Electroweak Physics at the EIC

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Parity-Violating Electron-Deuteron Asymmetry I. INTRODUCTION Party and the settlement of the settlement of the settlement of the set of the set of the set of the set of th
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International contract of the set of the set

e! (2)

 γ,Z

γ*, Z* (3)

 X

D \leqslant \leq \leq \leq \leq \leq

[⊥] (0)δ(*^P* [−] *zn*¯ *· ^p*1)*B^A*

 \bullet Asymmetry in the • Asymmetry in the Cahn-Gilman limit:

*A*_{CG}^{*RL*} =
$$
-\frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{9}{10} \Big[\Big(1 - \frac{20}{9} \sin^2 \theta_W\Big) + \Big(1 - 4 \sin^2 \theta_W\Big) \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \Big]
$$

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Parity-Violating Electron-Deuteron Asymmetry I. INTRODUCTION Party and the settlement of the settlement of the settlement of the set of the set of the set of the set of th
International contract of the set of the set

 \bullet Asymmetry in the • Asymmetry in the Cahn-Gilman limit:

$$
A_{\rm CG}^{RL} = -\frac{G_F Q^2}{2\sqrt{2\pi\alpha}} \frac{9}{10} \Big[\left(1 - \frac{20}{9} \sin^2 \theta_W \right) + \left(1 - 4 \sin^2 \theta_W \right) \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \Big]
$$

Hadronic effects cancel! [Prescott, et al (1978)]

*d*²σ *z deak* mi *f*_{*i*}, *p*_{*i*}*micus P*_{*i*}, *incusurences is the curvery* a *incusurence of the weak mixing angle.* γ*, Z* (4) • Asymmetry measurement is is effectively a measurement of the weak mixing angle!

Corrections to the Cahn-Gilman Limit *^µ* denote the four momenta of the deuteron, the incoming electron, and **Corrections to the Cahn-Gilman Limit**

• Hadronic effects appear as corrections to the Cahn-Gilman formula: **E Exercise of the energy denotes of the corrections to the Cahn-Gilman formula: •** Hadronic effects appear as corrections to the Cahn-Gilman formula:

$$
A_{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{9}{10} \Big[\tilde{a}_1 + \tilde{a}_2 \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \Big]
$$

$$
\tilde{a}_j = -\frac{2}{3} \frac{(2C_{ju} - C_{jd})}{(2C_{ju} - C_{jd})} [1 + R_j(\text{new}) + R_j(\text{sea}) + R_j(\text{CSV}) + R_j(\text{TMC}) + R_j(\text{HT})]
$$

Next
Next
See a quarks
See quarks
Target mass
Target mass

and **R**
8 Hadronic effects must be well understood before any claim for evidence of new physics can be made. The SM, sea quark effects, CB and the California in Eq. (12) are under the California in Eq. (12) and • Hadronic effects must be well understood before any claim for evidence of new physics can be made.

corrections (TMC), and take an alternative viewpoint and interested in the set of *Belitsky*, Mashanov, Schafer; singlet S . The SM that can leave a footprint in the asymmetry via the asym probe of hadronic physics that models the Cannon Seng, Ramsey-Musolf, \ldots] SM, Ramsey-Musolf, Sacco; Belitsky, Mashanov, Schafer;

Contact Interactions the weak mixing angle will provide a window to access the window to access the second their provide a window t
The window to access the w results deviate from the predictions. The predictions of the predictions of the predictions. atact Interactions and a series of the set o passed to psychological contracts of psychological contracts of psychological contracts of psychological contracts of \mathcal{L}_{O}

< (M_Z)∠ limit, electron-‹
eractions: *q*uark scattering via t *a k e e e d e de weak neutral curr q* • For Q² << (M_Z)² limit, electron-quark scattering via the weak neutral current is mediated by
contact interactions: Moller PV is insensitive to the Cij contact interactions: • For Q² << (I*12)² limit, electron-quark scattering via the weak neutral current is mediated by contact interactions:

$$
\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q} \bar{\ell} \gamma^{\mu} \gamma_5 \ell \bar{q} \gamma_{\mu} q + C_{2q} \bar{\ell} \gamma^{\mu} \mathcal{R} \bar{q} \gamma_{\overline{\mu}} \gamma_5 \gamma_6 \bar{q} + \mathcal{E}_{1} \bar{\ell} \gamma_7 \bar{\ell} \gamma_8 \bar{q} \bar{\ell} \gamma_7 \bar{\ell} \gamma_8 \gamma_9 \right]
$$

, (1)

• Tree-level Standard Model values: e-level Standard Mo

• free-level standard PIOdel values:
\n
$$
\in \qquad \qquad \in
$$
\n
$$
C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W), \quad C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W), \quad C_{3u} = \frac{1}{2},
$$
\n
$$
C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W), \quad C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W), \quad C_{3d} = -\frac{1}{2}
$$

New Physics Effects ENEW FIJSICS EIIECUS propriet to propriet the property of psychology p

 C ^{*C*} *C* and *C C* and *C* and tions via the weak neutral curren parameterized by contact interactions: • In the $Q^2 \ll M_Z^2$ limit, electron-quark interactions via the weak neutral current can be parameterized by contact interactions:

$$
\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q}^{\rho} \frac{Q_{w\bar{q}\bar{q}}^p}{\gamma^{\mu} \gamma_5 \ell \bar{q} \gamma_{\mu} q} + C_{2q}^{\alpha} \frac{1 - 4 \sin^2 \vartheta}{\ell \gamma^{\mu} \ell \bar{q} \gamma_{\mu} \gamma_5 q} + C_{3q} \bar{\ell} \gamma^{\mu} \gamma_5 \ell \bar{q} \gamma_{\mu} \gamma_5 q \right]
$$

, (1) \sim (1)

• New physics contact interagtions arise as a shift in the WNC couplings compared to the SM *one combination can be accessed in PV DIS* prediction: • New phy $\hat{\mathbf{g}}$ cs contact intera \mathbf{g} tions arise as a shift in the WNC or 1, allowing for the prediction:
The possibility of constructive interference with the SM contributions. The SM contributions of the SM contributions. The SM contributions of the SM contributions. The SM contributions of prediction:

• Deviations from the SM prediction of the WNC couplings will lead to corresponding deviations in the extracted value of the weak mixing angle.

Accessing C_{iq} via Parity-Violating Observables $\mathcal{L}_{\mathbf{I}}$ \log V_{iq} via r and V_{i} violating observables $\log C_{ia}$ via Parity-Violating Observables

•Atomic Parity Violation (APV): Sensitive to C_{1q} couplings via $\mathcal{Q}_W(Z, N)$ $\frac{1}{2}$

• Parity Violating Elastic Scattering (Qweak, P2): Sensitive to C_{1q} couplings through $Q_W(Z=1,\!N=0)$ and $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ $\sum_{i=1}^{N}$ Ing Elastic Scattering (Qweak, P2):

$$
Q_W(Z, N) = -2\left[\frac{C_{1u}(2Z+N) + C_{1d}(Z+2N)}{C_{1d}(Z+2N)}\right]
$$

