A combined analysis of Higgs and top quark data within the Standard Model Effective Field Theory

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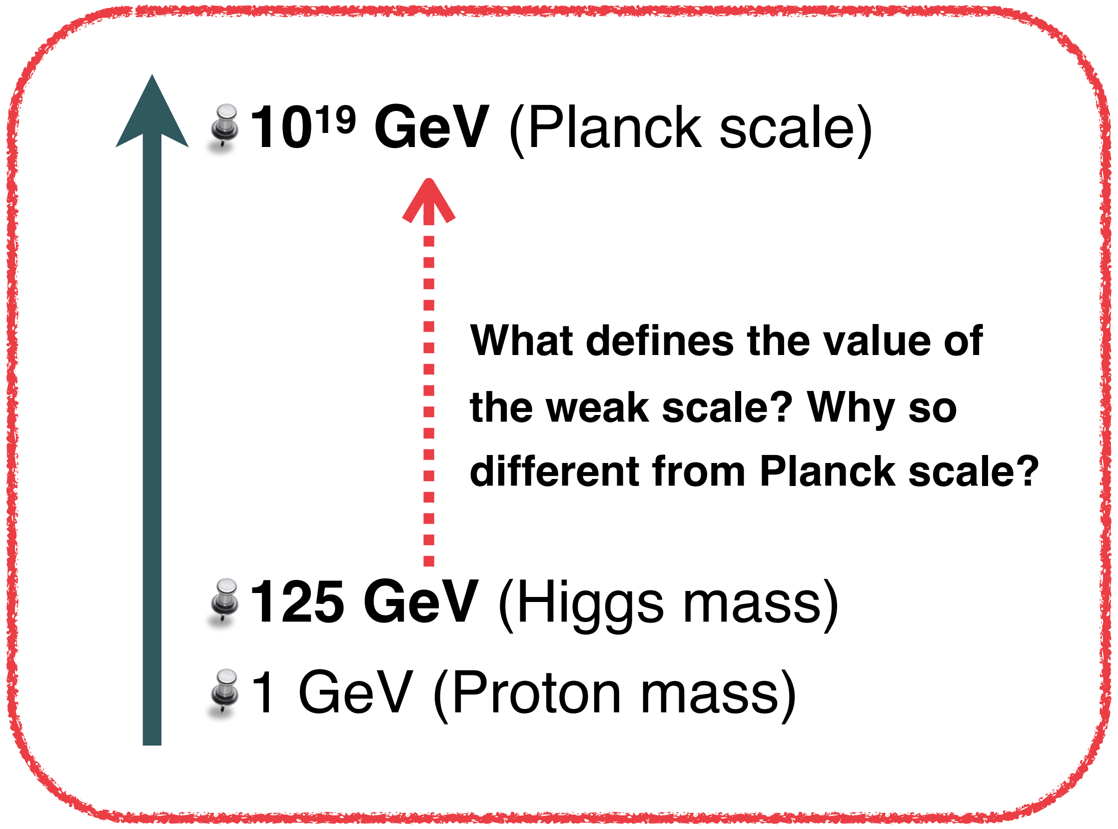
Particle physics in the LHC precision era

Open questions in particle physics

The Higgs boson

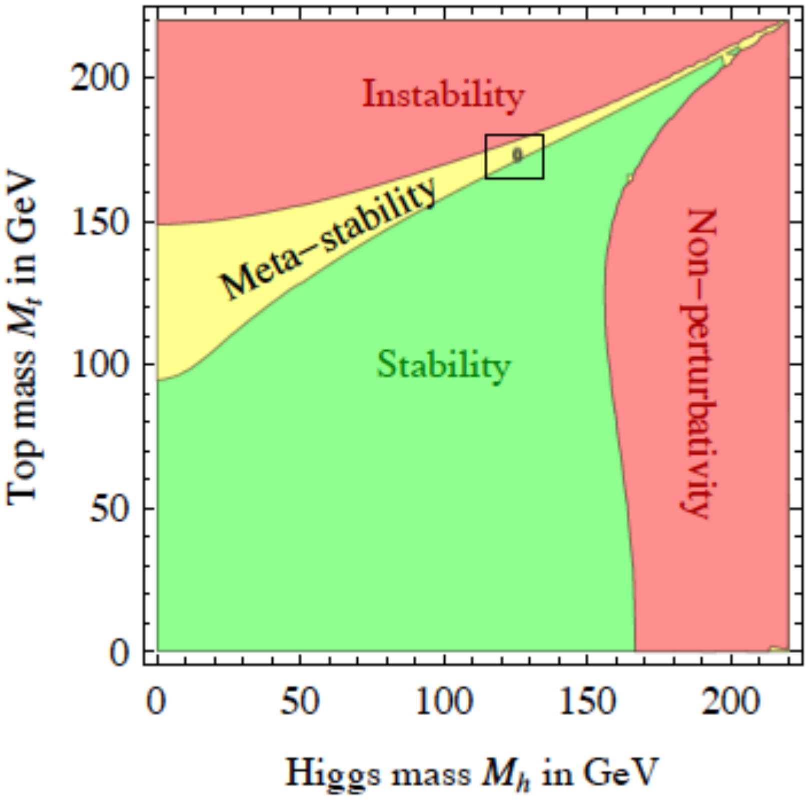
- Huge gap between **weak** and **Plank scales?**
- **Compositeness**? Non-minimal Higgs sector?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?

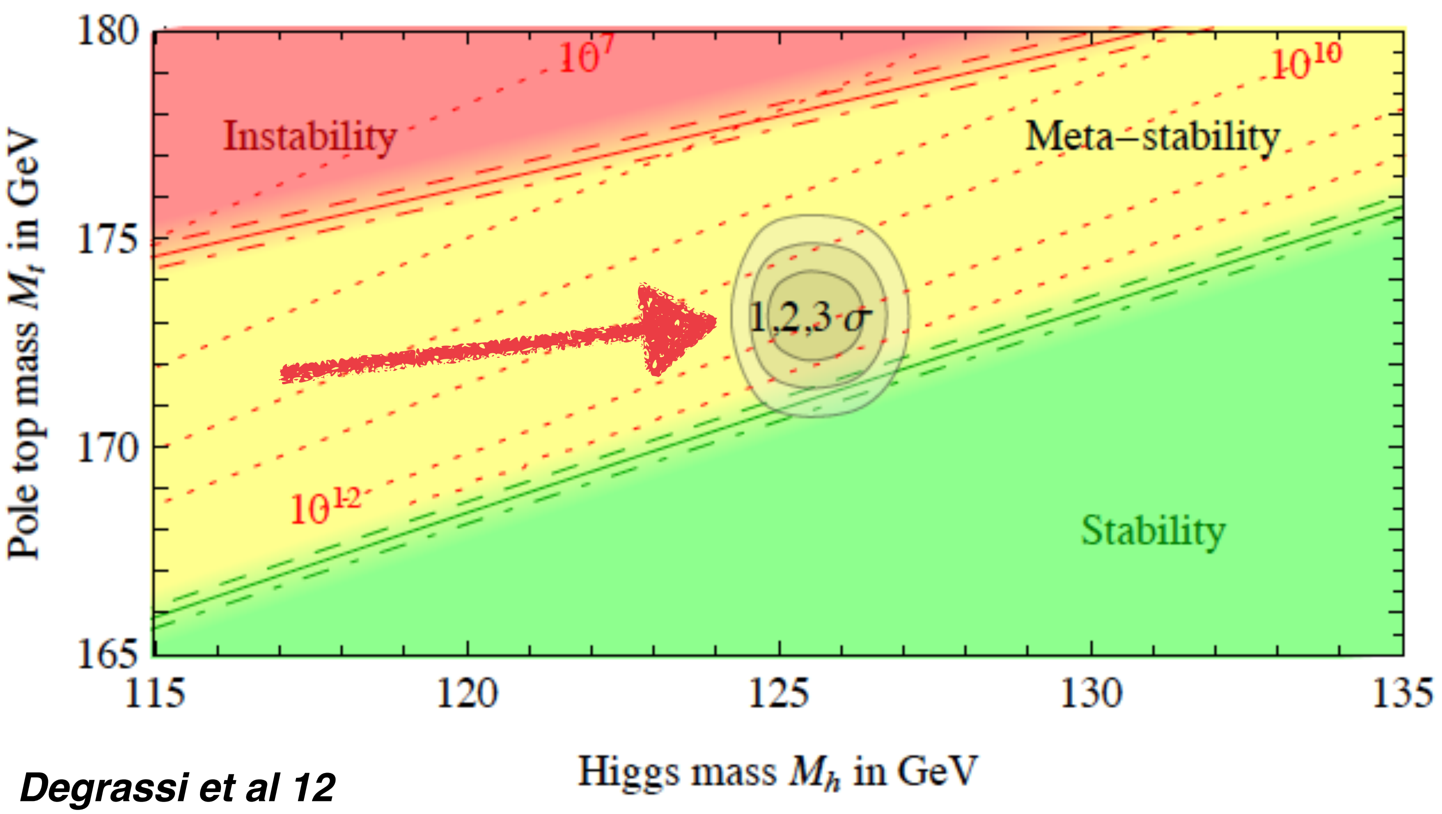


- **10^{19} GeV** (Planck scale)

What defines the value of the weak scale? Why so different from Planck scale?

- **125 GeV** (Higgs mass)
- 1 GeV (Proton mass)





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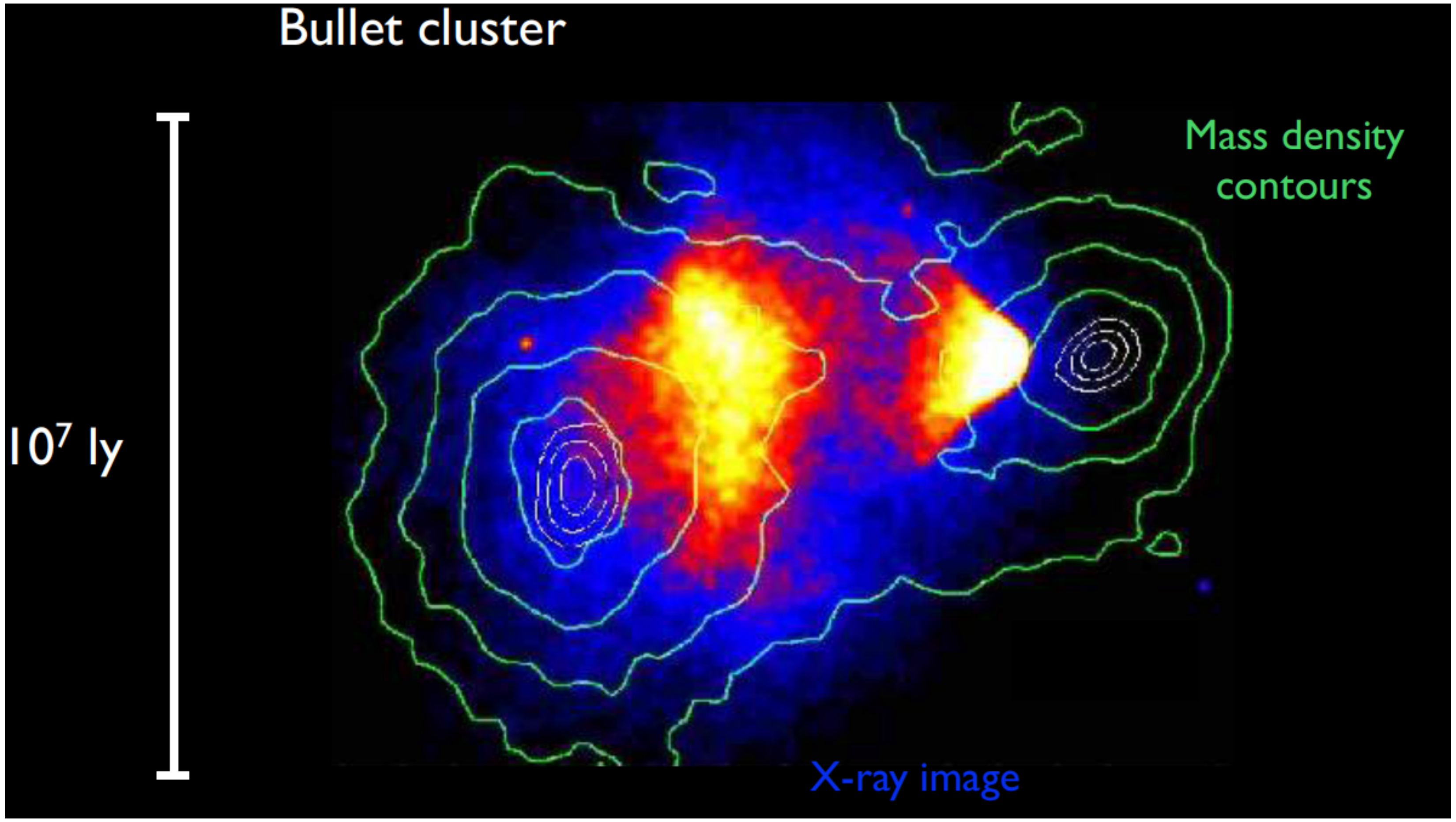
Dark matter

- **Weakly interacting massive particles**? Neutrinos? Ultralight particles (axions)?
- **Interactions** with SM particles? Self-interactions?
- **Structure** of the Dark Sector?



Open questions in particle physics

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Quarks and leptons

- Why **3 families?** Origin of **masses, mixings**?
- Origin of **Matter-Antimatter asymmetry?**
- Lepton Flavour **Universality?**
- Origin of **neutrino masses?** Are neutrinos Majorana or Dirac?

Dark matter

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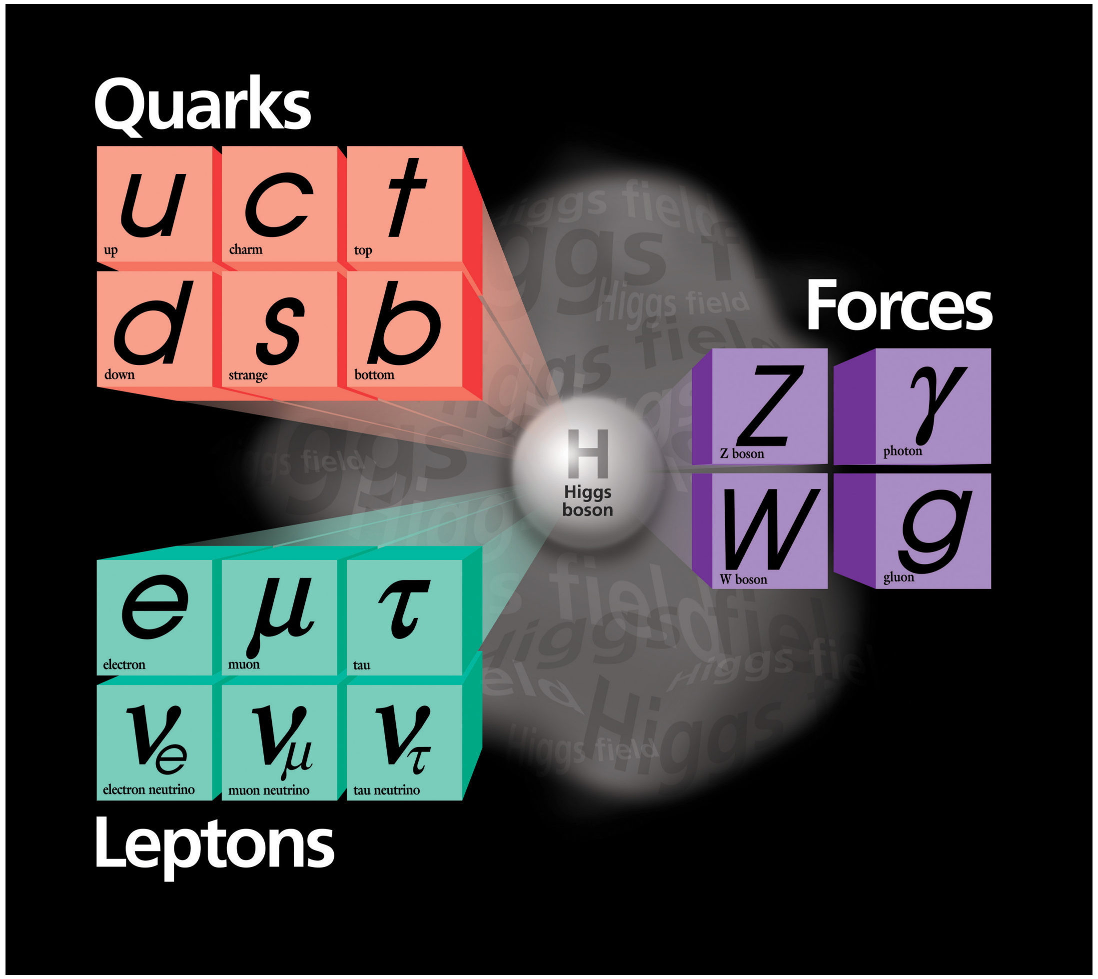
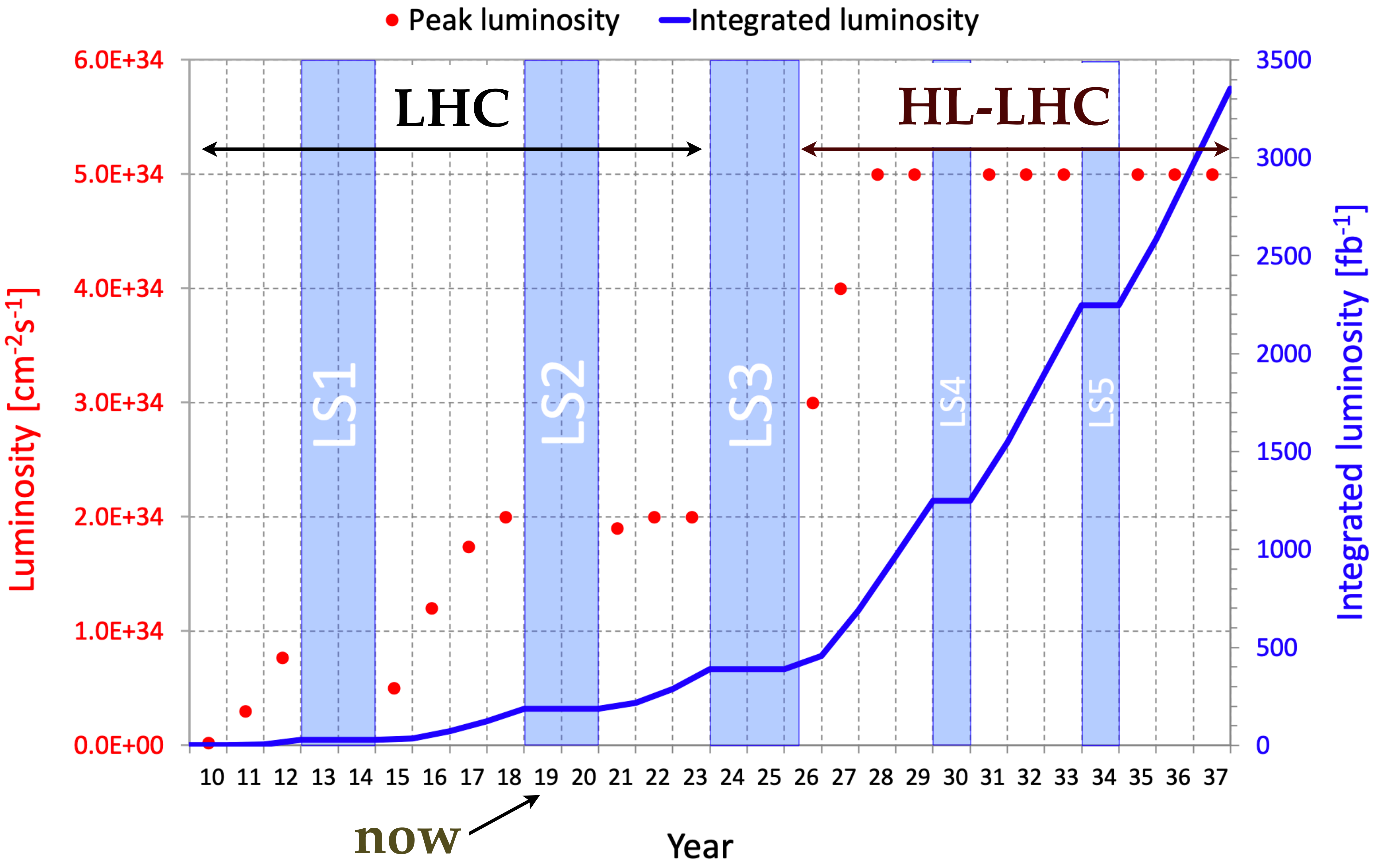


Open questions in particle physics

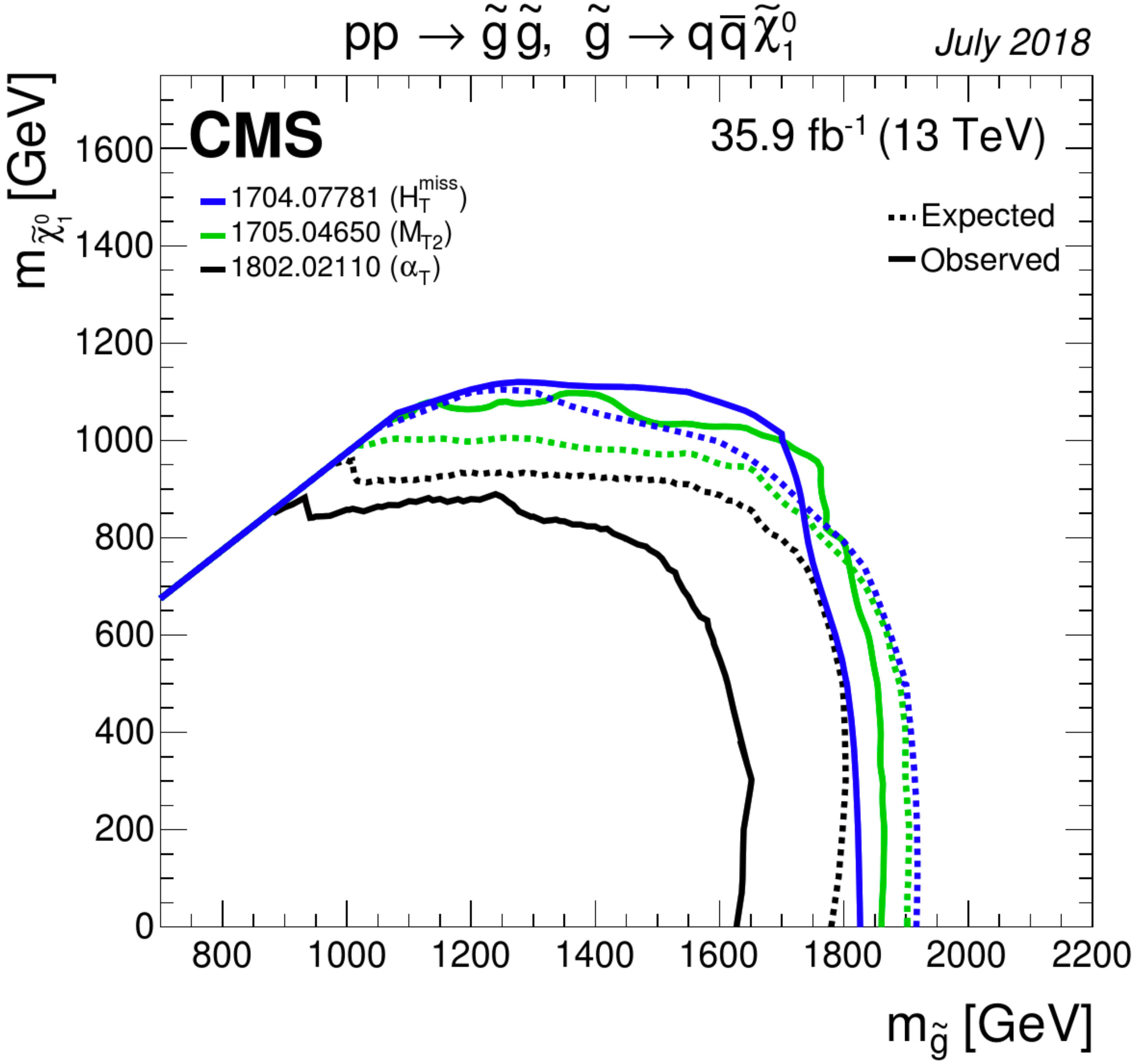


Crucial information on these fundamental questions will be provided by the LHC: the **exploration of the high-energy frontier** has just started!

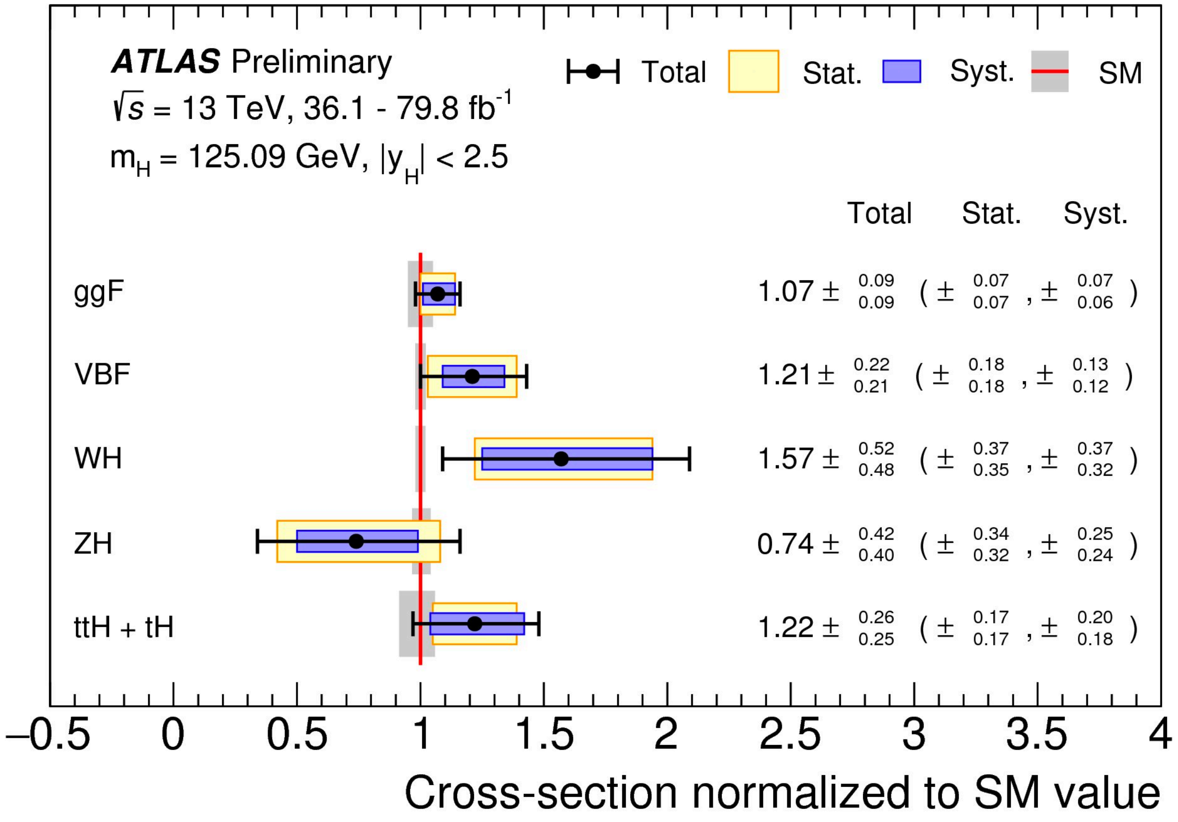
The quest for New Physics at the LHC

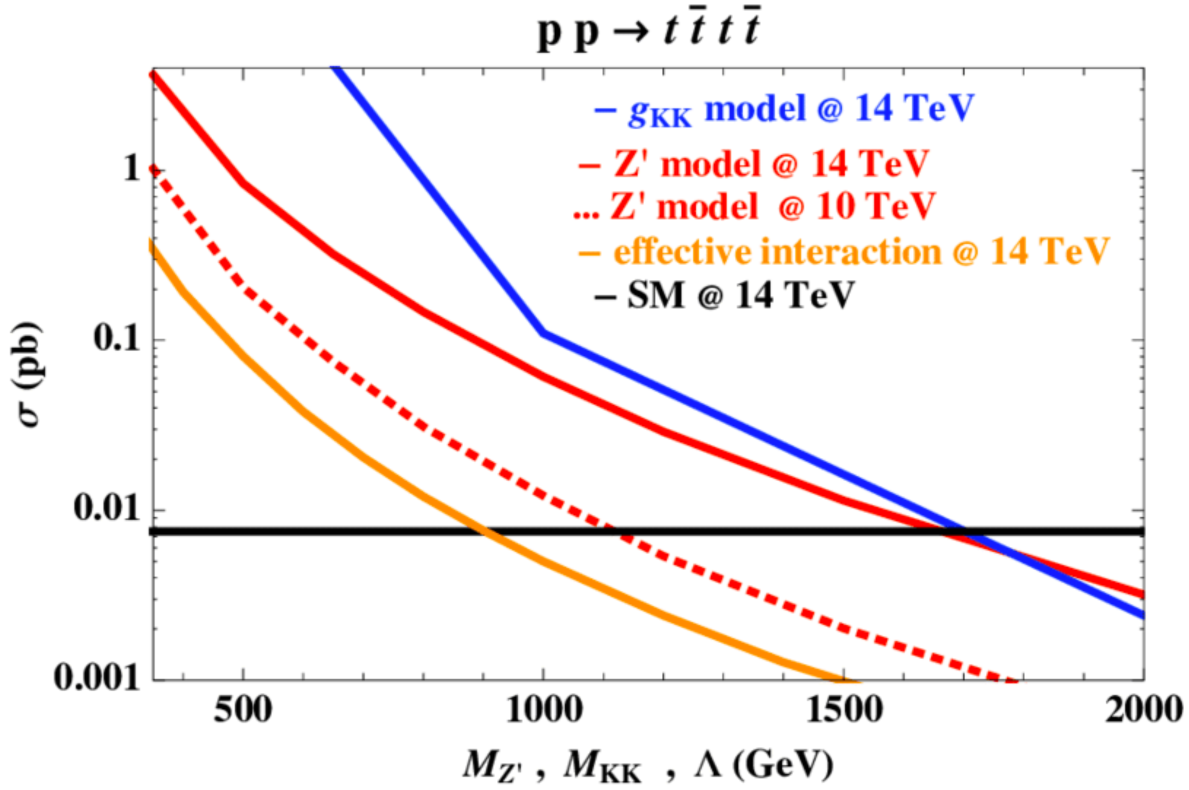
Model-Dependent Searches

- ☑ Map parameter space of **specific theories**, or specific realisations of theories (SUSY, Higgs compositeness, …)
- ☑ **Reinterpretation/recasting** challenging, since requires Monte Carlo showering, detector simulation, …
- ☑ Ad-hoc **restrictions of the BSM parameter space** to facilitate interpretation
- ☑ Sensitive to **O(1) deviations**



The quest for New Physics at the LHC





Model-Independent Searches

☑ ``**SM'' measurements** to constrain BSM

☑ Allows the use of **highest possible precision** in theory calculations

☑ Interpreted in **multiple BSM frameworks** (including those not thought of yet!)

☑ In the long-term, measurements have the **largest impact** in the HEP community

☑ Sensitive to **O(0.1) or O(0.01) deviations** (or even better!)

Outline

- The Standard Model as an Effective Field Theory
- SMEFiT: the top quark case

  arXiv:1901.05965 (JHEP)

- Towards a global SMEFT analysis of Higgs, gauge, and top quark data

  in preparation

- Constraining the SMEFT with Bayesian inference

  arXiv:1906.05296

- Can New Physics hide inside the proton? Joint PDF+SMEFT fits

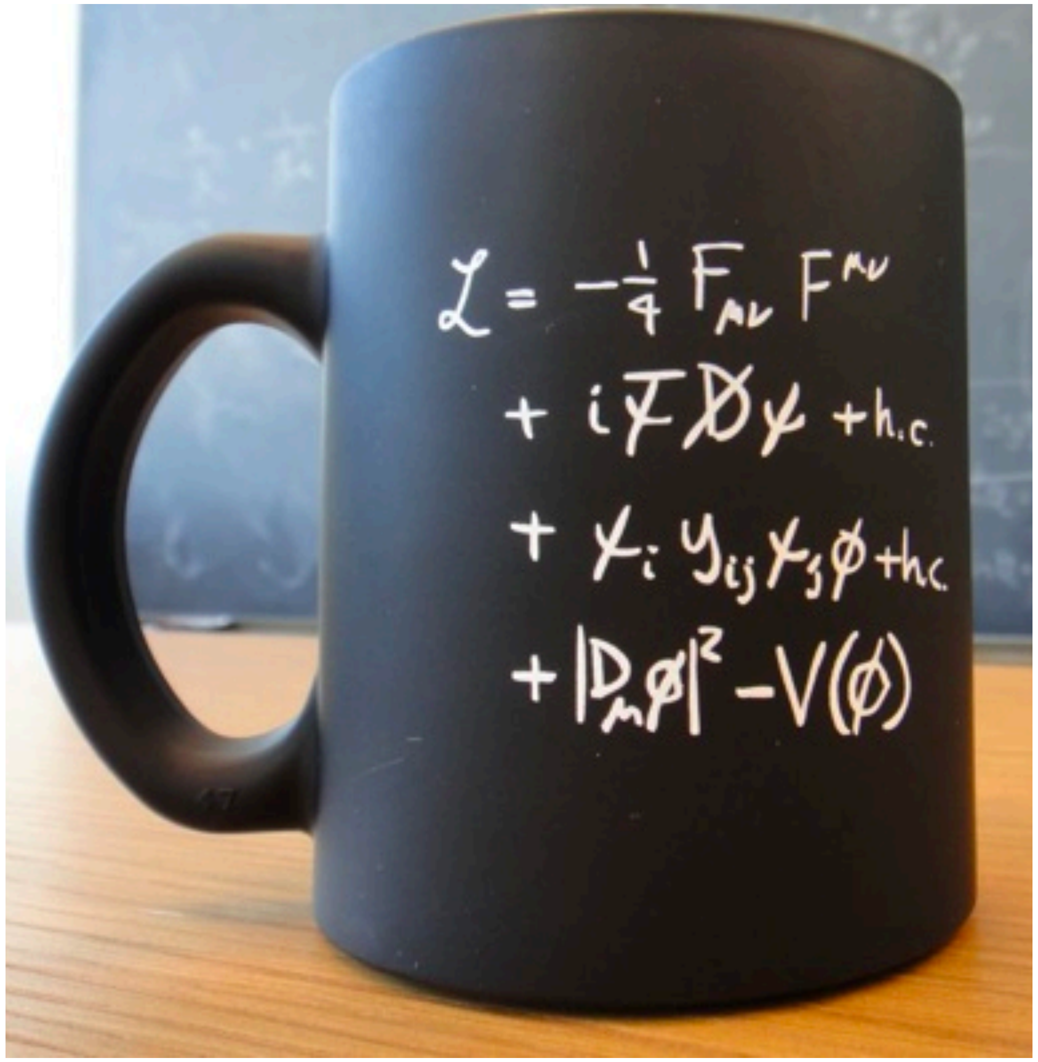
  arXiv:1905.05215 (PRL)

SMEFT: the new Standard Model

The Standard Model

The Standard Model is defined by:

- **Particle (matter) content**: quarks and leptons
- **Gauge** (local) symmetries and their eventual breaking mechanisms
- Global symmetries: **Lorentz** invariance
- Renormalizablity: validity up to **arbitrarily high scales**



$$\mathscr{L}_{\rm SM} = \sum_i c_i \mathcal{O}_i^{(d4)}$$

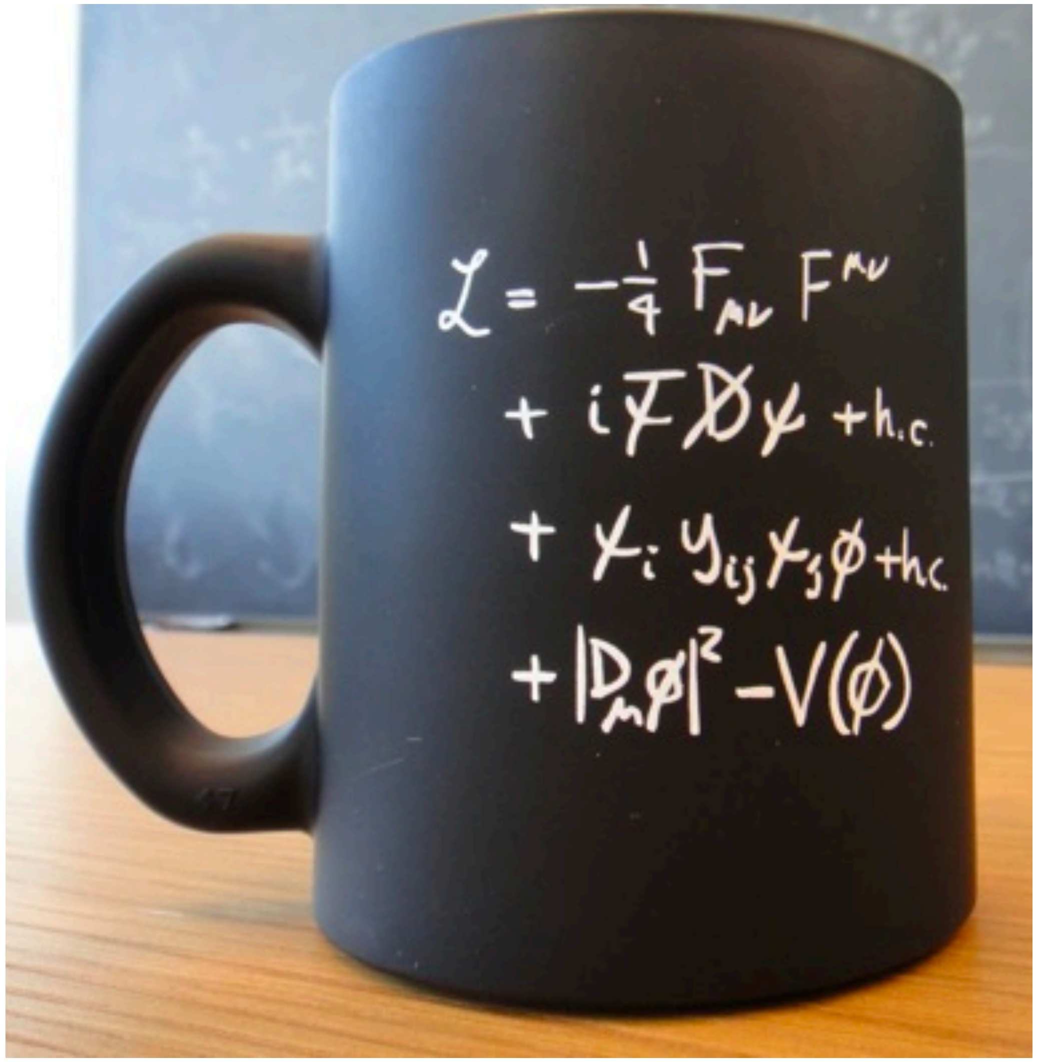
dimensionless couplings
(before EWS breaking)

All possible operators of **mass-dimension <=4**
consistent with above requirements

The Standard Model as an EFT

The Standard Model EFT is defined by:

- **Particle (matter) content**: quarks and leptons
- **Gauge** (local) symmetries and their eventual breaking mechanisms
- Global symmetries: **Lorentz** invariance
- **Validity only up to certain energy scale Λ**



$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathscr{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^2} \mathscr{O}_i^{(8)} + \ldots$$

All possible operators of **mass-dimension 6** consistent with above requirements

All possible operators of **mass-dimension 8** consistent with above requirements

focus here on LHC physics: dim-5 and dim-7 not relevant since violate either L or B

Why the SMEFT?

