Neutral-current SMEFT studies at the EIC

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Reference: 2204.07557

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X. Zheng *et al.* (JLab EIC Group)

Outline

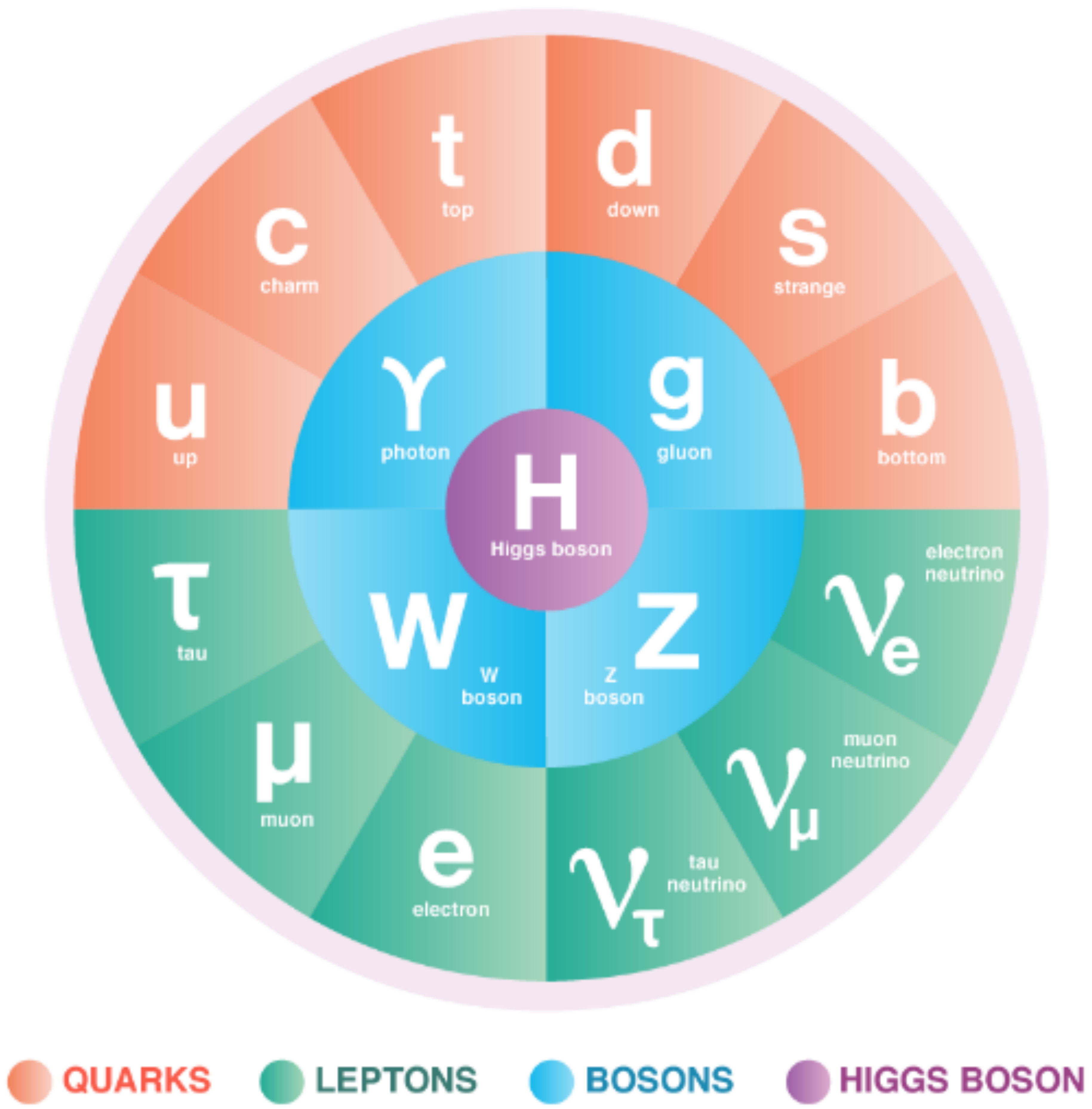
- Introduction
- Neutral-current DIS and SMEFT
- Projections of PV and LC asymmetry data
- Uncertainties
- Framework of the SMEFT analysis
- SMEFT fit results
- Conclusion

Introduction

Standard Model

SM of particle physics:

- Successful in all lab phenomena
- Spectrum completely observed
- No new particles observed so far



Standard Model

SM of particle physics:

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Shortcomings:

- Dark matter
- Baryon-antibaryon asymmetry
- Neutrino mass
- Hierarchy problem

EIC

An experimental program under design: the Electric-Ion Collider (EIC)

- Brookhaven National Laboratory, Upton, NY
- electron + proton/nuclei collisions

bnl.gov

EIC

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Unique features:

- Energy between fixed-target scattering and high-energy colliders
- Luminosity orders of magnitude higher than HERA
- First lepton-ion collider to polarize both beams
- First collider with fast spin-flip capacity

EIC

From these unique features:

- Extraction of $A_{\mathrm{PV}}^{(\ell)}$ and $A_{\mathrm{PV}}^{(H)}$ in EW NC cross section
- Reduced uncertainties from luminosity and detector acceptance/efficiency
- Explore issues in QCD
- Probes of BSM physics

EIC

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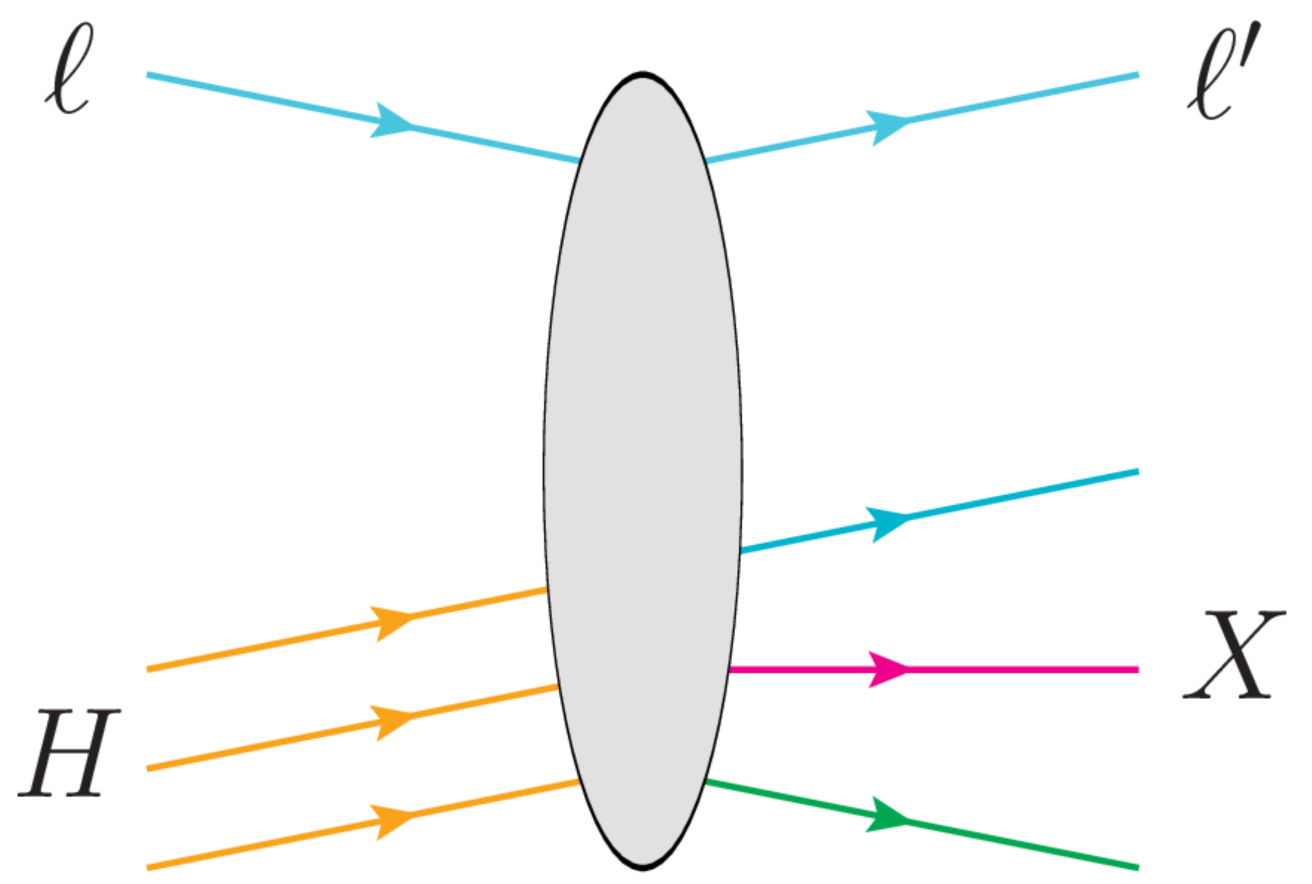
- Extraction of $A_{\mathrm{PV}}^{(\ell)}$ and $A_{\mathrm{PV}}^{(H)}$ in EW NC cross section
- Reduced uncertainties from luminosity and detector acceptance/efficiency
- Explore issues in QCD
- Probes of BSM physics

What's new:

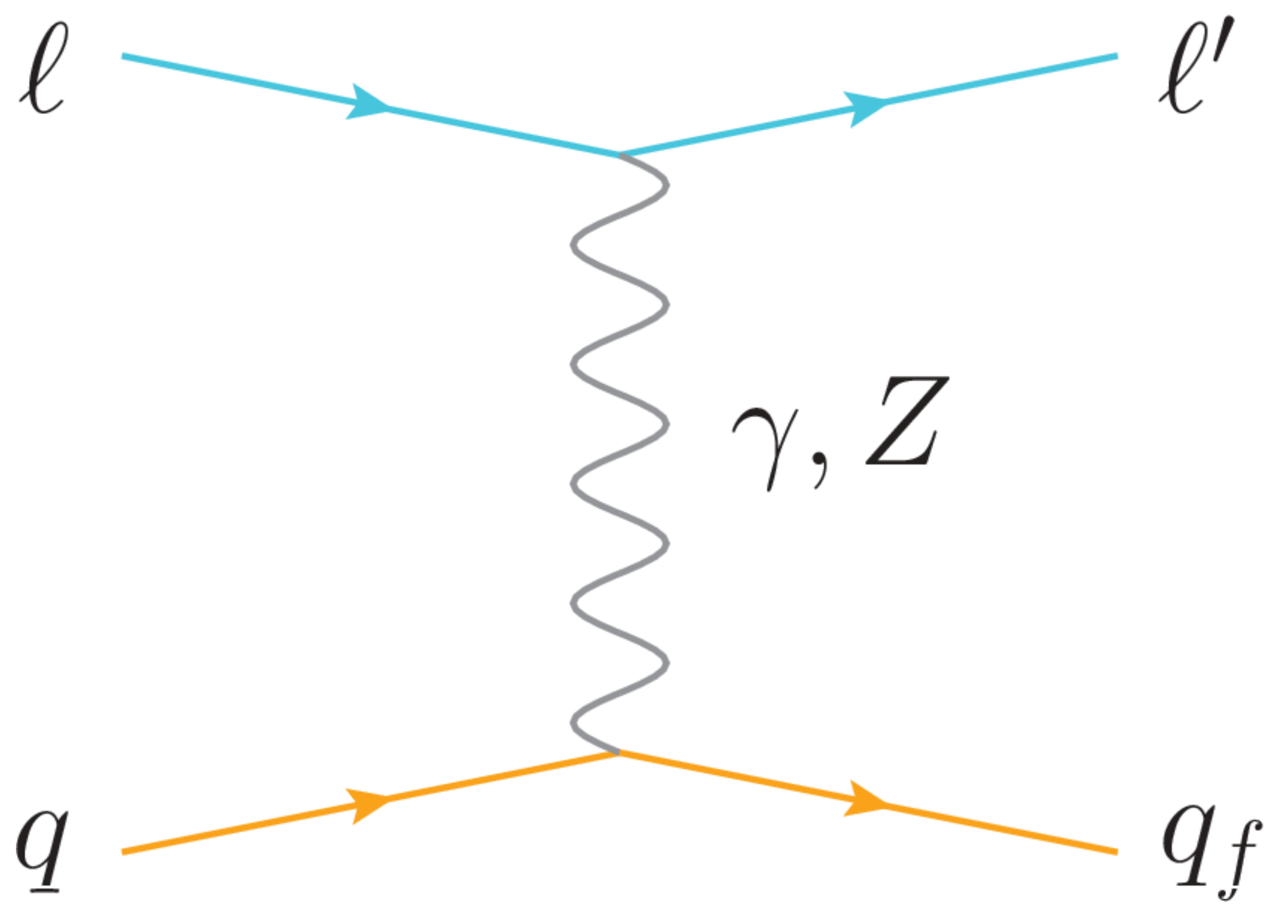
- Positron beam in the future: $A_{\mathrm{LC}}^{(H)}$

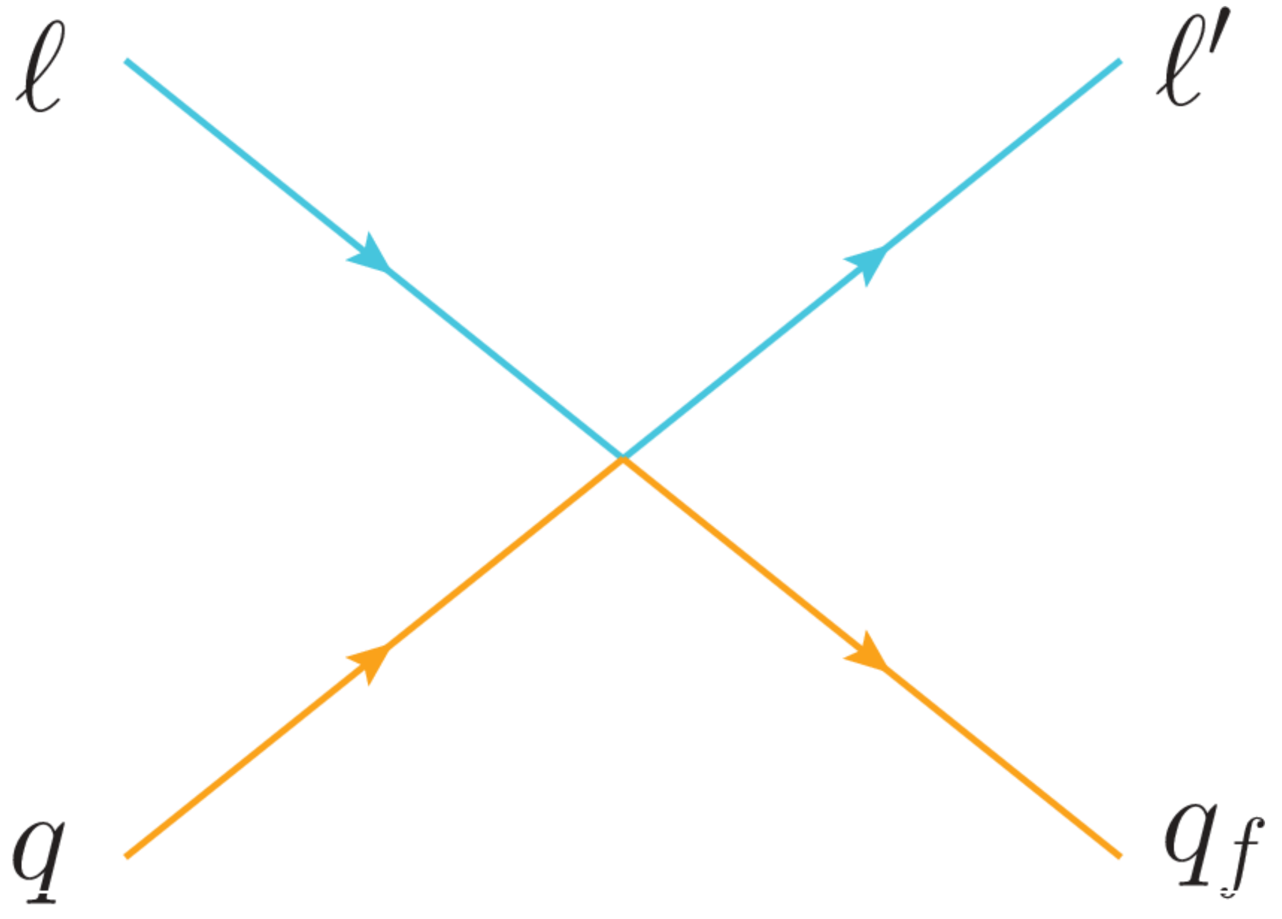
Neutral-current DIS
and
SMEFT

NC DIS and SMEFT



NC DIS in the process $\ell + H \to \ell' + X$:





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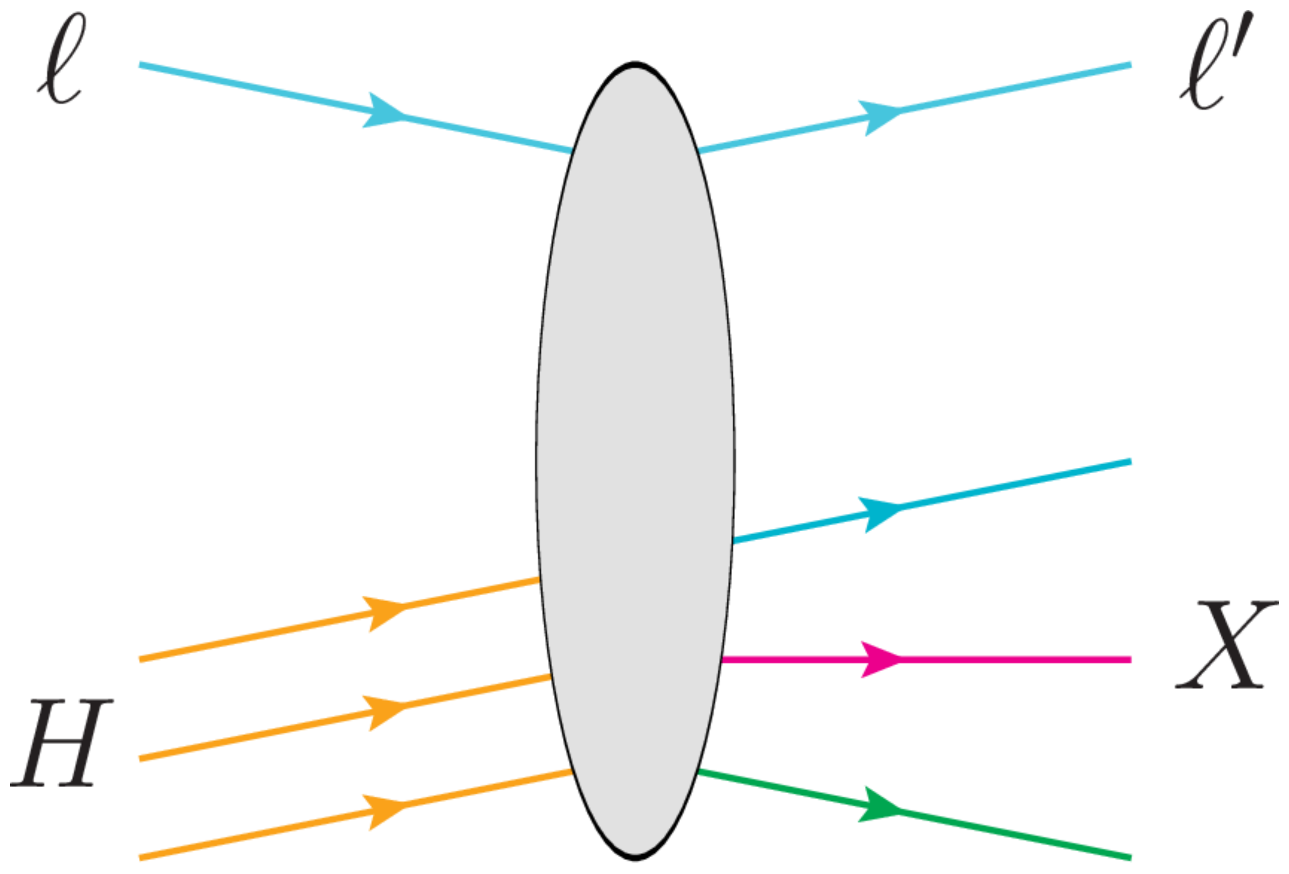

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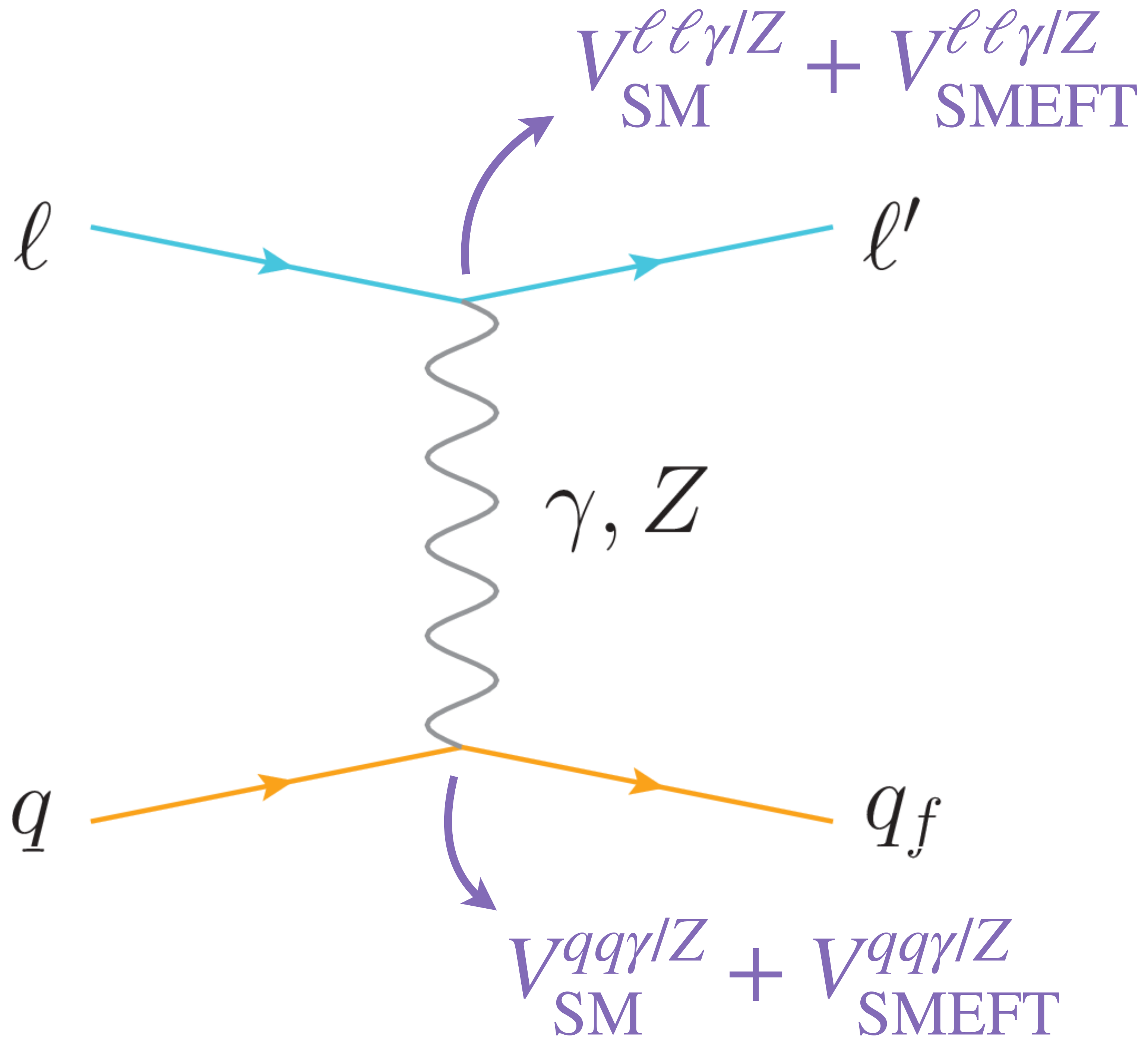

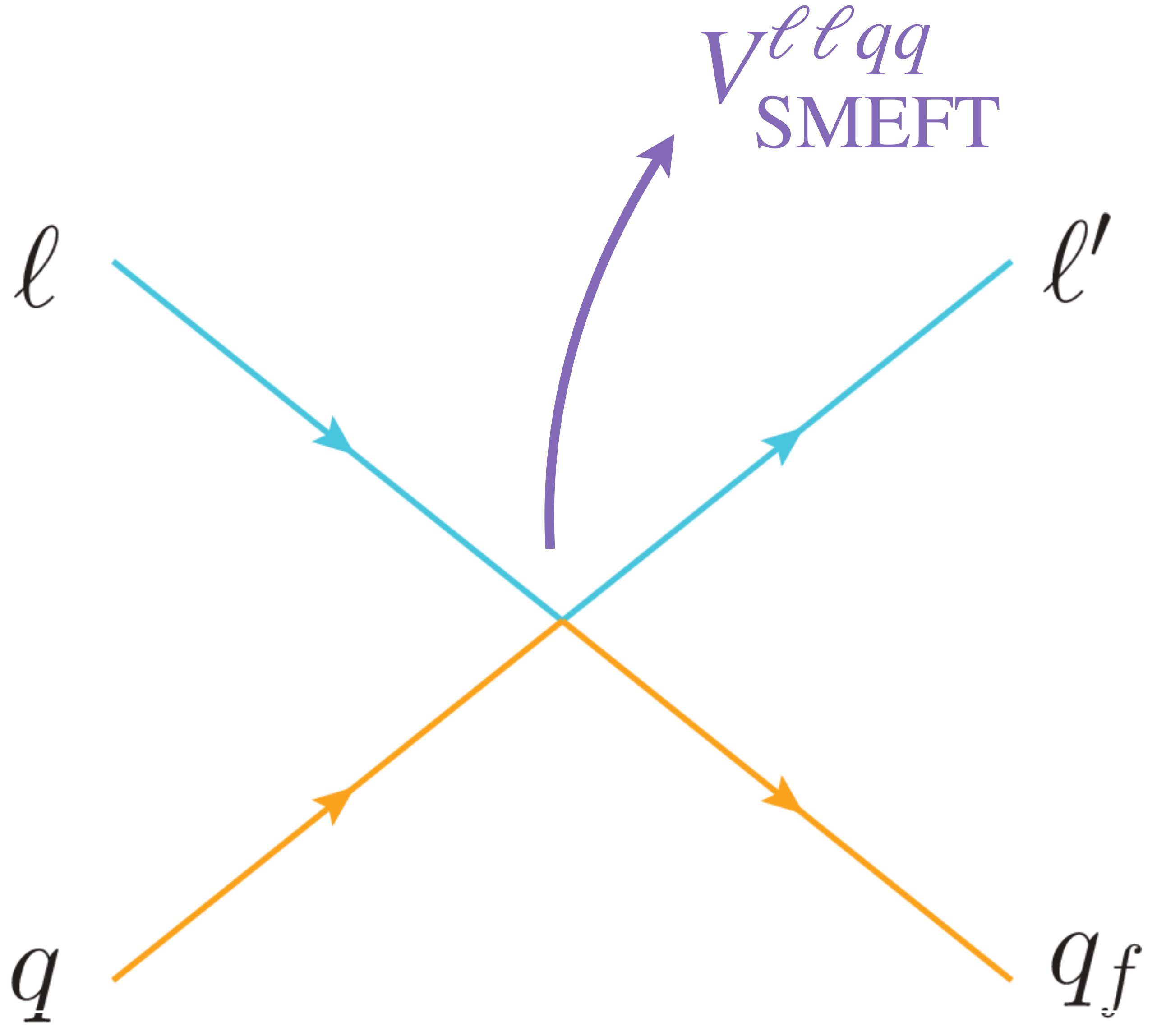

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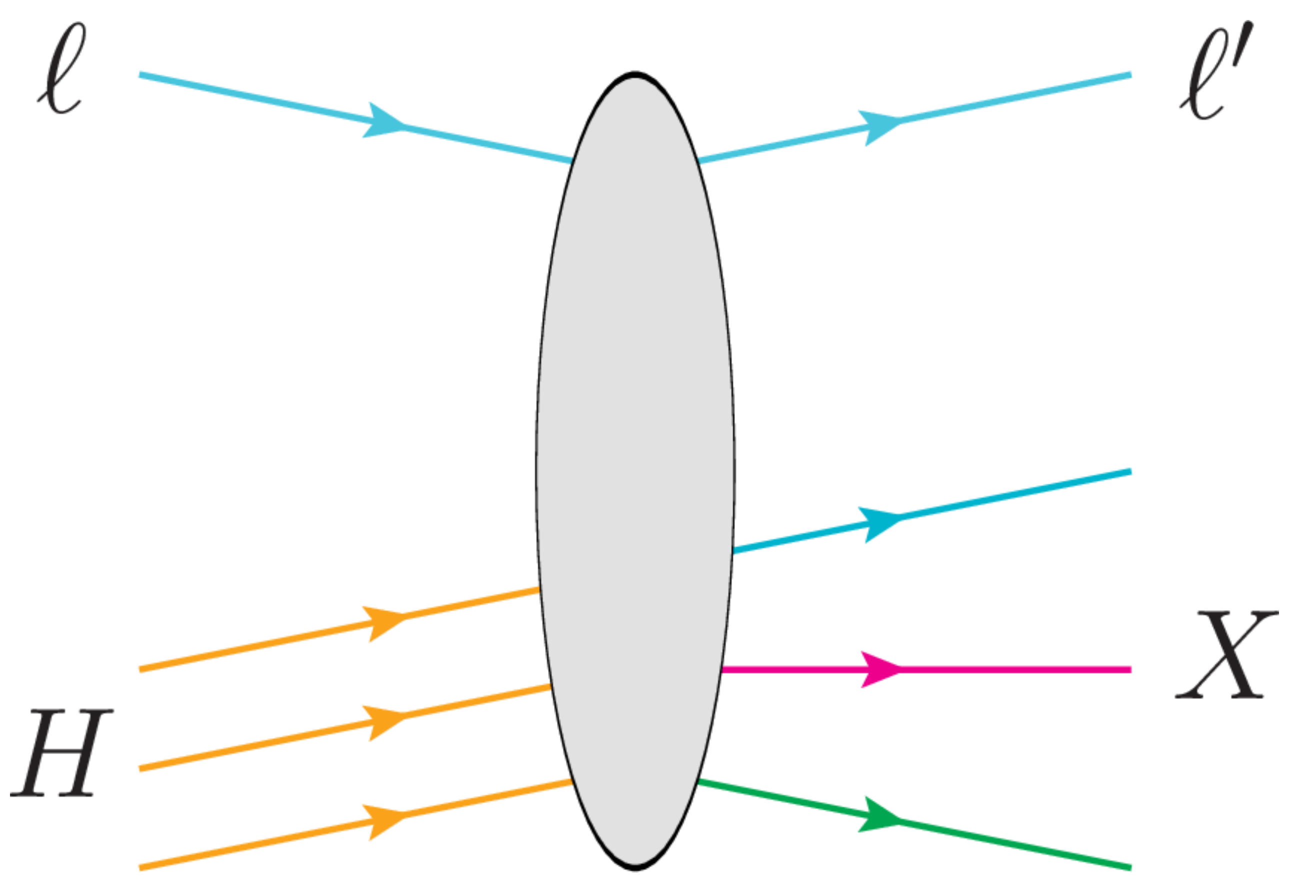

