EW/BSM physics at HERA and EIC

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New opportunities for BSM/EW physics at EIC
Jul 21 – 24, 2025
CFNS workshop, Stony Brook University

U.S. DEPARTMENT OF ENERGY   JSA   Jefferson Lab   EIC[2] EIC Center at Jefferson Lab

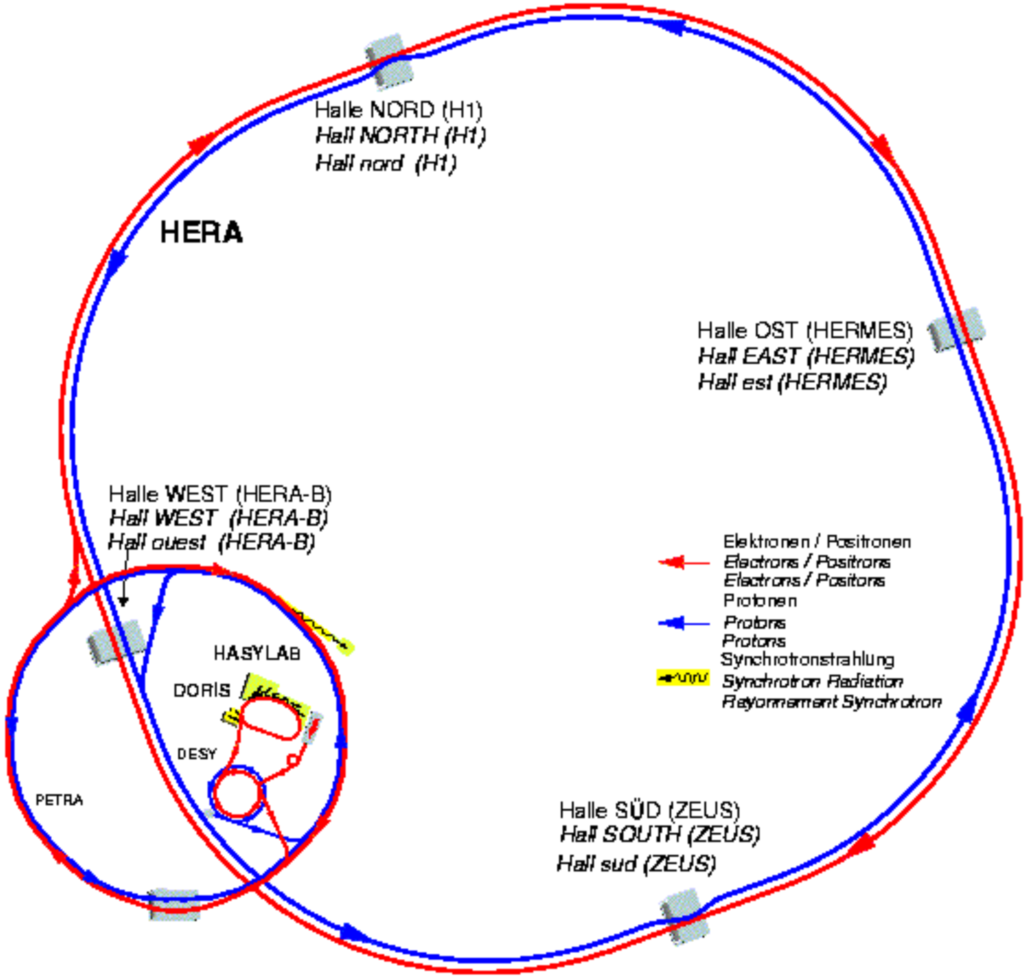
Outline

- HERA vs EIC colliders: CM, luminosity, polarisation, etc…
- Two parts Electroweak(EW) and Exotic/Beyond the Standard Model (BSM)
  - HERA EW/BSM : results and lessons learned
  - EIC EW/BSM: physics projections
- Summary

HERA collider

The **H**adron-**E**lectron **R**ing **A**ccelerator facility (HERA) was **the worldwide first and only storage ring facility accelerating two different types of particles (electrons and protons)**

- Operated from 1992 to 2007
- Circumference 6.3 km
- Electrons or **positrons** colliding with protons
- Proton: 460-820 GeV (unto 920 GeV after upgrade)
- Leptons 27.6 GeV
- Center of mass energies up to 319GeV
- Peak luminosity ~7×10^{31} cm-2s-1
- 96ns bunch crossing
- Only lepton beam polarisation up to 40-60% (Sokolov-Ternov effect, rise-time ~30 minutes)



Experiments at HERA

Two main colliding-beam experiments:

General purpose detectors, but different focus

- **H1** (focused on electron ID: High resolution EMCAL - Liquid Ar with high transverse and longitudinal segmentation)
- **ZEUS** (focused on hadrons and jets measurements: best in the world U calorimeter with resolution of 35%/$\sqrt{E}$, compensating e/h =1)

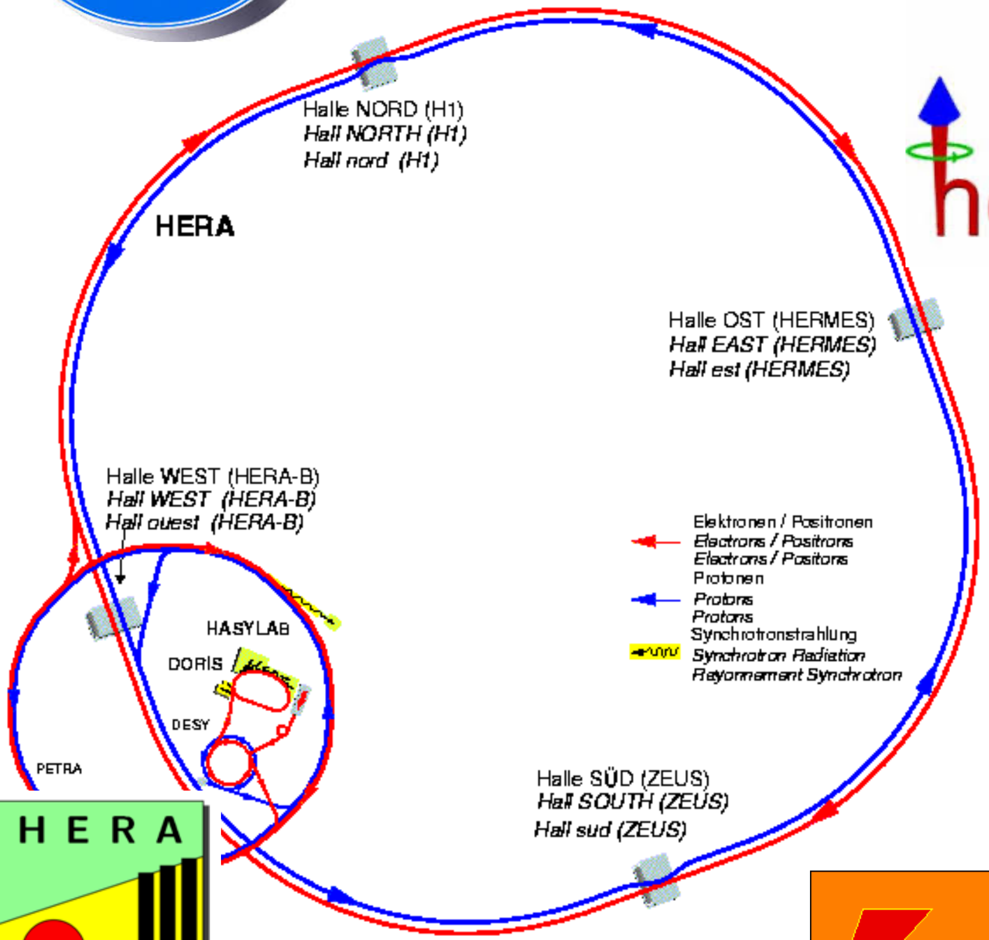
=> (allowed to reduce systematics for combined data)

Fixed target (using only e-beam) :

- **HERMES**: study nucleon spin structure by colliding the polarized electron beam with a gas jet of polarized nucleons

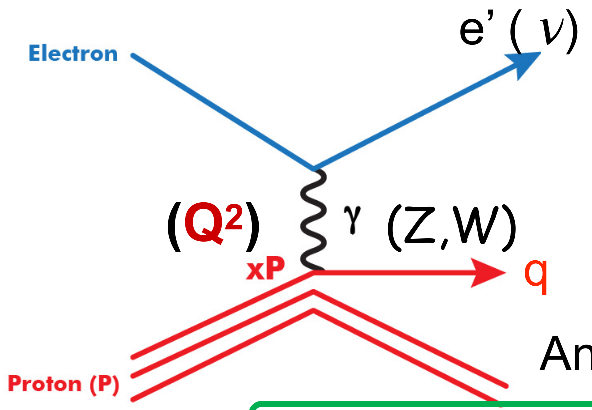
Fixed target (using only p-beam):

- **HERA-B:** to measure CP violation in the $b\bar{b}$system



Deep Inelastic Scattering

Kinematic reconstruction



Systematic effects.

And many other methods ….

$Q^2 = -q^2$: 4-momentum transfer squared

x (0<x<1) - fraction of proton momentum carried by the struck quark

y (0<y<1)=(Ee-Ee')/Ee - fractional energy transfer

a) Electron method uses information ONLY from scattered electron (E', θ'):

$$Q^2_{\rm EM} = 2E_e E_{e'}\,(1+\cos\theta_{e'})\,,$$

$$y_{\rm EM} = 1 - \frac{E_{e'}}{2E_e}(1-\cos\theta_{e'})\,,$$

$$x = \frac{Q^2}{4E_e E_{\rm ion}}\,\frac{1}{y}$$

Note: Linear dependence on $E_{e'}$ of the Q^2

This method could NOT be used for y < 0.1

b) Jacquet –Blondel method (only method for Charged Current reactions)

$$y_{\rm JB} = \frac{1}{2E_e}\sum_h (E_h - p_{z,h})\,,$$

$$Q^2_{\rm JB} = \frac{1}{1-y_{\rm JB}}\left[\left(\sum_h p_{x,h}\right)^2 + \left(\sum_h p_{y,h}\right)^2\right].$$

Note: depends only on measurements of hadrons

c) Double angle method

$$Q^2_{\rm DA} = \frac{4E_e^2\,\sin\gamma_h\,(1+\cos\theta_{e'})}{\sin\gamma_h + \sin\theta_{e'} - \sin(\theta_{e'}+\gamma_h)},$$

$$y_{\rm DA} = \frac{\sin\theta_{e'}\,(1-\cos\gamma_h)}{\sin\gamma_h + \sin\theta_{e'} - \sin(\theta_{e'}+\gamma_h)},$$

Note: Does not require measurements of scattered electron energy

$$\cos\gamma_h = \frac{P^2_{T,h} - \left(\sum_h (E_h - p_{z,h})\right)^2}{P^2_{T,h} + \left(\sum_h (E_h - p_{z,h})\right)^2}$$

d) Sigma method

$$y_{e\Sigma} = \frac{\sum_h (E_h - p_{z,h})}{E - P_z},$$

$$Q^2_{e\Sigma} = \frac{(E_{e'}\,\sin\theta_{e'})^2}{1-y}.$$

Note: Does not depend on initial electron beam energy, **less influenced by a initial state radiation**

Physics at HERA

https://cds.cern.ch/record/177680/files/p453.pdf

Mar 1987 Reinhold Rückl

(A) strong interaction physics

- proton structure and quark/gluon densities
- QCD scaling violations and running of α_s
- properties of structure functions such as longitudinal SF, sum rules, behaviour at very small x
- jets and energy flow
- single particle inclusive production
- low Q^2 photoproduction
- QED/QCD Compton scattering
- heavy quark (in particular top) and quarkonium production

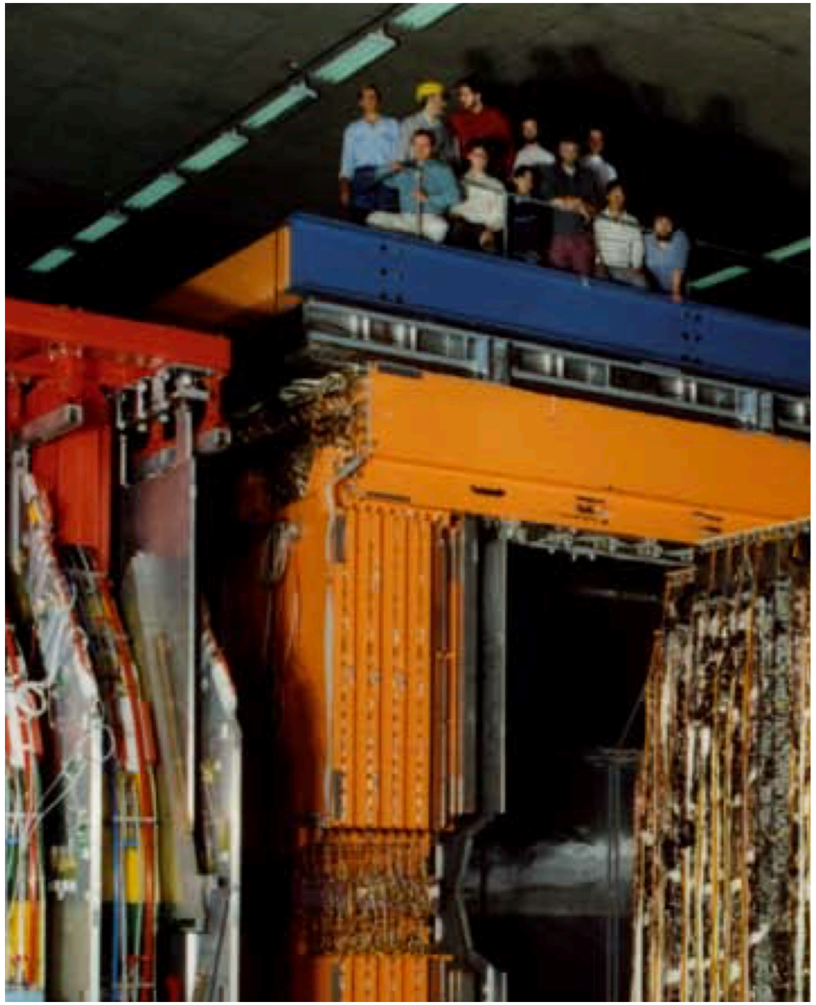
(B) electroweak interaction physics

- structure of neutral and charged weak currents
- W and Z properties
- 1-loop effects

(C) possible new physics

- new weak bosons and currents
- non-standard (pseudo-) scalar bosons
- leptoquarks
- supersymmetric particles
- compositeness of leptons and quarks

First data from HERA: Leptoquarks ???



Eckhard Elsen •

The particle physicist Eckhard Elsen was the spokesperson of the H1 experiment at HERA from 1999 to 2002. Although he is now coordinating many of the lines of responsibility for the planned International Linear Collider ILC, he has been "on shift" at H1 until the very last day of the data taking.

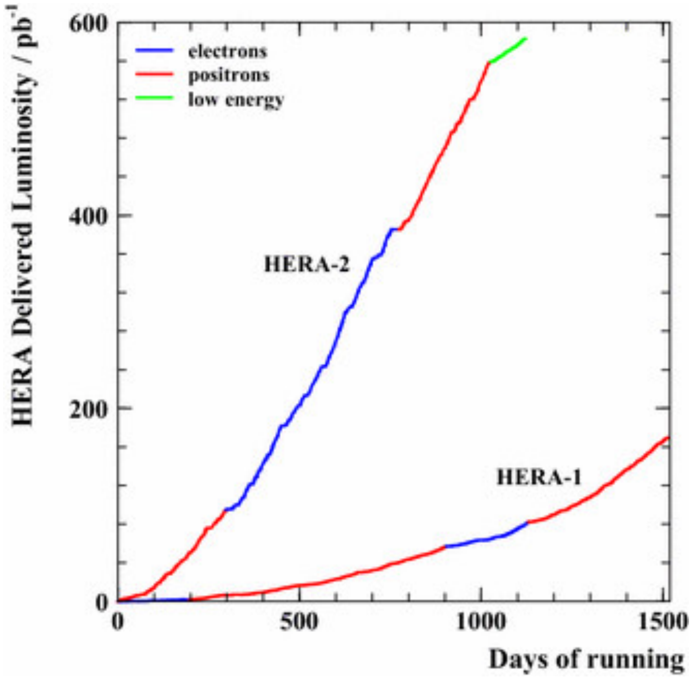
With analyses entering the high-energy regime at HERA in late 1996, we observed an excess of events in the mass spectrum that some physicists interpreted as leptoquarks. This would have revolutionized particle physics. We recorded 12 events (with only five expected), and everyone in the collaboration was very excited. We worked at top speed to analyze the data, interpret it and determine the statistical significance of this observation. Everyone contributed, and enthusiasts and skeptics alike worked in a spirit of selfless competition. The team working on our rival experiment ZEUS also observed indications of an excess of events. When we finally issued a careful statement, it caused a sensation in the physics world and the news even made it into the New York Times. Not until a few years later, when we had recorded much more data, were we able to show that "our leptoquarks" were merely a statistical fluctuation. Nonetheless the H1 team benefited from the experience: because of this quirk of nature, we developed an intense collaboration style that still characterizes our work today.

late 1996:
Mass spectrum
12 events (only 5 expected)
Leptoquarks?!

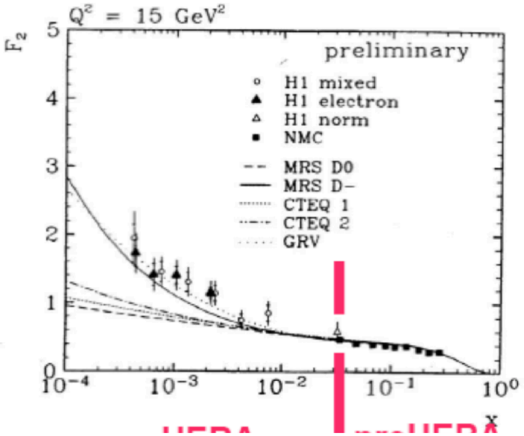
https://pr.desy.de/sites/sites_desygroups/sites_extern/site_pr/content/e104098/e104111/HERA_Pointing_the_way_eng.pd

First data from HERA

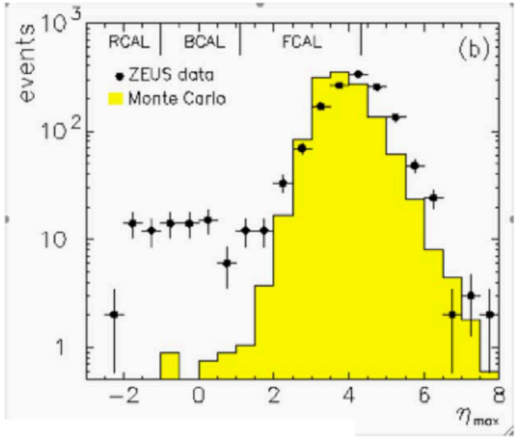
E.Gallo



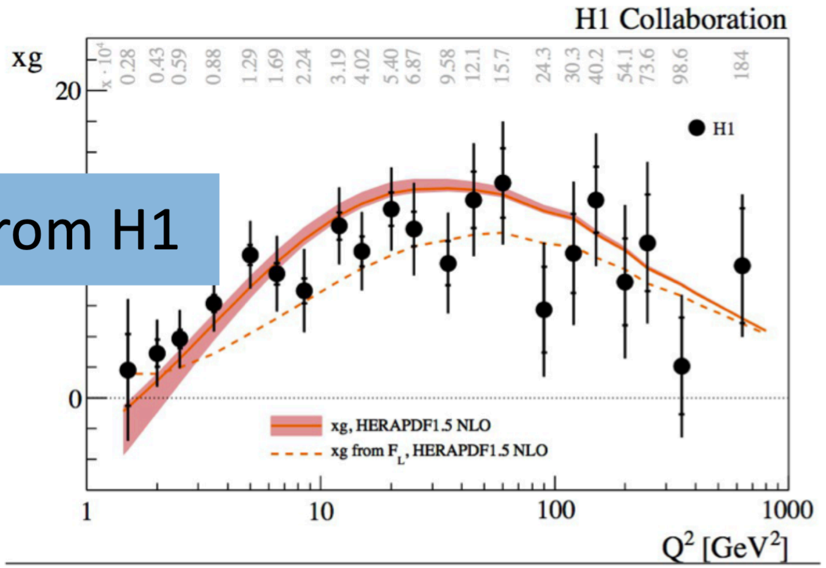
First F_2 presented by H1 at Durham 1993



Diffractive events discovered by ZEUS, DESY seminar 1993



F_L from H1

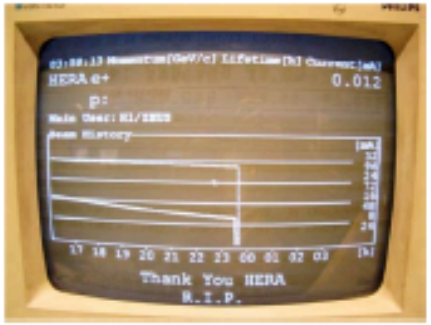


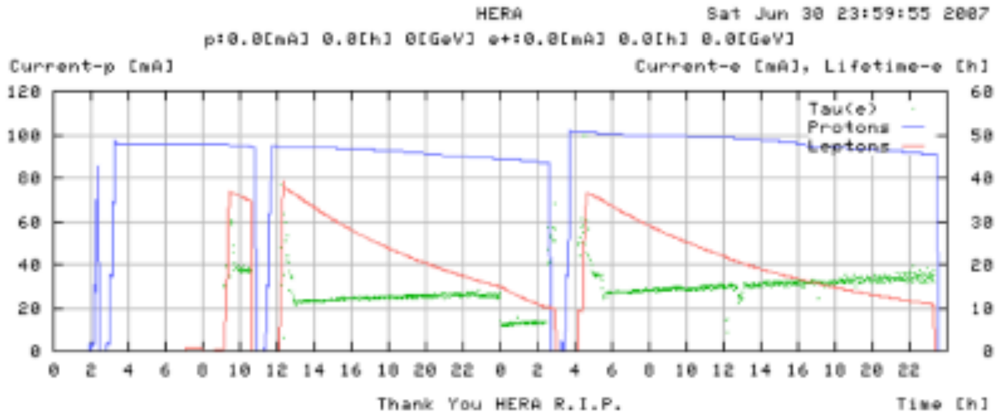
Each experiment (H1,ZEUS) collected ca 0.5 fb-1 each.
Electron and **positron** data (HERA-I mostly positrons)
-Main focus on high-Q2 measurements
-Structure functions F_2
-Discovery of diffractive events
- Low-Q2 and F_L physics

Last HERA fill

slide from Elisabetta Gallo

Last fill 30/6/2007 at 23:30



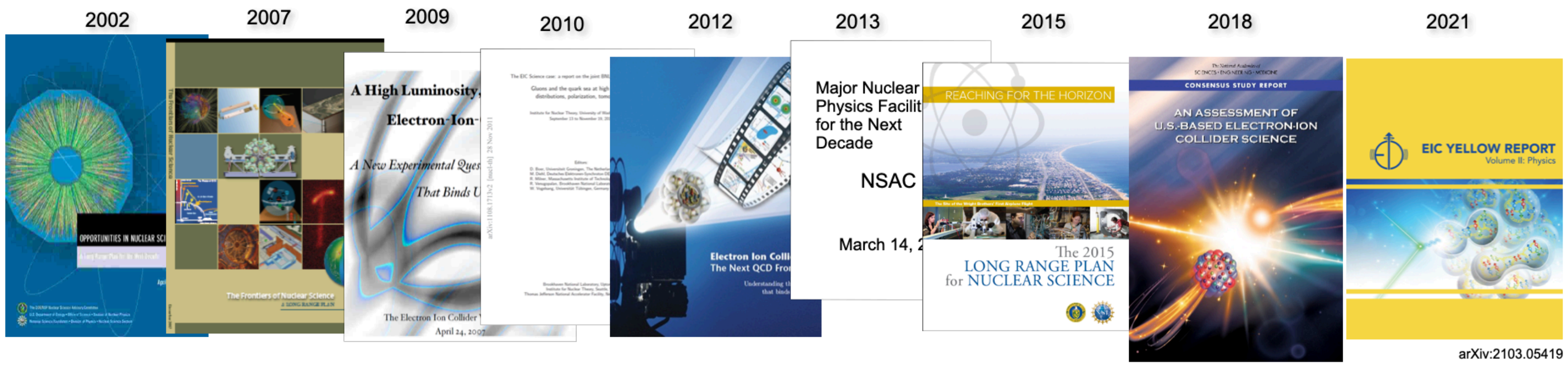


- Picture taken at the party after the last fill
- You have all a new project to start in DIS

From HERA to EIC

The science and requirements for an EIC were built over last two decades

- ✓ DIS facility => control of the kinematic (x, y, Q^2)
- ✓ Nuclear beams A = 2-208 => first in the world eA collider !
- ✓ Variable center of mass energy $\sqrt{s}$ (eN) : 30–140 GeV
  - ➢ E_e : ~5 - 18 GeV
  - ➢ E_p: ~ 41-275 GeV
  - ➢ wide coverage for Q^2, x_B ;
  - ➢ include non-perturbative, perturbative and transition regimes.
  - ➢ overlap with existing measurements

