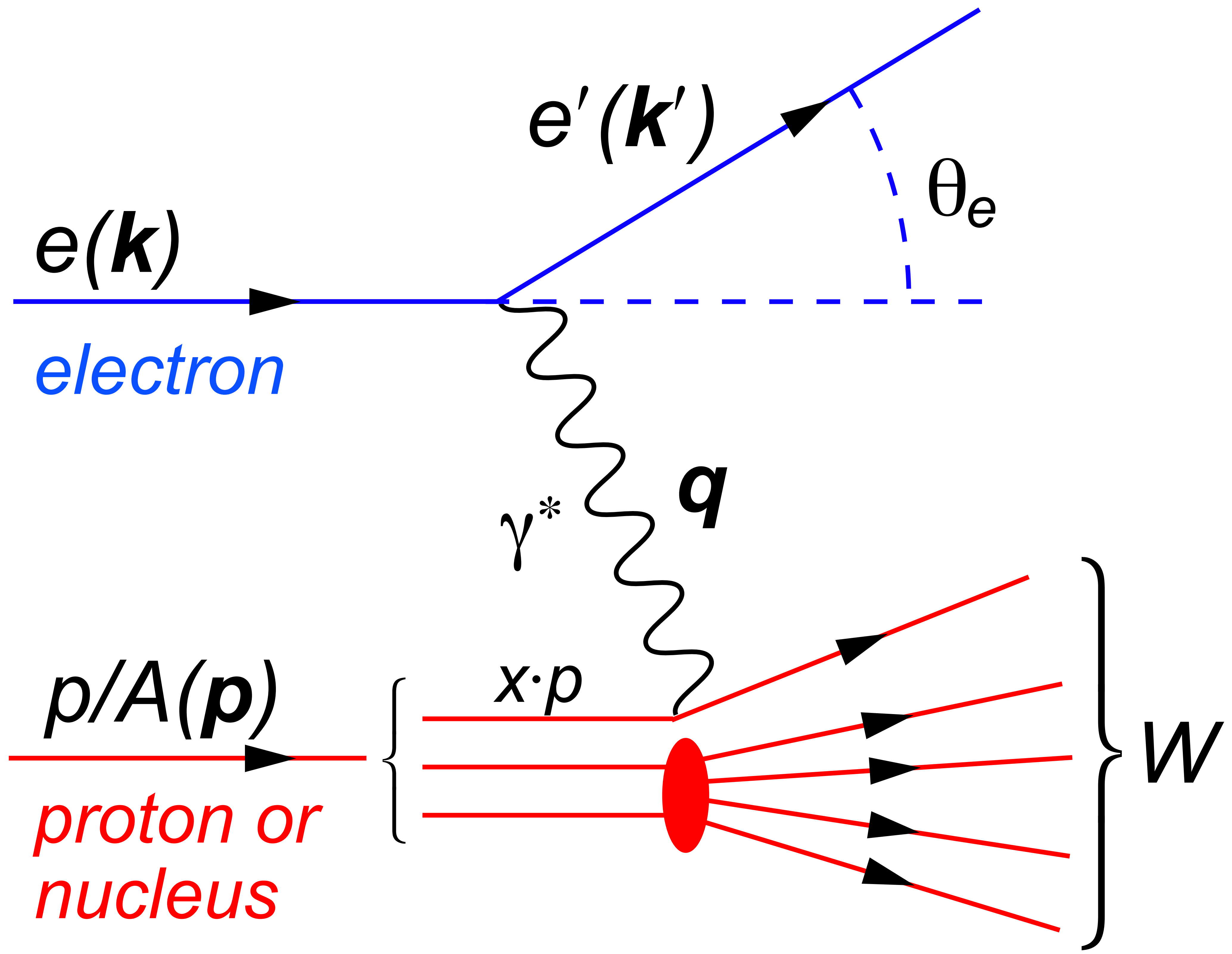
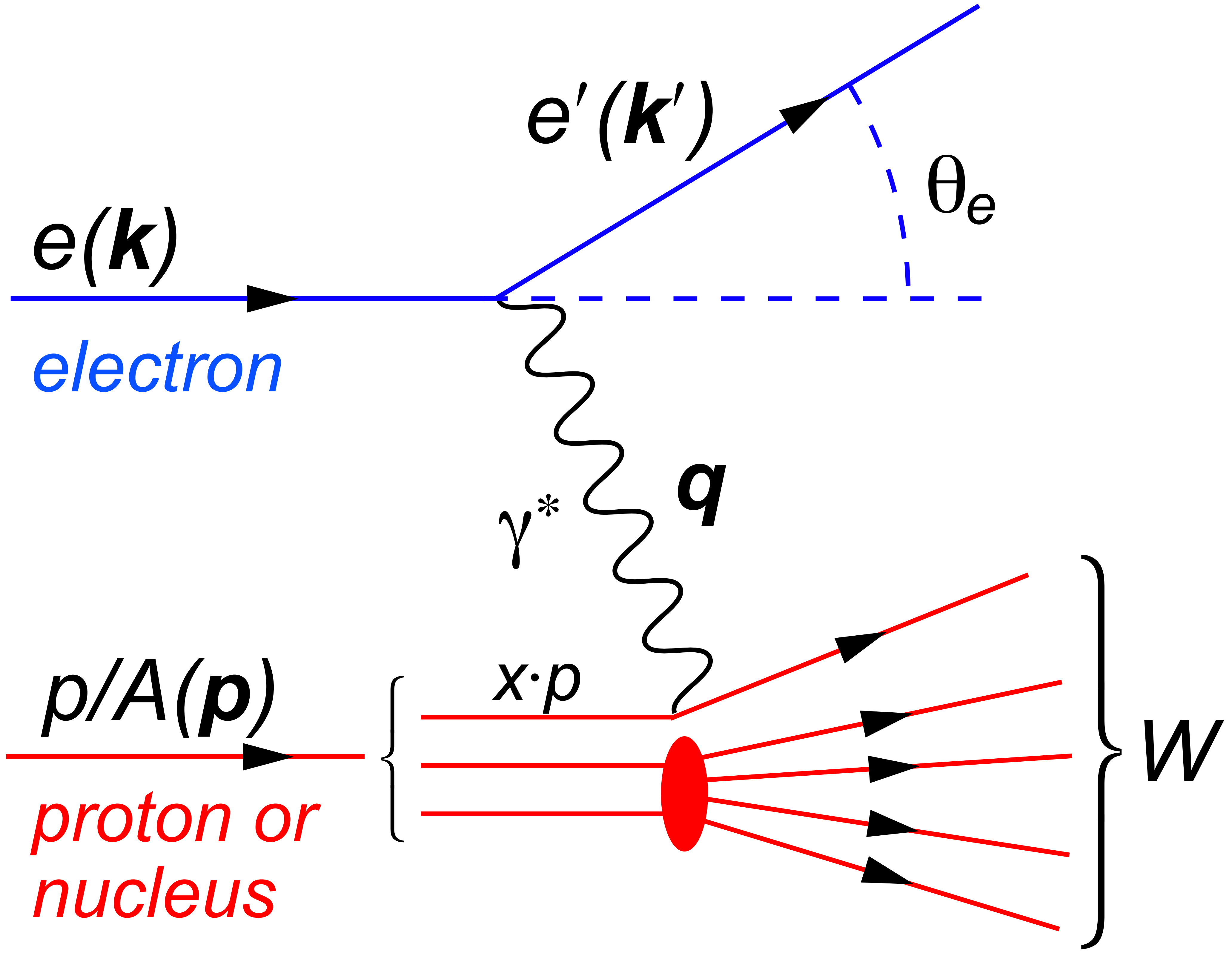
Reminder: Deep Inelastic Scattering (DIS)



DIS:

- As a probe, electron beams provide unmatched precision of the e.m. interaction
- Direct, model independent, determination of kinematics of physics processes

Reminder: Deep Inelastic Scattering (DIS)



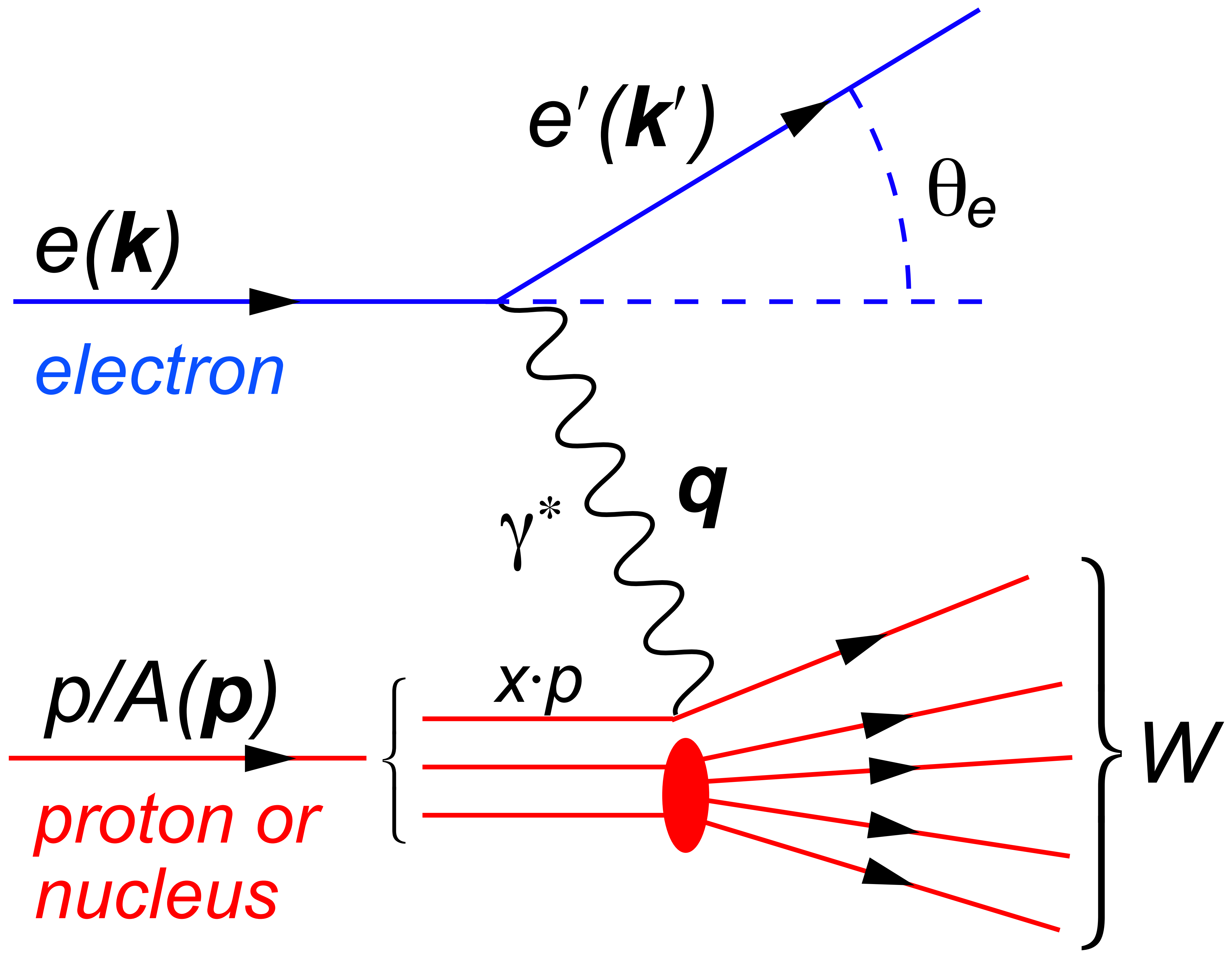
s: center-of-mass energy squared

s:

- square of center-of-mass energy of electron-hadron system

$$\sqrt{s} \simeq 2\sqrt{E_e E_p}$$

Reminder: Deep Inelastic Scattering (DIS)



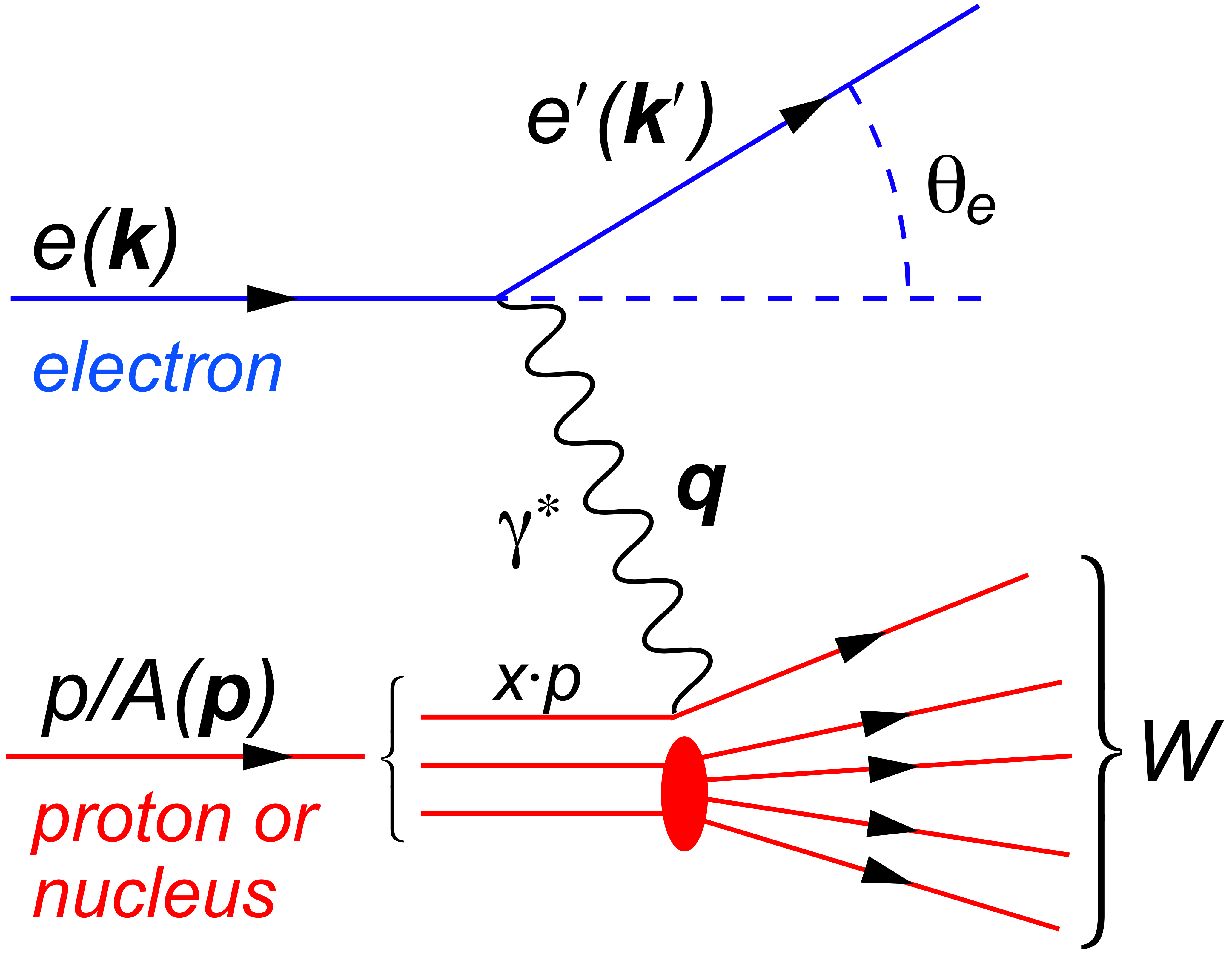
s: center-of-mass energy squared

Q^2: resolution power

Q^2:

- squared momentum transfer from scattered electron
- Virtuality
- “Resolution” power

Reminder: Deep Inelastic Scattering (DIS)



s: center-of-mass energy squared

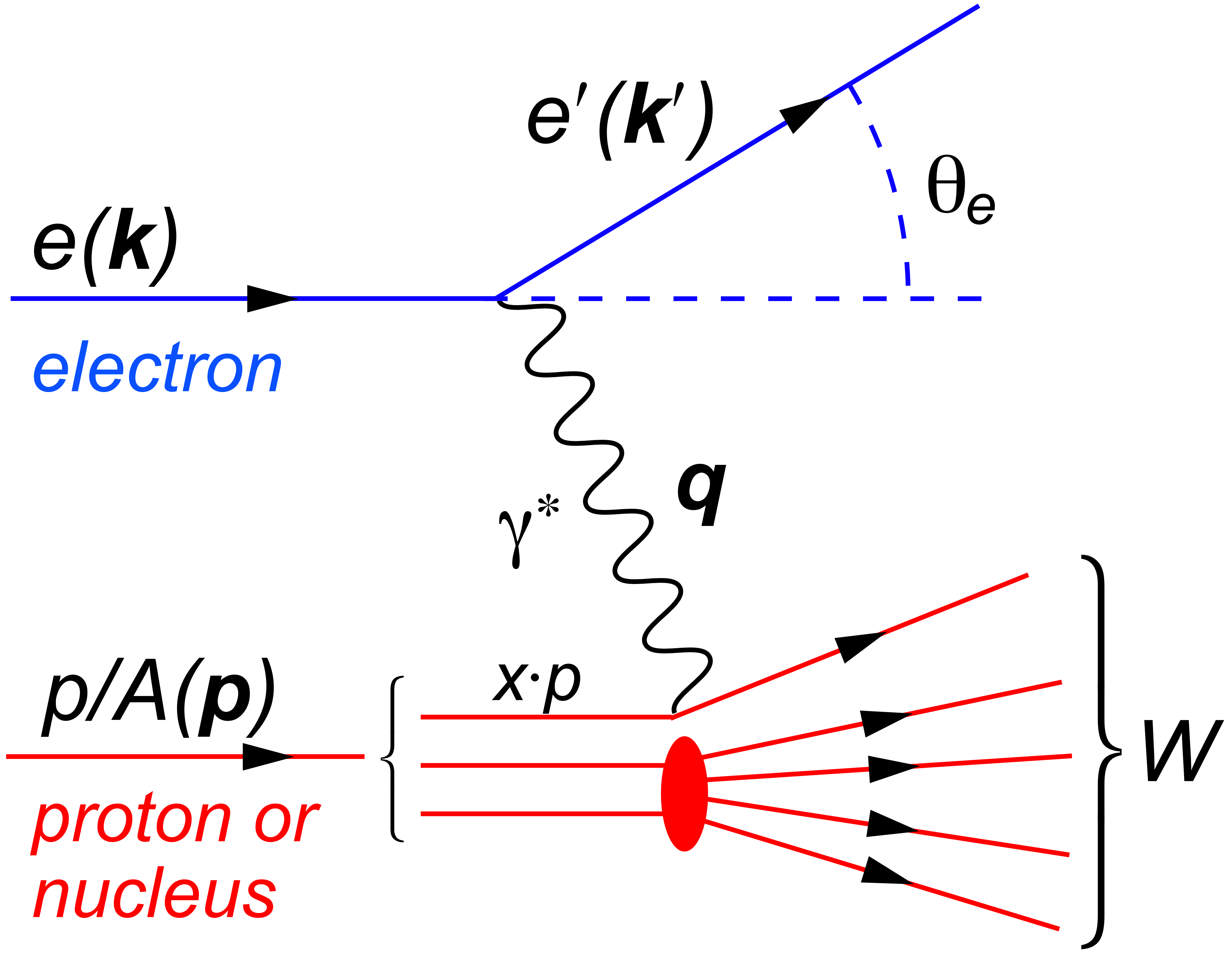
$\mathbf{Q^2}$: resolution power

x: momentum fraction of parton

x:

- Bjorken-x
- x is fraction of the nucleon's momentum carried by the struck quark
- $0 < x < 1$

Reminder: Deep Inelastic Scattering (DIS)



s: center-of-mass energy squared

Q²: resolution power

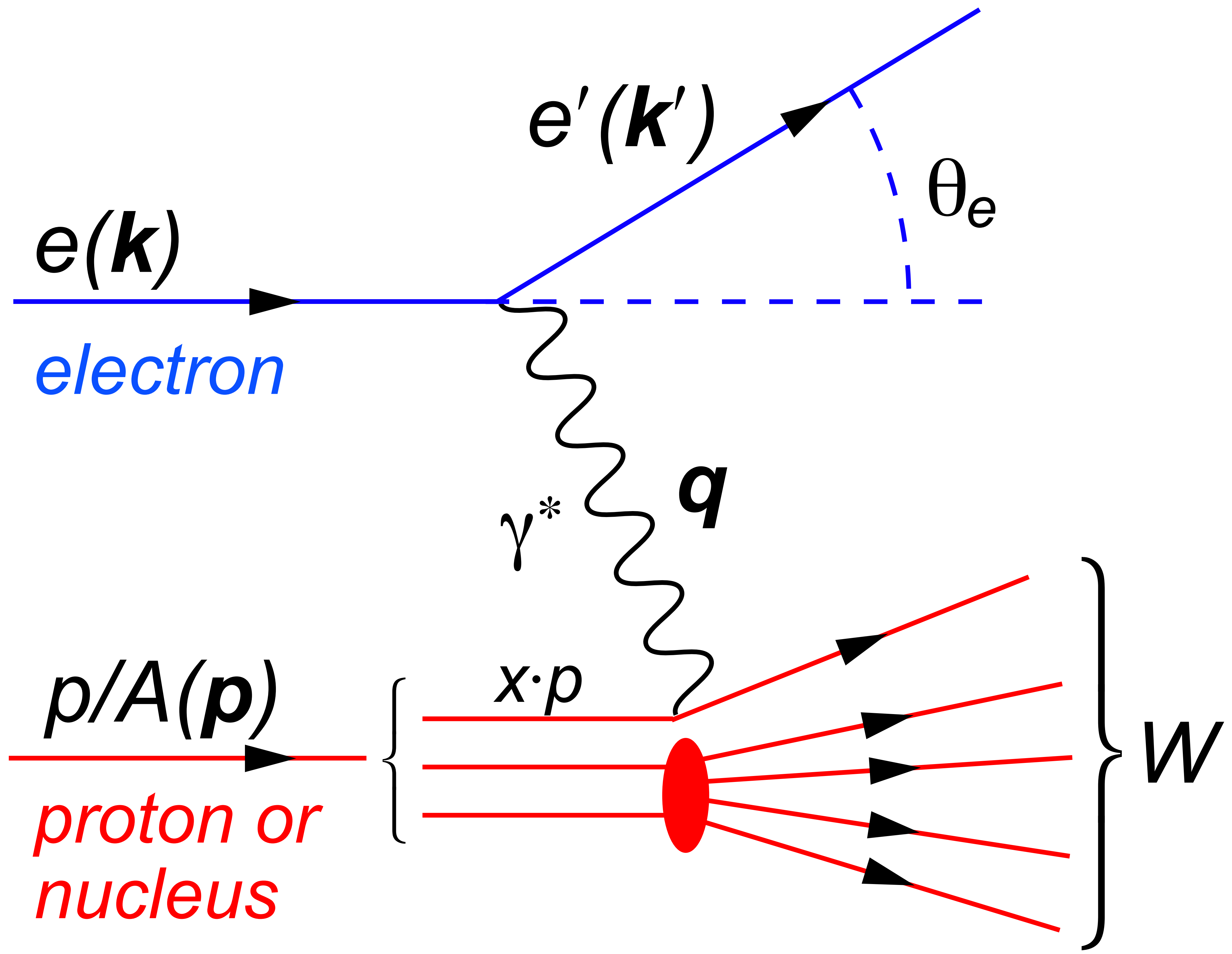
x: momentum fraction of parton

y: inelasticity

y:

- Inelasticity
- Fraction of electron's energy lost in nucleon restframe
- $0 < y < 1$

Reminder: Deep Inelastic Scattering (DIS)



s: center-of-mass energy squared

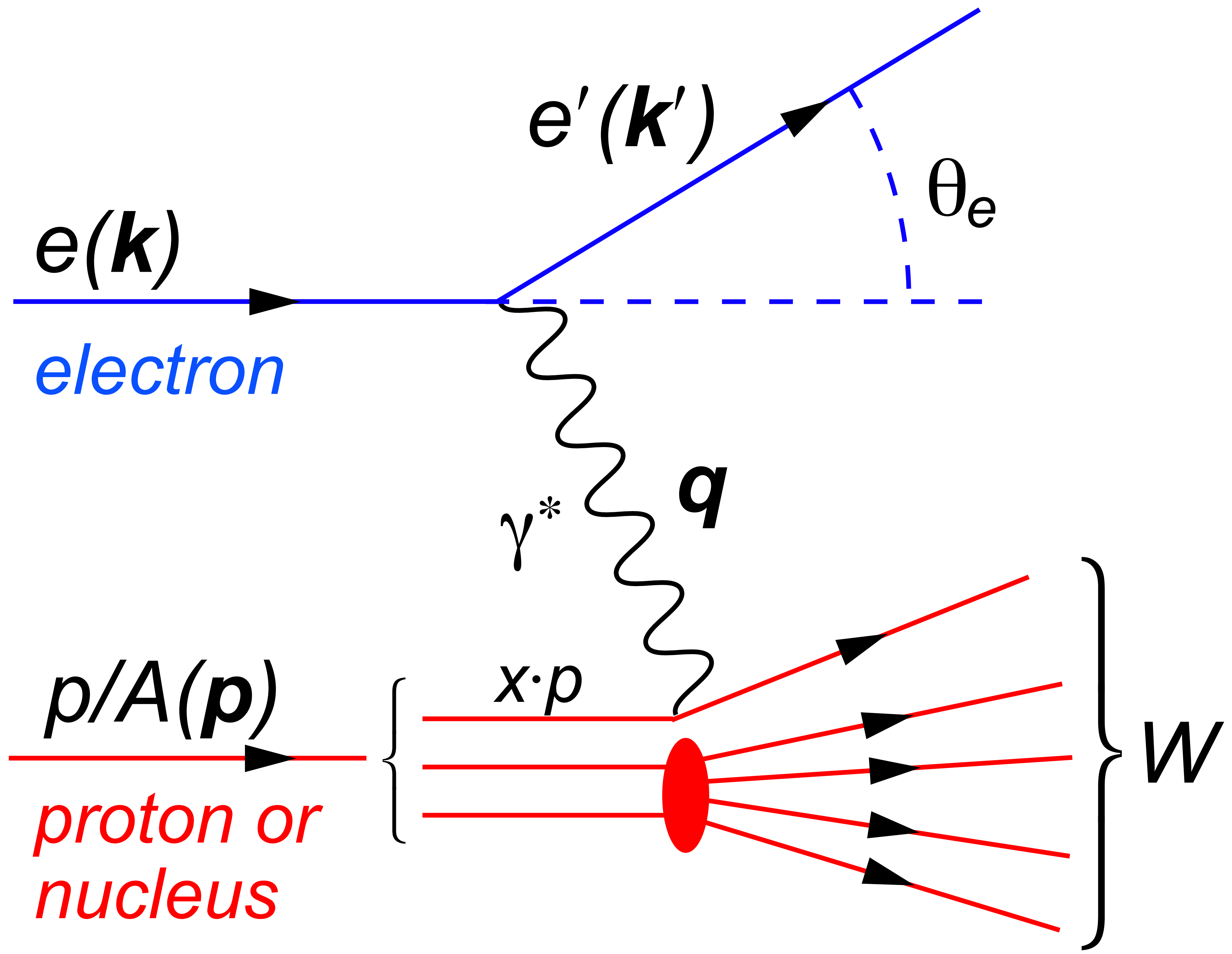
Q²: resolution power

x: momentum fraction of parton

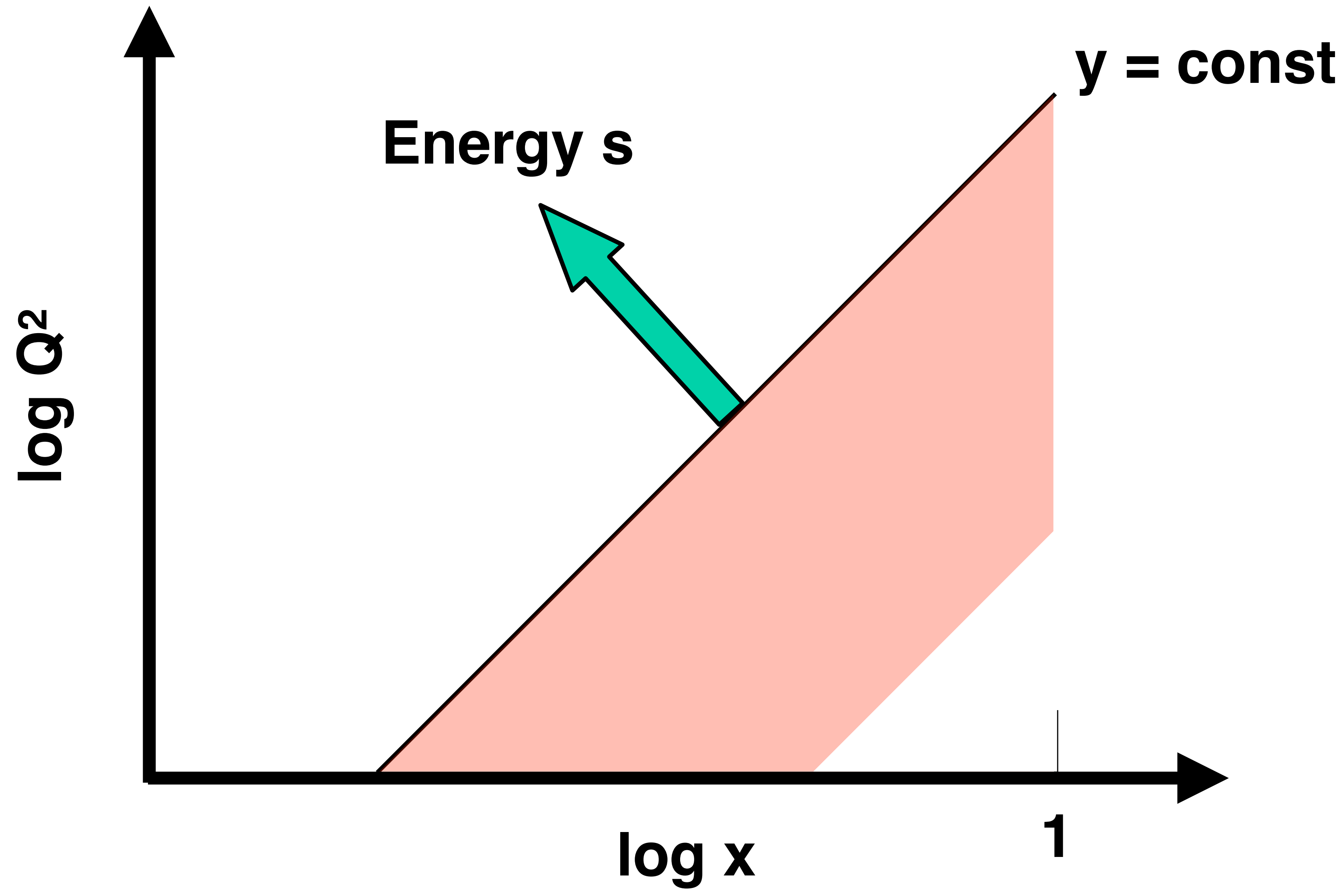
y: inelasticity

$$Q^2 \approx s \cdot x \cdot y$$

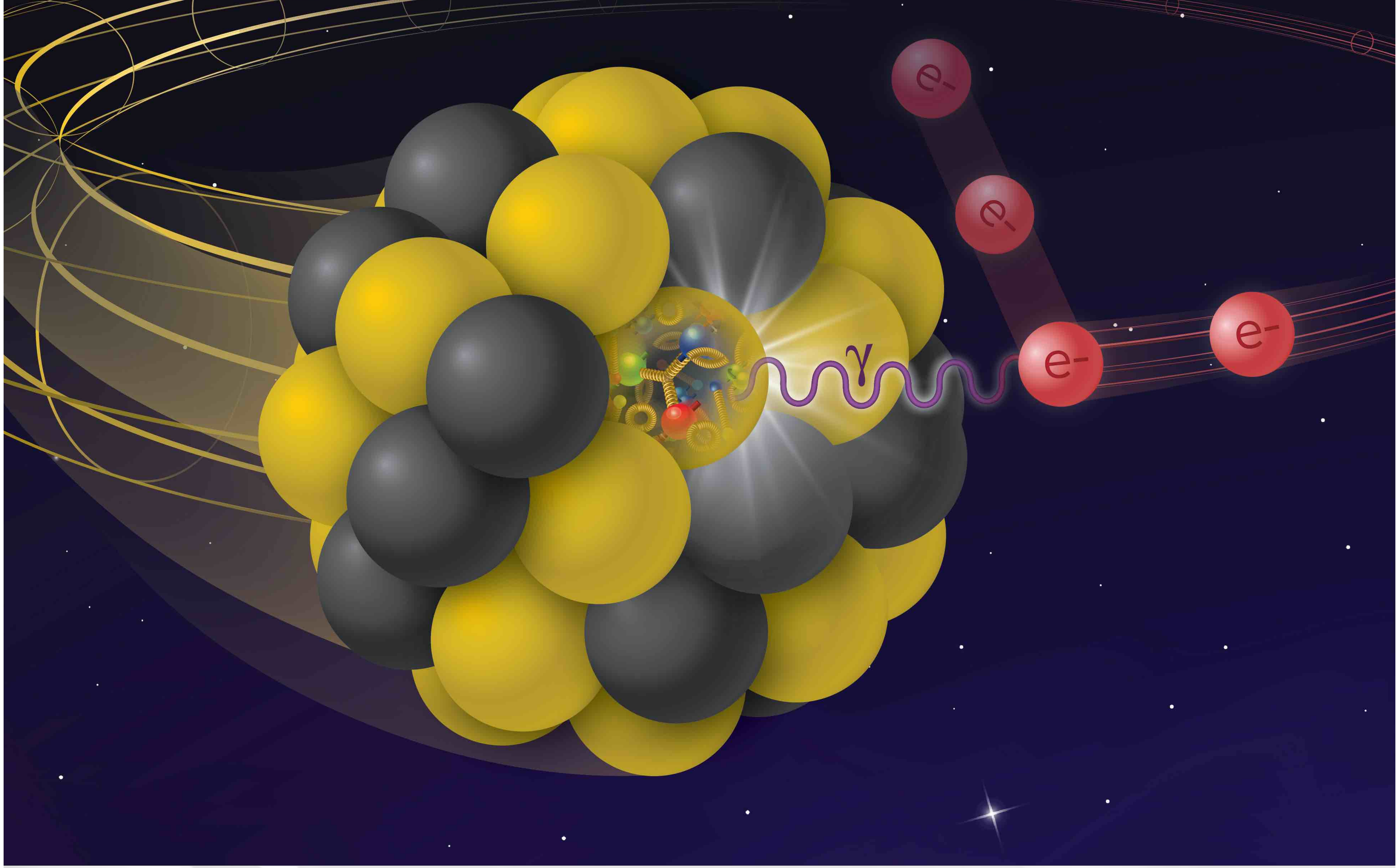
Reminder: Deep Inelastic Scattering (DIS)



$$Q^2 \approx s \cdot x \cdot y$$



Towards the Electron-Ion Collider



Thomas Ullrich
RAL Seminar

July 14, 2021

Yale
BROOKHAVEN
NATIONAL LABORATORY

Quantum ChromoDynamics (QCD)

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

"Emergent" Phenomena not evident from Lagrangian

- Asymptotic Freedom
- Confinement

Quantum ChromoDynamics (QCD)

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

“Emergent” Phenomena not evident from Lagrangian

- Asymptotic Freedom
- Confinement

There is an elegance and simplicity to nature’s strongest force we do not understand

- (Nearly) all visible matter is made up of quarks and gluons
- All strongly interacting matter is an emergent consequence of many-body quark-gluon dynamics.

Quantum ChromoDynamics (QCD)

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

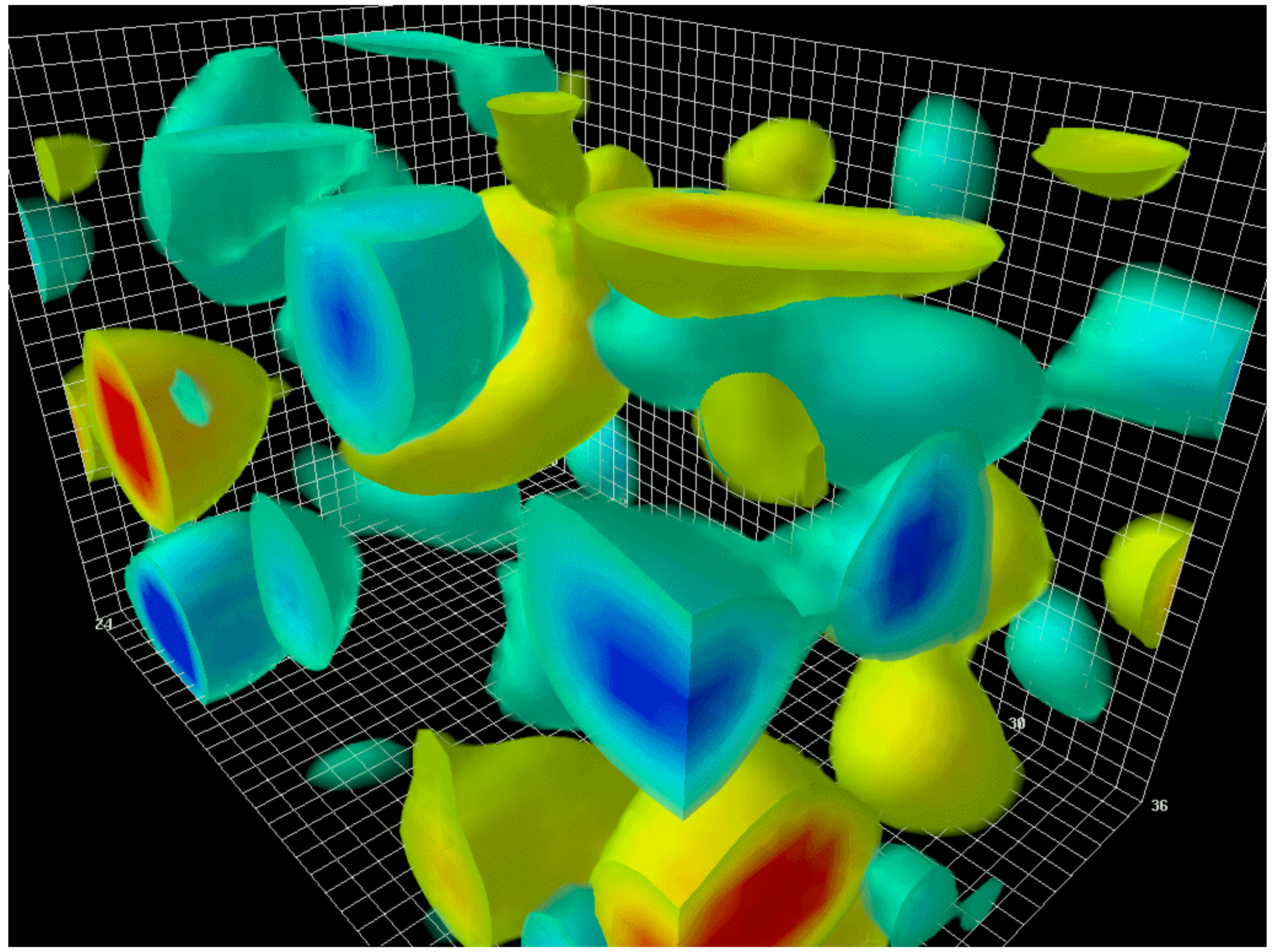
"Emergent" Phenomena not evident from Lagrangian

- Asymptotic Freedom
- Confinement

Understanding the origins of matter demands we develop a deep and varied knowledge of this emergent dynamics

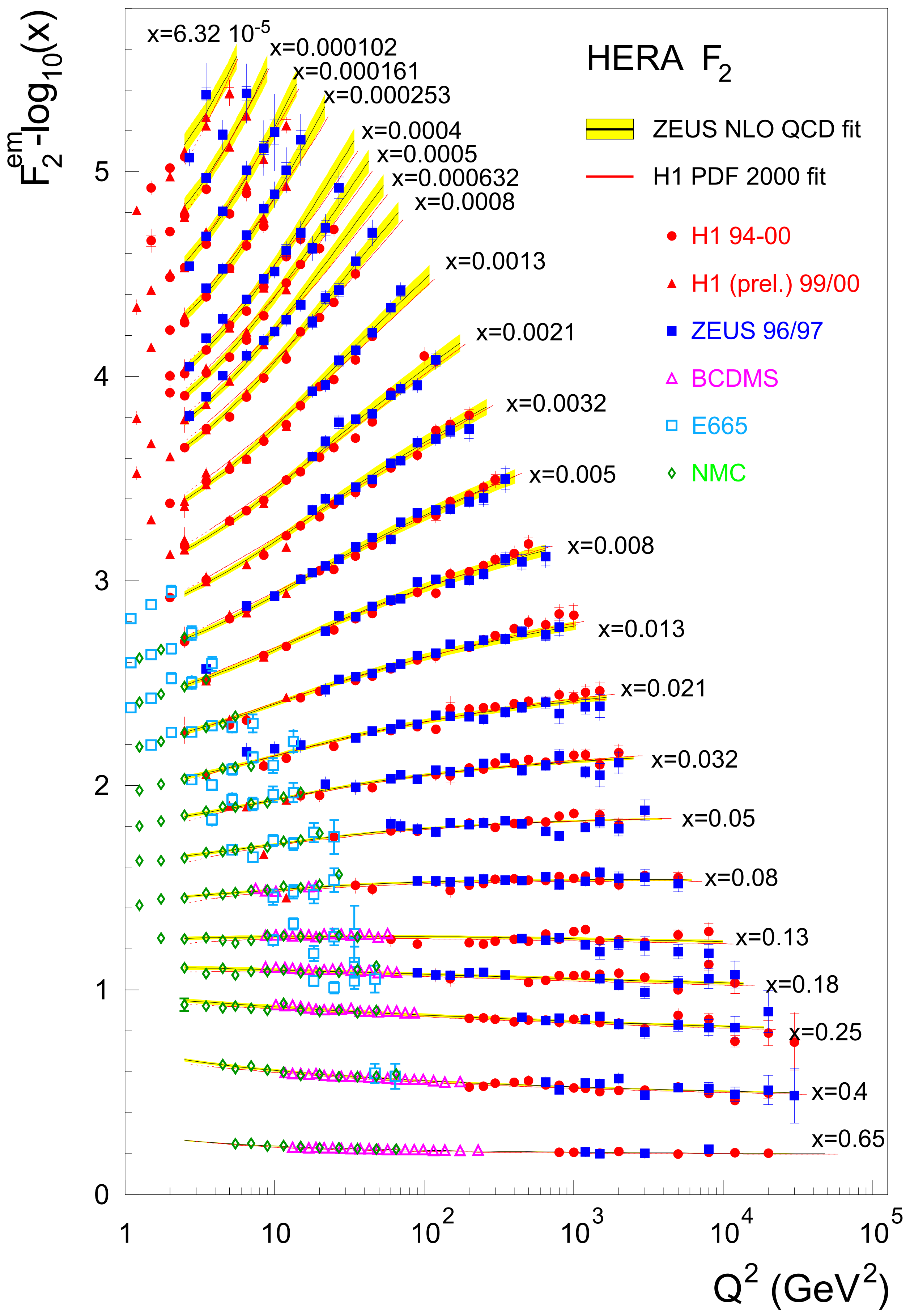
There is an elegance and simplicity to nature's strongest force we do not understand

- (Nearly) all visible matter is made up of quarks and gluons
- All strongly interacting matter is an emergent consequence of many-body quark-gluon dynamics.

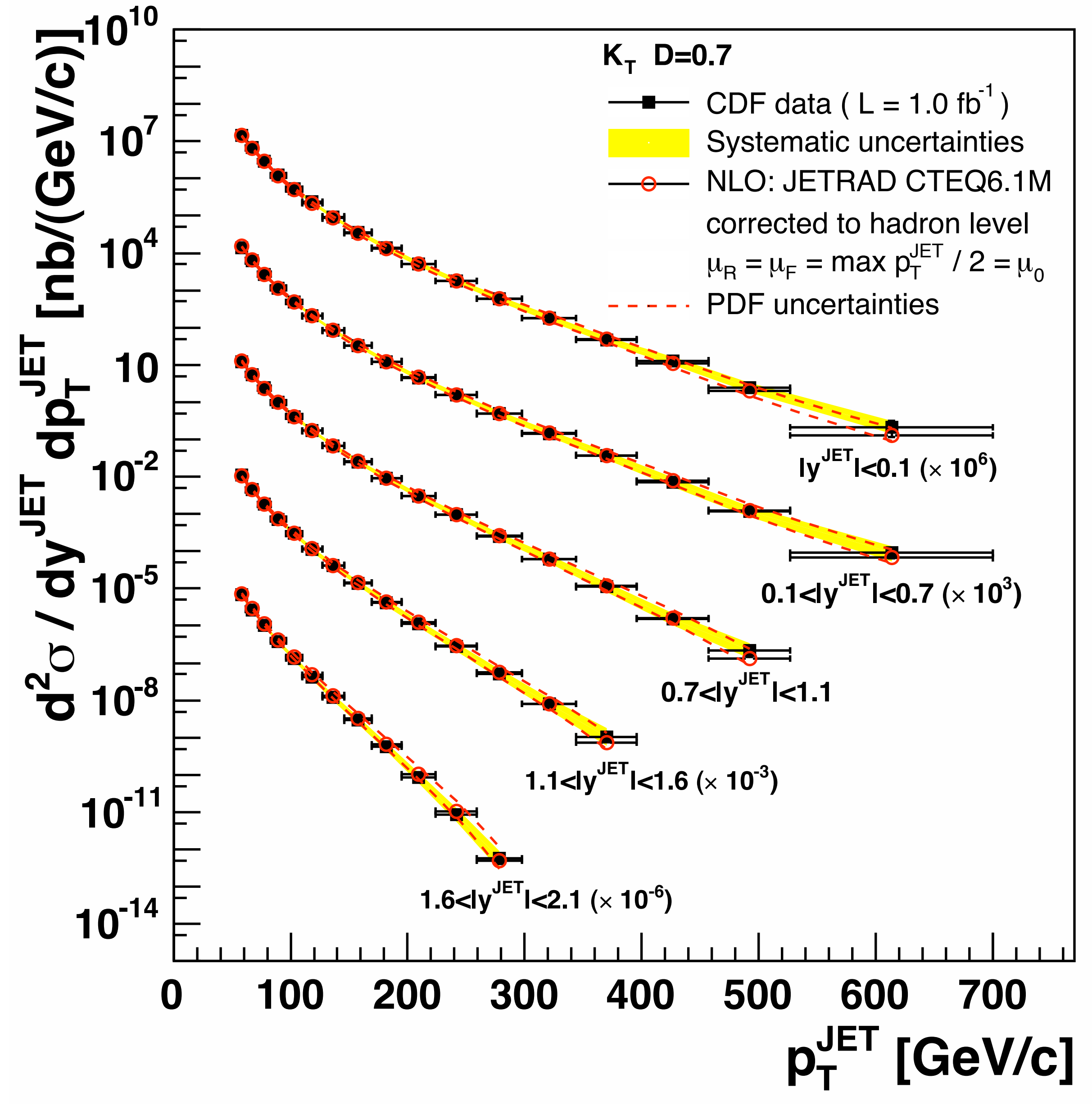


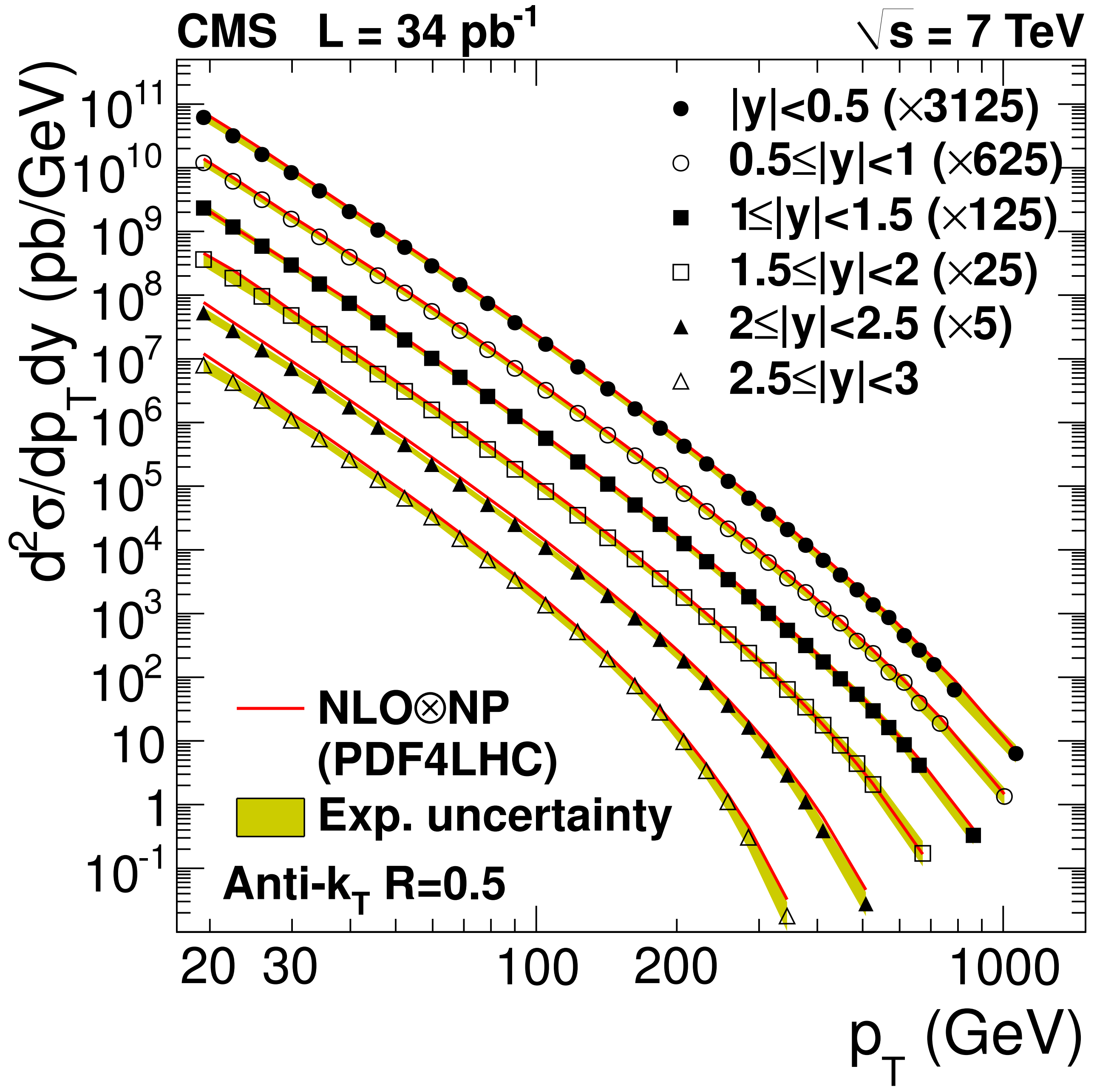
Perturbative QCD: Benchmark for New Physics

