The Electron-Ion Collider

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LPT, GDR summer school
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- Introduction
- Accelerator concepts at JLab and RHIC
- EIC physics case (overview)
- Detector design for an EIC
- Summary and Conclusion

BROOKHAVEN
NATIONAL LABORATORY

Jefferson Lab
EXPLORING THE NATURE OF MATTER

Challenges of Strong Interaction

$$L_{QCD} = \bar{q}(i\gamma^\mu \partial_\mu - m)q - g(\bar{q}\gamma^\mu T_a q)A^a_\mu - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

QCD is the "nearly perfect" fundamental theory of the strong interaction

F. Wilczek, hep-ph/9907340

We are only beginning to explore the high energy, many body dynamics of this theory

What are the right effective degrees of freedom at high energies

- gluons & sea quarks, dipoles, pomerons, strong fields?

How do these degrees of freedom interact with each other and with hard probes?

- Much efforts and progress in the valence & sea quark sector at JLab, HERA, EMC…COMPASS, etc

What about Glue ?

"On closer inspection, the quarks appear as the showier, but gluons as the weightier and more dynamic, constituents of matter"

F. Wilzcek (Nature 400, 21 - "You are glue")

Challenge of Strong Interaction

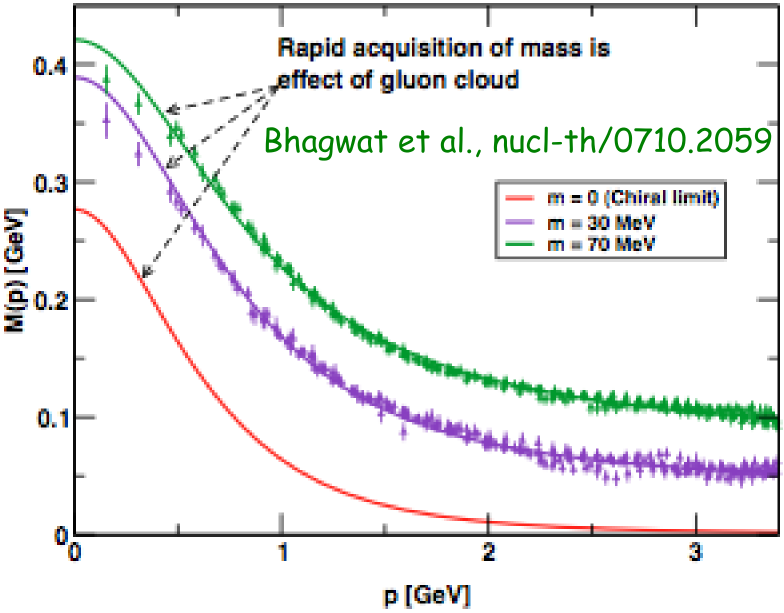
$$L_{QCD} = \bar{q}(i\gamma^{\mu}\partial_{\mu} - m)q - g(\bar{q}\gamma^{\mu}T_a q)A^a_{\mu} - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

Gluons

- Self-interacting force carriers
- Dominate structure of QCD vacuum
- Responsible for >94% of visible

Quenched QCD explains mass spectrum to ± 10%

- Determine essential features of QCD



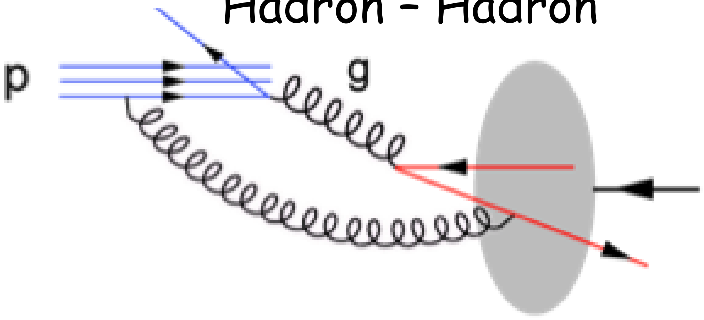
Bhagwat et al., nucl-th/0710.2059

Despite this dominance, the properties of gluons in matter remain largely unexplored

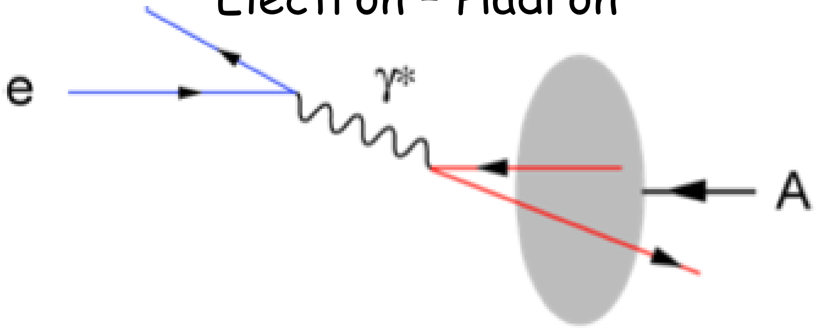
Necessity for an EIC to explore the gluon-dominated matter

How to measure glue ?... two options

Hadron – Hadron



Electron – Hadron



- › Test QCD
- › Direct interaction via gluons
- › No direct access to x_B and Q^2
- › «Scattering of hadrons on hadrons is like colliding Swiss watches to find out how they are build» (R. Feynman)

- › Explore QCD and hadron structure
- › Indirect access to gluons
- › Access to partonic kinematics
- › High precision is possible

Both are complementary and provide excellent information on properties of gluons in the nuclear wave functions

However, high precision measurements only possible with e-p/e-A !

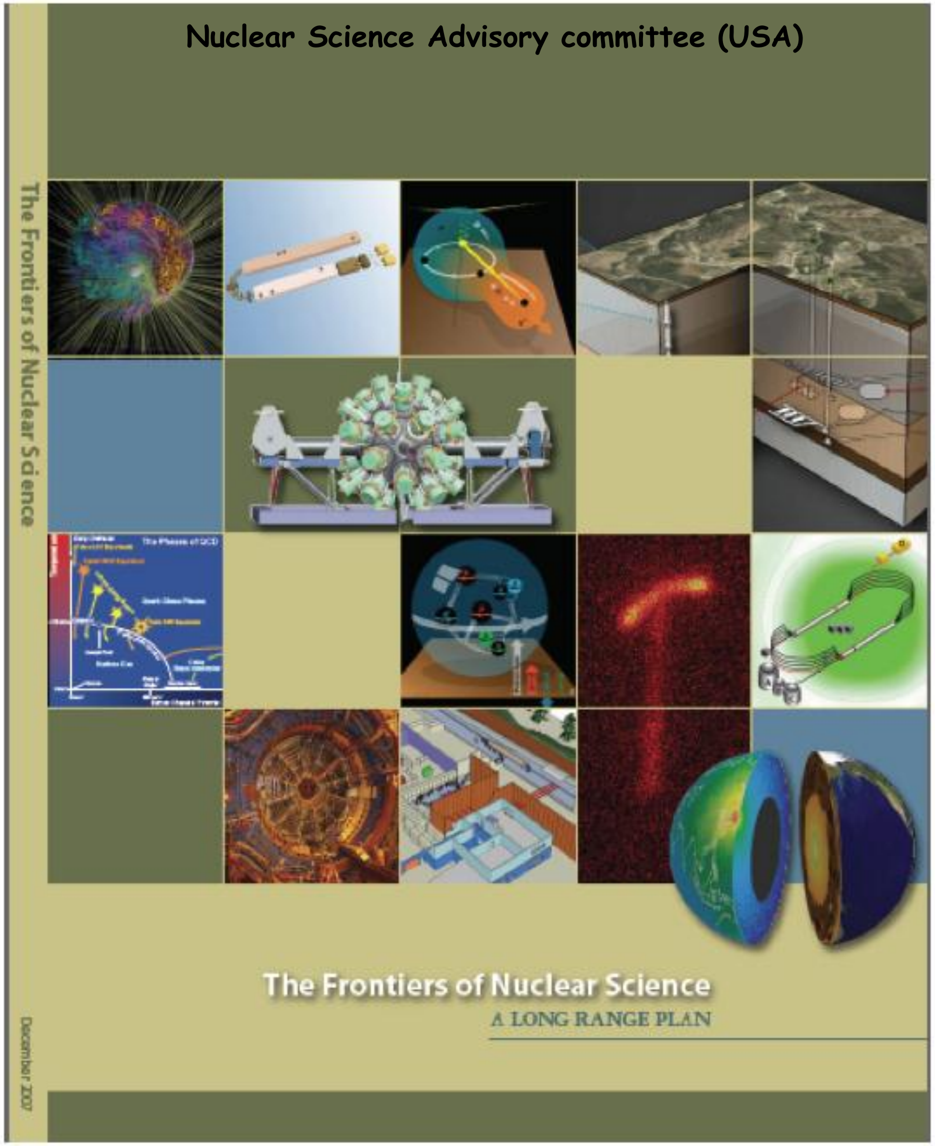
› EIC ‹

EIC : Electron-Ion Collider

NSAC 2007 Long Range Plan

"An **Electron-Ion Collider (EIC)** with polarized beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. **EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide** and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton."



Nuclear Science Advisory committee (USA)

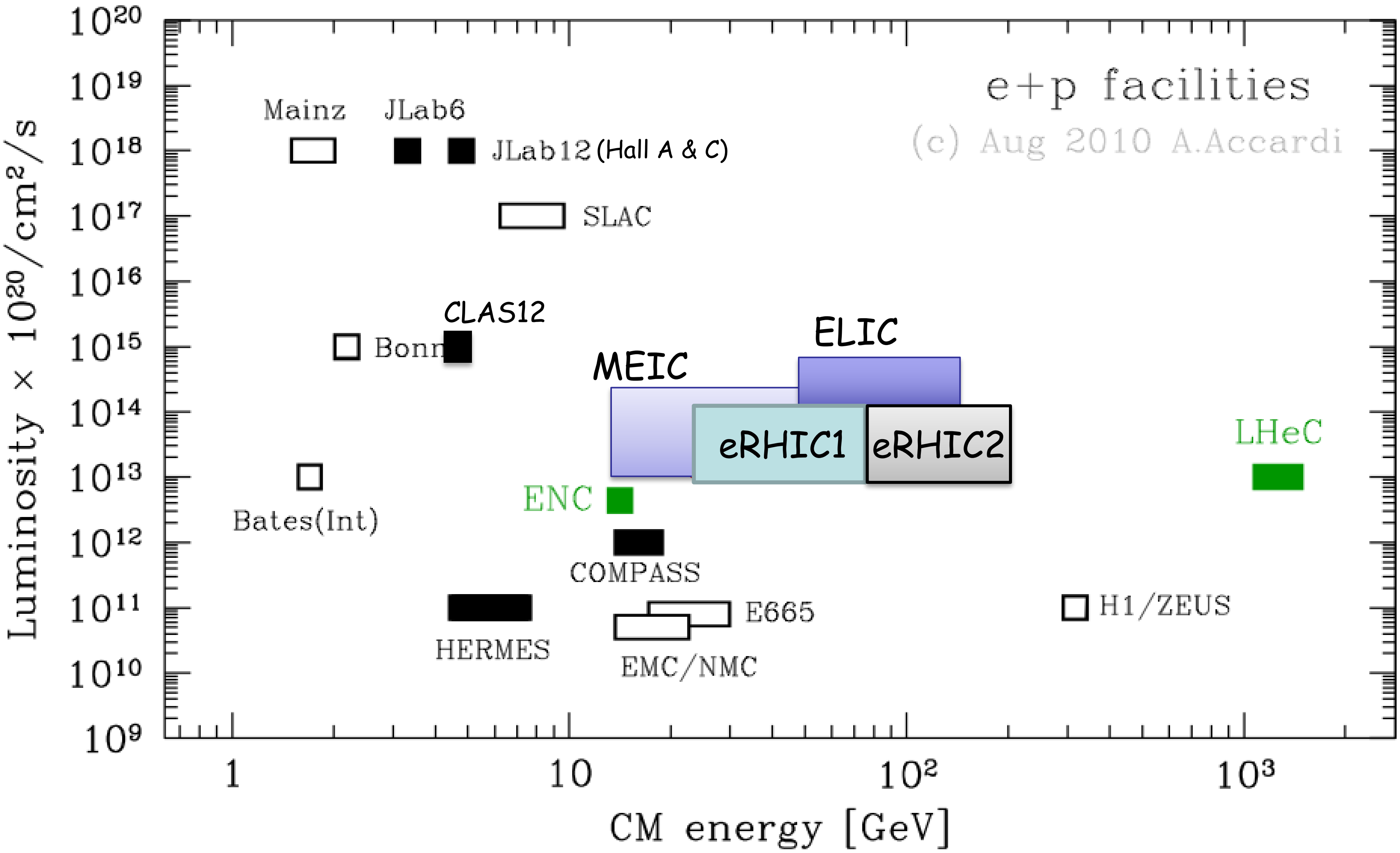
The Frontiers of Nuclear Science

A LONG RANGE PLAN

The Frontiers of Nuclear Science

December 2007

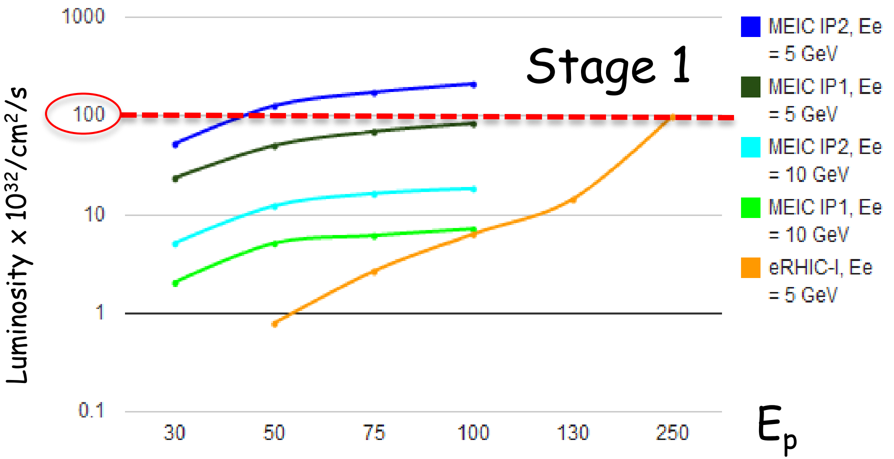
Lepton-Proton/Ion machines world-wide

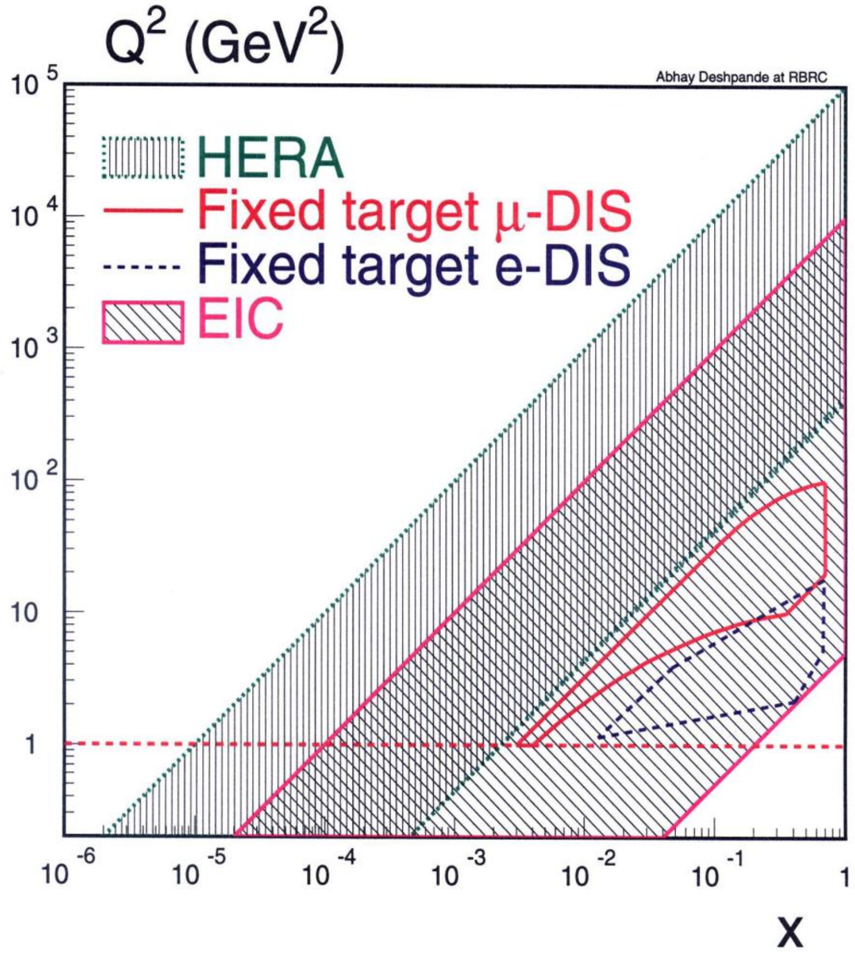


Basic machine parameters

Base EIC Requirements *per Executive Summary INT Report :*

- Range in cm energies **$\sqrt{s}$~20-70** & variable
- Fully-polarized (>70%), longitudinal and transverse
- Ion species up to A = 200 or so
- High luminosity: **about 10^{34}** e-nucleons cm^{-2} s^{-1}
- Multiple interaction regions
- Upgradable to higher energies

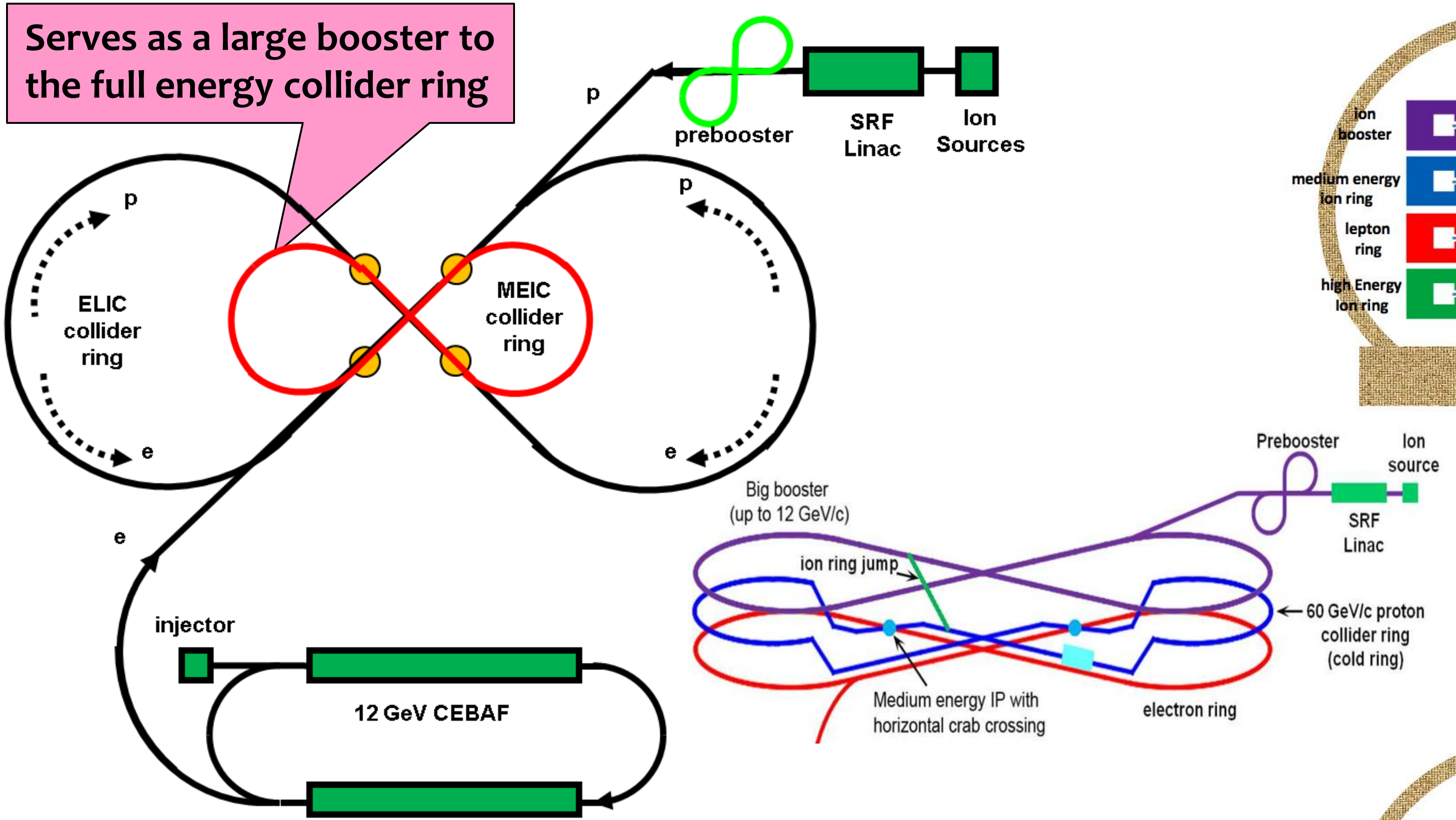




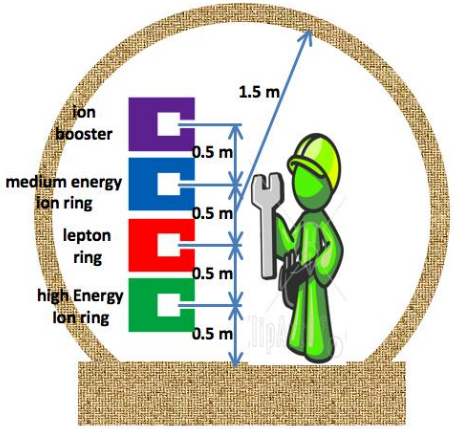
JLab : 749MHz
RHIC : 13.5 MHz

JLab design, Stages 1 (MEIC) & 2 (ELIC)

