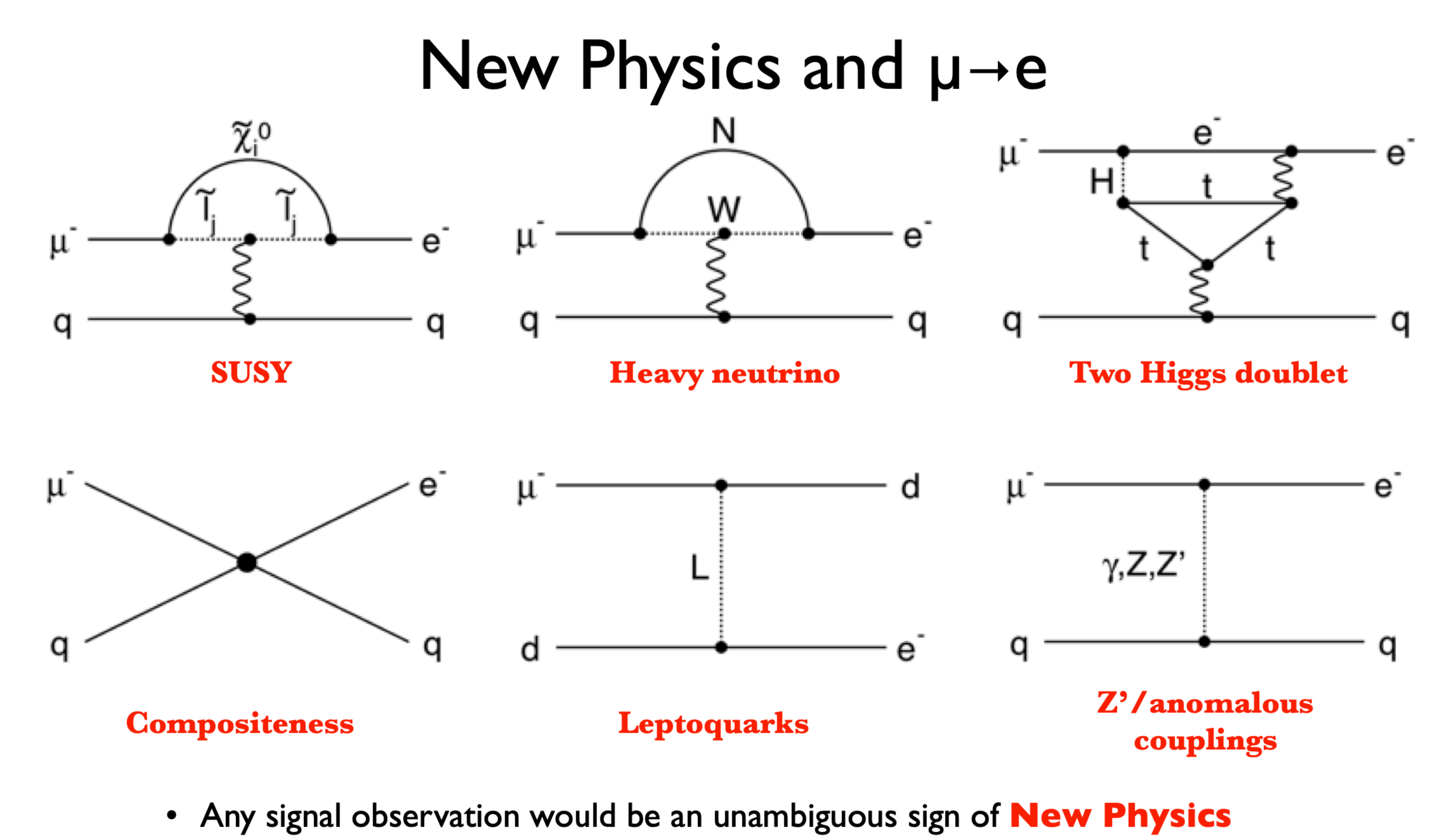
CLFV at a TeV scale muon-ion collider

Charged Lepton Flavor Violation 2023
June 22, 2023

D. Acosta, E. Barberis, P. Boyella, N. Hurley,
W. Li, O. M. Colin, Y. Wang, D. Wood, **X. Zuo**

In a nutshell



G. Pezzullo @CLFV 2019

Any new physics inducing $\mu \leftrightarrow e$ can be directly probed with muon-ion collisions.

Direct probe of $\mu \leftrightarrow \tau$, especially with NP modifications at high energy

Sizable production of Z, H, B_s, potential production of Z' and leptoquarks

All in one experiment.

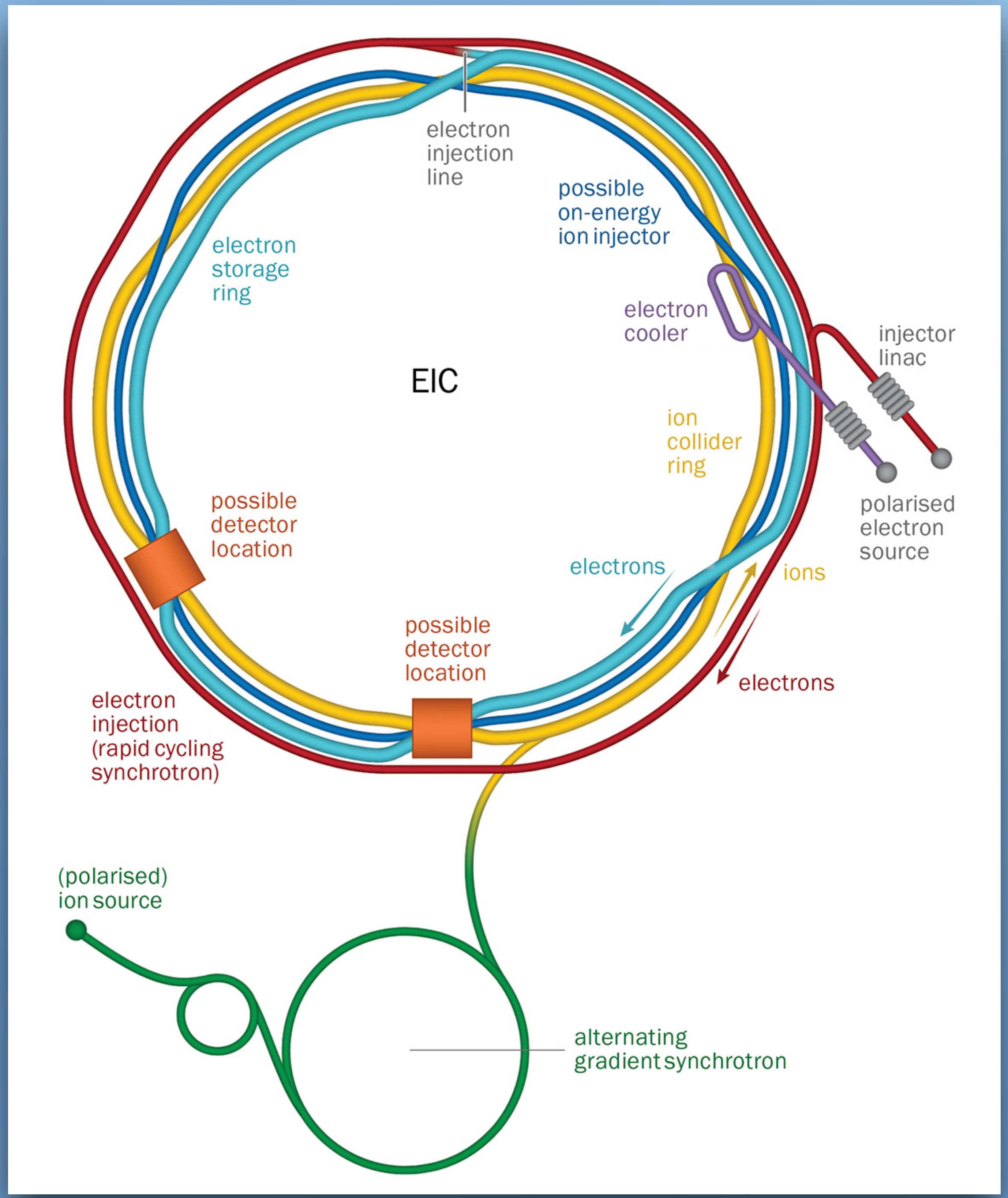
Outline

- MuIC concept
- Physics potential overview
- Case studies
  - $e \leftrightarrow \tau$ at EIC
  - $e \leftrightarrow \mu, \tau$ at LHeC
  - HNL at LHeC
  - Z' at MuIC
  - Leptoquark at MuIC

MuIC concept

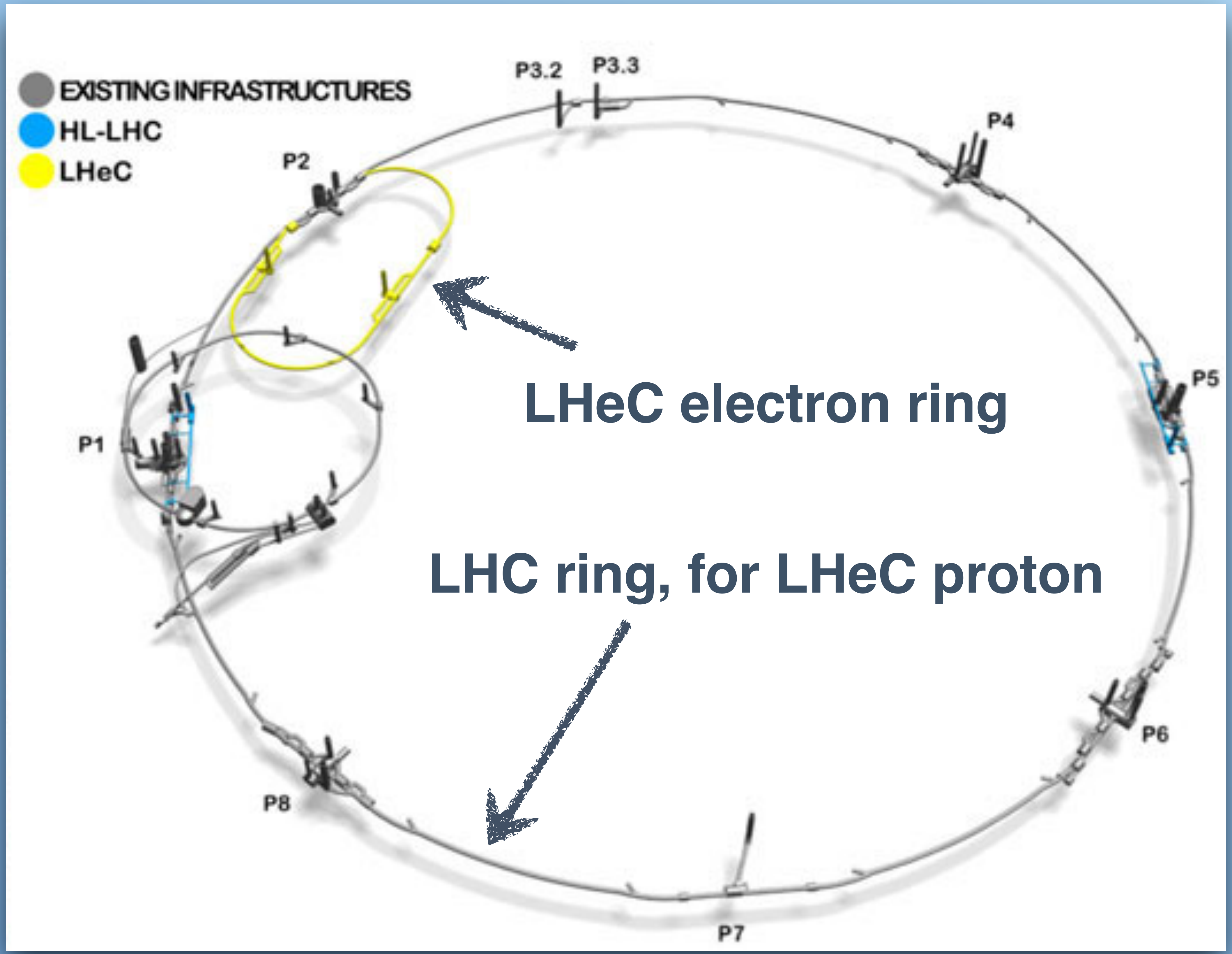
MuIC - inspirations

EIC at BNL



- $\sqrt{s} = 20 - 140$ GeV
- $\mathscr{L} = 100 - 1000$ fb^{-1}
- Approved, data-taking in 2030s

LHeC at CERN

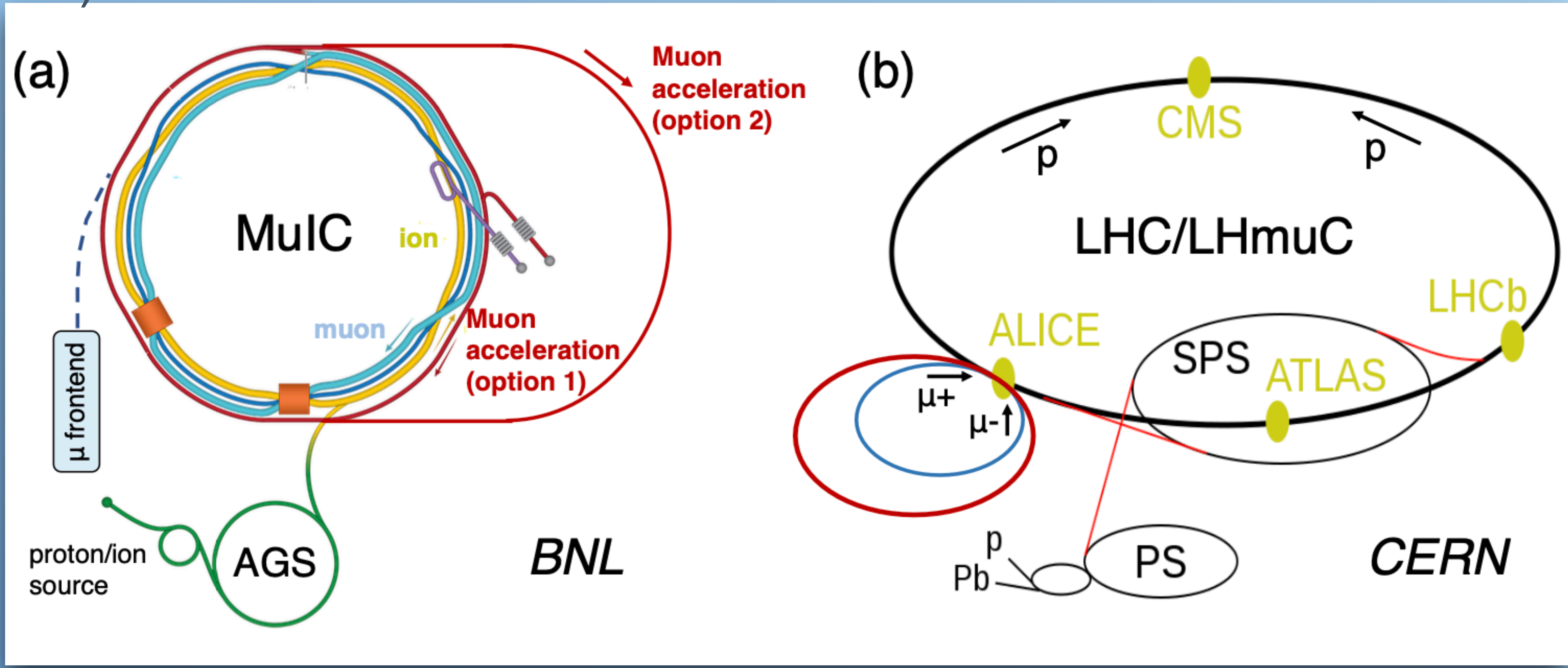


- $\sqrt{s} \sim 1.2$ TeV
- $\mathscr{L} \sim 1000$ fb^{-1}
- Proposed to be concurrent with HL-LHC

MuIC - proposal

Upgrade (alternative) of EIC (LHeC)

- For MuIC, $\sqrt{s} \sim 1$ TeV
- For LHmuC, $\sqrt{s} \sim 6.5$ TeV



Broad science program

- PDF determination
- QCD precision measurements
- EWK, Higgs physics
- BSM searches (**in particular, CLFV**)

MuIC proposals:

arXiv: 2107.02073

arXiv: 2203.06258

- A path toward muon accelerator technology
- Complementary and concurrent with mega-projects in HEP

