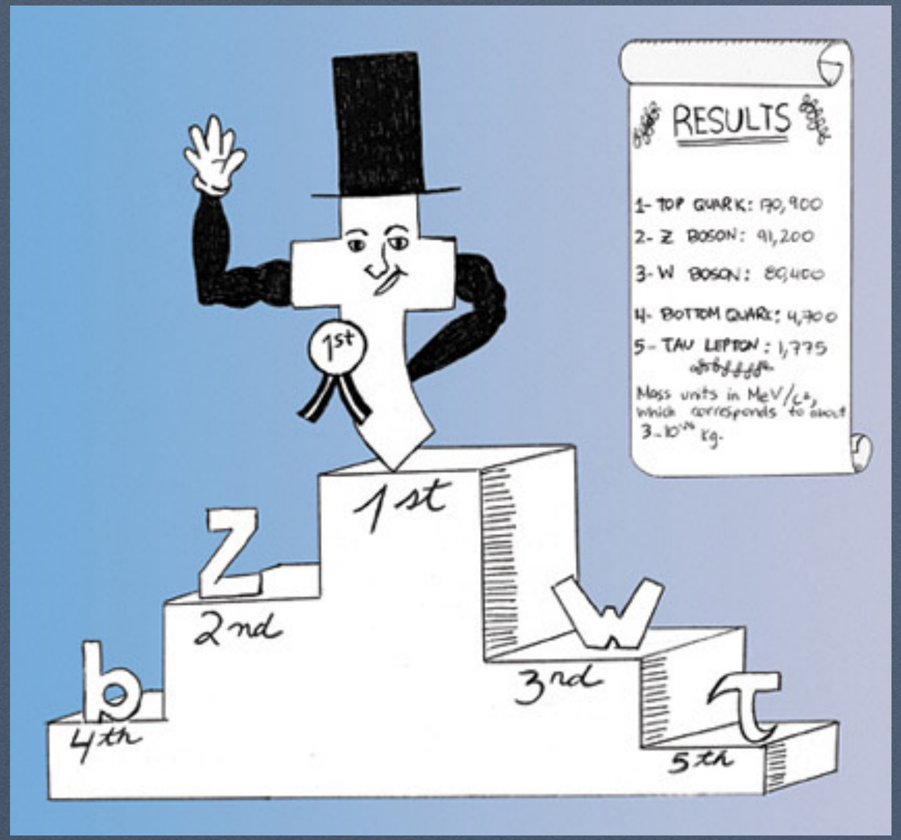
The top quark – a gateway to discoveries

María Moreno Llácer, James Keaveney

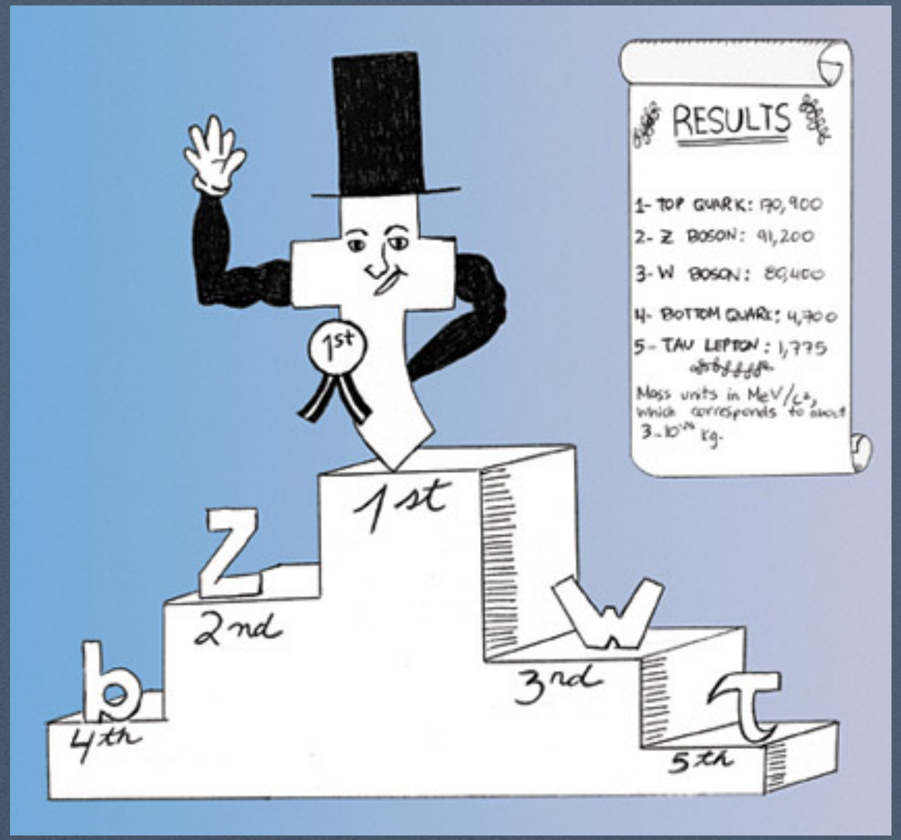
The Top quark and the Higgs boson



Top quark mass far larger than other particle masses

Large Top mass

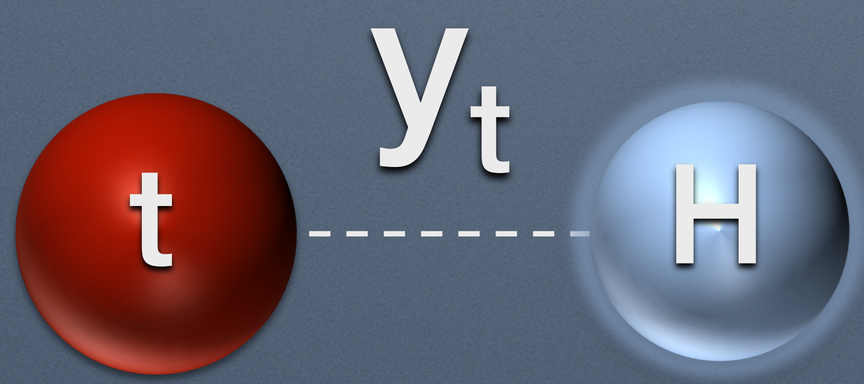
The Top quark and the Higgs boson



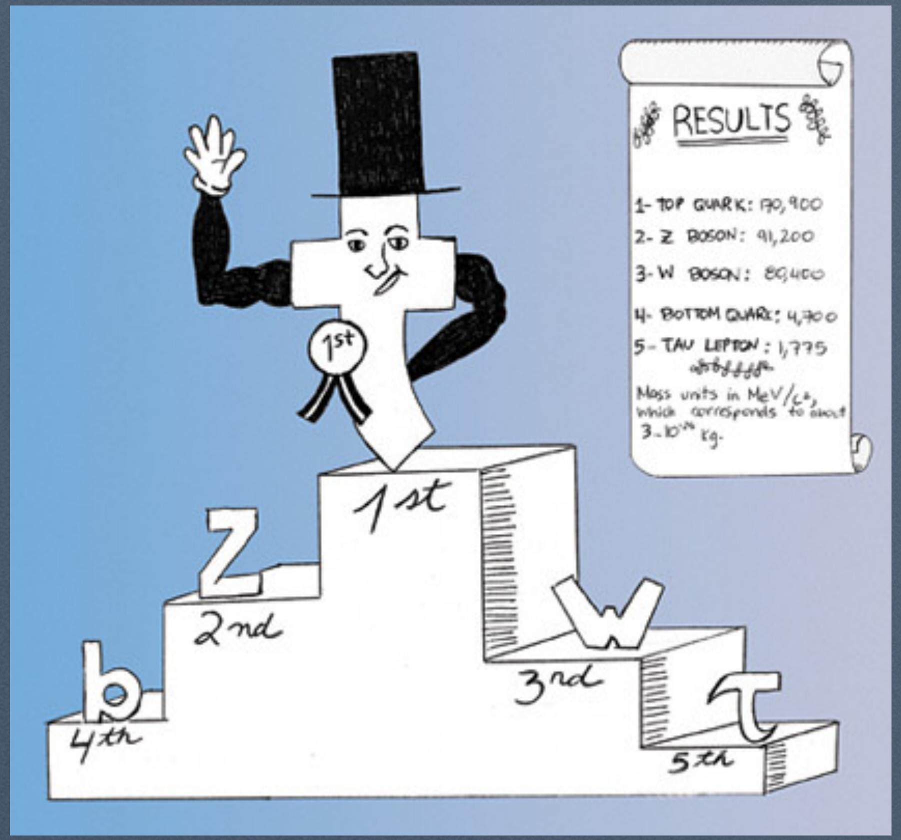
Top quark mass far larger than other particle masses

Large Top mass

Top-Higgs interaction

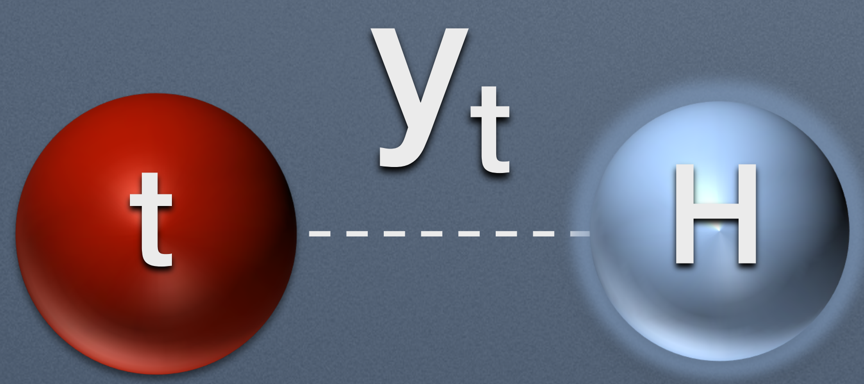


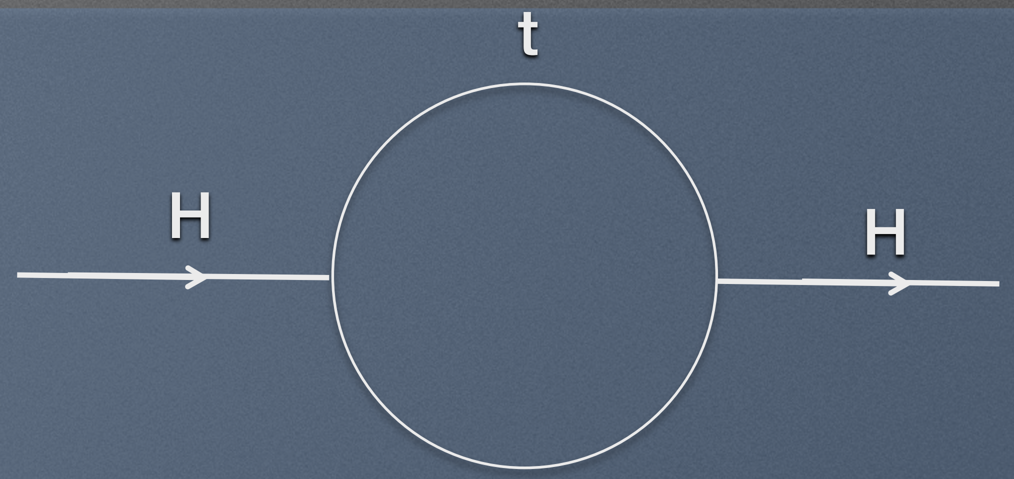
The Top quark and the Higgs boson



Top quark mass far larger than other particle masses

Top-Higgs interaction





quantum corrections -> divergent Higgs mass

$$M_H^2 = M_0^2 + b\lambdabar^2 + \ ...$$

- quantum corrections to M_H^2 driven by Yukawa couplings
- heavy particles matter most (top, W,Z)

