Projected BSM constraints from SoLID in the Standard Model EFT framework

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Boughezal, FP, Wiegand, PRD 104 (2021) 016005; arXiv:2104.03979

SoLID collaboration meeting

December 16, 2021

Model-independent searches for BSM

- No new particles found at the LHC! Need new experimental probes that can access regions of parameter space not covered at the LHC
- Model-independent approach: adapt an effective field theory framework that encapsulates a large swath of new physics models.

- Standard Model Effective Field Theory (SMEFT): all operators consistent with SM symmetries, containing SM particles, and assuming a mass gap to any new physics

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

Dimension-6 **Dimension-8**

(odd dimensions not considered here; lepton-number violating)

$\Lambda \gg M_{SM}$, E

Expand in large Λ

Warsaw basis

- Complete and independent dim-6 basis known: 2499 baryon conserving operators for 3 fermion generations; (can reduce assuming minimal flavor violation to O(100)) Grzadkoswki, Iskrzynski, Misiak, Rosiek 1008.4884; Brivio, Jiang, Trott 1709.06492
- Dim-8 basis derived Li, Ren, Shu, Xiao, Yu, Zheng 2005.00008; Murphy 2005.00059

Dimension 6		Dimension 8	
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma^\mu l)\,(\bar{q}\gamma_\mu q)$	$\mathcal{O}_{l^2q^2D^2}^{(1)}$	$D^\nu\,(\bar{l}\gamma^\mu l)\,D_\nu\,(\bar{q}\gamma_\mu q)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma^\mu\tau^i l)\,(\bar{q}\gamma_\mu\tau^i q)$	$\mathcal{O}_{l^2q^2D^2}^{(3)}$	$D^\nu\,(\bar{l}\gamma^\mu\tau^i l)\,D_\nu\,(\bar{q}\gamma_\mu\tau^i q)$
$\mathcal{O}_{eu}$	$(\bar{e}\gamma^\mu e)\,(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{e^2u^2D^2}^{(1)}$	$D^\nu\,(\bar{e}\gamma^\mu e)\,D_\nu\,(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{ed}$	$(\bar{e}\gamma^\mu e)\,(\bar{d}\gamma_\mu d)$	$\mathcal{O}_{e^2d^2D^2}^{(1)}$	$D^\nu\,(\bar{e}\gamma^\mu e)\,D_\nu\,(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{lu}$	$(\bar{l}\gamma^\mu l)\,(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{l^2u^2D^2}^{(1)}$	$D^\nu\,(\bar{l}\gamma^\mu l)\,D_\nu\,(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{ld}$	$(\bar{l}\gamma^\mu l)\,(\bar{d}\gamma_\mu d)$	$\mathcal{O}_{l^2d^2D^2}^{(1)}$	$D^\nu\,(\bar{l}\gamma^\mu l)\,D_\nu\,(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{qe}$	$(\bar{q}\gamma^\mu q)\,(\bar{e}\gamma_\mu e)$	$\mathcal{O}_{q^2e^2D^2}^{(1)}$	$D^\nu\,(\bar{q}\gamma^\mu q)\,D_\nu\,(\bar{e}\gamma_\mu e)$

Relevant operators for our analysis; note q,l are left-handed doublets; e,u,d are right-handed singlets

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Structure of a SMEFT cross section:

$$\sigma \sim |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} 2\mathrm{Re}\left[\mathcal{M}_6 \mathcal{M}_{SM}^*\right] + \frac{1}{\Lambda^4}\left\{|\mathcal{M}_6|^2 + 2\mathrm{Re}\left[\mathcal{M}_8 \mathcal{M}_{SM}^*\right]\right\}$$

Leading SMEFT correction

Sub-leading; neglected in many analyses but shown to have significant effects on LHC Drell-Yan fits

Boughezal, Mereghetti, FP2106.05337

Issues in SMEFT analyses

- Are there combinations of Wilson coefficients to which current probes are blind?

