Drell-Yan measurements for EFT

Status and prospects

EFTs at the LHC :Theory and Experiment
IJCLab - Orsay

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Introduction

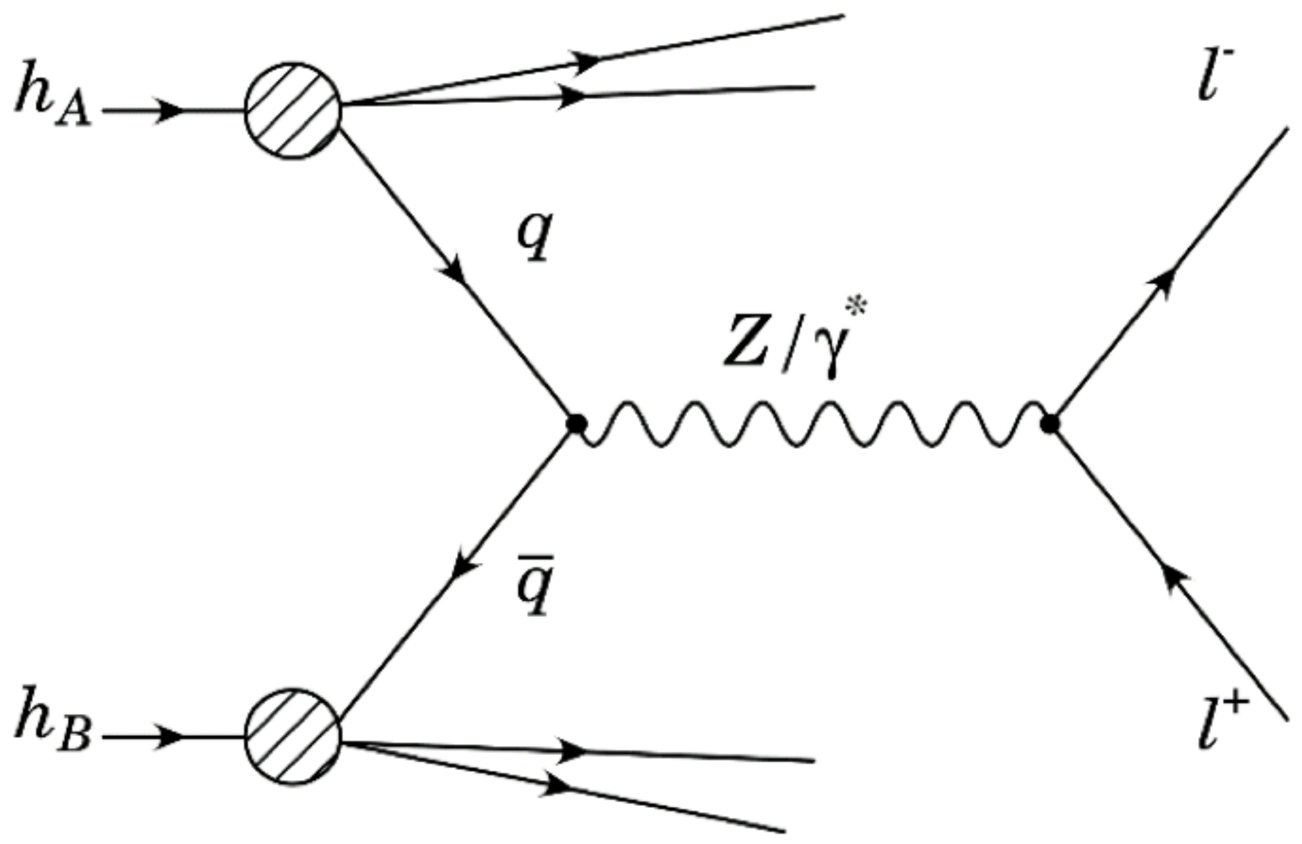
High-Mass Drell–Yan (HMDY) pp $\rightarrow ll/l\nu$ is a clean, high-statistics probe of electroweak dynamics at the LHC

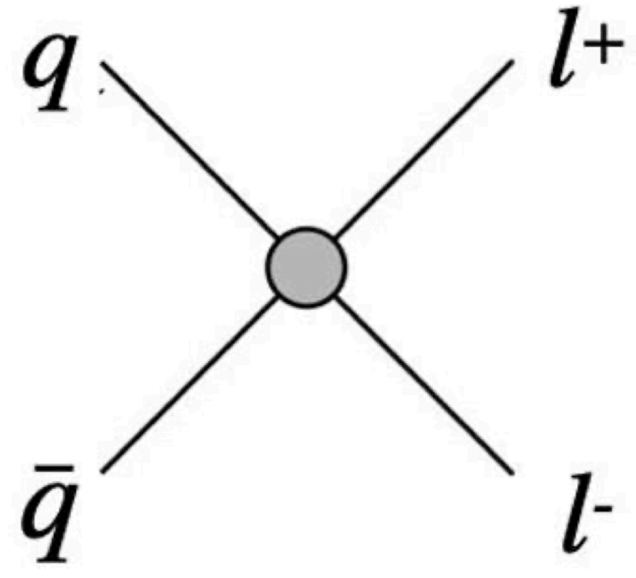
Experimental access to high-Q^2 region with excellent precision and precise SM predictions

Important for SMEFT, notably four-fermion operators with effects that grow with energy

Complementary constraints to operators also probed by low-energy flavour

This talk, experimental overview of current (ATLAS) measurements in HMDY and relevance for SMEFT and future prospects