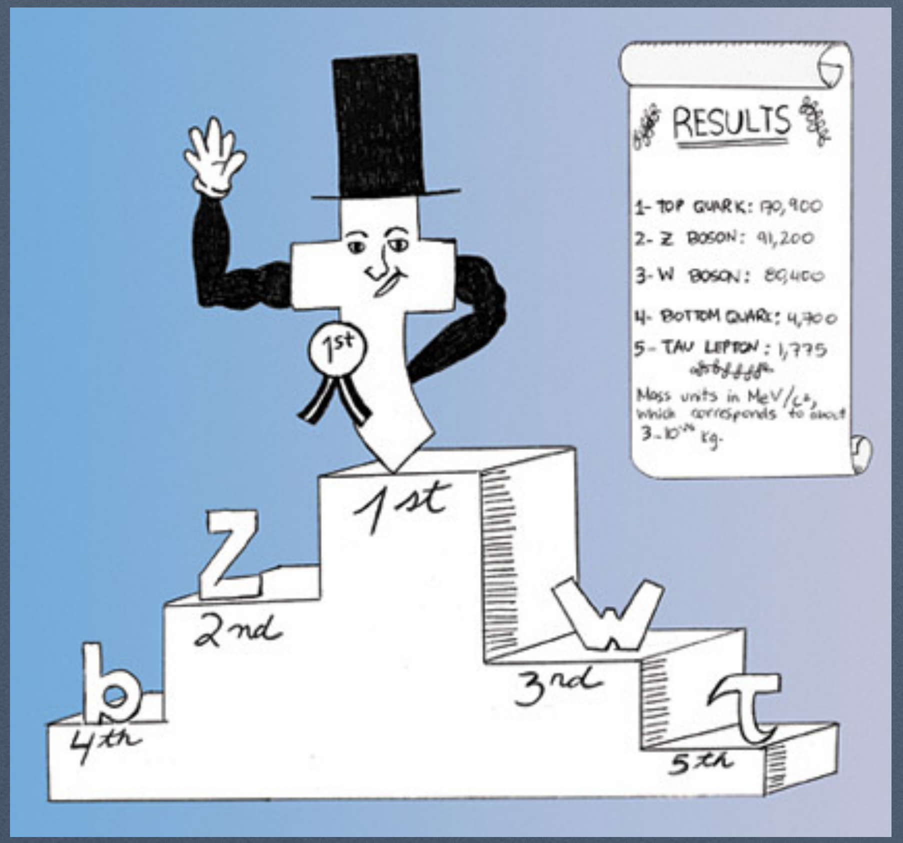
$\lambdabar$ = cut off scale where SM stops being valid
-> should be very large w.r.t. EW scale

So shouldn't M_H^2 be naturally huge too?
-> Yes! But we measure it at a mere ~ 125 GeV!!

How can this be? Idea:
- some large cancellation between M_0^2 and $b\lambdabar^2$ -> 'fine tuning'

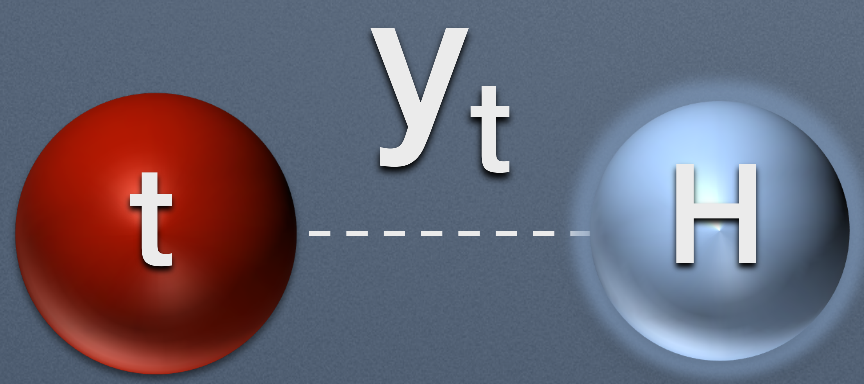
- **Top quark must play a special role in stabilizing M_H^2**
- **Studying the top quark's couplings can shed light on the mechanism that stabilizes M_H^2**

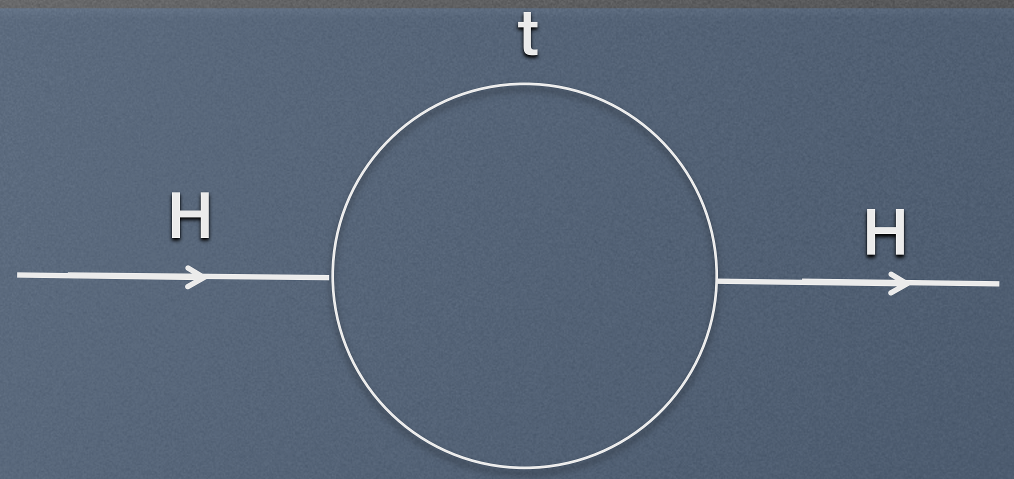
The Top quark and the Higgs boson



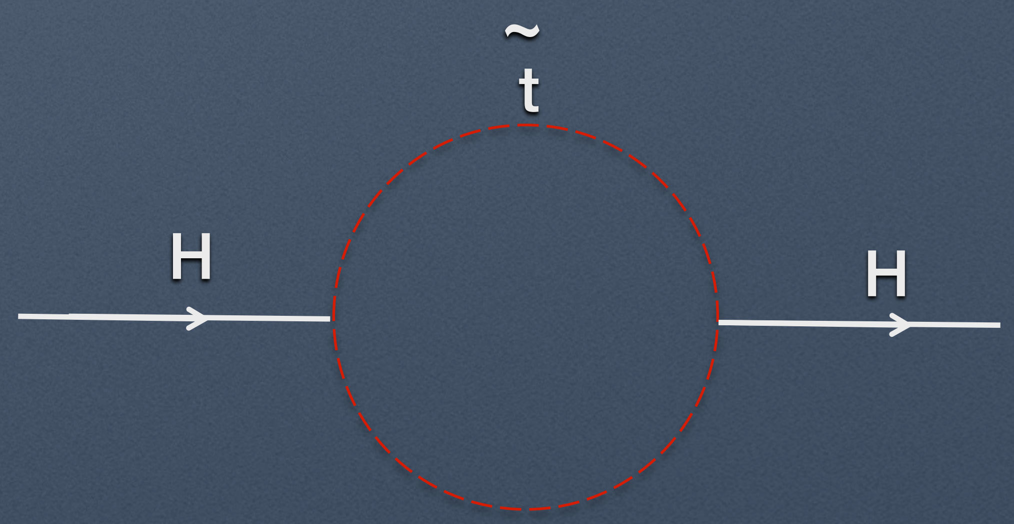
Top quark mass far larger than other particle masses

Top-Higgs interaction





quantum corrections -> divergent Higgs mass



ƛ = cut off scale where SM stops being valid
-> should be very large w.r.t. EW scale

So shouldn't M_H^2 be naturally huge too?
-> Yes! But we measure it at a mere ~ 125 GeV!!

How can this be? Idea:

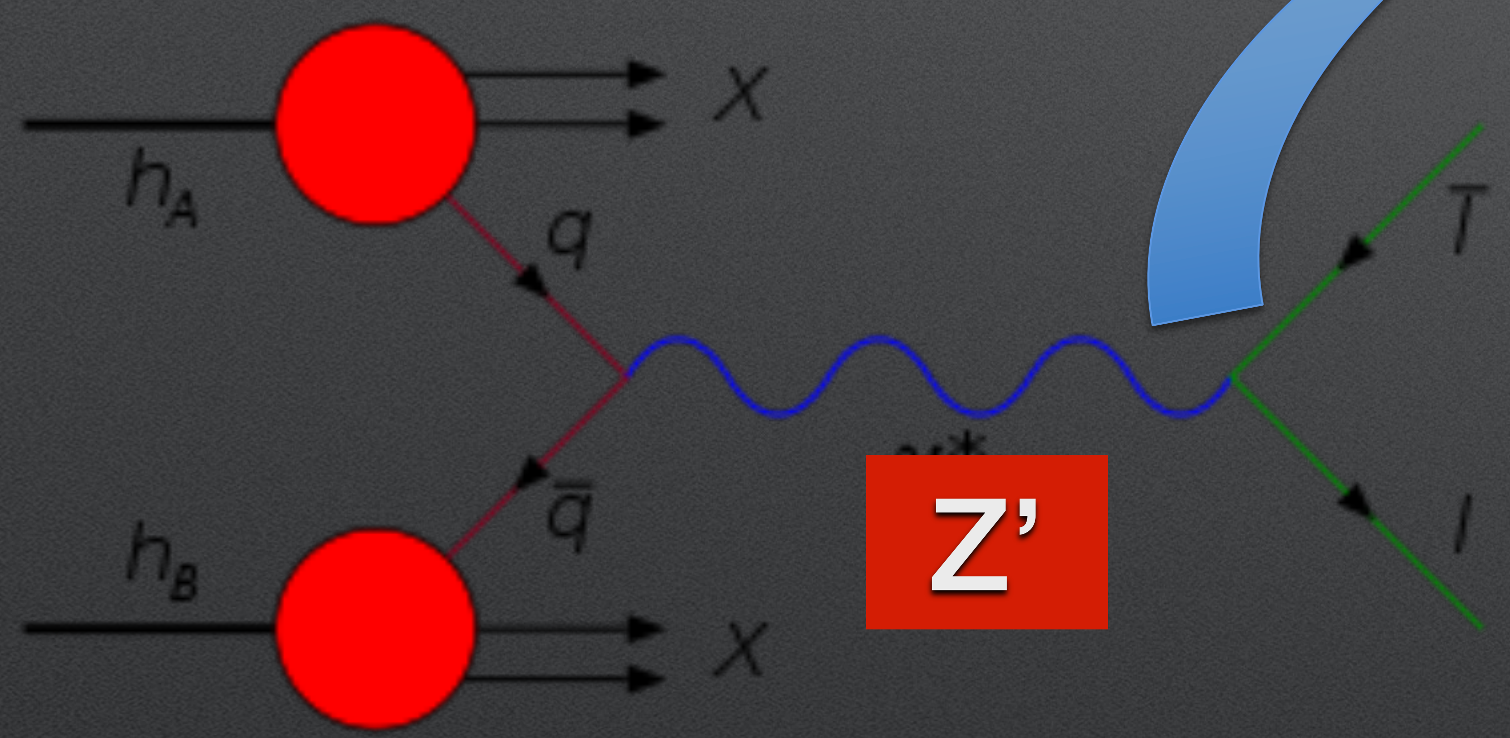
- some large cancellation between M_0^2 and $b ƛ^2$ -> 'fine tuning'
- not only SM particles involved in b …Supersymmetry?

