Novel angular dependence in Drell-Yan lepton production via dimension-8 SMEFT operators

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

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CERN QCD Lunch

24th April 2020

Based on:

SA, R. Boughezal, E. Mereghetti, F. Petriello ArXiv:2003.11615

SA, W. Dekens, M. Girard, E. Mereghetti JHEP 08 (2018) 205

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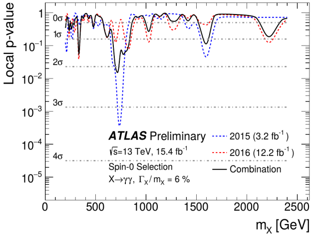
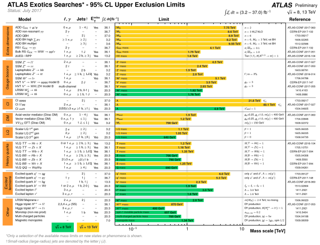
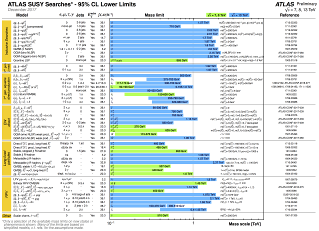
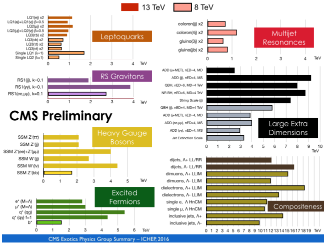
Motivations

- 8 years after the celebrations for the discovery of the Higgs boson, the lack of New Physics is troubling.
- There have been hints coming and going, but nothing conclusive yet.

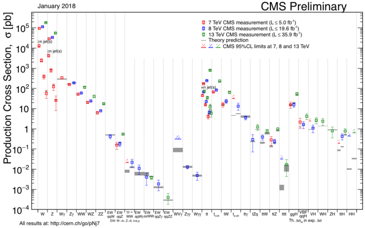


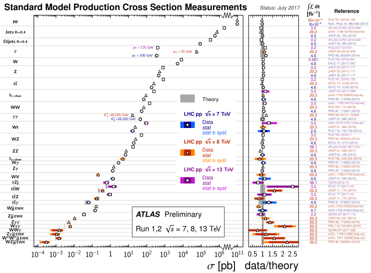


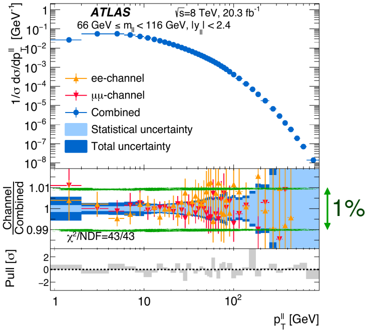




Meanwhile the SM is measured very precisely







- The SM is probed at extraordinary accuracy, over 14 orders of magnitudes.
- For some processes, the goal of 1% accuracy in distributions seems reachable.
- It is very important to take advantage of this wealth of data to constrain New Physics or to find significant deviations.

Introduction

- The LHC reach in terms of the mass scale Λ of New Physics particles that can be directly produced is beginning to asymptote
- We are facing the possibility that Λ might be too heavy for LHC to see it directly.
- Framework of SM EFT gives a general description of physics in the regime $E \ll \Lambda$
- Assuming a linear representation for the Higgs, no new light particles and only SM symmetries and following a bottom-up approach

$$\mathcal{L}_{SM\,EFT} = \mathcal{L}_{SM} + \frac{c^{(5)}}{\Lambda}\mathcal{O}^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_k \sum_j \frac{c_j^{(6+k)}}{\Lambda^{2+k}}\mathcal{O}_j^{(6+k)}$$

- Usually neglecting 1 dim-5 and 20 dim-7 operators that violates lepton number conservation.
- Amplitudes are modified by higher dimension-even terms

$$\mathcal{A}_{SM\,EFT} = \mathcal{A}_{SM} + \frac{g^*}{\Lambda^2}\mathcal{A}_6 + \frac{(g^*)^2}{\Lambda^4}\mathcal{A}_8 + \dots$$

