Constraints on Tau LFV decays from high-p_T studies at LHC

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Topical workshop on LFV decays of the tau — IJCLab — Orsay

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Lepton Flavor as an accidental symmetry of the SM

- Lepton flavor conservation is an accidental symmetry of the SM Lagrangian at $d = 4$
  - Only a single LFV gauge invariant $d = 4$ operator: $[Y_e]_{pr}(\overline{\ell}_p e_r)H + \mathrm{H.c.}$
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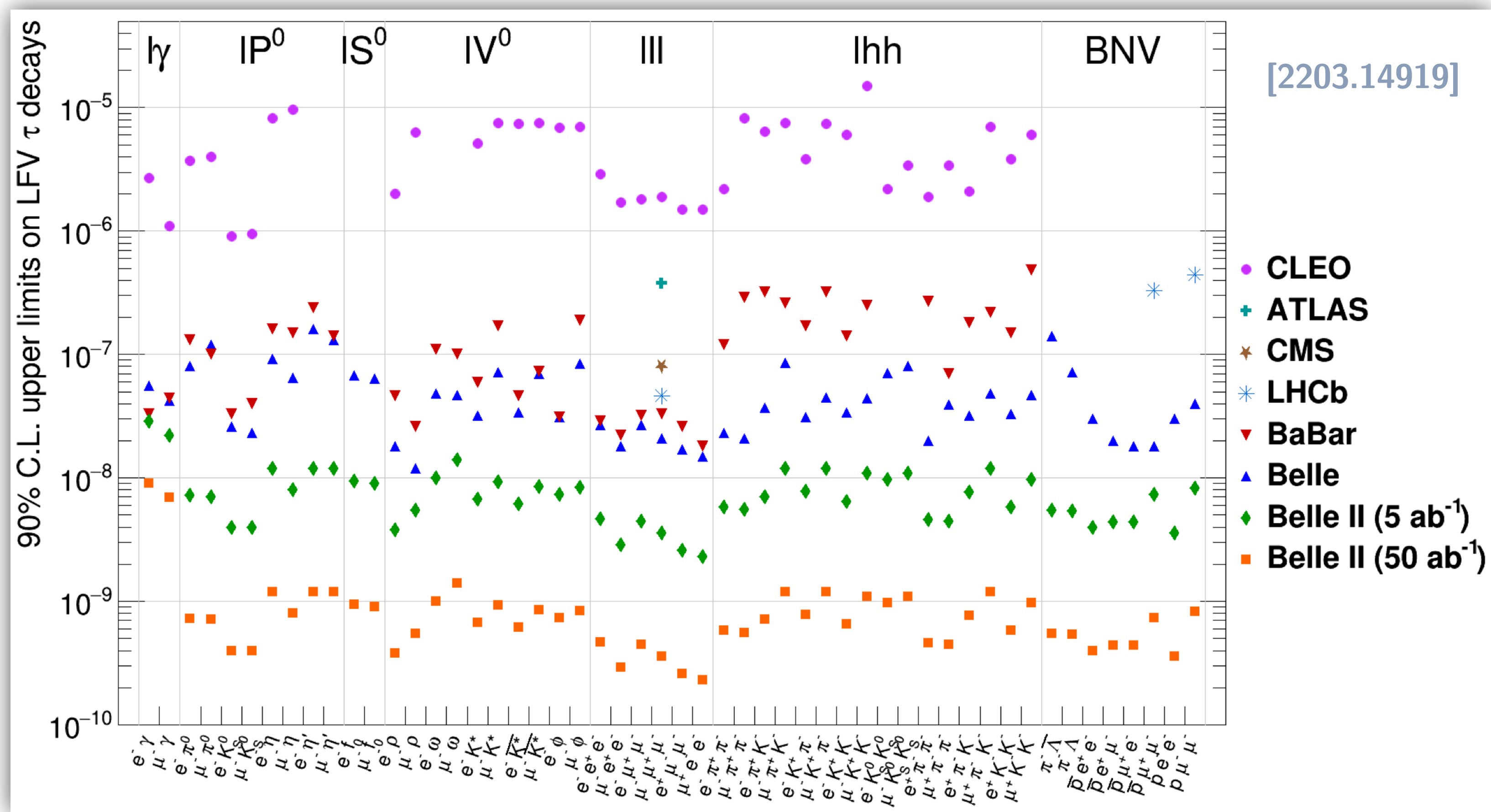
- We can probe heavy BSM particles with masses $1\,\mathrm{TeV} \lesssim M$ with LFV couplings at
  - Low-energy experiments (high precision)
  - LHC in high-p_T tails (higher energies)

  complementarity
- LHC particularly relevant for NP in 3^{rd} generation → LFV τ transitions

Tau LFV: from low energies to high-p_T at LHC

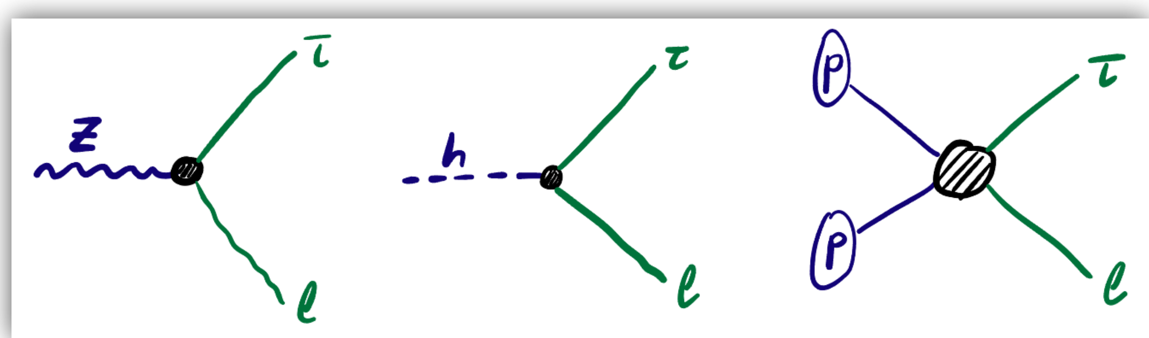
- Many BSM models predict NP dominantly coupled to the 3rd generation
  - Largest LFV contributions in the τ sector
- Many precision measurements from low-energy flavor experiments



Weaker bounds than for LFV μ measurements

$\rightarrow$ Can high-p_T offer complementary information?

- High-p_T LHC measurements of LFV transitions involving τ leptons:
  - Z boson decays
  - Higgs boson decays
  - Drell-Yan

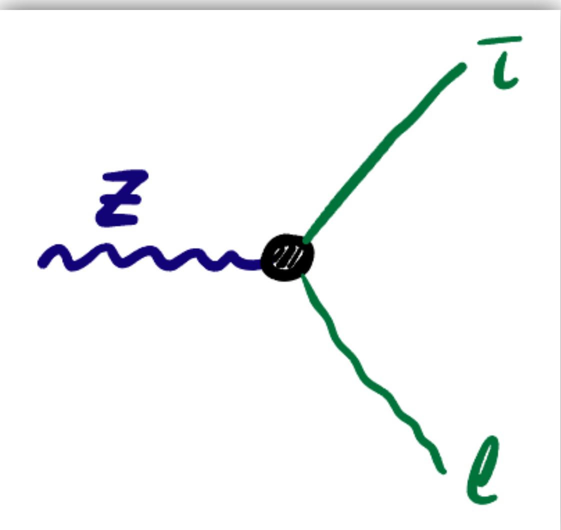


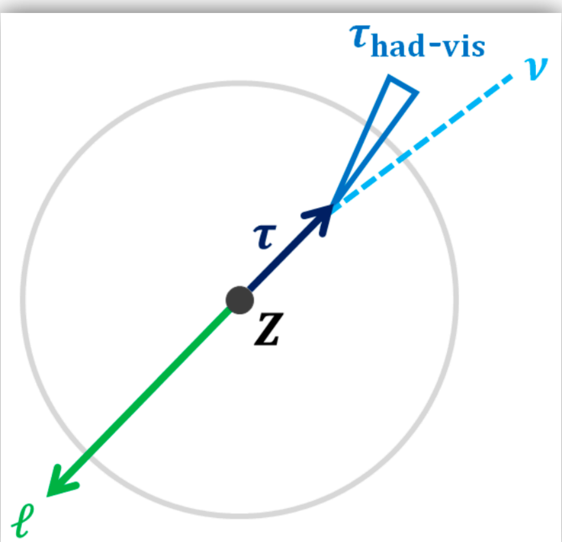
LFV Z boson decays involving taus

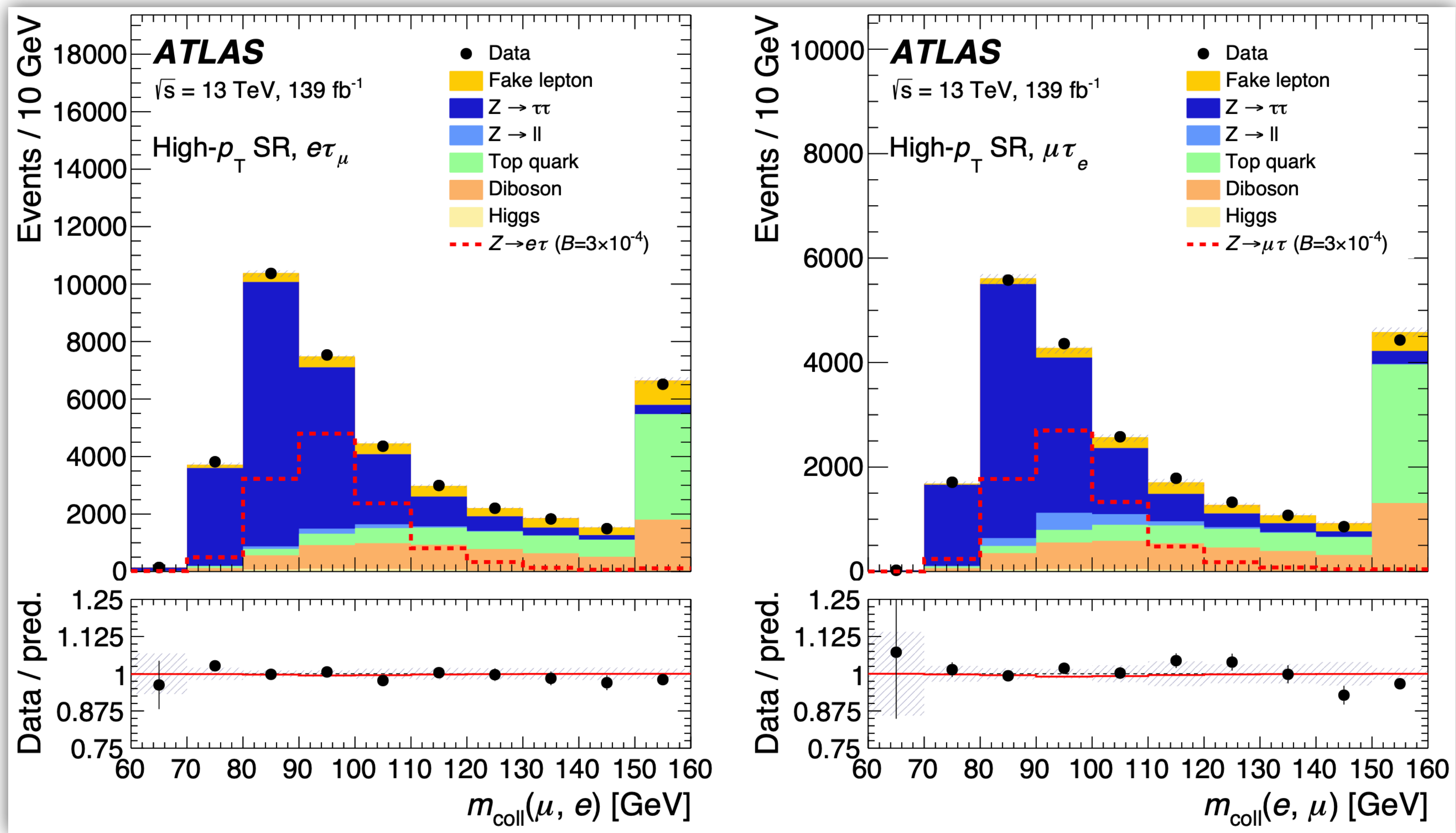
- ATLAS constraints on $\mathscr{B}(Z \to \tau\ell)$ with $\ell \in \{\mu, e\}$ with $\sim 140\,\text{fb}^{-1}$ for

ATLAS [2010.02566], [2105.12491]

  - Hadronic τ decays ($\tau \to$ hadrons) and leptonic τ decays ($\tau e \to \mu e$ and $\tau\mu \to e\mu$)







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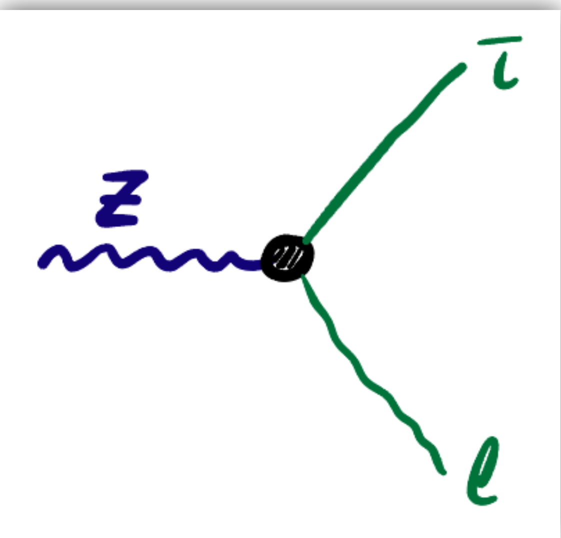

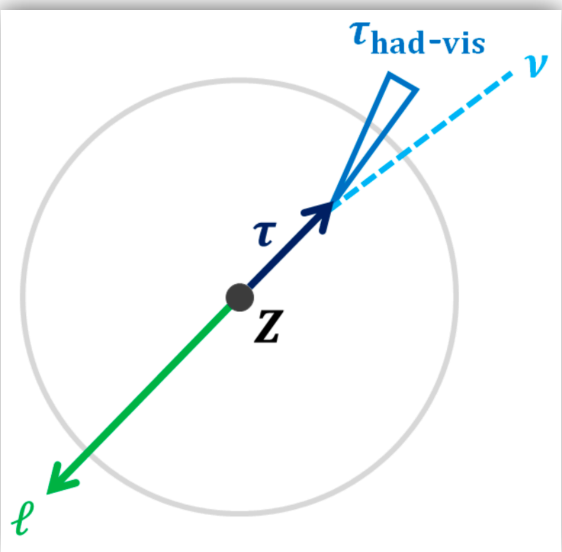

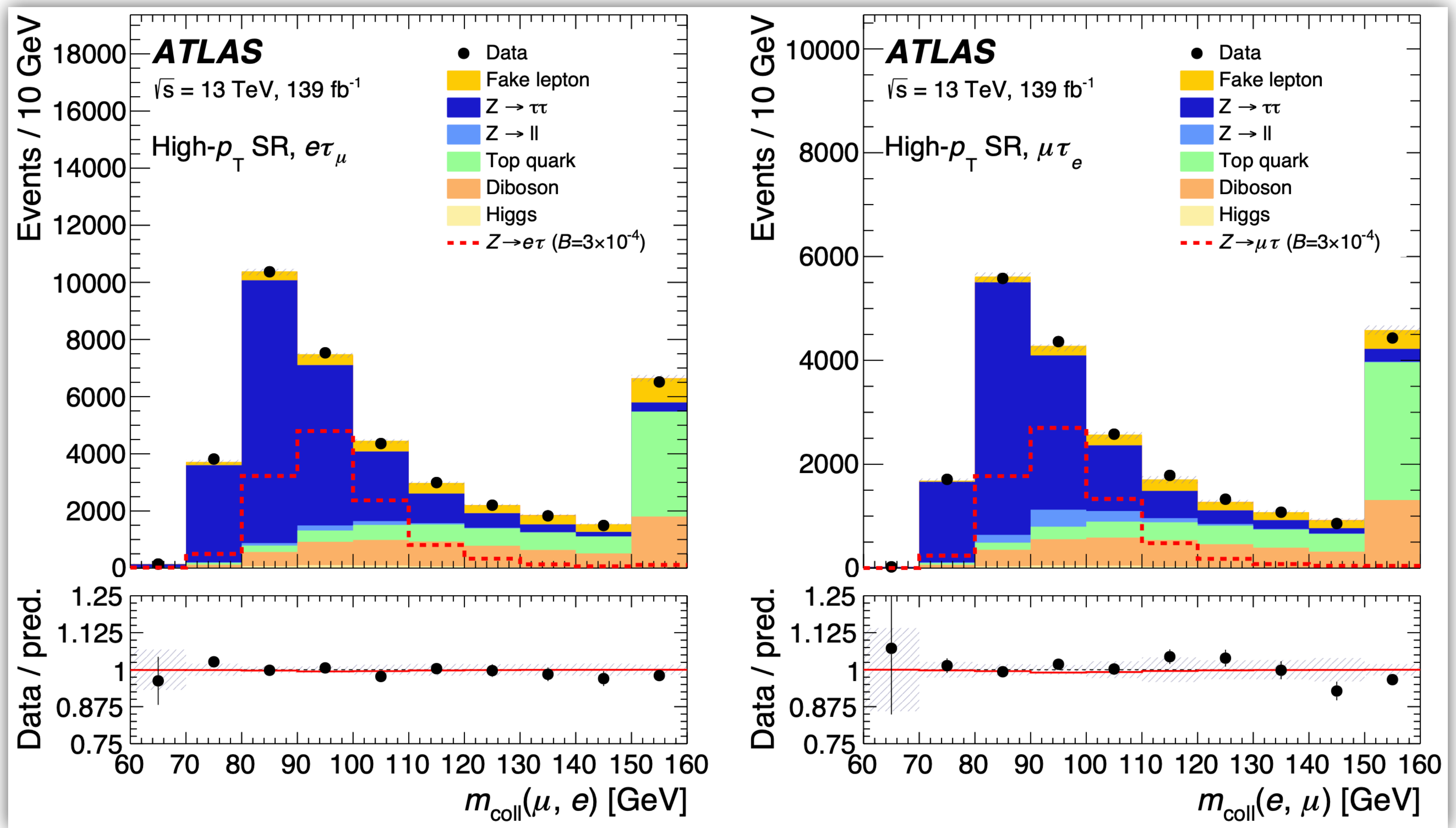

- $\mathscr{B}(Z \to \tau\mu) < 6.5 \times 10^{-6}$ and $\mathscr{B}(Z \to \tau e) < 5.0 \times 10^{-6}$ at 95 % CL (superseding LEP limits)
  - SMEFT: tree-level contributions by: $C_{Hl}^{(1+3)}$, C_{He}, C_{eW}, C_{eB}

