Institute for Theoretical Particle Physics and Cosmology | RWTH Aachen University

Collaborative Research Center TRR 257
P³H
Particle Physics Phenomenology after the Higgs Discovery

EFT validity for high-p_T Drell-Yan tails

Felix Wilsch

Institute for Theoretical Particle Physics and Cosmology
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Based on: [2207.10714], [2207.10756], w.i.p

In collaboration with: L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari

Outline

- **Introduction:**
  EFT methods for High-p_T Drell-Yan tails

- **Deriving EFT limits from Drell-Yan tails**
  - HighPT: a tool to constrain NP scenarios with generic flavor structure from high-p_T Drell-Yan tails

https://highpt.github.io/
Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10756]

see also `smelli`:
Greljo, Salko, Smolkovič, Stangl [2212.10497]

- **Validity of the EFT approach to high-p_T Drell-Yan tails**
  - Sensitivity of Drell-Yan limits on different energy regions
  - Truncation of the EFT series: $\sigma = \mathcal{O}(\Lambda^{-2})$ vs. $\sigma = \mathcal{O}(\Lambda^{-4})$
  - Effect of higher-dimensional operators: $d \geq 8$ required?
  - Convergence of the EFT series for specific NP scenarios

Combining different measurements with EFT

- LHC pushes NP scale to several TeV for many BSM scenarios → scale separation → EFTs
  - Allows for model independent data analysis at LHC using EFT methods
  - EFTs can be used to systematically combine different data sets
    - Employing RG methods we can combine low- and high-energy measurements
- Example: Drell-Yan tails probing semi-leptonic 4-fermion operators

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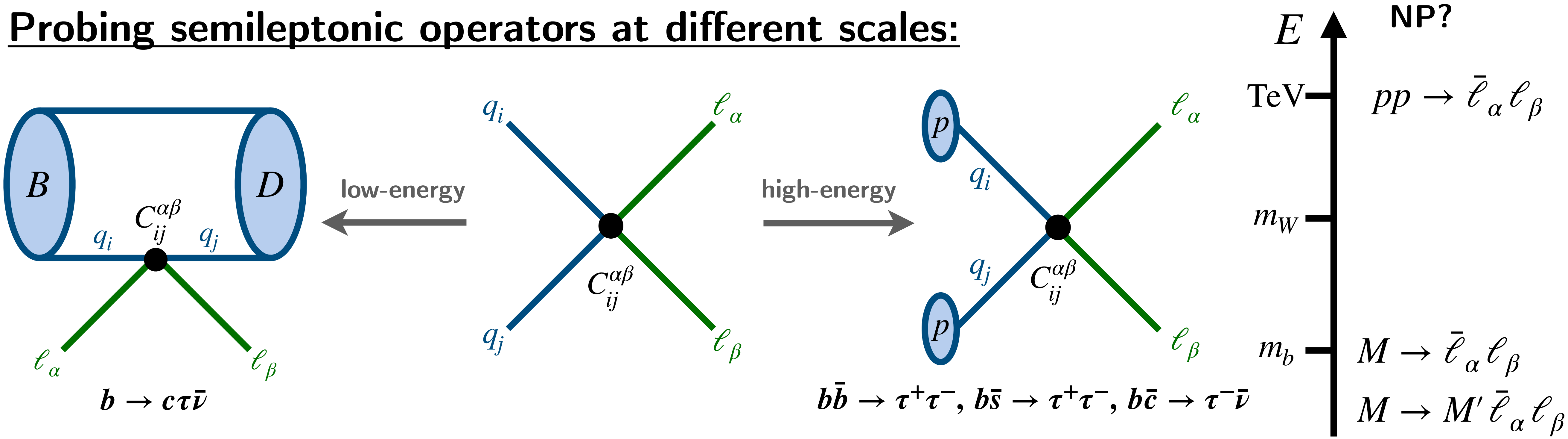
Probing semileptonic operators at different scales:



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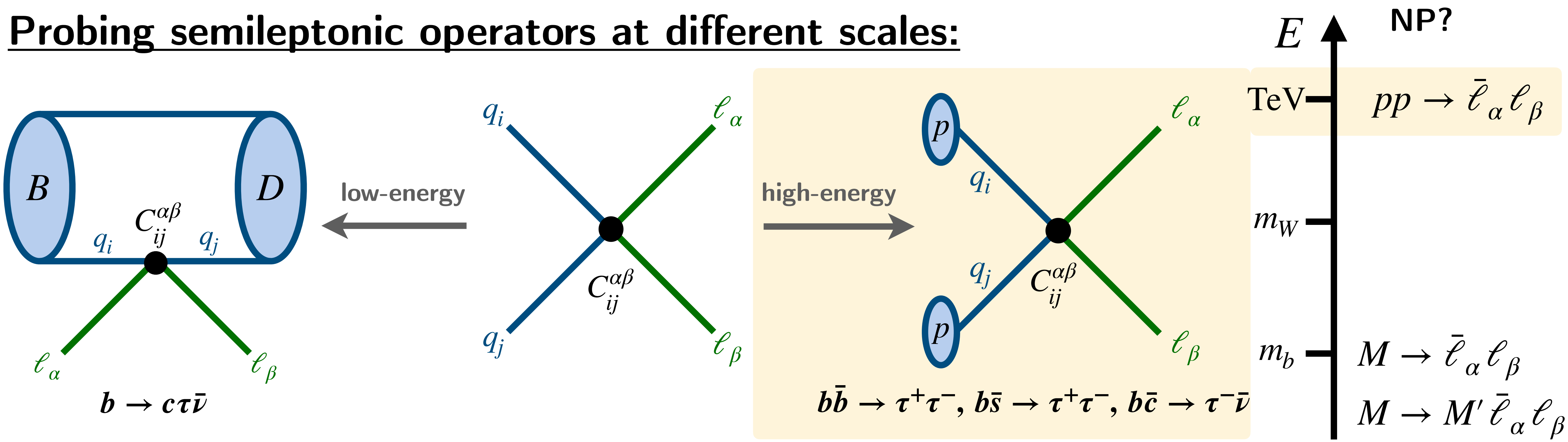
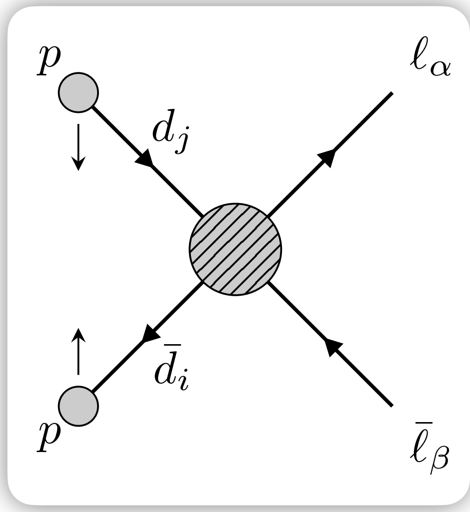


➡ **Is the EFT approach justified for high-energy measurements?**

Probing flavor at high energies in Drell-Yan

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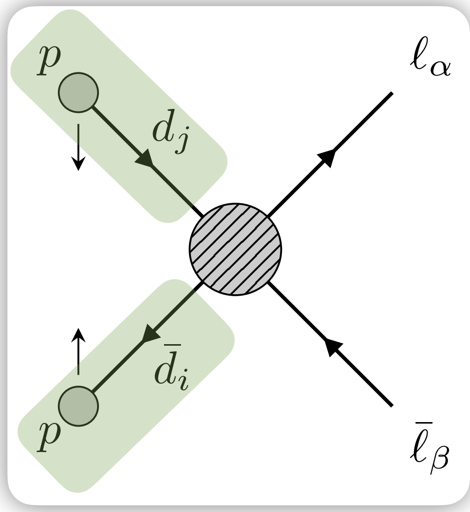
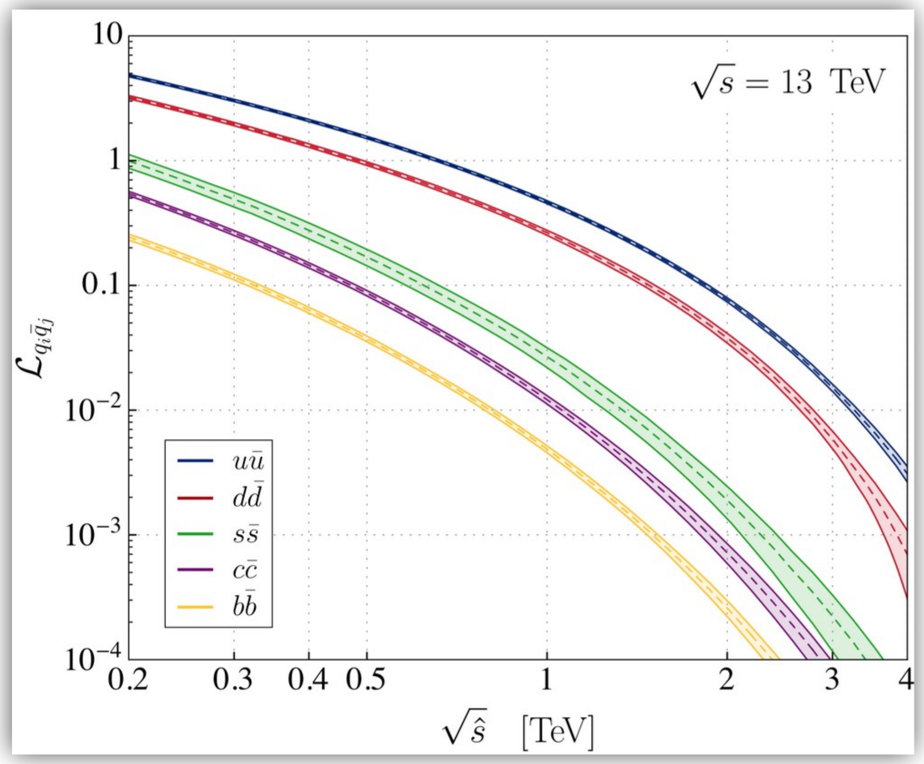
$$\mathcal{L}_{ij}(\hat{s}) = \int_{\frac{\hat{s}}{s}}^{1} \frac{\mathrm{d}x}{x} \left[f_{\bar{q}_i}(x,\mu)\, f_{q_j}\left(\frac{\hat{s}}{sx},\mu\right) + (\bar{q}_i \leftrightarrow q_j) \right]$$





Angelescu, Faroughy, Sumensari [2002.05684]

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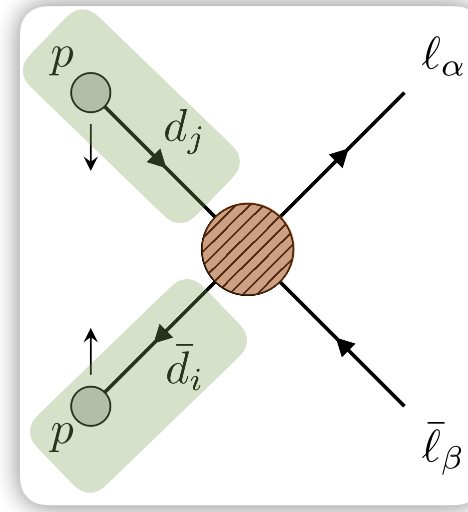

