The Standard Model and Beyond: From the LHC to Black Hole Microstructure

James Inglis

Queen Mary University of London

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Overview of Talk

This talk will be based on two different projects:

1. Using LHC data to constrain the Standard Model Effective Field Theory:

   ATLAS Collaboration. ***"Measurement of double-differential charged-current Drell-Yan cross-sections at high transverse masses in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector".*** (JHEP link)

2. Investigating black hole microstructure:

   Stefano Giusto, James Inglis, Rodolfo Russo. "***Fortuity beyond counting: an explicit construction*".** (JHEP link)

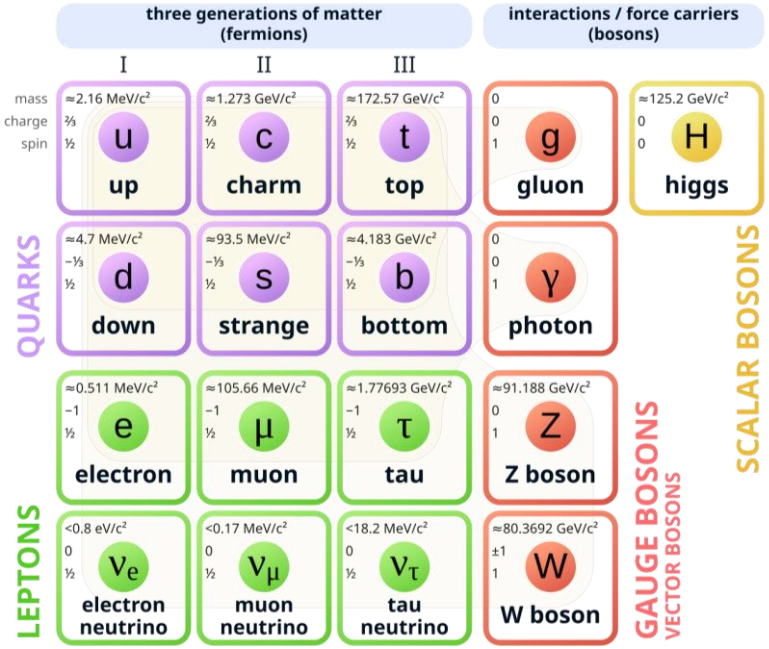
Project 1: SMEFT Interpretation of CCDY

1. Introduction to the Standard Model Effective Field Theory (SMEFT)
2. SMEFT Interpretation of the Charged-Current Drell-Yan process
3. Summary
4. * Global fits (if I have time)

The Standard Model

The current model of particle physics:

The **Standard Model (SM)**

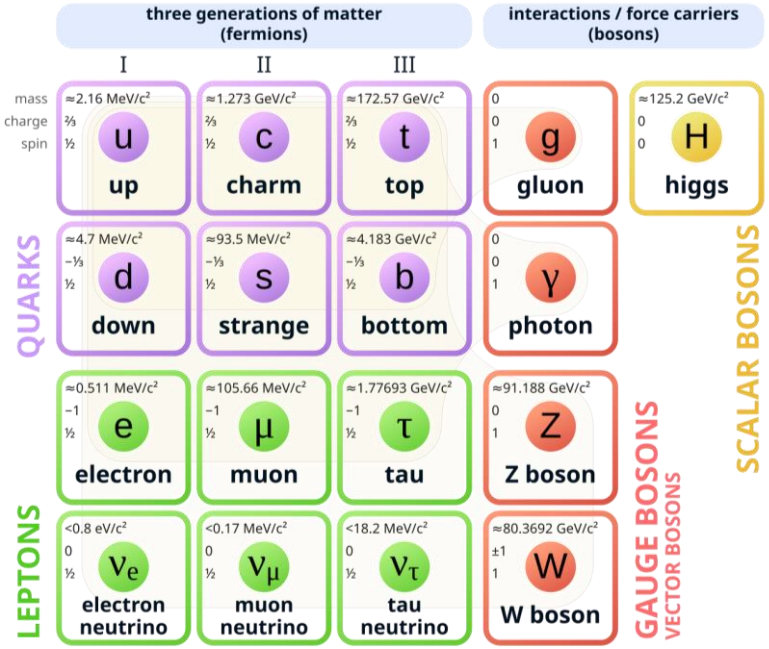


→ Describes how these 17 particles behave and interact

The Standard Model

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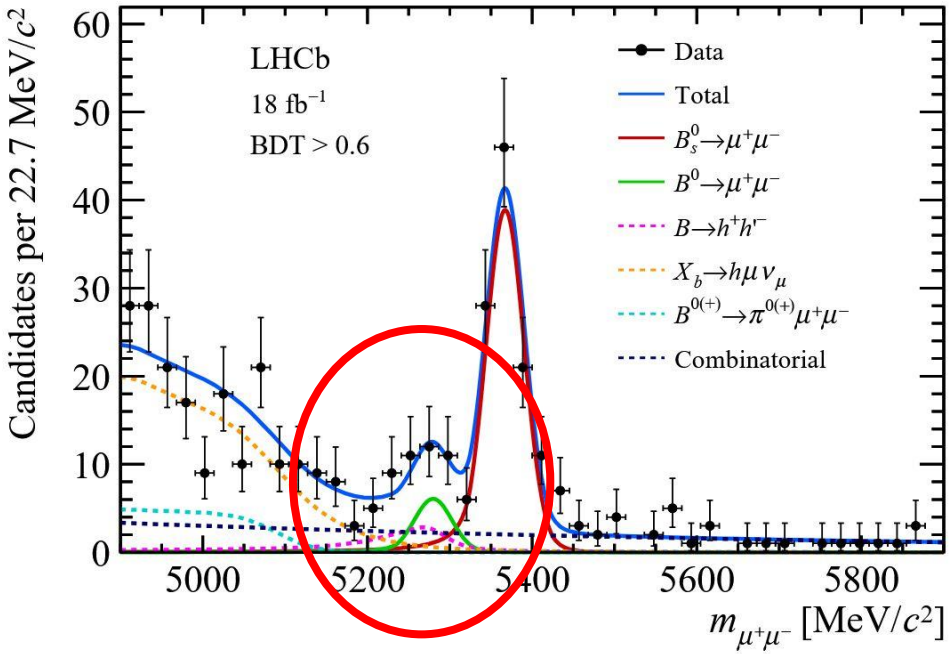
The **Standard Model (SM)**