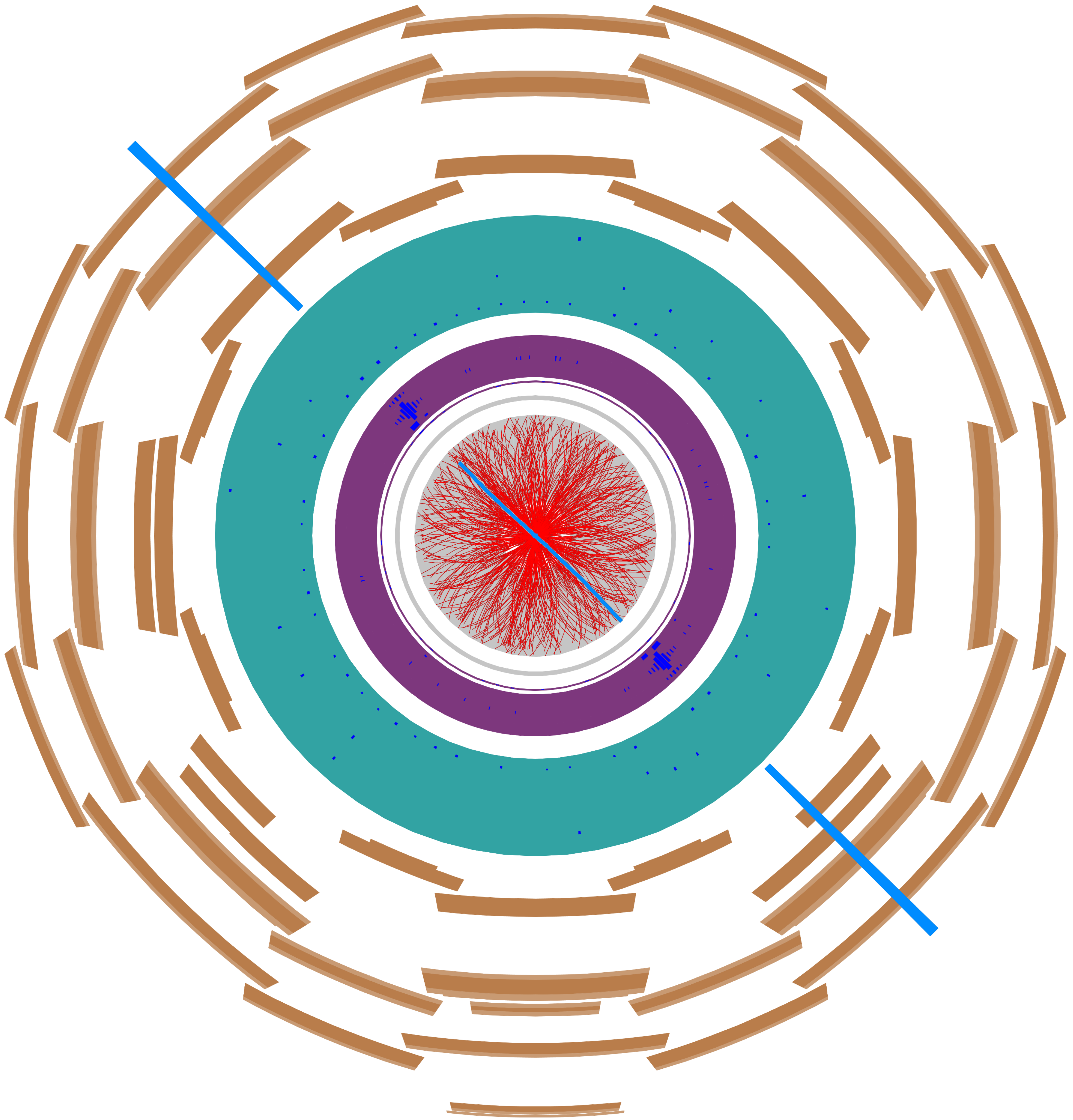


Experimental reach

Process can be reliably studied in the high-mass region over a large mass range reliable statistics, even at high-Q^2

Clean (e, μ) final states:
– High efficiency and excellent resolution → enables precise differential measurements
– Requires tight control of backgrounds (top, fake leptons, and EW) and detector systematics for accuracy

τ final states:
- Enhanced sensitivity to flavour dependent New Physics
- limited by jet→τ fakes and missing neutrinos
- low efficiency and poor m_t resolution.



Relevant SMEFT operators

Four-fermion couplings

($\ell\ell qq$) operators dominate at tree level

and produce contact-interaction like deviations (especially at high m_{ll}).

Gauge-fermion couplings

modifications to gauge-fermion couplings, more precisely controlled in on-shell region

Gauge propagator

Shift in gauge bosons wave function

Dipole operators

Suppressed by fermion mass, effect can be probed in τ channel

Bosonic operators

Enter at one-loop level, theory calculations available [Phys. Rev. D 99, 035044]

Warsaw basis SMEFT at d=6

$\mathcal{L}_6^{(1)} - X^3$	
Q_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
$Q_{\widetilde{G}}$	$f^{abc}\widetilde{G}_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
Q_W	$\varepsilon^{ijk}W_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk}\widetilde{W}_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$

$\mathcal{L}_6^{(2)} - H^6$	
Q_H	$(H^\dagger H)^3$

$\mathcal{L}_6^{(3)} - H^4D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$

$\mathcal{L}_6^{(4)} - X^2H^2$	
Q_{HG}	$H^\dagger H\,G^a_{\mu\nu}G^{a\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\,\widetilde{G}^a_{\mu\nu}G^{a\mu\nu}$
Q_{HW}	$H^\dagger H\,W^i_{\mu\nu}W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\,\widetilde{W}^i_{\mu\nu}W^{i\mu\nu}$
Q_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$
Q_{HWB}	$H^\dagger\sigma^i H\,W^i_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\,\widetilde{W}^i_{\mu\nu}B^{\mu\nu}$

$\mathcal{L}_6^{(5)} - \psi^2H^3$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$\mathcal{L}_6^{(6)} - \psi^2XH$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\sigma^i H W^i_{\mu\nu}$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^a u_r)\widetilde{H}\,G^a_{\mu\nu}$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\sigma^i\widetilde{H}\,W^i_{\mu\nu}$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^a d_r)H\,G^a_{\mu\nu}$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\sigma^i H\,W^i_{\mu\nu}$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\,B_{\mu\nu}$

$\mathcal{L}_6^{(7)} - \psi^2H^2D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p\sigma^i\gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p\sigma^i\gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\sigma^i l_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$

$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^a u_r)(\bar{d}_s\gamma^\mu T^a d_t)$

$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{u}_s\gamma^\mu T^a u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{d}_s\gamma^\mu T^a d_t)$

$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^a u_r)\varepsilon_{jk}(\bar{q}_s^k T^a d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$

10.1007/JHEP 04 (2021) 073

$U(3)^5$ flavour symmetry : all generations affected by the same effect

Flavour assumptions and parameterisation

Relax symmetries →

	$U(3)^5$		topU3l		top		general	
	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$	all	$\not{CP}$
X^3	4	2	4	2	4	2	4	2
H^6	1	-	1	-	1	-	1	-
H^4D^2	2	-	2	-	2	-	2	-
X^2H^2	8	4	8	4	8	4	8	4
ψ^2H^3	6	3	10	5	14	7	54	27
ψ^2XH	16	8	28	14	36	18	144	72
ψ^2H^2D	9	1	15	2	21	2	81	30
$(\bar{L}L)(\bar{L}L)$	8	-	16	-	31	-	297	126
$(\bar{R}R)(\bar{R}R)$	9	-	27	2	40	2	450	195
$(\bar{L}L)(\bar{R}R)$	8	-	31	4	54	4	648	288
$(\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	14	7	40	20	64	32	810	405
tot	85	25	182	53	275	71	2499	1149

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- Parameterisation derived from SMEFTsim UFO, (LO SM), currently top scheme is the most popular as it allows for dedicated lepton operators in addition to dedicated operators for top and bottom quarks.

