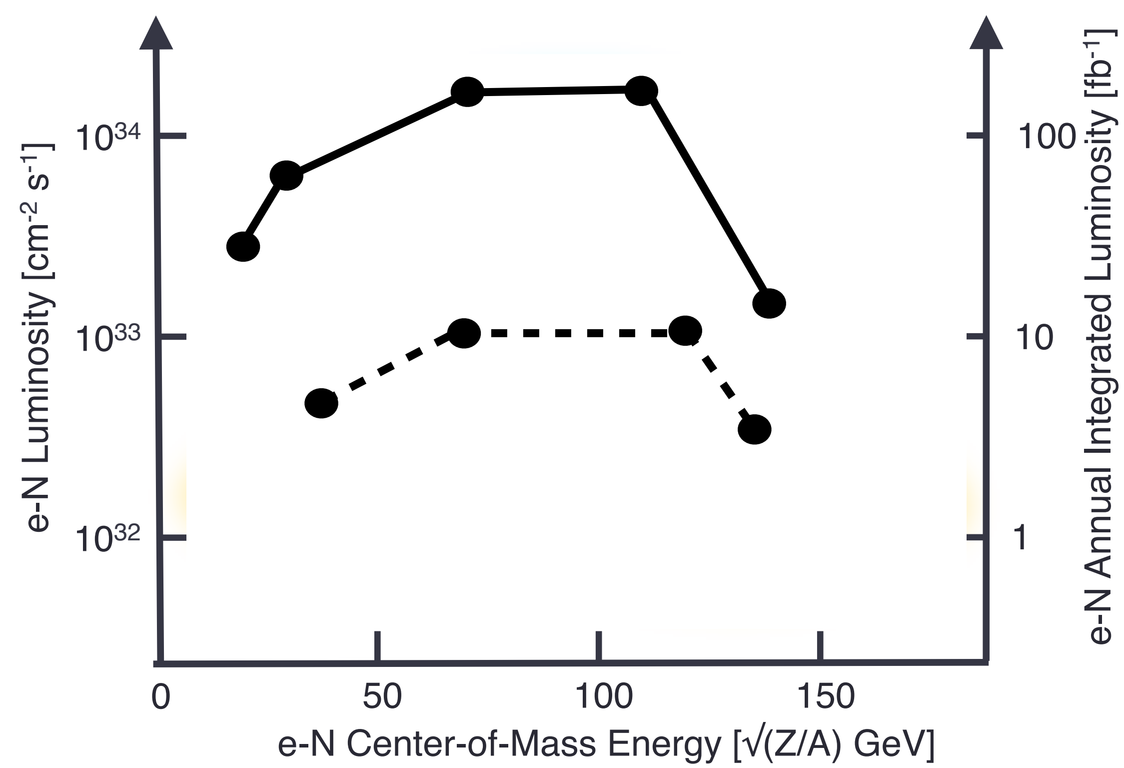
- use existing RHIC: tunnel, detector halls, hadron injector

- add 18 GeV e^- accelerator in same tunnel (use either Electron Storage Ring or Energy Recovery Linac)