Introduction

- Effects on cross section depend on interference with SM

$$\sigma_{SM\,EFT} = |\mathcal{A}_{SM}|^2 + \frac{g^*}{\Lambda^2} 2\mathrm{Re}\left\{\mathcal{A}_6 \mathcal{A}_{SM}^*\right\} + \frac{(g^*)^2}{\Lambda^4}\left[|\mathcal{A}_6|^2 + 2\mathrm{Re}\left\{\mathcal{A}_8 \mathcal{A}_{SM}^*\right\}\right] + \dots$$

  and are classified as linear dim-6 EFT contributions or as quadratic or dim-8.
- In order to understand the SMEFT range of validity one needs to make assumptions about the power counting, i.e. a way to estimate the coefficients of the effective operators in terms of the couplings and mass scales of the UV dynamics.
- Effects on a generic observable

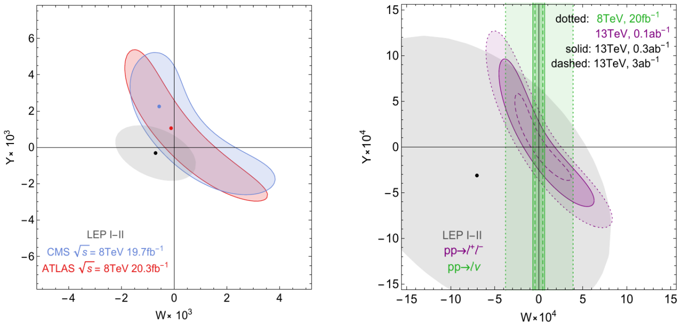
$$O(E) = O_{SM}(E)\left(1 + \sum_i \kappa_i' \times \frac{c_i m_{SM}^2}{\Lambda^2} + \sum_i \kappa_i \times \frac{c_i E^2}{\Lambda^2} + \dots\right)$$

- Measuring $O(E)$ with precision $\Delta O/O = \delta \ll 1$ it is possible to constrain c_i/Λ^2. Two cases, depending on the energy of the probe:
  - At SM scales $E \sim m_{SM}$, the sensitivity is up to $\Lambda \lesssim m_{SM}\sqrt{c_i/\delta}$
  - At high energies $E \gg m_{SM}$, the sensitivity can be pushed up to $\Lambda \lesssim E\sqrt{c_i/\delta}$

Energy helps accuracy: oblique corrections to Drell-Yan

- LHC Drell-Yan data can already surpass LEP bounds for W, Y oblique parameters

[Panico et al. 1609.08157]



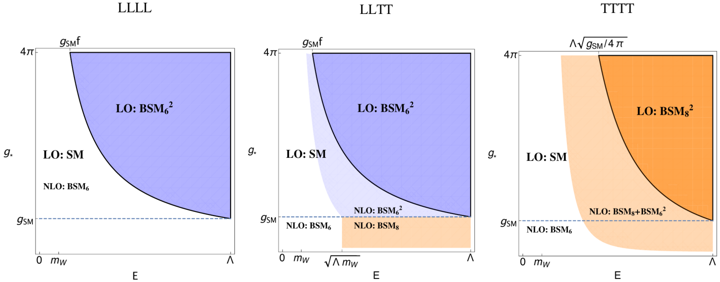
✦ Neutral DY at **8 TeV** is roughly competitive with LEP

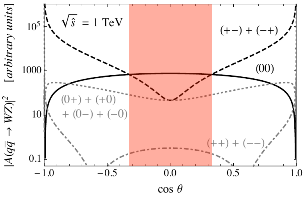
✦ Charged DY at **8 TeV** could **improve** LEP bound on W
(experimental analysis not available, our extrapolation assumes 5% syst.)

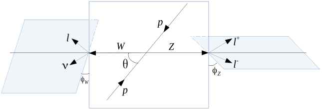
✦ **13 TeV** measurements will be **much better than LEP**

Energy helps accuracy: diboson production

- Similar strategy followed for diboson production. Complicated by non-interfering helicities. [Azatov et al. 1607.05236]
- Dominant interference terms can be recovered by being less inclusive, e.g. using selection cuts and angular variables. [Panico et al. 1708.07823]