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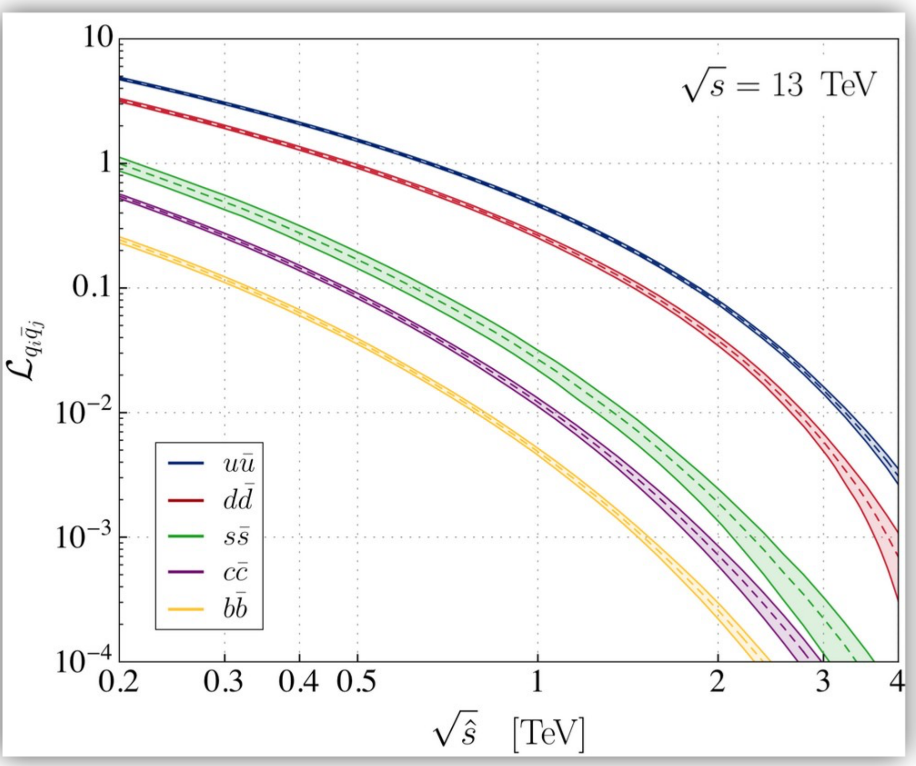
  - $[\hat{\sigma}]_{ij}^{\alpha\beta}$ partonic cross section $\to$ energy enhanced in EFT $\quad [\hat{\sigma}]_{ij}^{\alpha\beta} \propto \frac{\hat{s}}{\Lambda^4} \left| C \right|^2$



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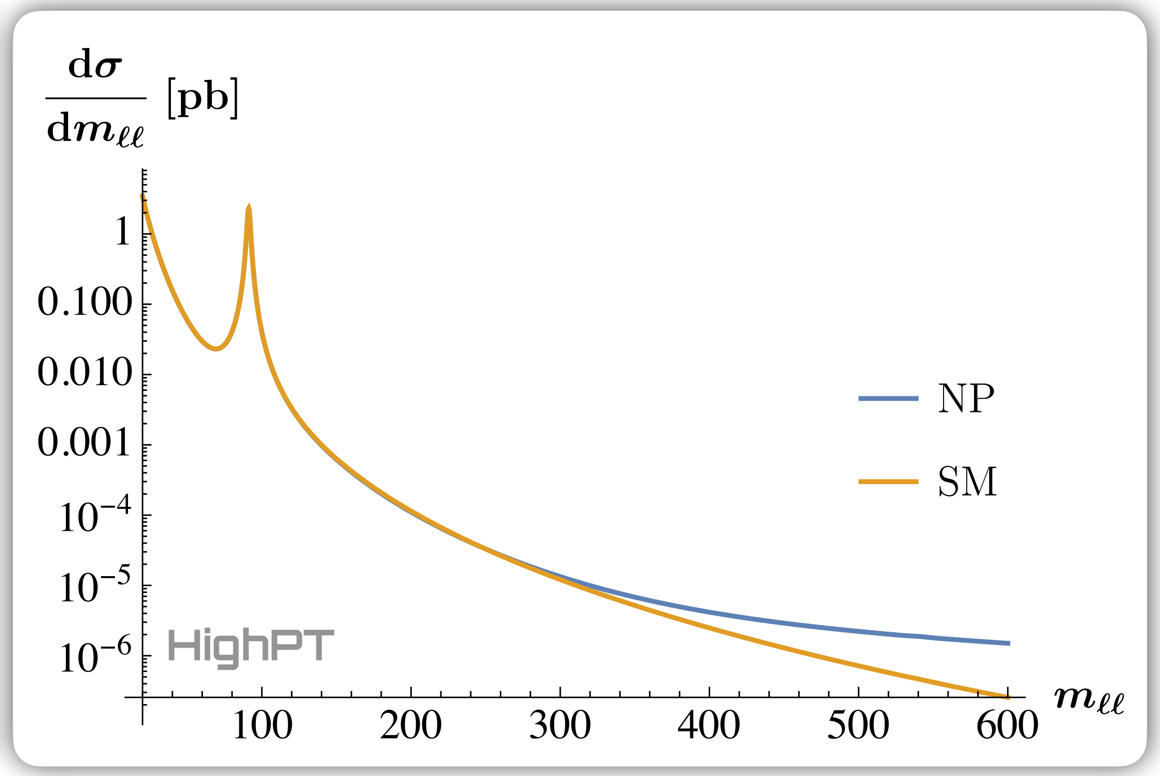

NP Drell-Yan tails analyses:

Greljo, Marzocca [1704.09015]

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Marzocca, Min, Son [2008.07541]

... many more ...

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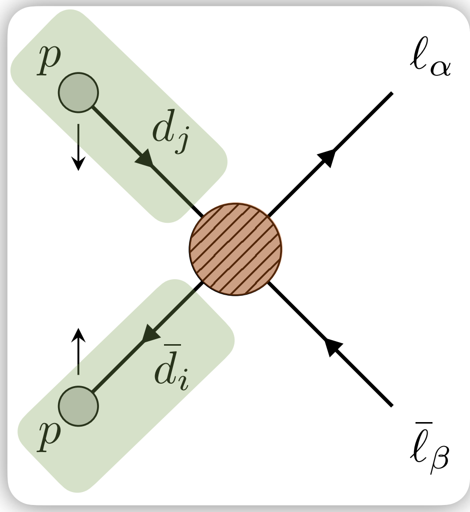

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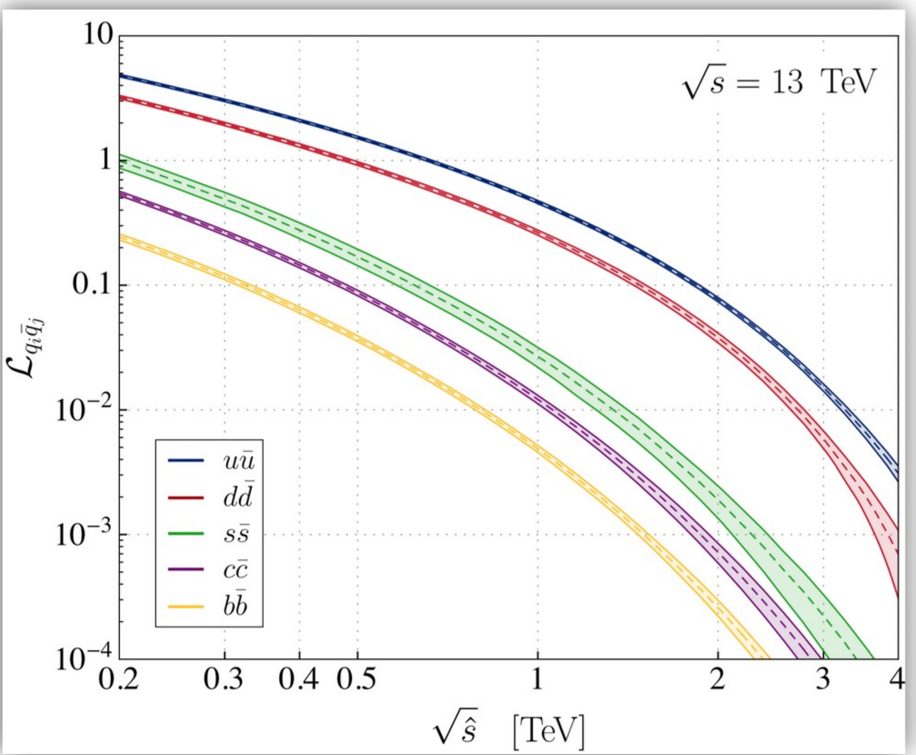

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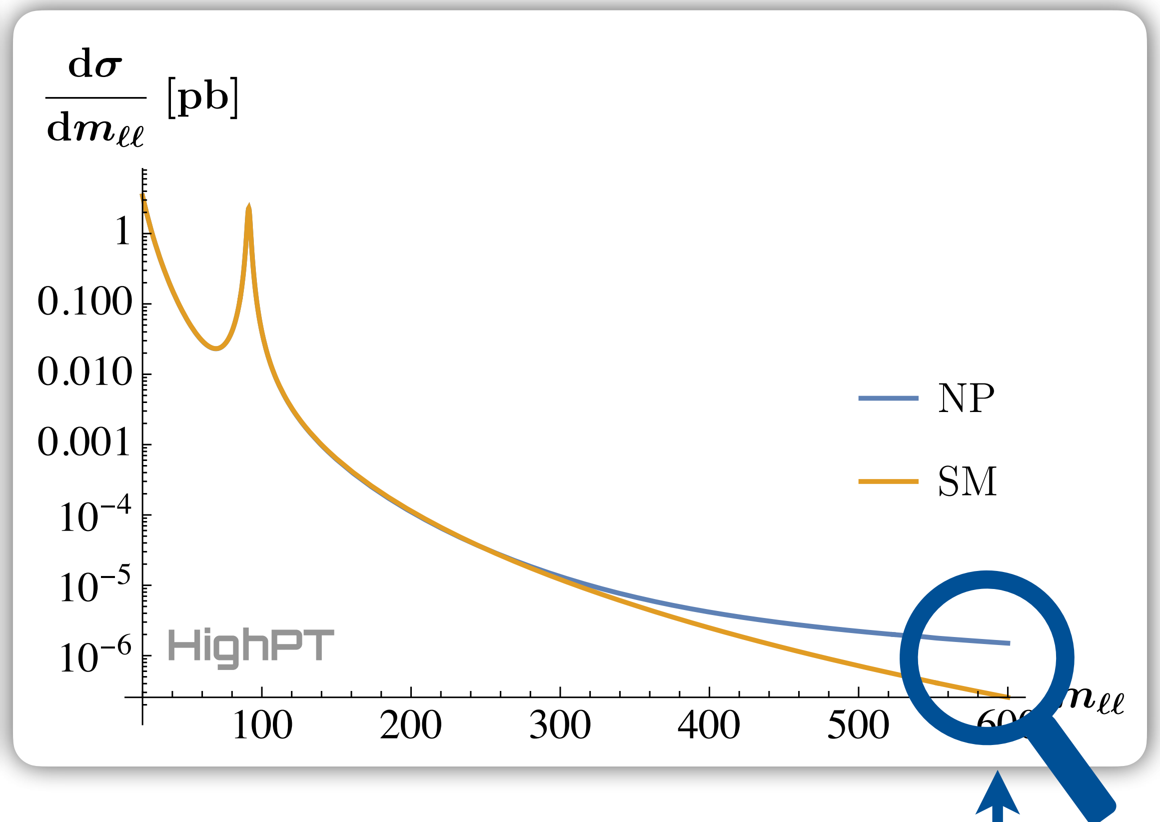

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- Possible breakdown of EFT assumption p^2/Λ^2 at high energies?