- achieve high Lumi, high energy e-p/A collisions with full acceptance detector



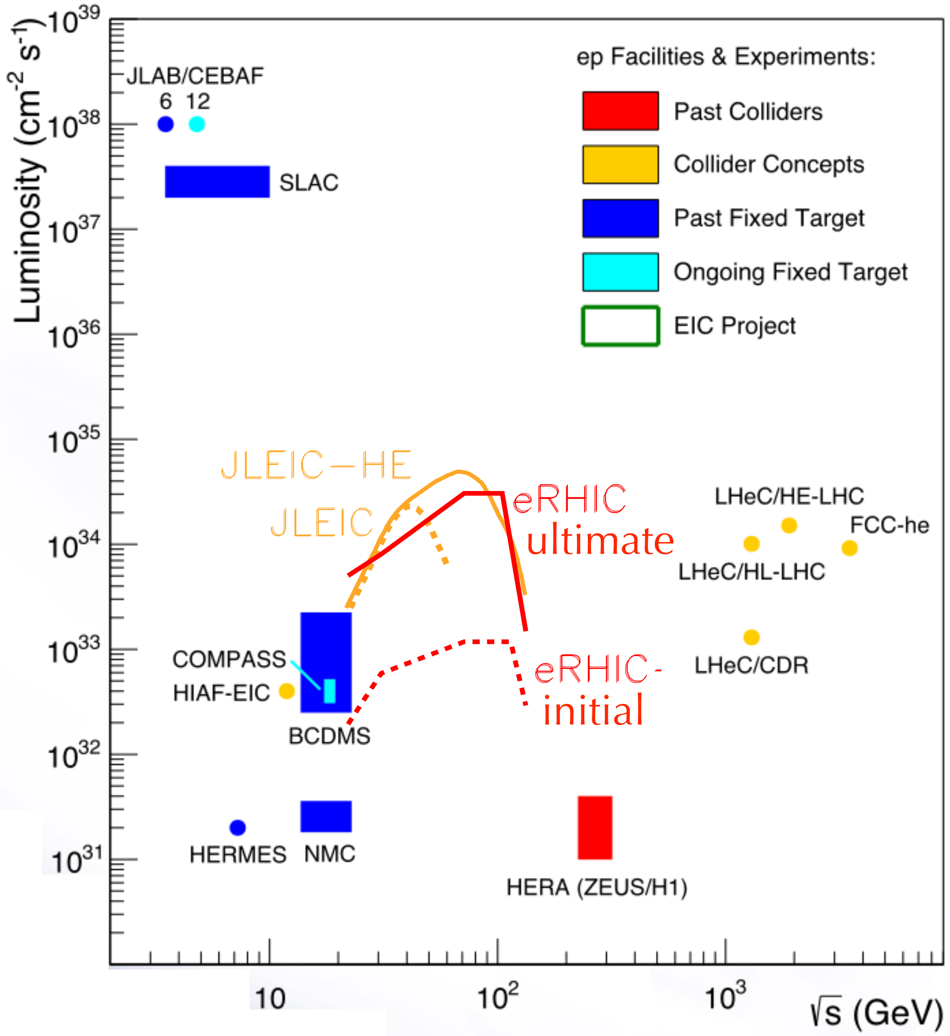
- - - - - - - initial
——— ultimate
configurations



