



UNIVERSITY OF
NOTRE DAME

Chasing down New Physics with massive particles at the LHC with CMS

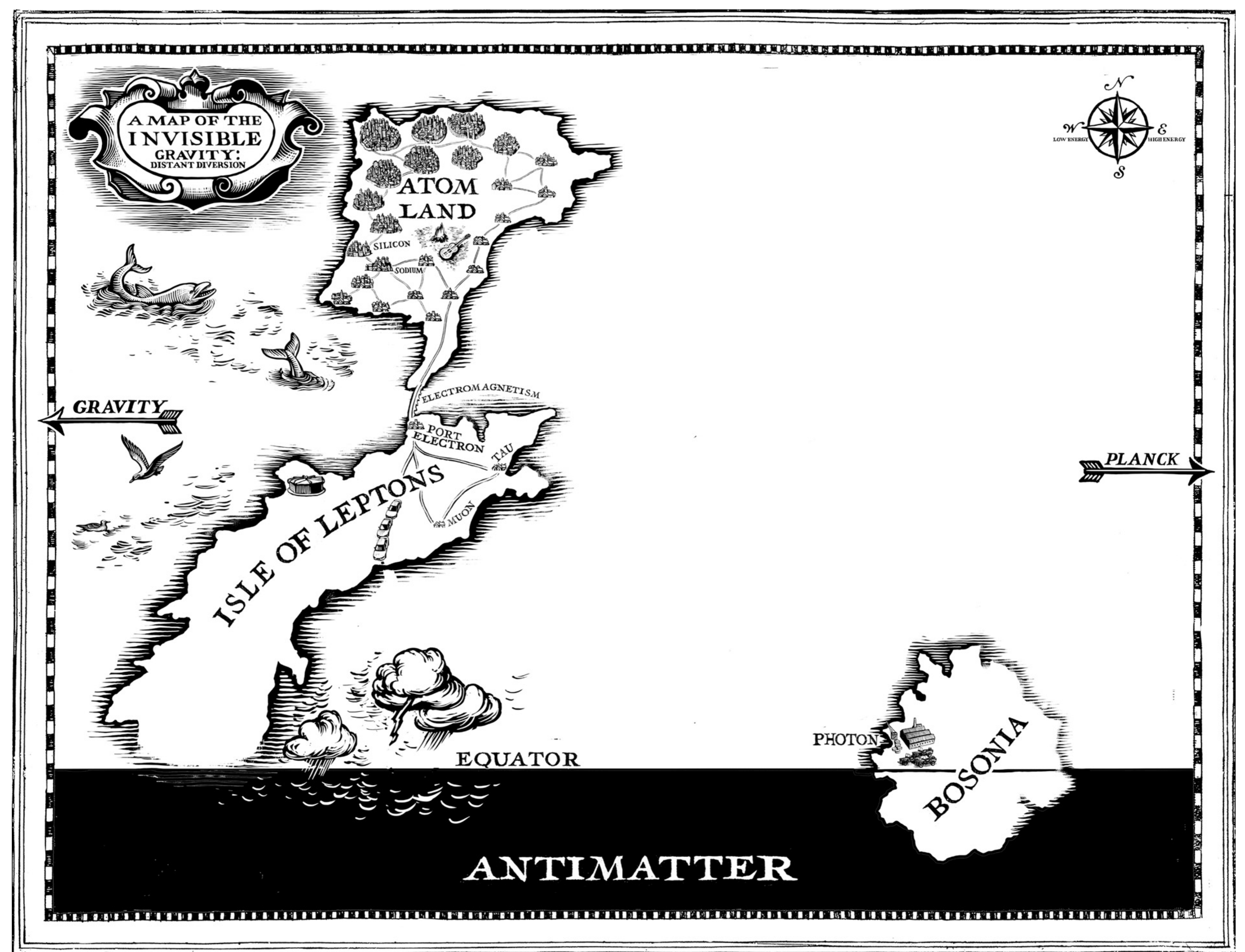
Andrea Piccinelli (University of Notre Dame)

andrea.piccinelli@cern.ch

Université catholique de Louvain - Louvain-la-Neuve, February 25th 2025

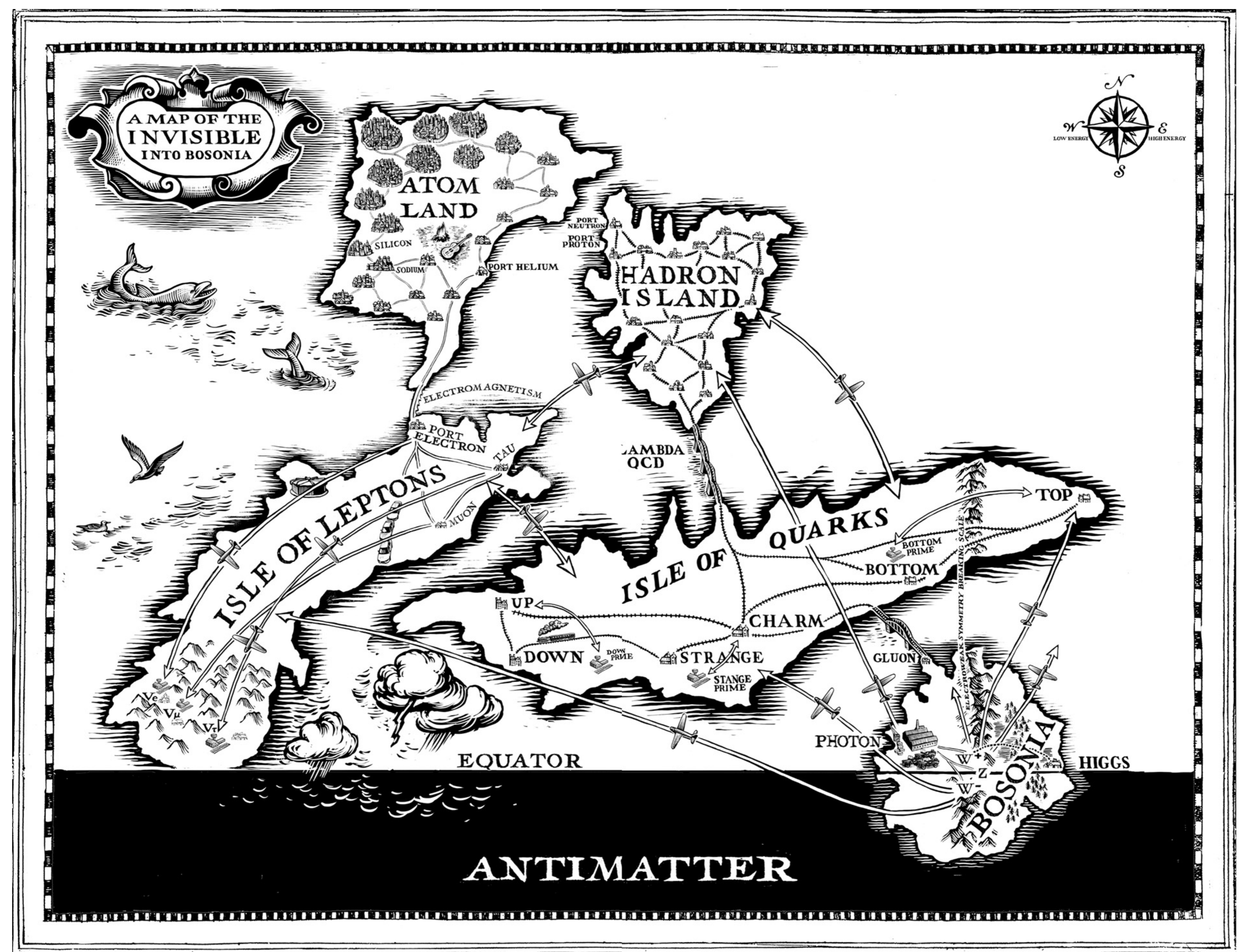
The journey

The first steps
in the particle world...



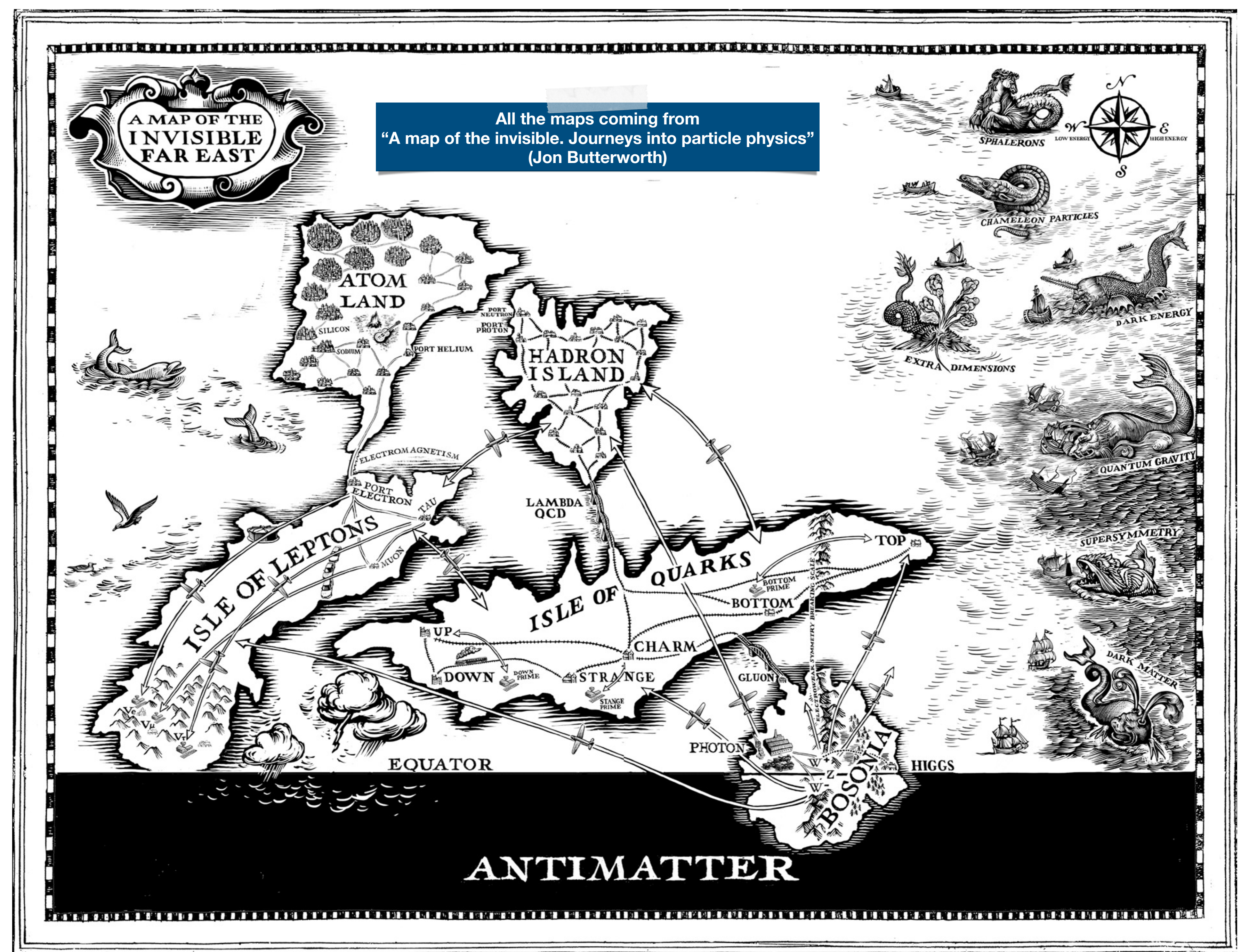
The journey

...completing the picture
of what's close to us...



The journey

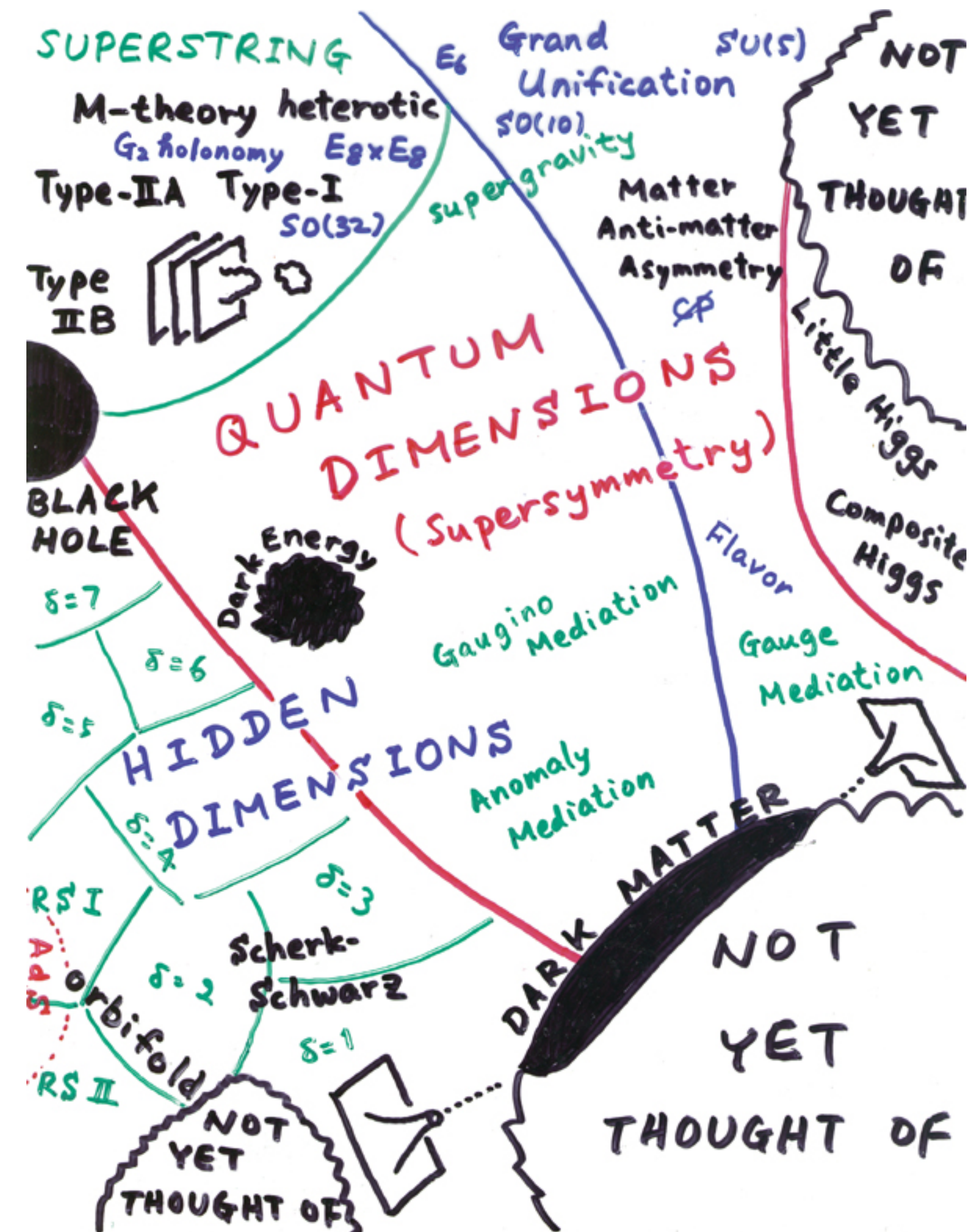
...and where
to head now?



Any good ToE candidates?

The ultimate Theory of Everything

Plenty of candidates from theory departments!

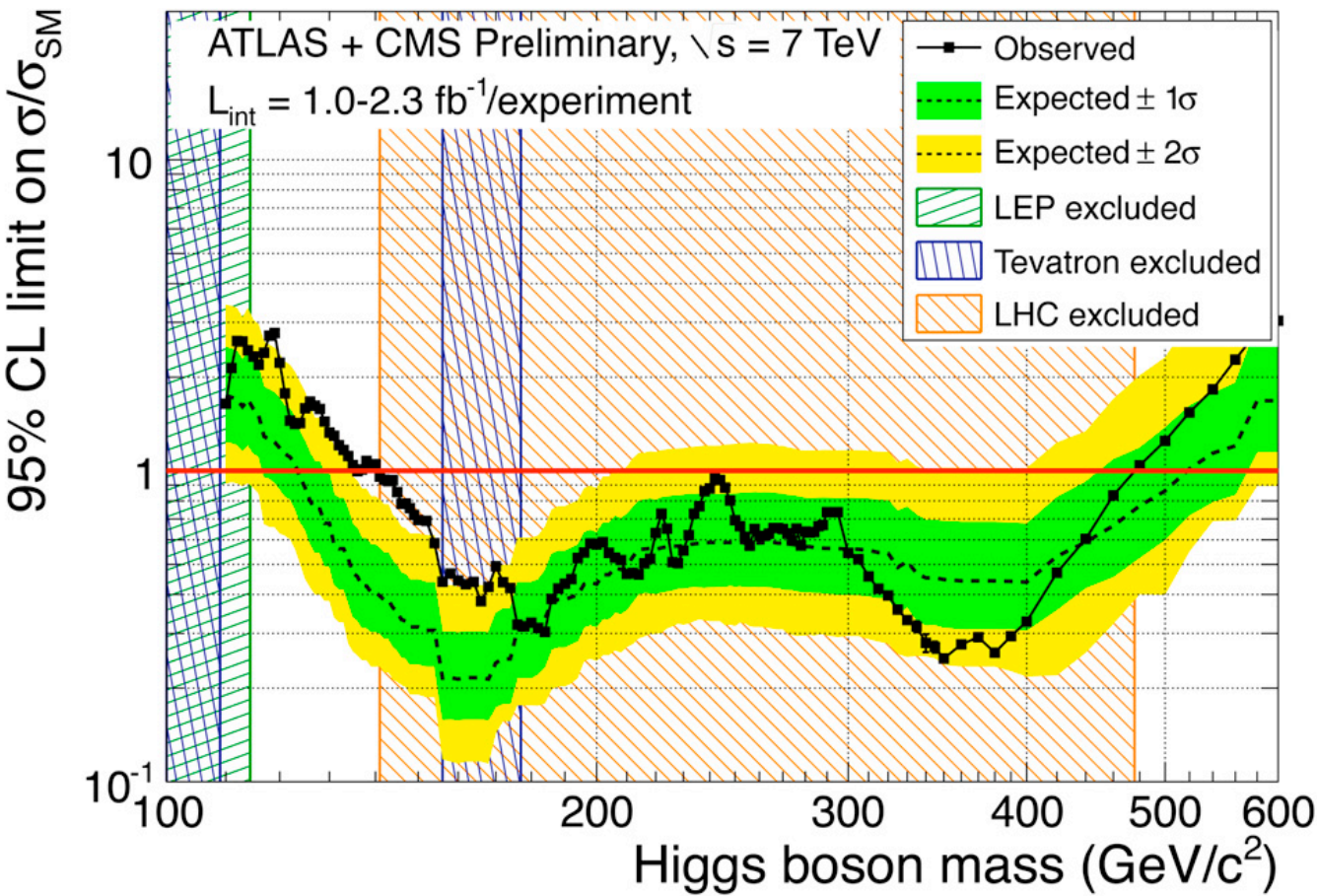
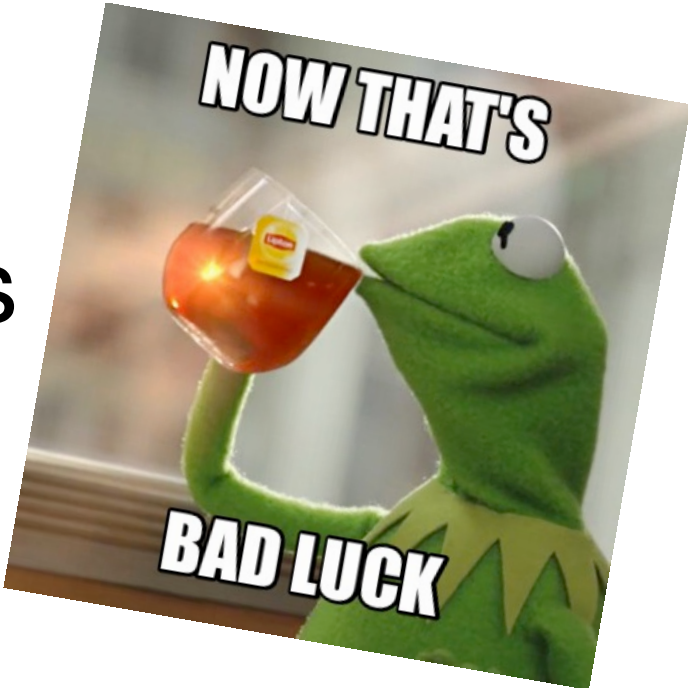


Any good ToE candidates?

The ultimate Theory of Everything

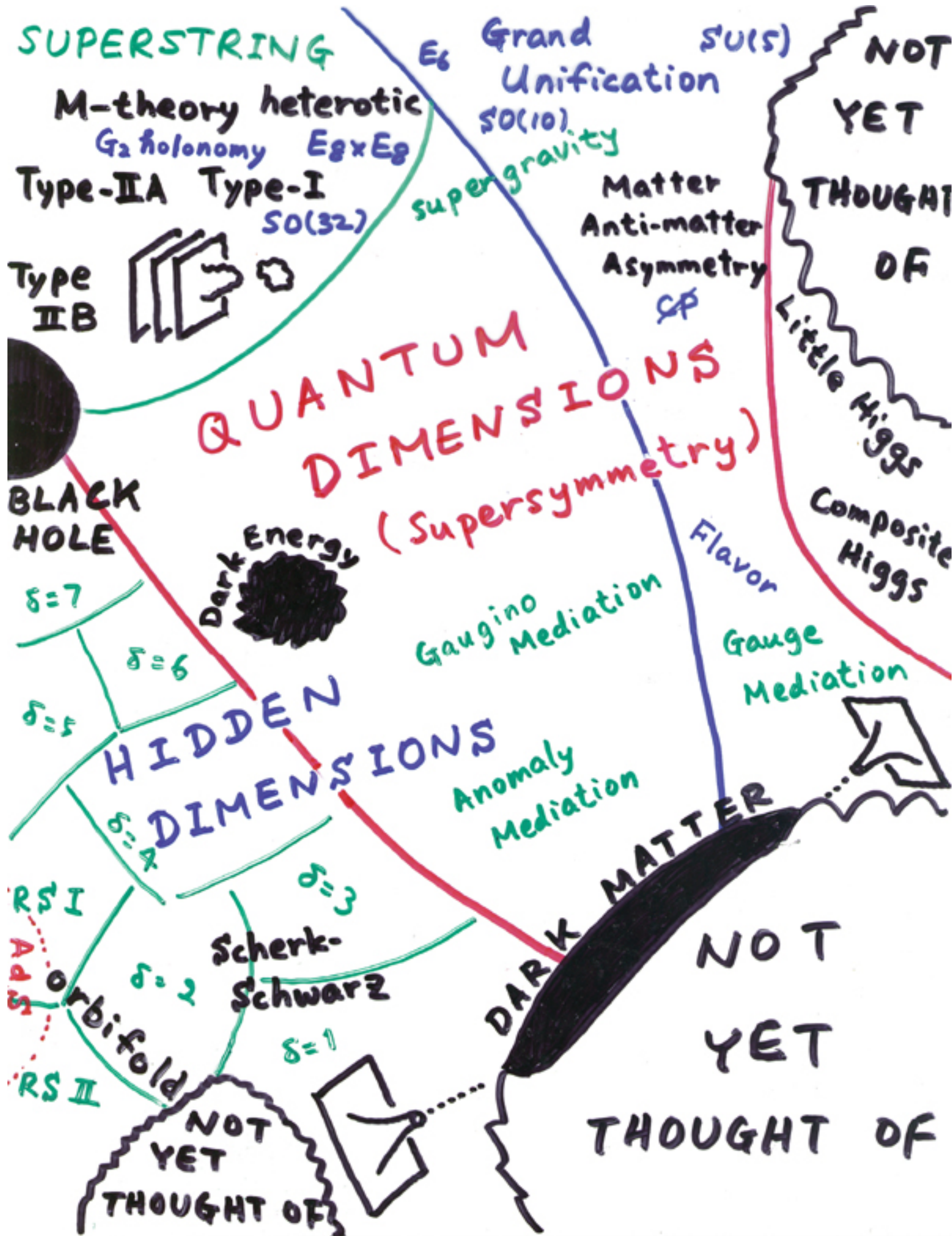
Plenty of candidates from theory departments!

No clear “preference” from experimental results

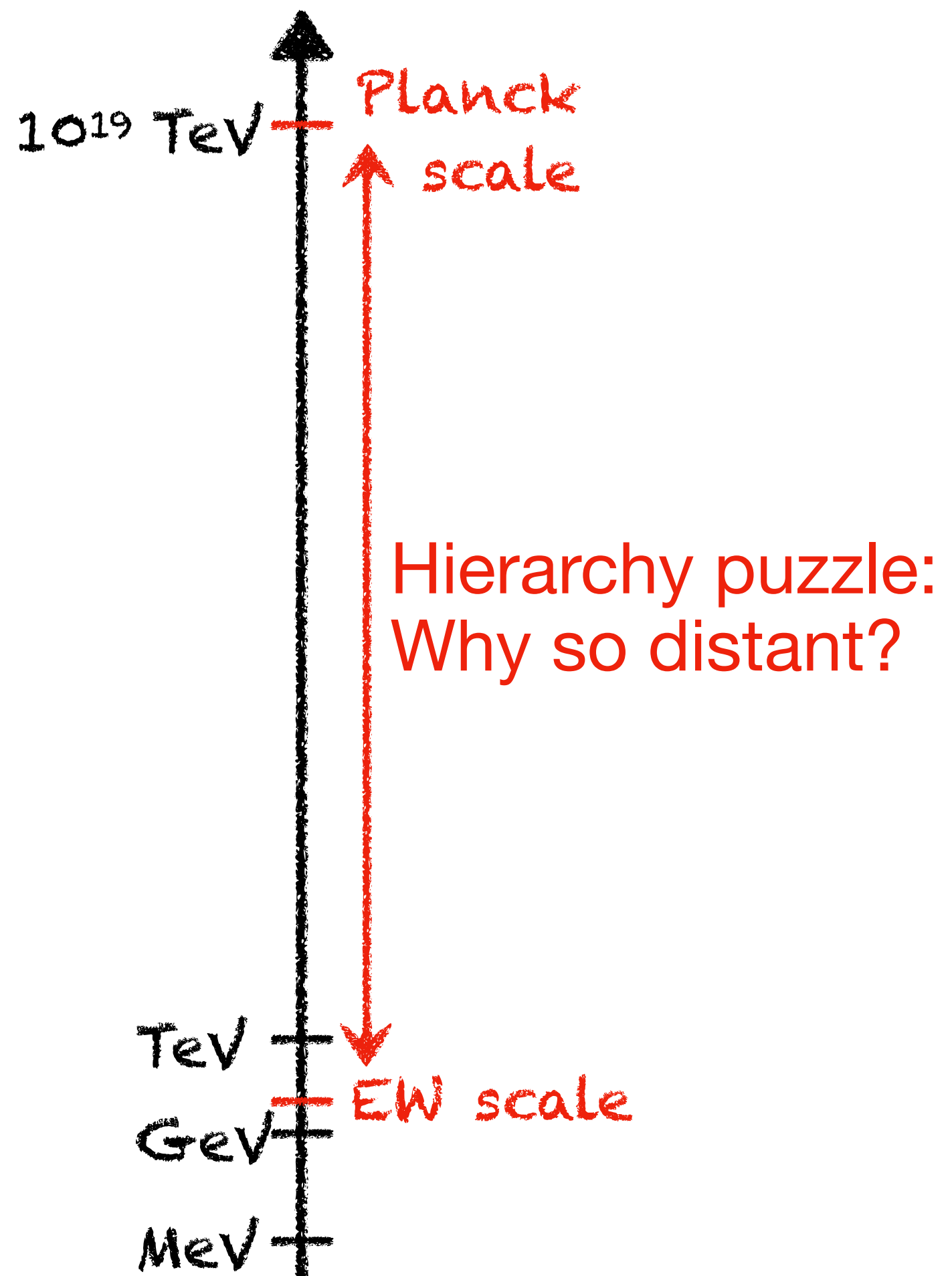


If we don't have a clear target, how to run searches with efficacy?

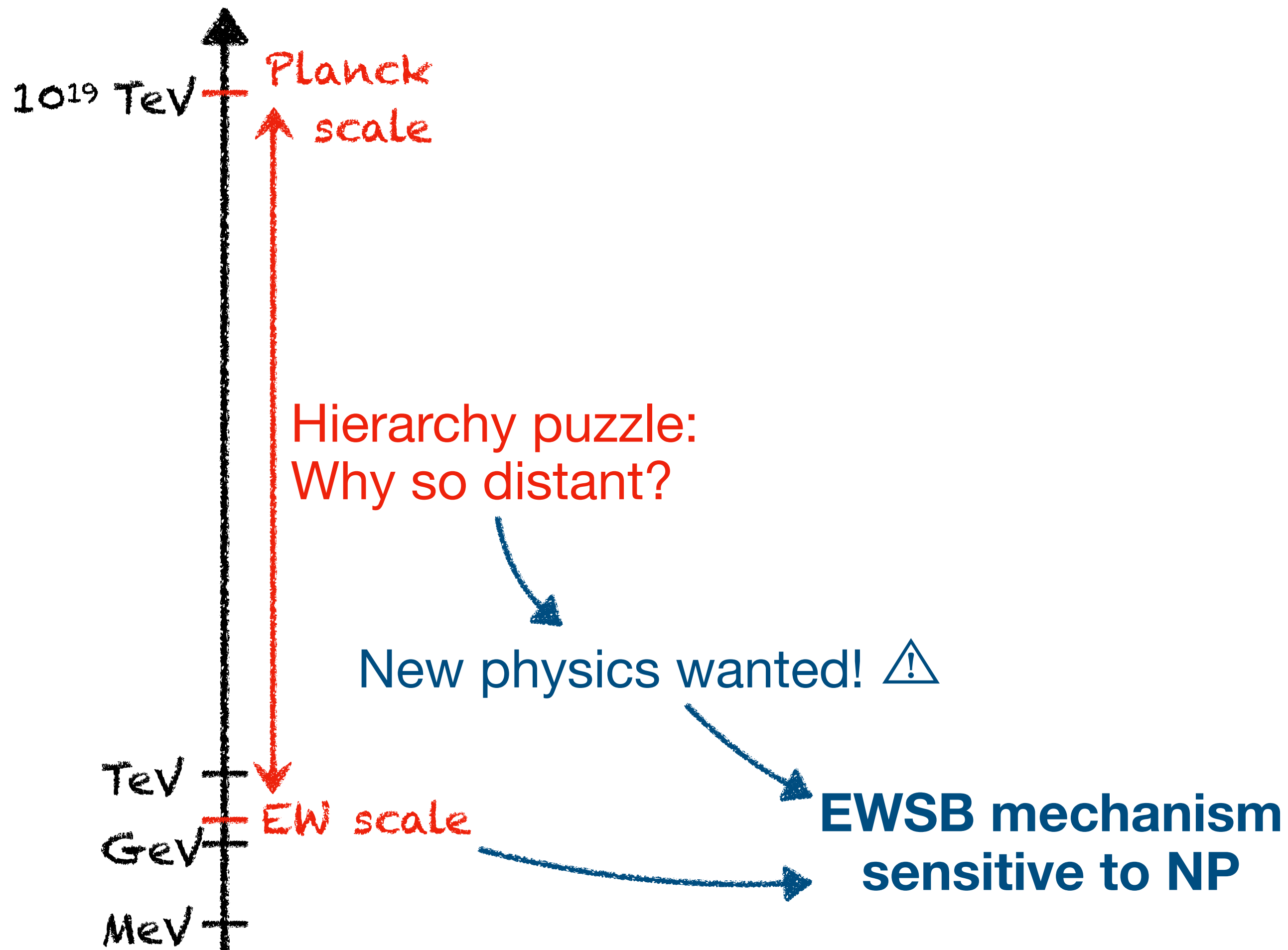
Not a Higgs-like hunting!



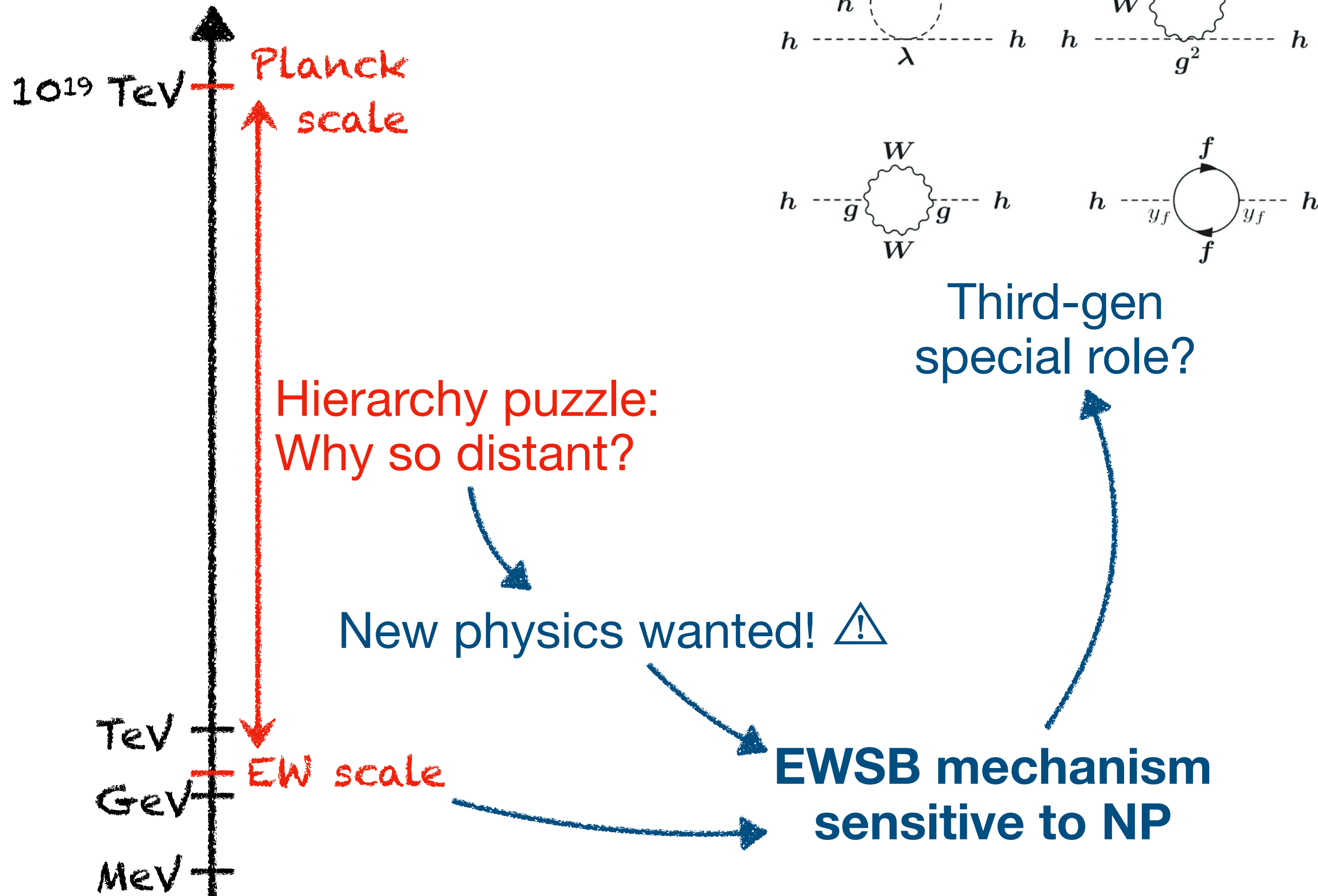
Messengers from BSM land



Messengers from BSM land



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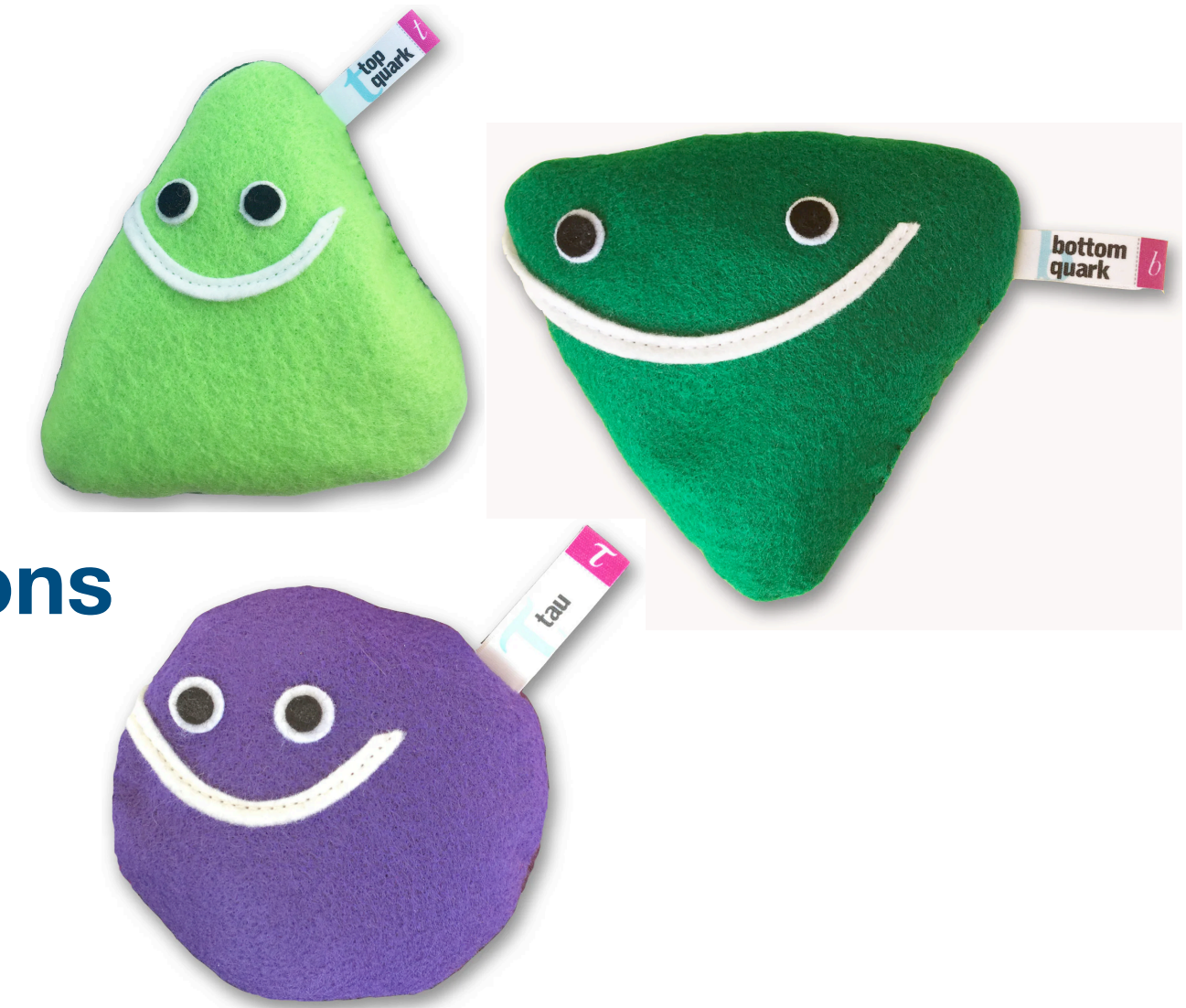


Probes for NP

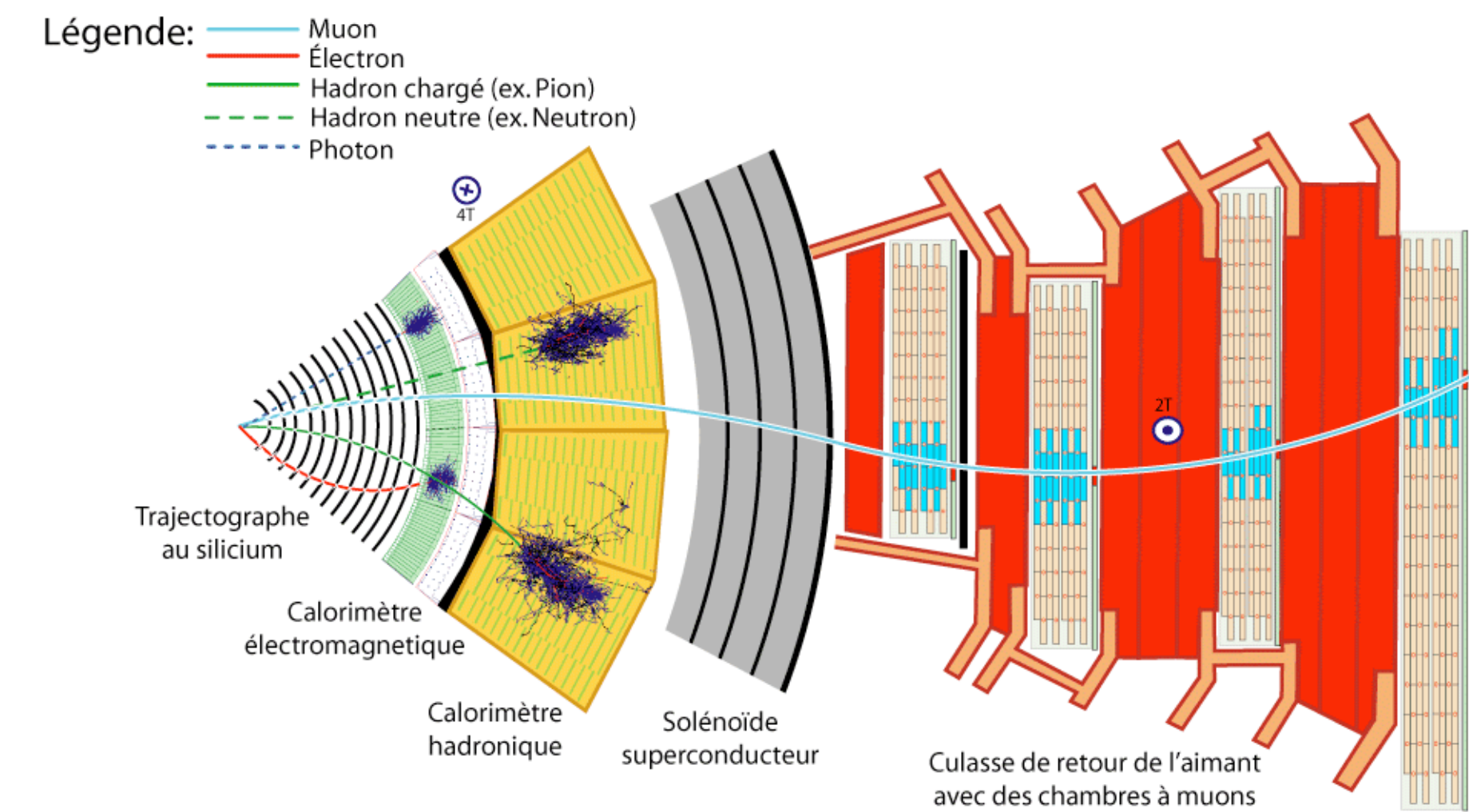
Massive bosons



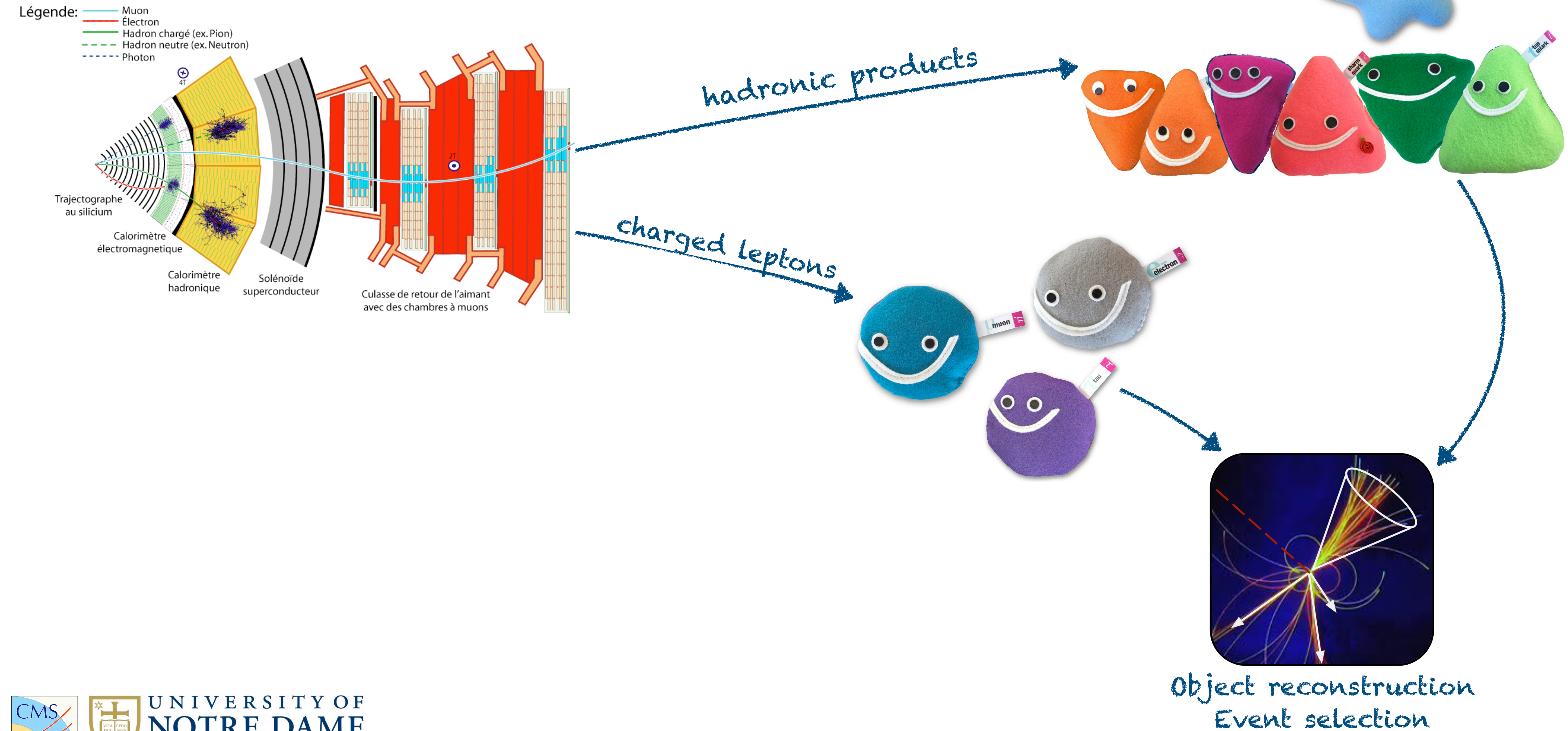
Massive fermions



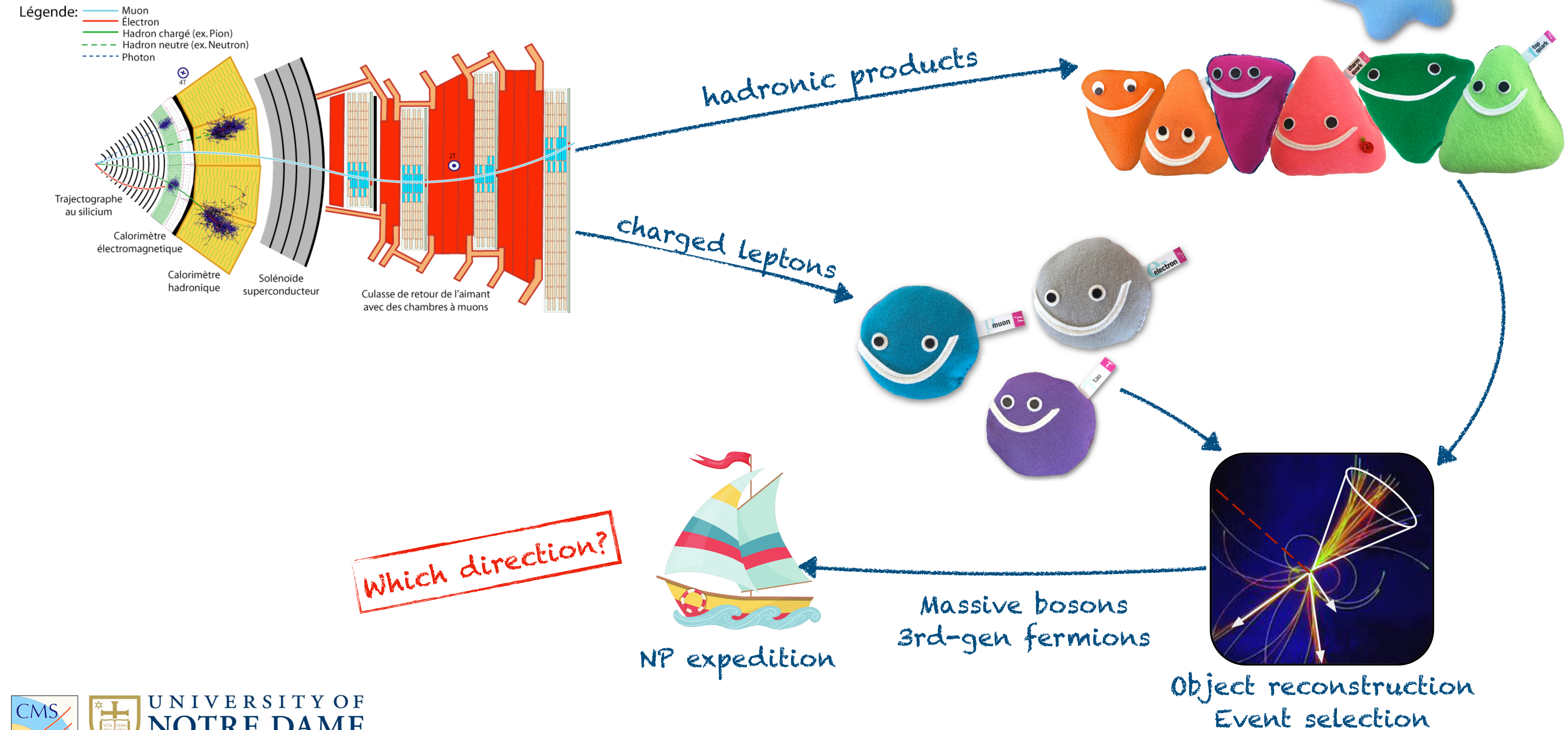
From theory to the experiment



From theory to the experiment



From theory to the experiment



A route to new phenomena

Searching for new particles

Pick a specific NP candidate?

