XLVIII International Meeting on Fundamental Physics

2021, Sep 06 -- Sep 11

*Organizers:*
M. Asorey (U. Zaragoza)
I. G. Irastorza (U. Zaragoza)

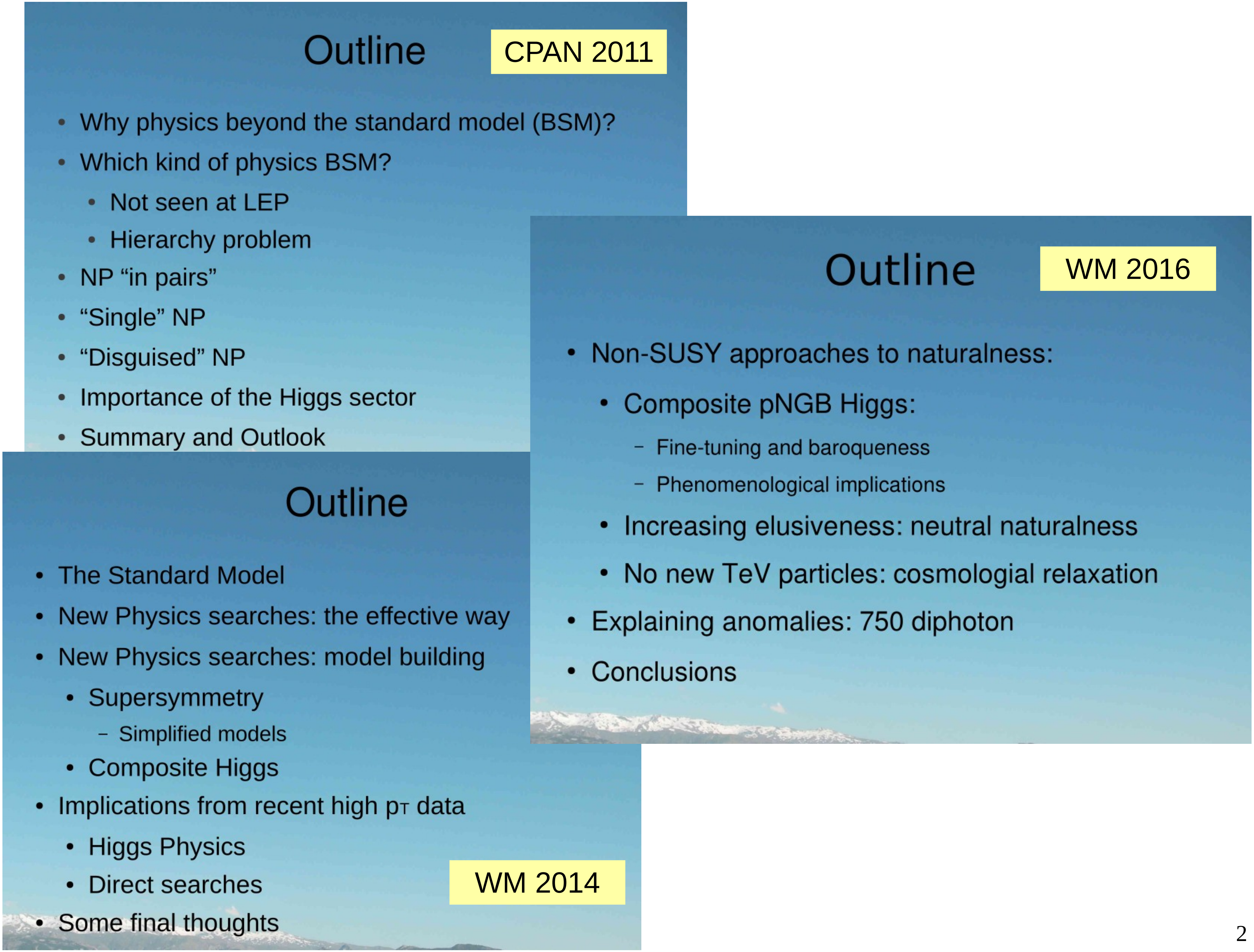
CENTRO DE CIENCIAS
DE BENASQUE
PEDRO PASCUAL

# Beyond the Standard Model

José Santiago

FTAE
High Energy Theory

ugr Universidad de Granada



## Outline

CPAN 2011

- Why physics beyond the standard model (BSM)?
- Which kind of physics BSM?
  - Not seen at LEP
  - Hierarchy problem
- NP “in pairs”
- “Single” NP
- “Disguised” NP
- Importance of the Higgs sector
- Summary and Outlook

## Outline

WM 2014

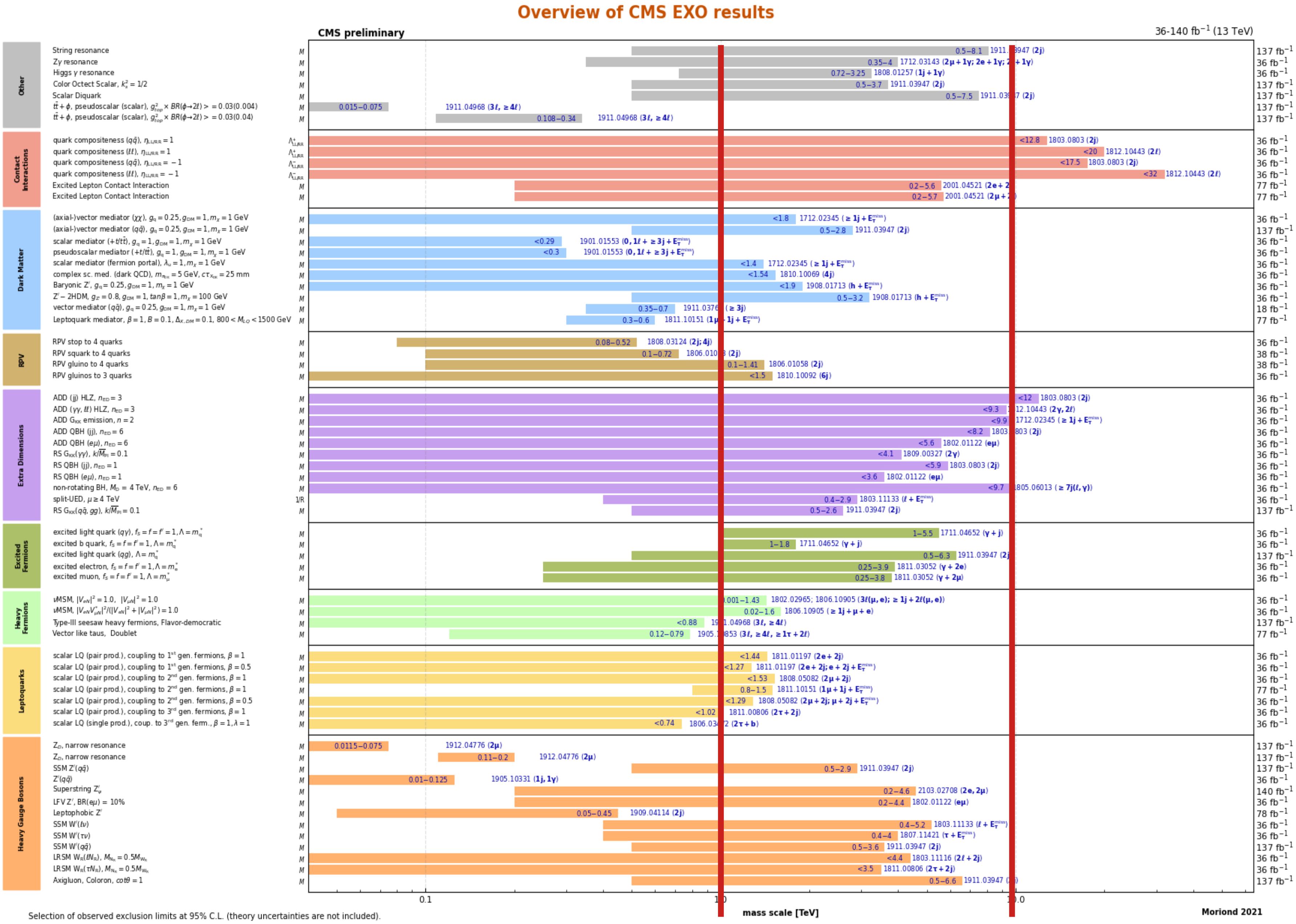
- The Standard Model
- New Physics searches: the effective way
- New Physics searches: model building
  - Supersymmetry
    - Simplified models
  - Composite Higgs
- Implications from recent high $p_T$ data
  - Higgs Physics
  - Direct searches
- Some final thoughts

## Outline

WM 2016

- Non-SUSY approaches to naturalness:
  - Composite pNGB Higgs:
    - Fine-tuning and baroqueness
    - Phenomenological implications
  - Increasing elusiveness: neutral naturalness
  - No new TeV particles: cosmologial relaxation
- Explaining anomalies: 750 diphoton
- Conclusions

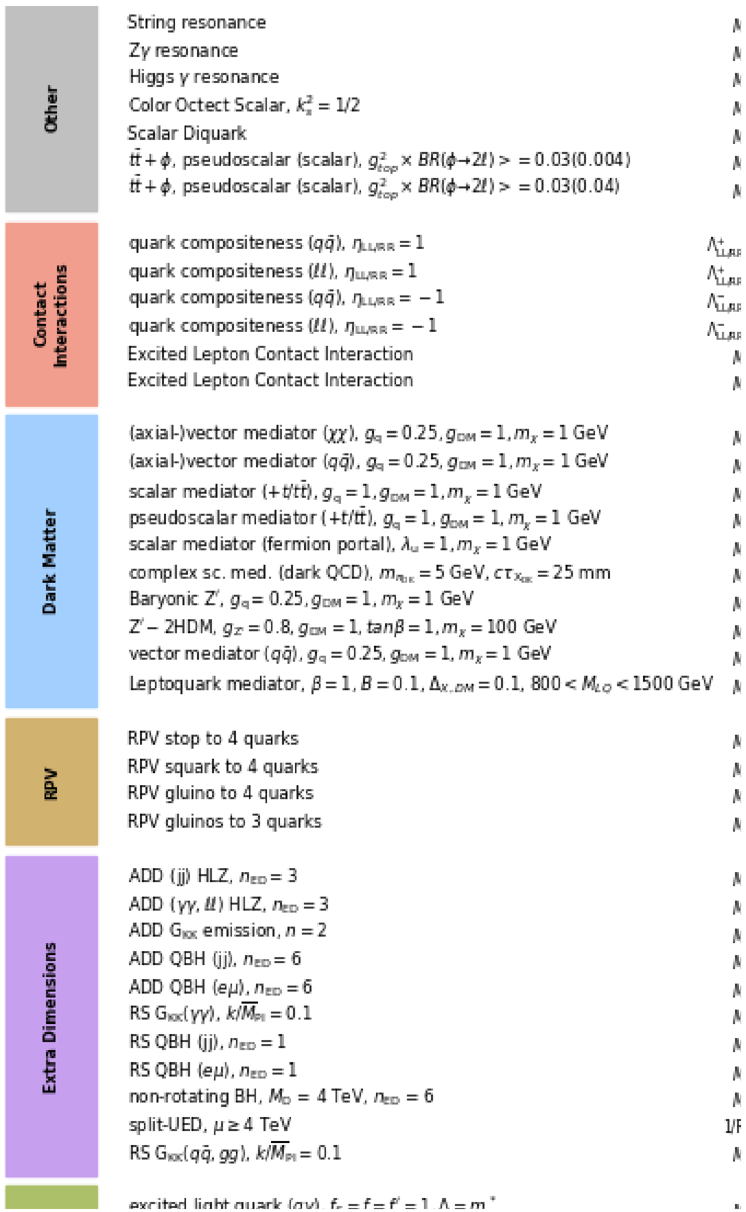
# What’s happened recently in BSM?



1 TeV

10 TeV

# What’s happened recently in BSM?



**Other**

String resonance
$Z\gamma$ resonance
Higgs $\gamma$ resonance
Color Octect Scalar, $k_s^2 = 1/2$
Scalar Diquark
$t\bar{t}+\phi$, pseudoscalar (scalar), $g_{top}^2 \times BR(\phi\to 2\ell) > = 0.03(0.004)$
$t\bar{t}+\phi$, pseudoscalar (scalar), $g_{top}^2 \times BR(\phi\to 2\ell) > = 0.03(0.04)$

**Contact Interactions**

quark compositeness $(q\bar{q})$, $\eta_{LL/RR} = 1$
quark compositeness $(\ell\ell)$, $\eta_{LL/RR} = 1$
quark compositeness $(q\bar{q})$, $\eta_{LL/RR} = -1$
quark compositeness $(\ell\ell)$, $\eta_{LL/RR} = -1$
Excited Lepton Contact Interaction
Excited Lepton Contact Interaction

**Dark Matter**

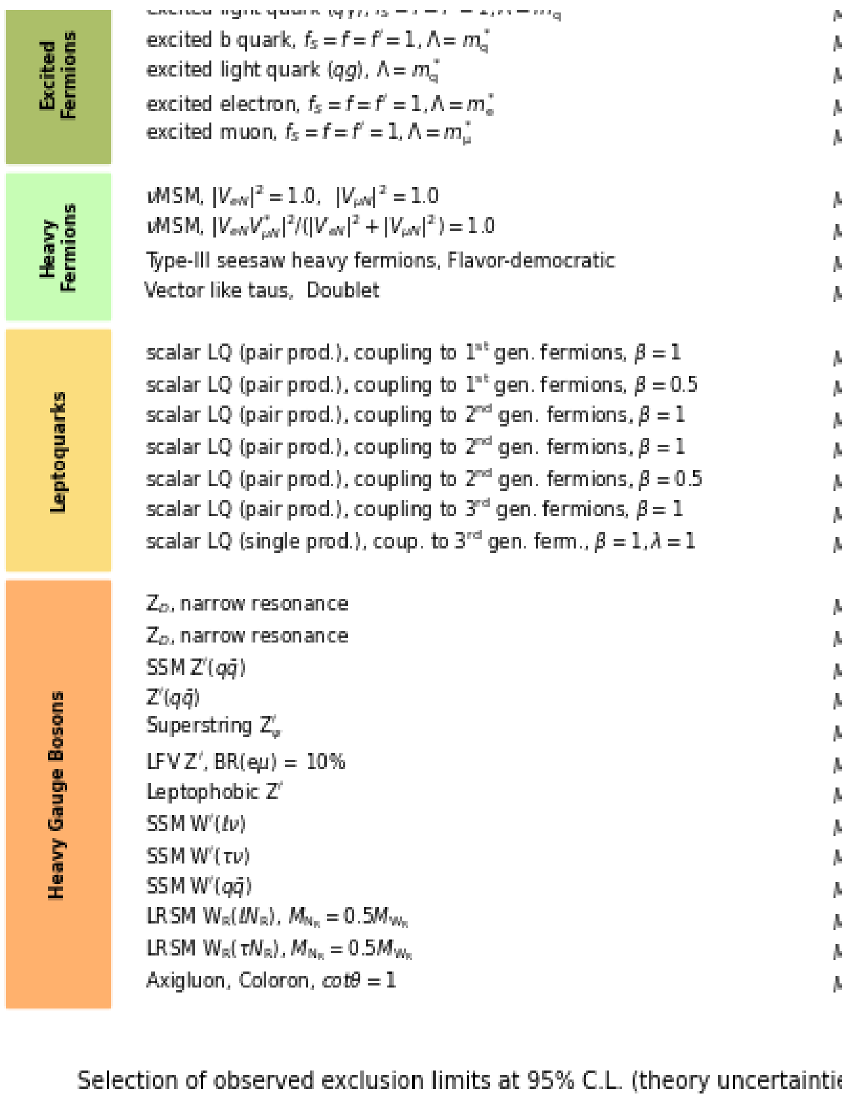
(axial-)vector mediator $(\chi\chi)$, $g_q = 0.25, g_{DM} = 1, m_\chi = 1$ GeV
(axial-)vector mediator $(q\bar{q})$, $g_q = 0.25, g_{DM} = 1, m_\chi = 1$ GeV
scalar mediator $(+t/t\bar{t})$, $g_q = 1, g_{DM} = 1, m_\chi = 1$ GeV
pseudoscalar mediator $(+t/t\bar{t})$, $g_q = 1, g_{DM} = 1, m_\chi = 1$ GeV
scalar mediator (fermion portal), $\lambda_u = 1, m_\chi = 1$ GeV
complex sc. med. (dark QCD), $m_{\pi_{DK}} = 5$ GeV, $c\tau_{\chi_{DK}} = 25$ mm
Baryonic $Z'$, $g_q = 0.25, g_{DM} = 1, m_\chi = 1$ GeV
$Z' - 2$HDM, $g_{Z'} = 0.8, g_{DM} = 1, \tan\beta = 1, m_\chi = 100$ GeV
vector mediator $(q\bar{q})$, $g_q = 0.25, g_{DM} = 1, m_\chi = 1$ GeV
Leptoquark mediator, $\beta = 1, B = 0.1, \Delta_{X,DM} = 0.1$, $800 < M_{LQ} < 1500$ GeV

**RPV**

RPV stop to 4 quarks
RPV squark to 4 quarks
RPV gluino to 4 quarks
RPV gluinos to 3 quarks

**Extra Dimensions**

ADD (jj) HLZ, $n_{ED} = 3$
ADD $(\gamma\gamma, \ell\ell)$ HLZ, $n_{ED} = 3$
ADD $G_{KK}$ emission, $n = 2$
ADD QBH (jj), $n_{ED} = 6$
ADD QBH $(e\mu)$, $n_{ED} = 6$
RS $G_{KK}(\gamma\gamma)$, $k/\overline{M}_{Pl} = 0.1$
RS QBH (jj), $n_{ED} = 1$
RS QBH $(e\mu)$, $n_{ED} = 1$
non-rotating BH, $M_D = 4$ TeV, $n_{ED} = 6$
split-UED, $\mu \geq 4$ TeV
RS $G_{KK}(q\bar{q}, gg)$, $k/\overline{M}_{Pl} = 0.1$



**Excited Fermions**

excited b quark, $f_s = f = f' = 1, \Lambda = m_q^*$
excited light quark $(qg)$, $\Lambda = m_q^*$
excited electron, $f_s = f = f' = 1, \Lambda = m_e^*$
excited muon, $f_s = f = f' = 1, \Lambda = m_\mu^*$

**Heavy Fermions**

$\nu$MSM, $|V_{eN}|^2 = 1.0$, $|V_{\mu N}|^2 = 1.0$
$\nu$MSM, $|V_{eN}V_{\mu N}^*|^2/(|V_{eN}|^2 + |V_{\mu N}|^2) = 1.0$
Type-III seesaw heavy fermions, Flavor-democratic
Vector like taus, Doublet

**Leptoquarks**

scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 1$
scalar LQ (pair prod.), coupling to 1st gen. fermions, $\beta = 0.5$
scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 1$
scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 1$
scalar LQ (pair prod.), coupling to 2nd gen. fermions, $\beta = 0.5$
scalar LQ (pair prod.), coupling to 3rd gen. fermions, $\beta = 1$
scalar LQ (single prod.), coup. to 3rd gen. ferm., $\beta = 1, \lambda = 1$