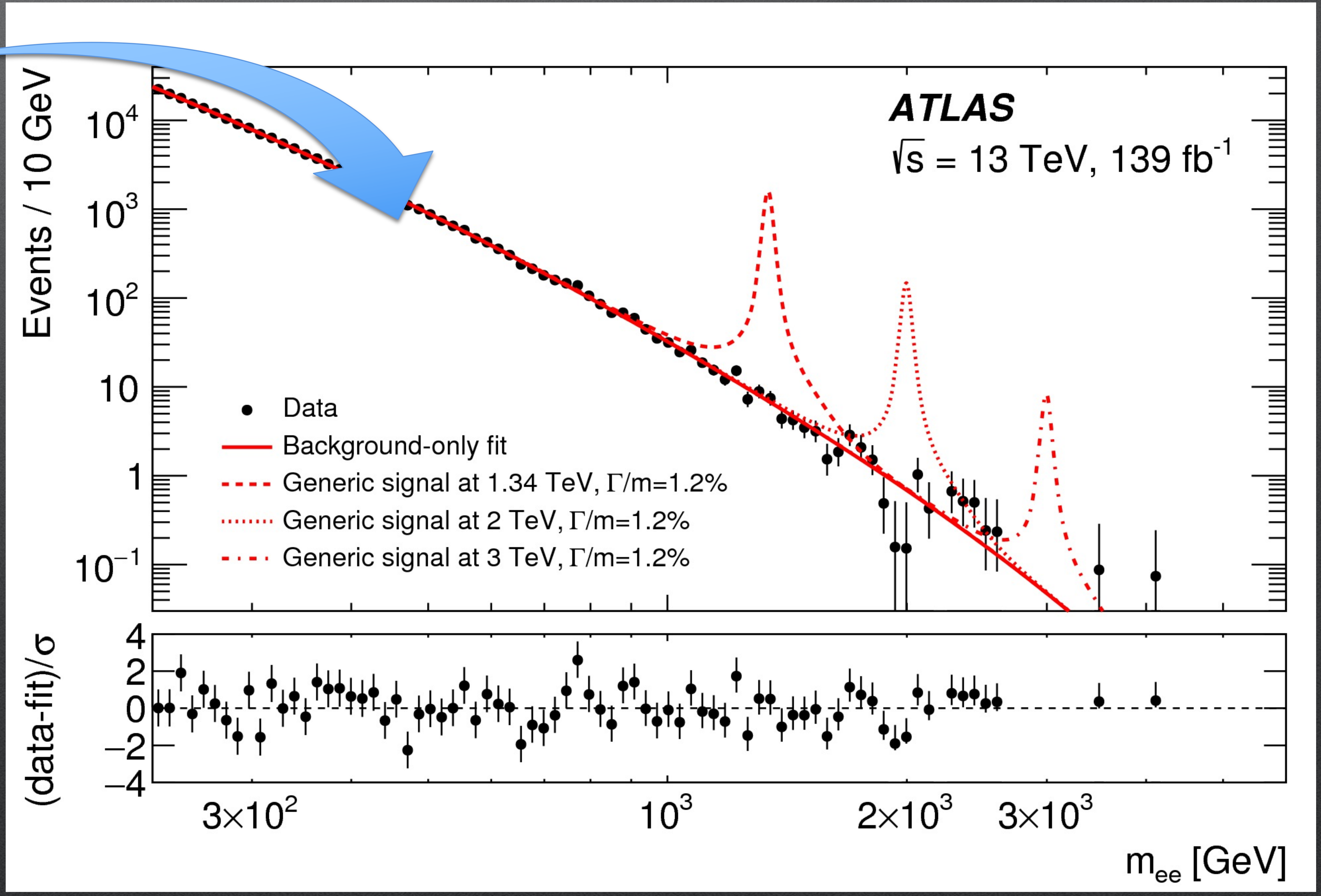
new physics to cancel divergences?

The state of play at the LHC

- We have so far looked for direct production of new particle (bump-hunting)

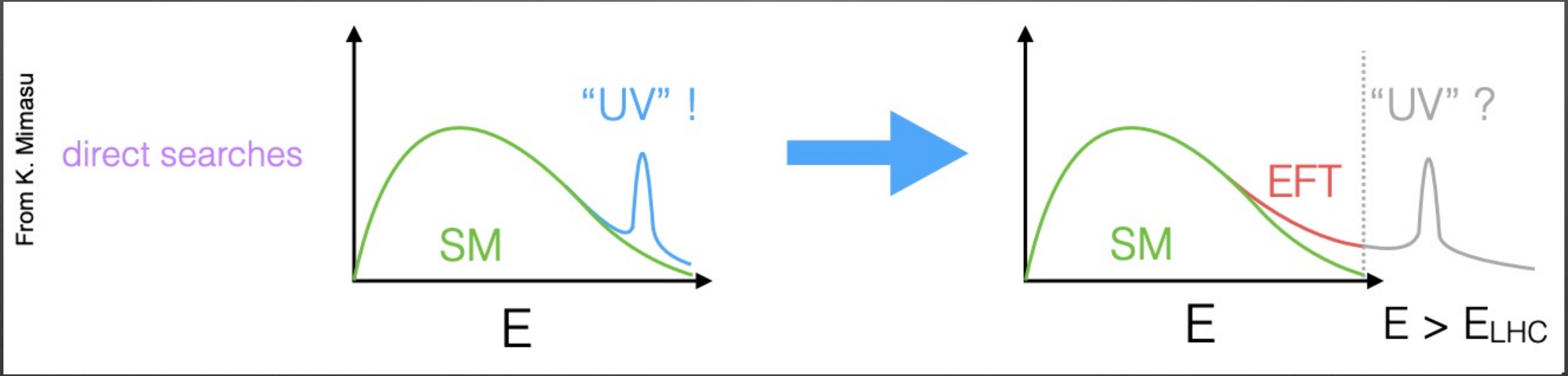
  e.g. search for X->ee





The *Bad* News

- The LHC experiments have **not** observed any new light state


From K. Mimasu
direct searches
"UV" !
SM
E
SM
EFT
"UV" ?
E
E > ELHC

The particle physics version:

we are confident that there is “new physics” out there

- don’t know its energy scale (could be ~ E_{planck})

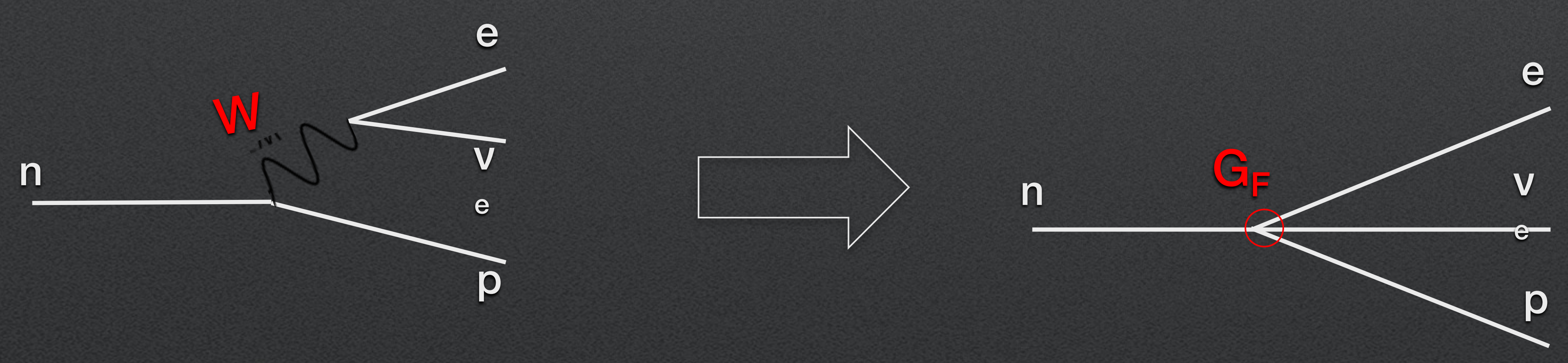
- we look at ~ E_{EW}— few TeV the energies we can directly access)

“the light is better here”

Is the NP scale (Λ_{NP}) far larger than the LHC scale?

- EFT tells the effect of high-scale NP on low energy observables
- Integrate out heavy particles… replace with new operators and effective couplings
- Specific details of new particles invisible at low energy

famous example of Fermi theory of Beta decay



SMEFT in practice

- Re-imagine the SM as a low energy effective theory
  - extend the SM Lagrangian with higher-order operators
  - most important operators are dimension 6

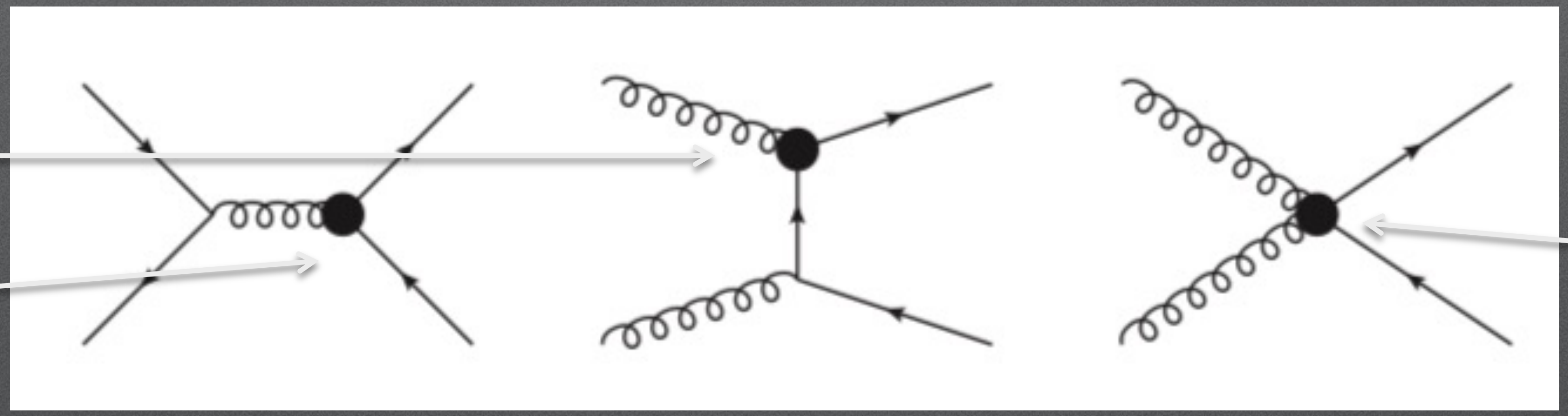
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