Fascinating, but **strong assumptions!**

Several NP models predict new interactions



A route to new phenomena

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Pick a specific NP candidate?

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 Minimal SM extension with new gauge bosons
Sequential Standard Model



**Can be reinterpreted in
different BSM scenarios**

New W-like boson!

$$\mathcal{L}^{\text{eff}} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_{W'} \bar{f}_i \gamma_\mu \left[\alpha_R^{f_i f_j} (1 + \gamma^5) + \alpha_L^{f_i f_j} (1 - \gamma^5) \right] W'^\mu f_j + h.c.$$

Searching for a W'

JHEP 05 (2024) 046

New massive W' boson

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Searching for a W'

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Making some choices

- EW-like interaction

$$V_{fif_j} = V_{CKM} \quad g_{W'} = g_{EW}$$

- Mixed couplings varying α_R, α_L

- only RH coupling: $\alpha_R = 1, \alpha_L = 0$

- only LH coupling: $\alpha_R = 0, \alpha_L = 1$

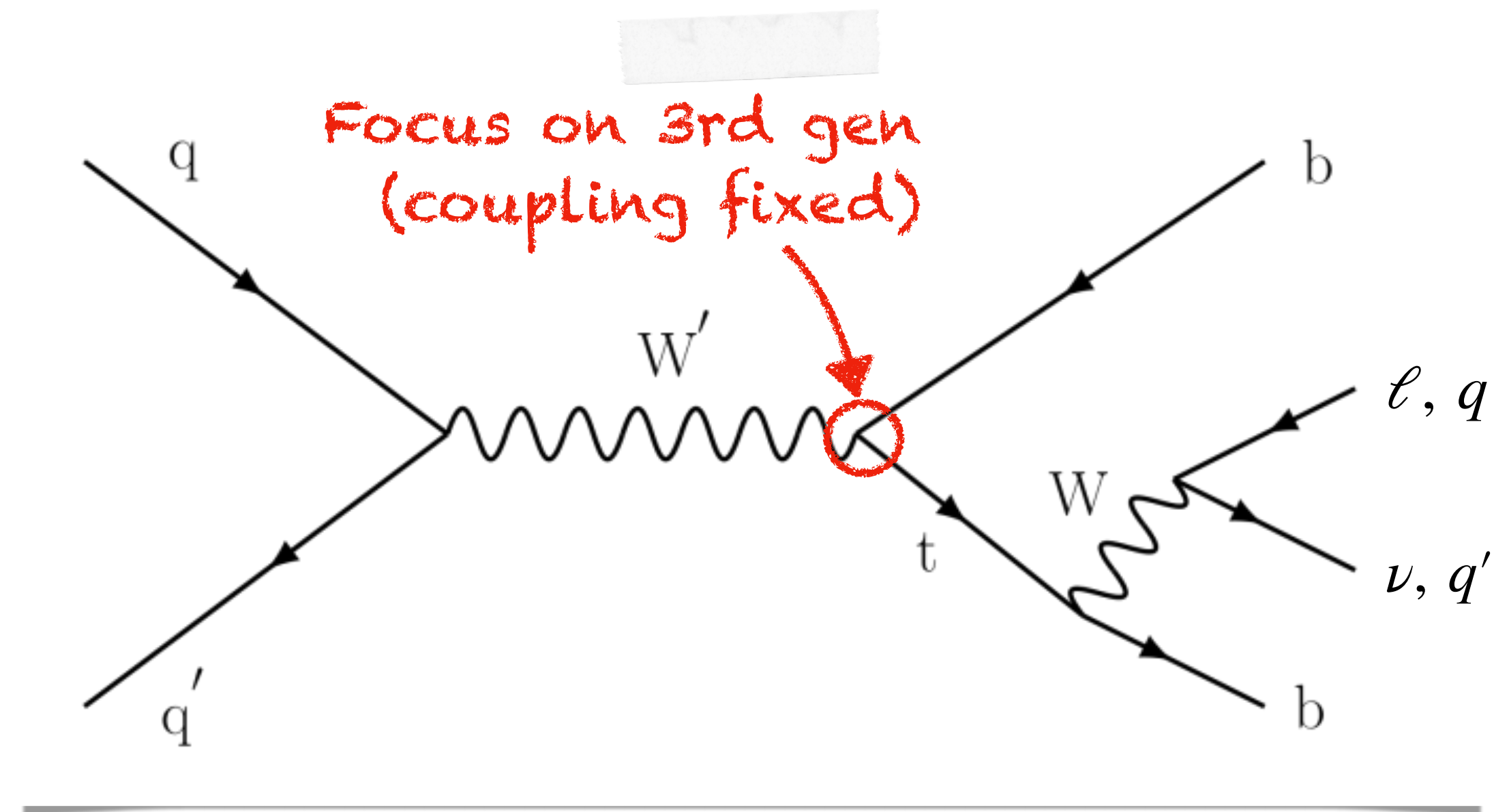
- Possibility to investigate several scenarios

- $2 \text{ TeV} < m_{W'} < 6 \text{ TeV}$

- 4 decay widths per mass point

New massive W' boson

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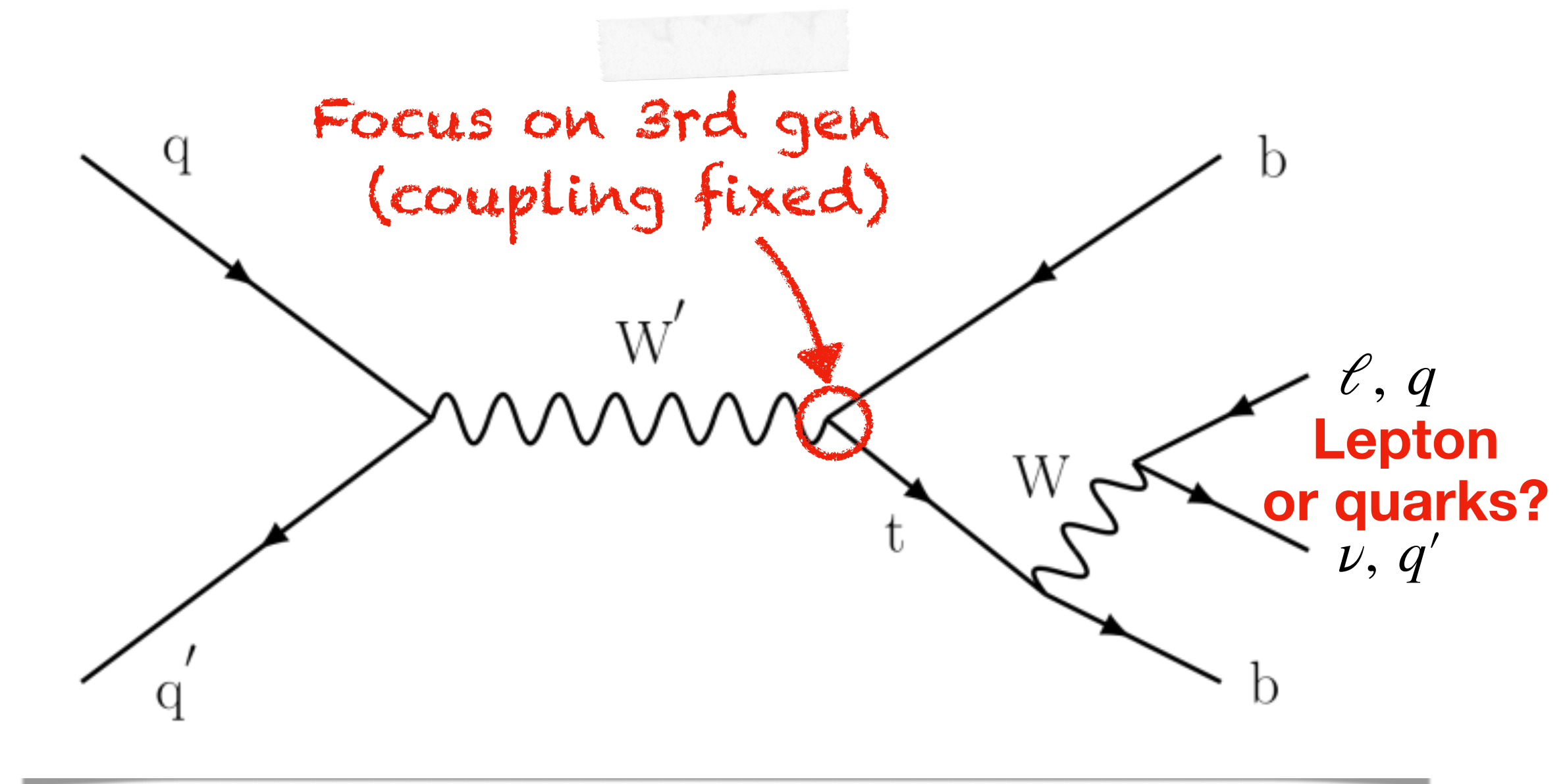
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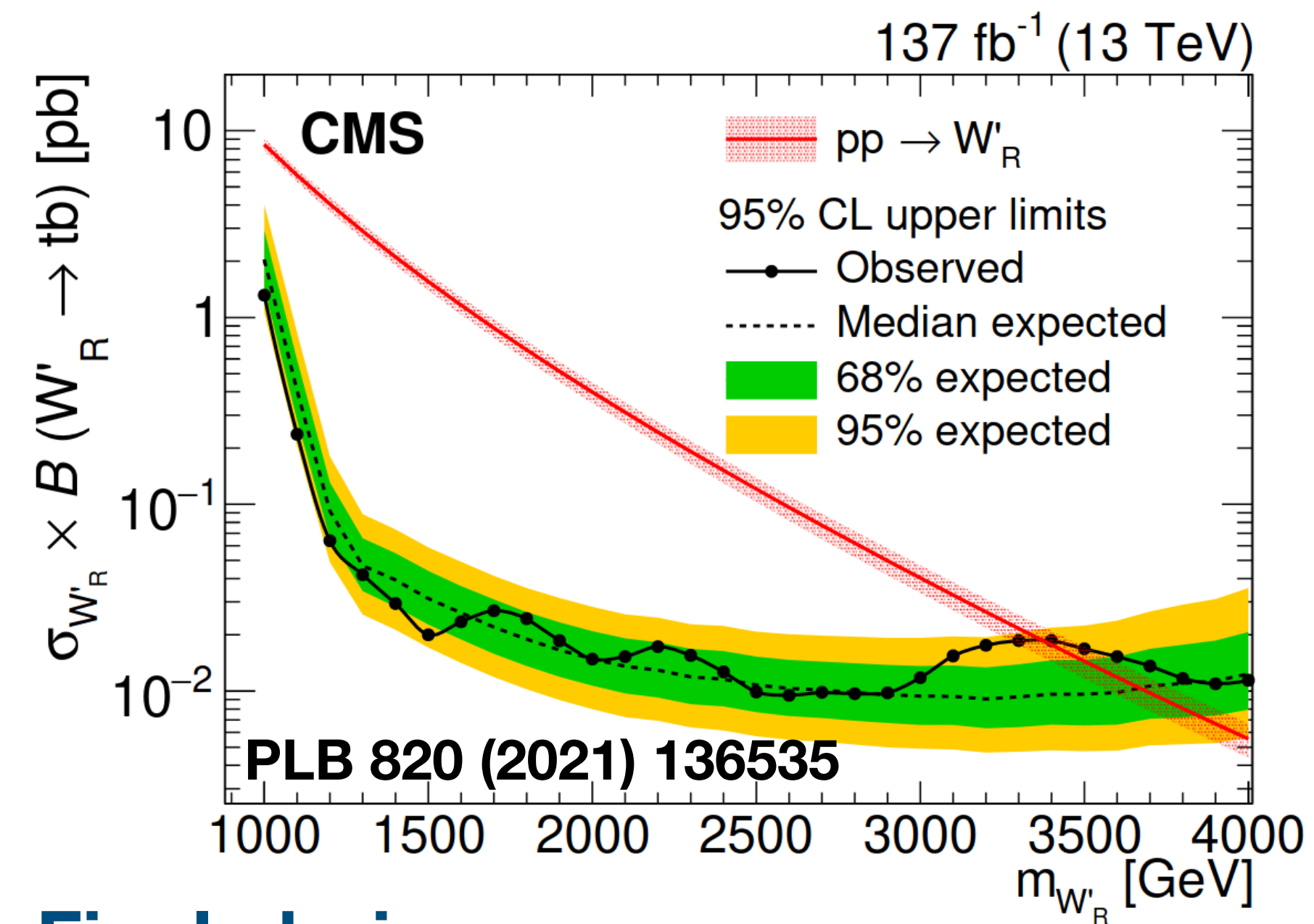
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New massive W' boson

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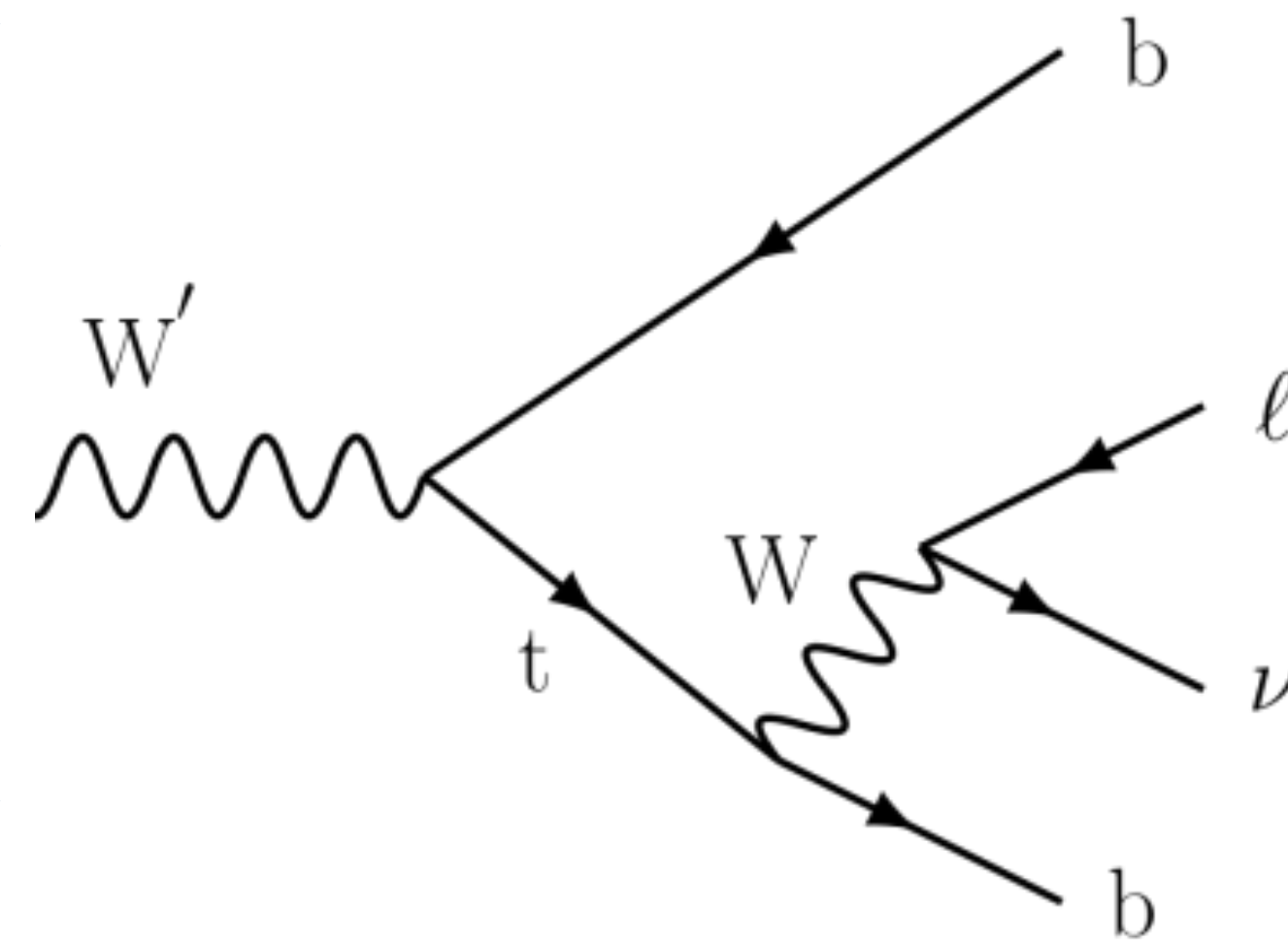
Targeting the final state



Final choice

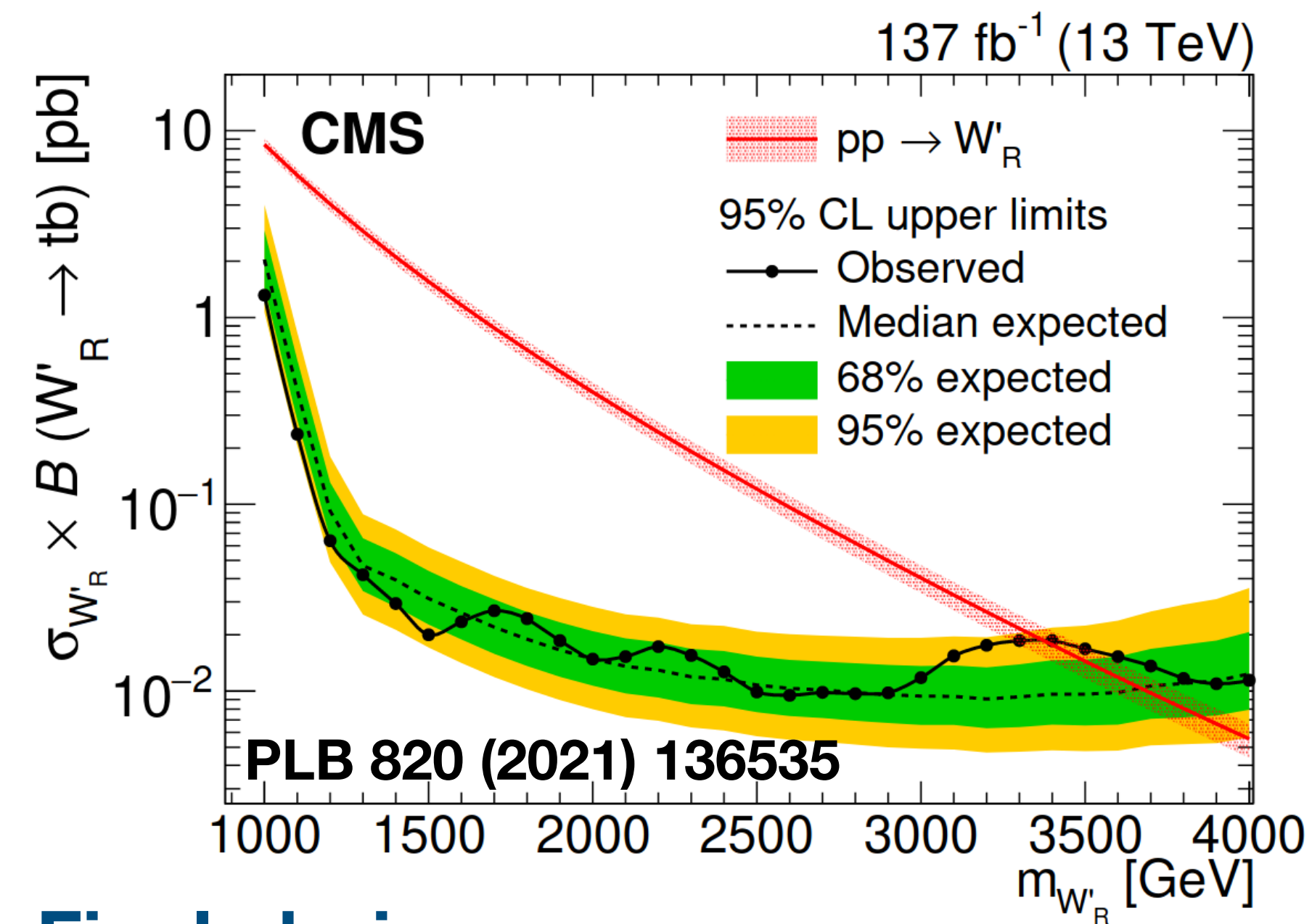
- Complementing the hadronic search

Theory perspective



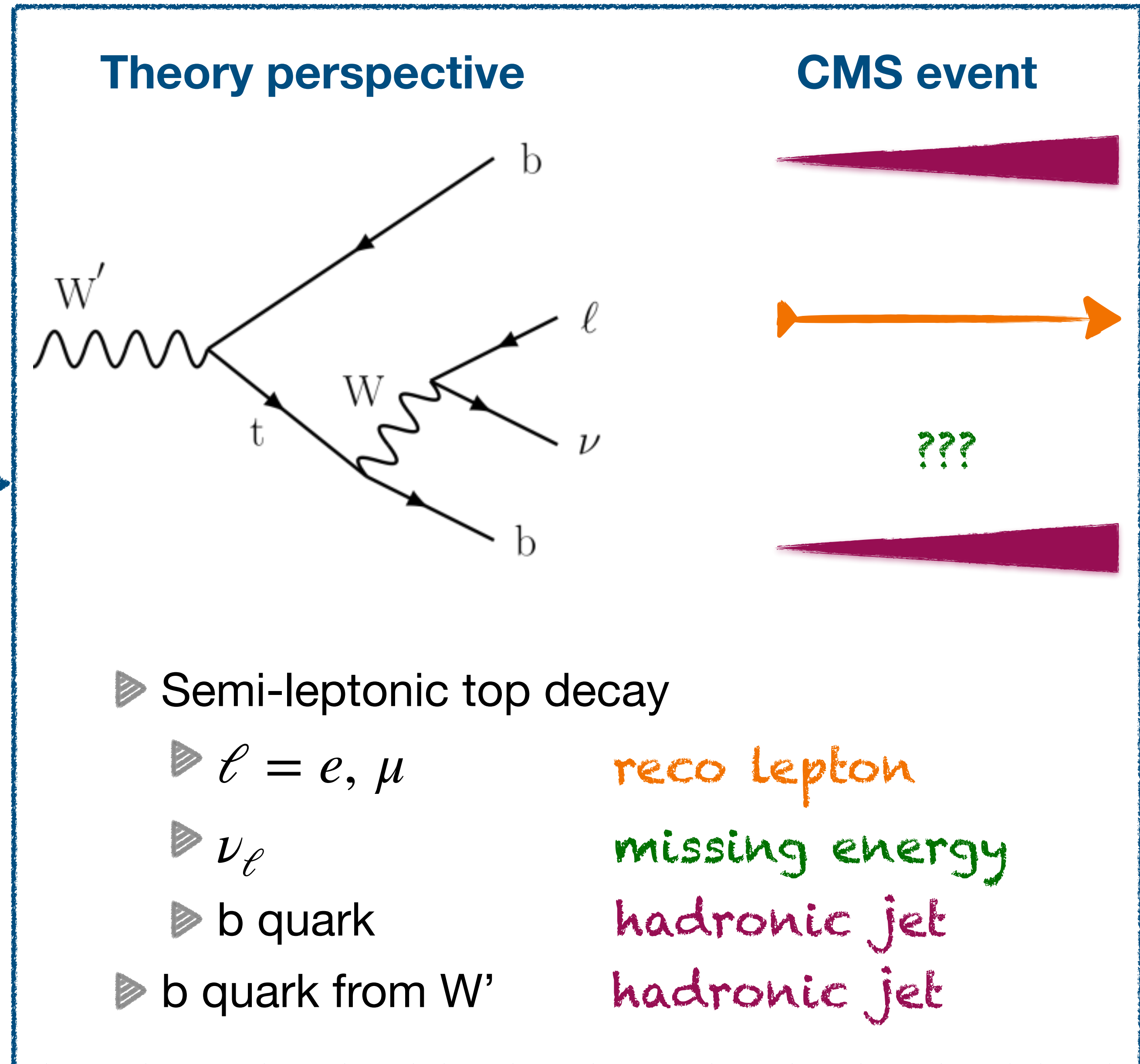
- Semi-leptonic top decay
 - $\ell = e, \mu$
 - ν_ℓ
 - b quark
 - b quark from W'

Targeting the final state



Final choice

- Complementing the hadronic search



Ready to hunt a W'!

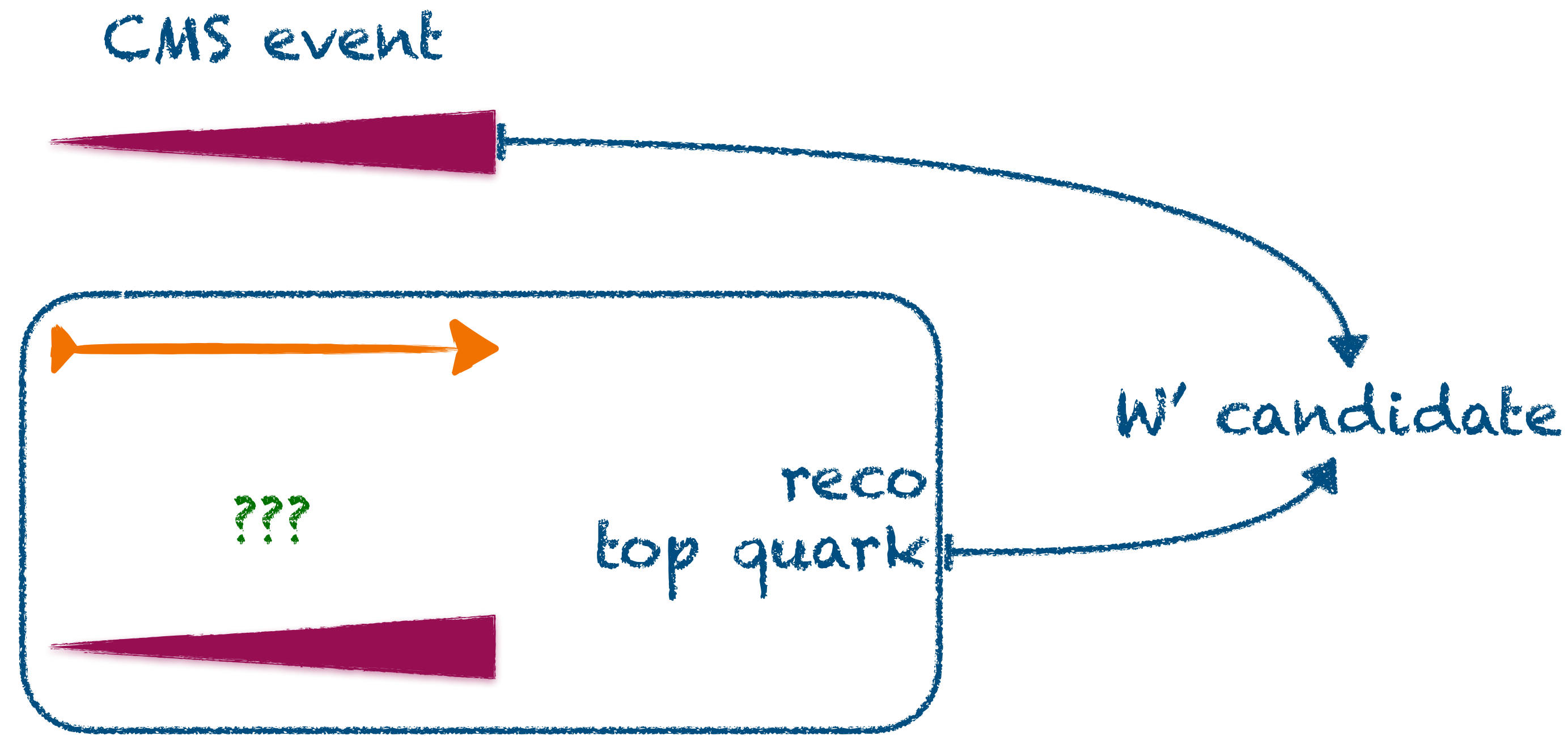
CMS event



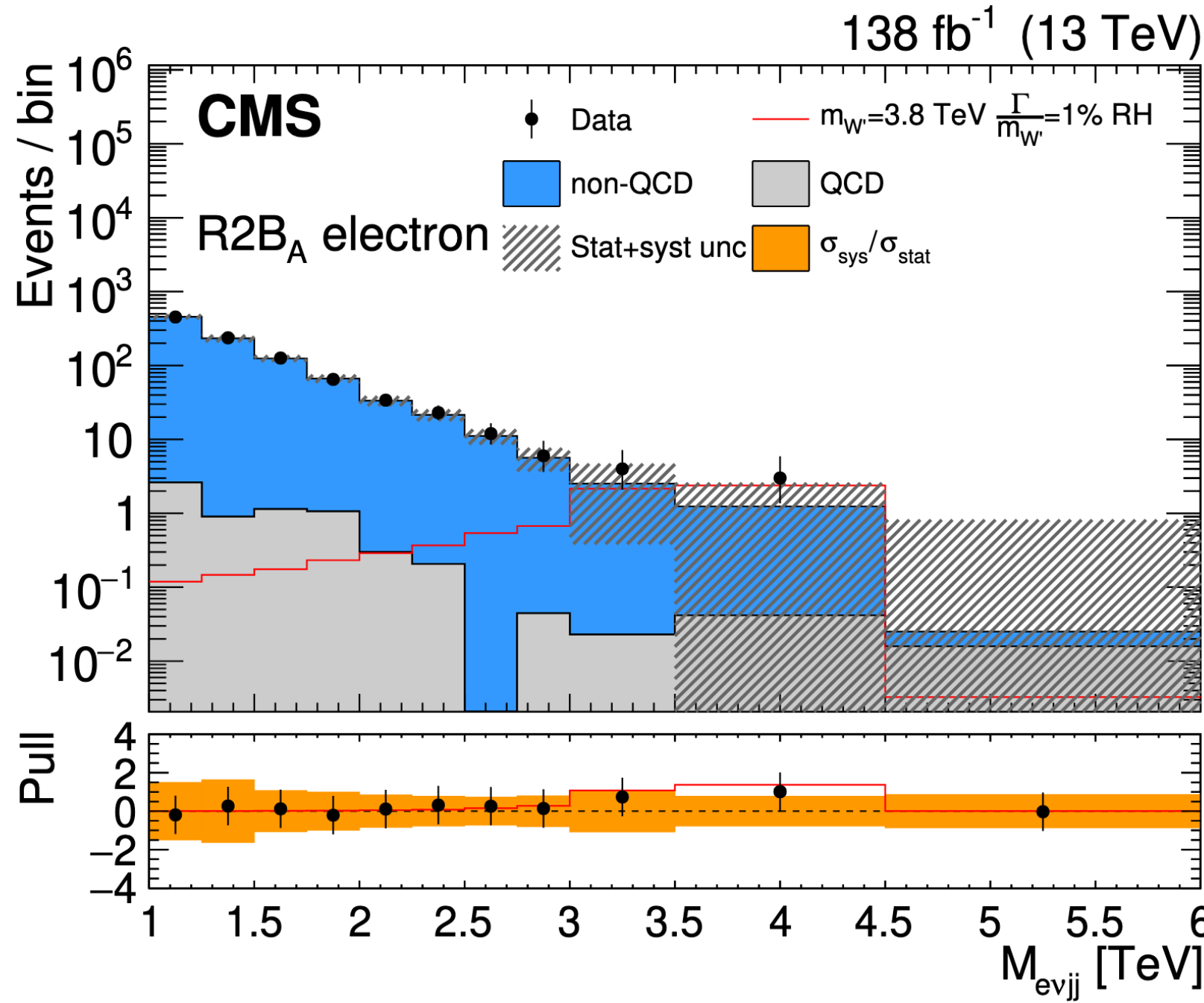
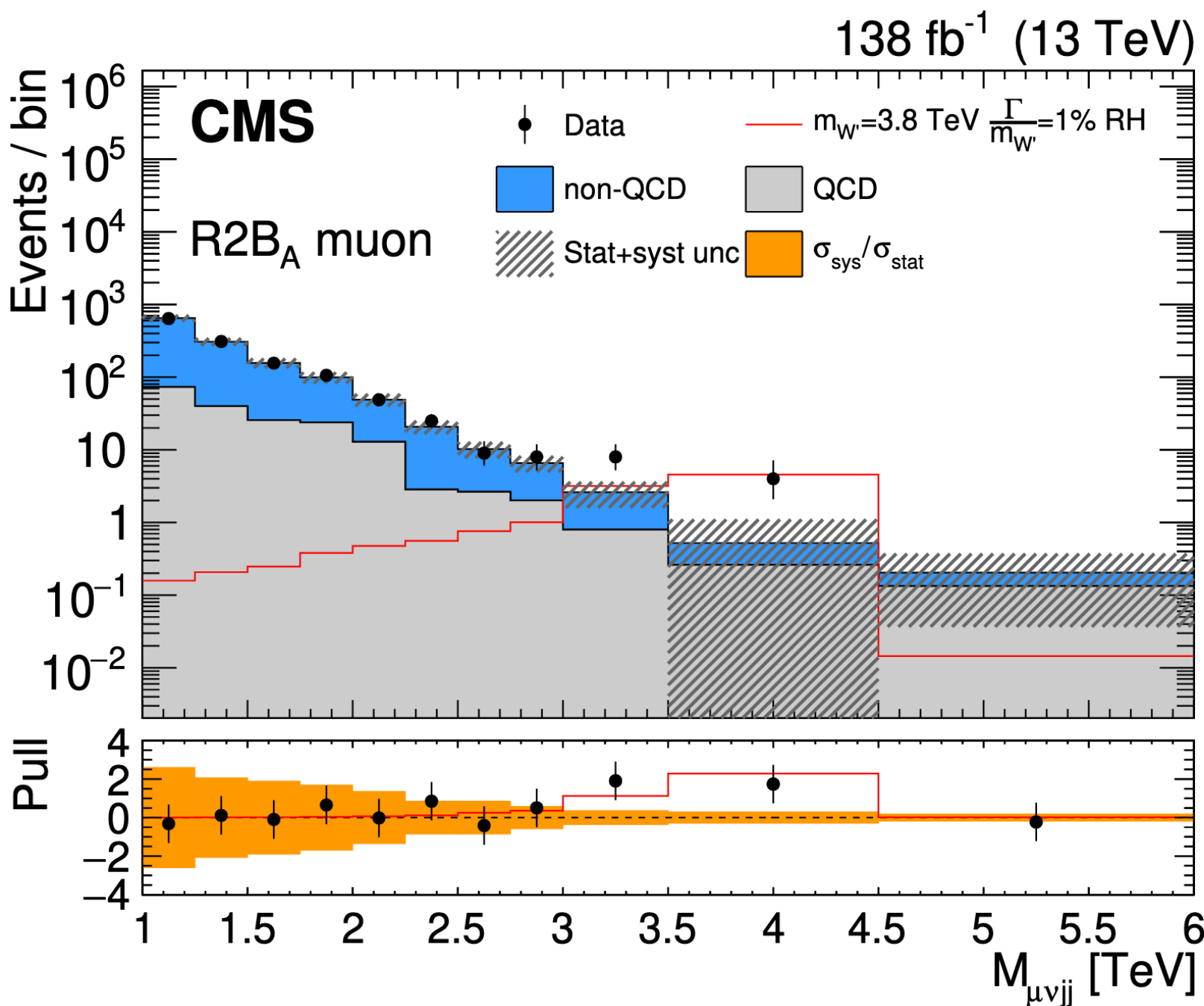
???



Ready to hunt a W'!

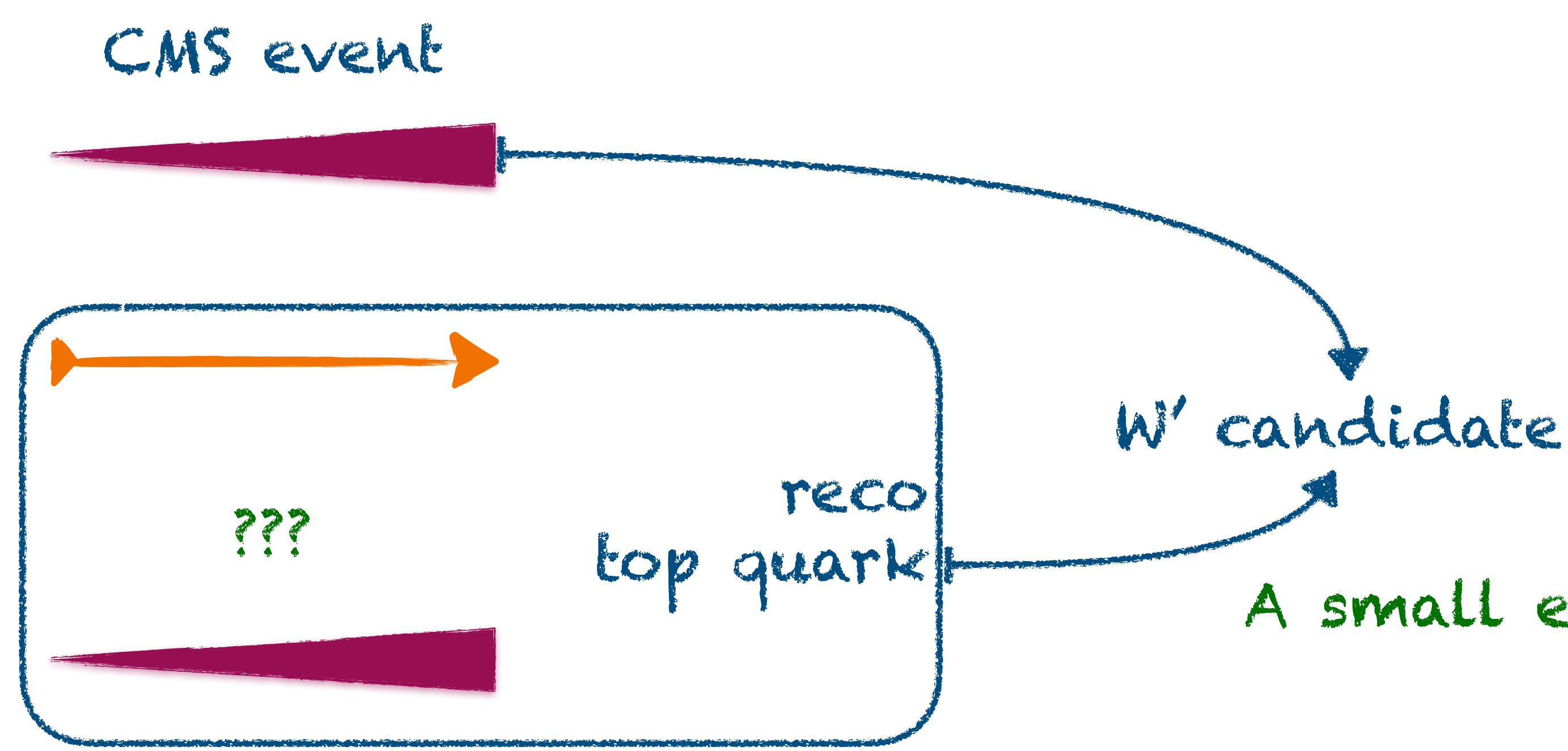


region	top b-jet	W' b-jet	total #b-jets
SR #1	☒	☒	2+
SR #2	☒	☐	1
SR #3	☐	☒	1
CR	☐	☐	0

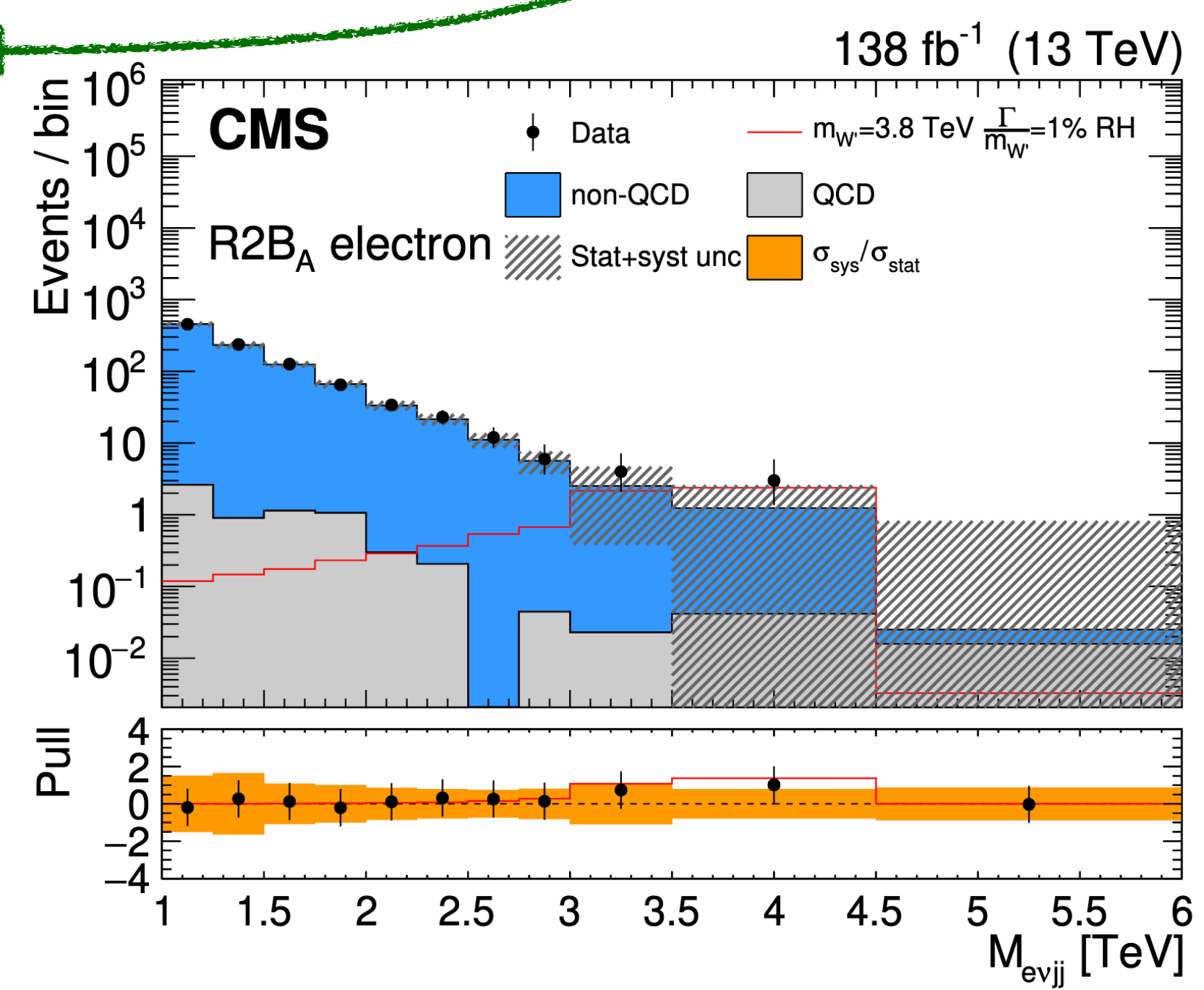
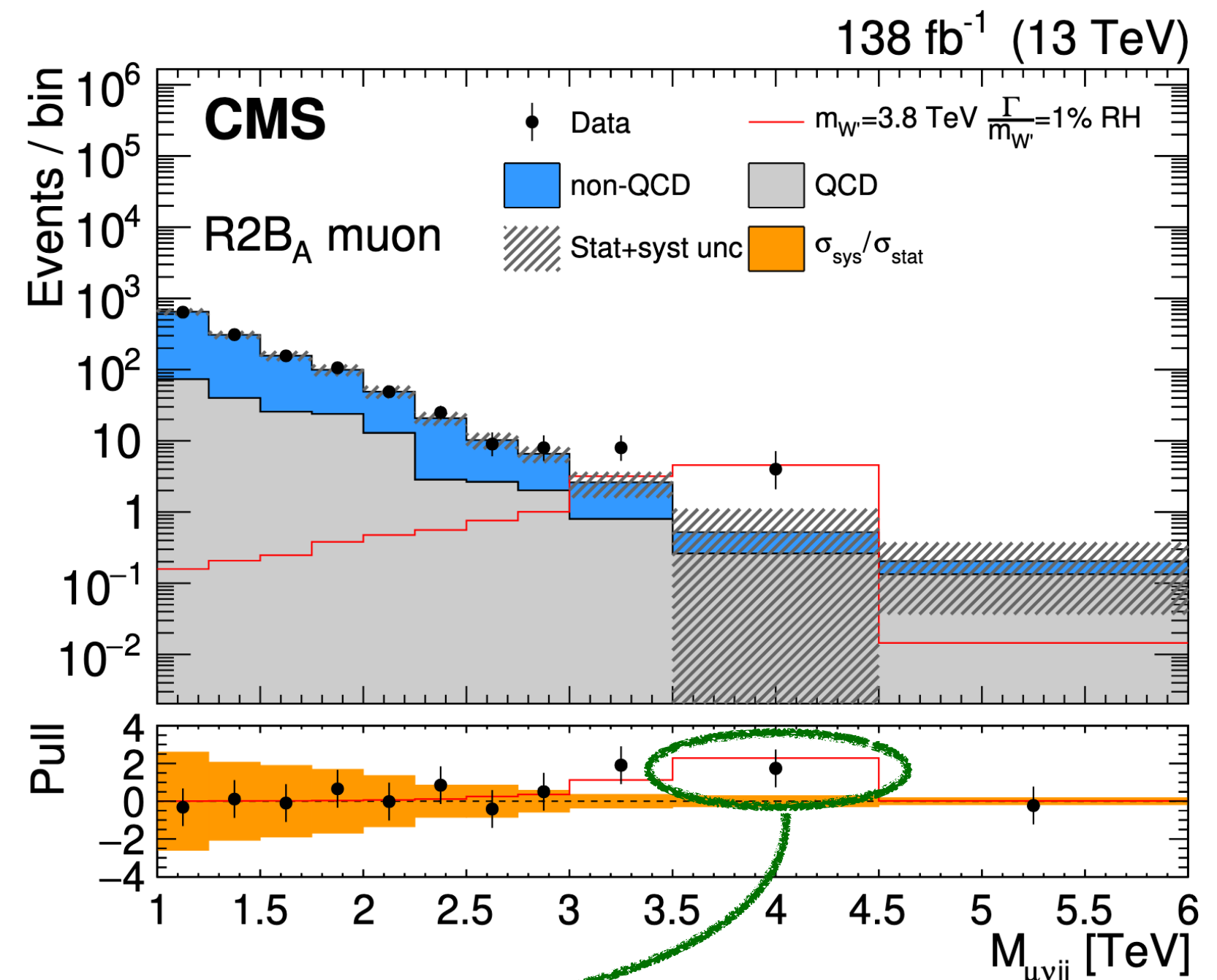


Using CMS Run 2 dataset

Ready to hunt a W'!