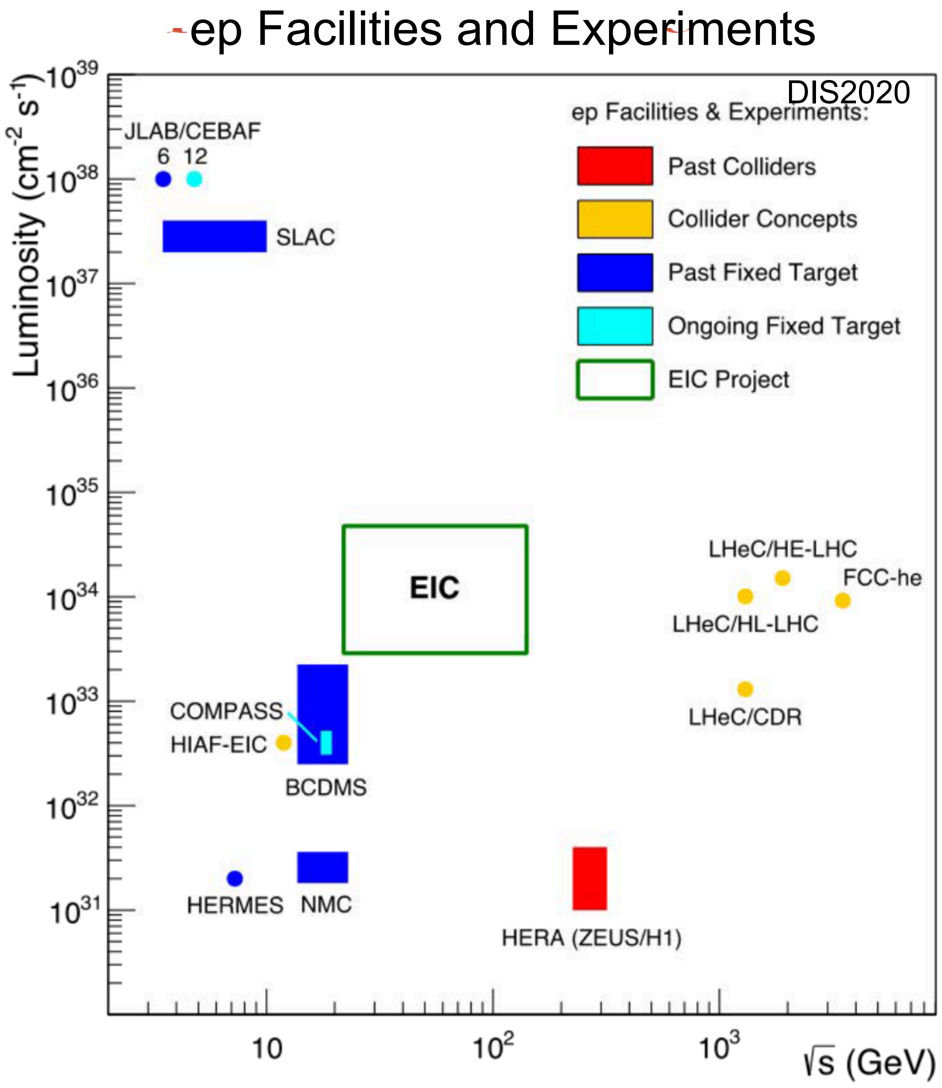


arXiv:2103.05419

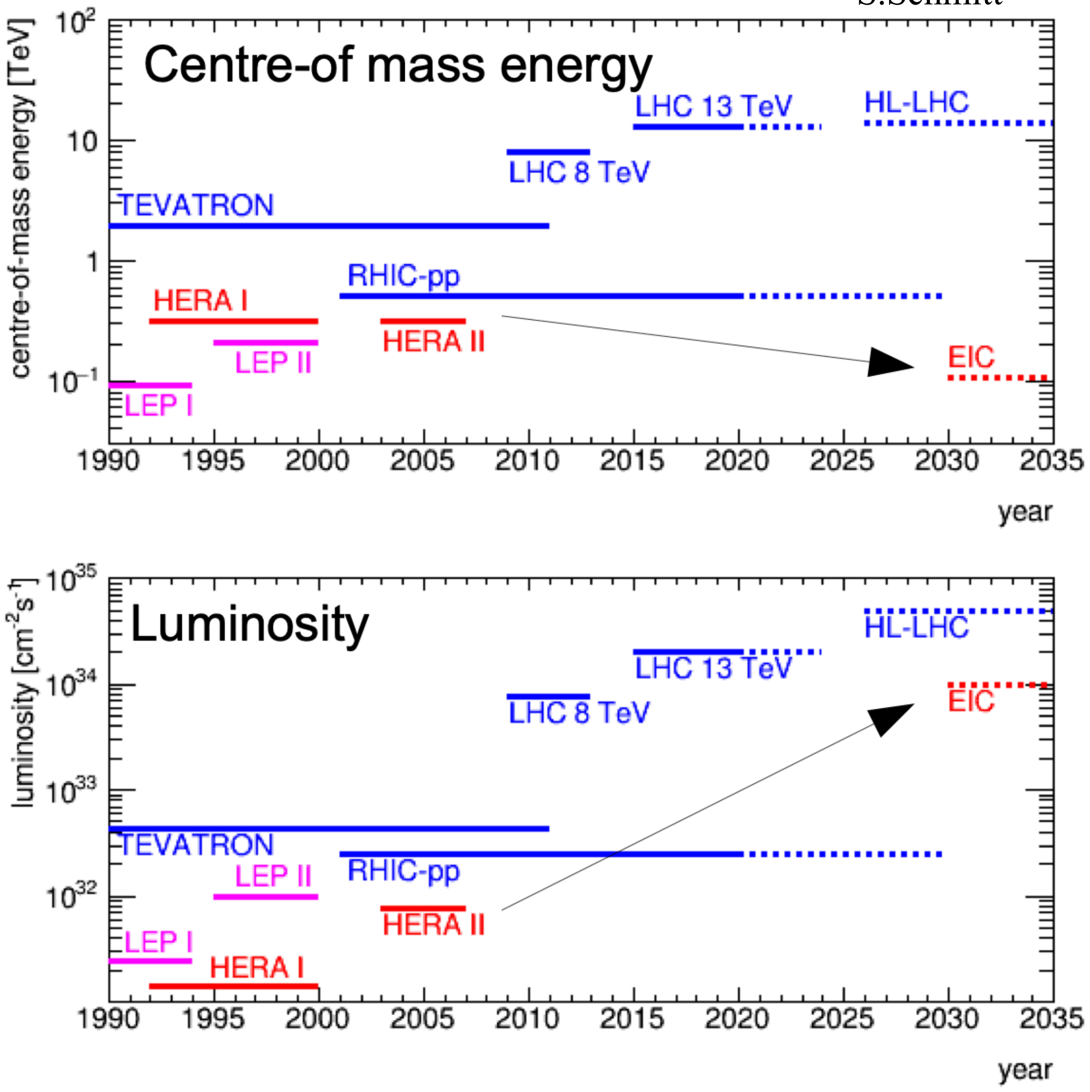
- ✓ Luminosity $L \sim 10^{34}\ cm^{-2}\ s^{-}$
- ➢ high precision physics;
- ➢ rare processes;
- ➢ different configurations(polarization, energies, ions, etc)
- ➢ 100 fb-1 in a year at EIC vs 1 fb-1 over 10 years at HERA

- ✓ polarized lepton & hadron beams (up to 80%) => Test of spin properties and spin dependences
- ✓ Next generation of detectors => systematics and various final states (PID)

From HERA to EIC



S.Schmitt

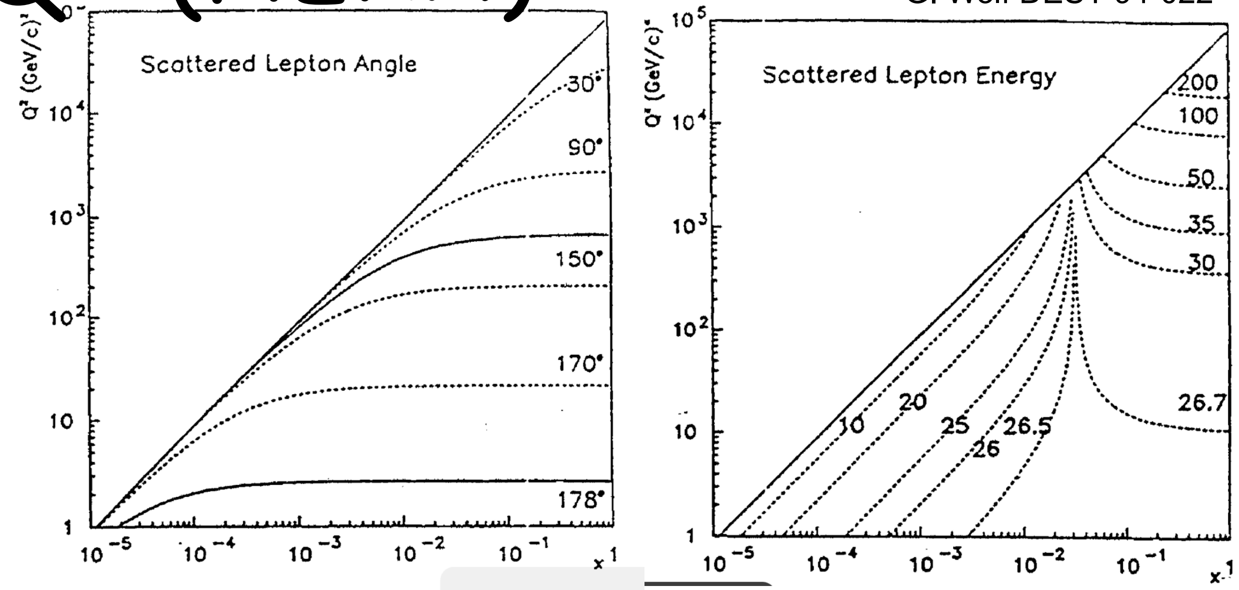


EW Physics at HERA and EIC

Neutral Current at high Q2 (HERA)

G. Wolf DESY-94-022

$$Q^2_{max} = 4 \cdot E_e \cdot E_p \quad => Q^2_{max} = 101{,}200\ GeV^2$$



At high Q^2

-

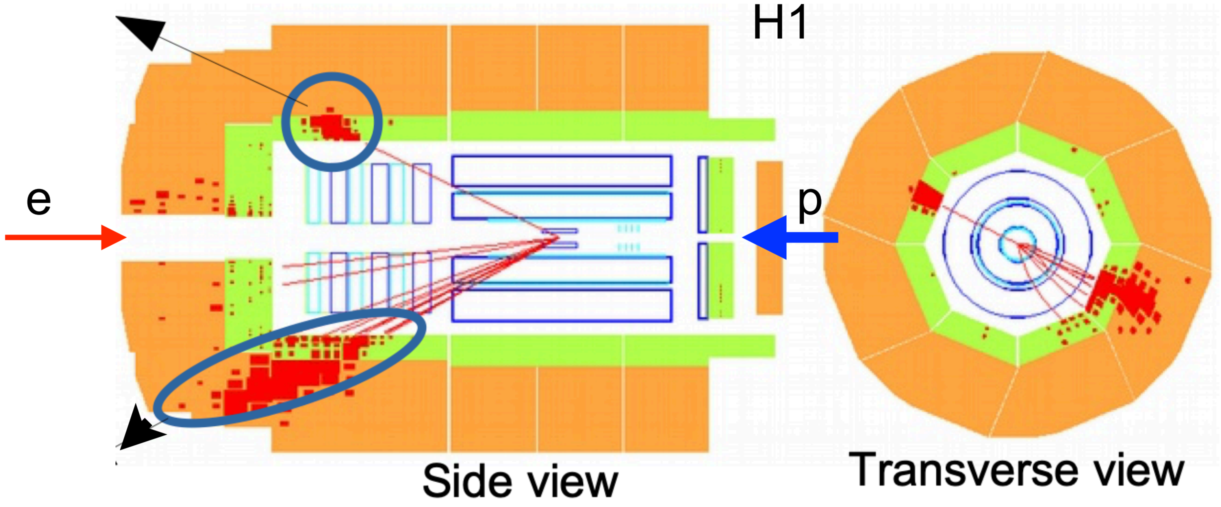
-Large electron **scattering angle** and energy.
-Need good electron identification in the forward region.
-Can NOT neglect xF3 team in the cross section.

$$\frac{d^2\sigma^{NC}}{dxdQ^2} \sim \left| \frac{A}{Q^2} + \frac{B}{Q^2 + M_Z^2} \right|^2 \times pdf's$$

$$\tilde{\sigma}^{\pm} = \frac{d^2\sigma^{\pm}}{dxdQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2^{\pm} \mp \frac{Y_-}{Y_+} x\tilde{F}_3^{\pm} - \frac{y^2}{Y_+}\tilde{F}_L^{\pm}$$

Inelasticity: $y = Q^2/(sx)$

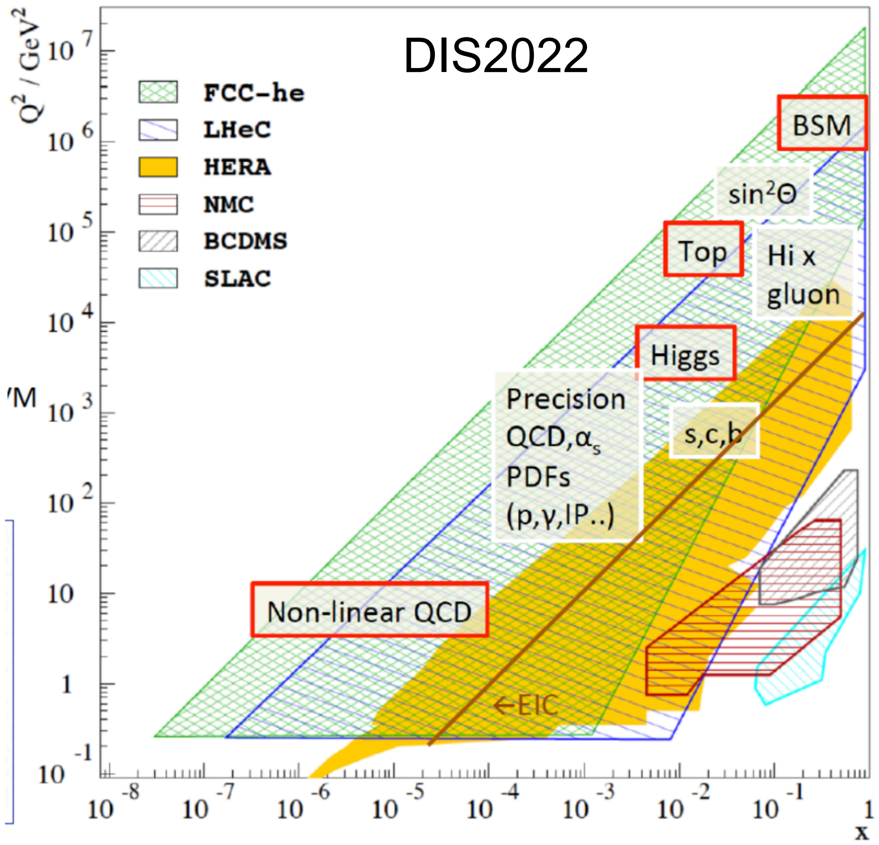
helicity factors: $Y_{\pm} = 1 \pm (1-y)^2$

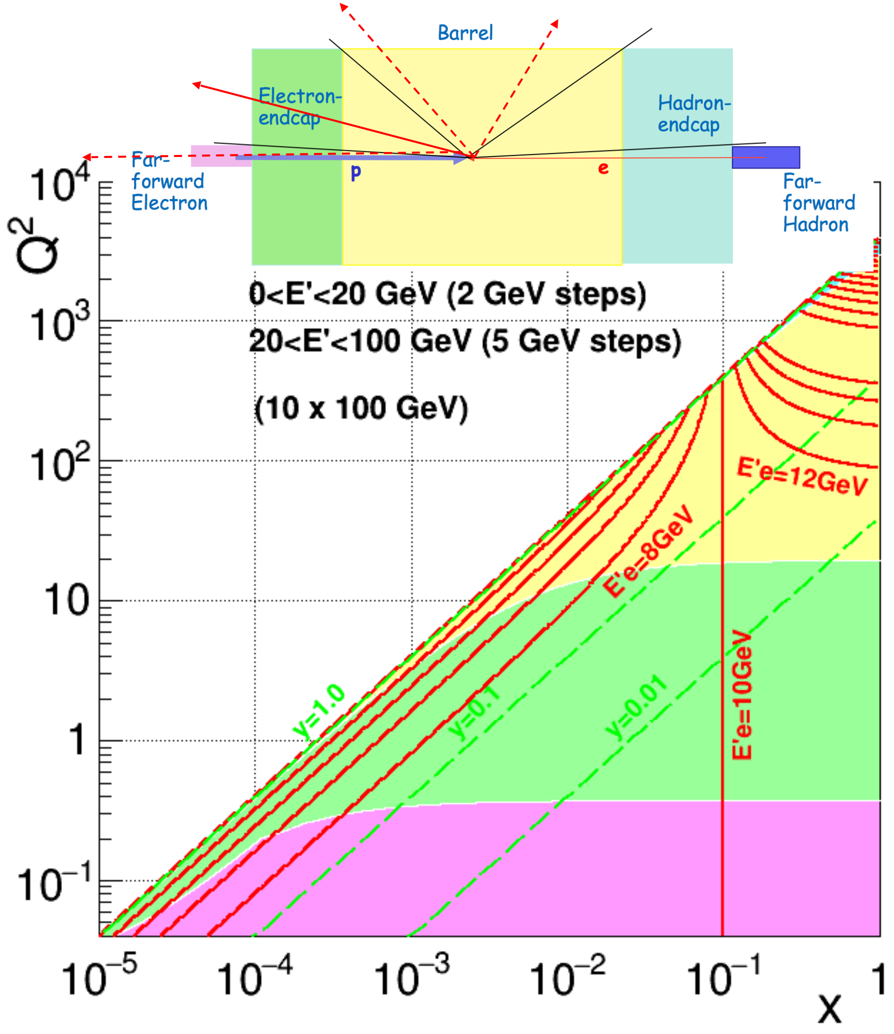


Neutral Current at high Q2 (EIC)

$$Q^2_{max} = 4 \cdot E_e \cdot E_p \quad => Q^2_{max} = 19{,}800\ GeV^2$$

Kinematics: more symmetric
Overlap with HERA and fixed-target experiments

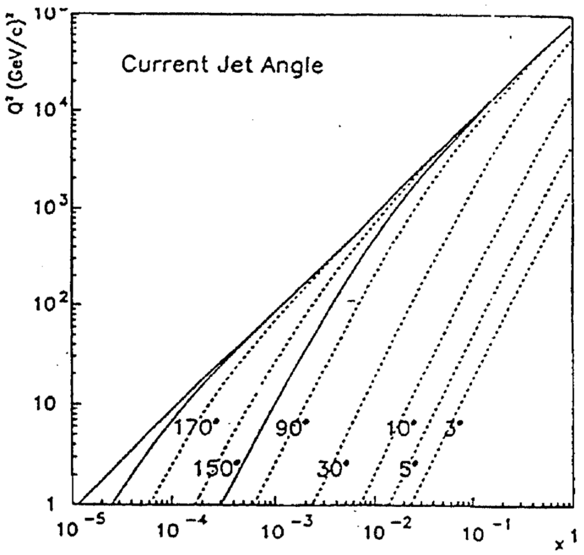


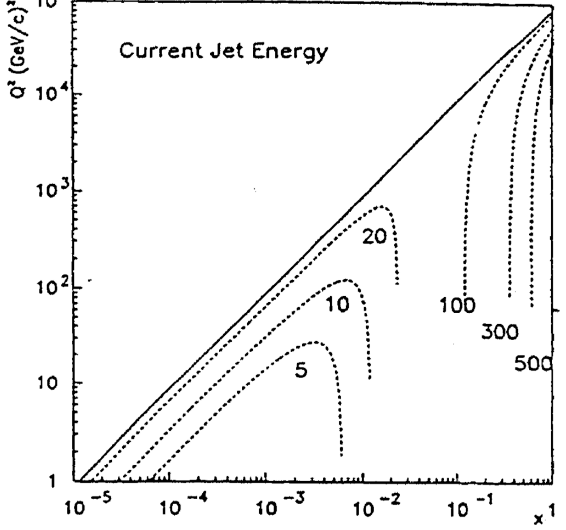


Charged Current at high Q2 (HERA)

Charged current DIS
– neutrino with high transverse momentum (escapes detection)
-Missing E_T
-Only Jacquet –Blondel method for x,y,Q2 reconstruction (hadrons only)
Kinematics is reconstructed from hadronic system only
=> Resolution of Hadronic calorimeter is crucial (!)

G. Wolf DESY-94-022



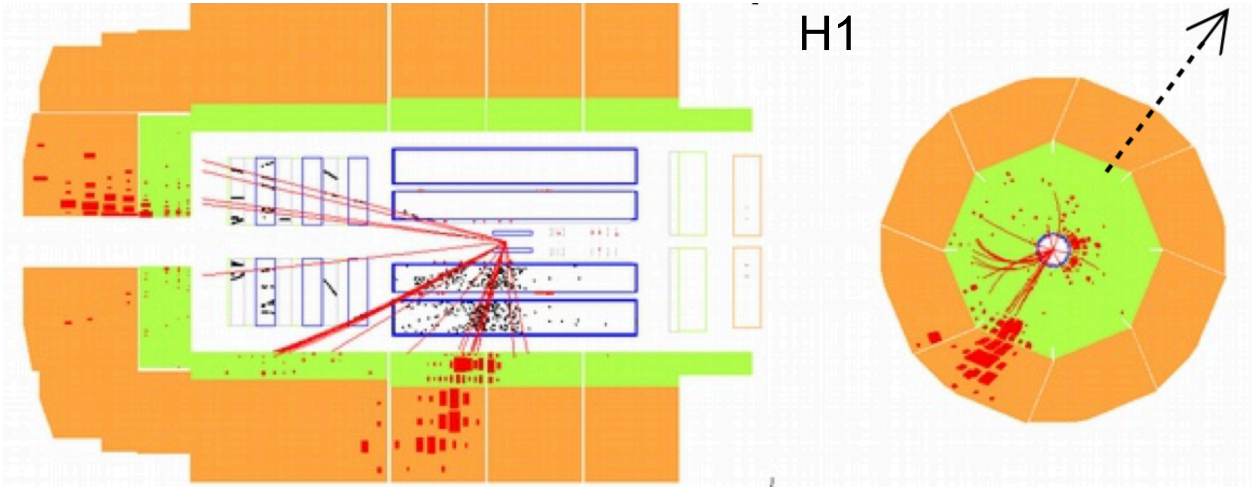


$$\frac{d^2\sigma^{CC}}{dxdQ^2} \sim G_F^2\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \times \mathrm{pdf's}$$

Charged Current DIS:

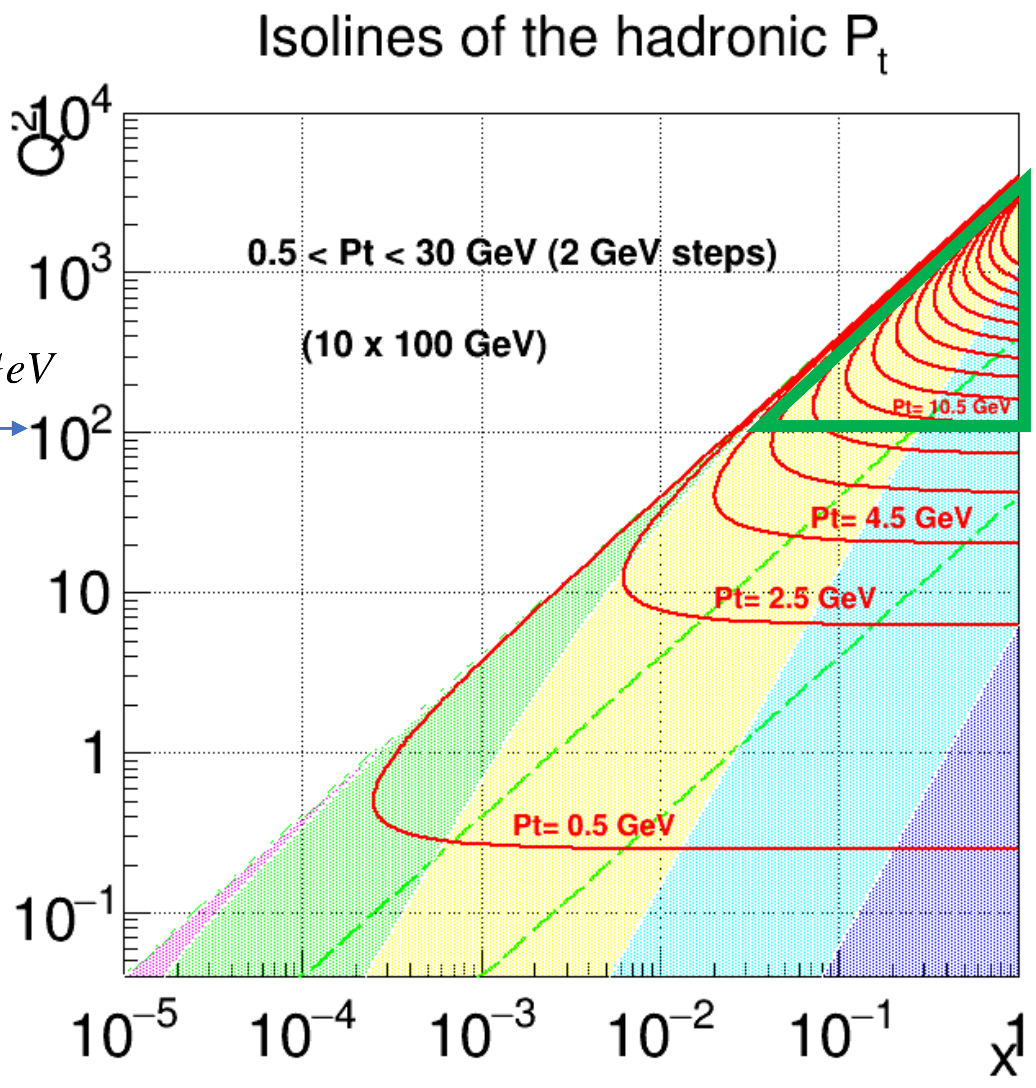
$$\frac{d^2\sigma(e^+p)}{dxdQ^2} = \frac{G_F^{\,2}}{2\pi}\left(\frac{M_W^{\,2}}{M_W^{\,2}+Q^2}\right)^2\{(\bar{u}+\bar{c})+(1-y)^2(d+s)\}$$

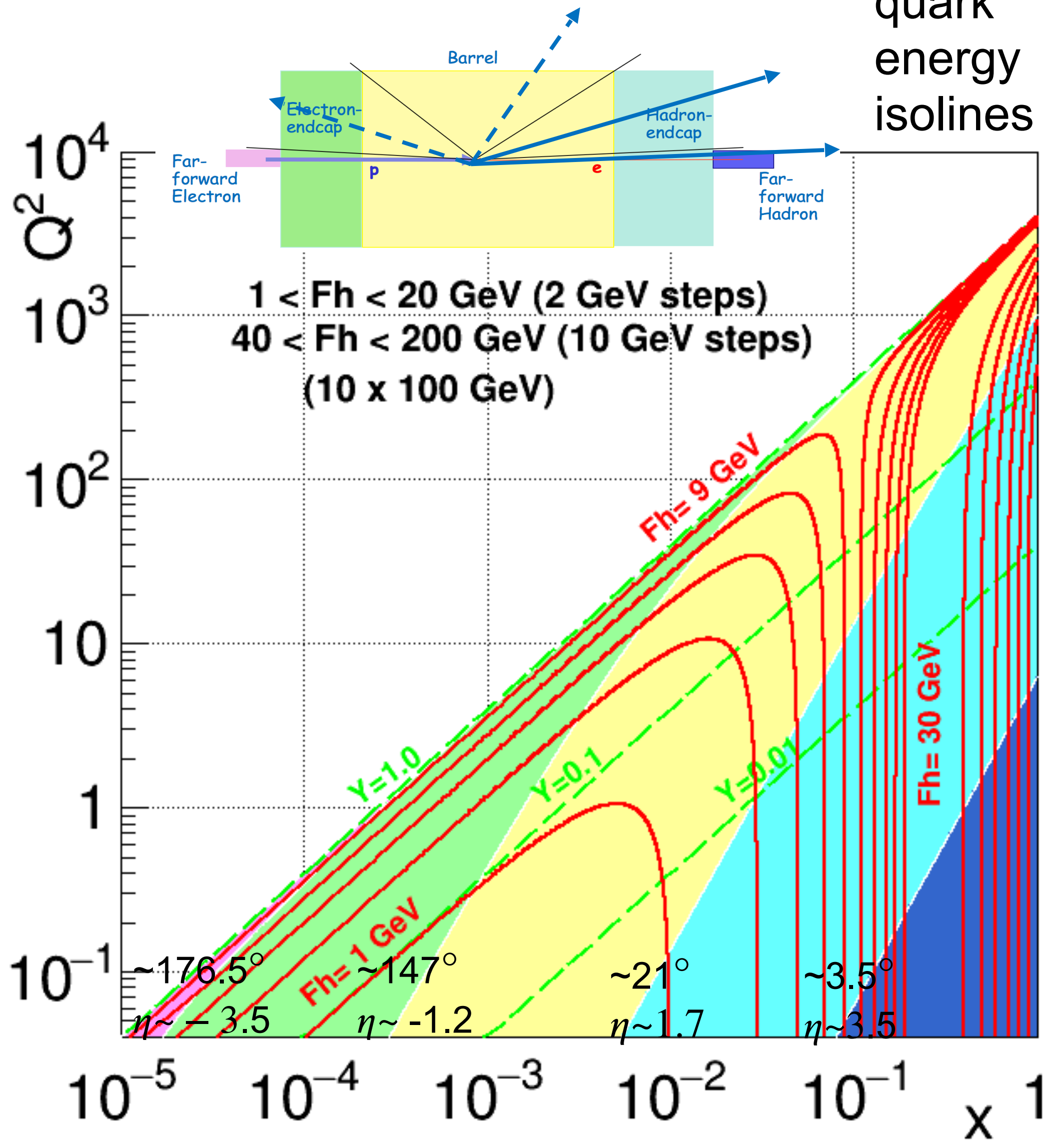
$$\frac{d^2\sigma(e^-p)}{dxdQ^2} = \frac{G_F^{\,2}}{2\pi}\left(\frac{M_W^{\,2}}{M_W^{\,2}+Q^2}\right)^2\{(u+c)+(1-y)^2(\bar{d}+\bar{s})\}$$



Charged Current at high Q2 (EIC)