LFV Higgs boson decays involving taus

CMS [2105.03007]

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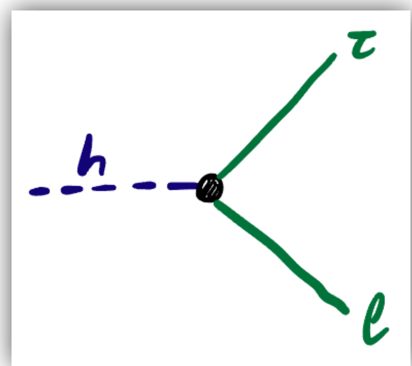

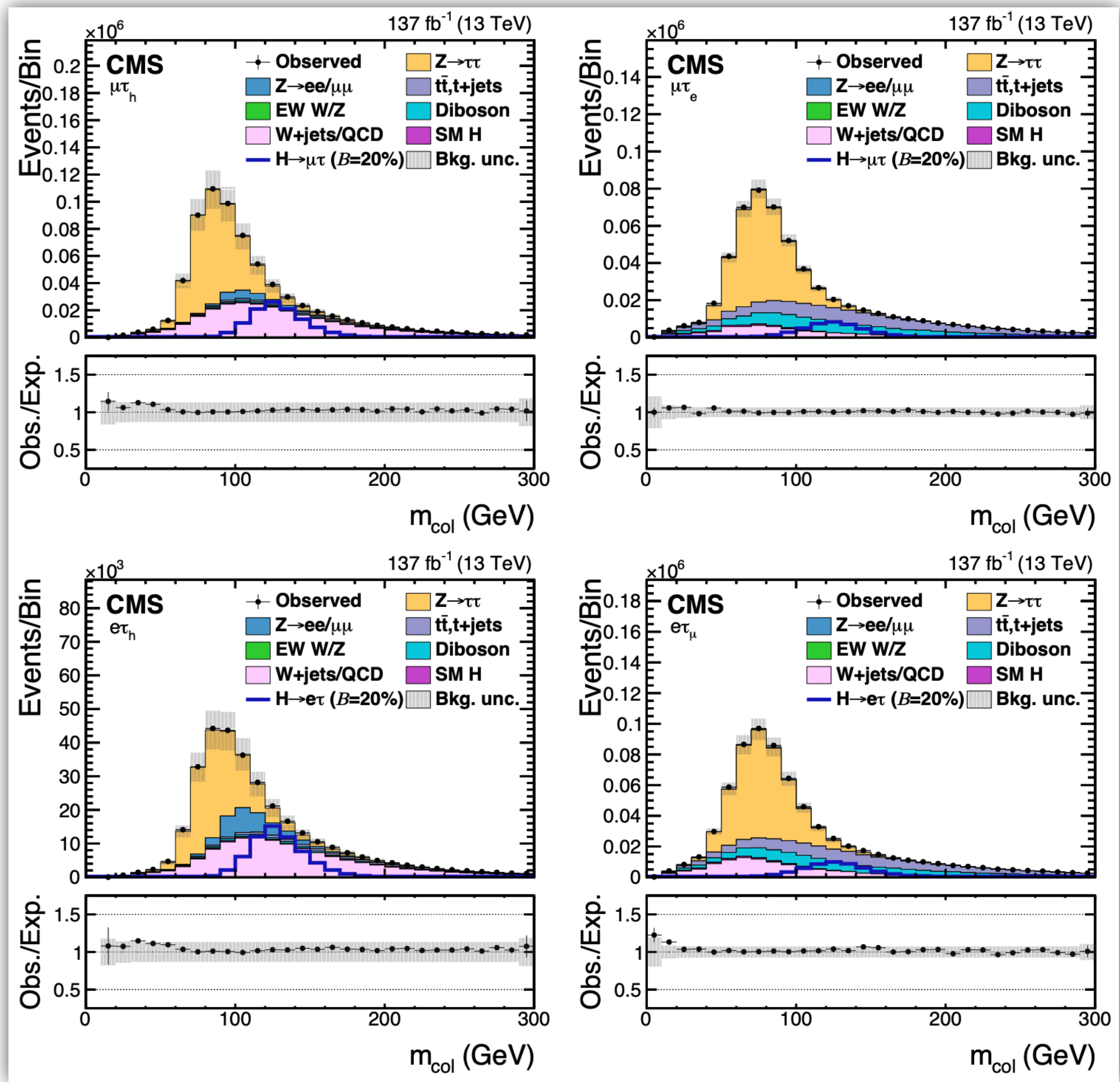

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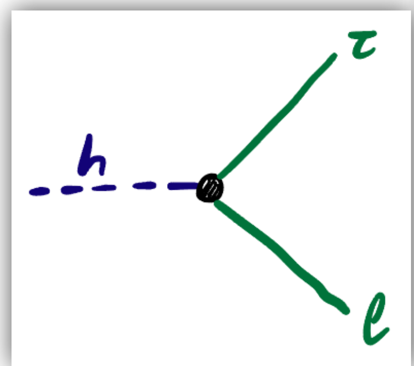

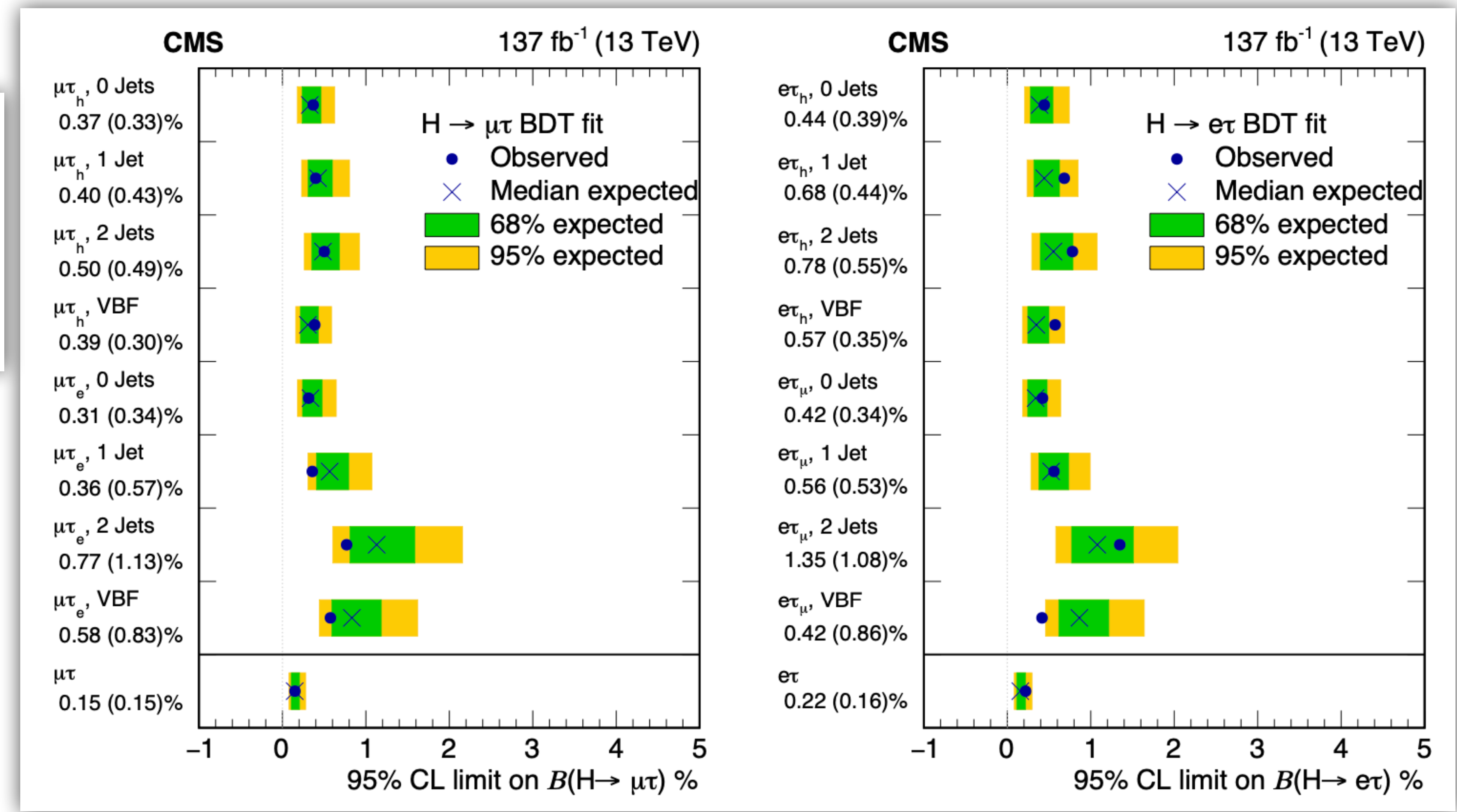

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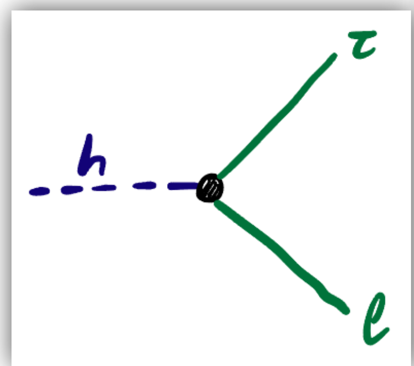
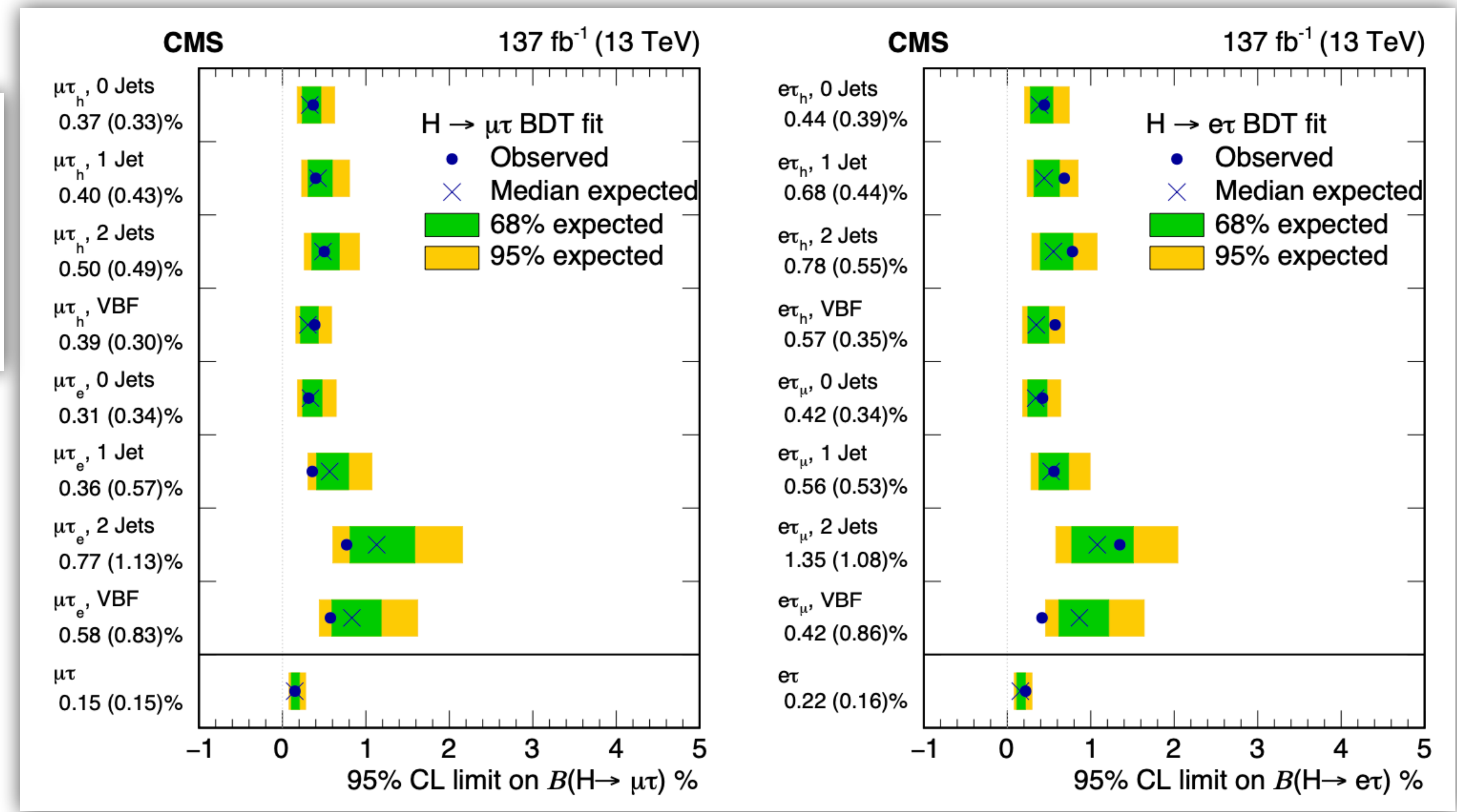




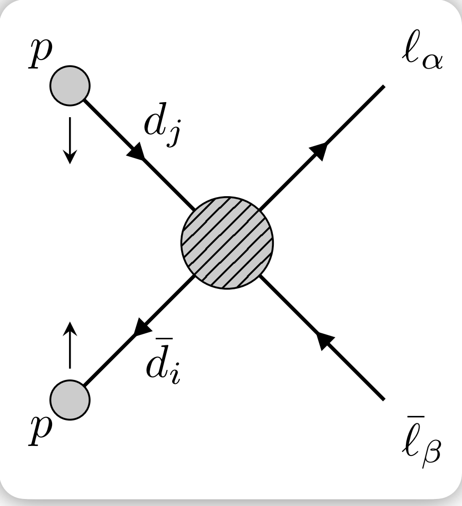
- Constraints on LFV Yukawa couplings: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.11 \times 10^{-3}$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$$

SMEFT: tree-level contribution by C_{eH}

Flavor physics in high-p_T Drell-Yan tails

- Hadronic cross-section: $$\sigma_{\text{had}}(pp \to \ell_\alpha \ell_\beta) = \mathscr{L}_{ij} \otimes [\hat{\sigma}]_{ij}^{\alpha\beta}$$