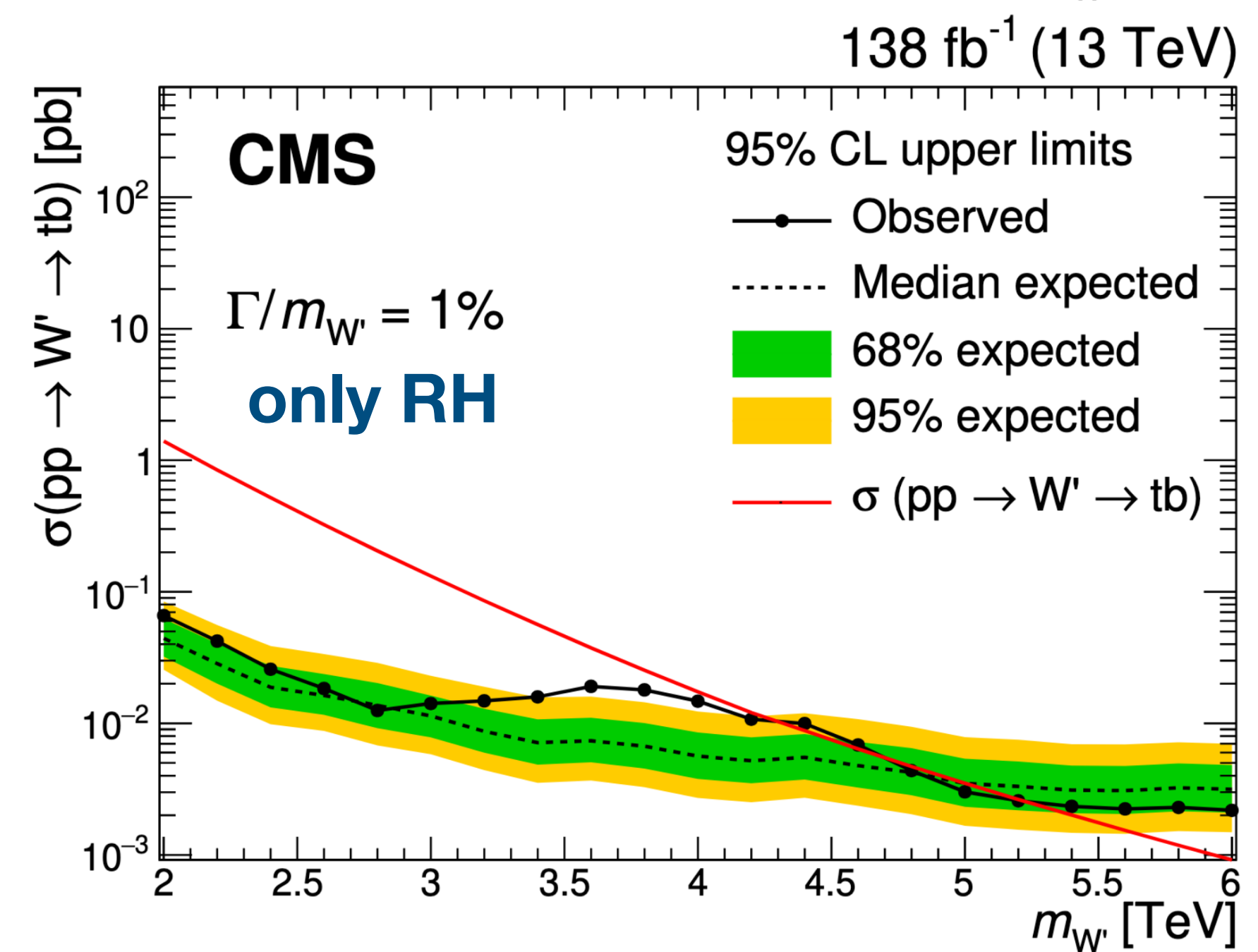
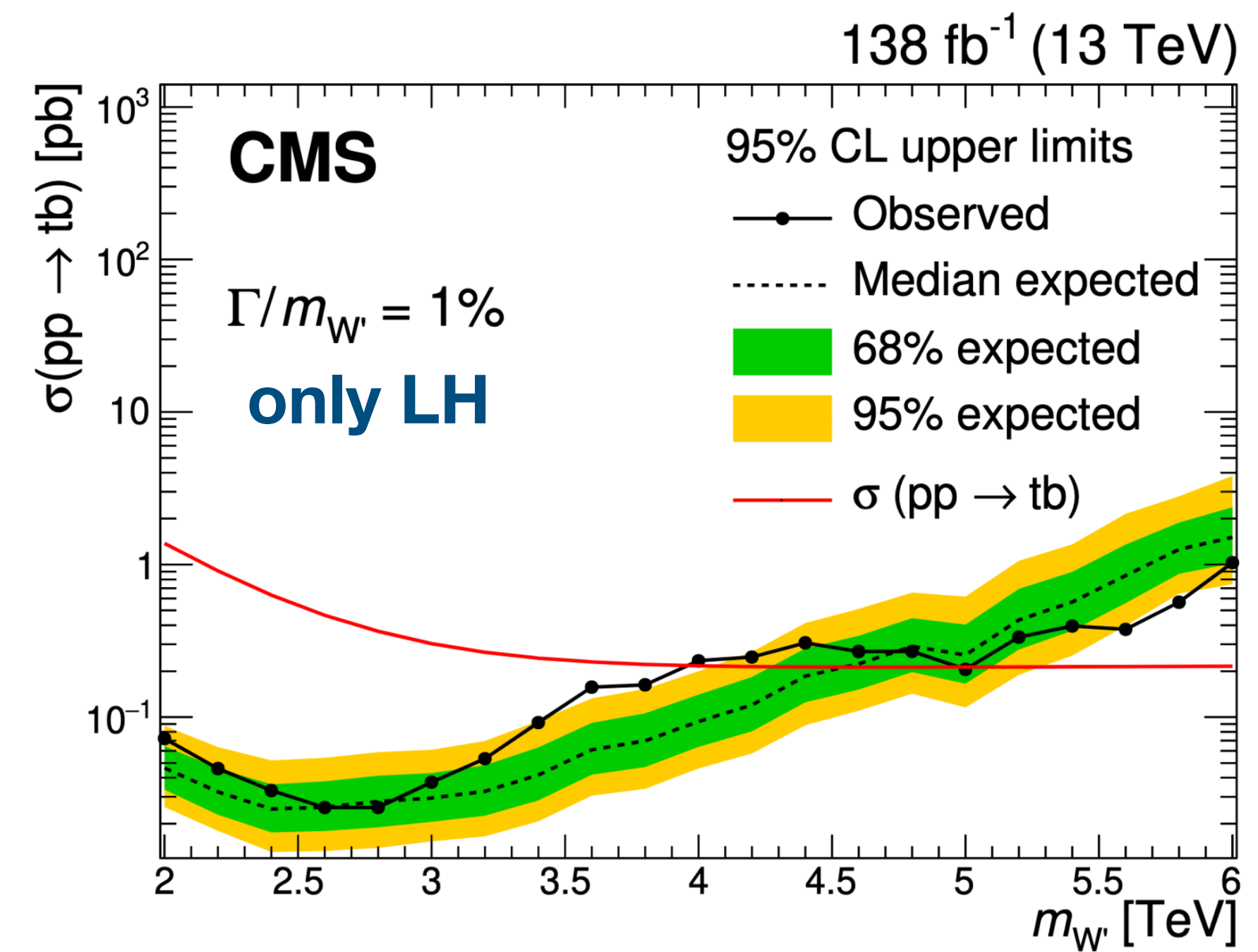
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Using CMS Run 2 dataset

Closer look to the results

Take-home messages from statistics



Closer look to the results

Take-home messages from statistics

95% CL upper limits
on $m_{W'}$ and cross-sections
for a wide range of scenarios:

► Mixed chiralities

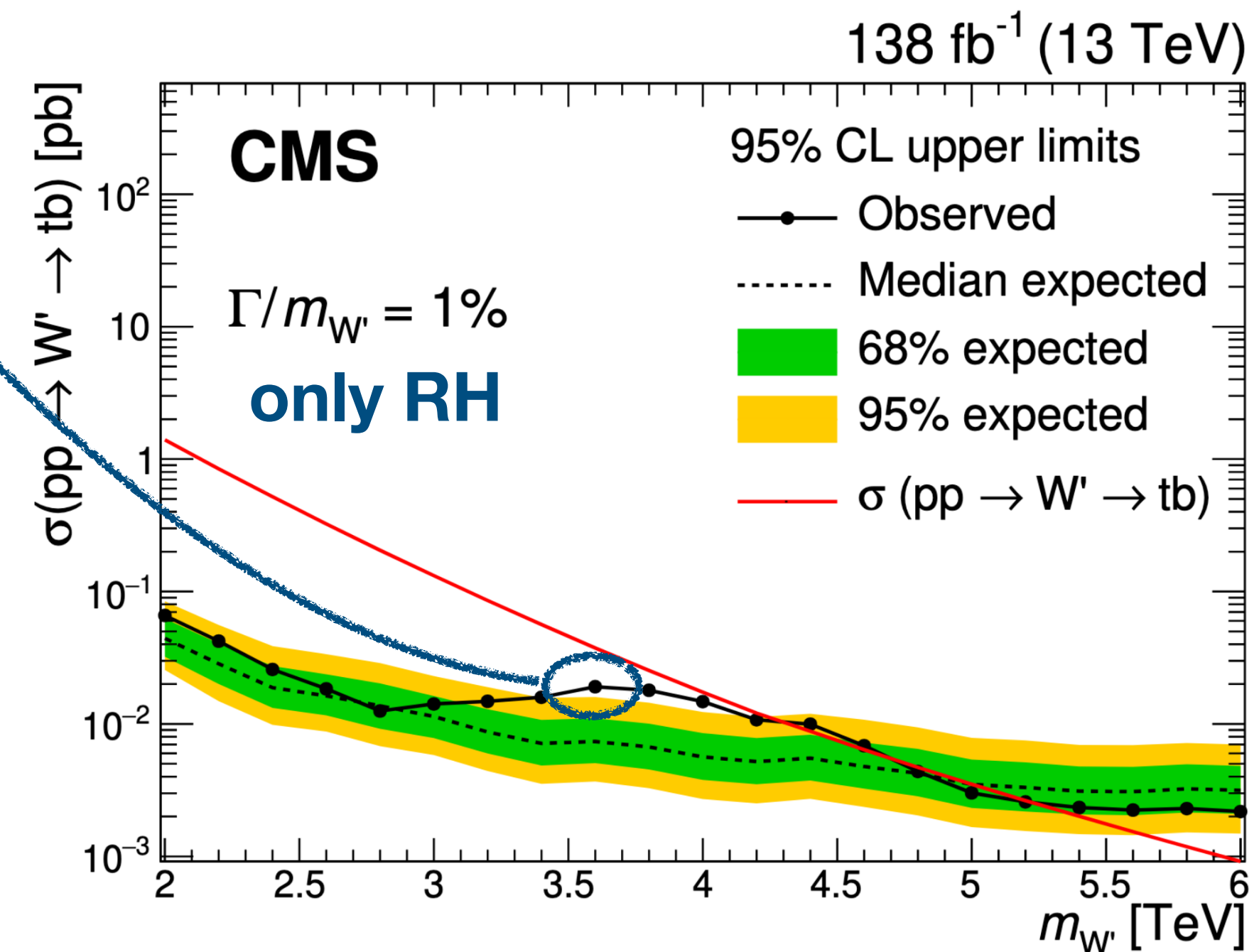
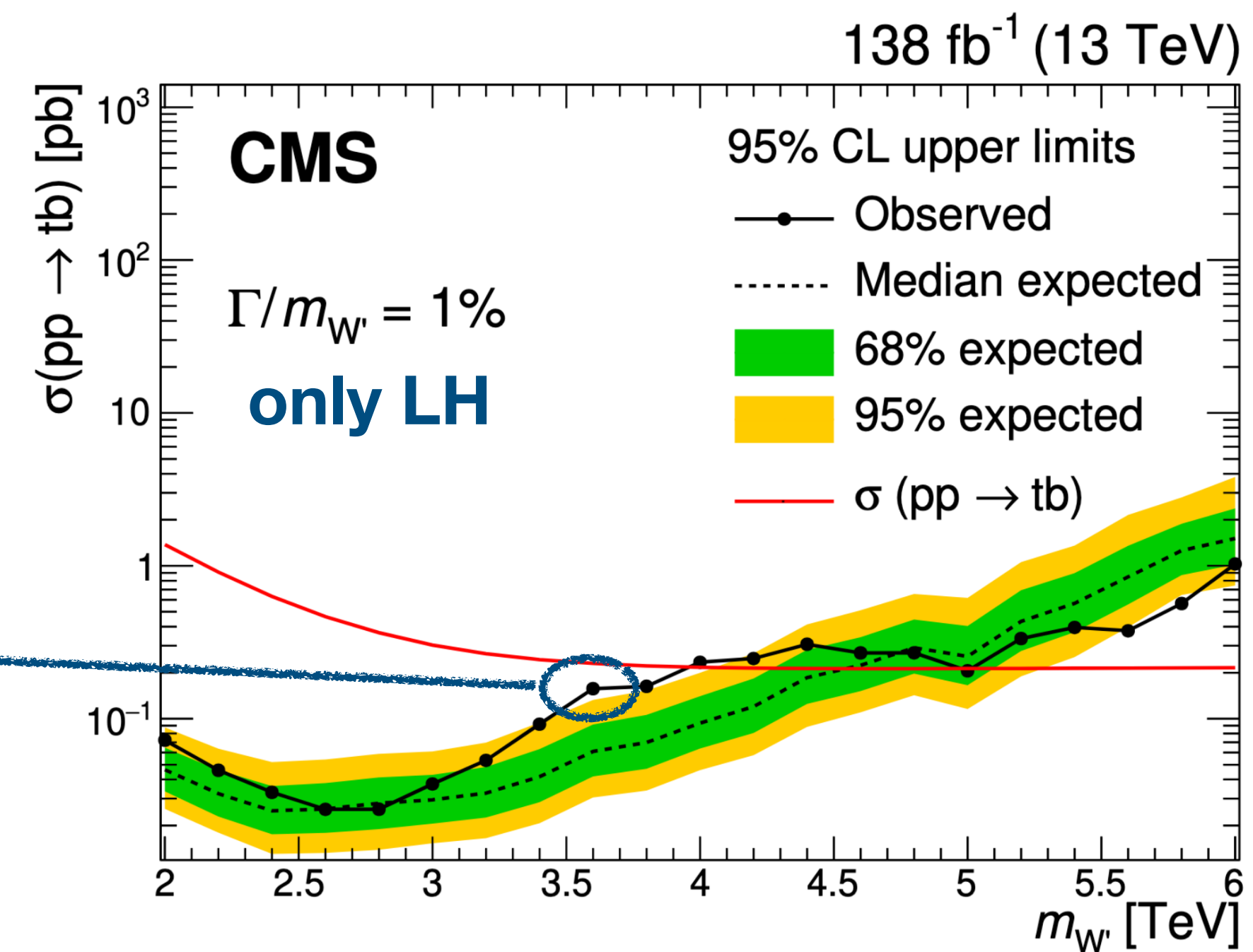
$\alpha_R \in [0,1], \alpha_L \in [0,1]$
with steps of 0.1

► 4 total width values
0.8, 10, 20 and 30%

Can be re-interpreted
in a specific NP model

Excess not strong enough
for a discovery

for RH $m_{W'} = 3.8$ TeV:
Local significance: 2.6σ
Global significance: 2.0σ



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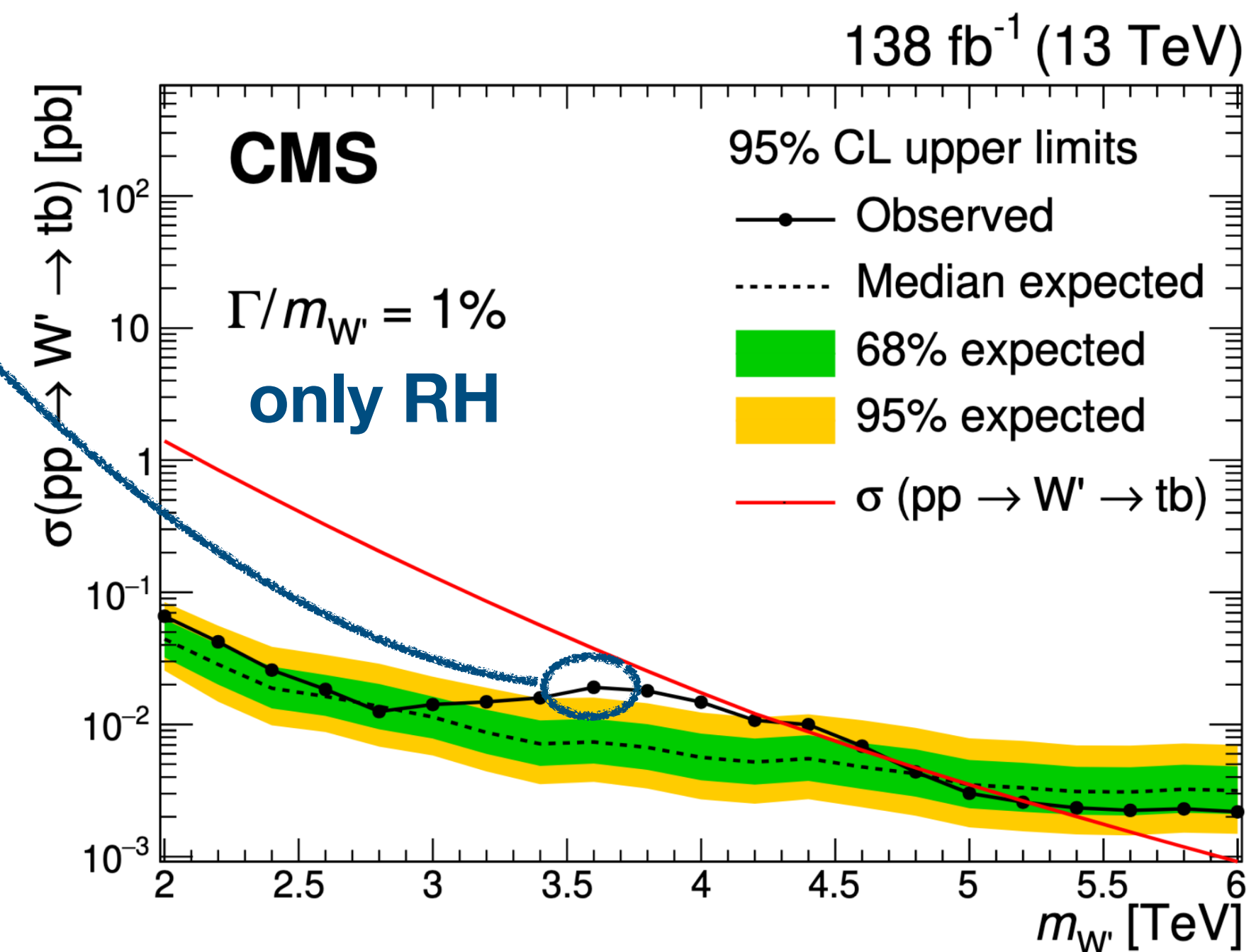
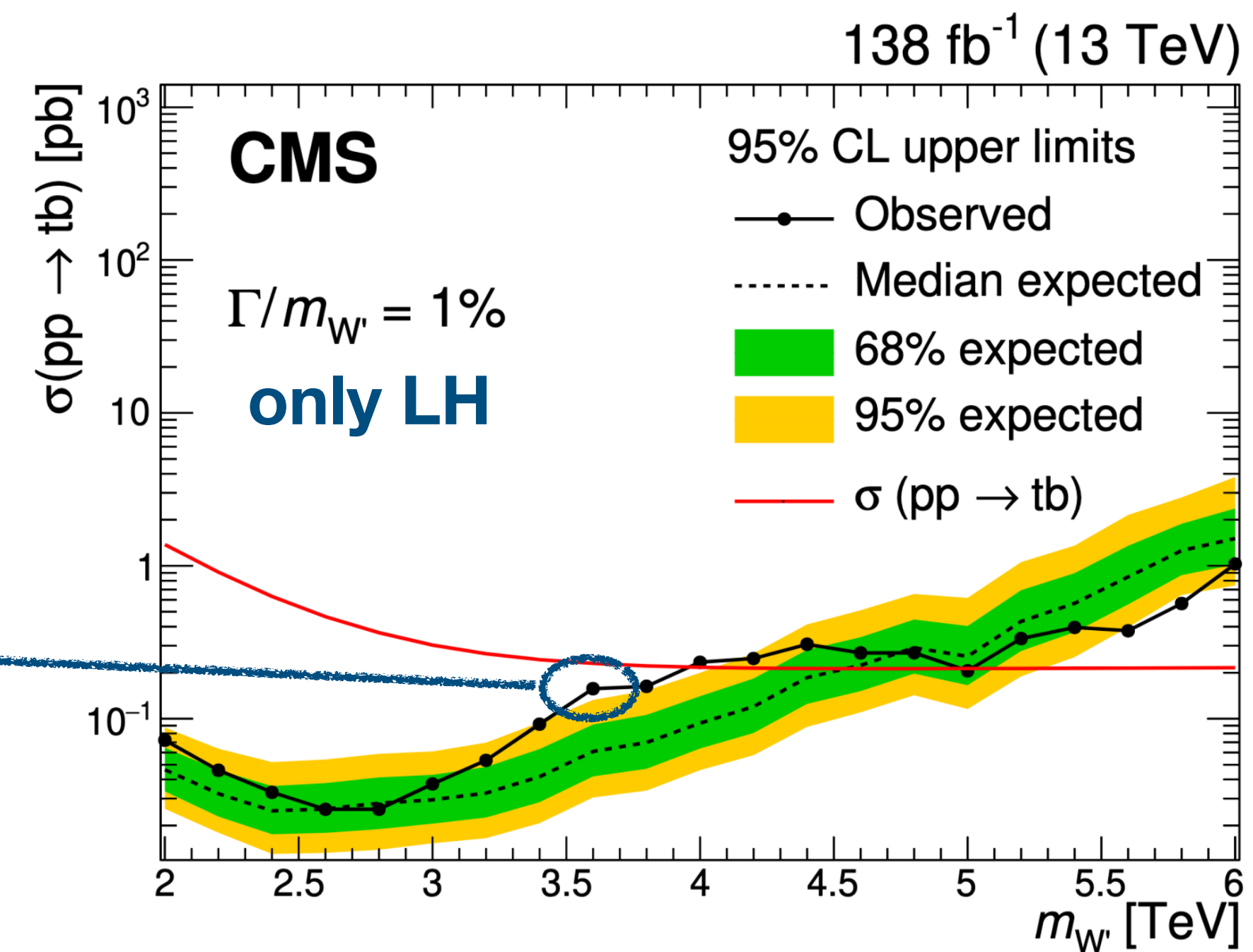


NP expedition

Excess not strong enough
for a discovery

for RH $m_{W'} = 3.8$ TeV:
Local significance: 2.6σ
Global significance: 2.0σ

Can we
learn more?

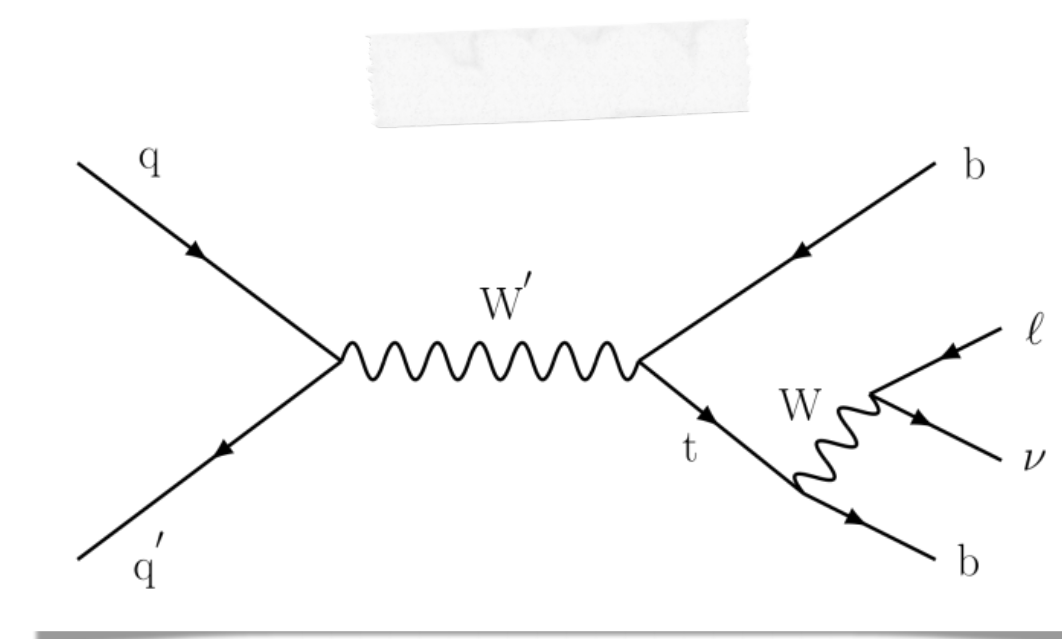
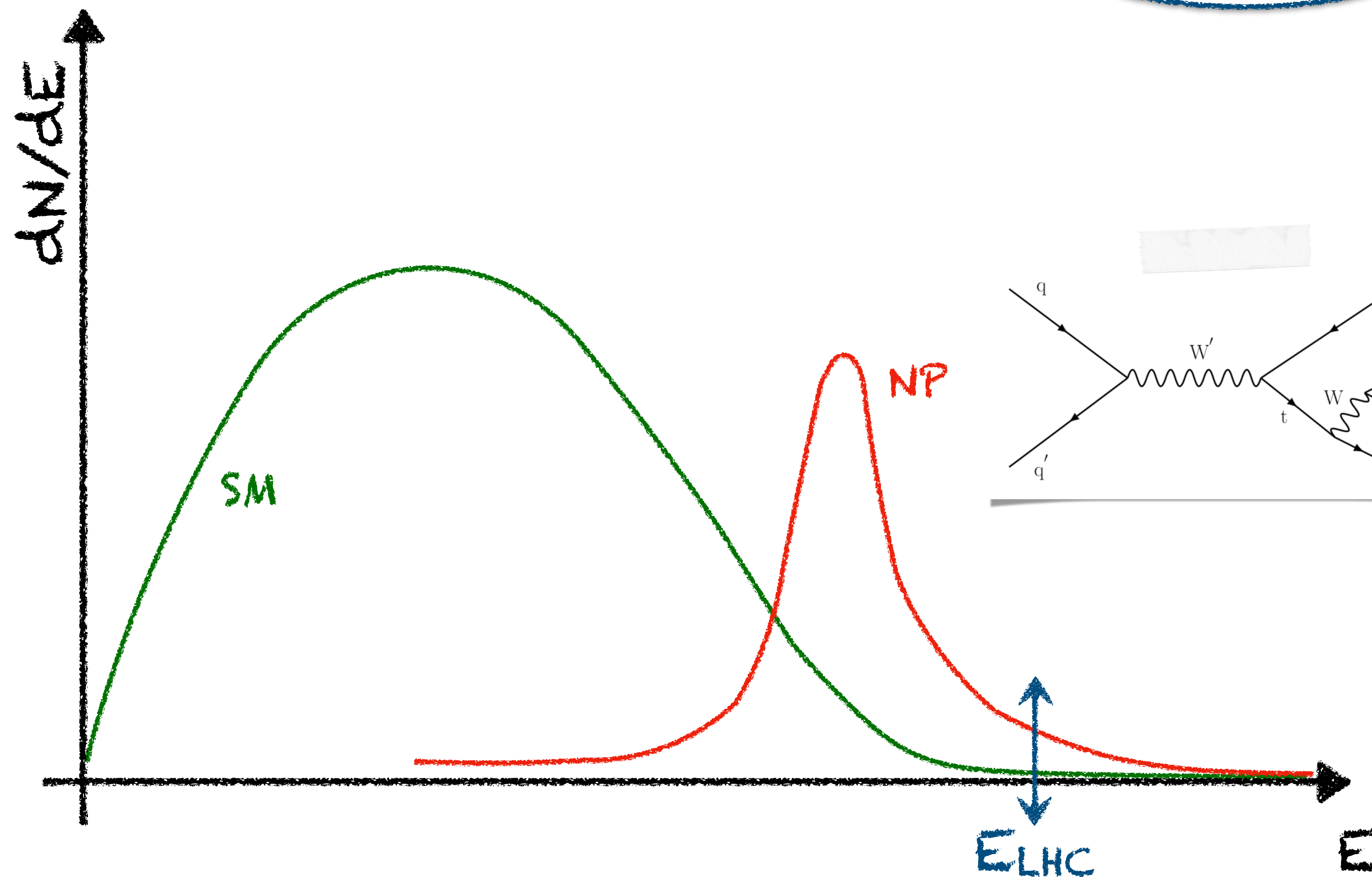


What if NP is out of reach?

Underlying assumption of direct searches

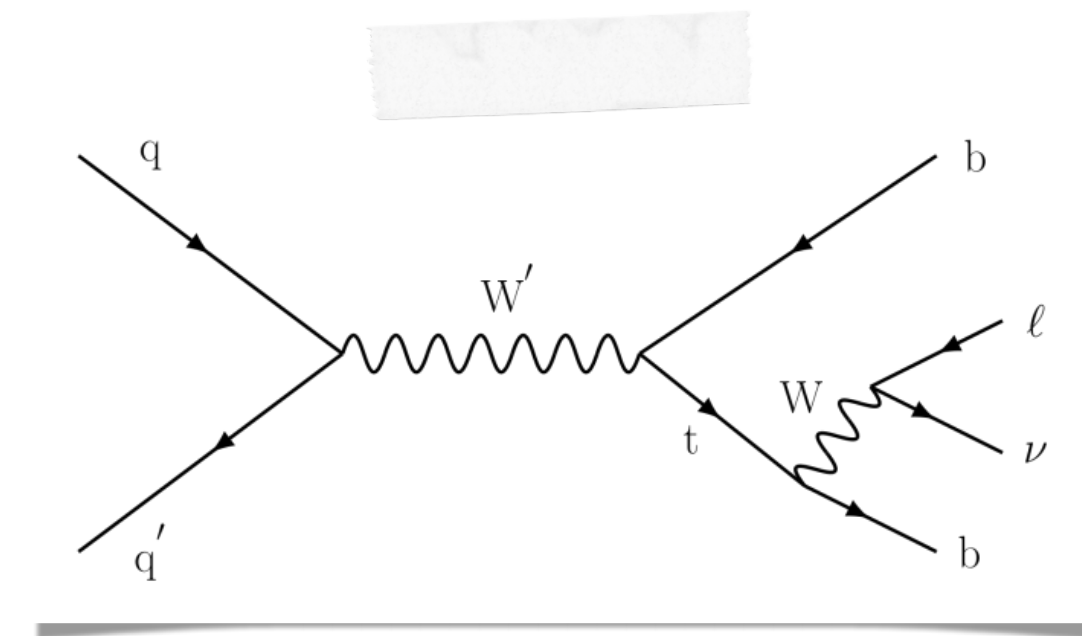
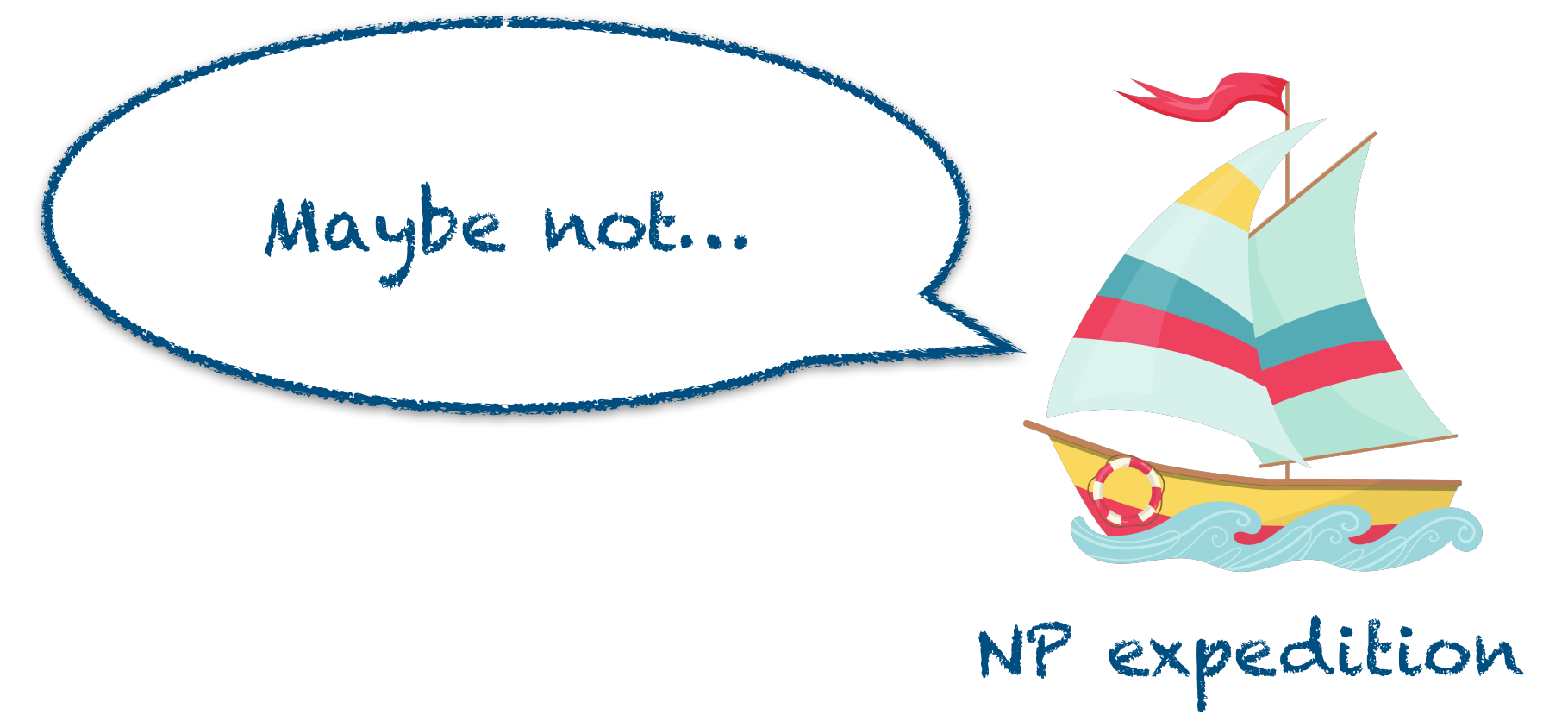
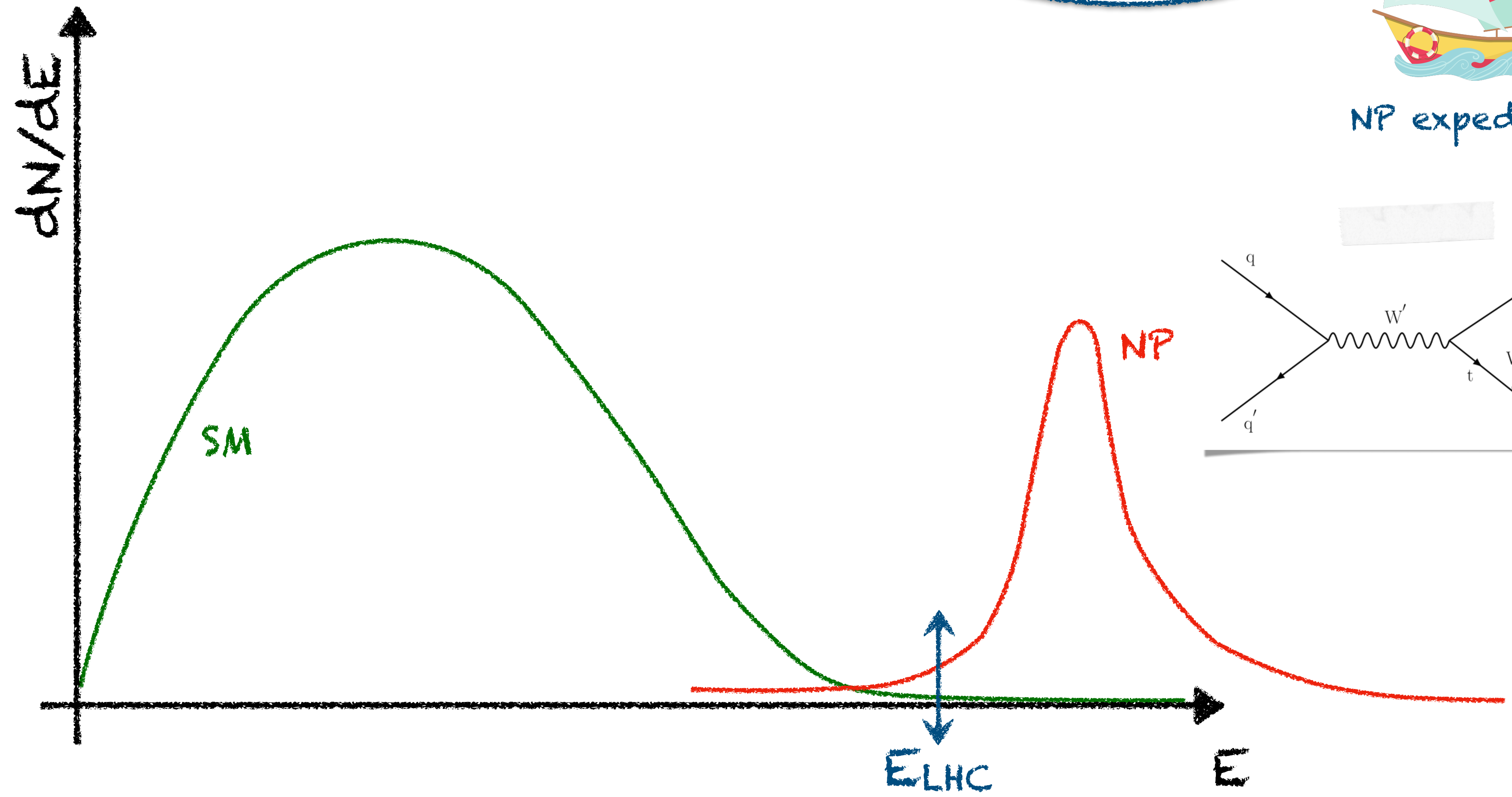


NP expedition



What if NP is out of reach?

Let's boost the peak...



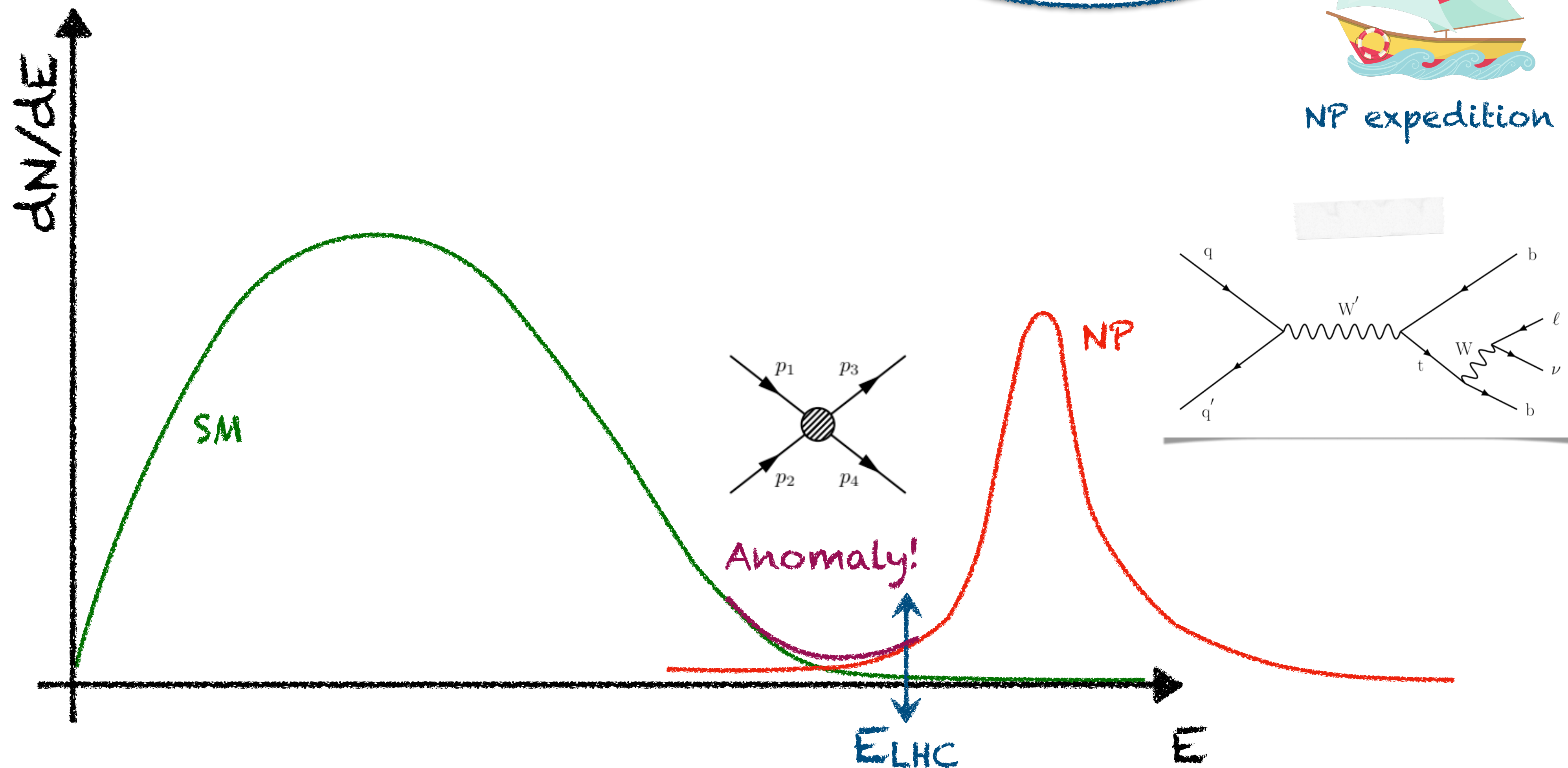
What if NP is out of reach?

...still detectable?

Some wrinkles
in the ocean!