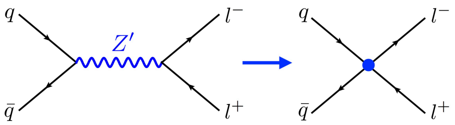




Energy helps accuracy: Minimal Z' models

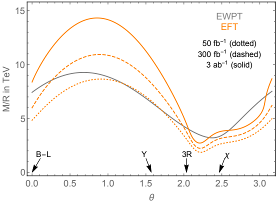
- New U(1) gauges linear combination of Y and B-L. Anomaly free if RH neutrinos present. Flavour universal interactions. No new scalars needed, no worsening of the hierarchy problem.
- Traditional bump-hunt searches exclude up to ~ 5 TeV at 13 TeV LHC. For larger masses or couplings, bump-hunt loose sensitivity, one can take advantage of EFT description

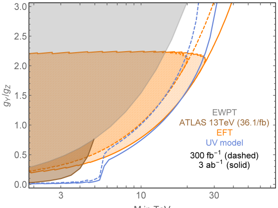
[SA et al. ArXiv:1712.02347]



$$L = -\frac{1}{4}\mathcal{Z}_{\mu\nu}^2 + \frac{M^2}{2}\mathcal{Z}_\mu^2 - \mathcal{Z}_\mu(g_Y J_H^\mu + g_Y J_Y^\mu + g_{BL} J_{BL}^\mu)$$

$$L_{EFT} = -\frac{1}{2M^2}\left(g_Y J_H^\mu + g_Y J_Y^\mu + g_{BL} J_{BL}^\mu\right)^2$$





The Dim-6 SMEFT basis

- The most general basis has 2499 operators. Assuming flavor symmetries they reduce to 59 (+4 violating baryon number).
- We work in the so-called Warsaw basis

B. Grzadkowski et al. ArXiv:1008.4884

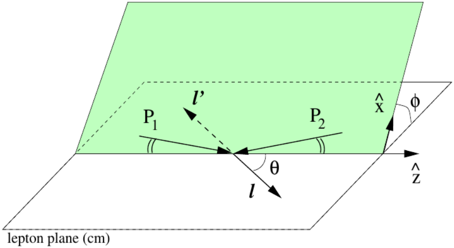
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger \varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger \varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

- Bosonic operators on the left, four-fermion operators on the right.
- Not all operators contribute at tree-level for a specific process.
- Including $D > 4$ operators affects the relations between the SM couplings $g, g', e, G_F, \sin\theta_W$, gauge boson masses M_W, M_Z and the Higgs mass M_H and VEV v

Angular distributions and the Collins-Soper frame

- The most generic angular dependence of a vector-boson cross-section based on Lorentz invariance, kinematics and at the lowest order in EW interactions can be written in terms of angular distributions in the Collins-Soper frame.
- Rest frame for the dilepton system with θ angle taken to bisect the beam directions as seen in the dilepton rest frame.



$$
\begin{aligned}
\frac{d\sigma}{dm_{ll}^2 dy d\Omega_l} = & \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2 dy}\left\{(1+c_\theta^2) + \frac{A_0}{2}(1-3c_\theta^2)\right. \\
& + A_1 s_{2\theta} c_\phi + \frac{A_2}{2} s_\theta^2 c_{2\phi} + A_3 s_\theta c_\phi + A_4 c_\theta \\
& \left. + A_5 s_\theta^2 s_{2\phi} + A_6 s_{2\theta} s_\phi + A_7 s_\theta s_\phi \right\}
\end{aligned}
$$

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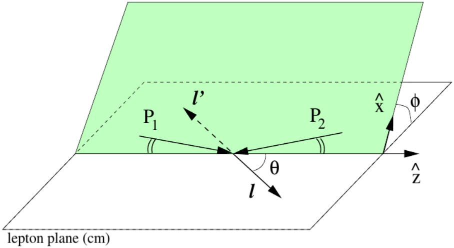


$$< f(\theta^*, \phi^*) >= \int_{-1}^{1} d(\cos\theta^*) \int_0^{2\pi} d\phi^* \frac{1}{\sigma} \frac{d\sigma}{d(\cos\theta^*) d\phi^*} f(\theta^*, \phi^*)$$

$$A_0 = 4- < 10\cos^2\theta^* >, \quad A_1 = < 5\sin 2\theta^* \cos\phi^* >, \quad A_2 = < 10\sin^2\theta^* \cos 2\phi^* >,$$
$$A_3 =< 4\sin\theta^* \cos\phi^* >, \quad A_4 = < 4\cos\theta^* >, \quad A_5 = < 5\sin^2\theta^* \sin 2\phi^* >,$$
$$A_6 =< 5\sin 2\theta^* \sin\phi^* >, \quad A_7 = < 4\sin\theta^* \sin\phi^* > .$$

Dim-6 operators affecting Drell-Yan production: $\mathcal{O}(1/\Lambda^2)$

- Focusing on Drell-Yan production, there are only 2 classes of operators with non-vanishing tree-level interference with the SM:

- $\psi^2\varphi^2 D$: These include operators like

$$\mathcal{O}_{6,\varphi e} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$$

which shifts the couplings of fermions to gauge bosons.