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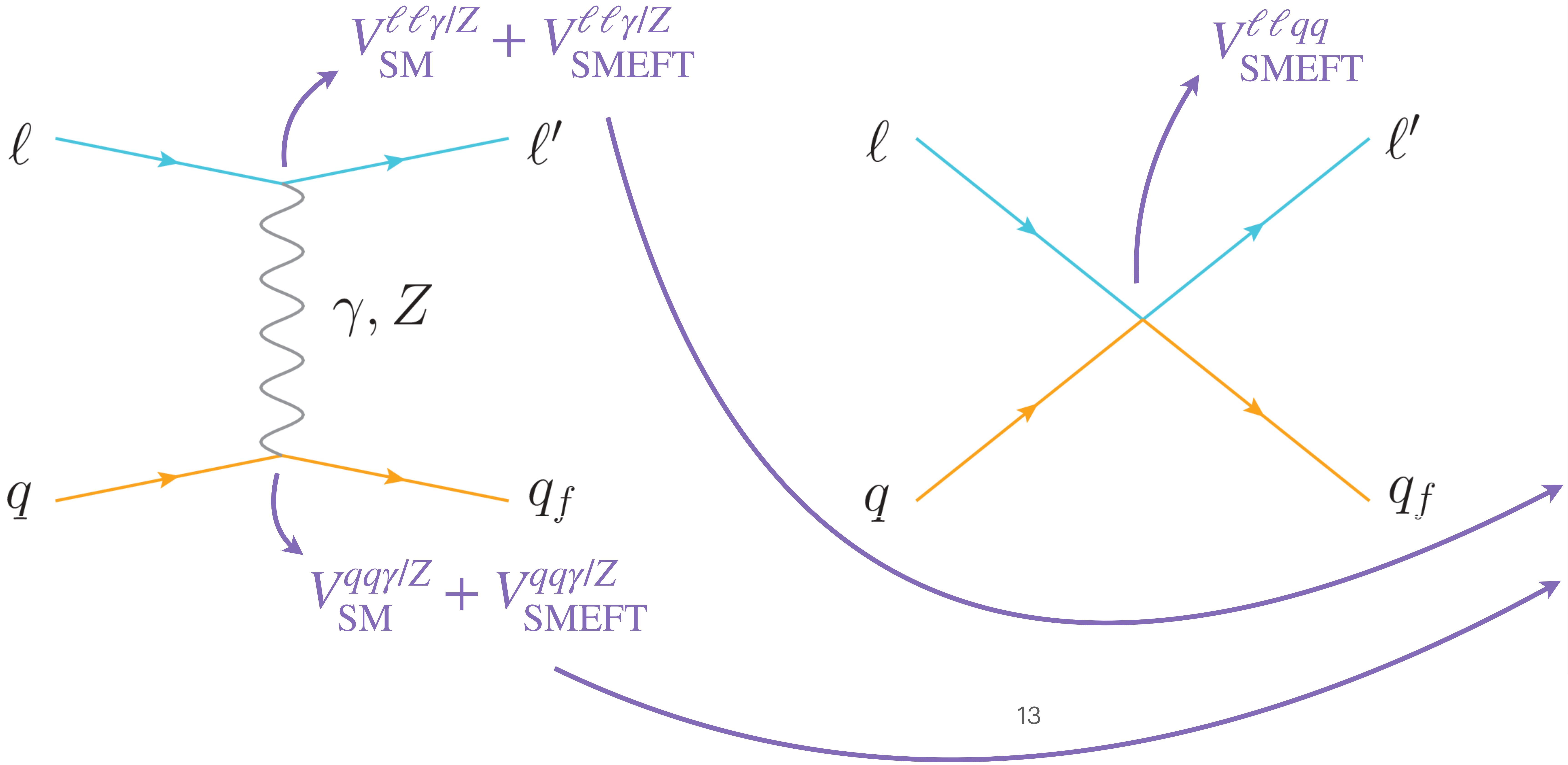
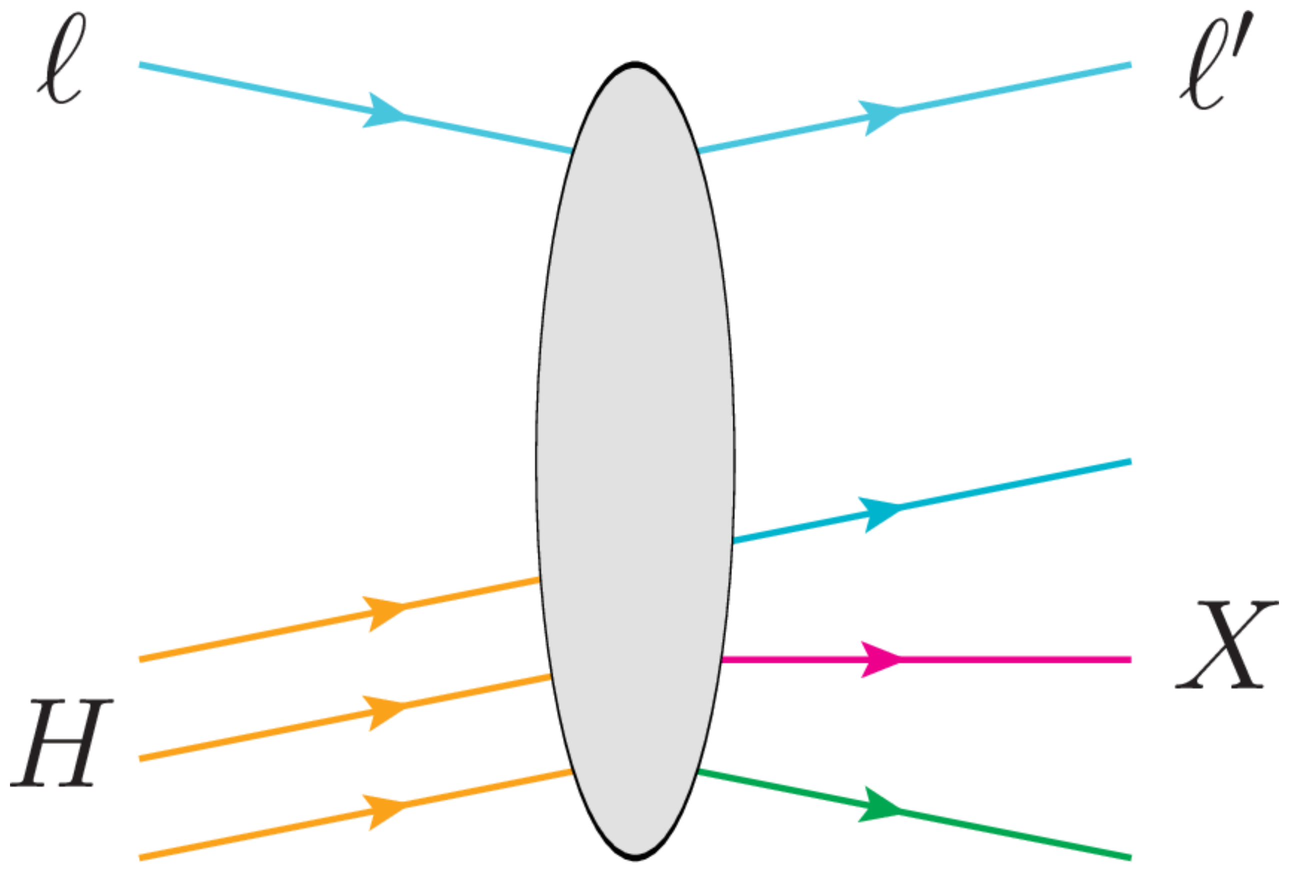


C	95 % CL, $\Lambda = 1$ TeV
$C_{\varphi WB}$	$[-0.0088,\ 0.0013]$
$C_{\varphi u}$	$[-0.072,\ 0.091]$
$C^{(3)}_{\varphi q}$	$[-0.011,\ 0.014]$
$C^{(1)}_{\varphi q}$	$[-0.027,\ 0.043]$
$C^{(3)}_{\varphi \ell}$	$[-0.012,\ 0.0029]$
$C^{(1)}_{\varphi \ell}$	$[-0.0043,\ 0.012]$
$C_{\varphi e}$	$[-0.013,\ 0.0094]$
$C_{\varphi d}$	$[-0.16,\ 0.060]$

from Z and W pole observables

Dawson, Giardino 1909.02000

NC DIS and SMEFT



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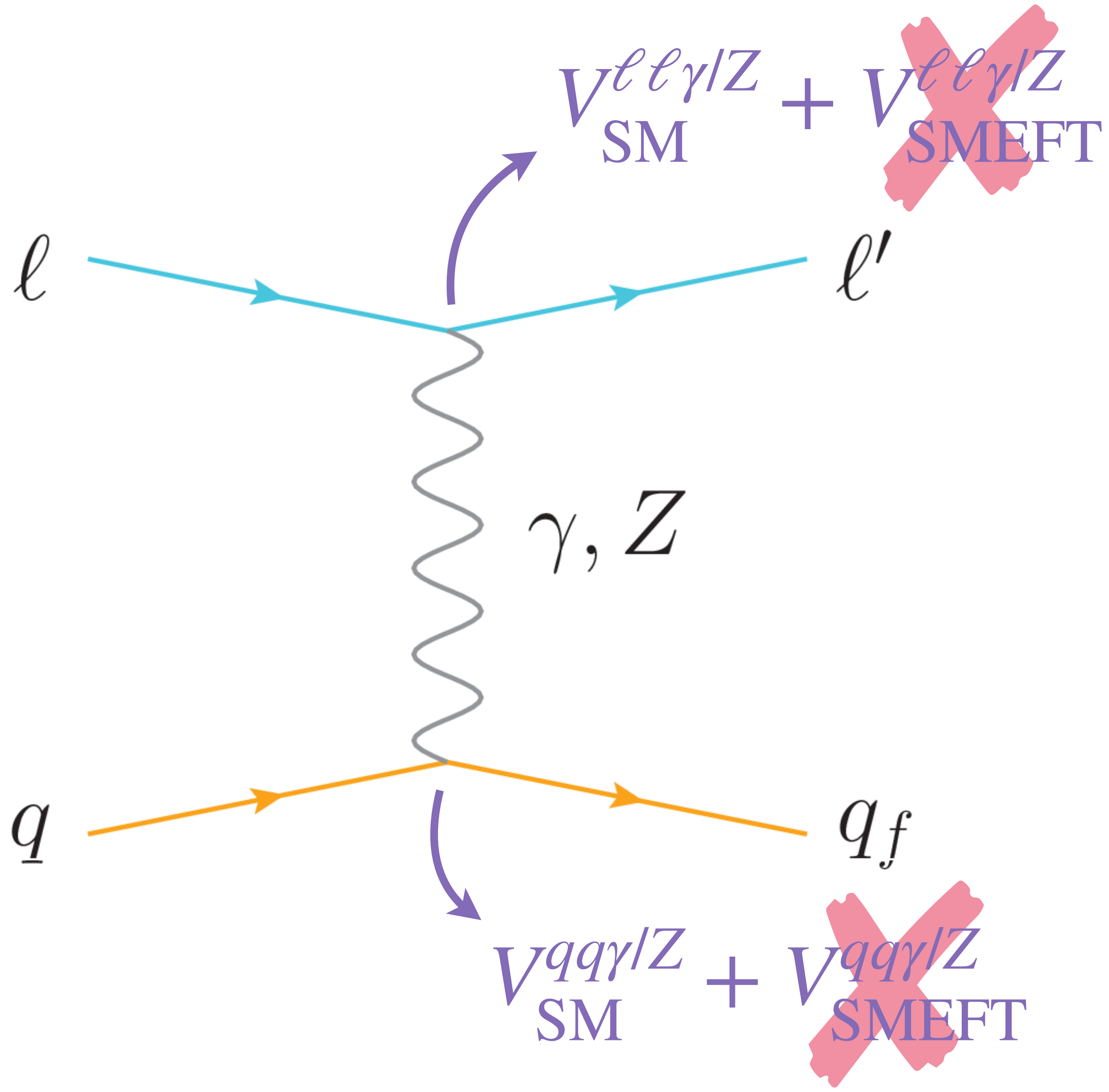

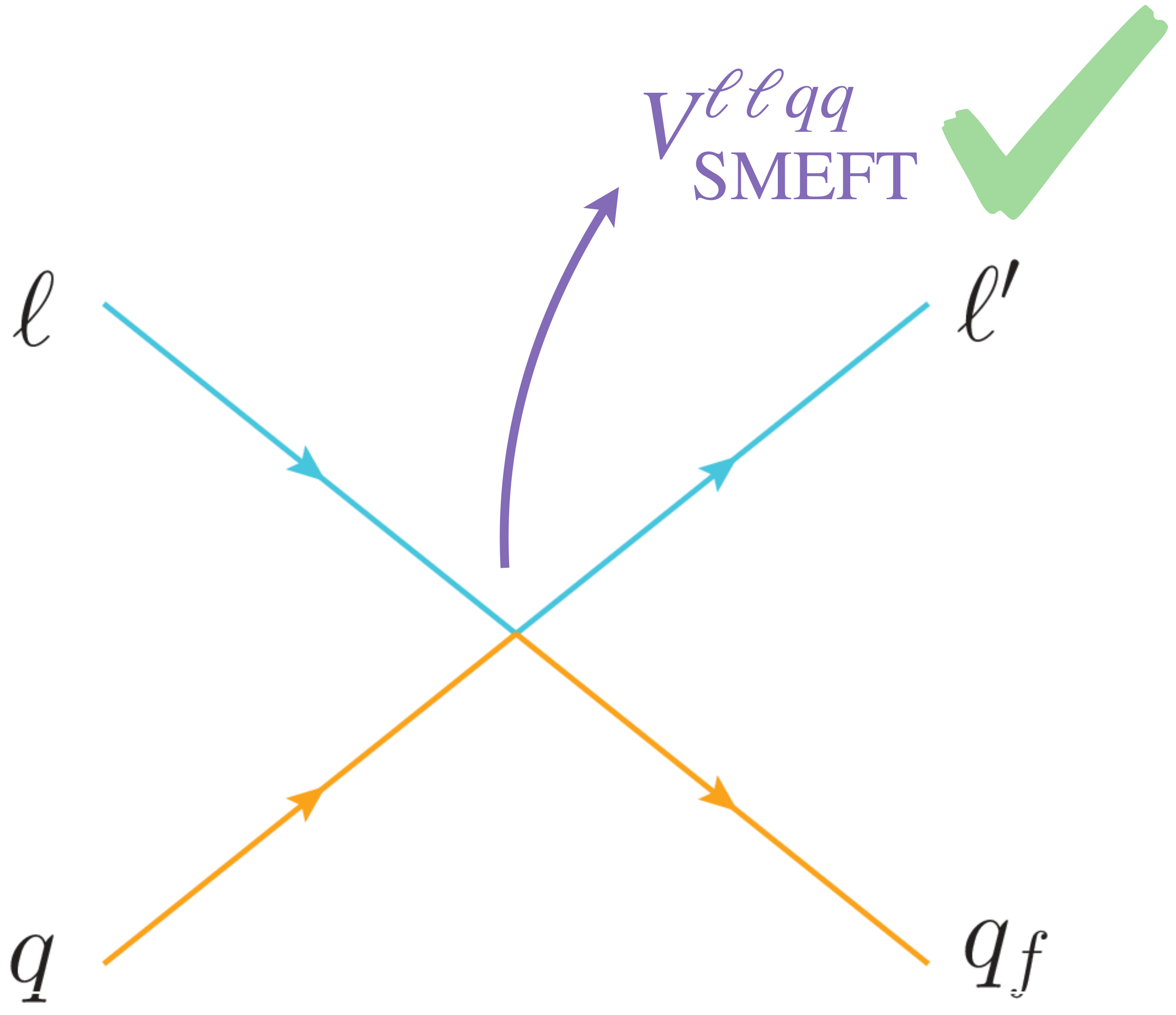

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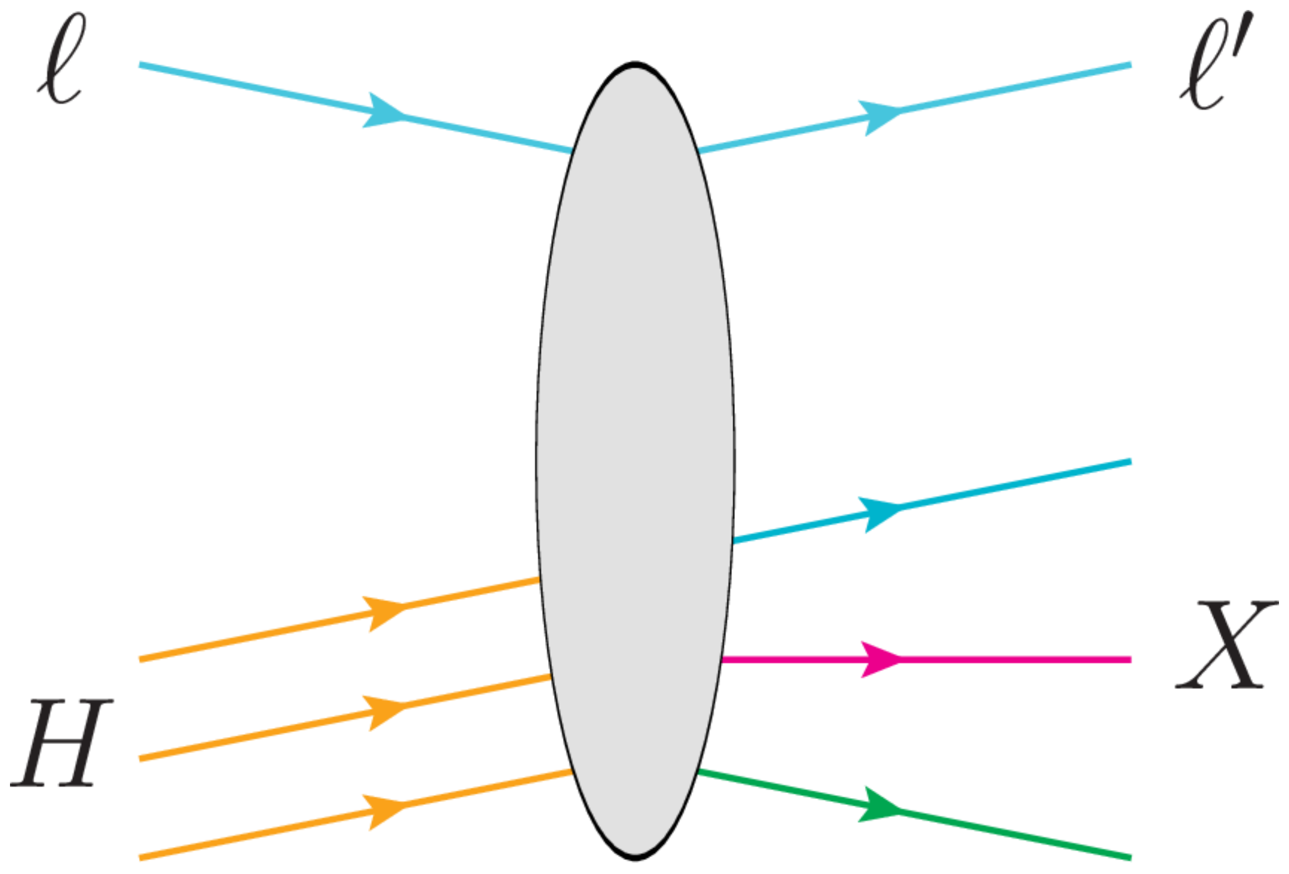
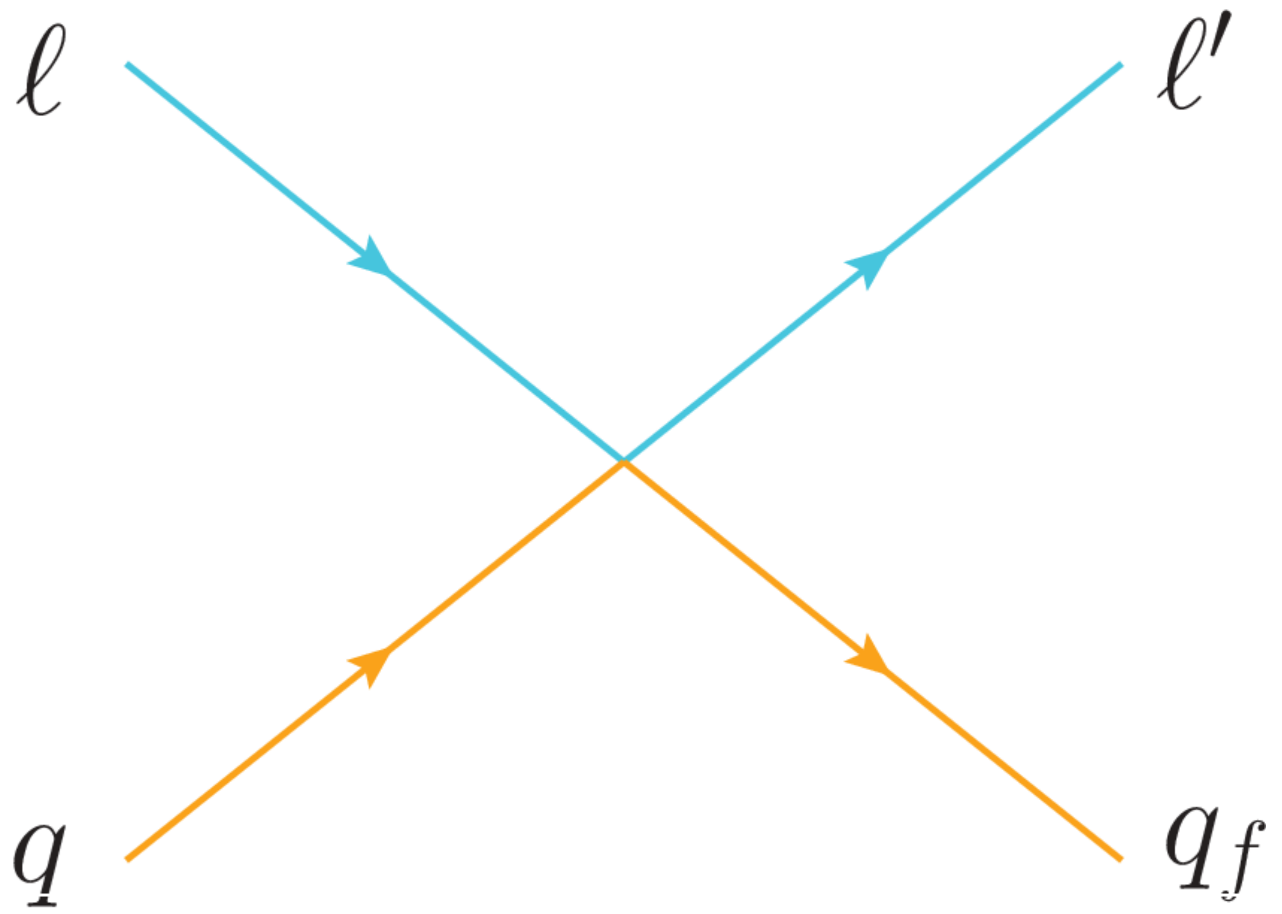
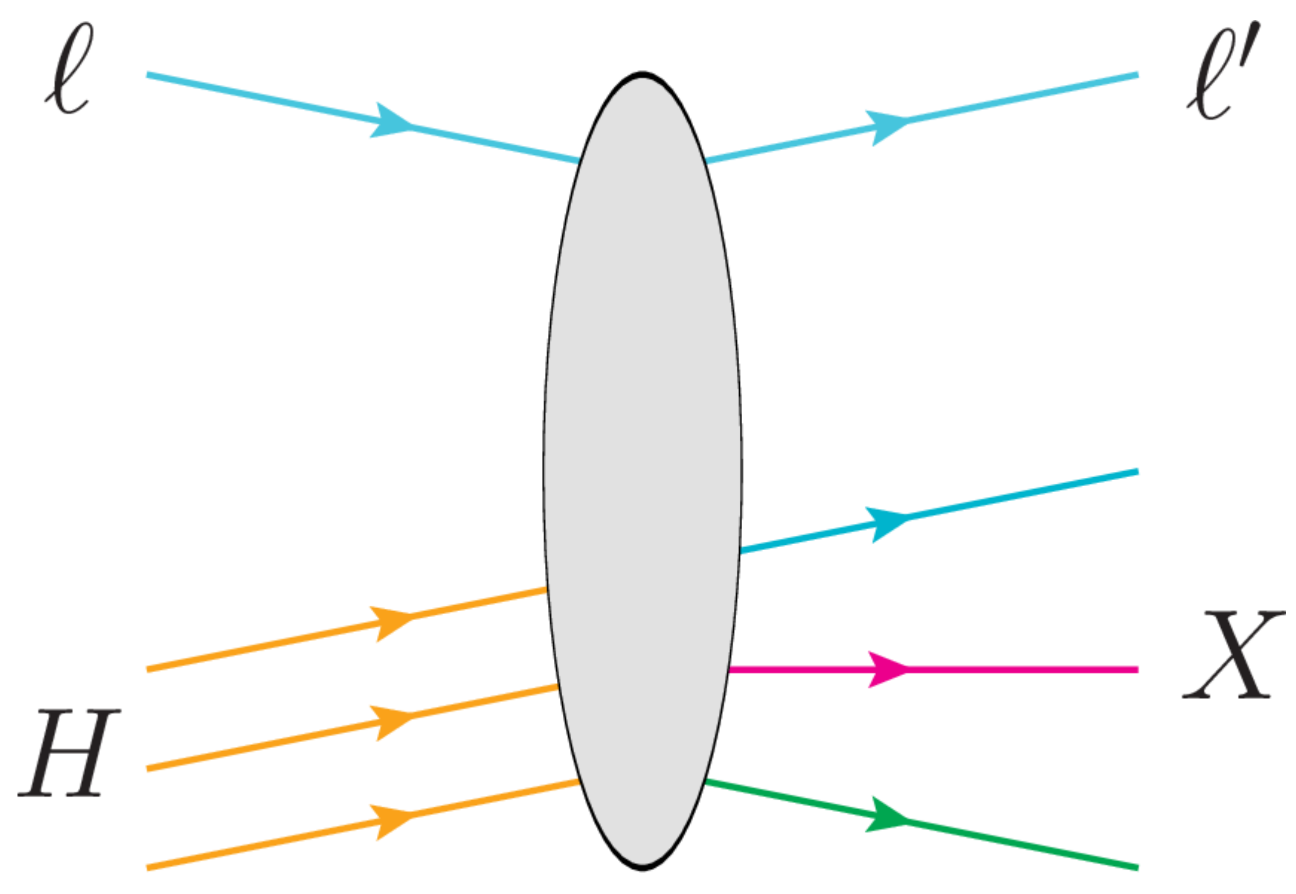




$$\mathscr{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2} \sum_r C_r O_r$$