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^2}\mathcal{O}_i^{(8)} + \ldots$$

☑ The SMEFT is the **low-energy limit** of generic UV-complete theories at high energies

☑ **Complete basis** at any given mass-dimension: systematic parametrisation of BSM effects

☑ **Fully renormalizable**, full-fledged QFT: can compute higher orders in QCD and EW

☑ Can be matched to **any BSM model** that reduces to the SM at low energies: exploits the full power of SM ``measurements" for model-independent BSM searches

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The SMEFT is not some new theory: **it is the SM** once we remove the **theoretical prejudice** of its validity up to arbitrarily large scales

The Standard Model EFT

Systematic parametrisation of the **theory space** in vicinity of Standard Model

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^2}\mathcal{O}_i^{(8)} + \ldots$$

- Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

$$\sigma(E) = \sigma_{\rm SM} \times (E)\left(1 + \sum_i^{N_{d6}} \omega_i \frac{c_i\, v^2}{\Lambda^2} + \sum_i^{N_{d6}} \widetilde{\omega}_i \frac{c_i\, E^2}{\Lambda^2} + \mathcal{O}\left(\Lambda^{-4}\right)\right)$$

The Standard Model EFT

Systematic parametrisation of the **theory space** in vicinity of Standard Model

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^2}\mathcal{O}_i^{(8)} + \dots$$

- Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

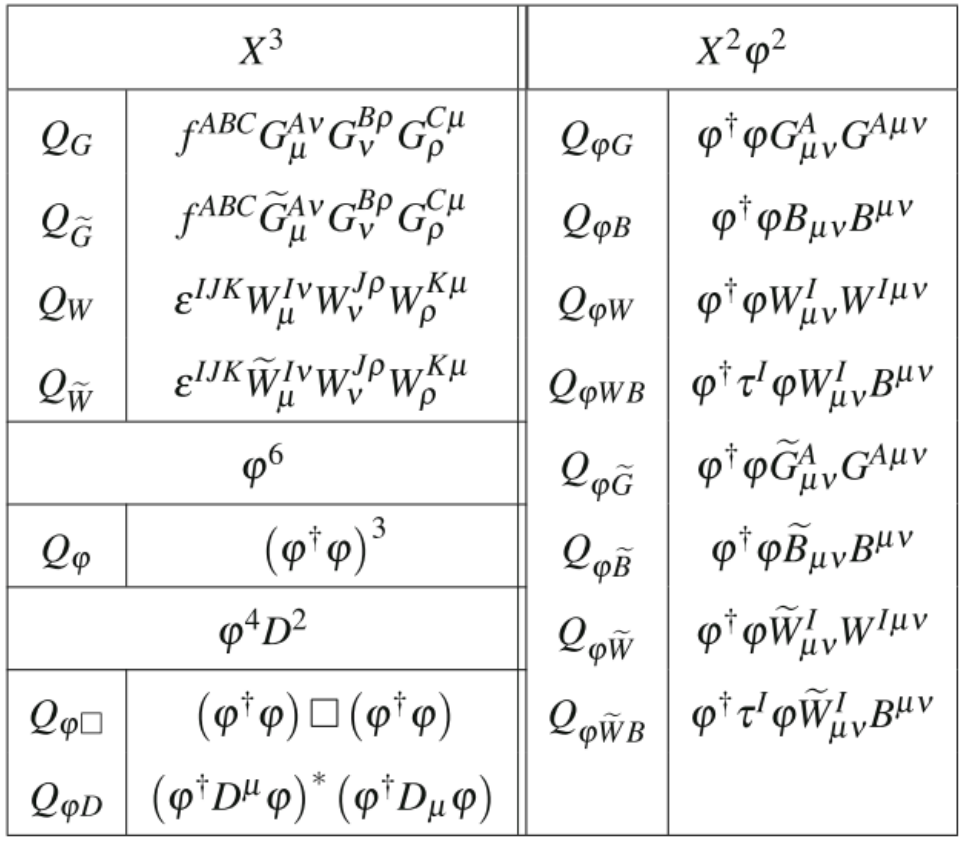
$$\sigma(E) = \sigma_{\mathrm{SM}} \times (E)\left(1 + \sum_{i}^{N_{d6}} \omega_i \underbrace{\frac{c_i\, v^2}{\Lambda^2}}_{\text{well constrained from LEP}} + \sum_{i}^{N_{d6}} \widetilde{\omega}_i \underbrace{\frac{c_i\, E^2}{\Lambda^2}}_{\text{enhanced sensitivity from TeV-scale processes: unique feature of LHC}} + \mathcal{O}\left(\Lambda^{-4}\right)\right)$$

well constrained from LEP

*enhanced sensitivity from **TeV-scale processes:** unique feature of LHC*

The Standard Model EFT

- The number of SMEFT operators is large: **59 non-redundant operators at dimension 6** for one fermion generation, **2499 operators** without any flavour assumption
- A global SMEFT analysis needs to explore a **huge complicated parameter space**

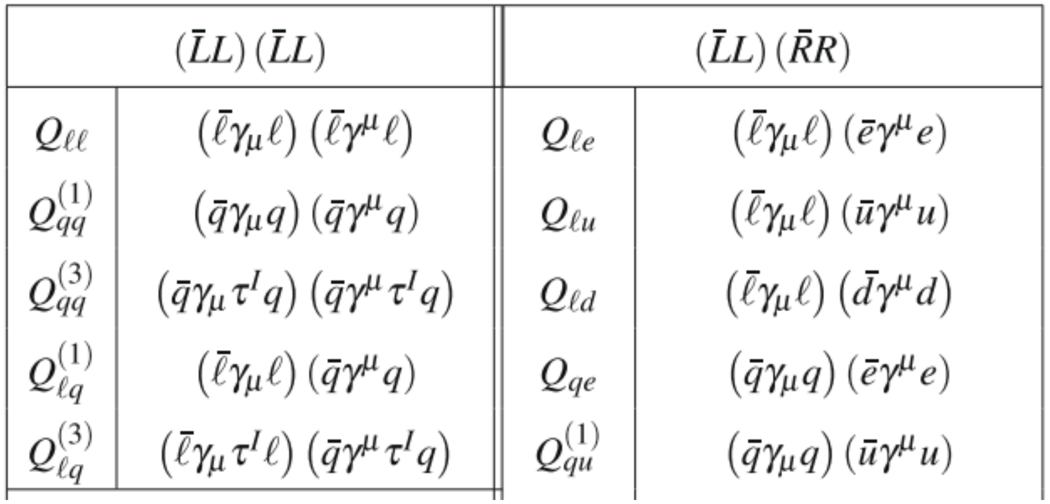


X^3		$X^2\varphi^2$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi G}$	$\varphi^\dagger\varphi G^A_{\mu\nu}G^{A\mu\nu}$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi B}$	$\varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu}$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi W}$	$\varphi^\dagger\varphi W^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi W^I_{\mu\nu}B^{\mu\nu}$
φ^6		$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$
Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\widetilde{B}_{\mu\nu}B^{\mu\nu}$
φ^4D^2		$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$		

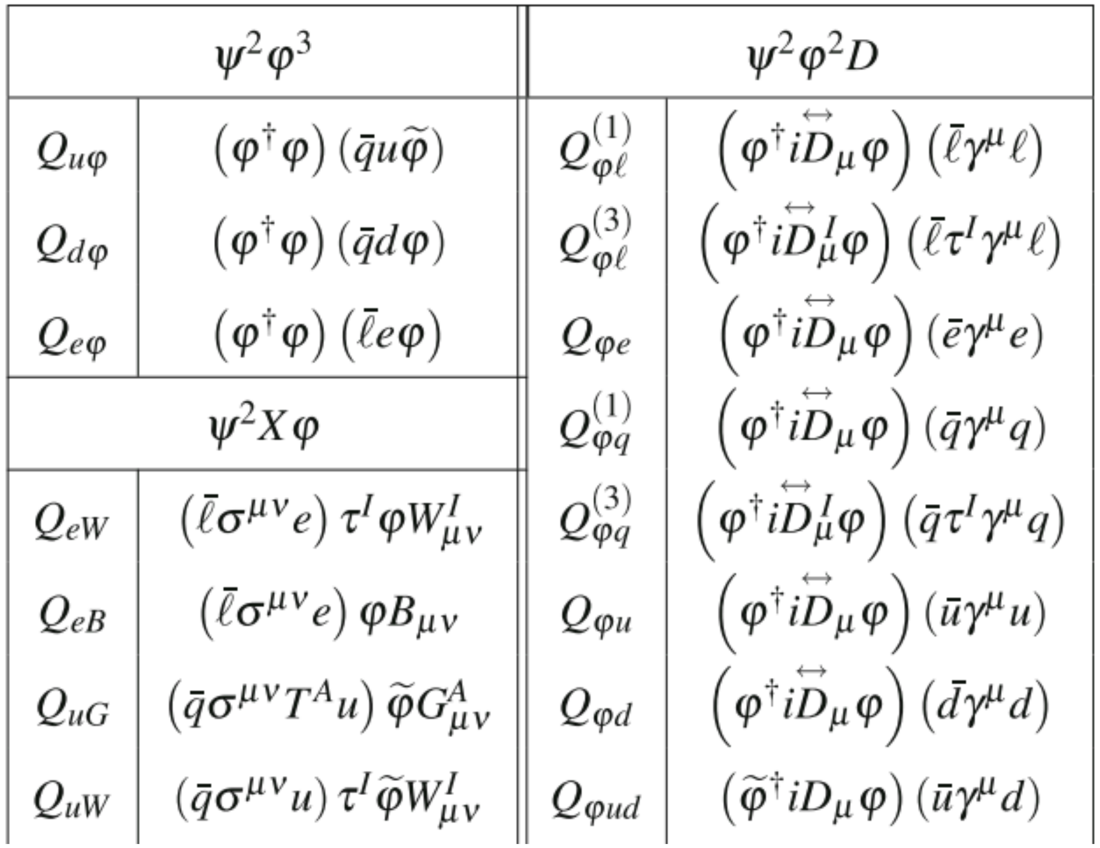
pure bosonic

four-fermion operators

bosonic-fermionic



$(\bar{L}L)(\bar{L}L)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{\ell\ell}$	$(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)$	$Q_{\ell e}$	$(\bar\ell\gamma_\mu\ell)(\bar e\gamma^\mu e)$
$Q_{qq}^{(1)}$	$(\bar q\gamma_\mu q)(\bar q\gamma^\mu q)$	$Q_{\ell u}$	$(\bar\ell\gamma_\mu\ell)(\bar u\gamma^\mu u)$
$Q_{qq}^{(3)}$	$(\bar q\gamma_\mu\tau^I q)(\bar q\gamma^\mu\tau^I q)$	$Q_{\ell d}$	$(\bar\ell\gamma_\mu\ell)(\bar d\gamma^\mu d)$
$Q_{\ell q}^{(1)}$	$(\bar\ell\gamma_\mu\ell)(\bar q\gamma^\mu q)$	Q_{qe}	$(\bar q\gamma_\mu q)(\bar e\gamma^\mu e)$
$Q_{\ell q}^{(3)}$	$(\bar\ell\gamma_\mu\tau^I\ell)(\bar q\gamma^\mu\tau^I q)$	$Q_{qu}^{(1)}$	$(\bar q\gamma_\mu q)(\bar u\gamma^\mu u)$

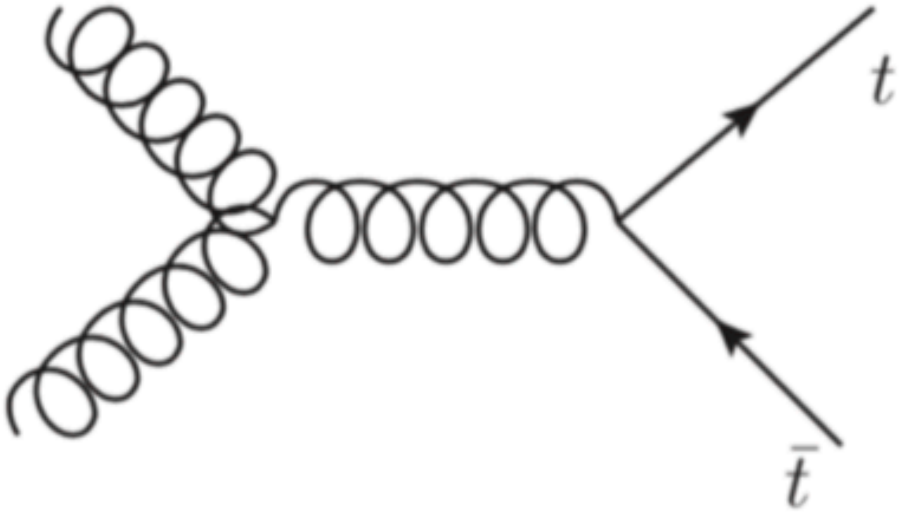


$\psi^2\varphi^3$		$\psi^2\varphi^2D$	
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q u\widetilde\varphi)$	$Q_{\varphi\ell}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar\ell\gamma^\mu\ell)$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q d\varphi)$	$Q_{\varphi\ell}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar\ell\tau^I\gamma^\mu\ell)$
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar\ell e\varphi)$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e\gamma^\mu e)$
$\psi^2X\varphi$		$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q\gamma^\mu q)$
Q_{eW}	$(\bar\ell\sigma^{\mu\nu}e)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q\tau^I\gamma^\mu q)$
Q_{eB}	$(\bar\ell\sigma^{\mu\nu}e)\varphi B_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u\gamma^\mu u)$
Q_{uG}	$(\bar q\sigma^{\mu\nu}T^A u)\widetilde\varphi G^A_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d\gamma^\mu d)$
Q_{uW}	$(\bar q\sigma^{\mu\nu}u)\tau^I\widetilde\varphi W^I_{\mu\nu}$	$Q_{\varphi ud}$	$(\widetilde\varphi^\dagger iD_\mu\varphi)(\bar u\gamma^\mu d)$

SMEFT effects in top quark pair production

Standard Model

‡$O_{uG}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} T^A u_j)\, \tilde{\varphi} G^A_{\mu\nu}$,



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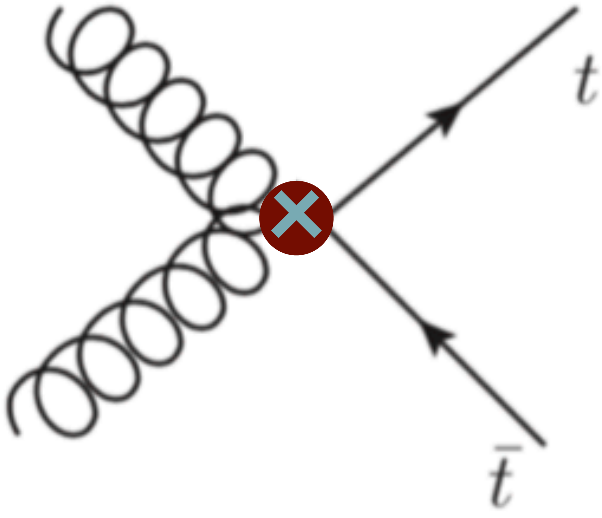


$$= \sigma_{SM} \times \left(1 + a\frac{c_{tG}}{\Lambda^2} + b\frac{c_{tG}^2}{\Lambda^4}\right)$$

SM: N(NLO) QCD

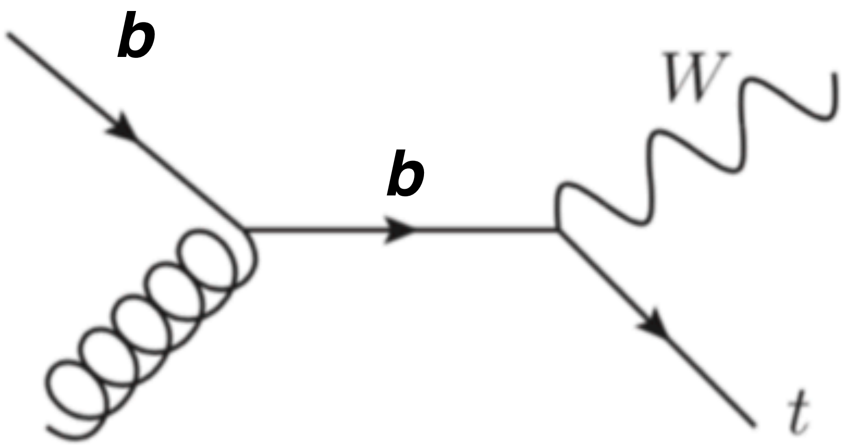
interference

squared

SMEFT effects in single top production

Standard Model

$O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\, \tilde{\varphi} W^I_{\mu\nu}$



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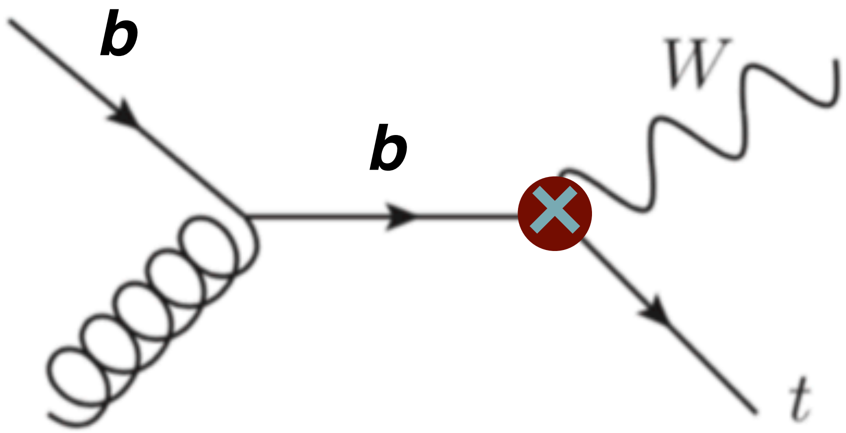


$$= \sigma_{SM} \times \left(1 + a\frac{c_{tW}}{\Lambda^2} + b\frac{c_{tW}^2}{\Lambda^4} \right)$$

SM: N(NLO) QCD **interference** **squared**

Recipe for a global SMEFT analysis

Theory

(N)NLO QCD + NLO EW for SM xsecs

NLO QCD for SMEFT contributions

State-of-the-art **Parton Distributions**

Data

Higgs and **gauge boson** production

Top quark and **jet** production

Precision **LEP**, **low energy**, **flavour, ….**

Global SMEFT fit

Bounds can be compared with

specific UV completions

New data incorporated without redoing fit

Delivery

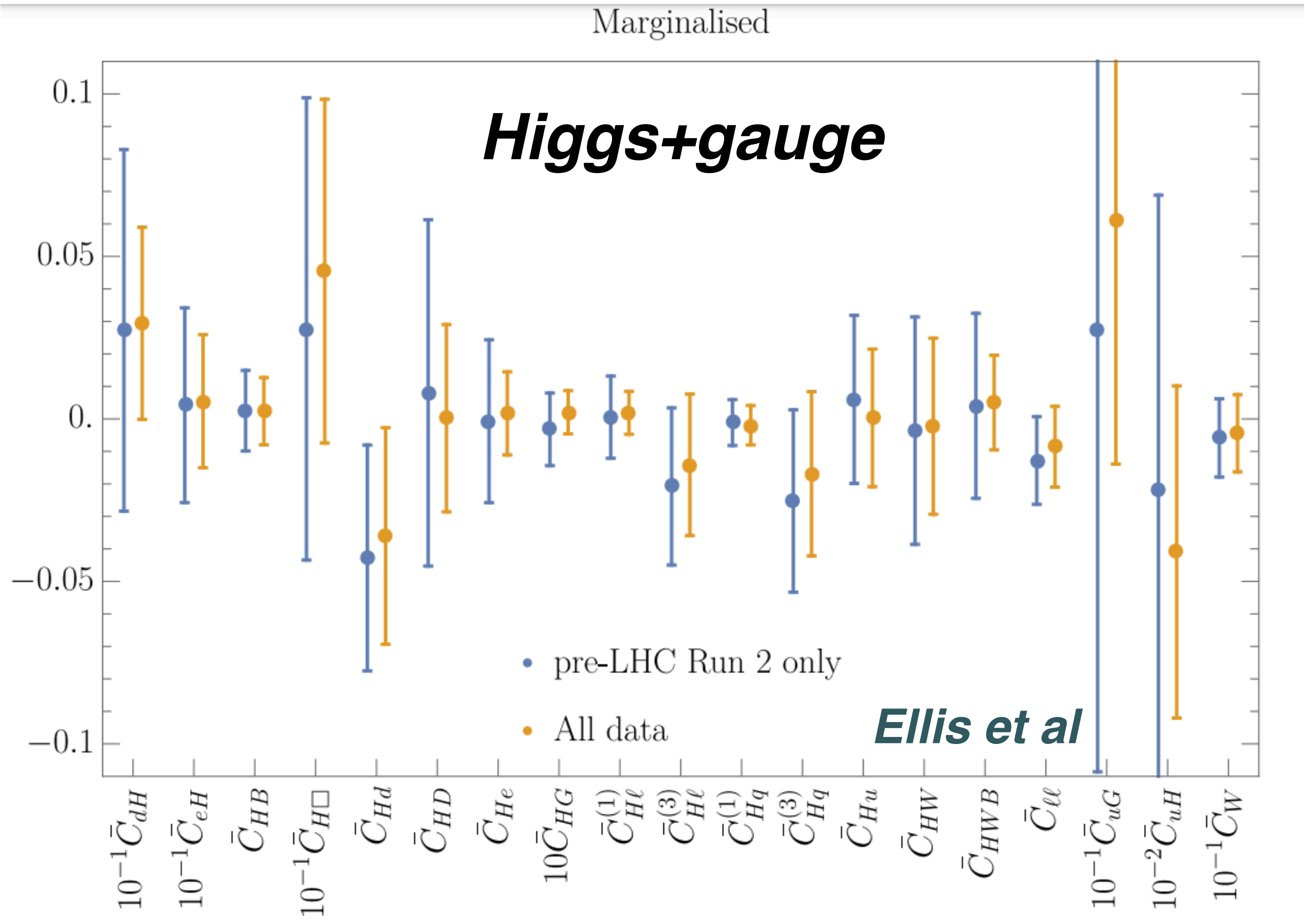
Efficient exploration of **parameter space**

Faithful **uncertainty estimate** (exp & th)

Avoiding under- and over-fitting

Methodology

SMEFT analyses in the market



low-energy constraints

$$\begin{pmatrix} [c^{(3)}_{\ell q}]_{1111} \\ [\hat{c}_{eq}]_{1111} \\ [\hat{c}_{\ell u}]_{1111} \\ [\hat{c}_{\ell d}]_{1111} \\ [\hat{c}_{eu}]_{1111} \\ [\hat{c}_{ed}]_{1111} \\ [\hat{c}^{(3)}_{\ell q}]_{1122} \\ [c_{\ell u}]_{1122} \\ [\hat{c}_{\ell d}]_{1122} \\ [c_{eq}]_{1122} \\ [c_{eu}]_{1122} \\ [\hat{c}_{ed}]_{1122} \\ [\hat{c}^{(3)}_{\ell q}]_{1133} \\ [c_{\ell d}]_{1133} \end{pmatrix} = \begin{pmatrix} -2.2 \pm 3.2 \\ 100 \pm 180 \\ -5 \pm 11 \\ -5 \pm 23 \\ -1 \pm 12 \\ -4 \pm 21 \\ -61 \pm 32 \\ 2.4 \pm 8.0 \\ -310 \pm 130 \\ -21 \pm 28 \\ -87 \pm 46 \\ 270 \pm 140 \\ -8.6 \pm 8.0 \\ -1.4 \pm 10 \end{pmatrix} \times 10^{-2}.$$

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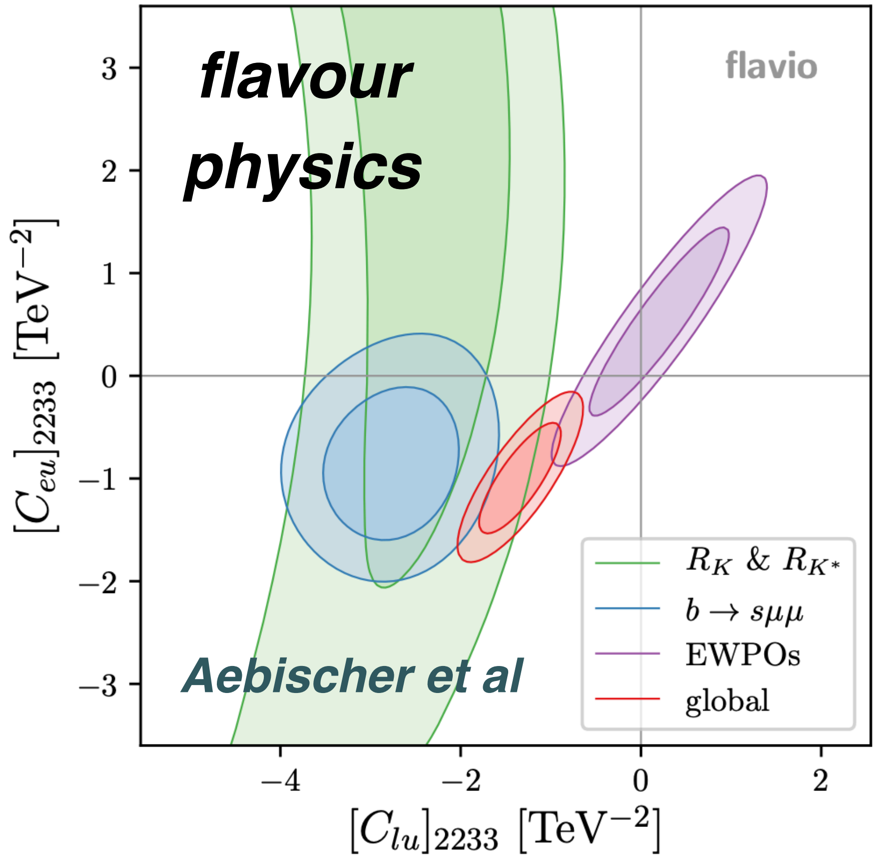
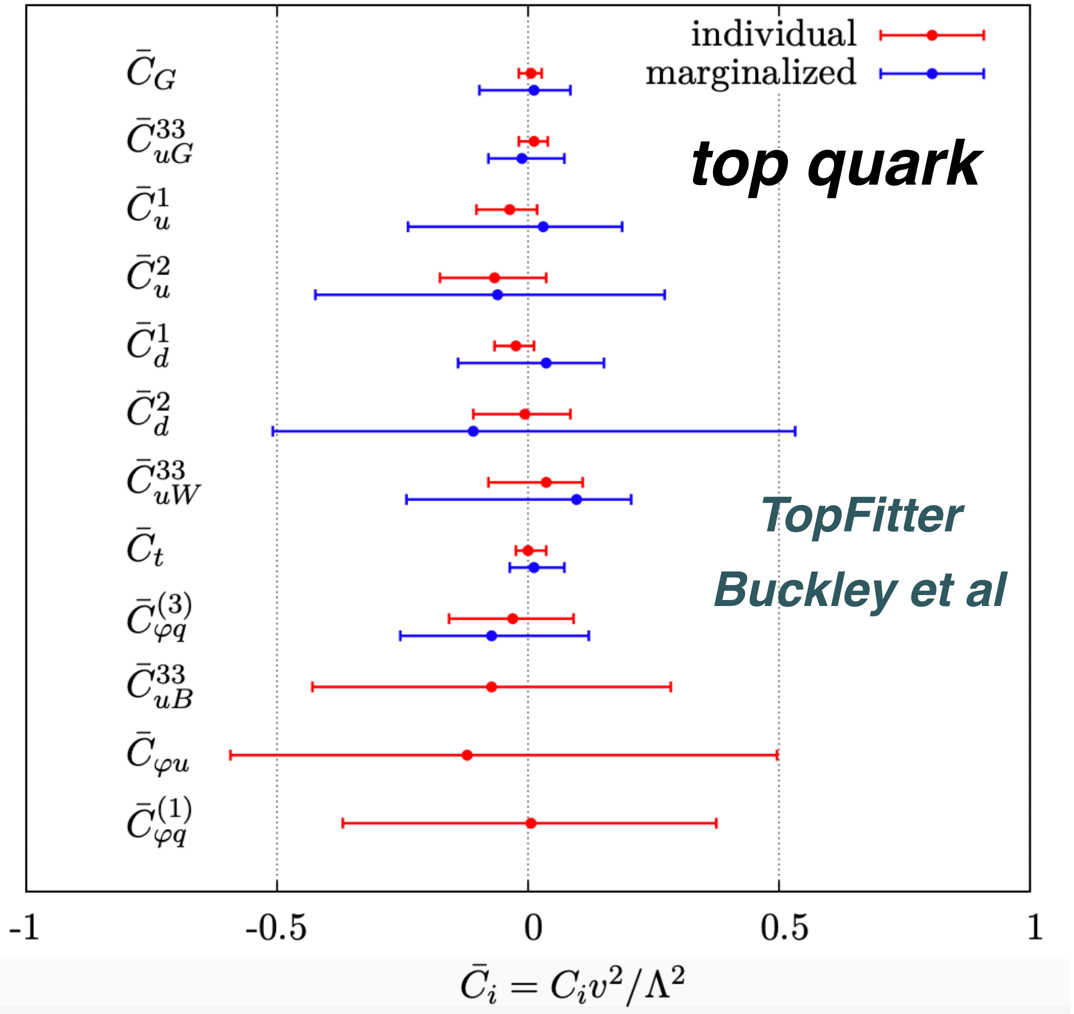
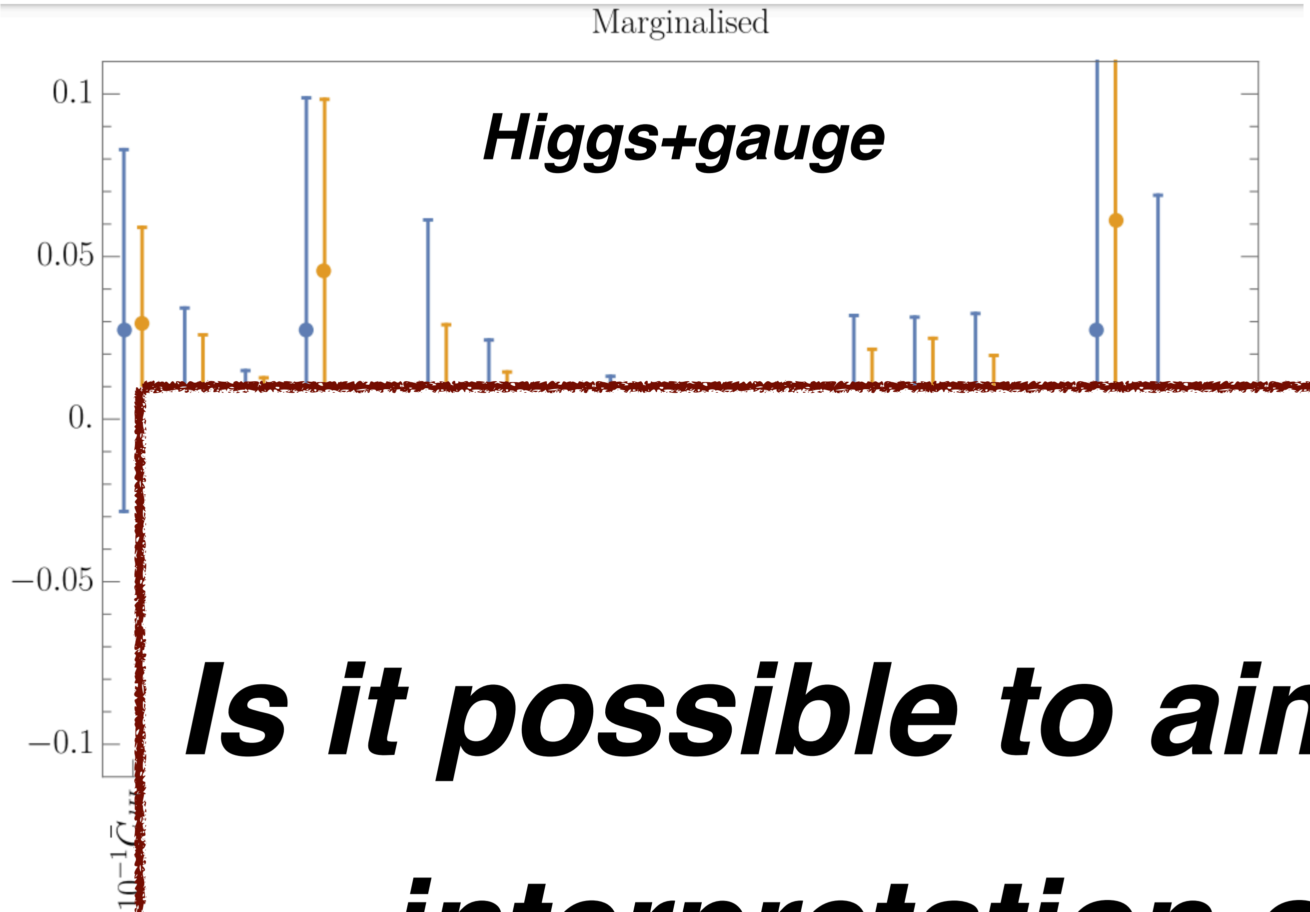




SMEFT analyses in the market

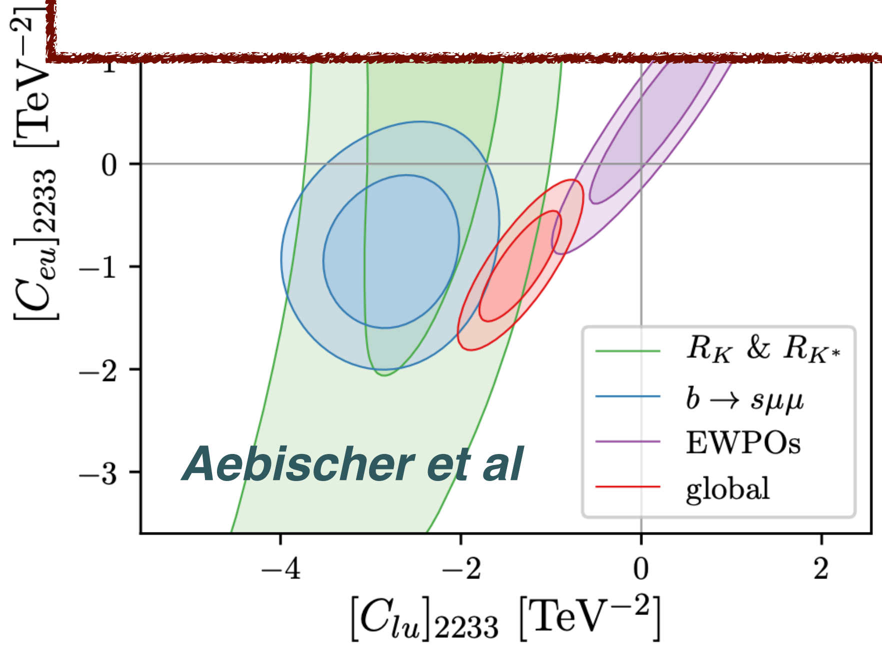


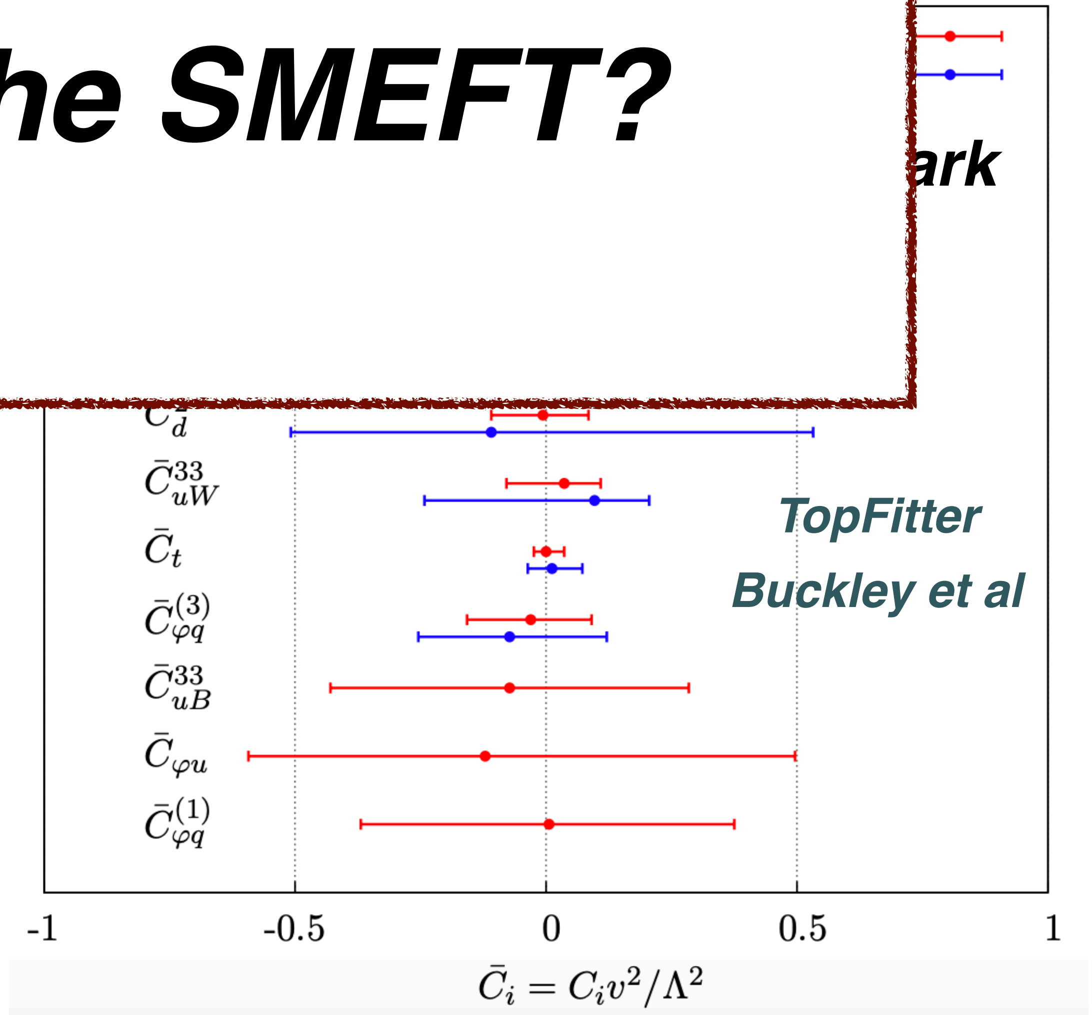
low-energy constraints

$$\begin{pmatrix} [c_{\ell q}^{(3)}]_{1111} \\ [\hat{c}_{eq}]_{1111} \\ [\hat{c}_{\ell u}]_{1111} \\ [\hat{c}_{\ell d}]_{1111} \\ [\hat{c}_{eu}]_{1111} \\ [\hat{c}_{ed}]_{1111} \end{pmatrix} \quad \begin{pmatrix} -2.2 \pm 3.2 \\ 100 \pm 180 \\ -5 \pm 11 \\ -5 \pm 23 \\ -1 \pm 12 \\ -4 \pm 21 \end{pmatrix}$$

0^{-2}.

