INFN PISA
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

Portorož 2023

Probing flavor in semileptonic transition at High-p_T

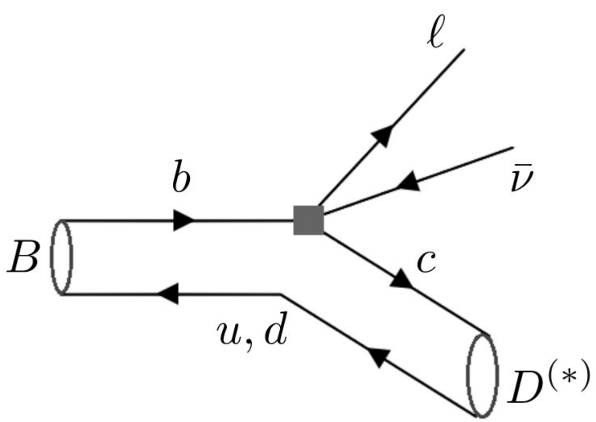
Florentin Jaffredo, INFN,

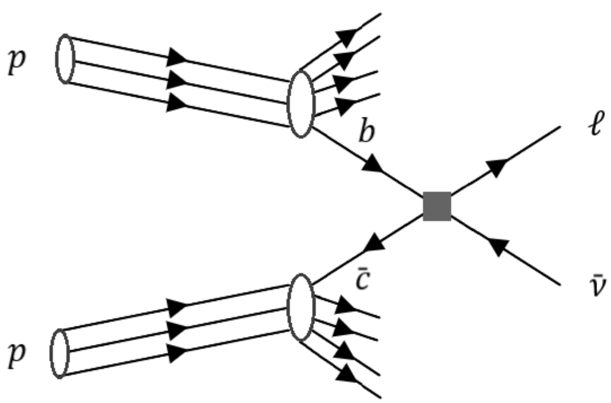
In collaboration with :
L. Allwicher, D. A. Faroughy, O. Sumensari, F. Wilsch
[2207.10714] & [2207.10756]

Motivations

- The flavor content of the proton can be used to probe New Physics at the LHC.
- Constraints resulting from the distribution of high-p_T tails are complementary to low-energy observables.

Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer [1609.08157]
Faroughy, Greljo, Kamenik [1609.07138]
Greljo, Marzocca [1704.09015]
Greljo, Camalich, Ruiz-Álvarez [1811.07920]
Angelescu, Faroughy, Sumensari [2002.05684]
Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez [2003.12421]
Endo, Iguro, Kitahara, Takeuchi, Watanabe [2111.04748]





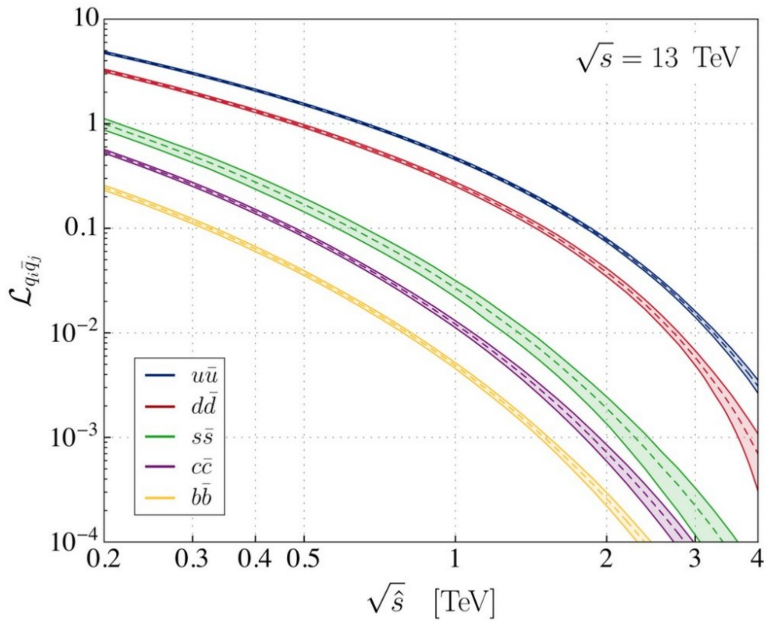
- Reinterpreting high-energy measurements for specific scenarios requires heavy machinery.

Drell-Yan and Flavor

- We consider $\begin{cases} pp \to \ell\nu \ + \text{soft jets} \\ pp \to \ell^+\ell^- \ + \text{soft jets} \end{cases}$
- Factorization leads to 2 distinct flavor effects:

$$\sigma\left(pp \to \ell_\alpha \bar{\ell}'_\beta\right) = \sum_{ij} \int \frac{\hat{s}}{s} \ \boxed{\mathcal{L}_{ij}(\hat{s})} \ \boxed{\hat{\sigma}(\bar{q}_i q_j \to \ell_\alpha \bar{\ell}'_\beta)}$$

Parton-parton luminosity



Hard scattering

$$\mathcal{A}(\bar{q}_i q_j \to \ell_\alpha \bar{\ell}'_\beta)$$

$\propto C^{ij}_{\alpha\beta}$	(EFT)
$\propto g^{ij} g^{\alpha\beta}$	(s-channel)
$\propto y^{i\alpha} y^{j\beta}$, ...	(t,u-channel, ...)

Energy Enhanced

Form Factor Parameterization

- We parameterize the amplitude in terms of Form Factors:

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

$X, Y \in \{L, R\}$
$k = p_\alpha + p_\beta$

Vector

Scalar

Tensor

Dipoles

$$
\begin{aligned}
u_i \bar{u}_j &\to \ell_\alpha^+ \ell_\beta^-, \\
d_i \bar{d}_j &\to \ell_\alpha^+ \ell_\beta^-, \\
u_i \bar{d}_j &\to \ell_\alpha^+ \nu_\beta.
\end{aligned}
$$

- Encodes every possible tree-level dynamics.

  → Local and non-local interaction

- For NLO corrections, see [Haisch, Schnella, Schultea `22 '23],

Form Factor Parameterization

- Analyticity hypothesis:

$$\mathcal{F}^I(\hat{s},\hat{t}) = \boxed{\mathcal{F}^I_{\mathrm{Reg}}}(\hat{s},\hat{t}) + \boxed{\mathcal{F}^I_{\mathrm{Poles}}}(\hat{s},\hat{t})$$

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

- Contact interaction.
- Sum over coupling dimension.

