レプトン-核子散乱
を用いた新物理探索

東城 順治

九州大学

素粒子現象論研究会

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(荷電)レプトン-核子散乱

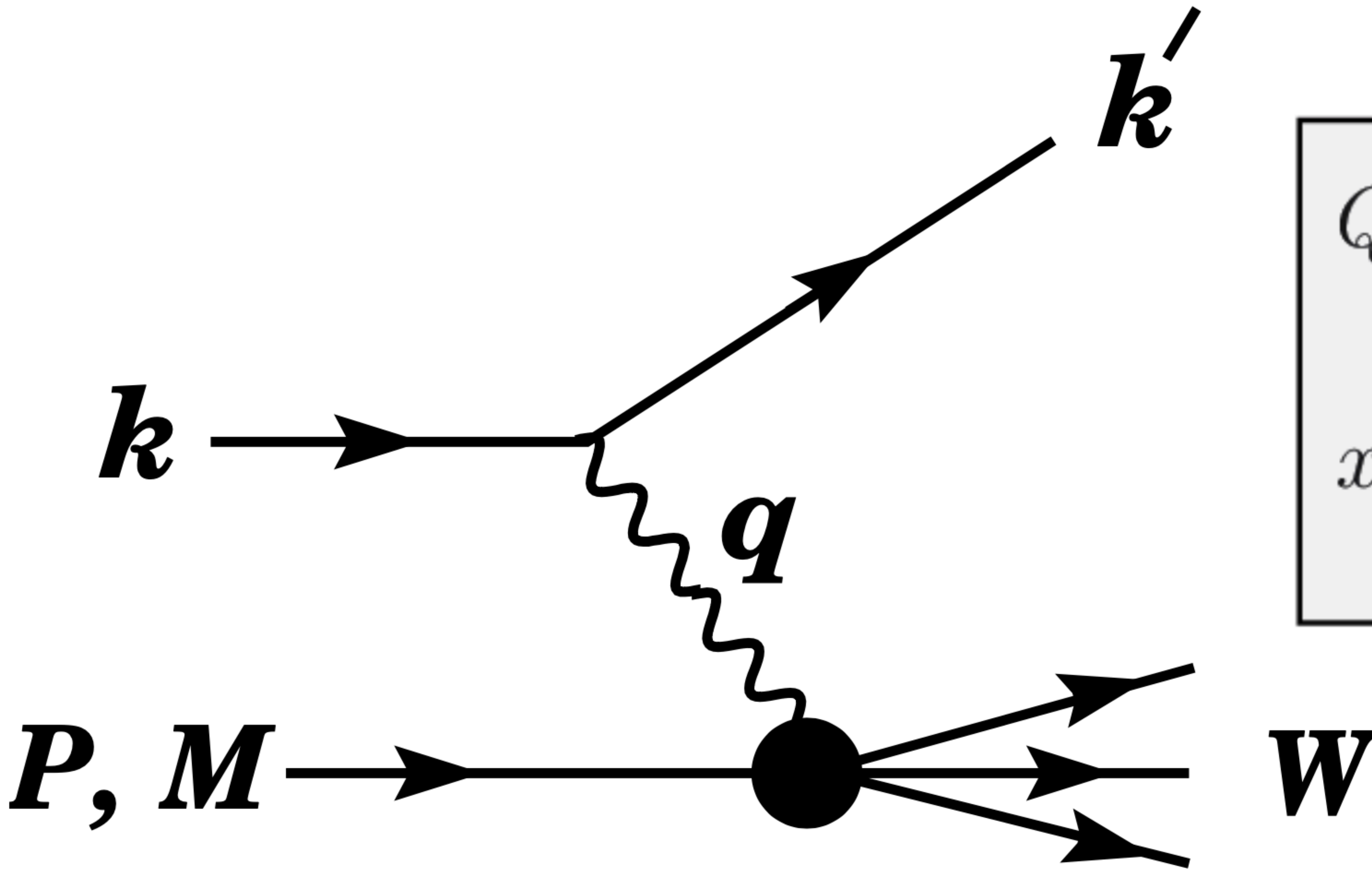
永い歴史と大きな発見

- 電子-核子弾性散乱
  - 形状因子、電荷分布
- 深非弾性散乱
  - 実験手法
    - 高エネルギー電子・ミューオンの利用
    - 衝突型加速器 (HERA)
  - 核子構造、パートン分布関数
  - DGLAP QCD evolution
  - EMC効果
  - スピン構造：”Spin Crisis”
  - 新物理探索

ニュートリノ-核子散乱もアリ

Weak neutral current
Weinberg angle
(NuTeV anomaly)