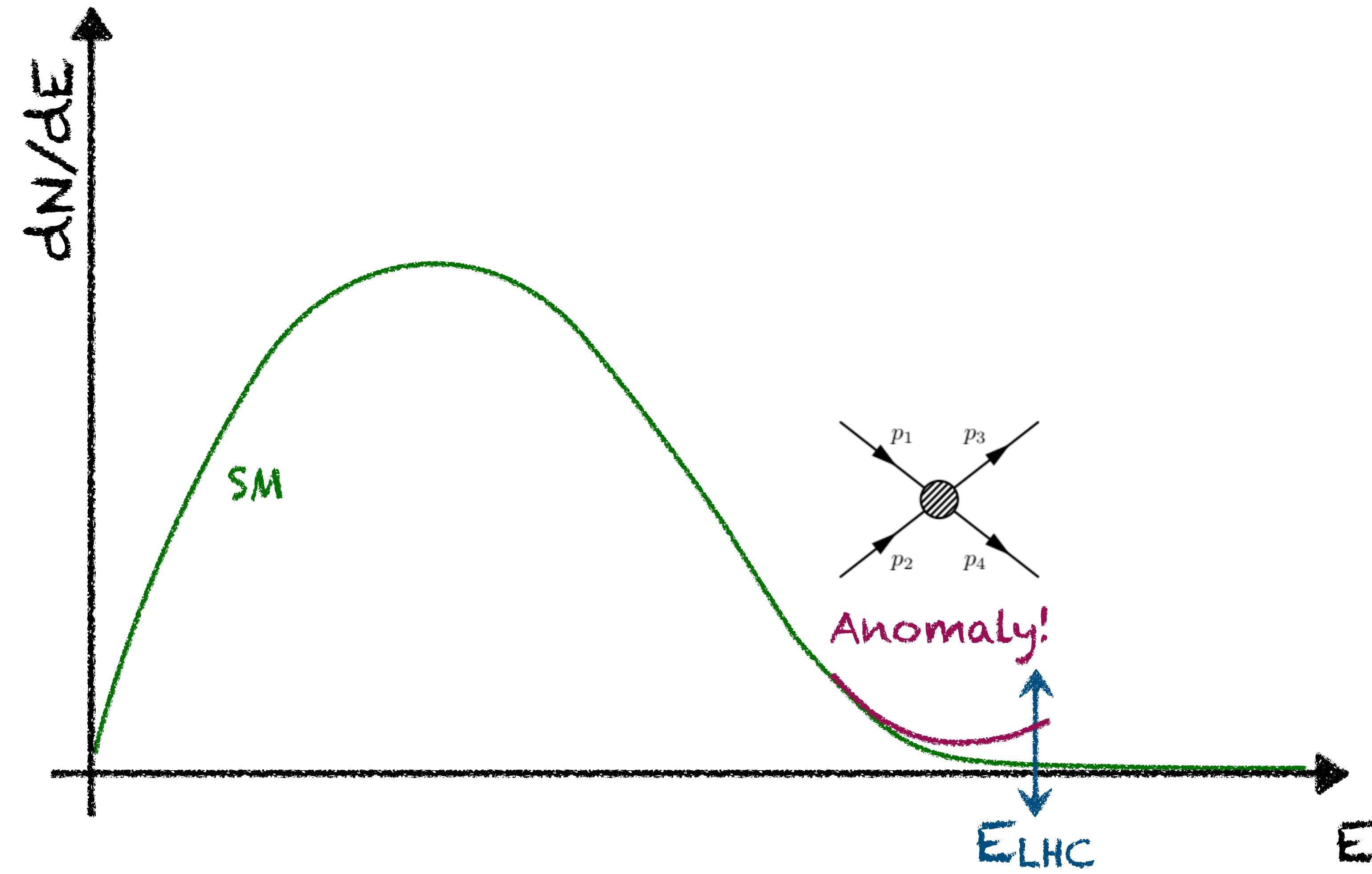


NP expedition



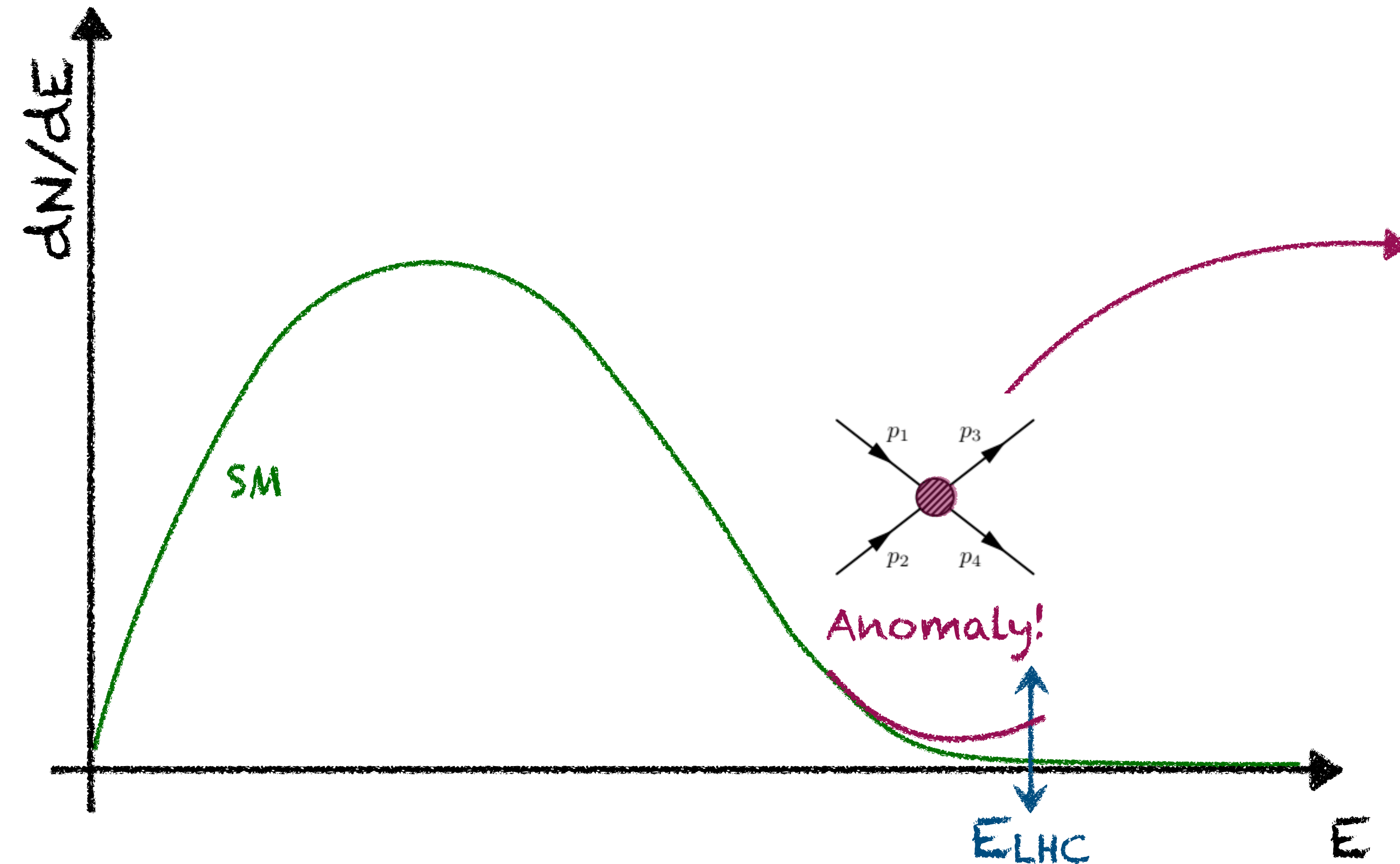
Another route to new phenomena

Chasing down the anomalies



Another route to new phenomena

Chasing down the anomalies



How to model potential anomalies

$$\mathcal{N}_{\text{tot}} = \mathcal{N}_{\text{SM}} + \mathcal{N}_{\text{anomalies}} \propto \mathcal{L}_{\text{eff}}$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_k \boxed{C_k \mathcal{O}^{(k)}}$$

QFT operator affecting interactions

A guide for the EFT operators

The SMEFT bottom-up approach

SM EFT Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_k \frac{c_k^{(D)} \mathcal{O}_k^{(D)}}{\Lambda^{D-4}}$$

c_k Wilson coefficient

A guide for the EFT operators

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- Use only SM fields and symmetries to build $\mathcal{O}_k^{(D)}$
- Classify operators according to mass dimensionality D
- Introduce an NP energy scale Λ

D odd $\longrightarrow$ Breaks lepton flavor universality

D even $\longrightarrow$ Leading terms in SMEFT
dim-6, dim-8

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dim-6, dim-8

Ultimate goal
Match EFT results
to NP models



NP expedition

From $\mathcal{L}$ to observables

$$\sigma \propto$$

$$\sigma \propto \left| \begin{array}{c} \text{SM} \\ + \\ \text{EFT} \end{array} \right|^2$$

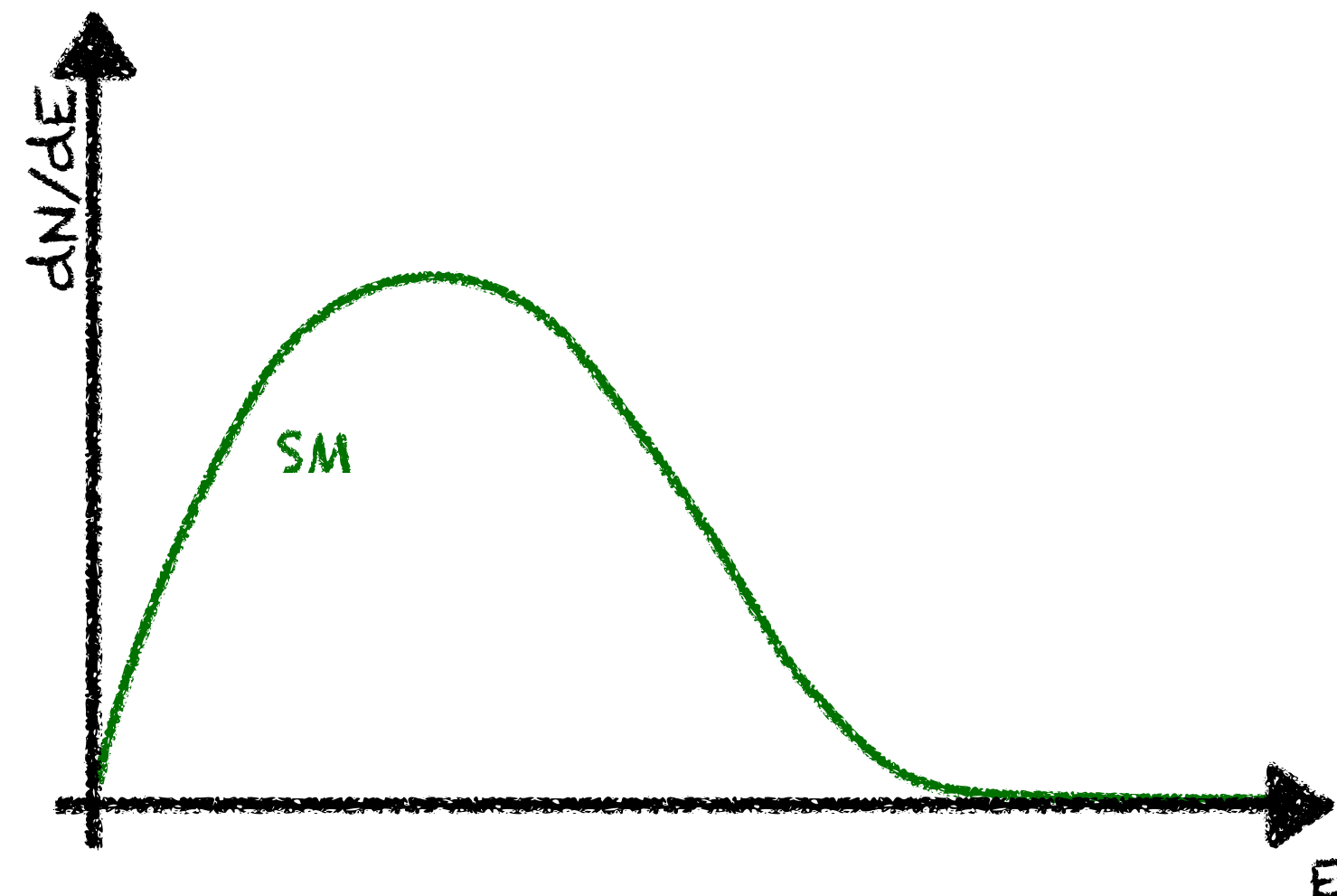


From $\mathcal{L}$ to observables

$$\sigma \propto |\mathcal{A}_{\text{SM}}|^2$$

SM

$$\sigma \propto \left| \begin{array}{c} \text{SM} \\ + \\ \text{EFT} \end{array} \right|^2 \propto \boxed{\text{SM} \times \text{SM}}$$

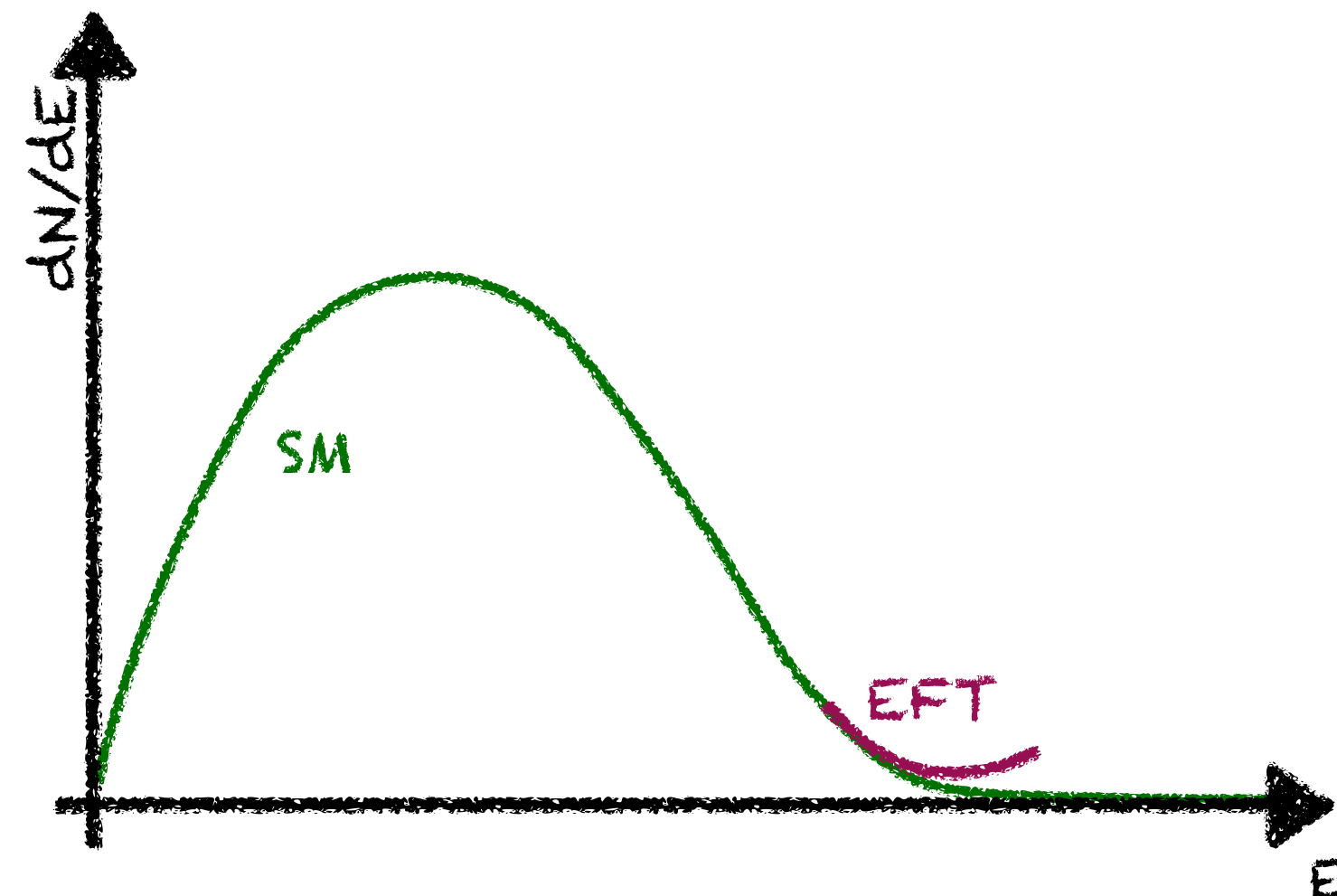


From $\mathcal{L}$ to observables

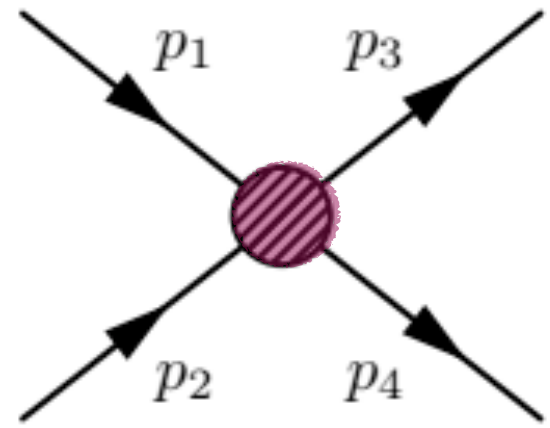
$$\sigma \propto \boxed{|\mathcal{A}_{\text{SM}}|^2}_{\text{SM}} + \boxed{\sum_k \frac{c_k}{\Lambda^{D_k-4}} 2\text{Re}\left(\mathcal{A}_{\text{SM}}^\dagger \mathcal{A}_{\text{EFT}}^{(k)}\right)}_{\text{SM-EFT Interference}} + \boxed{\sum_{i \neq j} \frac{c_i}{\Lambda^{D_i-4}} \frac{c_j}{\Lambda^{D_j-4}} 2\text{Re}\left(\mathcal{A}_{\text{EFT}}^{(i)\dagger} \mathcal{A}_{\text{EFT}}^{(j)}\right)}_{\text{Pure EFT terms}}$$

$$\sigma \propto \left| \begin{array}{c} \text{SM} \\ \text{EFT} \end{array} \right|^2 \propto \boxed{\text{SM} \times \text{SM}} + \boxed{\text{SM} \times \text{EFT}} + \boxed{\text{EFT} \times \text{EFT}}$$

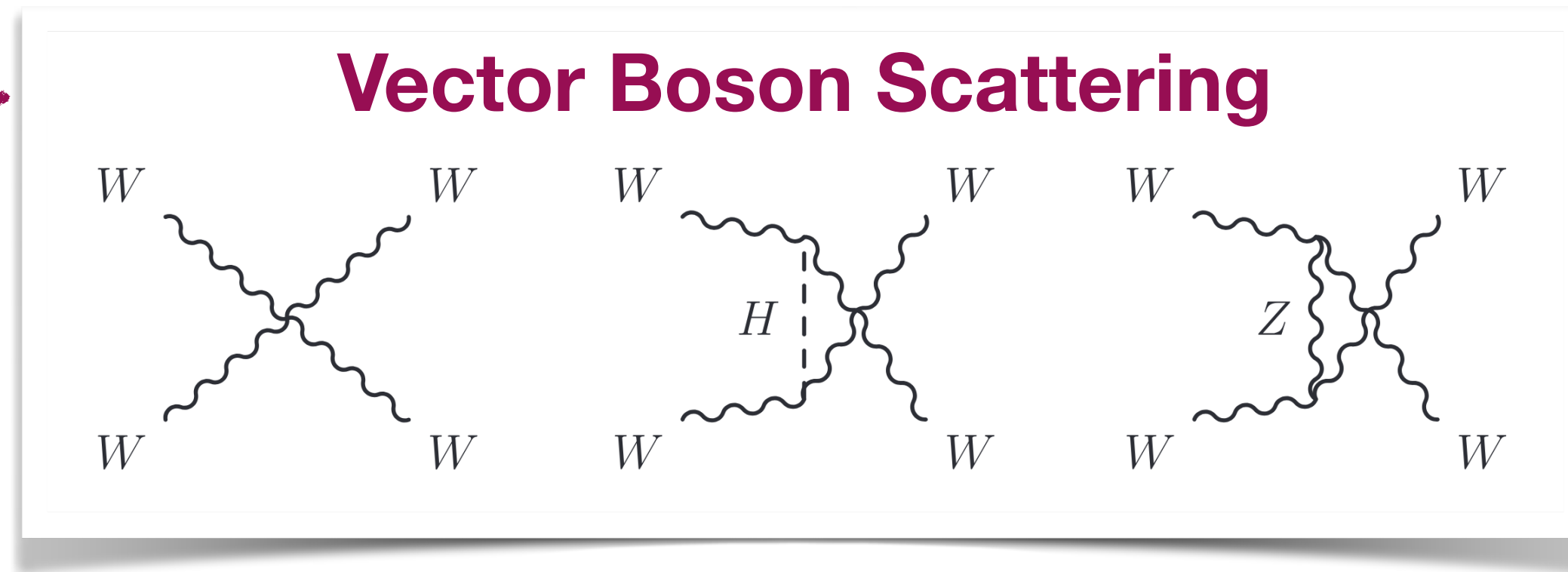
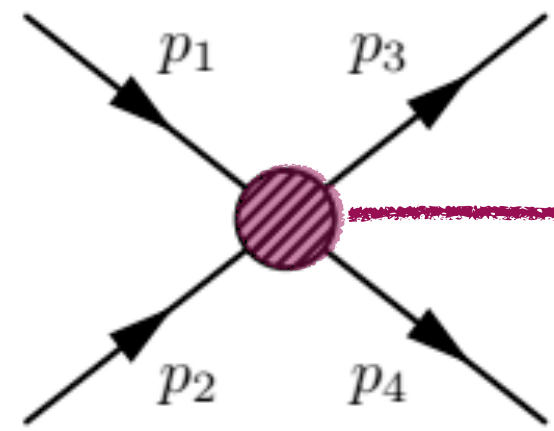
EFT profile
of a distribution



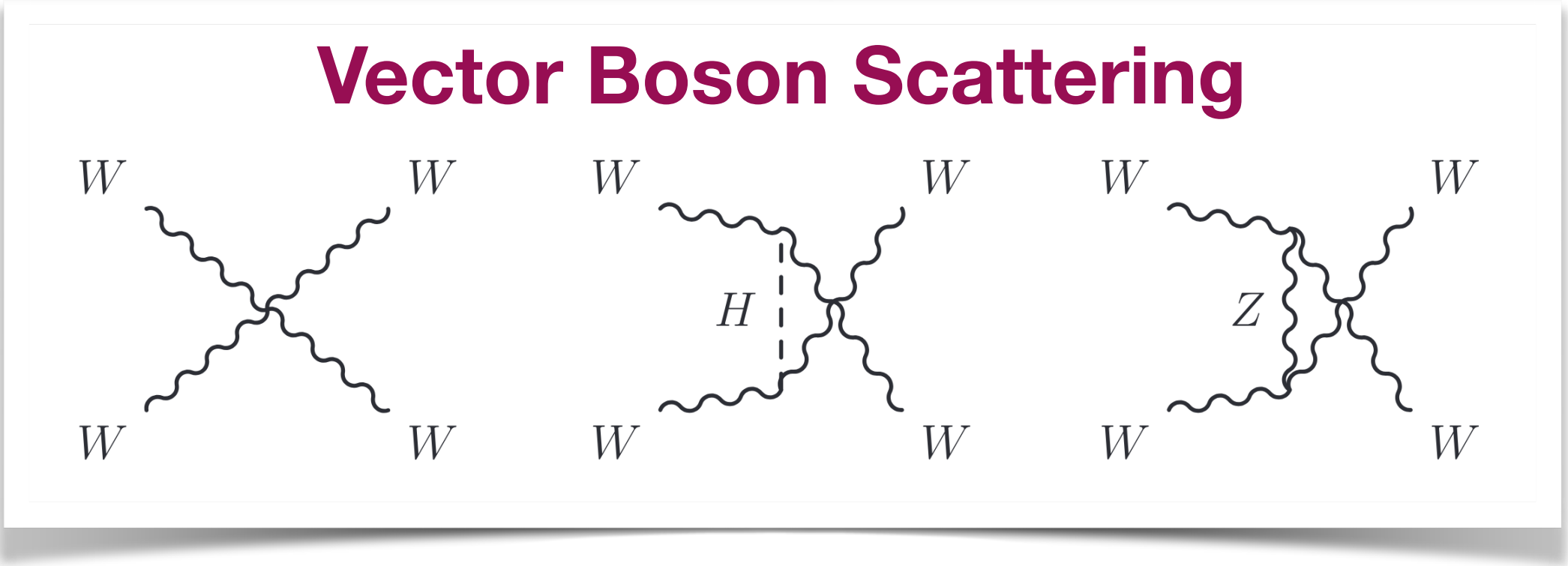
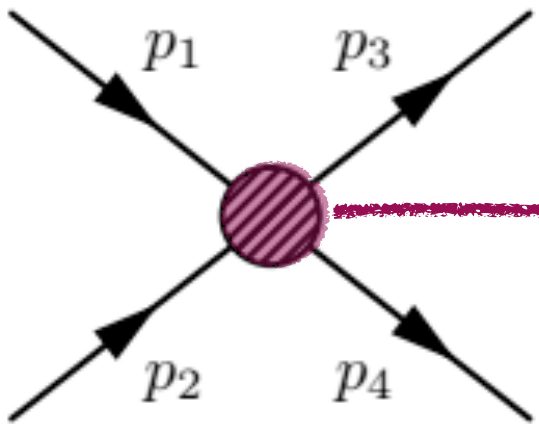
Where to search for EFT anomalies



Where to search for EFT anomalies



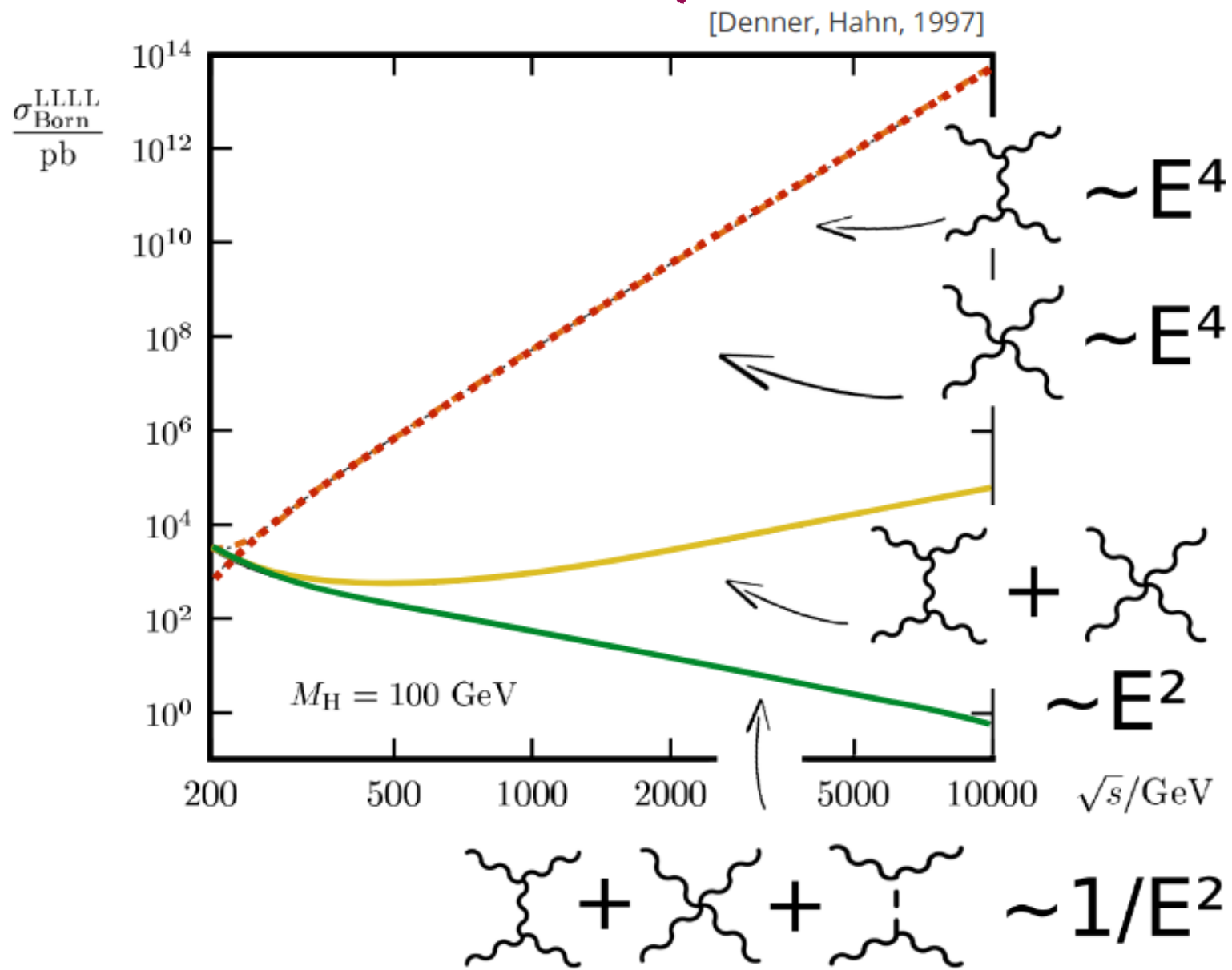
Where to search for EFT anomalies



Sounds like
a plan!



NP expedition



Potential anomalies
of gauge couplings!

How to inject EFT effects?

The goal of the EFT studies

- ▶ Find the most promising directions in the EFT phase space
 - ▶ Find WC values different from SM expectations
 - ▶ Constraints on WCs and Λ energy scale

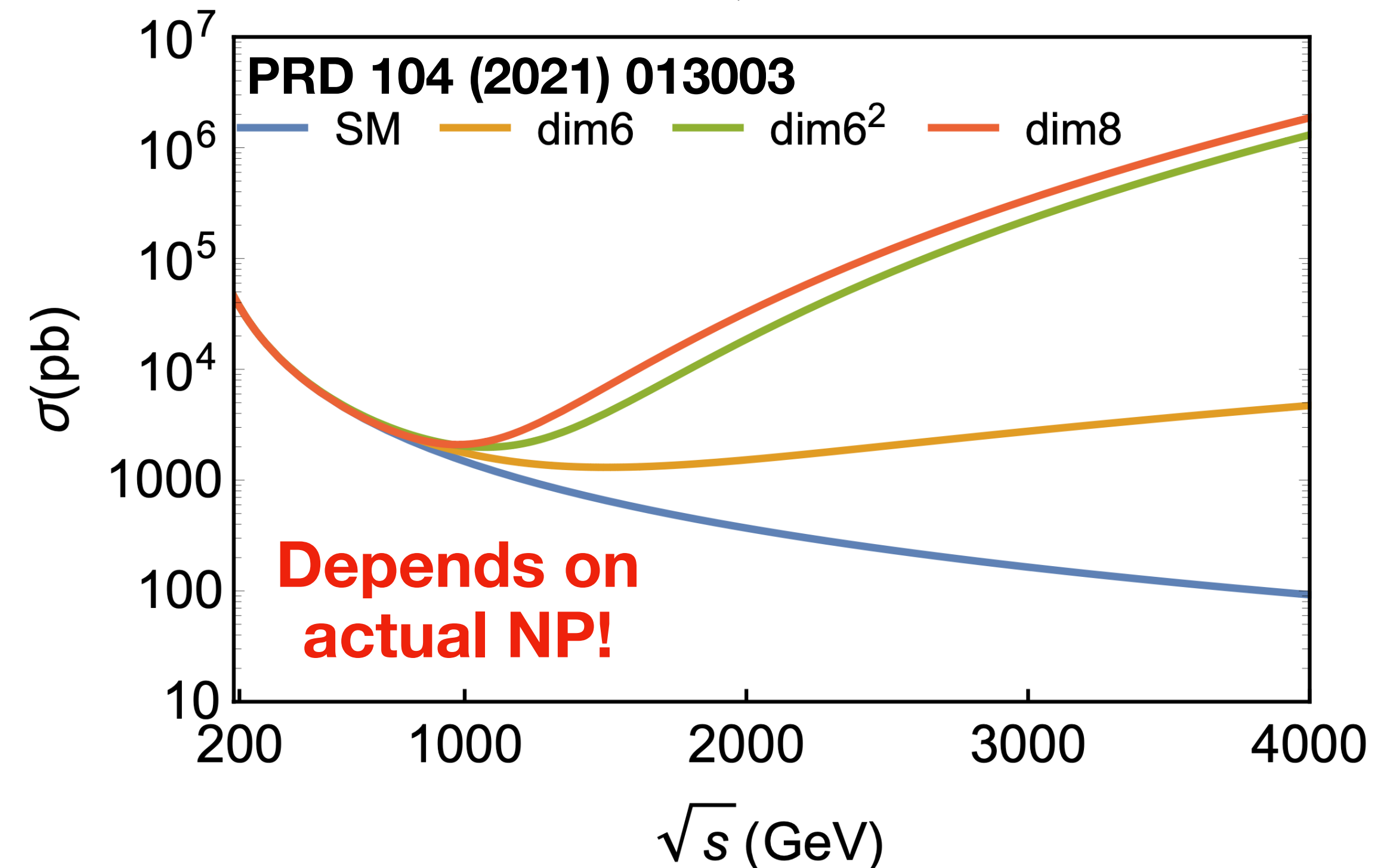
...a priori assumptions?

- ▶ Choose 1 dimension?
 - ▶ Restrict to a manageable # of operators?

How to inject EFT effects?

$$\text{VBS } W_T W_T \longrightarrow W_T W_T$$

$\Lambda=4$ TeV, Remedios



The goal of the EFT studies

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...a priori assumptions?

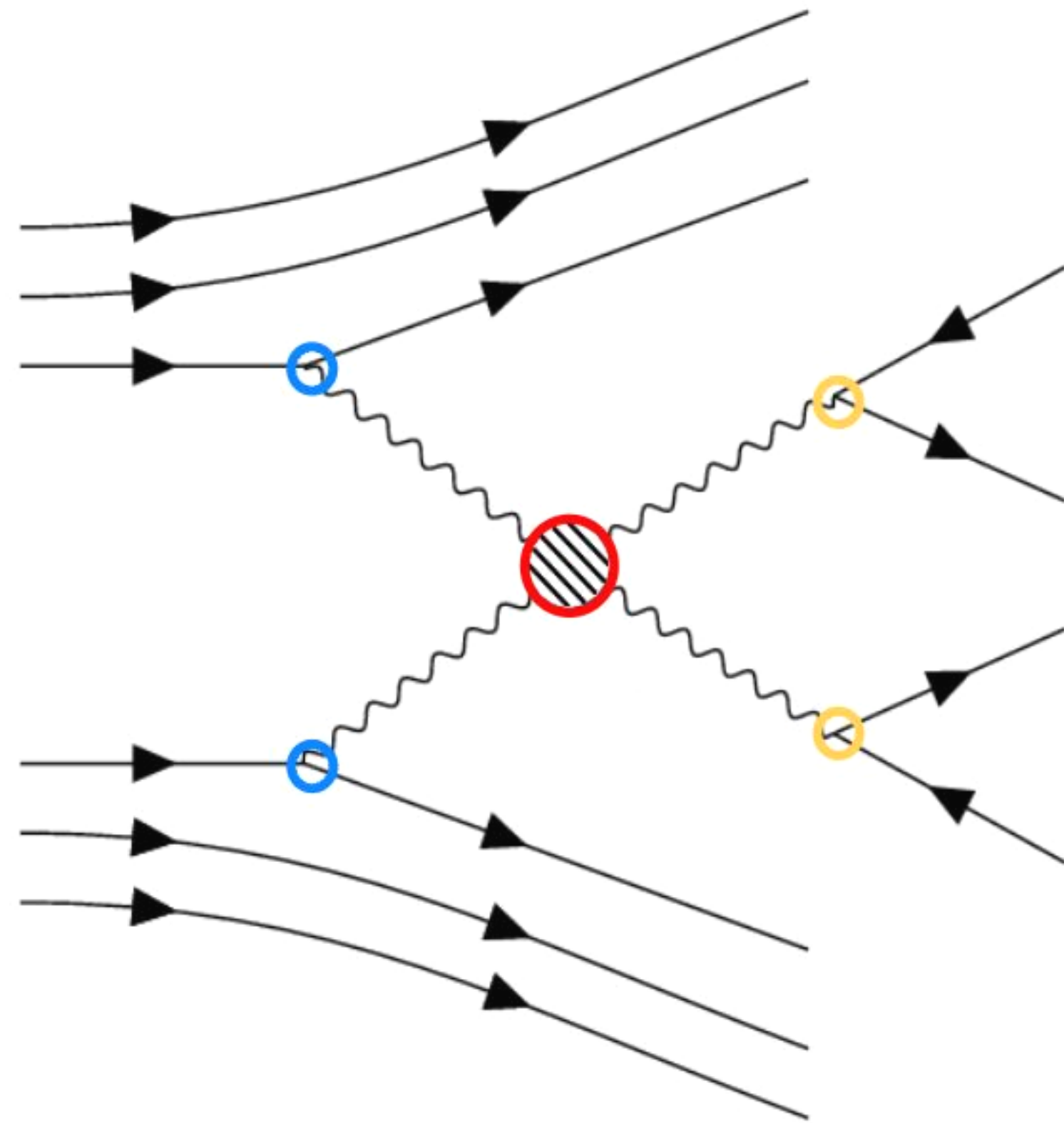
- Choose 1 dimension?
 - Restrict to a manageable # of operators?

Effects of assumptions

- Favoring some NP models
- Unexpected divergences
- Biased constraints on WCs



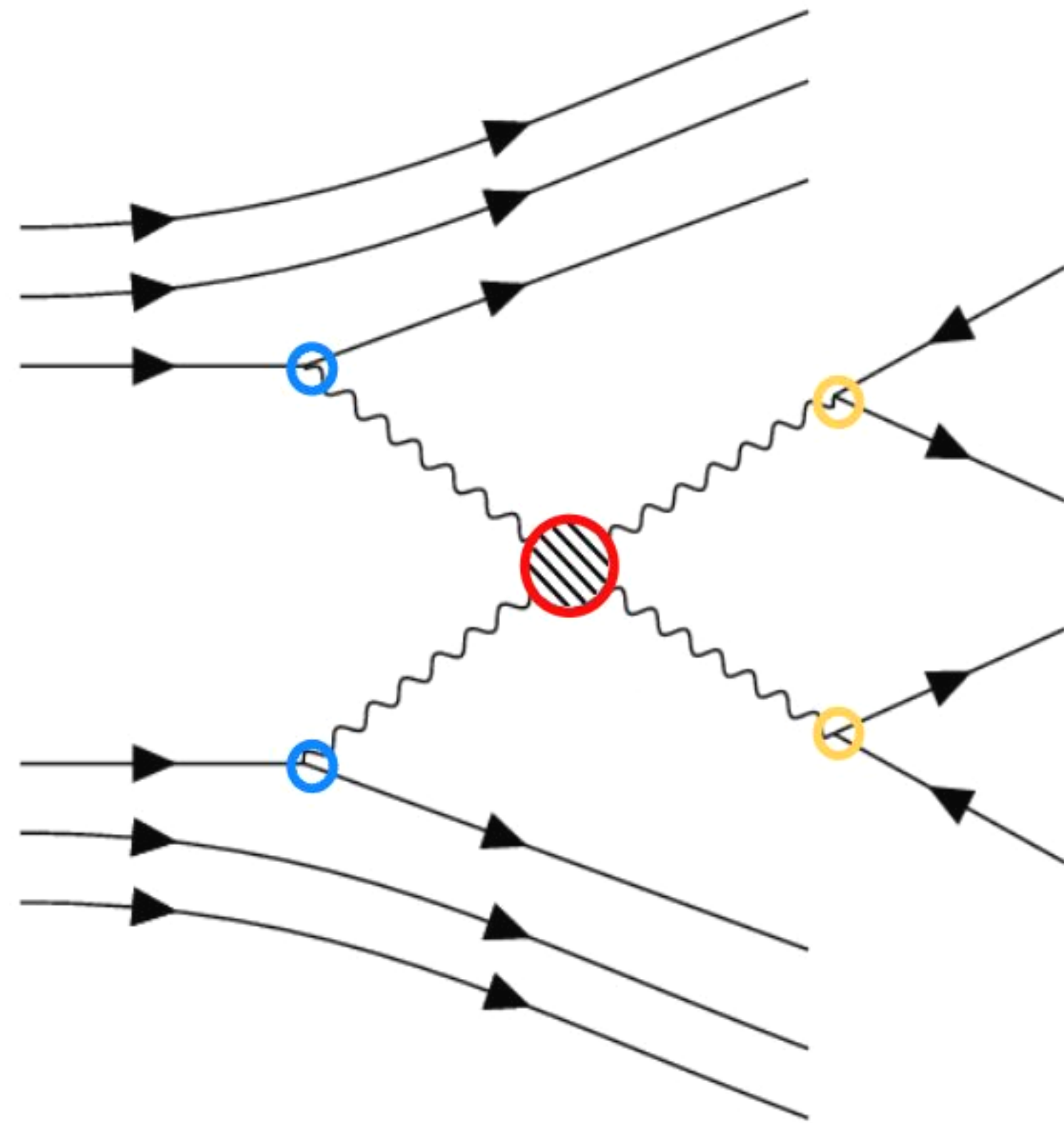
Buckle up for multiple dimensions!



SM EFT Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_k \frac{c_k \mathcal{Q}_k}{\Lambda^2} + \sum_j \frac{f_j \mathcal{O}_j}{\Lambda^4}$$

Buckle up for multiple dimensions!



SM EFT Lagrangian

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$D = 6 \longrightarrow$ SMEFT Warsaw basis $\longrightarrow 15 \mathcal{Q}_k$

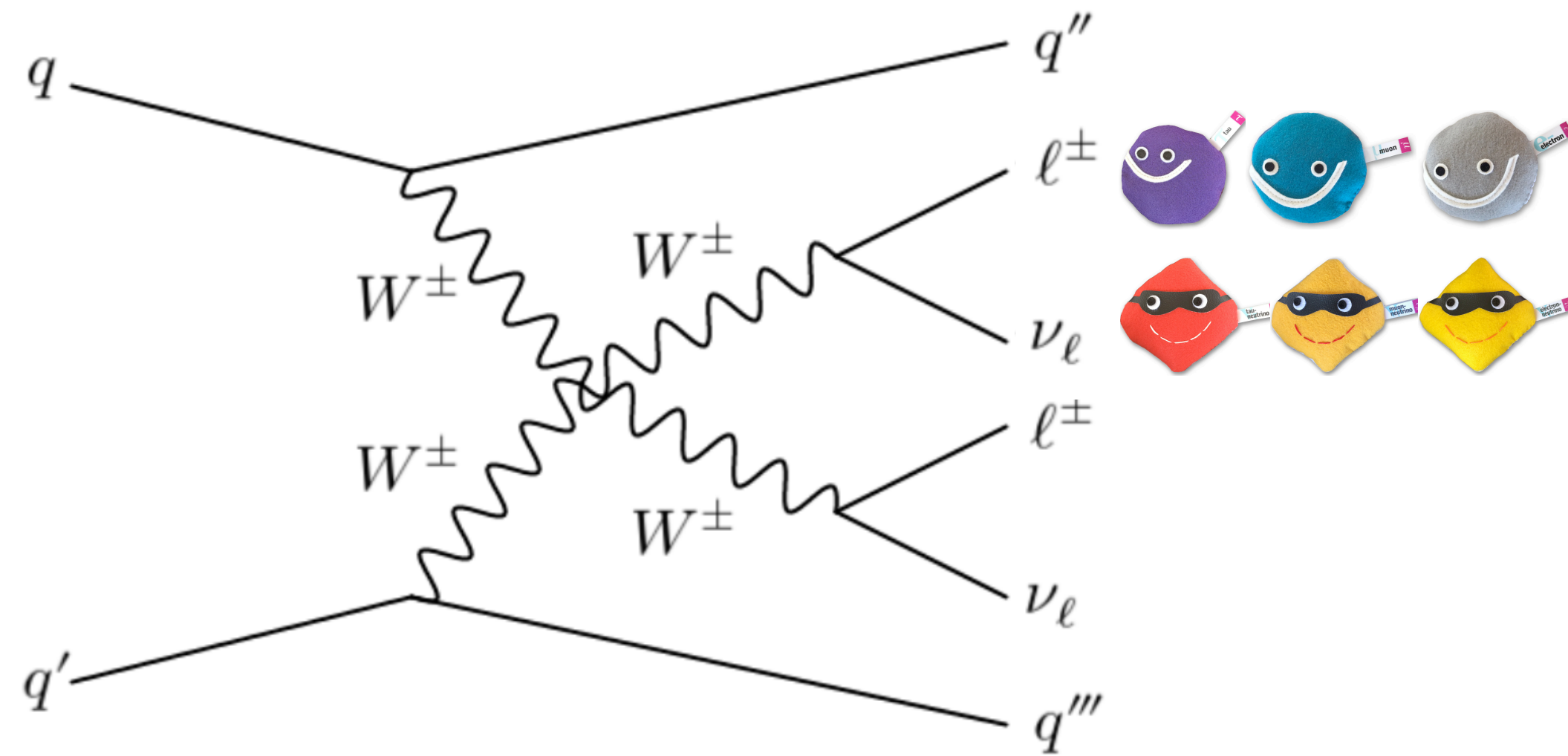
■
■
■

$D = 8 \longrightarrow$ SMEFT Éboli basis $\longrightarrow 9 \mathcal{O}_j$

■

Multiple dimensions with...

arXiv:2410.04210

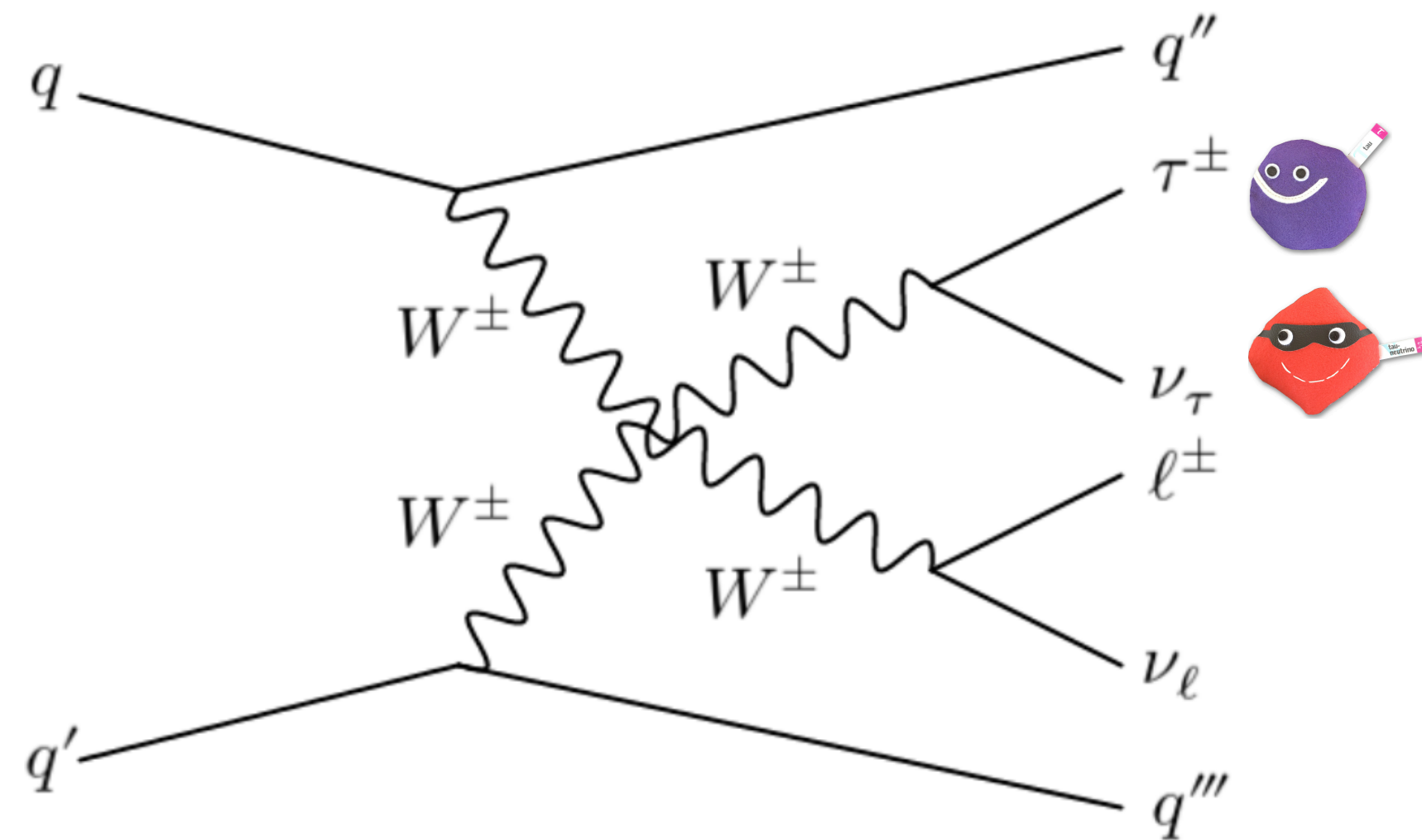


Focus on same-sign WW scattering

► $W \longrightarrow ?$

Multiple dimensions with 3rd-gen!

