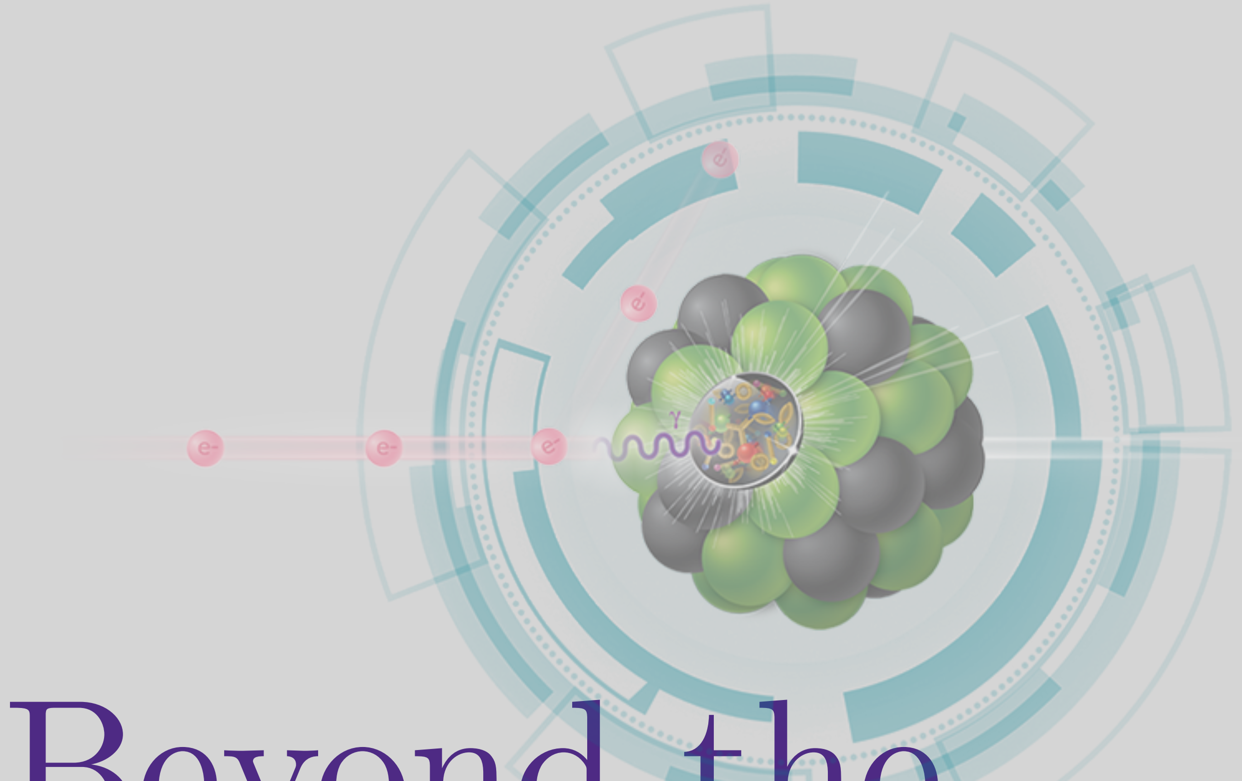
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Precision Electroweak Measurements and Beyond the Standard Model Searches at the Electron-Ion Collider

Kaan Şimşek

Northwestern University

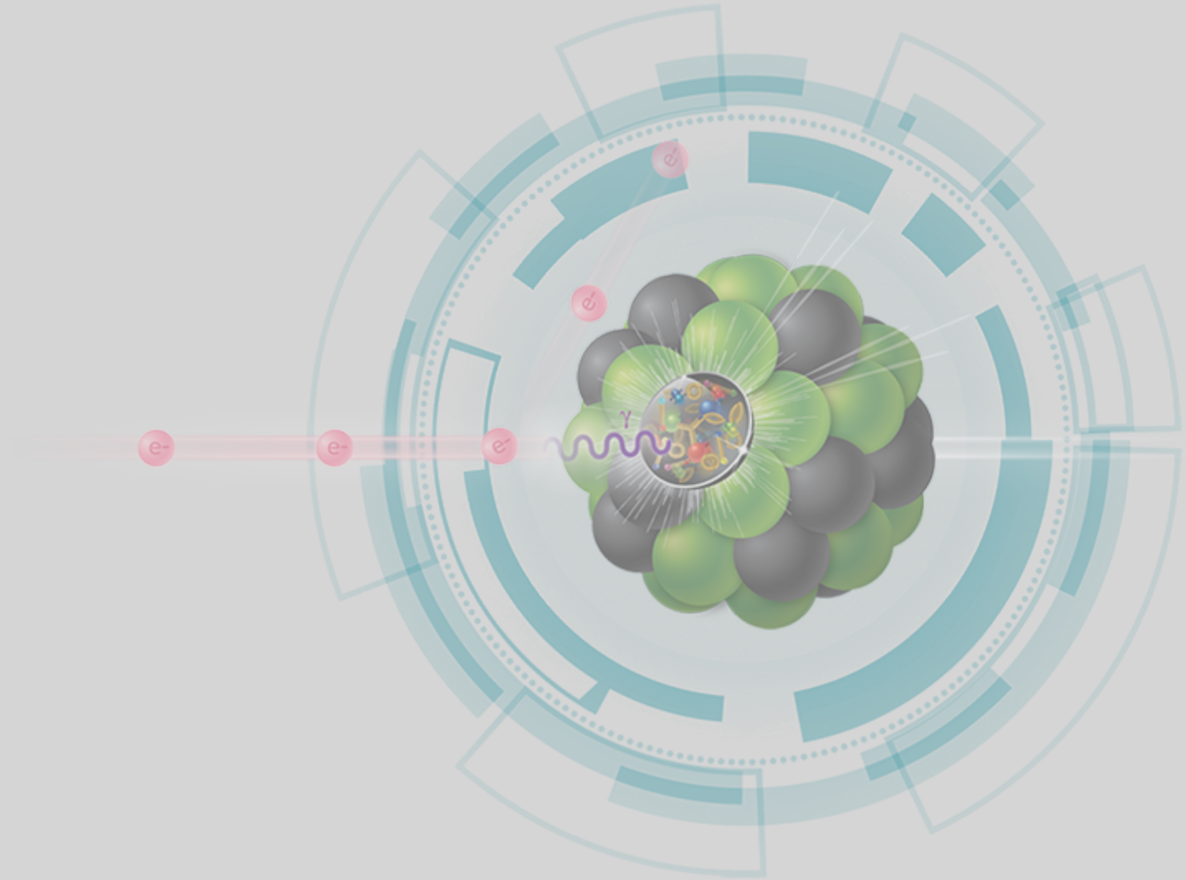
Argonne NATIONAL LABORATORY

DIS23 MICHIGAN STATE UNIVERSITY

References:
2204.07557, 2207.10261

Collaborators:
R. Boughezal, F. Petriello, D. Wiegand, and
S. Mantry *et al.* (EIC Group)

March 30, 2023



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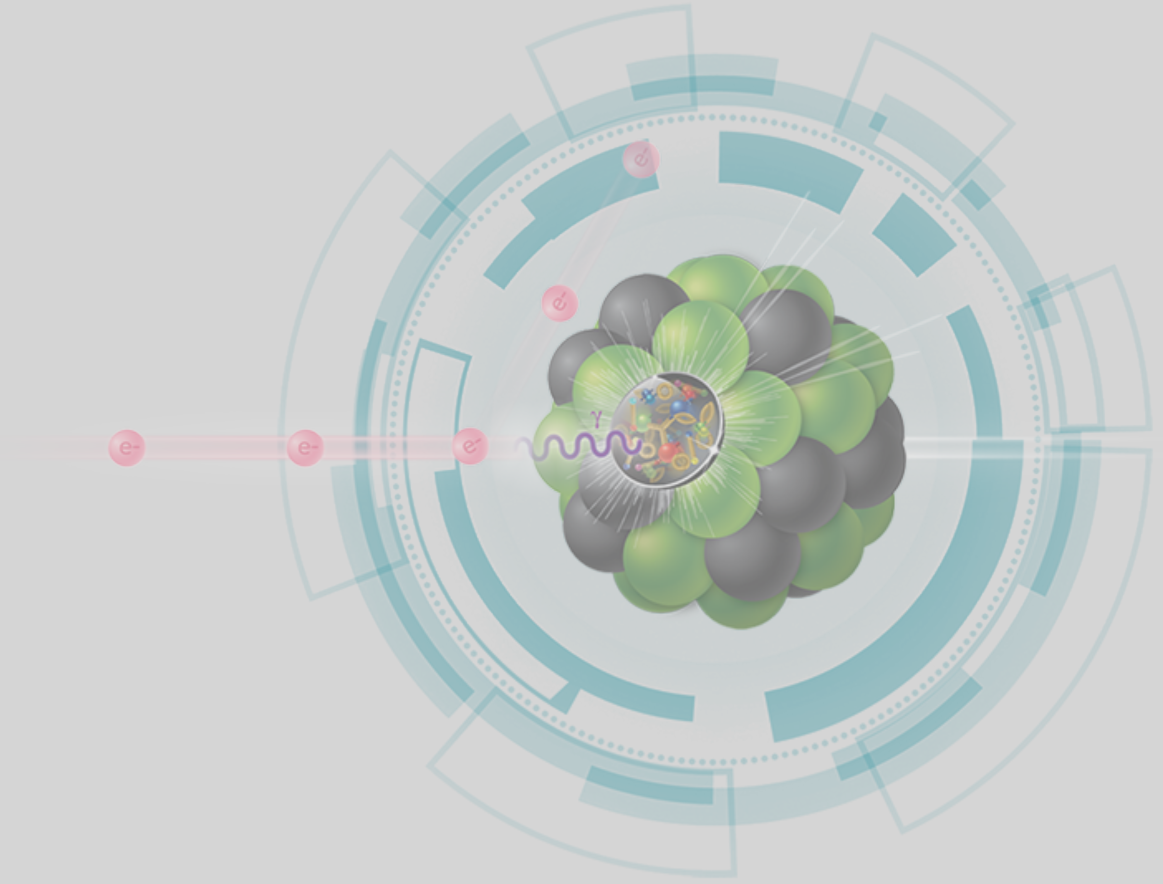
Prelude

Electron-Ion Collider

A next-gen electron-hadron collider

Accardi *et al.* 1212.1701



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- A US DOE project under design at BNL, Upton, NY.
- It will use the Relativistic Heavy Ion Collider (RHIC @ BNL, in operation since 2000) acceleration complex. (RHIC is the first heavy-ion collider and also the world's only spin-polarized proton collider.)
- It will combine experience from HERA to deliver polarized e^- beams with experience from RHIC to be the first machine that provides polarized e^- with polarized p, and later polarized ^{2}H and ^{3}He.
- It is planned to start operating in a decade.

Electron-Ion Collider

A next-gen electron-hadron collider

Accardi *et al.* 1212.1701

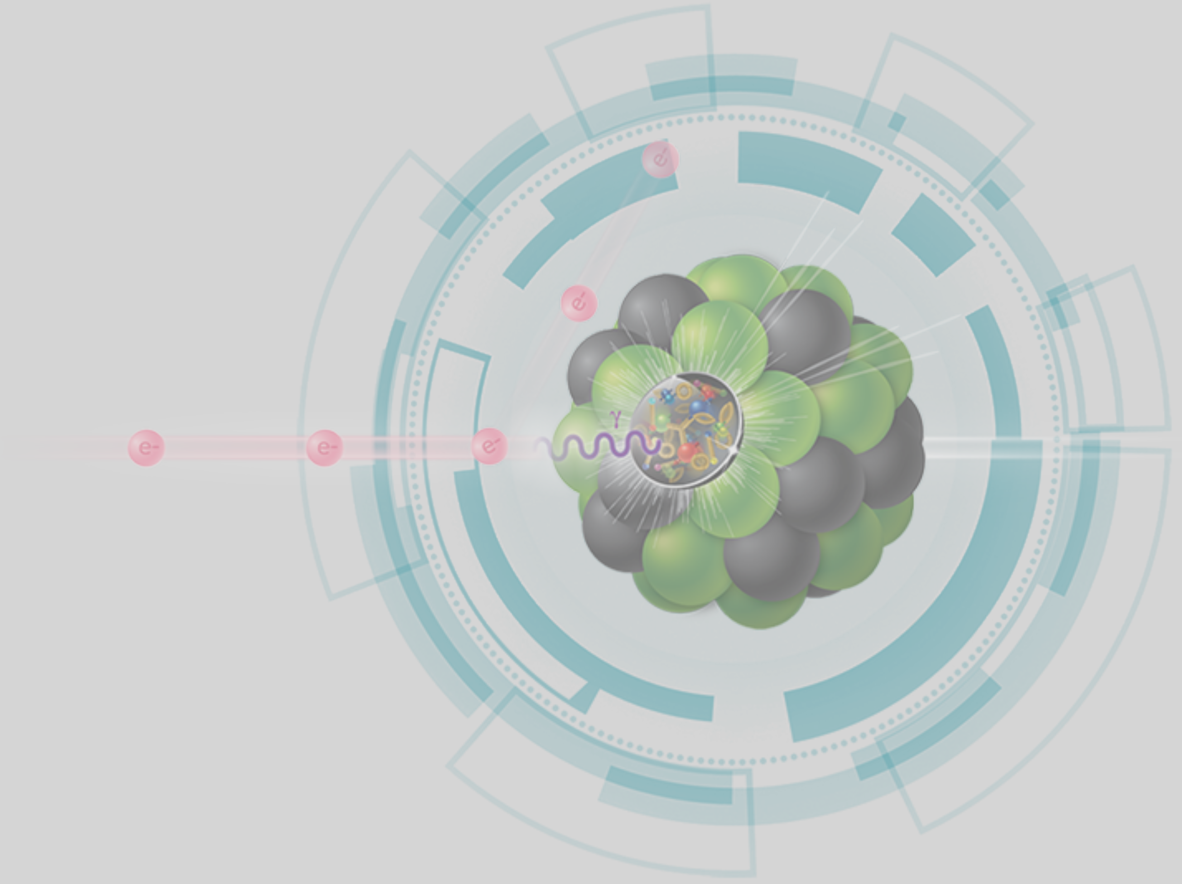


Image credit: bnl.gov

Unique features:

- Designed to collide 5 to 18 GeV e^- beams with 41 to 275 GeV polarized p beams, polarized light ions with energies up to 137 GeV (^{2}H) and 166 GeV (^{3}He), and unpolarized heavy ion beams up to 110 GeV
- CM energies between fixed-target scattering and high-energy collisions, 70 to 140 GeV
- First lepton-ion collider to polarize both beams
- Luminosity orders of magnitude higher than HERA
- Reduced point-to-point luminosity uncertainties $\sim 10^{-4}$
- First collider with fast spin-flip capacity*: distinguished from HERA