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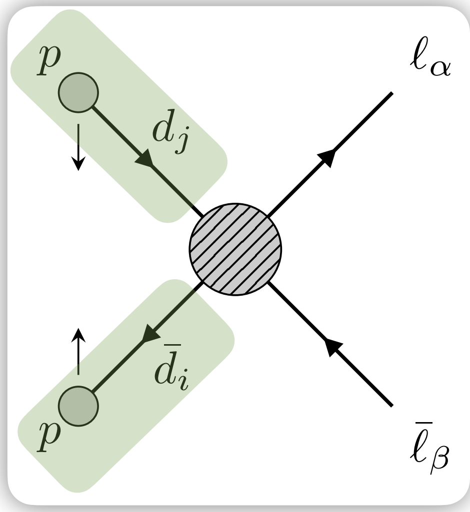
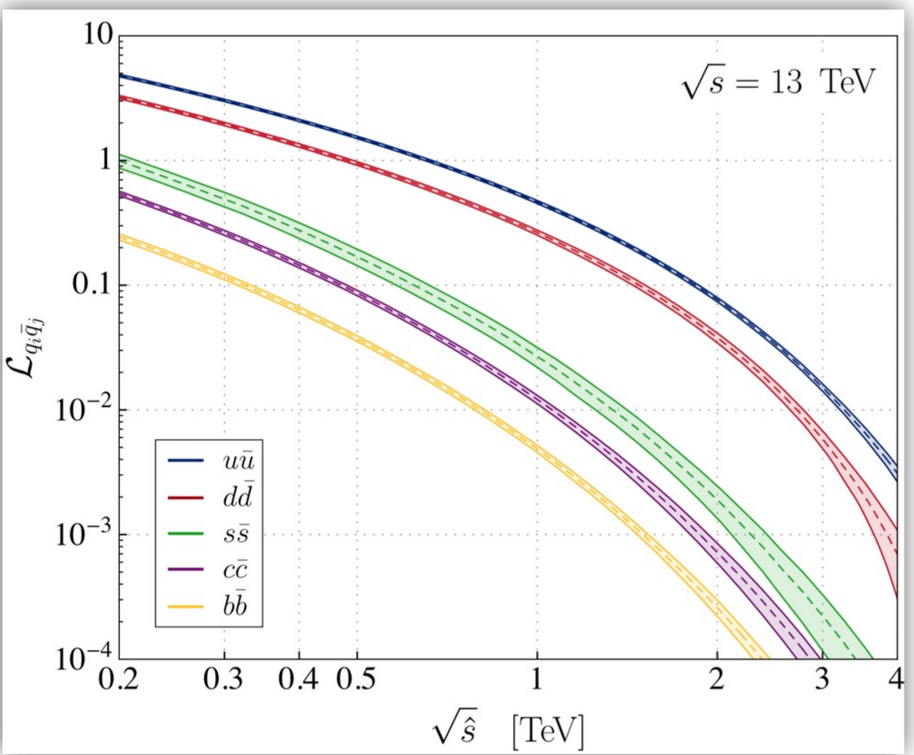
$$\mathcal{L}_{ij}(\hat{s}) = \int_{\frac{\hat{s}}{s}}^{1} \frac{\mathrm{d}x}{x} \left[f_{\bar{q}_i}(x,\mu)\, f_{q_j}\left(\frac{\hat{s}}{sx},\mu\right) + (\bar{q}_i \leftrightarrow q_j) \right]$$





Angelescu, Faroughy, Sumensari [2002.05684]

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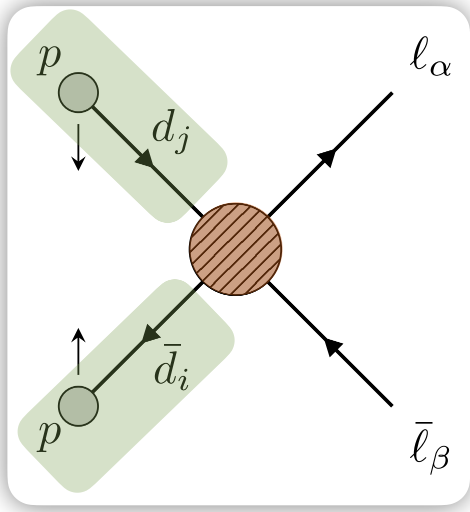

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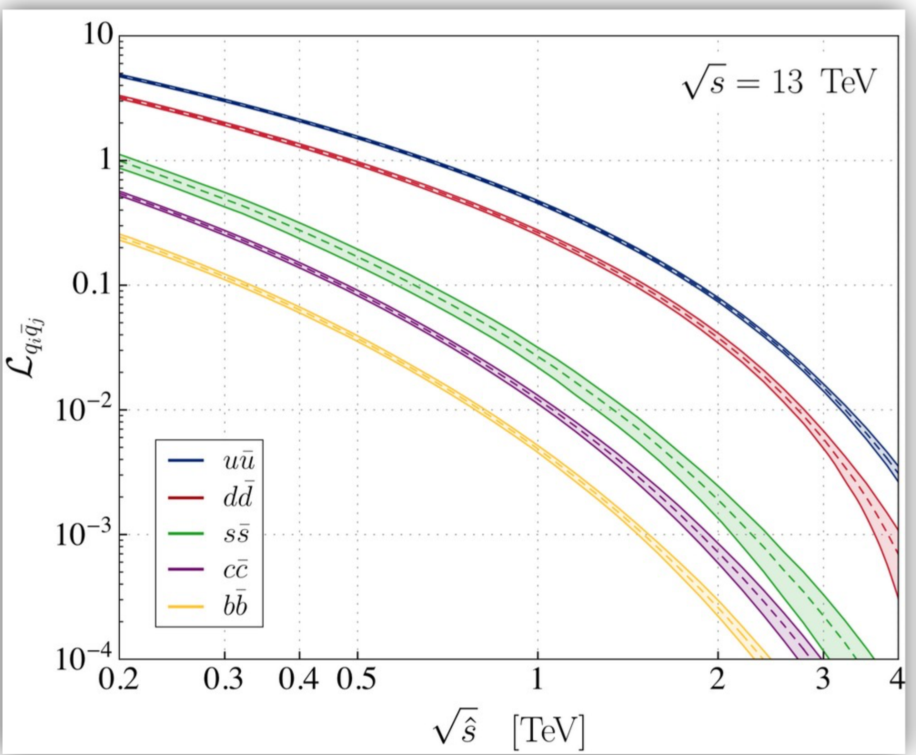
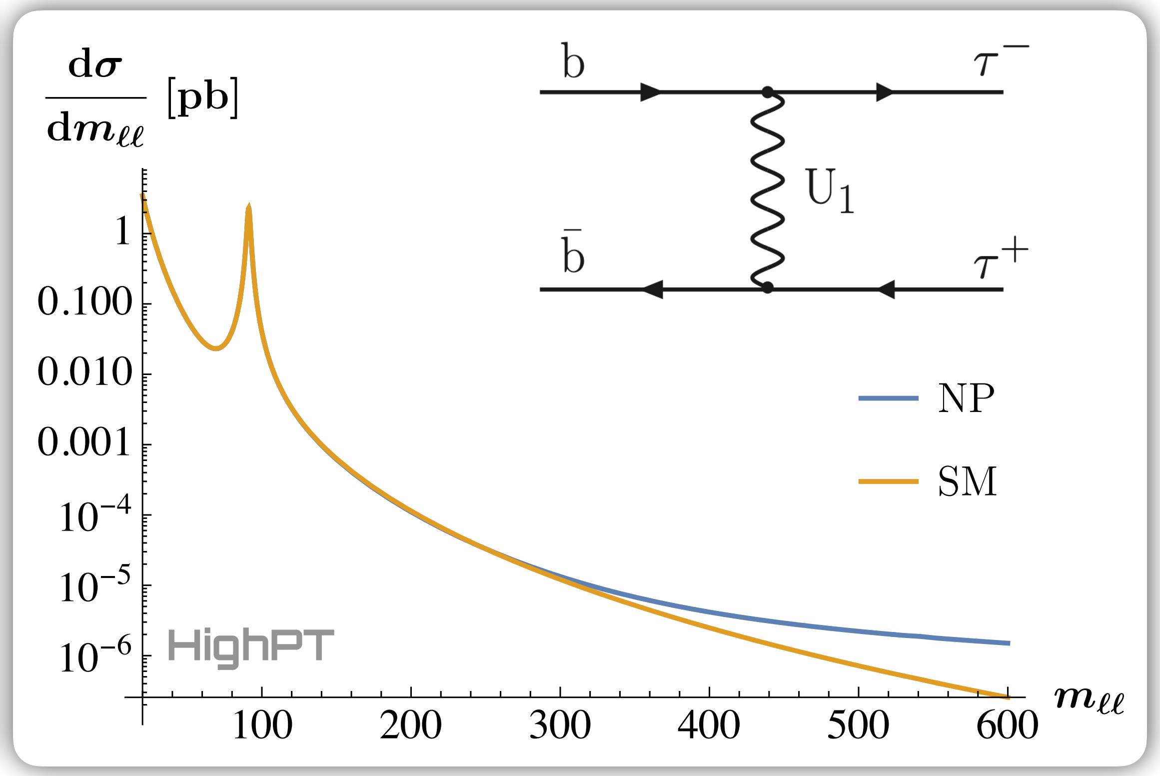
  - $[\hat{\sigma}]_{ij}^{\alpha\beta}$ partonic cross section $\to$ energy enhanced in EFT $\quad [\hat{\sigma}]_{ij}^{\alpha\beta} \propto \dfrac{\hat{s}}{\Lambda^4} \left| C \right|^2$





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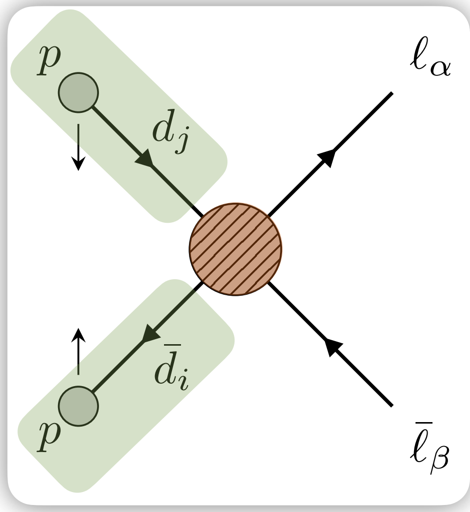

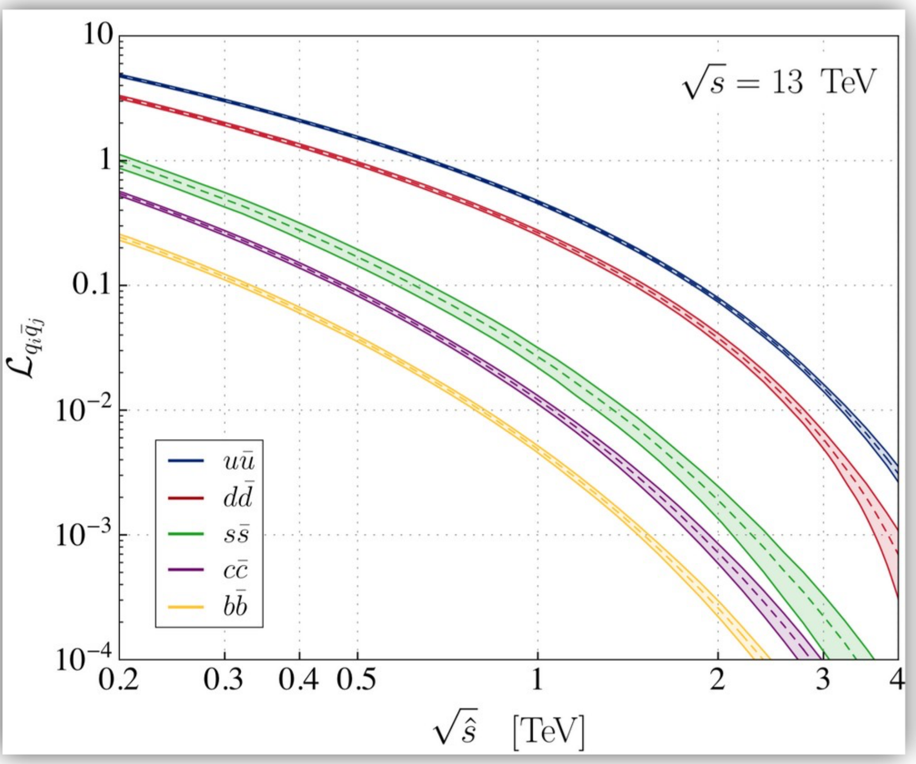

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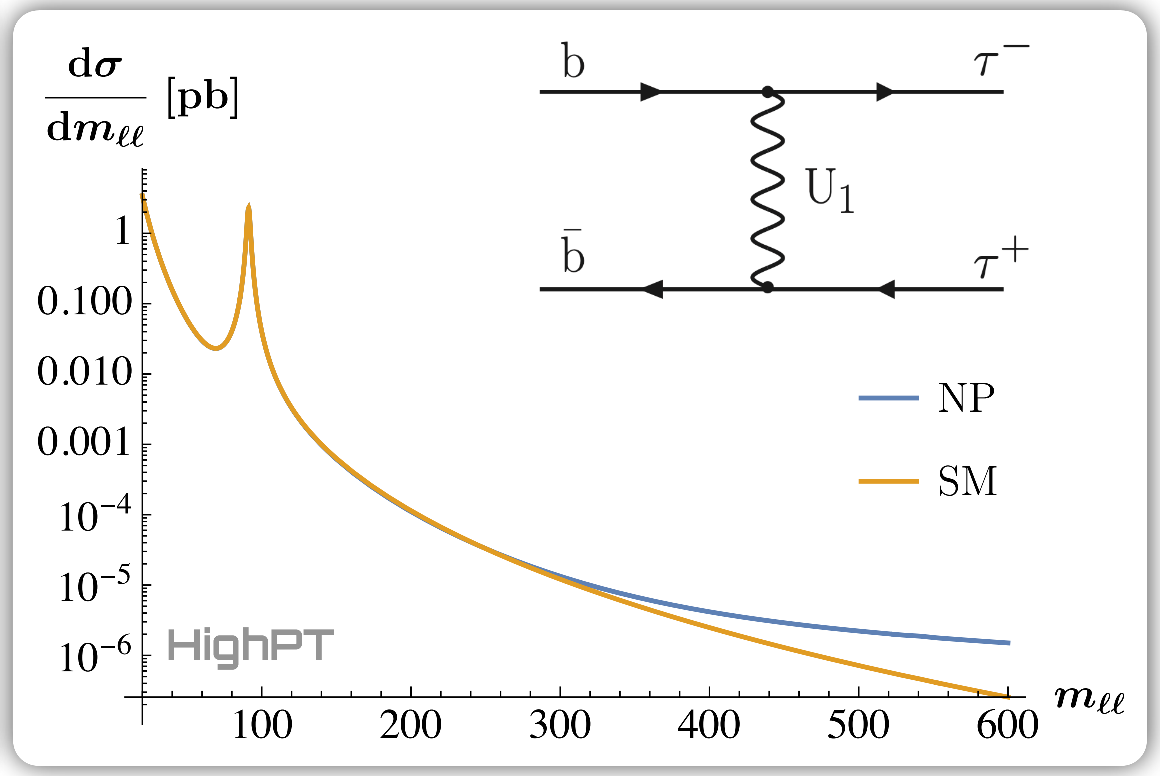


NP Drell-Yan tails analyses:

Greljo, Marzocca [1704.09015]

Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez [2003.12421]

de Blas, Chala, Santiago [1307.5068]

Angelescu, Faroughy, Sumensari [2002.05684]

Dawson, Giardino, Ismail [1811.12260]

Marzocca, Min, Son [2008.07541]

... many more ...

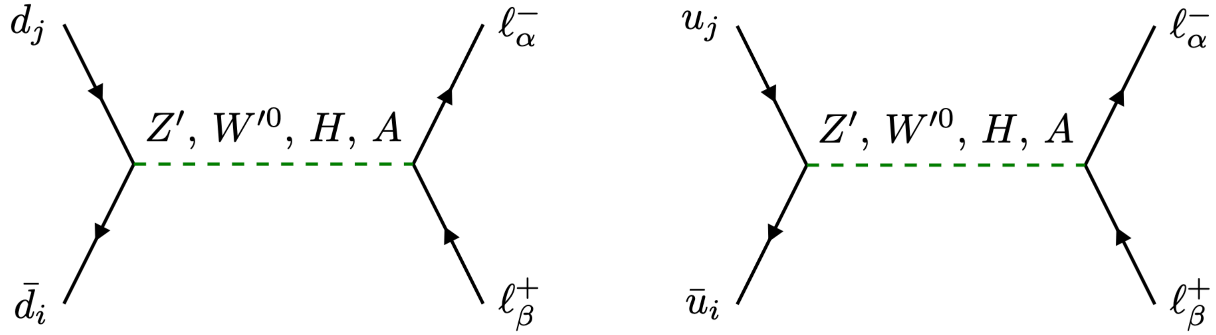
- τ-tails particularly relevant for models with large 3^{rd} generation couplings

Faroughy, Greljo, Kamenik [1609.07138]

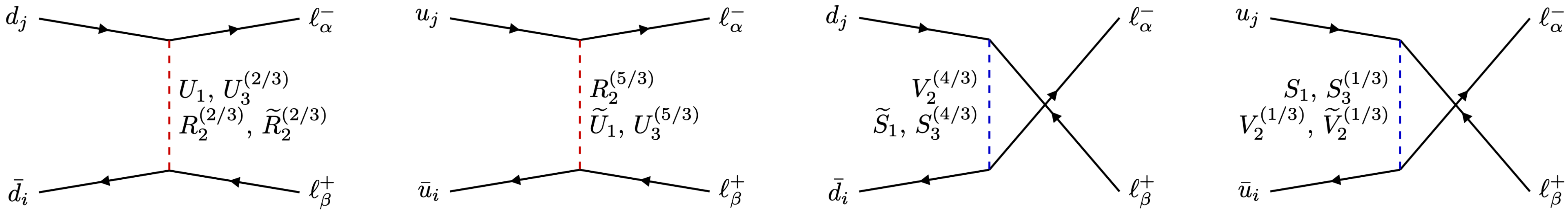
LFV in high-p_T Drell-Yan tails

Types of LFV probed in high-p_T Drell-Yan tails:

- Explicit LFV BSM mediators coupling to both quarks and leptons
  - s-channel: neutral vector bosons Z', heavy scalars Φ, ...



