Drell-Yan Tails Beyond the Standard Model

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Outline:

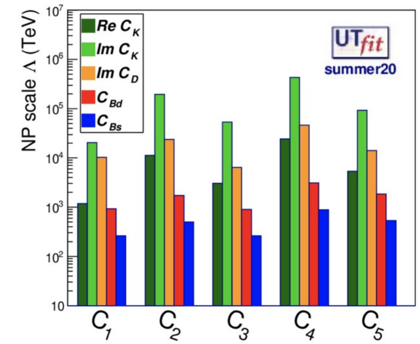
- Motivations [Flavor at High-p_T colliders]
- General framework for describing Drell-Yan Tails BSM
- HighPT
- Some results for SMEFT / Leptoquarks

- Based on papers [2207.10714] [2207.10756]

In collaboration with L. Allwicher, F. Jaffredo, O. Sumensari and F. Wilsch

[23.XX.XXX] [24.XX.XXX] ...

Motivations



$B - \bar{B}$

$\Lambda > \mathcal{O}(10^5)$ TeV

- New Physics at the TeV scale needs a non-trivial flavor structure to be consistent with flavor experiments

SMEFT assumption:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d=1}^{\infty} \frac{\mathcal{C}_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d$$

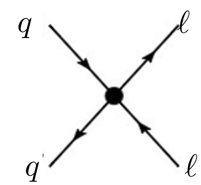
$d = 6,\ n_f = 1 \implies$ 59 operators

$d = 6,\ n_f = 3 \implies$ 2599 operators

Proliferation for 3 flavors mostly in four-fermion category $\boxed{\psi^4}$ $[\mathcal{O}_I^{(6)}]_{ijkl} = (\bar{\psi}_i \Gamma^I \psi_j)(\bar{\psi}_k \Gamma^I \psi_l)$

- Semi-leptonic operators can be used as testing ground for the flavor structure of BSM

$(\bar{\ell}_i \Gamma^I \ell_j)(\bar{q}_k \Gamma^I q_l)$

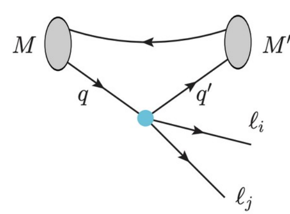


Meson decays

$M \to M'\ell\ell$

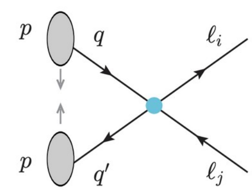
$M \to \ell\ell$

$\ell \to \ell' M$



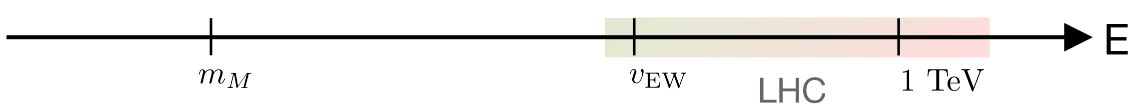
crossing symmetry

Drell-Yan scattering



$pp \to \ell\ell$

$pp \to \ell\nu$



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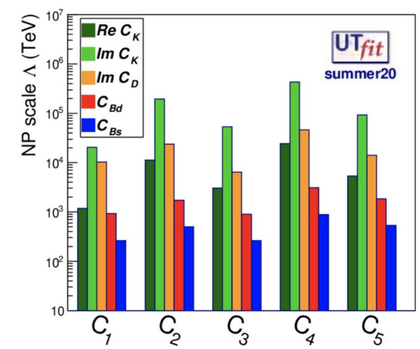

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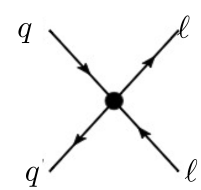

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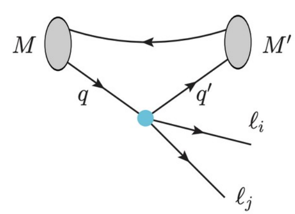
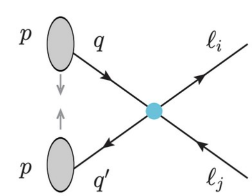


crossing symmetry

this talk

Drell-Yan scattering



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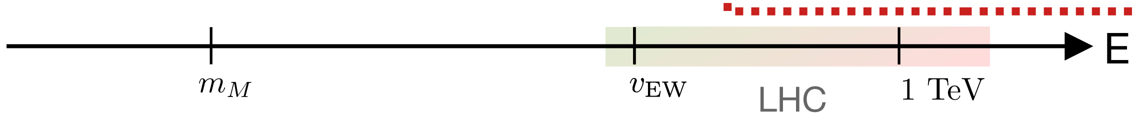


LHC complements low-energy flavor

Complementarity: High-p_T LHC $\leftrightarrow$ Low-p_T Flavor

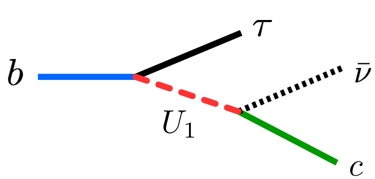
- *Example: RD(*) anomalies* $b \to c\tau\nu$

$$\mathrm{R}_{D^{(*)}} = \frac{\mathcal{B}(B \to D(*)\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

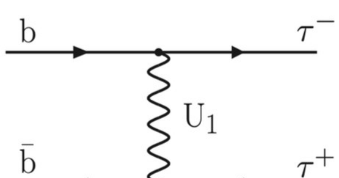
$$U_1^\mu \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

$$\mathcal{L}_{\rm int} = [x_1^L]_{i\alpha}\, U_1^\mu (\bar{q}_i \gamma_\mu \ell_\alpha) + \text{h.c}$$

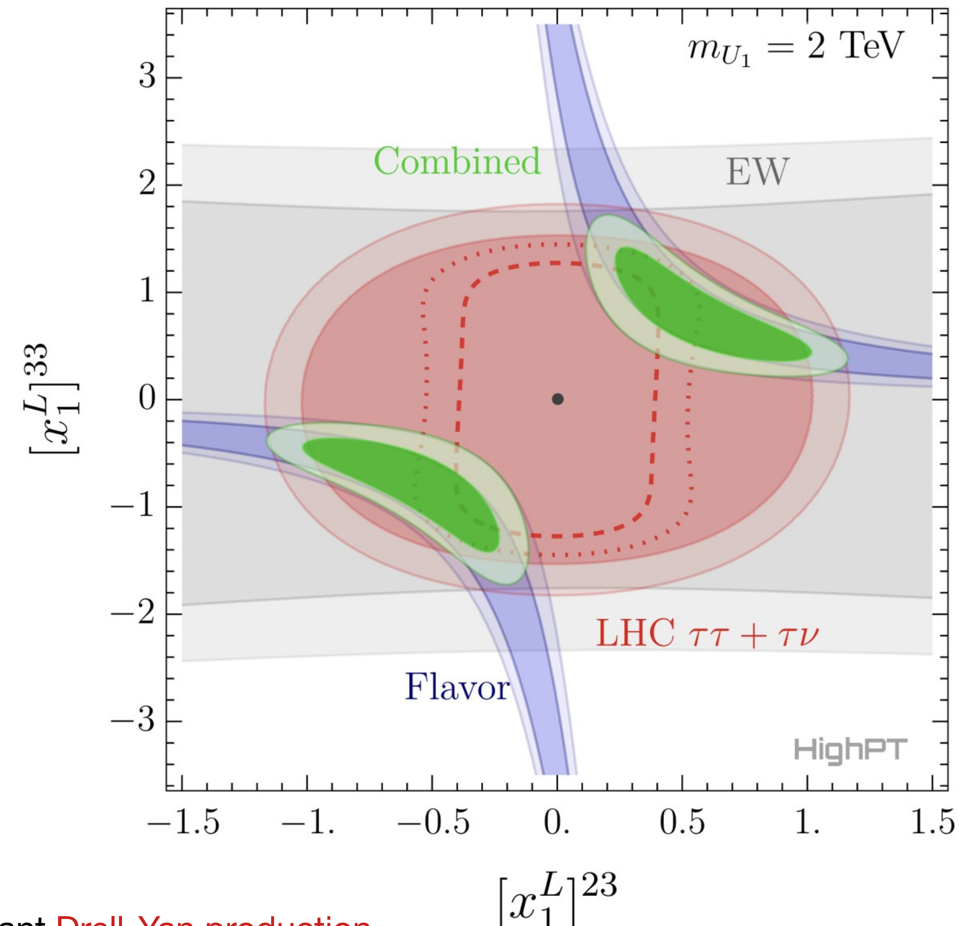
$b \to c\tau\nu$



$p\bar{p} \to \tau^+\tau^-$



Non-resonant Drell-Yan production



Flavor at High-p_T colliders?

High-p_T LHC can probe generic ***semi-leptonic operators***

[1609.07138] [1704.09015] [1811.12260] [1807.04753] ...
[1912.00425] [2003.12421] [2008.07541] [2212.10497]...

<u>Ultimate goal</u>:
Extract combined limits on BSM
Physics for arbitrary flavor structures

We need the full Drell-Yan tails likelihood

Allwicher, DAF, Jaffredo,
Sumensari, Wilsch [2207.10756]

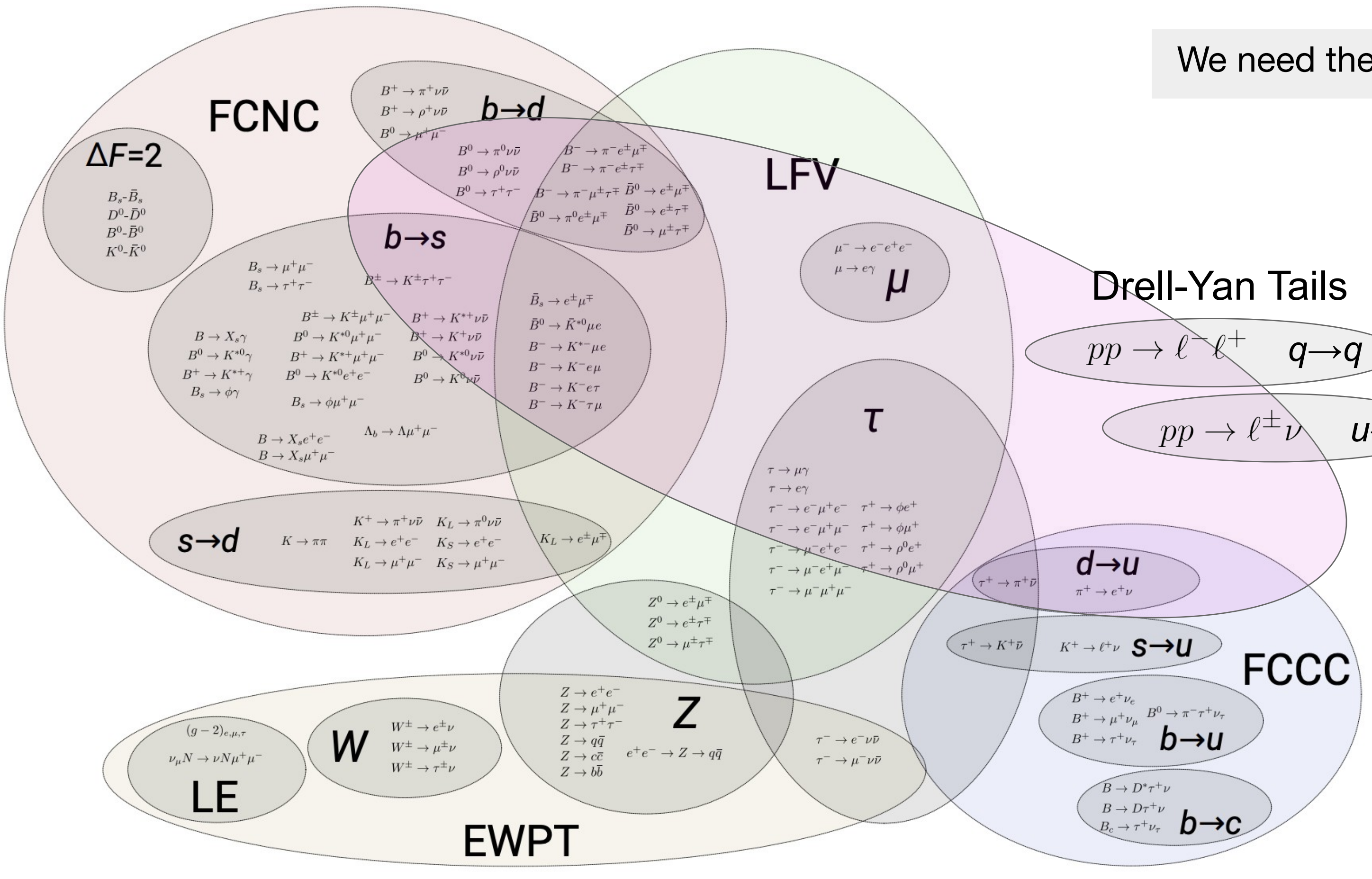
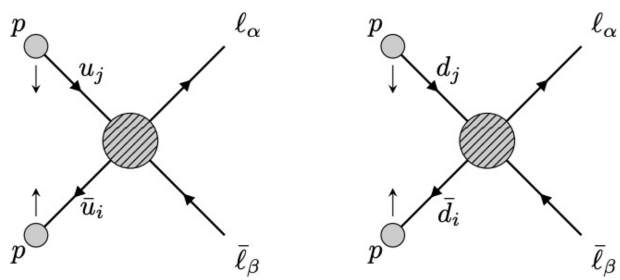


Image by D. Straub

Drell-Yan Tails: Framework

Drell-Yan Tails

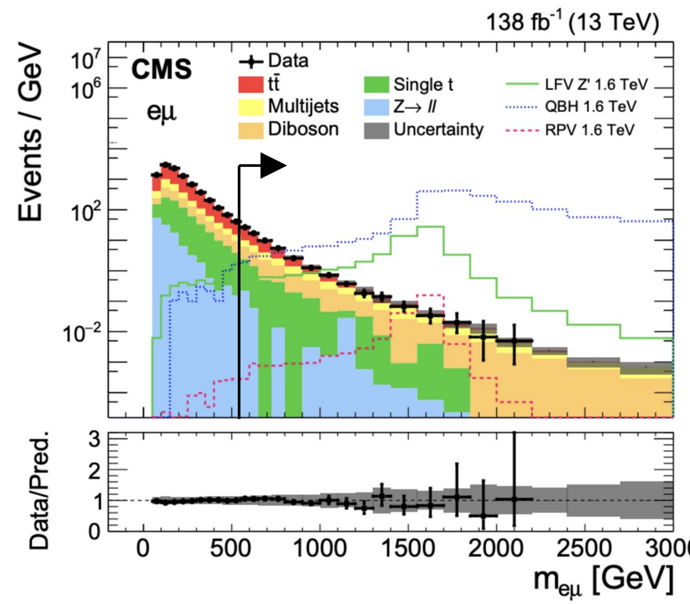
- Neutral Drell-Yan process: $pp \to \ell_\alpha^+ \ell_\beta^-$



$u_i \bar{u}_j \to \ell_\alpha \bar{\ell}_\beta$ $\quad$ $d_i \bar{d}_j \to \ell_\alpha \bar{\ell}_\beta$

invariant-mass tails

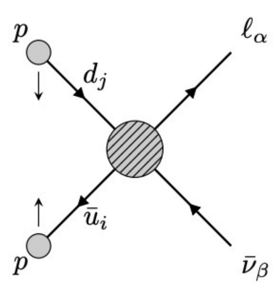
$$\frac{d\sigma}{dm_{\ell\ell}}$$



[latin] Quark-flavor: $i, j = 1\,2\,(3)$

[greek] Lepton-flavor: $\alpha, \beta = 1\;2\;3$

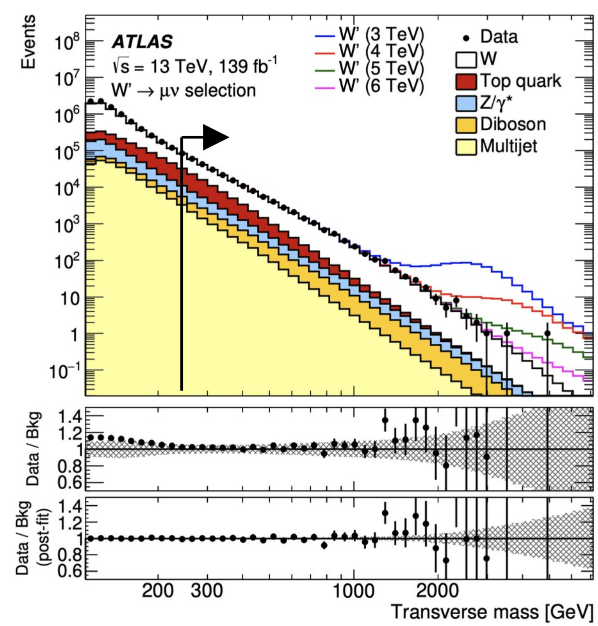
- Charged Drell-Yan process: $pp \to \ell_\alpha^\pm \nu_\beta$



$d_i \bar{u}_j \to \ell_\alpha \bar{\nu}_\beta$

p_T tails

$$\frac{d\sigma}{dp_T^\ell}$$



Flavor at the LHC

- In Drell-Yan there are two sources of flavor (factorization theorem):

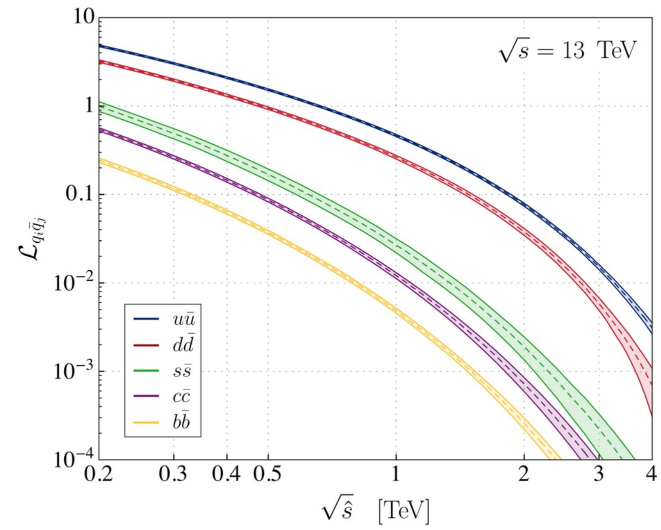
$$\sigma(pp \to \ell^\alpha \ell^\beta) = \mathcal{L}_{ij} \otimes \hat{\sigma}^{ij\alpha\beta}$$

Non-perturbative: *parton-parton Luminosity functions*

$$\mathcal{L}_{q_i \bar{q}_j}(\tau) = \tau \int_\tau^1 \frac{\mathrm{d}x}{x} \left[f_{q_i}(x, \mu_F) f_{\bar{q}_j}(\tau/x, \mu_F) + (i \leftrightarrow j) \right]$$

$$\tau = \hat{s}/s$$

- 5 active flavors in proton
- PDFs are very hierarchical
- Heavy flavor are quite supressed!