Electron-Ion Collider

A next-gen electron-hadron collider

Accardi *et al.* 1212.1701

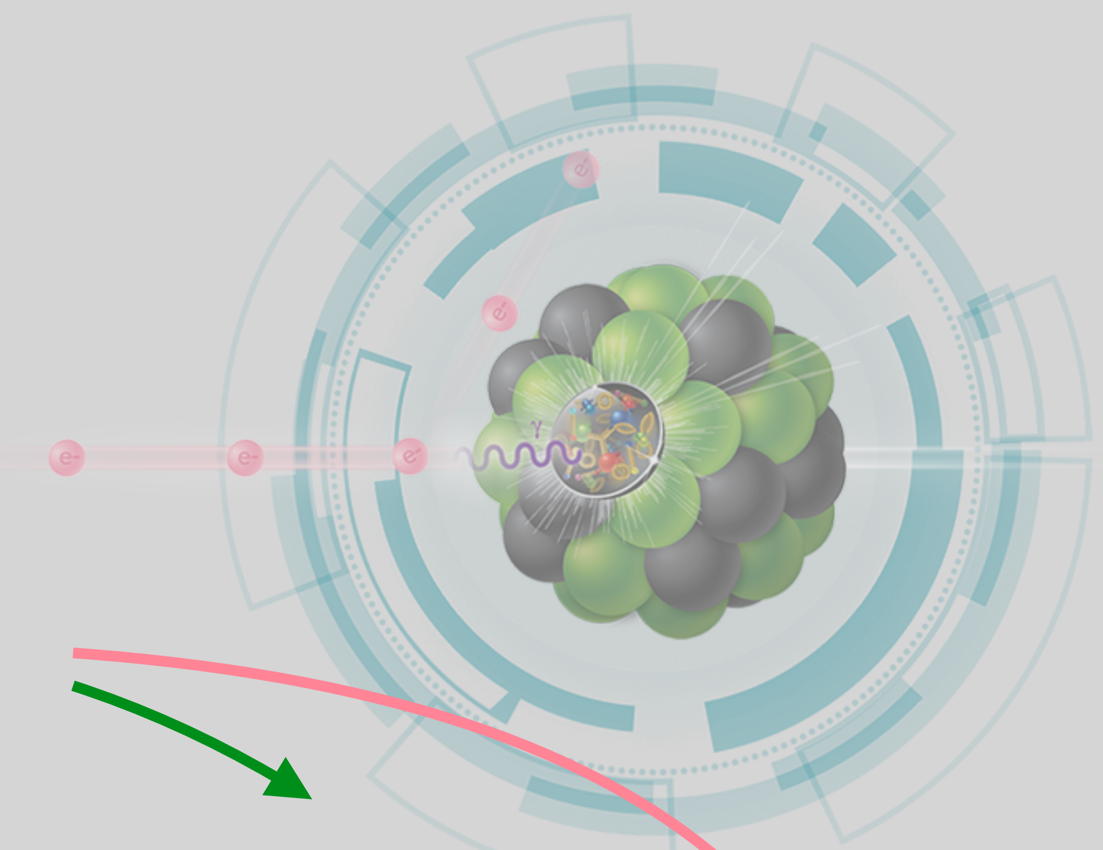


Image credit: bnl.gov

Data sets:

Label	E_e [GeV] × E_H [GeV]	$\mathcal{L}$ [fb^{-1}]
D1	5 × 41	4.4
D2	5 × 100	36.8
D3	10 × 100	44.8
D4	10 × 137	100
D5	18 × 137	15.4
P1	5 × 41	4.4
P2	5 × 100	36.8
P3	10 × 100	44.8
P4	10 × 275	100
P5	18 × 275	15.4
P5	18 × 275	100

YR reference

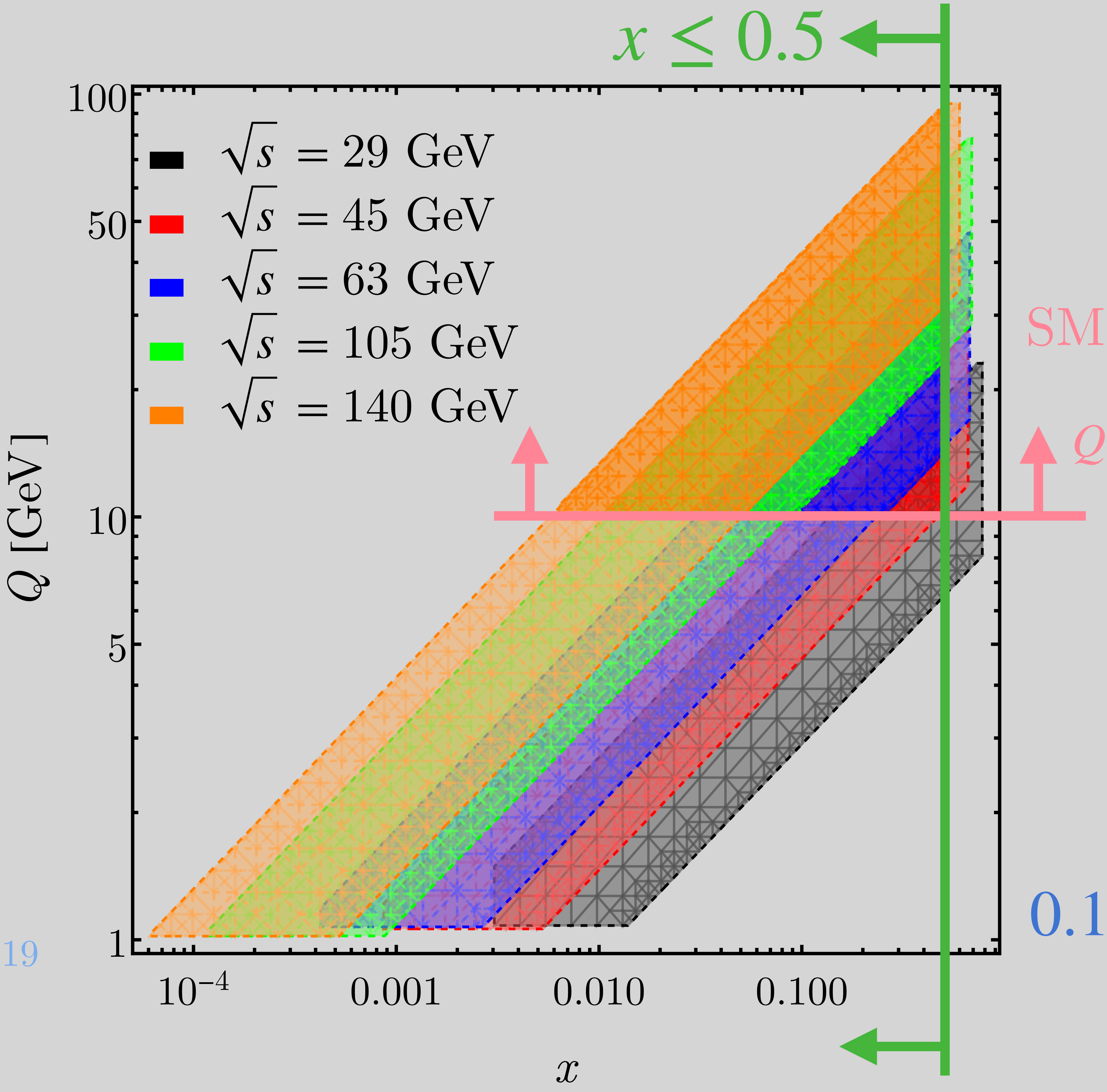
Khalek *et al.* 2103.05419

Kinematic coverage:

cuts to avoid nonperturbative QCD and nuclear dynamics

SMEFT

SMEFT & LQ



$0.1 \leq y \leq 0.9$ for all

Electron-Ion Collider

A next-gen electron-hadron collider

Accardi *et al.* 1212.1701

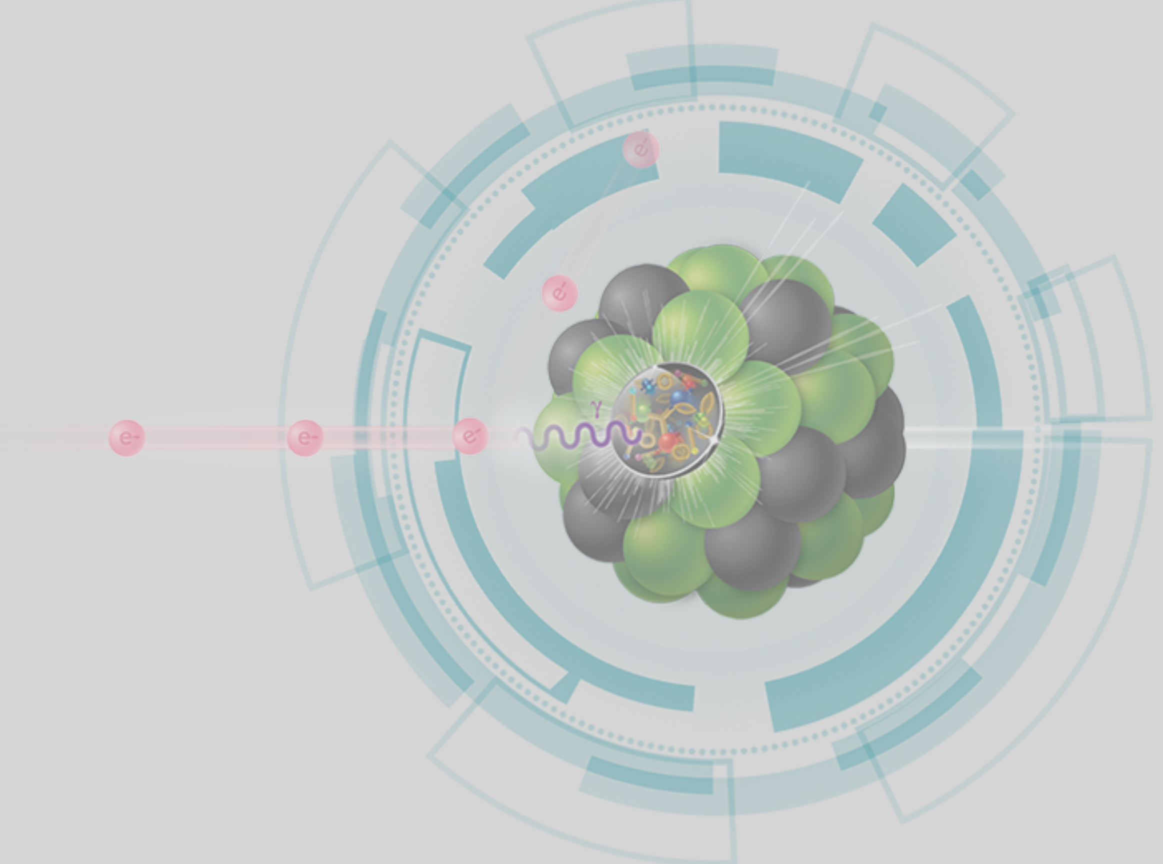


Image credit: bnl.gov

Observable of interest:

$$A_{\mathrm{PV}} = \frac{\sigma^{+}_{\mathrm{NC}} - \sigma^{-}_{\mathrm{NC}}}{\sigma^{+}_{\mathrm{NC}} + \sigma^{-}_{\mathrm{NC}}}$$

unpolarized

PV asymmetry

$$\Delta A_{\mathrm{PV}} = \frac{\Delta\sigma^{0}_{\mathrm{NC}}}{\sigma^{0}_{\mathrm{NC}}}$$

polarized

PV asymmetry

$$A_{\mathrm{LC}} = \frac{\sigma^{e^-}_{\mathrm{NC}} - \sigma^{e^+}_{\mathrm{NC}}}{\sigma^{e^-}_{\mathrm{NC}} + \sigma^{e^+}_{\mathrm{NC}}}$$

lepton-charge (LC) asymmetry

$(\Delta)\sigma^{\pm}_{\mathrm{NC}}$: un(polarized) NC e^-H DIS cross section with only one beam polarized

$(\Delta)\sigma^{0}_{\mathrm{NC}}$: un(polarized) NC e^-H DIS cross section with no beams polarized

$\sigma^{e^\pm}_{\mathrm{NC}}$: unpolarized NC $e^\pm H$ DIS cross section with no beams polarized

Electron-Ion Collider

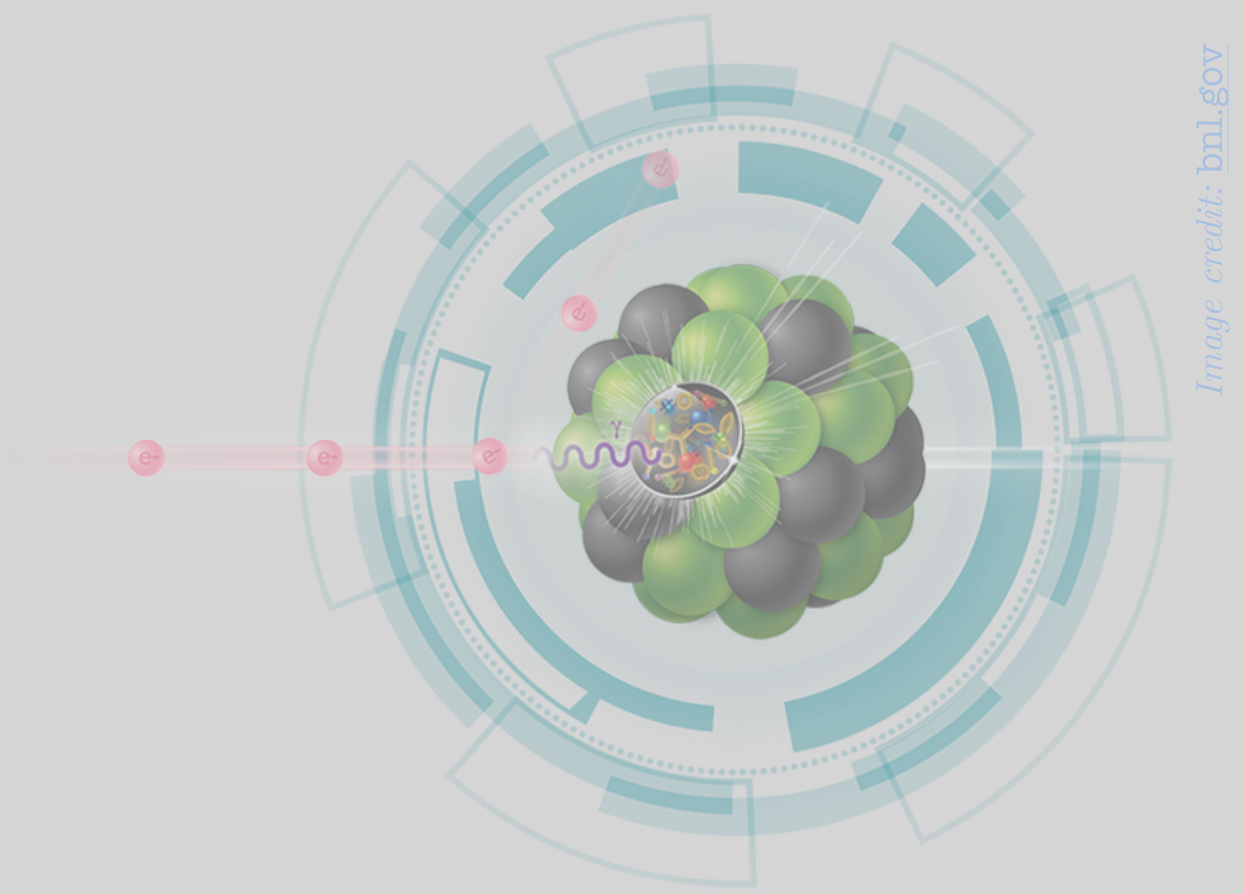


Image credit: bnl.gov

A next-gen electron-hadron collider

Accardi *et al.* 1212.1701

Uncertainty	A_{PV}	ΔA_{PV}	A_{LC}
Statistical (NL)	$\delta A_{\mathrm{PV,stat}} = \frac{1}{P_\ell \sqrt{N}}$	$\frac{P_\ell}{P_H}\delta A_{\mathrm{PV,stat}}$	$\sqrt{10}P_\ell \delta A_{\mathrm{PV,stat}}$
Statistical (HL)	$\frac{1}{\sqrt{10}}\delta A_{\mathrm{PV,stat}}$	$\frac{1}{\sqrt{10}}\frac{P_\ell}{P_H \delta A_{\mathrm{PV,stat}}}$	NO
Uncorrelated systematic	1% rel.	1% rel.	1% rel.
Fully correlated beam polarization	1% rel.	2% rel.	NO
Fully correlated luminosity	NO	NO	2% abs.
Uncorrelated NLO QED	NO	NO	$5\% \times (A_{\mathrm{LC}}^{\mathrm{NLO\ QED}} - A_{\mathrm{LC}}^{\mathrm{Born}})$
Fully correlated PDF	YES	YES	YES

