Dimension-8 SMEFT Effects in the Drell-Yan process

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In collaboration with:

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Northwestern University

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May 13th @ LoopFest XX

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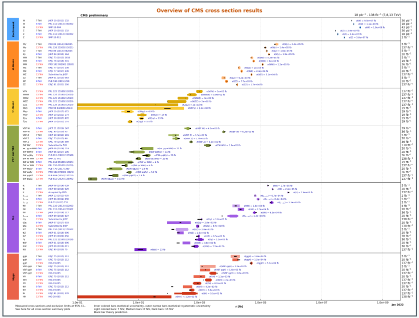
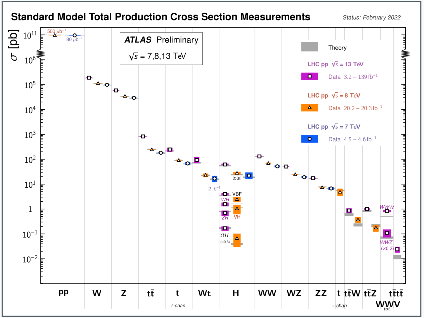
Introduction

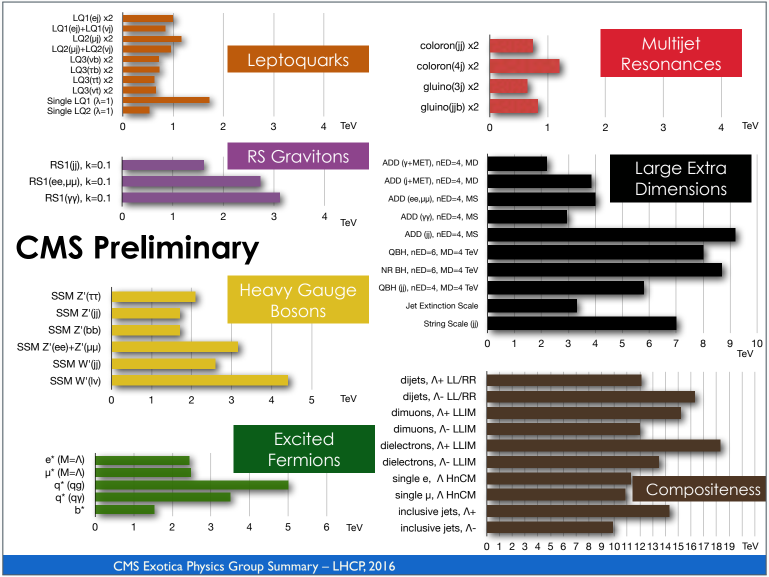
Examples:





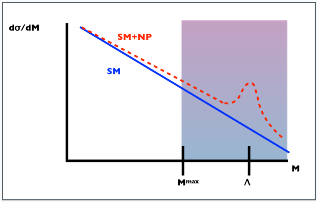
Remarkable agreement between theory predictions and the experiment measurements!

BSM SEARCHES



SMEFT a model-independent approach

- No BSM particle found
- Calls for precision test of SM



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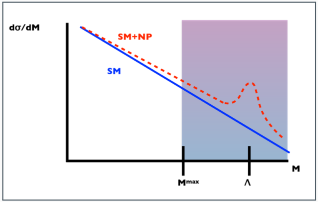

- Standard Model Effective Field Theory (SMEFT)
  - SM particles
  - all possible operators satisfying symmetries of the SM
  - power counting: new physics scale Λ

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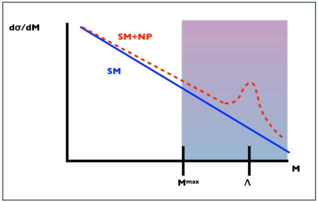

- Standard Model Effective Field Theory (SMEFT)
  - SM particles
  - all possible operators satisfying symmetries of the SM
  - power counting: new physics scale Λ

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \boxed{\frac{1}{\Lambda^2}\sum C_6\mathcal{O}_6} + \boxed{\frac{1}{\Lambda^4}\sum C_8\mathcal{O}_8} + \cdots$$

  - No odd dimensions in this talk
  - ▶ $\mathcal{L}_6$: 76 B-preserving Lagrangian terms, 2499 parameters **Grzadkowski et al. 2010**
  - ▶ $\mathcal{L}_8$: 1031 Lagrangian terms, 44807 parameters **Murphy 2020; Li et al. 2021**
- No specific model needed

SMEFT a model-independent approach

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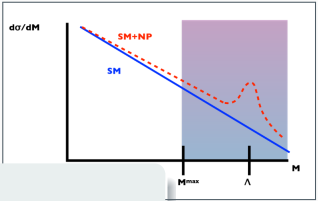

In this talk:

Warsaw basis for dimension-6

Murphy's basis for dimension-8

- Standard M
  - SM par
  - all pos
  - power

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \boxed{\frac{1}{\Lambda^2}\sum C_6 \mathcal{O}_6} + \boxed{\frac{1}{\Lambda^4}\sum C_8 \mathcal{O}_8} + \cdots$$

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- No specific model needed

Motivation for the inclusion of dimension-8 operators

- How important are the dim-8 effects at LHC?

- How sensitive are current fits to the dim-8 effects?

Sally Dawson's talk

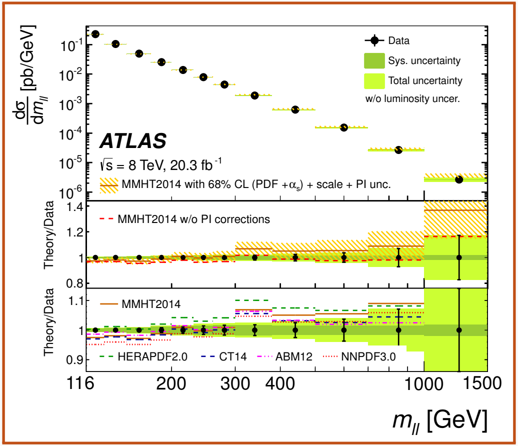
We'll investigate those questions using LHC Drell-Yan data as an example:

- dilepton invariant mass spectrum **Boughezal, Mereghetti and Petriello, 2106.05337**
- dilepton double differential cross section (m_{ll} and p_T)
  will address as p_T spectra in this talk **Boughezal YH, and Petriello to appear**

Dilepton invariant mass spectra

EXPERIMENTAL MEASUREMENTS 1606.01736

- Probe high m_{ll} up to 1.5 TeV
- 12 m_{ll} bins: [116,130,150,175,200, 230,260,300,380,500, 700,1000,1500]



Relevant operators dimension-6

- Study scaling of cross sections in high energy limit
- Only show some examples for each category
- q, l: left-handed fermion doublets
  e, u, d: right-handed fermion singlets
  ϕ: Higgs doublet

$\mathcal{L}_{\psi^2 X^2 \phi}$

$$\frac{C_{eB}}{\Lambda^2}\bar{l}\sigma^{\mu\nu}B_{\mu\nu}\phi e$$

$$\frac{C_{uW}}{\Lambda^2}\bar{q}\sigma^{\mu\nu}\tau^I W^I_{\mu\nu}\phi u$$

Dipole coupling

assume massless fermion

$\sim \mathcal{O}(v^2 s/\Lambda^4)$

$\mathcal{L}_{\psi^2 \phi^2 D}$

$$\frac{C^{(1)}_{Hl}}{\Lambda^2}\phi^\dagger \overleftrightarrow{D}^\mu \phi \bar{l}\gamma_\mu l$$

$$\frac{C_{Hu}}{\Lambda^2}\phi^\dagger \overleftrightarrow{D}^\mu \phi \bar{u}\gamma_\mu u$$