Is it possible to aim to a truly global interpretation of the SMEFT?





SMEFiT:
the Top Quark Case

N. P. Hartland, F. Maltoni, E. R. Nocera, J. Rojo,
E. Slade, E. Vryonidou, C. Zhang, ***arXiv:1901.05965*** *(JHEP)*

The SMEFiT method

- Generate a large sample of **Monte Carlo replicas** to construct the **probability distribution** in the space of experimental data

$$\mathcal{O}_i^{(\mathrm{art})(k)} = S_{i,N}^{(k)} \mathcal{O}_i^{(\mathrm{exp})} \left(1 + \sum_{\alpha=1}^{N_{\mathrm{sys}}} r_{i,\alpha}^{(k)} \sigma_{i,c}^{(\mathrm{sys})} + r_i^{(k)} \sigma_i^{(\mathrm{stat})} \right) \,, \quad k = 1, \ldots, N_{\mathrm{rep}}$$

cross-section for k-th replica

central value (data)

correlated systematic uncertainties

statistical uncertainties

 # MC replicas

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- Construct theory calculations where the SM is **extended by SMEFT corrections**

to be determined from the data

$$\sigma_i^{\mathrm{th}} \left(\{ c_n \} \right) = \sigma_{\mathrm{SM},i} + \sum_{n=1}^{N_{\mathrm{op}}} \tilde{\sigma}_{i,n} \frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\mathrm{op}}} \tilde{\sigma}_{i,nm} \frac{c_n c_m}{\Lambda^4} , \quad i = 1 \ \ldots, N_{\mathrm{dat}}$$

SM: compute at (N)NLO QCD

SMEFT: compute at (N)LO QCD with aMC@NLO

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$$\mathcal{O}_i^{\mathrm{th}} \left(\{c_n\} \right) = \sigma_{\mathrm{SM},i} + \sum_{n=1}^{N_{\mathrm{op}}} \widetilde{\sigma}_{i,n} \frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\mathrm{op}}} \widetilde{\sigma}_{i,nm} \frac{c_n c_m}{\Lambda^4} , \quad i = 1 \ \ldots, N_{\mathrm{dat}}$$

- Determine the SMEFT coefficients **replica-by-replica** by minimising a cost function

$$E(\{c_l^{(k)}\}) \equiv \frac{1}{N_{\mathrm{dat}}} \sum_{i,j=1}^{N_{\mathrm{dat}}} \left(\mathcal{O}_i^{(\mathrm{th})} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_i^{(\mathrm{art})(k)} \right) (\mathrm{cov}^{-1})_{ij} \left(\mathcal{O}_j^{(\mathrm{th})} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_j^{(\mathrm{art})(k)} \right)$$

The SMEFiT method

- Determine the SMEFT coefficients **replica-by-replica** by minimising a cost function

$$E(\{c_l^{(k)}\}) \equiv \frac{1}{N_{\rm dat}} \sum_{i,j=1}^{N_{\rm dat}} \left(\mathcal{O}_i^{\rm (th)} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_i^{{\rm (art)}(k)} \right) ({\rm cov}^{-1})_{ij} \left(\mathcal{O}_j^{\rm (th)} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_j^{{\rm (art)}(k)} \right)$$

- The covariance matrix includes **all sources of experimental errors** + some theory errors

t_0 prescription

$$({\rm cov}_{t_0})_{ij}^{\rm (exp)} \equiv \left(\sigma_i^{\rm (stat)} \right)^2 \delta_{ij} + \left(\sum_{\alpha=1}^{N_{\rm sys}} \sigma_{i,\alpha}^{\rm (sys)} \sigma_{j,\alpha}^{\rm (sys)} \mathcal{O}_i^{\rm (exp)} \mathcal{O}_j^{\rm (exp)} + \sum_{\beta=1}^{N_{\rm norm}} \sigma_{i,\beta}^{\rm (norm)} \sigma_{j,\beta}^{\rm (norm)} \mathcal{O}_i^{\rm (th,0)} \mathcal{O}_j^{\rm (th,0)} \right)$$

$${\rm cov}_{ij} = {\rm cov}_{ij}^{\rm (exp)} + {\rm cov}_{ij}^{\rm (th)}$$

th uncertainties: PDFs

can be extended to MHOUs

$${\rm cov}_{ij}^{\rm (th)} = \left\langle \mathcal{O}_i^{\rm (th)(r)} \mathcal{O}_j^{\rm (th)(r)} \right\rangle_{\rm rep} - \left\langle \mathcal{O}_i^{\rm (th)(r)} \right\rangle_{\rm rep} \left\langle \mathcal{O}_j^{\rm (th)(r)} \right\rangle_{\rm rep} ,$$

The SMEFiT method

- Determine the SMEFT coefficients **replica-by-replica** by minimising a cost function

$$E(\{c_l^{(k)}\}) \equiv \frac{1}{N_{\rm dat}} \sum_{i,j=1}^{N_{\rm dat}} \left(\mathcal{O}_i^{(\rm th)} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_i^{(\rm art)(k)} \right) ({\rm cov}^{-1})_{ij} \left(\mathcal{O}_j^{(\rm th)} \left(\{c_n^{(k)}\} \right) - \mathcal{O}_j^{(\rm art)(k)} \right)$$

- The covariance matrix includes **all sources of experimental errors** + some theory errors

$${\rm cov}_{ij} = {\rm cov}_{ij}^{(\rm exp)} + {\rm cov}_{ij}^{(\rm th)}$$

- The ensemble of coefficients $\{c_l^{(k)}\}$ then provides a sampling of the **probability density** in the **SMEFT parameter space**

$$\left\langle c_l \right\rangle \equiv \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} c_l^{(k)} \qquad \rho\left(c_i, c_j\right) = \frac{\frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} c_i^{(k)} c_j^{(k)} - \left\langle c_i \right\rangle \left\langle c_j \right\rangle}{\delta c_i \delta c_j} .$$

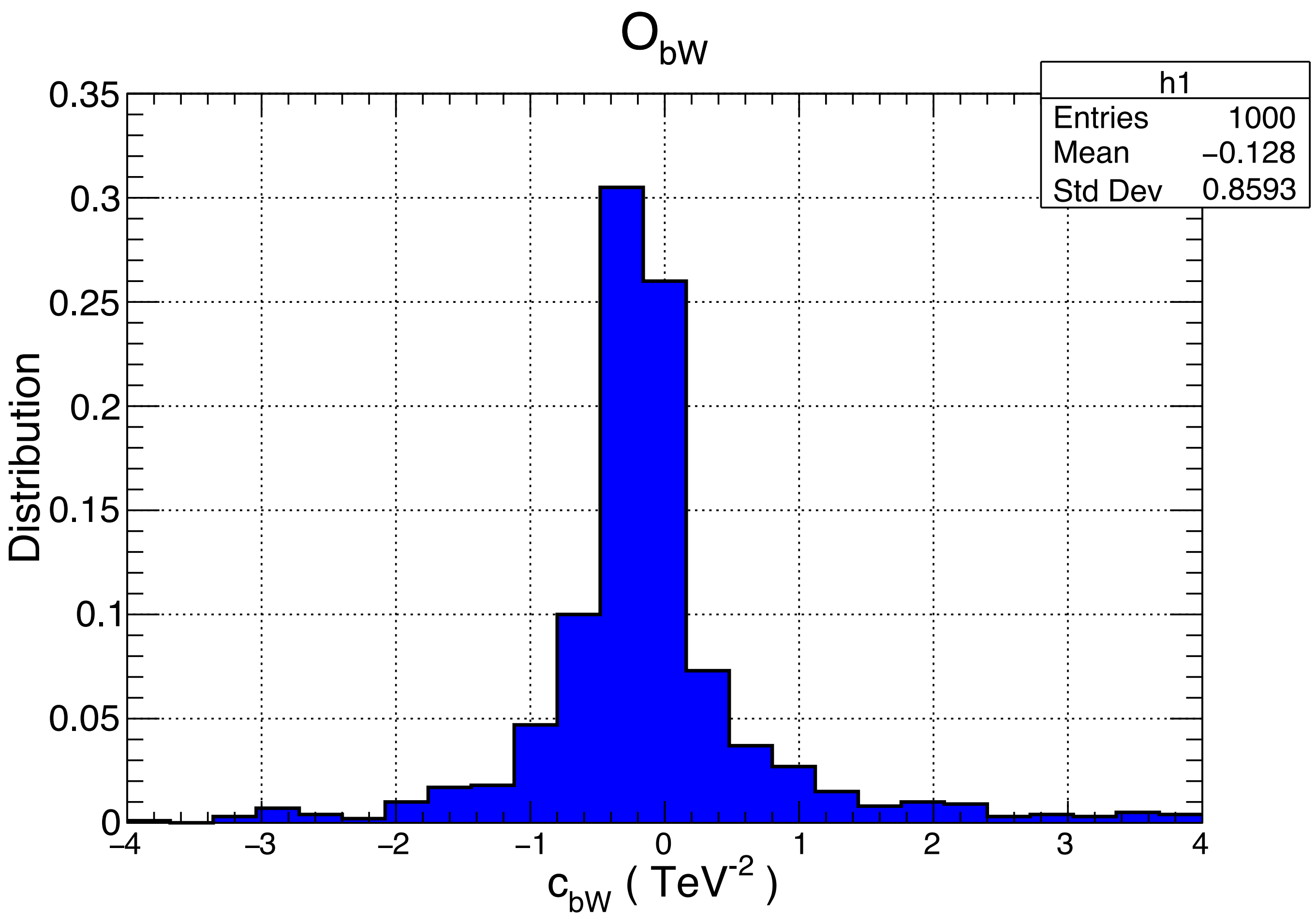
Sampling the SMEFT probability distribution

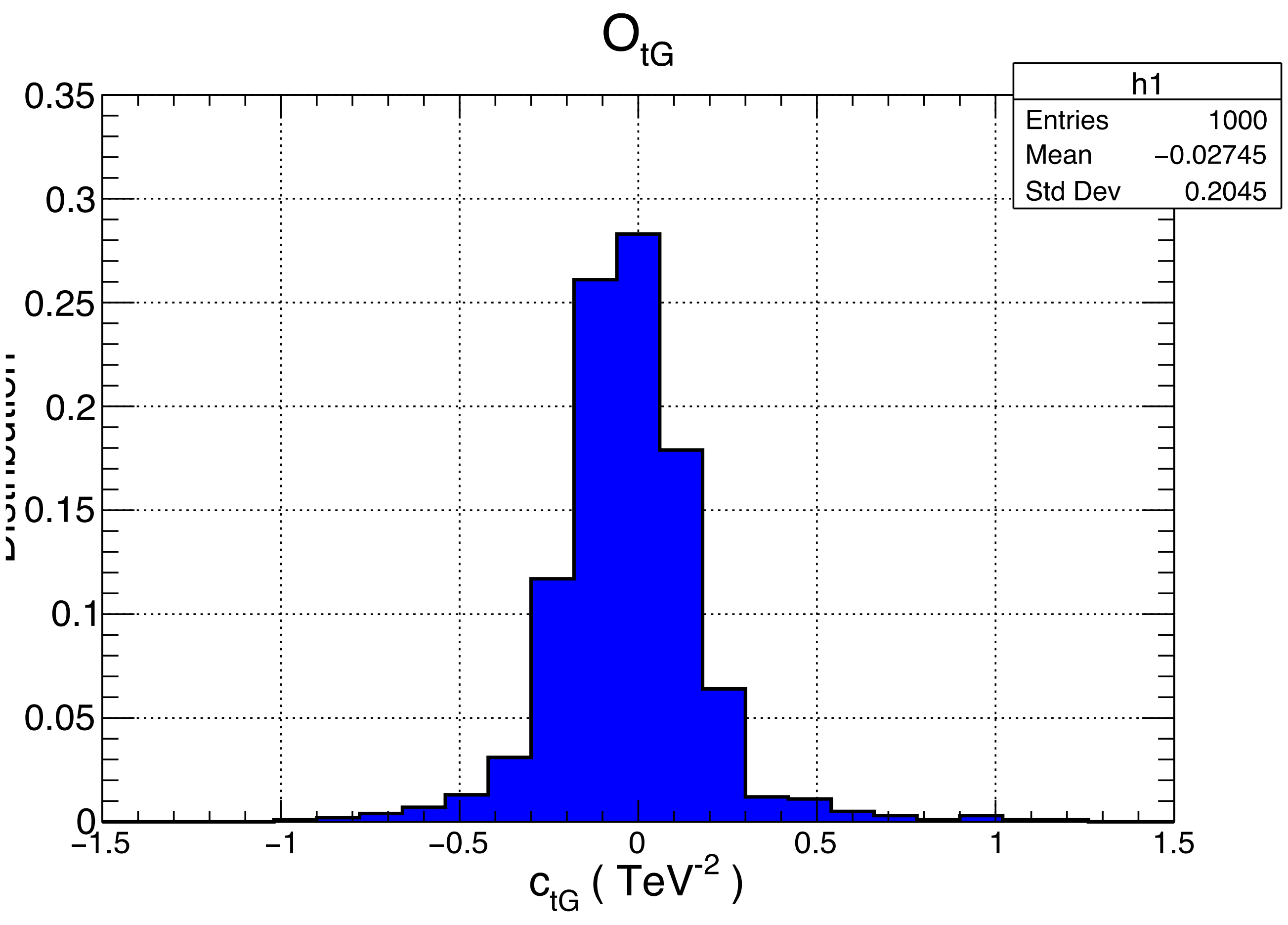
- The output of SMEFiT is a sampling of the **probability distribution** in the SMEFT space

$$\left\{ c_n^{(k)} \right\} , \quad n = 1 \ \ldots, N_{\rm op} \, , \quad k = 1 \ \ldots, N_{\rm rep}$$

- Used to **evaluate statistical estimators** such as variances, correlations, higher moments, …

- Distributions are **reasonably Gaussian** for well-constrained degrees of freedom ….





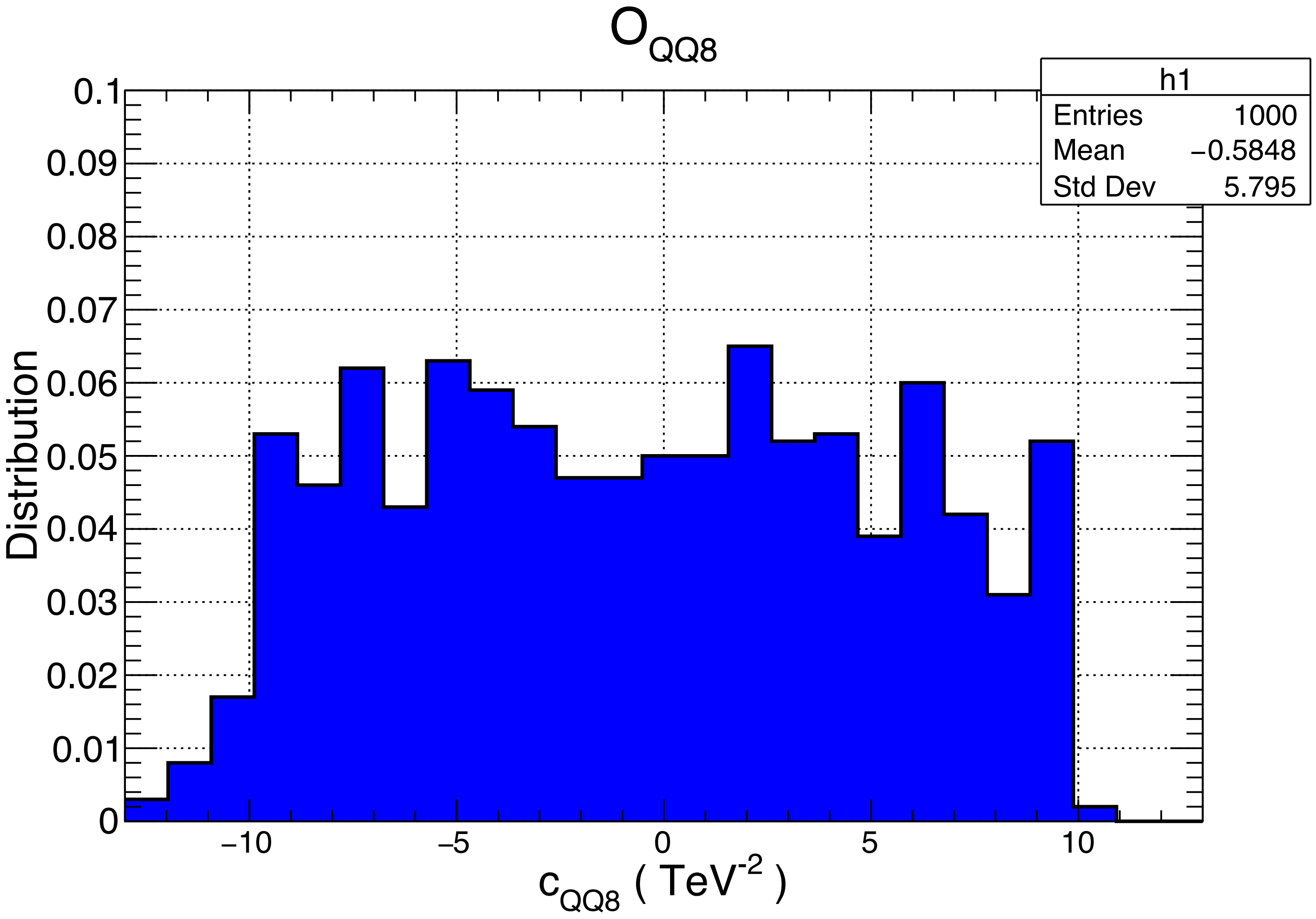
Sampling the SMEFT probability distribution

- The output of SMEFiT is a sampling of the **probability distribution** in the SMEFT space

$$\left\{ c_n^{(k)} \right\}, \quad n = 1 \;\ldots, N_{\rm op}\,, \quad k = 1 \;\ldots, N_{\rm rep}$$

- Used to **evaluate statistical estimators** such as variances, correlations, higher moments, …

- …. but much less so for **under-constrained** or **redundant** operators



The SMEFiT method

- Uncertainties on the SMEFT degrees of freedom evaluated from **variance of MC sample**

$$\left(\delta c_n\right)^2 = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} \left(c_n^{(k)}\right)^2 - \left\langle c_n \right\rangle^2$$

- For single-parameter fits, **Monte Carlo results** benchmarked with **Hessian method** (quartic fit), finding good agreement

$$\chi^2(\{c_n\}) = \chi_0^2 + \sum_n c_n a_n + \sum_{n,m} c_n c_m b_{nm}$$

with only interference terms

$$\chi^2(\{c_n\}) = \chi_0^2 + \sum_n c_n a_n + \sum_{n,m} c_n c_m b_{nm} + \sum_{n,m,l} c_n c_m c_l d_{nml} + \sum_{n,m,l,p} c_n c_m c_l c_p e_{nmlp}$$

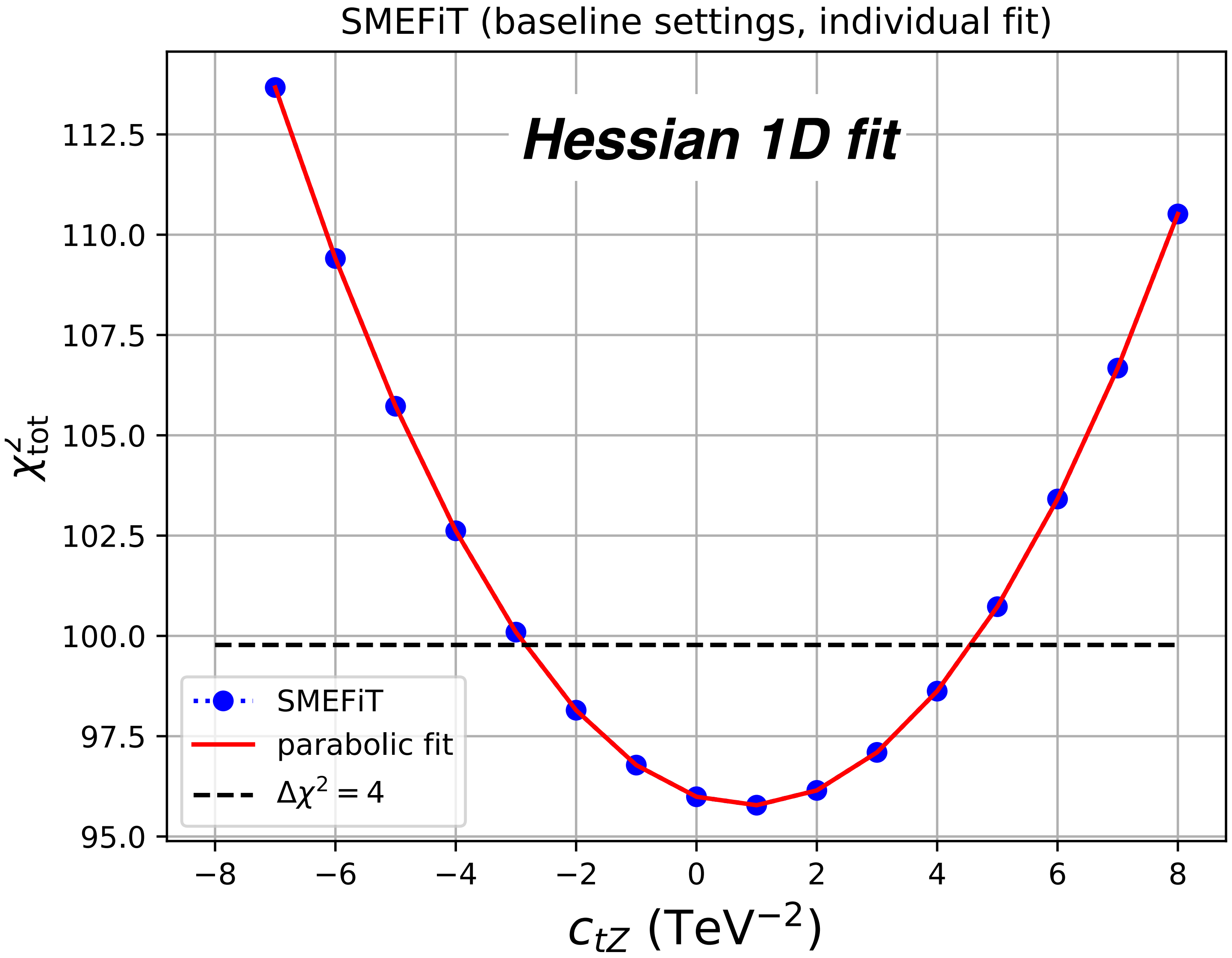
with interference+quadratic terms

Fitting the coefficients of the **likelihood expansion** from data only feasible with a few operators

The SMEFiT method

- Uncertainties on the SMEFT degrees of freedom evaluated from **variance of MC sample**

$$\left(\delta c_n\right)^2 = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} \left(c_n^{(k)}\right)^2 - \left\langle c_n \right\rangle^2$$

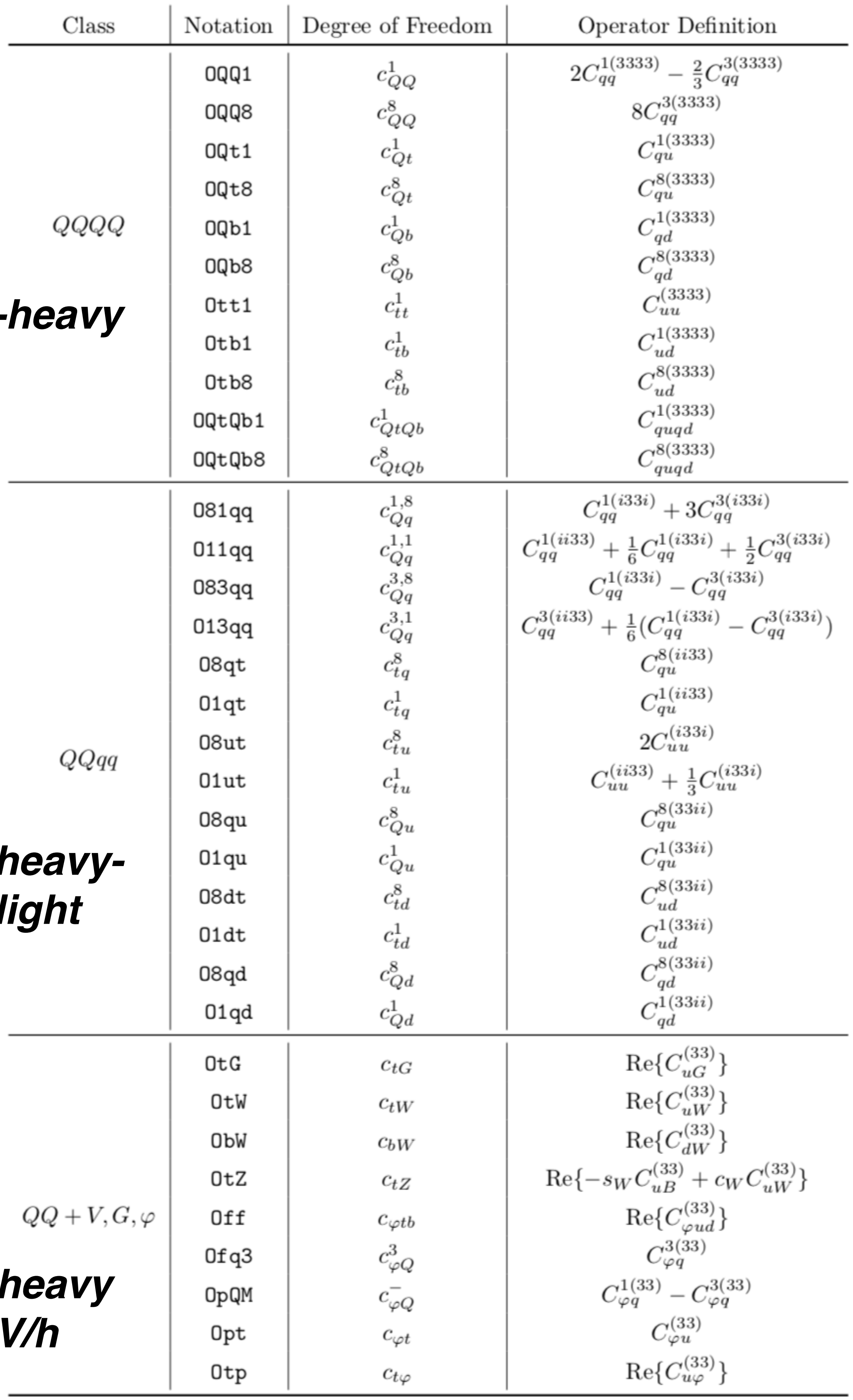


- For single-parameter fits, **Monte Carlo results** benchmarked with **Hessian method** (quartic fit), finding good agreement

- The Hessian method **numerically less stable** as dimensionality of parameter space increases

SMEFiT analysis of top quark sector

- We follow the same flavour assumptions as in the **LHC Top WG note**
- Minimal Flavour Violation (MFV), diagonal CKM, zero Yukawas for first two quark gens, CP conservation assumed
- Include those SMEFT dimension-6 operators of Warsaw basis with **at least one top quark**
- The fit includes a total of **34 independent degrees of freedom**
- Include both **interference** and **quadratic contributions** from these operators



Class	Notation	Degree of Freedom	Operator Definition
$QQQQ$	`OQQ1`	c_{QQ}^{1}	$2C_{qq}^{1(3333)} - \frac{2}{3}C_{qq}^{3(3333)}$
	`OQQ8`	c_{QQ}^{8}	$8C_{qq}^{3(3333)}$
	`OQt1`	c_{Qt}^{1}	$C_{qu}^{1(3333)}$
	`OQt8`	c_{Qt}^{8}	$C_{qu}^{8(3333)}$
	`OQb1`	c_{Qb}^{1}	$C_{qd}^{1(3333)}$
	`OQb8`	c_{Qb}^{8}	$C_{qd}^{8(3333)}$
	`Ott1`	c_{tt}^{1}	$C_{uu}^{(3333)}$
	`Otb1`	c_{tb}^{1}	$C_{ud}^{1(3333)}$
	`Otb8`	c_{tb}^{8}	$C_{ud}^{8(3333)}$
	`OQtQb1`	c_{QtQb}^{1}	$C_{quqd}^{1(3333)}$
	`OQtQb8`	c_{QtQb}^{8}	$C_{quqd}^{8(3333)}$
$QQqq$	`O81qq`	$c_{Qq}^{1,8}$	$C_{qq}^{1(i33i)} + 3C_{qq}^{3(i33i)}$
	`O11qq`	$c_{Qq}^{1,1}$	$C_{qq}^{1(ii33)} + \frac{1}{6}C_{qq}^{1(i33i)} + \frac{1}{2}C_{qq}^{3(i33i)}$
	`O83qq`	$c_{Qq}^{3,8}$	$C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}$
	`O13qq`	$c_{Qq}^{3,1}$	$C_{qq}^{3(ii33)} + \frac{1}{6}(C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)})$
	`O8qt`	c_{tq}^{8}	$C_{qu}^{8(ii33)}$
	`O1qt`	c_{tq}^{1}	$C_{qu}^{1(ii33)}$
	`O8ut`	c_{tu}^{8}	$2C_{uu}^{(i33i)}$
	`O1ut`	c_{tu}^{1}	$C_{uu}^{(ii33)} + \frac{1}{3}C_{uu}^{(i33i)}$
	`O8qu`	c_{Qu}^{8}	$C_{qu}^{8(33ii)}$
	`O1qu`	c_{Qu}^{1}	$C_{qu}^{1(33ii)}$
	`O8dt`	c_{td}^{8}	$C_{ud}^{8(33ii)}$
	`O1dt`	c_{td}^{1}	$C_{ud}^{1(33ii)}$
	`O8qd`	c_{Qd}^{8}	$C_{qd}^{8(33ii)}$
	`O1qd`	c_{Qd}^{1}	$C_{qd}^{1(33ii)}$
$QQ+V,G,\varphi$	`OtG`	c_{tG}	$\mathrm{Re}\{C_{uG}^{(33)}\}$
	`OtW`	c_{tW}	$\mathrm{Re}\{C_{uW}^{(33)}\}$
	`ObW`	c_{bW}	$\mathrm{Re}\{C_{dW}^{(33)}\}$
	`OtZ`	c_{tZ}	$\mathrm{Re}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\}$
	`Off`	$c_{\varphi tb}$	$\mathrm{Re}\{C_{\varphi ud}^{(33)}\}$
	`Ofq3`	$c_{\varphi Q}^{3}$	$C_{\varphi q}^{3(33)}$
	`OpQM`	$c_{\varphi Q}^{-}$	$C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$
	`Opt`	$c_{\varphi t}$	$C_{\varphi u}^{(33)}$
	`Otp`	$c_{t\varphi}$	$\mathrm{Re}\{C_{u\varphi}^{(33)}\}$

4-heavy

2-heavy-2-light

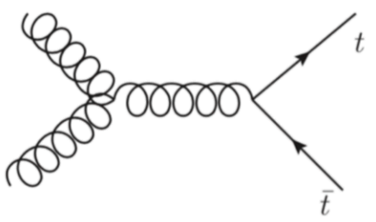
2-heavy + V/h

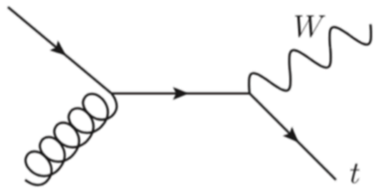
SMEFiT analysis of top quark sector

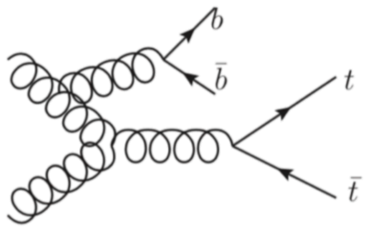
Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