Hard partonic scattering cross-section:

$$\hat{\sigma}_{ij\alpha\beta} \equiv \hat{\sigma}(q_i \bar{q}_j \to \ell_\alpha \bar{\ell}_\beta)$$

$$\mathcal{A}_{ij\alpha\beta} = [\mathcal{C}_I]_{ij\alpha\beta} (\bar{q}_i \Gamma^I q_j)(\bar{\ell}_\alpha \Gamma_I \ell_\beta)$$

Underlying flavor structure

Example: 4-fermion contact interaction

$$\hat{\sigma}_{ij\alpha\beta} \propto \frac{\hat{s}}{\Lambda^4} |\mathcal{C}_{ij\alpha\beta}|^2$$

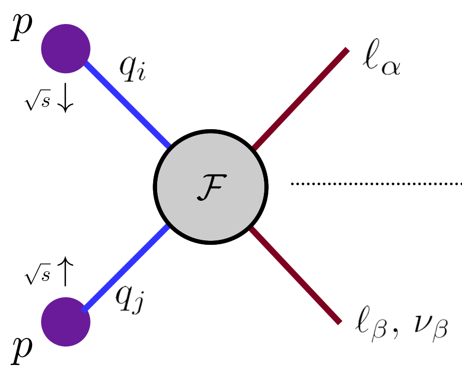
Energy-growth can overcome heavy flavor PDF suppression

- Drell-Yan are flavor semi-inclusive.
  - inclusive in quark-flavor
  - exclusive in lepton-flavor (LHC can resolve leptons)

Drell-Yan Form Factors

Allwicher, DAF, Jaffredo, Sumensari, Wilsch [2207.10714]

- We introduce dimensionless Form Factors for 2→2 semi-leptonic scattering: $\mathcal{A} = \mathcal{A}(\mathcal{F})$



$$u_i\bar{u}_j \to \ell_\alpha\bar{\ell}_\beta \ : \ \left[\mathcal{F}_I^{XY,uu}(\hat{s},\hat{t})\right]_{\alpha\beta ij}$$

$$d_i\bar{d}_j \to \ell_\alpha\bar{\ell}_\beta \ : \ \left[\mathcal{F}_I^{XY,dd}(\hat{s},\hat{t})\right]_{\alpha\beta ij}$$

$$u_i\bar{d}_j \to \ell_\alpha\bar{\nu}_\beta \ : \ \left[\mathcal{F}_I^{XY,ud}(\hat{s},\hat{t})\right]_{\alpha\beta ij}$$

$\hat{s} = (p_\alpha + p_\beta)^2 = k^2$
$\hat{t} = (p_i - p_\alpha)^2$ Mandelstams variables

$X, Y \in \{L, R\}$ lepton/quark chiralities

$I \in \{S, V, T, D_\ell, D_q\}$ 5 Lorentz structures

$ij\alpha\beta$ flavor 4-tensors

- These Form Factors parametrize both local and non-local semi-leptonic interactions.
- Most general Lorentz/Gauge invariant amplitude for $q_i\bar{q}_j \to \ell_\alpha\bar{\ell}_\beta$:

$$\begin{aligned}
\mathcal{A}_{ij\alpha\beta} = \frac{1}{v^2}\sum_{XY}\Big[& (\bar{\ell}_\alpha \mathbb{P}_X \ell_\beta)(\bar{q}_i \mathbb{P}_Y q_j)\,[\mathcal{F}_S^{XY,qq}(\hat{s},\hat{t})]_{\alpha\beta ij} && \text{Scalar} \\
& + (\bar{\ell}_\alpha \gamma^\mu \mathbb{P}_X \ell_\beta)(\bar{q}_i \gamma_\mu \mathbb{P}_Y q_j)\,[\mathcal{F}_V^{XY,qq}(\hat{s},\hat{t})]_{\alpha\beta ij} && \text{Vector} \\
& + (\bar{\ell}_\alpha \sigma^{\mu\nu} \mathbb{P}_X \ell_\beta)(\bar{q}_i \sigma_{\mu\nu} \mathbb{P}_Y q_j)\,[\mathcal{F}_T^{XY,qq}(\hat{s},\hat{t})]_{\alpha\beta ij} && \text{Tensor} \\
& + (\bar{\ell}_\alpha \gamma^\mu \mathbb{P}_X \ell_\beta)(\bar{q}_i \sigma_{\mu\nu} \mathbb{P}_Y q_j)\,\frac{ik^\nu}{v}\,[\mathcal{F}_{D_q}^{XY,qq}(\hat{s},\hat{t})]_{\alpha\beta ij} && \\
& + (\bar{\ell}_\alpha \sigma^{\mu\nu} \mathbb{P}_X \ell_\beta)(\bar{q}_i \gamma_\mu \mathbb{P}_Y q_j)\,\frac{ik_\nu}{v}\,[\mathcal{F}_{D_\ell}^{XY,qq}(\hat{s},\hat{t})]_{\alpha\beta ij}\Big] && \text{Dipoles}
\end{aligned}$$

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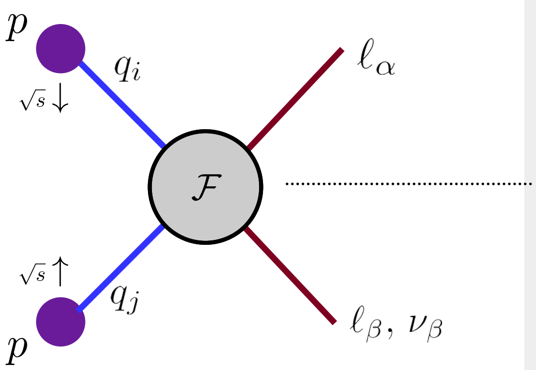

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- Drell-Yan differential partonic cross-sections:

$$\mathrm{d}\hat{\sigma}(\bar{q}_i q_j \to \ell_\alpha^- \ell_\beta^+) = \frac{\mathrm{d}\hat{t}}{48\pi\, v^4} \sum_{XY,IJ} M_{IJ}^{XY}(\hat{t}/\hat{s}) \left[\mathcal{F}_I^{XY}(\hat{s},\hat{t})\right]_{\alpha\beta ij} \left[\mathcal{F}_J^{XY\,*}(\hat{s},\hat{t})\right]_{\alpha\beta ij}$$

$$M_{VV}^{XY}(x) = (1+2x)\delta^{XY} + x^2$$
$$M_{SS}^{XY}(x) = 1/4$$
$$M_{ST}^{XY}(x) = -(1+2x)\delta^{XY}$$
$$M_{TT}^{XY}(x) = 4(1+2x)^2\delta^{XY}$$
$$M_{DD}^{XY}(x) = -\frac{s}{v^2}x(1+x)$$

interference between scalar and tensor FF ⟶ (M_{ST}^{XY})

$I \in \{S, V, T, D_\ell, D_q\}$

$$\mathcal{F}(\hat{s},\hat{t}) \;=\; \mathcal{F}_{\text{Reg}}(\hat{s},\hat{t}) \;+\; \mathcal{F}_{\text{Poles}}(\hat{s},\hat{t},\Omega_k) \qquad \hat{s},\hat{t}\in\mathbb{C}$$

Analytic function

Singular function with isolated simple poles $\Omega_k \in \mathbb{C}$
in complex Mandelstam planes

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Analytic function

Singular function with *isolated simple poles* $\Omega_k \in \mathbb{C}$
in complex Mandelstam planes

$$\begin{cases} \mathcal{F}_{\rm Reg}(\hat{s},\hat{t}) = \displaystyle\sum_{n,m=0}^{\infty} \mathcal{F}_{(n,m)} \left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m \\ \mathcal{F}_{\rm Poles}(\hat{s},\hat{t}) = \displaystyle\sum_a \frac{v^2\,\mathcal{S}_{(a)}}{\hat{s}-\Omega_a} + \sum_b \frac{v^2\,\mathcal{T}_{(b)}}{\hat{t}-\Omega_b} + \sum_c \frac{v^2\,\mathcal{U}_{(c)}}{\hat{u}+\Omega_c} \end{cases}$$

Mandelstam power expansion:
within convergence radius $\hat{s},\hat{t} \leq \Lambda^2$
[unresolved d.o.f] local interactions

[resolved d.o.f] massive tree-level mediators

$$\Omega_k = m_k^2 - i m_k \Gamma_k$$

s-channel t-channel u-channel

$$\hat{u} = -\hat{s} - \hat{t}$$

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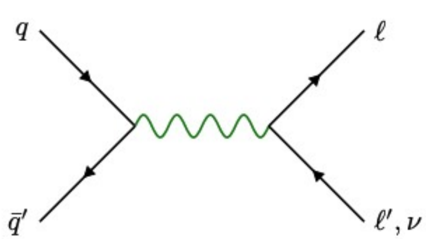
- *Example: SM* $\mathcal{F}_{\rm Reg}(\hat{s},\hat{t}) = 0$ *only s-channel vector poles via guage boson exchange* $\Omega_a \quad a \in \{\gamma, Z, W^\pm\}$



$$\begin{cases} q_i\bar{q}_j \to \gamma^* \to \ell_\alpha^+\ell_\beta^- & \left[\mathcal{S}^{XY,qq}_{V\,(\gamma)}\right]_{\alpha\beta ij} = -4\pi\alpha\, Q_q\, \delta_{\alpha\beta}\,\delta_{ij} \\ q_i\bar{q}_j \to Z \to \ell_\alpha^+\ell_\beta^- & \left[\mathcal{S}^{XY,qq}_{V\,(Z)}\right]_{\alpha\beta ij} = \dfrac{4\pi\alpha}{c_W^2 s_W^2}\, g_\ell^X g_q^Y \,\delta_{\alpha\beta}\delta_{ij} \\ u_i\bar{d}_j \to W^\pm \to \ell_\alpha^\pm \nu_\beta^- & \left[\mathcal{S}^{XY,ud}_{V\,(W)}\right]_{\alpha\beta ij} = \dfrac{1}{2} g^2\, \delta_{\alpha\beta}\, [V_{\rm CKM}]_{ij} \end{cases}$$

$$\mathcal{S}_{V,(a)} = \mathcal{S}_{{\rm SM},(a)} + \delta\mathcal{S}_{V,(a)}$$ *gauge coupling modifications*

$$\mathcal{F}(\hat{s},\hat{t}) = \mathcal{F}_{\rm Reg}(\hat{s},\hat{t}) + \mathcal{F}_{\rm Poles}(\hat{s},\hat{t},\Omega_k) \qquad \hat{s},\hat{t}\in\mathbb{C}$$

Analytic function

Singular function with isolated simple poles $\Omega_k \in \mathbb{C}$ *in complex Mandelstam planes*

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$$\Omega_k = m_k^2 - i m_k \Gamma_k$$

s-channel t-channel u-channel

$$\hat{u} = -\hat{s} - \hat{t}$$

- In practice, pole residues are analytic functions of the Mandelstam variables

$$\begin{cases} \mathcal{S}_{(a)}(\hat{s}) \\ \mathcal{T}_{(b)}(\hat{t}) \\ \mathcal{U}_{(c)}(\hat{u}) \end{cases}$$

Remove Mandelstam dependence with partial fraction decomposition

$$\frac{f(\hat{z})}{\hat{z}-\Omega} = \frac{f(\Omega)}{\hat{z}-\Omega} + g(\hat{z},\Omega)$$

reabsorb into $\mathcal{F}_{\rm Reg}(\hat{s},\hat{t})$ redefintion

- Parametrization captures all tree-level effects into regular coefficients and pole residues: $\mathcal{F}_{(n,m)}$ $\mathcal{S}_{(a)}$ $\mathcal{T}_{(b)}$ $\mathcal{U}_{(c)}$

- *All energy-growing interactions (local and non-local) are systematicaly organized in the analytic part* $\mathcal{F}_{\rm Reg}(\hat{s},\hat{t})$

Form factors give a unified description of BSM models:

$$\mathcal{F}(\hat{s},\hat{t}) = \sum_{n,m=0}^{\infty} \mathcal{F}_{(n,m)} \left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m + \sum_a \frac{v^2\,\mathcal{S}_{(a)}}{\hat{s}-\Omega_a} + \sum_b \frac{v^2\,\mathcal{T}_{(b)}}{\hat{t}-\Omega_b} - \sum_c \frac{v^2\,\mathcal{U}_{(c)}}{\hat{s}+\hat{t}+\Omega_c} \qquad \Omega \in \mathbb{C}$$

- SMEFT $d \geq 6$ (energy-growth)

- SMEFT $d \geq 4$
- new colorless mediators

- leptoquarks

SMEFT

- SM effective Lagrangian: $\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{\mathcal{C}_i^6}{\Lambda^2}\mathcal{O}_i^6 + \sum_i \frac{\mathcal{C}_i^8}{\Lambda^4}\mathcal{O}_i^8 + \cdots$

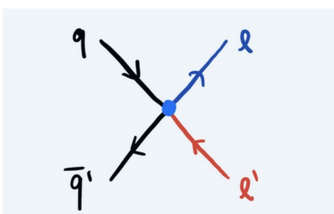
Consistent truncation at $\mathcal{O}(\Lambda^{-4})$ *requires d=6 and d=8 operators*

$$d\sigma \sim |\mathcal{A}_{\rm SM}|^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{C}_i^6 \mathcal{A}_i^6 \mathcal{A}_{\rm SM}^* + \frac{1}{\Lambda^4}\left(\sum_{ij}\mathcal{C}_i^6\mathcal{C}_j^{6*}\mathcal{A}_i^6\mathcal{A}_j^{6*} + \sum_i \mathcal{C}_i^8 \mathcal{A}_i^8 \mathcal{A}_{\rm SM}^*\right) + \mathcal{O}\left(\frac{1}{\Lambda^6}\right).$$

- Operator classes for Drell-Yan at d=6 in *Warsaw basis*:

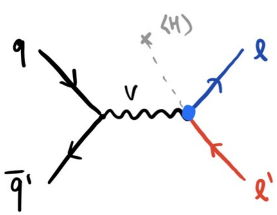
Grzadkowski et al. [2010]
Buchmuller et al. [1985]

ψ^4



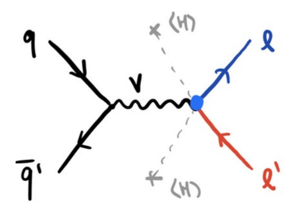
$\hat{\sigma} \sim \hat{s}$ *O(500) semi-leptonic energy-growing operators!*