Z-vertex corrections

$\sim \mathcal{O}(v^2/\Lambda^2)$

$\mathcal{L}_{\psi^4}$

$$\frac{C^{(1)}_{lq}}{\Lambda^2}\bar{l}\gamma^\mu l q\gamma_\mu q$$

$$\frac{C_{ld}}{\Lambda^2}\bar{l}\gamma^\mu l d\gamma_\mu d$$

Four-fermion interactions

$\sim \mathcal{O}(s/\Lambda^2)$

Relevant operators dimension-6

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$\mathcal{L}_{\psi^2 X^2 \phi}$	$\mathcal{L}_{\psi^2 \phi^2 D}$	$\mathcal{L}_{\psi^4}$
$\frac{C_{eB}}{\Lambda^2}\bar{l}\sigma^{\mu\nu}B_{\mu\nu}\phi e$	$\frac{C_{Hl}^{(1)}}{\Lambda^2}\phi^\dagger \overleftrightarrow{D}^{\mu}\phi\bar{l}\gamma_\mu l$	$\frac{C_{lq}^{(1)}}{\Lambda^2}\bar{l}\gamma^\mu l q\gamma_\mu q$
$\frac{C_{uW}}{\Lambda^2}\bar{q}\sigma^{\mu\nu}\tau^I W^I_{\mu\nu}\phi u$	$\frac{C_{Hu}}{\Lambda^2}\phi^\dagger \overleftrightarrow{D}^{\mu}\phi\bar{u}\gamma_\mu u$	$\frac{C_{ld}}{\Lambda^2}\bar{l}\gamma^\mu l d\gamma_\mu d$
Dipole coupling	Z-vertex corrections	Four-fermion interactions
assume massless fermion		
$\sim \mathcal{O}(v^2 s/\Lambda^4)$	$\sim \mathcal{O}(v^2/\Lambda^2)$	$\sim \mathcal{O}(s/\Lambda^2)$

Relevant operators dimension-8 four-fermion

- Study scaling of cross sections in high energy limit
- Only show some examples for each category
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$\mathcal{L}_{\psi^4 D^2}$

$$\frac{C^{(1)}_{l^2 q^2 D^2}}{\Lambda^4} \partial_\nu \left(\bar{l}\gamma^\mu l\right) \partial^\nu \left(\bar{q}\gamma_\mu q\right)$$

$$\frac{C^{(1)}_{l^2 d^2 D^2}}{\Lambda^4} \partial_\nu \left(\bar{l}\gamma^\mu l\right) \partial^\nu \left(\bar{d}\gamma_\mu d\right)$$

Momentum-dependent four-fermion interactions

$$\sim \mathcal{O}(s^2/\Lambda^4)$$

$\mathcal{L}_{\psi^4 H^2}$

$$\frac{C^{(1)}_{l^2 q^2 H^2}}{\Lambda^4} \left(\bar{l}\gamma^\mu l\right) \left(\bar{q}\gamma_\mu q\right) \phi^\dagger \phi$$

$$\frac{C^{(1)}_{l^2 d^2 H^2}}{\Lambda^4} \left(\bar{l}\gamma^\mu l\right) \left(\bar{d}\gamma_\mu d\right) \phi^\dagger \phi$$

Momentum-independent four-fermion interactions

$$\sim \mathcal{O}(v^2 s/\Lambda^4)$$

RELEVANT OPERATORS dimension-8 four-fermion

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$\mathcal{L}_{\psi^4 D^2}$

$$\frac{C^{(2)}_{l^2 q^2 D^2}}{\Lambda^4} \bar{q}\gamma^{(\mu} \overleftrightarrow{D}^{\nu)} q \bar{l}\gamma_{(\mu} \overleftrightarrow{D}_{\nu)} l$$

$$\frac{C^{(2)}_{l^2 d^2 D^2}}{\Lambda^4} \bar{q}\gamma^{(\mu} \overleftrightarrow{D}^{\nu)} q \bar{d}\gamma_{(\mu} \overleftrightarrow{D}_{\nu)} d$$

Momentum-dependent four-fermion interactions

$\sim \mathcal{O}(s^2/\Lambda^4)$

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$$\frac{C^{(1)}_{l^2 q^2 H^2}}{\Lambda^4} \left(\bar{l}\gamma^\mu l\right)\left(\bar{q}\gamma_\mu q\right)\phi^\dagger\phi$$

$$\frac{C^{(1)}_{l^2 d^2 H^2}}{\Lambda^4} \left(\bar{l}\gamma^\mu l\right)\left(\bar{d}\gamma_\mu d\right)\phi^\dagger\phi$$

Momentum-independent four-fermion interactions

$\sim \mathcal{O}(v^2 s/\Lambda^4)$

$\gamma^{(\mu} \overleftrightarrow{D}^{\nu)} = \left(\gamma^\mu \overleftrightarrow{D}^\nu + \gamma^\nu \overleftrightarrow{D}^\mu\right)$

- Study scaling of cross sections in high energy limit, only highest in s
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$$\frac{C^{(1)}_{l^2 q^2 H^2}}{\Lambda^4} \left(\bar{l}\gamma^{\mu} l\right)\left(\bar{q}\gamma_{\mu} q\right)\phi^{\dagger}\phi$$

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$\mathcal{L}_{\psi^2 D^3}$

$$\frac{C^{(1)}_{l^2 H^2 D^3}}{\Lambda^4} i\bar{l}\gamma^\mu D^\nu l \left(D_{(\mu} D_{\nu)}\phi\right)^\dagger \phi$$

$$\frac{C^{(3)}_{q^2 H^2 D^3}}{\Lambda^4} i\bar{q}\gamma^\mu \tau^I D^\nu q \left(D_{(\mu} D_{\nu)}\phi\right)^\dagger \tau^I \phi$$

Momentum-dependent Z-vertex corrections

$$\sim \mathcal{O}(v^2 s/\Lambda^4)$$

$\mathcal{L}_{\psi^2 H^4 D}$

$$\frac{C^{(1)}_{l^2 H^4 D}}{\Lambda^4} i\left(\bar{l}\gamma^\mu l\right)\left(\phi^\dagger \overleftrightarrow{D}_\mu \phi\right)\left(\phi^\dagger \phi\right)$$

$$\frac{C^{(1)}_{u^2 H^4 D}}{\Lambda^4} i\left(\bar{u}\gamma^\mu u\right)\left(\phi^\dagger \overleftrightarrow{D}_\mu \phi\right)\left(\phi^\dagger \phi\right)$$

Momentum-independent Z-vertex corrections

$$\sim \mathcal{O}(v^4/\Lambda^4)$$

Relevant operators dimension-8 Z-vertex corrections

- Study scaling of cross sections in high energy limit, only highest in s
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$\mathcal{L}_{\psi^2 D^3}$

$$\frac{C^{(1)}_{l^2 H^2 D^3}}{\Lambda^4} i\bar{l}\gamma^\mu D^\nu l \left(D_{(\mu} D_{\nu)}\phi\right)^\dagger \phi$$

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Momentum-independent Z-vertex corrections

$$\sim \mathcal{O}(v^4/\Lambda^4)$$

SMEFT CROSS SECTIONS

Structure of the SMEFT cross section

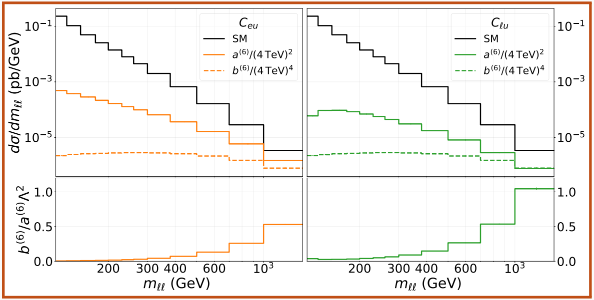
$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\ell\ell}} = \frac{\mathrm{d}\sigma_{\mathrm{SM}}}{\mathrm{d}m_{\ell\ell}} + \sum_i \left(\frac{a_i^{(6)}(m_{\ell\ell})}{\Lambda^2} C_i^{(6)} + \frac{a_i^{(8)}(m_{\ell\ell})}{\Lambda^4} C_i^{(8)} \right) + \sum_{i,} \frac{b_{ij}^{(6)}(m_{\ell\ell})}{\Lambda^4} C_i^{(6)} C_j^{(6)}$$

