Potential of a TeV scale muon-ion collider

SYSU-PKU collider physics forum
November 09, 2022

左训午 (KIT)

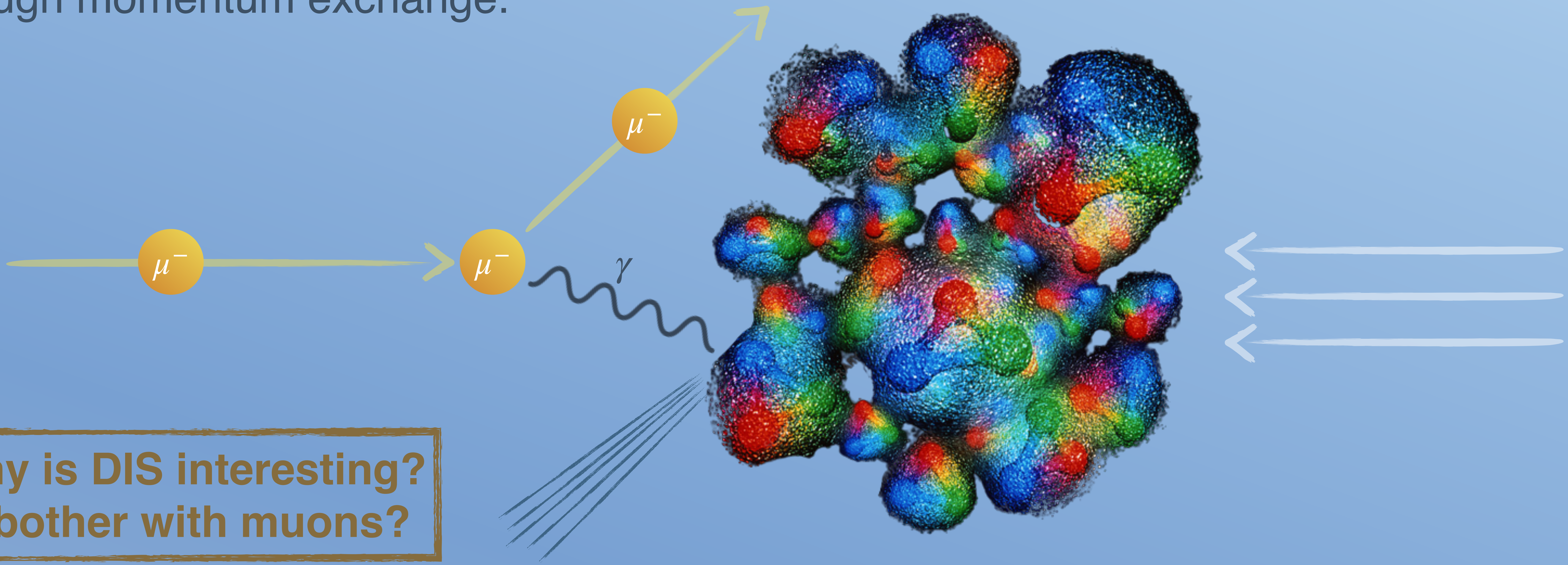
Based on:

- D. Acosta, W. Li, Nucl. Inst. Meth. A 1027 (2022) 166334
- D. Acosta, E. Barberis, N. Hurley, W. Li, O. M. Colin, D. Wood, X. Zuo, Snowmass 2021 white paper

Muon-ion collision

Typical process - deep inelastic scattering (DIS)

- Scattered lepton (neutrino) and quark in forward directions.
- In case of sufficient center-of-mass energy, production of other particles through momentum exchange.



Ok, but why is DIS interesting?
And why bother with muons?

Muon-ion collision

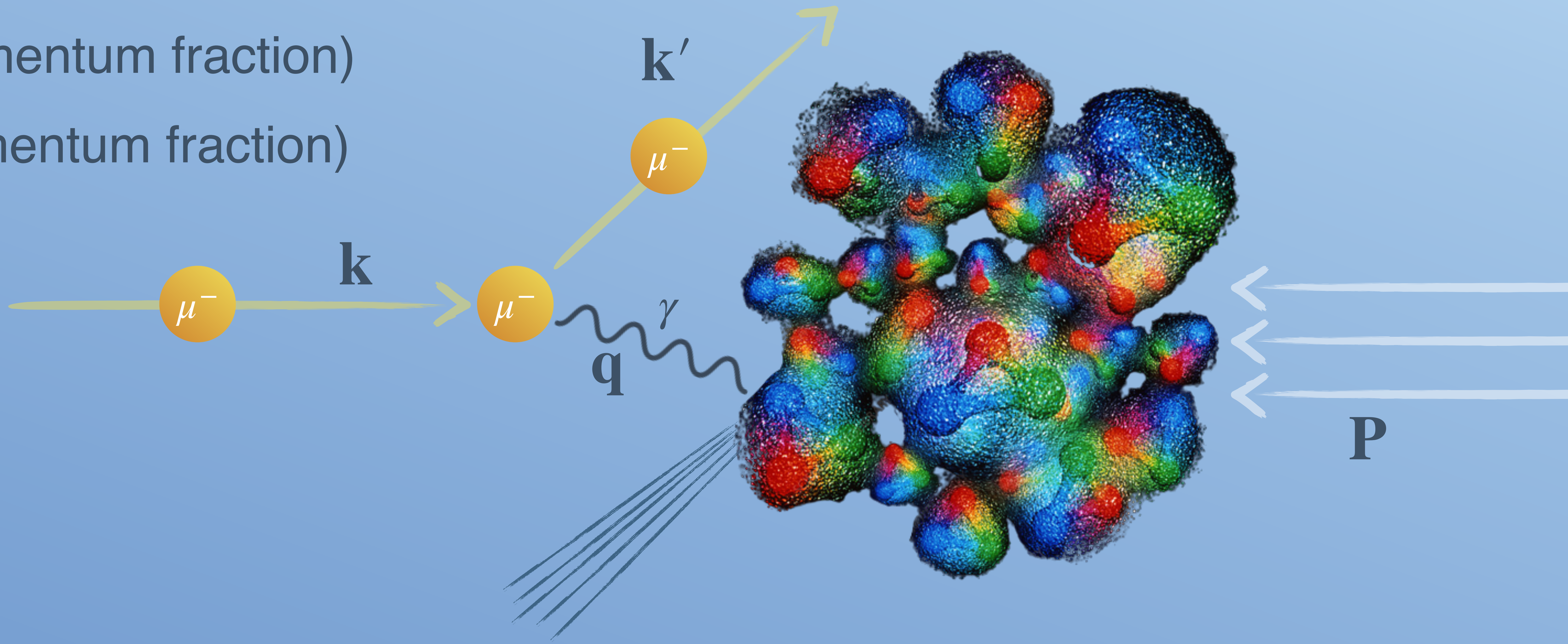
Physics descriptions:

- s - squared center-of-mass energy
- Q^2 - squared four-momentum transfer
- x - Bjorken scaling (parton momentum fraction)
- y - Bjorken scaling (lepton momentum fraction)

$$s = 4|\mathbf{k}||\mathbf{P}|$$

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

$$x = \frac{Q^2}{2\mathbf{P}\cdot\mathbf{q}}, \quad y = \frac{\mathbf{P}\cdot\mathbf{q}}{\mathbf{P}\cdot\mathbf{k}}$$



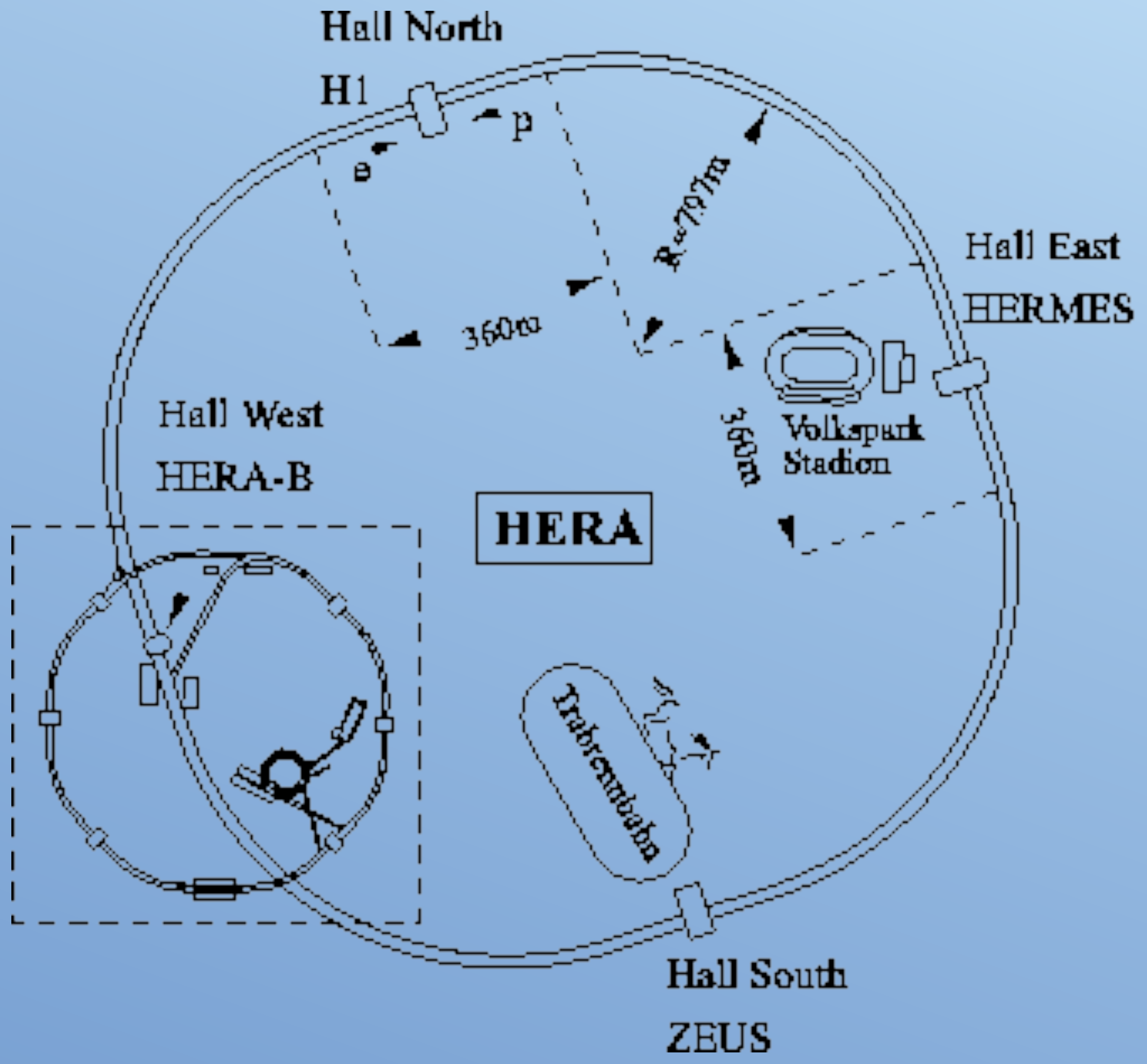
Prelude - legacy from HERA

Electron-proton experiment at DESY

- 6.3 km storage ring
- E_e 27.5 GeV $\times$ E_p 920 GeV ($\sqrt{s} \sim 318$ GeV)
- 2 collider experiments (H1 and ZEUS)
- 500 pb^{-1} from each experiment (1992 - 2007)

HERA provided profound understandings of **proton structure** and **QCD physics**

- Paved the way for precision measurements at the LHC



Prelude - legacy from HERA

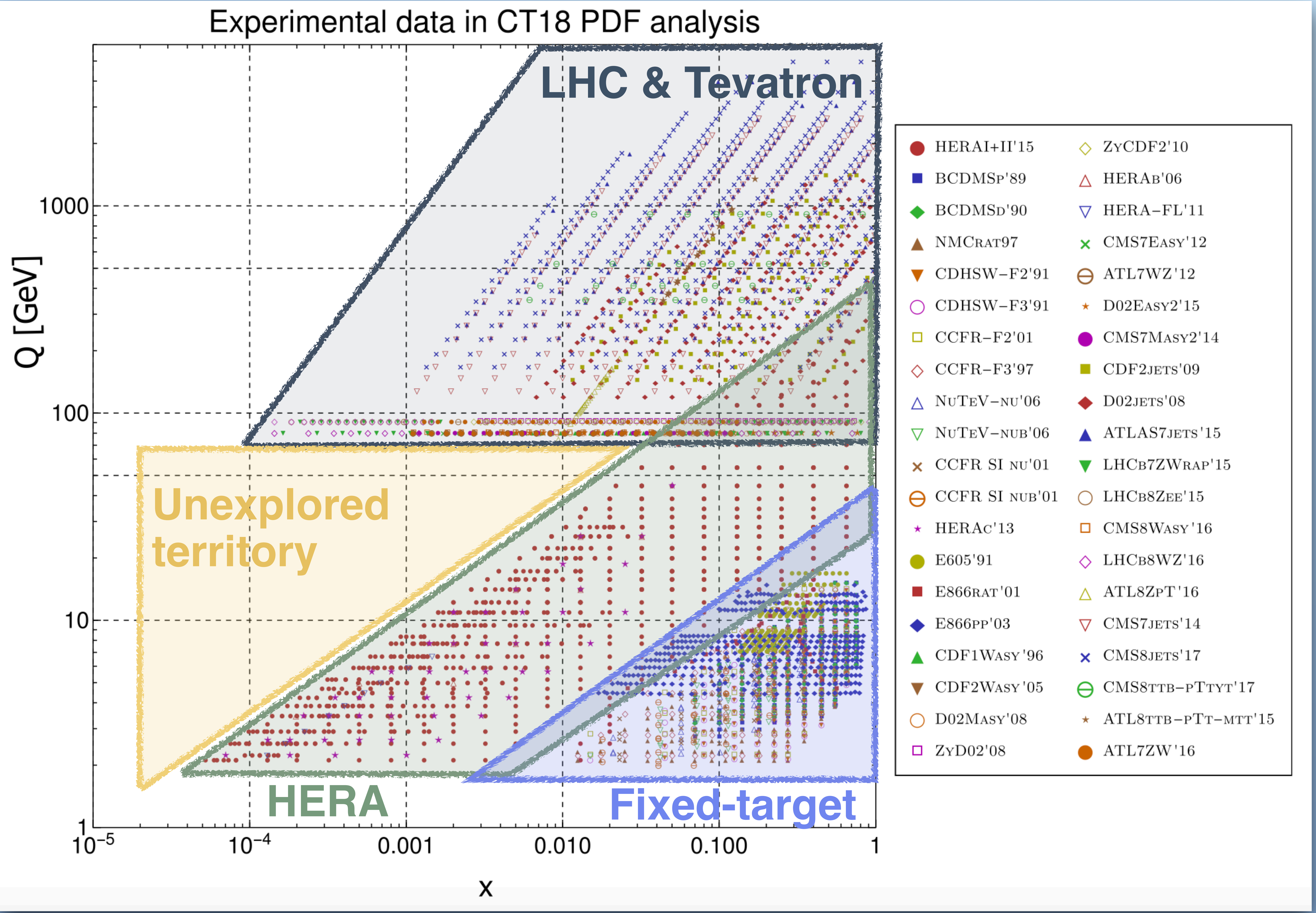
[CTEQ global fit]

HERA data are still crucial inputs to QCD fits nowadays

LHC also measures PDF, with caveats:

- Need SM (DY, top) cross sections to measure PDF, and need PDF to for SM cross sections
- Cannot decouple from complicated QCD processes
- Varying PDFs from both sides

Constrain one side with HERA PDF and measure the other



xunwu.zuo@cern.ch

Prelude - legacy from HERA

Gluon saturation: gluon density increases dramatically toward small x and reaches an equilibrium at some scale