arXiv:2410.04210



Final states

- $\ell = e, \mu$
- ν_ℓ, ν_τ
- 2 quarks
- hadronic tau

reco lepton

missing energy

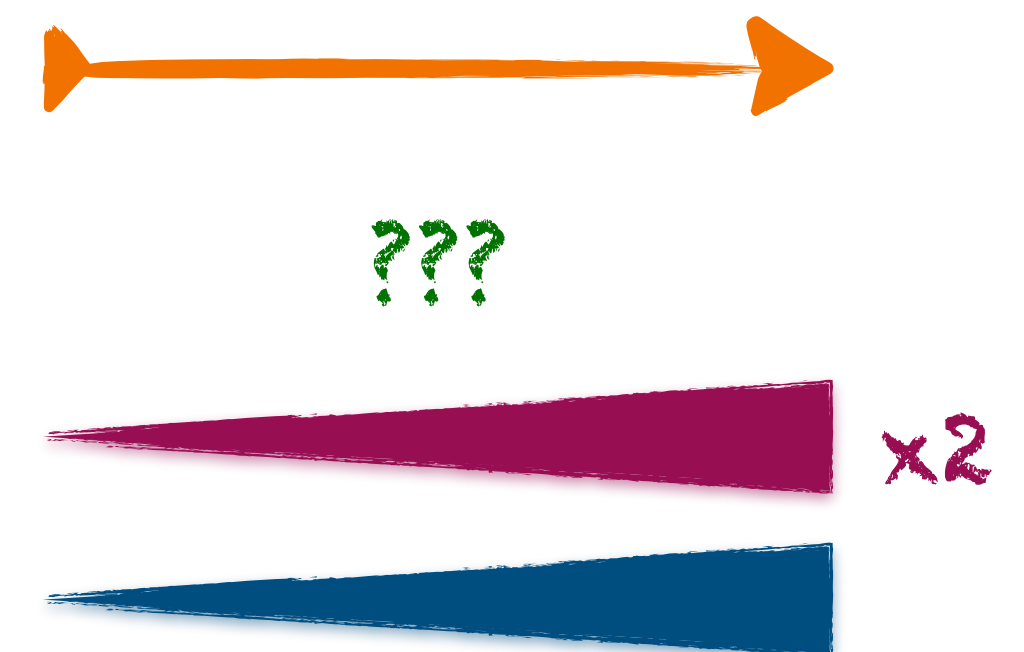
hadronic jets

tau jet

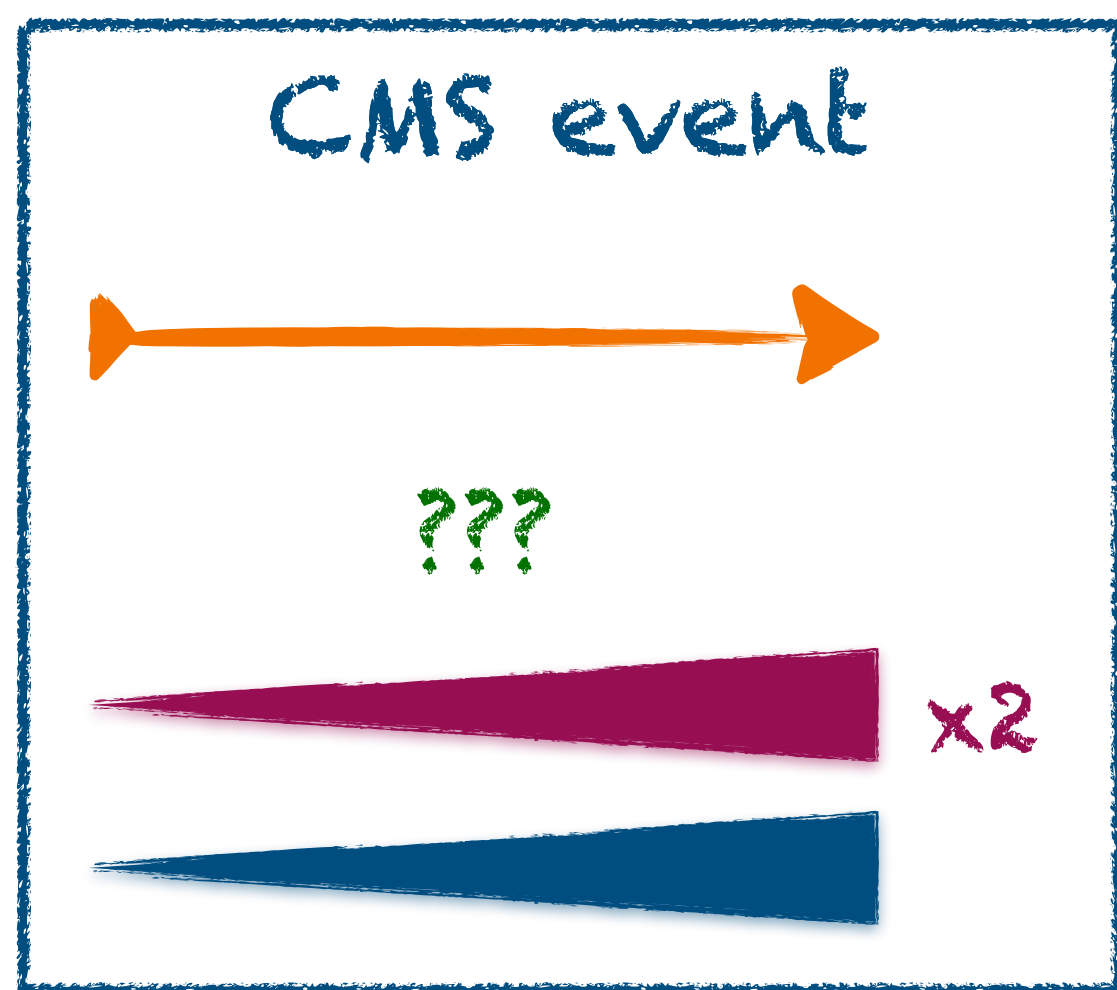
Focus on same-sign WW scattering

- $W \longrightarrow \tau \nu_\tau$ decay
 - Enhance sensitivity to Higgs operator
 - Probe for lepton flavor violation
 - Unobserved SM final state
- SM measurement and **EFT dim-6+dim-8 search**

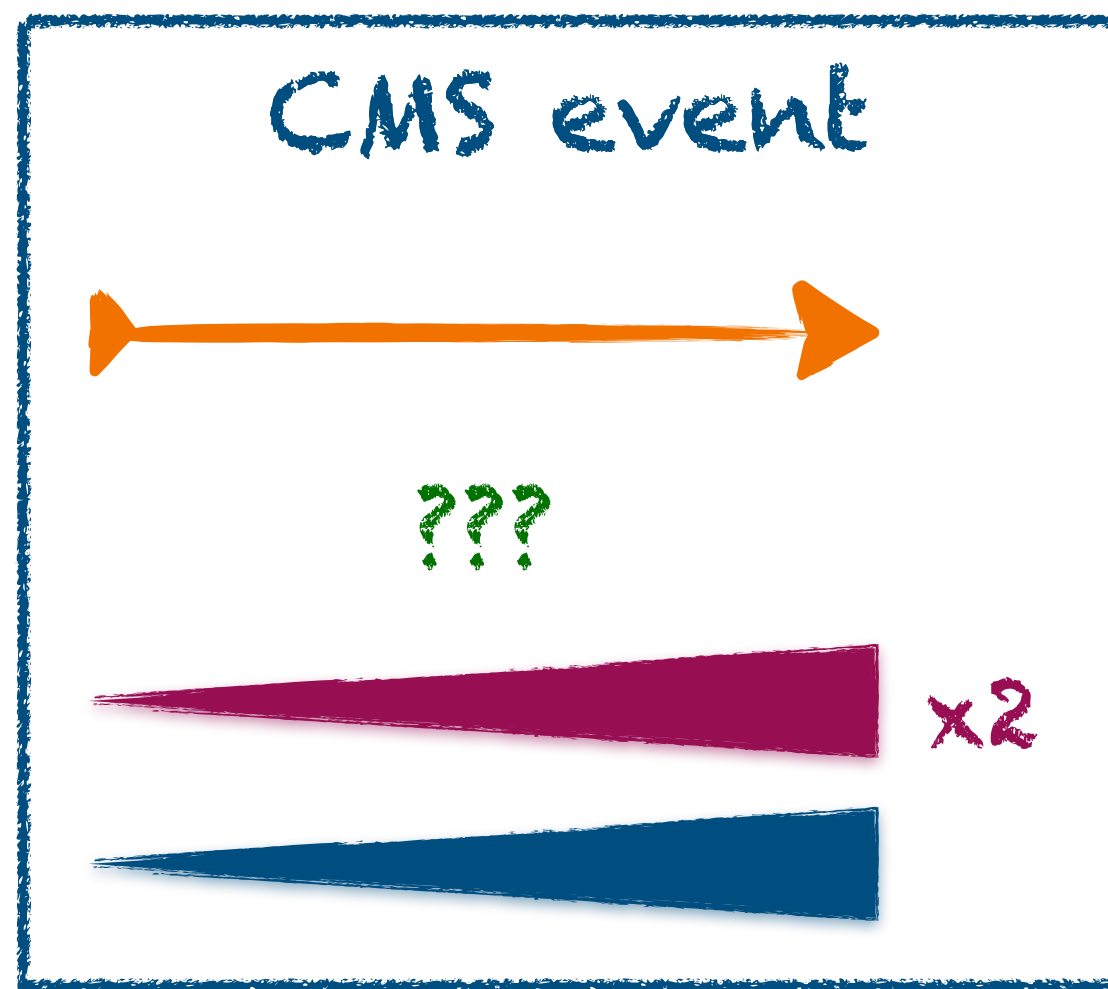
CMS event



Finding out VBS

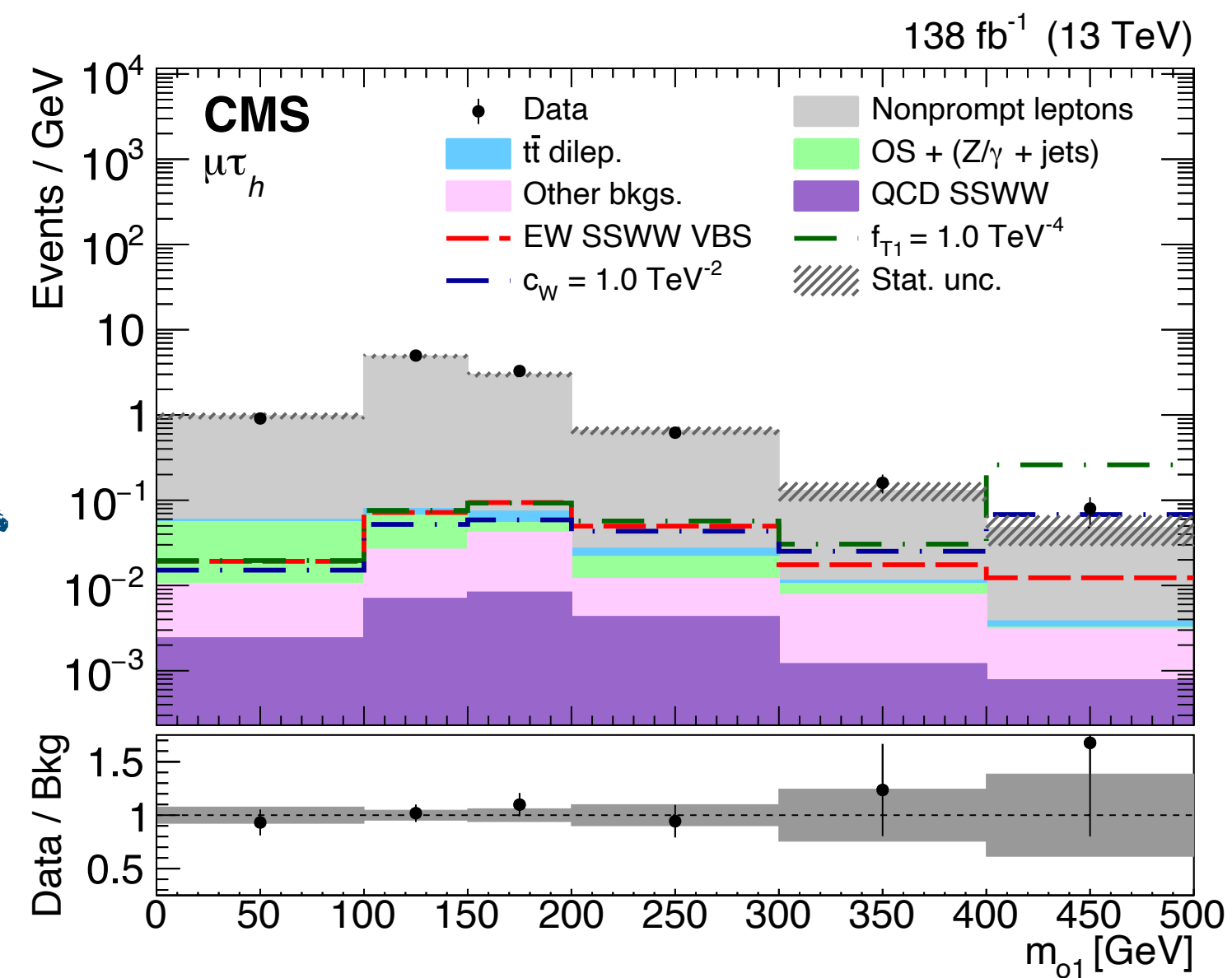
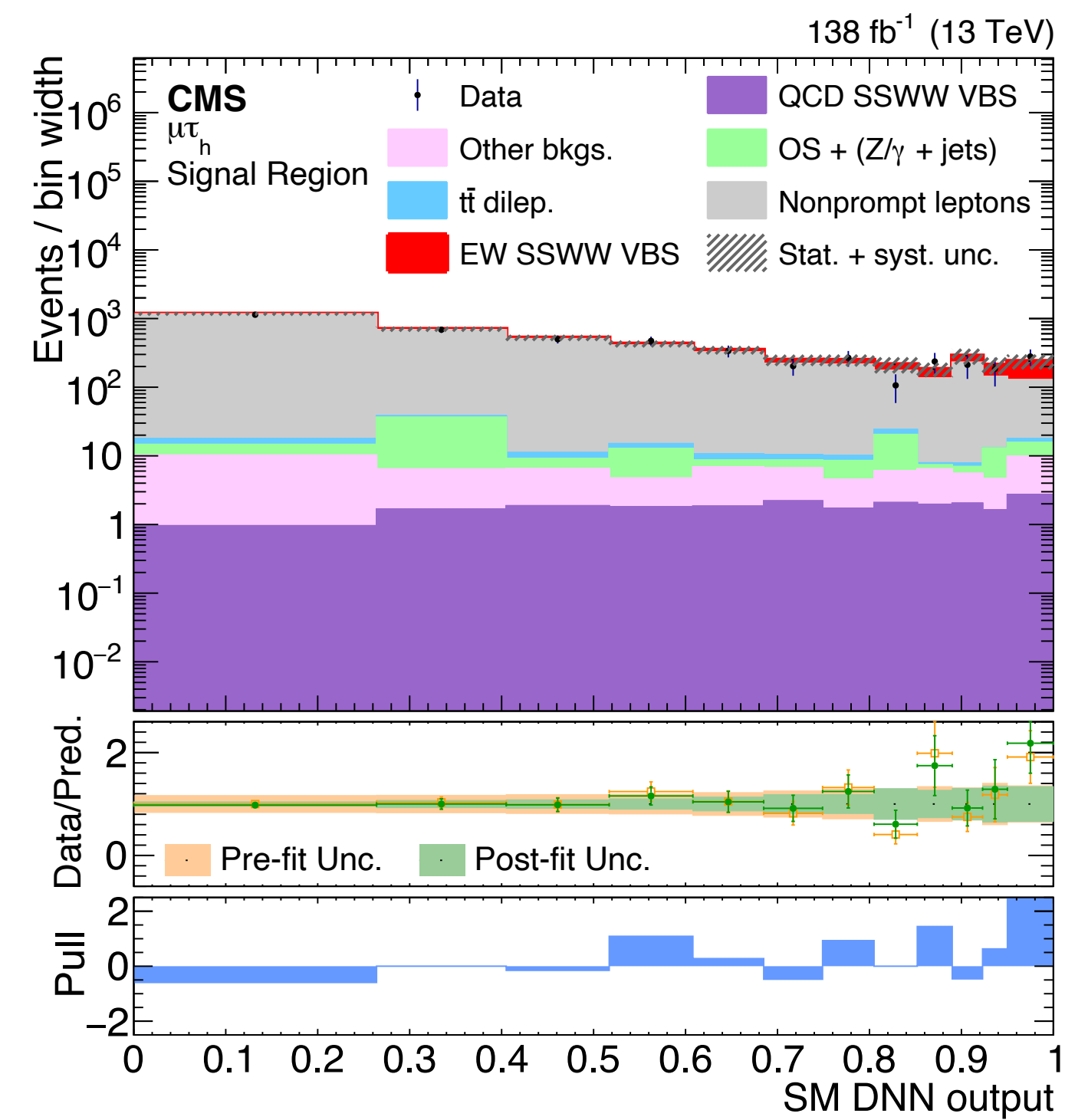


Finding out VBS

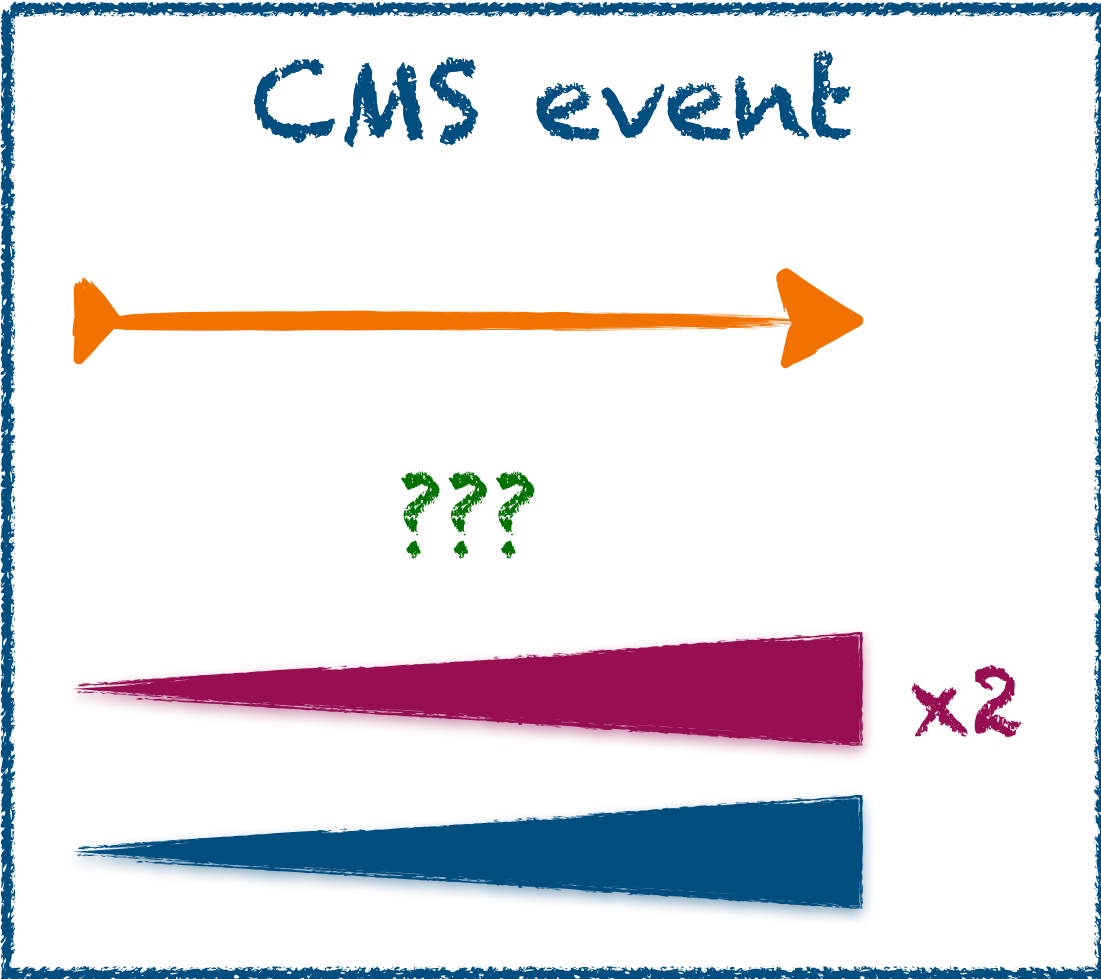


→ SM study

→ EFT search

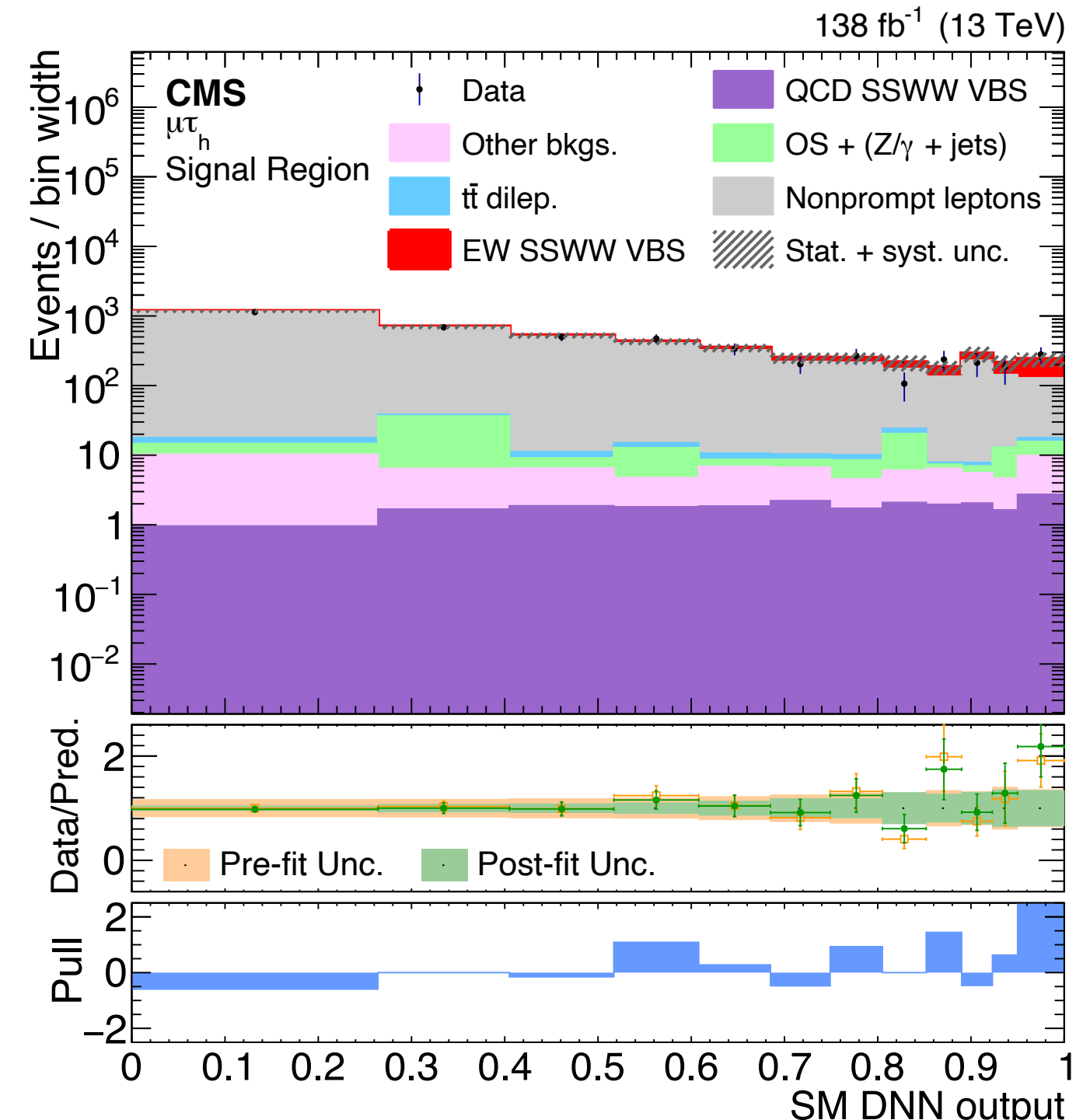


Finding out VBS

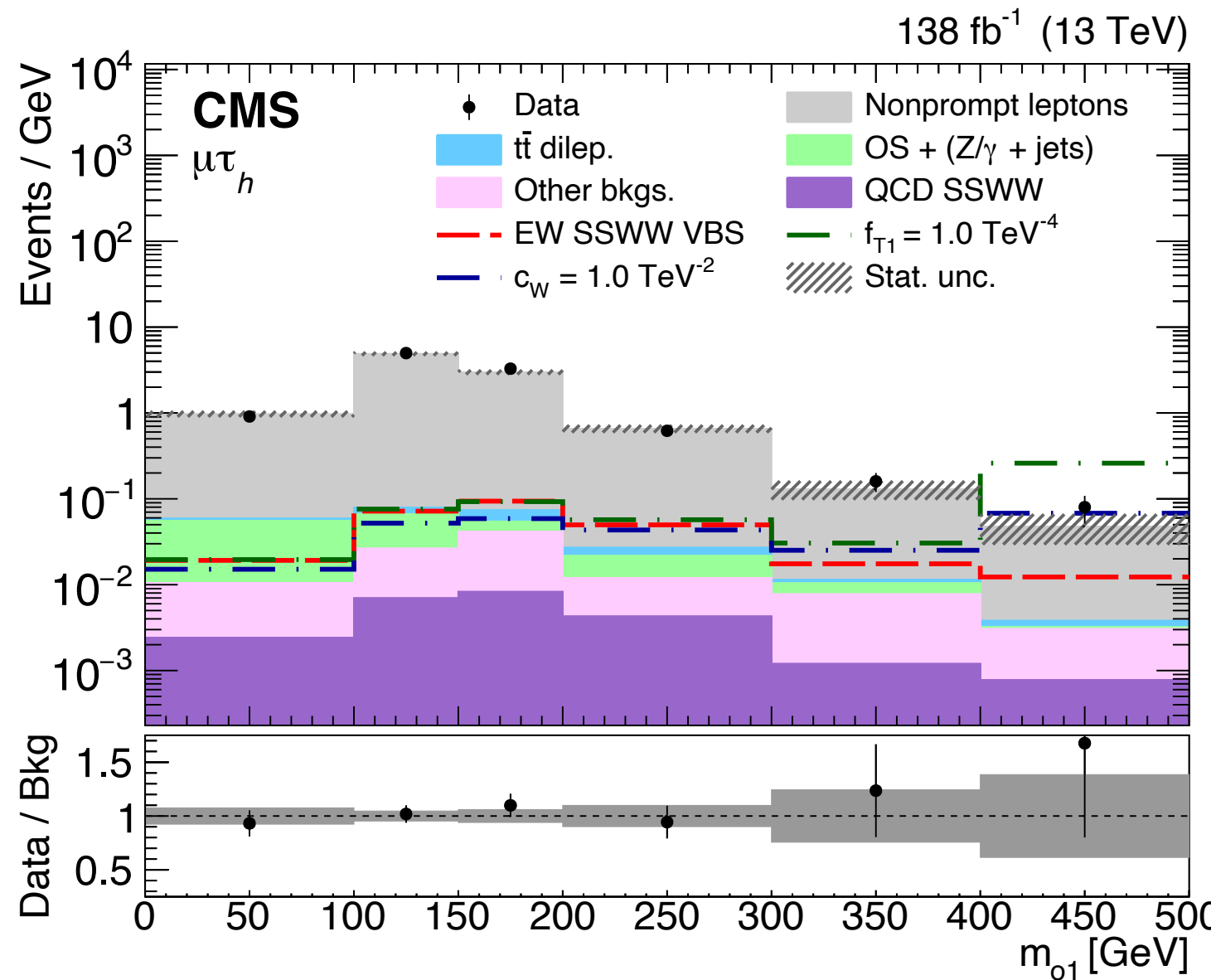


SM study

EFT search



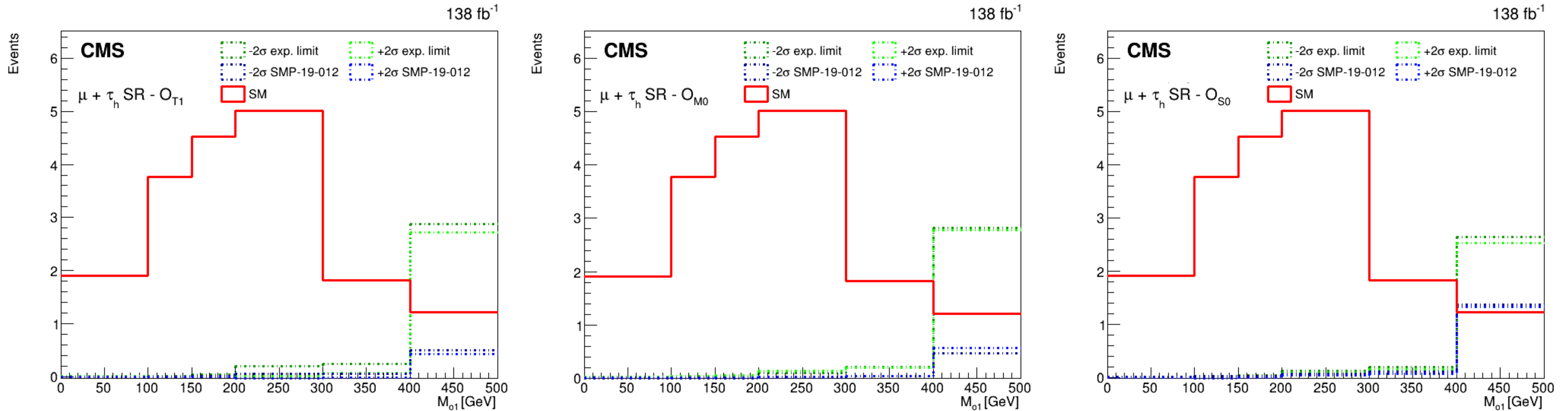
Observed
signal strength
 $\mu = 1.43^{+0.60}_{-0.54} \quad (2.7\sigma)$



Likelihood scans
- 1D scans
dim-6, dim-8
- 2D scans
dim-6 + dim-6,
dim-6 + dim-8

The tau effect on dim-8

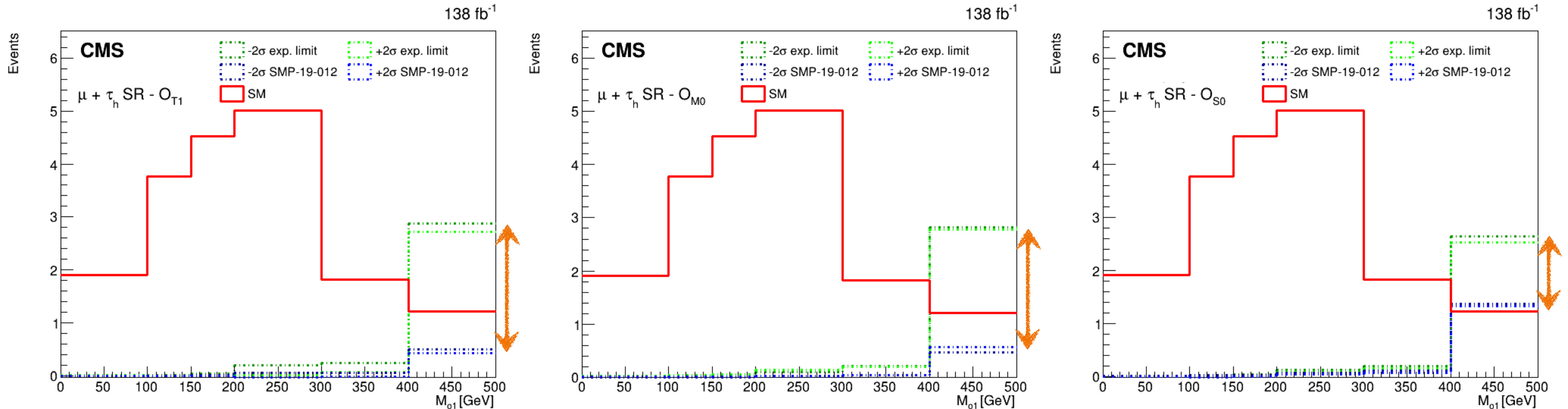
CMS-SMP-19-012: dilepton VBS analysis with only e, μ



$$\mathcal{O}_{T1} = \text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}] \xrightarrow{+1 H} \mathcal{O}_{M0} = \text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times [(D_\beta H)^\dagger D^\beta H] \xrightarrow{+1 H} \mathcal{O}_{S0} = [(D_\mu H)^\dagger D_\nu H] \times [(D^\mu H)^\dagger D^\nu H]$$

The tau effect on dim-8

CMS-SMP-19-012: dilepton VBS analysis with only e, μ

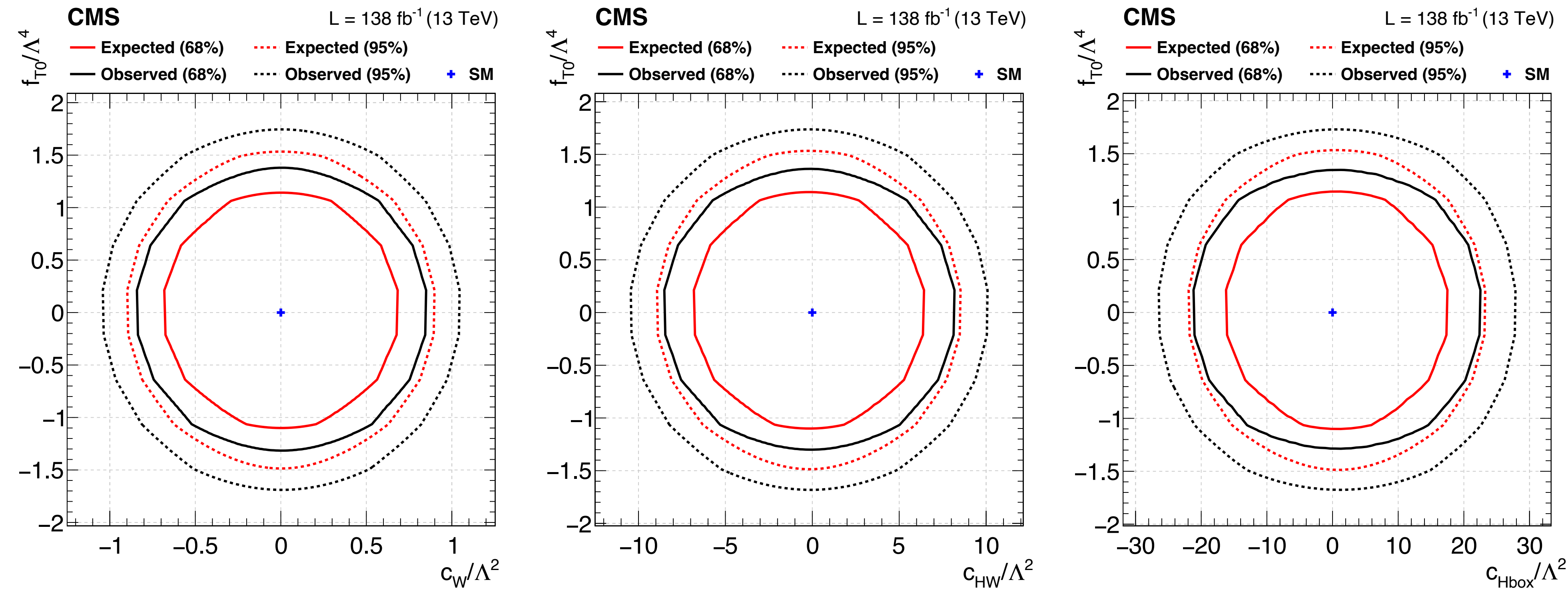


$$\mathcal{O}_{T1} = \text{Tr} \left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right] \xrightarrow{+1 H} \mathcal{O}_{M0} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta H)^\dagger D^\beta H \right] \xrightarrow{+1 H} \mathcal{O}_{S0} = \left[(D_\mu H)^\dagger D_\nu H \right] \times \left[(D^\mu H)^\dagger D^\nu H \right]$$

Adding a tau improves the sensitivity to EFT effects on the Higgs field

Adding up dim-6 and dim-8

First time ever

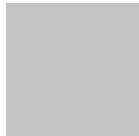


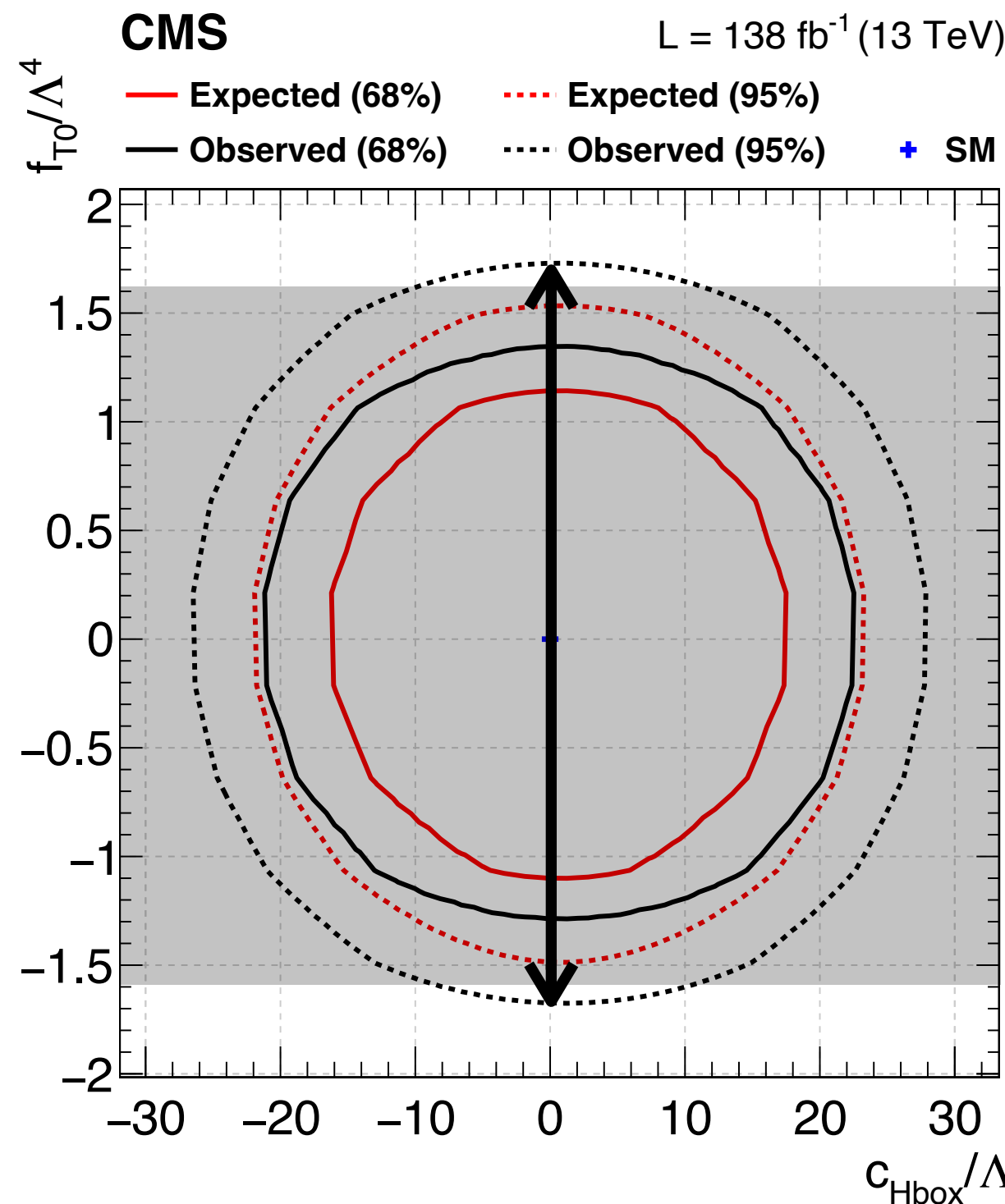
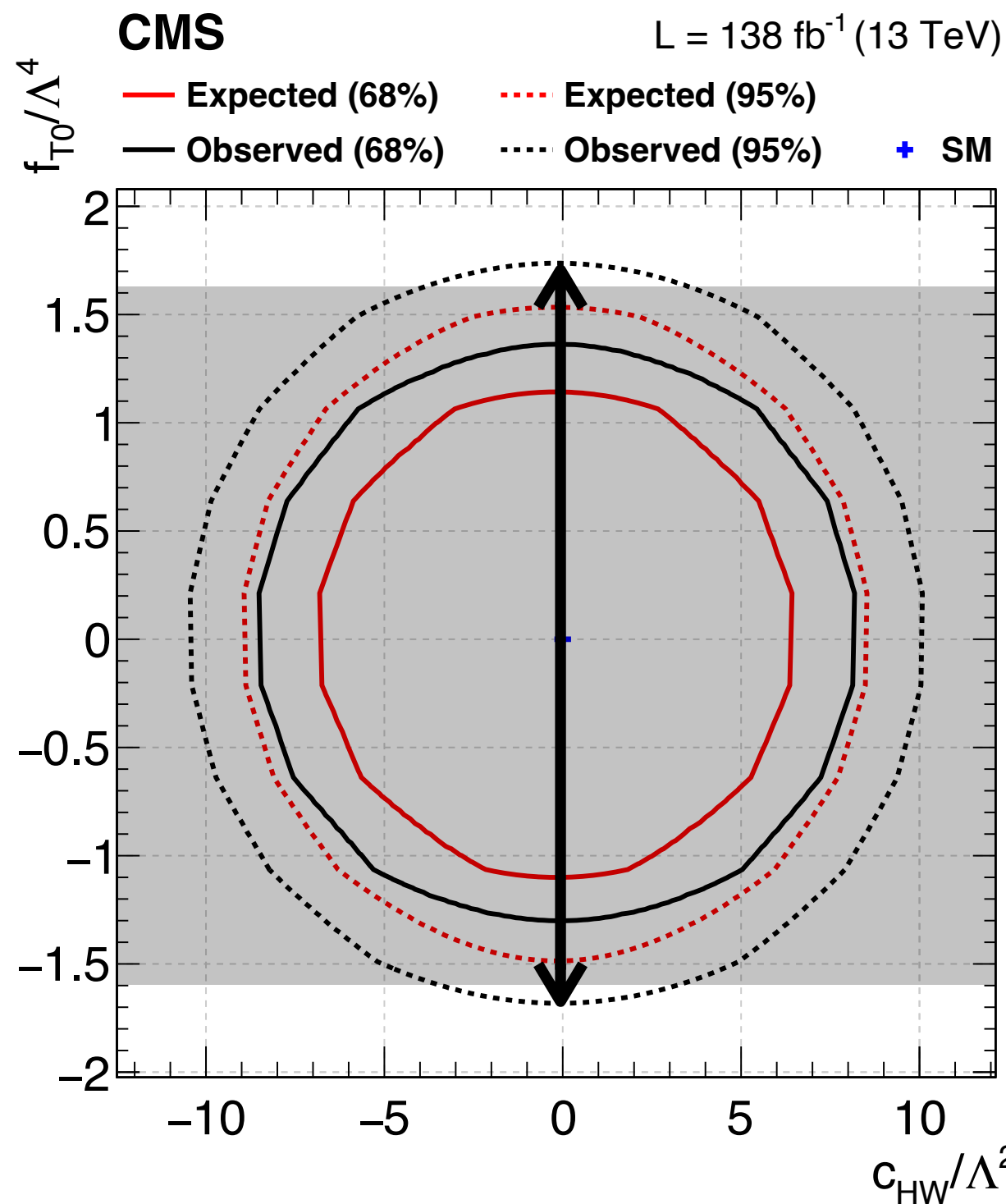
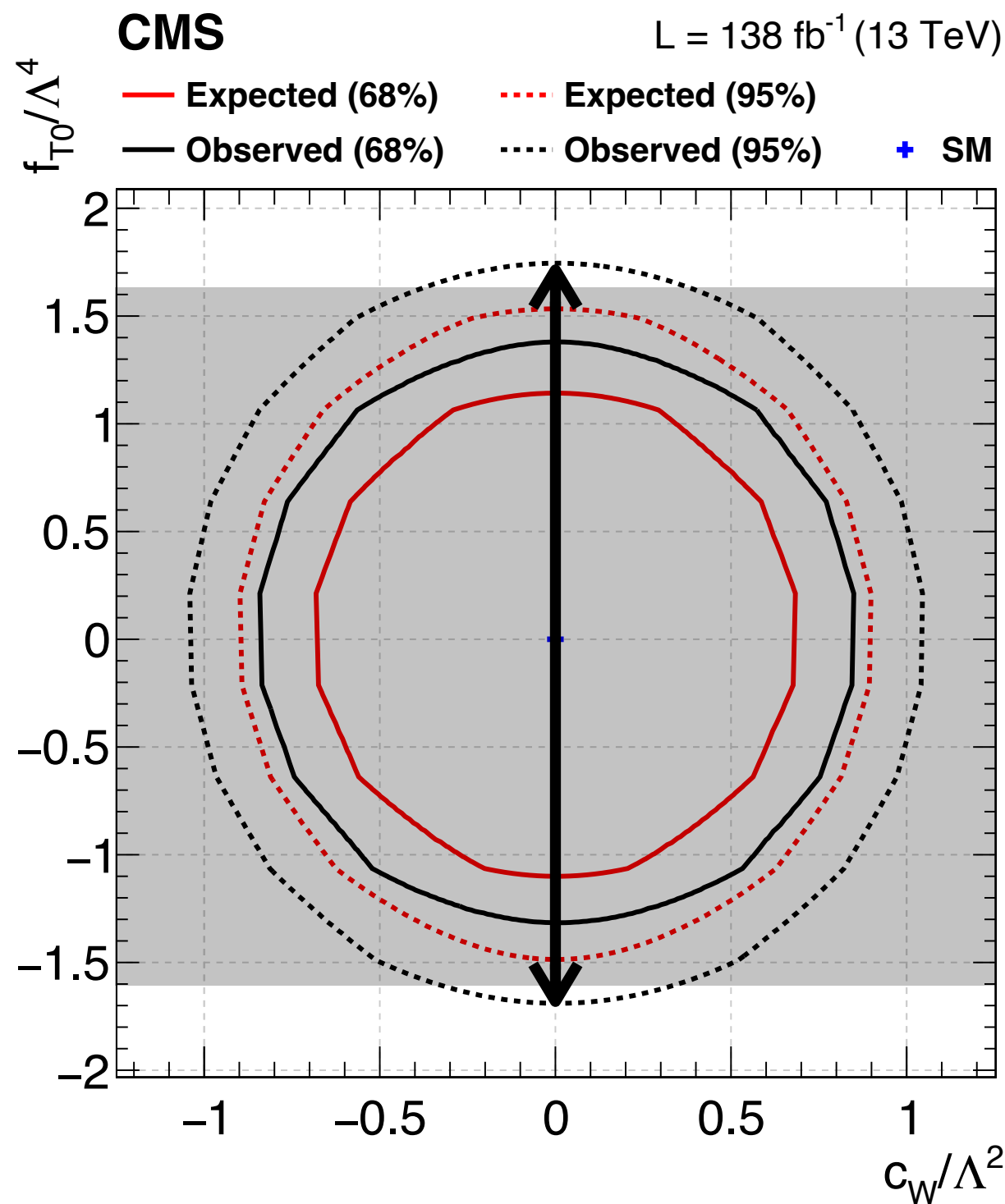
← Increasing dim-6 contribution