B. Mueller, POETIC 2016

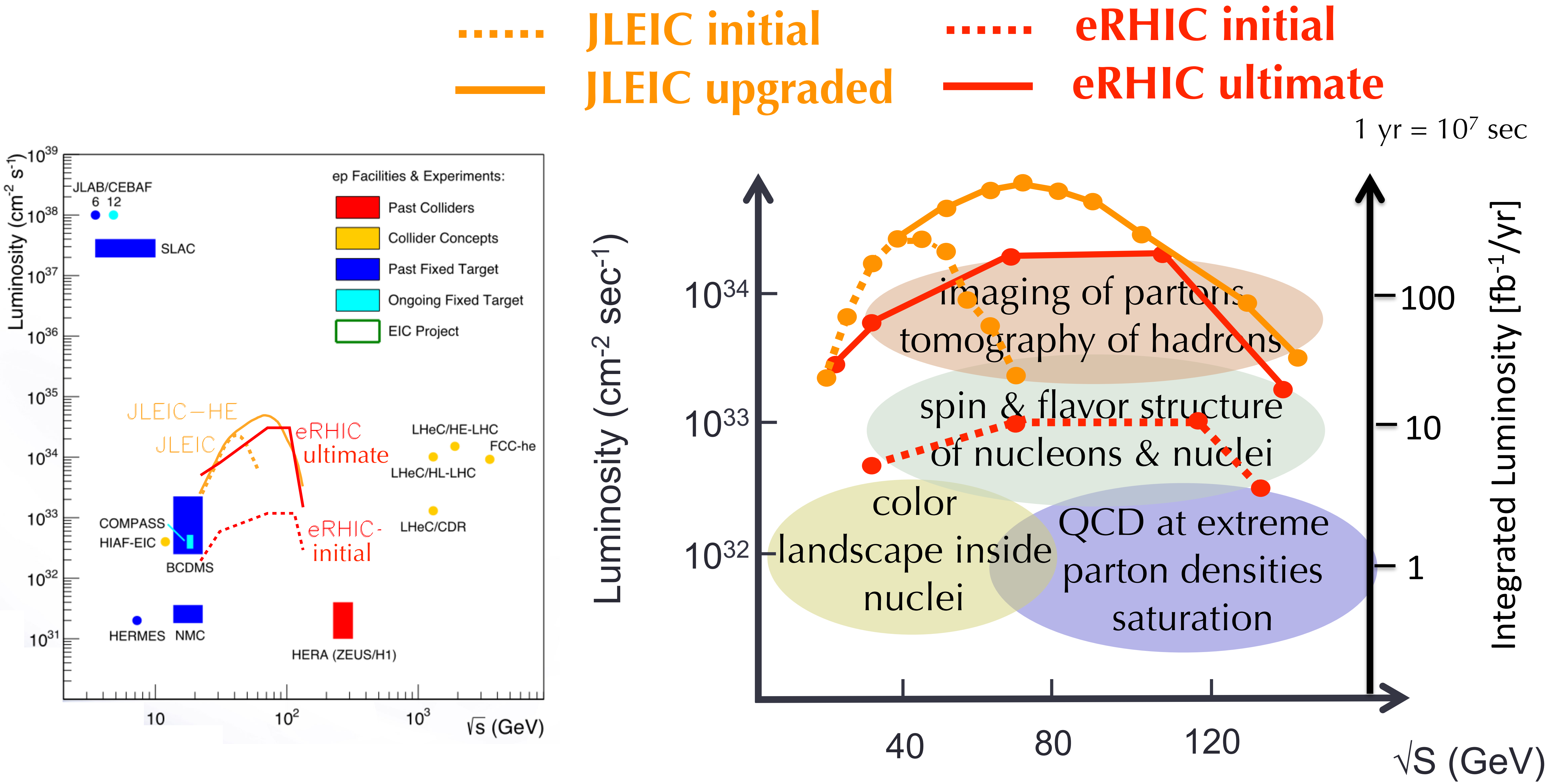
the EIC Science Matrix

JLEIC initial
JLEIC upgraded
eRHIC initial
eRHIC ultimate



Luminosity (cm-2 sec-1)

the EIC Science Matrix



very good matching to
high Lumi / wide energy range requirements
by the EIC physics case

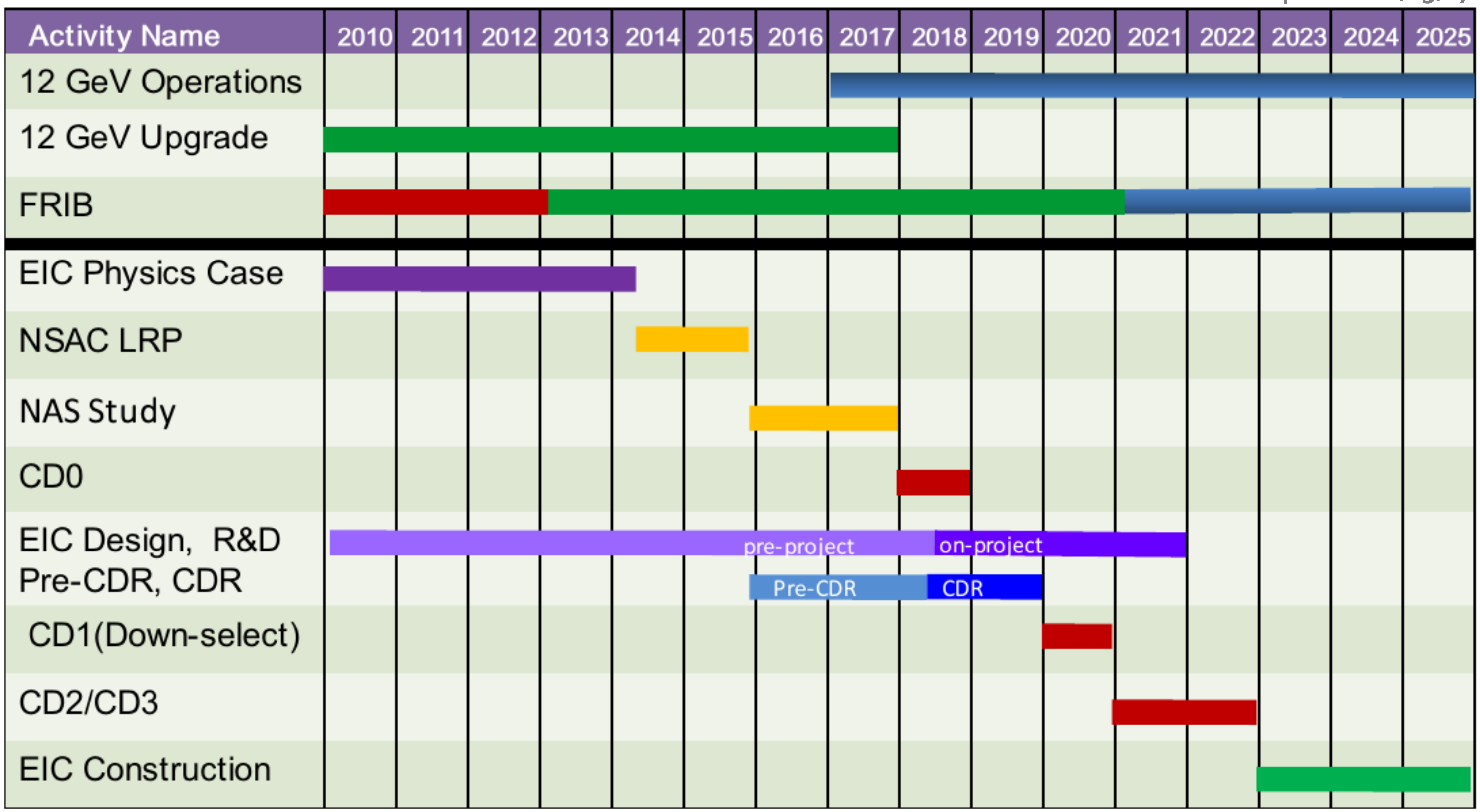
When ?