❖ Questions to be answered by more DIS experiments

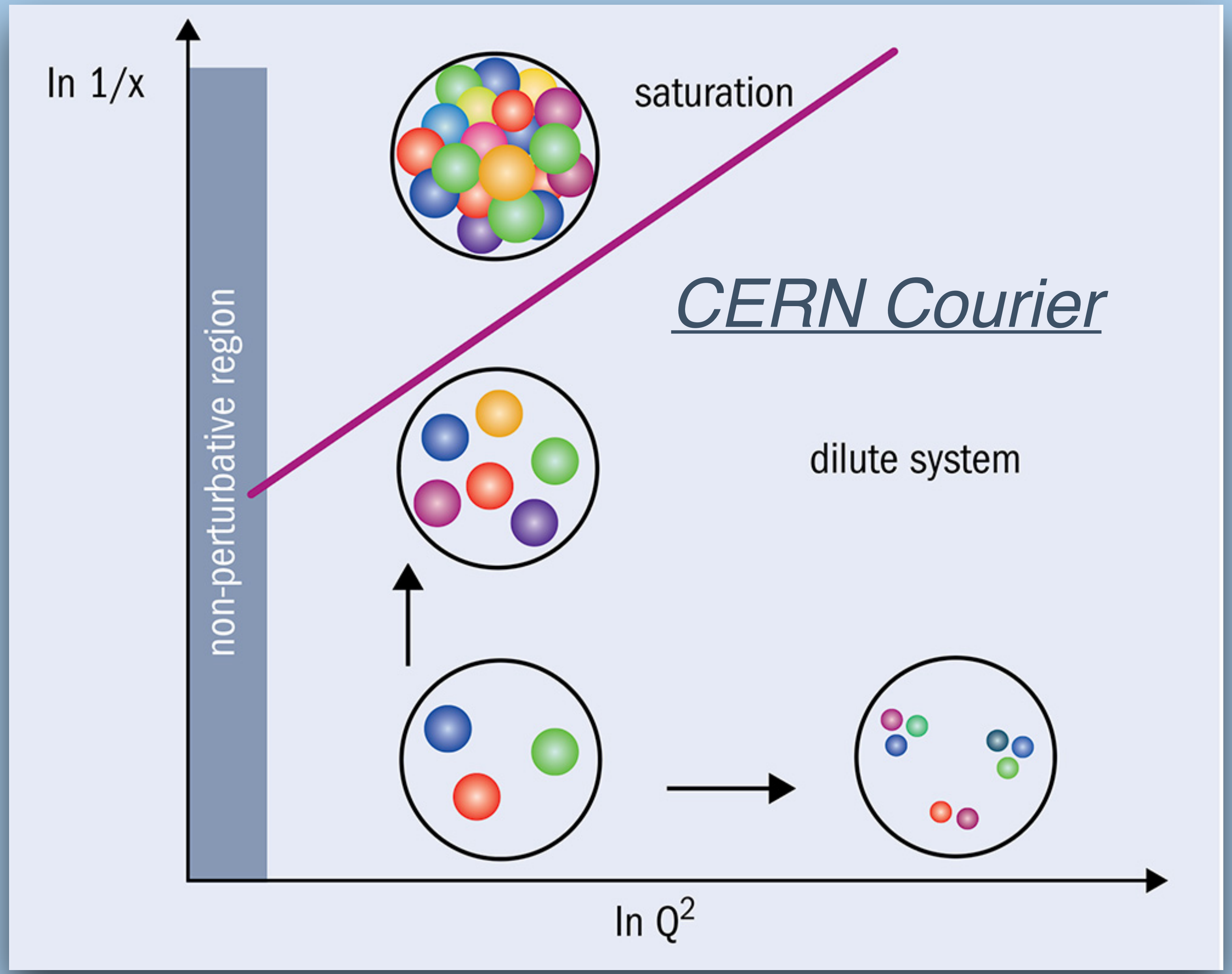
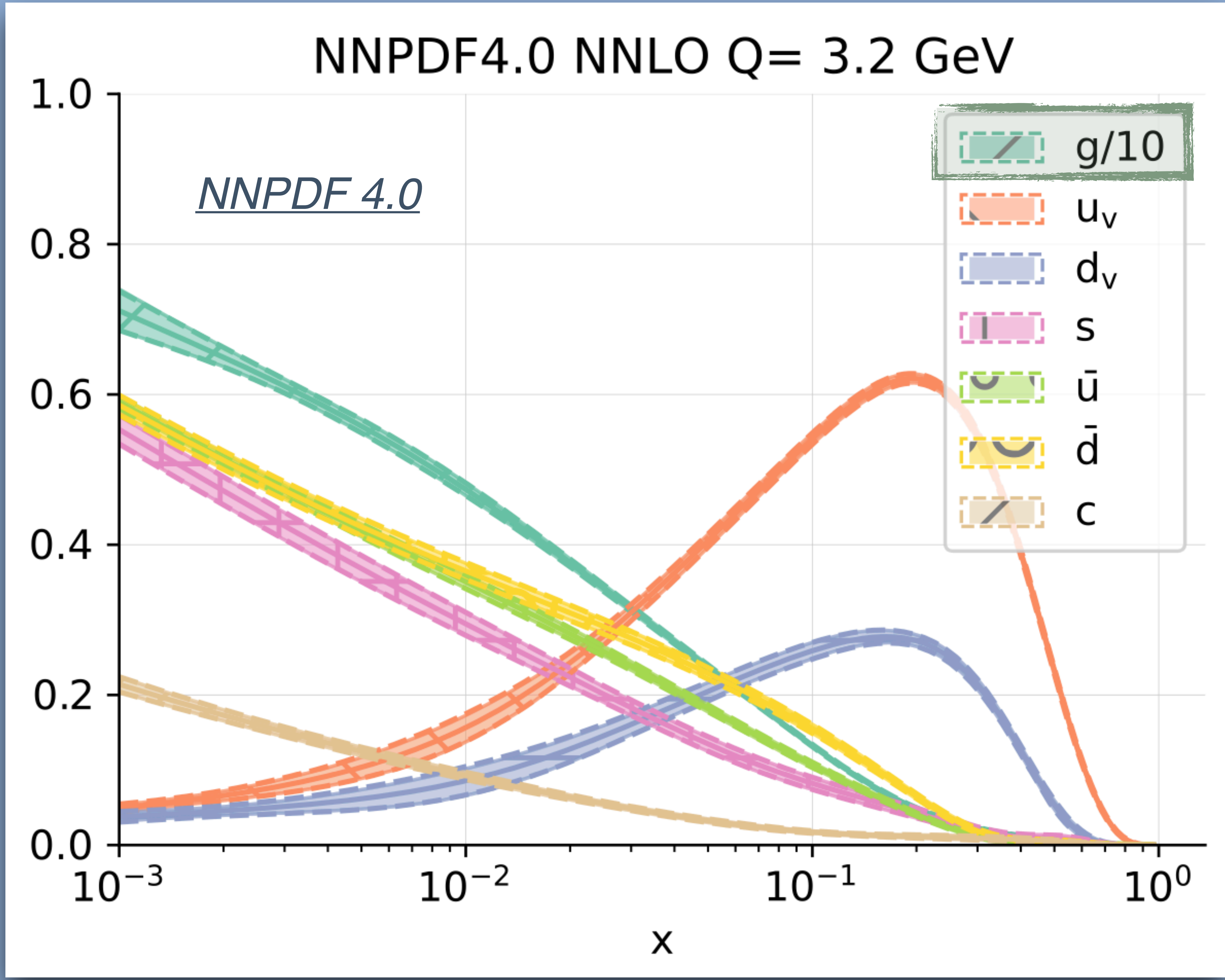


Illustration: gluon saturation

Example of proton PDF



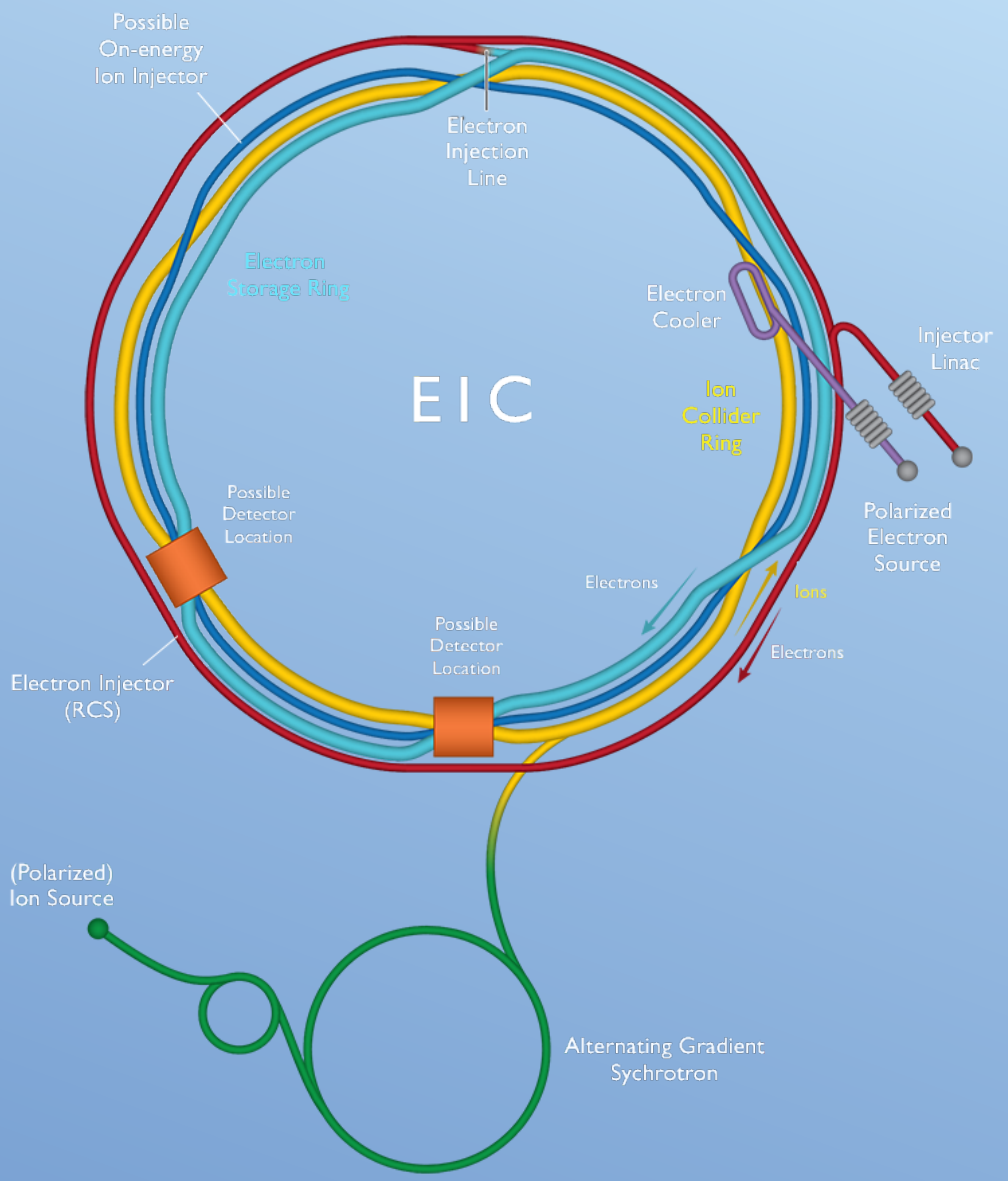
Prelude - physics at EIC

Electron-proton/ion experiment planned at BNL

- 3.8 km storage ring
- $E_e \rightarrow 18$ GeV $\times E_p \rightarrow 275$ GeV ($\sqrt{s} \sim 140$ GeV)
- Polarization of both beams

Steady progresses toward construction, expect data-taking in 2030s

- $L_{inst} = 10^{33} - 10^{34}$ cm^{-2}s^{-1}
- 100-1000 fb^{-1} in 10 years



Prelude - physics at EIC

Some highlights in QCD and nuclear physics

❖ Proton and nucleon structure

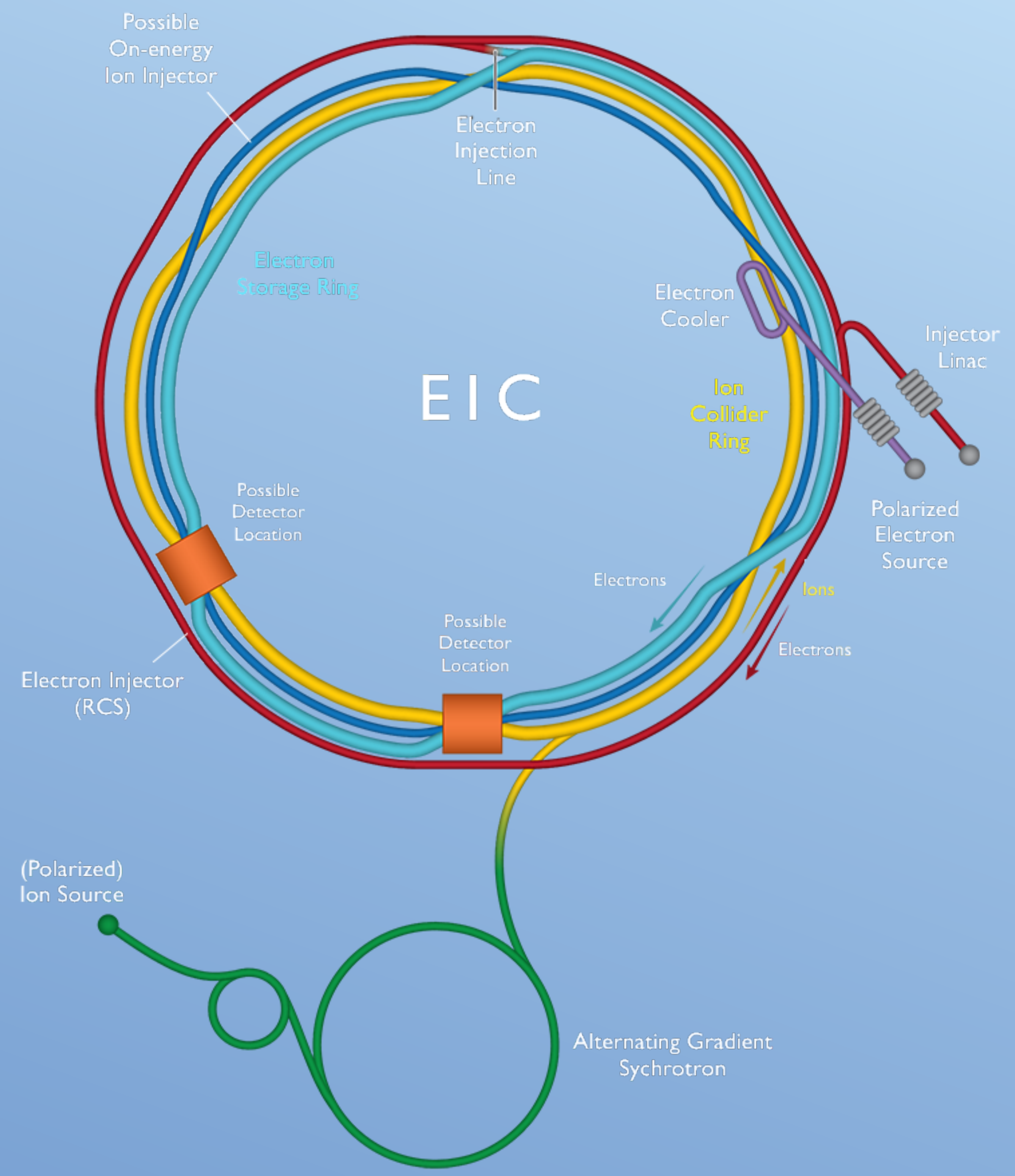
❖ Gluon saturation scale and mechanism

❖ Proton and nucleon spin

EIC white paper

Proton spin "crisis"

- Valence quark polarization accounts only for ~30% of proton spin
- Gluon polarization contributes ~20% (with large uncertainties)
- Sea quarks seem unpolarized
- What about the rest? (orbital angular momentum?)



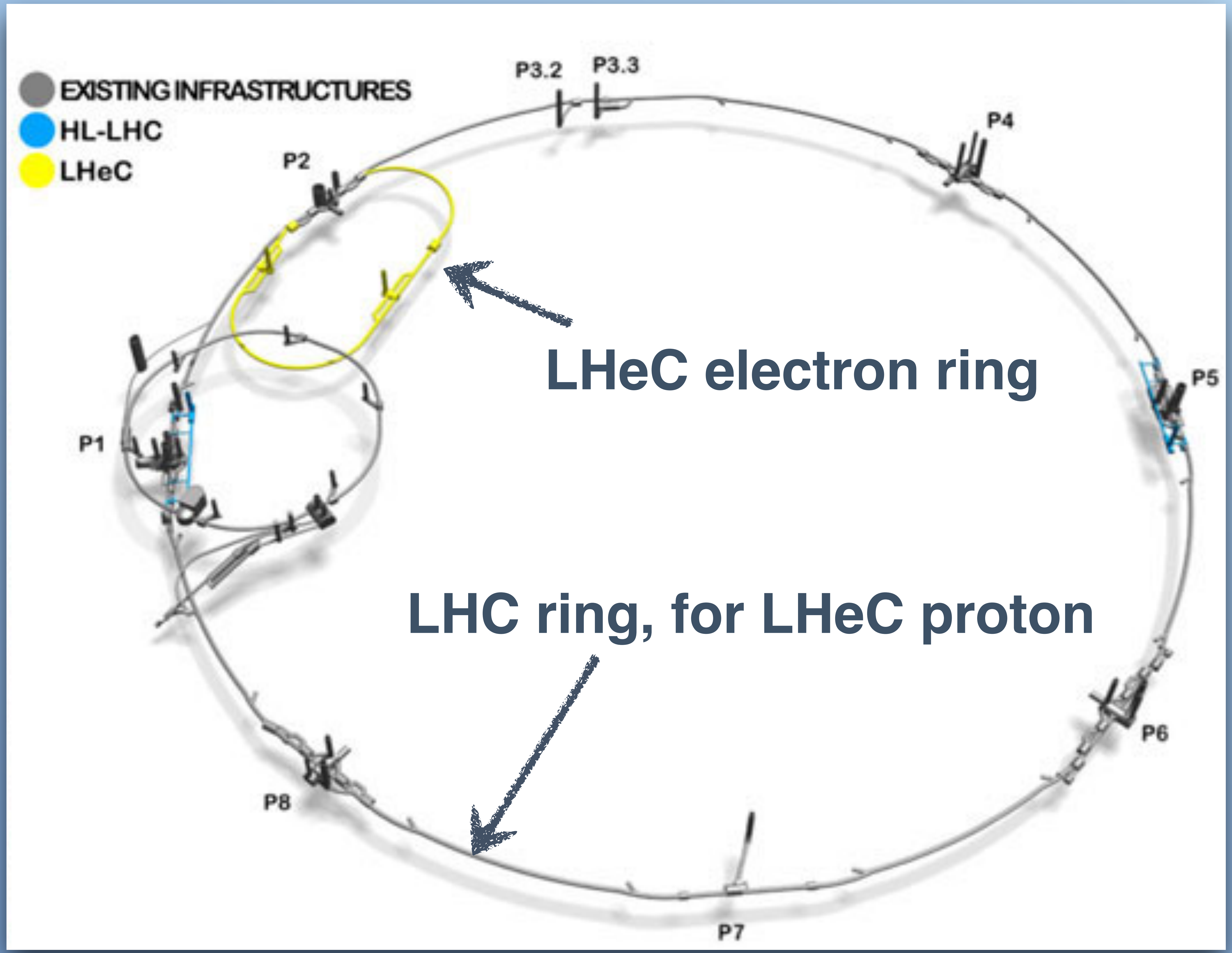
Prelude - the LHeC proposal

Electron-proton experiment proposed at CERN

- Existing LHC proton beam
- Extra electron ring
  - Total circ. 8.9 km, bending radius 550 m
- E_e 50 GeV × E_p 7 TeV ($\sqrt{s} \sim 1.2$ TeV)
- Concurrent with HL-LHC
  - Replace ALICE detector
  - Expect ~1 ab^{-1}