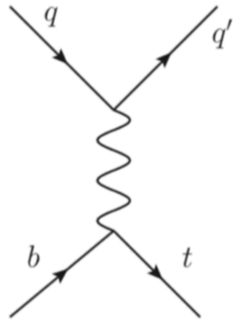
A large number of different dimension-6 SMEFT operators modify **top production at LHC**

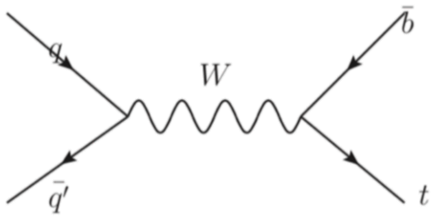
$$\sigma_i^{\rm th}\left(\{c_n\}\right) = \sigma_{{\rm SM},i} + \sum_{n=1}^{N_{\rm op}} \widetilde{\sigma}_{i,n}\frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\rm op}} \widetilde{\sigma}_{i,nm}\frac{c_n c_m}{\Lambda^4}$$

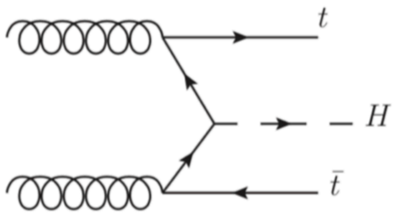

Top quark pair

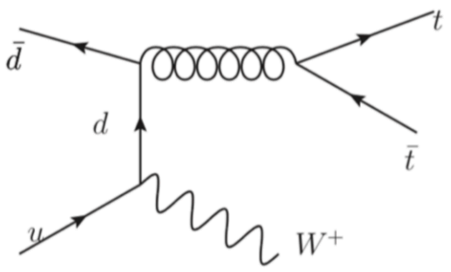

tW

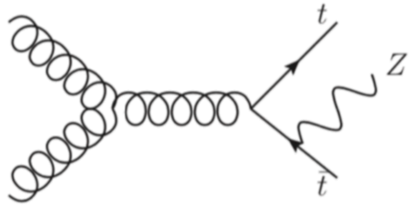

ttbb

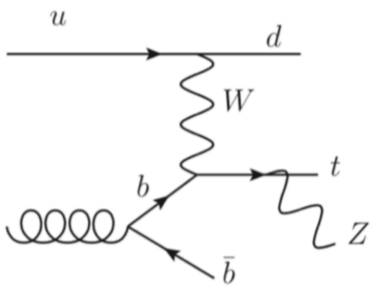

Single top (t-channel)


Single top (s-channel)


tt+H


tt+W


tt+Z


t+Z

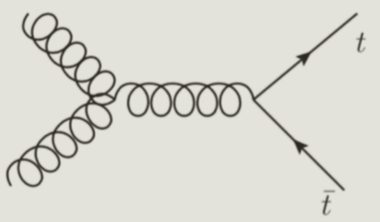
SMEFiT analysis of top quark sector

Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

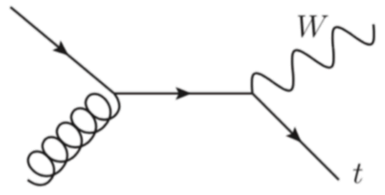
A large number of different dimension-6 SMEFT operators modify **top production at LHC**

$$\sigma_i^{\rm th}\left(\{c_n\}\right) = \sigma_{{\rm SM},i} + \sum_{n=1}^{N_{\rm op}} \widetilde{\sigma}_{i,n}\frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\rm op}} \widetilde{\sigma}_{i,nm}\frac{c_n c_m}{\Lambda^4}$$

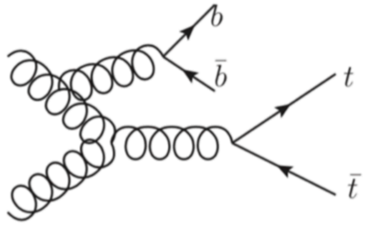
Top quark pair



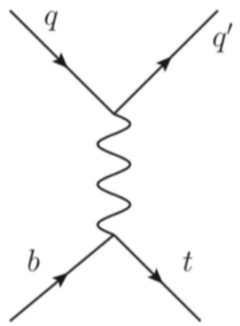
tW



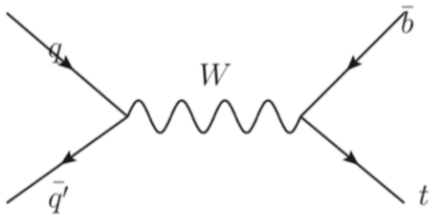
ttbb



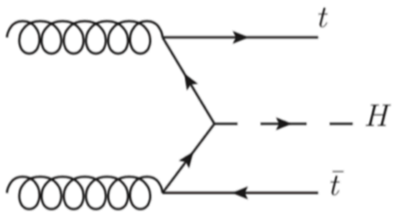
Single top (t-channel)



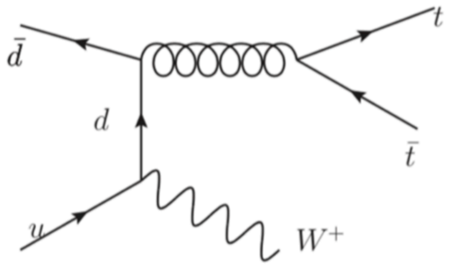
Single top (s-channel)



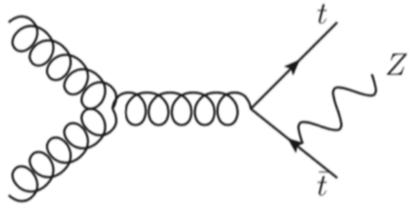
tt+H



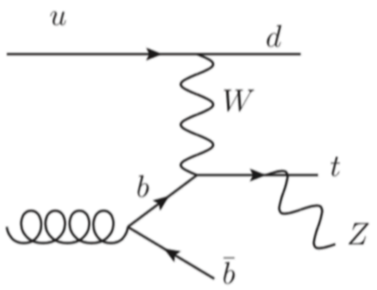
tt+W



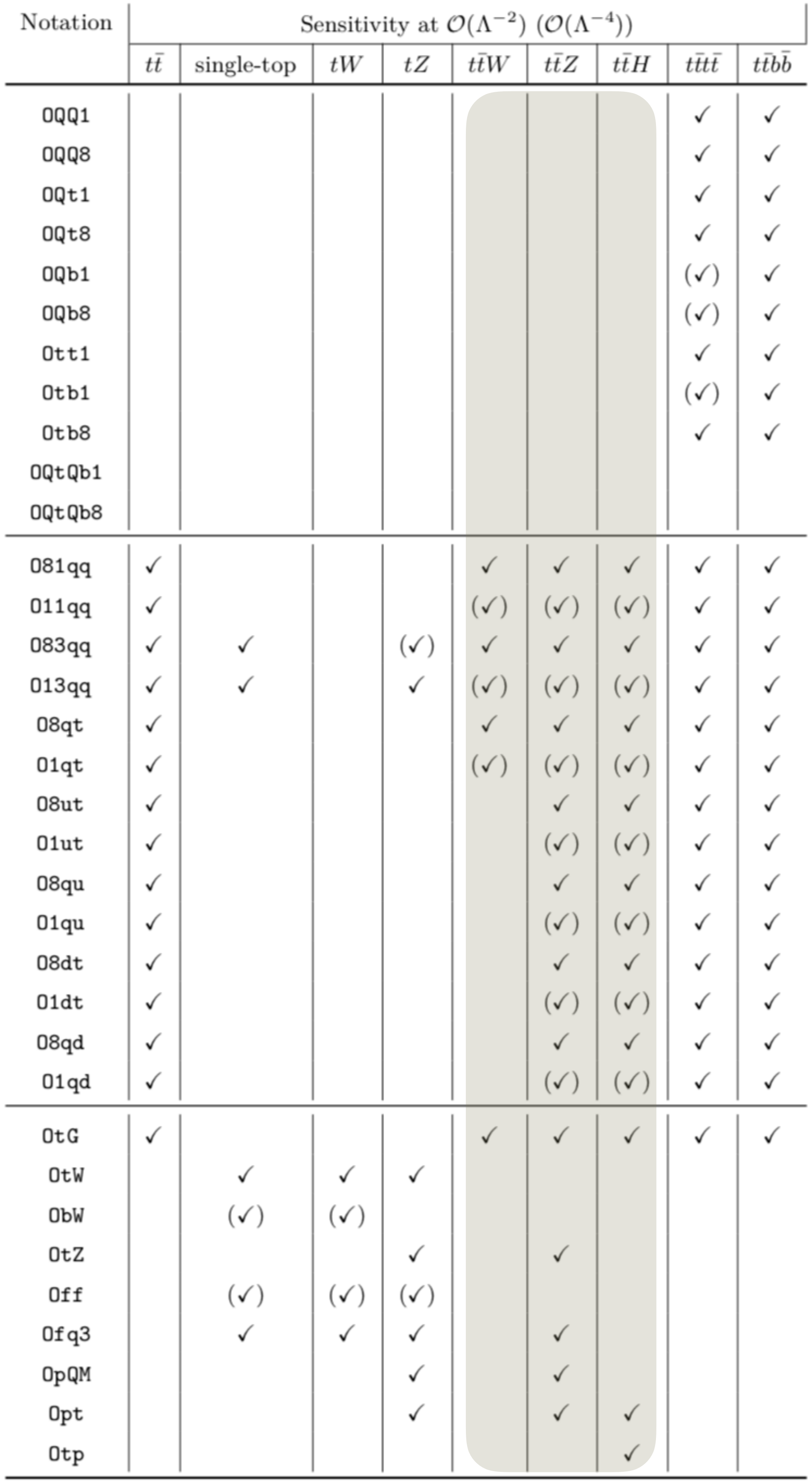
tt+Z



t+Z



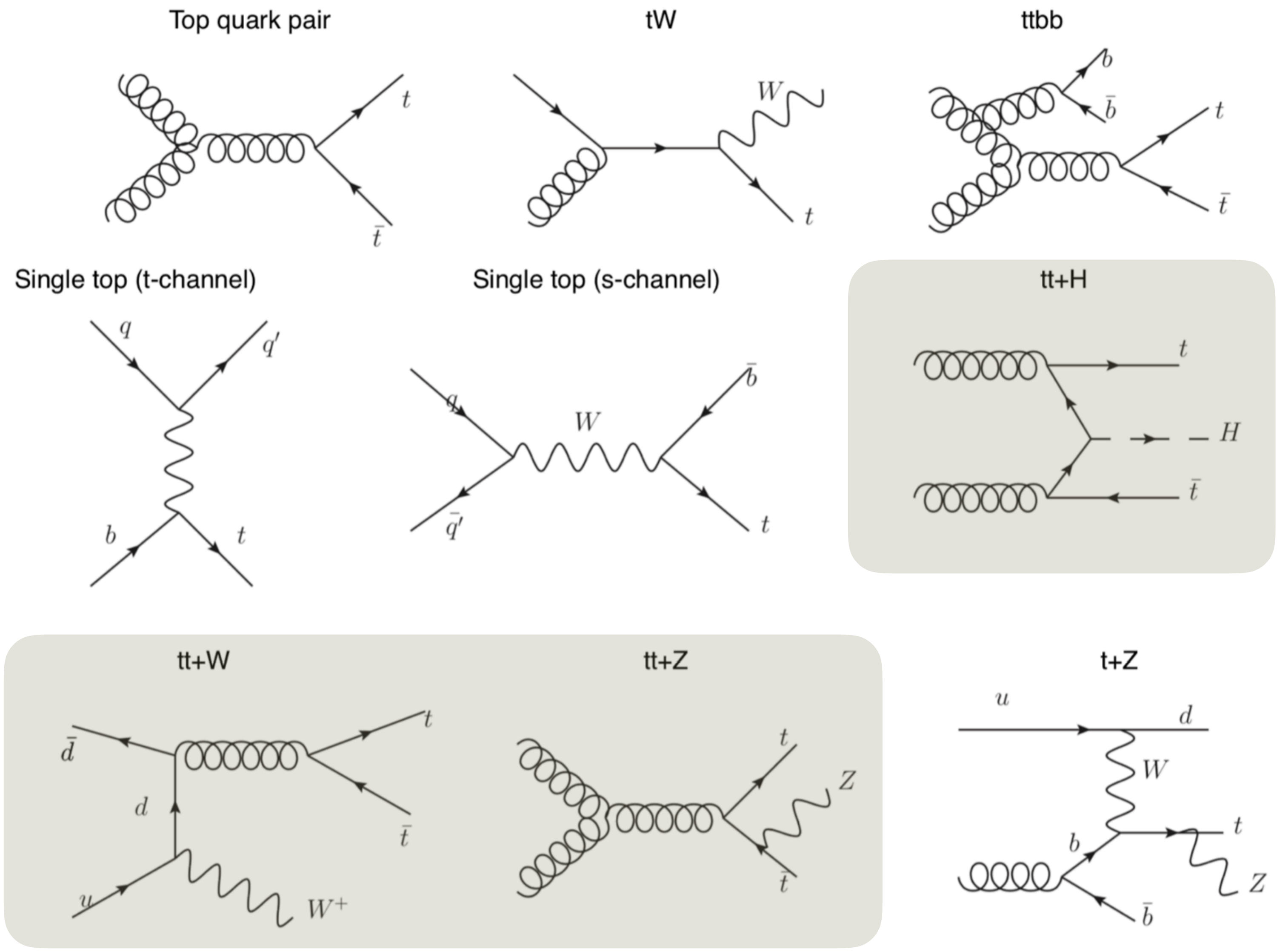
SMEFiT analysis of top quark sector



Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

A large number of different dimension-6 SMEFT operators modify **top production at LHC**

$$\sigma_i^{\rm th}\left(\{c_n\}\right) = \sigma_{{\rm SM},i} + \sum_{n=1}^{N_{\rm op}} \widetilde{\sigma}_{i,n}\frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\rm op}} \widetilde{\sigma}_{i,nm}\frac{c_n c_m}{\Lambda^4}$$



Juan Rojo

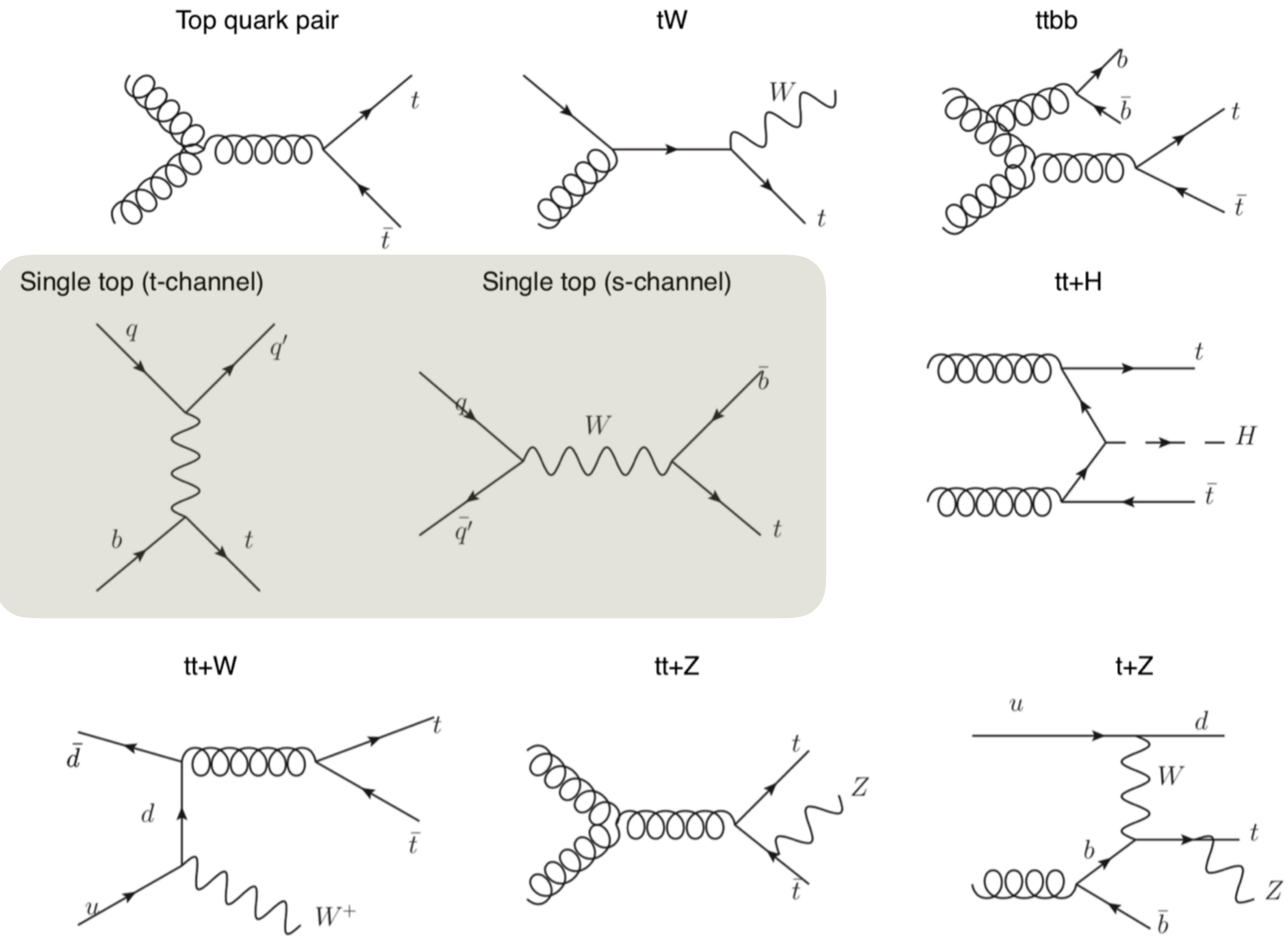
IPPP seminar, Durham

SMEFiT analysis of top quark sector

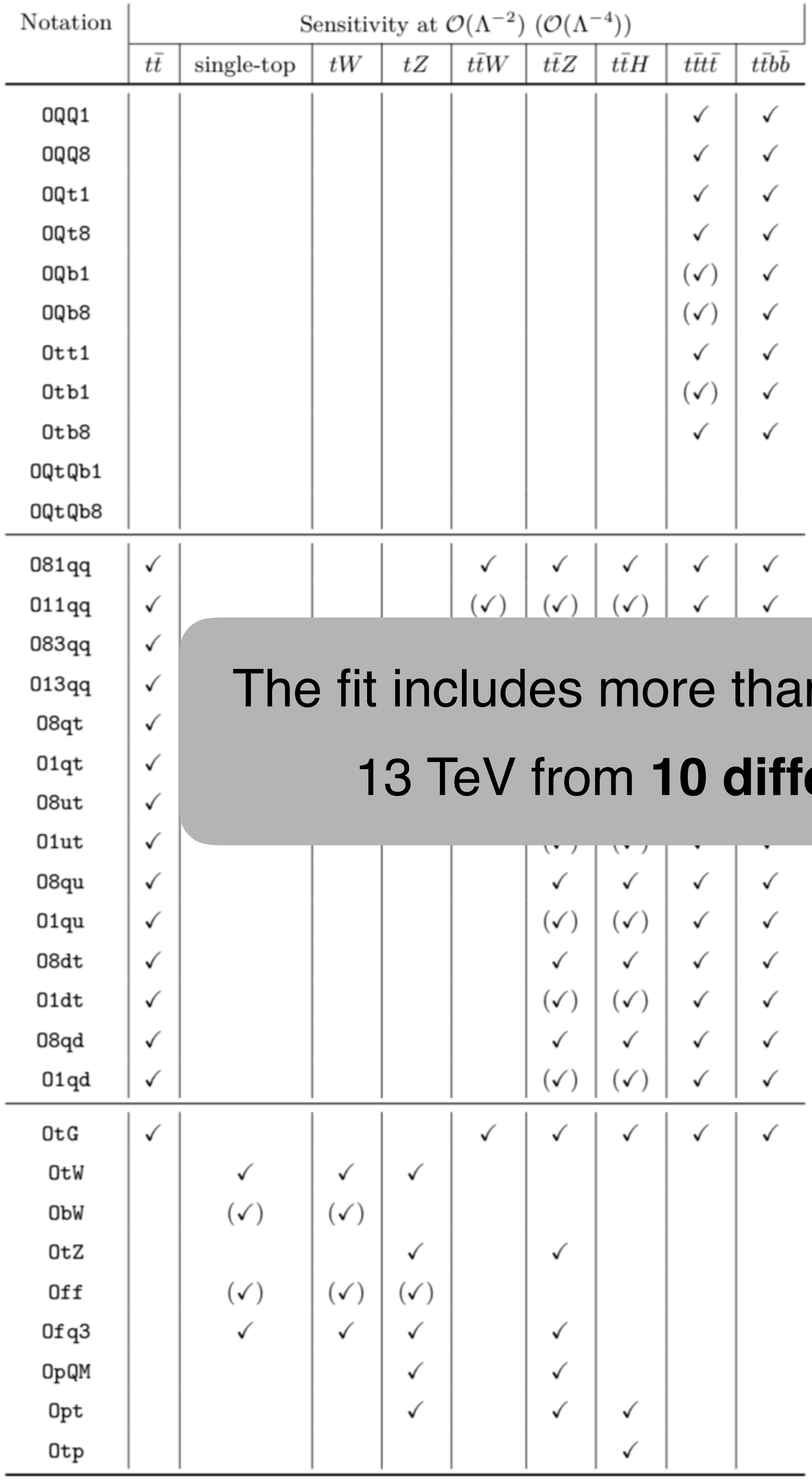
Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ $(\mathcal{O}(\Lambda^{-4}))$								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

A large number of different dimension-6 SMEFT operators modify **top production at LHC**

$$\sigma_i^{\rm th}\left(\{c_n\}\right) = \sigma_{{\rm SM},i} + \sum_{n=1}^{N_{\rm op}} \widetilde{\sigma}_{i,n}\frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\rm op}} \widetilde{\sigma}_{i,nm}\frac{c_n c_m}{\Lambda^4}$$



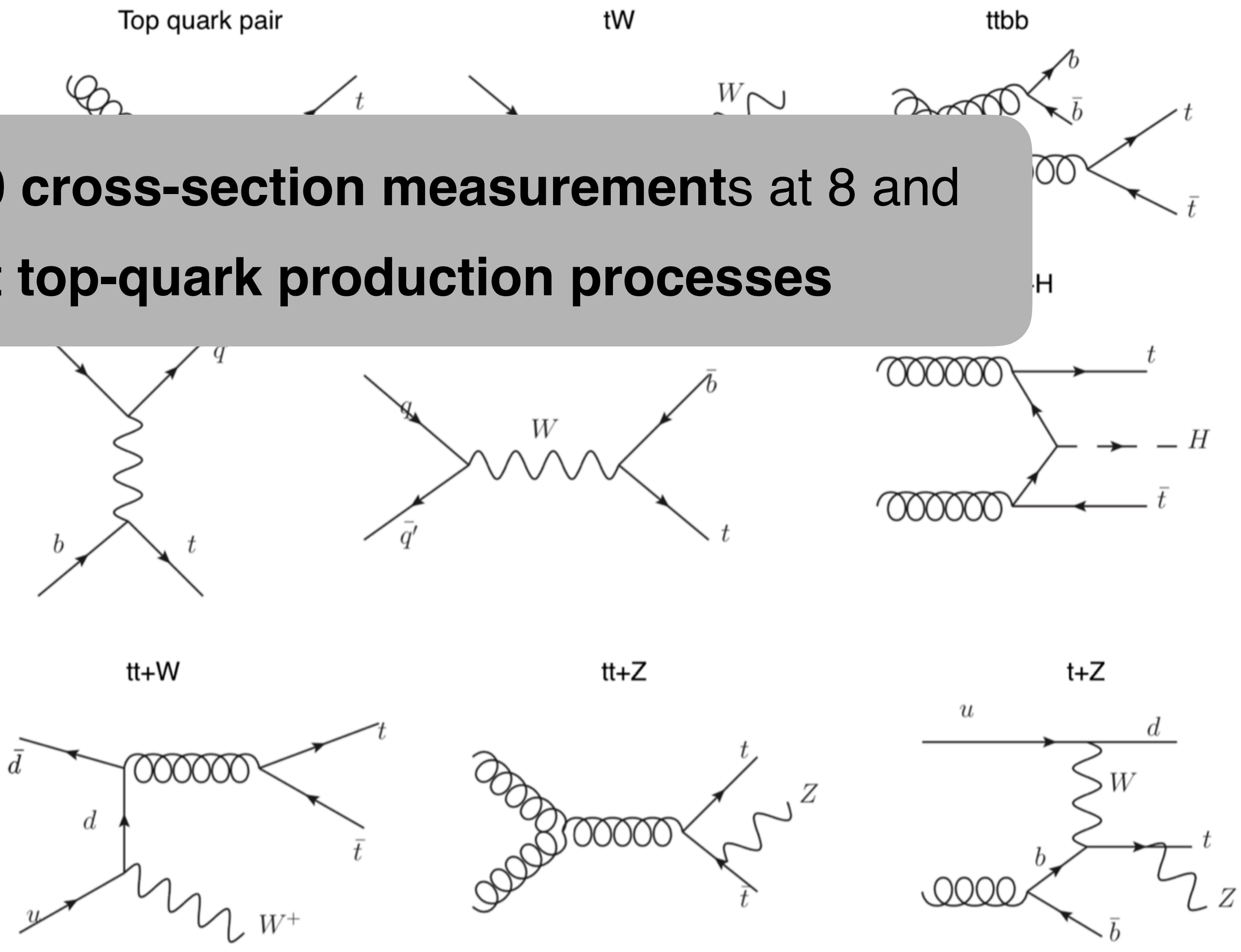
The top quark sector of the SMEFT



Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
O13qq	✓	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
O8qt	✓	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
O1qt	✓	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
O8ut	✓	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
O1ut	✓	[illegible]	[illegible]	[illegible]	[illegible]	(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

A large number of different dimension-6 SMEFT operators modify **top production at LHC**

$$\sigma_i^{\rm th}\left(\{c_n\}\right) = \sigma_{{\rm SM},i} + \sum_{n=1}^{N_{\rm op}} \widetilde{\sigma}_{i,n}\frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\rm op}} \widetilde{\sigma}_{i,nm}\frac{c_n c_m}{\Lambda^4}$$



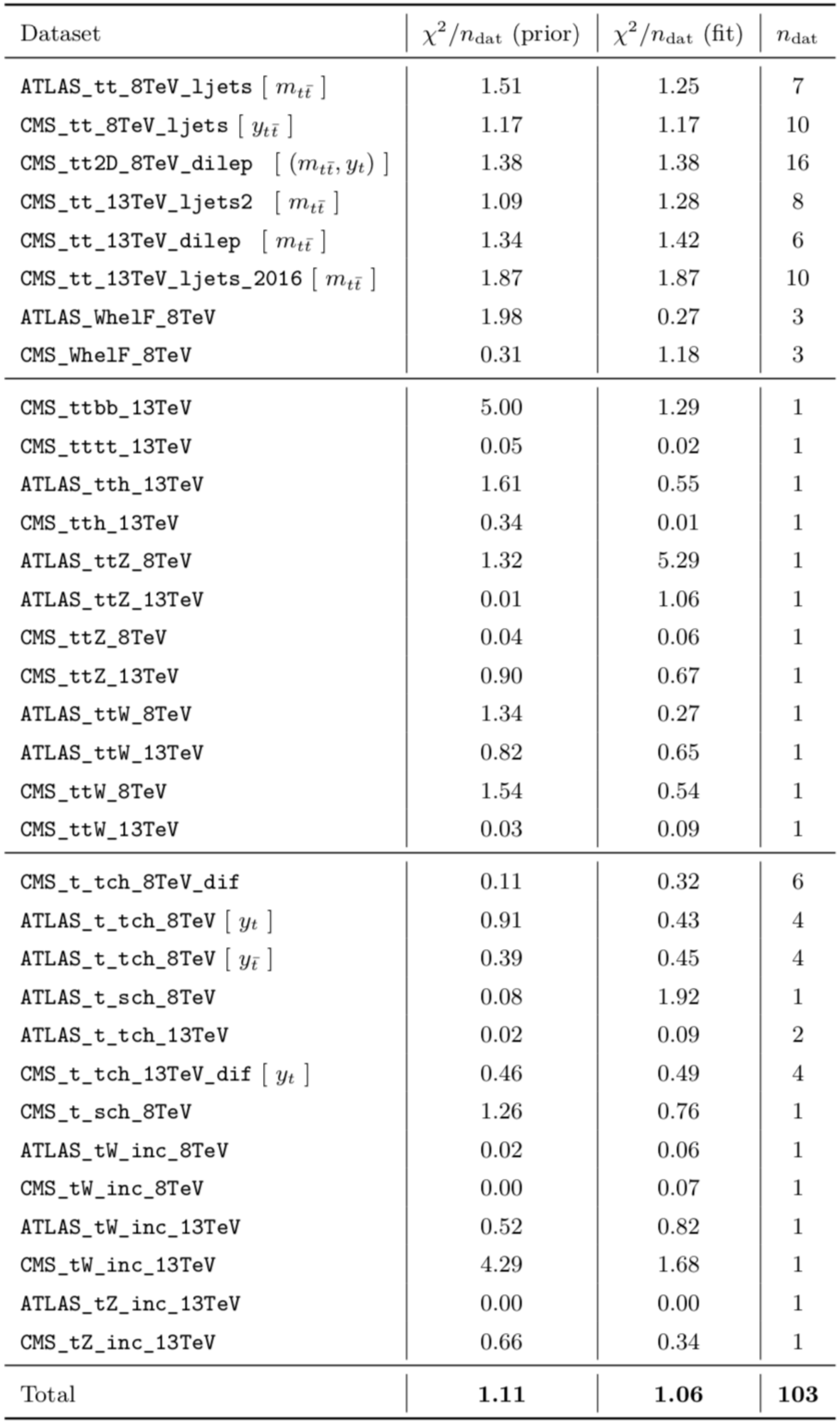
The fit includes more than **100 cross-section measurements** at 8 and 13 TeV from **10 different top-quark production processes**

Fit quality

- **Good agreement** between theory (SM and SMEFT) and data for most datasets

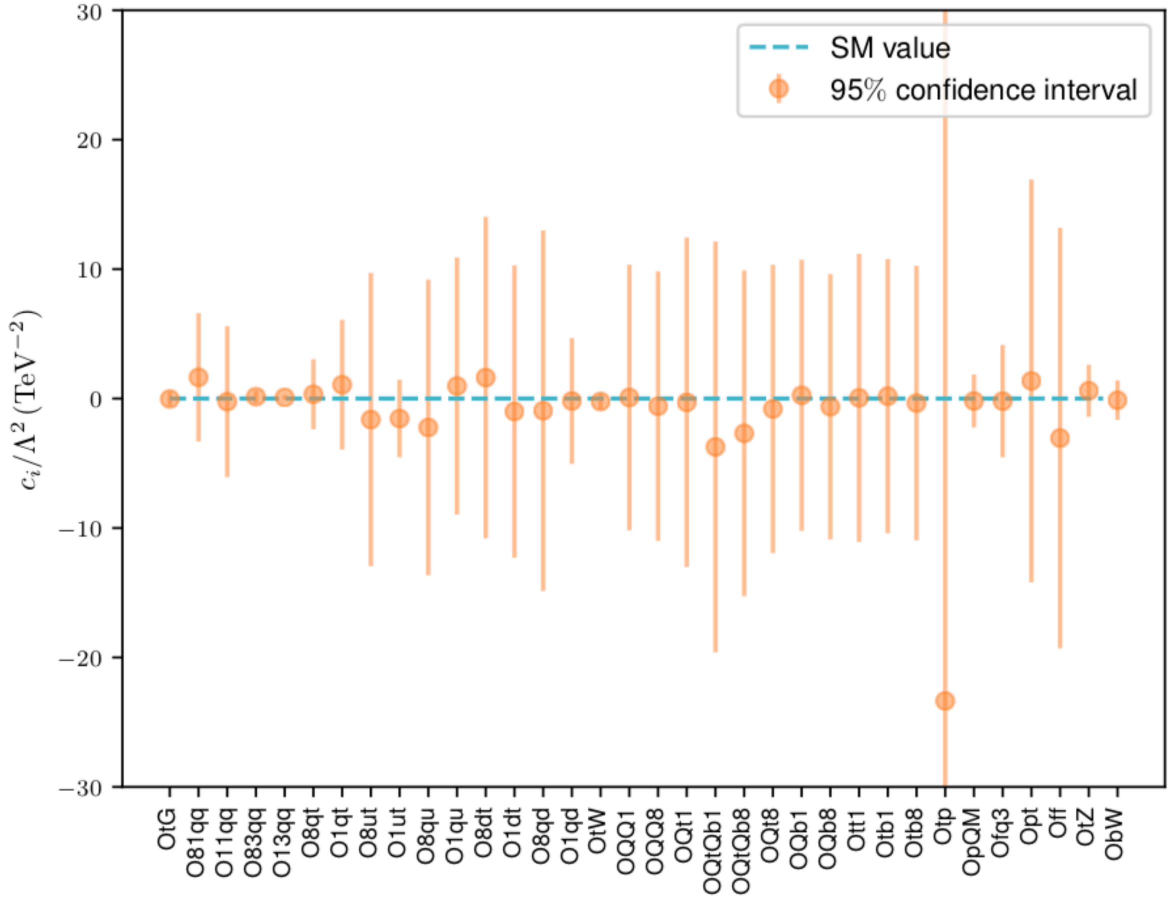
- For the **103 fitted cross-sections**, we find χ^2/n_{dat} *of* **1.11 (1.06)** before (after) fit

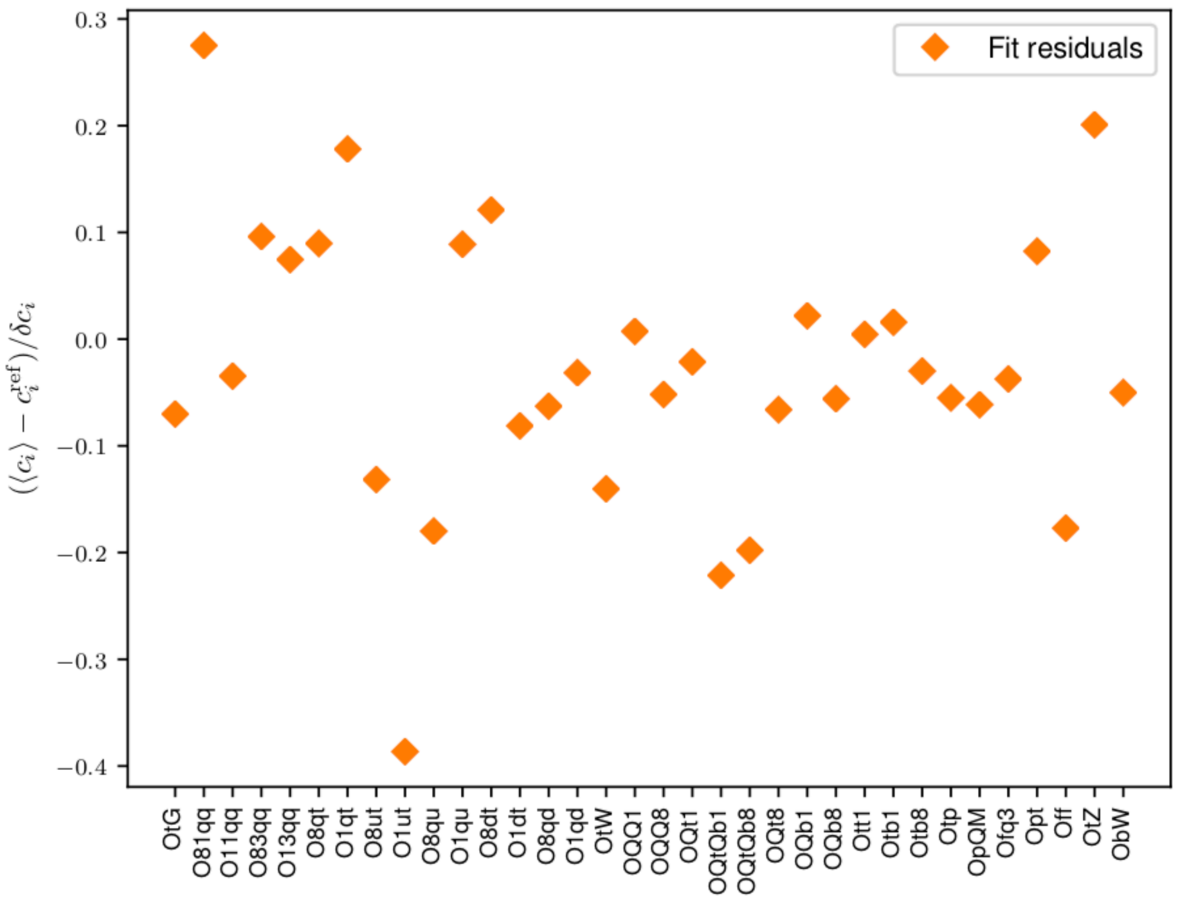
- Including SMEFT effects improves agreement with data: need to quantify how **significant** this improvement is