PDF sets used:

- Precision EW:
  - ⋆ CT18NLO
  - ⋆ MMHT2014nlo_68cl
  - ⋆ NNPDF31 NLO
- BSM analysis:
  - ⋆ NNPDF3.1 NLO
  - ⋆ NNPDFPOL1.1

Electron-Ion Collider

A next-gen electron-hadron collider

Accardi *et al.* 1212.1701

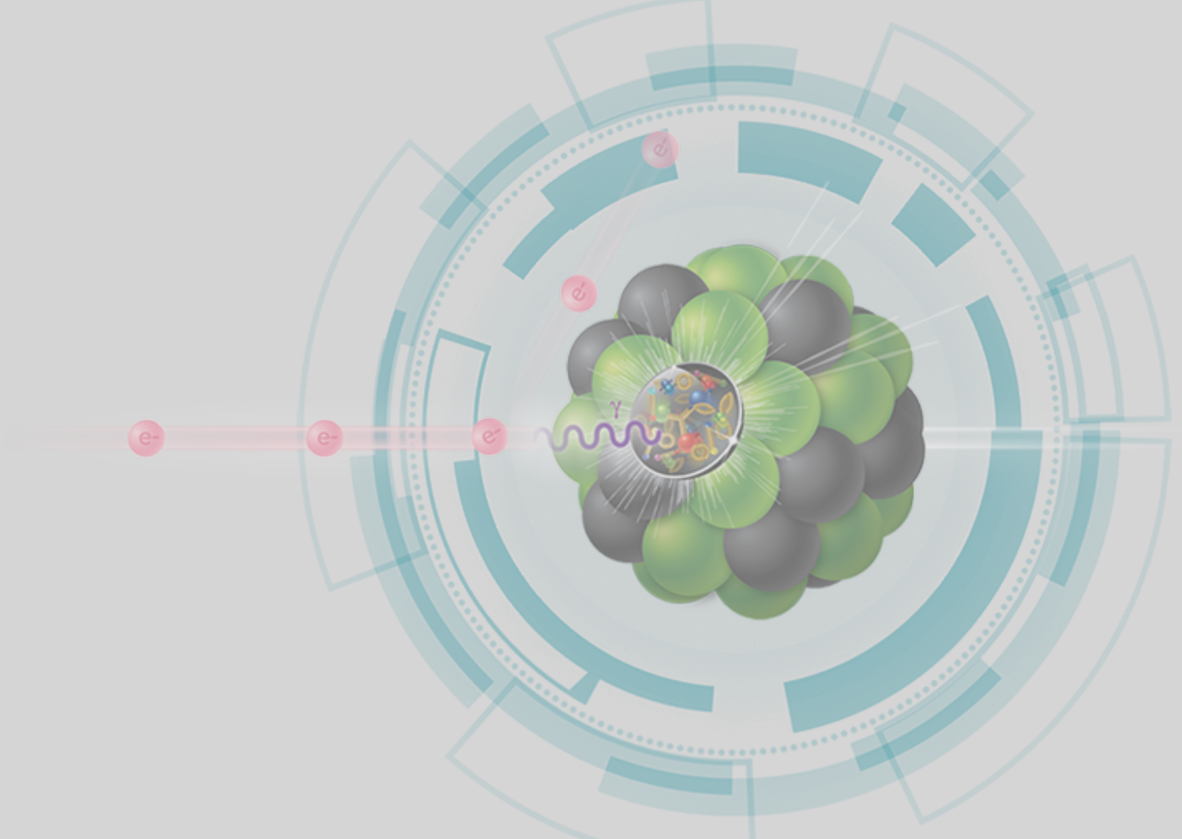
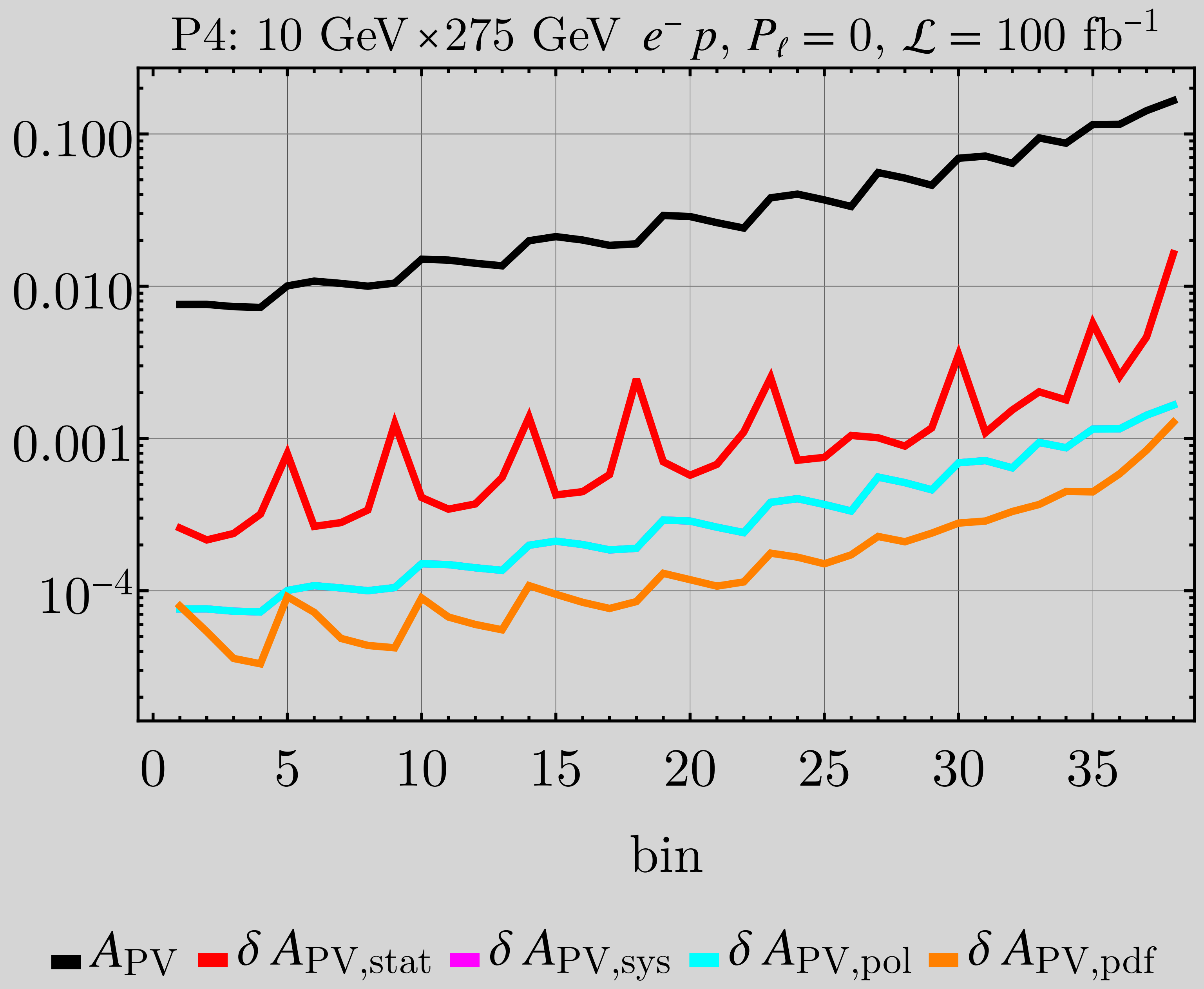
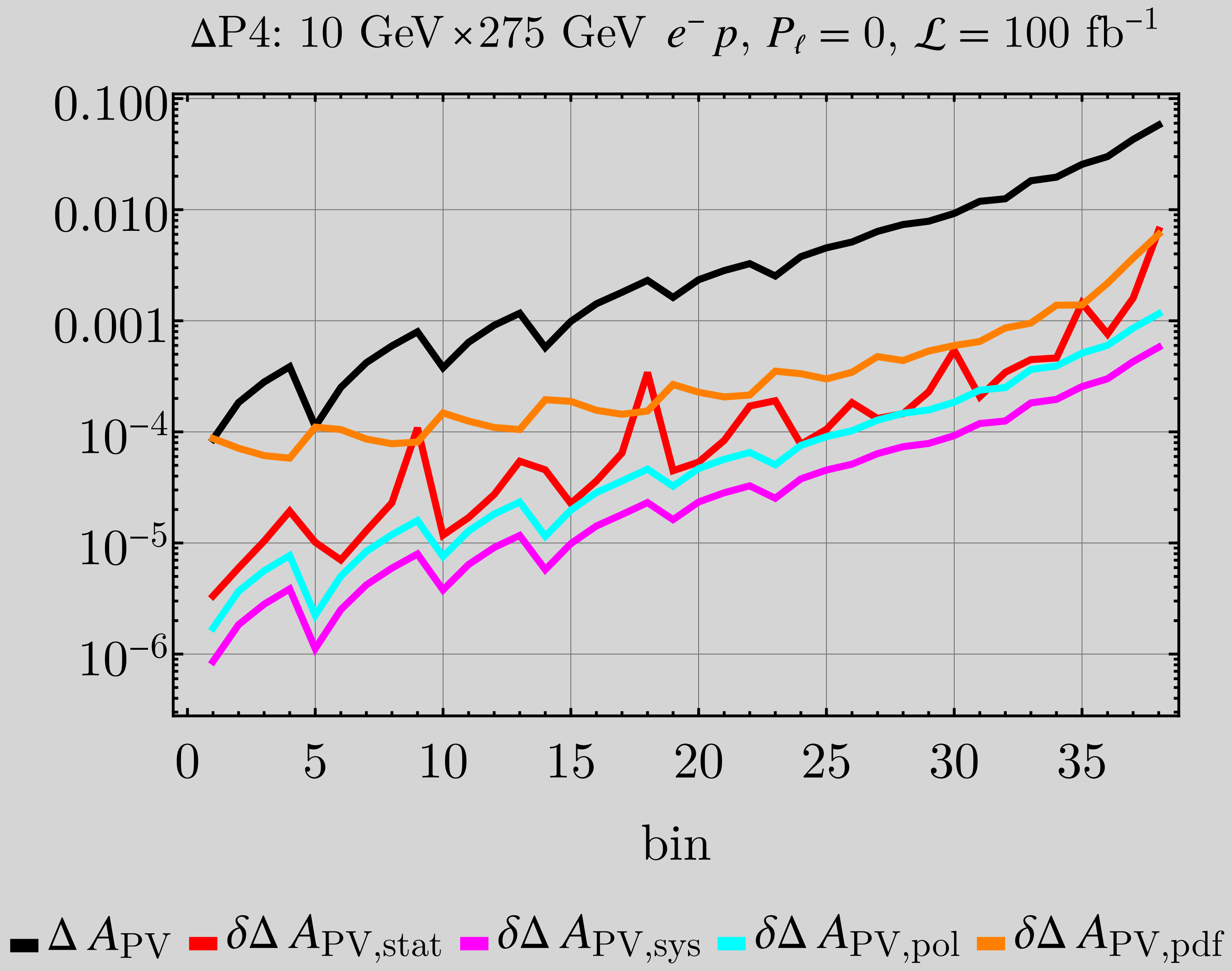