Structure functions measured at HERA



Jet cross-sections: pp collisions at LHC and $\bar{p}p$ collisions at Fermilab

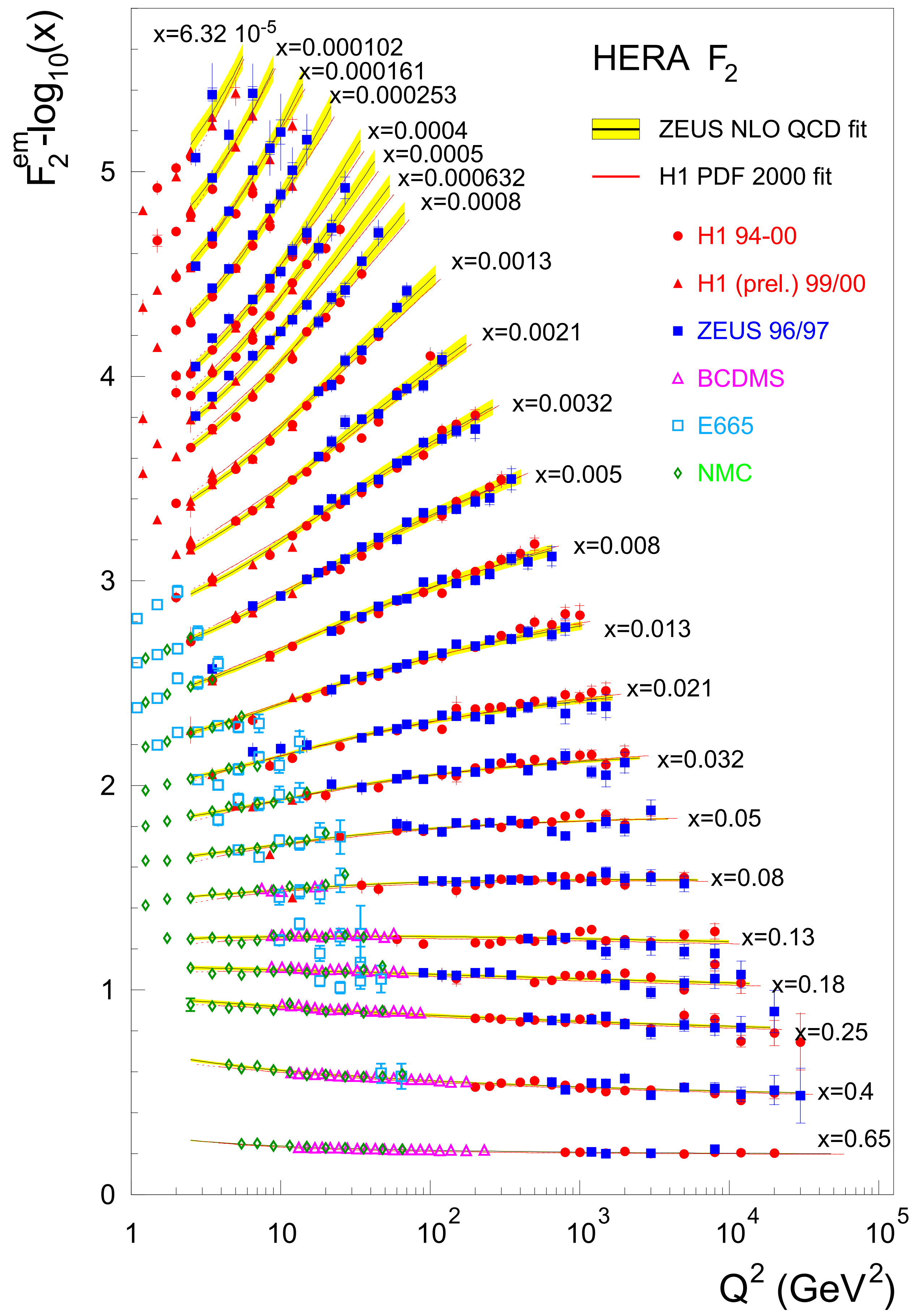




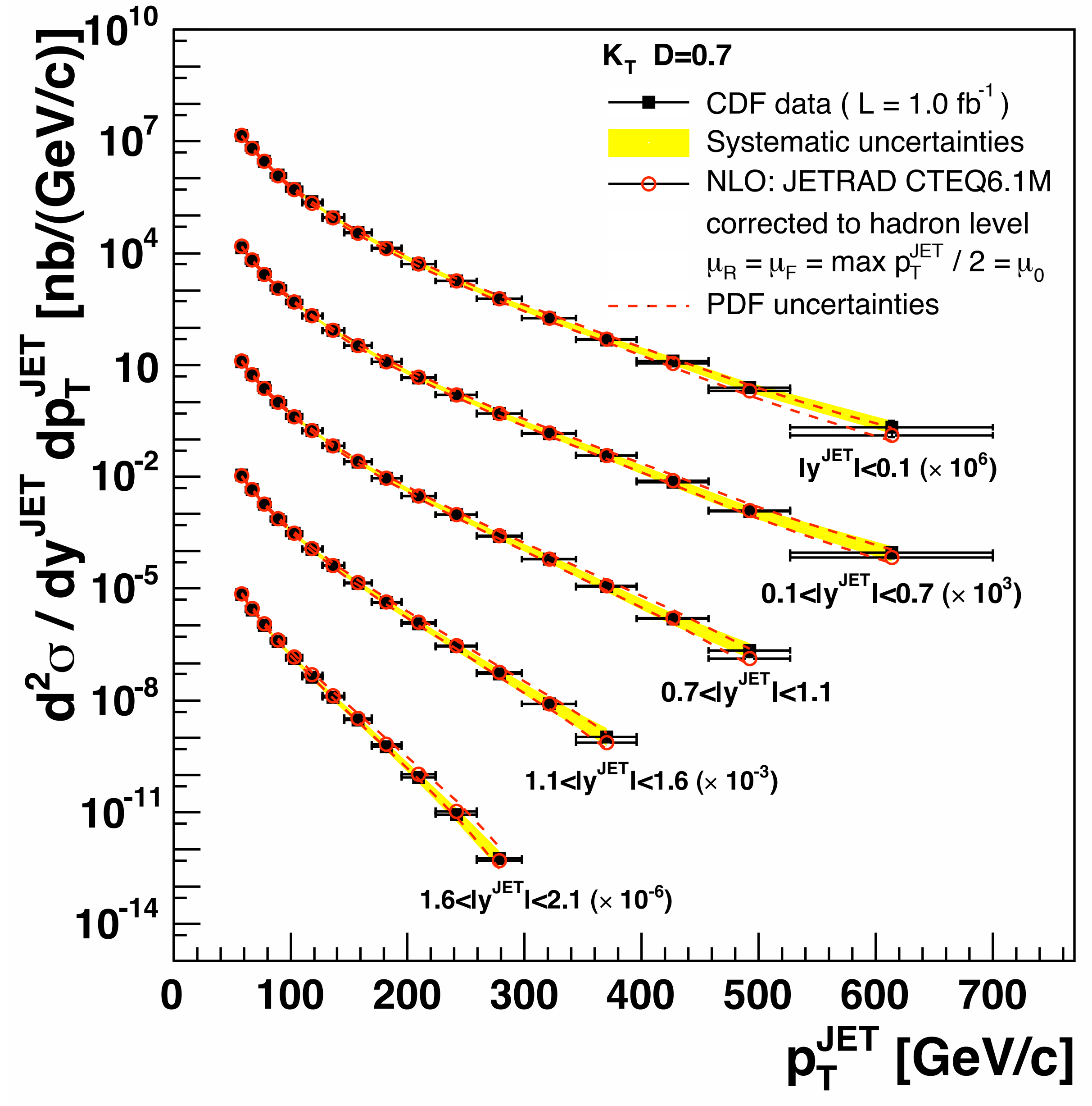
At large momenta, the weak QCD coupling (asymptotic freedom!) enables systematic computations

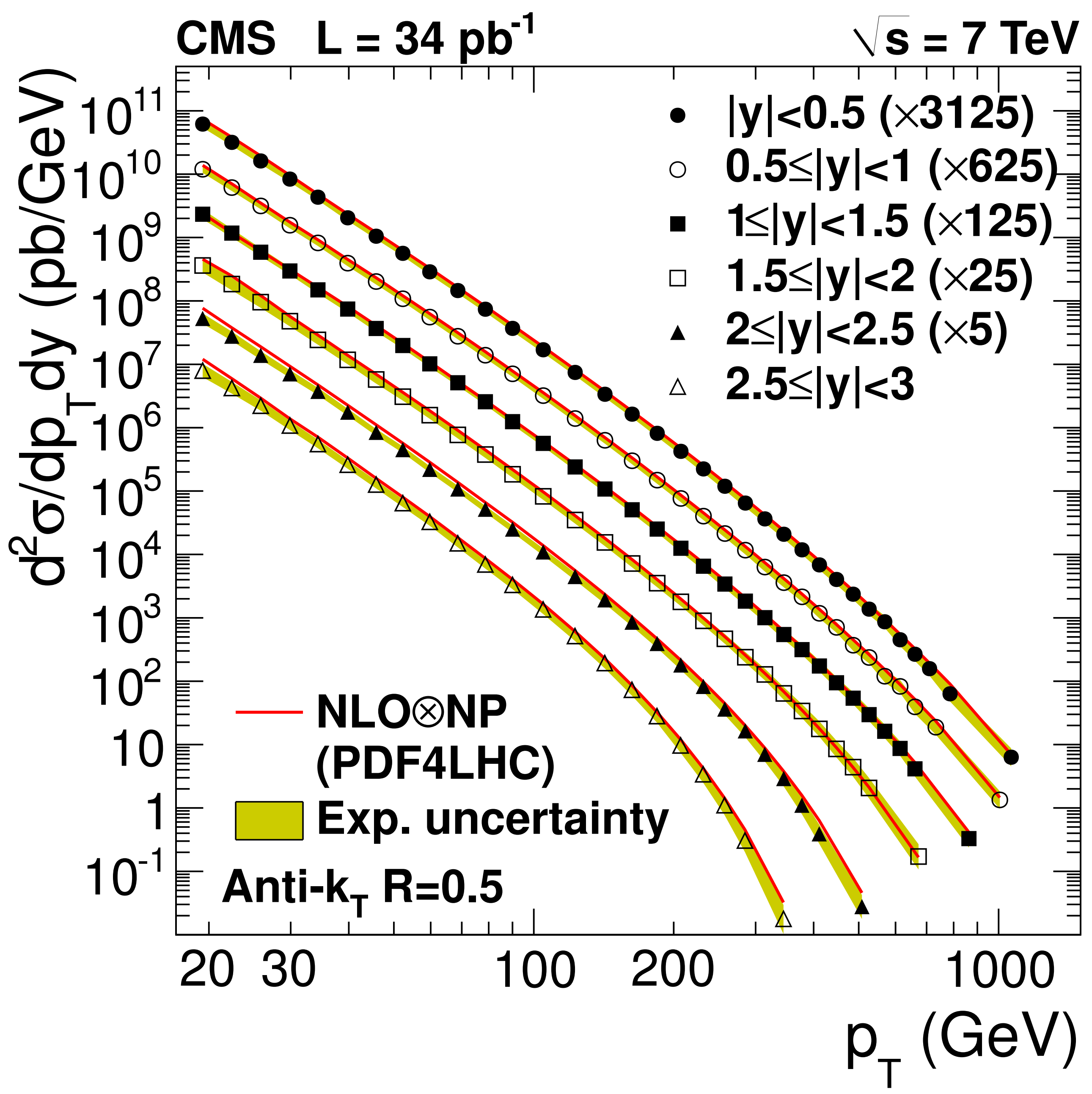
Perturbative QCD: Benchmark for New Physics

Structure functions measured at HERA



Jet cross-sections: pp collisions at LHC and $\bar{p}p$ collisions at Fermilab

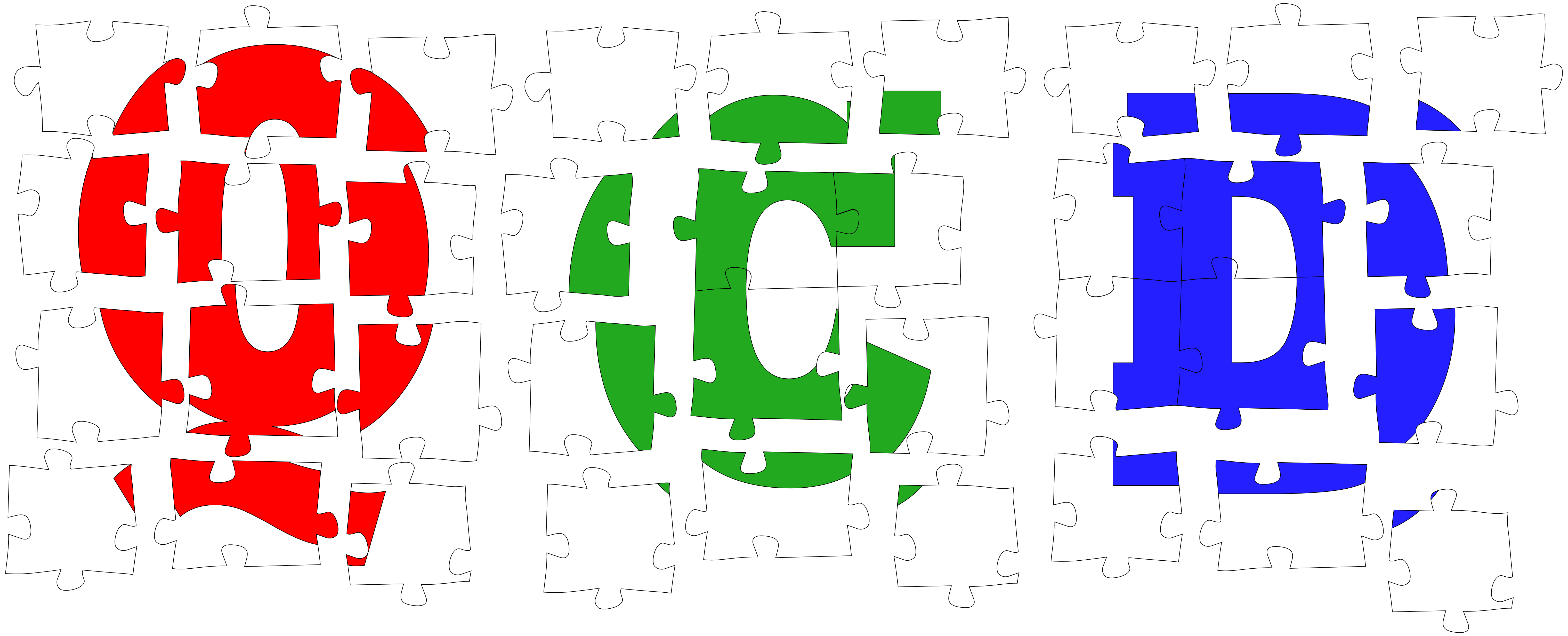




At large momenta, the weak QCD coupling (asymptotic freedom!) enables systematic computations

Are we done?

The Frontiers of Our Ignorance



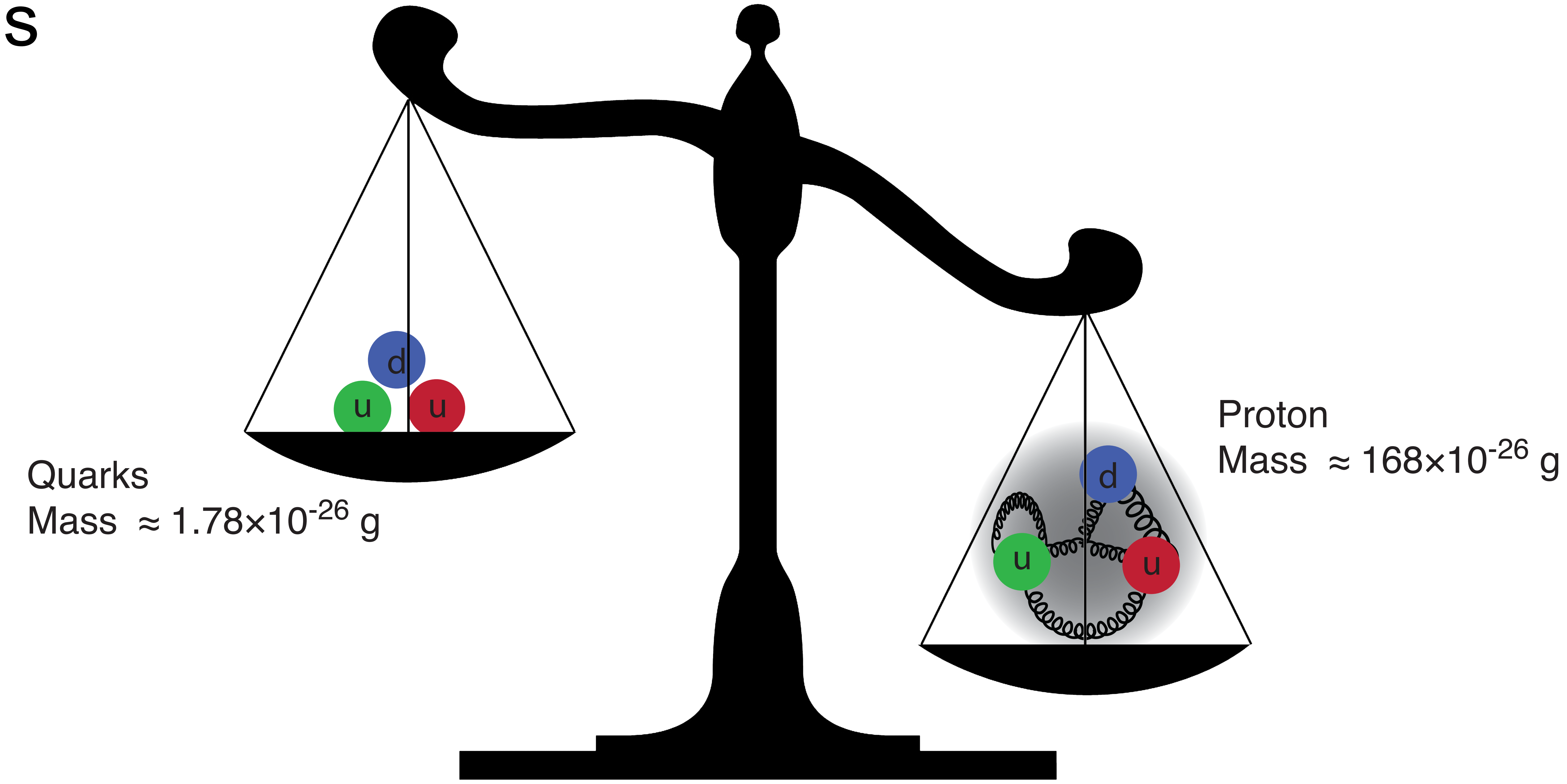
... that motivate the Electron-Ion Collider

The Mass Puzzle

The Higgs is responsible for quark masses that make up ~ 2% of the nucleon mass.

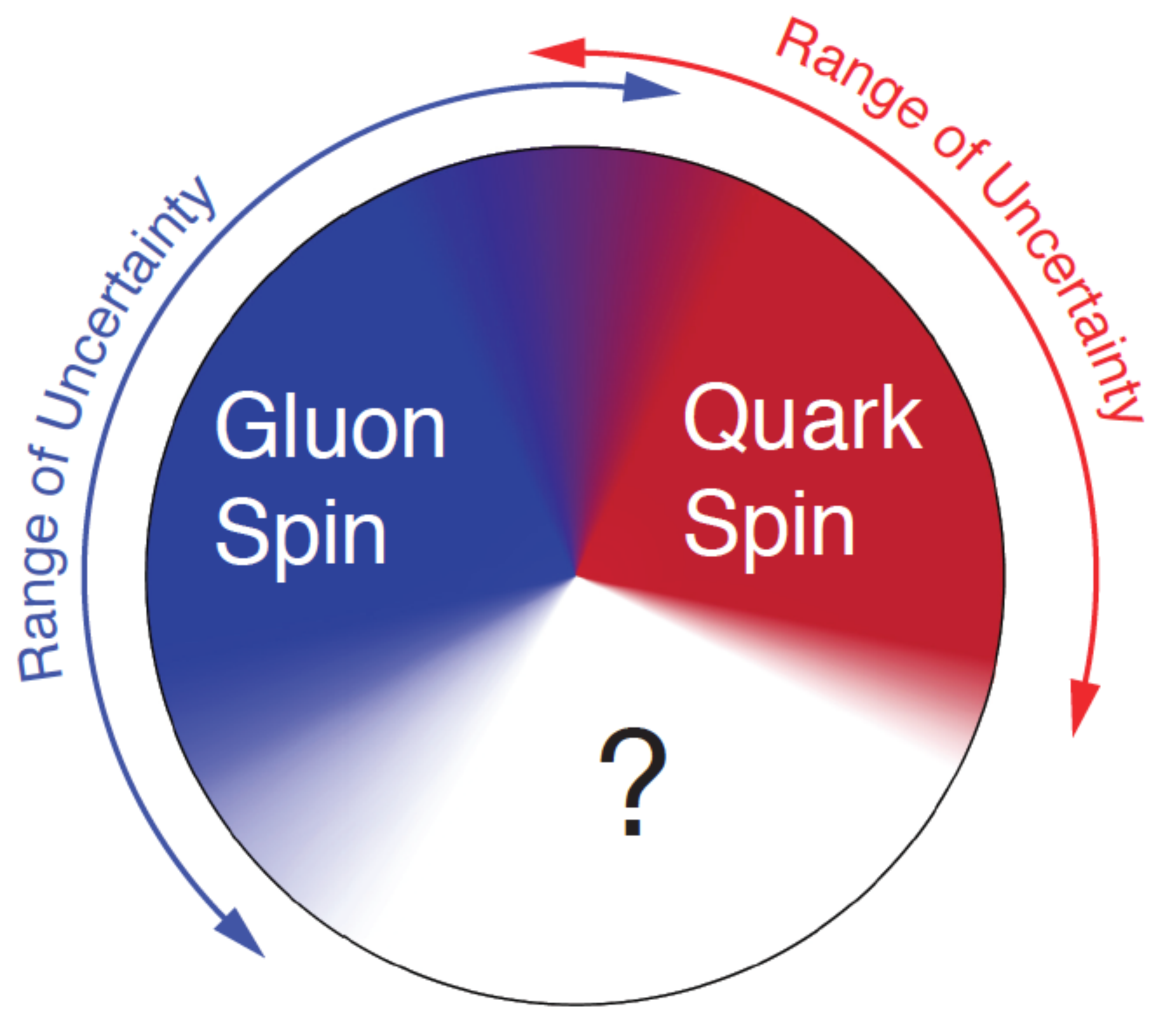
Gluons are massless…yet their dynamics are responsible for (nearly all) the mass in nucleons

We do not know how!



Proton Spin Puzzle

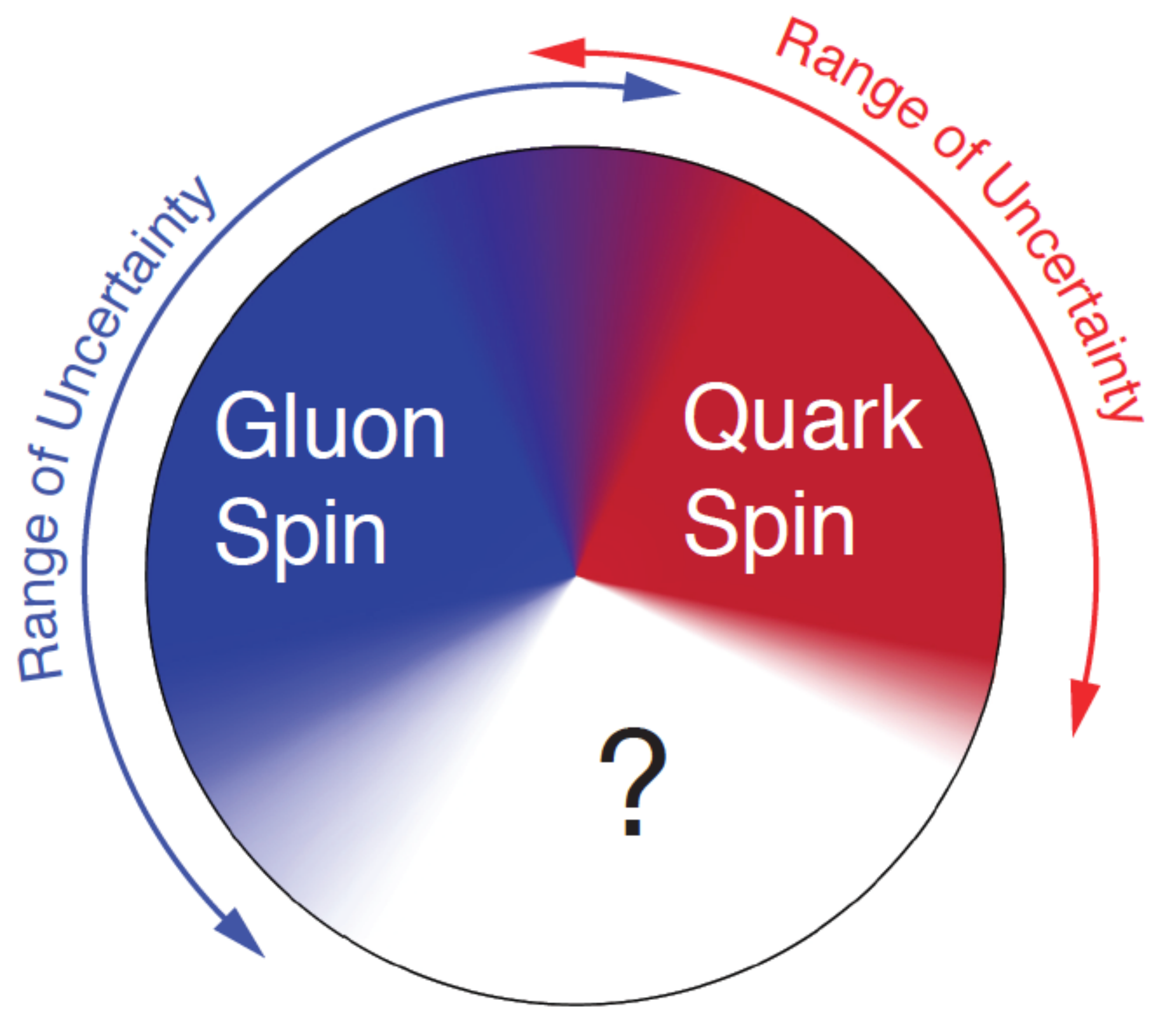
What are the appropriate degrees of freedom in QCD that would explain the "spin" of a proton?



- After 20 years effort
  - Quarks (valence and sea): ~30% of spin in limited x-range
  - Gluons (latest RHIC data): ~20% of spin in limited x-range
  - Where is the rest?

Proton Spin Puzzle

What are the appropriate degrees of freedom in QCD that would explain the "spin" of a proton?

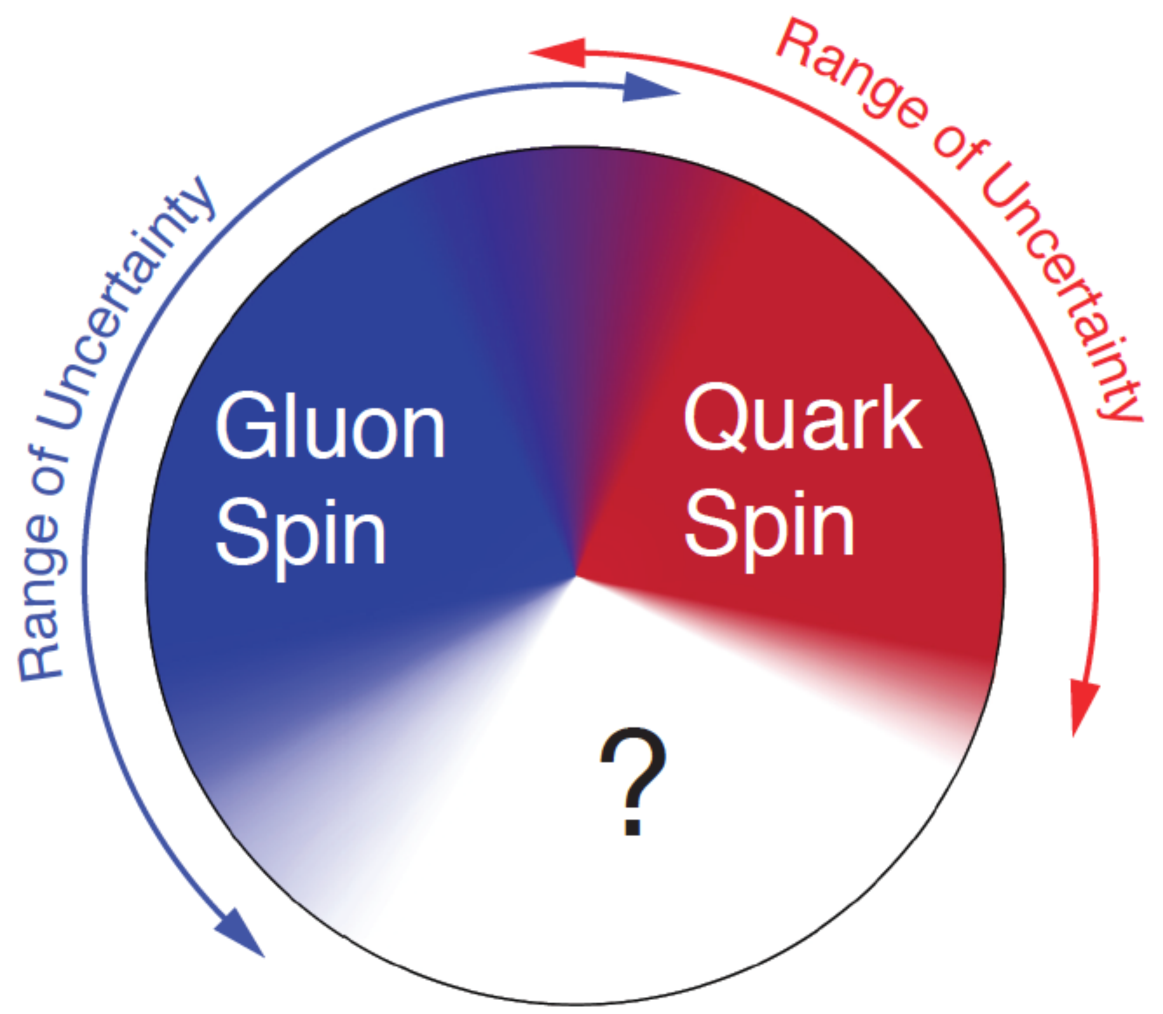


- After 20 years effort
  - Quarks (valence and sea): ~30% of spin in limited x-range
  - Gluons (latest RHIC data): ~20% of spin in limited x-range
  - Where is the rest?

It is more than the number ½! It is the interplay between intrinsic properties and interactions of quarks and gluons

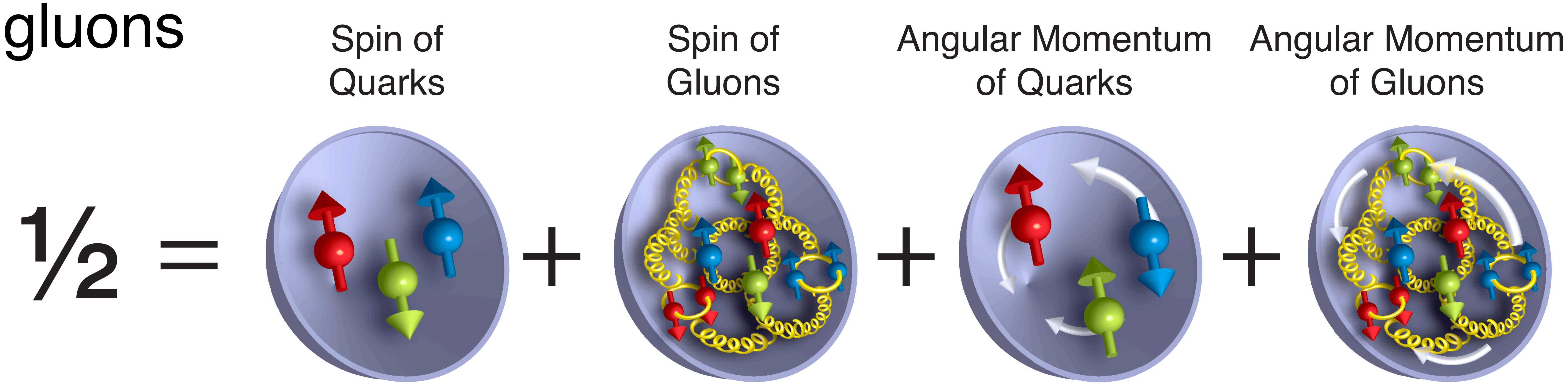
Proton Spin Puzzle

What are the appropriate degrees of freedom in QCD that would explain the "spin" of a proton?



- After 20 years effort
  - Quarks (valence and sea): ~30% of spin in limited x-range
  - Gluons (latest RHIC data): ~20% of spin in limited x-range
  - Where is the rest?

It is more than the number ½! It is the interplay between intrinsic properties and interactions of quarks and gluons



What Does a Proton Look Like?

- In transverse momentum?
- In transverse space?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

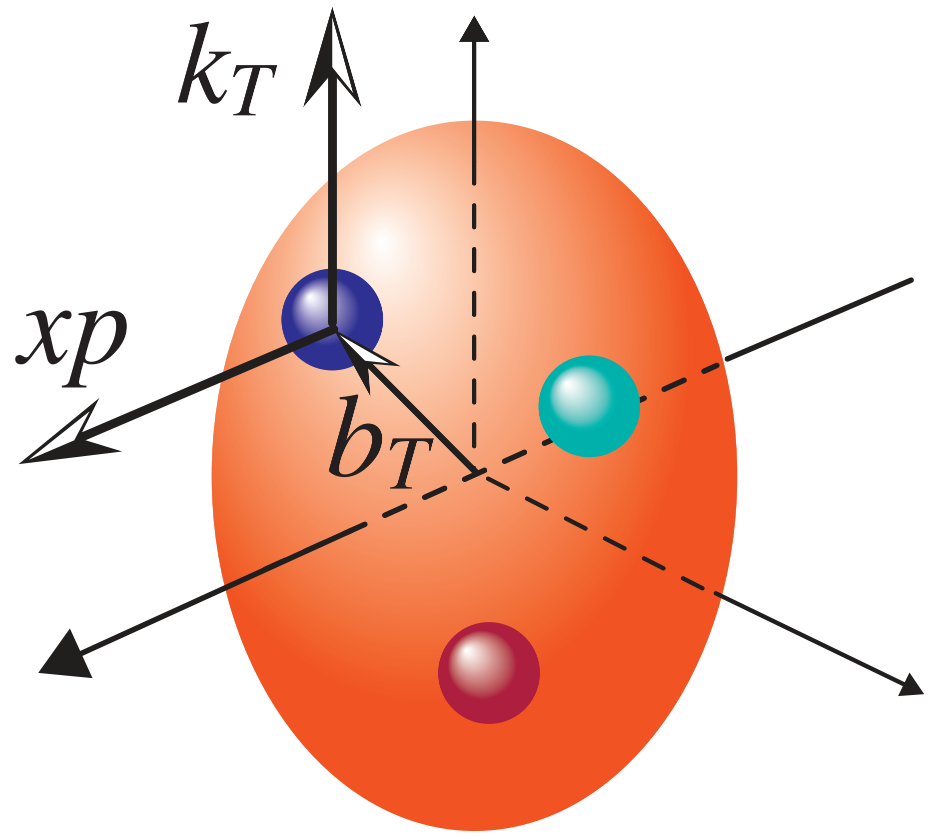
What Does a Proton Look Like?

- In transverse momentum?
- In transverse space?
- How are these distributions correlated with overall nucleon properties, such as spin direction?

3D Imaging

More Detail: 3-D Imaging of Quarks and Gluons

$W(x, b_T, k_T)$



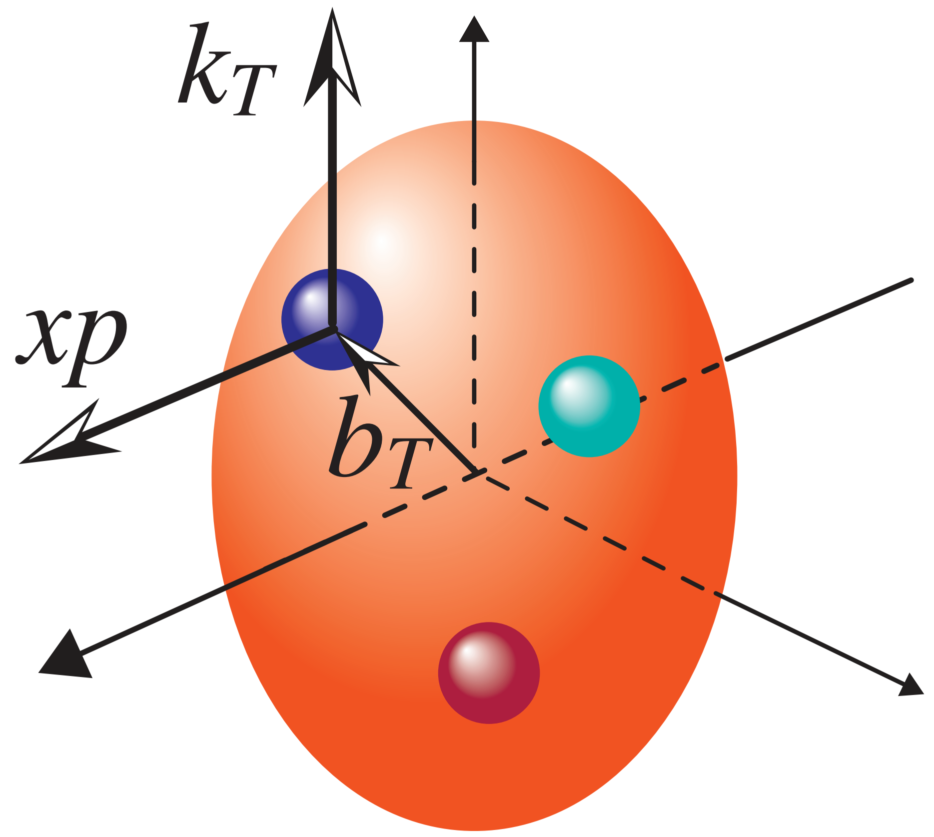
Mother of all functions describing the structure of the proton:

5D Wigner Function: $W(x, k_T, b_T)$

Was considered not measurable.
Recent efforts indicate opportunities via dijet measurements

More Detail: 3-D Imaging of Quarks and Gluons

$W(x, b_T, k_T)$

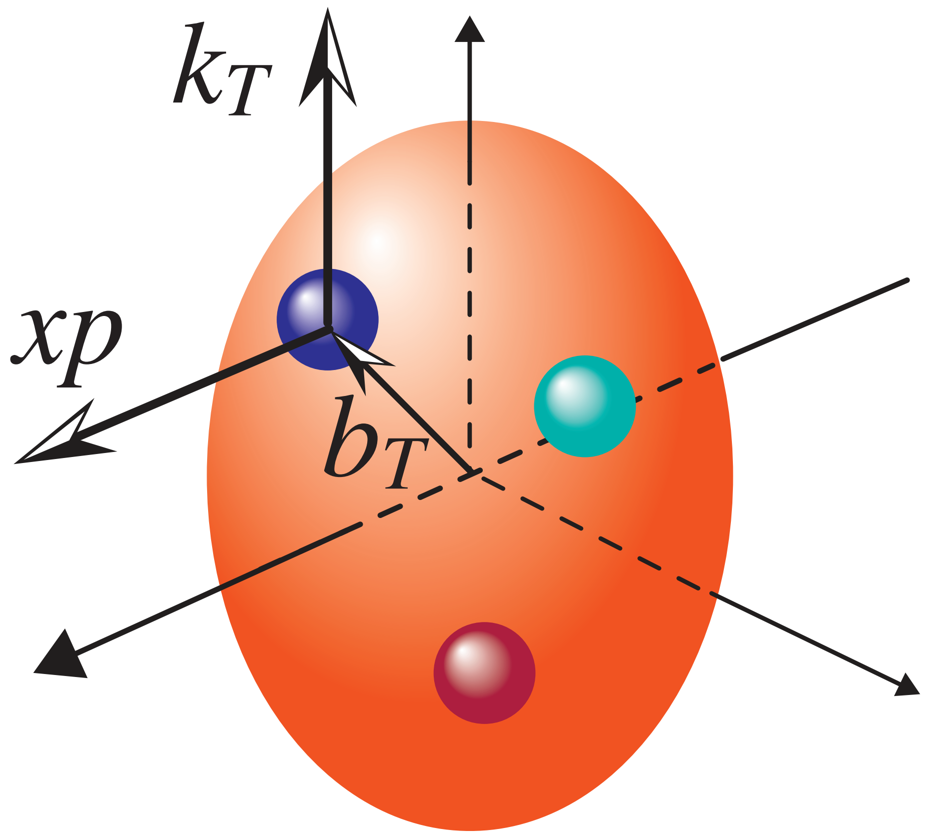


More Detail: 3-D Imaging of Quarks and Gluons

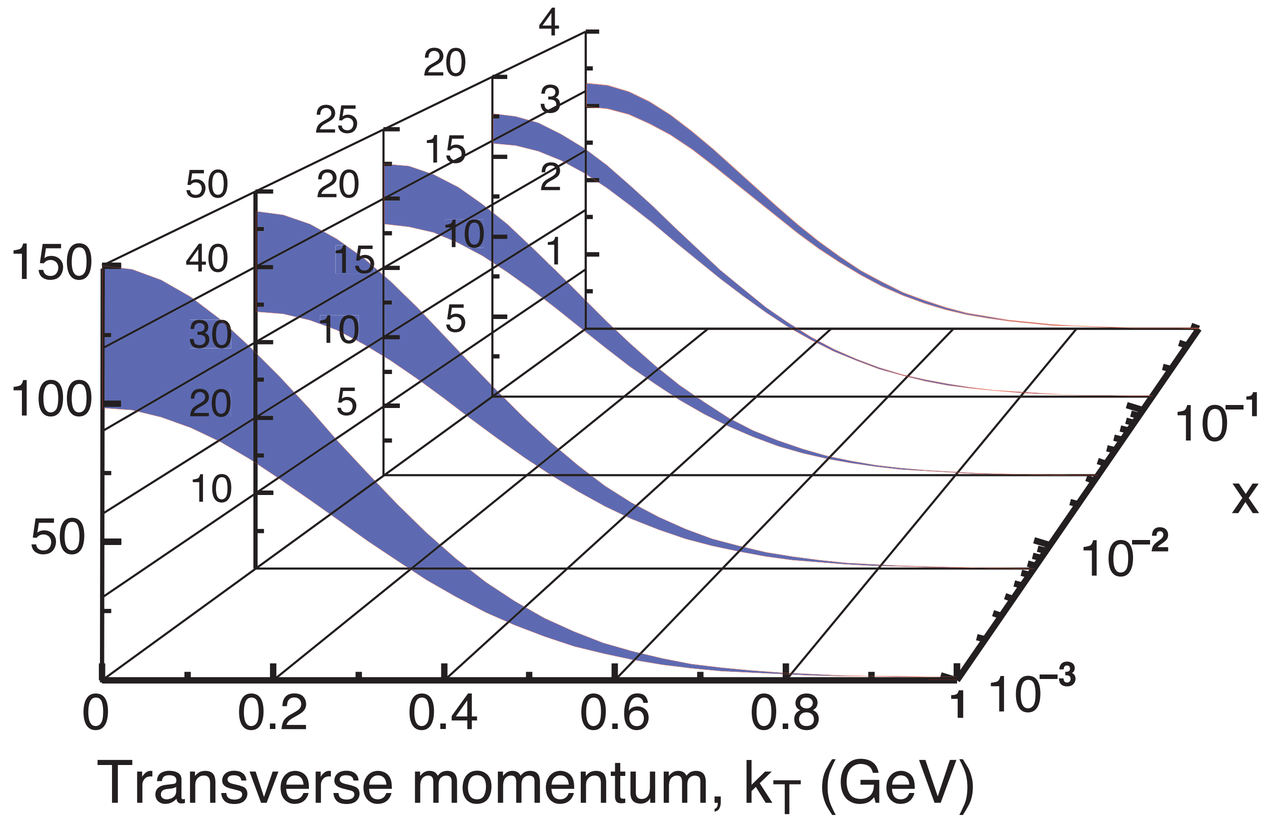
Momentum space

$W(x,b_T,k_T)$

$\int d^2b_T$



$f(x,k_T)$



Spin-dependent transverse dependent PDF

Transverse Momentum Distributions (TMDs)

More Detail: 3-D Imaging of Quarks and Gluons

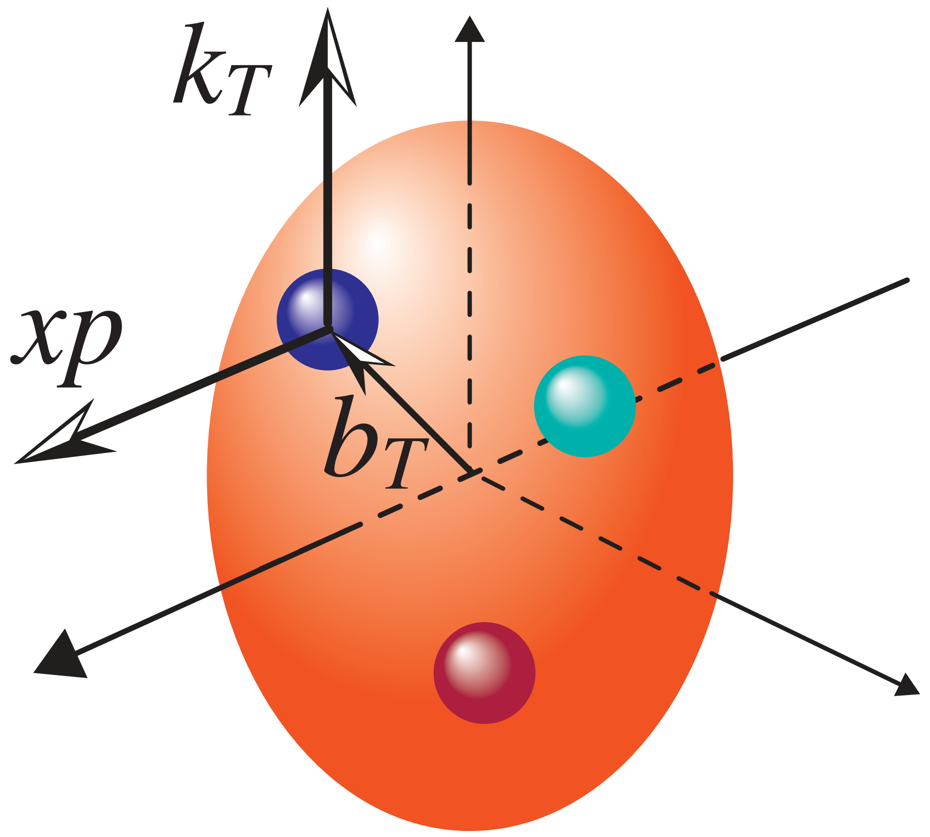
Momentum space

$W(x,b_T,k_T)$

Coordinate space

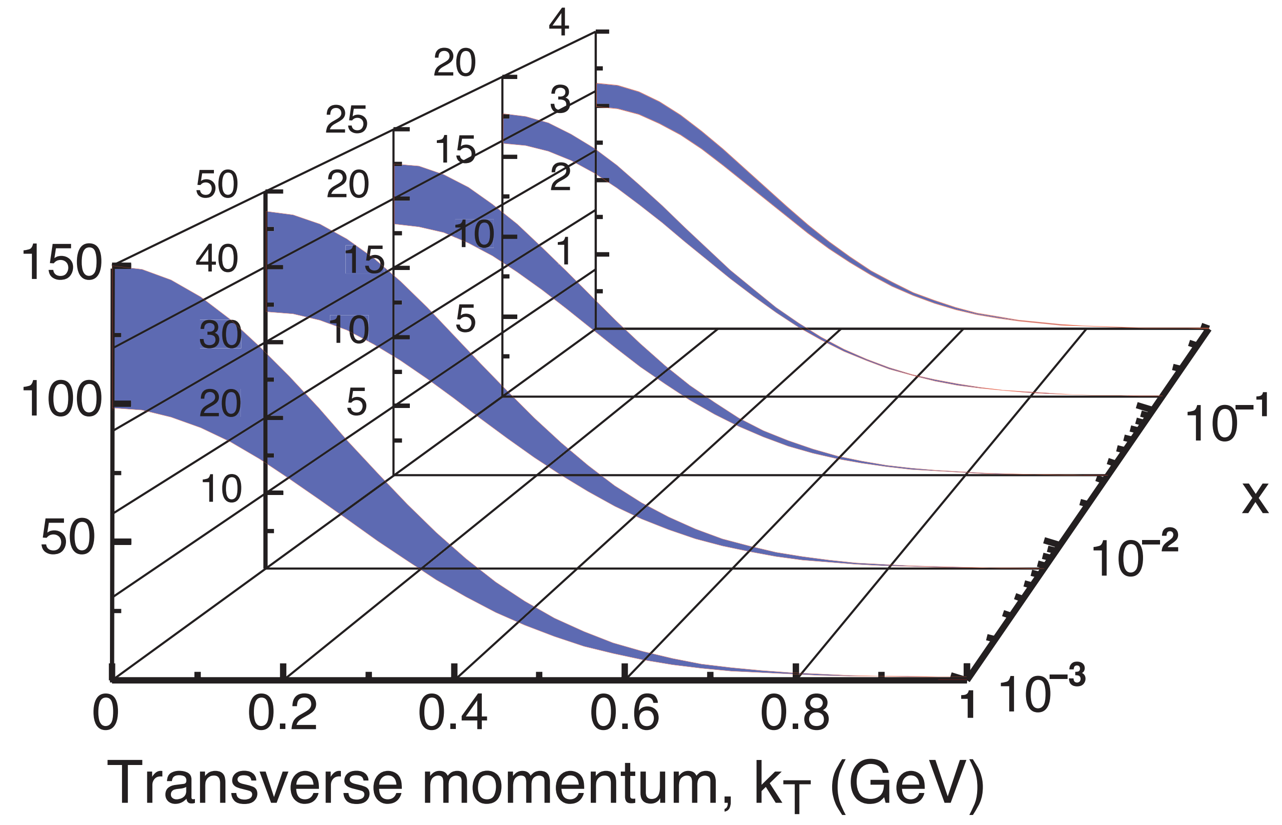
$\int d^2b_T$

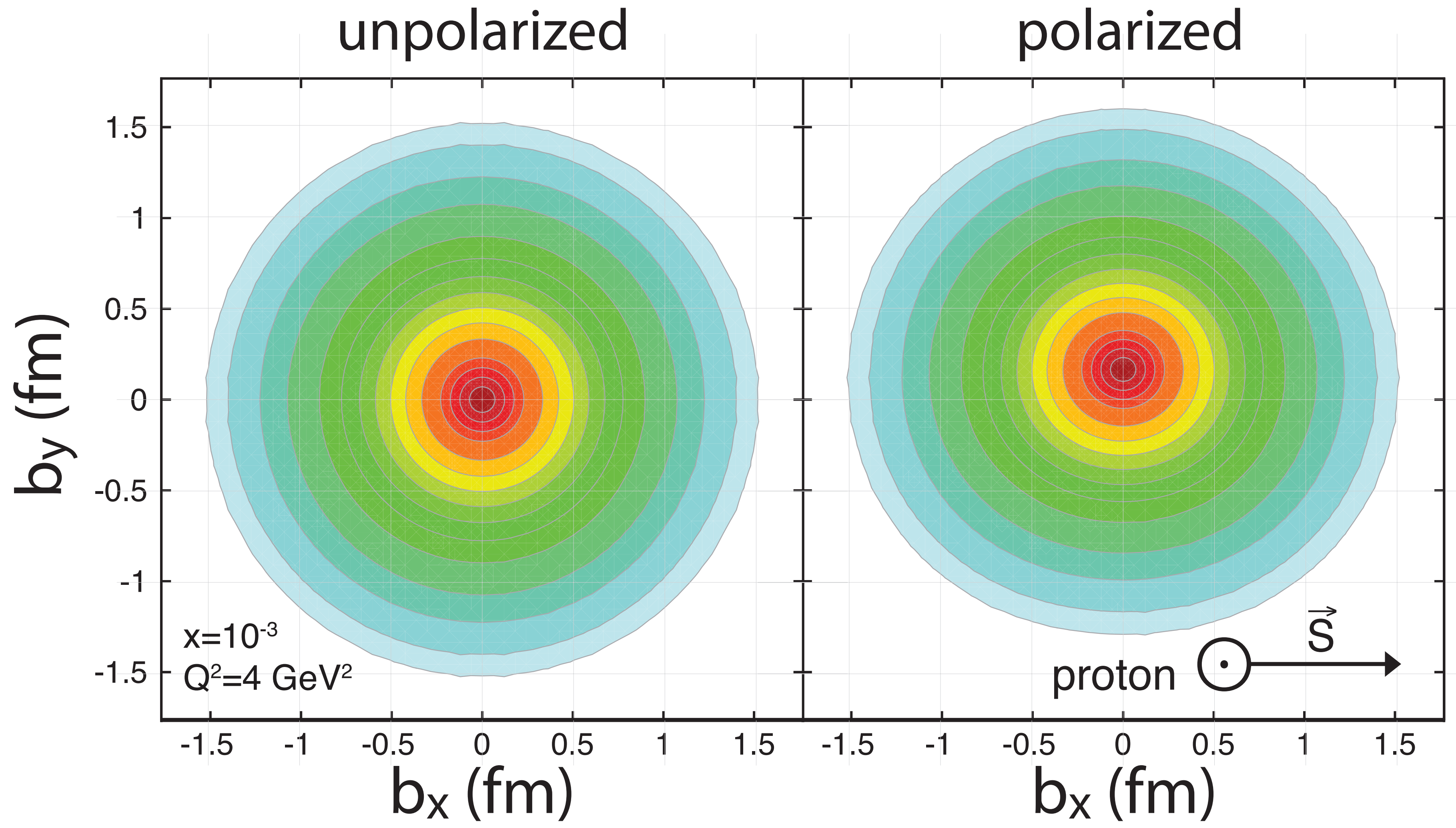
$\int d^2k_T$



$f(x,k_T)$

$f(x,b_T)$





Spin-dependent transverse dependent PDF

Spin and impact parameter dependent PDF

Transverse Momentum Distributions (TMDs)