- All relevant d=6 operators are considered and parameterisation is derived for linear and quadratic terms

Experimentally disentangling operators

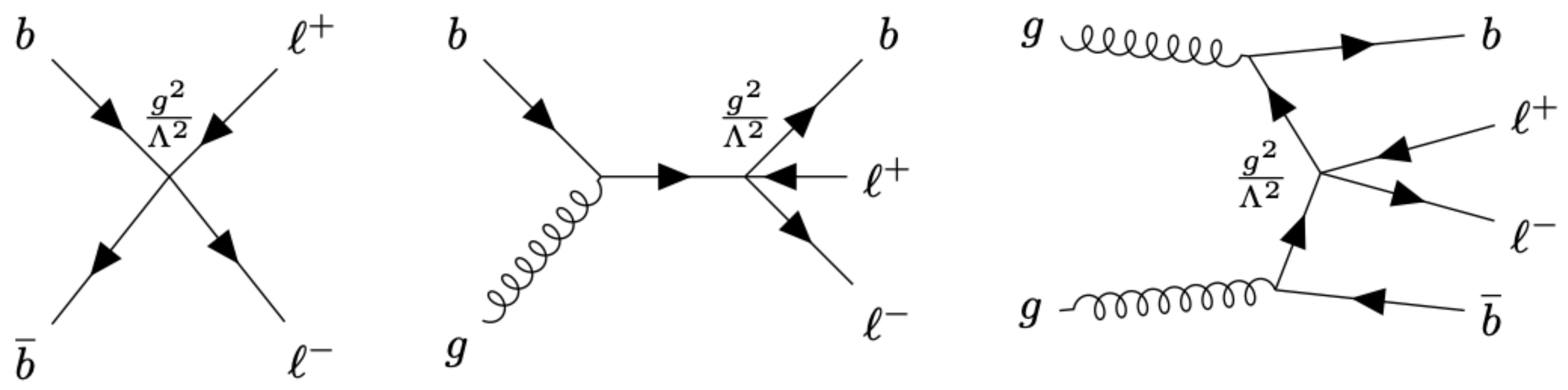
High-mass tails (m_{ll} / m_T): amplified sensitivity to four-fermion ($\ell\ell$qq) contact terms

Angular observables *($\cos\theta^*_{CS}$):* separate chiral structures (LL vs RR vs LR) and distinguish vector vs axial currents.

Charge asymmetries & lepton-flavor universality: W^+/W^- and e/μ/τ comparisons probe chiral and flavour structure

Multi-differential bins (m_{ll} vs $\cos\theta$,y_{ll}): break degeneracies between four-fermion operators and gauge coupling modifiers

Measuring in b-jet multiplicity: tagging b-jets in the final states allows to probe 4f fermion operators affecting b-quarks