Image credit: bnl.gov

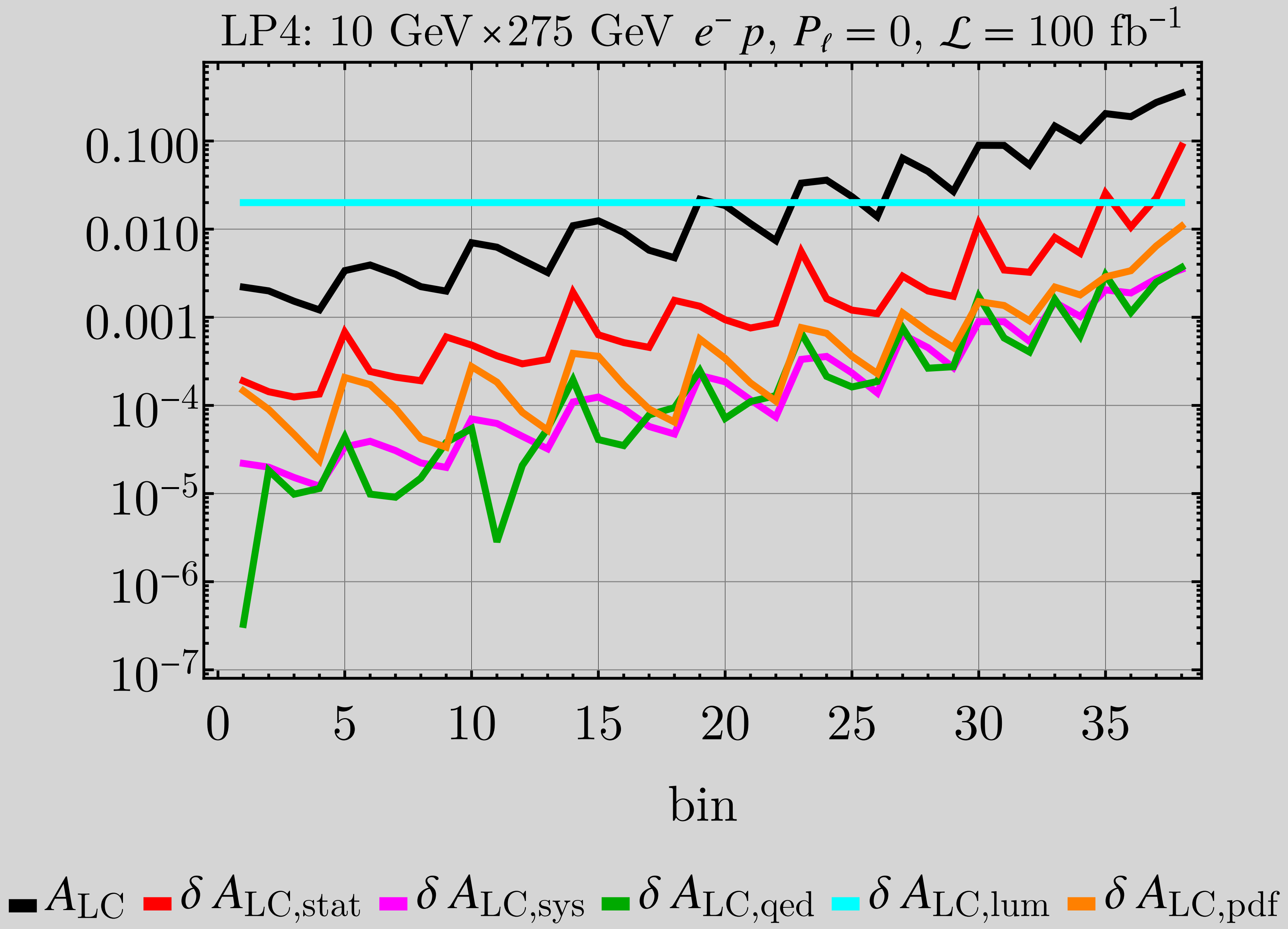
A_{PV}



ΔA_{PV}

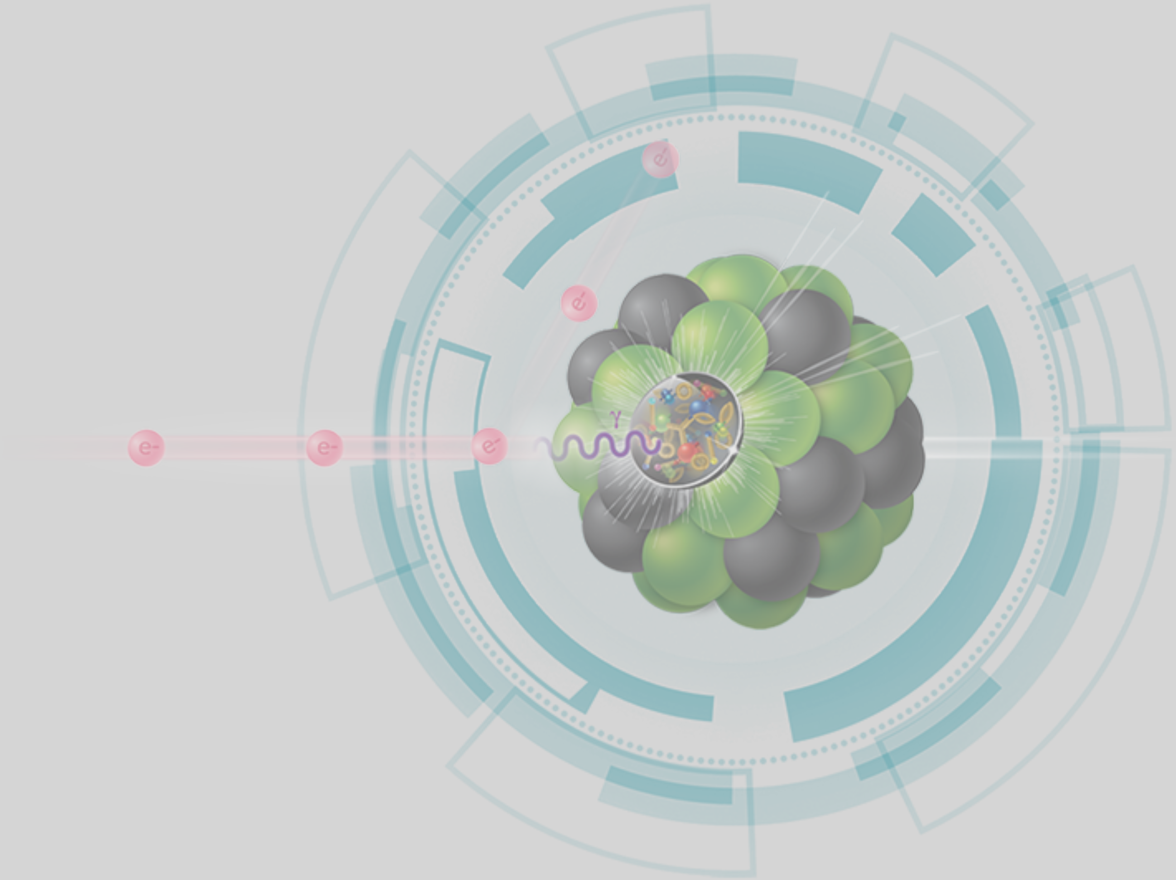


A_{LC}



Dominant uncertainties:

A_{PV} : statistical ΔA_{PV} : PDF A_{LC} : luminosity



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Phenomenology

Precision EW measurements

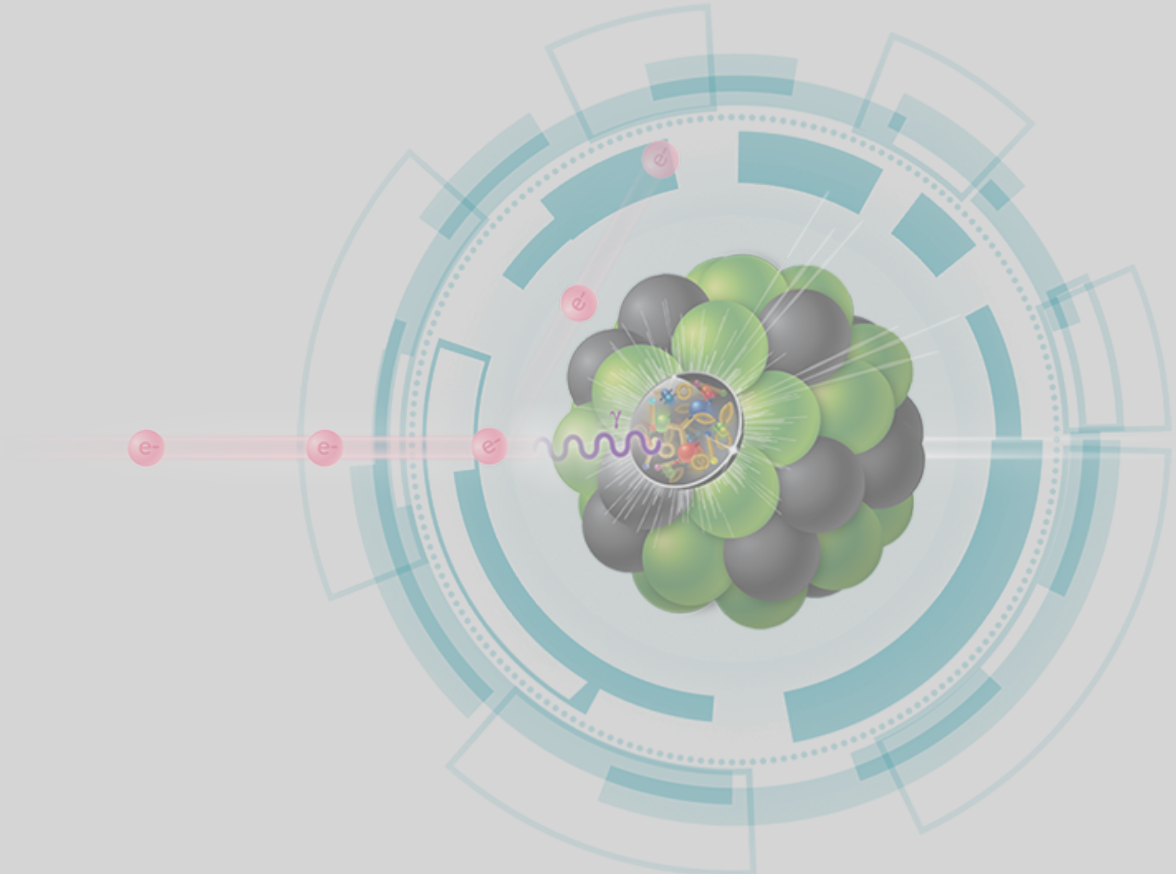


Image credit: bnl.gov

Extraction of $\sin(\theta_W)^2$

Boughezal *et al.* 2204.07557

Observable: unpolarized PV asymmetry including target-mass correction terms in the structure-function language

$$A_{\mathrm{PV}} = \frac{P_e \eta_{\gamma Z}\left[g_A^e 2yF_1^{\gamma Z} + g_A^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_V^e(2-y)F_3^{\gamma Z}\right]}{2yF_1^{\gamma} + \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma} - \eta_{\gamma Z}\left[g_V^e F_1^{\gamma Z} + g_V^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_A^e(2-y)F_3^{\gamma Z}\right]}$$

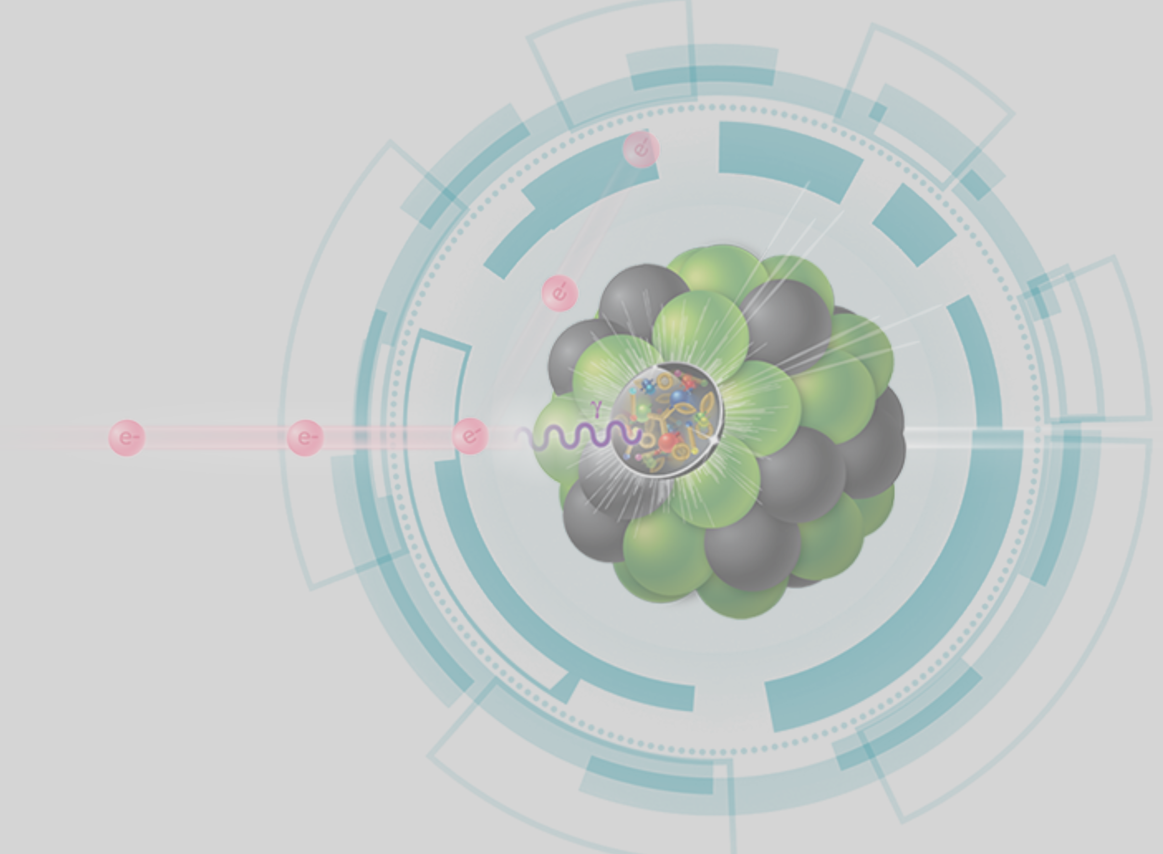
$\sin(\theta_W)^2$ enters through $g_{V,A}^e$ and $g_{V,A}^q$. One-loop RGE of $\sin(\theta_W)^2$ in the $\overline{\text{MS}}$ scheme and particle thresholds arising between $\mu = m_Z$ and $\mu = \sqrt{Q^2}$ are included.

Fitting procedure:

$$\chi^2 = (A^{\text{theory}} - A^{\text{pseudodata}})^{\top} H (A^{\text{theory}} - A^{\text{pseudodata}})$$

where pseudodata is generated by smearing uncertainties around the SM predictions with a gaussian profile.