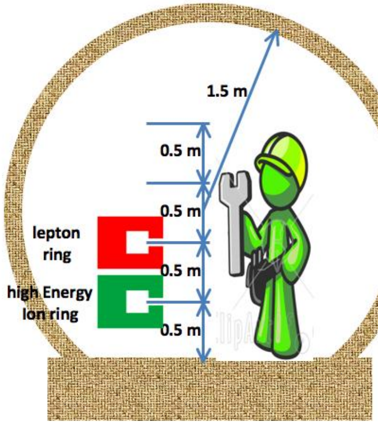
Serves as a large booster to the full energy collider ring



Straight section

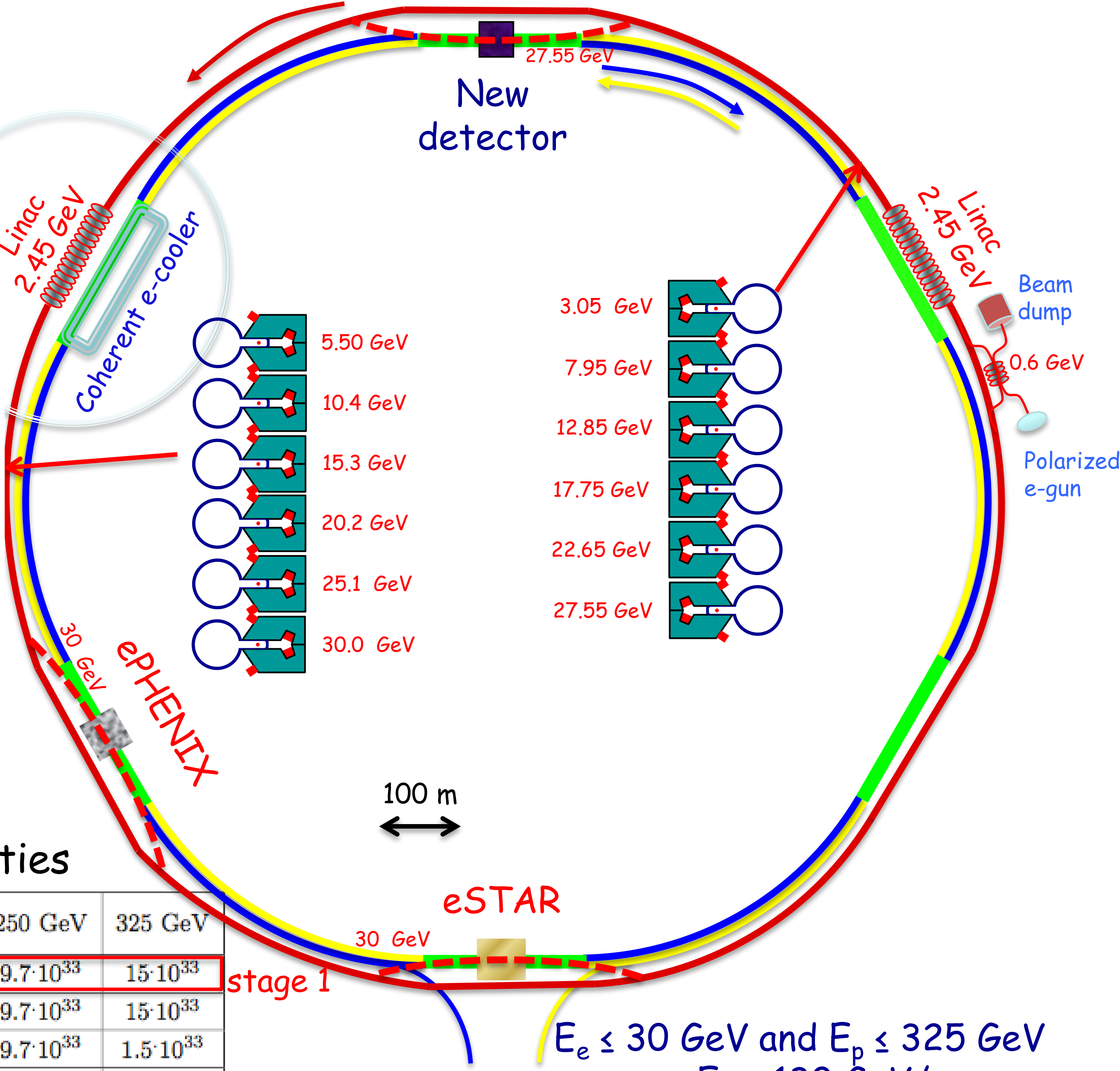


Arc



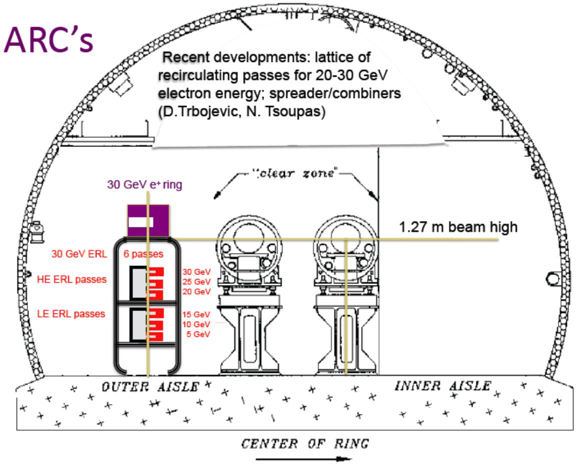
Stage	Max. Energy (GeV/c)		Ring Size (m)	Ring Type		IP #
	p	e		p	e	
Medium	96	11	1000	Cold	Warm	3
High	250	20	2500	Cold	Warm	4

RHIC realization



Same tunnel for all beams

ARC's



Recent developments: lattice of recirculating passes for 20-30 GeV electron energy; spreader/combiners (D.Trbojevic, N. Tsoupas)

polarized e & p luminosities

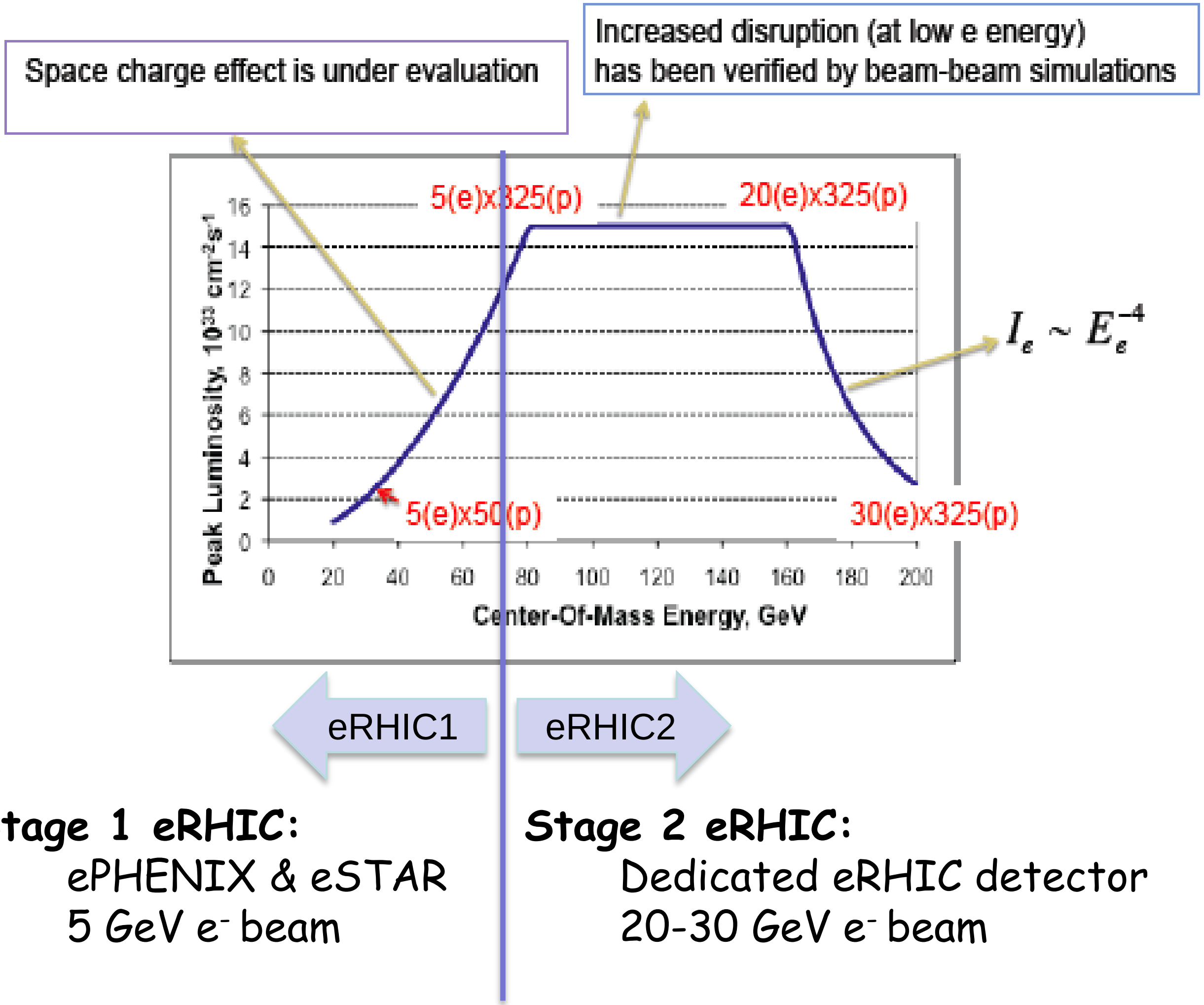
Electrons \ Protons	100 GeV	130 GeV	250 GeV	325 GeV
5 GeV	$0.62 \cdot 10^{33}$	$1.4 \cdot 10^{33}$	$9.7 \cdot 10^{33}$	$15 \cdot 10^{33}$
10 GeV	$0.62 \cdot 10^{33}$	$1.4 \cdot 10^{33}$	$9.7 \cdot 10^{33}$	$15 \cdot 10^{33}$
20 GeV	$0.62 \cdot 10^{33}$	$1.4 \cdot 10^{33}$	$9.7 \cdot 10^{33}$	$1.5 \cdot 10^{33}$
30 GeV	$0.12 \cdot 10^{33}$	$0.3 \cdot 10^{33}$	$1.9 \cdot 10^{33}$	$3 \cdot 10^{33}$

stage 1

$E_e \lesssim 30$ GeV and $E_p \lesssim 325$ GeV
or $E_A \lesssim 130$ GeV/u

eRHIC staged installation

Luminosity vs. √s



Space charge effect is under evaluation

Increased disruption (at low e energy) has been verified by beam-beam simulations

$I_e \sim E_e^{-4}$

Stage 1 eRHIC:

- ePHENIX & eSTAR
- 5 GeV e^- beam

Stage 2 eRHIC:

- Dedicated eRHIC detector
- 20-30 GeV e^- beam

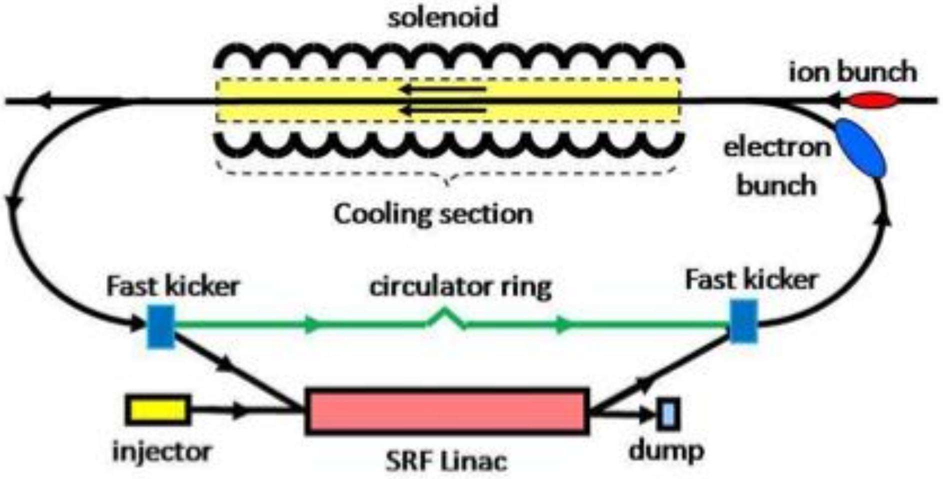
The key for high luminosity : electron cooling

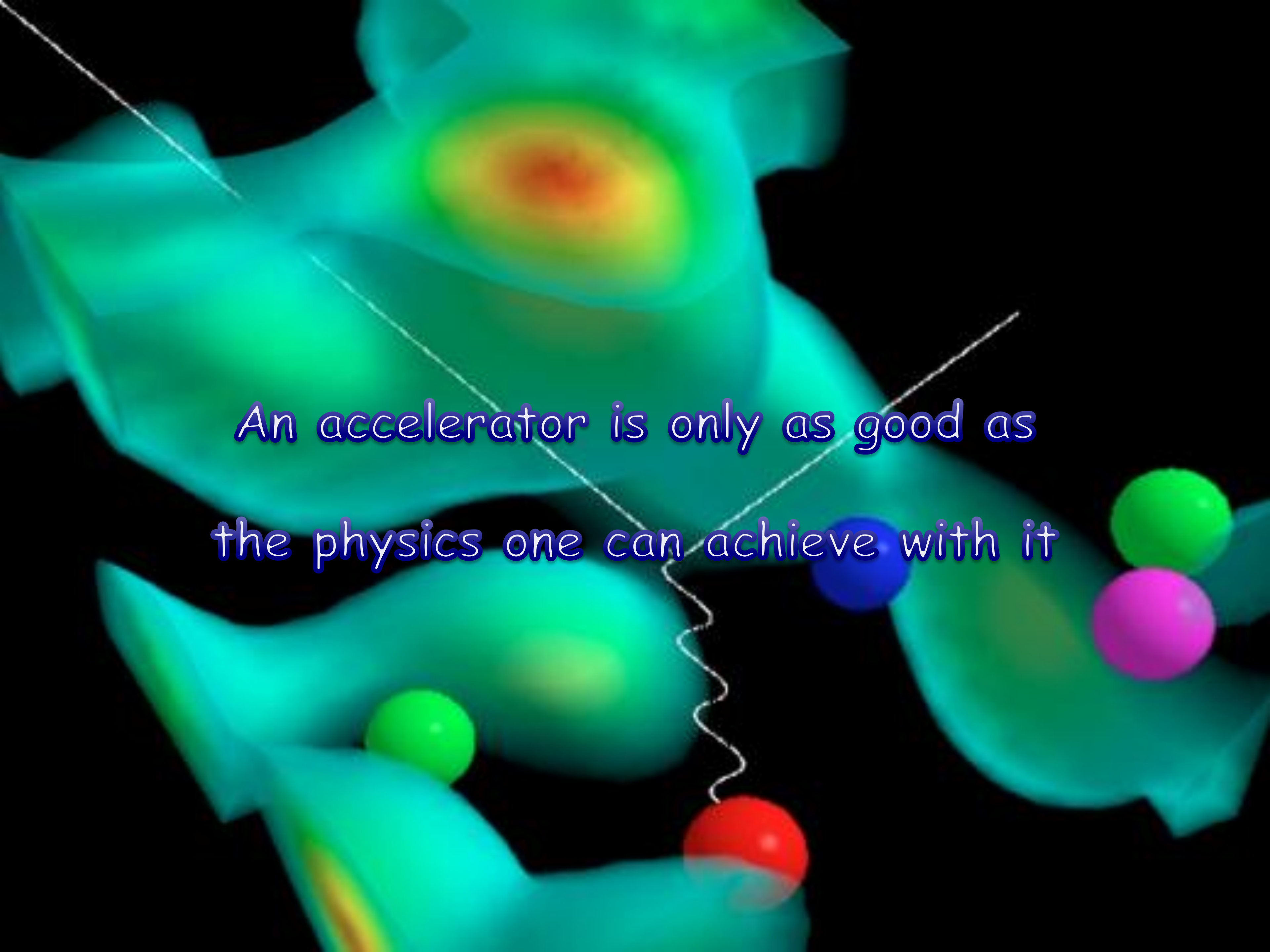
Electron cooling is a means to increase the phase space density of a stored ion beam. It is crucial to reduce the bunch length and suppress the intra-beam scattering, induced beam heating and emittance growth in collision mode. It is a necessity to achieve high luminosity.

How to :

- Mono-energetic cold electron beam is merged with ion beam which is cooled through Coulomb interaction.
- Electron beam is renewed and the velocity spread of the ion beam is reduced in all three planes.

Difficult R&D for JLab, even more so for RHIC because electron cooling efficiency drops as momentum squared.



