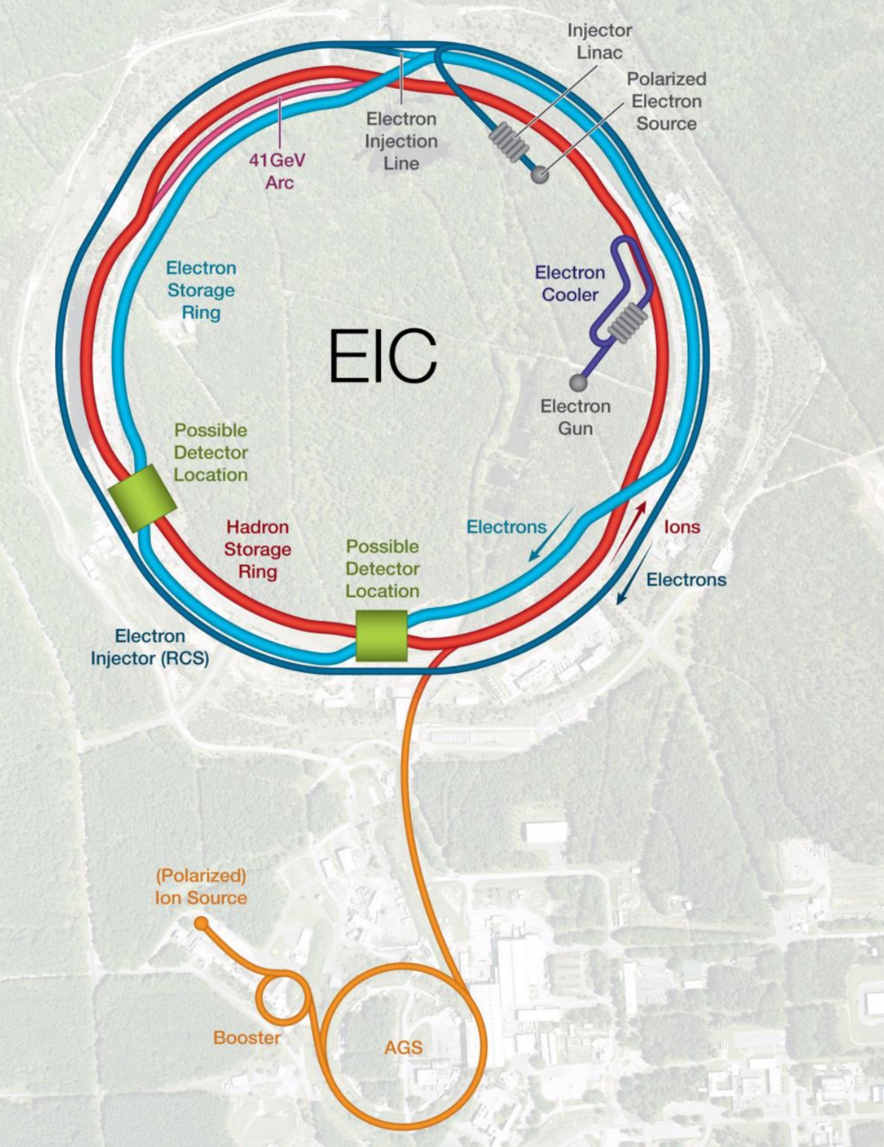
EW&BSM at EIC: a stool with more than 3 legs

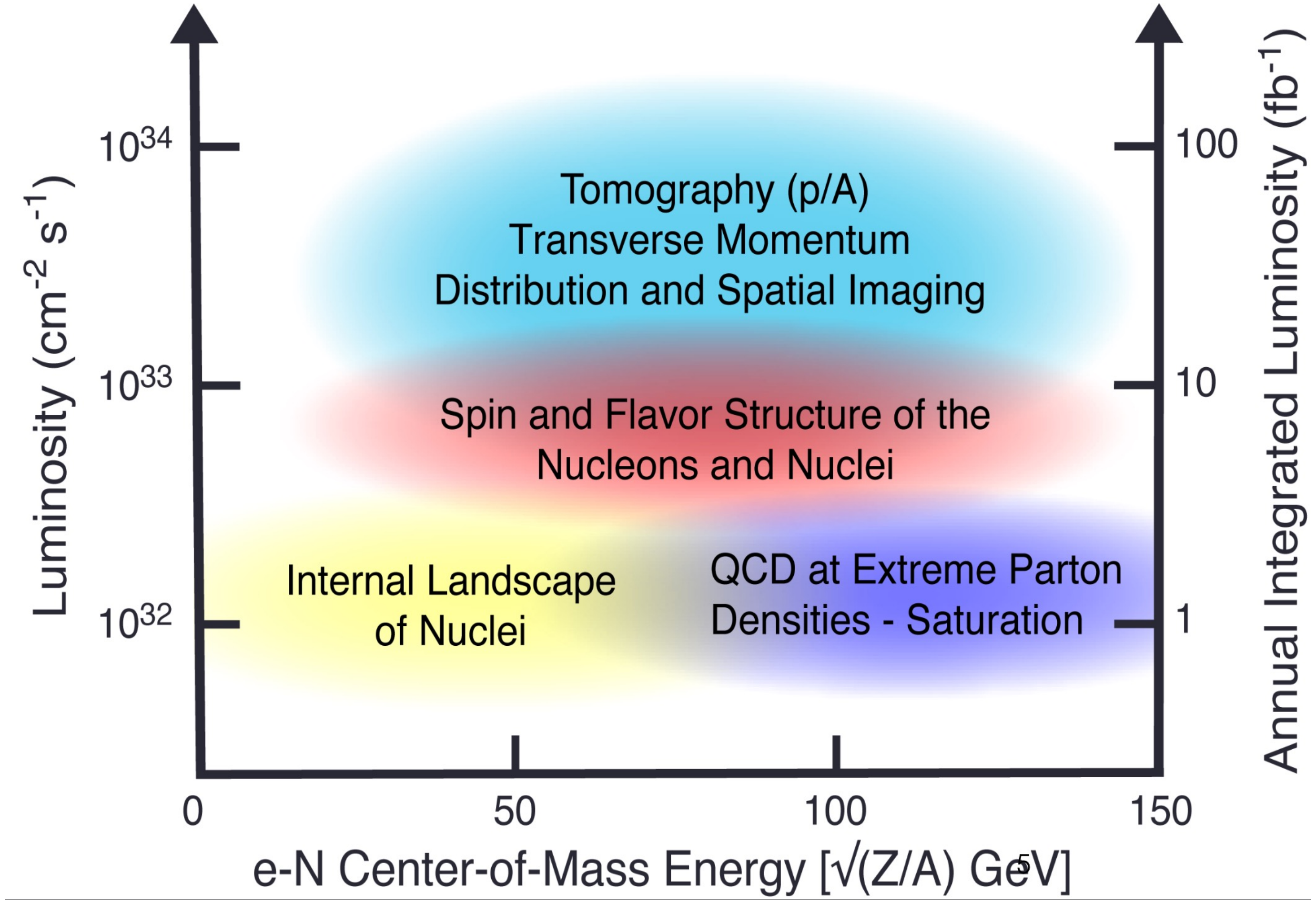
Ciprian Gal

SoLID Opportunities and Challenges of Nuclear Physics at the Luminosity Frontier

Jefferson Lab

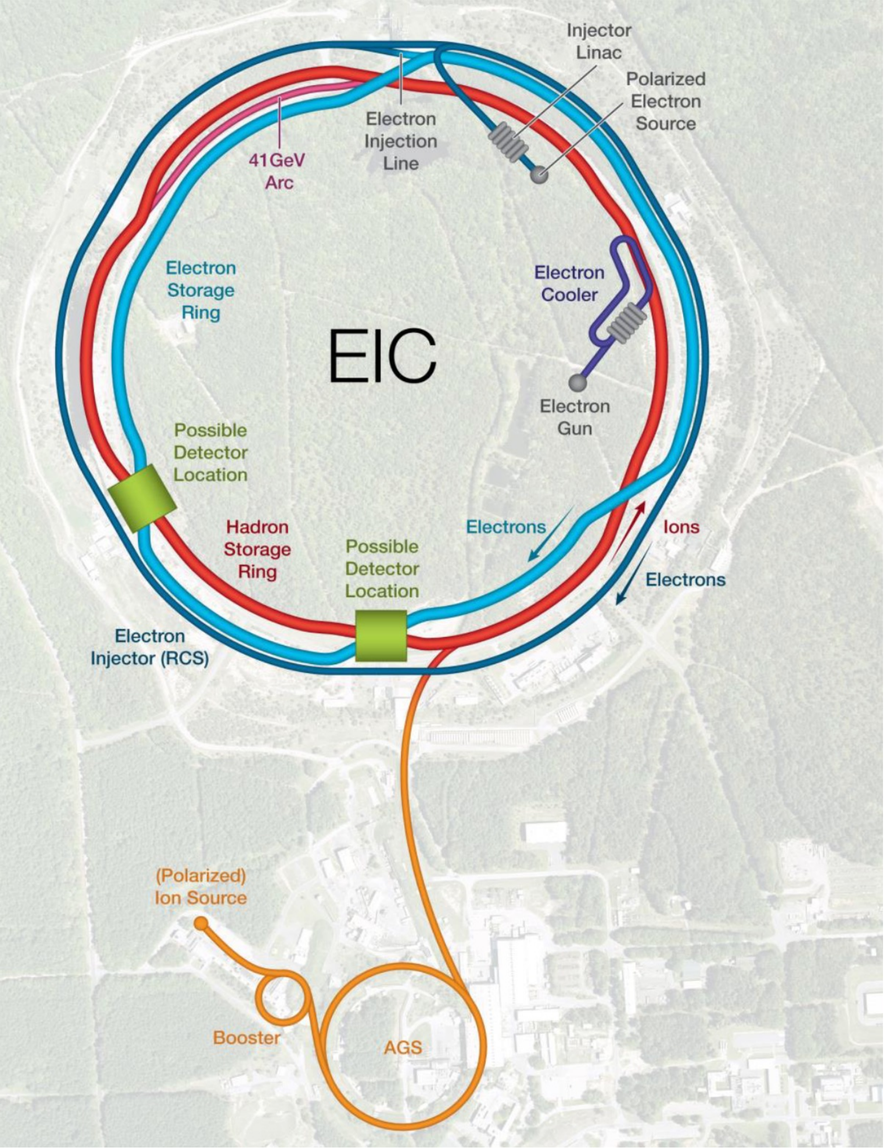
Electron Ion Collider

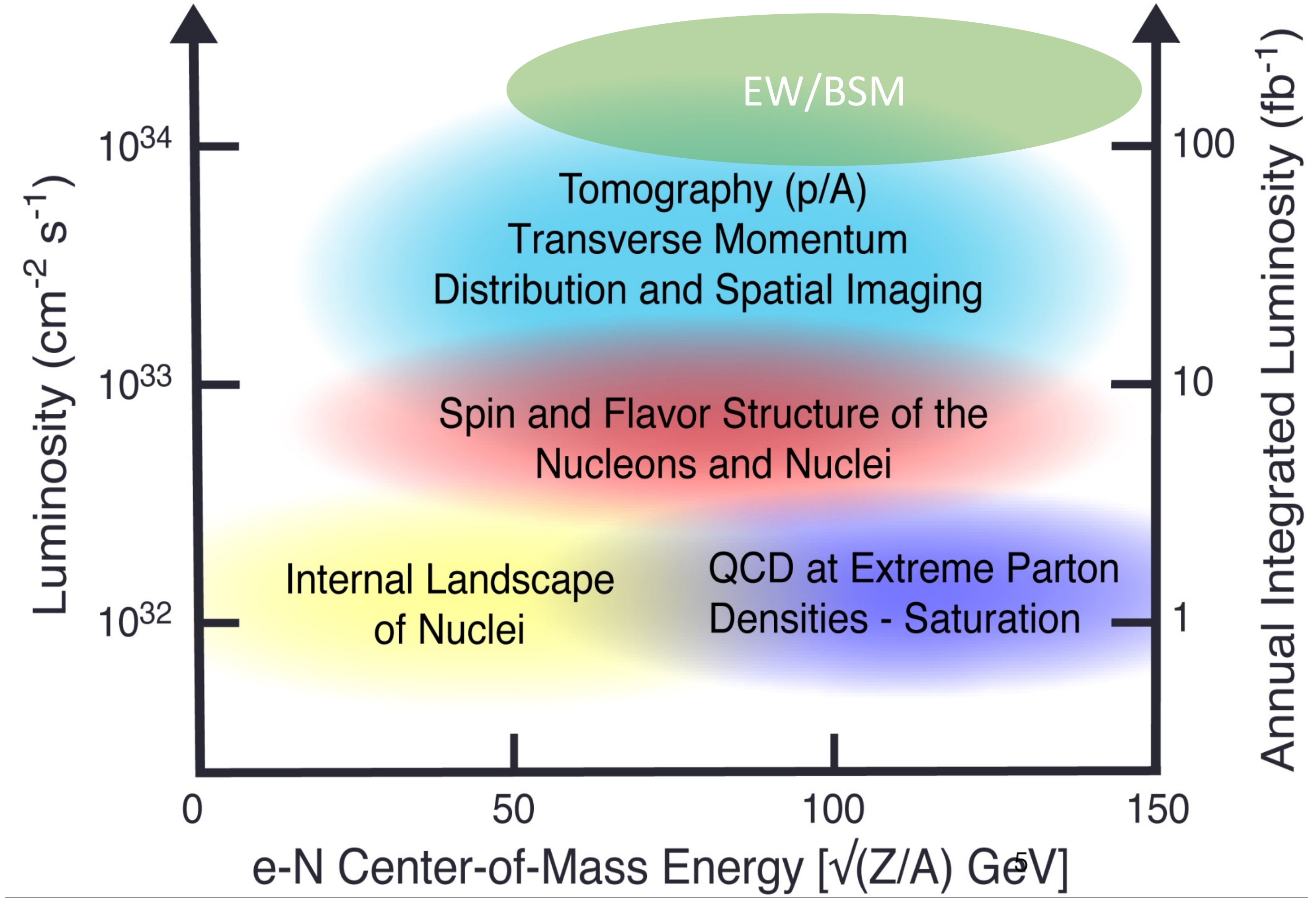




- The high luminosity and variable center of mass energy allow for studies to elucidate the role of gluons inside nucleons