Form-factor decomposition

- Form factor decomposition of the amplitude
- Most general parametrization of tree-level effects invariant under $SU(3)_c \times U(1)_e$

$$
\begin{aligned}
[\mathcal{A}]_{ij}^{\alpha\beta} &\equiv \mathcal{A}\left(\bar{q}_i q'_j \to \bar{\ell}_\alpha \ell'_\beta\right) \\
&= \frac{1}{v^2} \sum_{X,Y} \Big\{ \left(\bar{\ell}_\alpha \mathbb{P}_X \ell'_\beta\right) \left(\bar{q}_i \mathbb{P}_Y q'_j\right) \left[\mathcal{F}_S^{XY,qq'}\left(\hat{s},\hat{t}\right)\right]_{ij}^{\alpha\beta} && \text{Scalar} \\
&\quad + \left(\bar{\ell}_\alpha \gamma_\mu \mathbb{P}_X \ell'_\beta\right) \left(\bar{q}_i \gamma^\mu \mathbb{P}_Y q'_j\right) \left[\mathcal{F}_V^{XY,qq'}\left(\hat{s},\hat{t}\right)\right]_{ij}^{\alpha\beta} && \text{Vector} \\
&\quad + \left(\bar{\ell}_\alpha \sigma_{\mu\nu} \mathbb{P}_X \ell'_\beta\right) \left(\bar{q}_i \sigma^{\mu\nu} \mathbb{P}_Y q'_j\right) \delta^{XY} \left[\mathcal{F}_T^{XY,qq'}\left(\hat{s},\hat{t}\right)\right]_{ij}^{\alpha\beta} && \text{Tensor} \\
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\end{aligned}
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Hadronic cross-section (at tree-level)

$$
\sigma_{\mathcal{B}}(pp \to \ell_\alpha^- \ell_\beta^+) = \frac{1}{48\pi v^2} \sum_{XY,IJ} \sum_{ij} \int_{m_{\ell\ell_0}^2}^{m_{\ell\ell_1}^2} \frac{\mathrm{d}\hat{s}}{s} \int_{-\hat{s}}^{0} \frac{\mathrm{d}\hat{t}}{v^2} M_{IJ}^{XY} \mathcal{L}_{ij} \left[\mathcal{F}_I^{XY,qq}\right]_{ij}^{\alpha\beta} \left[\mathcal{F}_J^{XY,qq}\right]_{ij}^{\alpha\beta\,*}
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- Captures local and non-local effects

$$
\mathcal{F}_I(\hat{s},\hat{t}) = \mathcal{F}_{I,\mathrm{Reg}}(\hat{s},\hat{t}) + \mathcal{F}_{I,\mathrm{Poles}}(\hat{s},\hat{t})
$$

SMEFT contact interactions (B)SM mediators

Incorporates EFT and explicit BSM mediators

EFT expansion of the Drell-Yan cross section

- EFT series expansion for the Drell-Yan cross section:
  - Truncation possibilities and contributions at different orders in the power counting

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

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$d = 6$ **interference**

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linear $\sim \mathcal{O}(\Lambda^{-4})$
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- Energy scaling of the amplitude for SMEFT operator classes ($A_{\rm SM} \sim$ const. for $E \gg v$)

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^2E^2/Λ^4	v^4/Λ^4	v^2E^2/Λ^4

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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	$v^2 E^2/\Lambda^4$

Highest energy scaling

High-p_T 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]

Computation of:

- Drell-Yan cross sections
- Experimental observables
- χ^2 likelihoods

https://highpt.github.io/

Implemented BSM models:

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

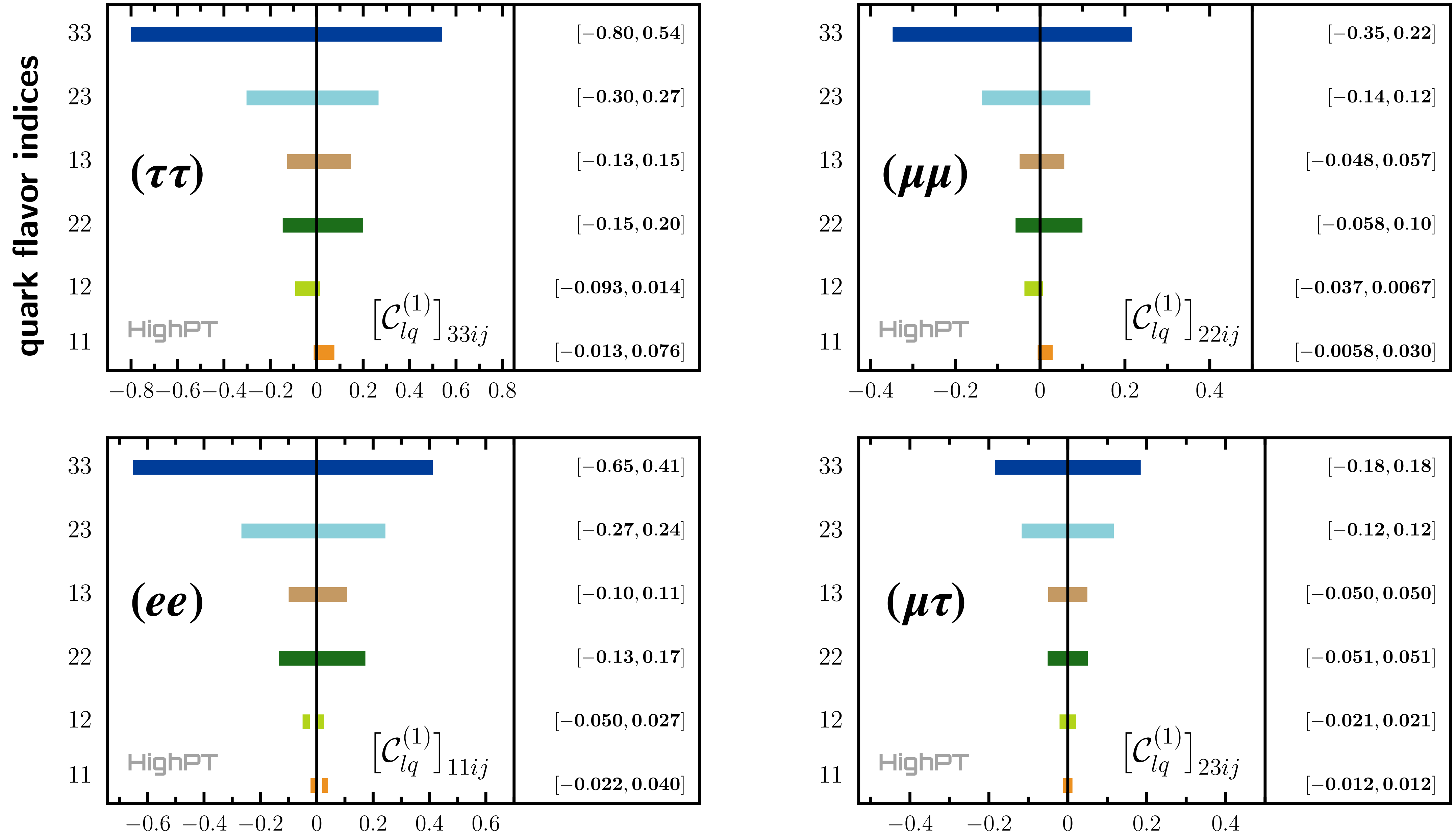
Recasted searches available:

- LHC run-II datasets for all flavors

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]

Application: single couplings constraints

- Constraint on individual SMEFT Wilson coefficient (one at a time)
- Example: $\left[Q_{lq}^{(1)}\right]_{\alpha\beta ij} = (\bar{\ell}_\alpha \gamma^\mu \ell_\beta)(\bar{q}_i \gamma_\mu q_j)$
  - Cross section to $\mathcal{O}(\Lambda^{-4})$ with $\Lambda = 1\,\text{TeV}$
  - Contributions from $pp \to \ell\ell$



EFT validity in high-p_T Drell-Yan tails

- High-p_T tails: events with highest invariant mass are around $\sqrt{\hat{s}} \lesssim 4\,\mathrm{TeV}$
- Validity of EFT approach for relatively light NP mediators (∼*few* TeV) ???
- Following *"LHC EFT WG note: Truncation, validity, uncertainties"* **[2201.04974]**
  - **<u>Option 1:</u>** drop highest bins of all searches
  - **<u>Option 2:</u>** include higher dimensional operators
    - How sizable is the effect of $d = 8$ operators compared to $d = 6$?
  - **<u>Option 3:</u>** simulate with explicit NP mediator rather than EFT
    - How does the explicit model compare to $d = 6, 8$ EFT operators?

see also:
Dawson, Fontes, Homiller, Sullivan [2205.01561],
Boughezal, Mereghetti, Petriello [2106.05337],
Alioli, Boughezal, Mereghetti, Petriello [2003.11615],
Kim, Martin [2203.11976], ...