- a_i, b_{ij} terms: NLO QCD corrections included (30%)
- SM: NNLO in QCD, NLL Sudakov logs through $\mathcal{O}(\alpha_s)$
- $\Lambda = 4\ \mathrm{TeV} \gg 1.5\ \mathrm{TeV}$ (the m_{ll} upper bound of the dataset)
- Complete to $\mathcal{O}(\alpha_s/\Lambda^2)$
  Complete to $\mathcal{O}(1/\Lambda^4)$
  at $\mathcal{O}(\alpha_s/\Lambda^4)$: missing $\psi^4 G$-type operators

Boughezal, Mereghetti and Petriello
2106.05337

- $\Lambda = 4$ TeV
- $s/\Lambda^2 \ll 1$

- Four-fermion operators: C_{eu}, C_{lu}
- Consider linear a_i terms $(1/\Lambda^2)$ and quadratic b_{ii} terms $(1/\Lambda^4)$



- Quadratic terms: 50% (C_{eu}) or 100% (C_{lu}) in $1 - 1.5$ TeV bin

IMPACT OF DIM-8 TERMS to the cross sections

Boughezal, Mereghetti and Petriello
2106.05337

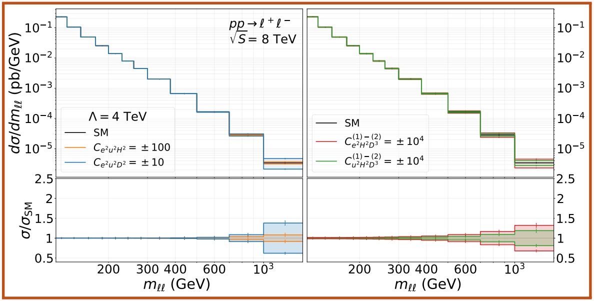
- $\Lambda = 4\ \mathrm{TeV}$
- $s/\Lambda^2 \ll 1$

- $\psi^4 D^2$-type: $C_{e^2u^2D^2}$

  $\psi^4 H^2$-type: $C_{e^2u^2H^2}$

  $\psi^2 D^3$-type:

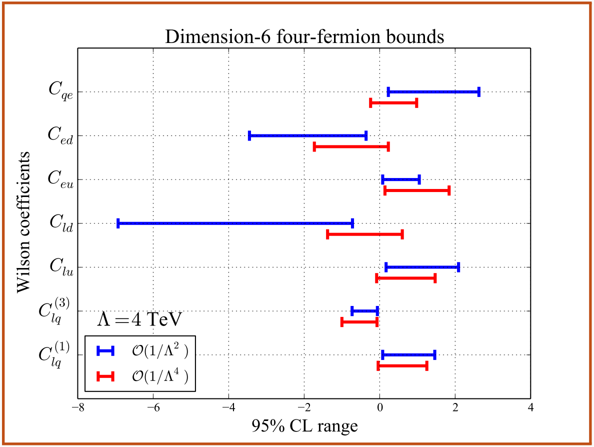
  $C_{e^2H^2D^3}$, $C_{u^2H^2D^3}$



- $\psi^4 D^2$-type: can reach 50%
- $\psi^4 H^2$-type: much smaller
- $\psi^2 D^3$-type: negligible unless Wilson coefficients go unrealistically large

Boughezal, Mereghetti and Petriello
2106.05337

- Turn on one coupling at a time
- Experimental error matrix; **1606.01736** NNPDF 3.1 PDF errors; NLO QCD scale variation errors

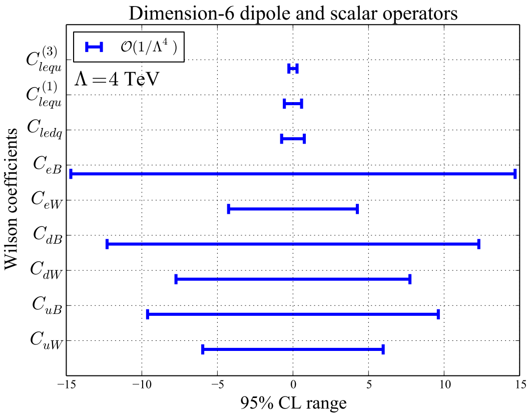


- effective scale $\Lambda/\sqrt{C} \sim 4\ \mathrm{TeV} \gg 1.5\ \mathrm{TeV}$
- Large shift from $\mathcal{O}(1/\Lambda^4)$ effects: factors of 2-3 for C_{qe}, C_{ld}

SINGLE-COUPLING FITS dim-6 dipole & scalar

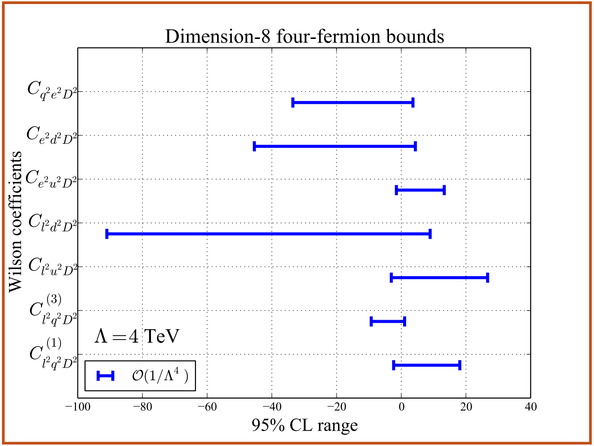
Boughezal, Mereghetti and Petriello
2106.05337

- Turn on one coupling at a time
- Experimental error matrix; **1606.01736** NNPDF 3.1 PDF errors; NLO QCD scale variation errors
- dim-6 dipole and scalar do not interfere with SM; first contribute at $\mathcal{O}(1/\Lambda^4)$



- dipole operators scale as $\mathcal{O}(v^2 s/\Lambda^4)$: looser bound
- scalar/tensor 4-fermion operators scale as $\mathcal{O}(s^2/\Lambda^4)$: tighter bound
- effective scale $\Lambda/\sqrt{C} \sim (1.0 - 1.8)$ TeV for dipole operators
- effective scale $\Lambda/\sqrt{C} \sim (4.6 - 7.7)$ TeV for scalar operators

- Turn on one coupling at a time
- Experimental error matrix; **1606.01736** NNPDF 3.1 PDF errors; NLO QCD scale variation errors



- effective scale $\Lambda/\sqrt[4]{C}$: reach $2\ \mathrm{TeV}$ for some operators
- scale as $\mathcal{O}(s^2/\Lambda^4)\Rightarrow$non-negligible effects in fits to current data