Azatov, Paul 1309.5273

$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu} \rightarrow O_g(m_H) \approx \frac{g_s^2}{48\pi^2} (c_g + c_t) \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

Flat direction: total cross section can't distinguish c_g, c_t; need other observables such as Higgs p_T or ttH measurement

- Such (approximate) flat directions appear in Drell-Yan as well

$$C_{ed} = \frac{Q_u e^2 - g_Z^2 g_L^u g_R^e}{Q_u e^2 - g_Z^2 g_R^e g_R^u} \frac{Q_d e^2 - g_Z^2 g_R^e g_R^d}{Q_d e^2 - g_Z^2 g_L^d g_R^e} C_{eu}$$

Drell-Yan cross section vanishes for $s \gg M_Z^2$ for this combination of parameters

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Can remove these flat directions with experiments such as SoLID

Flat directio… c_g, c_t; need other obs… …asurement

- Such (approxi… Drell-Yan as well

$$C_{ed} = \frac{Q_u e^2 - g_Z^2 g_L^u g_R^e}{Q_u e^2 - g_Z^2 g_R^e g_R^u} \frac{Q_d e^2 - g_Z^2 g_R^e g_R^d}{Q_d e^2 - g_Z^2 g_L^d g_R^e} C_{eu}$$

Drell-Yan cross section vanishes for $s \gg M_Z^2$ for this combination of parameters

Connection to PV basis

- We can convert the SMEFT operators to a basis in terms of vector and axial couplings

$$
\begin{aligned}
\mathcal{L}_{\mathbf{BSM}} = \frac{G_F}{\sqrt{2}}\Big[& (\bar{e}\gamma^\mu\gamma_5 e)(C^6_{1u}\bar{u}\gamma_\mu u + C^6_{1d}\bar{d}\gamma_\mu d) + (\bar{e}\gamma^\mu e)(C^6_{2u}\bar{u}\gamma_\mu\gamma_5 u + C^6_{2d}\bar{d}\gamma_\mu\gamma_5 d) \\
& + (\bar{e}\gamma^\mu e)(C^6_{Vu}\bar{u}\gamma_\mu u + C^6_{Vd}\bar{d}\gamma_\mu d) + (\bar{e}\gamma^\mu\gamma_5 e)(C^6_{Au}\bar{u}\gamma_\mu\gamma_5 u) \\
& + D^\nu\Big(\bar{e}\gamma^\mu\gamma_5 e\Big)D_\nu\Big(\frac{C^8_{1u}}{v^2}\bar{u}\gamma_\mu u + \frac{C^8_{1d}}{v^2}\bar{d}\gamma_\mu d\Big) + D^\nu\Big(\bar{e}\gamma^\mu e\Big)D_\nu\Big(\frac{C^8_{2u}}{v^2}\bar{u}\gamma_\mu\gamma_5 u + \frac{C^8_{2d}}{v^2}\bar{d}\gamma_\mu\gamma_5 d\Big) \\
& + D^\nu\Big(\bar{e}\gamma^\mu e\Big)D_\nu\Big(\frac{C^8_{Vu}}{v^2}\bar{u}\gamma_\mu u + \frac{C^8_{Vd}}{v^2}\bar{d}\gamma_\mu d\Big) + D^\nu\Big(\bar{e}\gamma^\mu\gamma_5 e\Big)D_\nu\Big(\frac{C^8_{Au}}{v^2}\bar{u}\gamma_\mu\gamma_5 u\Big)\Big].
\end{aligned}
$$

- Full C coefficients are the sum of SM and dim-6 contributions:

$$C_{1u} = C^{SM}_{1u} + C^6_{1u}$$

etc.

Dim-8 has momentum dependence; negligible for SoLID kinematics

Connection to PV basis

- Simple linear transformation between the PV and SMEFT bases:

$$C^6_{1u} = \frac{v^2}{2\Lambda^2}\left\{-\left(C^{(1)}_{lq} - C^{(3)}_{lq}\right) + C_{eu} + C_{qe} - C_{lu}\right\}$$
$$C^6_{2u} = \frac{v^2}{2\Lambda^2}\left\{-\left(C^{(1)}_{lq} - C^{(3)}_{lq}\right) + C_{eu} - C_{qe} + C_{lu}\right\}$$
$$C^6_{1d} = \frac{v^2}{2\Lambda^2}\left\{-\left(C^{(1)}_{lq} + C^{(3)}_{lq}\right) + C_{ed} + C_{qe} - C_{ld}\right\}$$
$$C^6_{2d} = \frac{v^2}{2\Lambda^2}\left\{-\left(C^{(1)}_{lq} + C^{(3)}_{lq}\right) + C_{ed} - C_{qe} + C_{ld}\right\}$$
$$C^6_{Vu} = \frac{v^2}{2\Lambda^2}\left\{\left(C^{(1)}_{lq} - C^{(3)}_{lq}\right) + C_{eu} + C_{qe} + C_{lu}\right\}$$
$$C^6_{Au} = \frac{v^2}{2\Lambda^2}\left\{\left(C^{(1)}_{lq} - C^{(3)}_{lq}\right) + C_{eu} - C_{qe} - C_{lu}\right\}$$
$$C^6_{Vd} = \frac{v^2}{2\Lambda^2}\left\{\left(C^{(1)}_{lq} + C^{(3)}_{lq}\right) + C_{ed} + C_{qe} + C_{ld}\right\}.$$

- Can analyze SoLID, other low-energy experiments, and LHC using either of these two bases.