For CC, only left-handed quarks and leptons involved, same angular dependence as in the SM

For NC, the relative importance on left- and right-handed couplings is shifted. This could be be visible in high-precision measurements of $\cos\theta$ coefficient A_4.

- ψ^4 : four-fermion operators with SM chiral structure, such as

$$\mathcal{O}_{6,eu} = (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$$

Extensively studied, produce the same angular dependence as the SM, can be obtained integrating out new Z' or W' spin-1 bosons.

Dim-6 operators affecting Drell-Yan production: $\mathcal{O}(1/\Lambda^4)$

- There are also 3 classes of dim-6 non-SM-interfering operators :

- $\psi^2 X \psi$: dipole operators coupled to gauge fields such as

$$\mathcal{O}_{6,eW} = (\bar{l}\sigma^{\mu\nu}e)\tau^I \varphi W^I_{\mu\nu}$$

- $\psi^2 \varphi^2 D$: right-handed charged-current operator

$$\mathcal{O}_{6,\varphi ud} = (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}\gamma^\mu d) + \text{h.c.}$$

- ψ^4 : four-fermion operators with chiral structure different from the SM, such as scalar operator

$$\mathcal{O}_{6,ledq} = \bar{l}^i e\, \bar{d} q^i$$

- All these operators can produce large shifts in the A_i coefficients, especially at large $M_{\ell\ell}$

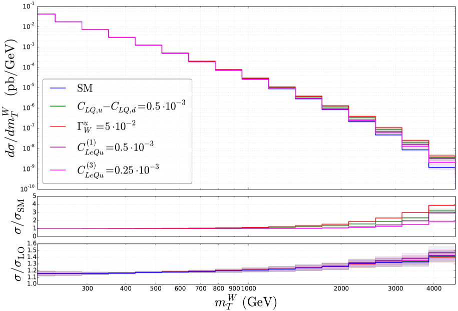
- High-mass NC and CC Drell-Yan put strong constraints on new vector, axial, scalar or tensor semileptonic contact operators competitive with the low-energy constraints from pion and kaon decays and nuclear beta decay.

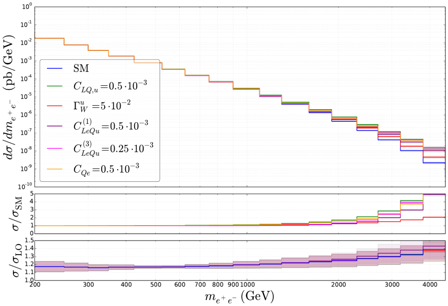
QCD corrections to Dim-6 effects

- We have implemented the effects of these dim-6 operators in POWHEG, including NLO QCD corrections and matching to the parton showers

SA, W. Dekens, M. Girard, E. Mereghetti JHEP 08 (2018) 205

- Also for Higgs-strahlung and vector-boson fusion.
- Code available in the `POWHEG-BOX`

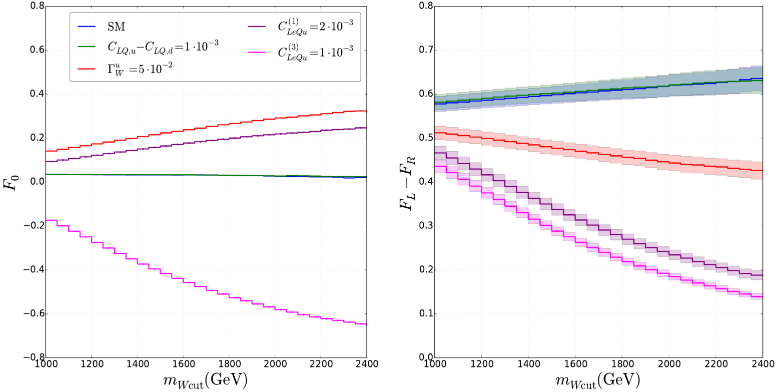




QCD corrections to Dim-6 effects

- Effects due to different operators can be disentangled looking at angular or polarization coefficients

$$F_0 = \frac{A_0}{2}\,, \qquad F_L = \frac{1}{4}(2 - A_0 \mp A_4)\,, \qquad F_R = \frac{1}{4}(2 - A_0 \pm A_4)$$