Electron Ion Collider

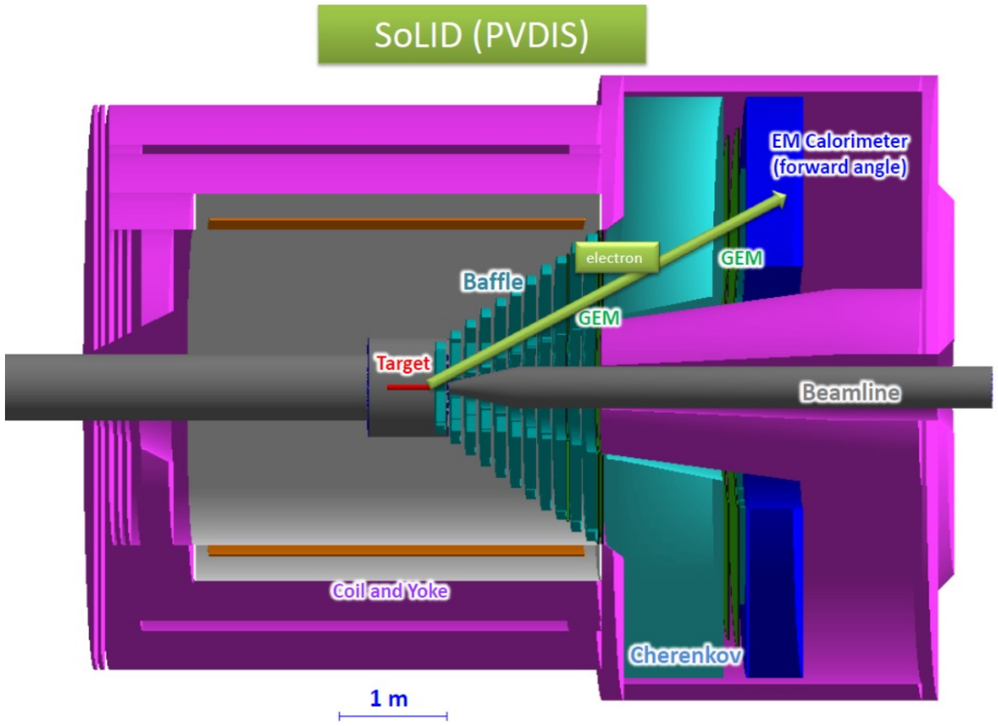


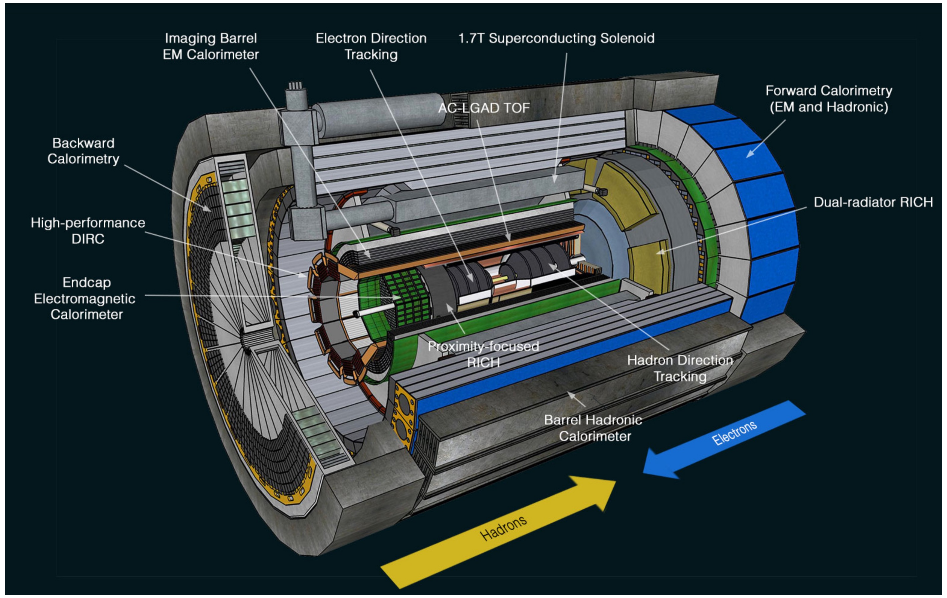


- To take full advantage of this machine we are exploring ways in which it can shed light on other aspects of physics

SoLID and EIC

- Impact of SoLID on EIC
  - PDF uncertainty reduction
  - weak mixing angle extraction
- I think SoLID can have a huge impact on BSM searches by including the high precision data into global analyses (such as the SMEFT framework)





Summary of EIC EW&BSM topics at the EIC

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Electroweak and Beyond the Standard Model Physics at the EIC

February 12, 2024 - February 16, 2024

https://www.int.washington.edu/index.php/program/schedule/24-87W

- Neutral current PV physics
  - weak mixing angle extraction
  - structure functions
- Charged lepton flavor violation
- Backwards physics/eA searches : dark sector
- Transverse physics

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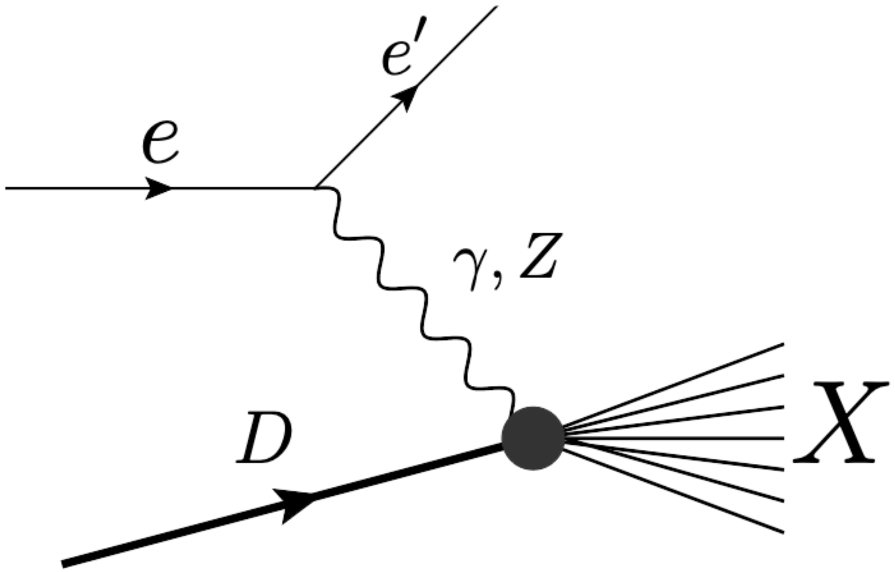
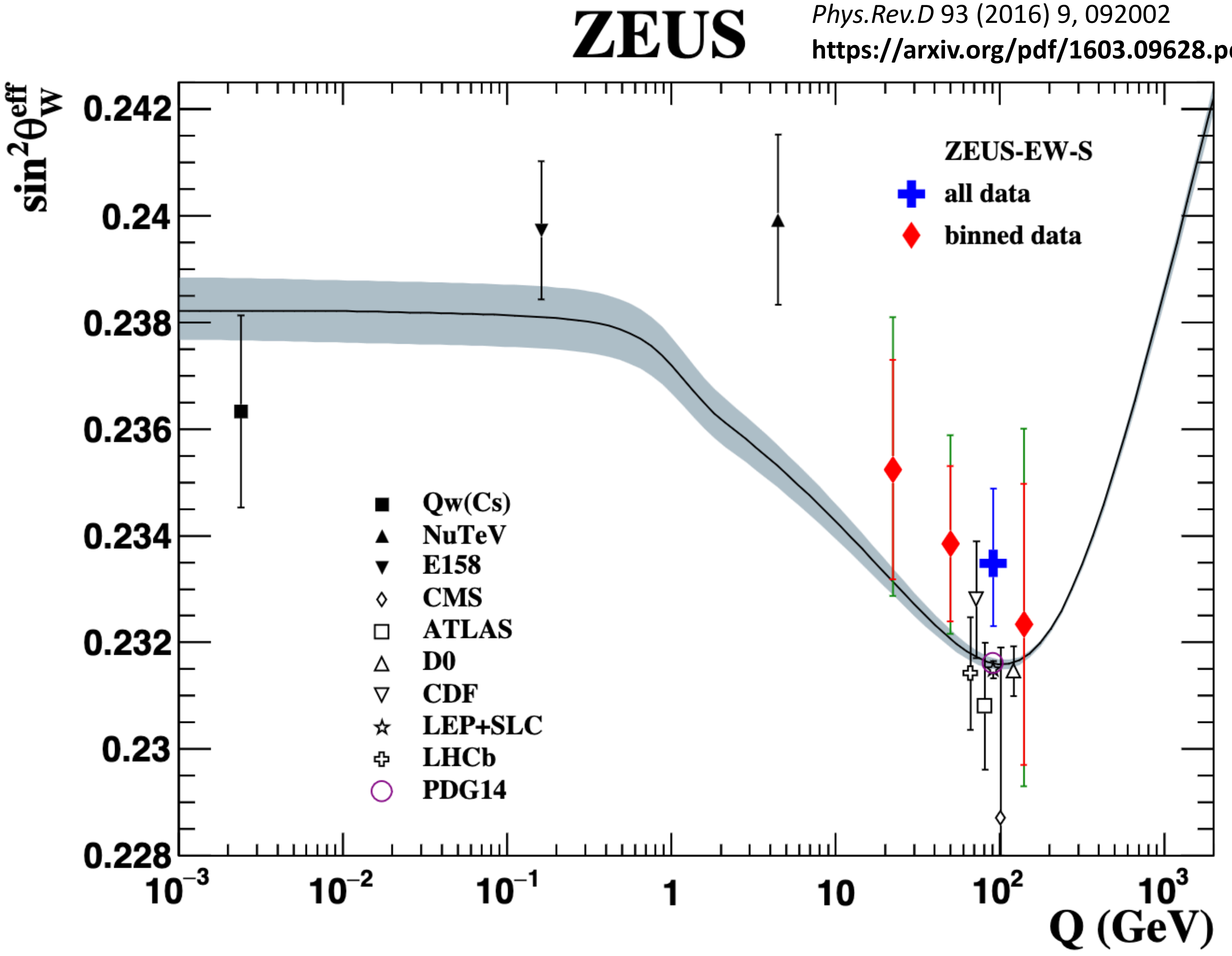


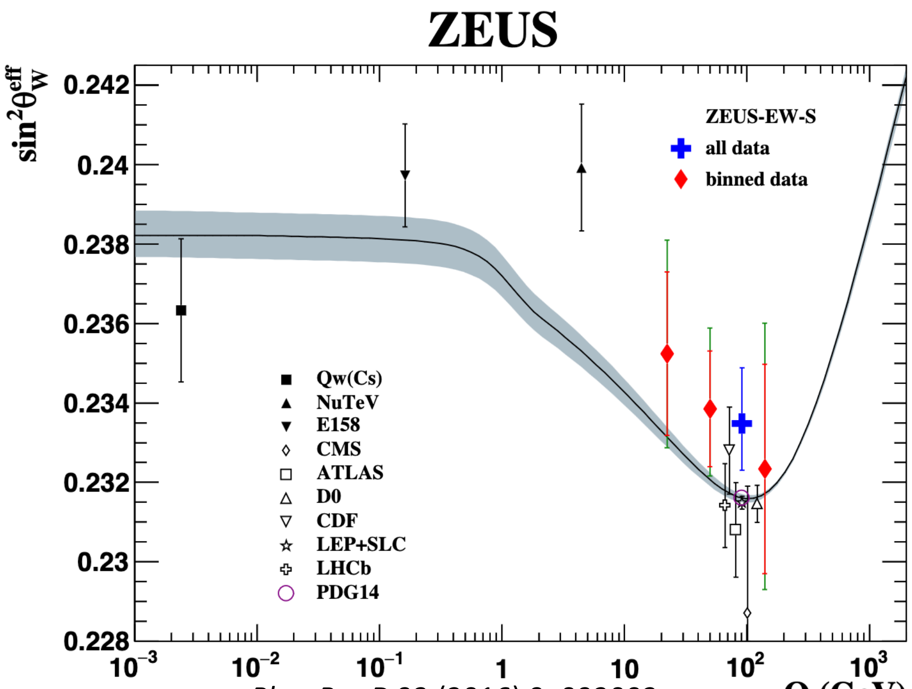
Weak mixing angle extraction

- As one of the parameters of the SM determinations the weak mixing angle are especially sensitive to BSM physics
- The most precise measurements are at the Z-pole and we will get new low Q^2 determinations in the next decade

Phys.Rev.D 93 (2016) 9, 092002
https://arxiv.org/pdf/1603.09628.pdf



Theoretical improvements



Phys.Rev.D 93 (2016) 9, 092002

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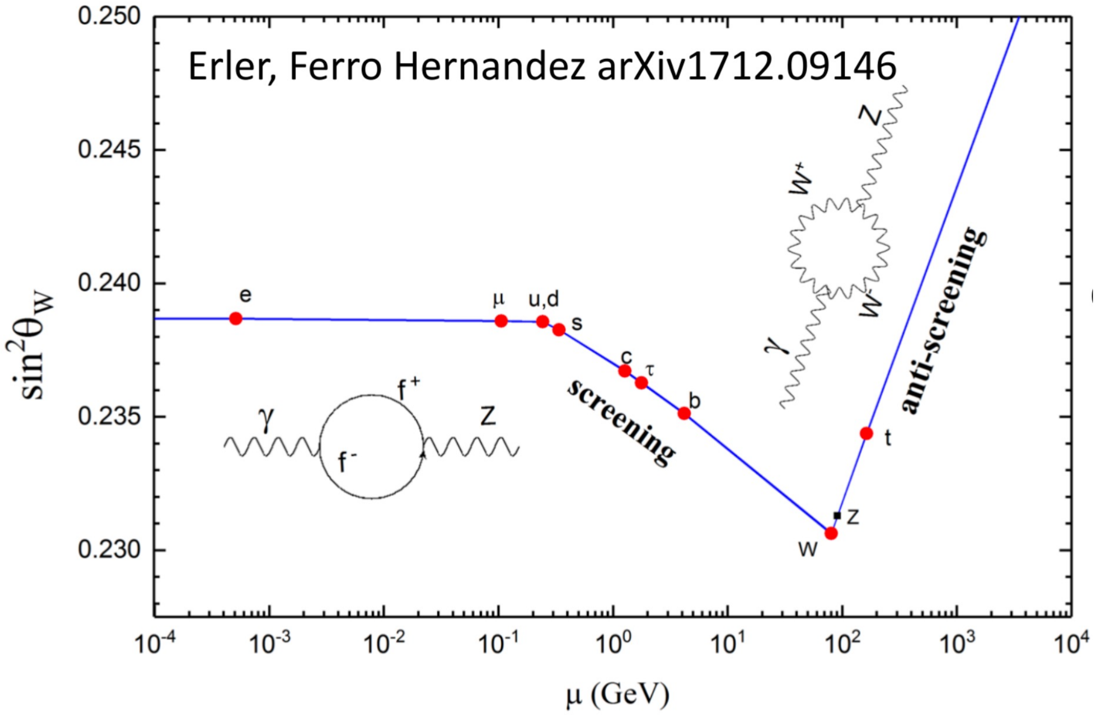
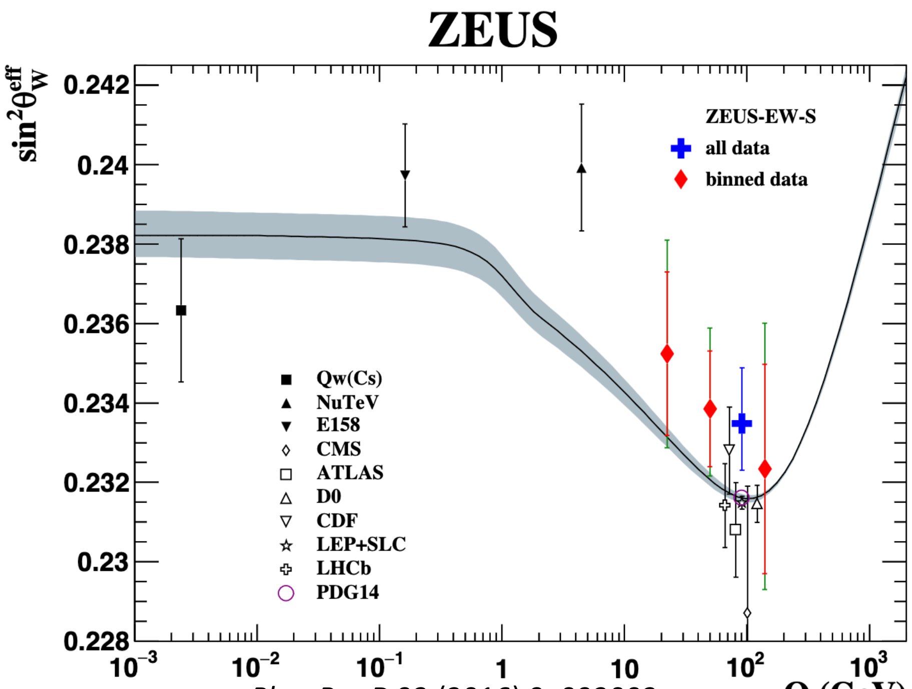


- Significant improvements in measurements and theoretical calculations have reduced the uncertainty on the weak mixing angle running
  - The uncertainty of the SM prediction is on the level of the thickness of the curve in the plot on the right