Details of analysis

- We study potential future constraints arising from the SoLID and P2 experiments using projections in the literature:

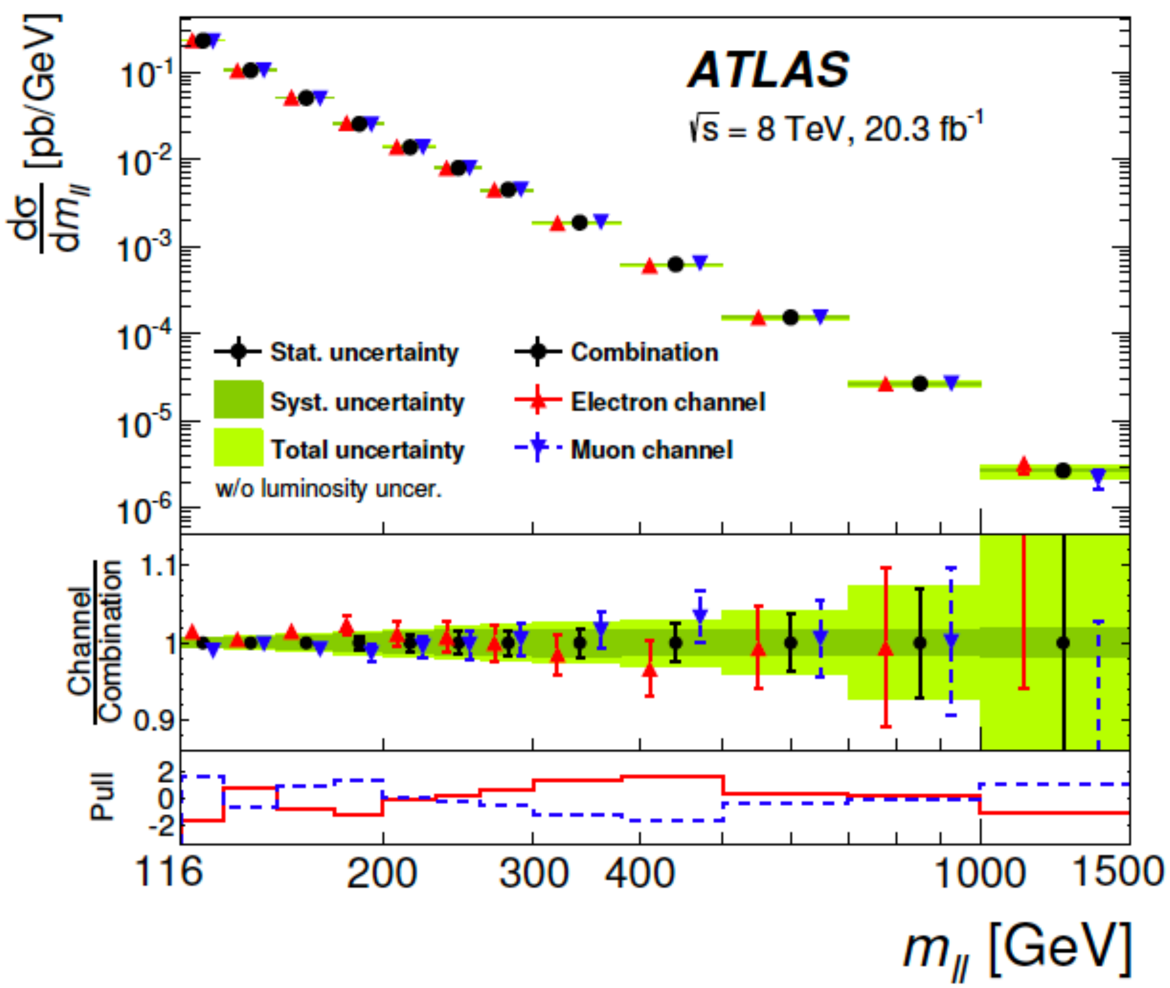
  SoLID: SoLID pre-CDR report (Nov 2019)

  P2: arXiv: 1802.04759

- SoLID: deuteron target measurements used for BSM searches; sensitivity from region $0.4<x<0.5$, $Q^2 \approx 6$ GeV^2. Total uncertainty, from both experiment and SM theory: 0.6%
- P2: following 1802.04759, projections includes Cesium APV, QWeak projection, E-158 constraints. Sensitive only to C_1 coefficients
- Turn on two coefficients at a time, to show correlations while allowing easy visualization