the time scale ?

the EIC project : When ?

JLEIC possible timeline (eRHIC similar)

Updated: 1/13/17



CD0 = DOE "Mission Need" statement; **CD1** = design choice and site selection
CD2/CD3 = establish project baseline cost and schedule

A. Accardi, Giornata sulle opportunità del progetto EIC, Genova Jan. 17 2017

Who ?

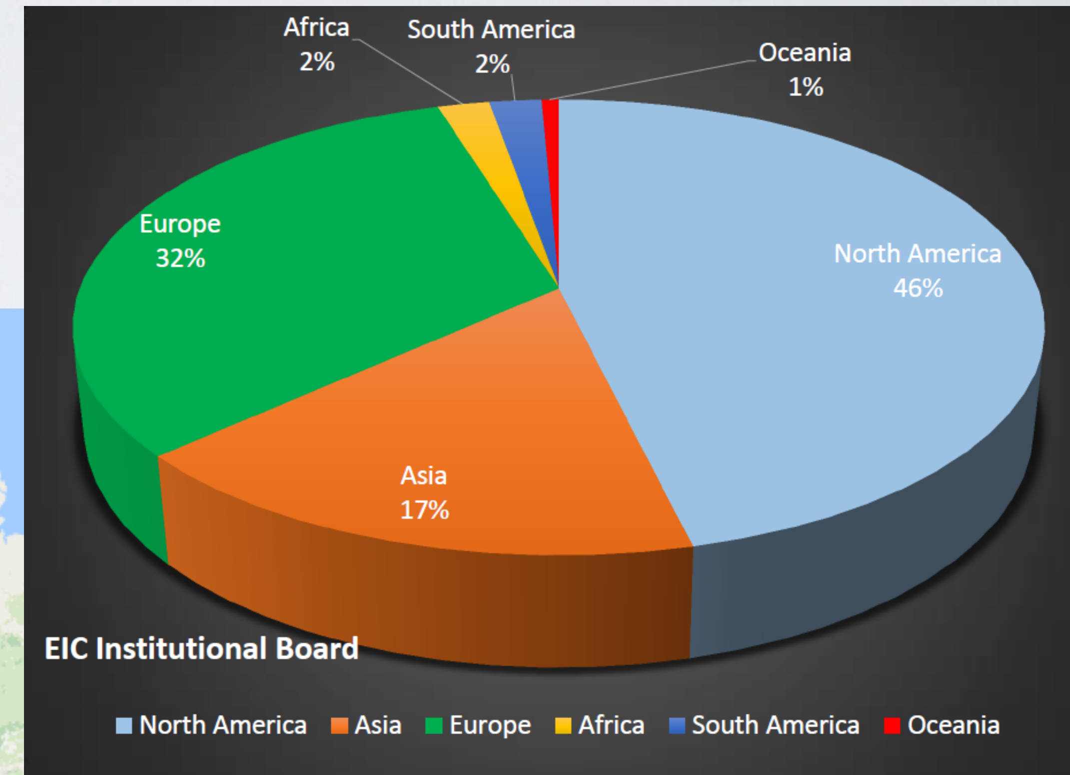
the Institutions involved ?

the EIC project : Who ?