Dataset	$\chi^2/n_{\rm dat}$ (prior)	$\chi^2/n_{\rm dat}$ (fit)	$n_{\rm dat}$
`ATLAS_tt_8TeV_ljets` [$m_{t\bar{t}}$]	1.51	1.25	7
`CMS_tt_8TeV_ljets` [$y_{t\bar{t}}$]	1.17	1.17	10
`CMS_tt2D_8TeV_dilep` [$(m_{t\bar{t}}, y_t)$]	1.38	1.38	16
`CMS_tt_13TeV_ljets2` [$m_{t\bar{t}}$]	1.09	1.28	8
`CMS_tt_13TeV_dilep` [$m_{t\bar{t}}$]	1.34	1.42	6
`CMS_tt_13TeV_ljets_2016` [$m_{t\bar{t}}$]	1.87	1.87	10
`ATLAS_WhelF_8TeV`	1.98	0.27	3
`CMS_WhelF_8TeV`	0.31	1.18	3
`CMS_ttbb_13TeV`	5.00	1.29	1
`CMS_tttt_13TeV`	0.05	0.02	1
`ATLAS_tth_13TeV`	1.61	0.55	1
`CMS_tth_13TeV`	0.34	0.01	1
`ATLAS_ttZ_8TeV`	1.32	5.29	1
`ATLAS_ttZ_13TeV`	0.01	1.06	1
`CMS_ttZ_8TeV`	0.04	0.06	1
`CMS_ttZ_13TeV`	0.90	0.67	1
`ATLAS_ttW_8TeV`	1.34	0.27	1
`ATLAS_ttW_13TeV`	0.82	0.65	1
`CMS_ttW_8TeV`	1.54	0.54	1
`CMS_ttW_13TeV`	0.03	0.09	1
`CMS_t_tch_8TeV_dif`	0.11	0.32	6
`ATLAS_t_tch_8TeV` [y_t]	0.91	0.43	4
`ATLAS_t_tch_8TeV` [$y_{\bar{t}}$]	0.39	0.45	4
`ATLAS_t_sch_8TeV`	0.08	1.92	1
`ATLAS_t_tch_13TeV`	0.02	0.09	2
`CMS_t_tch_13TeV_dif` [y_t]	0.46	0.49	4
`CMS_t_sch_8TeV`	1.26	0.76	1
`ATLAS_tW_inc_8TeV`	0.02	0.06	1
`CMS_tW_inc_8TeV`	0.00	0.07	1
`ATLAS_tW_inc_13TeV`	0.52	0.82	1
`CMS_tW_inc_13TeV`	4.29	1.68	1
`ATLAS_tZ_inc_13TeV`	0.00	0.00	1
`CMS_tZ_inc_13TeV`	0.66	0.34	1
Total	**1.11**	**1.06**	**103**

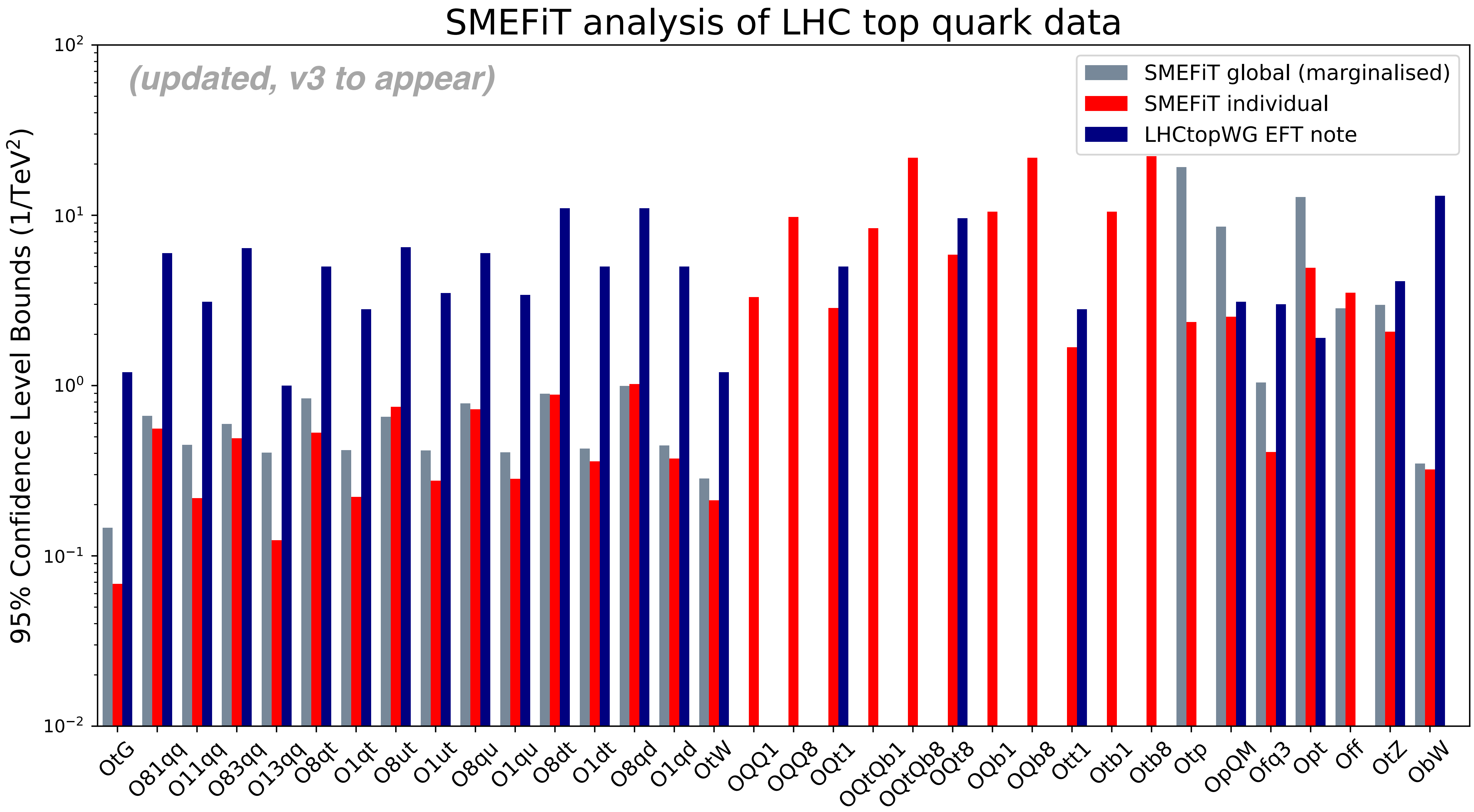
SMEFiT results





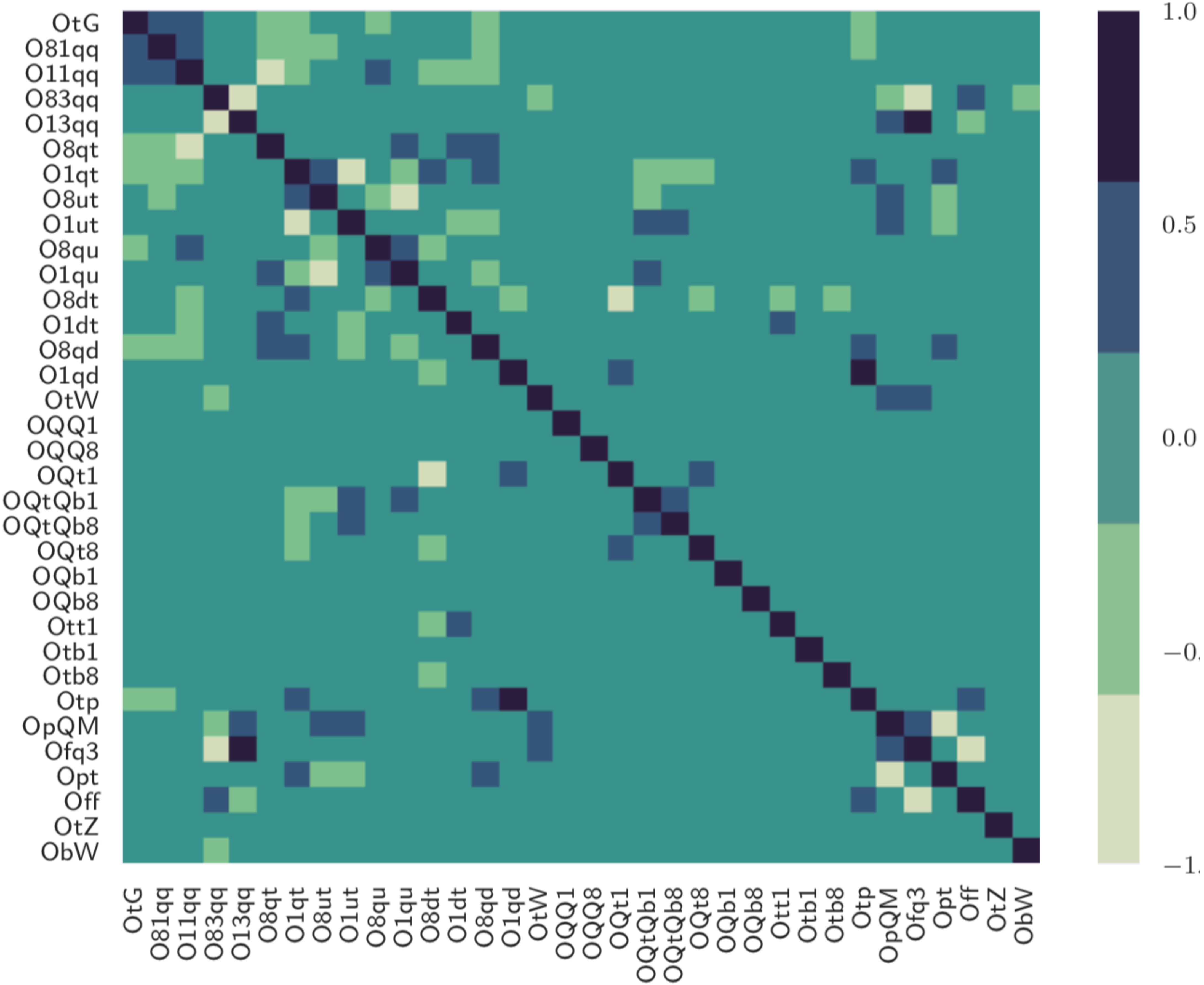
- Agreement with the SM expectation **within uncertainties**
- Bounds on individual operators are in general largely **correlated among them**
- Large differences between the bounds obtained from each operator

Comparison with 1D fits and previous bounds

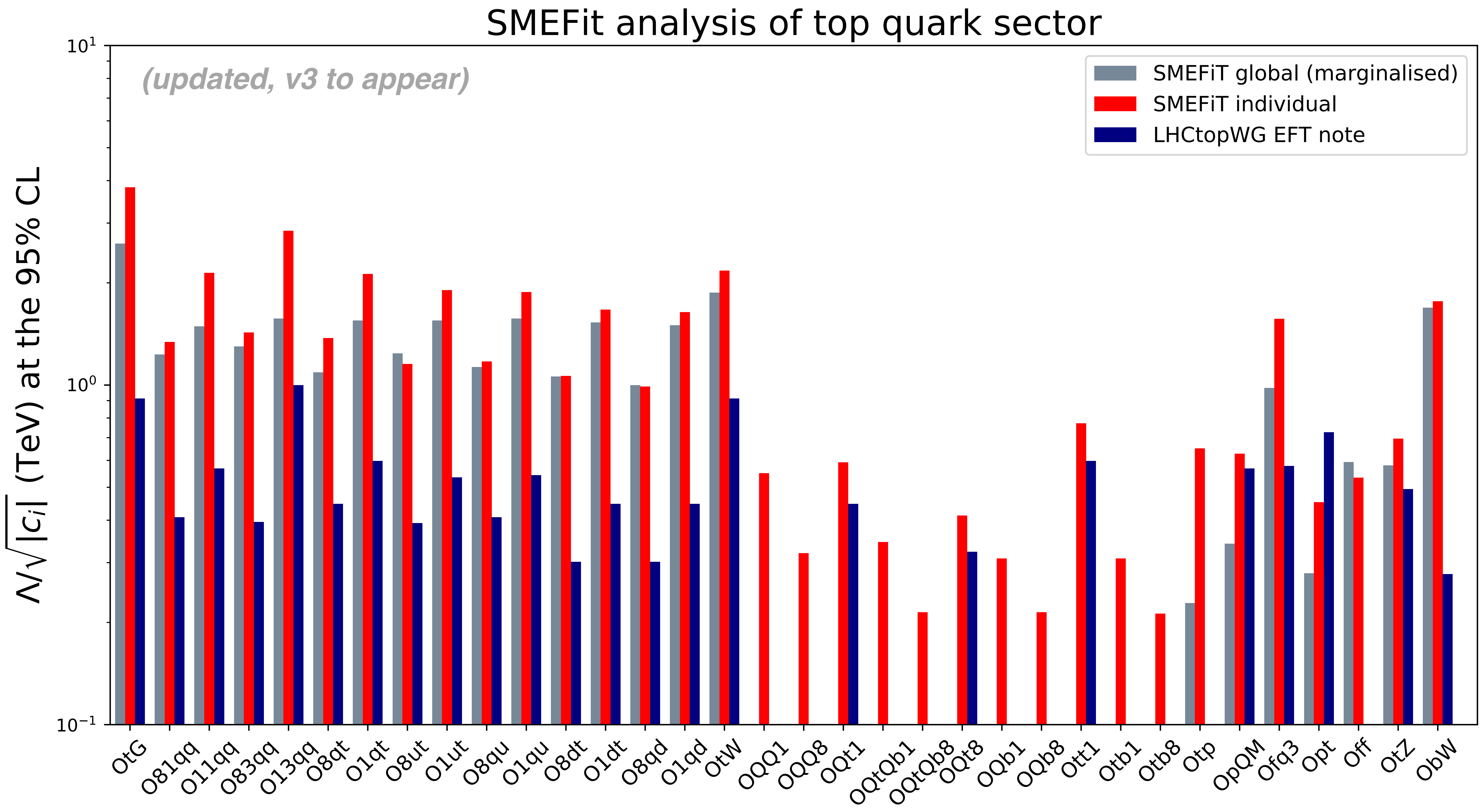


- **Improvement** found (more stringent bounds) in most fitted degrees of freedom
- For some specific operators **our bounds are the first ones** to be reported
- Individual bounds can **overestimate** the actual (marginalised) bounds

Correlation map



Energy reach



Sensitivity up to several TeV for many operators!

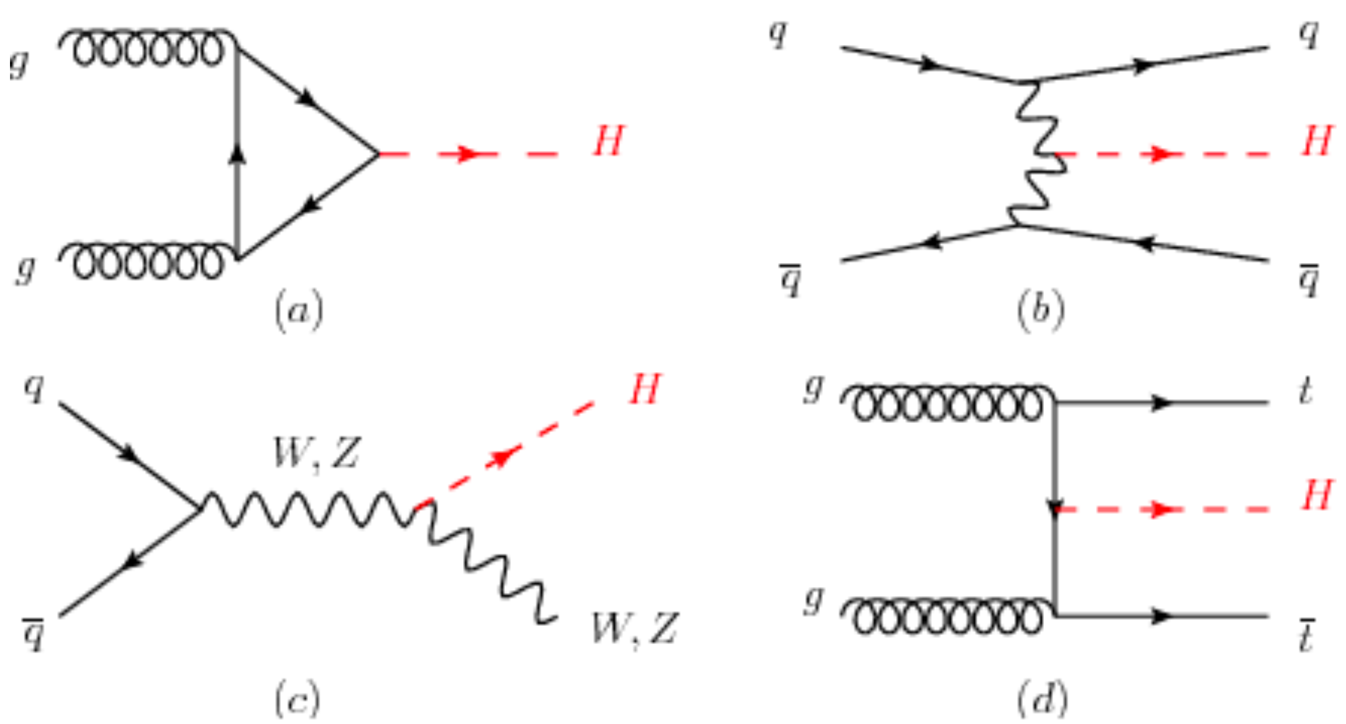
A global SMEFT analysis of Higgs, gauge & top data

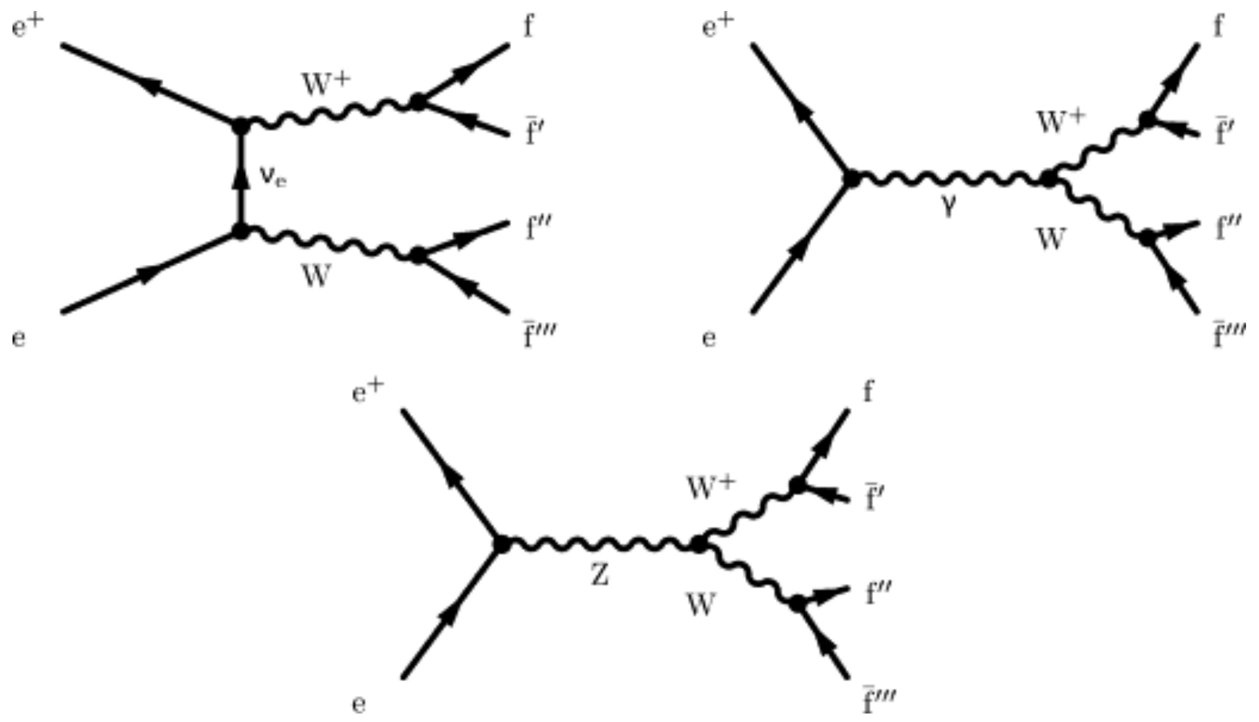
J. J. Ethier, F. Maltoni, L. Mantani, E. R. Nocera, J. Rojo,
E. Slade, E. Vryonidou, C. Zhang, ***in preparation***

Towards a global SMEFT analysis

Extend **top analysis** with **Higgs** and **gauge boson** production observables

- Include all available **LHC Higgs measurements** (signal strengths, distributions, STXS)
- Also **EWPO from LEP** and gauge boson pair production from LHC
- Perform restricted fits with **constrained scenarios** for UV models (eg flavour assumptions)
- Methodological improvements to efficiently explore parameters space

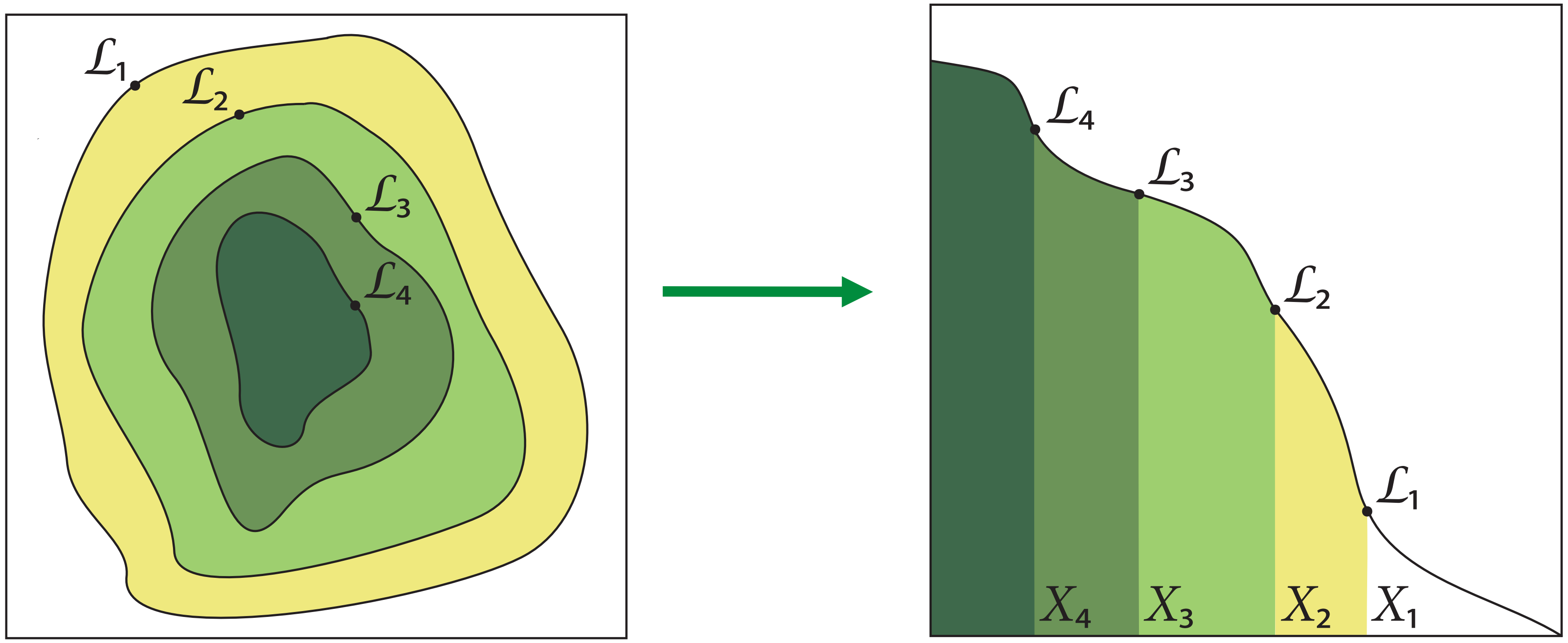




Nested Sampling

Statistical mapping of the *N*-dimensional likelihood profile to 1D

$$Z = \int d^N c \mathscr{L}\left(\mathrm{data} \,|\, \vec{c}\right) \pi(\vec{c}) = \int_0^1 dX \mathscr{L}(X)$$



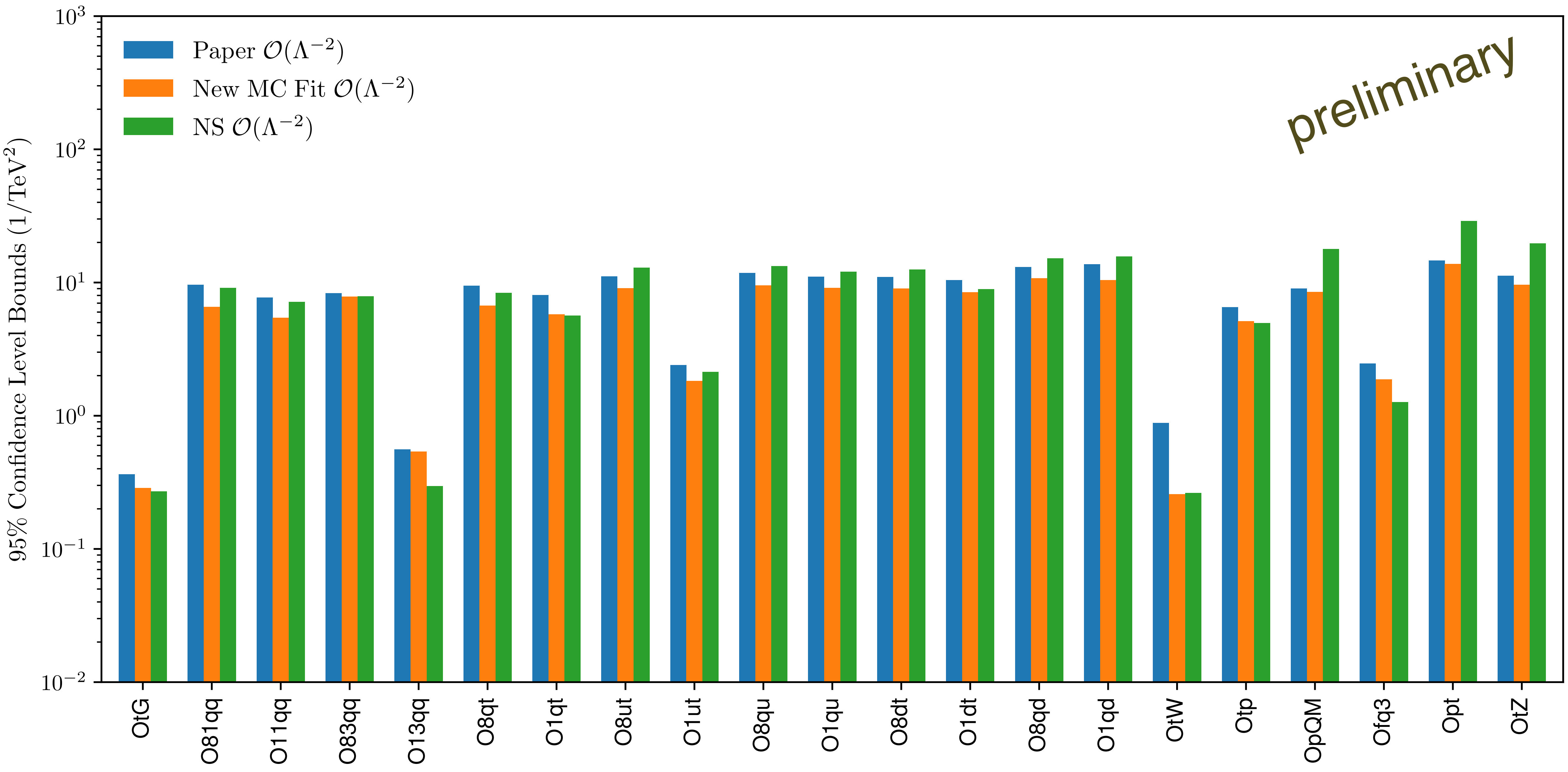
$$Z_i \sim \sum_i \mathcal{L}_i w_i$$

$$w_i = \frac{1}{2}\left(X_{i-1} - X_{i+1}\right)$$

Feroz et al. arXiv:1306.2144 [astro-ph]

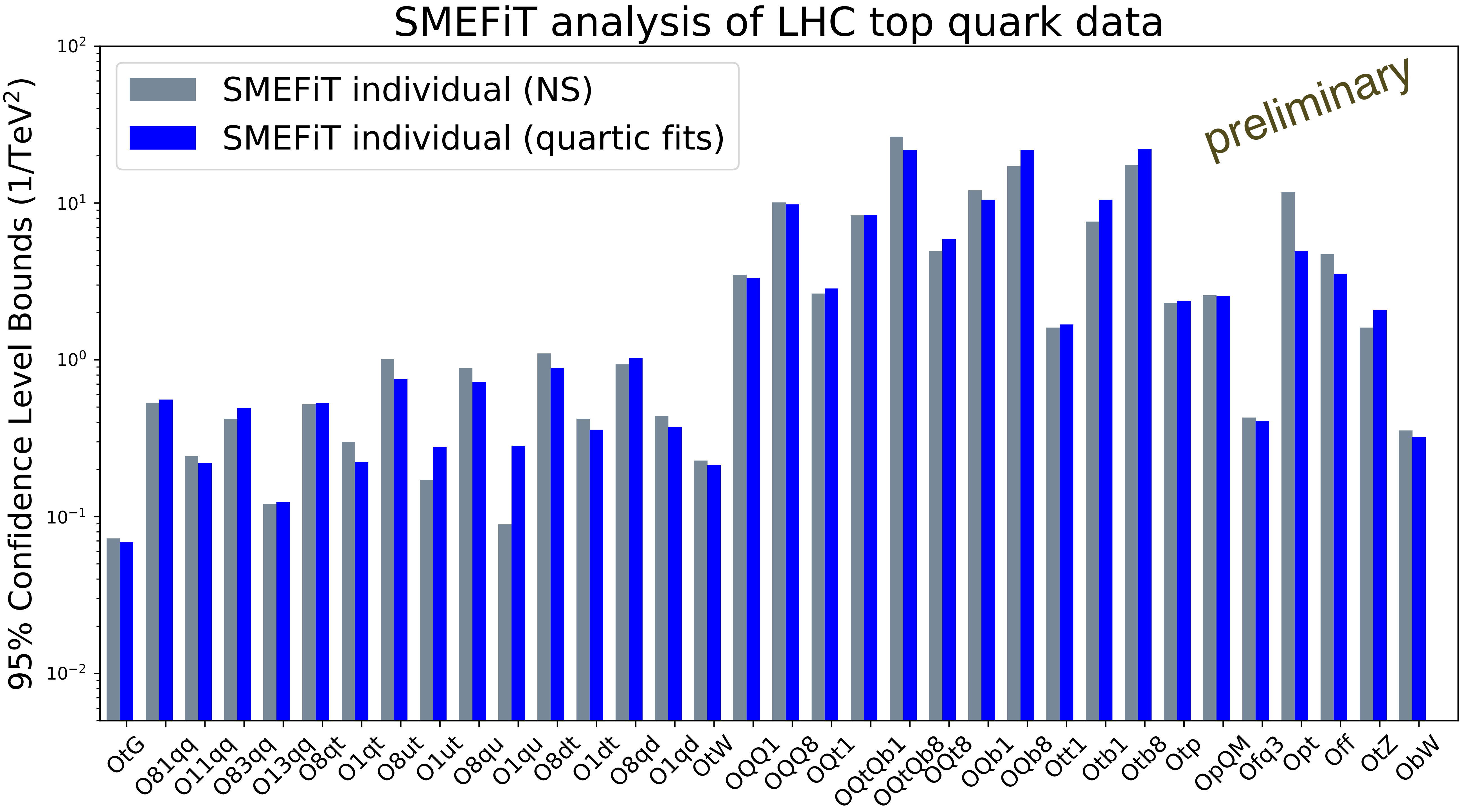
- Samples directly from prior space to locate **regions of maximum likelihood**
- Main advantage: **no need for optimiser** (fitting), cross-validation, …
- Bottleneck: exponential increase in runtime as prior volume increases

Nested Sampling



- In general good agreement with the MCfit approach
- **Fully independent validation** of the SMEFiT results with orthogonal methodology

Nested Sampling



for one-parameter fits, NS reproduces the bounds from **quartic fits to the χ^2 profile**