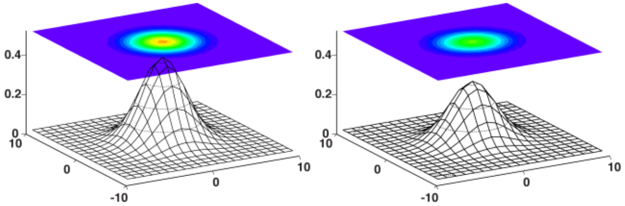


An accelerator is only as good as
the physics one can achieve with it

The new QCD Frontier

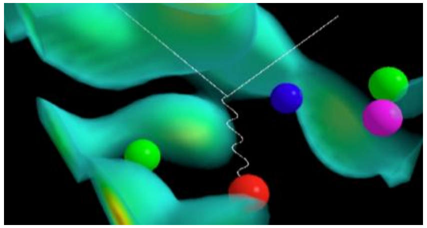
An Electron-Ion Collider will allow the unique exploration of some of the most intriguing open questions in modern nuclear physics:

The structure of visible matter



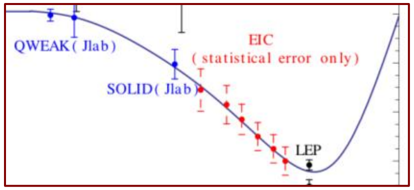
Quark distributions
polarized (L/T) or not
3D-imaging of the nucleon (GPD)
Transverse Momentum Distributions

The role of gluons in hadronic matter



Gluon distributions
polarized or not
F_2 and F_L measurements in nuclei
Study of gluon saturation (CGC)

Electroweak interaction and physics beyond the SM



Accurate measurement of $\sin^2\theta_W$
e-τ conversion

Short overview of the EIC physics case (QCD side)

> Saturation in QCD

> The gluon polarization

> 3D imaging …

> … with Transverse Momentum Distributions

> … with Generalized Parton Distributions (focus)

Quite a few more topics,
take a look at the EIC physics case in the INT report
ArXiv:1108.1713v1

Saturation in QCD

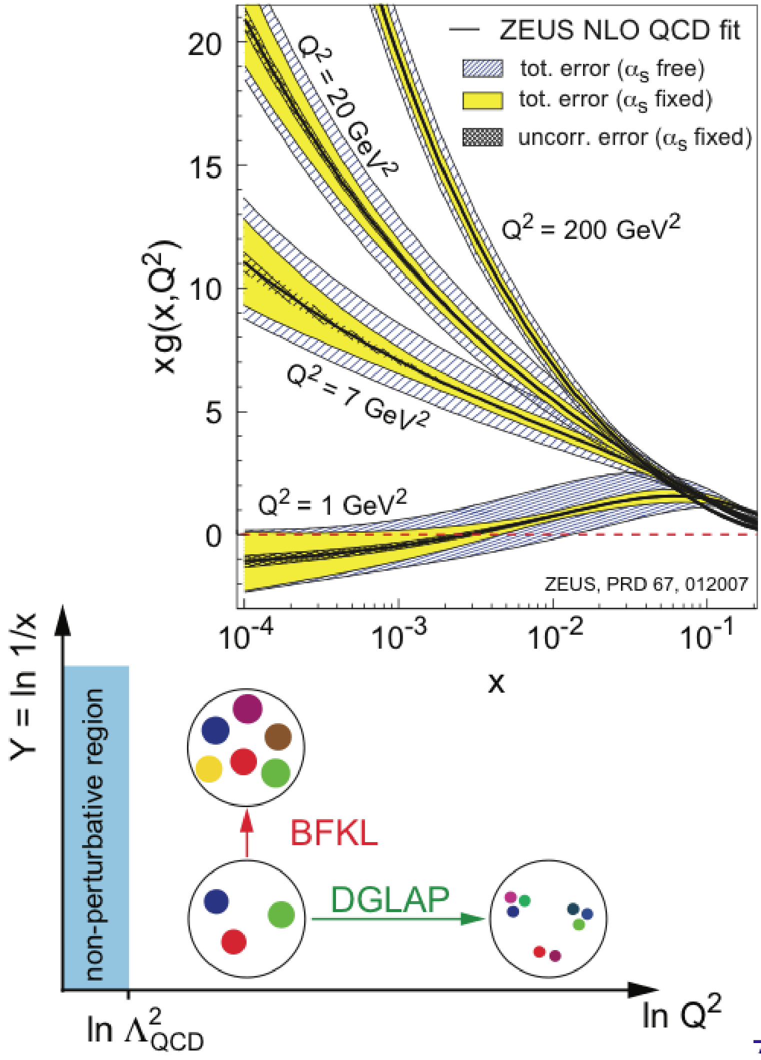
Issues with our current understanding:

Linear DGLAP evolution

- Weird behaviors of xg and F_L at small x and Q^2 (HERA)
- (too?) large diffractive cross-section
- (too?) fast increase of xg violates unitarity

Linear BFKL evolution

- Density along with σ grows as a power of energy: $N \sim s^{\Delta}$
- Can densities & cross-section rise forever?



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Linear BFKL evolution

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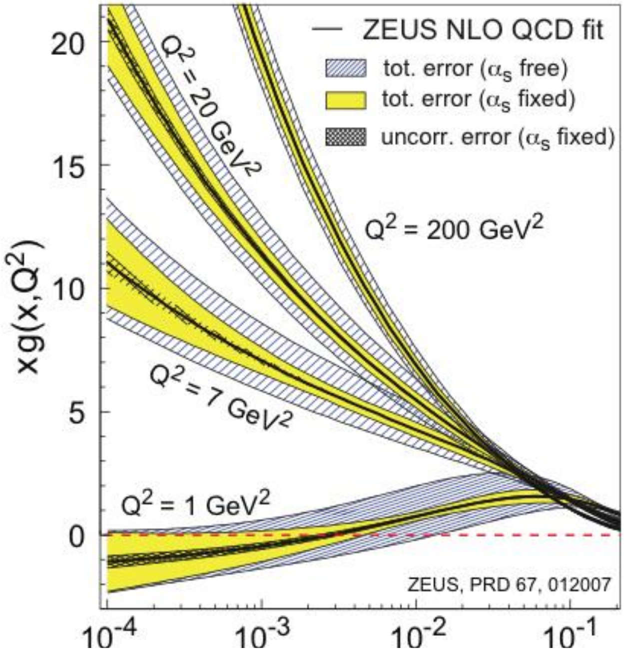
Non-linear evolution at small-x

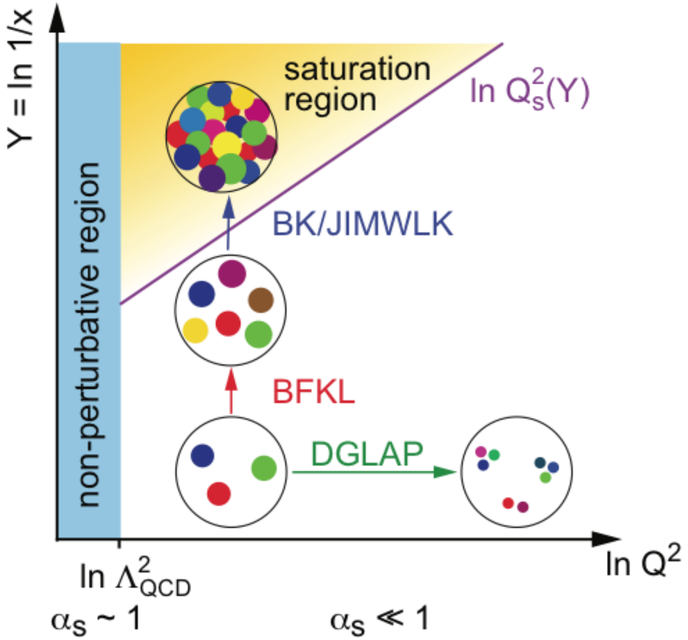
- Gluons are densely packed in the transverse plane
- Recombination limits the number of gluons

SATURATION

- The wave function is described in the IMF by a Color Glass Condensate

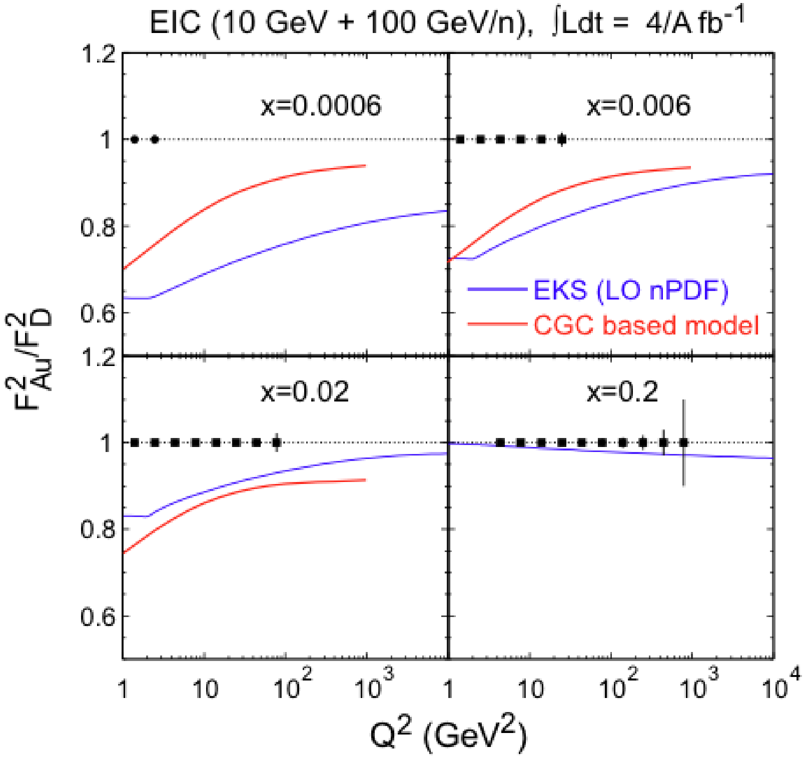
Terra Incognita in QCD !

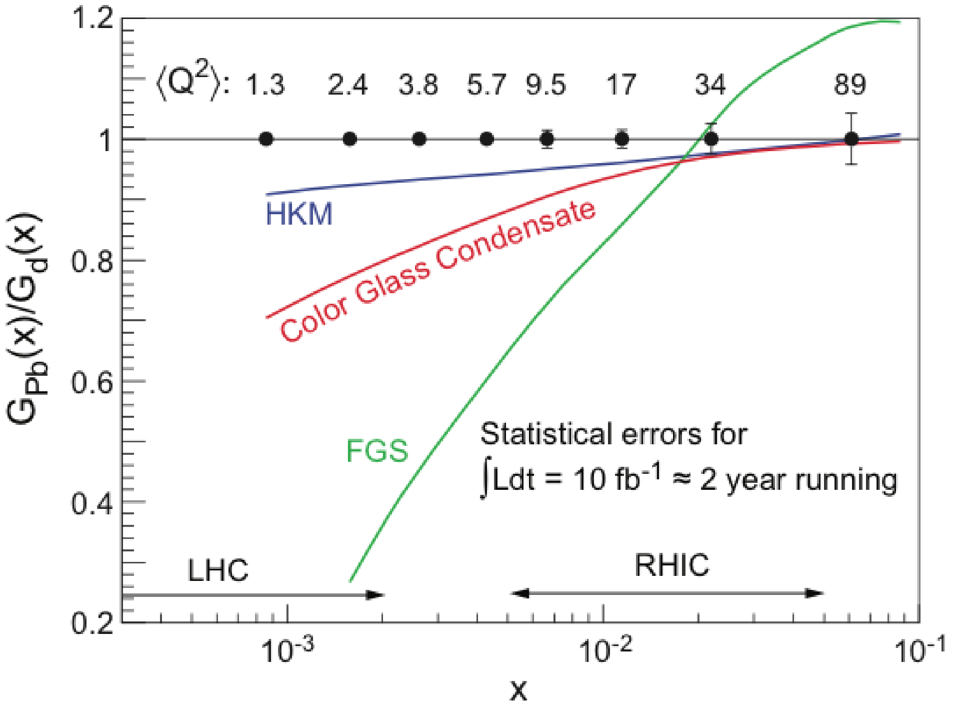




Key measurements for saturation : F_2 and F_L

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

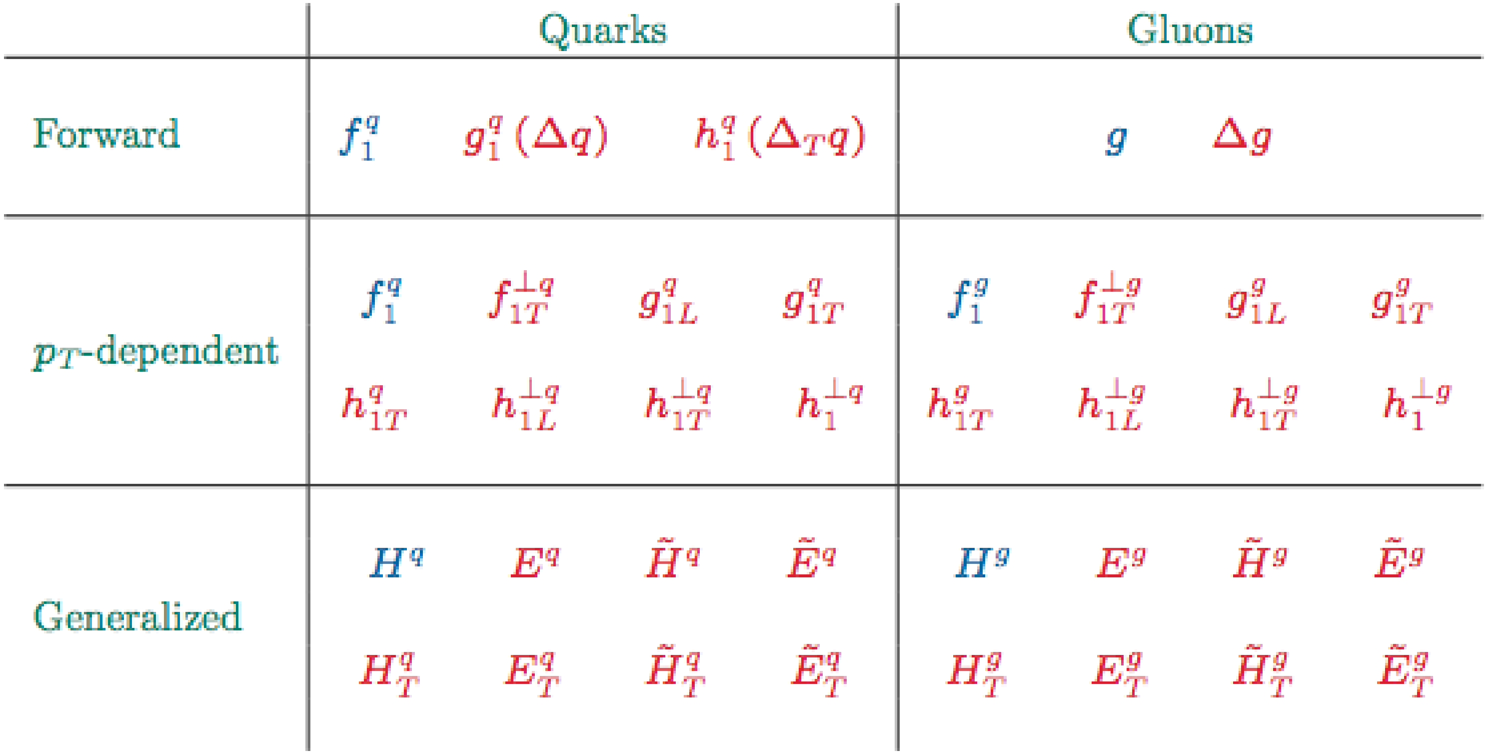




$L = 3{,}8\ 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (100x HERA)
4 weeks at 50% efficiency

$F_L \sim \alpha_S\, G(x,Q^2)$ requires an energy scan
For this plot E_exE_p = 10x100, 10x50, 5x50

(Leading-twist) parton distributions of the nucleon



	Quarks				Gluons			
Forward	f_1^q	$g_1^q\,(\Delta q)$	$h_1^q\,(\Delta_T q)$		g	Δg		
p_T-dependent	f_1^q	$f_{1T}^{\perp q}$	g_{1L}^q	g_{1T}^q	f_1^g	$f_{1T}^{\perp g}$	g_{1L}^g	g_{1T}^g
	h_{1T}^q	$h_{1L}^{\perp q}$	$h_{1T}^{\perp q}$	$h_1^{\perp q}$	h_{1T}^g	$h_{1L}^{\perp g}$	$h_{1T}^{\perp g}$	$h_1^{\perp g}$
Generalized	H^q	E^q	$\tilde{H}^q$	$\tilde{E}^q$	H^g	E^g	$\tilde{H}^g$	$\tilde{E}^g$
	H_T^q	E_T^q	$\tilde{H}_T^q$	$\tilde{E}_T^q$	H_T^g	E_T^g	$\tilde{H}_T^g$	$\tilde{E}_T^g$

Almost all distributions are related to spin (indicated in red)

Gluon distributions are the least known : **EIC will play a unique role !**

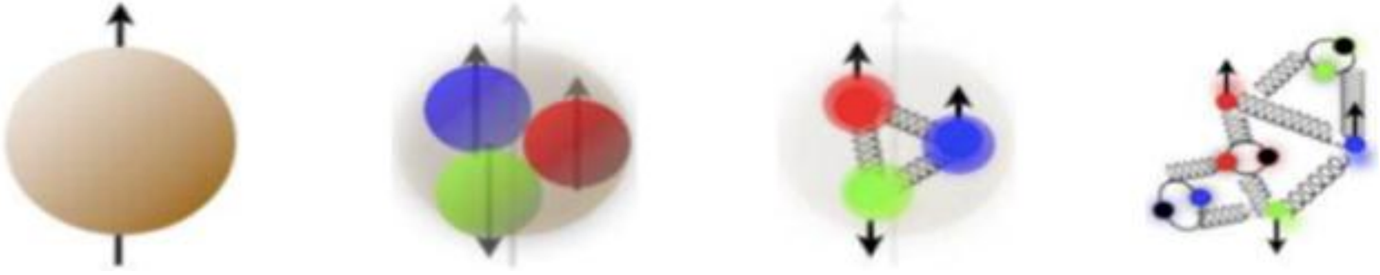
Proton Spin

The complexity of the proton state in the angular momentum sector :

Jaffe, Manohar; Ji, …

$$\frac{1}{2} = \left\langle P, \frac{1}{2} \middle| J^z_{\mathrm{QCD}} \middle| P, \frac{1}{2} \right\rangle = \frac{1}{2} \underset{\text{u+d+s}}{\Delta\Sigma} + \underset{\text{gluons}}{\Delta G} + \sum_q \underset{\text{OAM}}{L^z_q} + L^z_g$$

(A$^+$=0 gauge version)



$\mu \Rightarrow \infty$

Proton spin structure

Intrinsic spin vs. dynamical motion of quarks and gluons

Fixed target DIS measurements

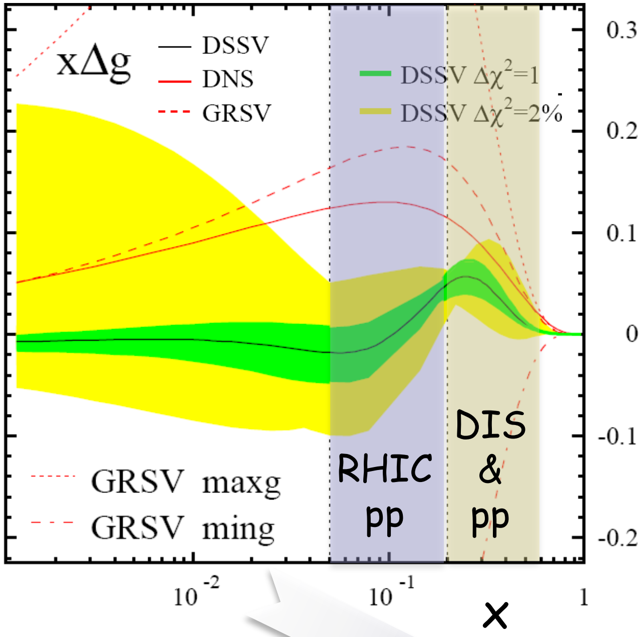
Total measured quark spin contribution ~ 25-30%

ΔG at RHIC and COMPASS

Total measured gluon spin contribution ~ 0% but large errors !