→ Match to the 4-fermion SMEFT (d=6).

$$\boxed{\mathcal{F}^I_{\mathrm{Poles}}}(\hat{s},\hat{t}) = \sum_a \frac{v^2\,\mathcal{S}_{I\,(a)}}{\hat{s}-\Omega_a} + \sum_b \frac{v^2\,\mathcal{T}_{I\,(b)}}{\hat{t}-\Omega_b} - \sum_c \frac{v^2\,\mathcal{U}_{I\,(c)}}{\hat{s}+\hat{t}+\Omega_c}$$

- Resolved interaction.
- Sum over all possible mediators.

→ Match to SM+NP mediators and 2-fermion SMEFT (d=6).

Matching to the SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \mathcal{O}\left(\frac{1}{\Lambda^6}\right).$$

- Consistent expansion up to order $\mathcal{O}\left(\Lambda^{-4}\right)$.

Grzadkowski, Iskrzynski, Misiak, Rosiek [1008.4884]
Murphy [2005.00059]

$$\sigma \sim |A_{\text{SM}}|^2 + \frac{2}{\Lambda^2}\text{Re}(A^*_{\text{SM}}\, A^{(6)}) + \frac{1}{\Lambda^4}|A^{(6)}|^2 + \frac{2}{\Lambda^4}\text{Re}(A^*_{\text{SM}}\, A^{(8)}) + \mathcal{O}\left(\frac{1}{\Lambda^6}\right)$$

Dimension		$d = 6$			$d = 8$			
Operator classes		ψ^4	$\psi^2 H^2 D$	$\psi^2 X H$	$\psi^4 D^2$	$\psi^4 H^2$	$\psi^2 H^4 D$	$\psi^2 H^2 D^3$
Amplitude scaling		E^2/Λ^2	v^2/Λ^2	vE/Λ^2	E^4/Λ^4	$v^2 E^2/\Lambda^4$	v^4/Λ^4	$v^2 E^2/\Lambda^4$
Parameters	# Re	456	45	48	168	171	44	52
	# Im	399	25	48	54	63	12	12

Most energy-enhanced

≈ 550 operators at dimension 6.

\+ 350 operators at dimension 8.

Comparing with data

- We introduce ***HighPT***, a Mathematica package for automatic extraction of bound from high-p_T tail distribution.
  - Support for the latest LHC searches relevant for semileptonic transitions.
  - Support for both SMEFT and tree-level mediators.

Process	Experiment	Luminosity
$pp \to \tau\tau$	ATLAS	$139\,\mathrm{fb}^{-1}$
$pp \to \mu\mu$	CMS	$140\,\mathrm{fb}^{-1}$
$pp \to ee$	CMS	$137\,\mathrm{fb}^{-1}$
$pp \to \tau\nu$	ATLAS	$139\,\mathrm{fb}^{-1}$
$pp \to \mu\nu$	ATLAS	$139\,\mathrm{fb}^{-1}$
$pp \to e\nu$	ATLAS	$139\,\mathrm{fb}^{-1}$
$pp \to \tau\mu$	CMS	$137.1\,\mathrm{fb}^{-1}$
$pp \to \tau e$	CMS	$137.1\,\mathrm{fb}^{-1}$
$pp \to \mu e$	CMS	$137.1\,\mathrm{fb}^{-1}$

$$\chi^2(\theta) = \sum_{A \in \mathcal{A}} \left(\frac{\boxed{\mathcal{N}_A}(\theta) + \boxed{\mathcal{N}_A^b} - \boxed{\mathcal{N}_A^{\text{obs}}}}{\sqrt{\boxed{\delta\mathcal{N}_A^b}^2 + \boxed{\mathcal{N}_A^{\text{obs}}}}} \right)^2$$

Data

Predicted number of events, NP only

SM+Background, provided by experiments

In[3]:=
```
chi2 = ChiSquareLHC["di-muon-CMS"] // Total;
```

Recast procedure

- To compare with experiment, we need to take into account detector effects.
- For Bins $[x_1, ...x_n]$:

$$\sigma^{\text{Vis}}(x_q, x_q + 1) = \sum_p K_{pq} \, \sigma^{\text{Had}}(x_p, x_p + 1)$$

To be compared with experiment

Kernel matrix, extracted from Monte-Carlo simulations

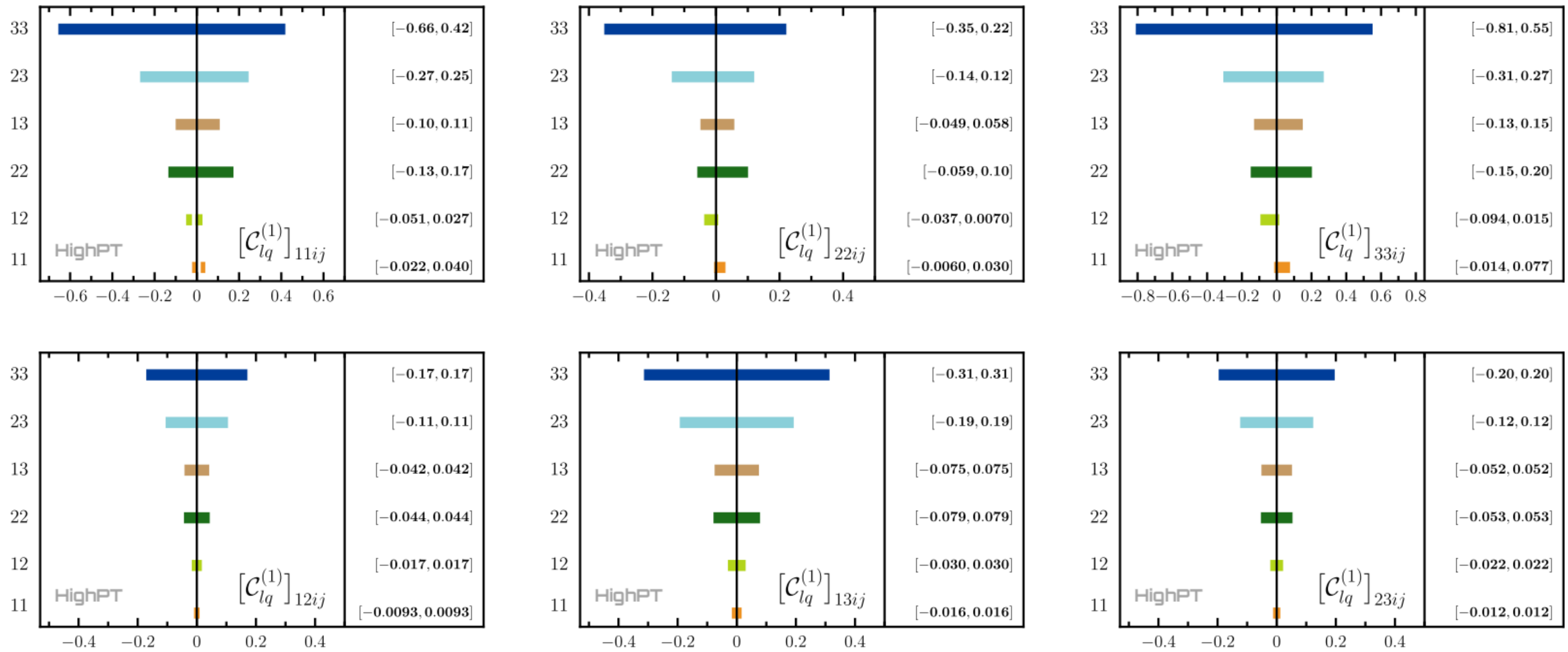
Computed exactly, as a polynomial in the NP couplings