C_r	O_r
$C_{\ell q}^{(1)}$	$O_{\ell q}^{(1)} = [\bar{\ell}\gamma^\mu \ell][\bar{q}\gamma_\mu q]$
$C_{\ell q}^{(3)}$	$O_{\ell q}^{(3)} = [\bar{\ell}\gamma^\mu \tau^I \ell][\bar{q}\gamma_\mu \tau^I q]$
C_{eu}	$O_{eu} = [\bar{e}\gamma^\mu e][\bar{u}\gamma_\mu u]$
C_{ed}	$O_{ed} = [\bar{e}\gamma^\mu e][\bar{d}\gamma_\mu d]$
$C_{\ell u}$	$O_{\ell u} = [\bar{\ell}\gamma^\mu \ell][\bar{u}\gamma_\mu u]$
$C_{\ell d}$	$O_{\ell d} = [\bar{\ell}\gamma^\mu \ell][\bar{d}\gamma_\mu d]$
C_{qe}	$O_{qe} = [\bar{q}\gamma^\mu q][\bar{e}\gamma_\mu e]$

NC DIS and SMEFT



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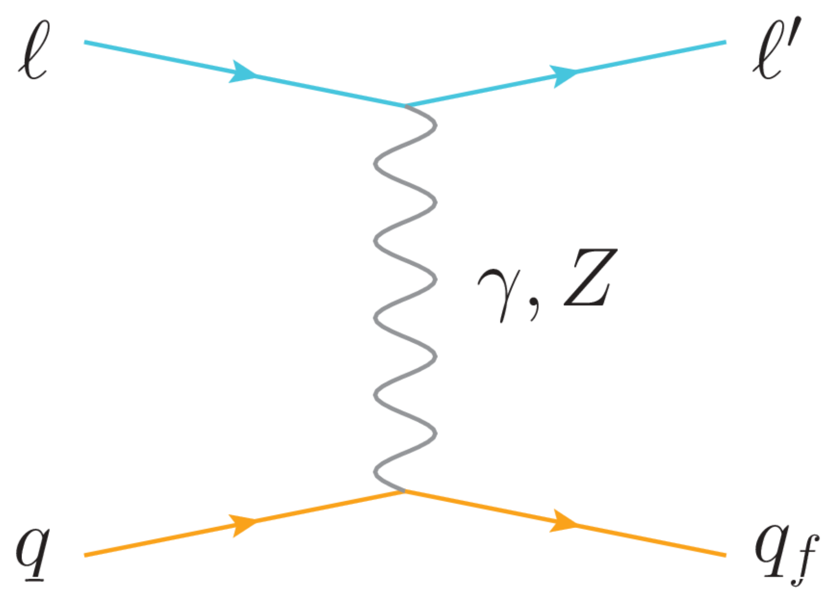

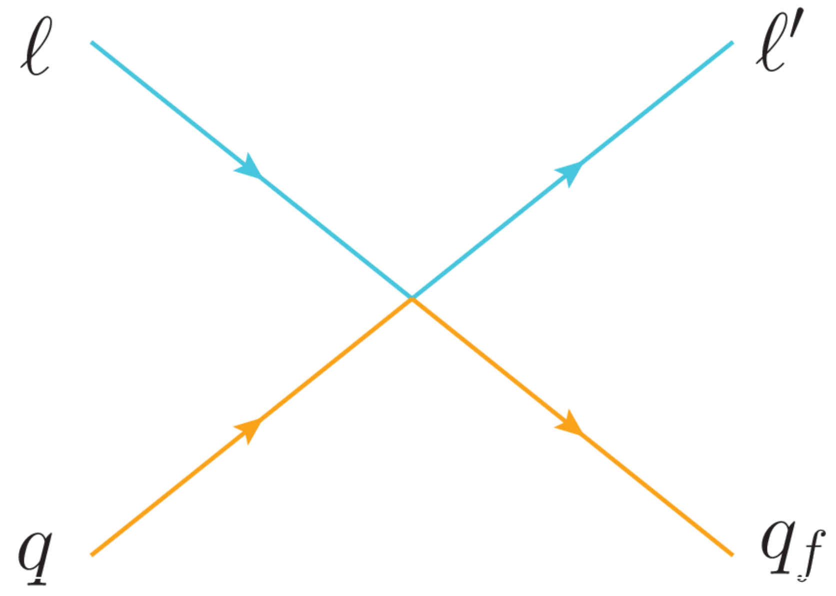

$$\mathcal{M} = \mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_\times$$

$$|\mathcal{M}|^2 = \mathcal{M}_{\gamma\gamma} + \mathcal{M}_{\gamma Z} + \mathcal{M}_{ZZ} + \mathcal{M}_{\gamma\times} + \mathcal{M}_{Z\times} + \mathcal{O}(C^2)$$

$$d\sigma^{\lambda_\ell \lambda_H} = \frac{d^2\sigma(\lambda_\ell, \lambda_H)}{dx\ dQ^2}$$

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Polarized and unpolarized cross sections

$$\mathrm{d}\sigma^{\lambda_\ell \lambda_H} = \frac{\mathrm{d}^2\sigma(\lambda_\ell, \lambda_H)}{\mathrm{d}x\ \mathrm{d}Q^2}$$

$$\mathrm{d}\sigma_0 = \frac{1}{4}\left[\mathrm{d}\sigma^{++} + \mathrm{d}\sigma^{+-} + \mathrm{d}\sigma^{-+} + \mathrm{d}\sigma^{--}\right]$$

unpolarized lepton + unpolarized hadron

$$\mathrm{d}\sigma_\ell = \frac{1}{4}\left[\mathrm{d}\sigma^{++} + \mathrm{d}\sigma^{+-} - \mathrm{d}\sigma^{-+} - \mathrm{d}\sigma^{--}\right]$$

polarized lepton + unpolarized hadron

$$\mathrm{d}\sigma_H = \frac{1}{4}\left[\mathrm{d}\sigma^{++} - \mathrm{d}\sigma^{+-} + \mathrm{d}\sigma^{-+} - \mathrm{d}\sigma^{--}\right]$$

unpolarized lepton + polarized hadron

$$\mathrm{d}\sigma_{\ell H} = \frac{1}{4}\left[\mathrm{d}\sigma^{++} - \mathrm{d}\sigma^{+-} - \mathrm{d}\sigma^{-+} + \mathrm{d}\sigma^{--}\right]$$

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$$\mathrm{d}\sigma_{\ell H} = \frac{1}{4}\left[\mathrm{d}\sigma^{++} - \mathrm{d}\sigma^{+-} - \mathrm{d}\sigma^{-+} + \mathrm{d}\sigma^{--}\right]$$

$$A_{\mathrm{PV}}^{(\ell)} := \frac{\mathrm{d}\sigma_\ell}{\mathrm{d}\sigma_0}$$

unpolarized A_{PV}

$$A_{\mathrm{PV}}^{(H)} := \frac{\mathrm{d}\sigma_H}{\mathrm{d}\sigma_0}$$

polarized A_{PV}

$$A_{\mathrm{LC}}^{(H)} := \frac{\mathrm{d}\sigma_0(e^+H) - \mathrm{d}\sigma_0(e^-H)}{\mathrm{d}\sigma_0(e^+H) + \mathrm{d}\sigma_0(e^-H)}$$

lepton-charge A

Measurement of PV asymmetries at the EIC

$$d\sigma = d\sigma_0 + P_\ell d\sigma_e + P_H d\sigma_H + P_\ell P_H d\sigma_{\ell H}$$

$$P_\ell, P_H \leftrightarrow \lambda_\ell, \lambda_H$$

$\downarrow$

$-1 \leq \quad \leq 1$

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integrated luminosity

$$N^{++} = a_{\det} L^{++}\left[\mathrm{d}\sigma_0 + |P_\ell^{++}|\mathrm{d}\sigma_\ell + |P_H^{++}|\mathrm{d}\sigma_H + |P_\ell^{++}||P_H^{++}|\mathrm{d}\sigma_{\ell H}\right]$$

$$N^{+-} = a_{\det} L^{+-}\left[\mathrm{d}\sigma_0 + |P_\ell^{+-}|\mathrm{d}\sigma_\ell - |P_H^{+-}|\mathrm{d}\sigma_H - |P_\ell^{+-}||P_H^{+-}|\mathrm{d}\sigma_{\ell H}\right]$$

$$N^{-+} = a_{\det} L^{-+}\left[\mathrm{d}\sigma_0 - |P_\ell^{-+}|\mathrm{d}\sigma_\ell + |P_H^{-+}|\mathrm{d}\sigma_H - |P_\ell^{-+}||P_H^{-+}|\mathrm{d}\sigma_{\ell H}\right]$$

$$N^{--} = a_{\det} L^{--}\left[\mathrm{d}\sigma_0 - |P_\ell^{--}|\mathrm{d}\sigma_\ell - |P_H^{--}|\mathrm{d}\sigma_H + |P_\ell^{--}||P_H^{--}|\mathrm{d}\sigma_{\ell H}\right]$$

event count

detector phase space acceptance and efficiency

Measurement of PV asymmetries at the EIC

$$d\sigma = d\sigma_0 + P_\ell d\sigma_e + P_H d\sigma_H + P_\ell P_H d\sigma_{\ell H}$$

$$P_\ell, P_H \leftrightarrow \lambda_\ell, \lambda_H$$

$$-1 \leq \quad \leq 1$$

Assuming $P_\ell^{ij}, P_H^{ij}, L^{ij}$, and a_{det} are constant:

$$d\sigma^{ij} = N^{ij}/L^{ij}/a_{\text{det}}$$

$$d\sigma_0 = \frac{1}{4}\left[d\sigma^{++} + d\sigma^{+-} + d\sigma^{-+} + d\sigma^{--}\right]$$

$$d\sigma_\ell = \frac{1}{4|P_\ell|}\left[d\sigma^{++} + d\sigma^{+-} - d\sigma^{-+} - d\sigma^{--}\right]$$

$$d\sigma_H = \frac{1}{4|P_H|}\left[d\sigma^{++} - d\sigma^{+-} + d\sigma^{-+} - d\sigma^{--}\right]$$

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$$d\sigma_{\ell H} = \frac{1}{4|P_\ell||P_H|}\left[d\sigma^{++} - d\sigma^{+-} - d\sigma^{-+} + d\sigma^{--}\right]$$

$$\Rightarrow$$

$$Y^{ij} = N^{ij}/L^{ij}$$

$$A_{\text{PV}}^{(\ell)} = \frac{d\sigma_\ell}{d\sigma_0} = \frac{1}{|P_\ell|}\frac{Y^{++} + Y^{+-} - Y^{-+} - Y^{--}}{Y^{++} + Y^{+-} + Y^{-+} + Y^{--}}$$

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

Measurement of PV asymmetries at the EIC

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point-to-point luminosity uncertainty $\sim 10^{-4}$

$$\Downarrow$$

dominant uncertainty: polarimetry

Measurement of LC asymmetries at the EIC

PV asymmetries:

- Compare scattering yields of LH and RH beams
- Short-time scale
- Dominant uncertainty: polarimetry

Measurement of LC asymmetries at the EIC

PV asymmetries:

- Compare scattering yields of LH and RH beams
- Short-time scale
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LC asymmetries:

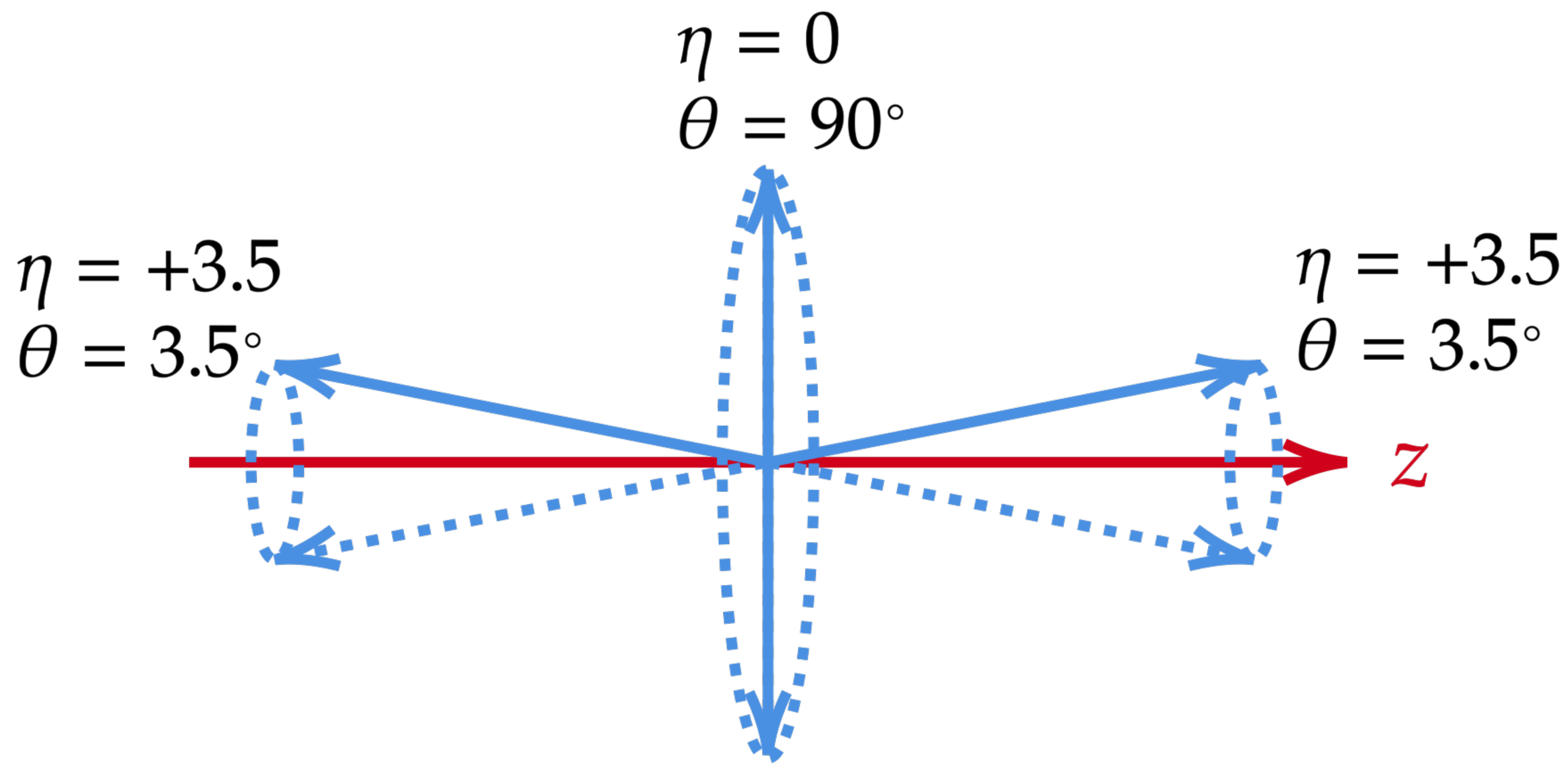
- Compare between e^- and e^+ runs
- Two independent cross-section measurements
- Reverse detector magnet polarity to minimize systematic errors in e^- and e^+ detection
- Dominant uncertainty: luminosity difference

Projections of PV and LC asymmetry data

ECCE detector configuration for inclusive NC study

Accardi *et al.* 1212.1701

- Hybrid tracking detector and EM calorimetry: $|\eta| \leq 3.5$ with full azimuthal coverage



- Determination of inclusive DIS kinematics:
  - Single-e^- simulations in full detector: p_e, θ_e, φ_e
  - Detected vs. true values: smearing
  - Apply smearing to simulated events without involving full detector

$\Rightarrow$ "fast-smearing"

https://wiki.bnl.gov/eic/index.php/Smearing

Simulation with fast-smearing

- Djangoh MC event generator: full EW radiative effects
- Apply fast-smearing to inclusive e^- events
- Get number of e^- using σ and L

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- Bin migration: PHENIX Collaboration 1402.1209
  - Due to radiative effects
  - Unfold

Simulation with fast-smearing

- Bin migration: PHENIX Collaboration 1402.1209
  - Due to radiative effects
  - Unfold

- Background reactions:
  - Due to hadronic final state
  - High at large values of y

Event selection

$Q > 1\ \mathrm{GeV}$	to avoid nonperturbative region of QCD
$y > 0.1$	to avoid bin migration and unfolding uncertainty
$y < 0.9$	to avoid high photoproduction background
$-3.5 < \eta < 3.5$	to restrict events in main acceptance of ECCE detector
$E' > 2\ \mathrm{GeV}$	to ensure high purity of e^- samples

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$E' > 2\ \text{GeV}$	to ensure high purity of e^- samples
$x < 0.5$ $Q > 10\ \text{GeV}$	additional cuts for SMEFT analysis: to remove *large* uncertainties from non-perturbative QCD and nuclear dynamics

Data sets

Beam energy, beam type, and nominal annual luminosity (NL) assumed for the EIC analysis:

eD scattering | *ep* scattering

D1	5 GeV $\times$ 41 GeV eD, 4.4 fb^{-1}	P1	5 GeV $\times$ 41 GeV ep, 4.4 fb^{-1}
D2	5 GeV $\times$ 100 GeV eD, 36.8 fb^{-1}	P2	5 GeV $\times$ 100 GeV ep, 36.8 fb^{-1}
D3	10 GeV $\times$ 100 GeV eD, 44.8 fb^{-1}	P3	10 GeV $\times$ 100 GeV ep, 44.8 fb^{-1}
D4	10 GeV $\times$ 137 GeV eD, 100 fb^{-1}	P4	10 GeV $\times$ 275 GeV ep, 100 fb^{-1}
D5	18 GeV $\times$ 137 GeV eD, 15.4 fb^{-1}	P5	18 GeV $\times$ 275 GeV ep, 15.4 fb^{-1}
		P6	18 GeV $\times$ 275 GeV ep, 100 fb^{-1}

CM energy

energy of electron beam

energy of hadron beam

YR reference setting [2103.05419]

Statistical uncertainty projection for PV asymmetries

For a given value of integrated luminosity:

$$\delta A_{\text{stat}}^{\text{measured}} = \frac{1}{\sqrt{N}}$$

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For PV asymmetries, corrections for beam polarization:

$$\left[\delta A_{\text{PV}}^{(\ell)}\right]_{\text{stat}} = \frac{1}{|P_\ell|}\frac{1}{\sqrt{N}}, \quad \left[\delta A_{\text{PV}}^{(H)}\right]_{\text{stat}} = \frac{1}{|P_H|}\frac{1}{\sqrt{N}}$$

Assume:

- $P_\ell = 80\,\%$ with $1\,\%$ rel. systematic uncertainty
- $P_H = 70\,\%$ with $2\,\%$ rel. systematic uncertainty

Statistical uncertainty projection for PV asymmetries

For a given value of integrated luminosity:

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large because $A_{\text{PV}}^{(H)} \ll A_{\text{PV}}^{(\ell)}$

Statistical uncertainty projection for LC asymmetries

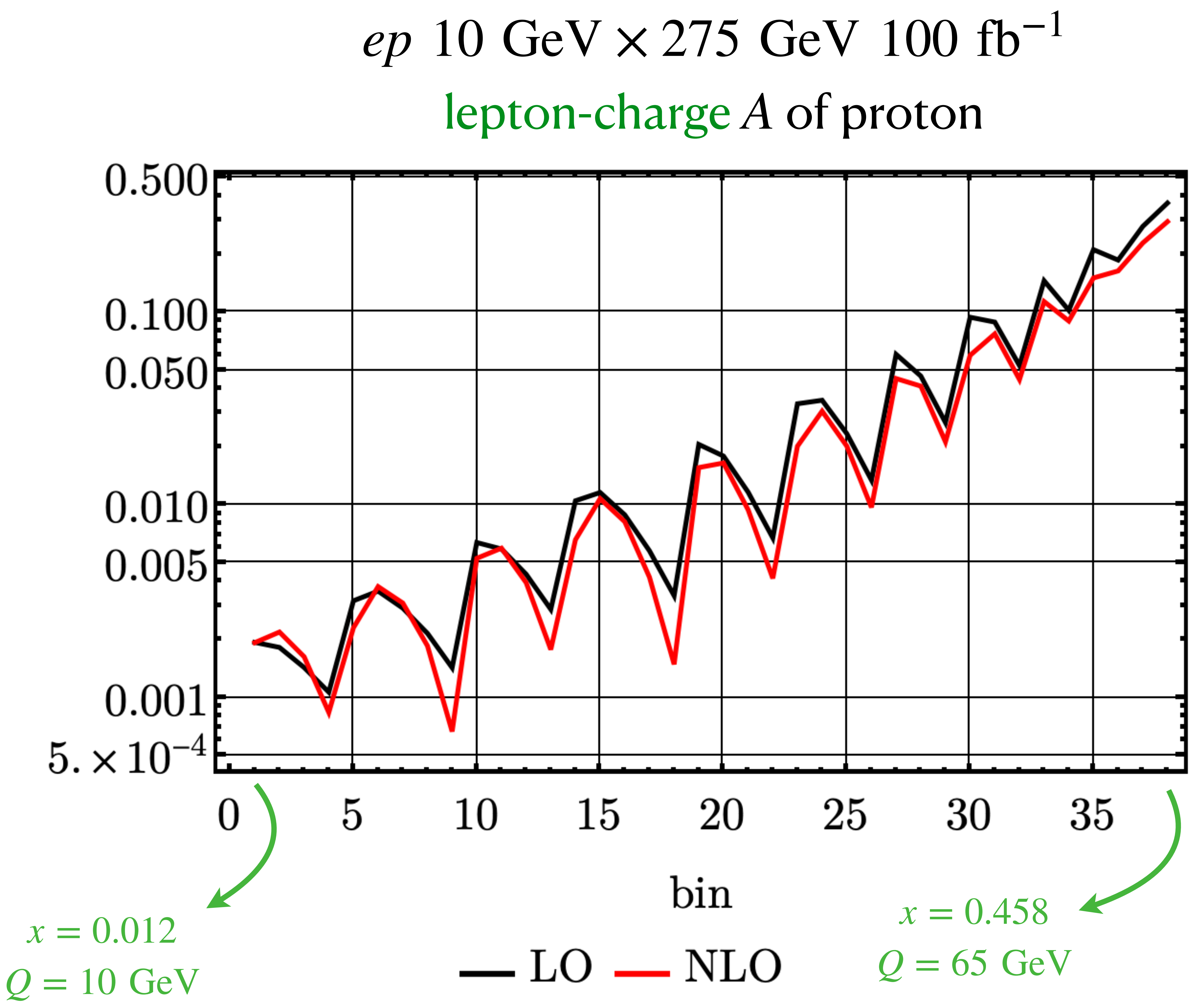
- Dominant uncertainty: luminosity difference between e^- and e^+ runs
- Assume $2\ \%$: relative in luminosity, absolute in $A_{\rm LC}^{(H)}$
- Reverse detector magnet polarity:

  $\Rightarrow$ detection of DIS $e^+ \sim$ detection of DIS e^-

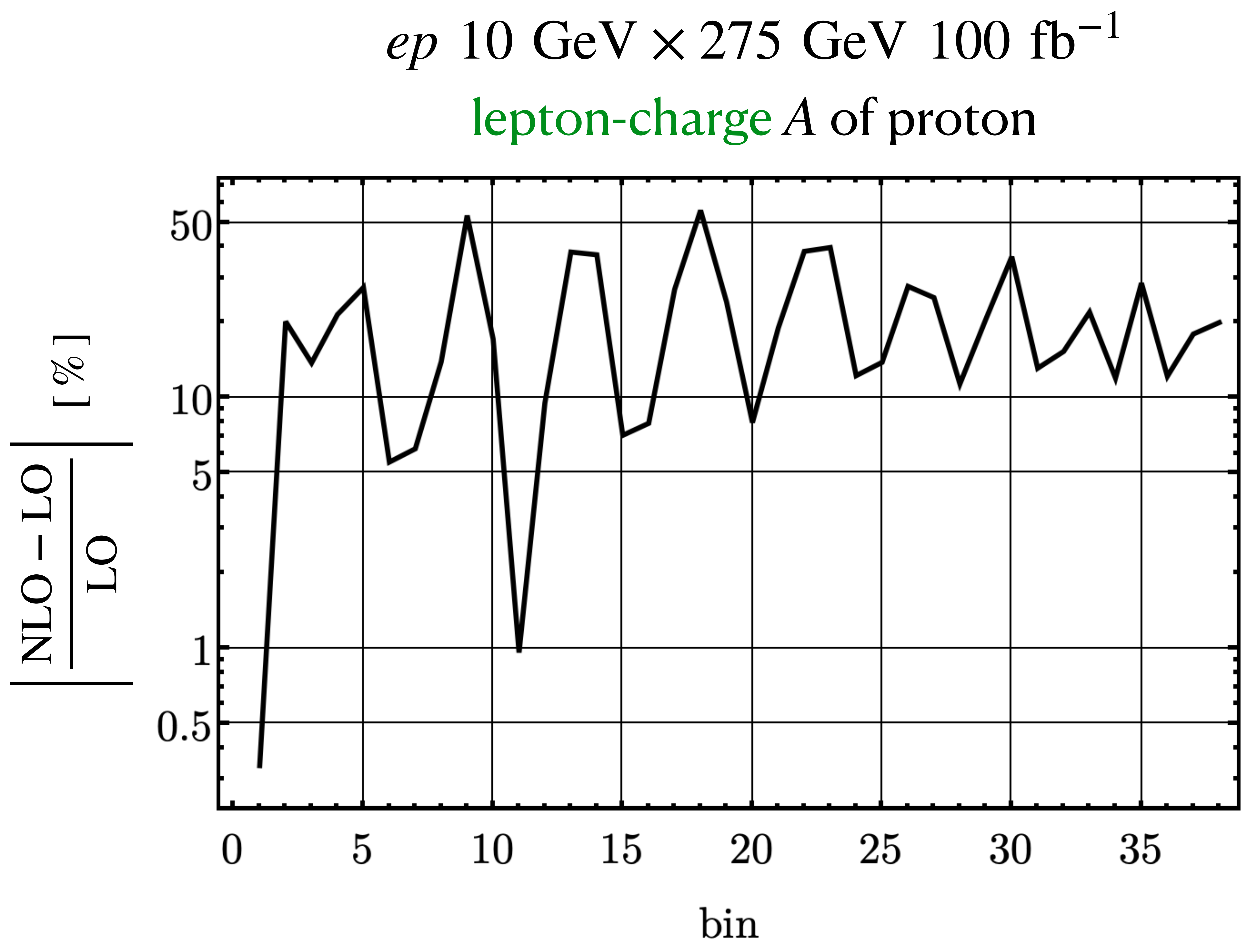
  $\Rightarrow \left[\delta A_{\rm LC}^{(H)}\right]_{\rm stat}$ determined by luminosity of e^+ run
- Assume $L^{e^+} = \dfrac{1}{10} L^{e^-}$.
- Polarimetry is irrelevant for $A_{\rm LC}$ measurements.