New phase-space



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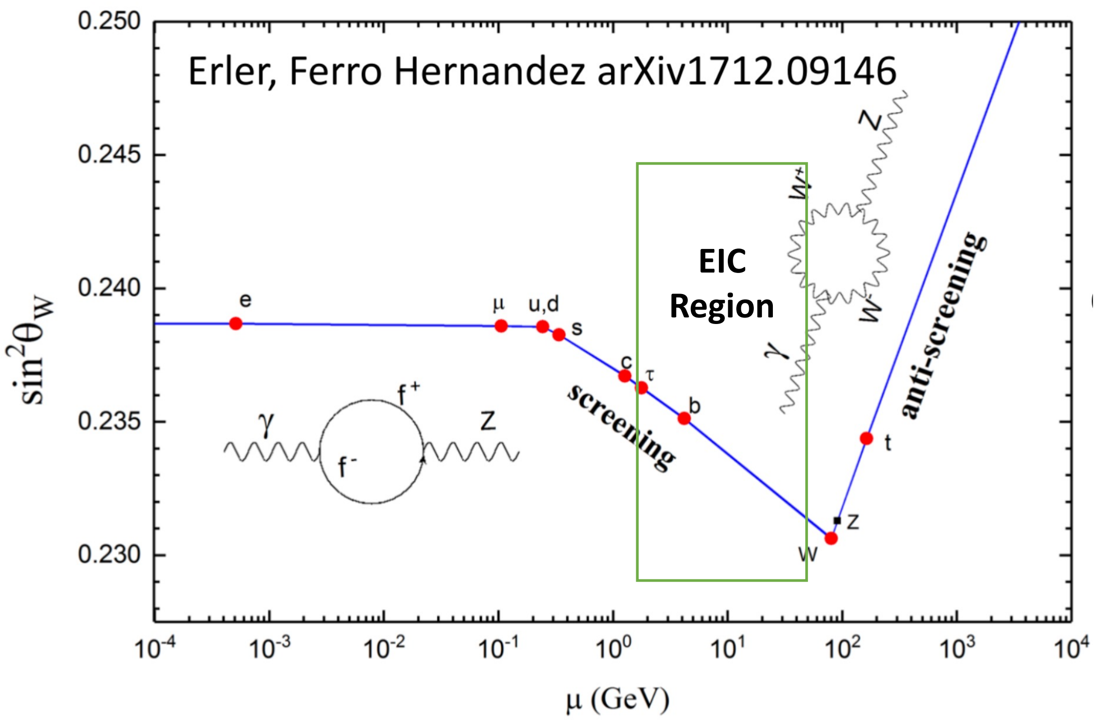
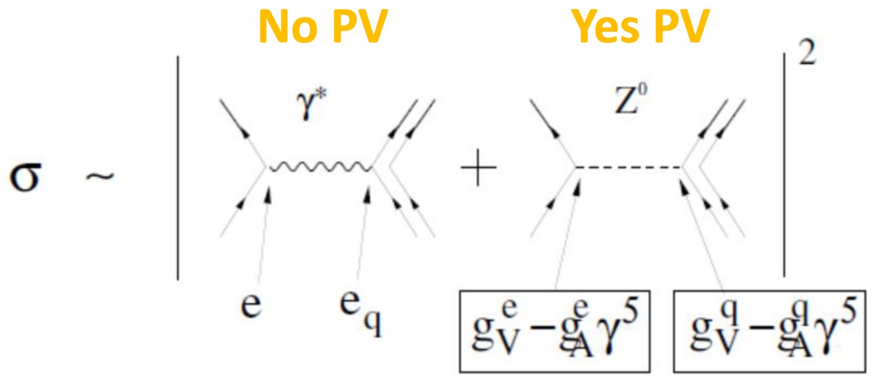


- The EIC will probe a region that has not investigated since HERA and with sufficient luminosity could verify the running
  - Although most of the precise data will be closer to the Z-pole

Parity violation at the EIC

Phys.Rev.D 106 (2022) 1, 016006
https://arxiv.org/pdf/2204.07557.pdf



$$d\sigma = d\sigma_0 + P_e\, d\sigma_e + P_H\, d\sigma_H + P_e P_H\, d\sigma_{eH}$$

$$N^{++} = a_{\rm det} L^{++} \left(d\sigma_0 + |P_e^{++}|\, d\sigma_e + |P_H^{++}|\, d\sigma_H + |P_e^{++}||P_H^{++}|\, d\sigma_{eH} \right)$$
$$N^{+-} = a_{\rm det} L^{+-} \left(d\sigma_0 + |P_e^{+-}|\, d\sigma_e - |P_H^{+-}|\, d\sigma_H - |P_e^{+-}||P_H^{+-}|\, d\sigma_{eH} \right)$$
$$N^{-+} = a_{\rm det} L^{-+} \left(d\sigma_0 - |P_e^{-+}|\, d\sigma_e + |P_H^{-+}|\, d\sigma_H - |P_e^{-+}||P_H^{-+}|\, d\sigma_{eH} \right)$$
$$N^{--} = a_{\rm det} L^{--} \left(d\sigma_0 - |P_e^{--}|\, d\sigma_e - |P_H^{--}|\, d\sigma_H + |P_e^{--}||P_H^{--}|\, d\sigma_{eH} \right)$$

$$Y^{ij} \equiv N^{ij}/L^{ij}$$

- The EIC can measure two parity violating asymmetries which give access to different structure functions
- The higher sensitivity to the weak mixing angle lies in the electron asymmetry

$$A_{\rm PV}^{(e)} \equiv \frac{d\sigma_e}{d\sigma_0} = \frac{1}{|P_e|} \frac{Y^{++} + Y^{+-} - Y^{-+} - Y^{--}}{Y^{++} + Y^{+-} + Y^{-+} + Y^{--}}$$

$$A_{\rm PV}^{(H)} \equiv \frac{d\sigma_H}{d\sigma_0} = \frac{1}{|P_H|} \frac{Y^{++} - Y^{+-} + Y^{-+} - Y^{--}}{Y^{++} + Y^{+-} + Y^{-+} + Y^{--}}$$

ECCE studies

Phys.Rev.D 106 (2022) 1, 016006
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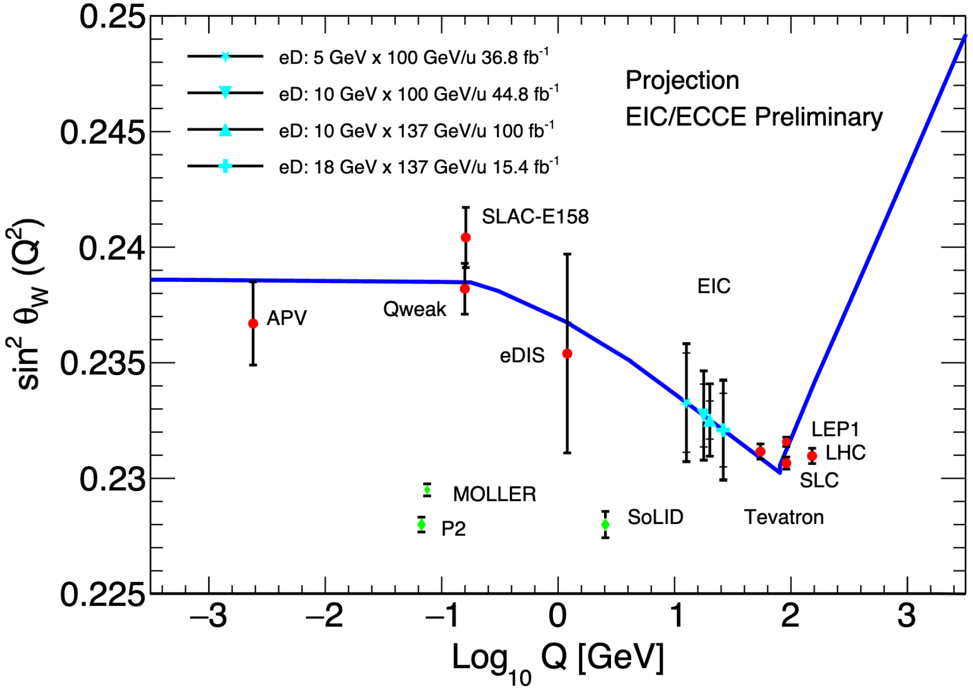
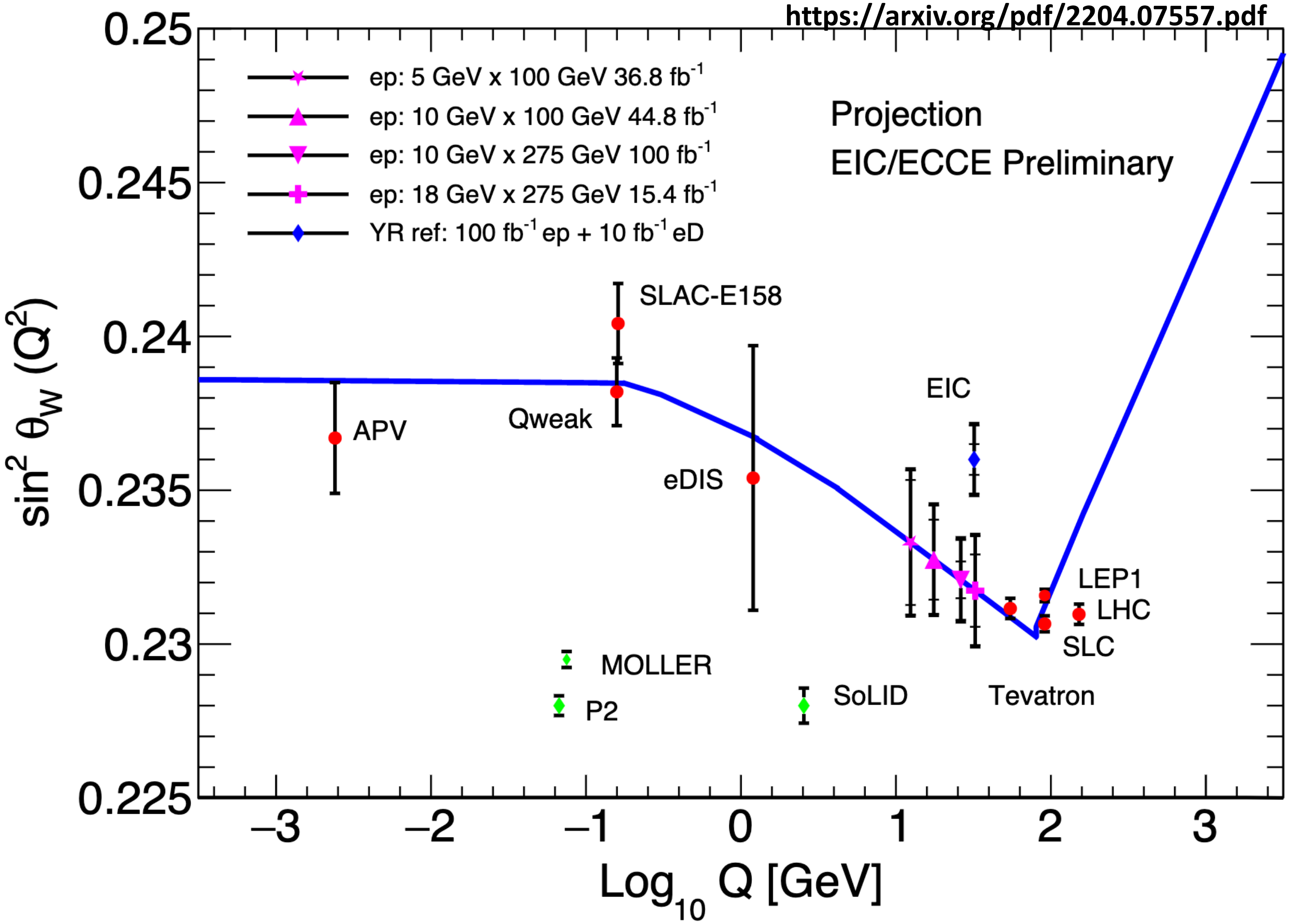


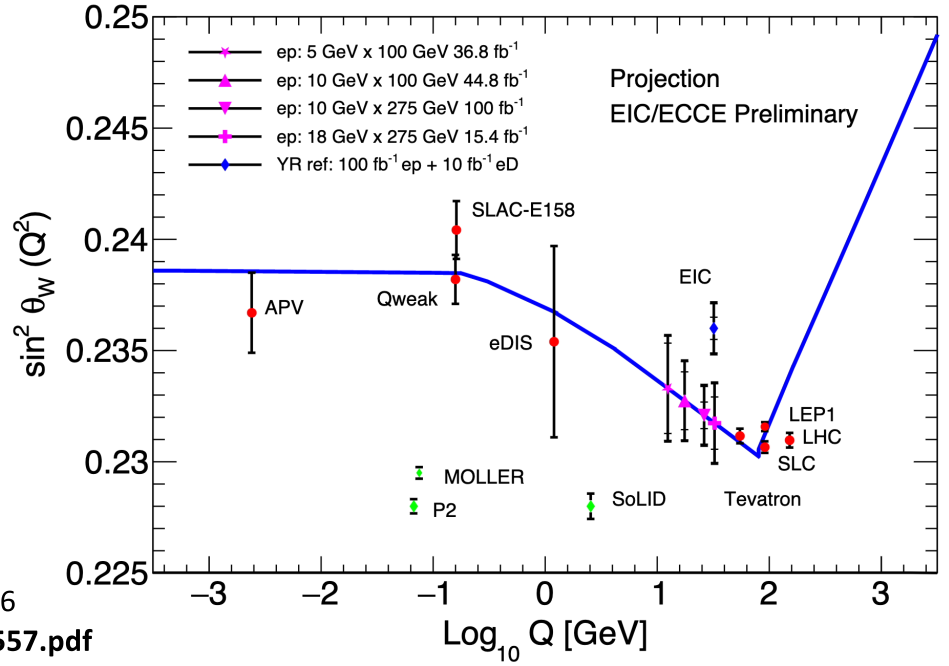


- The iso-singlet nature of deuterium made it an ideal candidate for precision measurements (PDF dependence cancels)

- Several recent analyses have shown that the PDF uncertainties have a small impact on the weak mixing angle extraction in ep
  - <u>Could this apply to SoLID?</u>

ECCE studies

- For the 2 highest sqrt(s) bins the polarization uncertainty is the dominant uncertainty on the parity violating asymmetry
- The PDF uncertainties were analyzed by looking at the impact of different replicas on the weak mixing angle extraction
  - They add very little to the overall experimental uncertainty



Phys.Rev.D 106 (2022) 1, 016006

https://arxiv.org/pdf/2204.07557.pdf

Beam type and energy Label	*ep* 5 × 100 P2	*ep* 10 × 100 P3	*ep* 10 × 275 P4	*ep* 18 × 275 P5	*ep* 18 × 275 P6
Luminosity (fb^{-1})	36.8	44.8	100	15.4	(100 YR ref)
$\langle Q^2\rangle$ (GeV^2)	154.4	308.1	687.3	1055.1	1055.1
$\langle A_{PV}\rangle$ ($P_e = 0.8$)	−0.00854	−0.01617	−0.03254	−0.04594	−0.04594
$(\mathrm{d}A/A)_{\mathrm{stat}}$	1.54%	0.98%	0.40%	0.80%	(0.31%)
$(\mathrm{d}A/A)_{\mathrm{stat+syst(bg)}}$	1.55%	1.00%	0.43%	0.81%	(0.35%)
$(\mathrm{d}A/A)_{1\%\mathrm{pol}}$	1.0%	1.0%	1.0%	1.0%	(1.0%)
$(\mathrm{d}A/A)_{\mathrm{tot}}$	1.84%	1.42%	1.09%	1.29%	(1.06%)
Experimental					
$\mathrm{d}(\sin^2\theta_W)_{\mathrm{stat+syst(bg)}}$	0.002032	0.001299	0.000597	0.001176	0.000516
$\mathrm{d}(\sin^2\theta_W)_{\mathrm{stat+syst+pol}}$	0.002342	0.001759	0.001297	0.001769	0.001244
with PDF					
$\mathrm{d}(\sin^2\theta_W)_{\mathrm{tot,CT18NLO}}$	0.002388	0.001807	0.001363	0.001823	0.001320
$\mathrm{d}(\sin^2\theta_W)_{\mathrm{tot,MMHT2014}}$	0.002353	0.001771	0.001319	0.001781	0.001270
$\mathrm{d}(\sin^2\theta_W)_{\mathrm{tot,NNPDF31}}$	0.002351	0.001789	0.001313	0.001801	0.001308