  - t-/u-channel: leptoquarks



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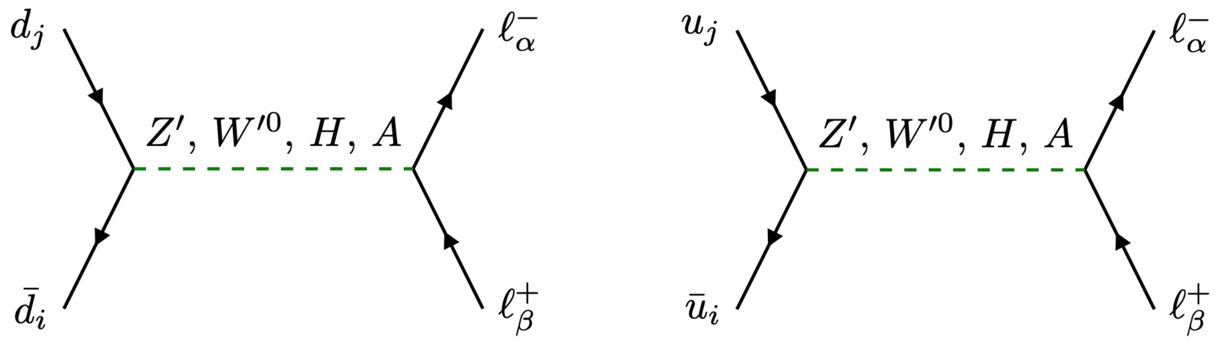

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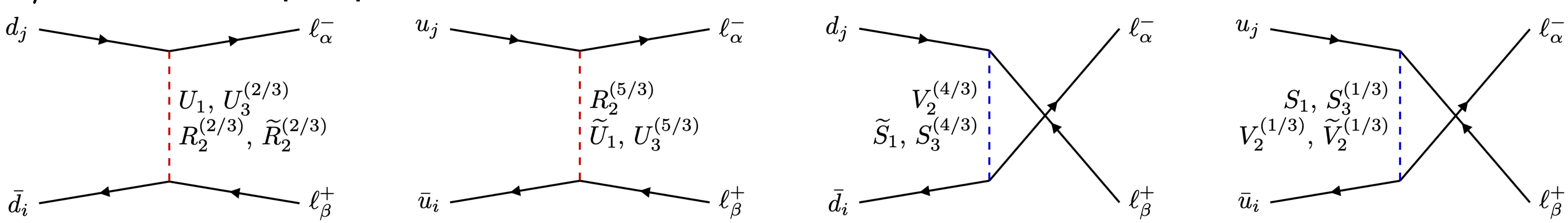
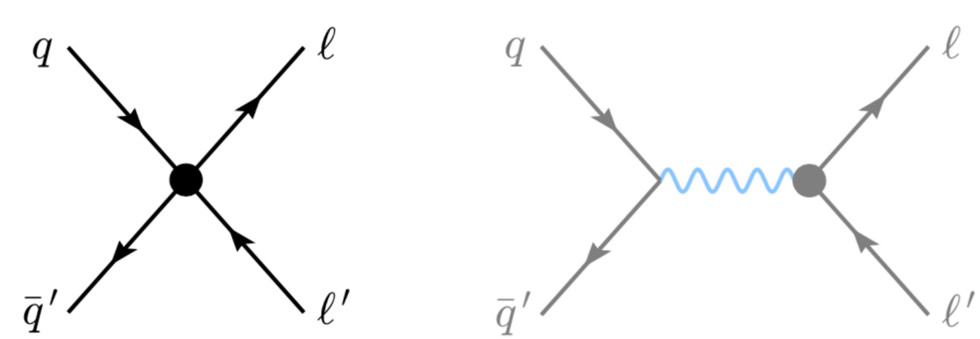
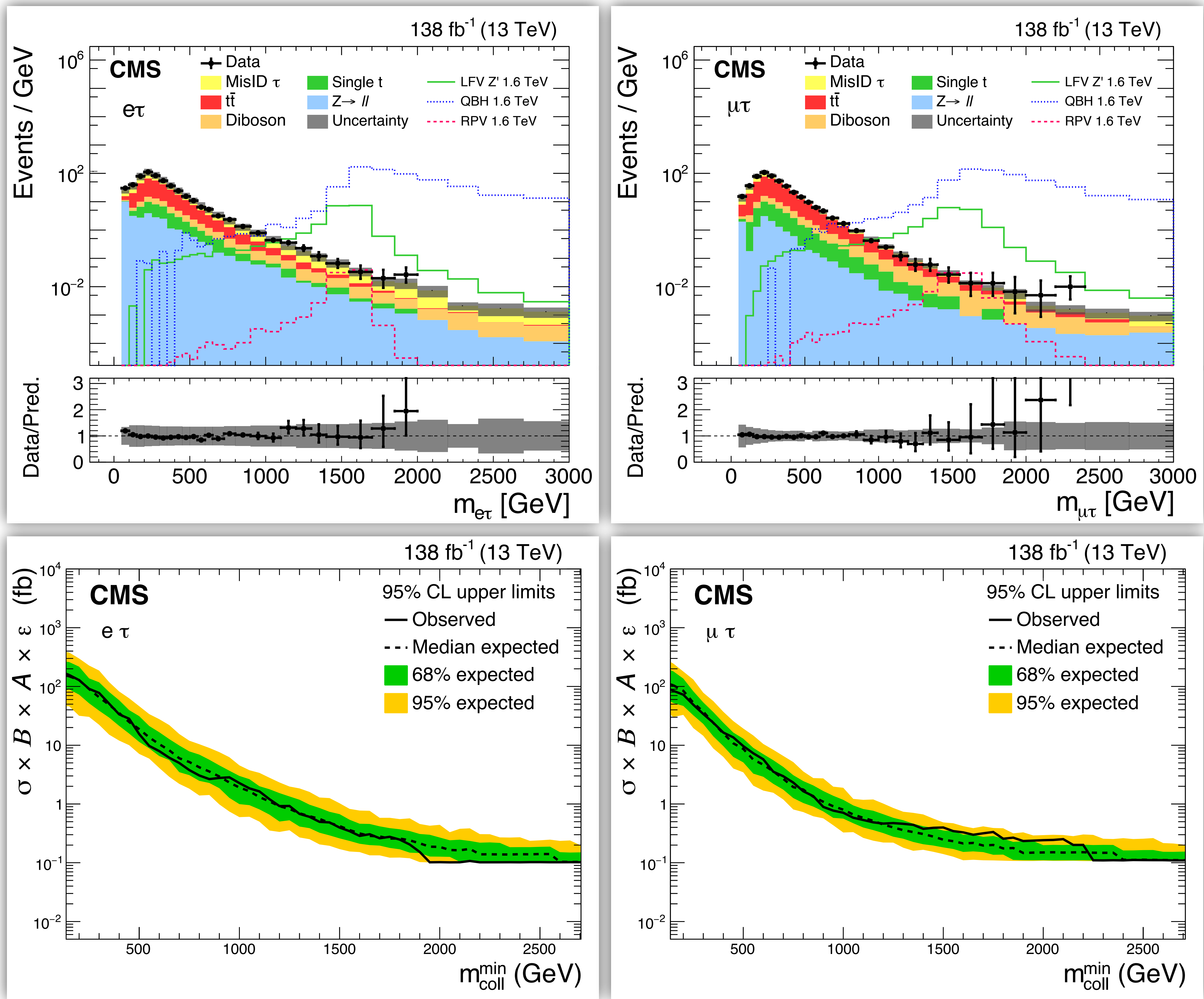


- LFV high-dimensional SMEFT operators
  - LFV semileptonic 4-fermion operators
  - LFV dipole operators Q_{eW}, Q_{eB} & modifications of Z boson couplings $Q_{Hl}^{(1,3)}$, Q_{He} $\rightarrow$ better probed by Z decays



Experimental searches for LFV in high-p_T Drell-Yan tails

- Searches for:
  $pp \to \tau\ell$
  where
  $\ell \in \{\mu, e\}$
  with
  $\mathscr{L} \sim 140\,\text{fb}^{-1}$
- CMS
  [2205.06709]
- ATLAS
  [2307.08567]
- $\tau \to$ hadrons
- Search also performed for
  $pp \to \mu e$



Constraining New Physics with Drell-Yan tails

HighPT: a `Mathematica` package for high-p_T Drell-Yan Tails Beyond the Standard Model

Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10756]

https://highpt.github.io/

Computation of:

- Drell-Yan cross sections
- Experimental observables
- Likelihoods

Implemented BSM models:

- SMEFT ($d = 6$ and $d = 8$)
- BSM mediators (leptoquarks)

Recasted searches available:

- Full LHC run-II datasets

Process	Experiment	Luminosity	
$pp \to \tau\tau$	ATLAS	$139\,\text{fb}^{-1}$	[2002.12223]
$pp \to \mu\mu$	CMS	$140\,\text{fb}^{-1}$	[2103.02708]
$pp \to ee$	CMS	$137\,\text{fb}^{-1}$	[2103.02708]
$pp \to \tau\nu$	ATLAS	$139\,\text{fb}^{-1}$	[ATLAS-CONF-2021-025]
$pp \to \mu\nu$	ATLAS	$139\,\text{fb}^{-1}$	[1906.05609]
$pp \to e\nu$	ATLAS	$139\,\text{fb}^{-1}$	[1906.05609]
$pp \to \tau\mu$	CMS	$138\,\text{fb}^{-1}$	[2205.06709]
$pp \to \tau e$	CMS	$138\,\text{fb}^{-1}$	[2205.06709]
$pp \to \mu e$	CMS	$138\,\text{fb}^{-1}$	[2205.06709]

Observables and likelihoods

- **High-p_T tail distributions:**
  - **Computed**: particle-level distribution $\frac{d\sigma}{dx}$ built from final state particles e, μ, τ, ν
  - **Measured**: detector-level distribution $\frac{d\sigma}{dx_{\rm obs}}$ built from reconstructed objects (isolated leptons, tagged jets, missing energy, ...)

- Relate $\frac{d\sigma}{dx}$ to $\frac{d\sigma}{dx_{\rm obs}}$ using **MC simulations** (`MadGraph+Pythia+Delphes`)

[1405.0301]; [1410.3012]; [1307.6346];

measured → $$\sigma_q(x_{\rm obs}) = \sum_{p=1}^{M} K_{pq}\, \sigma_p(x)$$ ← computed

response matrices

detector response, object reconstruction efficiencies, phase-space mismatch, ...

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- Extract likelihood (χ^2):

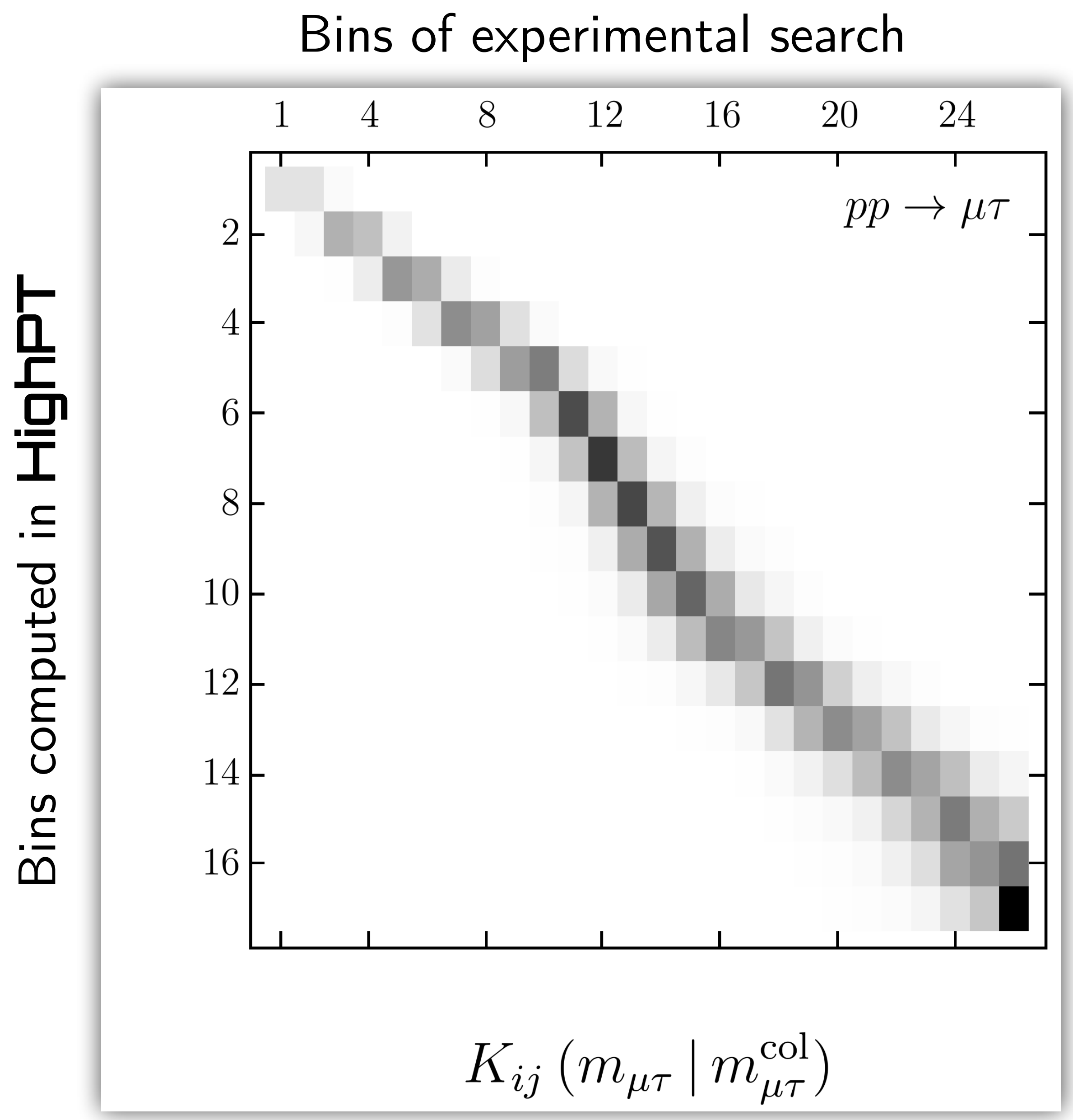
HighPT → N_{NP}

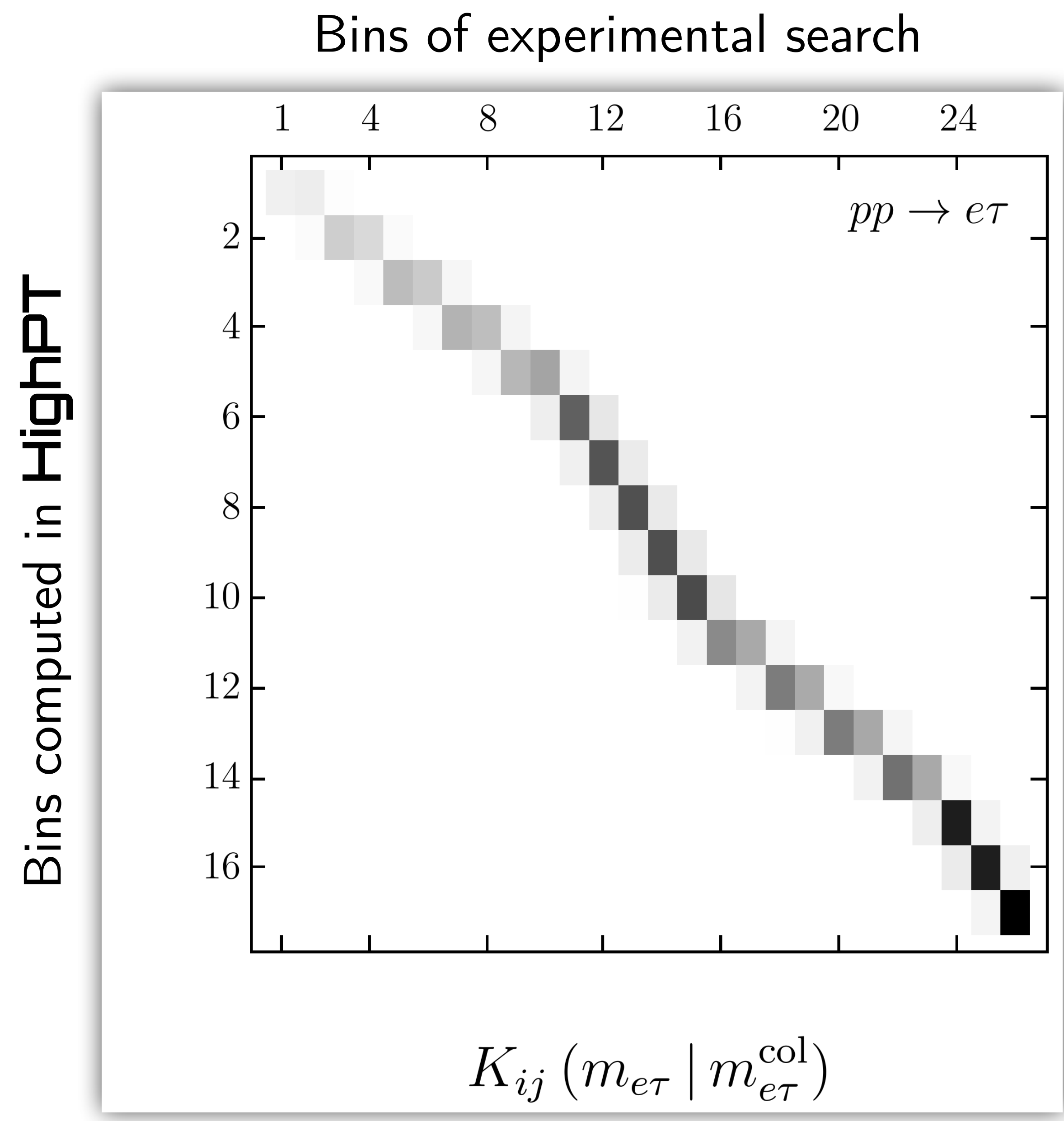
$$\chi^2 \sim \frac{(N_{\text{NP}} + N_{\text{SM}} - N_{\text{data}})^2}{\sigma^2}$$

provided by experiment (N_{SM}, N_{data}, σ^2)