Need a wider range of momentum fraction x in e-p scattering

Status of Δg measurements

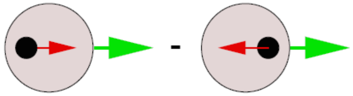


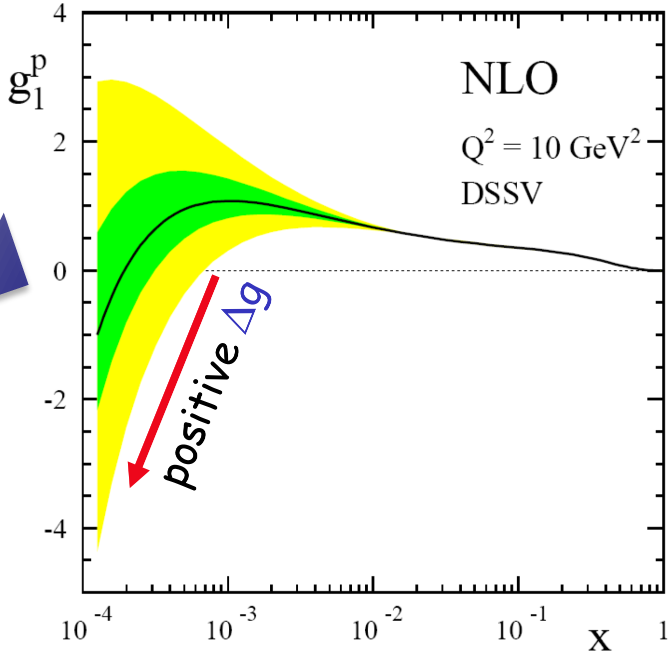
- low-x behavior unconstrained
- no *reliable* error estimate for 1st moment $\int_0^1 dx\, \Delta g(x,Q^2)$ (entering spin sum rule)
- find $\int_{0.05}^{0.2} dx\, \Delta g(x,Q^2) \approx 0$

pQCD scaling violations

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

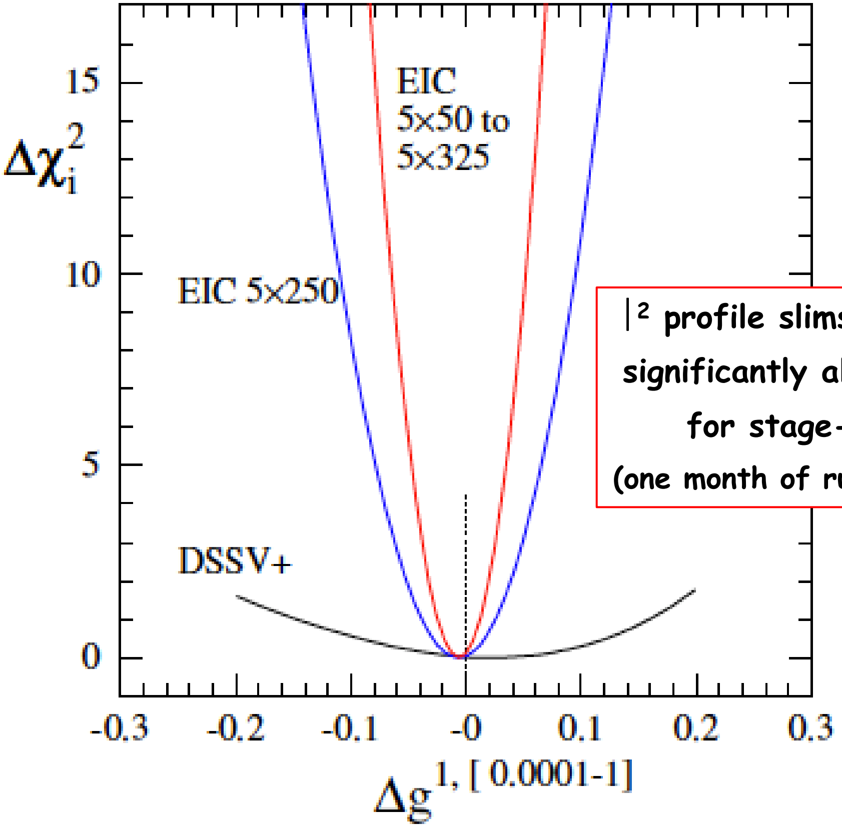
$$\boxed{\Delta f(x) \equiv f_+^{N_+}(x) - f_-^{N_+}(x)}$$



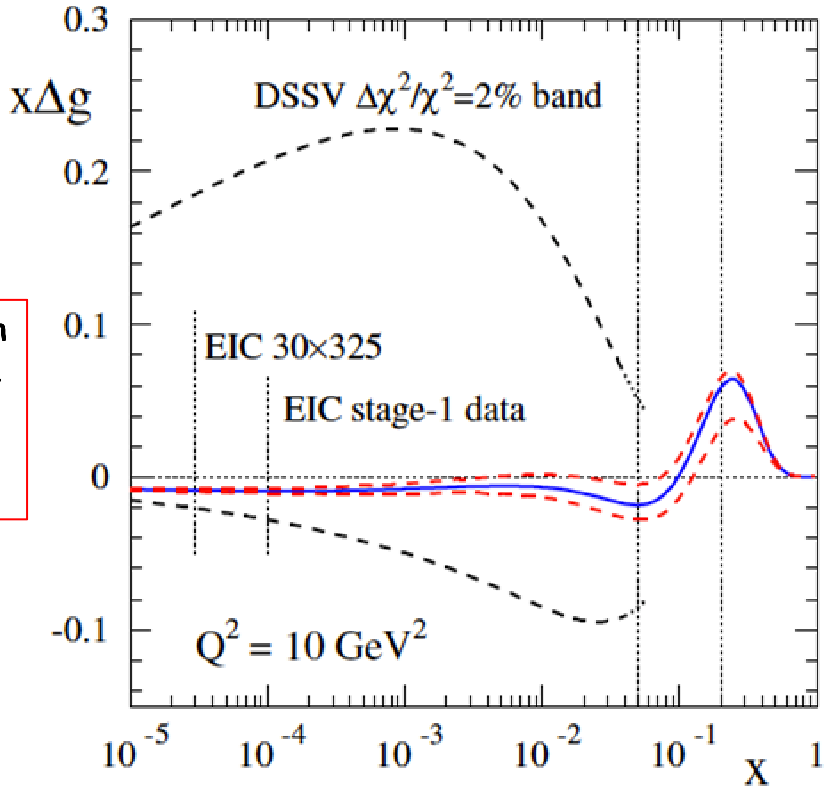


Indirect constraint on Δg at EIC

How effective are g_1 scaling violations to determine Δg with an EIC?

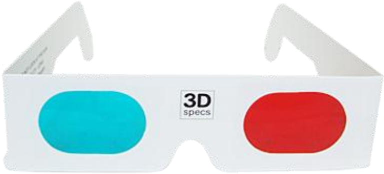


$|^2$ profile slims down significantly already for stage-1 (one month of running)



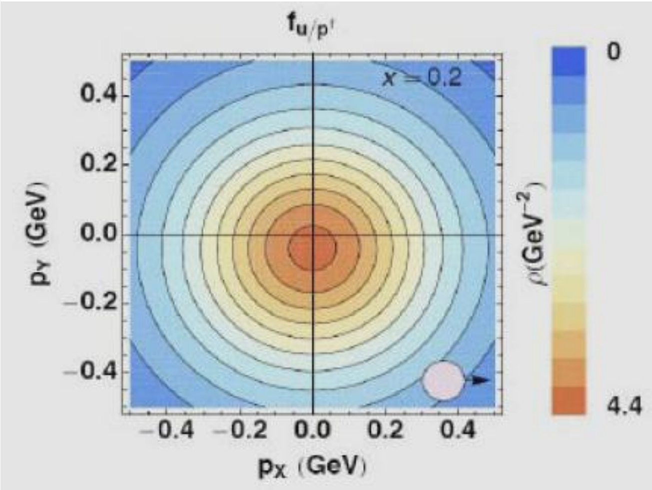
Even with flexible x-shape, EIC will determine $\int_0^1 dx\, \Delta g(x,Q^2)$ to about ± 0.07

Towards 3D imaging : away from the longitudinal picture



TMDs

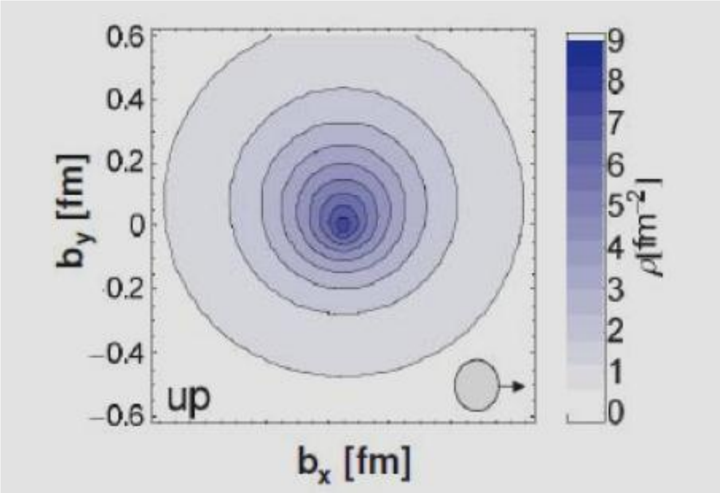
2+1 D picture in **momentum space**



Model by : Bacchetta, Conti, Radici

GPDs

2+1 D picture in **impact-parameter space**



Lattice result : QCDSF collaboration

Transverse position and motion of partons

Relativistic system/uncertainty principle: can localize only in *two* dimensions

TMDs

- intrinsic transverse *motion*
- spin-orbit correlations = *indicator* of OAM
- role of gluons "accompanying" partons (Wilson lines or gauge links)
- non-trivial factorization
- matching between small k_T (TMDs) and large, perturbative k_T (twist-3 parton correl.)

GPDs

- transverse parton *position*
- collinear but long. momentum transfer
- can *measure* OAM; access to Ji's total $J_{q,g}$
- existing *factorization proofs*
- difficult extraction (more later)

no direct, *model-indep.* connection known between TMDs and GPDs

average transverse mom. and position ***not*** Fourier conjugates:

average transv. mom <---> position difference

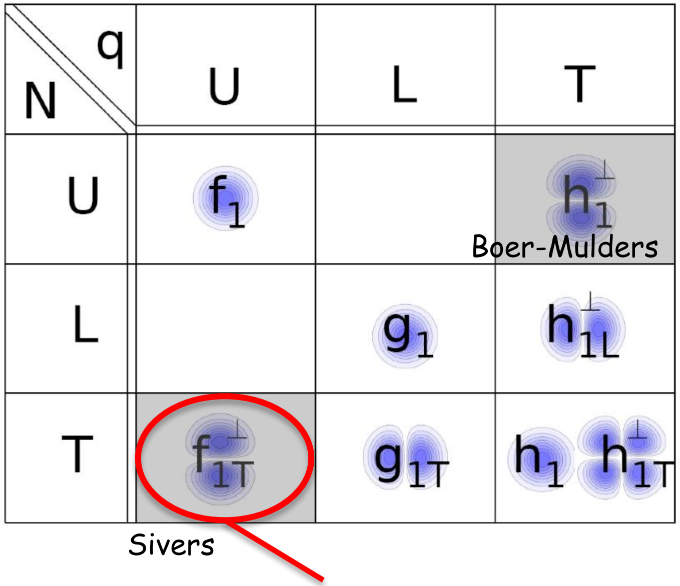
transv. mom. transfer <---> average position

"high level connection" through Wigner phase space distr. $W(x, k_T, b_T)$

Study of confined quark motion with TMDs

- Many observables possible in ep -> ehX if intrinsic k_T included and Φ kept
- Seen at HERMES and COMPASS (but mainly valence quark region & large uncertainties)

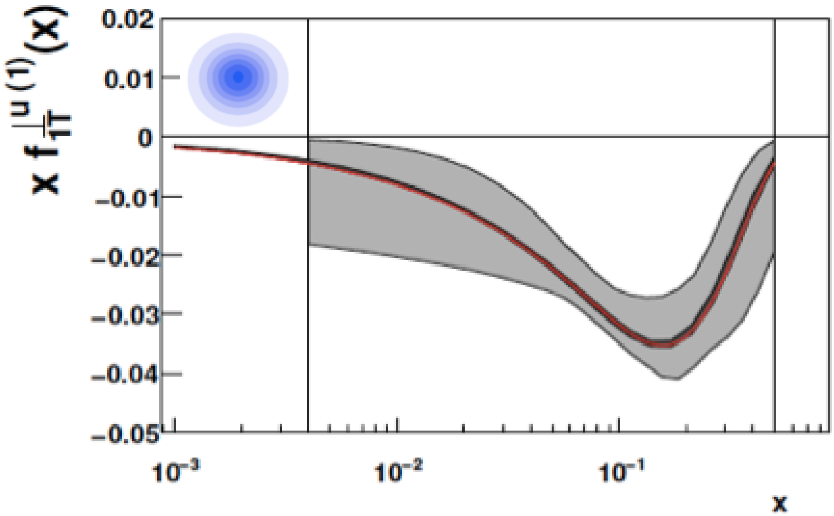
8 leading twist TMDs,
EIC can measure them all, focus on 2
Gluon TMDs accessible through
quarkonium production



N \ q	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$ Sivers	g_{1T}	h_1 $h_{1T}^\perp$

Access to 3D imaging in momentum space
Non-trivial role of Wilson lines
Role of spin-orbit correlations & OAM

Example of what EIC can do to Sivers function :

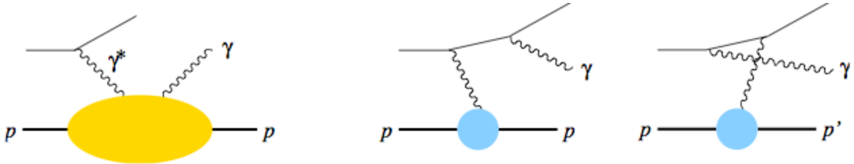


Exclusive Processes for parton transverse imaging

Deeply Virtual Compton Scattering

- Theory is under control : up to α_S^2, twist-3, target mass corrections, etc
- Sensitive to the quark combination : $\frac{4}{9}u + \frac{1}{9}d + \frac{1}{9}s + \frac{4}{9}c$
- At EIC energies, mostly sensitive to sea quarks
- Sensitive to gluon GPDs through Q^2 evolution at NLO or beyond
- Direct access to the Compton amplitude through

  interference with known Bethe-Heitler process



Hard Meson Electroproduction

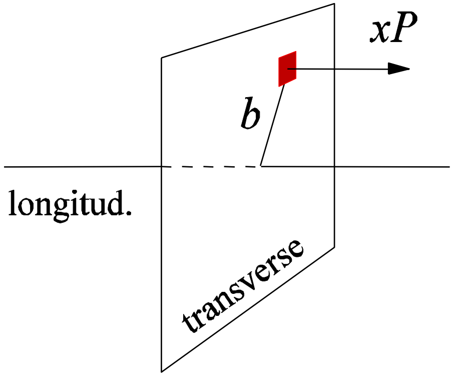
- Many channels available for flavor separation (ρ, ρ^+, π^0, π^+, ϕ, …)
- J/Ψ and ϕ are especially interesting to access gluon GPDs (H and even E)
- Theory less under control : convolution with (unknown) meson WF,

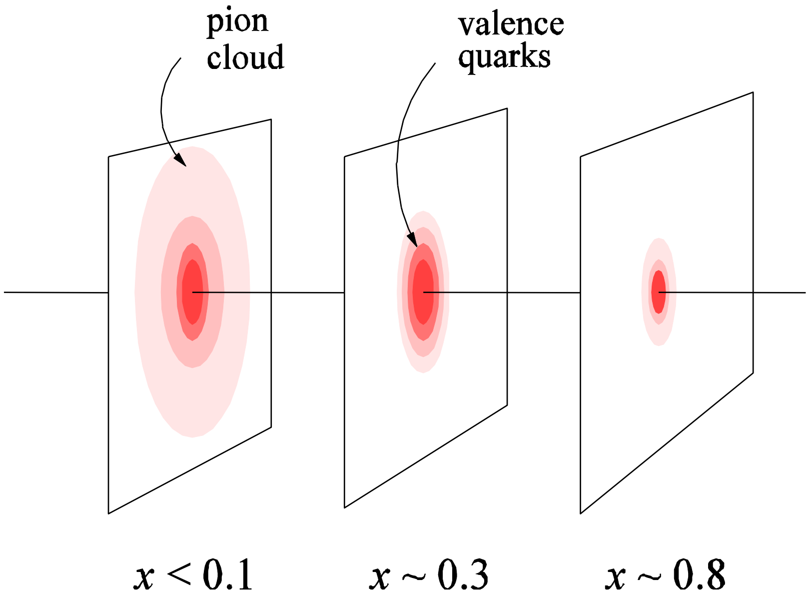
  large power and NLO corrections

Imaging partons with GPD H

At ξ=0, a GPD is the « form factor » of partons
carrying longitudinal momentum fraction x

$$f(x,\vec{b}) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{i\vec{b}\cdot\vec{\Delta}_\perp} H(x,\xi=0,-\Delta_\perp^2)$$

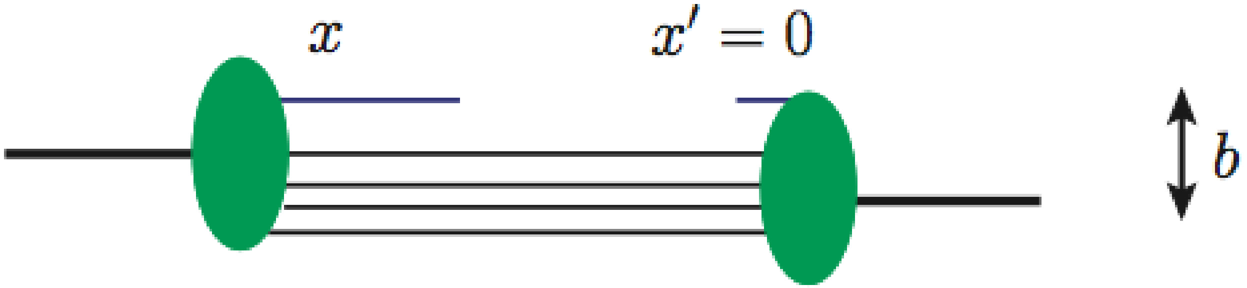




© C. Weiss

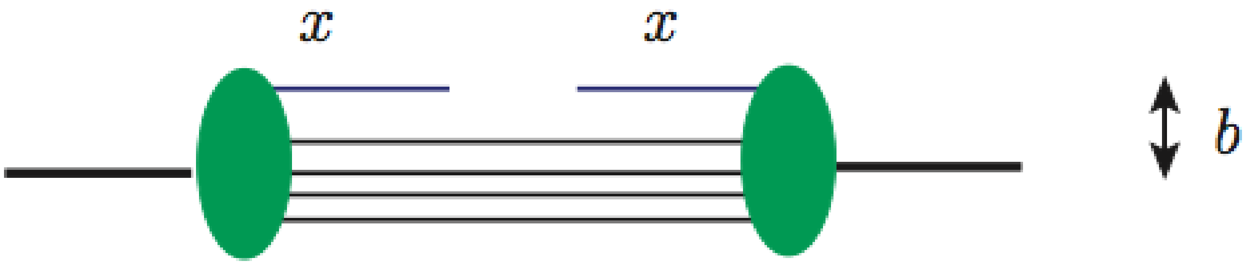
Imaging principle

The poor man's way



Pros: GPD($x=\xi,\xi,b$) directly accessible experimentally in DVCS
b is well defined (imaginary part of Compton amplitude)
Cons: No probability interpretation !