QED uncertainty projection for LC asymmetries

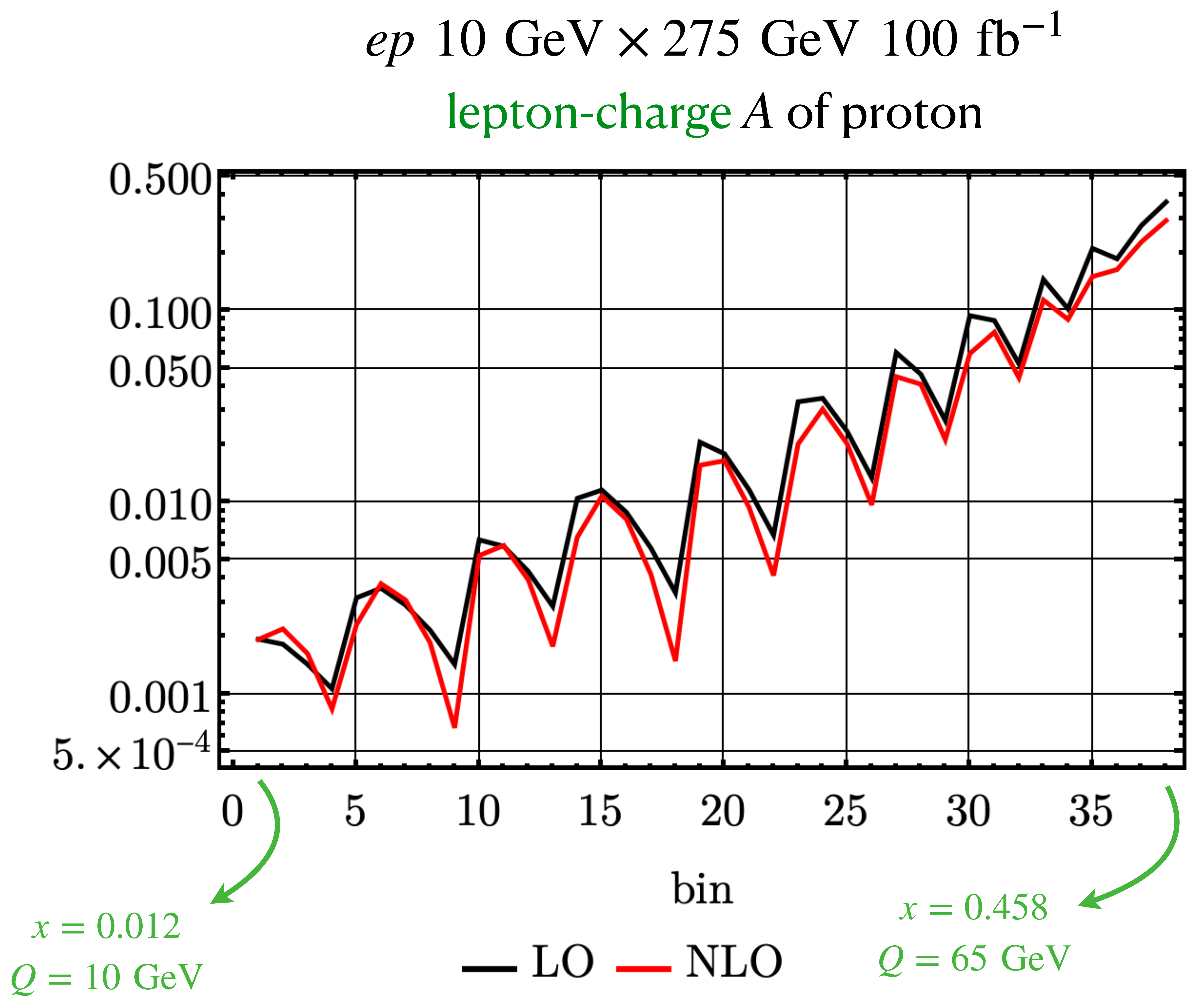
- Higher-order QED effects in e^- and e^+ DIS cross sections
- LO and NLO $A_{\mathrm{LC}}^{(H)}$ computed using `Djangoh`

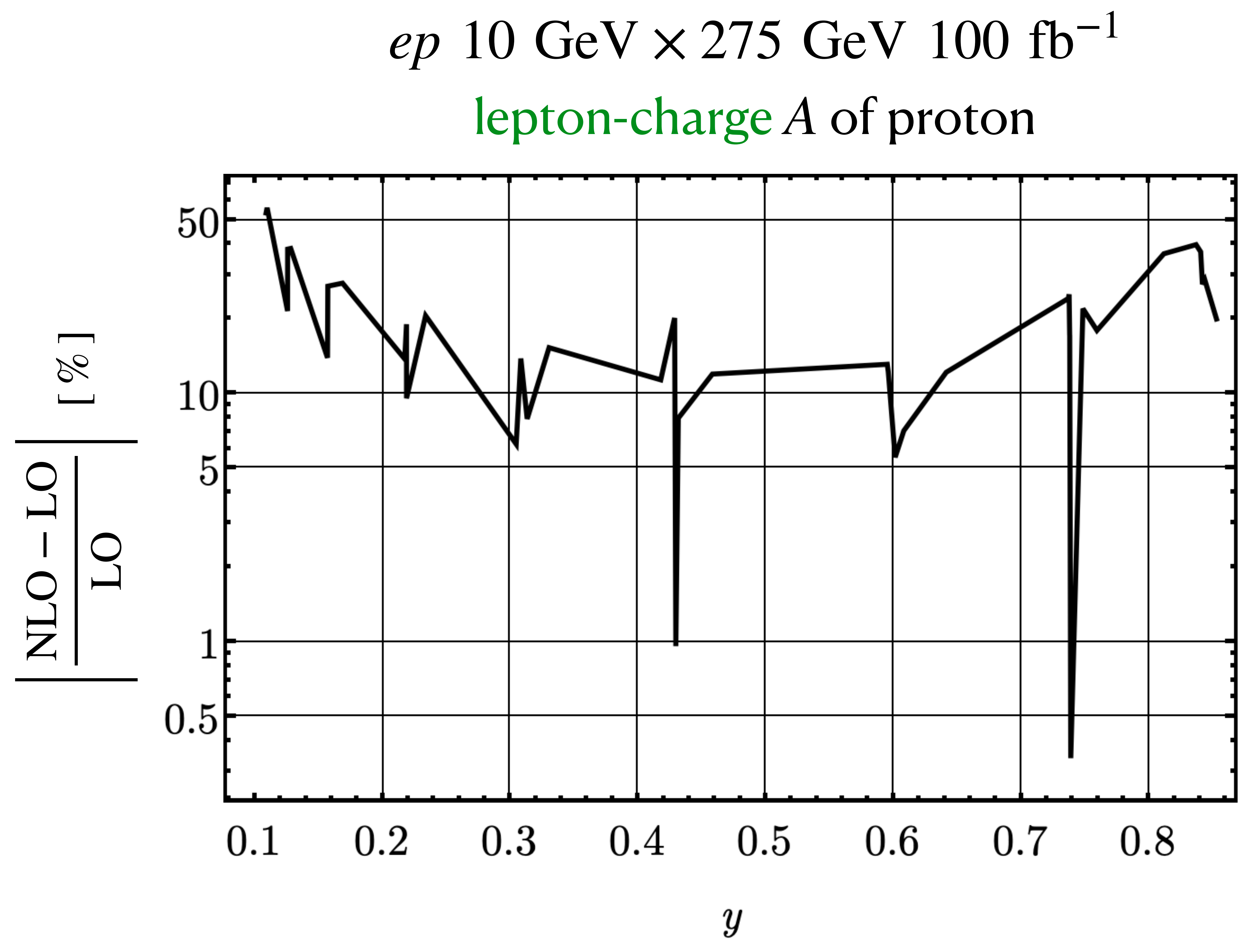


ep 10 GeV × 275 GeV 100 fb⁻¹
lepton-charge A of proton
0.500
0.100
0.050
0.010
0.005
0.001
5. × 10⁻⁴
0
5
10
15
20
25
30
35
bin
LO
NLO
x = 0.012
Q = 10 GeV
x = 0.458
Q = 65 GeV



ep 10 GeV × 275 GeV 100 fb⁻¹
lepton-charge A of proton
|NLO − LO / LO| [%]
50
10
5
1
0.5
0
5
10
15
20
25
30
35
bin


ep 10 GeV × 275 GeV 100 fb^-1
lepton-charge A of proton
0.500
0.100
0.050
0.010
0.005
0.001
5. × 10^-4
0
5
10
15
20
25
30
35
bin
LO
NLO
x = 0.012
Q = 10 GeV
x = 0.458
Q = 65 GeV


ep 10 GeV × 275 GeV 100 fb^-1
lepton-charge A of proton
|(NLO − LO)/LO| [%]
50
10
5
1
0.5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
y

QED uncertainty projection for LC asymmetries

- Higher-order QED effects in e^- and e^+ DIS cross sections
- LO and NLO $A_{\mathrm{LC}}^{(H)}$ computed using `Djangoh`
- Introduce $5\,\%$ of $\left[A_{\mathrm{LC}}^{(H)}\right]_{\mathrm{NLO}} - \left[A_{\mathrm{LC}}^{(H)}\right]_{\mathrm{LO}}$ as QED NLO uncertainty

Projection for High-Luminosity EIC

- Possibility of additional $10\times$ increase in annual luminosity beyond initial run
- Assuming all experimental systematic effects remain the same:

$$\sigma_{\text{stat}} \to \frac{1}{\sqrt{10}}\sigma_{\text{stat}}$$

Uncertainties

Anticipated uncertainties

PV asymmetries:

- σ_{stat}
- $\dfrac{\sigma_{\text{sys}}^{\text{unc}}}{A} = 1\,\%$ rel.
- $\dfrac{\sigma_{\text{pol}}^{\text{cor}}}{A} = \begin{cases} 1\,\% \text{ rel. for polarized } \ell \\ 2\,\% \text{ rel. for polarized } H \end{cases}$
- $\sigma_{\text{pdf}}^{\text{cor}}$

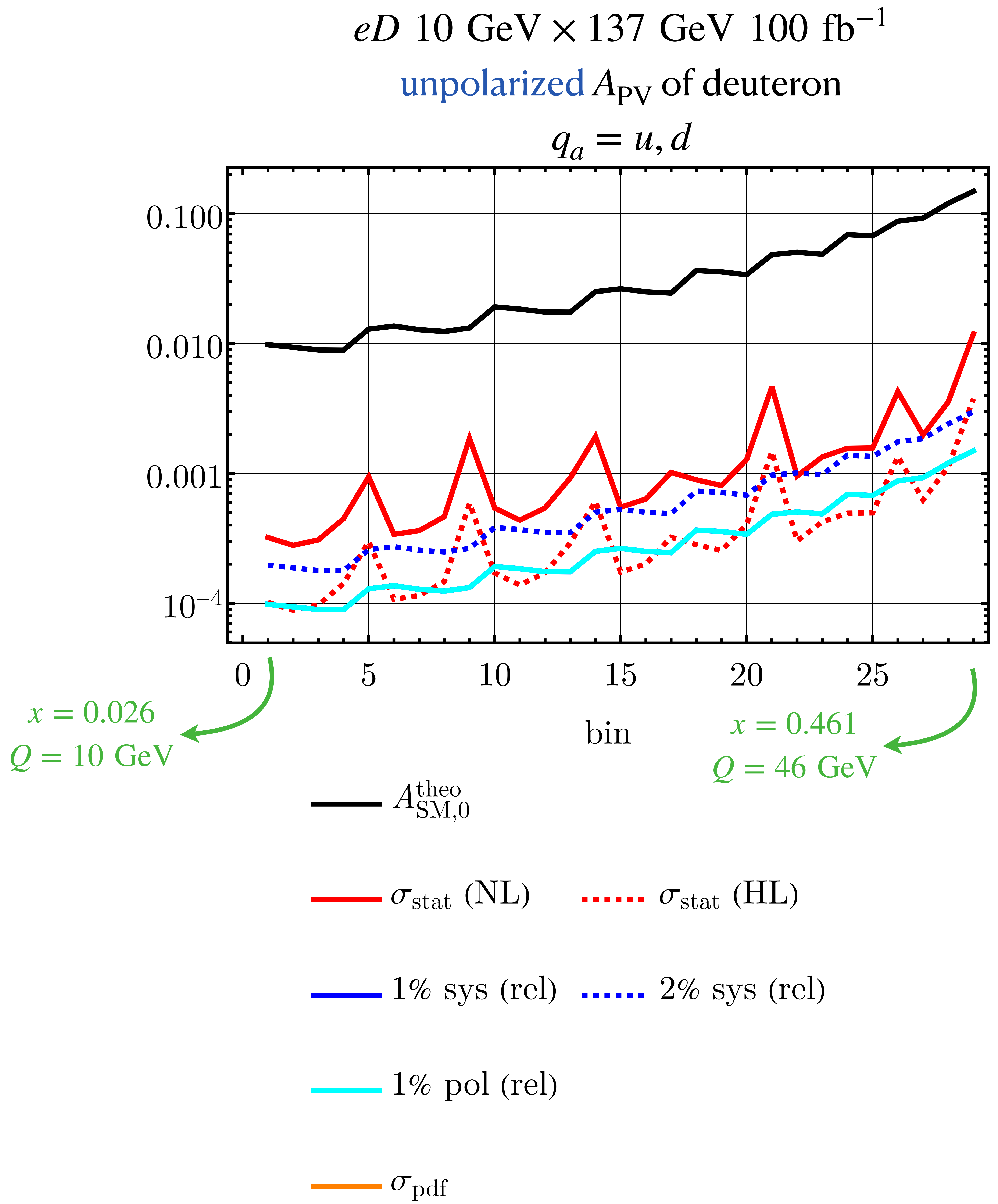
Anticipated uncertainties

PV asymmetries:

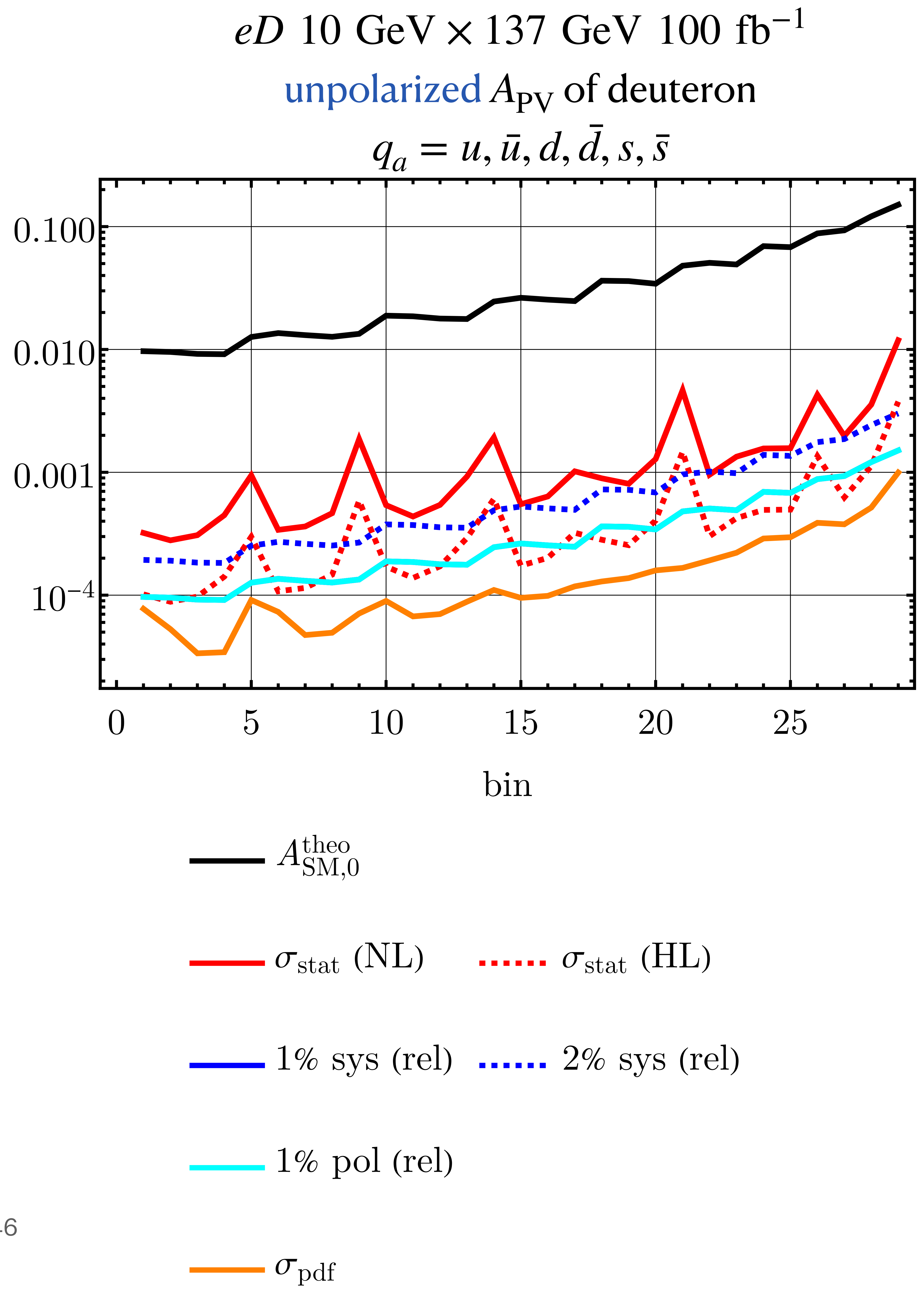
- σ_{stat}
- $\dfrac{\sigma_{\text{sys}}^{\text{unc}}}{A} = 1\,\%\ \text{rel.}$
- $\dfrac{\sigma_{\text{pol}}^{\text{cor}}}{A} = \begin{cases} 1\,\%\ \text{rel. for polarized } \ell \\ 2\,\%\ \text{rel. for polarized } H \end{cases}$
- $\sigma_{\text{pdf}}^{\text{cor}}$

LC asymmetries:

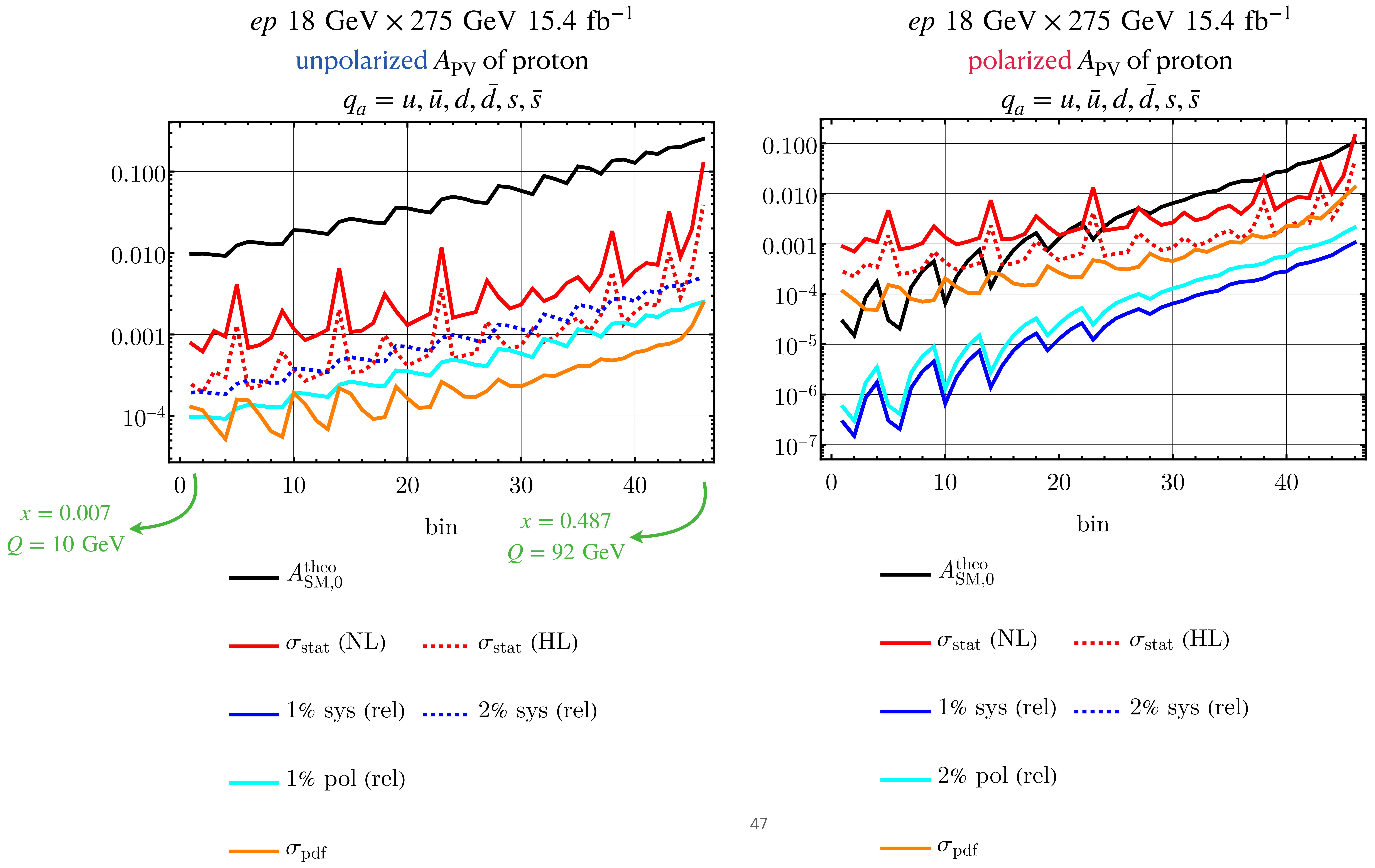
- σ_{stat}
- $\dfrac{\sigma_{\text{sys}}^{\text{unc}}}{A} = 1\,\%\ \text{rel.}$
- $\sigma_{\text{lum}}^{\text{cor}} = 2\,\%\ \text{abs.}$
- $\sigma_{\text{nlo}}^{\text{unc}} = 5\% \cdot (A_{\text{LC}}^{\text{NLO}} - A_{\text{LC}}^{\text{Born}})$
- $\sigma_{\text{pdf}}^{\text{cor}}$



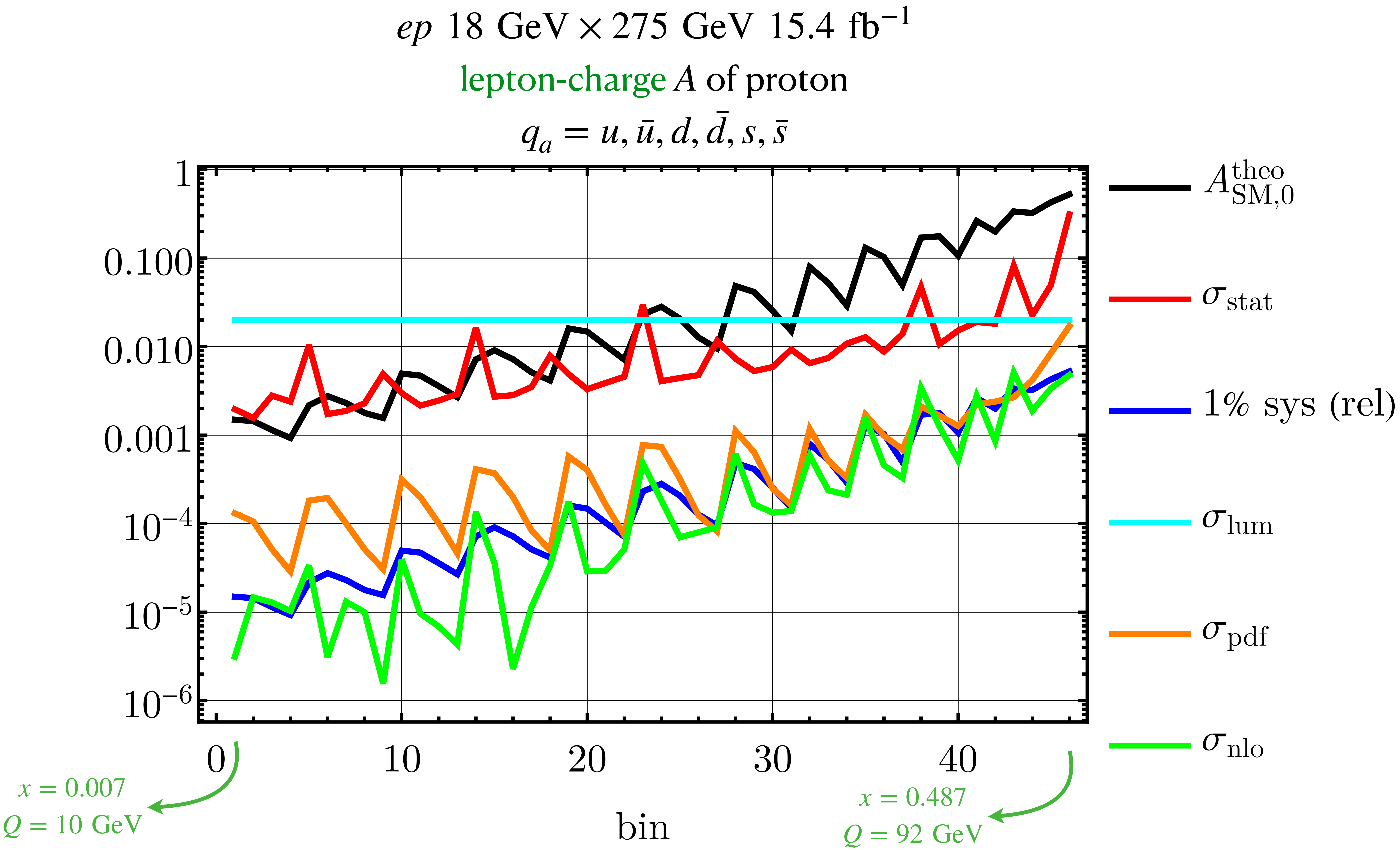
eD 10 GeV × 137 GeV 100 fb^{-1}
unpolarized A_{PV} of deuteron
$q_a = u, d$
0.100
0.010
0.001
10^{-4}
0
5
10
15
20
25
bin
$x = 0.026$
$Q = 10$ GeV
$x = 0.461$
$Q = 46$ GeV
$A^{\mathrm{theo}}_{\mathrm{SM},0}$
σ_{stat} (NL)
σ_{stat} (HL)
1% sys (rel)
2% sys (rel)
1% pol (rel)
σ_{pdf}