Detector response matrices K_{pq}

Mapping of computed to experimental bins:





LFV Drell-Yan tails: single SMEFT Wilson coefficients

- Constraints on single LFV Wilson coefficients: 2 examples

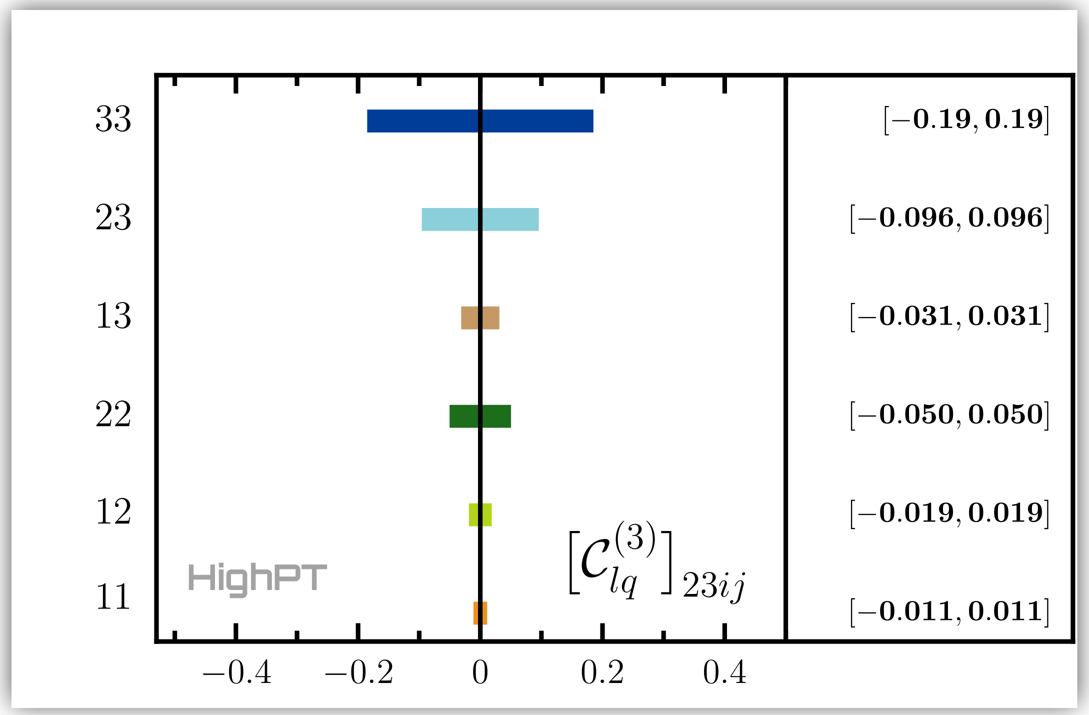
Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714]

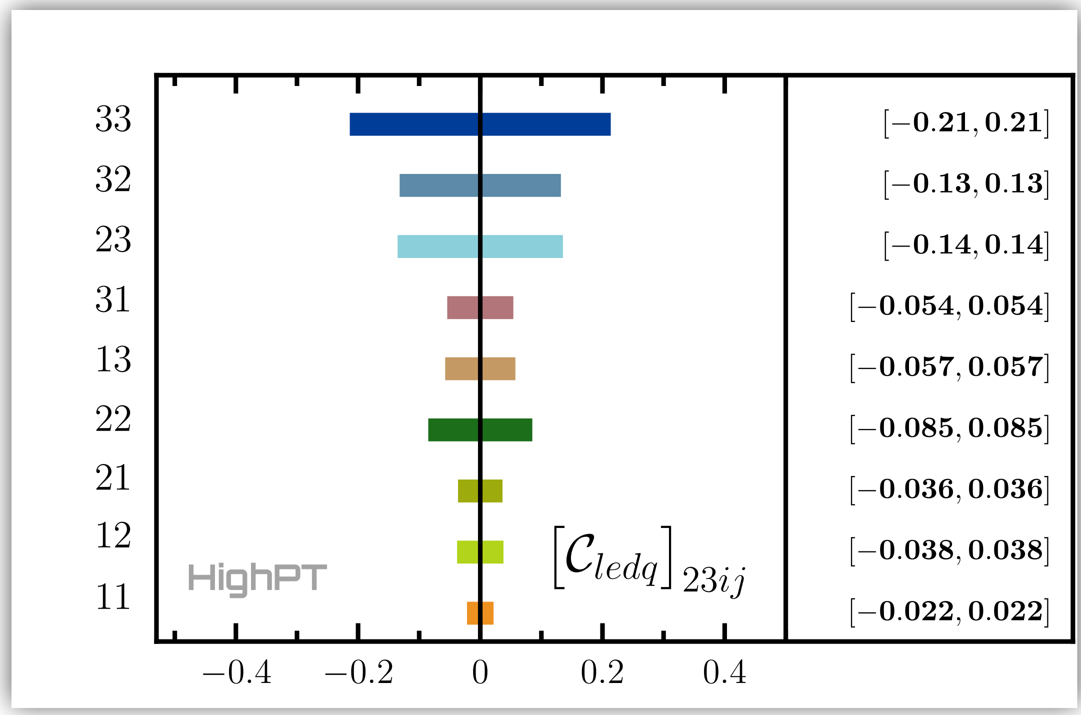
Reference scale $\Lambda = 1$ TeV

$$Q_{lq}^{(3)} = (\bar{\ell}_p \tau^I \gamma_\mu \ell_r)(\bar{q}_s \tau^I \gamma^\mu q_t)$$

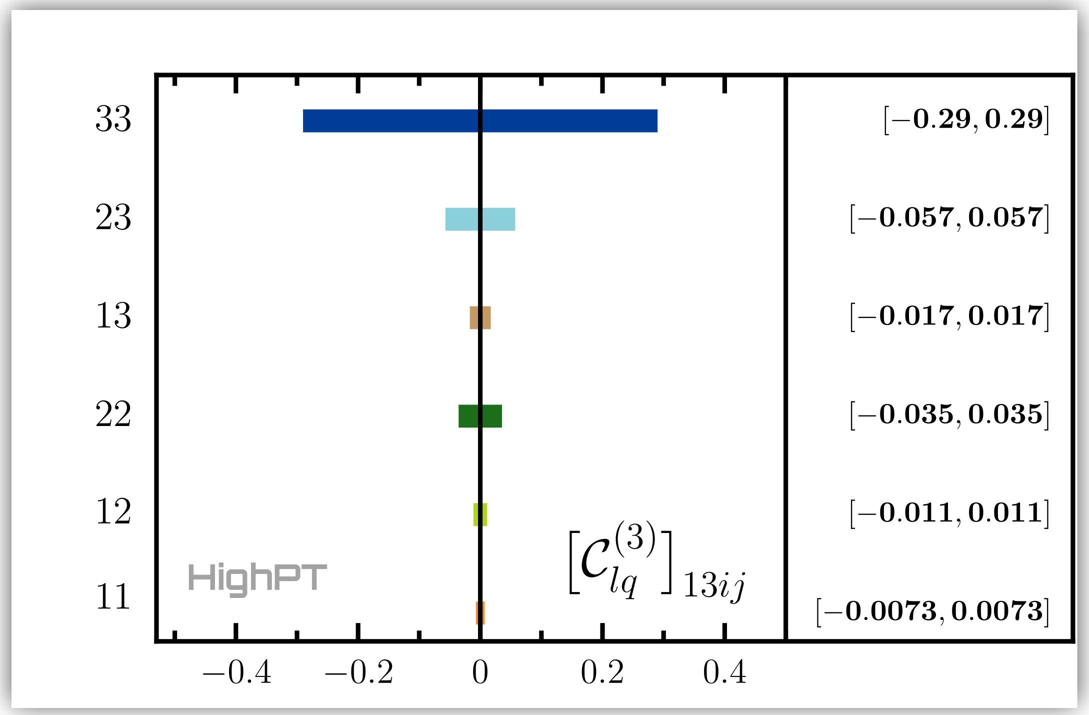
$$Q_{ledq} = (\bar{\ell}_p e_r)(\bar{d}_s q_t)$$

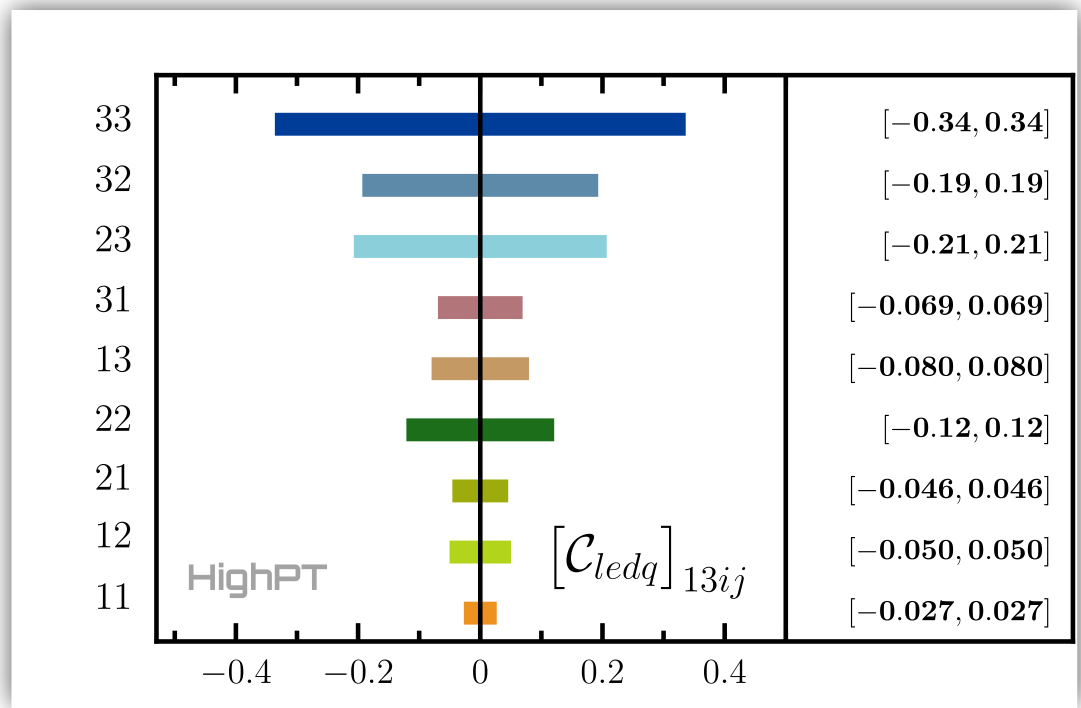
$pp \to \tau\mu$





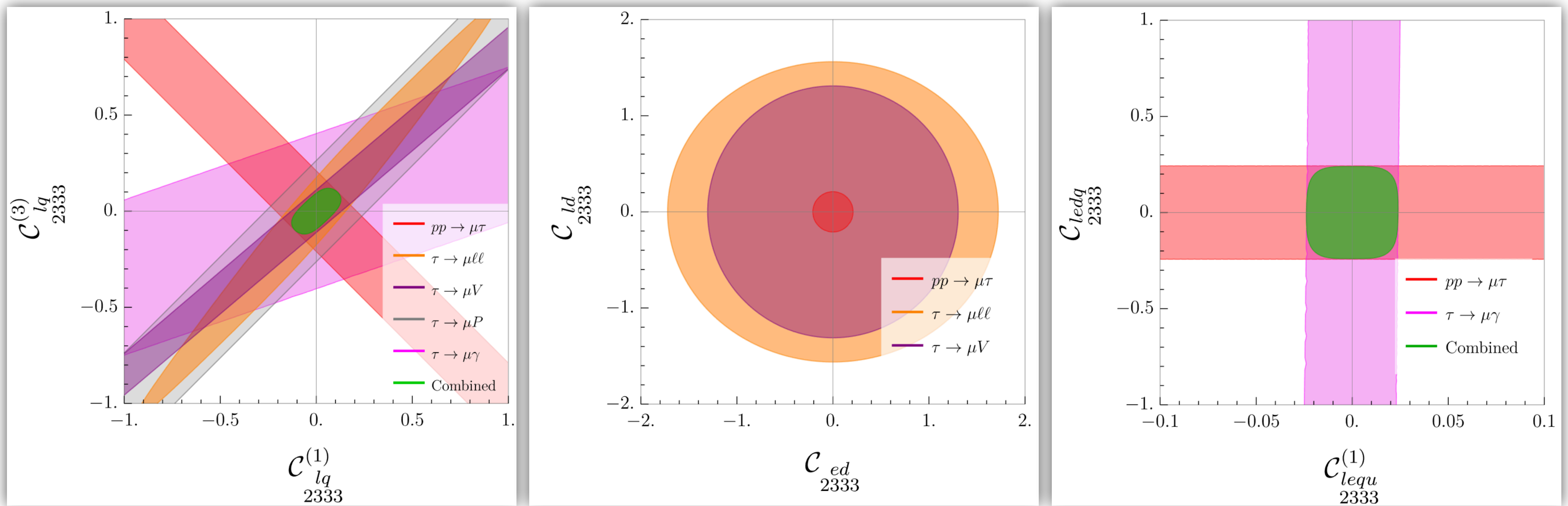
$pp \to \tau e$





SMEFT: complementarity of $pp \to \tau\mu$ and $\tau \to \mu X$

- Drell-Yan tails provide complementary information to low-energy τ decays when considering:
  - NP in semi-leptonic 4-fermion operators
  - Dominant couplings to 3[rd] generation quarks
    - Tree-level Drell-Yan competes with loop suppressed low-energy bounds
    - Operators with bottom quarks (negligible top quark PDF)



Plakias, Sumensari [2312.14070]

For further cases see also: Descotes-Genon, Faroughy, Plakias, Sumensari [2303.07521]

Tau LFV in Drell-Yan tails: SMEFT (LQ inspired)

- Consider multiple SMEFT Wilson coefficients for realistic NP scenarios

$[Q_{lq}^{(1)}]_{\alpha\beta ij} = (\bar{\ell}_\alpha \gamma_\mu \ell_\beta)(\bar{q}_i \gamma^\mu q_j)$
$[Q_{lq}^{(3)}]_{\alpha\beta ij} = (\bar{\ell}_\alpha \tau^I \gamma_\mu \ell_\beta)(\bar{q}_i \tau^I \gamma^\mu q_j)$
$[Q_{ed}]_{\alpha\beta ij} = (\bar{e}_\alpha \gamma_\mu e_\beta)(\bar{d}_i \gamma^\mu d_j)$
$[Q_{ledq}]_{\alpha\beta ij} = (\bar{l}_\alpha e_\beta)(\bar{d}_i q_j)$

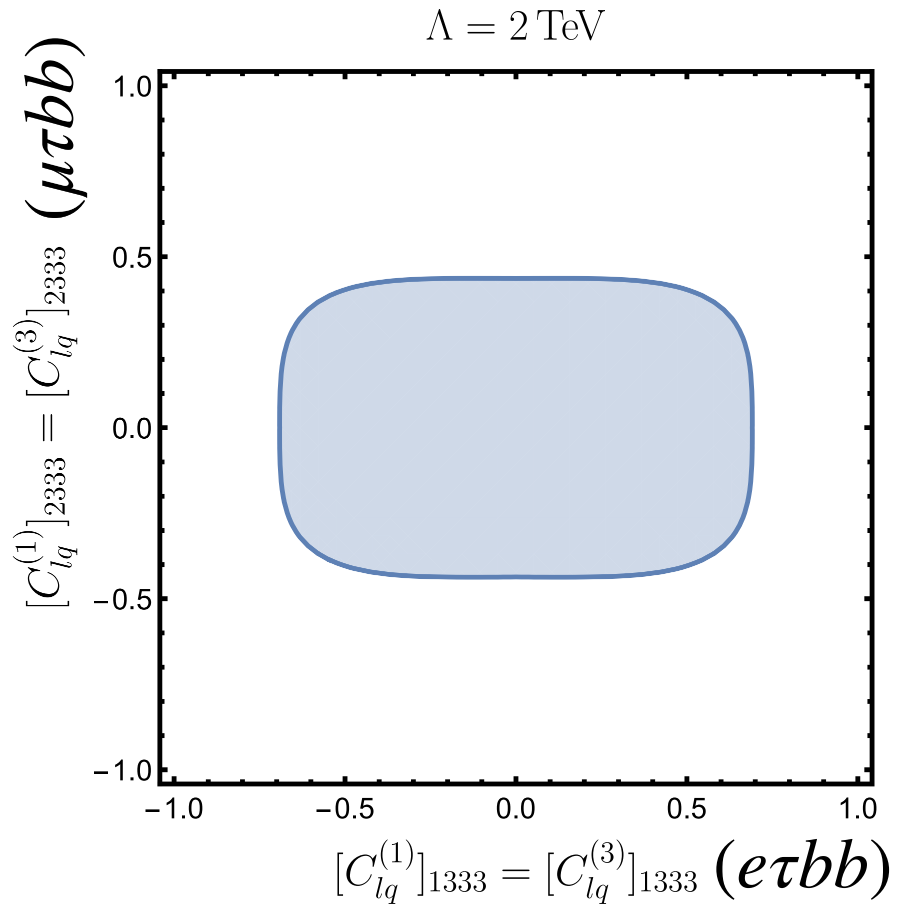
- <u>Example:</u> the $U_1 \sim (3,1)_{2/3}$ vector leptoquark