$p_T^{miss} > 10GeV$





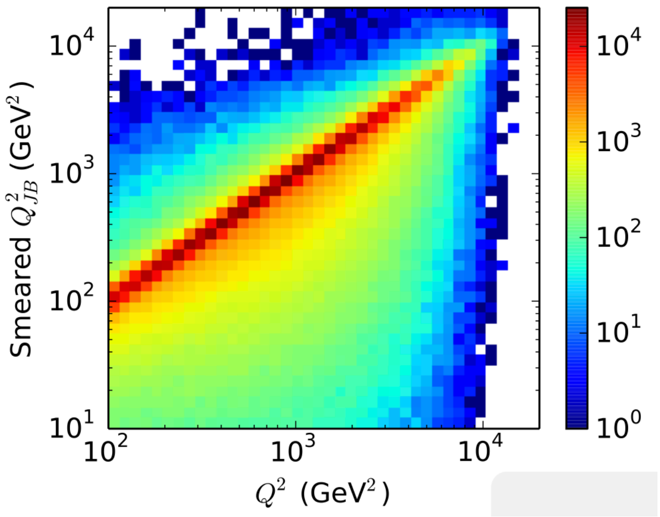
quark energy isolines

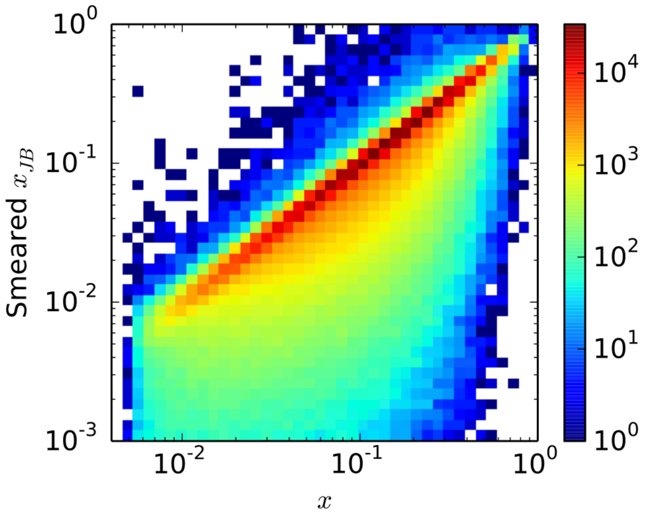
Charged current cross-section at EIC

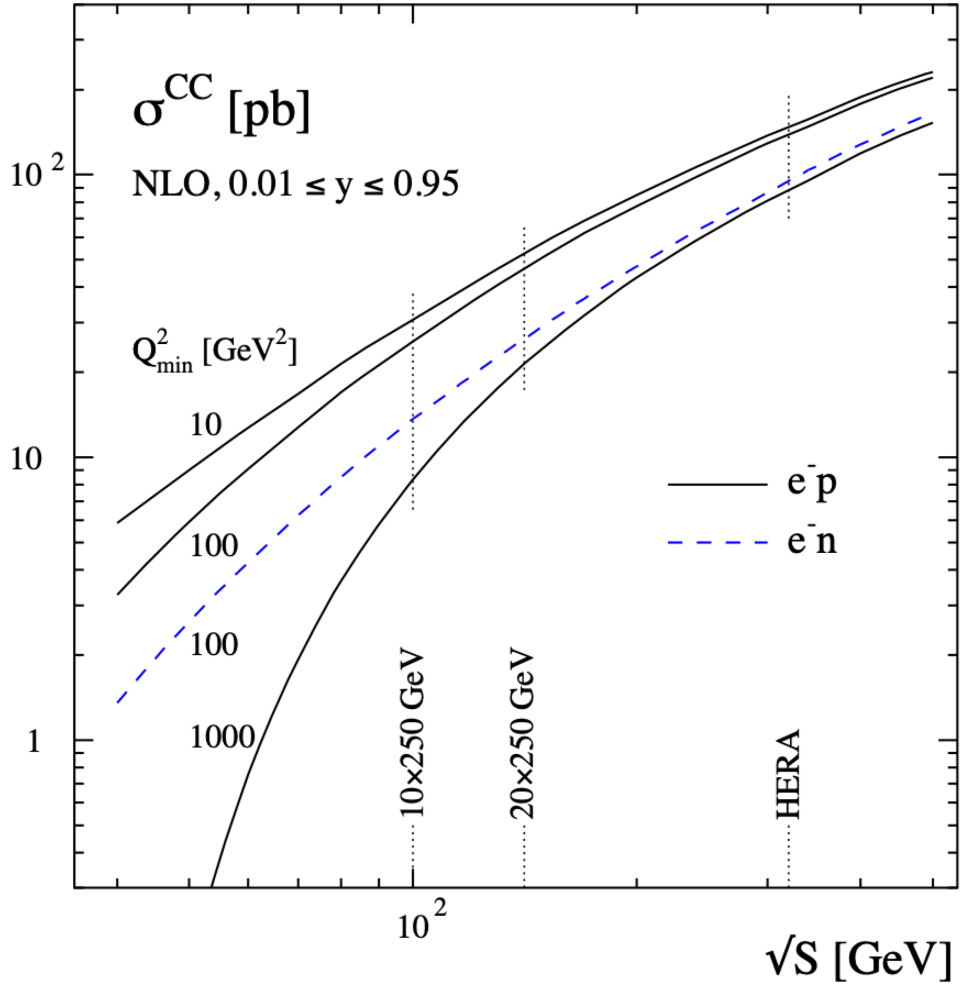
Elke C. Aschenauer, Thomas Burton, Marco Stratmann, Till Martini, Hubert Spiesberger

https://arxiv.org/pdf/1309.5327

- Dependence on the center-of-mass energy
- ep vs en
- Dependence on Q^2_{min} cut
- Resolution of JB method x,y.Q^2

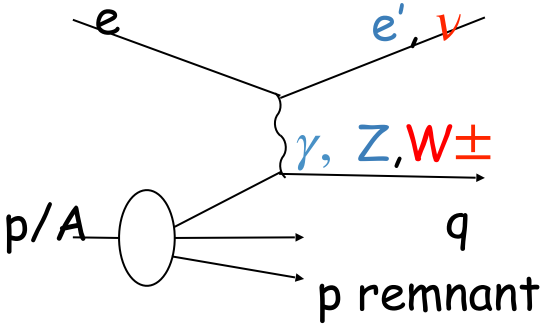




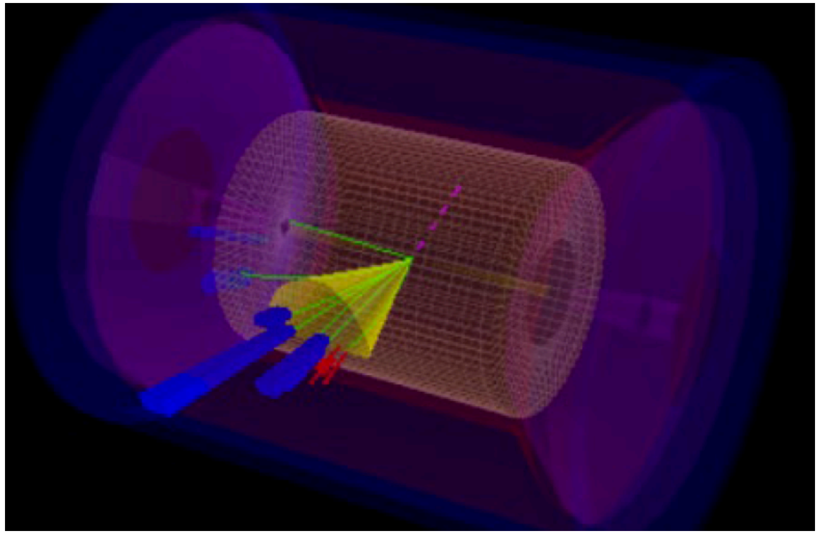


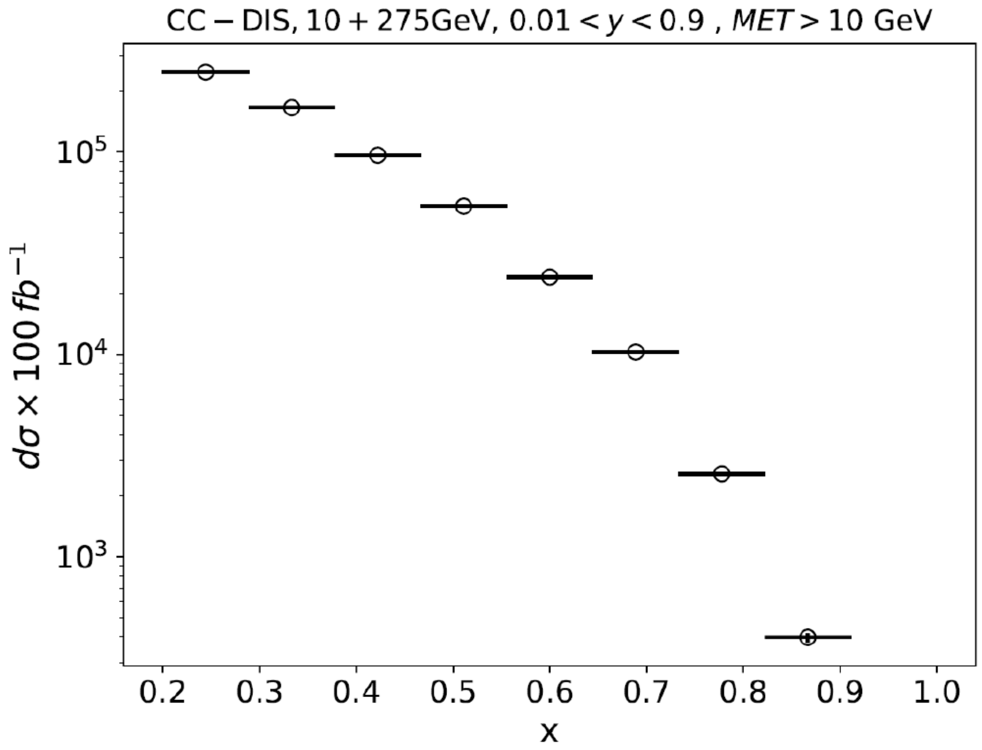
Charged Current at EIC

Miguel Arratia



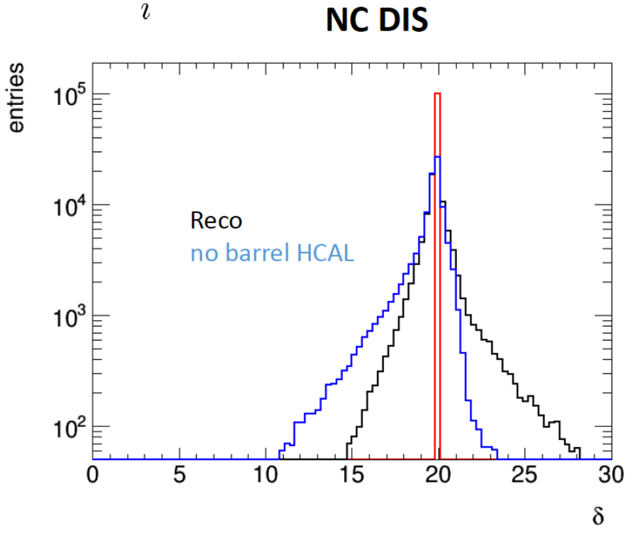
- Explore the high-x frontier
- flavor separation

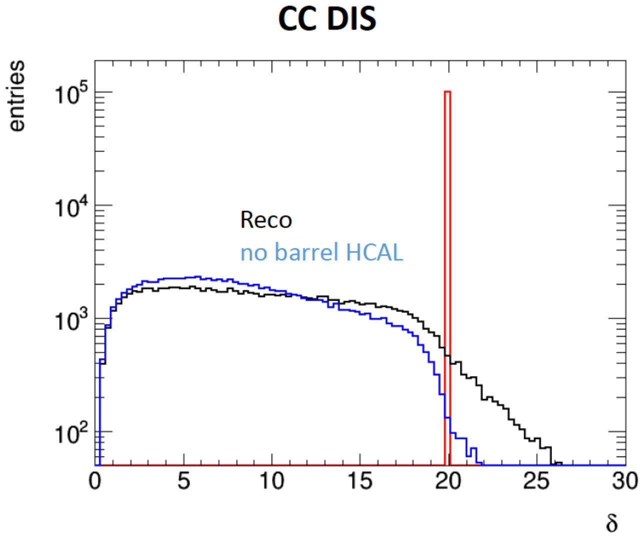




NC background rejection: need 4pi coverage for HCAL

$$\delta = \sum_i E_i(1 - \cos\theta_i)$$ E-Pz = 2*Ee $_{beam}$ (for NC)

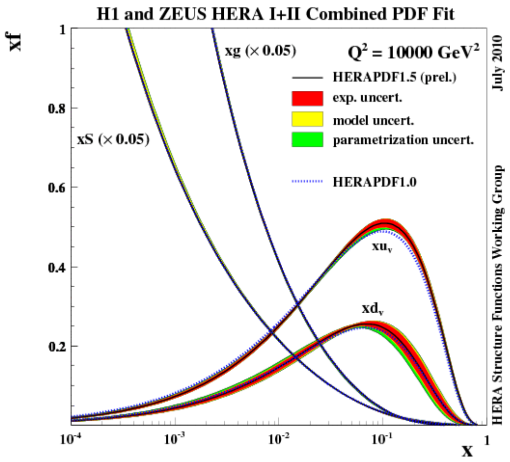




NC and CC HERA results

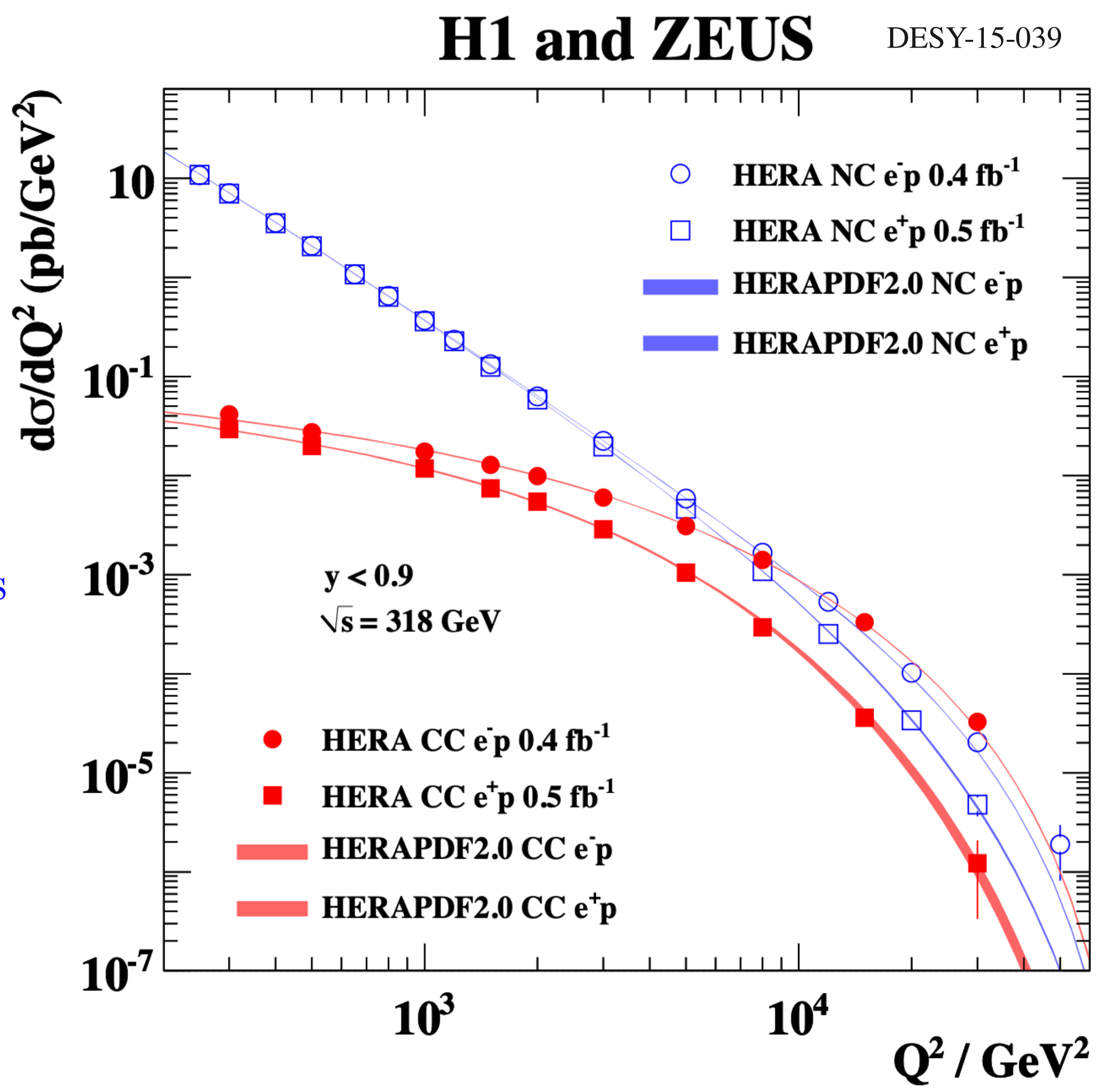
NC:
- photon, Z-boson exchange
– Cross section shape similar to $1/Q^4$

CC:
-W-boson exchange
-Cross section shape ~ $1/(Q^2 + M_W^2)^2$



$$\frac{d^2\sigma^{NC}}{dxdQ^2} \sim \left|\frac{A}{Q^2} + \frac{B}{Q^2+M_Z^2}\right|^2 \times \mathrm{pdf's}$$

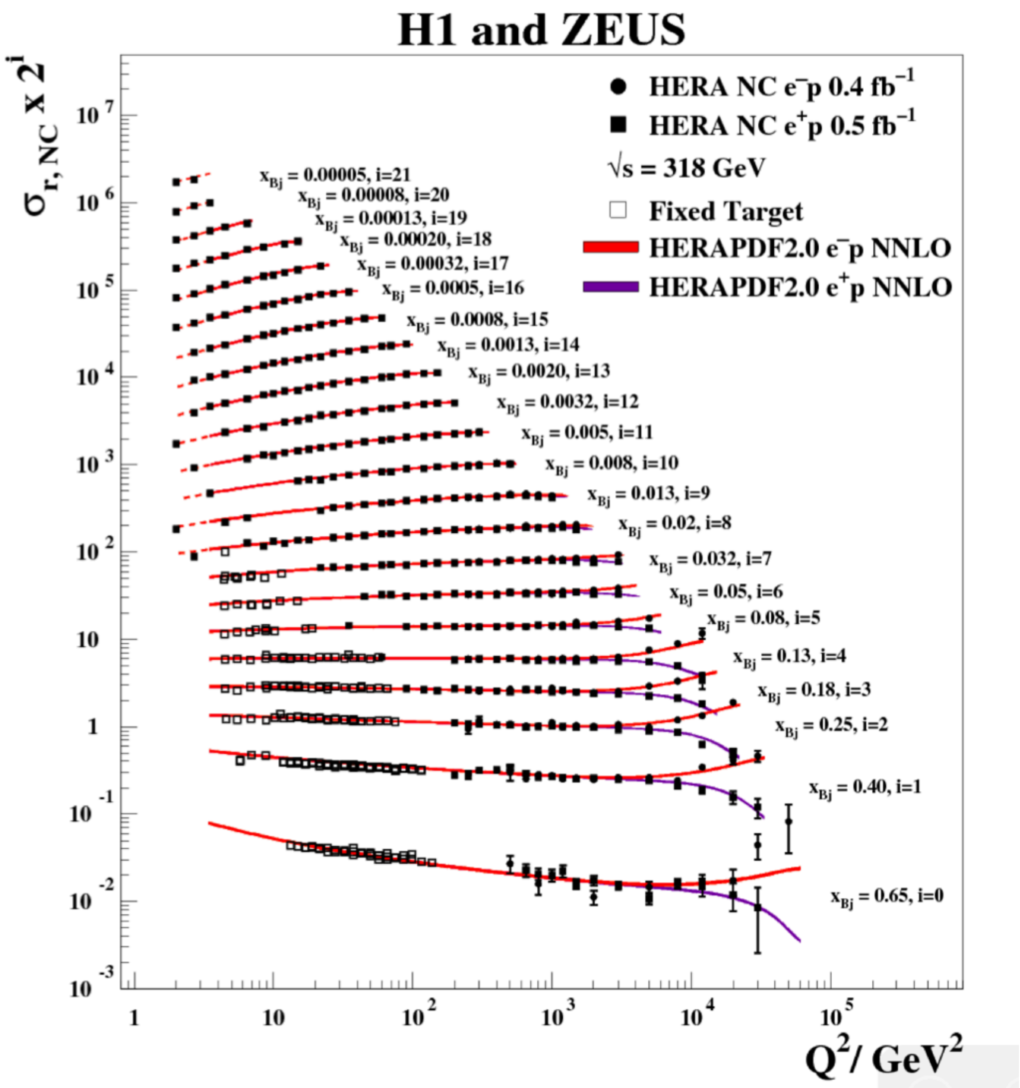
$$\frac{d^2\sigma^{CC}}{dxdQ^2} \sim G_F^2\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \times \mathrm{pdf's}$$



NC cross section at HERA

- Cross sections depend on Q² and Bjorken-x
- Scaling violations: for fixed x, the cross section does change with Q²
- gamma-Z interference and Z-exchange visible at very high Q^2
- High-x is probed at high Q² and statistically limited

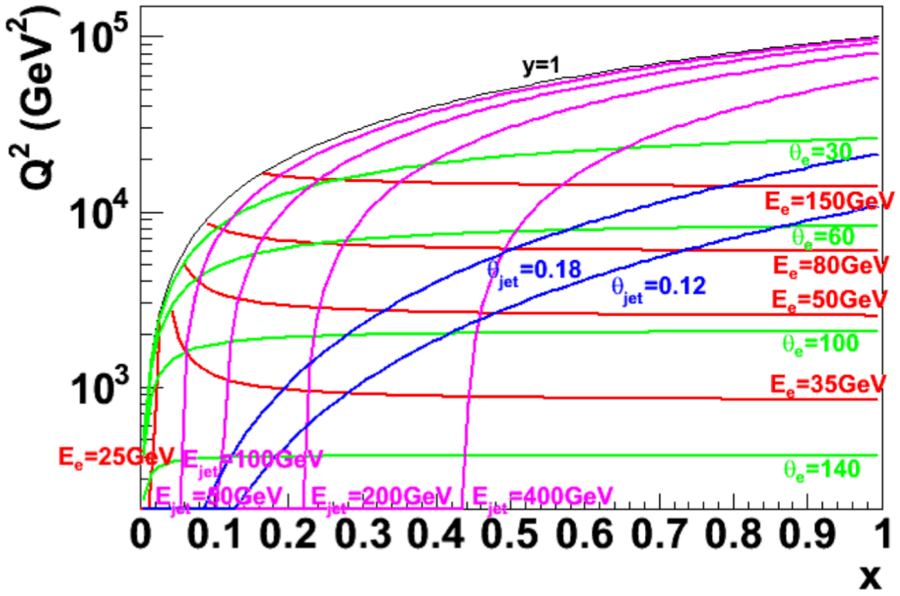
➡The EIC will improve substantially the precision at high x (with expected high luminosity)

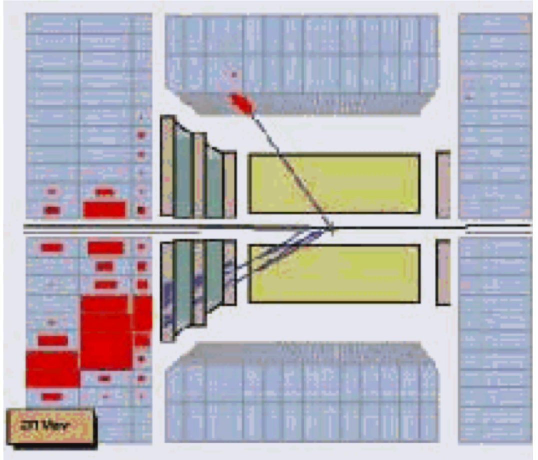


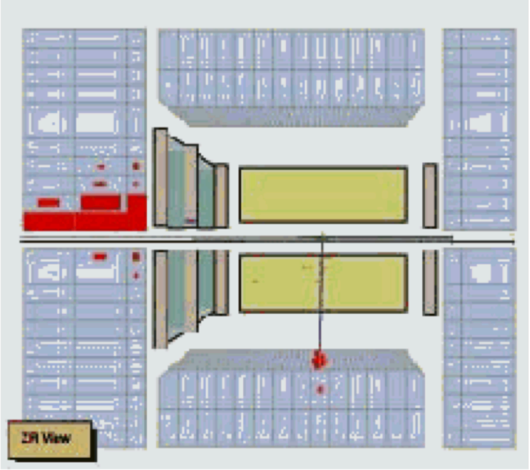
Very very high x at HERA

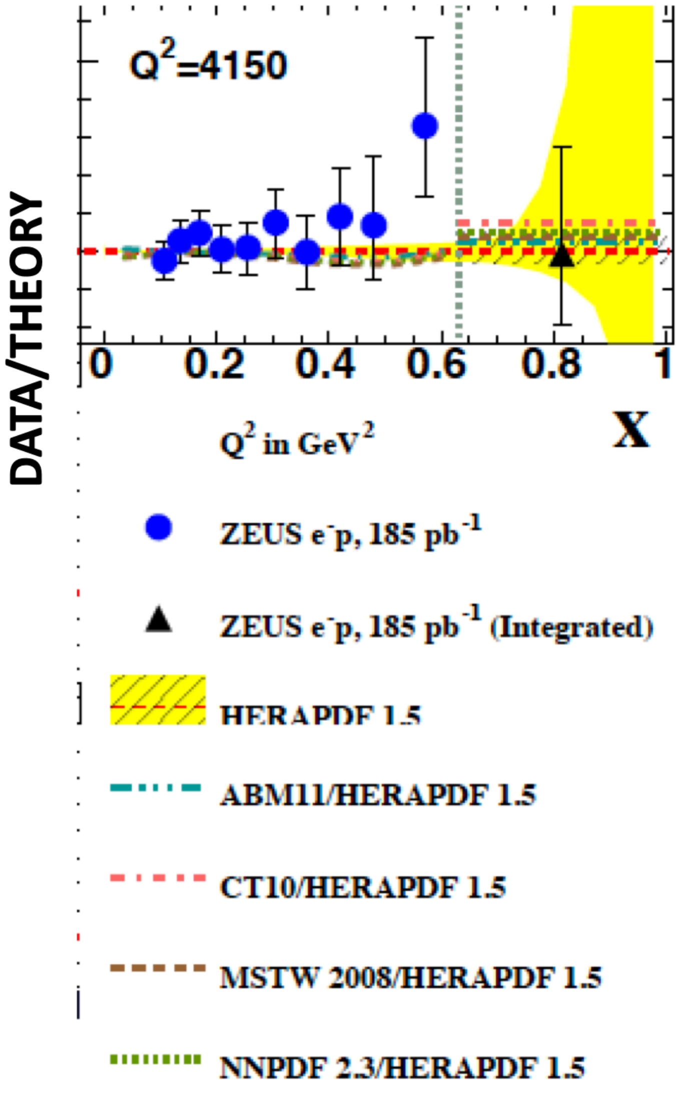
The PDF’s are poorly determined at high-x.
 At high-Q2 jet disappears in the fwd region