Restricted scenarios

- **Top-philic scenario** for UV-complete theory: new physics couples preferentially to third generation LH quark doublet and RH quark singlet
- Initial basis of 34 operators now reduced to **22 independent ones**
- These additional theory assumptions lead to more stringent bounds in the SMEFT coefficients (reduction of dimensional of parameter space)

$$c_{t\varphi}^{[I]}, \quad c_{\varphi q}^{-}, \quad c_{\varphi q}^{3}, \quad c_{\varphi t}, \quad c_{tW}^{[I]}, \quad c_{tB}^{[I]}, \quad c_{tG}^{[I]},$$

$$c_{\varphi tb}^{[I]} \quad \text{and} \quad c_{bW}^{[I]} \quad \text{appear proportional to } y_b$$

$$c_{QQ}^{1}, \quad c_{QQ}^{8}, \quad c_{Qt}^{1}, \quad c_{Qt}^{8}, \quad c_{tt}^{1},$$

$$c_{QDW} = c_{Qq}^{3,1} = c_{Ql}^{3(\ell)},$$

$$c_{QDB} = 6c_{Qq}^{1,1} = \frac{3}{2}c_{Qu}^{1} = -3c_{Qd}^{1} = -3c_{Qb}^{1} = -2c_{Ql}^{1(\ell)} = -c_{Qe}^{(\ell)},$$

$$c_{tDB} = 6c_{tq}^{1} = \frac{3}{2}c_{tu}^{1} = -3c_{td}^{1} = -3c_{tb}^{1} = -2c_{tl}^{(\ell)} = -c_{te}^{(\ell)},$$

$$c_{QDG} = c_{Qq}^{8} = c_{Qu}^{8} = c_{Qd}^{8} = c_{Qb}^{8},$$

$$c_{tDG} = c_{tq}^{8} = c_{tu}^{8} = c_{td}^{8} = c_{tb}^{8}.$$

Restricted scenarios

- **Top-philic scenario** for UV-complete theory: new physics couples preferentially to third generation LH quark doublet and RH quark singlet
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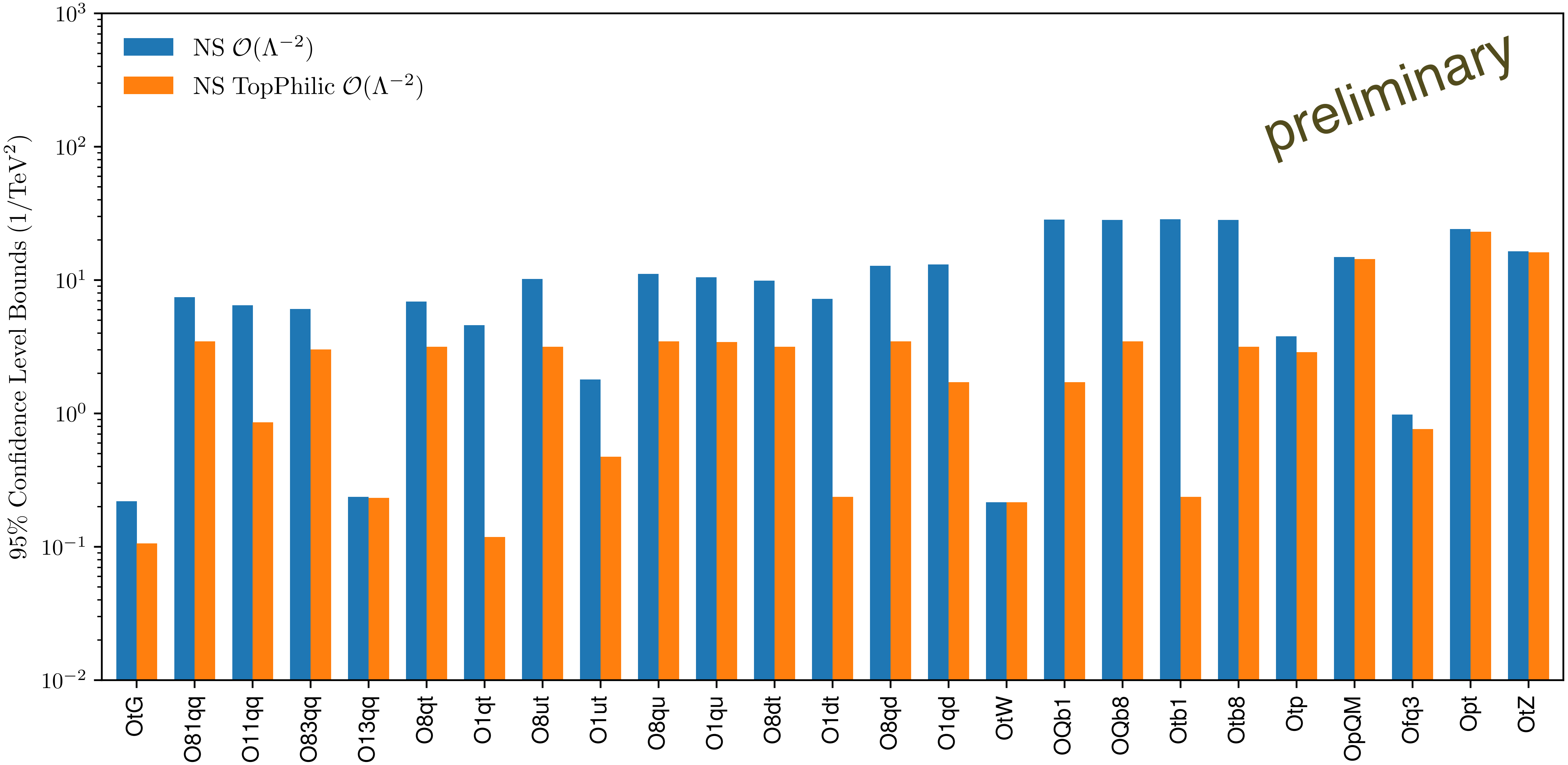
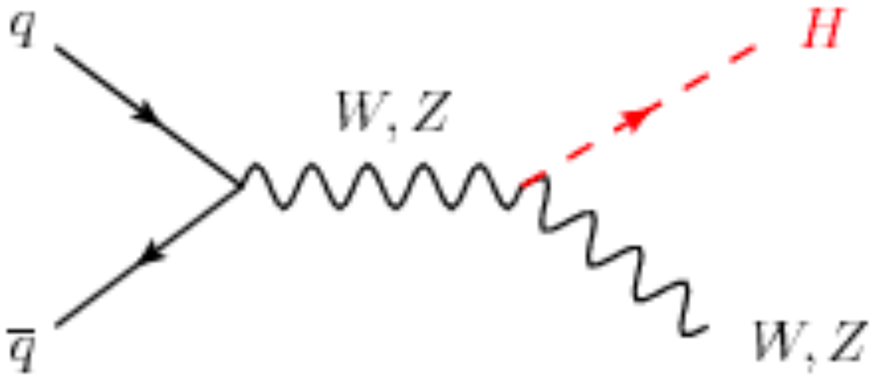
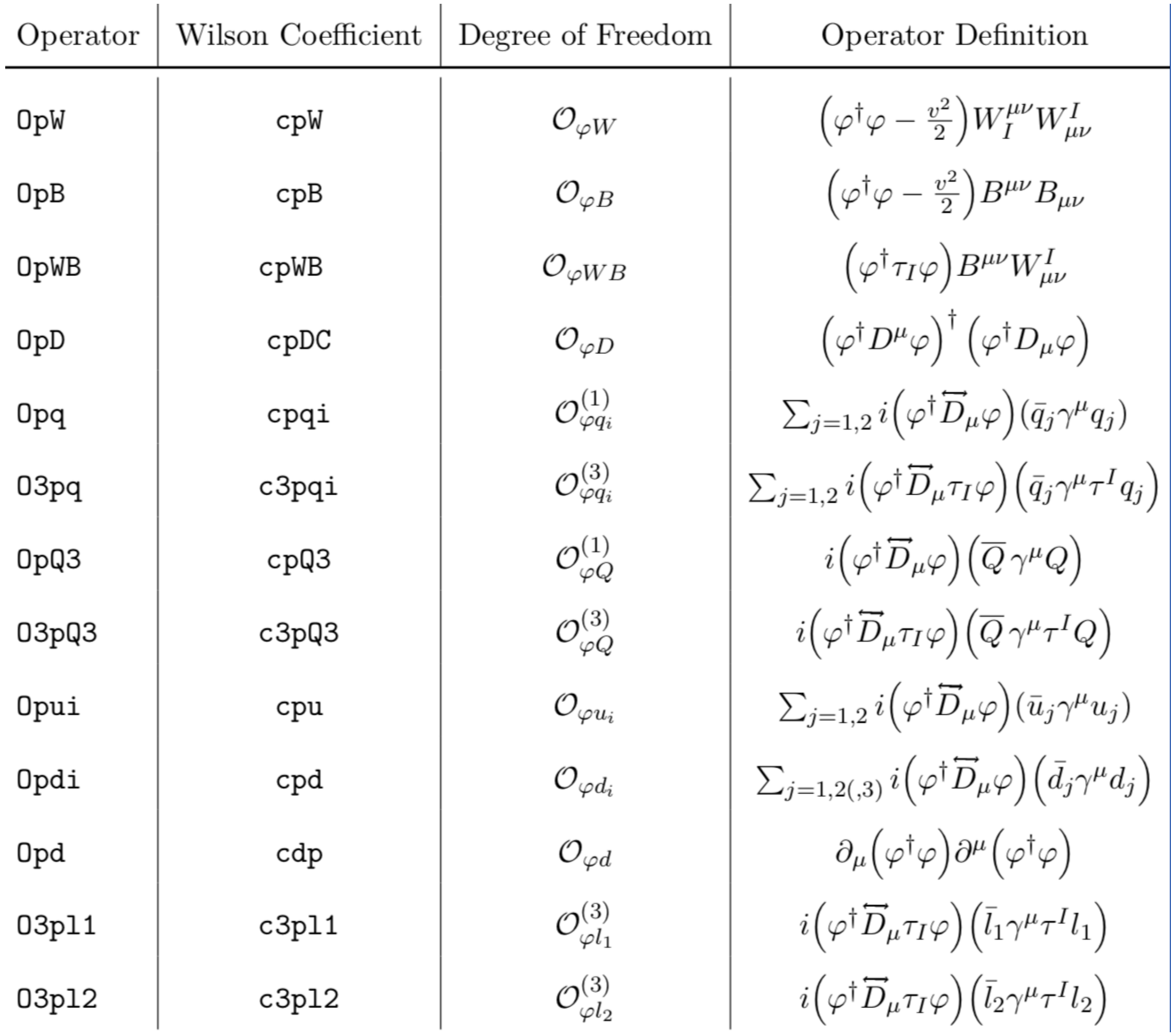


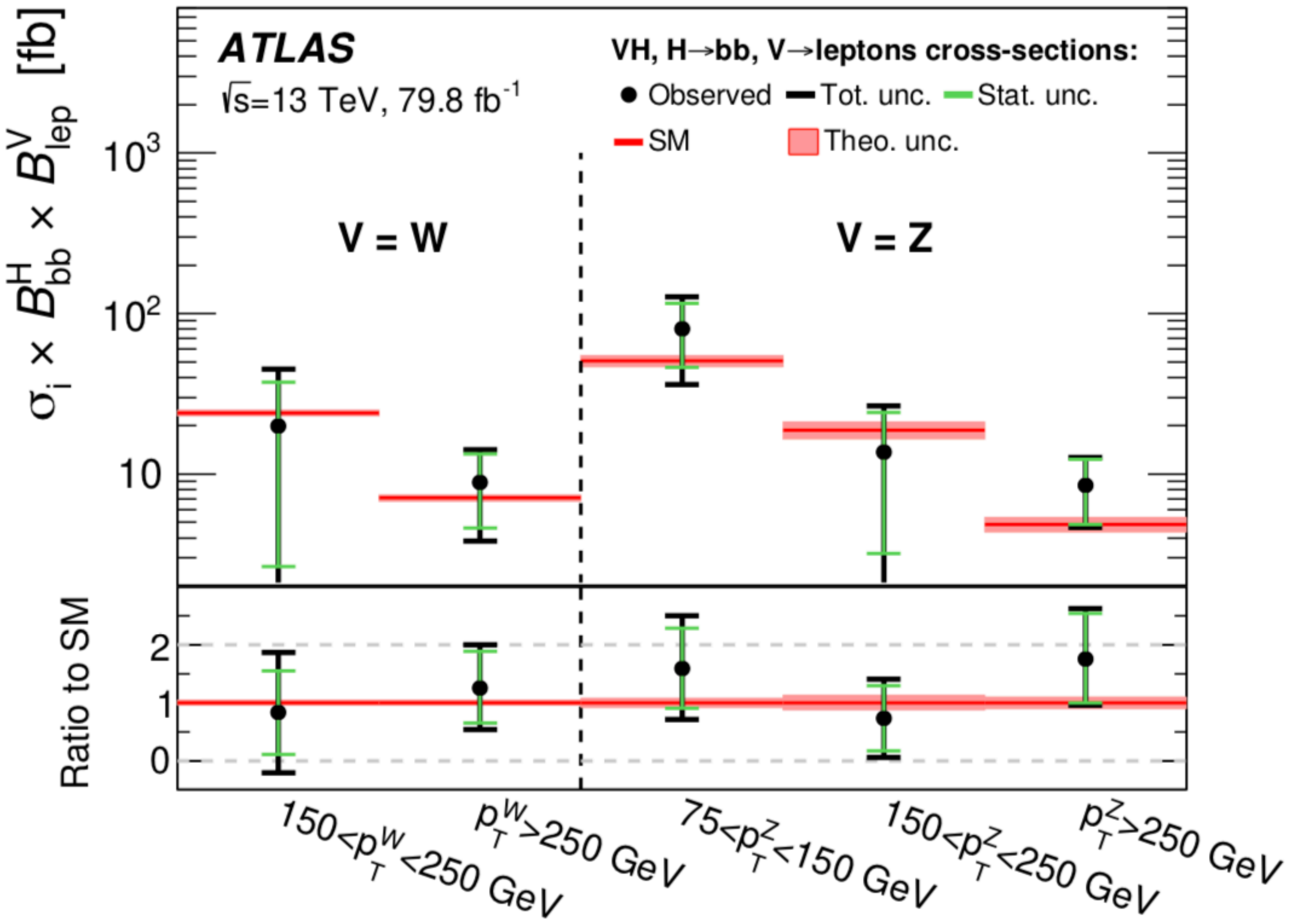
Adding Higgs data



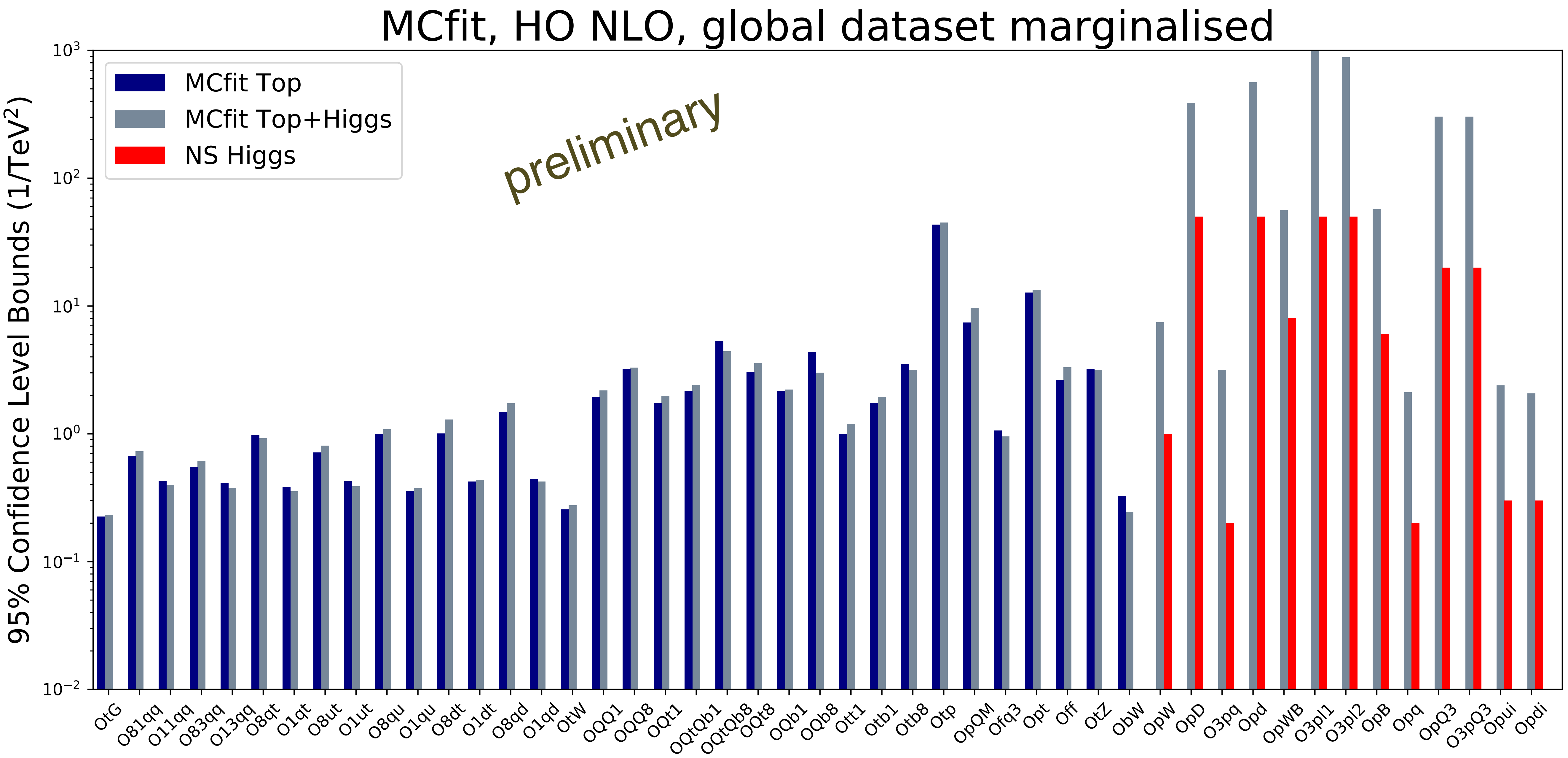
- Case study**:** associated *V+h* production at 13 TeV from ATLAS
- 13 new SMEFT operators, no cross-talk with the top sector
- Only 5 points but probes **several new directions** in parameter space



Operator	Wilson Coefficient	Degree of Freedom	Operator Definition
OpW	cpW	$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)W_I^{\mu\nu}W_{\mu\nu}^I$
OpB	cpB	$\mathcal{O}_{\varphi B}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)B^{\mu\nu}B_{\mu\nu}$
OpWB	cpWB	$\mathcal{O}_{\varphi WB}$	$\left(\varphi^\dagger\tau_I\varphi\right)B^{\mu\nu}W_{\mu\nu}^I$
OpD	cpDC	$\mathcal{O}_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\dagger\left(\varphi^\dagger D_\mu\varphi\right)$
Opq	cpqi	$\mathcal{O}_{\varphi q_i}^{(1)}$	$\sum_{j=1,2} i\left(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi\right)(\bar{q}_j\gamma^\mu q_j)$
O3pq	c3pqi	$\mathcal{O}_{\varphi q_i}^{(3)}$	$\sum_{j=1,2} i\left(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi\right)\left(\bar{q}_j\gamma^\mu\tau^I q_j\right)$
OpQ3	cpQ3	$\mathcal{O}_{\varphi Q}^{(1)}$	$i\left(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi\right)\left(\overline{Q}\,\gamma^\mu Q\right)$
O3pQ3	c3pQ3	$\mathcal{O}_{\varphi Q}^{(3)}$	$i\left(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi\right)\left(\overline{Q}\,\gamma^\mu\tau^I Q\right)$
Opui	cpu	$\mathcal{O}_{\varphi u_i}$	$\sum_{j=1,2} i\left(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi\right)(\bar{u}_j\gamma^\mu u_j)$
Opdi	cpd	$\mathcal{O}_{\varphi d_i}$	$\sum_{j=1,2(,3)} i\left(\varphi^\dagger\overleftrightarrow{D}_\mu\varphi\right)\left(\bar{d}_j\gamma^\mu d_j\right)$
Opd	cdp	$\mathcal{O}_{\varphi d}$	$\partial_\mu\left(\varphi^\dagger\varphi\right)\partial^\mu\left(\varphi^\dagger\varphi\right)$
O3pl1	c3pl1	$\mathcal{O}_{\varphi l_1}^{(3)}$	$i\left(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi\right)\left(\bar{l}_1\gamma^\mu\tau^I l_1\right)$
O3pl2	c3pl2	$\mathcal{O}_{\varphi l_2}^{(3)}$	$i\left(\varphi^\dagger\overleftrightarrow{D}_\mu\tau_I\varphi\right)\left(\bar{l}_2\gamma^\mu\tau^I l_2\right)$



Adding Higgs data



constraints **47 independent directions** in the SMEFT parameter space:

one of the most ambitious SMEFT analysis to date

Constraining the SMEFT with Bayesian inference

S. van Beek, E. R. Nocera, J. Rojo, and E. Slade,

arXiv:1906.05296 *(submitted to SciPost)*

Bayesian reweighting

- Under many circumstances, one would like to **quantify the impact of a new measurement** in the SMEFT parameter space **without having to redo the full analysis**
- One would also like to quantify (and compare) the **amount of information** contained in current and (possible) future measurements

Bayesian Inference tells us how to update (``reweight") the SMEFiT probability distribution with the information provided by **new measurements**

$$\omega_k \propto \left(\chi^2_k\right)^{(n_{\rm dat}-1)/2} \exp\left(-\chi^2_k/2\right) \, , \quad k = 1,\ldots,N_{\rm rep}$$

weight of k-th replica

number of data points in new data

total χ^2 of new data for k-th replica

MC replicas of a prior fit

- Extensive **validation** of reweighing by comparison with **direct fits** carried out in the PDF case. What about the SMEFT parameter space?

Bayesian reweighting

- Start from a variant of SMEFiT which excludes **LHC single top production data**

- To ensure sufficient statistics, this prior is constructed with **N_{rep} = 10000 MC replicas**

- Then add different combinations of single top data either by **reweighting** or by a **direct fit** and compare the results

- The amount of new information in each case is quantified by Shannon's entropy: the **effective number of replicas**

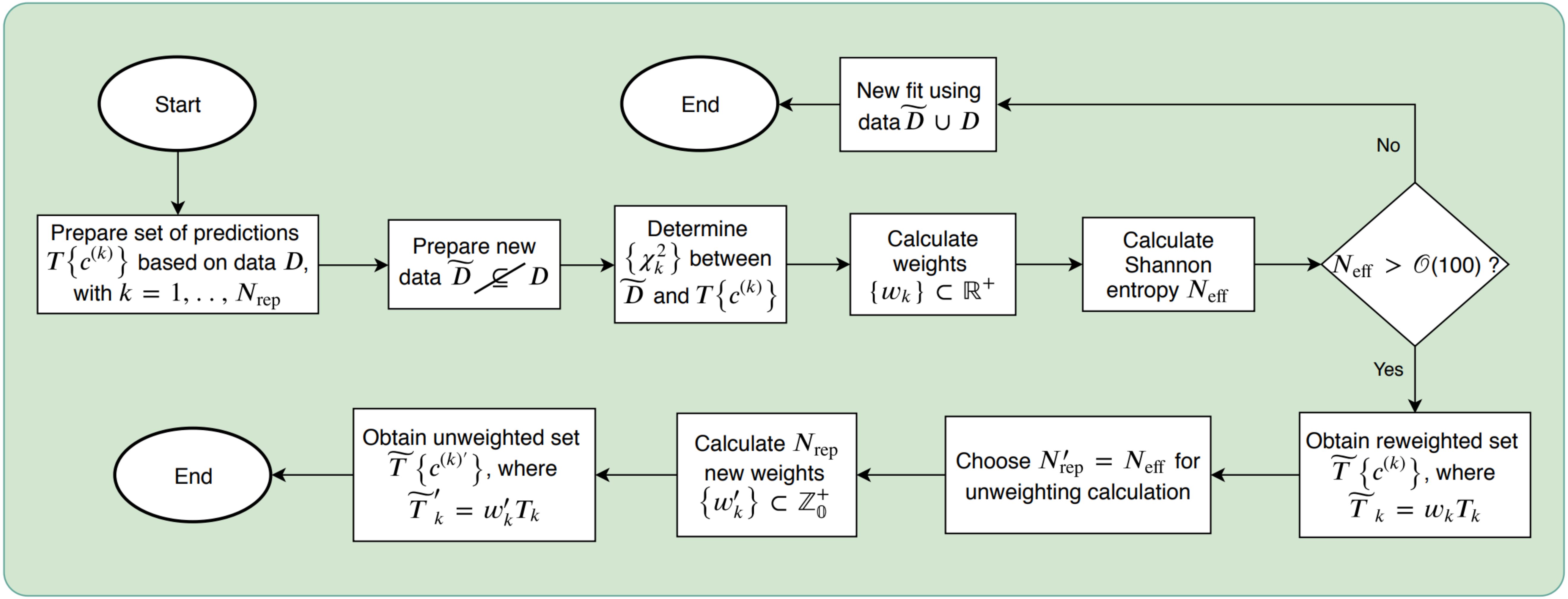
$$N_{\rm eff} = \exp\left(\frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} \omega_k \ln \frac{N_{\rm rep}}{\omega_k} \right)$$

- For Bayesian reweighting to be used reliably, one requires that **$N_{eff} > 50$,** else we run **out of statistics** and a direct refit is required

Bayesian reweighting

- To identify which SMEFT directions are more constrained by the new data, evaluate the Kolmogorov-Smirnov statistic between the **prior** and **reweighted probability distributions:** the larger the KS-statistic, the larger the effect of the new data

- Note that information can be added *(i)* due to **new direct constraints** and/or *(ii)* by **breaking degeneracies** in the parameter space



Start

Prepare set of predictions $T\{c^{(k)}\}$ based on data D, with $k = 1, \ldots, N_{\rm rep}$

Prepare new data $\widetilde{D} \not\subseteq D$

Determine $\{\chi^2_k\}$ between $\widetilde{D}$ and $T\{c^{(k)}\}$

Calculate weights $\{w_k\} \subset \mathbb{R}^+$

Calculate Shannon entropy $N_{\rm eff}$

$N_{\rm eff} > \mathcal{O}(100)$?

No

New fit using data $\widetilde{D} \cup D$

End

Yes

Obtain reweighted set $\widetilde{T}\{c^{(k)}\}$, where $\widetilde{T}_k = w_k T_k$

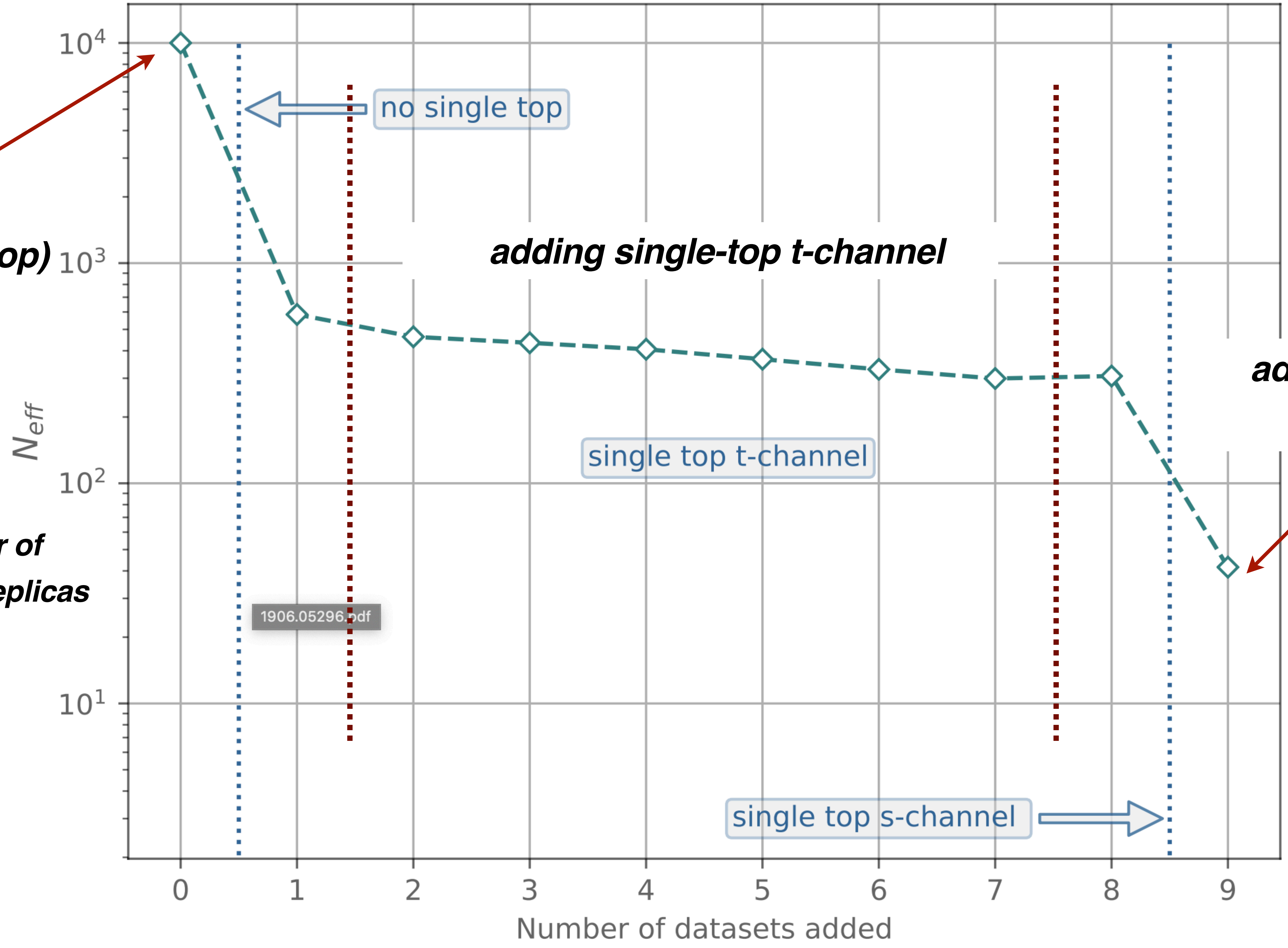
Choose $N'_{\rm rep} = N_{\rm eff}$ for unweighting calculation

Calculate $N_{\rm rep}$ new weights $\{w'_k\} \subset \mathbb{Z}^+_0$

Obtain unweighted set $\widetilde{T}\{c^{(k)'}\}$, where $\widetilde{T}'_k = w'_k T_k$

End

Reweighting efficiency



prior fit
(no single top)

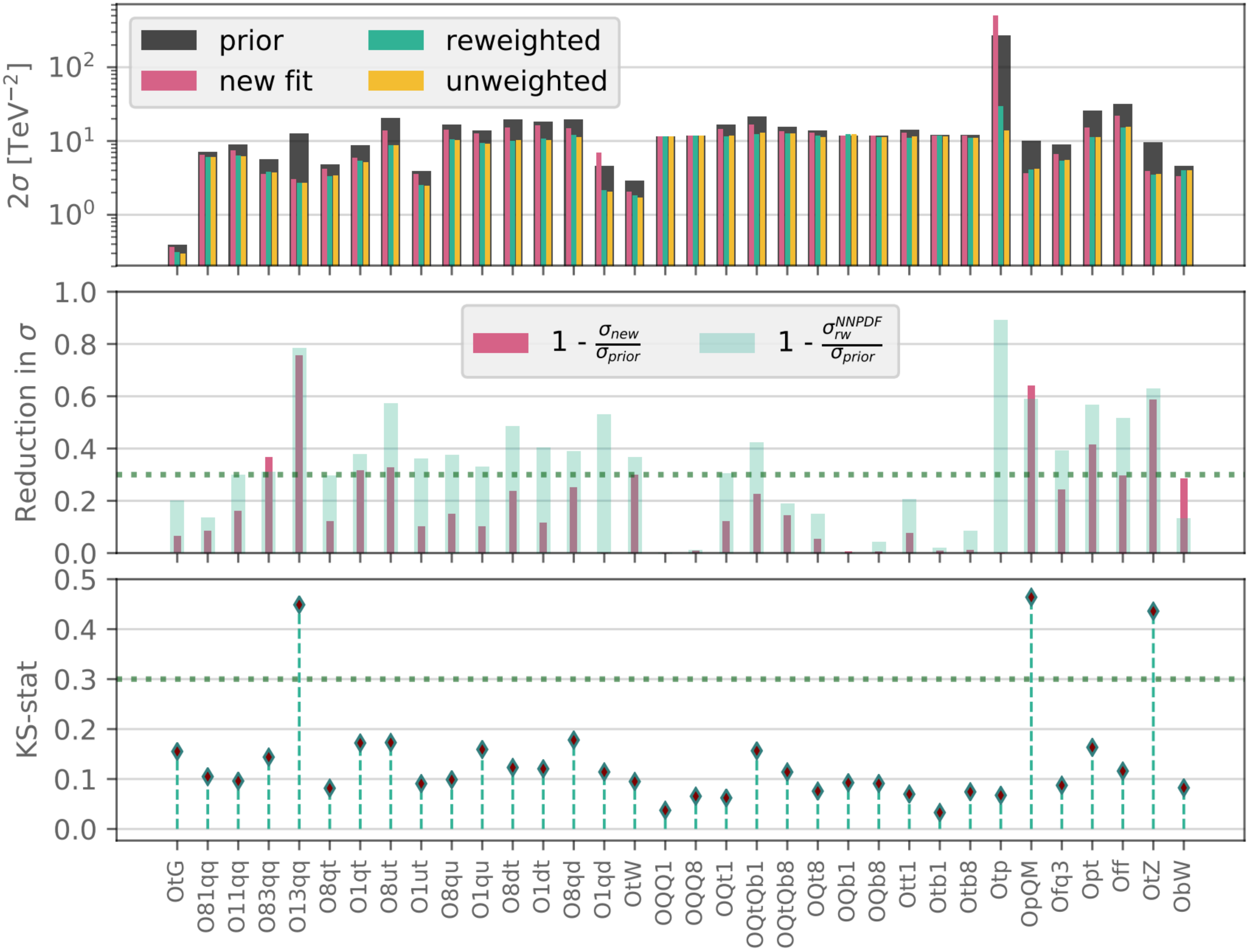
adding single-top t-channel

adding single-top
s-channel

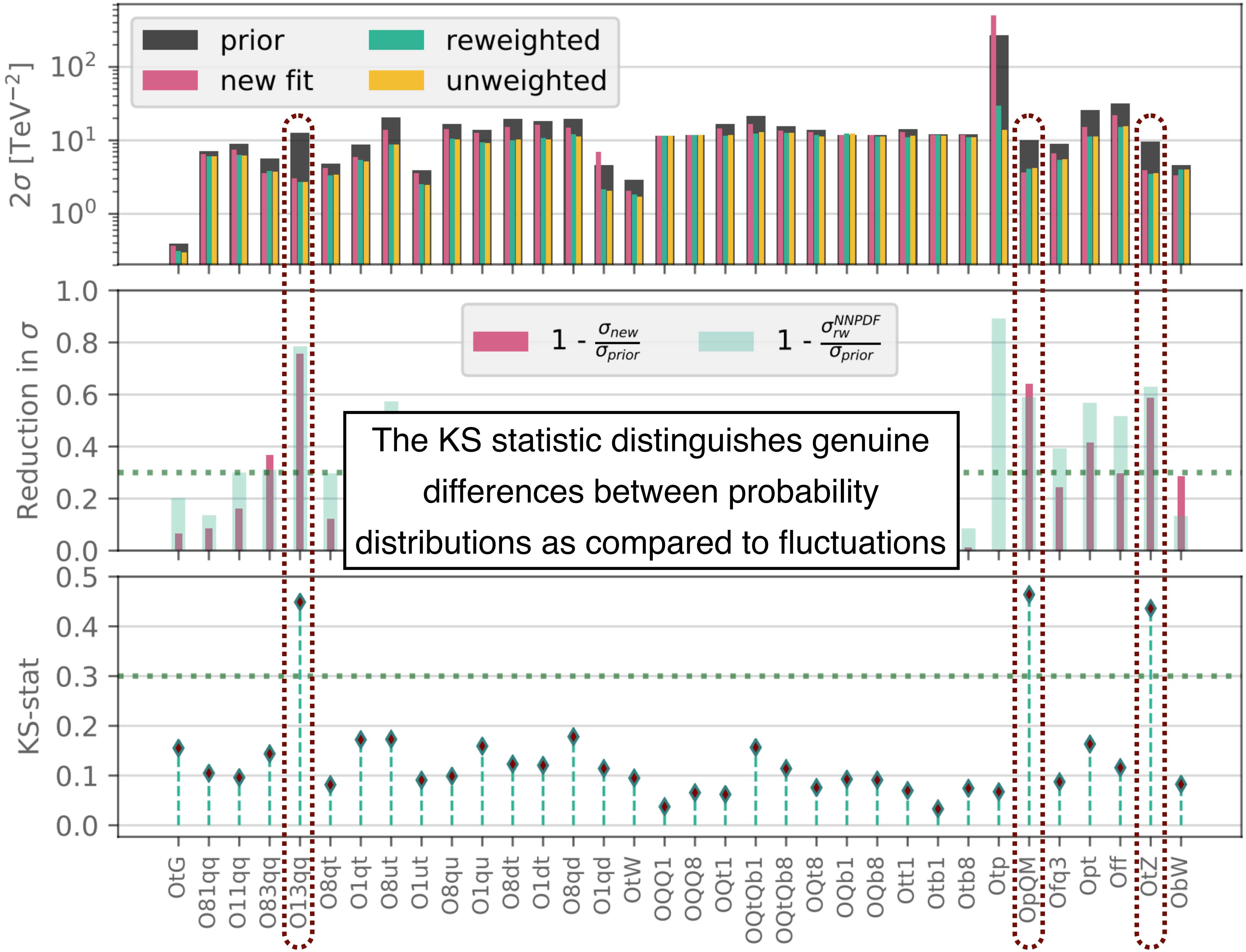
number of
effective replicas

Significant amount of **new information** each time new process added via reweighting: marked decrease in effective number of replicas