^A are the axial-vector

, C^d

 \sim

 Z *A^D* ⁼ *{C^e*

1

[⊥] (0)δ(*^P* [−] *zn*¯ *· ^p*1)*B^A*

 $\overline{}$

} = *{*1*,* 2*/*3*,* 1*/*3*}*. The cou-

 X

09/27/2016 Rakitha Beminiwattha ⁹ • Parity Violating DIS (E122, PVDIS-6, SOLID, EIC): **Sensitive to** C_{1q} **and** $C_{2q}^{09/27/2016}$ **example 2.4 and** C_{2q} **example** $\frac{1}{2}$ **\frac** $A_{\rm PV}^{\rm DIS} =$ $G_{F}Q^{2}$ $4\sqrt{2}(1+Q^2/M_Z^2)\pi\alpha$ $\sqrt{ }$ $a_1 +$ $\frac{1-(1-y)^2}{(1-y)^2}$ $\frac{1}{1 + (1 - y)^2} a_3$ \int_{A} DIS _ $G_F Q^2$ $\int_{A} 1 - (1 - y)^2$] $2\sum_{a}e_{a}C_{1a}(q+\bar{q})$ $2\sum_{a}e_{a}C_{2a}(q-\bar{q})$ $a_1 = \frac{2q+1+1}{\sum_{\alpha}a(\alpha+\overline{\alpha})} \qquad \qquad a_3 = \frac{-q+1+1}{\sum_{\alpha}a(\alpha+\overline{\alpha})}$ $\Box q \circ q \vee$ h a $\frac{1}{2}$ 9] $\frac{1}{2}$ *z* $\frac{e^{\prime}}{2}$ *C^a ^Z* = (cos ↵ ✏*^W* sin ↵)*C^a* ⁼ *{C^e* pling the photon $Y \leqslant X$ $\overline{}$ *a*1+ IS (E122, PVDIS-0, JC $A_{\rm PV}^{\rm 2.50} = \frac{1}{4.6(1 + \Omega^2/M^2) \pi \alpha} a_1 + \frac{1}{1 - \Omega^2/M^2}$ $a_1 =$ $2\sum_q e_q \overline{C_{1q}}(q+\bar{q})$ $\frac{dq}{\sum_{q} e_q^2(q + \bar{q})}$ *Cv* $\frac{1}{2}$ = (cost $\frac{1}{2}$ $\frac{$ *C^a Z* **Explosive**
Rakitha Beminiwattha *^Z*¯*,* (9) $(y)^2$ ⁷ *}* = *{*1*,* 2*/*3*,* 1*/*3*}*. The cou- $\frac{\partial}{\partial p}a_3$ e \mathcal{Y}) and by \mathcal{Y} $e_q C_{2q} (q - \bar{q})$ Z $e_q^2(q + \bar{q})$ D **Z** $\sum_{i=1}^{n}$ DIS (E122, PVDIS-6, SOLID, EIC):
In a 2007/016 \ddot{z} (PDFs), \ddot{z} *a*¹ = $\left[\frac{(-8)}{(1 - y)^2} a_3 \right]$ P **d** $4\sqrt{2}(1+Q^2/M_Z^2)\pi\alpha$ **i** $1+(1-y)^2$ **j** $a_3 =$ $2\sum_q e_q \overline{C_{2q}}(q-\bar{q})$ $\frac{Q}{\sum_{q} e_q^2 (q + \bar{q})}$ *D* plings of the physical dark photon *A^D* to SM particles $\overline{}$ Here ↵ is the *^Z*¯ *^A*⁰ mixing angle, $\sum_{q}e_{q}^{2}(q+\bar{q})$
r the isocalar c *e*! (2) γ*, Z* (3) $\overline{9}$ γ,Z and Z *^fg/P* (*z, µ*) = [−]*zn*¯ *· ^p*¹ ! *e* (1) *e*! (2) $\overline{1}$ $\overline{}$ $D \longrightarrow \leqslant A$ I. INTRODUCTION

nctic 2 P *^q eqC*1*q*(*q* + ¯*q*) *e*ffects largely ca P *^q eqC*2*q*(*q q*¯) $\overline{}$ *g* and isocement assection can god, and vector (VA) contains the section of $\frac{1}{2}$ of $\frac{1}{2}$ contains of $\frac{1}{2}$ contains of $\frac{1}{2}$ contains $\frac{1}{2}$ contains the section of $\frac{1}{2}$ contains the section of re isocalar deuteron targ
A function effects largely Here ↵ is the *^Z*¯ *^A*⁰ mixing angle, For the isocalar deuteron target, t_{t} ences and t_{t} cancer structure function effects largely cancel *^fg/P* (*z, µ*) = [−]*zn*¯ *· ^p*¹

knowledge of the couplings g_{VA}^{eq} (vertical axis). The latest the 6 GeV Qweak $[51]$ on g_{AV}^{eq} (yellow vertical band) and the JLab 6 GeV PVDIS $\left[53, 54\right]$ experiments (grey ellipse). The existing world data (magenta ellipse), centered at the current
boot fit values $\frac{1}{2}$ best fit values.

0.5

 ϵ The compinetion $2C$ is severaly constrained by Queak and Atomic Perity violation sections of polarized $2C_{ll} - C_{ld}$ is severely constrained by \leq weak and results rarief violation. • The combination $2C_{1u} - C_{1d}$ is severely constrained by Qweak and Atomic Parity violation. • The combination $2C_1 - C_1$ is severely constrained by Oweak and Atomic Parity. $\frac{1}{200}$ $\frac{1}{20}$ \overline{S} combination \overline{S} \overline{S} is soveraly conie combination $2C_{1u} - C_{1d}$ is severely com- α ined by Qweak and Atomic Parity violation. program at the EIC. \overline{a} *G*^{\overline{b} *G*^{\overline{c} *G*^{\overline{c}} *G*^{\overline{c} *G*^{\overline{c}} *G*^{\overline{c} *G*^{\overline{c} *G*^{\overline{c}} *G*^{\overline{c}}}}}}}

• The combination $2C_{2u} - C_{2d}$ is known to within ~50% from the JLAB 6 GeV experiment: NEUTRAL WEAK COUPLINGS J_{c} Compilation $\text{F} \in \mathbb{Z}$ is known to within F over the jurn of G of G experiment.

A muon/anti-muon beam energy of 200 GeV was used to extract the combination 0.81(2*C*2*^u C*2*^d*) + 2*C*3*^u C*3*^d* = $2C_{2u} - C_{2d} = -0.145 \pm 0.068$ \mathcal{L}^{tr} , the weak neutral current can be parameterized in terms of contact interactions of conta $2C_{2u} - C_{2d} = -0.14$ **∂** $\overline{68}$ $\overline{2}$ \overline creases (+1, decreases (1, decreases (1, decreases) or decreases (1, decreases) or decreases (1, decreases (1, decreases) or decreases (1, decreases) or decreases (1, decreases) or decreases (1, decreases) or decreases (1,

of *C*3*^q* couplings as 2*C*3*^u C*3*^d* = 1.65 ± 0.453. • SOLID is expected significantly improve on this result. count for possible hadronic e \mathbf{H} for higher twist \mathbf{H} (HT) and *CSV* for charge symmetry violation (CSV) \sim control to \sim control to \sim control to \sim from the P2 experiment $\mathcal{S}_{\mathcal{S}}$ experiment $\mathcal{S}_{\mathcal{S}}$ experiment $\mathcal{S}_{\mathcal{S}}$ that can be reached by the SoLID PVDIS deuteron mea-