A. Caldwell
https://indico.desy.de/indico/event/10523







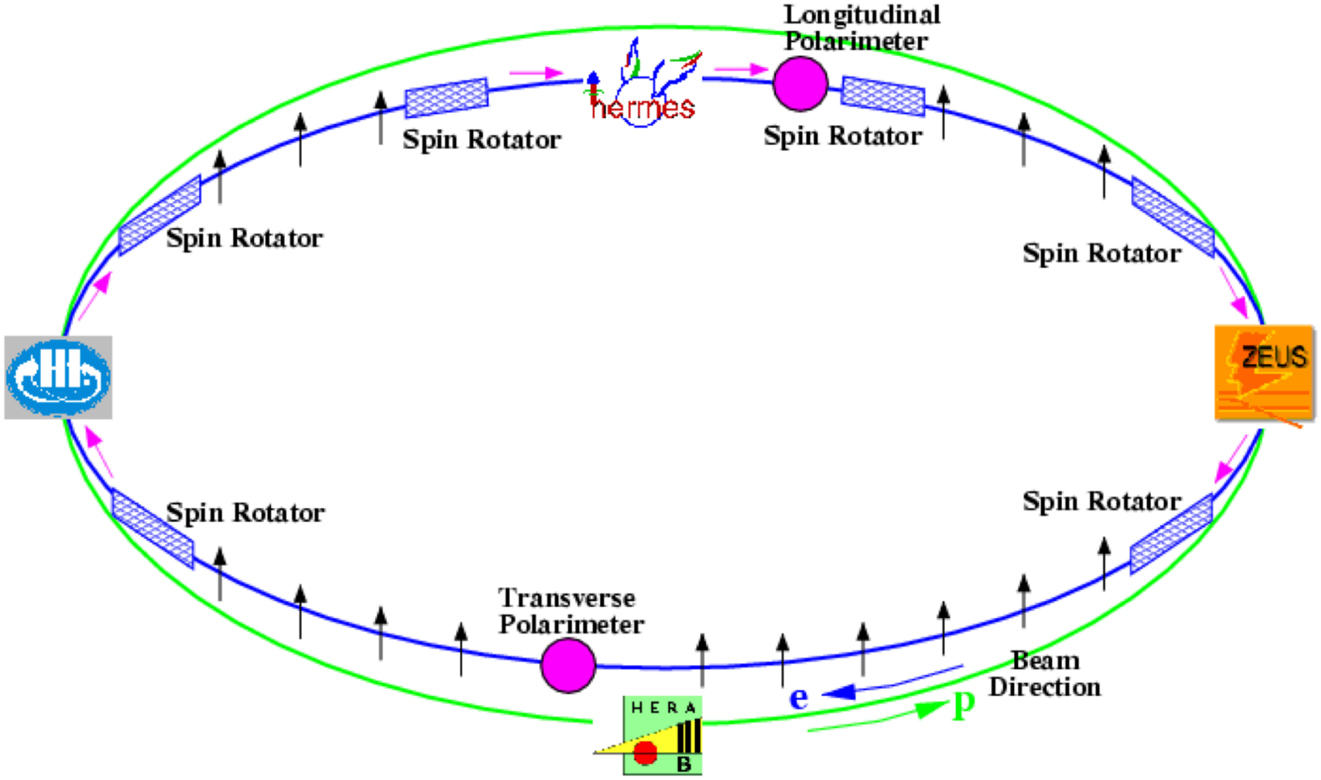


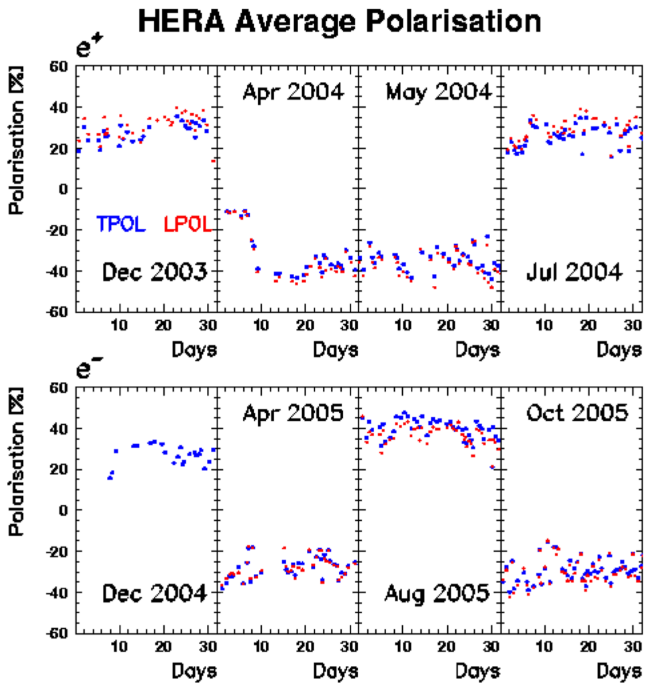
Phys. Rev. D 89 (2014) 072207

Polarisation at HERA

E.Gallo

- Electrons/positrons get naturally transverse polarized (Sokolov-Ternov effect)
- Spin rotators to change in long. polarization in the straight section before the experiments





$P = (N_R - N_L) / (N_R + N_L)$

- Polarization time ~ ½ h
- Polarization defined as: $P_e = \frac{N_R - N_L}{N_R + N_L}$
- Polarization 30-40%
- Measured Tpol,Lpol with resolution ~1% (Luminosity uncertainties ~2%)

=> Protons at HERA -unpolarized

Dave Gaskell

Figure from C. Montag (BNL)

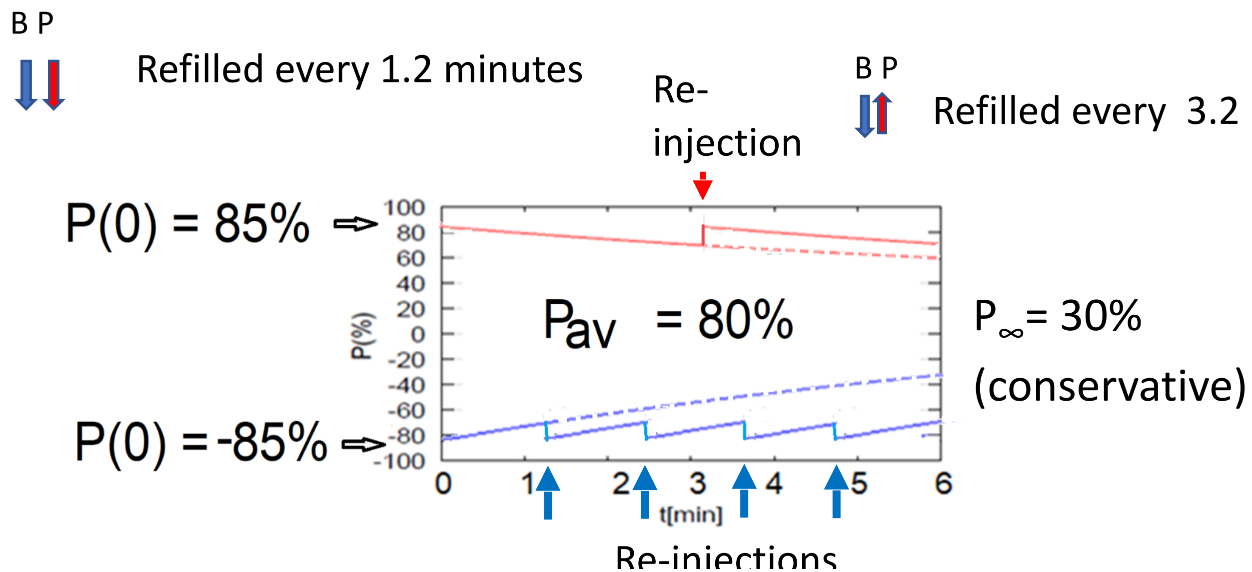
Electron beam polarization at EIC

- Polarized electrons are coming from the polarized source
- **Frequent injection of bunches** on energy with high initial polarization of 85%
- Sokolov-Ternov effect (self-polarization) will re-orient spins to be anti-parallel to main dipole field → electrons will have different lifetime depending on polarization
- **Bunches must be replaced relatively often to keep average polarization high**
- Bunch-by-bunch polarization measurement required

Bunches will be replaced about every 50 minutes at 5 and 10 GeV

→ 3 minutes at 18 GeV

→ Sets requirement for measurement time scale

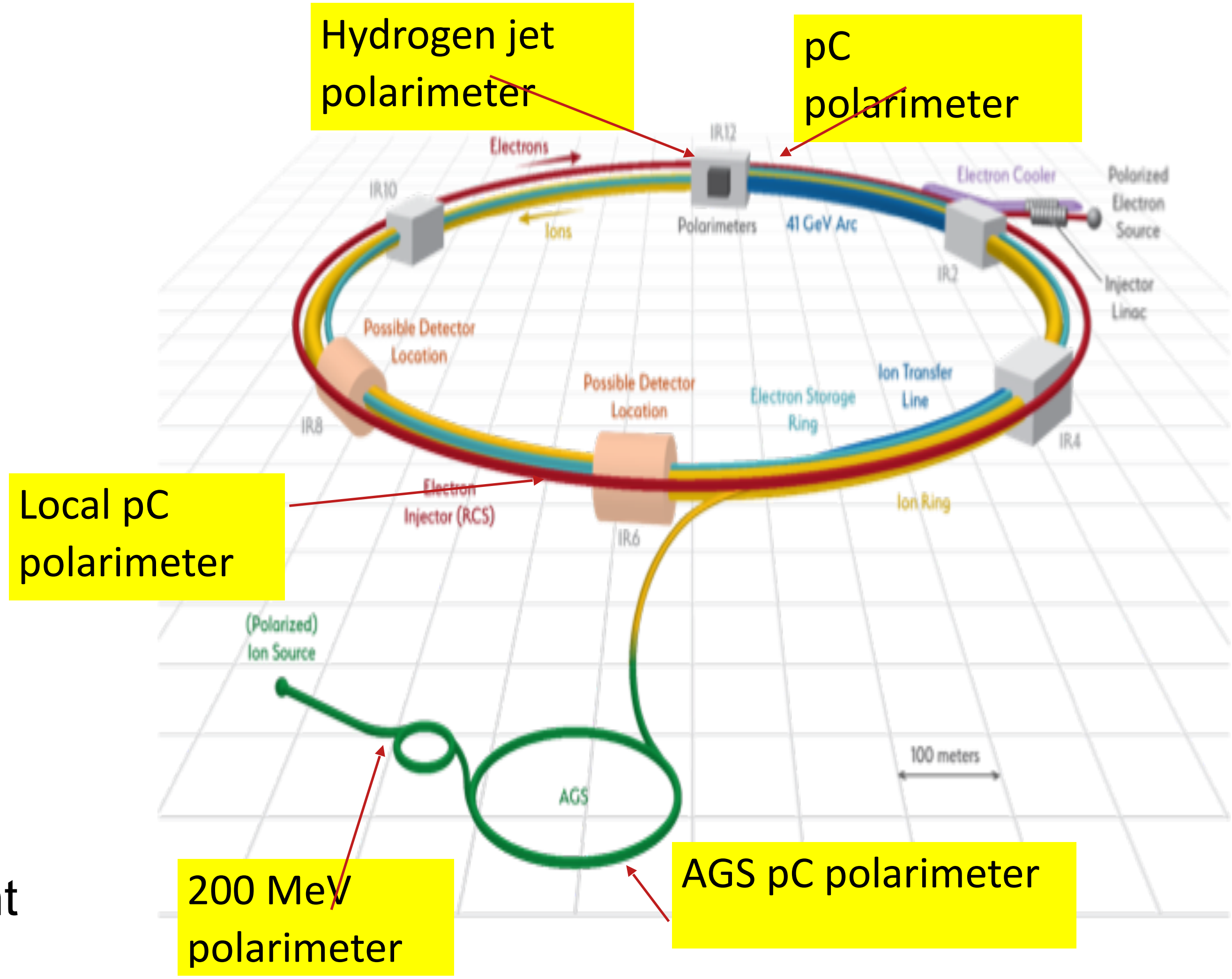


- Electron polarimetry techniques
  - Mott → high precision achieved (<1%). Only suitable up to MeV-scale energies (injectors)
  - Møller polarimetry → high precision, rapid measurements. Destructive (not good for storage rings)
  - **Compton polarimetry** → default technique for storage rings. Challenges due to energy dependence of analyzing power

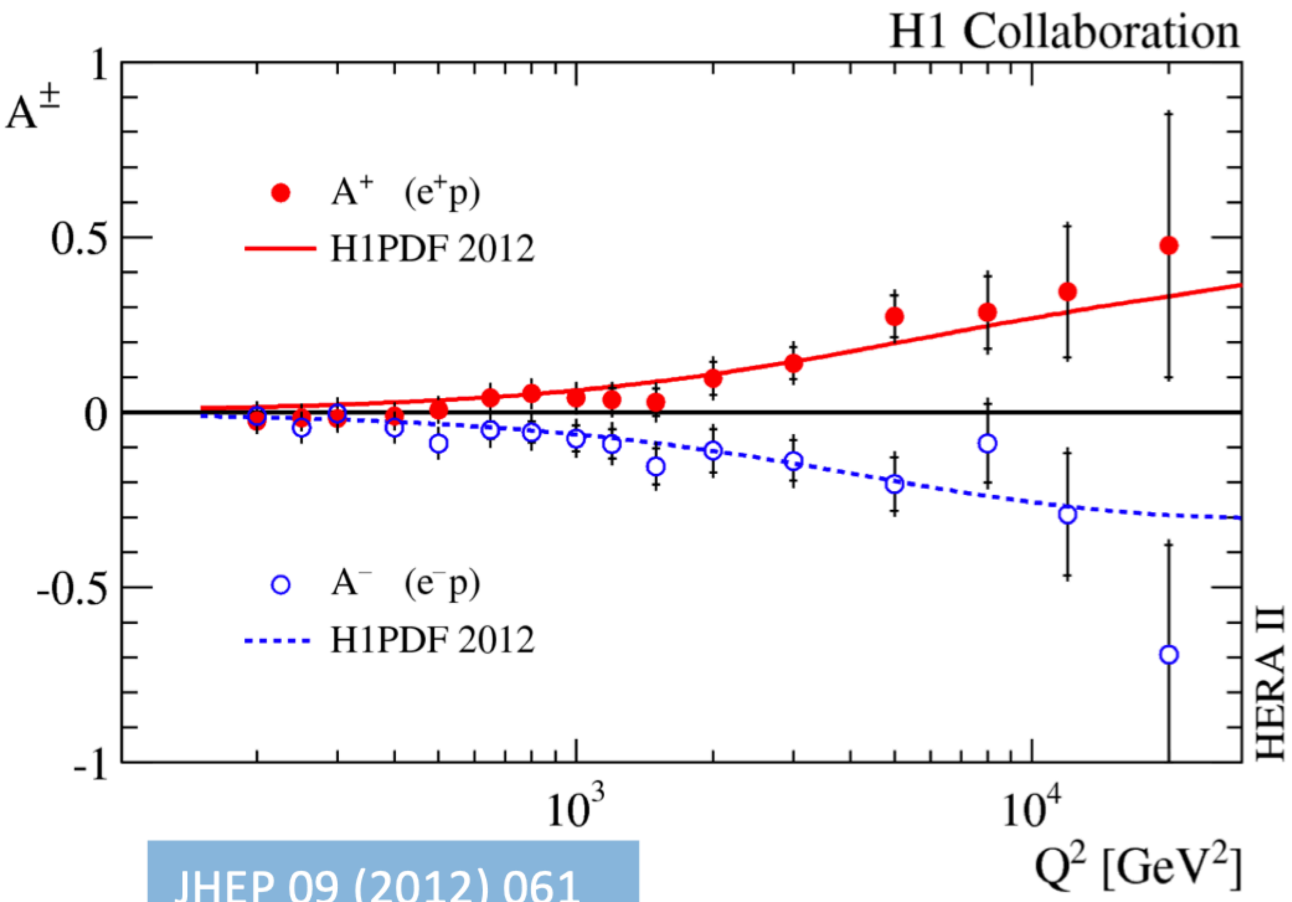
➡ Comparisons with multiple devices and techniques powerful tool for reducing systematic uncertainties

Hadron polarimeters at EIC

- EIC will make use of existing set of polarimeters that were used at RHIC for protons
  - 200 MeV polarimeter just after polarized source
  - p-Carbon polarimeter in AGS
  - Hydrogen Jet polarimeter for absolute measurement in ring (IP12)
  - p-Carbon polarimeter for fast, relative measurements in ring (IP12)
  - Additional p-Carbon polarimeter near experiment IP
  - Improvements for polarimeters in ring needed/planned
  - Extend existing polarimeters for use with light ions → ^{3}He (D)



Polarized neutral current cross section at HERA



JHEP 09 (2012) 061

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$

- Effect of polarization visible at very high Q^2
- Direct observation of parity-violation in NC

The magnitude of the asymmetry is observed to increase with increasing Q2 and is negative in e−p and positive in e+p scattering, in agreement with the SM prediction and confirming **parity violation in neutral current interactions.**

Parity violation at EIC

Yuxiang Zhao

Eur. Phys. J. A, 53 3 (2017) 55

$$A_{PV} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}.$$

Since both beams are polarized, parity violating measurements can be obtained for polarized electrons or polarized protons

With parity violation and Q² << Z²

Inclusive electron measurements

pol. electron & unpol. nucleon:

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$F_1^{\gamma Z} = \sum_f e_{q_f} (g_V)_{q_f} (q_f + \bar{q}_f)$$

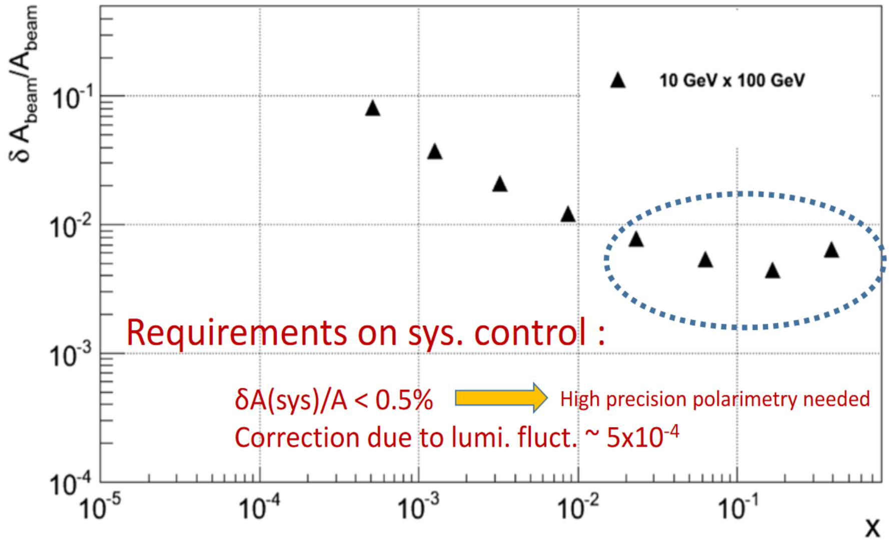
$$F_3^{\gamma Z} = 2\sum_f e_{q_f} (g_A)_{q_f} (q_f - \bar{q}_f)$$

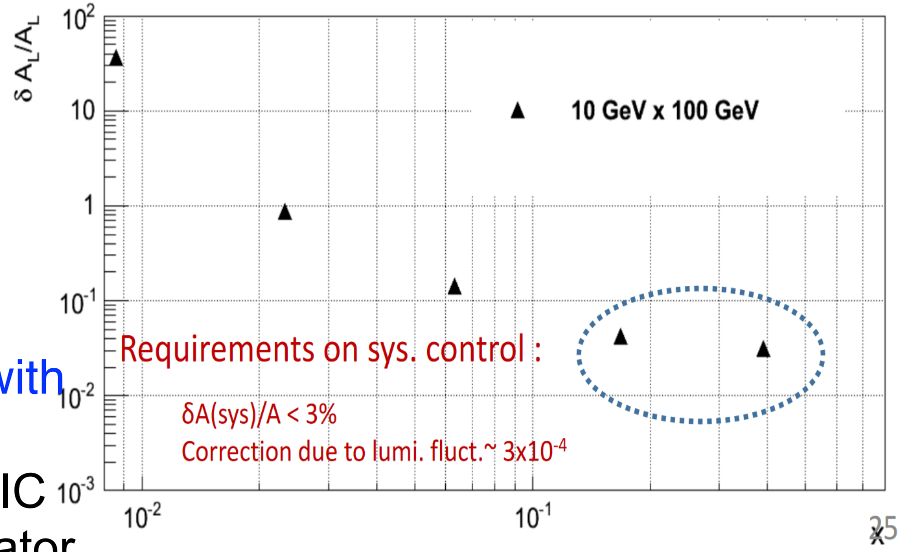
unpol. electron & pol. nucleon:

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$g_1^{\gamma Z} = \sum_f e_{q_f} (g_V)_{q_f} (\Delta q_f + \Delta\bar{q}_f)$$

$$g_5^{\gamma Z} = \sum_f e_{q_f} (g_A)_{q_f} (\Delta q_f - \Delta\bar{q}_f)$$





The deuteron beam would allow an extraction of the weak mixing angle with little PDF uncertainty

Comparisons of Ae PV measurements on heavy nuclei available at the EIC with the deuteron result would allow to test EMC effect with a weak mediator.

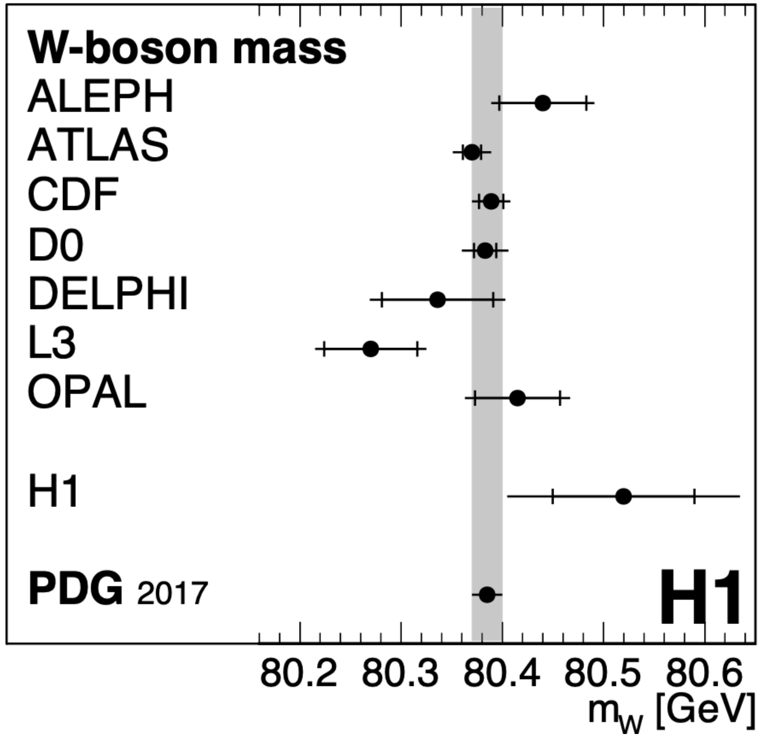
Weak mixing angle at HERA

$$\begin{pmatrix}\gamma \\ Z^0\end{pmatrix} = \begin{pmatrix}\cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}B^0 \\ W^0\end{pmatrix}.$$

The weak mixing angle θ_W is a fundamental parameter of the standard model (SM)

It governs the mechanism of spontaneous symmetry breaking of $SU(2) \times U(1)$ in which the original vector boson fields W and B_0 are transformed to the physical $W^{\pm}$, Z, and γ states

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$



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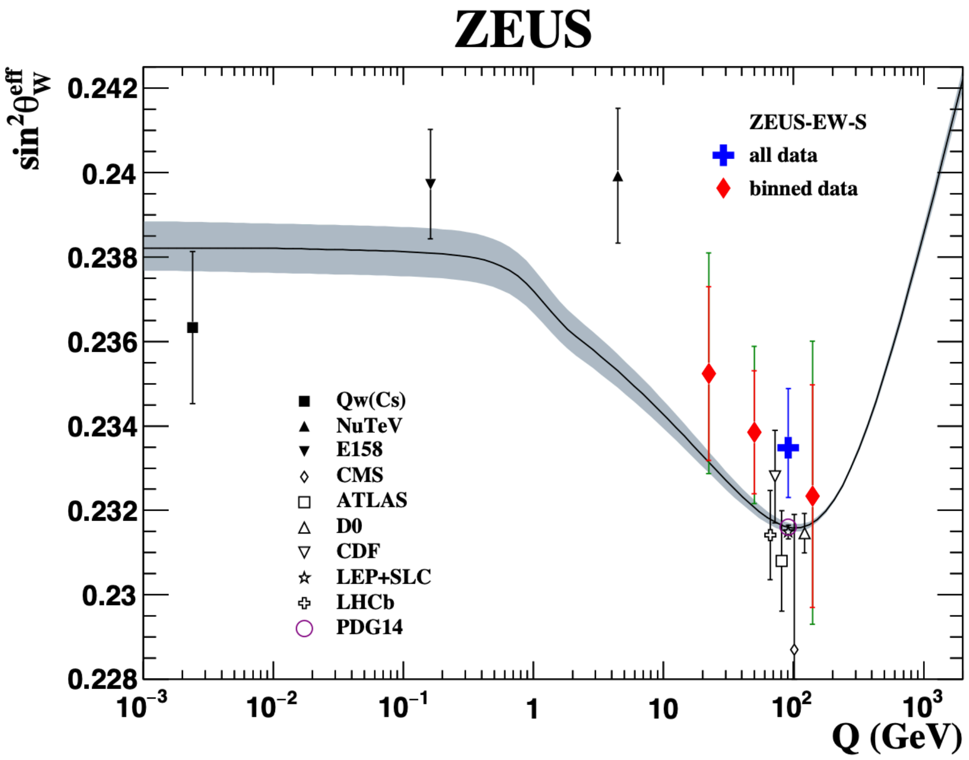
Eur.Phys.J.C78 (2018), 777



Phys. Rev. D 93 92016) 092202

Weak mixing angle extractions at EIC

Ayres Freitas
Yuxiang Zhao

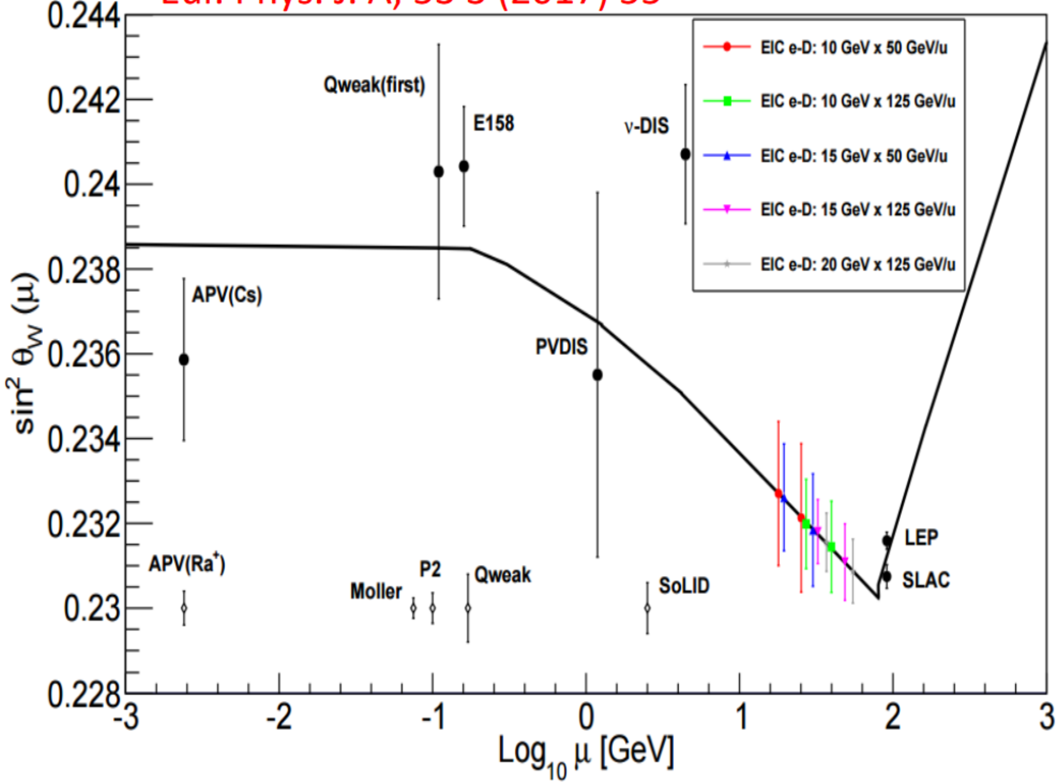
In the $Q^2 \ll M^2_Z$ limit, the weak neutral current contribution to DIS can be parameterized in terms of contact interactions