d-6 operators cause subtle effects in rates and kinematics of processes

SMEFT in practice

LHC example – O_{tG} affecting rate and kinematics of tt production

modified gtt vertices



new ggtt vertex

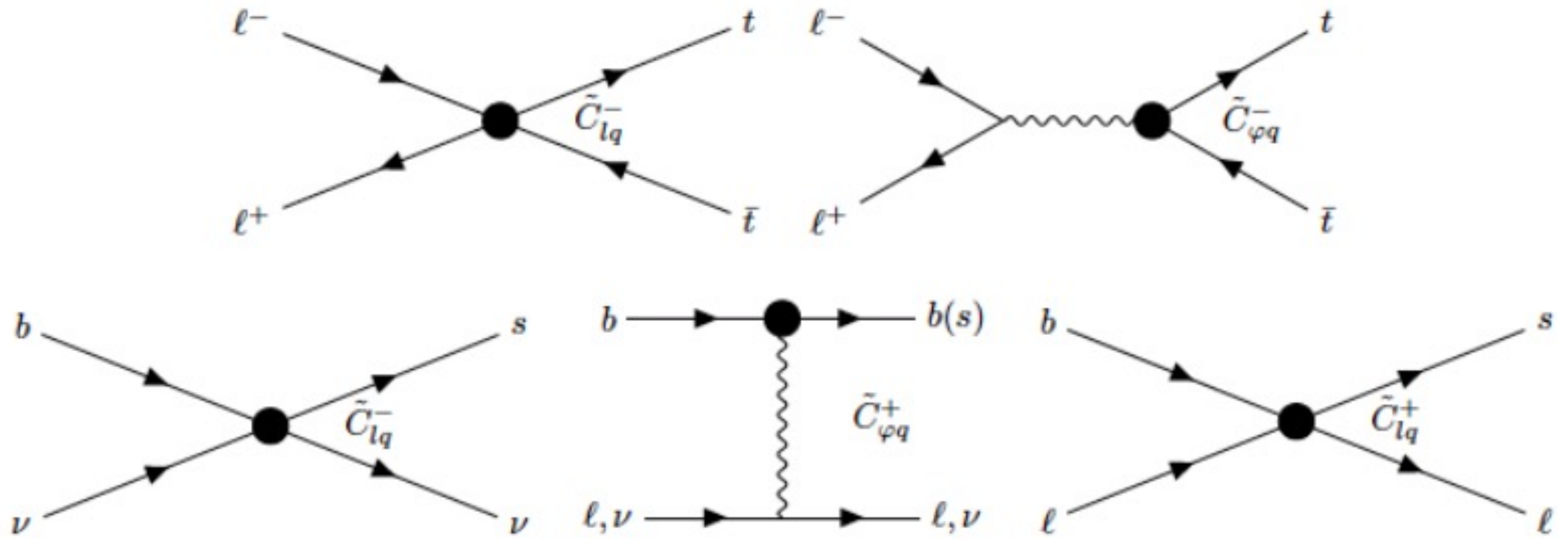
arXiv:1505.08841

searching for new particles ➔ searching for new interactions

bump-hunting ➔determining c_i

Synergy between top quark and flavour anomalies (G. Hiller)

top and beauty synergies



SMEFT coefficients $C^{\pm} = C^{(1)} \pm C^{(3)}$ top and beauty, leptons and neutrinos, linked and complementary; flat directions are removed

$b \to s\mu\mu$ (LHC), probes C^+

$b \to s\nu\nu$ (BelleII), probes C^-

$e^+e^- \to t\bar{t}$ (CLIC-like), probes C^- — quark flavor link implied $C_{23} = V_{tb}V^*_{ts}C_{33}$, lepton universality,....

The cutting edge

Study rare processes with unique sensitivity to EFT parameters

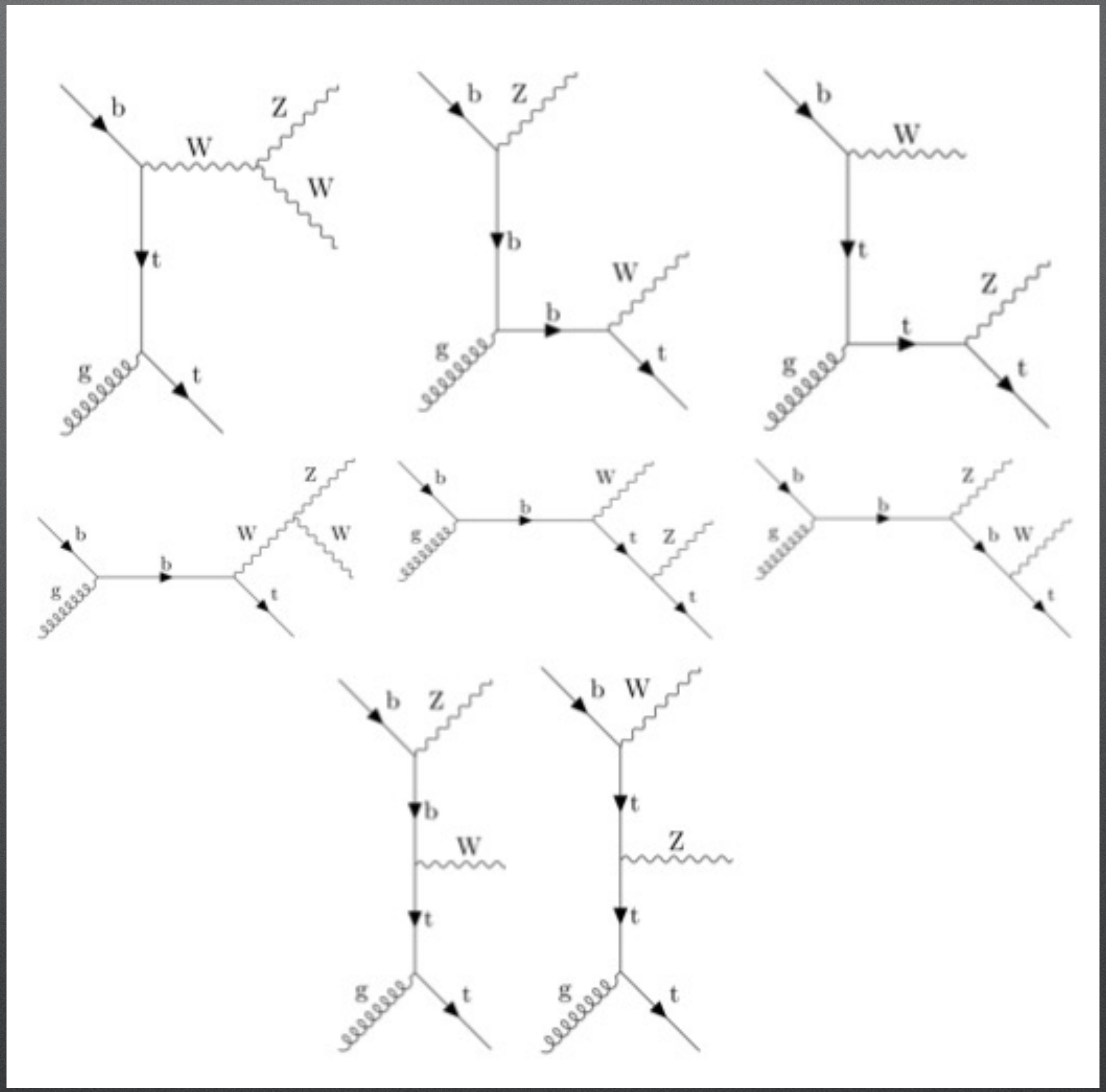
- ttZ, ttW, tZq, tWZ

- Projects with African involvement/leadership
  - ttW charge asymmetry (collaboration UCT-IFIC Valencia, within ATLAS)
  - tWZ search (led by UCT, within ATLAS)
  - prospects for tWZ at HL-LHC arXiv:2107.01053 (led by UCT, outside experiments)
  - development of *d*EFT tool for automated EFT analyses presentation at PyHEP 2021

- Related projects
  - Analyses of top quark EW couplings using Run II LHC data *JHEP* 02 (2022) 032

tWZ production at the LHC

- Top quarks can also be produced in association with W and Z bosons (tWZ)
- Much rarer than tt -> as yet unobserved
- Very sensitive to top electroweak couplings



ATLAS Note

ANA-TOPQ-2019-29-INT1

23rd September 2020

Draft version 0.1

Search for tWZ production in the tri- and tetra-lepton channels using the full Run II ATLAS dataset

The ATLAS Collaboration[1], J. Keaveney[a], B. Warren[b], J. Reich[a], S. Yacoob[a], James Keaveney[a], Benjamin Warren[a], Jake Reich[a]