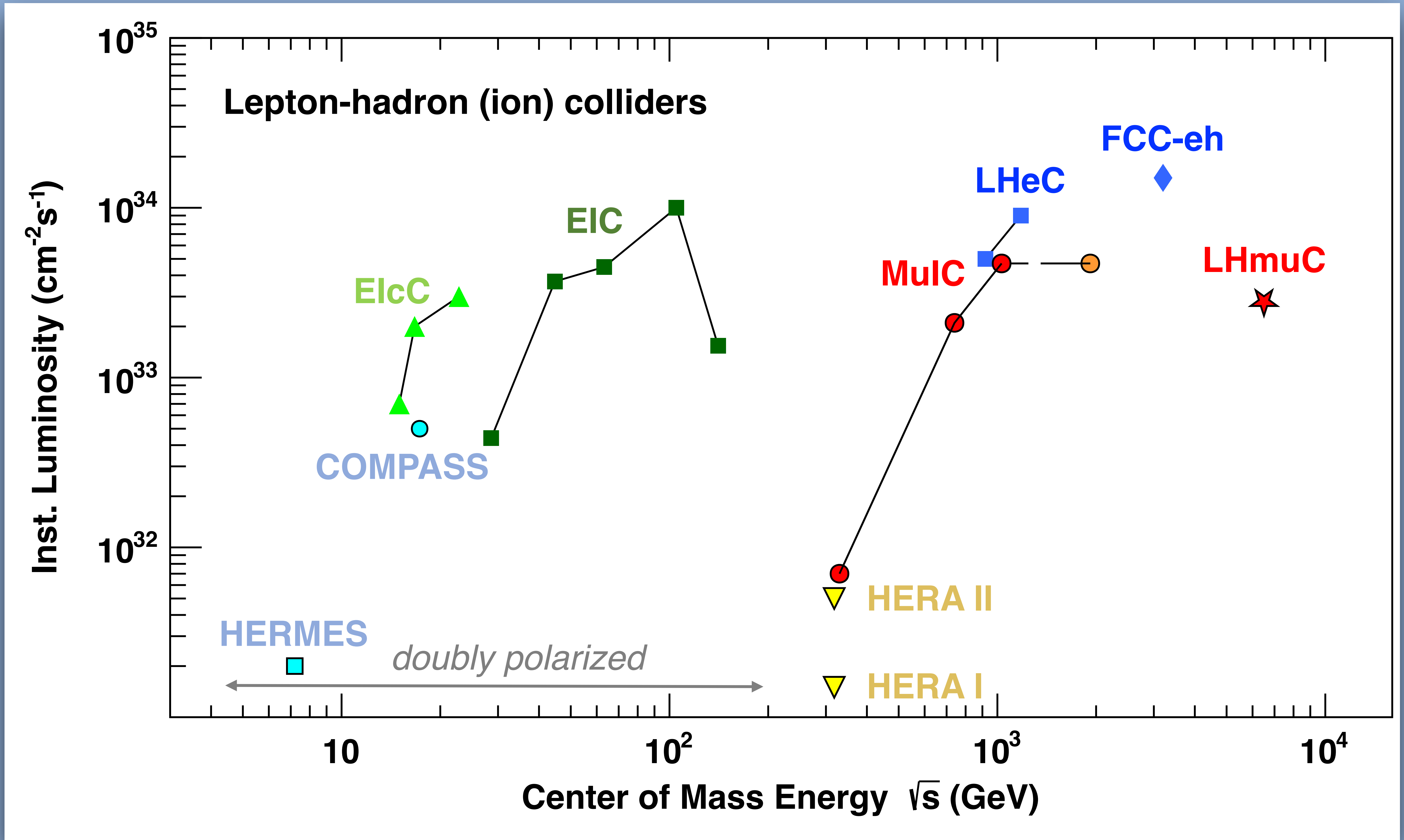
MuIC - dataset

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**

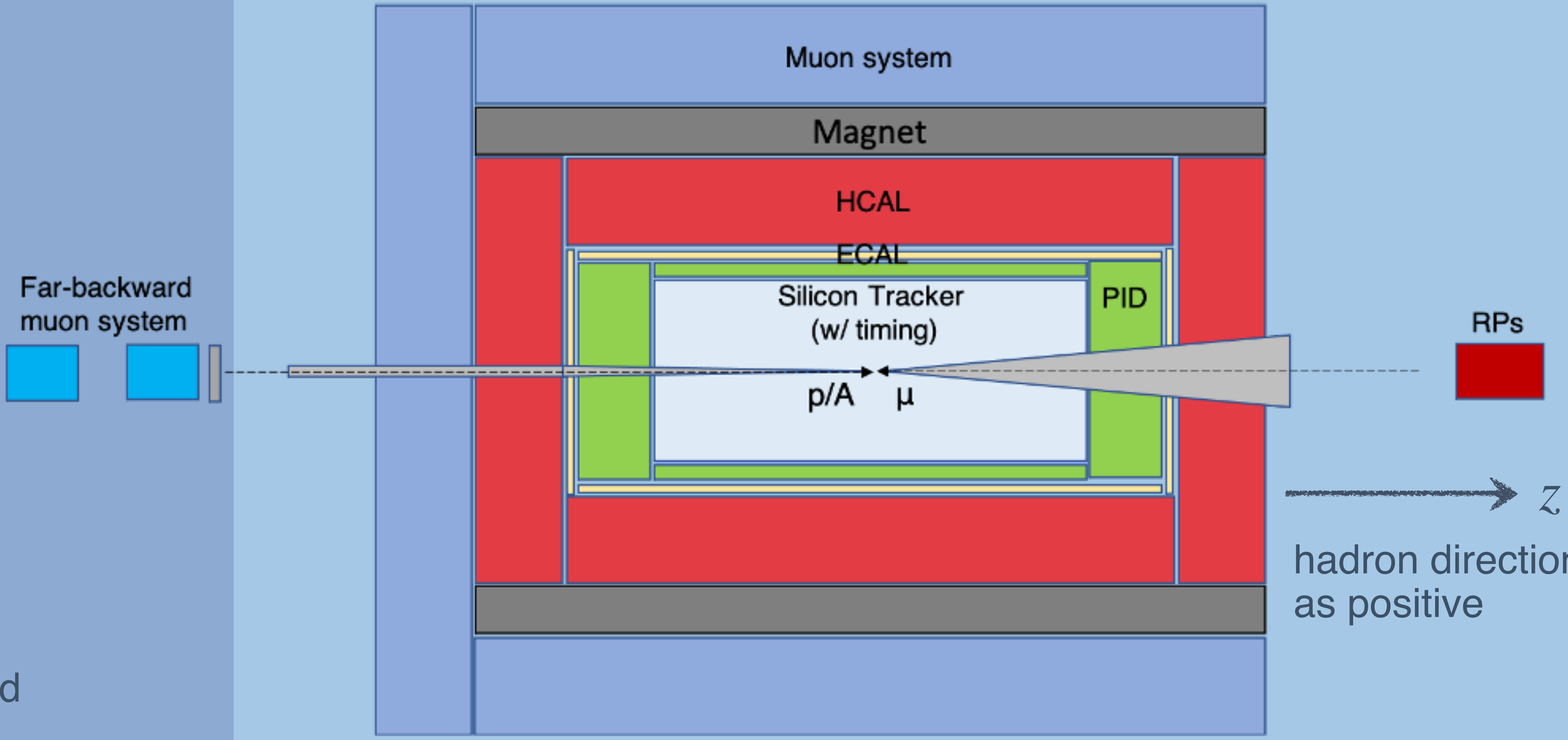
To clean electrons from the muon beam

(sacrifice some access to proton remnants)

- **Roman pot**

$5 < \eta < 8$

To detect elastically scattered protons



hadron direction as positive

Landscape of physics potential

Muon-ion collision

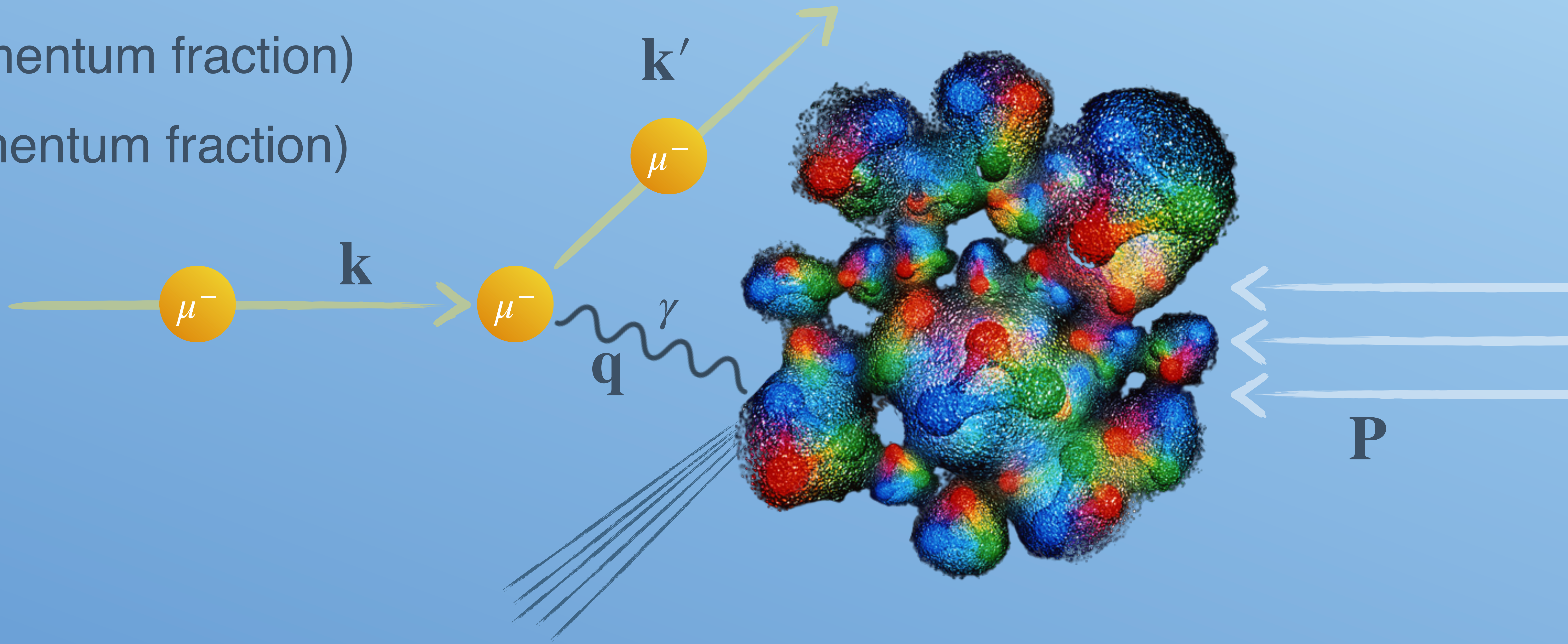
Physics descriptions:

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

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

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

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



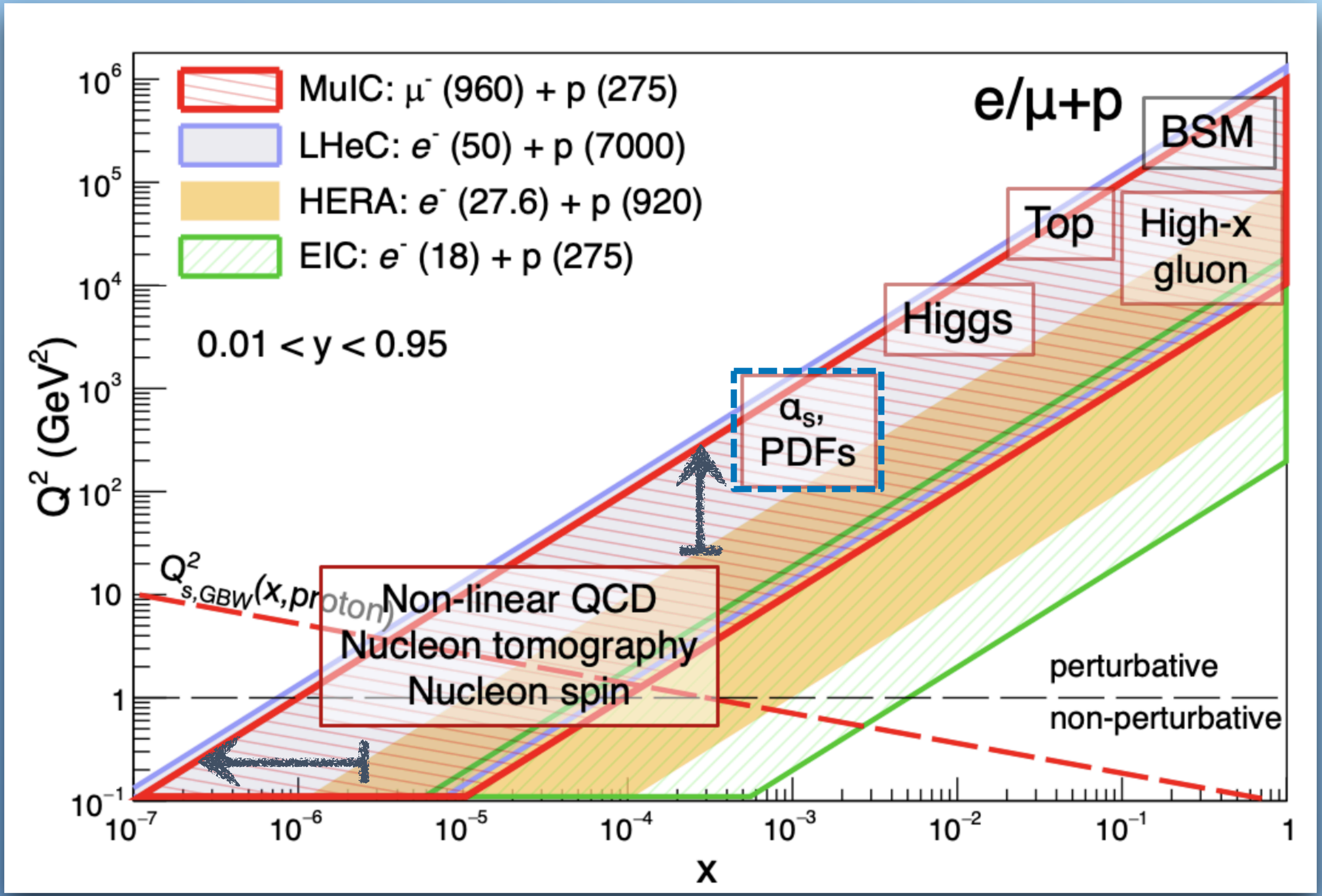
Physics landscape

The MuIC dataset

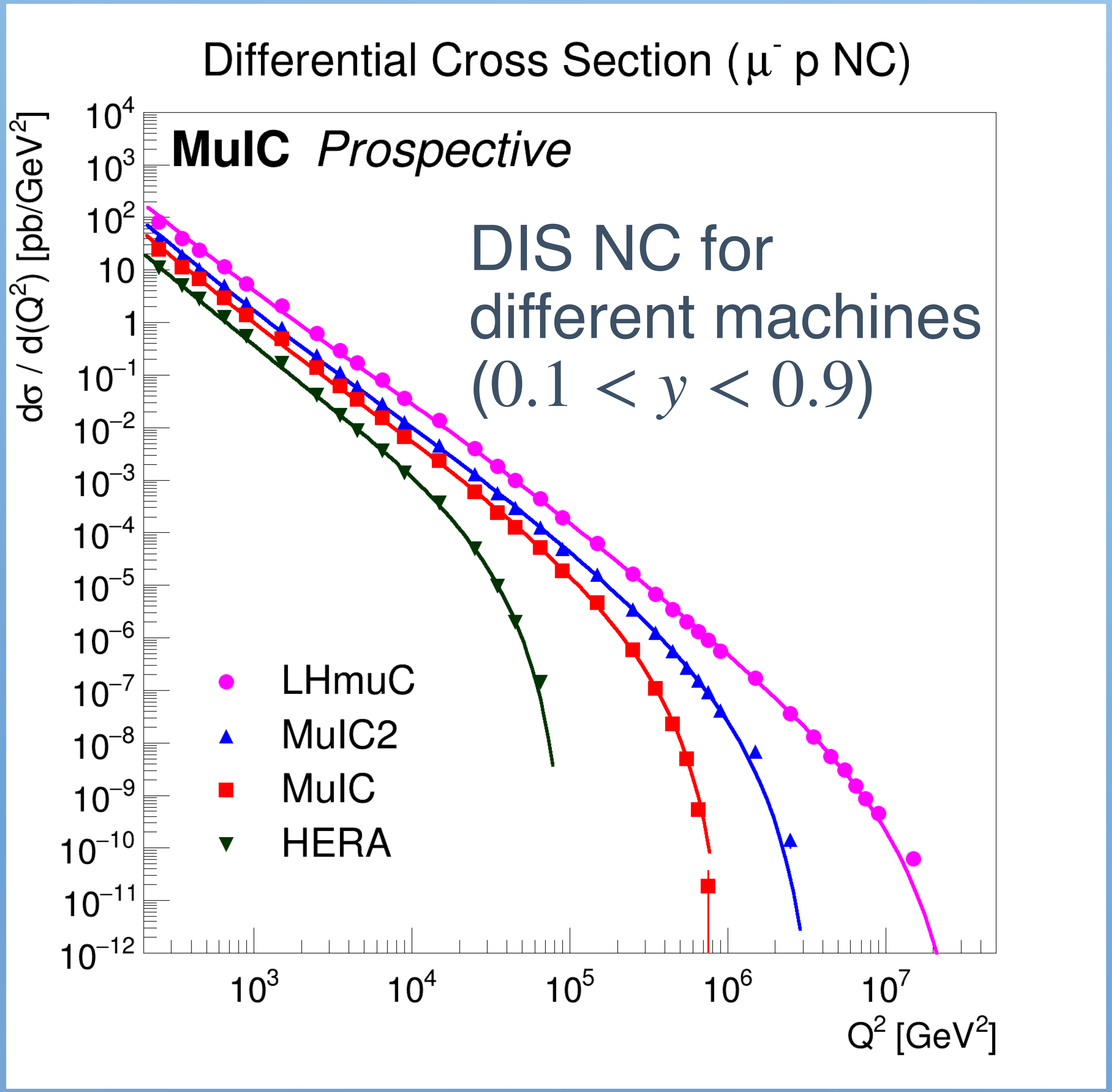
- Extends coverage of Q^2 and x by an order of magnitude
- Early datasets already good for nuclear physics and QCD measurements
- Opportunities open for EW physics and BSM searches as $\sqrt{s}$ and lumi increase

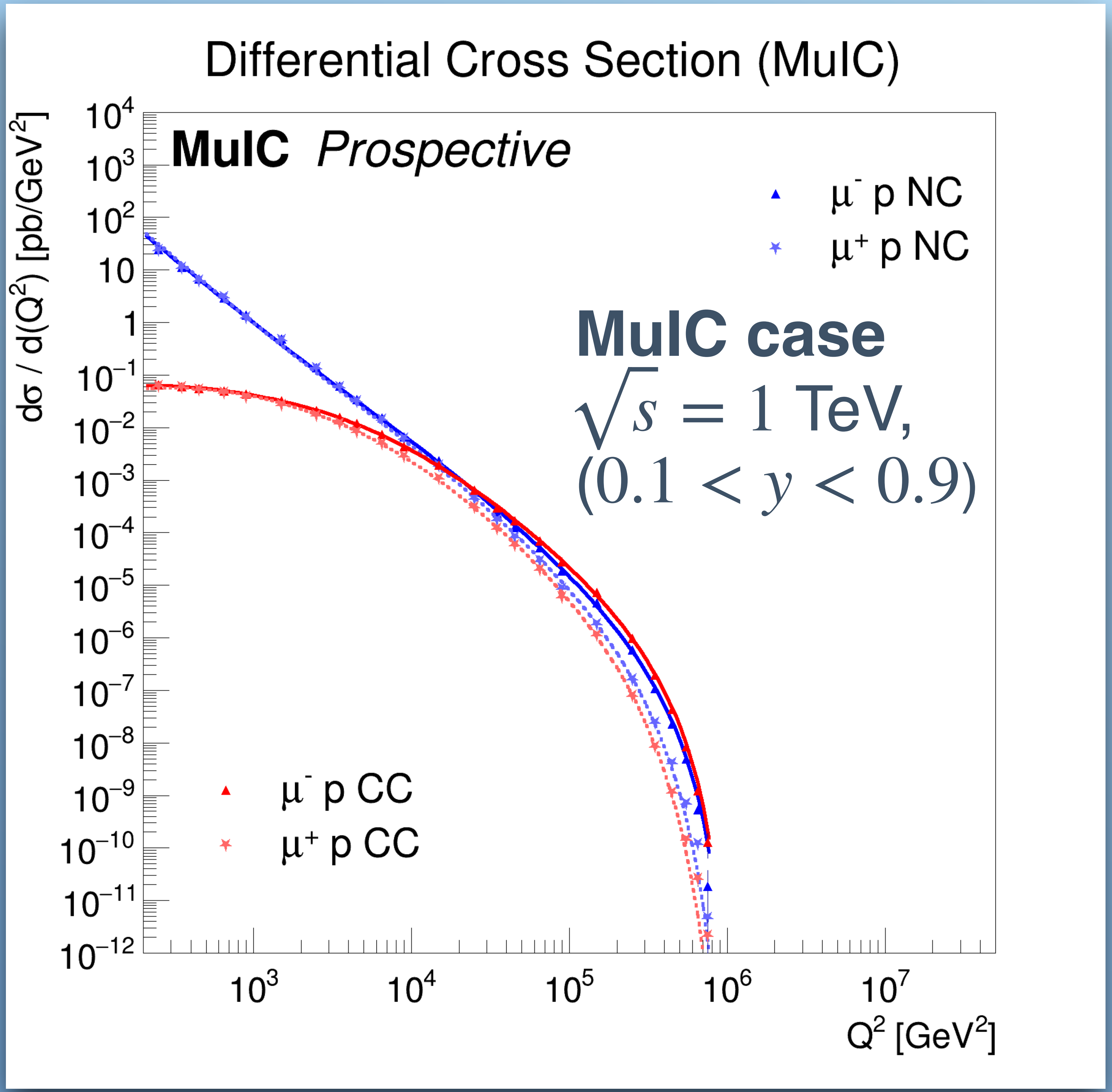
In view of CLFV

- Low Q^2 - light physics with $\mu \leftrightarrow e, \tau$
- Mid Q^2 - LFV decays of B_s, Z, H
- High Q^2 - Production of Z', LQ, etc.