MuIC expect to have very similar $\sqrt{s}$ and physics case to LHeC

(More comparisons in the rest of the talk)



Prelude - muon colliders

Muon-antimuon collision

- Much higher energy reach than electron beams
- Much cleaner environment than proton collisions

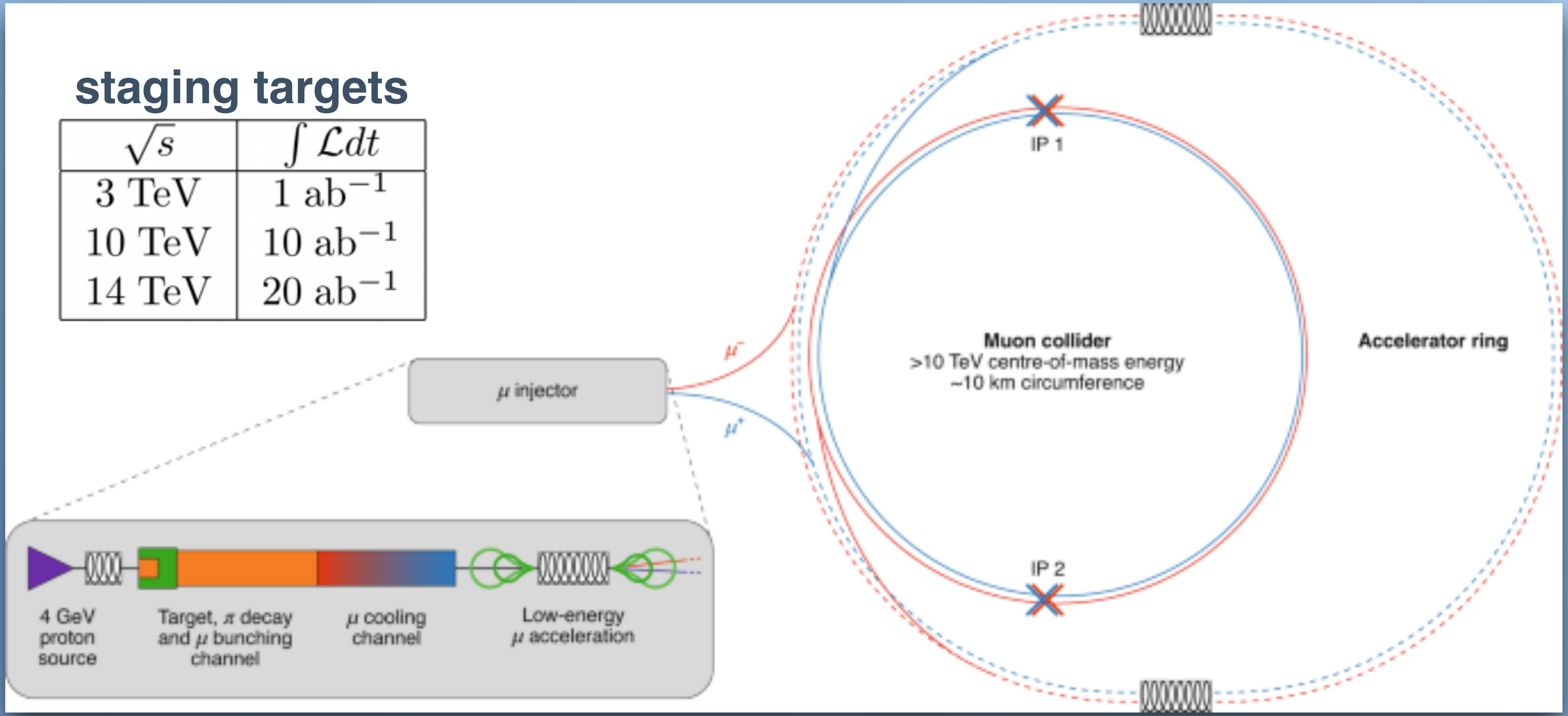
More information in talks from this series by *C. Zhang* and *K. Xie* and *X. Wang*

Very appealing idea, but a long way to go

- Only preferable to e^+e^- at very high energy
- Need to increase muon beam energy from currently available ones of O(10) GeV to the goal over 1 TeV

staging targets

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}



Now, the MuIC proposal

Wide coverage of physics topics, from nuclear physics to high energy physics

- Nucleon structure, spin structure
- QCD precision measurements, gluon saturation
- EW/Higgs/top production, BSM searches

Comparing to HERA and EIC

- Much higher $\sqrt{s}$
- better reach for high Q^2 and low x
- potential for HEP topics

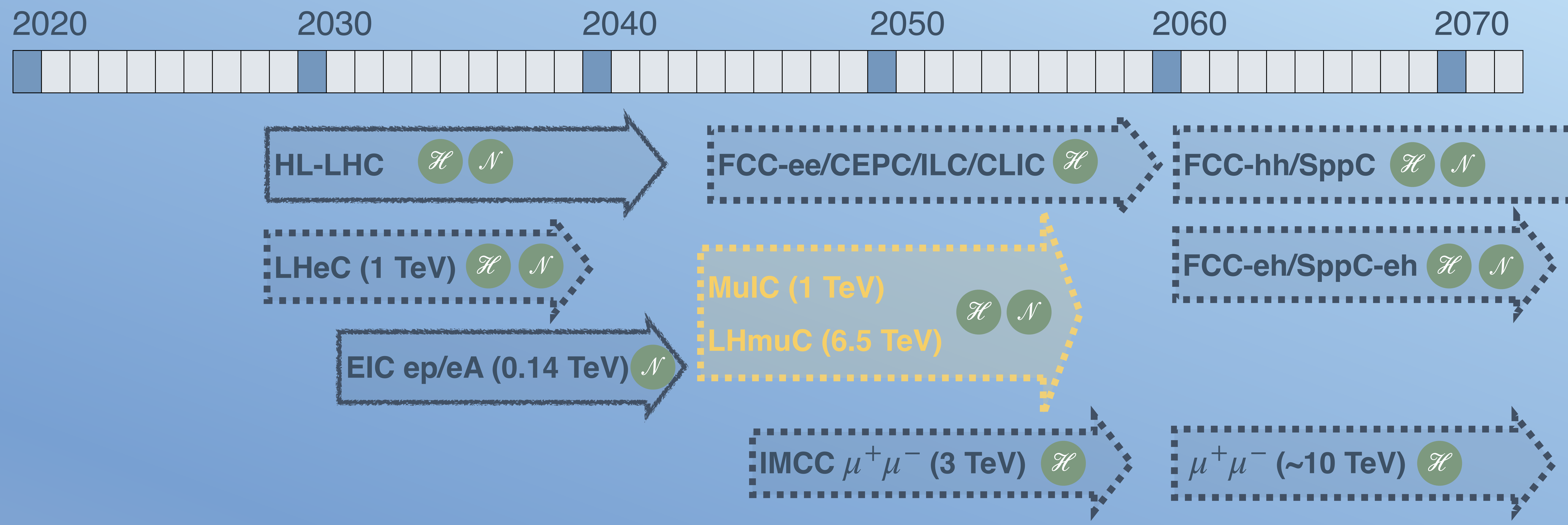
Comparing to LHeC

- Similar physics potential
- Better-balanced beam energies (better separation of final products)
- Potential to upgrade LHeC to LHmuC

Comparing to muon colliders

- Rich physics outputs starting from E_μ ~100 GeV
- Use existing infrastructure, can run concurrently with mega projects like FCC/CEPC
- R&D benefits muon colliders

A landscape of collider possibilities



Note:

$\mathscr{H}$ - High energy physics

$\mathscr{N}$ - Nuclear physics

The muon-ion option:

❖ Rich, and some unique, physics programs

❖ Can be concurrent with other mega projects

Outline

Conceptual design

- Benchmark configurations
- Detector requirements

Physics cases

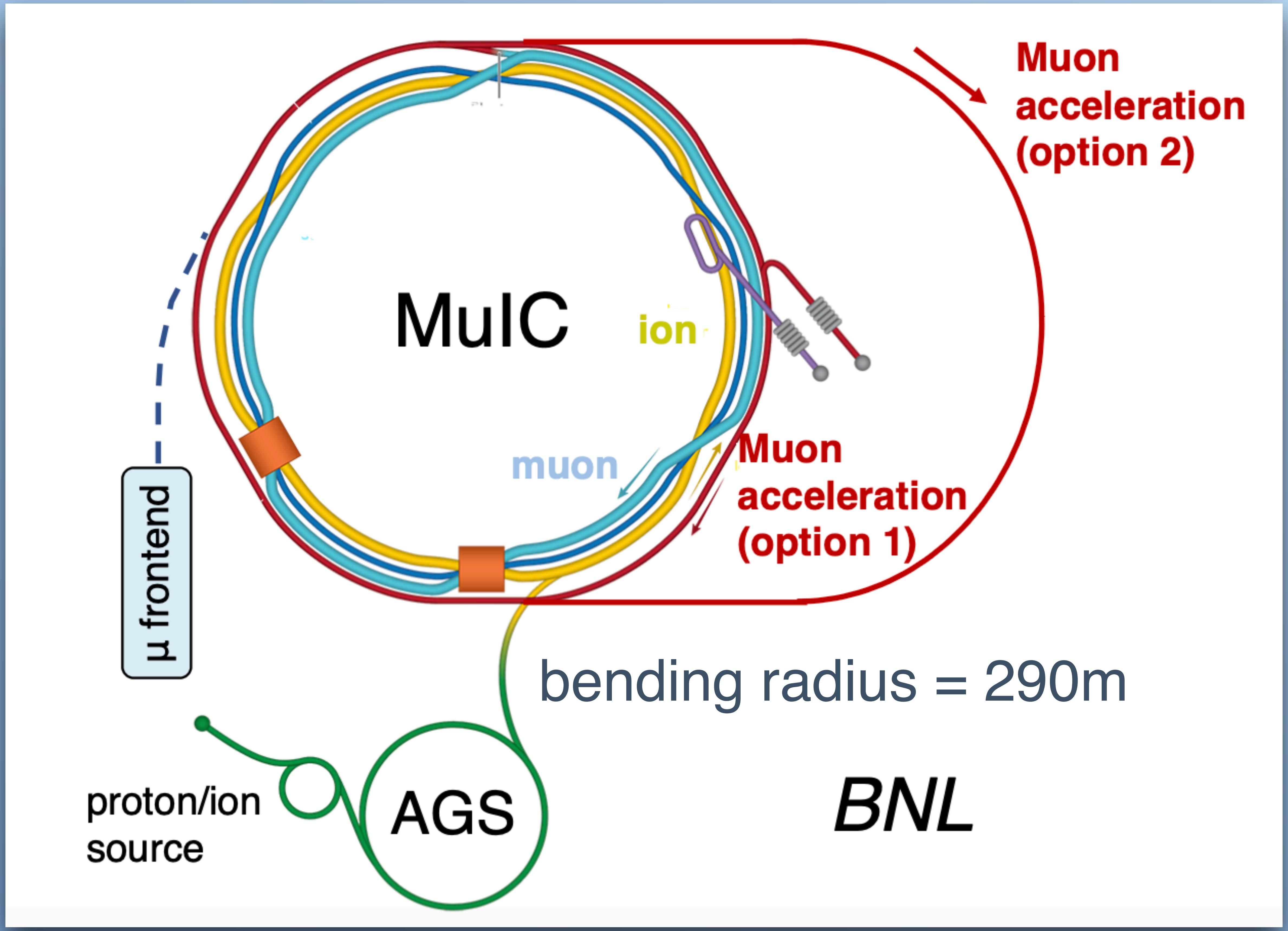
- Inclusive cross section
- EW precision measurements
- Higgs physics
- Top physics
- Leptoquark “factory”

Conceptual design

MuIC experiment

MuIC

- Reuse hadron ring of RHIC/EIC, replace electron beam by muon beam
- LHC-like magnets for muon beam ($E_\mu \sim 1$ TeV)
- Take the hadron beam from EIC ($E_p \sim 275$ GeV)
- 1-2 experiment sites



Physics cases overlap with LHeC

- Potential to upgrade LHeC to **LHmuC**

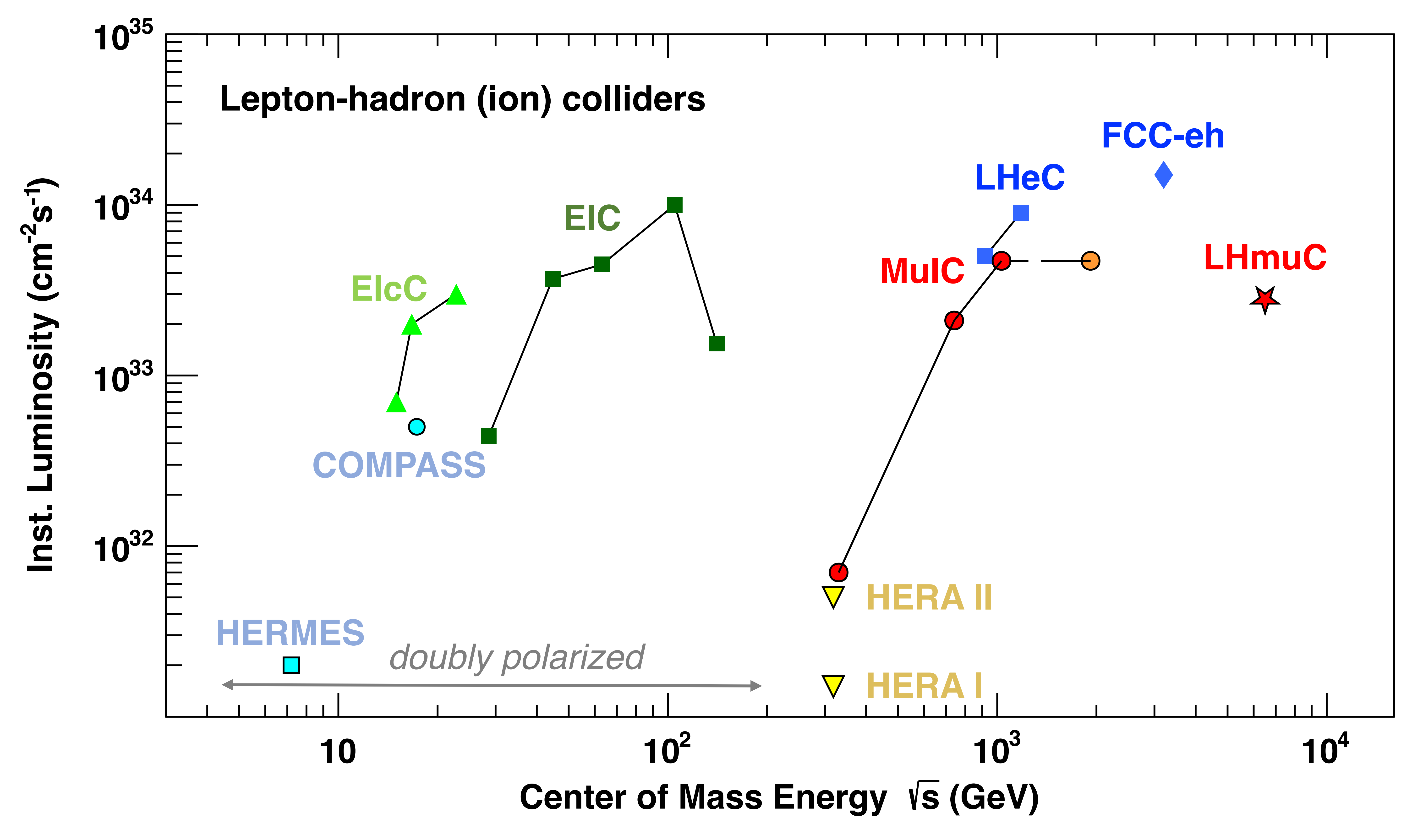
MuIC dataset

Staging of MuIC:

- Start with a muon beam with relatively low energy and low luminosity
- Early data-taking in parallel with accelerator R&D
- Stable running of MuIC at $\sqrt{s} \sim 1$ TeV as a realistic scenario.