Precision EW measurements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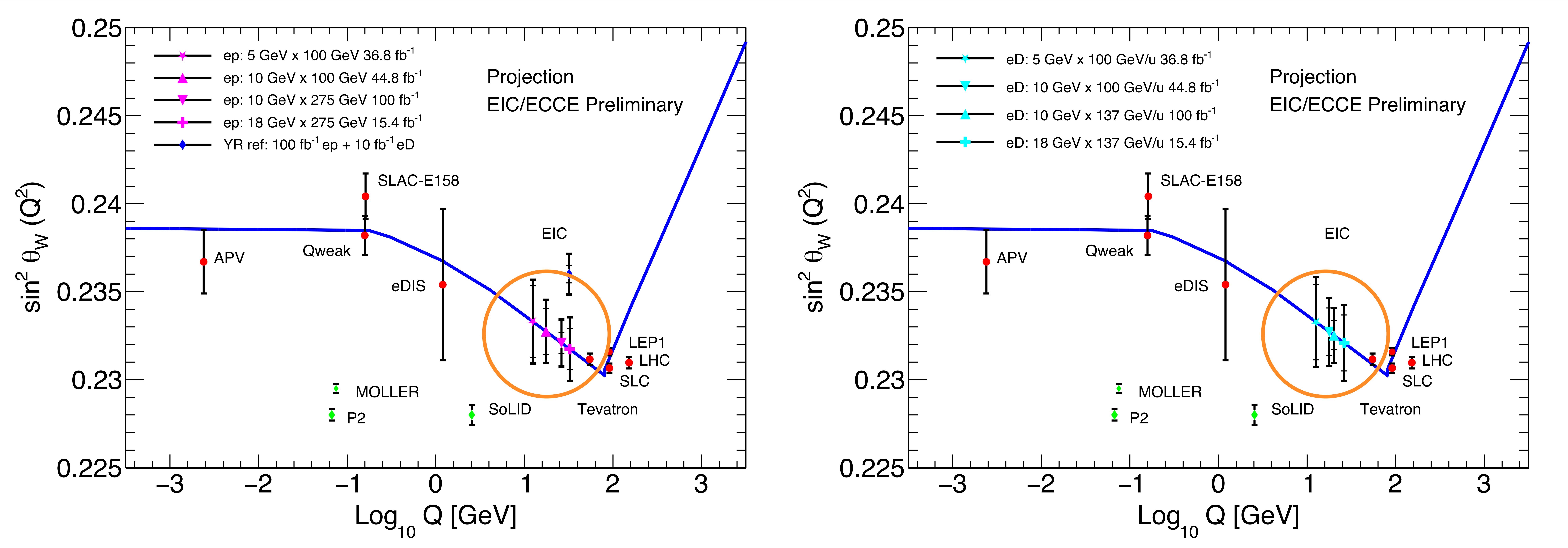
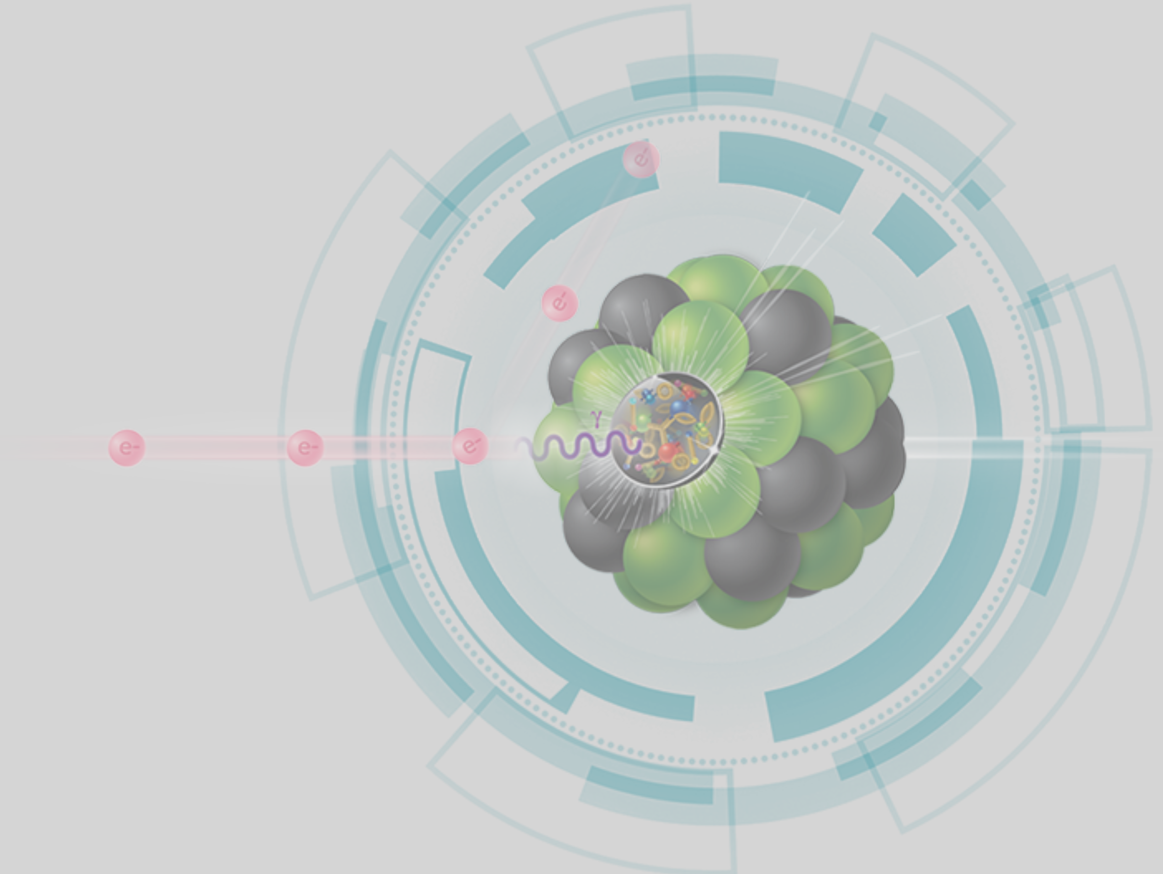
Extraction of $\sin(\theta_W)^2$

Boughezal *et al.* 2204.07557

bridge between high-energy colliders
and low- to medium-energy SM tests



BSM searches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Constraints on SMEFT parameters

Boughezal *et al.* 2204.07557

Extend SM Lagrangian with higher-dimensional operators, $O_k^{(n)}$, built up of SM fields at an energy scale Λ that is heaver than all SM fields and accessible collider energy, introducing Wilson coefficients, $C_k^{(n)}$, as effective couplings:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{n\geq 4} \frac{1}{\Lambda^{n-4}} \sum_k C_k^{(n)} O_k^{(n)}$$

SM couplings are shifted in a gauge-invariant manner, e.g.

$$g^f_{V,A} \to g^f_{V,A}[1 + c^f_{V,A}(M_Z, G_F, \alpha; C_k, \Lambda)]$$

We focus on the case $n = 6$ and semi-leptonic four-fermion operators that induce the contact interaction of leptons with quarks.

BSM searches

Constraints on SMEFT parameters

Boughezal *et al.* 2204.07557

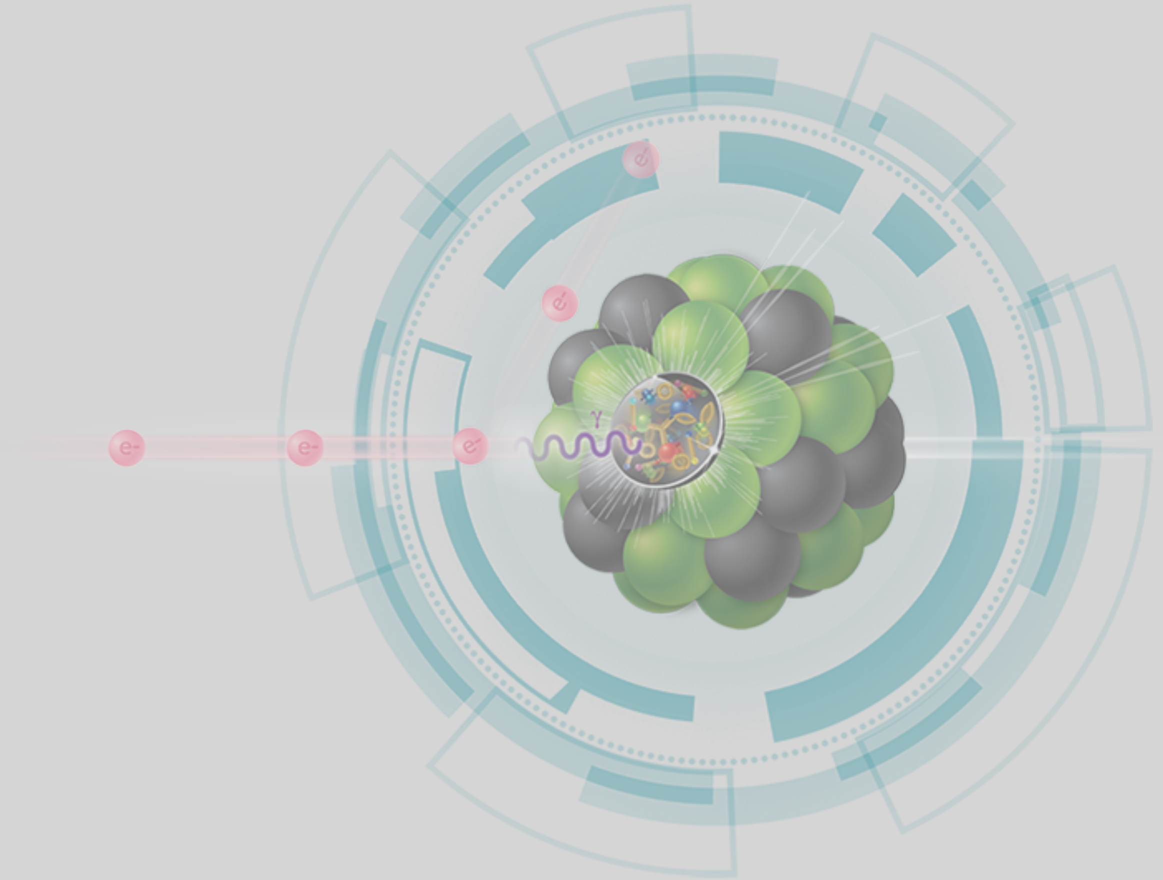


Image credit: bnl.gov

Observable: un(polarized) PV and lepton-charge asymmetries linearized w.r.t C_k

$$A = A_{\mathrm{SM}} + \sum_k C_k \, \delta A_k$$

Fitting procedure:

$$\chi^2 = (A^{\mathrm{theory}} - A^{\mathrm{pseudodata}})^\top H (A^{\mathrm{theory}} - A^{\mathrm{pseudodata}})$$

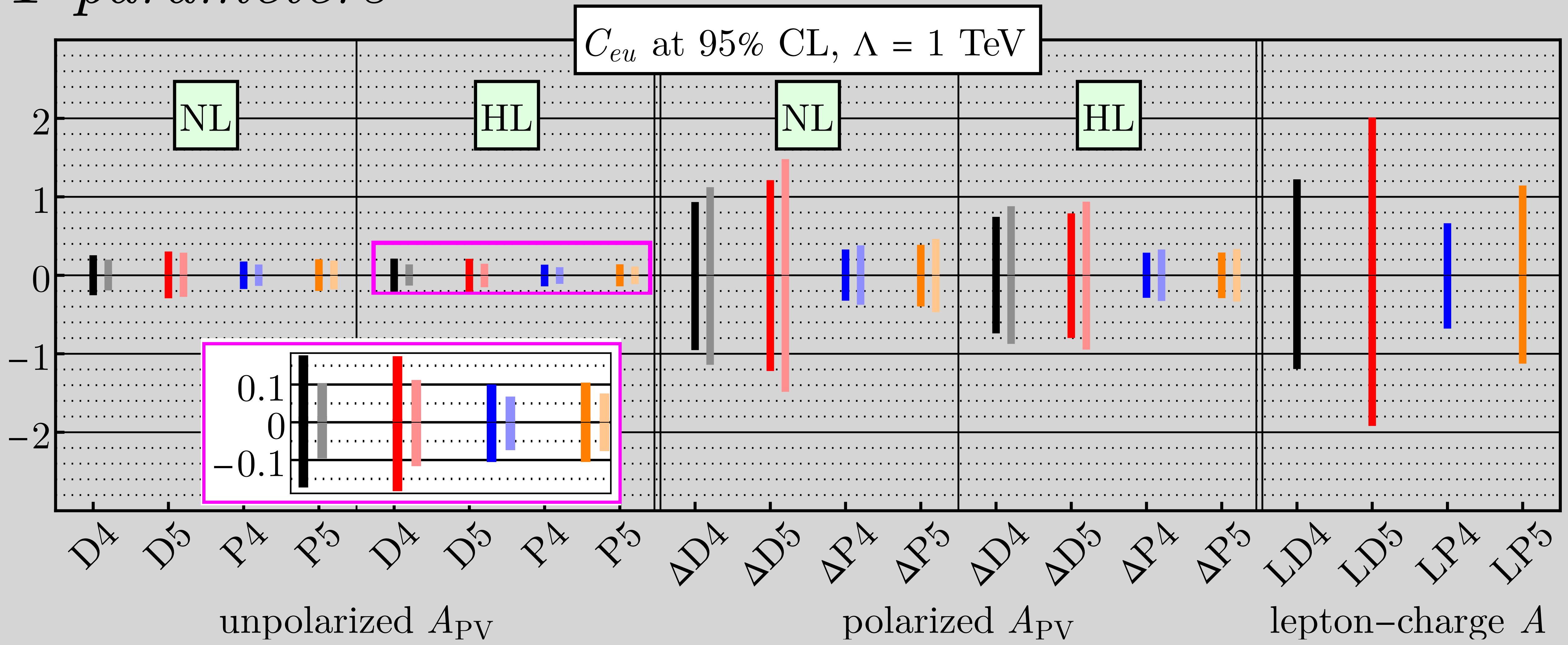
where pseudodata is generated by smearing uncertainties around the SM predictions with a gaussian profile.