Inclusive cross sections

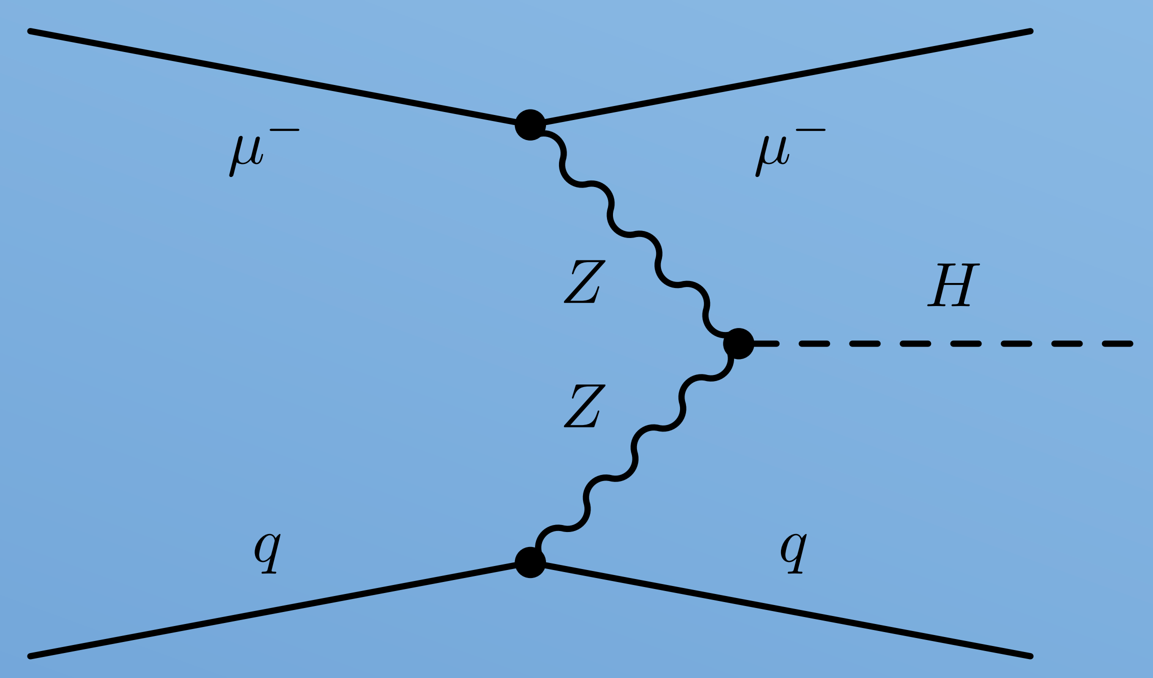




- Abundant cross sections for DIS at moderate Q^2 (including EW scale)
- Need very high luminosity to reach extreme Q^2

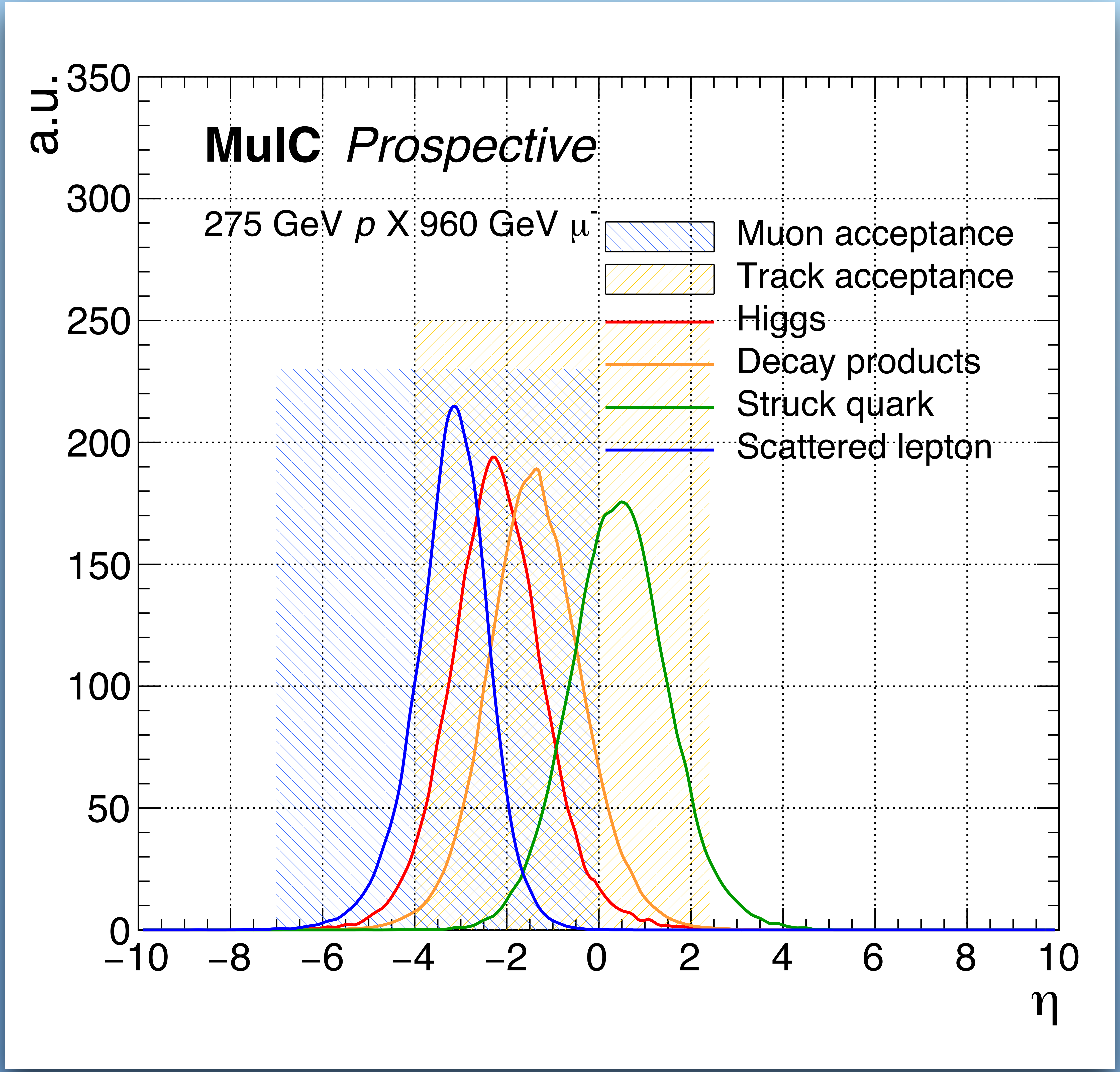
Event kinematics example

Consider a high Q^2 process (using Higgs production as an example)



Implication for CLFV searches:

- Scattered lepton is forward, even for high Q^2 processes $\longrightarrow$ beam backgrounds are rather collimated
- If heavy particles are produced, their decay products are well within the central acceptance
- Leptons originating from the hadron side (e.g. t-channel LQ exchange) do not mix with scattered leptons.



Selected case studies

with references from EIC and LHeC

$e \leftrightarrow \tau$ at EIC

LFV τ decay searches	Probe of $ep \to \tau X$ production
• Tag each decay mode individually • Some modes are difficult to reconstruct	• Measure the total size of all BSM modifications • Tag taus with well-understood decay modes

Detailed EFT description for τ productions and decays at EIC

Example table shows $\sigma(ep \to \tau X)$ with modifications from Z' ($c_{L\varphi}$) or four-fermion interactions ($(C_{LQ})_{qq}$).

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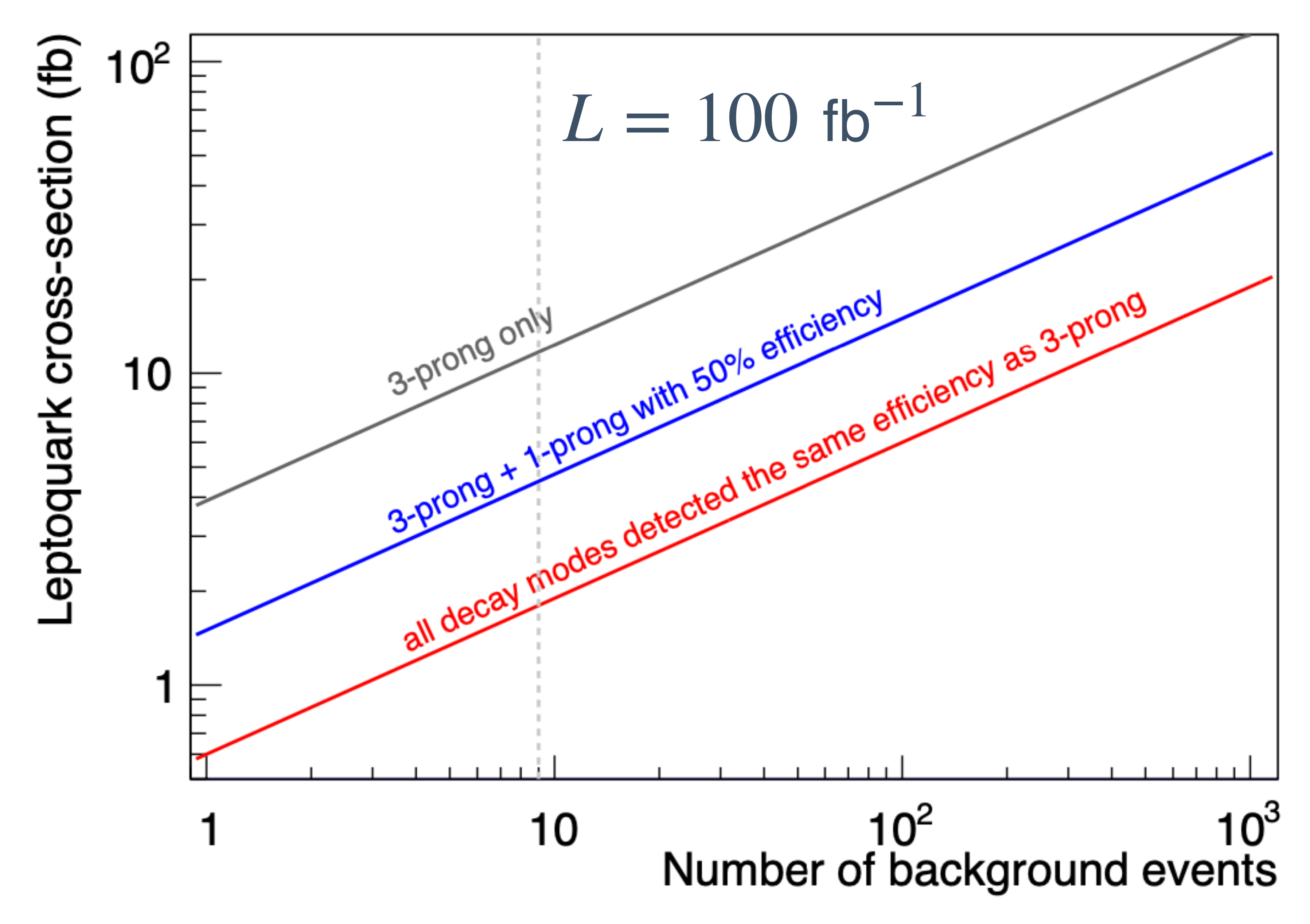
$\sqrt{S}$	63 GeV	100 GeV	141 GeV	$\sqrt{S}$	63 GeV	100 GeV	141 GeV
τ_L	σ_1 (pb)	σ_2 (pb)	σ_3 (pb)	τ_R	σ_1 (pb)	σ_2 (pb)	σ_3 (pb)
$c^{(1)}_{L\varphi} + c^{(3)}_{L\varphi}$	1.86(4)	4.2(1)	7.6(2)	$c_{e\varphi}$	1.30(3)	3.1(1)	5.6(2)
τ_L	σ_1 (pb)	σ_2 (pb)	σ_3 (pb)	τ_L	σ_1 (pb)	σ_2 (pb)	σ_3 (pb)
$(C_{LQ,U})_{uu}$	8.0(4)	20(1)	38(2)	$(C_{Lu})_{uu}$	3.9(2)	9.5(4)	19(1)
$(C_{LQ,U})_{cu}$	7.8(4)	20(1)	37(2)	$(C_{Lu})_{cu}$	3.1(3)	7.8(7)	15(1)
$(C_{LQ,U})_{uc}$	1.0(2)	2.5(6)	5.2(1.1)	$(C_{Lu})_{uc}$	1.4(2)	3.7(4)	7.5(8)
$(C_{LQ,U})_{cc}$	0.7(3)	1.9(7)	4.0(1.4)	$(C_{Lu})_{cc}$	0.7(3)	1.9(7)	4.0(1.4)
$(C_{LQ,D})_{dd}$	4.4(2)	10.8(4)	21(1)	$(C_{Ld})_{dd}$	2.8(1)	7.1(3)	14(1)
$(C_{LQ,D})_{sd}$	3.9(2)	9.7(4)	19(1)	$(C_{Ld})_{sd}$	1.6(2)	3.9(6)	7.8(1.2)
$(C_{LQ,D})_{bd}$	3.9(1)	9.5(3)	19(1)	$(C_{Ld})_{bd}$	1.4(1)	3.4(1)	7.0(3)
$(C_{LQ,D})_{ds}$	0.8(3)	2.0(8)	4.1(1.5)	$(C_{Ld})_{ds}$	1.6(2)	4.1(4)	8.3(9)
$(C_{LQ,D})_{ss}$	0.35(31)	1.0(8)	2.0(1.7)	$(C_{Ld})_{ss}$	0.33(27)	0.9(7)	1.9(1.5)
$(C_{LQ,D})_{bs}$	0.28(26)	0.8(7)	1.7(1.4)	$(C_{Ld})_{bs}$	0.14(10)	0.5(3)	1.1(6)
$(C_{LQ,D})_{db}$	0.57(7)	1.6(2)	3.2(3)	$(C_{Ld})_{db}$	1.6(1)	4.0(2)	8.0(5)
$(C_{LQ,D})_{sb}$	0.13(7)	0.4(2)	1.1(5)	$(C_{Ld})_{sb}$	0.26(19)	0.7(5)	1.6(1.1)
$(C_{LQ,D})_{bb}$	0.07(4)	0.3(2)	0.8(2)	$(C_{Ld})_{bb}$	0.07(6)	0.3(1)	0.8(0.5)
τ_R	σ_1 (pb)	σ_2 (pb)	σ_3 (pb)	τ_R	σ_1 (pb)	σ_2 (pb)	σ_3 (pb)
$(C_{Qe})_{dd}$	7.5(3)	19(1)	37(2)	$(C_{Qe})_{ds}$	5.7(5)	14(1)	29(2)
$(C_{Qe})_{sd}$	4.1(2)	10.3(5)	21(1)	$(C_{Qe})_{ss}$	2.3(2)	5.8(5)	12(1)
$(C_{Qe})_{bd}$	1.4(6)	3.7(1)	7.4(3)	$(C_{Qe})_{bs}$	0.20(11)	0.6(3)	1.4(7)
$(C_{Qe})_{db}$	1.7(1)	4.3(3)	8.7(5)	$(C_{Qe})_{sb}$	0.32(19)	0.9(5)	2.0(1.1)
$(C_{Qe})_{bb}$	0.07(6)	0.3(1)	0.8(5)				

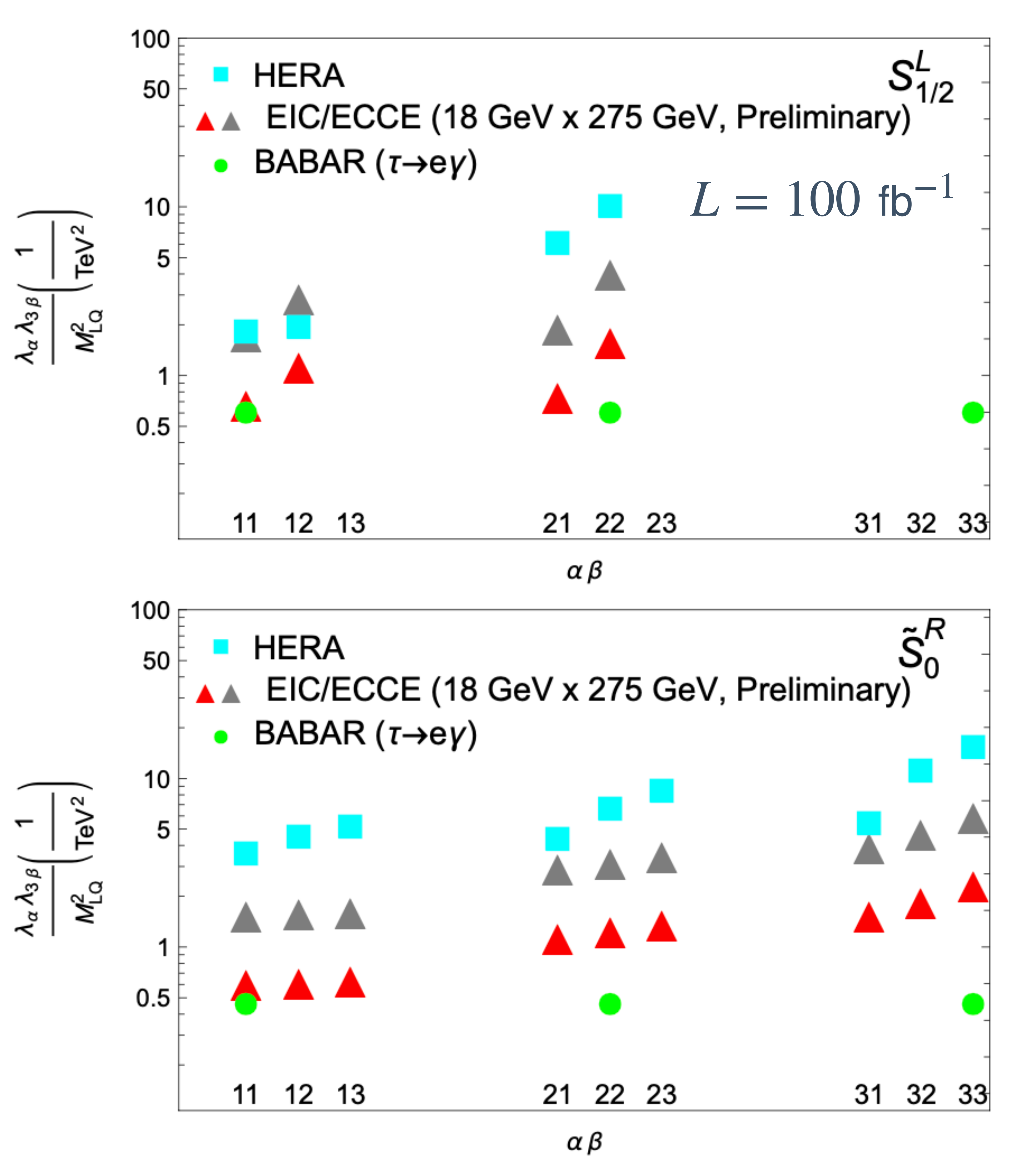
$e \leftrightarrow \tau$ at EIC

arXiv: 2207.10261

Full simulation study on the reconstruction efficiency of $e \rightarrow \tau$ events