The right way



Pros: Density interpretation GPD(x, ξ=0,b)=$f(x,b)$ (IP-PDF)
Cons: Not directly accessible experimentally ➔ model dependent extraction
(some hope through Q^2 dependence, but experimentally difficult)
Systematic errors due to ξ=0 extrapolation remain to be studied

Imaging partons with GPD E

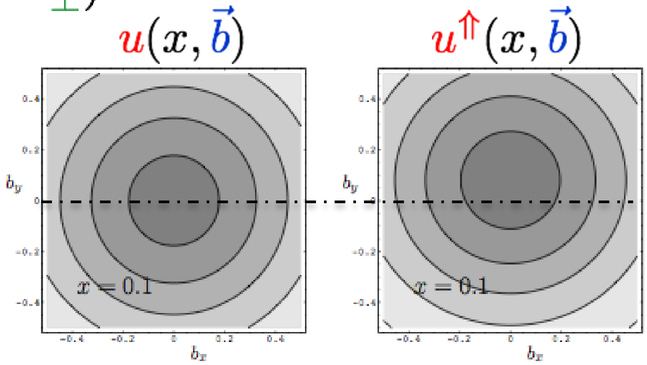
Burkardt '02, '05

GPD E ↔ nucleon helicity flip
interference between wave functions with L_z and $L_z \pm 1$

Access to GPD E via **transverse target polarization asymmetries**

Shift (*in y*) of the partons inside a polarized proton (*along x*)

$$f^{\Uparrow}(x,\vec{b}) = f(x,\vec{b}) - \frac{1}{2M}\frac{\partial}{\partial b_y}\int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{i\vec{b}\cdot\vec{\Delta}_\perp} E(x,0,-\Delta_\perp^2)$$



Shift seems large for valence u and d quarks,

but *unknown* for sea and gluons : great opportunity for EIC

Simulation of DVCS for EIC

Simulated DVCS data based on a fitted model for GPD H
Kumericki, Müller, Passek-Kumericki, Nucl. Phys. B794 (2008) 244-323
(fair description of H1 and ZEUS low-x_B DVCS data)

For GPD E, very simple ansatz : $E^i(x,\xi,t) = \kappa^i(t) H^i(x,\xi,t)$

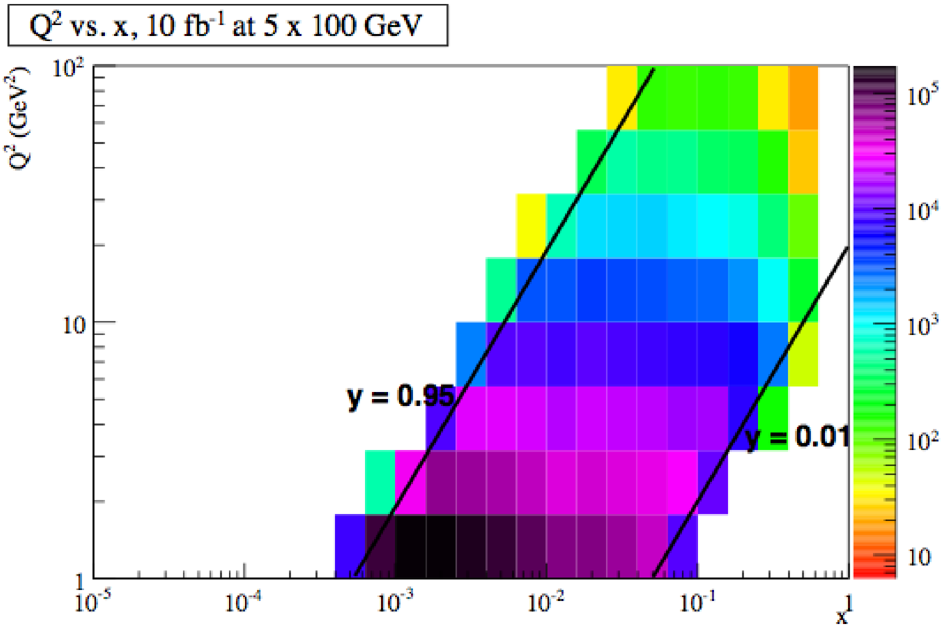
Used standard cuts for acceptance,
> for Roman pots, assumed $(0.175\ \mathrm{MeV})^2 < |t| < 0.88\ \mathrm{GeV}^2$

Kinematics were smeared according to expected resolution in t, Q^2, x_B

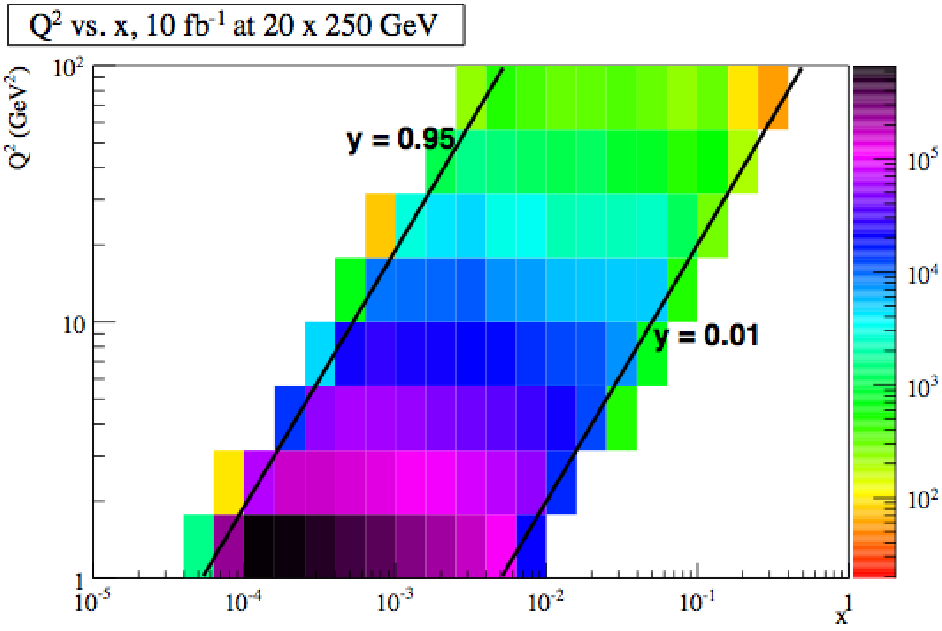
Assumed systematic errors of 5%, luminosity uncertainty *not included*

Simulation of DVCS for EIC : counting rates

EIC stage 1



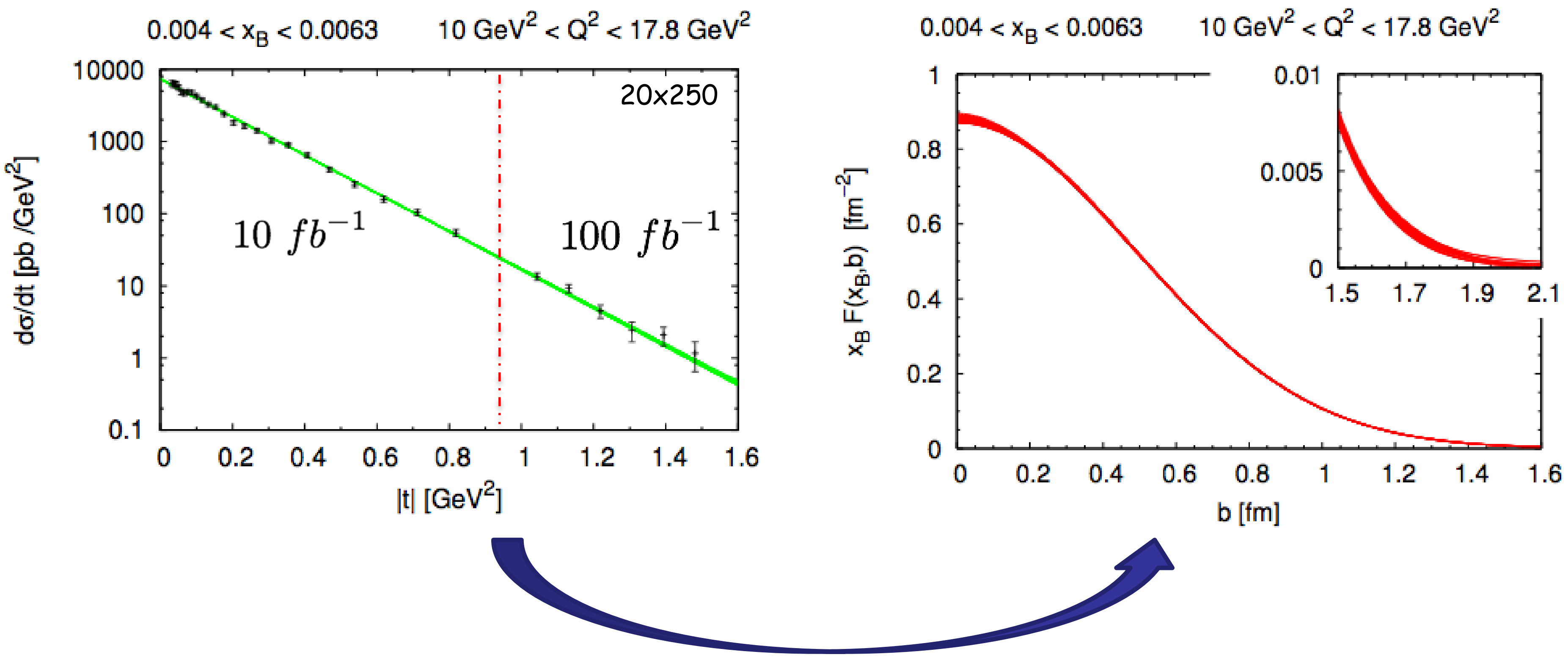
EIC stage 2



Reasonable counting rates for 4D binning (x_B,t,Q^2,Φ)

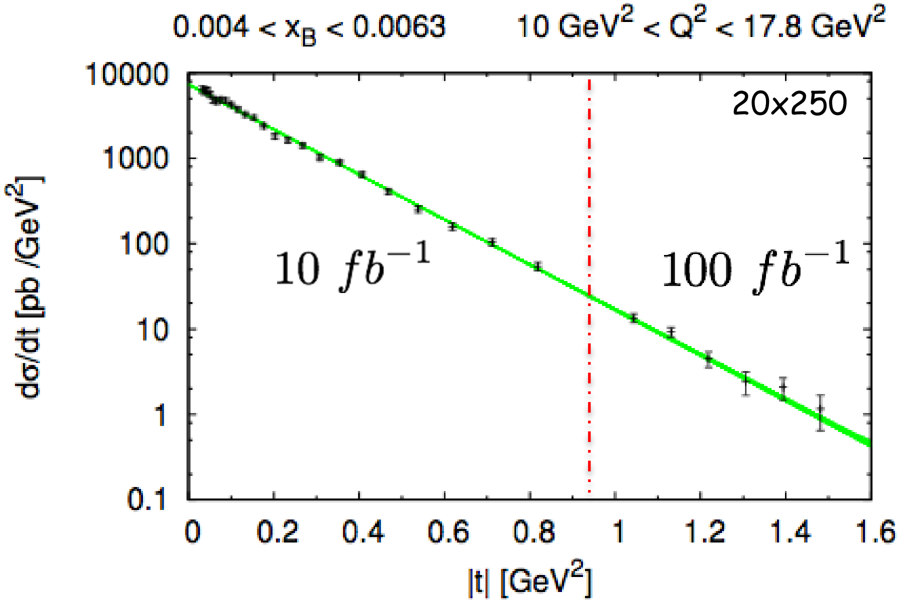
high-t usually needs higher luminosity (~100 fb^{-1})

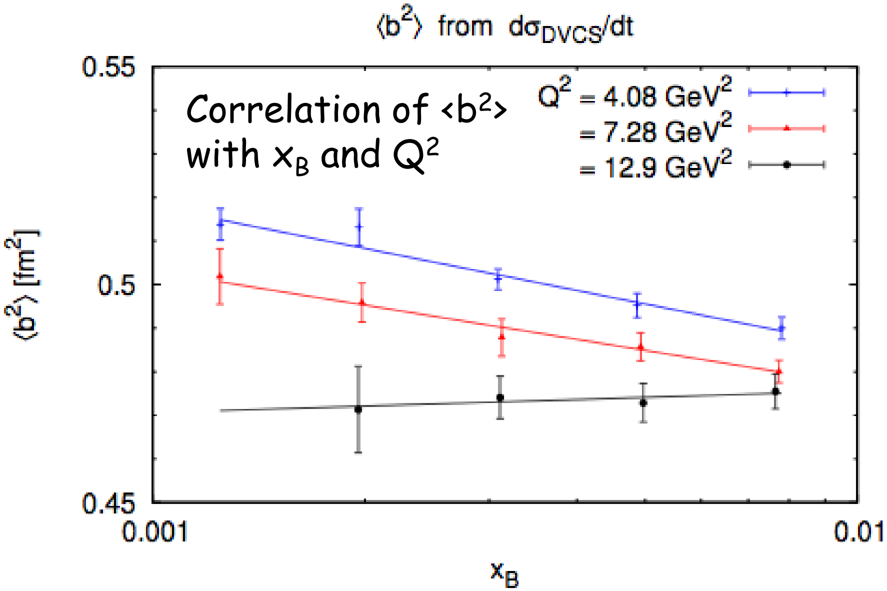
Simulation of DVCS for EIC : Imaging at x=ξ



- Subtract BH contribution (known to ~3%)
- Extract Compton amplitude from $d\sigma_{\gamma^* p \rightarrow \gamma p}/dt$
- Fourier transform
- Vary low-t and high-t extrapolations to estimate errors

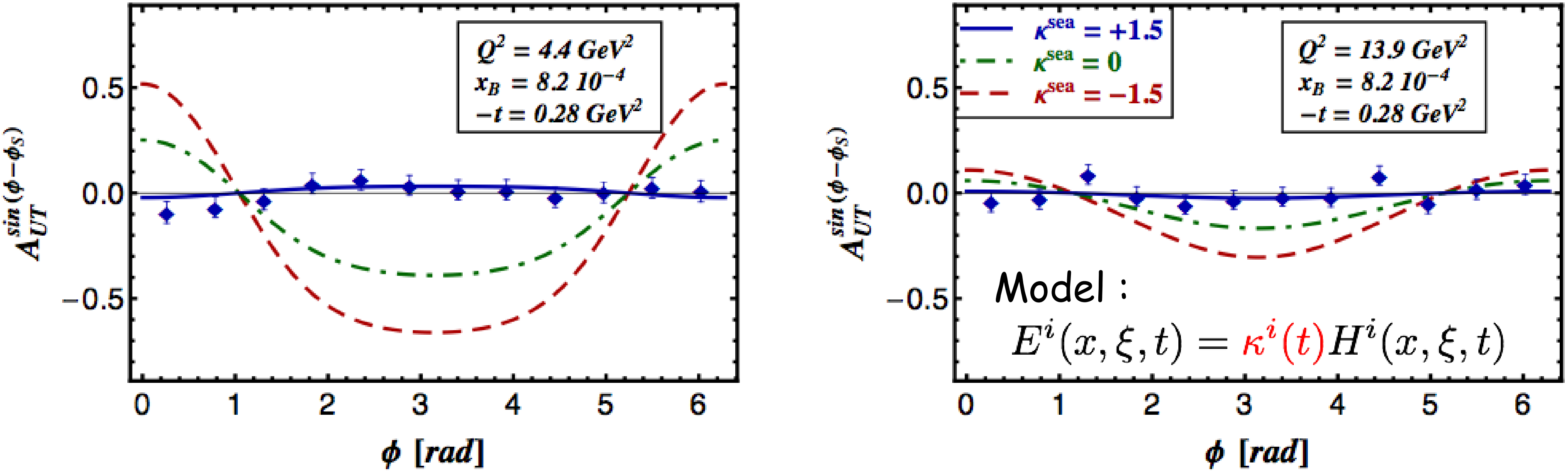
Simulation of DVCS for EIC : Imaging at x=ξ





- ❑ Subtract BH contribution (known to ~3%)
- ❑ Extract Compton amplitude from $d\sigma_{\gamma^* p\rightarrow\gamma p}/dt$
- ❑ Fourier transform to get IP-PDF
- ❑ Vary low-t and high-t extrapolations to estimate errors

Simulation of DVCS for EIC : the GPD E



Model :

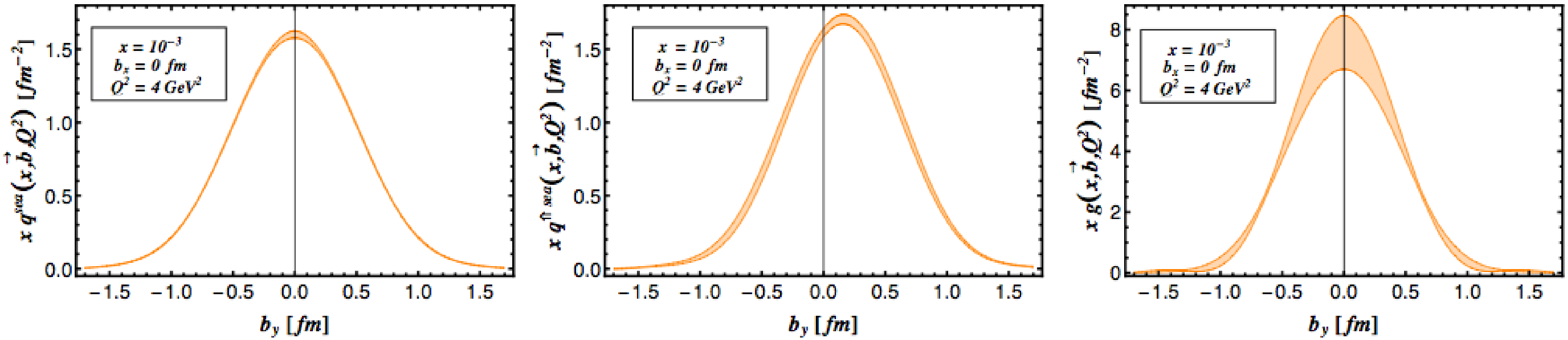
$$E^i(x,\xi,t) = \kappa^i(t) H^i(x,\xi,t)$$

- $d\sigma/dt$ is mostly sensitive to the GPD H
- GPD E is accessible through transversely polarized proton asymmetries such as $A_{UT}^{\sin(\phi-\phi_S)}$ **(H contributes as well !)**

- Data for $d\sigma/dt$ and $A_{UT}^{\sin(\phi-\phi_S)}$ have been fitted simultaneously
- Assume known forward distributions for H, unknown for E

Simulation of DVCS for EIC : Imaging at ξ=0

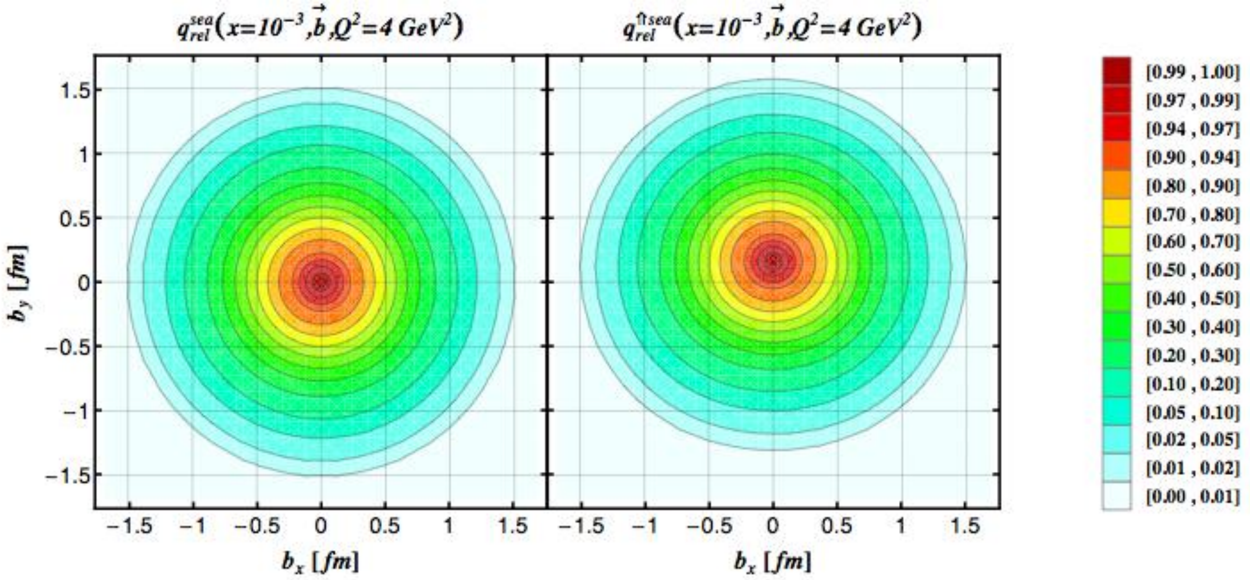
e^g badly constrained
from Q^2 evolution
(not shown)



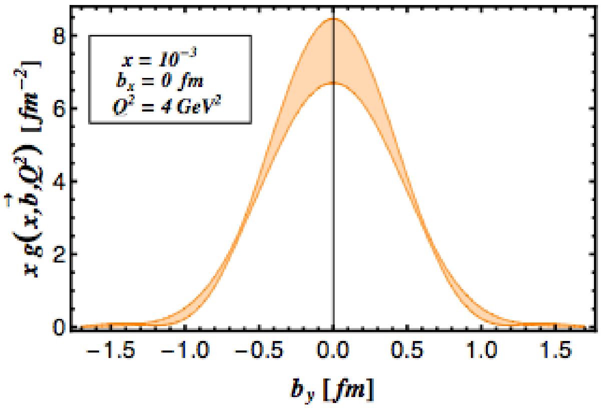
- ❑ $d\sigma/dt$ is mostly sensitive to the GPD H
- ❑ GPD E is accessible through transversely polarized proton asymmetries such as $A_{UT}^{\sin(\phi-\phi_S)}$ **(H contributes as well !)**

- ❑ Data for $d\sigma/dt$ and $A_{UT}^{\sin(\phi-\phi_S)}$ have been fitted simultaneously
- ❑ Assume known forward distributions for H, unknown for E
- ❑ Extrapolate fitted GPDs H and E to ξ=0, Fourier transform H and E

Simulation of DVCS for EIC : Imaging at ξ=0



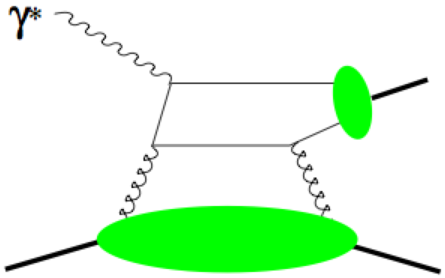
e^g badly constrained from Q^2 evolution (not shown)