**Heavy Gauge Bosons**

$Z_D$, narrow resonance
$Z_D$, narrow resonance
SSM $Z'(q\bar{q})$
$Z'(q\bar{q})$
Superstring $Z'_\psi$
LFV $Z'$, BR$(e\mu)$ = 10%
Leptophobic $Z'$
SSM $W'(\ell\nu)$
SSM $W'(\tau\nu)$
SSM $W'(q\bar{q})$
LRSM $W_R(\ell N_R)$, $M_{N_R} = 0.5 M_{W_R}$
LRSM $W_R(\tau N_R)$, $M_{N_R} = 0.5 M_{W_R}$
Axigluon, Coloron, $\cot\theta = 1$

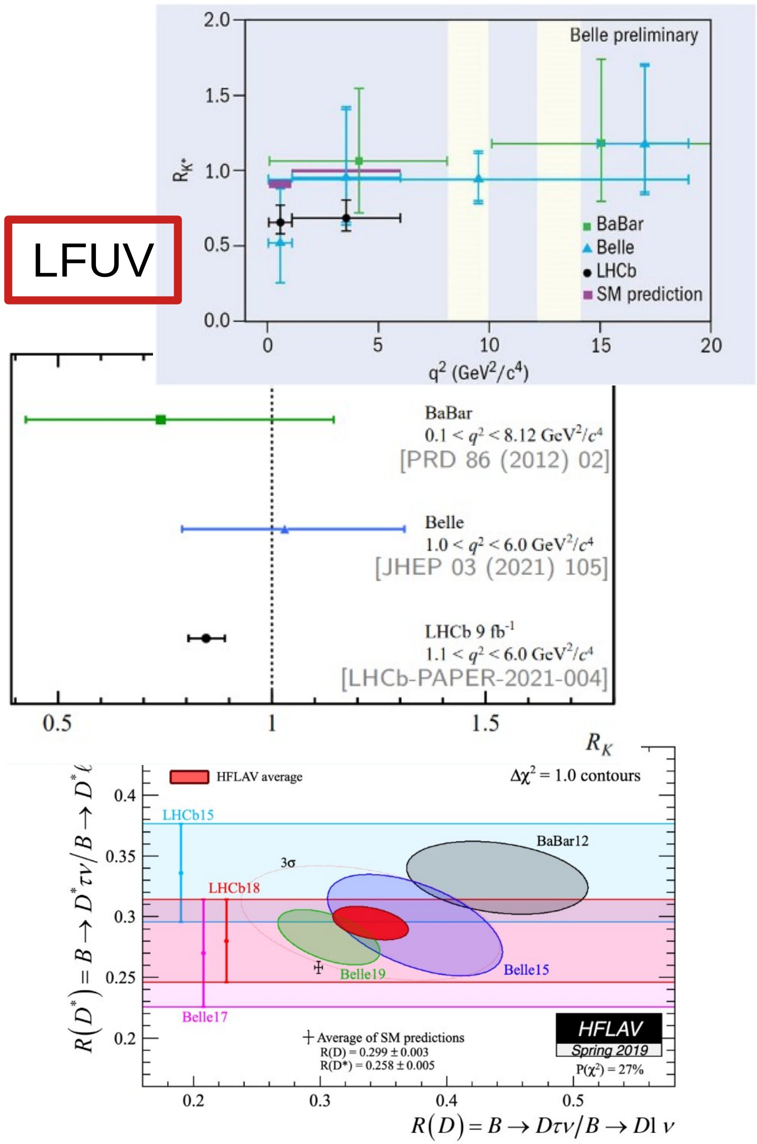
Selection of observed exclusion limits at 95% C.L. (theory uncertaintie

Turning all the stones! Allowed NP either more and more elusive or heavy

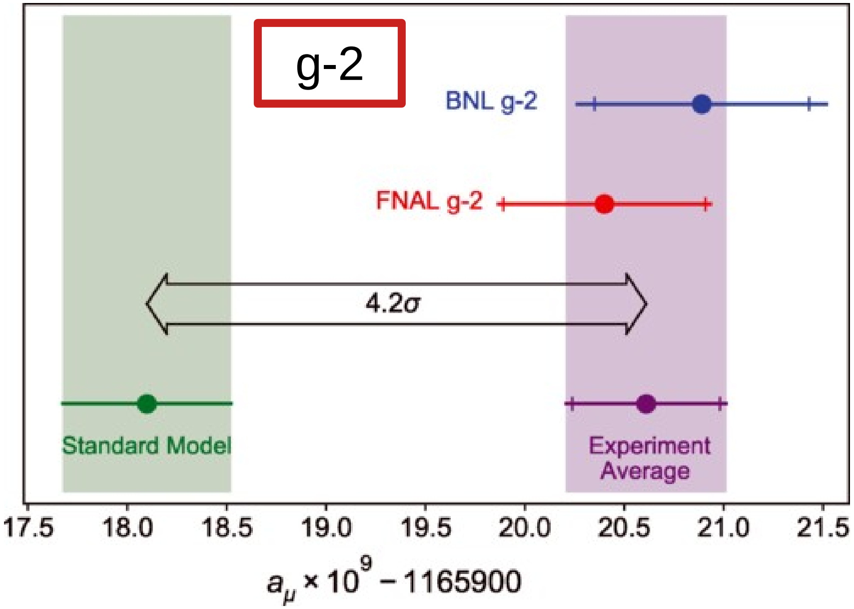
# What’s happened recently in BSM?

We got ourselves new (low-energy) anomalies!

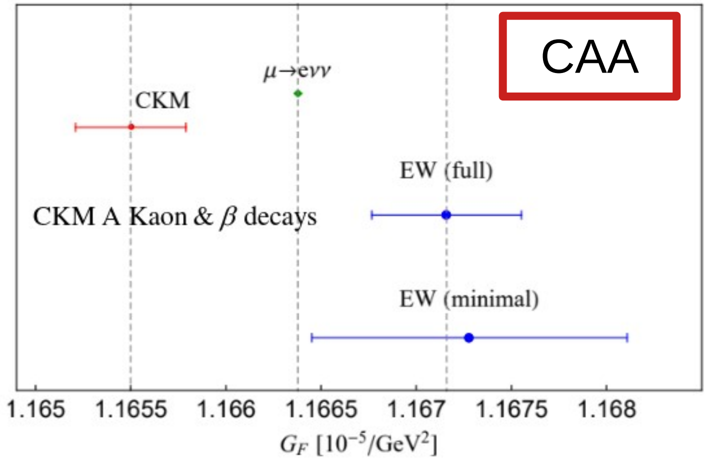
**LFUV**



**g-2**



**CAA**



# What’s happened recently in BSM?

Anomalies

Theory progress

Models

Flavor anomalies

g-2

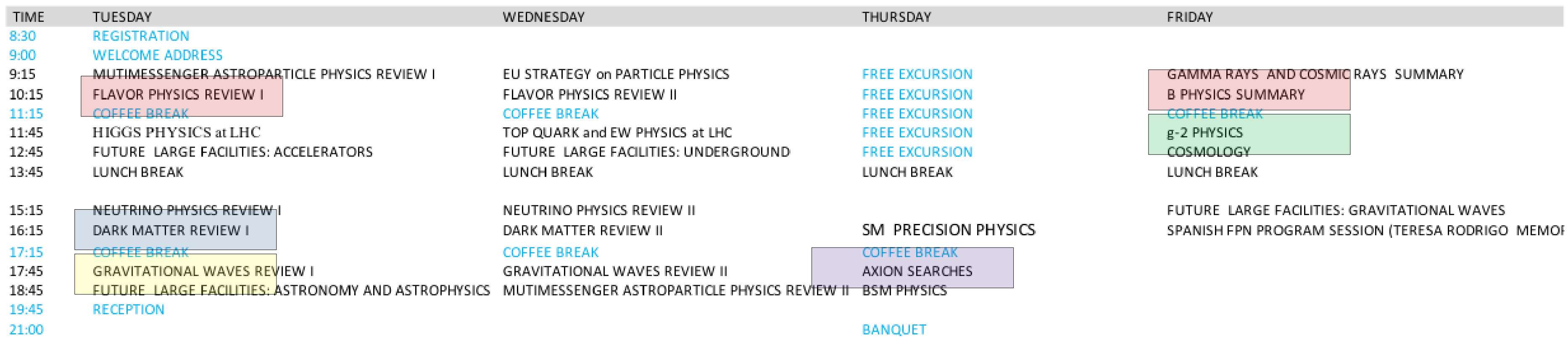
Dark matter

Axions (ALPs)

Grav. waves

?

PROGRAM, IMFP 2021, September 7-10



| TIME | TUESDAY | WEDNESDAY | THURSDAY | FRIDAY |
|---|---|---|---|---|
| 8:30 | REGISTRATION | | | |
| 9:00 | WELCOME ADDRESS | | | |
| 9:15 | MUTIMESSENGER ASTROPARTICLE PHYSICS REVIEW I | EU STRATEGY on PARTICLE PHYSICS | FREE EXCURSION | GAMMA RAYS AND COSMIC RAYS SUMMARY |
| 10:15 | FLAVOR PHYSICS REVIEW I | FLAVOR PHYSICS REVIEW II | FREE EXCURSION | B PHYSICS SUMMARY |
| 11:15 | COFFEE BREAK | COFFEE BREAK | FREE EXCURSION | COFFEE BREAK |
| 11:45 | HIGGS PHYSICS at LHC | TOP QUARK and EW PHYSICS at LHC | FREE EXCURSION | g-2 PHYSICS |
| 12:45 | FUTURE LARGE FACILITIES: ACCELERATORS | FUTURE LARGE FACILITIES: UNDERGROUND | FREE EXCURSION | COSMOLOGY |
| 13:45 | LUNCH BREAK | LUNCH BREAK | LUNCH BREAK | LUNCH BREAK |
| 15:15 | NEUTRINO PHYSICS REVIEW I | NEUTRINO PHYSICS REVIEW II | | FUTURE LARGE FACILITIES: GRAVITATIONAL WAVES |
| 16:15 | DARK MATTER REVIEW I | DARK MATTER REVIEW II | SM PRECISION PHYSICS | SPANISH FPN PROGRAM SESSION (TERESA RODRIGO MEMO |
| 17:15 | COFFEE BREAK | COFFEE BREAK | COFFEE BREAK | |
| 17:45 | GRAVITATIONAL WAVES REVIEW I | GRAVITATIONAL WAVES REVIEW II | AXION SEARCHES | |
| 18:45 | FUTURE LARGE FACILITIES: ASTRONOMY AND ASTROPHYSICS | MUTIMESSENGER ASTROPARTICLE PHYSICS REVIEW II | BSM PHYSICS | |
| 19:45 | RECEPTION | | | |
| 21:00 | | | BANQUET | |

# What’s happened recently in BSM?

Anomalies

~~Flavor anomalies~~

~~g-2~~

Theory progress

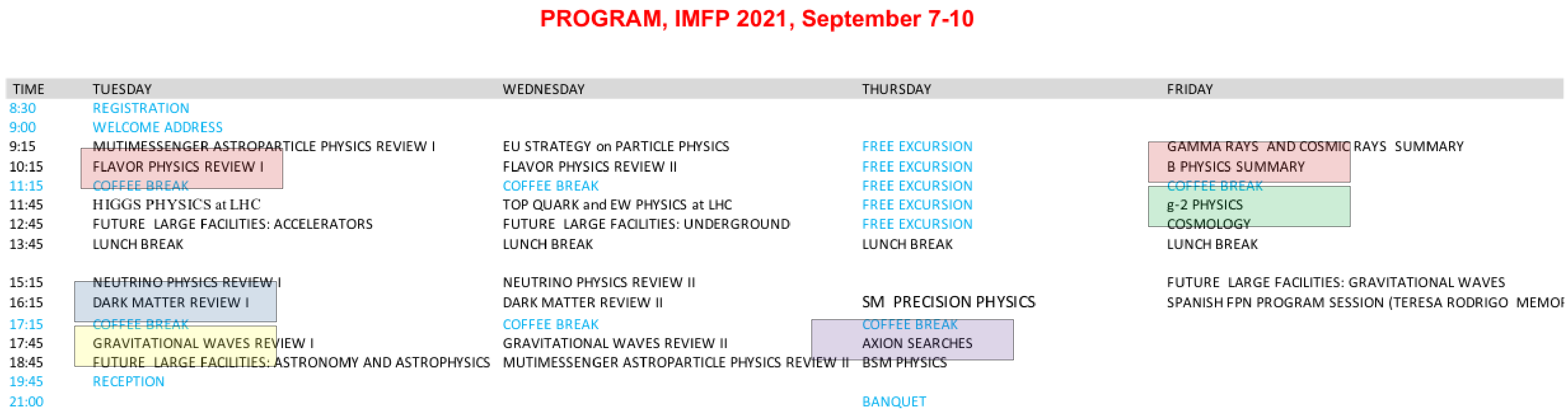
~~Dark matter~~

~~Axions (ALPs)~~

~~Grav. waves~~

Models

?



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| 19:45 | RECEPTION | | | |
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# BSM Models

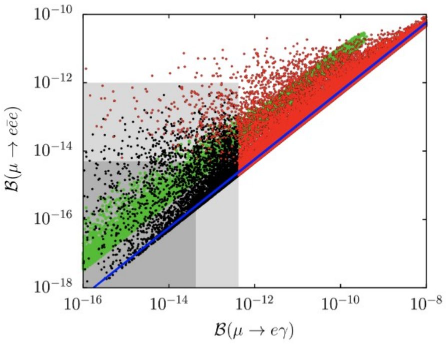
- In the 00’s naturalness arguments guaranteed discovery at the LHC.
- After a few years of smooth (bump-less) experimental searches we theorists “realized” that original predictions where to optimistic, based on minimal simplified scenarios and in “realistic” models it was “natural” for new physics to be more elusive than originally thought.
- Some more integrated luminosity later the BSM community is becoming less interested in specific models, rather in:
  - Mechanisms: Relaxation, clockwork, self-organised criticality, …
  - No models (or rather all models?): EFT
- Of course, there is still interest in specific models either because they have been poorly tested (ALPs, DM, …) or because existing phenomenological analyses are pre-LHC (and other experiments) and need to be updated with real data.

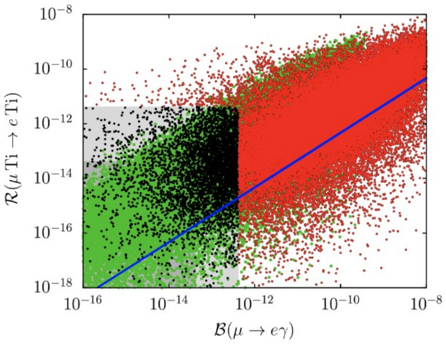
# New analysis of old models

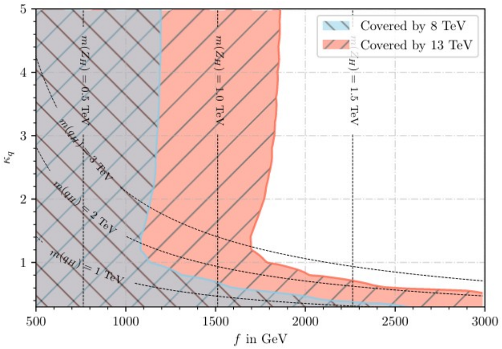
- Model building had a golden era in the 2000s. Most phenomenological studies simply assumed projected LHC (and other experiments) data.
- All these models will have to be revised with real data.

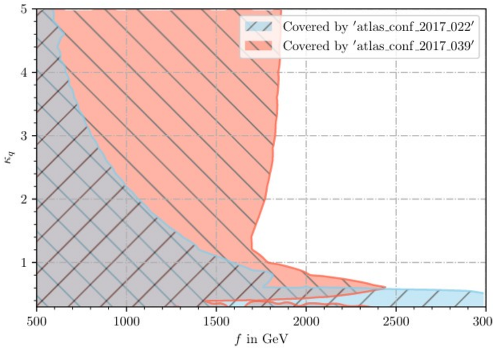
Little Higgs

Aguila, Ametller, Illana,Pérez-Poyatos, J.S., Talavera, Vega-Morales ‘17-’21
Dercks, Moortgat-Pick, Reuter, Shim ‘18



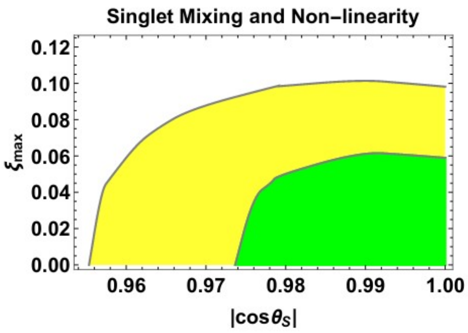






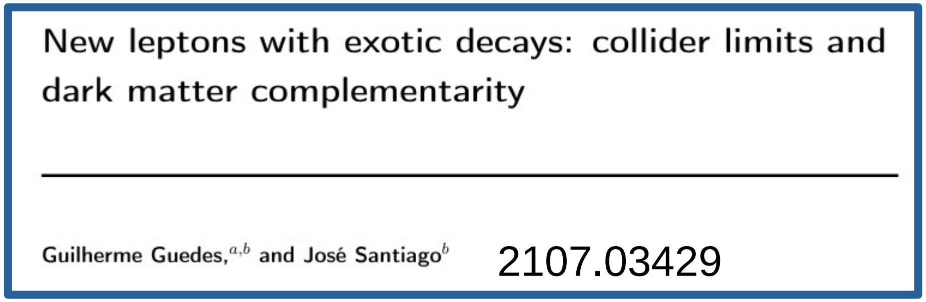
Composite Higgs

Kosha, Sanz ‘21



# New analysis of old models

- Model building had a golden era in the 2000s. Most phenomenological studies simply assumed projected LHC (and other experiments) data.
- All these models will have to be revised with real data.
- Also there are still models with signatures that are not being looked for in experiments.

