UNIVERSITY OF NOTRE DAME

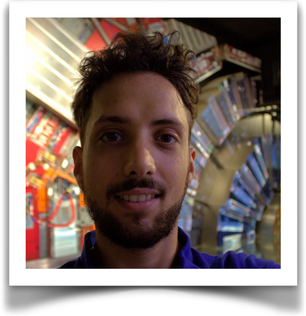
Chasing down New Physics with massive particles at the LHC with CMS

Andrea Piccinelli (University of Notre Dame)

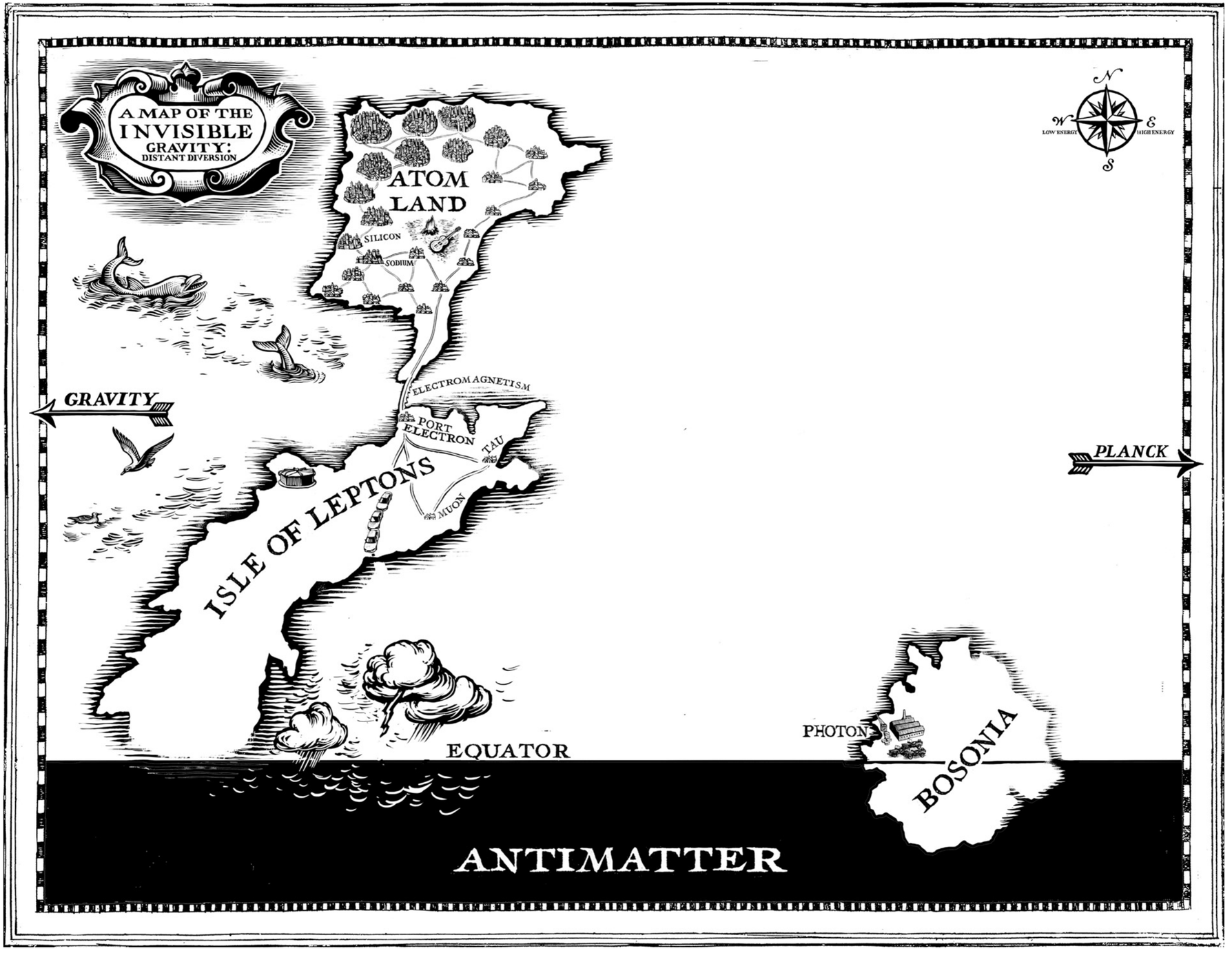
Fermilab - Batavia, November 13th 2024

The journey

A physics student's perspective



at the end of Bachelor's

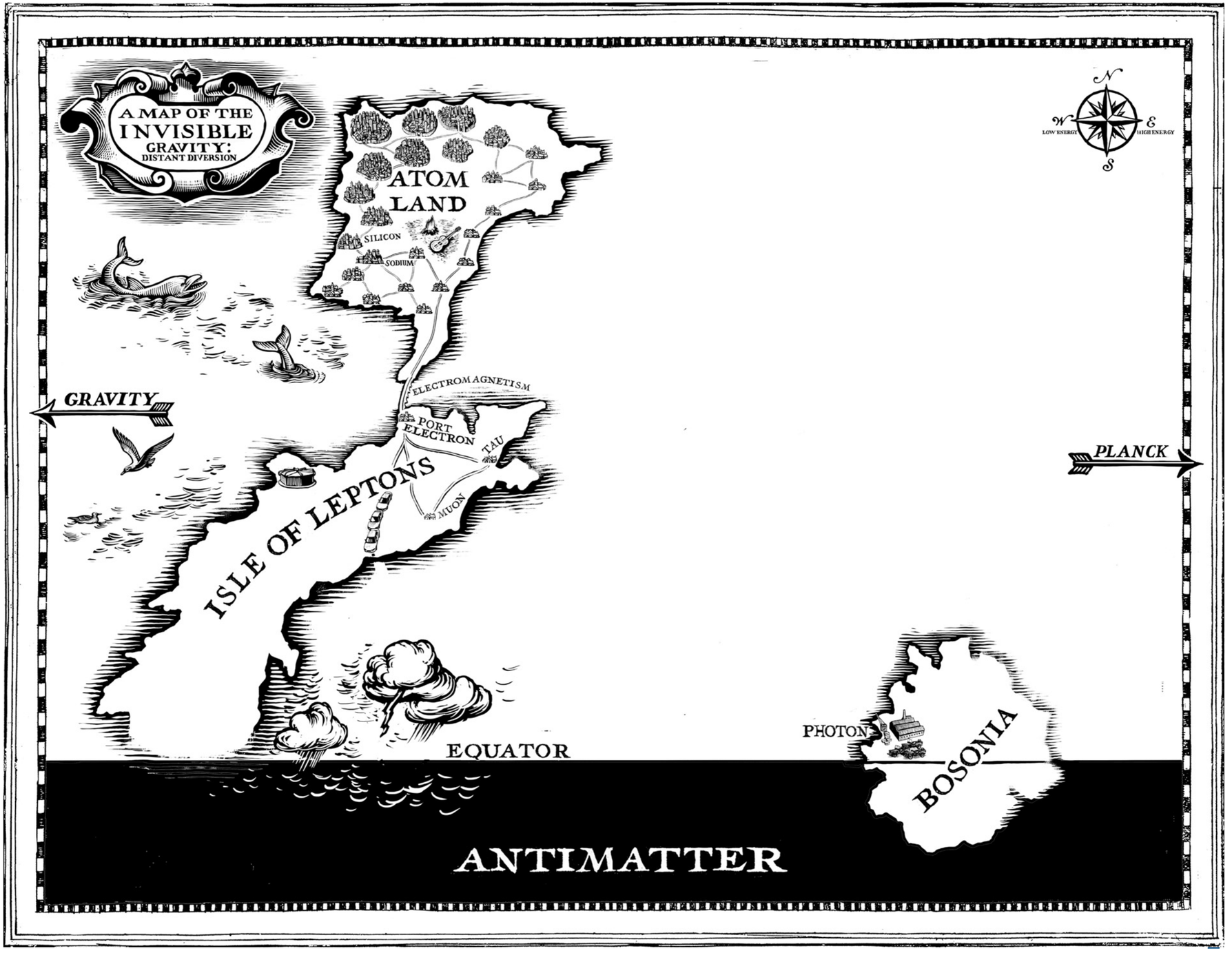


The journey

A physics student's perspective

I like navigating
this particle sea!
No relativity to deal with!

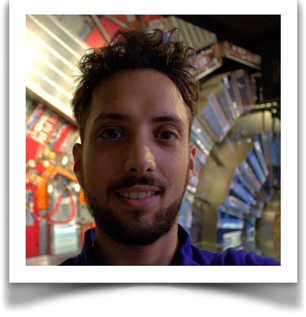
at the end of Bachelor's



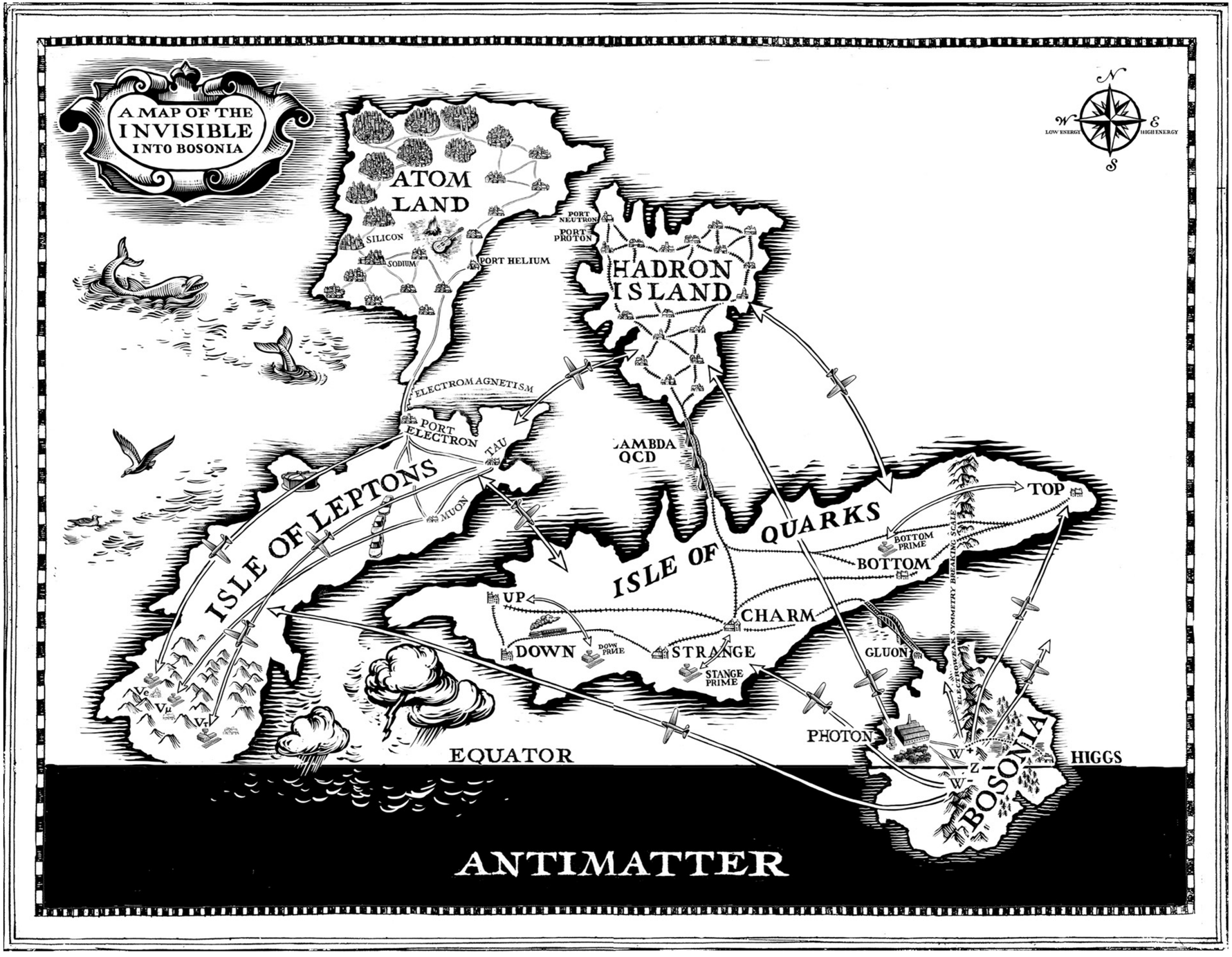
The journey

A physics student's perspective

Such a great job, SM!
What if general relativity actually matters?



during Master's



The journey

A physics student's perspective

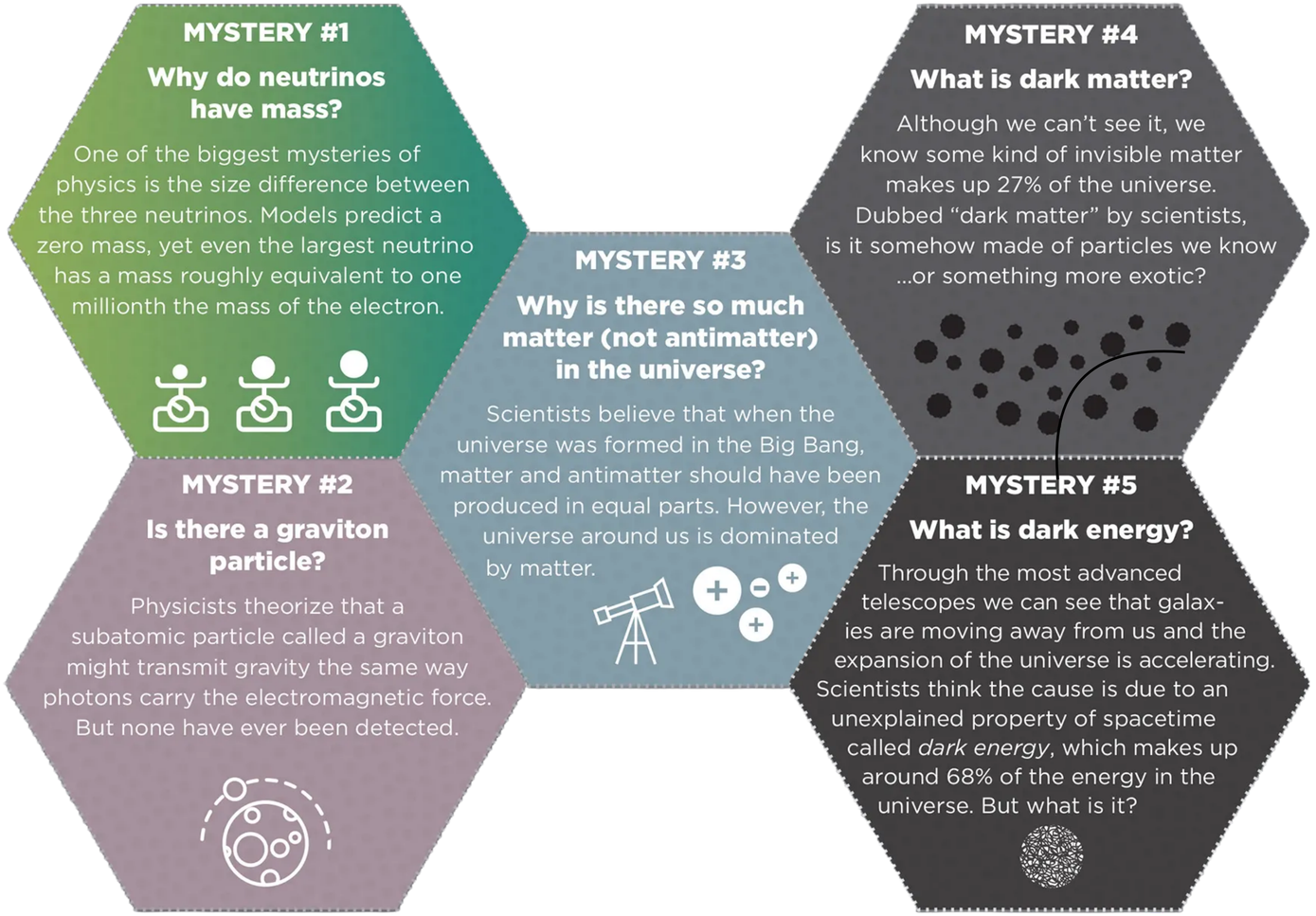
Wow, plenty of room for discovery! Let's chase down new phenomena!

when picking a PhD project

All the maps coming from
"A map of the invisible. Journeys into particle physics"
(Jon Butterworth)

Why we need to extend SM?

The question we are willing to answer



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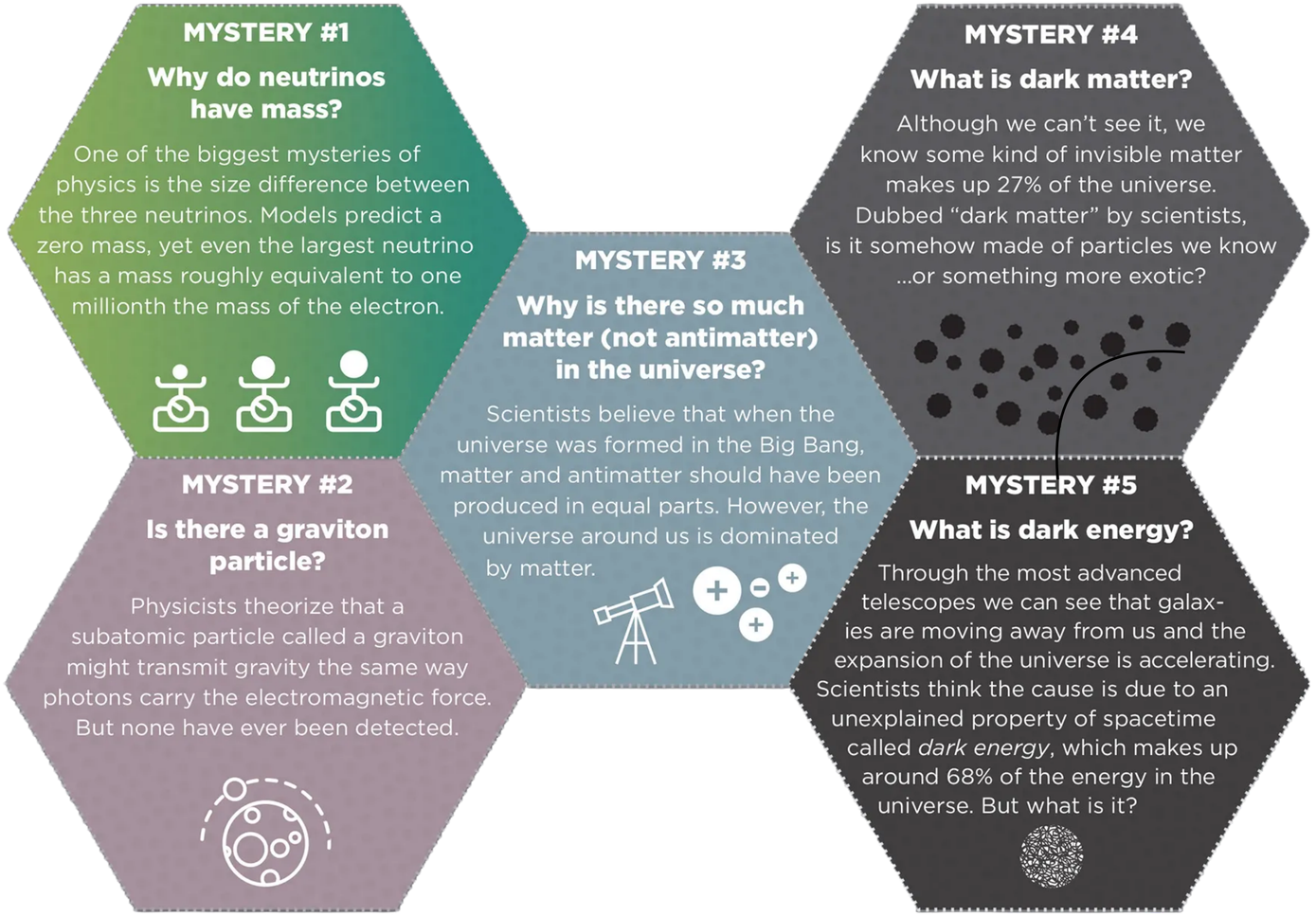
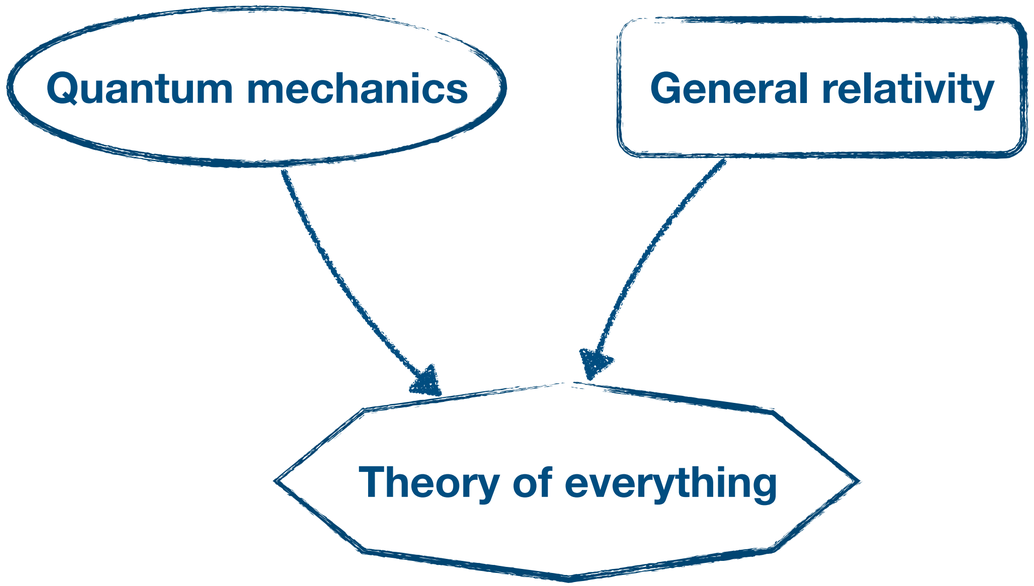


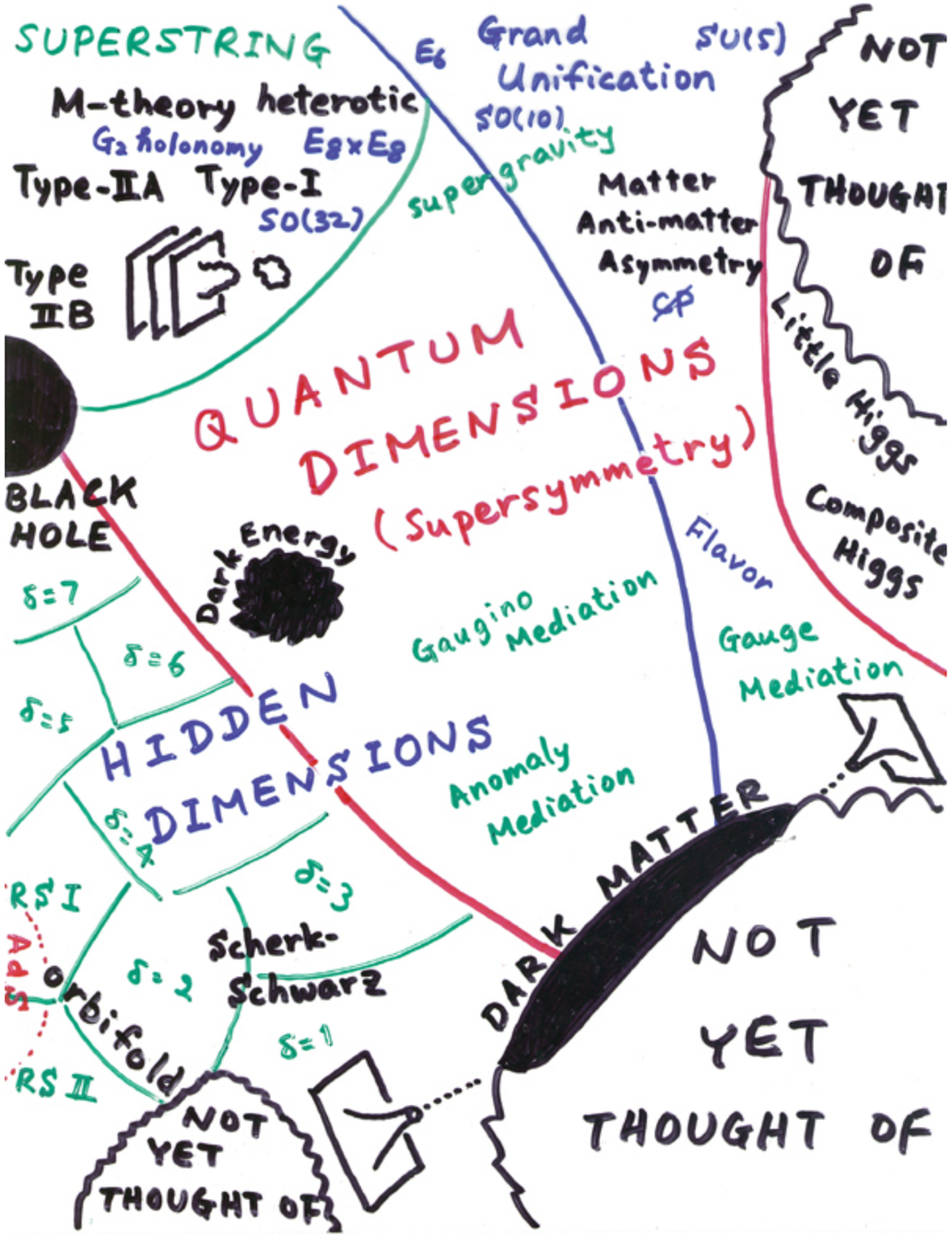
Desired solution



Any good ToE candidates?

The ultimate theory

Plenty of candidates from theory departments!

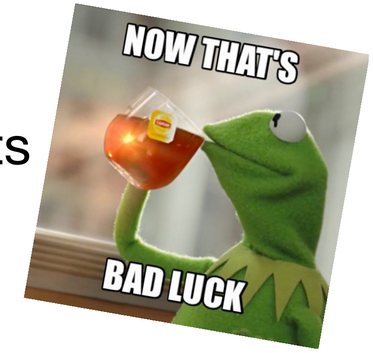


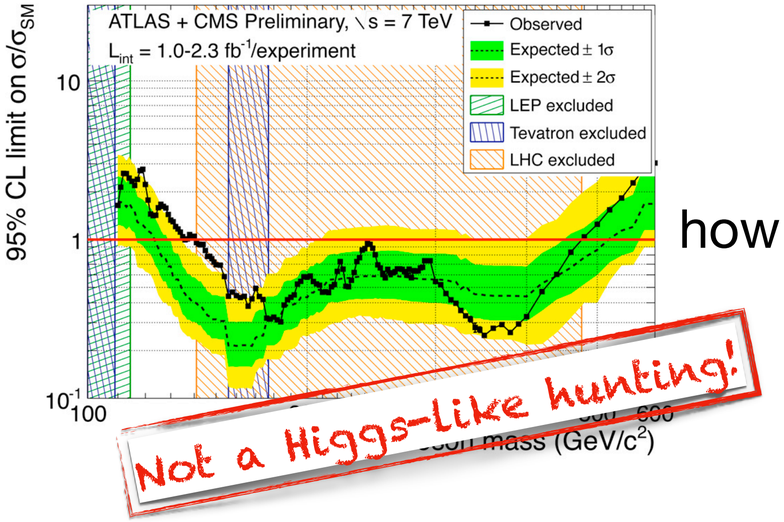
Any good ToE candidates?

The ultimate theory

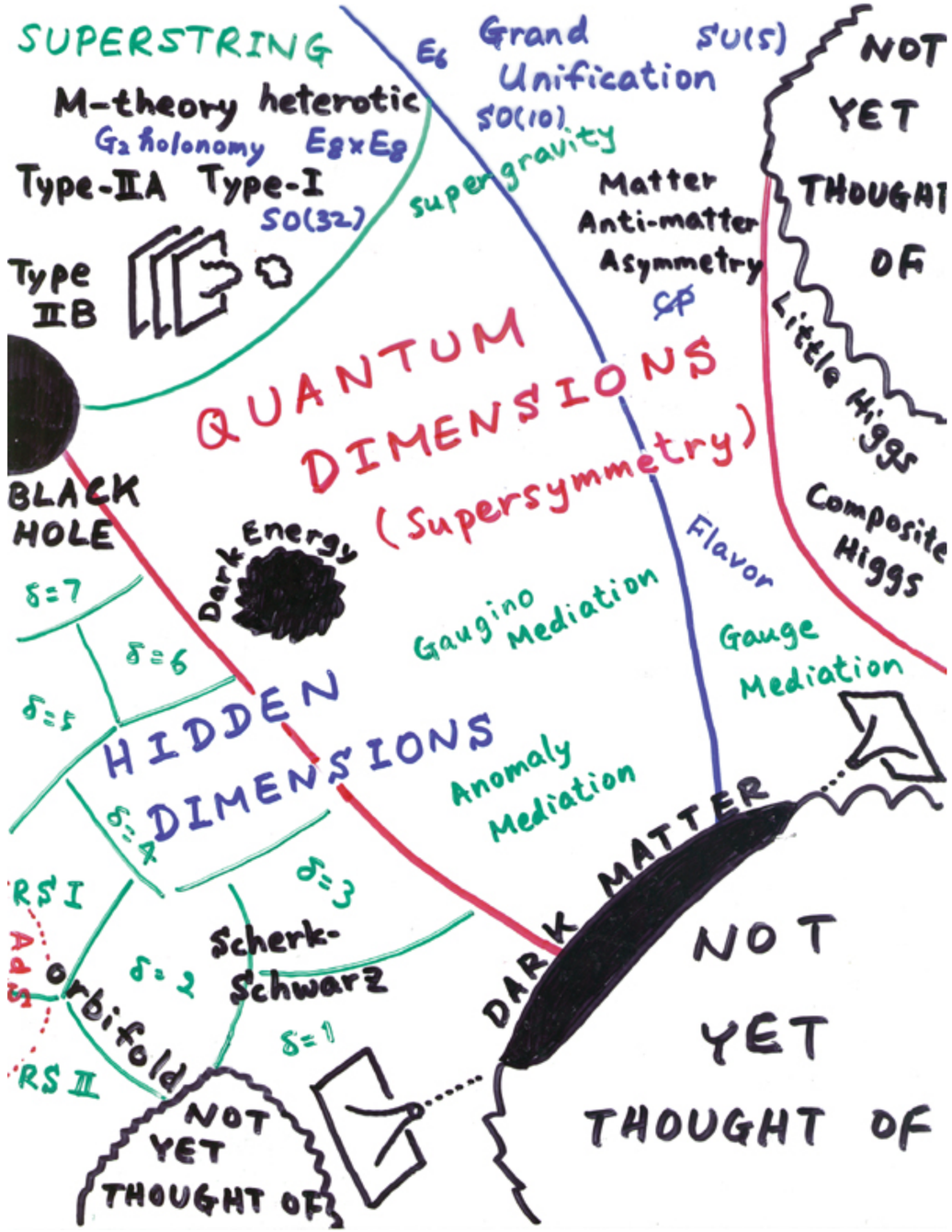
Plenty of candidates from theory departments!