Example LHC data

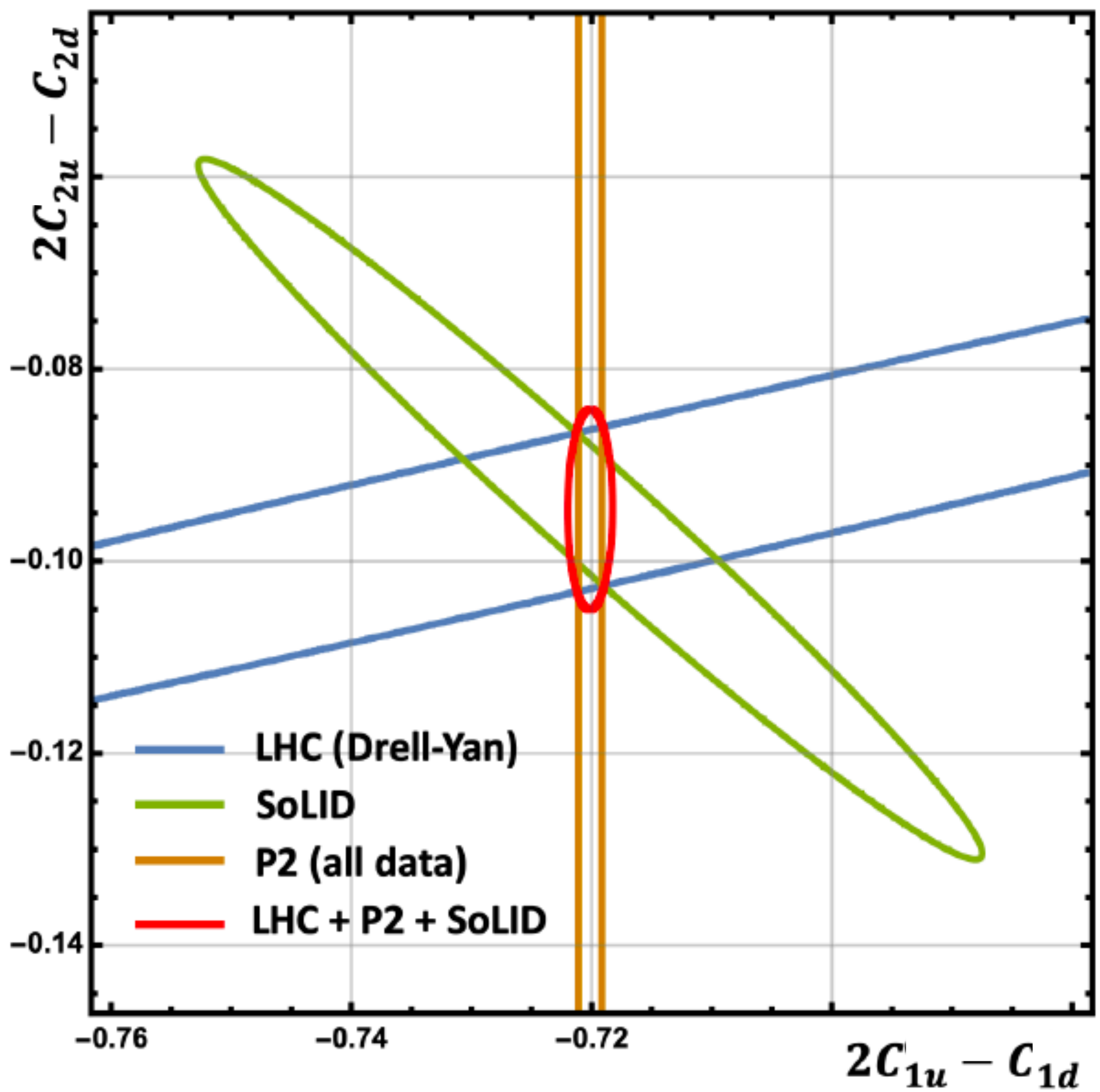
1606.04266



$m_{\ell\ell}$ [GeV]	$\frac{d\sigma}{dm_{\ell\ell}}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]
116–130	2.28×10^{-1}	0.34	0.53	0.63
130–150	1.04×10^{-1}	0.44	0.67	0.80
150–175	4.98×10^{-2}	0.57	0.91	1.08
175–200	2.54×10^{-2}	0.81	1.18	1.43
200–230	1.37×10^{-2}	1.02	1.42	1.75
230–260	7.89×10^{-3}	1.36	1.59	2.09
260–300	4.43×10^{-3}	1.58	1.67	2.30
300–380	1.87×10^{-3}	1.73	1.80	2.50
380–500	6.20×10^{-4}	2.42	1.71	2.96
500–700	1.53×10^{-4}	3.65	1.68	4.02
700–1000	2.66×10^{-5}	6.98	1.85	7.22
1000–1500	2.66×10^{-6}	17.05	2.95	17.31