Lepton-Nucleon Scattering

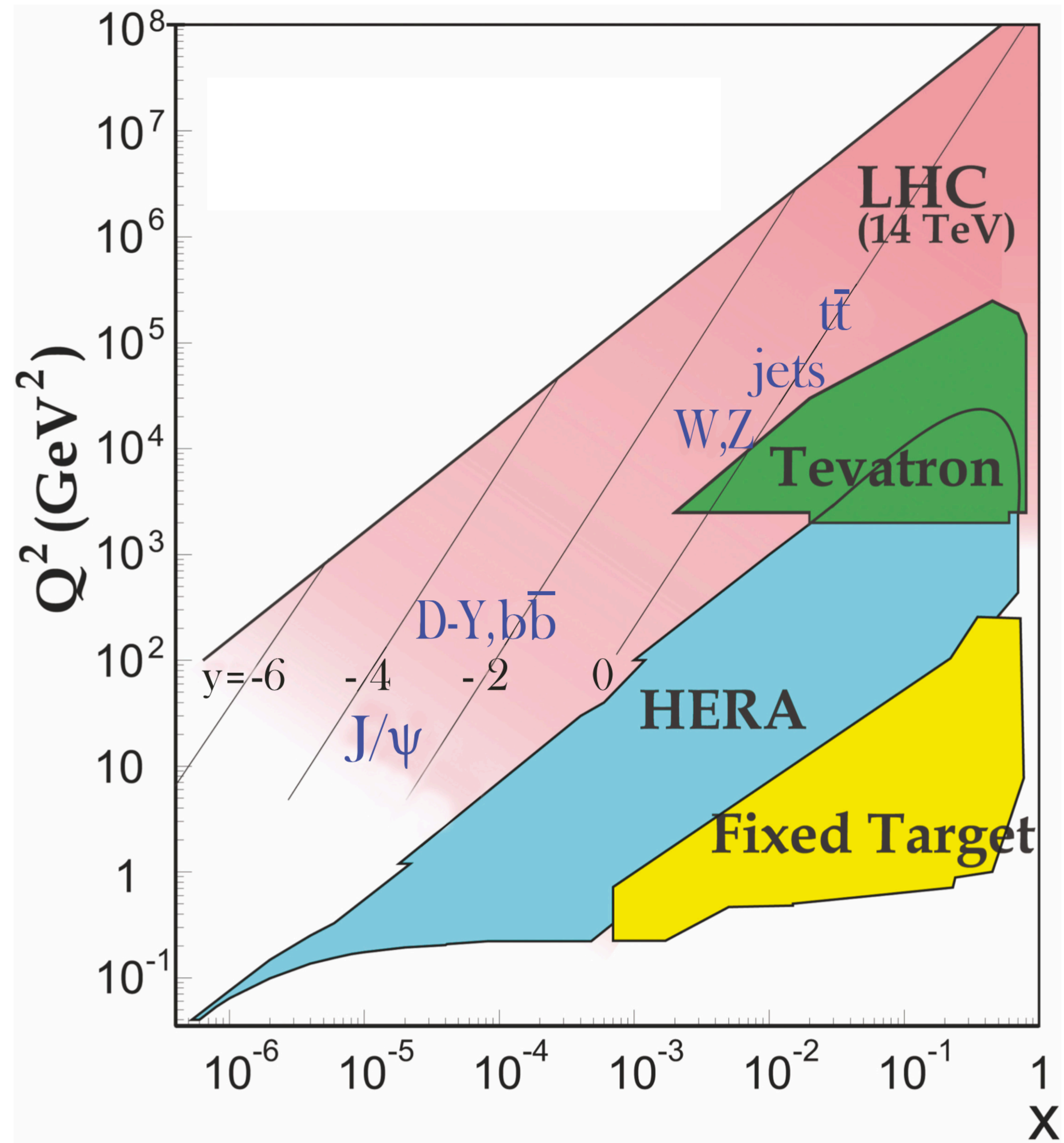


$$Q^2 = -q^2$$

$$x = \frac{Q^2}{2\,p \cdot q}$$

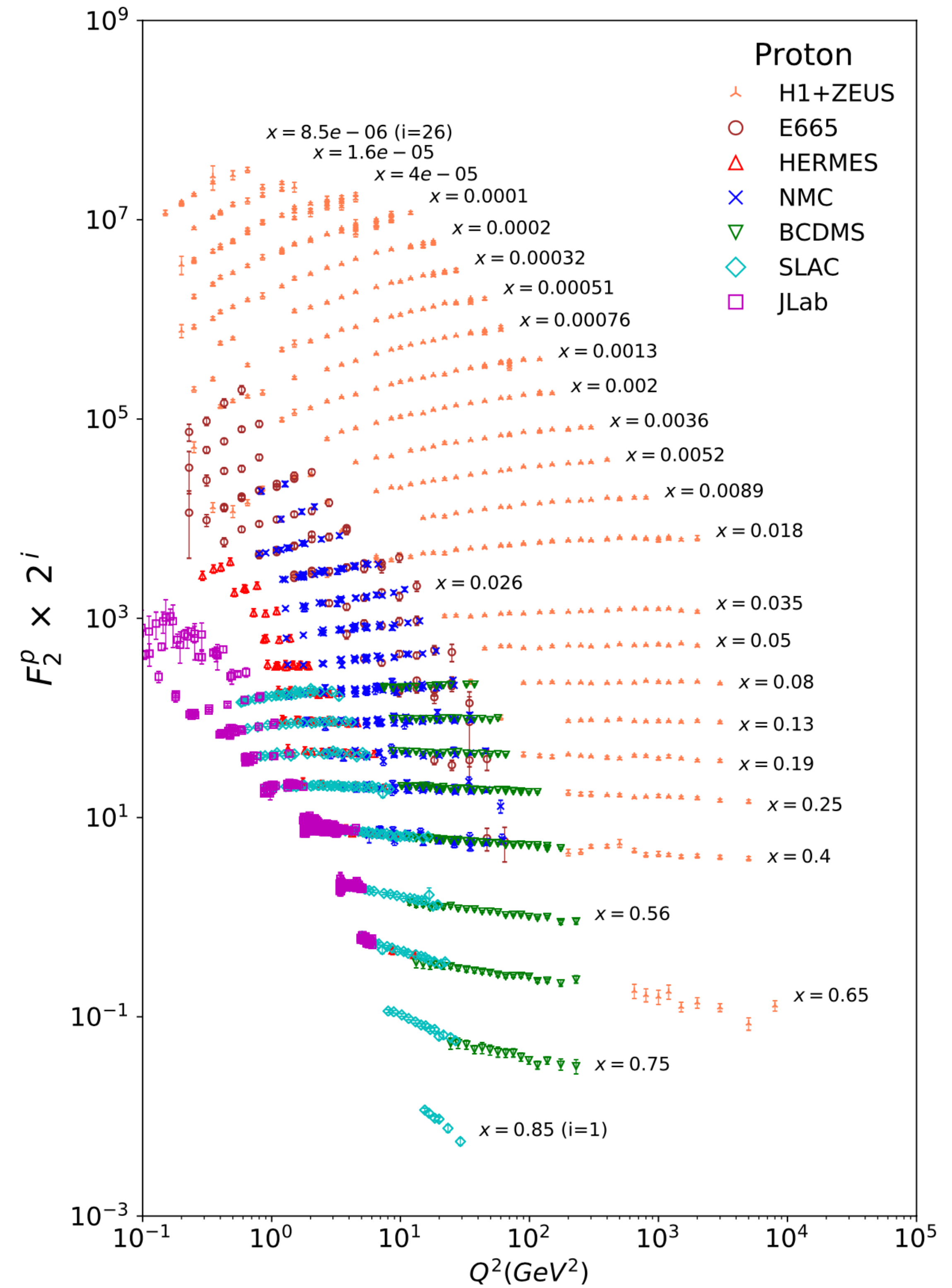
Lepton-Nucleon Scattering

- x-Q^2 range
  - Fixed targetとHERAの差
  - Hadron colliderとの差



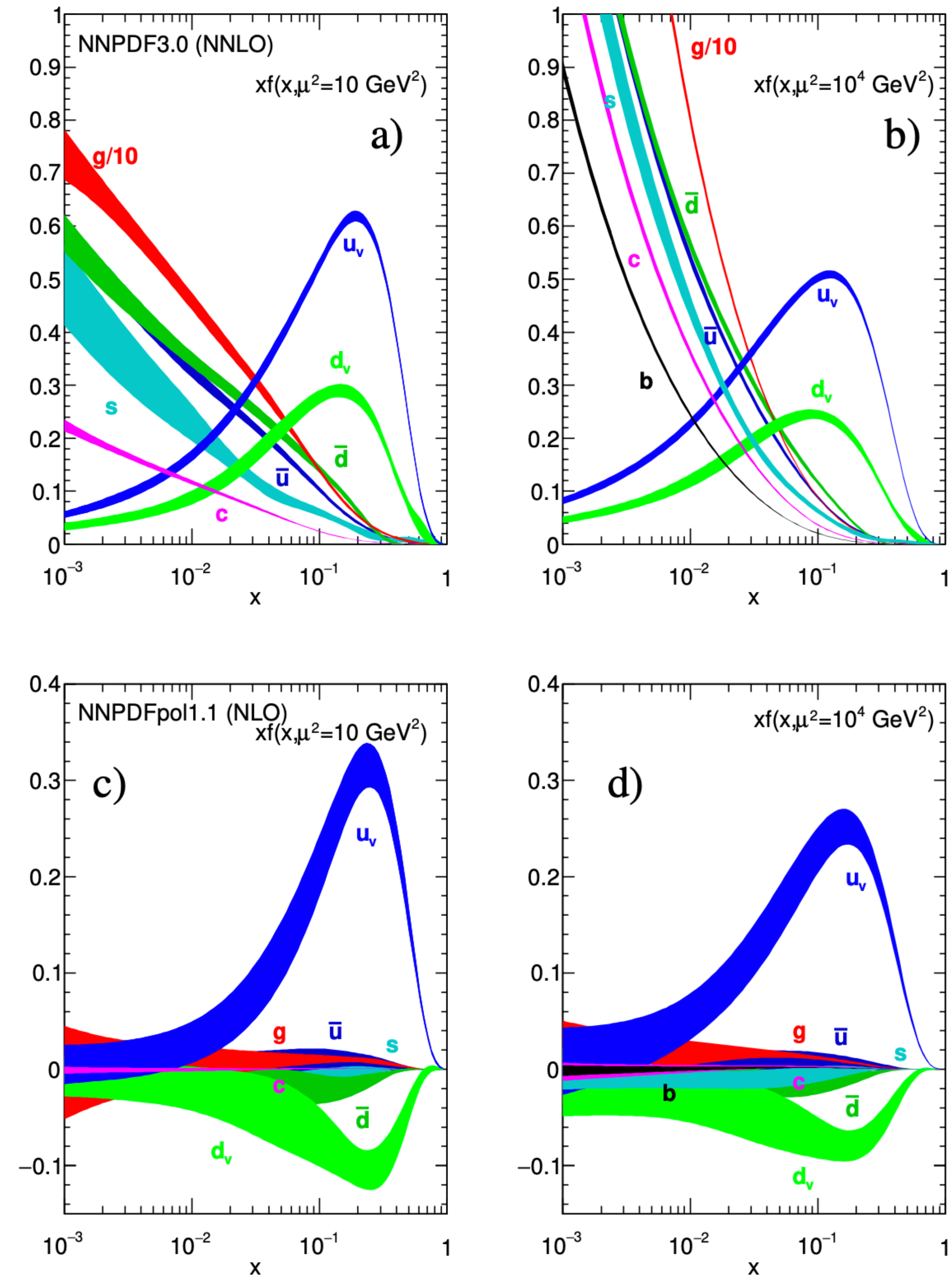
Lepton-Nucleon Scattering

- 核子構造
  - DGLAP evolution
  - Parton distribution function



Lepton-Nucleon Scattering

- 核子構造
  - Parton distribution function
    - Flavor dependence
    - Spin dependence



DESY 97-24
February 13th 1997

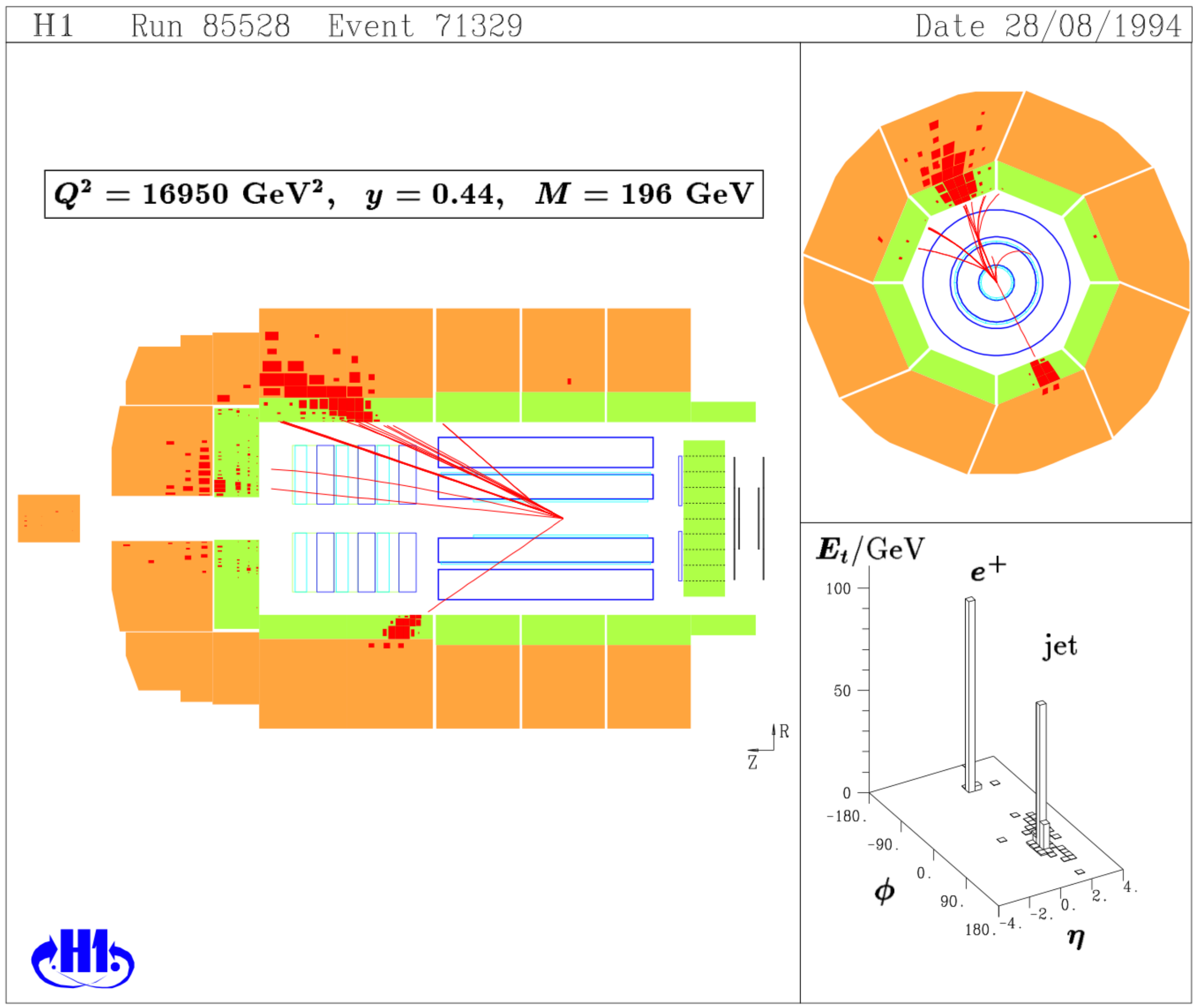
ISSN 0418-9833

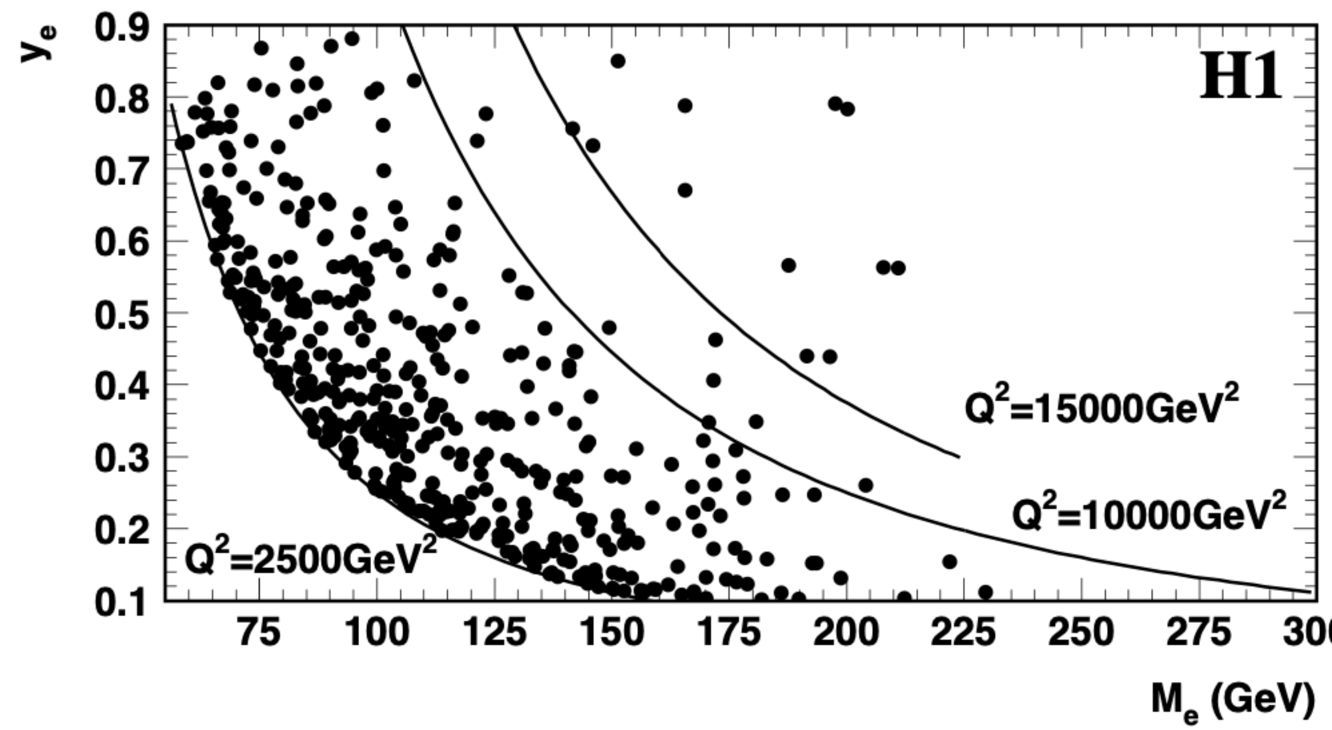
Observation of Events at Very High Q^2 in ep Collisions at HERA