SINGLE-COUPLING FITS dim-8 H^2 four-fermion

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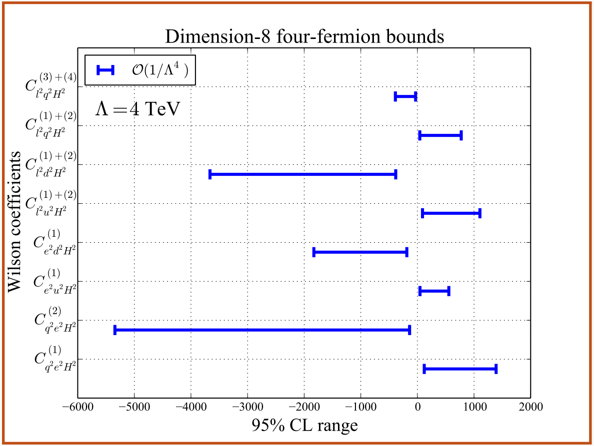
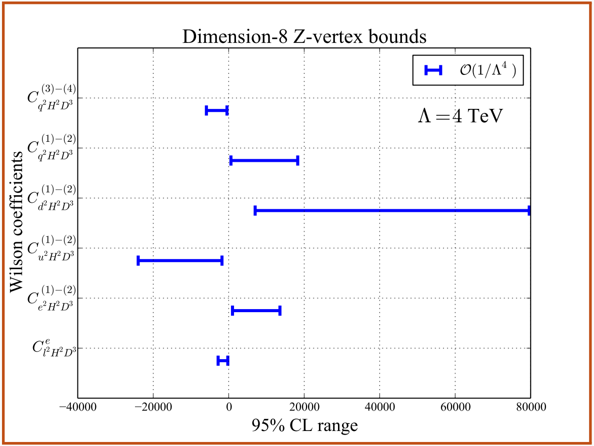
- Turn on one coupling at a time
- Experimental error matrix; **1606.01736** NNPDF 3.1 PDF errors; NLO QCD scale variation errors



- effective scale: below $1\ \mathrm{TeV}$ for most
- can neglect

 Boughezal, Mereghetti and Petriello 2106.05337

- Turn on one coupling at a time
- Experimental error matrix; **1606.01736** NNPDF 3.1 PDF errors; NLO QCD scale variation errors



- effective scale: even lower than $\psi^4 H^2$-type four-fermion
- can neglect

MULTI-COUPLING FITS

Boughezal, Mereghetti and Petriello
2106.05337

	dim-6	single coupling	marginalized	marginalized*
C_{eu}	$[\mathbf{0.08}, \mathbf{1.0}]$	$[\mathbf{0.1}, \mathbf{1.8}]$	$[-39, 39]$	$[\mathbf{-0.6}, \mathbf{2.4}]$
$C_{e^2u^2D^2}$	–	$[-1.5, 13]$	$[-17, 9.2 \cdot 10^3]$	$[-14, 18]$
$C_{e^2u^2H^2}$	–	$[45, 555]$	$[-1.9, 1.2] \cdot 10^4$	$[-256, 256]$
$C^{(1)-(2)}_{u^2H^2D^3}$	–	$[-24, -1.8] \cdot 10^3$	$[-1.2, 1.8] \cdot 10^5$	$[-256, 256]$

- dim-6: Turn on one coupling at a time, only include $\mathcal{O}(1/\Lambda^2)$
- single coupling: Turn on one coupling at a time, include $\mathcal{O}(1/\Lambda^4)$
- marginalized: Turn on all couplings
- marginalized*: Turn on all couplings, and demand effective scale greater than $1\ \mathrm{TeV}$ for last two operators

Bounds on dim-6 Wilson coefficient significantly weakened by turning on quadratic terms & dim-8 operators.

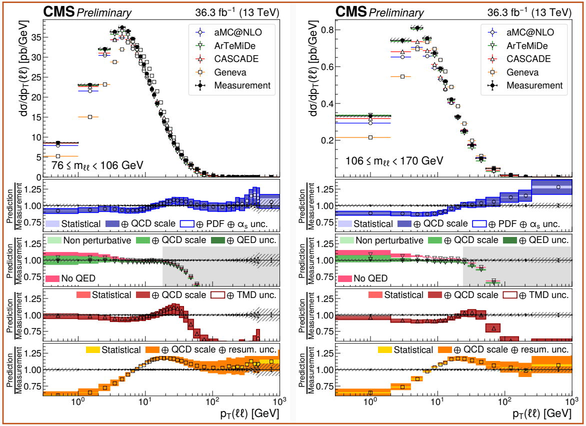
Dilepton mass-dependent p_T spectra

Boughezal, YH, and Petriello, to appear

Dilepton mass-dependent p_T spectra

with CMS data

- Drell-Yan double differential p_T spectra
- ~~$50 \leq m_{ll} < 76$ GeV~~
  $76 \leq m_{ll} < 106$ GeV
  $106 \leq m_{ll} < 170$ GeV
  $170 \leq m_{ll} < 350$ GeV
  $350 \leq m_{ll} < 1000$ GeV



- Drell-Yan double differential p_T spectra
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  $76 \leq m_{ll} < 106$ GeV
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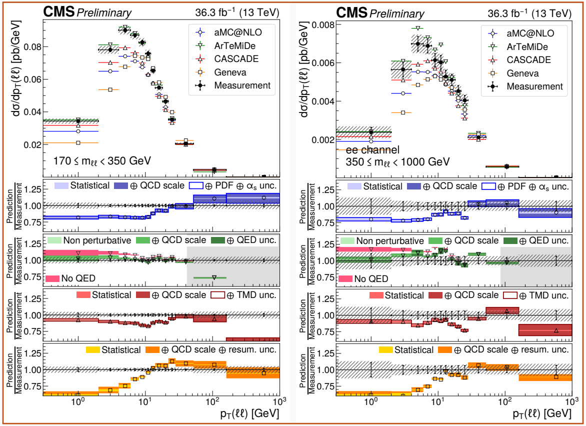
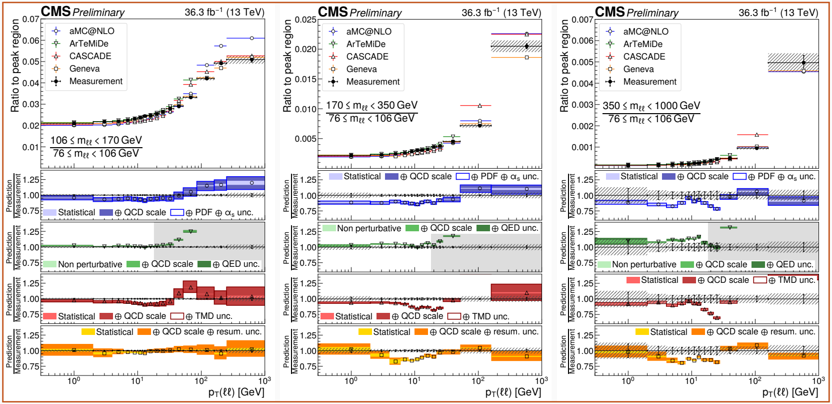


EXPERIMENTAL MEASUREMENTS ratio to peak region CMS-PAS-SMP-20-003



- Ratios of differential unfolded cross sections in $p_T(ll)$ for invariant mass ranges with respect to the peak region $76 \leq m_{ll} < 106$ GeV
- ~~$50 \leq m_{ll} < 76$ GeV~~ $106 \leq m_{ll} < 170$ GeV (left)
  $170 \leq m_{ll} < 350$ GeV (center) $350 \leq m_{ll} < 1000$ GeV (right)
- Smaller uncertainties than the cross sections
- We'll use the last 3 m_{ll} bins as the experimental dataset