- MC simulations using ***Madgraph*** + ***Pythia*** + ***Delphes***.
- Simulations have to reproduce the event selection of the experimental searches.
- One kernel matrix for each combination of interfering FF.

SMEFT Results

- Comparing with data, we obtain constraints on individual NP couplings.
- No excess is observed at more than 2σ.
- A few examples:

[Greljo, Camalich, Ruiz-Alvarez `19],
[Marzocca, Min, Son `20],
[Iguro, Takeuchi, Watanabe `21],[Jaffredo `21],

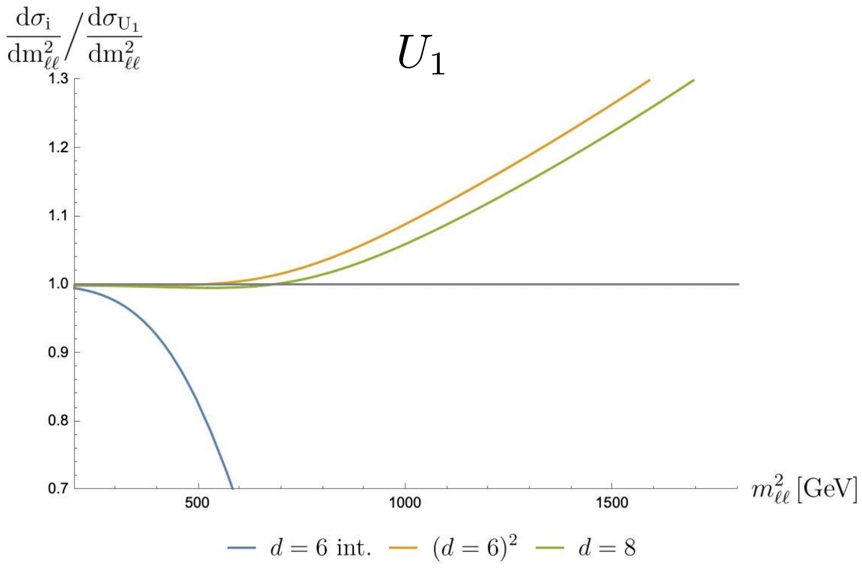


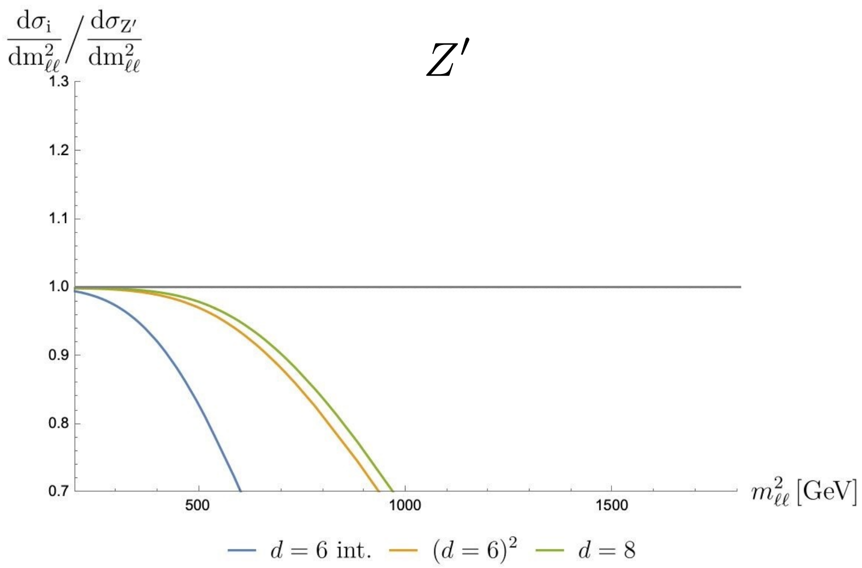
$$\mathcal{O}_{lq}^{(1)}{}_{\alpha\beta ij} = (\bar{L}_\alpha \gamma^\mu L_\beta)(\bar{Q}_i \gamma_\mu Q_j)$$

Concerning the EFT validity

- If the NP scale is not higher the most energetic events, effects can potentially be huge.
- Results in over-constraining bounds for t- and u-channel mediators:

$$\frac{1}{t-m^2} \simeq -\frac{1}{m^2}\left(1+\frac{t}{m^2}+\dots\right), \qquad t,u \in [-s,0]$$