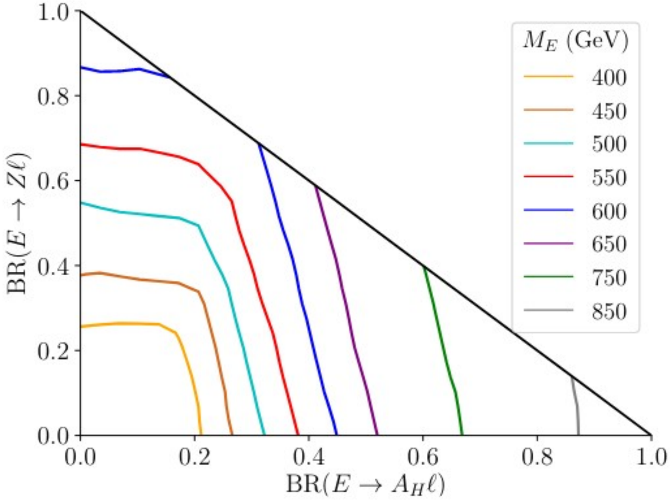


New leptons with exotic decays: collider limits and dark matter complementarity

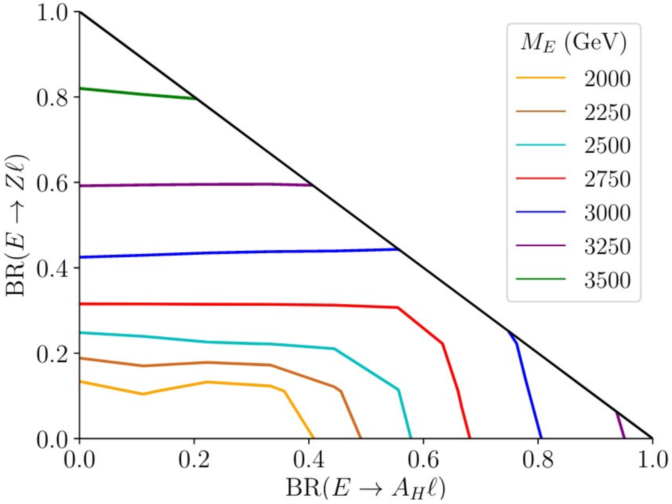
Guilherme Guedes,[a,b] and José Santiago[b]

2107.03429

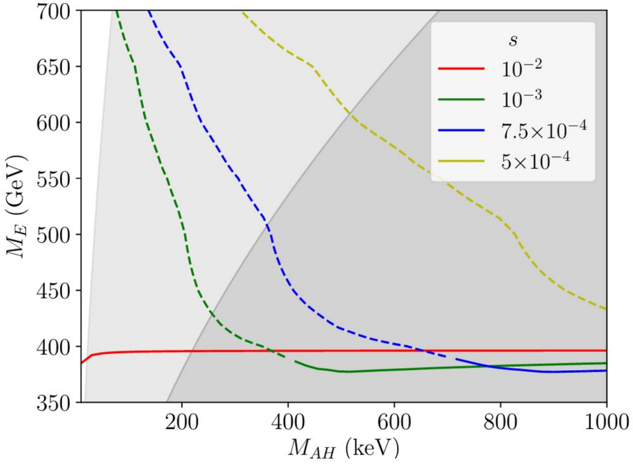
LHC current



FCC 100 TeV



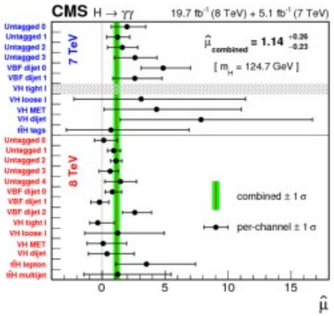
DM/collider interplay

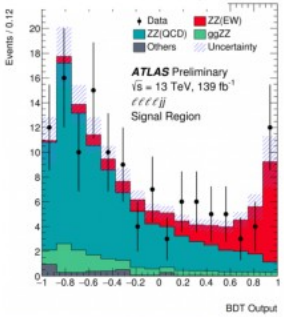


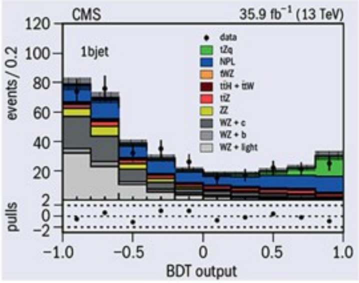
# Outline

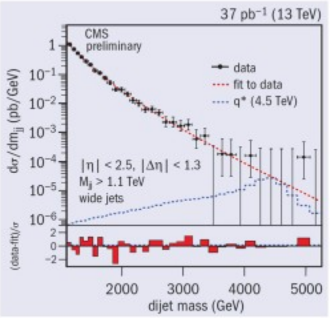
- The effective way beyond the SM
- Which EFT (basis)?
- Bottom-up: SMEFT global fits
  - Between bottom-up and top-down
  - Using the full bottom-up machinery
- Top-down: connecting NP to EFTs
  - IR/UV dictionaries
  - Automated matching
  - Towards the next IR/UV dictionaries
- Beyond the SMEFT
- Outlook

# The effective way beyond the SM

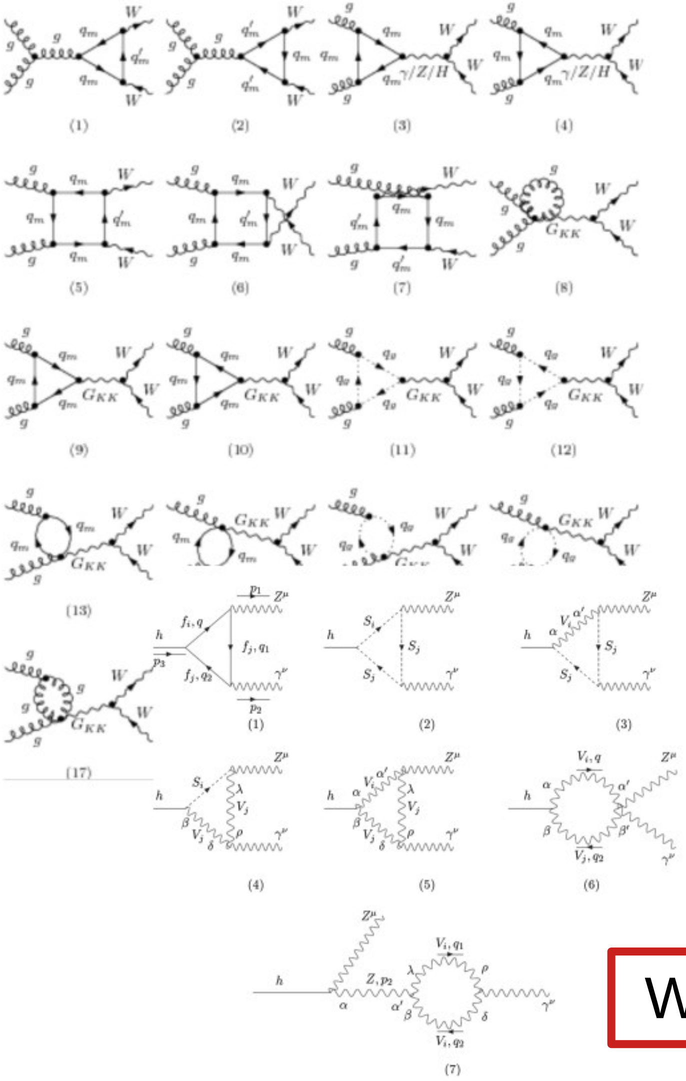


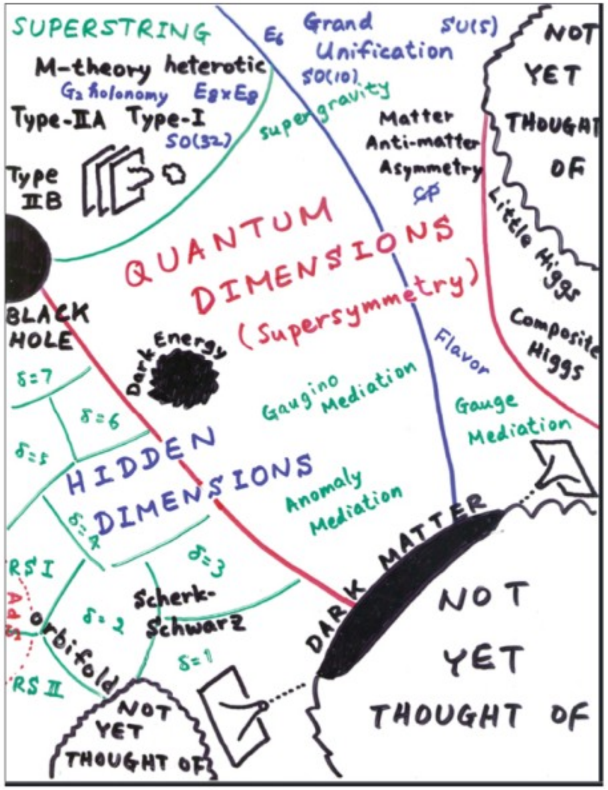






Getting implications of experimental data on new physics models is highly non trivial!

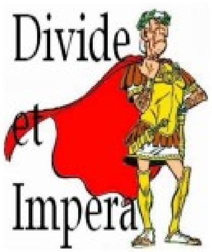




We need a global approach!!

# The effective way beyond the SM

The only way to go global is via EFTs



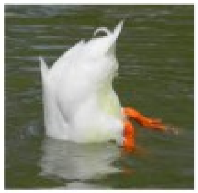
- Split the problem of computing the implications of experimental data to NP models in two (mostly independent) steps: bottom-up and top-down

EFTs have a number of extra bonus features

- Minimal theory bias (given a mass gap)
- Optimal to combine different data sets
- Can be consistently improved

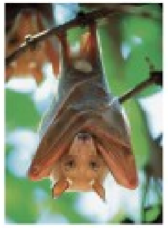
# The effective way beyond the SM

Efficient two-step comparison between theory and experiment



Bottom-up approach to EFT: model-independent parameterization of experimental data (global fit)

- Small number of models (EFTs)
- Global fit has to be done just once



Top-down approach to EFT: model discrimination

- Has to be done on a model by model basis
- Can be completely classified and automated
- Range of validity of EFT can be checked
- Comparison of direct and indirect limits

# The effective way beyond the SM

- EFTs are the optimal framework to simplify this comparison:
  - Minimal theory bias (in the presence of a mass gap).
  - Optimal to combine different data sets.
  - Can be systematically improved.
  - They split the problem of comparing experiment with models in two (mostly independent) steps: bottom-up (global fits, model independent) and top-down (matching specific new physics models to the EFT).
  - Thanks to power counting the number of models that contribute to experimental observables at certain order can be completely classified and computed: new guiding principle.
  - When combined (the bottom-up and top-down) we can build IR/UV dictionaries that directly connect experimental observables to any model of new physics.

# The effective way beyond the SM

- What is the SM?
  - It is the renormalizable part of the SMEFT (Standard Model Effective Field Theory = all local, Lorentz and gauge invariant operators built with the SM fields and their covariant derivatives).

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \ldots$$

$$\mathcal{L}_d = \sum_i c_i \mathcal{O}_i^{(d)}$$

Wilson Coeffs.

Ops. of dim. d

SMEFT parametrizes the low energy effects of any beyond the SM physics that lives at scales $\Lambda \gg v, \sqrt{s}, m$

# The effective way beyond the SM

- What is the SM?
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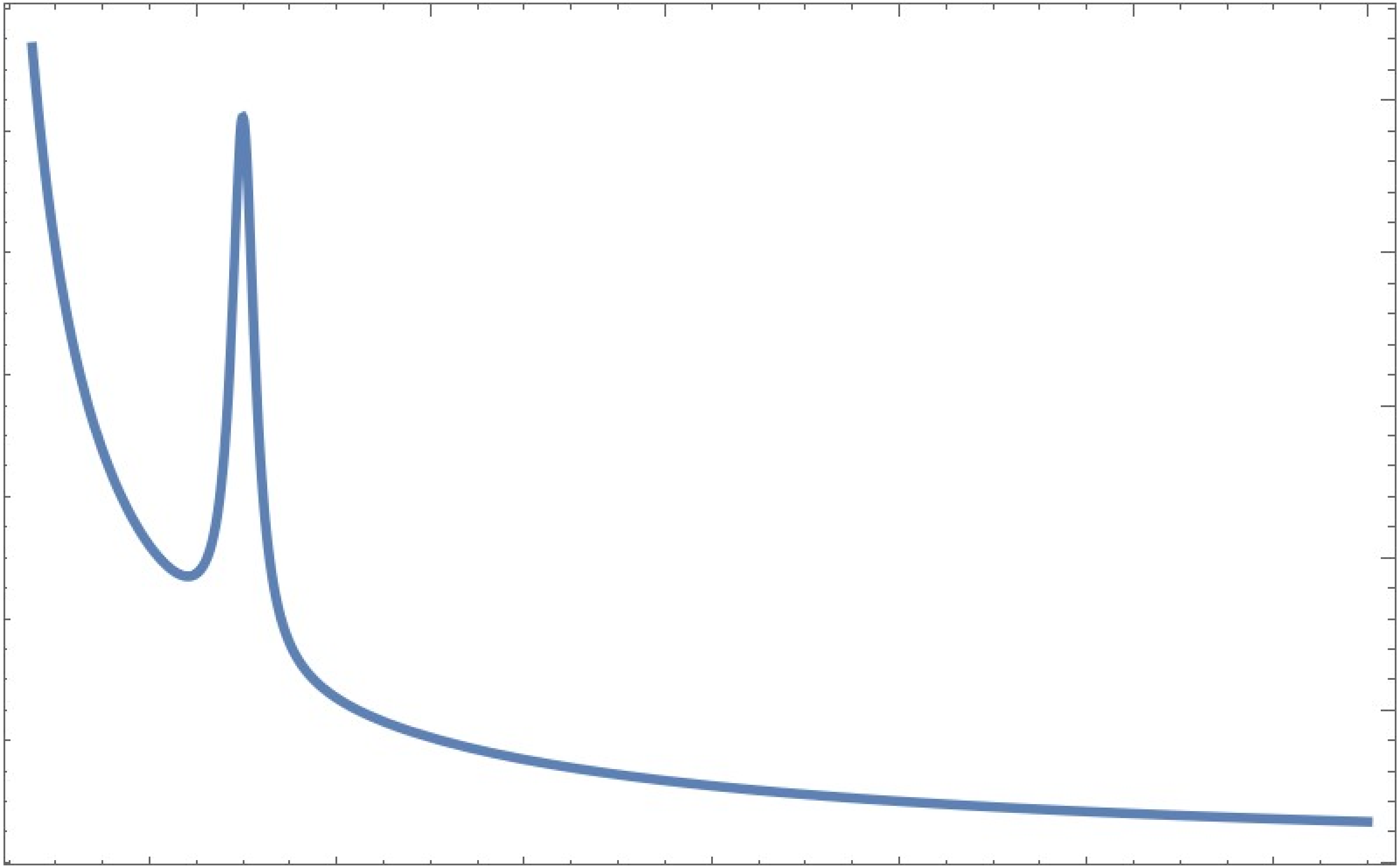
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \ldots$$

  - The low-energy effects of non-renormalizable operators are more suppressed the higher their dimension is: in practice we only need to consider a finite number of operators.
  - $\Lambda$ denotes de scale at which the EFT stops being valid (signals the scale at which new physics appears).

# The effective way beyond the SM

- How do we look for new physics the EFT way?



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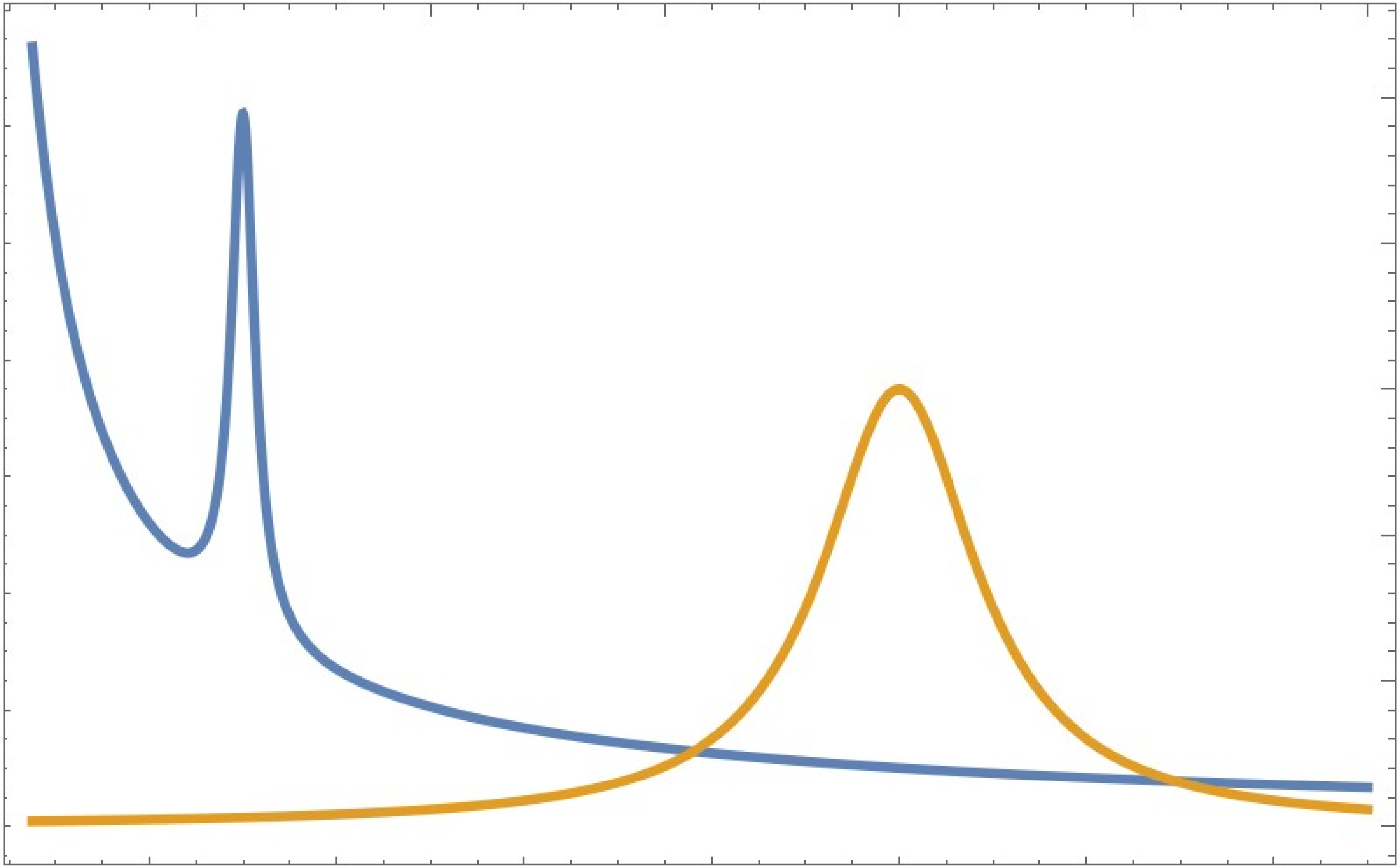