More Detail: 3-D Imaging of Quarks and Gluons

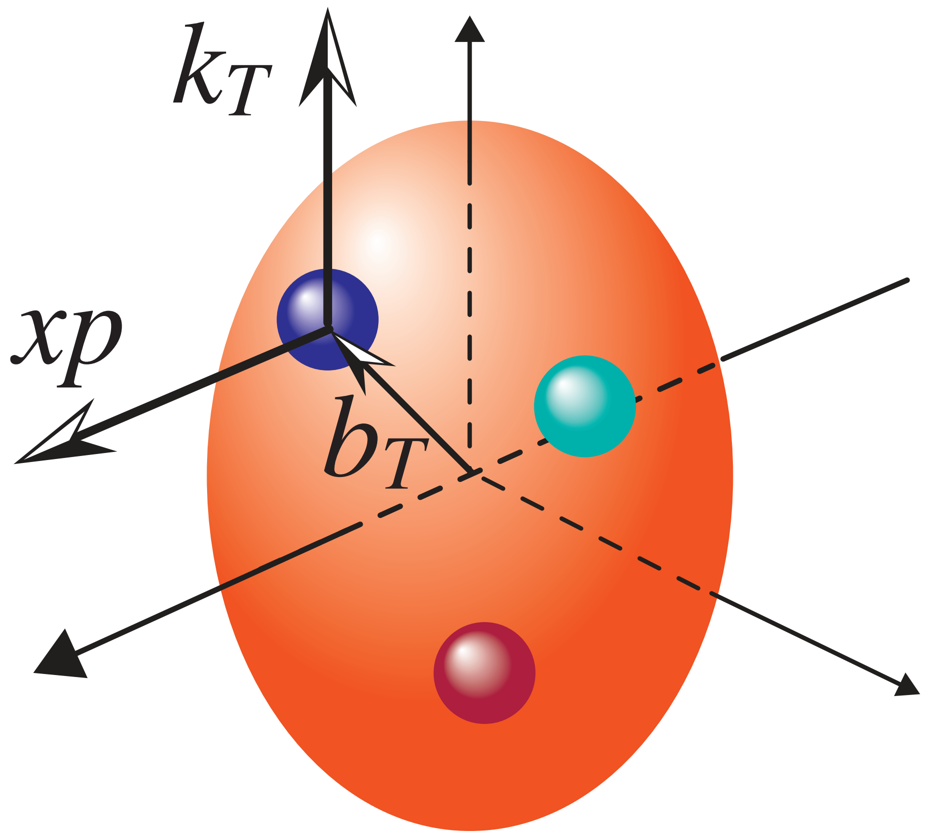
Momentum space

$W(x,b_T,k_T)$

Coordinate space

$\int d^2b_T$

$\int d^2k_T$



$f(x,k_T)$

$f(x,b_T)$

More Detail: 3-D Imaging of Quarks and Gluons

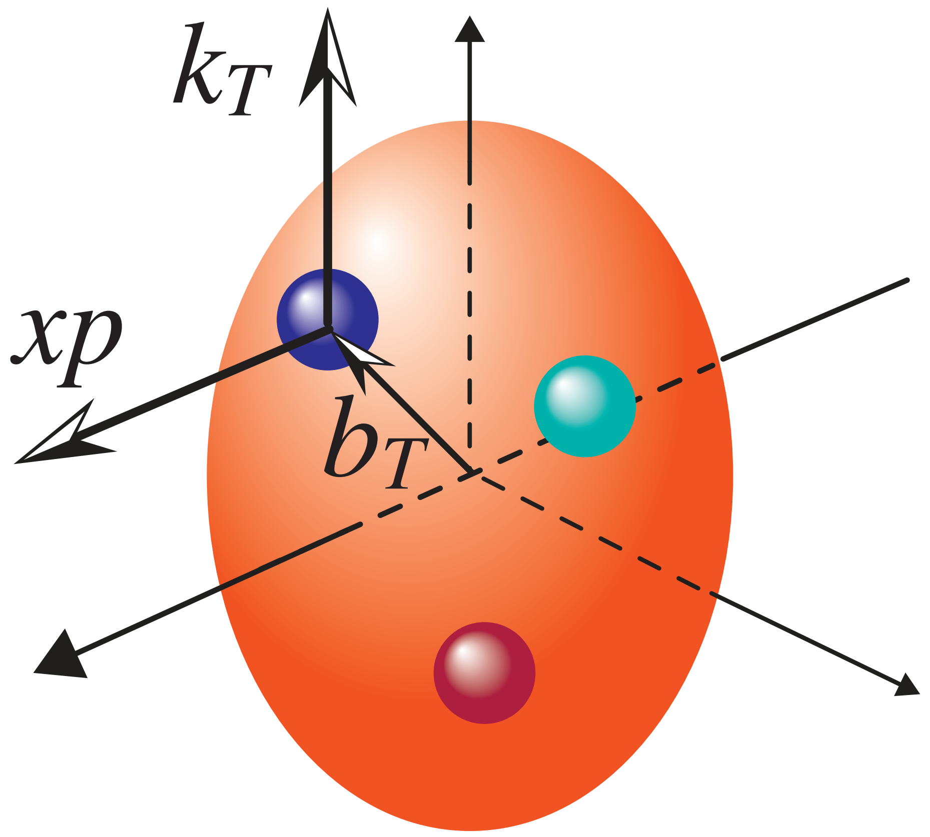
Momentum space

$W(x,b_T,k_T)$

Coordinate space

$\int d^2b_T$

$\int d^2k_T$



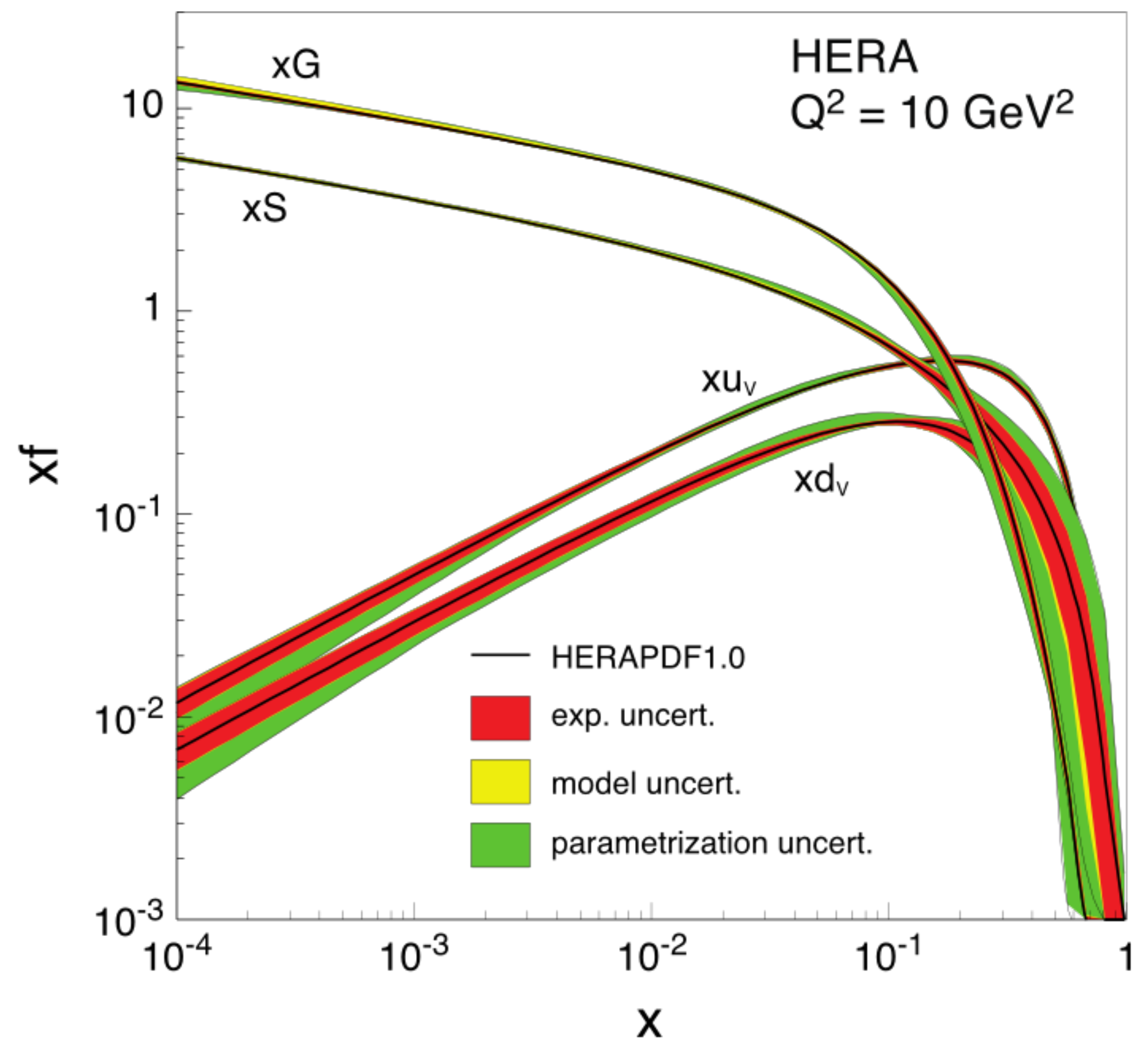
$f(x,k_T)$

$f(x,b_T)$

$\int d^2k_T$

$\int d^2b_T$

$f(x)$



Parton densities

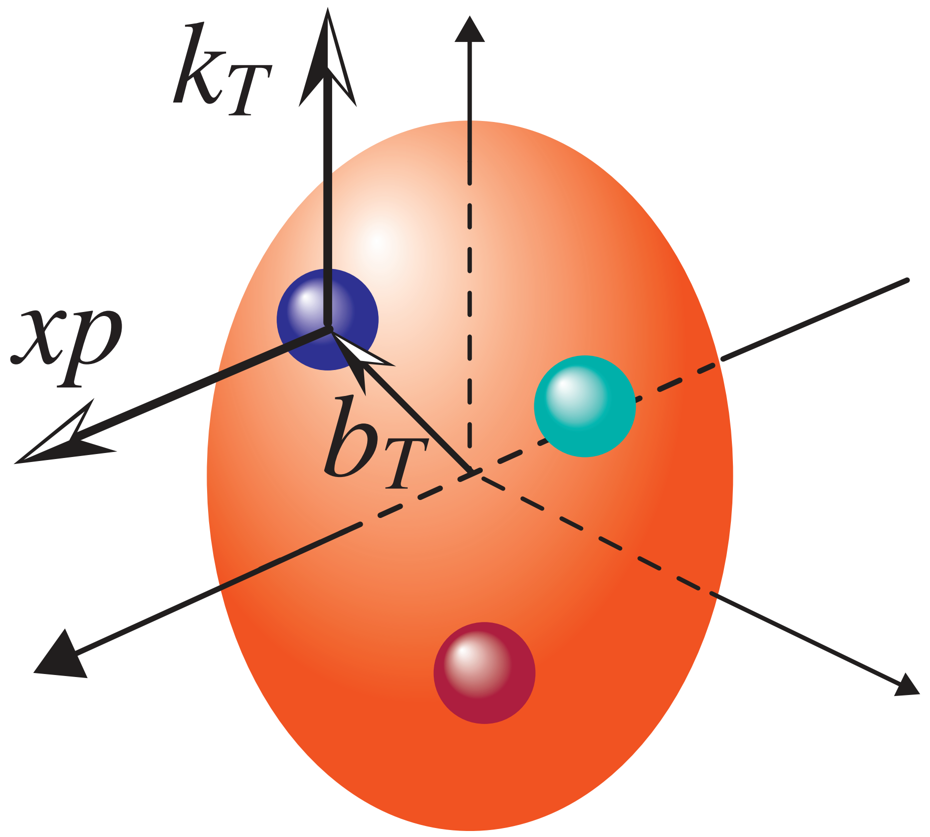
More Detail: 3-D Imaging of Quarks and Gluons

Momentum space

$W(x,b_T,k_T)$

Coordinate space

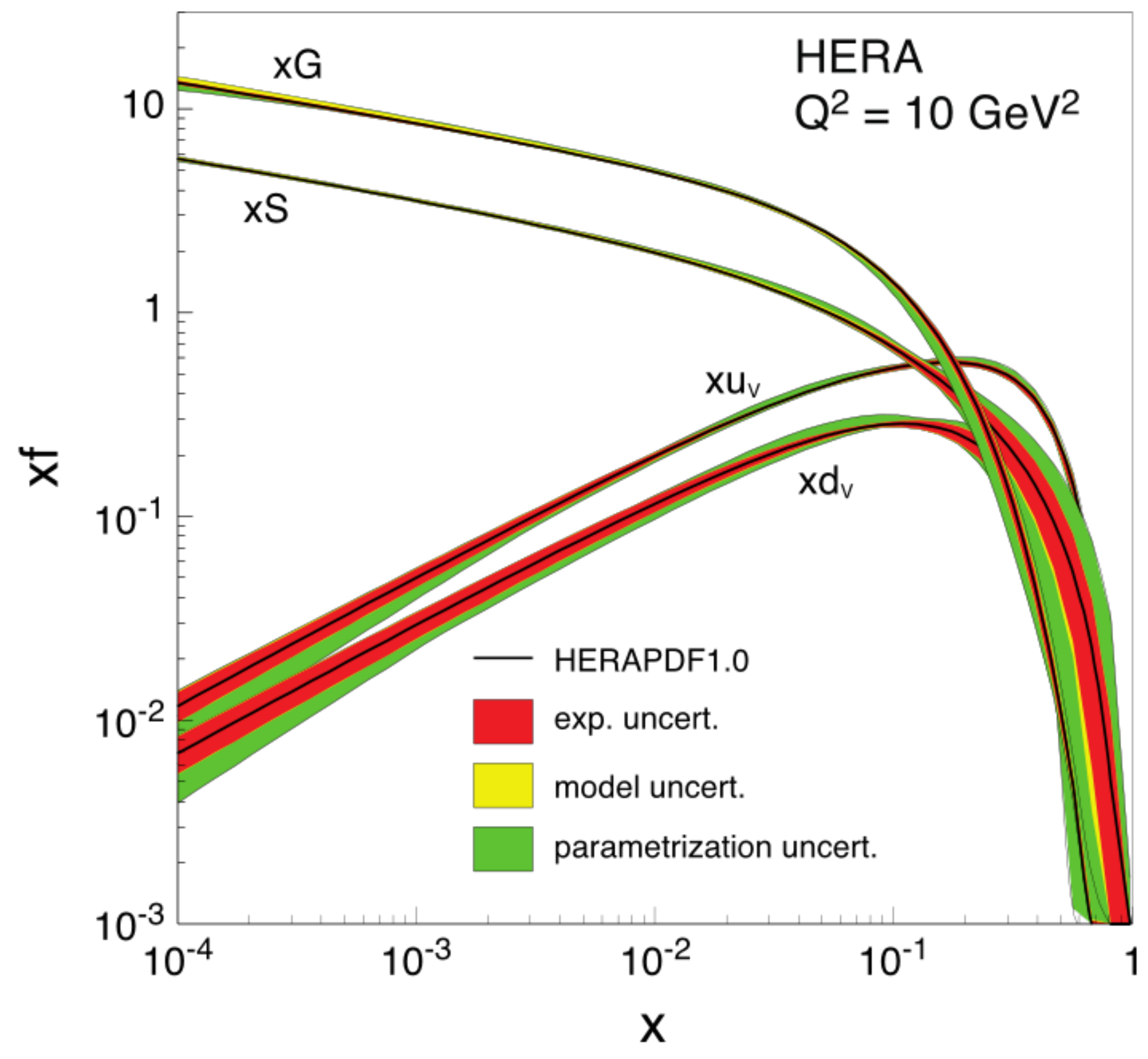
$\int d^2b_T$ $\int d^2k_T$



$f(x,k_T)$ $f(x,b_T)$

$\int d^2k_T$ $\int d^2b_T$

$f(x)$



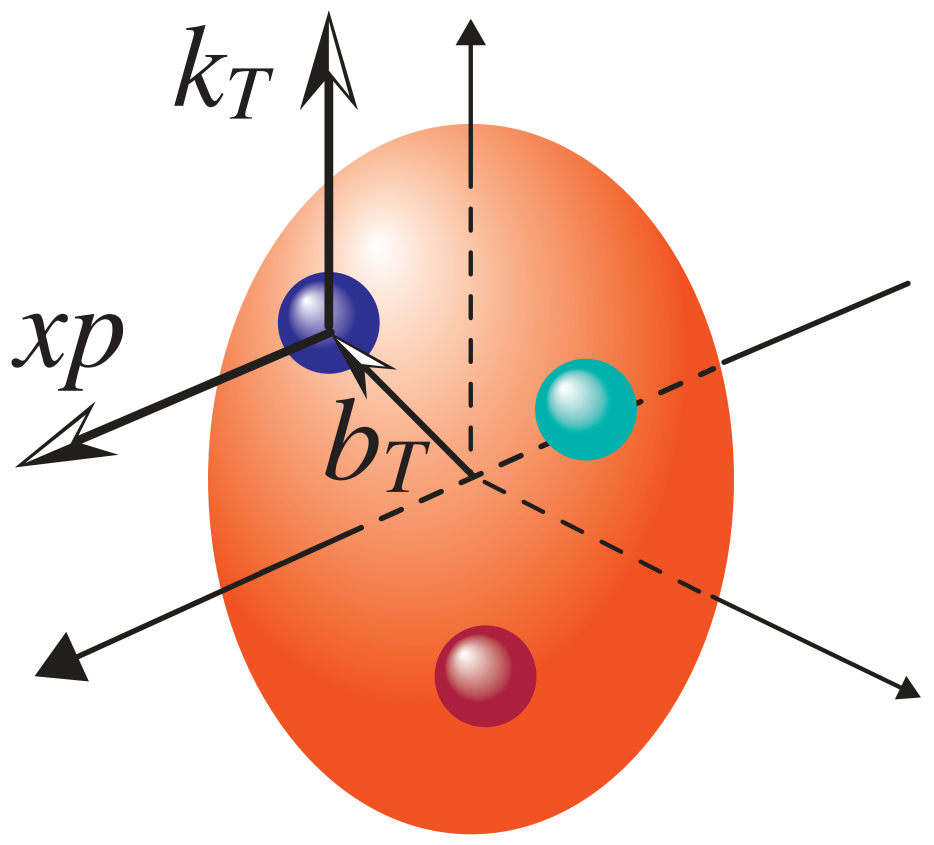
Parton densities

More Detail: 3-D Imaging of Quarks and Gluons

$W(x, b_T, k_T)$

Coordinate space

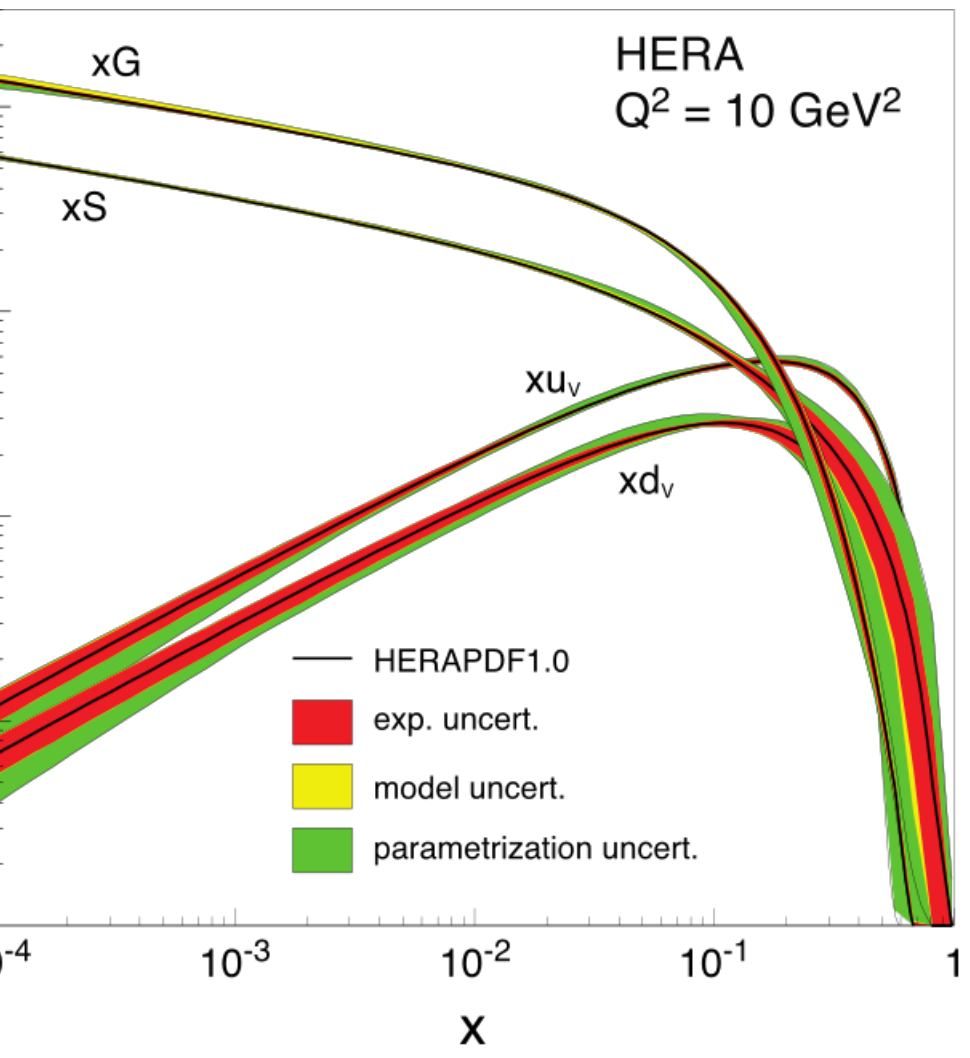
$\int d^2k_T$



$f(x, b_T)$

$\int d^2b_T$

$f(x)$

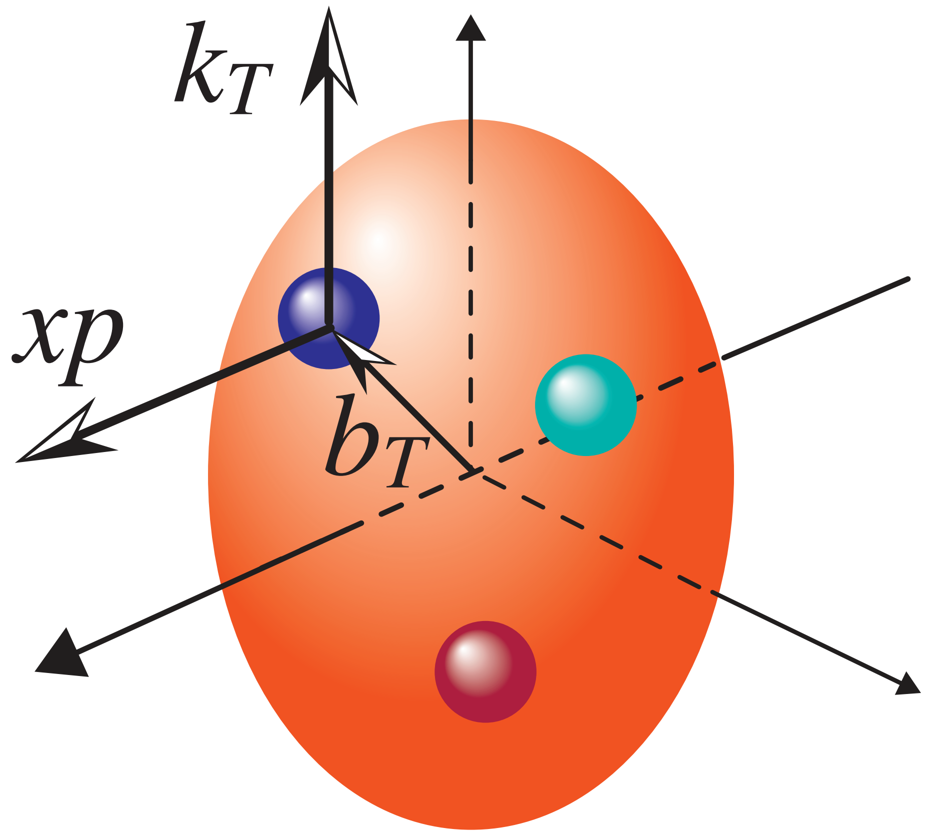


Parton densities

More Detail: 3-D Imaging of Quarks and Gluons

$W(x, b_T, k_T)$

Coordinate space



$\int d^2k_T$

$f(x, b_T)$

$b_T \longleftrightarrow t$

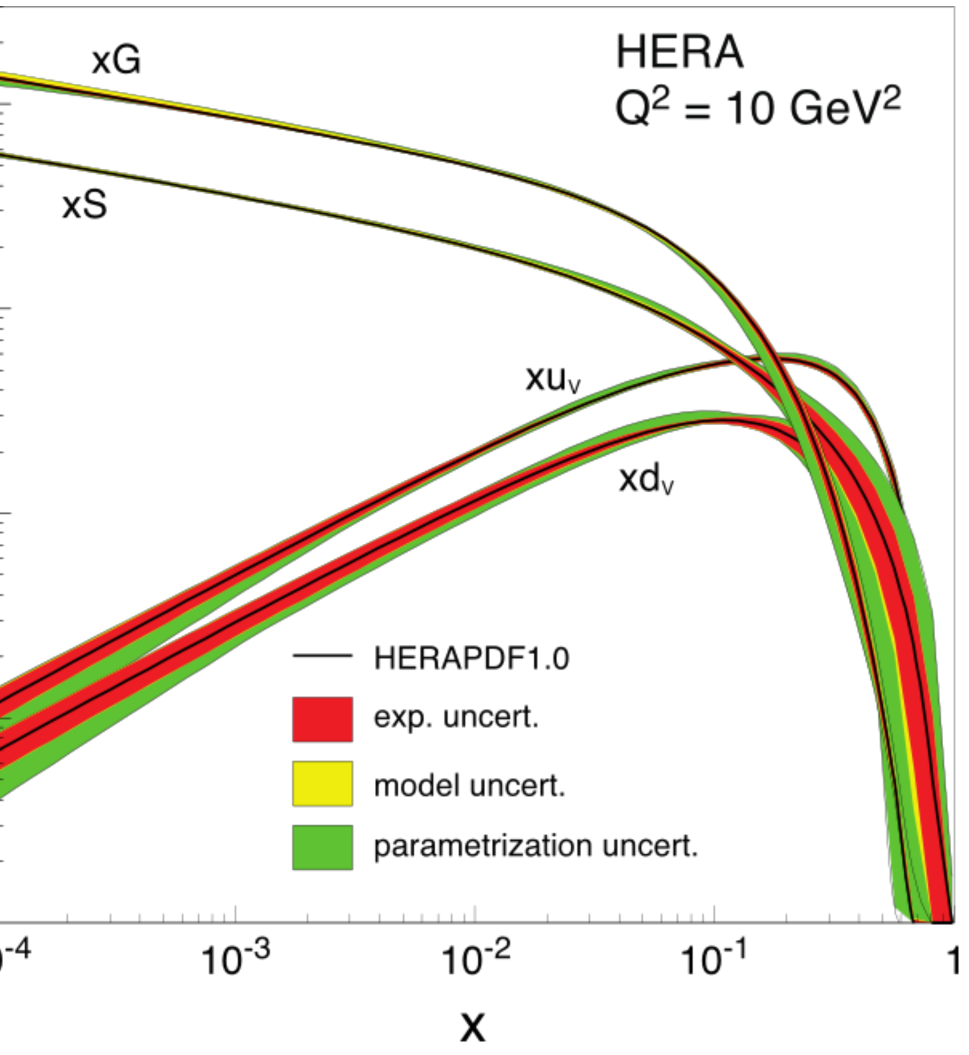
Fourier

$H(x, 0, t)$

$\int d^2b_T$

$\int dx$

$f(x)$



Parton densities

$F(t)$

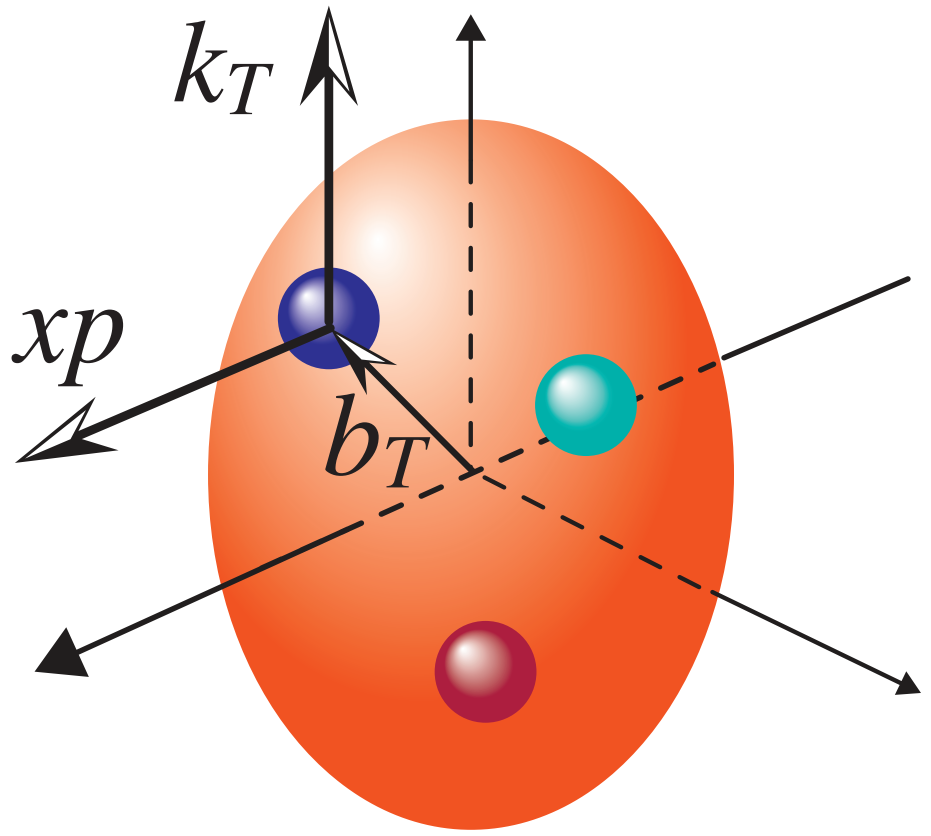
Form factor

More Detail: 3-D Imaging of Quarks and Gluons

$W(x, b_T, k_T)$

Coordinate space

$\int d^2k_T$



$f(x, b_T)$

$b_T \longleftrightarrow t$

Fourier

$H(x, 0, t)$

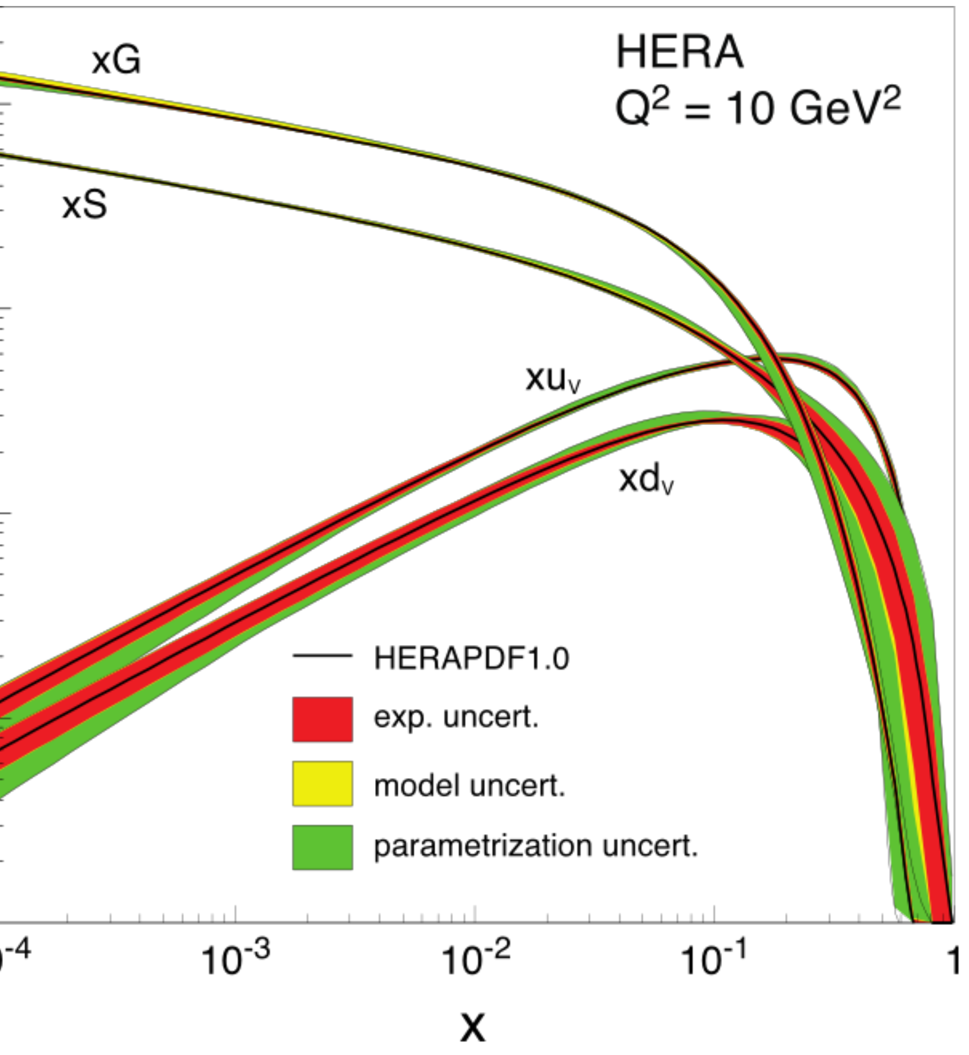
$H(x, \xi, t)$

Generalized Parton Distribution GPD

$\int d^2b_T$

$\int dx$

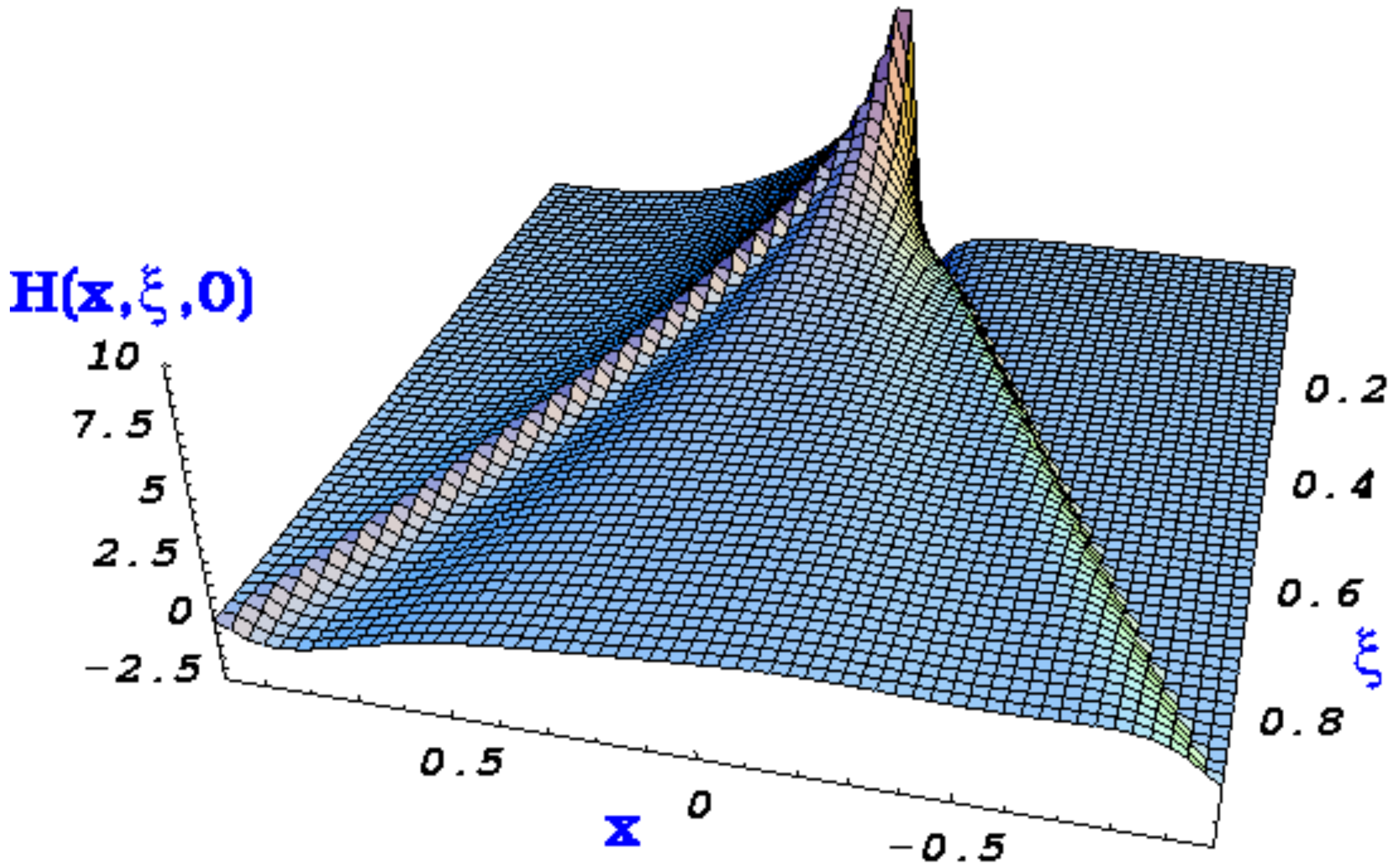
$f(x)$



Parton densities

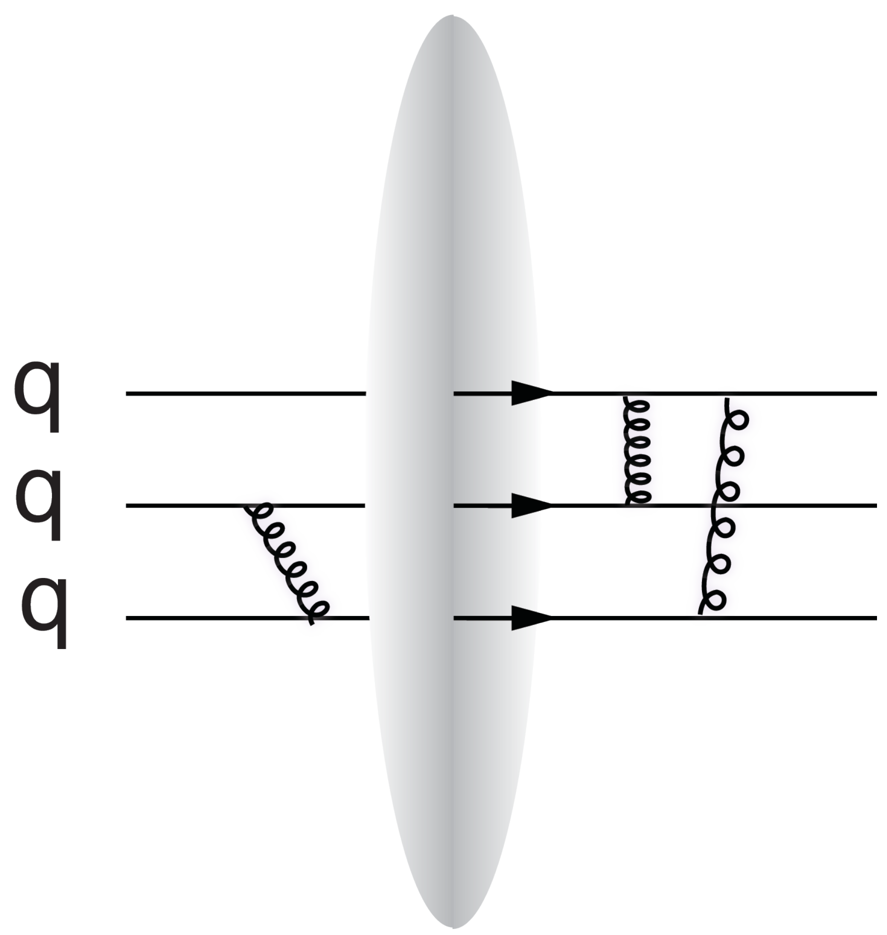
$F(t)$

Form factor

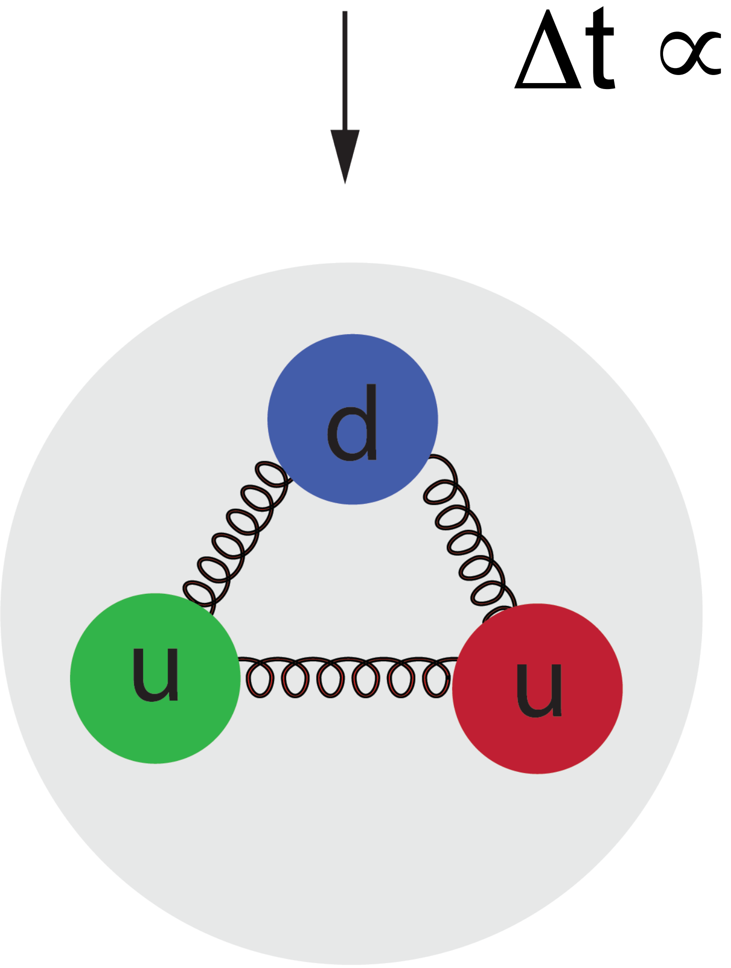


A Look Inside the Boosted Proton

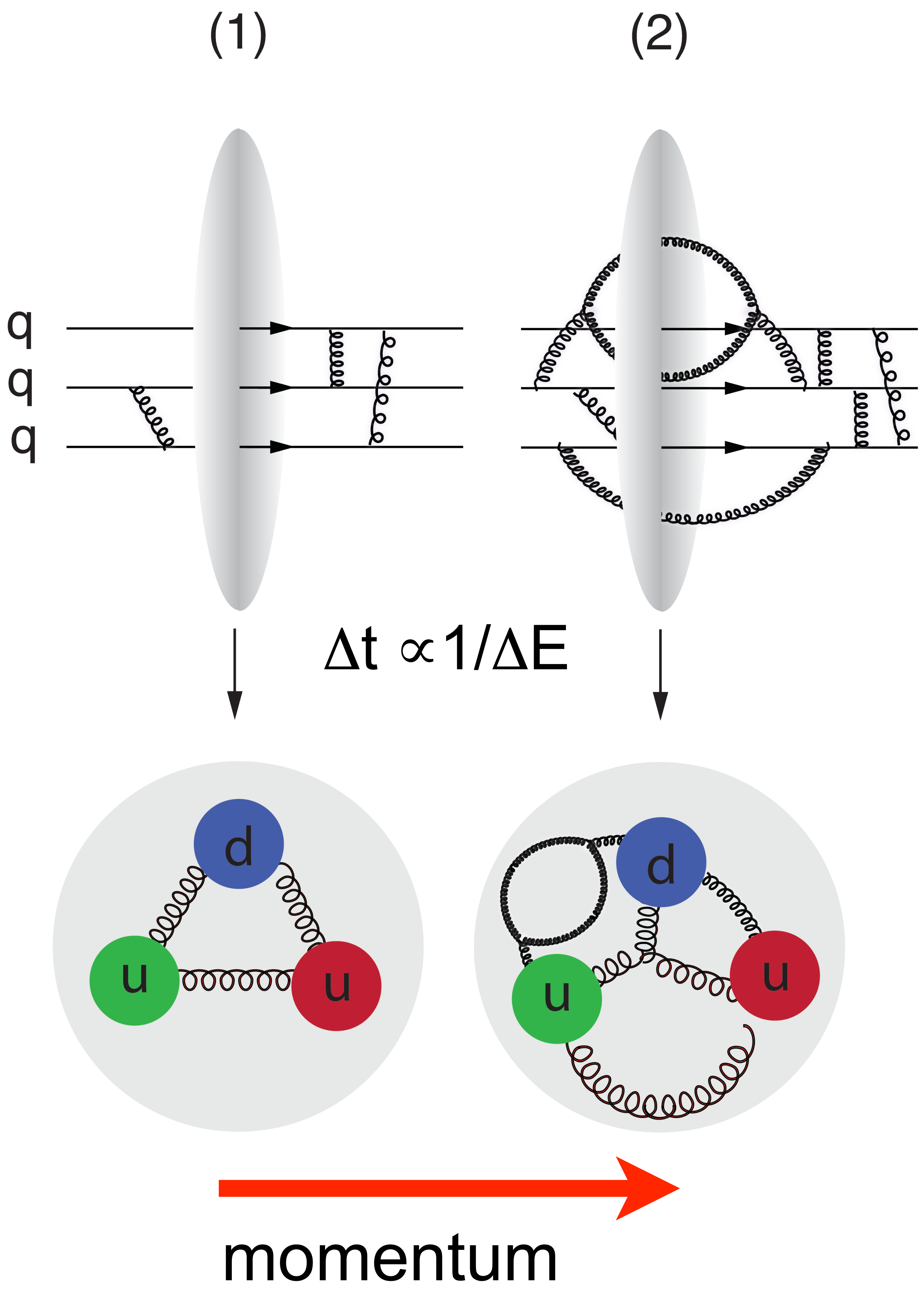
(1)



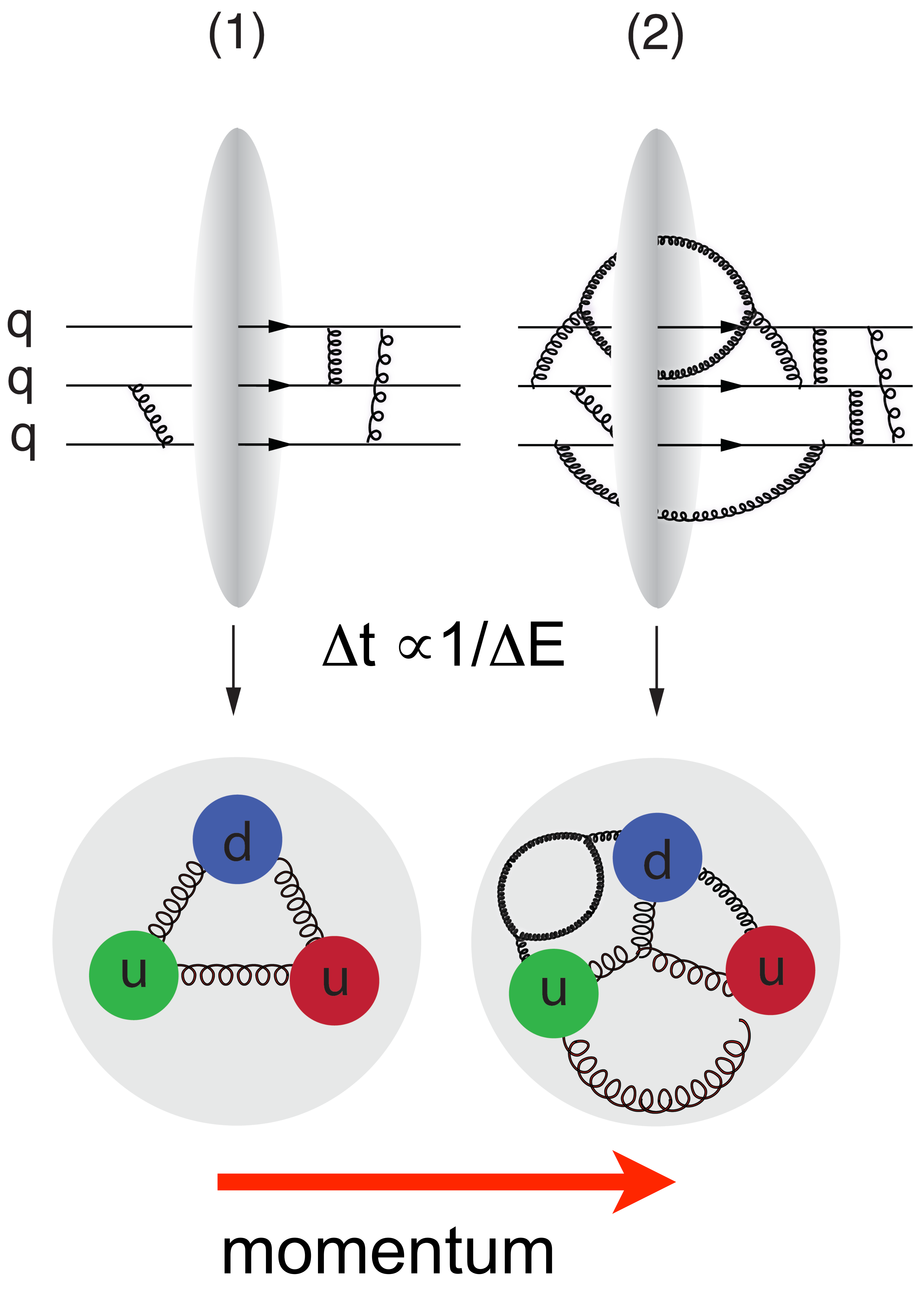
$\Delta t \propto 1/\Delta E$



A Look Inside the Boosted Proton



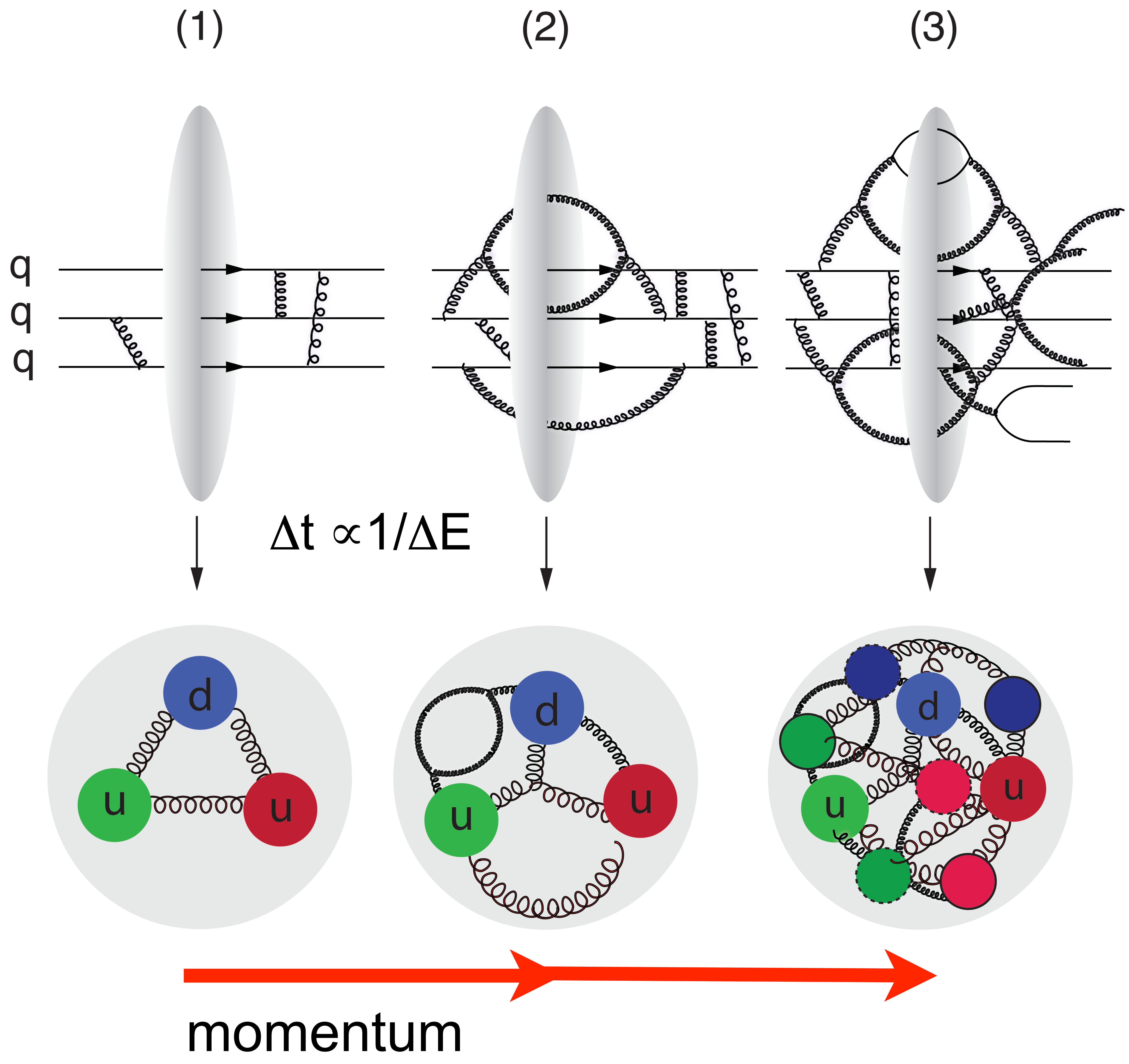
A Look Inside the Boosted Proton



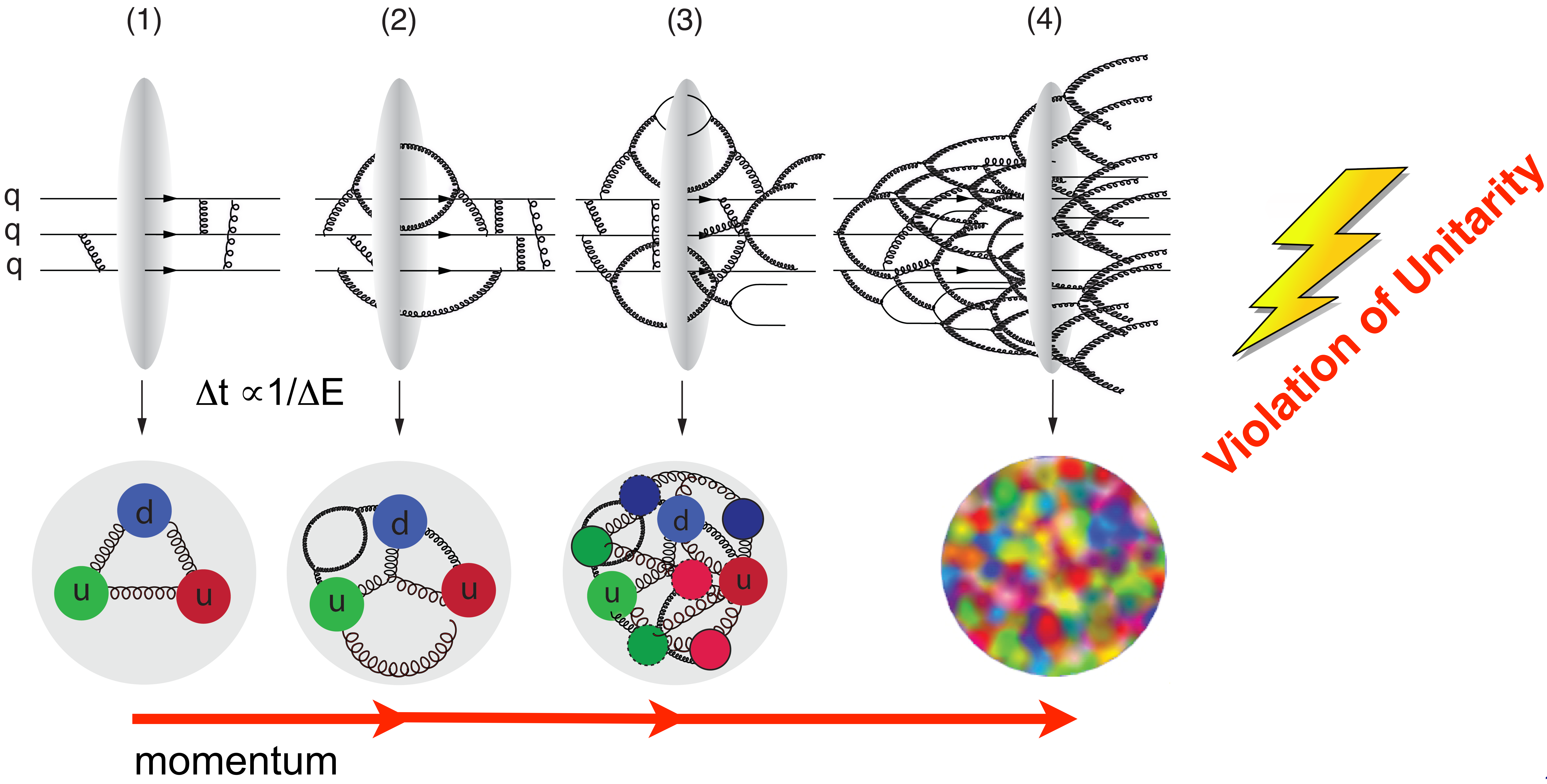
In QCD, the proton is made up of quanta that fluctuate in and out of existence