Leptophobic Z' interpretation of the measurements in terms in of fundamental electroweak physics. Parity-lepto-phobic Z⁰ with a mass *<* violating District D JLab measurements will be sensitive to a nificantly better than the current limit from the current limit from the current limit from the current limit from the current limit of th

namely 2*C*2*^u C*2*d*. A recent measurement • Leptophobic Z 's are an interesting BSM scenario since they or \mathbf{h} is the theory compliance in Λ shifts the C_{2q} couplings in A_{PV} $t_{\rm c}$ fit of electroweak couplings, higher-dependent couplings, higher-dependent couplings, ϵ • Leptophobic Z's are an interesting BSM scenario since they only

 \overline{a} to further improve on this constraint by \overline{a} \bullet Leptophobic \angle s \circ $\int_{\mathbb{R}} f(x) dx$ couplings function in $\int_{\mathbb{R}} f(x) dx$ • Leptophobic Z 's only affect the $b(x)$ term or the C_{2q} coefficients in A_{PV:}

Probing the Dark Sector

• Strong evidence for dark matter through gravitational effects:

- Galactic Rotation Curves
- **Gravitational Lensing**
- Cosmic Microwave Background
- Large Scale Structure Surveys
- WIMP dark matter paradigm
	- $-Mass \sim TeV$
	- Weak interaction strength couplings
	- Gives the required relic abundance
- However, so far no direct evidence for WIMP dark matter
- Perhaps dark sector has a rich structure including different species and gauge forces, just like the visible sector

a proposal \mathbb{R}^n of a spin-one gauge boson \mathbb{R}^n **Dark Photon Scenario**

• Dark $U(1)_{d}$ gauge group \blacksquare and \blacksquare and \blacksquare and \blacksquare \blacksquare and \blacksquare \blacksquare

mass region, to which we restrict our attention, the up $p = \frac{1}{2}$ [Also see talks by Neil, Liu]

hidden particles through this mixing. • Interacts with SM via kinetic mixing (and mass mixing)

$$
\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{m_{A'}^2}{2} A'_{\mu} A'^{\mu} + \frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}
$$

The mixing induces a coupling of the dark photon to the electromagnetic a
lak neutral currents. • The mixing induces a coupling of the dark photon to the electromagnetic and weak neutral currents.

$$
\mathscr{L}_{int} = -e\epsilon J^{\mu}_{em}A^{\prime}_{\mu}
$$

n
Could be • Could help explain astrophysical data and anomalies

TArkani-Hamed, Finkbeiner, Slatyer, Wi *dxdy* [Arkani-Hamed, Finkbeiner, Slatyer, Wiener, …]

Dark Photon Scenario

• Active experimental program to search for dark photon • Active experimental program to search for dark photons *Pospelov, Baten, Essig, Schuster, Toro; Baten, Pospelov, Bitter Leonius / Kunisis Schuster Town, L* Ritz; Izaguirre Krnjaic, Schuster, Toro] Visibly Decaying A' 10^{-7} $K \rightarrow \pi \vee \vee$ 10^{-4} $(\frac{a-2}{a})$ > 5 Hall Lavmannou 10^{-4}

S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

• Beam Dump Experiments:

[Bjorken, Essig, Schuster, Toro]

It was proposed that it might provide a portal to other <u>IK FIIOLOII SCENATIO.</u> Dark Photon Scenario: Impact on PVES

0.1 when **M**
December **1998 However, in the present context is in the present context in the present context** [Thomas, Wang, Williams]

$$
\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + \frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}
$$

on Dark Photon parameter space will be independent of the
weaking fractions of the device hates and and a successive of the SM neutral weak boson, and the SM neutral weak and the SM neutral weak and the SM n \mathbf{d} $t_{\rm max}$ and the double di α • Constraints on Dark Photon parameter space will be independent of the details of the decay branching fractions of the dark photon

After diagonalizing the mixing term through field re- μ K photon, the masses coupling to the weak neutral couplin $d\sigma$ de la Cancenation be • For a light dark photon, the induced coupling to the weak neutral coupling is suppressed (due to a cancellation between the kinetic and mass mixing induced couplings). [Gopalakrishna, Jung, Wells; Davoudiasl, Lee, Marciano]

current and a correspondingly sizable effect in PVES. • Let's consider a heavier dark photon for a sizable coupling to the weak neutral [Thomas, Wang, Williams]

reviewed by Filippine and Napoli an TR FIJOLOH SCENTIO. HIIPACL ON matically with the *U*(1)*^Y* boson in the Standard Model. or slightly stronger than the EWPO bound, ✏ 0*.*02 *MES* $\frac{1}{\pi}$ \mathbb{R}^3 , remains \mathbb{R}^3 Dark Photon Scenario: Impact on PVES [Thomas, Wang, Williams]

$$
\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}
$$

DIS asymmetry has the form: tively. photon and one-*Z*⁰ exchanges [25] • The usual PVDIS asymmetry has the form: tained with *C^a Z,e* and *C^a ^AD,e* being replaced by *C^a* al PVDIS asymmetry has the found the set of G_{E}

$$
A_{\rm PV}^{\rm DIS} = \frac{G_F Q^2}{4\sqrt{2}(1+Q^2/M_Z^2)\pi\alpha} \Big[a_1 + \frac{1-(1-y)^2}{1+(1-y)^2}a_3\Big]
$$

e effects of a dark photon are $e^{\frac{1}{2}}$ • Including the effects of a dark photon, we get additional terms:

$$
A_{\rm PV} = \frac{Q^2}{2\sin^2 2\theta_W (Q^2 + M_Z^2)} \Big[a_1^{\gamma Z} + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3^{\gamma Z} + \frac{Q^2 + M_Z^2}{Q^2 + M_{AD}^2} \Big(a_1^{\gamma A_D} + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3^{\gamma A_D} \Big) \Big],
$$

[*xy*²*FA^D* ¹ ⁺ *^f*1(*x, y*)*FA^D* where *f*1(*x, y*)=1 *y xyM/*2*E* and = +1(1) ω 0.10 **Here a** $\overline{0.20}$ *Angle***,** *A* $\overline{0.20}$ 0.15 $\overline{}$

Γ Dain Filoton Scenario. Impact on Fy ¹ (*aA^D* ¹) and *^a^Z* ³ (*aA^D* ³) have the same form as **Dark Photon Scenario: Impact on PV** defined by the physical couplings given in Eqs. (9-10). The physical coupling given in Eqs Dark Photon Scenario: Impact on PVES

Fermi constant *G^F* using the relation Ient to working with the usual PVDIS formula: as a simple form in leading \sim 1.0 \sim 1.0 \sim 0.0 \sim • Equivalent to working with the usual PVDIS formula:

$$
A_{\rm PV}^{\rm DIS} = \frac{G_F Q^2}{4\sqrt{2}(1 + Q^2/M_Z^2)\pi\alpha} \left[a_1 + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3 \right]
$$
 0.20

ith shifted C_{iq} couplings: • But with shifted C_{iq} couplings: i $\mathfrak{g}_{\mathfrak{g}}$

$$
C_{1q} = C_{1q}^{Z} + \frac{Q^{2} + M_{Z}^{2}}{Q^{2} + M_{A_{D}}^{2}} C_{1q}^{A_{D}} = C_{1q}^{SM} (1 + R_{1q})
$$
^{0.10}

$$
C_{2q} = C_{2q}^{Z} + \frac{Q^{2} + M_{Z}^{2}}{Q^{2} + M_{A_{D}}^{2}} \frac{C_{2q}^{A_{D}}}{C_{2q}^{2}} = C_{2q}^{SM} (1 + R_{2q})
$$