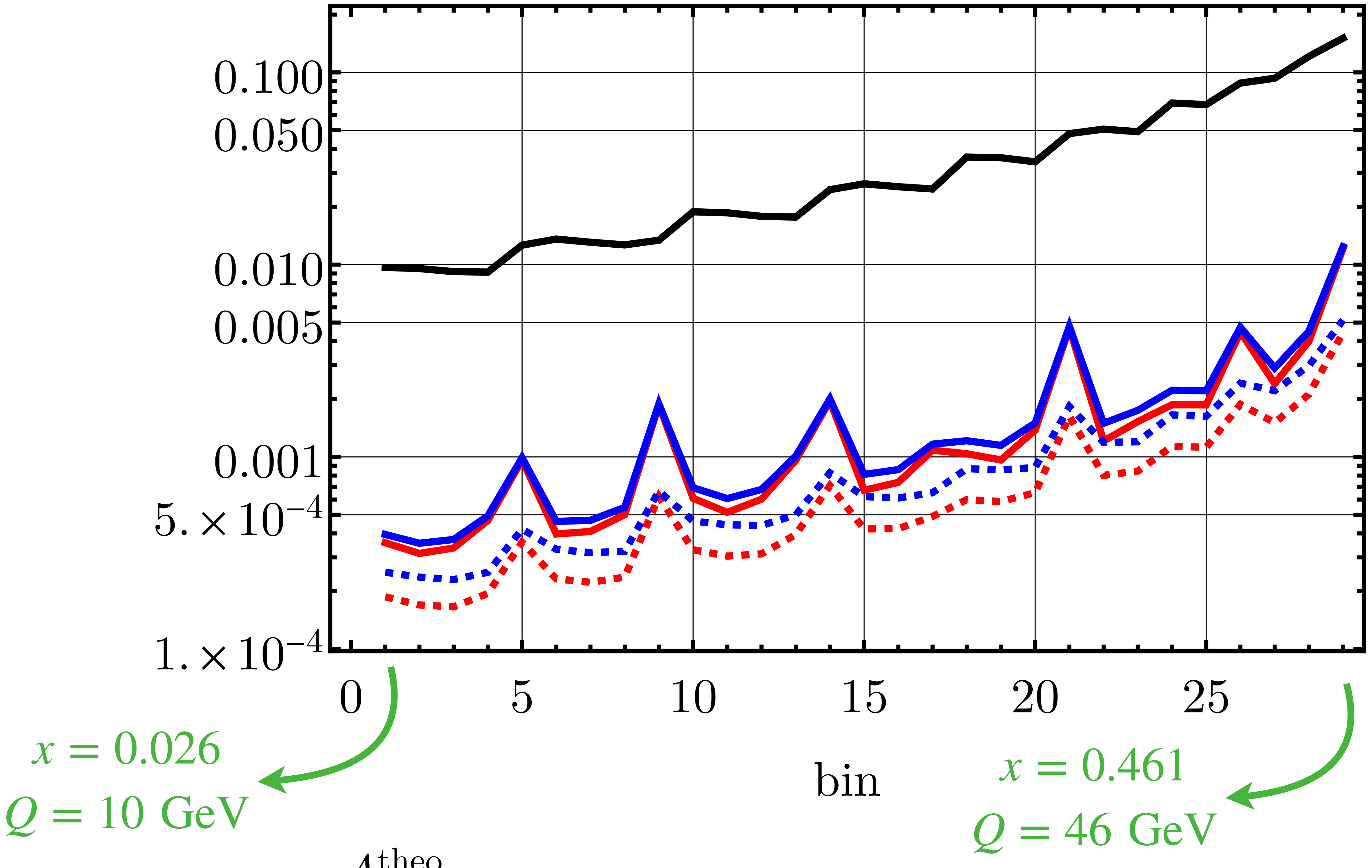
eD 10 GeV × 137 GeV 100 fb^{-1}
unpolarized A_{PV} of deuteron
$q_a = u, \bar{u}, d, \bar{d}, s, \bar{s}$
0.100
0.010
0.001
10^{-4}
0
5
10
15
20
25
bin
$A^{\mathrm{theo}}_{\mathrm{SM},0}$
σ_{stat} (NL)
σ_{stat} (HL)
1% sys (rel)
2% sys (rel)
1% pol (rel)
σ_{pdf}



ep 18 GeV × 275 GeV 15.4 fb^{-1}
unpolarized A_{PV} of proton
$q_a = u, \bar{u}, d, \bar{d}, s, \bar{s}$
0.100
0.010
0.001
10^{-4}
0
10
20
30
40
bin
x = 0.007
Q = 10 GeV
x = 0.487
Q = 92 GeV
$A^{\text{theo}}_{\text{SM},0}$
σ_{stat} (NL)
σ_{stat} (HL)
1% sys (rel)
2% sys (rel)
1% pol (rel)
σ_{pdf}
ep 18 GeV × 275 GeV 15.4 fb^{-1}
polarized A_{PV} of proton
$q_a = u, \bar{u}, d, \bar{d}, s, \bar{s}$
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
10
20
30
40
bin
$A^{\text{theo}}_{\text{SM},0}$
σ_{stat} (NL)
σ_{stat} (HL)
1% sys (rel)
2% sys (rel)
2% pol (rel)
σ_{pdf}

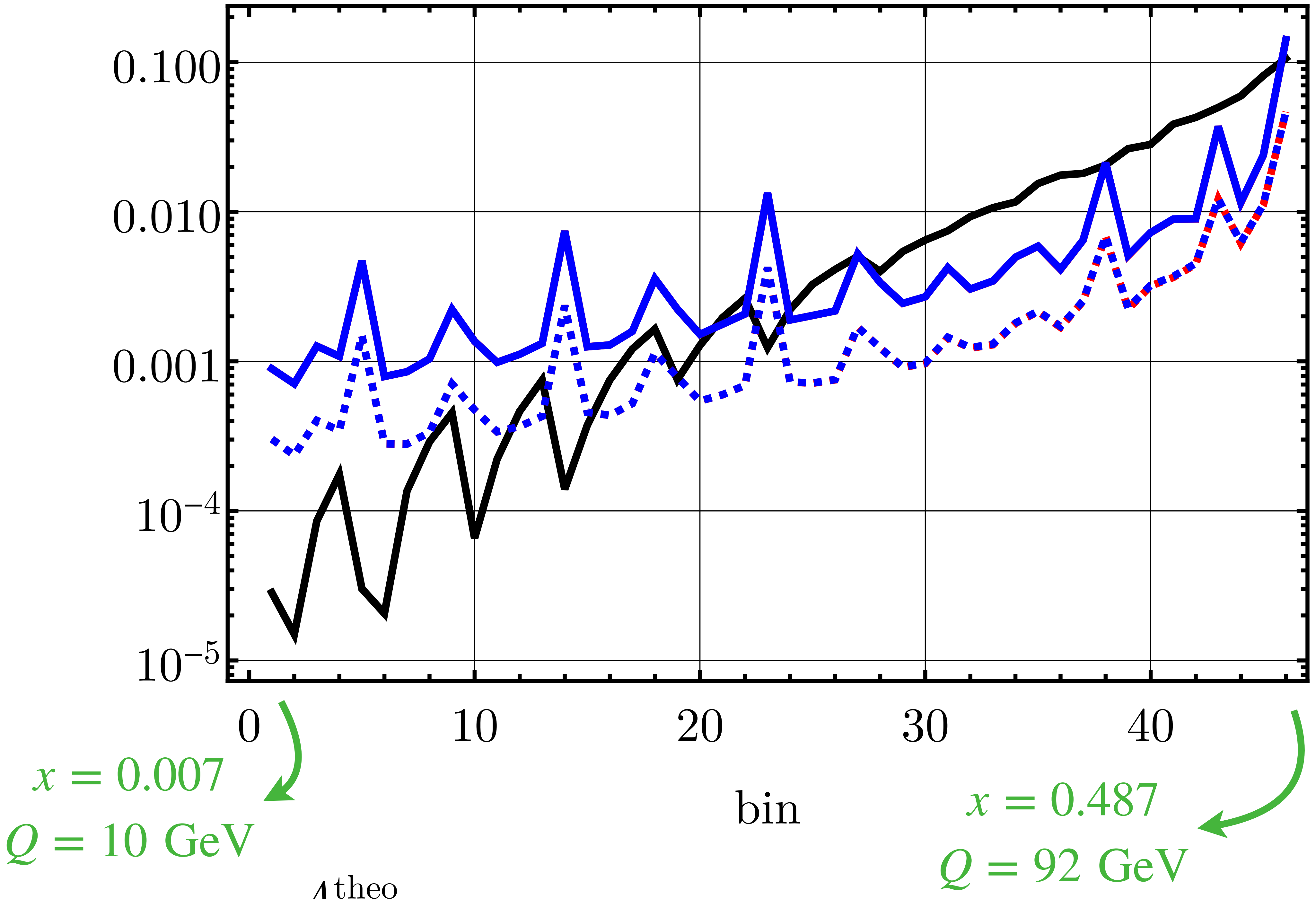

ep 18 GeV × 275 GeV 15.4 fb^{-1}
lepton-charge A of proton
$q_a = u, \bar{u}, d, \bar{d}, s, \bar{s}$
1
0.100
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
0
10
20
30
40
bin
$A^{\text{theo}}_{\text{SM},0}$
σ_{stat}
1% sys (rel)
σ_{lum}
σ_{pdf}
σ_{nlo}
$x = 0.007$
$Q = 10$ GeV
$x = 0.487$
$Q = 92$ GeV

eD 10 GeV × 137 GeV 100 fb^{-1}
unpolarized $A_{\rm PV}$ of deuteron



- $A^{\rm theo}_{\rm SM,0}$
- $\sigma_{\rm stat}$ (NL) + 1% sys (rel) + 1% pol (rel) + $\sigma_{\rm pdf}$
- $\sigma_{\rm stat}$ (HL) + 1% sys (rel) + 1% pol (rel) + $\sigma_{\rm pdf}$
- $\sigma_{\rm stat}$ (NL) + 2% sys (rel) + 1% pol (rel) + $\sigma_{\rm pdf}$
- $\sigma_{\rm stat}$ (HL) + 2% sys (rel) + 1% pol (rel) + $\sigma_{\rm pdf}$

ep 18 GeV × 275 GeV 15.4 fb^{-1}
polarized $A_{\rm PV}$ of proton



- $A^{\rm theo}_{\rm SM,0}$
- $\sigma_{\rm stat}$ (NL) + 1% sys (rel) + 2% pol (rel) + $\sigma_{\rm pdf}$
- $\sigma_{\rm stat}$ (HL) + 1% sys (rel) + 2% pol (rel) + $\sigma_{\rm pdf}$
- $\sigma_{\rm stat}$ (NL) + 2% sys (rel) + 2% pol (rel) + $\sigma_{\rm pdf}$
- $\sigma_{\rm stat}$ (HL) + 2% sys (rel) + 2% pol (rel) + $\sigma_{\rm pdf}$

Uncertainty assumptions

Brief summary:

- Quark flavors: up to strange or only at up and down.
- σ_{stat}: dominant for unpolarized A_{PV} in NL; comparable to σ_{sys} in HL.
- PDF uncertainties: negligible for unpolarized A_{PV}, significant for polarized A_{PV}.
- Luminosity effects > σ_{stat}.
- Higher-order QED corrections to lepton-charge A are negligible.

Framework of the SMEFT analysis

Data sets

Concentrate on the two highest-energy settings:

- $10\ \mathrm{GeV} \times 137\ \mathrm{GeV}\ eD\ 100\ \mathrm{fb}^{-1}$
- $10\ \mathrm{GeV} \times 275\ \mathrm{GeV}\ ep\ 100\ \mathrm{fb}^{-1}$
- $18\ \mathrm{GeV} \times 137\ \mathrm{GeV}\ eD\ 15.4\ \mathrm{fb}^{-1}$
- $18\ \mathrm{GeV} \times 275\ \mathrm{GeV}\ ep\ 15.4\ \mathrm{fb}^{-1}$

Data sets

Concentrate on the two highest-energy settings:

- $10\ \text{GeV} \times 137\ \text{GeV}\ eD\ 100\ \text{fb}^{-1}$
- $10\ \text{GeV} \times 275\ \text{GeV}\ ep\ 100\ \text{fb}^{-1}$

} low energy, high luminosity

- $18\ \text{GeV} \times 137\ \text{GeV}\ eD\ 15.4\ \text{fb}^{-1}$
- $18\ \text{GeV} \times 275\ \text{GeV}\ ep\ 15.4\ \text{fb}^{-1}$

} high energy, low luminosity

Data sets

Concentrate on the two highest-energy settings:

- $10\ \text{GeV} \times 137\ \text{GeV}\ eD\ 100\ \text{fb}^{-1}$: D4, ΔD4, LD4
- $10\ \text{GeV} \times 275\ \text{GeV}\ ep\ 100\ \text{fb}^{-1}$: P4, ΔP4, LP4
- $18\ \text{GeV} \times 137\ \text{GeV}\ eD\ 15.4\ \text{fb}^{-1}$: D5, ΔD5, LD5
- $18\ \text{GeV} \times 275\ \text{GeV}\ ep\ 15.4\ \text{fb}^{-1}$: P5, ΔP5, LP5

lepton-charge A

unpolarized A_{PV}

polarized A_{PV}

Pseudodata generation

For b^{th} bin:

$$A_b^{\text{pseudo}} = A_b^{\text{theo}} + r_b \sigma_b^{\text{unc}} + r' \sigma_b^{\text{cor}}$$

where

A_b^{theo} : Born-level SM prediction

$$\sigma_b^{\text{unc}} = \begin{cases} \sigma_{\text{stat},b} \oplus \sigma_{\text{sys},b}^{\text{unc}} \\ \sigma_{\text{stat},b} \oplus \sigma_{\text{sys},b}^{\text{unc}} \oplus \sigma_{\text{nlo},b}^{\text{unc}} \end{cases}, \quad \sigma_b^{\text{cor}} = \begin{cases} \sigma_{\text{pol},b}^{\text{cor}} & \text{(PV)} \\ \sigma_{\text{lum},b}^{\text{cor}} & \text{(LC)} \end{cases}$$

$r_b, r' \sim \mathcal{N}(0,1)$: random numbers

SMEFT asymmetry corrections

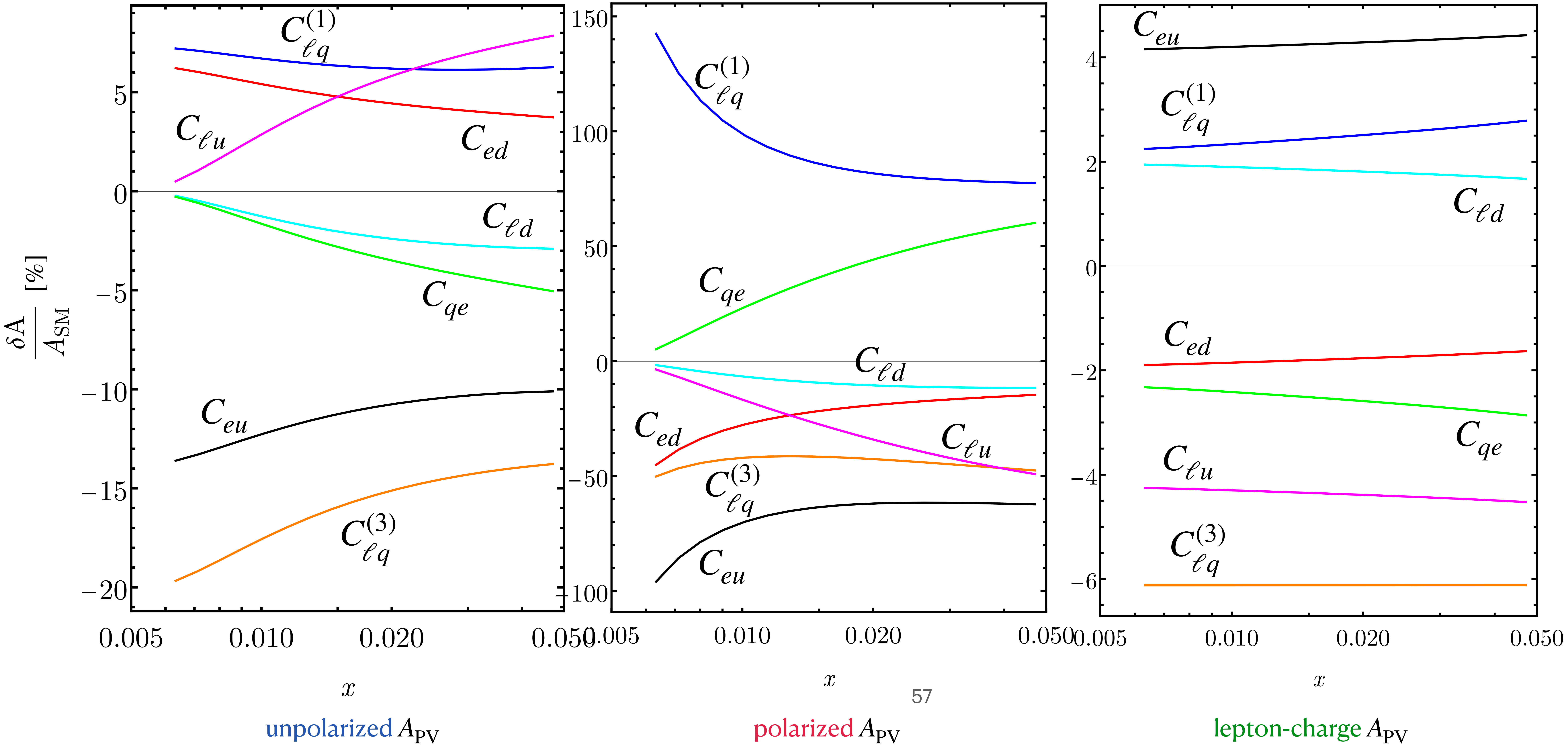
- Set $\Lambda = 1\ \text{TeV}$.
- Turn on only one or two Wilson coefficients at a time and linearize:

$$A_{\text{SMEFT}}(x, Q^2, C) = A_{\text{SM}}(x, Q^2) + C\,\delta A(x, Q^2)$$

$$A_{\text{SMEFT}}(x, Q^2, C_1, C_2) = A_{\text{SM}}(x, Q^2) + C_1\,\delta A_1(x, Q^2) + C_2\,\delta A_2(x, Q^2)$$

Sensitivity of SMEFT terms

$$A_{\mathrm{SMEFT}}(x, Q^2, C) = A_{\mathrm{SM}}(x, Q^2) + C\,\delta A(x, Q^2)$$

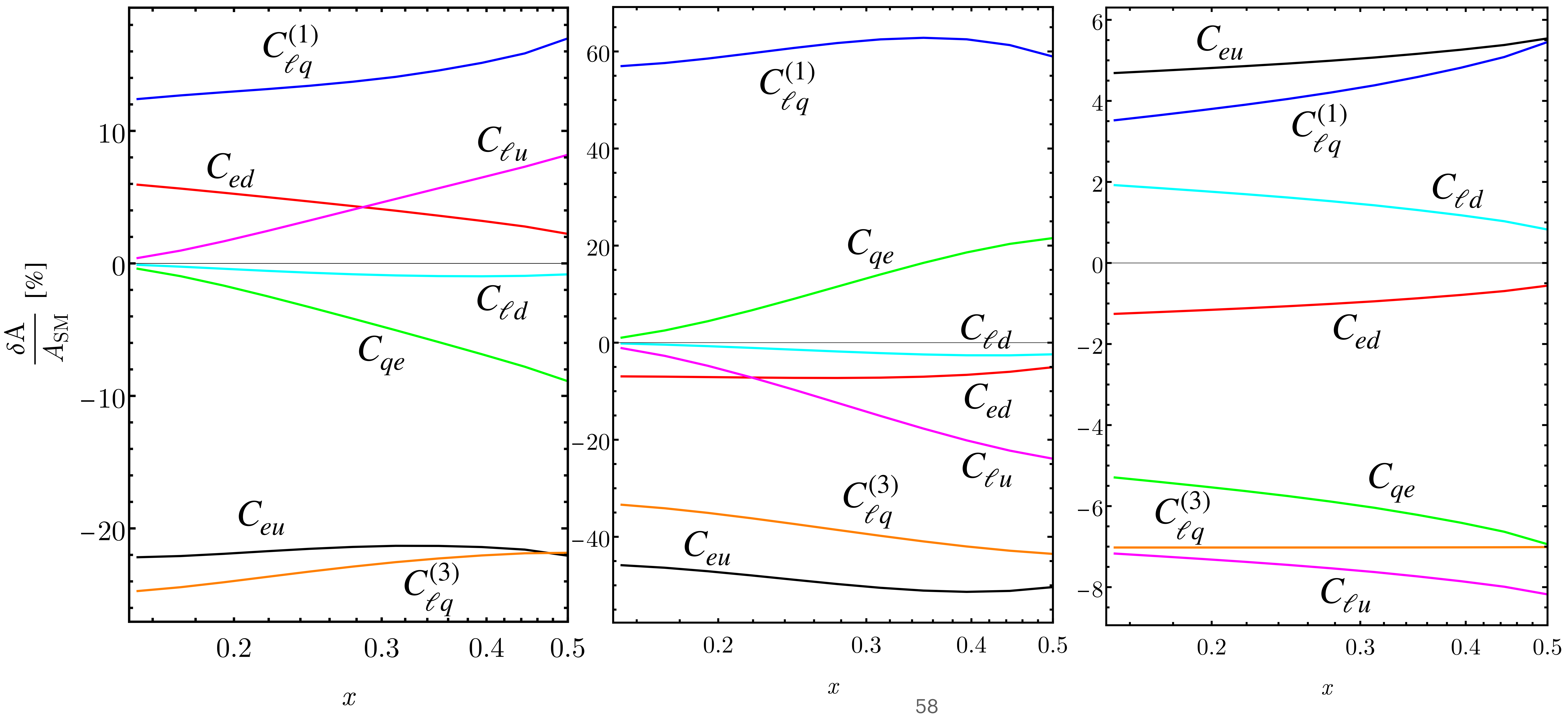


Comments:

- ep
- $Q = 10$ GeV
- $\sqrt{s} = 140$ GeV

Sensitivity of SMEFT terms

$$A_{\text{SMEFT}}(x, Q^2, C) = A_{\text{SM}}(x, Q^2) + C\,\delta A(x, Q^2)$$

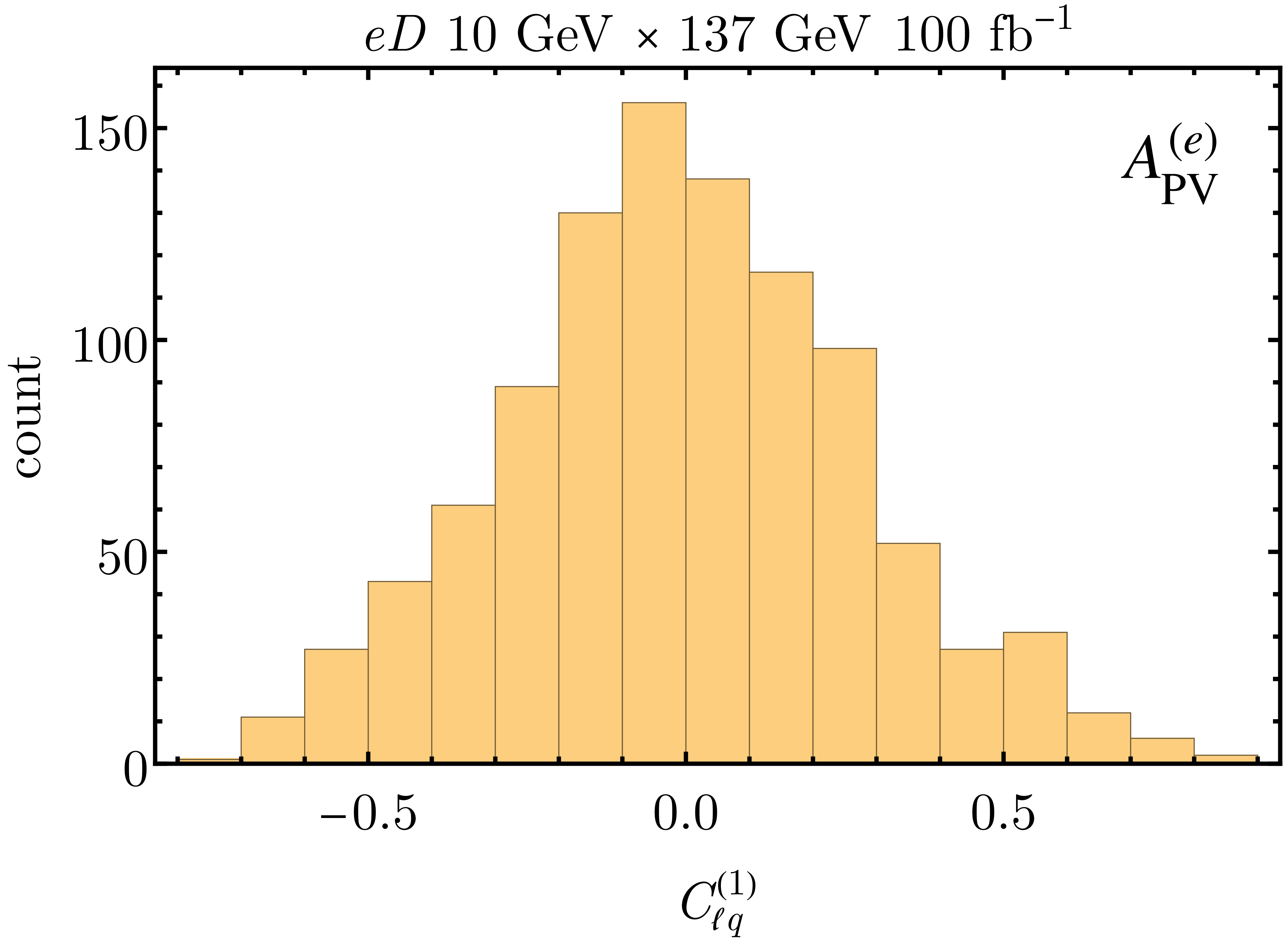


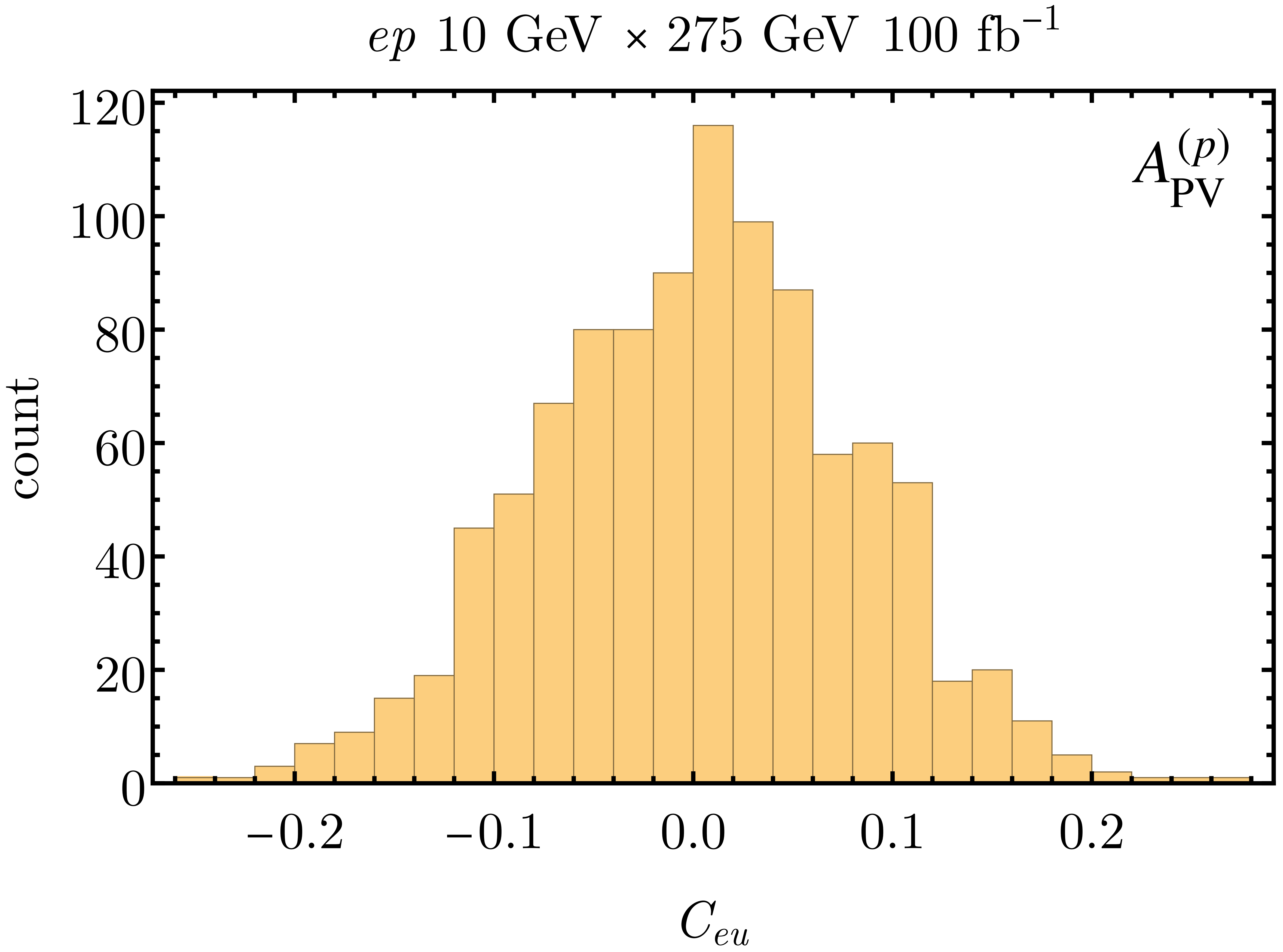
unpolarized A_{PV} | polarized A_{PV} | lepton-charge A_{PV}

Comments:

- *ep*
- $Q = 50$ GeV
- $\sqrt{s} = 140$ GeV

Distribution of best-fit values of Wilson coefficients





Best-fit analysis

χ^2 test statistic for the fits of Wilson coefficients:

$$\chi^2 = \sum_{b=1}^{N_{\text{bin}}} \sum_{b'=1}^{N_{\text{bin}}} \left[A_{\text{SMEFT}} - A^{\text{pseudo}}\right]_b H_{bb'} \left[A_{\text{SMEFT}} - A^{\text{pseudo}}\right]_{b'}$$

PV asymmetries:

$\sigma_{\text{stat}}, \sigma_{\text{sys}}^{\text{unc}}, \sigma_{\text{pol}}^{\text{cor}}, \sigma_{\text{pdf}}^{\text{cor}}$

LC asymmetries:

$\sigma_{\text{stat}}, \sigma_{\text{sys}}^{\text{unc}}, \sigma_{\text{pol}}^{\text{lum}}, \sigma_{\text{nlo}}^{\text{unc}}, \sigma_{\text{pdf}}^{\text{cor}}$

Best-fit analysis

χ^2 test statistic for the fits of Wilson coefficients:

$$\chi^2 = \sum_{b=1}^{N_{\text{bin}}} \sum_{b'=1}^{N_{\text{bin}}} \left[A_{\text{SMEFT}} - A^{\text{pseudo}}\right]_b H_{bb'} \left[A_{\text{SMEFT}} - A^{\text{pseudo}}\right]_{b'}$$

Polarimetry and luminosity difference can be limiting factors.