BSM searches

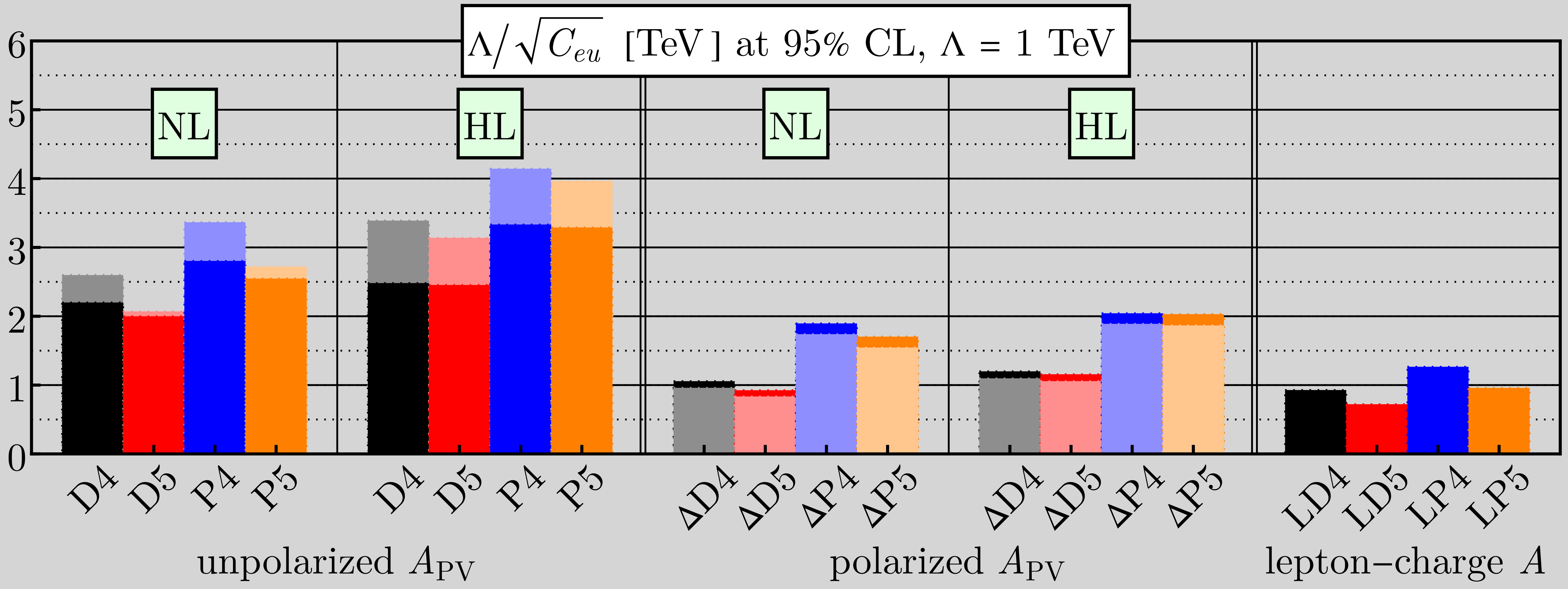
Constraints on SMEFT parameters

Boughezal *et al.* 2204.07557

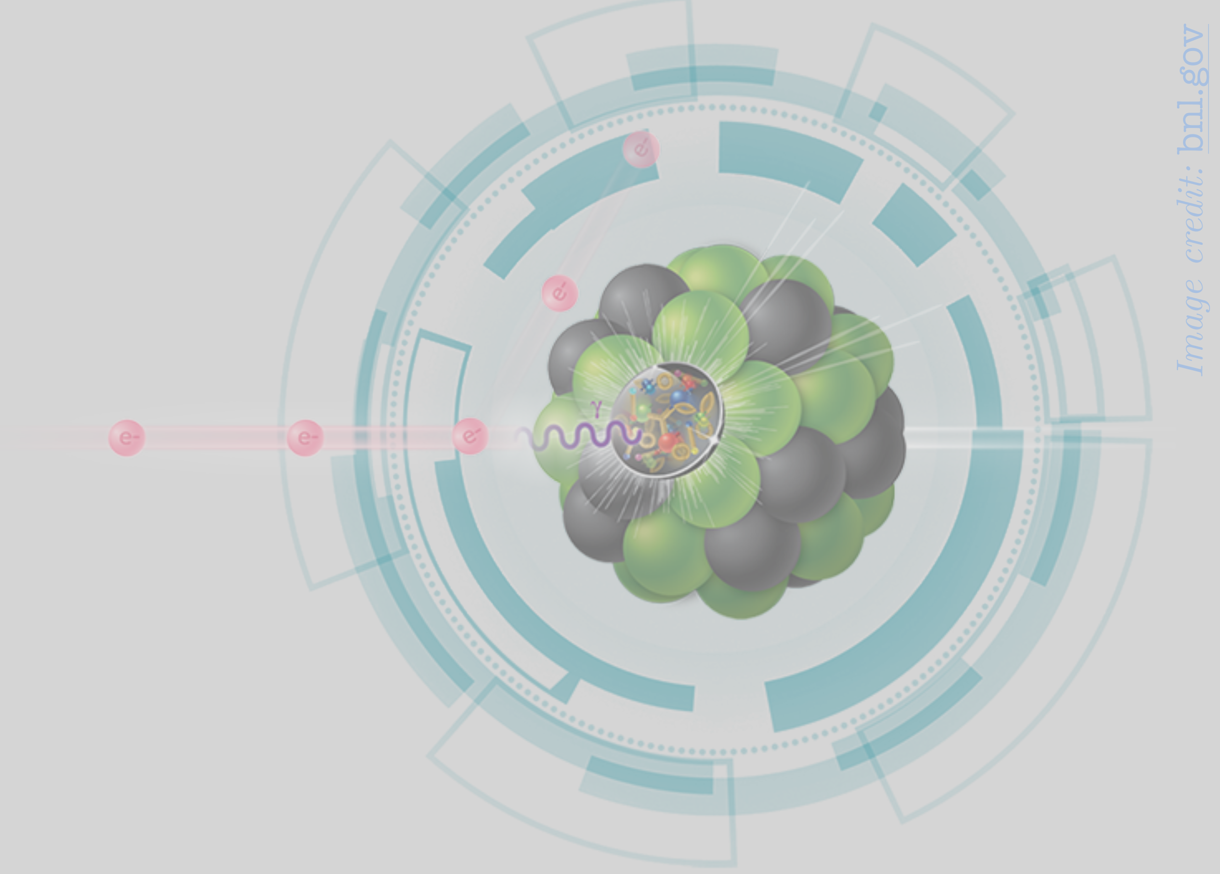
95% CL nonmarginalized bounds at $\Lambda = 1$ TeV in single-parameter fits



Corresponding effective UV scales



~ 4 TeV with high-lum EIC

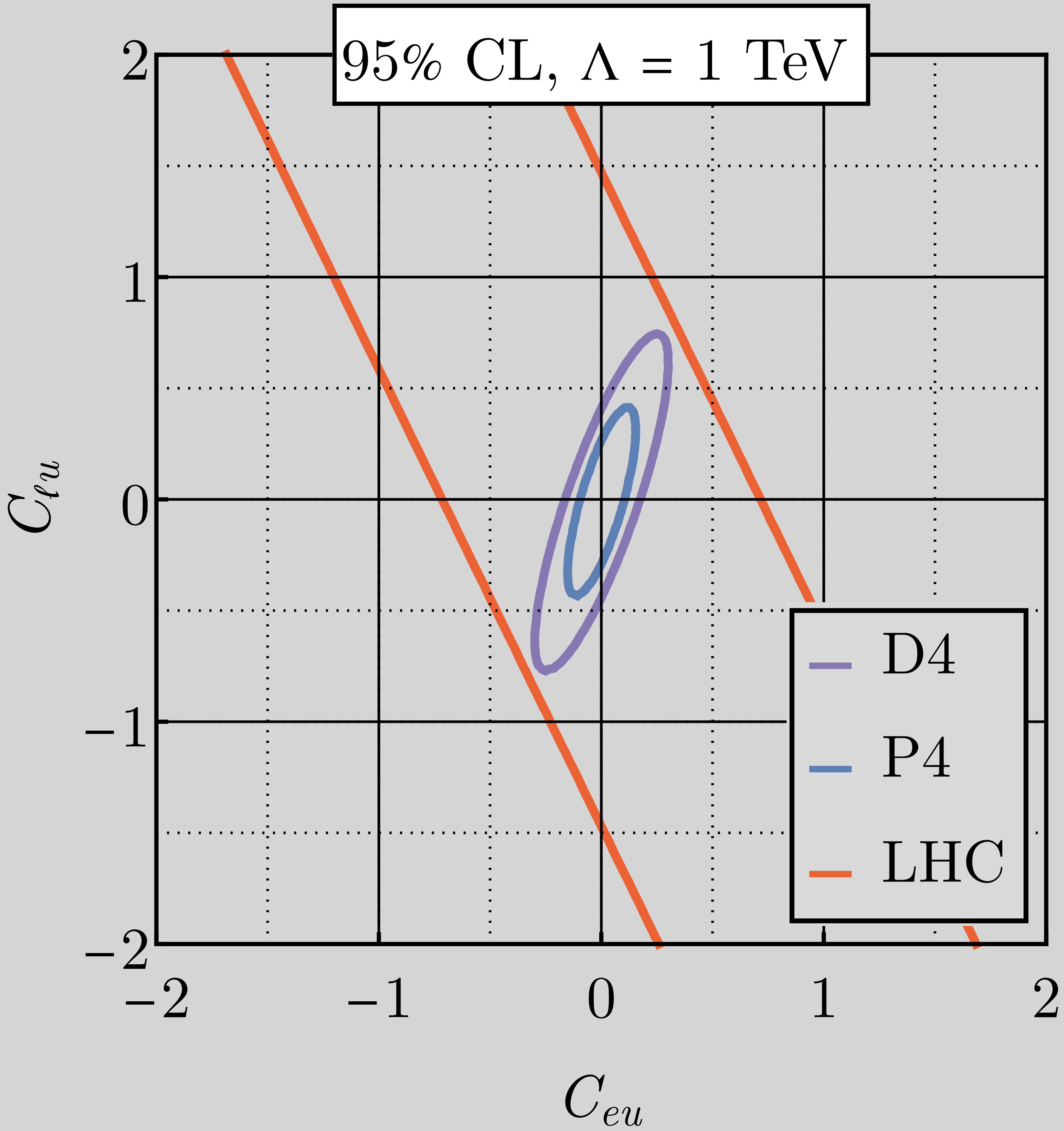


BSM searches

Constraints on SMEFT parameters

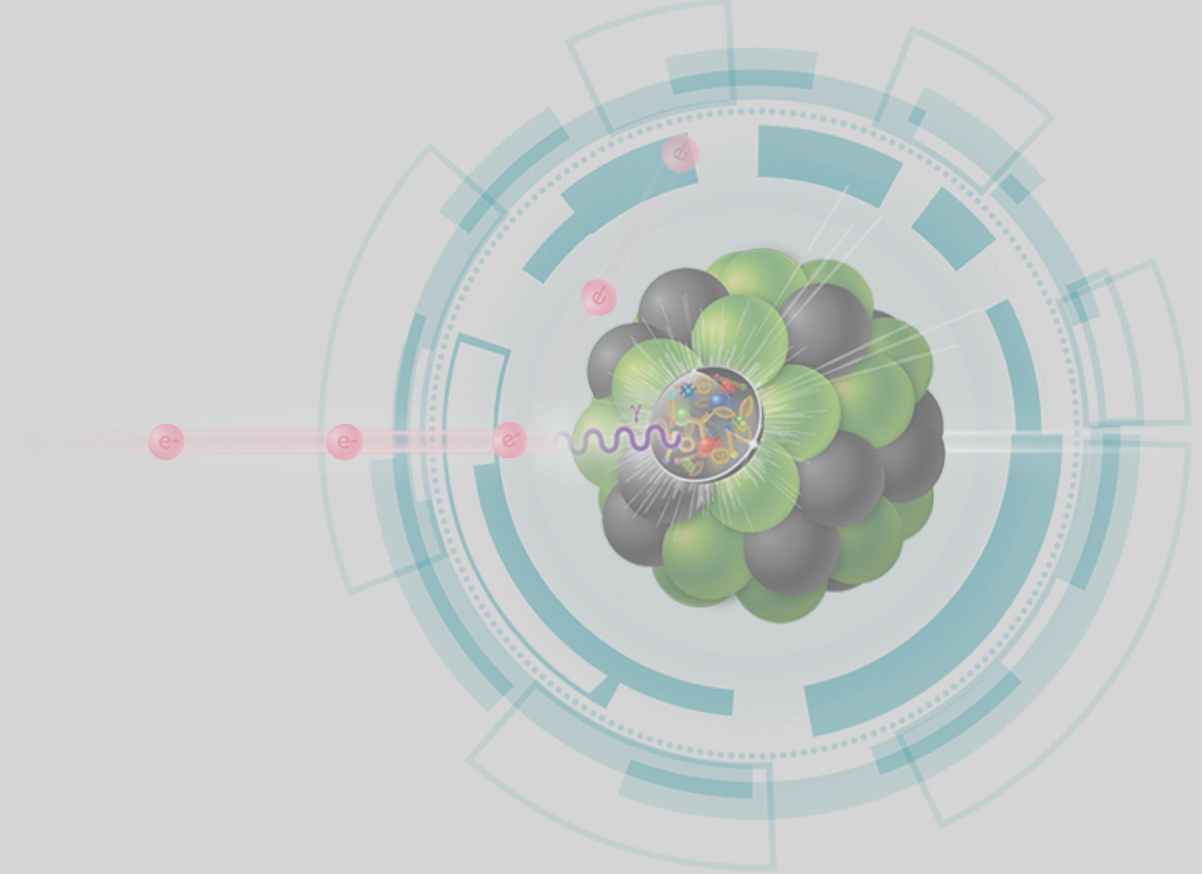
Boughezal *et al.* 2204.07557

95% confidence
ellipse at $\Lambda = 1$ TeV
in two-parameter fits

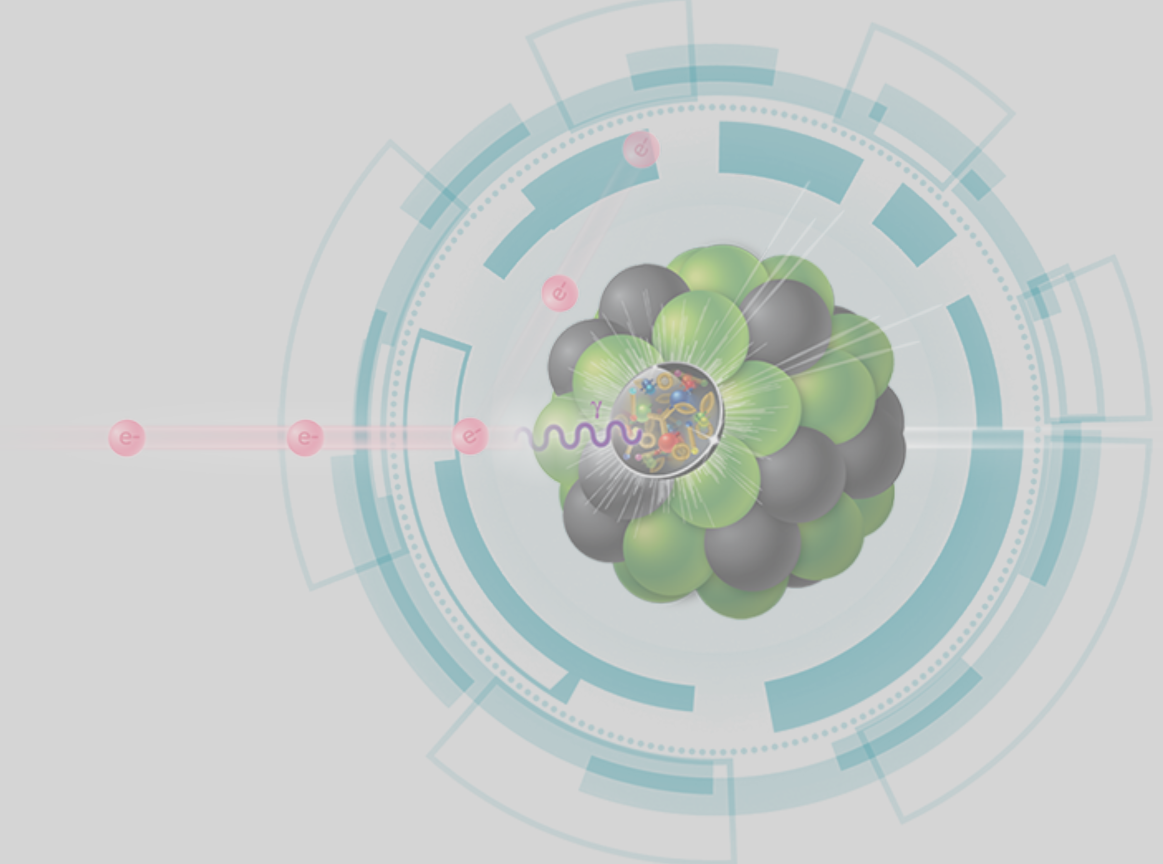


LHC NC Drell-Yan
8 TeV 20 fb^{-1}
not 13 TeV high lum

Boughezal *et al.* 2104.03979



BSM searches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Limits on $e \leftrightarrow \tau$ in leptoquark framework