No clear “preference” from experimental results

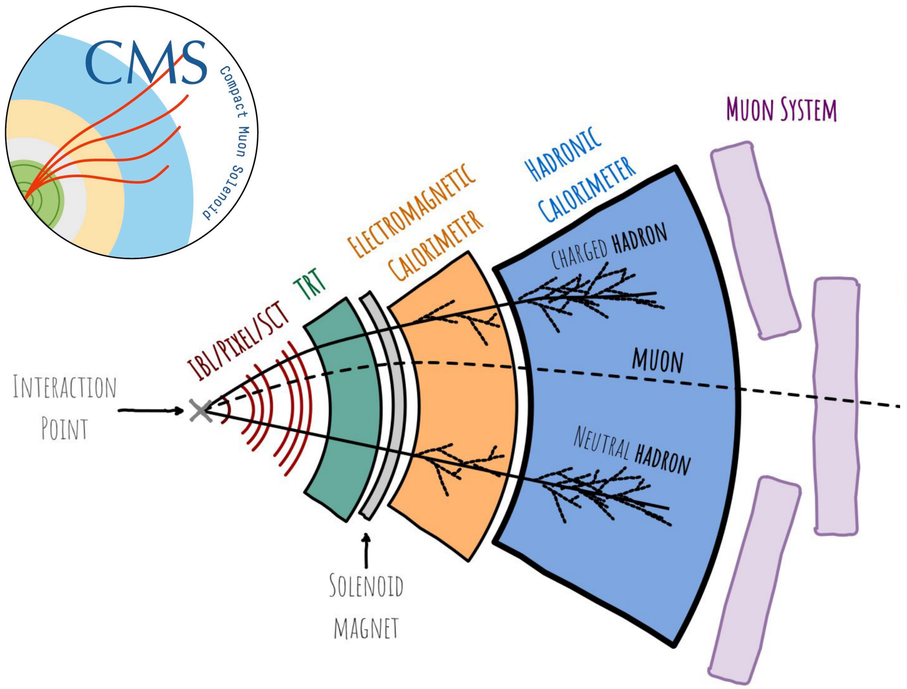




If we don’t have a clear target, how to run searches with efficacy?



What we get from the experiment?



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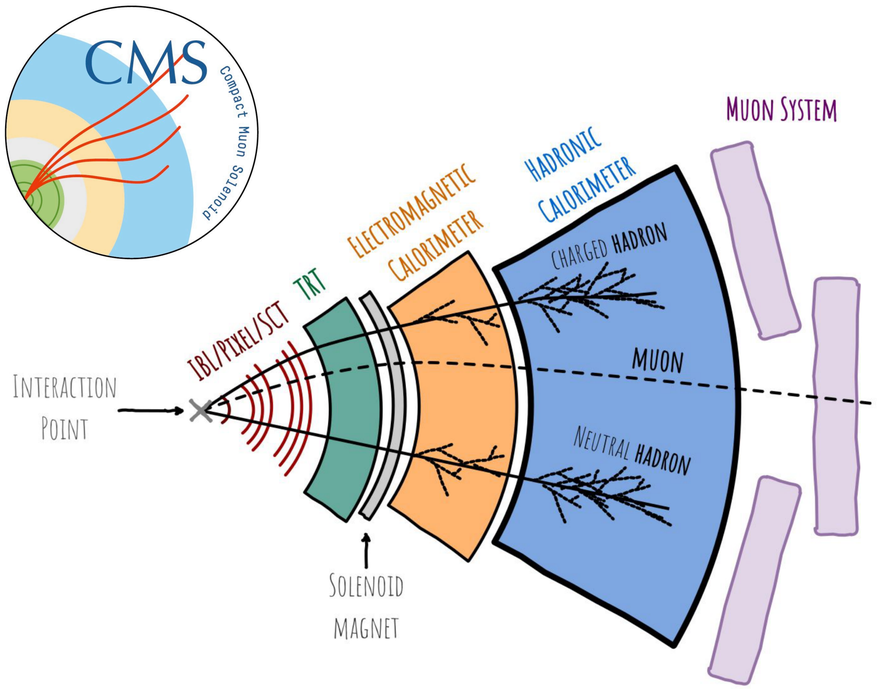
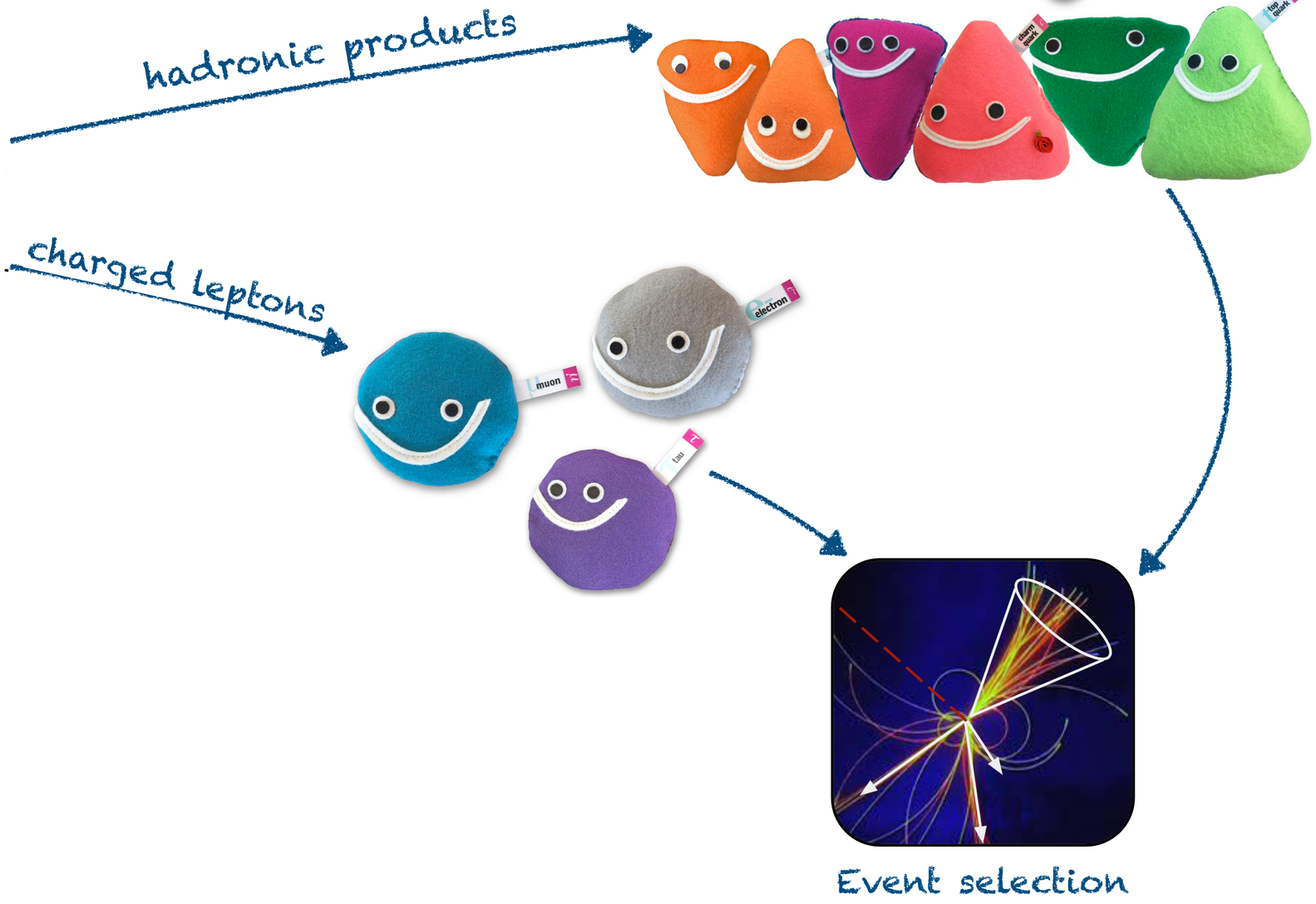
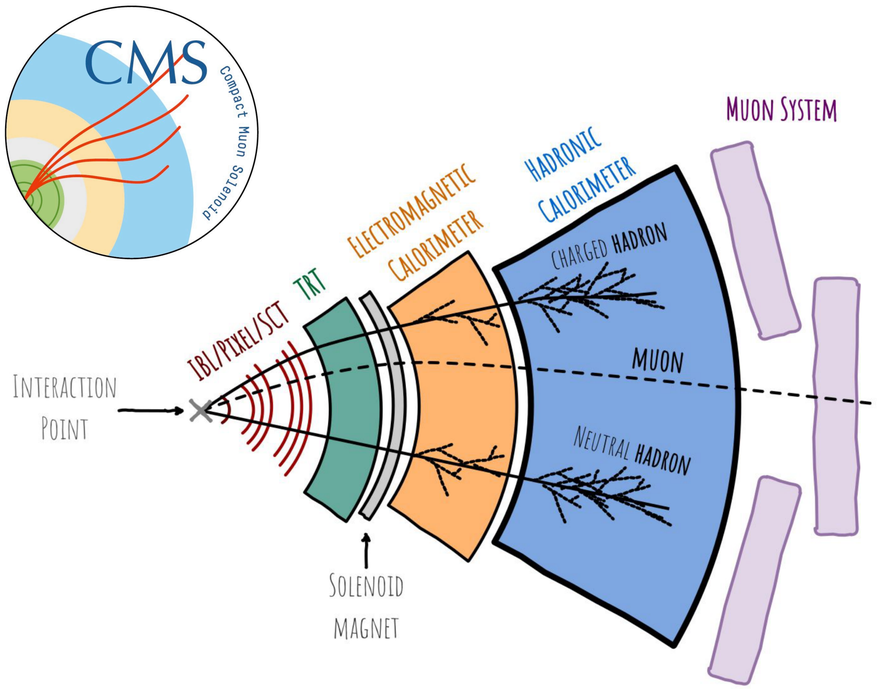




Event selection

What we get from the experiment?



hadronic products

charged leptons

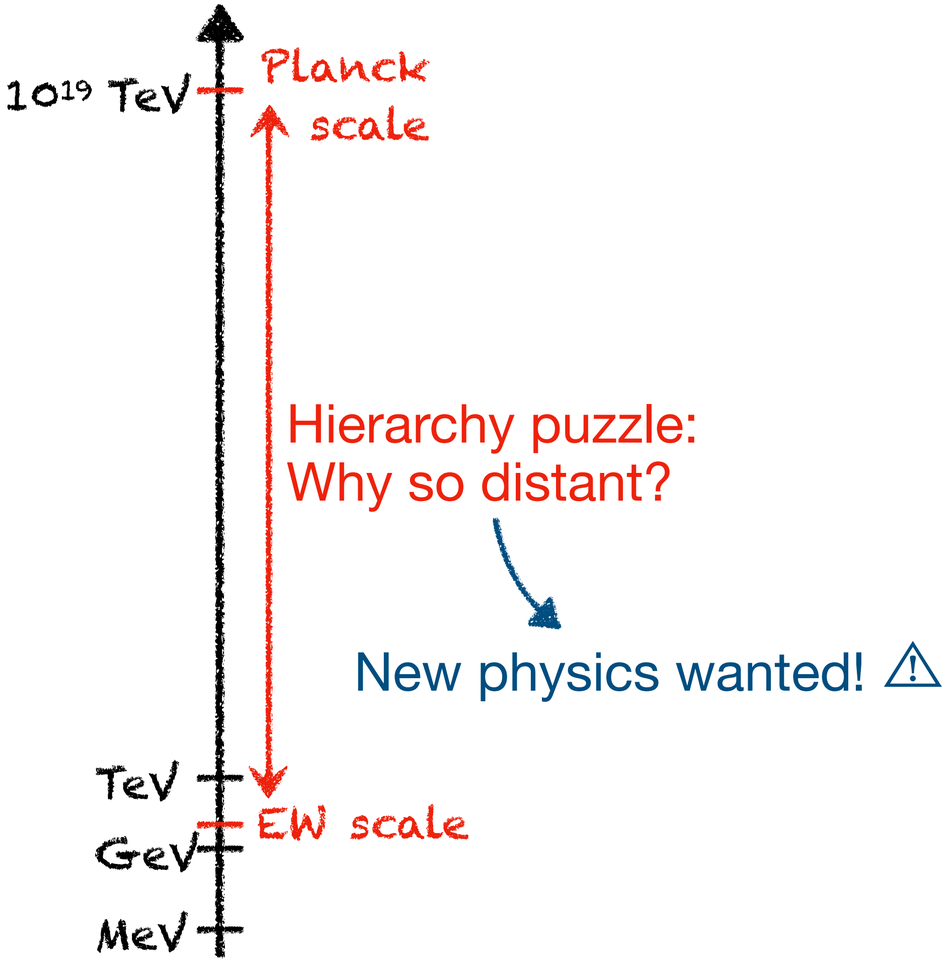
Which direction?

NP expedition

Event selection

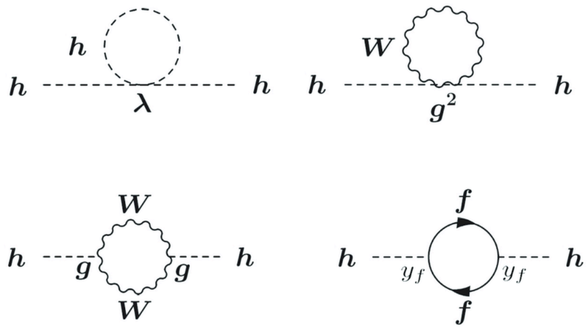
A route to new phenomena

A route to new phenomena



Set of probes for NP

A route to new phenomena



Hierarchy puzzle:
Why so distant?

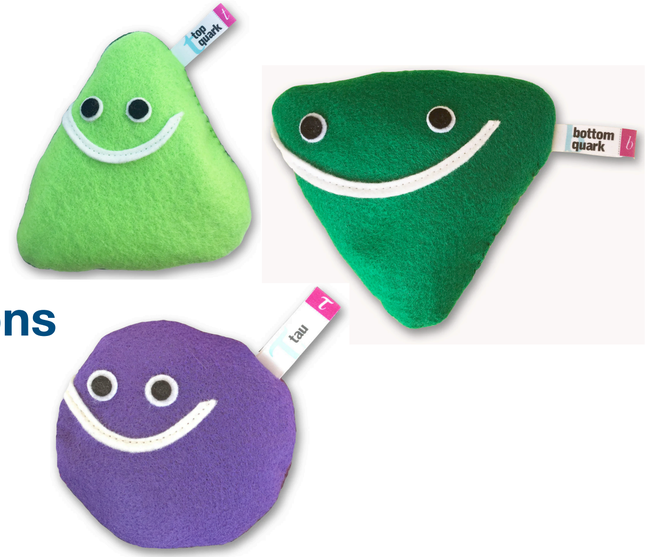
New physics wanted! ⚠

Third-gen special role?

EWSB mechanism sensitive to NP

Set of probes for NP

Massive bosons



Massive fermions

Where does the route lead?

A direction for the ship

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Pick a specific NP candidate?
Fascinating, but strong assumptions!

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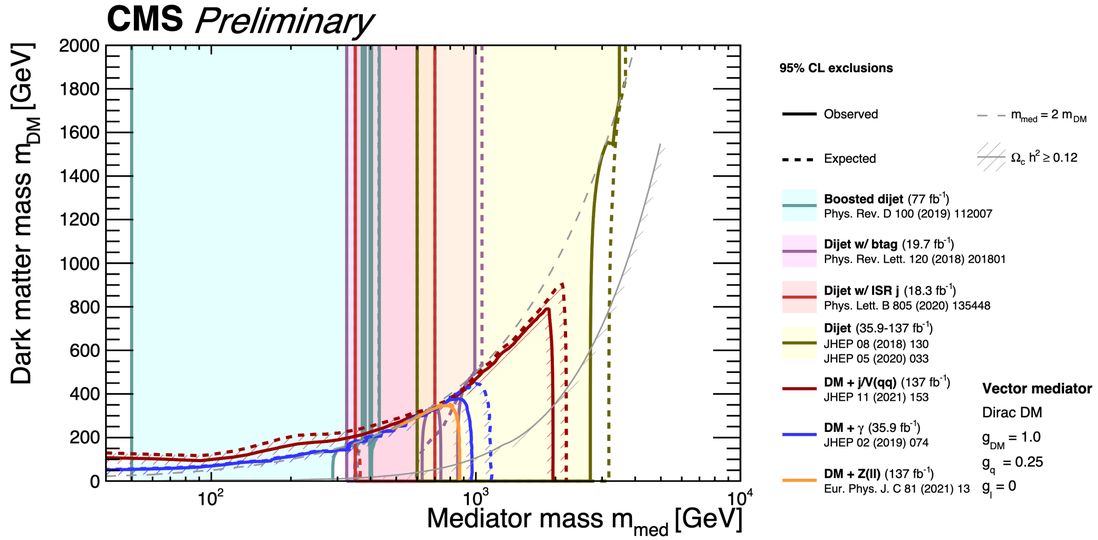
Sensitivity of a single study
restricted to a specific phase space



Connecting with theory

Adopting a wider point of view: approach #1

Several NP models predict new interactions

Minimal SM extension with new gauge bosons
Sequential Standard Model

Connecting with theory

Adopting a wider point of view: approach #1

New W-like boson!

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

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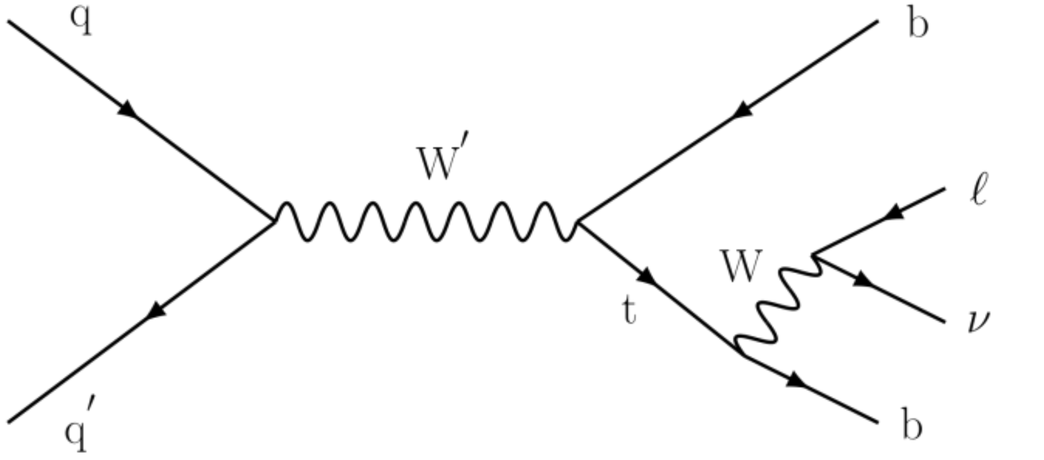

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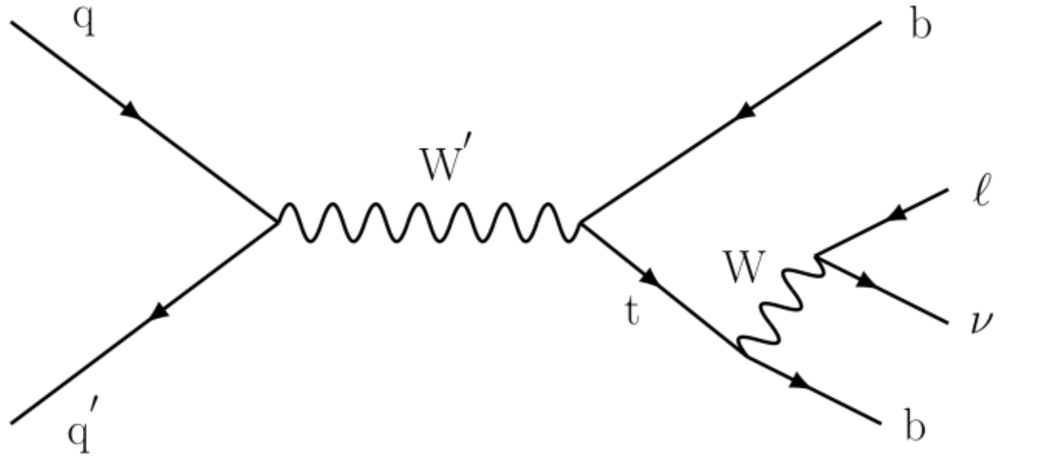

Searching for a W’

10.1007/JHEP 05 (2024) 046

New massive W’ boson

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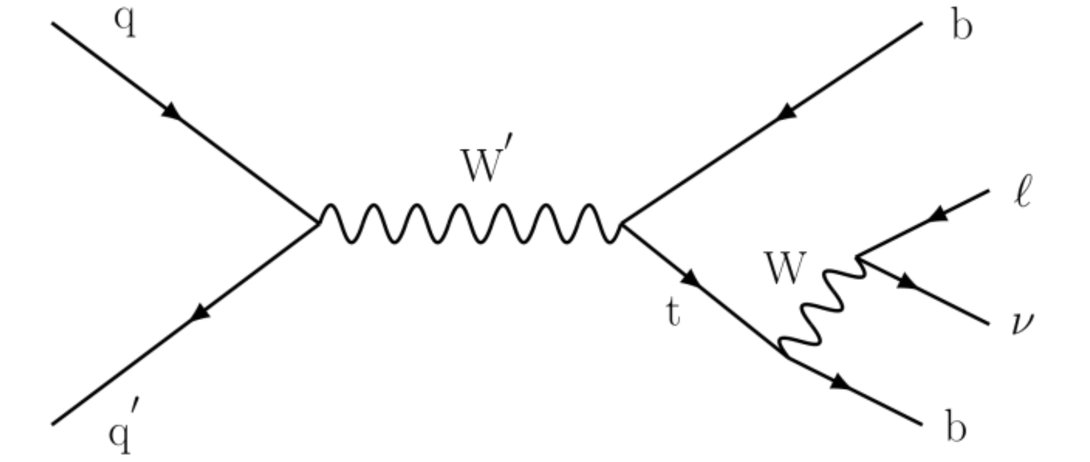

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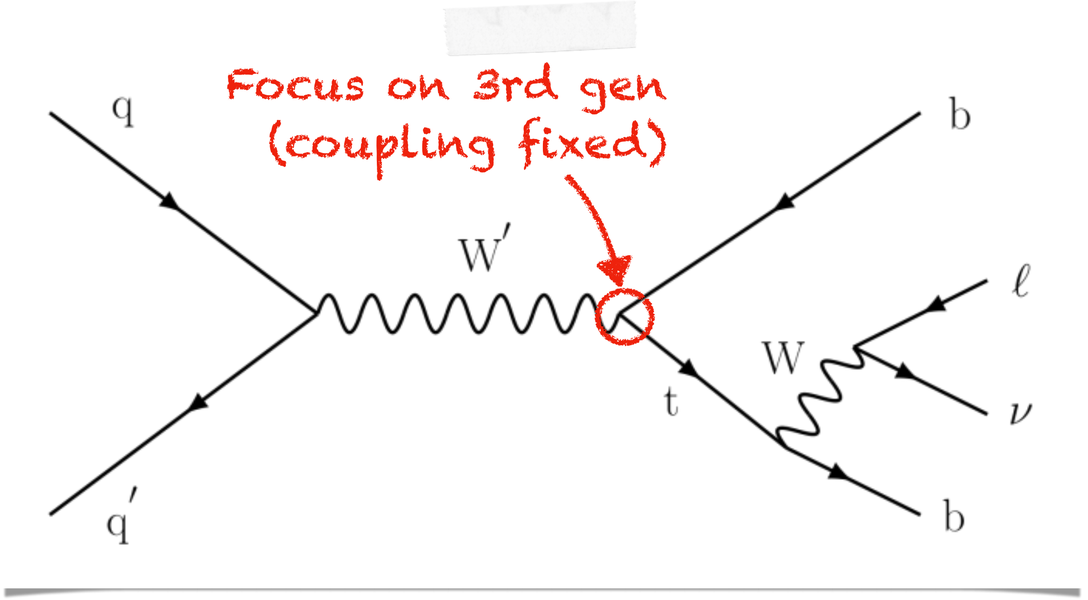
- EW-like interaction

  $V_{f_i f_j} = V_{CKM} \qquad g_{W'} = g_{EW}$

- Mixed couplings varying α_R, α_L
  - only RH coupling: $\alpha_R = 1,\ \alpha_L = 0$
  - only LH coupling: $\alpha_R = 0,\ \alpha_L = 1$



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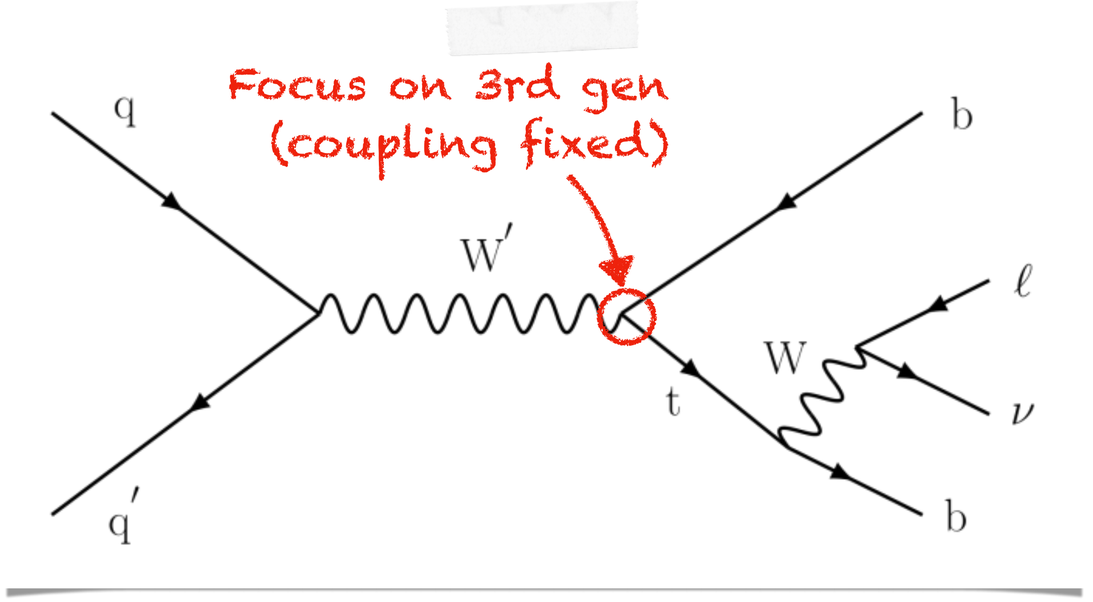
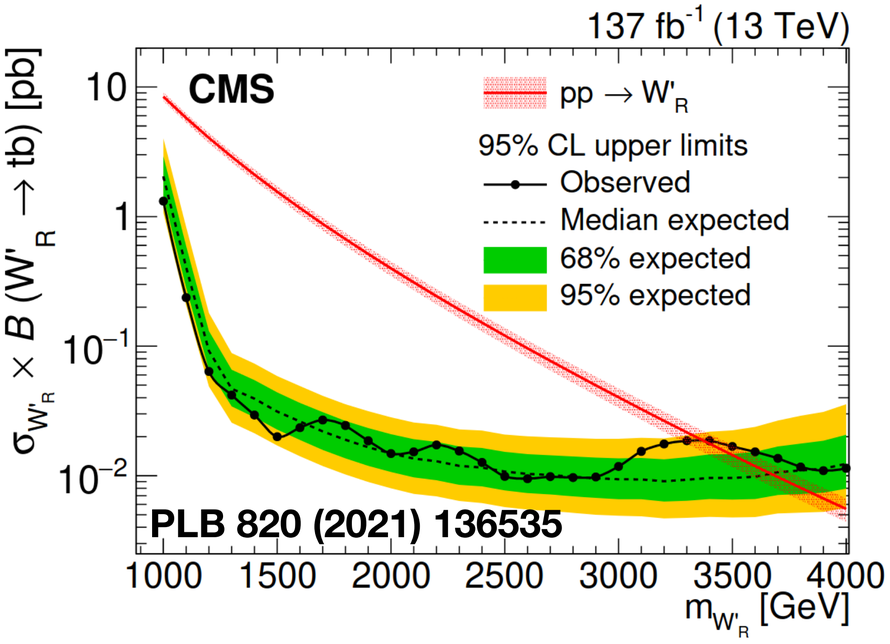
- EW-like interaction