Most relevant operators

- Study scaling of cross sections in high energy limit, only highest in s
- Only show some examples for each category
- q, l: left-handed fermion doublets

  e, u, d: right-handed fermion singlets

  ϕ: Higgs doublet, G: Gluon field strength tensor

$\mathcal{L}_{\psi^4}$	$\mathcal{L}_{\psi^4 D^2}$	$\mathcal{L}_{\psi^4 G}$
$\frac{C_{eu}}{\Lambda^2}(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$	$\frac{C^{(1)}_{e^2u^2D^2}}{\Lambda^4} D^\nu\,(\bar{e}\gamma^\mu e)\,D_\nu\,(\bar{u}\gamma_\mu u)$	$\frac{C^{(1)}_{e^2u^2G}}{\Lambda^4}\,(\bar{e}\gamma^\mu e)\,(\bar{u}\gamma^\nu T^a u)\,G^a_{\mu\nu}$
$\frac{C_{qe}}{\Lambda^2}(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$	$\frac{C^{(1)}_{q^2e^2D^2}}{\Lambda^4} D^\nu\,(\bar{q}\gamma^\mu q)\,D_\nu\,(\bar{e}\gamma_\mu e)$	$\frac{C^{(1)}_{l^2q^2G}}{\Lambda^4}\,(\bar{q}\gamma^\mu T^a q)\,(\bar{l}\gamma_\nu l)\,G^a_{\mu\nu}$
Four-fermion interactions	Momentum-dependent four-fermion interactions	Four-fermion interactions with gluon field strength tensor
$\sim \mathcal{O}(s/\Lambda^2)$	$\sim \mathcal{O}(s^2/\Lambda^4)$	$\sim \mathcal{O}(s^2/\Lambda^4)$

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  e, u, d: right-handed fermion singlets

  ϕ: Higgs doublet, G: Gluon field strength tensor

$\mathcal{L}_{\psi^4}$

$$\frac{C_{eu}}{\Lambda^2}(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$$
$$\frac{C_{qe}}{\Lambda^2}(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$$

Four-fermion interactions

$$\sim \mathcal{O}(s/\Lambda^2)$$

$\mathcal{L}_{\psi^4 D^2}$

$$\frac{C^{(2)}_{e^2u^2D^2}}{\Lambda^4}\left(\bar{e}\gamma^\mu \overleftrightarrow{D}^\nu e\right)\left(\bar{u}\gamma_\mu \overleftrightarrow{D}_\nu u\right)$$
$$\frac{C^{(2)}_{q^2e^2D^2}}{\Lambda^4}\left(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q\right)\left(\bar{e}\gamma_\mu \overleftrightarrow{D} D_\nu e\right)$$

Momentum-dependent four-fermion interactions

$$\sim \mathcal{O}(s^2/\Lambda^4)$$

$\mathcal{L}_{\psi^4 G}$

$$\frac{C^{(2)}_{e^2u^2G}}{\Lambda^4}(\bar{e}\gamma^\mu e)(\bar{u}\gamma^\nu T^a u)\,\tilde{G}^a_{\mu\nu}$$
$$\frac{C^{(2)}_{l^2q^2G}}{\Lambda^4}(\bar{q}\gamma^\mu T^a q)\left(\bar{l}\gamma_\nu l\right)\tilde{G}^a_{\mu\nu}$$

Four-fermion interactions with gluon field strength tensor

$$\sim \mathcal{O}(s^2/\Lambda^4)$$

$\gamma^{(\mu}\overleftrightarrow{D}^{\nu)} = \left(\gamma^\mu \overleftrightarrow{D}^\nu + \gamma^\nu \overleftrightarrow{D}^\mu\right)$, $\tilde{G}^a_{\mu\nu} = G^{\rho\sigma,a}\varepsilon_{\mu\nu\rho\sigma}$

Most relevant operators

- Study scaling of cross sections in high energy limit, only highest in s
- Only show some examples for each category
- q, l: left-handed fermion doublets

  e, u, d: right-handed fermion singlets

  ϕ: Higgs doublet, G: Gluon field strength tensor

Only consider $\psi^4 \tilde{G}$-type operators ($\psi^4 G$-type w/ $\tilde{G}$)

Do not consider $\psi^4 D^2$-type operators with $\overleftrightarrow{D}$ derivatives

(Discarding terms that vanish after intergrating over angular variables)

$$\frac{C_{qe}}{\Lambda^2}(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e) \qquad \frac{C_{q^2e^2D^2}}{\Lambda^4}\left(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q\right)\left(\bar{e}\gamma_\mu \overleftrightarrow{D} D_\nu e\right) \qquad \frac{C^{(2)}_{l^2q^2G}}{\Lambda^4}(\bar{q}\gamma^\mu T^a q)\left(\bar{l}\gamma_\nu l\right)\tilde{G}^a_{\mu\nu}$$

Four-fermion interactions	Momentum-dependent four-fermion interactions	Four-fermion interactions with gluon field strength tensor
$\sim \mathcal{O}(s/\Lambda^2)$	$\sim \mathcal{O}(s^2/\Lambda^4)$	$\sim \mathcal{O}(s^2/\Lambda^4)$

$\gamma^{(\mu}\overleftrightarrow{D}^{\nu)} = \left(\gamma^\mu \overleftrightarrow{D}^\nu + \gamma^\nu \overleftrightarrow{D}^\mu\right)$, $\tilde{G}^a_{\mu\nu} = G^{\rho\sigma,a}\varepsilon_{\mu\nu\rho\sigma}$

SMEFT CROSS SECTIONS

Structure of the SMEFT cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_T(\ell\ell)} = \frac{\mathrm{d}\sigma_{\mathrm{SM}}}{\mathrm{d}p_T} + \sum_i \left(\frac{a_i^{(6)}(p_T)}{\Lambda^2} C_i^{(6)} + \frac{a_i^{(8)}(p_T)}{\Lambda^4} C_i^{(8)} \right) + \sum_{i,} \frac{b_{ij}^{(6)}(p_T)}{\Lambda^4} C_i^{(6)} C_j^{(6)}$$

- Choose 3 operators (involving right-handed quarks and leptons) as example:

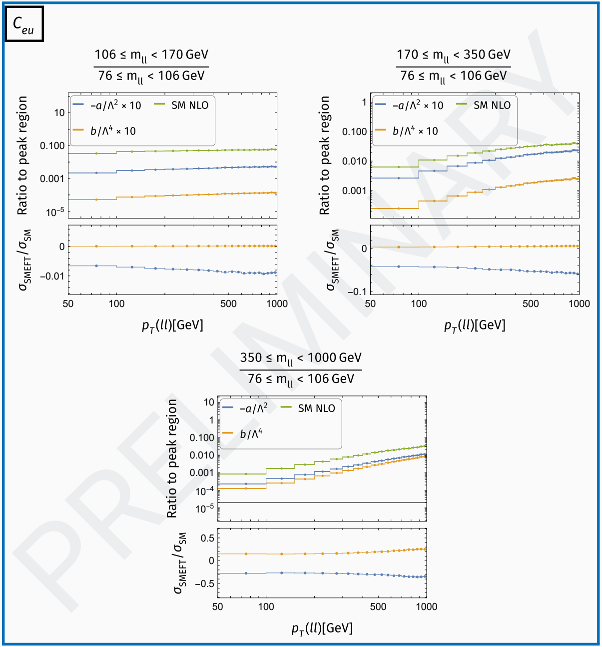
Q_{eu}: $\frac{C_{eu}}{\Lambda^2}(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$ $\Leftarrow$ dim-6

$$\left.\begin{array}{l} Q^{(1)}_{e^2u^2D^2}: \ \frac{C^{(1)}_{e^2u^2D^2}}{\Lambda^4} D^\nu\,(\bar{e}\gamma^\mu e)\, D_\nu\,(\bar{u}\gamma_\mu u) \\ Q^{(2)}_{e^2u^2G}: \ \frac{C^{(2)}_{e^2u^2G}}{\Lambda^4}\,(\bar{e}\gamma^\mu e)\,(\bar{u}\gamma^\nu T^a u)\,\tilde{G}^a_{\mu\nu} \end{array}\right\}\ \text{dim-8}$$