SM couplings, and the e Γ is used to a dark photon. The e Γ is not a dark photon. FIG. 1. The correction factors *R*1*^u* and *R*1*^d* at *Q*² with *R*1*^q* and *R*2*^q* characterizing the corrections to the [Thomas, Wang, Williams] \blacksquare and vector axial-vector axial-vector \blacksquare and vector \blacksquare sign(1 ⇢²)

 0.05

⁼ *{C^e*

kinetic mixing [29]

 \overline{a}

A, g^u

Here ↵ is the *^Z*¯ *^A*⁰ mixing angle,

40

, C^u

40

, C^d

plings of the physical dark photon *A^D* to SM particles

4 FIG. 2. The correction factors *R*1*^u* and *R*1*^d* at *Q*² = *M*² *Z* . \sim \sim \sim the symmetry, the numerator receives con-. In C_{ia} (PVDIS, HERA) VVang, VVII
— tained with *C^a Z,e* and *C^a ^AD,e* being replaced by *C^a Z,e* and ark Photon Since the purely electromagnetic cross section and the purely section of \mathbb{R}^n measurement. For example, a value of *R*1*^q* of order 4% in C. (PVDIS HERA) $PQ \sim P$ is the mass λ /s and λ /illiance Dark Photon Scenario: Shift in C_{iq} (PVDIS, HERA) **Example 21 Thomas, Wang, Williams**

³*^q* = *C*SM

R^V (2*geu*

AA ^ged

5+4*R^C* + *R^S*

Z

 $\sqrt{2}$

Z

A^D

AA)

C^A^D

C^A^D

, (17)

¹*^q* = *C*SM

²*^q* = *C*SM

³*^q* (1 + *R*3*q*)*.* (16)

Z)

 $\left\{\begin{matrix} \mathbf{A} & \mathbf{a} & \mathbf{b} \\ \mathbf{a} & \mathbf{b} & \mathbf{b} \end{matrix}\right\}$

(*aA^D* $\mathcal{L} = \frac{1}{2} \sum_{i=1}^n \mathcal{L}_i$ **a**
a
1

10 - - - - - - - - - - - - - - - - - - ا⁰

1*q*(*C^A^D*

^Z) ⁼ *^GFQ*²

1 a²⁰
2 - 2 *a*^D - 2 a²⁰
2 - 2 a²⁰

 $\frac{1}{2}$) $\frac{1}{2}$ (10)

¹*^q*) and *C^Z*

1 **a**² **b**² *a***⁴⁰ a**⁴⁰

³)

 $\begin{array}{c} \hline \end{array}$.

 $\overline{140}$

¹*^q* (1 + *R*1*q*)*,*

 $\begin{array}{|c|c|c|c|c|}\n\hline\n\text{ } & \text{ } & \text{ } \\
\hline\n\text{ } & \text{ } & \text{ } \\
\hline\n\text{ } & \text{ } & \text{ } \\
\hline\n\text{ } & \text{ } & \text{ } \\
\hline\n\text{ } & \text{ } & \text{ } \\
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\hline\n\text{ } & \text{ } & \text{ } \\
\hline\n\text{ } & \text{ } & \text{ } \\
\hline\n\text{ } & \text{ } & \text{ } \\
\hline\n\text{ } & \text{ } & \text{ } \\
\hline\n\text{ } & \text{$

 t_1 deviations as $\frac{1}{2}$ \vert ¹⁰ \vert

tributions to parity-violating electron scattering (PVES). $\vert 0 \vert$ to the standard model couplings *C*1*q, C*2*^q* and *C*3*q*. For \vert -5 atively large correction to the neutron radius of the Pb I_{-10}

 \vert ¹⁰ to HERA, the dark photon could induce substantial cor- $\begin{bmatrix} 5 \end{bmatrix}$ duced from the DIS data. Finally, the electron-positron $\vert 0 \vert$

2*C*3*^u C*3*d*, where e↵ects as large as 5% are possible.

able to have a dedicated program to test for the existence

 \vert

²*^q*)

2*q*(*C^A^D*

 $\big|_{-10}$

Light Dark-Z Parity Violation and beam-dump processes do not severely constrain the **interactions of dark Dark Z which, as discussed below, as discussed below, and F** of small α and does not measurably affect α $\mathbf{E} = \begin{bmatrix} \mathbf{E} & \mathbf{$ range interaction [20]). boson scenario. It is a new U(1) of the U(1) of the scenario scenario. It is a new U(1) of the scenario scenario symmetry of the dark matter or any hidden sector innew phenomenology which overcomes the mZ^d /m^Z sup-**As the first example, we consider very low CD** and \blacksquare [Davoudias],

[Davoudiasl, Lee, Marciano] L above U(1) above U(α or α in the smallness of m α duced Zd couplings is offset by the main \mathcal{E}

 \int

f

 \bar{f} *f*

f

 \bar{f} *f*

 p_{max}

 γ *Z'*

Z′ *Z*

ε*Z*

×

×

 ν _{kin}

4

 \mathbf{H}

 Δ new phenomenology which overcomes the m Δ

 $\overline{\mathcal{E}}$ effects where the smallness of m $\overline{\mathcal{E}}$

 \mathcal{L}

 $\begin{array}{cc} \diagup & \diagup \\ \diagdown & \diagdown \end{array}$

 \sum_{α}^{∞}

mH/mZ^d enhancements, respectively, in the longitudinal

 $\frac{1}{\sqrt{2}}$ and $\frac{2}{\sqrt{2}}$ and $\frac{2}{\sqrt{2}}$

 $\vec{B}_{\mu\nu}B^{\mu\nu}$

As the first example, we consider very low Q² parity vi-

 ϵ
 λ \wedge \wedge \wedge

 $\begin{matrix} 2 & 3 & 4 \ 7 & 1 & 1 \end{matrix}$

 \bar{f} and \bar{f}

 $\frac{1}{2}$

 Z'

 $\mathcal{L}_{\mu\nu}B^{\mu\nu}$

- \mathbf{A} is coupling to our particle world via the output of \mathbf{B} the \mathbf{B} • An interesting scenario is that of a "light" Dark-Z. \int \sum interesting scenarious that or a light $\sum a_i x_i^2$. $\mathcal C$ • An interesting scenario is that of a "light" Dark-Z.
- The standard kinetic mixing scenario: • The standard kinetic mixing scenario:

$$
\mathcal{L}_{\text{gauge}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} \frac{\varepsilon}{\cos \theta_W} B_{\mu\nu} Z_d^{\mu\nu} - \frac{1}{4} Z_{d\mu\nu} Z_d^{\mu\nu}
$$