  $V_{f_i f_j} = V_{CKM} \qquad g_{W'} = g_{EW}$

- 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

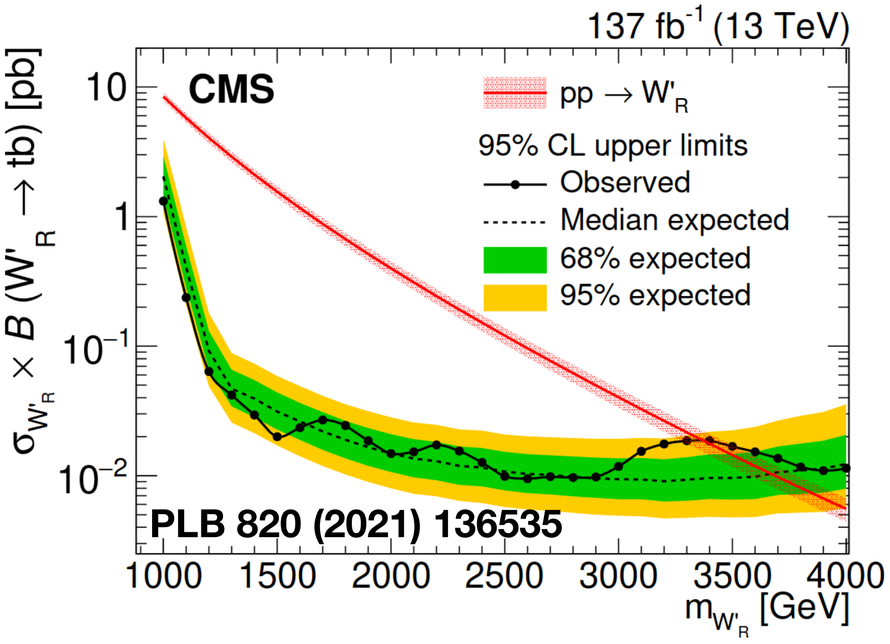


Targeting the final state



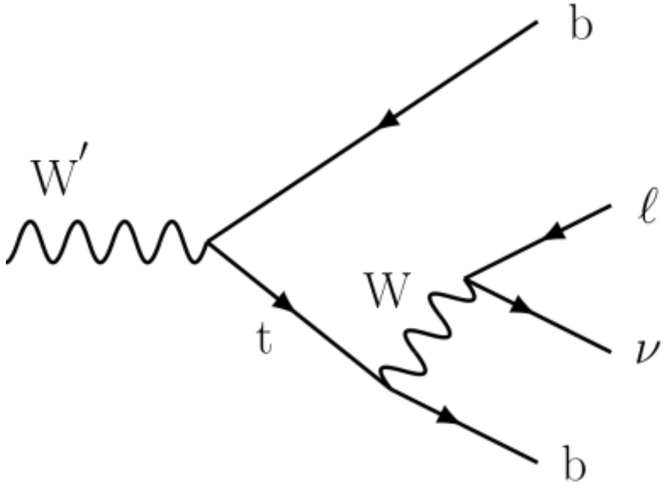
Complementing the hadronic search

Targeting the final state



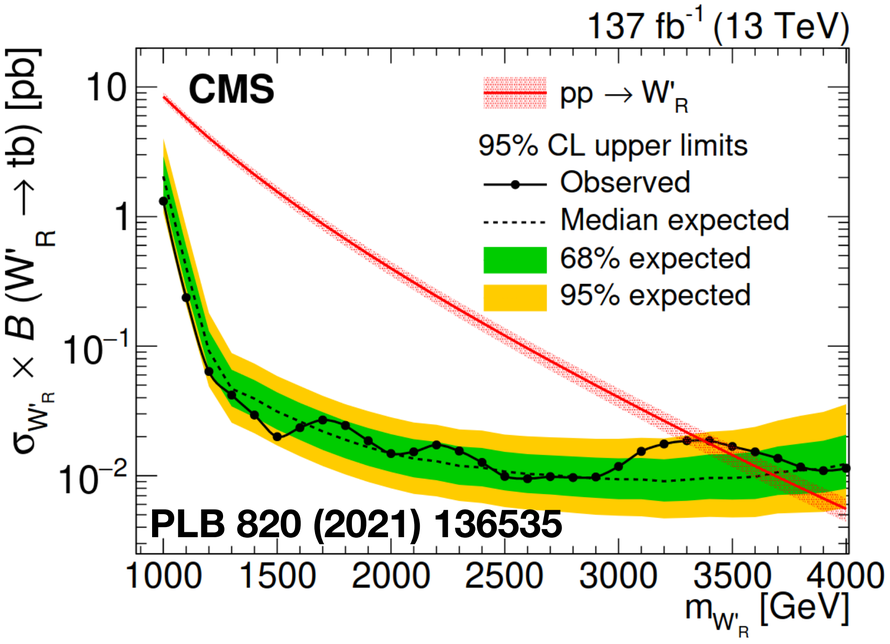
Complementing the hadronic search

Theory perspective



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

Targeting the final state



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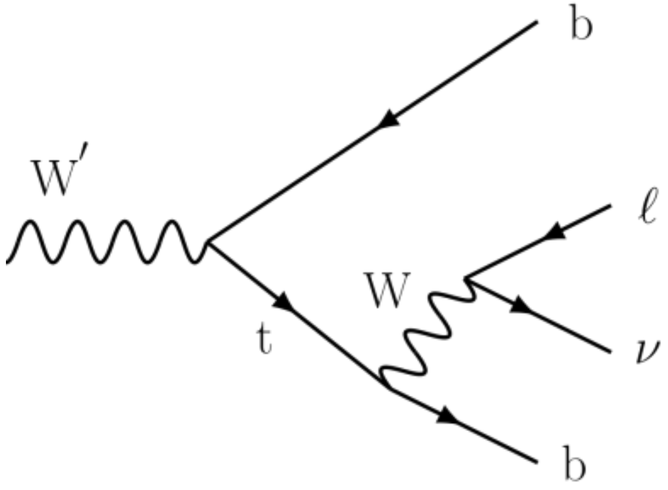
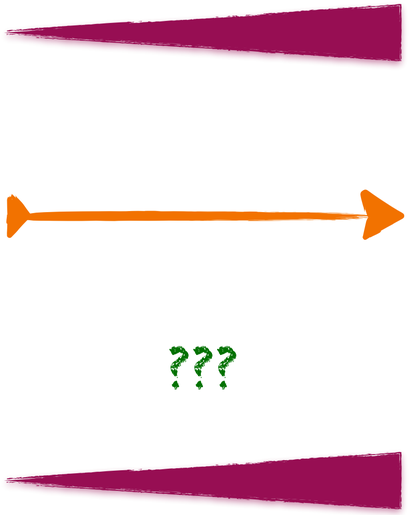
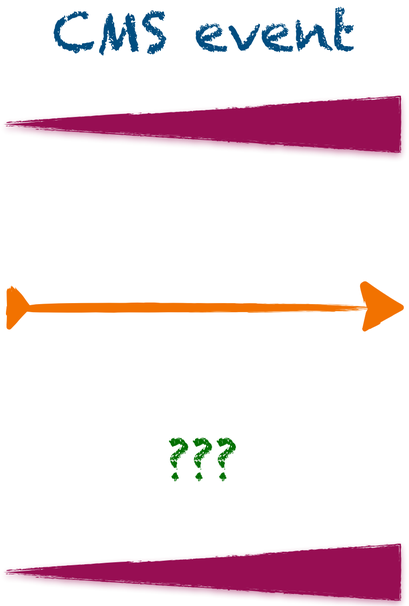


CMS event

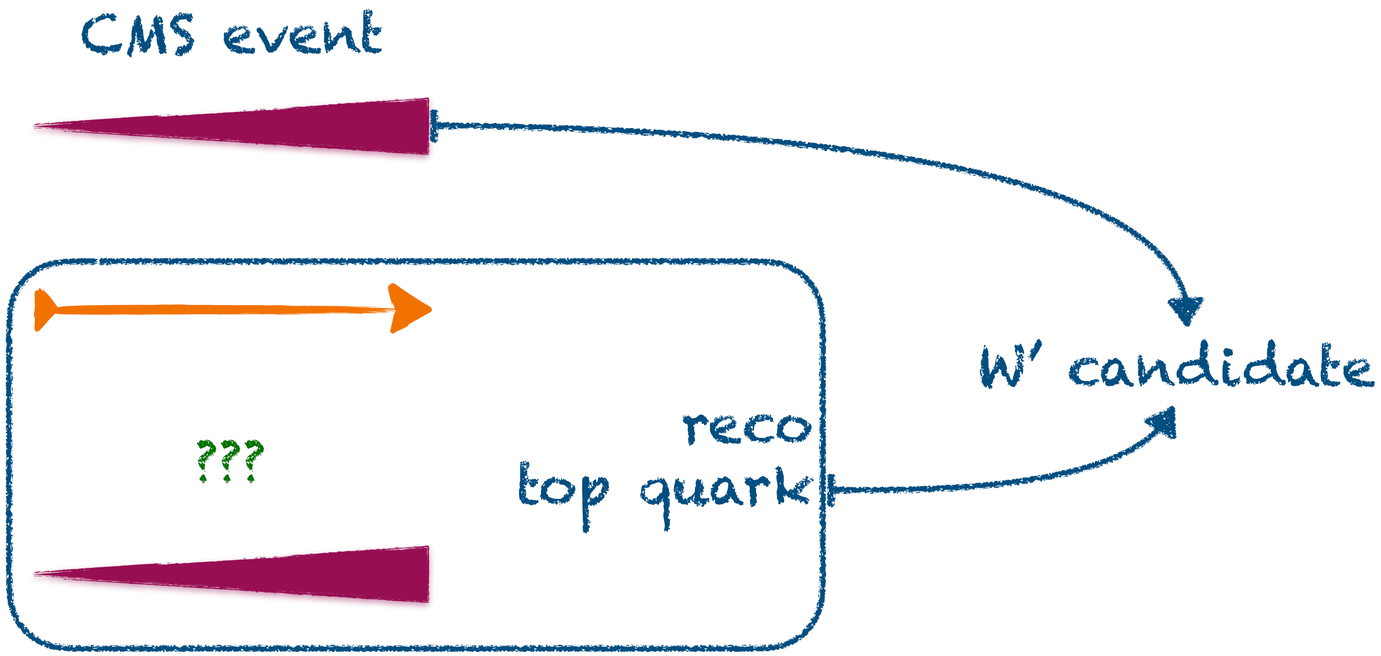


- Semi-leptonic top decay
  - $\ell = e,\ \mu$ — reco leptons
  - ν_ℓ — missing energy
  - b quark — hadronic jet
- b quark from W' — hadronic jet

Ready to hunt a W'!



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

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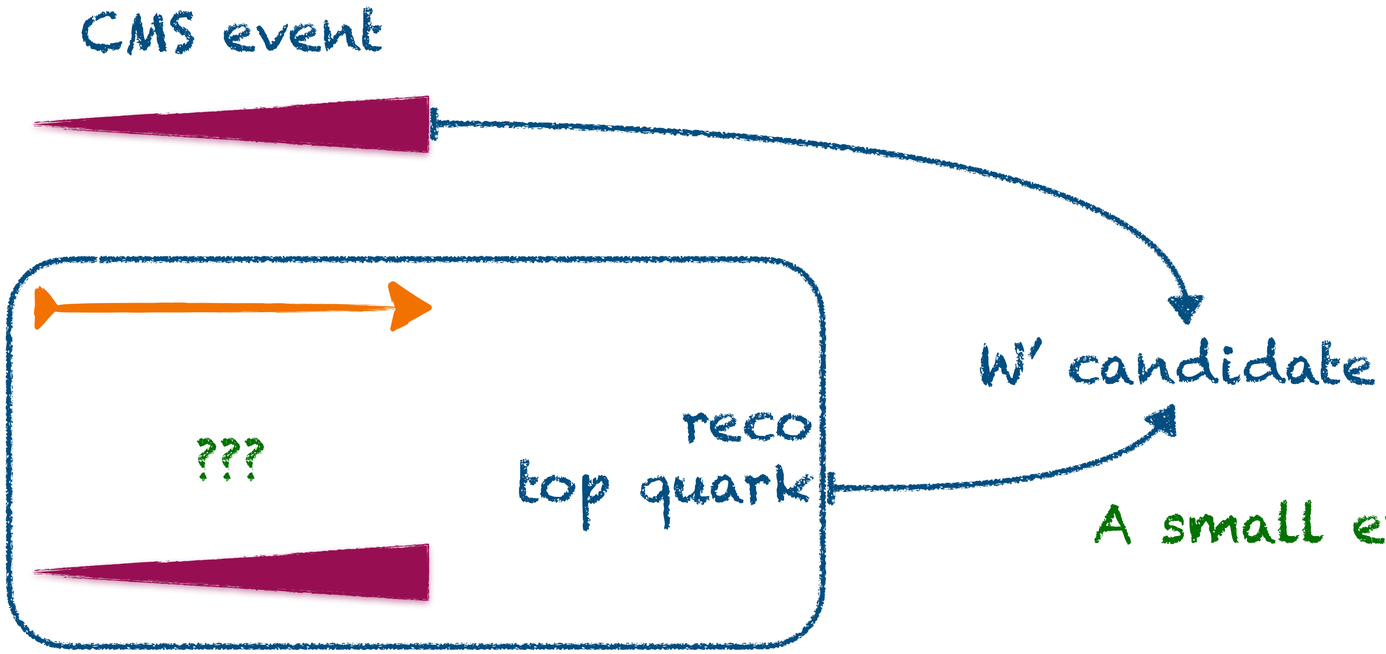

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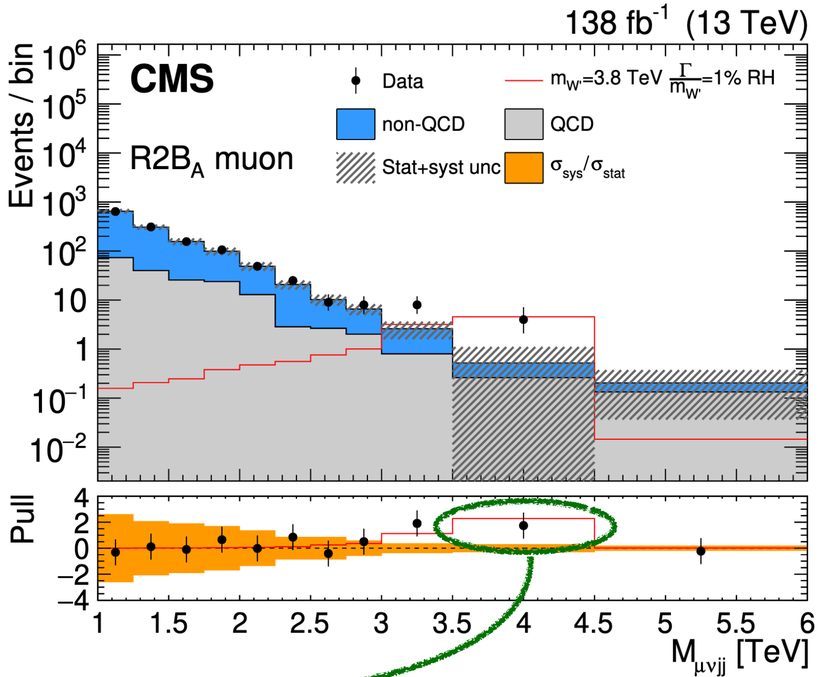
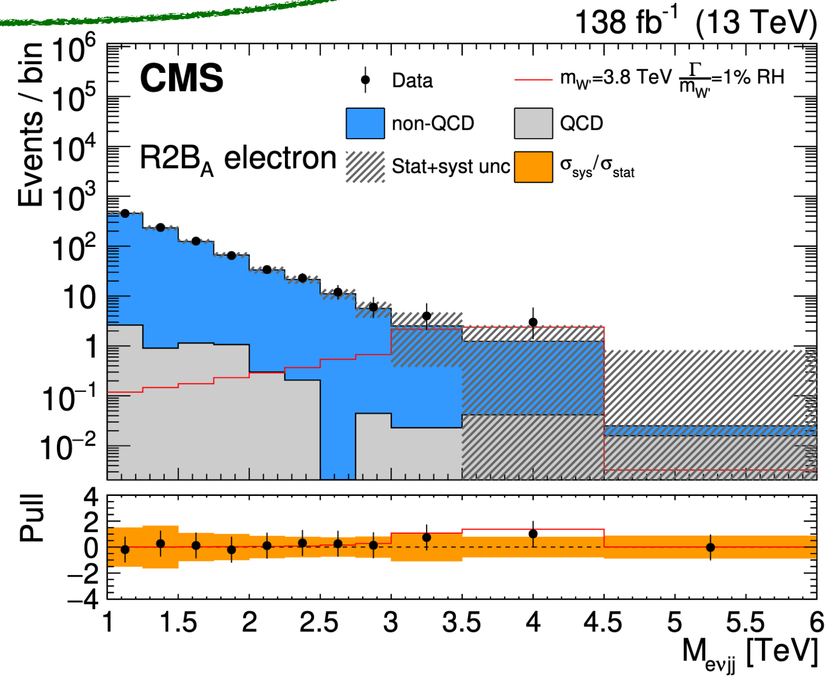
A small excess!





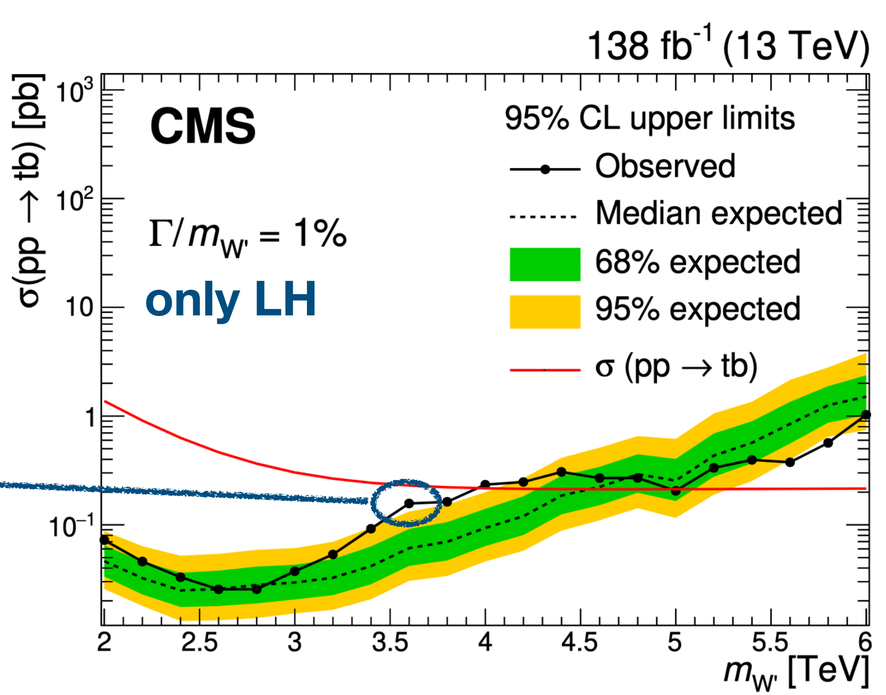
Using CMS Run 2 dataset

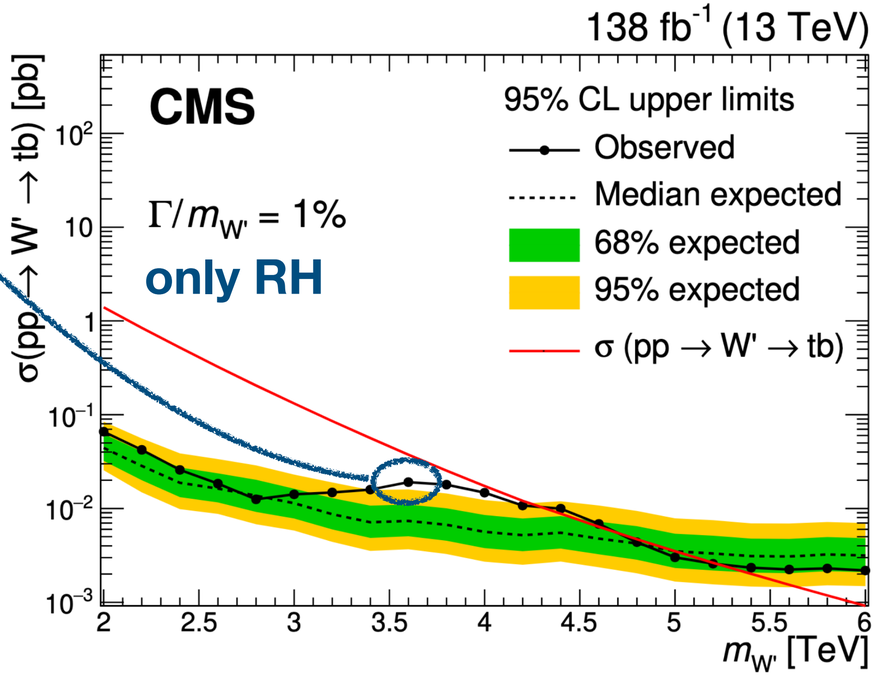
Closer look to the results

Take-home messages from statistics

Excess not strong enough for a discovery

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





Closer look to the results

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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

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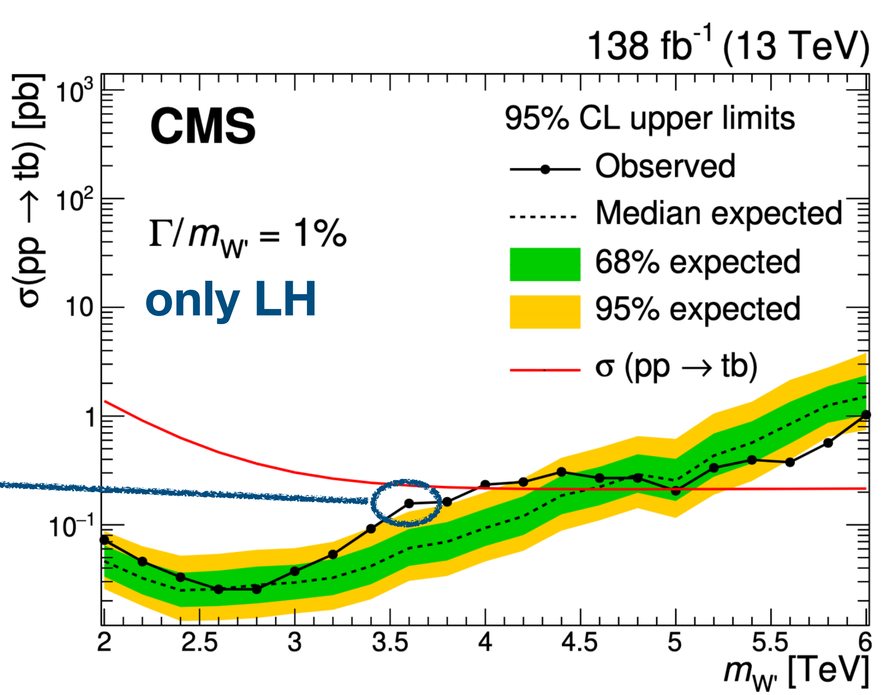

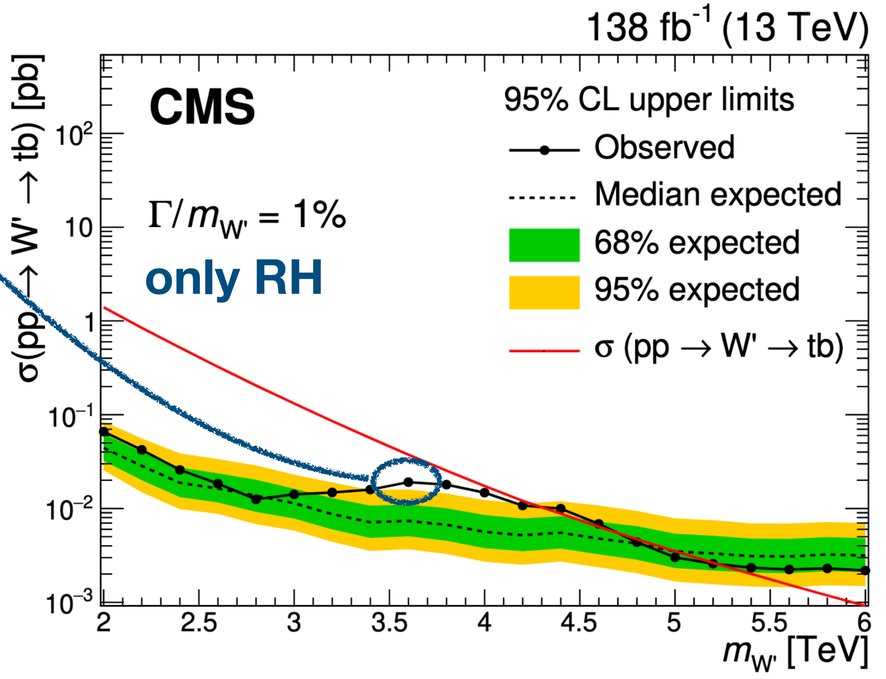

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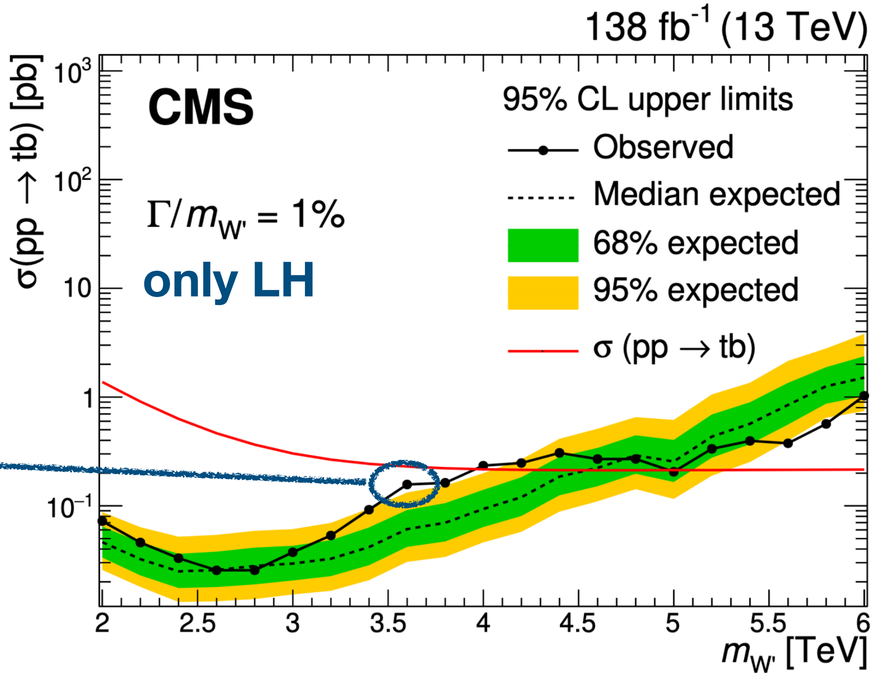
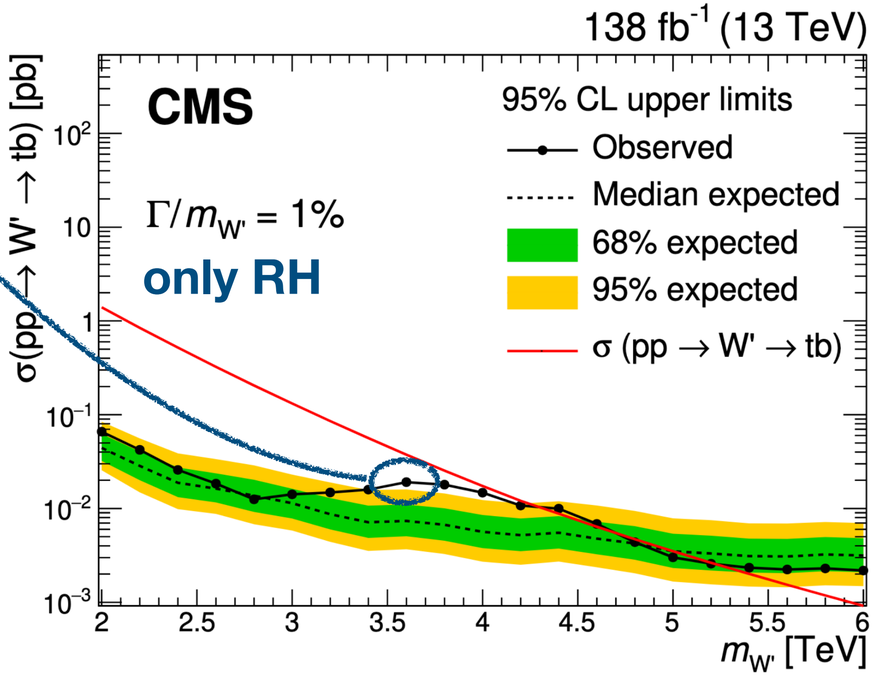


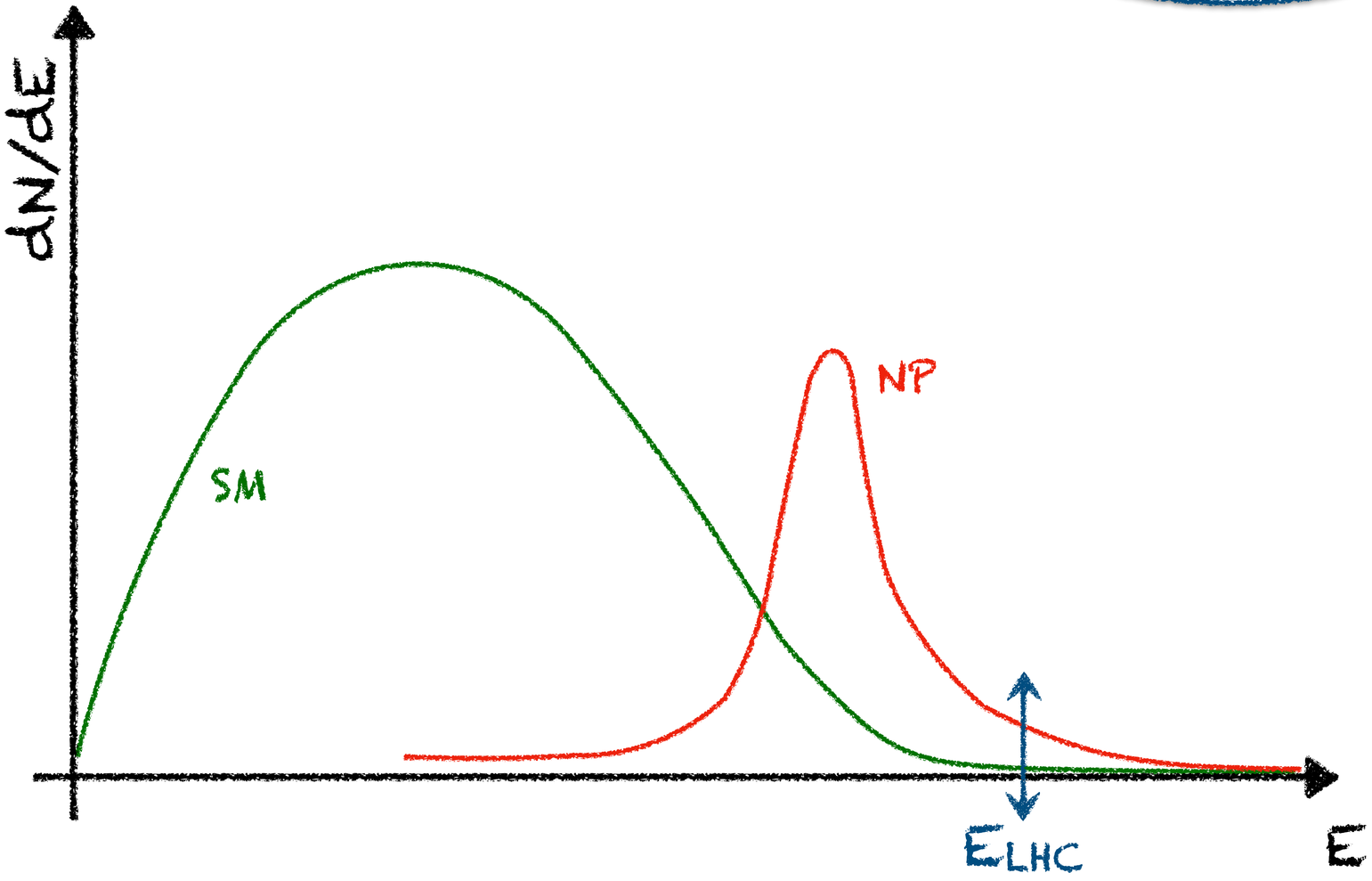


Lots of no-go destinations!