In the realistic scenario, expect **400 fb**$^{-1}$ of data for 10 years operation

	MuIC			MuIC2	LHmuC
E_p (TeV)	0.275			0.96	7
E_μ (TeV)	0.1	0.5	0.96	0.96	1.5
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	1.92	6.5
L_{int} (x10^{33} cm^{-2}s^{-1})	0.07	2.1	4.7	4.7	2.8



Detector concept

- **Tracking and PID**

$-4 < \eta < 2.4$

PID is crucial for QCD and nuclear physics

- **Calorimeter**

$-5 < \eta < 2.4$

Wide coverage to retain sensitivity to missing energy

- **Muon detector**

$-7 < \eta < 0$

Important to detect scattered muons at high η

- **Tungsten nozzle**

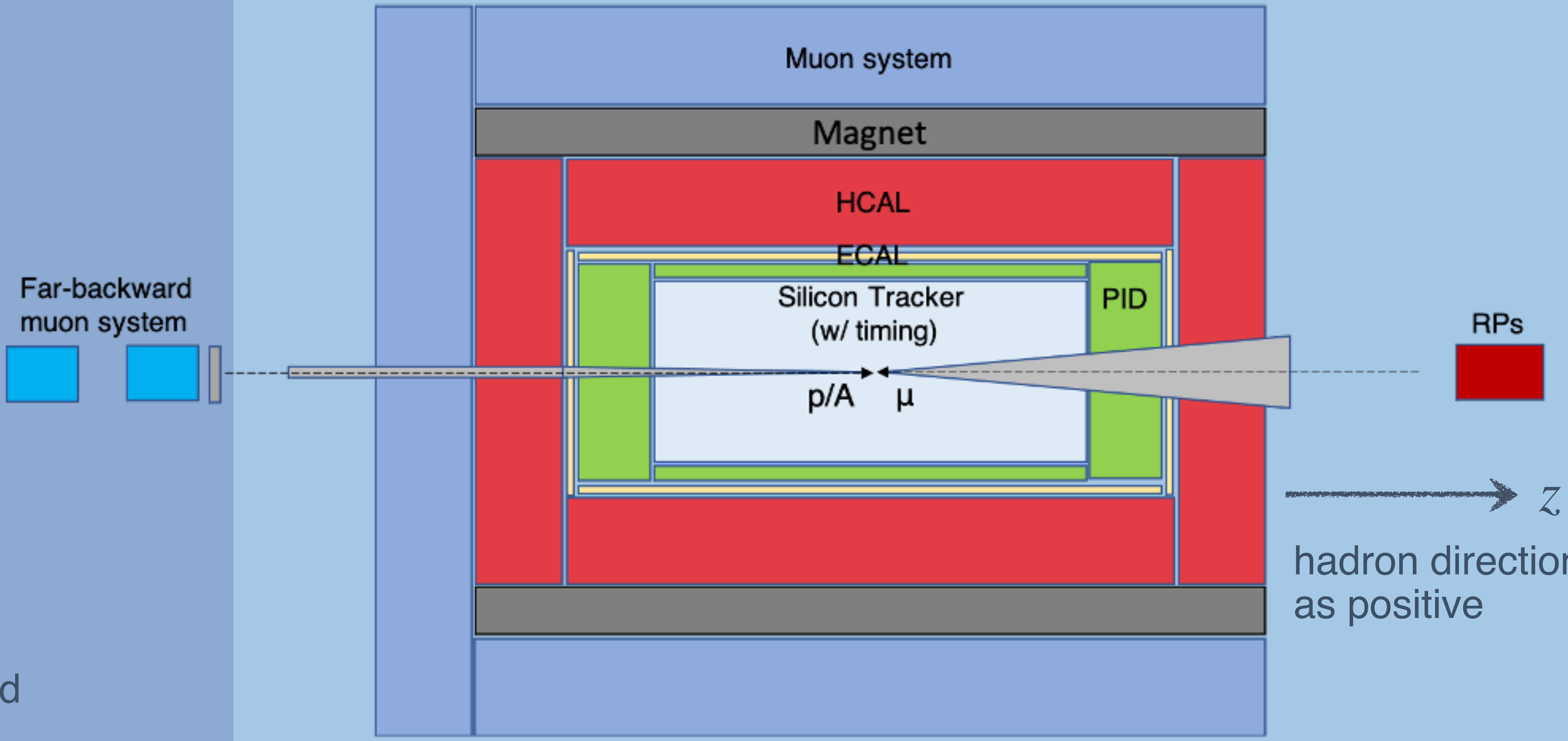
To clean electrons from the muon beam

(sacrifice some access to proton remnants)

- **Roman pot**

$5 < \eta < 8$

To detect elastically scattered protons

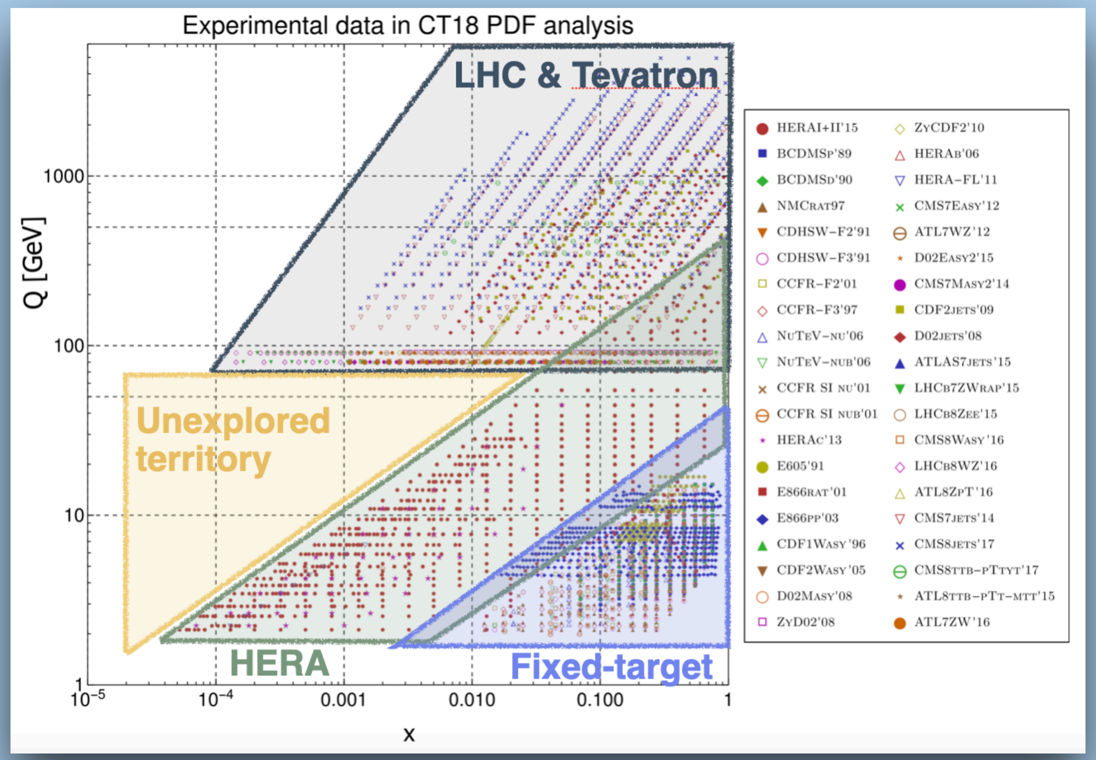


hadron direction as positive

Physics cases

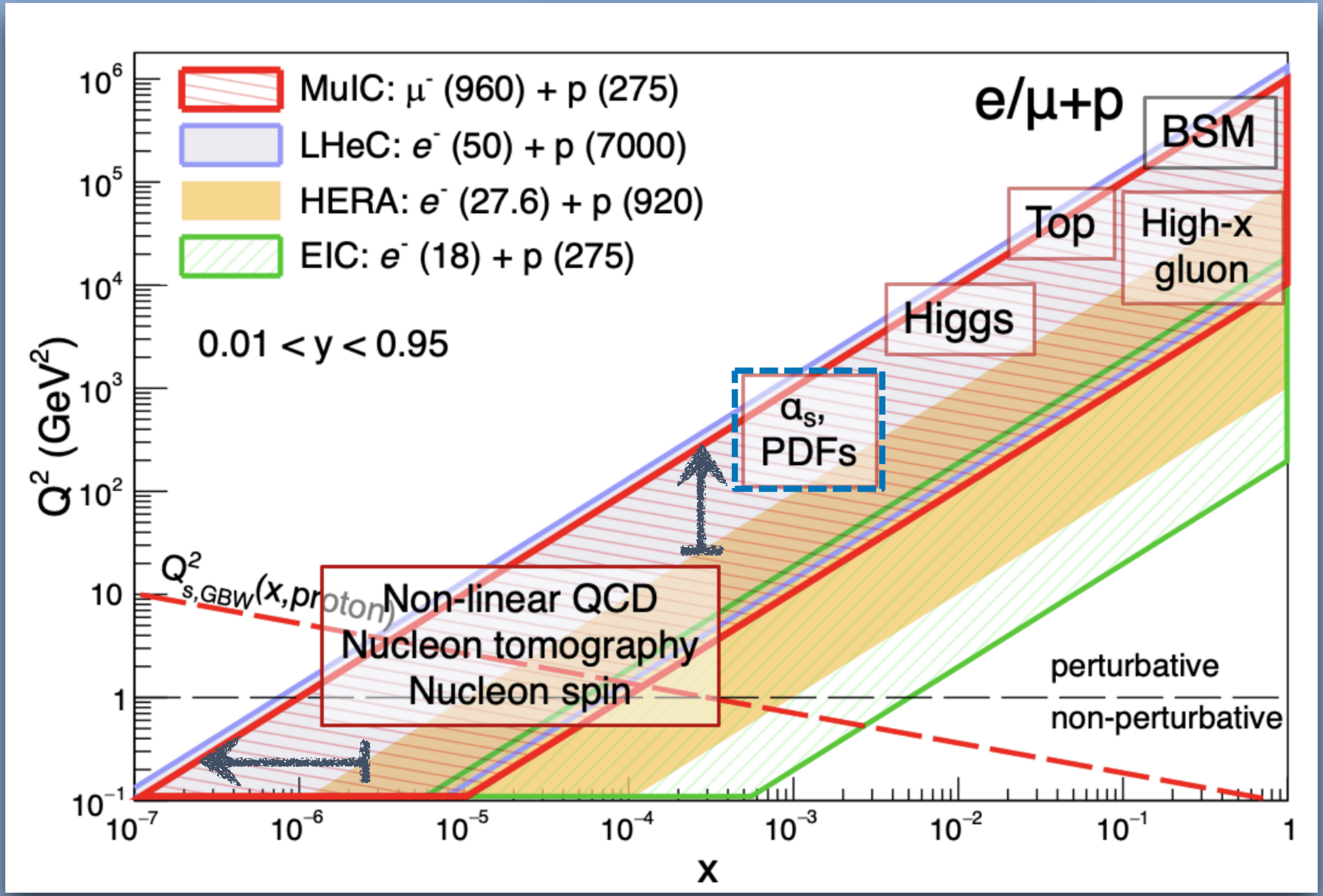
Physics landscape

Remember this plot on QCD fit?

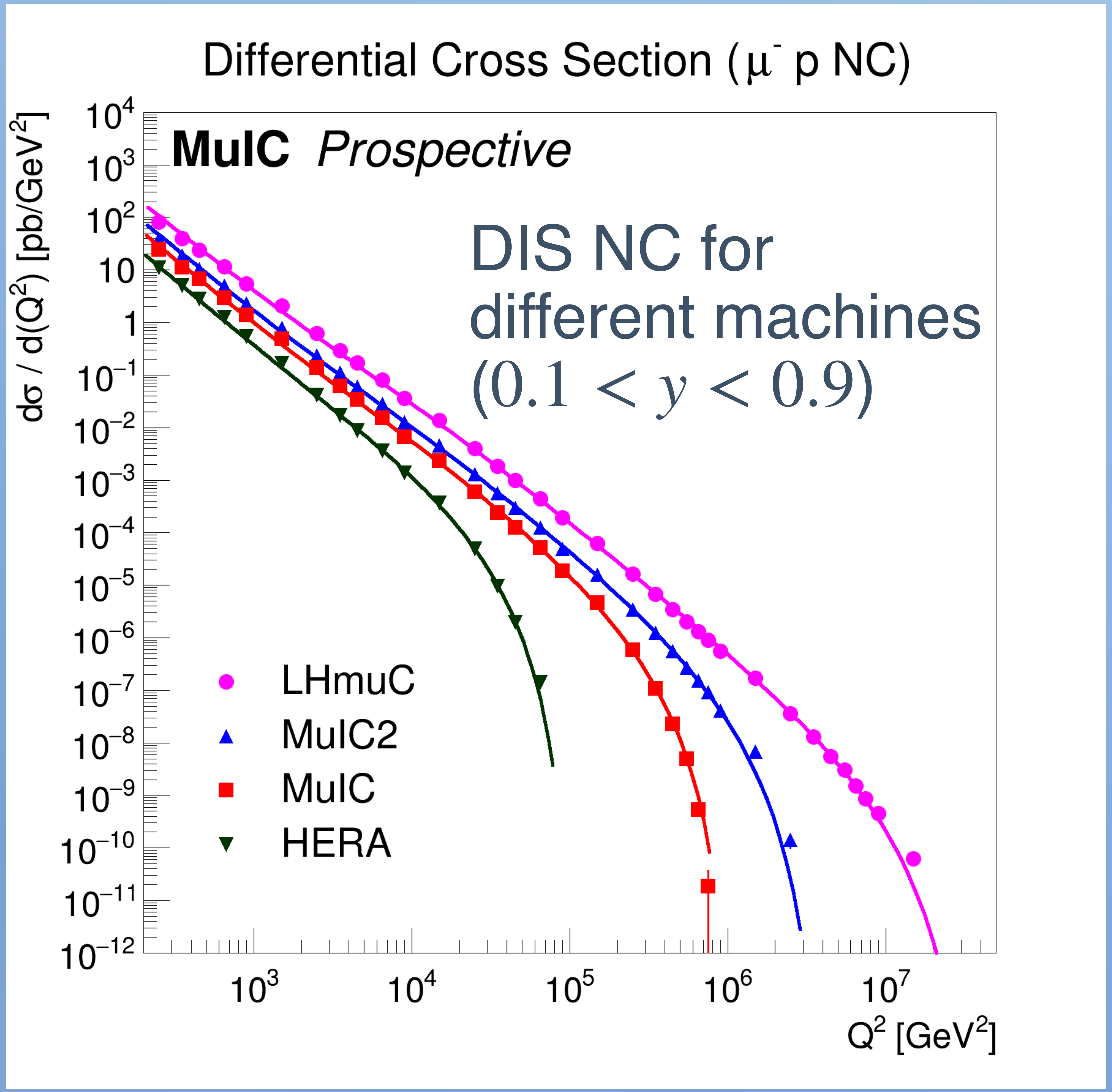


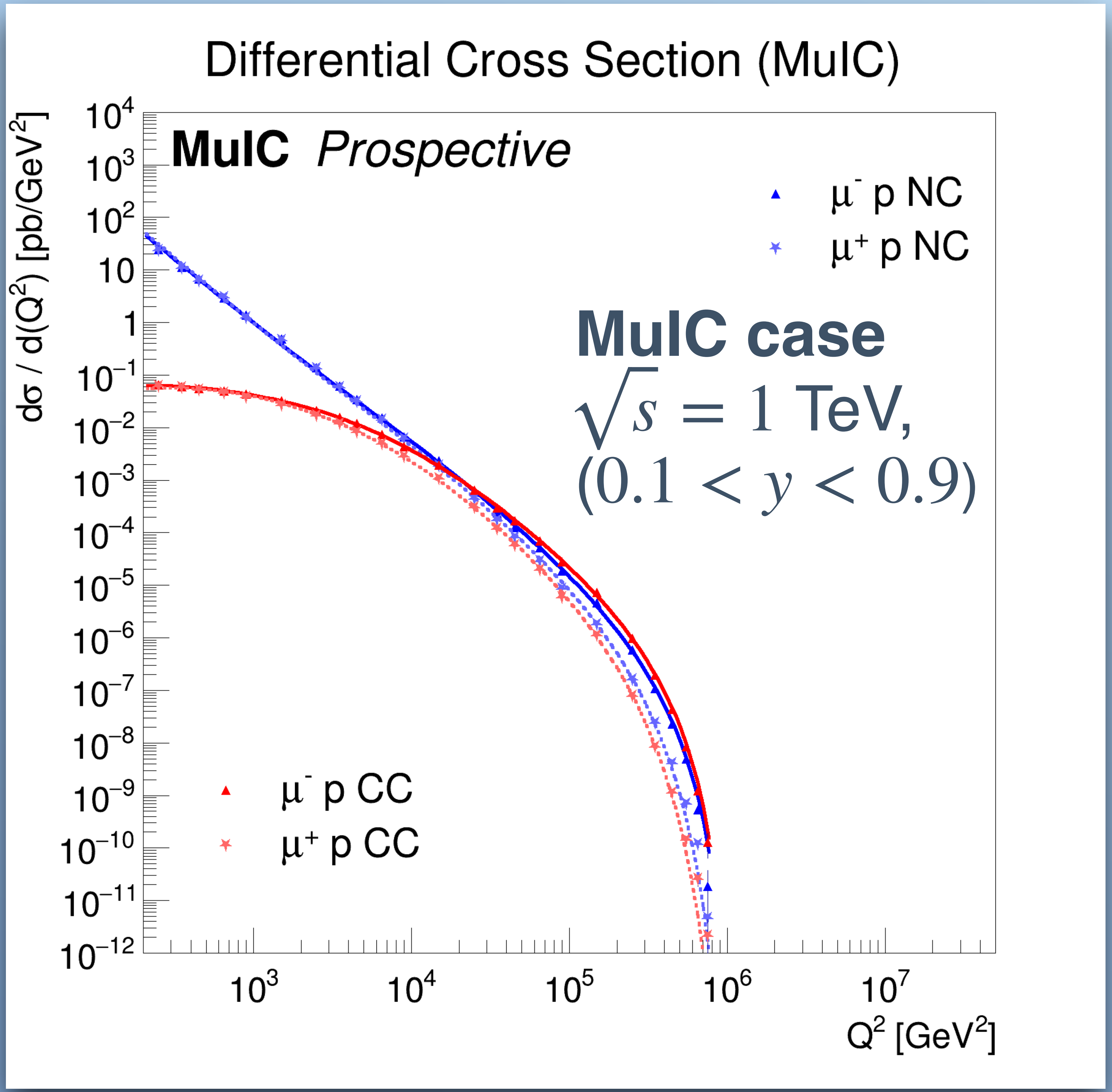
The MuIC dataset

- Extends coverage of Q^2 and x by an order of magnitude
- Early datasets already good for nuclear physics and QCD measurements
- Opportunities open for EW physics and BSM searches as $\sqrt{s}$ and lumi increase