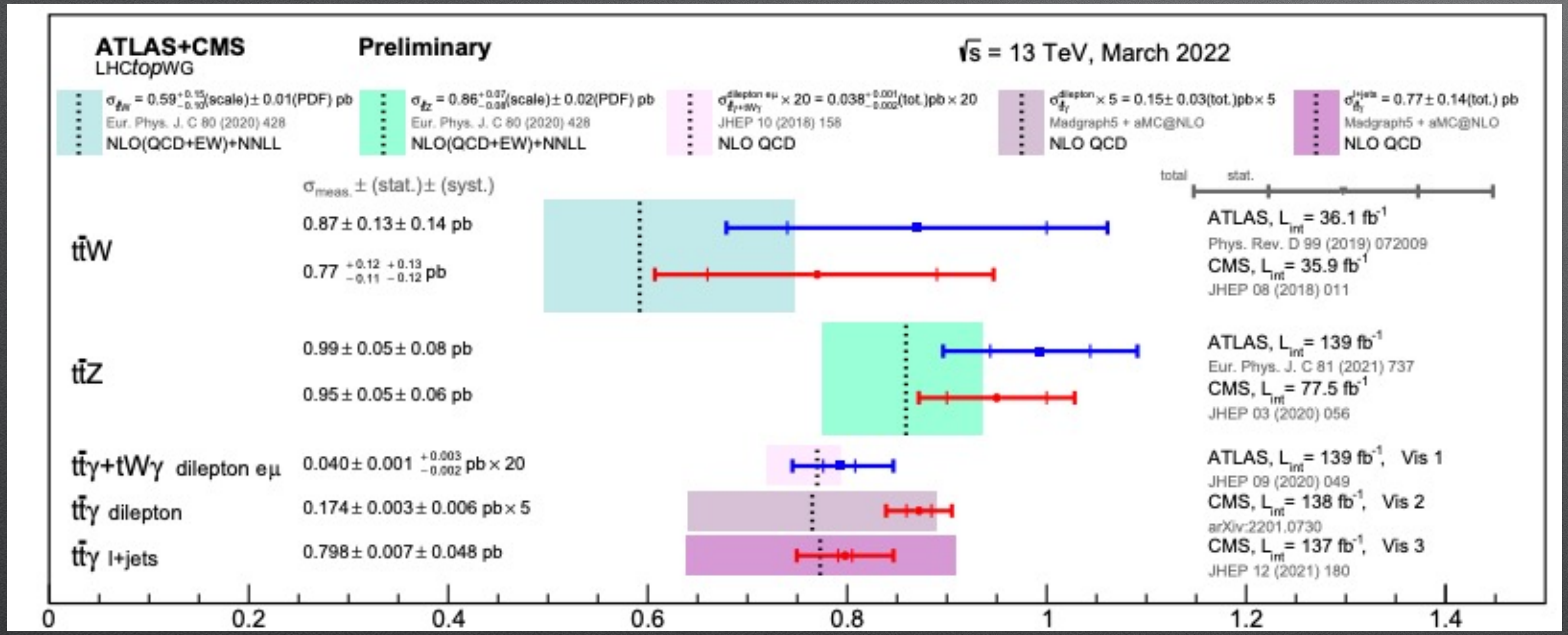
[a]*University of Cape Town*

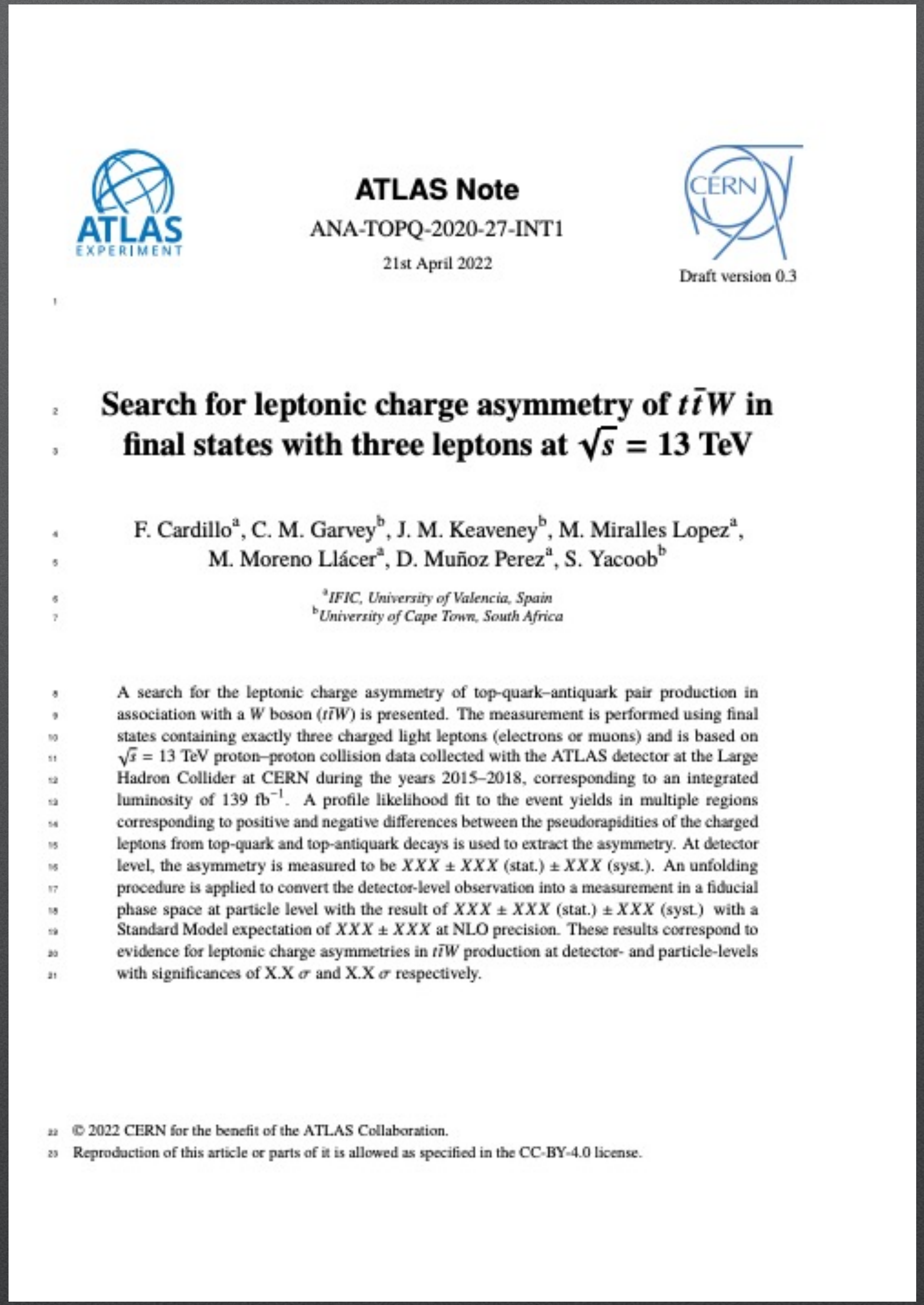
A search for the Standard Model tWZ process using the data collected by the ATLAS experiment in 2016 to 2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV is presented. Events containing either exactly 3 or 4 electrons or muons are selected with additional criteria based on the number of jets, the number of b-tagged jets, and the number of Z boson candidates used to define signal, control, and validation regions. In the tri-lepton channel, the large background from WZ production is suppressed by reconstructing hadronically-decaying W bosons with a BDT-based algorithm. The signal strength is extracted via a maximum-likelihood fit to mulitple signal and control regions. The measured signal strength is $\mu_{tWZ} = XX^{+YY}_{-ZZ}$ (stat.) $\pm$ AA (syst.) fb = XX^{+YY}_{-ZZ} fb. This result is converted to a cross section for $pp \to t\ell^+\ell^- q$ in the fiducial phase space region $m_{\ell\ell} > 30$ GeV using a MC-based correction factor. The cross section result is XX^{+YY}_{-ZZ} (stat.) $\pm$ AA (syst.) fb = XX^{+YY}_{-ZZ} fb, and is to be compared with the Standard Model expectation of XX^{+YY}_{-ZZ} (stat.) $\pm$ AA (syst.) fb = XX^{+YY}_{-ZZ} fb calculated at NLO in QCD and a five-flavour PDF scheme.

Ongoing research project led by UCT

ttW charge asymmetry at the LHC

- ttW cross section consistenty measured larger than SM predictions





ATLAS Note

ANA-TOPQ-2020-27-INT1

21st April 2022

Draft version 0.3

Search for leptonic charge asymmetry of $t\bar{t}W$ in final states with three leptons at $\sqrt{s}$ = 13 TeV

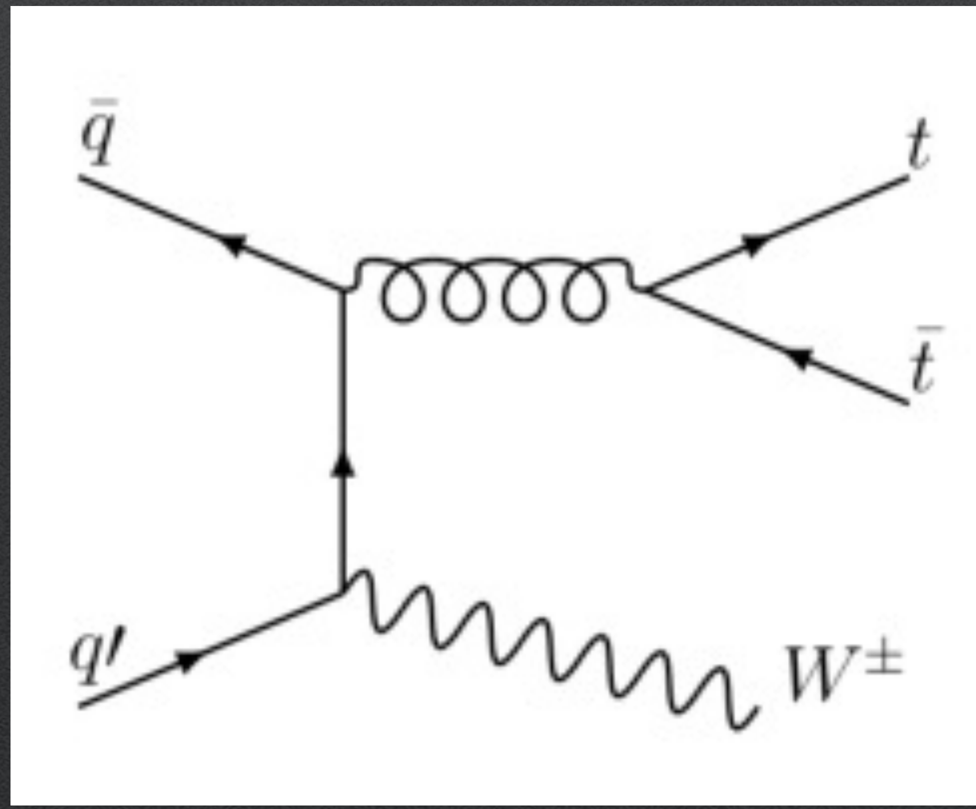
F. Cardillo[a], C. M. Garvey[b], J. M. Keaveney[b], M. Miralles Lopez[a], M. Moreno Llácer[a], D. Muñoz Perez[a], S. Yacoob[b]

[a] IFIC, University of Valencia, Spain
[b] University of Cape Town, South Africa

A search for the leptonic charge asymmetry of top-quark–antiquark pair production in association with a W boson ($t\bar{t}W$) is presented. The measurement is performed using final states containing exactly three charged light leptons (electrons or muons) and is based on $\sqrt{s}$ = 13 TeV proton–proton collision data collected with the ATLAS detector at the Large Hadron Collider at CERN during the years 2015–2018, corresponding to an integrated luminosity of 139 fb^{-1}. A profile likelihood fit to the event yields in multiple regions corresponding to positive and negative differences between the pseudorapidities of the charged leptons from top-quark and top-antiquark decays is used to extract the asymmetry. At detector level, the asymmetry is measured to be $XXX \pm XXX$ (stat.) $\pm XXX$ (syst.). An unfolding procedure is applied to convert the detector-level observation into a measurement in a fiducial phase space at particle level with the result of $XXX \pm XXX$ (stat.) $\pm XXX$ (syst.) with a Standard Model expectation of $XXX \pm XXX$ at NLO precision. These results correspond to evidence for leptonic charge asymmetries in $t\bar{t}W$ production at detector- and particle-levels with significances of X.X σ and X.X σ respectively.

Ongoing research project led by UCT/IFIC

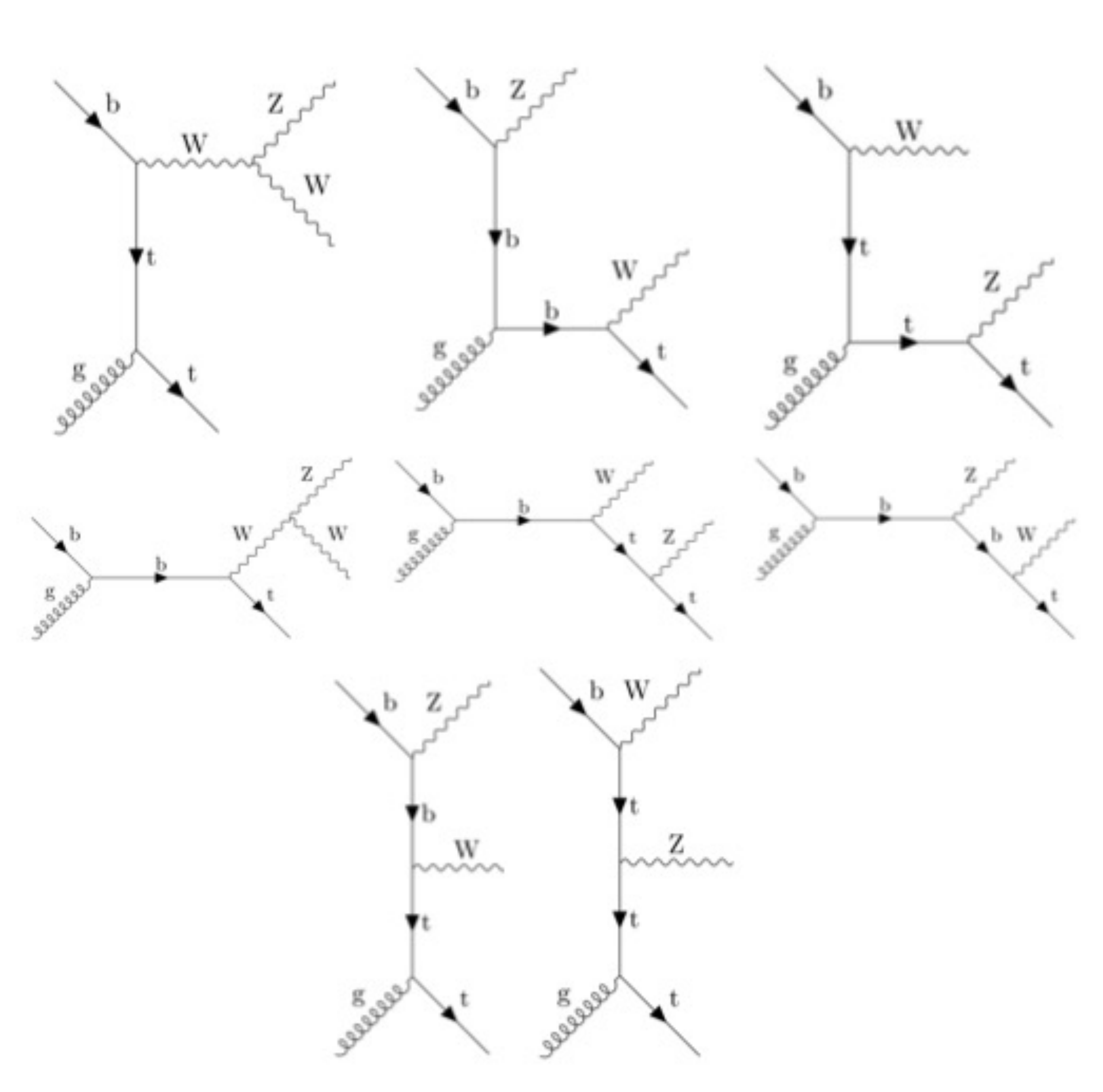
- ttW charge asymmetry large in SM due to dominance of qq initial state
- sensitive to new physics effects that might explain the discrepancy