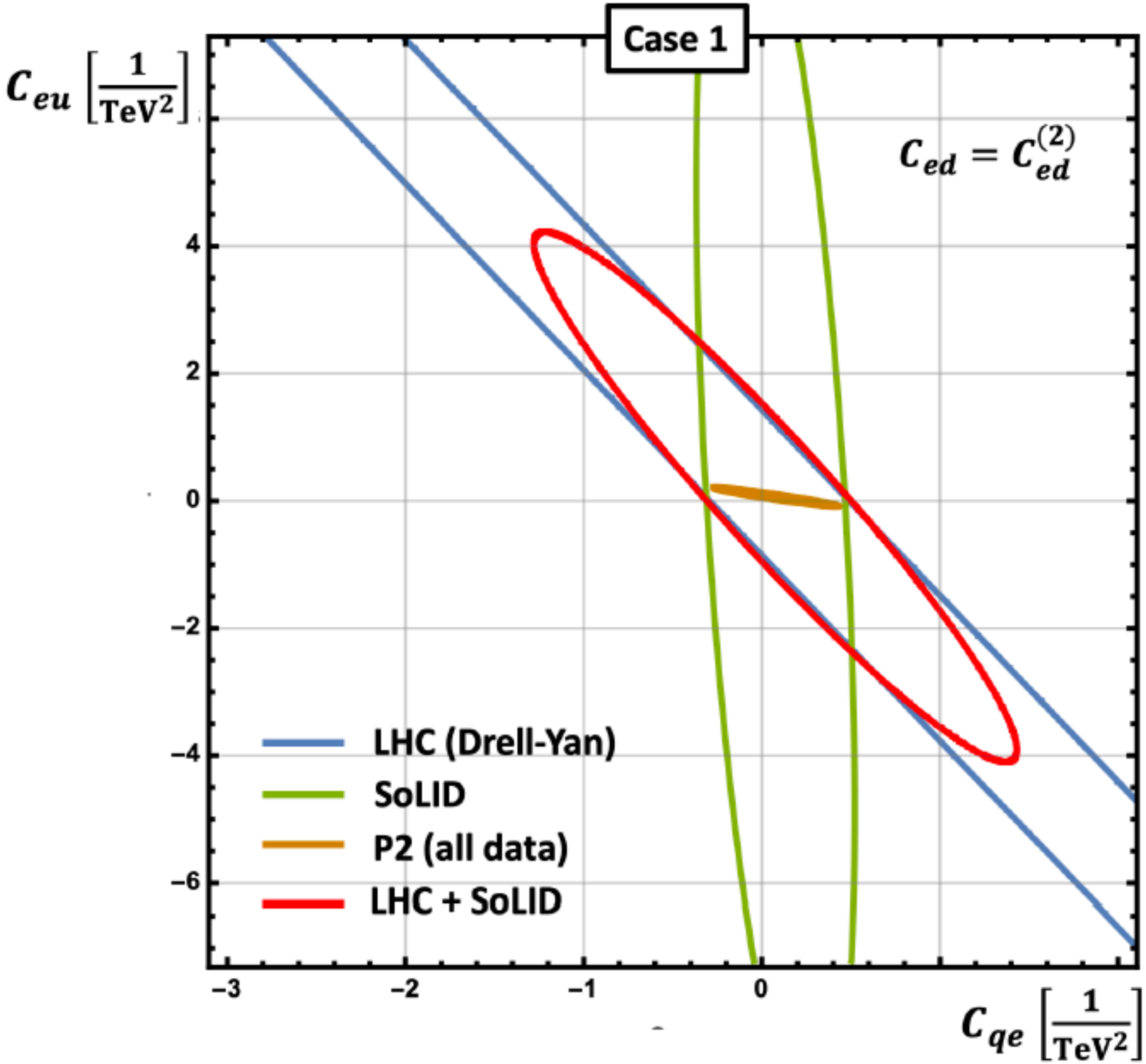
- Originally designed to measure the photon PDF; necessitated high invariant mass and control over systematic errors
- Twelve invariant mass bins
- Higher LHC luminosity won't help much; already systematics dominated in many bins