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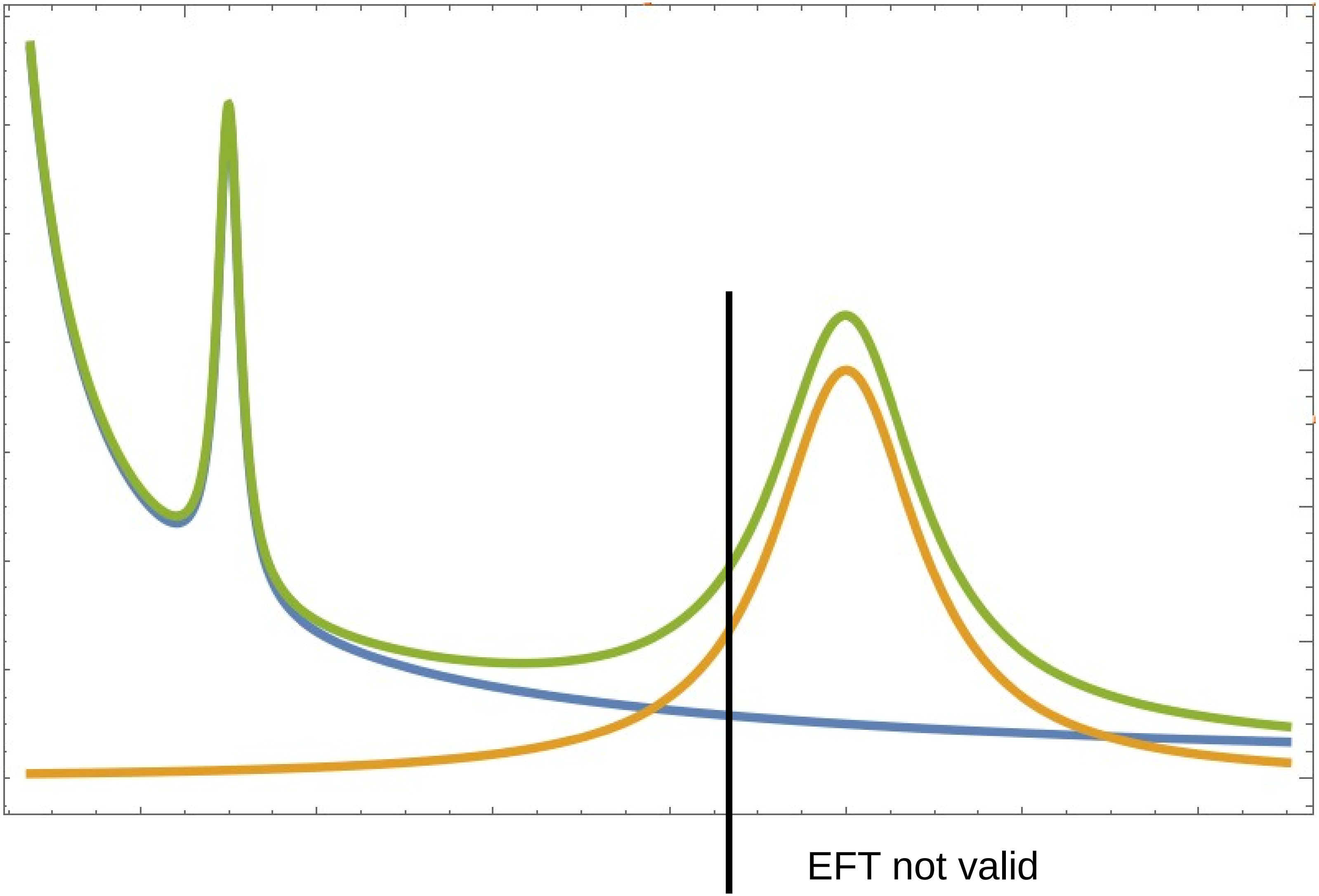

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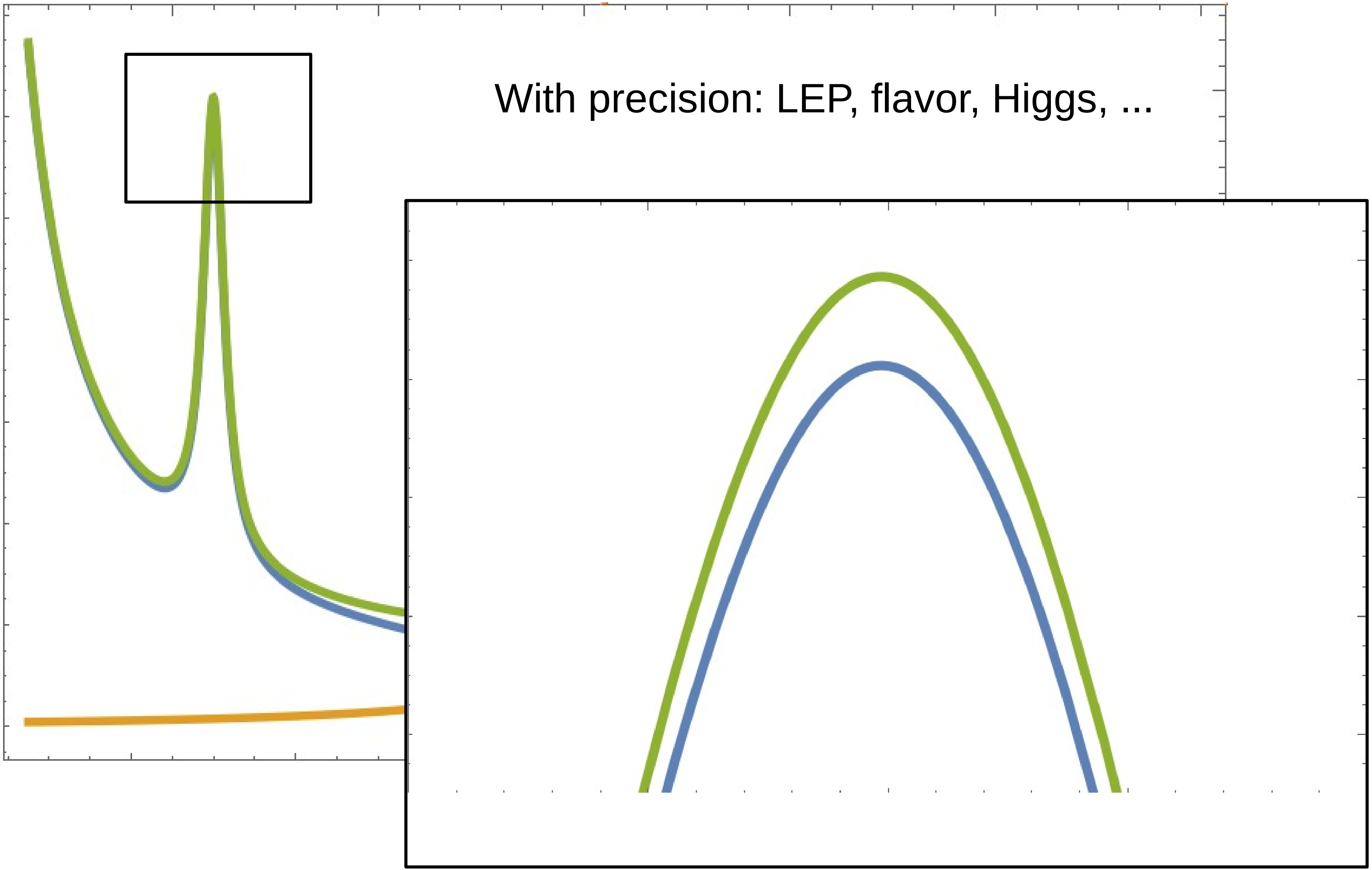

With precision: LEP, flavor, Higgs, ...

# The effective way beyond the SM

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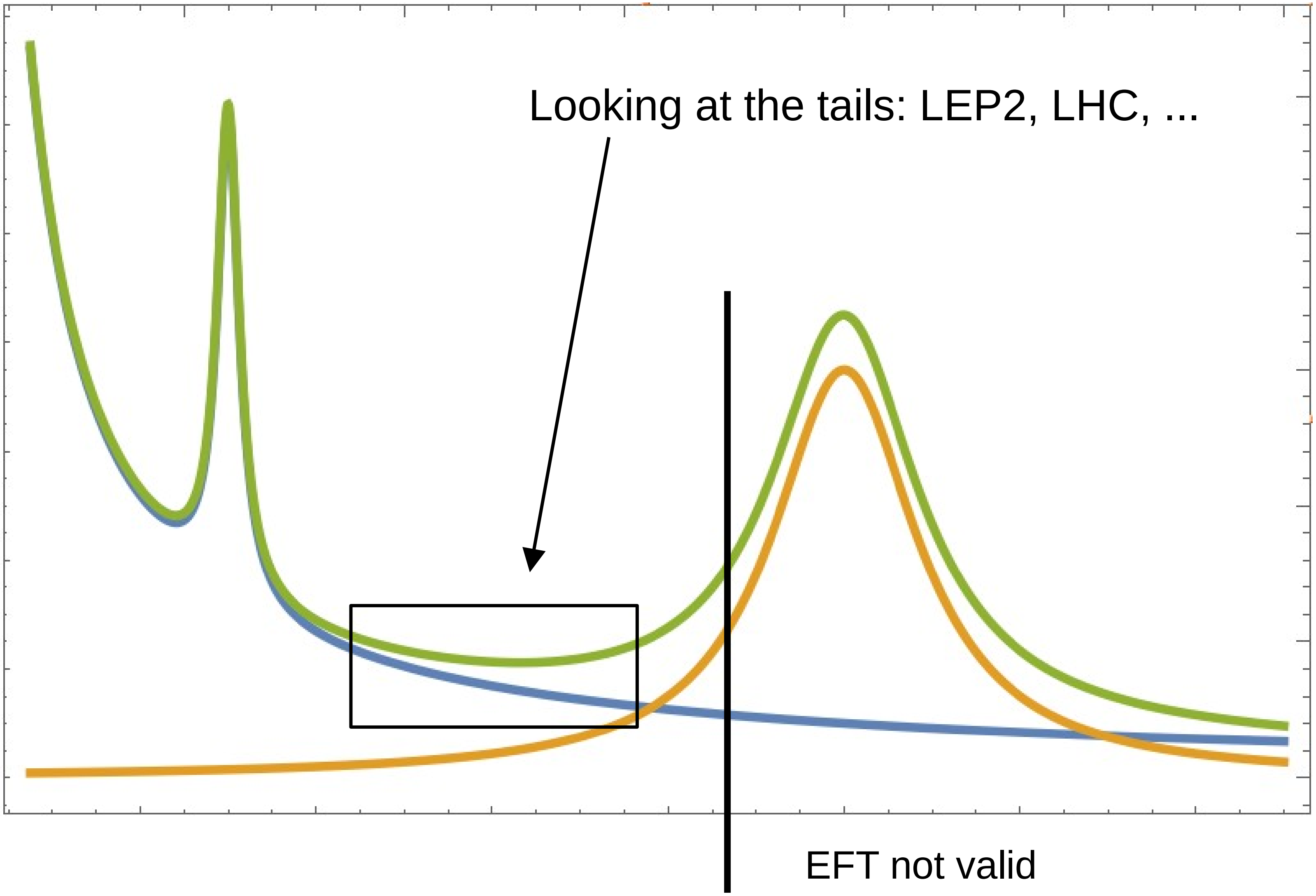
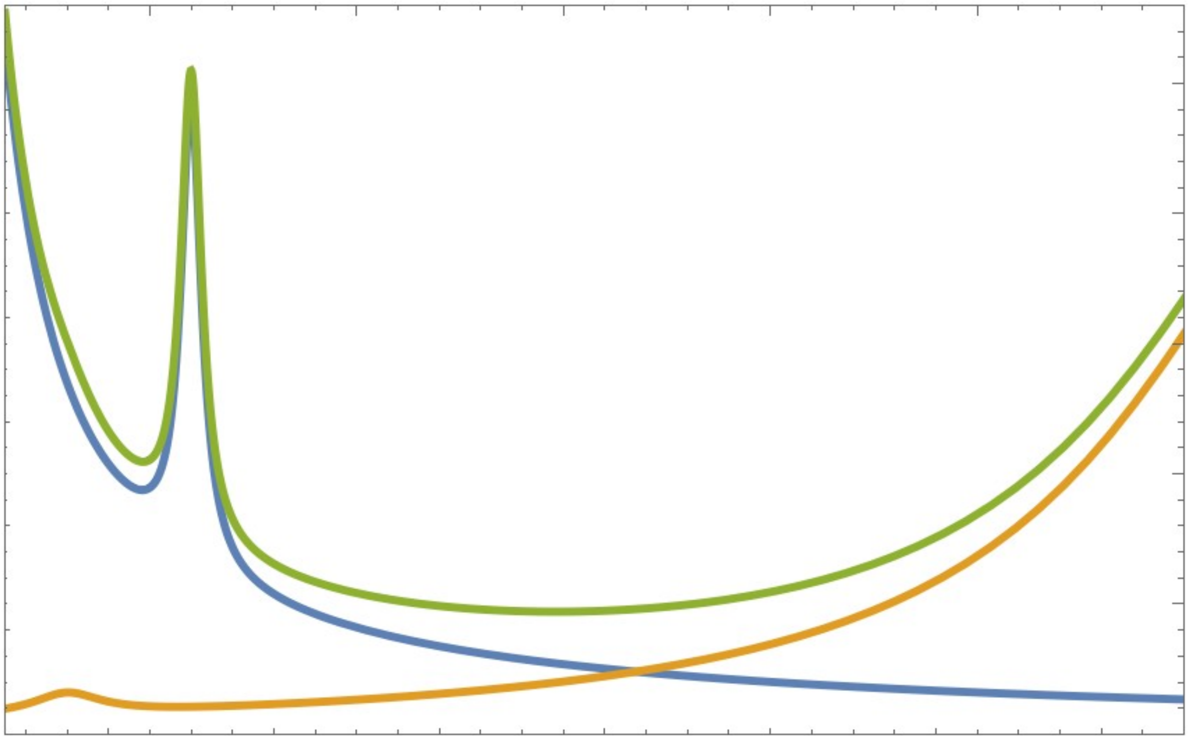


Looking at the tails: LEP2, LHC, ...

EFT not valid

# The effective way beyond the SM

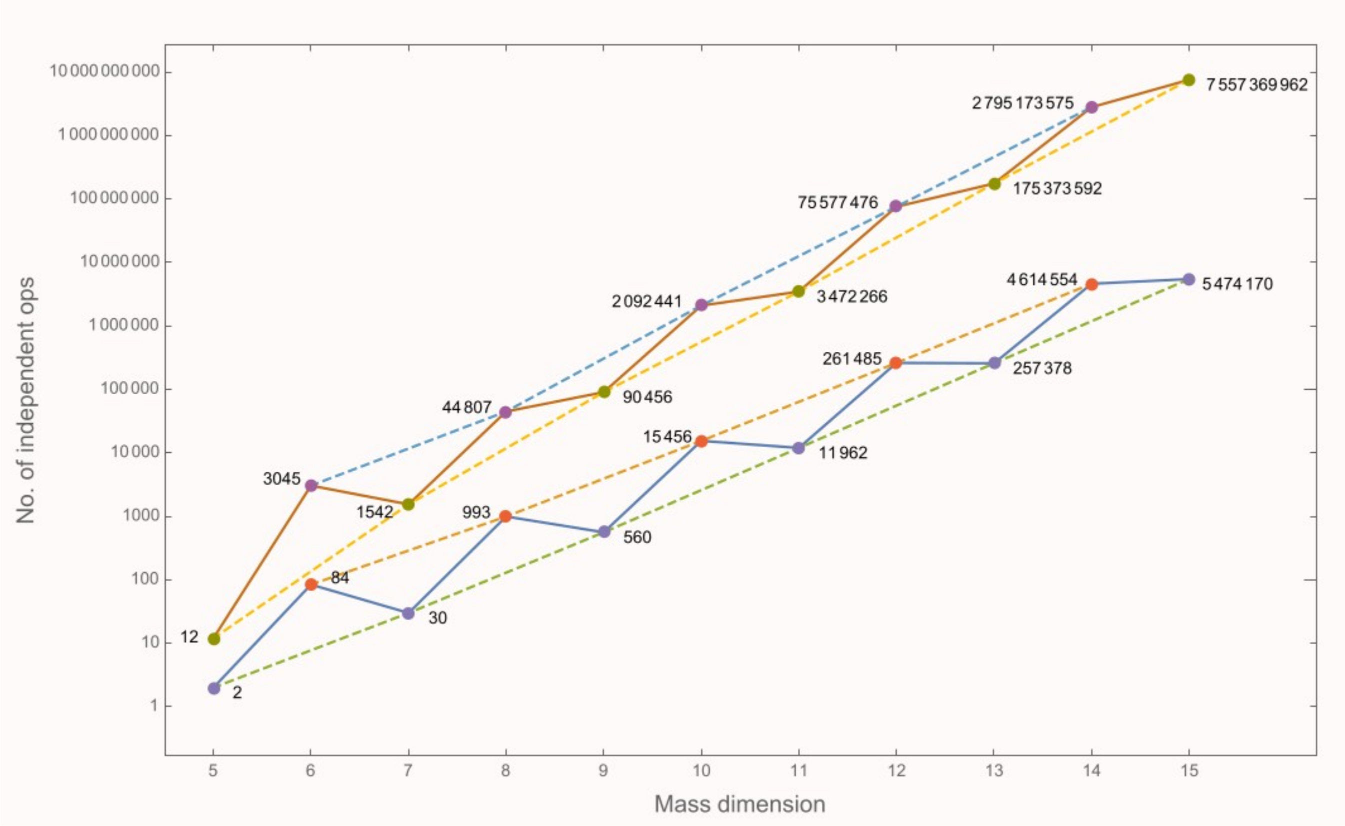
- How do we look for new physics the EFT way?
  - With low-energy precision measurements
  - Looking at the tails (can be also useful for light new physics that couples via non-renormalizable/derivative operators). Be careful with range of validity of EFT.

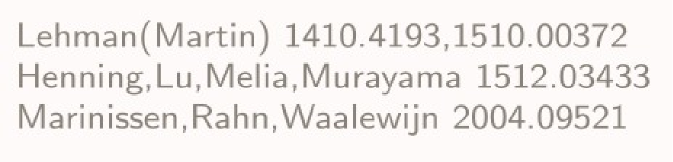


# Which EFT?

- We will consider the SMEFT as our EFT.
  - Where do we stop? Model independence comes at a price.
    - Dim 6 has 84 (3045) parameters for 1 (3) families (not all contribute to each experimental observable)

Need some organizing principle!!!




Lehman(Martin) 1410.4193,1510.00372
Henning,Lu,Melia,Murayama 1512.03433
Marinissen,Rahn,Waalewijn 2004.09521

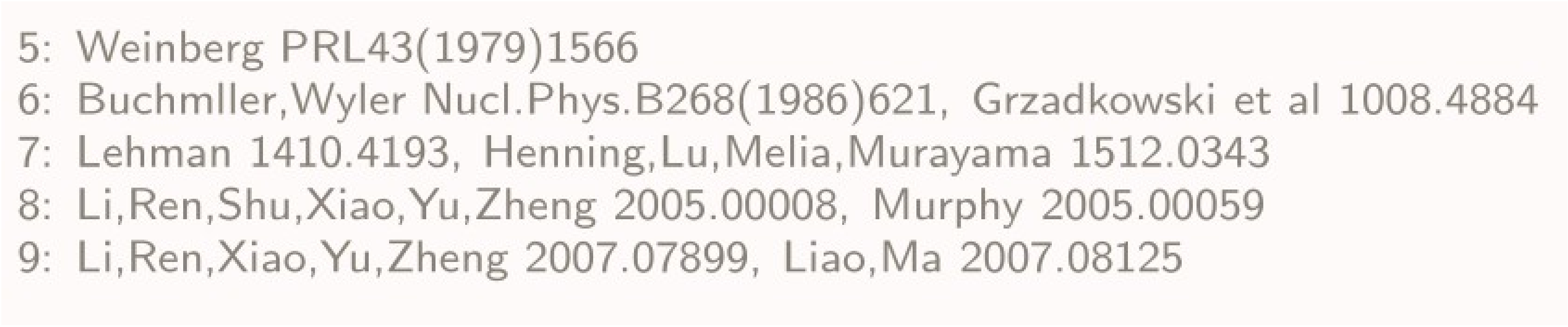
# Which EFT basis?

- All bases are equivalent if treated consistently, each has its strengths and weaknesses:
  - Warsaw basis: Easy to construct, widely used (more results available).

    [Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884]
  - Primary/Higgs basis: Good for phenomenology (bottom up).