- $d\sigma/dt$ is mostly sensitive to the GPD H
- GPD E is accessible through transversely polarized proton asymmetries such as $A_{UT}^{\sin(\phi-\phi_S)}$ **(H contributes as well !)**

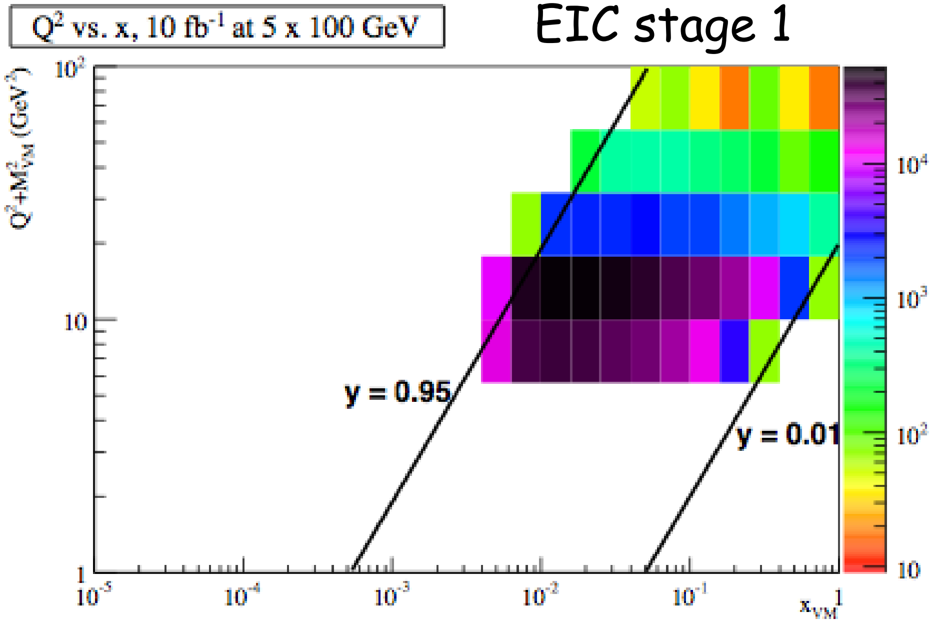
- Data for $d\sigma/dt$ and $A_{UT}^{\sin(\phi-\phi_S)}$ have been fitted simultaneously
- Assume known forward distributions for H, unknown for E
- Extrapolate fitted GPDs H and E to ξ=0, Fourier transform H and E

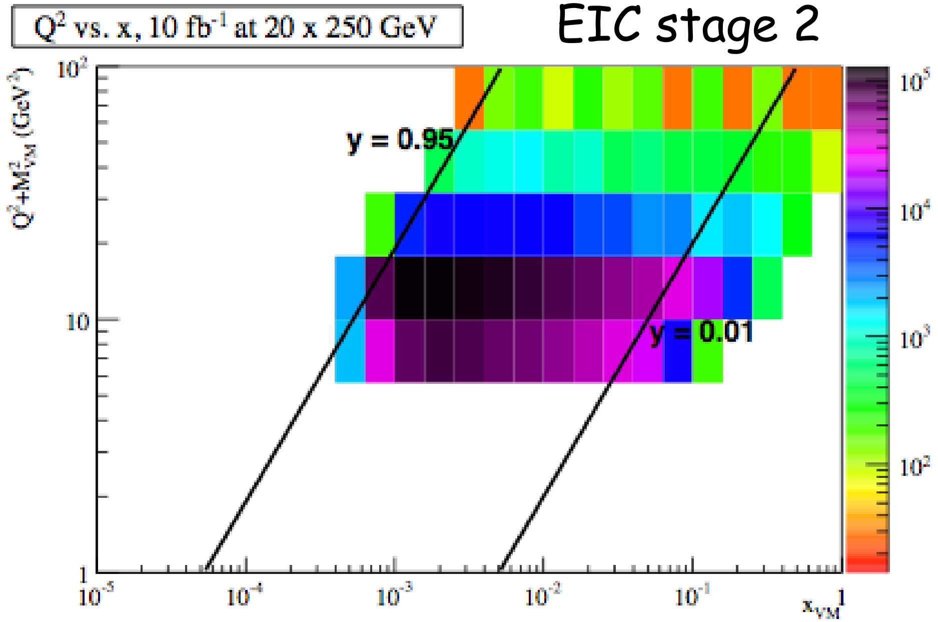
Simulation of DVCS for EIC : Imaging gluons



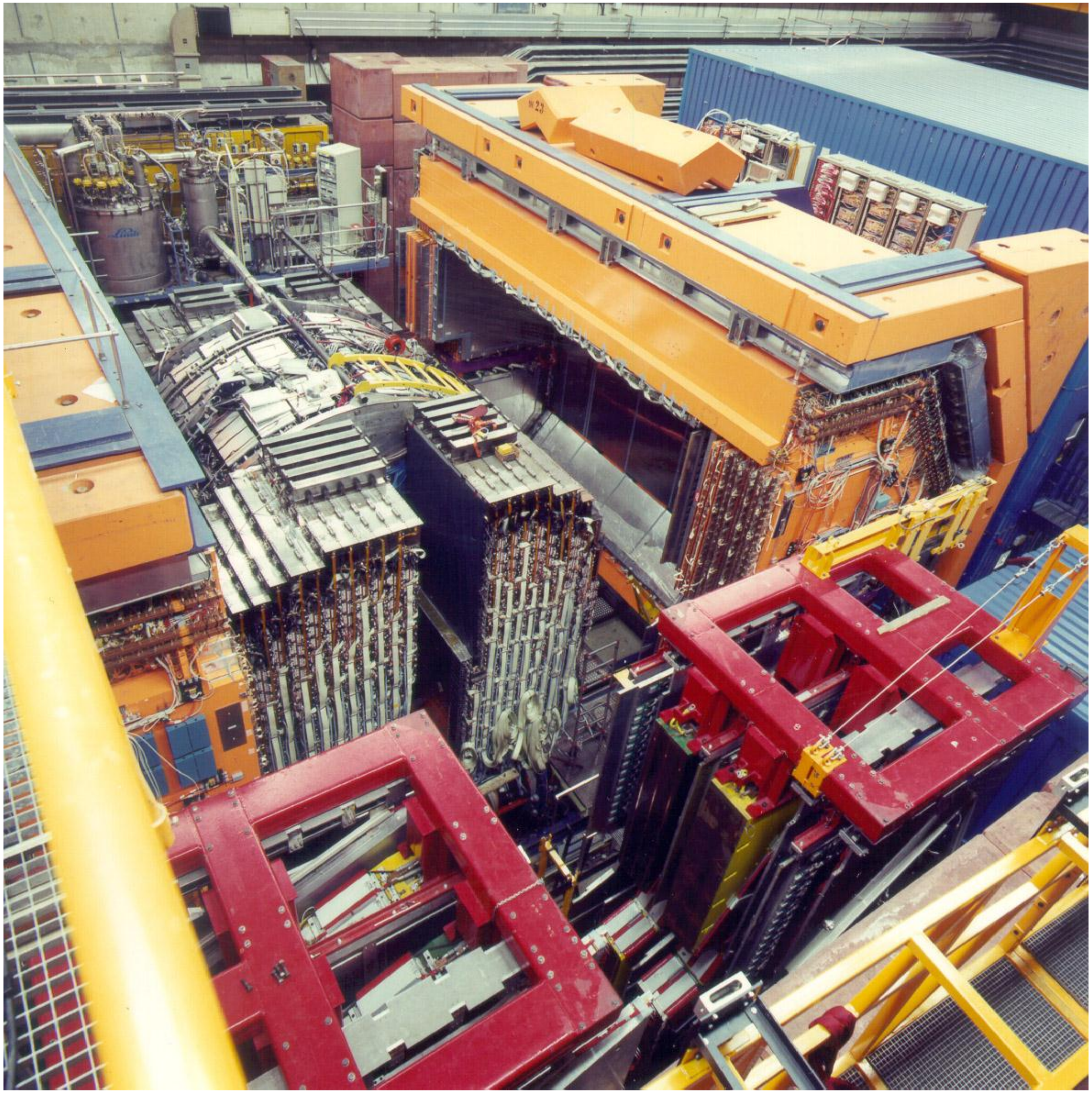
- Another golden channel : $\gamma^* p \rightarrow J/\Psi p$
- Directly sensitive to gluons
- Theory rather well in control for a meson
- The hard scale is given by $Q^2 + M^2_{J/\Psi}$ (photoproduction possible)
- In principle, can be detected with both e^+e^- and $\mu^+\mu^-$ decay channels
- Cross section : H^g

Transverse Spin Asymmetry : E^g


EIC stage 1


EIC stage 2

So, how do we measure all that !



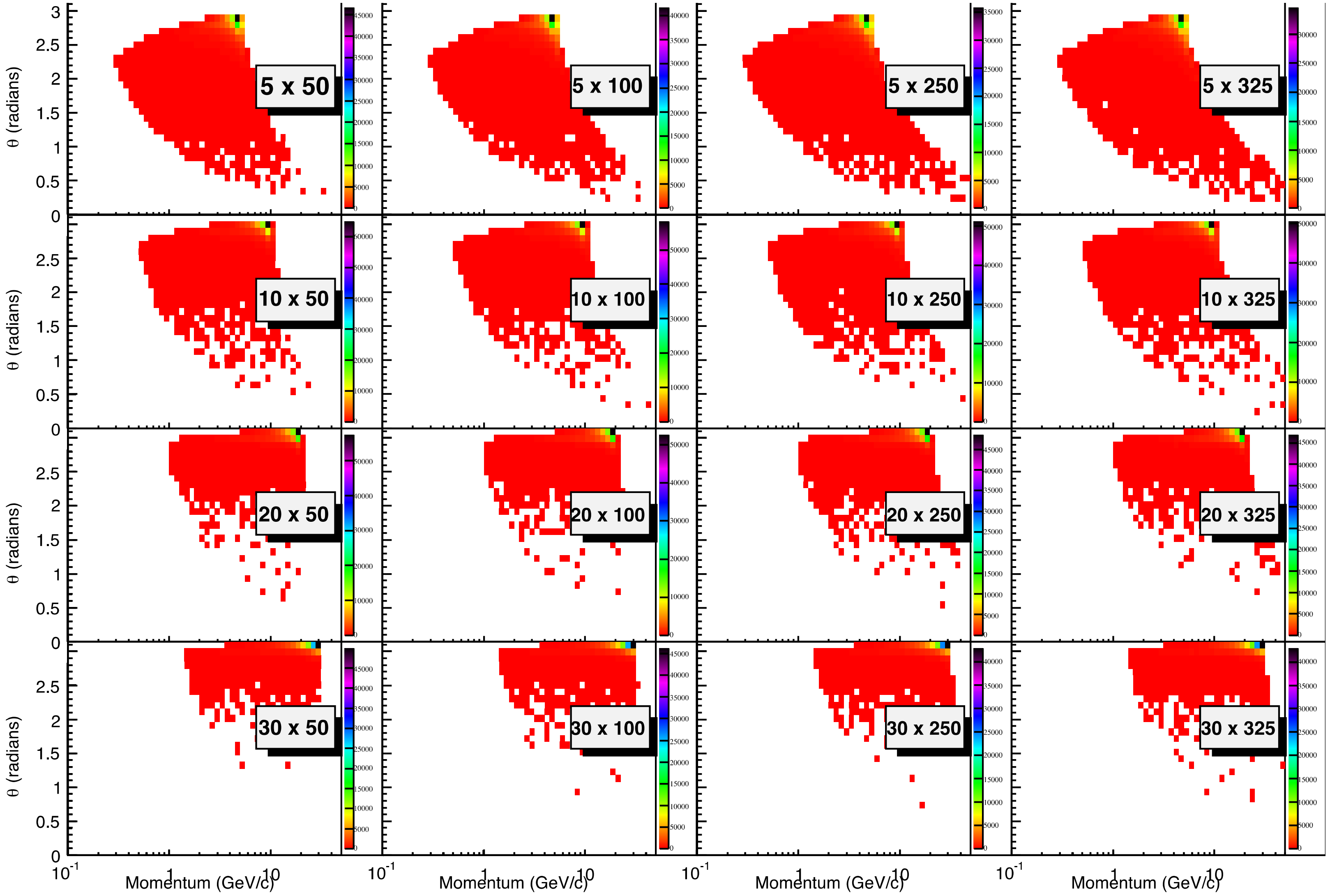
EIC detector requirements

Mostly driven by exclusive or semi-inclusive physics

- Hermeticity (also for hadronic reconstruction methods in DIS)
- Particle identification (needed for SIDIS too)
- Momentum resolution
- Forward detection of recoil baryons (also baryons from nuclei)
- Muon detection (J/Ψ)
- Photon detection (**DVCS**, π^0)
- Very forward detection (spectator tagging, diffractive mechanisms, coherent nuclear, etc)
- Vertex resolution (displaced vertex, i.e. charm)
- Hadronic calorimetry (jet)

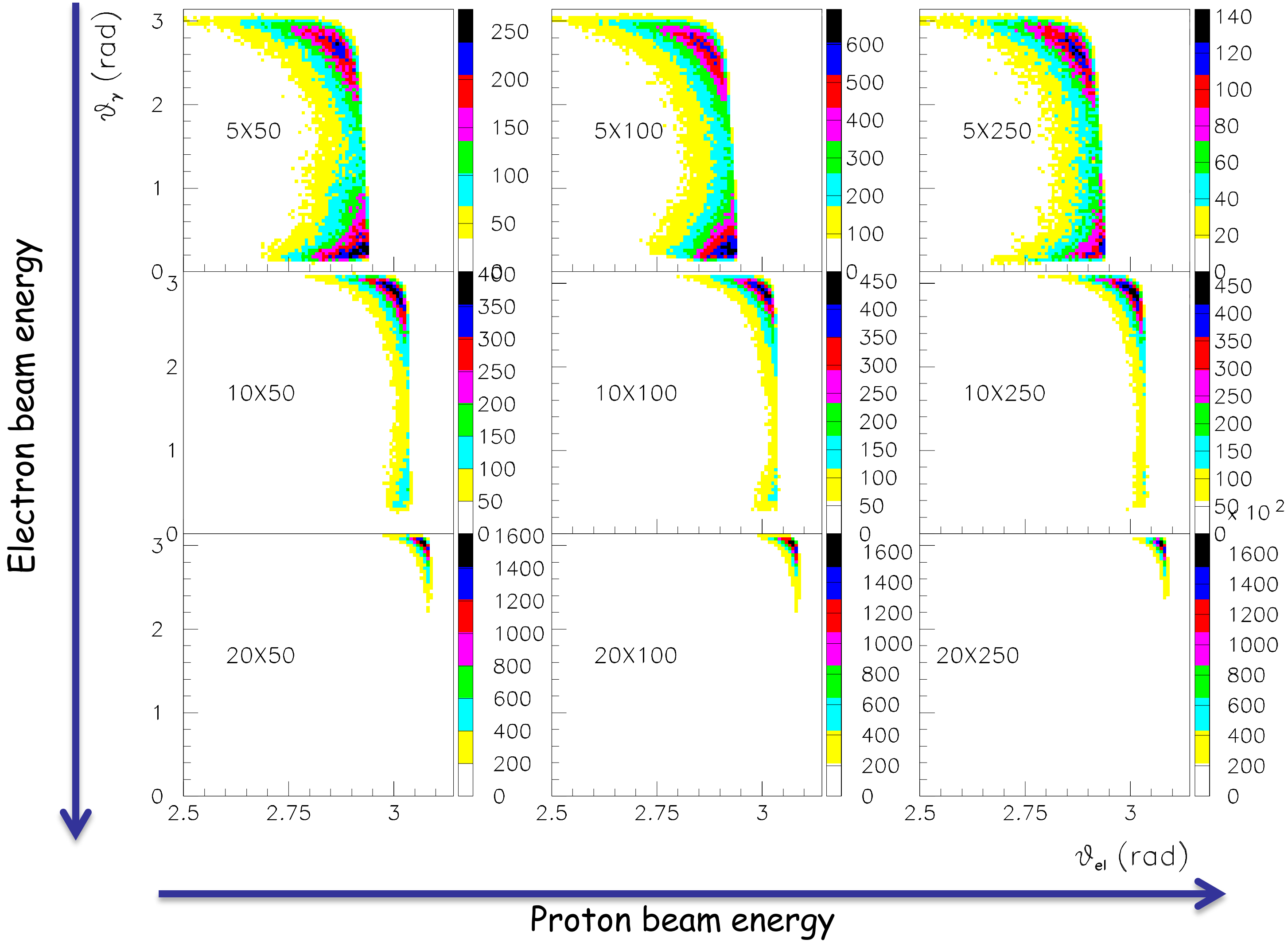
In general, e-p and even more e-A colliders have a large fraction of their science related to the detection of what happens to the ion beam. The struck quark remnants can be guided to go to the central detector region with Q^2 cuts, but the spectator quark or struck nucleus remnants will go in the forward (ion) direction.

Detector considerations : scattered electron



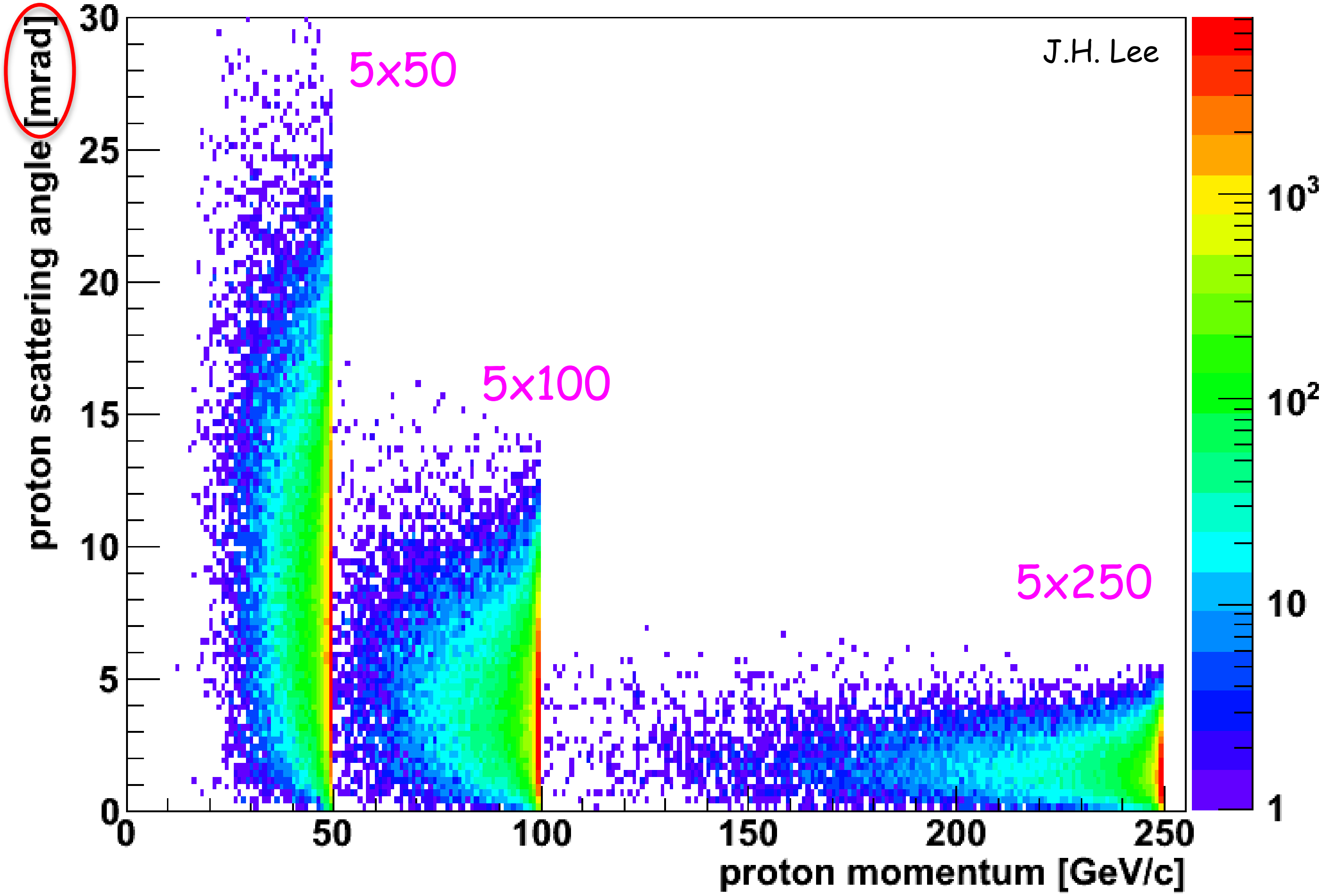
For all lepton-hadron beam energy combinations, the scattered electron goes in the direction of the original electron beam for low Q^2 and more and more into the central detector acceptance for higher Q^2