Jack-knife analysis

$$R_{\text{Jack}} \sim \frac{\text{constraint holding out a single bin from } \chi^2}{\text{constraint from full } \chi^2}$$

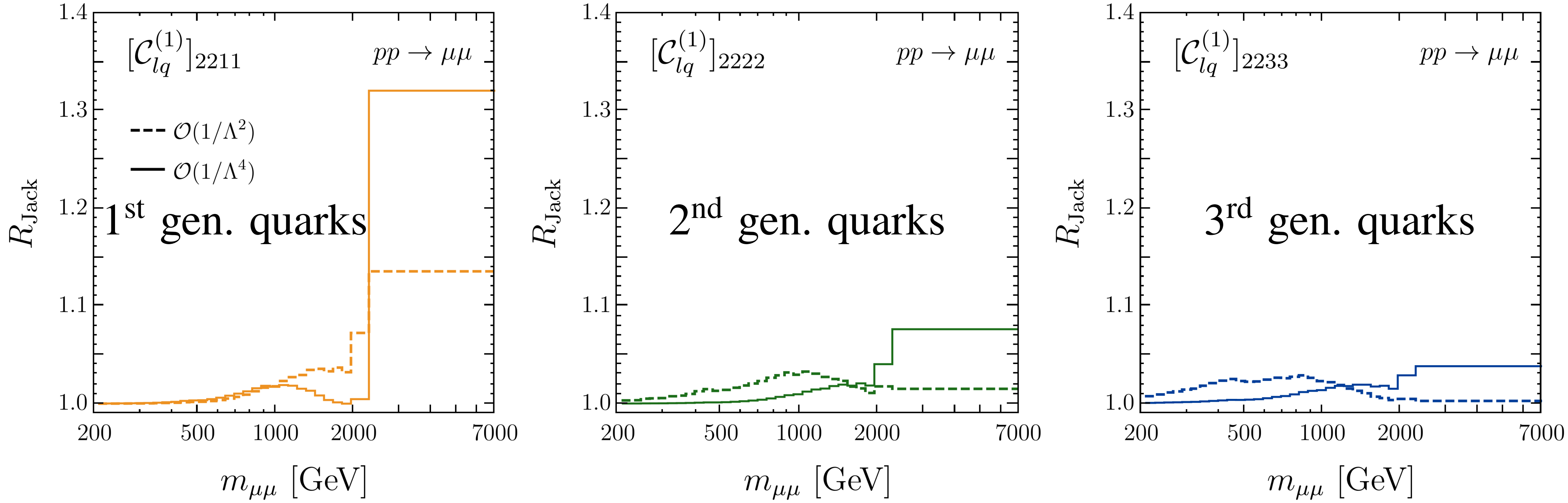
(for expected limits)

- Measure of sensitivity to individual energy bins
- Depends on: operator, flavor, truncation order

4-fermion →

$\mathcal{O}(\Lambda^{-2})$ --------

$\mathcal{O}(\Lambda^{-4})$ ———



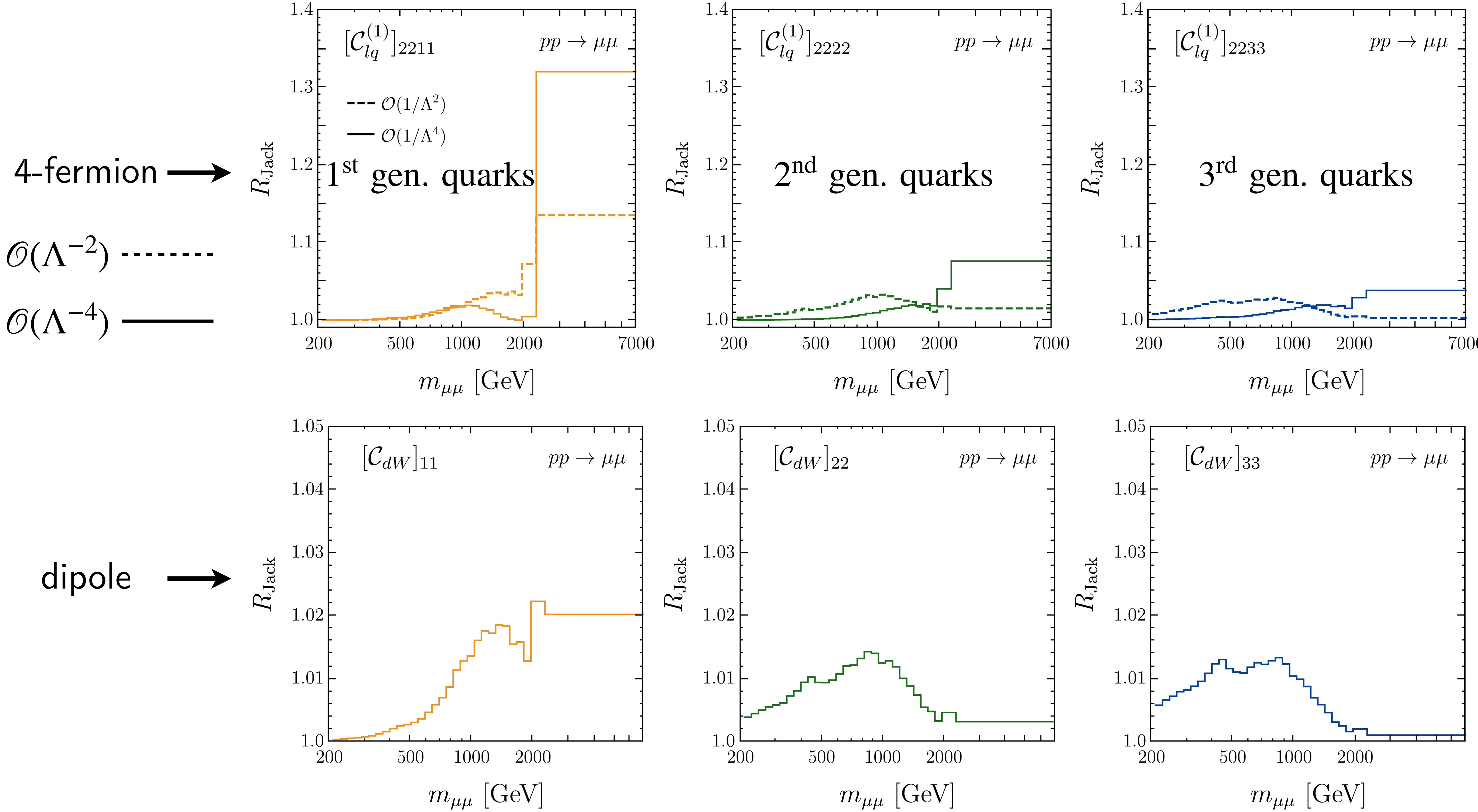
Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714]

Jack-knife analysis

$$R_{\text{Jack}} \sim \frac{\text{constraint holding out a single bin from } \chi^2}{\text{constraint from full } \chi^2}$$

(for expected limits)

- Measure of sensitivity to individual energy bins
- Depends on: operator, flavor, truncation order

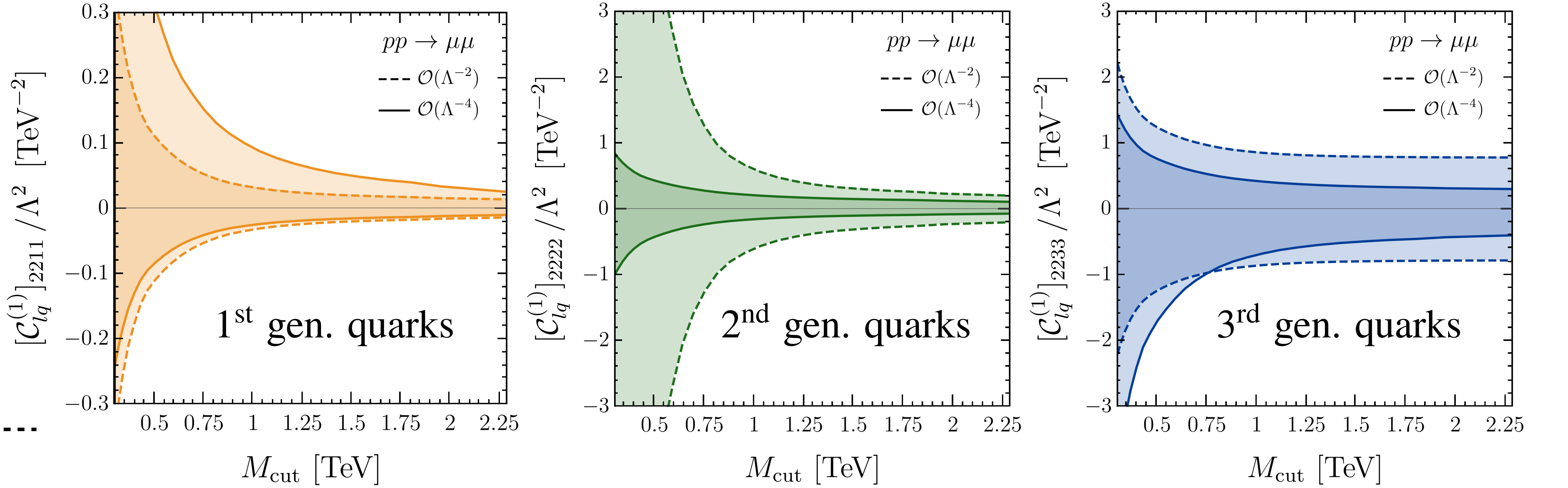


Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714]

Clipped limits

- Constraints obtained with sliding upper cut M_{cut} for experimental observables
- All events with $E_{\text{event}} > M_{\text{cut}}$ are removed from data set (example $pp \to \mu\mu$)

4-fermion



$\mathcal{O}(\Lambda^{-2})$ - - - - - -

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

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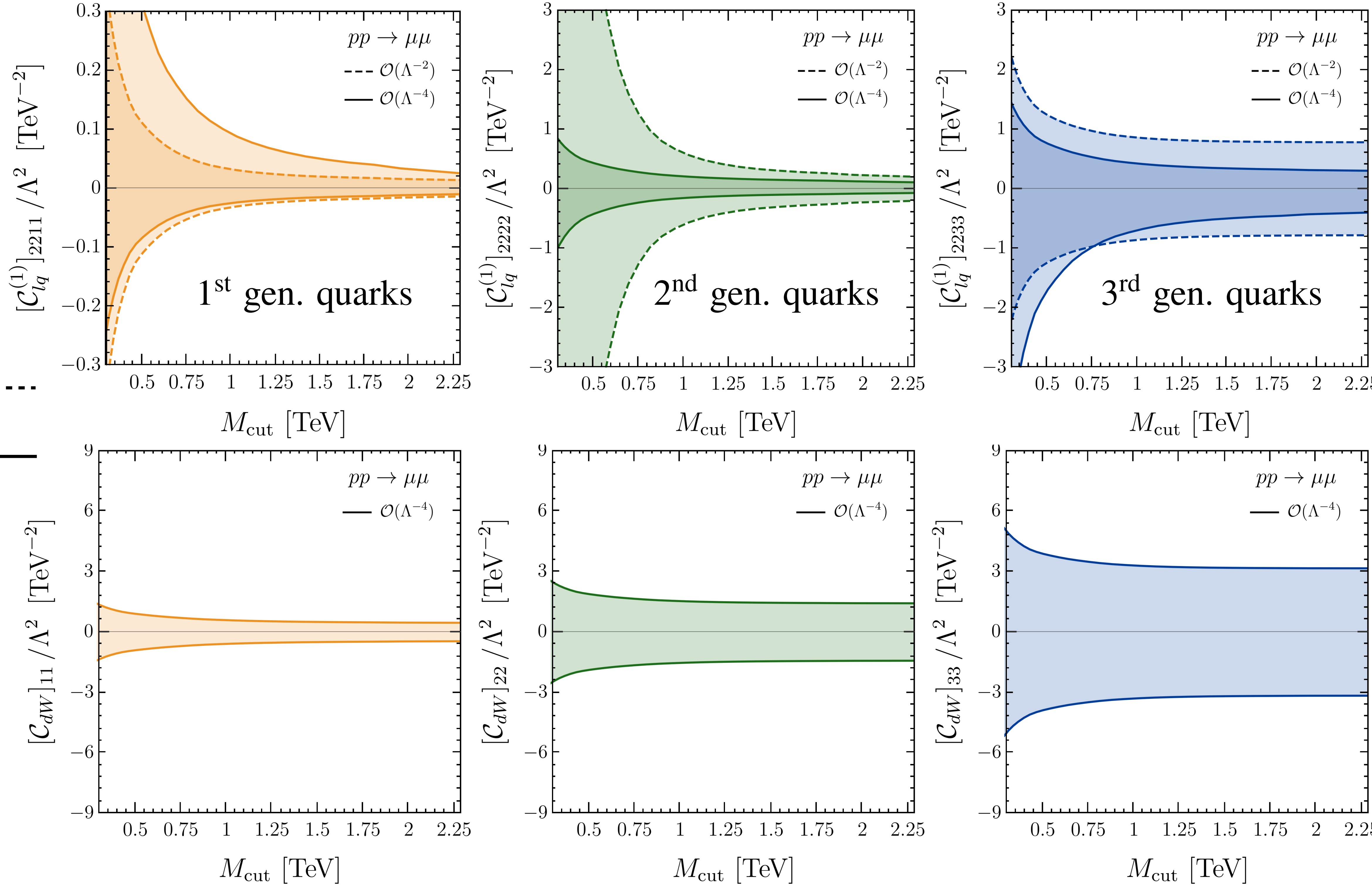
- All events with $E_{\rm event} > M_{\rm cut}$ are removed from data set (example $pp \to \mu\mu$)