$\psi^2 X H^2$



$\hat{\sigma} \sim \text{const}$

$\psi^2 H^2 D$



$\hat{\sigma} \sim 1/\hat{s}$

$d=6$	ψ^4	$pp \to \ell\ell$	$pp \to \ell\nu$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{q}_i\gamma_\mu q_j)$	✓	–
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_\alpha\gamma^\mu\tau^I l_\beta)(\bar{q}_i\gamma_\mu\tau^I q_j)$	✓	✓
$\mathcal{O}_{lu}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{u}_i\gamma_\mu u_j)$	✓	–
$\mathcal{O}_{ld}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{d}_i\gamma_\mu d_j)$	✓	–
$\mathcal{O}_{eq}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{q}_i\gamma_\mu q_j)$	✓	–
$\mathcal{O}_{eu}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{u}_i\gamma_\mu u_j)$	✓	–
$\mathcal{O}_{ed}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{d}_i\gamma_\mu d_j)$	✓	–
$\mathcal{O}_{ledq}$ + h.c.	$(\bar{l}_\alpha e_\beta)(\bar{d}_i q_j)$	✓	✓
$\mathcal{O}_{lequ}^{(1)}$ + h.c.	$(\bar{l}_\alpha e_\beta)\varepsilon(\bar{q}_i u_j)$	✓	✓
$\mathcal{O}_{lequ}^{(3)}$ + h.c.	$(\bar{l}_\alpha\sigma^{\mu\nu} e_\beta)\varepsilon(\bar{q}_i\sigma_{\mu\nu} u_j)$	✓	✓

- d=8 semi-leptonic operators: Murphy [2005.00059]

$d=8$	$\psi^4 H^2$
$\mathcal{O}^{(1)}_{L^2Q^2H^2}$	$(\bar{L}_\alpha\gamma^\mu L_\beta)(\bar{Q}_i\gamma_\mu Q_j)(H^\dagger H)$
$\mathcal{O}^{(2)}_{L^2Q^2H^2}$	$(\bar{L}_\alpha\gamma^\mu\tau^I L_\beta)(\bar{Q}_i\gamma_\mu Q_j)(H^\dagger\tau^I H)$
$\mathcal{O}^{(3)}_{L^2Q^2H^2}$	$(\bar{L}_\alpha\gamma^\mu\tau^I L_\beta)(\bar{Q}_i\gamma_\mu\tau^I Q_j)(H^\dagger H)$
$\mathcal{O}^{(4)}_{L^2Q^2H^2}$	$(\bar{L}_\alpha\gamma^\mu L_\beta)(\bar{Q}_i\gamma_\mu\tau^I Q_j)(H^\dagger\tau^I H)$
$\mathcal{O}^{(5)}_{L^2Q^2H^2}$	$\epsilon^{IJK}(\bar{L}_\alpha\gamma^\mu\tau^I L_\beta)(\bar{Q}_i\gamma_\mu\tau^J Q_j)(H^\dagger\tau^K H$
$\mathcal{O}^{(1)}_{L^2u^2H^2}$	$(\bar{L}_\alpha\gamma^\mu L_\beta)(\bar{u}_i\gamma_\mu u_j)(H^\dagger H)$
$\mathcal{O}^{(2)}_{L^2u^2H^2}$	$(\bar{L}_\alpha\gamma^\mu\tau^I L_\beta)(\bar{u}_i\gamma_\mu u_j)(H^\dagger\tau^I H)$
$\mathcal{O}^{(1)}_{L^2d^2H^2}$	$(\bar{L}_\alpha\gamma^\mu L_\beta)(\bar{d}_i\gamma_\mu d_j)(H^\dagger H)$
$\mathcal{O}^{(2)}_{L^2d^2H^2}$	$(\bar{L}_\alpha\gamma^\mu\tau^I L_\beta)(\bar{d}_i\gamma_\mu d_j)(H^\dagger\tau^I H)$
$\mathcal{O}^{(1)}_{Q^2e^2H^2}$	$(\bar{Q}_i\gamma^\mu Q_j)(\bar{e}_\alpha\gamma_\mu e_\beta)(H^\dagger H)$
$\mathcal{O}^{(2)}_{Q^2e^2H^2}$	$(\bar{Q}_i\gamma^\mu\tau^I Q_j)(\bar{e}_\alpha\gamma_\mu e_\beta)(H^\dagger\tau^I H)$
$\mathcal{O}_{e^2u^2H^2}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{u}_i\gamma_\mu u_j)(H^\dagger H)$
$\mathcal{O}_{e^2d^2H^2}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{d}_i\gamma_\mu d_j)(H^\dagger H)$

$d=8$	$\psi^2 H^4 D$
$\mathcal{O}^{(1)}_{L^2H^4D}$	$i(\bar{L}_\alpha\gamma^\mu L_\beta)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}^{(2)}_{L^2H^4D}$	$i(\bar{L}_\alpha\gamma^\mu\tau^I L_\beta)[(H^\dagger\overleftrightarrow{D}^I_\mu H)(H^\dagger H)+(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger\tau^I H)]$
$\mathcal{O}^{(3)}_{L^2H^4D}$	$i\epsilon^{IJK}(\bar{L}_\alpha\gamma^\mu\tau^I L_\beta)(H^\dagger\overleftrightarrow{D}^J_\mu H)(H^\dagger\tau^K H)$
$\mathcal{O}^{(4)}_{L^2H^4D}$	$\epsilon^{IJK}(\bar{L}_\alpha\gamma^\mu\tau^I L_\beta)(H^\dagger\tau^J H)(D_\mu H)^\dagger\tau^K H$
$\mathcal{O}^{(1)}_{Q^2H^4D}$	$i(\bar{Q}_i\gamma^\mu Q_j)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}^{(2)}_{Q^2H^4D}$	$i(\bar{Q}_i\gamma^\mu\tau^I Q_j)[(H^\dagger\overleftrightarrow{D}^I_\mu H)(H^\dagger H)+(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger\tau^I H)]$
$\mathcal{O}^{(3)}_{Q^2H^4D}$	$i\epsilon^{IJK}(\bar{Q}_i\gamma^\mu\tau^I Q_j)(H^\dagger\overleftrightarrow{D}^J_\mu H)(H^\dagger\tau^K H)$
$\mathcal{O}^{(4)}_{Q^2H^4D}$	$\epsilon^{IJK}(\bar{Q}_i\gamma^\mu\tau^I Q_j)(H^\dagger\tau^J H)(D_\mu H)^\dagger\tau^K H$
$\mathcal{O}_{e^2H^4D}$	$i(\bar{e}_\alpha\gamma^\mu e_\beta)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}_{u^2H^4D}$	$i(\bar{u}_i\gamma^\mu u_j)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}_{d^2H^4D}$	$i(\bar{d}_i\gamma^\mu d_j)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}_{udH^4D}$ + h.c.	$i(\bar{u}_i\gamma^\mu d_j)(\tilde{H}^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$

$d=8$	$\psi^4 D^2$
$\mathcal{O}^{(1)}_{L^2Q^2D^2}$	$D^\nu(\bar{L}_\alpha\gamma^\mu L_\beta)D_\nu(\bar{Q}_i\gamma_\mu Q_j)$
$\mathcal{O}^{(2)}_{L^2Q^2D^2}$	$(\bar{L}_\alpha\gamma^\mu\overleftrightarrow{D}^\nu L_\beta)(\bar{Q}_i\gamma_\mu\overleftrightarrow{D}_\nu Q_j)$
$\mathcal{O}^{(3)}_{L^2Q^2D^2}$	$D^\nu(\bar{L}_\alpha\gamma^\mu\tau^I L_\beta)D_\nu(\bar{Q}_i\gamma_\mu\tau^I Q_j)$
$\mathcal{O}^{(4)}_{L^2Q^2D^2}$	$(\bar{L}_\alpha\gamma^\mu\overleftrightarrow{D}^{I\nu} L_\beta)(\bar{Q}_i\gamma_\mu\overleftrightarrow{D}^I_\nu Q_j)$
$\mathcal{O}^{(1)}_{L^2u^2D^2}$	$D^\nu(\bar{L}_\alpha\gamma^\mu L_\beta)D_\nu(\bar{u}_i\gamma_\mu u_j)$
$\mathcal{O}^{(2)}_{L^2u^2D^2}$	$(\bar{L}_\alpha\gamma^\mu\overleftrightarrow{D}^\nu L_\beta)(\bar{u}_i\gamma_\mu\overleftrightarrow{D}_\nu u_j)$
$\mathcal{O}^{(1)}_{L^2d^2D^2}$	$D^\nu(\bar{L}_\alpha\gamma^\mu L_\beta)D_\nu(\bar{d}_i\gamma_\mu d_j)$
$\mathcal{O}^{(2)}_{L^2d^2D^2}$	$(\bar{L}_\alpha\gamma^\mu\overleftrightarrow{D}^\nu L_\beta)(\bar{d}_i\gamma_\mu\overleftrightarrow{D}_\nu d_j)$
$\mathcal{O}^{(1)}_{Q^2e^2D^2}$	$D^\nu(\bar{Q}_i\gamma^\mu Q_j)D_\nu(\bar{e}_\alpha\gamma_\mu e_\beta)$
$\mathcal{O}^{(2)}_{Q^2e^2D^2}$	$(\bar{Q}_i\gamma^\mu\overleftrightarrow{D}^\nu Q_j)(\bar{e}_\alpha\gamma_\mu\overleftrightarrow{D}_\nu e_\beta)$
$\mathcal{O}^{(1)}_{e^2u^2D^2}$	$D^\nu(\bar{e}_\alpha\gamma^\mu e_\beta)D_\nu(\bar{u}_i\gamma_\mu u_j)$
$\mathcal{O}^{(2)}_{e^2u^2D^2}$	$(\bar{e}_\alpha\gamma^\mu\overleftrightarrow{D}^\nu e_\beta)(\bar{u}_i\gamma_\mu\overleftrightarrow{D}_\nu u_j)$
$\mathcal{O}^{(1)}_{e^2d^2D^2}$	$D^\nu(\bar{e}_\alpha\gamma^\mu e_\beta)D_\nu(\bar{d}_i\gamma_\mu d_j)$
$\mathcal{O}^{(2)}_{e^2d^2D^2}$	$(\bar{e}_\alpha\gamma^\mu\overleftrightarrow{D}^\nu e_\beta)(\bar{d}_i\gamma_\mu\overleftrightarrow{D}_\nu d_j)$

$d=8$	$\psi^2 H^2 D^3$
$\mathcal{O}^{(1)}_{L^2H^2D^3}$	$i(\bar{L}_\alpha\gamma^\mu D^\nu L_\beta)\,(D_{(\mu}D_{\nu)}H)^\dagger H$
$\mathcal{O}^{(2)}_{l^2H^2D^3}$	$i(\bar{l}_\alpha\gamma^\mu D^\nu l_\beta)\,H^\dagger(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(3)}_{L^2H^2D^3}$	$i(\bar{l}_\alpha\gamma^\mu\tau^I D^\nu l_\beta)\,(D_{(\mu}D_{\nu)}H)^\dagger\tau^I H)$
$\mathcal{O}^{(4)}_{L^2H^2D^3}$	$i(\bar{l}_\alpha\gamma^\mu\tau^I D^\nu l_\beta)\,H^\dagger\tau^I(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(1)}_{e^2H^2D^3}$	$i(\bar{e}_\alpha\gamma^\mu D^\nu e_\beta)\,(D_{(\mu}D_{\nu)}H)^\dagger H)$
$\mathcal{O}^{(2)}_{e^2H^2D^3}$	$i(\bar{e}_\alpha\gamma^\mu D^\nu e_\beta)\,H^\dagger(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(1)}_{Q^2H^2D^3}$	$i(\bar{Q}_i\gamma^\mu D^\nu Q_j)\,(D_{(\mu}D_{\nu)}H)^\dagger H$
$\mathcal{O}^{(2)}_{Q^2H^2D^3}$	$i(\bar{Q}_i\gamma^\mu D^\nu Q_j)\,H^\dagger(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(3)}_{Q^2H^2D^3}$	$i(\bar{Q}_i\gamma^\mu\tau^I D^\nu Q_j)\,(D_{(\mu}D_{\nu)}H)^\dagger\tau^I H$
$\mathcal{O}^{(4)}_{Q^2H^2D^3}$	$i(\bar{Q}_i\gamma^\mu\tau^I D^\nu Q_j)\,H^\dagger\tau^I(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(1)}_{u^2H^2D^3}$	$i(\bar{u}_i\gamma^\mu D^\nu u_j)\,(D_{(\mu}D_{\nu)}H)^\dagger H$
$\mathcal{O}^{(2)}_{u^2H^2D^3}$	$i(\bar{u}_i\gamma^\mu D^\nu u_j)\,H^\dagger(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(1)}_{d^2H^2D^3}$	$i(\bar{d}_i\gamma^\mu D^\nu d_j)\,(D_{(\mu}D_{\nu)}H)^\dagger H$
$\mathcal{O}^{(2)}_{d^2H^2D^3}$	$i(\bar{d}_i\gamma^\mu D^\nu d_j)\,H^\dagger(D_{(\mu}D_{\nu)}H)$

$\psi^4 D^2$ *energy-growing operators at d=8*

~ 300 parameters d=8

$\mathcal{O}(\Lambda^{-4})$ effects

- The SMEFT for scattering is a double expansion in two small parameters $\frac{E}{\Lambda}, \frac{v}{\Lambda}$

$$\mathcal{F}_{\mathrm{Reg}}(\hat{s},\hat{t}) = \sum_{n,m=0}^{\infty} \mathcal{F}_{(n,m)} \left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m$$

The regular form factor coefficients and the pole residues are infinite series in $\frac{v}{\Lambda}$

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The regular form factor coefficients and the pole residues are infinite series in $\frac{v}{\Lambda}$

$$\mathcal{F}_{(n,m)} = \sum_{d \geq 2(n+m+3)}^{\infty} \mathcal{C}^d_{(n,m)} \left(\frac{v}{\Lambda}\right)^{d-4}$$

*Linear combination of **d-dimensional** SMEFT Wilson coefficients*

- SMEFT Matching structure to egular Form Factors:

$n+m=0 \longleftarrow d = \mathbf{6}, \mathbf{8}, 10, \cdots$

$$\mathcal{F}_{(0,0)} = \mathcal{C}^6_{(0,0)} \frac{v^2}{\Lambda^2} + \mathcal{C}^8_{(0,0)} \frac{v^4}{\Lambda^4} + \mathcal{C}^{10}_{(0,0)} \frac{v^6}{\Lambda^6} \cdots$$

$n+m=1 \longleftarrow d = \mathbf{8}, 10, \cdots$

$$\mathcal{F}_{(1,0)} = \mathcal{C}^8_{(1,0)} \frac{v^4}{\Lambda^4} + \mathcal{C}^{10}_{(1,0)} \frac{v^6}{\Lambda^6} + \mathcal{C}^{12}_{(1,0)} \frac{v^8}{\Lambda^8} \cdots$$

$$\mathcal{F}_{(0,1)} = \mathcal{C}^8_{(0,1)} \frac{v^4}{\Lambda^4} + \mathcal{C}^{10}_{(0,1)} \frac{v^6}{\Lambda^6} + \cdots$$

$n+m=2 \longleftarrow d = 10, \cdots$

$$\mathcal{F}_{(1,1)} = \mathcal{C}^{10}_{(1,1)} \frac{v^6}{\Lambda^6} + \mathcal{C}^{12}_{(1,1)} \frac{v^8}{\Lambda^8} + \cdots$$

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$n+m=1 \longleftarrow d = \mathbf{8}, 10, \cdots$

$$\mathcal{F}_{(1,0)} = \mathcal{C}^8_{(1,0)} \frac{v^4}{\Lambda^4} + \mathcal{C}^{10}_{(1,0)} \frac{v^6}{\Lambda^6} + \mathcal{C}^{12}_{(1,0)} \frac{v^8}{\Lambda^8} \cdots$$

$$\mathcal{F}_{(0,1)} = \mathcal{C}^8_{(0,1)} \frac{v^4}{\Lambda^4} + \mathcal{C}^{10}_{(0,1)} \frac{v^6}{\Lambda^6} + \cdots$$

$n+m=2 \longleftarrow d = 10, \cdots$

$$\mathcal{F}_{(1,1)} = \mathcal{C}^{10}_{(1,1)} \frac{v^6}{\Lambda^6} + \mathcal{C}^{12}_{(1,1)} \frac{v^8}{\Lambda^8} + \cdots$$

- $d \leq 8 \implies$ truncate Mandelstam expantion at linear order

$$\mathcal{F}_{\text{Reg}}(\hat{s},\hat{t}) = \mathcal{F}_{(0,0)} + \mathcal{F}_{(1,0)} \frac{\hat{s}}{v^2} + \mathcal{F}_{(0,1)} \frac{\hat{t}}{v^2}$$