    [Gupta, Pomarol, Riva, 1405.0181]
    [Masso, 1406.6376]
    [Falkowski, LHCHXSWG-INT-2015-001]
  - Silh basis: Good for matching (in specific models)

    [Giudice, Grojean, Pomarol, Rattazzi, 1008.4884]
- SMEFT bases known up to dim 9



5: Weinberg PRL43(1979)1566
6: Buchmller,Wyler Nucl.Phys.B268(1986)621, Grzadkowski et al 1008.4884
7: Lehman 1410.4193, Henning,Lu,Melia,Murayama 1512.0343
8: Li,Ren,Shu,Xiao,Yu,Zheng 2005.00008, Murphy 2005.00059
9: Li,Ren,Xiao,Yu,Zheng 2007.07899, Liao,Ma 2007.08125

# Which EFT basis?

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  - Silh basis: Good for matching (in specific models)

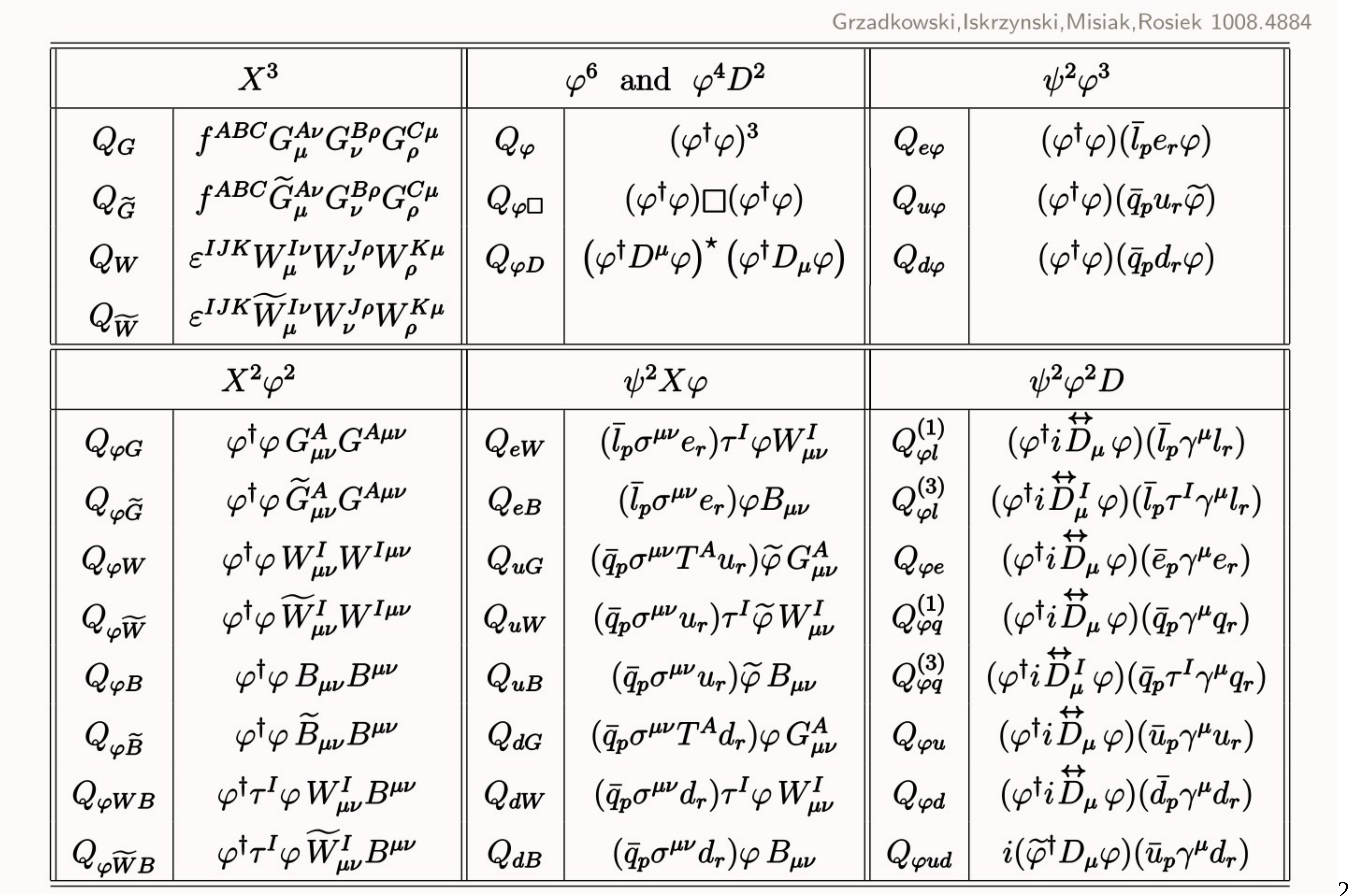
    [Giudice, Grojean, Pomarol, Rattazzi, 1008.4884]

- SMEFT bases known up to dim 9
- Interplay with on-shell methods very interesting for basis construction, matching, RGE calculations.

Shadmi, Weiss ‘18
Henning, Melia ‘19
Ma, Shu, Xiao ‘19
Aoude, Machado ‘19
Durieux, Kitahara, (Machado), Shadmi, Weiss, ‘19,’20

Durieux, Machado ‘19
Pomarol, Pujolas, Salas ‘19
Craig, Jiang, Li, Sutherland ‘20
Baratella, Fernandez, Pomarol ‘20
Elias-Miró, Ingoldby, Riembau ‘20

# Warsaw basis

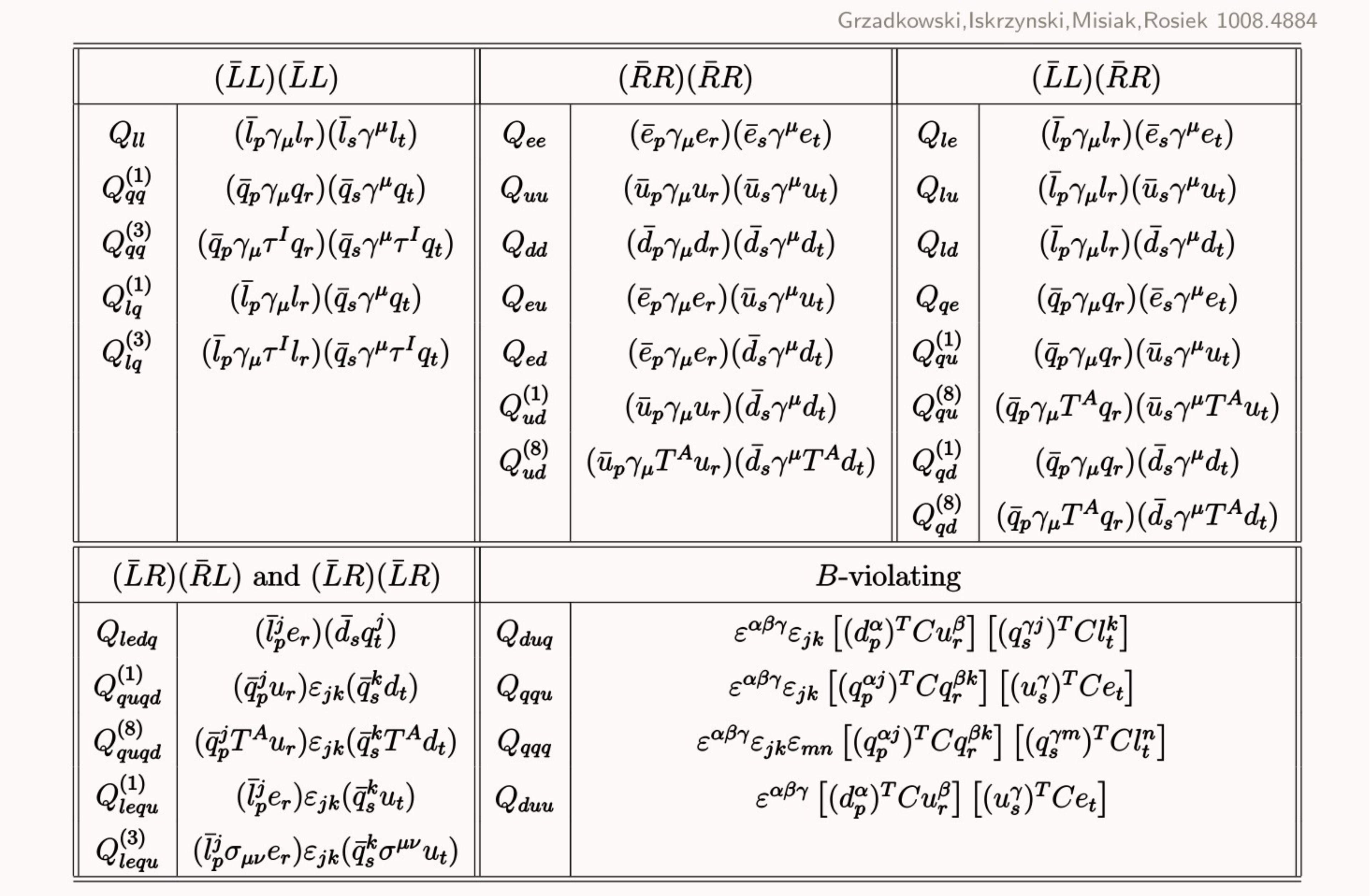


Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r\varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r\widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | | | | |

| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
|---|---|---|---|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p\gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar e_p\gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p\gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p\gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p\gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$ |

# Warsaw basis



Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | $B$-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ |
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$ | $Q_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$ | | |

# SMEFT global fits

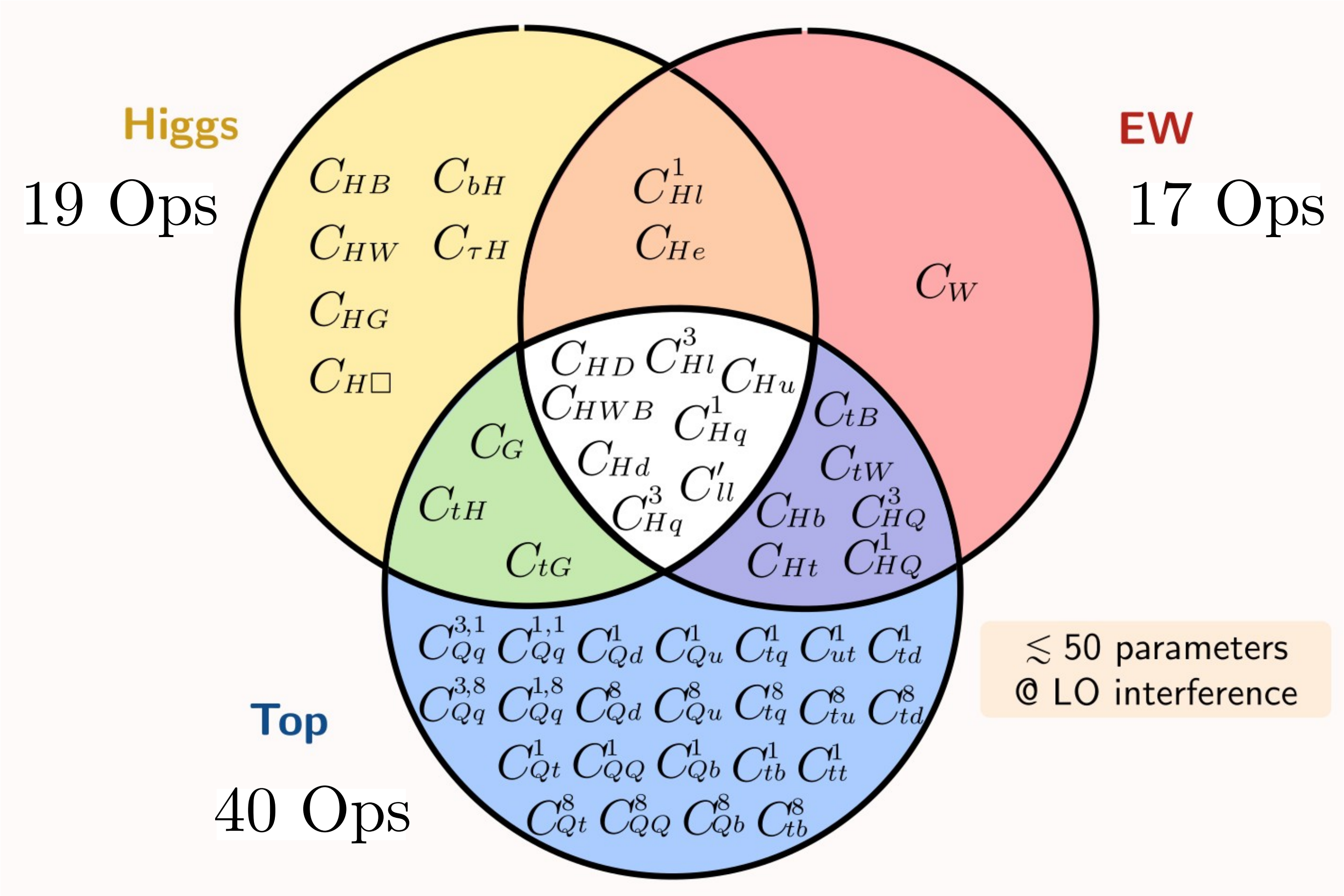
- Interpretation of experimental data in terms of EFT is crucial but very challenging:
  - Linear vs quadratic analysis (dim 6 vs dim 8)

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} 2\,\mathrm{Re}\,\mathcal{M}_{SM}\mathcal{M}_6^* + \frac{1}{\Lambda^4}[|\mathcal{M}_6|^2 + 2\,\mathrm{Re}\,\mathcal{M}_{SM}\mathcal{M}_8^*] + \dots$$

  - Flavor assumptions
  - NLO effects (tree-level vs one-loop)
- Increasing globality (number of different observables) adds complexity (more operators) but also correlations (relations between observables)
- Differential observables break kinematic flat directions: better operator discrimination

# SMEFT global fits

- Interpretation of experimental data in terms of EFT is crucial but very challenging