H1 Collaboration

Abstract

Measurements of ep scattering with squared 4–momentum transfer Q^2 up to 35000 GeV^2 are compared with the expectation of the standard deep-inelastic model of lepton–nucleon scattering (DIS). For $Q^2 > 15000$ GeV^2, $N_{obs} = 12$ neutral current candidate events are observed where the expectation is $N_{DIS} = 4.71 \pm 0.76$ events. In the same Q^2 range, $N_{obs} = 4$ charged current candidates are observed where the expectation is $N_{DIS} = 1.77 \pm 0.87$ events. The probability $\mathcal{P}(N \geq N_{obs})$ that the DIS model signal N fluctuates to $N \geq N_{obs}$ in a random set of experiments is 6×10^{-3} for neutral current and 0.14 for charged current. The difference in the observed and expected number of Neutral Current events is mostly due to events at large masses $M = \sqrt{x\,s}$ in which the positron is backscattered at large $y = Q^2/M^2$.





Intensive discussions on SUSY, leptoquark etc

(荷電)レプトン-核子散乱 (続き)

永い発展の歴史と大きな発見

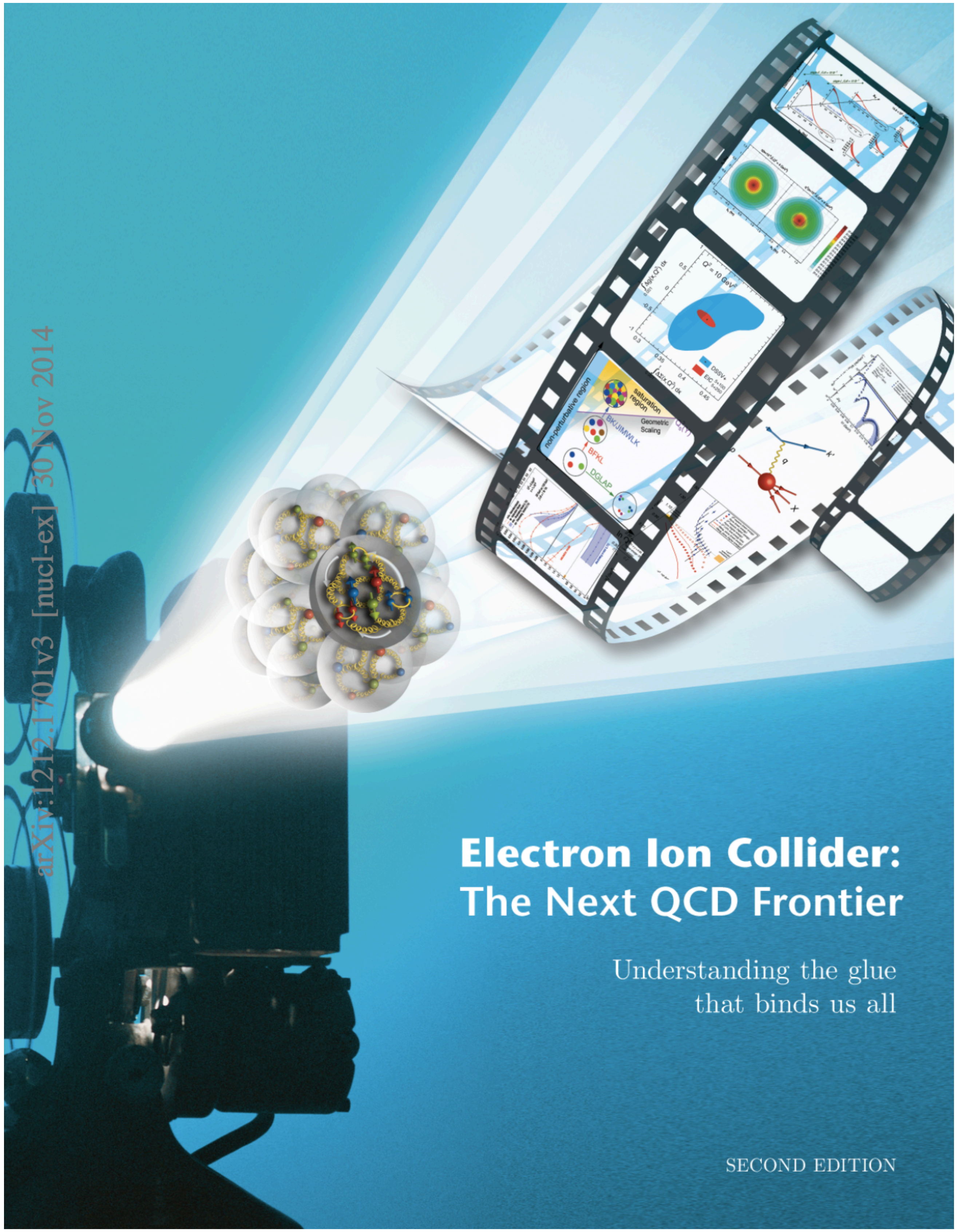
- HERA計画の終盤：2000年代後半
  - 将来計画の策定
    - ビーム輝度
    - スピン偏極陽子ビーム
  - 惜しまれつつも terminate
- 近年の動向
  - EIC計画：Bookhaven
  - (LHeC：CERN)
  - 約20年来の復活

In the World-Wide Community

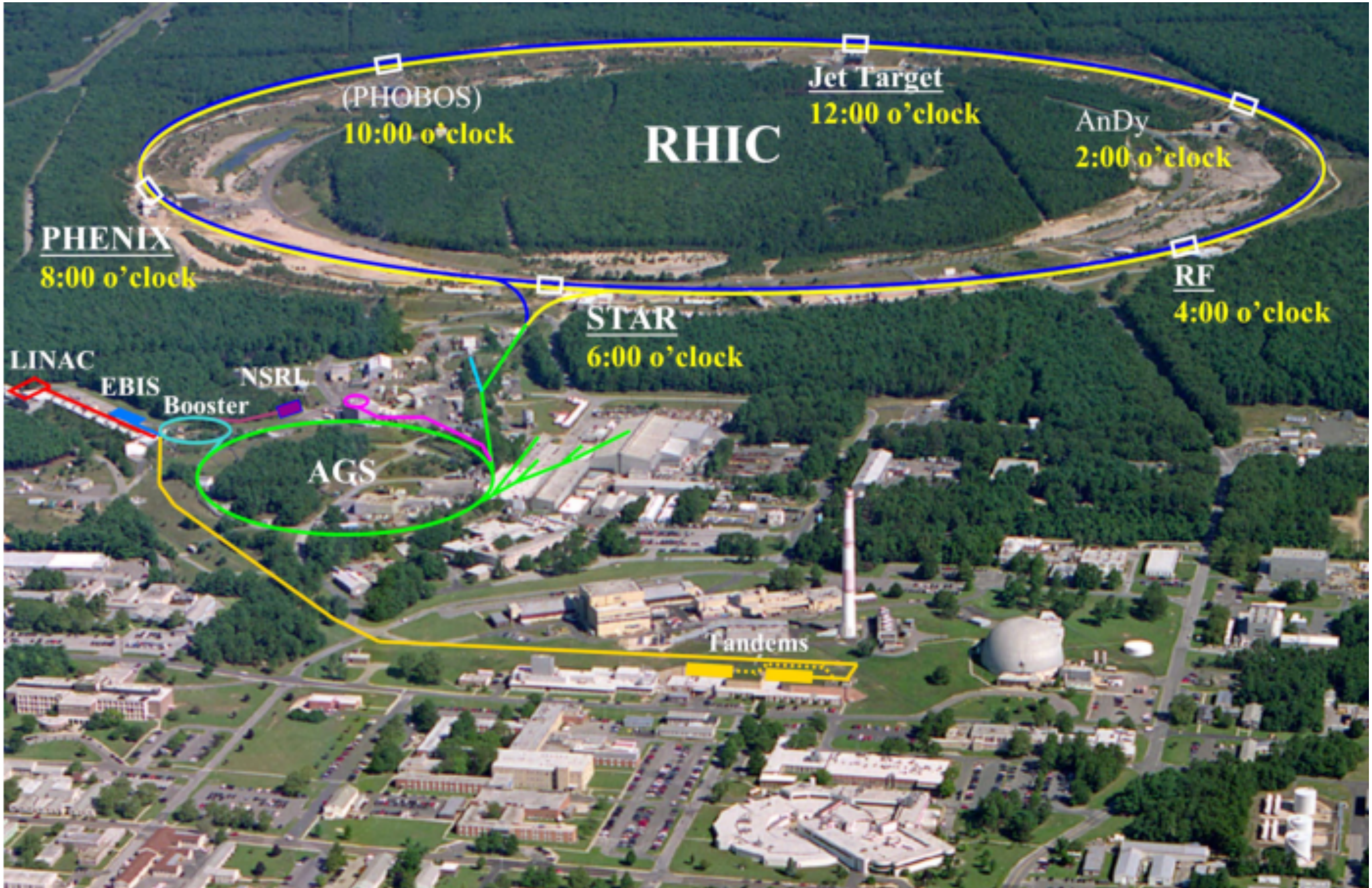
Recent discussions

- Europe
  - 2020 update of European strategy for particle physics
  - Synergies between EIC and the European particle physics
- US
  - Snowmass2021/2022
  - Topics of particle physics at EIC
- Japan
  - Building EIC-J community
  - Including nuclear physics and particle physics