Bosonic operators

Adding up dim-6 and dim-8

First time ever

 dim-8 1D 95% CI
 dim-8 2D 95% CI
 when dim-6 = 0

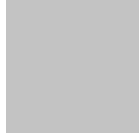



 Increasing dim-6 contribution

Bosonic operators

Adding up dim-6 and dim-8

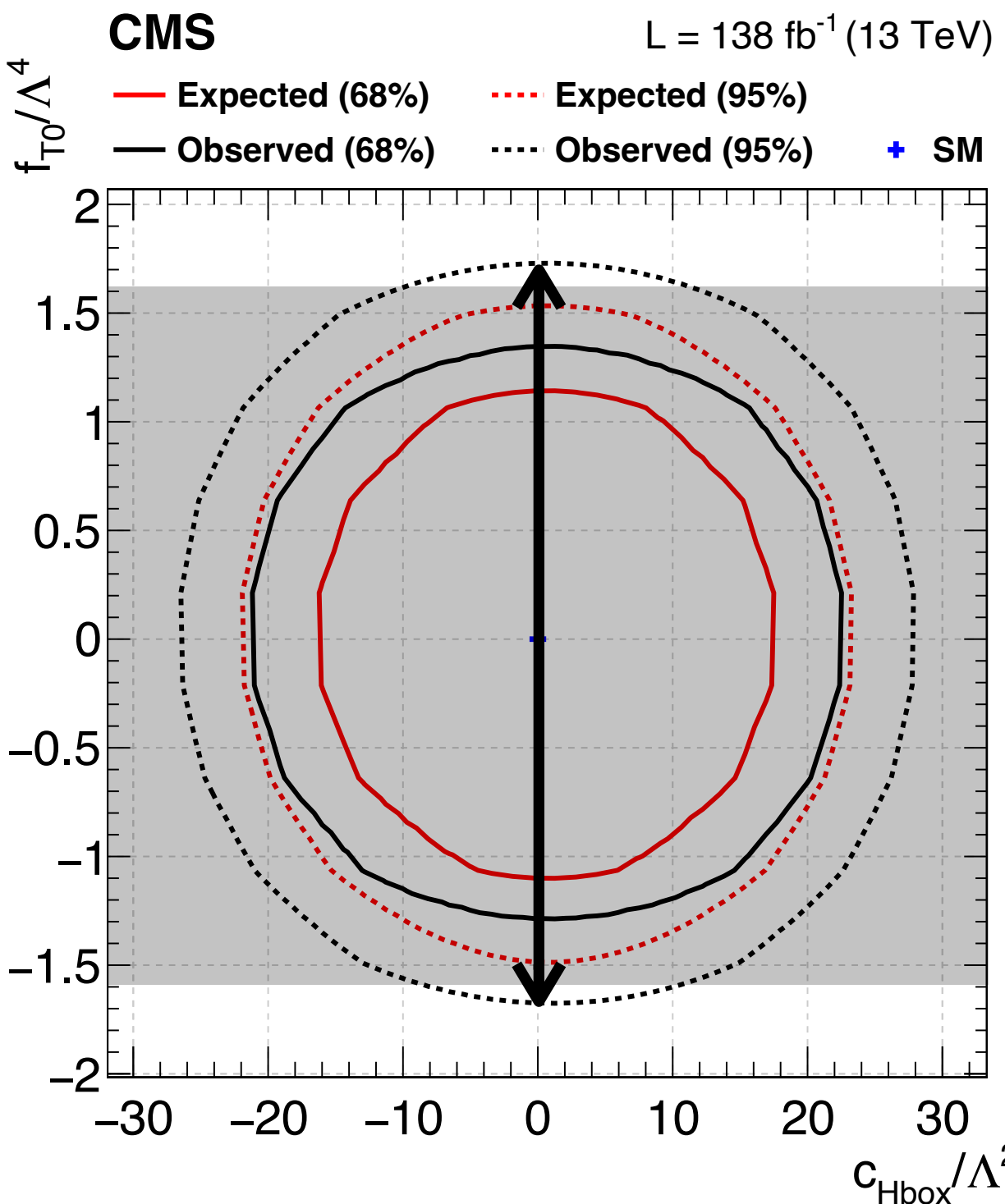
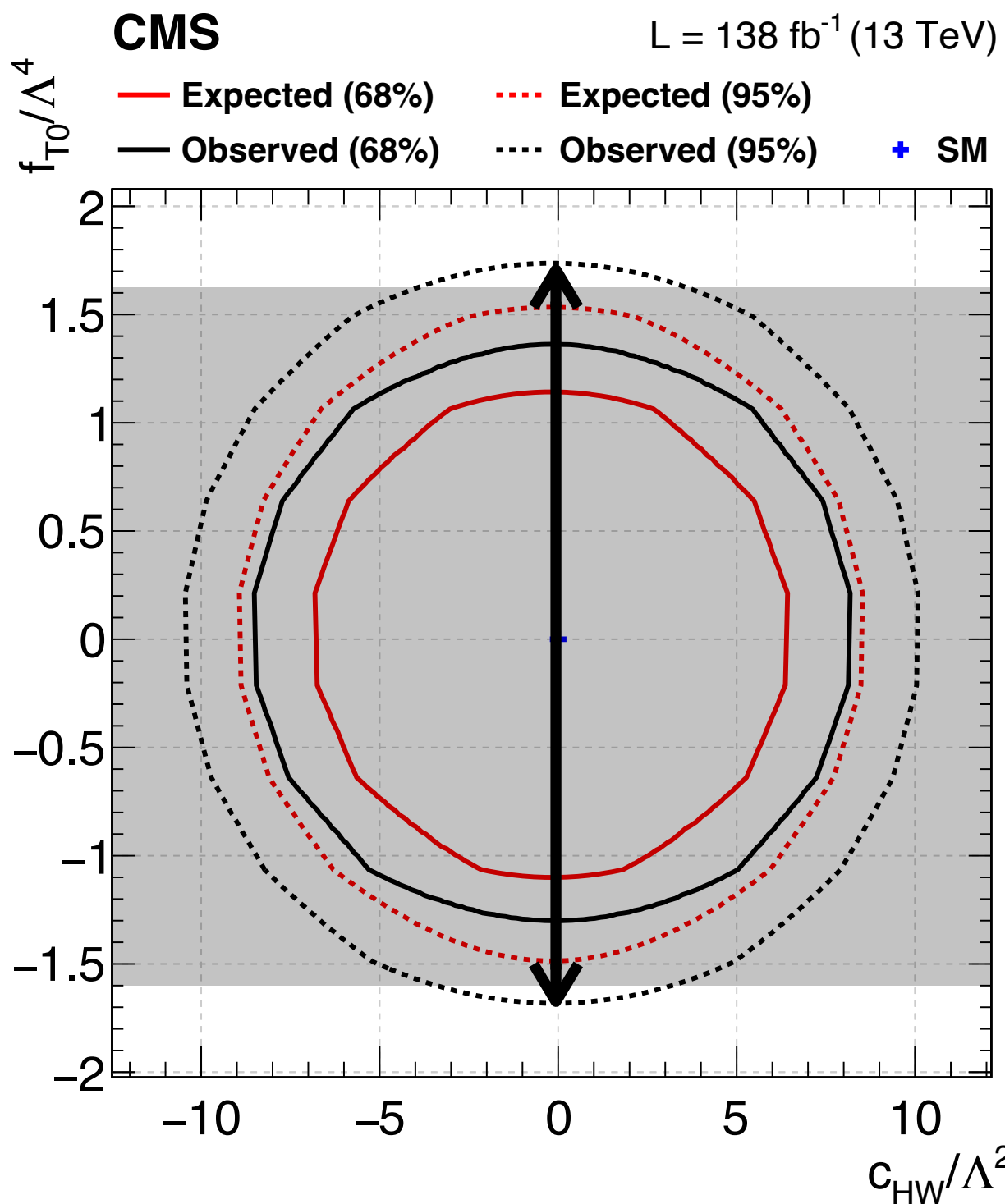
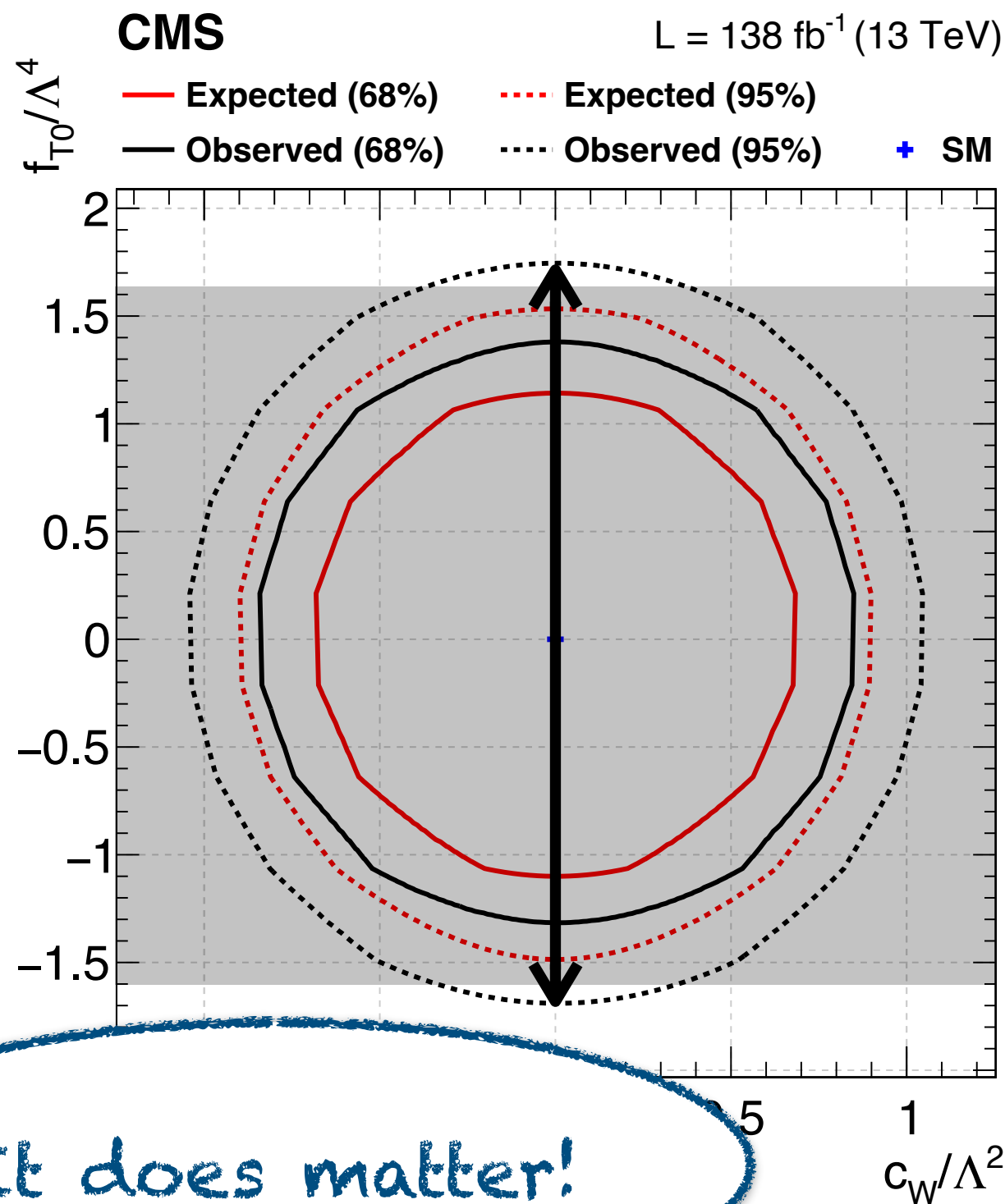
First time ever

 dim-8 1D 95% CI
 dim-8 2D 95% CI
 when dim-6 = 0



NP expedition

It does matter!



Increasing dim-6 contribution

Bosonic operators

Do that regularly?

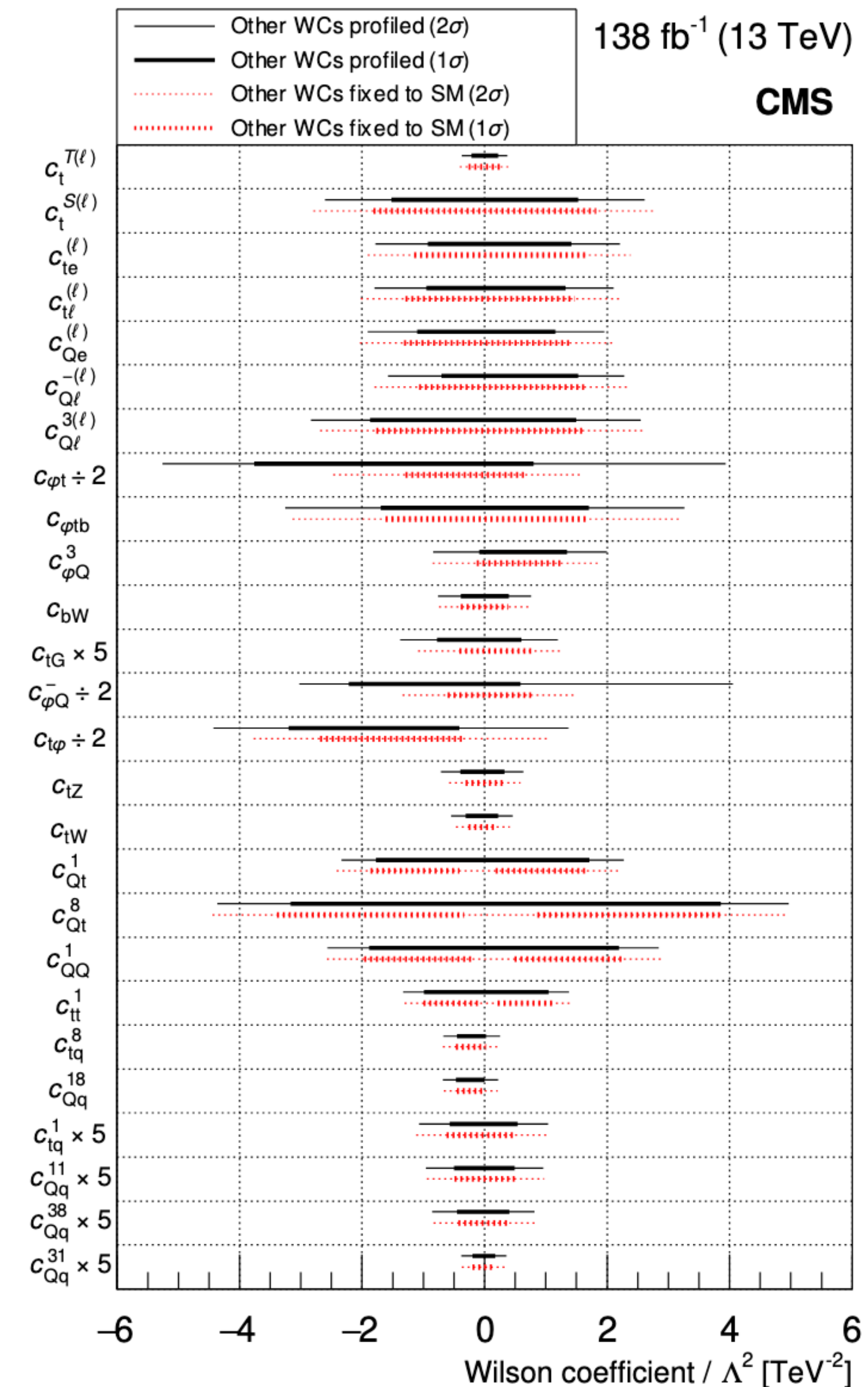
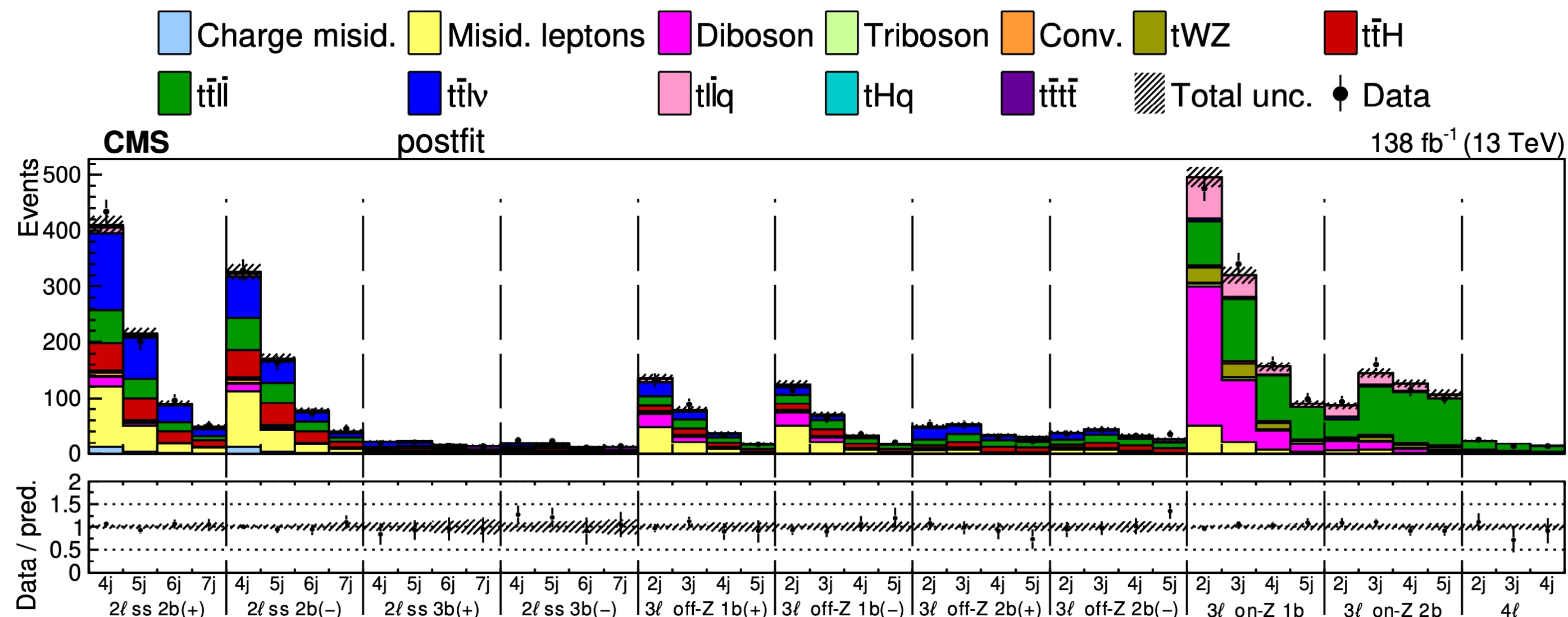
Watch out for the operators!

► VBS study: **24 operators** (dim-6 + dim-8)

Do that regularly?

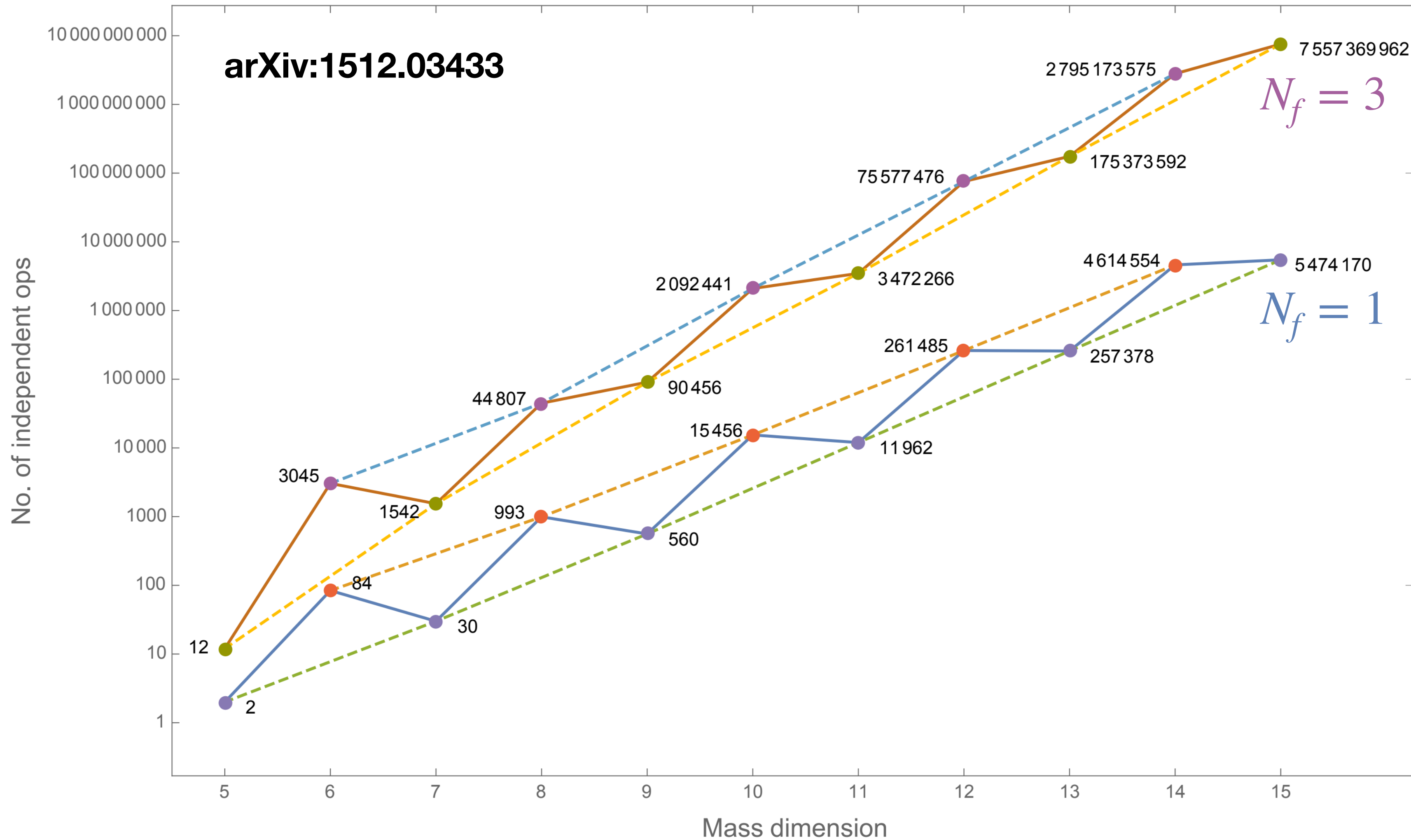
Watch out for the operators!

- VBS study: **24 operators** (dim-6 + dim-8)
- EFT search with ttX processes in multilepton final states
26 operators (dim-6 only) — JHEP 12 (2023) 068
- Limitations imposed by statistics and technologies available
 - ...too many parameters to deal with!



A scalability problem

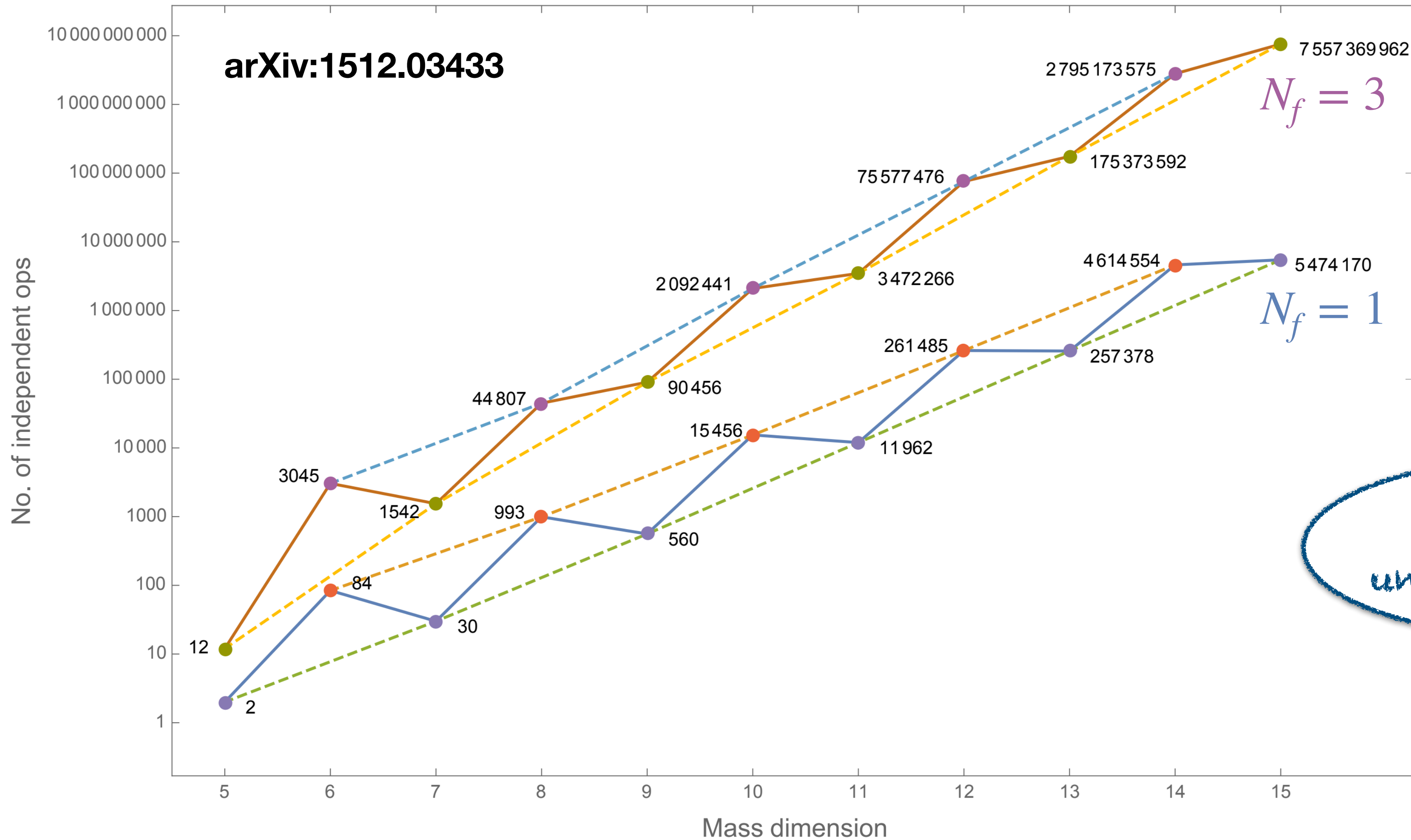
How many operators?



- ▶ Number of operators unmanageable (even at dim-8)
- ▶ But a-priori assumptions are dangerous...

A scalability problem

How many operators?



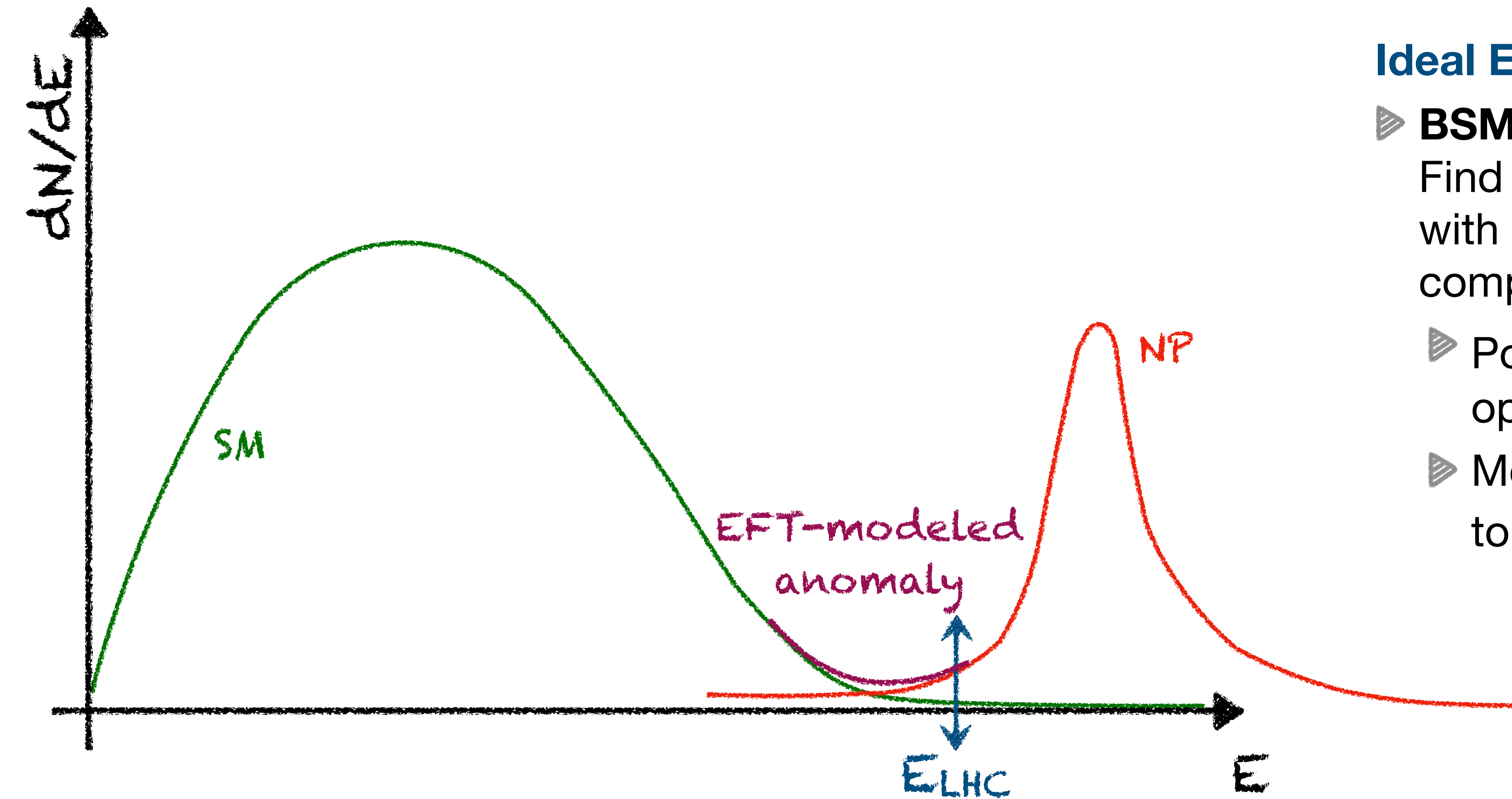
- ▶ Number of operators unmanageable (even at dim-8)
- ▶ But a-priori assumptions are dangerous...

Is this an untamable storm?



NP expedition

Bracing for the dimensions storm



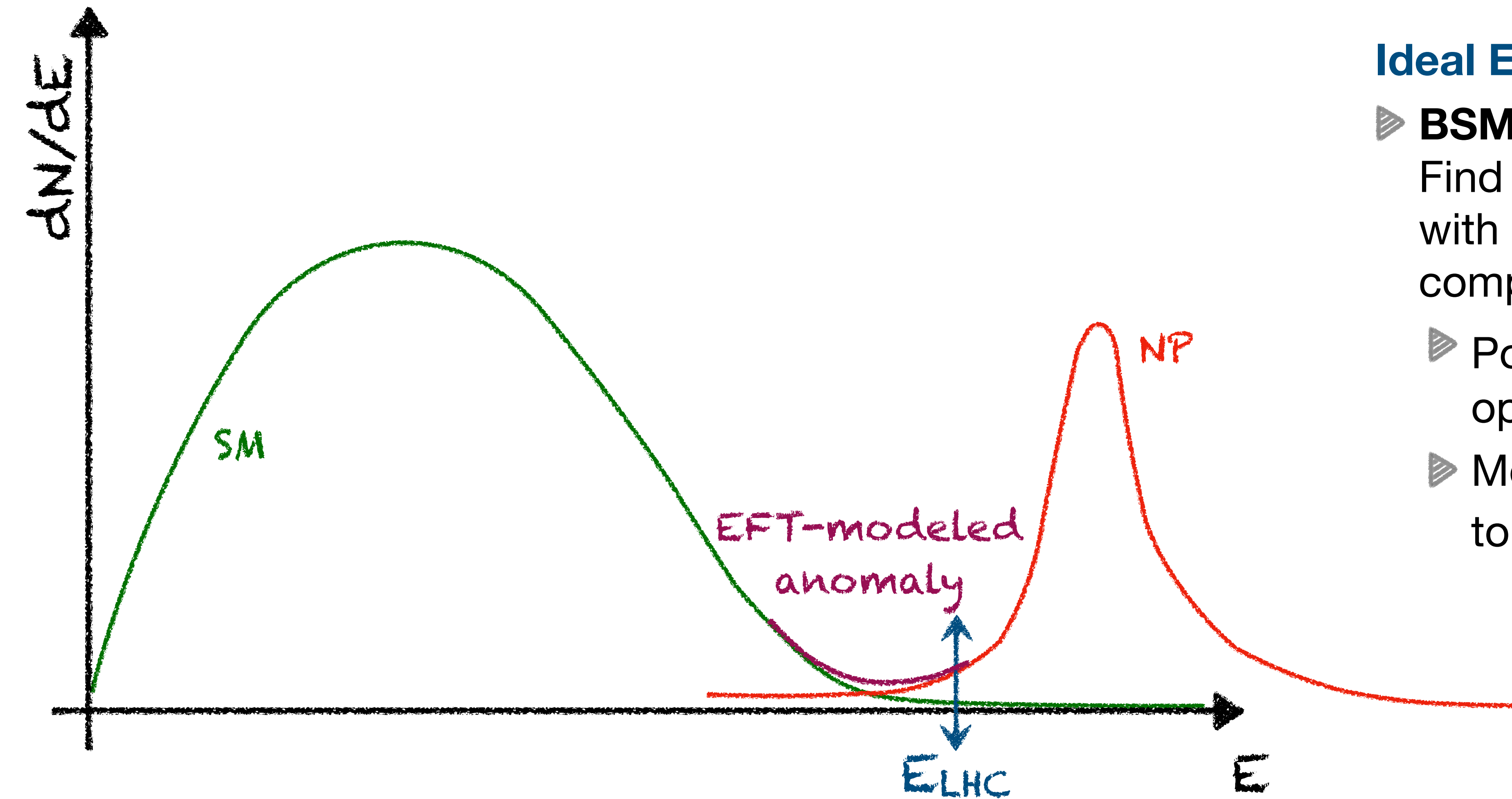
Ideal EFT study

► BSM Matching

Find a connection with a given NP model comparing the Lagrangians

- Power-counting of $\Lambda \gg$ operator dimensions!
- More dimensions contribute to a given power of Λ

Bracing for the dimensions storm



Ideal EFT study

► BSM Matching

Find a connection with a given NP model comparing the Lagrangians

- Power-counting of $\Lambda \gg$ operator dimensions!
- More dimensions contribute to a given power of Λ



What if we focus on Λ powers?

Heuristic approach

A Warsaw-basis-like for dim-8

Heuristic approach

A Warsaw-basis-like for dim-8

- ▶ Complete SMEFT basis for dim-8 interactions
 - ▶ **Murphy basis**
- ▶ Full integration of dim-6 and dim-8 operators
 - ▶ **SmeftFR package**
- ▶ Pick the relevant subset of SMEFT operators for the process of interest via phenomenology



PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: May 13, 2020
REVISED: September 15, 2020
ACCEPTED: September 19, 2020
PUBLISHED: October 27, 2020

Murphy basis

JHEP10(2020)174

Dimension-8 operators in the Standard Model Effective Field Theory

Christopher W. Murphy
*Home Point Financial,
Ann Arbor, MI 48105, U.S.A.*
E-mail: chrismurphybnl@gmail.com

ABSTRACT: We present a complete basis of dimension-8 operators in the Standard Model Effective Field Theory. Attention is paid to operators that vanish in the absence of flavor structure. The 44,807 operators are encoded in 1,031 Lagrangian terms. We also briefly discuss a few aspects of phenomenology involving dimension-8 operators, including light-by-light scattering and electroweak precision data.

KEYWORDS: Effective Field Theories, Beyond Standard Model

ARXIV EPRINT: [2005.00059](https://arxiv.org/abs/2005.00059)

Computer Physics Communications 294 (2024) 108943



Contents lists available at ScienceDirect

Computer Physics Communications

journal homepage: www.elsevier.com/locate/cpc



Computer Programs in Physics

SmeftFR v3 – Feynman rules generator for the Standard Model Effective Field Theory ☆☆☆

A. Dedes^a, J. Rosiek^{b,*}, M. Ryczkowski^b, K. Suxho^a, L. Trifyllis^a

^a Department of Physics, University of Ioannina, GR 45110, Ioannina, Greece
^b Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

ARTICLE INFO

Keywords:
Standard Model Effective Field Theory
Feynman rules
Unitary and R_ξ -gauges

ABSTRACT

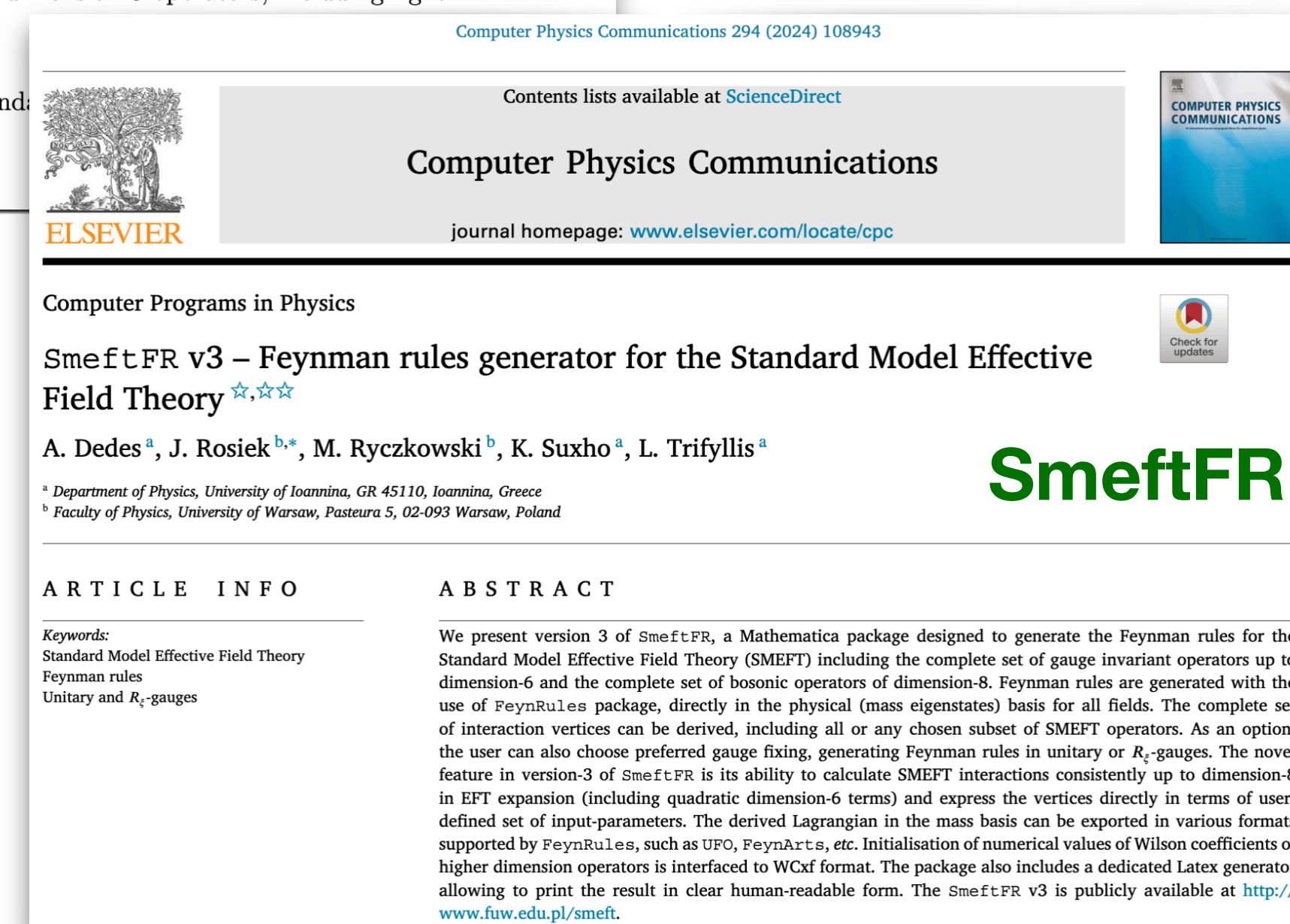
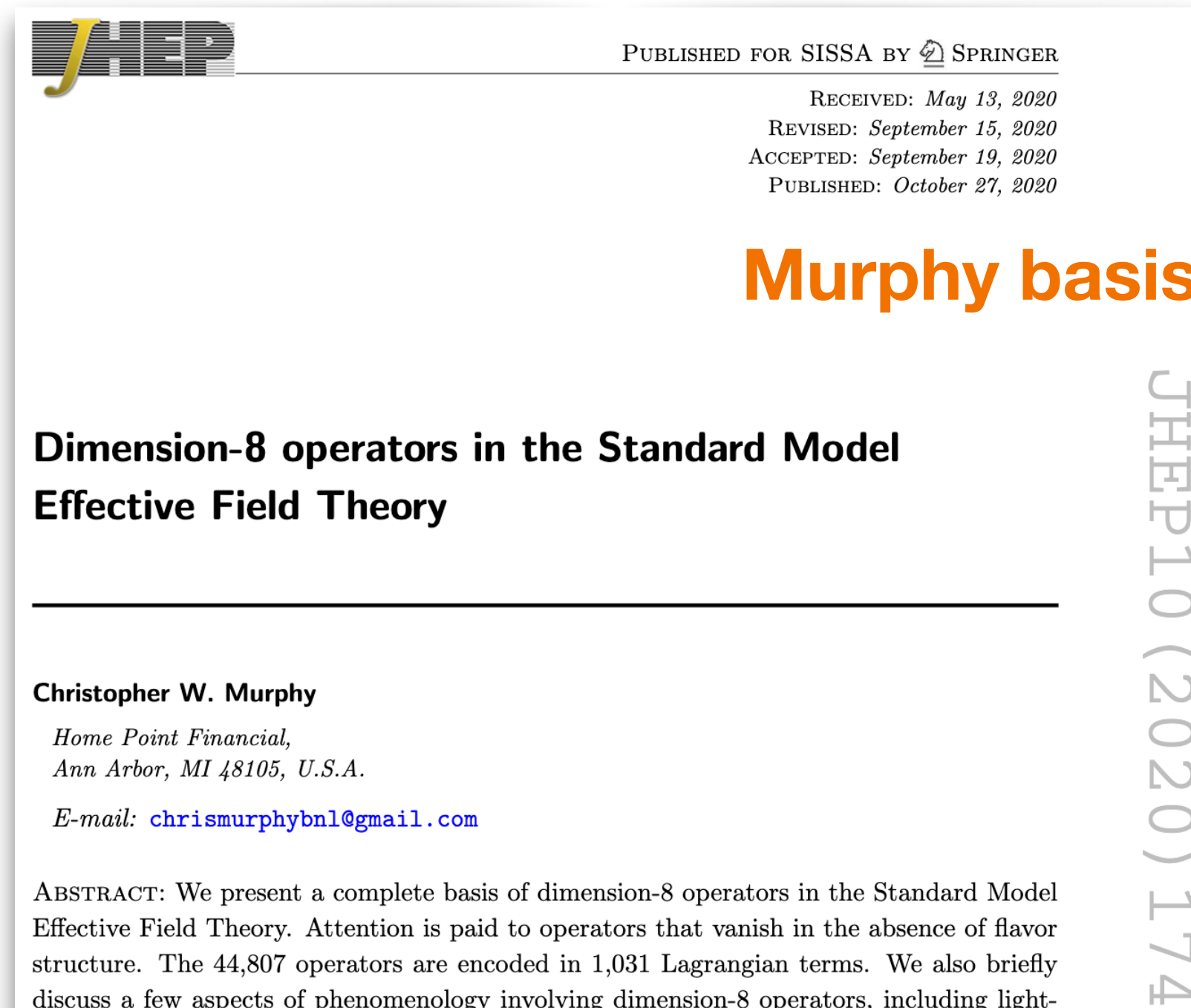
We present version 3 of SmeftFR, a Mathematica package designed to generate the Feynman rules for the Standard Model Effective Field Theory (SMEFT) including the complete set of gauge invariant operators up to dimension-6 and the complete set of bosonic operators of dimension-8. Feynman rules are generated with the use of FeynRules package, directly in the physical (mass eigenstates) basis for all fields. The complete set of interaction vertices can be derived, including all or any chosen subset of SMEFT operators. As an option, the user can also choose preferred gauge fixing, generating Feynman rules in unitary or R_ξ -gauges. The novel feature in version-3 of SmeftFR is its ability to calculate SMEFT interactions consistently up to dimension-8 in EFT expansion (including quadratic dimension-6 terms) and express the vertices directly in terms of user-defined set of input-parameters. The derived Lagrangian in the mass basis can be exported in various formats supported by FeynRules, such as UFO, FeynArts, etc. Initialisation of numerical values of Wilson coefficients of higher dimension operators is interfaced to WCxf format. The package also includes a dedicated Latex generator allowing to print the result in clear human-readable form. The SmeftFR v3 is publicly available at <http://www.fuw.edu.pl/smeft>.

Heuristic approach

A Warsaw-basis-like for dim-8

- ▶ Complete SMEFT basis for dim-8 interactions
 - ▶ **Murphy basis**
- ▶ Full integration of dim-6 and dim-8 operators
 - ▶ **SmeftFR package**
- ▶ Pick the relevant subset of SMEFT operators for the process of interest via phenomenology

...could we do better?



A different perspective

Grasp similarities among dim-6 and dim-8 operators

Pheno inputs

- ▶ EFT effects mainly at high energy
- ▶ Kinematic impact of EFT on a given vertex independent from the dimensions
 - ▶ Operator structure fixed by physics

A different perspective

Grasp similarities among dim-6 and dim-8 operators

Pheno inputs

- ▶ EFT effects mainly at high energy
- ▶ Kinematic impact of EFT on a given vertex independent from the dimensions
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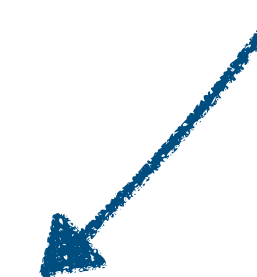
Geometric interpretation



of the SMEFT Λ expansion



Reorganize operators in terms of
 Λ —power expansion



Regroup operators according to
the simplest interactions they act on

A different perspective

Grasp similarities among dim-6 and dim-8 operators

Pheno inputs

- ▶ EFT effects mainly at high energy
- ▶ Kinematic impact of EFT on a given vertex independent from the dimensions
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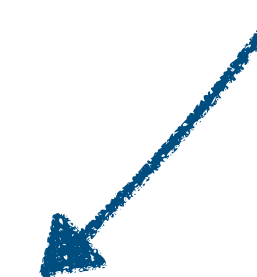
Geometric interpretation



of the SMEFT Λ expansion



Reorganize operators in terms of Λ -power expansion

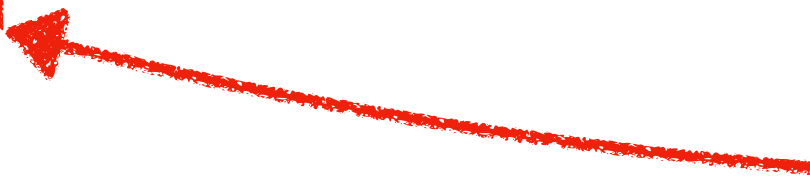


Regroup operators according to the simplest interactions they act on

JHEP 03 (2020) 163 (Martin et al.)

geoSMEFT

Reduce # of operators needed for a consistent EFT treatment of a given interaction



Benefits of the geometric approach

$$\sigma_{\Lambda^4} \propto |\mathcal{A}_{\text{SM}}|^2 + \sum_k \frac{c_k^{(6)}}{\Lambda^2} 2\text{Re}\left(\mathcal{A}_{\text{SM}}^\dagger \mathcal{A}_k^{(6)}\right) + \sum_{i \neq j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\text{Re}\left(\mathcal{A}_i^{(6)\dagger} \mathcal{A}_j^{(6)}\right) + \sum_h \frac{c^{(8)}}{\Lambda^4} 2\text{Re}\left(\mathcal{A}_{\text{SM}}^\dagger \mathcal{A}_k^{(8)}\right)$$

Benefits of the geometric approach

$$\sigma_{\Lambda^4} \propto |\mathcal{A}_{\text{SM}}|^2 + \underbrace{\sum_k \frac{c_k^{(6)}}{\Lambda^2} 2\text{Re}\left(\mathcal{A}_{\text{SM}}^\dagger \mathcal{A}_k^{(6)}\right)}_{\Lambda^2 \text{ order}} + \underbrace{\sum_{i \neq j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\text{Re}\left(\mathcal{A}_i^{(6)\dagger} \mathcal{A}_j^{(6)}\right) + \sum_h \frac{c_h^{(8)}}{\Lambda^4} 2\text{Re}\left(\mathcal{A}_{\text{SM}}^\dagger \mathcal{A}_h^{(8)}\right)}_{\Lambda^4 \text{ order}}$$

Leading contributions

**Consistent treatment with
the minimum # of operators**

**Exact EFT treatment up to Λ^{-4}
with a manageable amount of operators!**

Benefits of the geometric approach

$$\sigma_{\Lambda^4} \propto |\mathcal{A}_{\text{SM}}|^2 + \underbrace{\sum_k \frac{c_k^{(6)}}{\Lambda^2} 2\text{Re}\left(\mathcal{A}_{\text{SM}}^\dagger \mathcal{A}_k^{(6)}\right)}_{\Lambda^2 \text{ order}} + \underbrace{\sum_{i \neq j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\text{Re}\left(\mathcal{A}_i^{(6)\dagger} \mathcal{A}_j^{(6)}\right) + \sum_h \frac{c_h^{(8)}}{\Lambda^4} 2\text{Re}\left(\mathcal{A}_{\text{SM}}^\dagger \mathcal{A}_h^{(8)}\right)}_{\Lambda^4 \text{ order}}$$

Leading contributions

Consistent treatment with the minimum # of operators

Exact EFT treatment up to Λ^{-4} with a manageable amount of operators!

Potential step forward matching direct and anomalies searches!