- No new angular dependence in A_i's induced by QCD corrections since the spin-1 current attached to the leptons is not affected.
- Angular-dependent cuts and higher-order EW corrections can instead modify the angular dependence.

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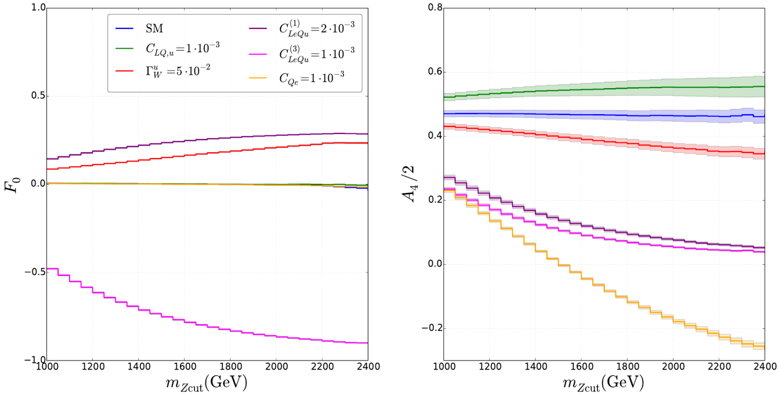

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Dimension 8 effects

- Since we include dim-6 squared $\mathcal{O}(1/\Lambda^4)$ contributions in our analysis, we should also include dim-8 interference with the SM. This could:
  - Weaken the competitive bounds we get on scalar and tensor currents
  - Pollute the clear separation we observe in angular distributions
  - Provide an estimate for the uncertainty in the EFT expansion parameter Λ.
- In order to address these issues we started looking into dim-8 effects to CC and NC Drell-Yan.
- No basis available, need to be careful to include only operators really independent.
- `HSmethod` gives 993 dim-8 operators already with $N_f = 1$

B. Henning et al. JHEP 08 (2017) 016

- Only a few of them interfere with the SM at tree-level
- Some already considered in previous study for W^+H

C. Hays et al. ArXiv:1808.00442

Dim-8 operators affecting Drell-Yan production: $\mathcal{O}(1/\Lambda^4)$

- Only 7 classes of operators with non-vanishing SM tree-level interference

- $\psi^2\varphi^4 D$: these contain e.g.

$$\mathcal{O}_{8,q1} = i(\bar{q}\gamma^\mu q)(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\varphi^\dagger \varphi)$$

and only shift the fermion-gauge-boson vertex. No new kinematic effects.

- $\psi^2\varphi^2 D^3$: contain e.g.

$$\mathcal{O}_{8,3q1} = i(\bar{q}\gamma^\mu D^\nu q)(D^2_{(\mu\nu)}\varphi^\dagger \varphi)$$

As above, no new kinematic effects.

- $\psi^4\varphi^2$: include e.g. four-fermion operators as

$$\mathcal{O}_{8,eu} = (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)(\varphi^\dagger \varphi)$$

They shift dim-6 couplings, no new angular dependence.

Dim-8 operators affecting Drell-Yan production: $\mathcal{O}(1/\Lambda^4)$

- $\psi^4 D^2$: There are 4 with only left-handed fermion doublets

$$
\begin{aligned}
\mathcal{O}_{8,lq\partial 1} &= (\bar{l}\gamma_\mu l)\partial^2(\bar{q}\gamma^\mu q), \\
\mathcal{O}_{8,lq\partial 2} &= (\bar{l}\tau^I\gamma_\mu l)\partial^2(\bar{q}\tau^I\gamma^\mu q), \\
\mathcal{O}_{8,lq\partial 3} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q), \\
\mathcal{O}_{8,lq\partial 4} &= (\bar{l}\tau^I\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{q}\tau^I\gamma^\mu \overleftrightarrow{D}^\nu q).
\end{aligned}
$$

The first two give an energy-dependent shift of the dim-6 four-fermion couplings.