Inclusive cross sections





- Abundant cross sections for DIS at moderate Q^2 (including EW scale)
- Need very high luminosity to reach extreme Q^2

W, Z production

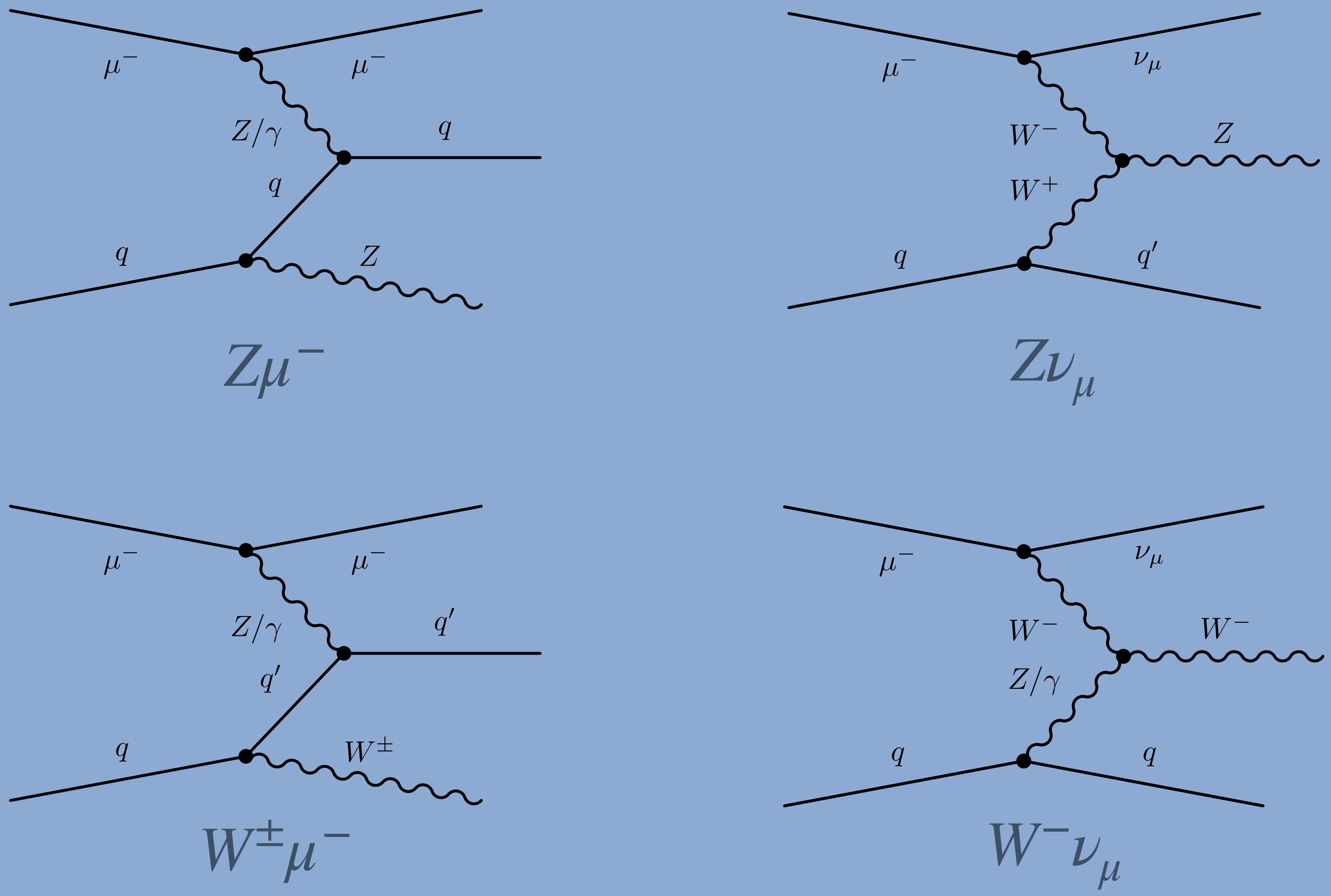
Many different modes for W, Z production

For MuIC at $\sqrt{s} \sim 1$ TeV

- $\sigma_{W^{\pm}}$ =19.4 pb
- σ_Z = 3.6 pb

With 400 fb^{-1} data

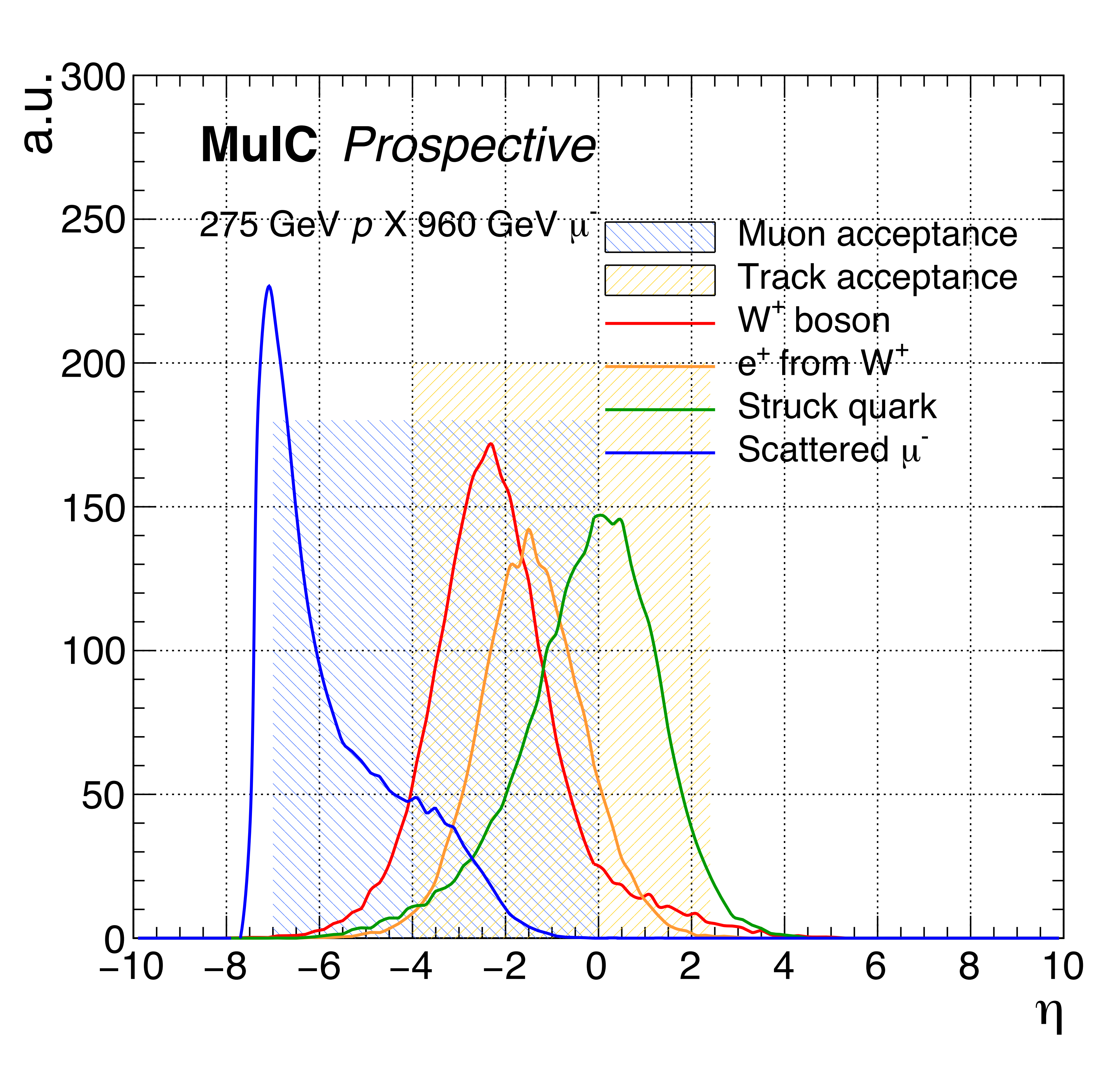
- expect 8M W, 1.5M Z
- All are EWK production (no DY, no QCD-induced backgrounds)
- Clean and sufficient dataset for precision measurement on (SM and anomalous) triple gauge coupling.



Example diagrams for vector boson production

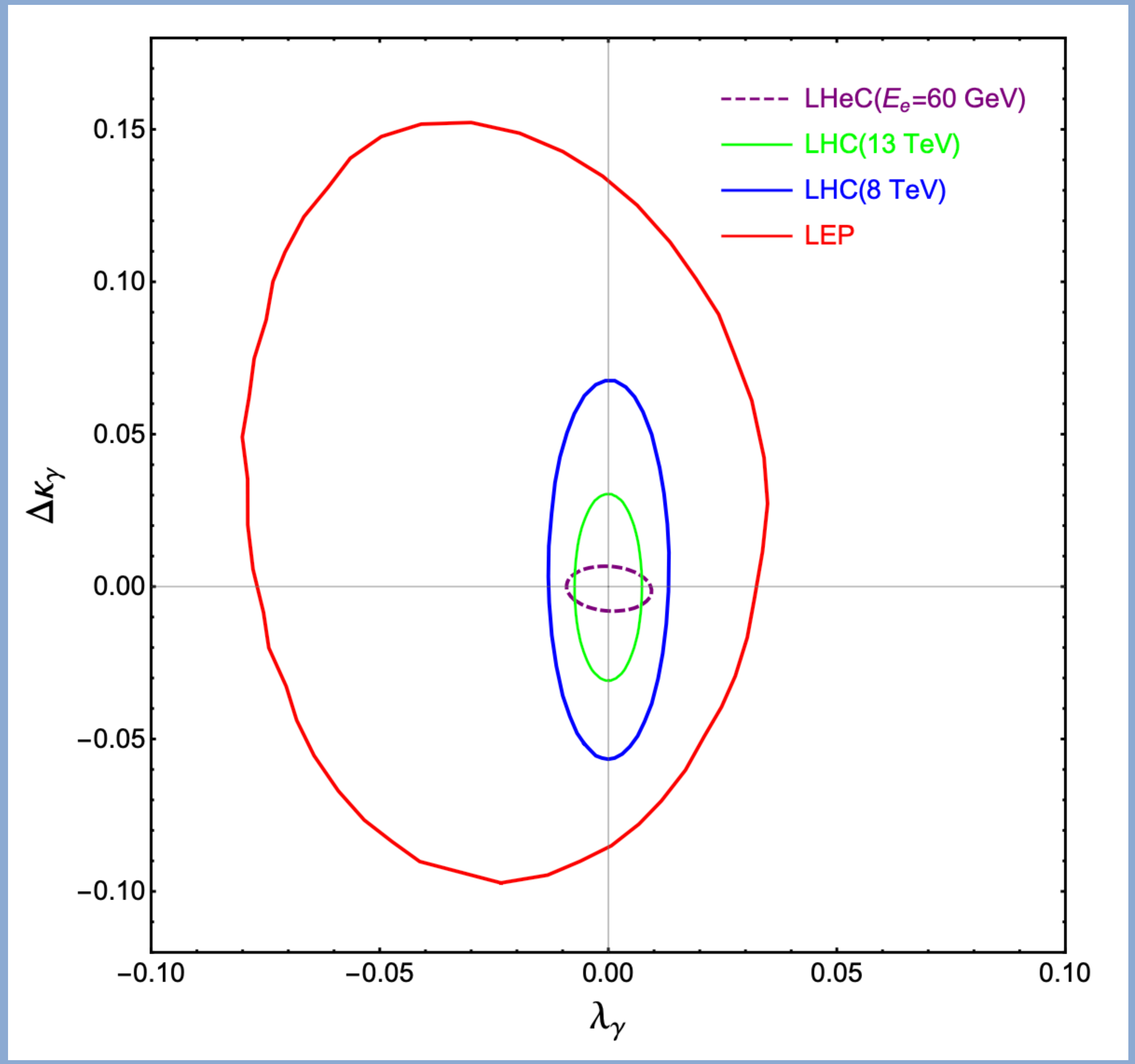
EW measurements

- Most final objects within the acceptance
- Little overlap between the scattered muon and the lepton(s) from V boson decay.



- Similar performance expected at MuIC and LHeC

LHeC report



$WW\gamma$ coupling at LHeC assuming $1\ \mathrm{ab}^{-1}$

Higgs production

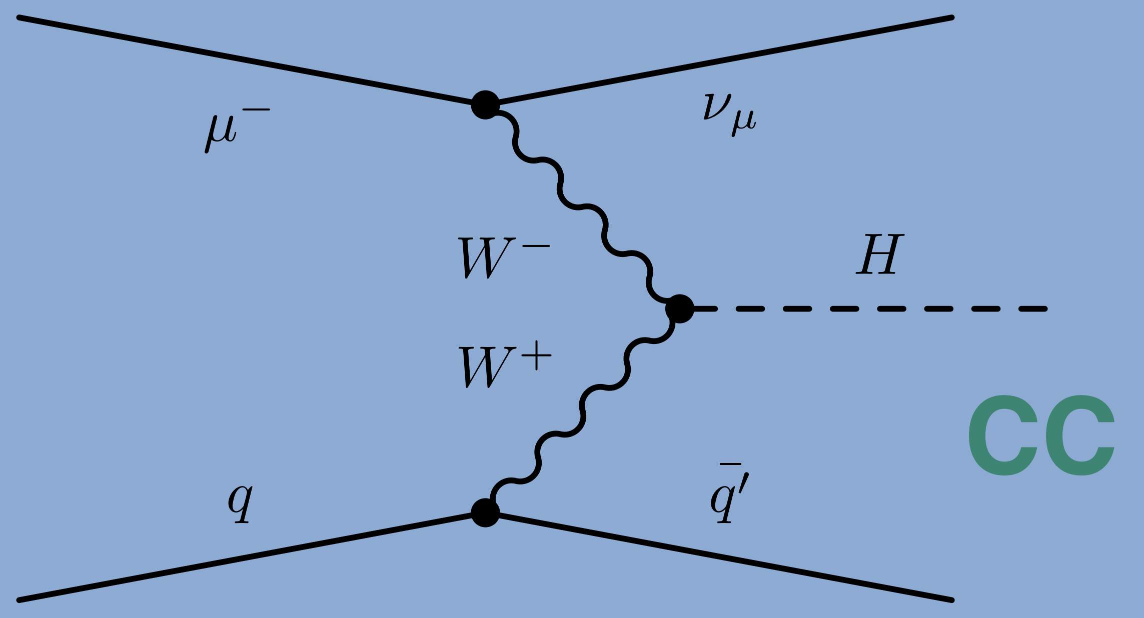
Mainly produced via VBF process, with both charged current (CC) and neutral current (NC) exchanges