Matching for Vector Form Factors are more invoved

$$\mathcal{F}_V(\hat{s},\hat{t}) = \mathcal{F}_{V\,(0,0)} + \mathcal{F}_{V\,(1,0)}\frac{\hat{s}}{v^2} + \mathcal{F}_{V\,(0,1)}\frac{\hat{t}}{v^2} + \sum_{a\in\{\gamma,Z,W\}} \frac{v^2\left[\mathcal{S}_{\mathrm{SM}\,(a)} + \delta\mathcal{S}_{V\,(a)}\right]}{\hat{s} - m_a^2 - i m_a \Gamma_a}$$

$$\begin{cases} \mathcal{F}_{V\,(0,0)} = \\ \mathcal{F}_{V\,(1,0)} = \\ \mathcal{F}_{V\,(0,1)} = \\ \delta\mathcal{S}_{V\,(a)} = \end{cases}$$

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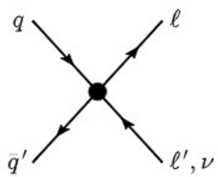
$$\begin{cases} \mathcal{F}_{V\,(0,0)} = \dfrac{v^2}{\Lambda^2}\mathcal{C}^{6}_{\psi^4} \\ \mathcal{F}_{V\,(1,0)} = \\ \mathcal{F}_{V\,(0,1)} = \\ \delta\mathcal{S}_{V\,(a)} = \end{cases}$$

d=6 ψ^4 "current-current" operators $\mathcal{O}^{(1)}_{\ell q}$ $\mathcal{O}^{(3)}_{\ell q}$ $\mathcal{O}_{\ell u}$ $\mathcal{O}_{\ell d}$ $\mathcal{O}_{eq}$ $\mathcal{O}_{eu}$ $\mathcal{O}_{ed}$



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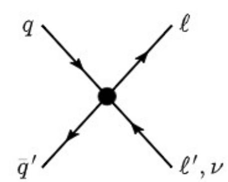
$$\mathcal{F}_V(\hat{s},\hat{t}) = \mathcal{F}_{V\,(0,0)} + \mathcal{F}_{V\,(1,0)}\frac{\hat{s}}{v^2} + \mathcal{F}_{V\,(0,1)}\frac{\hat{t}}{v^2} + \sum_{a\in\{\gamma,Z,W\}} \frac{v^2\left[\mathcal{S}_{\mathrm{SM}\,(a)} + \delta\mathcal{S}_{V\,(a)}\right]}{\hat{s}-m_a^2-im_a\Gamma_a}$$

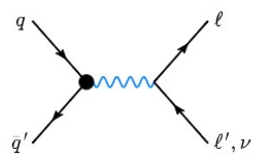
$$\begin{cases} \mathcal{F}_{V\,(0,0)} = \dfrac{v^2}{\Lambda^2}\mathcal{C}^{6}_{\psi^4} \\ \mathcal{F}_{V\,(1,0)} = \\ \mathcal{F}_{V\,(0,1)} = \\ \delta\mathcal{S}_{V\,(a)} = \dfrac{m_a^2}{\Lambda^2}\mathcal{C}^{6}_{\psi^2H^2D} + \dfrac{v^2m_a^2}{\Lambda^4}\left[\mathcal{C}^{6}_{\psi^2H^2D}\right]^2 \end{cases}$$

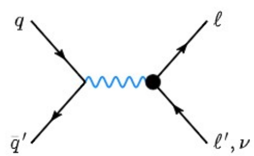
d=6 ψ^4 "current-current" operators $\mathcal{O}^{(1)}_{\ell q}$ $\mathcal{O}^{(3)}_{\ell q}$ $\mathcal{O}_{\ell u}$

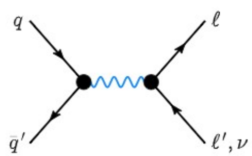
$\mathcal{O}_{\ell d}$ $\mathcal{O}_{eq}$ $\mathcal{O}_{eu}$ $\mathcal{O}_{ed}$



d=6 ψ^2H^2D "Higgs-current" operators $\mathcal{O}^{(1)}_{H\psi} = (\bar{\psi}\gamma^\mu\psi)H^\dagger D_\mu H \supset v^2 Z_\mu(\bar{\psi}\gamma^\mu\psi)$ e.g. modified Z vertex







$\propto \mathcal{C}^{(1)}_{H\ell}\mathcal{C}^{(1)}_{Hq}$

Matching for Vector Form Factors are more invoved

$$\mathcal{F}_{V}(\hat{s},\hat{t}) = \mathcal{F}_{V\,(0,0)} + \mathcal{F}_{V\,(1,0)}\frac{\hat{s}}{v^2} + \mathcal{F}_{V\,(0,1)}\frac{\hat{t}}{v^2} + \sum_{a\in\{\gamma,Z,W\}} \frac{v^2\left[\mathcal{S}_{\mathrm{SM}\,(a)} + \delta\mathcal{S}_{V\,(a)}\right]}{\hat{s} - m_a^2 - i m_a\Gamma_a}$$

$$\begin{cases} \mathcal{F}_{V\,(0,0)} = \dfrac{v^2}{\Lambda^2}\mathcal{C}^{6}_{\psi^4} + \dfrac{v^4}{\Lambda^4}\mathcal{C}^{8}_{\psi^4 H^2} \\ \mathcal{F}_{V\,(1,0)} = \\ \mathcal{F}_{V\,(0,1)} = \\ \delta\mathcal{S}_{V\,(a)} = \dfrac{m_a^2}{\Lambda^2}\mathcal{C}^{6}_{\psi^2 H^2 D} + \dfrac{v^2 m_a^2}{\Lambda^4}\left(\left[\mathcal{C}^{6}_{\psi^2 H^2 D}\right]^2 + \mathcal{C}^{8}_{\psi^2 H^4 D}\right) \end{cases}$$

d=8 $\psi^4 H^2$ $\psi^2 H^4 D$ operators that shift the leading d=6 effects by $\mathcal{O}(v^2/\Lambda^2)$

subleading effects
Negligeable...

Matching for Vector Form Factors are more invoved

$$\mathcal{F}_V(\hat{s},\hat{t}) = \mathcal{F}_{V\,(0,0)} + \mathcal{F}_{V\,(1,0)}\frac{\hat{s}}{v^2} + \mathcal{F}_{V\,(0,1)}\frac{\hat{t}}{v^2} + \sum_{a\in\{\gamma,Z,W\}} \frac{v^2\left[\mathcal{S}_{\mathrm{SM}\,(a)} + \delta\mathcal{S}_{V(a)}\right]}{\hat{s} - m_a^2 - i m_a \Gamma_a}$$

$$\begin{cases} \mathcal{F}_{V\,(0,0)} = \dfrac{v^2}{\Lambda^2}\mathcal{C}^{\,6}_{\psi^4} + \dfrac{v^4}{\Lambda^4}\mathcal{C}^{\,8}_{\psi^4 H^2} + \dfrac{v^2 m_a^2}{\Lambda^4}\mathcal{C}^{\,8}_{\psi^2 H^2 D^3} \\ \mathcal{F}_{V\,(1,0)} = \\ \mathcal{F}_{V\,(0,1)} = \\ \delta\mathcal{S}_{V\,(a)} = \dfrac{m_a^2}{\Lambda^2}\mathcal{C}^{\,6}_{\psi^2 H^2 D} + \dfrac{v^2 m_a^2}{\Lambda^4}\left(\left[\mathcal{C}^{\,6}_{\psi^2 H^2 D}\right]^2 + \mathcal{C}^{\,8}_{\psi^2 H^4 D}\right) + \dfrac{m_a^4}{\Lambda^4}\mathcal{C}^{\,8}_{\psi^2 H^2 D^3} \end{cases}$$

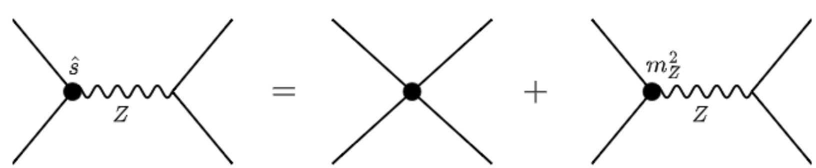
d=8 $\psi^4 H^2$ $\psi^2 H^4 D$ operators that shift the leading d=6 effects by $\mathcal{O}(v^2/\Lambda^2)$

subleading effects
Negligeable in tails...

d=8 $\psi^2 H^2 D^3$ Energy-enhanced Gauge boson vertex modfication

$$\mathcal{O}^{(1)}_{\ell^2 H^2 D^3} = (\bar{\ell}_\alpha \gamma^\mu D^\nu \ell_\beta) D_{(\mu} D_{\nu)} H^\dagger H \quad \supset \quad v\, m_Z\, \hat{s}\, Z_\mu (\bar{\ell}_\alpha \gamma^\mu \ell_\beta)$$

$$\mathcal{A} \propto \frac{\hat{s}}{\hat{s} - m_Z^2} = 1 + \frac{m_Z^2}{\hat{s} - m_Z^2} \sim$$



partial frac. decomp.

$\mathcal{F}_{V\,(0,0)}$ $\delta\mathcal{S}_{V,(Z)}$

subleading effects
Negligeable in tails...

Matching for Vector Form Factors are more invoved

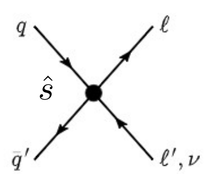
$$\mathcal{F}_V(\hat{s},\hat{t}) = \mathcal{F}_{V\,(0,0)} + \mathcal{F}_{V\,(1,0)}\frac{\hat{s}}{v^2} + \mathcal{F}_{V\,(0,1)}\frac{\hat{t}}{v^2} + \sum_{a\in\{\gamma,Z,W\}} \frac{v^2\left[\mathcal{S}_{\mathrm{SM}\,(a)} + \delta\mathcal{S}_{V\,(a)}\right]}{\hat{s} - m_a^2 - i m_a \Gamma_a}$$

$$\begin{cases} \mathcal{F}_{V\,(0,0)} = \dfrac{v^2}{\Lambda^2}\mathcal{C}^6_{\psi^4} + \dfrac{v^4}{\Lambda^4}\mathcal{C}^8_{\psi^4 H^2} + \dfrac{v^2 m_a^2}{\Lambda^4}\mathcal{C}^8_{\psi^2 H^2 D^3} \\ \mathcal{F}_{V\,(1,0)} = \dfrac{v^4}{\Lambda^4}\mathcal{C}^8_{\psi^4 D^2} \\ \mathcal{F}_{V\,(0,1)} = \dfrac{v^4}{\Lambda^4}\mathcal{C}^8_{\psi^4 D^2} \\ \delta\mathcal{S}_{V\,(a)} = \dfrac{m_a^2}{\Lambda^2}\mathcal{C}^6_{\psi^2 H^2 D} + \dfrac{v^2 m_a^2}{\Lambda^4}\left(\left[\mathcal{C}^6_{\psi^2 H^2 D}\right]^2 + \mathcal{C}^8_{\psi^2 H^4 D}\right) + \dfrac{m_a^4}{\Lambda^4}\mathcal{C}^8_{\psi^2 H^2 D^3} \end{cases}$$

d=8 $\psi^4 D^2$ operators that give rise to new effects

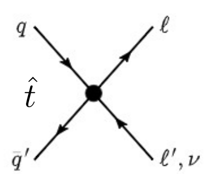
Boughezal et al. [2106.05337]
Allwicher et al. [2207.10714]

$$\mathcal{O}^{(1)}_{\ell^2 q^2 D^2} = D^\mu(\bar{\ell}\gamma^\mu \ell) D_\nu(\bar{q}\gamma_\mu q)$$



Energy-enhanced effects
can be relevant for Drell-Yan tails

$$\mathcal{O}^{(2)}_{\ell^2 q^2 D^2} = (\bar{\ell}\gamma^\mu \overleftrightarrow{D}^\nu \ell)(\bar{q}\gamma_\mu \overleftrightarrow{D}_\nu q)$$



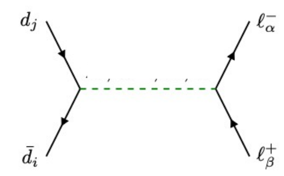
New d=8 angular effects Alioli et al. [2003.11615]

$$\hat{t} = -\frac{\hat{s}}{2}(1 - \cos\theta_*)$$

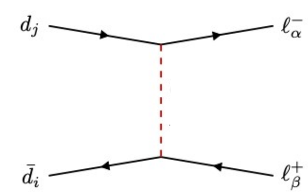
UV mediators

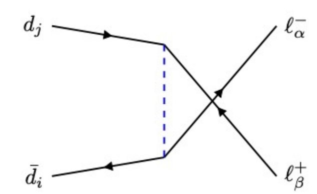
- Tree-level bosonic mediators can be classified by color, spin and fermion number (F)

		SM rep.	Spin ≤ 1	$\mathcal{L}_{\rm int}$
Colorless mediators	Z'	$(\mathbf{1},\mathbf{1},0)$	1	$\mathcal{L}_{Z'} = \sum_\psi [g_1^\psi]_{ab}\, \bar\psi_a \not{Z}' \psi_b \;,\;\; \psi \in \{u,d,e,q,l\}$
	$\widetilde{Z}$	$(\mathbf{1},\mathbf{1},1)$	1	$\mathcal{L}_{\widetilde{Z}} = [\widetilde{g}_1^q]_{ij}\, \bar u_i \not{\widetilde{Z}} d_j + [\widetilde{g}_1^\ell]_{\alpha\beta}\, \bar e_\alpha \not{\widetilde{Z}} N_\beta$
	$\Phi_{1,2}$	$(\mathbf{1},\mathbf{2},1/2)$	0	$\mathcal{L}_\Phi = \sum_{a=1,2} \Big\{ [y_u^{(a)}]_{ij}\, \bar q_i u_j \widetilde{H}_a + [y_d^{(a)}]_{ij}\, \bar q_i d_j H_a + [y_e^{(a)}]_{\alpha\beta}\, \bar l_\alpha e_\beta H_a \Big\} + \text{h.c.}$
	W'	$(\mathbf{1},\mathbf{3},0)$	1	$\mathcal{L}_{W'} = [g_3^q]_{ij}\, \bar q_i (\tau^I \not{W}'^I) q_j + [g_3^l]_{\alpha\beta}\, \bar l_\alpha (\tau^I \not{W}'^I) l_\beta$
10 Leptoquarks	S_1	$(\bar{\mathbf{3}},\, \mathbf{1},\, 1/3)$	0	$\mathcal{L}_{S_1} = [y_1^L]_{i\alpha}\, S_1 \bar q_i^c \epsilon l_\alpha + [y_1^R]_{i\alpha}\, S_1 \bar u_i^c e_\alpha + [\bar y_1^R]_{i\alpha}\, S_1 \bar d_i^c N_\alpha + \text{h.c.}$
	$\widetilde{S}_1$	$(\bar{\mathbf{3}},\, \mathbf{1},\, 4/3)$	0	$\mathcal{L}_{\widetilde{S}_1} = [\widetilde{y}_1^R]_{i\alpha}\, \widetilde{S}_1 \bar d_i^c e_\alpha + \text{h.c.}$
	U_1	$(\mathbf{3},\, \mathbf{1},\, 2/3)$	1	$\mathcal{L}_{U_1} = [x_1^L]_{i\alpha}\, \bar q_i \not{U}_1 l_\alpha + [x_1^R]_{i\alpha}\, \bar d_i \not{U}_1 e_\alpha + [\bar x_1^R]_{i\alpha}\, \bar u_i \not{U}_1 N_\alpha + \text{h.c.}$
	$\widetilde{U}_1$	$(\mathbf{3},\mathbf{1},5/3)$	1	$\mathcal{L}_{\widetilde{U}_1} = [\widetilde{x}_1^R]_{i\alpha}\, \bar u_i \not{\widetilde{U}}_1 e_\alpha + \text{h.c.}$
	R_2	$(\mathbf{3},\mathbf{2},7/6)$	0	$\mathcal{L}_{R_2} = -[y_2^L]_{i\alpha}\, \bar u_i R_2 \epsilon l_\alpha + [y_2^R]_{i\alpha}\, \bar q_i e_\alpha R_2 + \text{h.c.}$
	$\widetilde{R}_2$	$(\mathbf{3},\mathbf{2},1/6)$	0	$\mathcal{L}_{\widetilde{R}_2} = -[\widetilde{y}_2^L]_{i\alpha}\, \bar d_i \widetilde{R}_2 \epsilon l_\alpha + [\widetilde{y}_2^R]_{i\alpha}\, \bar q_i N_\alpha \widetilde{R}_2 + \text{h.c.}$
	V_2	$(\bar{\mathbf{3}},\, \mathbf{2},\, 5/6)$	1	$\mathcal{L}_{V_2} = [x_2^L]_{i\alpha}\, \bar d_i^c \not{V}_2 \epsilon l_\alpha + [x_2^R]_{i\alpha}\, \bar q_i^c \epsilon \not{V}_2 e_\alpha + \text{h.c.}$
	$\widetilde{V}_2$	$(\bar{\mathbf{3}},\, \mathbf{2},\, -1/6)$	1	$\mathcal{L}_{\widetilde{V}_2} = [\widetilde{x}_2^L]_{i\alpha}\, \bar u_i^c \not{\widetilde{V}}_2 \epsilon l_\alpha + [\widetilde{x}_2^R]_{i\alpha}\, \bar q_i^c \epsilon \not{\widetilde{V}}_2 N_\alpha + \text{h.c.}$
	S_3	$(\bar{\mathbf{3}},\, \mathbf{3},\, 1/3)$	0	$\mathcal{L}_{S_3} = [y_3^L]_{i\alpha}\, \bar q_i^c \epsilon (\tau^I S_3^I) l_\alpha + \text{h.c.}$
	U_3	$(\mathbf{3},\, \mathbf{3},\, 2/3)$	1	$\mathcal{L}_{U_3} = [x_3^L]_{i\alpha}\, \bar q_i (\tau^I \not{U}_3^I) l_\alpha + \text{h.c.}$



s





t

u

$|F| = 0$

$|F| = 2$

$$[\mathcal{F}_{\rm Poles}(\hat s, \hat t)]_{ij\alpha\beta} = \sum_a \frac{v^2\, [g_a^*]_{ij} [g_a^*]_{\alpha\beta}}{\hat s - m_a^2} + \sum_b \frac{v^2\, [g_b^*]_{i\beta} [g_b^*]_{j\alpha}}{\hat t - m_b^2} - \sum_c \frac{v^2\, [g_c^*]_{i\alpha} [g_c^*]_{j\beta}}{\hat s + \hat t + m_c^2}$$

$a \in \{\gamma, Z, W, Z', W', \widetilde{Z}, \Phi_{1,2}\}$ $\qquad b \in \{U_1, \widetilde{U}_1, R_2, \widetilde{R}_2, U_3\}$ $\qquad c \in \{S_1, \widetilde{S}_1, V_2, \widetilde{V}_2, S_3\}$

HighPT

“hyped” /haɪpt/

Authors: **Lukas Allwicher, Darius A. Faroughy, Florentin Jaffredo, Olcyr Sumensari, and Felix Wilsch**

References: **arXiv:2207.10756**, **arXiv:2207.10714**

Website: **https://highpt.github.io**

Version: 1.0.1

Authors: Lukas Allwicher, Darius A. Faroughy, Florentin Jaffredo, Olcyr Sumensari, and Felix Wilsch

References: arXiv:2207.10756, arXiv:2207.10714

Website: https://highpt.github.io

HighPT is free software released under the terms of the MIT License.