The last two are more interesting: they contain two free Lorentz indexes that gets contracted as a spin-2 current.

In a UV completion it could be generated e.g. by integrating out of a massive spin-2 d.o.f.

The amplitude contains a new $l = 2$ partial wave contribution, not present before.

For CC DY the only contribution comes from $\mathcal{O}_{8,lq\partial 4}$. For NC both $\mathcal{O}_{8,lq\partial 3}$ and $\mathcal{O}_{8,lq\partial 4}$.

Dim-8 operators affecting Drell-Yan production: $\mathcal{O}(1/\Lambda^4)$

- $\psi^4 D^2$: Adding also right-handed singlets one finds 5 more with the same $\gamma_\mu \overleftrightarrow{D}_\nu$ structure

$$
\begin{aligned}
\mathcal{O}_{8,ed\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d), \\
\mathcal{O}_{8,eu\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u), \\
\mathcal{O}_{8,ld\partial 2} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d), \\
\mathcal{O}_{8,lu\partial 2} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u), \\
\mathcal{O}_{8,qe\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q).
\end{aligned}
$$

  - In total we find 7 dim-8 operators that can contribute to $l = 2$ partial waves for DY NC amplitudes
  - These conclusions are not affected by NLO QCD corrections.

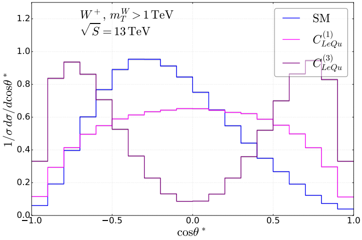
    For LH fermions there are 3 new classes: $\psi^4 G$, $\psi^2\varphi^2 DG$ and $\psi^2 DXG$ which do not give rise to new angular dependence.
  - EW corrections on the other hand can affect these results. The effect starts at NLL, as the LL corrections only depends on partonic $\hat{s}$ and do not induce any new angular dependence.

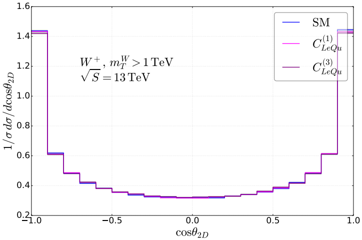
Problems with W and its rest frame

- The exp definition of the Collins-Soper frame in case of CC DY is complicated by the missing neutrino.
- Same is true for helicity frame, they both need to reconstruct the W rest-frame without the full kinematic information.
- One could reconstruct the transverse part using missing E_T, but cannot rely anymore on on-shell condition to constrain the longitudinal part if interested in off-shell DY production.
- Several alternatives proposed based exclusively on transverse plane

$$\cos\theta_{2\mathrm{D}} = \frac{\vec{p}_{\mathrm{T}}^{\,\ell*} \cdot \vec{p}_{\mathrm{T}}^{\,W}}{|\vec{p}_{\mathrm{T}}^{\,\ell*}|\,|\vec{p}_{\mathrm{T}}^{\,W}|}, \qquad L_P = \frac{\vec{p}_T(\ell)\cdot\vec{p}_T(\mathrm{W})}{|\vec{p}_T(\mathrm{W})|^2}$$

- We find resolution power very much degraded





Dimension 8 operators inducing novel angular dependency

- We calculate $u(p_1)\bar{u}(p_2) \to l(p_3)\bar{l}(p_4)$ at LO focusing on the contribution from $\mathcal{O}_{8,lq\partial 3}$
- The leading interference term is given by

$$\Delta|\mathcal{M}_{u\bar{u}}|^2 \quad = \quad -\frac{C_{8,lq\partial 3}}{\Lambda^4}\,\hat{c}_\theta(1+\hat{c}_\theta)^2\,\frac{\hat{s}^2}{6}\left[e^2 Q_u Q_e + \frac{g^2 g_L^u g_L^e\,\hat{s}}{c_W^2(\hat{s}-M_Z^2)}\right]$$