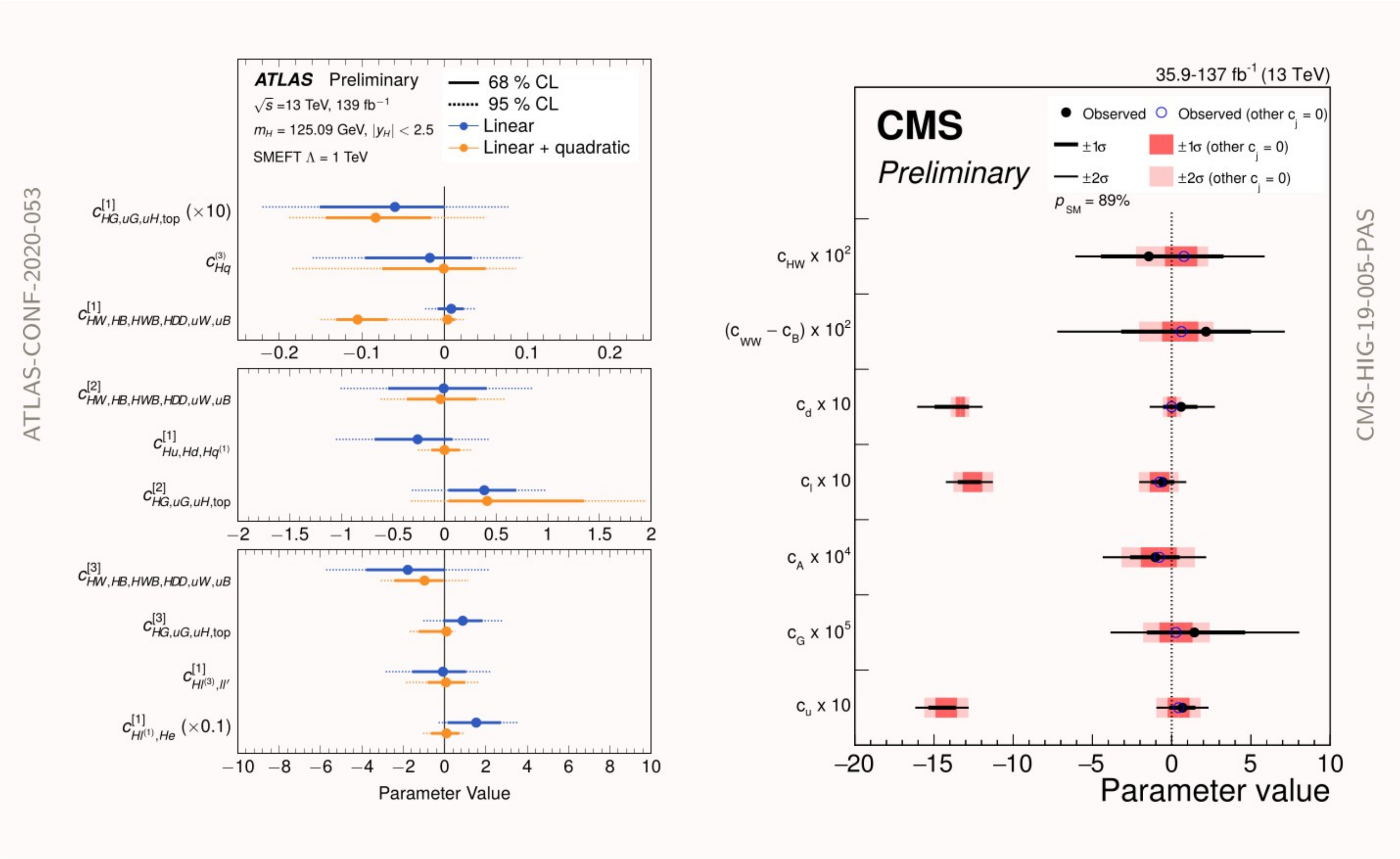


Brivio @ Planck21

Even more operators if quadratic, dim 8, NLO, … effects included

# SMEFT global fits

- EFT interpretation by experimental collaborations is becoming standard

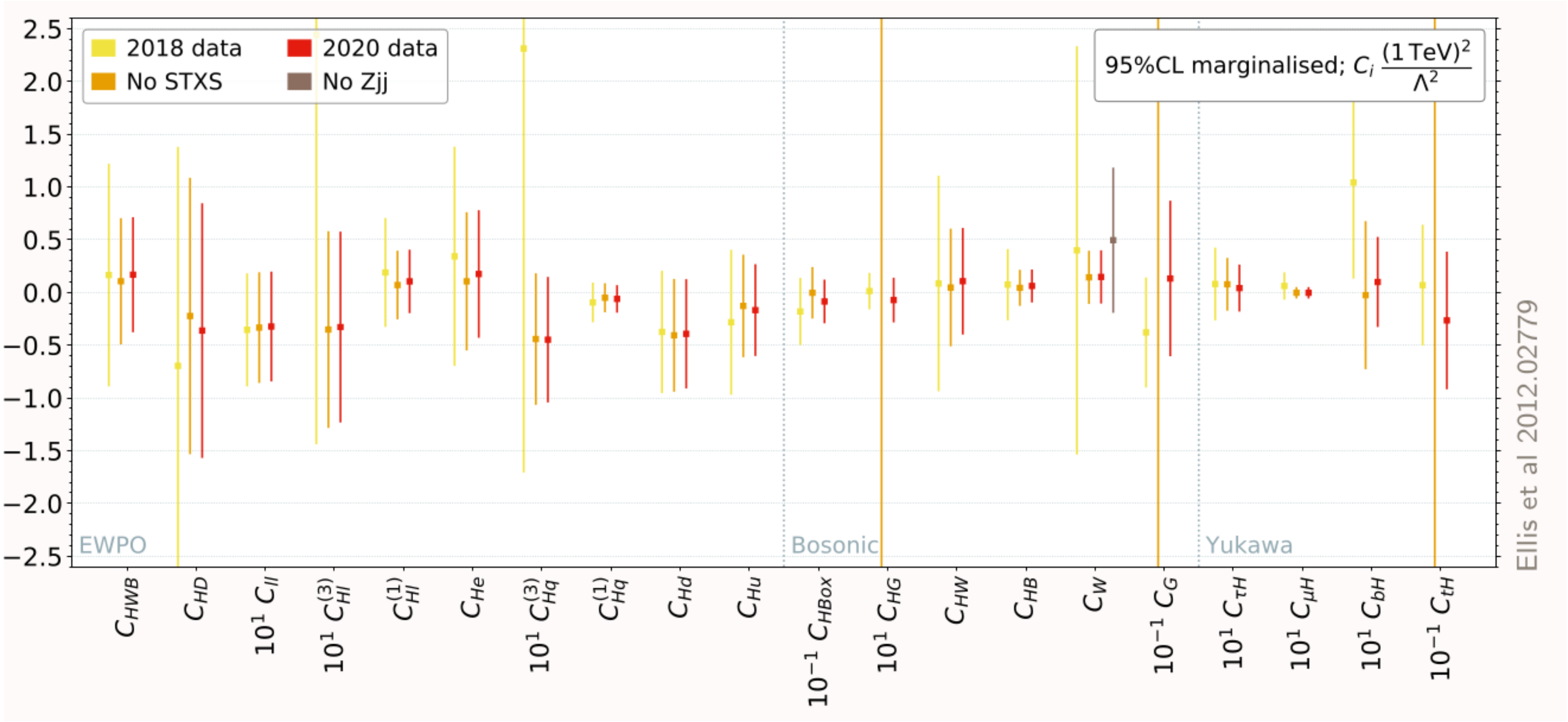


ATLAS-CONF-2020-053

CMS-HIG-19-005-PAS

# SMEFT global fits

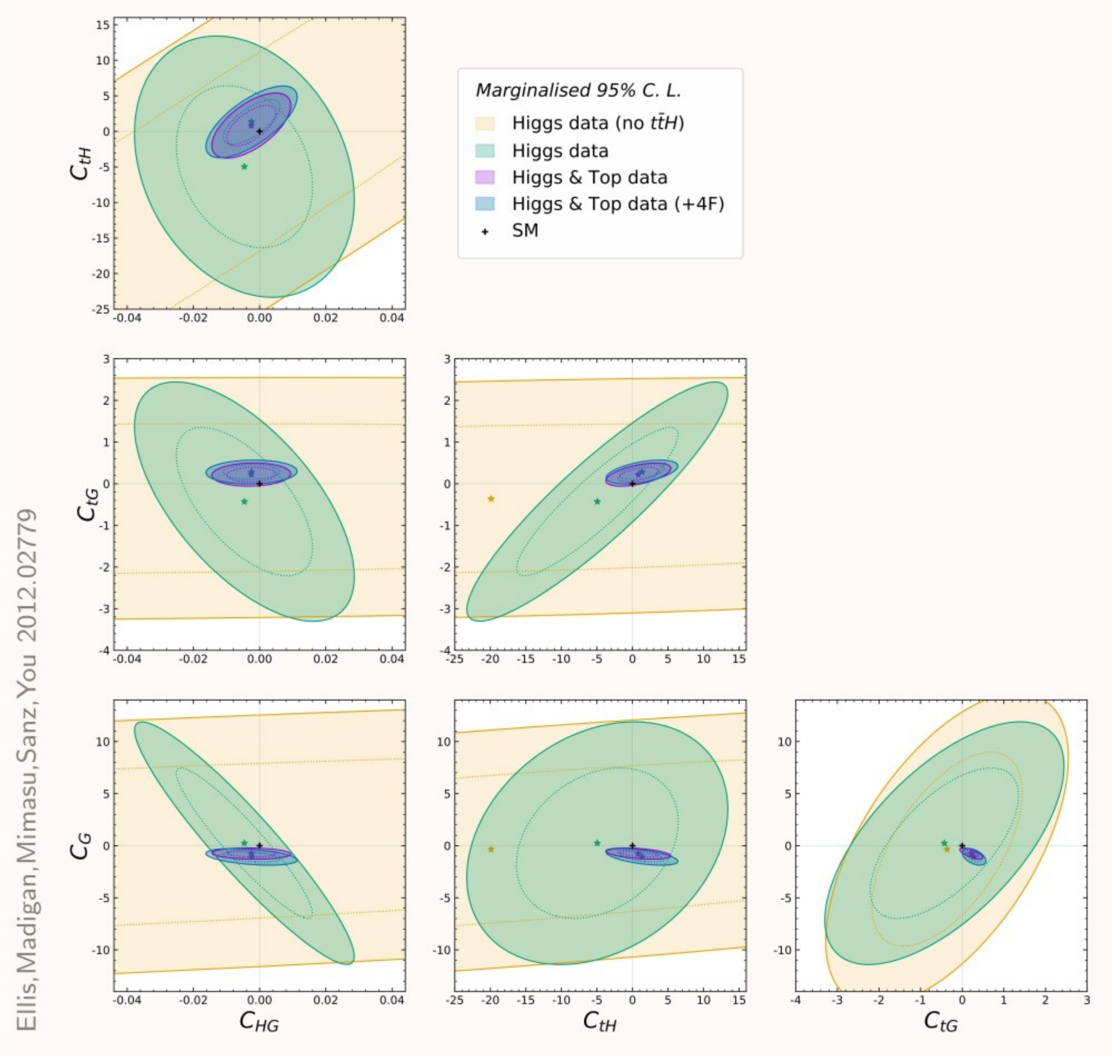
- Higgs plus EWPD combination



Ellis et al 2012.02779

# SMEFT global fits

- Correlations between different data sets can be very important

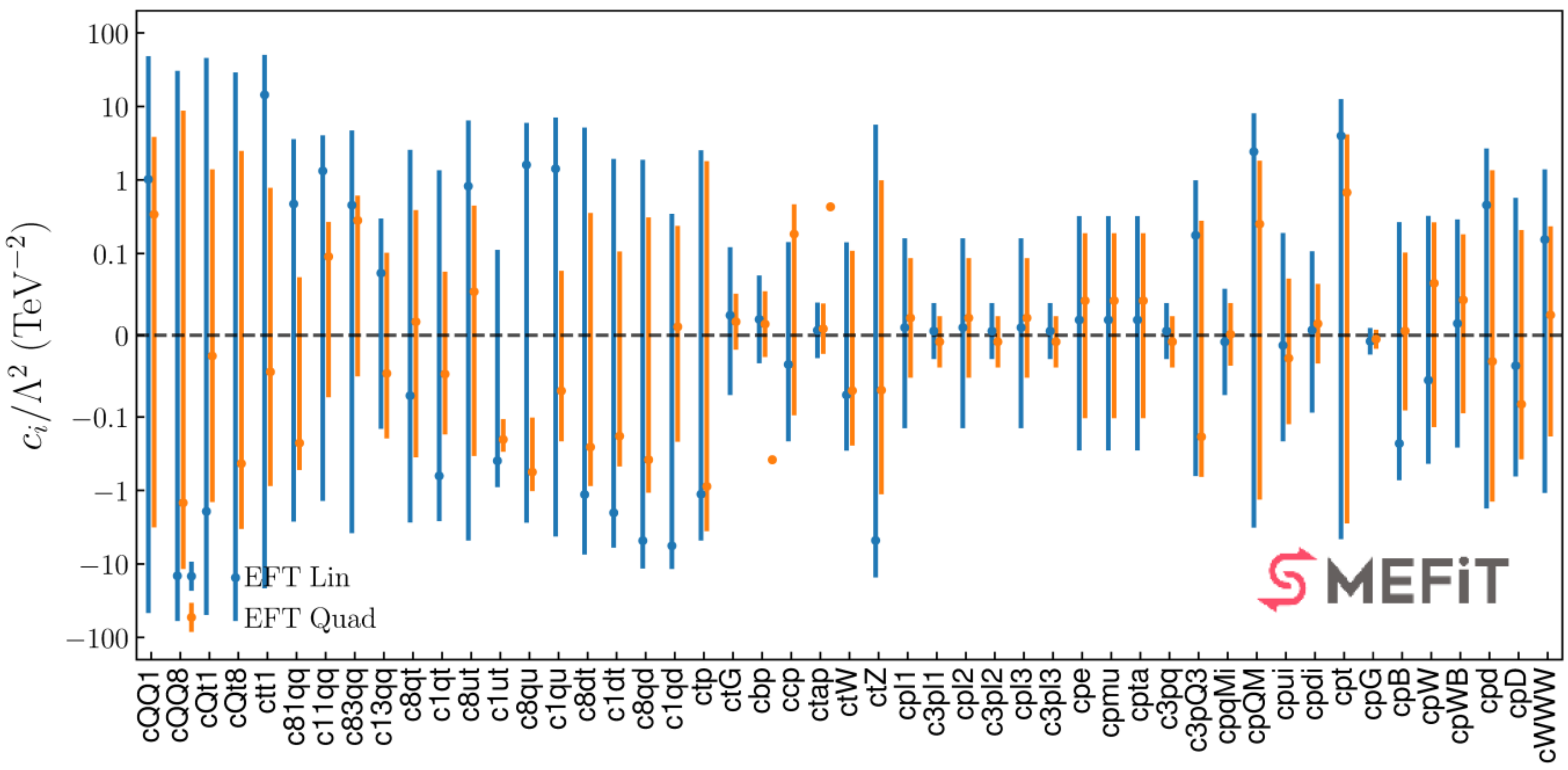


Ellis,Madigan,Mimasu,Sanz,You 2012.02779

# SMEFT global fits

- Global fit to Higgs, EWPD, top

Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006

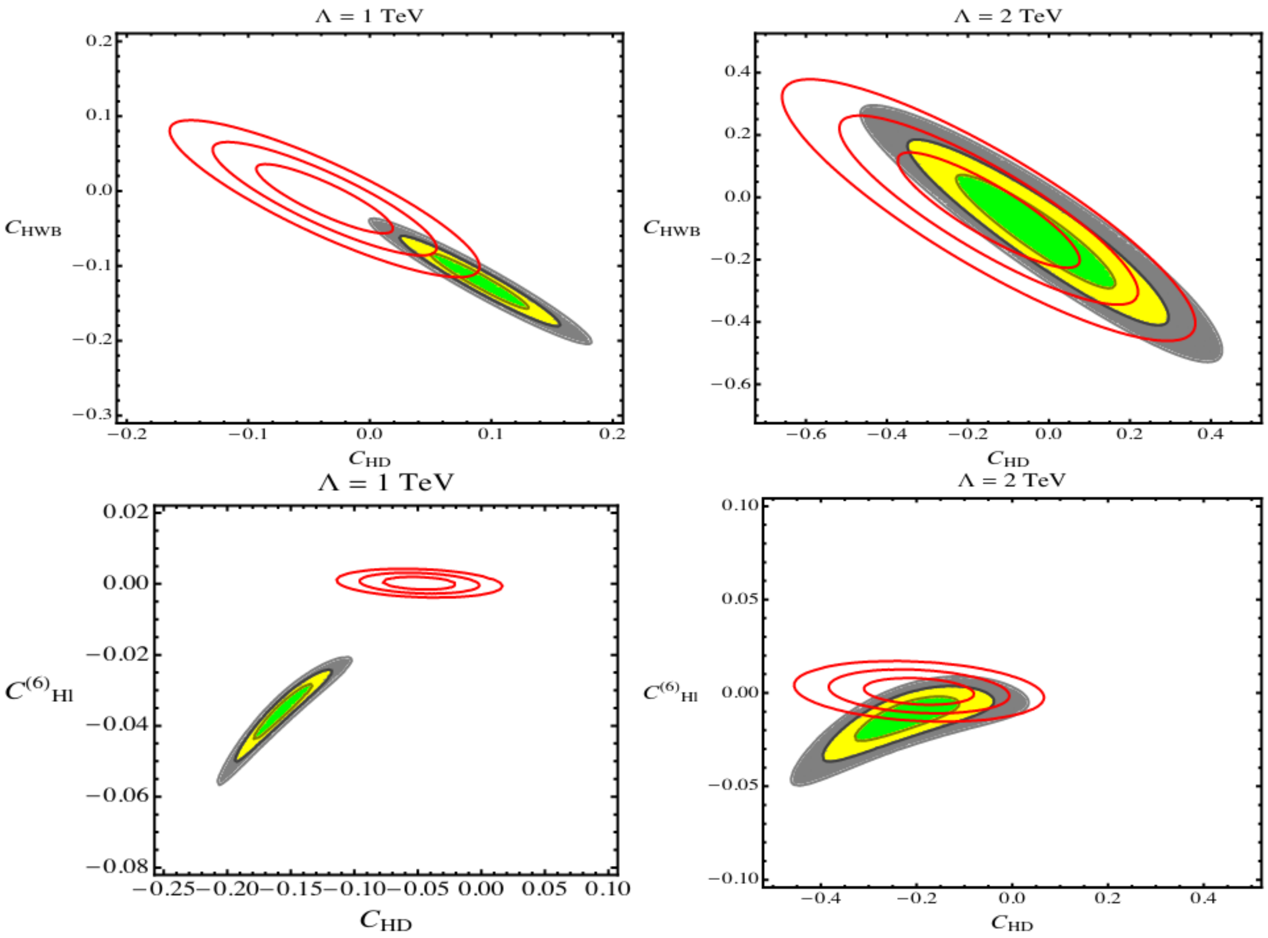


49 param, linear+quadratic, NLO QCD

# SMEFT global fits

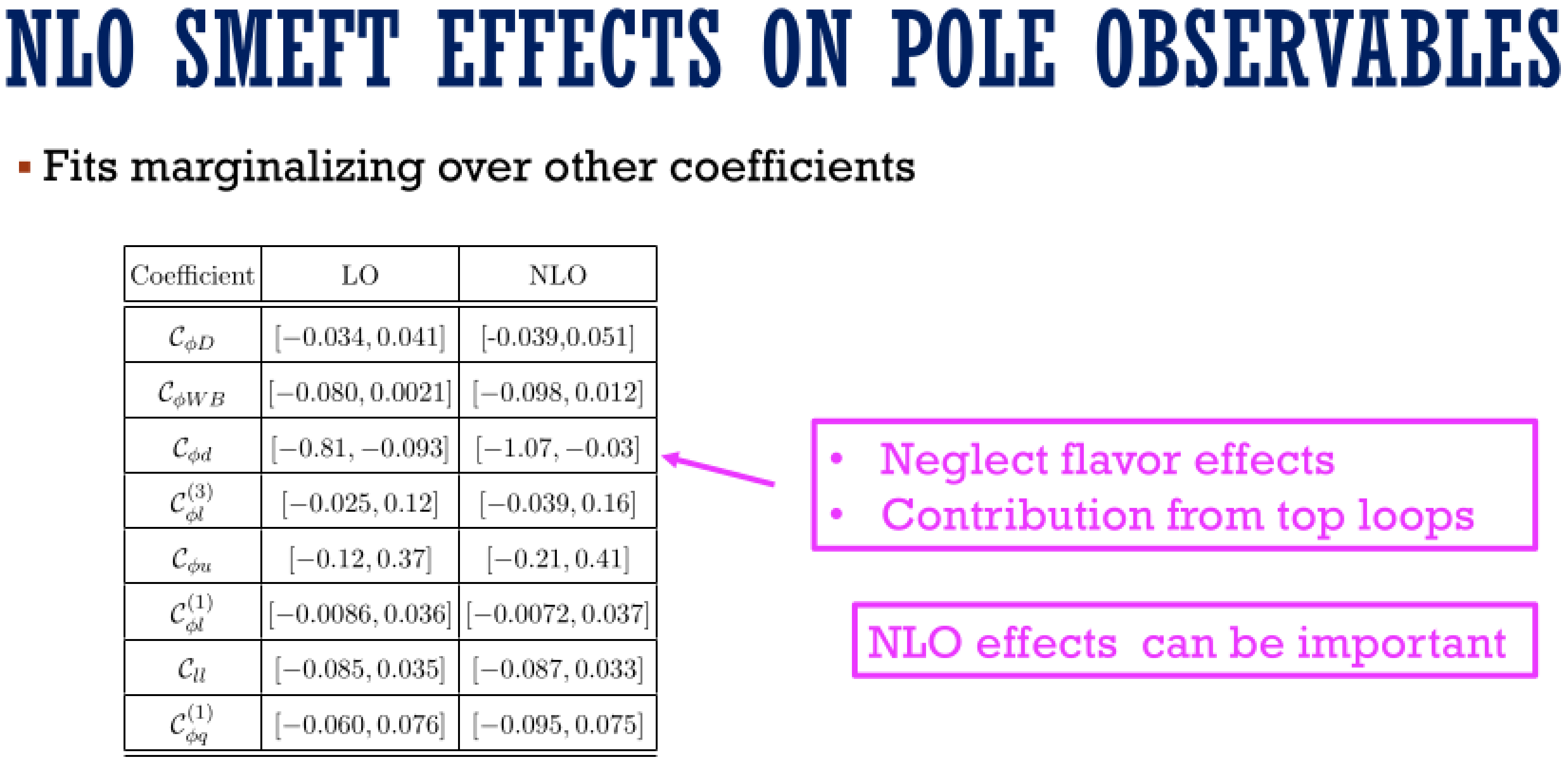
- Dim 6 vs dim 8

Corbett, Helset, Martin, Trott 2102.02819



# SMEFT global fits

- Including (QCD and EW) NLO effects



## NLO SMEFT EFFECTS ON POLE OBSERVABLES

- Fits marginalizing over other coefficients

| Coefficient | LO | NLO |
|---|---|---|
| $\mathcal{C}_{\phi D}$ | $[-0.034, 0.041]$ | [-0.039,0.051] |
| $\mathcal{C}_{\phi WB}$ | $[-0.080, 0.0021]$ | $[-0.098, 0.012]$ |
| $\mathcal{C}_{\phi d}$ | $[-0.81, -0.093]$ | $[-1.07, -0.03]$ |
| $\mathcal{C}^{(3)}_{\phi l}$ | $[-0.025, 0.12]$ | $[-0.039, 0.16]$ |
| $\mathcal{C}_{\phi u}$ | $[-0.12, 0.37]$ | $[-0.21, 0.41]$ |
| $\mathcal{C}^{(1)}_{\phi l}$ | $[-0.0086, 0.036]$ | $[-0.0072, 0.037]$ |
| $\mathcal{C}_{ll}$ | $[-0.085, 0.035]$ | $[-0.087, 0.033]$ |
| $\mathcal{C}^{(1)}_{\phi q}$ | $[-0.060, 0.076]$ | $[-0.095, 0.075]$ |

- Neglect flavor effects
- Contribution from top loops

NLO effects can be important

Dawson @ HEFT21

# Bottom-up: summary and outlook

- Global fits represent a model-independent parametrization of experimental data.
- The number of operators needed is very large: we go step by step (linear, quadratic, dim 6 tree level, dim 6 one loop, dim 8, …).
- Actually fitting is becoming more and more difficult, the crucial “object” to produce (and preserve) is the global likelihood (specific NP models have much less free parameters).
- Combination of different data sets is straight-forward but needs theory if at different scales (RGE, solved at dim 6, in infancy at dim 8).
- Experimental-theoretical interplay is crucial for a successful parametrization:
  - How much SM input goes in the exp results and what’s its impact? (PDFs, unfolding, …).
  - Experimental and theoretical correlations, error estimation, … in the presence of higher-dimensional operators.