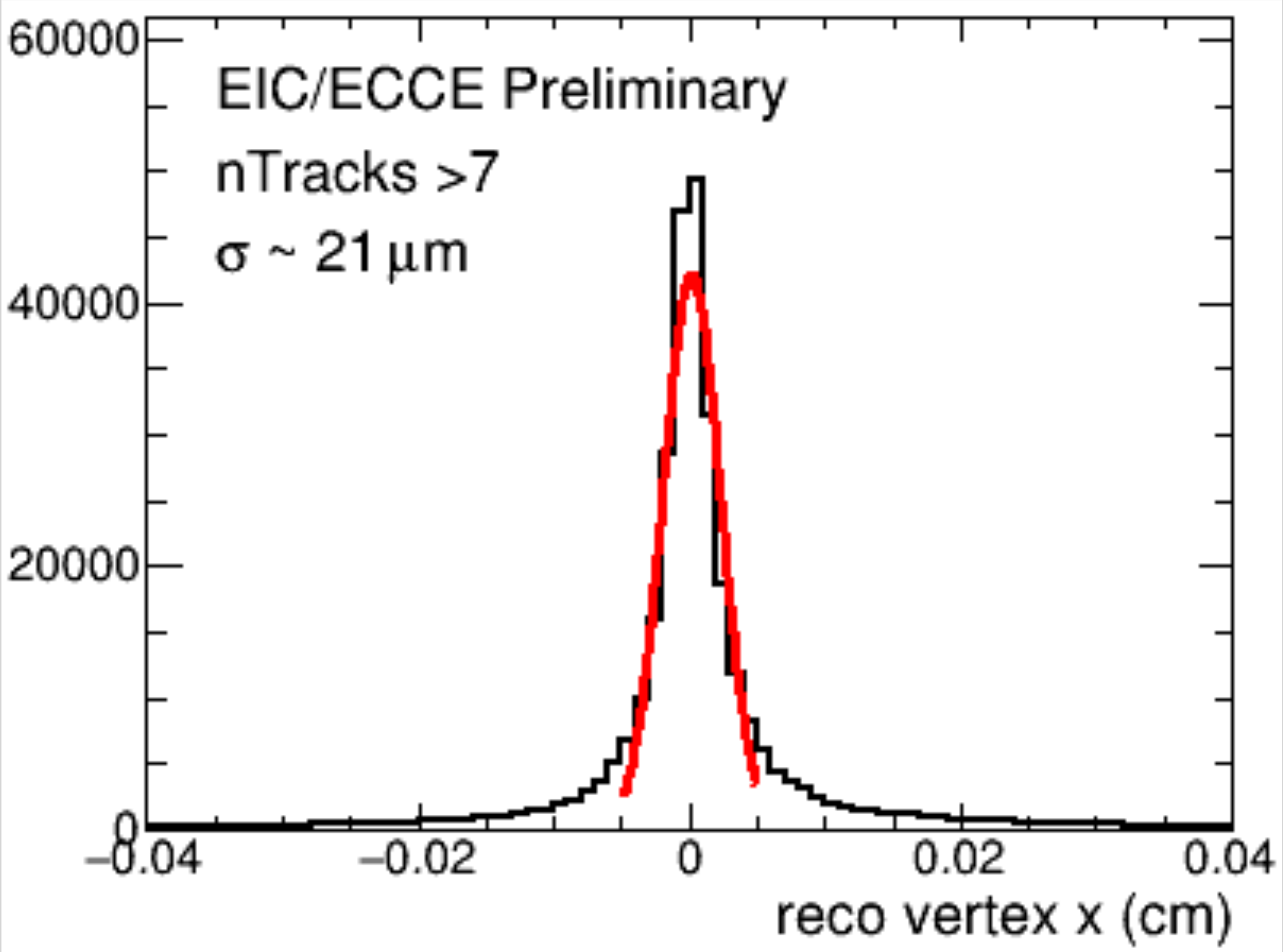
Zhang *et al.* 2207.10261

$\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ and bounds on $e \leftrightarrow \tau$ are much stronger. However, some BSM models seem to enhance $e \leftrightarrow \tau$. The goal is to test sensitivity of the EIC to $e \leftrightarrow \tau$ in LQ framework in the limit $M_{\mathrm{LQ}} \gg \sqrt{Q^2}, \sqrt{s}$.

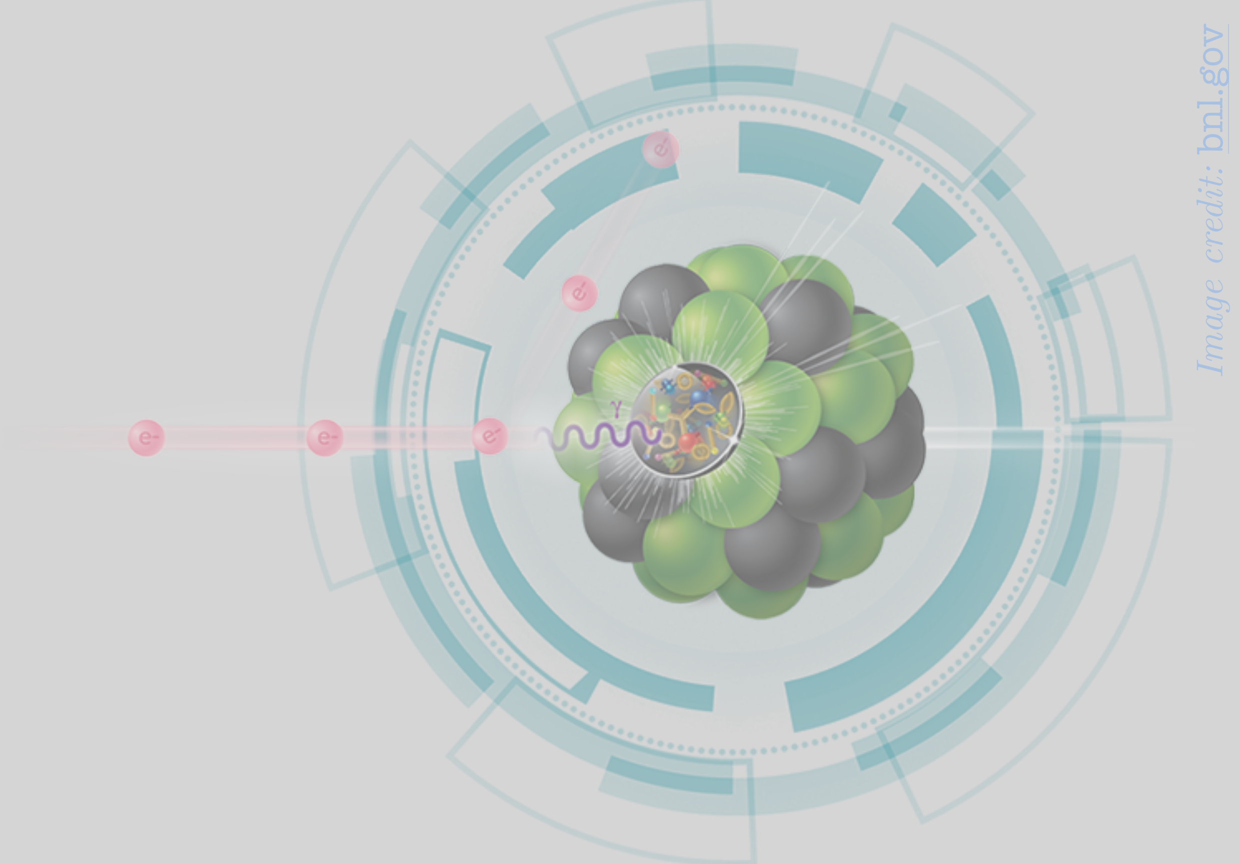
Consider 3-prong τ decay following $e^- + p \to \tau + X$ using the data set 18 GeV × 275 GeV with 100 fb^{-1} (P6, YR reference config).

First, need to reconstruct the τ vertex: Decay length of τ is 87 μm. ECCE can resolve 20-30 μm.

Then, identify τ decays by reconstructing the 3π candidates.



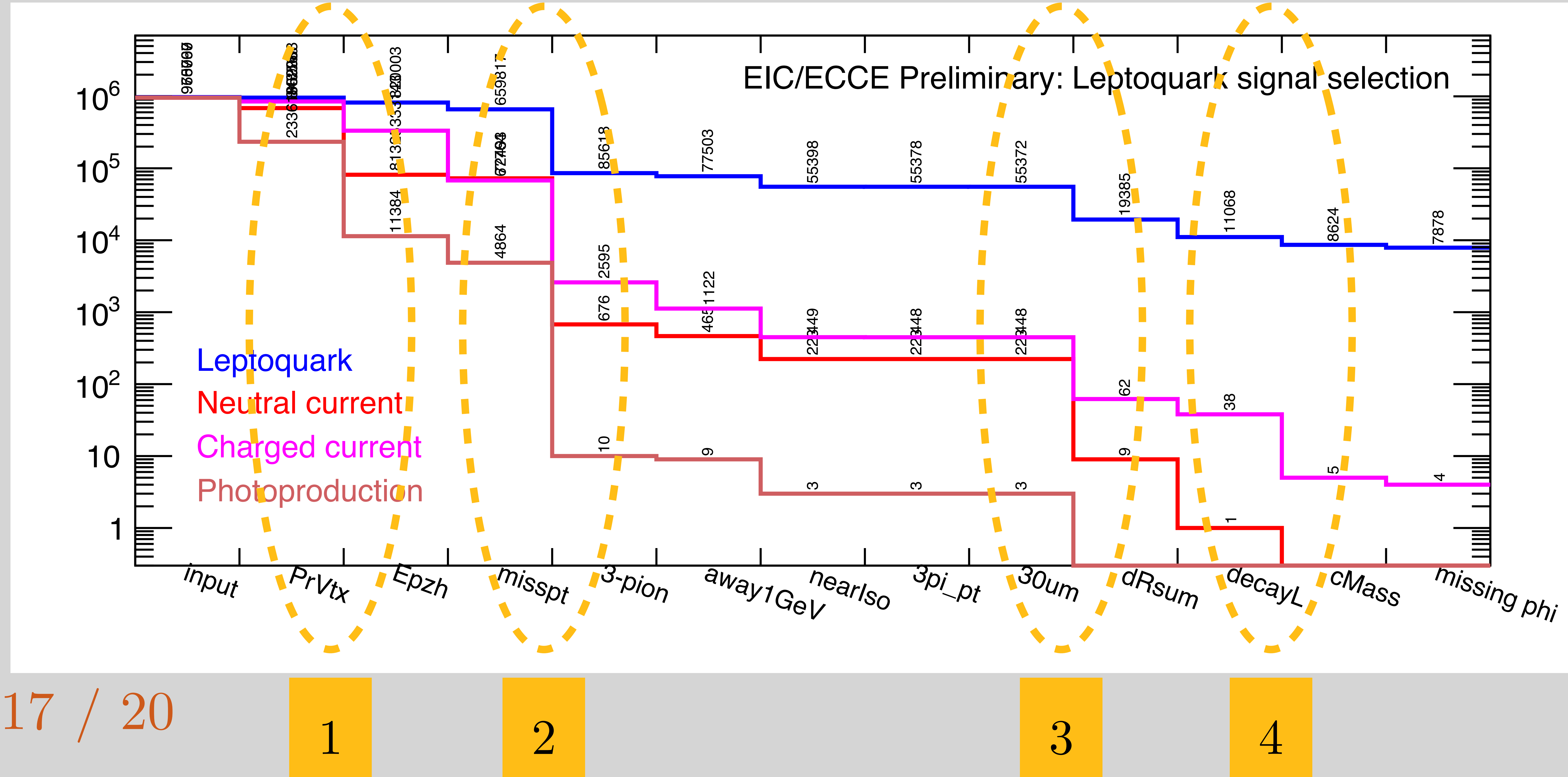
BSM searches



Limits on $e \leftrightarrow \tau$ in leptoquark framework

Zhang *et al.* 2207.10261

Generate events for LQ as the main event and NC DIS, CC DIS, and γ production as background (1M each). Then start cutting events.



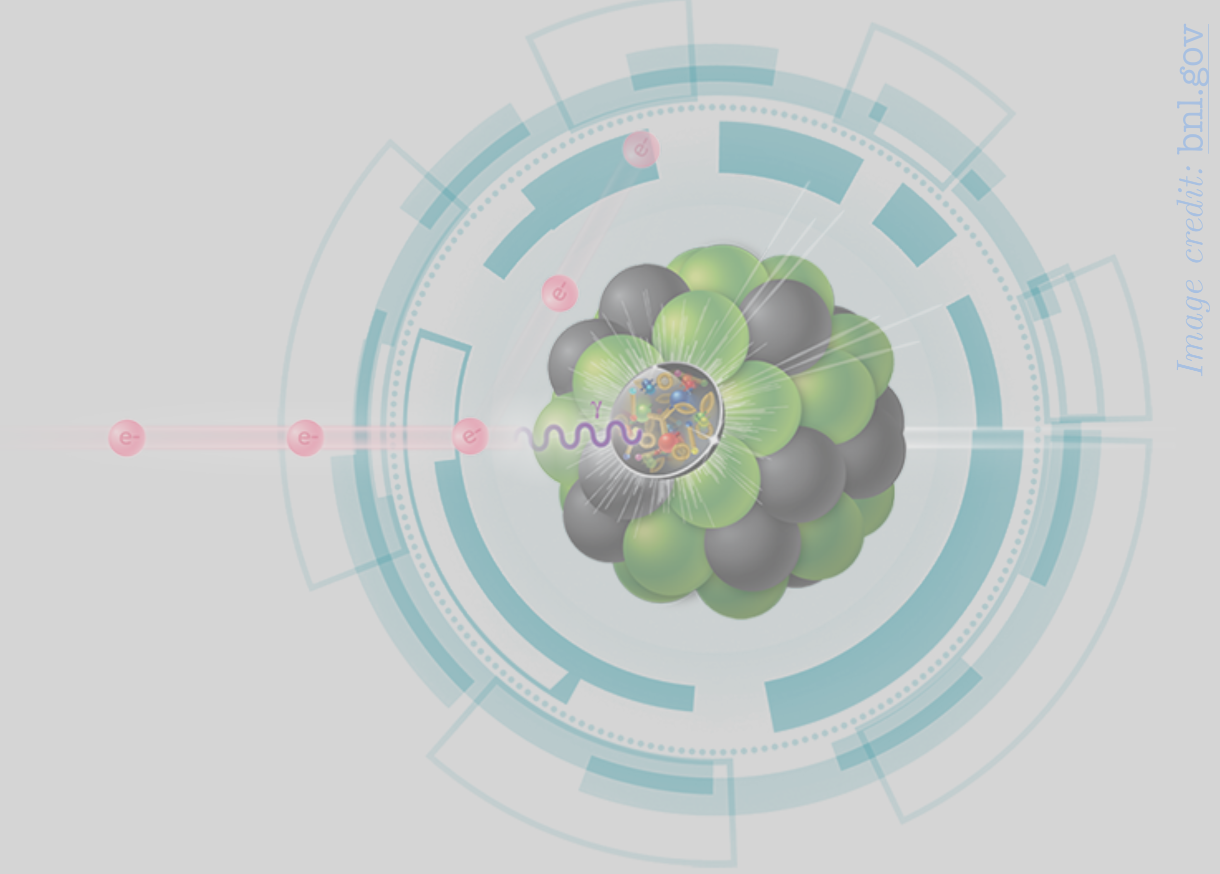
1 Primary vertex:
τ must be identified.