Detector considerations : θ_γ vs. θ_e



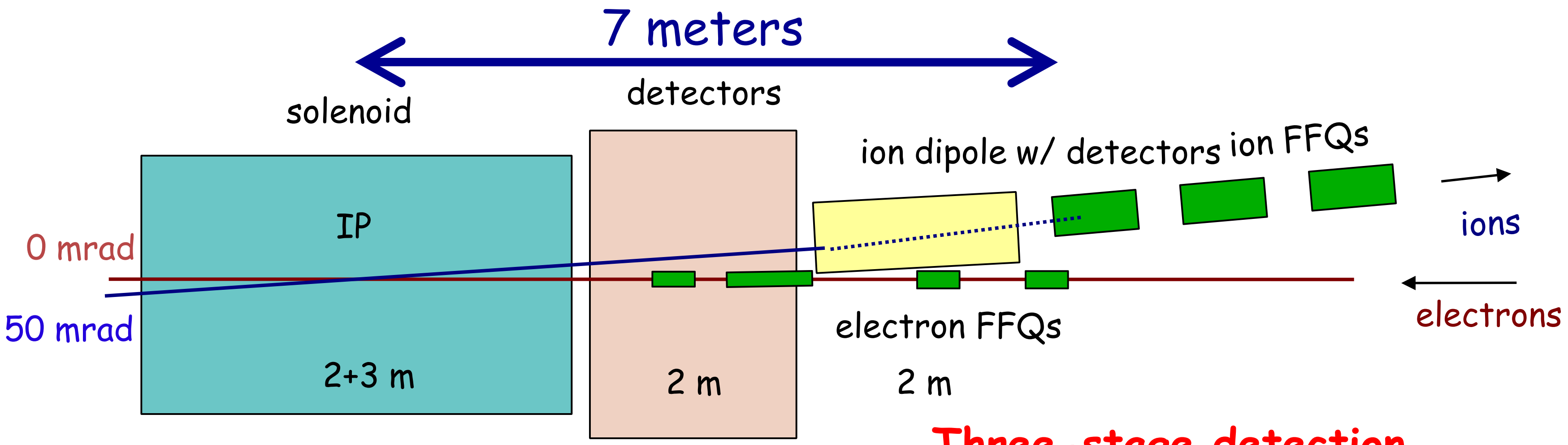
With increasing electron energy, the real photon gets closer to the electron beam

Detector considerations : recoil proton

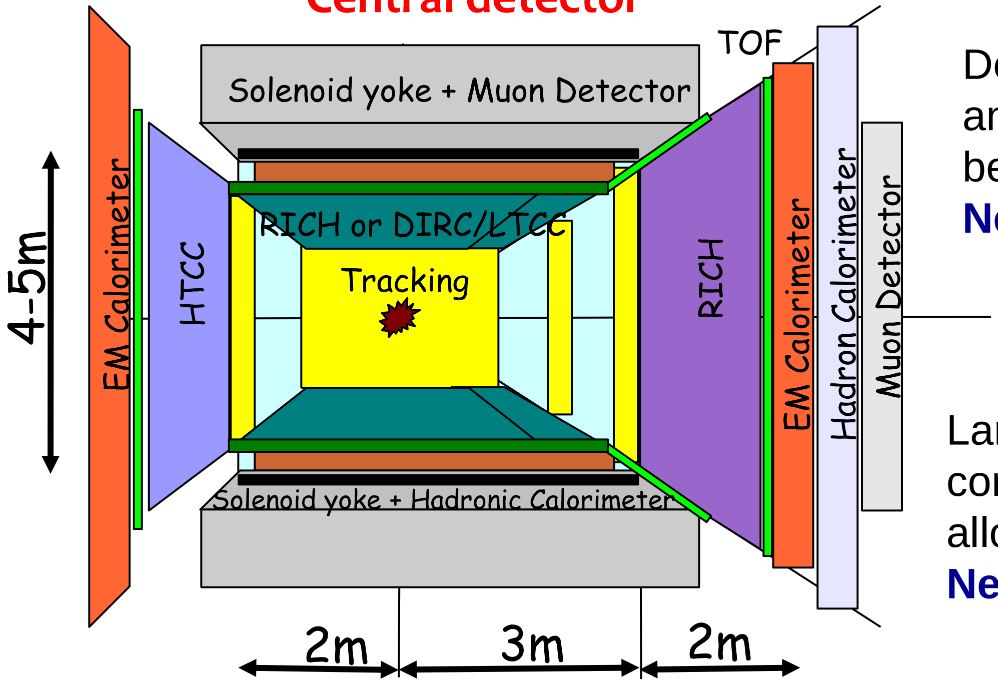


Roman pots are an essential part of the detector/IR design

MEIC/ELIC detector



Central detector



Three-stage detection

Detect particles with angles down to 0.5^{o} before ion FFQs.
Need 1-2 Tm dipole.

Detect particles with angles below 0.5^{o} beyond ion FFQs and in arcs.
Need 4 m machine element free region

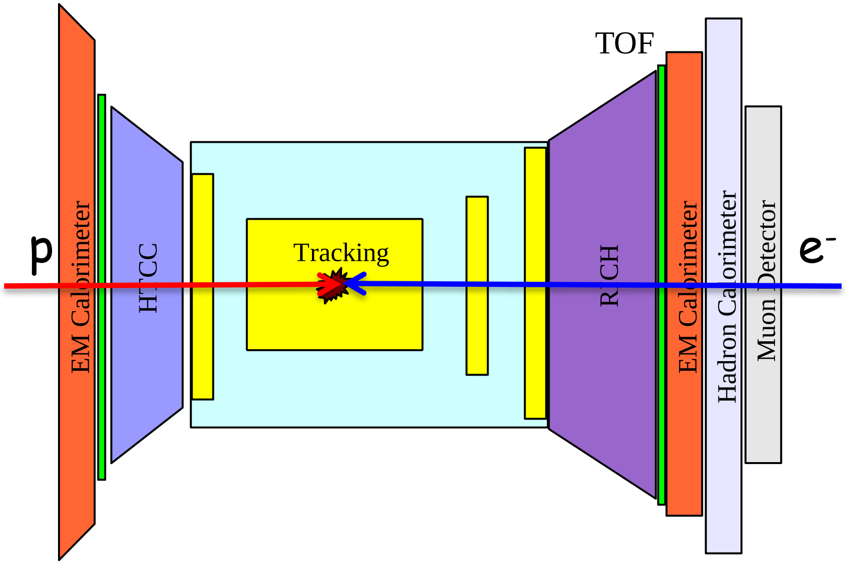
Very-forward detector

Large dipole bend @ 20 meter from IP (to correct the 50 mr ion horizontal crossing angle) allows for very-small angle detection ($<0.3^{o}$).
Need 20 m machine element free region

MEIC/ELIC detector : Endcaps

Electron side (left)

- Bore angle: ~45° (line-of-sight from IP)
- High-Threshold Cerenkov (e/π)
- Time-of-Flight Detectors
  - Hadrons, event reconstruction, trigger
- Electromagnetic Calorimeter (e/π)



Ion side (right)

- Bore angle: 30-40° (line-of-sight from IP)
- Ring-Imaging Cerenkov (RICH)
- Time-of-Flight Detectors (event recon., trigger)
- Electromagnetic Calorimeter
  - Pre-shower for $\gamma/\pi^\circ \rightarrow \gamma\gamma$
    (very small opening angle at high p)
- Hadronic Calorimeter (jets)
- Muon detector (J/Ψ production at low Q^2)

Space constraints

- Electron side has a lot of space
- Ion side limited by distance to FFQ quads (7 m)

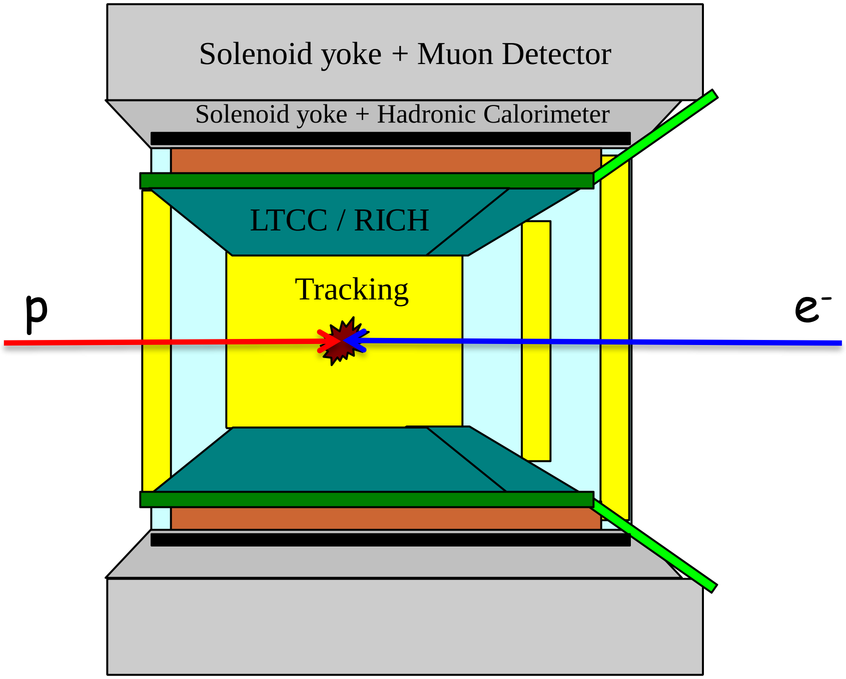
MEIC/ELIC detector : Central Detector

Solenoid Yoke, Hadron Calorimeter, Muons

- 3-4 T solenoid with about 4 m diameter
- Hadronic calorimeter and muon detector integrated with the return yoke (*à la* CMS)

Particle Identification

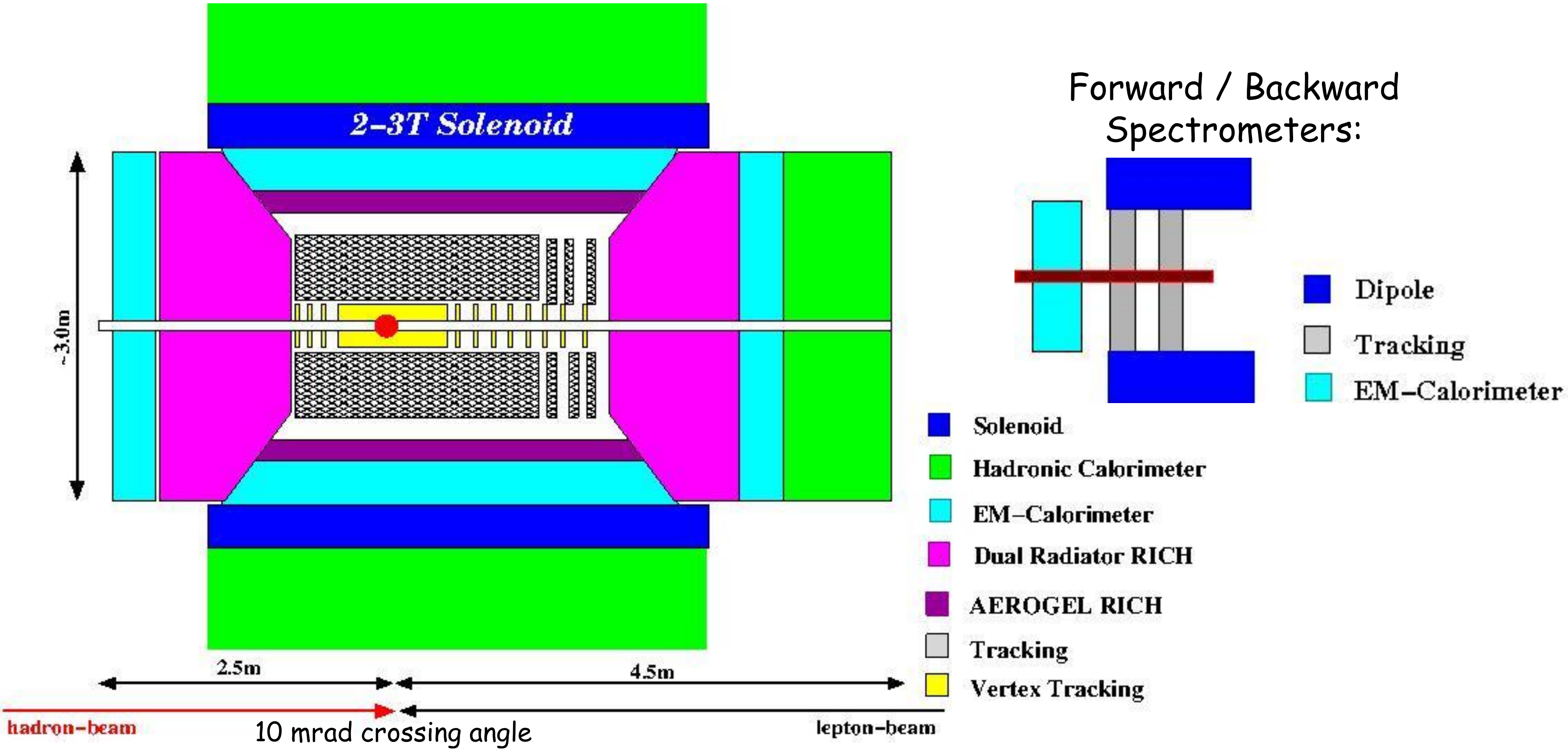
- TOF for low momenta
- π/K separation options
  - DIRC up to 4 GeV
  - DIRC + LTCC (or RICH): up to 9 GeV
- p/K separation
  - DIRC up to 7 GeV
- e/π separation
  - C_4F_8O Low Threshold CC up to 3 GeV



Tracking

- Low-mass vertex tracker
- GEM-Micromegas-based central tracker
- Endcap trackers

New eRHIC detector

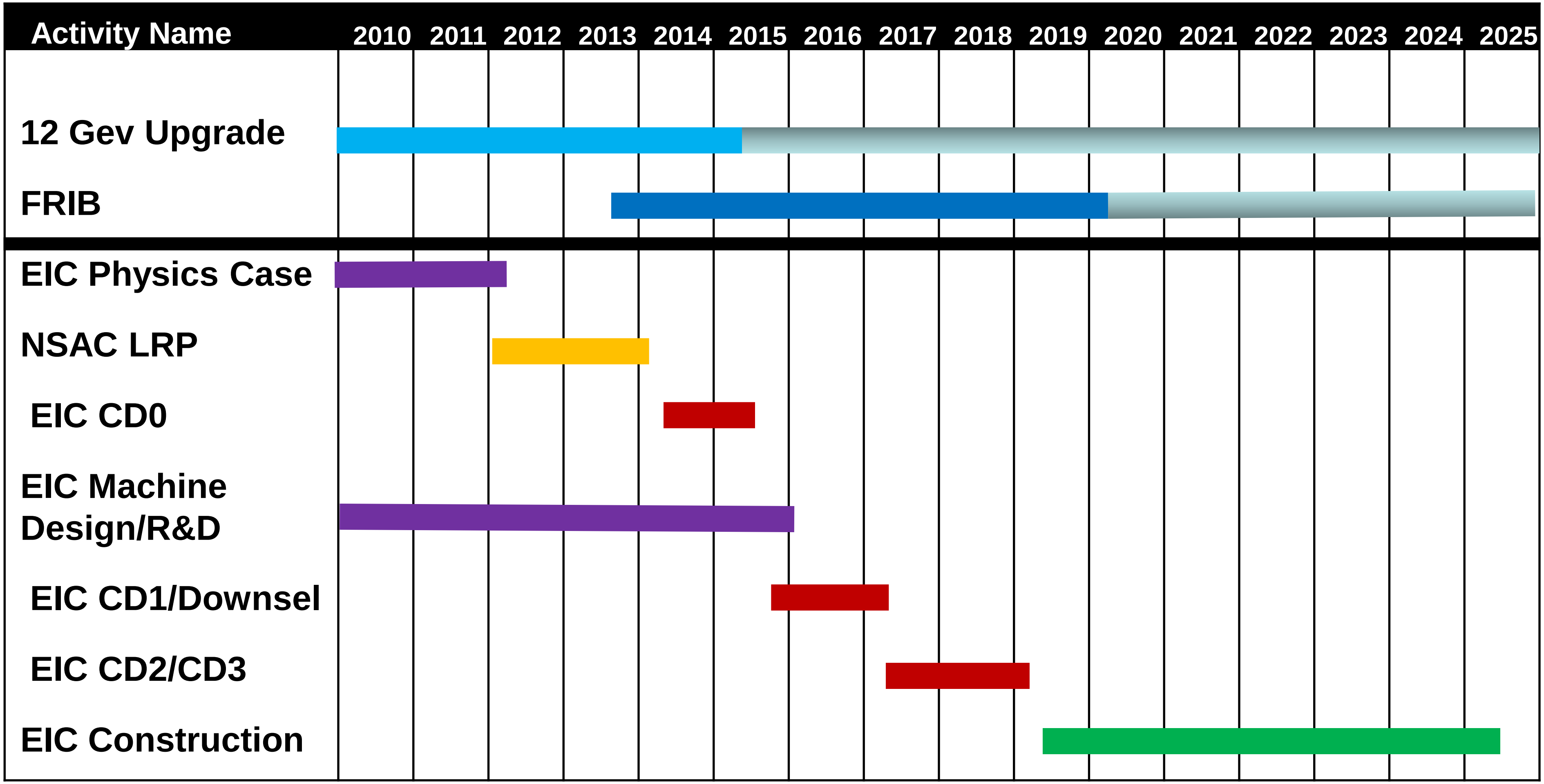


Forward / Backward Spectrometers:

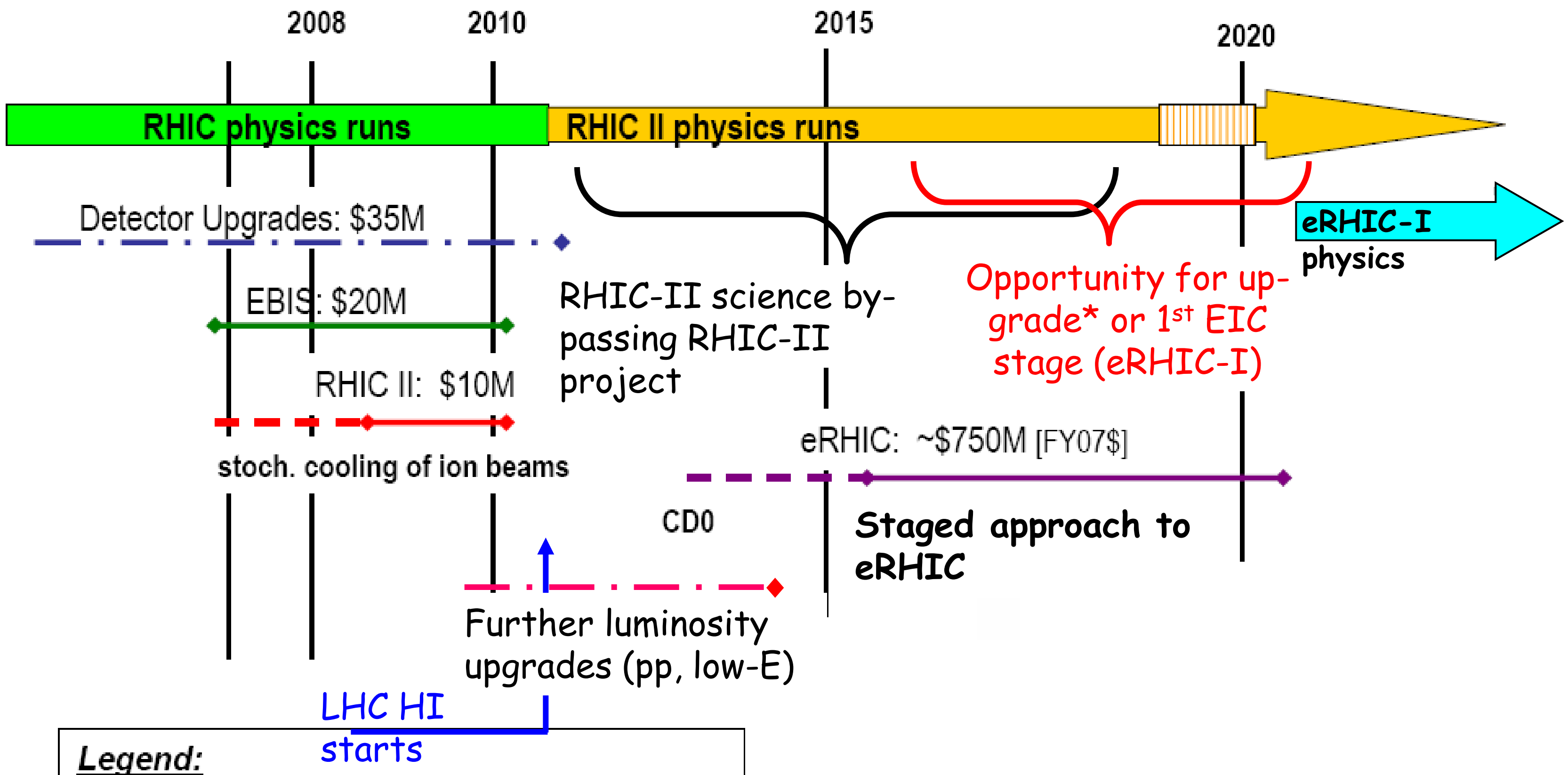
10 mrad crossing angle
with crab-crossing