Results: adding single top t-channel

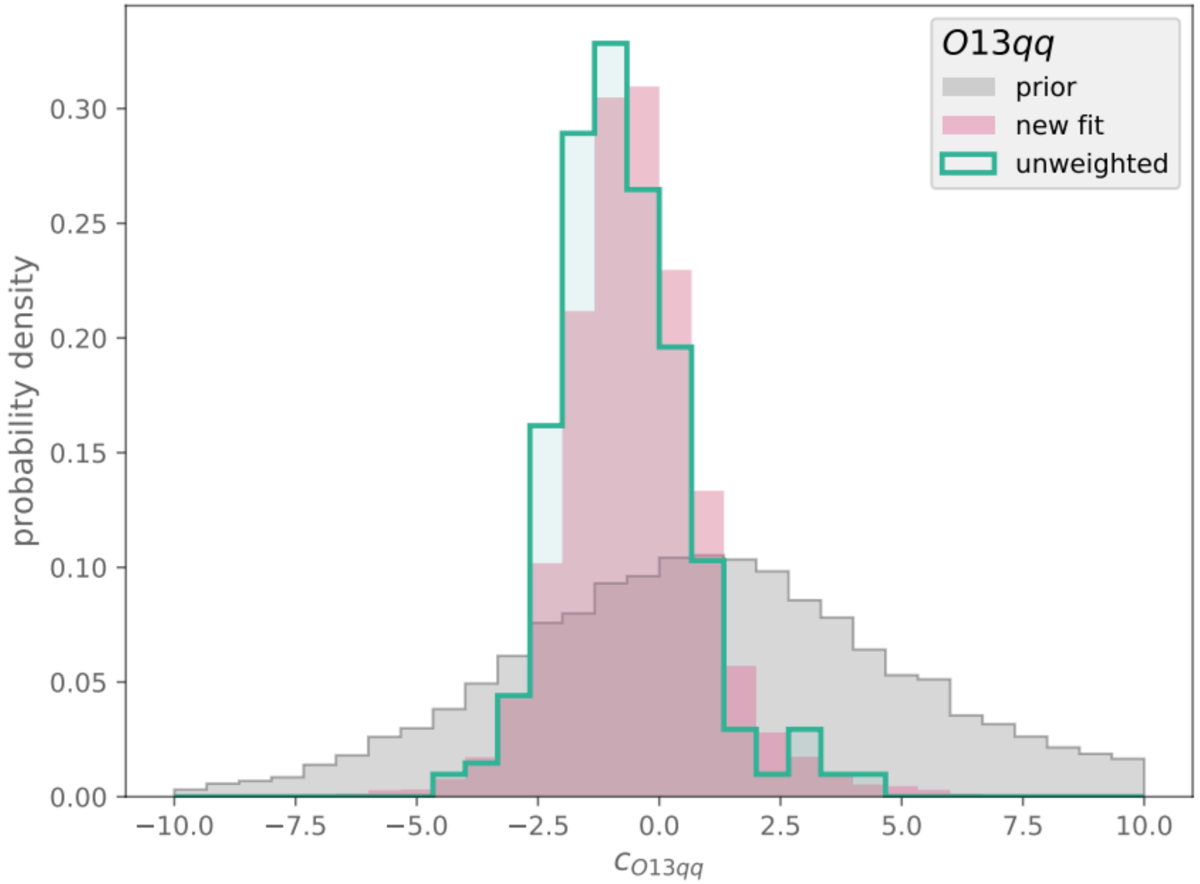


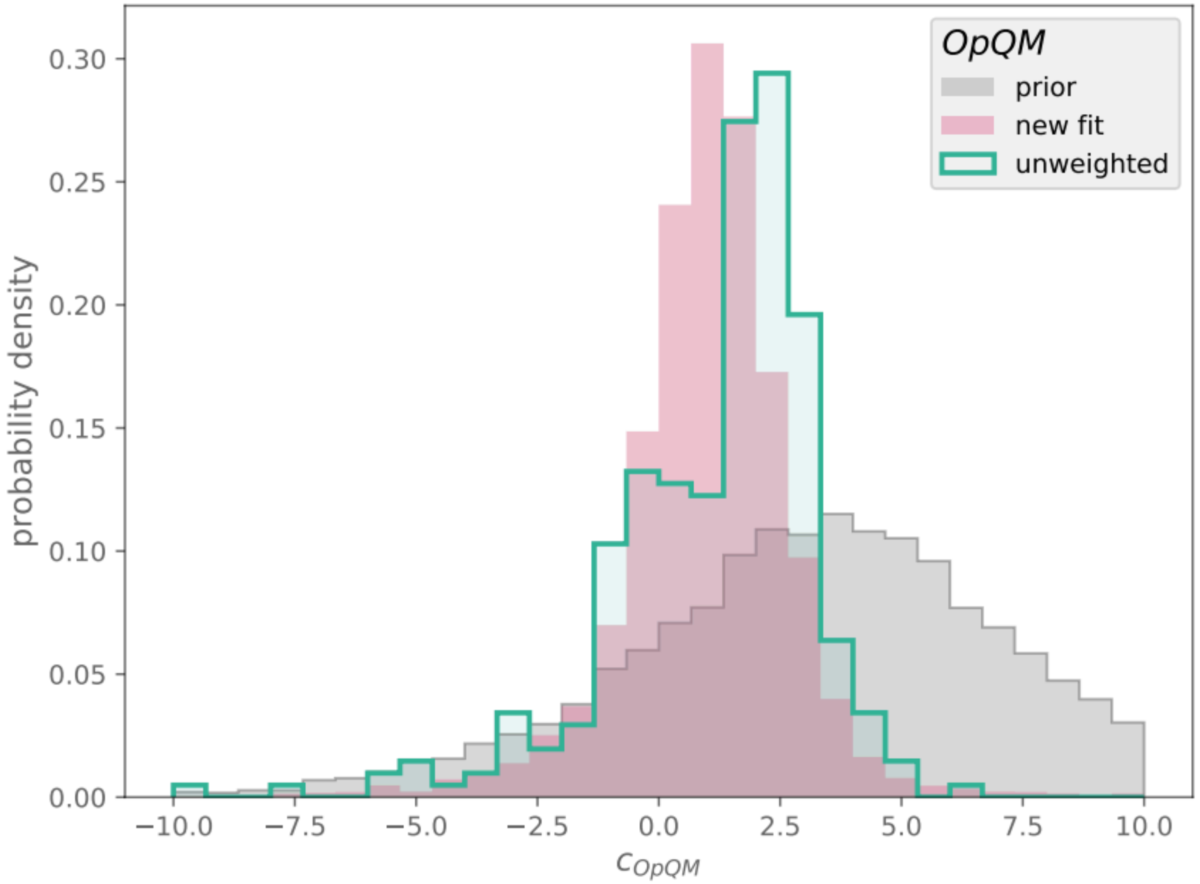
Results: adding single top t-channel

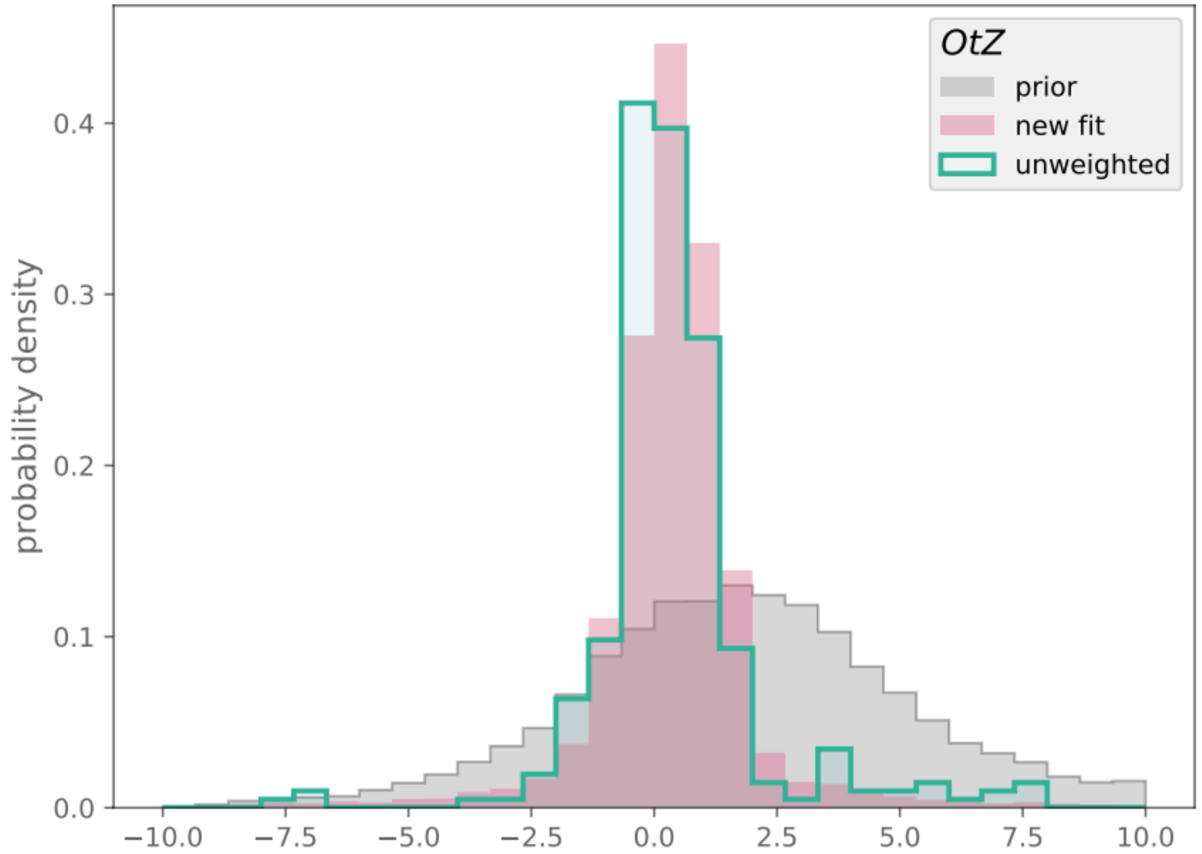


The KS statistic distinguishes genuine differences between probability distributions as compared to fluctuations

Results: adding single top t-channel







- Good agreement between the probability distributions after a new fit and when using bayesian reweighting

- Provided ***N*_*eff*** is large enough, fit and reweighed results are indistinguishable

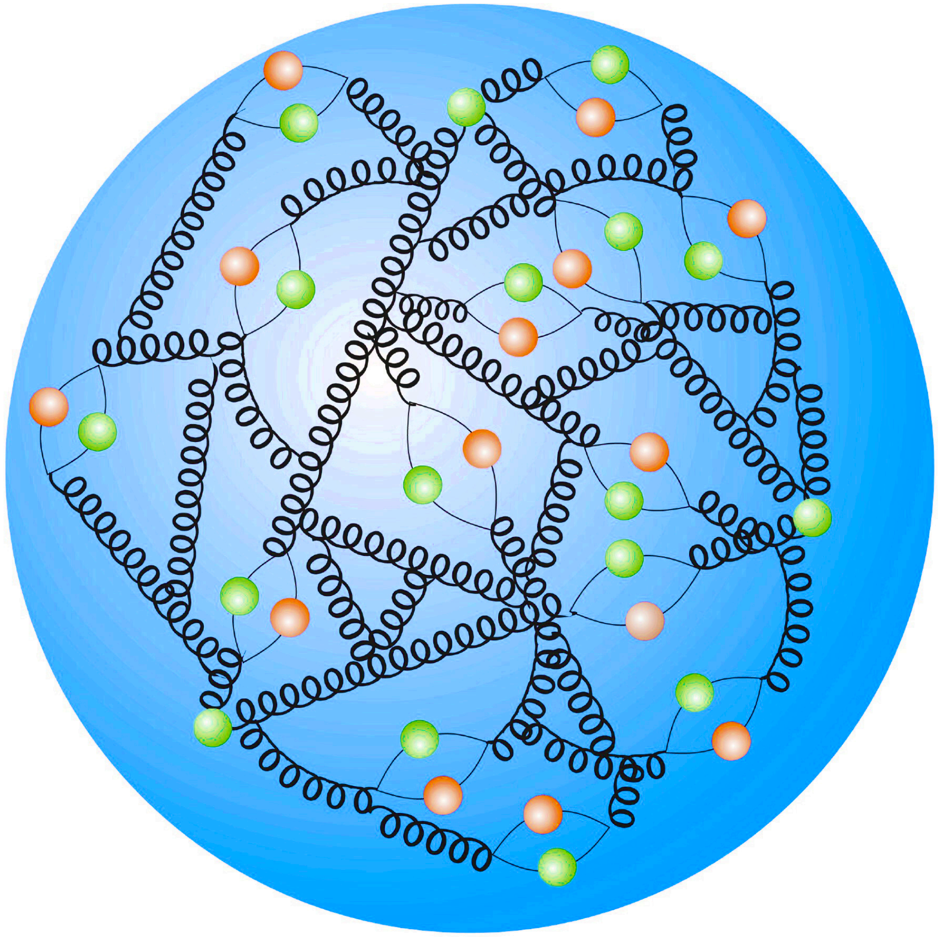
Can New Physics Hide Inside the Proton?

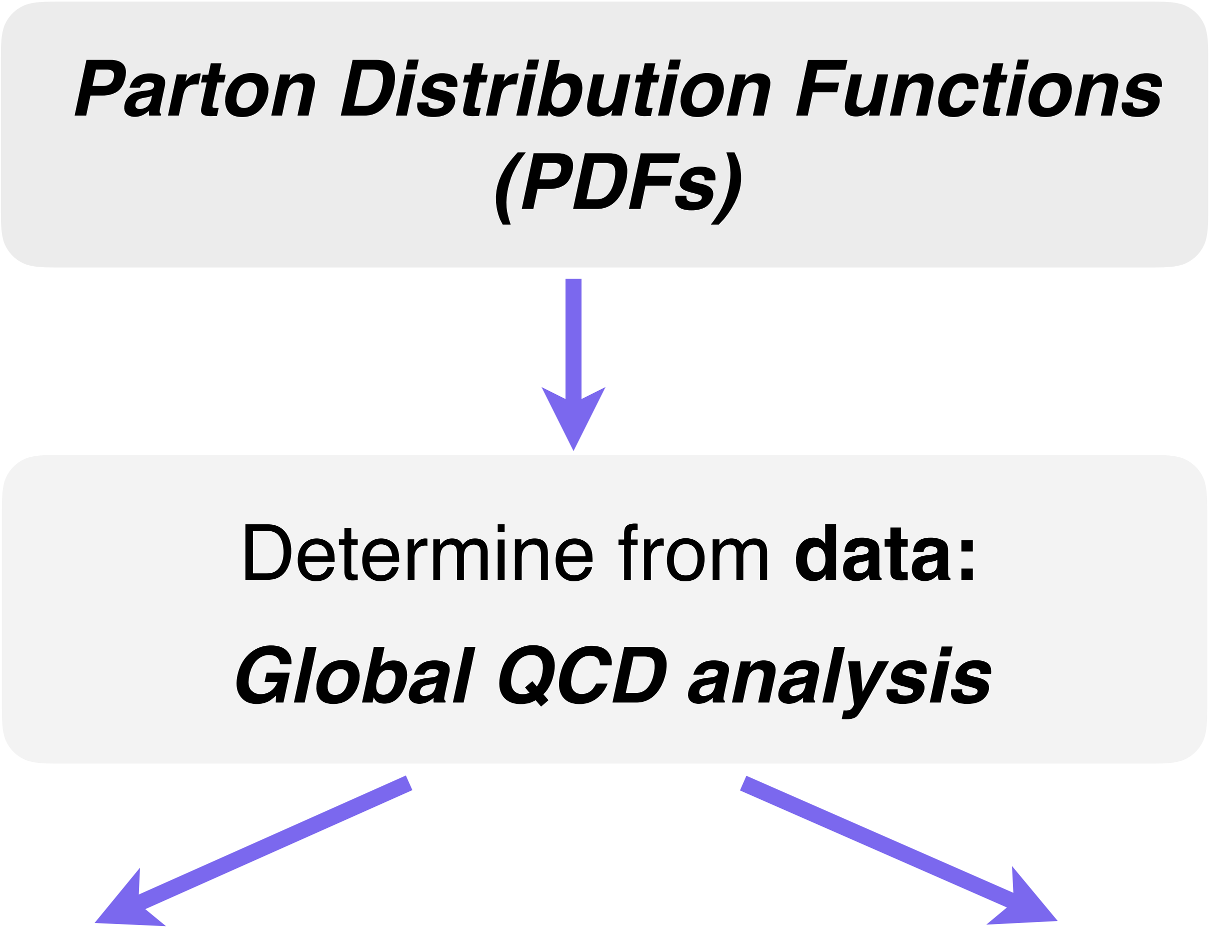
S. Carrazza, C. Degrande, S. Iranipour, J. Rojo, and M. Ubiali

arXiv:1905.05215* (*PRL)

Proton structure: parton distributions

Proton energy divided among constituents: **quarks** and **gluons**





Parton Distribution Functions (PDFs)

Determine from **data:**

Global QCD analysis

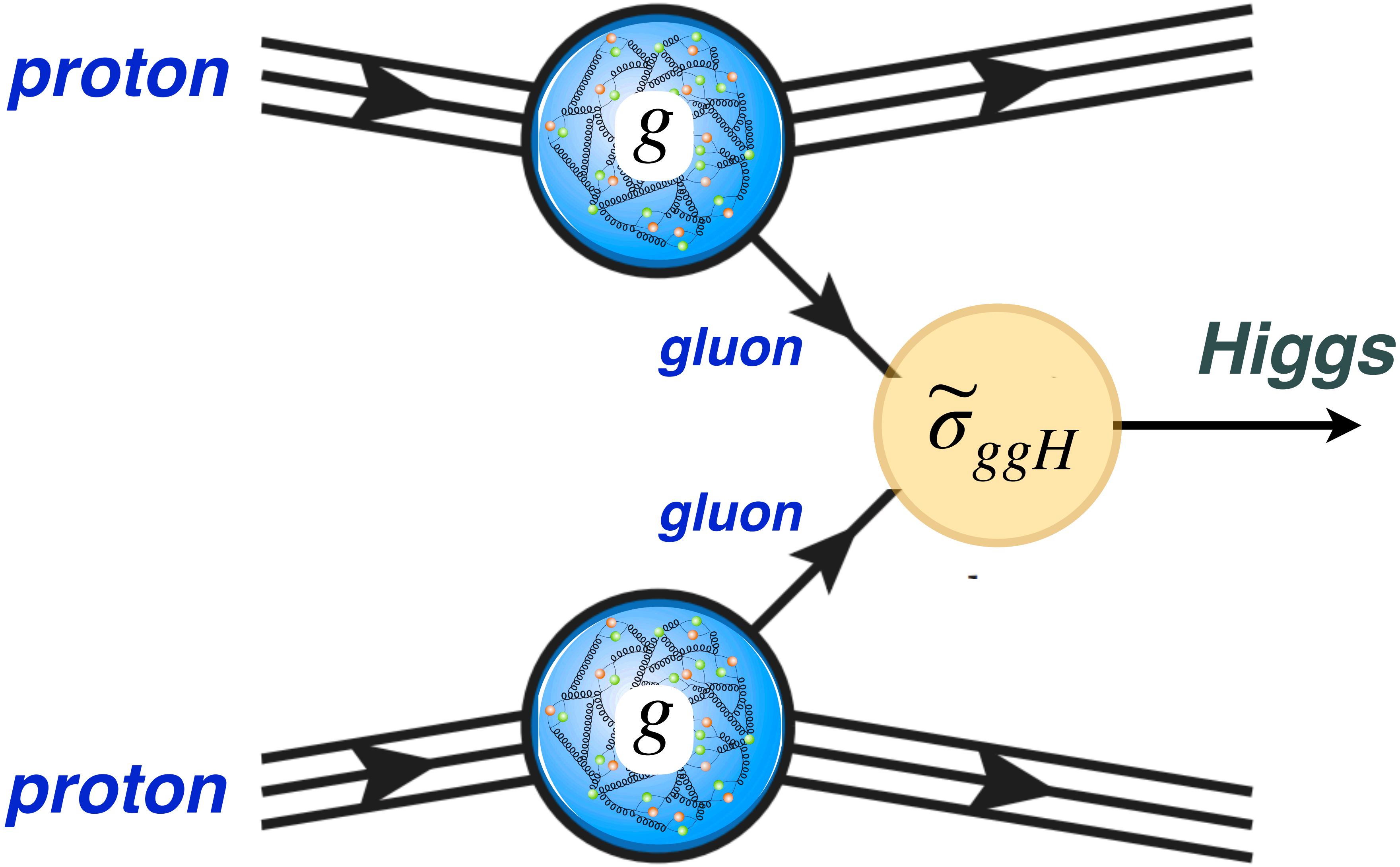
Mass? Spin?
Heavy quark content?
Novel QCD dynamics?

Theoretical predictions
for LHC, RHIC, IceCube?

Proton structure: parton distributions

$$N_{\mathrm{LHC}}(H) \sim g \otimes g \otimes \tilde{\sigma}_{ggH}$$

Parton Distributions



All-order structure: **QCD factorisation theorems**

Parton Distributions

$$g(x, Q)$$

Energy of hard-scattering reaction**:**
inverse of resolution length

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

- **Energy conservation**: momentum sum rule

$$\int_0^1 dx\, x \left(\sum_{i=1}^{n_f} \left[q_i((x,Q^2) + \bar{q}_i(x,Q^2) \right] + g(x,Q^2) \right) = 1$$

- **Quark number conservation**: valence sum rules

$$\int_0^1 dx\, \left(u(x,Q^2) + \bar{u}(x,Q^2) \right) = 2$$

Parton Distributions

$$g(x, Q)$$

Energy of hard-scattering reaction**:**
inverse of resolution length

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Dependence on ***Q*** fixed by **perturbative QCD dynamics**: computed up to $\mathcal{O}\left(\alpha_s^4\right)$

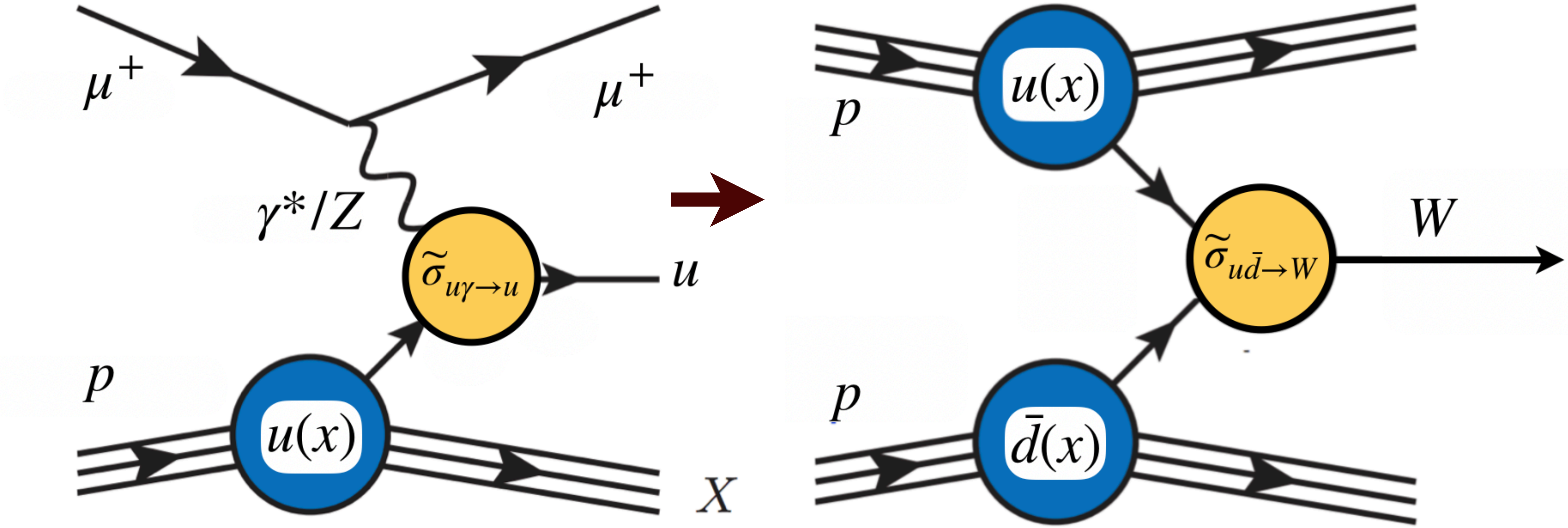
$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) q_j(z, Q^2)$$

***DGLAP** parton evolution equations*

The Global QCD analysis paradigm

QCD factorisation theorems: **PDF universality**

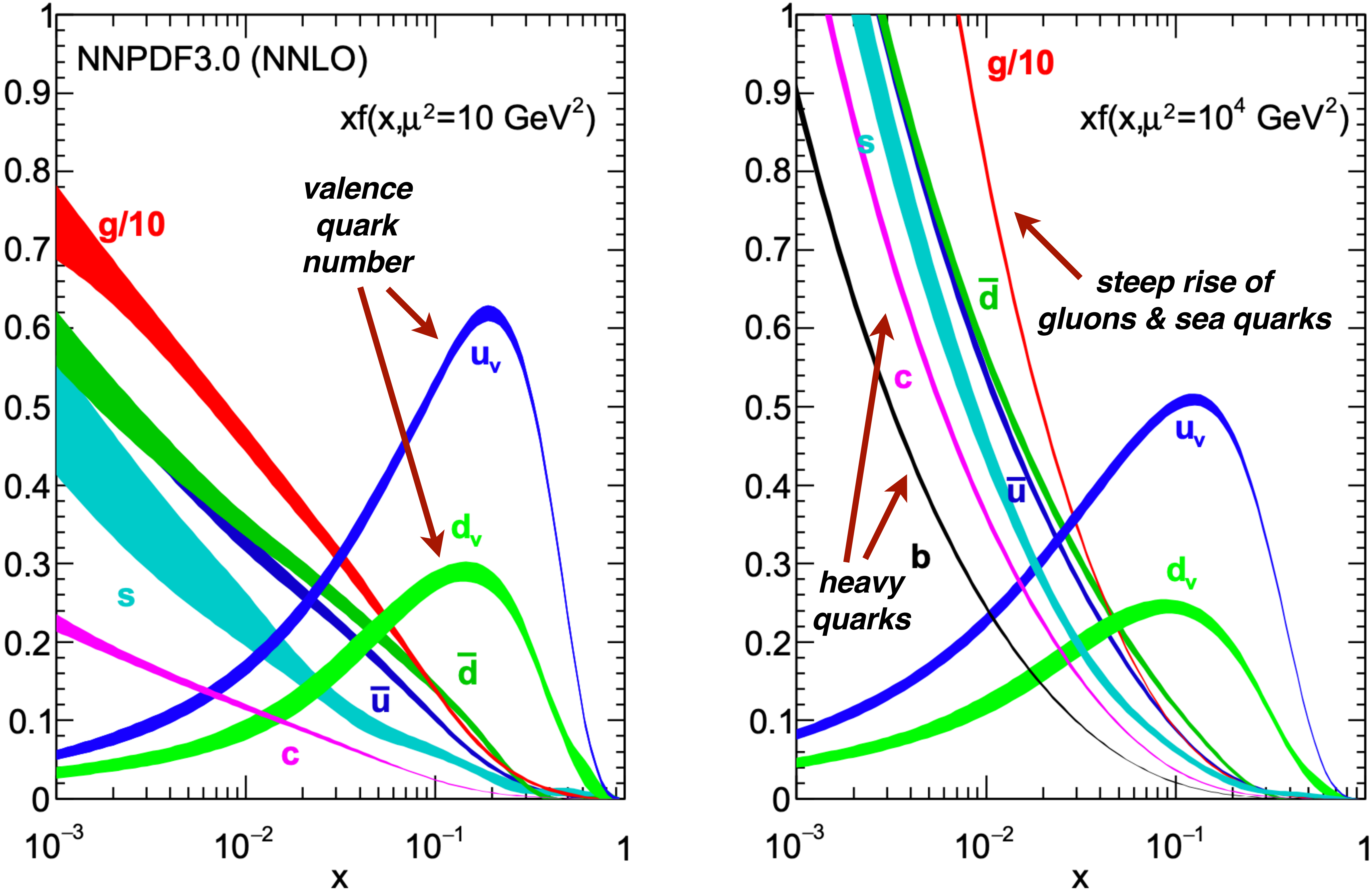
$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \quad \rightarrow \quad \sigma_{p\,p\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$



*Determine PDFs from **deep-inelastic scattering**…*

*… and use them to compute predictions for **proton-proton collisions***

A proton structure snapshop

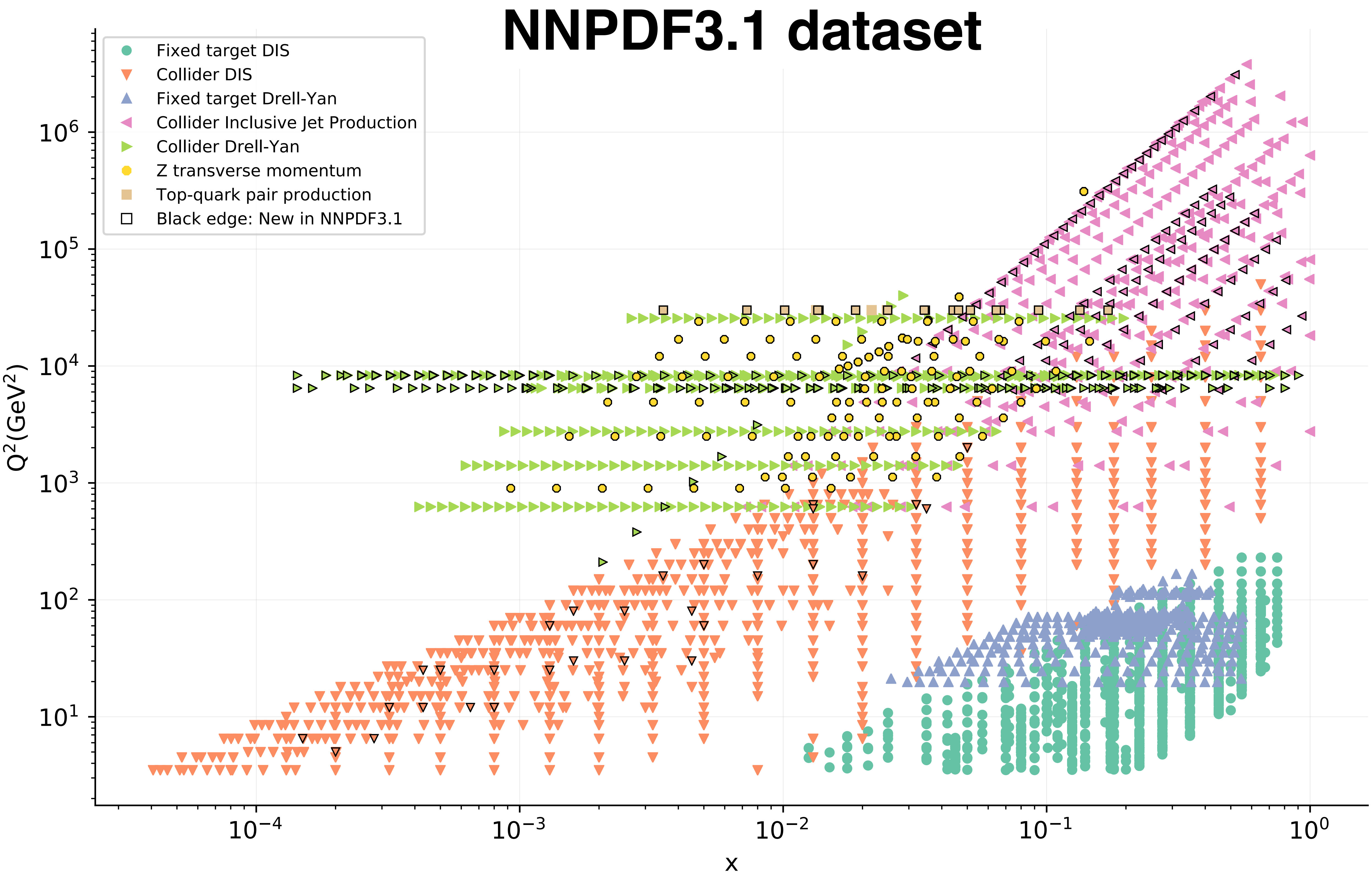


valence quark number

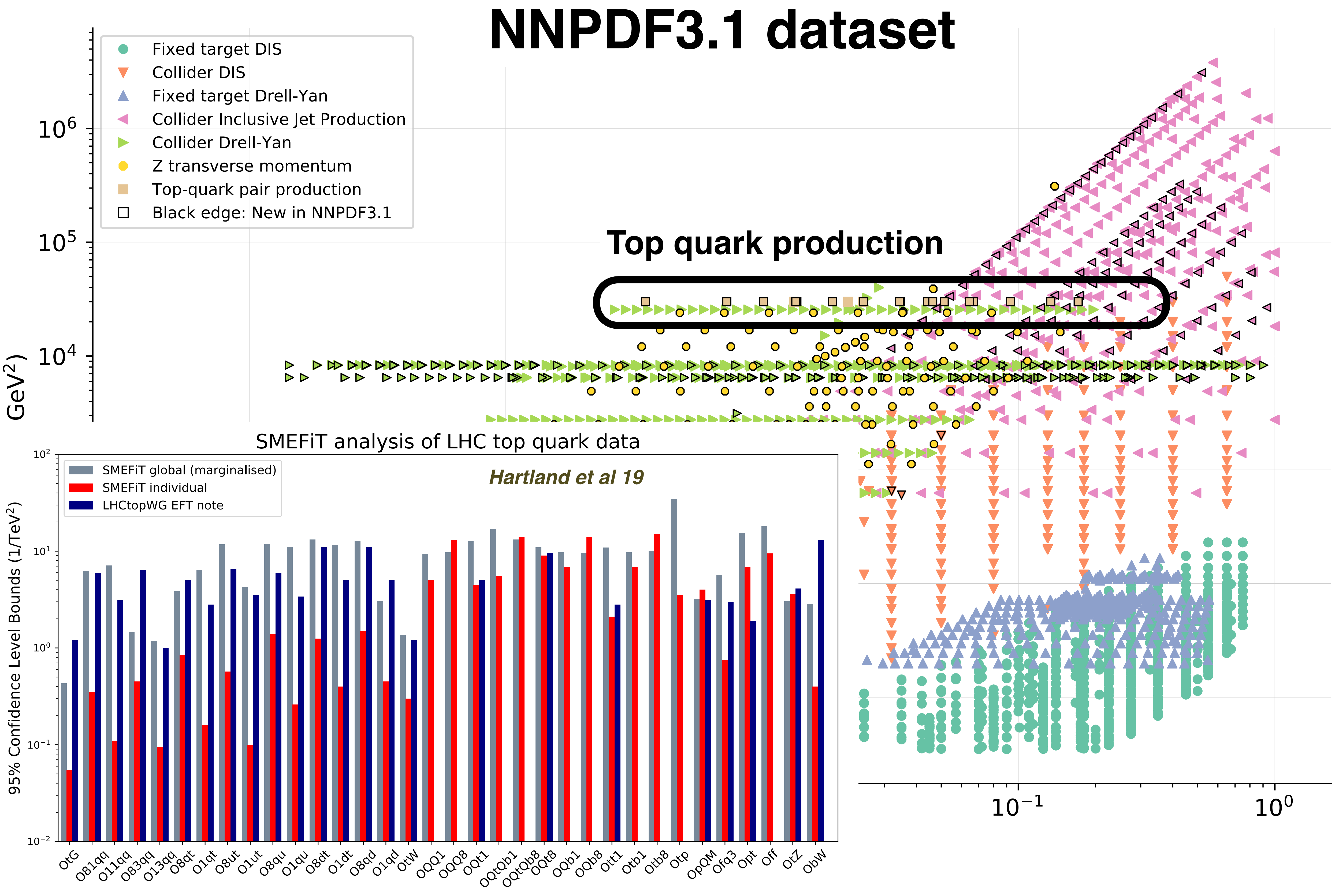
steep rise of gluons & sea quarks

heavy quarks

SMEFT & PDFs


NNPDF3.1 dataset
● Fixed target DIS
▼ Collider DIS
▲ Fixed target Drell-Yan
◀ Collider Inclusive Jet Production
▶ Collider Drell-Yan
● Z transverse momentum
■ Top-quark pair production
☐ Black edge: New in NNPDF3.1
$Q^2(\mathrm{GeV}^2)$
10^1
10^2
10^3
10^4
10^5
10^6
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
x

SMEFT & PDFs


NNPDF3.1 dataset
Fixed target DIS
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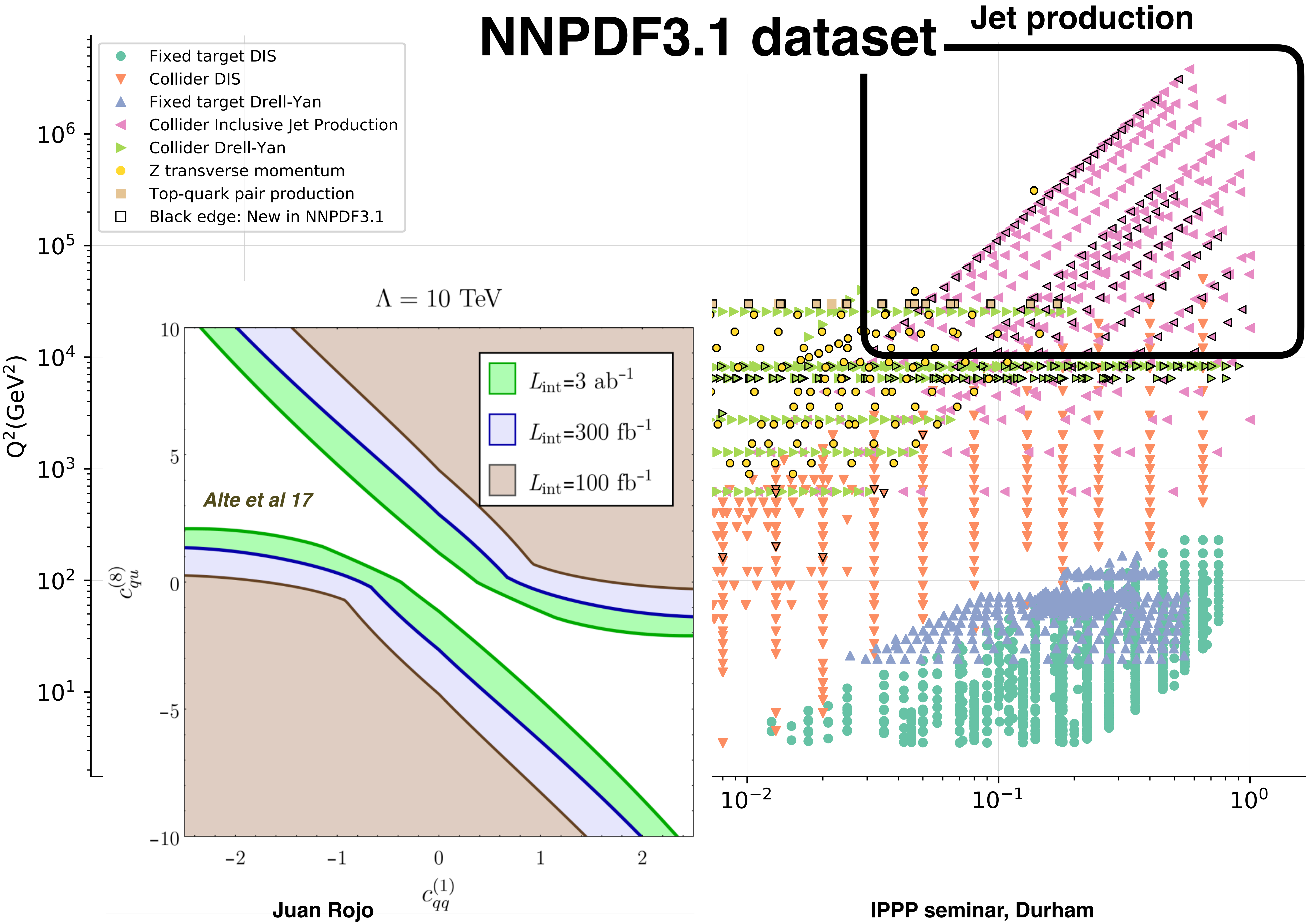
Black edge: New in NNPDF3.1
10^6
10^5
10^4
GeV^2)
10^{-1}
10^0
Top quark production
SMEFiT analysis of LHC top quark data
SMEFiT global (marginalised)
SMEFiT individual
LHCtopWG EFT note
Hartland et al 19
95% Confidence Level Bounds (1/TeV^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
OtG
O81qq
O11qq
O83qq
O13qq
O8qt
O1qt
O8ut
O1ut
O8qu
O1qu
O8dt
O1dt
O8qd
O1qd
OtW
OQQ1
OQQ8
OQt1
OQtQb1
OQtQb8
OQt8
OQb1
OQb8
Ott1
Otb1
Otb8
Otp
OpQM
Ofq3
Opt
Off
OtZ
ObW