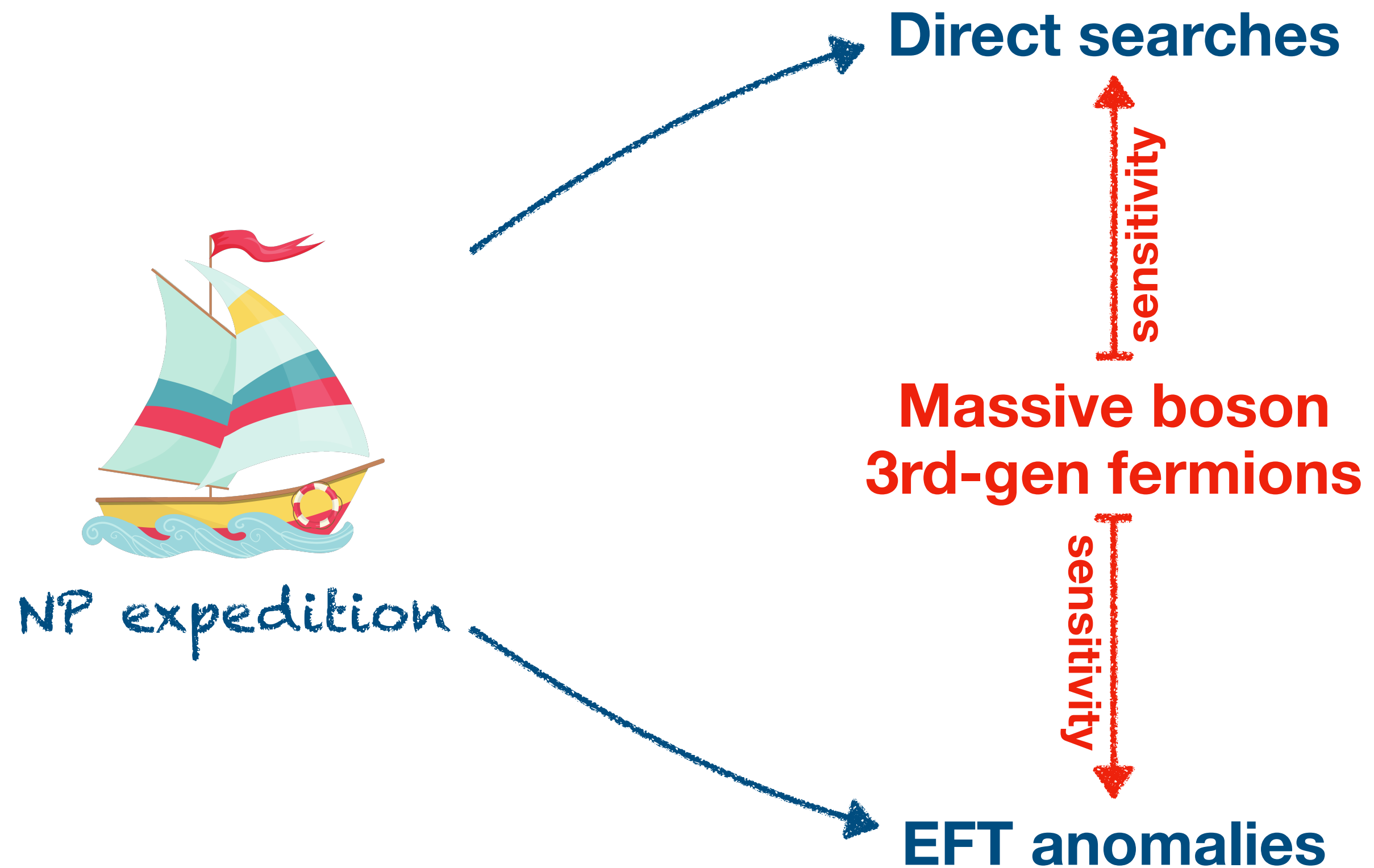


A postcard from the journey

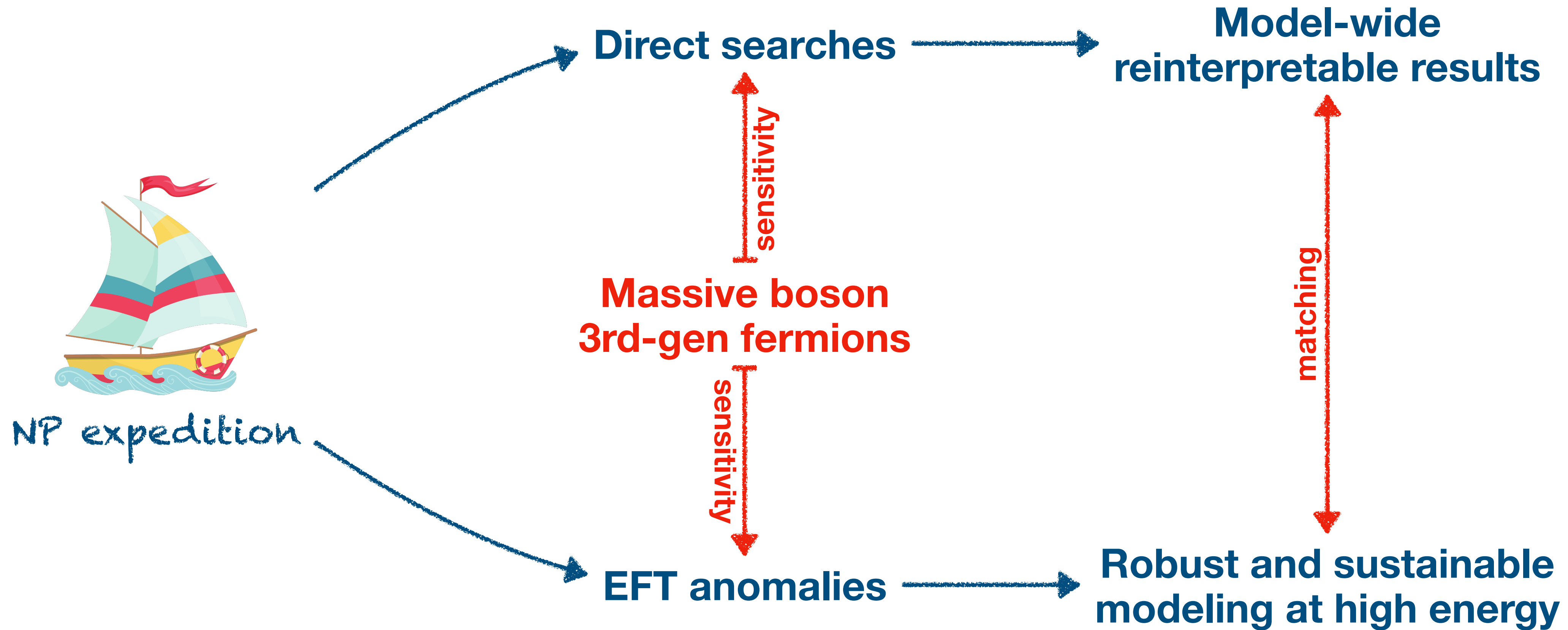


NP expedition

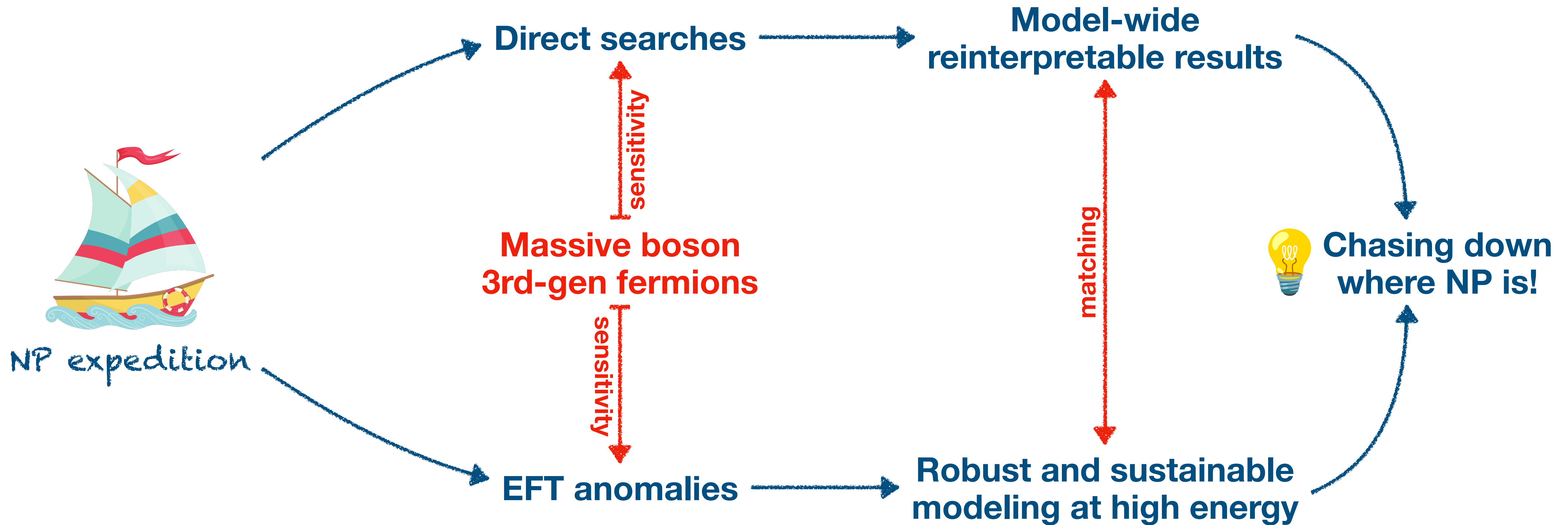
A postcard from the journey



A postcard from the journey



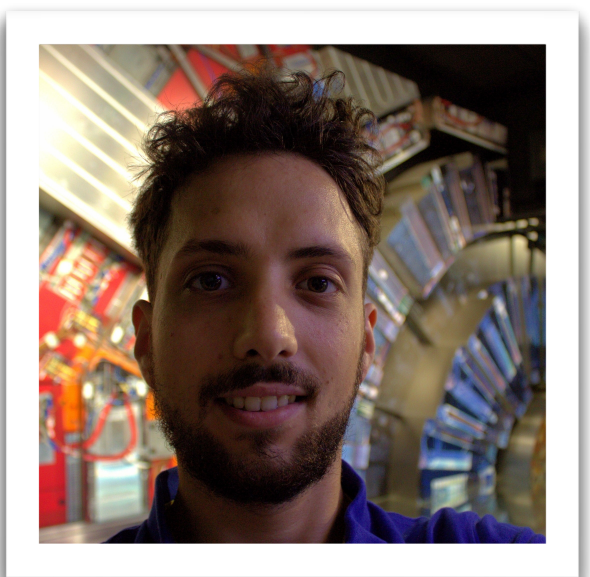
A postcard from the journey





NP expedition
(EFT + BSM searches)

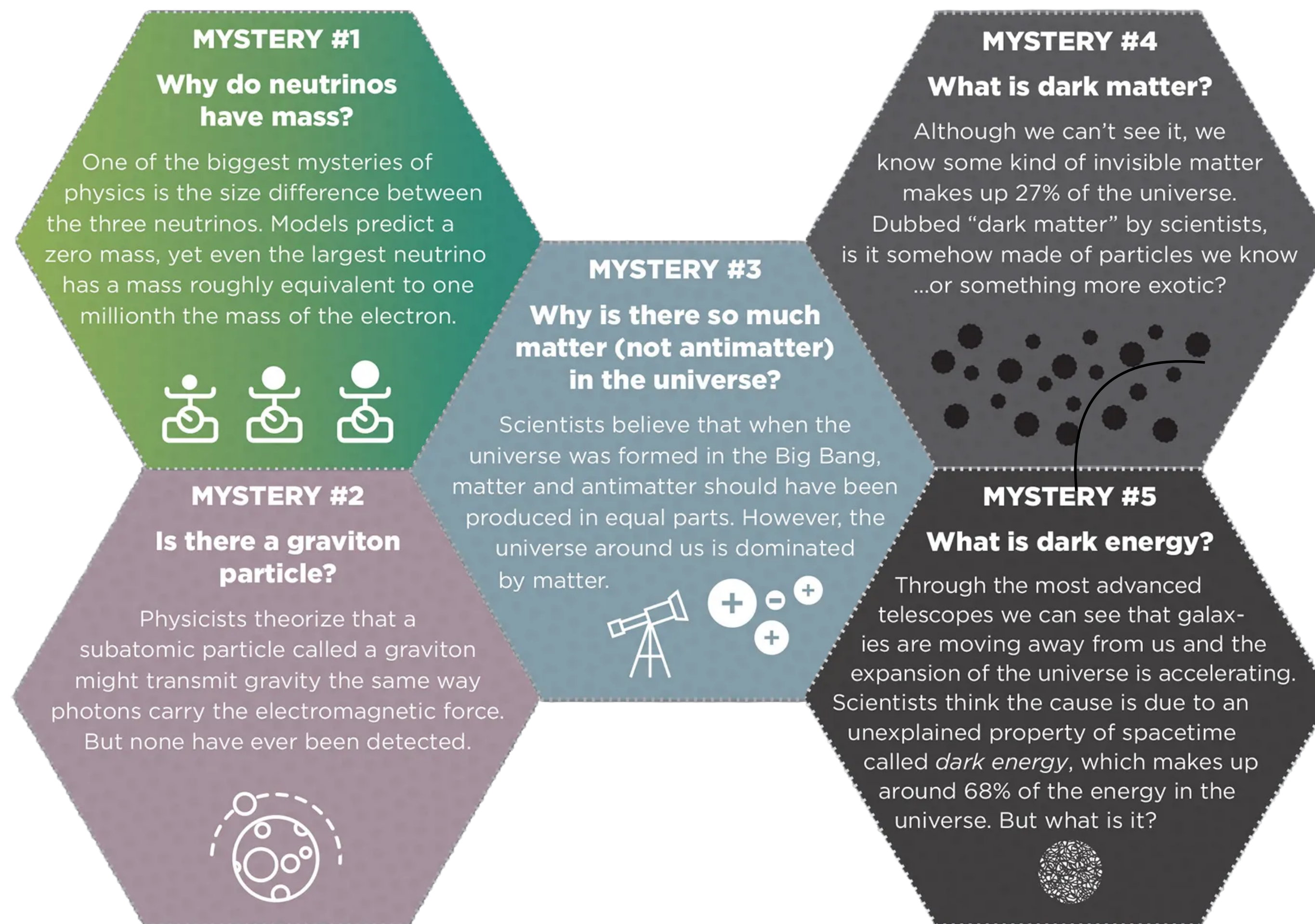
Merci
beaucoup!



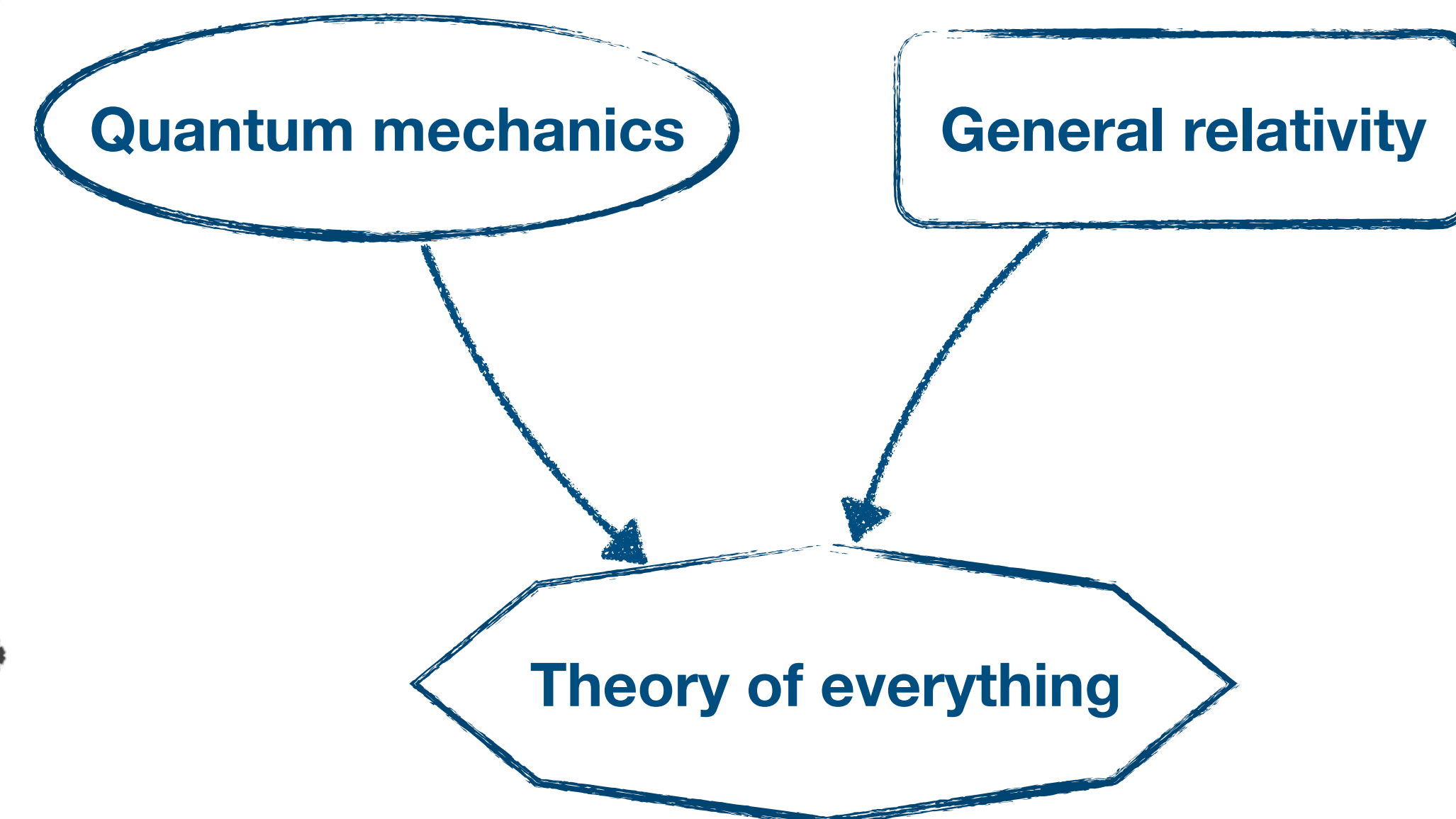
Additional slides

Why we need to extend SM?

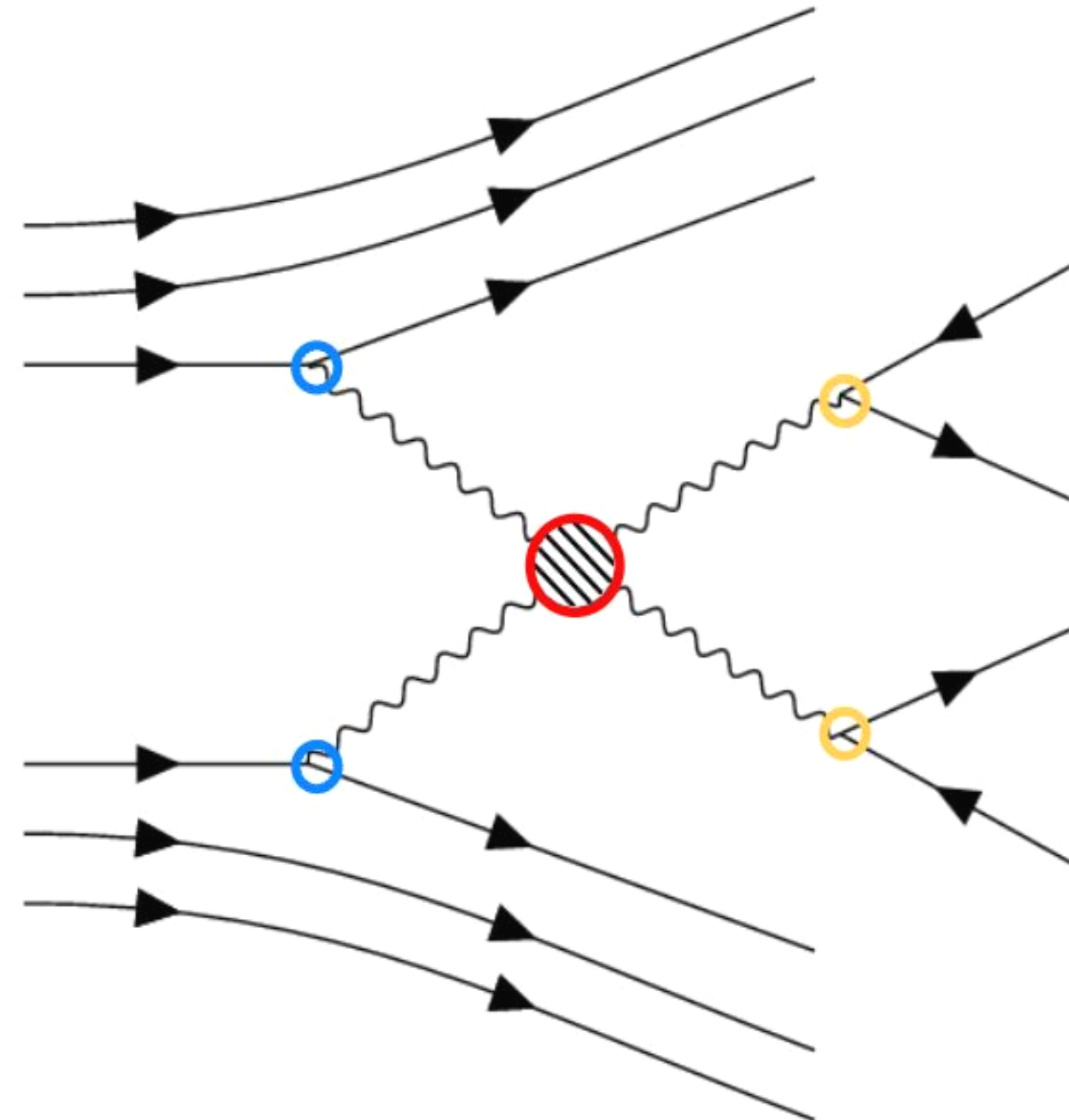
The question we are willing to answer



Desired solution



Inducing anomalies in VBS



SM EFT Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \boxed{\sum_k \frac{c_k \mathcal{Q}_k}{\Lambda^2}} + \sum_j \frac{f_j \mathcal{O}_j}{\Lambda^4}$$

dim-6 operators
Warsaw basis

$qq' \longrightarrow WW$

$$\begin{aligned} Q_{Hq}^{(1)} &= (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{q}_p \gamma^\mu q_p) \\ Q_{Hq}^{(3)} &= (H^\dagger i \overleftrightarrow{D}_\mu^j H) (\bar{q}_p \sigma^j \gamma^\mu q_p) \\ Q_{qq}^{(1)} &= \delta_{pr} \delta_{st} (\bar{q}_p \gamma_\mu q_r) (\bar{q}_s \gamma^\mu q_t) \\ Q_{qq}^{(1,1)} &= \delta_{pt} \delta_{sr} (\bar{q}_p \gamma_\mu q_r) (\bar{q}_s \gamma^\mu q_t) \\ Q_{qq}^{(3)} &= \delta_{pr} \delta_{st} (\bar{q}_p \gamma_\mu \sigma^i q_r) (\bar{q}_s \gamma^\mu \sigma^i q_t) \\ Q_{qq}^{(3,1)} &= \delta_{pt} \delta_{sr} (\bar{q}_p \gamma_\mu \sigma^i q_r) (\bar{q}_s \gamma^\mu \sigma^i q_t) \end{aligned}$$

$WW \longrightarrow WW$

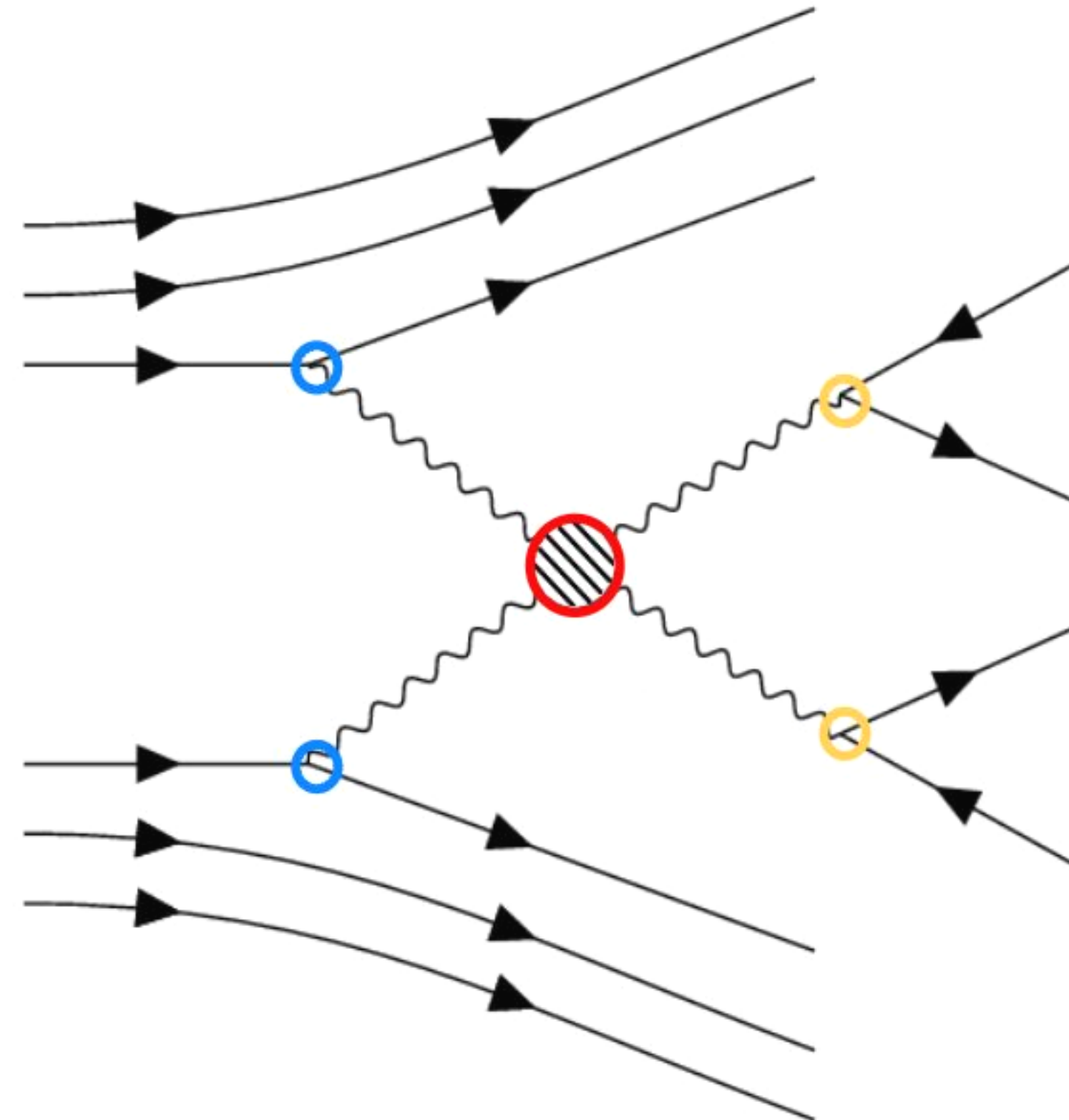
$$\begin{aligned} Q_W &= \varepsilon^{ijk} W_\mu^{vi} W_\nu^{\rho j} W_\rho^{\mu k} \\ Q_{H\Box} &= (H^\dagger H) \Box (H^\dagger H) \\ Q_{HD} &= (H^\dagger D^\mu H) (H^\dagger D_\mu H) \\ Q_{HW} &= H^\dagger H W_{\mu\nu}^i W^{\mu\nu i} \\ Q_{HWB} &= H^\dagger \sigma^i H W_{\mu\nu}^i B^{\mu\nu} \end{aligned}$$

$WW \longrightarrow \ell \nu_\ell$

$$\begin{aligned} Q_{Hl}^{(1)} &= (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{l}_p \gamma^\mu l_p) \\ Q_{Hl}^{(3)} &= (H^\dagger i \overleftrightarrow{D}_\mu^j H) (\bar{l}_p \sigma^j \gamma^\mu l_p) \\ Q_{ll} &= \delta_{pr} \delta_{st} (\bar{l}_p \gamma_\mu l_r) (\bar{l}_s \gamma^\mu l_t) \\ Q_{ll}^{(1)} &= \delta_{pt} \delta_{sr} (\bar{l}_p \gamma_\mu l_r) (\bar{l}_s \gamma^\mu l_t) \end{aligned}$$

Sensitive to LFV

Inducing anomalies in VBS



SM EFT Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_k \frac{c_k \mathcal{Q}_k}{\Lambda^2} + \boxed{\sum_j \frac{f_j \mathcal{O}_j}{\Lambda^4}}$$

dim-8 operators
Éboli basis

$WW \longrightarrow WW$

$$\mathcal{O}_{S0} = \left[(D_\mu H)^\dagger D_\nu H \right] \times \left[(D^\mu H)^\dagger D^\nu H \right]$$

$$\mathcal{O}_{S1} = \left[(D_\mu H)^\dagger D^\mu H \right] \times \left[(D_\nu H)^\dagger D^\nu H \right]$$

$$\mathcal{O}_{S2} = \left[(D_\mu H)^\dagger D_\nu H \right] \times \left[(D^\nu H)^\dagger D^\mu H \right]$$

$$\mathcal{O}_{M0} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta H)^\dagger D^\beta H \right] \quad \mathcal{O}_{T0} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \text{Tr} \left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right]$$

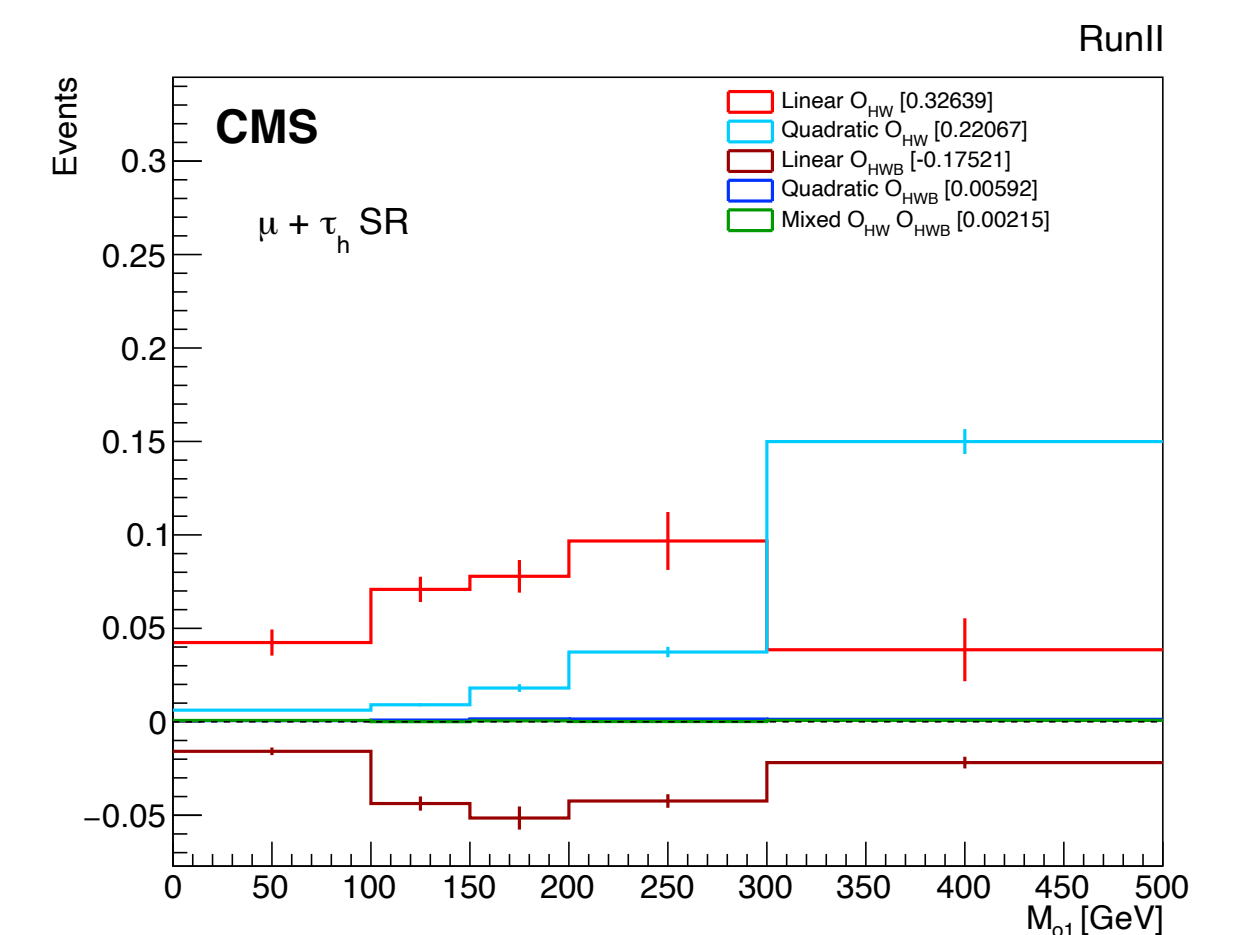
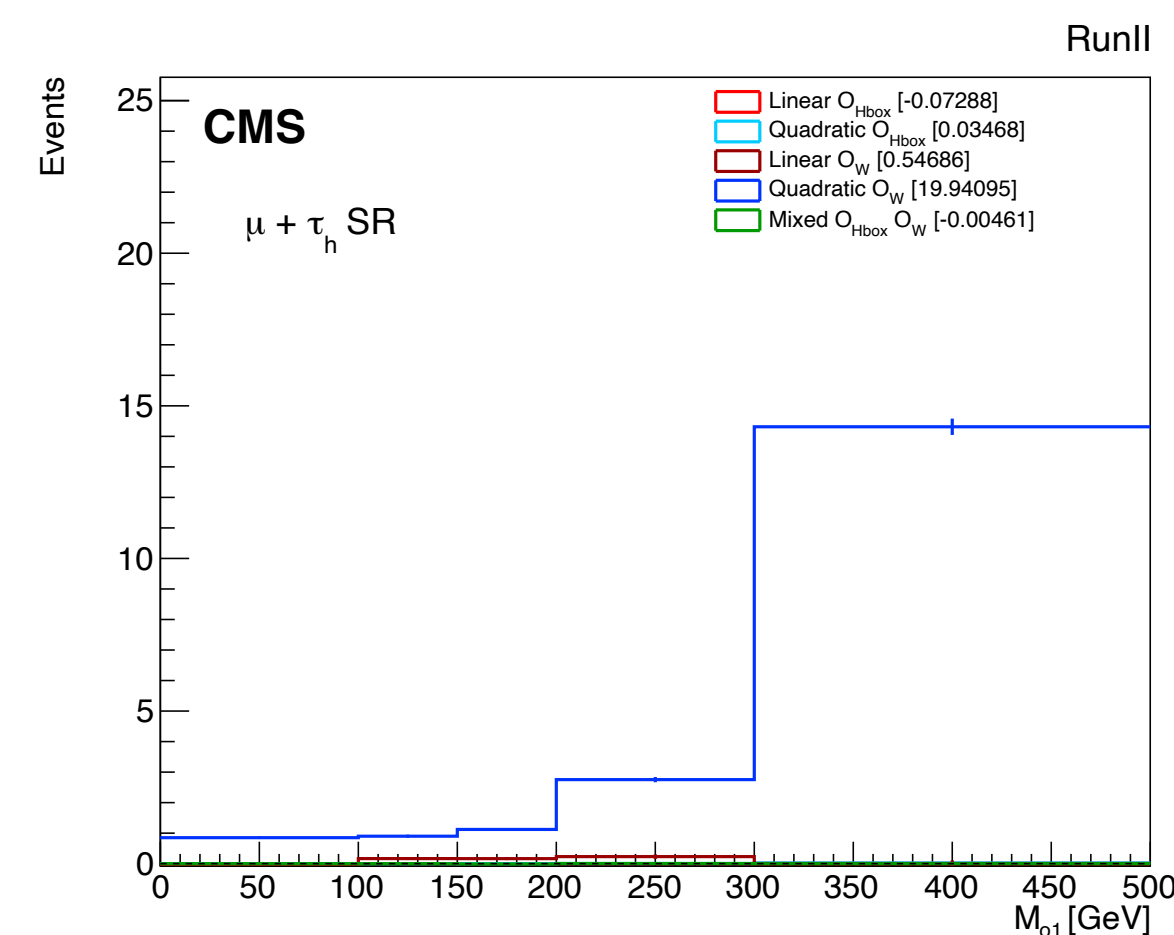
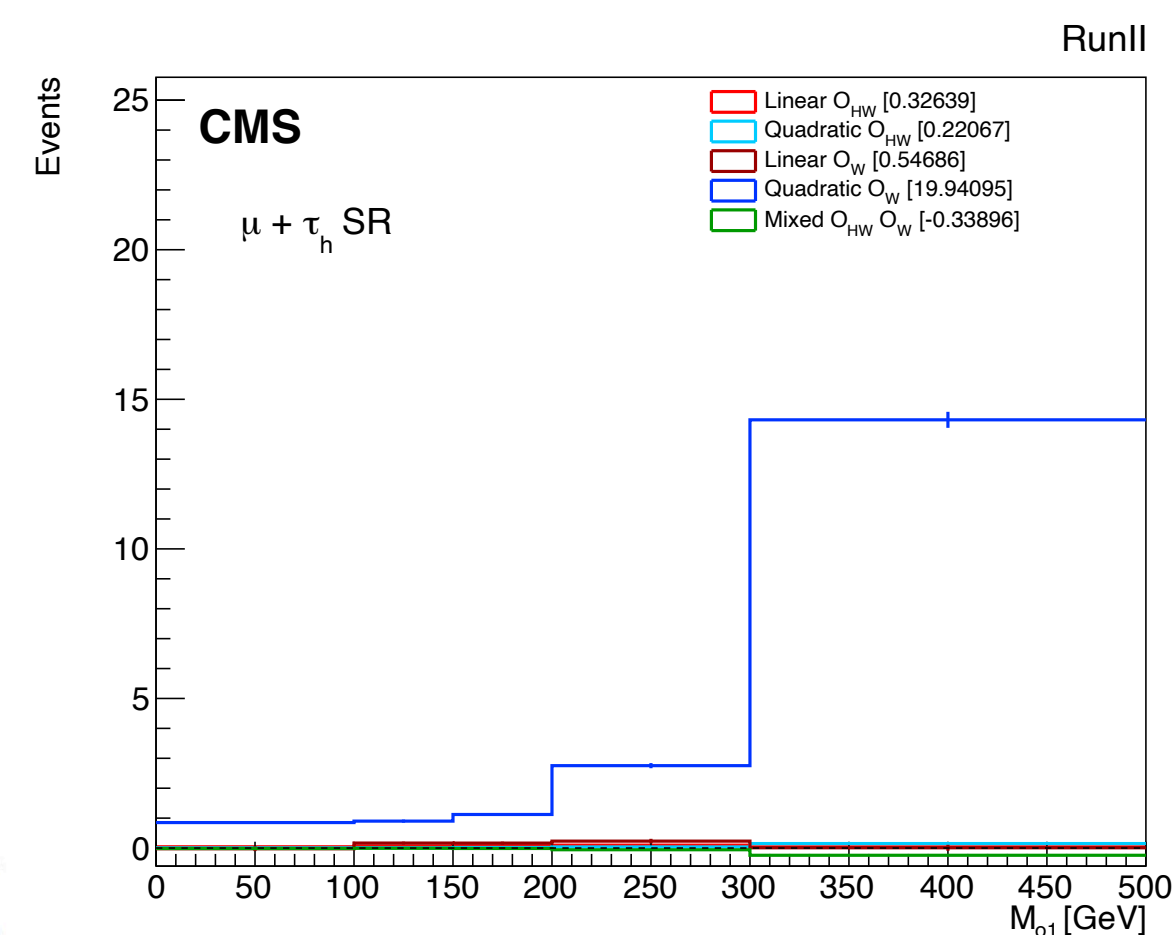
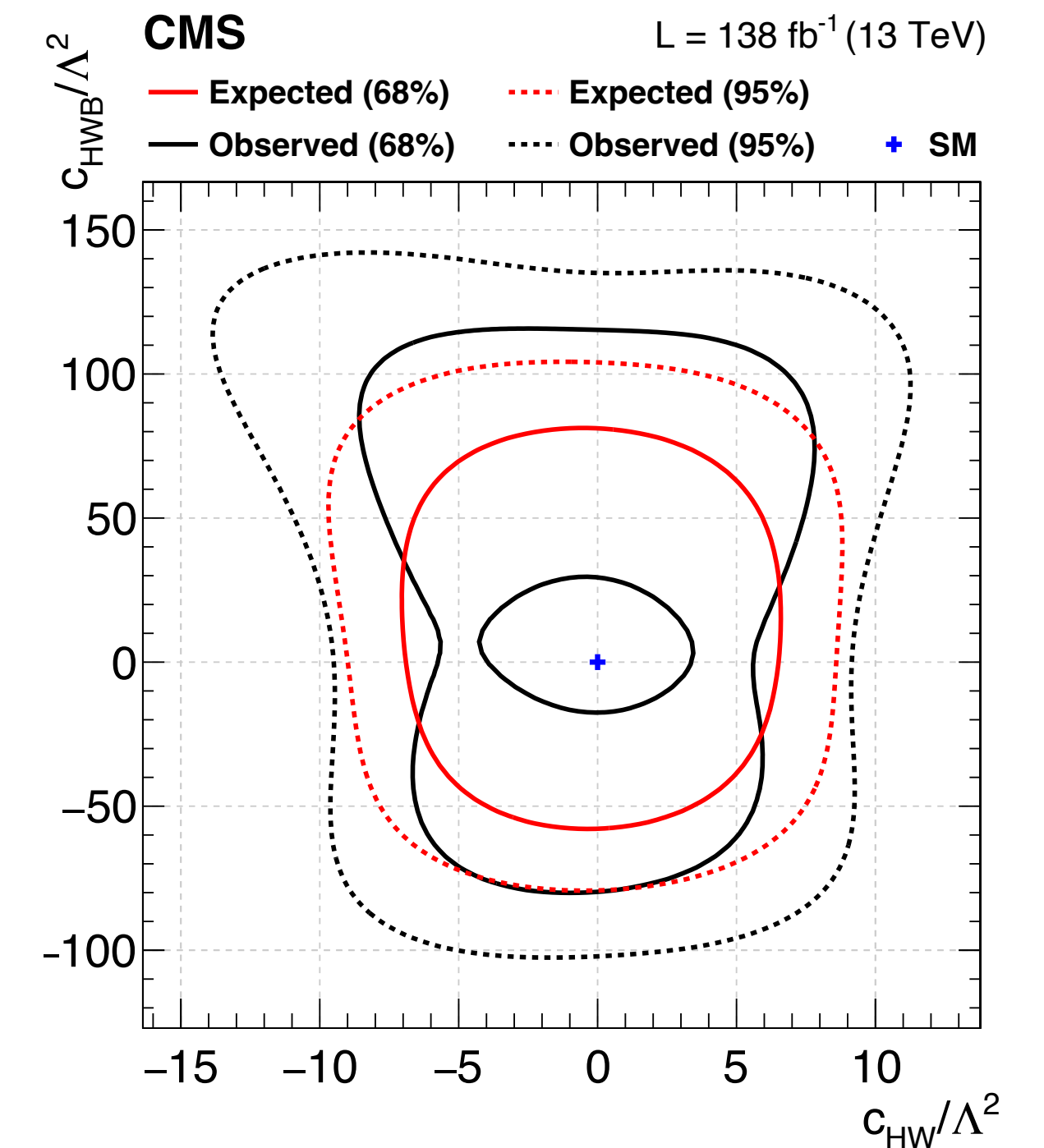
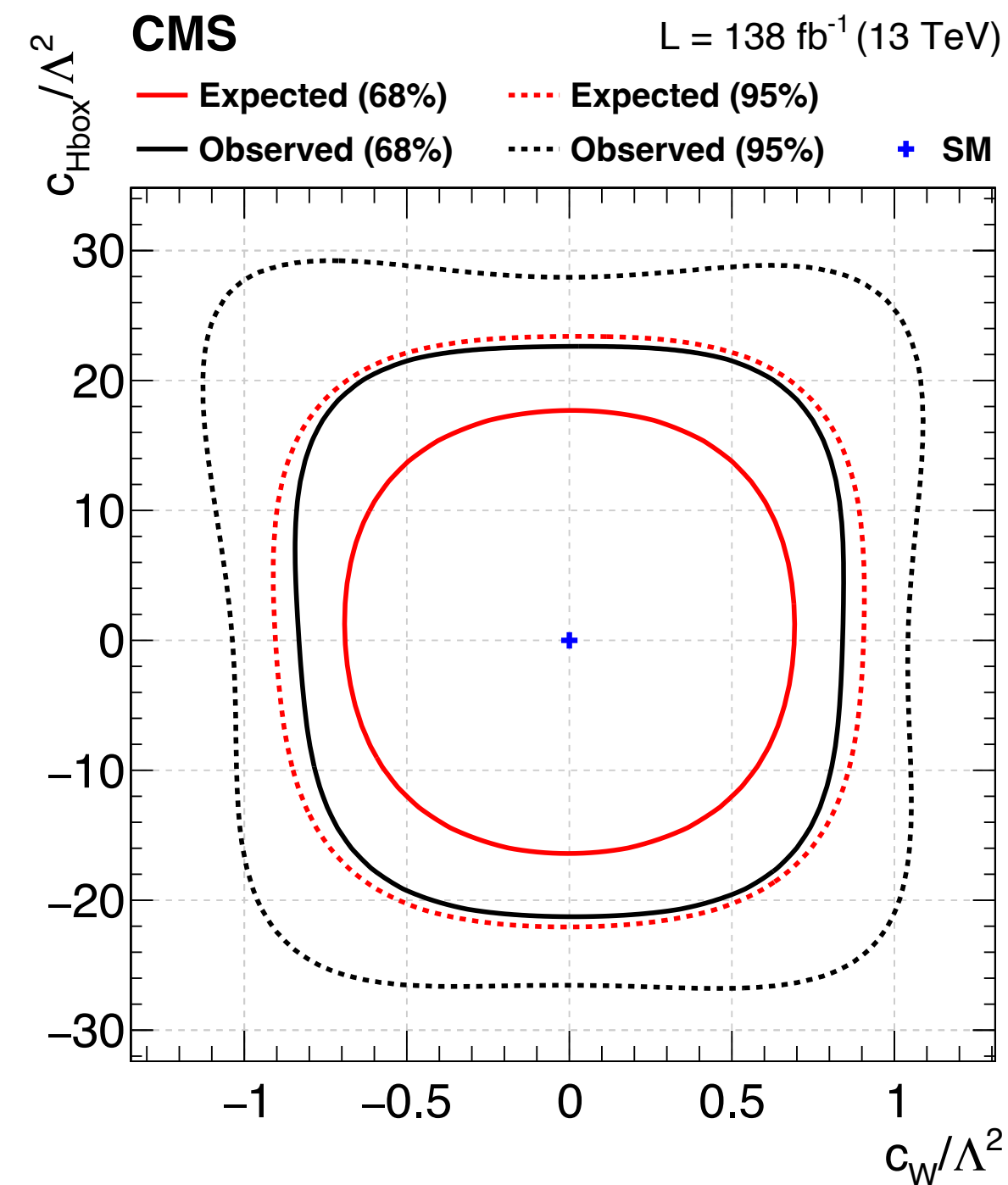
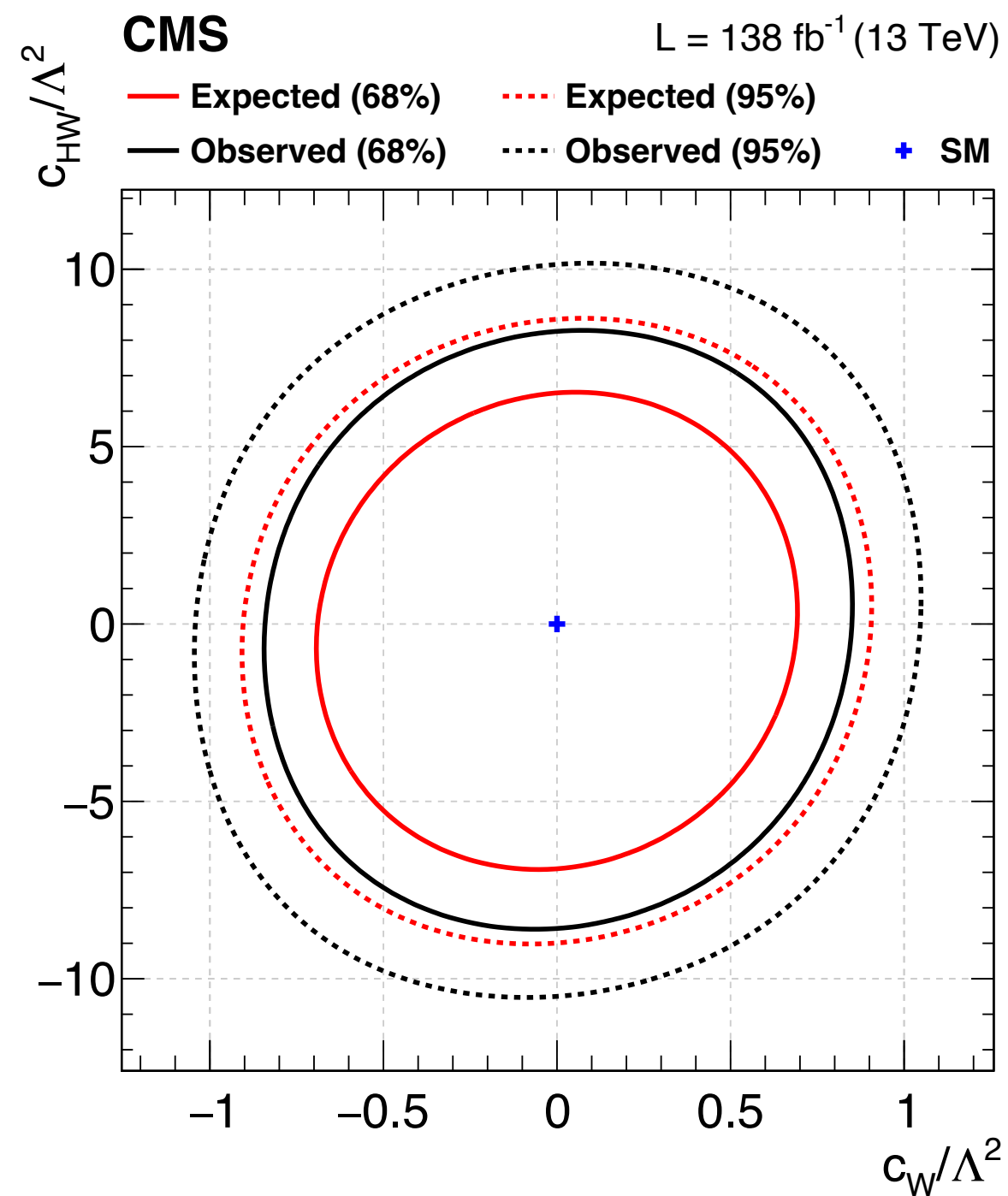
$$\mathcal{O}_{M1} = \text{Tr} \left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta H)^\dagger D^\beta H \right] \quad \mathcal{O}_{T1} = \text{Tr} \left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right]$$

$$\mathcal{O}_{M7} = \text{Tr} \left[(D_\mu H)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu H \right] \quad \mathcal{O}_{T0} = \text{Tr} \left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times \text{Tr} \left[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right]$$