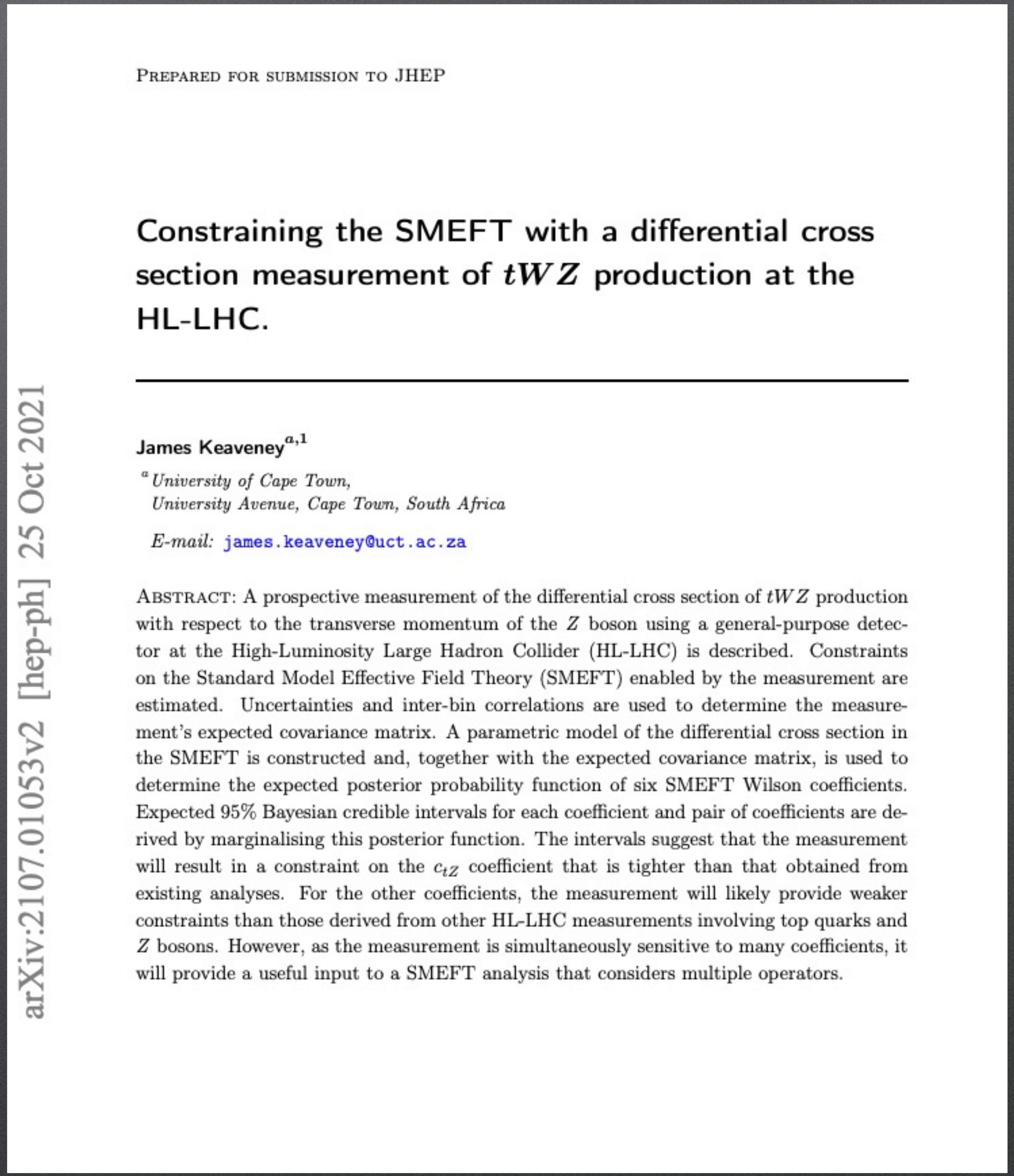


tWZ production at the HL-LHC

- tWZ is observable with sufficient data
- How far can we go with the HL-LHC data?
- prospects for a differential cross section measurement, preprint.
- The project involved development of a open source tool, to ease and automate EFT analyses using differential cross section data

dEFT





PREPARED FOR SUBMISSION TO JHEP

Constraining the SMEFT with a differential cross section measurement of tWZ production at the HL-LHC.

James Keaveney[a,1]

[a] University of Cape Town, University Avenue, Cape Town, South Africa

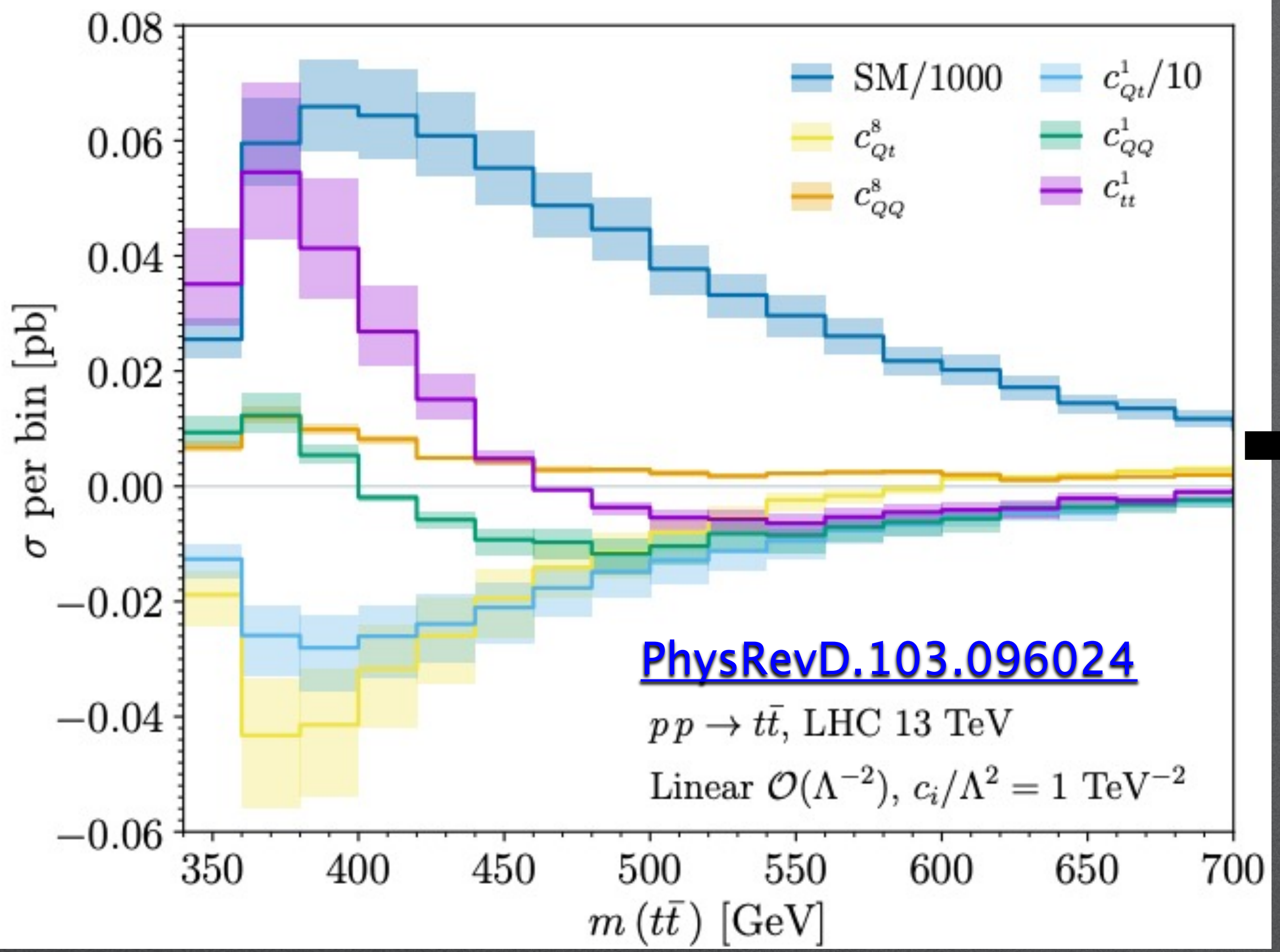
E-mail: james.keaveney@uct.ac.za

arXiv:2107.01053v2 [hep-ph] 25 Oct 2021

ABSTRACT: A prospective measurement of the differential cross section of tWZ production with respect to the transverse momentum of the Z boson using a general-purpose detector at the High-Luminosity Large Hadron Collider (HL-LHC) is described. Constraints on the Standard Model Effective Field Theory (SMEFT) enabled by the measurement are estimated. Uncertainties and inter-bin correlations are used to determine the measurement's expected covariance matrix. A parametric model of the differential cross section in the SMEFT is constructed and, together with the expected covariance matrix, is used to determine the expected posterior probability function of six SMEFT Wilson coefficients. Expected 95% Bayesian credible intervals for each coefficient and pair of coefficients are derived by marginalising this posterior function. The intervals suggest that the measurement will result in a constraint on the c_{tZ} coefficient that is tighter than that obtained from existing analyses. For the other coefficients, the measurement will likely provide weaker constraints than those derived from other HL-LHC measurements involving top quarks and Z bosons. However, as the measurement is simultaneously sensitive to many coefficients, it will provide a useful input to a SMEFT analysis that considers multiple operators.