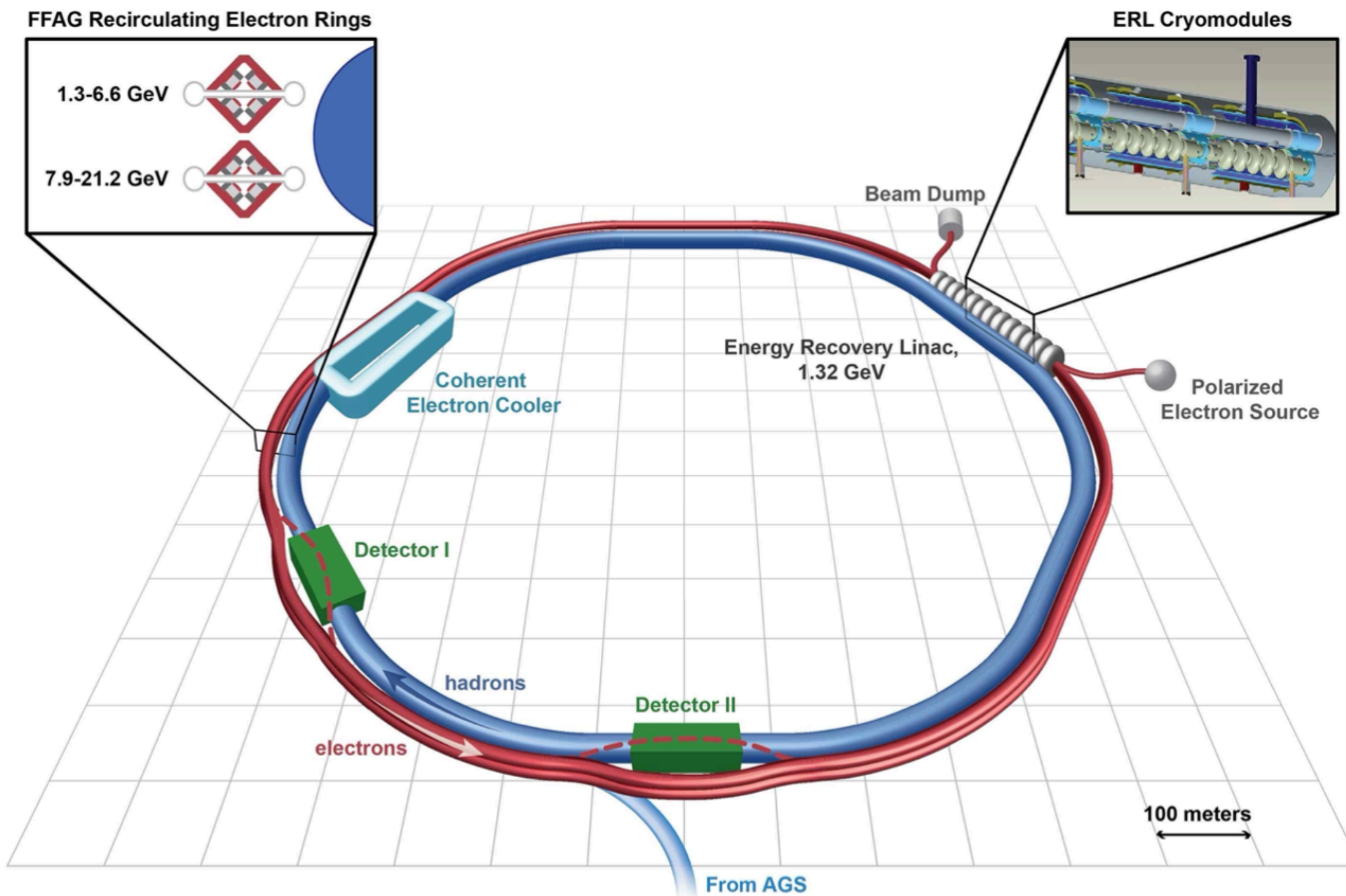
Electron-Ion Collider at BNL



Electron-Ion Collider at BNL



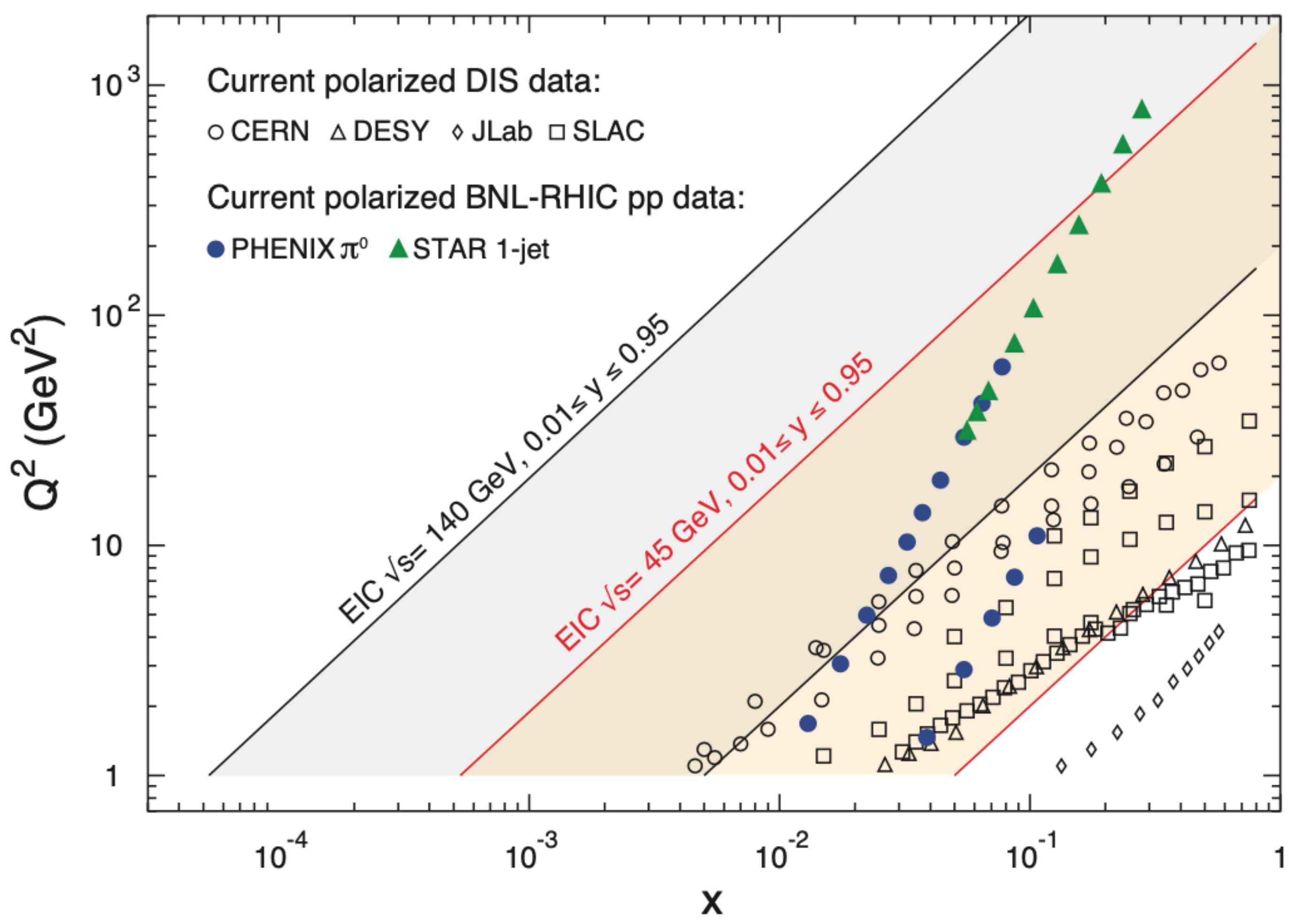
Electron-Ion Collider at BNL

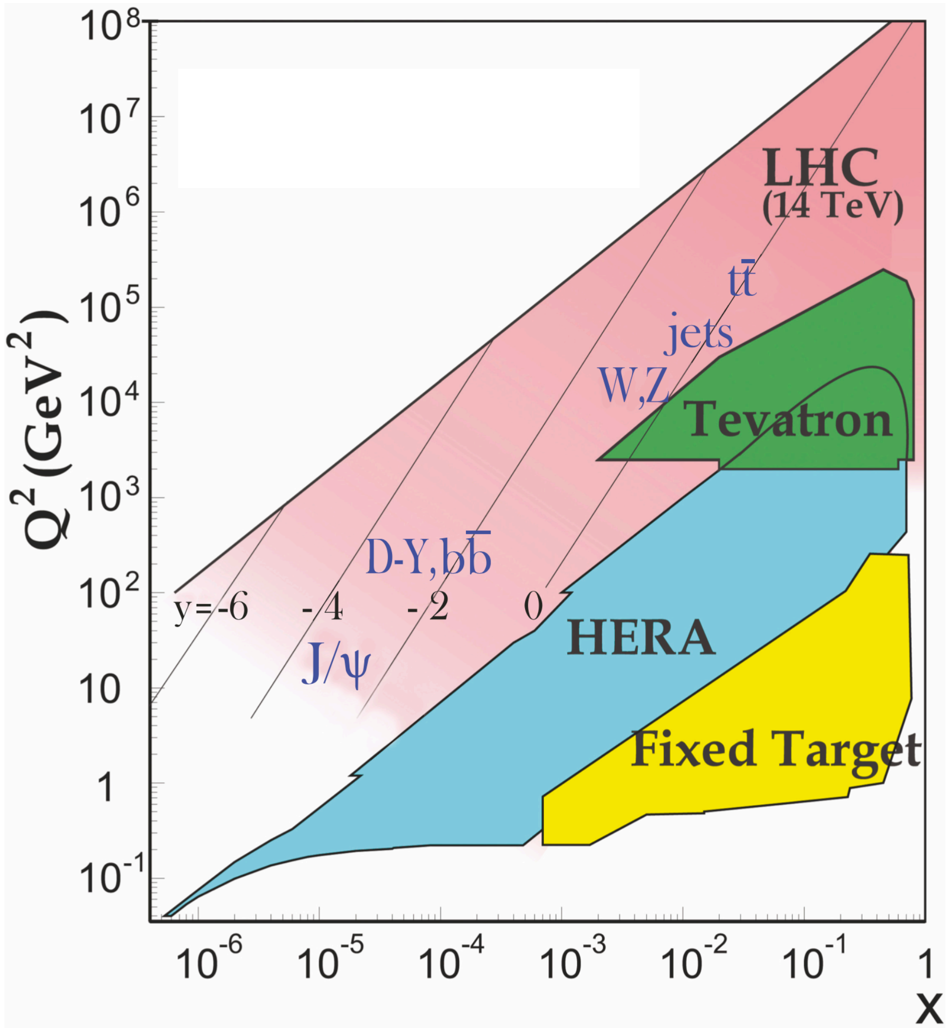


Electron-Ion Collider at BNL

For QCD and SM/BSM

- EIC as "Intensity/Precision Frontier"
    - CM energy, luminosity
    - Polarization in both electron and proton (+ light ions)





SM and BSM Physics at EIC

- Electroweak
  - Weak neural current couplings
    - Parity-violating asymmetry in e-d collisions
    - Weinberg angle measurement : $\sin^2\theta_W$

- Charged lepton flavor violation
  - e-τ transition

- BSM
  - More ideas???