Version: 1.0.1

In[∘]:=
```
<<HighPT`
```

- *We provide the complete Drell-Yan Likelihoods for non-resonant New Physics in tails* $-2\log\mathcal{L}$

- Current functionalities:
  - All SMEFT operators dim = 6,8 $\mathcal{O}(\Lambda^{-4})$
  - Any leptoquark mediator (multiple non-interfering)
  - Arbitrary flavor structures and CKM alignment
  - Analytic cross-sections and per-bin event yields
  - Includes detector effects! (fast simulations)
  - Likelihoods for different data binnings

Process	HighPT label	Experiment	Lumi.	$x_{\rm obs}$
$pp\to\tau^+\tau^-$	"di-tau-ATLAS"	ATLAS	$139\,\mathrm{fb}^{-1}$	$m_T^{\rm tot}(\tau_h^1,\tau_h^2,\not{E}_T)$
$pp\to\mu^+\mu^-$	"di-muon-CMS"	CMS	$140\,\mathrm{fb}^{-1}$	$m_{\mu\mu}$
$pp\to e^+e^-$	"di-electron-CMS"	CMS	$137\,\mathrm{fb}^{-1}$	m_{ee}
$pp\to\tau^\pm\nu$	"mono-tau-ATLAS"	ATLAS	$139\,\mathrm{fb}^{-1}$	$m_T(\tau_h,\not{E}_T)$
$pp\to\mu^\pm\nu$	"mono-muon-ATLAS"	ATLAS	$139\,\mathrm{fb}^{-1}$	$m_T(\mu,\not{E}_T)$
$pp\to e^\pm\nu$	"mono-electron-ATLAS"	ATLAS	$139\,\mathrm{fb}^{-1}$	$m_T(e,\not{E}_T)$
$pp\to\tau^\pm\mu^\mp$	"muon-tau-CMS"	CMS	$138\,\mathrm{fb}^{-1}$	$m_{\tau_h\mu}^{\rm col}$
$pp\to\tau^\pm e^\mp$	"electron-tau-CMS"	CMS	$138\,\mathrm{fb}^{-1}$	$m_{\tau_h e}^{\rm col}$
$pp\to\mu^\pm e^\mp$	"electron-muon-CMS"	CMS	$138\,\mathrm{fb}^{-1}$	$m_{\mu e}$

Recasted heavy resonance searches

[arXiv:1906.05609]
[arXiv:2002.12223]
CMS-PAS-EXO-19-019
CMS-PAS-EXO-19-014
ATLAS-CONF-2021-025

HighPT : under the hood

- Hard-coded analytical expressions for all Drell-Yan tails in terms of $\{\mathcal{F}_{(0,0)}, \mathcal{F}_{(1,0)}, \mathcal{F}_{(0,1)}, \mathcal{S}_{(a)}, \mathcal{T}_{(b)}, \mathcal{U}_{(c)}, \}$
- We use ‘folding functions’ to make contact with LHC experiments:

$$\frac{d\sigma}{dx_{\rm obs}} = \int dx\, \kappa(x_{\rm obs}|x)\, \frac{d\sigma}{dx}$$

detector-level distributions

e.g. $\dfrac{d\sigma(pp \to \tau\tau)}{dm_T^{\rm tot}}$, $\dfrac{d\sigma(pp \to \tau\nu)}{dm_T}$

particle-level distributions $\dfrac{d\sigma}{dm_{\tau\tau}}$, $\dfrac{d\sigma}{dp_T^{\tau}}$

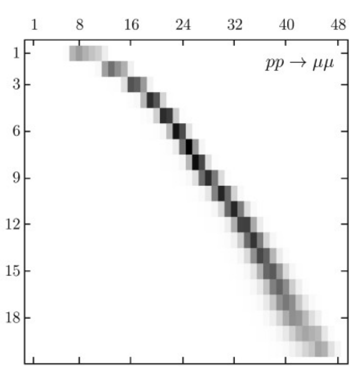
‘folding’ or ‘efficiency’ kernels

$\kappa(m_T^{\rm tot}\,|\,m_{\tau\tau})$ $\kappa(m_T\,|\,p_T^{\tau})$

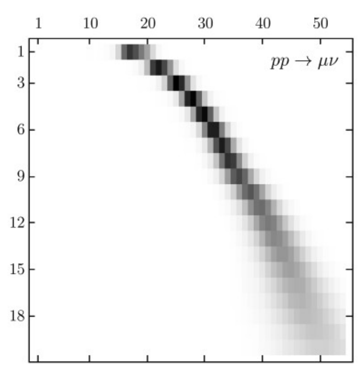
- Object reconstruction
- Detector response
- Phase space mismatch
- Parton showers (Recoil from ISR)

- Binned distributions: kernel matrices $\kappa(x_{\rm obs}\,|\,x) \longrightarrow \kappa_{ij} = {\rm Prob}(x_{\rm obs} \in {\rm bin}_i\,|\,x \in {\rm bin}_j)$

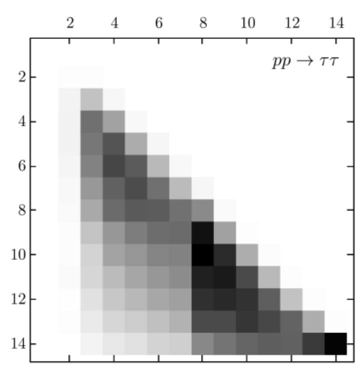
Painfully extracted using MC simulations `(Madgraph5 + Pythia + Delphes)`



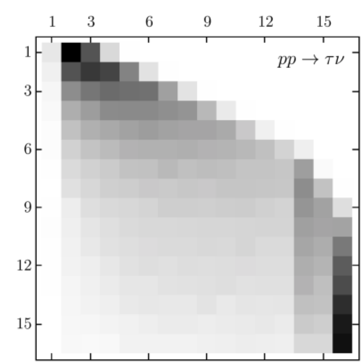
$K_{ij}\,(m_{\mu\mu}|\,m_{\mu\mu})$



$K_{ij}\,(m_T\,|\,p_T)$



$K_{ij}\,(m_T^{\rm tot}|\,m_{\tau\tau})$



$K_{ij}\,(m_T\,|\,p_T)$

Drell-Yan tails Likelihoods

- Likelihood function of $\vec{\theta} = \{\mathcal{F}_{(0,0)}, \mathcal{F}_{(1,0)}, \mathcal{F}_{(0,1)}, \mathcal{S}_{(a)}, \mathcal{T}_{(b)}, \mathcal{U}_{(c)}, \}$

$$-2\log\mathcal{L}(\vec{\theta}) = \chi^2(\vec{\theta}) = \sum_{k\in\text{bin}} \left(\mathcal{N}^k_{\text{sig}}(\vec{\theta}) + \mathcal{N}^k_{\text{bkg}} - \mathcal{N}^k_{\text{obs}}\right)^2 \frac{1}{\sigma^2}$$

HighPT ATLAS EXPERIMENT CMS

Also for SMEFT and leptoquark mediators:

$$\vec{\theta} = \{\mathcal{C}_i^6, \mathcal{C}_i^8\}$$

$$\vec{\theta} = \{[x]_{i\alpha}, [y]_{i\alpha}\} \quad m_{\text{LQ}} = \{1,2,3,4,5\}\,\text{TeV}$$

- Minimization with native `Nminimize[]` or… export Liklihood in format `WCxF` format to external tools like `Flavio`!

- Quick "SMEFT mode" likelihoods: `ChiSquareLHC[]`

```
ChiSquareLHC["di-muon-CMS", EFTorder → 4, OperatorDimension → 6,
  Coefficients → {WC["lq1", {2, 2, 1, 1}]}] // Total

Out[13]= 13.37 - 57.6784 WC[lq1, {2, 2, 1, 1}] + 1453.54 WC[lq1, {2, 2, 1, 1}]^2 -
   22476.1 WC[lq1, {2, 2, 1, 1}]^3 + 133553. WC[lq1, {2, 2, 1, 1}]^4
```

$$[\mathcal{O}_{\ell q}^{(1)}]_{2211} = (\bar{\ell}_2\gamma^\mu\ell_2)(\bar{q}_1\gamma_\mu q_1)$$

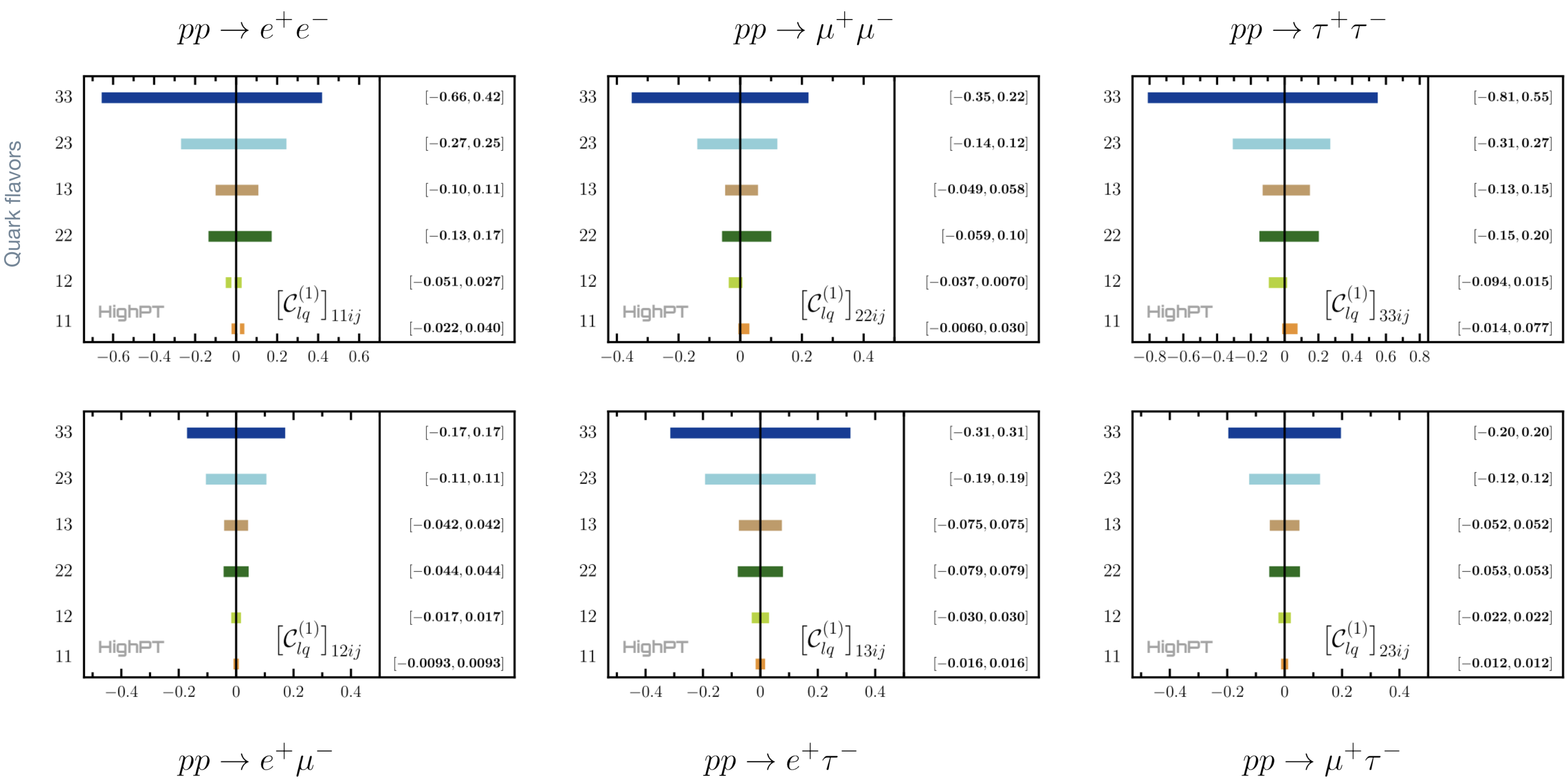
```
ChiSquareLHC["di-muon-CMS", EFTorder → 4, OperatorDimension → 8,
   Coefficients → {WC["lq1", {2, 2, 1, 1}], WC["l2q2D21", {2, 2, 1, 1}]}] // Total

Out[15]= 13.37 + 1289.88 WC[l2q2D21, {2, 2, 1, 1}]^2 - 57.6784 WC[lq1, {2, 2, 1, 1}] +
   1453.54 WC[lq1, {2, 2, 1, 1}]^2 - 22476.1 WC[lq1, {2, 2, 1, 1}]^3 + 133553. WC[lq1, {2, 2, 1, 1}]^4 +
   WC[l2q2D21, {2, 2, 1, 1}] (-6.29833 + 2058.28 WC[lq1, {2, 2, 1, 1}] - 26006.8 WC[lq1, {2, 2, 1, 1}]^2)
```

$$[\mathcal{O}_{\ell q}^{(1)}]_{2211} = (\bar{\ell}_2\gamma^\mu\ell_2)(\bar{q}_1\gamma_\mu q_1)$$

$$[\mathcal{O}_{\ell^2 q^2 D^2}^{(1)}]_{2211} = D^\nu(\bar{\ell}_2\gamma^\mu\ell_2)D_\nu(\bar{q}_1\gamma_\mu q_1)$$

SMEFT limits

- Single-parameter fits: $[\mathcal{O}_{\ell q}^{(1)}]_{\alpha\beta ij} = (\bar{\ell}_\alpha \gamma^\mu \ell_\beta)(\bar{q}_i \gamma_\mu q_j)$



Allwicher et al. [2207.10714]

Limits on Leptoquark mediators

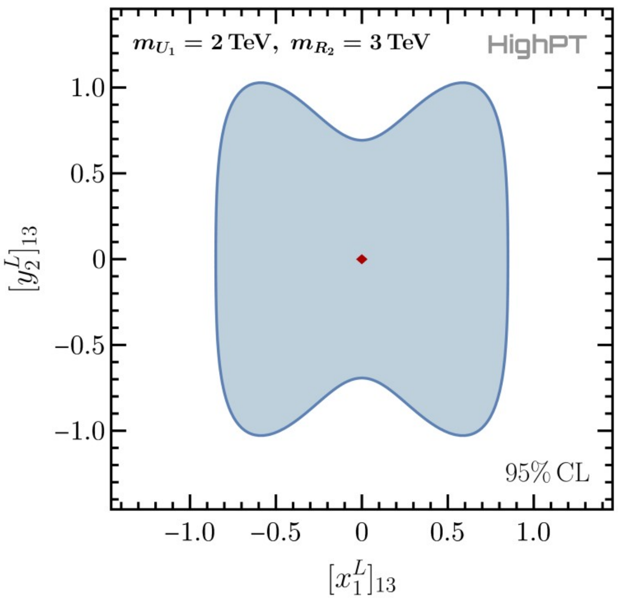
- Two-parameter fits:

$U_1^\mu \sim (\mathbf{3},\mathbf{1},2/3) \quad R_2 \sim (\mathbf{3},\mathbf{2},7/6)$

$$\mathcal{L}_{\rm int} = [x_1^L]_{i\alpha}\,(\bar{q}_i \not{U}_1 \ell_\alpha) - [y_2^L]_{i\alpha}\,(\bar{u}_i R_2 \epsilon \ell_\alpha) + \text{h.c}$$

$$x_1^L = y_2^L = \begin{pmatrix} 0 & 0 & \times \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$u\bar{u} \to \tau\tau$
$d\bar{d} \to \tau\tau$
$u\bar{d} \to \tau\nu$



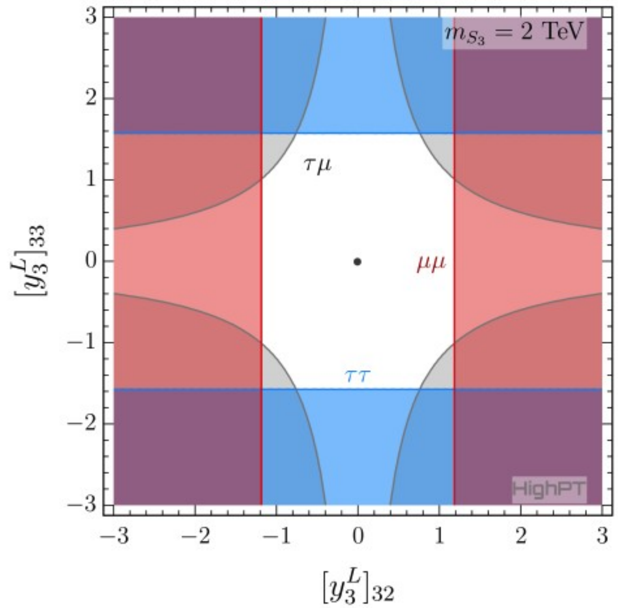

```
In[17]:= InitializeModel["Mediators",
           Mediators -> {"U1" -> {2000, 0}, "R2" -> {3000, 0}}];

In[18]:= χSqLQττ = Total[ChiSquareLHC["di-tau-ATLAS"]];
         χSqLQτν = Total[ChiSquareLHC["mono-tau-ATLAS"]];
```

$S_3 \sim (\mathbf{3},\mathbf{3},1/3)$

$$\mathcal{L}_{S_3} = [y_3^L]_{i\alpha}\, S_3^I (\bar{q}_i^c \epsilon \tau^I \ell_\alpha) + \text{h.c}$$

$$y_3^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \times & \times \end{pmatrix}$$

$b\bar{b} \to \tau\tau$
$b\bar{b} \to \mu\mu$
$b\bar{b} \to \mu\tau$




```
In[23]:= InitializeModel["Mediators", Mediators -> {"S3" -> {2000, 0}}];
         Lμτ = ChiSquareLHC["muon-tau-CMS"] // Total;
         Lττ = ChiSquareLHC["di-tau-ATLAS"] // Total;
         Lμμ = ChiSquareLHC["di-muon-CMS"] // Total;
```

SMEFT truncation

- Where do we truncate the EFT expansion?

$$d\sigma \sim |\mathcal{A}_{\rm SM}|^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{C}_i^6 \mathcal{A}_i^6 \mathcal{A}_{\rm SM}^* + \frac{1}{\Lambda^4}\left(\sum_{ij} \overset{?}{\mathcal{C}_i^6 \mathcal{C}_j^{6*} \mathcal{A}_i^6 \mathcal{A}_j^{6*}} + \sum_i \mathcal{C}_i^8 \mathcal{A}_i^8 \mathcal{A}_{\rm SM}^*\right)$$

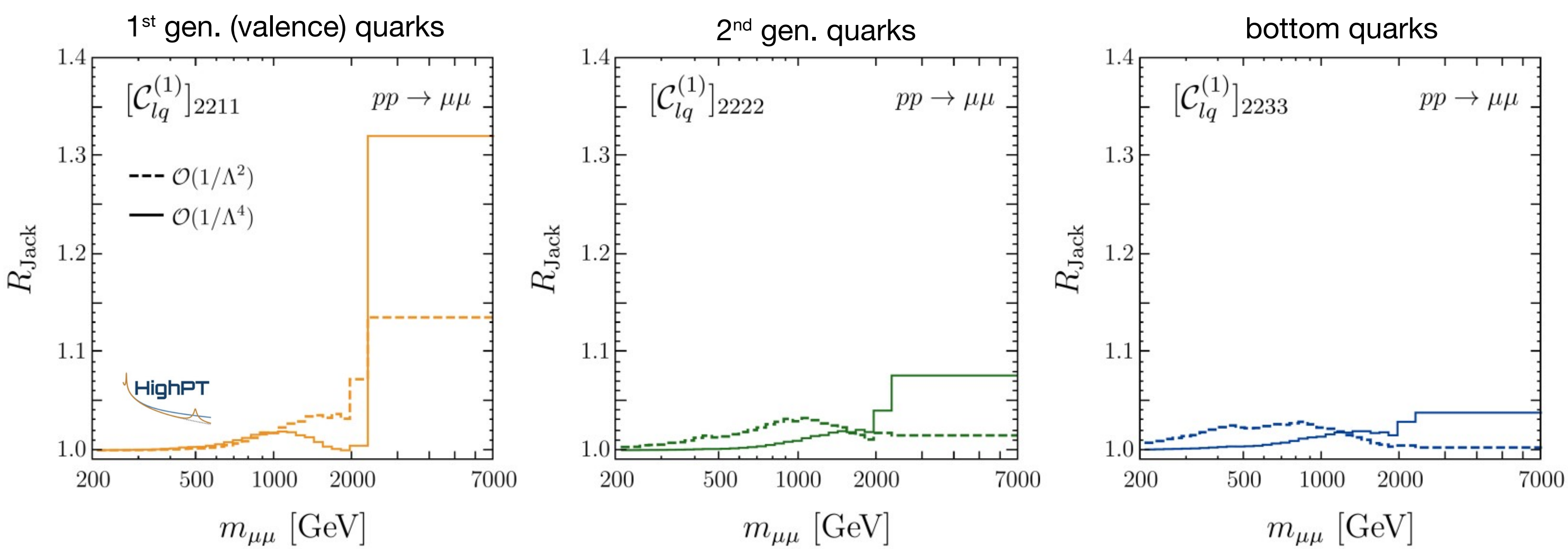
$\mathcal{O}(\Lambda^{-4})$ *effects are very important in the tails! Should not be neglected at the LHC*

Boughezal et al. [2106.05337]
Allwicher et al. [2207.10714]

- “Jacksaw analysis”: which is the most sensitive LHC bin?

$$R_{\rm Jack} = \frac{\text{Limits without one bin}}{\text{Limits with all bins}}\,.$$

$$[\mathcal{O}_{\ell q}^{(1)}]_{22ii} = (\bar{\ell}_2\gamma^\mu \ell_2)(\bar{q}_i\gamma_\mu q_i)$$



Allwicher et al. [2207.10714]

- At around O(1) TeV NP^2 terms becomes relevant
- Last bin is always the most sensitive “single bin” because of energy-growth

Dim=8 corrections

$$d\sigma \sim |\mathcal{A}_{\rm SM}|^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{C}_i^6 \mathcal{A}_i^6 \mathcal{A}_{\rm SM}^* + \frac{1}{\Lambda^4}\left(\sum_{ij}\mathcal{C}_i^6\mathcal{C}_j^{6*}\mathcal{A}_i^6\mathcal{A}_j^{6*} + \sum_i \overset{?}{\mathcal{C}_i^8 \mathcal{A}_i^8 \mathcal{A}_{\rm SM}^*}\right)$$

- We focus on LL vector form factors to analyse **dim=8 effects**

$$\mathcal{F}^{LL}_{V,{\rm Reg}} = \mathcal{F}^{LL}_{V\,(0,0)} + \mathcal{F}^{LL}_{V\,(1,0)}\frac{\hat{s}}{v^2} + \mathcal{F}^{LL}_{V\,(0,1)}\frac{\hat{t}}{v^2}$$

$d=8$	$\psi^4 D^2$
$\mathcal{O}^{(1)}_{l^2q^2D^2}$	$D^\nu(\bar{l}_\alpha\gamma^\mu l_\beta)D_\nu(\bar{q}_i\gamma_\mu q_j)$
$\mathcal{O}^{(2)}_{l^2q^2D^2}$	$(\bar{l}_\alpha\gamma^\mu \overleftrightarrow{D}^\nu l_\beta)(\bar{q}_i\gamma_\mu \overleftrightarrow{D}_\nu q_j)$
$\mathcal{O}^{(3)}_{l^2q^2D^2}$	$D^\nu(\bar{l}_\alpha\gamma^\mu\tau^I l_\beta)D_\nu(\bar{q}_i\gamma_\mu\tau^I q_j)$
$\mathcal{O}^{(4)}_{l^2q^2D^2}$	$(\bar{l}_\alpha\gamma^\mu \overleftrightarrow{D}^{I\nu} l_\beta)(\bar{q}_i\gamma_\mu \overleftrightarrow{D}^I_\nu q_j)$

At leading order SMEFT matching:

$$\mathcal{C}^{(1)}_{\ell^2q^2D^2} + \mathcal{C}^{(2)}_{\ell^2q^2D^2} - \mathcal{C}^{(3)}_{\ell^2q^2D^2} - \mathcal{C}^{(4)}_{\ell^2q^2D^2}$$

$$\mathcal{F}^{LL,\,uu}_{V\,(0,0)} \simeq \frac{v^2}{\Lambda^2}\mathcal{C}^{(1-3)}_{\ell q}$$
$$\mathcal{F}^{LL,\,dd}_{V\,(0,0)} \simeq \frac{v^2}{\Lambda^2}\mathcal{C}^{(1+3)}_{\ell q}$$
$$\mathcal{F}^{LL,\,ud}_{V\,(0,0)} \simeq 2\frac{v^2}{\Lambda^2}\mathcal{C}^{(3)}_{\ell q}$$

d=6

$$\mathcal{F}^{LL,\,uu}_{V\,(1,0)} \simeq \frac{v^4}{\Lambda^4}\mathcal{C}^{(1+2-3-4)}_{\ell^2q^2D^2}$$
$$\mathcal{F}^{LL,\,dd}_{V\,(1,0)} \simeq \frac{v^4}{\Lambda^4}\mathcal{C}^{(1+2+3+4)}_{\ell^2q^2D^2}$$
$$\mathcal{F}^{LL,\,ud}_{V\,(1,0)} \simeq 2\frac{v^4}{\Lambda^4}\mathcal{C}^{(3+4)}_{\ell^2q^2D^2}$$

d=8

$$\mathcal{F}^{LL,\,uu}_{V\,(0,1)} \simeq 2\frac{v^4}{\Lambda^4}\mathcal{C}^{(2-4)}_{\ell^2q^2D^2}$$
$$\mathcal{F}^{LL,\,dd}_{V\,(0,1)} \simeq 2\frac{v^4}{\Lambda^4}\mathcal{C}^{(2+4)}_{\ell^2q^{@}D^2}$$
$$\mathcal{F}^{LL,\,ud}_{V\,(0,1)} \simeq 2\frac{v^4}{\Lambda^4}\mathcal{C}^{(4)}_{\ell^2q^{@}D^2}$$

d=8

UV assumptions:

$$|\mathcal{F}^{LL}_{V\,(0,0)}| \leq g_*^2 v^2/\Lambda^2$$
$$|\mathcal{F}^{LL}_{V\,(1,0)}| \leq g_*^2 v^4/\Lambda^4$$
$$|\mathcal{F}^{LL}_{V\,(0,1)}| \leq g_*^2 v^4/\Lambda^4$$
$$g_* = \sqrt{4\pi}$$

Sub-leading corrections from other d=8 operators are negligible $\boxed{\psi^4H^2}$ $\boxed{\psi^2H^4D}$ $\boxed{\psi^2H^2D^3}$

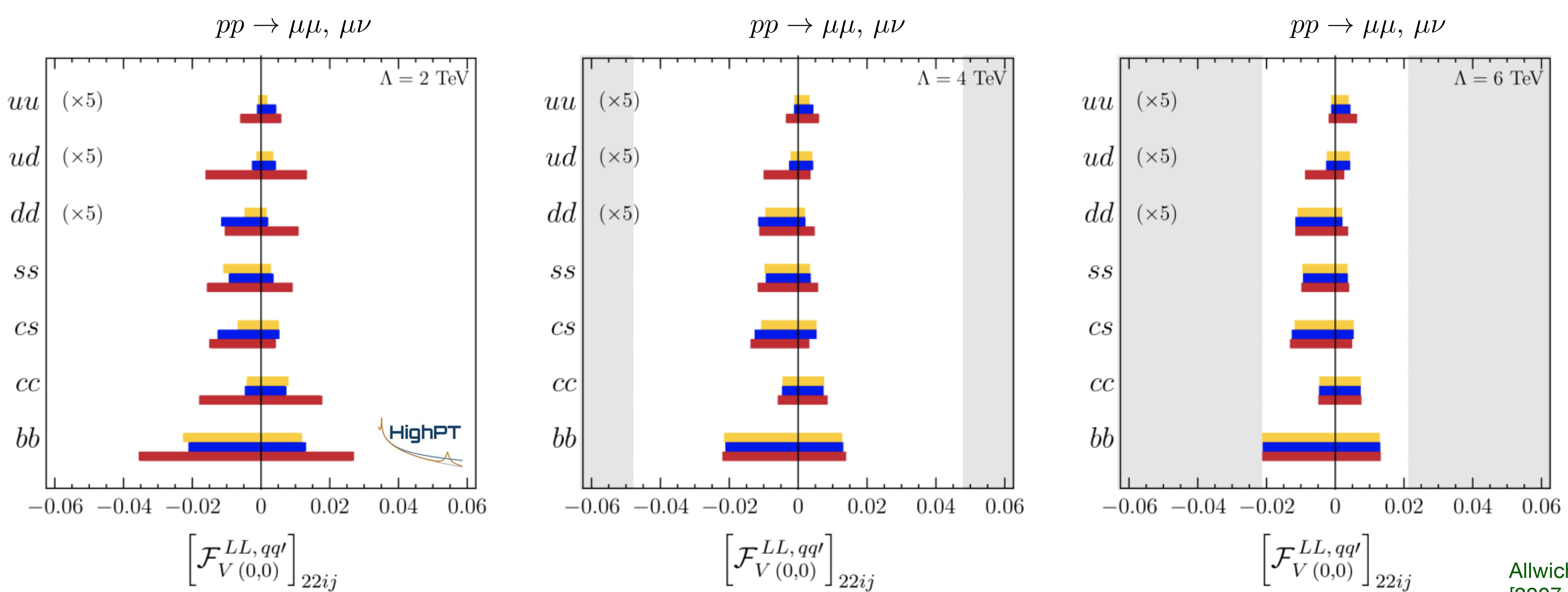
- We set limits on $\mathcal{F}^{LL}_{V\,(0,0)}$ assuming 3 scenarios:

(1) Neglecting all dim=8 corrections (benchmark)

(2) **Maximal correlation** between dim=6 and dim=8 form factors:
$$\begin{cases} \mathcal{F}^{LL}_{V\,(1,0)} = \dfrac{v^2}{\Lambda^2}\,\mathcal{F}^{LL}_{V\,(0,0)} \\ \mathcal{F}^{LL}_{V\,(0,1)} = 0 \end{cases}$$

Arises when integrating out vector-triplet in UV

(3) **Uncorrelated** form factors. We marginalize over dim=8 $\mathcal{F}^{LL}_{V\,(1,0)}$, $\mathcal{F}^{L}_{V\,(0,1)}$



Allwicher et al. [2207.10714]

We find that d=8 corrections are not large except for scenario (3) and only for valence quarks.

- Can d=8 effects dominate over d=6 in Drell-Yan?

UV requirements:

1 – Two states with almost degenerate masses.
2 – States must interfere.
3 – Contribute to Drell-Yan in different scattering chanels.
4 – Couplings fine-tuned such that the d=6 effects cancel.