⇒ use data itself to constrain these systematic effects

⇒ simultaneous fits of Wilson coefficients with beam polarization, P

⇒ simultaneous fits of Wilson coefficients with luminosity difference, A_{lum}

Best-fit analysis

χ^2 test statistic for the fits of Wilson coefficients:

$$\chi^2 = \sum_{b=1}^{N_{\text{bin}}} \sum_{b'=1}^{N_{\text{bin}}} \left[A_{\text{SMEFT}} - A^{\text{pseudo}}\right]_b H_{bb'} \left[A_{\text{SMEFT}} - A^{\text{pseudo}}\right]_{b'}$$

assumed 1.0
for simplicity

$$\chi^2 = \sum_{b=1}^{N_{\text{bin}}} \sum_{b'=1}^{N_{\text{bin}}} \left[P(A_{\text{PV}})_{\text{SMEFT}} - A^{\text{pseudo}}\right]_b \left[H\Big|_{\sigma_{\text{pol}}\to 0}\right]_{bb'} \left[P(A_{\text{PV}})_{\text{SMEFT}} - A^{\text{pseudo}}\right]_{b'} + \frac{(P-\bar{P})^2}{\delta P^2}$$

beam polarization
as a nuance parameter

beam polarization uncertainty
1 % for lepton beam
2 % for hadron beam

Best-fit analysis

χ^2 test statistic for the fits of Wilson coefficients:

$$\chi^2 = \sum_{b=1}^{N_{\text{bin}}} \sum_{b'=1}^{N_{\text{bin}}} \left[A_{\text{SMEFT}} - A^{\text{pseudo}}\right]_b H_{bb'} \left[A_{\text{SMEFT}} - A^{\text{pseudo}}\right]_{b'}$$

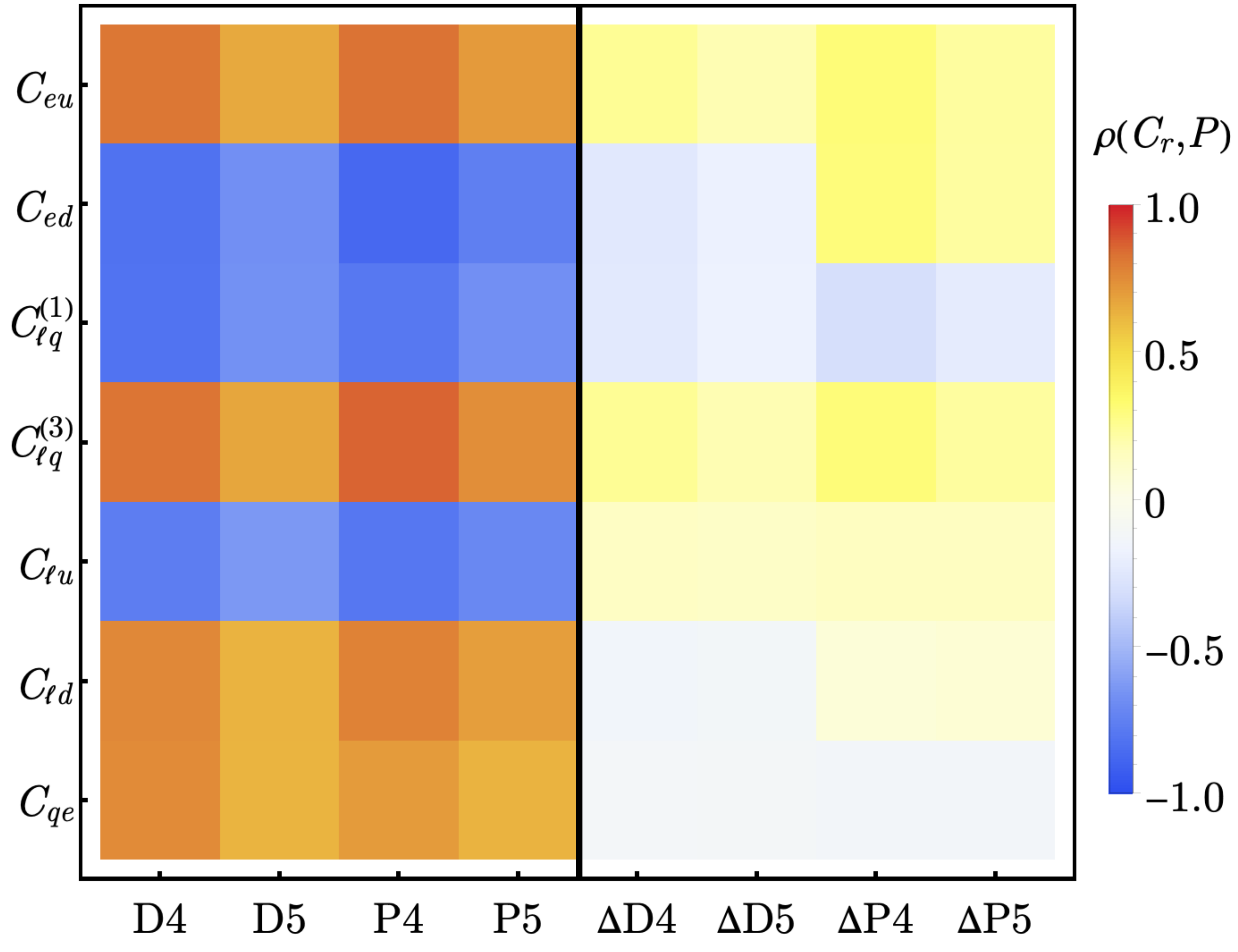
$$\chi^2 = \sum_{b=1}^{N_{\text{bin}}} \sum_{b'=1}^{N_{\text{bin}}} \left[P(A_{\text{PV}})_{\text{SMEFT}} - A^{\text{pseudo}}\right]_b \left[H\Big|_{\sigma_{\text{pol}}\to 0}\right]_{bb'} \left[P(A_{\text{PV}})_{\text{SMEFT}} - A^{\text{pseudo}}\right]_{b'} + \frac{(P-\bar{P})^2}{\delta P^2}$$

$$\chi^2 = \sum_{b=1}^{N_{\text{bin}}} \sum_{b'=1}^{N_{\text{bin}}} \left[(A_{\text{LC}})_{\text{SMEFT}} - A^{\text{pseudo}} - A_{\text{lum}}\right]_b \left[H\Big|_{\sigma_{\text{lum}}\to 0}\right]_{bb'} \left[(A_{\text{LC}})_{\text{SMEFT}} - A^{\text{pseudo}} - A_{\text{lum}}\right]_{b'}$$

shift in pseudodata
by a residual amount

Simultaneous fits with polarization parameter

nominal luminosity

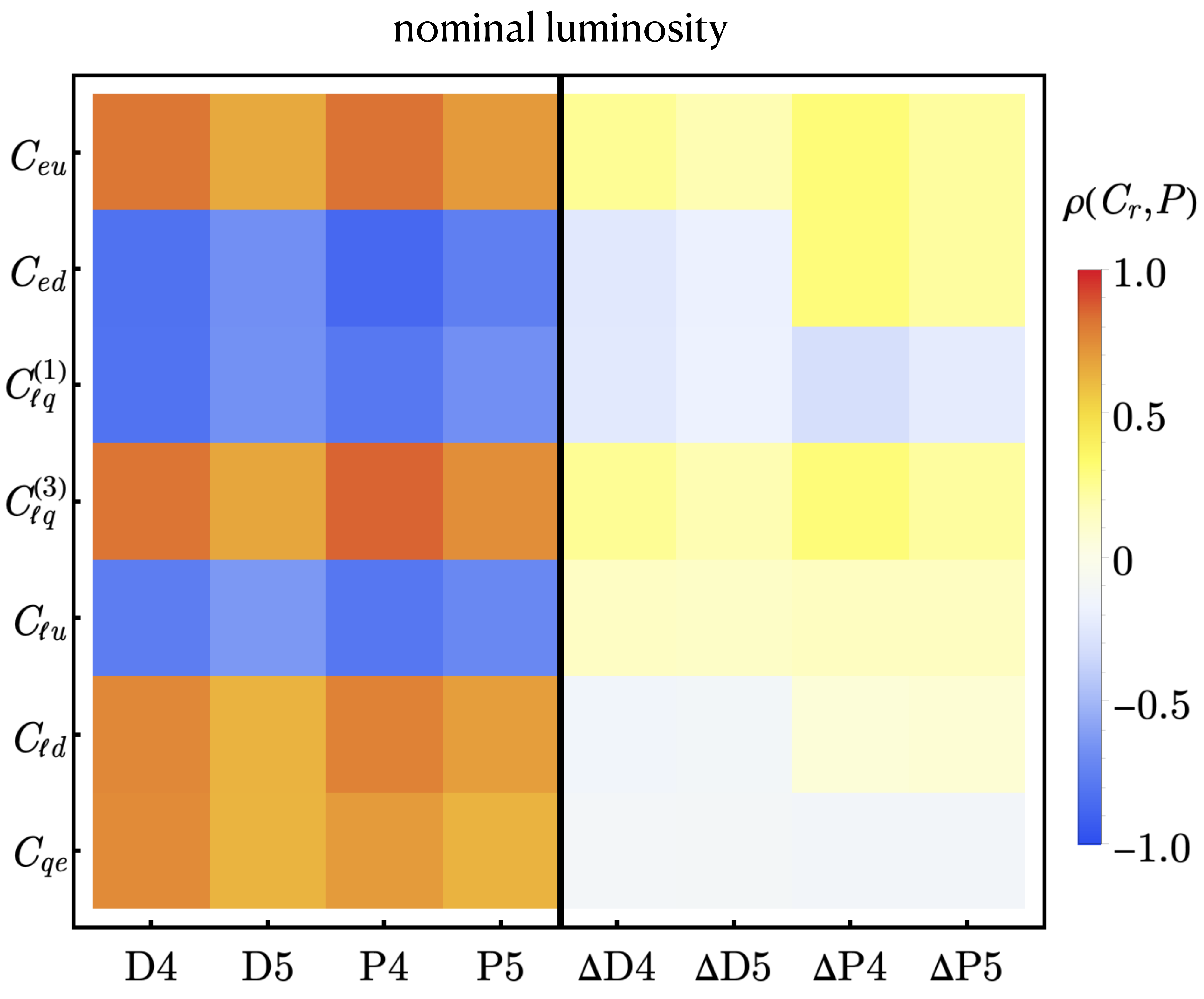


unpolarized $A_{\rm PV}$ polarized $A_{\rm PV}$

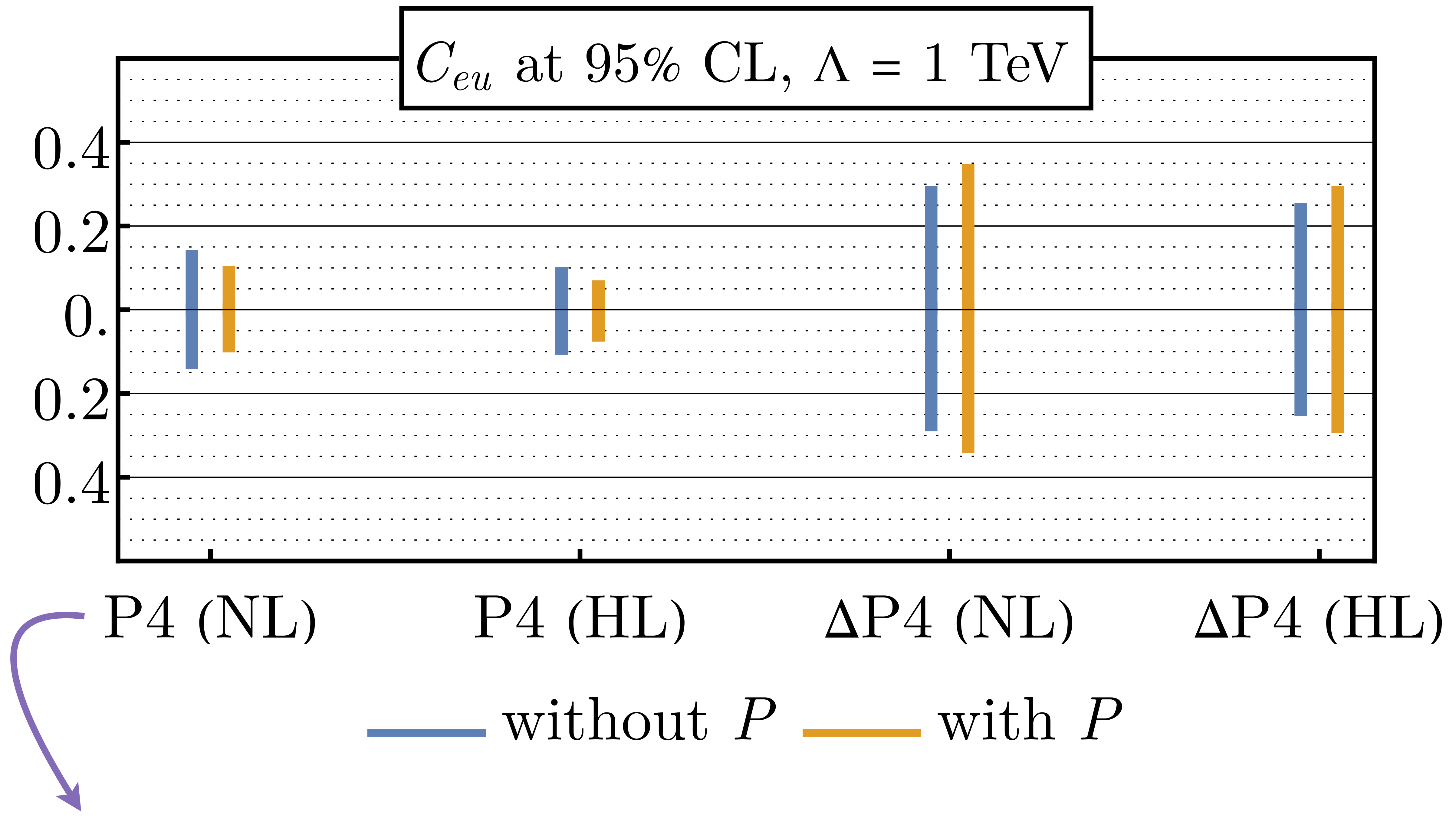
strong correlations between C_r and P in unpolarized $A_{\rm PV}$ data sets