Results: PV basis



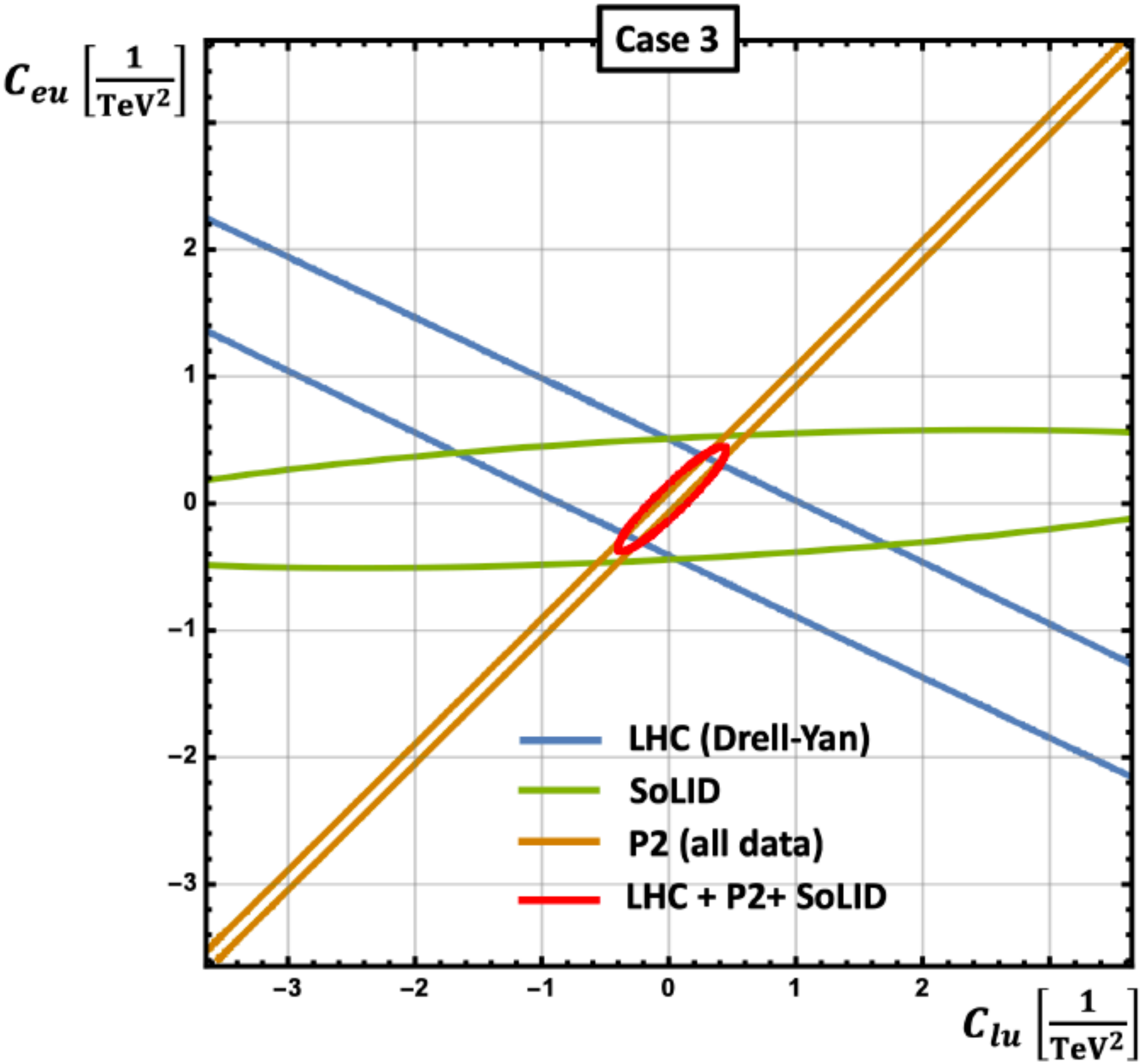
- Note the elongated LHC ellipse; degeneracy in the Drell-Yan matrix elements; occurs at high m_{ll} where BSM effects are largest
- P2 sensitive only to C_l coefficients
- Important contributions from SoLID; constraints orthogonal to LHC constraints