Eur. Phys. J. A (2017) 53: 55
https://arxiv.org/pdf/1612.06927

Structure functions

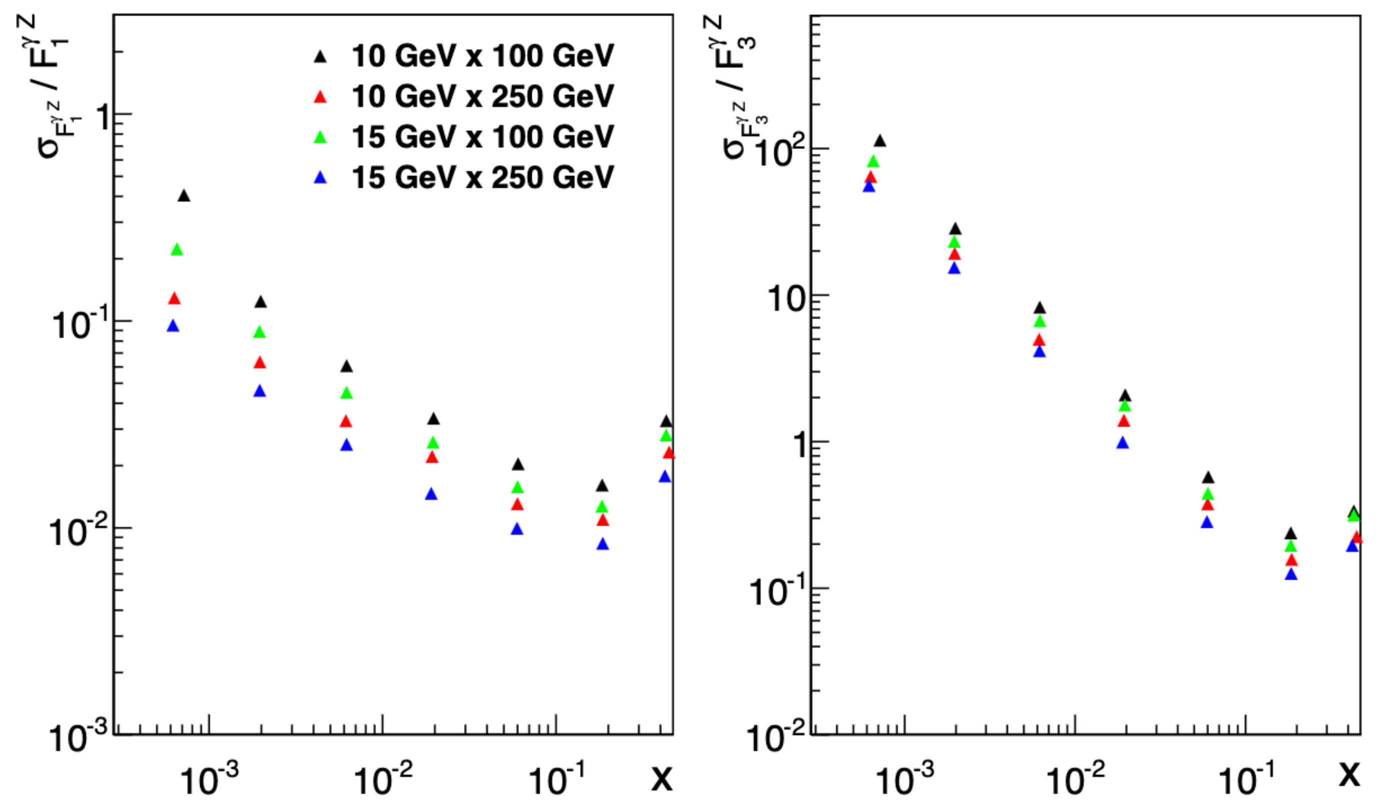
$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$F_1^{p,\gamma Z} \approx \frac{1}{9}(u+\bar{u}+d+\bar{d}+s+\bar{s}+c+\bar{c})$$

$$F_1^{n,\gamma Z} \approx \frac{1}{9}(u+\bar{u}+d+\bar{d}+s+\bar{s}+c+\bar{c})$$

$$F_3^{p,\gamma Z} = \frac{2}{3}(u_V+c-\bar{c})+\frac{1}{3}(d_V+s-\bar{s})$$

$$F_3^{n,\gamma Z} = \frac{2}{3}(d_V+s-\bar{s})+\frac{1}{3}(u_V+c-\bar{c})$$



- High x points will require tight control of systematics (especially polarimetry)
- Old study with much higher statistics than is expected at the EIC but still an interesting avenue of study

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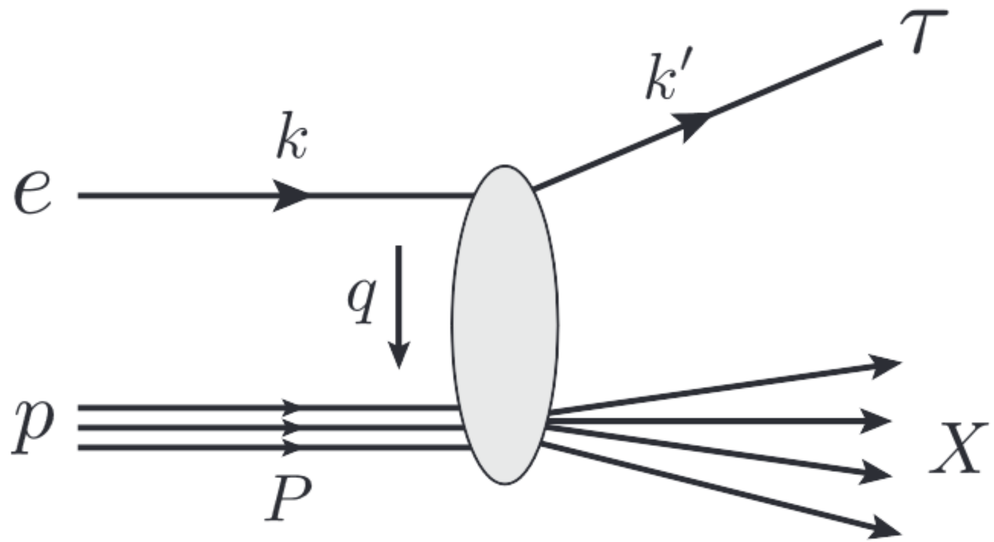
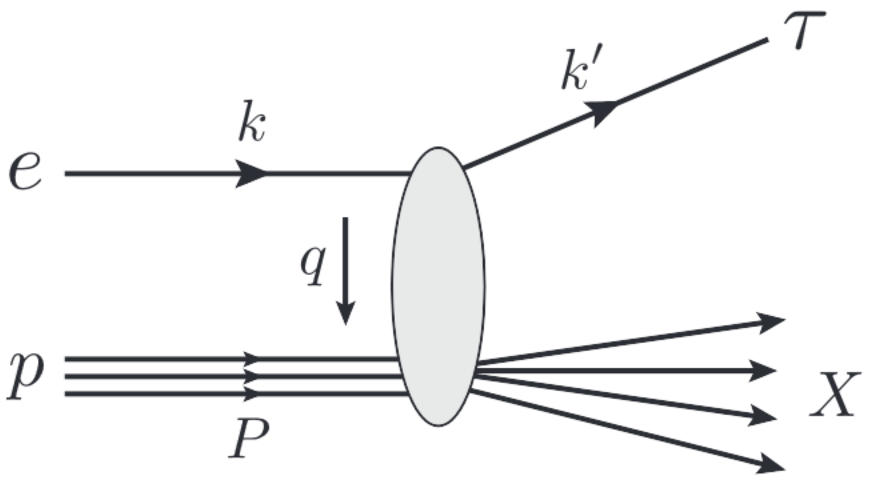


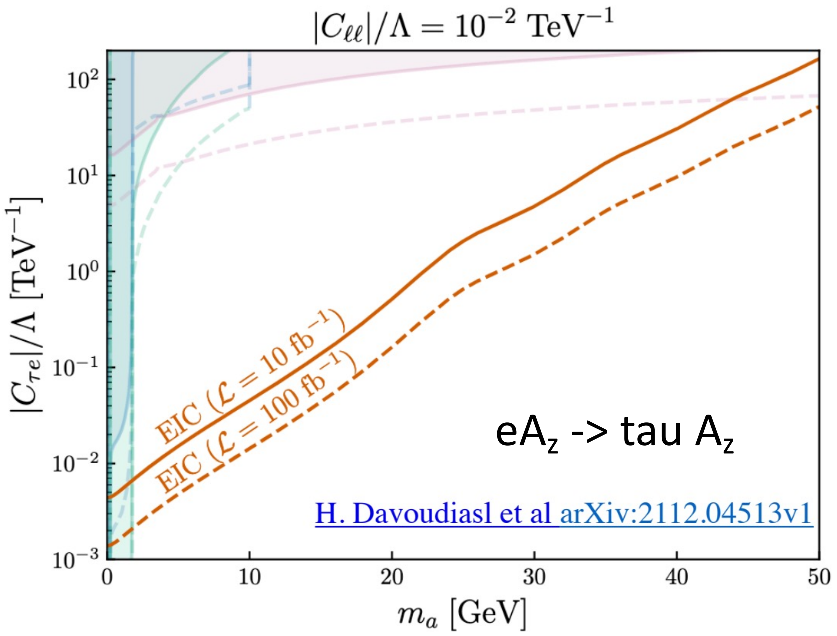
Charged lepton flavor violation

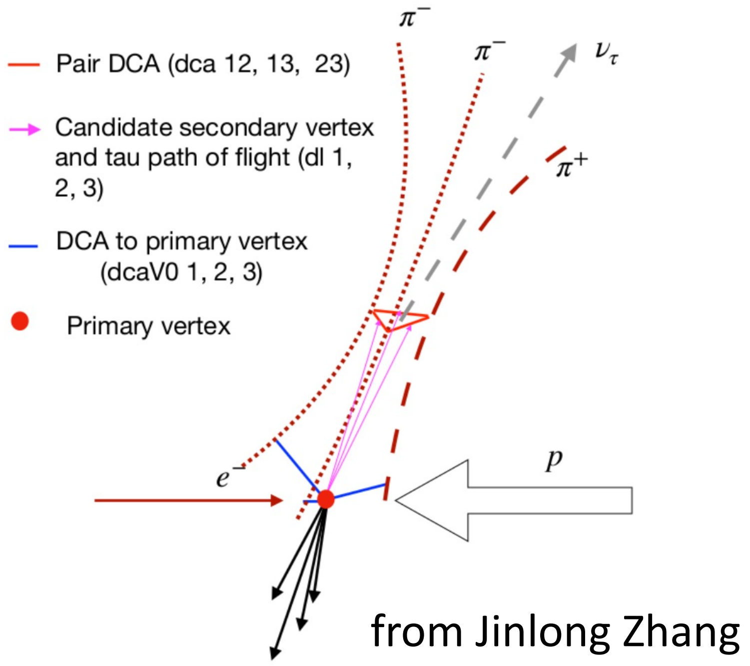
- The e -> tau constraints currently still allow for the EIC to probe new phase space
- Initial interest in the e -> tau conversions was on the three-pion decay mode due to its topological signature
  - Studies done by Jinlong Zhang indicate that this channel alone could increase the limits set by HERA by a factor of 2 (at 100 fb^{-1}) and comparable to limits set by BABAR



JHEP 03 (2021) 256
https://arxiv.org/pdf/2102.06176.pdf

- Sensitivity to axion-like particles has been shown to be quite high for the EIC in eA collisions through similar measurements (where nucleus stays intact)



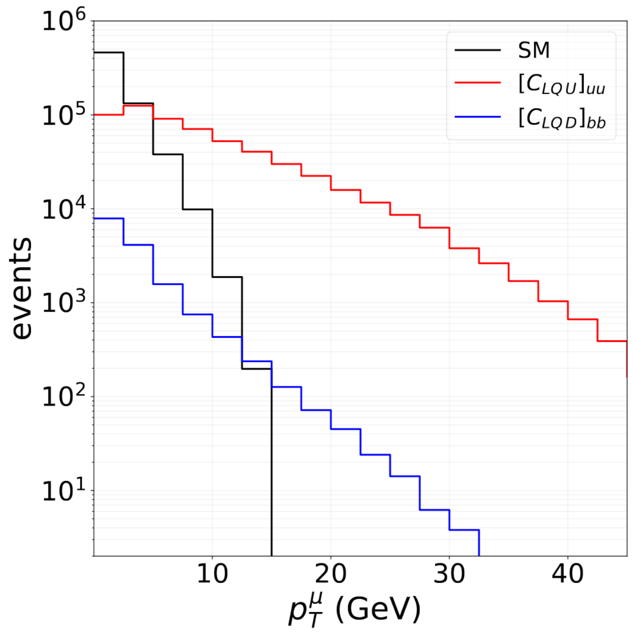


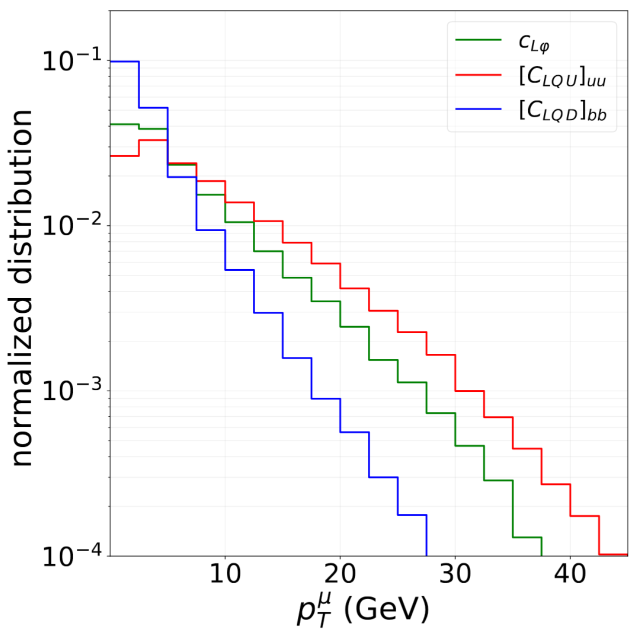
from Jinlong Zhang

Charged lepton flavor violation

JHEP 03 (2021) 256
https://arxiv.org/pdf/2102.06176.pdf

- An analysis by Emanuele and collaborators shows that looking at the 1-prong muon decay of the tau allows for very efficient background suppression
- Analysis used ATHENA Delphes card and looked at SM processes and a leptoquark generator