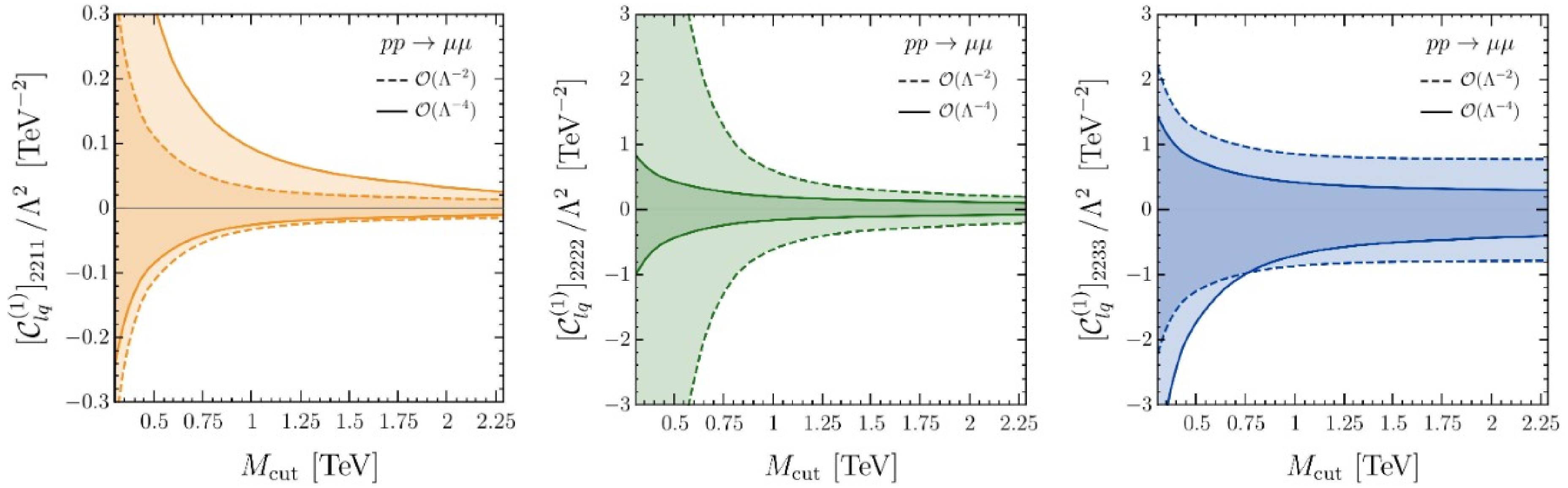


- Effects can be ≈40% for $m = 1.5$ TeV, even for non-resonant processes.

Iguro, Takeuchi, Watanabe [2011.02486]
Jaffredo [2112.14604]

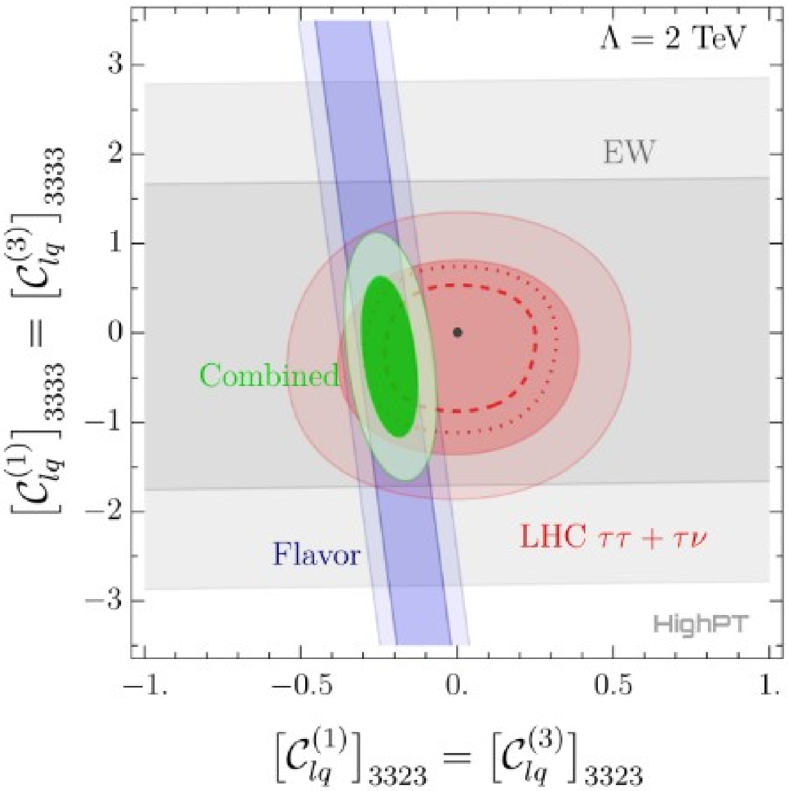
Concerning the EFT validity

- To ensure the validity of the EFT, neglect events above a threshold.
- Removing highest bins lead to comparatively worse constraints.

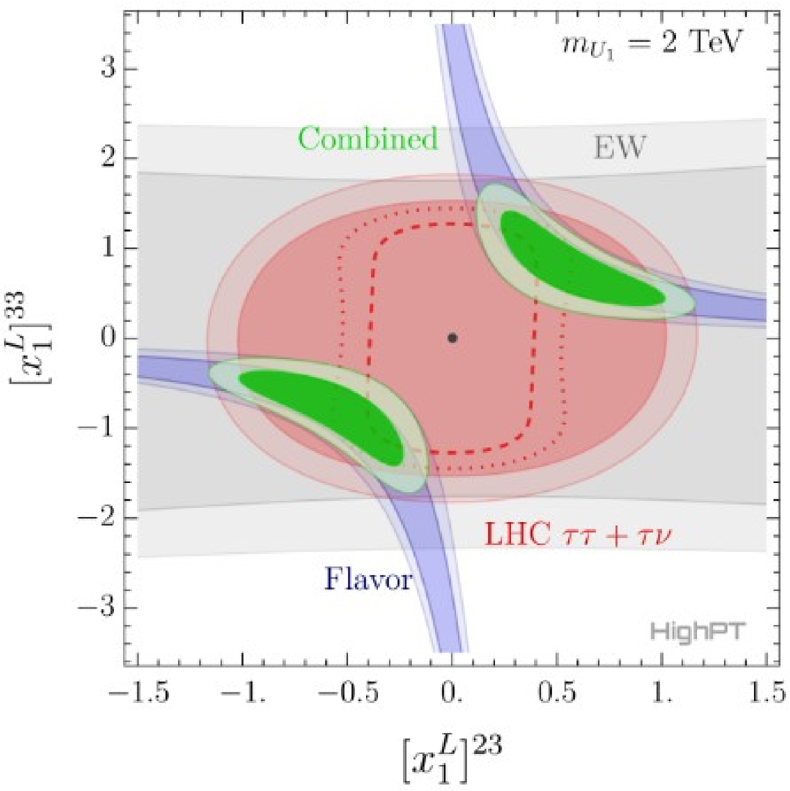


High-p_T tails applied to $R_{D^{(*)}}$

- We combine flavor, EW pole, and high-p_T observables.
- High-p_T constraints are already competitive.