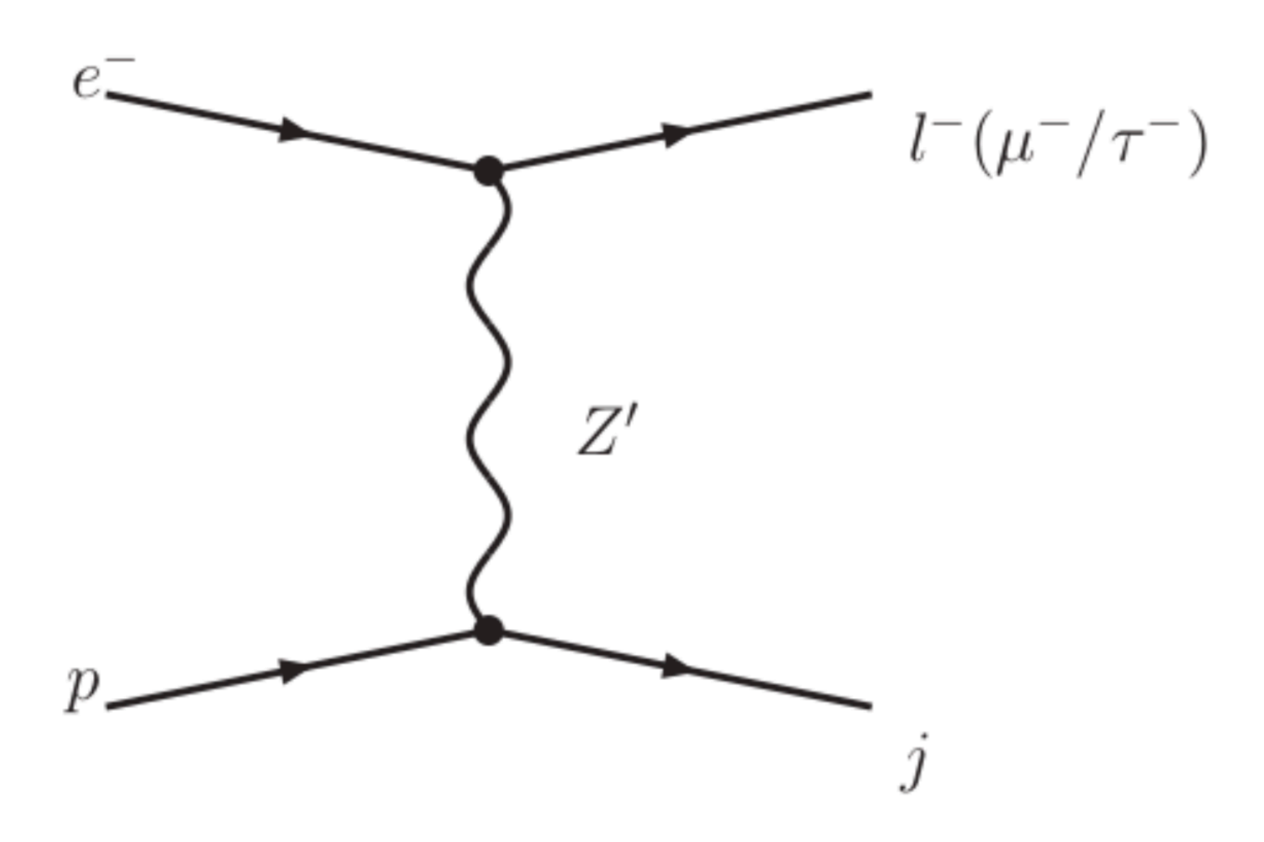
- Much cleaner selection with on 3-prong decays
- Consider single modification from LQ, limits on interaction strength from $ep \rightarrow \tau X$ comparable to the BABAR $\tau \rightarrow e\gamma$ result





$e \to \mu, \tau$ at LHeC

- Search for direct FCNC mediated by Z'
- Tag outgoing tau or mu
- $e \to \mu$ sensitivity not comparable with muon conversion results.
- Competitive results in $e \to \tau$ conversion



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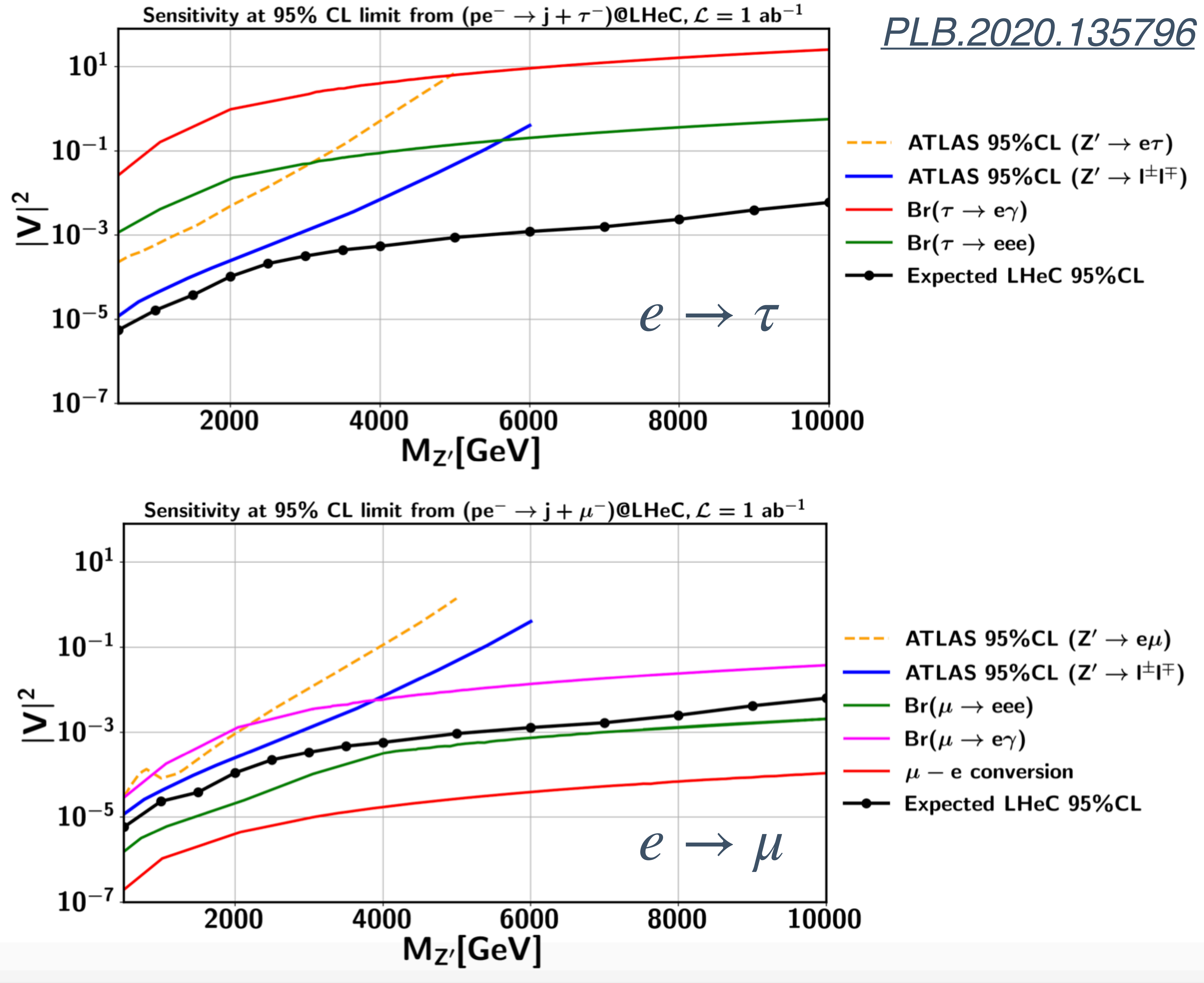
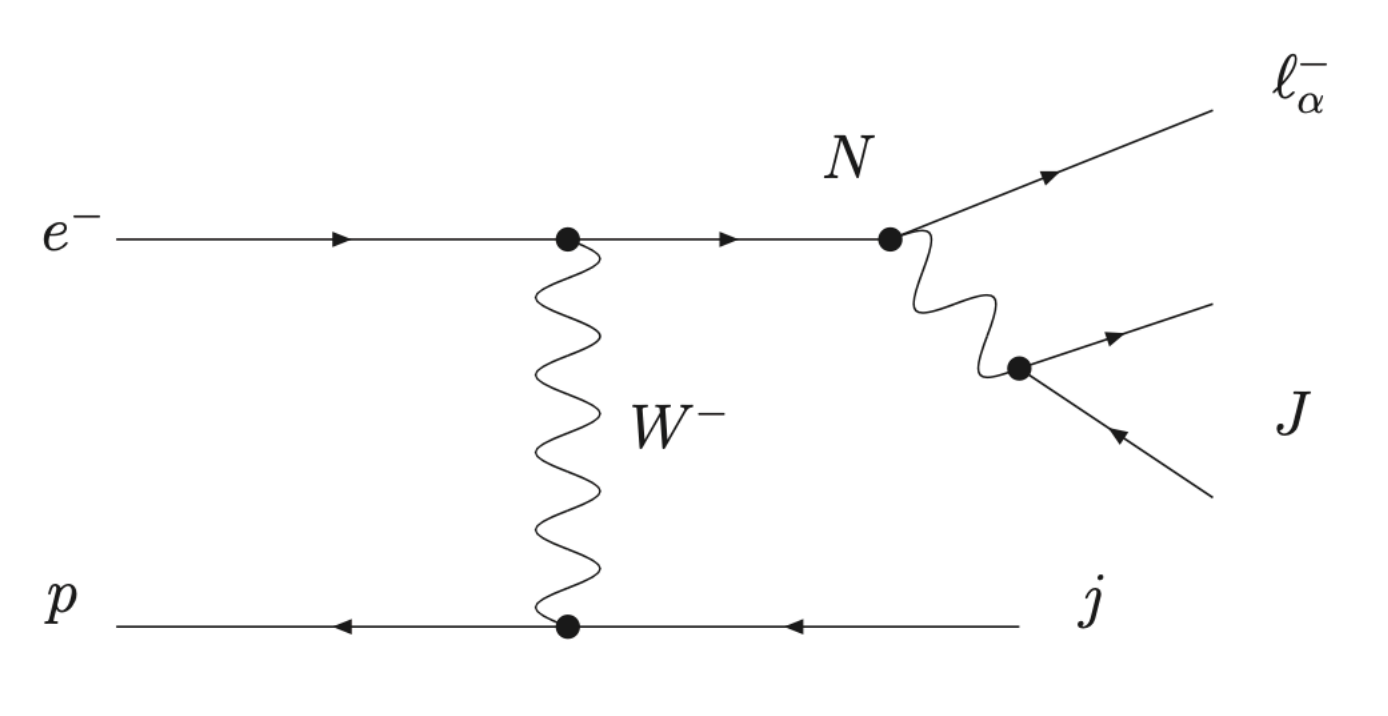


Production of HNL at LHeC

- Consider HNL in "Symmetry Protected Seesaw Scenario" model, assuming mixing angles $|\theta_e|^2 = |\theta_\mu|^2, |\theta_\tau|^2 = 0$
- Prompt search for $\mu + 3j$ final state, with dijet compatible with W mass
- Also search for displaced $N \rightarrow$ visible with reconstructable vertex



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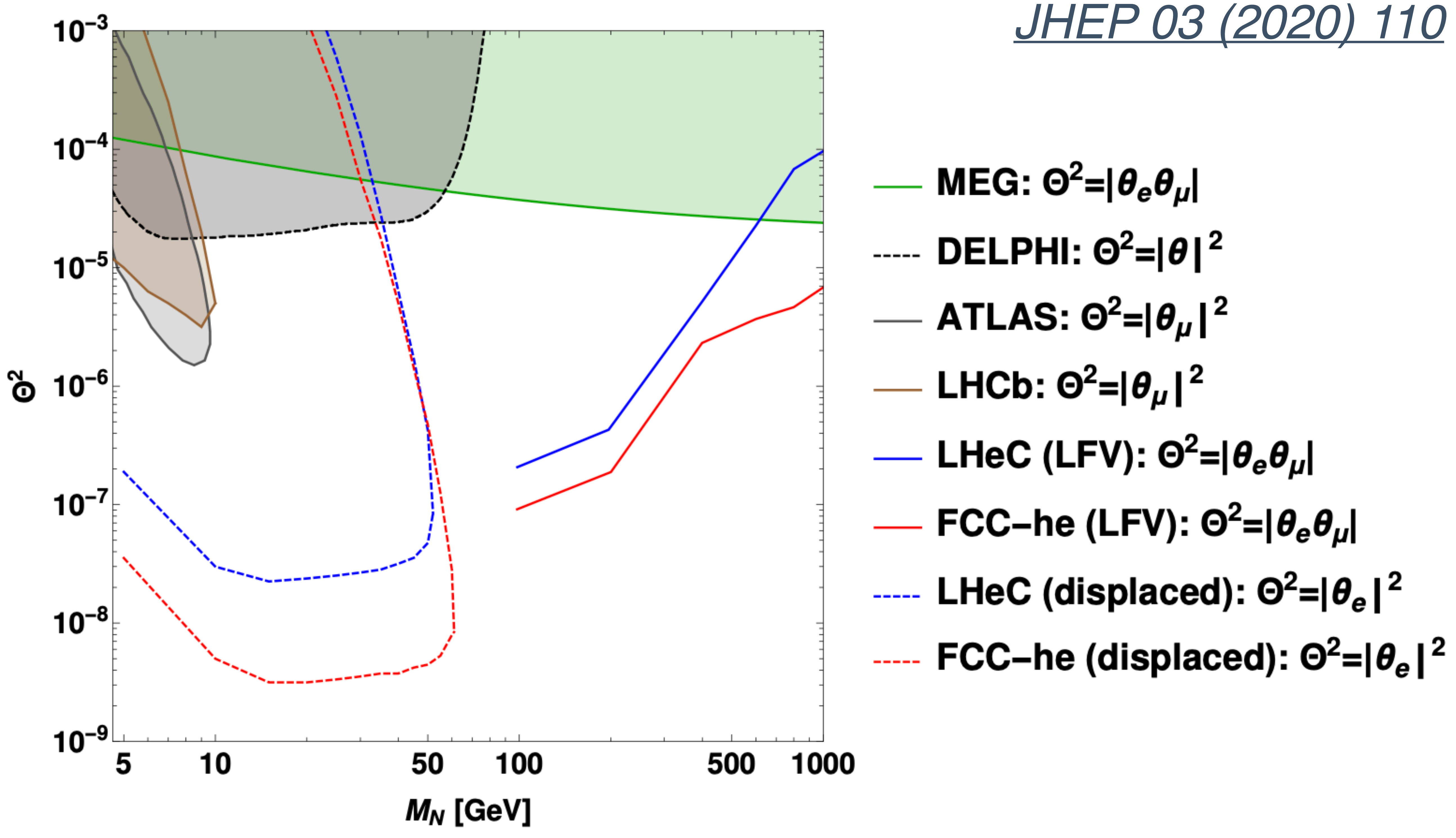


Remarkable exclusion sensitivities: potential "golden channel" for direct HNL search

Z' at MuIC

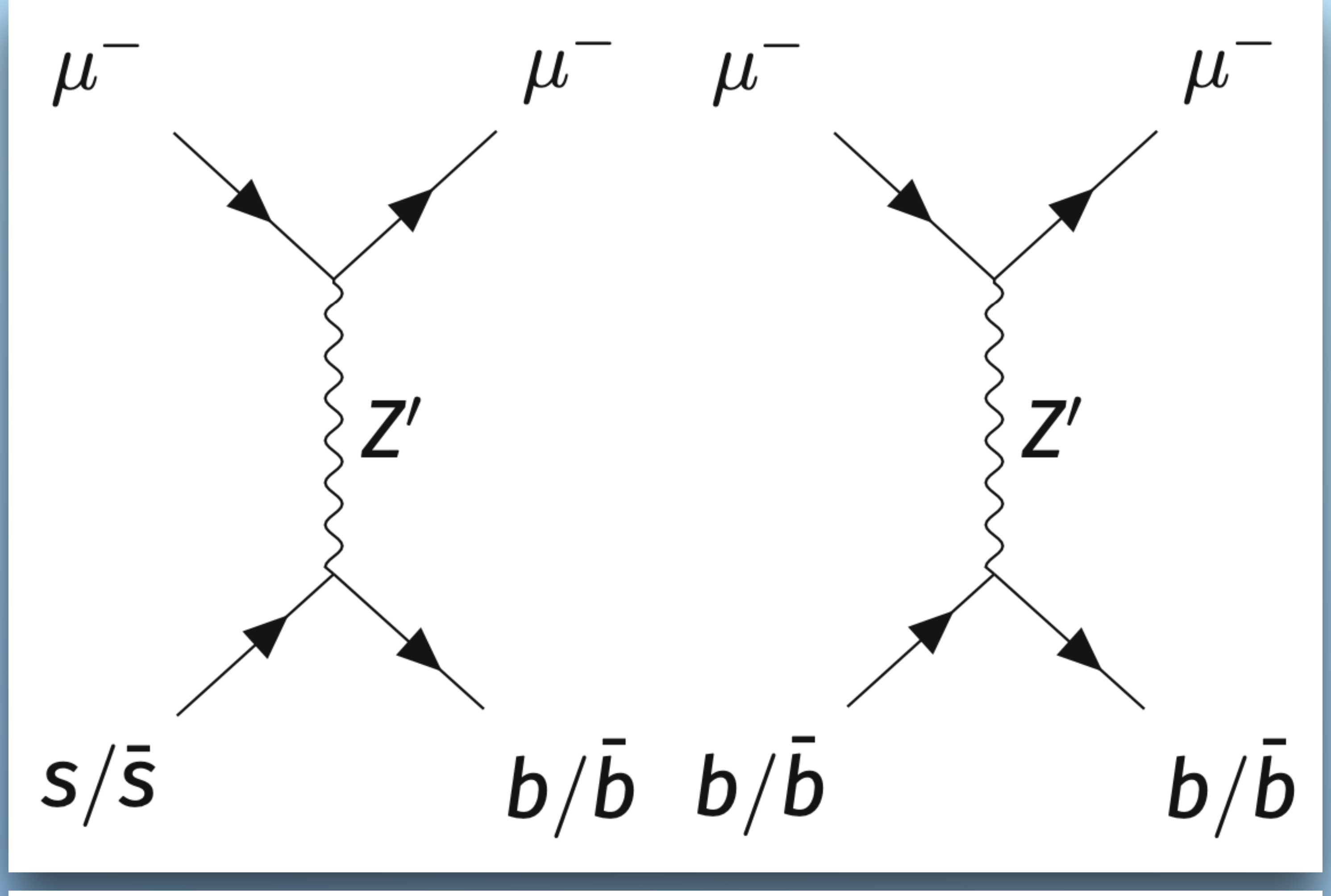
- Consider model discussed in Phys. Rev. D 97.075035

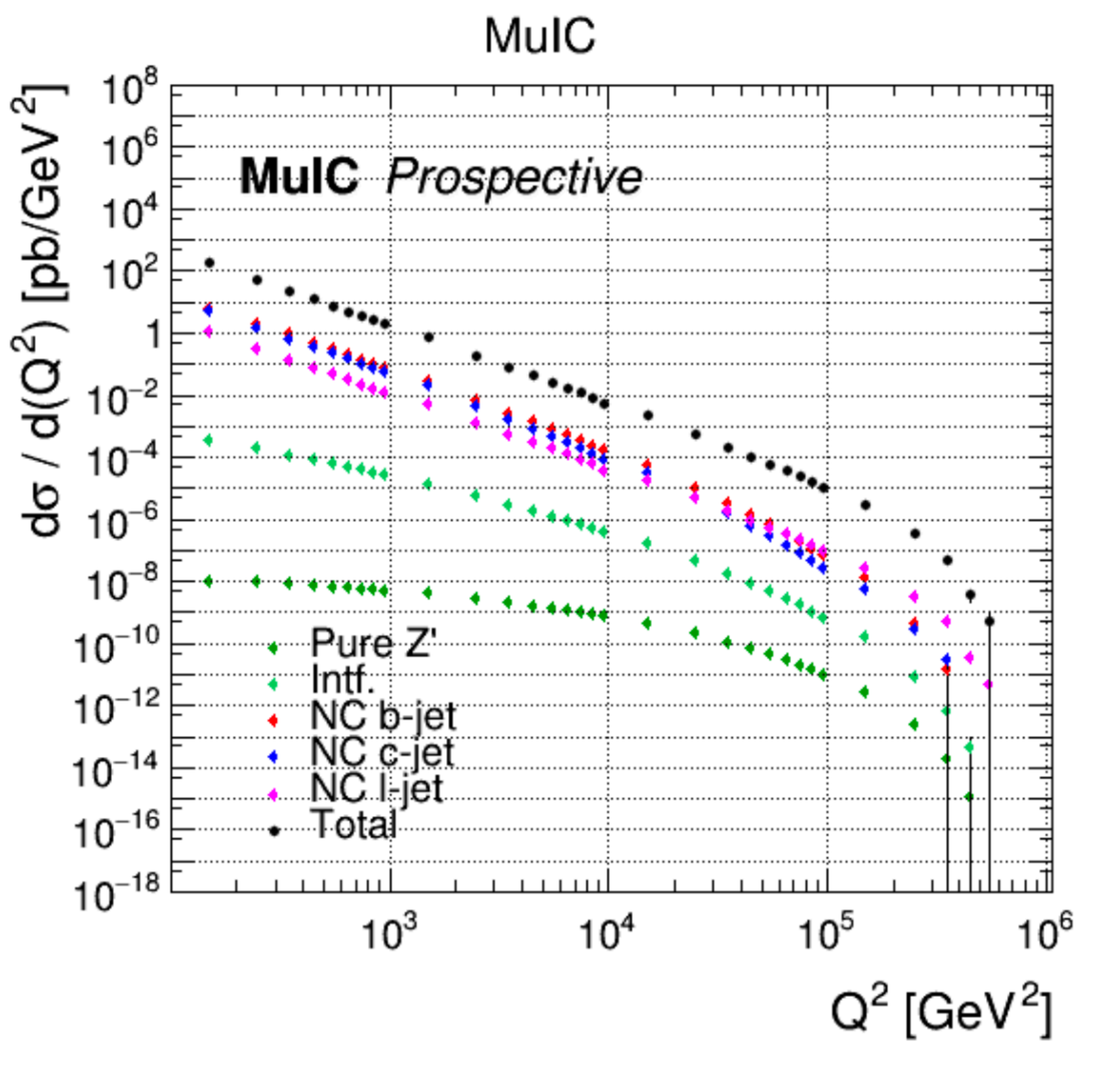
$$L \supset Z'^{\mu}[g_{\mu}\bar{\mu}\gamma^{\mu}\mu + g_{\mu}\bar{\nu}_{\mu}\gamma^{\mu}P_L\nu_{\mu} + g_b \sum_{q=t,b} \bar{q}\gamma^{\mu}P_L q + (g_b\delta_{bs}\bar{s}\gamma^{\mu}P_L b + \text{h.c.})]$$