4-fermion

$\mathcal{O}(\Lambda^{-2})$ - - - - -

$\mathcal{O}(\Lambda^{-4})$ ———

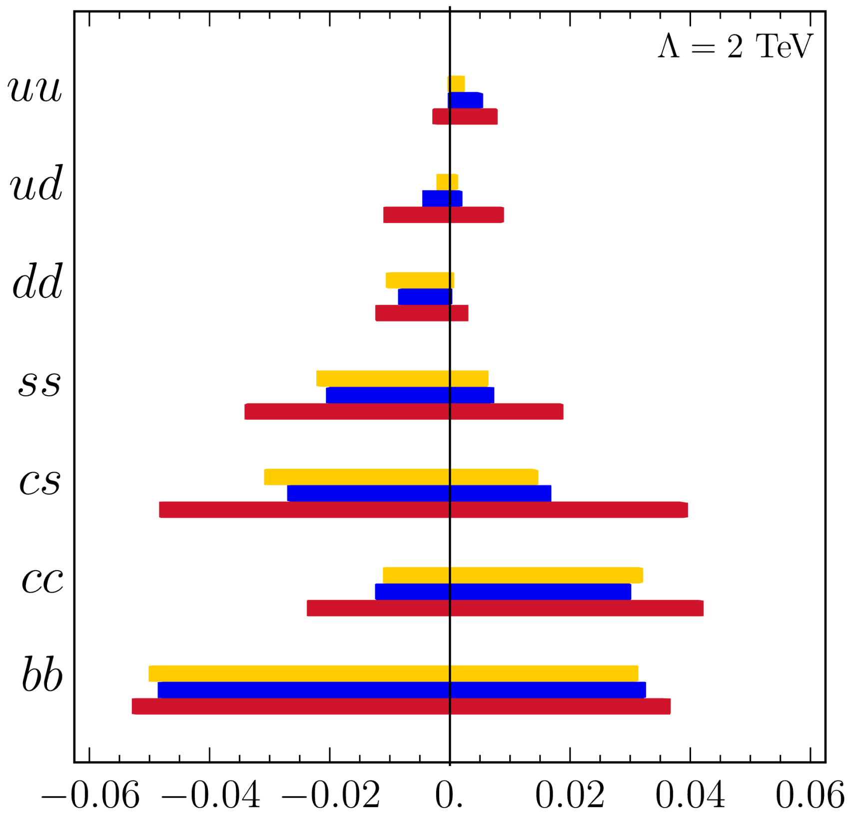
dipole



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

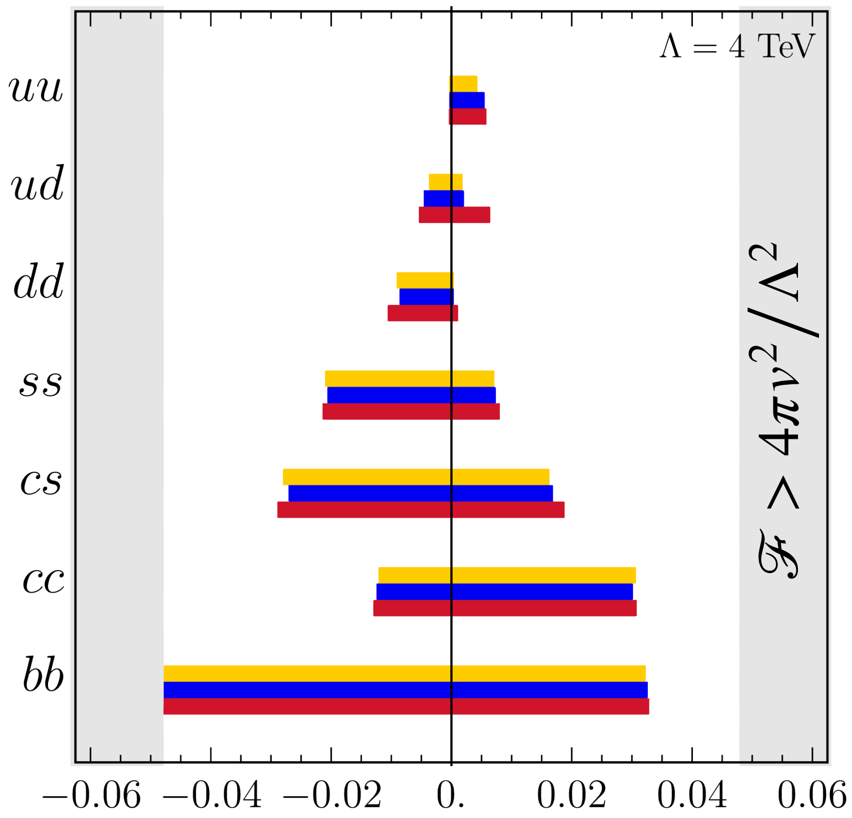
Effect of higher-dimensional operators

$\Lambda = 2\,\mathrm{TeV}$



$\left[\mathcal{F}^{LL,\,qq'}_{V\,(0,0)}\right]_{33ij}$

$\Lambda = 4\,\mathrm{TeV}$



$\left[\mathcal{F}^{LL,\,qq'}_{V\,(0,0)}\right]_{33ij}$

Constraints on form factors:

$$F^{LL,uu}_{V\,(0,0)} = \frac{v^2}{\Lambda^2} C^{(1-3)}_{lq}$$

$$F^{LL,dd}_{V\,(0,0)} = \frac{v^2}{\Lambda^2} C^{(1+3)}_{lq}$$

Single parameter limits for $d = 6$ $\sim C^{(1,3)}_{lq}$

Marginalizing over $d = 8$ operators $\sim C^{(k)}_{l^2q^2D^2}$

Operators of $d = 6$ and $d = 8$ assuming Z' scenario

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

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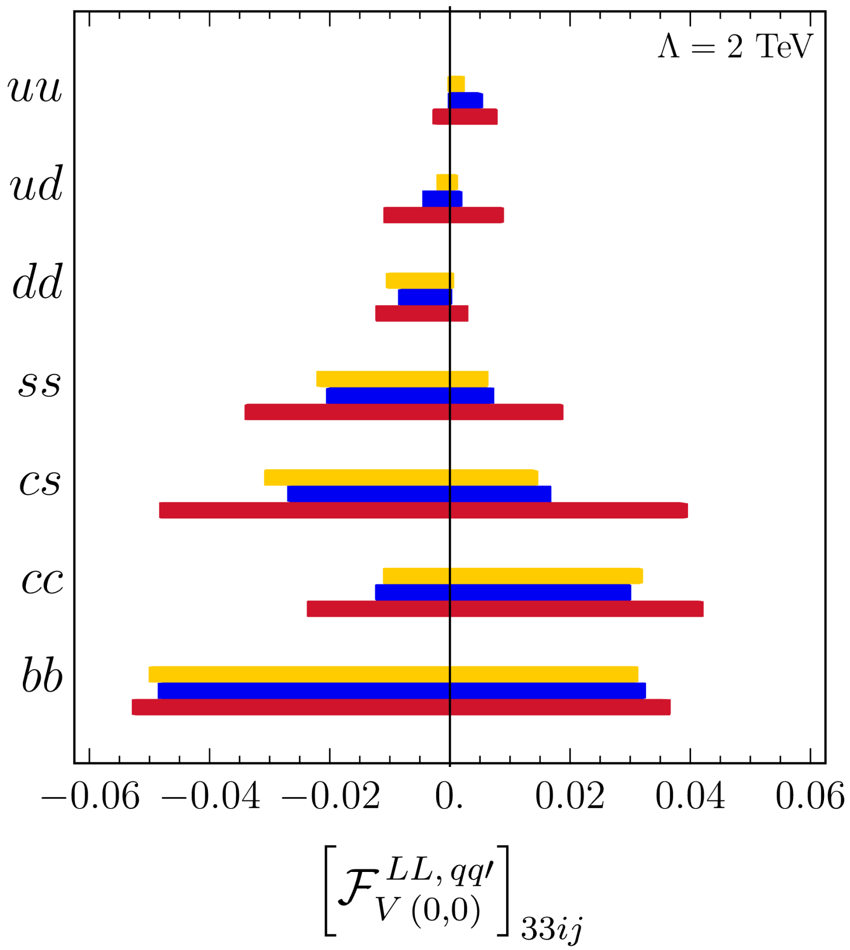