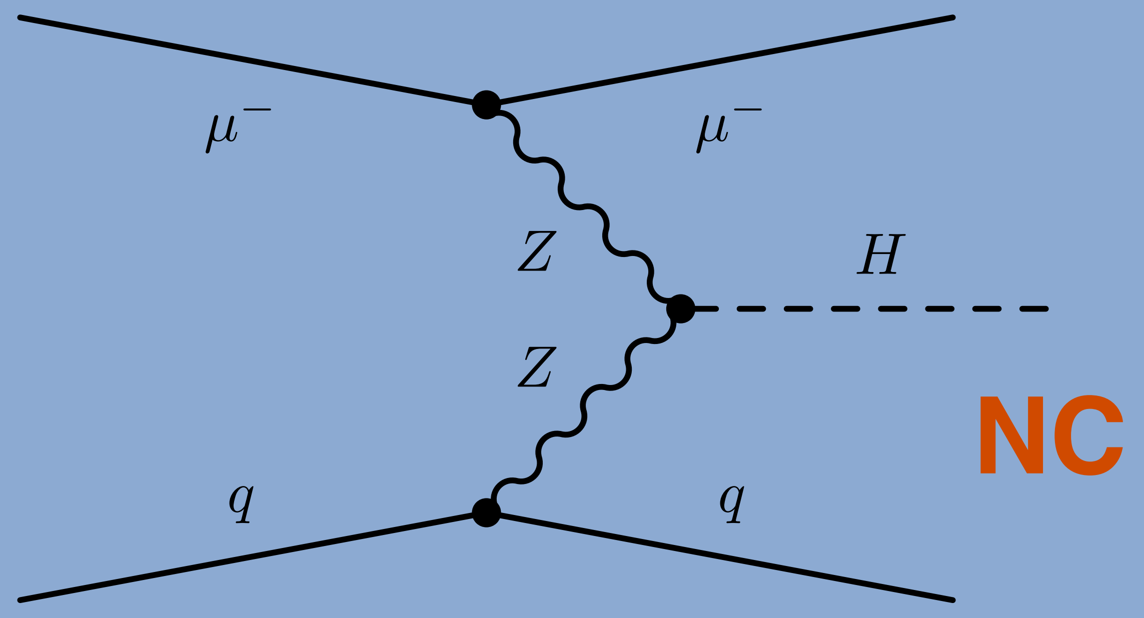
For MuIC at $\sqrt{s} \sim 1$ TeV

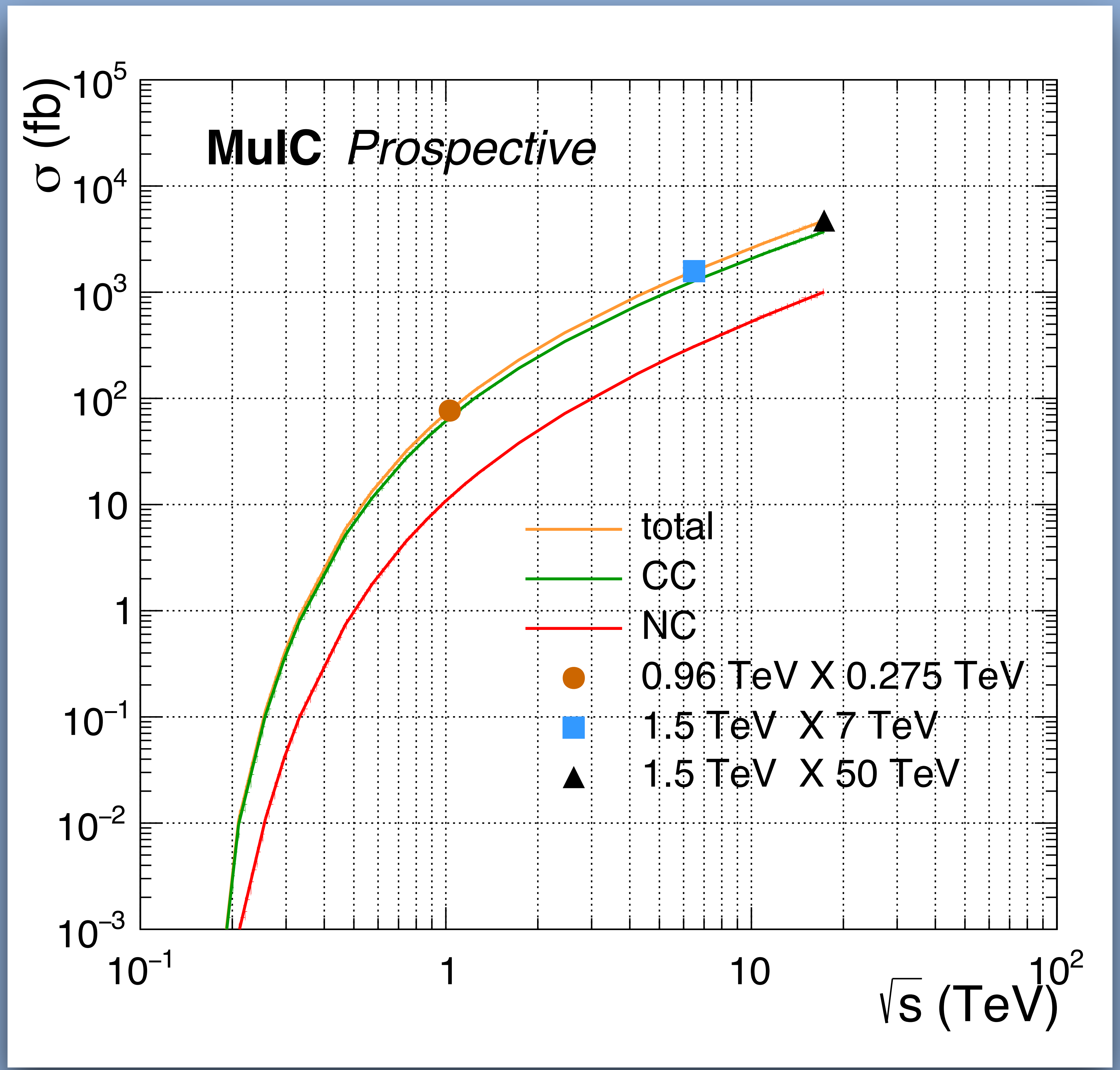
- $\sigma_{CC} = 64.5$ fb
- $\sigma_{NC} = 11.6$ fb
- Expect 30k Higgs with 400 fb^{-1} at MuIC
- Very clean environment

Note: tH production also possible, but much less

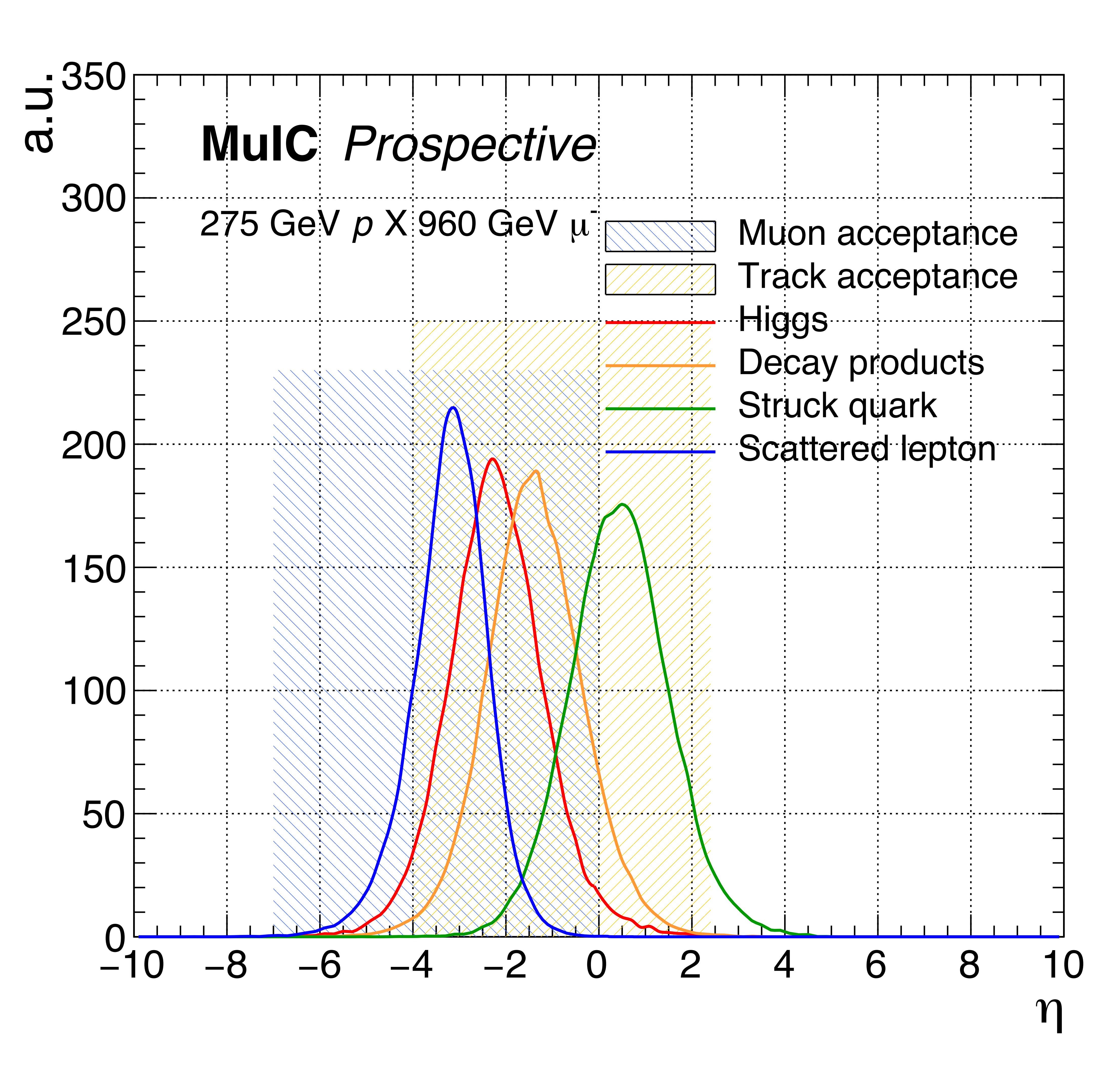
- Negligible ($\sigma_{tH} \ll 1$ fb) at MuIC ($\sqrt{s} \sim 1$ TeV)
- Visible ($\sigma_{tH} > 10$ fb) at LHmuC ($\sqrt{s} \sim 7$ TeV)





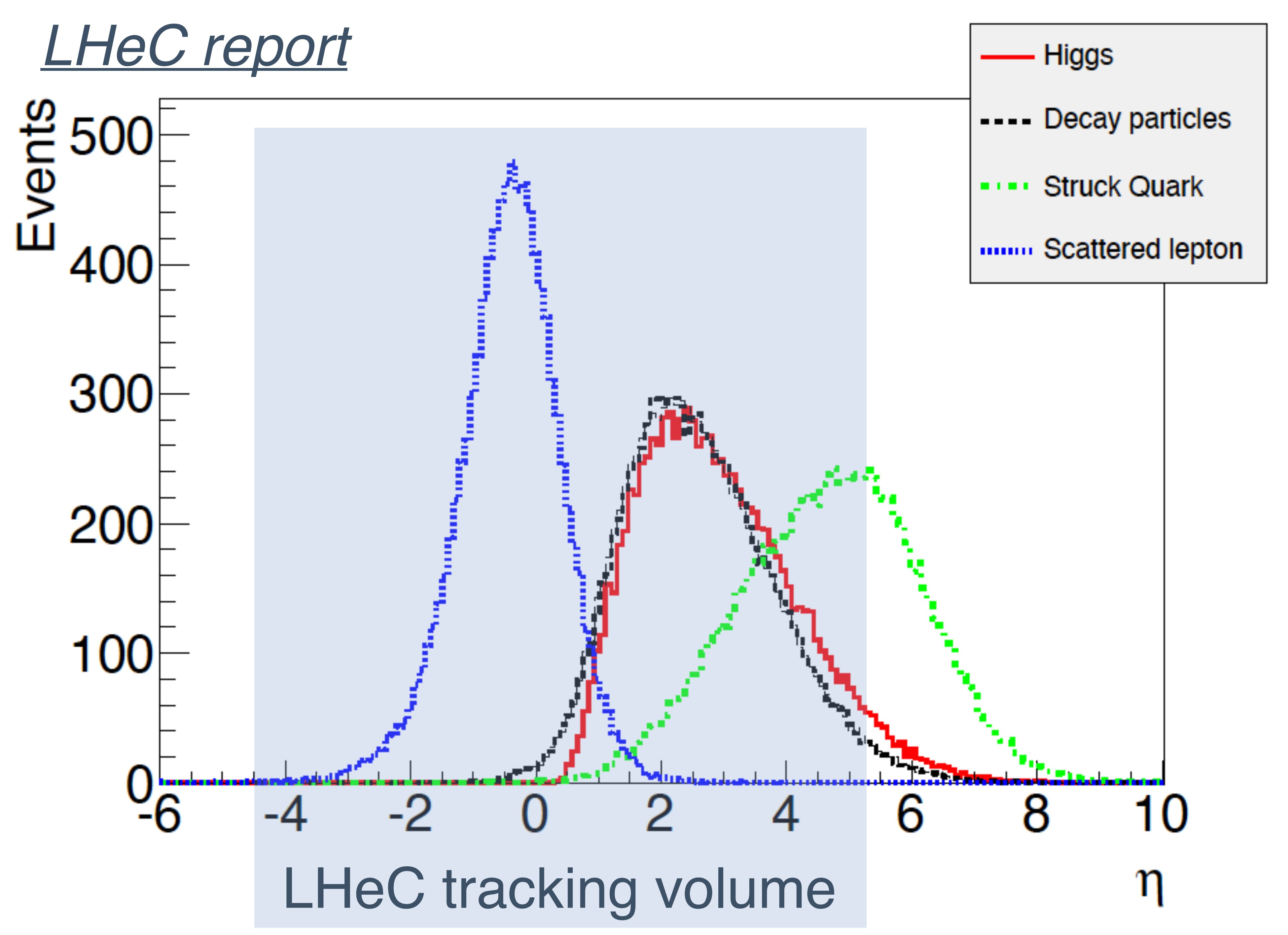


Higgs event kinematics



At MuIC, all final objects within the acceptance

- Decay products and struck quarks in central detector (in contrast to LHeC)
- Forward muon detector is essential