- Boosted proton:
  - Fluctuations time dilated on strong interaction time scales
  - Long lived gluons can radiate further small x gluons…
  - Explosion of gluon density

A Look Inside the Boosted Proton



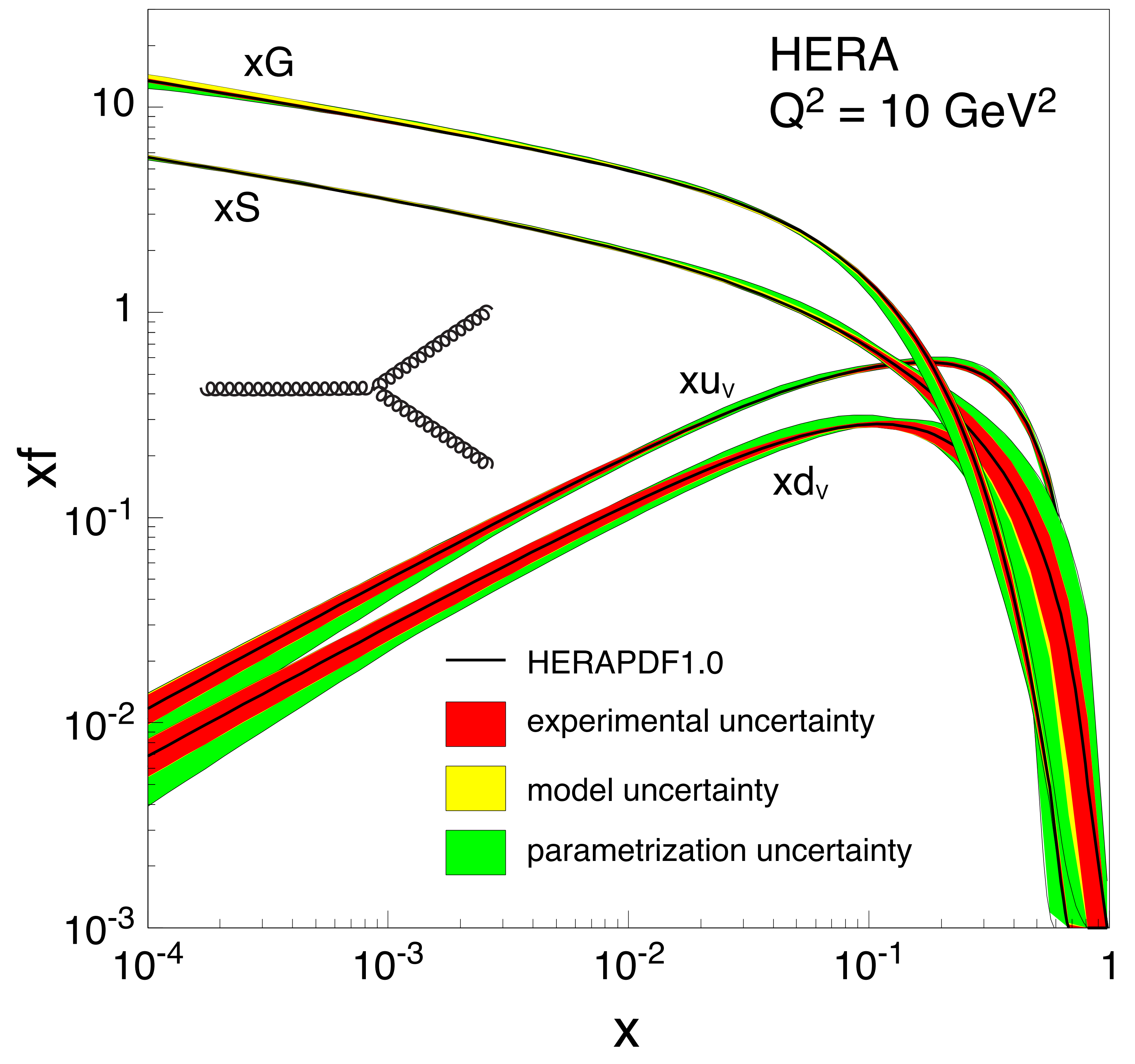
A Look Inside the Boosted Proton

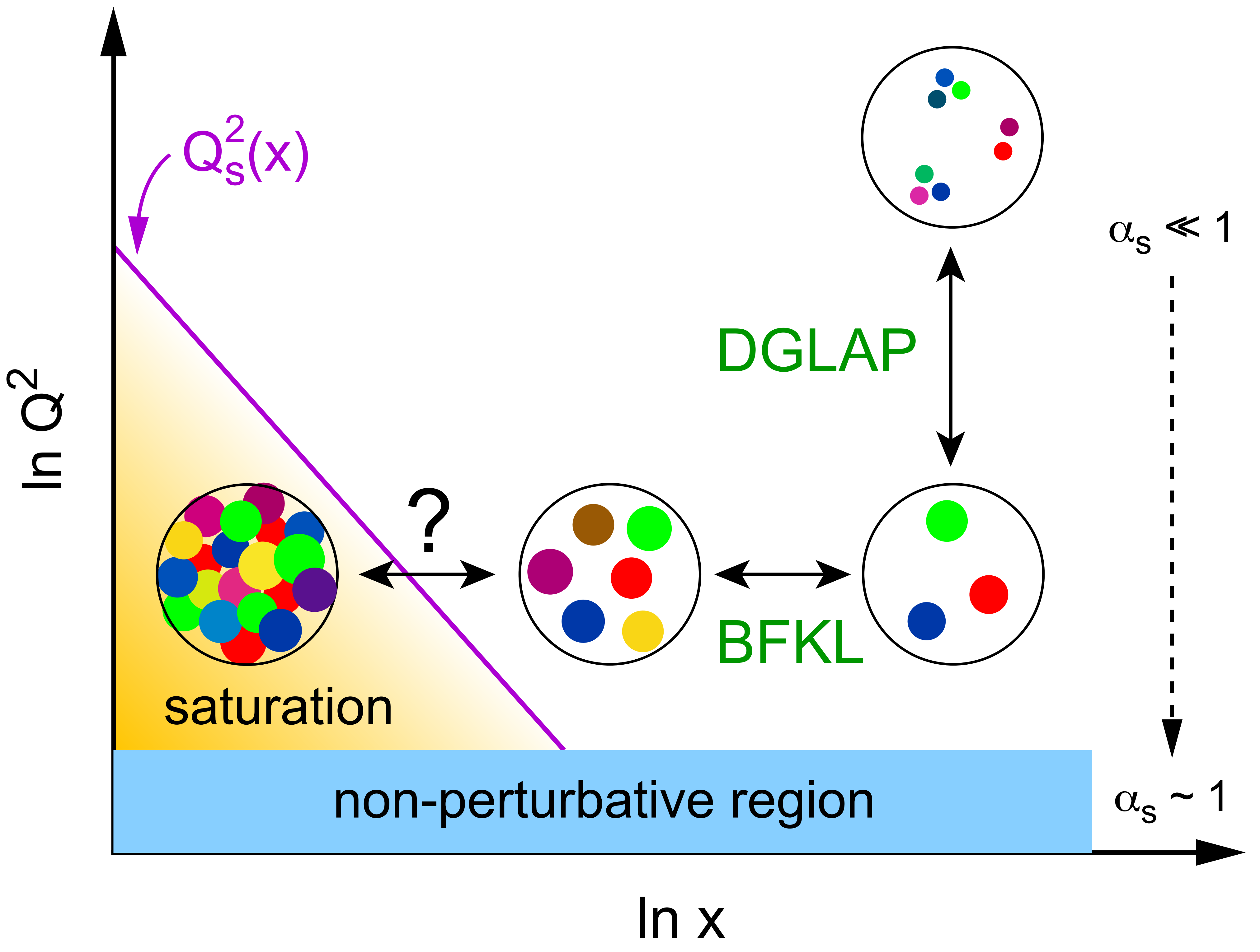


Gluon Saturation

Ever growing $G(x,Q^2)$?

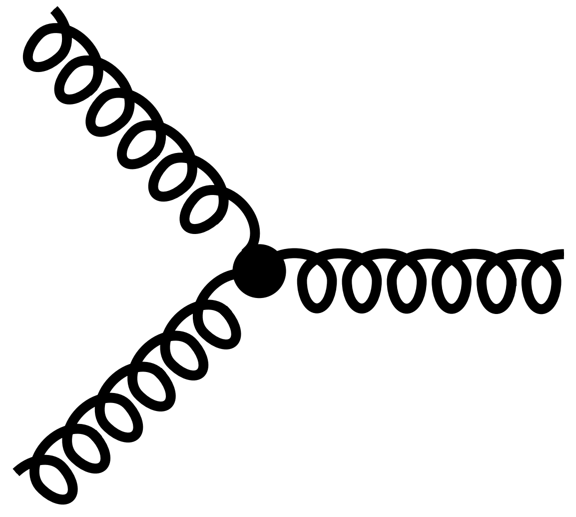
Saturation ⇒ Color-Glass-Condensate (CGC)



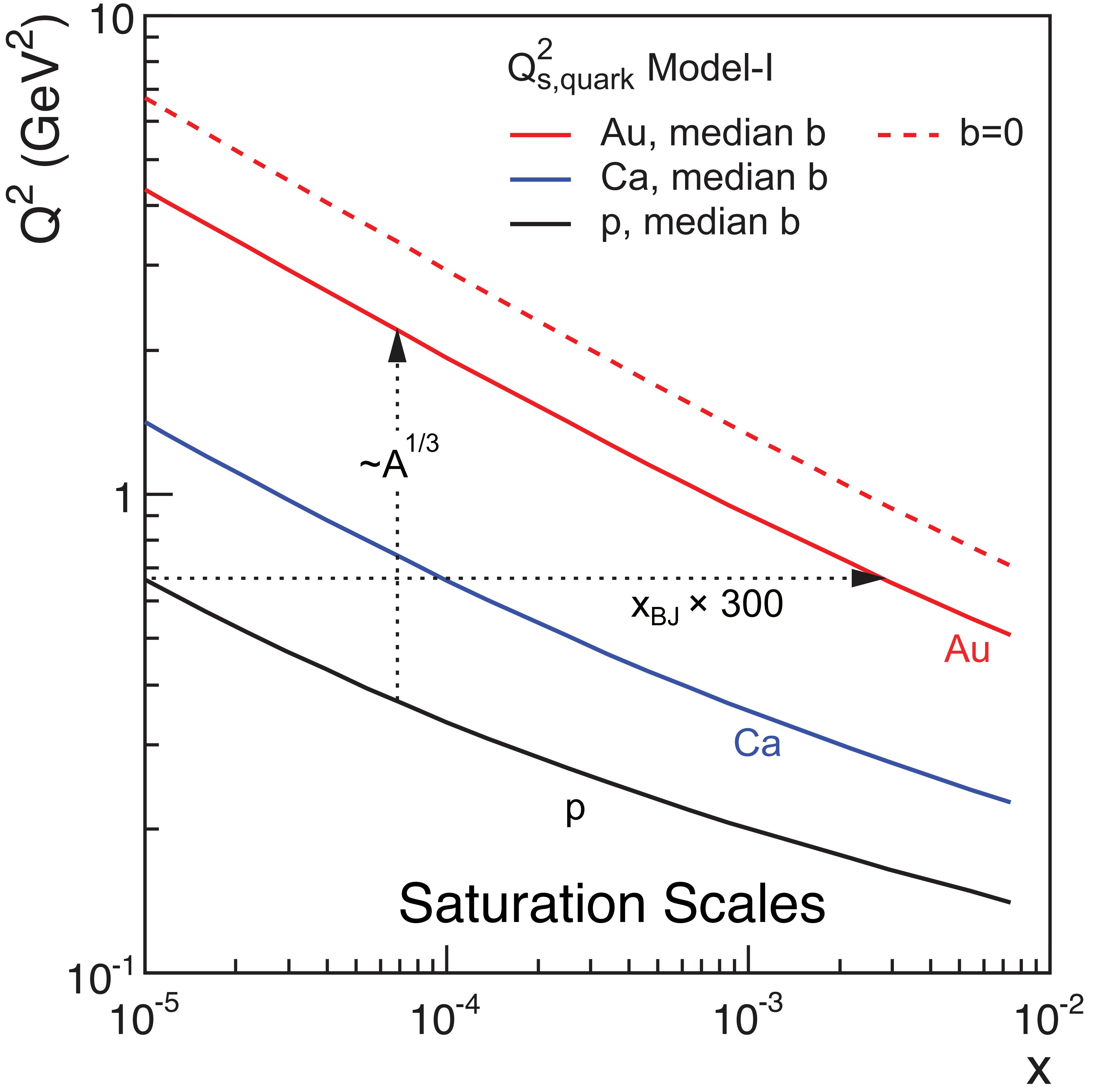


New Approach: Non-Linear Evolution

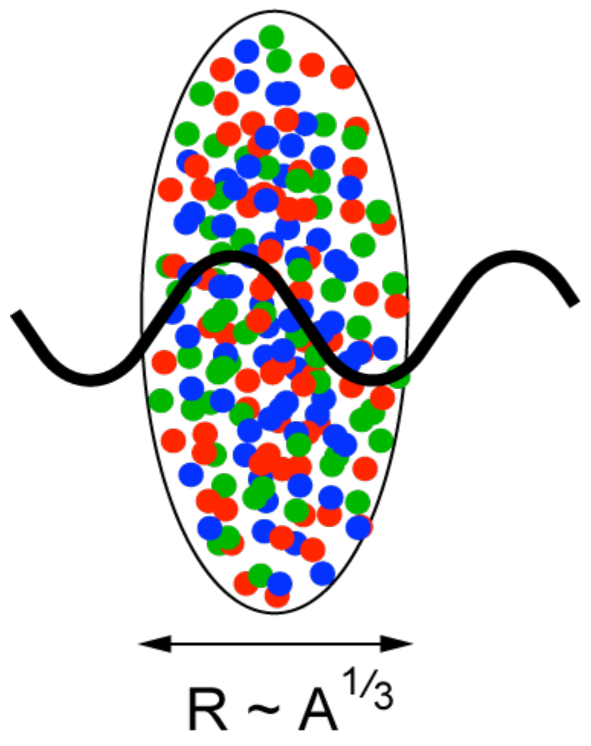
- *Recombination* compensates gluon splitting
- New evolution equations (JMWLK/BK)
- Saturation of gluon densities characterized by scale $Q_s(x)$



Gluon Saturation in Nuclei: The Oomph



Nucleus serves as **amplifier** of the saturation scale



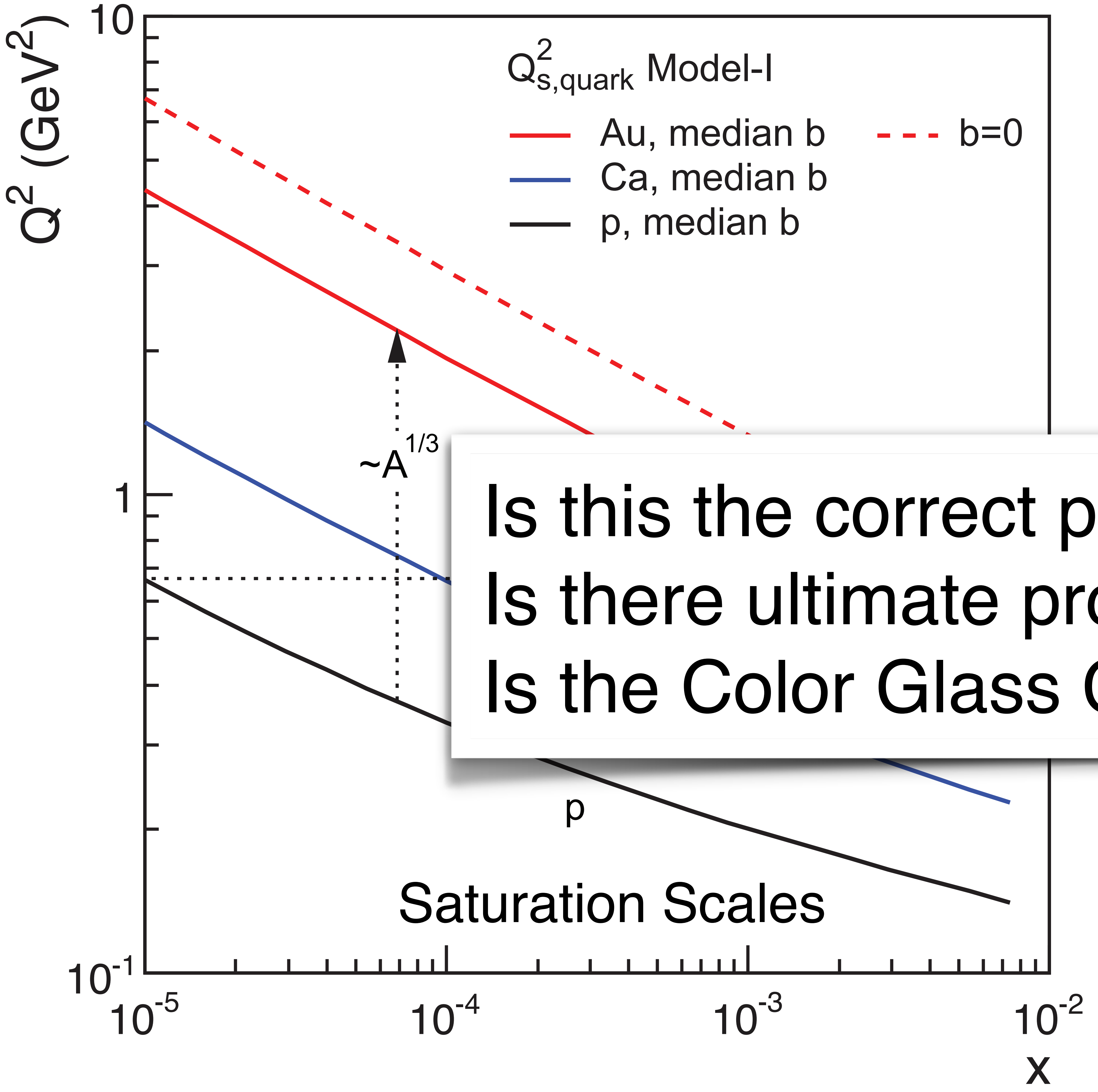
$$(Q_s^A)^2 \approx c Q_0^2 \left(\frac{A}{x}\right)^{1/3}$$

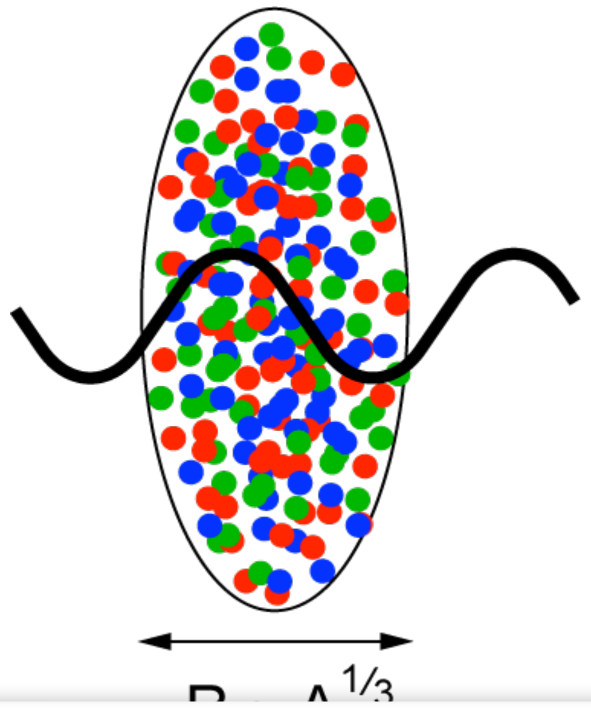
Probes interact over distances $L \sim (2m_N x)^{-1}$

Probe interacts coherently with all nucleons for $L > 2\,R_A \sim A^{1/3}$

Enhancement of Q_S with A:
saturation regime reached at significantly lower energy in nuclei (and lower cost)

Gluon Saturation in Nuclei: The Oomph





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

Is this the correct picture?
Is there ultimate proof for gluon saturation?
Is the Color Glass Condensate the correct theory?

nces

Probe interacts coherently with all nucleons for $L > 2\,R_A \sim A^{1/3}$

Nucleus serves as **amplifier** of the saturation scale

Enhancement of Q_S with A:
saturation regime reached at significantly lower energy in nuclei (and lower cost)

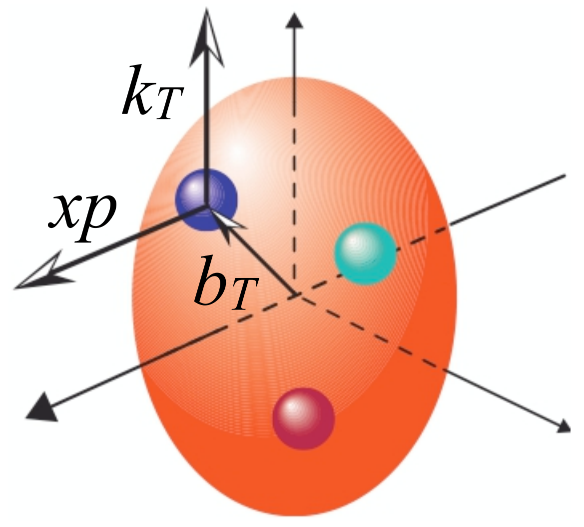
EIC Physics (= QCD Physics)

Investigate with precision universal dynamics of gluons to understand the emergence of hadronic and nuclear matter and their properties

EIC Physics (= QCD Physics)

Investigate with precision universal dynamics of gluons to understand the emergence of hadronic and nuclear matter and their properties

Central Questions:



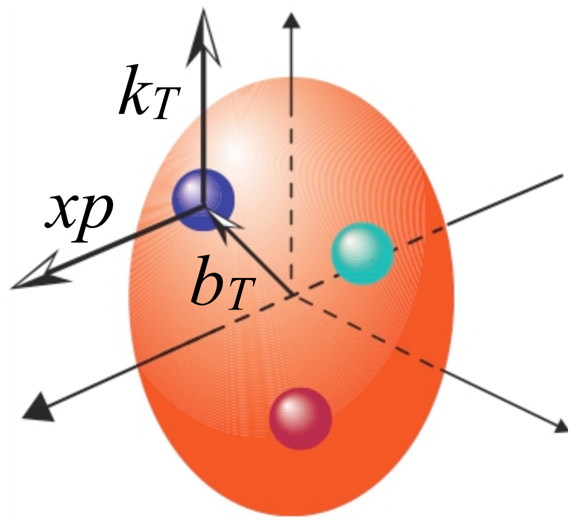
- How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from them and their interactions?

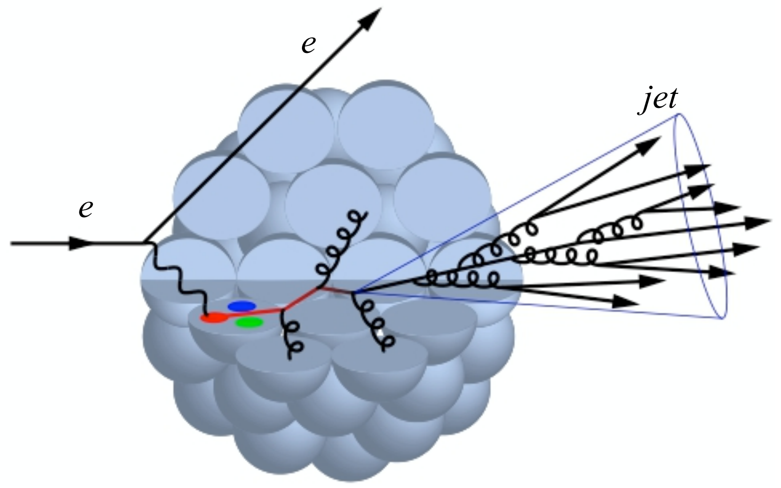
EIC Physics (= QCD Physics)

Investigate with precision universal dynamics of gluons to understand the emergence of hadronic and nuclear matter and their properties

Central Questions:

- How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from them and their interactions?
- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?



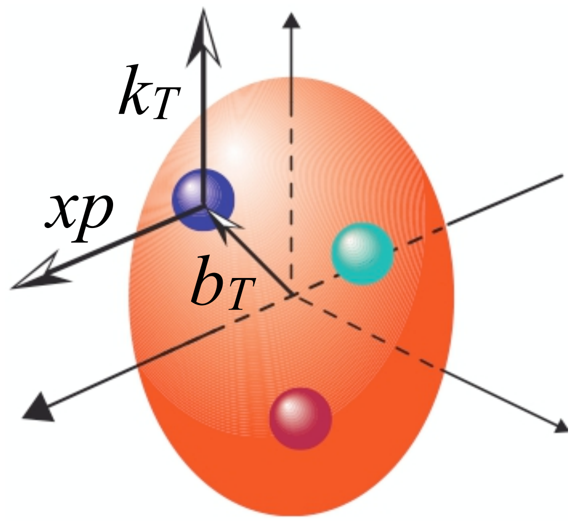


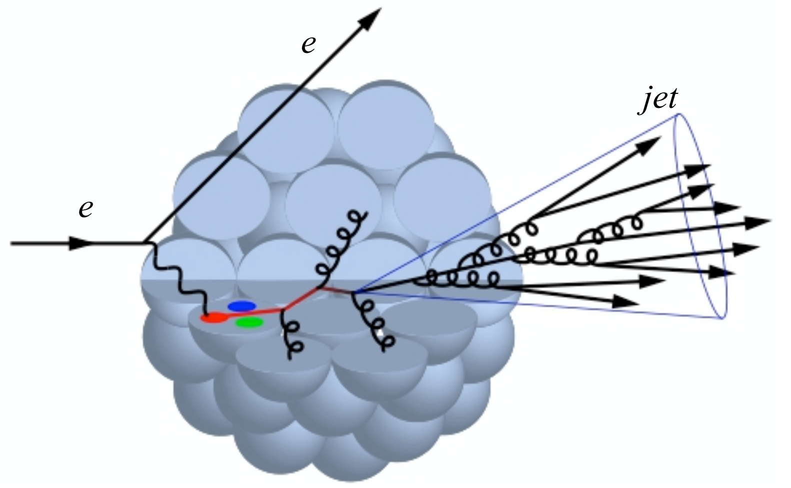
EIC Physics (= QCD Physics)

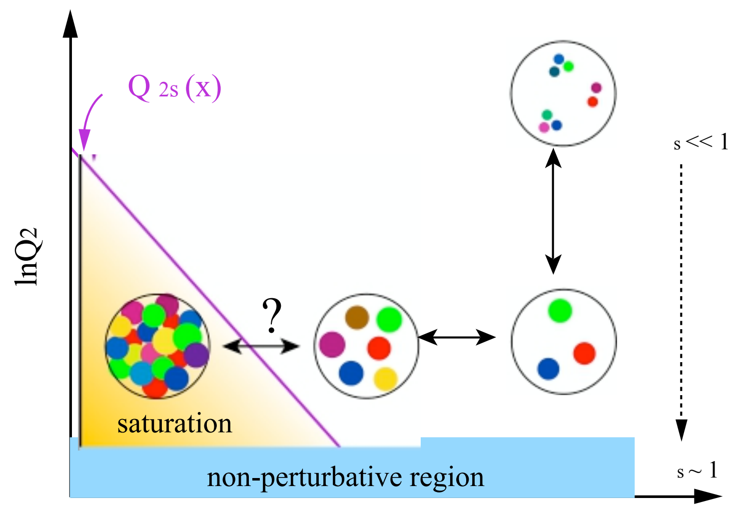
Investigate with precision universal dynamics of gluons to understand the emergence of hadronic and nuclear matter and their properties

Central Questions:

- How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from them and their interactions?
- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?
- How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions? What happens to the exploding gluon density at low-x in hadronic matter? Does it saturate at high energy, giving rise to a gluonic matter with universal properties?

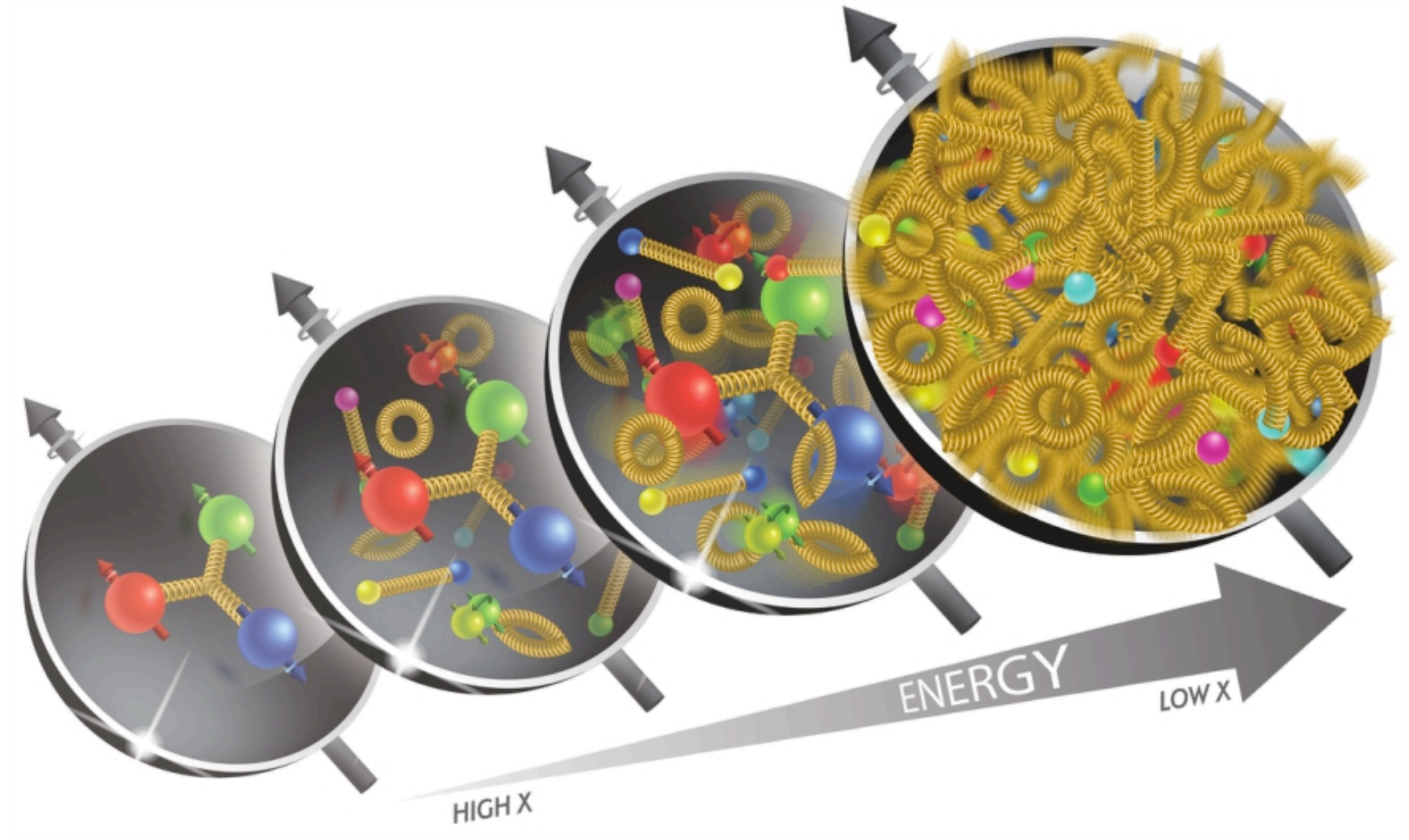


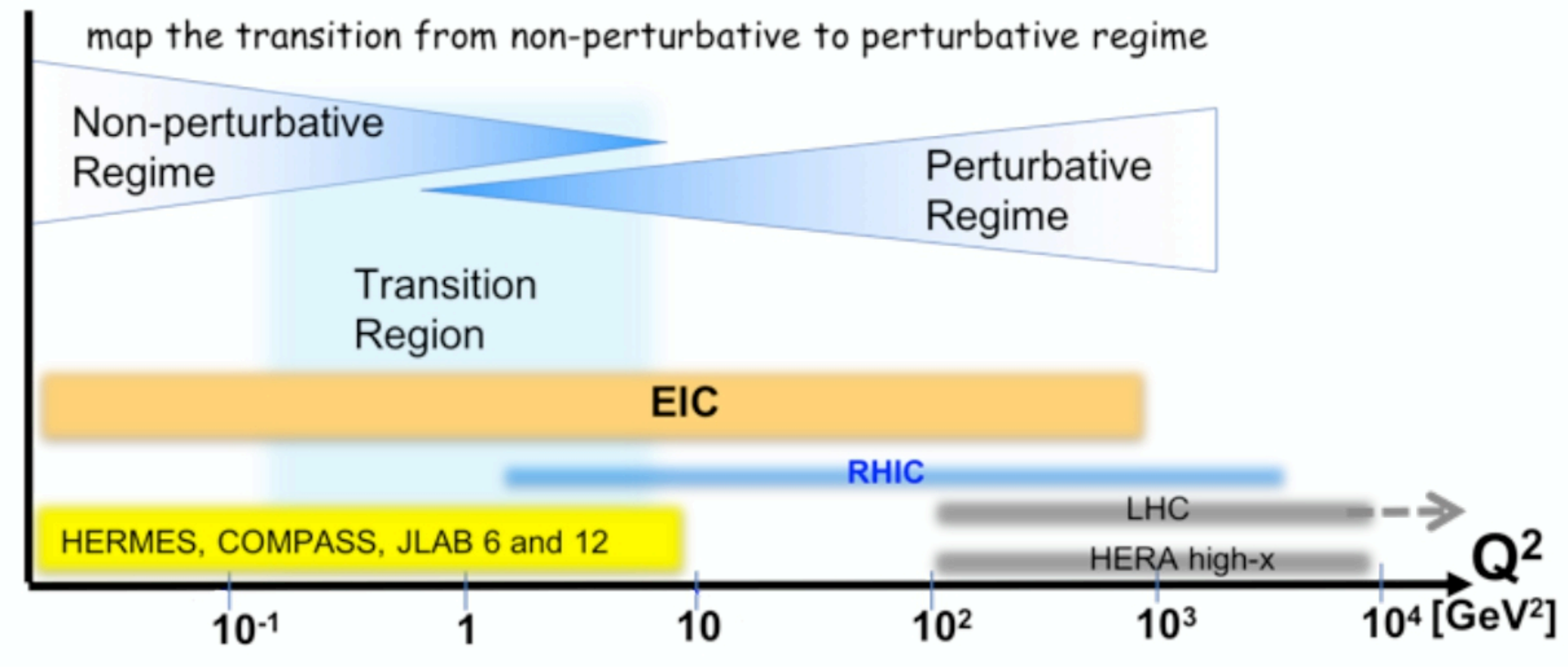


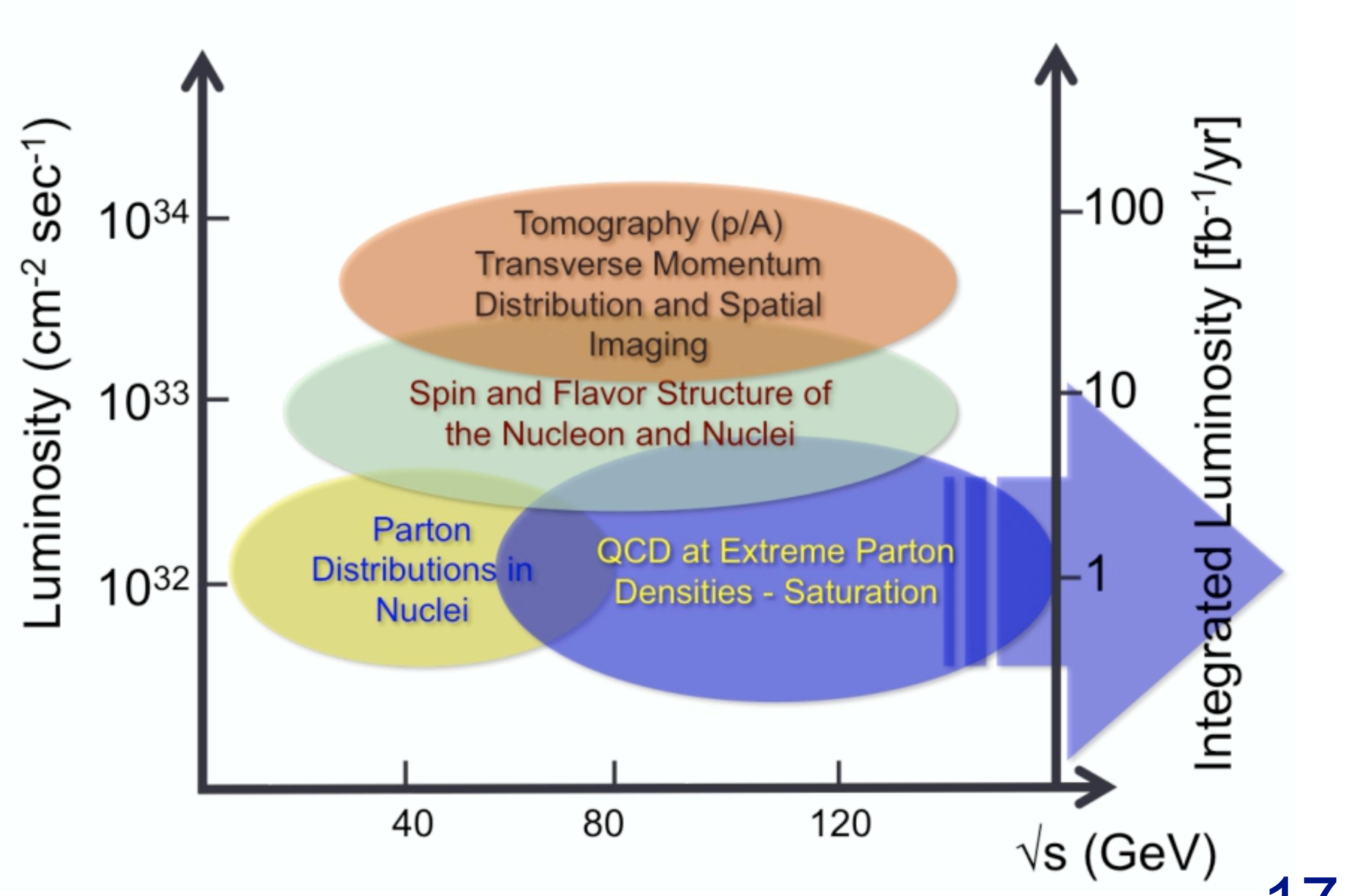


Machine Requirements

- Access to gluon dominated region and wide kinematic range in x and Q^2
  - ➡ Large center-of-mass energy range $\sqrt{s}$ = 20 -140 GeV
- Access to spin structure and 3D spatial and momentum structure
  - ➡ Polarized electron and proton and light nuclear beams ≥ 70% for both
- Accessing the highest gluon densities ($Q_S^2 \sim A^{1/3}$)
  - ➡ Nuclear beams, the heavier the better (up to U)
- Studying observables as a fct. of x, Q^2, A, etc.
  - ➡ High luminosity (100x HERA): $10^{33\text{-}34}$ cm^{-2} s^{-1}







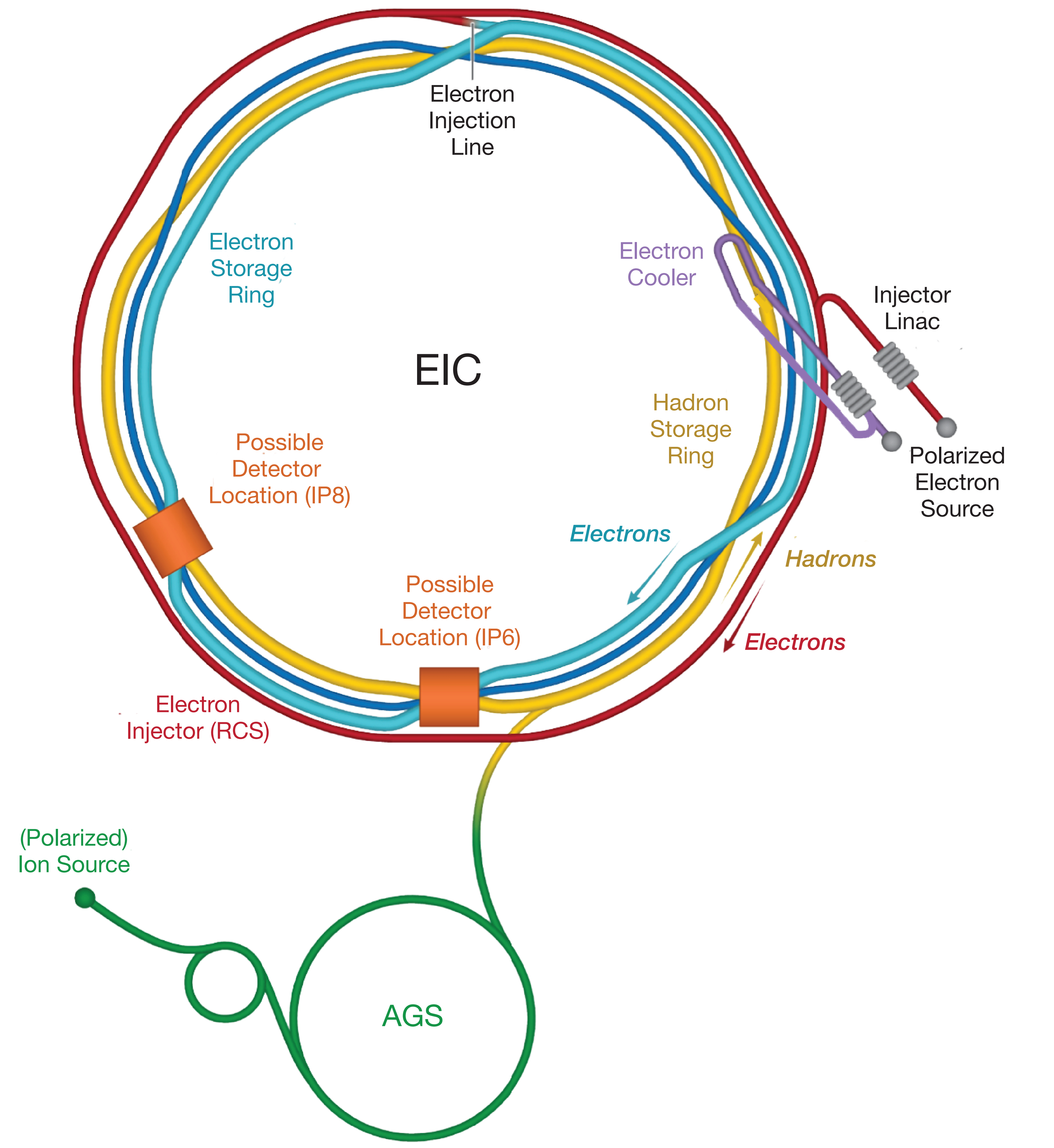
EIC Machine Overview

EIC is using part of RHIC facility at BNL which is operating at its peak

EIC Machine Overview

EIC is using part of RHIC facility at BNL which is operating at its peak

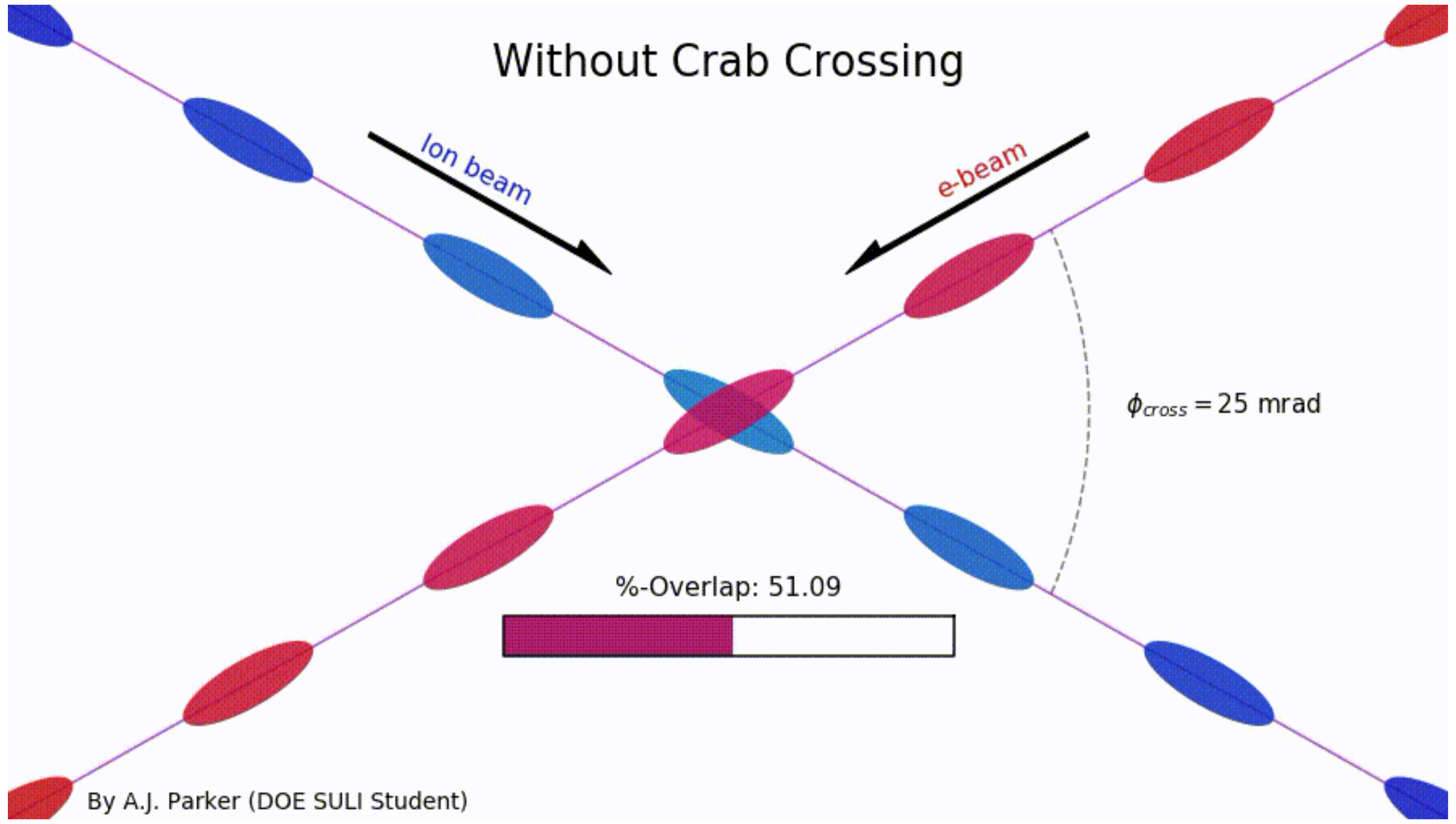
- Hadron storage ring 40-275 GeV (existing)
  - Many bunches, 1160 @ 1A beam current
  - Need strong cooling
- Electron storage ring (2.5–18 GeV, new)
  - Many bunches
  - Large beam current (2.5 A) ➔10 MW S.R. power
  - S.C. RF cavities
- Electron rapid cycling synchrotron (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- High luminosity interaction region(s) (new)
  - $L = 10^{34} cm^{-2} s^{-1}$
  - Superconducting magnets
  - 25 mrad crossing angle with crab cavities



Why a Crossing Angle?

- Brings focusing magnets close to IP
  - higher luminosity
- Beam separation without separation dipoles
  - reduced synchrotron radiation

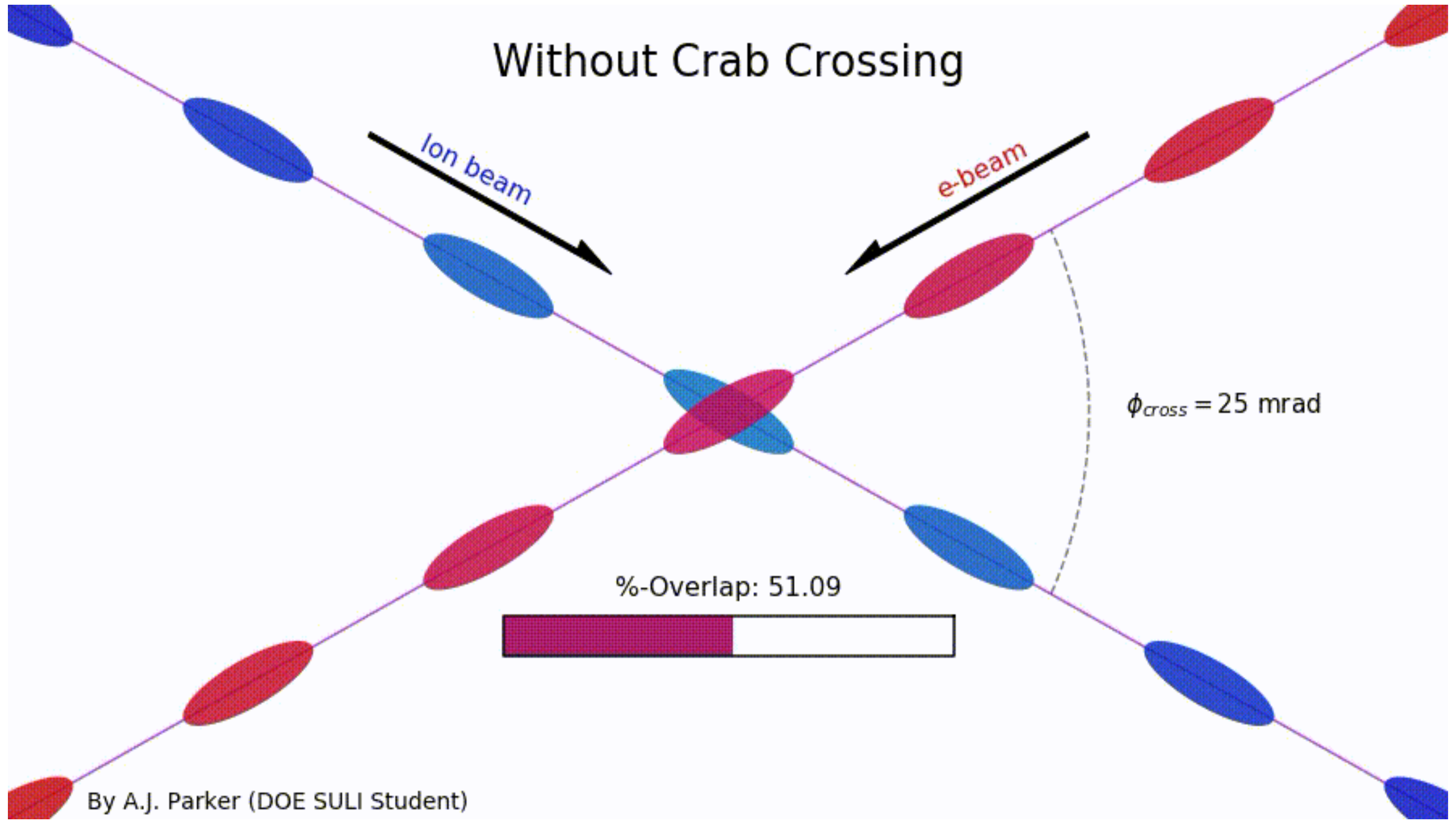
But significant loss of luminosity



Why a Crossing Angle?