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_{\ell,q} \Big[C_{1q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu q + C_{2q}\ \bar{\ell}\gamma^\mu\ell\bar{q}\gamma_\mu\gamma_5 q + C_{3q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu\gamma_5 q \Big],$$

where C_{iq} denote the weak neutral current couplings.
A comparison of the measured values of the C_{iq} couplings with the SM predictions can be used to set limits on the new physics scale Λ.

the C_{1q} and C_{2q} couplings are functions of the weak mixing angle θ_W

Eur. Phys. J. A, 53 3 (2017) 55



$$A_{LR}^{ep} \approx \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{G_\mu(-q^2)}{4\sqrt{2}\pi\alpha} Q_W(p)$$

$$y \approx \tfrac{1}{2}(1 - \cos\theta_{CM})$$

$$A_{LR}^{ep} \approx \frac{G_\mu(-q^2)}{4\sqrt{2}\pi\alpha} \left[\frac{9}{5} - \sin^2\theta_W + \frac{9}{5}(1 - 4\sin^2\theta_W) \frac{y(1-y)}{1+(1-y)^2} \right]$$

Neutral Current: xF3 (at HERA)

$$\frac{d^2\sigma^{NC}(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+ F_2(x,Q^2) \mp Y_- xF_3(x,Q^2) - y^2 F_L(x,Q^2)]$$

EM
•PDFs

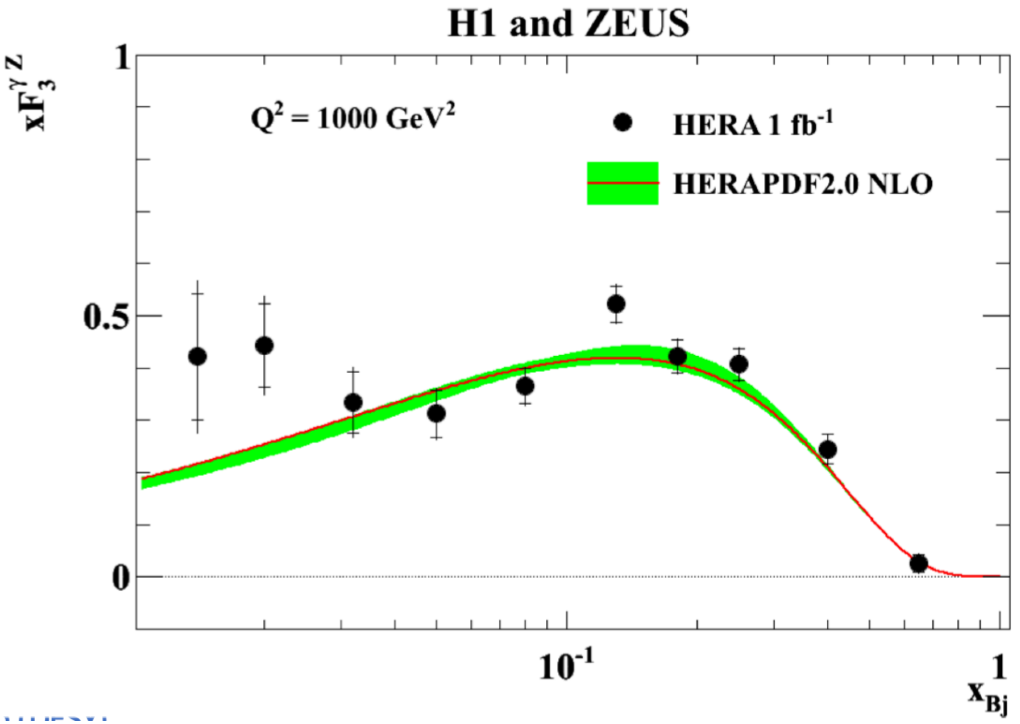
EW
•important at high Q2,
•changes sign for e+/e-
•sensitiv to γZ interference
•sensitiv to valence quarks

EW
•negligible
at high Q2& x

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}[\tilde{\sigma}(e^- p) - \tilde{\sigma}(e^+ p)]$$

$$Y_\pm = 1 \pm (1-y)^2$$

$$F_2^{\gamma Z} = 2e_f v_f \Sigma_i x[q_f + \overline{q_f}]$$
$$F_2^{Z} = (v_f^2 + a_f^2)\Sigma_i x[q_f + \overline{q_f}]$$
$$F_3^{\gamma Z} = 2e_f a_f \Sigma_i x[q_f - \overline{q_f}]$$
$$F_3^{Z} = 2v_f a_f \Sigma_i x[q_f - \overline{q_f}]$$



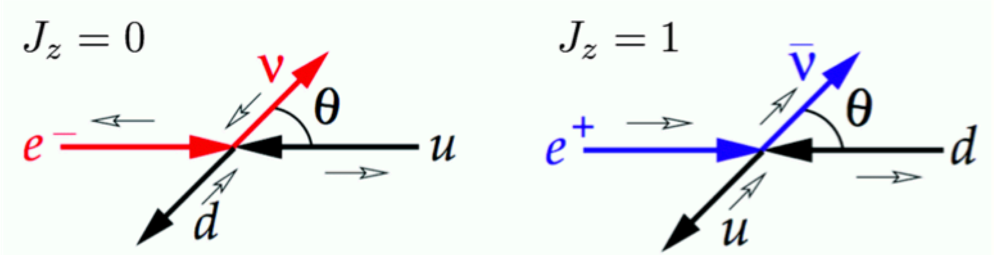
•Four combinations of lepton beams (+ and -, L and R) give vector- and axial-vector coupling of quarks (mainly u and d quarks)

•The difference between the e+p and e-p NC cross sections give direct access to the structure function xF3 .

Integral= 1.790±0.078 (stat)+0.078
~ 5/3 as predicted

Testing the chiral structure of the week interaction with Charged Current DIS (HERA)

the CC cross section goes to zero for right-handed electrons, as predicted by the SM



- linear dependence from lepton polarization:

$$\sigma_{CC}^{e^\pm p}(P_e) = (1 \pm P_e) \cdot \sigma_{CC}^{e^\pm p}(P_e = 0)$$

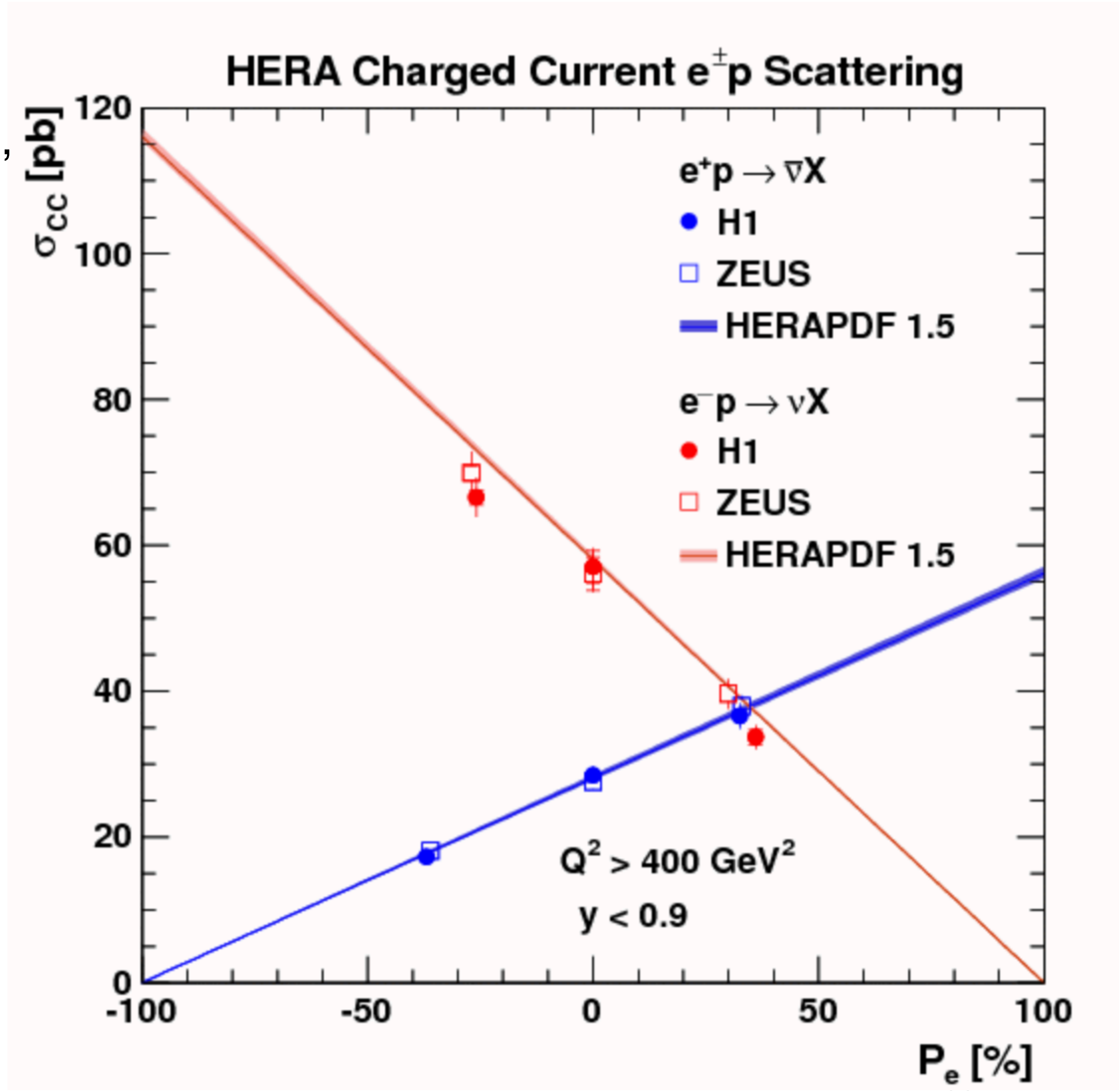
Clear left-handed nature of weak currents (W_L):

extrapolation to $P_{e^+} = -1$:

- $\sigma_{CC}^{tot} = -1.0 \pm 1.8_{stat} \pm 1.1_{sys}$ pb

If not 0 for e- @P=1 or e+@ P=-1
=> new physics

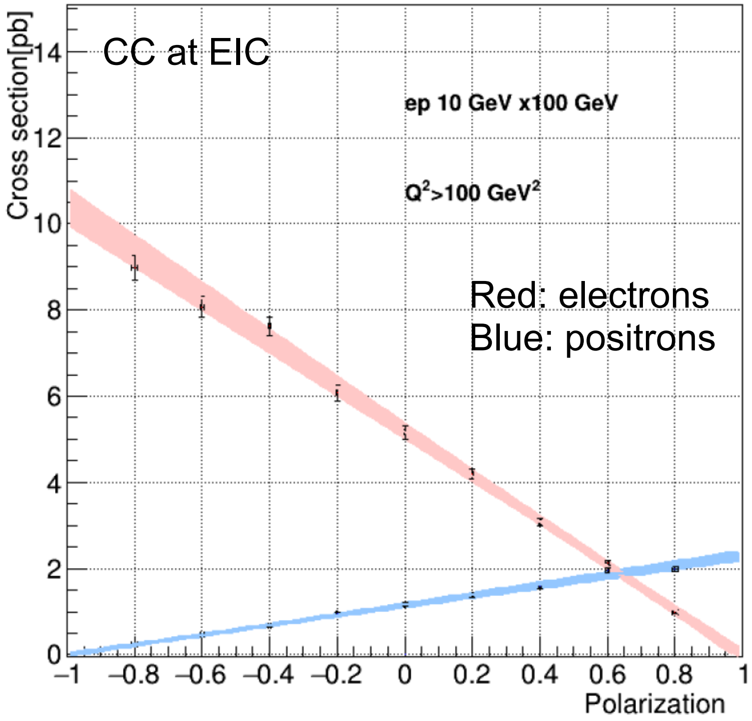
Extrapolation to P=±1 => limits on W_R

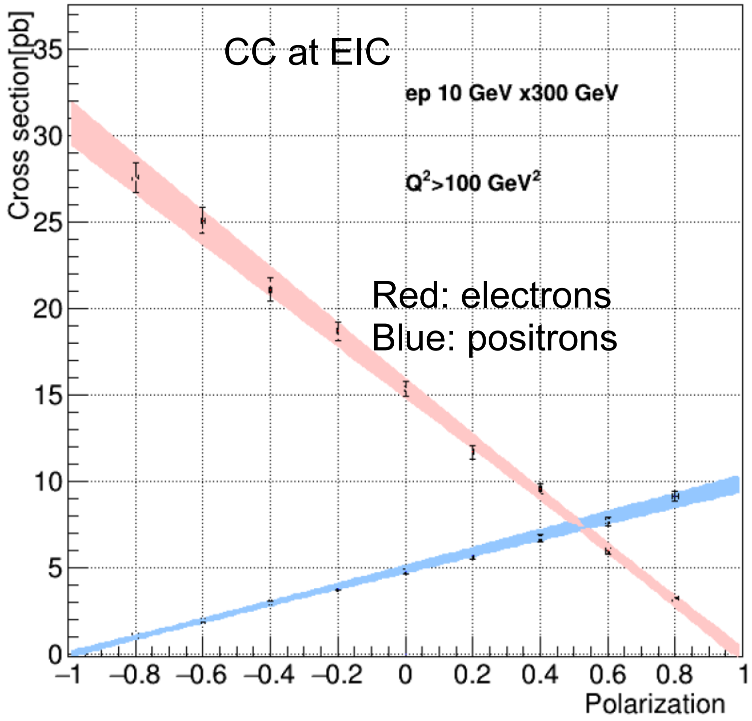


Testing the chiral structure of the week interaction with Charged Current DIS at EIC

Yulia Furletova, and Sonny Mantry

- High energy, high luminosity and high polarization are needed
- High control under systematic uncertainties for lepton polarization (~1%)



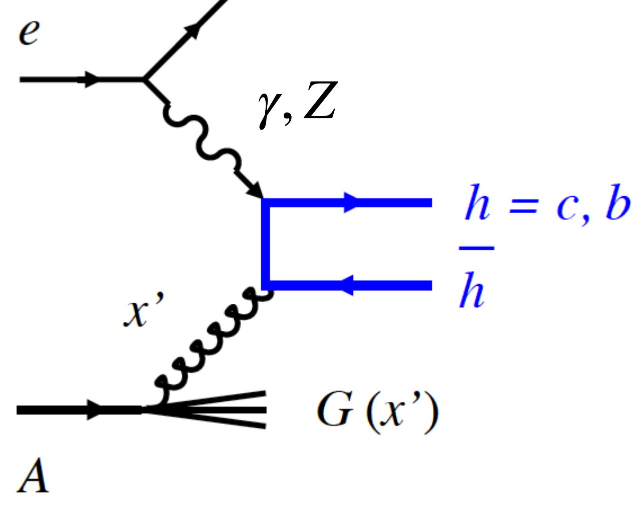


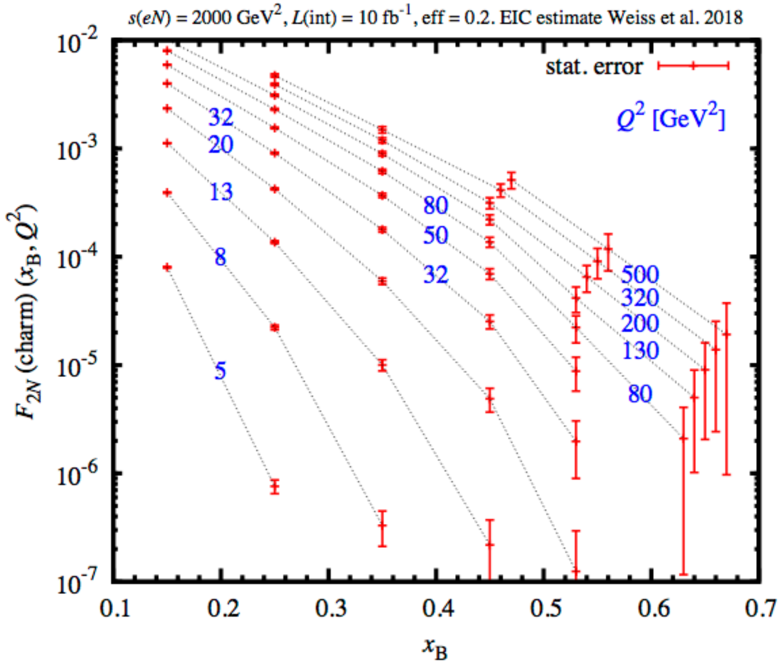
https://doi.org/10.1063/1.5040210

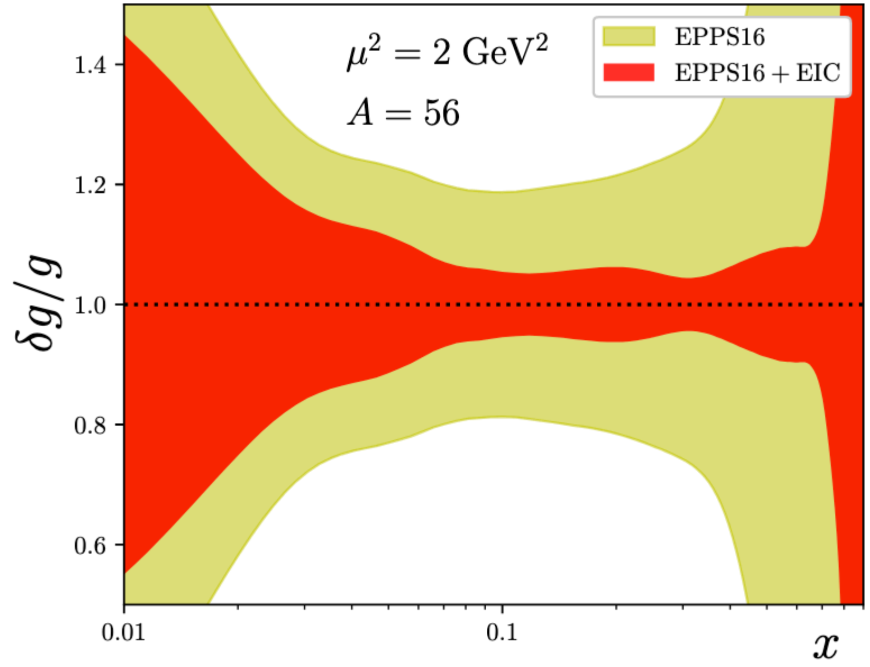
Boson (γ, Z) -gluon fusion (BGF)

Christian Weiss

Boson Gluon Fusion (**BGF**)







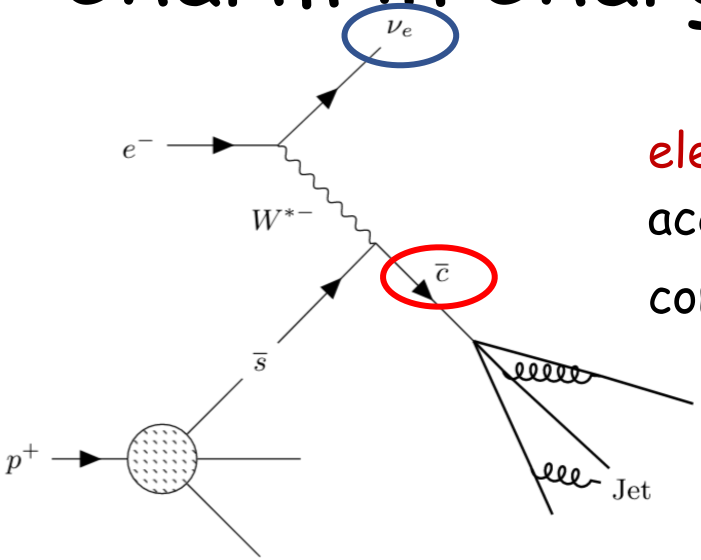
- Charm MonteCarlo:
  Fc2 (x,Q2), assumed 10% total uncertainty, dominated by systematics, point-to-point
  Here EPPS16 (ongoing work Nobuo Sato, Christian Weiss)
- Substantial impact on large–x nuclear gluons

See also: Aschenauer et al, PRD 96 114005 (2017)

Int lumi 10 fb^{-1}, 10x100 GeV
charm reconstruction efficiency 20%

Statistical errors only

Charm in Charged Current reactions



electron/positron beams at EIC would allow to access to the anti-strange/strange PDFs, complementary to neutrino facilities (νN).

W+d → c is suppressed, but should be taken into account at high-x region

$$s' = |V_{cs}|^2 s + |V_{cd}|^2 d + |V_{cb}|^2 b.$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 0.97 & 0.22 & 0.0037 \\ 0.22 & 0.97 & 0.042 \\ 0.094 & 0.040 & 1.0 \end{pmatrix}$$

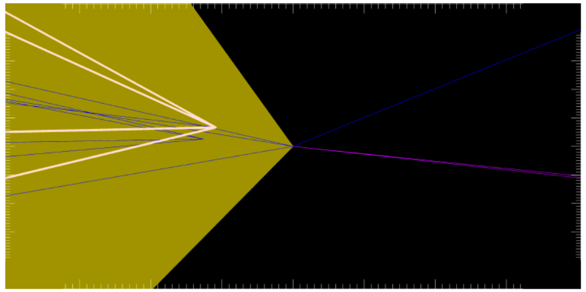
"Charm jets as a probe for strangeness at the future Electron-Ion Collider"
M. Arratia, Y.Furletova,T. J. Hobbs, F. Olness and S. Sekula

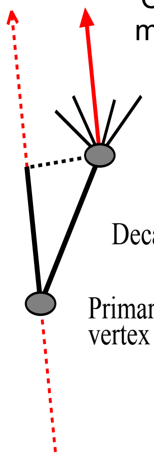
JLAB-PHY-20-3205, SMU-HEP-20-05

Note, in such CC processes charm-jets will be also used for measurements of x/Q^2 => next generation detectors/methods

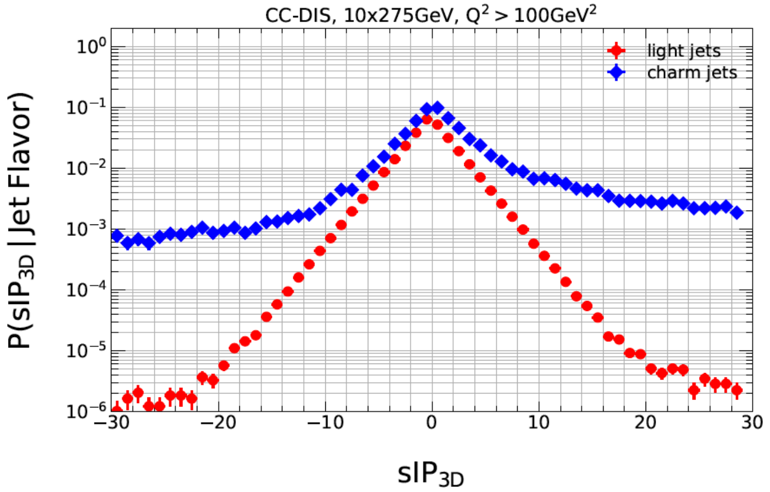
Charm jets in the Charged Current reactions as a probe for strangeness

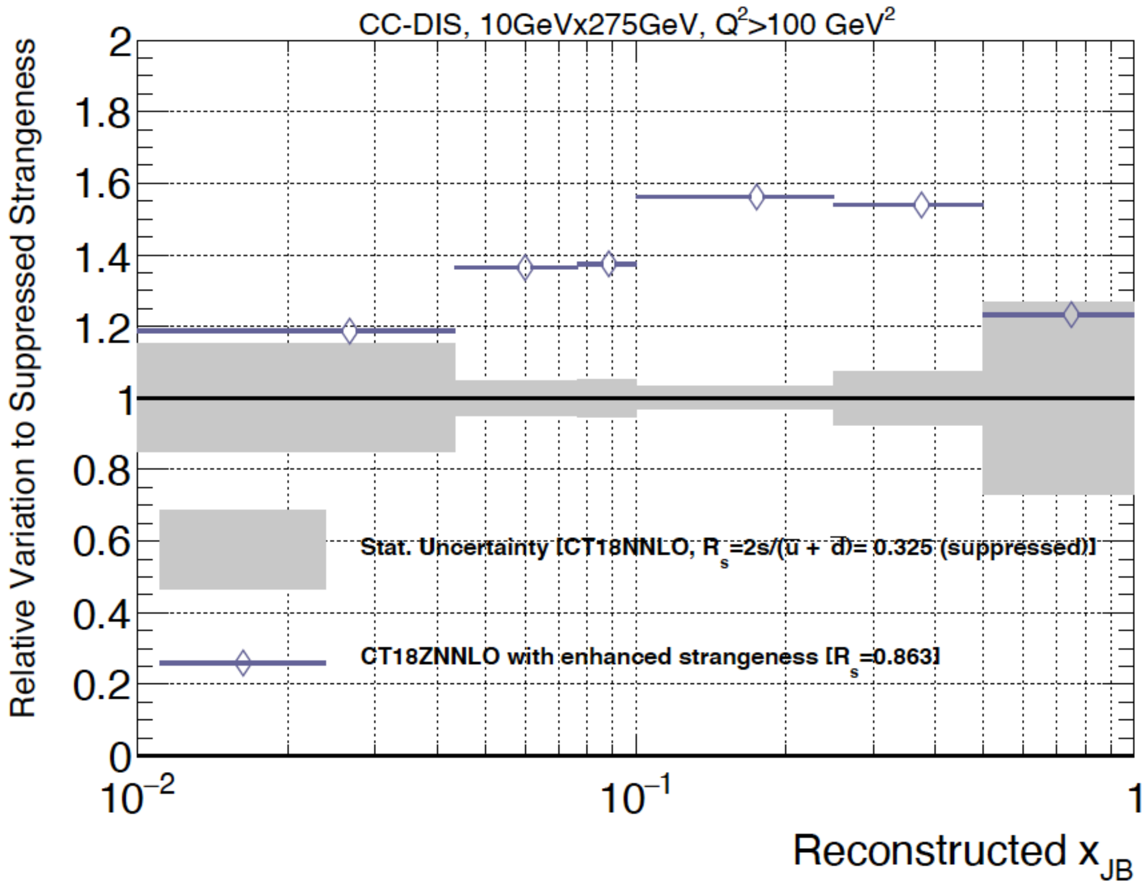
arXiv:2006.12520
"Charm jets as a probe for strangeness at the future Electron-Ion Collider", M. Arratia, Y.Furletova,T. J. Hobbs, F. Olness and S. Sekula





- Vertexing is essential to jet tagging
  → vertex resolution of <25μm
- Hadron and/or lepton PID





With $100fb^{-1}$ luminosity EIC should provide the ability to resolve extremal intrinsic strangeness cases unresolved by current data/constraints

Charm in diffractive Ds ($c\bar{s}, \bar{c}s$) production in Charged Current DIS

Neutrino facilities

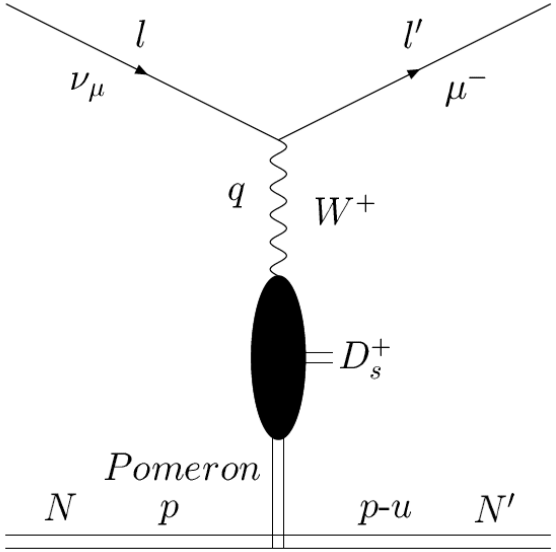
$\nu_\mu + N \rightarrow \mu^- + N' + D_s^+$.