weak correlations between C_r and P in polarized $A_{\rm PV}$ data sets

Simultaneous fits with polarization parameter

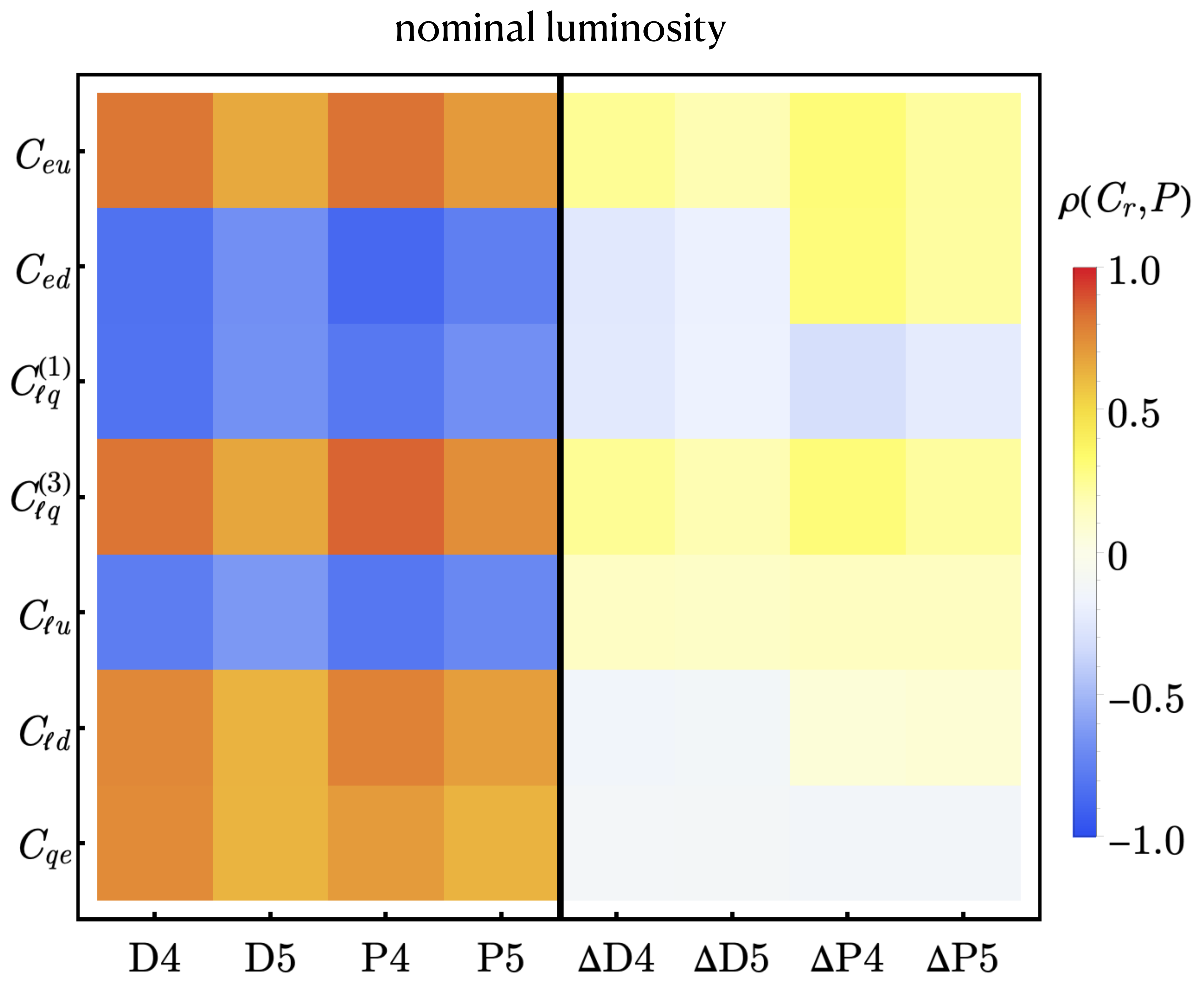


unpolarized $A_{\rm PV}$ polarized $A_{\rm PV}$

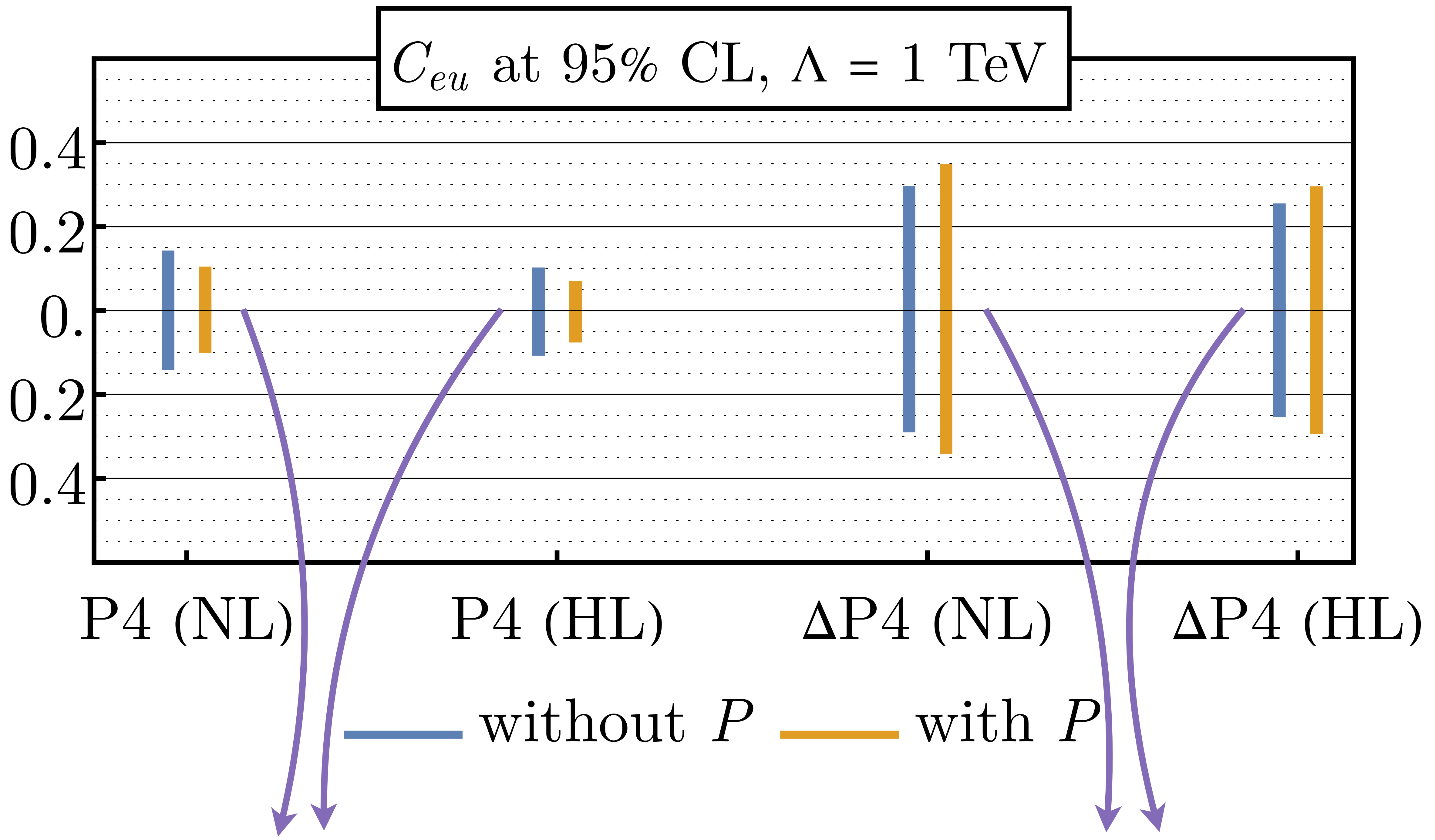


ep 10 GeV × 275 GeV 100 fb^{-1}

Simultaneous fits with polarization parameter



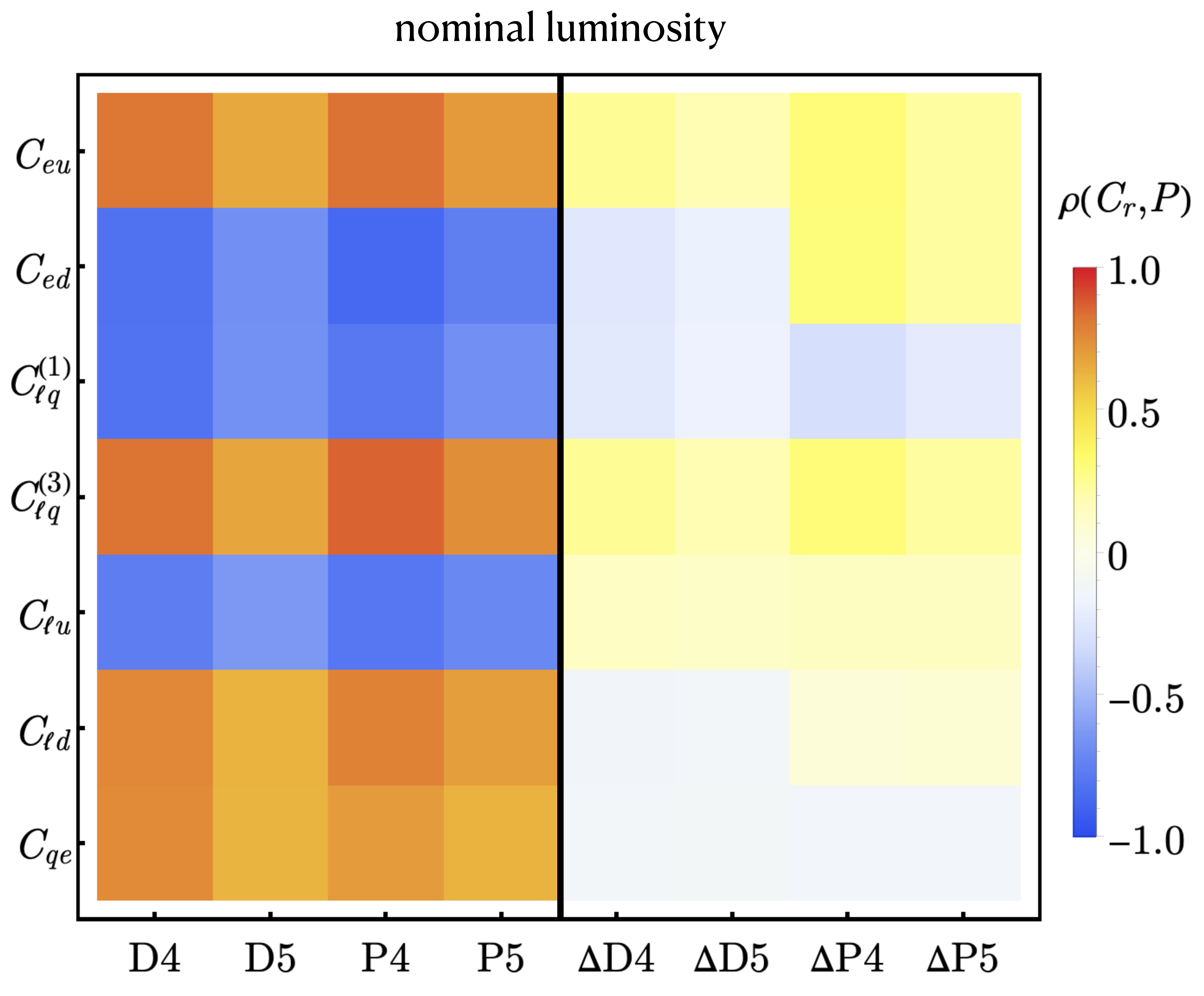
unpolarized A_{PV} polarized A_{PV}



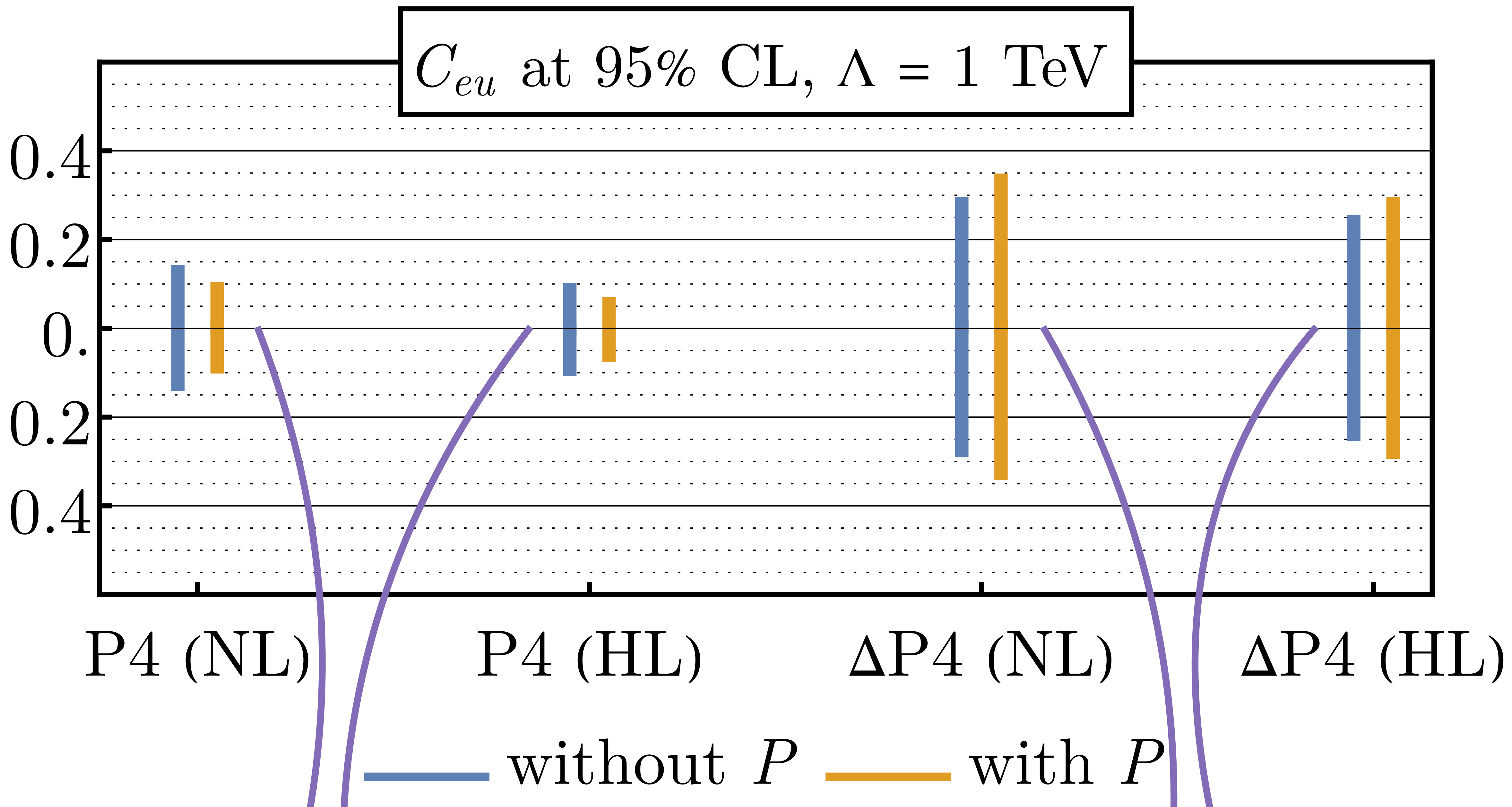
30 to 50 % improvement in bounds from unpolarized A_{PV}

15 to 20 % worsening in bounds from polarized A_{PV}

Simultaneous fits with polarization parameter



unpolarized $A_{\rm PV}$ polarized $A_{\rm PV}$

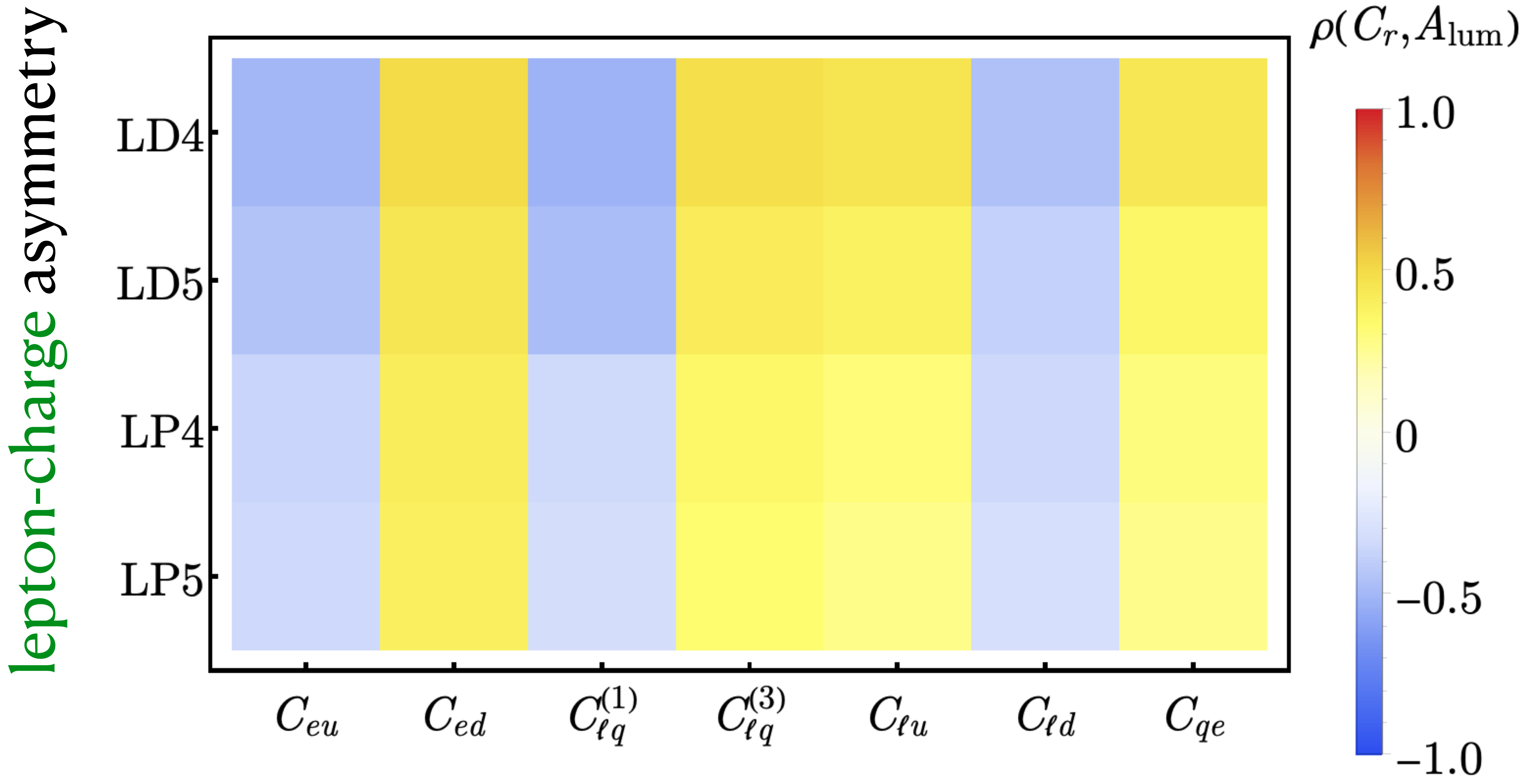


30 to 50 % improvement in bounds from unpolarized $A_{\rm PV}$

15 to 20 % worsening in bounds from polarized $A_{\rm PV}$

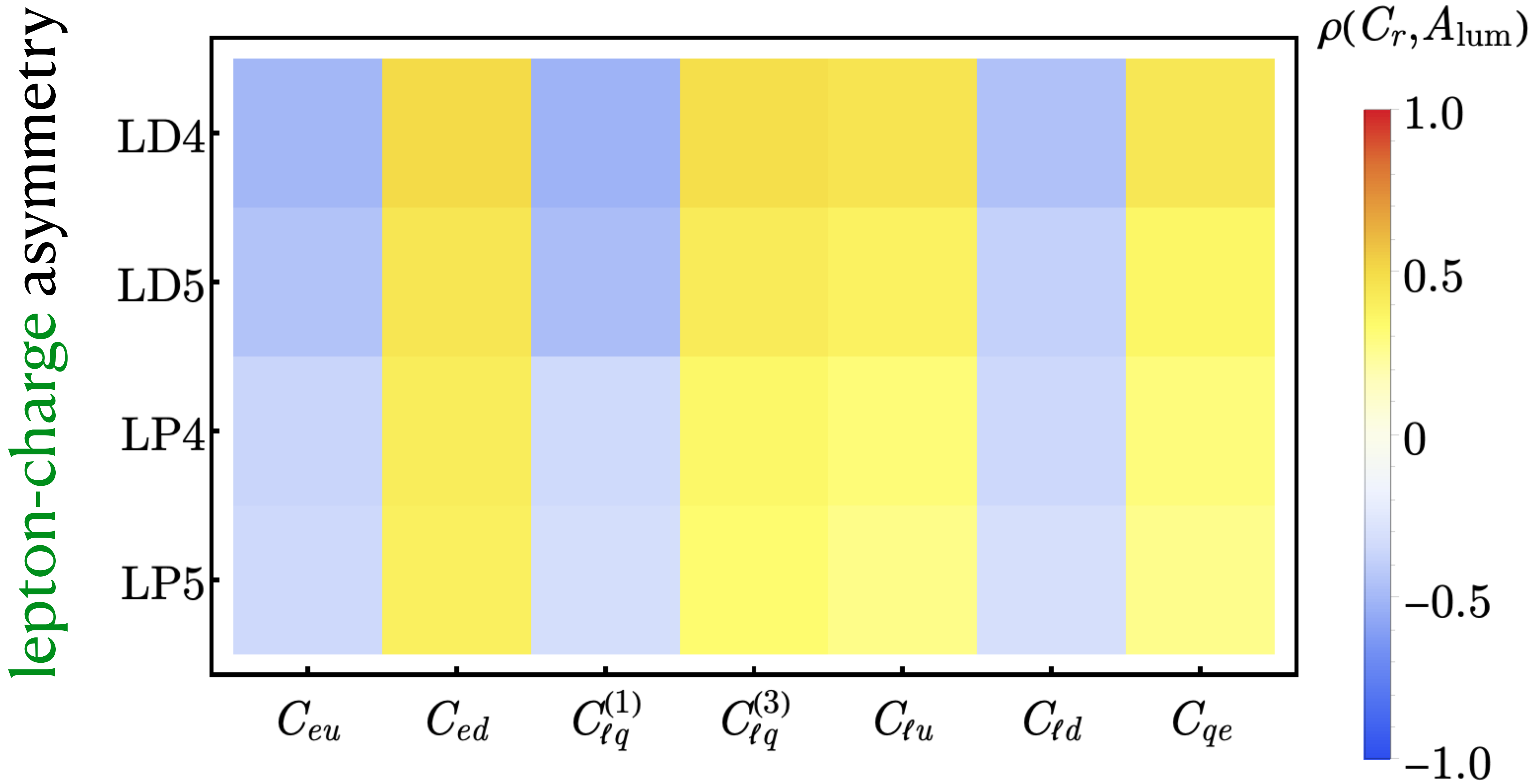
include P in the fits of Wilson coefficients

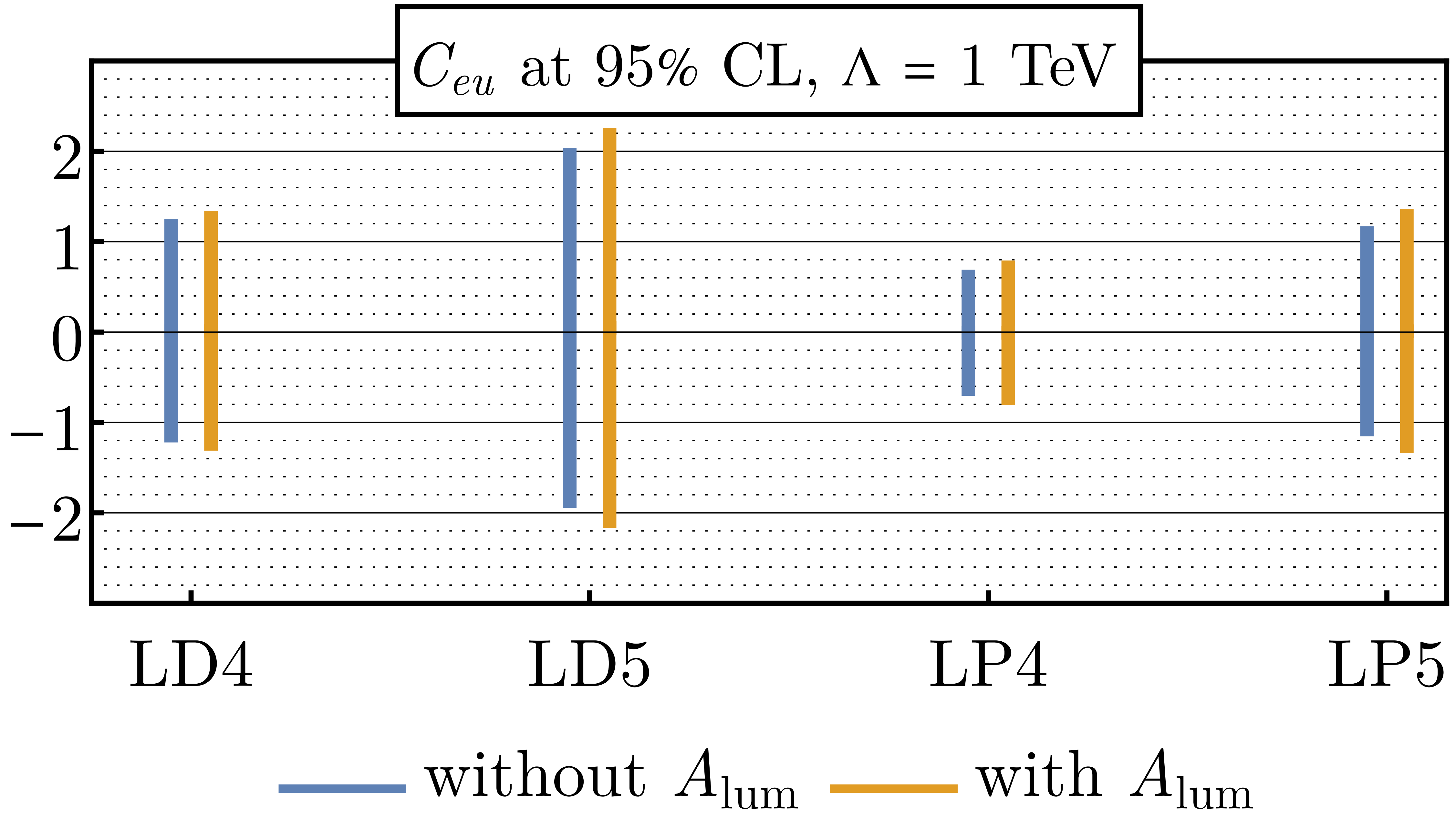
Simultaneous fits with luminosity difference



weak to mild correlations between C_r and A_{lum}

Simultaneous fits with luminosity difference



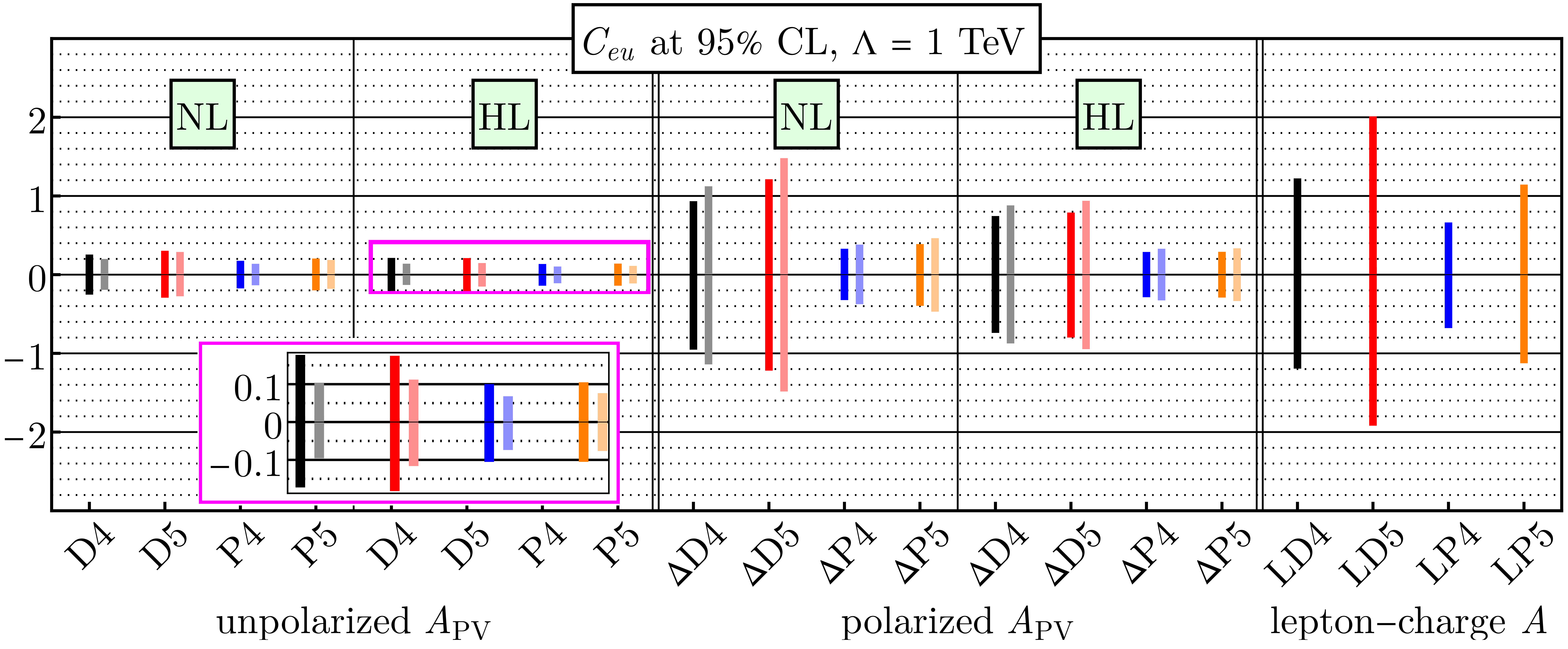


15 to 20 % worsening in bounds from lepton-charge A

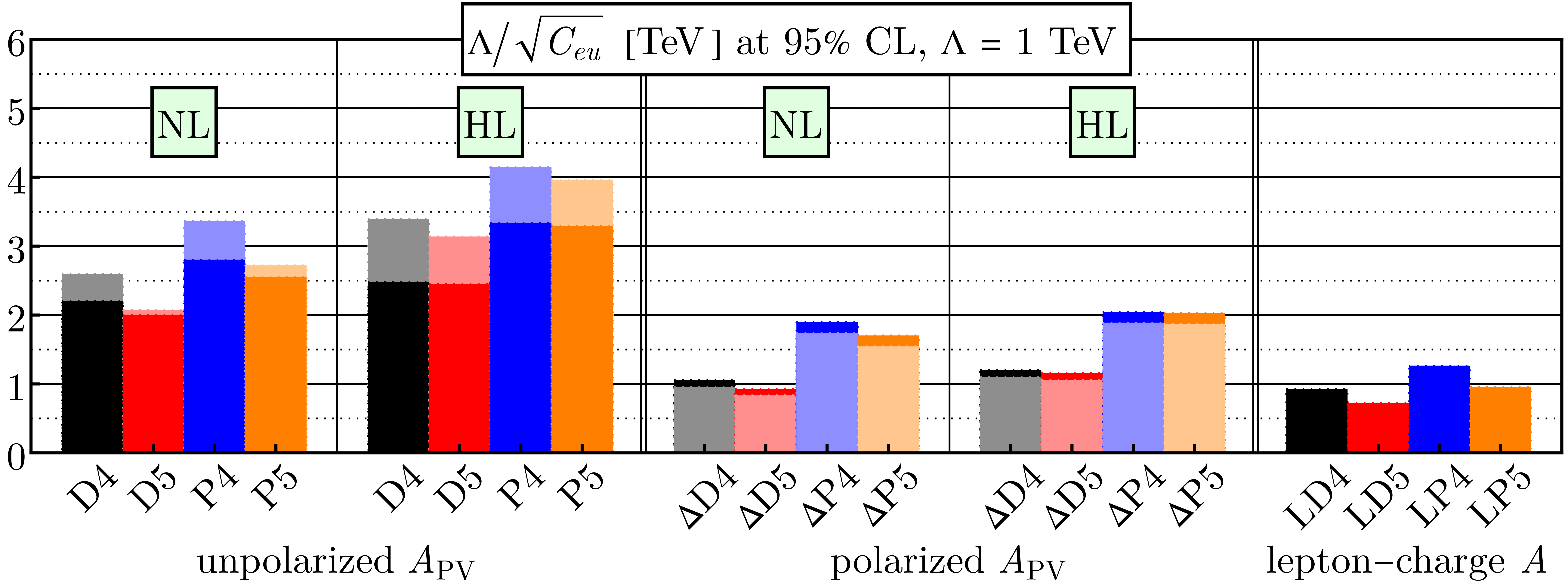
don't include $A_{\rm lum}$ in the fits of Wilson coefficients

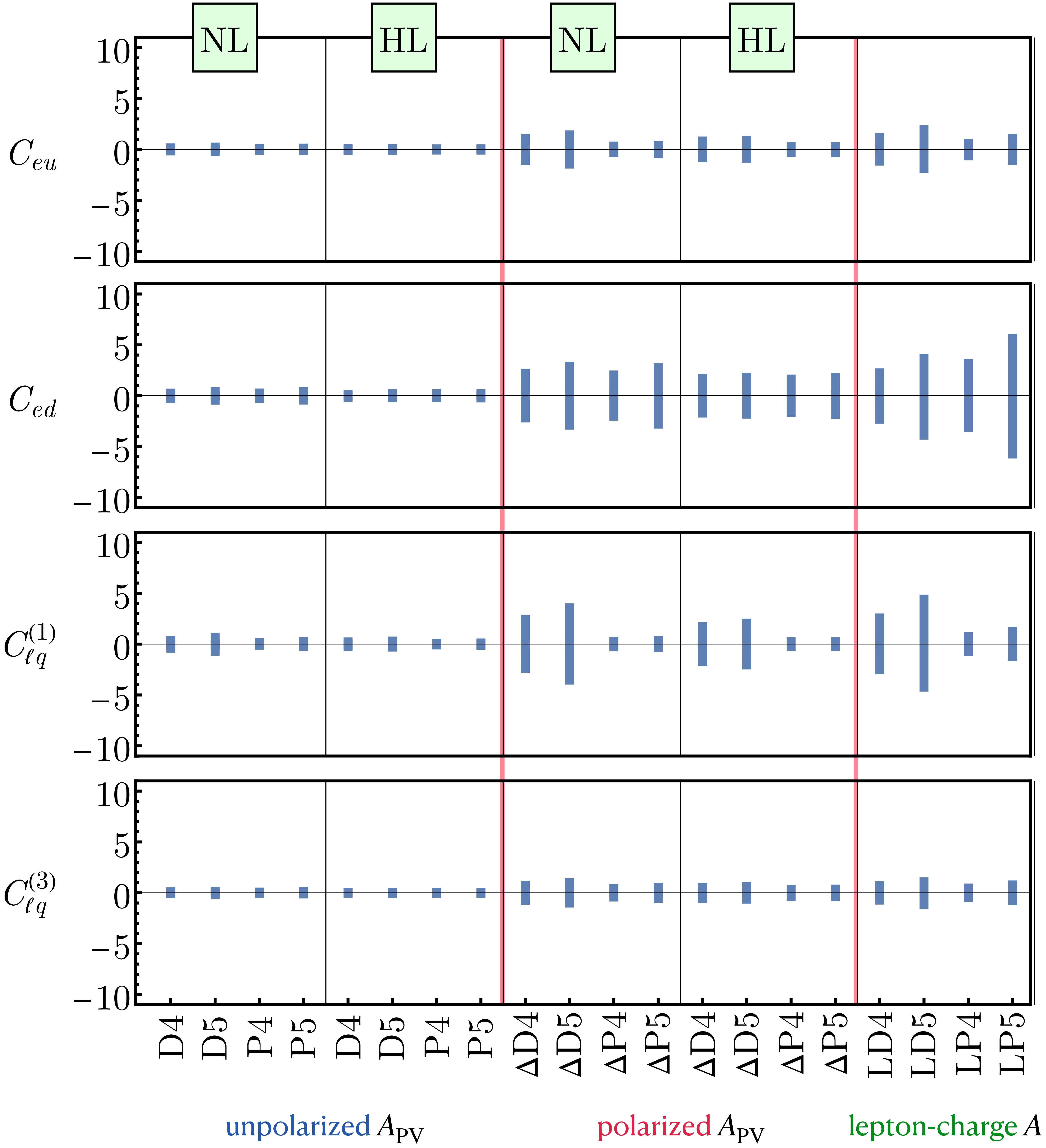
SMEFT fit results

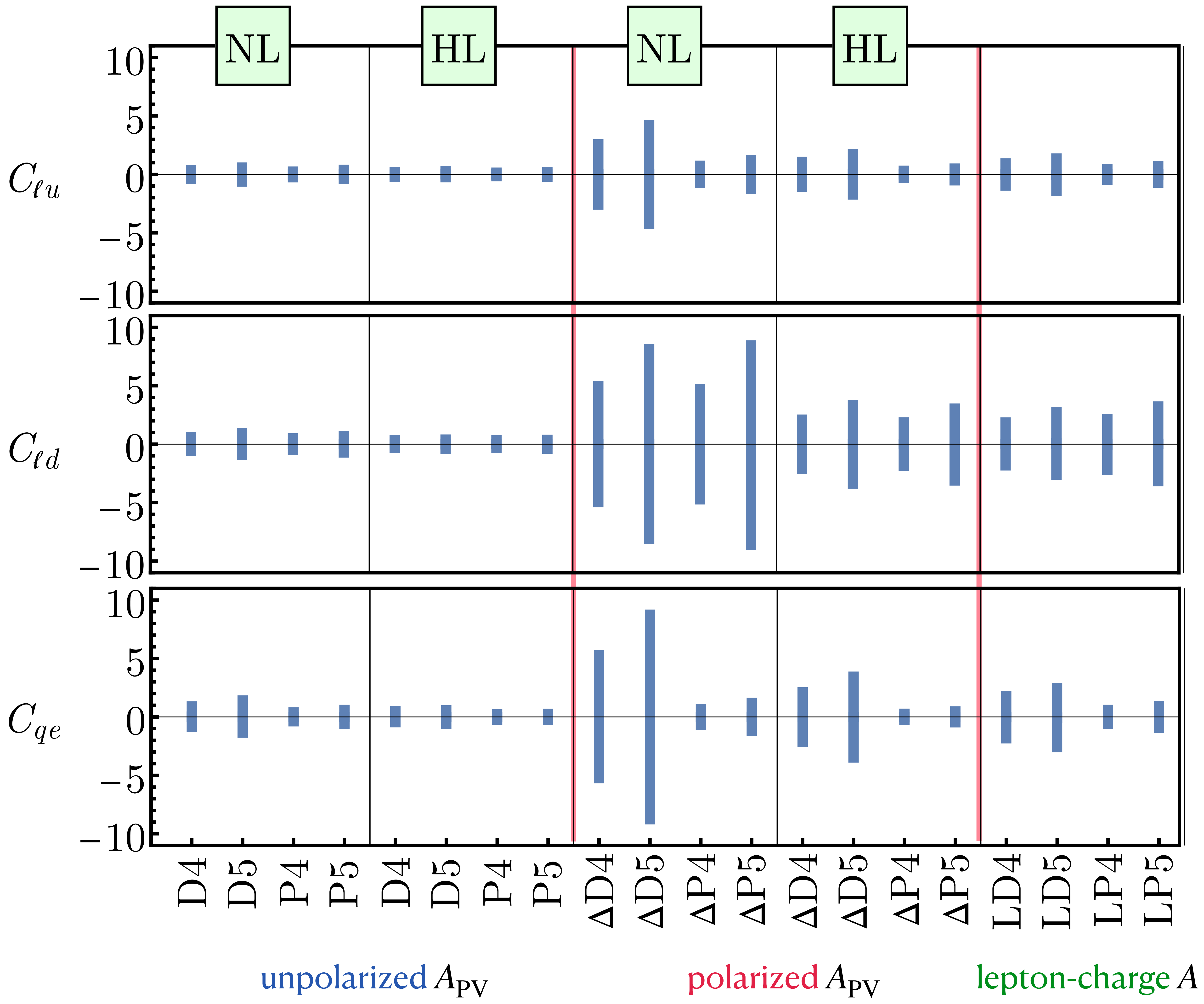
Single Wilson coefficients



Single Wilson coefficients







Comments:

- 95 % CL
- $\Lambda = 1$ TeV
- A_{PV} fits with beam polarization

Double Wilson coefficients

	C_{eu}	C_{ed}	$C_{\ell q}^{(1)}$	$C_{\ell q}^{(3)}$	$C_{\ell u}$	$C_{\ell d}$	C_{qe}
C_{eu}	1.00	0.71	0.98	−0.97	0.27	−0.09	−0.38
C_{ed}	0.71	1.00	−0.56	0.85	−0.49	0.69	0.21
$C_{\ell q}^{(1)}$	0.98	−0.56	1.00	0.91	−0.26	−0.07	0.47
$C_{\ell q}^{(3)}$	−0.97	0.85	0.91	1.00	0.40	−0.29	−0.40
$C_{\ell u}$	0.27	−0.49	−0.26	0.40	1.00	0.74	0.85
$C_{\ell d}$	−0.09	0.69	−0.07	−0.29	0.74	1.00	−0.29
C_{qe}	−0.38	0.21	0.47	−0.40	0.85	−0.29	1.00

P4 (NL)

	C_{eu}	C_{ed}	$C_{\ell q}^{(1)}$	$C_{\ell q}^{(3)}$	$C_{\ell u}$	$C_{\ell d}$	C_{qe}
C_{eu}	1.00	0.99	0.99	−1.00	0.54	−0.53	−0.58
C_{ed}	0.99	1.00	−0.97	1.00	−0.59	0.60	0.59
$C_{\ell q}^{(1)}$	0.99	−0.97	1.00	0.99	−0.60	0.56	0.67
$C_{\ell q}^{(3)}$	−1.00	1.00	0.99	1.00	0.60	−0.59	−0.61
$C_{\ell u}$	0.54	−0.59	−0.60	0.60	1.00	0.98	0.94
$C_{\ell d}$	−0.53	0.60	0.56	−0.59	0.98	1.00	−0.86
C_{qe}	−0.58	0.59	0.67	−0.61	0.94	−0.86	1.00

D4 (NL)

Double Wilson coefficients

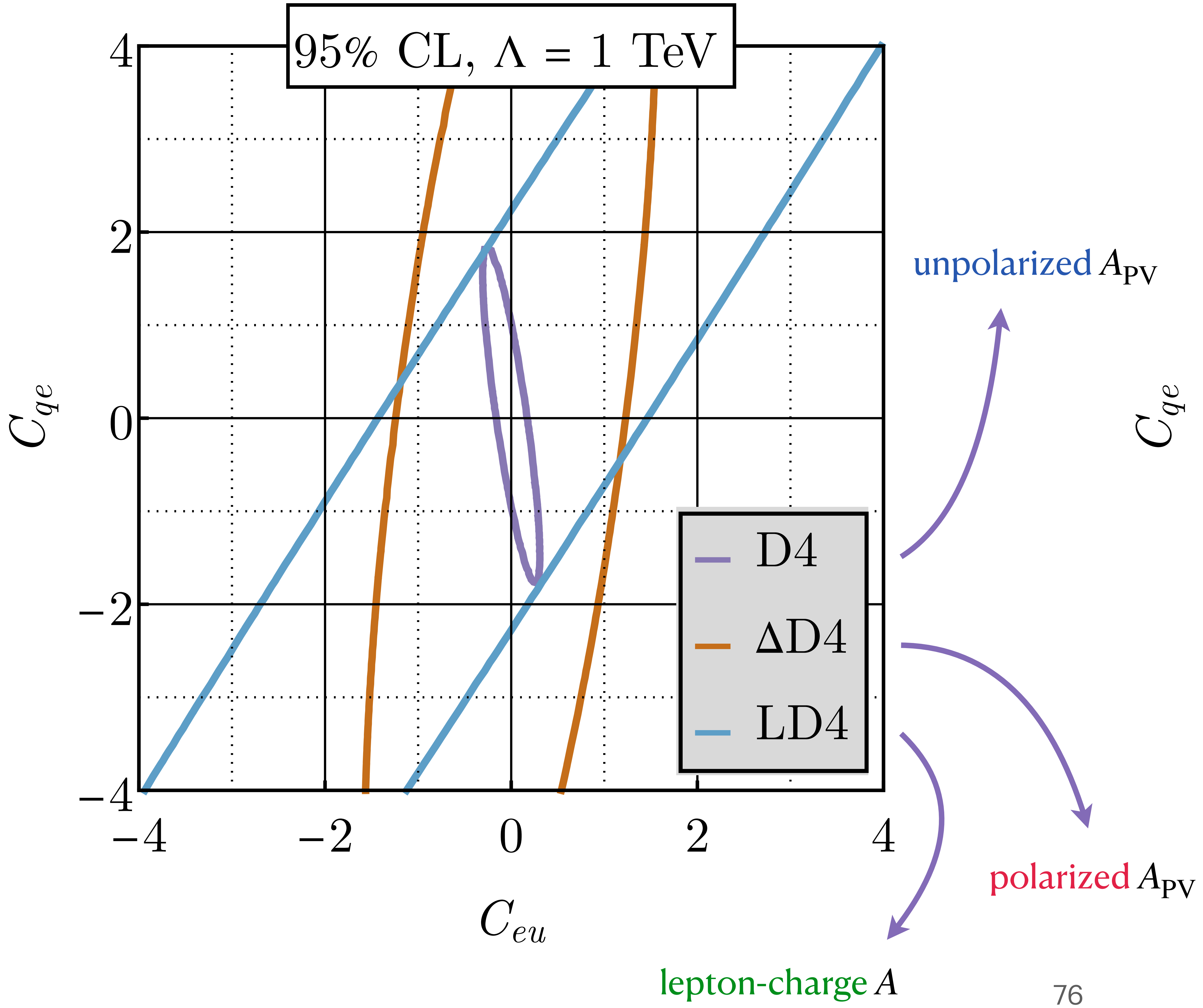
	C_{eu}	C_{ed}	$C_{\ell q}^{(1)}$	$C_{\ell q}^{(3)}$	$C_{\ell u}$	$C_{\ell d}$	C_{qe}
C_{eu}	1.00	−0.98	1.00	−1.00	−0.52	−0.28	0.48
C_{ed}	−0.98	1.00	0.98	−0.98	−0.55	−0.27	0.50
$C_{\ell q}^{(1)}$	1.00	0.98	1.00	1.00	0.51	0.26	−0.47
$C_{\ell q}^{(3)}$	−1.00	−0.98	1.00	1.00	−0.57	−0.34	0.53
$C_{\ell u}$	−0.52	−0.55	0.51	−0.57	1.00	−0.94	1.00
$C_{\ell d}$	−0.28	−0.27	0.26	−0.34	−0.94	1.00	0.96
C_{qe}	0.48	0.50	−0.47	0.53	1.00	0.96	1.00

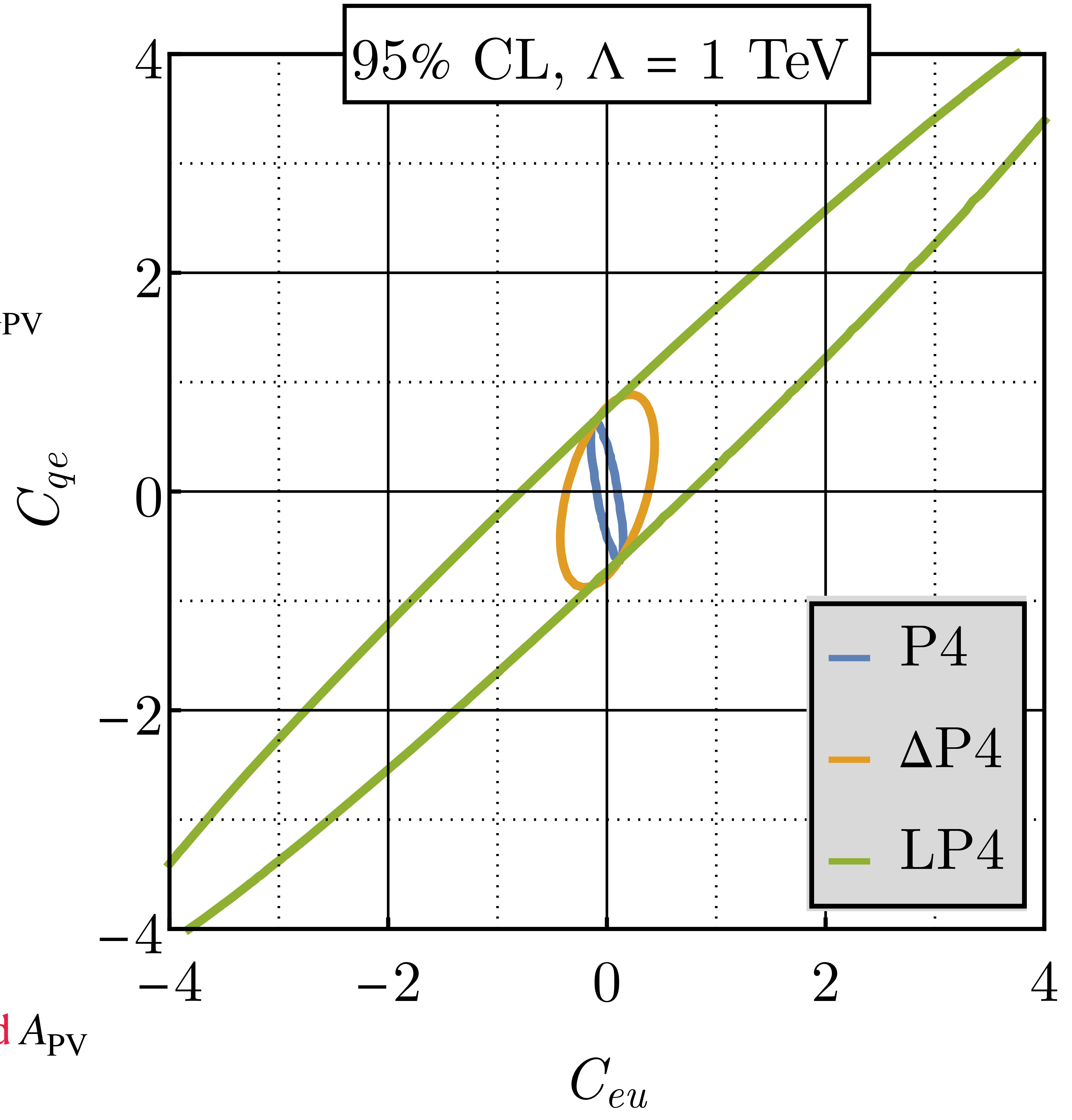
ΔP4 (NL)

	C_{eu}	C_{ed}	$C_{\ell q}^{(1)}$	$C_{\ell q}^{(3)}$	$C_{\ell u}$	$C_{\ell d}$	C_{qe}
C_{eu}	1.00	1.00	0.99	−1.00	−0.65	0.68	0.61
C_{ed}	1.00	1.00	−0.98	1.00	0.65	−0.67	−0.61
$C_{\ell q}^{(1)}$	0.99	−0.98	1.00	0.99	0.73	−0.76	−0.68
$C_{\ell q}^{(3)}$	−1.00	1.00	0.99	1.00	−0.69	0.71	0.64
$C_{\ell u}$	−0.65	0.65	0.73	−0.69	1.00	0.99	0.99
$C_{\ell d}$	0.68	−0.67	−0.76	0.71	0.99	1.00	−0.98
C_{qe}	0.61	−0.61	−0.68	0.64	0.99	−0.98	1.00

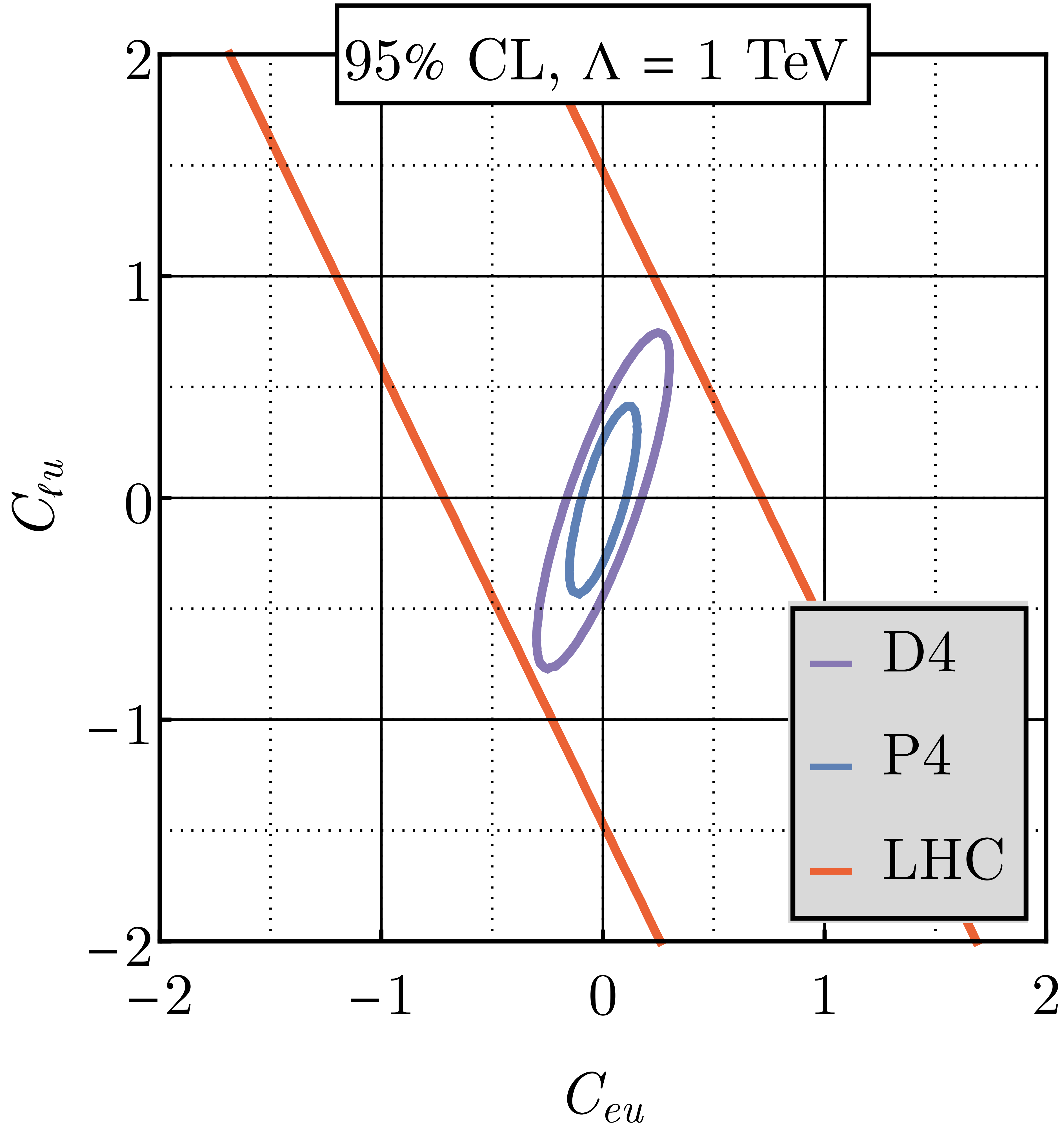
ΔD4 (NL)

Double Wilson coefficients





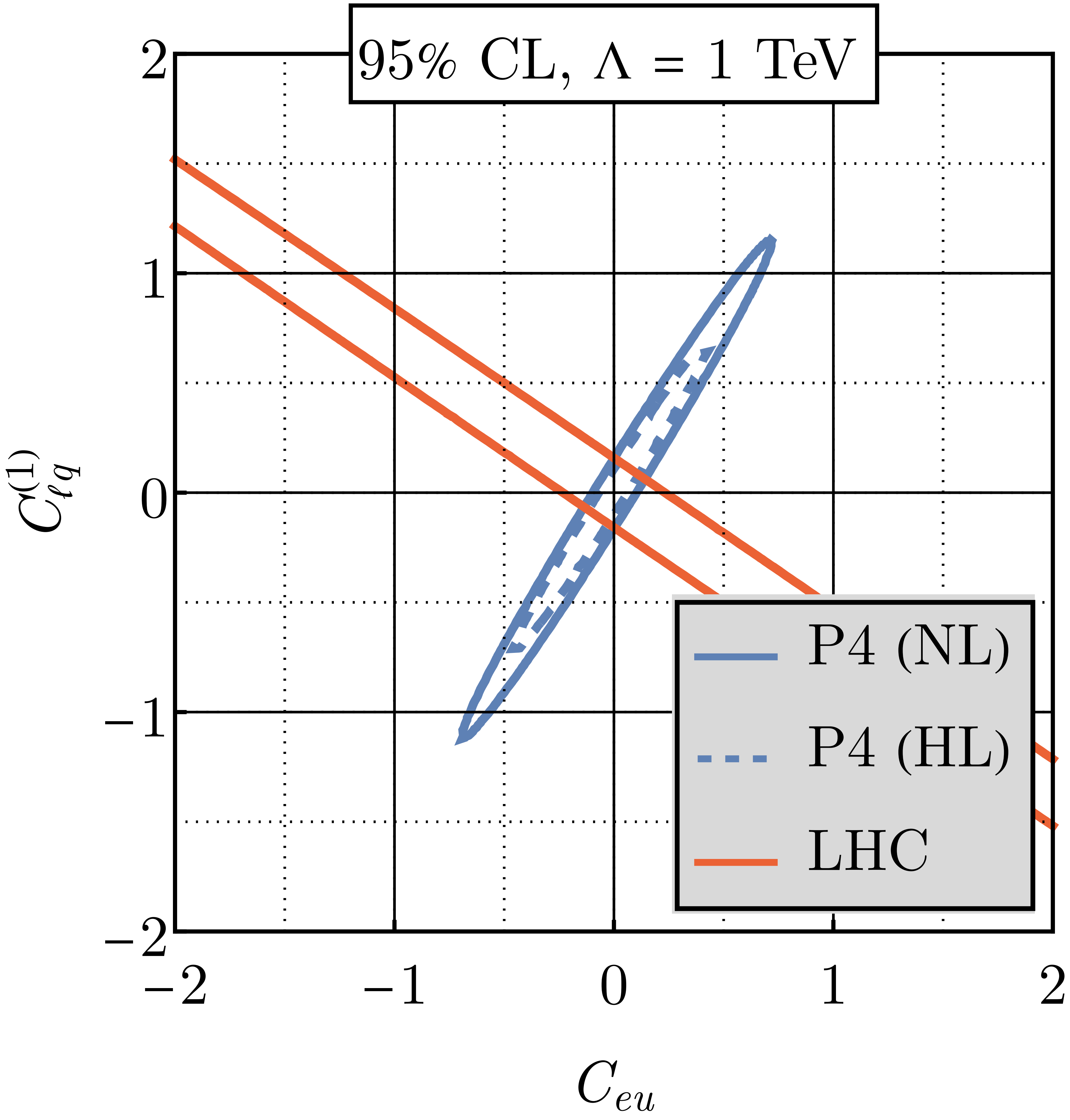
Double Wilson coefficients



LHC Drell-Yan adapted from
RB, FP, DW 2104.03979

LHC: 8 TeV and 20 fb^{-1}
not 13 TeV and HL

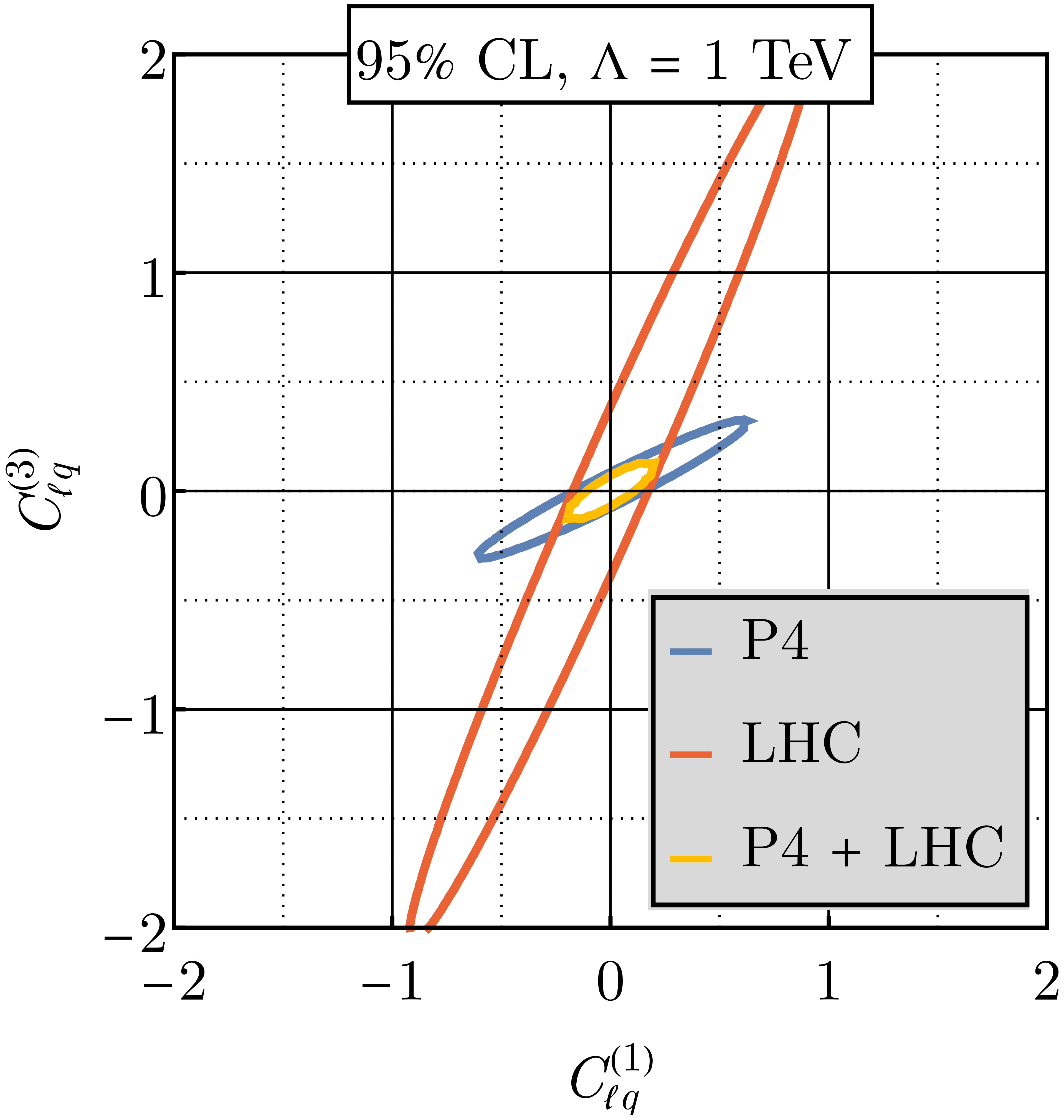
Double Wilson coefficients



LHC Drell-Yan adapted from
RB, FP, DW 2004.00748

LHC: 8 TeV and 20 fb^{-1}
not 13 TeV and HL

Double Wilson coefficients



LHC Drell-Yan adapted from
RB, FP, DW 2004.00748

LHC: 8 TeV and 20 fb^{-1}
not 13 TeV and HL

Summary of SMEFT fits

- Bound strength: proton > deuteron
- Bound strength: unpolarized A_{PV} > polarized A_{PV} > lepton-charge A
- All distinct correlations
- Complementary to LHC
- Flat directions in LHC Drell-Yan resolved by EIC
- Even stronger bounds by EIC than LHC

Conclusion

Philosophy and methodology

- BSM potential of EIC
- Model-independent SMEFT framework
- Semi-leptonic four-fermion operator sector
- Detailed accounting of anticipated uncertainties
- Simultaneous fits of Wilson coefficients with beam polarization and luminosity difference

Findings

- UV scales > 3 TeV with nominal annual luminosity
- UV scales > 4 TeV with $10 \times$ luminosity upgrade
- Strongest bounds from polarized electron + unpolarized proton scattering
- Complementary and competitive to LHC: EIC can
  - resolve degeneracies
  - impose even stronger bounds

EIC: designed as a QCD machine, also a powerful probe of BSM

The End