NP expedition

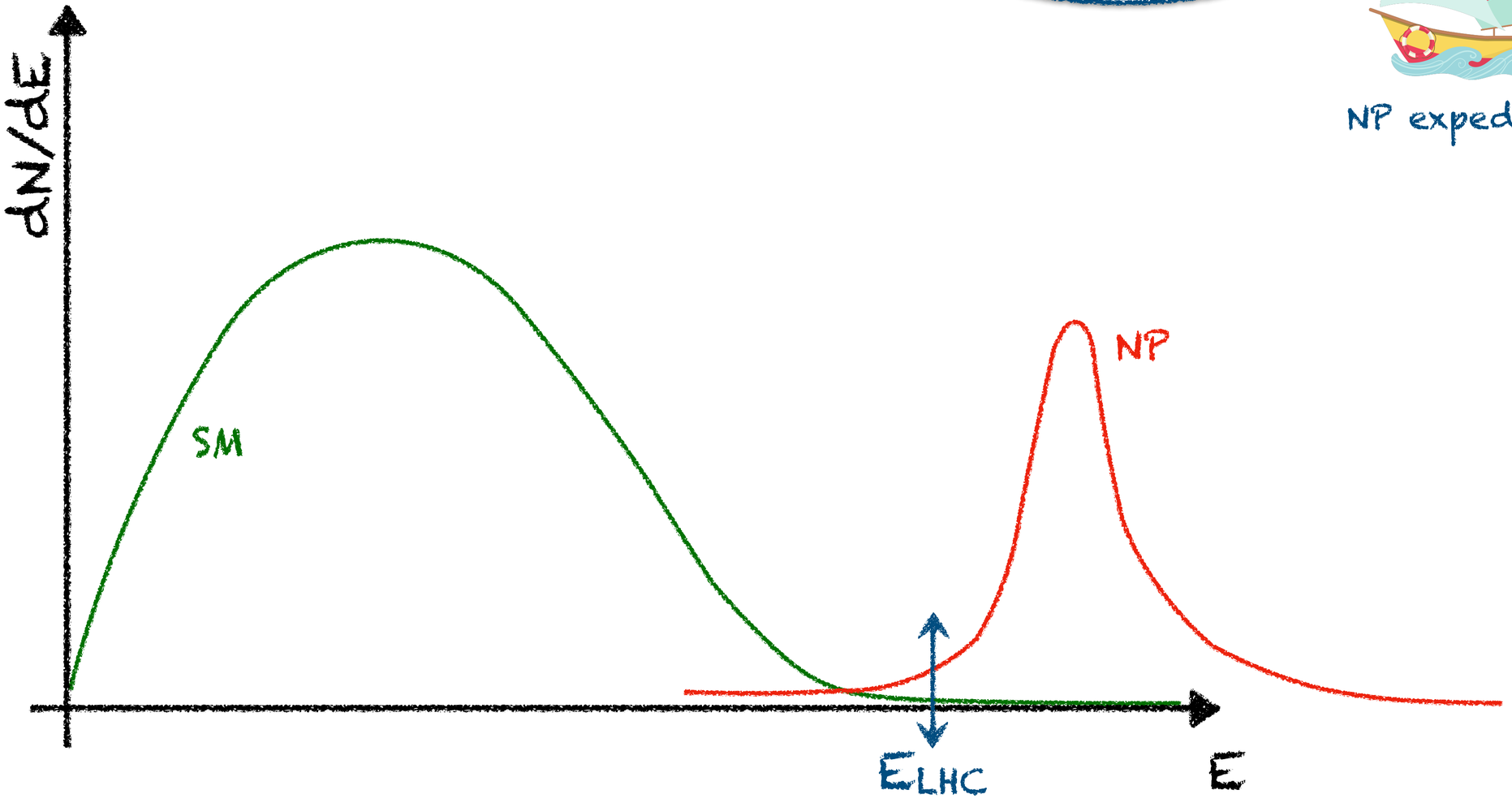
What if NP is out of reach?

Underlying assumption of direct searches



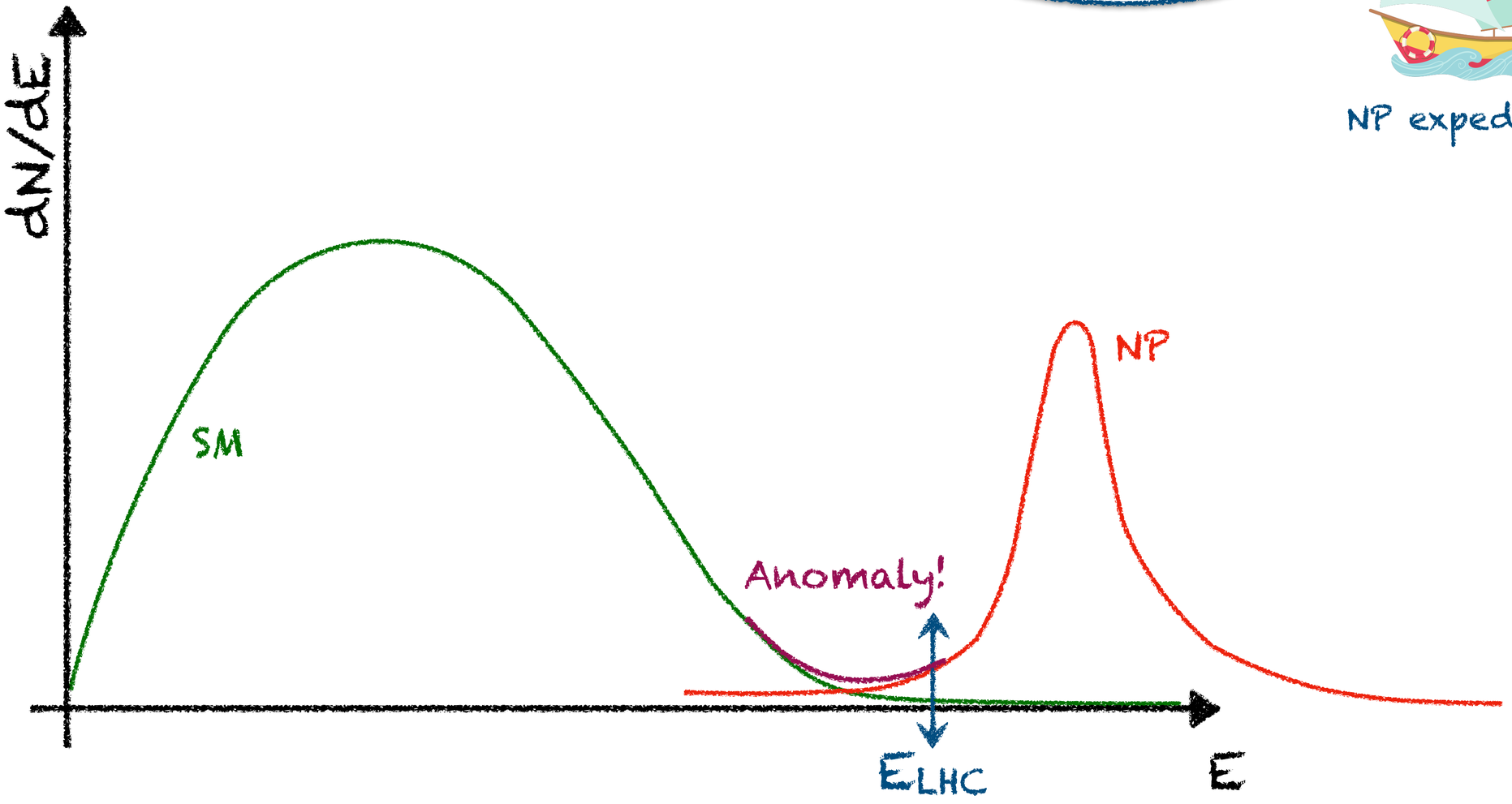
What if NP is out of reach?

Let's boost the peak…



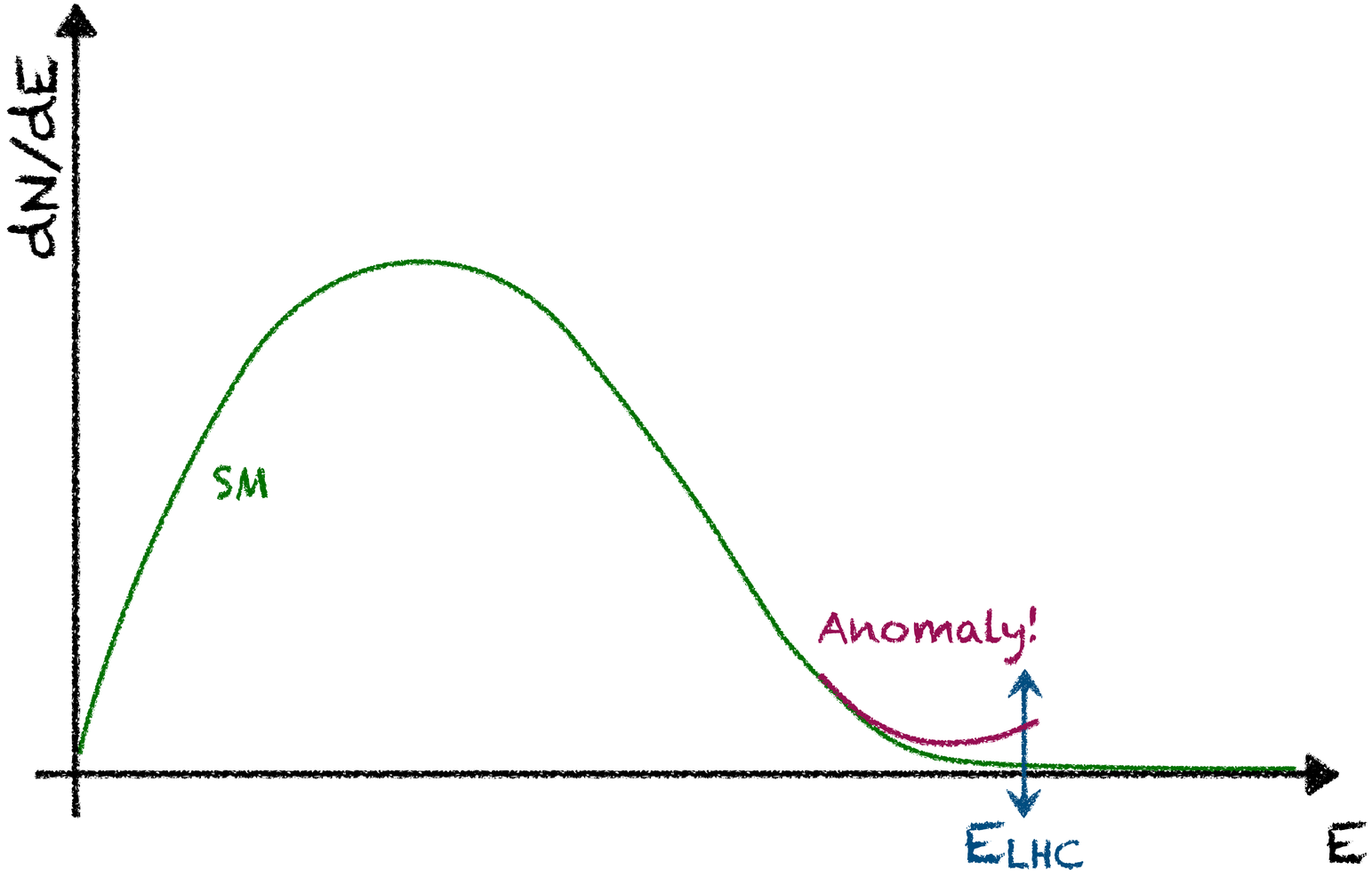
What if NP is out of reach?

…still detectable?



Chasing down the anomalies

Adopting a wider point of view: approach #2



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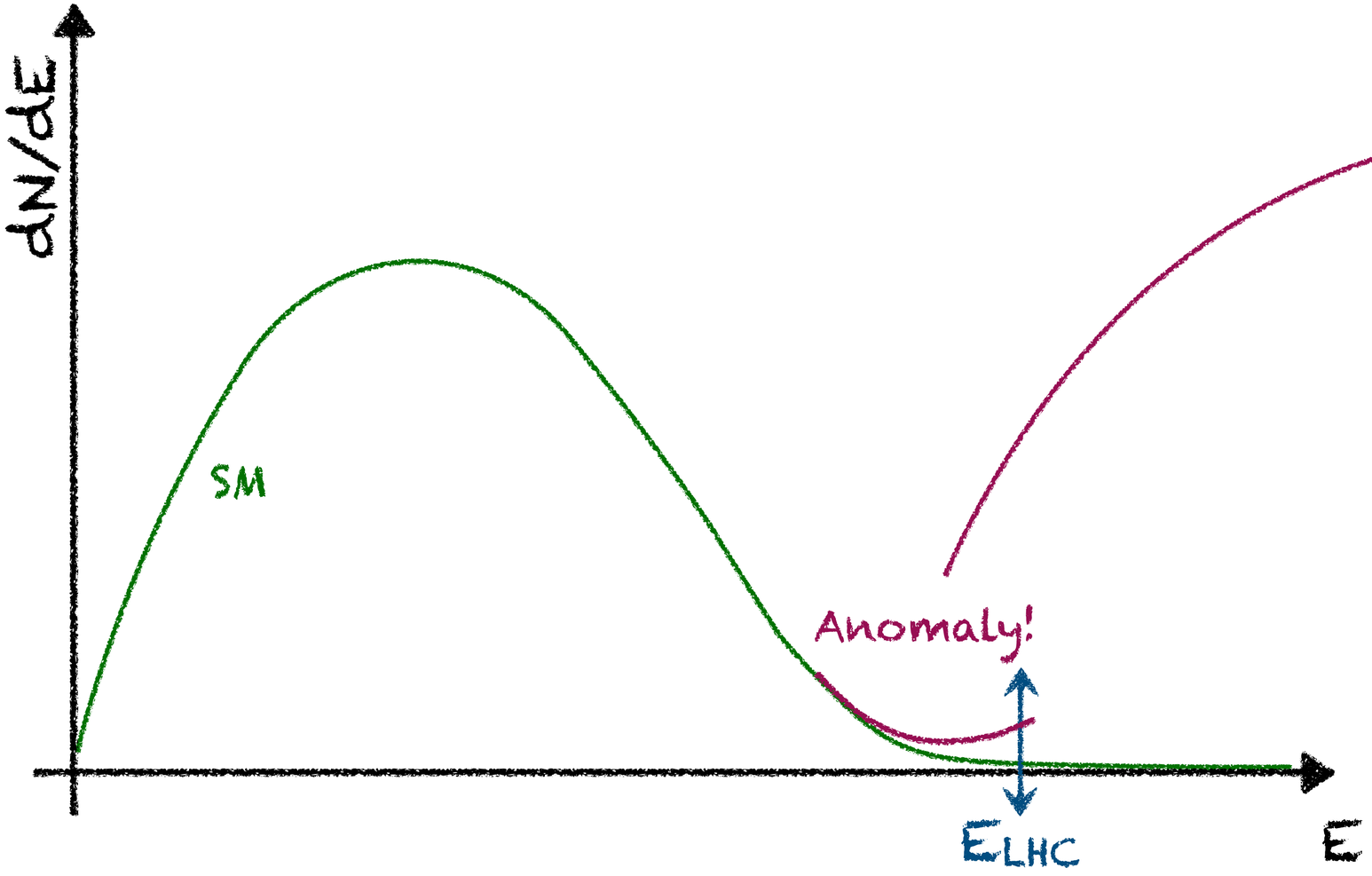

How to model potential anomalies

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

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

Chasing down the anomalies

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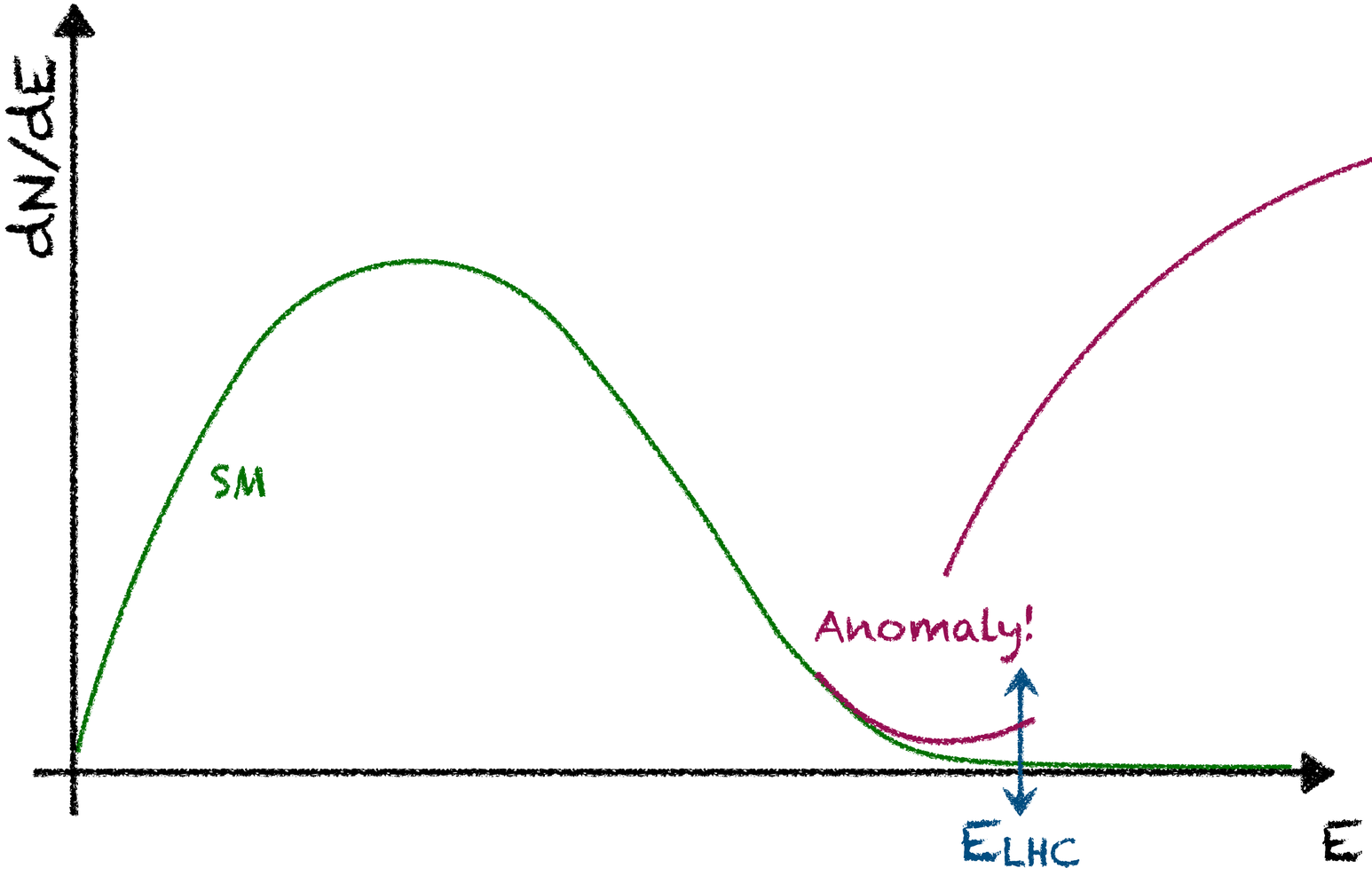
aka Effective Field Theory



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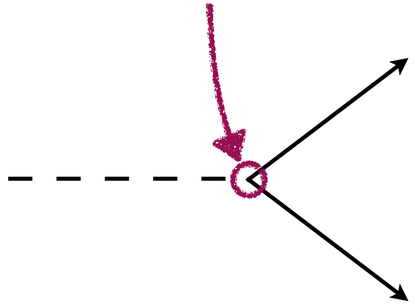
QFT operator affecting interactions



Defining the EFT operators

An SM-based bottom-up approach

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- Classify operators according to mass dimensionality D
- Introduce an NP energy scale Λ

SM EFT Lagrangian

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

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c_k **Wilson coefficient**

D odd → Breaks lepton flavor universality

D even → Leading terms in SMEFT dim-6, dim-8

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Ultimate goal
Match EFT results to NP models

From $\mathscr{L}$ to observables

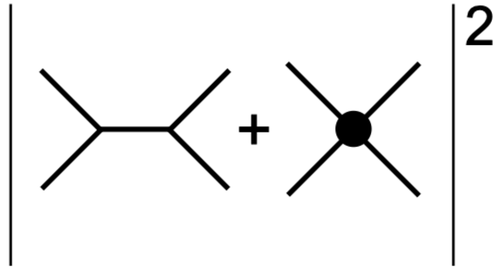
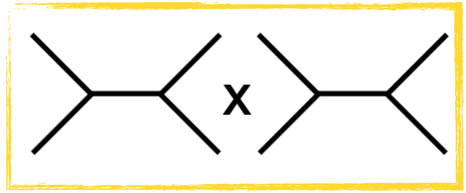
$$\sigma \propto$$

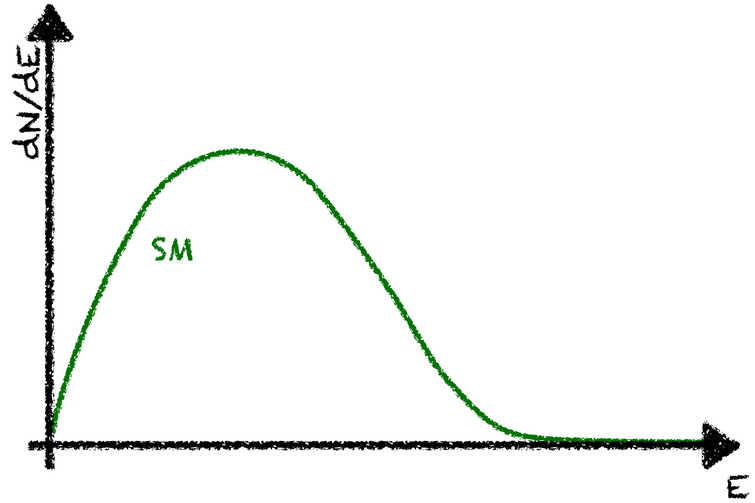
$$\sigma \propto \left| \quad + \quad \right|^2$$

From $\mathscr{L}$ to observables

$$\sigma \propto |\mathscr{A}_{\mathrm{SM}}|^2 \,.$$

SM

$\sigma \propto$  $\propto$ 



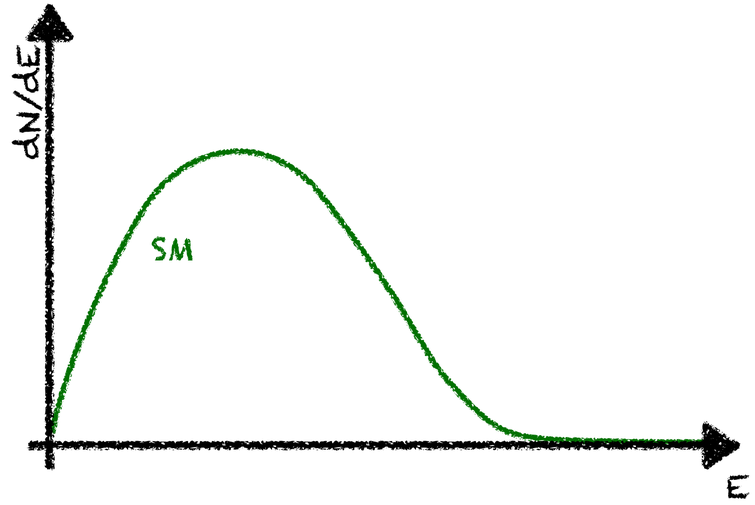
From $\mathscr{L}$ to observables

$$\sigma \propto |\mathscr{A}_{\mathrm{SM}}|^2 + \sum_k \frac{c_k}{\Lambda^{D_k-4}} 2\mathrm{Re}\left(\mathscr{A}^{\dagger}_{\mathrm{SM}} \mathscr{A}^{(k)}_{\mathrm{EFT}}\right).$$

SM

SM-EFT Interfence

$$\sigma \propto \left| \quad + \quad \right|^2 \propto \quad \times \quad + \quad \times$$



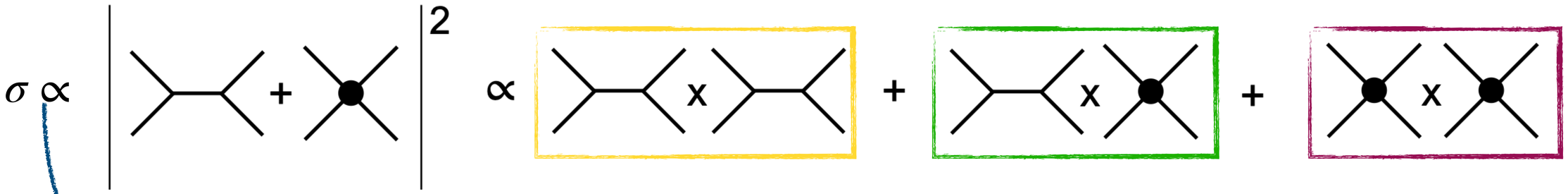
From $\mathscr{L}$ to observables

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

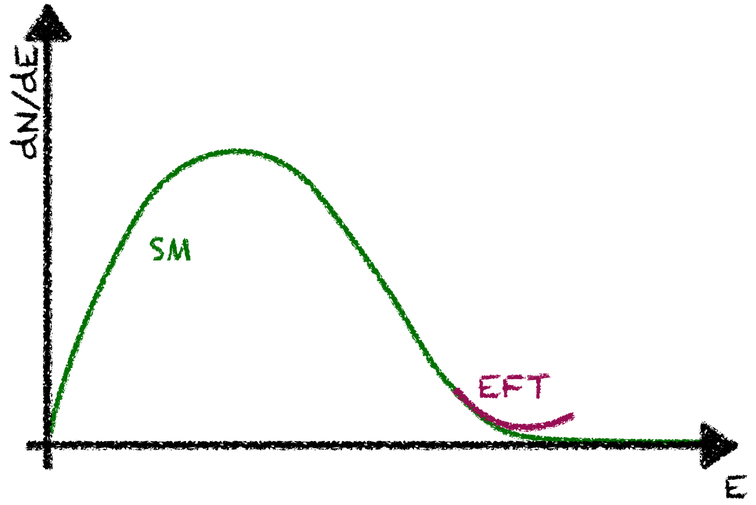
SM

SM-EFT Interfence

Pure EFT terms



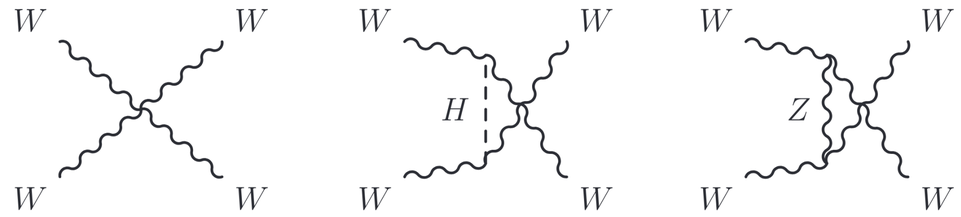
EFT profile of a distribution



Where to search for EFT anomalies

EWSB mechanism sensitive to NP

Vector Boson Scattering



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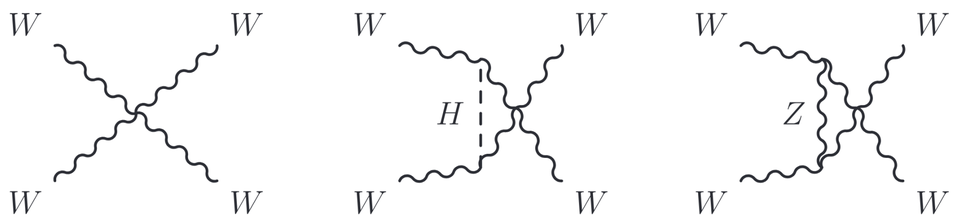
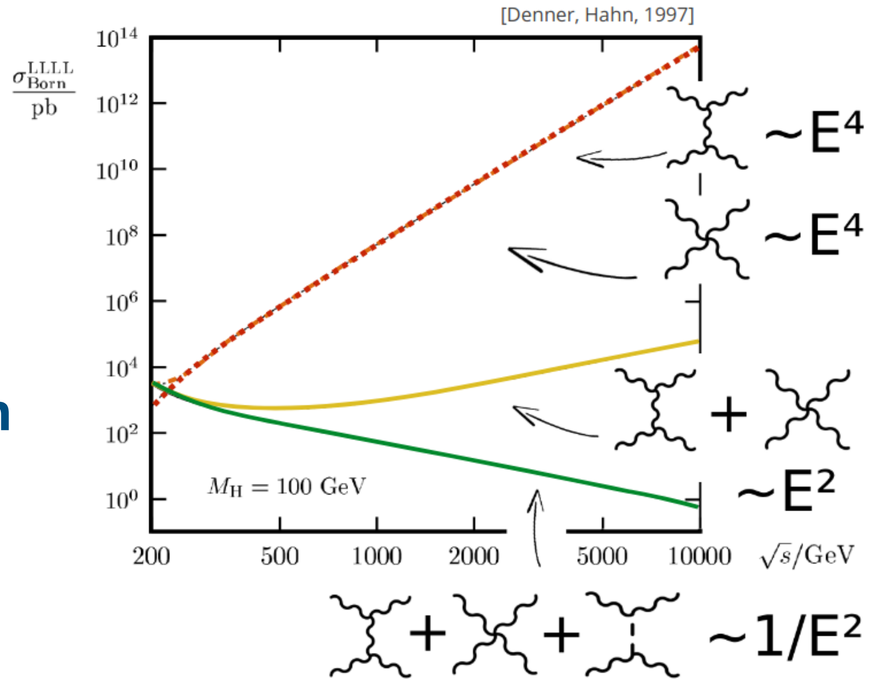


Cross-section unitarity relies on Higgs contribution



Where to search for EFT anomalies

EWSB mechanism sensitive to NP

Potential anomalies affecting gauge couplings

Cross-section unitarity relies on Higgs contribution

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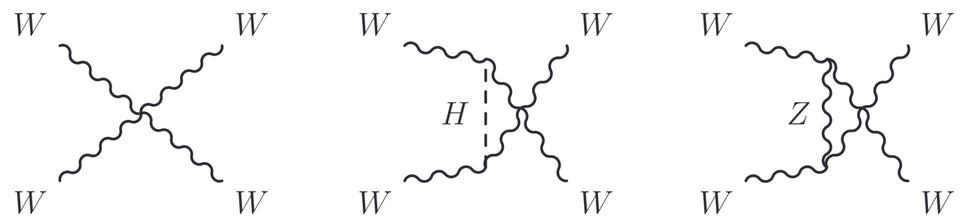
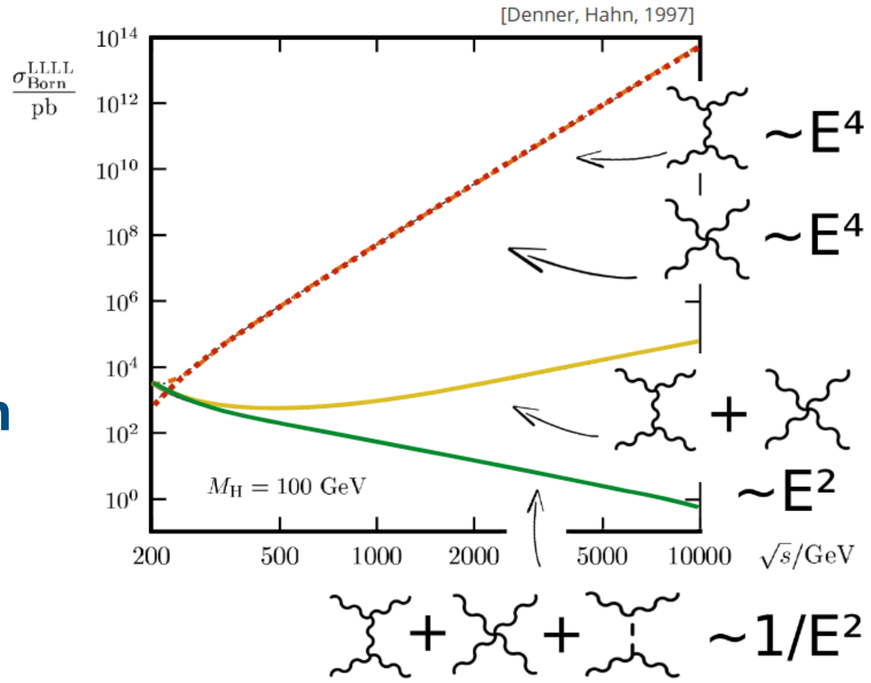


[Denner, Hahn, 1997]



Which dimension?