- Brings focusing magnets close to IP
  - higher luminosity
- Beam separation without separation dipoles
  - reduced synchrotron radiation

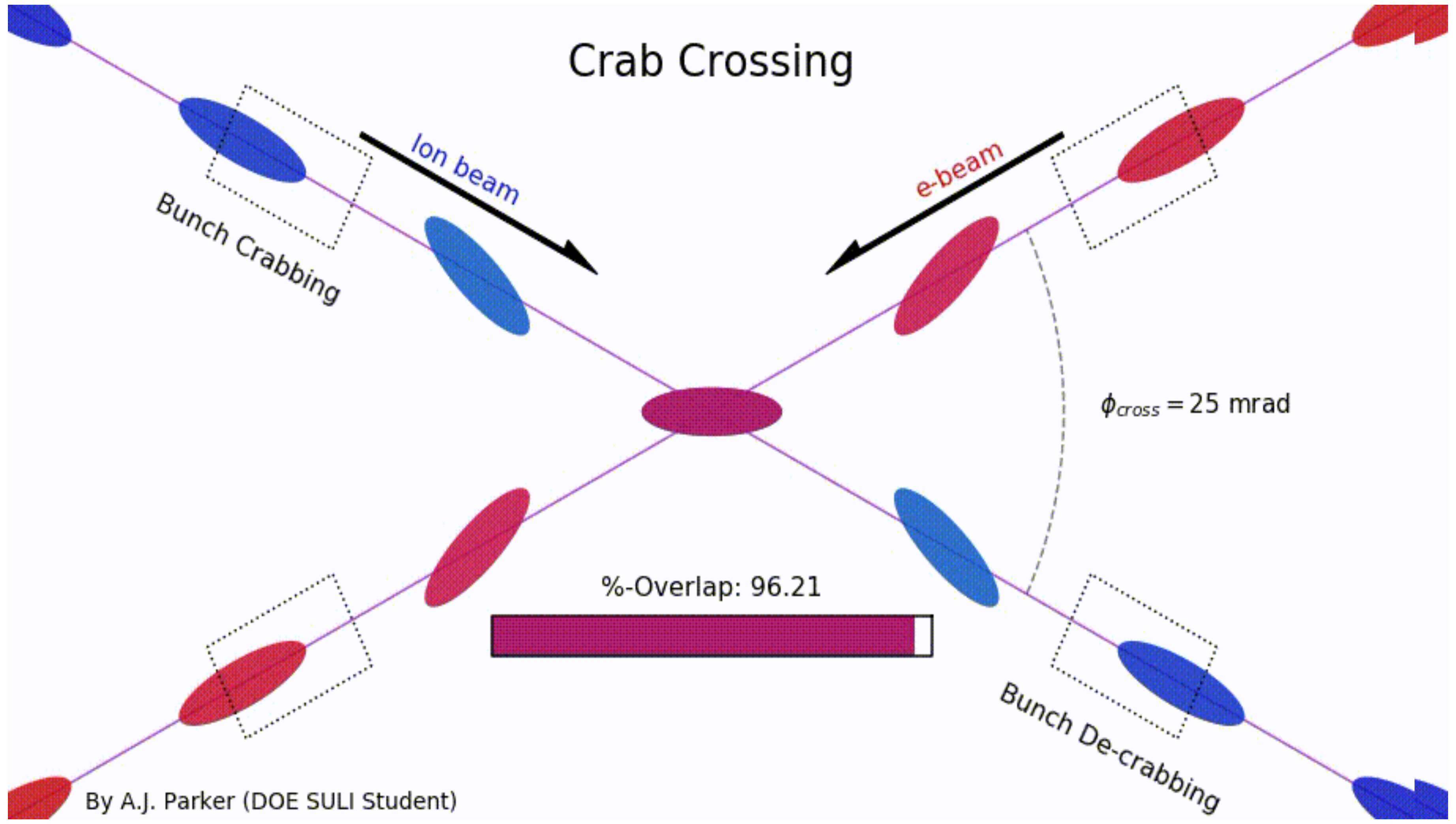
But significant loss of luminosity



Why a Crossing Angle?

- Brings focusing magnets close to IP
  - higher luminosity
- Beam separation without separation dipoles
  - reduced synchrotron radiation

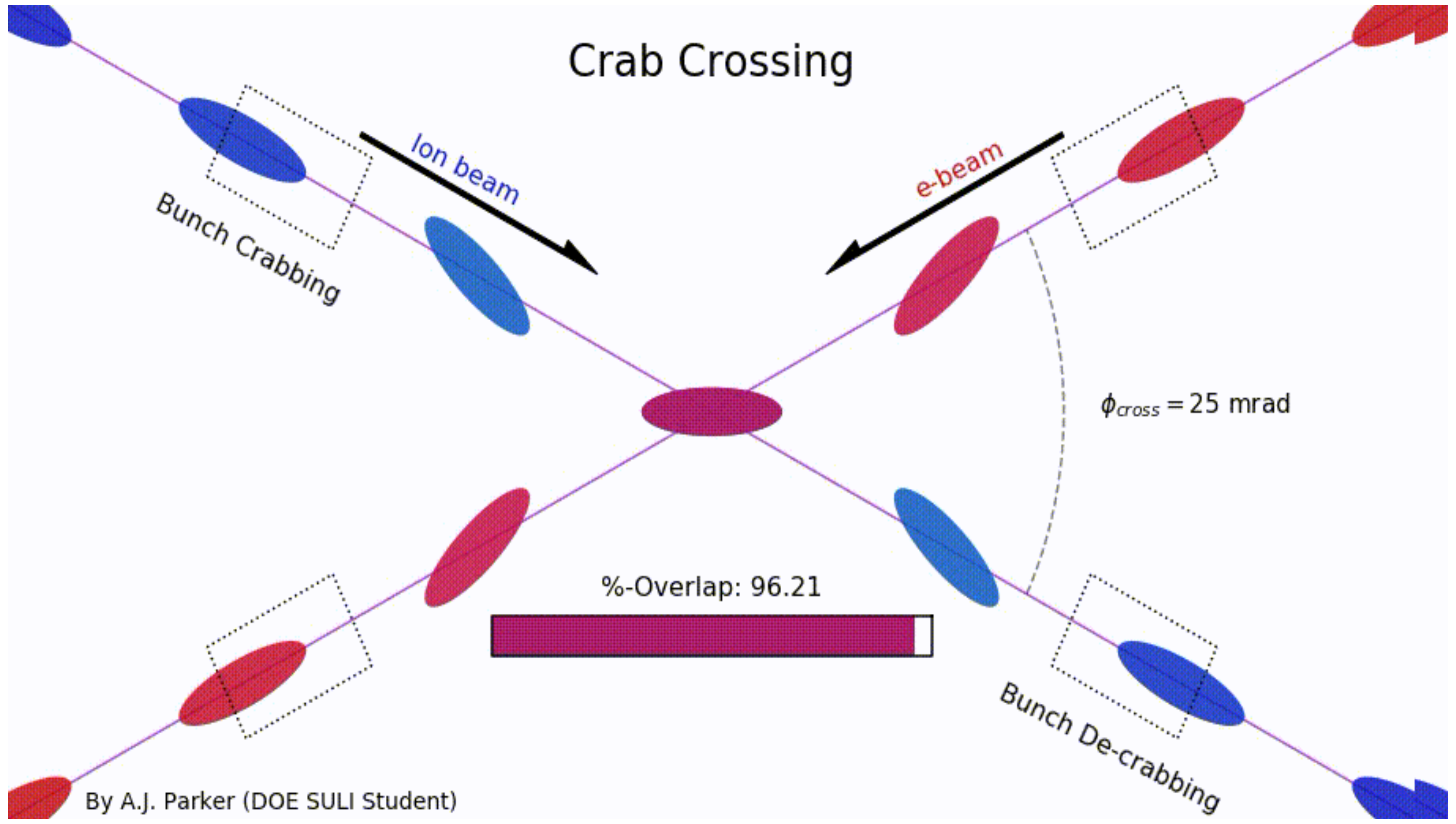
But significant loss of luminosity



Why a Crossing Angle?

- Brings focusing magnets close to IP
  - higher luminosity
- Beam separation without separation dipoles
  - reduced synchrotron radiation

But significant loss of luminosity



Solution: Crab crossing

- Head-on collision geometry is restored by rotating the bunches before colliding
- Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- Actual collision point moves laterally during bunch interaction
- Challenges
  - Bunch rotation (crabbing) is not linear causing severe beam dynamics effects
  - Physical size of crab cavities

The EIC: A Unique Collider with Challenges

EIC

- Collide different beam species: ep & eA
- Asymmetric beam energies
  - boosted kinematics
  - high activity at high $|\eta|$
- Additional beam backgrounds
  - hadron beam backgrounds, i.e. beam gas events
  - synchrotron radiation
- Small bunch spacing $\geq$ 9 ns
- Crossing angle: 25 mrad
- Wide range in center of mass energies
  - factor 6
- Both beams are polarized
  - stat uncertainty ~ $1/(P_1 P_2 (\int L\,dt)^{1/2})$

LHC

- Collide same beam species: pp, AA
- Symmetric beam energies
  - kinematics not boosted
  - most activity at mid rapidity
- Beam backgrounds
  - hadron beam backgrounds, i.e. beam gas events
  - high pile-up
- Moderate bunch spacing ~ 25 ns
- No crossing angle (yet)
- Limited range in center of mass energies
  - LHC factor 2
- No beam polarization
  - stat uncertainty ~ $1/(\int L\,dt)^{1/2}$

The EIC: A Unique Collider with Challenges

EIC

- Collide different beam species: ep & eA
- Asymmetric beam energies
  - boosted kinematics
  - high activity at high |η|
- Additional bear
  - hadron beam
    events
  - synchrotron radiation
- Small bunch spacing $\geq$ 9 ns
- Crossing angle: 25 mrad
- Wide range in center of mass energies
  - factor 6
- Both beams are polarized
  - stat uncertainty ~ $1/(P_1 P_2 (\int L\, dt)^{1/2})$

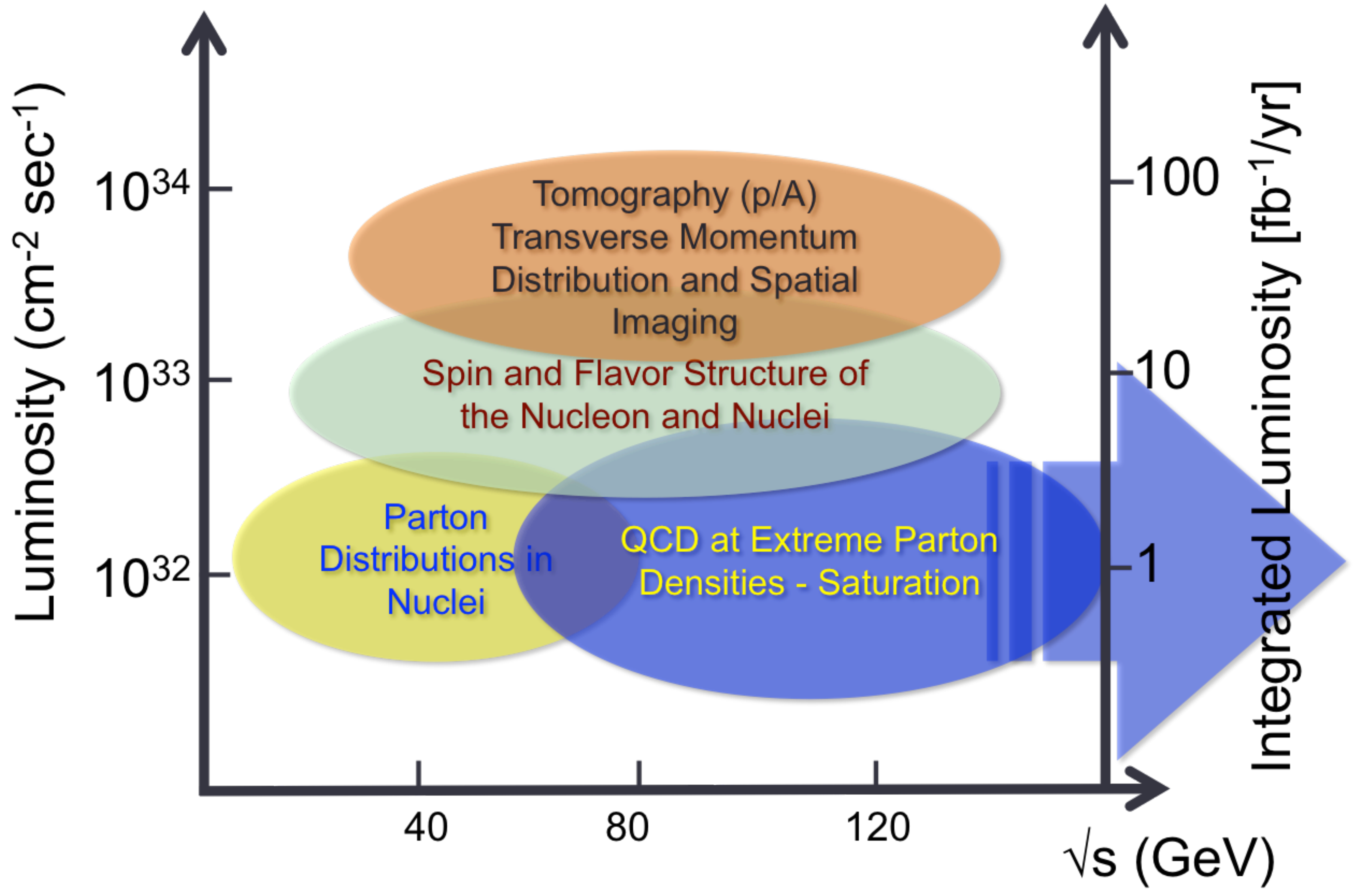
LHC

- Collide same beam species: pp, AA
- Symmetric beam energies
  - kinematics not boosted
  - most activity at mid rapidity
  - nds, i.e. beam gas
  - high pile-up
- Moderate bunch spacing ~ 25 ns
- No crossing angle (yet)
- Limited range in center of mass energies
  - LHC factor 2
- No beam polarization
  - stat uncertainty ~ $1/(\int L\, dt)^{1/2}$

Differences impact detector acceptance and possible detector technologies

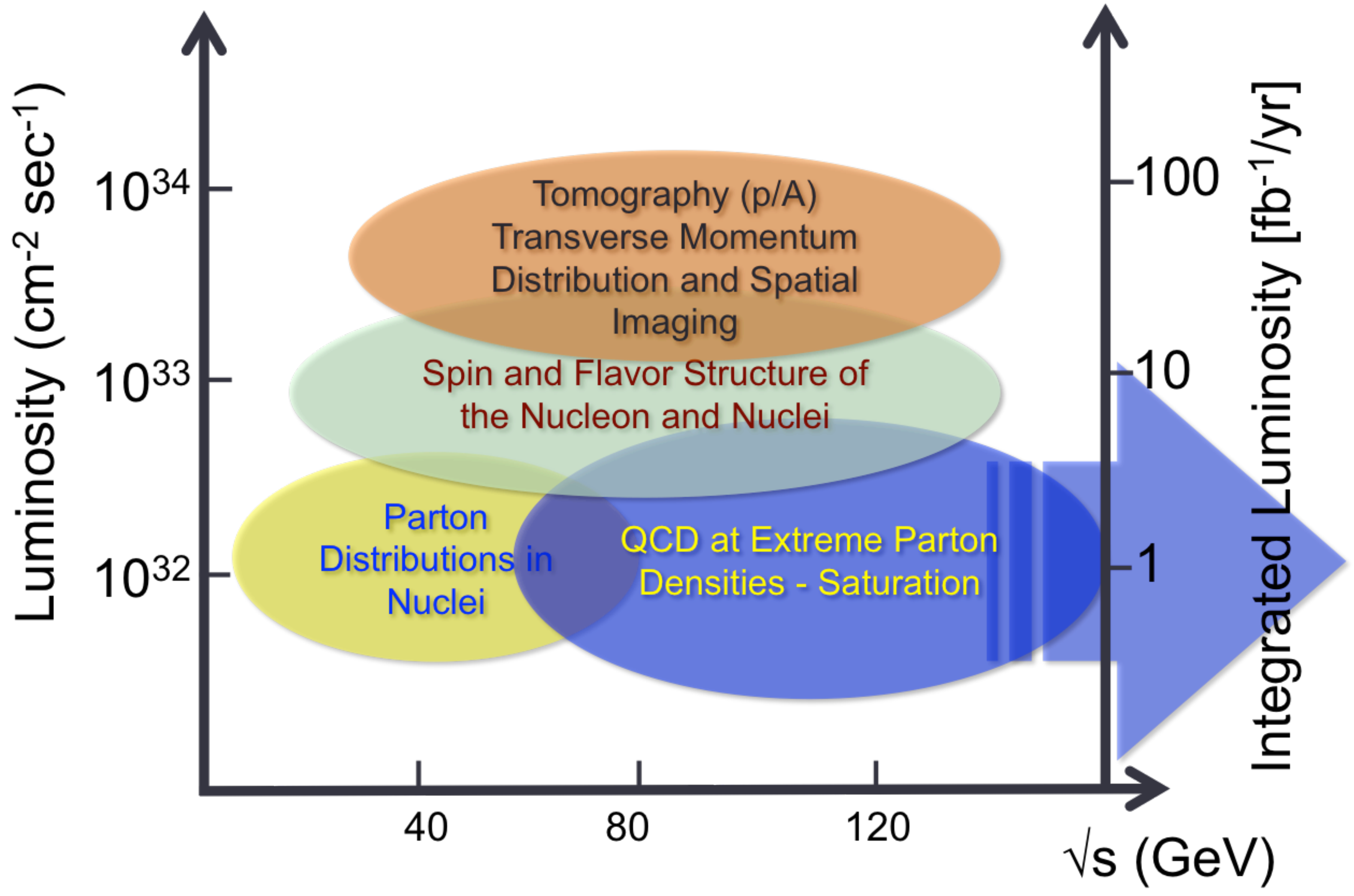
The Experimental Landscape

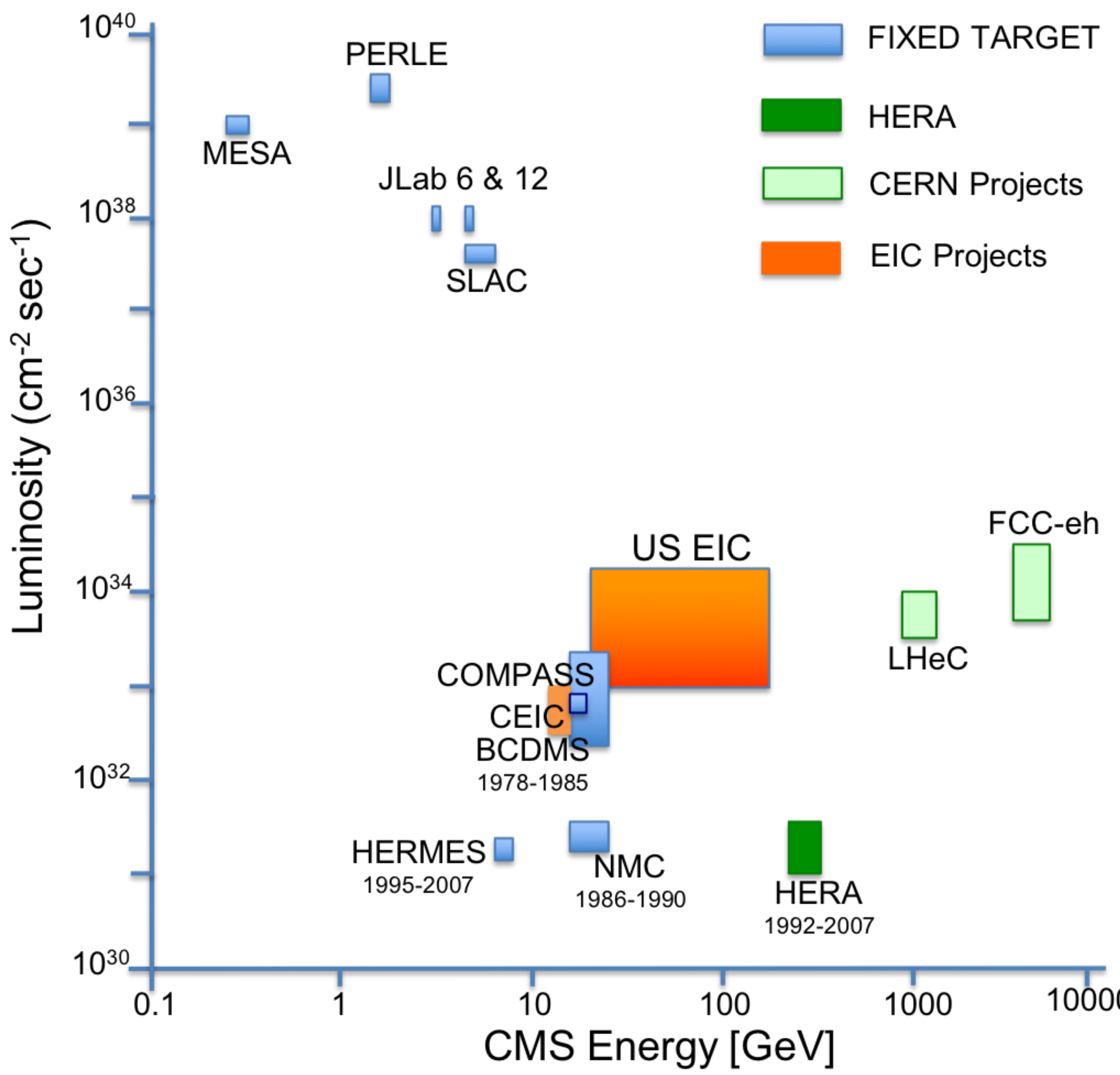
Luminosity - √s Energy
and EIC Physics:



The Experimental Landscape

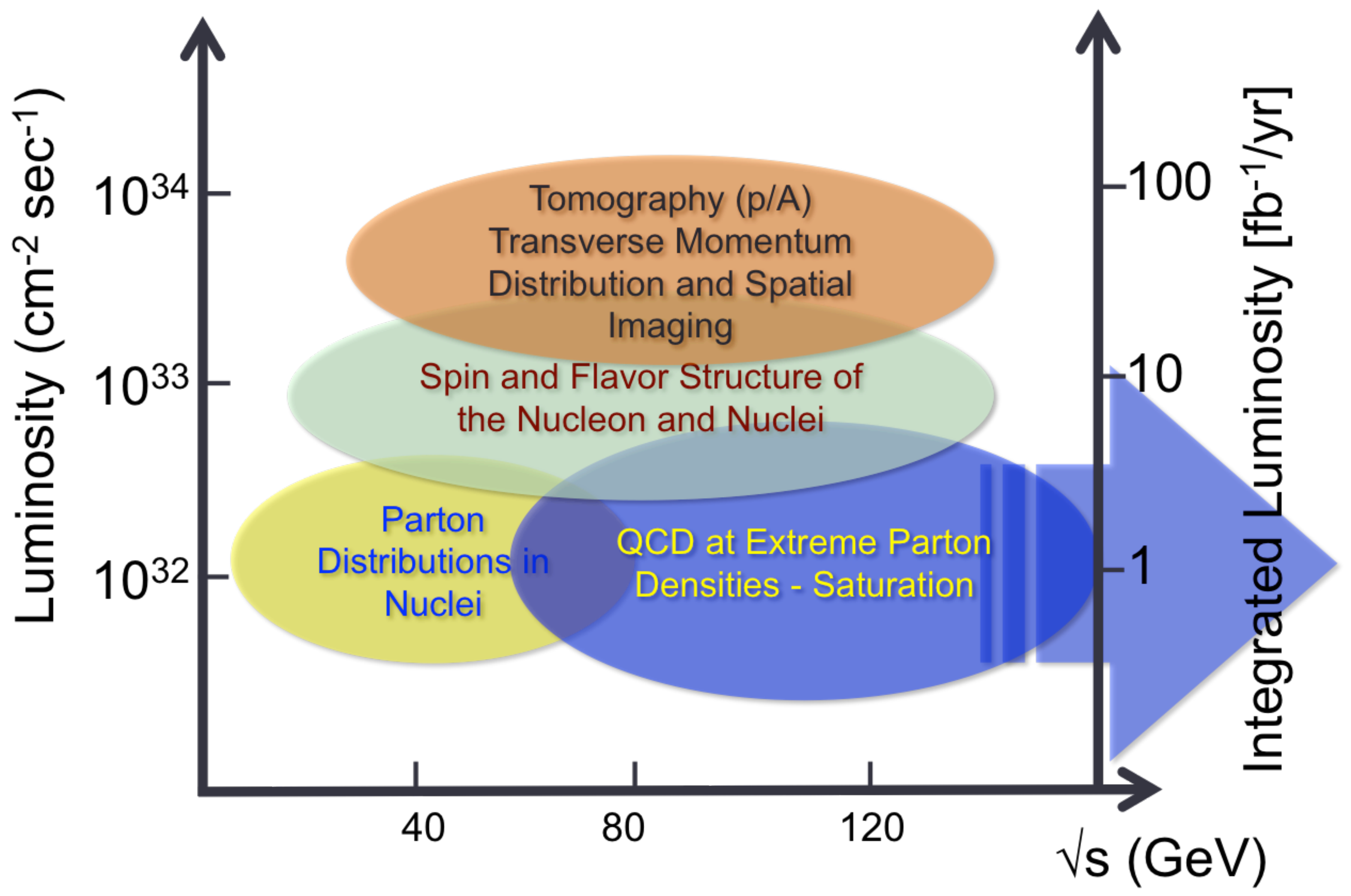
Luminosity - √s Energy and EIC Physics:

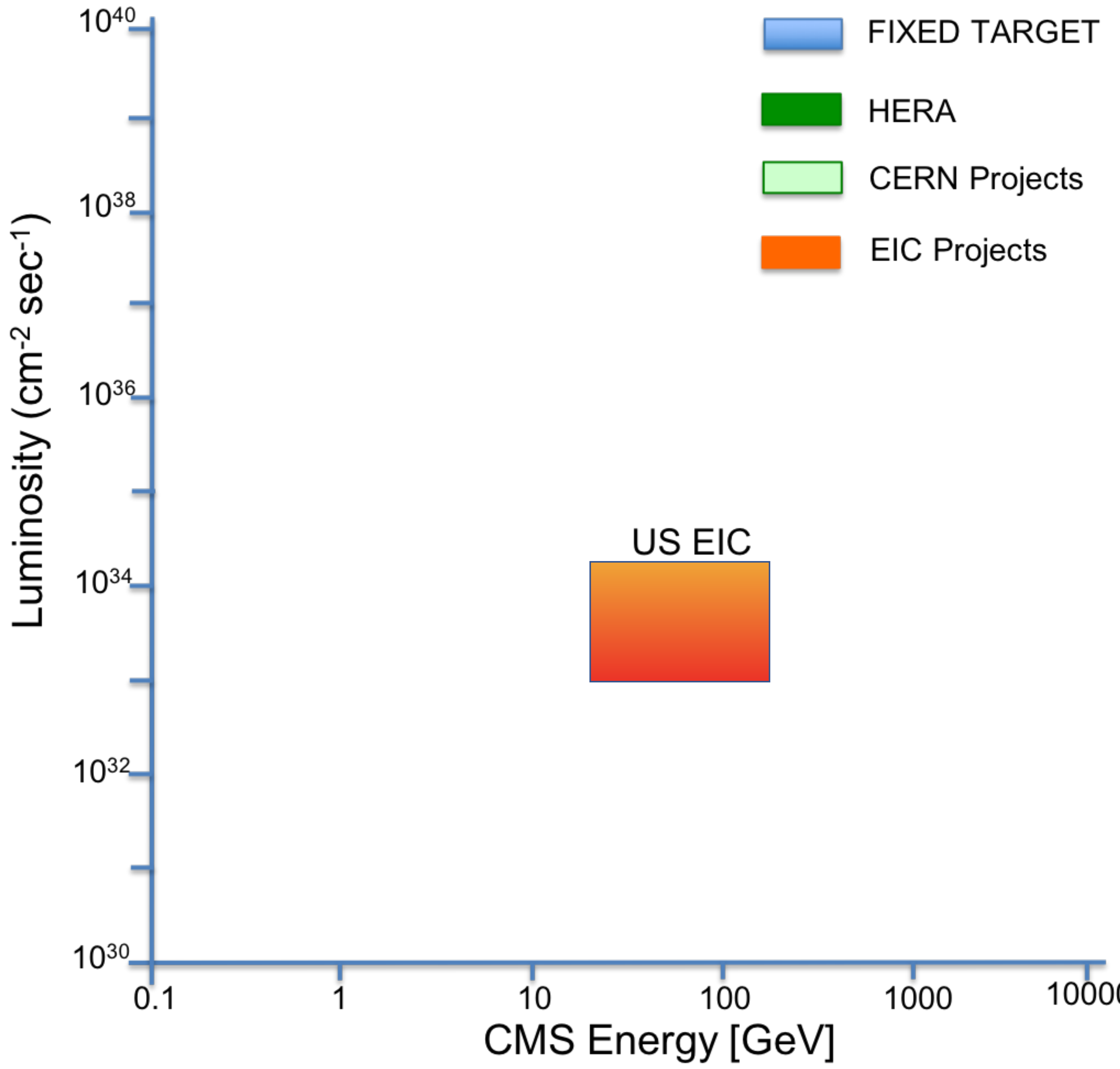




The Experimental Landscape

Luminosity - √s Energy
and EIC Physics:

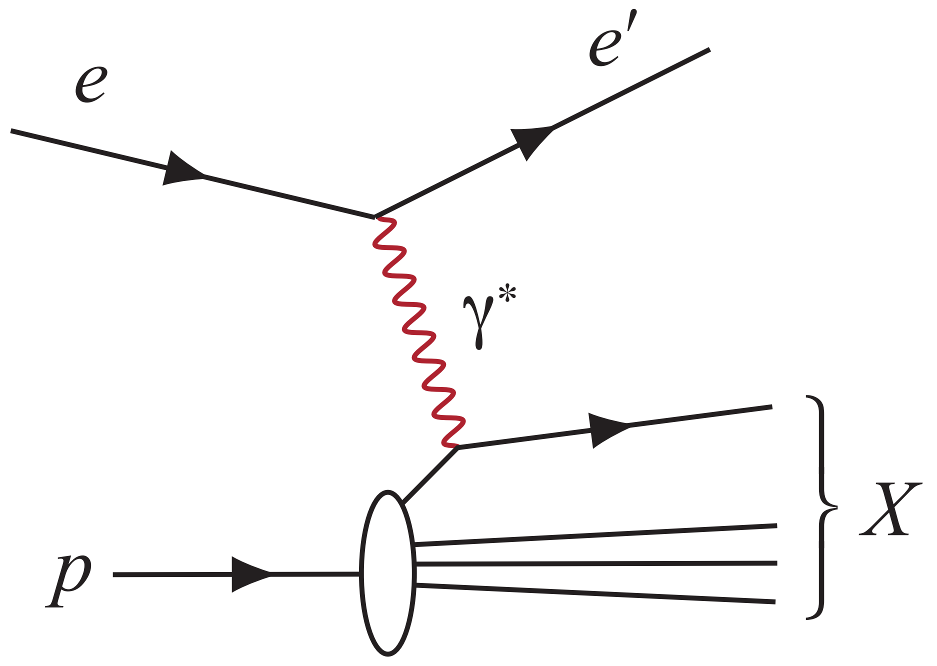




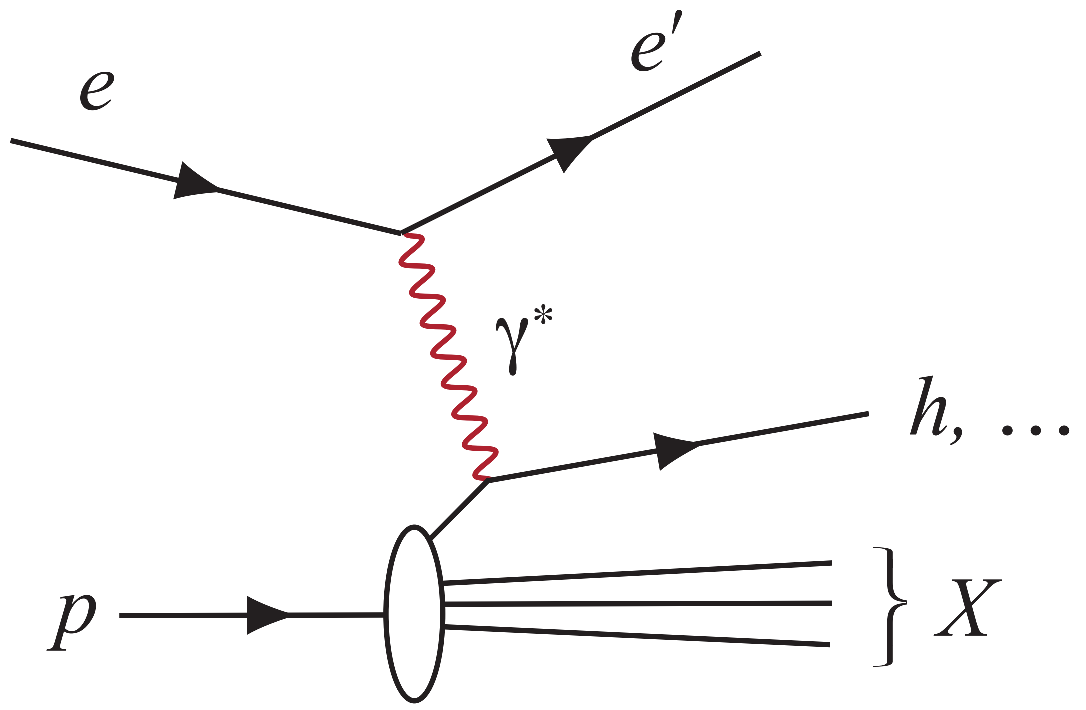
Polarization, p to U ion species together with its luminosity and √s coverage makes it a completely unique machine world-wide.

What is Needed Experimentally?

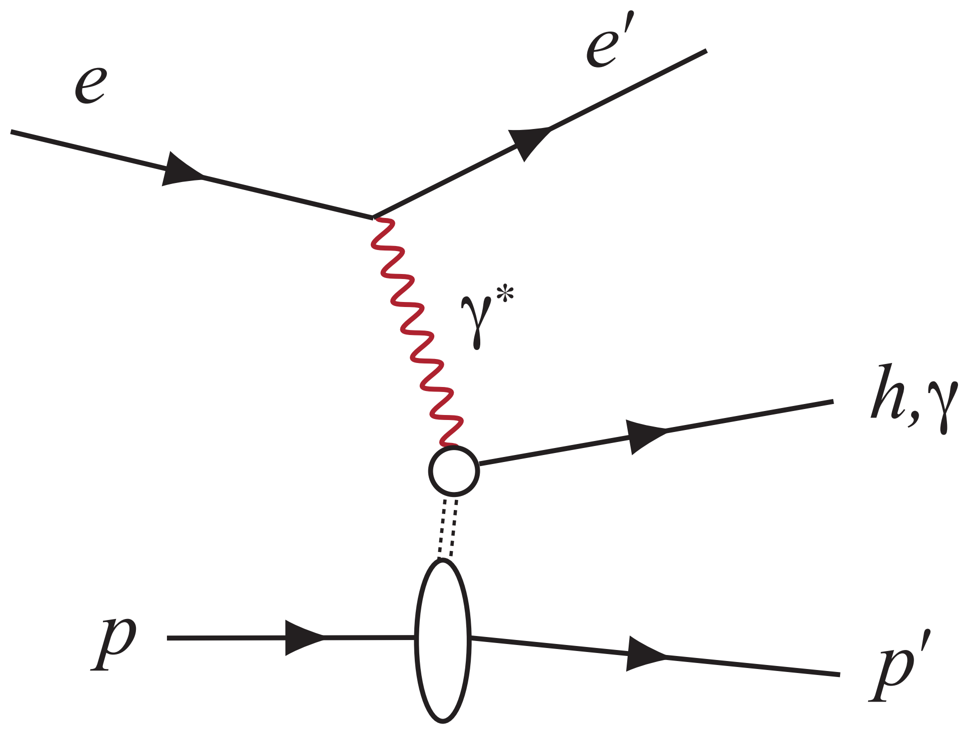
Measurement categories to address EIC physics:



- Inclusive DIS
  - fine multi-dimensional binning in x, Q^2

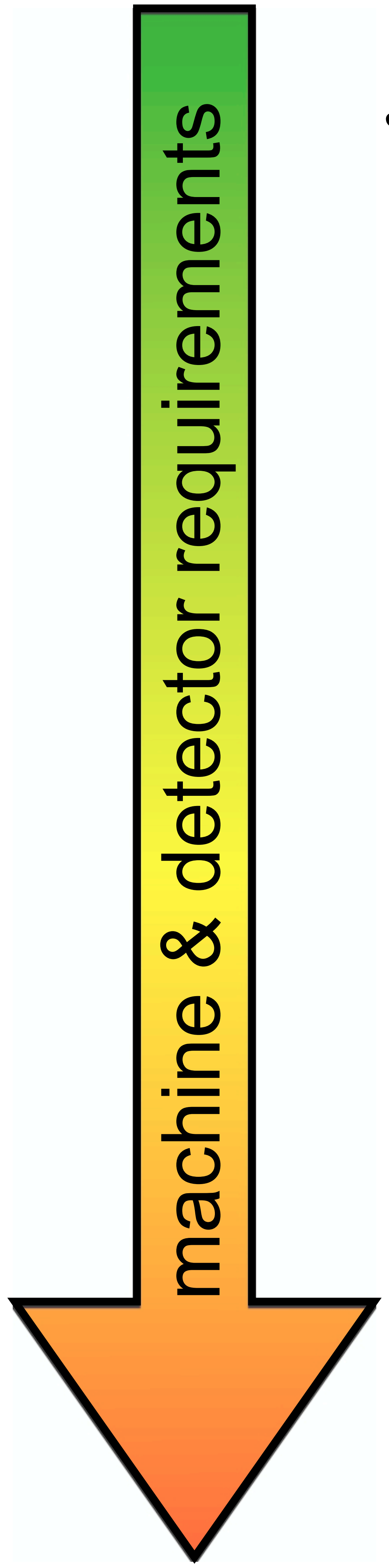


- Semi-inclusive DIS
  - 5-dimensional binning in x, Q^2, z, p_T, θ



- Exclusive processes
  - 4-dimensional binning in x, Q^2, t, θ to reach |t| > 1 GeV^2

$\int \mathscr{L} dt$



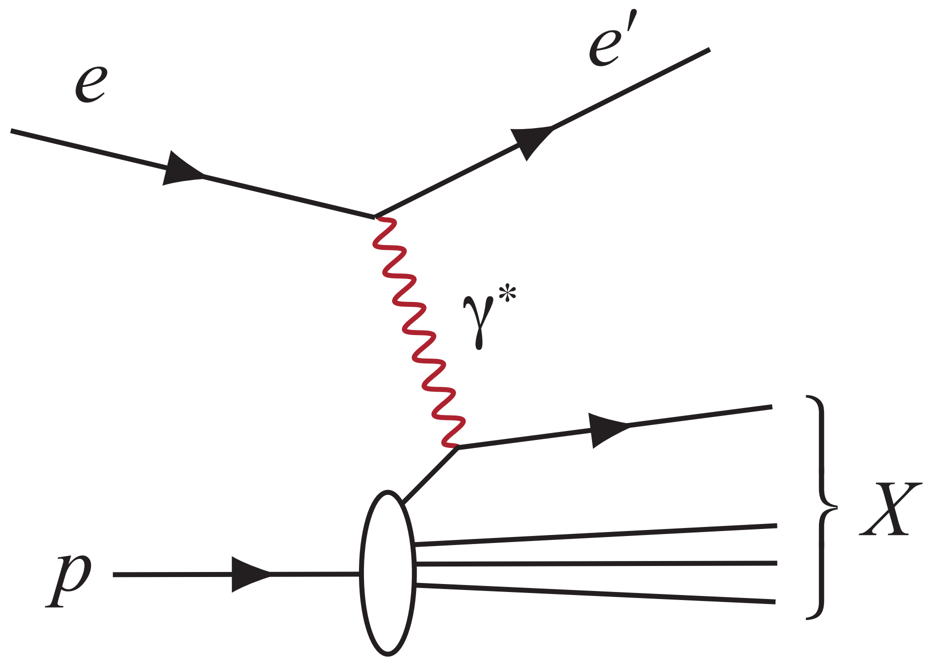
1 fb^{-1}

10 fb^{-1}

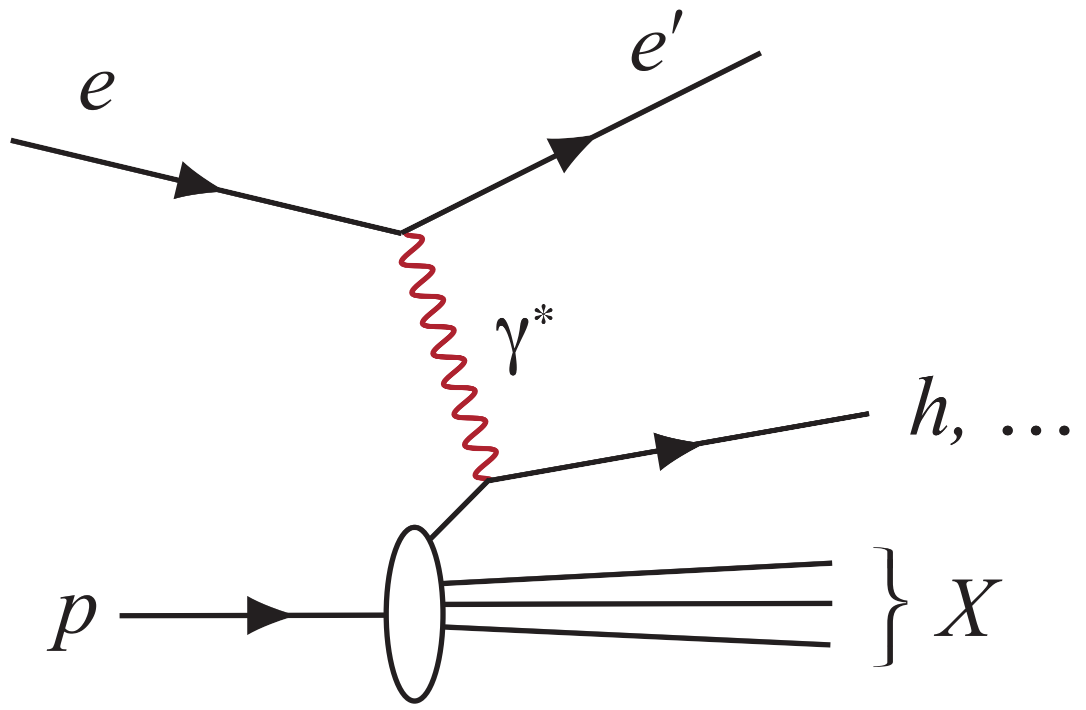
10-100 fb^{-1}

What is Needed Experimentally?

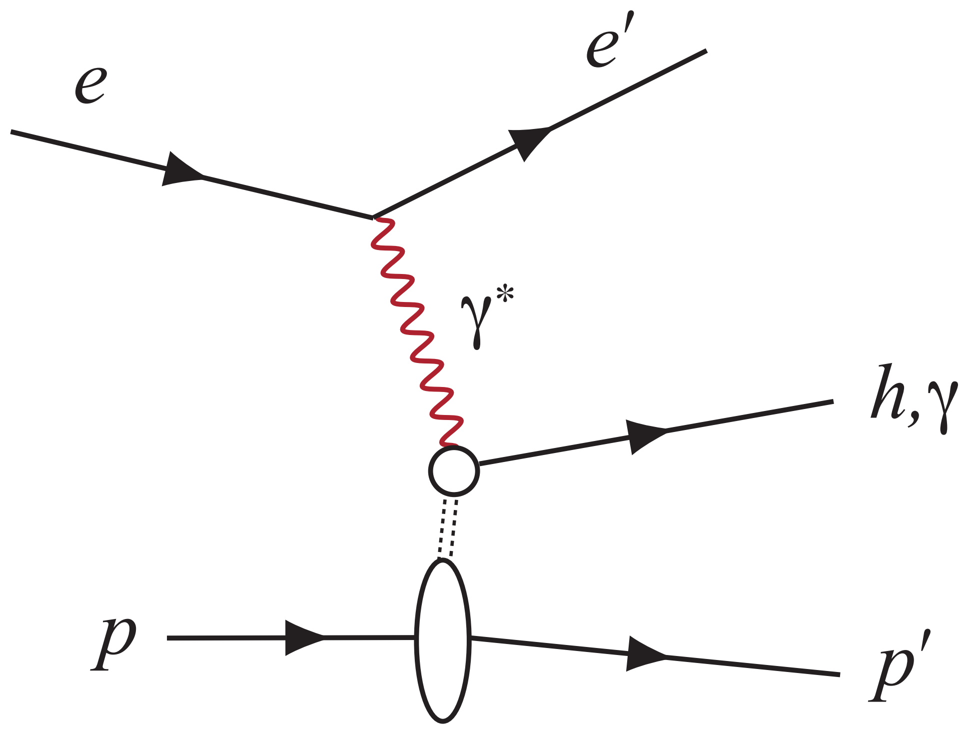
Measurement categories to address EIC physics:



- Inclusive DIS
  - fine multi-dimensional binning in x, Q^2



- Semi-inclusive DIS
  - 5-dimensional binning in x, Q^2, z, p_T, θ



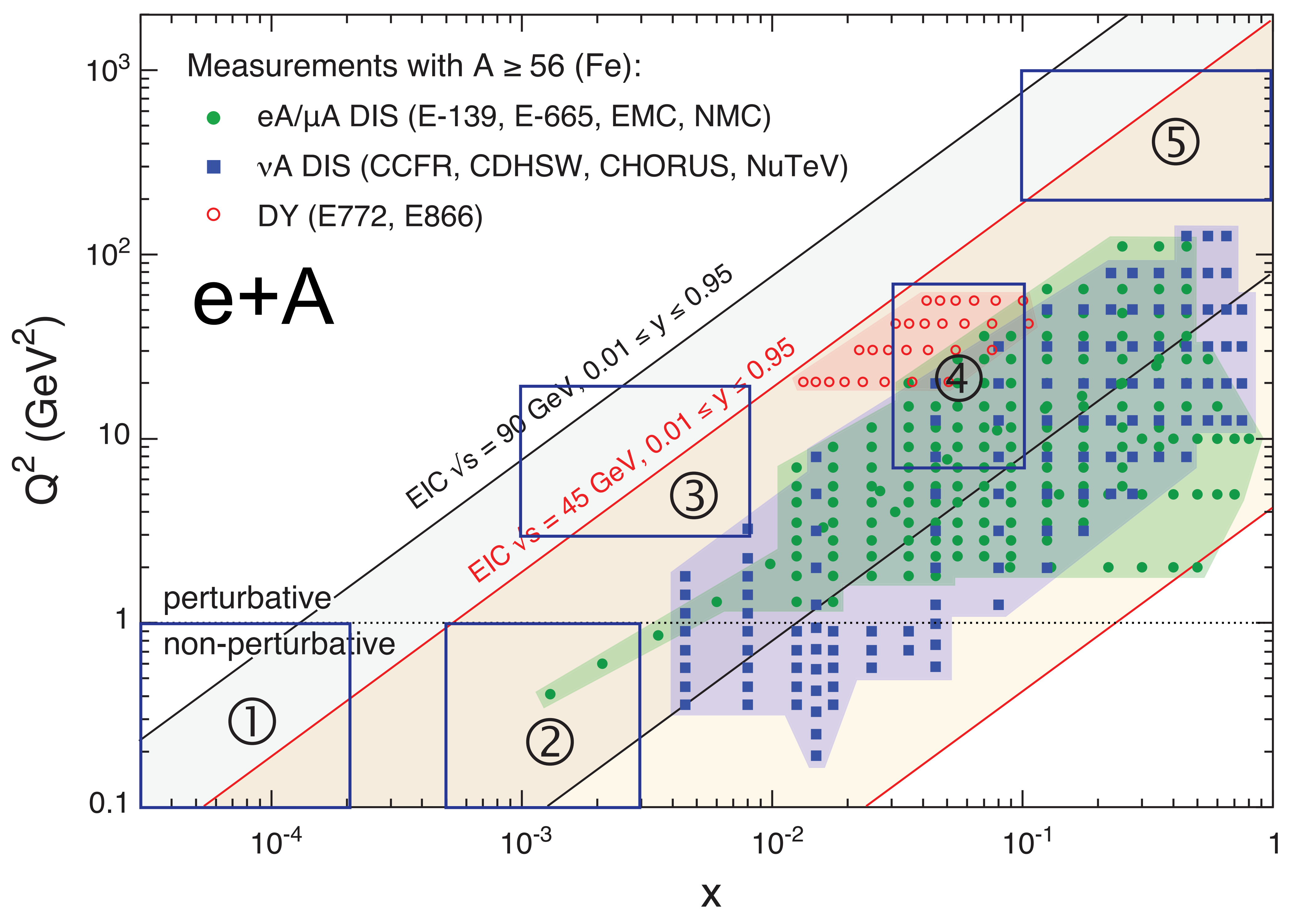
- Exclusive processes
  - 4-dimensional binning in x, Q^2, t, θ to reach $|t| > 1\ \mathrm{GeV}^2$

- e ID
- Reaching lowest x, Q^2

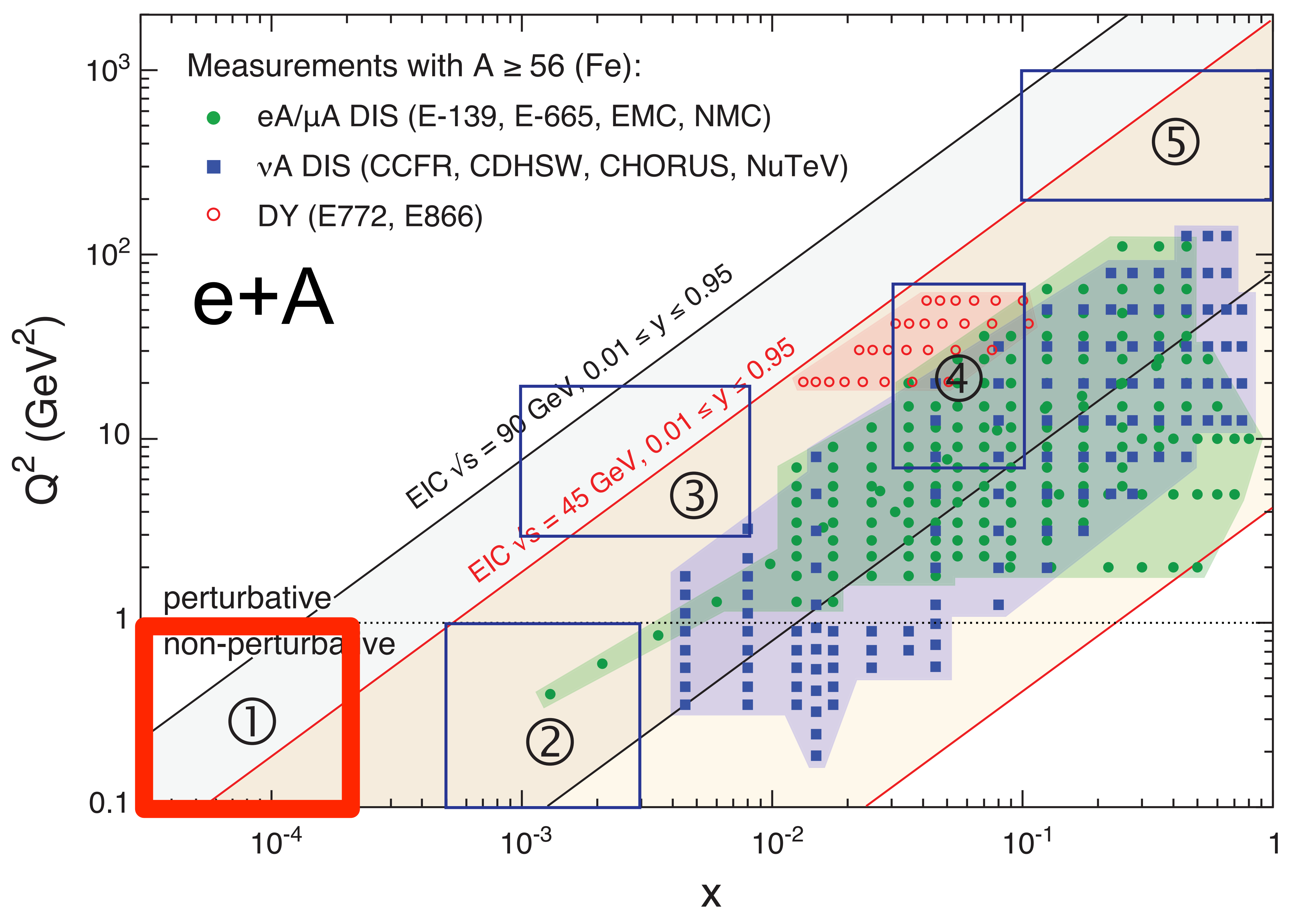
- Hadron PID over wide range is critical