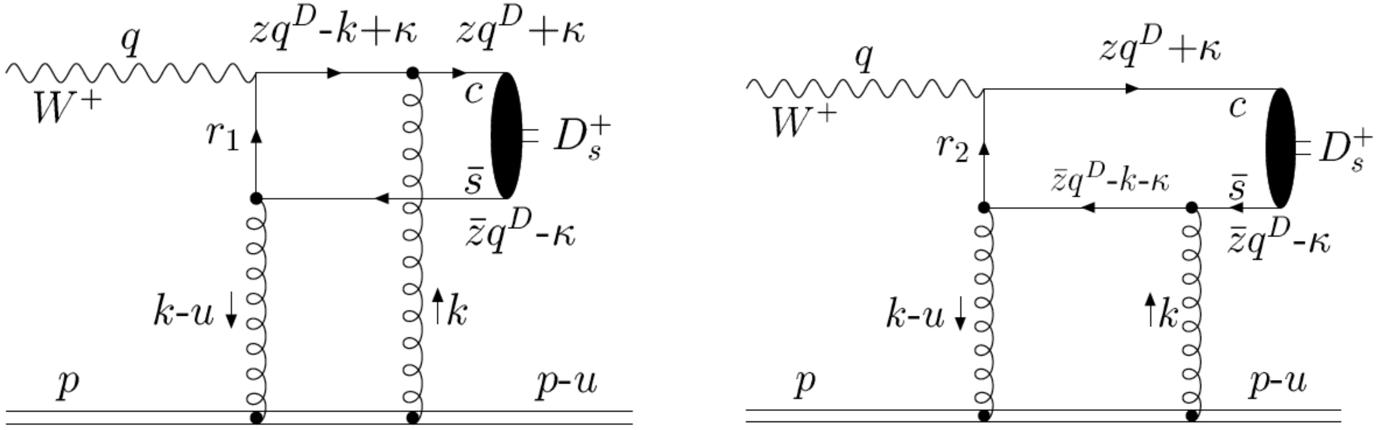
hep-ph/0112192

(Zhongzhi Song (PKU), Kuang-Ta Chao)

At ep (charged current) :

$e + N \rightarrow \nu_e + N' + D_s^+$.





(a) (b)

BSM and Exotic

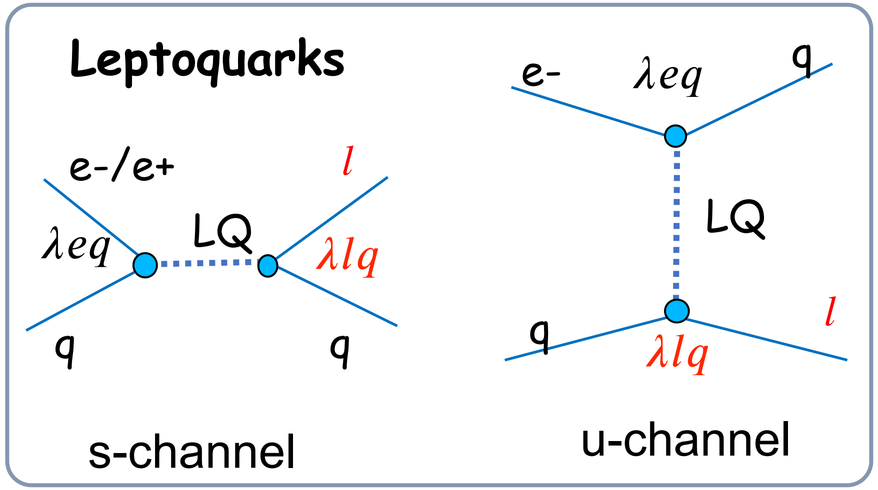
Leptoquarks

Both quarks and leptons are fermions - symmetry
LQ- boson which provides transition between fermion sectors.
Fermion number F = 3B + L

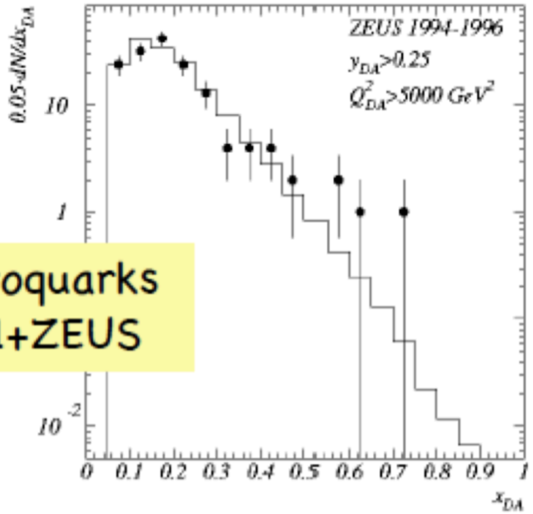
s-channel : resonance in x expected

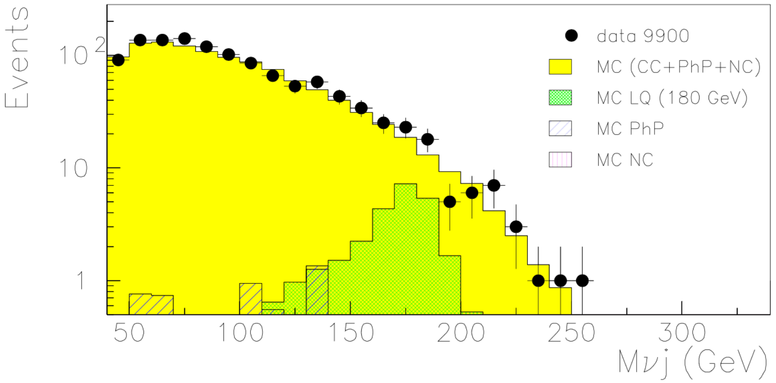
Early possible signal ~ 200-220 GeV observed with 1996 data by both H1 and ZEUS (at high y), not confirmed later with more statistic

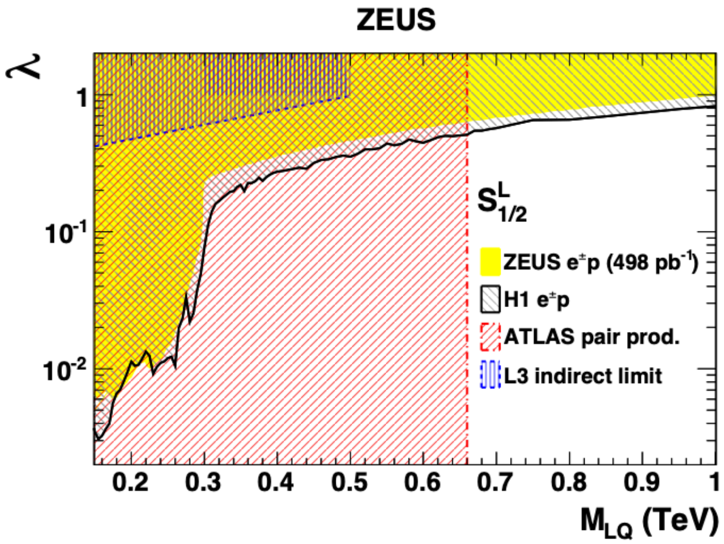
LQ in Charged current (with neutrino in the final state)



Leptoquarks in H1+ZEUS

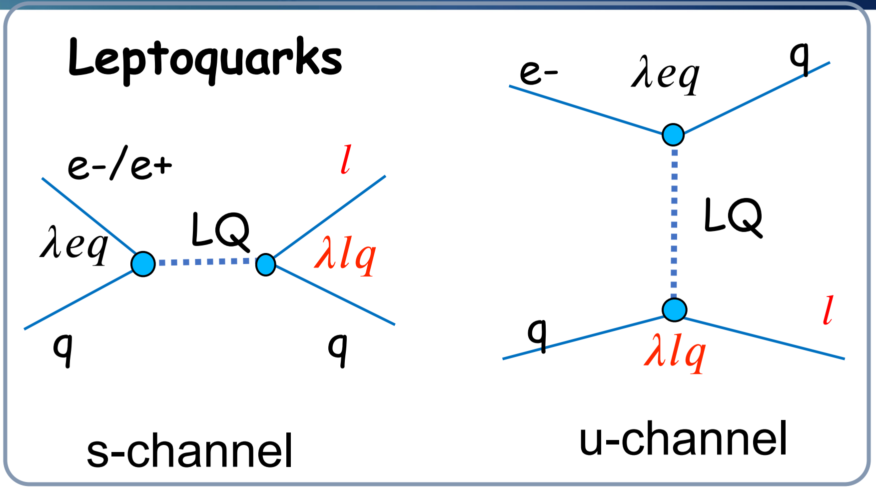






Phys. Rev. D 86 (2012) 012005

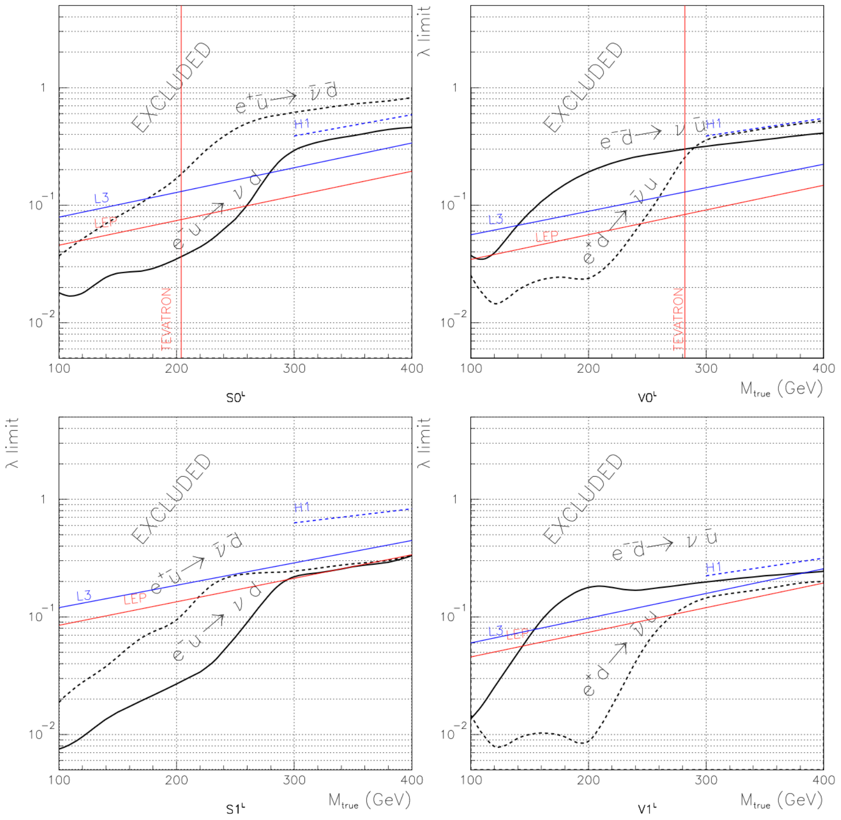
Limit setting on coupling



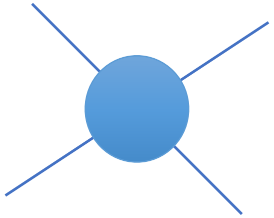
BRW model/classification of LQs

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$ / $\nu_\ell d$	λ_L / $-\lambda_L$	1/2 / 1/2
S_0^R	0	2	$-1/3$	$e_R^- u_R \to \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \to \ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$ / $-4/3$	$e_L^- u_L \to \ell^- u$ / $\nu_\ell d$; $e_L^- d_L \to \ell^- d$	$-\lambda_L$ / $-\lambda_L$ / $-\sqrt{2}\lambda_L$	1/2 / 1/2 / 1
$V_{1/2}^L$	1	2	$-4/3$	$e_L^- d_R \to \ell^- d$	λ_L	1
$V_{1/2}^R$	1	2	$-1/3$ / $-4/3$	$e_R^- u_L \to \ell^- u$; $e_R^- d_L \to \ell^- d$	λ_R / λ_R	1 / 1
$\tilde{V}_{1/2}^L$	1	2	$-1/3$	$e_L^- u_R \to \ell^- u$	λ_L	1

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
V_0^L	1	0	$+2/3$	$e_R^+ d_L \to \ell^+ d$ / $\bar{\nu}_\ell u$	λ_L / λ_L	1/2 / 1/2
V_0^R	1	0	$+2/3$	$e_L^+ d_R \to \ell^+ d$	λ_R	1
$\tilde{V}_0^R$	1	0	$+5/3$	$e_L^+ u_R \to \ell^+ u$	λ_R	1
V_1^L	1	0	$+2/3$ / $+5/3$	$e_R^+ d_L \to \ell^+ d$ / $\bar{\nu}_\ell u$; $e_R^+ u_L \to \ell^+ u$	$-\lambda_L$ / λ_L / $\sqrt{2}\lambda_L$	1/2 / 1/2 / 1
$S_{1/2}^L$	0	0	$+5/3$	$e_R^+ u_R \to \ell^+ u$	λ_L	1
$S_{1/2}^R$	0	0	$+2/3$ / $+5/3$	$e_L^+ d_L \to \ell^+ d$; $e_L^+ u_L \to \ell^+ u$	$-\lambda_R$ / λ_R	1 / 1
$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e_R^+ d_R \to \ell^+ d$	λ_L	1



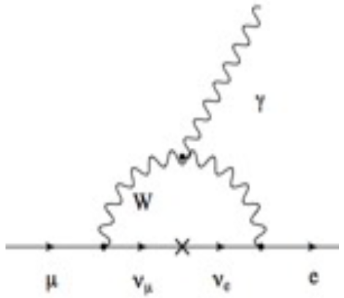
For $M_{LQ} < \sqrt{s}$: s-channel resonant



For $M_{LQ} > \sqrt{s}$: exchange - contact interaction

Charged Lepton Flavor Violation (CLFV)

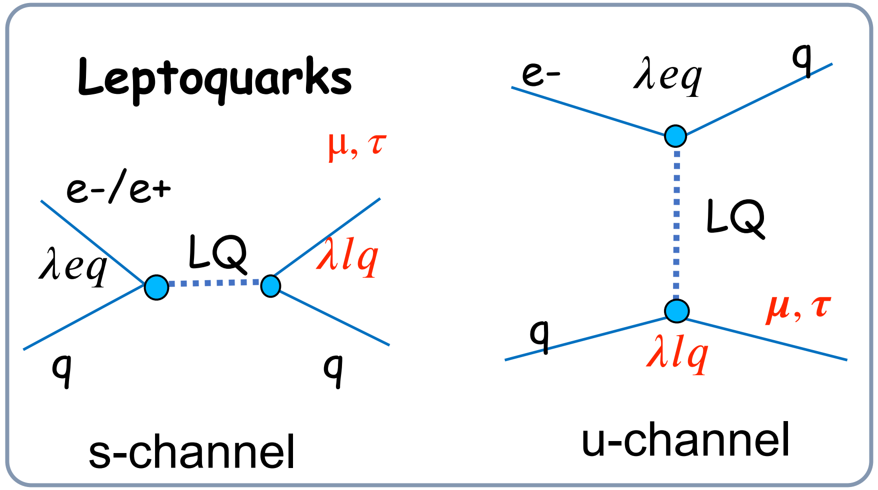
- LFV in the neutrinos also implies Charged Lepton Flavor Violation (CLFV):



$$BR(\mu \to e\gamma) < 10^{-54}$$

However, SM rate for CLFV is tiny due to small neutrino masses

- No hope of detecting such small rates for CLFV at any present or future planned experiments!



However, many BSM scenarios predict enhanced CLFV rate (LQ, RPV-SUSY , SU(5) etc….

➢ High luminosity (~100-1000 higher then HERA)

➢ Electron and positron beam will probe different types of LQs

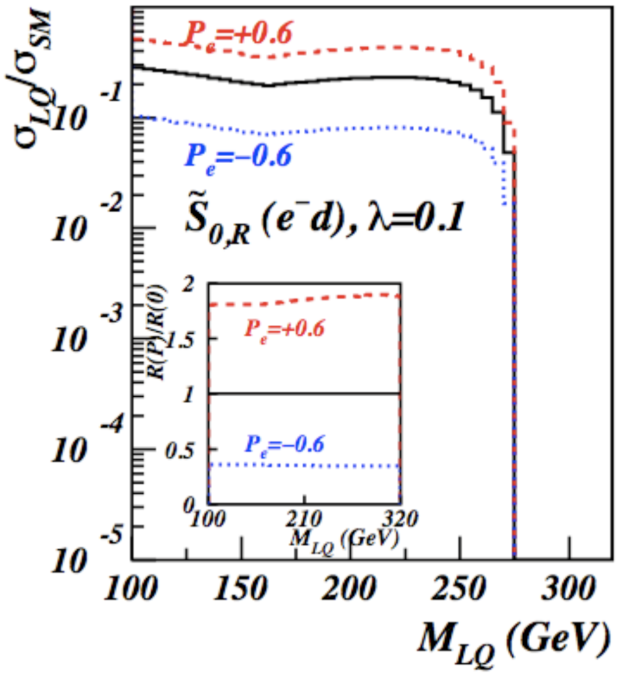
-electron-proton collisions, mainly F=2 LQs produced

-positron-proton collisions, mainly F=0 LQs produced

➢ eD (deuterium) vs ep collisions

➢ LQs are chiral particles, gain in sensitivity due to polarized beams

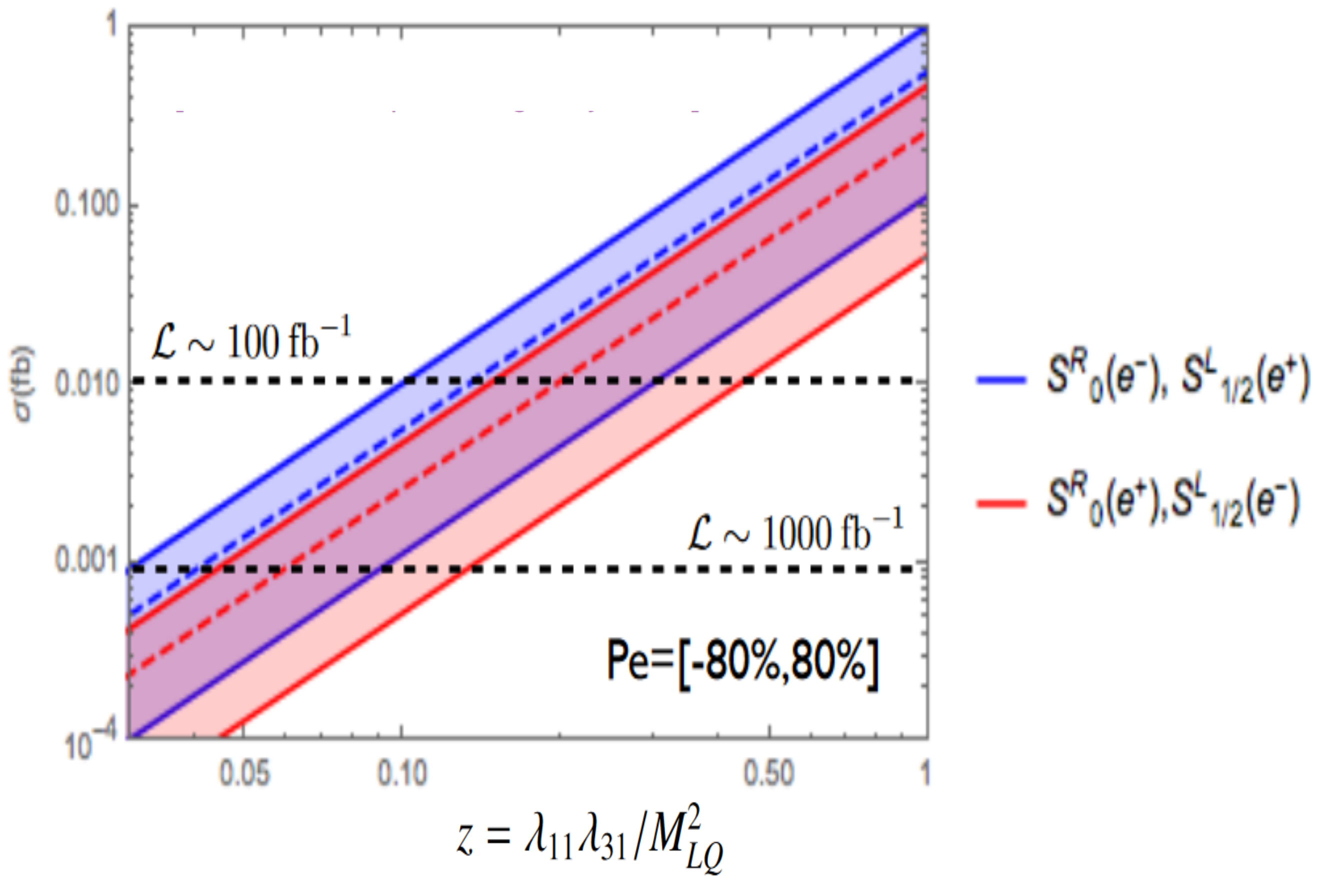
Polarisation dependence



David South ICHEP 2012

Leptoquark sensitivity at EIC

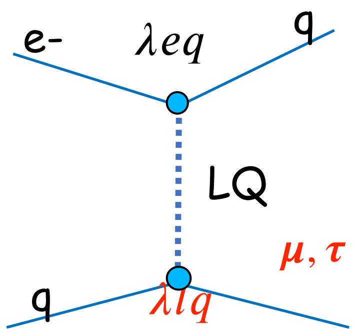
Yulia Furletova, and Sonny Mantry



https://doi.org/10.1063/1.5040210

- Sensitivities to the CLFV(1,3) would be enhanced with positron beams (can search for specific LQ)
- Current limits set by HERA sitting at sensitivities of a few fb
  - The high luminosity of the EIC will gain us 2 orders of magnitude

The blue (red) dotted line gives the unpolarized, Pe = 0

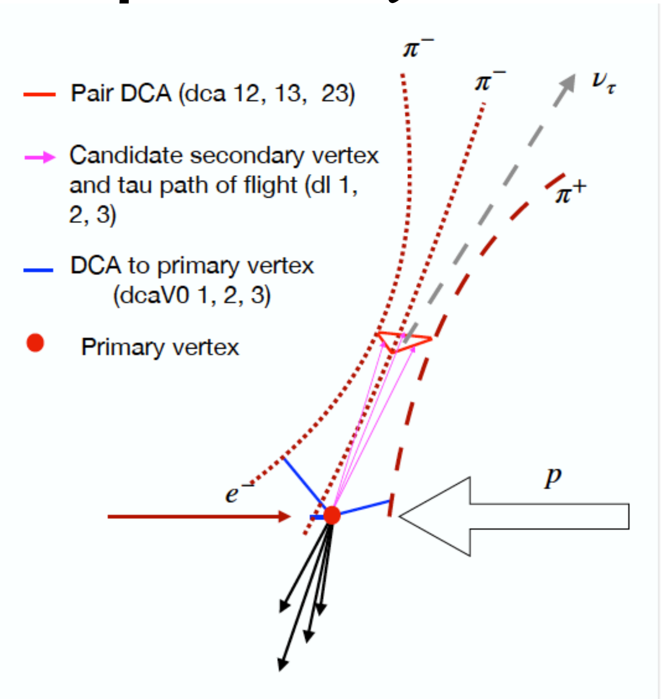


CLFV: e to tau (leptoquarks)

- **Tau vertex displaced at cm level**
  - 3-prong tau jet; decay topology important for τ jet ID
  - 1-prong: recovering higher branching ratios; but background control is much more demanding

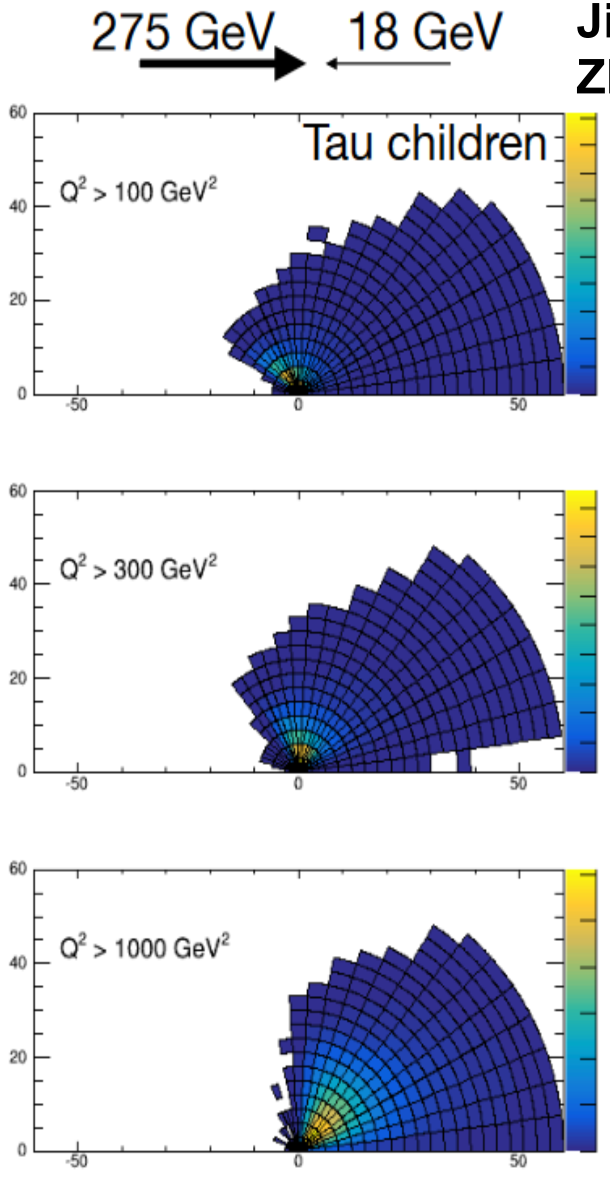
Tau decay mode and branching ratio

- **3-prong** **15.21 (0.06)%**
  - $\pi^-\pi^+\pi^-\nu_\tau$ 9.31 (0.05)%
  - $\pi^-\pi^+\pi^-\pi^0\nu_\tau$ 4.62 (0.05)%
  - others (kaon, etc) 1.28%
- **1-prong** **84.58 (0.06)%**
  - $\mu^-\bar{\nu}_\mu\nu_\tau$ 17.39 (0.04)%
  - $e^-\bar{\nu}_e\nu_\tau$ 17.82 (0.04)%
  - $\pi^-\nu_\tau$ 10.82 (0.05)%
  - $\pi^-\pi^0\nu_\tau$ 25.49 (0.09)%
  - $\pi^-2\pi^0\nu_\tau$ 9.26 (0.10)%
  - $\pi^-3\pi^0\nu_\tau$ 1.04 (0.07)%
  - others (kaon, etc) 3.24%
- others 0.21%



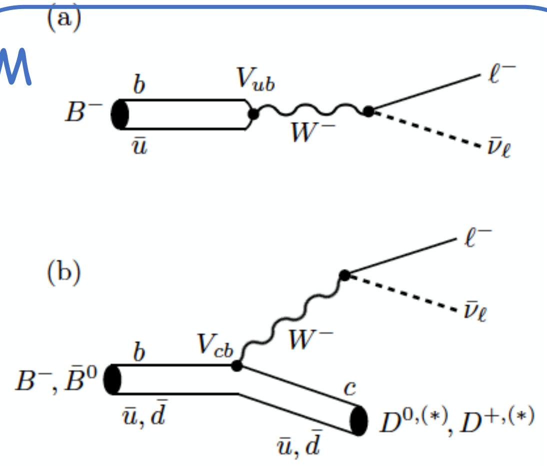
- Isolated tau, Pt balance with q-jet.
- Tau-Jet identification (narrow cone, displaced vertex)
- Precise measurements of vertex (tau vertex displacements 200 to 3000 microns)

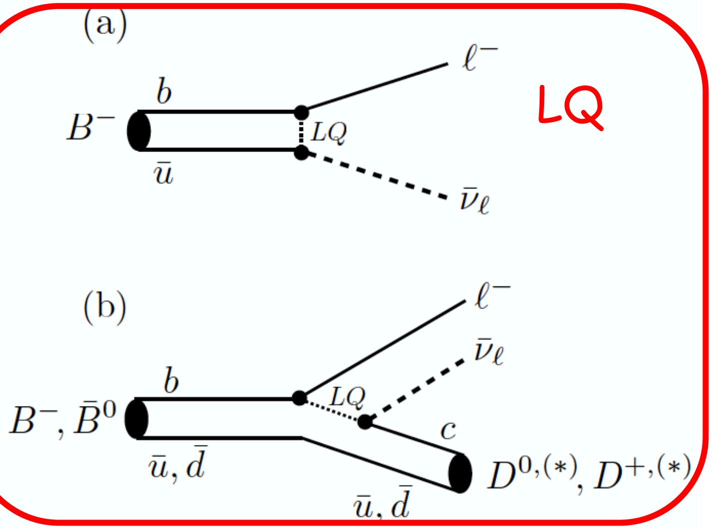
Jinlong Zhang



Angle for theta, radius for momentum

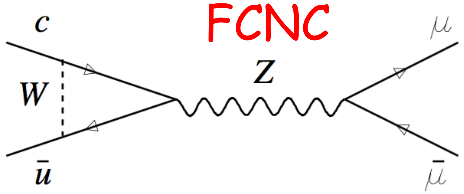
Semi-leptonic decay channels of HF particles for BSM





- Enhance of semi-leptonic decay BRs via **Leptoquark** process
- Comparisons of e vs μ decays
- Comparisons (c/c-bar, b/b-bar) rates (mixing)
- Rare decay processes (FCNC, LFV, etc)

FCNC



$D^0 \to \mu+\mu-$

LFV

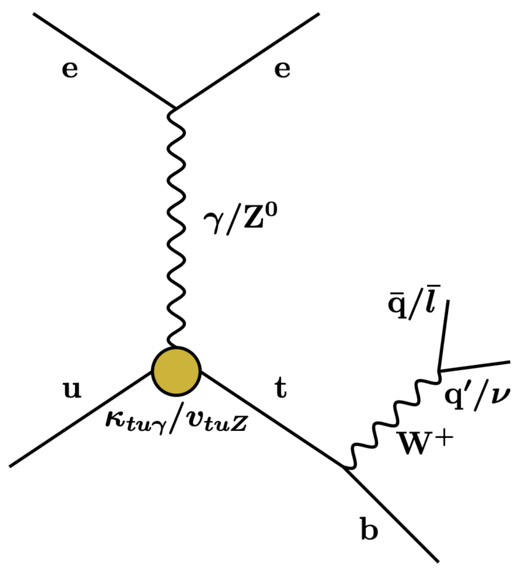
$D^0 \to e+\mu-$

arXiv:1703.01766v3
G. Ciezare and etc.