Goal of the EFT studies

- Find fitted WC values different from SM expectations
  - Find the most promising directions in the EFT phase space
- Otherwise, constraints on WCs and Λ energy scale

Which dimension?

Focus on the leading contributions!

Target a process

Pick a dimension

Pick a set of leading operators

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…drawbacks?

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Experimentalist POV

Pick 1 dimension

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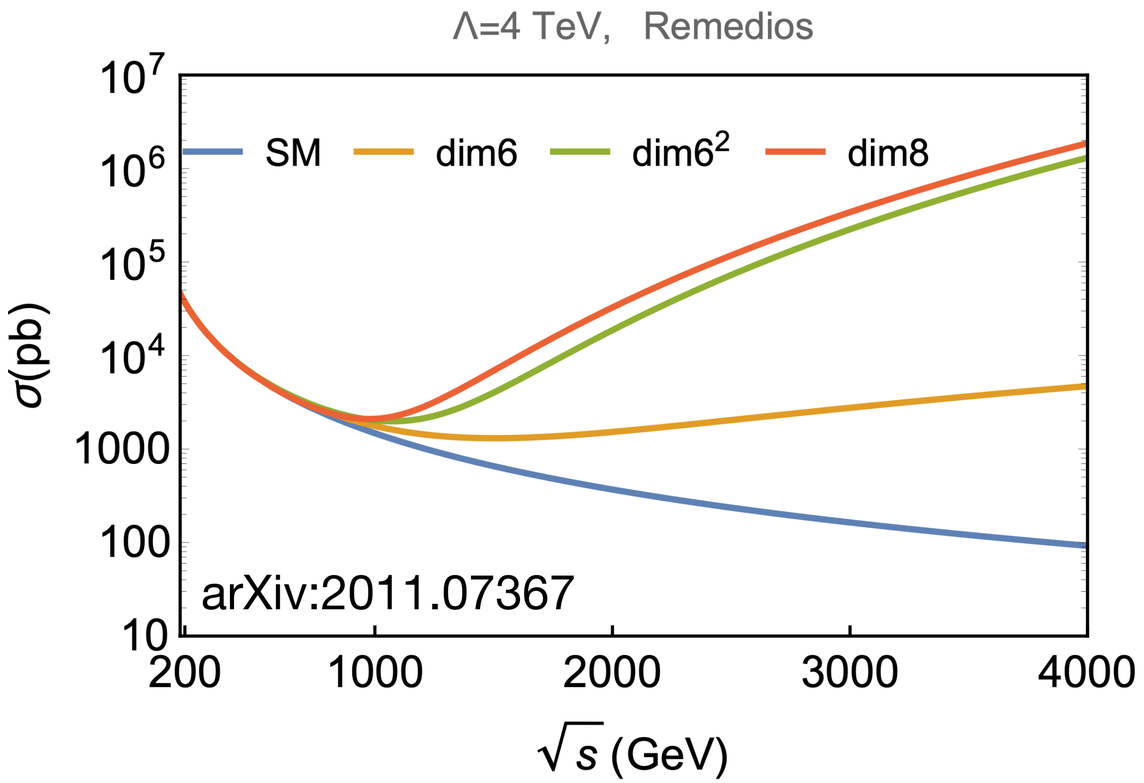
- Assuming all the others do not give competitive contributions
  - …is that true? **Not always!**
  - It implies favoring some NP models
- Unexpected divergences
- Biased constraints on WCs

VBS $W_T W_T \longrightarrow W_T W_T$



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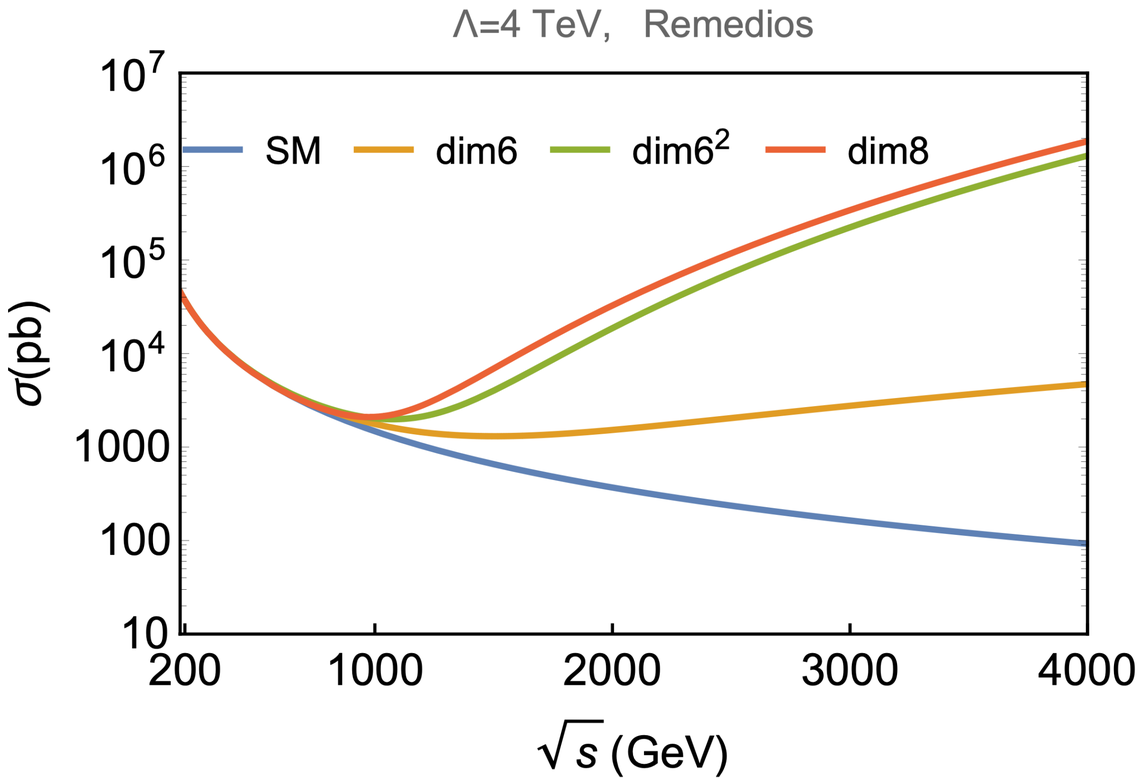
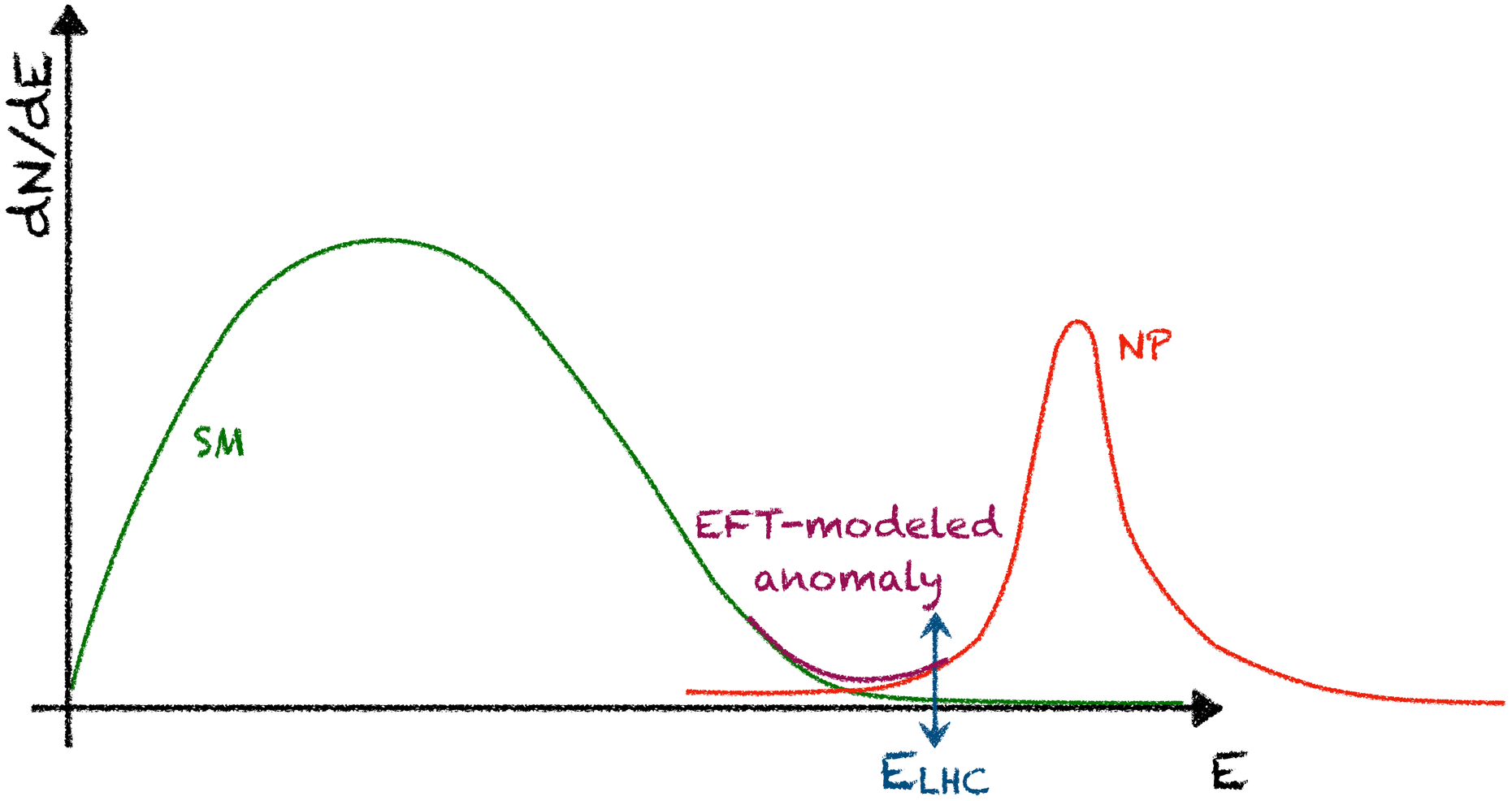
Not exploiting the full EFT potential

VBS $W_T W_T \longrightarrow W_T W_T$



Theorist POV



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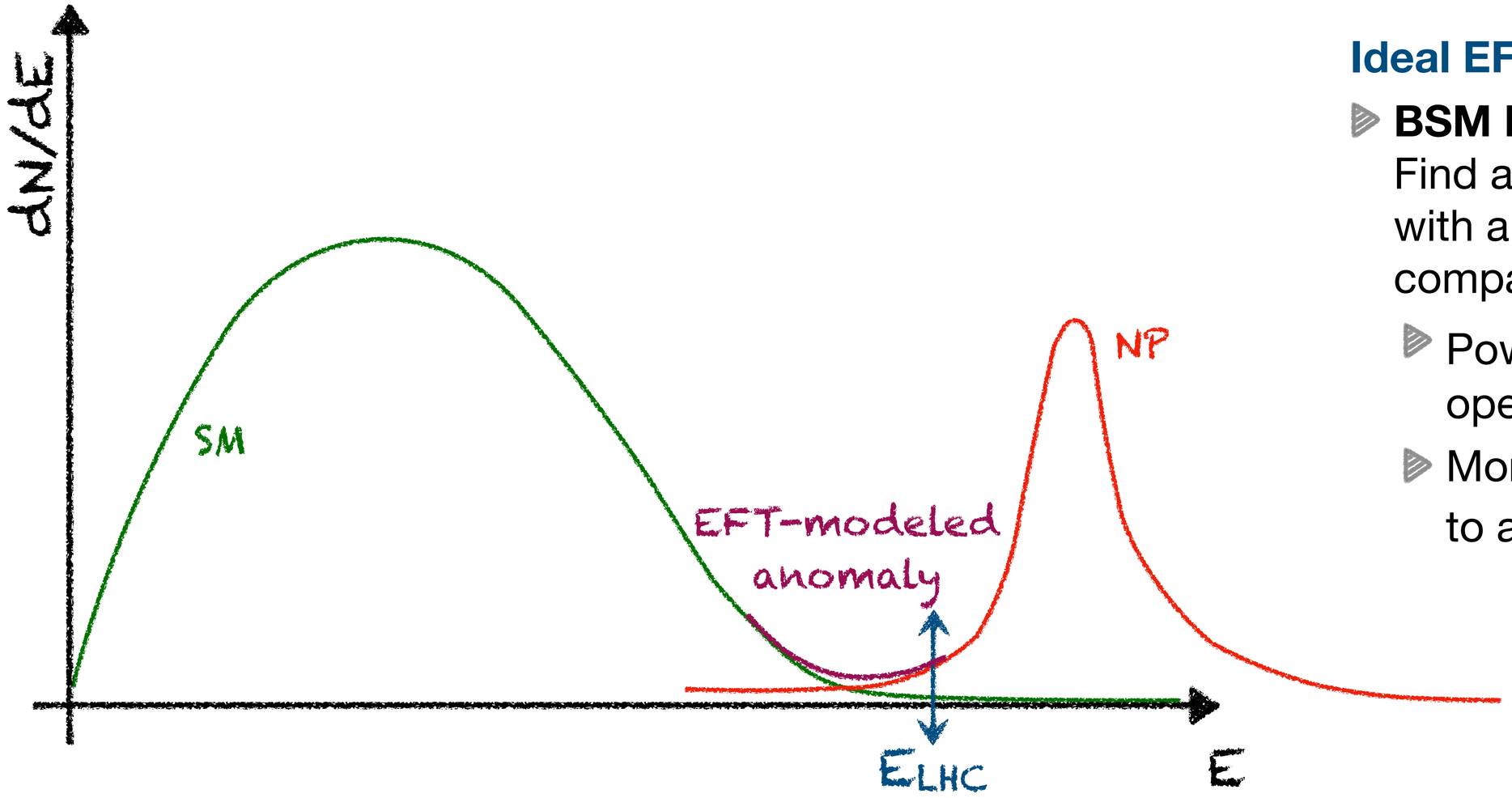

Ideal EFT study

- **BSM Matching**
  Find a connection
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  - Power-counting of Λ >>> operator dimensions!
  - More dimensions contribute to a given power of Λ

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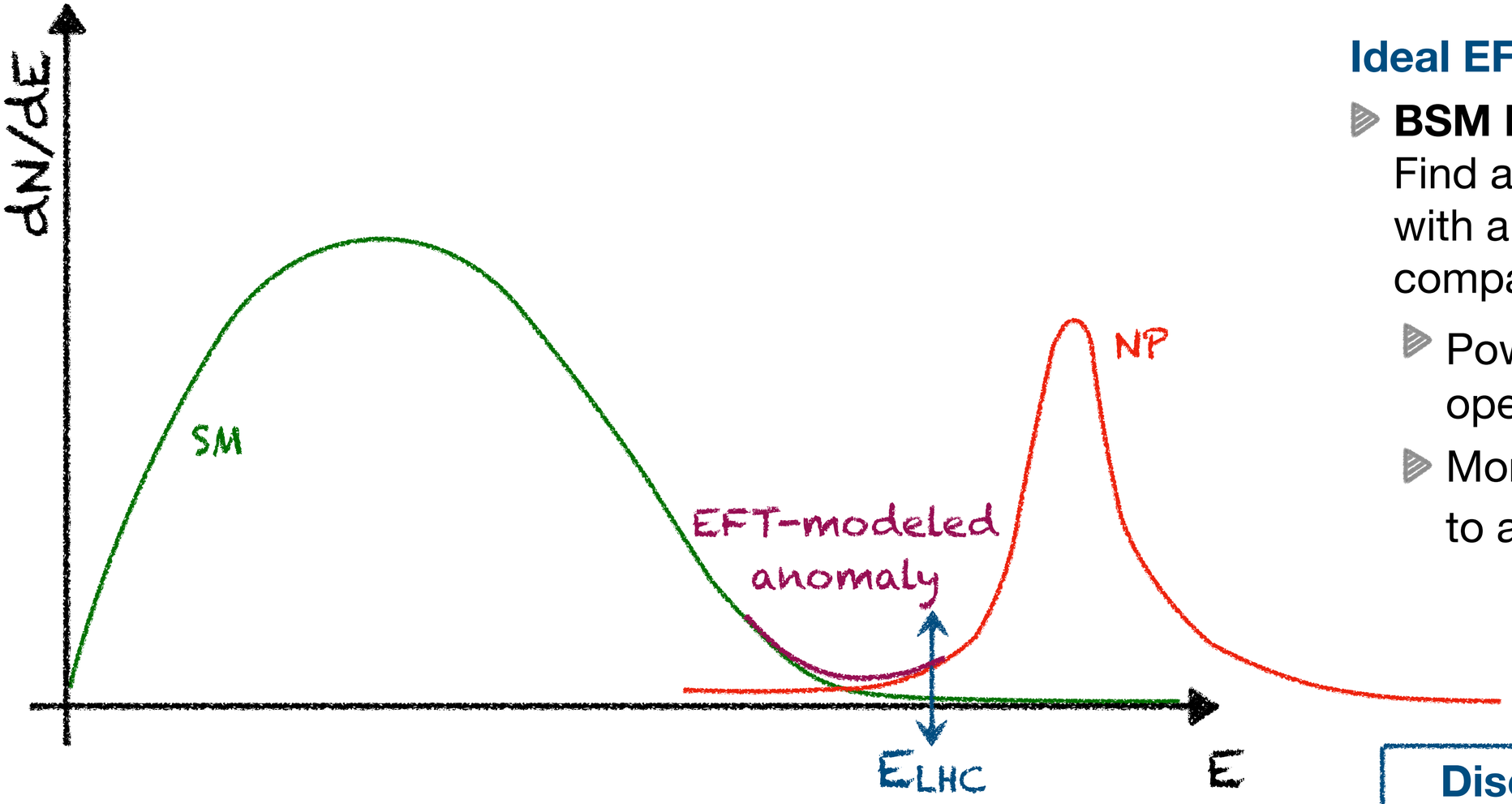

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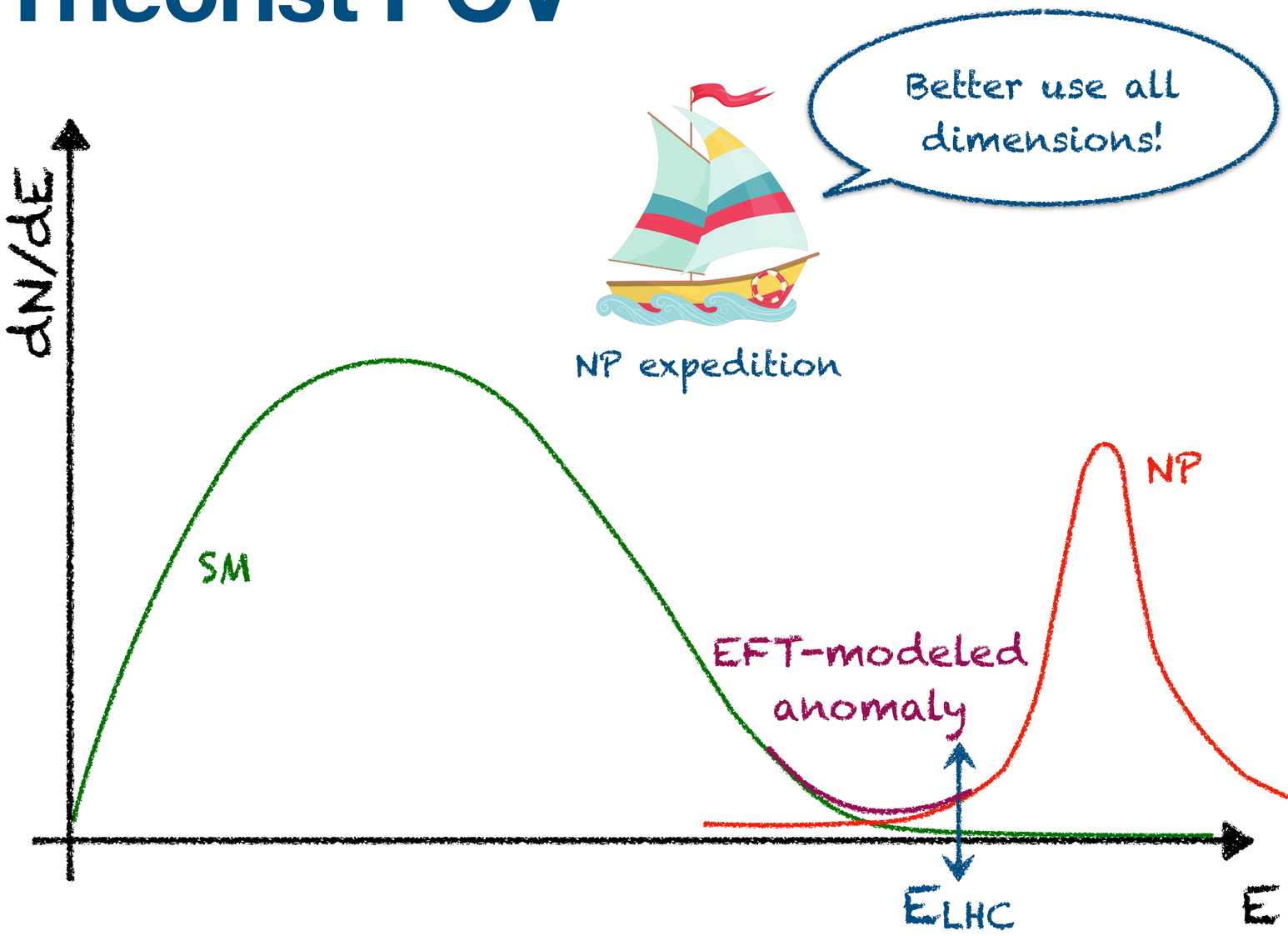

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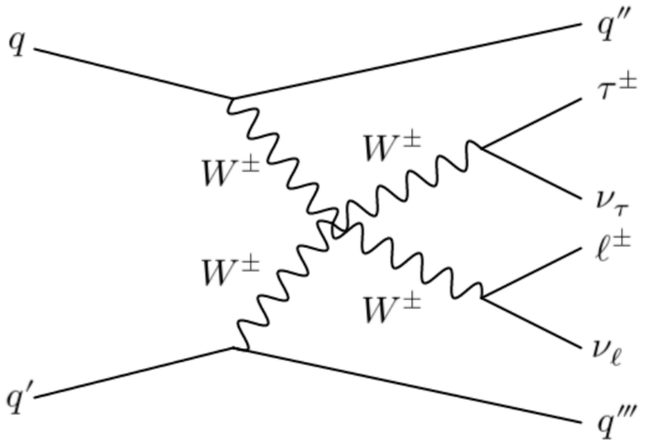
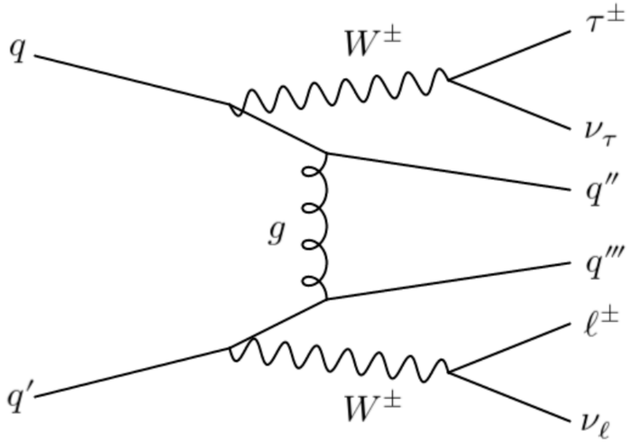
Studying multiple dimensions with VBS

arXiv:2410.04210





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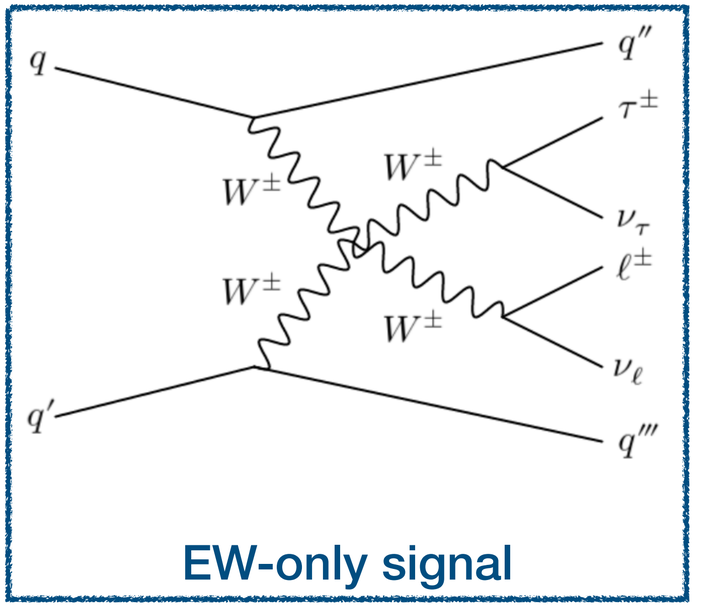
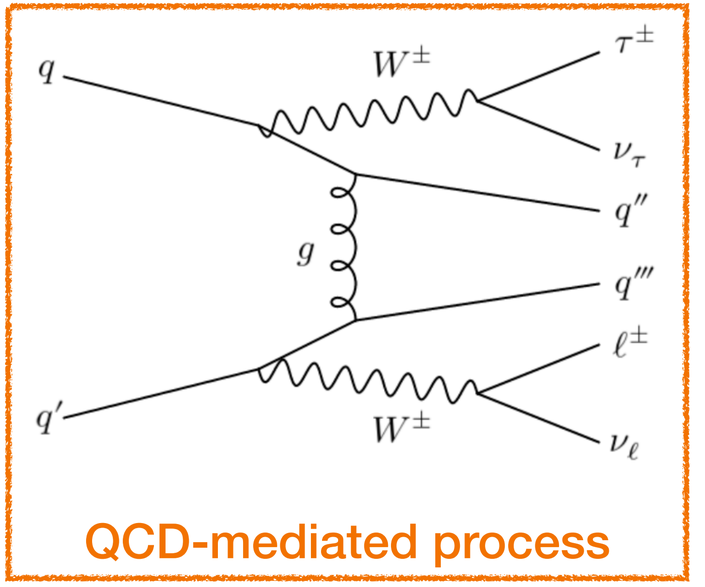
Focus on same-sign WW scattering

- Reduce the **QCD-mediated contribution**
- Targeting the $W \longrightarrow \tau\nu_\tau$ decay
  - Enhance sensitivity to Higgs operator
  - Probe for lepton flavor violation
- SM measurement and **EFT dim-6+dim-8 search**



EW-only signal



QCD-mediated process

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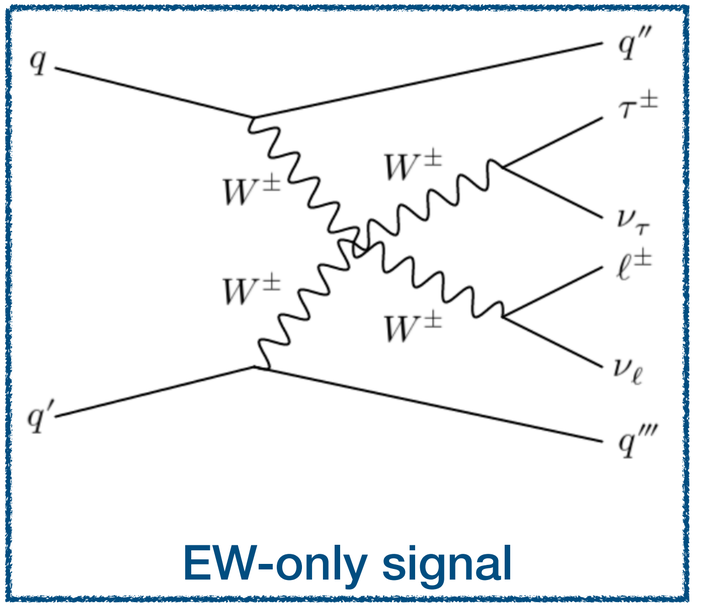
Final states

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



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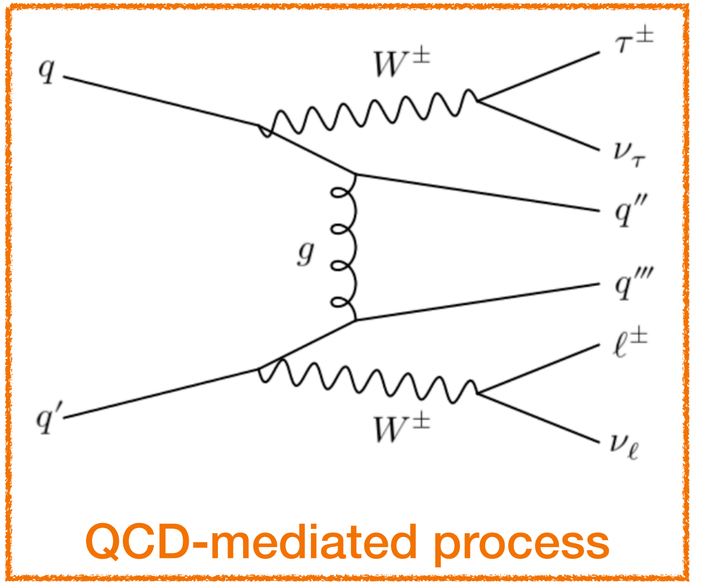