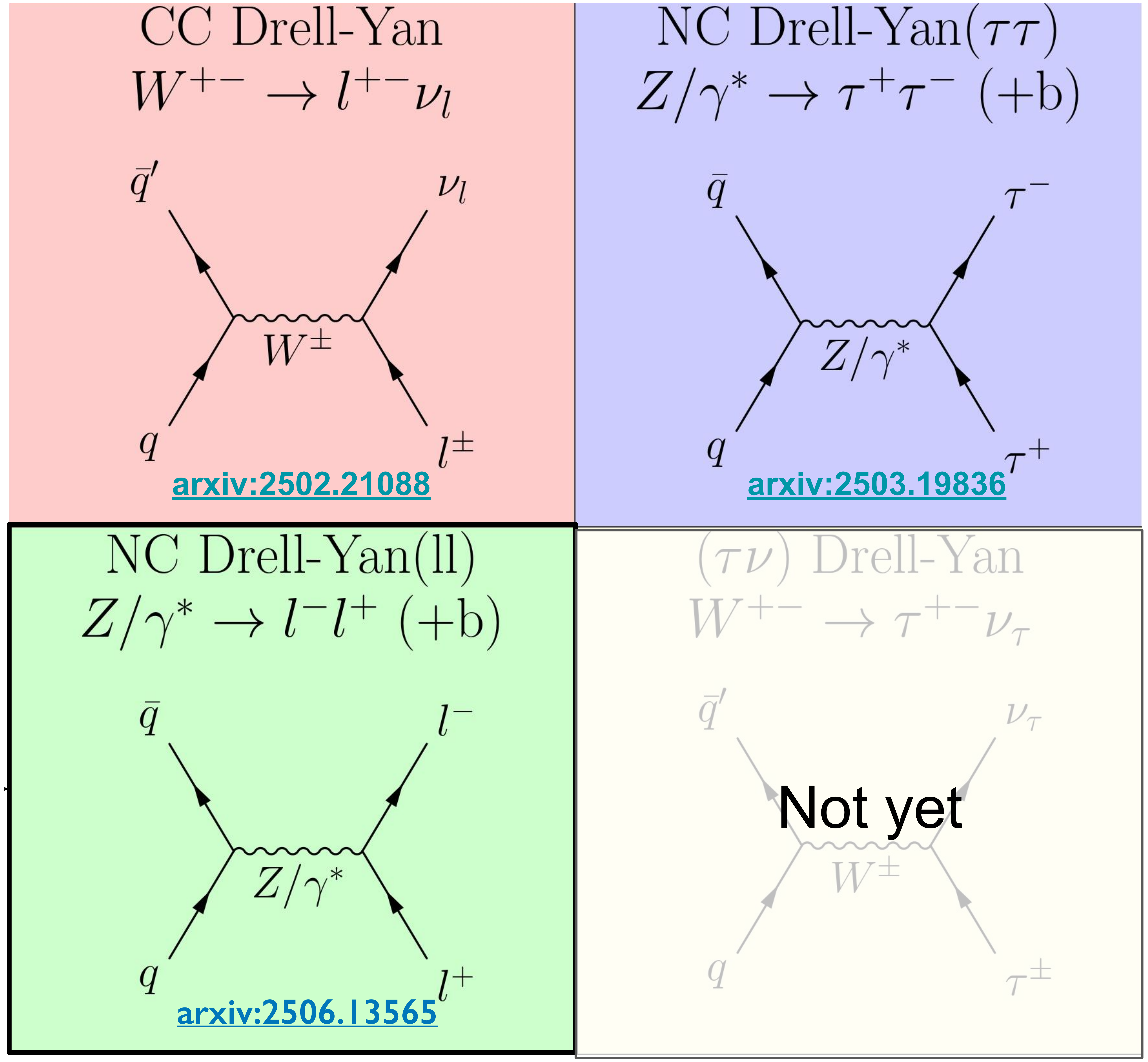


Physics Letters B, 807,2020.135541

τ polarization: dedicated **τ** polarisation can also be used to disentangle dipole operators and chiral combinations of four-fermion operators

Current HMDY measurements

- Searches performed with Run-2 dataset across all channels, already used for EFT interpretations for instance, in HighPT
- Next step, performing measurements to provide unfolded differential cross-sections
- Two recent results this year, both containing EFT interpretations
- NC HMDY for light-leptons being finalised and should be published soon
- CMS HMDY measurements pertaining to NC Drell-Yan(*ll*)
  i. 2103.02708 : di-lepton search includes unfolded ratio $R_{\mu\mu}/R_{ee}$
  ii. 2506.13565: di-lepton unfolded ratio as a function of b-jet multiplicity