→ Describes how these 17 particles behave and interact

The SM has proved to be very successful!

- E.g. new result from LHCb: evidence of rare decay, probing distances 10 billion times smaller than an atom → SM still in agreement!

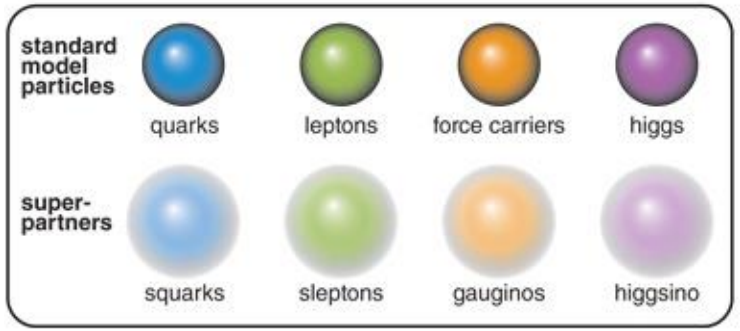


→ But it incomplete….

The Standard Model

- Shortcomings of the SM:
  - Fails to explain several important physics phenomena (dark matter, dark energy, gravity…)
  - Fine-tuning: many SM parameters appear to take ``unnatural'' values → is there a deeper explanation why?
- The SM provides an accurate description of observations at the LHC so far, no clear signs of new physics…
- New physics effects are likely at energies currently beyond the reach of the LHC, $E > E_{LHC}$
- Not clear what the new physics is…

  There are many attractive models:
  - e.g. supersymmetry (every force particle has a matter particle "superpartner")

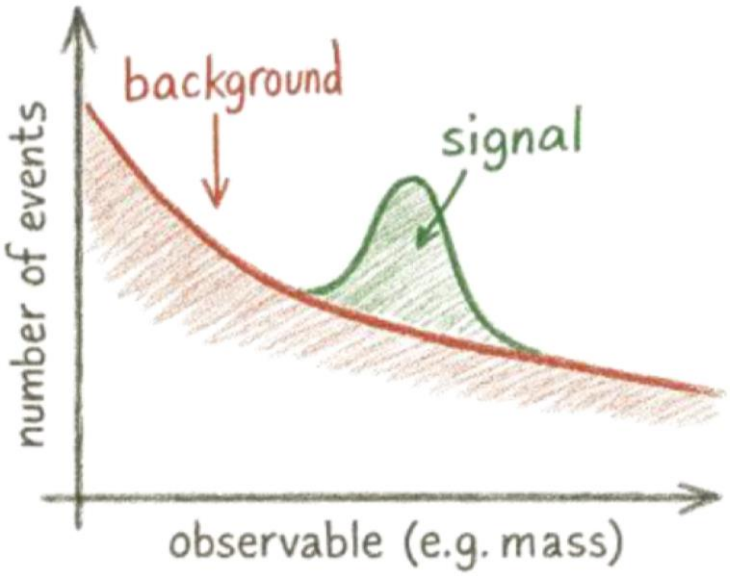


Searching for New Physics

- How do we actually search for new, beyond the Standard Model (BSM) physics?

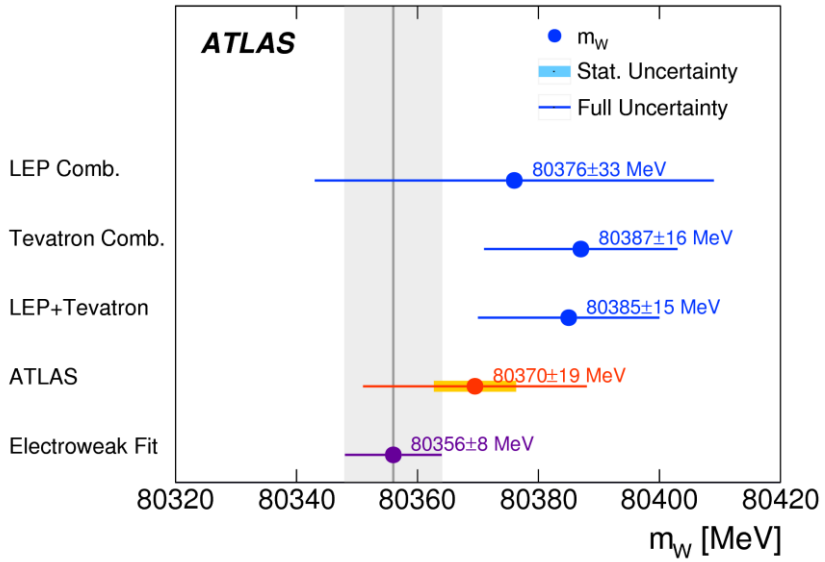
1) Direct Search

→ Search for experimental signature associated with specific particle



2) Indirect Search

→ Compare measurement with SM prediction: observed deviation signals new physics effects