At least one leptoquark

- Two leptoquarks: one t-channel (F=0), the other u-channel (F=-2)

$$\frac{g_1^2}{t-M^2} - \frac{g_2^2}{u-M^2} = -(g_1^2 - g_2^2)\frac{1}{M^2} - (t\,g_1^2 - u\,g_2^2)\frac{1}{M^4} + \mathcal{O}\left(\frac{1}{M^6}\right)$$

$$= (u-t)\frac{g_1^2}{M^4} + \mathcal{O}\left(\frac{1}{M^6}\right) \qquad g_1 \approx g_2$$

Explicit model:

$$\widetilde{U}_1^\mu \sim (\mathbf{3}, \mathbf{1}, 5/3) \qquad S_1 \sim (\mathbf{3}, \mathbf{1}, -1/3)$$

$$\mathcal{L}_{\rm int} = \frac{g}{\sqrt{2}}\, \widetilde{U}_1^\mu (\bar{e}\gamma_\mu u) + g\, S_1 (\bar{e}^c u) + \text{h.c.}$$

$\psi^4 D^2$

$$\mathcal{F}^{RR,uu}_{(0,0)} = 0$$

$$\mathcal{F}^{RR,uu}_{V\,(1,0)} = -\frac{g^2}{2} \qquad \mathcal{O}^{(1)}_{e^2u^2D^2} = D^\nu(\bar{e}\gamma_\mu e) D_\nu(\bar{u}\gamma^\mu u)$$

$$\mathcal{F}^{RR,uu}_{V,(0,1)} = -g^2 \qquad \mathcal{O}^{(2)}_{e^2u^2D^2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}^\nu e)(\bar{u}\gamma^\mu \overleftrightarrow{D}_\nu u)$$

$u\bar{u} \to \ell^+\ell^-$ is driven by d=8 operators

Effects of different CKM-alignments

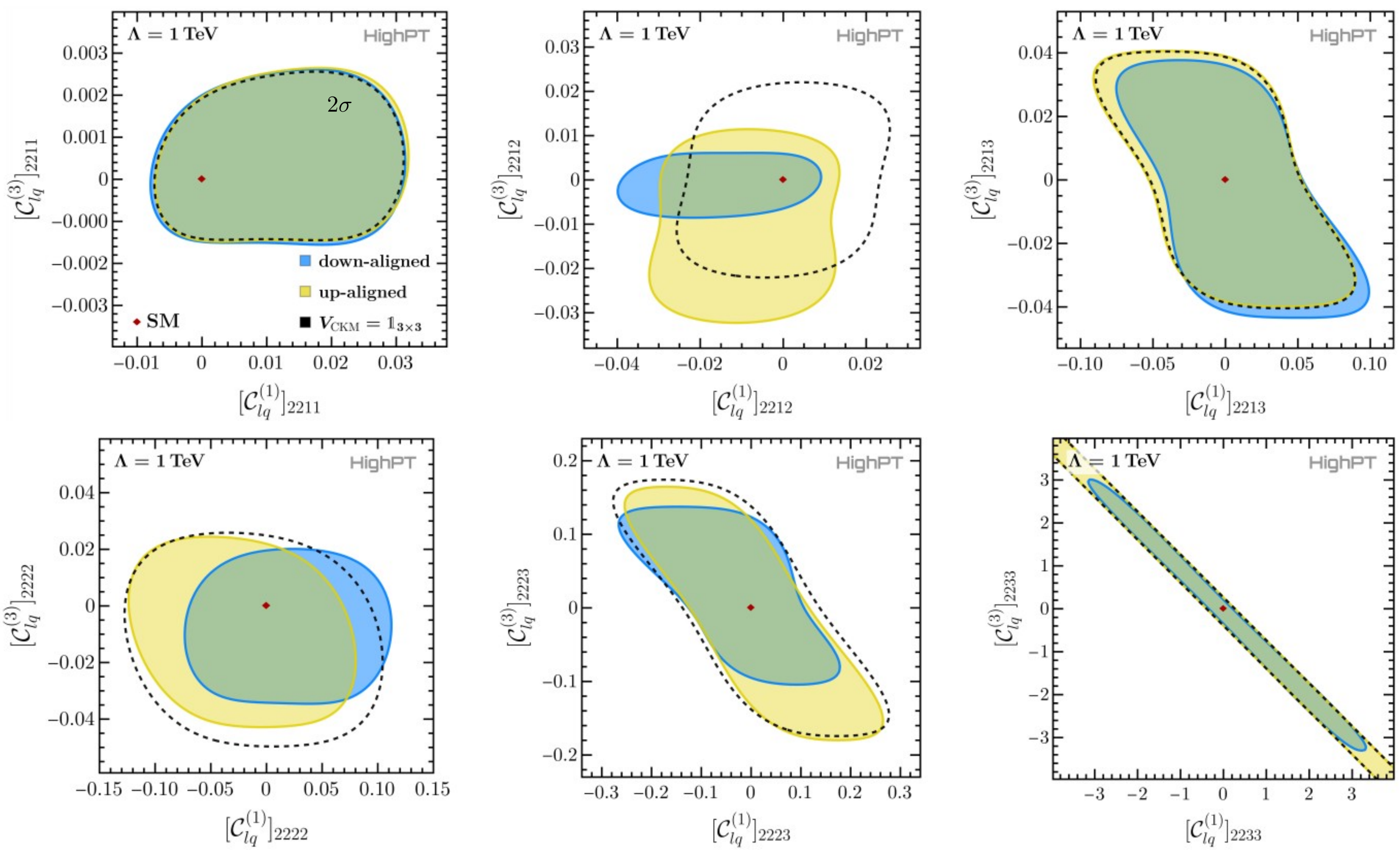
$$q = \begin{pmatrix} V_{\rm CKM}^\dagger \cdot u_L \\ d_L \end{pmatrix}$$ down-alignment

vs

$$q = \begin{pmatrix} u_L \\ V_{\rm CKM} \cdot d_L \end{pmatrix}$$ up-alignment

$$q_i \bar{q}_j \to \mu^+ \mu^-$$
$$u_i \bar{d}_j \to \mu^\pm \nu$$

$$\begin{cases} [\mathcal{O}_{\ell q}^{(1)}]_{\alpha\beta ij} = (\bar{\ell}_\alpha \gamma^\mu \ell_\beta)(\bar{q}_i \gamma_\mu q_j) \\ [\mathcal{O}_{\ell q}^{(3)}]_{\alpha\beta ij} = (\bar{\ell}_\alpha \gamma^\mu \tau^I \ell_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j) \end{cases}$$



Allwicher et al. [2207.10714]

Conclusions

- Drell-Yan tails at the LHC are powerful probes of BSM in semi-leptonic interactions with arbitrary flavor structures.

- We provided a general description of Drell-Yan based on form factors

  E.g. we identified the relevant SMEFT operator class at d=8 $\psi^4 D^2$

- We introduced **HighPT**, a mathematica package that provides the full flavor likelihood for high-pT Drell-Yan.
  - SMEFT to order $\mathcal{O}(\Lambda^{-4})$ including dim=8 effects
  - Any Leptoquark model for TeV masses

HighPT

https://highpt.github.io

- We discussed the effects of different flavor alignments, SMEFT truncations and d=8 corrections

- Currently including low-energy flavor observables and EWPO in **HighPT 2.0**

- Backup -

Combined fit: Drell-Yan + RD(*) + EWPT

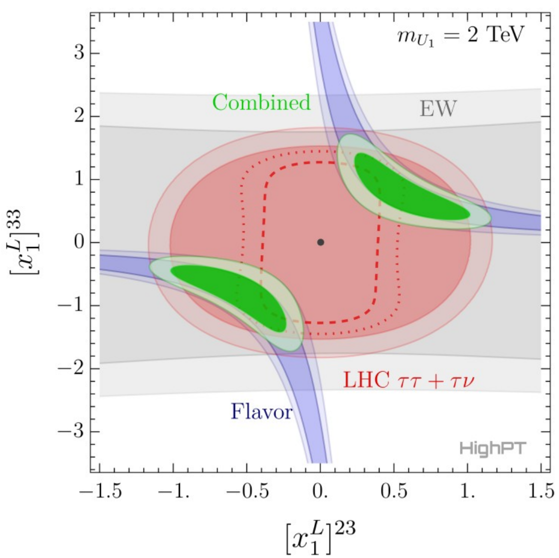
- We focus on NP in RD(*): $\mathcal{O}_{\ell q}^{(3)}$, $\mathcal{O}_{\ell equ}^{(1)}$, $\mathcal{O}_{\ell edq}$, $\mathcal{O}_{\ell equ}^{(3)}$ with correlated Wilson coefficients from the UV

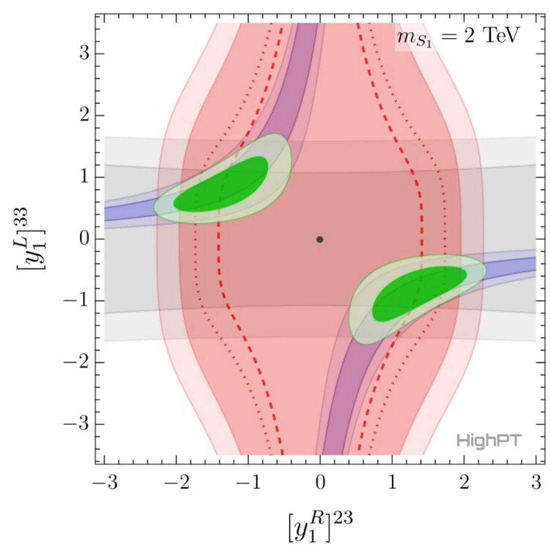
$U_1^\mu \sim (\mathbf{3},\mathbf{1},2/3)$	$S_1 \sim (\mathbf{3},\mathbf{1},2/3)$	$R_2 \sim (\mathbf{3},\mathbf{2},7/6)$
$[\mathcal{C}_{\ell q}^{(1)}]_{3333} = [\mathcal{C}_{\ell q}^{(3)}]_{3333}$	$[\mathcal{C}_{\ell q}^{(1)}]_{3333} = -[\mathcal{C}_{\ell q}^{(3)}]_{3333}$	$[\mathcal{C}_{\ell q}^{(1)}]_{3333} = -[\mathcal{C}_{\ell q}^{(3)}]_{3333}$
$[\mathcal{C}_{\ell q}^{(1)}]_{3323} = [\mathcal{C}_{\ell q}^{(3)}]_{3323}$	$[\mathcal{C}_{\ell equ}^{(1)}]_{3332} = -4[\mathcal{C}_{\ell equ}^{(3)}]_{3332}$	$[\mathcal{C}_{\ell equ}^{(1)}]_{3332} = -4[\mathcal{C}_{\ell equ}^{(3)}]_{3332}$

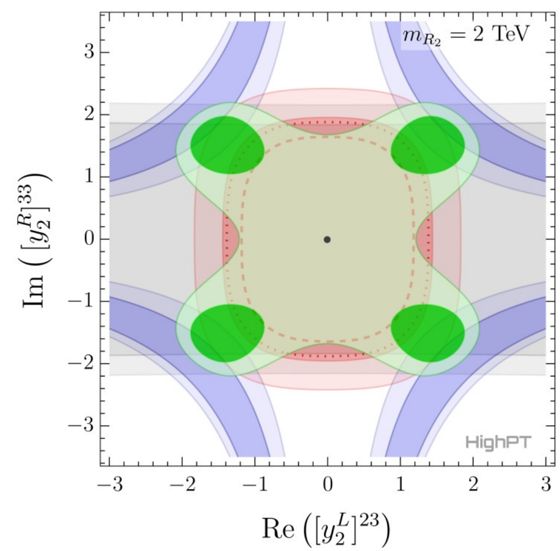
$$\mathcal{L}_{U_1} = [x_1^L]_{i\alpha}\,\bar{q}_i \not{U}_1 l_\alpha$$

$$\mathcal{L}_{S_1} = [y_1^L]_{i\alpha}\,S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]_{i\alpha}\,S_1 \bar{u}_i^c e_\alpha$$

$$\mathcal{L}_{R_2} = -[y_2^L]_{i\alpha}\,\bar{u}_i R_2 \epsilon l_\alpha + [y_2^R]_{i\alpha}\,\bar{q}_i e_\alpha R_2$$





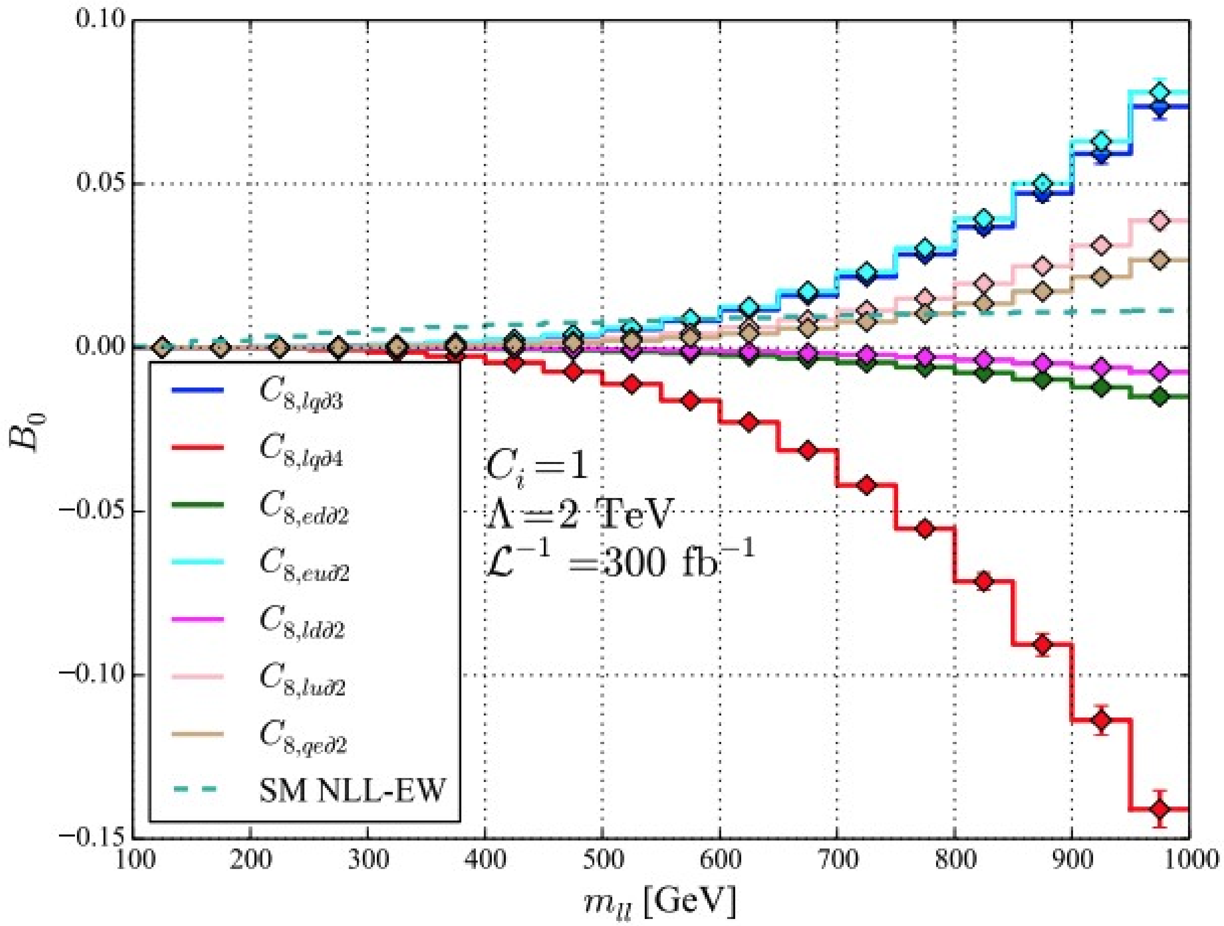


These new d=8 angular effects require
higher harmonics in the standard parametrization

$$\mathcal{O}^{(2)}_{\ell^2 q^2 D^2} = (\bar{\ell}\gamma^{\mu}\overleftrightarrow{D}^{\nu}\ell)(\bar{q}\gamma_{\mu}\overleftrightarrow{D}_{\nu}q)$$

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

Alioli et al. [2003.11615]



Lepton Flavor Violation at high-p_T ?