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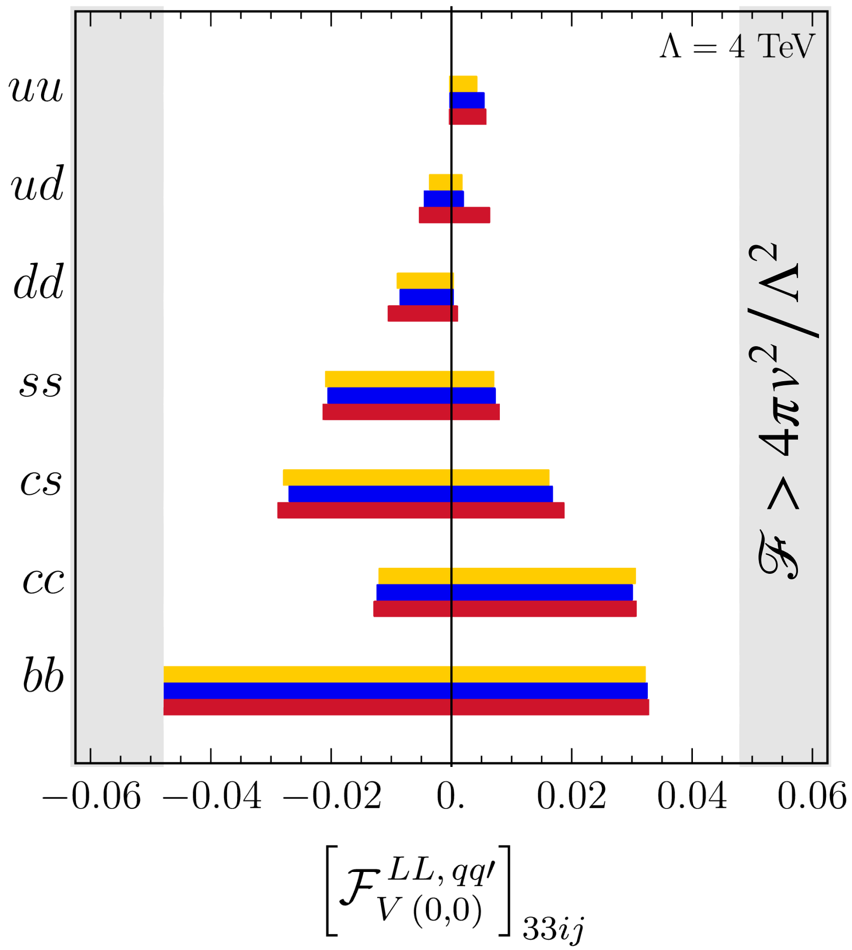

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⇒ Effect of $d = 8$ operators mostly washed out once correlation to $d = 6$ operators is assumed

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

Convergence of EFT series: resonant mediators

$\Gamma_Z = 0$

- EFT cross sections to different orders in Λ^{-1} normalized to full model cross section
- Example: Z' boson $\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} + \frac{m_{Z'}^2}{2} Z'_\mu Z'^{\,\mu} + J^\mu Z'_\mu$ $\quad J_\mu = g_{ij}^{(q)}\, \bar{q}_i \gamma_\mu q_j + g_{\alpha\beta}^{(l)}\, \bar{l}_\alpha \gamma_\mu l_\beta$

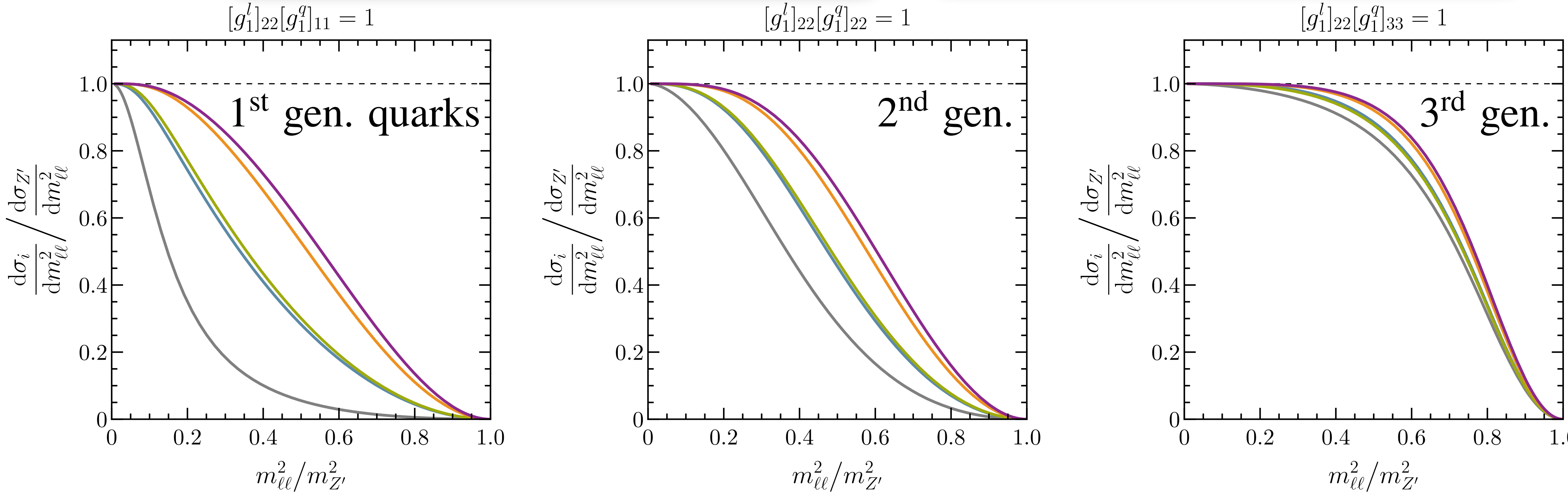
$\mathcal{O}(\Lambda^{-2})$, $d \leq 6$

$\mathcal{O}(\Lambda^{-4})$, $d \leq 6$

$\mathcal{O}(\Lambda^{-4})$, $d \leq 8$

$\mathcal{O}(\Lambda^{-6})$, $d \leq 8$

$\mathcal{O}(\Lambda^{-8})$, $d \leq 8$



Allwicher, Faroughy, Jaffredo, Sumensari, FW [w.i.p.]

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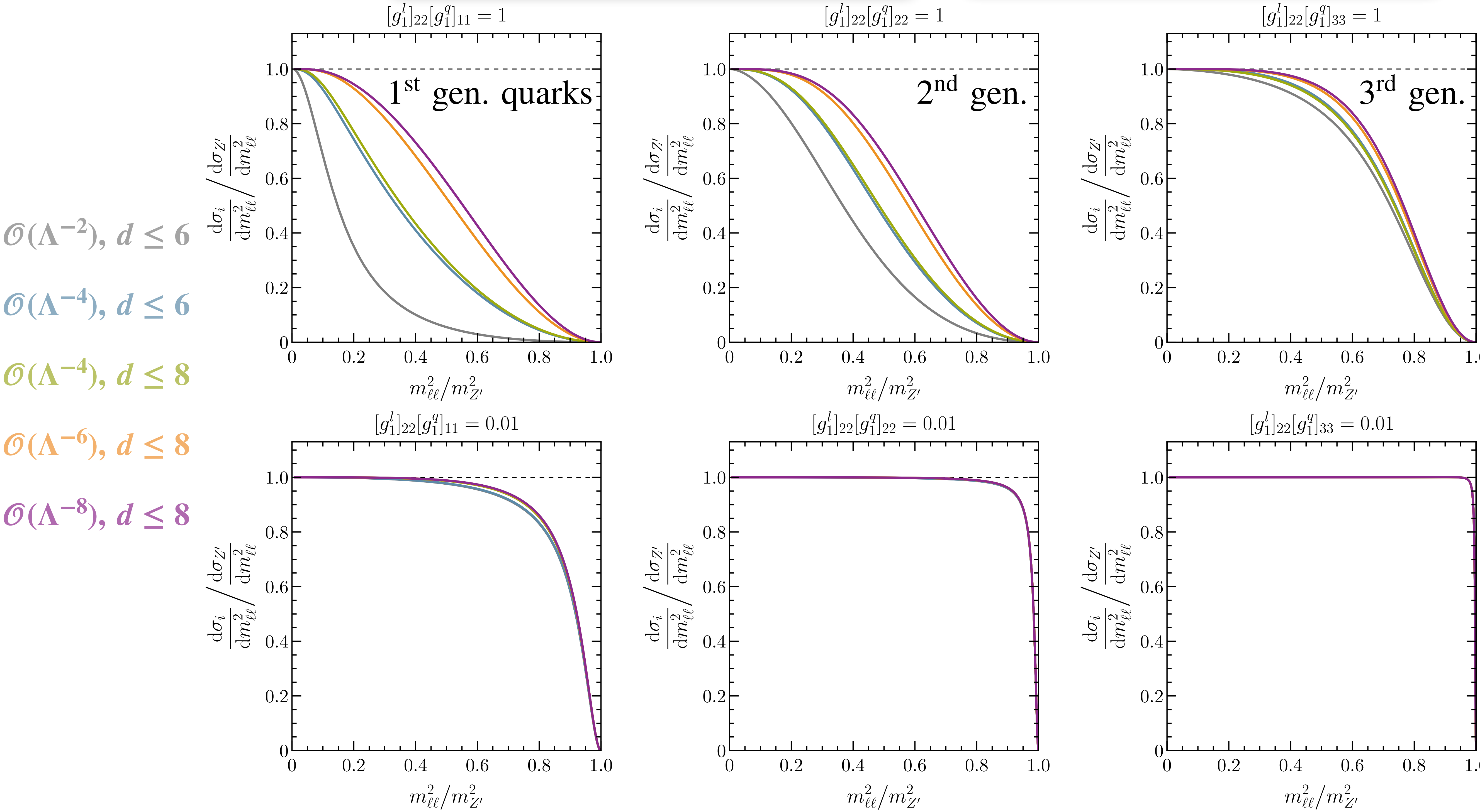
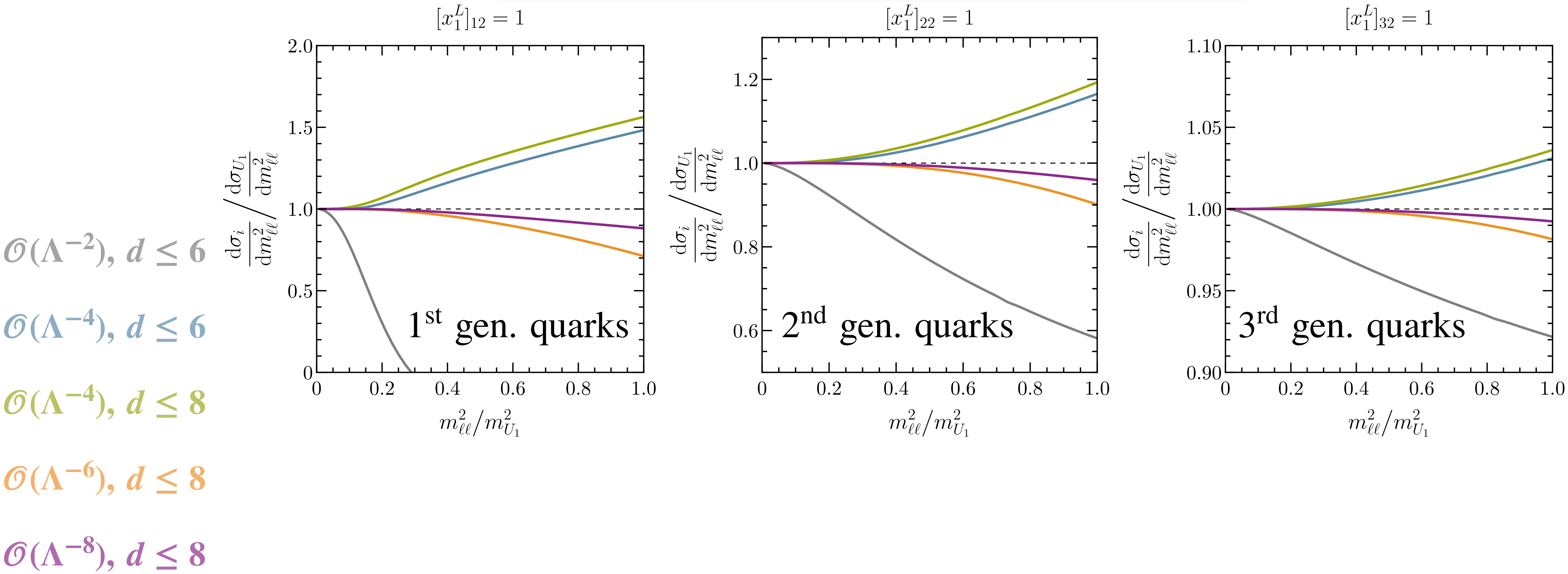


Allwicher, Faroughy, Jaffredo, Sumensari, FW [w.i.p.]