Electron-Quark Scattering

Contact (4-fermion) interactions

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\Big[\bar{e}\gamma^{\mu}\gamma_5 e\big(C_{1u}\bar{u}\gamma_{\mu}u + C_{1d}\bar{d}\gamma_{\mu}d\big) + \bar{e}\gamma^{\mu}e\big(C_{2u}\bar{u}\gamma_{\mu}\gamma_5 u + C_{2d}\bar{d}\gamma_{\mu}\gamma_5 d\big)\Big]$$

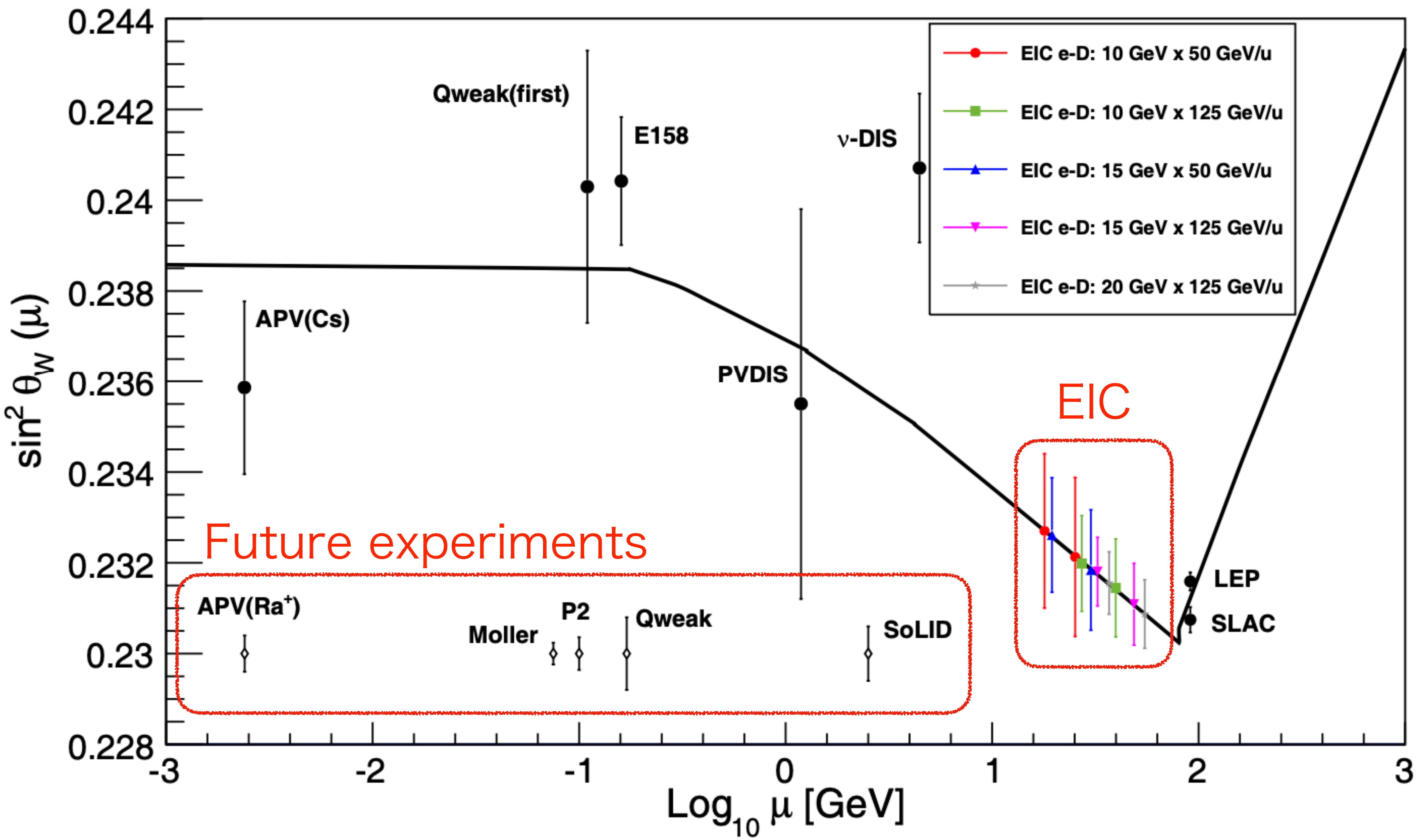
- At tree-level

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W)\,, \quad C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W)\,,$$
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W)\,, \quad C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W)\,,$$

- BSM affects to those couplings
  - Deviation of $\sin^2\theta_W$ from the SM

Weinberg Angle Measurements

From Atomic PV to LEP



Charged Lepton Flavor Violation

Long history and several methods

- Muon rare decays (tau similar)

$$\mu^+ \to e^+ \gamma$$ MEG/MEG-II

$$\mu^+ \to e^+ e^+ e^-$$ Mu3e

- Conversion/Transition

$$\mu^- N \to e^- N$$ COMET/Mu2e

$$\mu^+ e^- \to \mu^- e^+$$

- Energy-frontier colliders

$$Z \to e\mu$$

$$H \to \mu\tau$$

A. de Gouvea, P. Vogel,
Prog. Part. Nucl. Phys. 71, 75 (2013)

CLFV Interaction

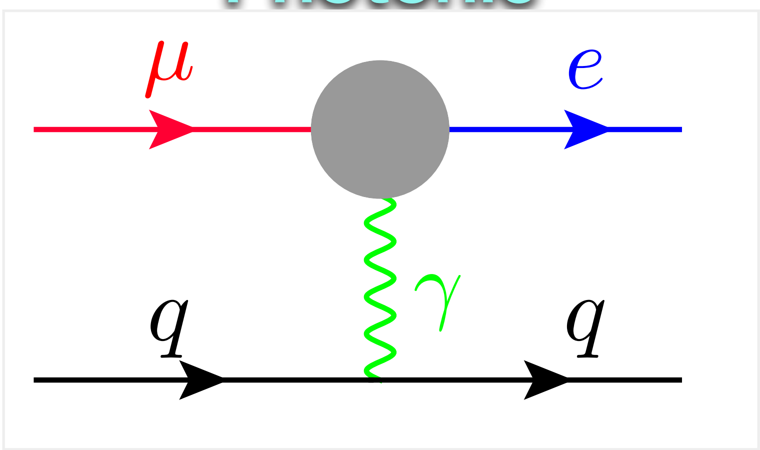
Effective Lagrangian

κ : photonic ($\kappa \ll 1$), non-photonic ($\kappa \gg 1$)

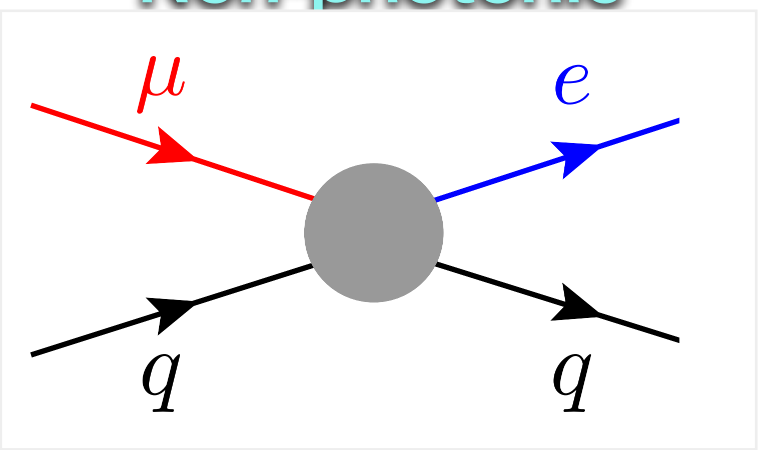
Λ : Effective energy scale

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}\left(\bar{\mu}_L\gamma^\mu e_L\right)\left(\bar{q}_L\gamma^\mu q_L\right)$$

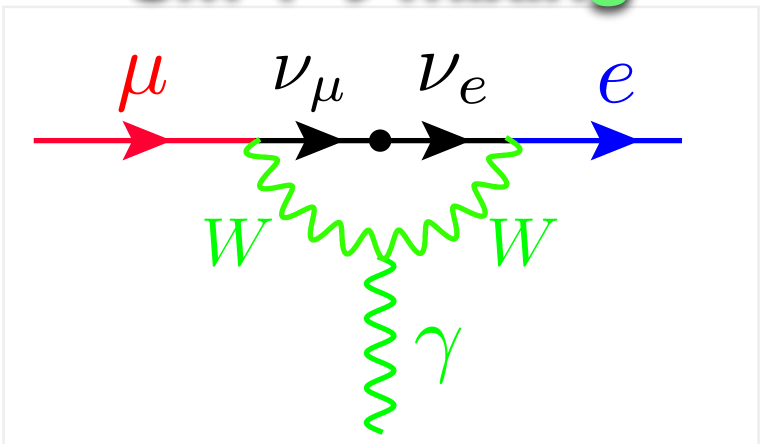
Photonic



Non-photonic



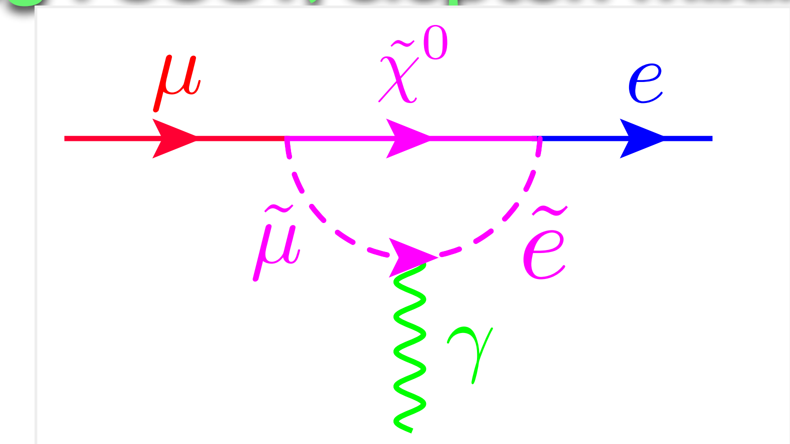
SM + ν mixing



$Br\left(\mu \rightarrow e\gamma\right) < 10^{-54}$

GIM-suppressed

Eg : SUSY, slepton mixing



BSM !