"Rare D Meson Decays at HERA "
C. Grab

Search for single-top production at HERA

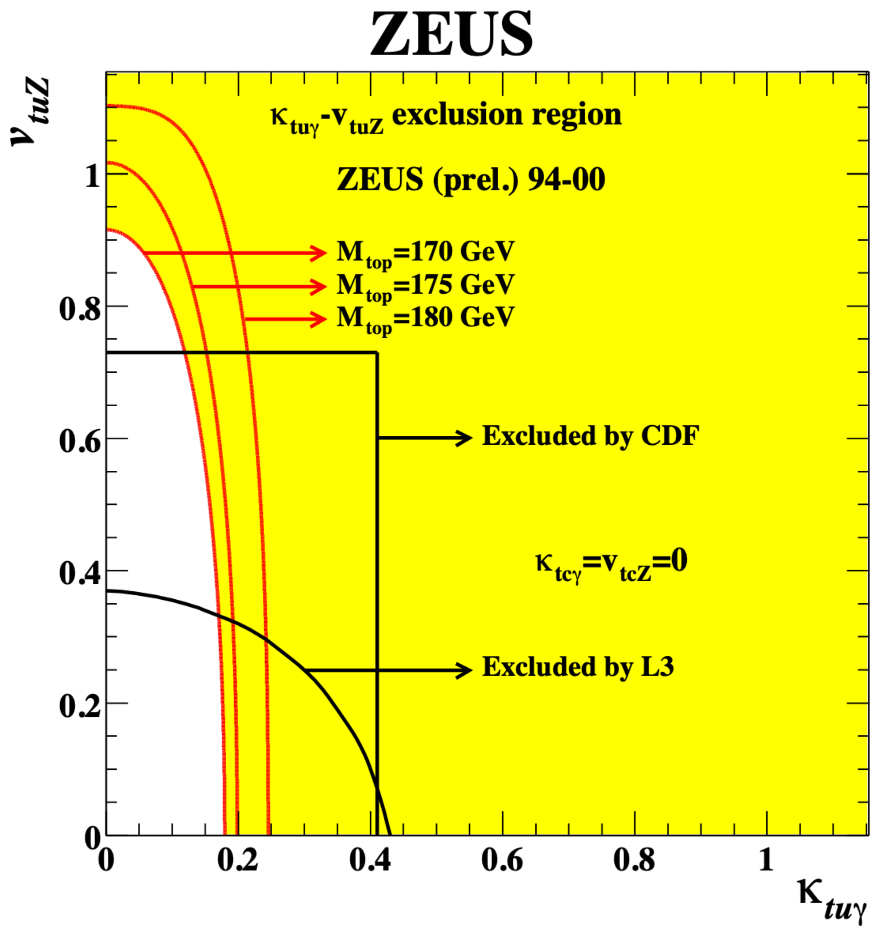
arXiv:hep-ex/0308058



At tree level, the production proceeds through the charged current (CC) reaction $ep \to \nu t\bar{b}X$ (< 1fb)

Via flavour-changing neutral current (FCNC) interactions ($u \to t$)

Leptonic decay of W (11% branching ratio per channel)- isolated high-energy lepton, significant missing transverse momentum and high Pt hadrons from b-decay (~ 1 pb)



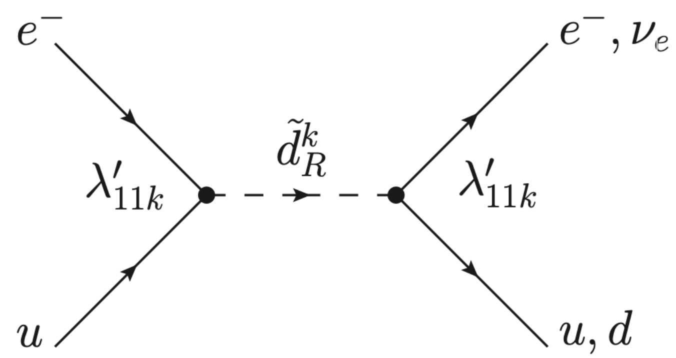
Supersymmetry (SUSY)

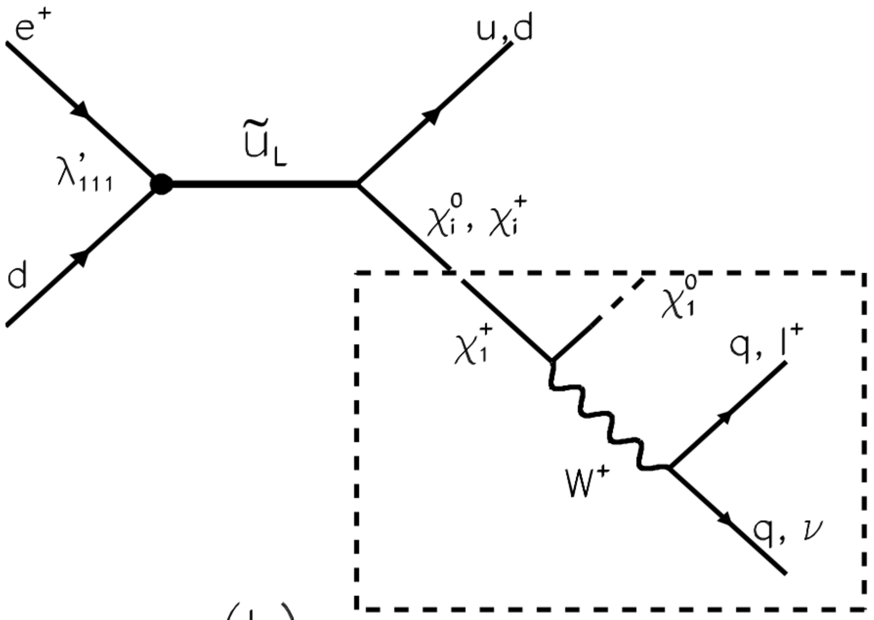
https://arxiv.org/pdf/1011.6359

Many extensions of the Standard Model (SM) require a new fundamental symmetry between bosons and fermions, known as supersymmetry (SUSY)
Attempt to unify fermions and bosons by assigning each fermion a supersymmetric boson partner and each boson a supersymmetric fermion partner(sparticles)

The minimal supersymmetric extension of the Standard Model (MSSM) conserves a quantity known as R-parity, defined as

$R_P = (-1)^{(2S+3B+L)}$, where
S - spin,
B - baryon number
L - lepton number.
R_P is equal to +1 for all particles in the Standard Model and–1 for their supersymmetric partners.

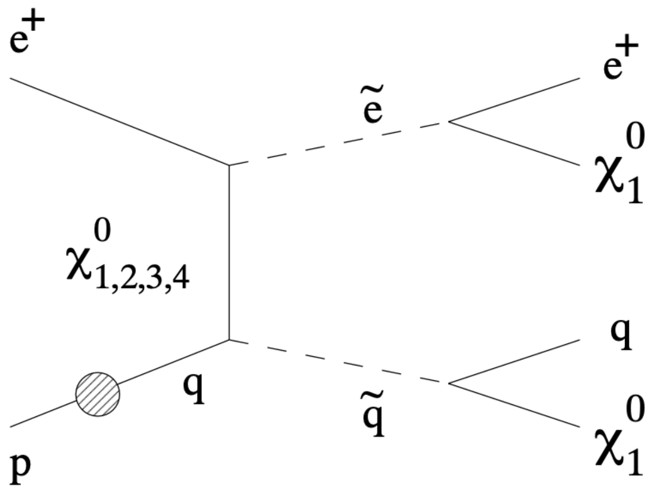




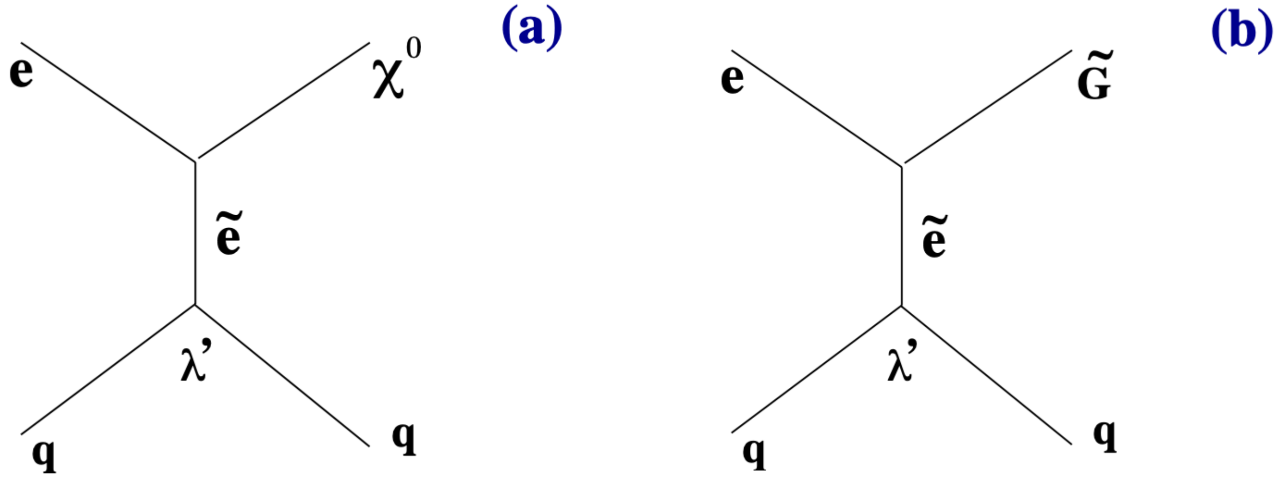
(b)

Supersymmetry (SUSY)

Selectron-squark production via neutralino exchange and the following decays to the Light Supersymmetic Partners and SM partner.



Possible processes containing a **neutralino** (χ0) or **gravitino** (G) in the final state.

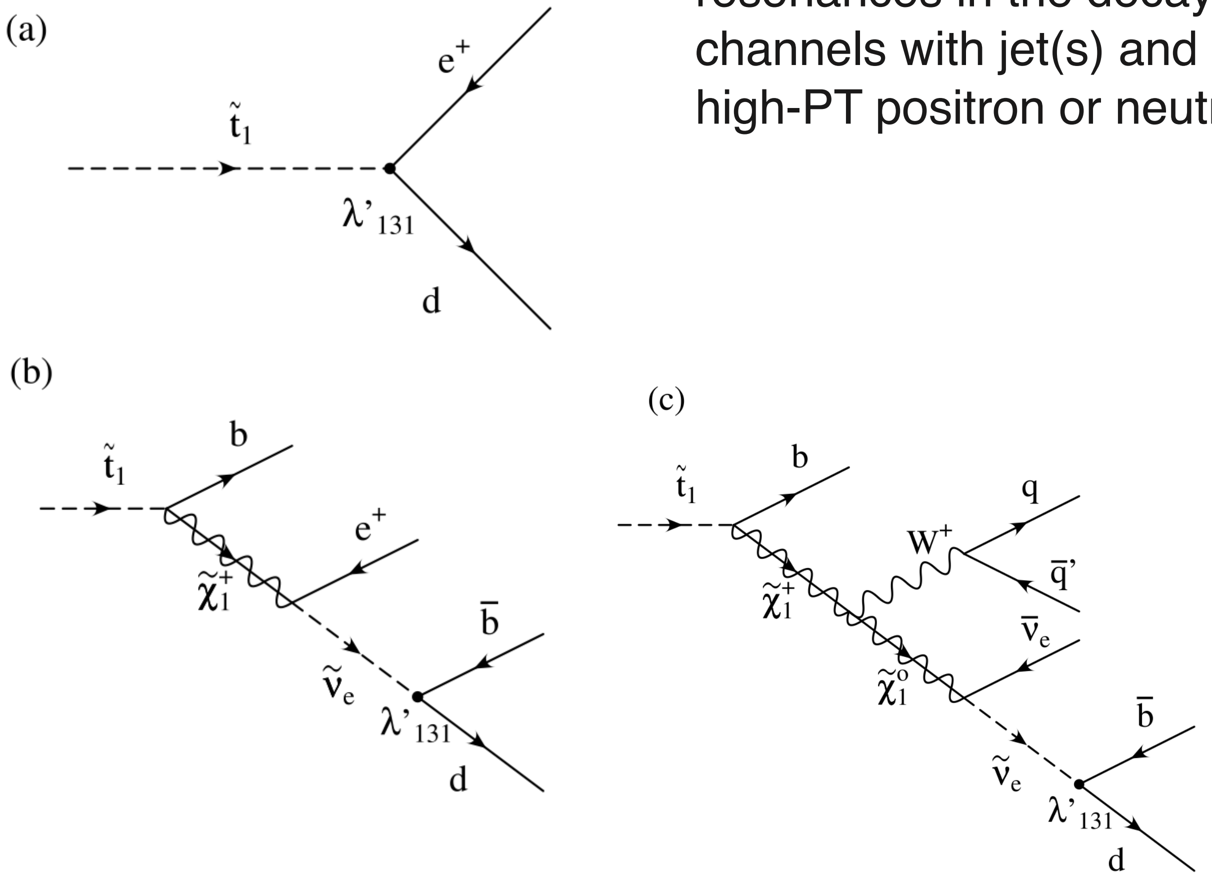


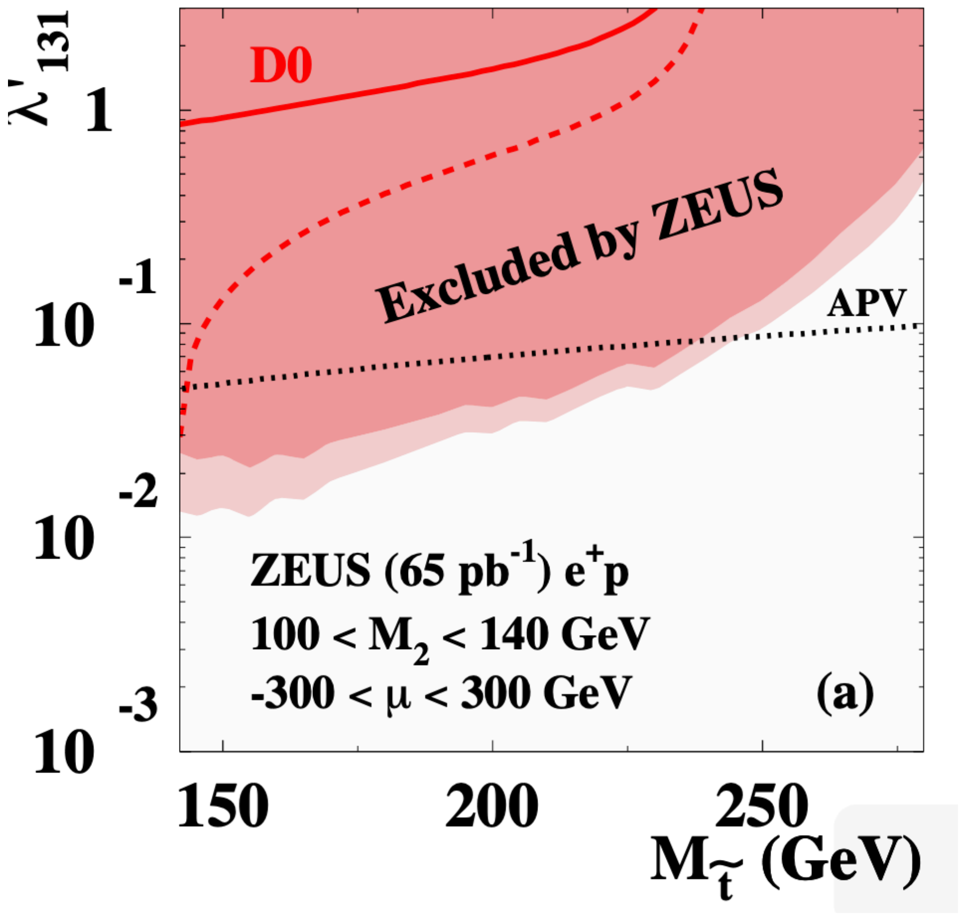
Neutralinos and gravitinos are particles which could be stable and could traverse the detector without interaction (large missing P_T signature)

Search for stop production in R-parity-violating supersymmetry at HERA

https://arxiv.org/pdf/hep-ex/0611018

No evidence was found for resonances in the decay channels with jet(s) and one high-PT positron or neutrino.



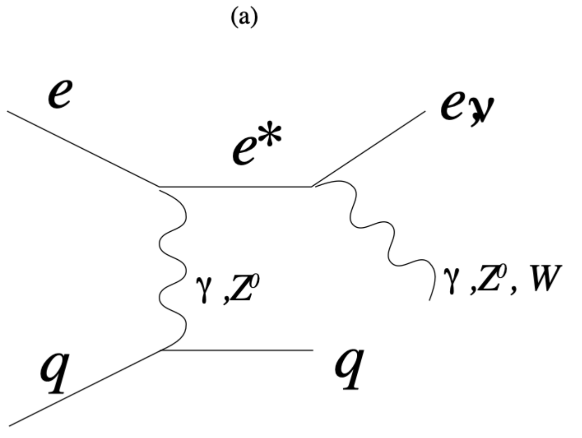


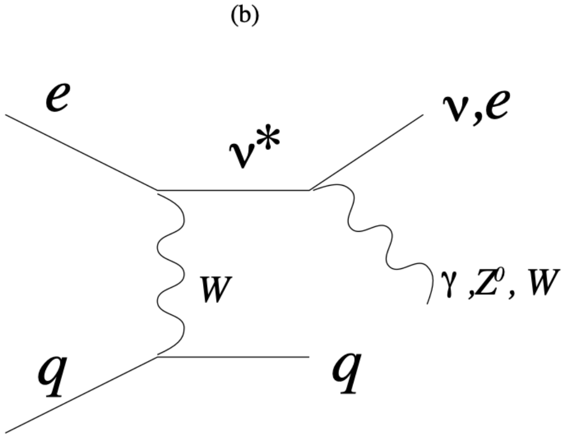
Search for exited leptons and quarks

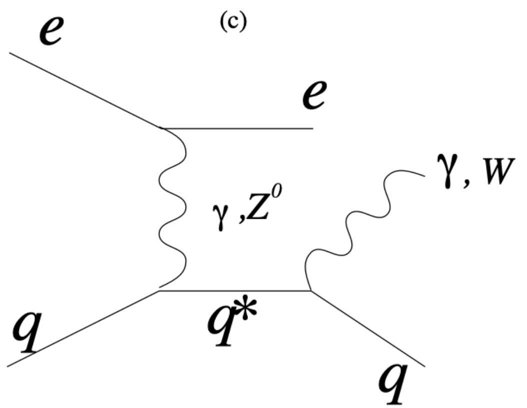
Puzzle: three- family structure and mass hierarchy
Composite structure of quarks and leptons? => the existence of **exited leptons or quarks**

At HERA single excited electrons, quarks and neutrinos can be **singly produced** via processes (exchange of γ, Z, W):

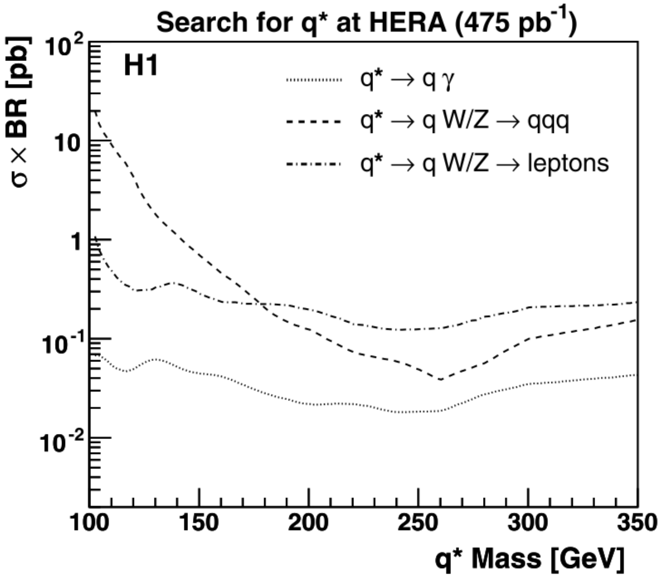
$$ep \to f^*X, f^* \to fV$$

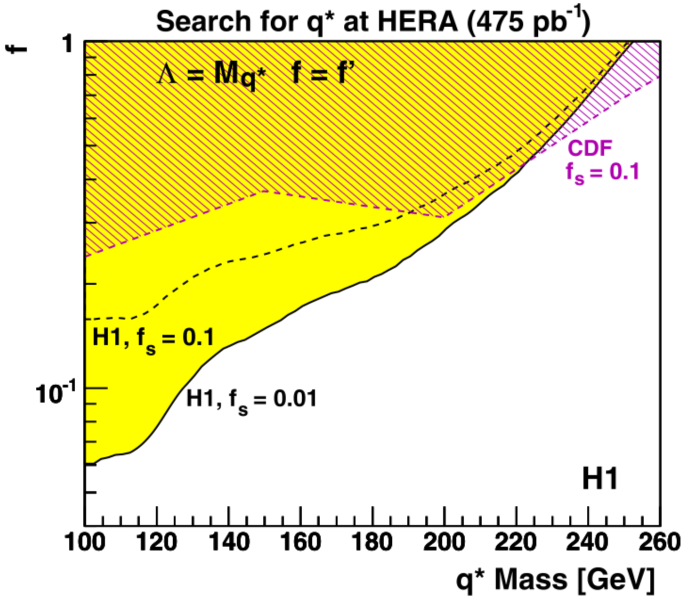






Physics Letters B 678 (2009) 335–343





Electron and Quark radius at HERA

https://doi.org/10.48550/arXiv.1604.01280

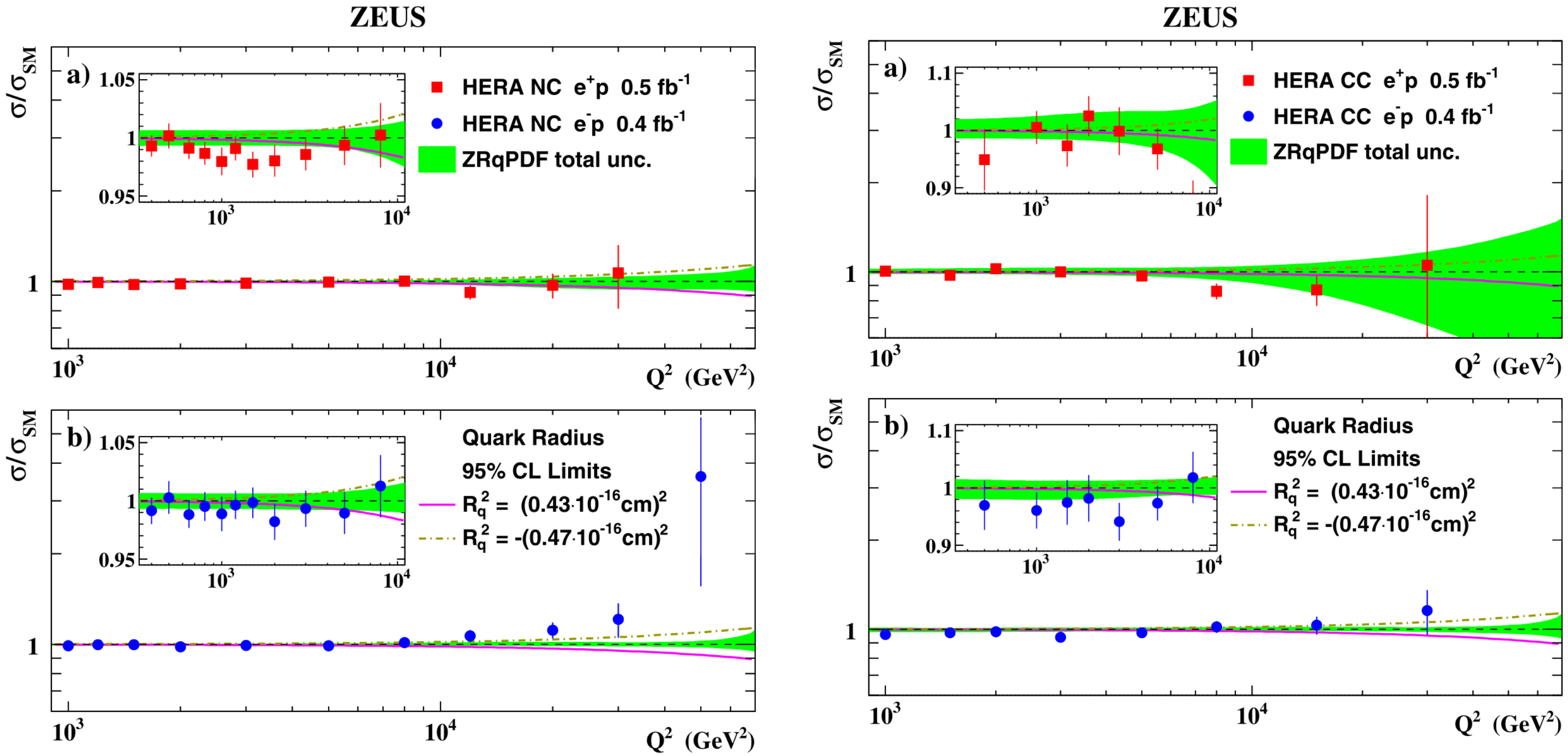
ep/eA colliders are natural place to study a quark substructure

Deviation from the SM, especially at high Q2:

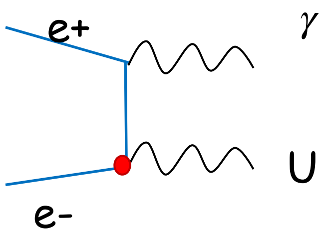
$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_e^2}{6}Q^2\right)^2 \left(1 - \frac{R_q^2}{6}Q^2\right)^2$$