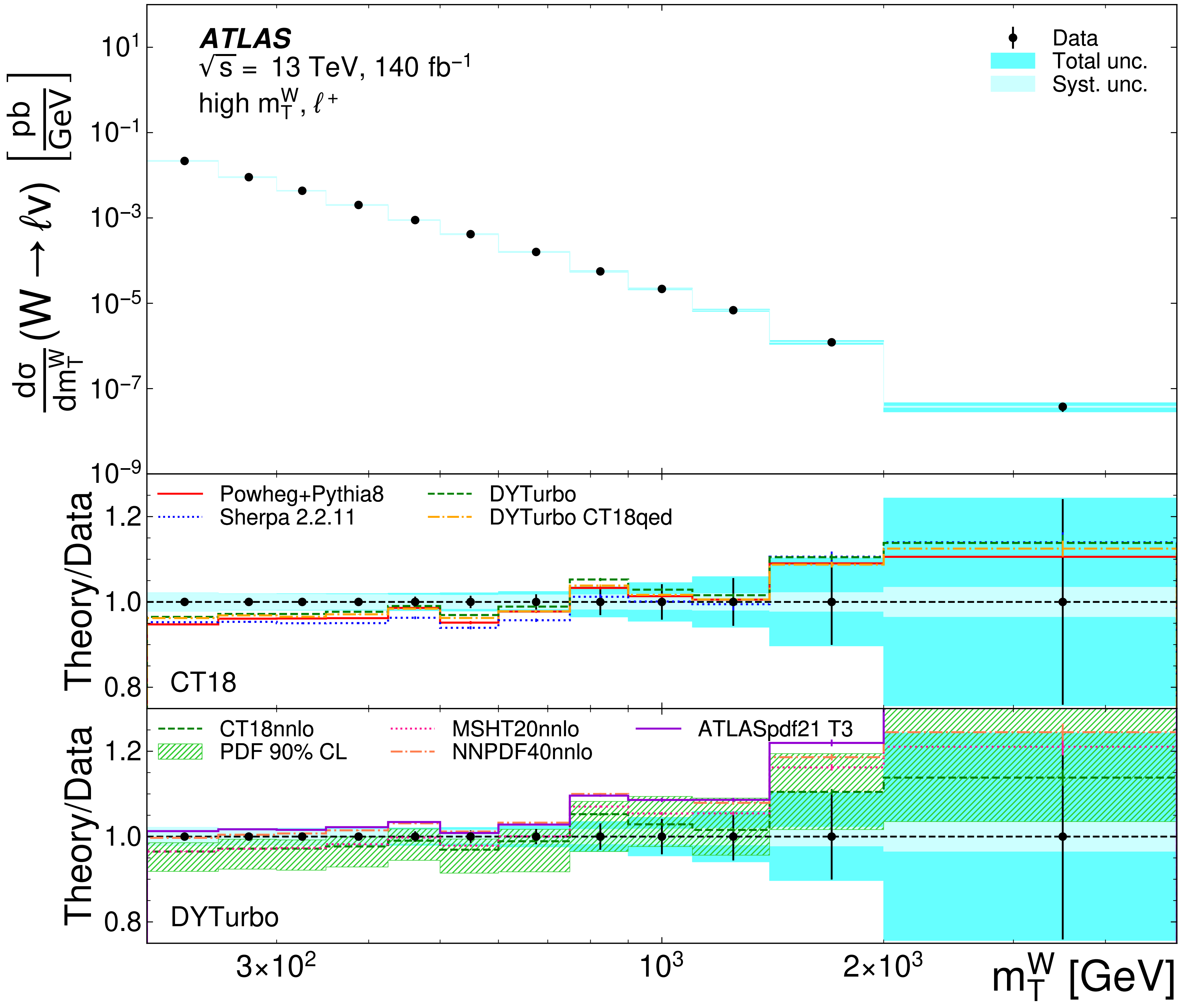


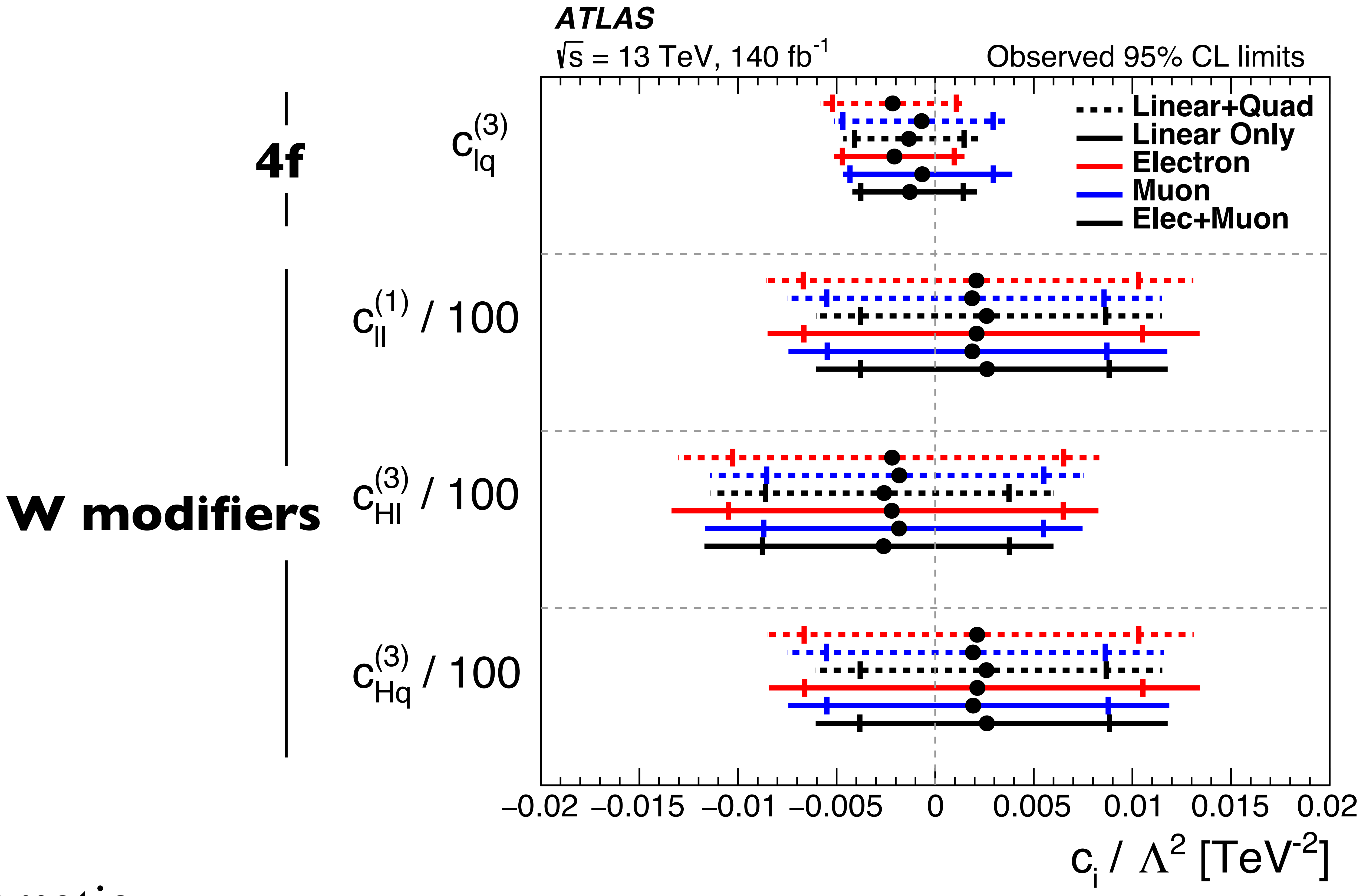
Charged-current HMDY with ATLAS

2502.21088

- Analysis provides unfolded cross-sections of m_T^W for $W^{\pm}$ and for $l = e, \mu$ and also as a function for lepton pseudo-rapidity $|\eta|$.

- EFT Interpretation performed for m_T^W observable, only affected by four SMEFT operators !