$$ep \to \tau X \to \mu + \not{E} + X$$

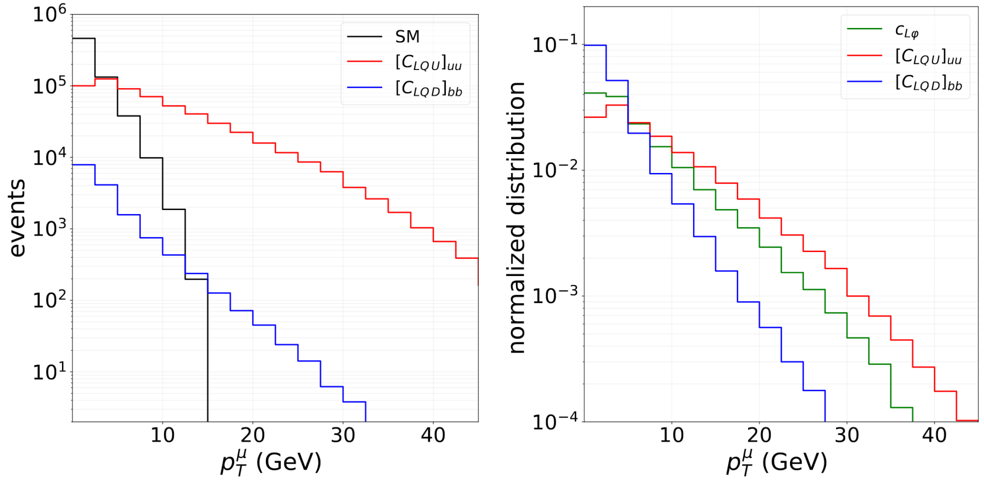
from E. Mereghetti

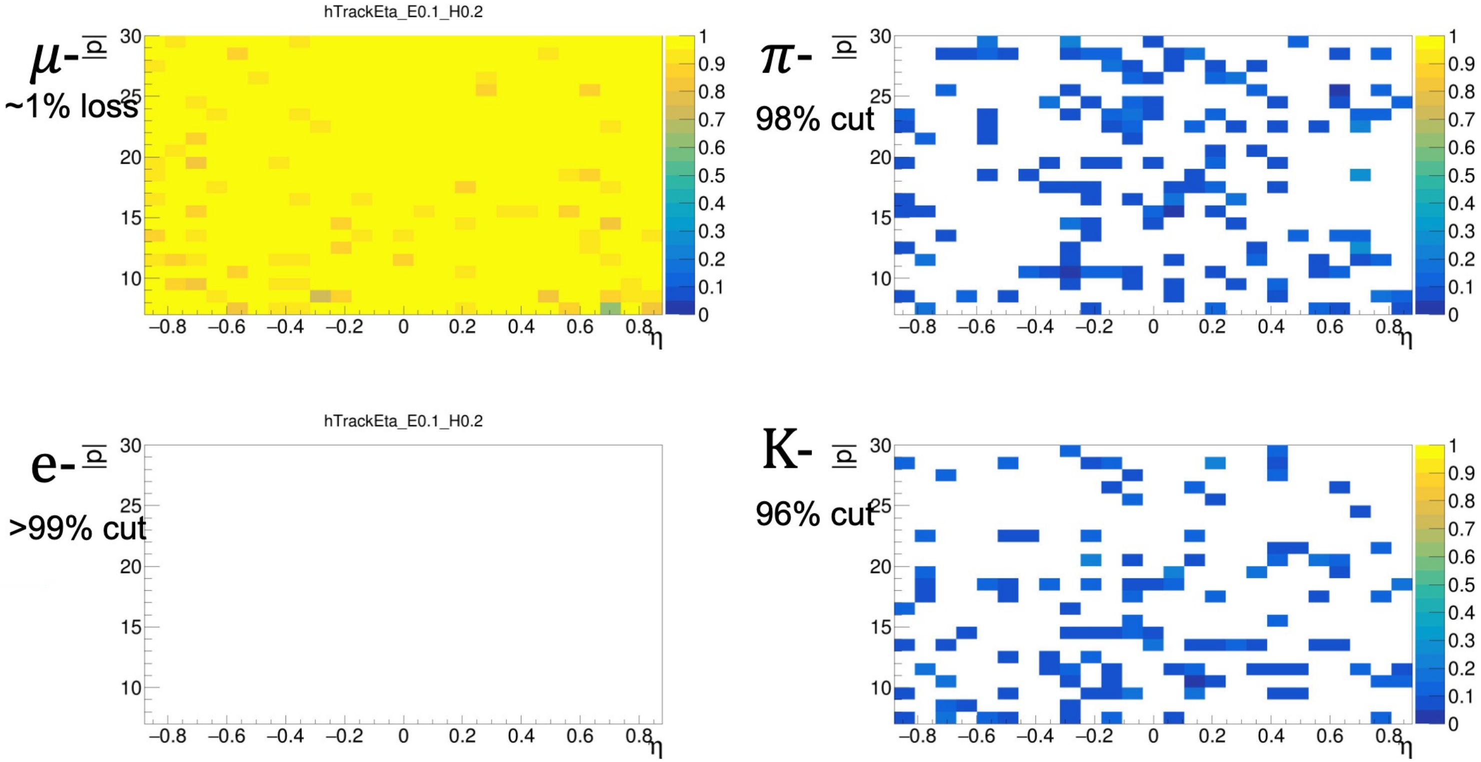
$$p_T^\mu > 10\,\text{GeV}, \quad \not{E}_T > 15\,\text{GeV}, \quad p_T^{j_1} > 20\,\text{GeV}$$

eliminates all SM background

Charged lepton flavor violation

$$ep \to \tau X \to \mu + \not{E} + X$$





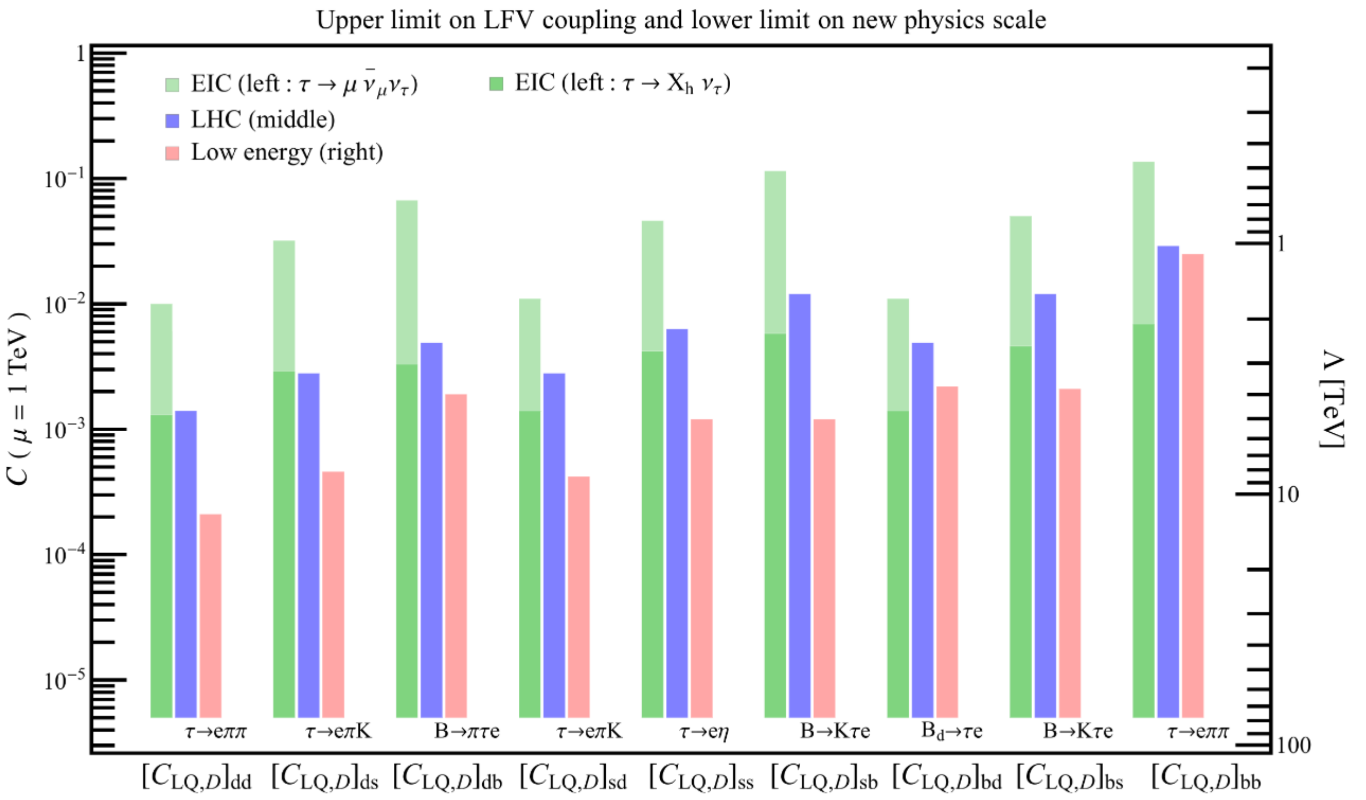
A. Hurley:
https://www.int.washington.edu/sites/default/files/schedule_session_files/Hurley_A.pdf

- Initial analysis using the ePIC detector shows a good background rejection giving hopes towards muon ID

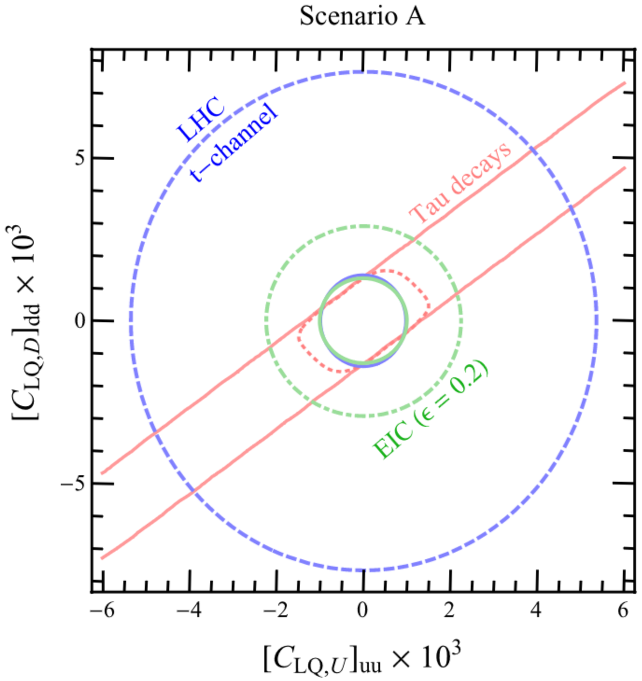
Charged lepton flavor violation

JHEP 03 (2021) 256
https://arxiv.org/pdf/2102.06176.pdf

- Depending on the LQ model involved the EIC has varying degrees of constraining power
- When taken into a global context the EIC data can provide significant constraints on contact interaction terms together with low energy and LHC data



The additional inclusion of hadronic tau decays (dark green) increases the sensitivity by more than a factor of 10 in some cases bringing the EIC close to LHC limits



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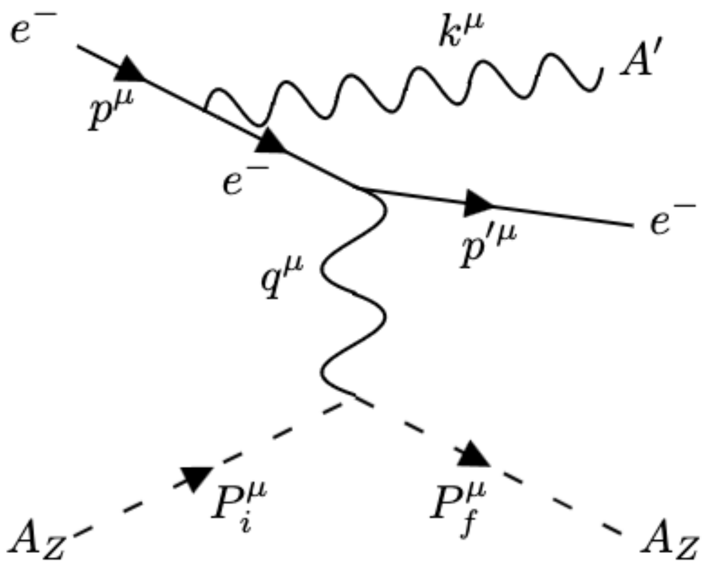
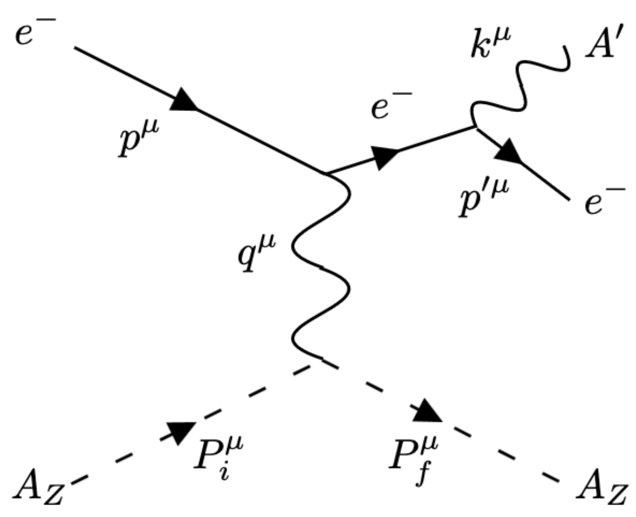


Backwards physics/eA searches

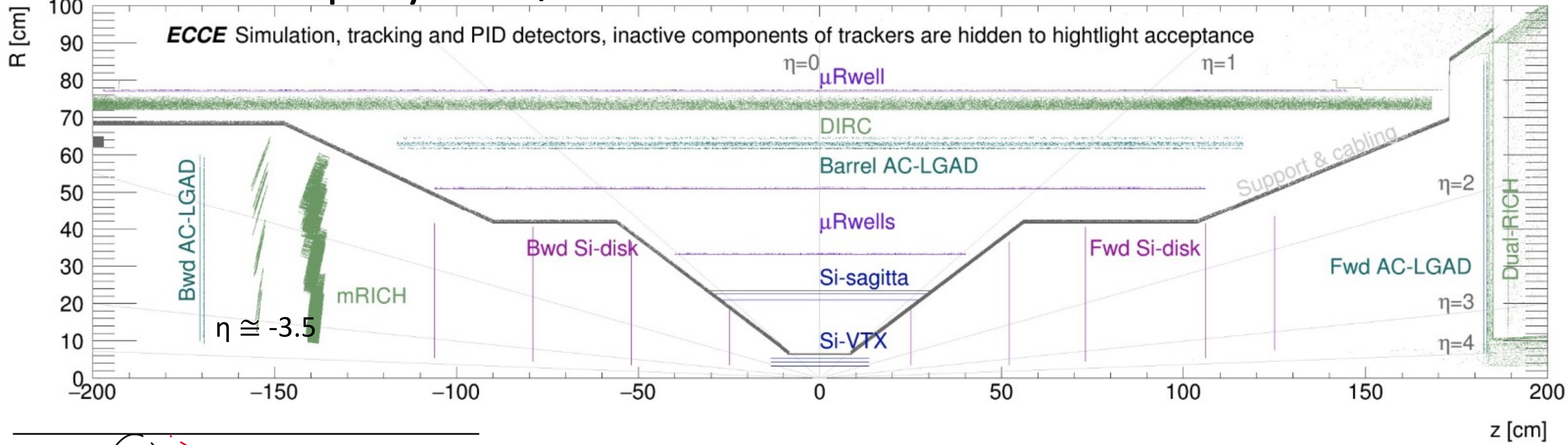
- Dark vector bosons:
  - dark U(1), analog to visible EM
  - dark photon (kinetic mixing) or dark Z (mass mixing)
  - very weakly interacting gauge bosons
- Dark scalars:
  - axion-like particles, analog to pions

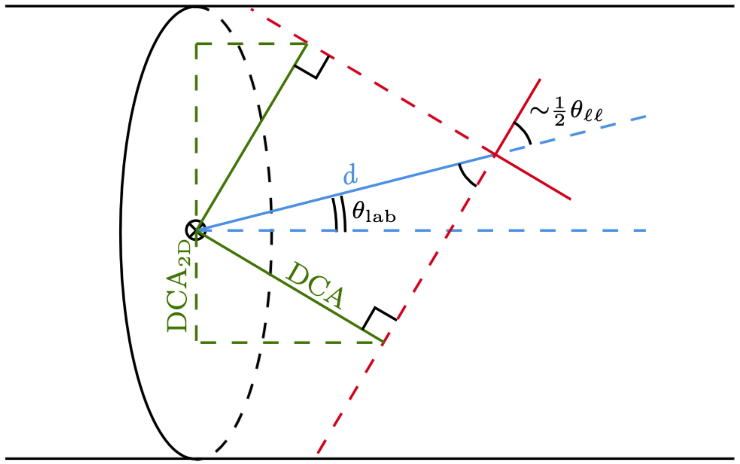


- eA collisions at very low Q^2 (~10MeV)
- coherent production of the new particle is enhanced by a factor of Z^2
- Ion emission suppressed by the form factor

$$iV^\mu(q^2, P_i, P_f) = ieZF(q^2)P^\mu$$

Backwards physics/eA searches





H. Davoudiasl, E. Niel

- The area -6 < η < -4 is mostly free of SM background
- Requires very good DCA (200μm) at a 5m distance from the vertex
  - No current detection capability planned in ePIC

https://www.int.washington.edu/sites/default/files/schedule_session_files/Davoudiasl_H.pdf
https://www.int.washington.edu/sites/default/files/schedule_session_files/Neil_E.pdf

Backwards physics/eA searches

https://arxiv.org/pdf/2307.00102

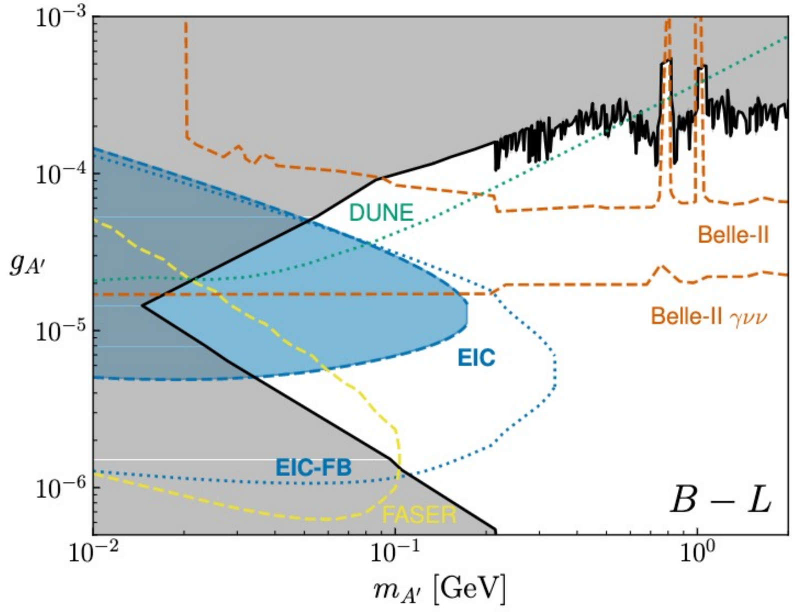


FIG. 3: Projected constraints (95% C.L.) on the interaction strength of a $U(1)_{B-L}$ vector gauge boson at the EIC. Colors and references follow Fig. 2. The excluded region