• And additional mass mixing (for example, from extended Higgs who deducional mass mixing (for example, iron excended ringgotor) can induce sizable dark-Z coupling to the weak neutral current: $\frac{1}{4}$ $\frac{\mu\nu}{\mu\nu}$ $\frac{1}{2}$ $\cos \theta_W$ $\frac{\mu\nu Z_d}{4}$ $\frac{1}{4}$ $\frac{2 \alpha \mu \nu^2}{4 \mu \nu^2}$
additional mass mixing (for example, from extend where many contracts where \mathcal{L} $\sum_{i=1}^{n}$ \int $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ is $\frac{1}{\sqrt{2}}$ and $\frac{1$ polarization component of the \overline{C} polarization and \overline{C} production and \overline{C} • And additional mass mixing (for example, from extended Higgs

$$
\begin{aligned}\n\overline{\xi} & \sim \text{Var} \\
\overline{Z'} & \text{Var} \\
\over
$$

 m_Z $\mathop{\mathsf{trom}}$ \mathbf{I} III. \mathbf{I} \sim m_Z **• Dark-Z couples to the electromagnetic and neutral current coupling:** It may interact with DM, but SM particles have zero charges

$$
\mathcal{L}_{int} = \left(-e \varepsilon J_{\mu}^{em} - \frac{g}{2 \cos \theta_{W}} \varepsilon_{Z} J_{\mu}^{NC} \right) Z_{d}^{\mu}
$$

$$
= -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} \frac{\varepsilon}{\cos \theta_{W}} B_{\mu\nu} Z'^{\mu\nu} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}
$$

$$
\mathcal{L}_{int} = -\varepsilon e J_{em}^{\mu} Z'_{\mu}
$$

Log₁₀ dright Dark-Z Parity Violation -2 -1 Log_{10} $\overline{-2}$ $\overline{-1}$ *m^Z^d* ⌧ *mZ*, the second term in Eq. (8) [34] is generally $\begin{array}{ccc} 3 & 1 & 2 \end{array}$ -2 -1 0 $\frac{1}{2}$ $\overline{2}$ $\overline{\mathbf{P}}$ $v\Delta$ iolotiqu Log_{10} Q igent Dark- \angle Parity Violation -2 -1 0 1 2 3 where $\frac{1}{2}$ propagator can probably $\frac{1}{2}$ Log_{10} digent Dark-Z overall effect for parity violating amplitudes ^MPV NC = \overline{c} \overline{O} (we note that the fine tuning experimental system is similar to the fine tuning experimental system in the fine tuning experimental system in the fine tuning experimental system in the fine tuning experimental sy arity Violation employed in Ref. arcs who discrete in data appears to be discrete in data and the discrete in data and the search of t $s-2$ and if $s=1$ be significant if $s=2$. $T = \frac{1}{2}$ or $T = \frac{1}{2}$ or $T = \frac{1}{2}$ or $T = \frac{1}{2}$ \log_{10} O is the minimal important for experiments. \sum_{10} \sum_{10} probability $\mathbf{F} \bullet \mathbf{F}$ become different and $\mathbf{F} \bullet \mathbf{F}$ become different and $\mathbf{F} \bullet \mathbf{F}$ **the possibility violation** of cancel 0.8. (We note that the fine tuning ε/ε^Z " 0.8 is similar

[Davoudiasl, Lee, Marciano]
resence of dark=7 for

• Effective change in presence of dark-Z for rective change in presend
parity violating asymmetries: sin² ✓*^W* (*mZ*)MS of 0² is induced if *R*⌫ (the ratio of neuparity violating a
correlation of the *Z* **C** Fffective change ● Effective change in presence of dark-7 for \bullet Effective change in presence of dark- \angle for pari ity violating asymmetries:

Eq. (11), is particularly important for experiments

$$
G_F \to \rho_d G_F
$$

\n
$$
\sin^2 \theta_W \to \kappa_d \sin^2 \theta_W
$$

\n
$$
\otimes^{0.242}_{\geq 0.240}
$$

\n
$$
\otimes^{0.242}_{\geq 0.238}
$$

 $-z$ $-$

$$
\rho_d = 1 + \delta^2 \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}
$$

\n
$$
\kappa_d = 1 - \frac{\varepsilon}{\varepsilon_Z} \delta^2 \frac{\cos \theta_W}{\sin \theta_W} \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}
$$

\n
$$
0.232 \left[\frac{1}{\text{APV(Ra*)}} \right]
$$

\n
$$
0.230 \left[\frac{1}{\text{APV(Ra*)}} \right]
$$

EIC/ECCE Simulation Studies than the EIC is not the EIC in Table III status wet built is not yet built, the EIC is no technical basis to a

[Boughezal, Emmert, Kutz, SM, Nycz,Petriello, Simsek, Wiegand, Zheng]

• Energy and integrated luminosity configurations used in the study: projections will be denoted with an "High Luminosity (HL)" label hereafter.

Electron-Deuteron PVDIS Electron-Proton PVDIS

• Also considered High Luminosity (HL) configurations corresponding to an increase by a factor of 10 .

> $\sum_{i=1}^{\infty}$ and $\sum_{i=1}^{\infty}$ $\sum_{i=1$ • 20 million MC events generated D JANGOH + fast smearing method for each of the configurations above. 10 million events for all Q^2 and 10 million for Q^2 > 50 ${\rm GeV^2}$.

For a given value of the statistical uncertainty of an asymmetry measurement is: • Also, considered possibility of a positron beam.

• Observables studied:

$$
A_{PV}^e, \quad A_{PV}^p, \quad A_{PV}^D, \quad A_{LC}^p, \quad A_{LC}^D
$$

Electron-Deuteron PVDIS Asymmetry(A_{PV}^e)

- Statistical uncertainty dominates
- PDF uncertainty has a small impact

FIG. 6. Comparison of the uncertainty components for the data set D4 in the valence-only scenario (ud) and with the rig. 6. Comparison of the uncertainty components for the data set D4 in the valence-only scenario (ud) and with the
contributions from the sea quarks (uds). Here, "NL" refers to the currently planned annual luminosity of t refers to a potential ten-fold luminosity upgrade.

[Boughezal, Emmert, Kutz, SM, Nycz,Petriello, Simsek, Wiegand, Zheng]

Electron-Proton PVDIS Asymmetries: A_{PV}^e and A_{PV}^p

• Statistical uncertainty dominates

• PDF uncertainties have a small impact for

[Boughezal, Emmert, Kutz, SM, Nycz,Petriello, Simsek, Wiegand, Zheng]

Precision Extraction of the Weak Mixing Angle

[Boughezal, Emmert, Kutz, SM, Nycz, Petriello, Simsek, Wiegand, Zheng]

Projection eD: **ETG ex 100 GeV/u 36.8 fbr** FIG. 11. Projected results for sin² ✓*^W* using *ep* (top, solid magenta markers) and *eD* (bottom, solid cyan markers) collision • The EIC can extract the weak mixing angle over a previously unexplored trange of Q^2 projections we denote the weak mixing angle over a previous.

 ∂ araticle thresholds between $\mathcal{L}^\mathcal{P\!E}$ affd $^{\mathsf{refH}^\mathcal{P}}$ eD: 10 GeV x 100 GeV/u 44.8 fb⁻¹ ED: 101 GOV 1734 GOVERNME solid circles) and near-future projections (green diamonds); see text for details. Data points for Tevatron and LHC are shifted \bullet Analysis included one loop MS running including particle • Analysis included one loop \overline{MS} running including particle thresholds between \mathcal{D}^2 after M_Z