- Introducing coupling to muons and between s, b quarks to explain anomalies in B meson decays.
- In which, $g_b\delta_{bs}$ is the non-flavor conserving component,

$$g_b\delta_{bs}g_{\mu}(100\ \text{GeV}/m_{Z'})^2 \sim 1.3 \times 10^{-5}$$

- The flavor conserving part has significant interference with the SM neutral current process





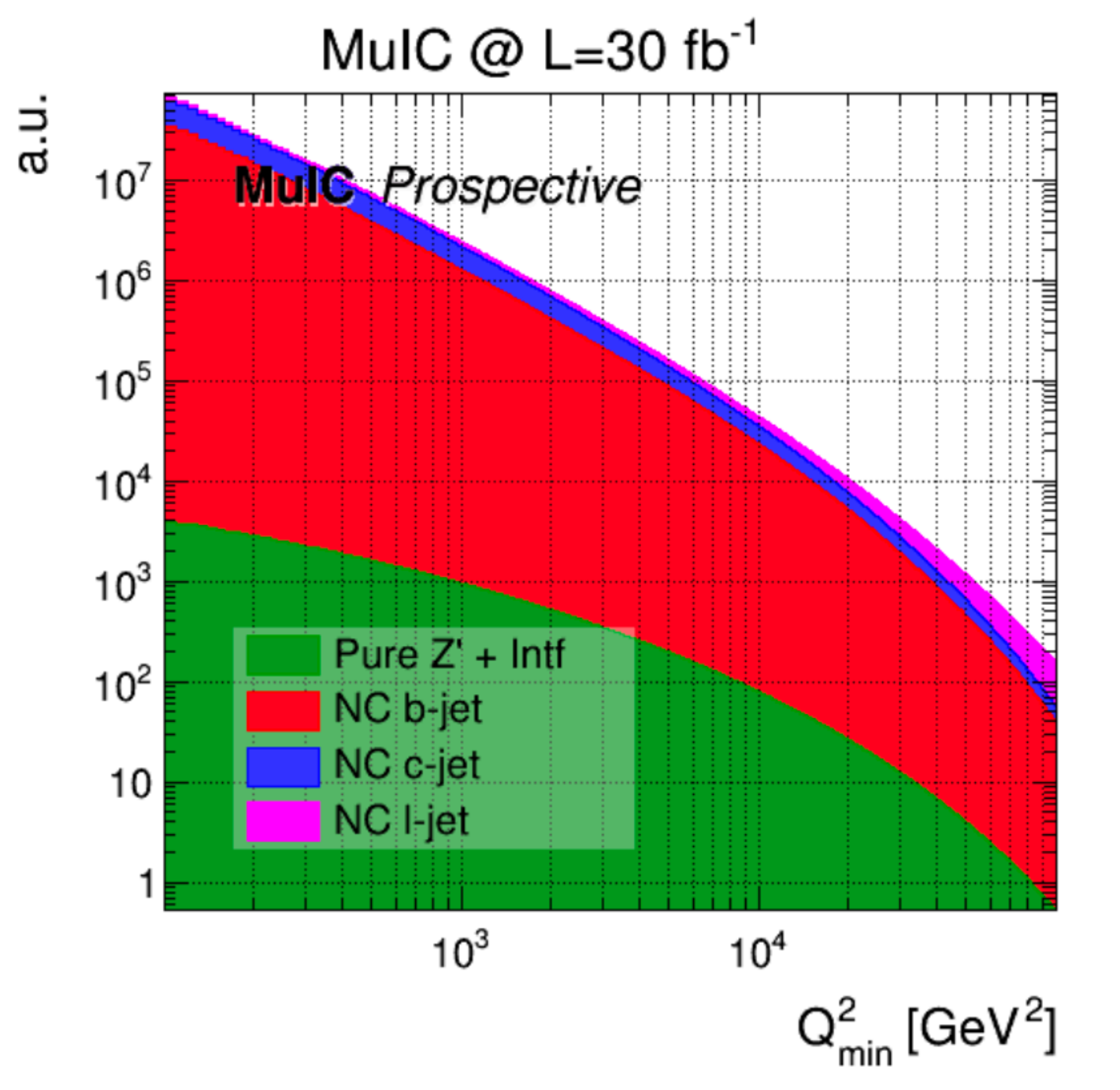
$m_{Z'} = 500\ GeV$

Z' pseudo-analysis

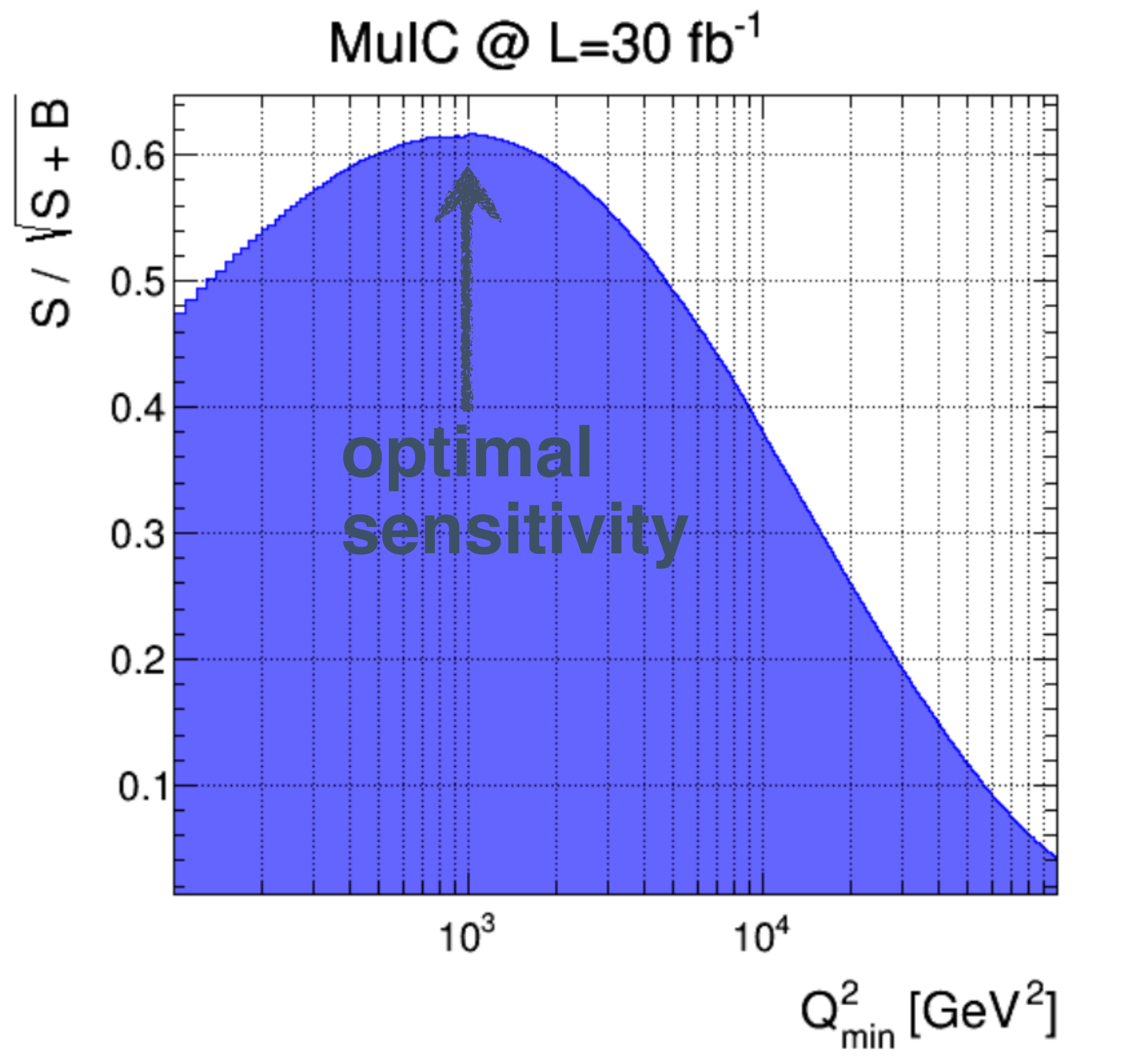
Scan the reconstructed Q^2 with simple cut-and -count estimates

b-tagging and mis-tagging efficiencies for $b, c, q(u, d, s)$ jets are assumed at 70%, 10%, 1%

- Full simulation planned to understand requirements for detectors



$m_{Z'} = 500\ GeV$



$m_{Z'} = 500\ GeV$

xunwu.zuo@cern.ch

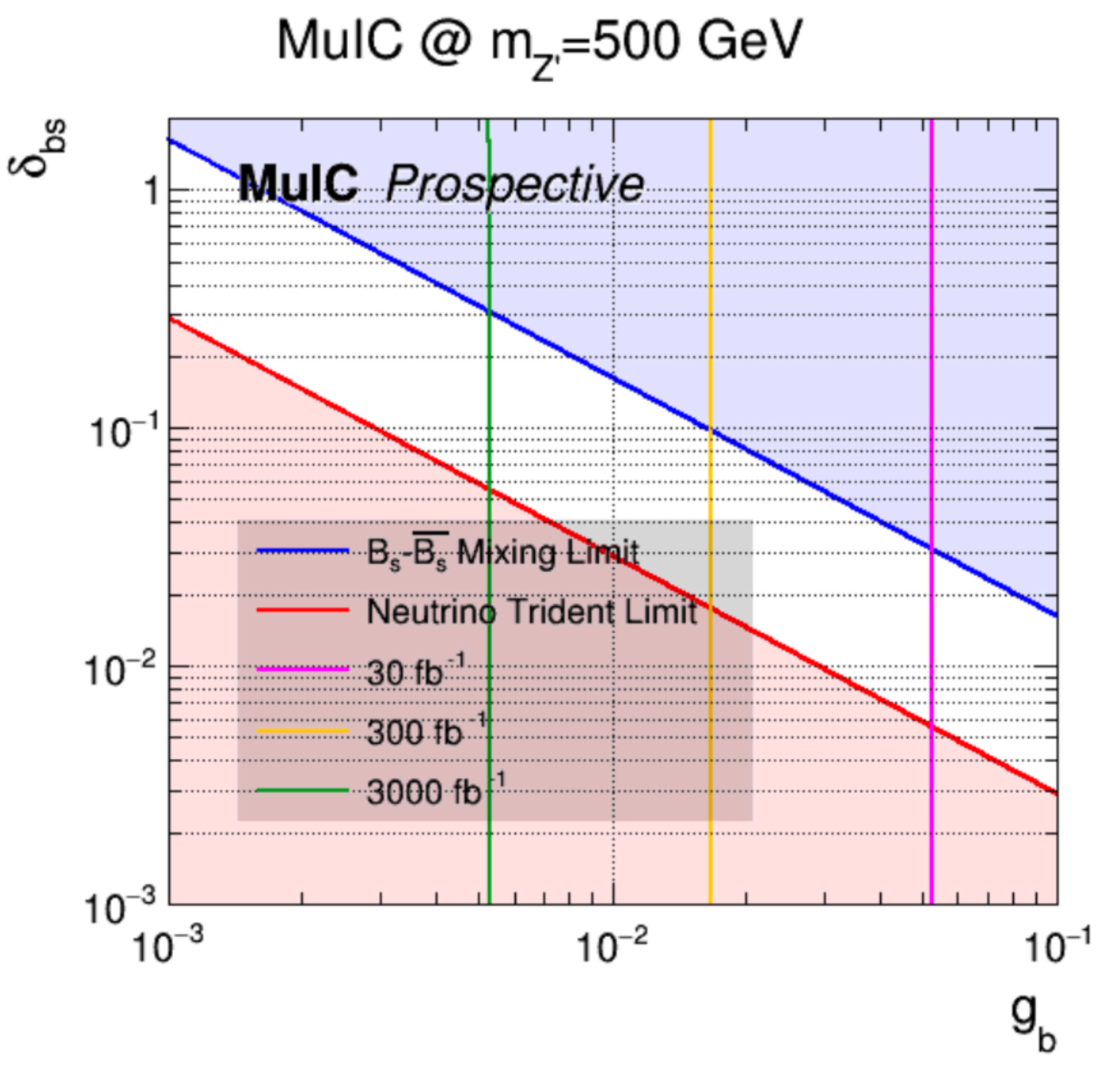
Z' Projected Limits

Exclusion phase-space complementary to current B results and neutrino experiments

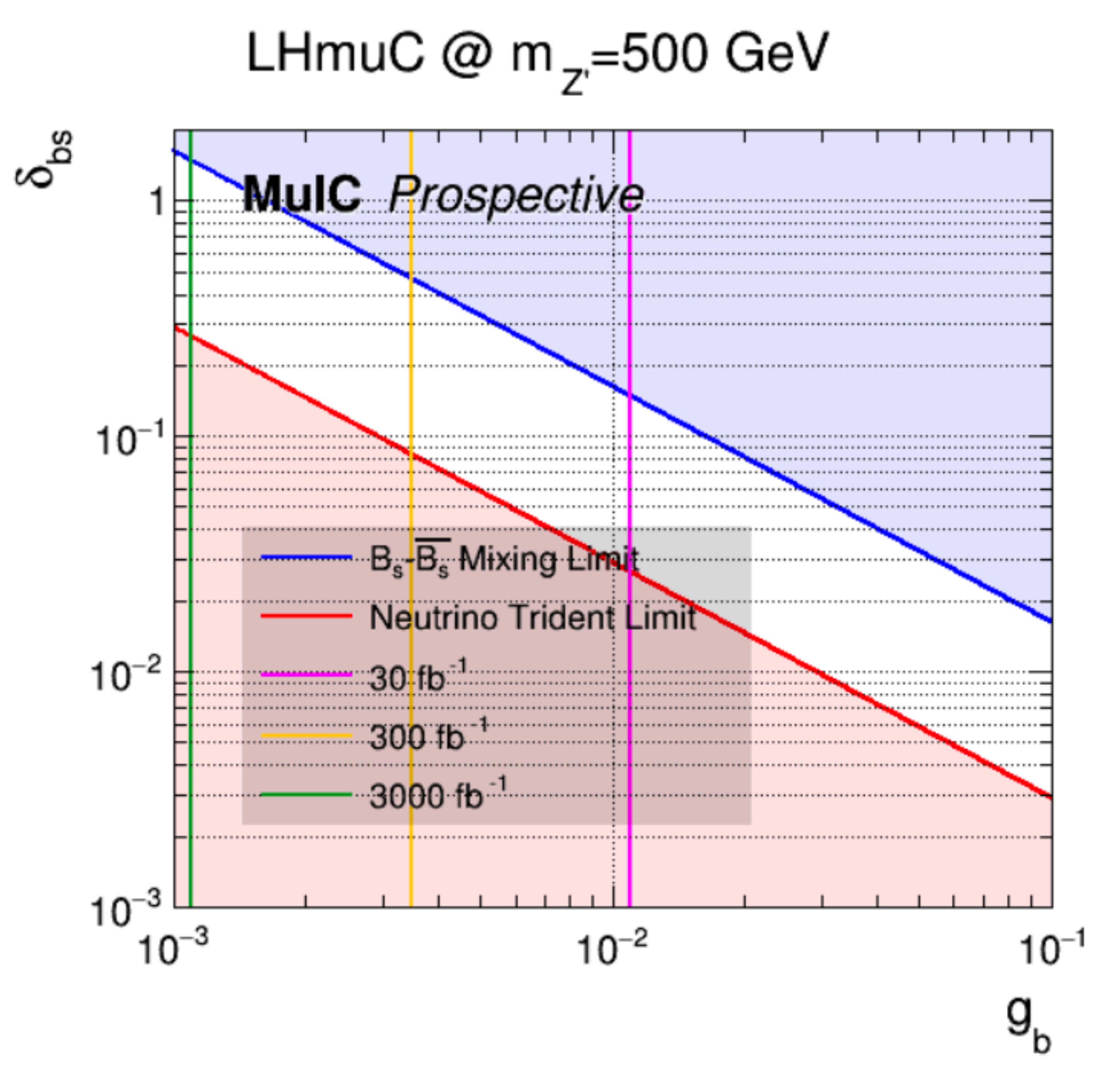
Also need to compete with direct Z' searches at HL-LHC.

- Comparing to HL-LHC projection in Phys. Rev. D 97, 075035, need about $120\ \text{fb}^{-1}$ at LHmuC

More studies on different channels and interpretations planned.