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

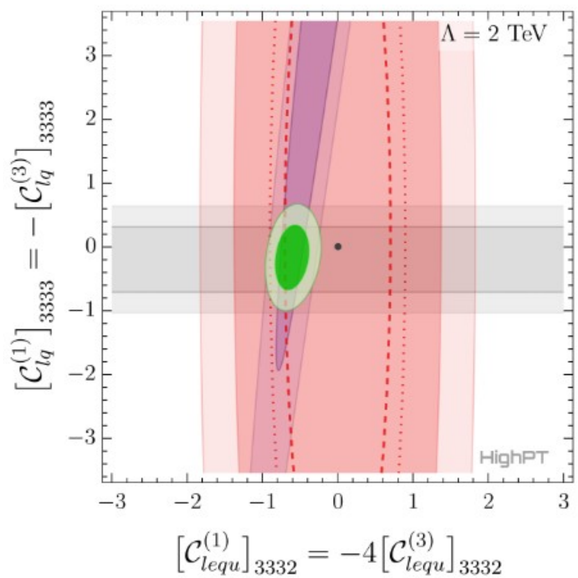


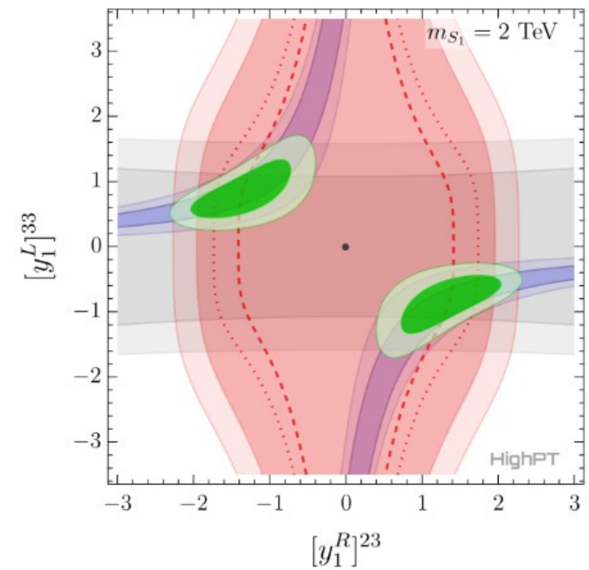
High-p_T tails applied to $R_{D^{(*)}}$

EFT

Leptoquark

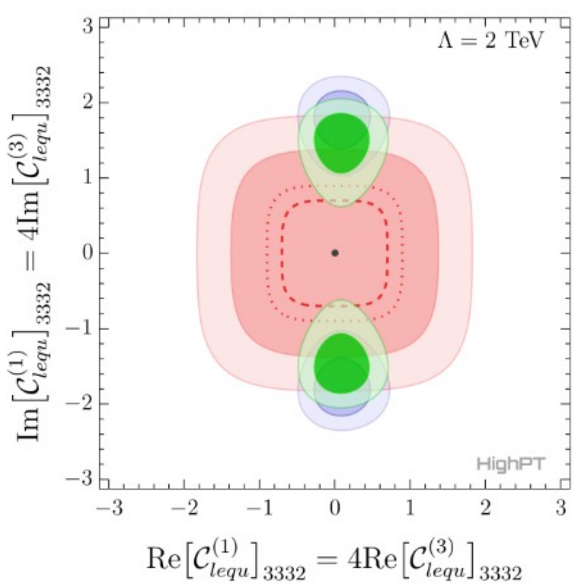
$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