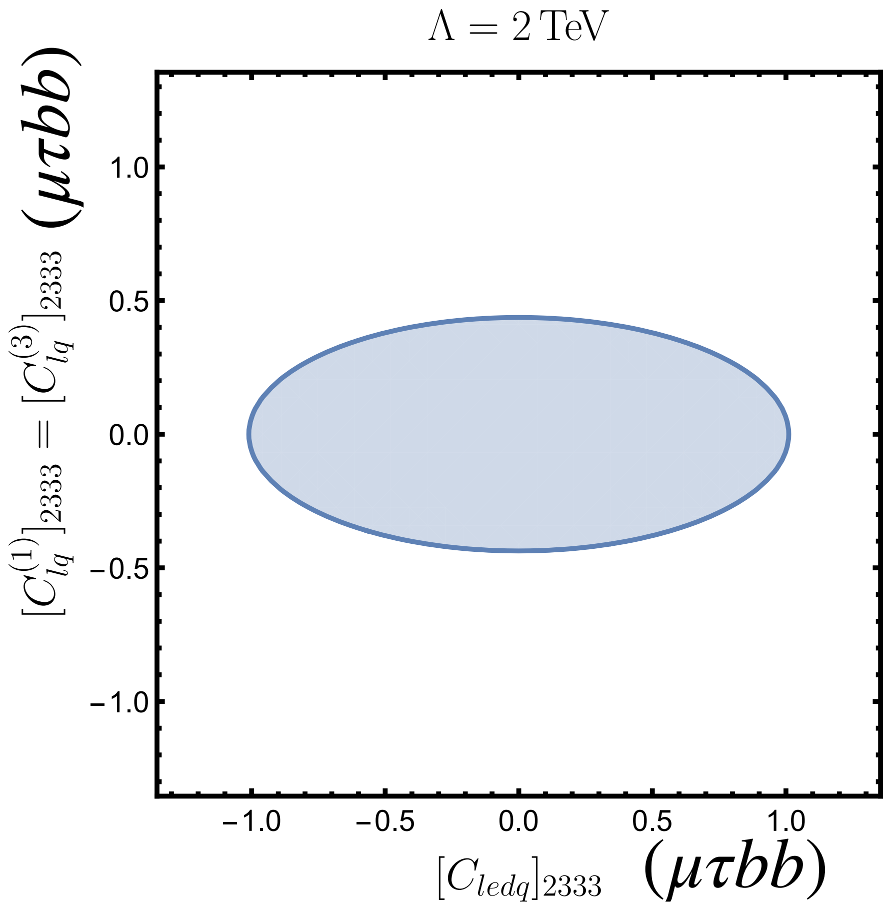
$$\mathscr{L}_{U_1} = [x_1^L]_{i\alpha} U_1^\mu (\bar{q}_i \gamma_\mu \ell_\alpha) + [x_1^R]_{i\alpha} U_1^\mu (\bar{d}_i \gamma_\mu e_\alpha) + \mathrm{h.c.}$$

- Matching onto SMEFT:

$$[C_{lq}^{(1,3)}]_{\alpha\beta ij} = -\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}, \qquad [C_{eq}]_{\alpha\beta ij} = -[x_1^R]_{i\beta}[x_1^R]^*_{j\alpha}, \qquad [C_{ledq}]_{\alpha\beta ij} = 2[x_1^R]_{j\beta}[x_1^L]^*_{i\alpha}$$

- Consider U_1 predominantly coupled to 3rd generation quarks (weakest low energy bounds)

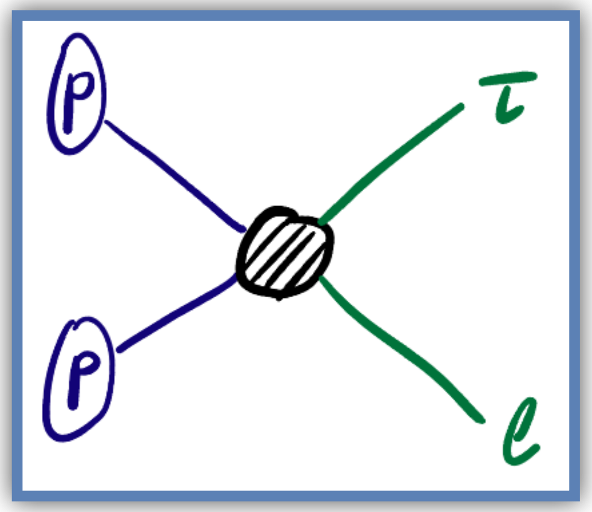


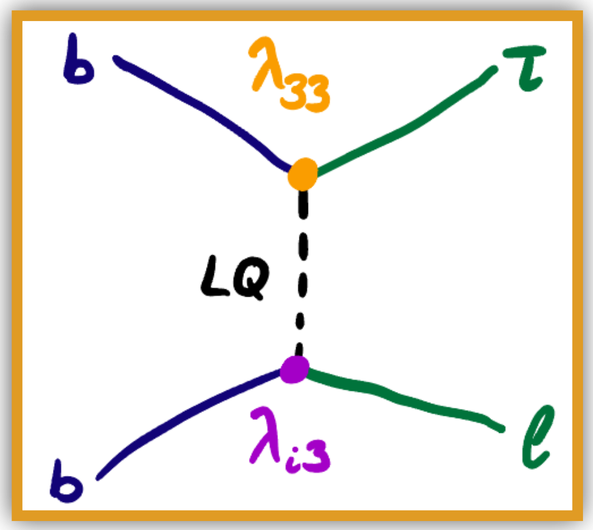


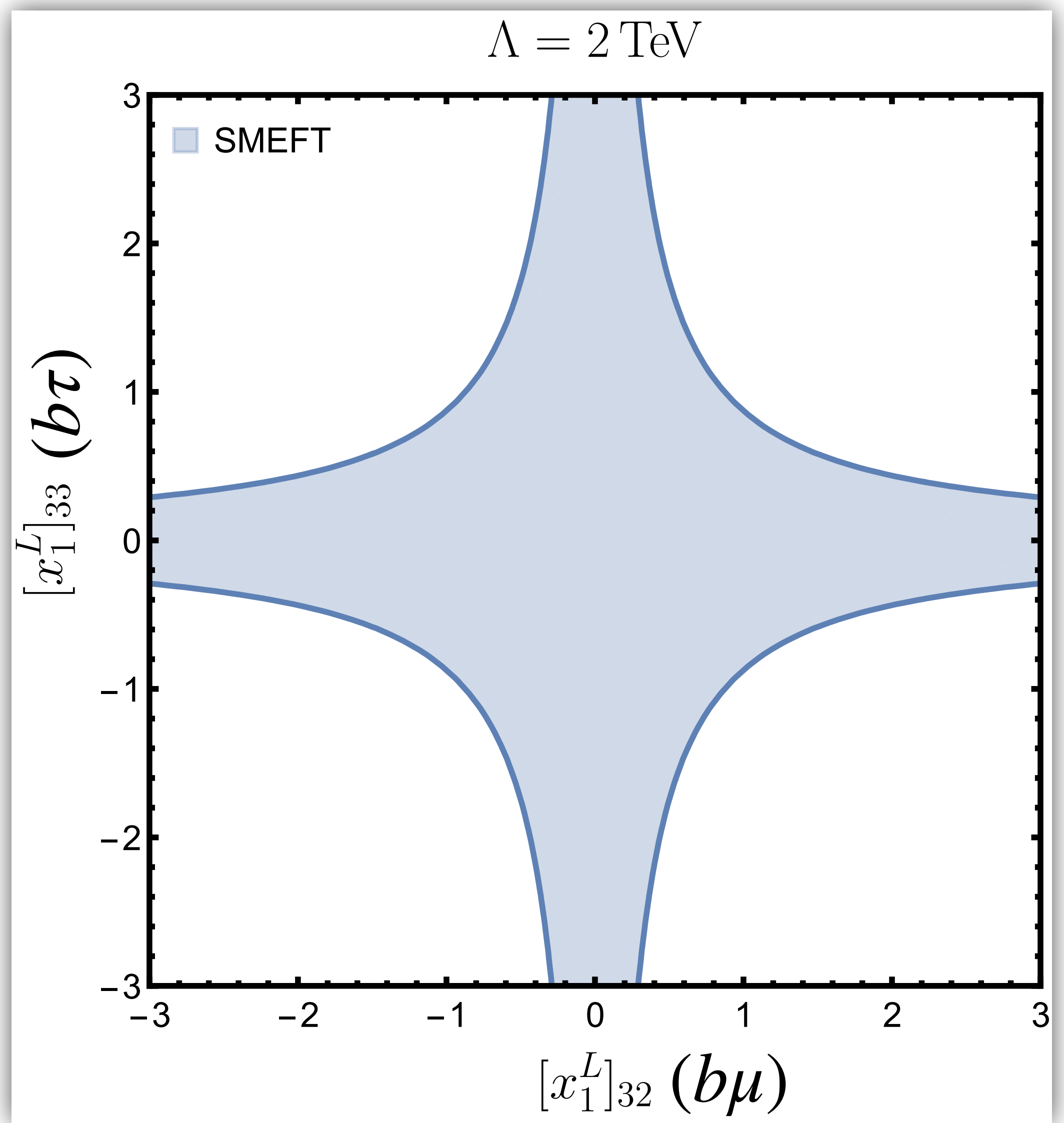
LFV in leptoquark models

[see also talk by Nejc]

- Generic leptoquark coupling: $\lambda_{pr}\, \chi_{\rm LQ} (\overline{\ell}_p \Gamma\, q_r)$
  - Need to consider at least two non-vanishing couplings for LFV transitions
  - Any leptoquark that has non-vanishing couplings to more than one lepton generation leads to LFV
- Plot constraints in terms of the two leptoquark couplings instead of Wilson coefficients







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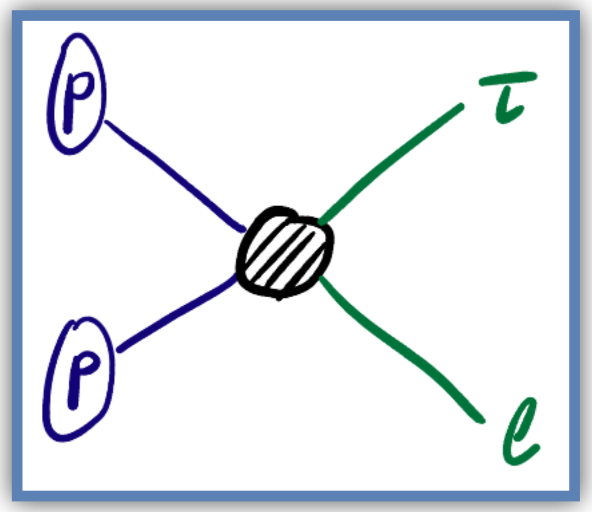

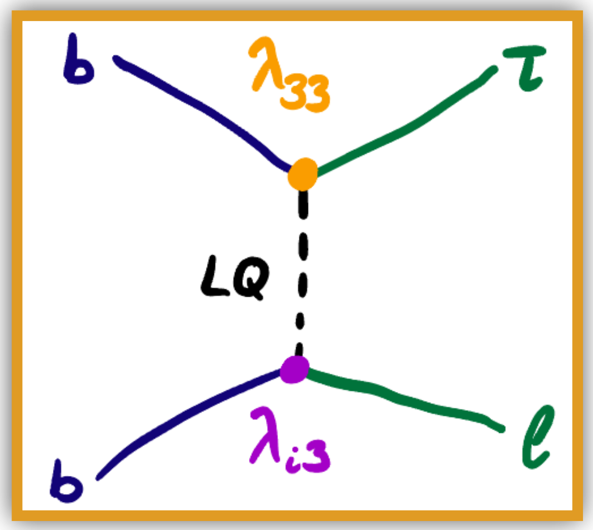

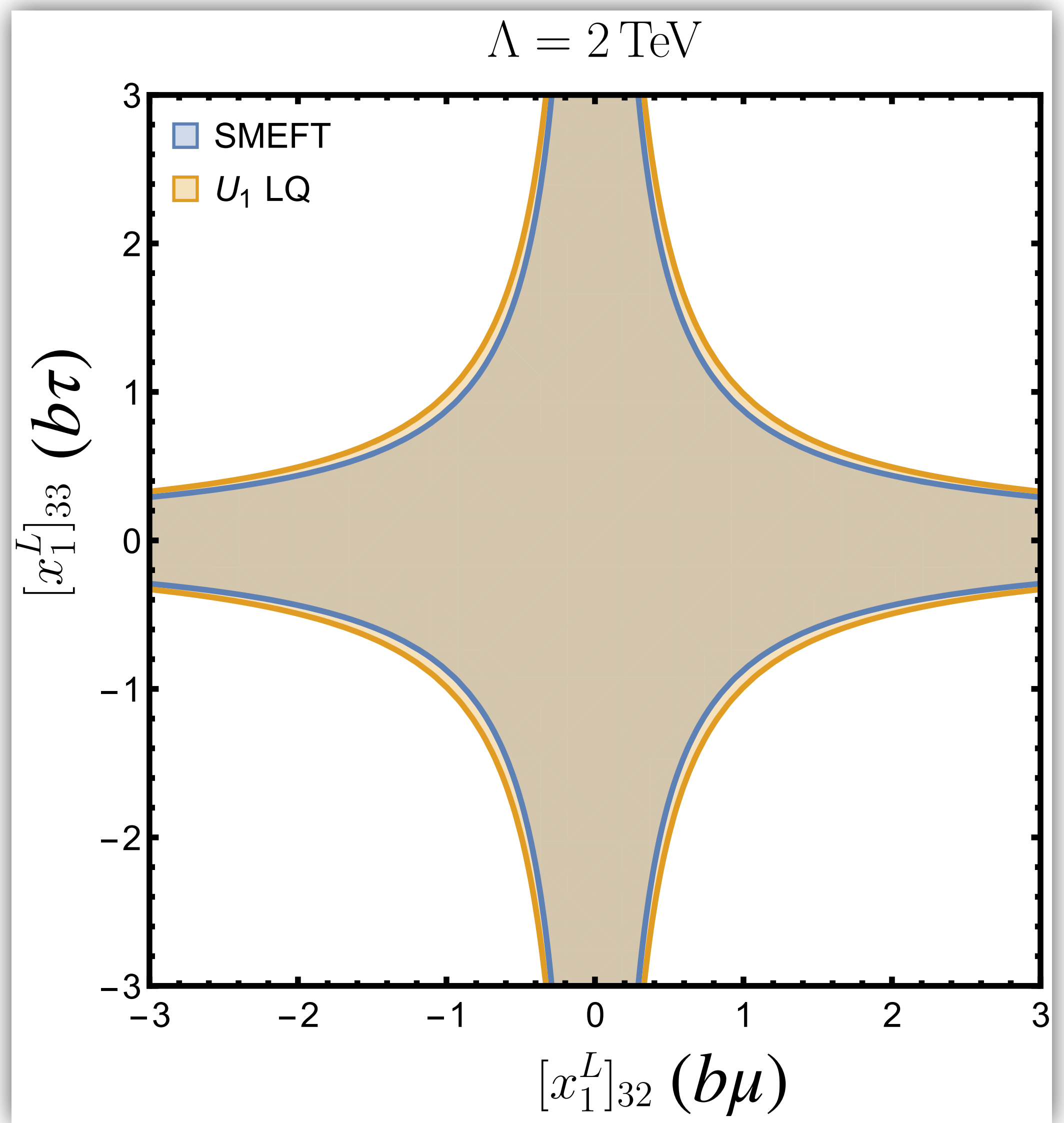

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Compare to constraints derived in full U_1 model

↓

EFT offers here a good approximation for the underlying leptoquark model

Tau LFV in Drell-Yan tails: the U_1 leptoquark

Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714]

- LFV process $pp \to \ell\bar{\ell}'$ requires 2 non-vanishing leptoquark couplings
  - Flavor conserving processes $pp \to \ell\bar{\ell}$ and $pp \to \ell'\bar{\ell}'$ generated as well
  - Are flavor conserving limits stronger?
- <u>Example:</u> consider again the U_1 with only left-handed couplings to 3^{rd} generation quarks