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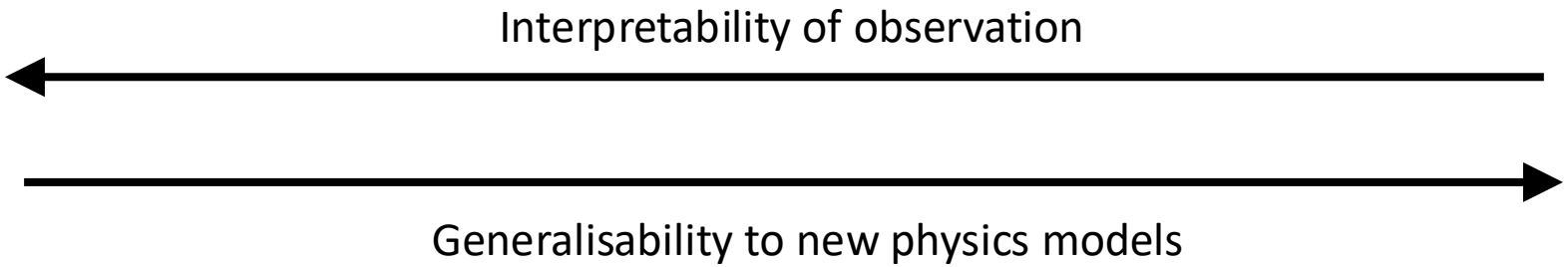
→ Search for experimental signature associated with specific particle

✓ Can explicitly constrain new physics
✗ Model-dependent

2) Indirect Search

→ Compare measurement with SM prediction: observed deviation signals new physics effects

✓ Model-independent
✗ Hard to place explicit constraints on new physics



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→ Can we characterise SM deviations is model-indendent and quantifiable way?

Searching for New Physics

Treat SM as an **Effective Field Theory** (EFT):

- Assume Standard Model is an effective description of some more (unknown) fundamental theory.
- Assume the Standard Model accurately describes physics up to some **energy cutoff scale Λ** ~ a few TeV

→ **Standard Model Effective Field Theory (SMEFT)**

Standard Model Effective Field Theory

- How do we treat the SM as an EFT?

  → Modify the SM Lagrangian

Standard Model Effective Field Theory

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→ Modify the SM Lagrangian

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

$\mathcal{O}_i^{(d)}$ = d-dim. operator (built from the SM fields)

- $c_i^{(d)}$ = **Wilson coefficient** (control the weight of each operator)
- Λ^{d-4} means each term has dimension 4

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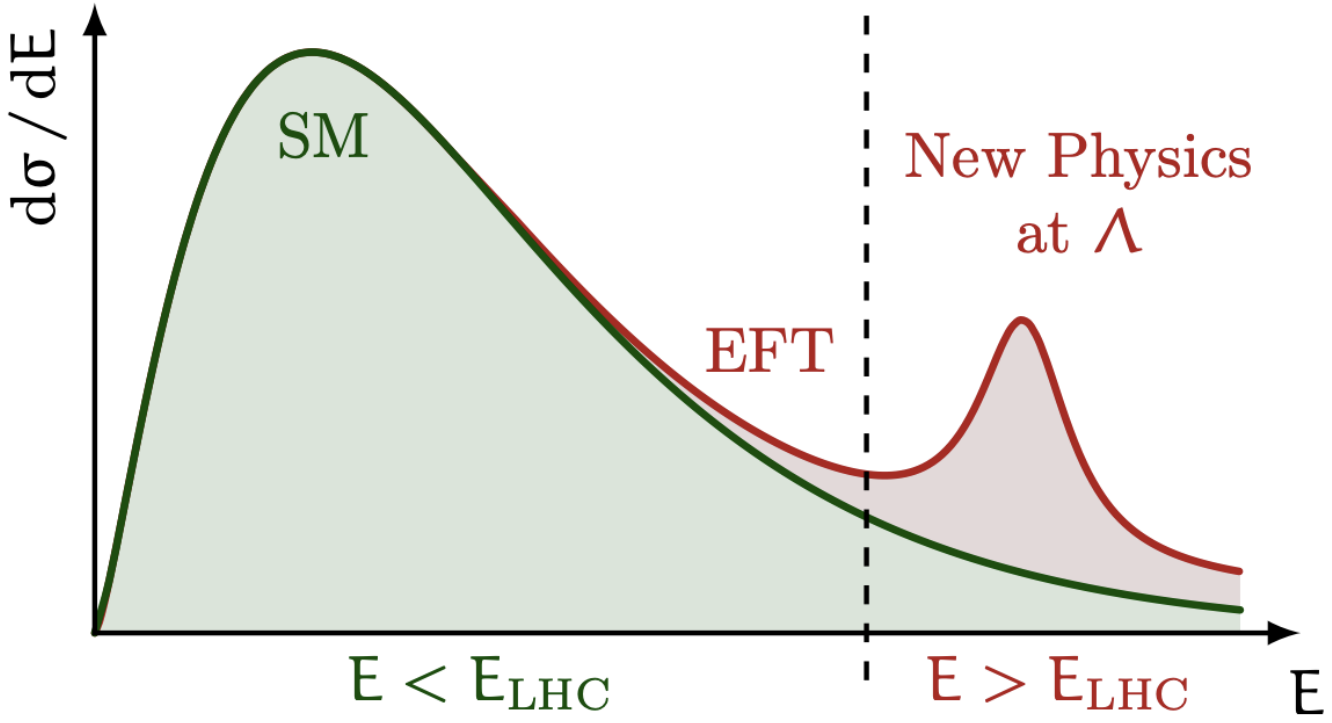
- $c_i^{(d)}$ = **Wilson coefficient** (control the weight of each operator)
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This is the most general Lagrangian which:

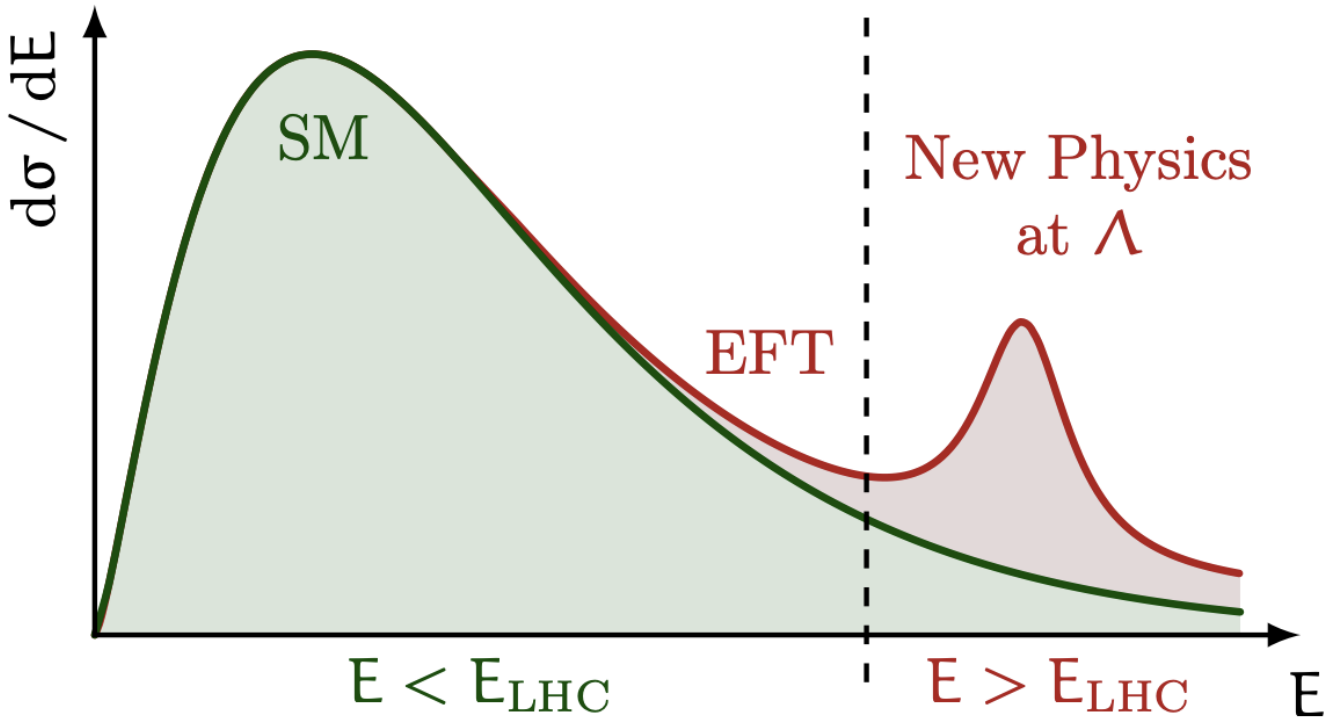
- Contains the same field content as the SM,
- Obeys the same symmetries as the SM,
- Has mass dimension $d = 4$.

→ The SMEFT offers a **broad** and **generalised** way of characterising new physics