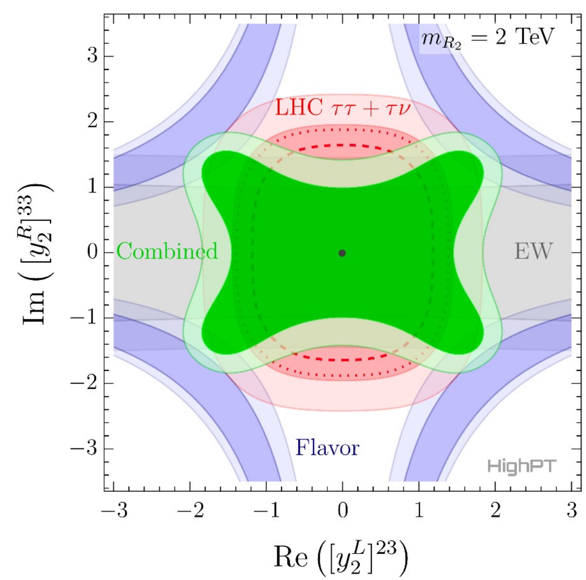




$R_2 \sim (\mathbf{3}, \mathbf{2}, 7/6)$

$R_2 \sim (\mathbf{3}, \mathbf{2}, 7/6)$



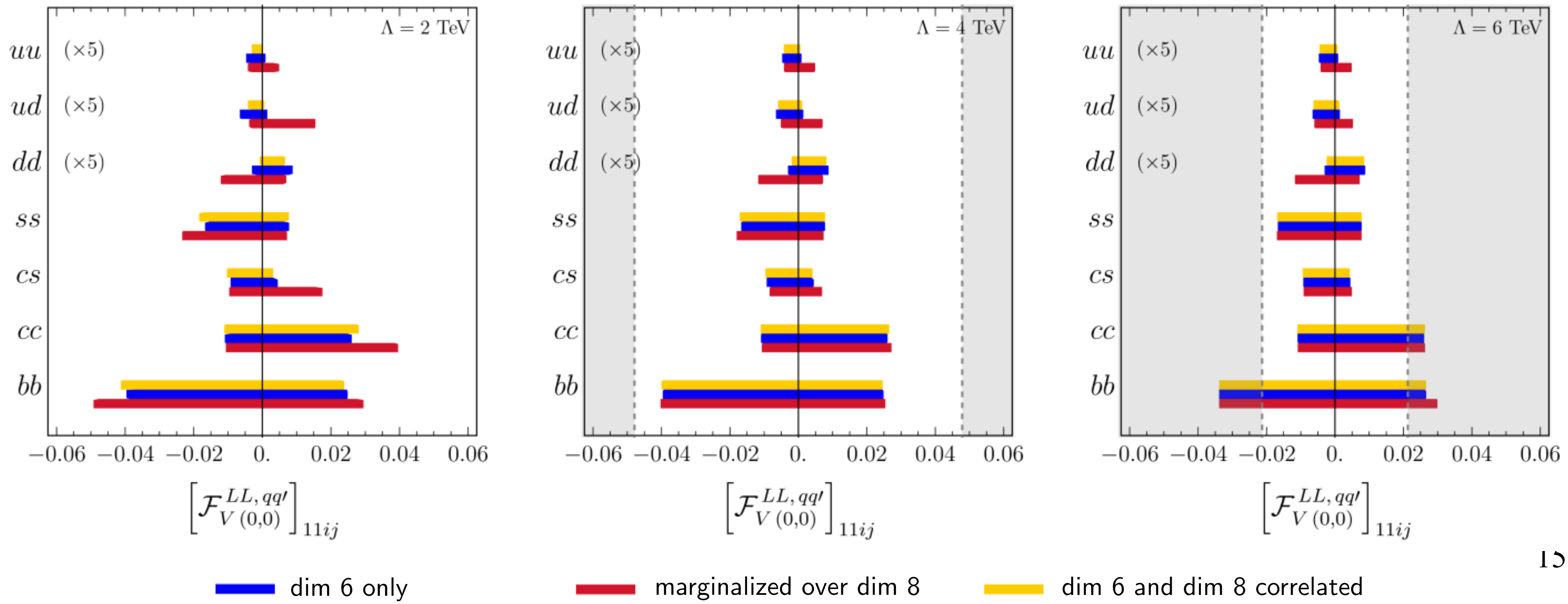


Conclusion

- Drell-Yan high-p_T tails are crucial probes of NP, complementary to low-energy observables.
- We construted the full flavor likelihood for Drell-Yan processes at LHC, both for the SMEFT and for tree-level BSM mediators.
- No significant excess is observed, but we are able to constrain a large number of NP coefficients
- All results are available in the package ***HighPT***.
- We explicitly checked the validity of the EFT expansion.
- Resulting constraints are already competitive with flavor.
- What next?
  - More observable: Forward-Backward Asymmetry, EW pole, Flavor, ...
  - Future experimental searches
  - Refinement of current constraints: QCD correction, b-jet tagging...

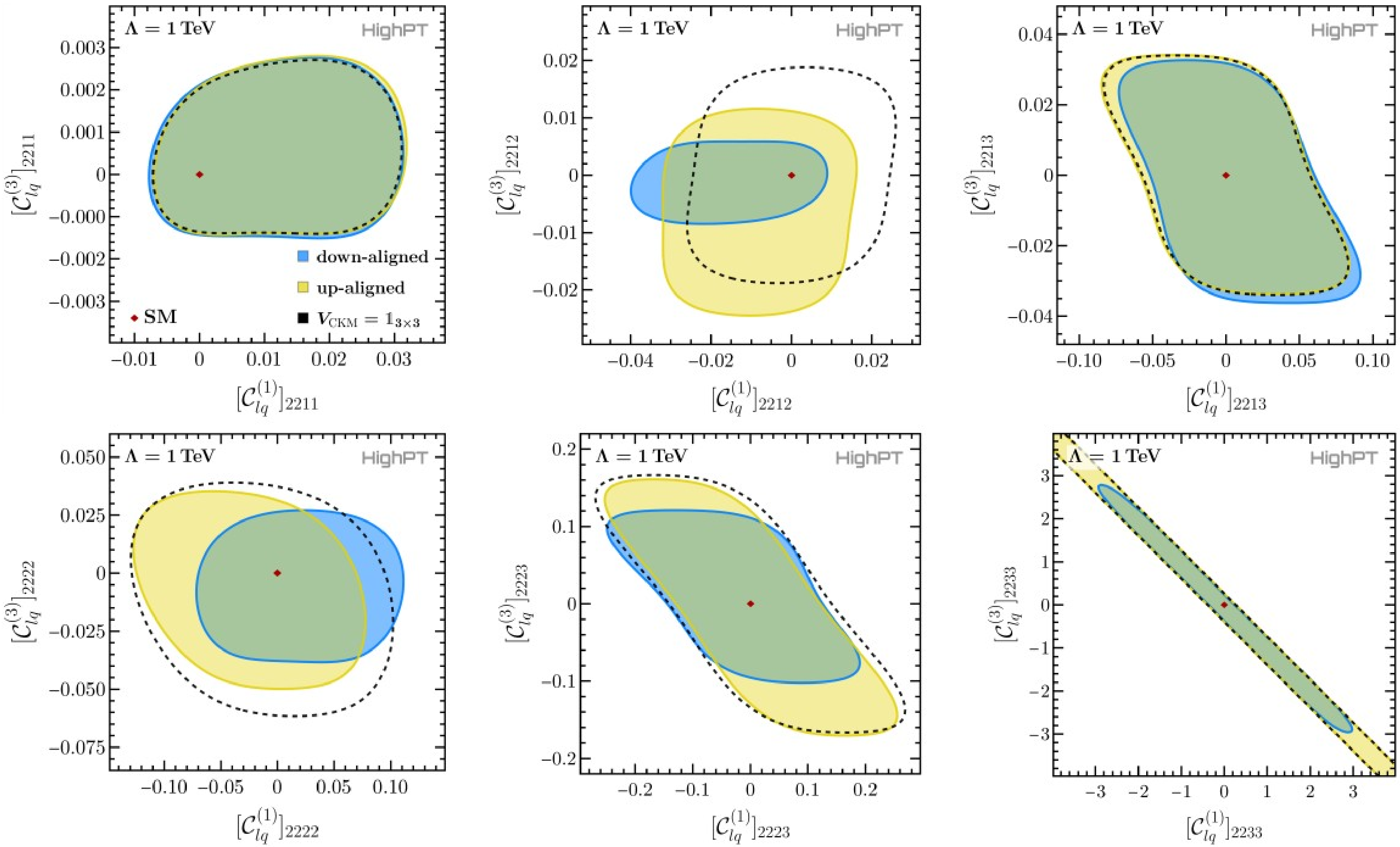
Backup: Impact of dimension 8 operators

- Dimension 8 operators do ***not*** increase the validity range of the EFT. They modify the last term of the expansion, but the truncation remains $1/\Lambda^4$.
- They can have a sizable impact on the constraints for dimension 6 operators (light flavors), depending in the NP scale.
- Generally not relevant for explicit scenarios.