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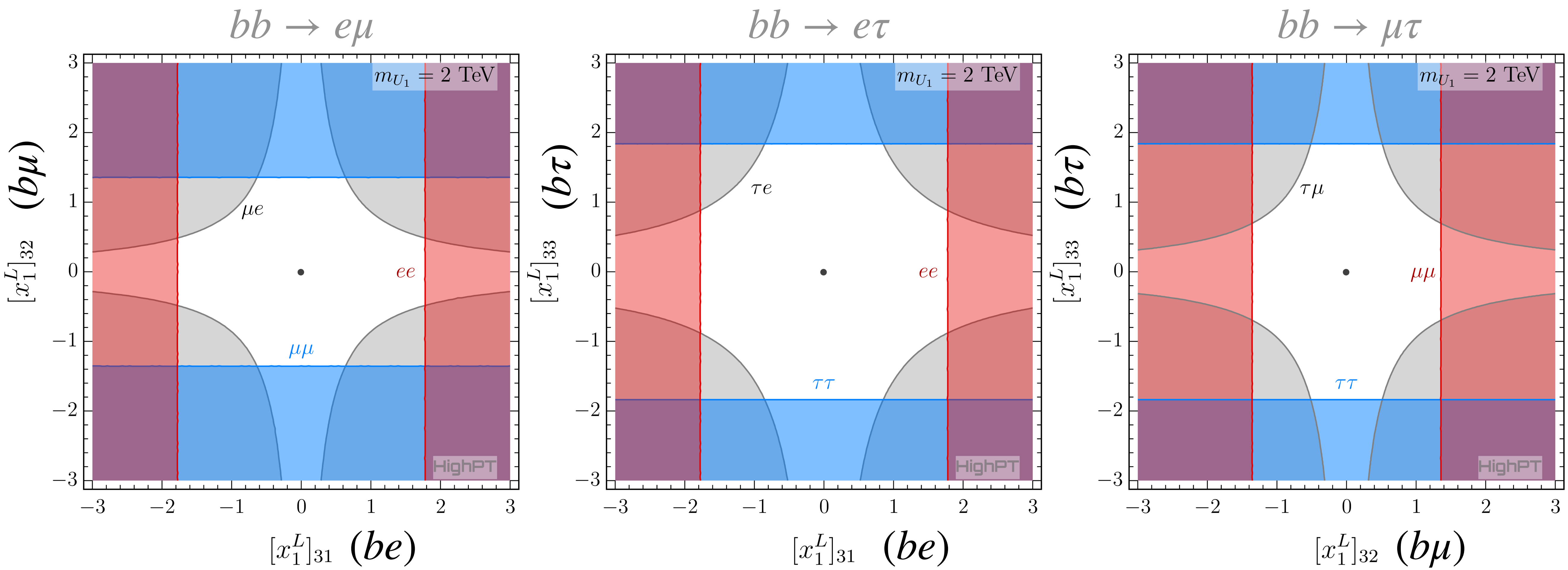
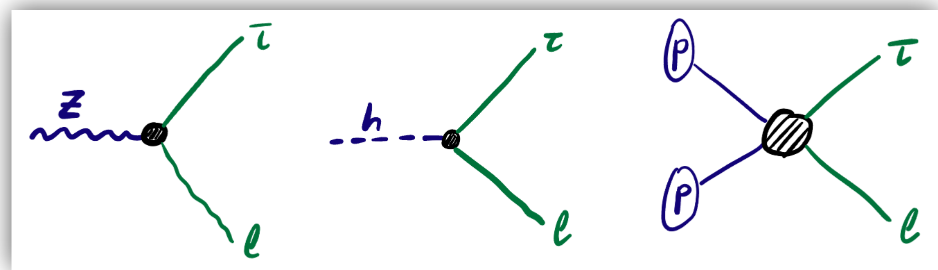


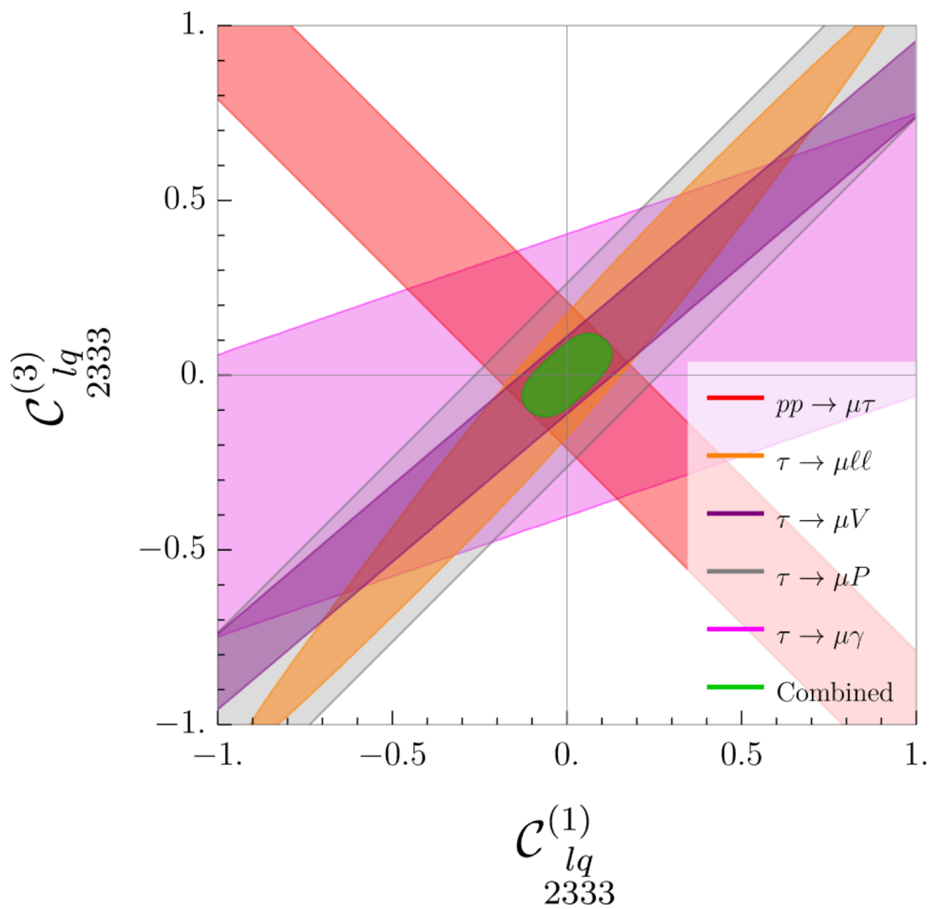
$\Rightarrow$ Complementarity of LFV Drell-Yan searches and flavor conserving searches

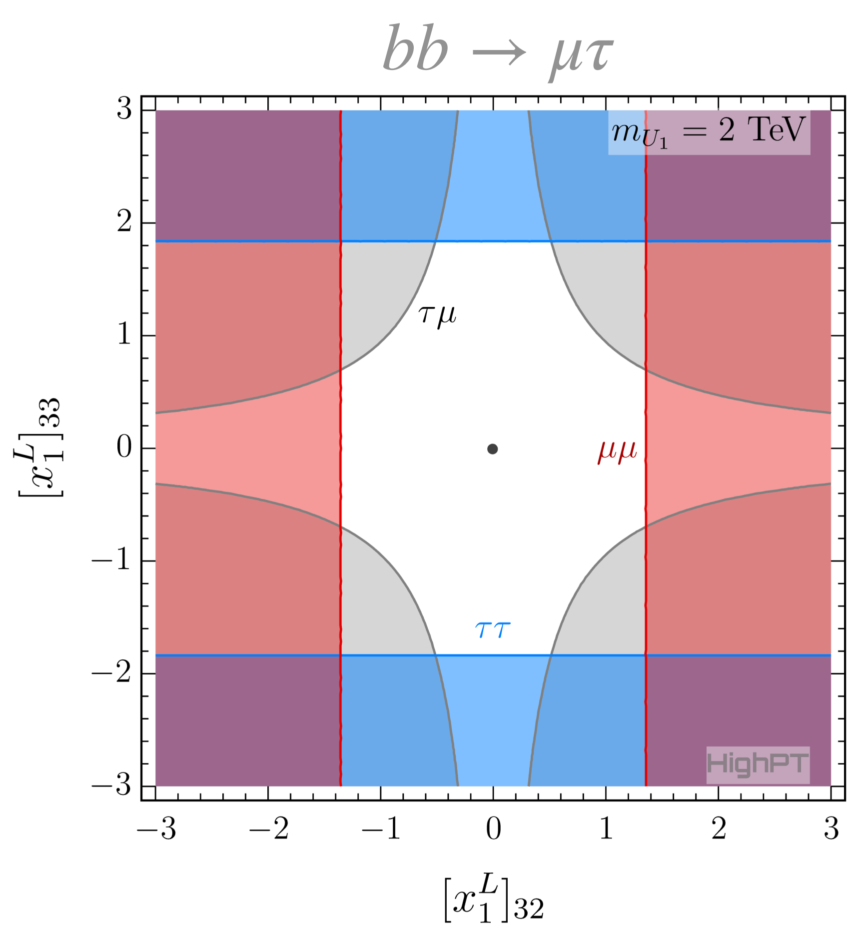
$$2\left|[x_1^L]_{i\alpha}[x_1^L]^*_{i\beta}\right| \leq \left|[x_1^L]_{i\alpha}\right|^2 + \left|[x_1^L]^*_{i\beta}\right|^2$$

Conclusions



- LHC constraints on τ lepton flavor violating transitions
  - $Z \to \tau\ell$, $h \to \tau\ell$, $pp \to \tau\ell$
- LFV high-p_T Drell-Yan tails probe LFV at very high energies in semi-leptonic operators
  - Especially relevant for BSM models with NP dominantly affecting the 3[rd] generation
  - Allows to probe large variety of both SMEFT operators and NP models
- LFV Drell-Yan tails complementary to flavor conserving Drell-Yan tails and low-energy



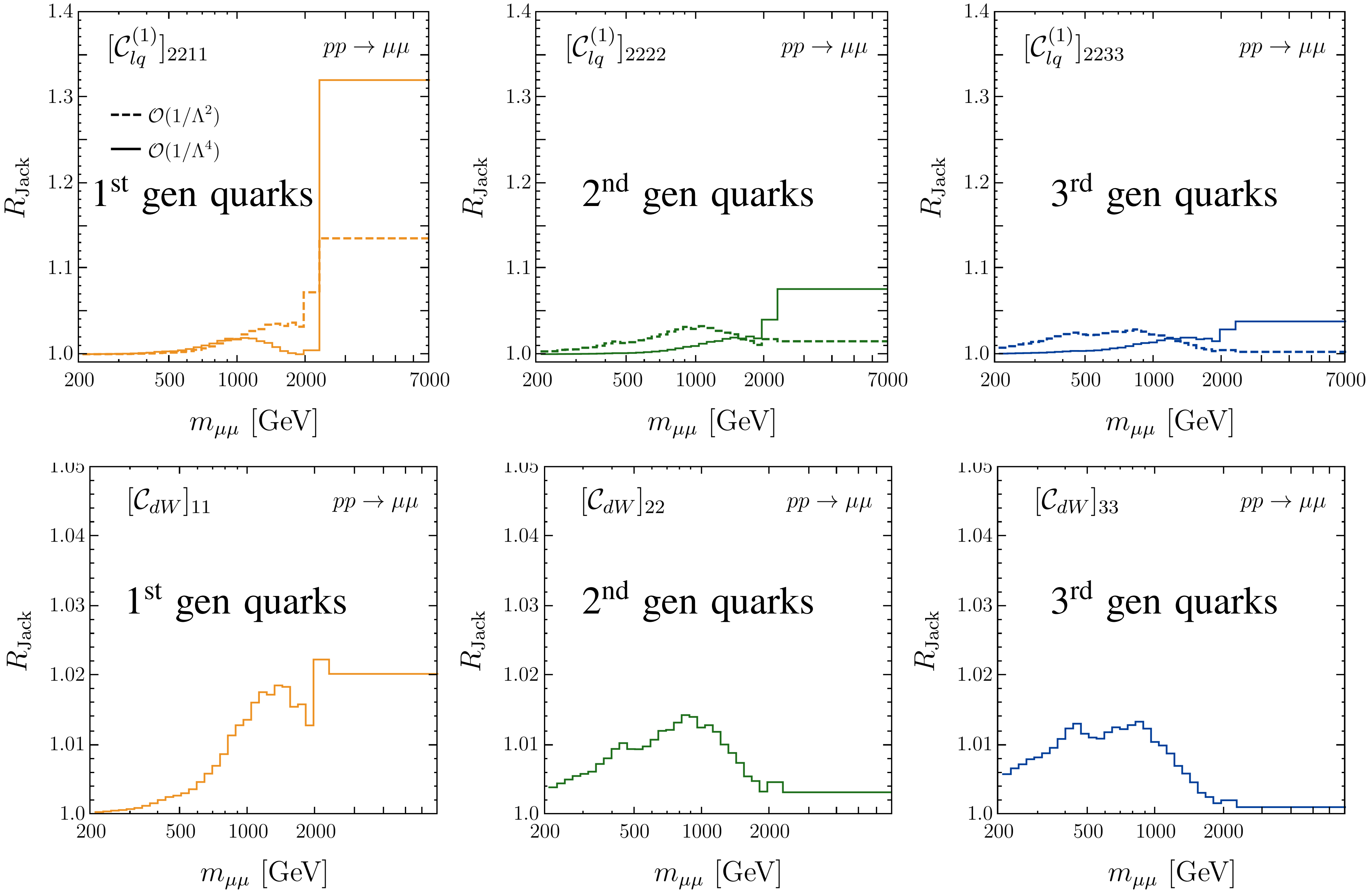


Thank you for your attention!

Backup

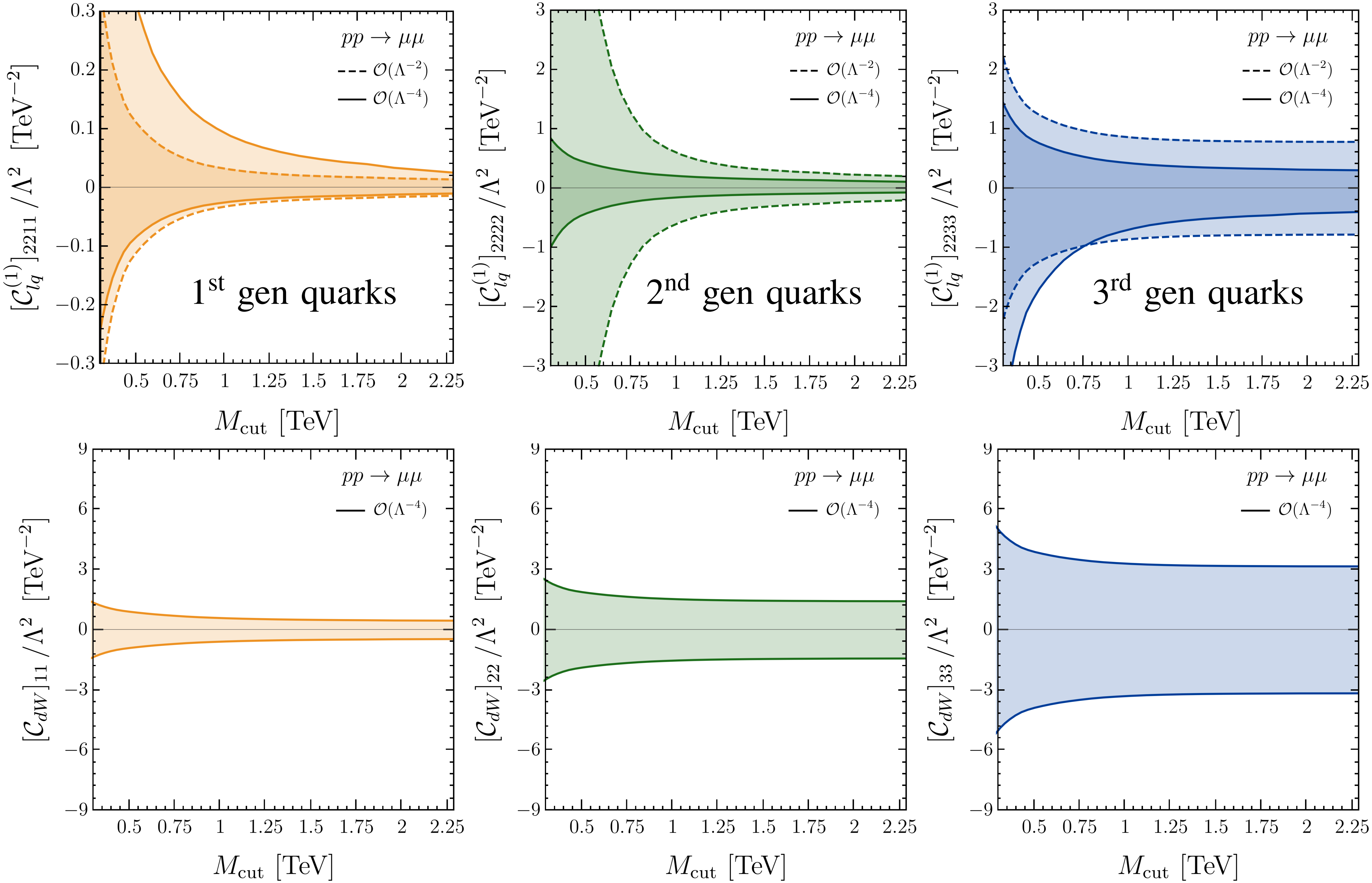
Jack-knife analysis

- $R_{\text{Jack}} \sim \dfrac{\text{constraint holding out a single bin from } \chi^2}{\text{constraint from full } \chi^2}$ (for expected limits)
- Measure of sensitivity of search to individual bins