# Between bottom-up and top-down

- SMEFT is a good description above the EWSB scale
- At lower energies it is no longer the correct EFT and we have to use the LEFT (low energy effective theory) in which the top, Higgs, W and Z have been integrated out.
- Matching between the SMEFT and LEFT is known up to one loop

  Jenkins, Manohar, Stoffer 1709.04486
  Dekens, Stoffer, 1908.05295

- 1 loop RGEs known for the SMEFT (dim 6, partial dim 8)

  Alonso, Jenkins, Manohar, Trott ‘13
  Chala, Guedes, Ramos, J.S., 2106.05291

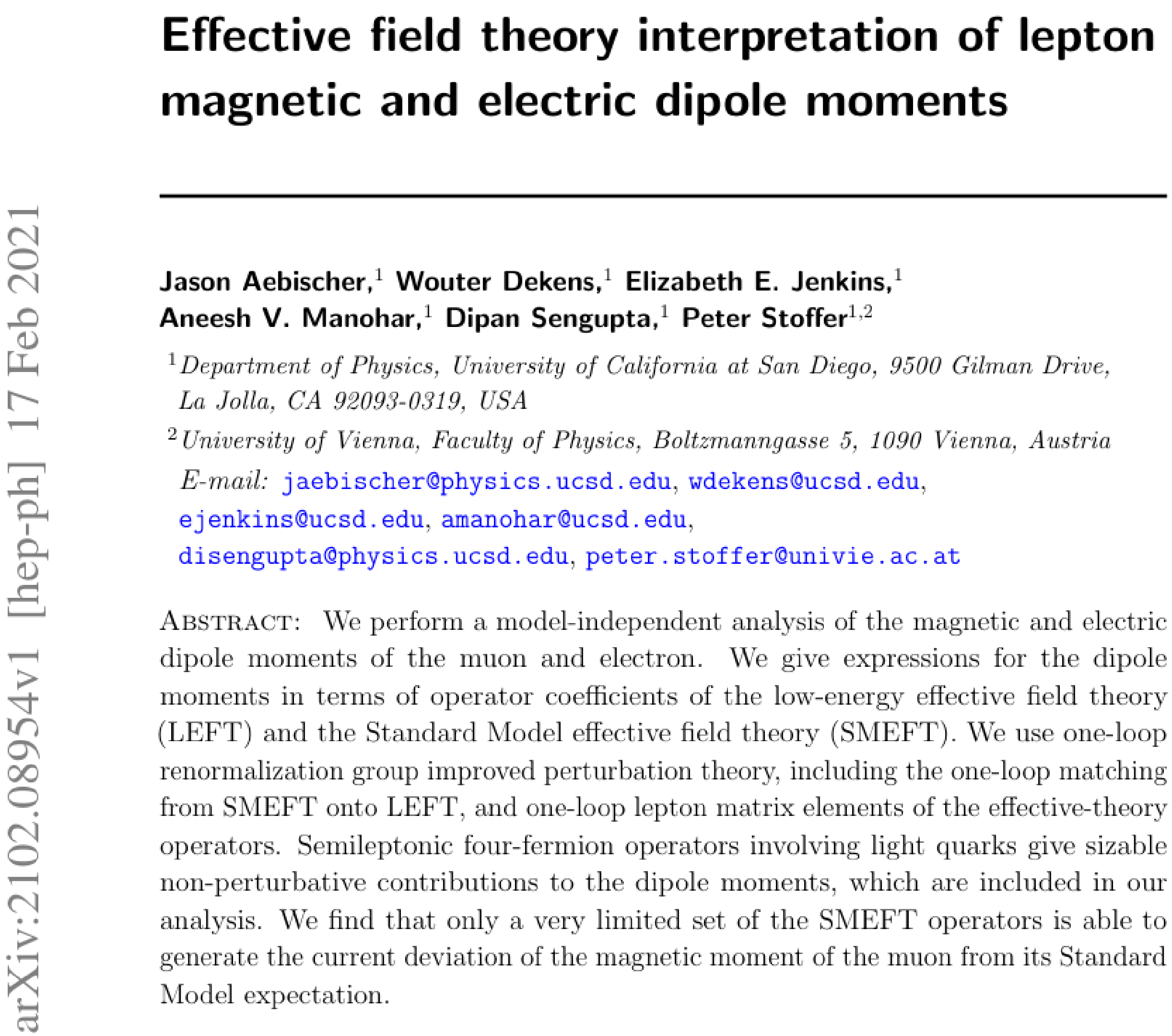
- 1 loop RGEs known for LEFT

  Jenkins, Manohar, Stoffer 1911.05270

- Matching and running between the two EFTs is now implemented in computer tools

  DsixTools 2.0. Fuentes-Martín, Ruíz-Femenia, Vicente, Virto, 2010.16341

# Using the full bottom-up machinery



## Effective field theory interpretation of lepton magnetic and electric dipole moments

---

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**Aneesh V. Manohar,**[1] **Dipan Sengupta,**[1] **Peter Stoffer**[1,2]

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ABSTRACT: We perform a model-independent analysis of the magnetic and electric dipole moments of the muon and electron. We give expressions for the dipole moments in terms of operator coefficients of the low-energy effective field theory (LEFT) and the Standard Model effective field theory (SMEFT). We use one-loop renormalization group improved perturbation theory, including the one-loop matching from SMEFT onto LEFT, and one-loop lepton matrix elements of the effective-theory operators. Semileptonic four-fermion operators involving light quarks give sizable non-perturbative contributions to the dipole moments, which are included in our analysis. We find that only a very limited set of the SMEFT operators is able to generate the current deviation of the magnetic moment of the muon from its Standard Model expectation.

# Using the full bottom-up machinery

- Low-energy measurement: LEFT is the correct EFT

$$
\begin{aligned}
\mathcal{L} = \Big[ & L_{\substack{e\gamma\\pr}} (\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr})\, F_{\mu\nu} + L^{S,RR}_{\substack{ee\\prst}} (\bar{e}_{Lp} e_{Rr})(\bar{e}_{Ls} e_{Rt}) \\
& + L^{S,RL}_{\substack{eu\\prst}} (\bar{e}_{Lp} e_{Rr})(\bar{u}_{Rs} u_{Lt}) + L^{S,RL}_{\substack{ed\\prst}} (\bar{e}_{Lp} e_{Rr})(\bar{d}_{Rs} d_{Lt}) \\
& + L^{S,RR}_{\substack{eu\\prst}} (\bar{e}_{Lp} e_{Rr})(\bar{u}_{Ls} u_{Rt}) + L^{S,RR}_{\substack{ed\\prst}} (\bar{e}_{Lp} e_{Rr})(\bar{d}_{Ls} d_{Rt}) \\
& + L^{T,RR}_{\substack{eu\\prst}} (\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr})(\bar{u}_{Ls}\sigma_{\mu\nu} u_{Rt}) + L^{T,RR}_{\substack{ed\\prst}} (\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu} d_{Rt}) + \text{h.c.} \Big] \\
& + L^{V,LR}_{\substack{ee\\prst}} (\bar{e}_{Lp}\gamma^{\mu} e_{Lr})(\bar{e}_{Rs}\gamma_{\mu} e_{Rt}) \,,
\end{aligned}
$$

$$
\boxed{a_\ell = \frac{\alpha \mathsf{q}_e^2}{2\pi} - 4\frac{m_\ell}{e\mathsf{q}_e}\,\mathrm{Re}\, L_{\substack{e\gamma\\ \ell\ell}}(\mu) \left\{ 1 - \frac{\alpha \mathsf{q}_e^2}{4\pi} \left[ 2 + 5\log\left(\frac{\mu^2}{m_\ell^2}\right)\right]\right\} + a_\ell^{4\ell} + a_\ell^{2\ell 2q} + \mathcal{O}(L_{e\gamma}^2)\,,}
$$

# Using the full bottom-up machinery

- To get information at higher energies we run with the RGE and match to the SMEFT

$$
\begin{aligned}
\Delta a_\ell^{250\text{ GeV}} = \frac{m_\ell}{m_\mu}\mathrm{Re}\Bigg[ & \begin{matrix}2.9_\mu\\2.8_e\end{matrix}\times 10^{-3}\widetilde{C}_{\substack{eB\\\ell\ell}} - \begin{matrix}1.6_\mu\\1.5_e\end{matrix}\times10^{-3}\widetilde{C}_{\substack{eW\\\ell\ell}}\\
& - \begin{matrix}4.3_\mu\\4.1_e\end{matrix}\times10^{-5}\widetilde{C}^{(3)}_{\substack{\ell equ\\\ell\ell 33}} - \left(2.6+0.37c_T^{(c)}\right)\times10^{-6}\widetilde{C}^{(3)}_{\substack{\ell equ\\\ell\ell22}}\\
& -7.9\times10^{-8}\widetilde{C}_{\substack{\ell e\\\ell 33\ell}} + \left(5.7c_T - \begin{matrix}0.49_\mu\\0.48_e\end{matrix}\right)\times10^{-8}\widetilde{C}^{(3)}_{\substack{\ell equ\\\ell\ell11}} + 1.4\times10^{-8}\widetilde{C}^{(1)}_{\substack{\ell equ\\\ell\ell33}}\\
& + \left(\begin{matrix}10_\mu\\9.8_e\end{matrix}+2.5c_T^{(c)}\right)\times10^{-9}\widetilde{C}^{(1)}_{\substack{\ell equ\\\ell\ell22}} - \begin{matrix}4.6_\mu\\4.7_e\end{matrix}\times10^{-9}\widetilde{C}_{\substack{\ell e\\\ell22\ell}}\\
& + \frac{m_\ell}{m_\mu}\Bigg\{ \begin{matrix}2.5_\mu\\2.4_e\end{matrix}\times10^{-8}\left(\widetilde{C}_{HWB}+i\widetilde{C}_{H\widetilde{W}B}\right) - \begin{matrix}1.8_\mu\\1.7_e\end{matrix}\times10^{-8}\left(\widetilde{C}_{HB}+i\widetilde{C}_{H\widetilde{B}}\right)\\
& - \begin{matrix}6.0_\mu\\5.7_e\end{matrix}\times10^{-9}\left(\widetilde{C}_{HW}+i\widetilde{C}_{H\widetilde{W}}\right) + 3.8\times10^{-9}\widetilde{C}_{\substack{He\\\ell\ell}} - \begin{matrix}3.7_\mu\\3.6_e\end{matrix}\times10^{-9}\widetilde{C}^{(1)}_{\substack{Hl\\\ell\ell}}\\
& + \begin{matrix}3.6_\mu\\3.3_e\end{matrix}\times10^{-9}\widetilde{C}^{(3)}_{\substack{Hl\\\ell\ell}} + \begin{matrix}1.8_\mu\\1.7_e\end{matrix}\times10^{-9}\widetilde{C}_{HD} + \begin{matrix}2.1_\mu\\2.0_e\end{matrix}\times10^{-9}\widetilde{C}_W\\
& +1.1\times10^{-9}i\widetilde{C}_{\widetilde{W}}\Bigg\}\Bigg], \qquad (5.1)
\end{aligned}
$$

# Using the full bottom-up machinery

- To get information at higher energies we run with the RGE and match to the SMEFT

$$\Delta a_\ell^{10\ \mathrm{TeV}} = \frac{m_\ell}{m_\mu}\mathrm{Re}\Bigg[1.7\times 10^{-6}\widetilde{C}_{\substack{eB\\ \ell\ell}} - \begin{matrix}9.2_\mu\\ 8.9_e\end{matrix}\times 10^{-7}\widetilde{C}_{\substack{eW\\ \ell\ell}} - \begin{matrix}2.2_\mu\\ 2.1_e\end{matrix}\times 10^{-7}\widetilde{C}^{(3)}_{\substack{\ell equ\\ \ell\ell 33}} \\ - \left(\begin{matrix}2.5_\mu\\ 2.4_e\end{matrix} + 0.22c_T^{(c)}\right)\times 10^{-9}\widetilde{C}^{(3)}_{\substack{\ell equ\\ \ell\ell 22}}\Bigg].$$

- The only thing to do now is to know which models can generate these Wilson coefficients!

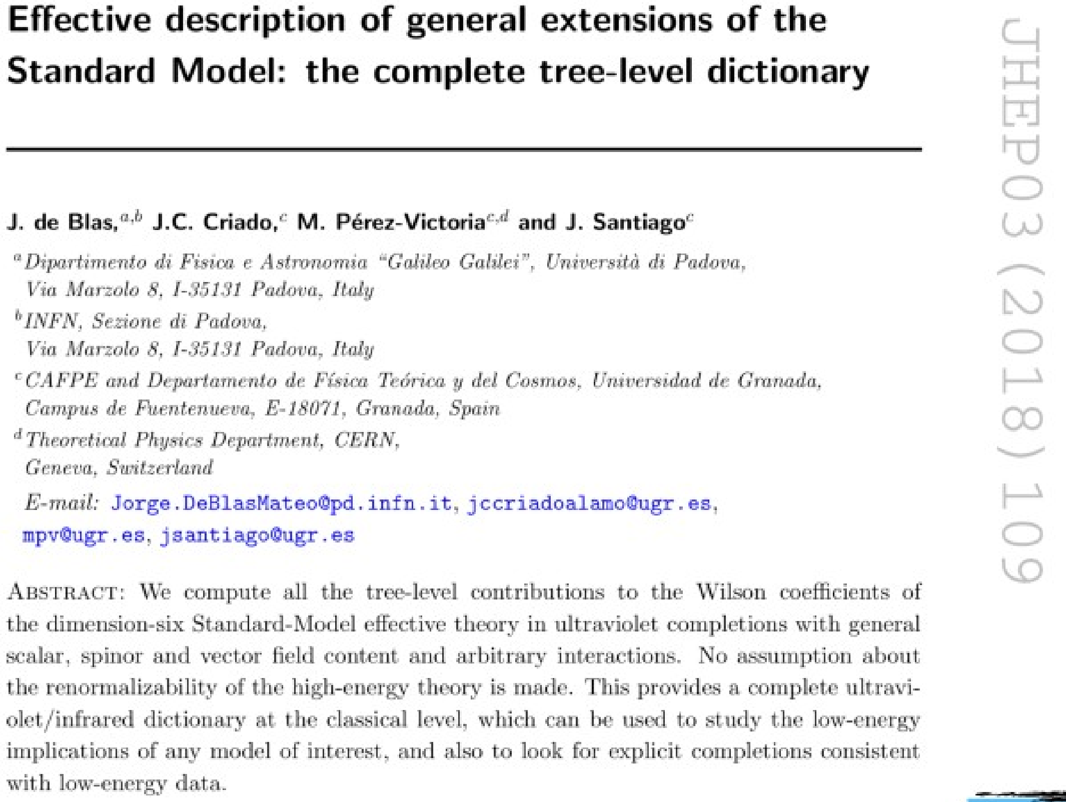
# Top-down: connecting NP to EFTs

- The top-down approach consists on matching specific NP models to the EFT: computing the EFT Wilson coefficients in terms of the parameters of the NP model.
- We sacrifice model independence in favor of model discrimination.
- This is the only way to:
  - Test the range of validity of our EFT analysis.
  - Compare direct (bump searches) and indirect (EFTs) limits on NP.
  - Extract physical implications on NP models.
- Are we willing to give up model independence? Yes!
  - Power counting makes the problem of classifying the models that contribute at a certain order solvable.
  - Computer techniques allow us to automate the matching calculations.
- We give up model independence in favor of model discrimination and model completeness

IR/UV dictionaries

# Top-down: connecting NP to EFTs

The leading contribution (tree level, dimension 6) in the SMEFT has been recently completed (no spins higher than 1) J. Blas, JC Criado, M Pérez-Victoria, JS ’18



**Effective description of general extensions of the Standard Model: the complete tree-level dictionary**

JHEP03(2018)109

J. de Blas,[a,b] J.C. Criado,[c] M. Pérez-Victoria[c,d] and J. Santiago[c]

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*Via Marzolo 8, I-35131 Padova, Italy*
[b] *INFN, Sezione di Padova,*
*Via Marzolo 8, I-35131 Padova, Italy*
[c] *CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada,*
*Campus de Fuentenueva, E-18071, Granada, Spain*
[d] *Theoretical Physics Department, CERN,*
*Geneva, Switzerland*
*E-mail:* Jorge.DeBlasMateo@pd.infn.it, jccriadoalamo@ugr.es, mpv@ugr.es, jsantiago@ugr.es

Abstract: We compute all the tree-level contributions to the Wilson coefficients of the dimension-six Standard-Model effective theory in ultraviolet completions with general scalar, spinor and vector field content and arbitrary interactions. No assumption about the renormalizability of the high-energy theory is made. This provides a complete ultraviolet/infrared dictionary at the classical level, which can be used to study the low-energy implications of any model of interest, and also to look for explicit completions consistent with low-energy data.