- SM: NLO QCD
- SMEFT corrections: LO
- $\Lambda = 2$ TeV

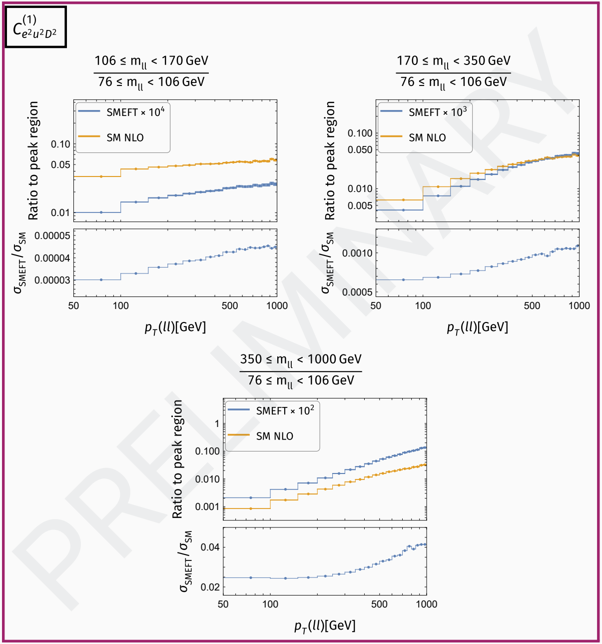
Impact of dim-6 terms

- p_T bins: 50 GeV constant bin widths
- Largest corrections to the ratio
- 10-30% for the highest m_{ll} bin
- Slowest increase as p_T goes higher



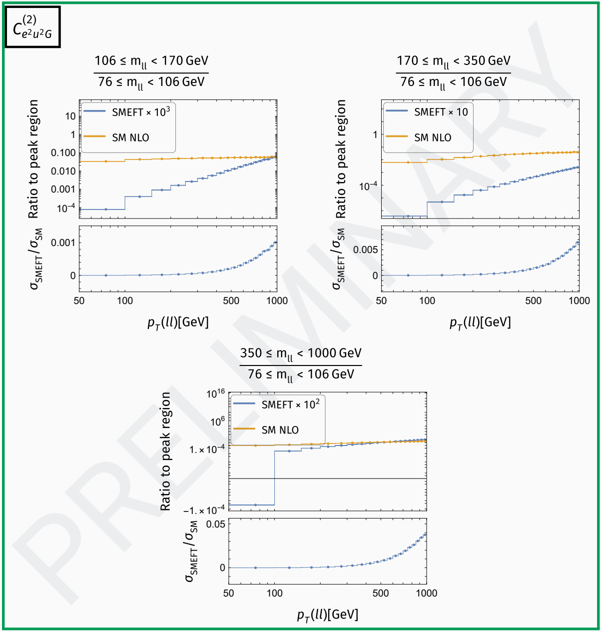
Impact of dim-8 terms $\psi^4 D^2$-type

- p_T bins: 50 GeV constant bin widths
- Smaller corrections to the ratio than dim-6
- Slower increase than $\psi^4 G$-type as p_T goes higher, but faster than dim-6



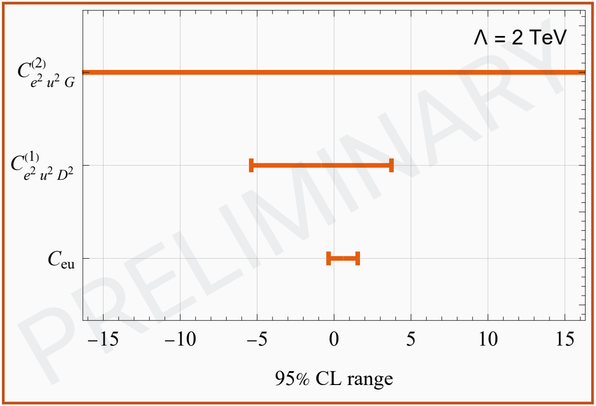
Impact of dim-8 terms $\psi^4 G$-type

- p_T bins: 50 GeV constant bin widths
- Smaller corrections to the ratio than dim-6
- Fastest increase as p_T goes higher



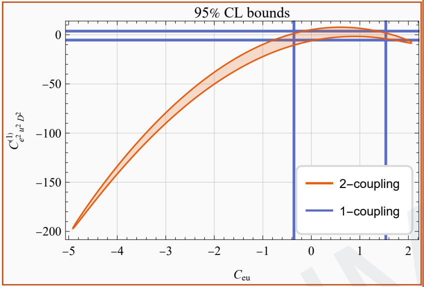
SINGLE-COUPLING FITS

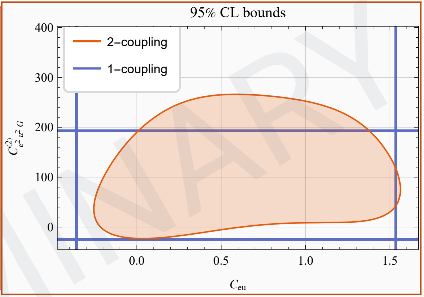
- Fit with CMS data
- Experimental error matrix;
  CMS-PAS-SMP-20-003
  NNPDF 3.1 PDF errors;
  SM NLO QCD +
  LO SMEFT corrections
  for scale variation errors
- Only includes bins with $p_T \geq 52$ GeV

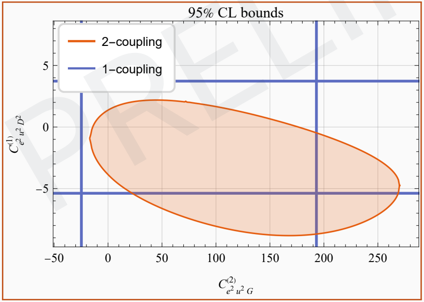


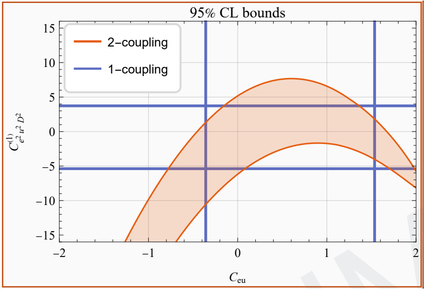
- effective scale $\gtrsim 1$ TeV $\Rightarrow |C_6| \leq 4$, $|C_8| \leq 16$

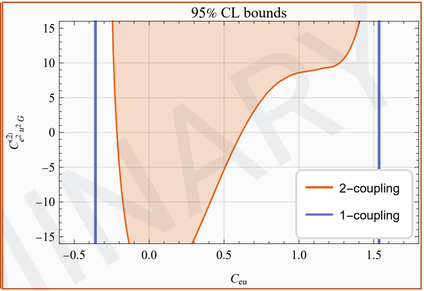
Multi-coupling fits Enabling 2 operators

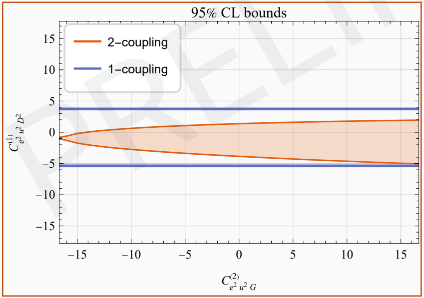












- effective scale $\gtrsim 1\ \mathrm{TeV}$
  $\Rightarrow |C_6| \leq 4, |C_8| \leq 16$
- Strong correlation between C_{eu} & $C^{(1)}_{e^2u^2D^2}$

MULTI-COUPLING FITS Enabling 2 or 3 operators

Wilson coefficient	Single coupling	Marginalized	Marginalized*
	$C_{eu} \& C^{(1)}_{e^2u^2D^2}$		
C_{eu}	$[\mathbf{-0.358, 1.53}]$	$[-4.12, 1.72]$	$[\mathbf{-1.42, 1.43}]$
$C^{(1)}_{e^2u^2D^2}$	$[-5.38, 3.73]$	$[-122., 53.7]$	$[-15.6, 8.03]$
	$C_{eu} \& C^{(2)}_{e^2u^2G}$		
C_{eu}	$[\mathbf{-0.358, 1.53}]$	$[-0.197, 1.40]$	$[\mathbf{-0.581, 1.43}]$
$C^{(2)}_{e^2u^2G}$	$[-24.7, 193.]$	$[-7.05, 231.]$	$[-14.6, 16.0]$
	all 3 operators		
C_{eu}	$[\mathbf{-0.358, 1.53}]$	$[-4.57, 2.00]$	$[\mathbf{-1.41, 1.44}]$
$C^{(1)}_{e^2u^2D^2}$	$[-5.38, 3.73]$	$[-155., 69.6]$	$[-15.5, 7.94]$
$C^{(2)}_{e^2u^2G}$	$[-24.7, 193.]$	$[-5.95, 250.]$	$[-15.1, 16.0]$