- At LO $\hat{c}_\theta$ is related to the CS c_θ by a sign, depending on the longitudinal momentum of the dilepton pair wrt the beam direction. The amplitude $\bar{u}(p_1)u(p_2) \to l(p_3)\bar{l}(p_4)$ can be obtained by $\hat{c}_\theta \to -\hat{c}_\theta$ and the one with down-quarks changing the SM couplings.
- It contains a $\cos^3\theta$ dependence not accounted for in the usual Collins-Soper angular separation, which assumes production in the s-channel by a spin-1 current
- Only the 7 dim-8 operators in category $\psi^4 D^2$ manifest this new angular dependence.
- Adding the following combination of $l=3$ spherical harmonics

$$Y_3^0,\;\; Y_3^1 \pm Y_3^{-1},\;\; Y_3^2 \pm Y_3^{-2},\;\; Y_3^3 \pm Y_3^{-3}$$

Dimension 8 operators inducing novel angular dependency

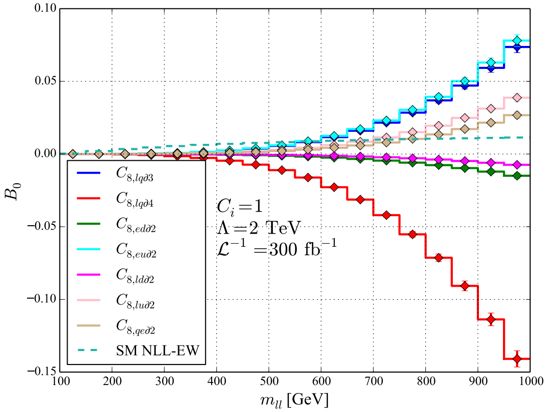
- We propose the following new parametrization

$$
\begin{aligned}
\frac{d\sigma}{dm_{ll}^2 dy d\Omega_l} \quad = \quad & \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2 dy}\Big\{(1+c_\theta^2) + \frac{A_0}{2}(1-3c_\theta^2) \\
& + A_1 s_{2\theta} c_\phi + \frac{A_2}{2} s_\theta^2 c_{2\phi} + A_3 s_\theta c_\phi + A_4 c_\theta \\
& + A_5 s_\theta^2 s_{2\phi} + A_6 s_{2\theta} s_\phi + A_7 s_\theta s_\phi \\
& + B_3^e s_\theta^3 c_\phi + B_3^o s_\theta^3 s_\phi + B_2^e s_\theta^2 c_\theta c_{2\phi} \\
& + B_2^o s_\theta^2 c_\theta s_{2\phi} + \frac{B_1^e}{2} s_\theta (5c_\theta^2 - 1) c_\phi \\
& + \frac{B_1^o}{2} s_\theta (5c_\theta^2 - 1) s_\phi + \frac{B_0}{2}(5c_\theta^3 - 3c_\theta)\Big\}
\end{aligned}
$$

- B_i^e are even and B_i^o are odd under T-reversal.
- B_0 is already populated at LO.
- B_i's with $i > 0$ start to be populated at $\mathcal{O}(\alpha\alpha_S)$ or $\mathcal{O}(\alpha^2)$. Depending on ϕ they need both a spin-2 current and a non-zero transverse momentum.
- In the SM EW corrections affect B_0 starting at NLL.

Numerical results

- Using $\sqrt{s} = 14$ TeV , $\mu_R = \mu_F = m_{ll}$ and NNPDF3.1 pdfs. Set $C_i = 1$ individually. $\Lambda = 2$ TeV, compatible with results from dim-6 fits.
- $m_{ll} \leq 1$ TeV for EFT convergence. Estimated statistical errors with 300 fb^{-1} integrated luminosity



- SM EW contribution is small and grows logarithmically rather than polynomially
- Similar large effects in CC DY by operator $\mathcal{O}_{8,lq\partial 4}$. Analysis more complicated, due to off-shell W.

Summary and Outlook

- Precision measurements probing the high-energy regime provide strong constraints on New Physics effects.
- We have identified large dim-6 effects in angular distributions which yield bounds competitive with low-energy precision measurements.
- We have started to investigate how dim-8 corrections alter this picture.
- In doing so we have identified a new angular dependence appearing at dim-8, not accounted for in current exp. analyses.
- Proposed a new base, invite experimental collaborations to perform measurements.
- Discuss possible resolution of problems associated with angular distributions in the rest-frame of far off-shell W's

Outlook:
Completing the dim-8 analysis for DY and inclusion in POWHEG, stay tuned.

Thank you for your attention!