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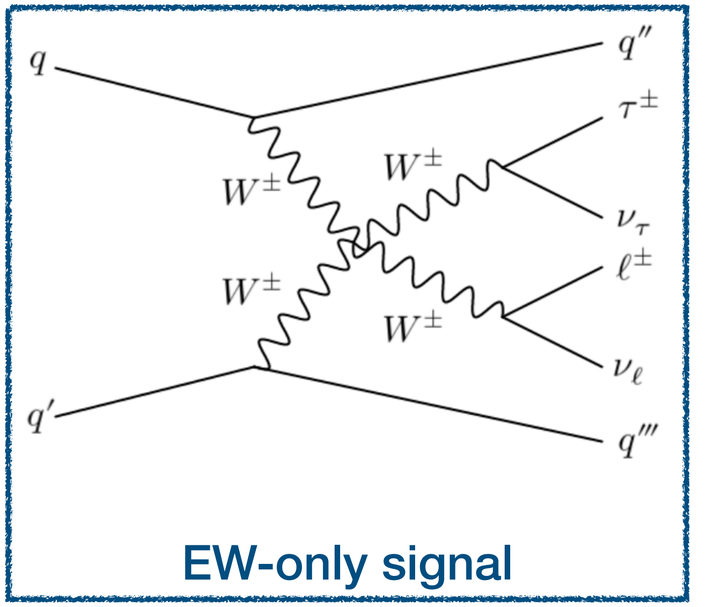
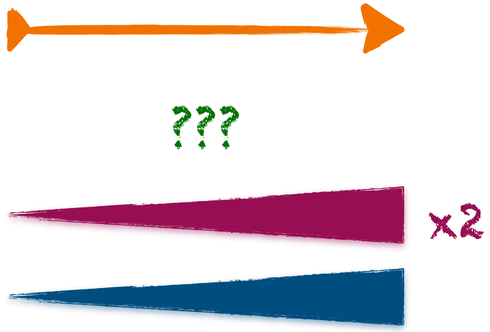
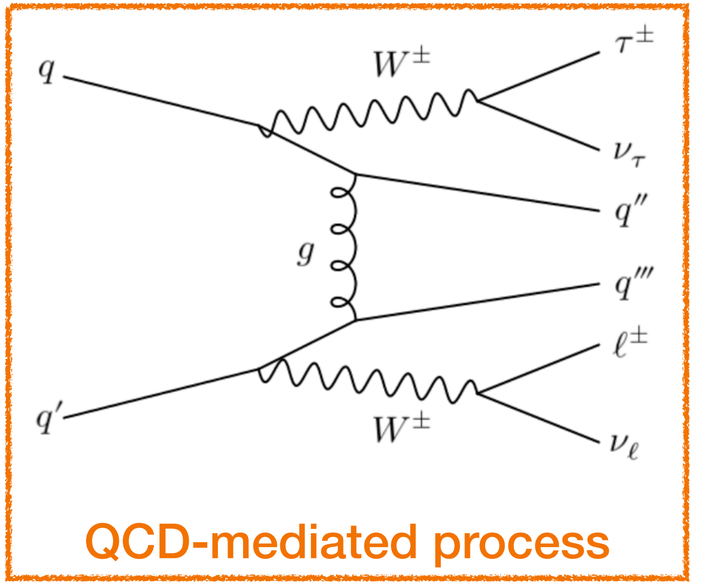


EW-only signal

Final states

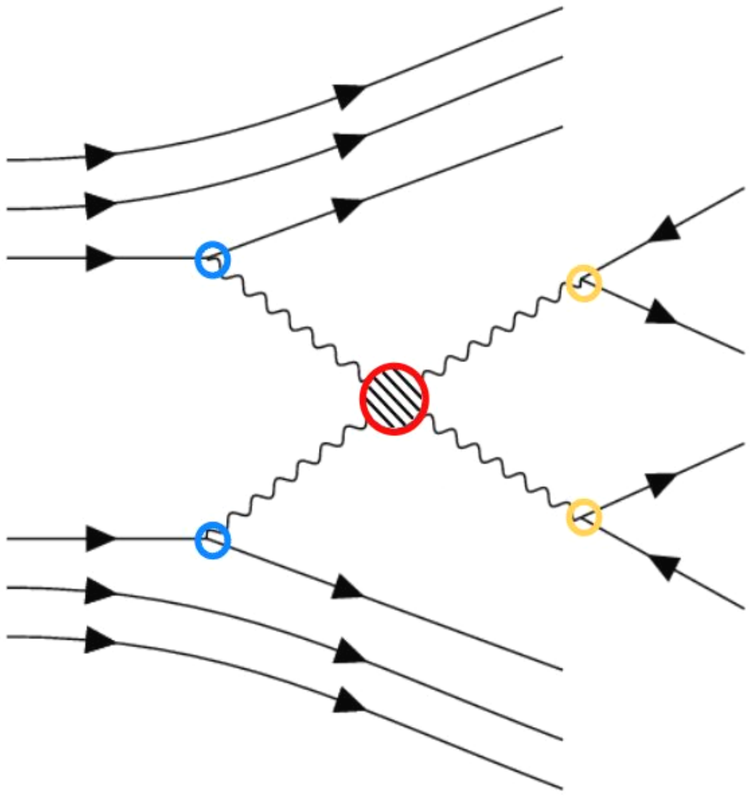
- $\ell = e,\ \mu$ — reco leptons
- ν_ℓ, ν_τ — missing energy
- 2 quarks — hadronic jets
- hadronic tau — tau jet





QCD-mediated process

Inducing anomalies in VBS



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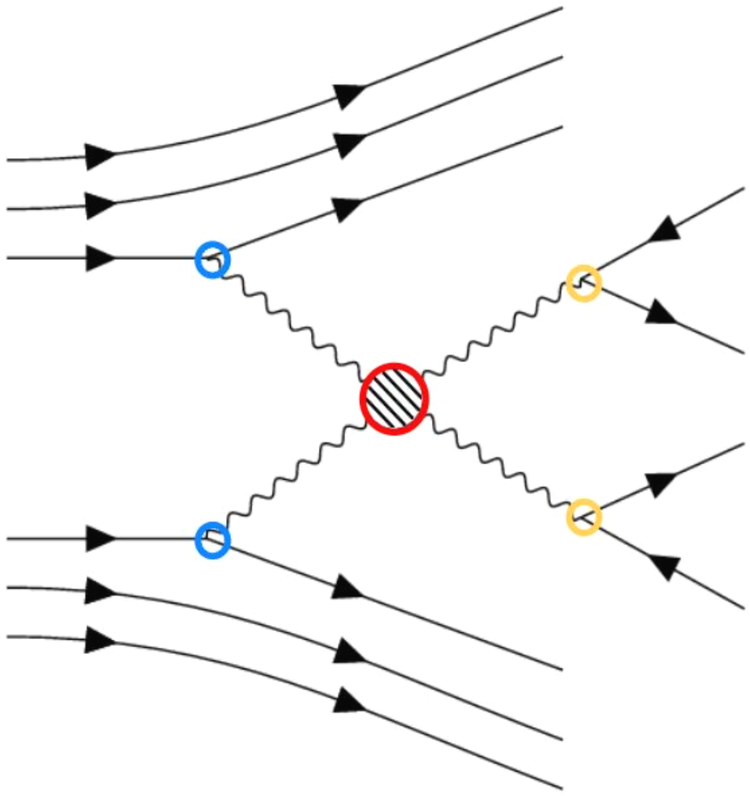

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dim-6 operators Warsaw basis

$qq' \longrightarrow WW$

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

$WW \longrightarrow WW$

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

$WW \longrightarrow \ell\nu_\ell$

$$Q_{Hl}^{(1)} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{l}_p \gamma^\mu l_p\right)$$
$$Q_{Hl}^{(3)} = \left(H^\dagger i \overleftrightarrow{D}_\mu^j H\right)\left(\bar{l}_p \sigma^j \gamma^\mu l_p\right)$$
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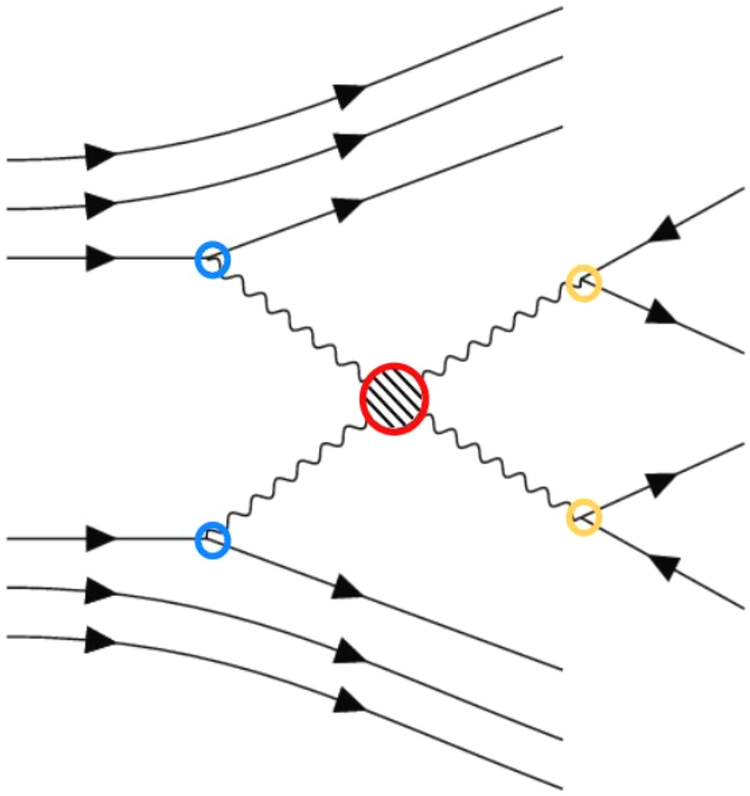
Sensitive to LFV

Inducing anomalies in VBS



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dim-8 operators
Éboli basis

$$WW \longrightarrow WW$$

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

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

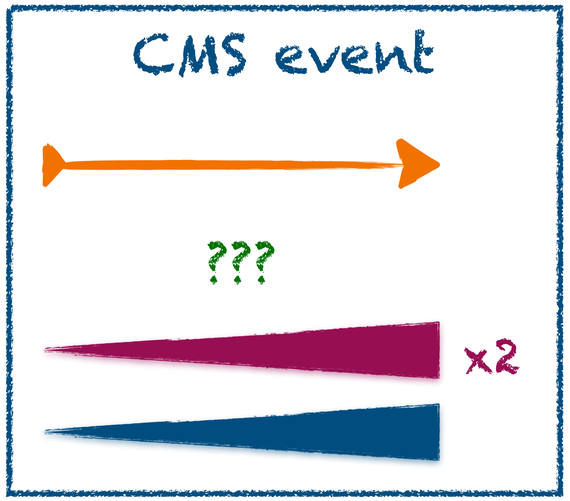
$$\mathcal{O}_{S2} = \left[(D_\mu H)^\dagger D_\nu H\right] \times \left[(D^\nu H)^\dagger D^\mu H\right]$$

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

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

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

Finding out VBS



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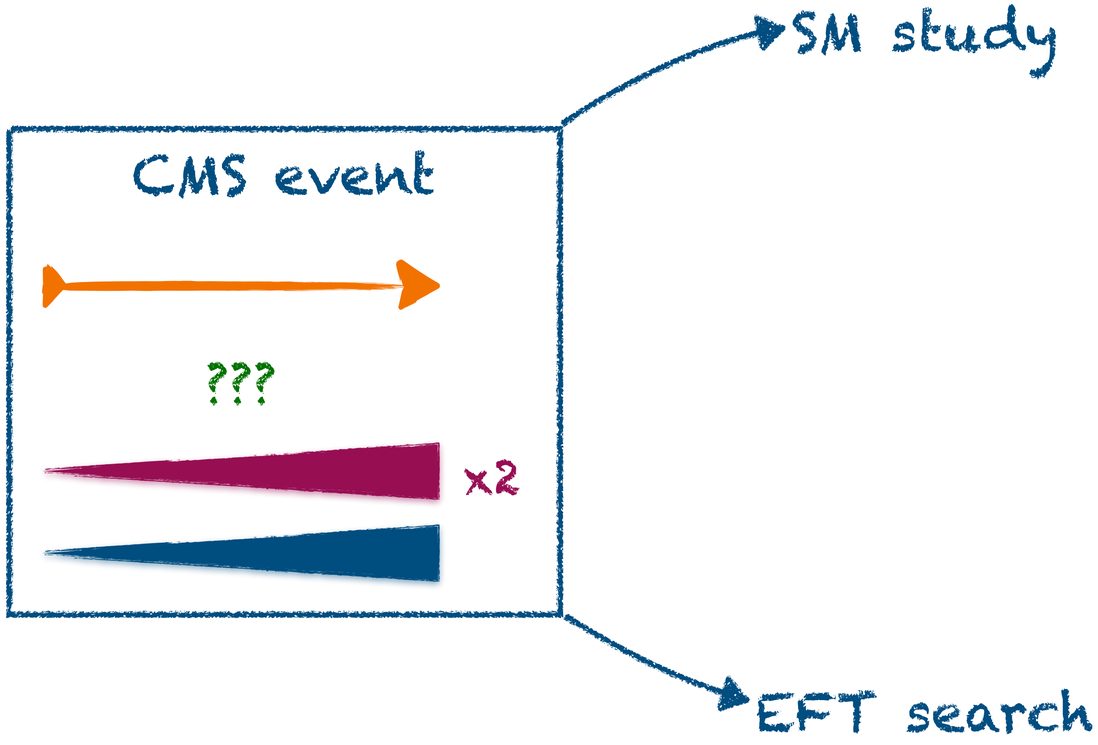

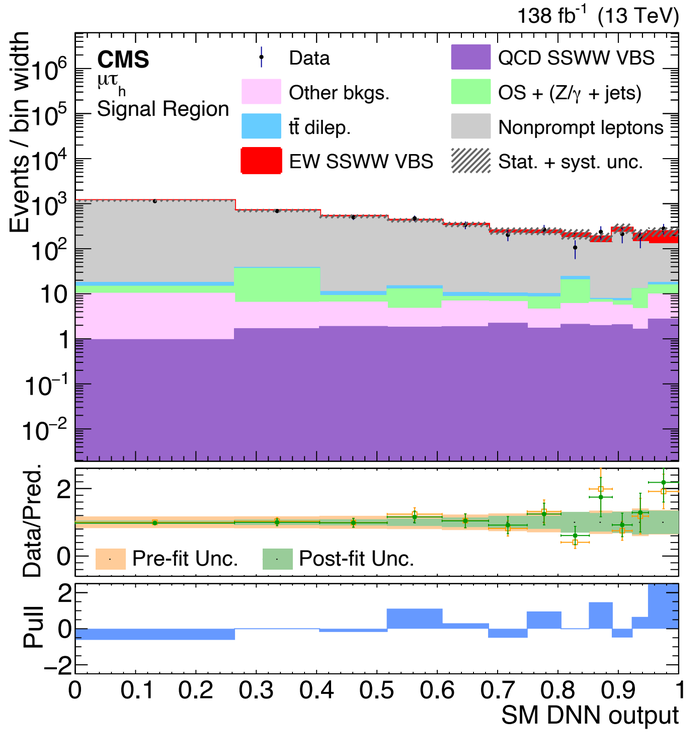

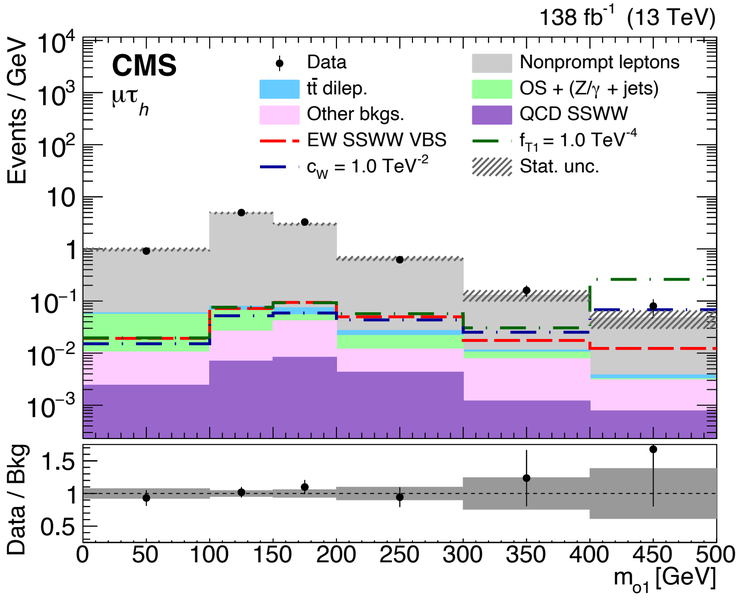

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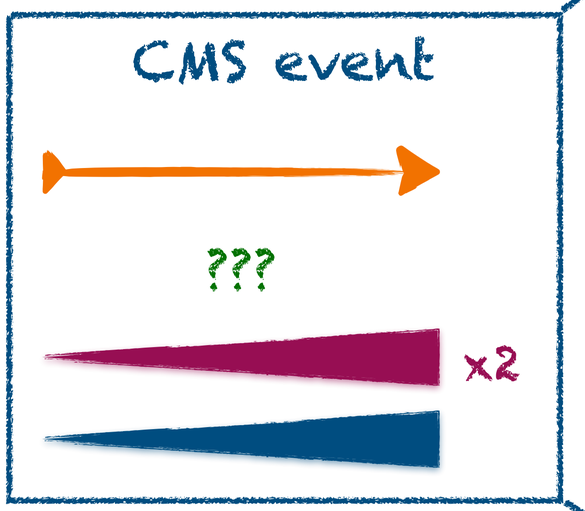
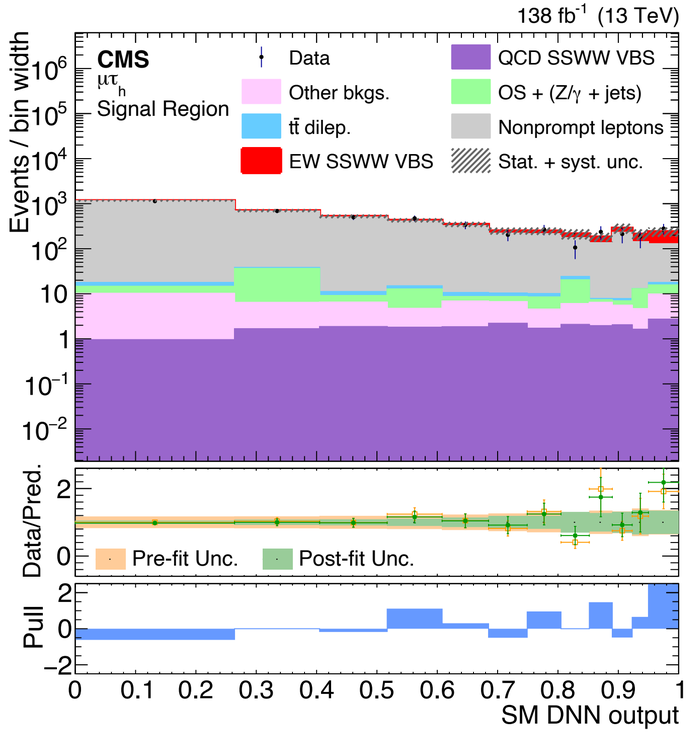


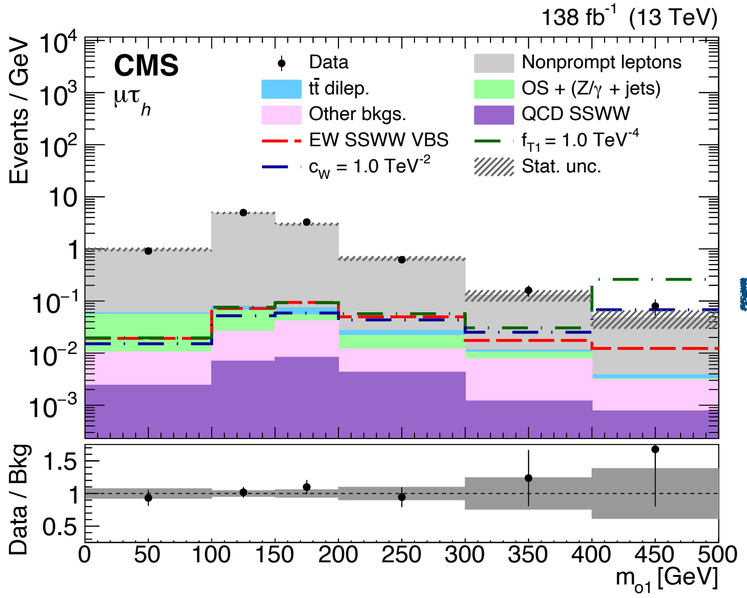
SM study



Observed signal strength

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

EFT search



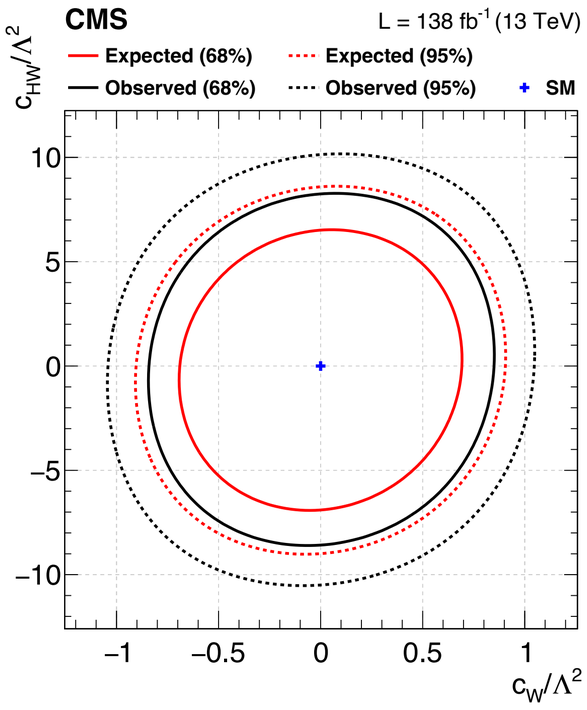
Likelihood scans

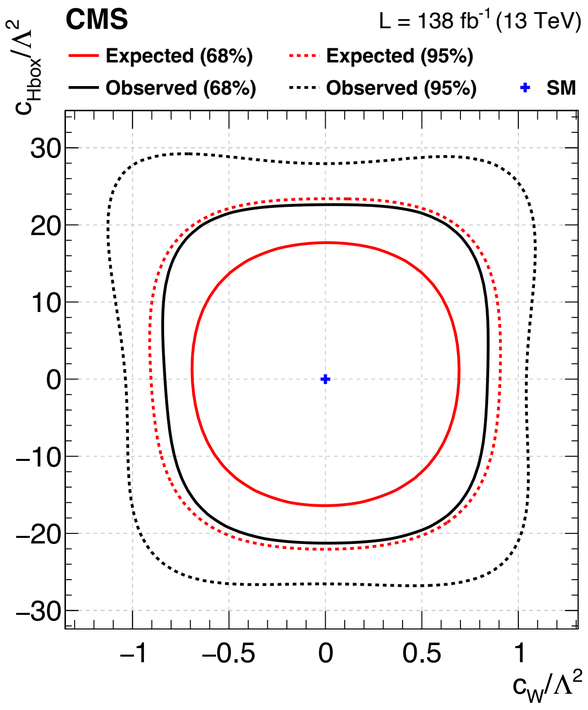
- 1D scans
  dim-6, dim-8
- 2D scans
  dim-6 + dim-6,
  dim-6 + dim-8