SMEFT Picture

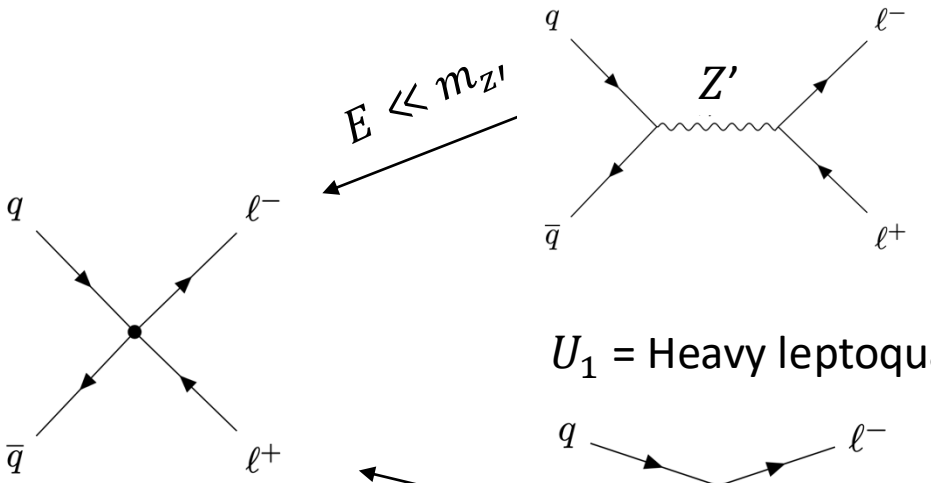


SMEFT Picture



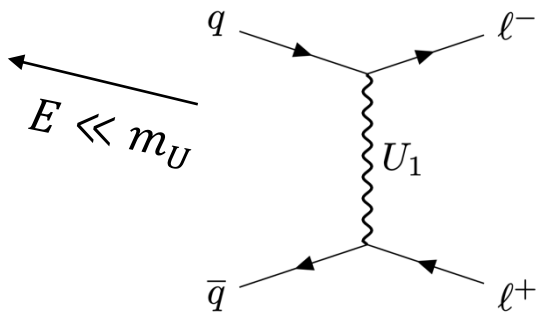
Could be multiple different BSM models

Z' = Heavy Z-boson



SMEFT operator

U_1 = Heavy leptoquark



Fitting with the SMEFT

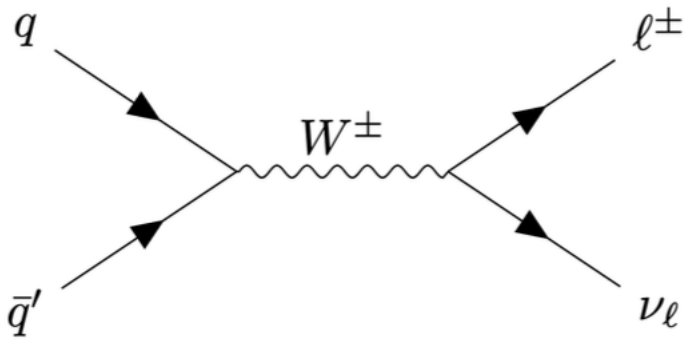
- **Goal:** Use collider data to determine the values of the Wilson coefficients
  - SM deviation → new physics → nonzero Wilson coefficients

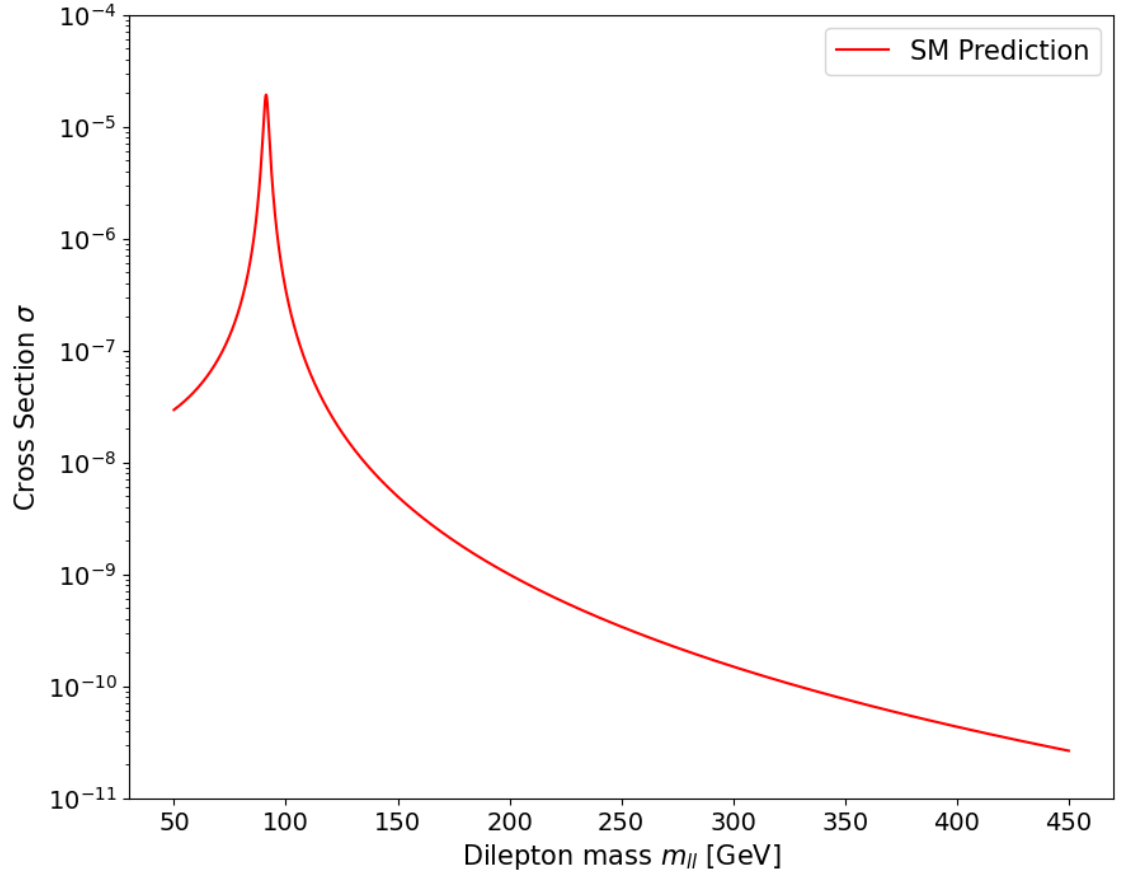
SMEFT Example

- **Goal:** Use collider data to determine the values of the Wilson coefficients

- **Example:** charged-current Drell-Yan ($qq \to lv$)