MuIC



LHmuC

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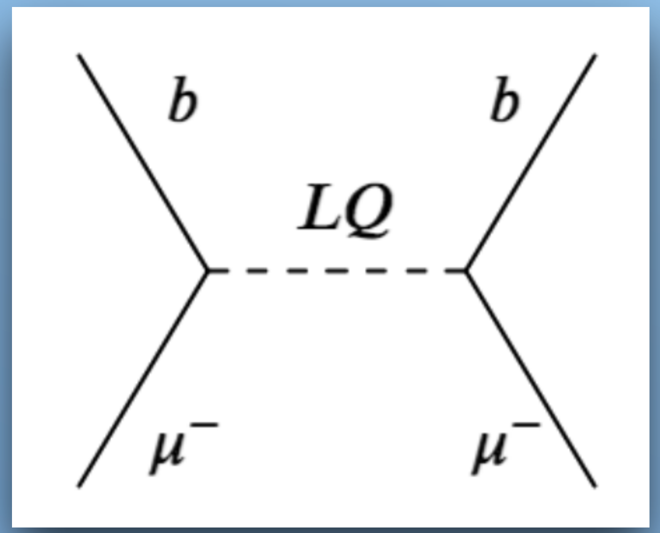
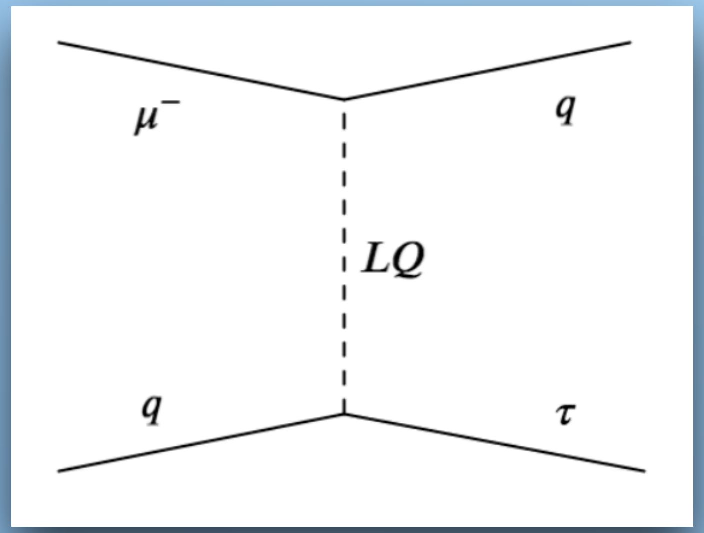
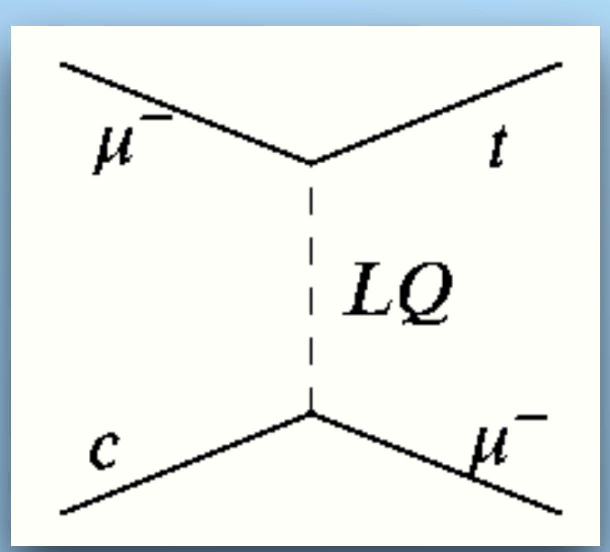
Leptoquark signatures at MuIC



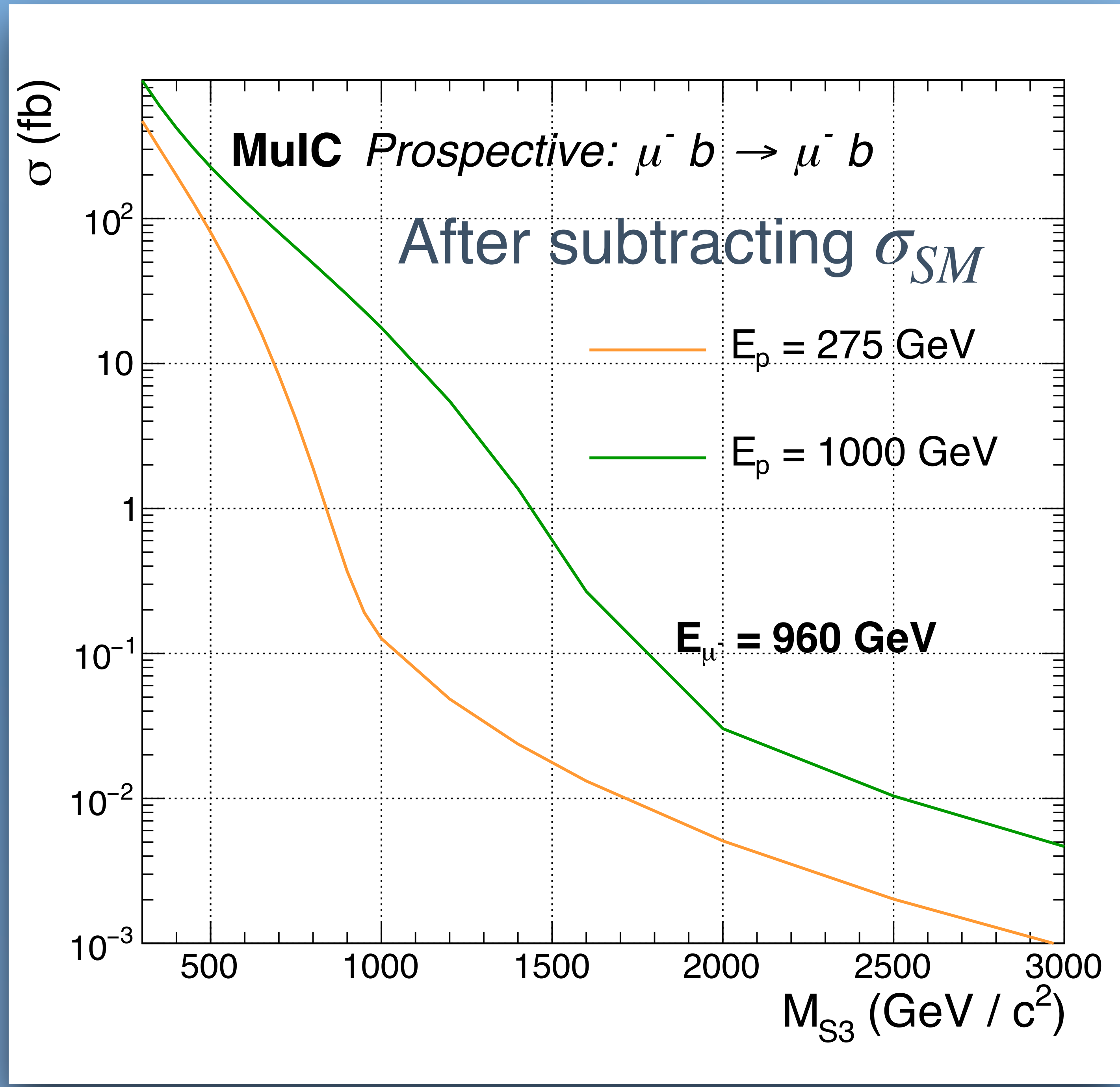
Signature related to B-anomalies

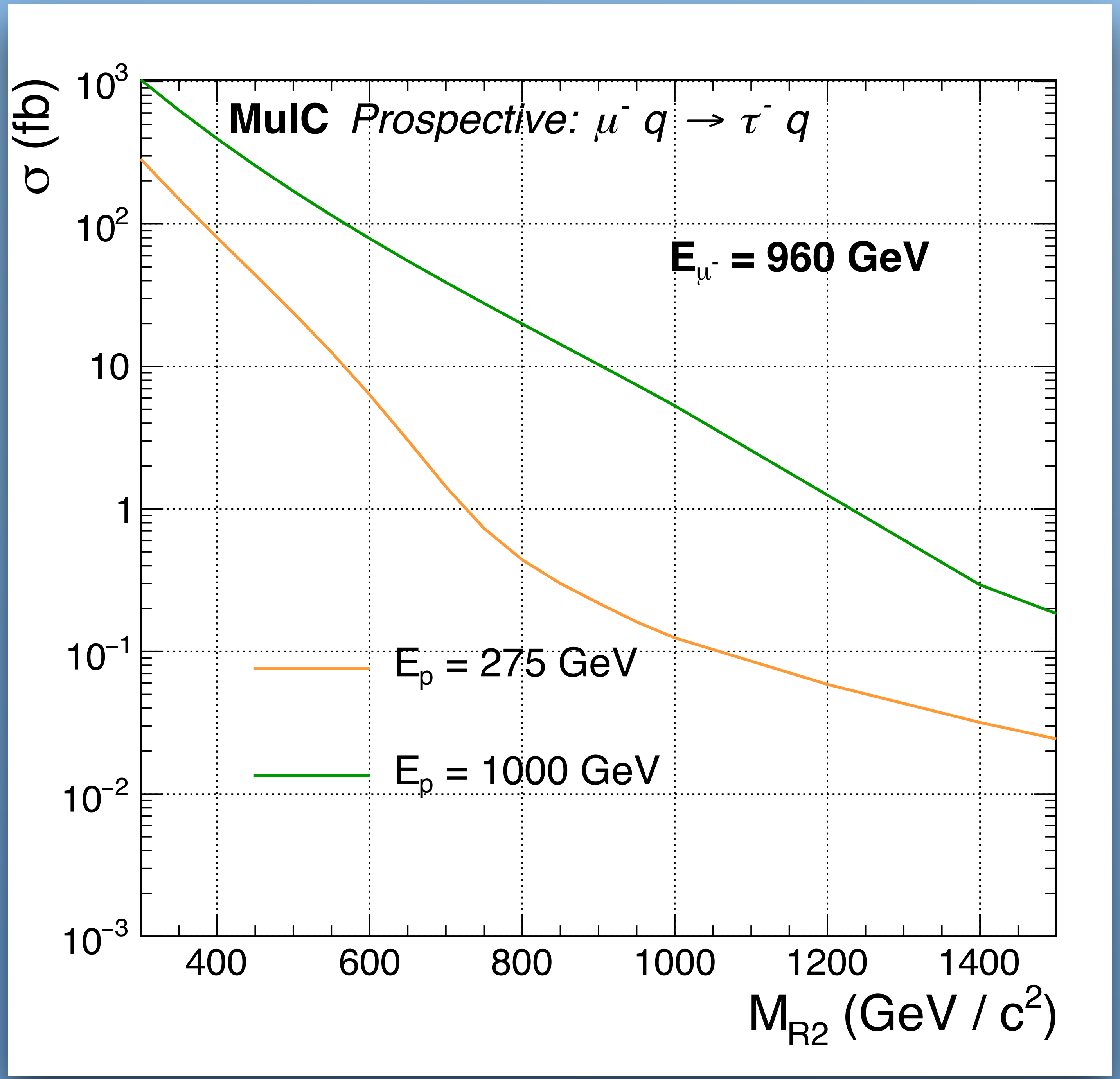


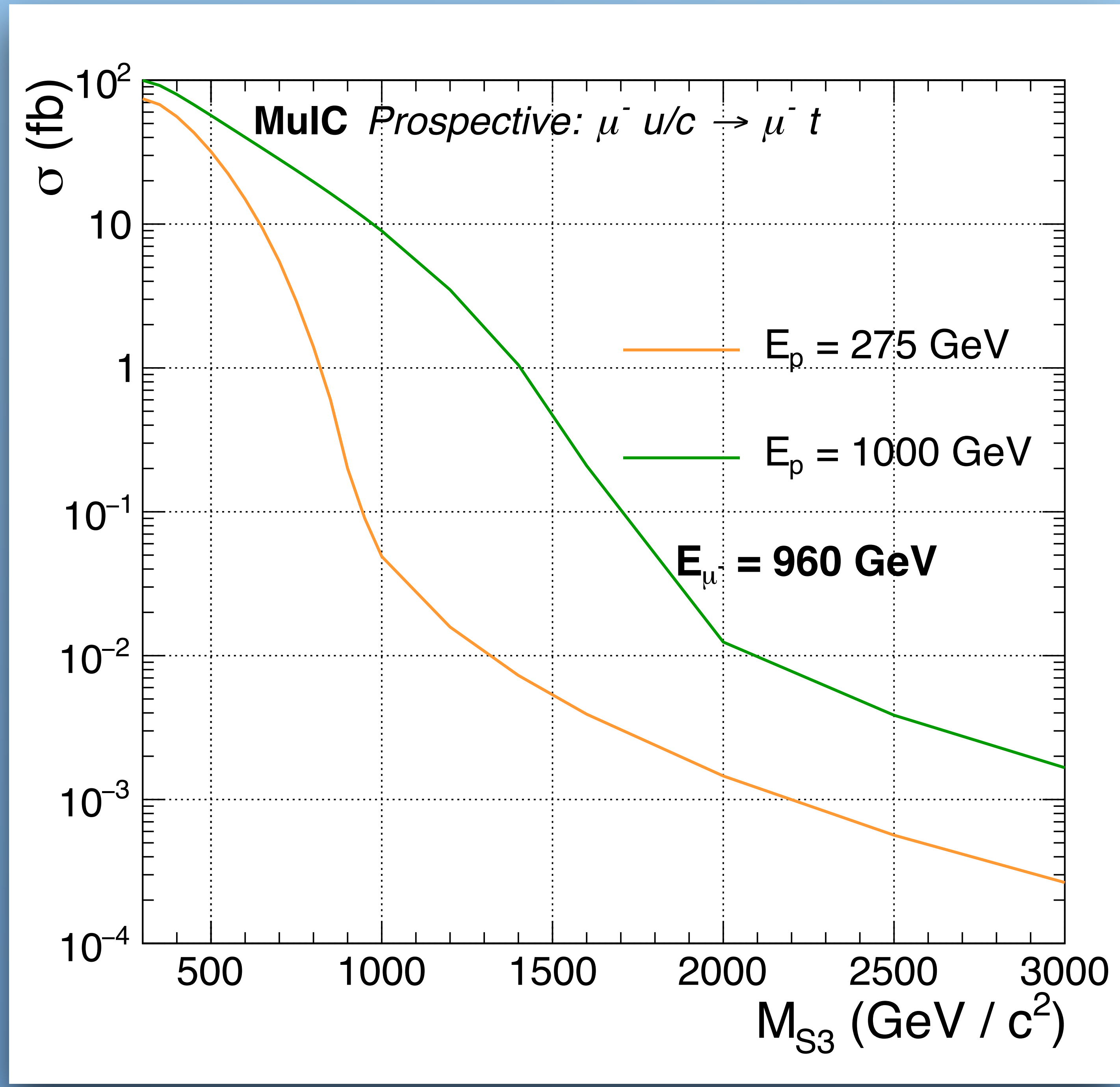
Flavor changing signature involving τ



Flavor changing signature involving top





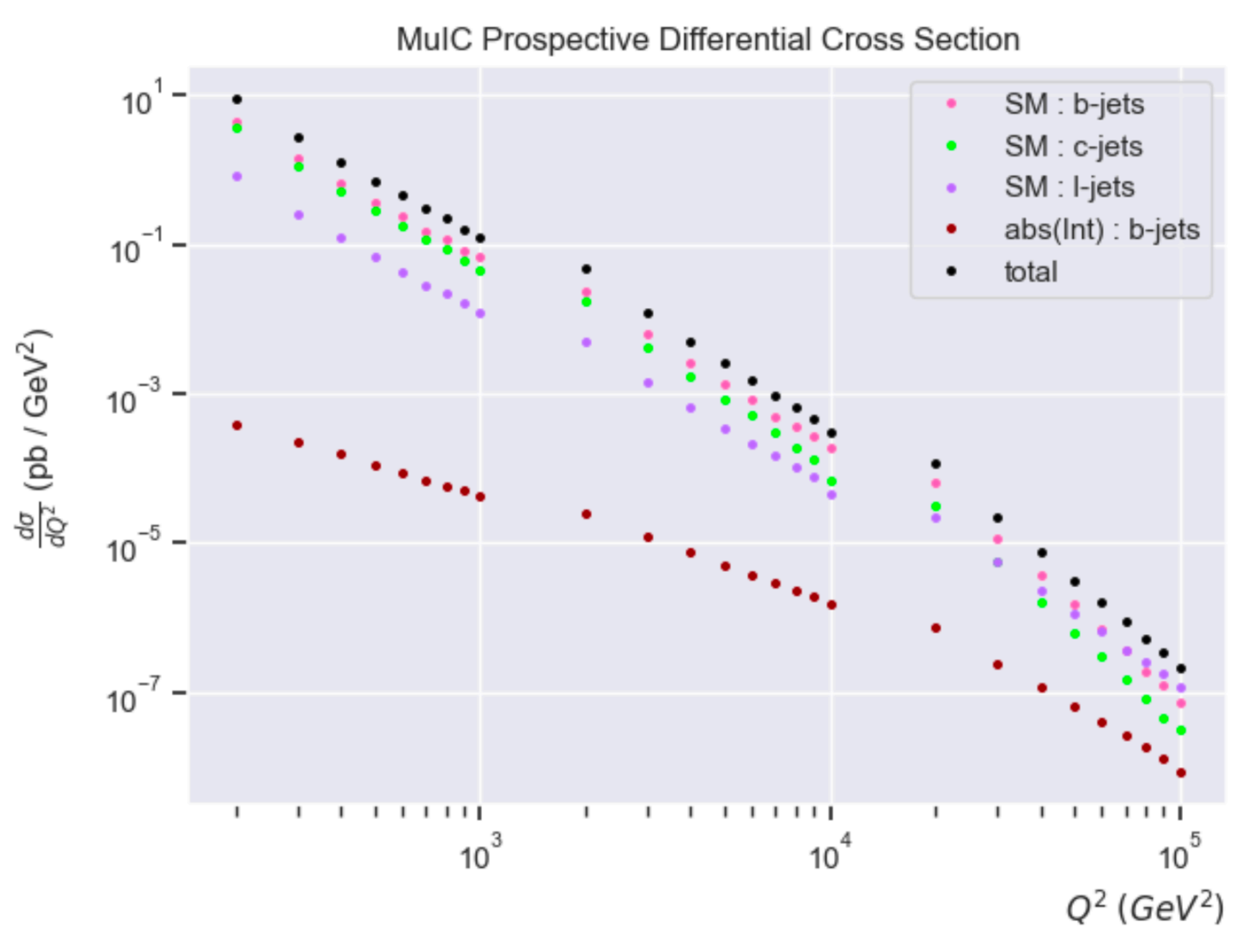


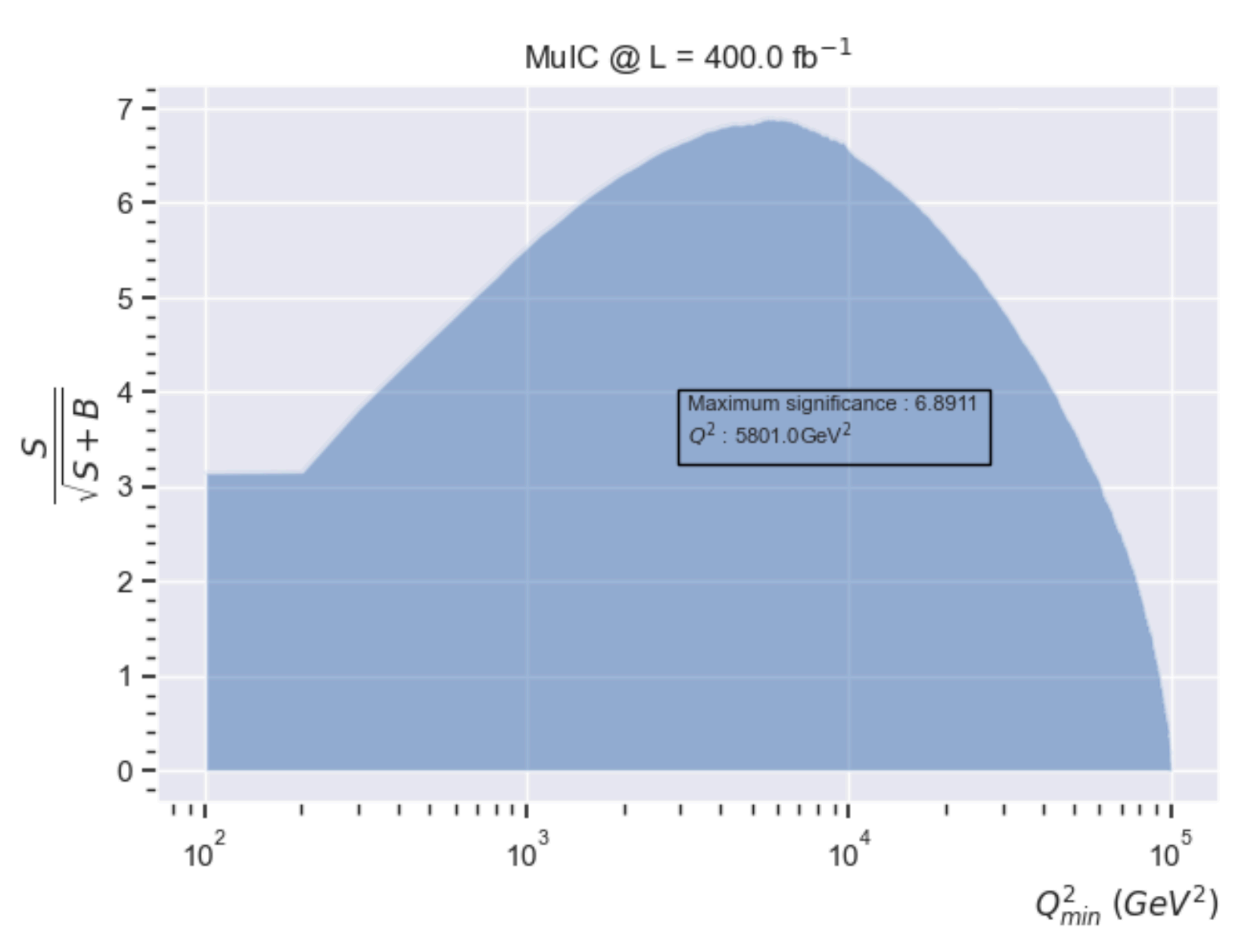
Note: all cross section results assume Yukawa coupling strength of $LQ - lq$ at 0.1