- $C^{(2)}_{e^2u^2G}$ does not change the bounds on C_{eu} very much
- $C^{(1)}_{e^2u^2D^2}$ changes the bounds on C_{eu} by a lot

Marginalized*: effective scale constraint ($\gtrsim 1$ TeV) on dim-8 operators

Dilepton mass-dependent p_T spectra

with HL-LHC pseudo-data

Generation of pseudo-data

- m_{ll} bins: Panico, Ricci, and Wulzer 2021

  $[300, 360, 450, 600, 800, 1100, 1500, 2000, 2600]$
- p_T bins:
  - Assuming all stat. errors $< 5\%$, coarser binning

m_{ll}/GeV	p_T/GeV bins
$300 - 360$	$[100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 250, 270, 290, 310, 330, 360, 380, 410, 440, 490, 570, 7000]$
$360 - 450$	$[100, 110, 120, 130, 140, 150, 160, 170, 180, 200, 230, 250, 270, 290, 310, 330, 350, 370, 400, 440, 490, 580, 7000]$
$450 - 600$	$[100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 210, 230, 250, 270, 290, 320, 340, 360, 390, 430, 480, 580, 7000]$
$600 - 800$	$[100, 110, 120, 130, 150, 170, 200, 220, 250, 290, 320, 360, 420, 520, 7000]$
$800 - 1100$	$[100, 110, 120, 150, 170, 200, 230, 270, 330, 430, 7000]$
$1100 - 1500$	$[100, 200, 290, 7000]$
$1500 - 2000$	$[100, 7000]$
$2000 - 2600$	$[100, 7000]$

Generation of pseudo-data

- m_{ll} bins:

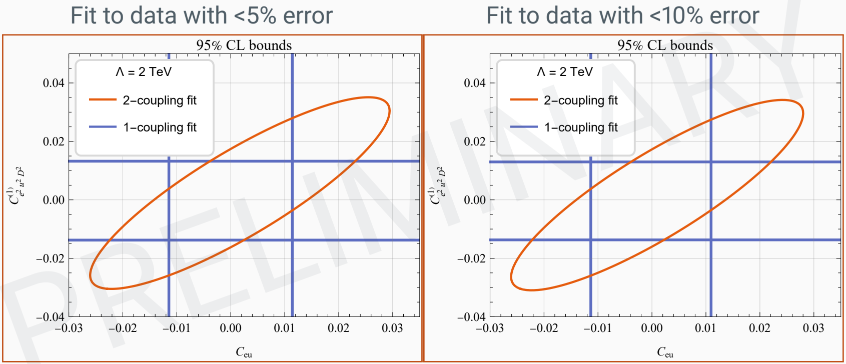
  $[300, 360, 450, 600, 800, 1100, 1500, 2000, 2600]$
- p_T bins:
  - Assuming all stat. errors $< 5\%$, coarser binning
  - Assuming all stat. errors $< 10\%$, finer binning

m_{ll}/GeV	p_T bins$/\text{GeV}$
$300 - 360$	$[100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 250, 270, 290, 310, 330, 350, 370, 400, 420, 440, 470, 500, 530, 560, 600, 660, 760, 7000]$
$360 - 450$	$[100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 240, 260, 290, 310, 330, 350, 370, 390, 410, 440, 470, 500, 530, 560, 610, 670, 770, 7000]$
$450 - 600$	$[100, 110, 120, 130, 140, 150, 160, 190, 210, 230, 250, 270, 290, 320, 340, 370, 390, 420, 460, 490, 520, 550, 580, 620, 680, 780, 7000]$
$600 - 800$	$[100, 110, 120, 130, 150, 170, 200, 220, 240, 260, 280, 310, 340, 380, 410, 440, 470, 510, 550, 620, 730, 7000]$
$800 - 1100$	$[100, 110, 120, 140, 160, 180, 200, 220, 250, 270, 300, 330, 360, 410, 460, 540, 660, 7000]$
$1100 - 1500$	$[100, 130, 160, 190, 230, 270, 320, 400, 520, 7000]$
$1500 - 2000$	$[100, 210, 330, 7000]$
$2000 - 2600$	$[100, 7000]$

Generation of pseudo-data

- m_{ll} bins:
  $[300, 360, 450, 600, 800, 1100, 1500, 2000, 2600]$
- p_T bins:
  - Assuming all stat. errors $< 5\%$, coarser binning
  - Assuming all stat. errors $< 10\%$, finer binning
- assume 1% uncorrelated sys. error and 2% correlated sys. error

2-COUPLING FITS C_{eu} & $C^{(1)}_{e^2u^2D^2}$

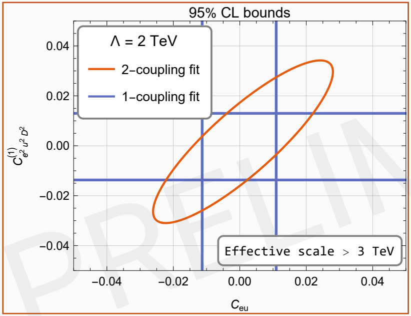


- C_{eu} & $C^{(1)}_{e^2u^2D^2}$ are highly correlated
- need other experiments to independently constrain C_{eu}

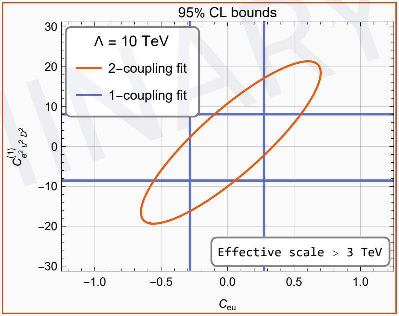
  i.e. low-energy PVES experiments such as SoLID
- Tighter bounds from “<10%” dataset

2-COUPLING FITS C_{eu} & $C^{(1)}_{e^2u^2D^2}$ w/ "<10%" error dataset

$\Lambda = 2$ TeV

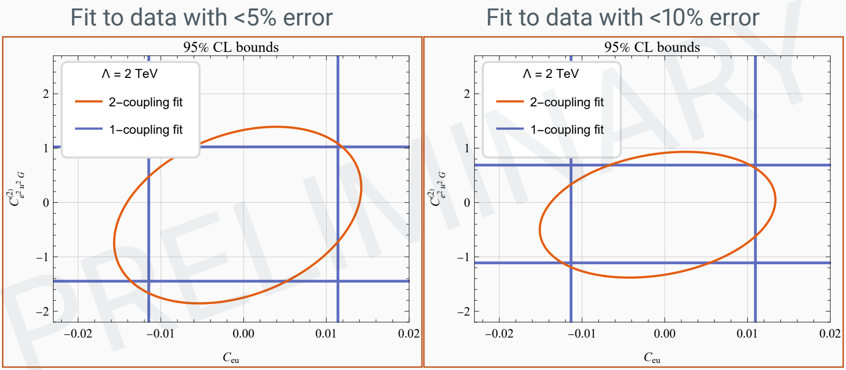


$\Lambda = 10$ TeV



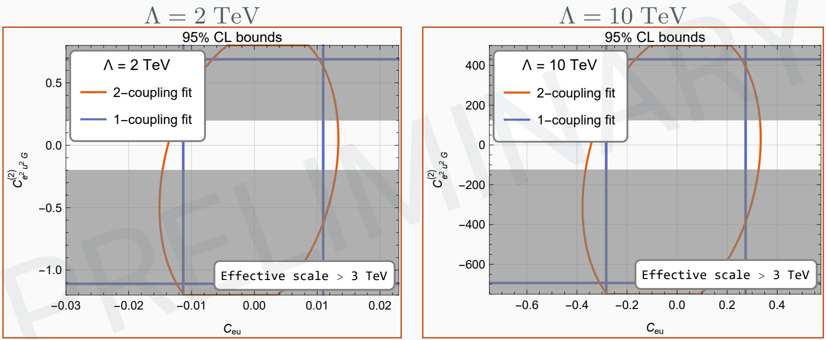
- effective scale $\Lambda/\sqrt{C_6}$ or $\Lambda/\sqrt[4]{C_8} > 3$ TeV for all values of C_{eu} & $C^{(1)}_{e^2u^2D^2}$