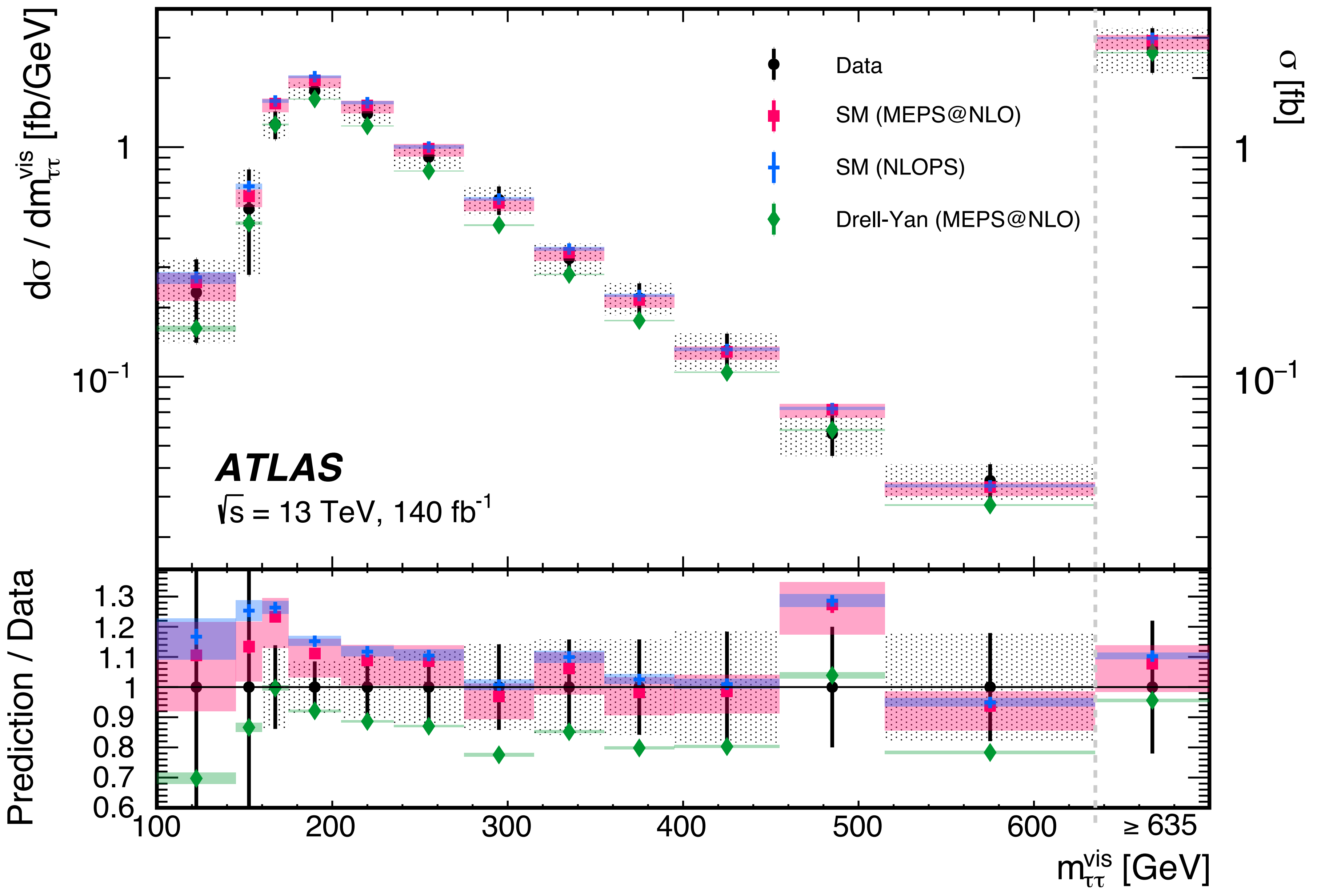


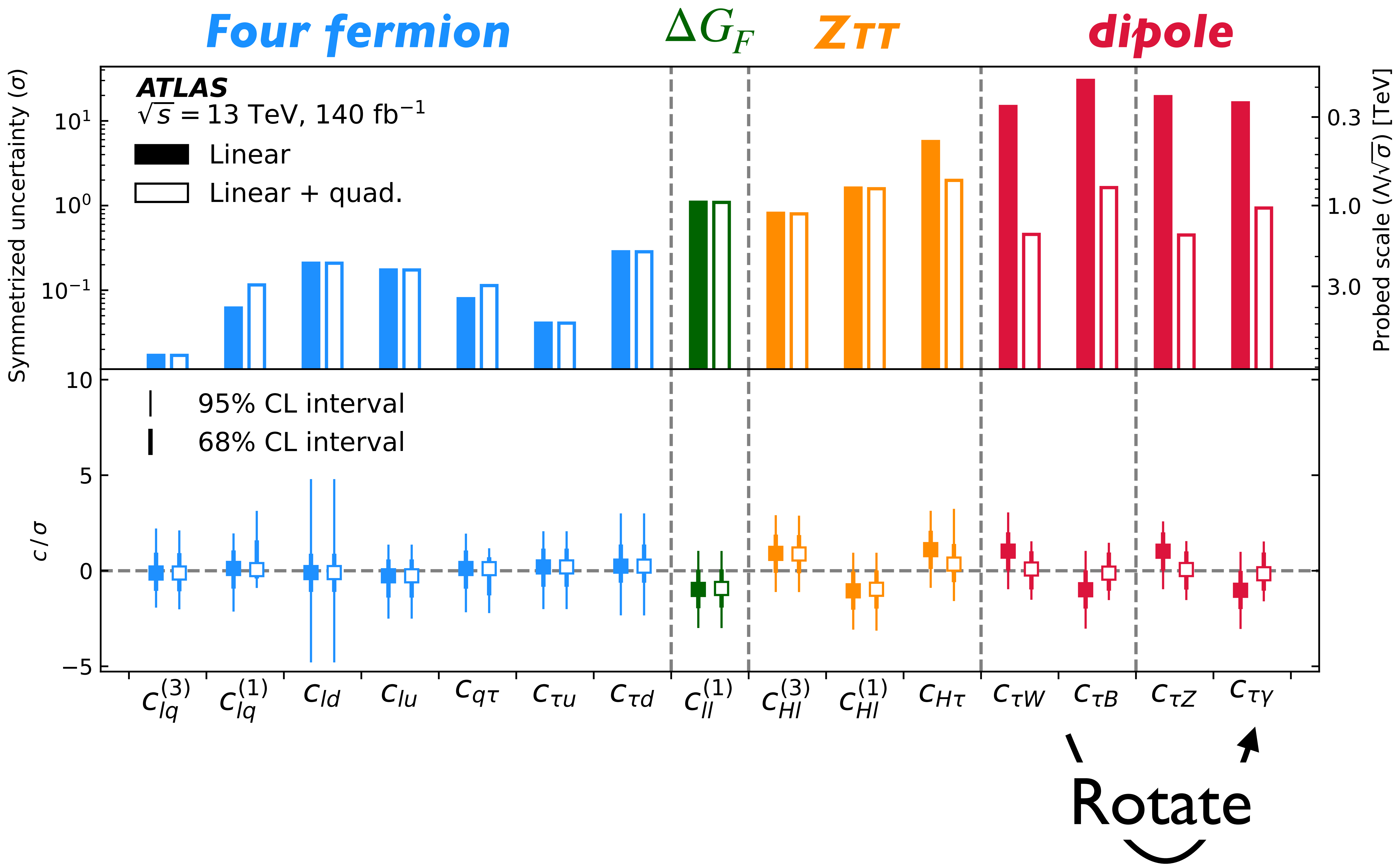
- PDF unc. on SM predictions are an important systematic
- Leading constraint on 4f fermion operators, important input for global fits

Neutral-current HMDY ($\tau\tau$) with ATLAS

2503.19836

- Analysis provides unfolded cross-sections of $m_{\tau\tau}^{vis}$ and also has dedicated leptoquark interpretation at reco. level
- Unfolded cross-sections used to set one-at-a-time constraints to all SMEFT operators affecting the process





- Direct handle on four-fermion operators containing ττ, and provides better constraint on τ-anomalous magnetic moment ($\propto \Re(c_{\tau\gamma})$) than dedicated photon-induced ττ measurement