Ongoing research project led by UCT

theory predictions for $\frac{d\sigma}{dX}$ in SMEFT

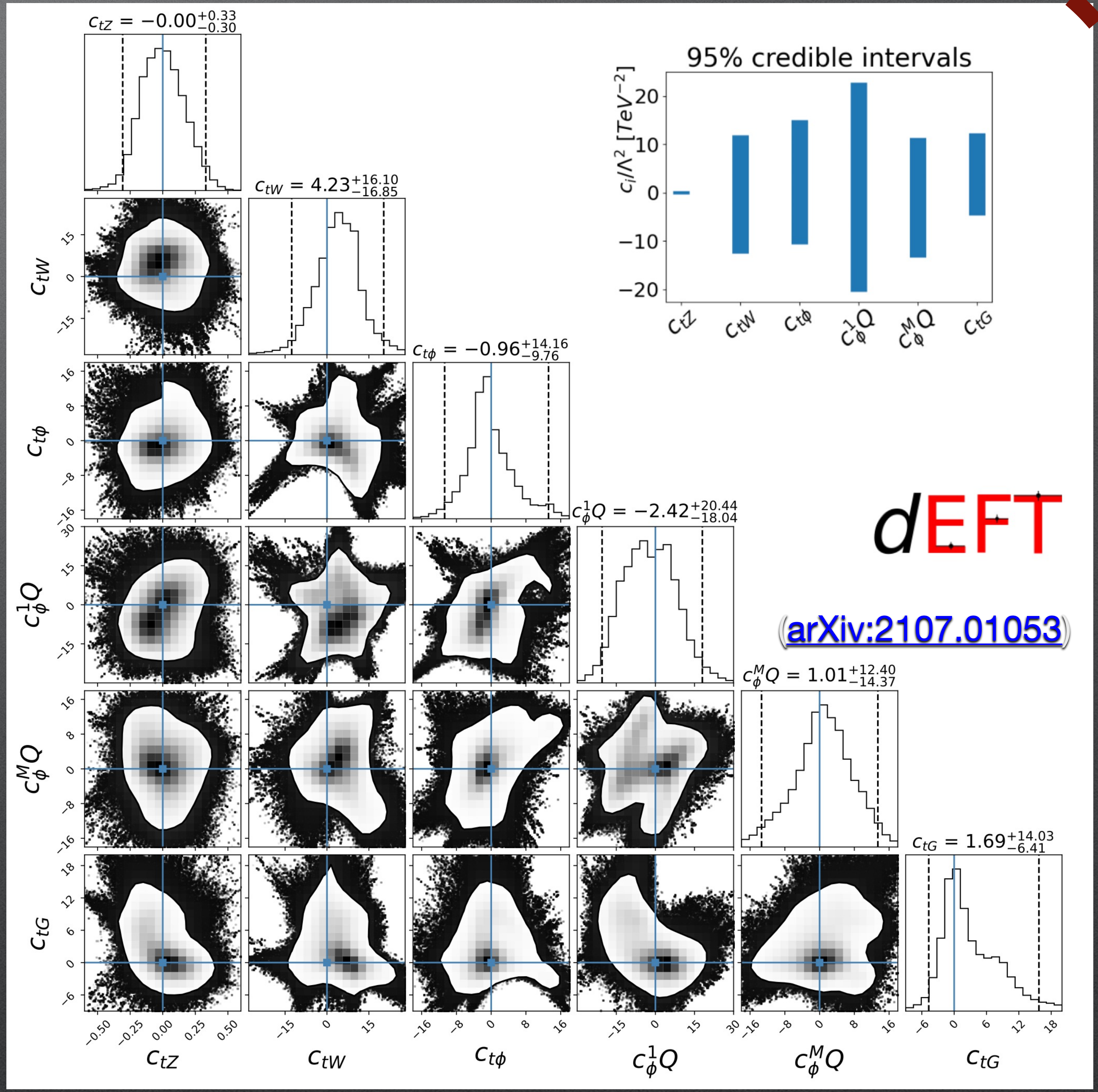


dEFT

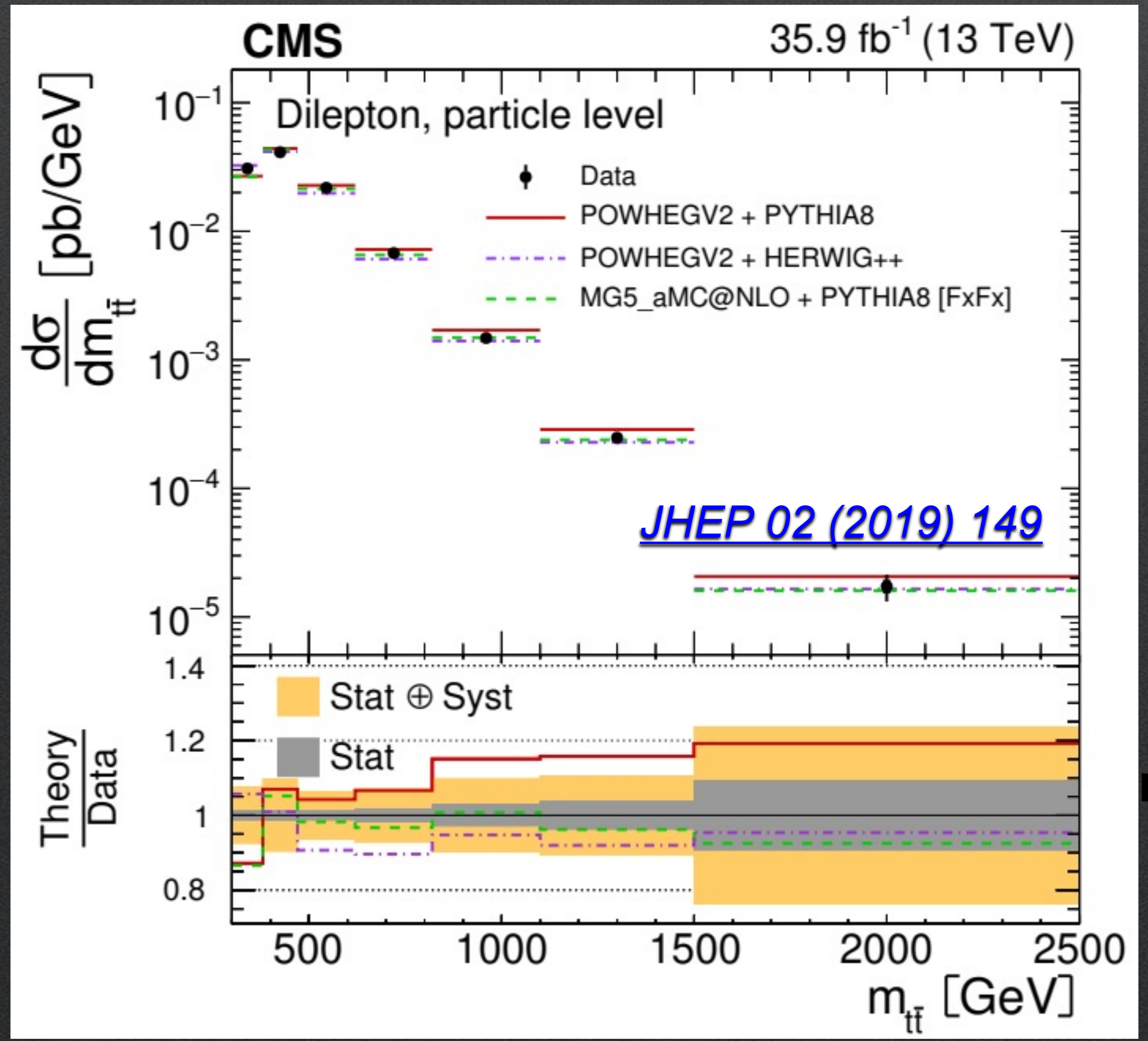
presentation at PyHEP 2021

regression morphing model

$$\frac{d\sigma}{dX}(c_i)$$



differential cross sections ($\frac{d\sigma}{dX}$)