Convergence of EFT series: non-resonant mediators

- EFT cross section computed to different orders in Λ^{-1} and normalized to full model
- U_1 vector leptoquark: $\mathcal{L}_{U_1} = -\frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + m_U^2\, U_1^{\mu\,\dagger} U_{1\,\mu} + (J^\dagger_\mu U_1^\mu + \text{h.c.})$ $\quad J^\dagger_\mu = x_L^{i\alpha}\,\bar{q}_i\gamma_\mu l_\alpha$



Allwicher, Faroughy, Jaffredo, Sumensari, FW [w.i.p.]

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$\mathcal{O}(\Lambda^{-2}),\ d \leq 6$

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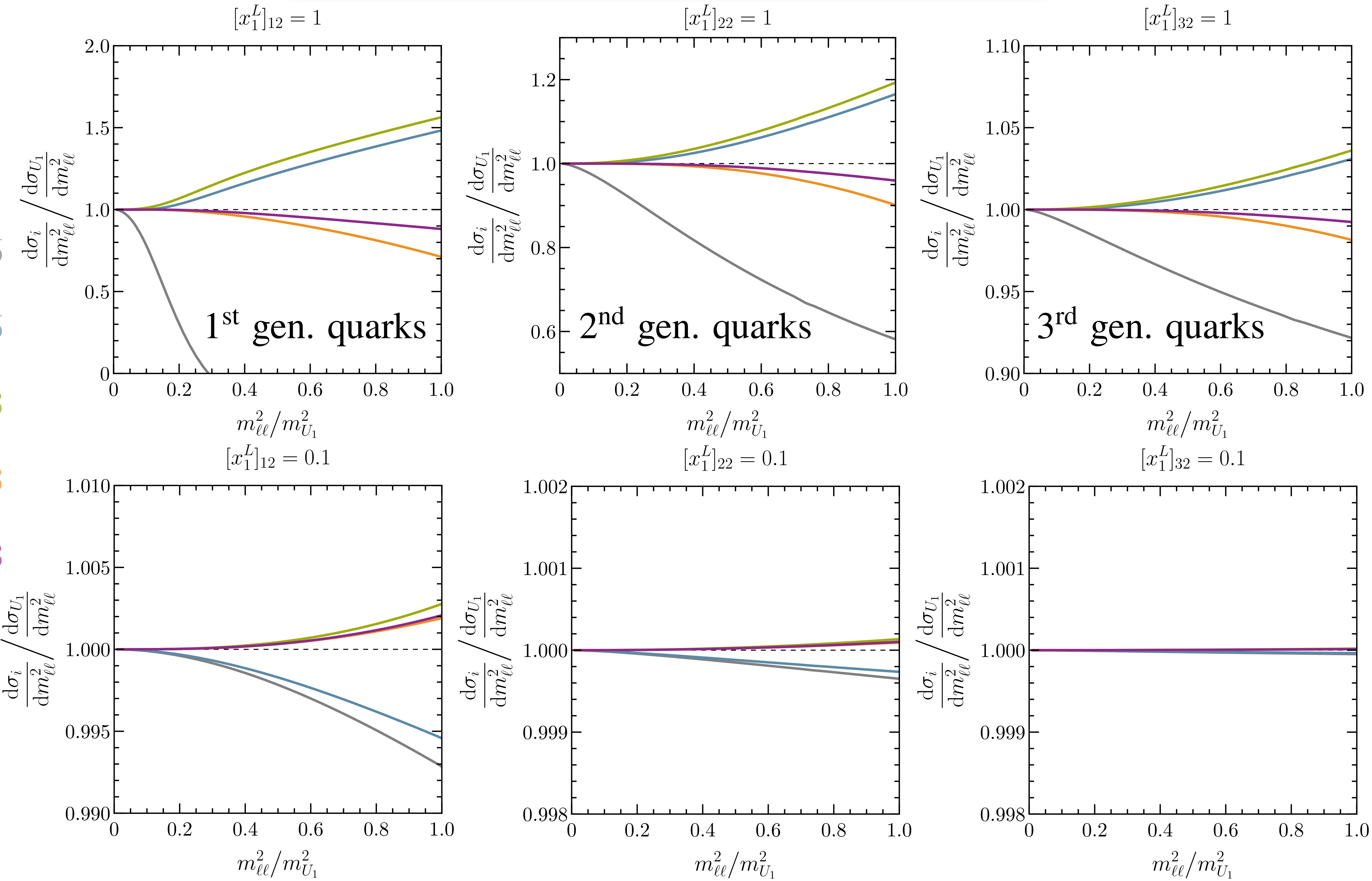


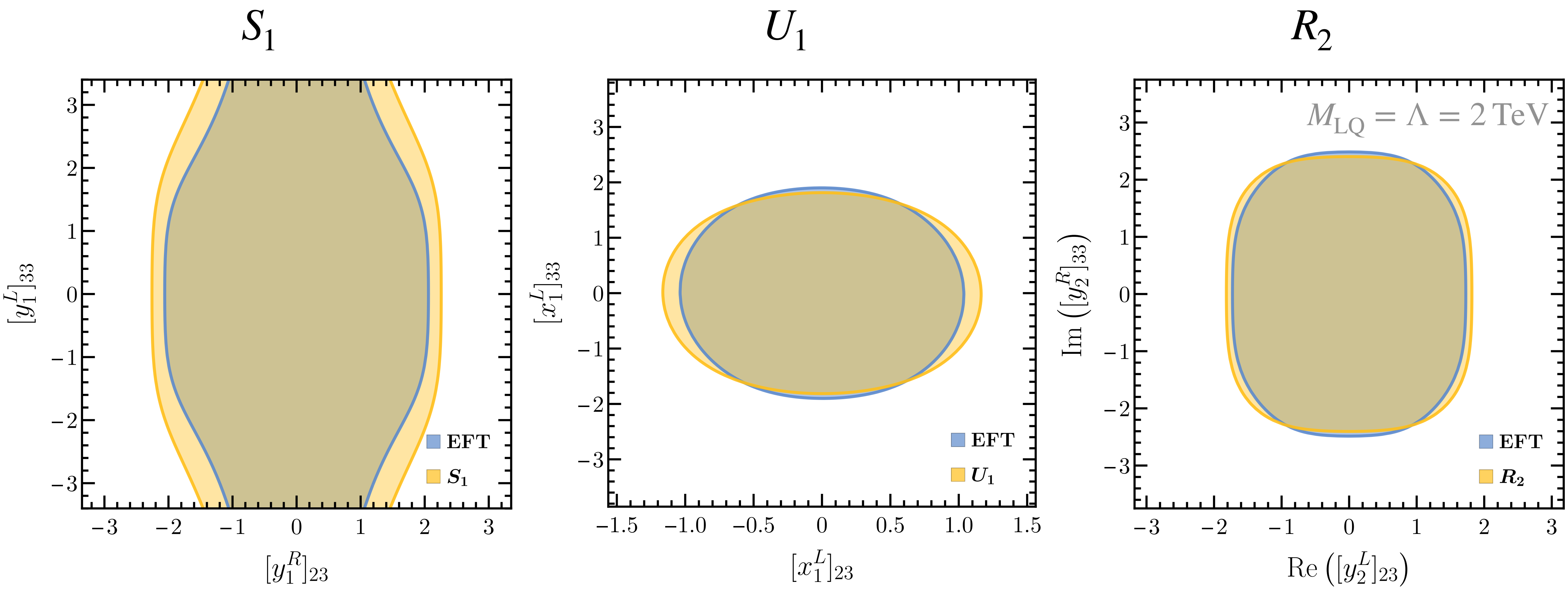
Allwicher, Faroughy, Jaffredo, Sumensari, FW [w.i.p.]

Limits: leptoquark models versus EFTs

negative subleading EFT correction

$$\frac{1}{t-M^2} = -\frac{1}{M^2}\left(1+\frac{t}{M^2}\right) + \mathcal{O}(\Lambda^{-6}), \quad \text{with } t<0$$

- **Compare constraints obtained using:**
  - **The full leptoquark model** with
  - **The SMEFT using the matching conditions to the leptoquark models**



In most parameter space: leptoquark constraints relaxed w.r.t. EFT limits due to t-channel exchange

Conclusion

- High-p_T Drell-Yan tails are powerful flavor probes, complementary to low-energy observables
- Desirable: systematic combination with low-energy flavor data using EFTs
- Can we consistently use EFT to describe these high-p_T tails?
  - Available tools: HighPT, `smelli`
  - Allow to investigate the validity of EFT assumption
- Many possibilities to check EFT validity:
  - Jack-knife analyses *(sensitivity to individual energy bins)*
  - Clipped limits *(upper energy cut for experimental data)*
  - Including higher-dimensional operators
  - Checking the EFT series convergence on cross-section level
  - Comparing EFT limits to constraints with concrete BSM models

➡ **Validity of EFT approach is model and process dependent!**

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Thank you for your Attention !!!

Backup

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 $\frac{d\sigma}{dx_{\text{obs}}}$ built from reconstructed objects (isolated leptons, tagged jets, missing energy, ...)