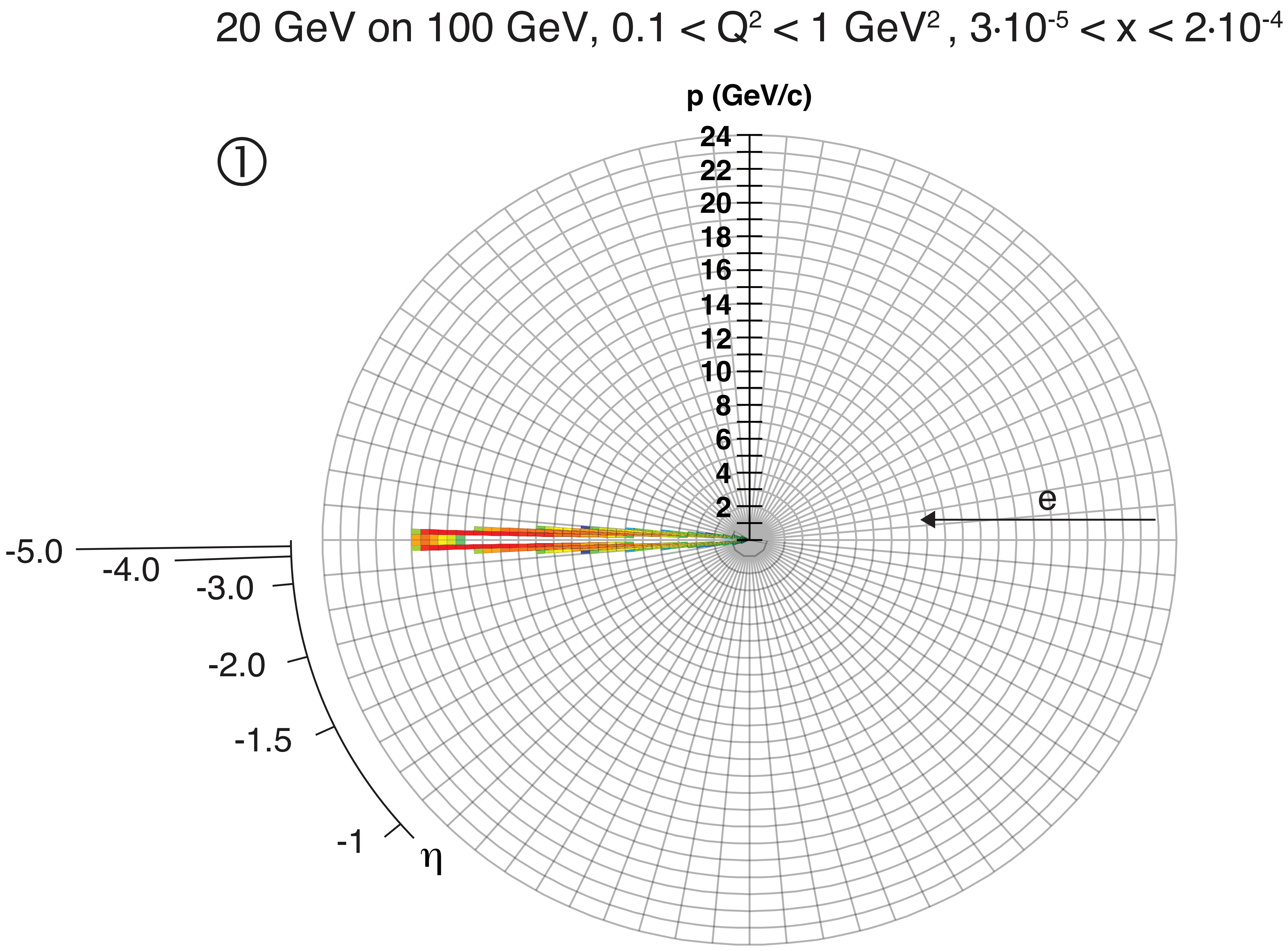
- Forward, backward region is key

Electron Measurement: Range and Kinematics

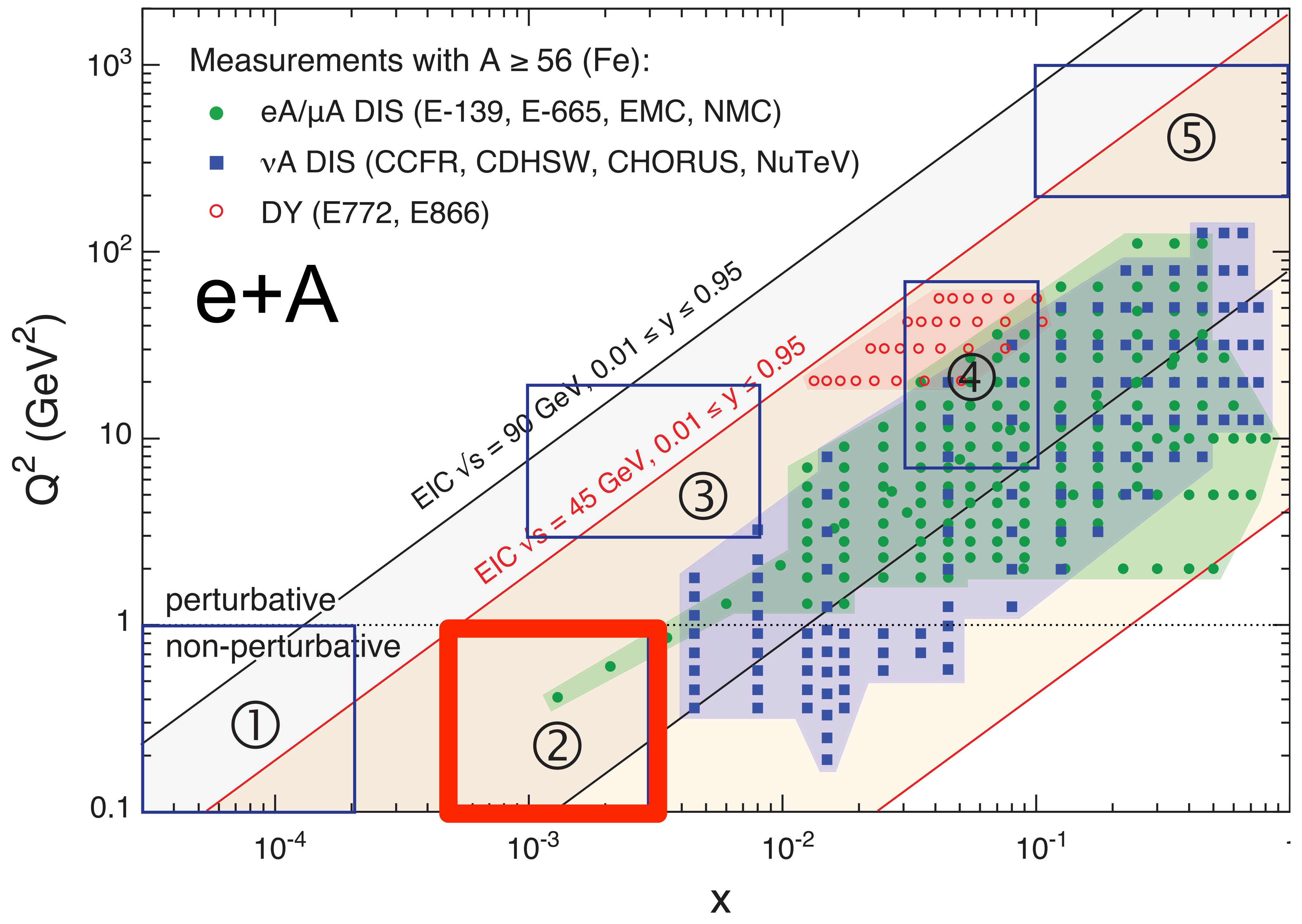


Electron Measurement: Range and Kinematics

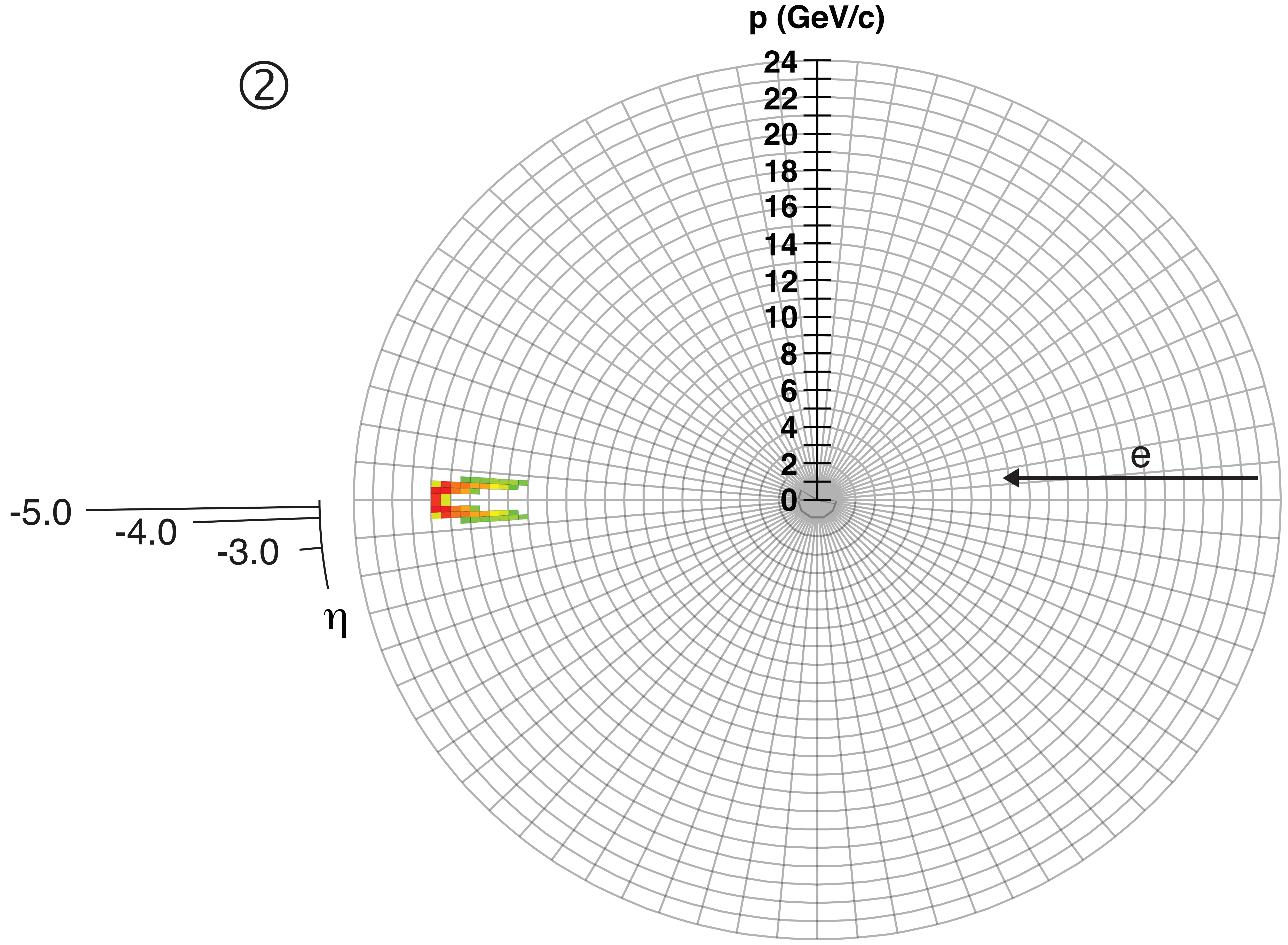




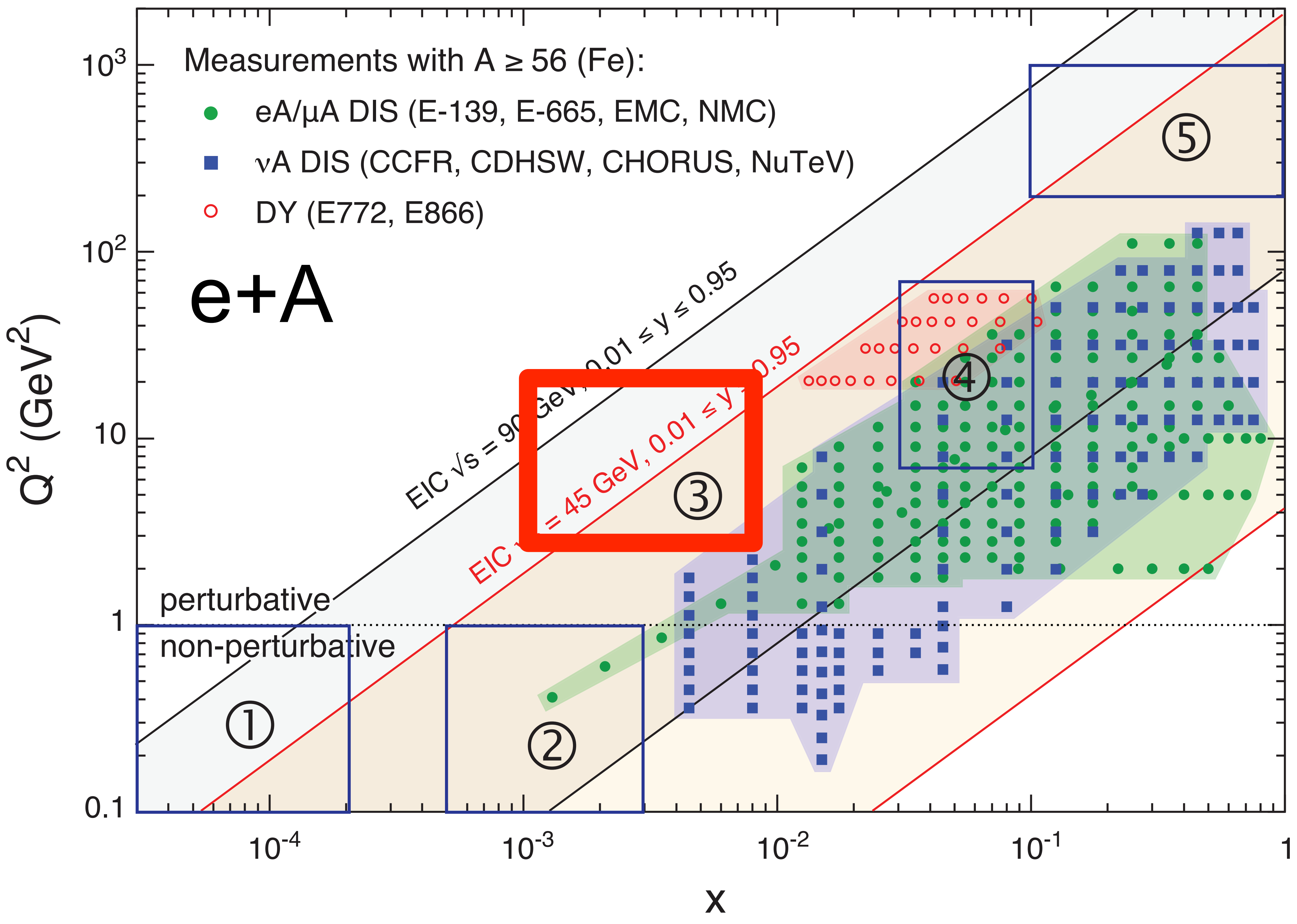
Electron Measurement: Range and Kinematics



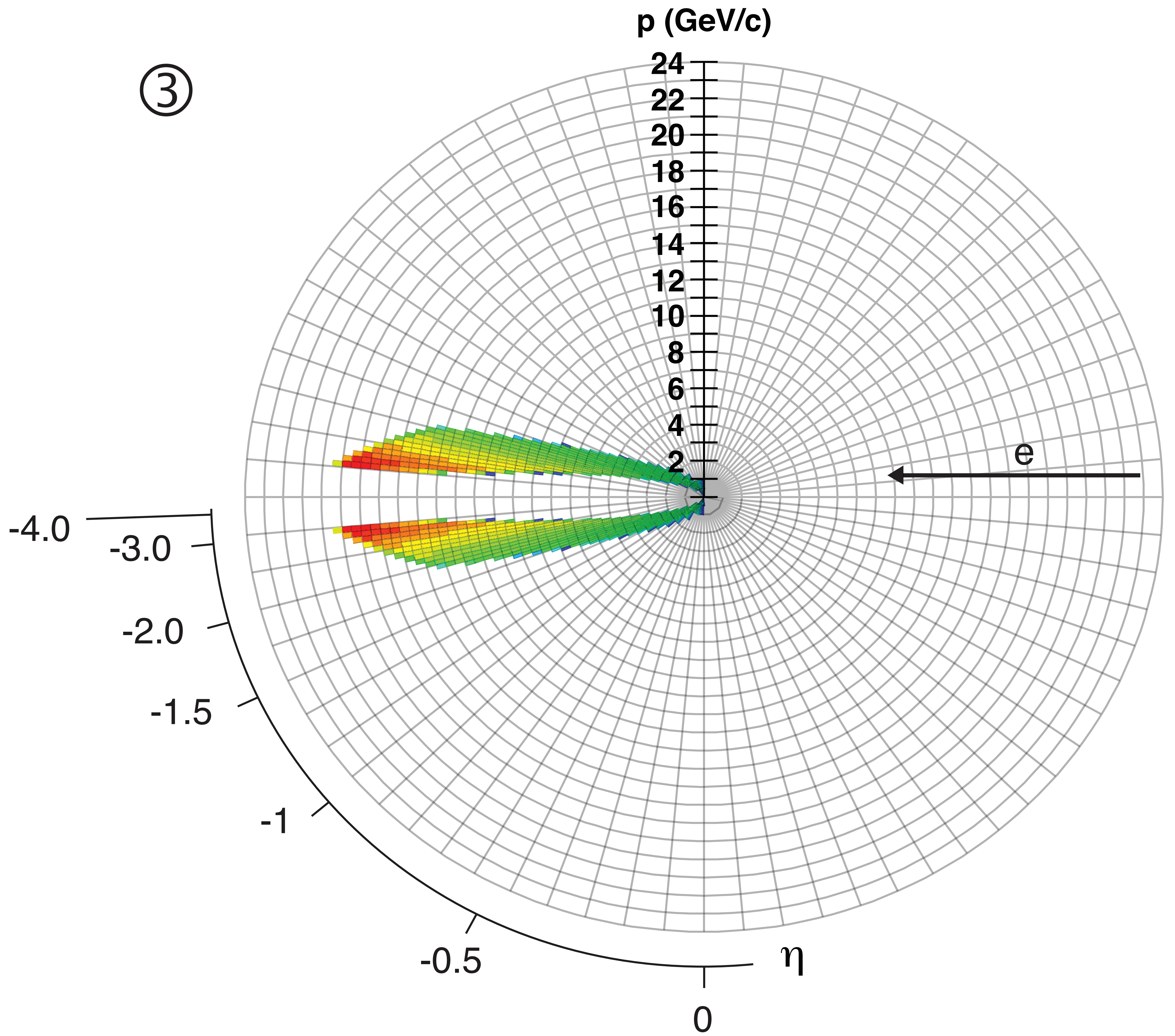
20 GeV on 100 GeV, $0.1 < Q^2 < 1$ GeV², $5 \cdot 10^{-4} < x < 3 \cdot 10^{-3}$



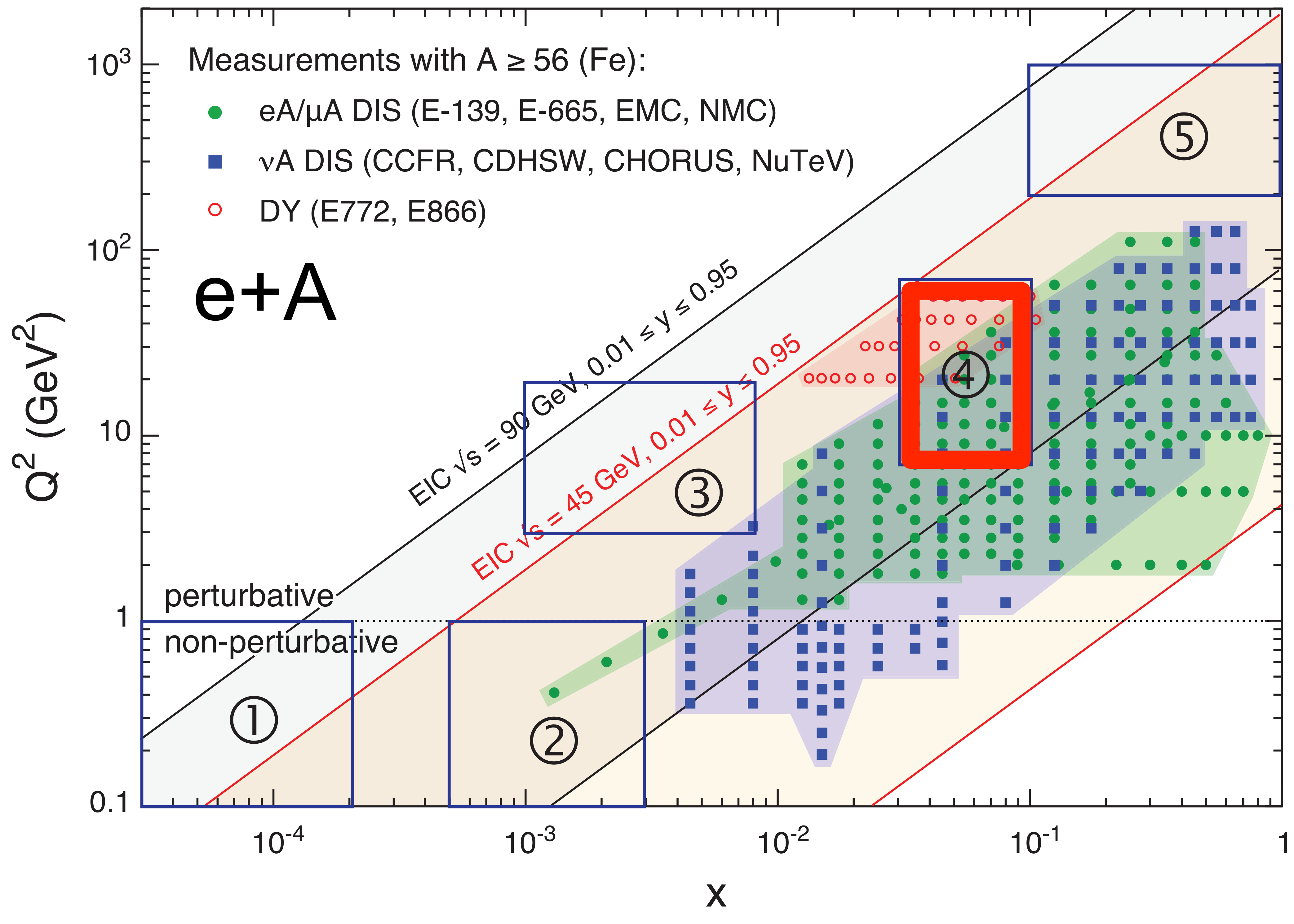
Electron Measurement: Range and Kinematics



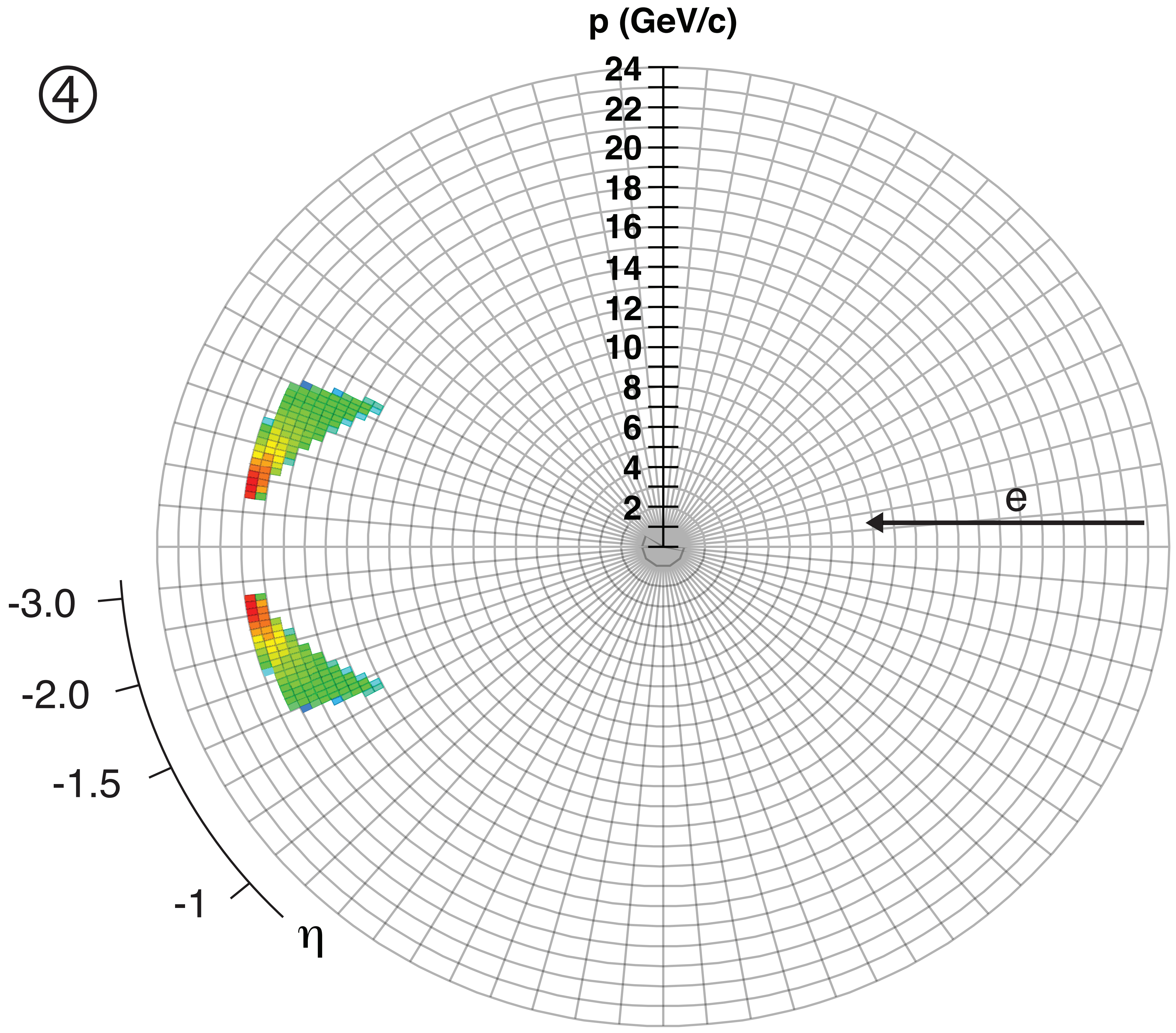
20 GeV on 100 GeV, $3 < Q^2 < 20$ GeV^2, $1\cdot10^{-3} < x < 8\cdot10^{-3}$



Electron Measurement: Range and Kinematics

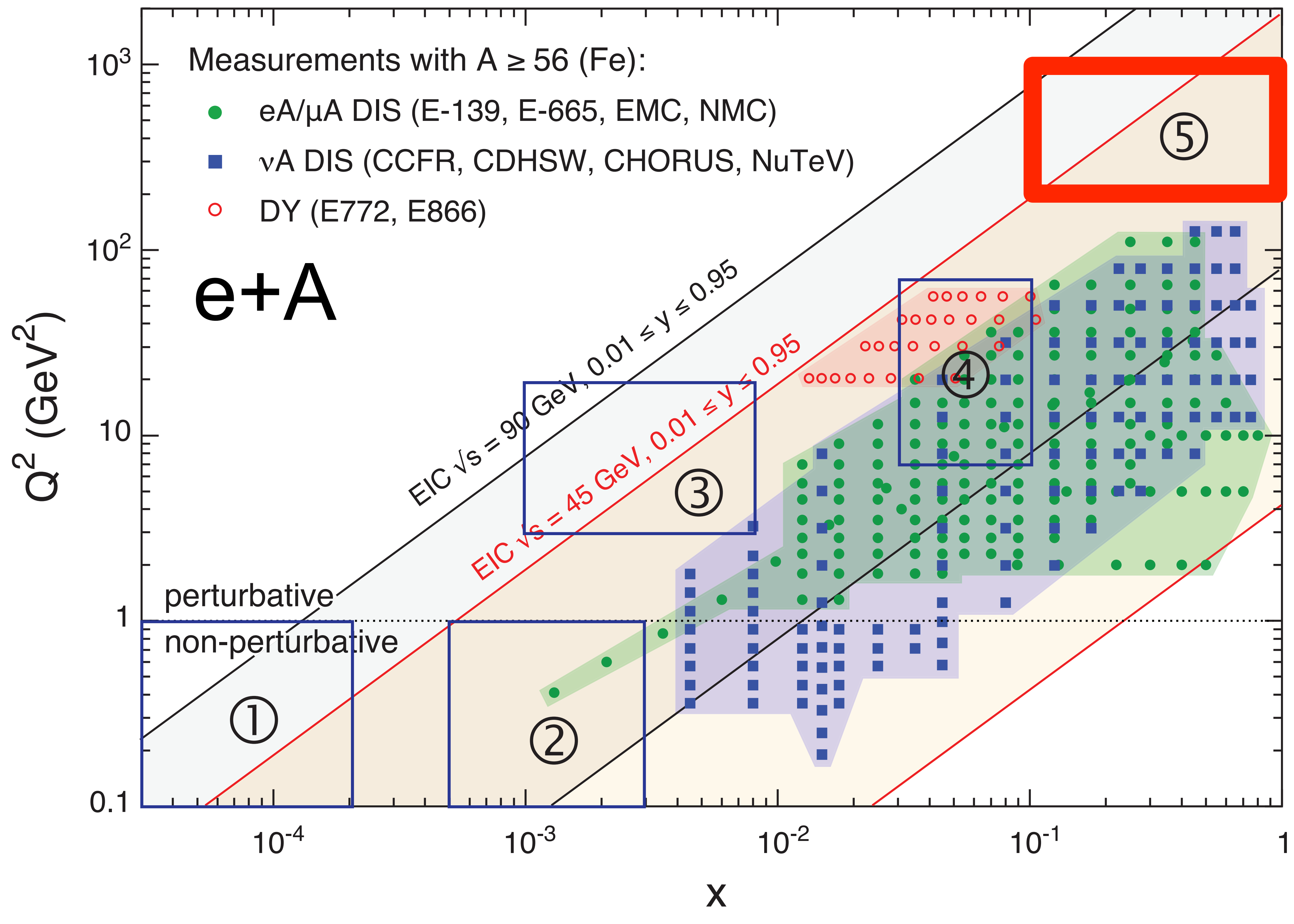


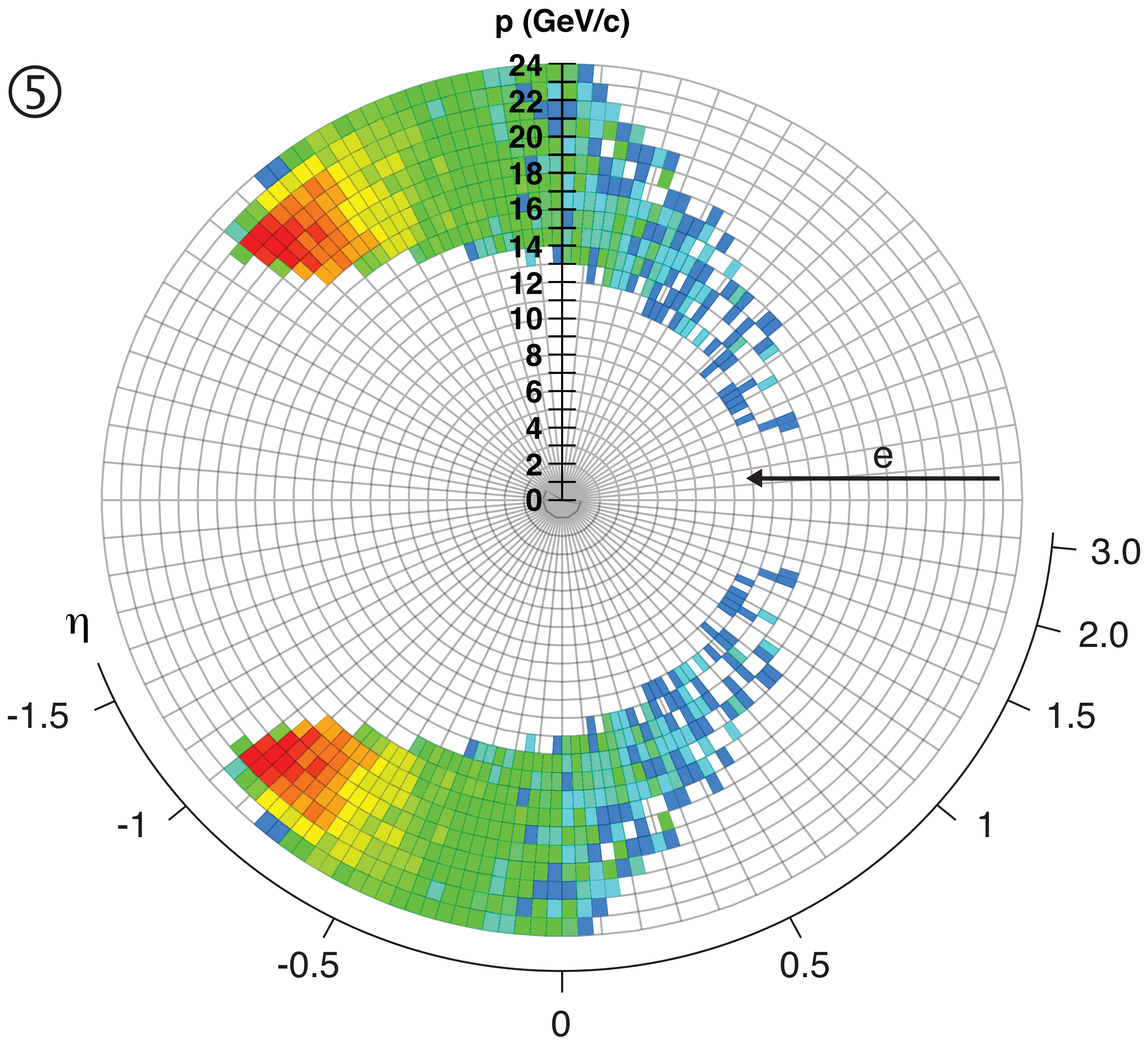
20 GeV on 100 GeV, $7 < Q^2 < 70$ GeV², $3\cdot10^{-2} < x < 1\cdot10^{-1}$



Electron Measurement: Range and Kinematics

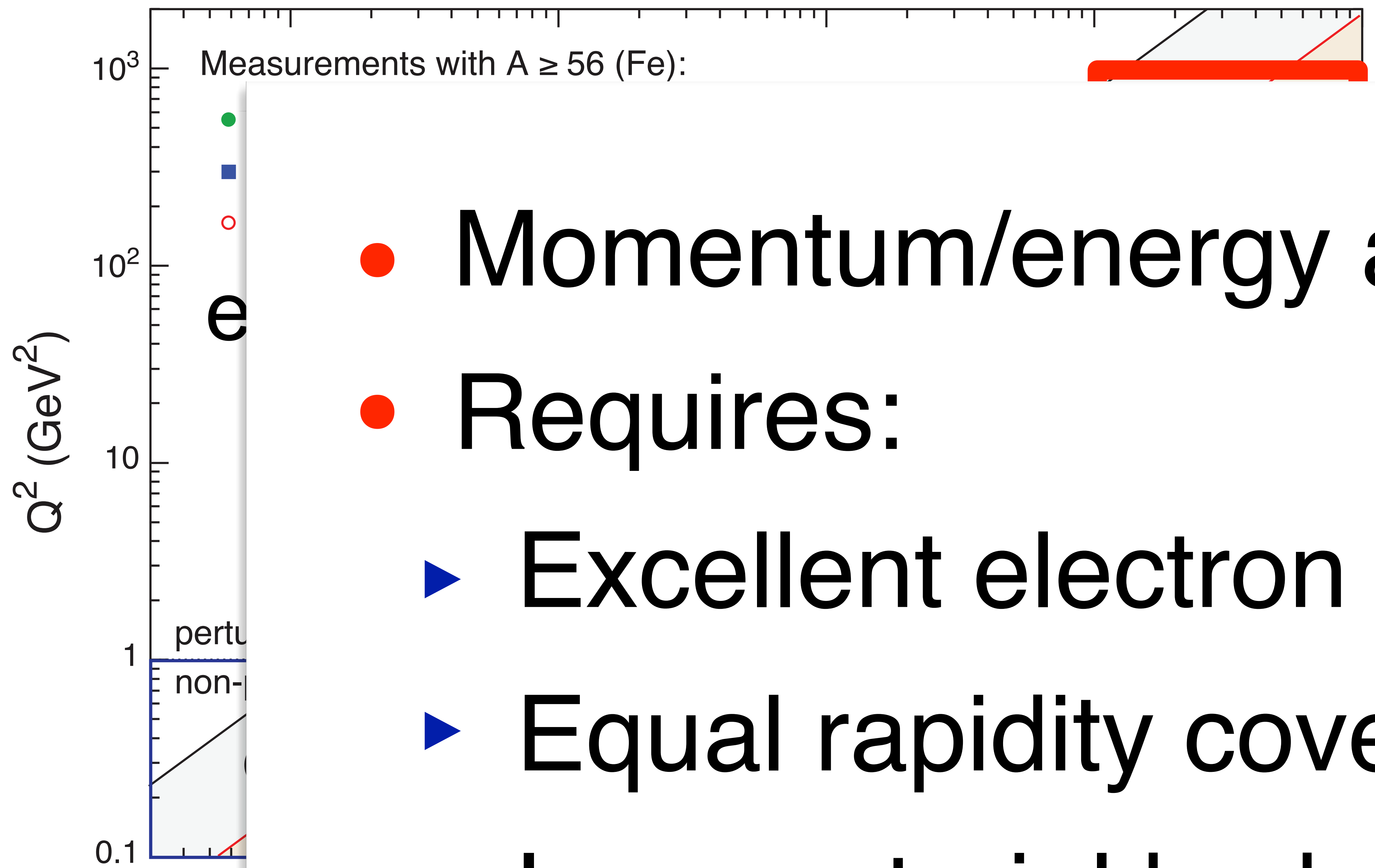
The energy and angle of scatter electron gives x , Q^2





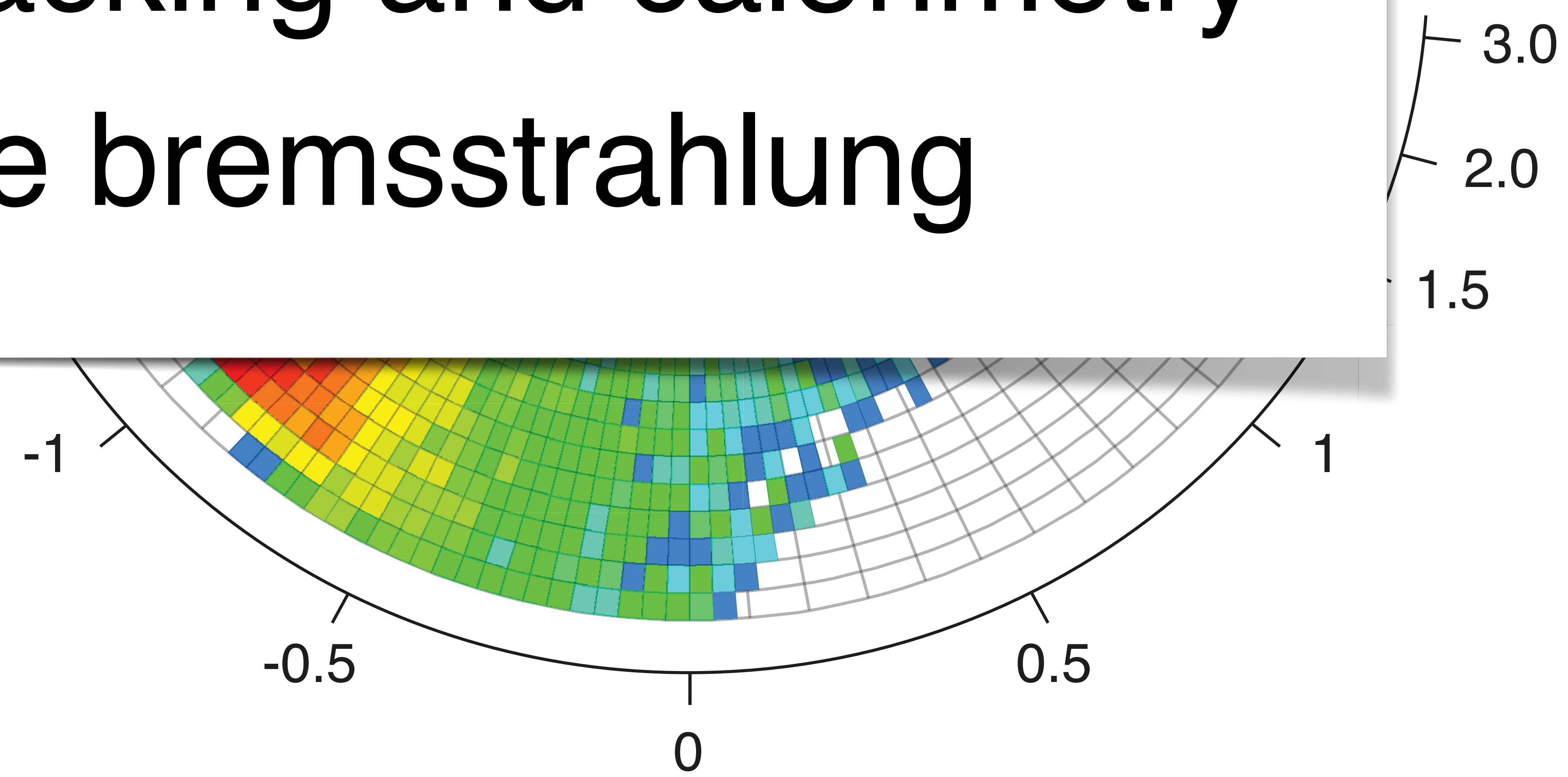
Electron Measurement: Range and Kinematics

The energy and angle of scatter electron gives x , Q^2



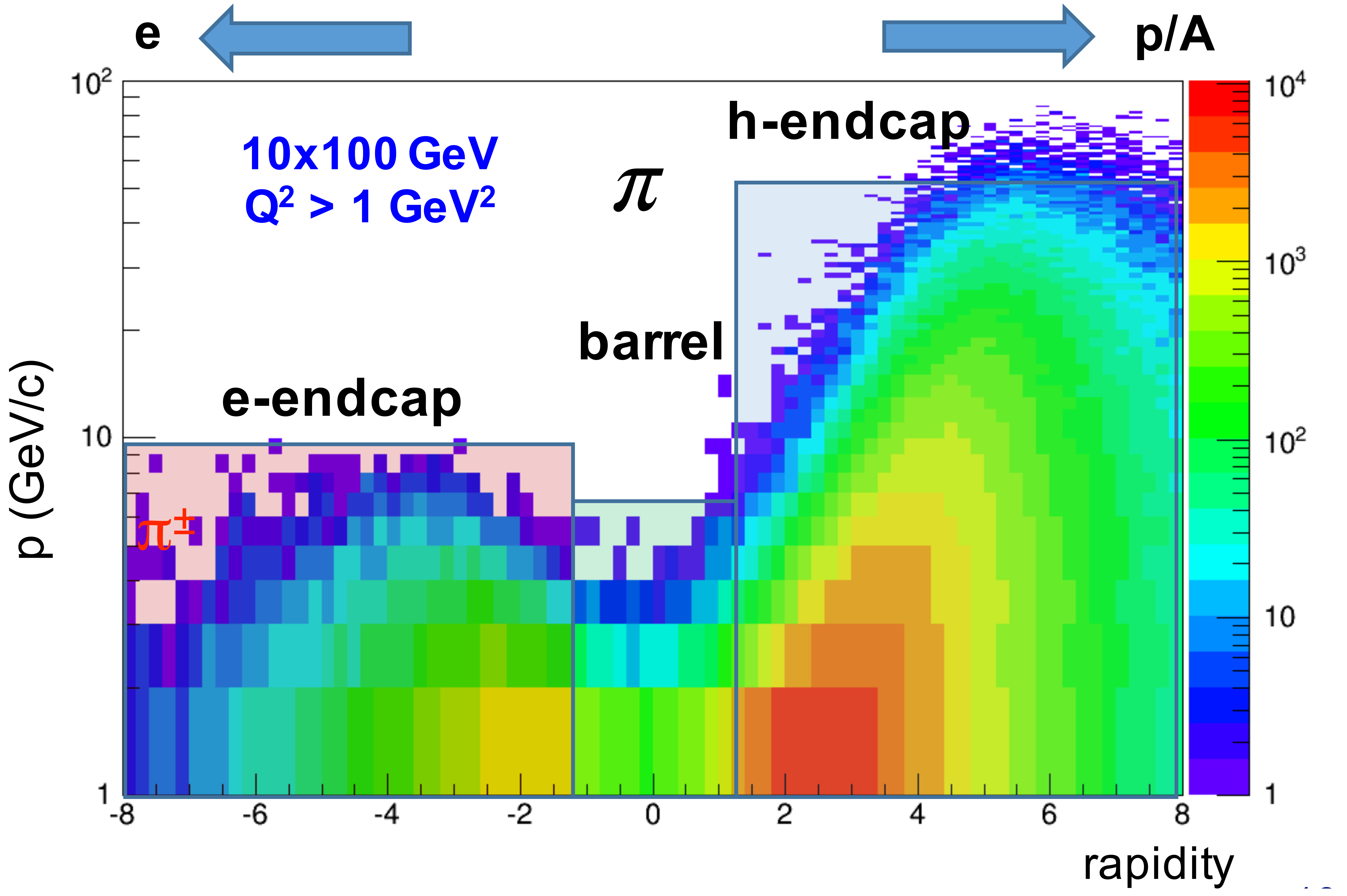
20 GeV on 100 GeV. 200 < Q^2 < 1000 GeV^2 . 0.1 < x < 1

- Momentum/energy and angular resolute of e' critical
- Requires:
  - Excellent electron ID (e/h)
  - Equal rapidity coverage for tracking and calorimetry
  - Low material budget to reduce bremsstrahlung



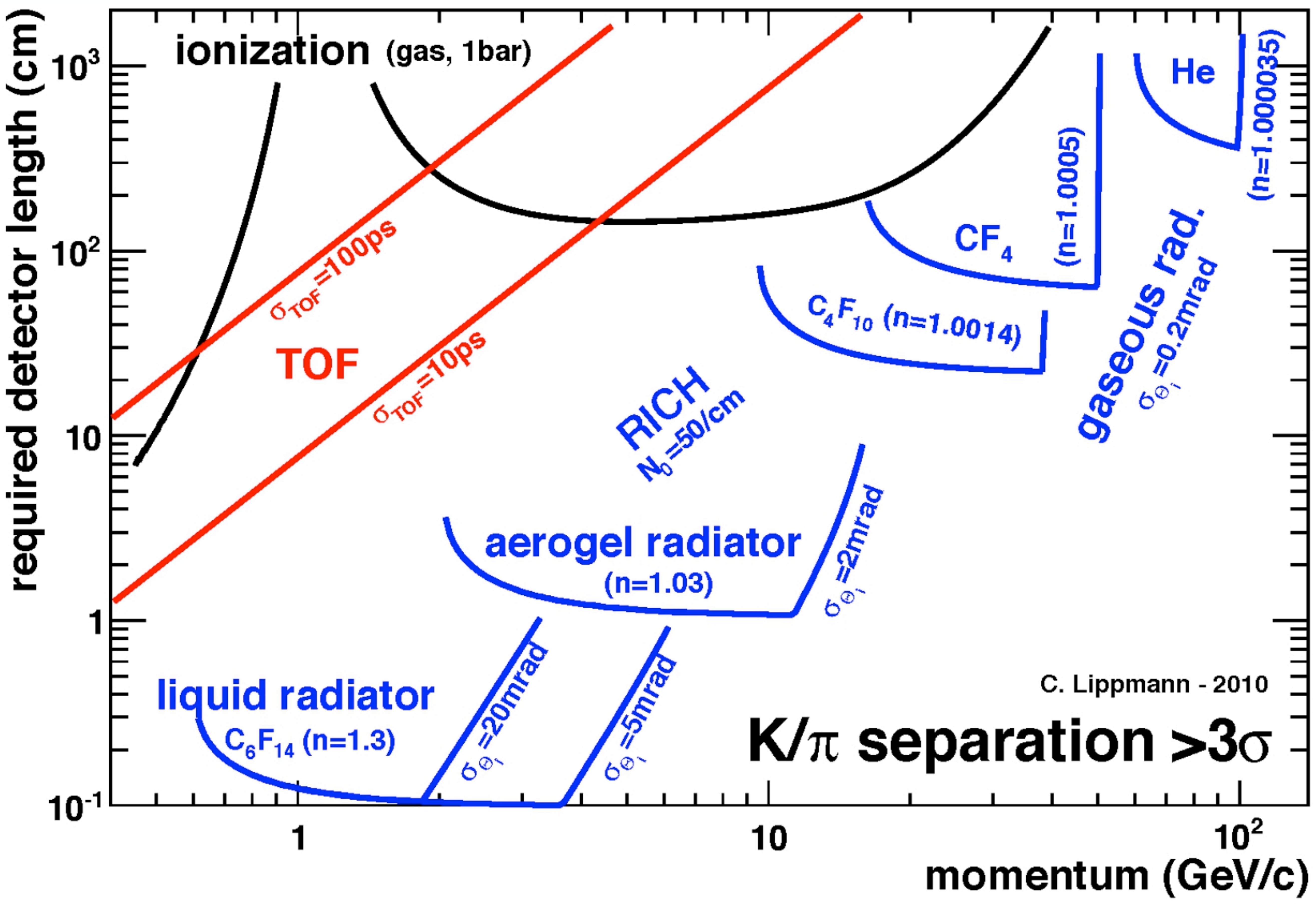
Major Challenge for EIC Detectors: PID

- Physics Requirements
  - $\pi^{\pm}, K^{\pm}, p^{\pm}$ separation over a wide range $|\eta| \leq 3.5$
  - Resolution
    - $\pi/K \sim 3-4\sigma$
    - $K/p > 1\sigma$
- Momentum–η correlation ⇒ different PID detector technology
  - backward: 0.2 < p < 10 GeV/c
  - forward: 0.2 < p < 50 GeV/c



- Hadron-cut off:
  - 1T-Magnet ⇒ p_T > 200 MeV/c
  - 3T-Magnet ⇒ p_T > 500 MeV/c

PID Techniques



- EIC will need for most of the physics 3-4 σ separation for π/K and good K/p separation
- Need more than one technology to cover the entire momentum ranges at different rapidities

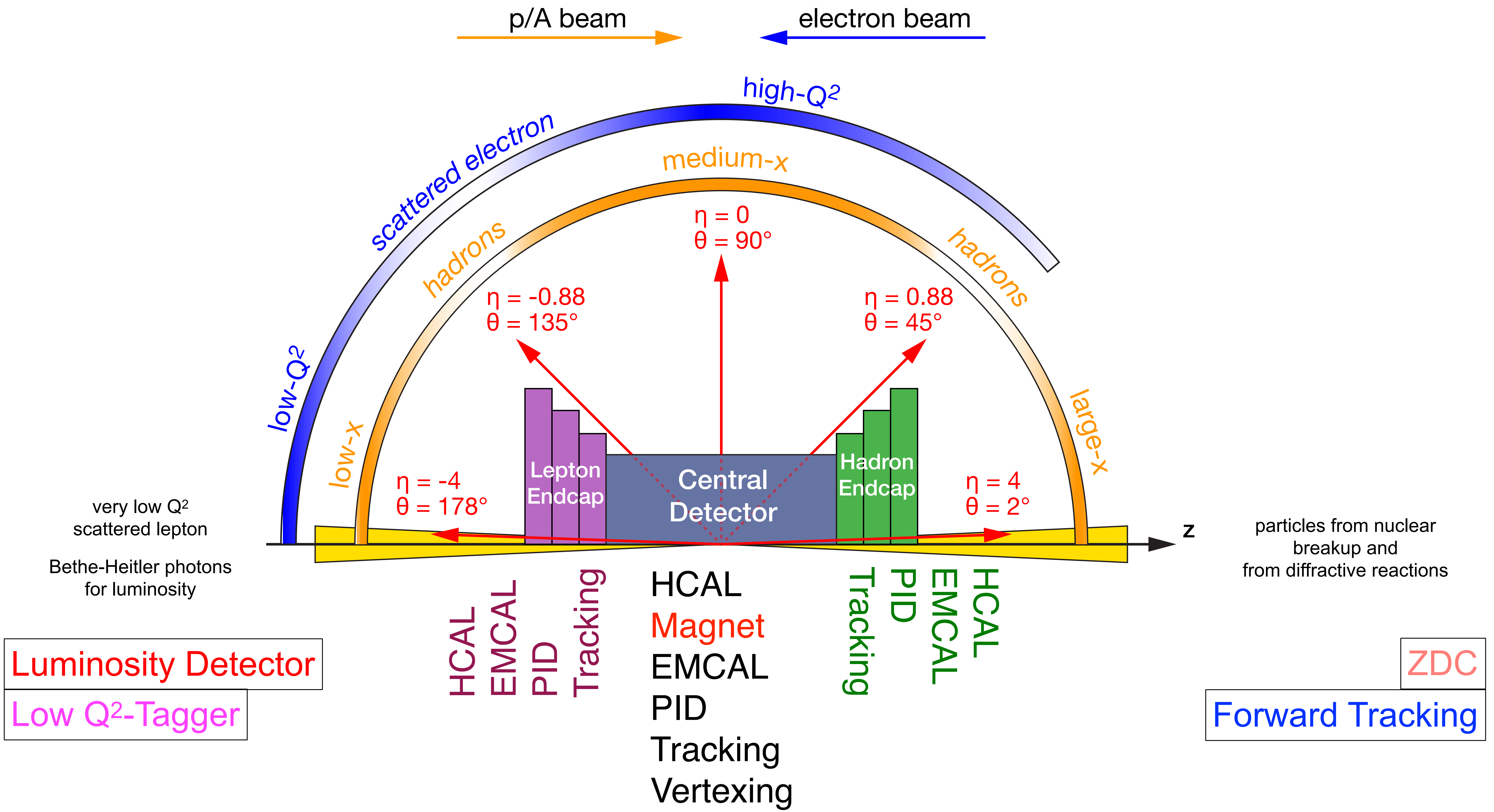
- Need absolute particle numbers at high purity and low contamination
- EIC PID needs are more demanding then at most collider detector