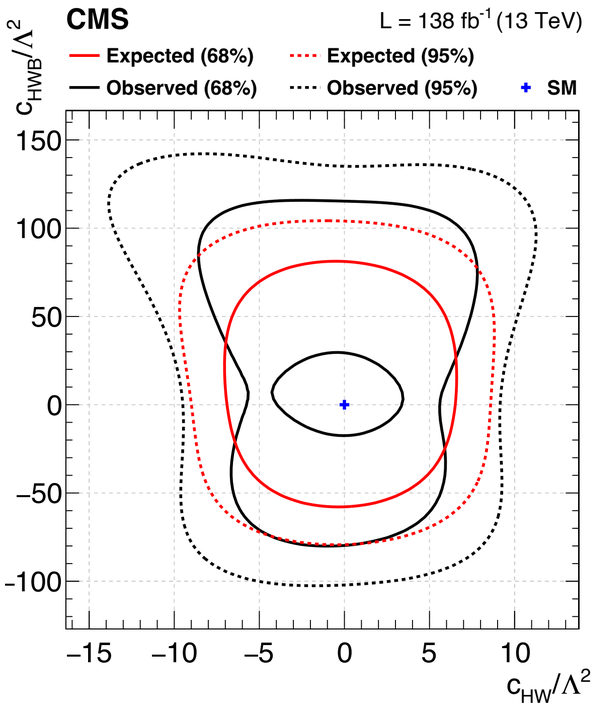
Considering only dim-6

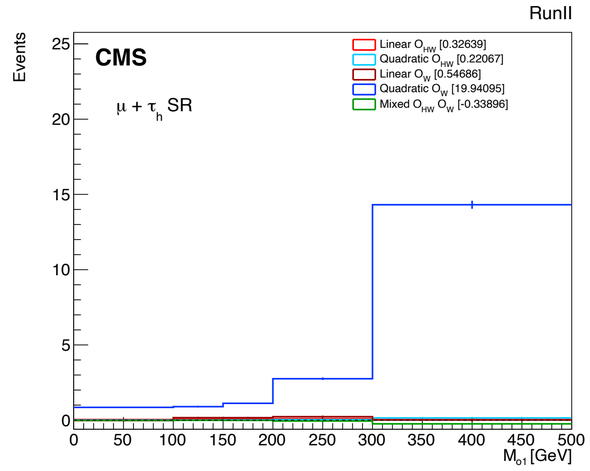
First time with VBS

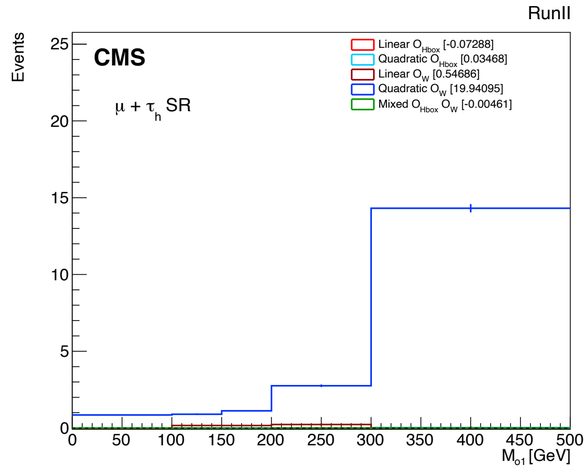
Bosonic operators

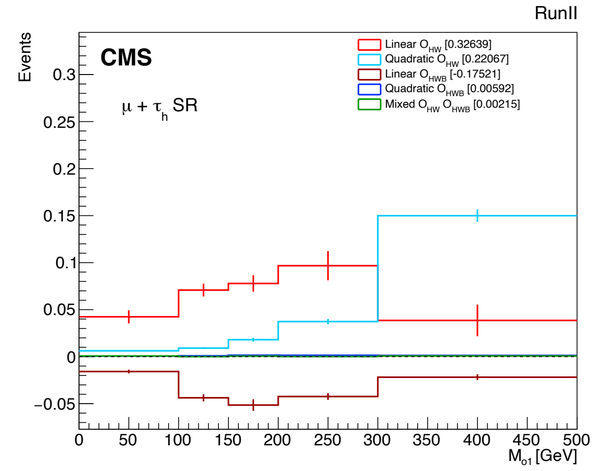








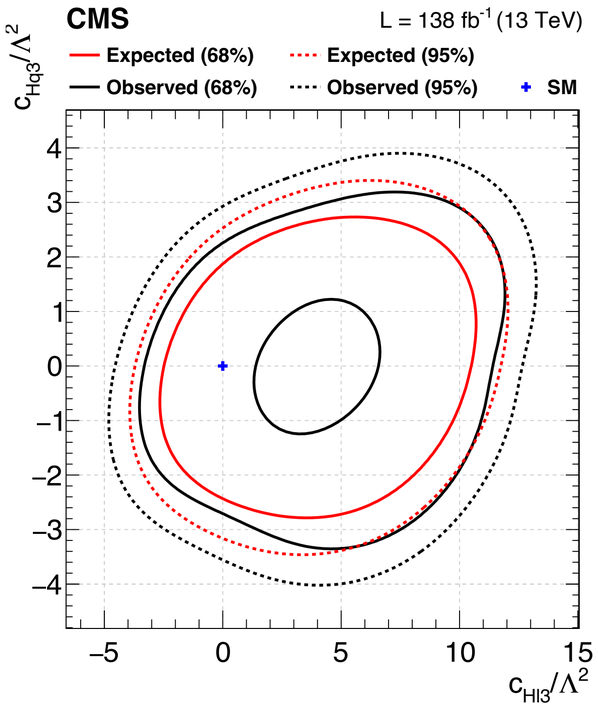


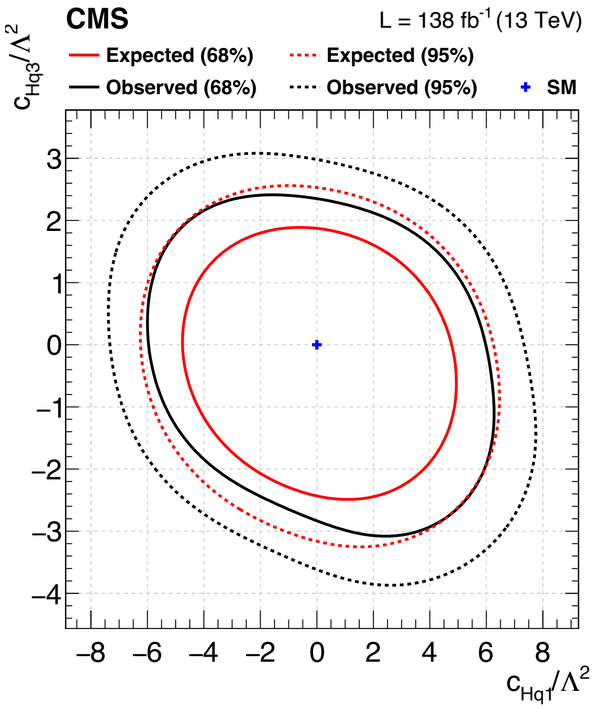


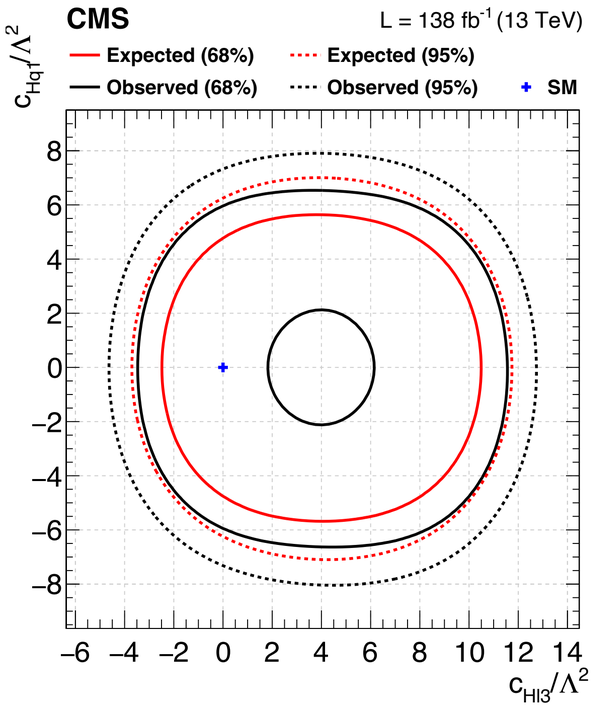
Considering only dim-6

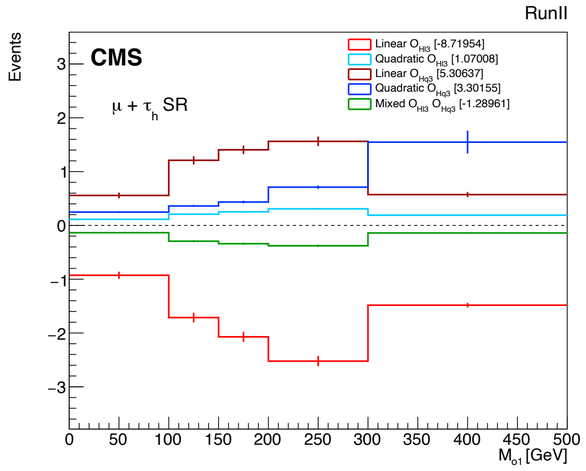
First time with VBS

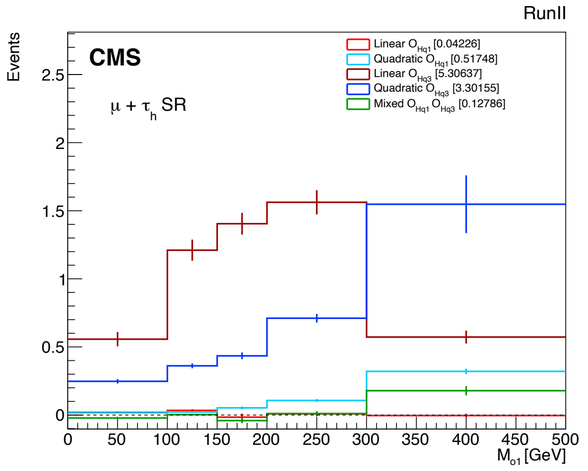
Mixed operators

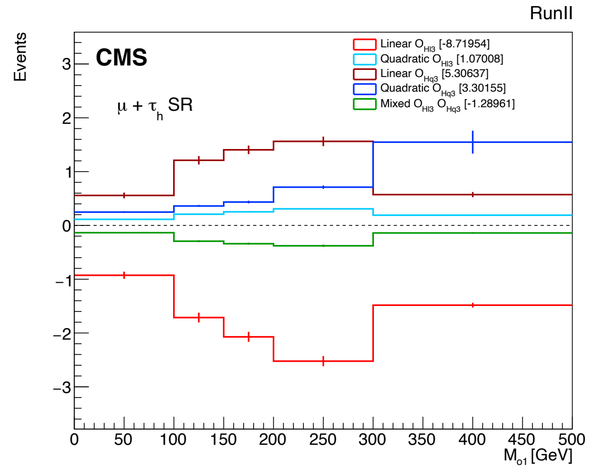










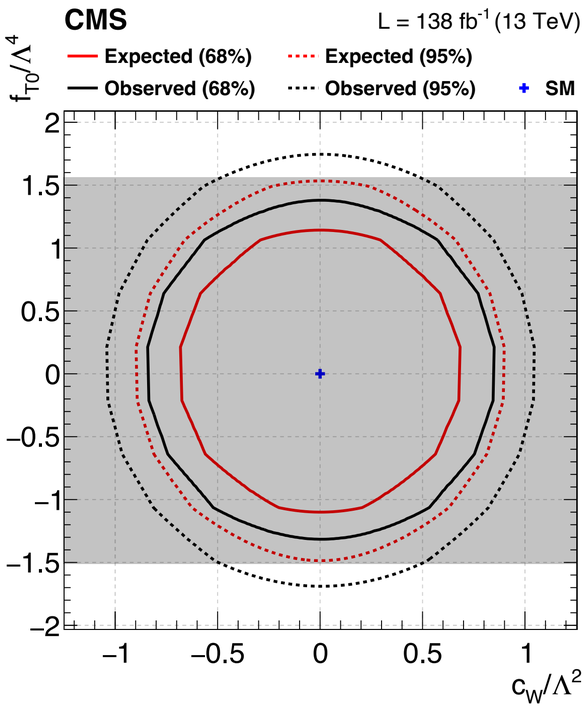


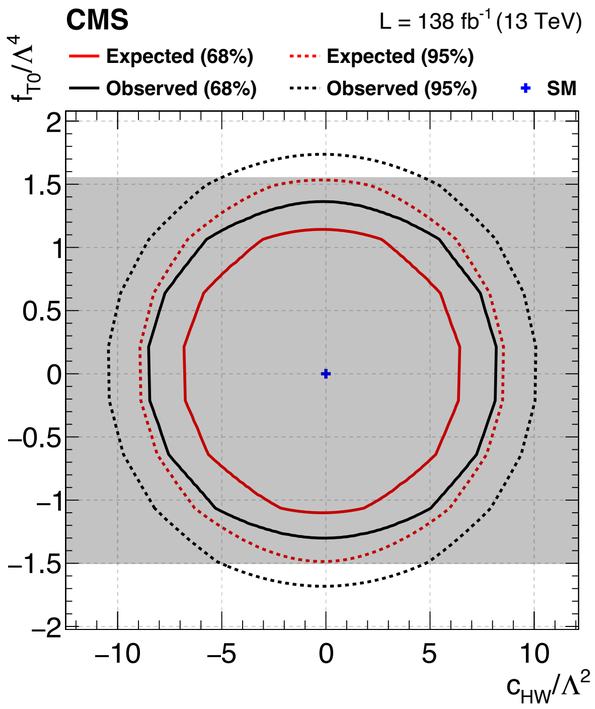
Adding up dim-6 and dim-8

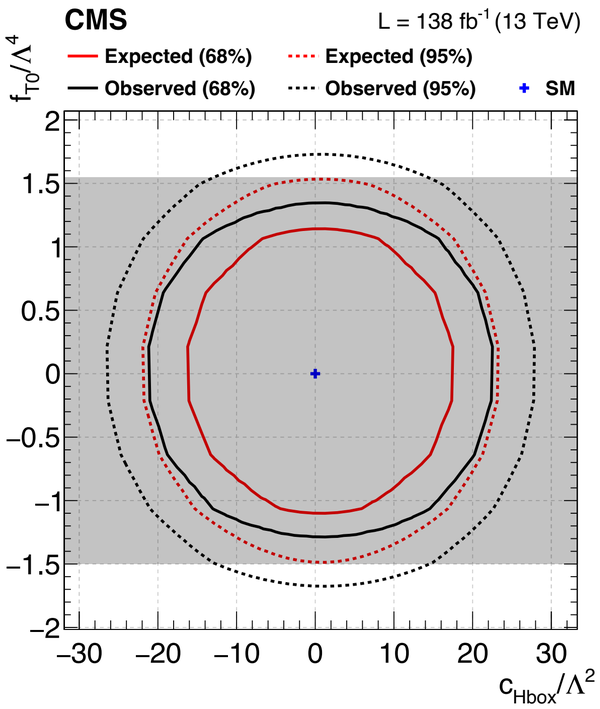
First time ever

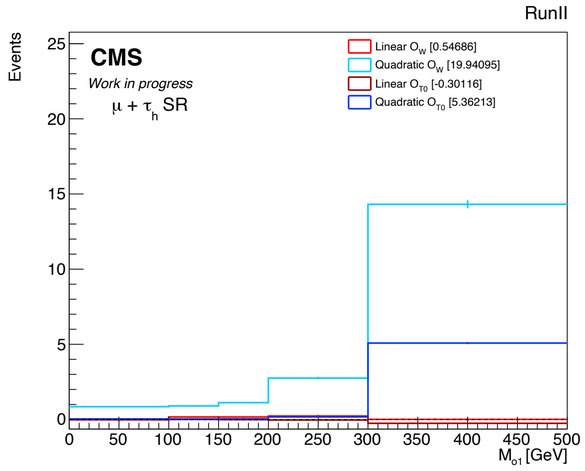
dim-8 1D 95% CI

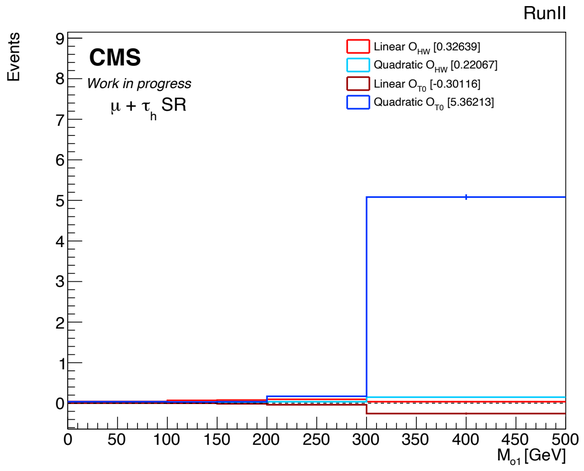
Bosonic operators

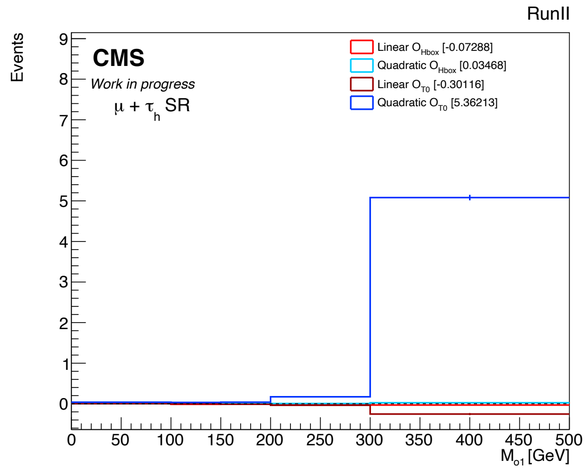












The tau effect on dim-8

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

The tau effect on dim-8

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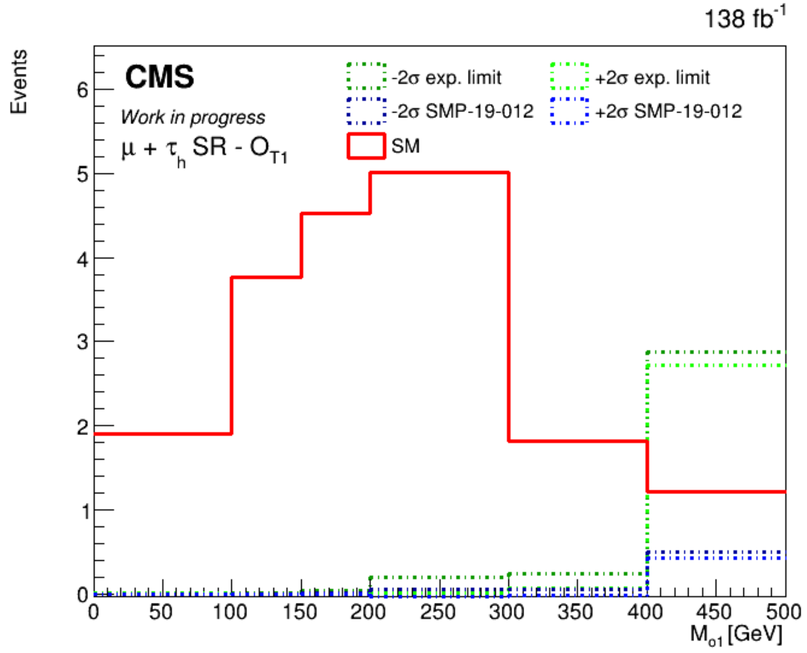

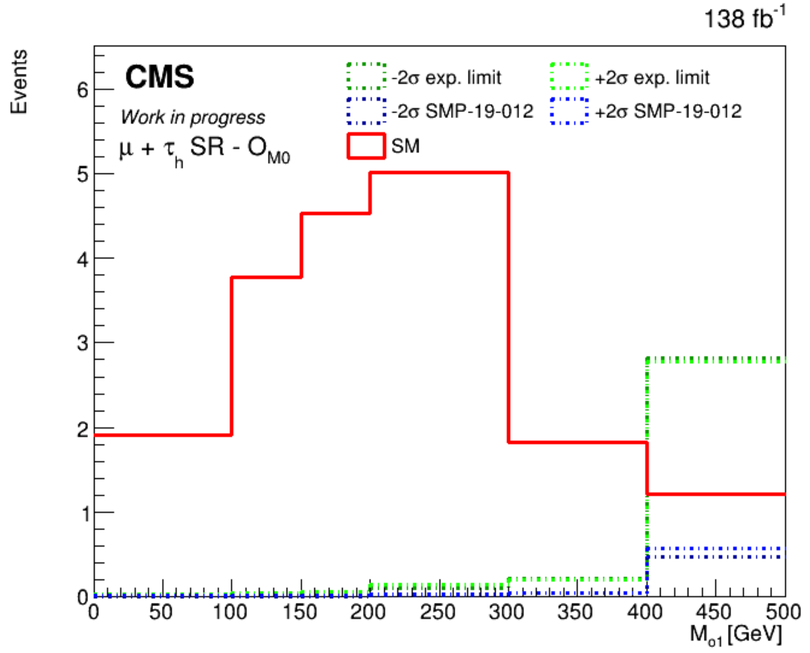

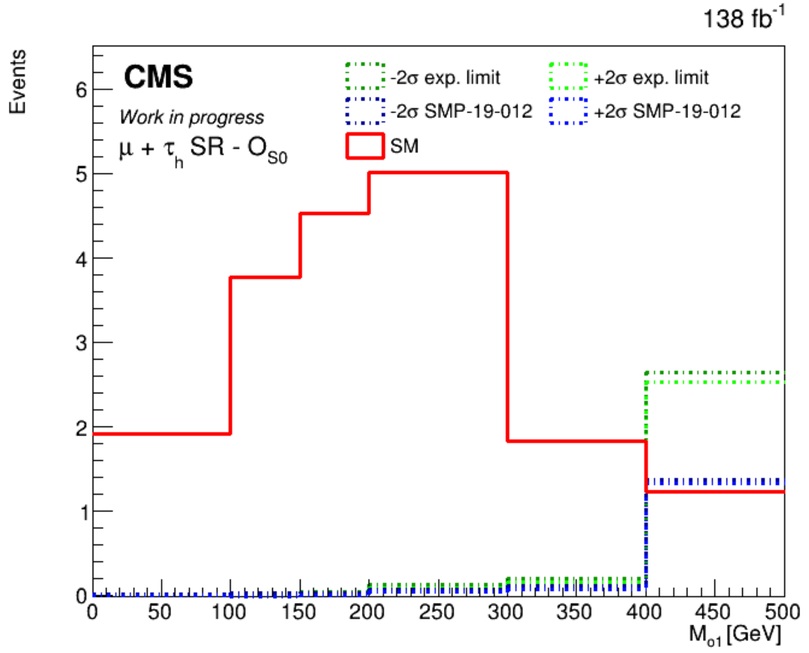

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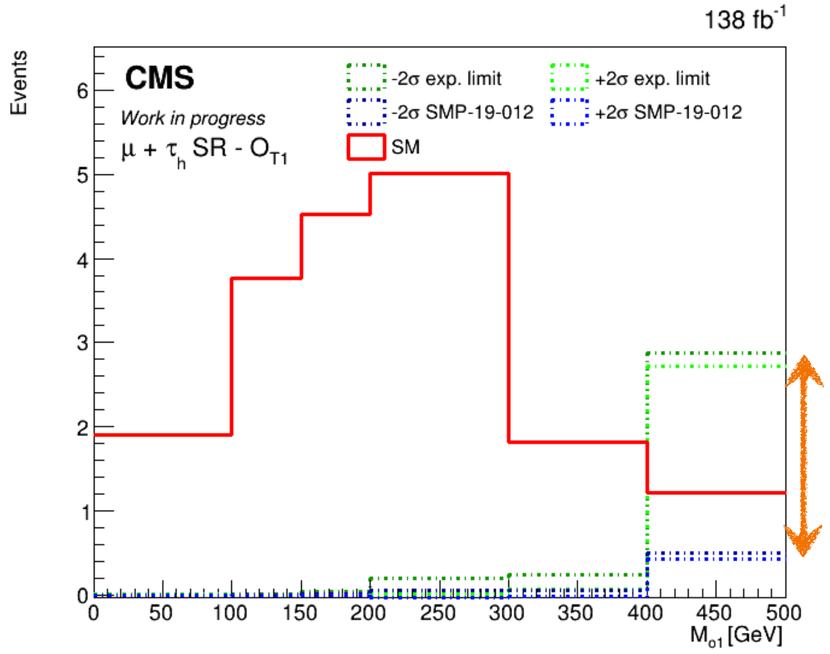

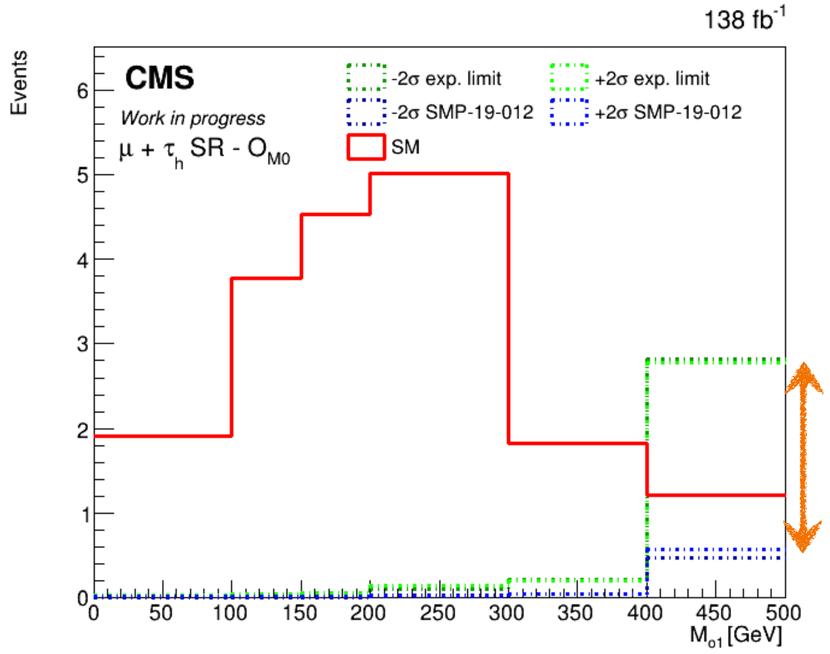

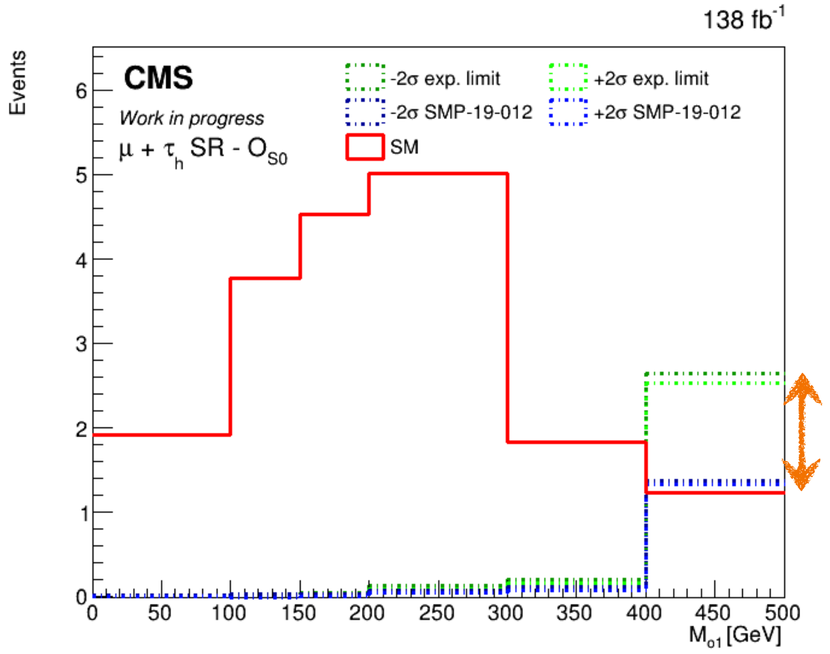

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Adding a tau improves the sensitivity to EFT effects on the Higgs field

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From arXiv:2311.16897
Example with Z2RSE model

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

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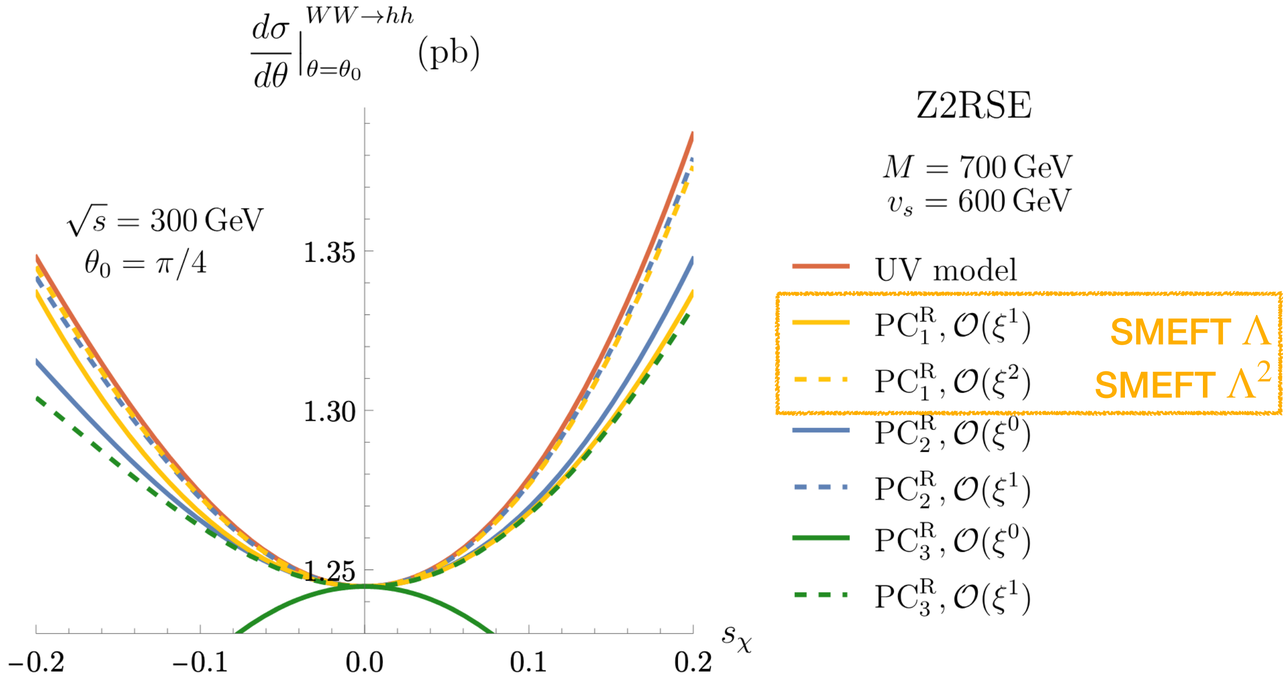

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NP expedition

Connecting the two approaches: a dream!

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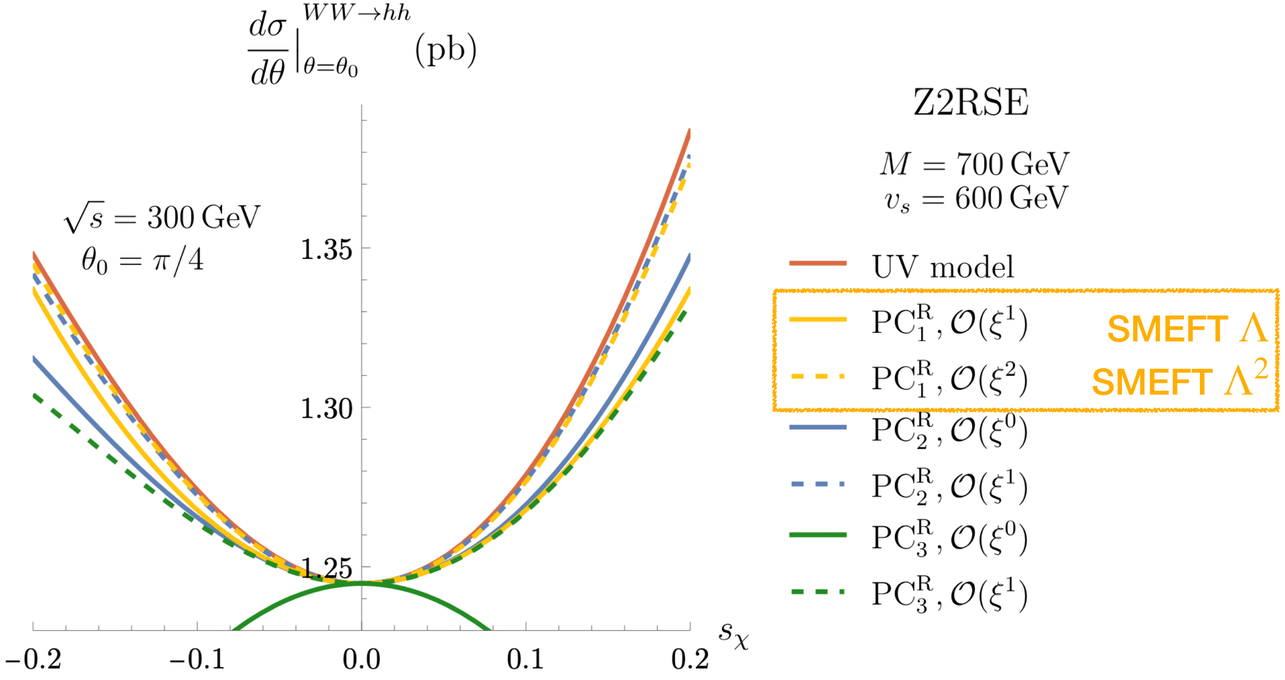

From dreams to reality

How many operators?