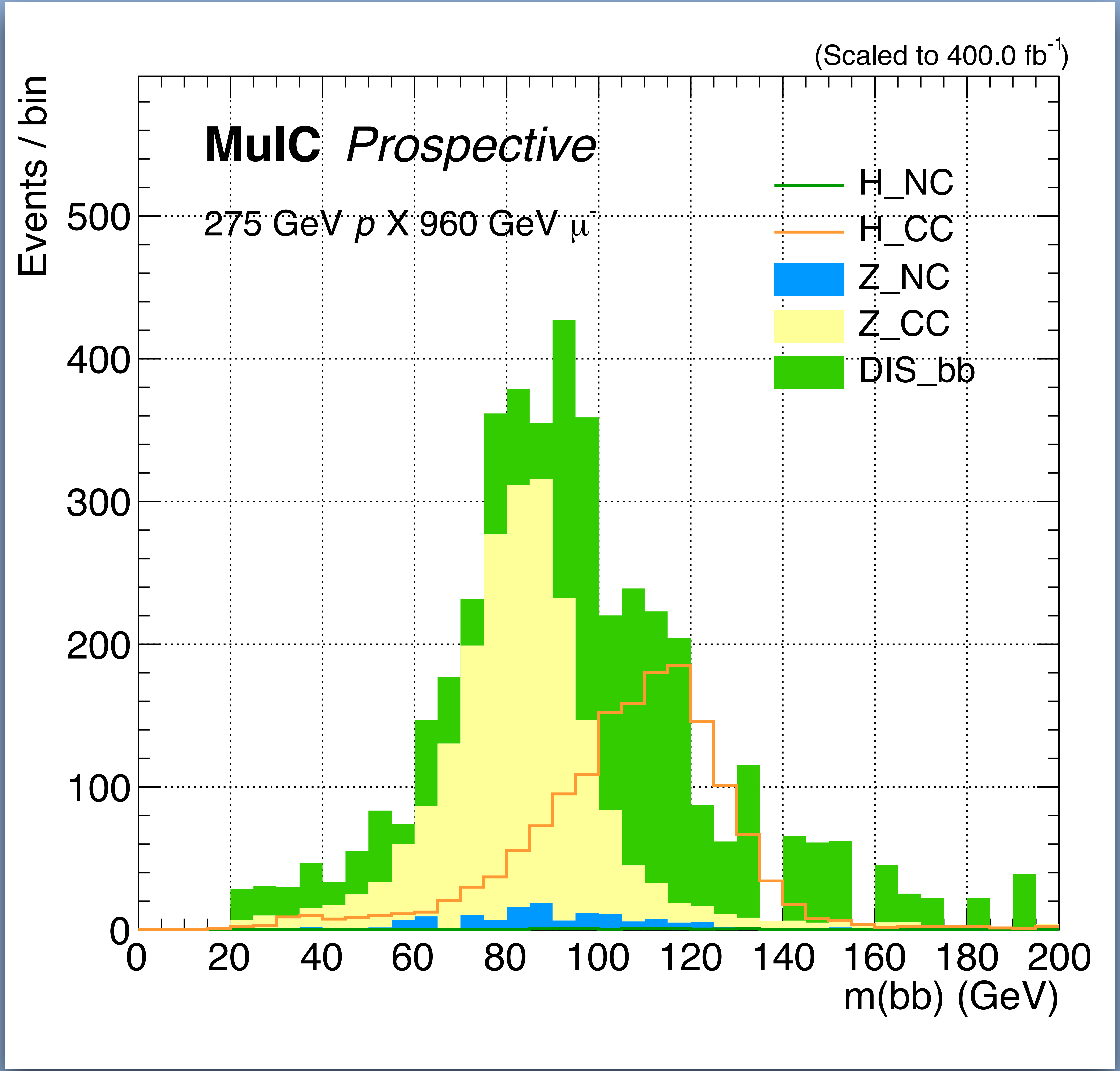


$H \to b\bar{b}$ case study

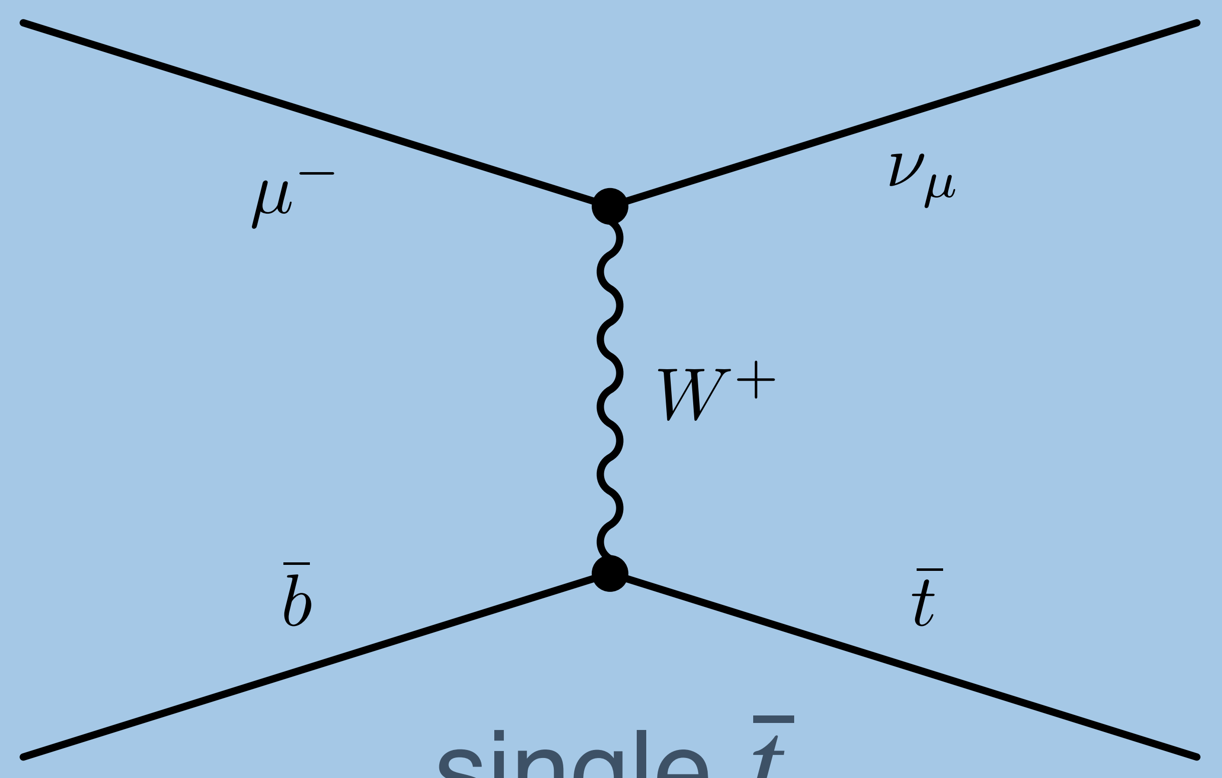
- **Selection:** Target CC VBF-H signal over NC DIS bb background
  - 2 b-tagged jets + 1 light jet
  - $p_T(b\bar{b}) > 20$ GeV
  - Muon veto, $E_T^{miss} > 30$ GeV

- Expected statistical precision ~ 3%
  - Comparable with HL-LHC expectation
  - Consistent with LHeC, which has a greater cross section but less acceptance than MuIC
- Expect 10X more signal at LHmuC

MadGraph LO samples + Delphes simulation



top quark production



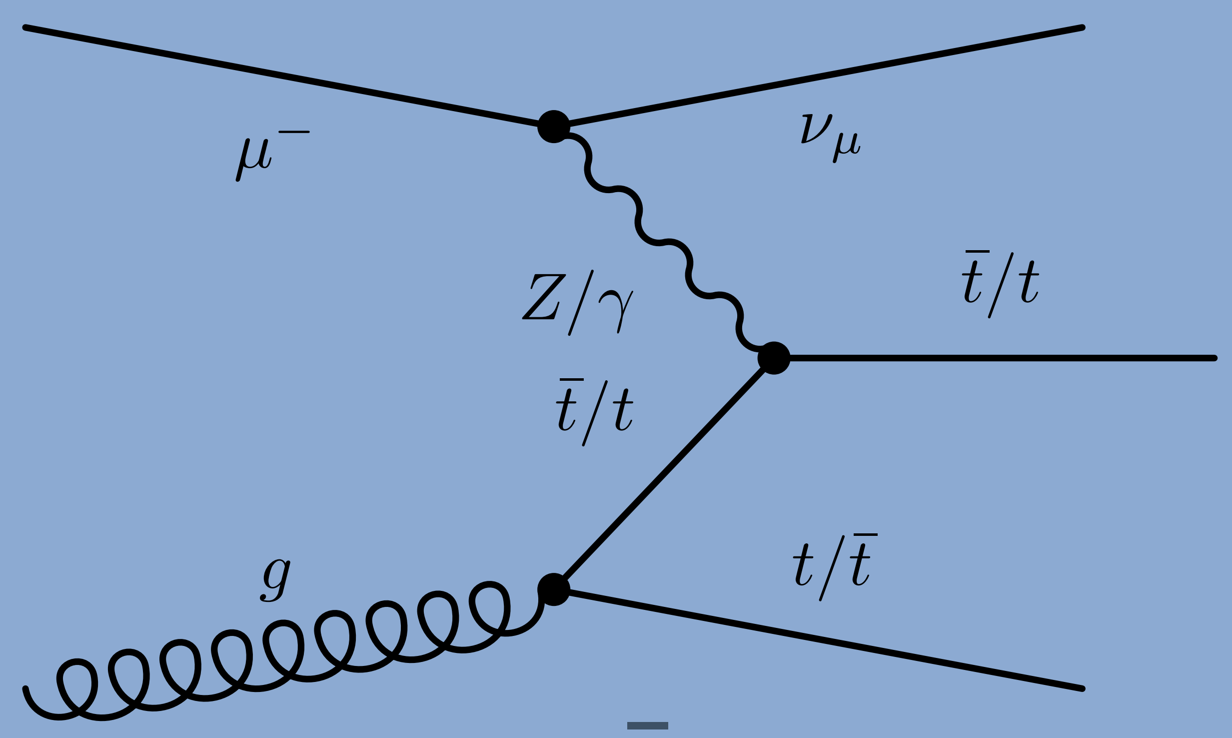
single $\bar{t}$

Cross section grows fast as Q^2 becomes less suppressed

MuIC $\sqrt{s} \sim 1$ TeV	0.95 pb
MuIC2 $\sqrt{s} \sim 2$ TeV	5.44 pb
LHmuC $\sqrt{s} \sim 6.5$ TeV	48.1 pb

Distinct final states in $\mu - p$ environment

- Direct measurement of $|V_{tb}|$
- Potential to probe $|V_{td}|$ and $|V_{ts}|$ as well



$t\bar{t}$

MuIC $\sqrt{s} \sim 1$ TeV	0.014 pb
MuIC2 $\sqrt{s} \sim 2$ TeV	0.22 pb
LHmuC $\sqrt{s} \sim 6.5$ TeV	4.62 pb

- With enough data, direct measurement on $t\bar{t}\gamma$ and $t\bar{t}Z$ couplings

What about positive t quark? — FCNC

Single t quark production in $\mu^- p$ collisions only possible via FCNC $tq\gamma$, tqZ, and tqH couplings

- Extremely suppressed in SM
- Tag scattered μ^- and $t \to W^+(\ell^+\nu)b$ decay
- **Null test** with **distinct final states**

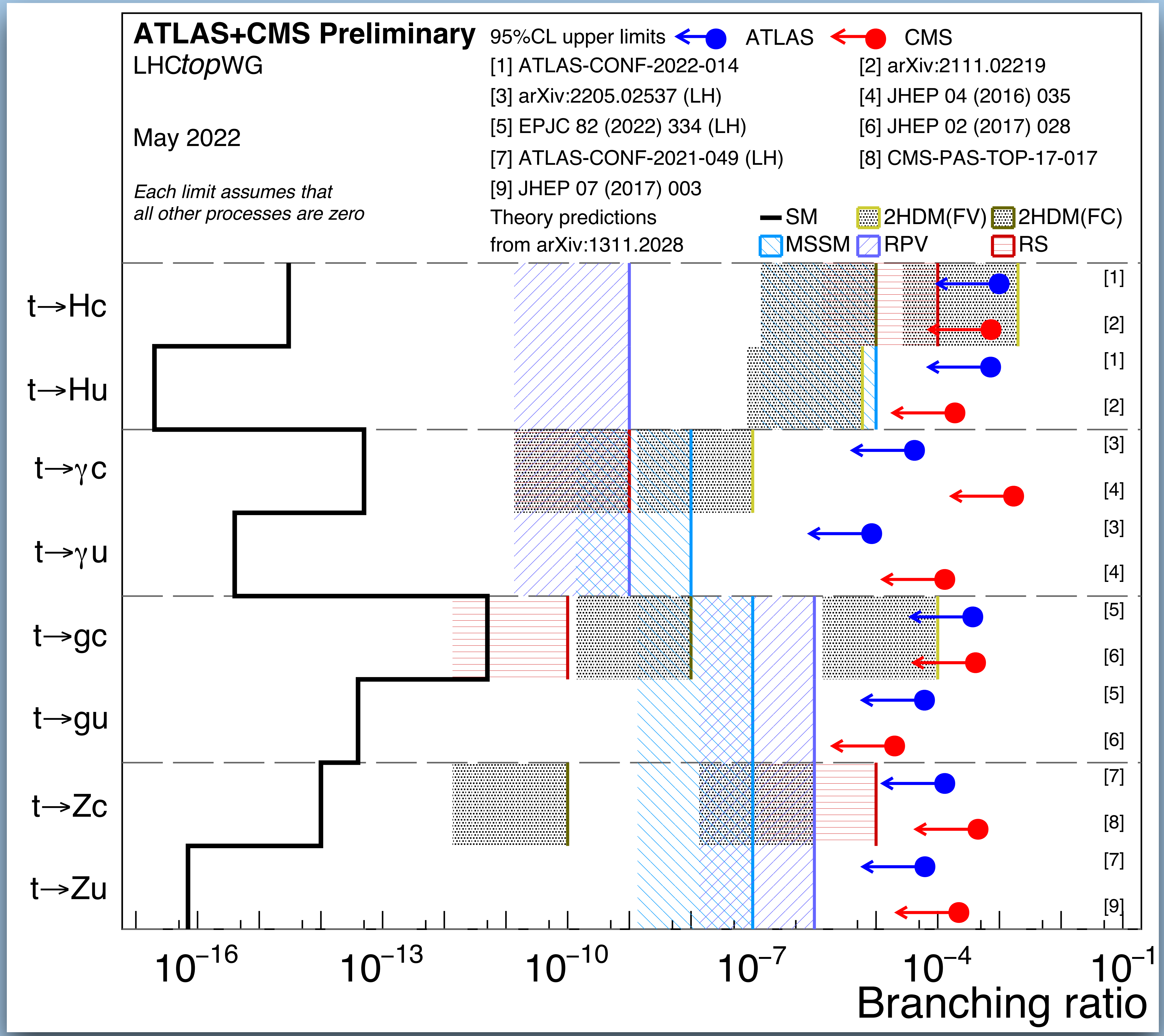
From LHeC report, expectation at $400\ \text{fb}^{-1}$

- $BR(t \to q\gamma) < 2 \times 10^{-5}$ at 95% CL
- $BR(t \to qZ) < 1 \times 10^{-4}$ at 95% CL