Results: SMEFT basis



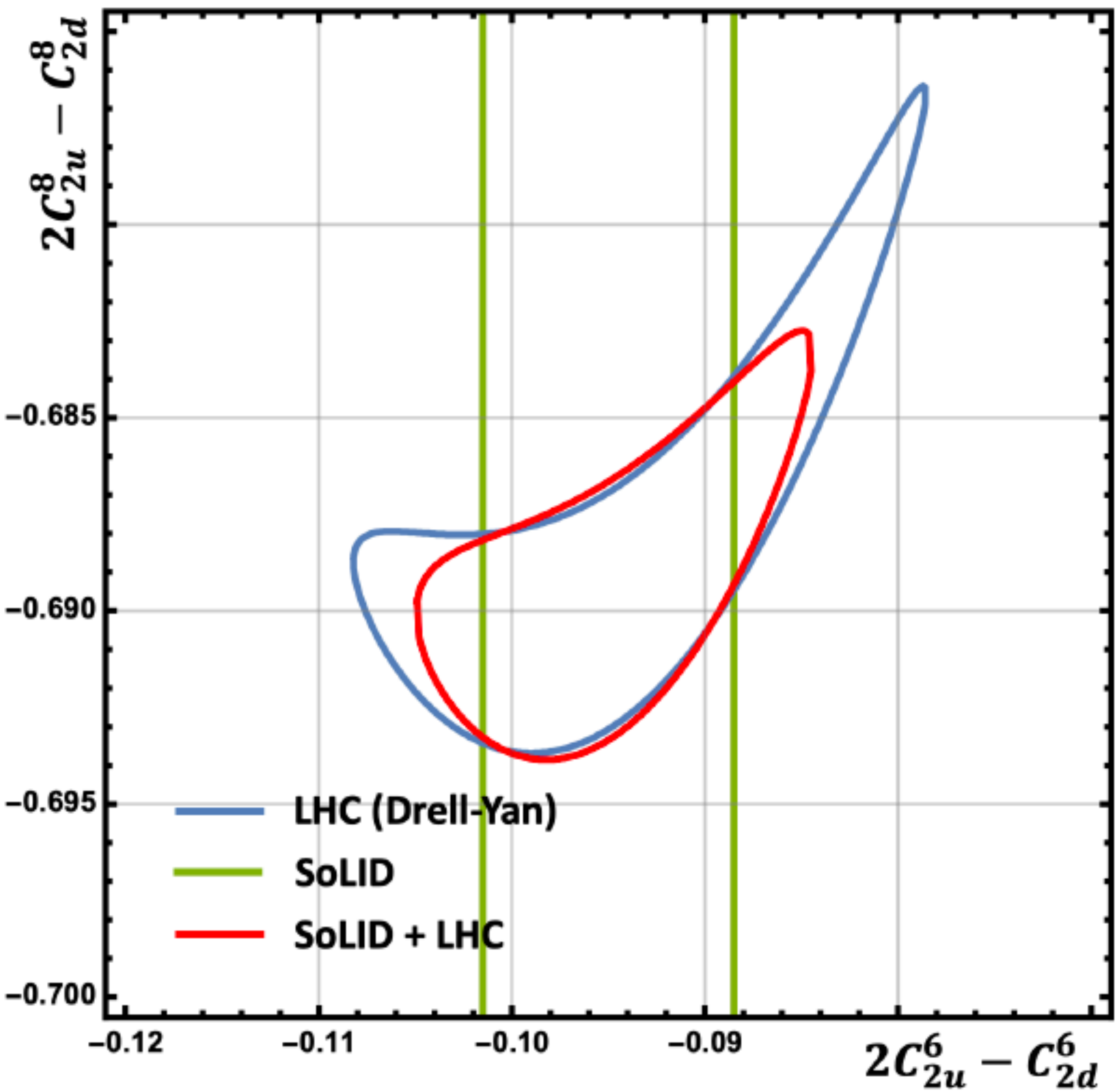
- Now consider an example in the SMEFT basis. Much stronger P2 constraints.
- Example of a generic trend: projected C_1 constraints from P2 are so strong that any SMEFT coefficient that has a projection into C_1 will be dominated by P2 bounds