Building on previous results

Blas, Chala, Pérez-Victoria, JS ‘14;
Águila, Blas, Pérez-Victoria ‘08, ‘10;
Águila, Pérez-Victoria, JS ‘00

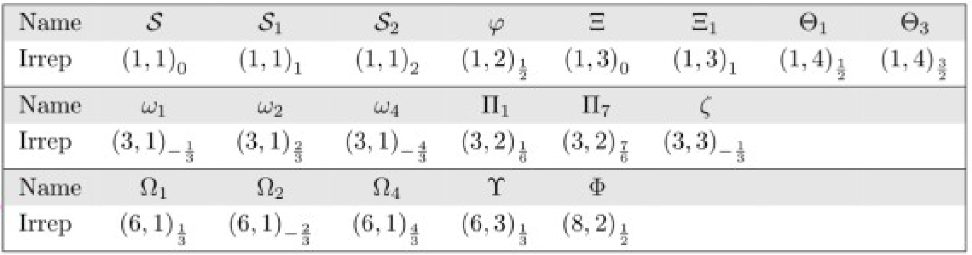
Results given in Warsaw basis

# Top-down: connecting NP to EFTs

The leading contribution (tree level, dimension 6) in the SMEFT has been recently completed (no spins higher than 1)

J. Blas, JC Criado, M Pérez-Victoria, JS ’18

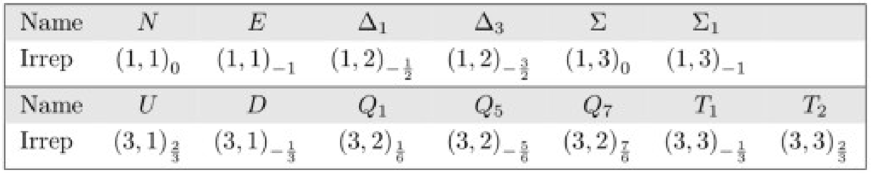
19 scalars



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Name | $\mathcal{S}$ | $\mathcal{S}_1$ | $\mathcal{S}_2$ | $\varphi$ | $\Xi$ | $\Xi_1$ | $\Theta_1$ | $\Theta_3$ |
| Irrep | $(1,1)_0$ | $(1,1)_1$ | $(1,1)_2$ | $(1,2)_{\frac{1}{2}}$ | $(1,3)_0$ | $(1,3)_1$ | $(1,4)_{\frac{1}{2}}$ | $(1,4)_{\frac{3}{2}}$ |
| Name | $\omega_1$ | $\omega_2$ | $\omega_4$ | $\Pi_1$ | $\Pi_7$ | $\zeta$ | | |
| Irrep | $(3,1)_{-\frac{1}{3}}$ | $(3,1)_{\frac{2}{3}}$ | $(3,1)_{-\frac{4}{3}}$ | $(3,2)_{\frac{1}{6}}$ | $(3,2)_{\frac{7}{6}}$ | $(3,3)_{-\frac{1}{3}}$ | | |
| Name | $\Omega_1$ | $\Omega_2$ | $\Omega_4$ | $\Upsilon$ | $\Phi$ | | | |
| Irrep | $(6,1)_{\frac{1}{3}}$ | $(6,1)_{-\frac{2}{3}}$ | $(6,1)_{\frac{4}{3}}$ | $(6,3)_{\frac{1}{3}}$ | $(8,2)_{\frac{1}{2}}$ | | | |

**Table 1**. New scalar bosons contributing to the dimension-six SMEFT at tree level.

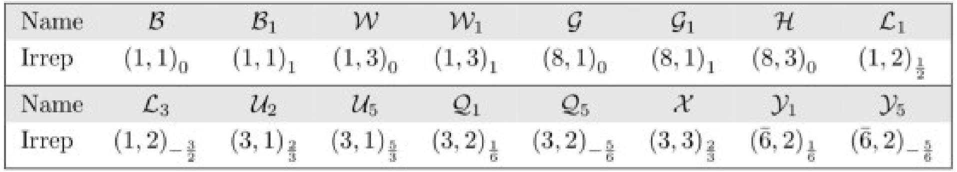
13 fermions



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Name | $N$ | $E$ | $\Delta_1$ | $\Delta_3$ | $\Sigma$ | $\Sigma_1$ | |
| Irrep | $(1,1)_0$ | $(1,1)_{-1}$ | $(1,2)_{-\frac{1}{2}}$ | $(1,2)_{-\frac{3}{2}}$ | $(1,3)_0$ | $(1,3)_{-1}$ | |
| Name | $U$ | $D$ | $Q_1$ | $Q_5$ | $Q_7$ | $T_1$ | $T_2$ |
| Irrep | $(3,1)_{\frac{2}{3}}$ | $(3,1)_{-\frac{1}{3}}$ | $(3,2)_{\frac{1}{6}}$ | $(3,2)_{-\frac{5}{6}}$ | $(3,2)_{\frac{7}{6}}$ | $(3,3)_{-\frac{1}{3}}$ | $(3,3)_{\frac{2}{3}}$ |

**Table 2**. New vector-like fermions contributing to the dimension-six SMEFT at tree level.

16 vectors



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Name | $\mathcal{B}$ | $\mathcal{B}_1$ | $\mathcal{W}$ | $\mathcal{W}_1$ | $\mathcal{G}$ | $\mathcal{G}_1$ | $\mathcal{H}$ | $\mathcal{L}_1$ |
| Irrep | $(1,1)_0$ | $(1,1)_1$ | $(1,3)_0$ | $(1,3)_1$ | $(8,1)_0$ | $(8,1)_1$ | $(8,3)_0$ | $(1,2)_{\frac{1}{2}}$ |
| Name | $\mathcal{L}_3$ | $\mathcal{U}_2$ | $\mathcal{U}_5$ | $\mathcal{Q}_1$ | $\mathcal{Q}_5$ | $\mathcal{X}$ | $\mathcal{Y}_1$ | $\mathcal{Y}_5$ |
| Irrep | $(1,2)_{-\frac{3}{2}}$ | $(3,1)_{\frac{2}{3}}$ | $(3,1)_{\frac{5}{3}}$ | $(3,2)_{\frac{1}{6}}$ | $(3,2)_{-\frac{5}{6}}$ | $(3,3)_{\frac{2}{3}}$ | $(\bar{6},2)_{\frac{1}{6}}$ | $(\bar{6},2)_{-\frac{5}{6}}$ |

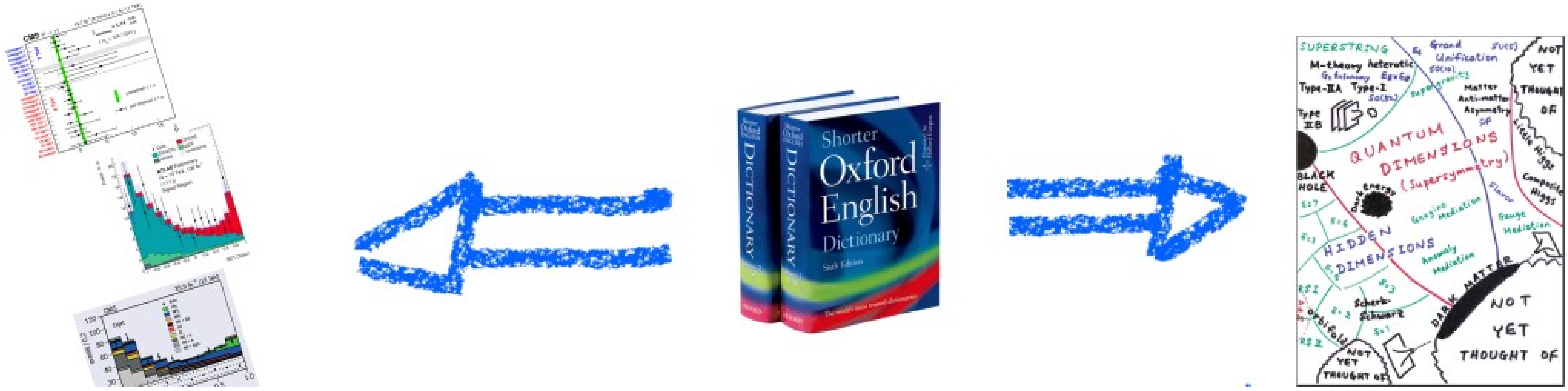
**Table 3**. New vector bosons contributing to the dimension-six SMEFT at tree level.

48 new fields

# Top-down: connecting NP to EFTs

The leading contribution (tree level, dimension 6) in the SMEFT has been recently completed (no spins higher than 1) J. Blas, JC Criado, M Pérez-Victoria, JS ’18

Using this dictionary we can systematically explore the implications of experimental data (via global fits) on arbitrary models of new physics



# Top-down: connecting NP to EFTs

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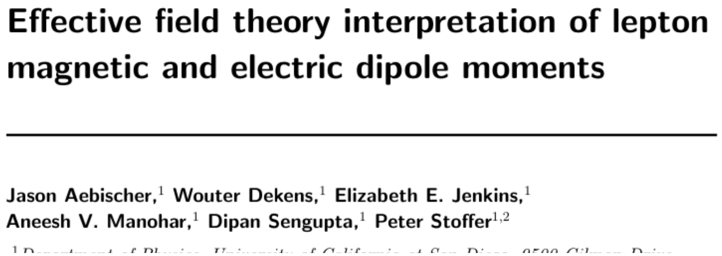
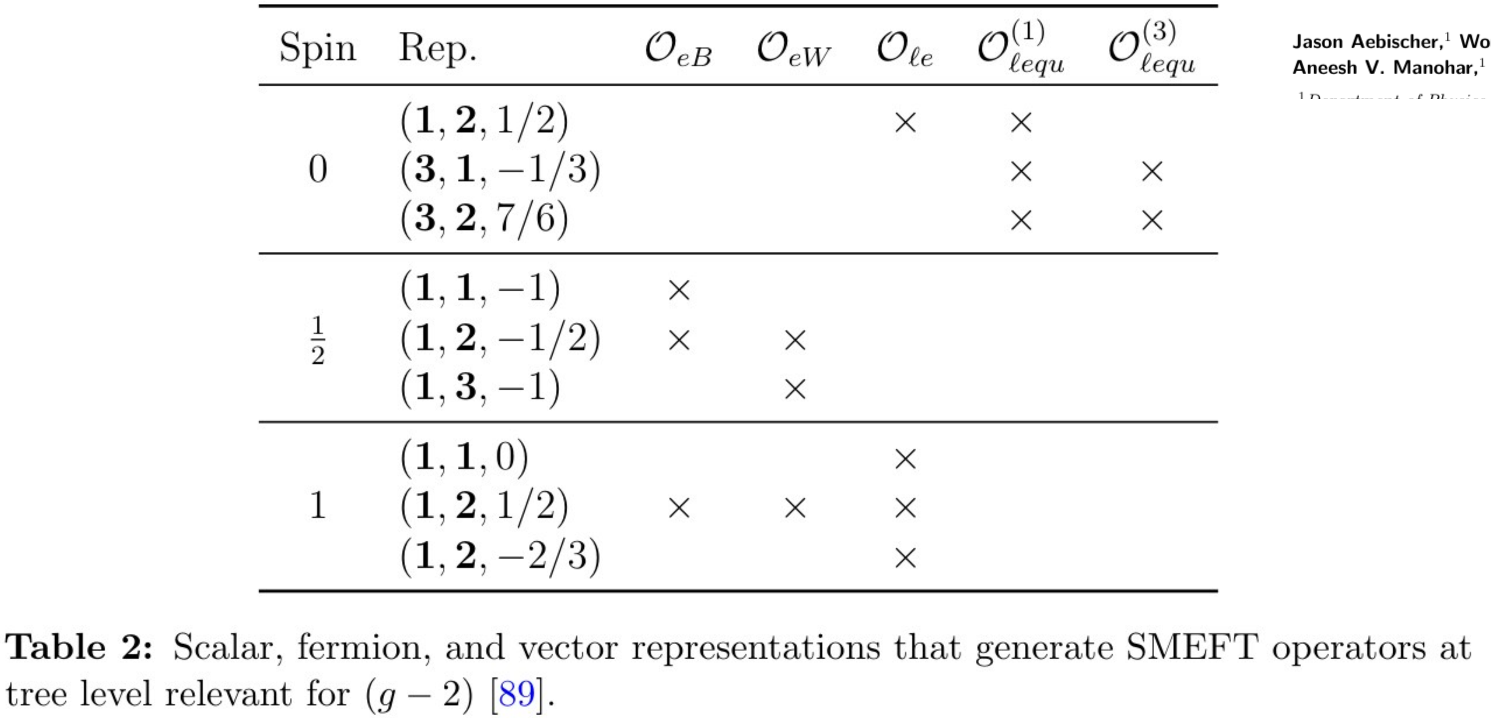


**Effective field theory interpretation of lepton magnetic and electric dipole moments**

Jason Aebischer,[1] Wouter Dekens,[1] Elizabeth E. Jenkins,[1]
Aneesh V. Manohar,[1] Dipan Sengupta,[1] Peter Stoffer[1,2]



| Spin | Rep. | $\mathcal{O}_{eB}$ | $\mathcal{O}_{eW}$ | $\mathcal{O}_{\ell e}$ | $\mathcal{O}^{(1)}_{\ell equ}$ | $\mathcal{O}^{(3)}_{\ell equ}$ |
|---|---|---|---|---|---|---|
| 0 | $(\mathbf{1},\mathbf{2},1/2)$ | | | × | × | |
| | $(\mathbf{3},\mathbf{1},-1/3)$ | | | | × | × |
| | $(\mathbf{3},\mathbf{2},7/6)$ | | | | × | × |
| $\frac{1}{2}$ | $(\mathbf{1},\mathbf{1},-1)$ | × | | | | |
| | $(\mathbf{1},\mathbf{2},-1/2)$ | × | × | | | |
| | $(\mathbf{1},\mathbf{3},-1)$ | | × | | | |
| 1 | $(\mathbf{1},\mathbf{1},0)$ | | | × | | |
| | $(\mathbf{1},\mathbf{2},1/2)$ | × | × | × | | |
| | $(\mathbf{1},\mathbf{2},-2/3)$ | | | × | | |

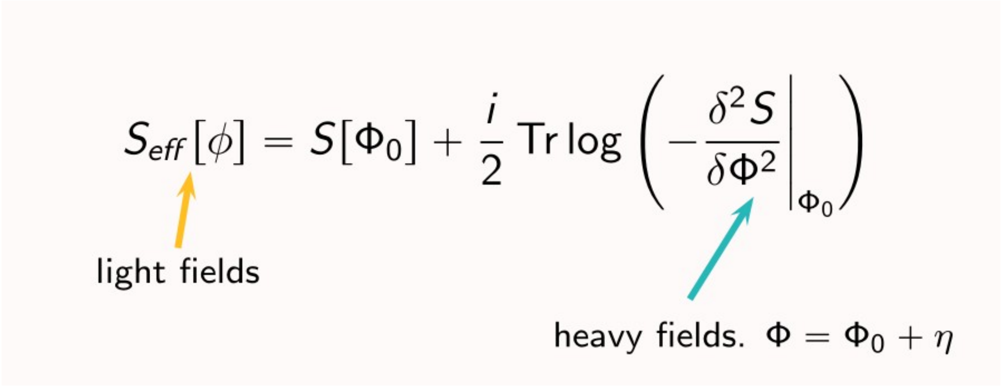
**Table 2:** Scalar, fermion, and vector representations that generate SMEFT operators at tree level relevant for $(g-2)$ [89].

# IR/UV dictionaries

- IR/UV dictionaries tell us all possible models that can contribute to a specific experimental observable at certain order in the EFT expansion: A new, alternative guiding principle beyond naturalness.
- Tree-level, dimension 6 is the leading contribution but it’s not enough given the variety and precision of experimental data:
  - Some observables are so precise that are sensitive to 1-loop dim 6 or tree-level dim 8 operators.
  - Some operators can only be generated at one loop in minimally coupled extensions of the SM.
- Extending the leading dictionary to the next perturbative level (1-loop dim 6 and tree-level dim 8) requires automated tools.
- Significant progress in the last few years in the automation of matching calculations up to one loop.

# Automated matching

- Matching can be done:
  - Via functional methods (Covariant Derivative Expansion):
    - Maintains gauge invariance explicitly
    - No need to know the EFT basis



$$S_{eff}[\phi] = S[\Phi_0] + \frac{i}{2}\,\mathrm{Tr}\log\left(-\left.\frac{\delta^2 S}{\delta\Phi^2}\right|_{\Phi_0}\right)$$

light fields

heavy fields. $\Phi = \Phi_0 + \eta$

Henning, Lu, Murayama ‘14, ‘16
Aguila, Kunszt, J.S. ‘16
Drozd, Ellis, Quevillon, You ‘15
Boggia, Gomez-Ambrosio, Passarino ‘16
Zhang ‘16
Ellis, quevillon, (Vuong), You, Zhang ‘16, ‘17, ‘20
Fuentes-Martin, Portoles, Ruiz-Femenia ‘16
(Kämer), Summ, Voigt ‘18, ‘19
Cohen, Lu, Zhang ‘20

- Tools towards (partial) automation of the matching are available

Criado ‘17
Bakshi, Chakrabortty, Kumar, Patra ‘18
Cohen, Lu, Zhang ‘20
Fuentes-Martín, König, Pagès, Thomsen, Wilsch ‘20

# Automated matching

- Matching can be done:
  - Via functional methods (Covariant Derivative Expansion)
  - Via diagrammatic methods:
    - Well tested methods and tools
    - Easy to fully automate
    - Extra redundancies (off-shell matching, gauge invariance, …) provide many very useful cross checks
  - We are developing a fully automated tool to perform the tree-level and one-loop matching of arbitrary models onto arbitrary EFTs.

MatchMaker: automated tree-level and 1-loop matching of arbitrary models on arbitrary EFTs

Carmona, Lazopoulos, Olgoso, J.S.

# Automated matching

- We are developing a fully automated tool to perform the tree-level and one-loop matching of arbitrary models onto arbitrary EFTs.

**MatchMaker: automated tree-level and 1-loop matching of arbitrary models on arbitrary EFTs**

Carmona, Lazopoulos, Olgoso, J.S.

- Written in python: easy to install, cross-platform.
- Uses well-tested tools: Feynrules, QGRAF, FORM, Mathematica.
- Fully automated off-shell matching in the background field gauge of arbitrary models onto arbitrary EFTs (large degree of redundancy provides many non-trivial cross-checks of the results).
- Flexible, reliable and fast: less than 1 minute to get correctly the matching up to one loop of the scalar singlet extension of the SM (which took several iterations to be correctly computed in the literature)

Henning, Lu, Murayama ‘14
Ellis, Quevillon, You, Zhang ‘17
Jiang, Craig, Li, Sutherland ‘18
Haisch, Ruhdorfer, Salvioni, Venturini, Weiler ‘20

# Towards the next IR/UV dictionaries

- These tools will allow us to go beyond the current IR/UV dictionary at tree-level and dimension 6. These extensions have severe challenges that will have to be dealt with:
  - 1-loop, dimension 6:
    - Number of models can be classified but it is no longer finite.
    - Expressions become large, difficult to provide the results in print.
  - Tree level, dimension 8:
    - The number of operators is very large (from ~80 at dim 6 to ~ 1000 at dim 8).
    - The number of models is finite but also very large.
- It is likely that the next order dictionaries will have to be provided in electronic form. We have to figure out what the best way for providing the results is:
  - Large searchable data-base with all the results?
  - Data-base with the classification of models but calculation of matching on the fly?

# Beyond the SMEFT

- The assumption that the SMEFT is the correct description of nature is a reasonable one but it misses some possible scenarios:
  - If EWSB does not proceed only via a scalar doublet but is rather non-linearly realized: HEFT instead of SMEFT

    ...
    Cohen, Craig, Lu, Sutherland, 2008.08597
    Espriu, Mescia, Asiáin, 2109.02673
  - If there are some new light particles beyond the SM ones:
    - ALPs: complete RGEs only very recently computed, matching from ALP+SMEFT to ALP+LEFT.

      Chala, Guedes, Ramos, J.S., 2012.09017
      Bauer, Neubert, Renner, Schnubel, Thamm, 2012.12272
      Bonilla, Brivio, Gavela, Sanz, 2107.11392
    - Light RH neutrino (vSMEFT)

      Aguila, Bar-Shalom, Soni, Wudka, 0806.0876
      Liao, Ma, 1612.04527
      Chala, Titov, 2001.07732

# Outlook

- We still don’t have any significant direct indication of new physics: NP either very elusive or heavy.
- There are some intriguing anomalies, mainly at low energies.
- In this situation, EFTs are the best way to tackle the problem of learning about NP from experimental measurements.
- The bottom-up approach represents a very efficient parametrization of experimental data. It is very challenging but can be done in a systematically improvable way.
- The top-down approach allows us to discriminate among models. Much progress has happened recently and there is more to come.
- IR/UV dictionaries allow for a complete classification of NP models and their effects: a new guiding principle beyond naturalness.

# Thank you!