		~	<u>UNER</u>		$\overline{ }$	
	D1 5 GeV \times 41 GeV eD , 4.4 fb ⁻¹		$\vert P1 \vert 5 \text{ GeV} \vert$	<u>18 GeV x 137 GeV/u 15.4 fb</u> \times 41 GeV <i>ep</i> , 4.4 fb		
	$D2 5 \text{ GeV} \times 100 \text{ GeV }eD, 36.8 \text{ fb}^{-1}$			$ P2 $ $Gd/2$ $ P2 $ $Gd/2$ $ Q100$ $GeVep$, 36.8 $ f $		
	D3 10 GeV \times 100 GeV eD , 44.8 fb ⁻¹			$ \overline{P3} \overline{19}$ GeV $\times 100$ GeV ep_{dweak} 44.8 fb	EIC	
D41	10 GeV \times 137 GeV eD , 100 fb ⁻¹		GeV	\sqrt{k} 275 GeV ep , 100 fb ⁻¹ pos		
D5 ₁	18 GeV \times 137 GeV <i>eD</i> , 15.4 fb ⁻¹			$\sqrt{P5}$ $\frac{1}{28}$ $\frac{1}{28}$ $\frac{1}{275}$ $\frac{1}{275}$ $\frac{1}{28}$ $\frac{1}{29}$		
				$ P6 18 \text{ GeV} \times 275 \text{ GeV }ep, 100 \text{ fb}^{-1}$	LEP1 \bullet LHC	
			0.23	$\overline{\mathbf{2}}$ MOLLER		

electron polarization is, for the settings where the integrated luminosity approaches 100 fb1. Consequently, upgrading the luminosity of the eight of the EIC does not be uncertainty on the uncertainty on the uncertainty of the unc • Projections for weak mixing angle extraction at the EIC from electron-proton PVDIS.

TABLE III. Projected PVDIS asymmetry and fitted results for $\sin^2 \theta_W$ using ep collision data and the nominal annual luminosity. Here, $\langle Q^2 \rangle$ denotes the value averaged over all (x, Q^2) bins, weighted by $(dA/A)_{\text{stat}}^{-2}$ for each bin. The electron beam polarization is assumed to be 80% with a relative 1% uncertainty. The total ("tot") uncertainty is from combining all of statistical, 1% systematic (background), 1% beam polarization, and PDF uncertainties evaluated using three different PDF sets. The rightmost column is for comparison with the YR.

n • Projections for weak mixing angle extraction at the EIC from electron-deuteron PVDIS.

Beam type and energy	$eD\,5\times100$	10×100 eD	$eD\ 10\times137$	$eD\ 18\times 137$	$eD\ 18\times 137$
Label	D ₂	D ₃	D4	D5	N/A
Luminosity (h^{-1})	36.8	44.8	100	15.4	(10 YR ref)
$\langle Q^2 \rangle$ (GeV ²)	160.0	316.9	403.5	687.2	687.2
$\langle A_{PV} \rangle$ $(P_e = 0.8)$	-0.01028	-0.01923	-0.02366	-0.03719	-0.03719
$(dA/A)_{\text{stat}}$	1.46\%	0.93%	0.54%	1.05%	(1.31%)
$(dA/A)_{\rm stat+bg}$	1.47%	0.95%	0.56%	1.07%	(1.32%)
$(dA/A)_{syst, 1\%pol}$	1.0%	1.0%	1.0%	1.0%	(1.0%)
$(dA/A)_{\text{tot}}$	1.78%	1.38%	1.15%	1.46\%	(1.66%)
Experimental					
$d(\sin^2 \theta_W)_{\rm stat+bg}$	0.002148	0.001359	0.000823	0.001591	0.001963
$d(\sin^2 \theta_W)_{\text{stat+bg+pol}}$	0.002515	0.001904	0.001544	0.002116	0.002414
with PDF					
$d(\sin^2\theta_W)_{\rm tot, CT18}$	0.002558	0.001936	0.001566	0.002173	0.00247
$\mathrm{d}(\sin^2\theta_W)_{\rm tot,MMHT2014}$	0.002527	0.001917	0.001562	0.002128	0.002424
$d(\sin^2 \theta_W)_{\text{tot,NNPDF31}}$	0.002526	0.001915	0.001560	0.002127	0.002423

TABLE IV. Projected PVDIS asymmetry and fitted results for $\sin^2 \theta_W$ using *eD* collision data and the nominal annual luminosity. The uncertainty evaluation is the same as Table III.

SMEFT Analysis

notational simplicity we will derive the experimental simplicity will be a set of the operators and Wilson lab $\bigcap_{n=1}^{\infty}$ ect the operators that a $\bigcap_{n=1}^{\infty}$ leading order in the coupling constants. We have used the notation of Ref. [4] for the dimension-8 operators. We assume massless fermions as well as minimal flavor violation for C_{tendadd} Madel $E_{\text{tendition}}$ Theory (CMEET) Standard Model Effective Theory (SMEFT) suppressed by an energy scale at an energy scale scale \bigcap **Operator Basis** [Boughazel, Petriello, Wiegand]

• The SMEFT basis often used in global fit analysis to constrain new physics beyond the electroweak scale: We note at this point that for each dimension t_{total} extensions that dimension-8 extensions that dimensions that different of the placement of the covariant derivatives. The placement of the covariant derivatives of the covariant derivatives of the covariant deriv

$$
\mathcal{L}=\mathcal{L}_{SM}+\frac{1}{\Lambda^2}\sum_i C_i^6 \mathcal{O}_{6,i}+\frac{1}{\Lambda^4}\sum_i C_i^8 \mathcal{O}_{8,i}+\ldots
$$

Explored type-2 operators for DIS processes at dim-6 extensions can therefore in principle be discussed the single • Relevant SMEFT operators for DIS processes at dim-6 and dim-8 above are dimensionless. We calculate cross sections to leading order in the coupling con-

SMEFT vs C_{iq} Basis **Coecier are in principalization in principalization scheme chosen.** In an *iq* MS U_{iq} Mean *Petrial* scheme they become scale-dependent and run with energy. As we perform only a leading- [Boughazel, Petriello, Wiegand] scheme scheme scheme scale-dependent and run with energy. As we perform only a leadingorder analysis in this work we neglect this running. \mathbf{u} is has been customary to parameterize the parity-violating, dimensionteractions in terms of the following phenomenological four-fermion Lagrangian [43]:

 α anough are originated this isolly the α this energy experiments, typically the C_{iq} basis of operators based on V-A $\,$ structure after EWSB is used: p2
2
2 $\ddot{}$ • For low energy experiments, typically the C_{iq} basis of operators based on V-A *V uuµu* + *C*⁶

$$
\mathcal{L}_{PV} = \frac{G_F}{\sqrt{2}} \bigg[(\overline{e}\gamma^{\mu}\gamma_5 e)(C_{1u}^6 \overline{u}\gamma_{\mu} u + C_{1d}^6 \overline{d}\gamma_{\mu} d) + (\overline{e}\gamma^{\mu}e)(C_{2u}^6 \overline{u}\gamma_{\mu}\gamma_5 u + C_{2d}^6 \overline{d}\gamma_{\mu}\gamma_5 d) \n+ (\overline{e}\gamma^{\mu}e)(C_{Vu}^6 \overline{u}\gamma_{\mu} u + C_{Vd}^6 \overline{d}\gamma_{\mu} d) + (\overline{e}\gamma^{\mu}\gamma_5 e)(C_{Au}^6 \overline{u}\gamma_{\mu}\gamma_5 u) \n+ D^{\nu} (\overline{e}\gamma^{\mu}\gamma_5 e) D_{\nu} (\frac{C_{1u}^8}{v^2} \overline{u}\gamma_{\mu} u + \frac{C_{1d}^8}{v^2} \overline{d}\gamma_{\mu} d) + D^{\nu} (\overline{e}\gamma^{\mu} e) D_{\nu} (\frac{C_{2u}^8}{v^2} \overline{u}\gamma_{\mu}\gamma_5 u + \frac{C_{2d}^8}{v^2} \overline{d}\gamma_{\mu}\gamma_5 d) \n+ D^{\nu} (\overline{e}\gamma^{\mu} e) D_{\nu} (\frac{C_{Vu}^8}{v^2} \overline{u}\gamma_{\mu} u + \frac{C_{Vd}^8}{v^2} \overline{d}\gamma_{\mu} d) + D^{\nu} (\overline{e}\gamma^{\mu}\gamma_5 e) D_{\nu} (\frac{C_{Au}^8}{v^2} \overline{u}\gamma_{\mu}\gamma_5 u) \bigg].
$$