$\mathcal{L}_{SM}$ ⟶



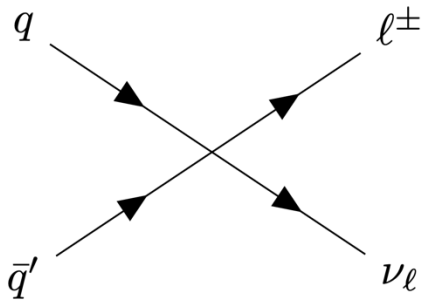


SMEFT Example

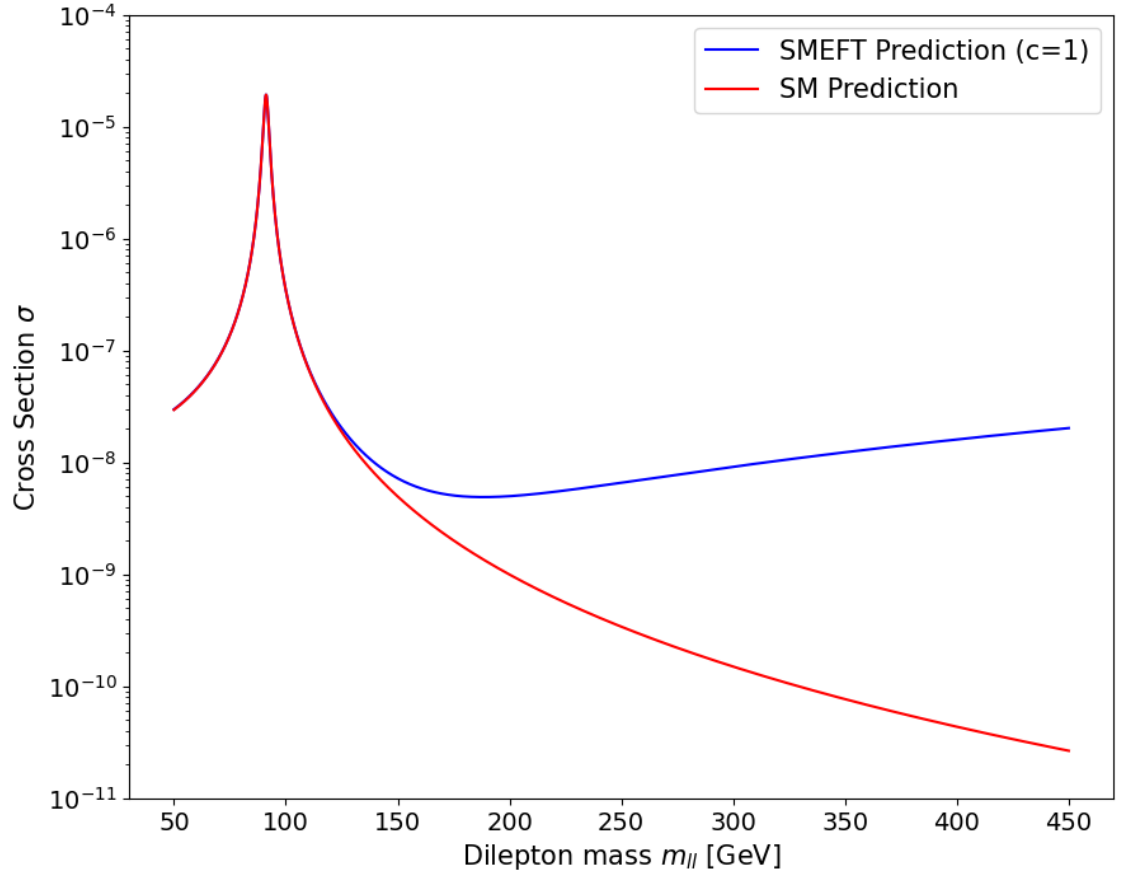
- **Goal:** Use collider data to determine the values of the Wilson coefficients

- **Example:** charged-current Drell-Yan ($qq \to lv$)

$$\mathcal{L}_{SMEFT} \xrightarrow{c_{lq}^{(3)} = 1}$$



$$\mathcal{O}_{lq}^{(3)} = (\bar{l}\sigma^I \gamma_\mu l)(\bar{q}\sigma^I \gamma^\mu q)$$