High acceptance -5 < η < 5 central detector
Good PID and vertex resolution
Tracking and calorimeter coverage the same → good momentum resolution, lepton PID
Low material density → minimal multiple scattering and bremsstrahlung
Very forward electron and proton detection → maybe dipole spectrometers

Realization of an EIC at JLab



Realization of an EIC at RHIC



RHIC-II science by-passing RHIC-II project

Opportunity for up-grade* or 1st EIC stage (eRHIC-I)

Staged approach to eRHIC

Further luminosity upgrades (pp, low-E)

Legend:

R&D

Construction

Multiple small projects

CD0: DOE Critical Decision, mission need

Summary : EIC has 3 important goals

Extract the confined motion of quarks and gluons in a nucleon with and without polarization, and in a nucleus

- ☐ Possible clue for color confinement, hadron – parton correlations, ...
- ☐ Ultimate solution of proton spin – hadron property in QCD
- ☐ Naturally measured at EIC, not easy, if not impossible, at other machines

Measure the confined spatial distribution of quarks and gluons in a nucleon with and without polarization, and in a nucleus

- ☐ Complementary to the motion measurement
- ☐ Sum rule for proton spin – hadron property in QCD
- ☐ EIC has the perfect kinematic reach for reliable imaging

Discover clear evidences of QCD's many-body non-linear dynamics and the range of color coherence

- ☐ Saturation scale – consequence of QCD non-linear dynamics
- ☐ Range of color coherence – nuclear property in QCD
- ☐ EIC can pioneer the search of non-linear dynamics

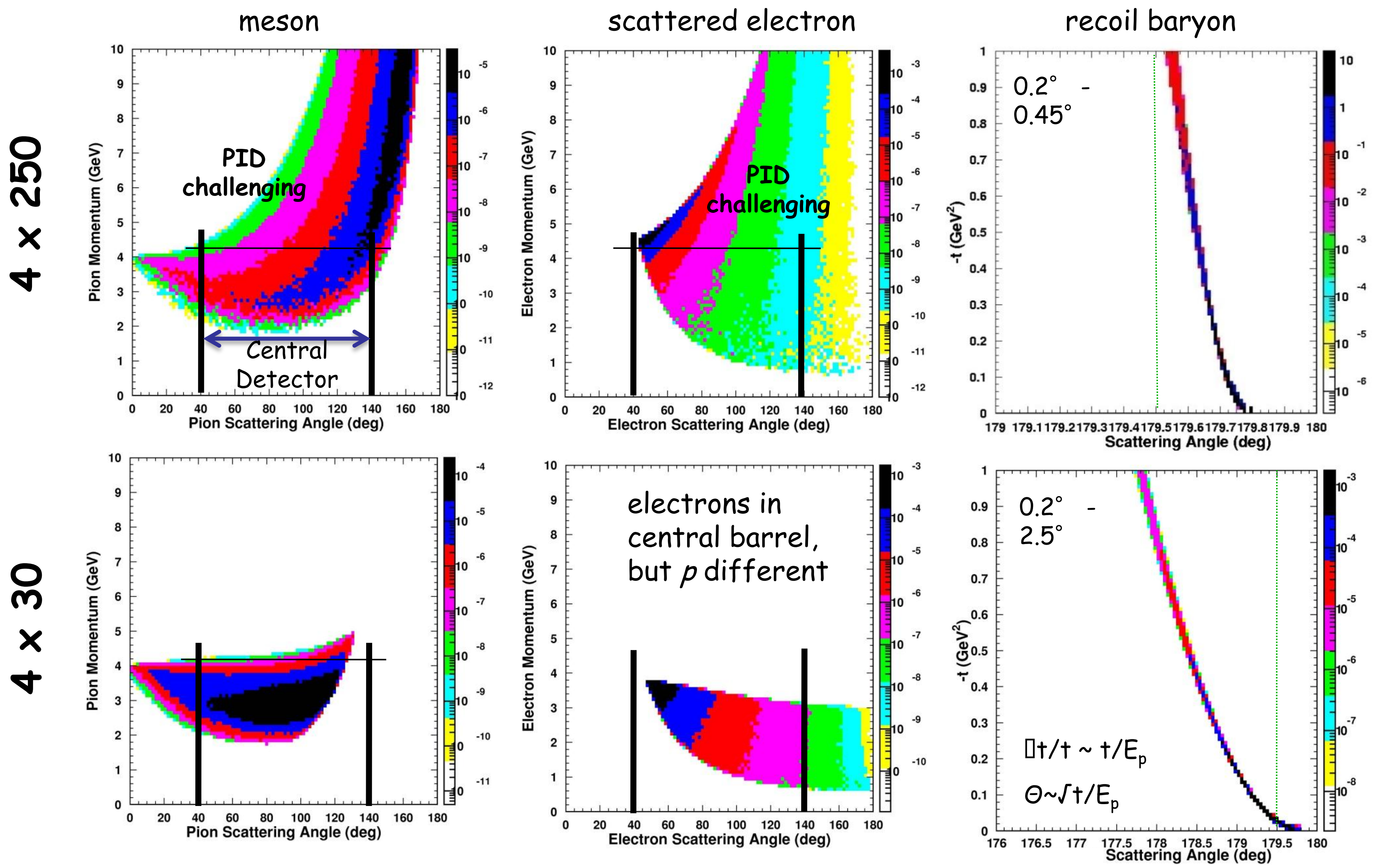
Conclusion

- After almost 40 years, we have learned a lot of QCD dynamics, but mostly in its most trivial asymptotic regime (less than 0.1 fm), and limited information on nucleon/nuclear structure, especially in the sea-quark and gluon sectors

- Many aspects of hadron's partonic structure can be naturally addressed by EIC, but, not other machines: e+e-, pp, pA, AA

- EIC with polarization provides a new program to explore new frontier research of QCD dynamics – key to the visible matter

Example : light meson electroproduction



Challenges: PID for e- and mesons in central region,
very low angle baryon detection (need 0.2-5° with 1mr resolution !)

EIC and LHeC

EIC: L > 1×10^{33} cm^{-2}s^{-1}
E_{cm} = 20 - 100 GeV

- Variable energy range
- Polarized and heavy ion beams
- High luminosity in energy region of interest for nuclear science

Nuclear science goals:

- Explore the new QCD frontier: strong color fields in nuclei
- Precisely image the sea-quarks and gluons to determine the spin, flavor and spatial structure of the nucleon.

LHeC: L = 1.1×10^{33} cm^{-2}s^{-1}
E_{cm} = 1.4 TeV

- Add 70-100 GeV electron ring or Linac to interact with LHC ion beam
- Use LHC-B or ALICE IR
- High luminosity mainly due to large γ's (= E/m) of beams

High-Energy physics goals:

- Parton dynamics at the TeV scale
  - physics beyond the Standard Model
  - physics of high parton densities (low x)

Important cross fertilization of ideas:

- Significant European interest in an EIC
- EIC collaborators on LHeC Science Advisory Committee (with Research Directors of CERN, FNAL, DESY)

Connection to RHIC and LHC physics

Matter at RHIC:

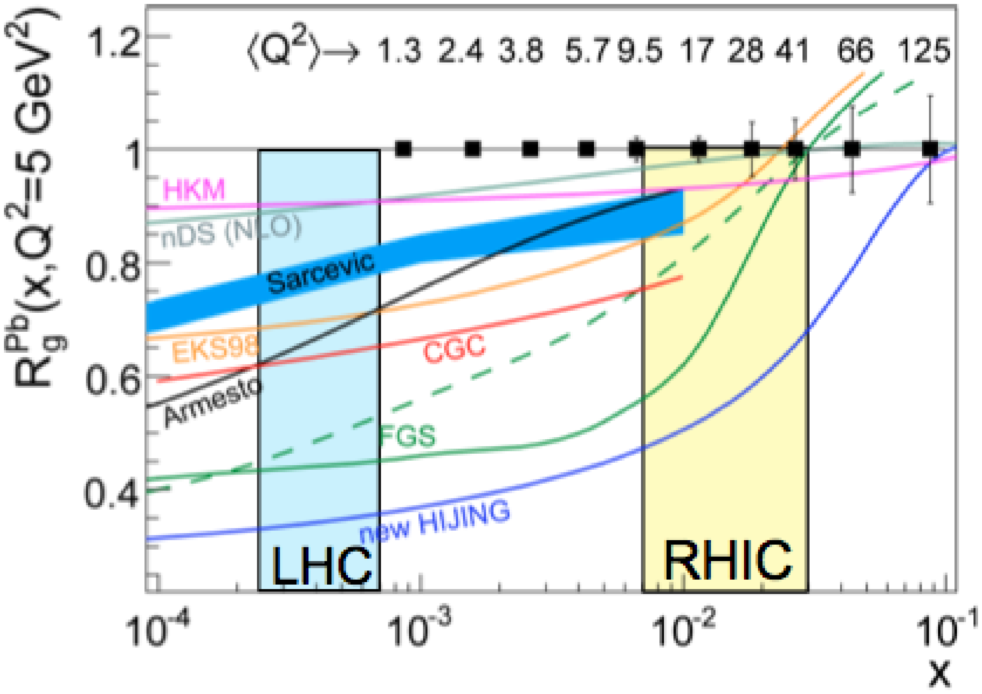
- thermalizes fast (τ_0 ~ 0.6 fm/c)
- We don't know why and how?
- Initial conditions? ⇒ $G(x, Q^2)$

Role of saturation ?

- RHIC → forward region
- LHC → midrapidity
  - bulk (low-p_T matter) & semi-hard jets

Jet Quenching:

- Need Refererence: E-loss in cold matter
- No HERMES data for
  - charm energy loss
  - in LHC energy range



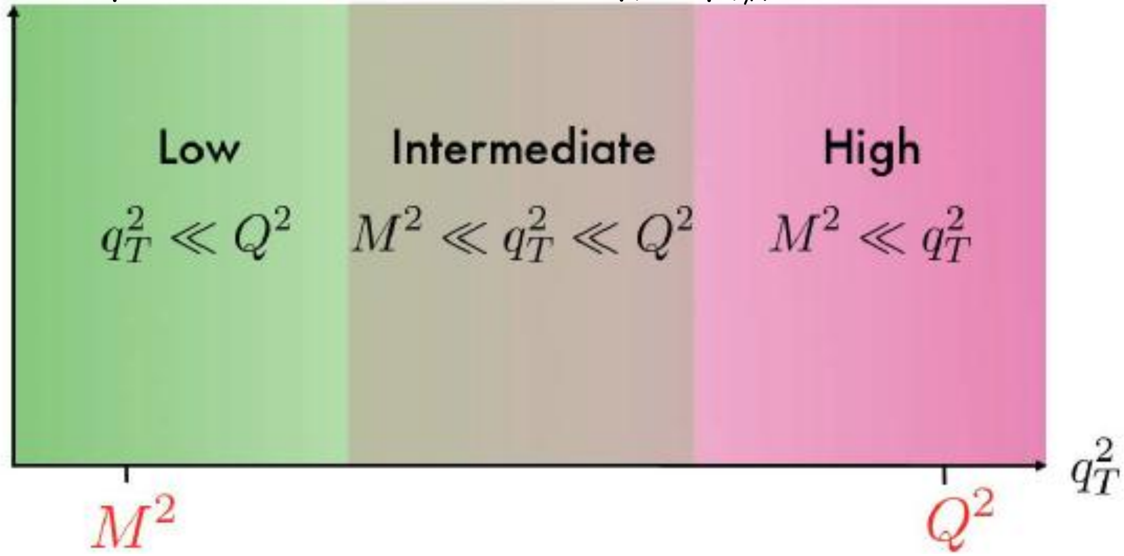
EIC provides new essential input:

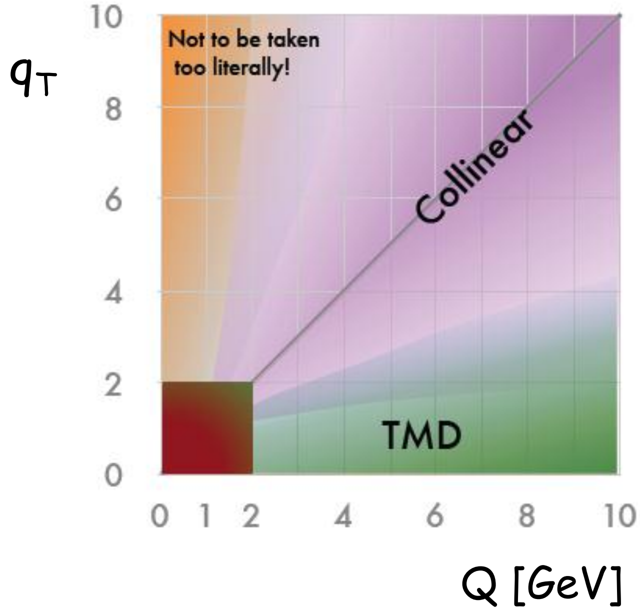
- Precise handle on x, Q^2
- Means to study exclusive effects

Connection between low and high p_T

- TMDs encode physics for small transverse momenta (or p_T differences) and $Q^2 \gg p_T$
- if p_T is large, it can be treated perturbatively
- no sharp boundary between "intrinsic" and "radiative" p_T --> **matching region**

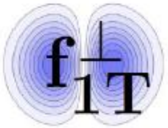
example: SIDIS (hadron mass M, $q_T^2 \approx p_{T,H}^2/z$)

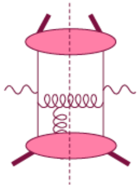




TMD factorization

collinear factorization





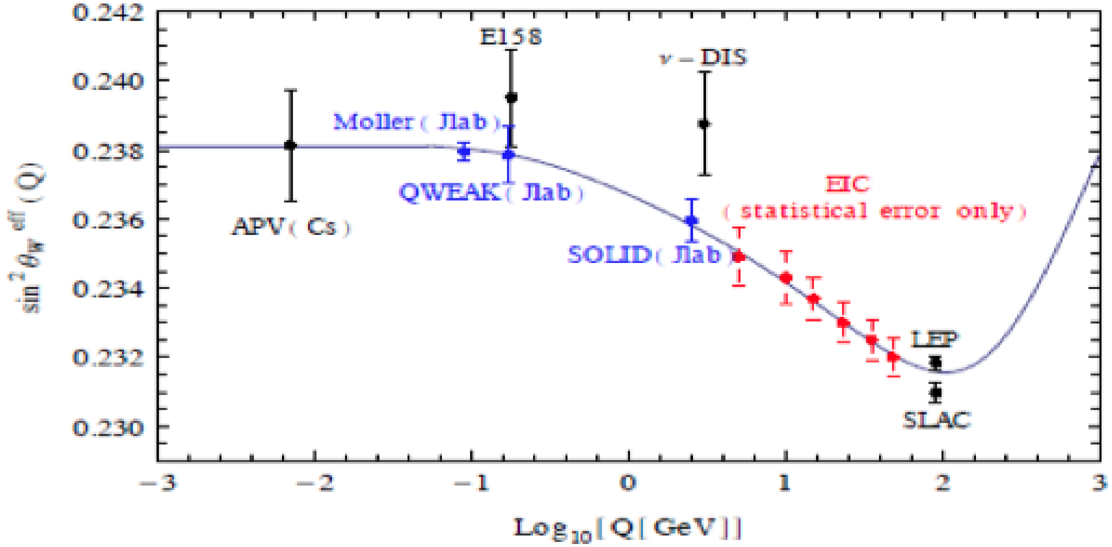
twist-3 parton-parton correlation

the leading high-p_T part should match with the p_T tail of the TMD

Collins, Soper, Sterman;
Ji, Qiu, Vogelsang, Yuan

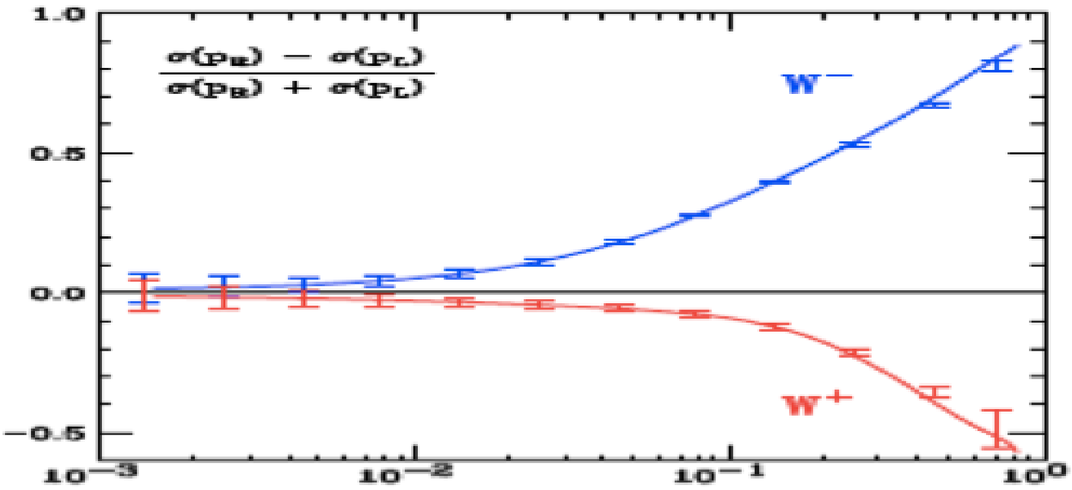
Electroweak physics at EIC

☐ Mixing angle of weak interaction – high luminosity:



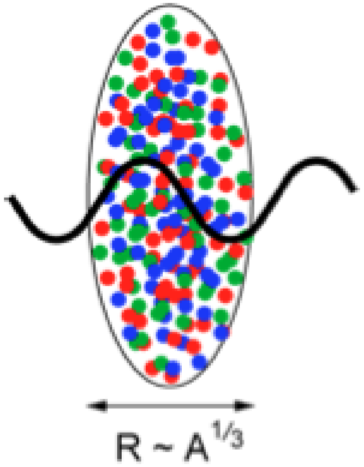
Fill the region never be measured

☐ Parity-violating single longitudinal asymmetries:



Flavor separation of helicity distributions

e-A helps reaching saturation



Scattering of electrons off nuclei:

Probes interact over distances $L \sim (2m_N x)^{-1}$

For $L > 2\,R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back of nucleon

Probe interacts *coherently* with all nucleons

$$Q_s^2 \sim \frac{\alpha_s\, xG(x, Q_s^2)}{\pi R_A^2} \qquad \text{HERA}: \; xG \sim \frac{1}{x^{0.3}} \qquad \text{A dependence}: \; xG_A \sim A$$

"Expected"
Nuclear Enhancement Factor
(Pocket Formula):

$$\boxed{(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}}$$

Enhancement of Q_S with A ⇒ non-linear QCD regime reached at significantly lower energy in A than in proton