SMEFT validity for Drell-Yan

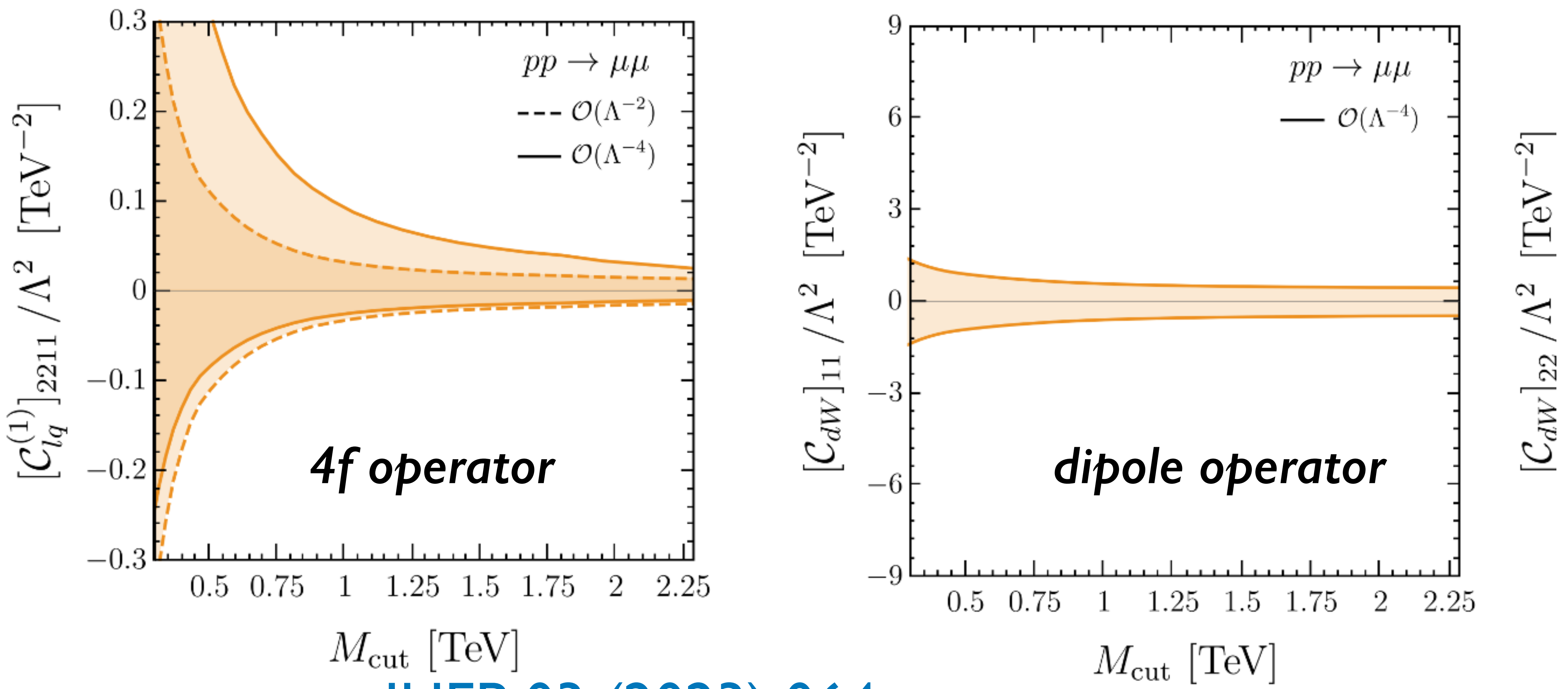
- *SMEFT fits typically assume scale of New Physics* $\Lambda = 1$ TeV, however Drell-Yan measurements probe region much higher than 1 TeV.

- For four-fermion operators, given the energy dependence, high-mass bins ends up driving the sensitivity despite lower experimental precision.

- No standard prescription on how to treat - different proposals from LHCEFTWG, documented in [CERN-LHCEFTWG-2021-002]

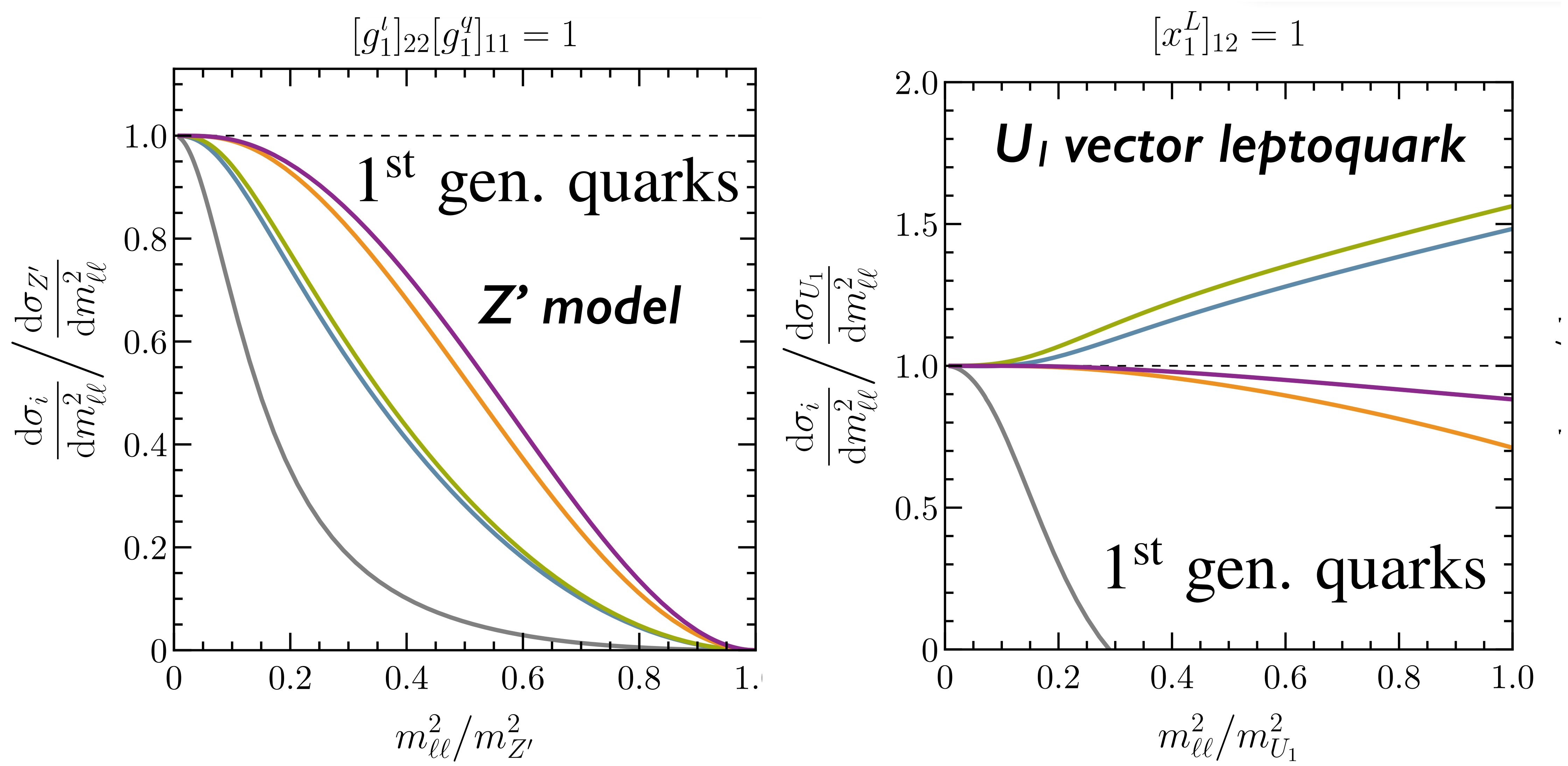
- Nice talk from Felix at EFT validity for Drell-Yan tails at LHCEFTWG ([link]) discussing source of contribution, EFT expansion (Λ^{-2} vs Λ^{-4}), and convergence for dedicated NP-models.