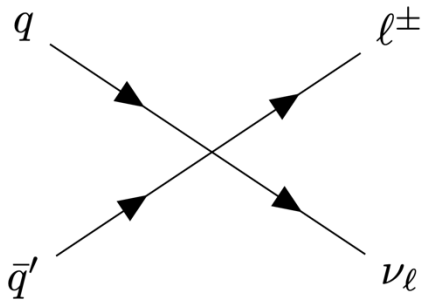


SMEFT Example

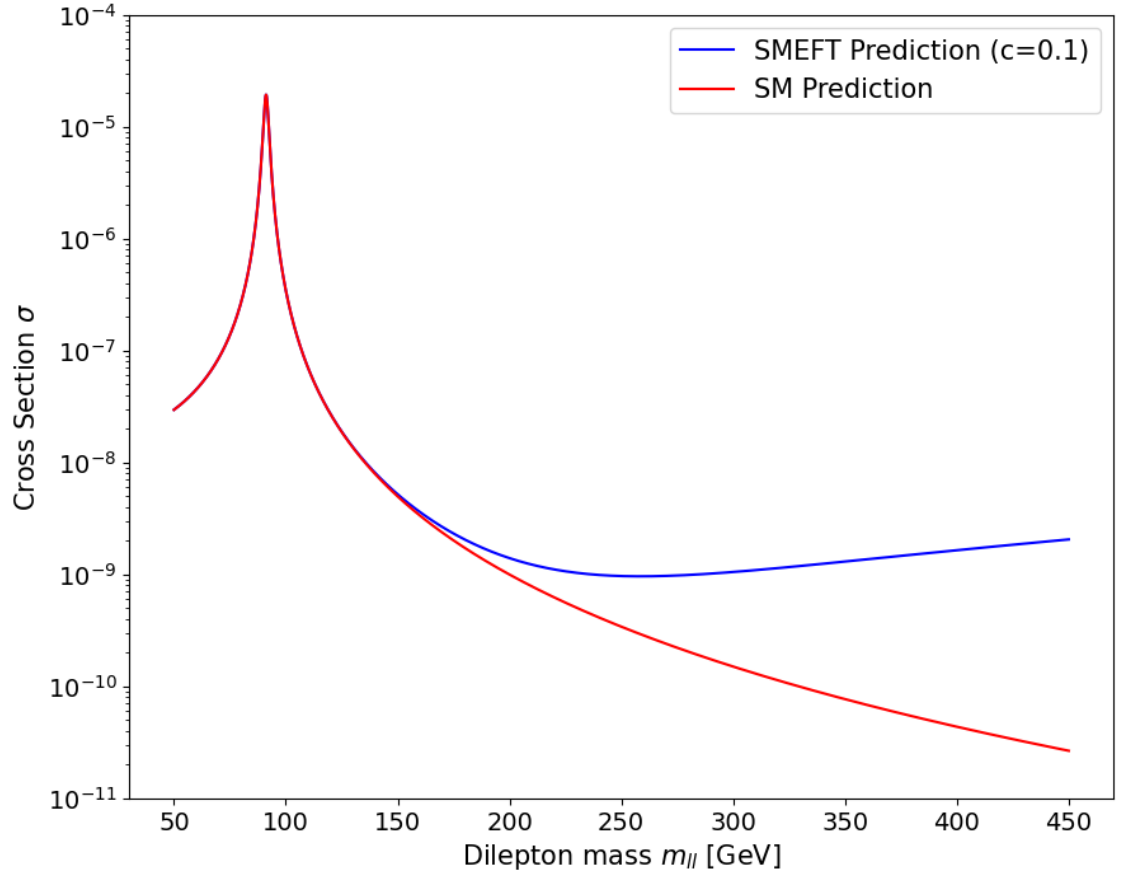
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$$\mathcal{L}_{SMEFT} \xrightarrow{c_{lq}^{(3)} = \mathbf{0.1}}$$



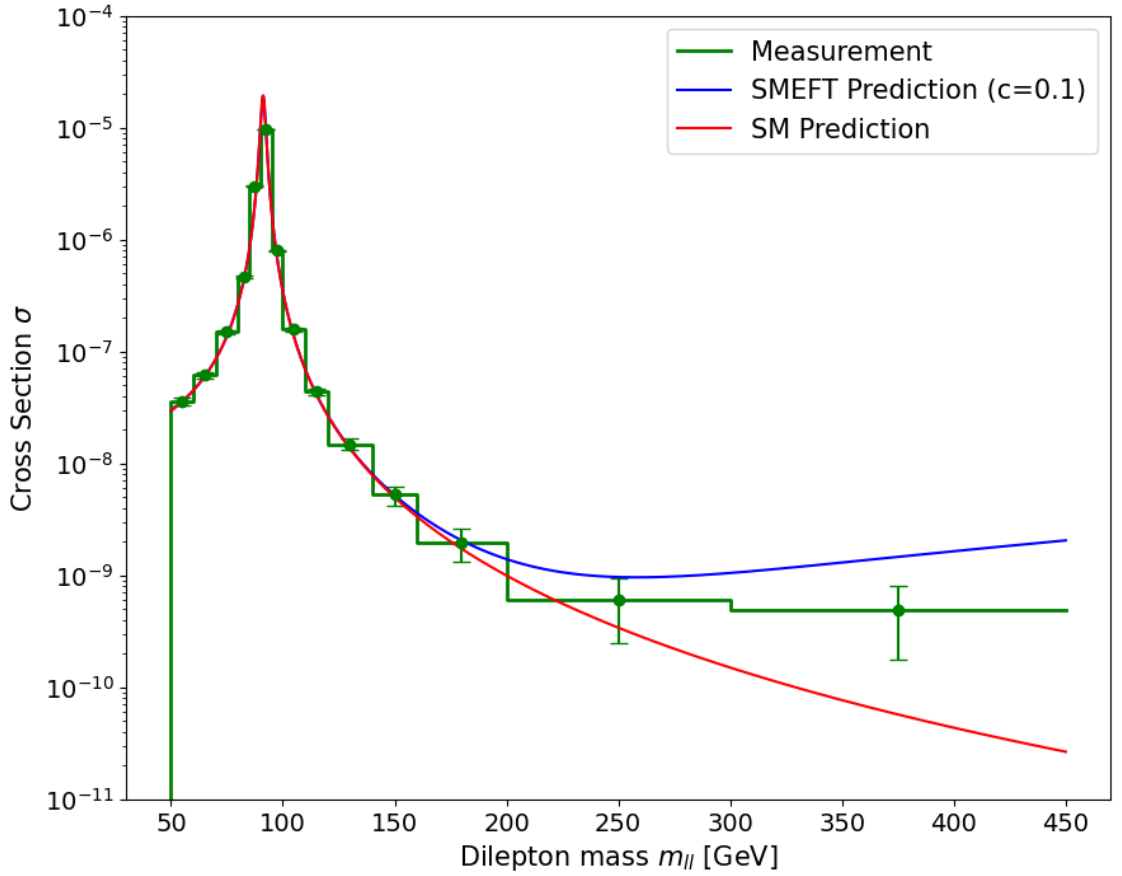
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SMEFT Example