Considering only dim-6

First time with VBS

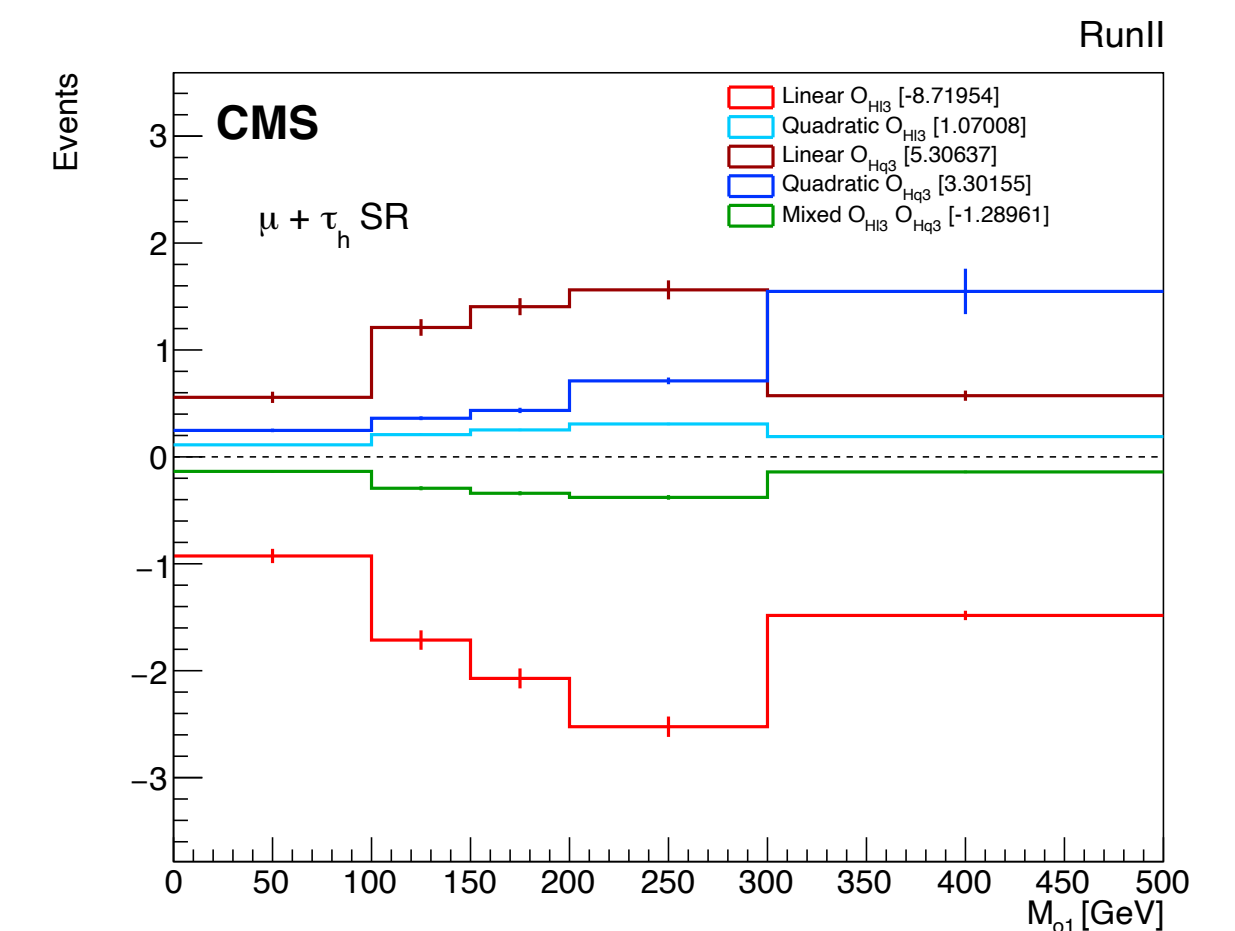
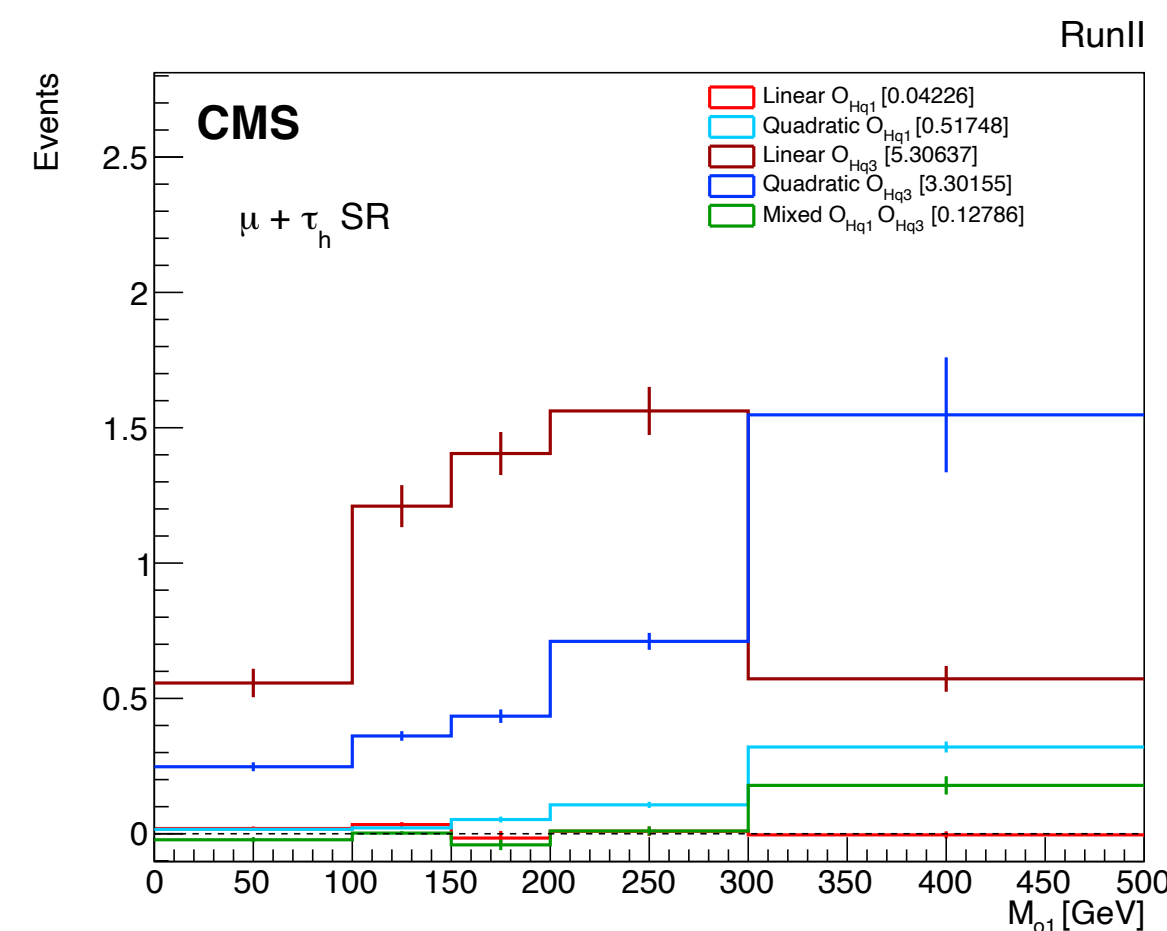
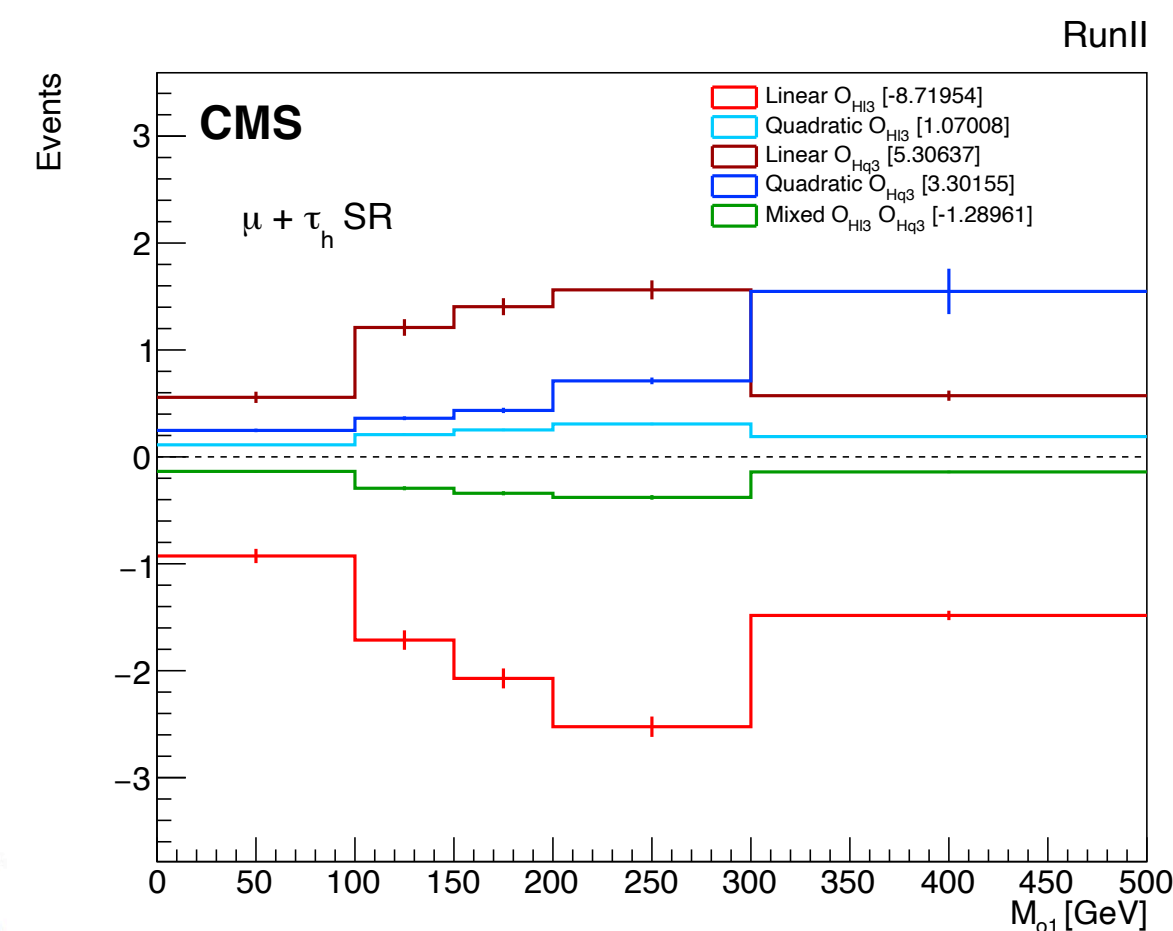
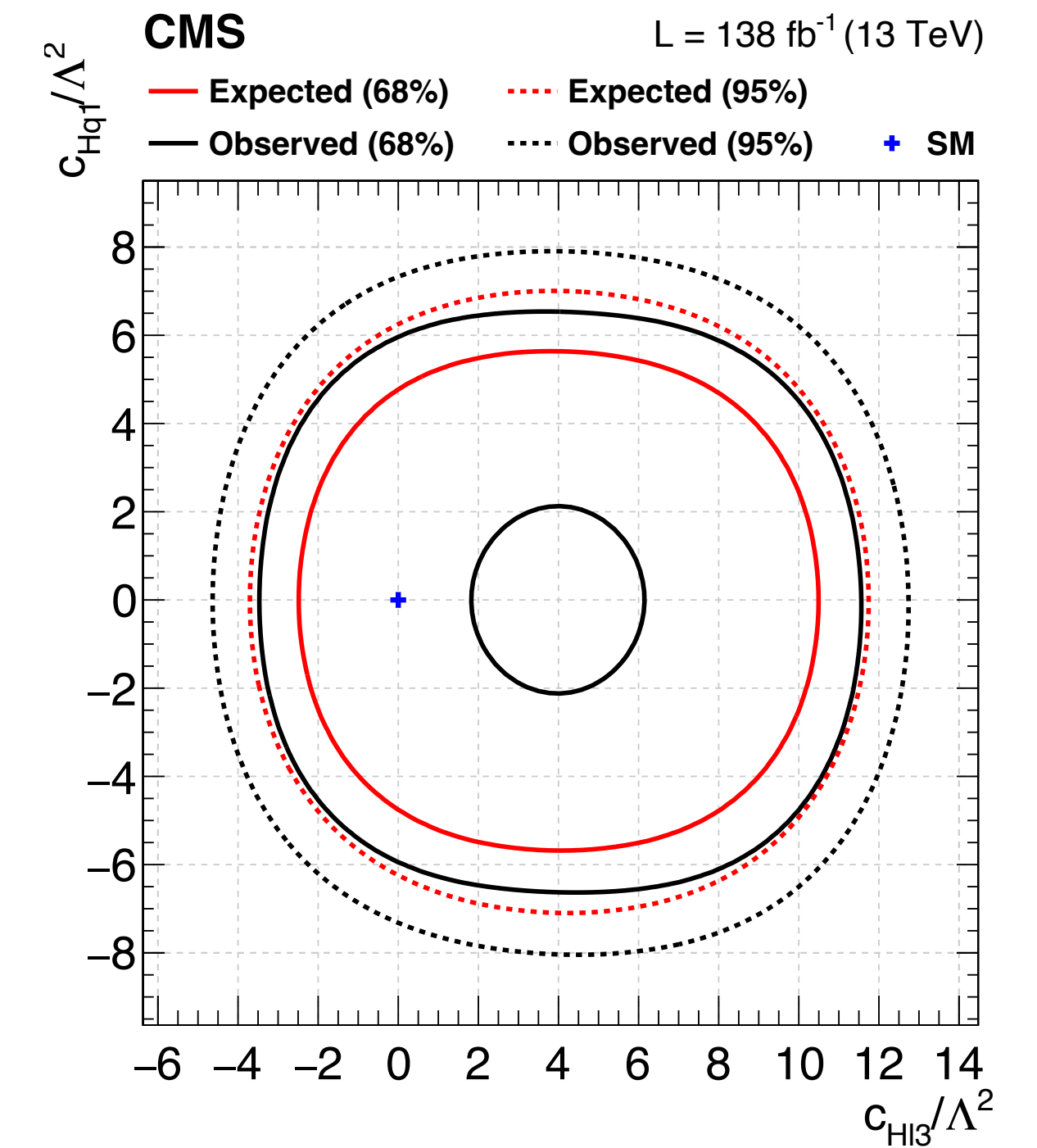
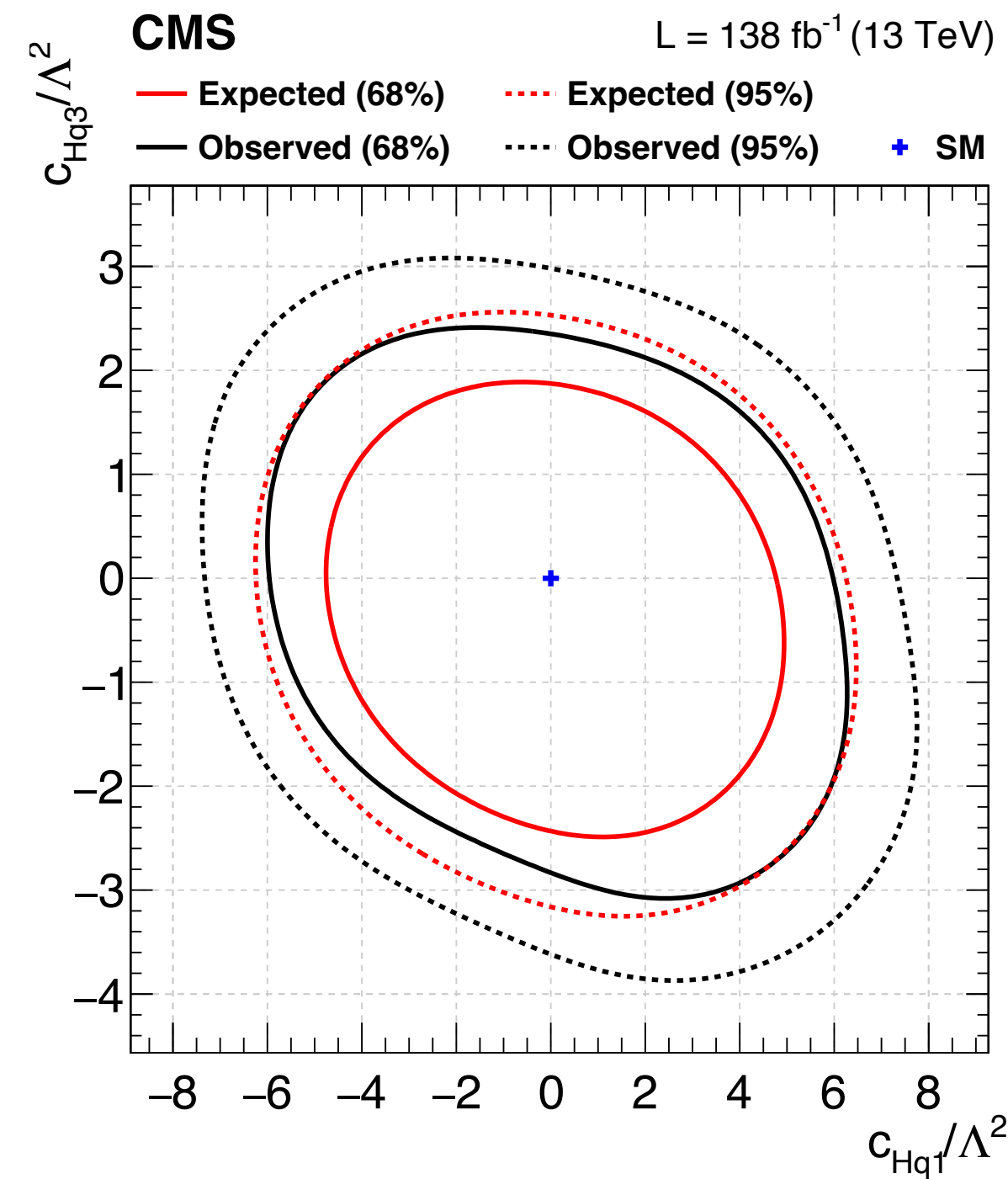
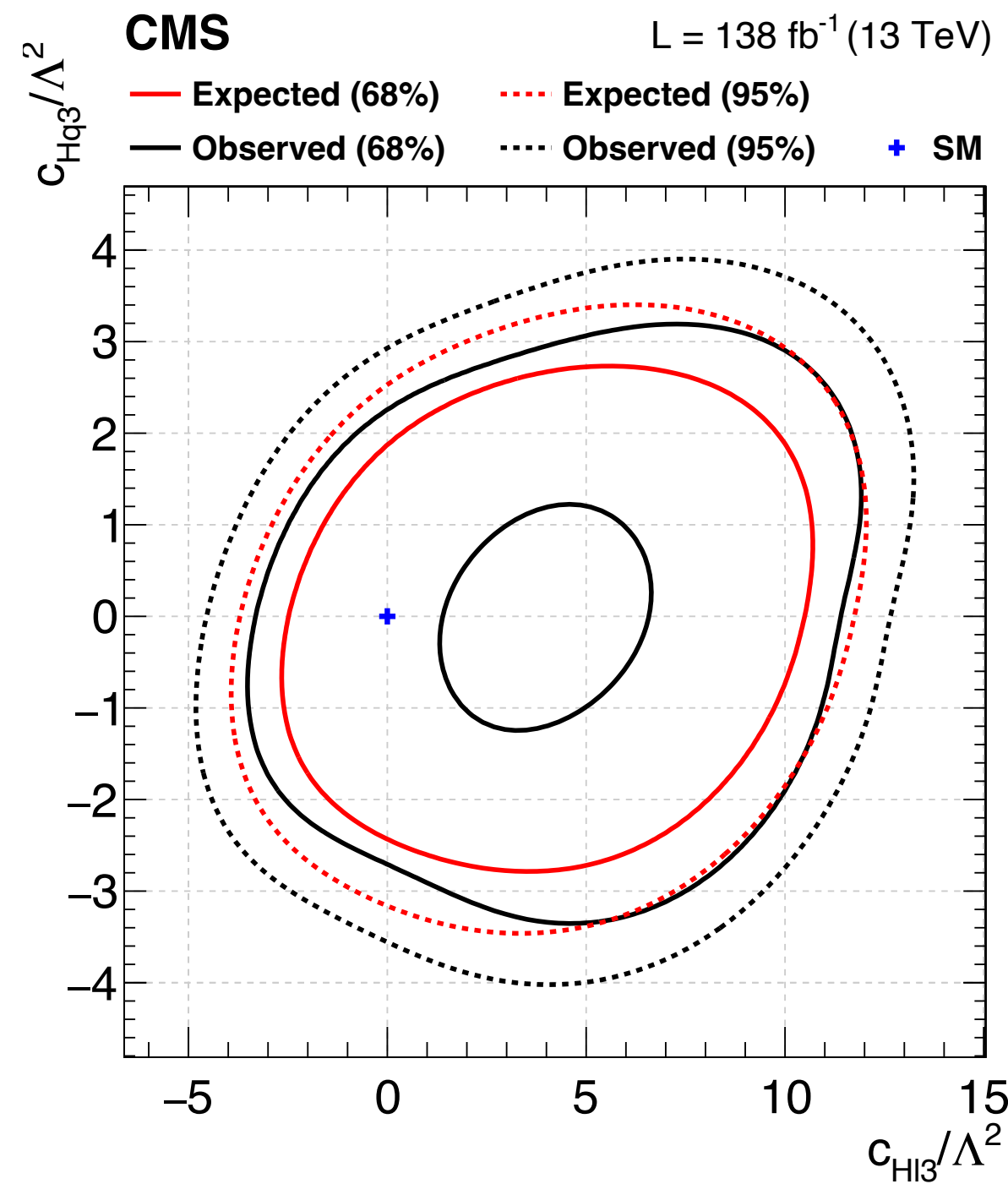
Bosonic operators



Considering only dim-6

First time with VBS

Mixed operators

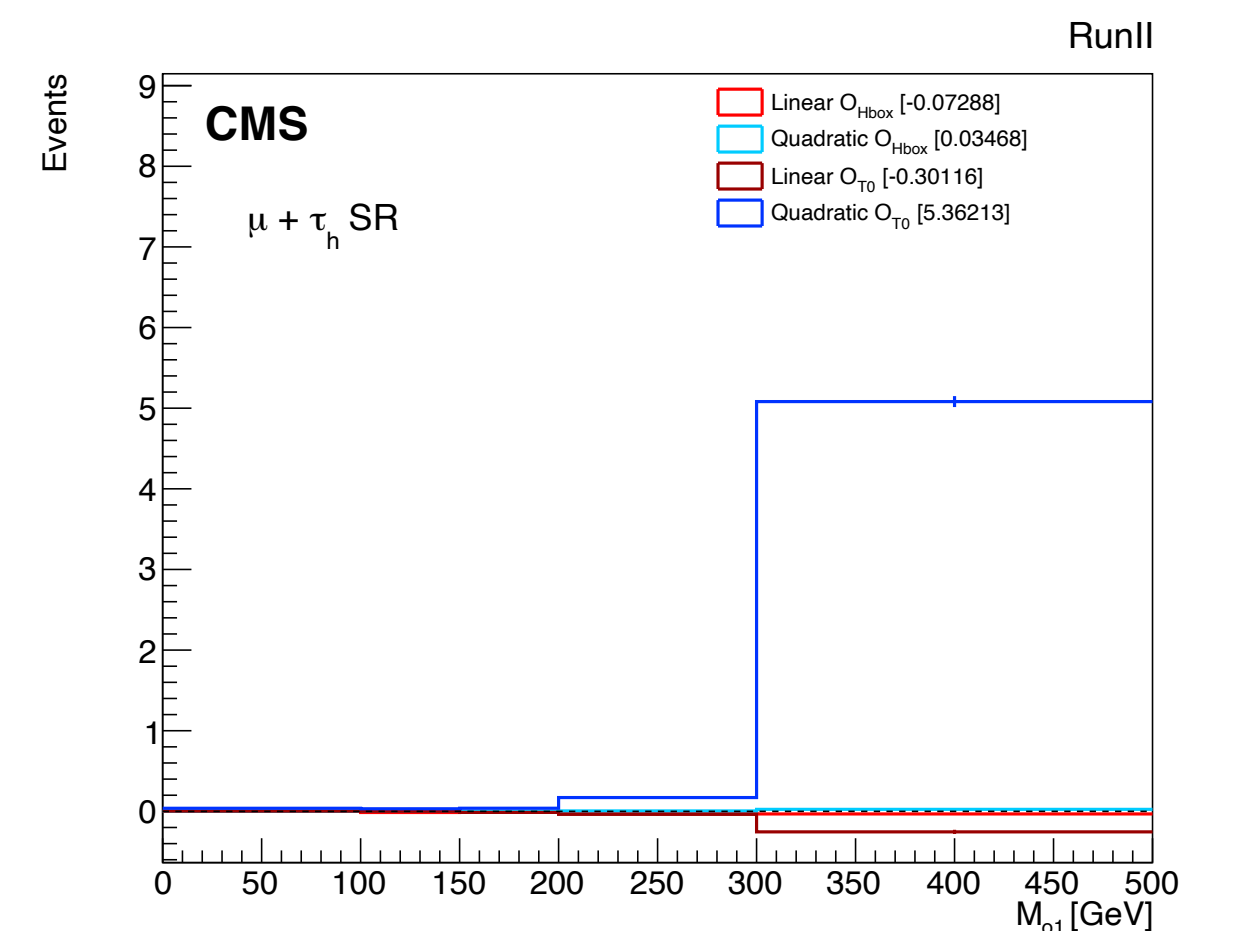
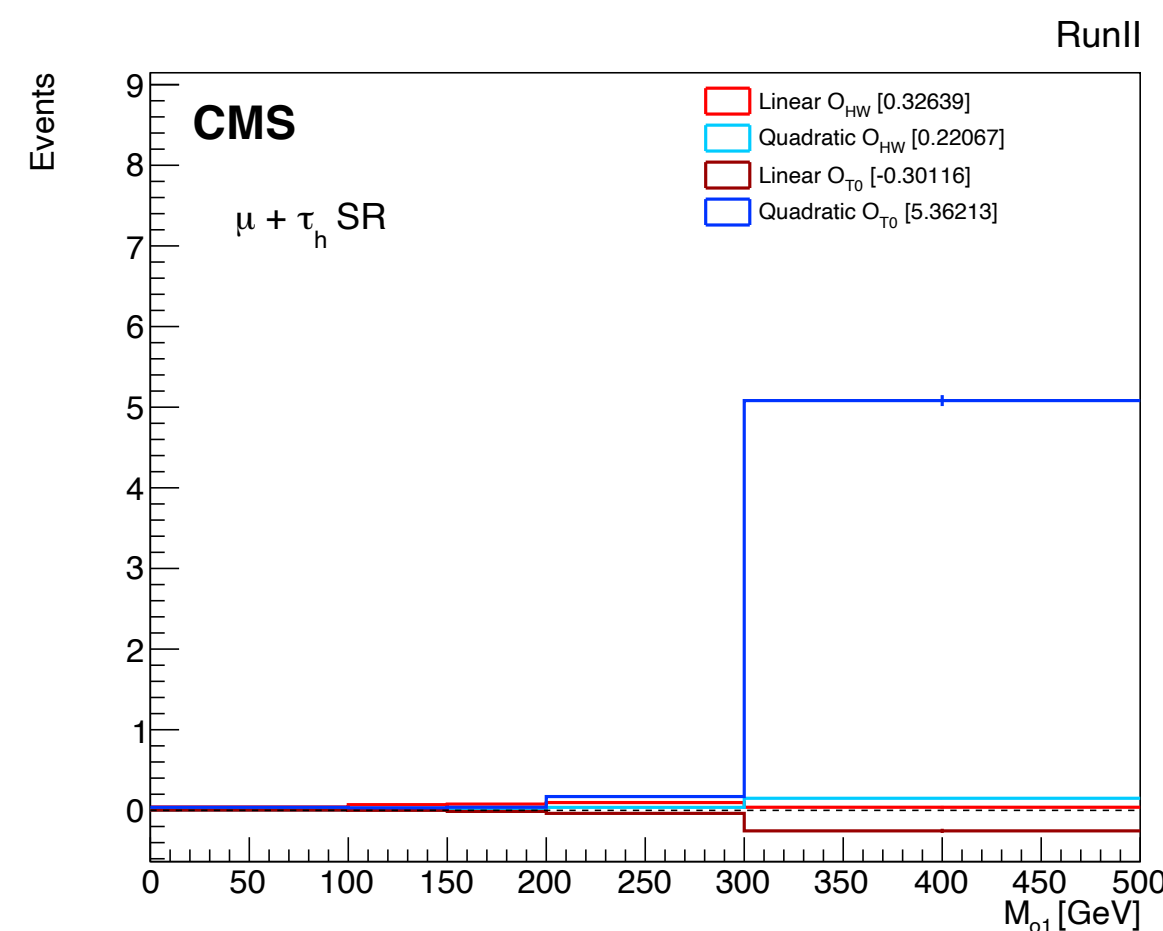
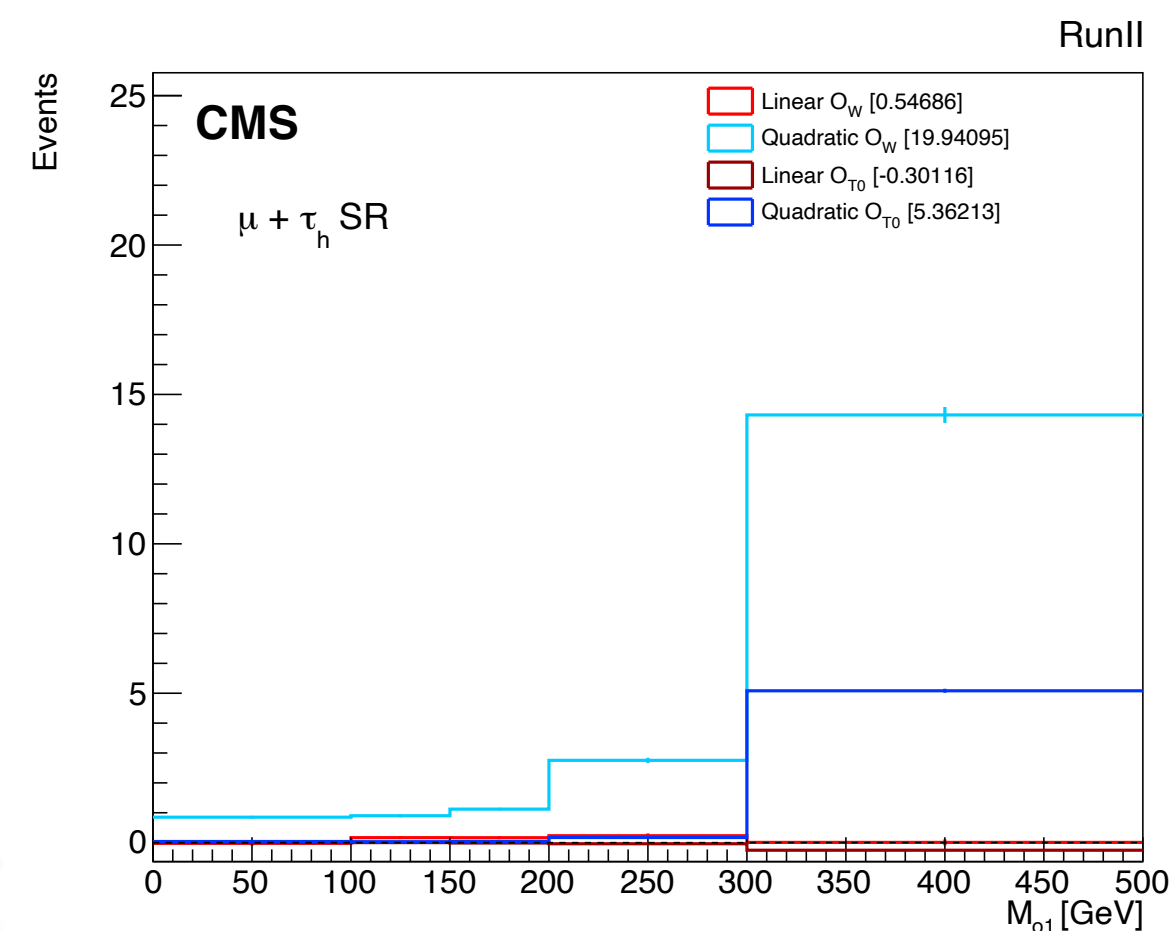
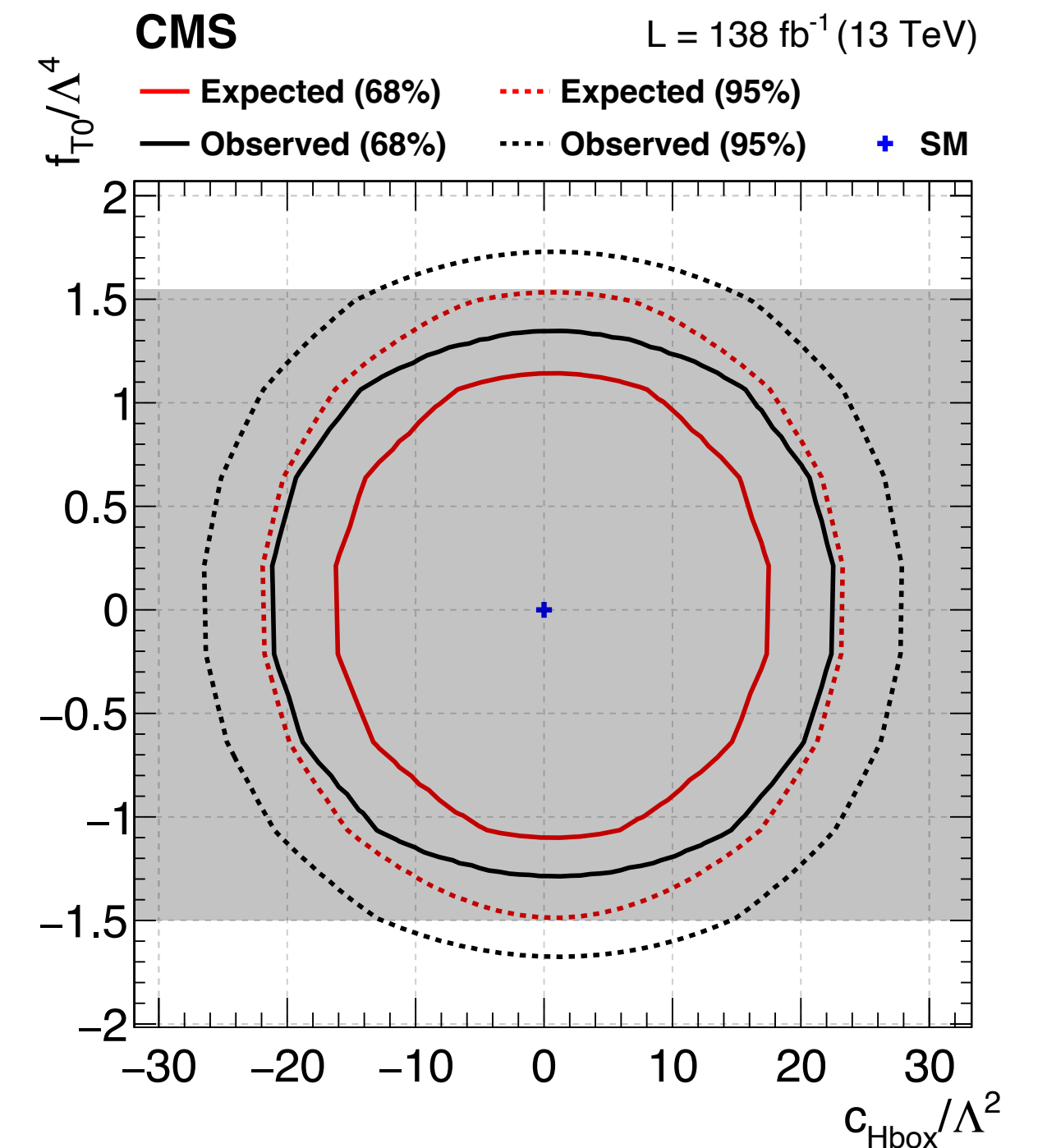
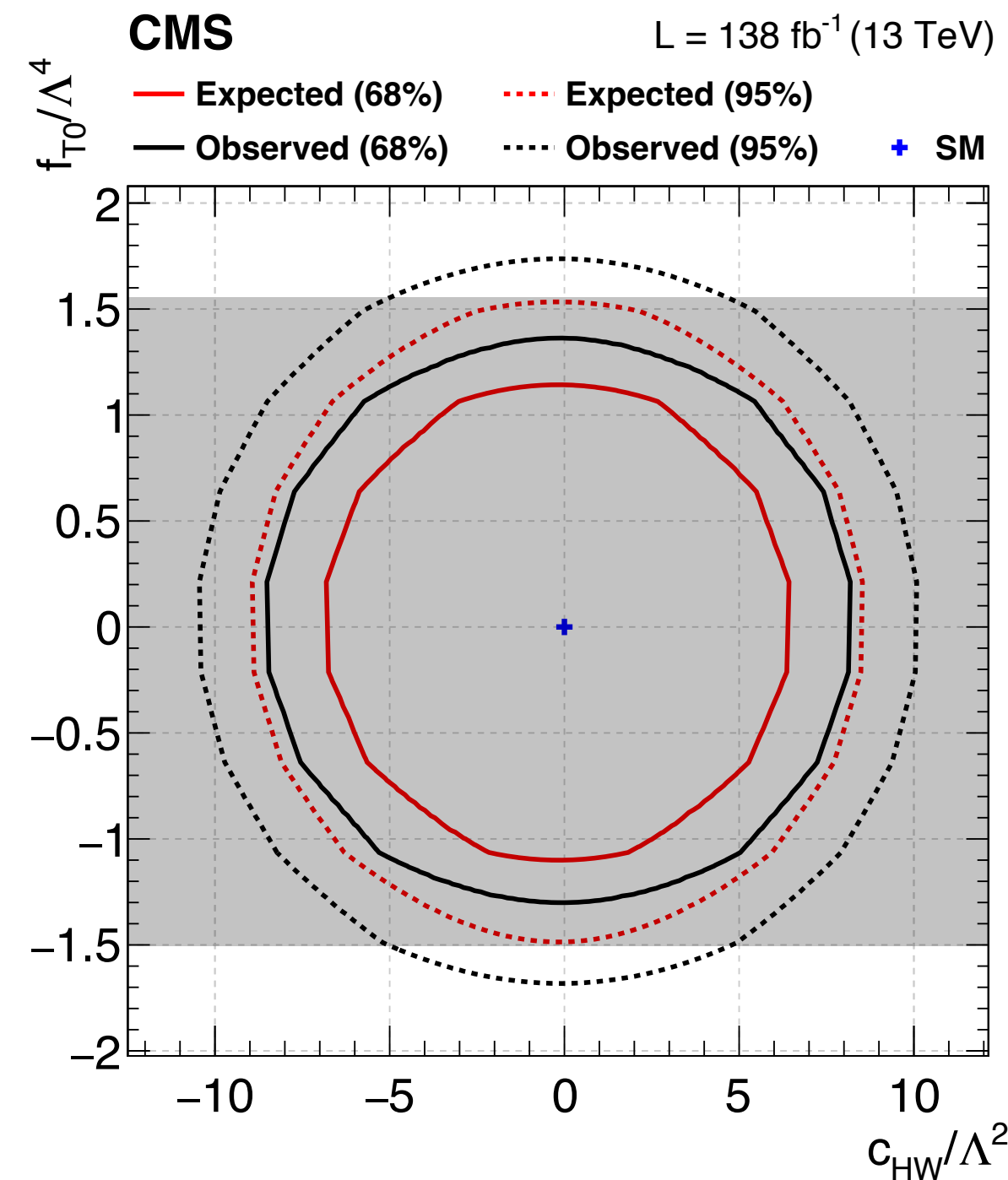
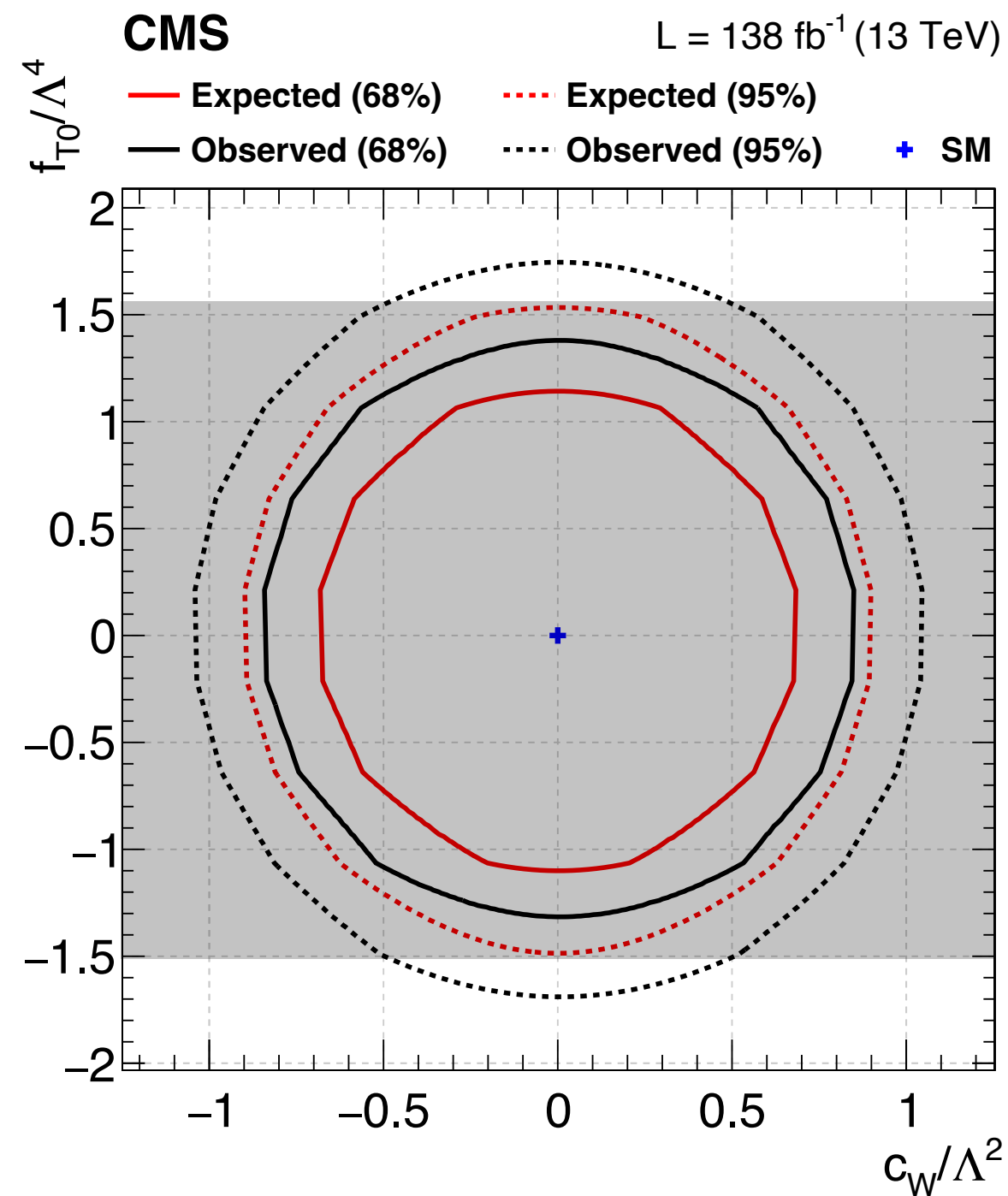


Adding up dim-6 and dim-8

First time ever

dim-8 1D 95% CI

Bosonic operators



Matching with BSM

From [arXiv:2311.16897](https://arxiv.org/abs/2311.16897)
Example with Z2RSE model

$$\phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG_0) \end{pmatrix}, \quad S = \frac{v_s + h_2}{\sqrt{2}}$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\chi & -s_\chi \\ s_\chi & c_\chi \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Benefits from including dimensions consistently with power counting

- More consistent results in terms of experimental findings
- Preserving model independence in EFT approach
- Unlock reliable matching with BSM models
 - Better hints on where NP hides