- Relate $\frac{d\sigma}{dx}$ to $\frac{d\sigma}{dx_{\text{obs}}}$ using **MC simulations** (`MadGraph+Pythia+Delphes`) [1405.0301]; [1410.3012]; [1307.6346];

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

response matrices

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

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

response matrices

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

- Extract likelihood (χ^2):

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

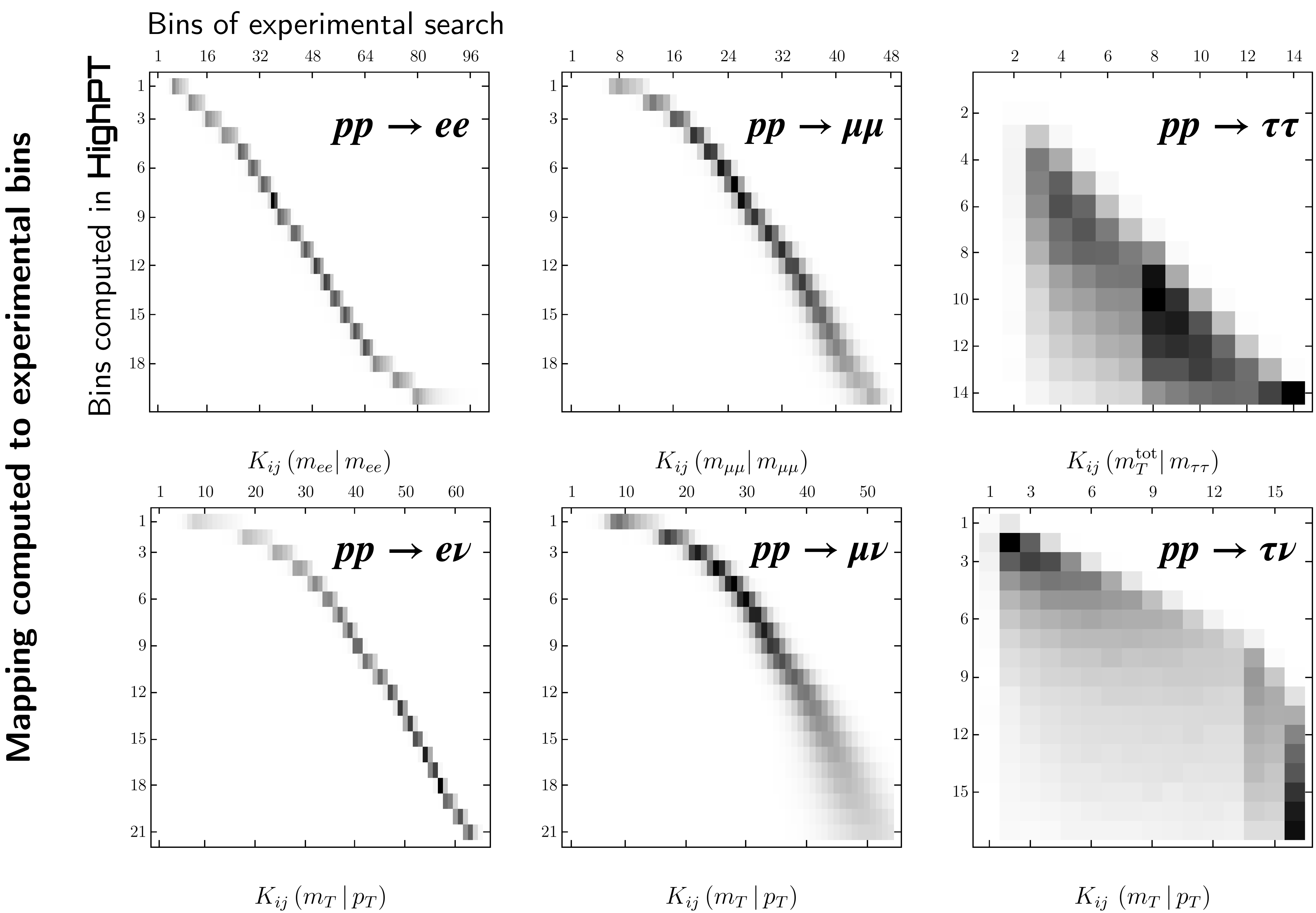
HighPT (N_{NP}) — provided by experiment (N_{SM}, N_{data}, σ^2)

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.	$\frac{\mathcal{A} \times \epsilon\vert_{\text{recast}}}{\mathcal{A} \times \epsilon\vert_{\text{search}}}$	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)

Detector response matrices K_{pq}



Local & Non-Local Form-Factor Contributions

Split form-factors into a regular and a singular piece

$$\mathcal{F}_I(\hat{s},\hat{t}) = \mathcal{F}_{I,\mathrm{Reg}}(\hat{s},\hat{t}) + \mathcal{F}_{I,\mathrm{Poles}}(\hat{s},\hat{t})$$

- Analytic function of $\hat{s}$, $\hat{t}$
- Describes EFT contact interactions
  - Can be matched to the SMEFT
- Formal expansion in validity range of the EFT: $v^2, |\hat{s}|, |\hat{t}| < \Lambda^2$

$$F_{I,Reg}(\hat{s},\hat{t}) = \sum_{n,m=0}^{\infty} F_{I,(n,m)} \left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m$$

- Isolated simple poles in $\hat{s}$, $\hat{t}$ (no branch-cuts at tree-level)
- Describes non-local effects due to exchange of mediators (SM & NP)

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

SM $(I=V)$ **NP**

$$\Omega_n = m_n^2 - i m_n \Gamma_n \qquad \hat{u} = -\hat{s} - \hat{t}$$

➡ **Form-factor framework can incorporate both EFT and explicit NP models**

Regular Form Factors

- **Regular form-factors:** analytic functions of $\hat{s}$, $\hat{t}$
- Describe unresolved d.o.f. $\rightarrow$ EFT
- Formal expansion in validity range of the EFT $|\hat{s}|, |\hat{t}| < \Lambda^2$:
  - **Derivative expansion:** $$F_{I,Reg}(\hat{s}, \hat{t}) = \sum_{n,m=0}^{\infty} F_{I,(n,m)} \left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m$$
  - **EFT expansion:** $$F_{I,(n,m)} = \sum_{k=n+m+1} \mathcal{O}\left((v^2/\Lambda^2)^k\right)$$
- Terms to consider at mass dimension d
  - $d = 6$: $(n, m) = (0,0)$
  - $d = 8$: $(n, m) = (0,0), (1,0), (0,1)$

Singular Form Factors

- **Pole form factors:** non-analytic functions with finite number of simple poles

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

  - a : sum over all s-channel (colorless) mediators
  - b : sum over all t-channel (colorful) mediators
  - c : sum over all u-channel (colorful) mediators

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

$$\Omega_n = m_n^2 - i m_n \Gamma_n$$

- SM contribution $\rightarrow$ $\mathcal{S}_{V(a)}$ $(a \in \{\gamma, Z, W\})$
- NP contribution $\rightarrow$ $\mathcal{S}_{I(a)}, \mathcal{T}_{I(b)}, \mathcal{U}_{I(c)}$

- Residues can be made independent of $\hat{s}$, $\hat{t}$ by partial fraction decomposition:

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

$g(z,\Omega)$ → redefines $F_{I,\mathrm{Reg}}$

$$\mathcal{S}_{I(a)}(\hat{s}) \rightarrow \mathcal{S}_{I(a)}$$
$$\mathcal{T}_{I(b)}(\hat{t}) \rightarrow \mathcal{T}_{I(b)}$$
$$\mathcal{U}_{I(c)}(\hat{u}) \rightarrow \mathcal{U}_{I(c)}$$

SMEFT — Form-Factor Matching

- **Example: vector form-factors**

NC: $a \in \{\gamma, Z\}$
CC: $a \in \{W\}$

Include BSM mediators similarly

$$F_V = F_{V(0,0)} + F_{V(1,0)}\frac{\hat{s}}{v^2} + F_{V(0,1)}\frac{\hat{t}}{v^2} + \sum_a \frac{v^2}{\hat{s} - M_a^2 + iM_a\Gamma_A}\left(\mathcal{S}_{(a,\mathrm{SM})} + \delta\mathcal{S}_{(a)}\right)$$

$$\mathcal{S}_{(\gamma,\mathrm{SM})} = 4\pi\alpha_{\mathrm{em}} Q_l Q_q$$

$$\mathcal{S}_{(Z,\mathrm{SM})} = \frac{4\pi\alpha_{\mathrm{em}}}{c_W^2 s_W^2} g_l^X g_q^Y$$

$$\mathcal{S}_{(W,\mathrm{SM})} = \frac{1}{2} g_2^2$$

- **Schematic form-factor matching to $\mathcal{O}(\Lambda^{-4})$:**

$$F_{V(0,0)} = \frac{v^2}{\Lambda^2} C^{(6)}_{\psi^4} + \frac{v^4}{\Lambda^4} C^{(8)}_{\psi^4 H^2} + \frac{v^2 m_a^2}{\Lambda^4} C^{(8)}_{\psi^2 H^2 D^3} + \cdots$$

$$F_{V(1,0)} = \frac{v^4}{\Lambda^4} C^{(8)}_{\psi^4 D^2} + \cdots$$

$$F_{V(0,1)} = \frac{v^4}{\Lambda^4} C^{(8)}_{\psi^4 D^2} + \cdots$$

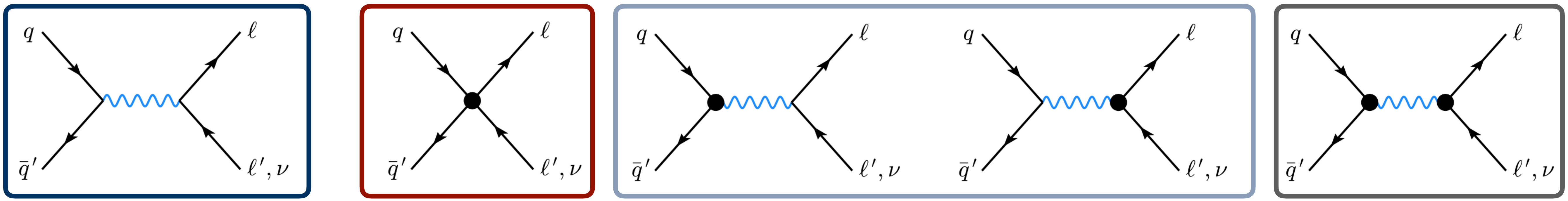
$$\delta\mathcal{S}_{(a)} = \frac{m_a^2}{\Lambda^2} C^{(6)}_{\psi^2 H^2 D} + \frac{v^2 m_a^2}{\Lambda^4}\left(\left[C^{(6)}_{\psi^2 H^2 D}\right]^2 + C^{(8)}_{\psi^2 H^4 D}\right) + \frac{m_a^4}{\Lambda^4} C^{(8)}_{\psi^2 H^2 D^3} + \cdots$$

$d = 6$
$d = 8$

$$\frac{s}{s - \Omega} = 1 + \frac{\Omega}{s - \Omega}$$ partial fractioning

Energy Scaling for SMEFT Operators

- Feynman diagrams for Drell-Yan in the SMEFT to $\mathcal{O}(\Lambda^{-4})$



SM | ψ^4, $\psi^4 H^2, \psi^4 D^2$ | $\psi^2 XH, \psi^2 H^2 D, \psi^2 H^4 D, \psi^2 H^2 D^3$ | $\psi^2 H^2 D$

- EFT operator counting and energy scaling

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	$v^2 E^2/\Lambda^4$

Only contributions interfering with the SM

Most enhanced contributions