• One can find relations between the two bases:

$$
C_{1u}^{6} = 2(g_{R}^{e} - g_{L}^{e})(g_{R}^{u} + g_{L}^{u}) + \frac{v^{2}}{2\Lambda^{2}} \left\{-\left(C_{lq}^{(1)} - C_{lq}^{(3)}\right) + C_{eu} + C_{qe} - C_{lu}\right\}
$$

\n
$$
C_{2u}^{6} = 2(g_{R}^{e} + g_{L}^{e})(g_{R}^{u} - g_{L}^{u}) + \frac{v^{2}}{2\Lambda^{2}} \left\{-\left(C_{lq}^{(1)} - C_{lq}^{(3)}\right) + C_{eu} - C_{qe} + C_{lu}\right\}
$$

\n
$$
C_{1d}^{6} = 2(g_{R}^{e} - g_{L}^{e})(g_{R}^{d} + g_{L}^{d}) + \frac{v^{2}}{2\Lambda^{2}} \left\{-\left(C_{lq}^{(1)} + C_{lq}^{(3)}\right) + C_{ed} + C_{qe} - C_{ld}\right\}
$$

\n
$$
C_{2d}^{6} = 2(g_{R}^{e} + g_{L}^{e})(g_{R}^{d} - g_{L}^{d}) + \frac{v^{2}}{2\Lambda^{2}} \left\{-\left(C_{lq}^{(1)} + C_{lq}^{(3)}\right) + C_{ed} - C_{qe} + C_{ld}\right\}
$$

\n
$$
C_{Vu}^{6} = 2(g_{R}^{e} + g_{L}^{e})(g_{R}^{u} + g_{L}^{u}) + \frac{v^{2}}{2\Lambda^{2}} \left\{\left(C_{lq}^{(1)} - C_{lq}^{(3)}\right) + C_{eu} + C_{qe} + C_{lu}\right\}
$$

\n
$$
C_{Au}^{6} = 2(g_{R}^{e} - g_{L}^{e})(g_{R}^{u} - g_{L}^{u}) + \frac{v^{2}}{2\Lambda^{2}} \left\{\left(C_{lq}^{(1)} - C_{lq}^{(3)}\right) + C_{eu} - C_{qe} - C_{lu}\right\}
$$

\n
$$
C_{Vu}^{6} = 2(g_{R}^{e} + g_{L}^{e})(g_{R}^{d} + g_{L}^{d}) + \frac{v^{2}}{2\Lambda^{2}} \left\{\left(C_{lq}^{(1)} + C_{lq}^{(3)}\right) + C_{
$$

3 Review of Drell-Yan and PVES Formulae Formulae Formulae Formulae Formulae Formulae Formulae Formulae Formula
Politica SMEFT Constraints from Drell-Yan at LHC

End this section we review the formulation we review the parity-section $[{\sf Boughazel, Petriello, Wiegand}]\$

violating asymmetry parameter *AP V* in PVES. The review of the Drell-Yan cross sections • The SMEFT Wilson coefficients that affect PVES $\mathcal{L} \sim \mathcal{L} \sim \mathcal{L}$ \mathcal{M}_a , i.e. section is the differential contract section into the SM pieces stemming from photon photon photon photon photon photon into the SM pieces stemming from photon photon photon into the SM pieces stemming fro $\overline{\mathscr{D}}$ h_A of the dimension-dimension-dimension $d\sigma_{q\bar{q}}$ $dm_{ll}^2 dY dc_{\theta}$ $=\frac{1}{20}$ $32\pi m_{ll}^2 \hat{s}$ $f_q(x_1) f_{\bar{q}}(x_2)$ $\int d\hat{\sigma}^{\gamma\gamma}_{q\bar{q}}$ $dm_{ll}^2 dY dc_{\theta}$ $+$ $d\hat{\sigma}^{\gamma Z}_{q\bar{q}}$ $dm_{ll}^2 dY dc_{\theta}$ $+$ $d\hat{\sigma}^{ZZ}_{q\bar{q}}$ $dm_{ll}^2 dY dc_{\theta}$ $+$ $d\hat{\sigma}^{\gamma SMEFT6}_{q\bar{q}}$ $dm_{ll}^2 dY dc_{\theta}$ $+$ $d\hat{\sigma}^{ZSMEFT6}_{q\bar{q}}$ $dm_{ll}^2 dY dc_{\theta}$ $+$ $d\hat{\sigma}^{\gamma SMEFT8}_{q\bar{q}}$ $dm_{ll}^2 dY dc_{\theta}$ $+$ $d\hat{\sigma}^{ZSMEFT8}_{q\bar{q}}$ $dm_{ll}^2 dY dc_{\theta}$ $+$ $d\hat{\sigma}_{q\bar{q}}^{SMEFT6^2}$ $dm_{ll}^2 dY dc_{\theta}$ \mathcal{L} also contribute to the Drell-Yan process at the LHC

describing the probability of finding a parton *q* of momentum fraction x inside the proton. • PVES and the LHC can be complementary to each other in constraining cosine of the center of mass scattering angle of the negatively charged lepton. The hadronic charged lepto new physics

P6 is the YR reference setting.

• PVDIS can lift "flat directions" by probing orthogonal directions in the *eD* pseudodata sets as D1, D2, D3, D4, and D5; see Table II. The YR reference point is denoted by P6. Simulated $\frac{1}{\text{S}}$ and SMEFT parameter space compared to the LHC **e** PVDIS can lift "flat directions" by abbreviate the *ep* point α p_1 browing orthogonal directions in the product p_1 –5 and p_2 –6, while positron data sets are referred to p_1 As an exercise, we consider the additional statistical power that could be obtained by a hypothetical future high- $\left(\nabla^{\mu}l\right)D_{\nu}\left(\overline{q}\gamma_{\mu}q\right)$ (Fig.

P6 is the YR reference setting.

dApv(H)/Apv(H) (unfolded)

• PVDIS can lift "flat directions" by **eddark** probing orthogonal directions in the *probing* sets as \overline{P} \sum_{N} and \sum_{N} and \sum_{N} and \sum_{N} for lepton \sum_{N} and \sum_{N} for $\sum_{$ LHC $\rule{1em}{0.15mm}$ probing or diogonal directions in the $\overline{}$ and additional statistical power that could be obtained by a hypothetical future high- $(\bar{l}\gamma^{\mu}l)\; D_{\nu}\left(\overline{q}\gamma_{\mu}q\right)$ (in the integral integration in the integration of Γ

Disentangling Dim-6 and Dim-8 SMEFT Operators

Figure 5: Combining the 68% C.L. bounds derived from Drell-Yan data and the P2 pro-• Another advantage of low energy PVES experiments: Figure 6: Combining the 68% C.L. bounds derived from Drell-Yan data and the SoLID

The large energy of the LHC can make it difficult to disentangle the δ changes of dim δ and in δ (and dim δ coursed) the planets of anti-o of anti-o (and anti-o squared) through the use of the parameter space \mathbf{r} P are complementary and how the standard SMEFT basis of the standard SMEFT basis \mathcal{P} effects of dim-6 or dim-8 (and dim-6 squared) operators.