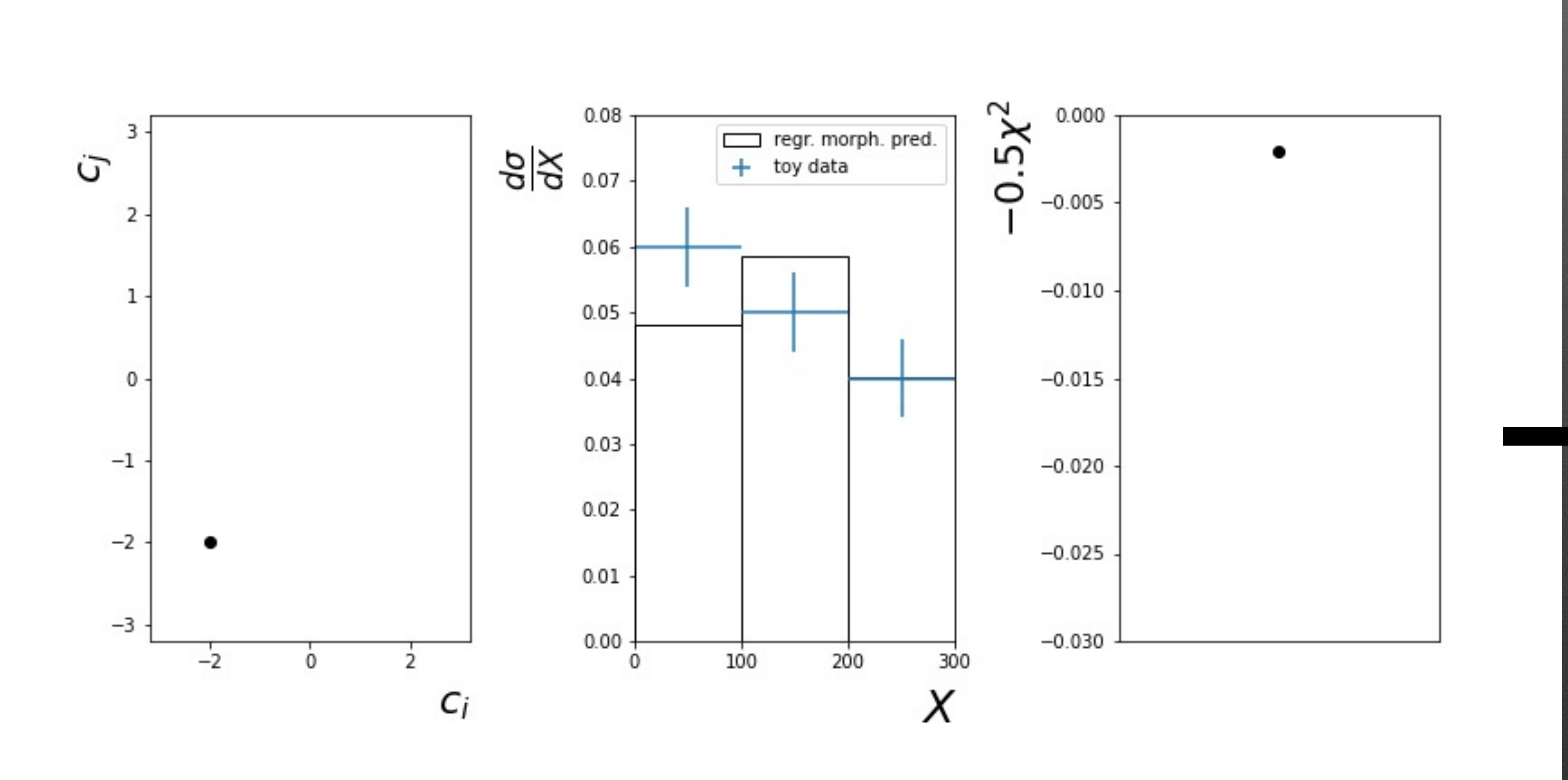


Constraints on c_i via estimation of n-dimensional posterior pdf

Estimating the posterior pdf

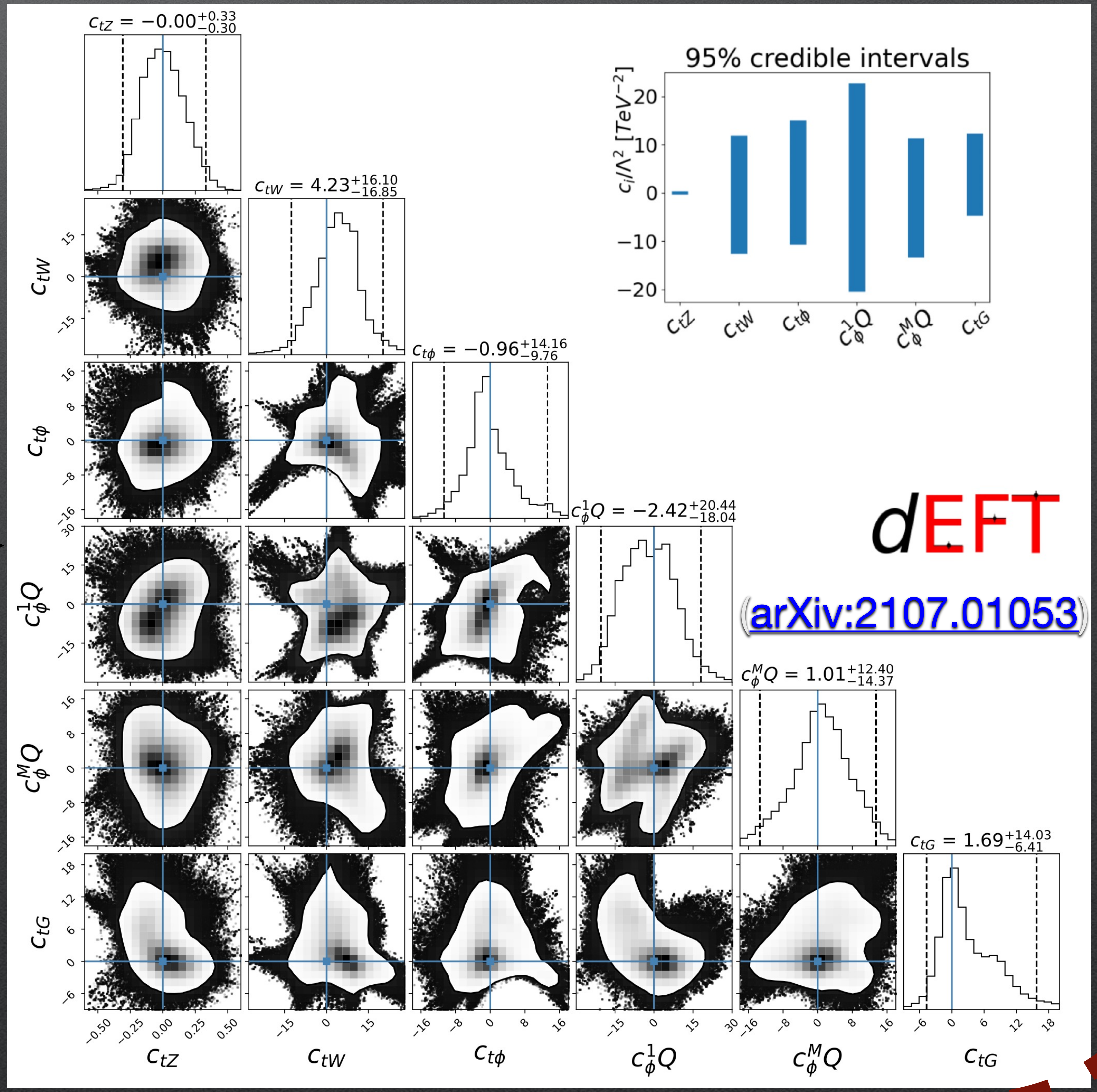
emcee

- explores c_i space and numerically estimates posterior



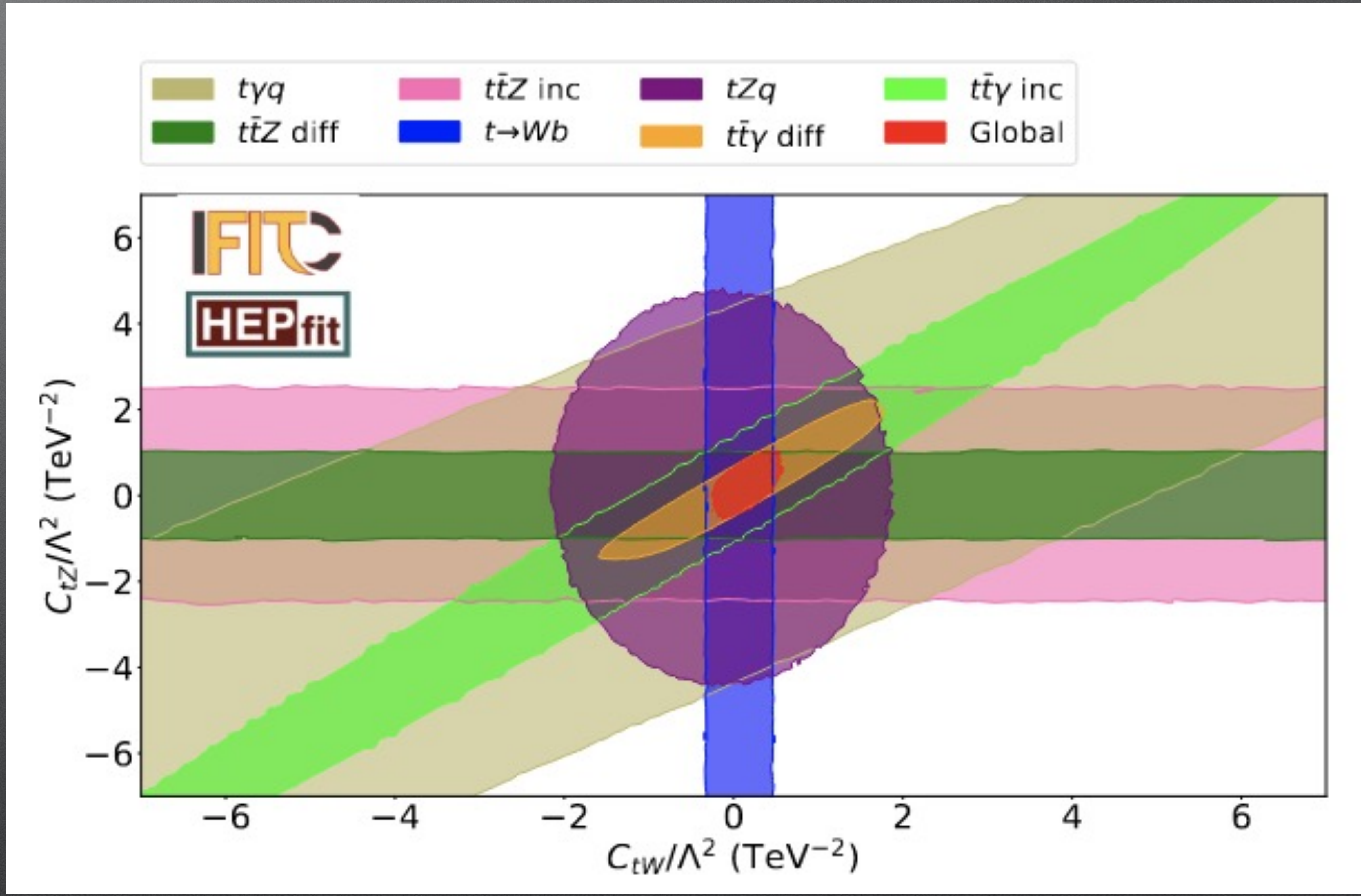
corner

- marginalises n-dimensional posterior pdf and estimates Bayesian credible intervals



Constraints on top EW coulings in SMEFT from Run II data

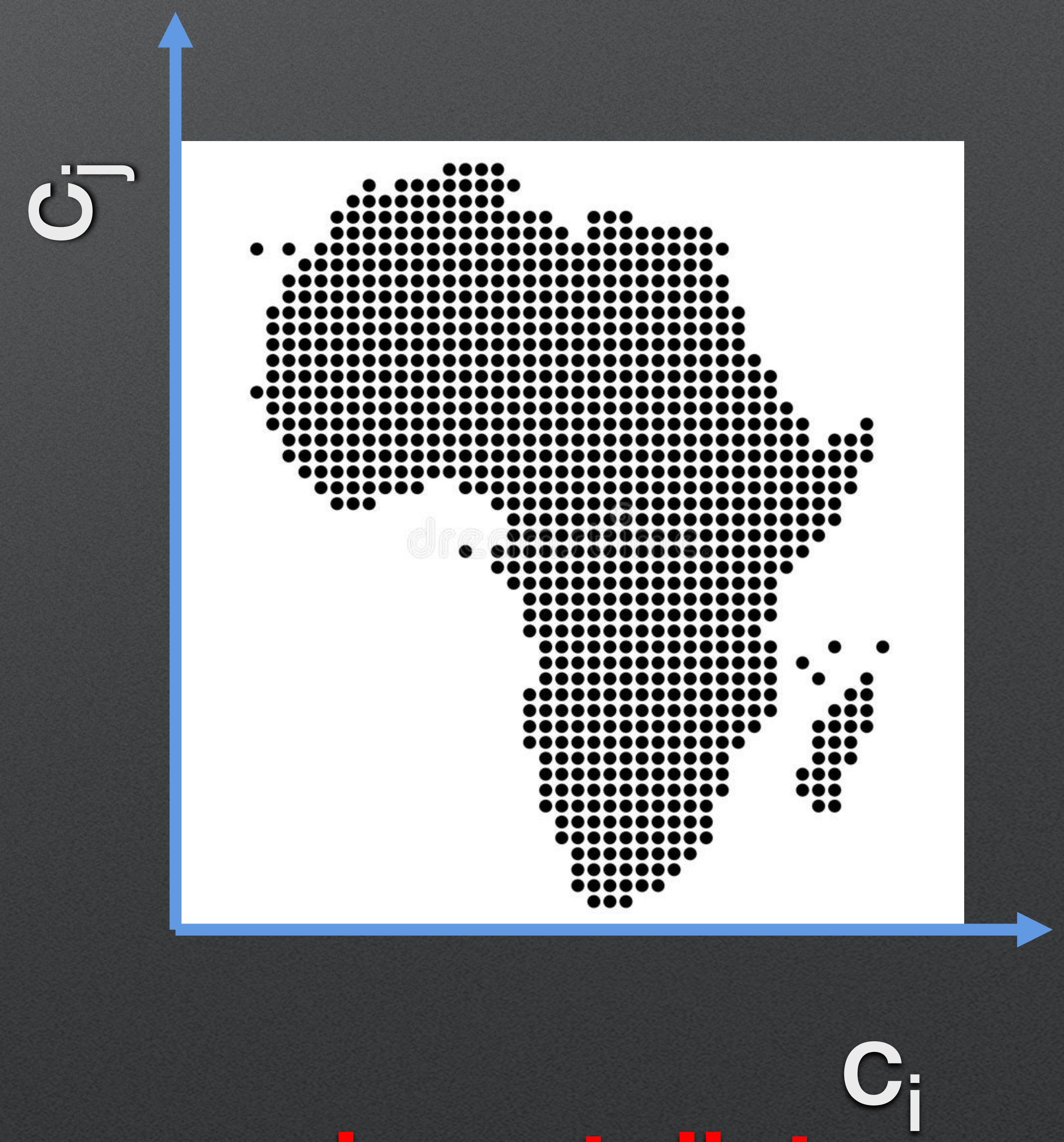
- a given SMEFT operator can affect many LHC observables
- *global* analyses that simultaneously consider all available data are crucial -> **we cannot cherry-pick the most discrepant results!**
- global SMEFT analysis at NLO including LHC, LEP/SLD and Tevatron data in the SMEFT
- careful treatment of data correlations



Summary and African context

Searching for new physics via modified top interactions in the SMEFT
is a discovery frontier in particle physics for the next decade

- Ample opportunity to gradually build African collaboration
  - diverse physics measurements
    - Top, Higgs, EW, b-physics…
  - collaboration with theorists
  - inter-experiment collaboration



- A Pan-African (and beyond) collaboration bringing together experimentalists and theorists for EFT studies is a no-brainer!