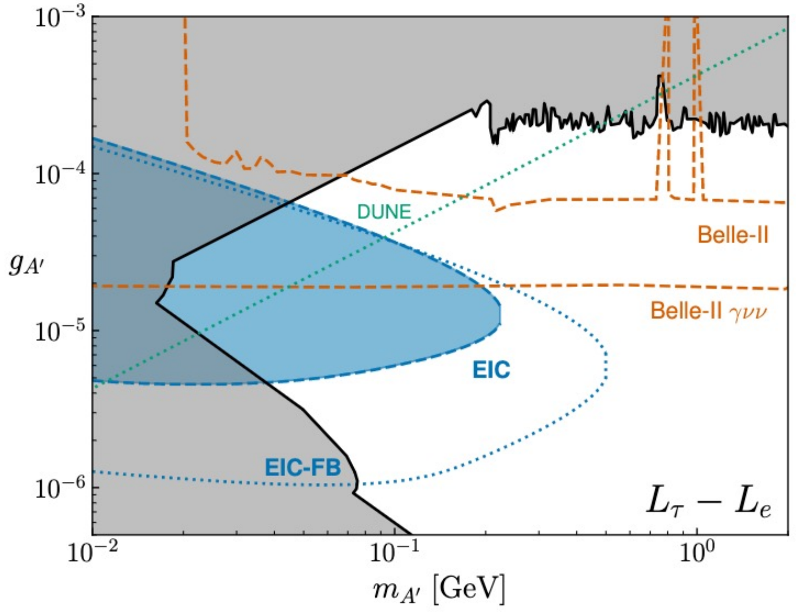


FIG. 5: Projected constraints (95% C.L.) on the interaction strength of a $U(1)_{L_\tau - L_e}$ vector gauge boson at the EIC. Details of the regions shown follow Fig. 4.

- The EIC is very competitive with future experiments especially if one takes into account the very backward region

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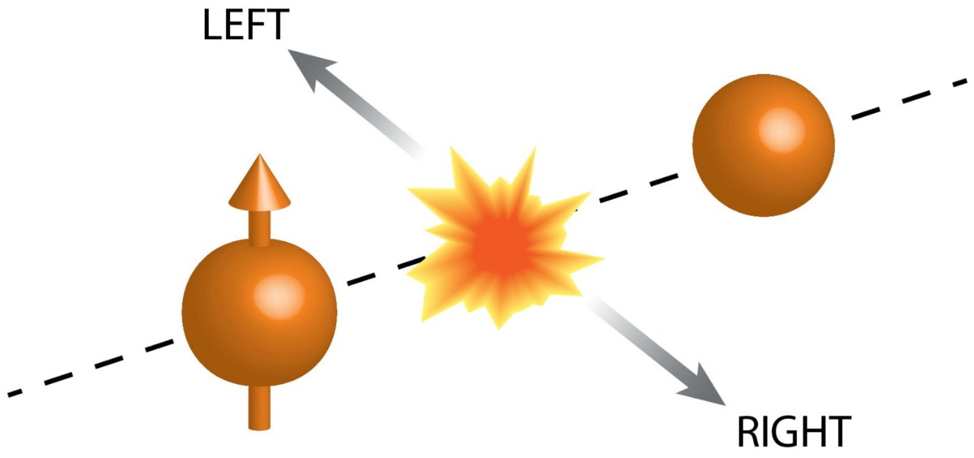
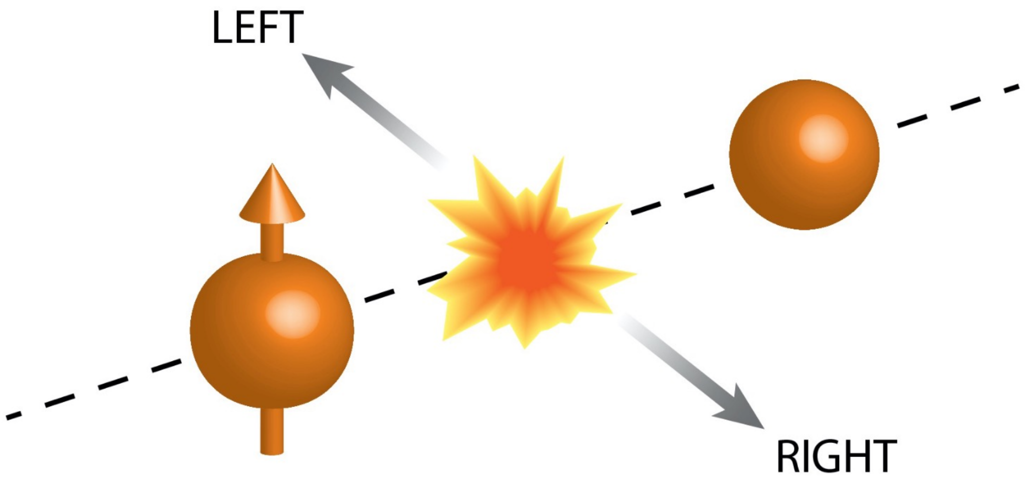


Transverse asymmetries



- Collecting precision data with transverse polarizations (electron or ion) at the EIC can constrain new couplings within the SMEFT framework
  - The asymmetry is between same or opposite direction alignments of the spin and the cross product of the incoming and outgoing lepton momentum

$$A_{TU} = \frac{\sigma(e^{\uparrow}) - \sigma(e^{\downarrow})}{\sigma(e^{\uparrow}) + \sigma(e^{\downarrow})},$$

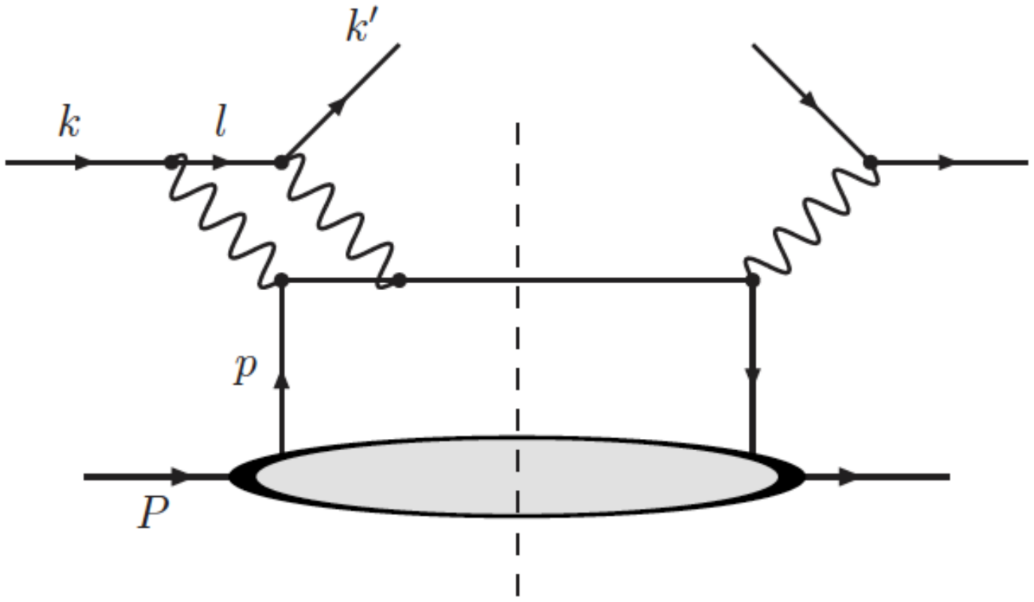
$$A_{UT} = \frac{\sigma(p^{\uparrow}) - \sigma(p^{\downarrow})}{\sigma(p^{\uparrow}) + \sigma(p^{\downarrow})}$$

$$A_{TU}^{\gamma\gamma}(\phi) = \alpha \frac{m_l}{2Q} \sin(\phi) \frac{y^2\sqrt{1-y}}{1-y+y^2/2} \frac{\sum_q Q_q^3 f_q(x)}{\sum_q Q_q^2 f_q(x)}.$$

https://www.int.washington.edu/sites/default/files/schedule_session_files/Petriello_F.pdf

Transverse asymmetries

- Collecting precision data with transverse polarizations (electron or ion) at the EIC can constrain new couplings within the SMEFT framework
  - The asymmetry is between same or opposite direction alignments of the spin and the cros product of the incoming and outgoing leptor momentum
- In the SM the leading QED contribution comes from two photon exchanges



$$A_{TU}^{\gamma\gamma}(\phi) = \alpha \frac{m_l}{2Q} \sin(\phi) \frac{y^2\sqrt{1-y}}{1-y+y^2/2} \frac{\sum_q Q_q^3 f_q(x)}{\sum_q Q_q^2 f_q(x)}.$$

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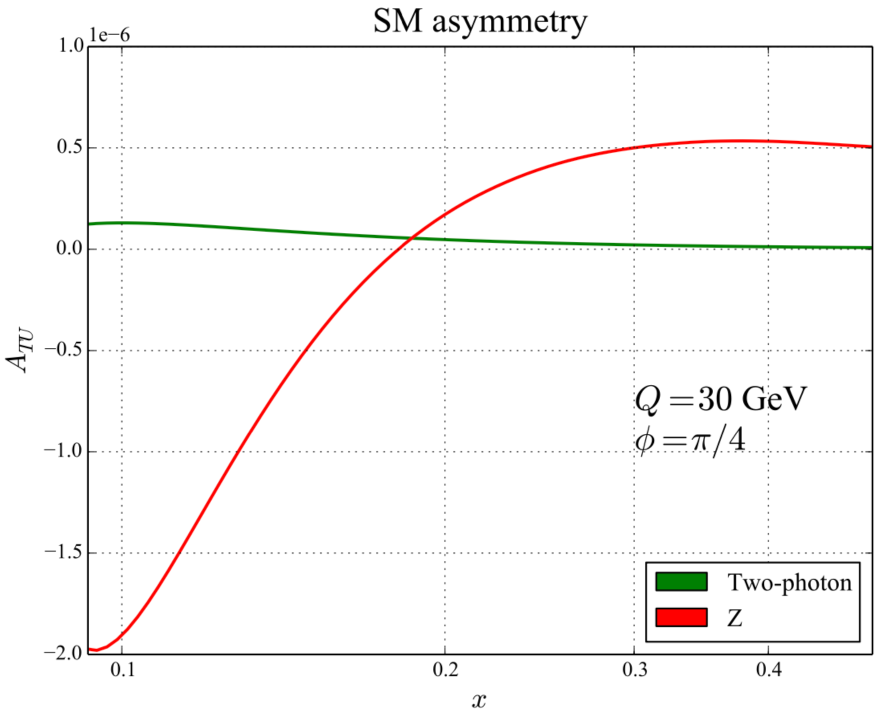
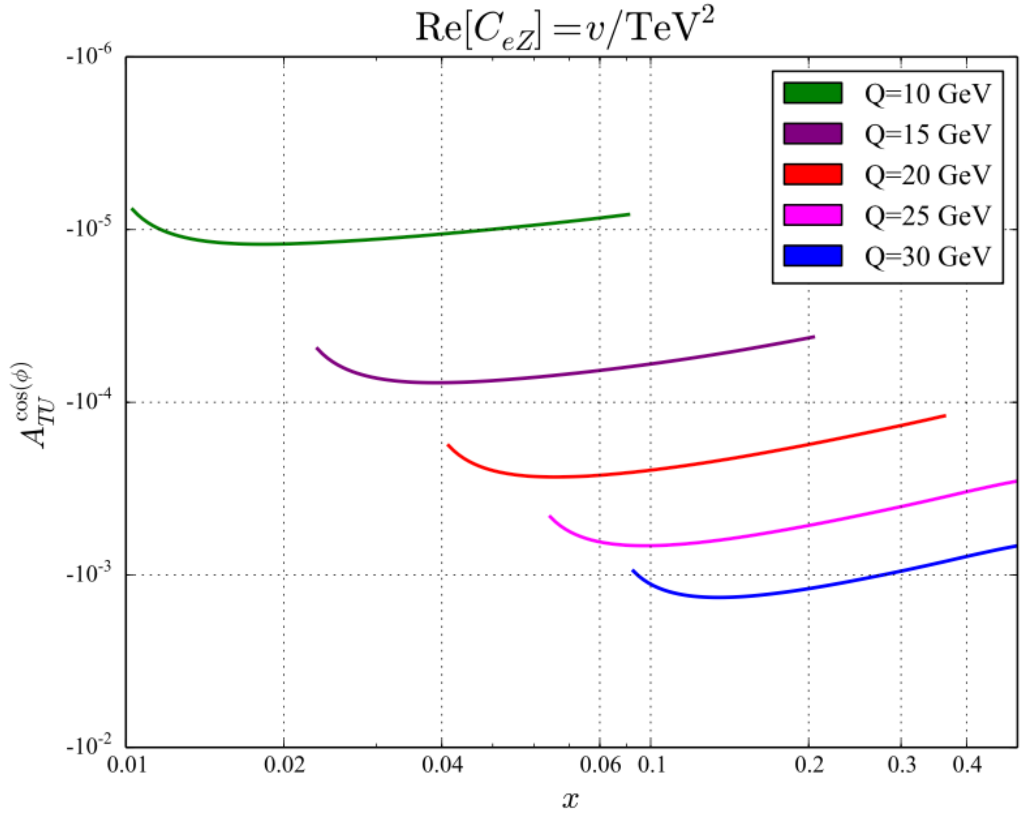
Phys.Rev.D 107 (2023) 7, 075028
(arXiv 2301.02304)

Transverse asymmetries

$$A_{TU}^{Z}(\phi) = \frac{2}{s_W^2 c_W^2} \frac{m_l Q}{M_Z^2} \frac{y\sqrt{1-y}}{1-y+y^2/2} \cos(\phi) \frac{\sum_q Q_q f_q(x) \left[g_{al} g_{vq}(1-y) + g_{vl} g_{aq} y\right]}{\sum_q Q_q^2 f_q(x)}.$$





- The analysis done by Radja B and collaborators has identified a new contribution to the SSA from the gamma-Z interference in inclusive reactions

- Using this data in the SMEFT framework shows that constraints can be placed on different dipole couplings at TeV scales complementary to anomalous electric or magnetic dipole measurements

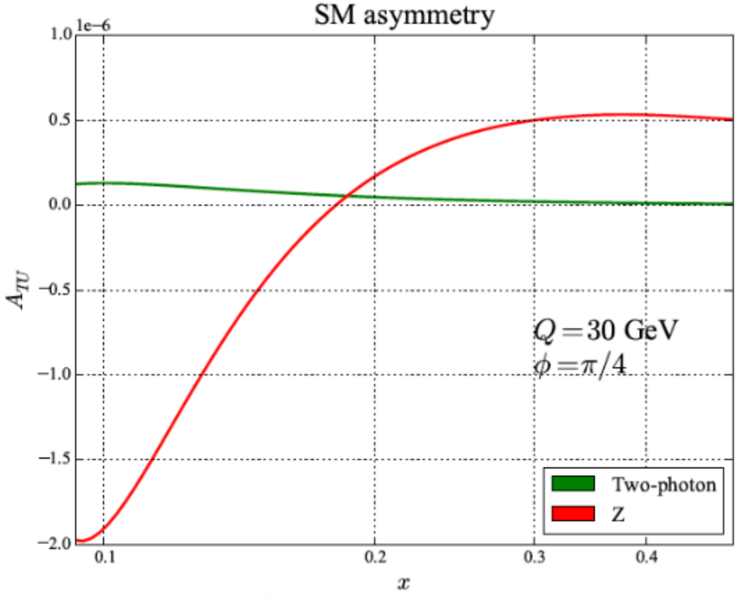
Phys.Rev.D 107 (2023) 7, 075028
(arXiv 2301.02304)