Results: SMEFT basis



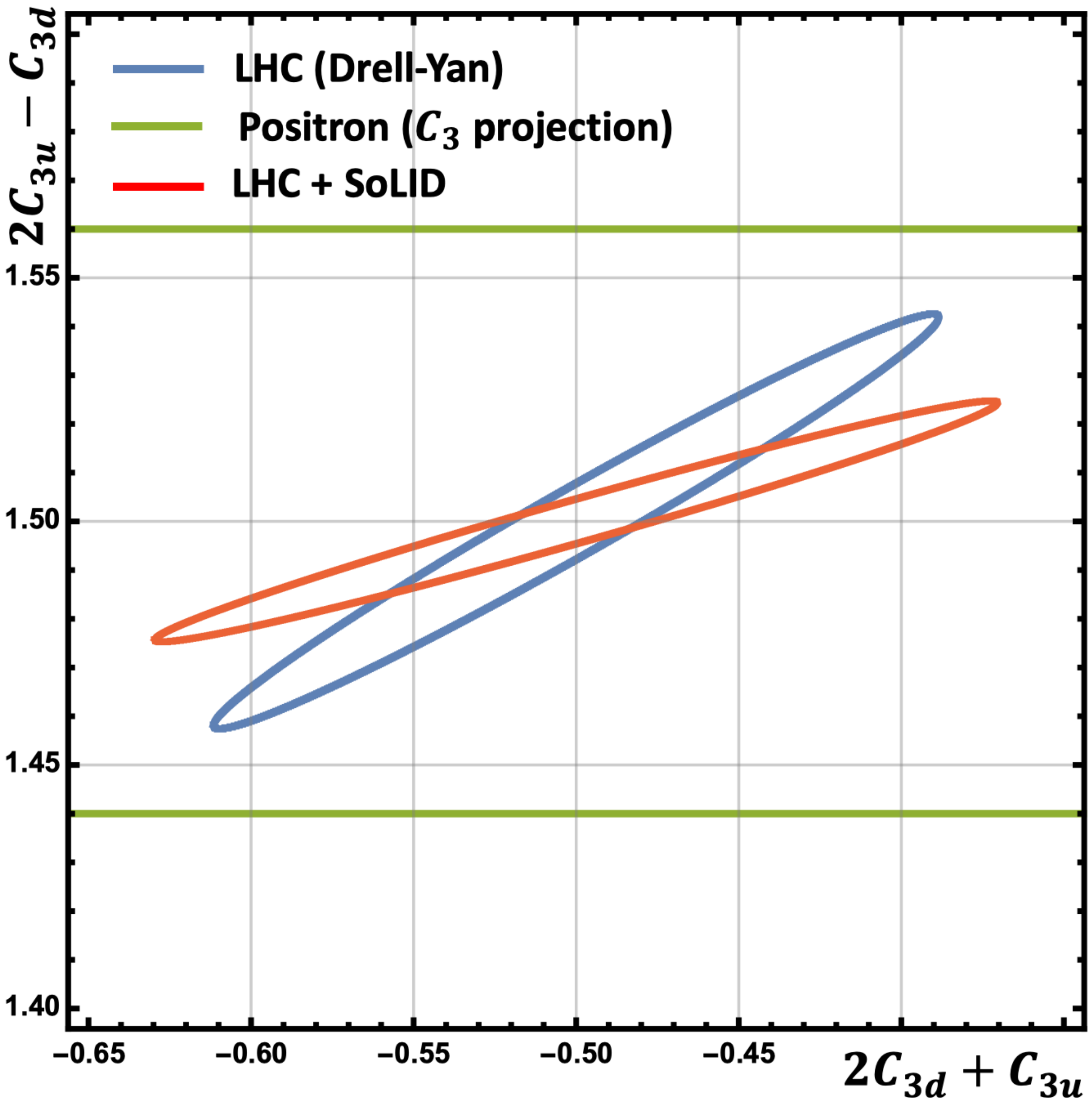
- Here is an example in the SMEFT basis where there is a flat direction for P2. It occurs because the chosen SMEFT coefficients has a direction where the C_l is vector-like
- SoLID again provides important information in this case

Results: Dimension-8



- Dimension-8 effects completely decouple in low-energy experiments; can help break degeneracies between dim-6 and dim-8 that occur at the LHC
- Here is an example where SoLID can help remove parameter space allowed with only LHC data

Results: positrons



- There is also a proposal to measure positron of deuterium to measure the electron-positron asymmetry
- Gives access to

$$\frac{G_F}{\sqrt{2}} C_{3q} (\bar{e}\gamma^{\mu}\gamma_5 e)(\bar{q}\gamma_{\mu}\gamma_5 q)$$

- Already probed by LHC; SoLID doesn't add much

Main points

- Low-energy parity violating experiments can probe BSM effects difficult to access at the LHC.
- The focus here has been on an EFT parameterization of four-fermion operators. Accessible with Drell-Yan at the LHC, but the structure of the DY matrix elements makes it blind to certain combinations of coefficients.
- SoLID and P2 can provide orthogonal constraints that give a more complete coverage of the possible BSM parameters.
- Can the coverage of parameter space be improved with LHC data alone? In principle yes, with precision measurements of new observables; angular distributions at high invariant mass can break the degeneracies that occur in DY.
- Higher energy or luminosity measurements of invariant mass or p_T distributions alone won't help.