SMEFT & PDFs

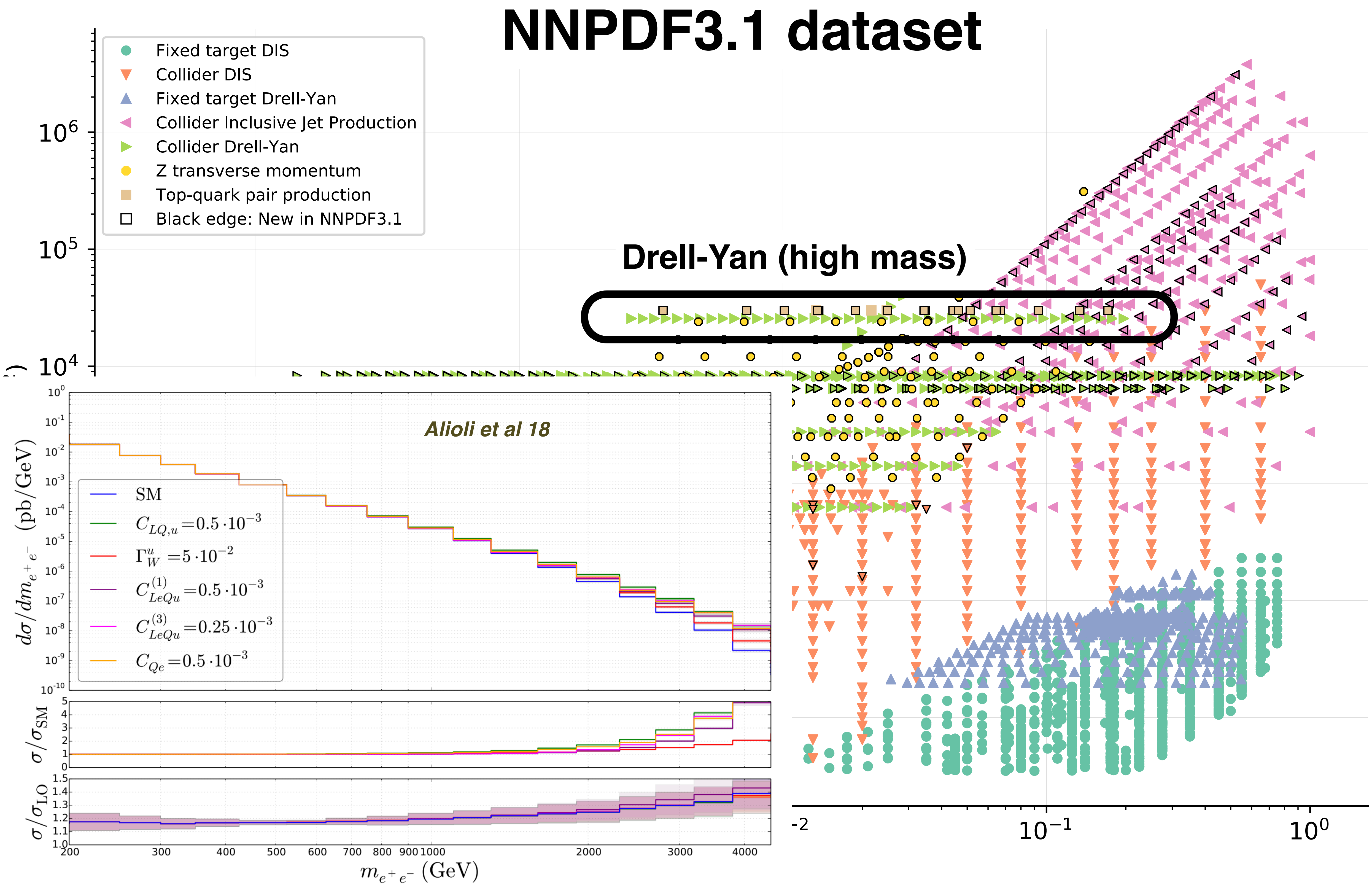


NNPDF3.1 dataset

Jet production

Alte et al 17

SMEFT & PDFs



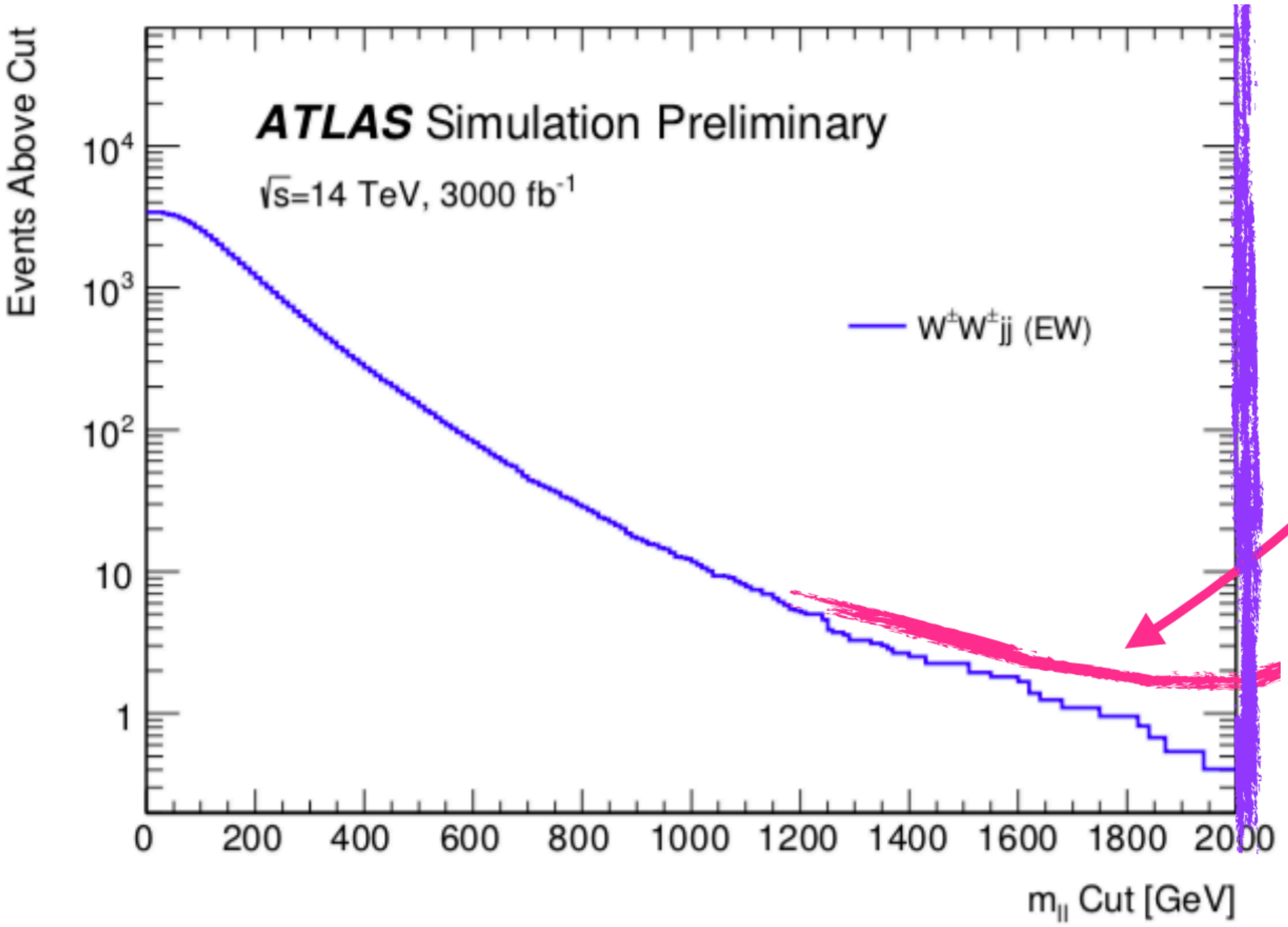
NNPDF3.1 dataset

Drell-Yan (high mass)

Alioli et al 18

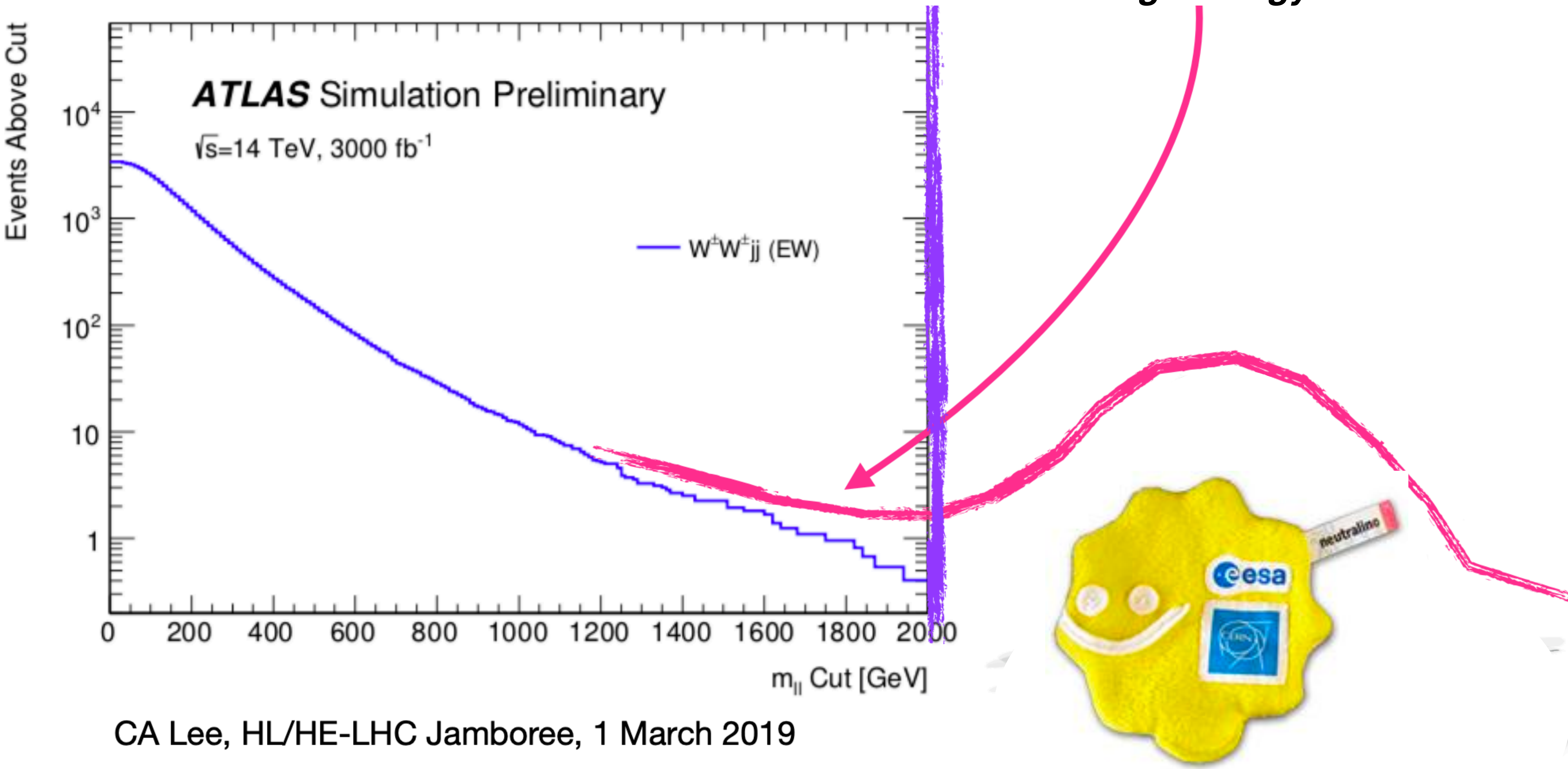
Why do we need better PDFs?

Deviation from SM prediction in high energy tails?



CA Lee, HL/HE-LHC Jamboree, 1 March 2019

Why do we need better PDFs?



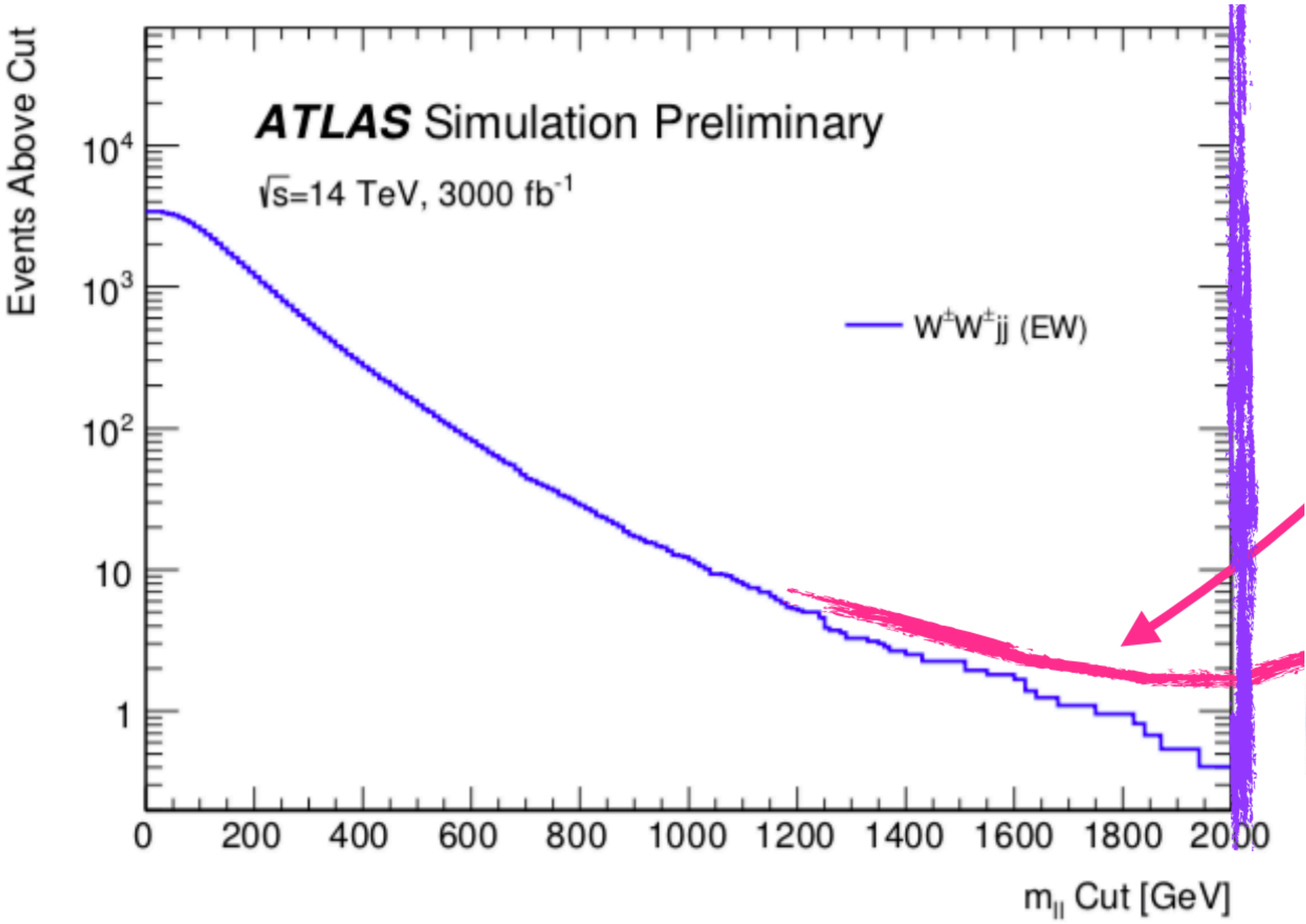
Deviation from SM prediction in high energy tails?

CA Lee, HL/HE-LHC Jamboree, 1 March 2019

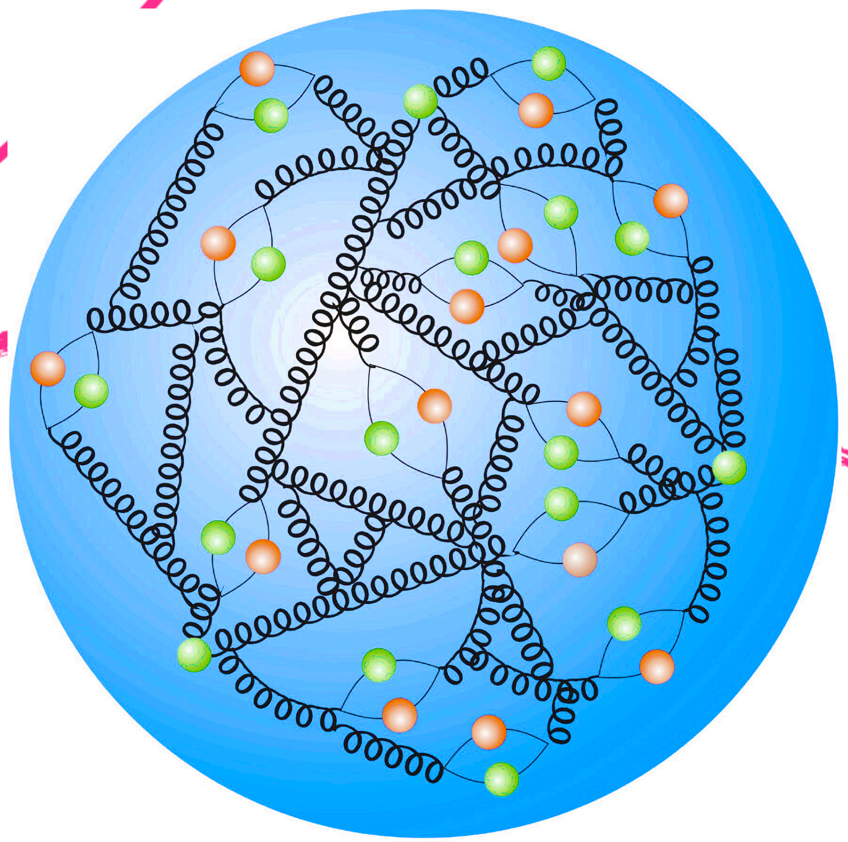
SMEFT interpretation: from a massive particle at high energies …

Why do we need better PDFs?

Deviation from SM prediction in high energy tails?



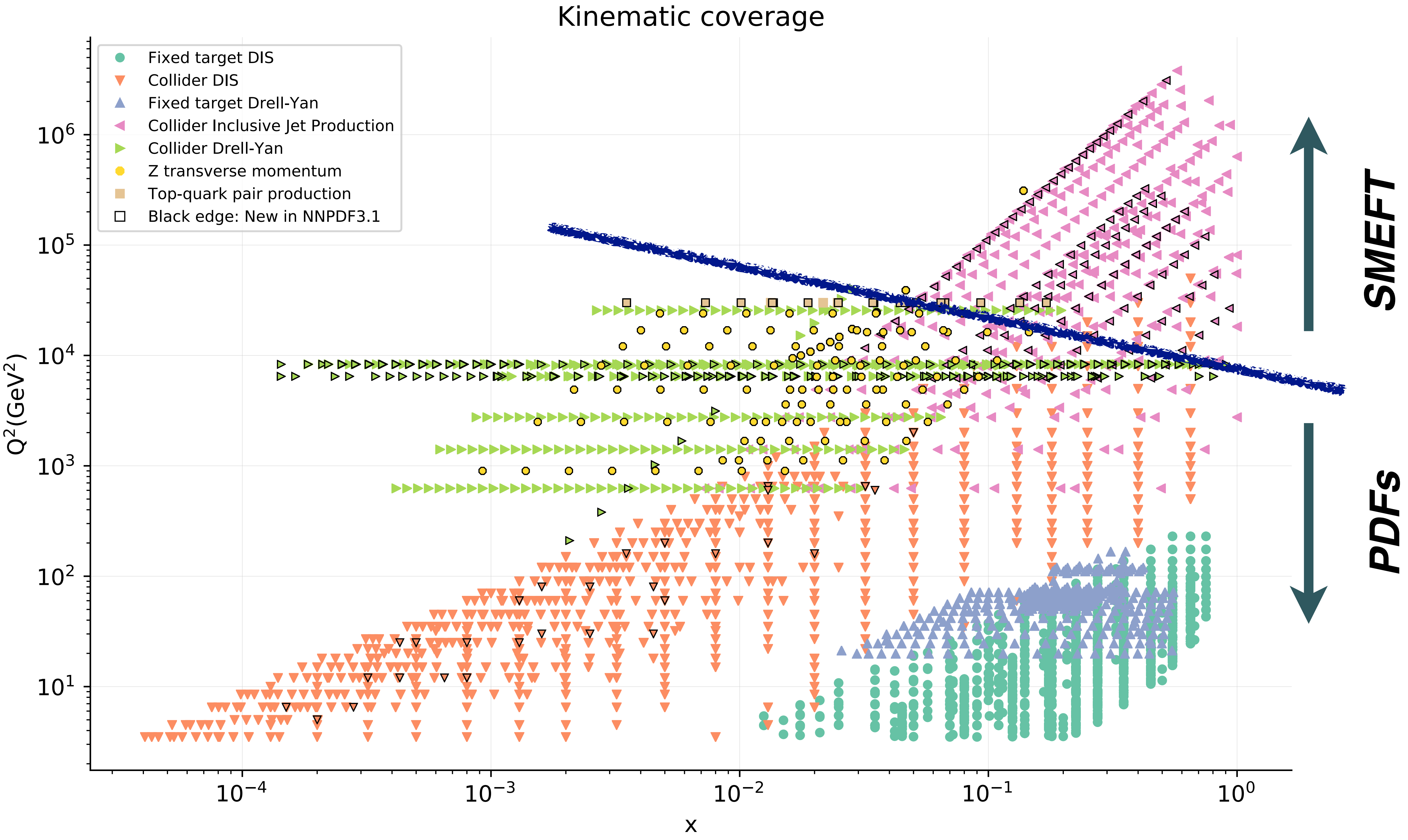
CA Lee, HL/HE-LHC Jamboree, 1 March 2019



…or reflecting our limited understating of proton structure?

Naive approach

Separate LHC data into **input for PDF fits** and **input for SMEFT studies?**



Can we do better?

Simultaneous PDF & SMEFT fits

Our goal: constrain **simultaneously** both the PDFs and SMEFT degrees of freedom

Proof of concept: DIS-only fits where SM theory is **augmented** by *d=6* SMEFT operators

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{q=u,d,s,c} \frac{a_q}{\Lambda^2} \left(\bar{l}_R \gamma^\mu l_R\right) \left(\bar{q}_R \gamma_\mu q_R\right)$$

which can arise *e.g.* from a ***Z'* boson** with non-universal couplings to quarks

These SMEFT operators modify the DIS structure functions and thus **affect the PDF fit**

$$\Delta F_2^{\rm SMEFT} \supset \frac{x}{12e^4}\left(4a_u e^2 \frac{Q^2}{\Lambda^2}(1+4K_Z \sin^4\theta_W) + 3a_u^2 \frac{Q^4}{\Lambda^4}\right)\left(u+\bar{u}\right)$$

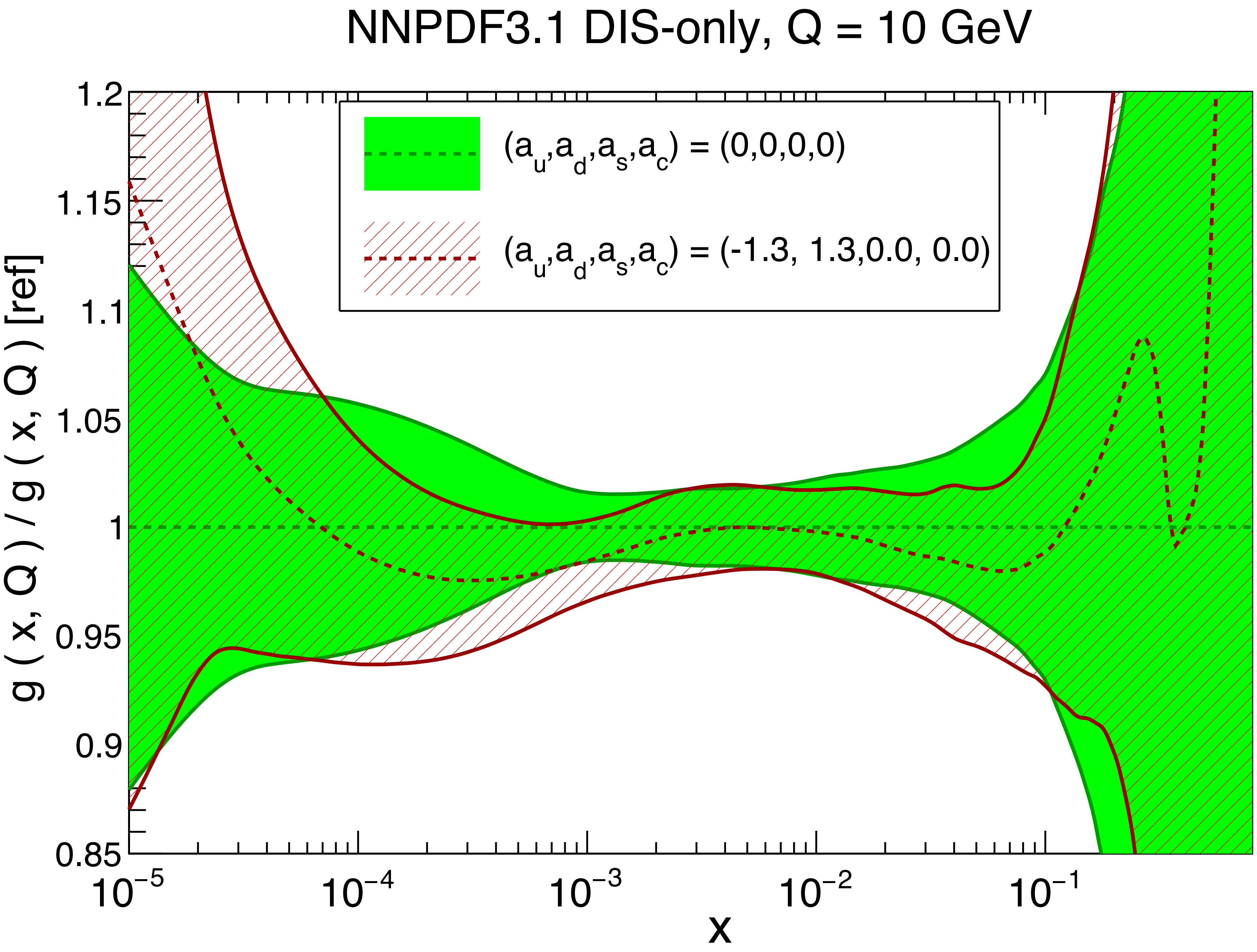
SMEFT effects enhanced by Q^2 :
constrain from HERA data

from interference with SM

from squared amplitude

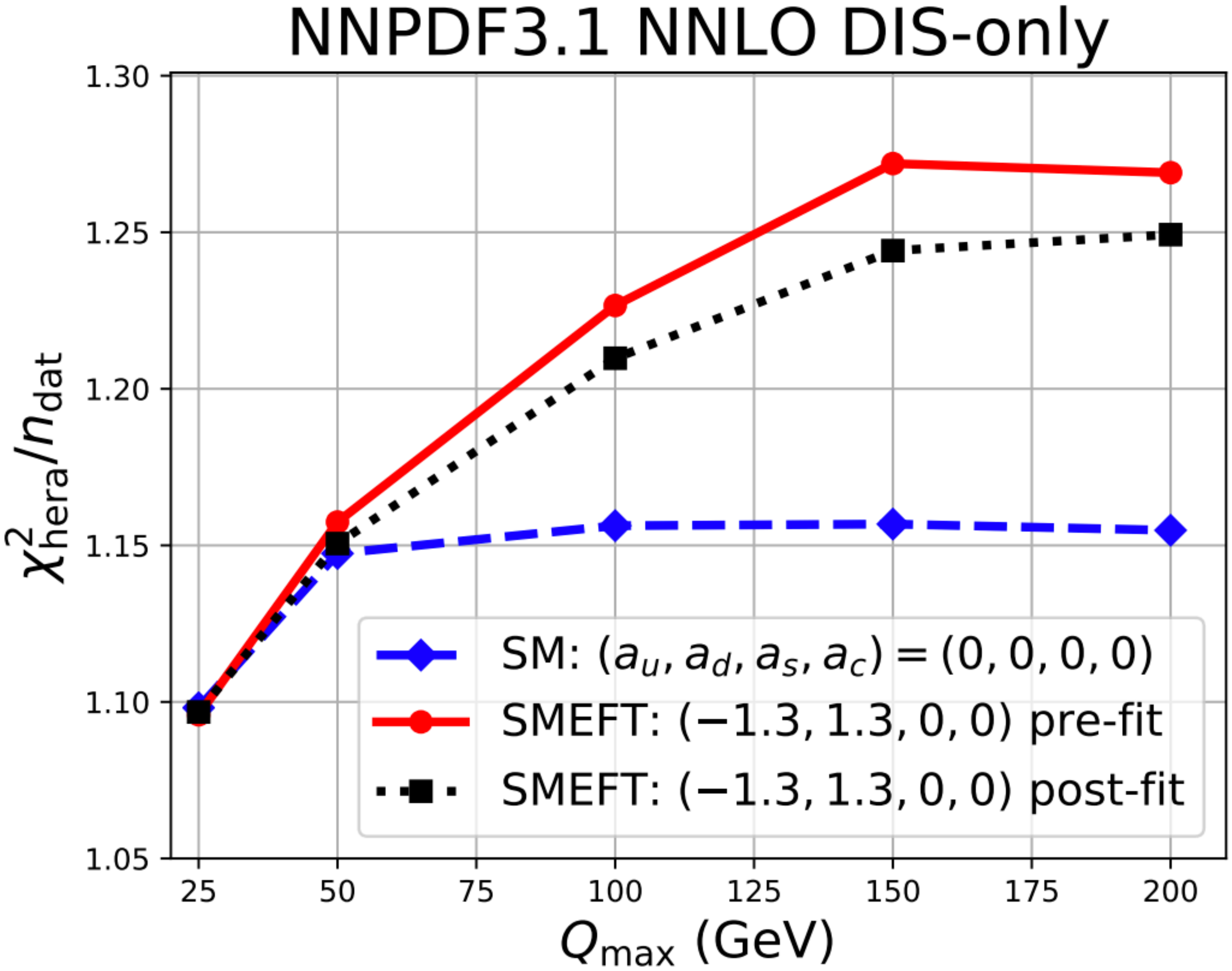
Impact on the PDFs

For a large region of the allowed parameter space,
SMEFT effects can be partially (but not completely) **reabsorbed into the PDFs**



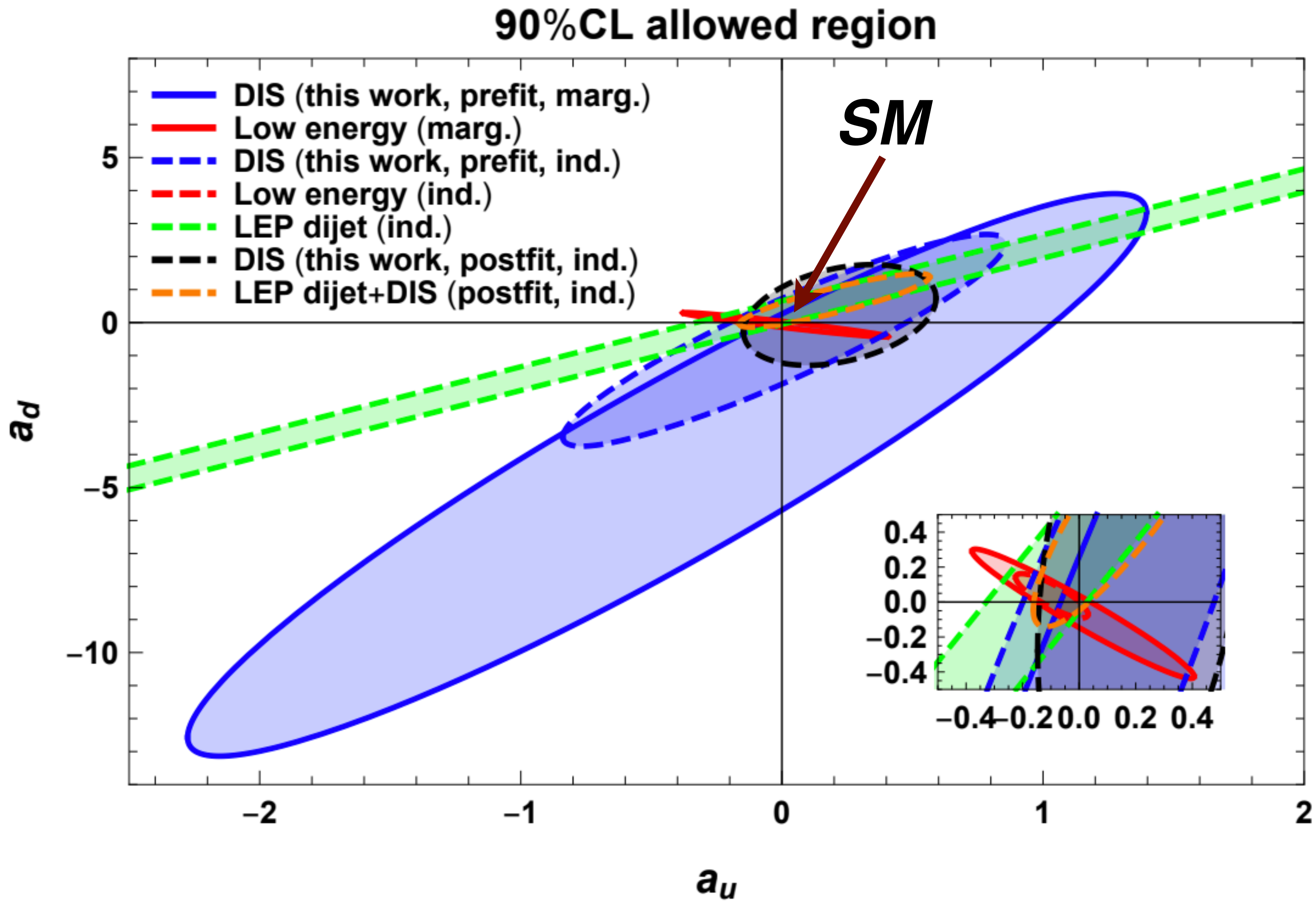
Fingerprinting BSM effects

Tell-tale sign of SMEFT effects: **rapid variation with *Q*** (DGLAP evolution slower)



Fingerprinting BSM effects

One can compare **bounds on SMEFT degrees of freedom** in the joint fit as compared to the usual approach where PDFs are kept fixed



Ultimate goal (HL-LHC timescale!): **simultaneous PDF & SMEFT global analysis**

Summary and outlook

- The **SMEFT is the new Standard Model:** a systematic, model-independent parametrisation of the low-energy deformations from any UV-complete BSM theories that reduces to the SM

- **SMEFiT** is a novel framework, suitable for global analyses of the SMEFT, which exploits expertise inherited from PDF fits

- As a proof-of-concept, applied this framework to the determination of the constraints in the SMEFT parameter space provided by **LHC top quark data**

- **Improved constraints** compared to previous studies (first-ever bounds in some cases)

- Next steps: enlarge the operator fitting basis and include **additional LHC cross-sections** (Higgs, electroweak, jets) as well as flavour and low-energy observables, and explore implications for specific **UV-complete models**

- Demonstrated the applicability of **Bayesian reweighting** for the *a posteriori* inclusion of the constraints from new measurements on SMEFiT without need of redoing fit

- The **simultaneous determination of PDFs and SMEFT** degrees of freedom will be required to fully exploit the LHC potential