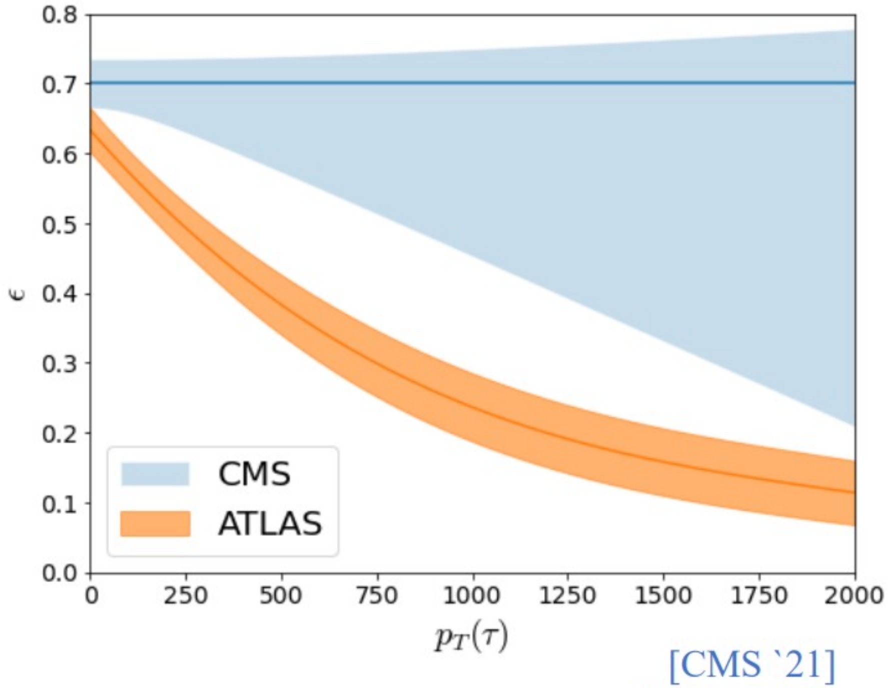
Backup: SMEFT flavor basis

- The choice of flavor basis (sometimes) matter.

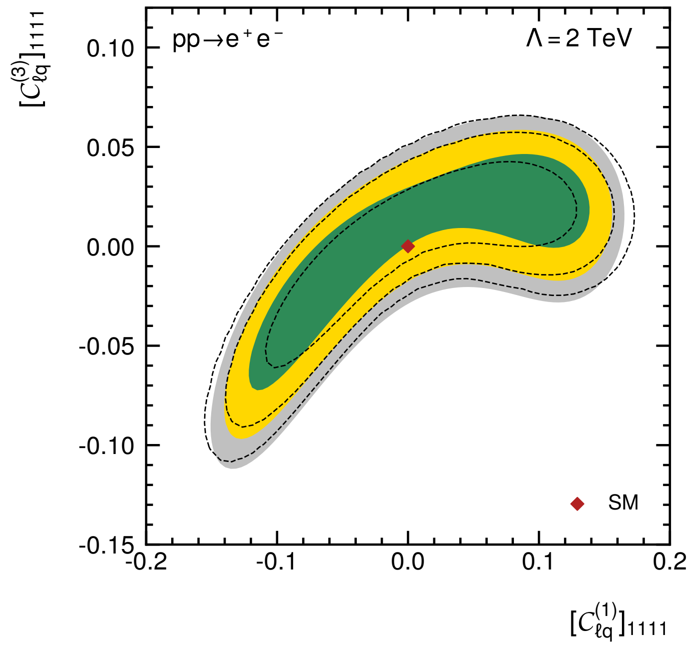


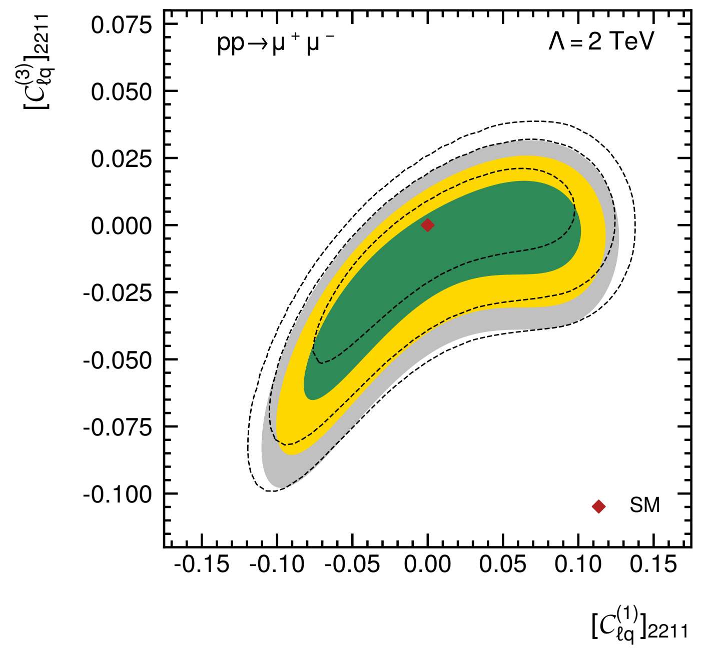
Backup: CLs vs Chi square

- Multiplicative effects such as the ***error on the tau reconstruction efficiency*** cannot be accounted for with a χ^2.