A_TU in DIS

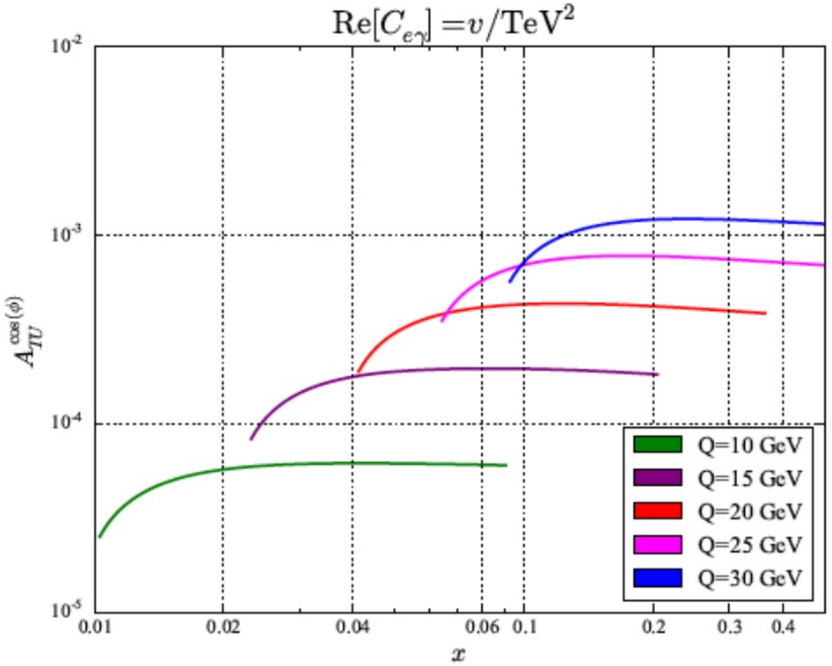
Dipole operators

$$\begin{aligned}
\mathcal{O}_{eW} &= (\bar{l}\sigma^{\mu\nu}e)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{eB} &= (\bar{l}\sigma^{\mu\nu}e)\varphi B_{\mu\nu},\\
\mathcal{O}_{uW} &= (\bar{q}\sigma^{\mu\nu}u)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{uB} &= (\bar{q}\sigma^{\mu\nu}u)\varphi B_{\mu\nu},\\
\mathcal{O}_{dW} &= (\bar{q}\sigma^{\mu\nu}d)\tau^I\varphi W^I_{\mu\nu},\\
\mathcal{O}_{dB} &= (\bar{q}\sigma^{\mu\nu}d)\varphi B_{\mu\nu}.
\end{aligned}$$

Dipole operators contribute when interfered with the SM. Transverse SSAs can isolate these same contributions that affect anomalous magnetic (and electric as we'll see) moments!



- The 2-photon exchange is on the level of 1e-7 at Q=30 GeV
- The potential contribution from the dipole operators is 1e-3 for Q=30 GeV
- There is a scaling with Q^2 so by the time you reach JLab energies you are on a similar level as the 2-photon exchange

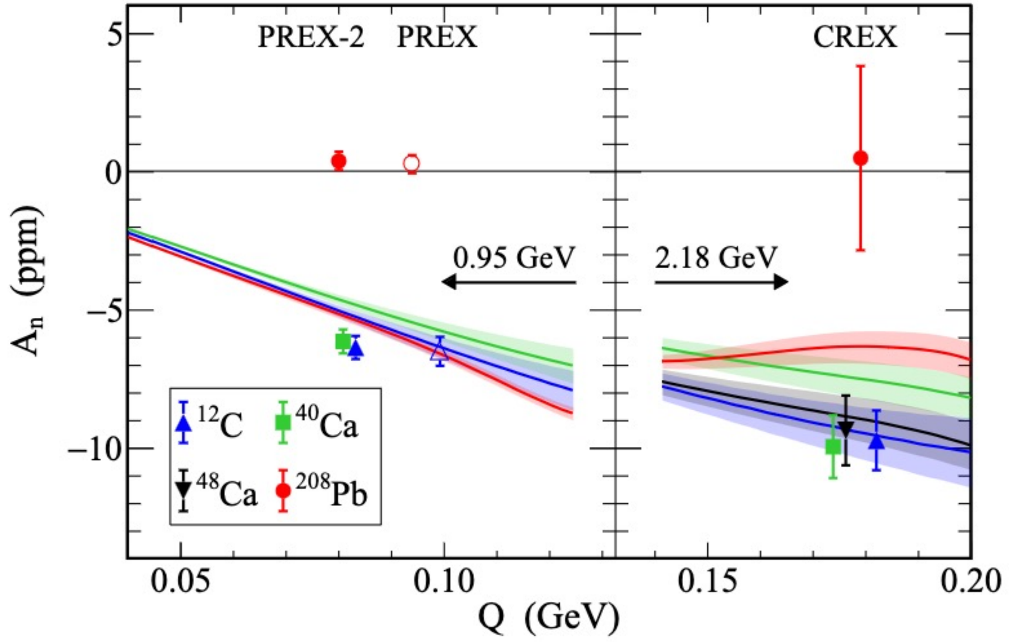


PREX, PREX-2, CREX ATU results

https://arxiv.org/pdf/2111.04250.pdf

E_{beam} (GeV)	Target	$\langle\theta_{lab}\rangle$ (deg)	$\langle Q^2\rangle$ (GeV^2)	$\langle\cos\phi\rangle$
0.95	^{12}C	4.87	0.0066	0.967
0.95	^{40}Ca	4.81	0.0065	0.964
0.95	^{208}Pb	4.69	0.0062	0.966
2.18	^{12}C	4.77	0.033	0.969
2.18	^{40}Ca	4.55	0.030	0.970
2.18	^{48}Ca	4.53	0.030	0.970
2.18	^{208}Pb	4.60	0.031	0.969

TABLE I. A_n measurement kinematics.



E_{beam} (GeV)	Target	A_n (ppm)	$A_{avg}^{Z\leq 20}$ (ppm)	$\frac{A_n - A_{avg}^{Z\leq 20}}{uncert}$
0.95	^{12}C	-6.3 ± 0.4	-6.2 ± 0.2	
0.95	^{40}Ca	-6.1 ± 0.3		
0.95	^{208}Pb	0.4 ± 0.2		21 σ
2.18	^{12}C	-9.7 ± 1.1	-9.7 ± 0.6	
2.18	^{40}Ca	-10.0 ± 1.1		
2.18	^{48}Ca	-9.4 ± 1.1		
2.18	^{208}Pb	0.6 ± 3.2		3.2 σ

- We measured the A_TU asymmetry in lead (and other nuclei)
- The low Z nuclei agree well with the 2-photon exchange expectations
- Lead however has a 21 sigma discrepancy that cannot be accounted for
  - in fact it has the opposite sign compared to the 2-photon exchange contribution (red curve in the plot)

Simple scaling argument

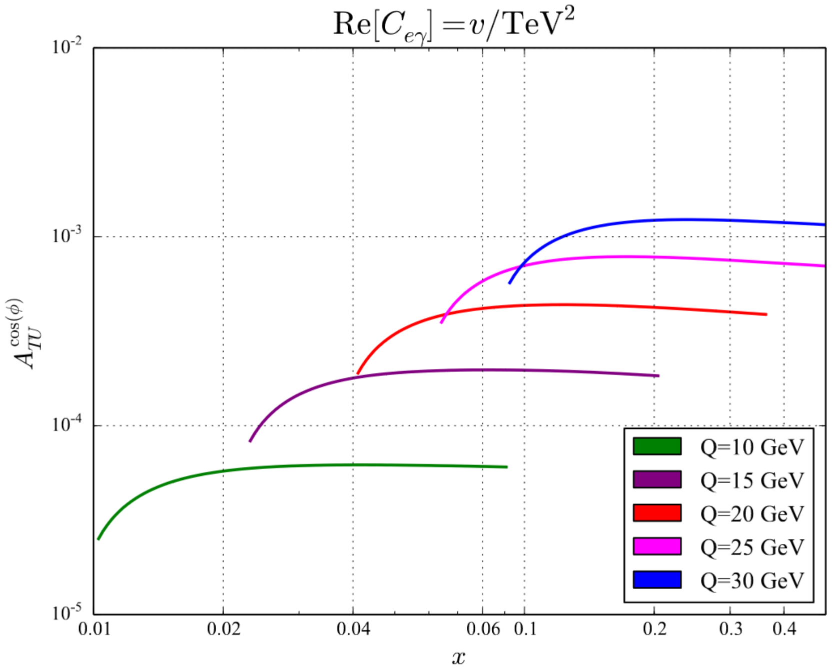
$$A_{TU\ Q=10MeV} = A_{TU\ Q=10GeV} \times f_{energyScale} \times f_{coherence}$$

$$f_{energyScale} = \frac{0.0062\ GeV^2}{100\ GeV^2} = 6 \cdot 10^{-5}$$

$$f_{coherence} = Z^2 = 82^2 = 6274$$

$$A_{TU\ PREX-2} = 4 \cdot 10^{-5} \times 6 \cdot 10^{-5} \cdot 6274$$

$$= 17\ ppm$$



- Doing a simple Q^2 scaling seems to indicate that the level of the effect in a coherent scattering off lead is indeed in the right ball-park as the 2-photon exchange contribution
- If the sign is opposite than the 2-photon exchange it could be the effect that we saw with these experiments
- New proposal scanning Z Ca to Th submitted using SHMS

E_{beam} (GeV)	Target	A_n (ppm)	$A_{avg}^{Z\leq 20}$ (ppm)	$\frac{A_n - A_{avg}^{Z\leq 20}}{uncert}$
0.95	^{12}C	-6.3 ± 0.4	-6.2 ± 0.2	
0.95	^{40}Ca	-6.1 ± 0.3		
0.95	^{208}Pb	0.4 ± 0.2		$21\ \sigma$
2.18	^{12}C	-9.7 ± 1.1	-9.7 ± 0.6	
2.18	^{40}Ca	-10.0 ± 1.1		
2.18	^{48}Ca	-9.4 ± 1.1		
2.18	^{208}Pb	0.6 ± 3.2		$3.2\ \sigma$

Summary of EIC EW&BSM topics at the EIC

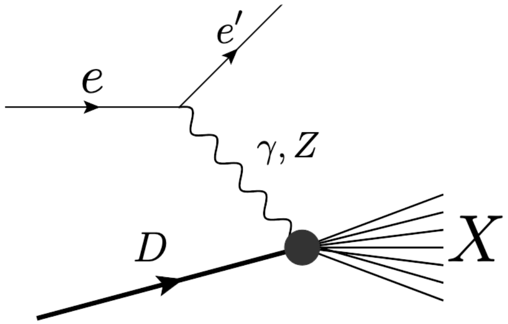
INT WORKSHOP INT-24-87W

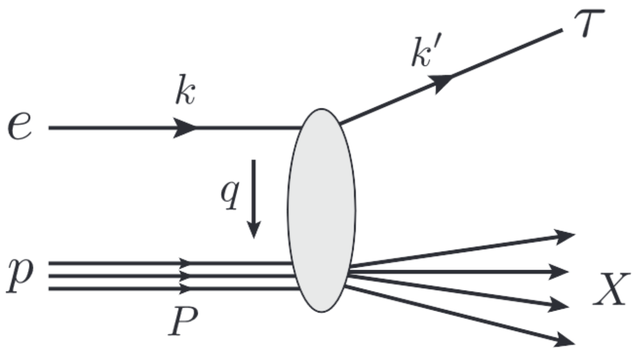
Electroweak and Beyond the Standard Model Physics at the EIC

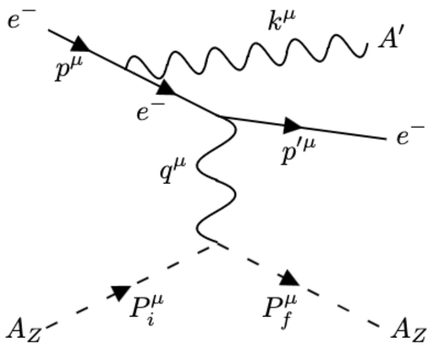
February 12, 2024 - February 16, 2024

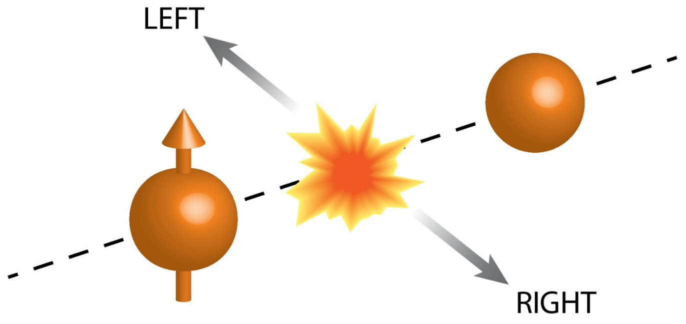
https://www.int.washington.edu/index.php/program/schedule/24-87W

- With the lack of direct observation of new physics precision measurements provide the only experimental direction for further theoretical developments







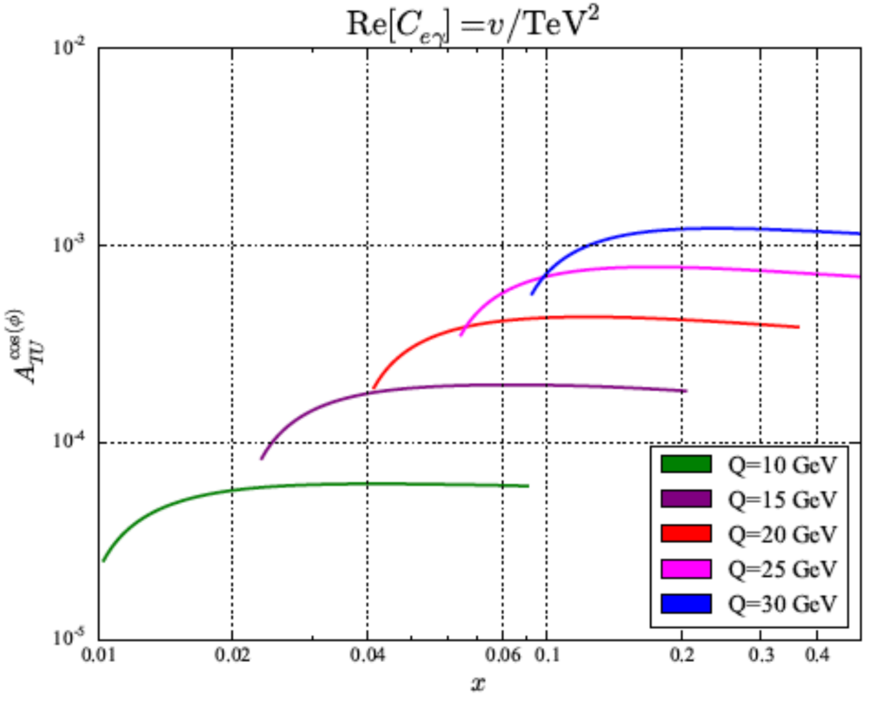


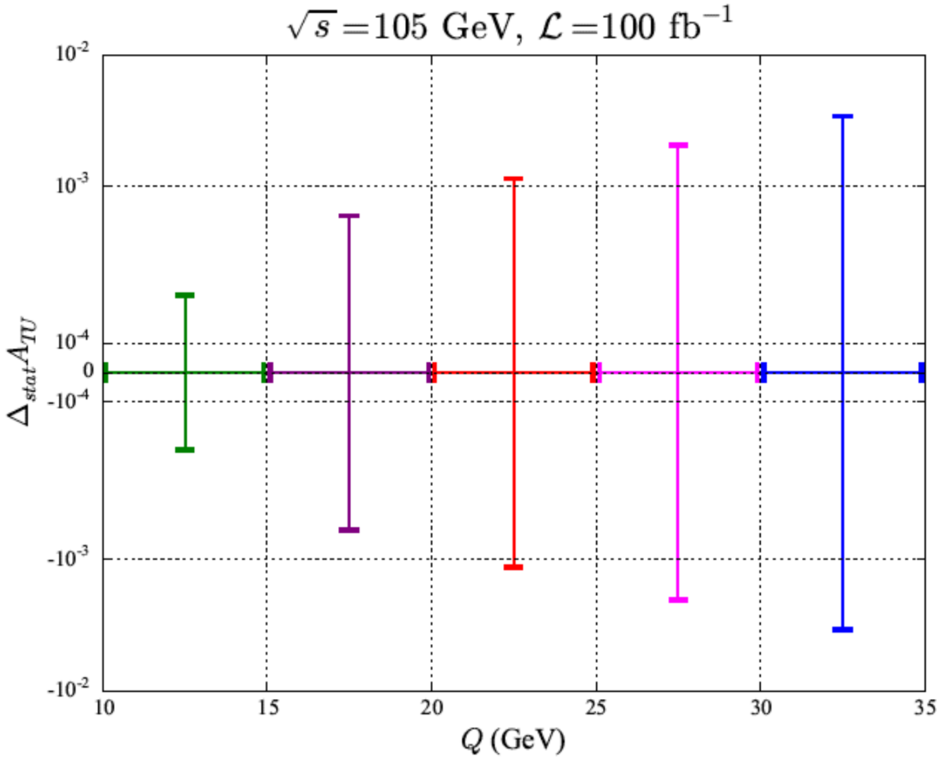
Backups

https://www.int.washington.edu/sites/default/files/schedule_session_files/Petriello_F.pdf