The EIC User Group: www.eicug.org

(April, 2017)
28 countries, **151** institutions
685 collaborators

49 Europe



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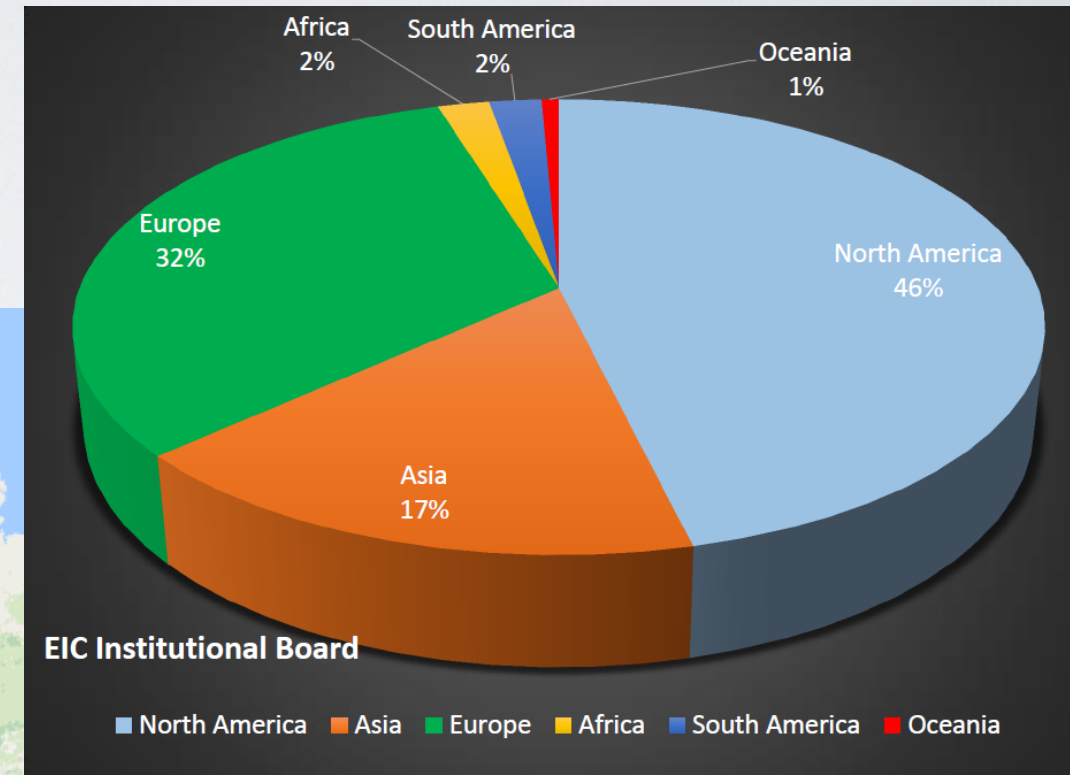

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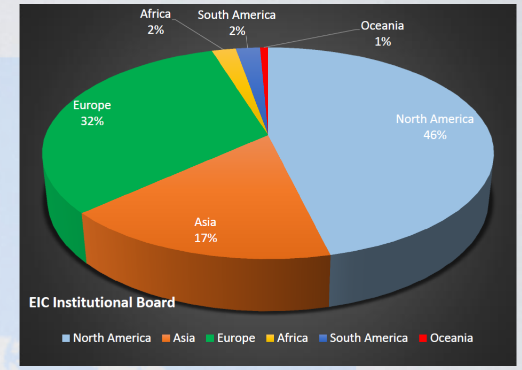


Institutional Board: one representative for each one of 151 institutions

elections (fall 2016)

Steering Committee:

President
A. Deshpande

Vice President
B. Surrow

Members elected

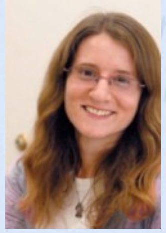
J. Arrington

C.E. Hyde

M. Radici

JLab repres.
R. Yoshida

BNL repres.
T. Ullrich



President IB
C. Aidala

Europe repres.

Asian repres.

running elections

the EIC project : Who ?

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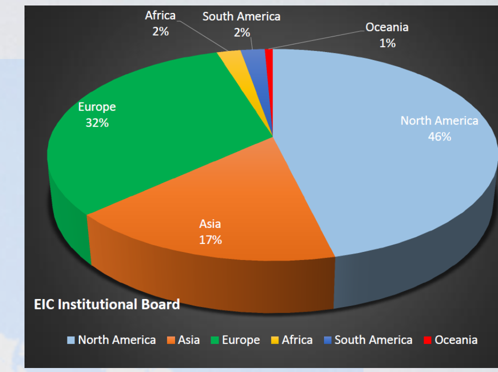

EICUG previous meetings

- Stony Brook, Jun. 2014 http://skypper.physics.sunysb.edu/~eicug/meeting1/SBU.html
- Berkeley, Jan. 6-9 2016 http://skypper.physics.sunysb.edu/~eicug/meeting2/UCB2016.html
- Argonne Nat. Lab., Jul. 7-10 2016 http://eic2016.phy.anl.gov/
- remote/web, Mar. 2017 (preparation of NAS review)

EICUG next meeting

Trieste, Jul. 18-22 2017

https://agenda.infn.it/conferenceDisplay.py?ovw=True&confId=13037