2 $1 < \not{p}_\perp < 9$ GeV
suppress γ prod.
suppress CC ν or NC misdetected e^-

3 Candidate decay length $> 30\ \mu$m

4 Avg. of reconstructed decay lengths from 3 pair combinations of the 3π candidates > 0.5 mm.

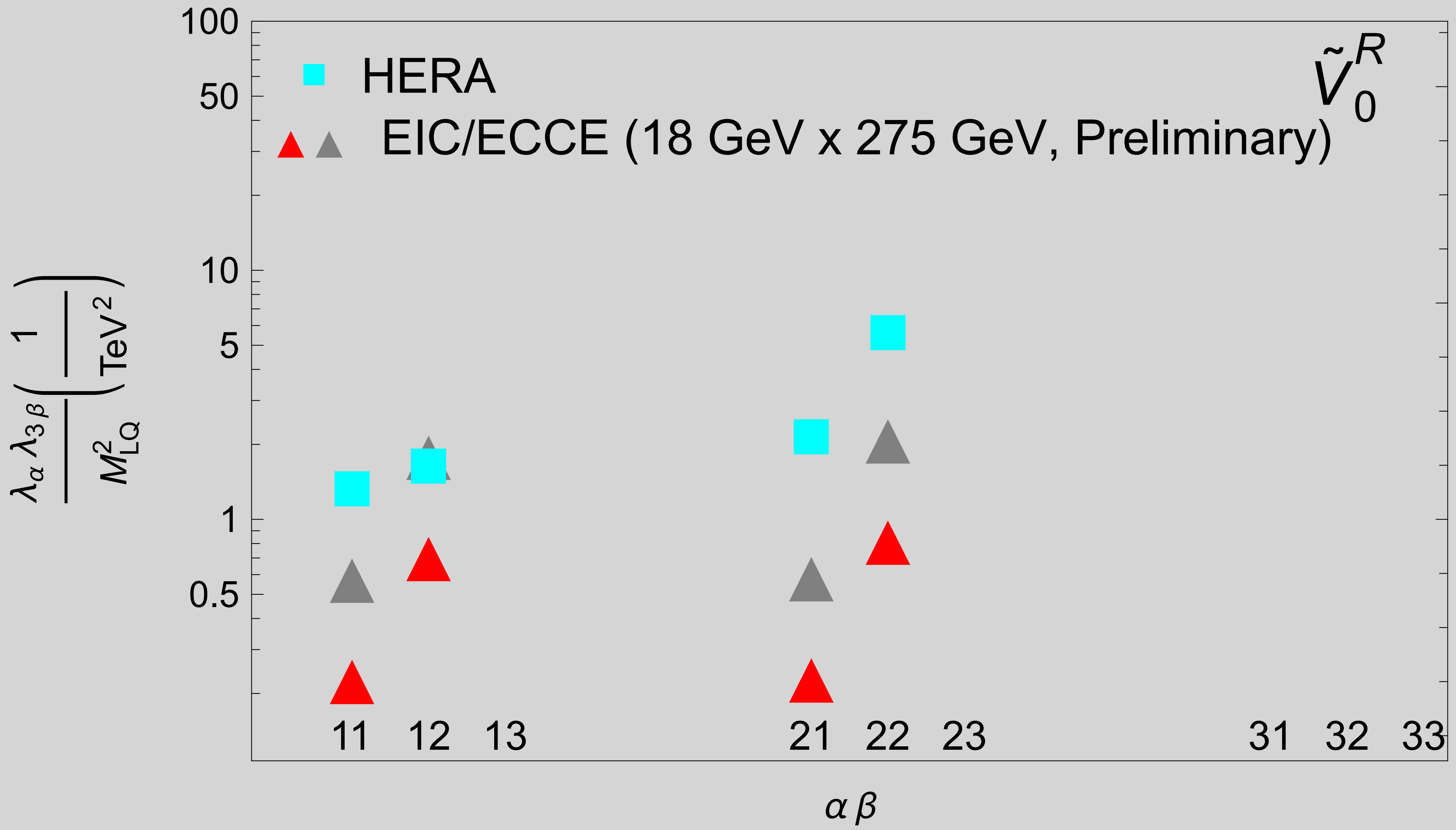
BSM searches

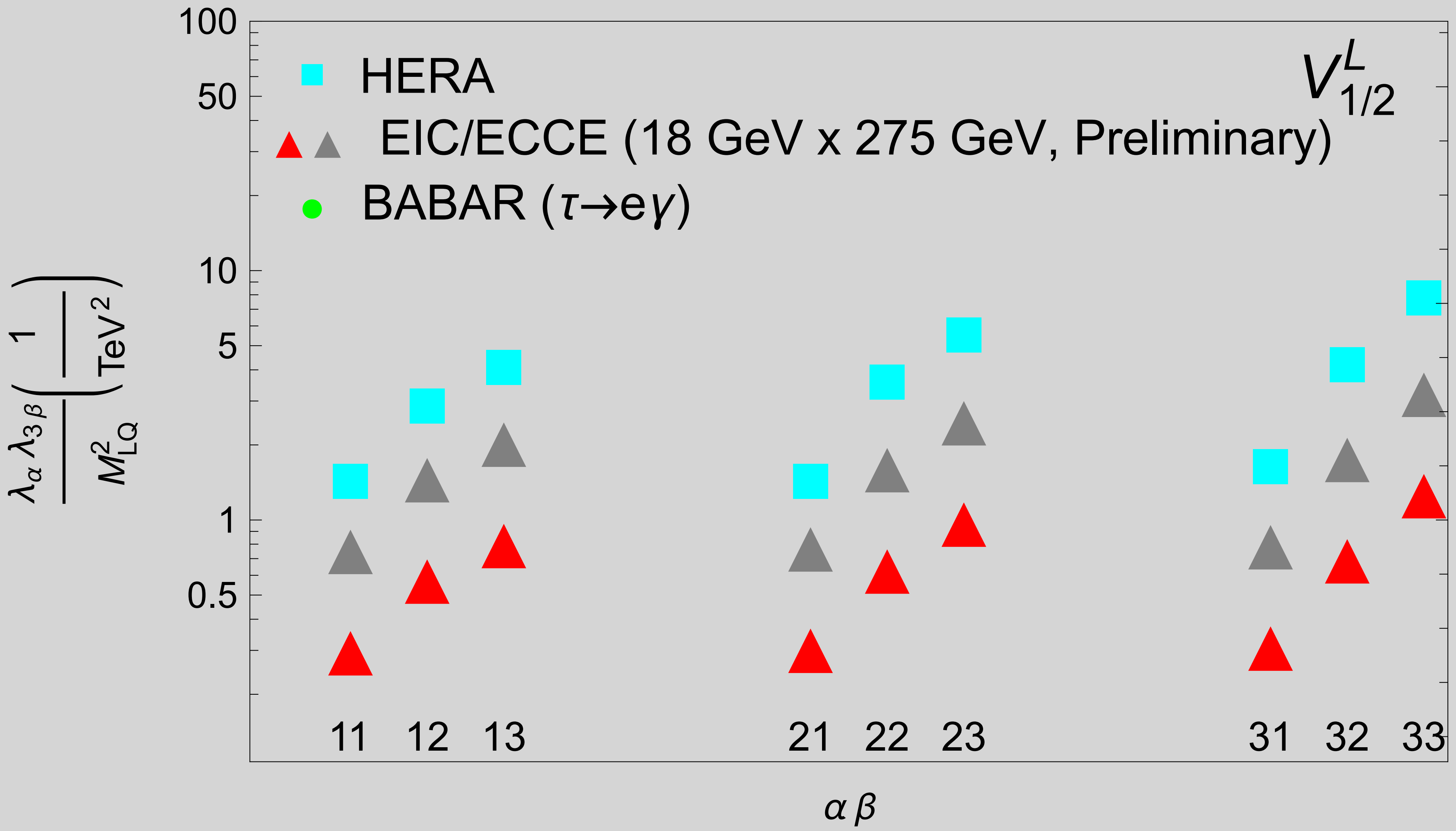


Limits on $e \leftrightarrow \tau$ in leptoquark framework

Zhang *et al.* 2207.10261

Bounds on $\dfrac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2}$:





λ_{ij} is the leptoquark coupling of i^{th} lepton generation and j^{th} quark generation.

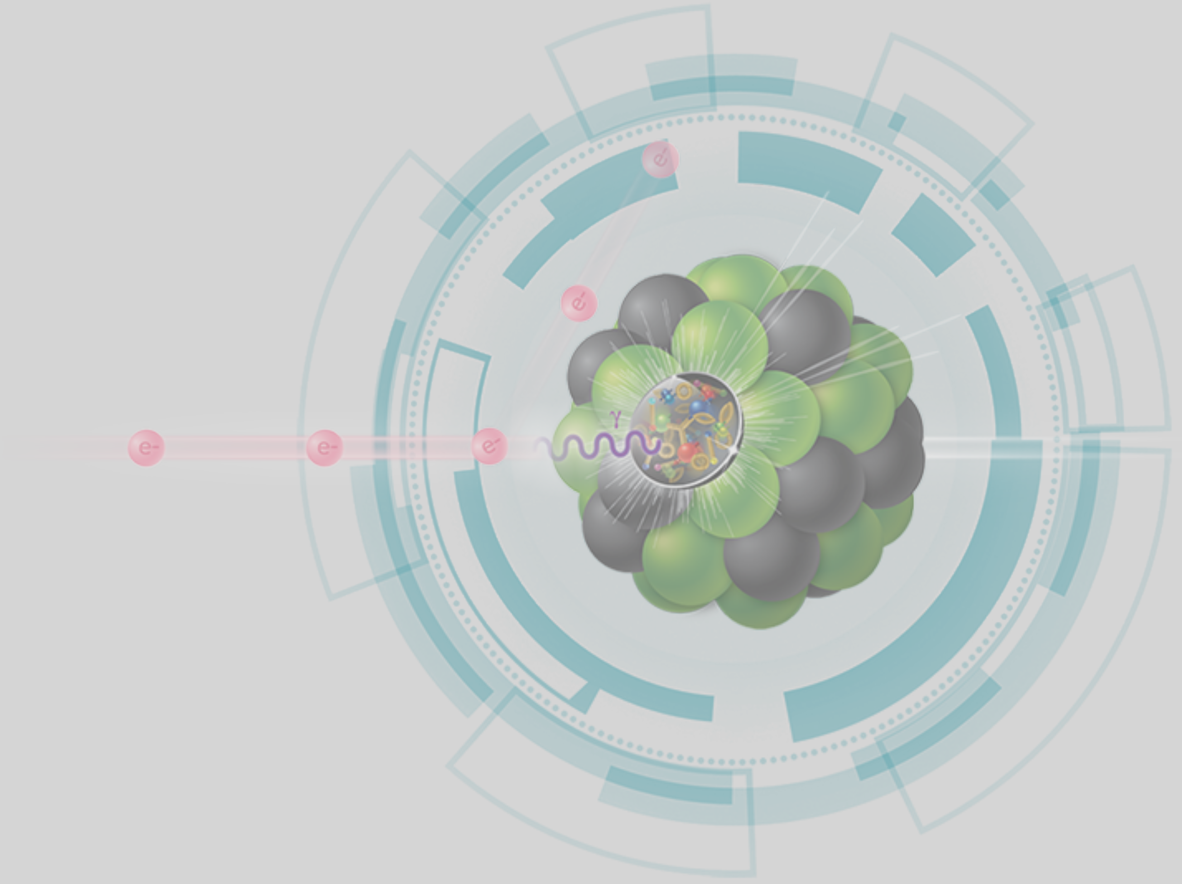


Image credit: bnl.gov

Coda

Conclusion

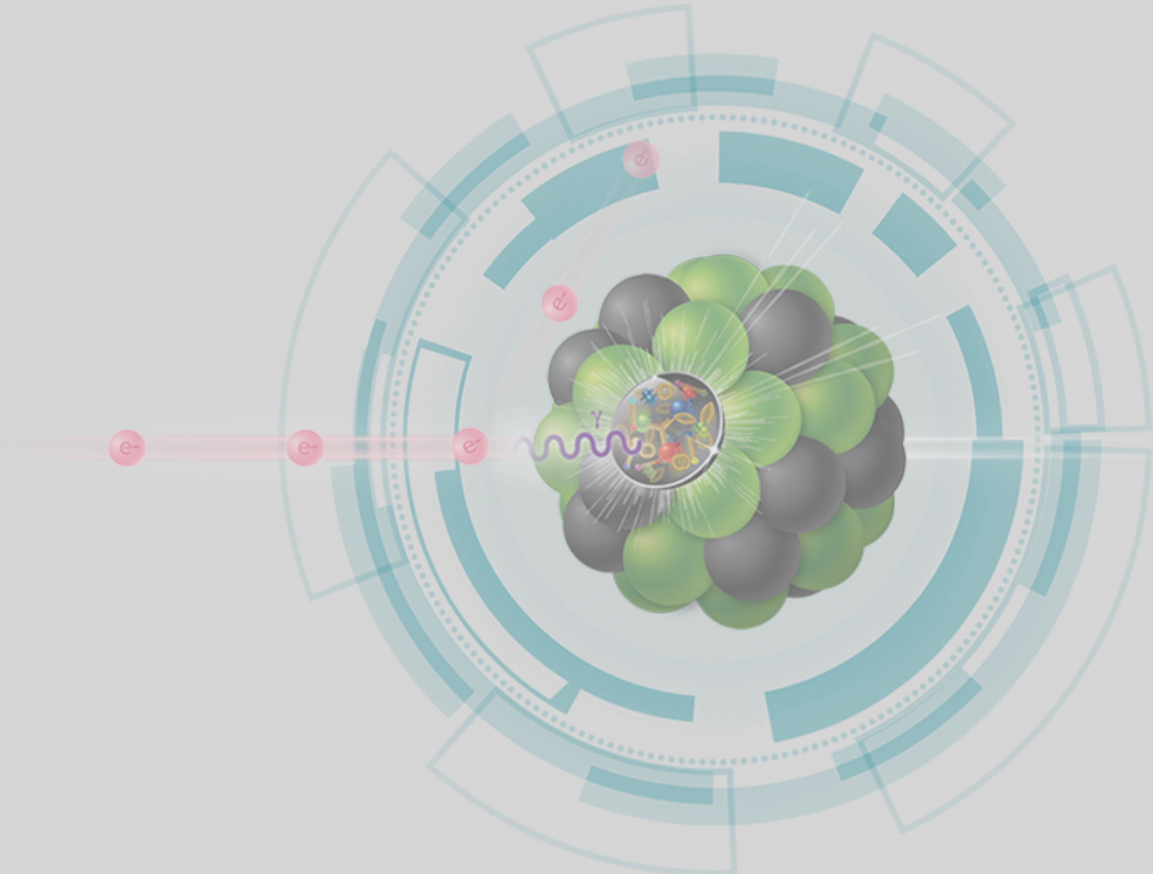


Image credit: bnl.gov

- The EIC will provide a determination of $\sin(\theta_W)^2$ at an energy scale that bridges higher-energy colliders with low- to medium-energy SM tests.
- It will offer distinct correlations compared to LHC Drell-Yan fits of SMEFT parameters, showing complementarity, and resolve blind spots, demonstrating superiority of the EIC.
- The EIC will place a more stringent limit on $e \leftrightarrow \tau$ mediated by LQs than the previous HERA data thanks to the very high vertex resolution of the ECCE detector configuration.

The EIC is designed as a QCD machine but seems promising as a useful probe of precision EW measurements, as well as BSM physics.