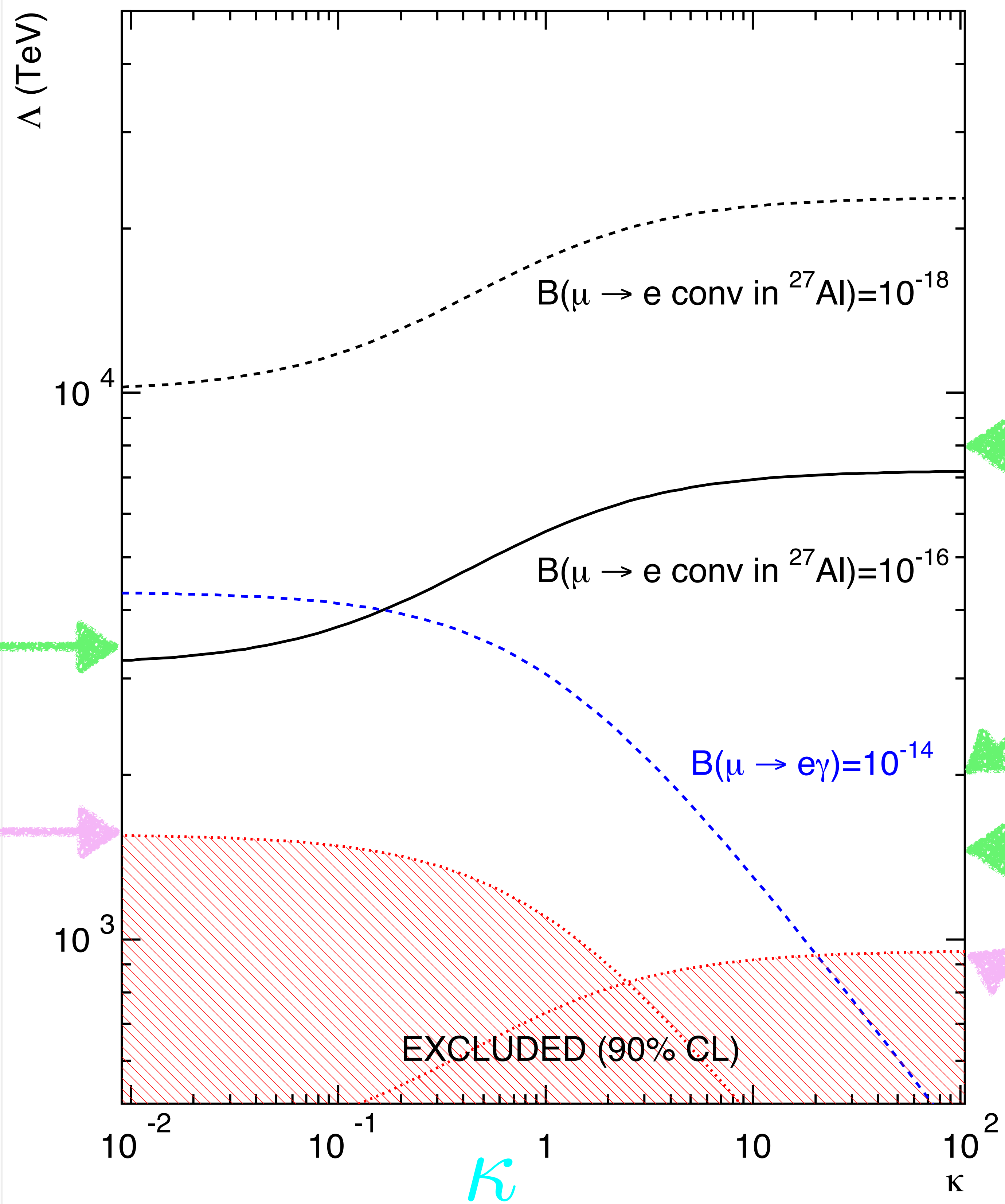
SM-background free

BSM Sensitivities

T. P. Gorringe, D. W. Hertzog, Prog. Part. Nucl. Phys. 84, 73 (2015)

$\mu^+ \to e^+\gamma$

$\mu^- N \to e^- N$



MEG II
5x10-14

MEG (2013)
5.7x10-13

Phys. Rev. Lett. 110, 201801 (2013)

COMET Phase-II
Mu2e
6x10-17

COMET Phase-I
7x10-15

DeeMe
1x10-14 - 5x10-15

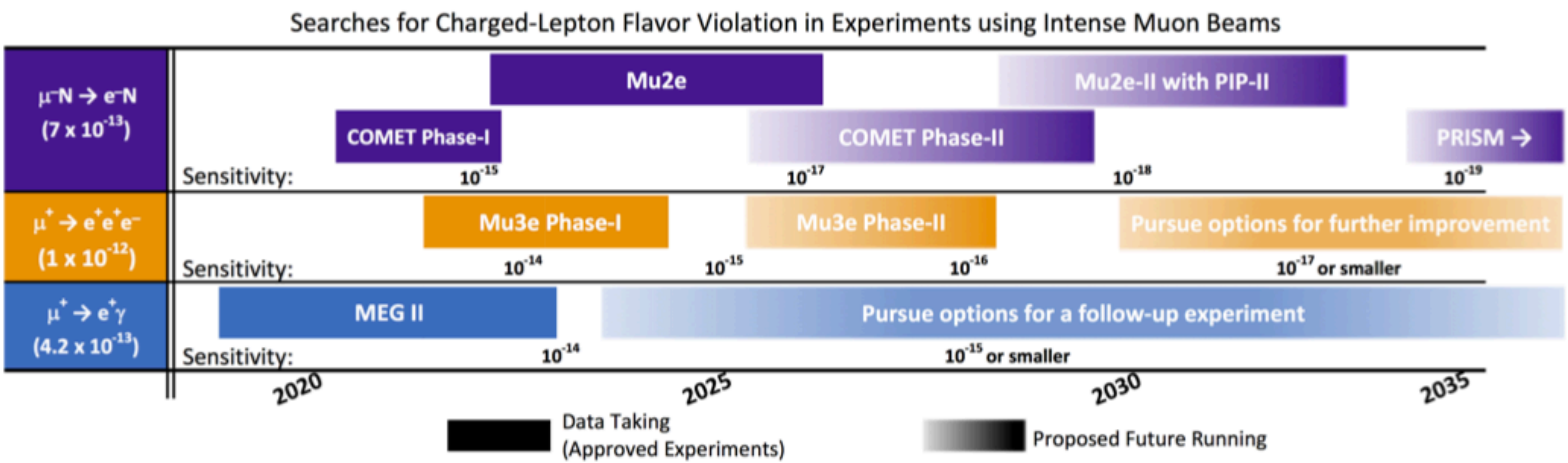
SINDRUM II (2006)
7x10-13

Eur. Phys. J. C47, 337 (2006)

Photonic κ Non-photonic

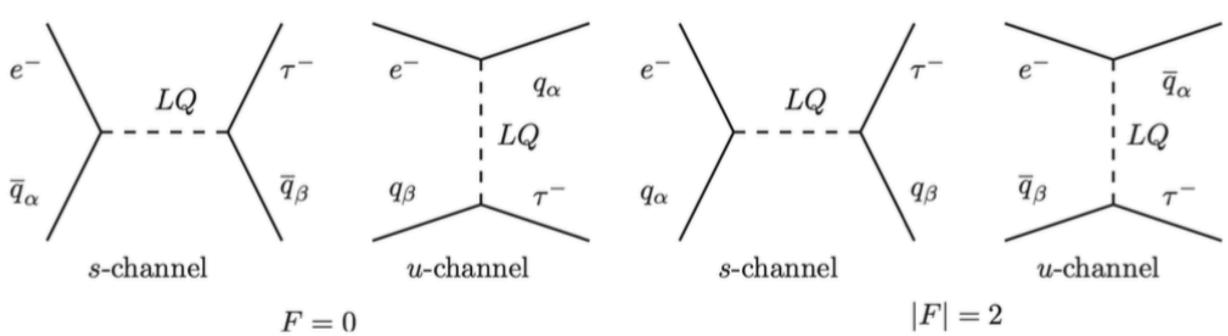
Muon CLFV

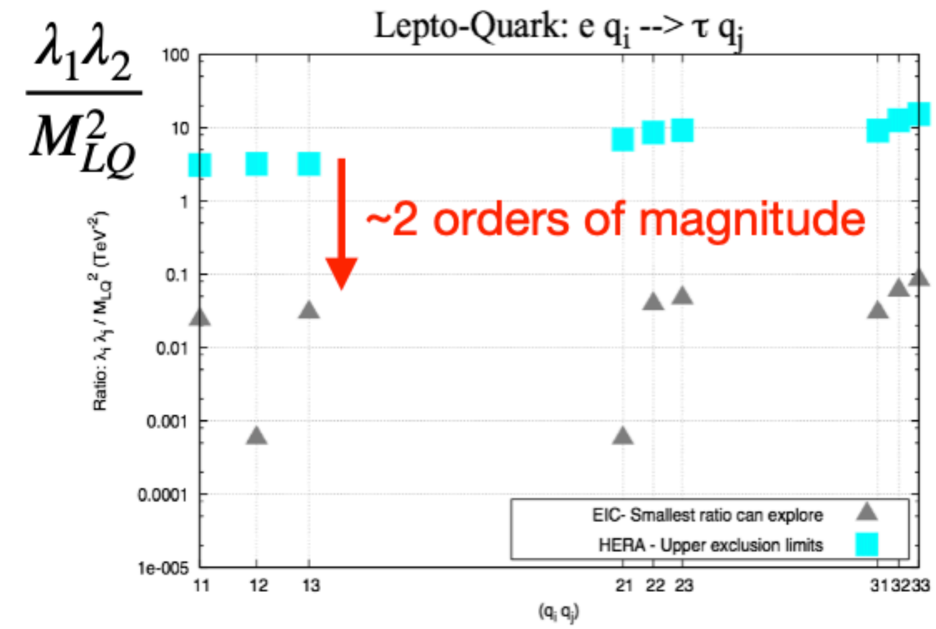
2020 European Strategy Update



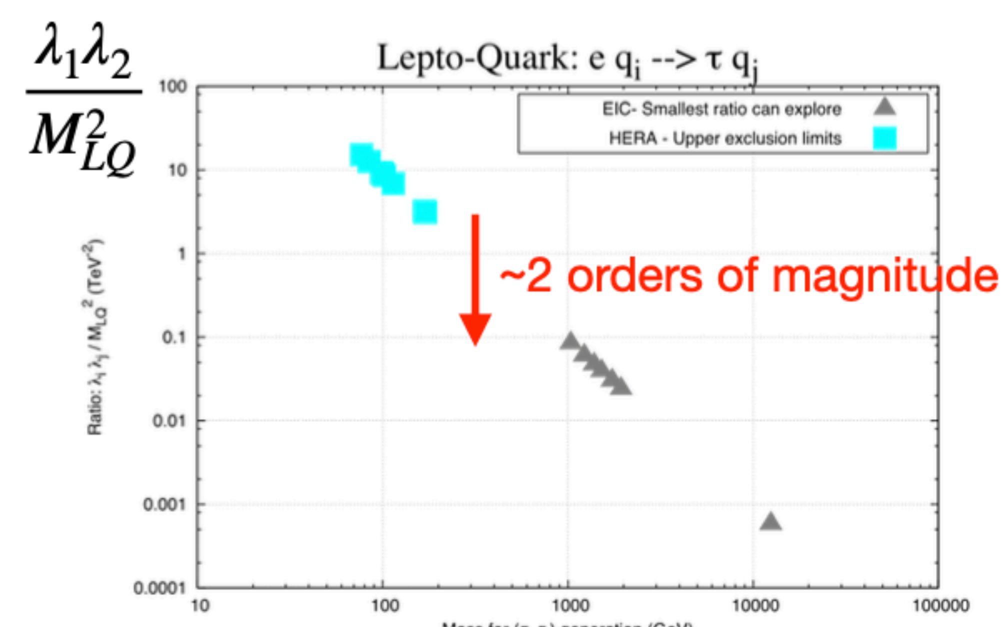
CLFV at EIC : e-tau Transition

- e+p → tau + X
  - Mediated by Lepto-quark
  - Studies in Snowmass2021
- Beyond HERA