Brief Review of Requirements (see Yellow Report)

- Hermetic detector, low mass inner tracking
- Moderate radiation hardness requirements
- Electron measurement & jets in approx. -4 < η < +4
- Good momentum resolution
  - central: $\sigma(p)/p = 0.05\% \oplus 0.5\,\%$
  - fwd/bkd: $\sigma(p)/p = 0.1\% \oplus 0.5\,\%$
- Good impact parameter resolution: $\sigma = 5 \oplus 15/p\sin^{3/2}\theta\ (\mu m)$
- Excellent EM resolution
  - central: $\sigma(E)/E = 10\,\%/\sqrt{E}$
  - backward: $\sigma(E)/E < 2\,\%/\sqrt{E}$
- Good hadronic energy resolution
  - forward: $\sigma(E)/E \approx 50\,\%/\sqrt{E}$
- Excellent PID π/K/p
  - forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c
- Low pile-up, low multiplicity, data rate ~500kHz (full lumi)

Main Challenges:
- PID
- EMCal at < 2%/√E

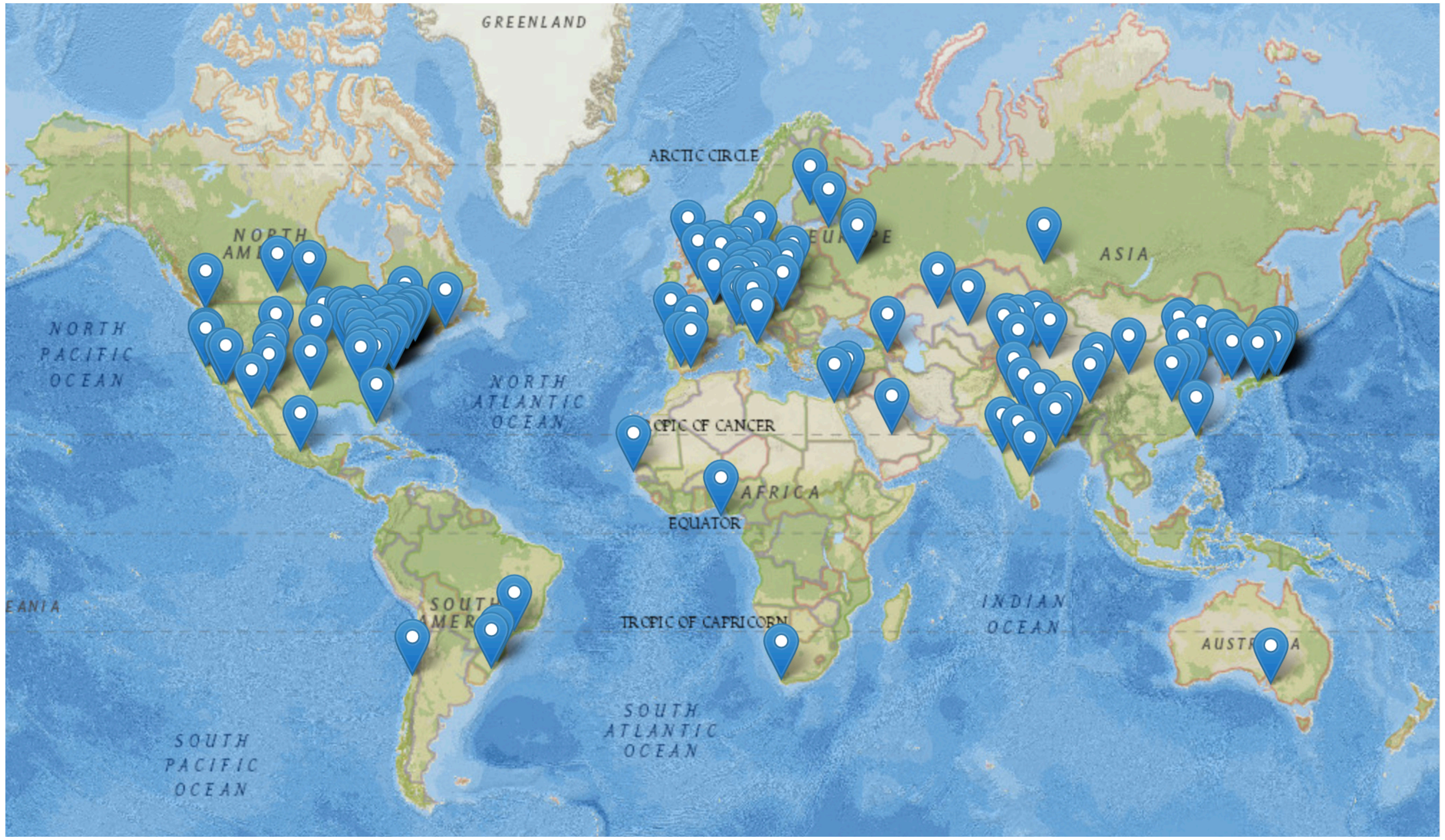
EIC General Purpose Detector Concept

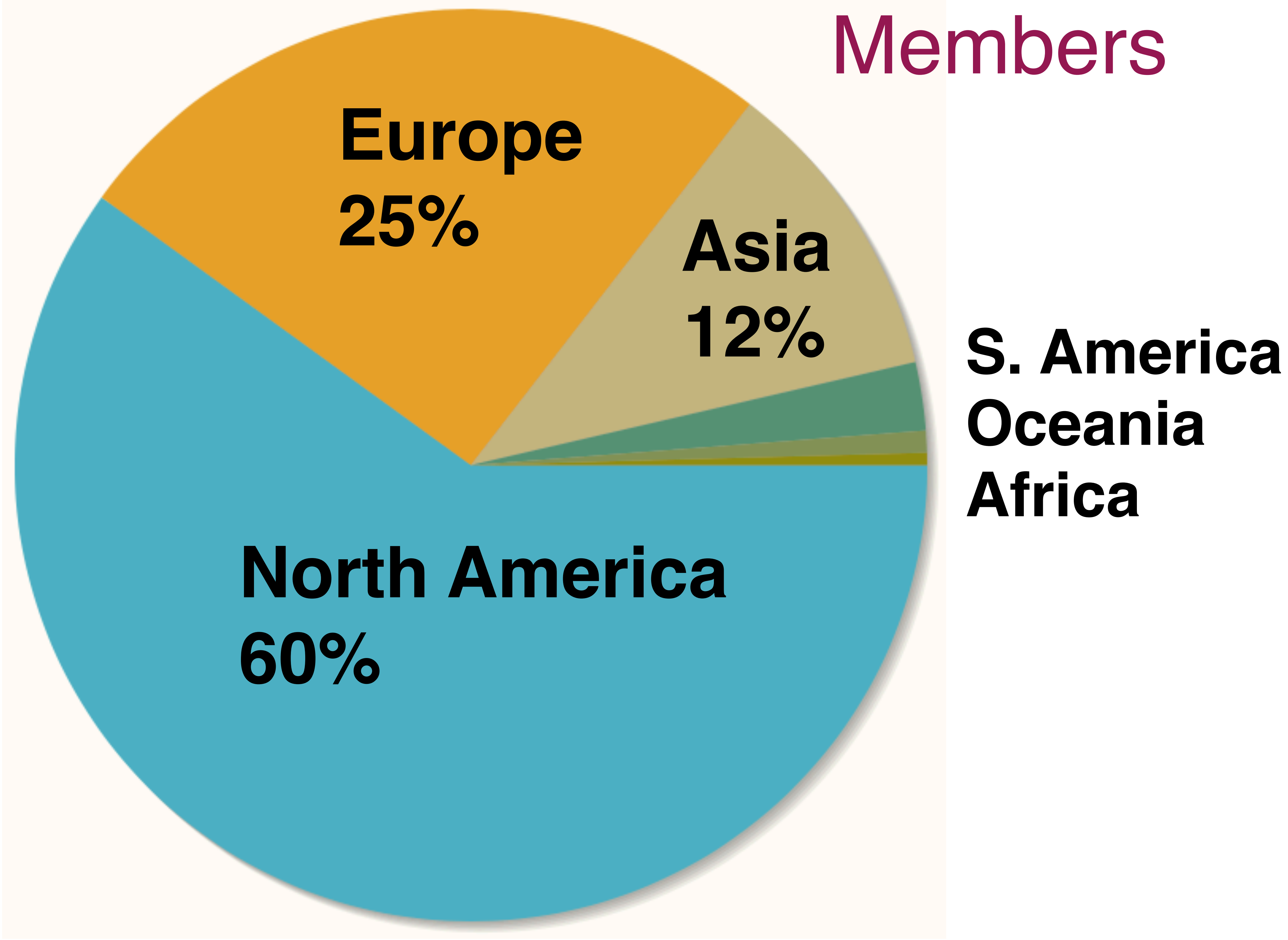


The Community Behind the EIC

The EIC User Group: http://eicug.org

- Formation of a formal EIC User Group in 2014/2015
- 1290 members, 259 institutions, 35 countries
- EIC Science Centers at JLab (EIC^2) and BNL/Stony Brook University (CFNS)

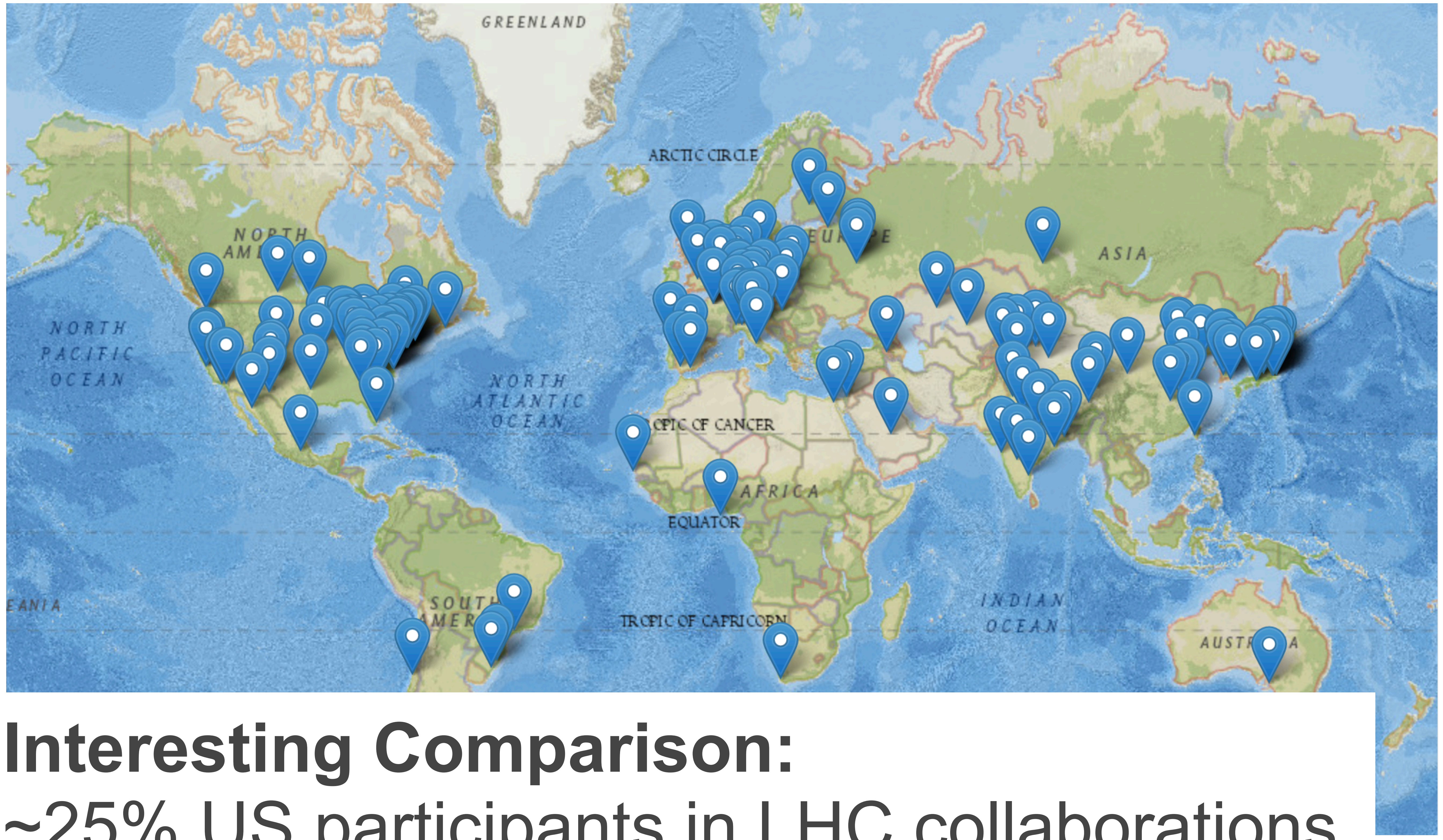




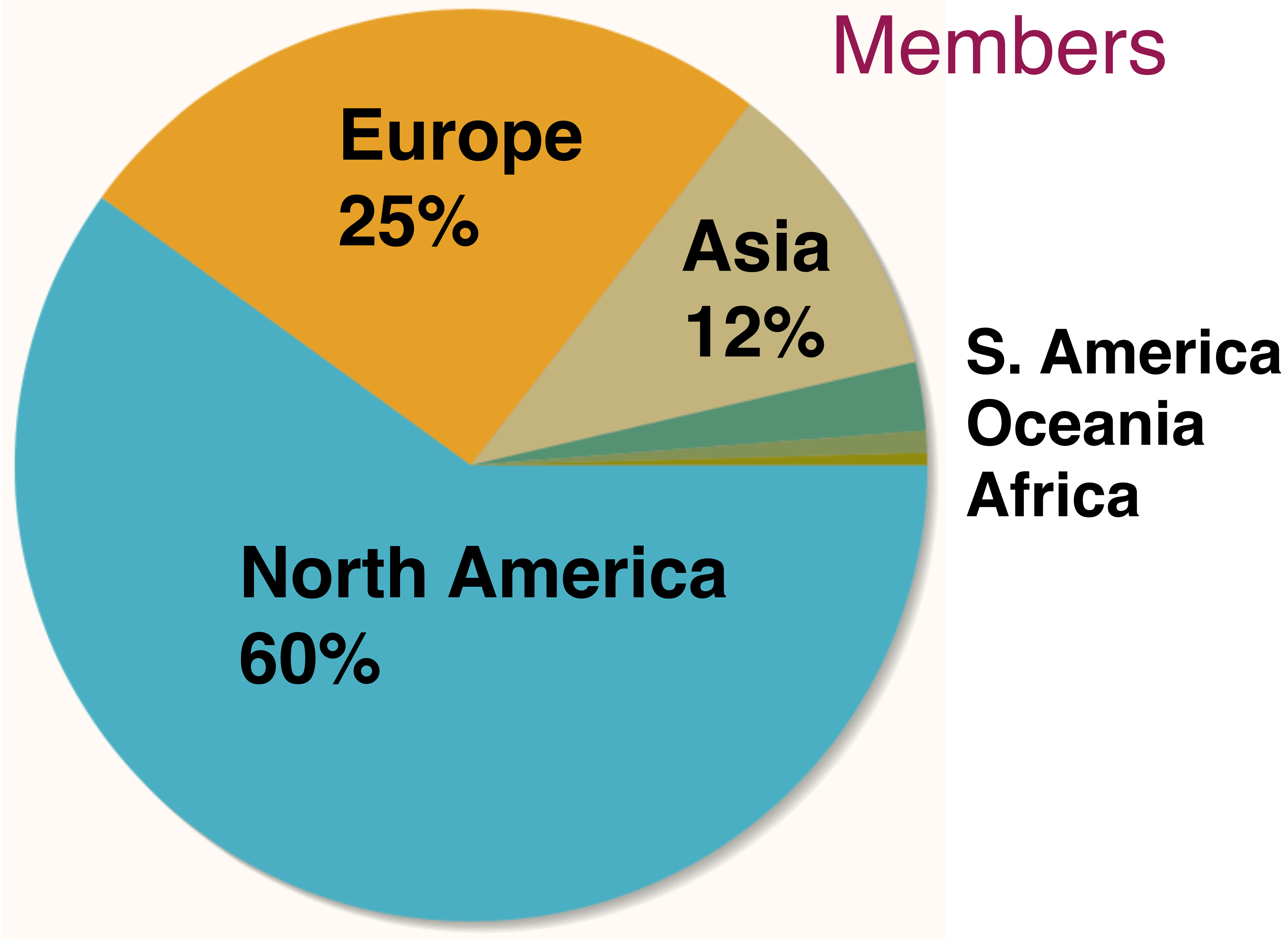
The Community Behind the EIC

The EIC User Group: http://eicug.org

- Formation of a formal EIC User Group in 2014/2015
- 1290 members, 259 institutions, 35 countries
- EIC Science Centers at JLab (EIC^2) and BNL/Stony Brook University (CFNS)



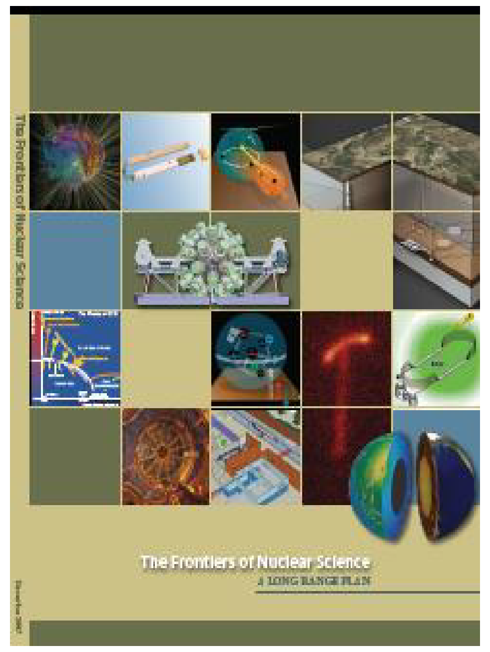
Interesting Comparison:
~25% US participants in LHC collaborations

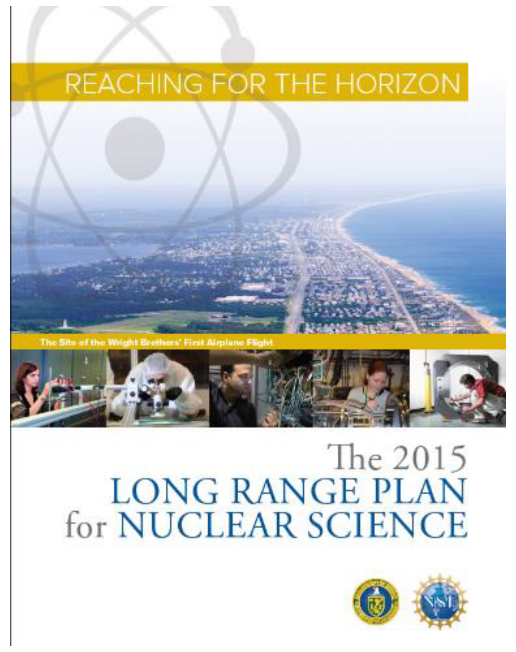


Long Path Towards the EIC .

US Nuclear Physics Long Range Plans

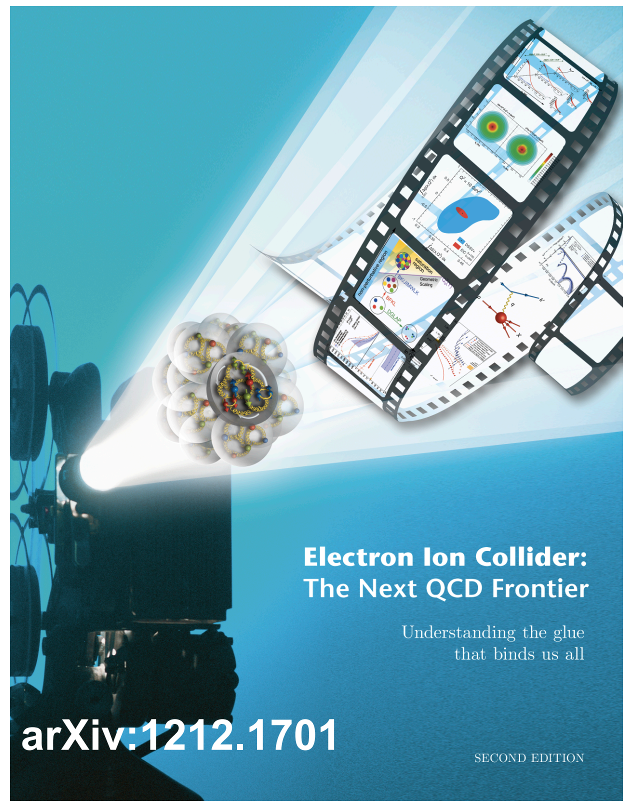
2002 2007 2015





"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."

EIC User Group Key Documents



White Paper 2012/2014

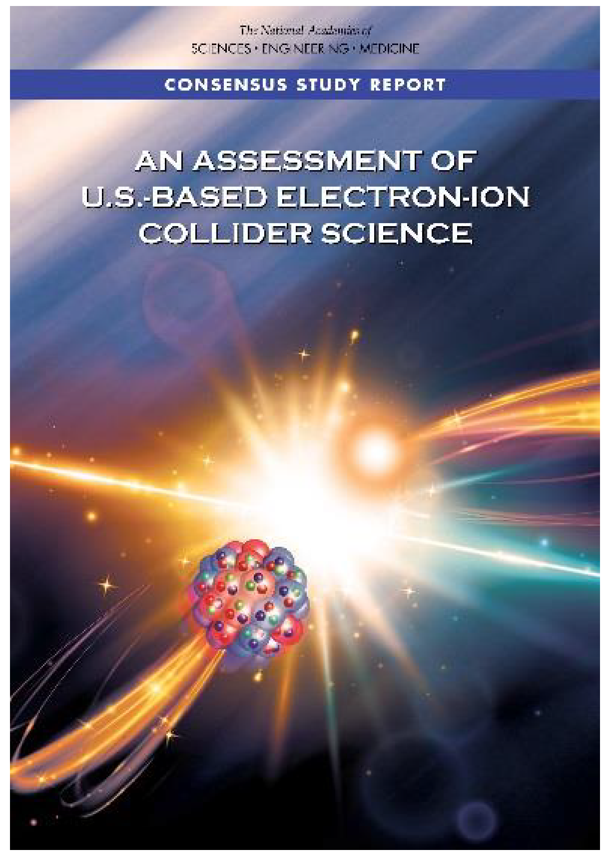
Physics Case

Yellow Report 2021

Physics Requirements
Detector Concepts

Long Path Towards the EIC ..

National Academy of Sciences

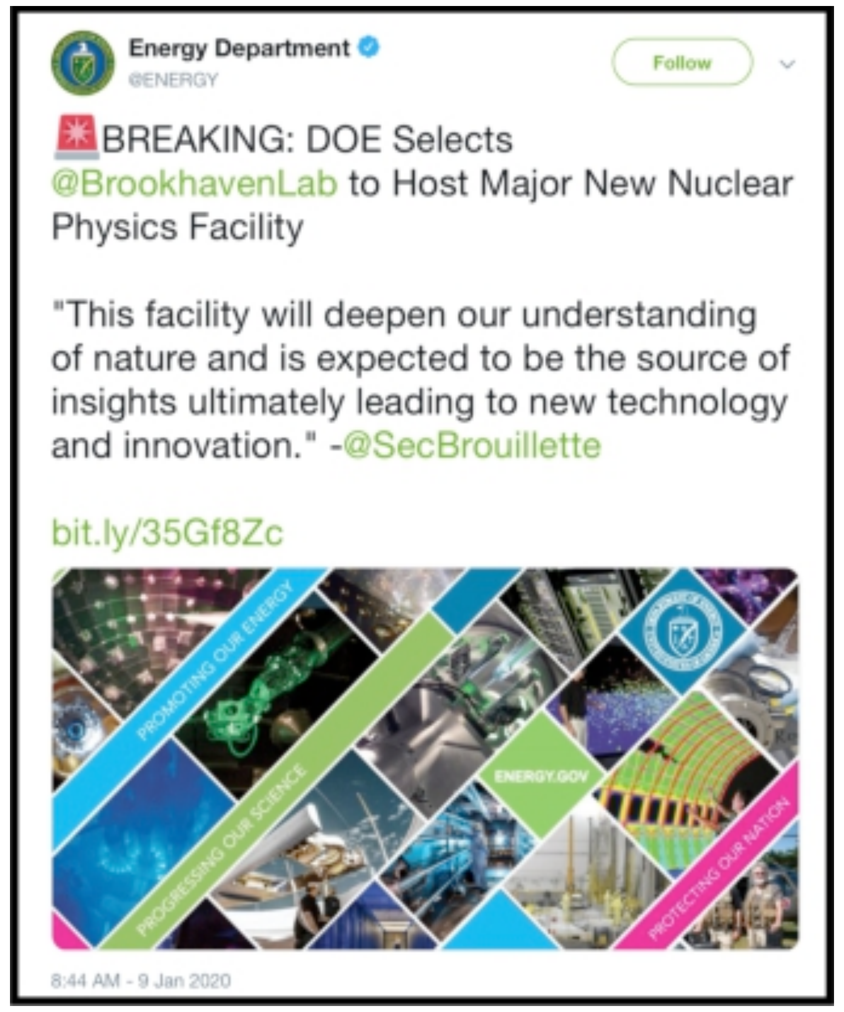


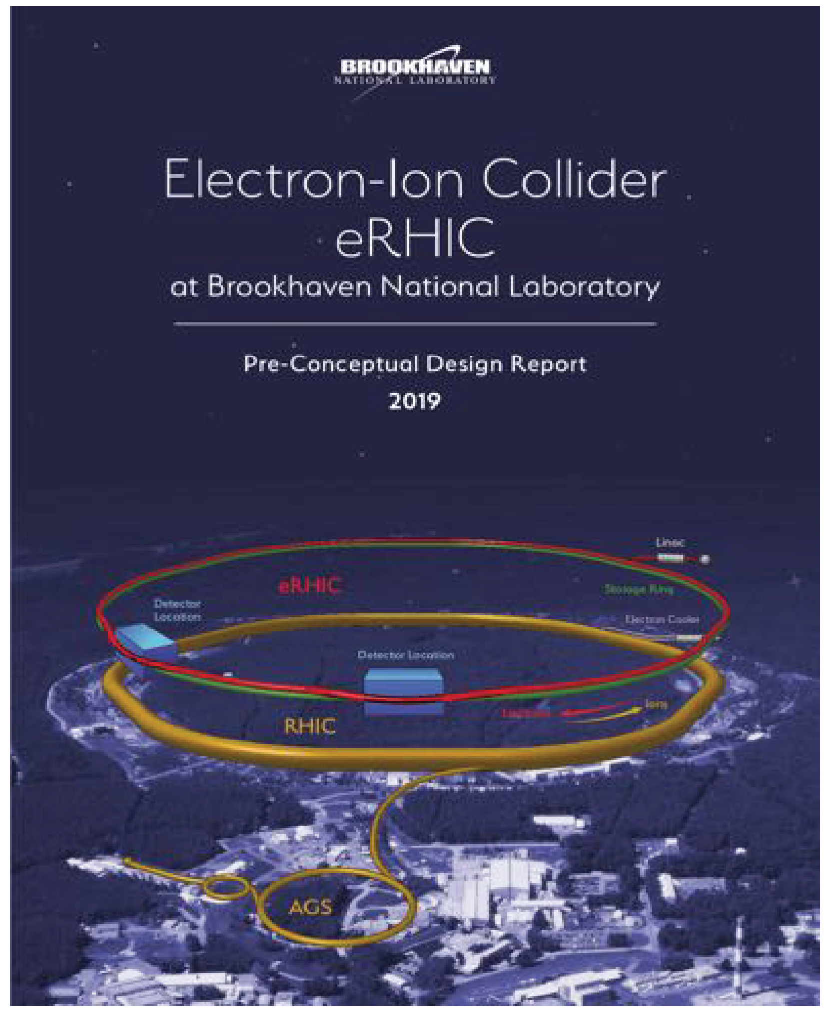
2018

“The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely.”

EIC Project

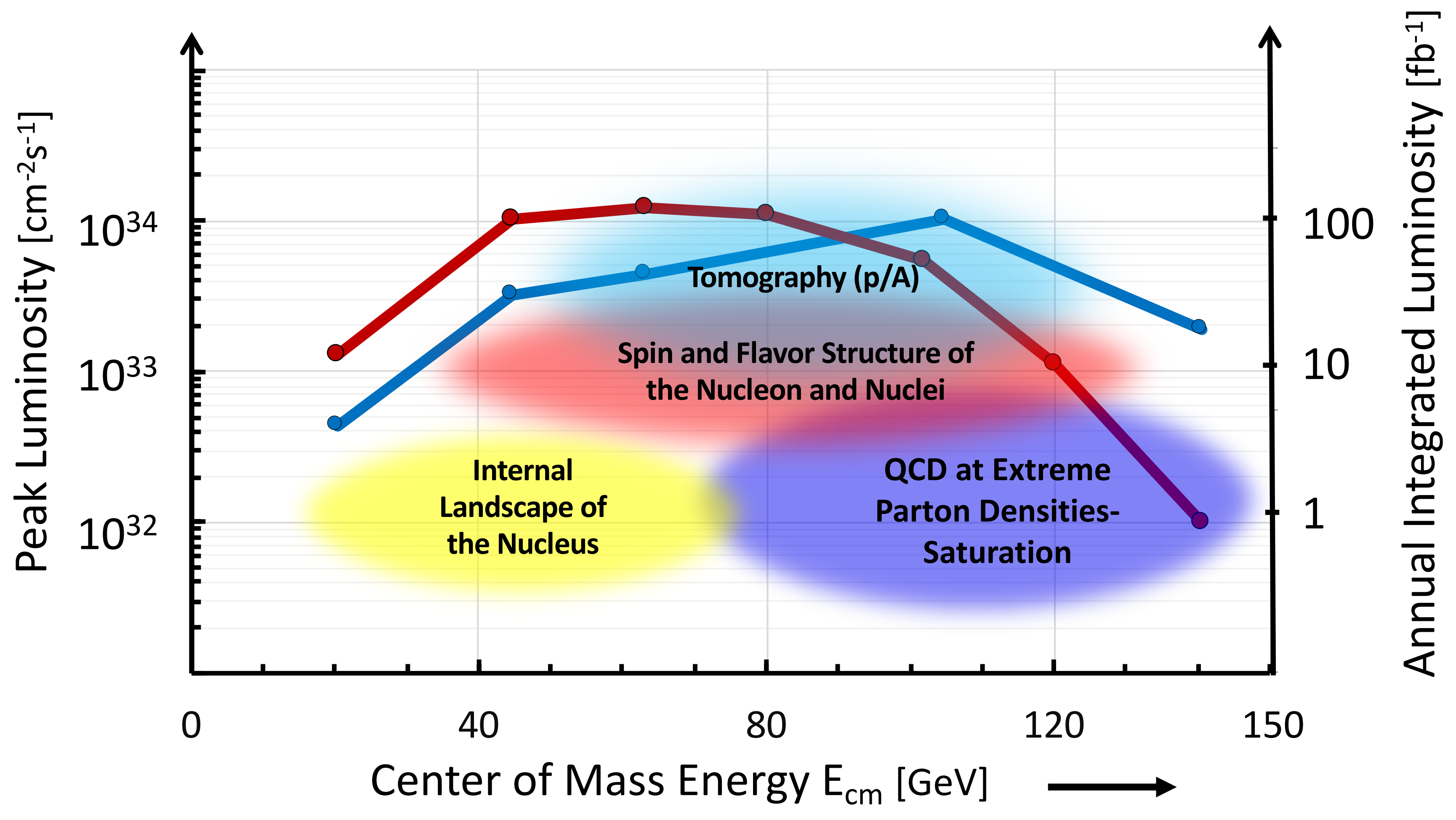
December 2019: Critical Decision 0 (Mission Need)
January 2020: BNL selection as EIC site
January 2021: DOE CD-1 Review & release of CDR
July 2021: CD-1 received



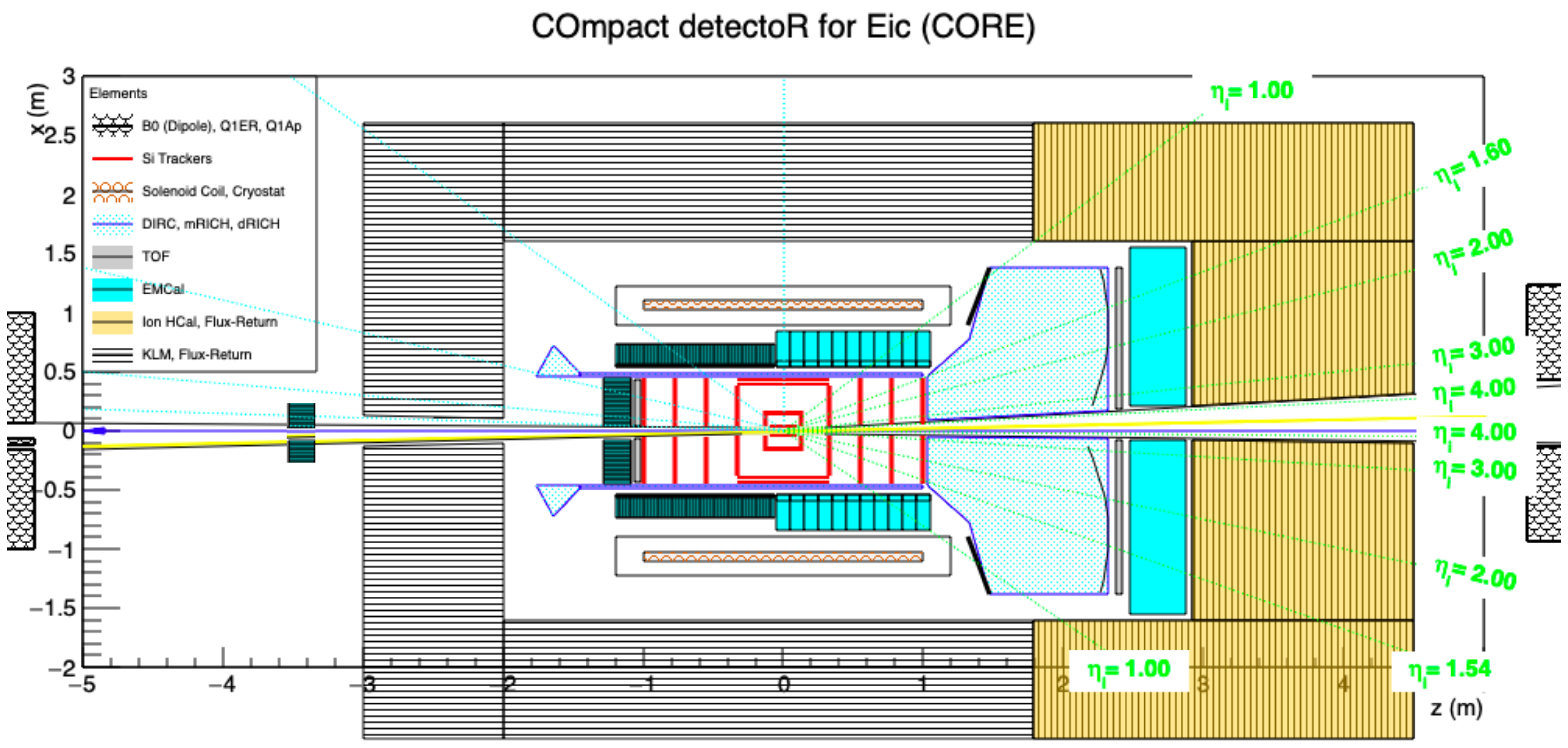


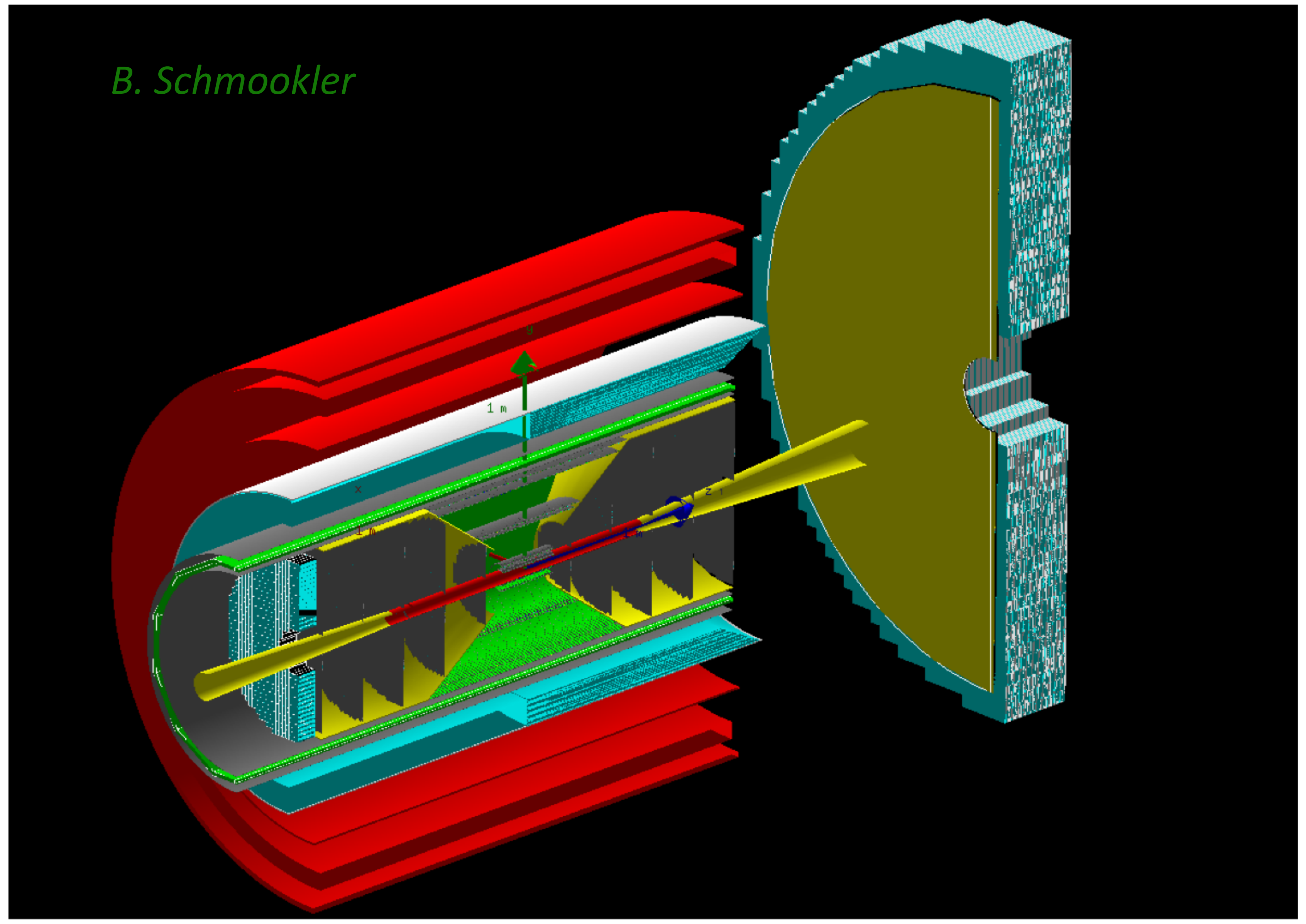
Detector Planning

- The DOE supported EIC Project includes **one detector** and **one IR** in the reference costing
- The EIC is capable of supporting a science program that includes **two detectors** and two interaction regions.
- The community (EIC User Group) is strongly in favor of **two general purpose detectors**
  - Complementarity
    - Cross-checks, improve systematics
  - IRs with different $\mathscr{L}(\sqrt{s})$ profile ?
- A second detector needs substantial international contributions to be realized
- EIC Project: Expression of Interest (EOI), May - November 2020
  - Call EoI for potential cooperation on the experimental equipment as required for a successful science program at the Electron-Ion Collider (EIC). Emphasized all detector components to facilitate the full EIC science program.
- Issue Call for Detector Proposals, March 2021
  - Call is for 2 detectors!
  - Deadline December 2021



CORE: a COmpact detectoR for the EIC

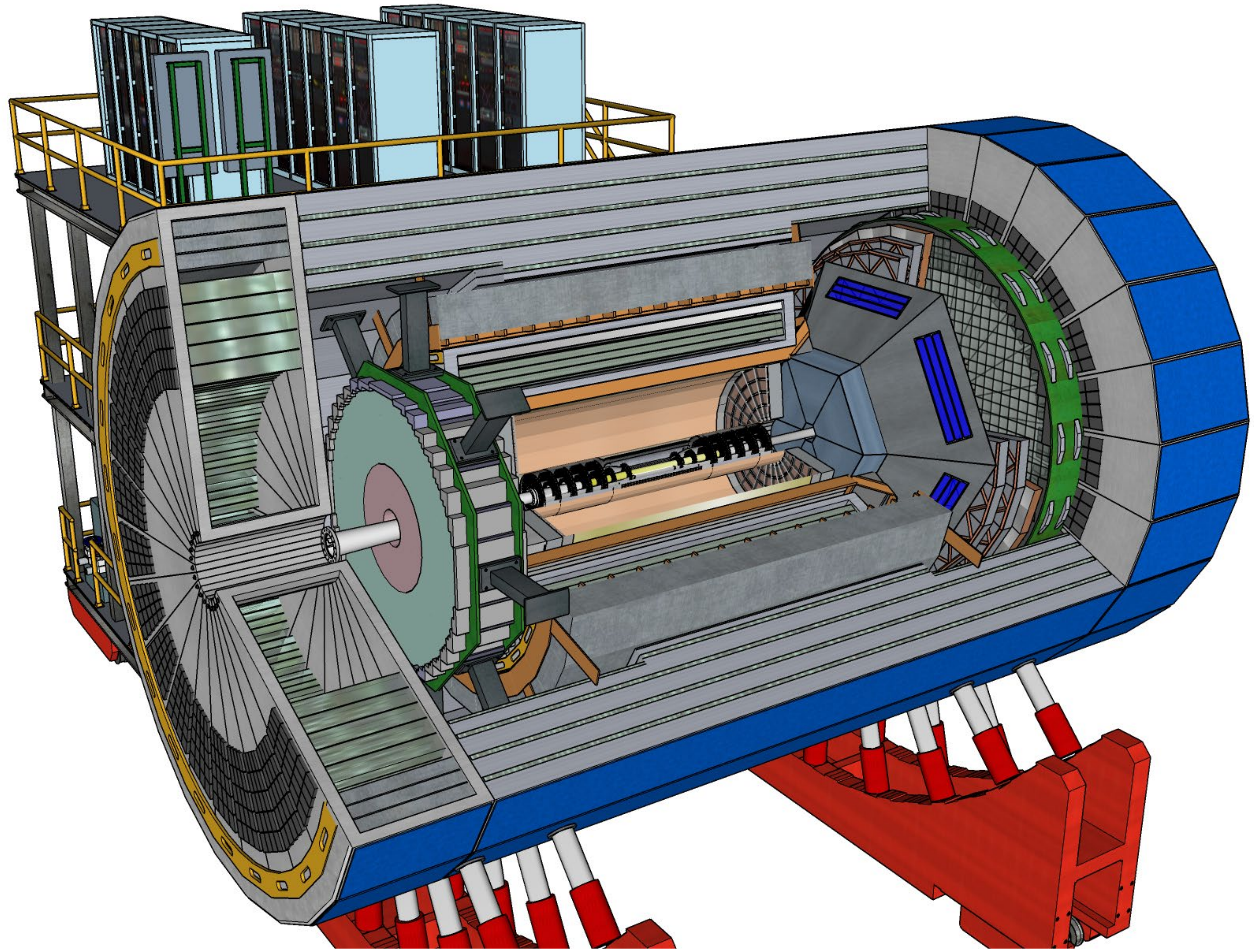




- Hermetic and compact general-purpose detector
  - New 2.5 T solenoid (2.5 m long, 1 m inner radius)
  - Tracking: central all-Si tracker and h-endcap GEM tracker
  - EMcal: PWO for $\eta < 0$ and W-Shashlyk for $\eta > 0$
  - Cherenkov PID: DIRC (50 cm radius) in barrel and dual-radiator RICH
  - TOF: LGADs in e-endcap and a simple TOF behind the dRICH Hcal / KLM detector integrated with the magnetic flux return

ECCE: **E**IC **C**omprehensive **C**hromodynamics **E**xperiment

- EIC detector offering full kinematic coverage using a design which incorporates the existing 1.5 T BaBar/sPHENIX magnet (3.7m long, 1.4m bore radius)



ECCE ELECTRON ENDCAP STRAWMAN

Tracking: MAPS, Micro Pattern Gaseous Detectors (MPGD)
Electron Detection: PWO&SciGlass
- Inner part: PWO crystals (reuse some)
- Outer part: SciGlass (backup PbGl)

h-PID: mRICH
- From yellow report

HCAL: Steel from magnet or Pb/Sc or Fe/Sc
- Not instrumented and only serve as flux return?
- Instrumented \w reduced thickness (lower energies)

ECCE CENTRAL BARREL STRAWMAN

Tracking: Silicon barrel tracker (optional Si/GEM hybrid)
Electron PID: SciGlass (backup: W/Sc (Pb/Sc) shashlik)
- SciGlass remains to be demonstrated
- Several backup options – lower resolution though

h-PID: hpDIRC & AC-LGAD
- Compact
- AC-LGAD never been shown for barrel configuration
- AC-LGAD backup: dE/dx (needs more space)

HCAL: magnet steel (**reuse**) - **Fe/Sc**

ECCE HADRON ENDCAP STRAWMAN

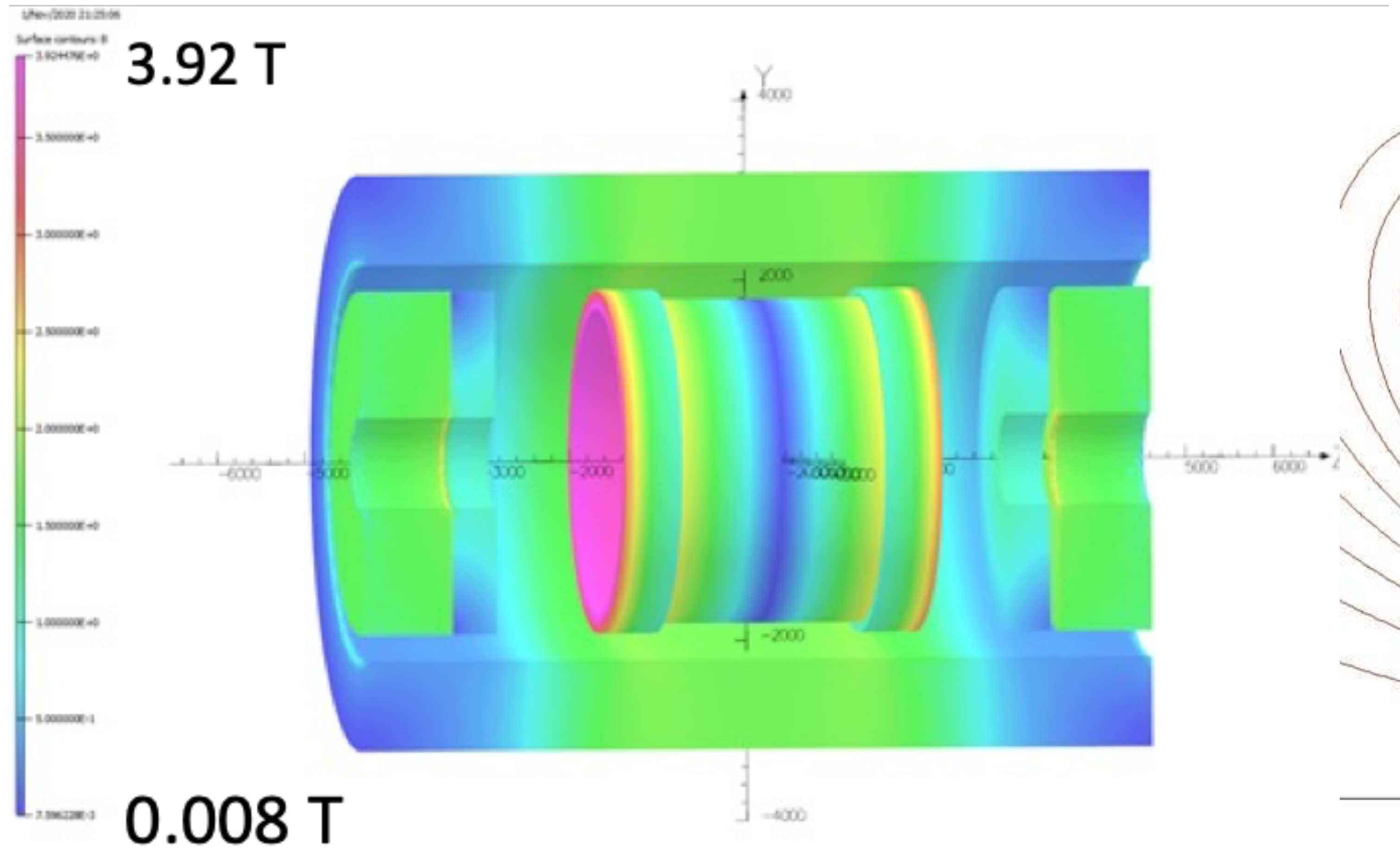
Tracking: MAPS, Micro Pattern Gaseous Detectors (MPGD)
h-PID: dRICH&TOF
e/h separation: TOF & aerogel
- TRD to separate electrons from high momentum hadrons?