2-COUPLING FITS C_{eu} & $C^{(2)}_{e^2 u^2 G}$



- C_{eu} & $C^{(2)}_{e^2 u^2 G}$ are almost uncorrelated
- Can independently determine C_{eu} with m_{ll} and $C^{(2)}_{e^2 u^2 G}$ with p_T spectra
- Tighter bounds from "<10%" dataset

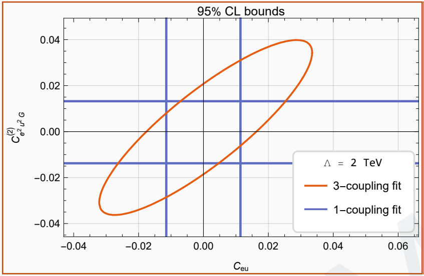
2-COUPLING FITS C_{eu} & $C^{(2)}_{e^2u^2G}$ w/ "<10%" error dataset

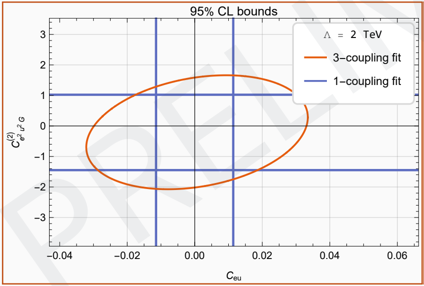


- Shaded area: effective scale $\Lambda/\sqrt{C_6}$ or $\Lambda/\sqrt[4]{C_8}$ smaller than the set scale $3\ \mathrm{TeV}$

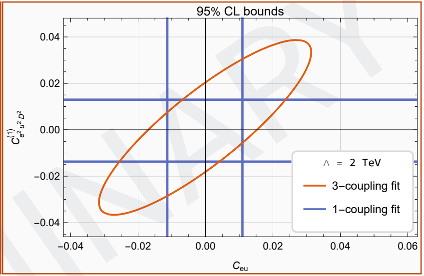
3-COUPLING FITS project to 2-d

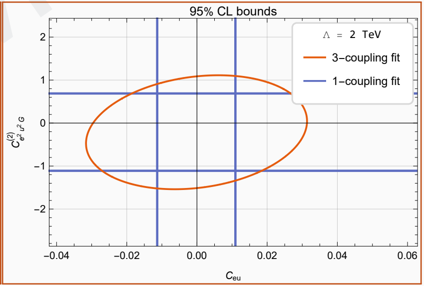
Fit to data with <5% error





Fit to data with <10% error

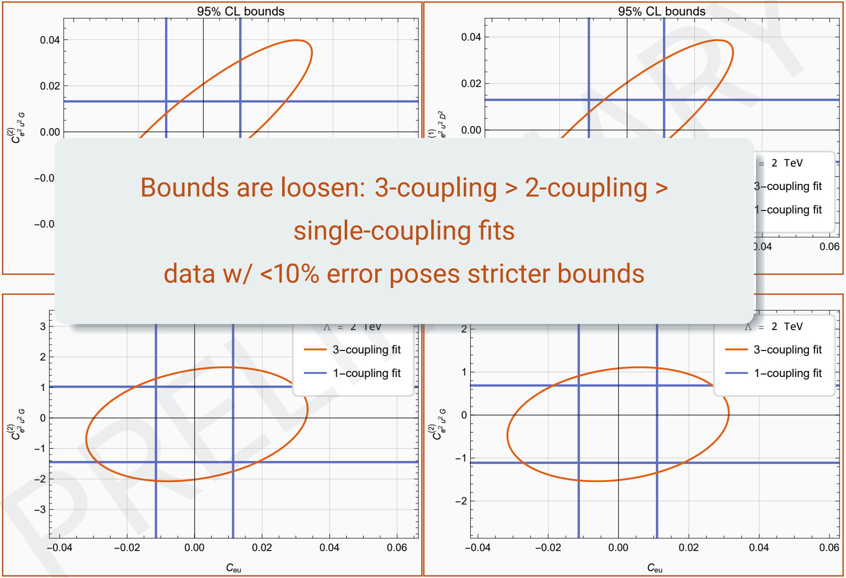




3-COUPLING FITS project to 2-d

Fit to data with <5% error

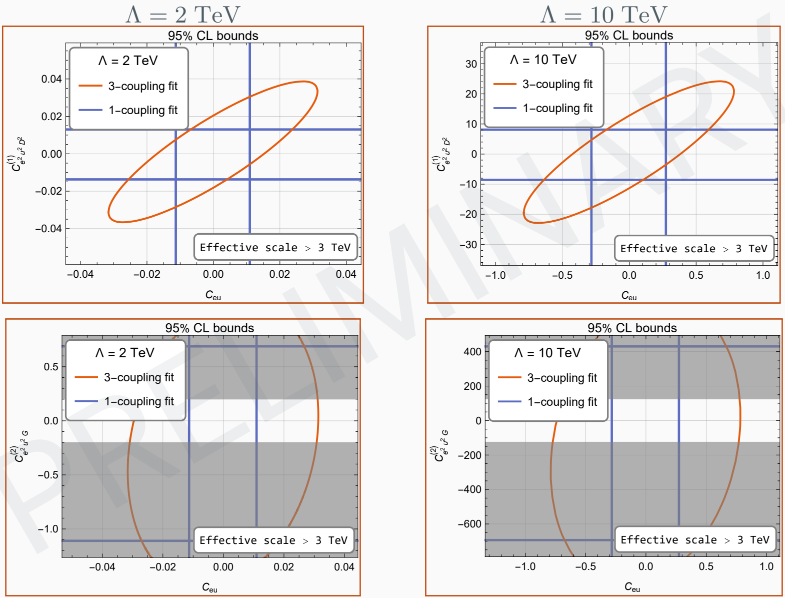
Fit to data with <10% error



Bounds are loosen: 3-coupling > 2-coupling > single-coupling fits

data w/ <10% error poses stricter bounds

3-COUPLING FITS w/ <10% error dataset



Summary

Summary

- Included $\mathcal{O}(1/\Lambda^4)$ effects
- Analyzed scaling in high energy limit: justified to only include operators with $\mathcal{O}(s/\Lambda^2)$ or $\mathcal{O}(s^2/\Lambda^4)$ scaling
- Effects of those dim-8 operators with highest scaling can not be neglected

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- Study on Drell-Yan m_{ll} and p_T spectra both indicate strong correlation between C_{eu} & $C^{(1)}_{e^2u^2D^2}$:
  flat direction; calls for other experiments such as low-energy PVES
- Study on Drell-Yan p_T spectra reveals nearly no correlation between C_{eu} & $C^{(2)}_{e^2u^2G}$

Thanks for your attention!

Backup