Same order as current LHC limits

- Probe via production vs decay
- Much more sensitive at LHmuC

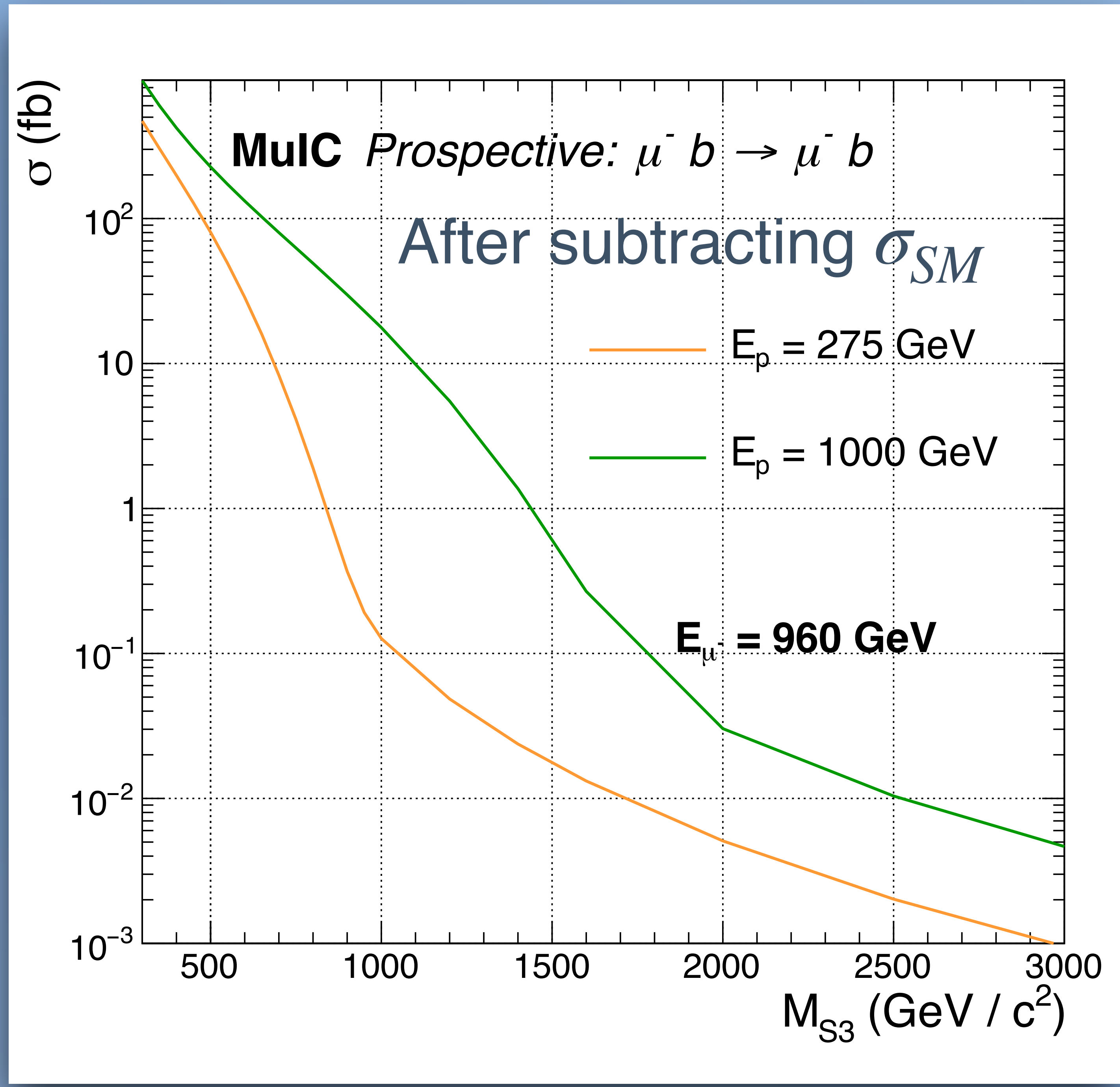
LHCtopWG



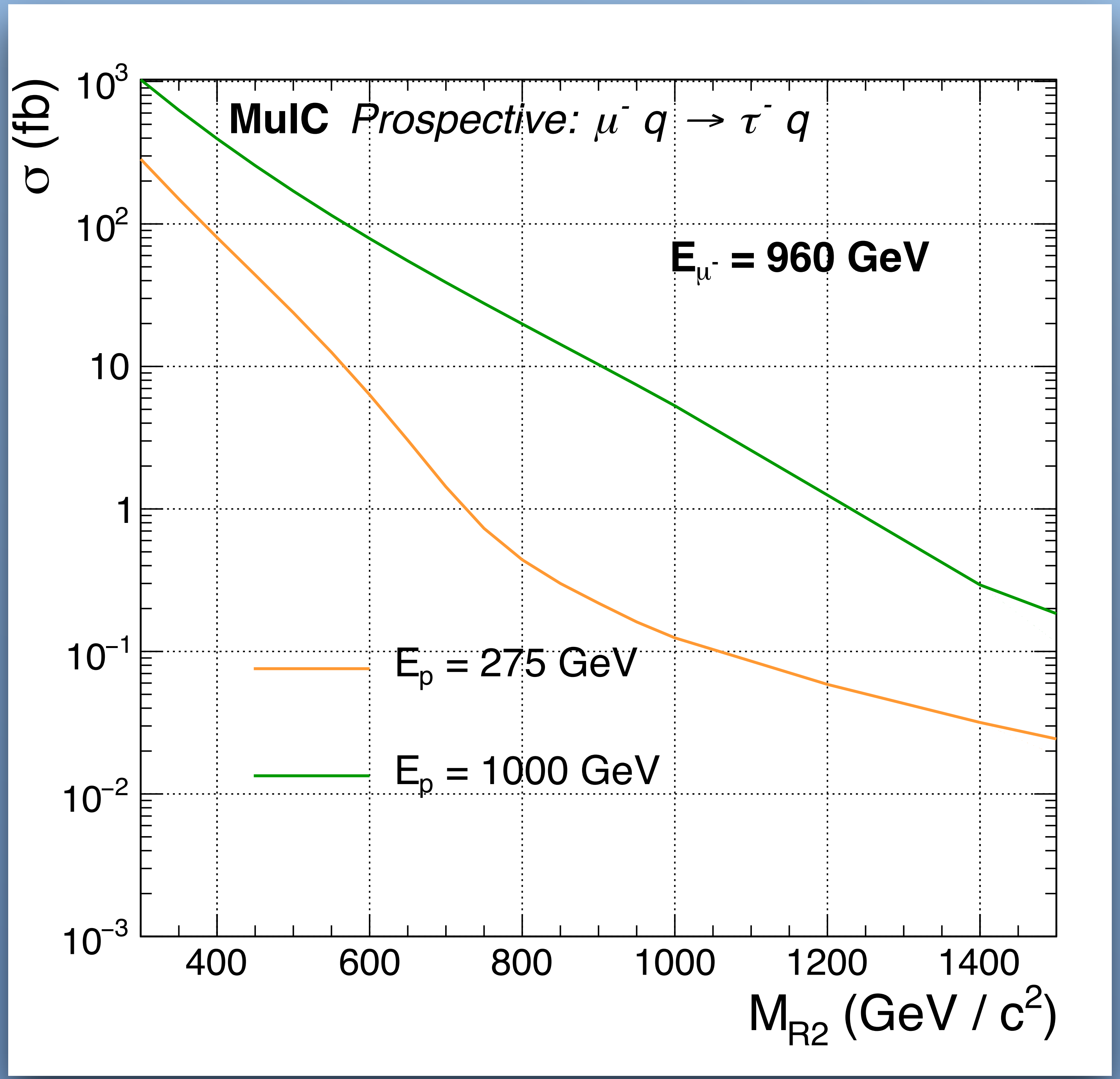
Direct probe of leptoquarks

- Direct single LQ production
- $\mu - q$ scatter through t-channel LQ exchange

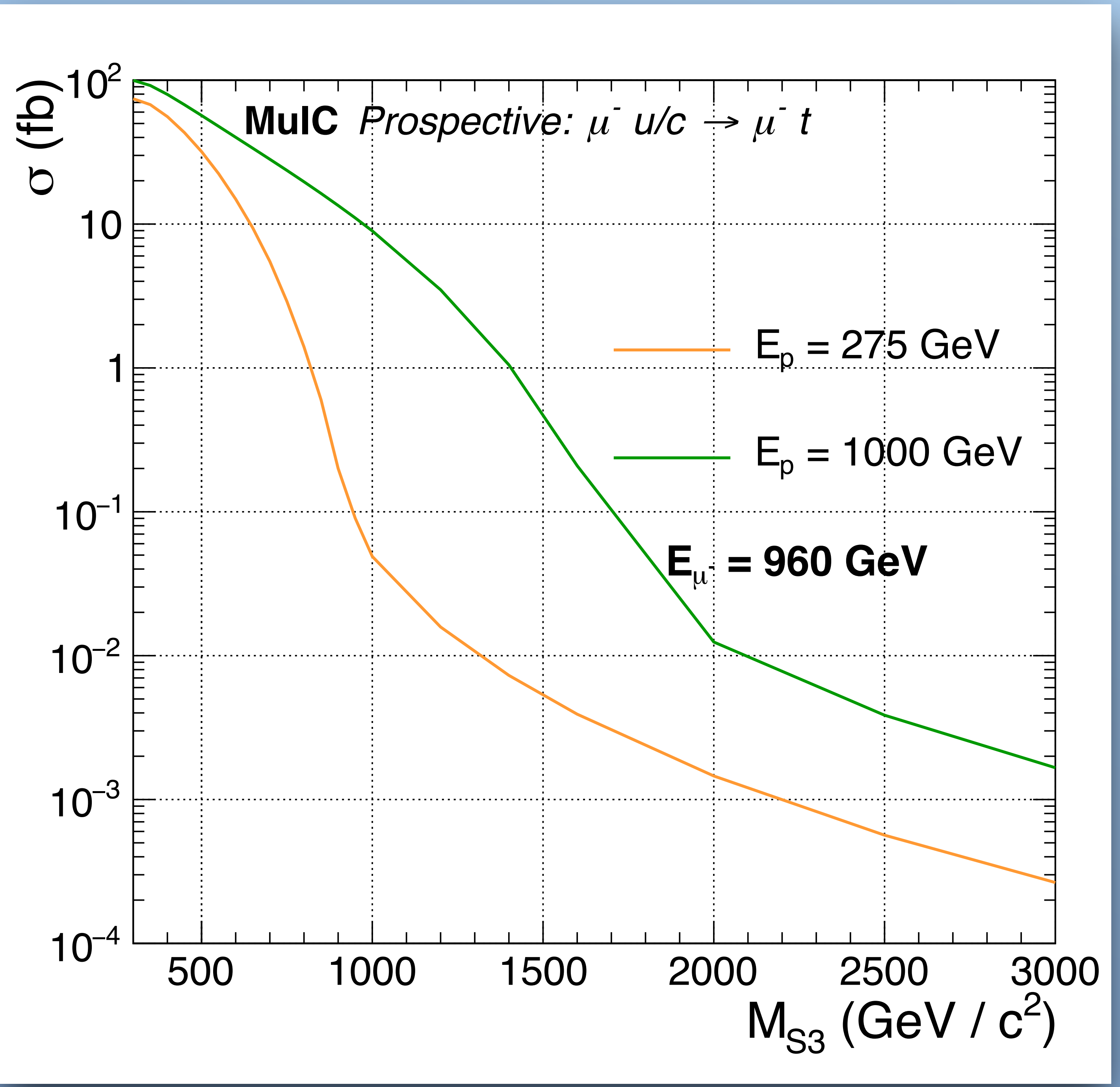
Signature related to B-anomalies



Flavor changing signature involving τ

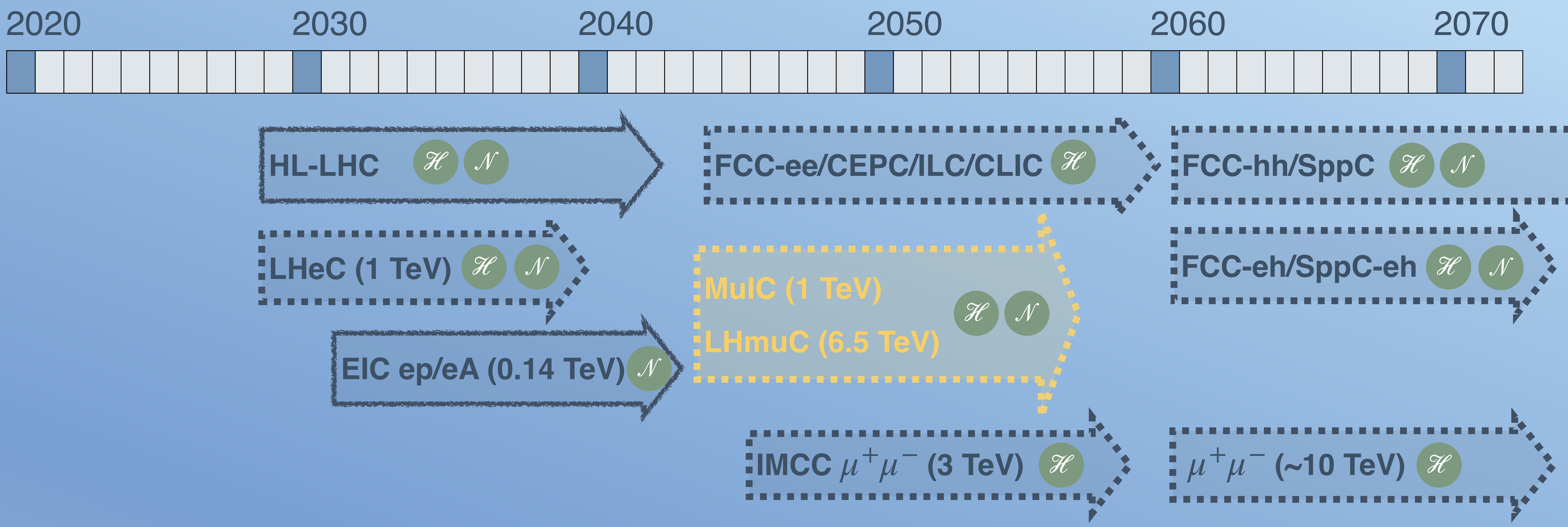


Flavor changing signature involving top



Note: all cross section results assume Yukawa coupling strength of $LQ - lq$ at 0.1

Summary - a future in our view



Note:

$\mathcal{H}$ - High energy physics

$\mathcal{N}$ - Nuclear physics

The muon-ion option:

❖ Rich, and some unique, physics programs

❖ Can be concurrent with other mega projects

Summary - key merits of MuIC

A versatile machine with unique specialities

- Nuclear physics and QCD measurements
- Measure certain EW parameters (TGC, κ_{Hbb}, and $|V_{tb}|$)
- Probe certain BSM signatures (top FCNC and leptoquarks)

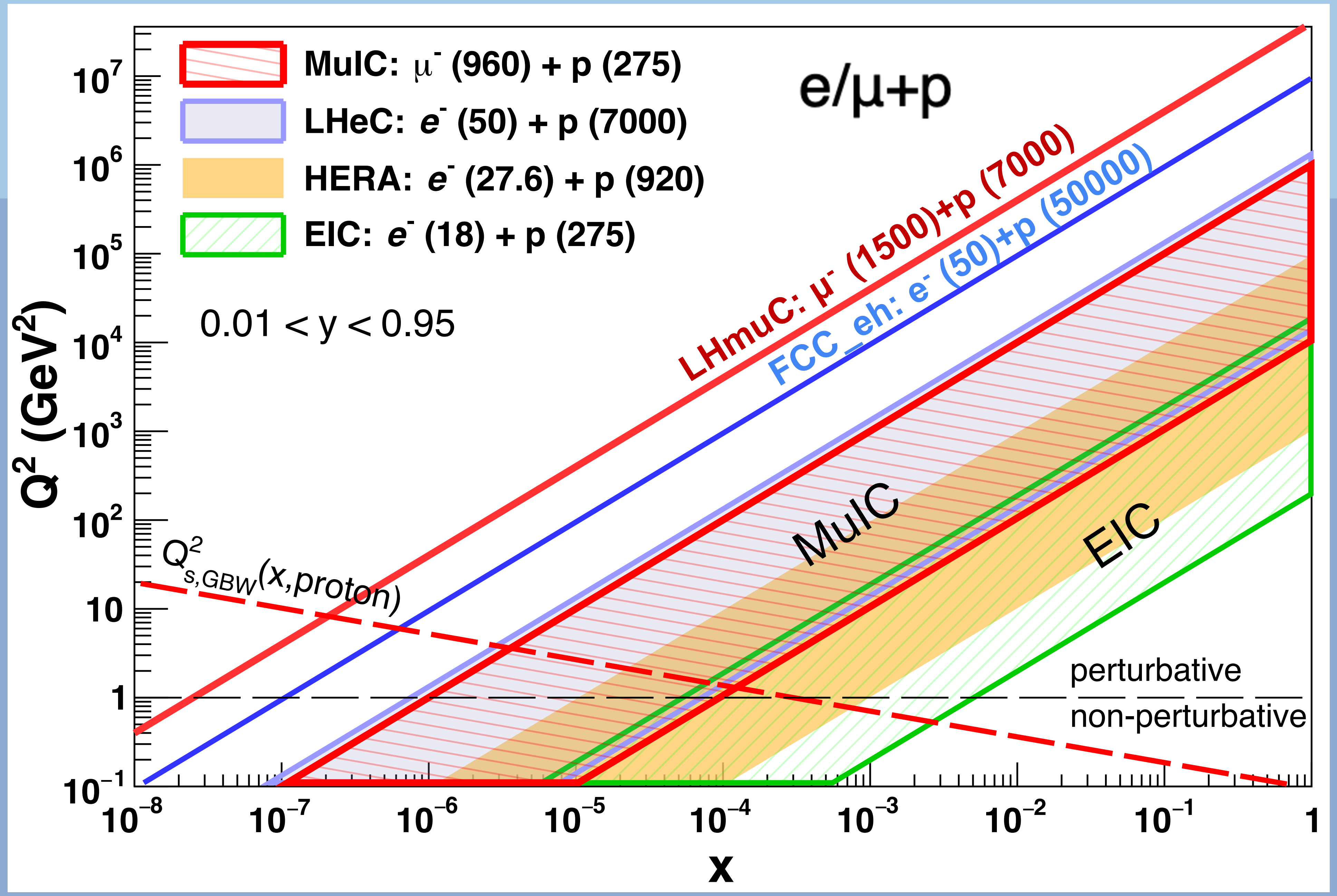
A relatively small and affordable experiment

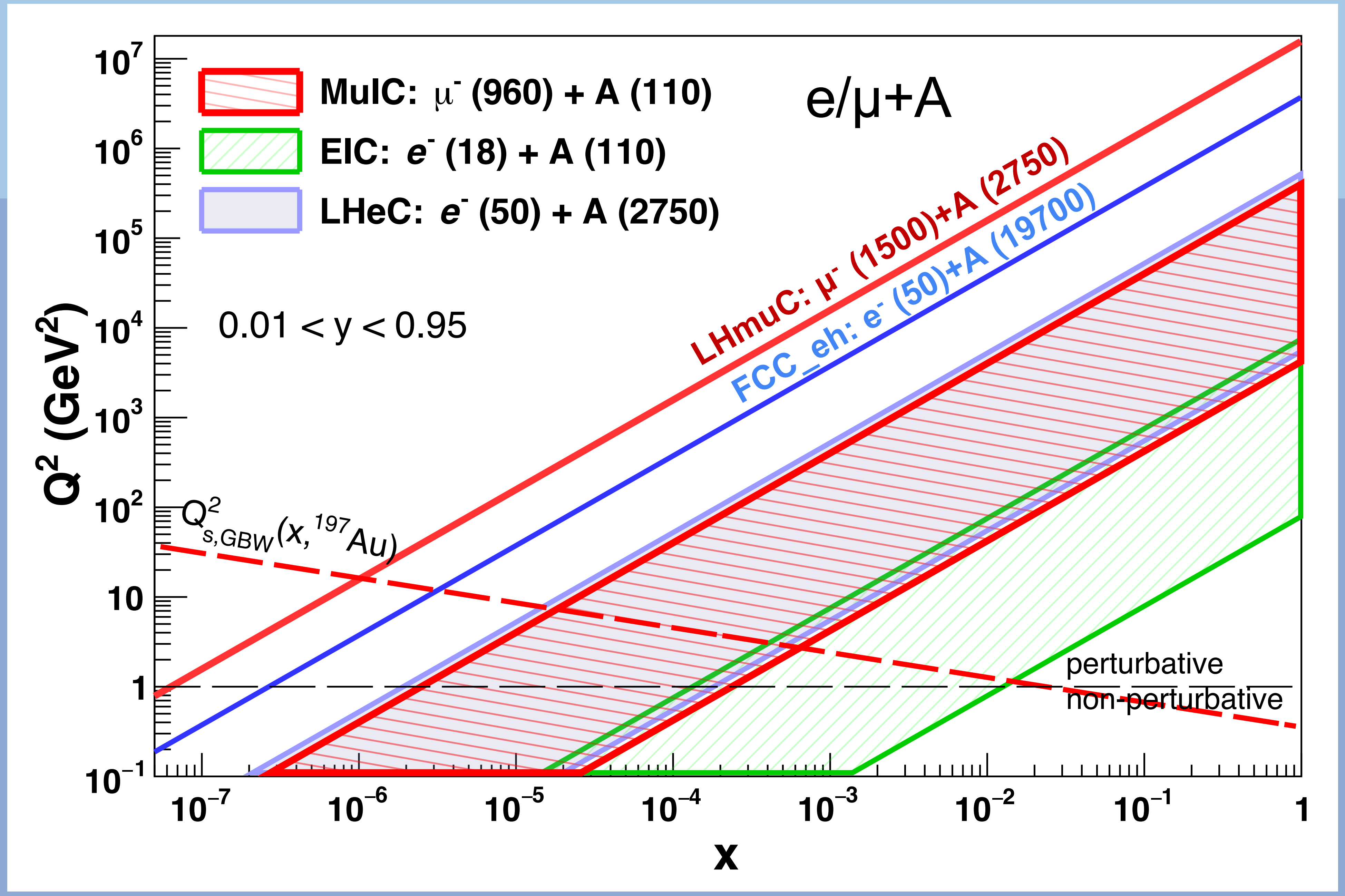
- Reuse existing facilities
- Can be complementary to and concurrent with other major projects

A path to muon accelerator technologies

- Gradual steps with rich physics yields along the way

Backups


MuIC: μ⁻ (960) + p (275)
LHeC: e⁻ (50) + p (7000)
HERA: e⁻ (27.6) + p (920)
EIC: e⁻ (18) + p (275)
e/μ+p
0.01 < y < 0.95
LHmuC: μ⁻ (1500)+p (7000)
FCC_eh: e⁻ (50)+p (50000)
MuIC
EIC
Q²s,GBW(x,proton)
perturbative
non-perturbative
Q² (GeV²)
x


MuIC: μ⁻ (960) + A (110)
EIC: e⁻ (18) + A (110)
LHeC: e⁻ (50) + A (2750)
e/μ+A
0.01 < y < 0.95
LHmuC: μ⁻ (1500)+A (2750)
FCC_eh: e⁻ (50)+A (19700)
Q²s,GBW(x,¹⁹⁷Au)
perturbative
non-perturbative
Q² (GeV²)
x