(Ongoing) leptoquark at MuIC

- Consider leptoquark model with coupling between muons and s, b quarks ($y^{LL}_{3,22} = y^{LL}_{3,32} = 0.1$)
- Motivated by anomalies in B decays and muon $(g-2)$
- At the moment, only studying the interference with the SM neutral current and the flavor conserving part in LQ

$$L_{S_3} \supset y^{LL}_{3ij} \bar{Q}^{Ci,a}_L \epsilon^{ab} (\sigma^k S^k_3)^{bc} L^{j,c}_L + hc$$





Summary

MuIC is a versatile machine with unique specialities

- TeV scale collisions with reach for extreme high Q^2 and low x
- Rich physics program spanning a wide phase-space

Exciting opportunities to probe CLFV

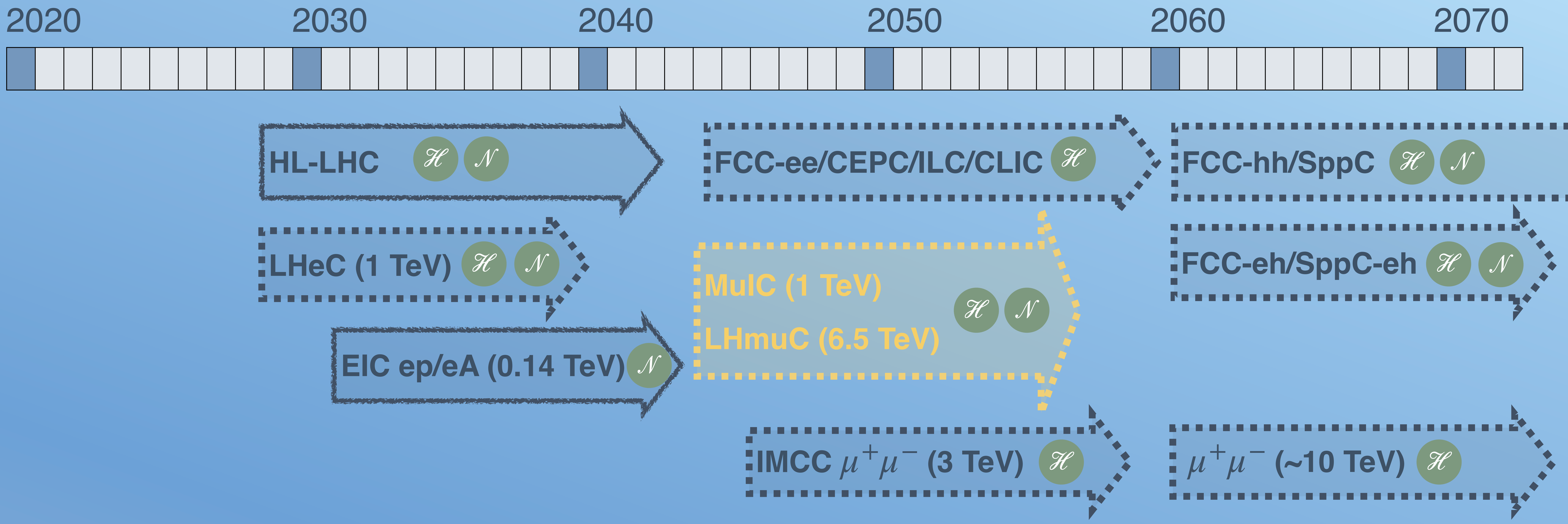
- Unique production channels
- High sensitivity to certain models

Also, synergy with different HEP areas

- Muon accelerator technology toward muon colliders
- Collaboration of nuclear and particle physics communities
- Can run concurrently with other major projects like FCC/CEPC, or muon colliders
- For CLFV: complementary physics program to low energy CLFV experiments

Backups

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

W, Z production

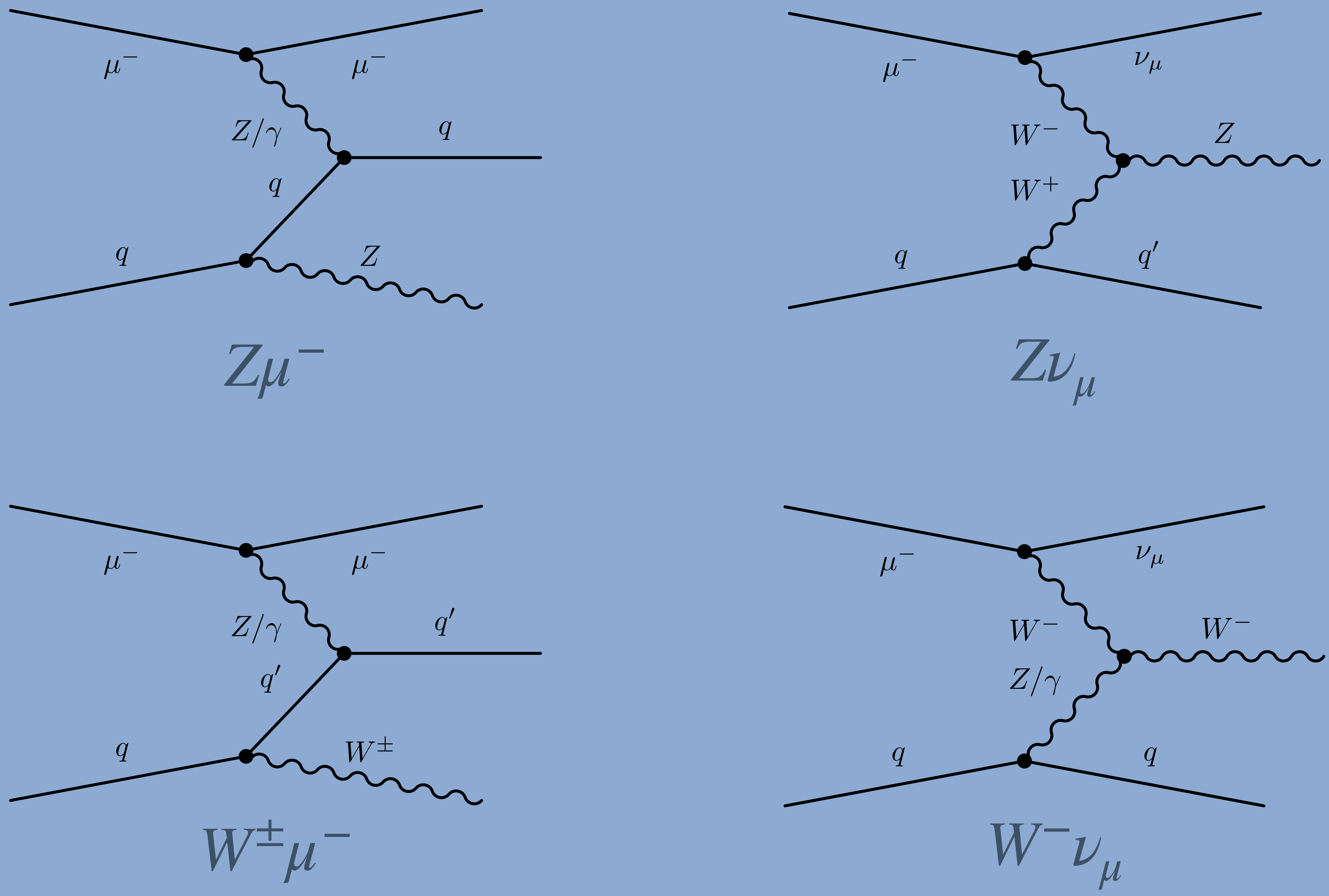
Many different modes for W, Z production

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

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

With 400 fb^{-1} data

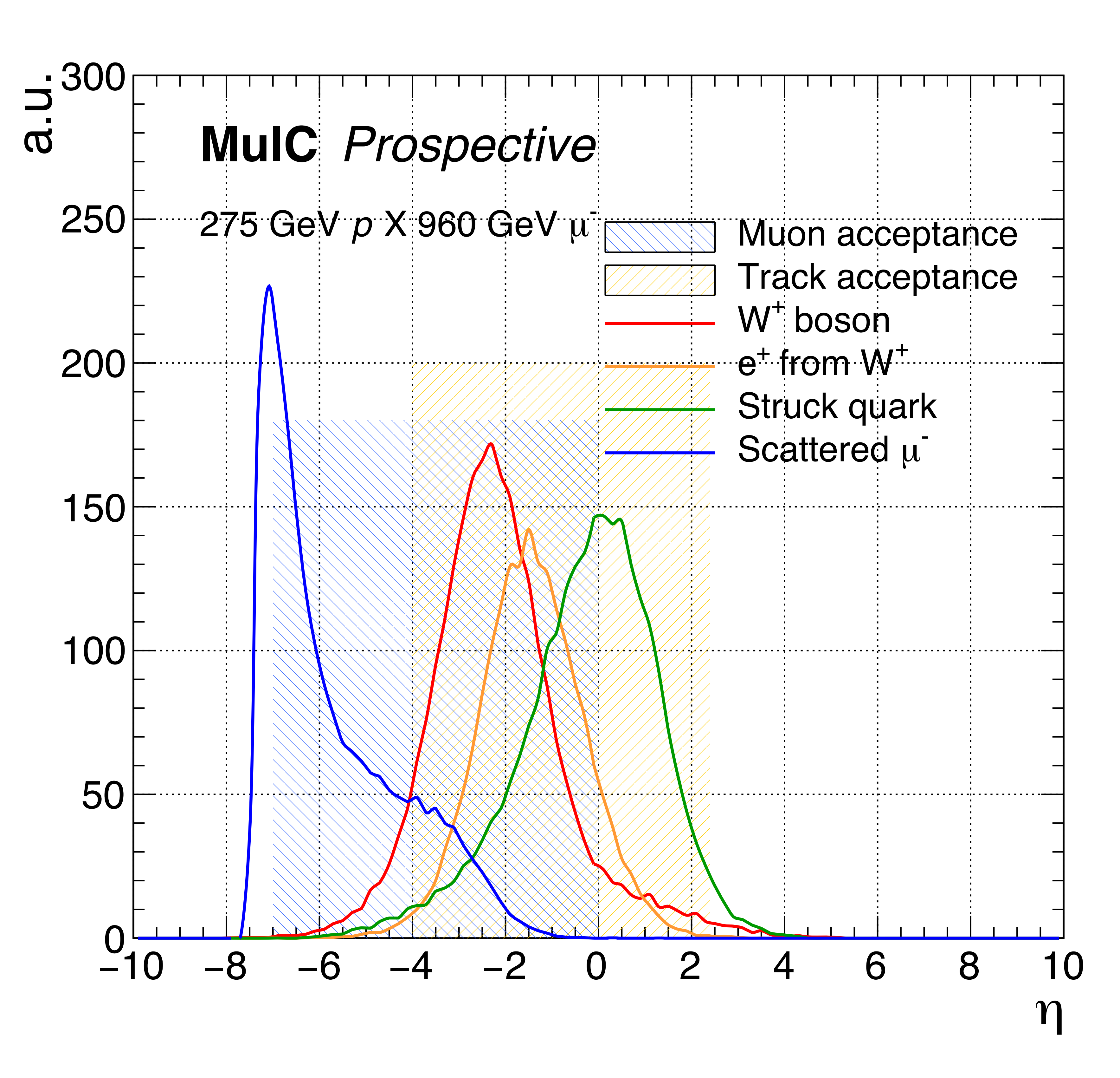
- expect 8M W, 1.5M Z
- All are EWK production (no DY, no QCD-induced backgrounds)
- Clean and sufficient dataset for precision measurement on (SM and anomalous) triple gauge coupling.



Example diagrams for vector boson production

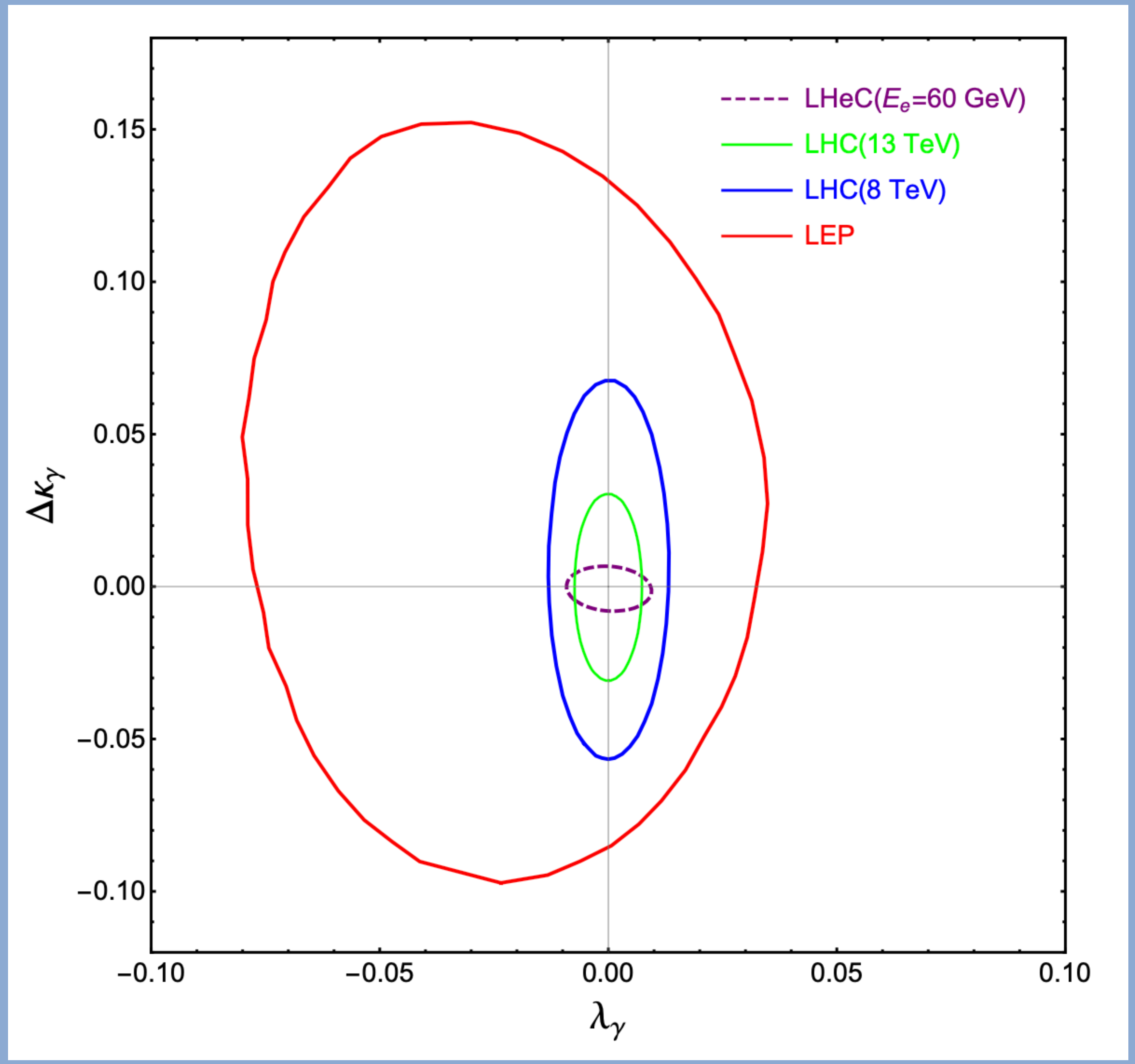
EW measurements

- ❖ 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

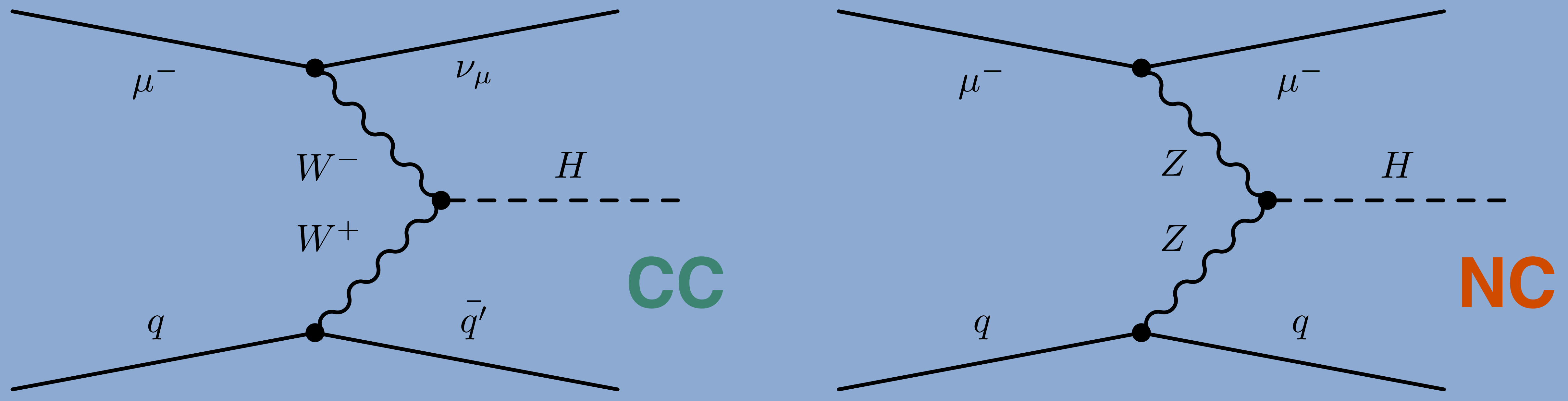
Mainly produced via VBF process, with both charged current (CC) and neutral current (NC) exchanges