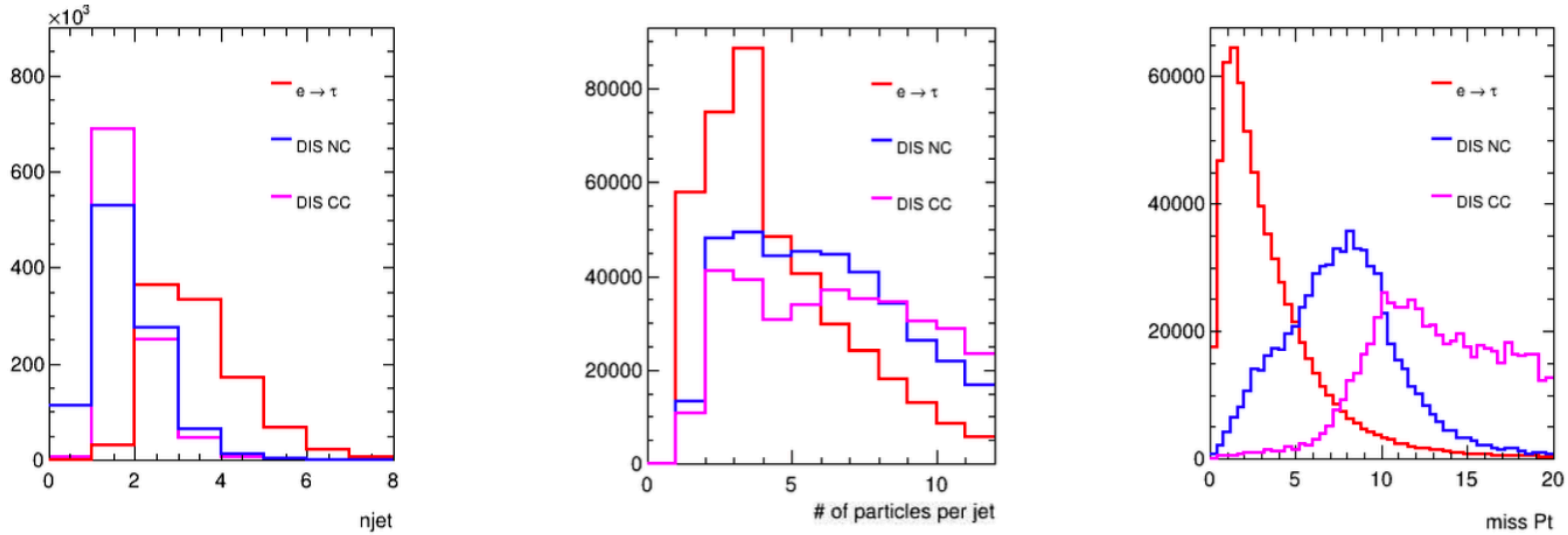


Assume 0.1 fb cross-section sensitivity



Features of LQ $e \rightarrow \tau$ event

18x275 GeV^2



Note: electron in DIS NC is masked; Fastjet, Anti-k_T, R = 1.0; jet pt > 2 GeV; Q^2>100 GeV^2

- $e \rightarrow \tau$ event
  - 2+ jets
  - Low particle multiplicity
  - Modest missing pT (partial of tau pT)
- DIS event
  - 1 jets dominating
  - Higher particle multiplicity
  - Missing pT ~ lepton pT

Beyond the Standard Model

Something more

- Utilizing proton & light ions polarization
  - Polarized ^{3}He as pseudo-neutron
  - Easy to construct parity-violating asymmetry
    - Similar to PV asymmetry in Weinberg angle measurement
  - Campaign again!

Search for Scalar Leptoquarks with polarized protons (and neutrons) at HERA and future $ep(n)$ Machines

J.-M. Virey[a*], E. Tuğcu[bcd] and P. Taxil [b c]

[a]Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany

[b]Centre de Physique Théorique, CNRS-Luminy, Case 907, F-13288 Marseille Cedex 9, France

[c]Université de Provence, 3 Place V. Hugo, F-13331 Marseille cedex 3, France

[d]Galatasaray University, Çırağan Cad. 102, Ortaköy 80840-İstanbul, Turkey

The effects of Scalar Leptoquarks in various channels have been analysed for the HERA collider and also for an eventual new *ep* machine running at higher energies. We emphasize the relevance of polarized beams.

1. Introduction

We present the effects of Scalar LQ in the Neutral Current (NC) and Charged Current (CC) channels at HERA, with high integrated luminosities and also at an eventual new *ep* collider running at higher energies, like the TESLAxHERA or LEPxLHC projects [1]. We estimate the constraints that can be reached using those facilities for several Leptoquark scenarios. We emphasize the relevance of having polarized lepton and proton beams as well as also having neutron beams (through polarized He^3 nuclei), in order to disentangle the chiral structure of these various models.

We adopt the "model independent" approach of Buchmüller-Rückl-Wyler [2] (BRW) where the LQ are classified according to their quantum numbers and have to fulfill several assumptions like B and L conservation, $SU(3)$x$SU(2)$x$U(1)$ invariance ... (see [2] for more details). The interaction lagrangian is given by :

$$\begin{aligned}\mathcal{L} &= (g_{1L}\bar{q}^c_L i\tau_2\ell_L + g_{1R}\bar{u}^c_R e_R)\,.\mathbf{S_1} + \tilde{g}_{1R}\bar{d}^c_R e_R.\tilde{\mathbf{S}}_\mathbf{1}\\ &+ g_{3L}\bar{q}^c_L i\tau_2\tau\ell_L.\mathbf{S_3} + \tilde{h}_2 L\bar{d}_R\ell_L.\tilde{\mathbf{R}}_\mathbf{2}\\ &+ (h_{2L}\bar{u}_R\ell_L + h_{2R}\bar{q}_L i\tau_2 e_R)\,.\mathbf{R_2}, \qquad (1)\end{aligned}$$

where the LQ S_1, $\tilde{S}_1$ are singlets, R_2, $\tilde{R}_2$ are doublets and S_3 is a triplet. ℓ_L, q_L (e_R, d_R, u_R) are the usual lepton and quark doublets (singlets). In what follows we denote generically by λ the LQ coupling and by M the associated mass.

These LQ are severely constrained by several different experiments, and we refer to [3] for some detailled discussions.

Now, in order to simplify the analysis, we make the following assumptions : *i)* the LQ couple to the first generation only, *ii)* one LQ multiplet is present at a time, *iii)* the different LQ components within one LQ multiplet are degenerate in mass, *iv)* there is no mixing among LQ's. From these assumptions and from eq.1, it is possible to deduce some of the coupling properties of the LQ, which are summarized in the table 1 of [4]. We stress from this table that the LQ couplings are flavour dependent and chiral.