4f operators are mainly constrained by high-mass bins, unlike dipole operator



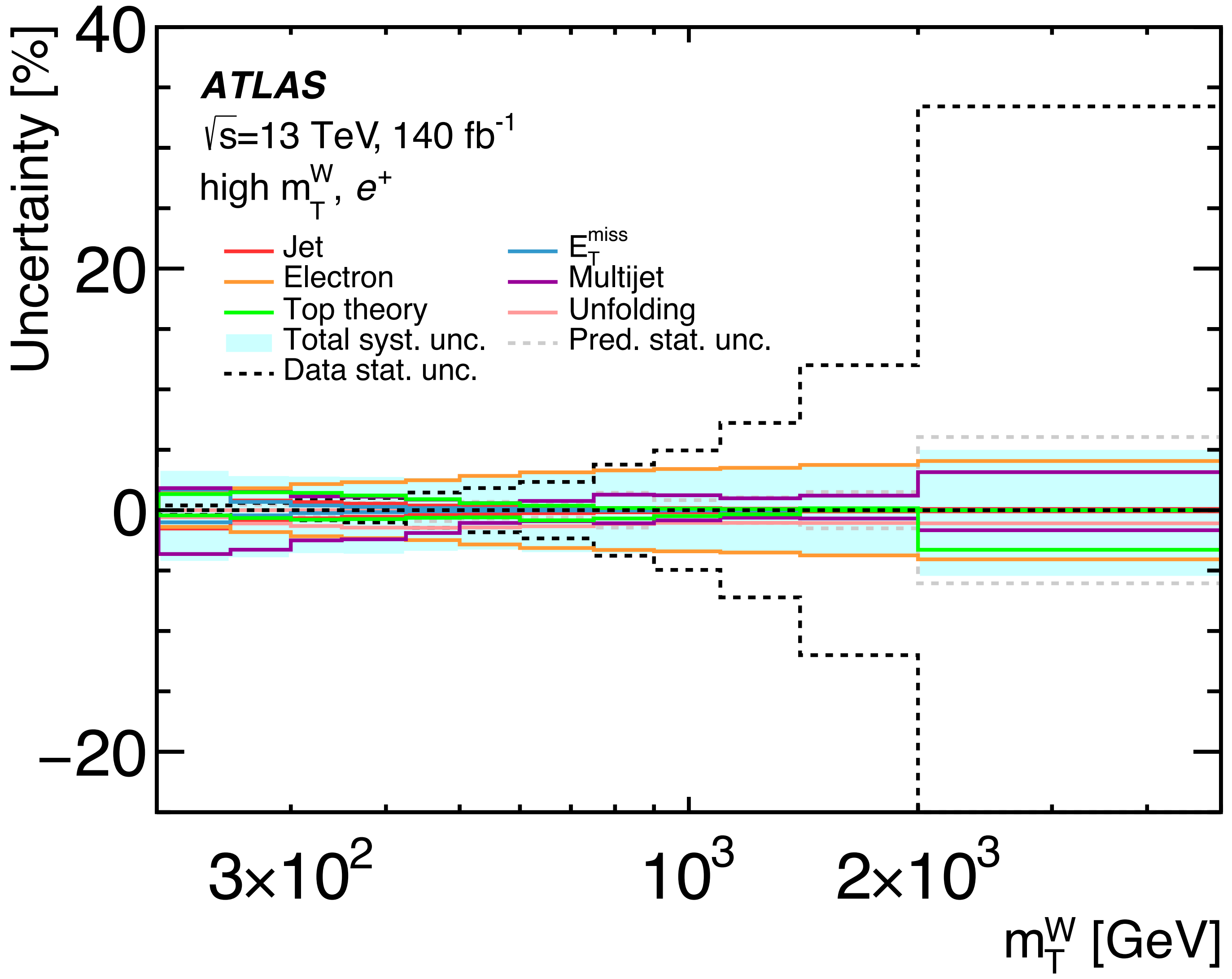
[JHEP 03 (2023) 064]

Matching to specific models to check for EFT validity



Improvements for future measurements

Unc. contribution Of m_T^W



(a)

- *While more data will improve the precision of the highest-mass bins, the rest of the spectrum requires improvement on experimental systematics sources*
- *Better feedback between unfolding observable choices and the EFT sensitivity can further help improve precision*
- *Better background handling : current background from physics process subtracted before unfolding - moving towards publish also more inclusive (in process) distributions would aid in handling better the SMEFT effects of different processes (top, diboson) that are considered as background*
- *Developing observables to separate different helicity operators will be crucial to disentangle 4f operators*
- *DrellYan measurements are also sensitive to PDF fits and could be handled consistently in a joint SMEFT+PDF fit*

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Conclusions

- HMDY measurements are an important input for SMEFT → crucial for 4-fermion operators, Searches have already been used as inputs for EFT fits, new suite of unfolded measurements underway.
  i. Charged current HMDY (light lepton) - allows to set stringent constraints on $clq^{(3)}$
  ii. Neutral current HMDY (ττ) - Allows to constrain τ-specific 4-fermion operators and τ-dipole moment operators
  iii. Neutral current HMDY (light lepton) - expected to set stringent constraints on a large set of 4-fermion operators

- Given the high-Q^2 of the measurement, additional complications regarding EFT validity - experimentalists needs recommendations from theorists, LHCEFTWG offers the opportunity to bring together the experts

- While Run-2 measurements are being consolidated and the EFT interpretation are treated as post-hoc, future measurements can be designed to help gain better EFT sensitivity.

Thank you !