Low energy PVES will only have sensitivity to dim-6 operators providing valuable input to disentangle dim-6 vs dim-8. bound to be smaller than 8. providing valuable input to disentangle dim-6 vs dim-8.

This is also true at the EIC

Electroweak Spin Structure Functions

Electroweak DIS

howing for haver separacion; • The γ , *Z*, W^{\pm} electroweak probes each probe different flavor combinations of nucleon structure functions, allowing for flavor separation.

-NC DIS γ , Z exchange + interference -CC DIS *W* exchange

$$
\frac{d\Delta\sigma^{e^{\mp},i}}{dxdy}=\frac{4\pi\alpha^2}{xyQ^2}\left[\pm y(2-\right.
$$

NC Target-flip Parity-Violating Asymmetry WC 1arget-flip Parity-Violating Asymmetr e.g., \mathbf{r} for details. We note that Eq. (1) agrees that WC Target-flip Parity-Violating Asyr factor 1/2 in our definition of d2∆σ, such that the experimental control of d2∆σ, such that the experimental co
The experimental control of d2∆σ, such that the experimental control of d2∆σ, such that the experimental cont

• Polarized beam ion beams at EIC provide a new direction for exploring the nucleon spin structure: an ection to
structure: Exploring the nucleon spin ion for cture: *ge* ploring the nu direction for exploring the nucleon

> • NC DIS asymmetry: **NC DIS asymmetry:** mmetrv
mmetrv metry:

$$
g_1^{\gamma Z} = \sum e_q(g_V)_q (\Delta q + \Delta \bar{q})
$$

$$
g_5^{\gamma Z} = \sum_q e_q(g_A)_q (\Delta q - \Delta \bar{q})
$$

• CC DIS asymmetry: \overline{C} DIS asymmetry:

$$
g_1^{W^-,p}(x) = \Delta u(x) + \Delta \bar{d}(x) + \Delta c(x) + \Delta \bar{s}(x) ,
$$

\n
$$
g_5^{W^-,p}(x) = -\Delta u(x) + \Delta \bar{d}(x) - \Delta c(x) + \Delta \bar{s}(x)
$$

 $d\Delta \sigma^{e^+,i}$

[See dedicated talk by de Florian]
[See El⊆ Simulation studies: Asch at the leading order (LO) order (LO) order (LO) order (LO) or naive parton model approximately $\frac{d\Delta\sigma^{c}}{dt}$ $\frac{dxdy}{dxdy}$ is the dedicated taik by the Fibrian jump is a set of $dxdy$ $\frac{1}{2}$ $\frac{1}{2}$ [See EIC Simulation studies: Aschenauer, Burton, Martini, Spiesberger, Stratmann, Sassot]

Jet Charge

Standard Jet Charge

[Feld, Feynman (1978); Krohn, Schwartz, Lin, Waalewijin (2012)]

 α discriminate jet flavor: • Jet Charge can be used to discriminate jet flavor:

In this work, we propose the dynamic group of the dynamic group $\mathbb{P}(\mathsf{C})$ is defined as a contract charge. Poor q vs. g discrimination

Dynamic Jet Charge \blacksquare function in Eq. (12) can still be done directly in Eq. (12) can still be done directly in Eq. (12) can still be done \blacksquare

For each hadron *in the jet said in the jet said in the jet said [Kang, Liu, SM, Spraker, Wilson (2021)]*

$$
Q_{\text{dyn}}^i = \sum_{h \in i \text{-jet}} z_h^{\kappa(z_h)} Q_h
$$

$$
\kappa(z_h) = \begin{cases} k_<, & z_h < \xi_{\text{cut}} \\ k_>, & z_h \ge \xi_{\text{cut}} \end{cases}
$$

 c rimination

Jet Charge ROC Curves

[Kang, Liu, SM, Spraker, Wilson (2021)]

u vs. d discrimination distributions in *pp*-collisions at p*s* =13 TeV, for quark (red)

in Fig. 8 **q** vs. g discrimination Fig. 6. The standard (top) standard (top) and dynamic control of the standard (top) α distributions in Heavy Ion (Pb-Pb) collisions at p*s* =2.760

Jet Momentum Momentum Imbalance in DIS

[Collins, Soper, Sterman; Ji, Ma, Yuan; Liu, Ringer, Vogelsang; Arratia, Kang, Prokudin, …]

- TMD PDFs give a 3-dimensional \Box view of the momentum distributions of partons in the proton
- This observable is sensitive to specific flavor combinations of TMDPDFs

$$
d\sigma \sim \sum_i \tilde{f}_i(x, k_T) \otimes H \otimes S \otimes J_i
$$

Jet Momentum Momentum Imbalance in DIS

• This observable is sensitive to specific flavor combinations of TMDPDFs

 $d\sigma \sim \sum_i \tilde{f}_i(x, k\tau) \otimes H \otimes S \otimes J_i$

Jet Momentum Momentum Imbalance in DIS

 $Q^i_{\kappa} = \sum z_h^{\kappa} Q_h$ $h\in i$ -jet

• This observable is sensitive to specific flavor combinations of TMDPDFs

 $d\sigma \sim \sum_i \tilde{f}_i(x, k\tau) \otimes H \otimes S \otimes \overline{J}_i$ Measure the jet electric charge $d\sigma \sim \sum_i \tilde{f}_i(x, k\tau) \otimes H \otimes S \otimes \mathcal{G}_i(g_3)$

[Kang, Liu, SM, Shao (2020)]

FIG. 2. The relative size of contributions from the unpolarized *u*-, *d*-, and sea quark TMDs.

Polarized TMD Flavor Separation with Jet Charge *i*=*u,d,··· ri,*bin *d* standard transverse-spin dependent cross section for a

T Polarized TMD PDFs probe correlations between proton spin and 3D momentum distributions of partons in the proton and can be accessed via the asymmetry. 1¹ asymmetry.

$$
A_{UT} = \frac{\mathrm{d}\sigma(S_{\perp}^{\uparrow}) - \mathrm{d}\sigma(S_{\perp}^{\downarrow})}{\mathrm{d}\sigma(S_{\perp}^{\uparrow}) + \mathrm{d}\sigma(S_{\perp}^{\downarrow})}
$$

 K ang Liu SM Shao (2020) 1 [Kang, Liu, SM, Shao (2020)]

FIG. 4. Sensitivities of the *d*-quark channels to the Sivers asymmetry asymmetry.

Electroweak Physics at the EIC

- The EIC is primarily a QCD machine.
- However, electroweak physics at the EIC can play an important role for:
- $\mathcal{L} = \mathcal{L} \cdot \mathcal{L} = \mathcal{L} \cdot \mathcal{L}$ measurements of electroweak couplings - constraining new physics via precision measurements of electroweak couplings - SMEFT Analyses
- proton's \mathbf{r} - electroweak probes of nucleon spin structure (NC, CC DIS)
- Jet electric charge probe
	- This is facilitated by:
- -high luminosity -wide kinematic range -polarized beams -range of nuclear targets

-0.5

∆ $\mathbf \Theta$