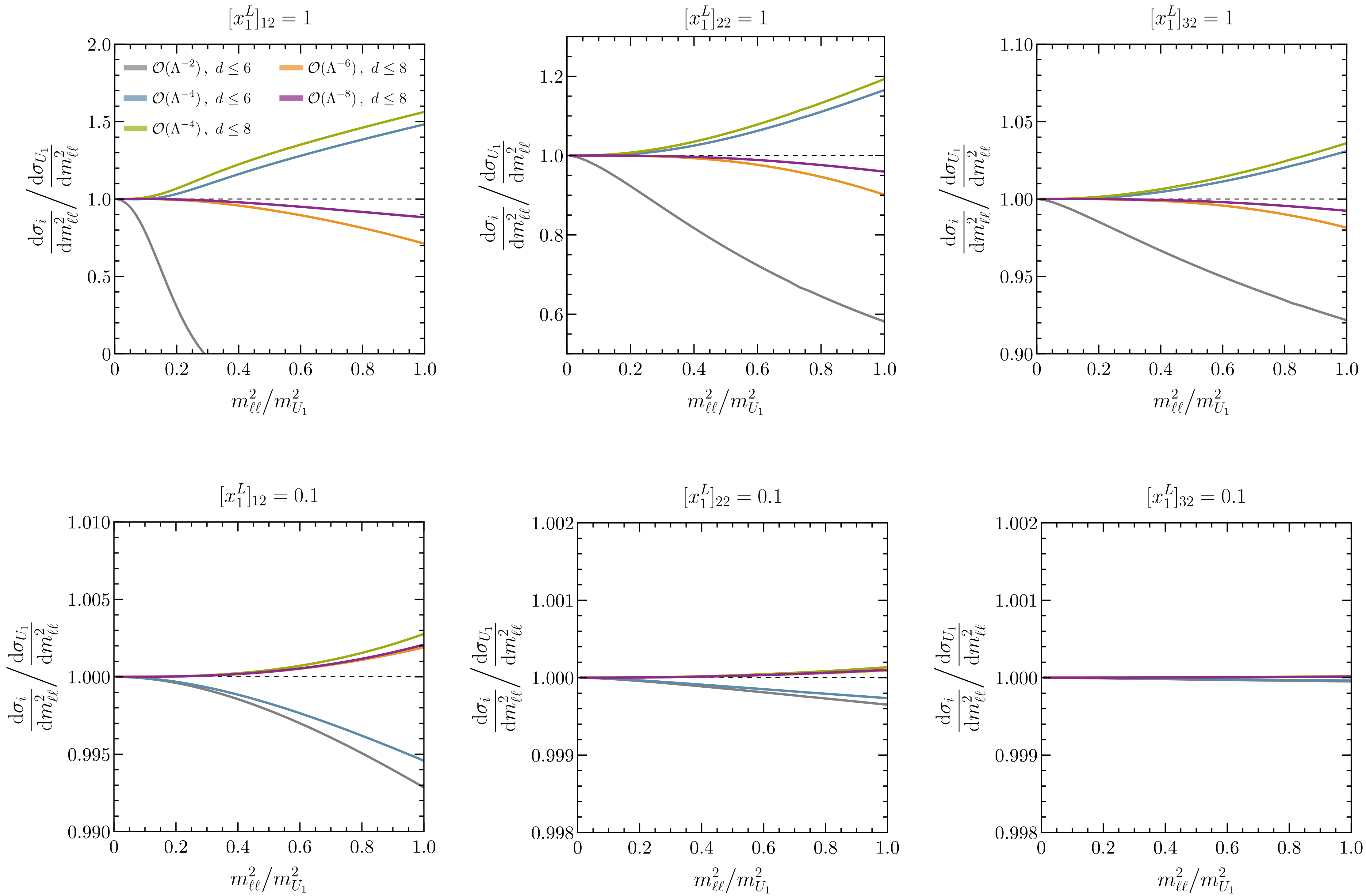
Clipped limits

- Constraints obtained with sliding upper cut M_{cut} for experimental observables
- Allows assessment of EFT validity range (example $pp \to \mu\mu$)



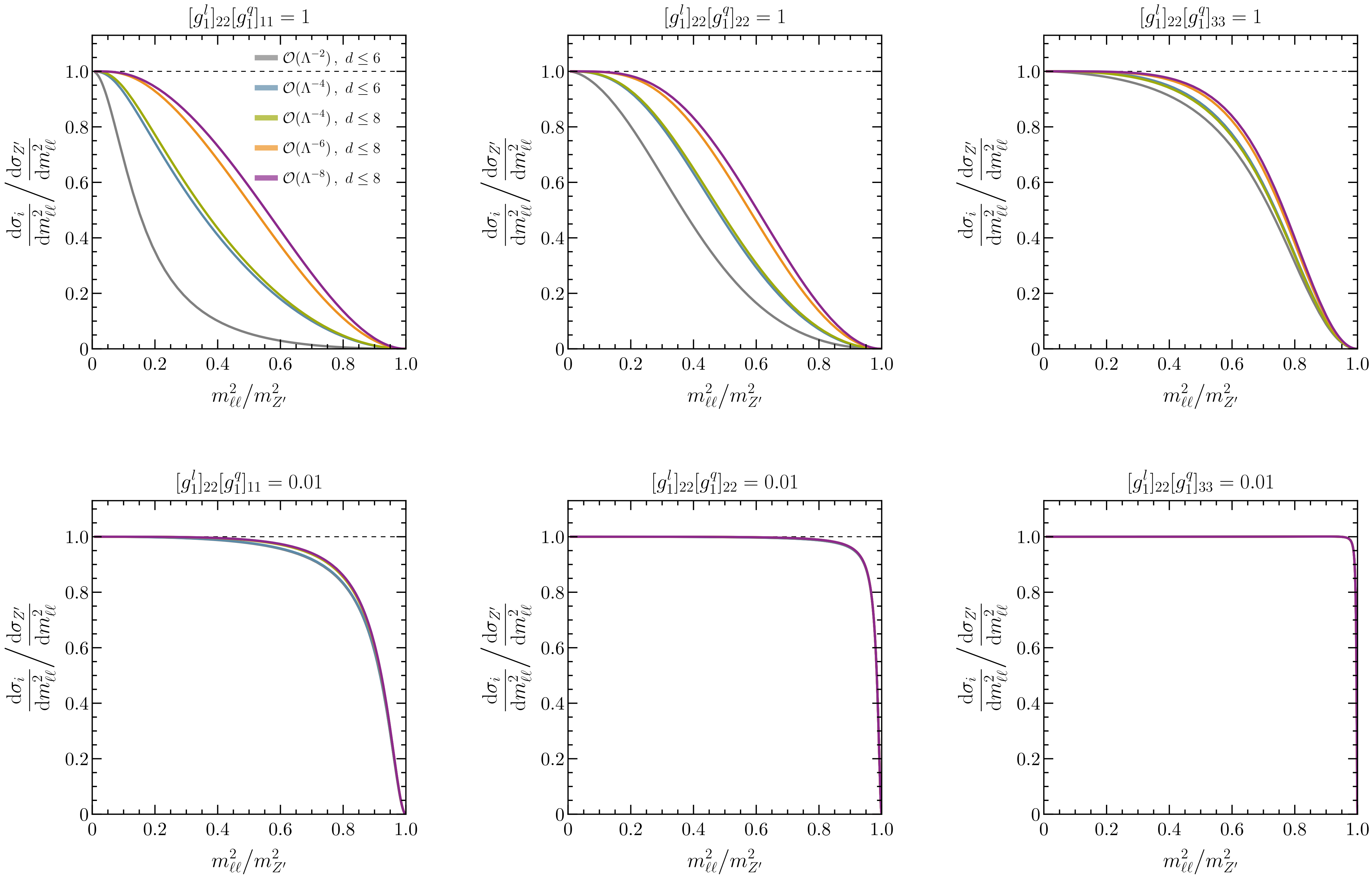
EFT Convergence for the U_1 Leptoquark

- EFT cross sections to different orders in Λ^{-1} normalized to full model cross section



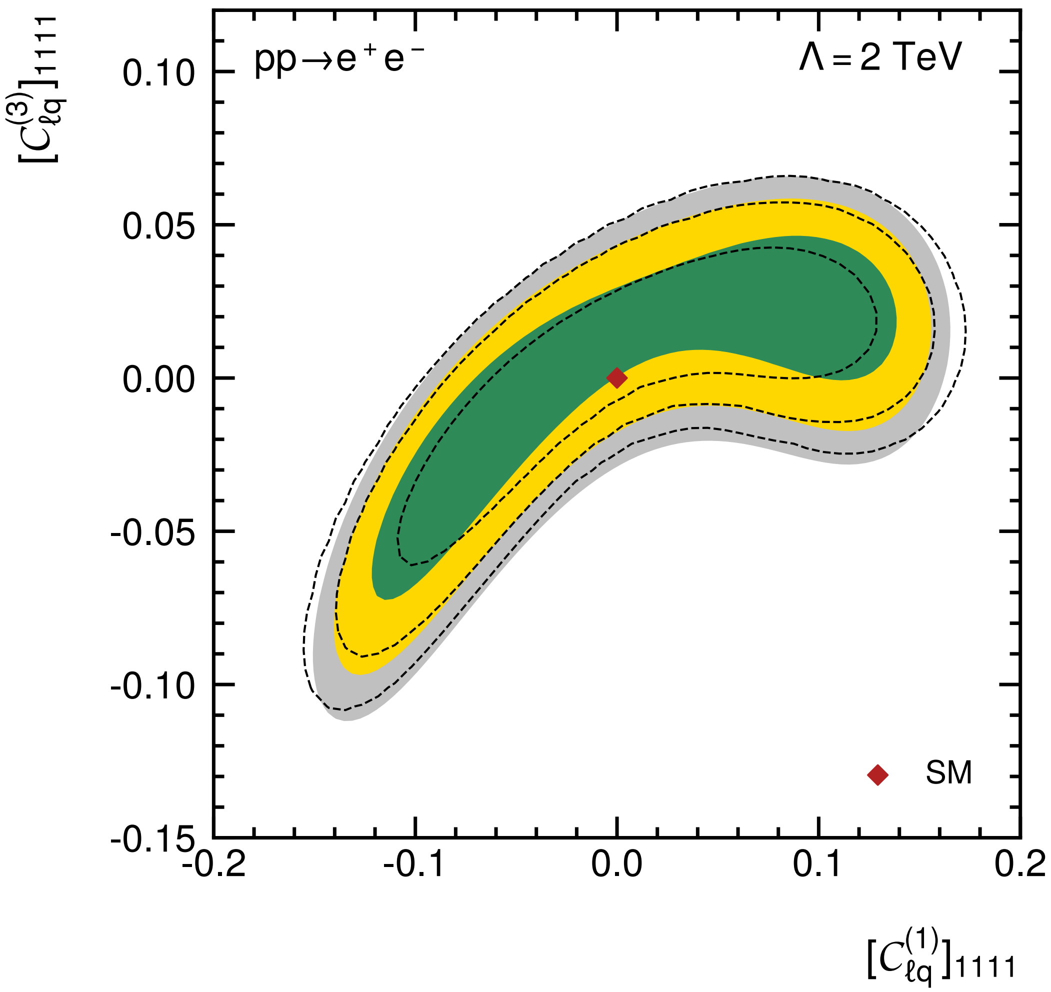
EFT Convergence for a Z' Boson

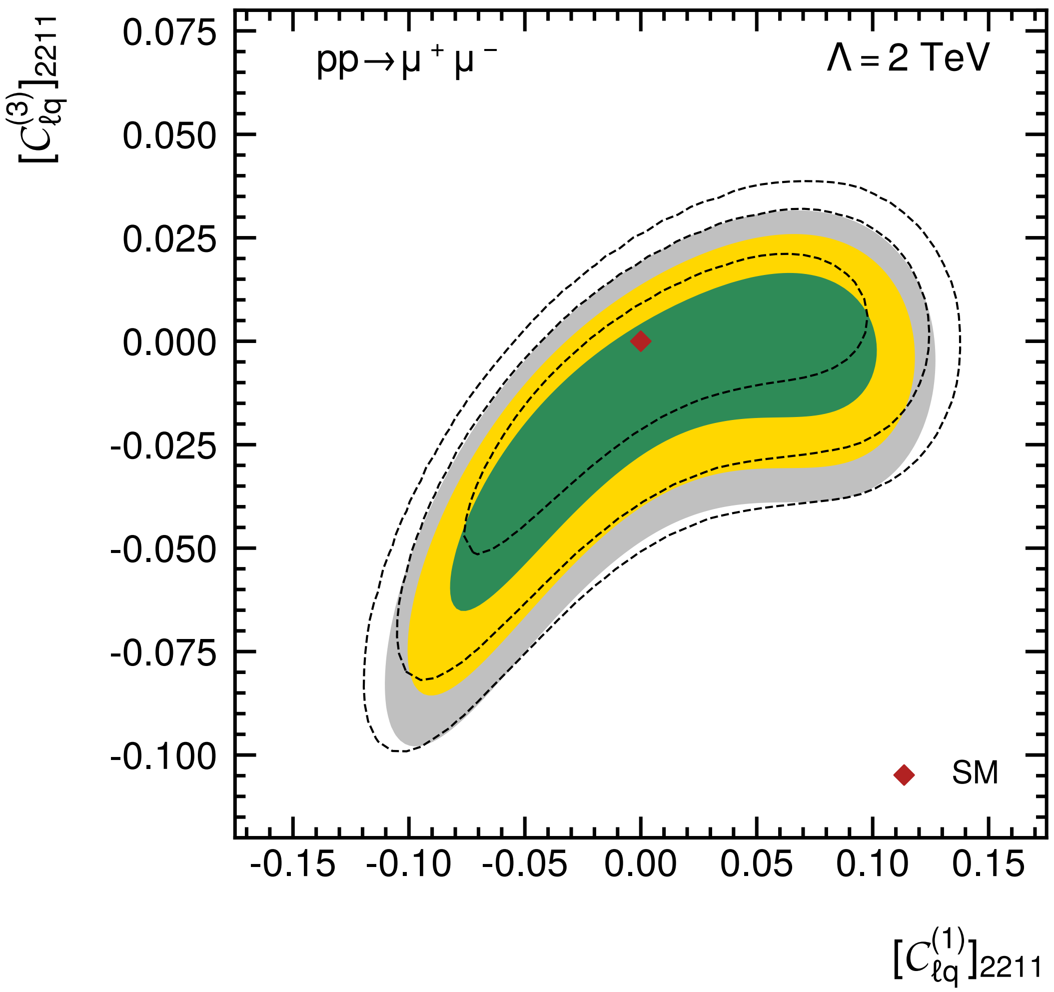
- EFT cross sections to different orders in Λ^{-1} normalized to full model cross section



χ^2 Likelihood vs. the CL_s Method

- χ^2 likelihood: combine experimental bins with low event count in the tails to validate the Gaussian approximation
  (1σ, 2σ, 3σ contours)
- Compare to $\mathrm{CL}_s = \dfrac{p_s}{1 - p_0}$ method (1σ, 2σ, 3σ dashed contours)
- CL_s tends to be more conservative, but overall good agreement with χ^2





Quality of Recasts

- Acceptance × efficiency ($\mathscr{A} \times \epsilon$) of our recast normalized to the experimental values
  - Good agreement apart from $\tau\tau$, $e\tau$, $\mu\tau$
  - Limited simulation of τ reconstruction in `Delphes`

Search	Experiment	Ref.	$\frac{\mathcal{A} \times \epsilon\|_{\text{recast}}}{\mathcal{A} \times \epsilon\|_{\text{search}}}$	Models
$pp \to \tau\tau$	ATLAS	[85]	33%–57%	H (0.2, 0.3, 0.4, 0.6, 1.0, 1.5, 2.0 and 2.5 TeV)
$pp \to \mu\mu$	CMS	[86]	93%–96%	Z' (0.4, 0.6, 1.0, 1.5, 2.0 and 2.5 TeV)
$pp \to ee$	CMS	[86]	58%–69%	Z' (0.4, 0.6, 1.0, 1.5, 2.0 and 2.5 TeV)
$pp \to \tau\nu$	ATLAS	[87]	93%–167%	W' (1, 2, 3, 4 and 5 TeV)
$pp \to \mu\nu$	ATLAS	[88]	127%–145%	W' (2 and 7 TeV)
$pp \to e\nu$	ATLAS	[88]	87%–100%	W' (2 and 7 TeV)
$pp \to \tau\mu$	CMS	[89]	180%	Z' (1.6 TeV)
$pp \to \tau e$	CMS	[89]	150%	Z' (1.6 TeV)
$pp \to \mu e$	CMS	[89]	97%	Z' (1.6 TeV)