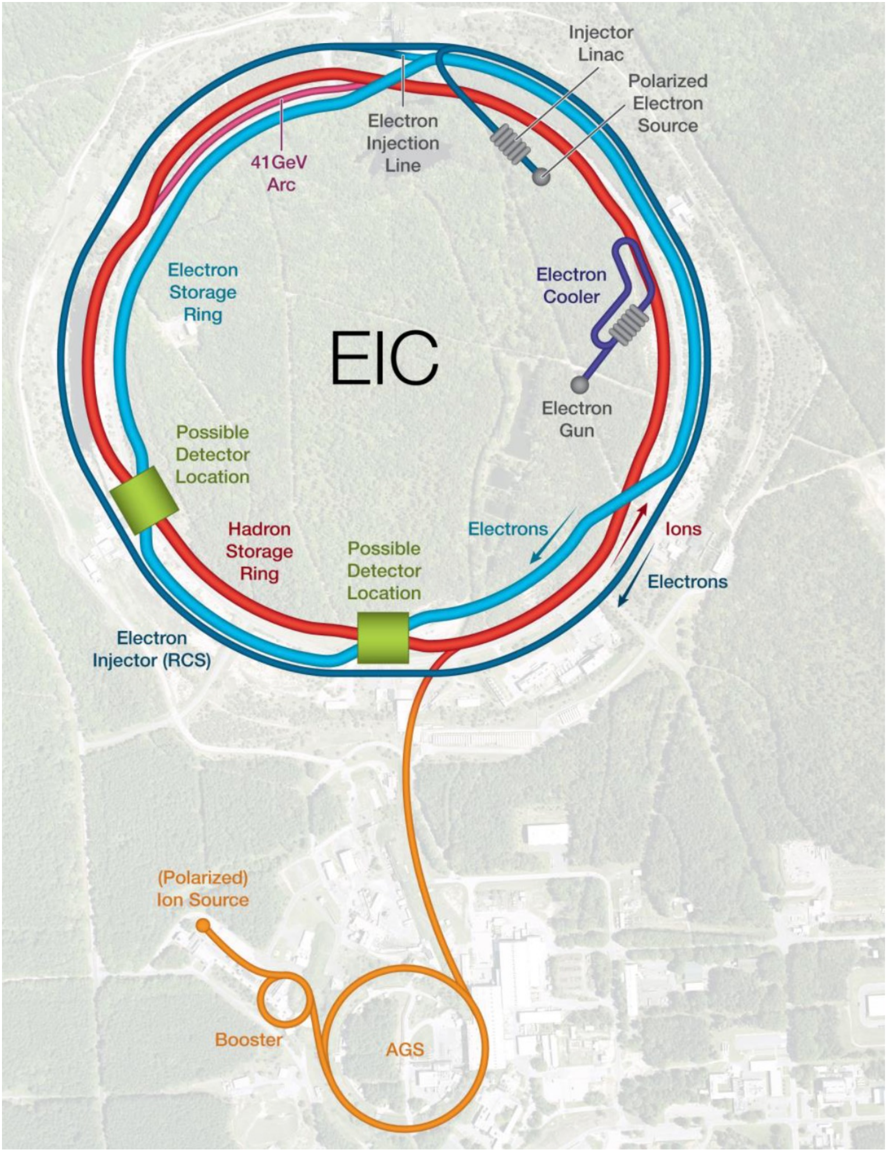
Numerics at an EIC

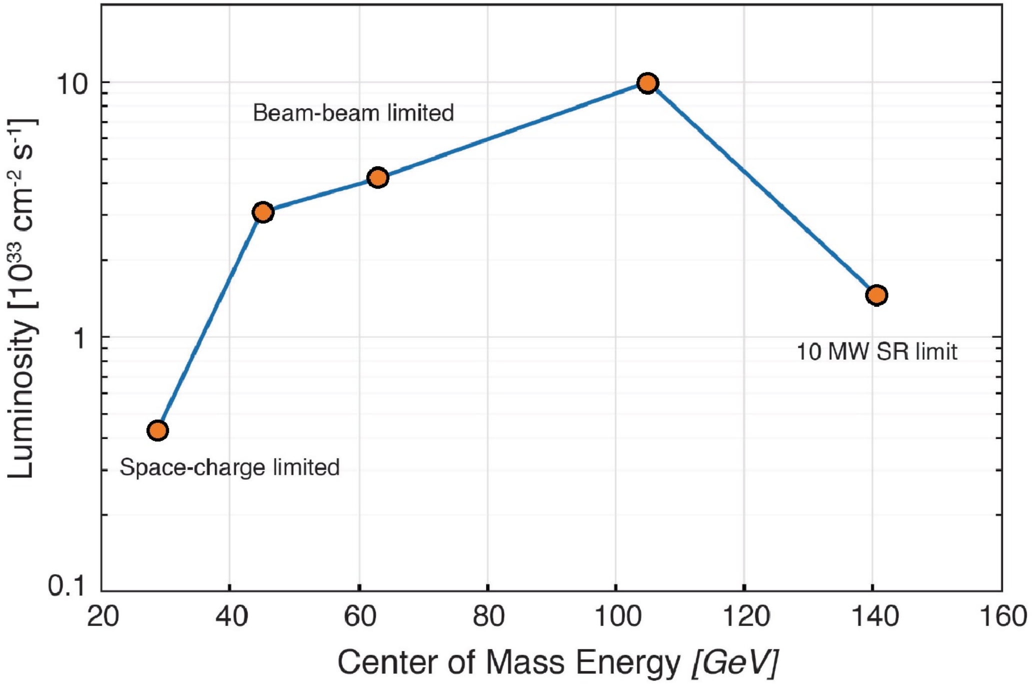
- Since we are unaware of any EIC simulation of transverse spin asymmetry data at the EIC, we can only do a rough calculation of the expected statistical uncertainty at the EIC. This figure show the uncertainty integrated over Bjorken-x. Integrating the asymmetry over x in each Q bin leads to a several sigma deviation from the SM for TeV-scale Wilson coefficients.





Electron Ion Collider



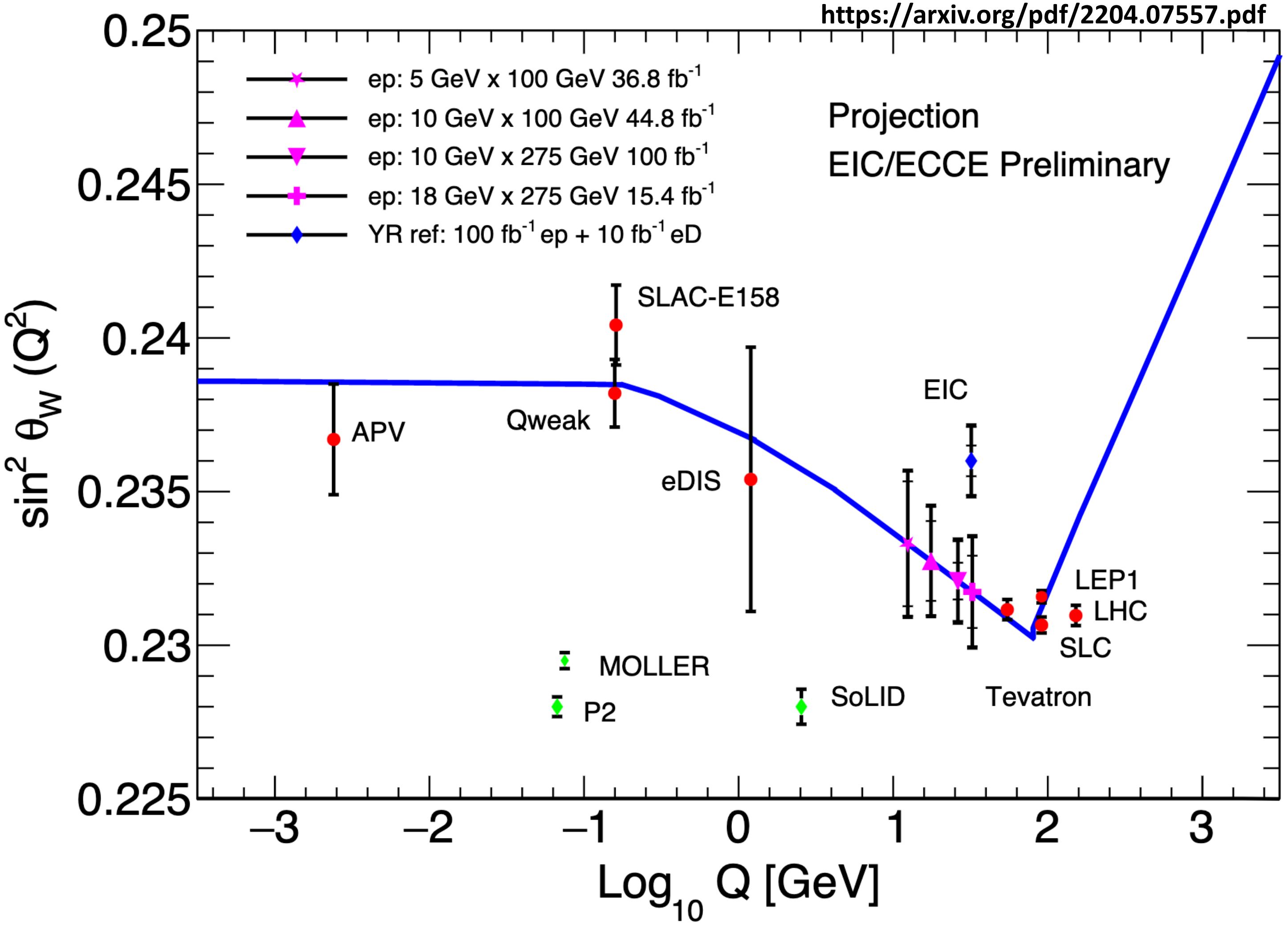


- The EIC will be built in the current RHIC tunnel and allow for up to two interaction regions
  - Colliding polarized electrons with polarized protons and light ions, or heavier nuclei (up to Uranium)
- The luminosity of this machine will be orders of magnitude higher than what was achieved at HERA

ECCE studies

- The studies performed by the ECCE EW&BSM group averaged all the statistics in each sqrt(s) configuration into one point
- The assumption of 1% background contamination was assumed to be subtractable by determining the parity violating asymmetry can be measured separately

Phys.Rev.D 106 (2022) 1, 016006
https://arxiv.org/pdf/2204.07557.pdf



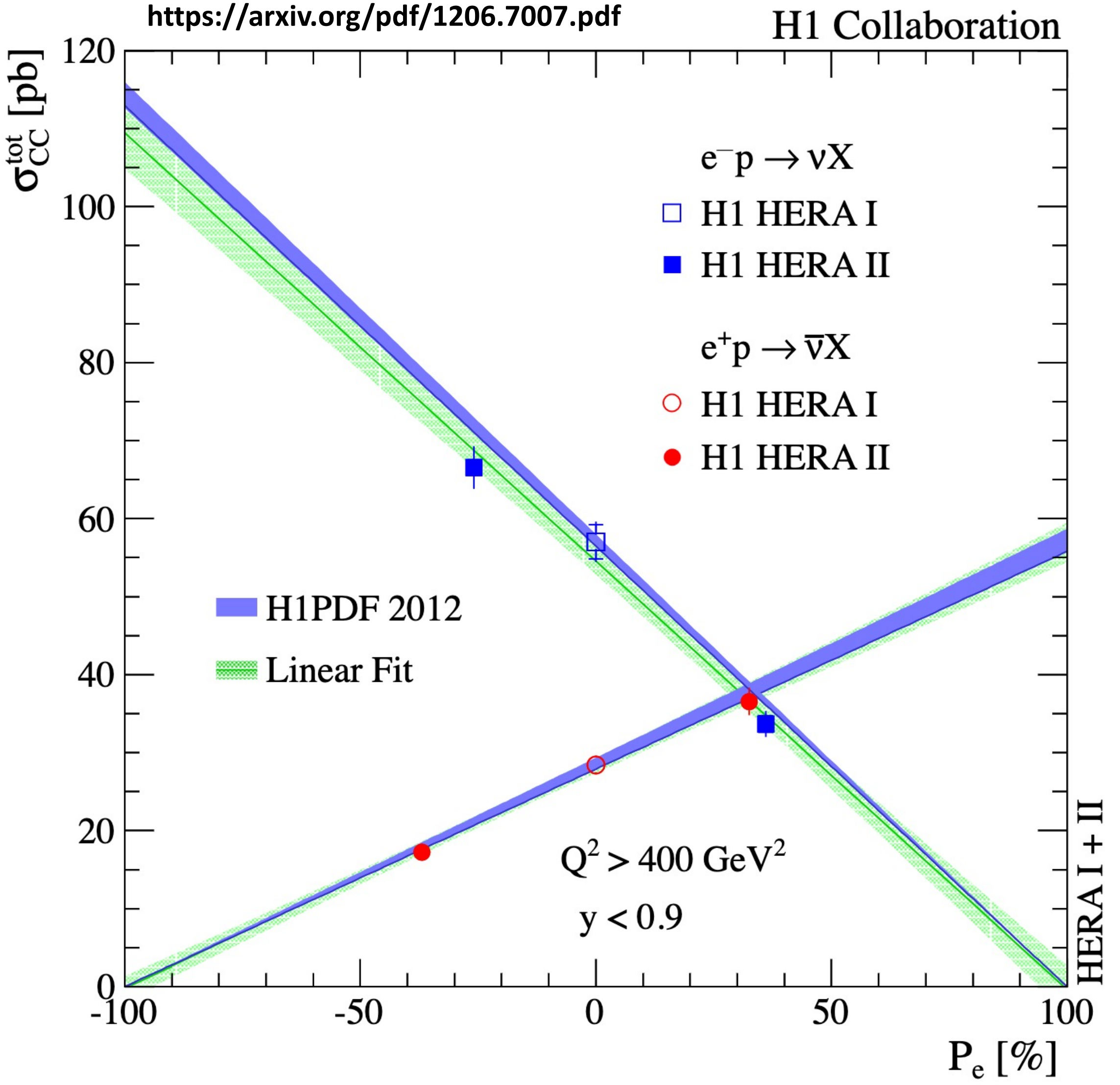
1% polarization uncertainty
1% background contamination

Charged current cross section

- Perhaps one of the most accessible BSM searches at the EIC is the polarization dependence of the charged current cross section
  - The extrapolated (linear) fits at P_e = +1 for electrons are compared to the SM prediction
- The combined HERA fits exclude the existence of charged currents involving right-handed fermions mediated by bosons below 214 GeV

JHEP 09 (2012) 061

https://arxiv.org/pdf/1206.7007.pdf



Charged current cross section

Yulia Furletova, Sonny Mantry
AIP Conf.Proc. 1970 (2018) 1, 030005

- The study assumed 1% polarization uncertainty and 3% experimental systematic and were performed at old sqrt(s) configurations
- The analysis from Yulia and Sonny needs some updating
  - Early indications are that we could start covering new phase space once we reach 30-50 fb^{-1}
- Due to the type of collisions involved the EIC limits would access different combinations of chiral and flavor structures making this study complementary to limits from the LHC (which are already in the TeV ranges)