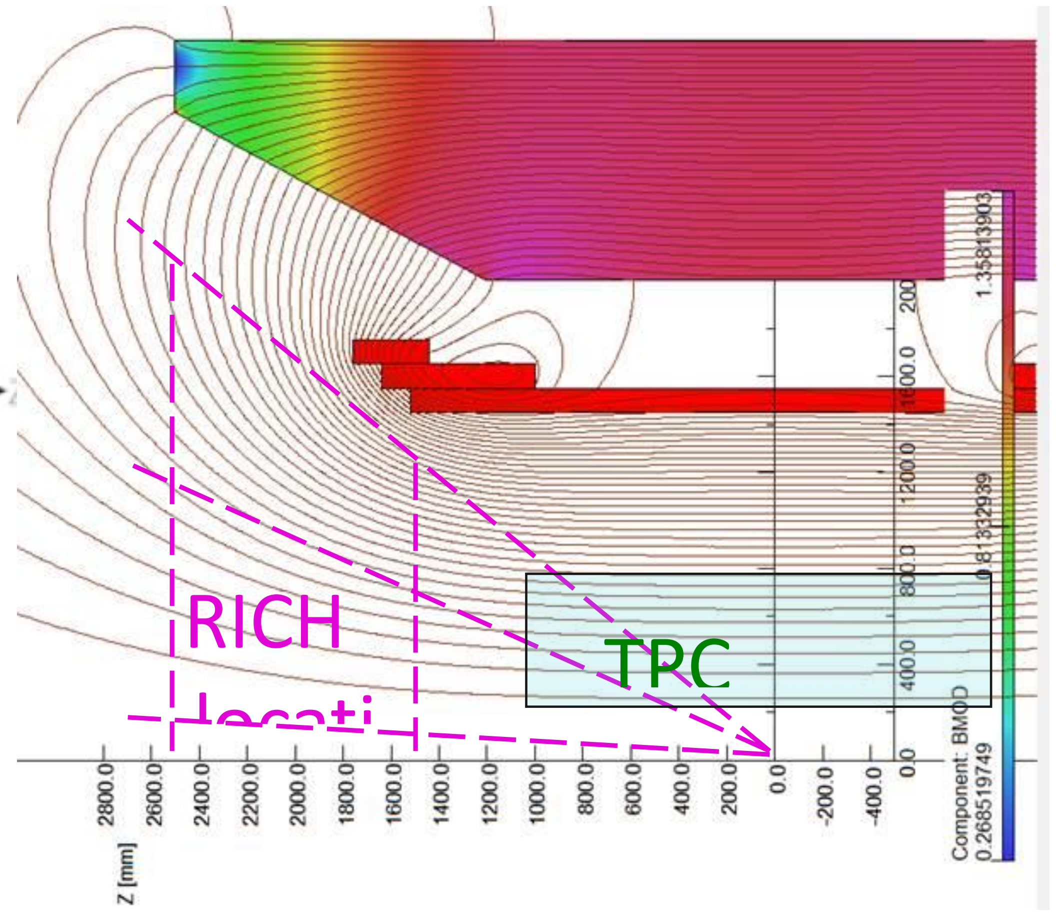
Electron PID: W/ScFi, Pb/Sc or W/Sc shashlik
HCAL: Pb/Sc or Fe/Sc
- Alternative for improved resolution: dual readout, high-granularity

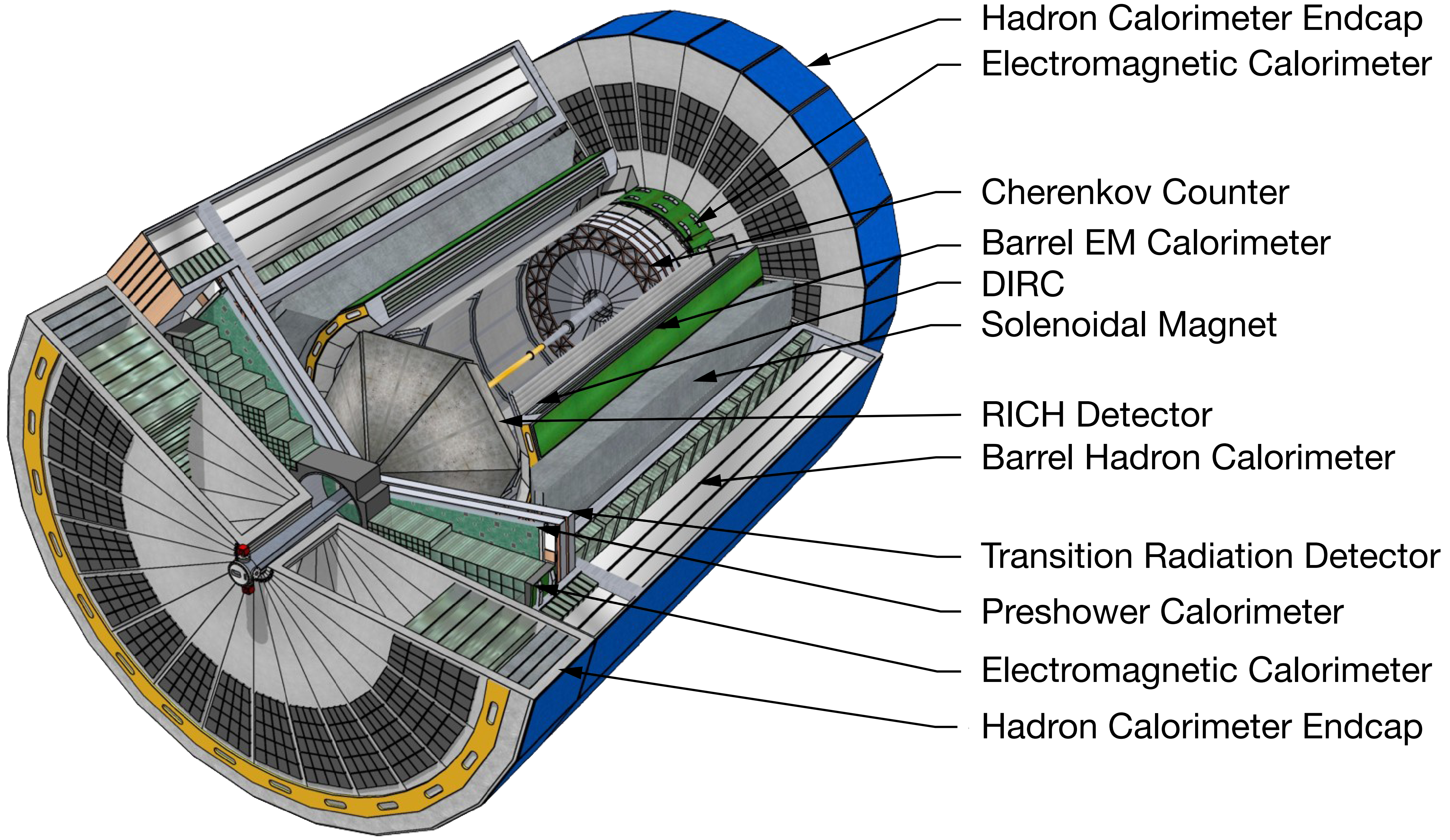
ATHENA: **A T**otally **HE**rmetic **E**lectron-**N**ucleus **A**pparatus

- Based on new magnet (≳ 3T) and Yellow Report reference detector
  - 3.6m long, 1.6m inner bore
  - Solenoidal and Hemholtz design under discussion
  - Optimize projectivity (tracking) at forward rapidities

- Concept presented at CD-1 review of the EIC and is included in the CDR
  - Major change TPC → Si Tracker + MPGD



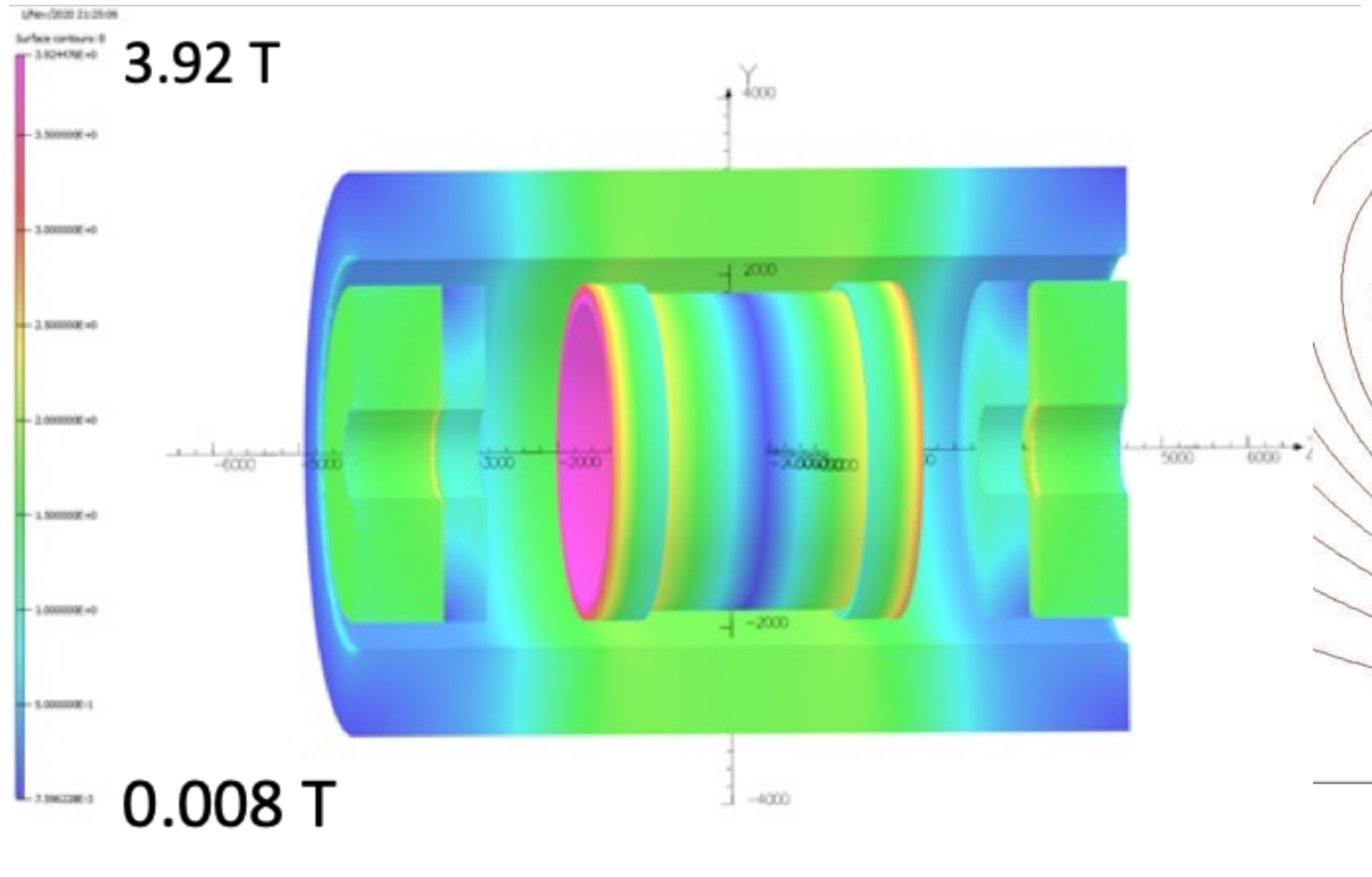


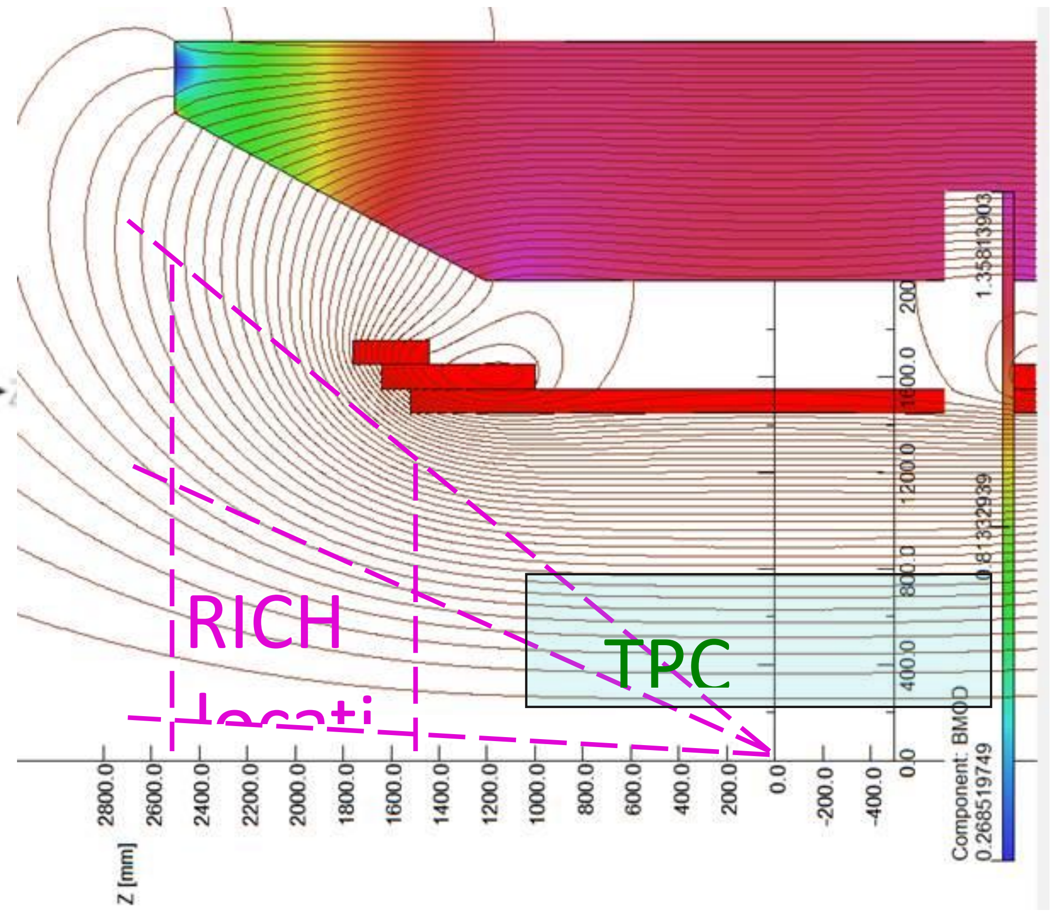


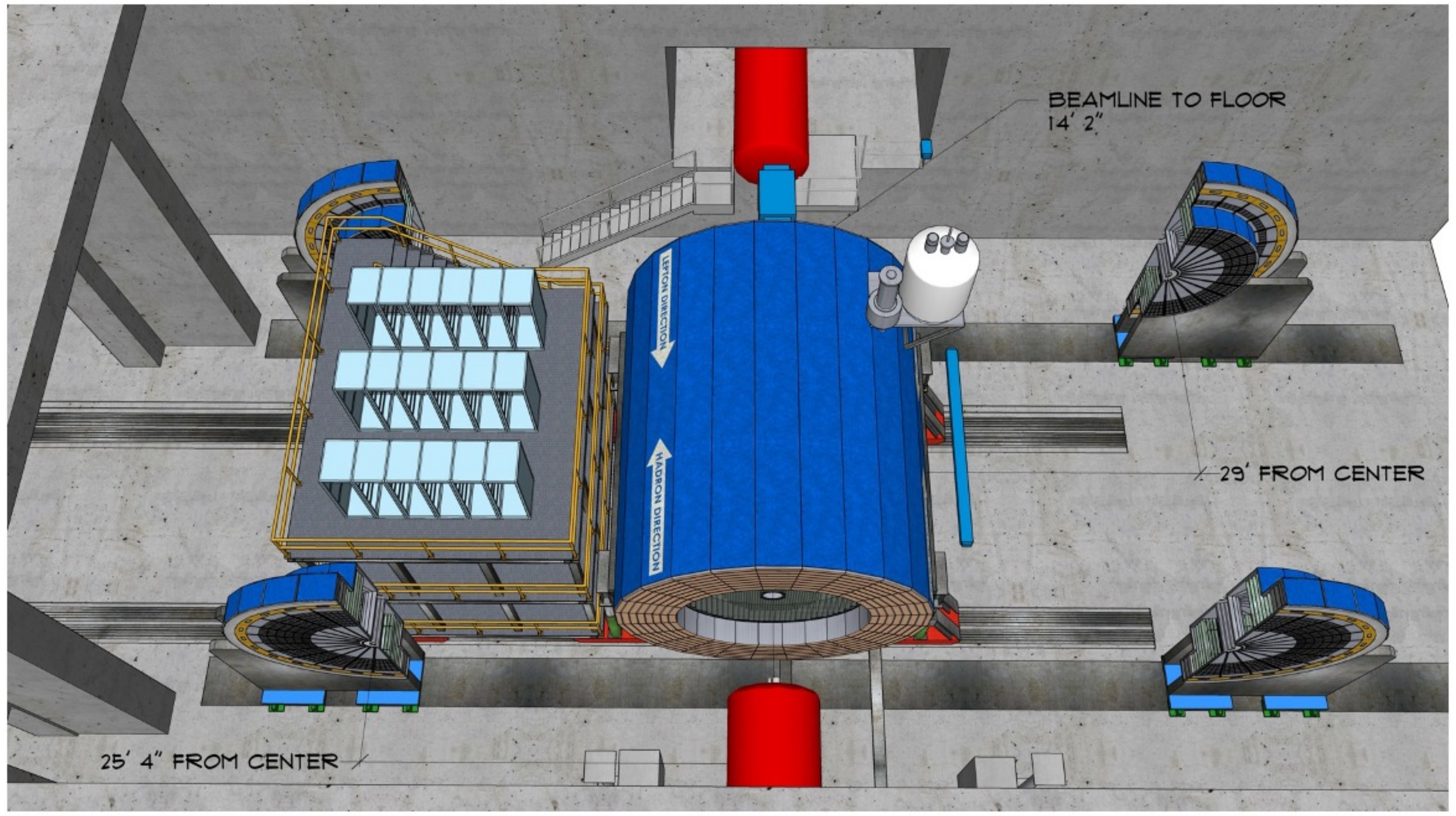
ATHENA: **A** **T**otally **HE**rmetic **E**lectron-**N**ucleus **A**pparatus

- Based on new magnet (≳ 3T) and Yellow Report reference detector
  - 3.6m long, 1.6m inner bore
  - Solenoidal and Hemholtz design under discussion
  - Optimize projectivity (tracking) at forward rapidities

- Concept presented at CD-1 review of the EIC and is included in the CDR
  - Major change TPC → Si Tracker + MPGD







Technology Readiness and R&D Efforts

Status

- Successful ***Generic EIC Detector R&D Program*** since 2011 (ends 9/2021)
- Funded by DOE through RHIC operations funds (~ 1M$/year)
- Over 281 participants from 75 institutions (37 non-US)
- Most technologies for the reference EIC detector are all established or in reach
  - need to complete R&D on several topics (~2 years)
  - some development will take longer: Si-sensors (DMAPS, AC-LGAD), Electronics (ASICS)
  - for most subsystems large scale prototypes are desirable

Next

- Targeted (project funded R&D) starting soon
- New Detector Advisory Committee (DAC)
- What gets supported ultimately depend on proposals and decisions
- Strong desire to continue with generic R&D for future upgrades (Labs?)

Example 1: Si-Vertex

Requirements:

- Spatial resolution: ~5 µm (20 µm pixel pitch), material budget: < 0.3% X/X_0 per layer, Integration time ~2 µs, low power consumption (air cooling)

Conclusions:

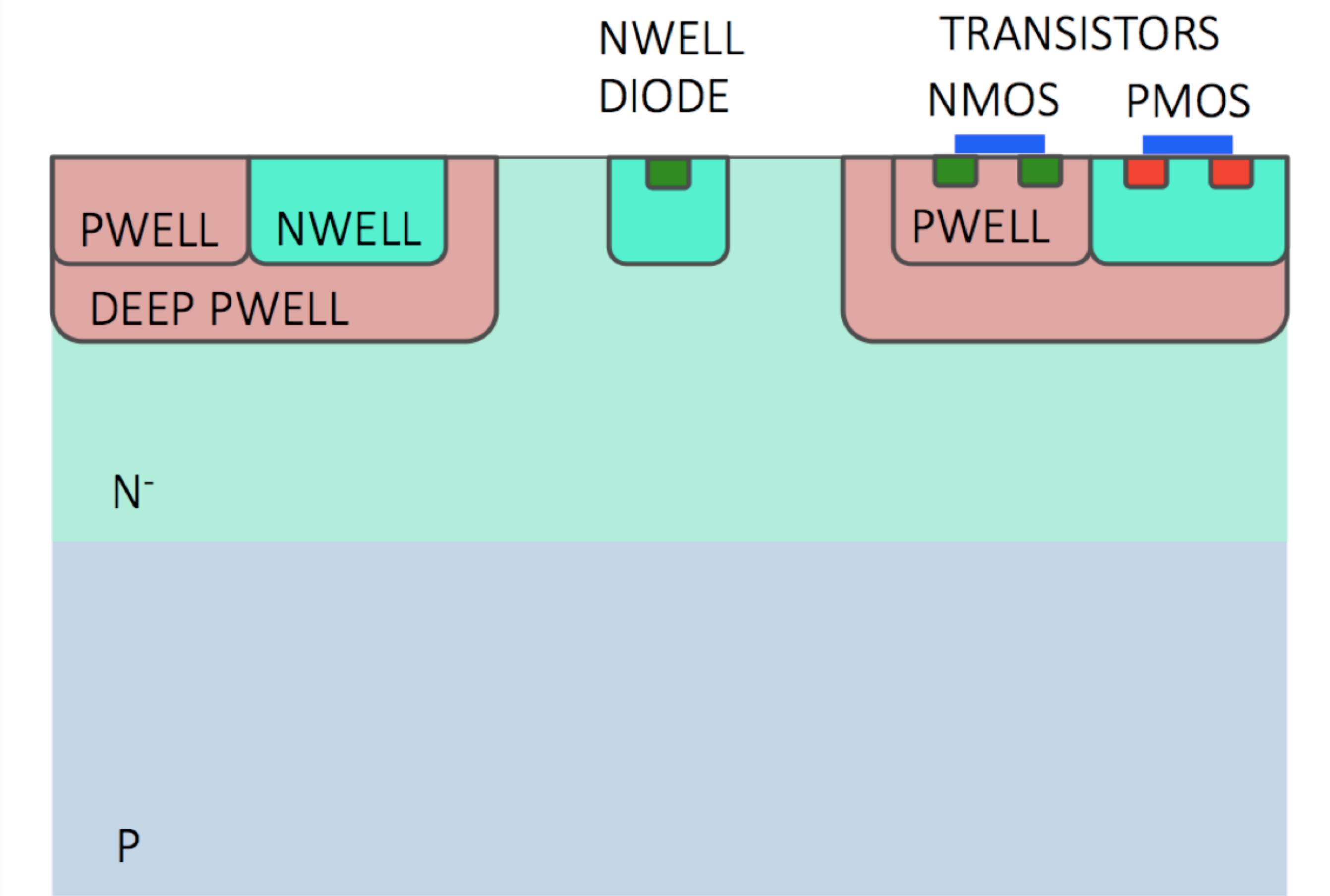
- Consensus that technology of choice is MAPS/DMAPS
- None of the existing MAPS sensors meets all of the requirements
- Existing ALPIDE chip, with some smaller modification is a reasonable candidate
- A dedicated EIC MAPS sensor is desired solution ⇒ generic R&D

Strategy:

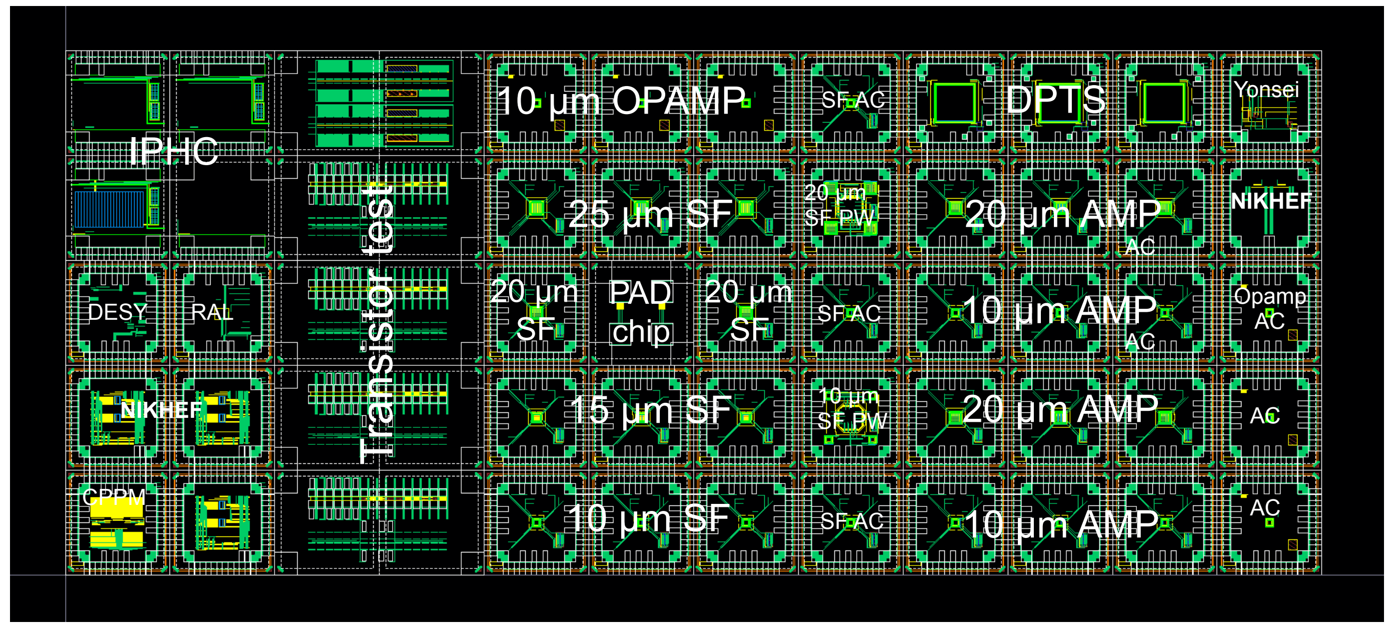
- Join ALICE ITS3 collaboration to develop new generation MAPS sensors in 65 nm CMOS imaging technology (1st MLR run 11/2020)
- Leverage on a large effort at CERN
- EIC sensor development needs to fork-off later to develop an ITS3-derived EIC MAPS sensor for outer layers (non stitched wafer-scale sensors)

DMAPS

- Advantage of depletion: charge collection by drift ⇒ larger Q, fast collection, small cluster multiplicity



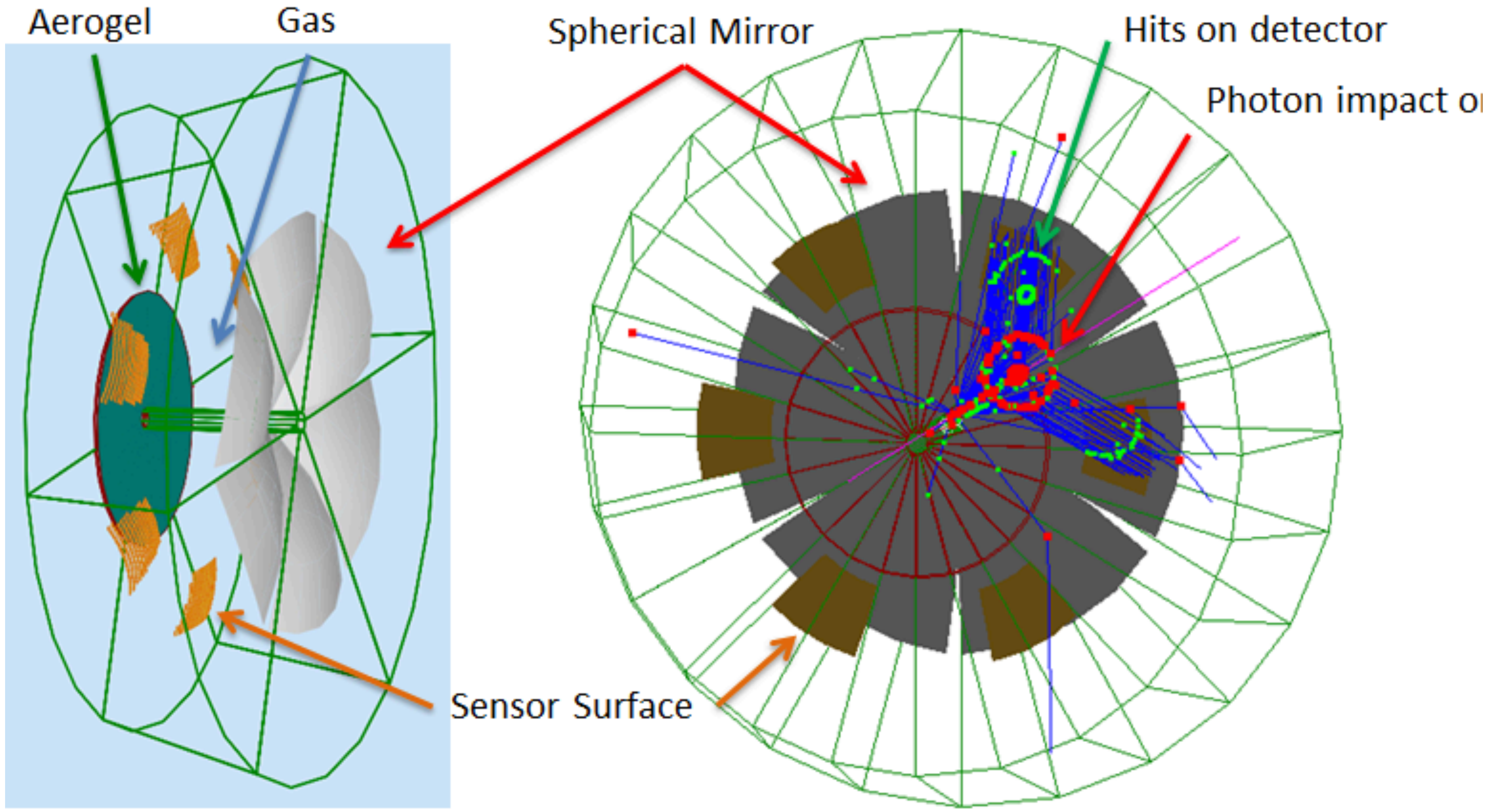
Modified pixel structure

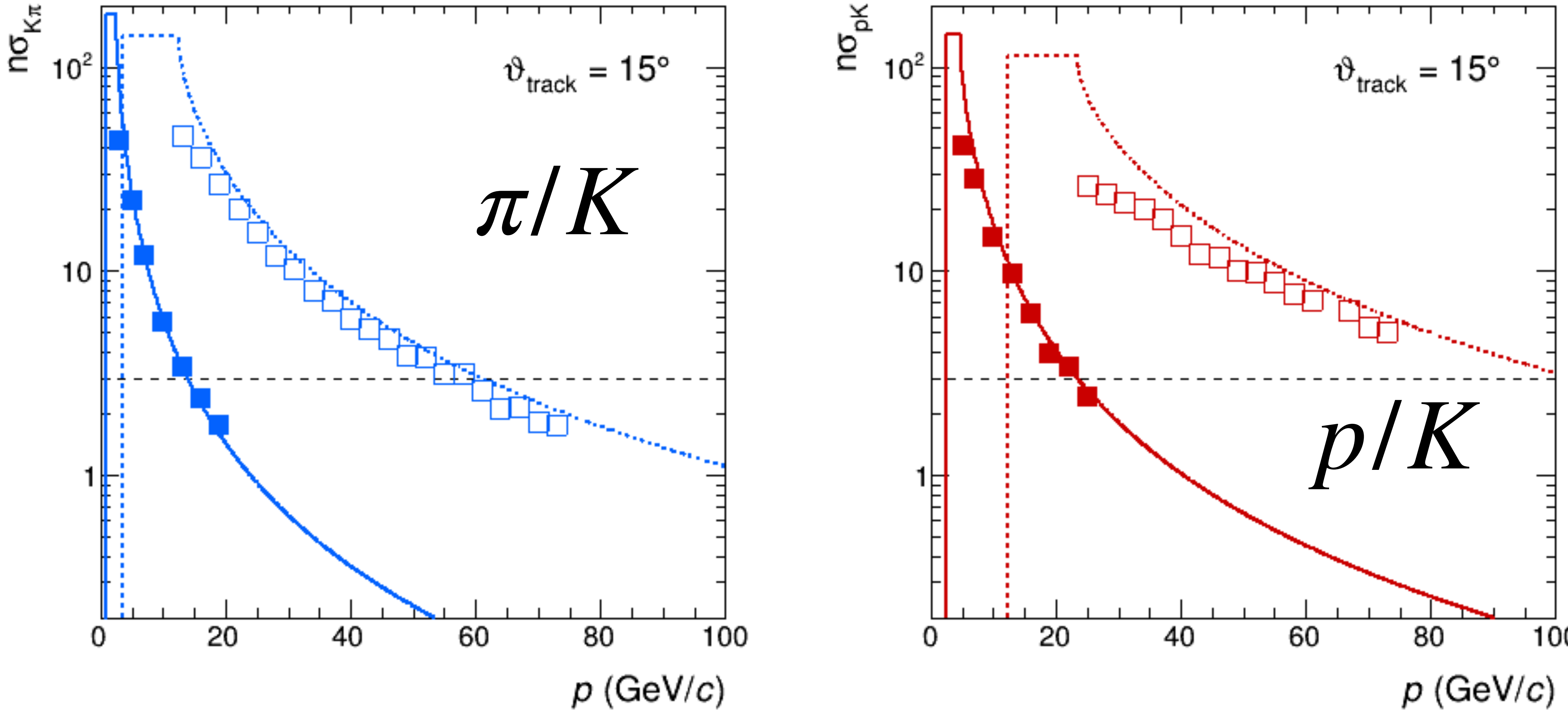


First MLR run of ITS3 chip submitted 11/2020

Example 2: Dual RICH Detector

- First dRICH for use in solenoidal field
- dRICH is compact and cost-effective solution for continuous momentum coverage (3-60 GeV/c)
- Combination of C_2F_6 gas and n=1.02 aerogel
- Outward-reflecting mirrors reduce backgrounds and (UV) scattering in aerogel
- Requires sophisticated 3D focusing to reduce photosensor area
- 2020/21: realize first prototype

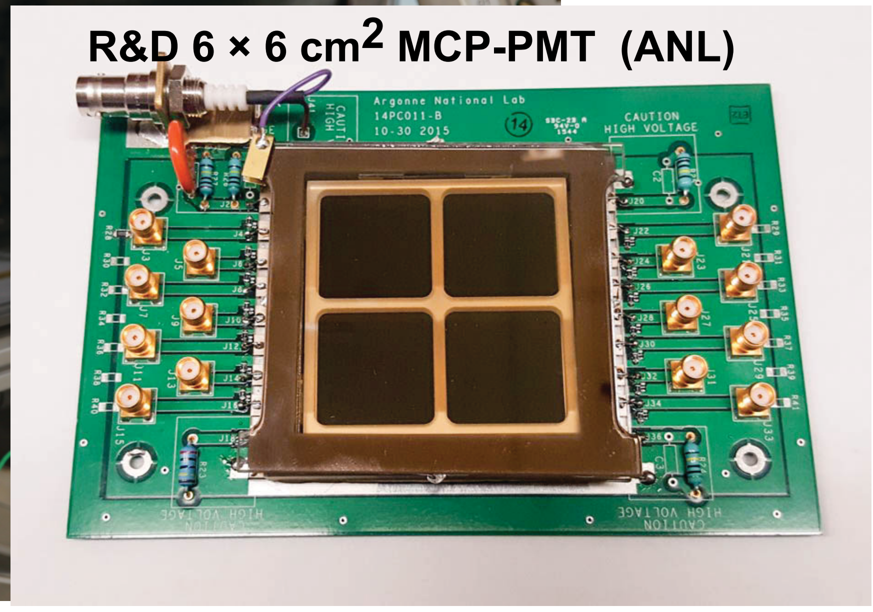


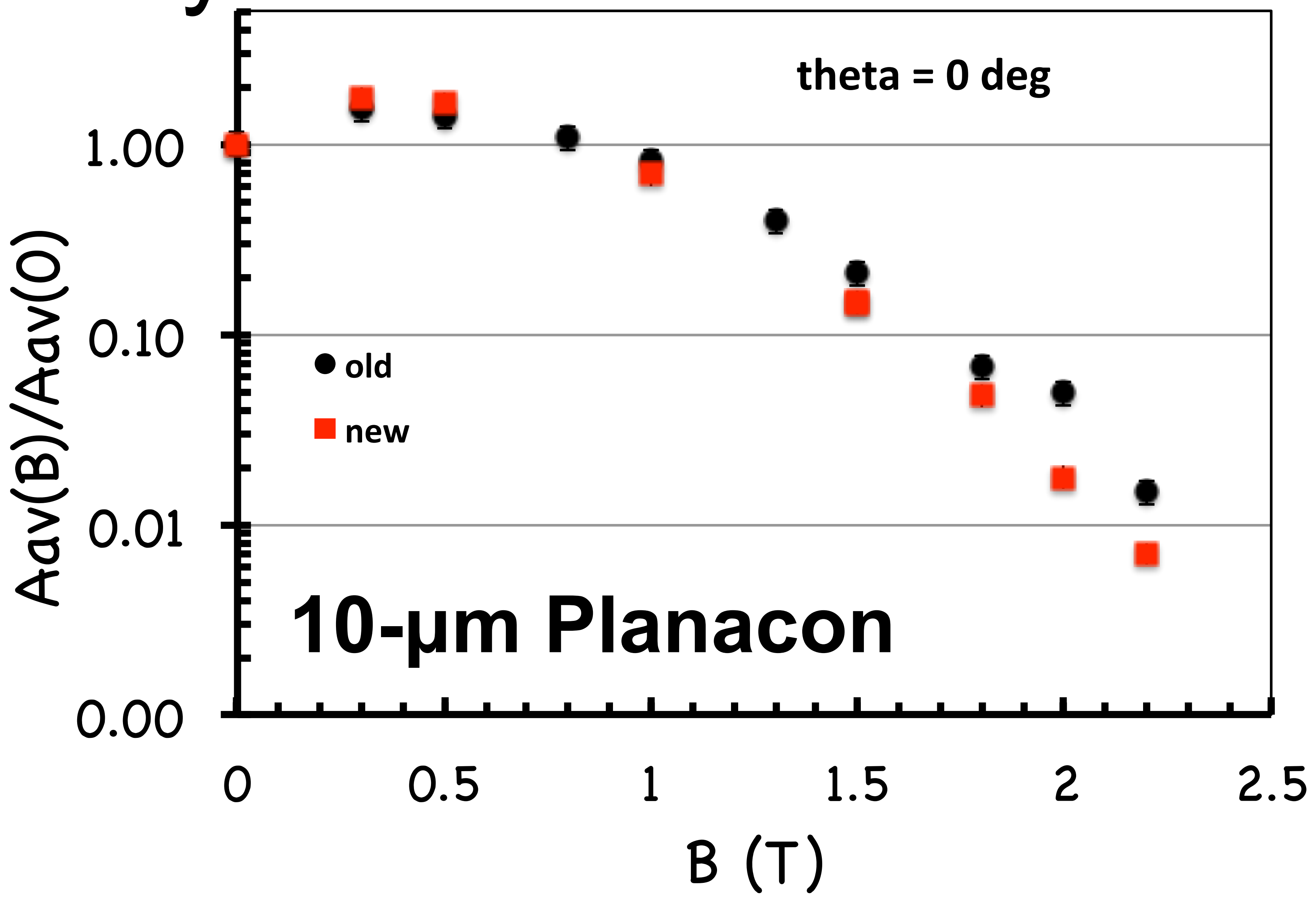


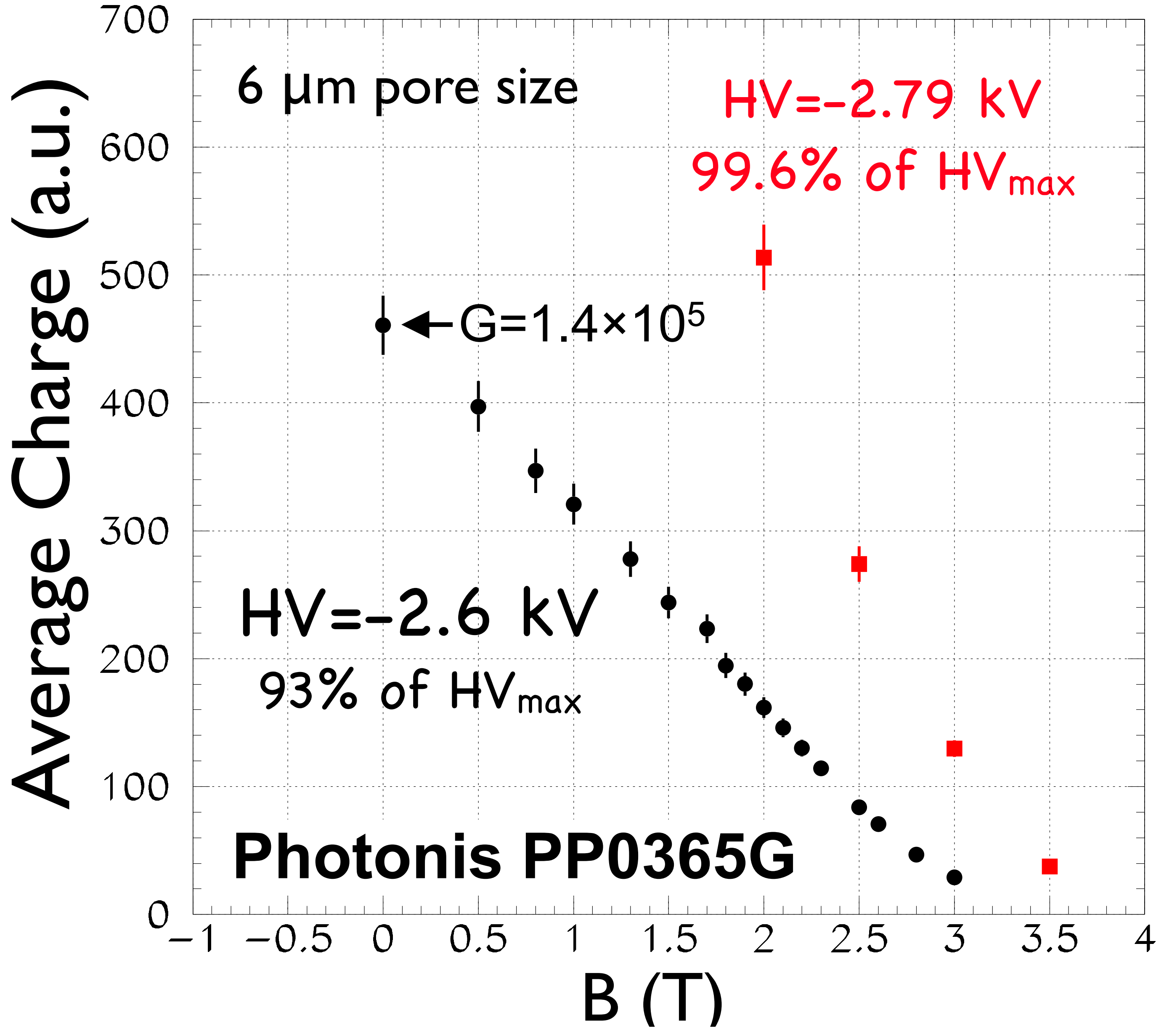
L. Barion et al., JINST 15 (2020) 02, C02040
E. Cisbani et al., JINST 15 (2020) 05, P05009

Challenges: Photodetectors

- Photo Detectors: Big challenge is to provide a reliable highly-pixilated photodetector working at 1.5-3 Tesla. This problem is not fully solved yet.
  - **SiPMT**s: in the past rejected for RICH detectors due to sensitivity to noise. Dedicated studies underway.
  - **MCP-PMT**s:
    - Very expensive
    - Not tolerant to magnetic fields



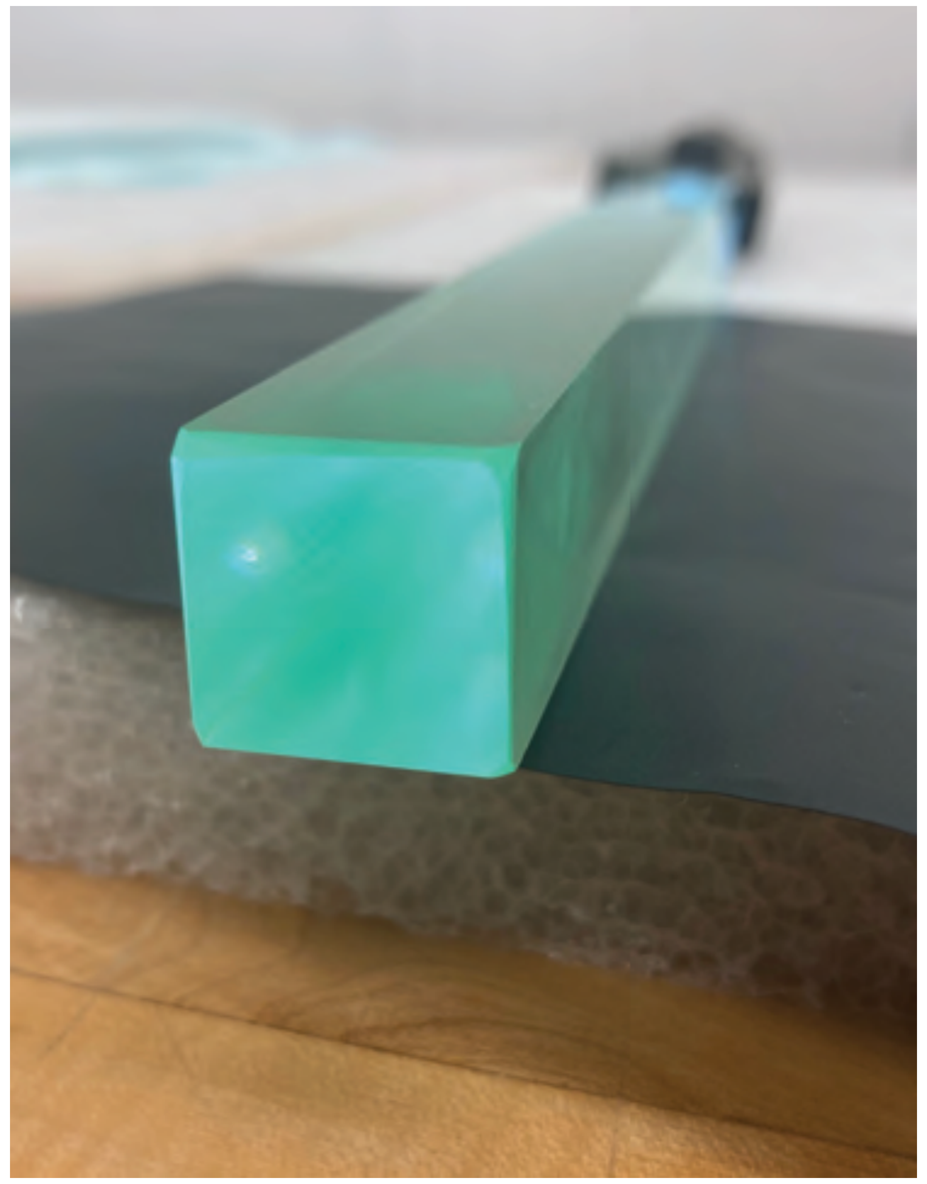




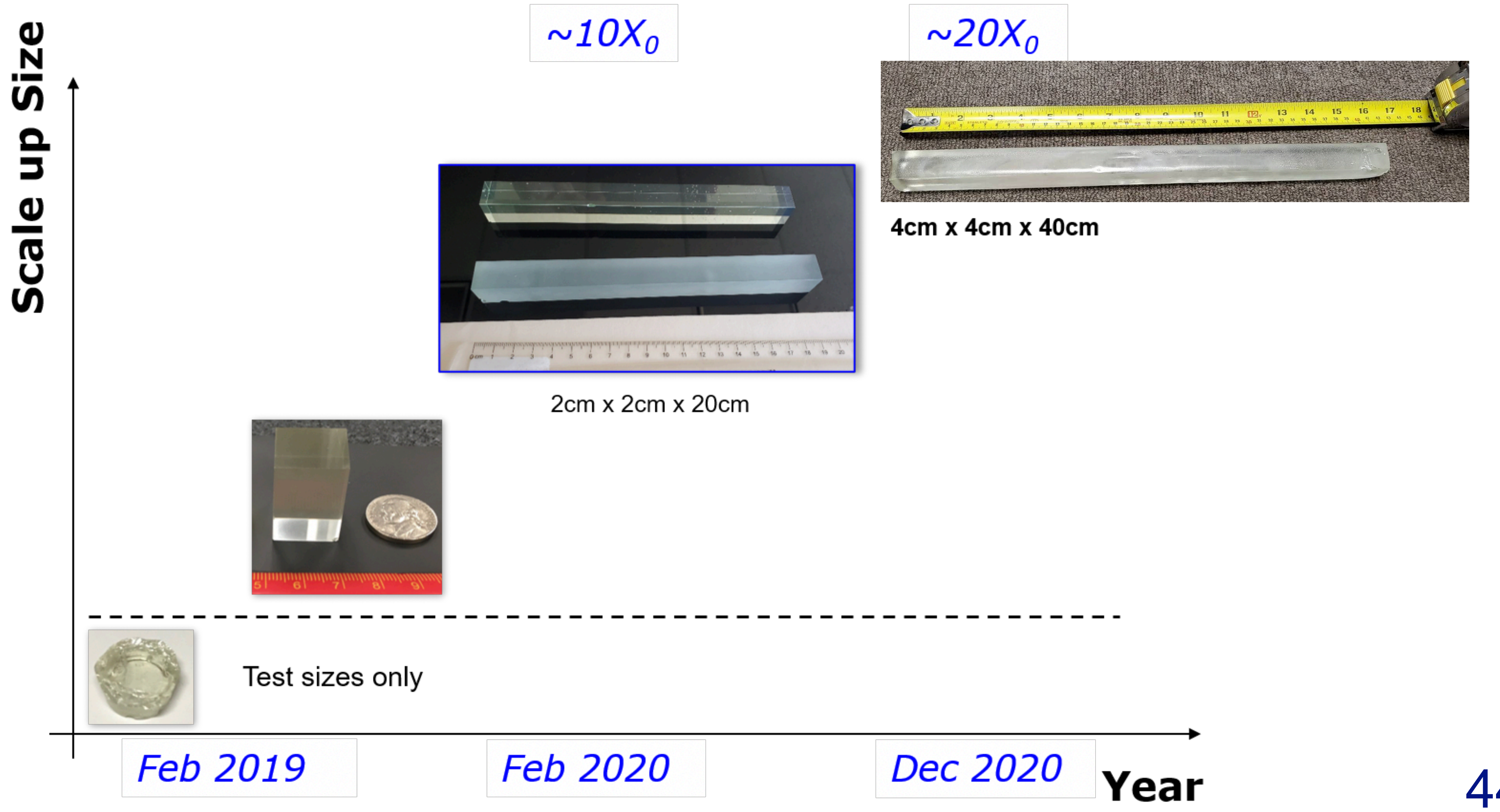
- Large-Area Picosecond PhotoDetector (**LAPPD**)
  - Promising but still not fully applicable for EIC yet
  - Need pixelation, efforts underway

Example 3: Scintillating Glasses

- e-going direction needs high precision calorimetry ($\lesssim 2\%/\sqrt{E}$)
- Typically requires Lead Tungstate ($PbWO_4$) crystals
- Crystals are expensive, few vendors (SICCAS, CRYTUR)
  - Quality and QA issues
  - Moderate production capacity, raw material shortage
- R&D: Scintillating glasses (CUA/Vitreous State Laboratory)
  - Similar to lead glass in many properties but exhibit >30× the light yield per GeV



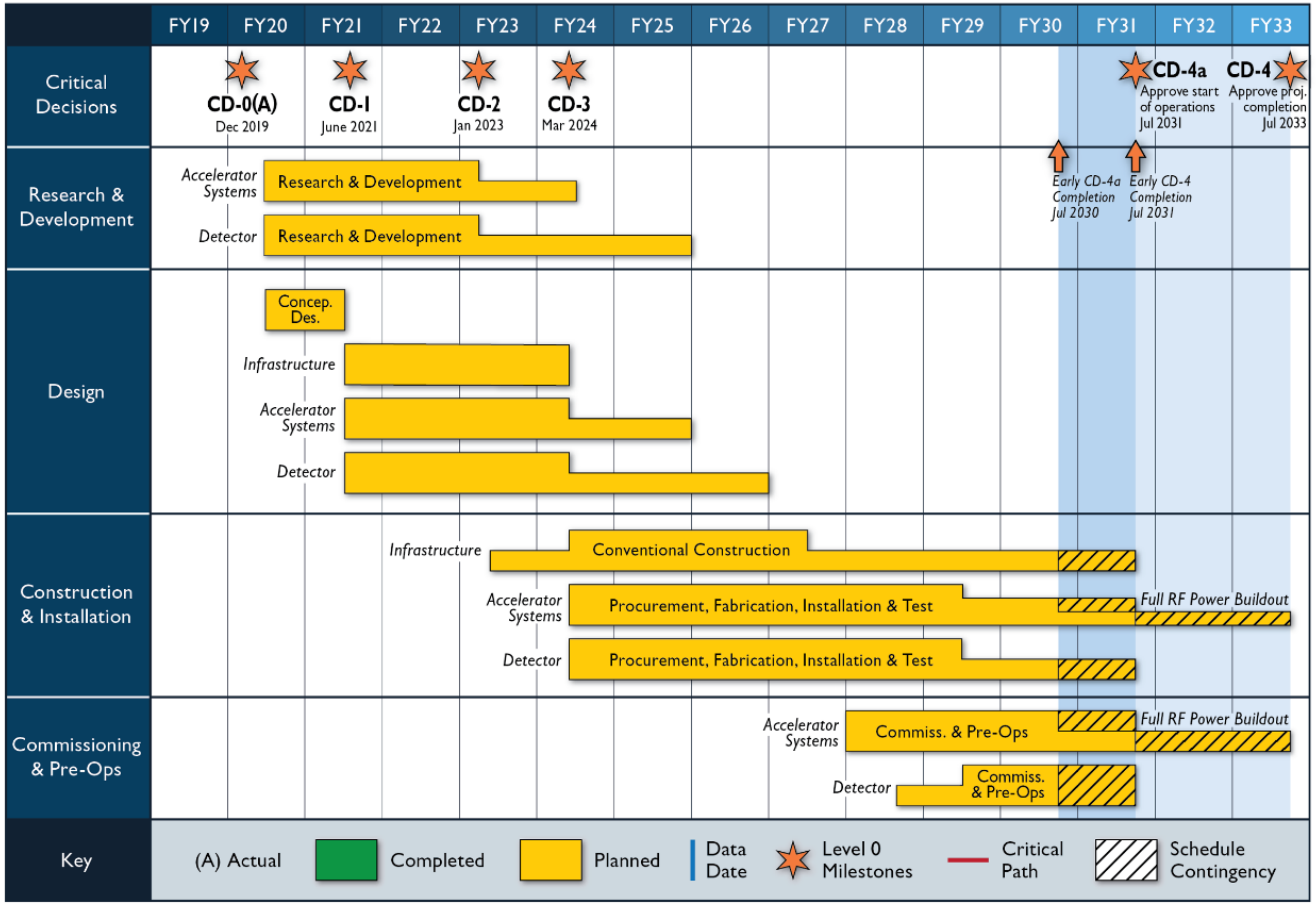
- Path to inexpensive high resolution EM calorimeters
  - 40 cm long bars will match $PbWO_4$ resolution (achieved 12/2020)
  - Radiation test very positive



EIC Future in Dates and Numbers

- <u>Milestones</u>
  - CD-2 April 2023
  - CD-3 December 2024
    - Design frozen
    - Construction funds start flowing
  - CD-4a December 2031
    - start of operation
  - CD-4 December 2033
    - completion of project

So far, all well on track!



Since you will ask anyway: Total Project Cost $2,249M includes 40% contingency ($643M)

Take Away Message

- An Electron-Ion Collider will contribute profoundly to the understanding of matter and be an important component in our suite of tools to revolutionize our knowledge in the next decades
- Machine design well established
  - Meets all requirements: high luminosity, polarized electron and light hadron beams, a wide range in center of mass energies, hadron beams with highest A
- EIC Detectors are unique and challenging
  - Hermiticity (forward and backward coverage) & Precision
  - EIC R&D program is a vital part of the EIC efforts
  - Most technologies at hand or in reach (many ideas for future)
    - Physics requirements and detector concepts developed for Yellow Report
- Three proto-collaboration compete for two IR's
  - ATHENA, CORE, and ECCE
  - Healthy, collaborative community
  - Funding challenging for second