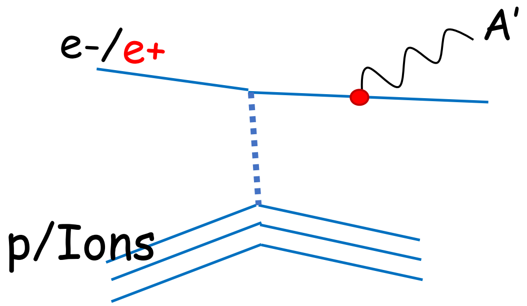
HERA limit:

$$R_q^2 < (0.43 \cdot 10^{-16}\,\mathrm{cm})^2$$



Dark Photon Searches



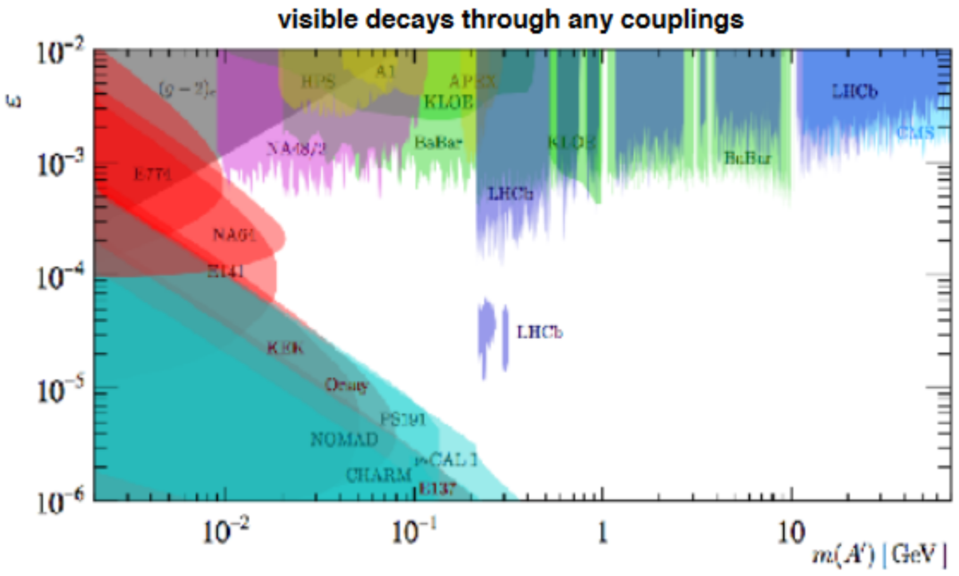


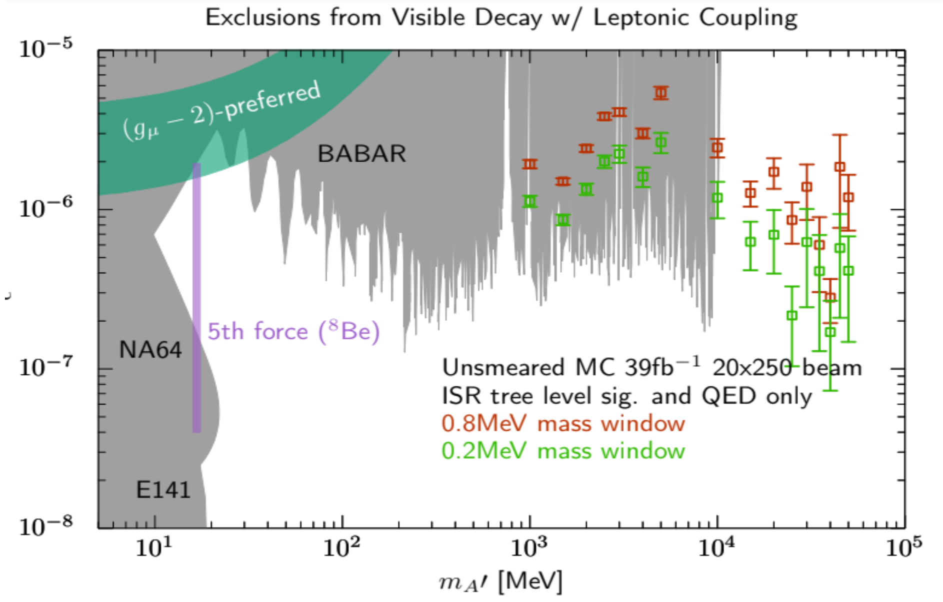
- Dark Photon (U,A'): new mediator to a sector of Dark Matter particles (MeV-GeV mass)

- Weakly coupled to Standard Model through kinetic mixing with ordinary photon → production in e^+e^- annihilation.

- A' can be probed with $e^{+/-}$ p(Ions) (e.g. target experiments PADME at LNF, Adv. High Energy Phys. 2014:959802; VEPP-3, arXiv:1207.5089 [hep-ex])

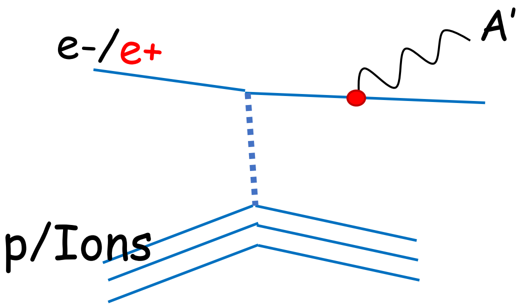
- Detection via decay into SM particles (e+/e-)
- High luminosity is needed

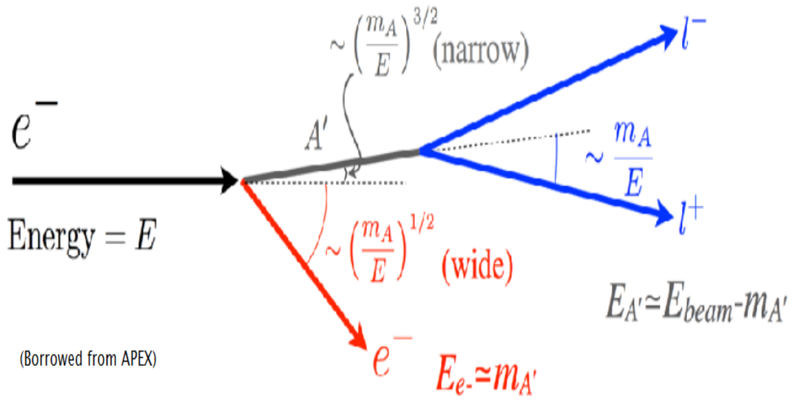




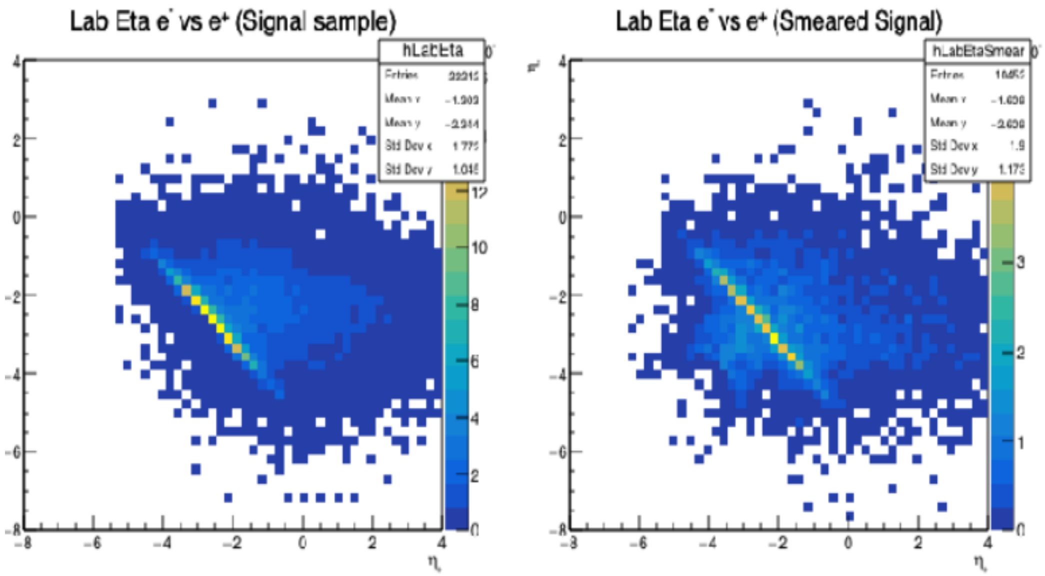
Dark Photon Searches

Ross Corliss





(Borrowed from APEX)

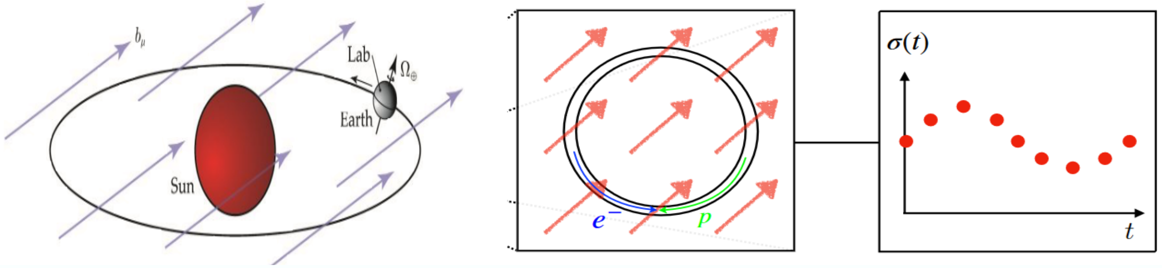


- First analysis looks at e+e- decay, but hadronic final states could be investigated as well
- The boosted kinematics significantly opens up the angle between the decay leptons creating a specific topology
- Measurement would benefit from improved charge sign reconstruction and good lepton PID (e/pi rejection)
- Higher eta coverage would lead to access to lower mass dark photons

- With 6 months of running 25 on 250 (~39 fb^{-1}) we could reach similar sensitivities than BABAR but in a wider mass range

Enrico Lunghi

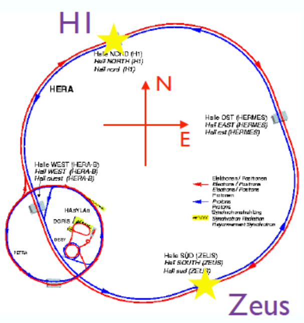
Lorentz violating effects



- **local sidereal time** $(T_\oplus)$

$$\sigma(T_\oplus) \sim \sigma_{SM}\,(1 + c_0 + c_1\cos(\omega_\oplus T_\oplus) + c_2\cos(2\omega_\oplus T_\oplus) + \cdots)$$

HERA

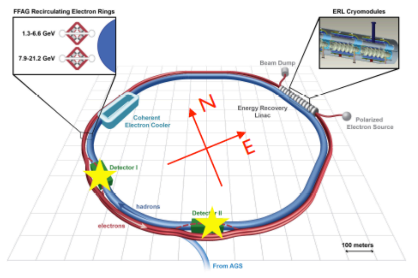


$\chi=36.4^o$

$\varphi_{ZEUS}=20^o$ NoE

$\varphi_{H1}=-20^o$ NoE

eRHIC

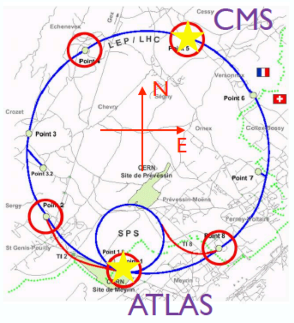


$\chi=49.1^o$

$\varphi_{eRHIC1}=-78.5^o$ NoE

$\varphi_{eRHIC2}=-16.8^o$ NoE

LHC



$\chi=46^o$

$\varphi_{ATLAS}=-14^o$ NoE

$\varphi_{CMS}=-14^o$ NoE

Recent studies suggest differential cross section measurements at the EIC will allow for precision tests of Lorentz and CPT symmetry in the quark sector and could increase bounds on quark sector coefficients by two orders of magnitude over data taken at HERA.

- Lorentz and CPT symmetry are among the most well established symmetries in physics.
- However, many BSM theories admit regimes where one or both of these symmetries can be spontaneously broken.

- Expected bounds in units of 10^{-5}

	HERA	JLEIC (one year)	eRHIC (one year)	JLEIC (ten years)	eRHIC (ten years)
$\lvert c_u^{TX}\rvert$	6.4 [6.7]	1.1 [11.]	0.26 [11.]	0.072 [9.3]	0.084 [11.]
$\lvert c_u^{TY}\rvert$	6.4 [6.7]	1.1 [11.]	0.27 [11.]	0.069 [9.4]	0.085 [11.]
$\lvert c_u^{XZ}\rvert$	32. [33.]	1.9 [16.]	0.36 [15.]	0.12 [16.]	0.11 [15.]
$\lvert c_u^{YZ}\rvert$	32. [33.]	1.8 [16.]	0.37 [15.]	0.12 [16.]	0.12 [15.]
$\lvert c_u^{XY}\rvert$	16. [16.]	7.0 [60.]	0.96 [40.]	0.44 [58.]	0.31 [40.]
$\lvert c_u^{XX} - c_u^{YY}\rvert$	50. [50.]	6.0 [51.]	2.8 [120.]	0.37 [50.]	0.89 [120.]

Summary

- EW (Charged current) physics is essential for PDF flavor decompositions.
- High luminosity at EIC will offer a precision measurements and access to a rare physics;
- Polarization is essential for EW/BSM physics
- Possibility to add e+ beam (currently not a part of EIC project) would allow to probe a charge symmetry
- Preliminary estimates on BSM physics at EIC looks promising.
- Next generation of detectors: control under systematics, precision, efficiency.
- Looking forward for new EW/BSM physics studies at EIC!

Backup

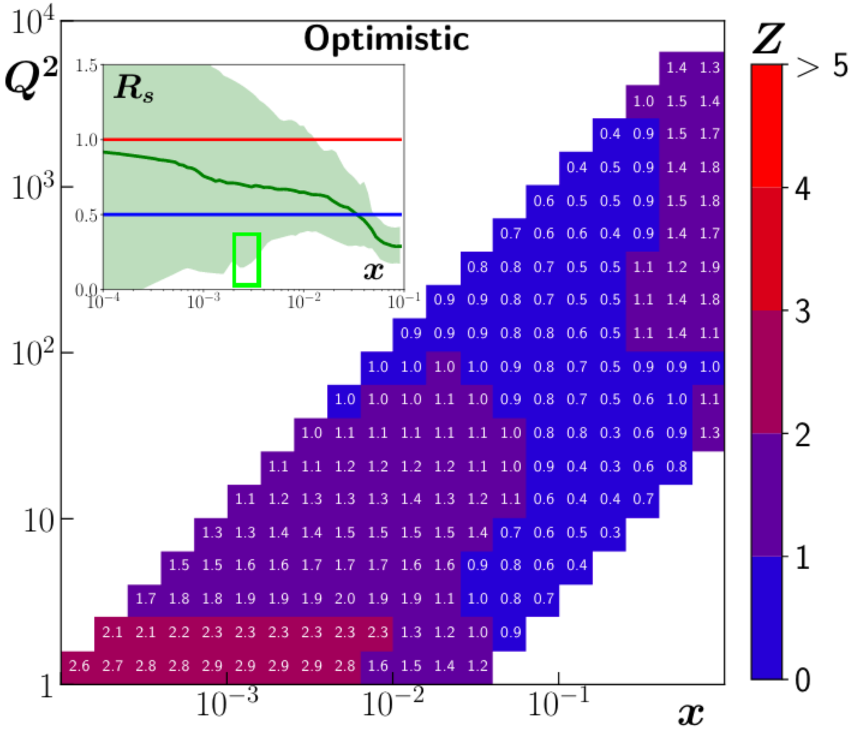
PDF fits

T. Hobbs

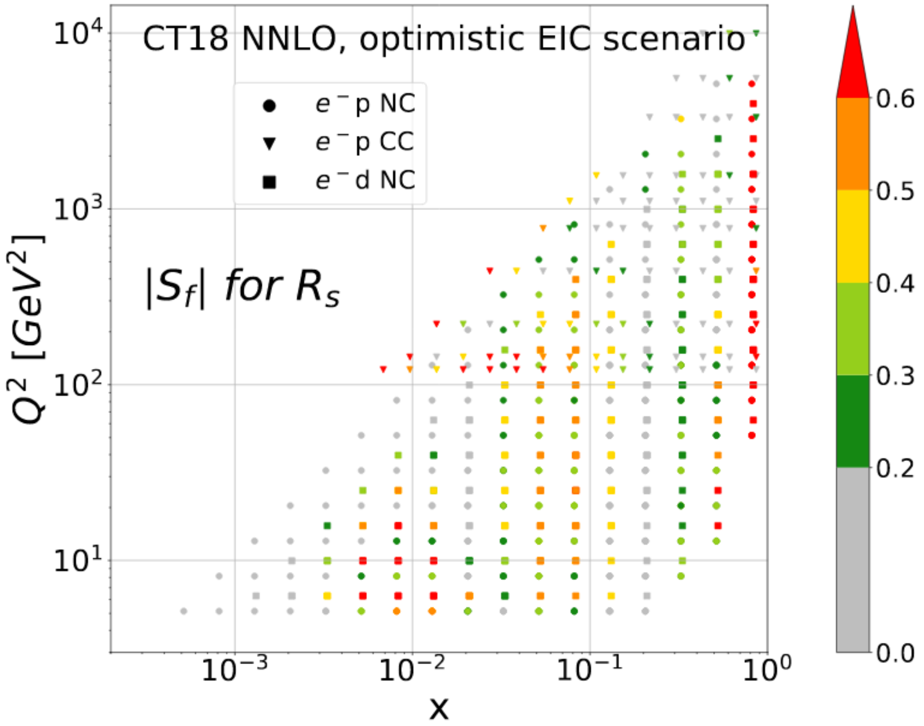
Our knowledge of unpolarized collinear parton distribution functions (PDFs)   driven by inclusive neutral current (NC) and charged current (CC) deep inelastic scattering(DIS) cross section.

Rs= (s+¯s)/(¯u+¯d)

Z-score analysis comparing the cross-sections generated from PDF replicas satisfying Rs= 0.5 (the null hypothesis in blue) and Rs= 1 (the alternative hypothesis in red)



The sensitivity,|Sf|, of the EIC e−pseudodata to the Rs PDF ratio;

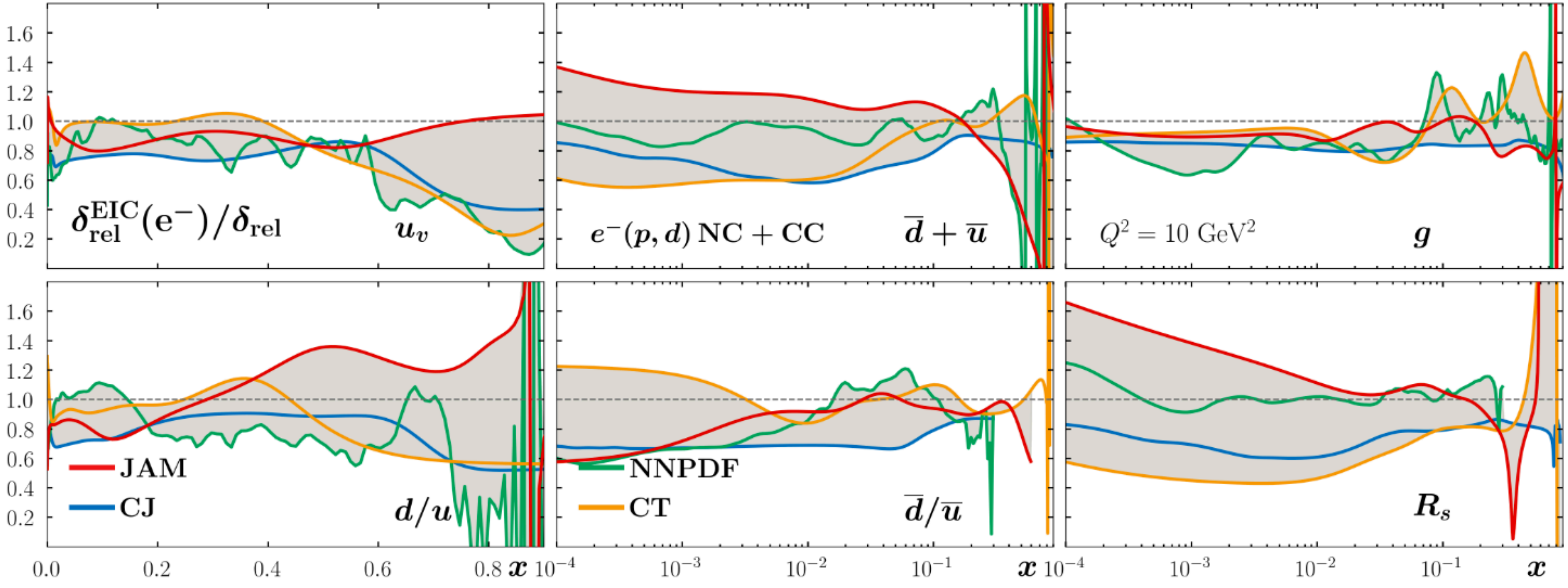


PDFSense

PDF fits

T. Hobbs

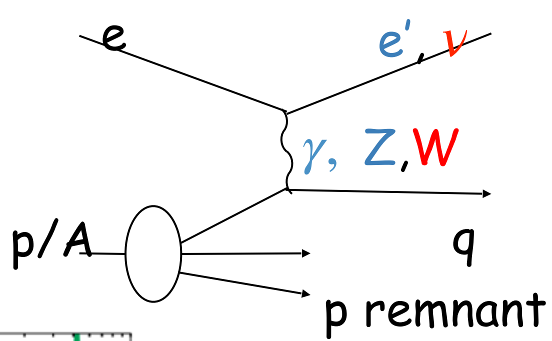
the potential impact of EIC's NC and CC with incident electron beam colliding with proton and deuterium beams from a selection of PDF global analyzers



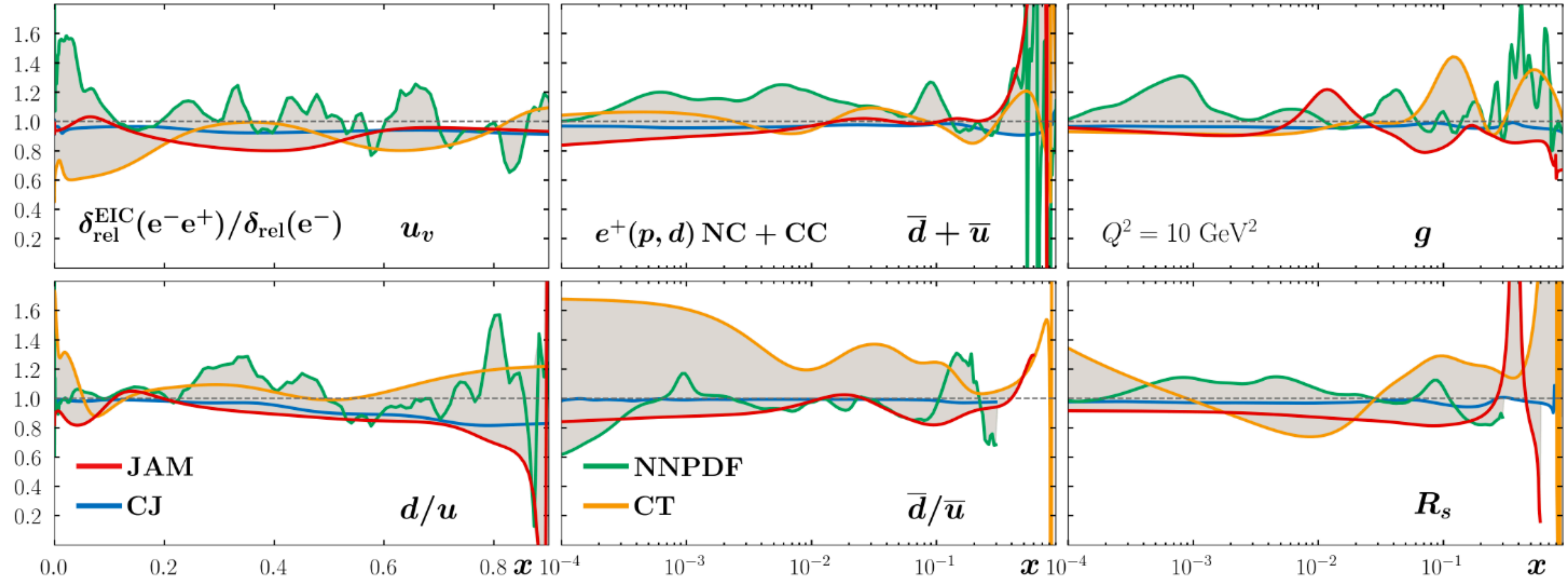
100 fb-1 $\sqrt{s}$ ~ 28.6, 44.7, 63.3, 140.7 GeV for NC and 140.7 GeV for CC
and deuteron beams L= 10fb−1 and consider only NC at √s= 28.6, 66.3, 89.0 GeV

PDF fits with positron beam

T. Hobbs

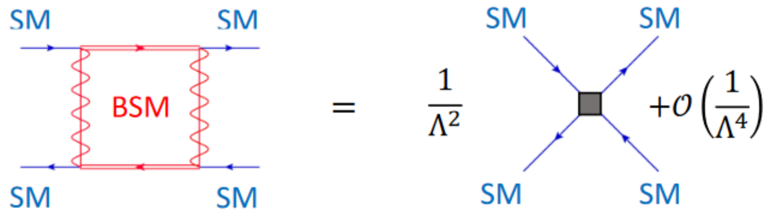


differing charge of the exchanged W+ boson is such that positron CC interactions are capable of probing a unique combination of flavor currents inside the target hadron relative to an electron beam.



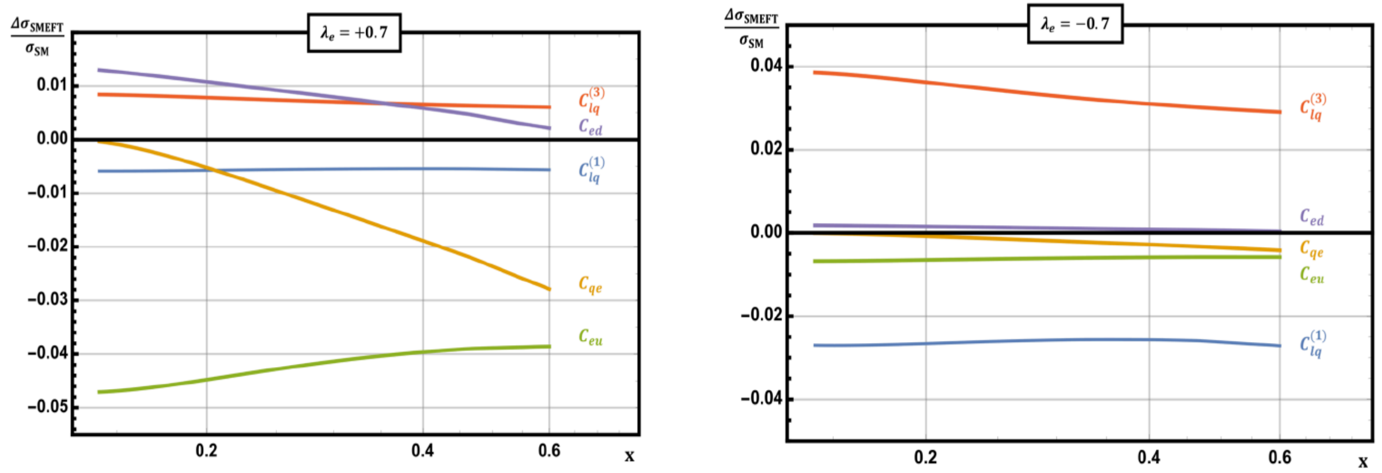
Complementarity of EIC and LHC probes of the SMEFT

Daniel Wiegand



The SM effective field theory (SMEFT) provides a convenient theoretical framework for investigating indirect signatures of heavy new physics without associated new particles at low energies. Considerable effort has been devoted to performing global analyses of the available data within the SMEFT and other frameworks.

Simultaneous fit of PDFs AND Wilson Coefficients



Different Wilson coefficients contribute for different electron polarizations