- VBS study: 26 operators (dim-6 + dim-8)

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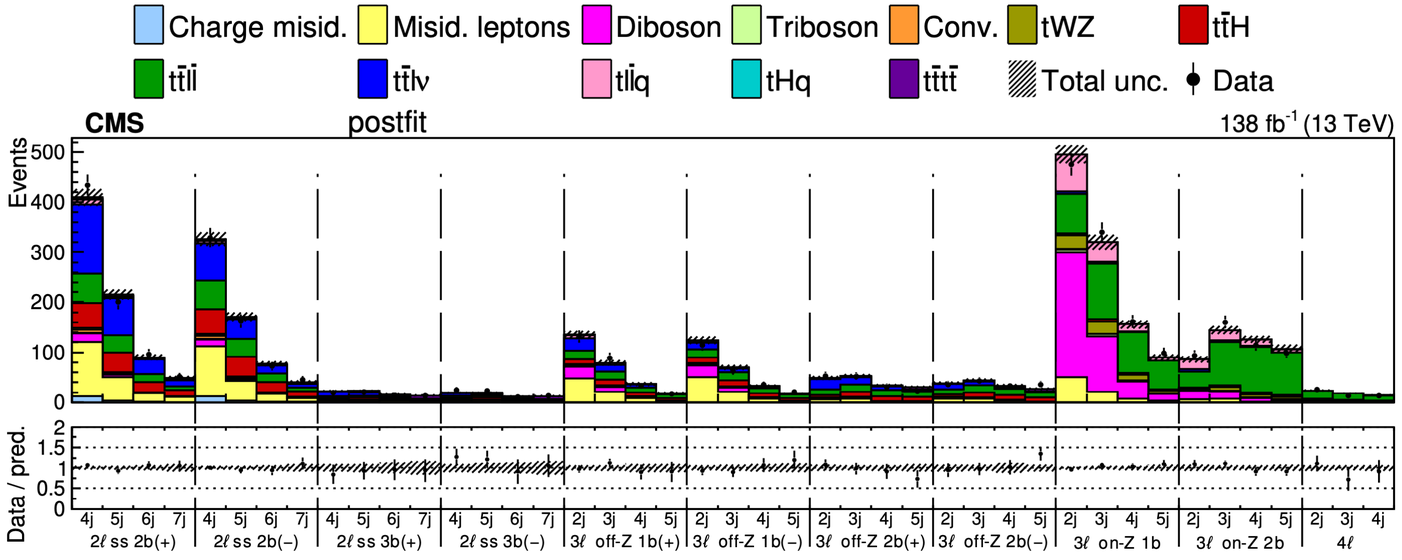

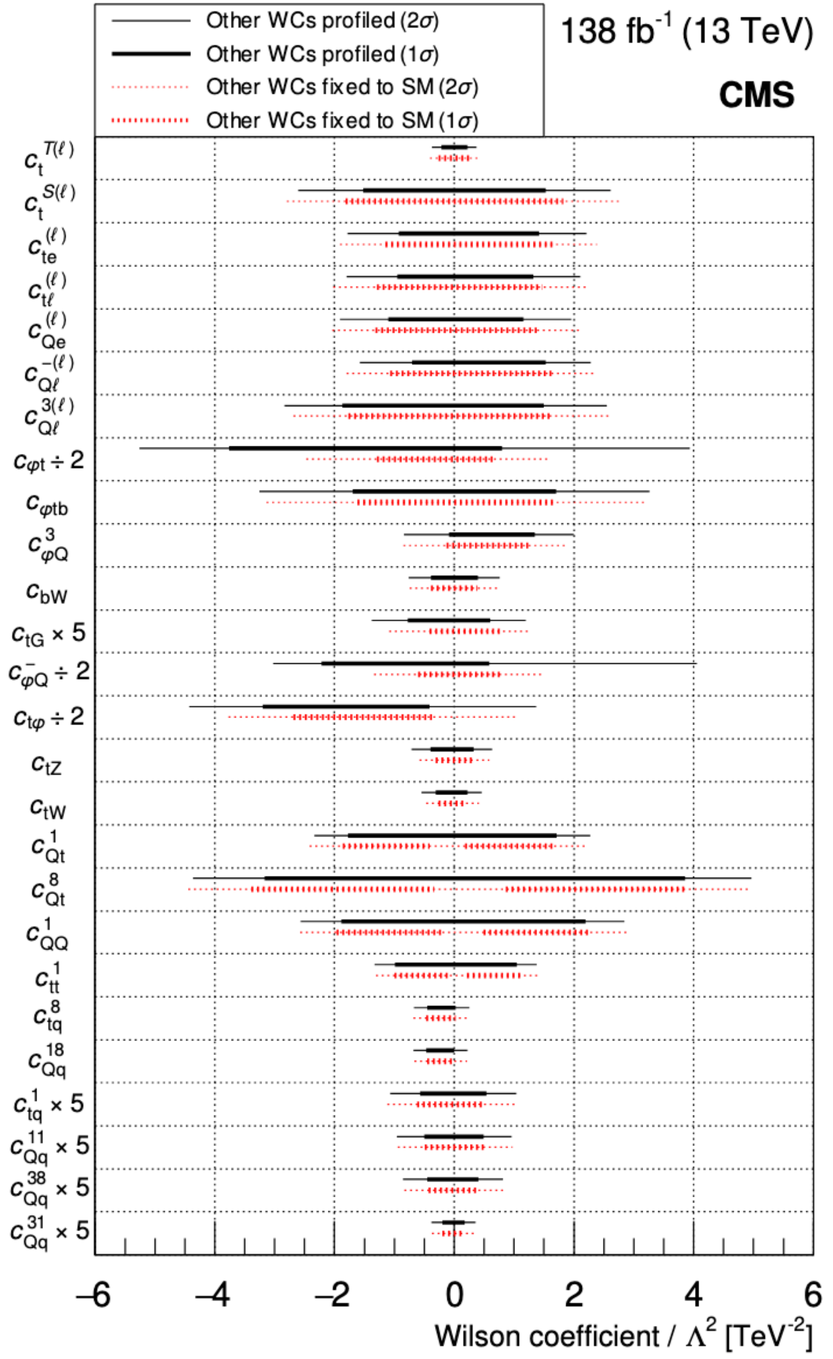

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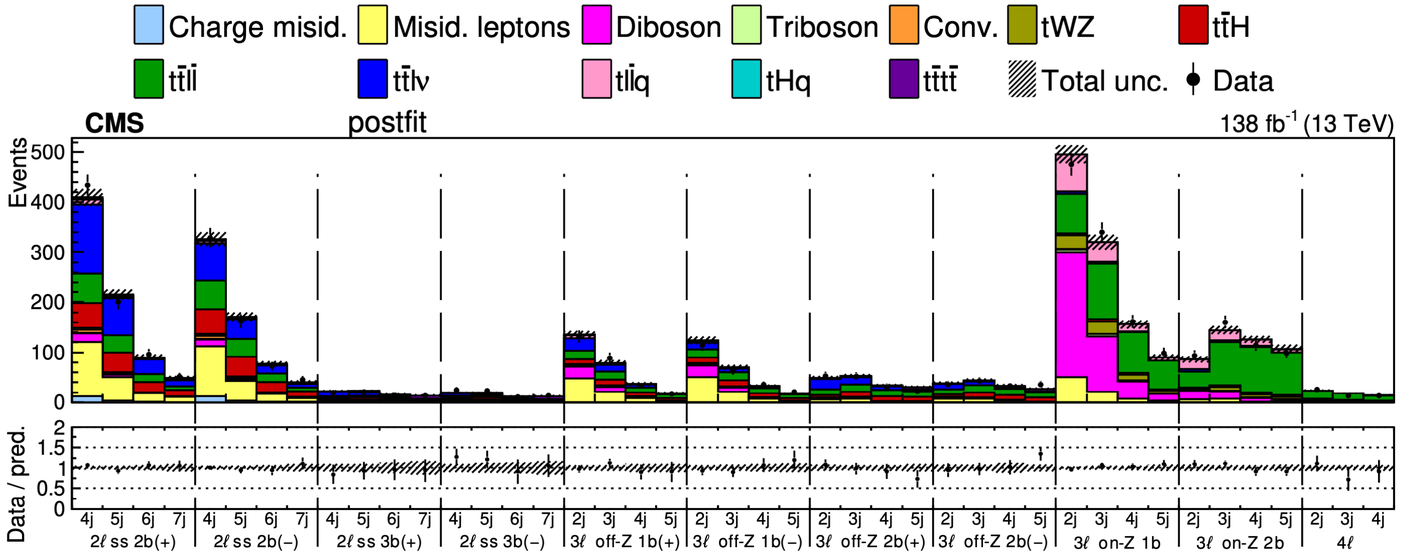
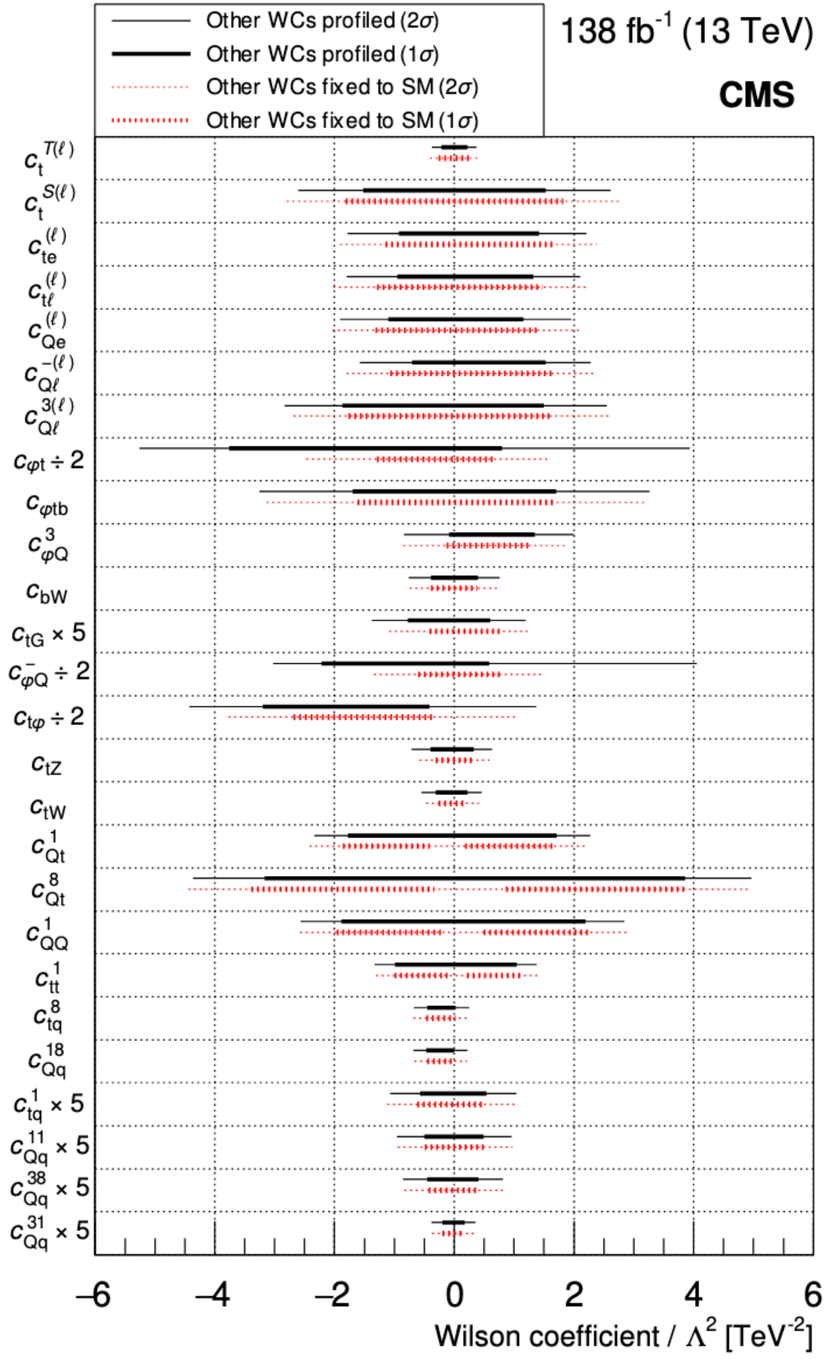
- Limitations imposed by statistics and technologies available
  - Too many parameters to deal with!





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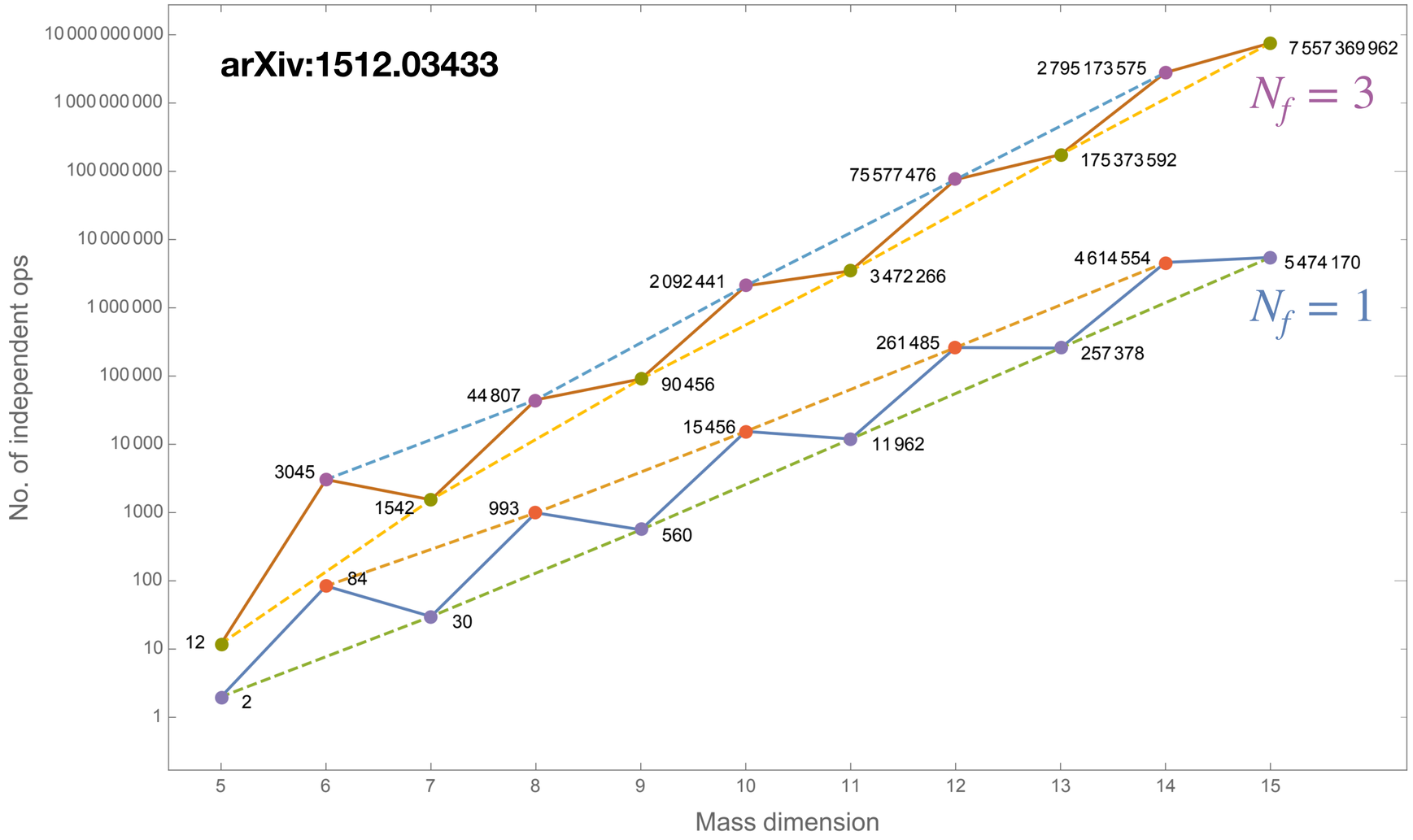

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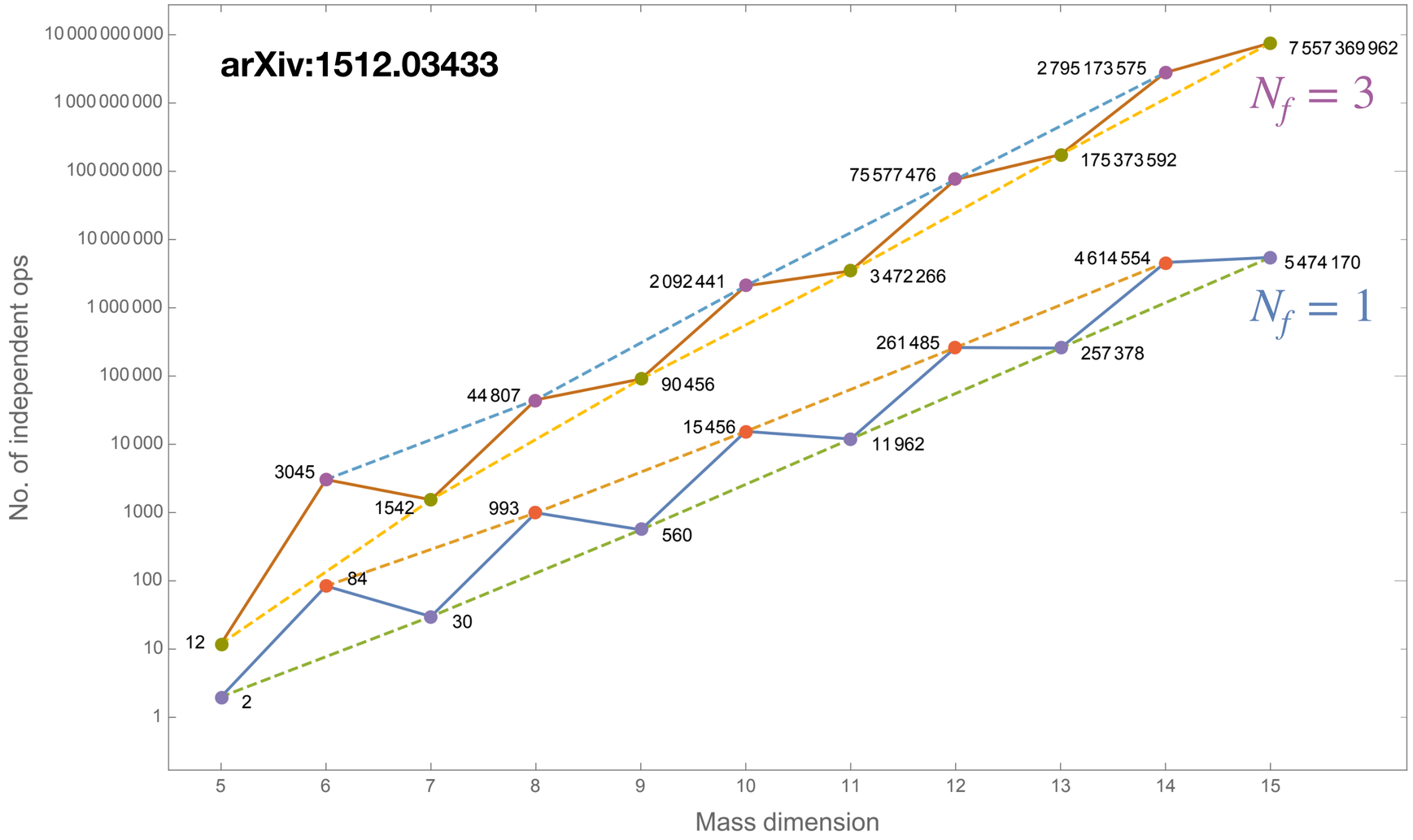

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A systematic regrouping across dimensions desired

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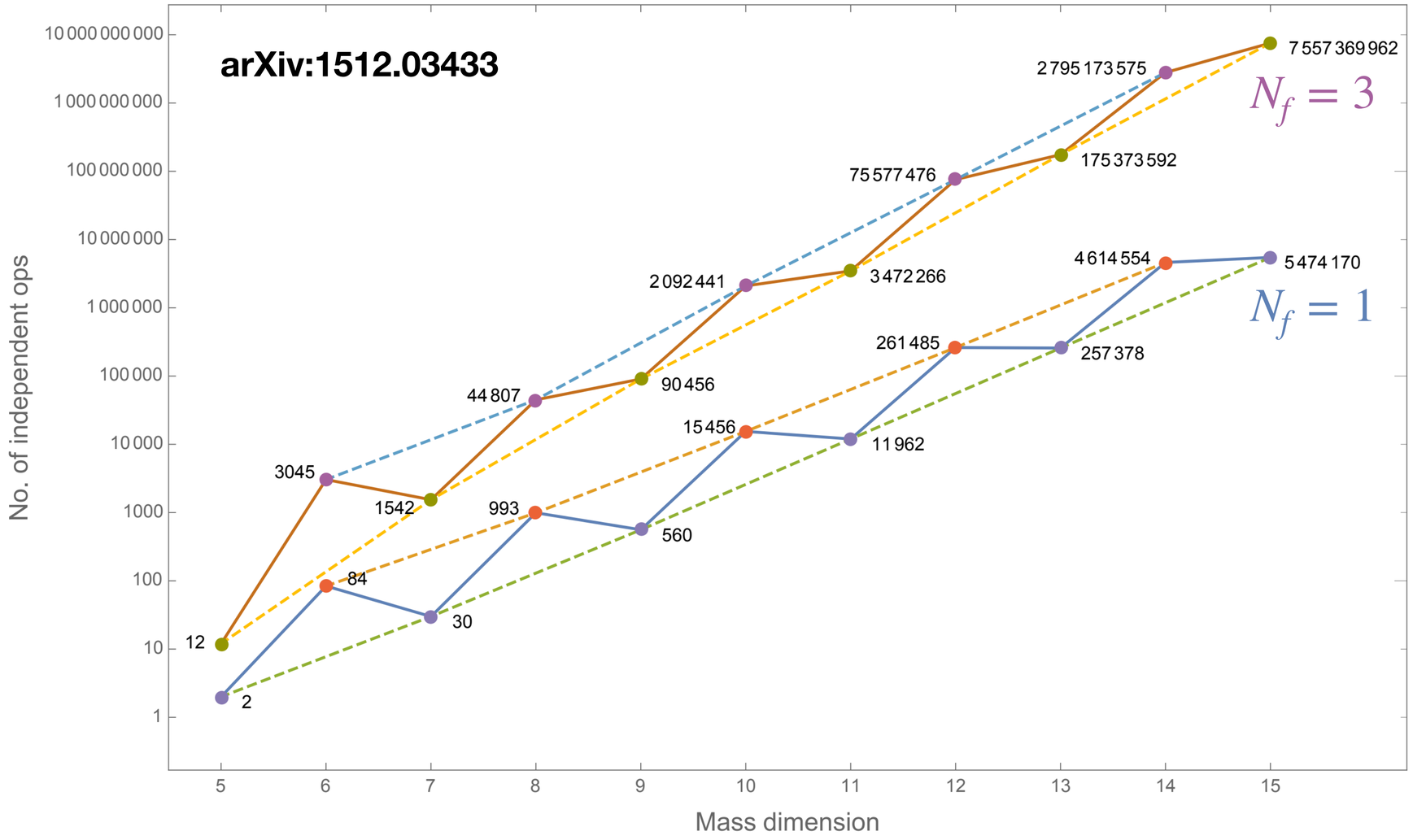

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A systematic regrouping across dimensions desired

What if we focus on Λ powers?

The geoSMEFT approach

Grasp similarities among dim-6 and dim-8 operators

The geoSMEFT approach

Grasp similarities among dim-6 and dim-8 operators

- EFT effects mainly at high energy
  - Focus on operators modifying kinematic distributions
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Geometric interpretation of the SMEFT Λ expansion

- Some theoretical magic to reorganize operators in terms of $(E, \mathrm{vev})/\Lambda$ expansion
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Exact EFT treatment up to Λ^{-4} with a manageable amount of operators!

Benefits of the geometric approach

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

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Λ^2 order

Leading contributions

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Λ^2 order

Λ^4 order

Leading contributions

Consistent treatment with the minimum # of operators

Benefits of the geometric approach

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

Λ^2 order

Λ^4 order

Leading contributions

Consistent treatment with the minimum # of operators

- Solid interpretation of the leading EFT contributions
  - Unbiased experimental constraints
- Paves the way for a sensible BSM-matching

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Potential step forward unifying direct and anomalies searches

A postcard from the journey

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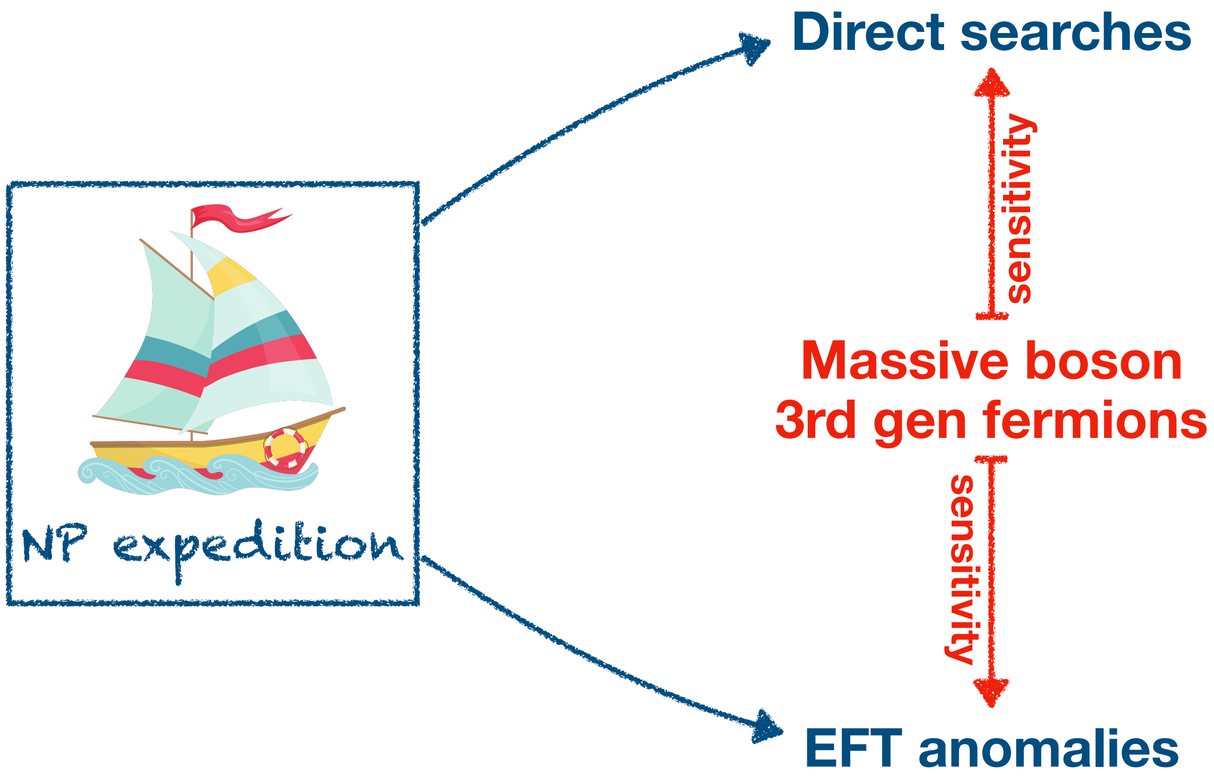
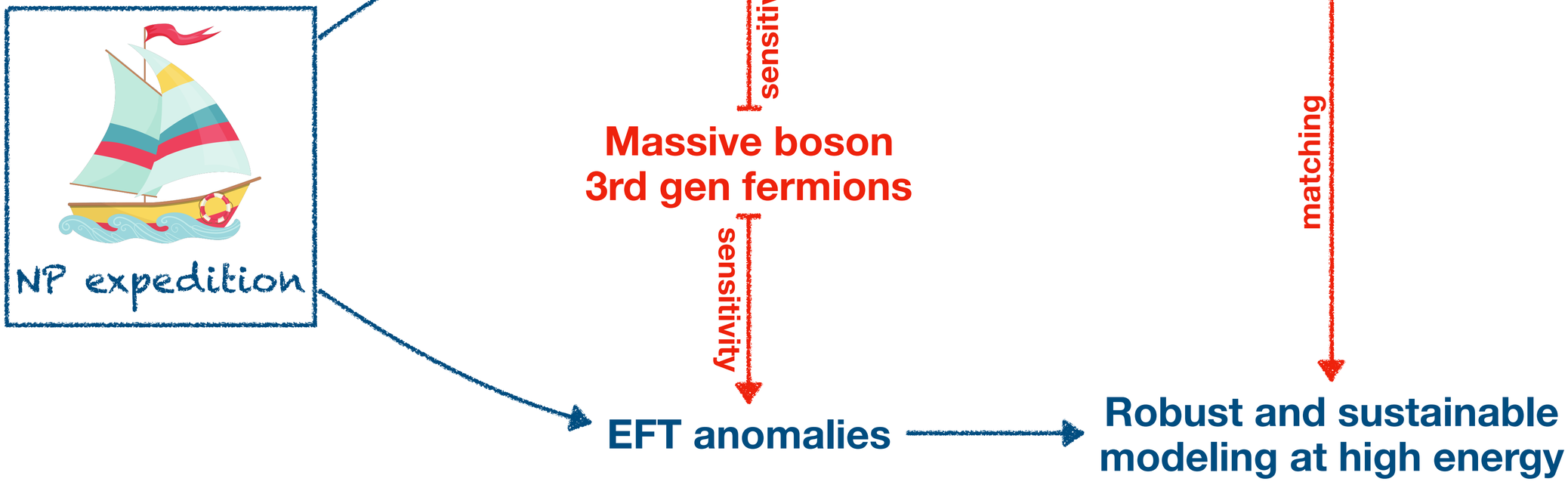


A postcard from the journey



A postcard from the journey

Direct searches

Model-wide reinterpretable results

sensitivity

Massive boson 3rd gen fermions

matching

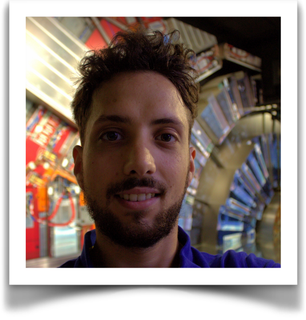
Chasing down where NP is!

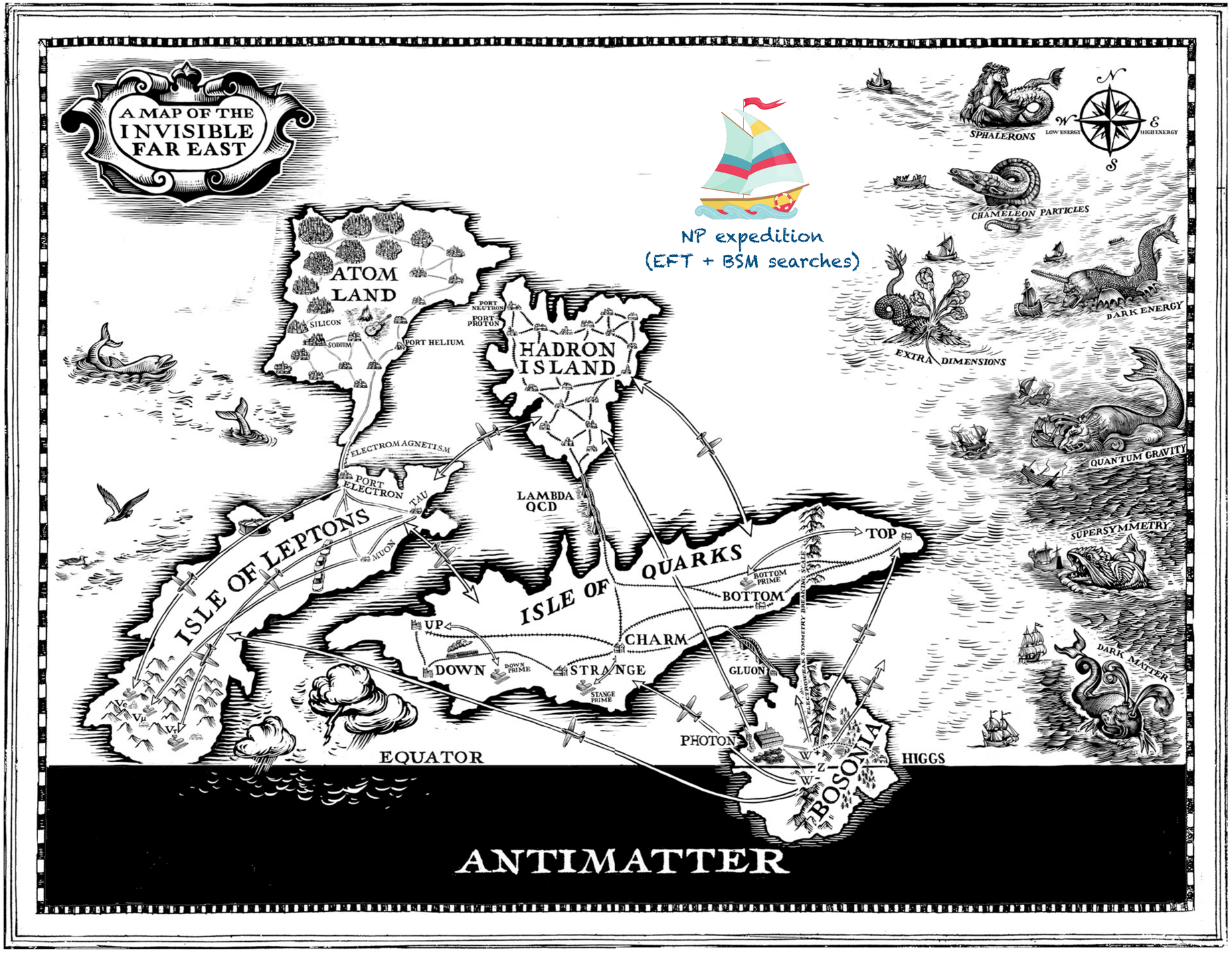
sensitivity

EFT anomalies

Robust and sustainable modeling at high energy

Thank you!





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Additional slides