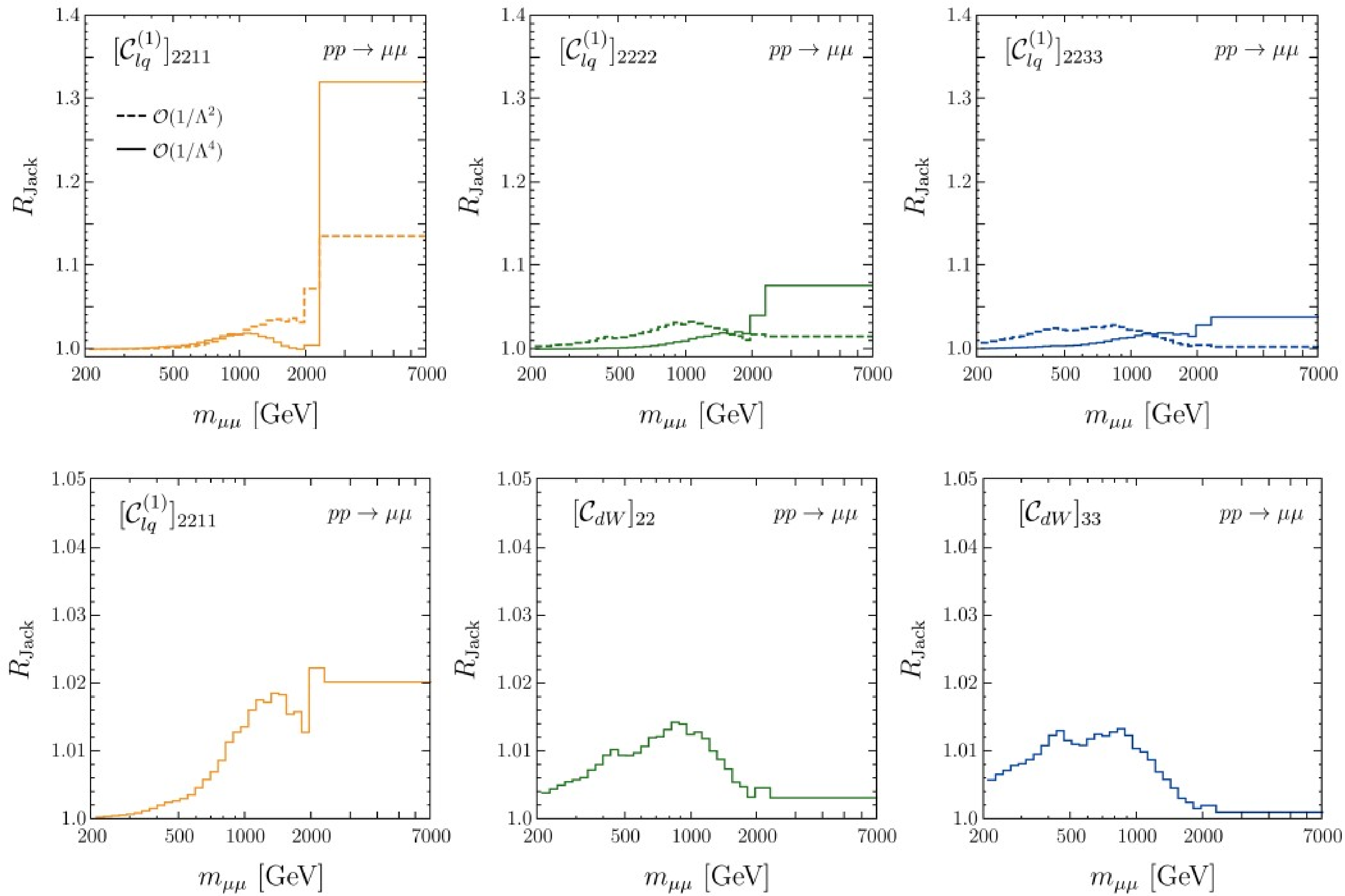


[CMS `21]
[ATLAS `21]





Backup: Jack-knife analysis

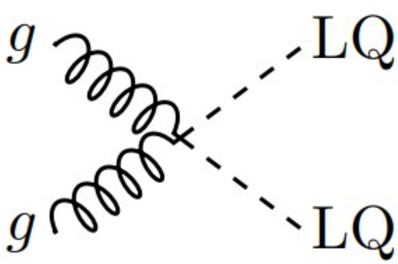


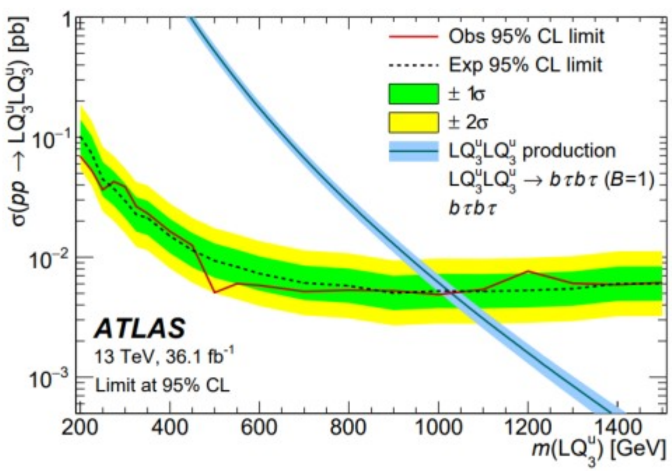
Backup: List of tree-level mediators

	SM rep.	Spin	$\mathcal{L}_{\rm int}$
Z'	$(\mathbf{1},\mathbf{1},0)$	1	$\mathcal{L}_{Z'} = \sum_\psi [g_1^\psi]_{ab}\,\bar\psi_a \not{Z}' \psi_b \ , \ \ \psi \in \{u,d,e,q,l\}$
W'	$(\mathbf{1},\mathbf{3},0)$	1	$\mathcal{L}_{W'} = [g_3^q]_{ij}\,\bar q_i \not{W}' q_j + [g_3^l]_{\alpha\beta}\,\bar l_\alpha \not{W}' l_\beta$
$\widetilde Z$	$(\mathbf{1},\mathbf{1},1)$	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	$\mathcal{L}_\Phi = \sum_{a=1,2} \left\{ [y_u^{(a)}]_{ij}\,\bar q_i u_j \widetilde\Phi_a + [y_d^{(a)}]_{ij}\,\bar q_i d_j \Phi_a + [y_e^{(a)}]_{\alpha\beta}\,\bar l_\alpha e_\beta \Phi_a \right\} + \text{h.c.}$
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	$\mathcal{L}_{S_3} = [y_3^L]_{i\alpha}\,\bar q_i^c \epsilon S_3 l_\alpha + \text{h.c.}$
U_3	$(\mathbf{3},\ \mathbf{3},\ 2/3)$	1	$\mathcal{L}_{U_3} = [x_3^L]_{i\alpha}\,\bar q_i (\tau \cdot \not{U}_3) l_\alpha + \text{h.c.}$

Backup: Limits from pair production

$\boxed{LQ(3, X, X)}$





Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$
$jj\tau\bar{\tau}$	-	-	-
$b\bar{b}\tau\bar{\tau}$	1.0(0.8) TeV	1.5(1.3) TeV	36 fb^{-1}
$t\bar{t}\tau\bar{\tau}$	1.4(1.2) TeV	2.0(1.8) TeV	140 fb^{-1}
$jj\mu\bar{\mu}$	1.7(1.4) TeV	2.3(2.1) TeV	140 fb^{-1}
$b\bar{b}\mu\bar{\mu}$	1.7(1.5) TeV	2.3(2.1) TeV	140 fb^{-1}
$t\bar{t}\mu\bar{\mu}$	1.5(1.3) TeV	2.0(1.8) TeV	140 fb^{-1}
$jj\nu\bar{\nu}$	1.0(0.6) TeV	1.8(1.5) TeV	36 fb^{-1}
$b\bar{b}\nu\bar{\nu}$	1.1(0.8) TeV	1.8(1.5) TeV	36 fb^{-1}
$t\bar{t}\nu\bar{\nu}$	1.2(0.9) TeV	1.8(1.6)TeV	140 fb^{-1}

[Atlas, CMS '18-'20]

Assuming a branching fraction of 1 (0.5).