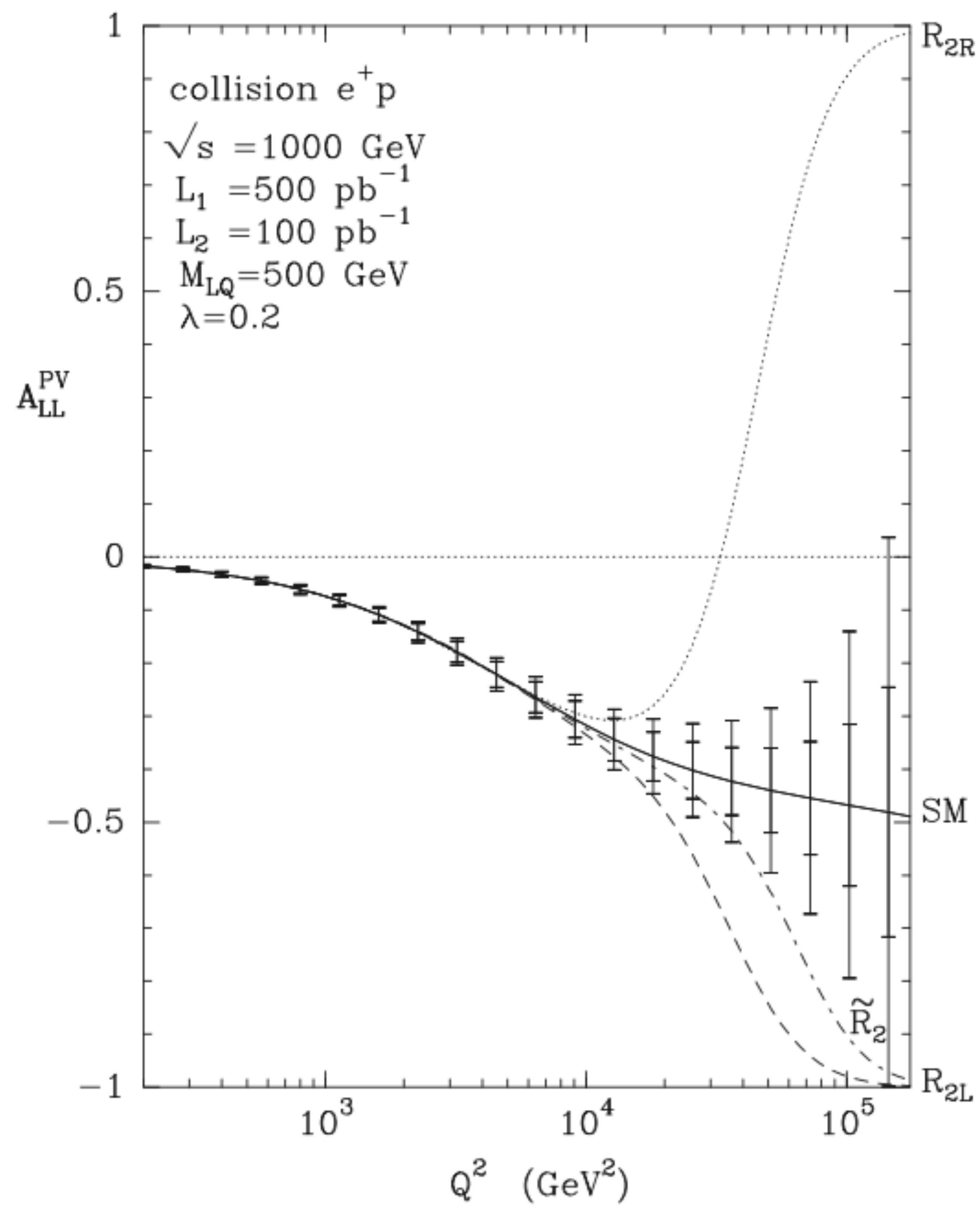
2. Future Constraints

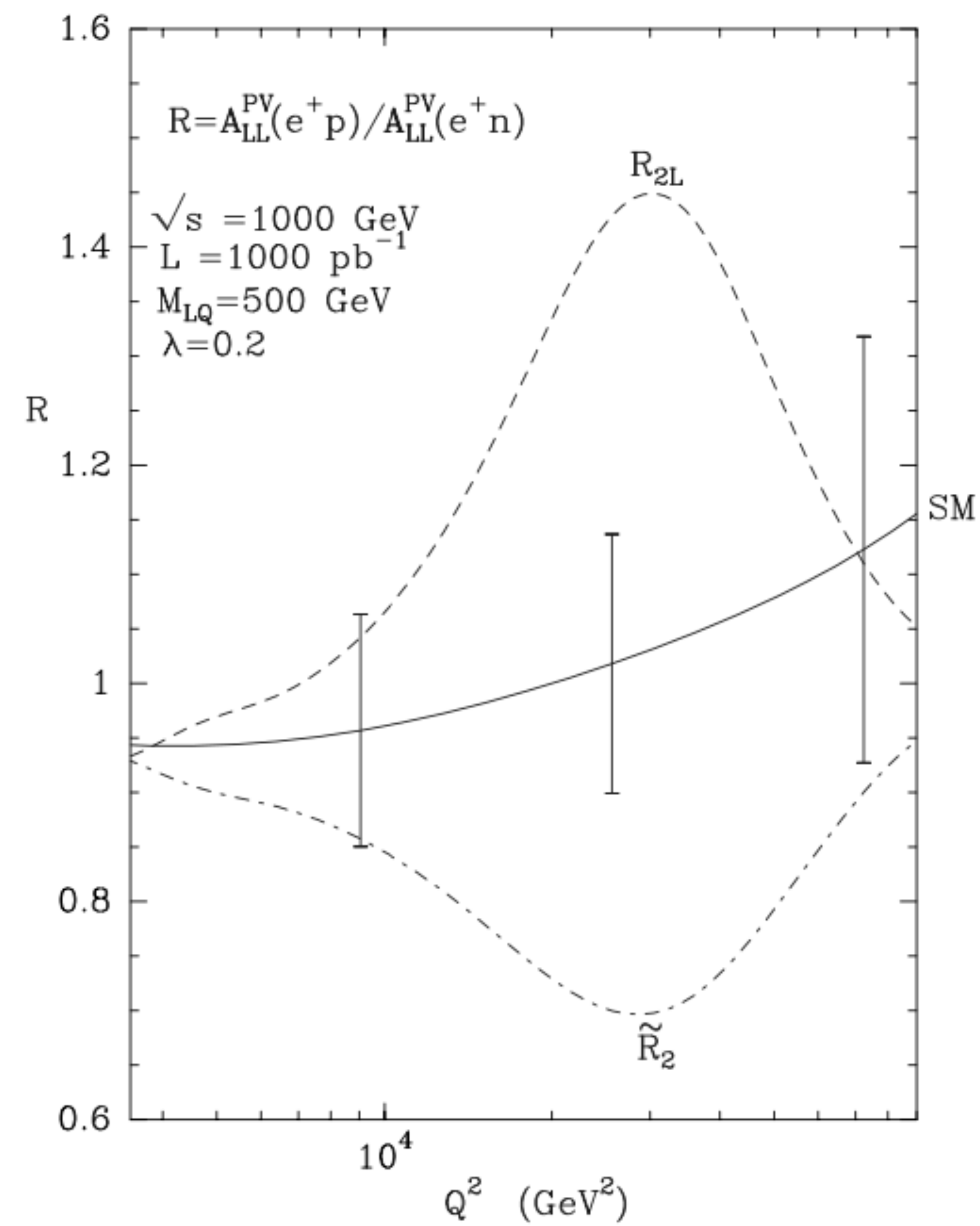
We consider the HERA collider but with some high integrated luminosities, namely $L_{e^-} = L_{e^+} = 500\,pb^{-1}$. The other parameters for the analysis being : $e^\pm p$ collisions, $\sqrt{s} = 300\,GeV$, $0.01 < y < 0.9$, $(\Delta\sigma/\sigma)_{syst} \sim 3\,\%$ and GRV pdf set [5]. We have considered also the impact on the constraints of higher energies by considering, in the one hand, an energy $\sqrt{s} = 380\,GeV$ which is closed to the maximal reach of HERA, and in the other hand, an energy $\sqrt{s} = 1\,TeV$ which

*Fellow of the "Alexander von Humboldt" Foundation

Beyond the Standard Model

Something more

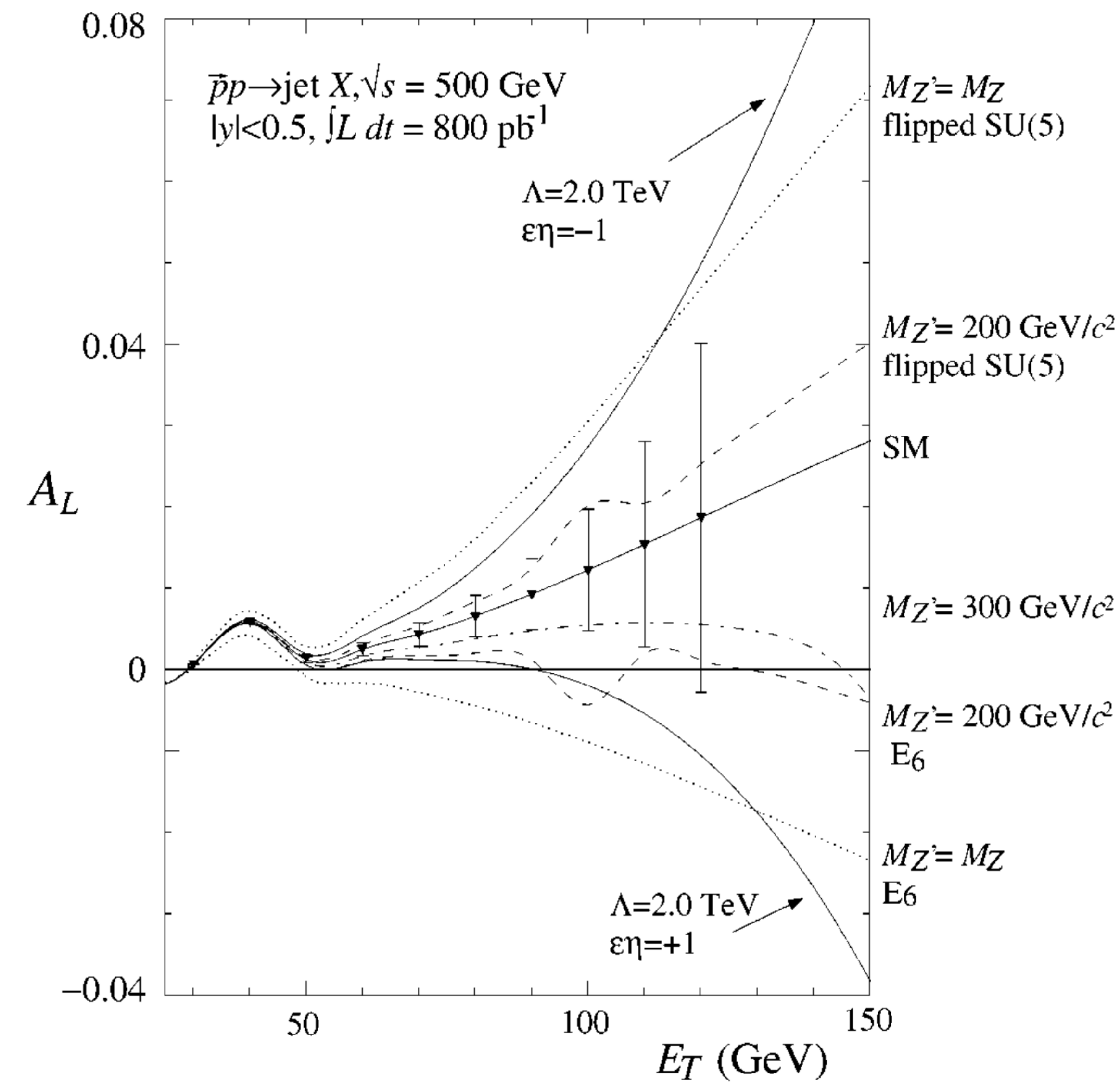




Beyond the Standard Model

Similar idea

- Polarized protons
- Parity violating asymmetry
  - PV in SM
  - Additional PV from BSM
  - Interference btw SM & BSM



Beyond the Standard Model

Similar idea

- Higgs sector CPV with polarized protons

VOLUME 71, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JULY 1993

Gluon Fusion: A Probe of Higgs Sector *CP* Violation

John F. Gunion and T. C. Yuan
Department of Physics, Davis Institute for High Energy Physics, University of California at Davis, Davis, California 95616

B. Grządkowski
CERN, Geneva, Switzerland and Institute for Theoretical Physics, University of Warsaw, Warsaw, Poland
(Received 12 February 1993)

We demonstrate that *CP* violation in the Higgs sector, e.g., of a multidoublet model, can be directly probed using gluon-gluon collisions at the Superconducting Super Collider.

PACS numbers: 11.30.Er, 12.15.Cc, 13.85.Qk, 14.80.Gt

Understanding the Higgs sector is one of the fundamental missions of future high energy colliders such as the Superconducting Super Collider (SSC) and CERN Large Hadron Collider (LHC). In particular, it will be important to know if *CP* violation is present in the Higgs sector. Generally, either spontaneous or explicit *CP* violation can be present if the Higgs sector consists of more than the single doublet field of the standard model (SM). (For a review of this and other issues summarized below, see Ref. [1], and references therein.) However, important classes of models with extended Higgs sectors either do not allow for Higgs sector *CP* violation or are inconsistent with current experiment if significant *CP* violation in the Higgs sector is present. Among such models, supersymmetric theories are the most important example. There, a phase for a Higgs field vacuum expectation value in excess of about 10^{-2} would imply imaginary components for slepton, squark, chargino, and neutralino propagators that would result in electric dipole moments of the electron and neutron in excess of experimental limits. Thus, once a Higgs boson is discovered, it

tion $\Delta g(x)$. For all but extremely conservative $\Delta g(x)$ choices, large asymmetries are possible since the gg coupling to the *CP*-even and *CP*-odd components of the ϕ are generically comparable (both arising at one loop). Indeed, we find that asymmetries larger than 10% are quite typical; these would be observable in the $\phi \to ZZ \to l^+ l^- X$ final state after 1–3 years of running. In the computations quoted here, we consider the situation in which the only extension of the SM occurs in the Higgs sector—ϕ production rates and asymmetries are generally larger in theories containing additional heavy colored fermions.

The procedure for computing the $gg \to \phi$ cross section in leading order is well known [1]. Our computations will employ the leading order formalism, but it should be noted that radiative corrections to this procedure have been computed, and for a typical value of α_s result in an enhancement factor of about 1.7 [3]. In this sense, our results will be conservative.

Crucial to our discussion is the degree of polarization that can be achieved for gluons at the SSC. The amount

Summary

- There are already some interesting topics in SM and BSM physics at EIC
- EIC as Intensity/Precision Frontier
  - Utilizing polarization
  - (Polarized) Nuclear beams
- More ideas might arise from both theory/experiment sides.