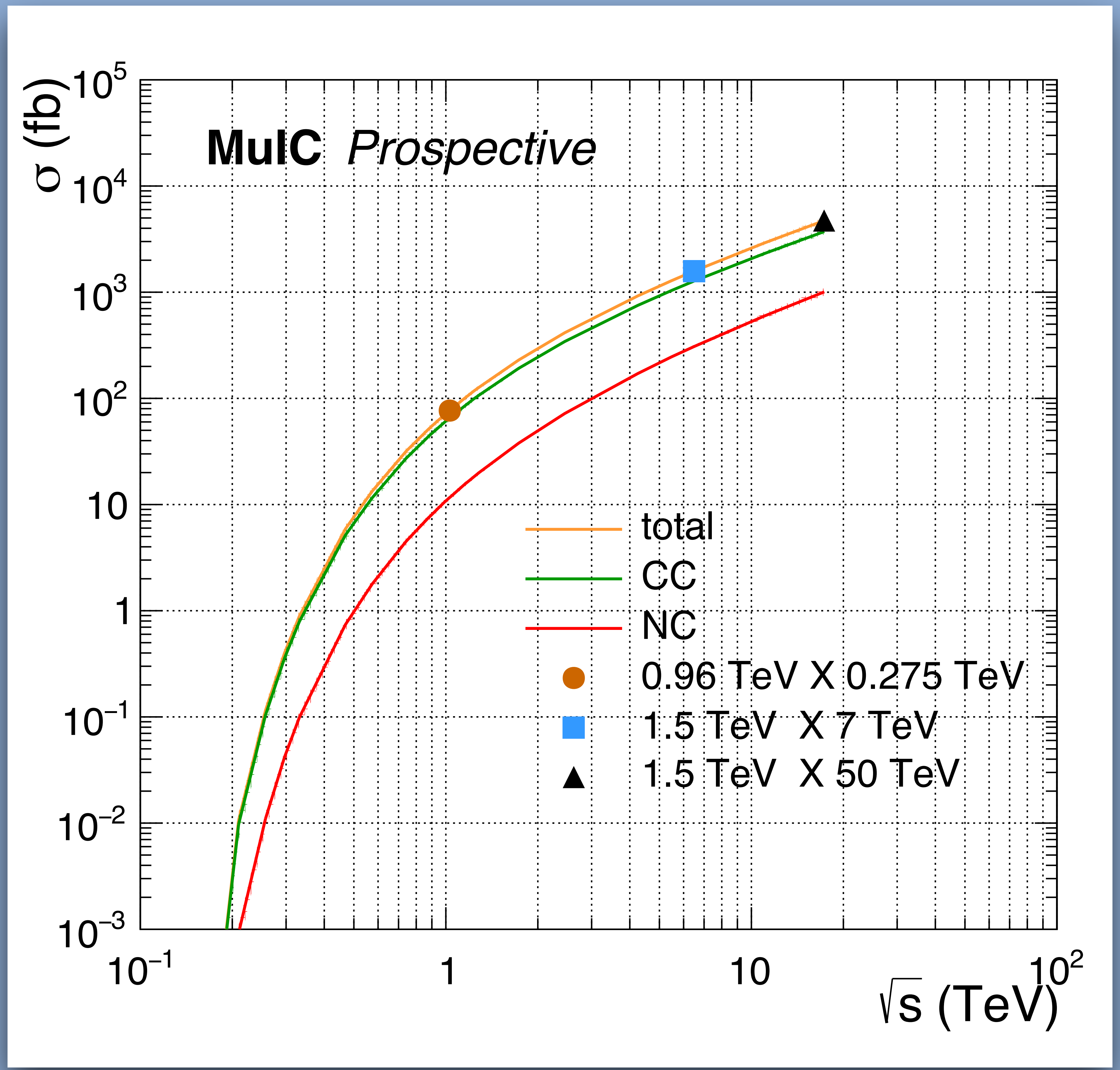
For MuIC at $\sqrt{s} \sim 1$ TeV

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

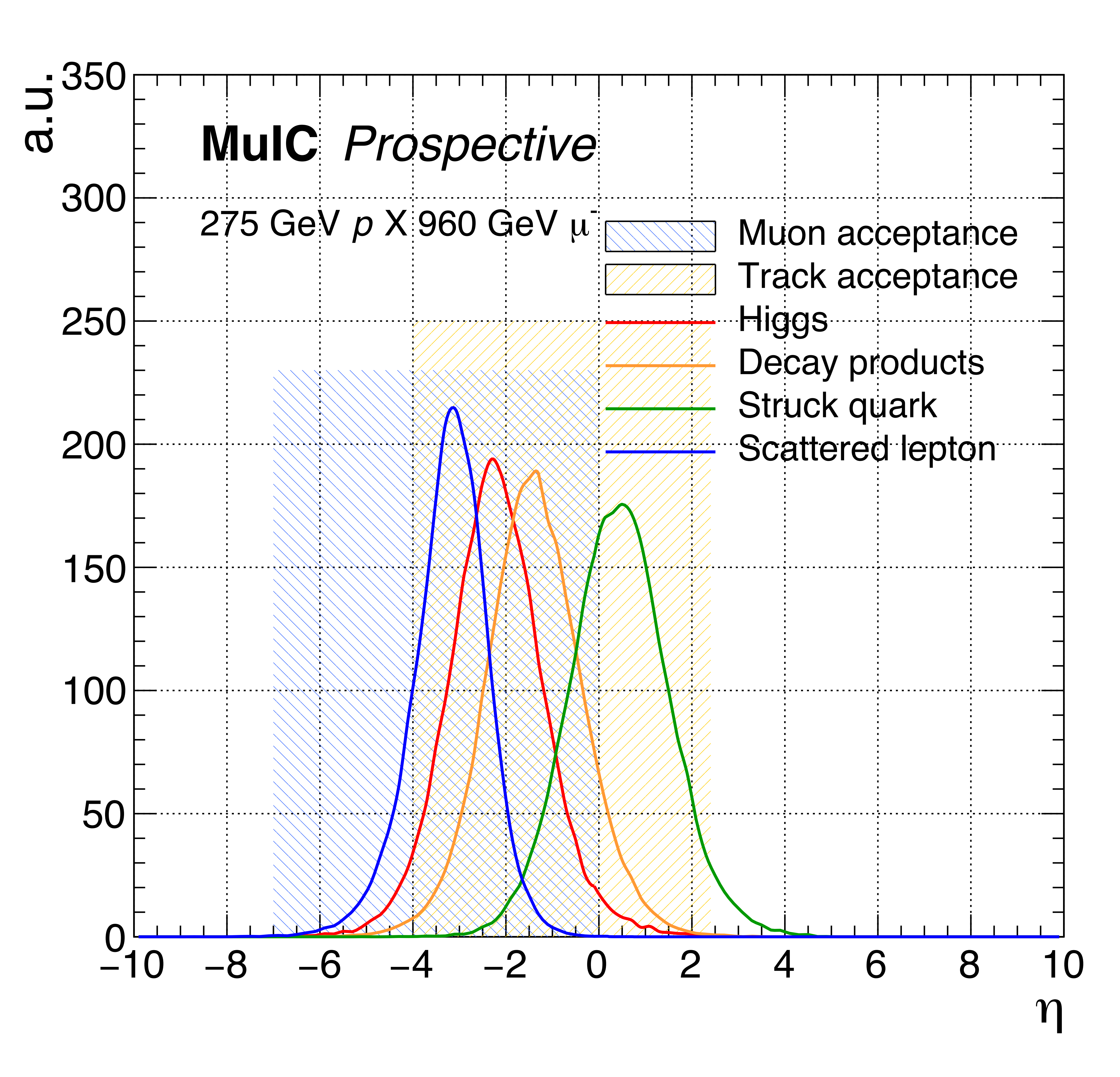
Note: tH production also possible, but much less

- 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)



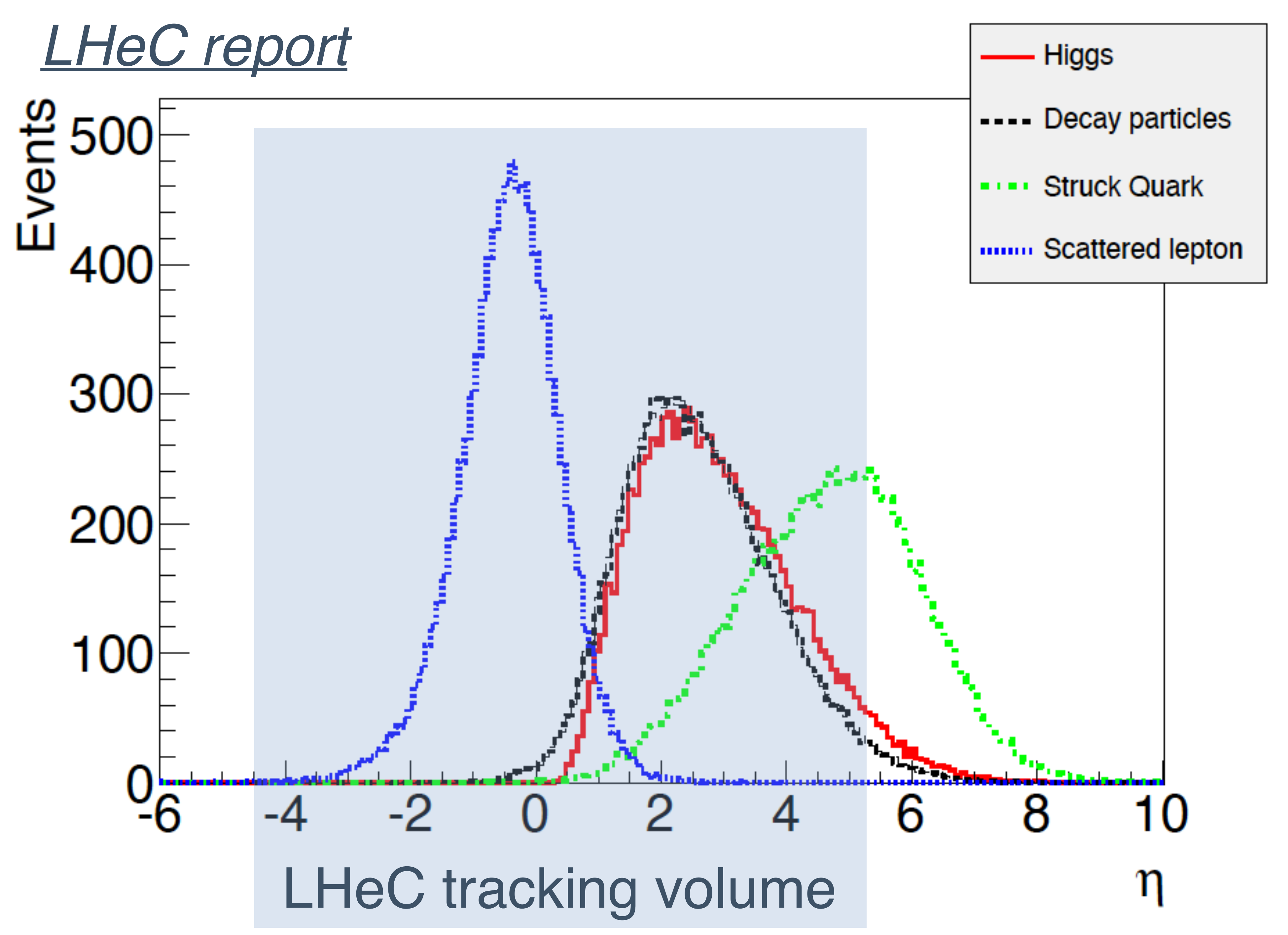


Higgs event kinematics



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

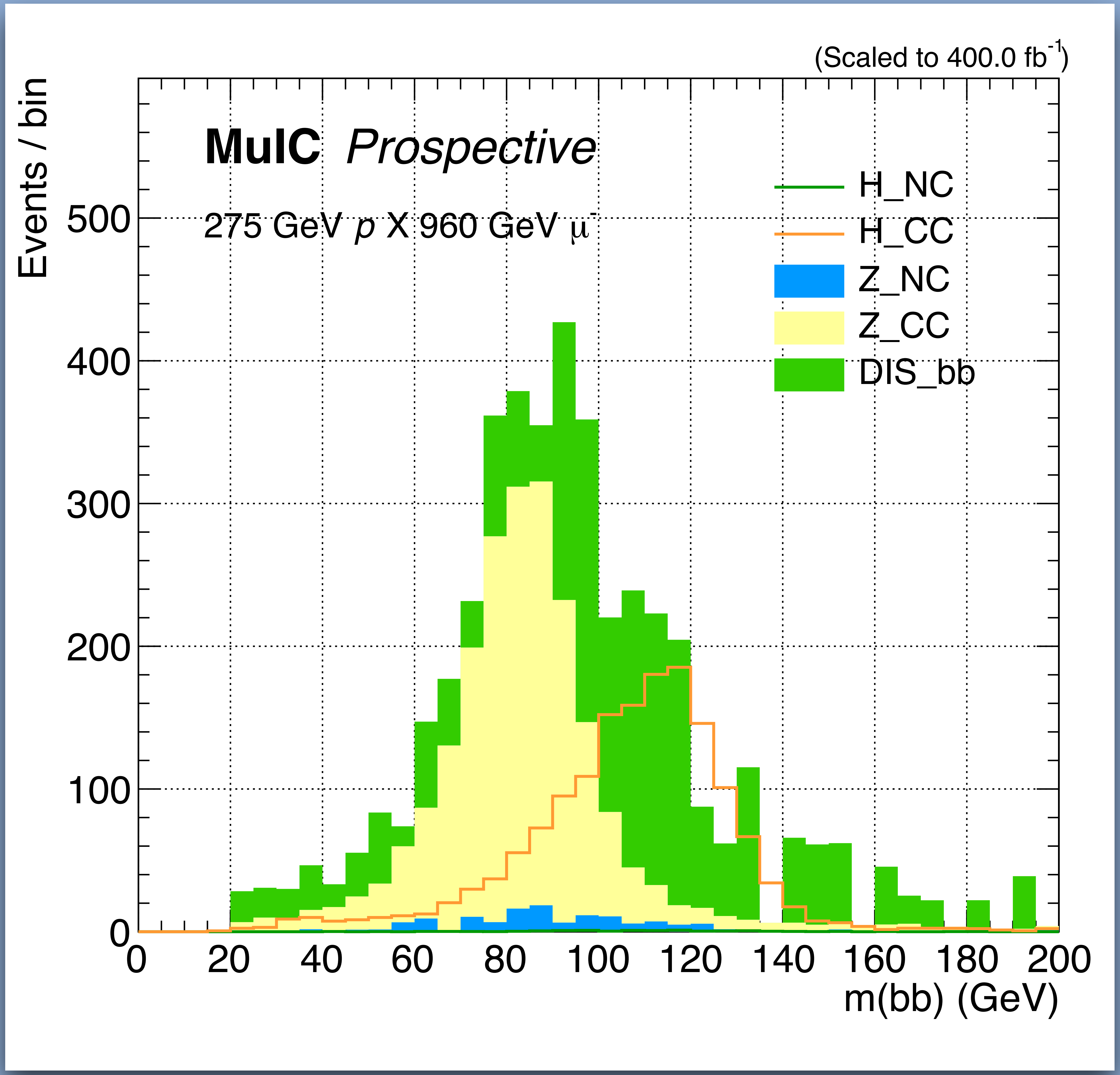


$H \rightarrow b\bar{b}$ case study

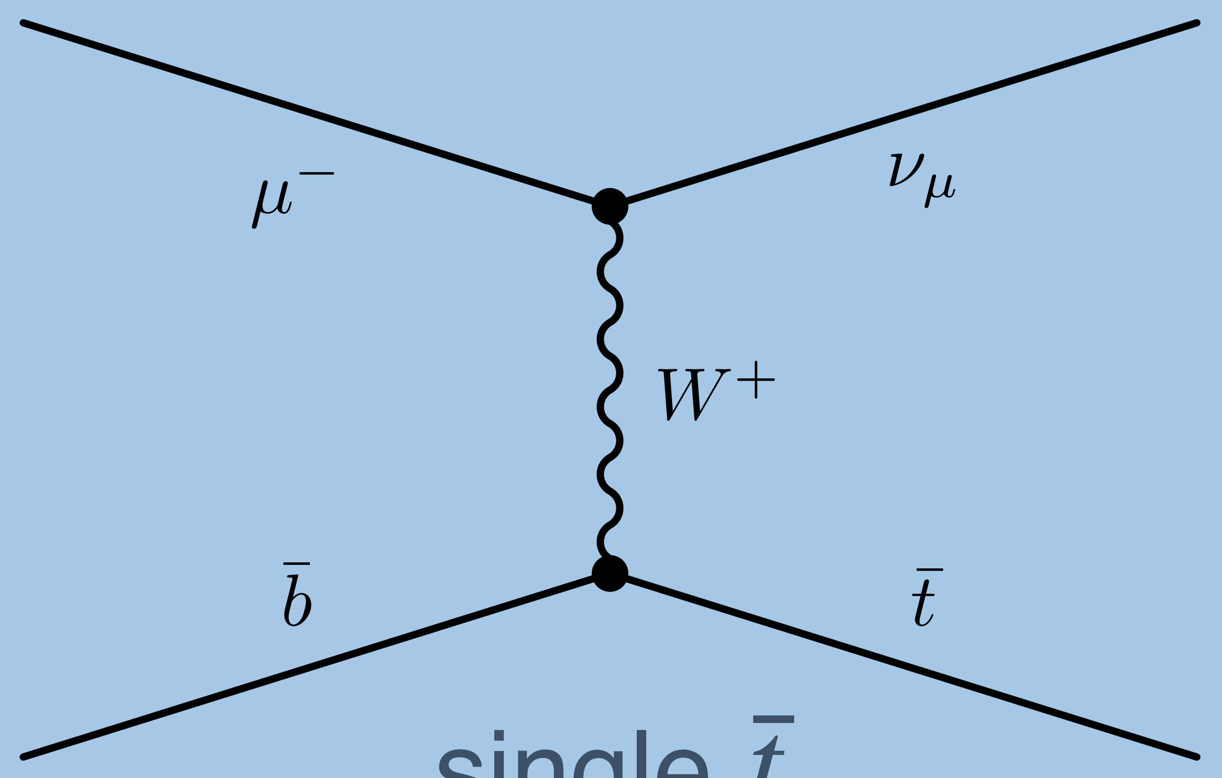
- **Selection:** Target CC VBF-H signal over NC DIS bb background
  - 2 b-tagged jets + 1 light jet
  - $p_T(b\bar{b}) > 20$ GeV
  - Muon veto, $E_T^{miss} > 30$ GeV

- 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



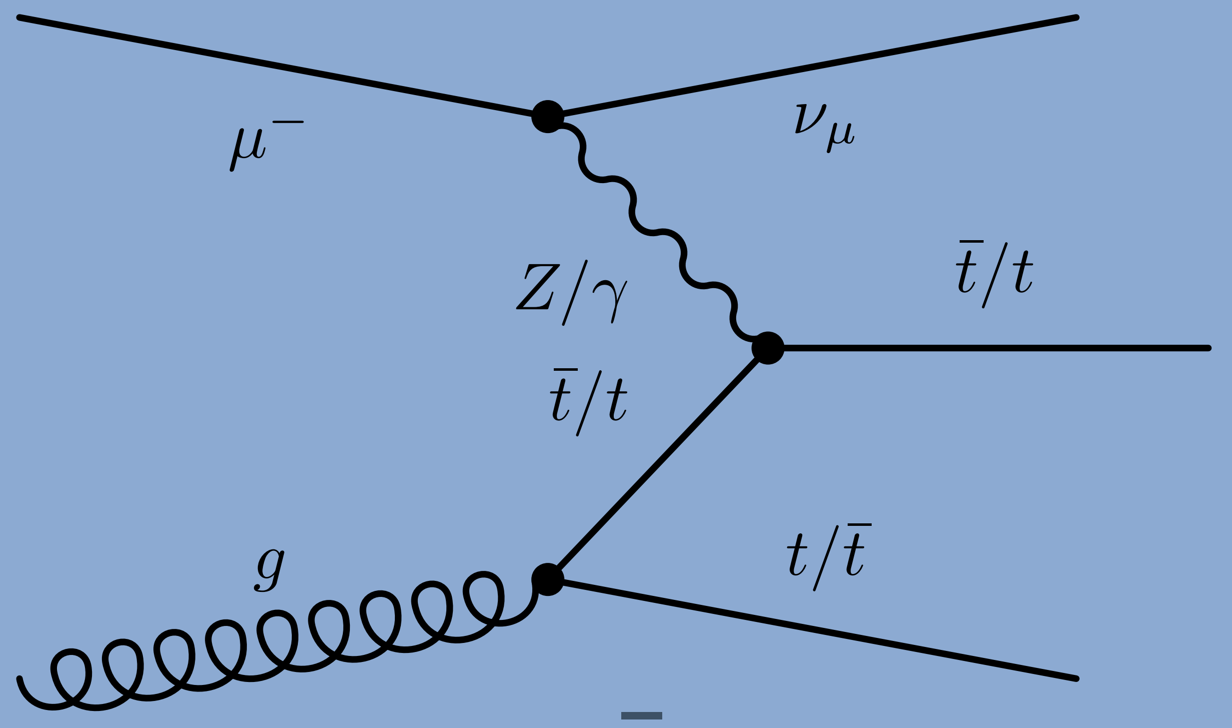
single $\bar{t}$

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