- LFV are excelent probes of BSM physics $U(1)_e \times U(1)_\mu \times U(1)_\tau$

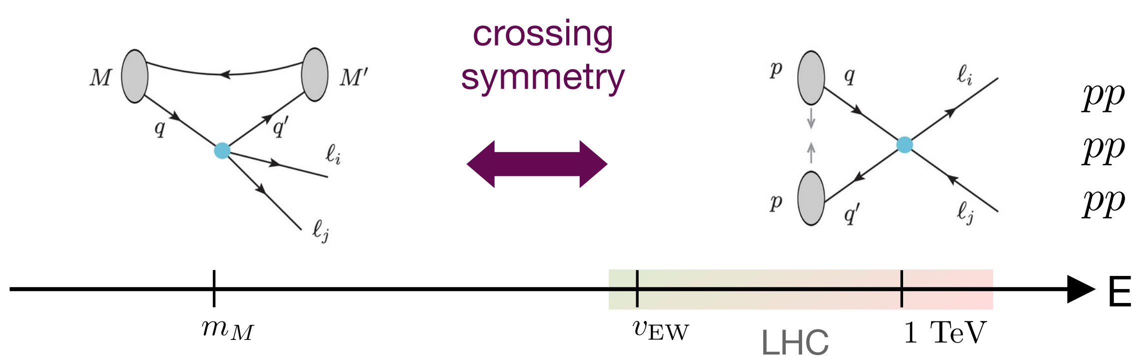
- Experimental probes targeting semi-leptonic modes:

  NA62, BES-II, KOTO, LHCb, Belle-II

$K_L \to e\mu$ $\quad K^+ \to \pi^+ e\mu$ $\quad D^0 \to e\mu$

$B_{(s)} \to e\mu$ $\quad B^{(*)} \to \pi^+ \mu e$ $\quad B^{(*)} \to K^+ \mu\tau$

$\tau \to \mu\pi$ $\quad \tau \to \mu\phi$ $\quad D^+ \to \pi^+ \mu e$



$pp \to e\mu$

$pp \to e\tau$

$pp \to \mu\tau$

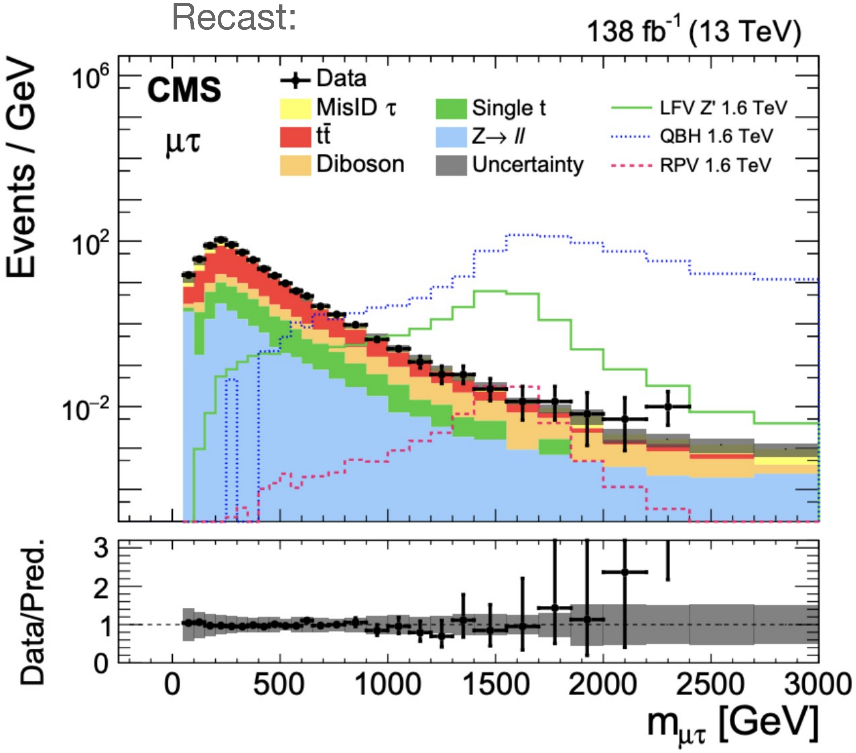
- Notice that other effects not constrained by Drell-Yan can affect meson decays, e.g. RGE effects

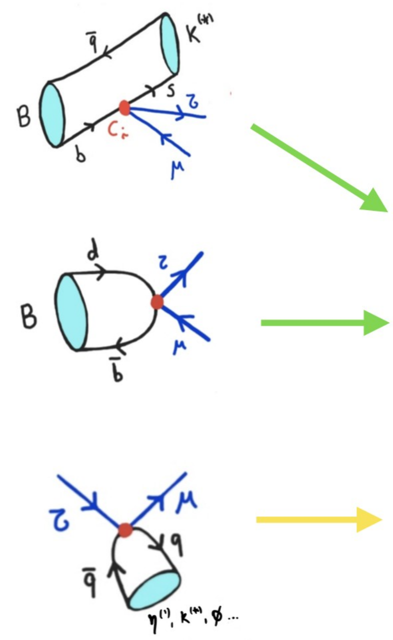
- Can we translate the Drell-Yan tail bounds into model-independent constraints on low-energy flavor observables?

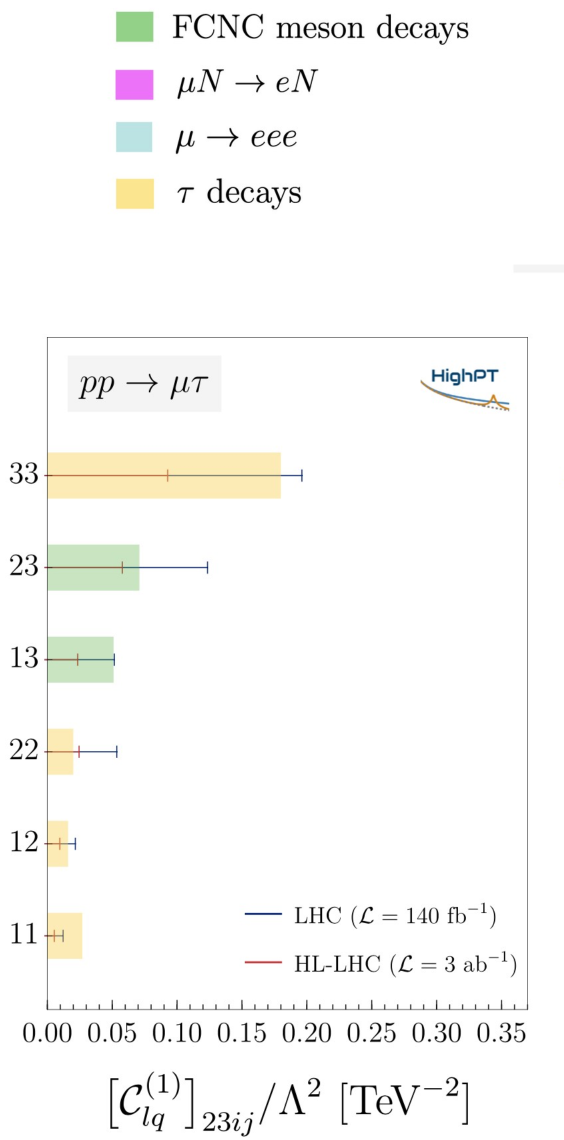
LFV Drell-Yan limits

$$[\mathcal{O}_{\ell q}^{(1)}]_{ij\alpha\beta} = (\bar{q}_i \gamma^\mu q_j)(\bar{\ell}_\alpha \gamma_\mu \ell_\beta) \quad \alpha \neq \beta$$

Recast:







Angelescu, DAF, Sumensari [2020]

Descotes-Genon et al [2303.07521]

LFV Drell-Yan limits

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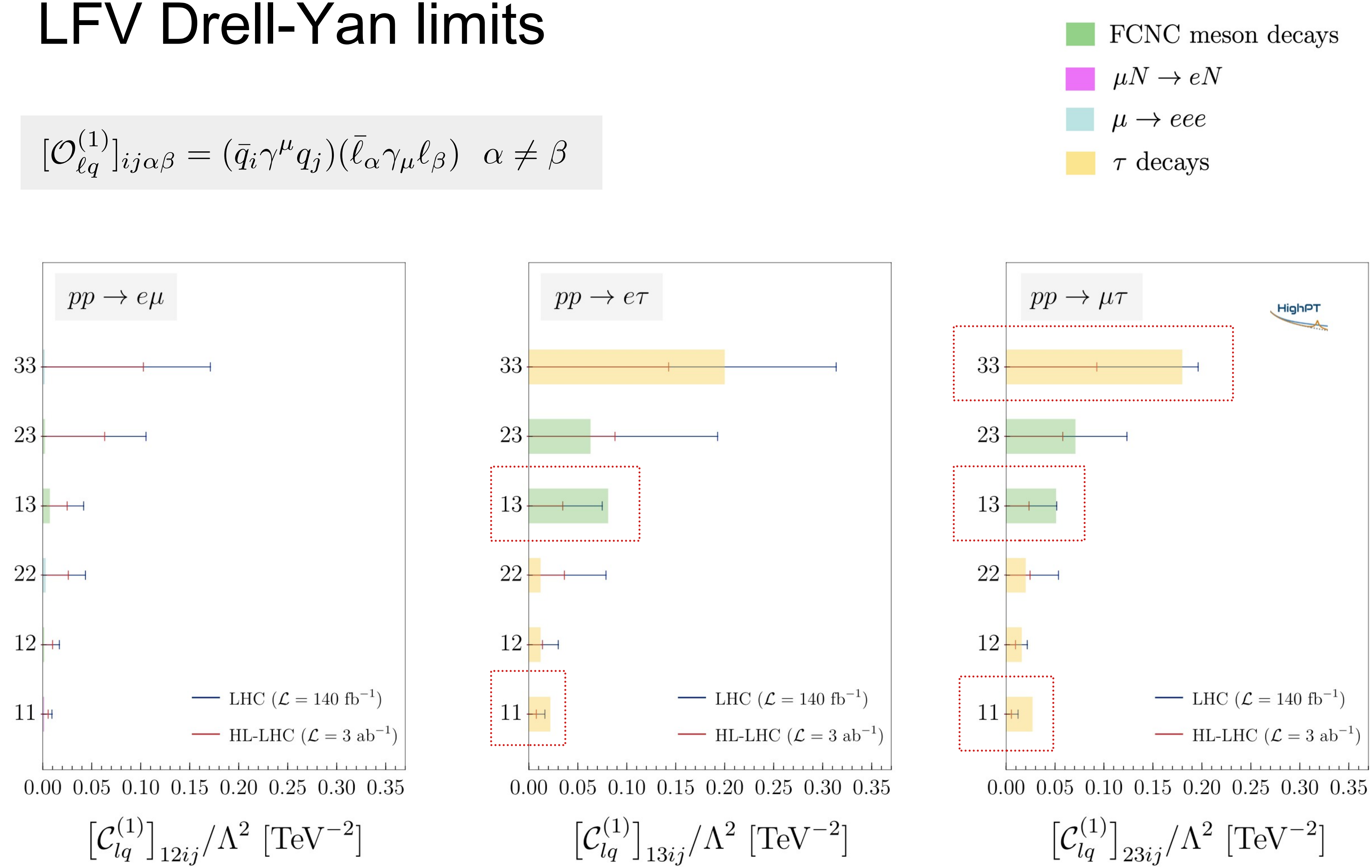


- For some tauonic LFV transitions LHC is quite competitive

$$d\bar{d} \to \mu\tau \quad b\bar{d} \to \mu\tau \quad b\bar{b} \to \mu\tau$$
$$d\bar{d} \to e\tau \quad b\bar{d} \to e\tau$$

Angelescu, DAF, Sumensari [2020]

Descotes-Genon et al [2303.07521]

- We further truncate the Drell-Yan cross-section to order $\mathcal{O}(\Lambda^{-4})$

d=8 effects come from interference with SM poles $|\mathcal{A}|^2 \supset 2\mathrm{Re}\left[\mathcal{F}^*_{\mathrm{Reg}} \cdot \mathcal{F}_{\mathrm{Pole}}\right]$

$$\mathcal{F}_S = \mathcal{F}_{S\,(0,0)} + \mathcal{F}_{S\,(1,0)}\frac{\hat{s}}{v^2} + \mathcal{F}_{S\,(0,1)}\frac{\hat{t}}{v^2} + \frac{v^2\left[\mathcal{S}_{\mathrm{SM}\,(h)} + \delta\mathcal{S}_{S\,(h)}\right]}{\hat{s} - m_h^2 - i m_h \Gamma_h}$$ Scalar

$$\mathcal{F}_T = \mathcal{F}_{T\,(0,0)} + \mathcal{F}_{T\,(1,0)}\frac{\hat{s}}{v^2} + \mathcal{F}_{T\,(0,1)}\frac{\hat{t}}{v^2}$$ Tensor

$$\mathcal{F}_V = \mathcal{F}_{V\,(0,0)} + \mathcal{F}_{V\,(1,0)}\frac{\hat{s}}{v^2} + \mathcal{F}_{V\,(0,1)}\frac{\hat{t}}{v^2} + \sum_{a\in\{\gamma,Z,W\}} \frac{v^2\left[\mathcal{S}_{\mathrm{SM}\,(a)} + \delta\mathcal{S}_{V\,(a)}\right]}{\hat{s} - m_a^2 - i m_a \Gamma_a}$$ Vector

$$\mathcal{F}_{D_q} = \sum_{a\in\{\gamma,Z,W\}} \frac{v^2\,\mathcal{S}_{D_q\,(a)}}{\hat{s} - m_a^2 - i m_a \Gamma_a}$$ Quark Dipole

$$\mathcal{F}_{D_\ell} = \sum_{a\in\{\gamma,Z,W\}} \frac{v^2\,\mathcal{S}_{D_\ell\,(a)}}{\hat{s} - m_a^2 - i m_a \Gamma_a}$$ Lepton Dipole

- d=6 SMEFT operators match trivially to Scalar, Tensor and Dipoles form factors

  - *Example: neutral currents Scalar/Tensor*

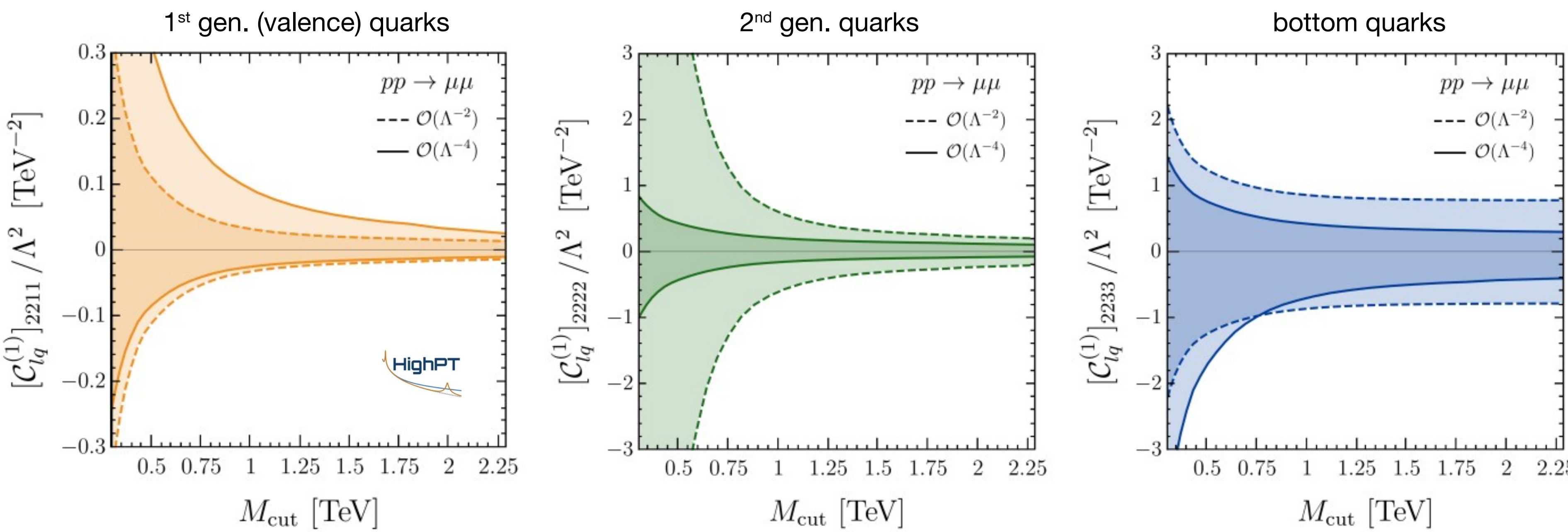
$$\mathcal{F}^{LL,uu}_{S\,(0,0)} = [\mathcal{F}^{RR,uu}_{S\,(0,0)}]^\dagger = -\frac{v^2}{\Lambda^2}\,\mathcal{C}^{(1)}_{\ell equ}$$

$$\mathcal{F}^{LR,dd}_{S\,(0,0)} = [\mathcal{F}^{RL,dd}_{S\,(0,0)}]^\dagger = \frac{v^2}{\Lambda^2}\,\mathcal{C}_{\ell edq}$$

$$\mathcal{F}^{LL,uu}_{T\,(0,0)} = [\mathcal{F}^{RR,u}_{T\,(0,0)}]^\dagger = -\frac{v^2}{\Lambda^2}\,\mathcal{C}^{(3)}_{\ell equ}$$

- Validity of EFT expansion? Contino et al.[1604.06444] Brivio et al. [2201.04974]

"Clipped limits": extract limits as a function of an upper-cut M_{cut} in data to facilitate the interpretation of the EFT limits.



Allwicher et al. [2207.10714]

- Jacksaw and clipped analysis are easy to implement in `HighPT`

Flexible binning: remove or combine experimental bins