- **Goal:** Use collider data to determine the values of the Wilson coefficients
- **Example:** charged-current Drell-Yan ($qq \to lv$)

$$\mathcal{L}_{SMEFT} \xrightarrow{c_{lq}^{(3)} = \mathbf{0.1}}$$



- Compare against measured 1d cross section
- Statistical fit for $c_{lq}^{(3)}$: $c_{lq}^{(3)} = \mathbf{0.05 \pm 0.01}$

Statistical Model

The values of the Wilson coefficients are estimated using a **maximum likelihood fit:**

- The likelihood is given by the product of the PDF for each measurement bin:

$$L(\vec{N} \mid \vec{\mu}, V) = \frac{1}{(2\pi)^{n/2}|V|^{1/2}} \exp\left(-\frac{1}{2}\left(\vec{N} - \vec{\mu}(c)\right)^T V^{-1}\left(\vec{N} - \vec{\mu}(c)\right)\right)$$

  - $\vec{N}$ = observed events counts in each bin,
  - $\vec{\mu}$ = vector of expected events counts,
  - V = covariance matrix (includes correlations between bins)

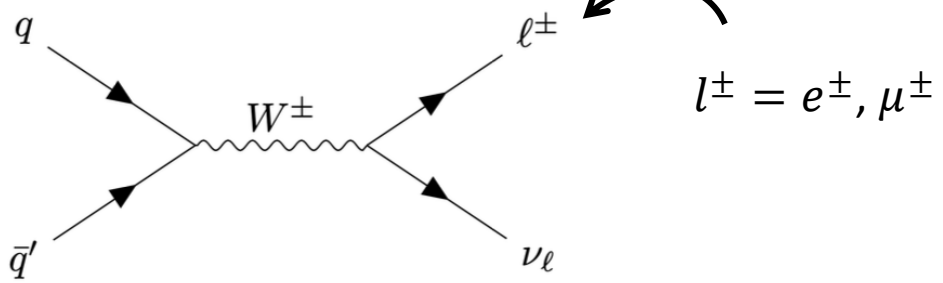
- Measures how well the SMEFT prediction explains the observations, for a given set of Wilson coefficents $\vec{c}$
- Maximum of likelihood → optimal values of $\vec{c}$.

- The observed number of events N_i in bin i follows a Gaussian distribution about some expected value $\mu_i(c)$

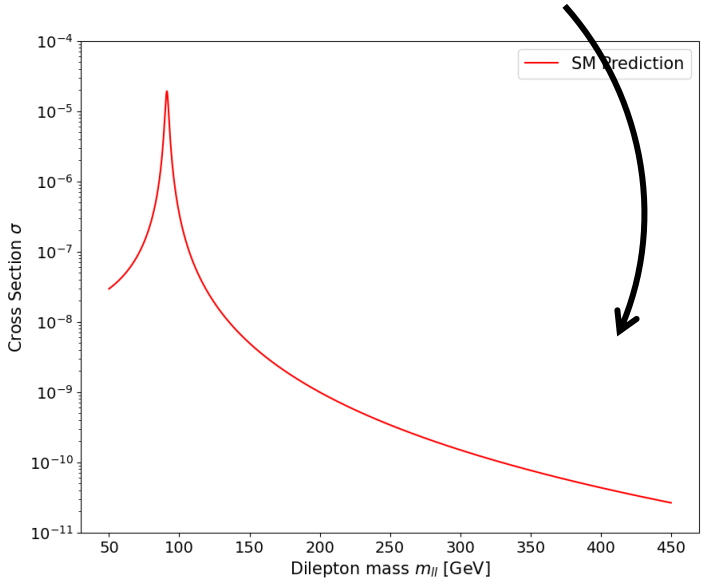
- The covariance matrix can contain many sources of uncertainty (statistical uncertainties, detector efficiencies, miscalibrations, theoretical parameters, etc).

High-Mass Charged-Current Drell-Yan

- Charged-Current Drell-Yan (CCDY) process: very common at LHC, but **rare** when W-boson is **very heavy**



$l^{\pm} = e^{\pm}, \mu^{\pm}$



- Measurement of cross-section at high mass is interesting:

  → Sensititive to new physics effects (e.g. W' boson, SMEFT)
  → Can constrain parton distribution functions (PDFs)
  → Never been measured before (until 2025)!

- Final-state neutrino is **invisable** to ATLAS

→ Measure W-boson **transverse mass** rather than invariant mass

$$m_T = \sqrt{2\, p_T^{\ell}\, p_T^{\nu} (1 - \cos\phi_{\ell\nu})}$$

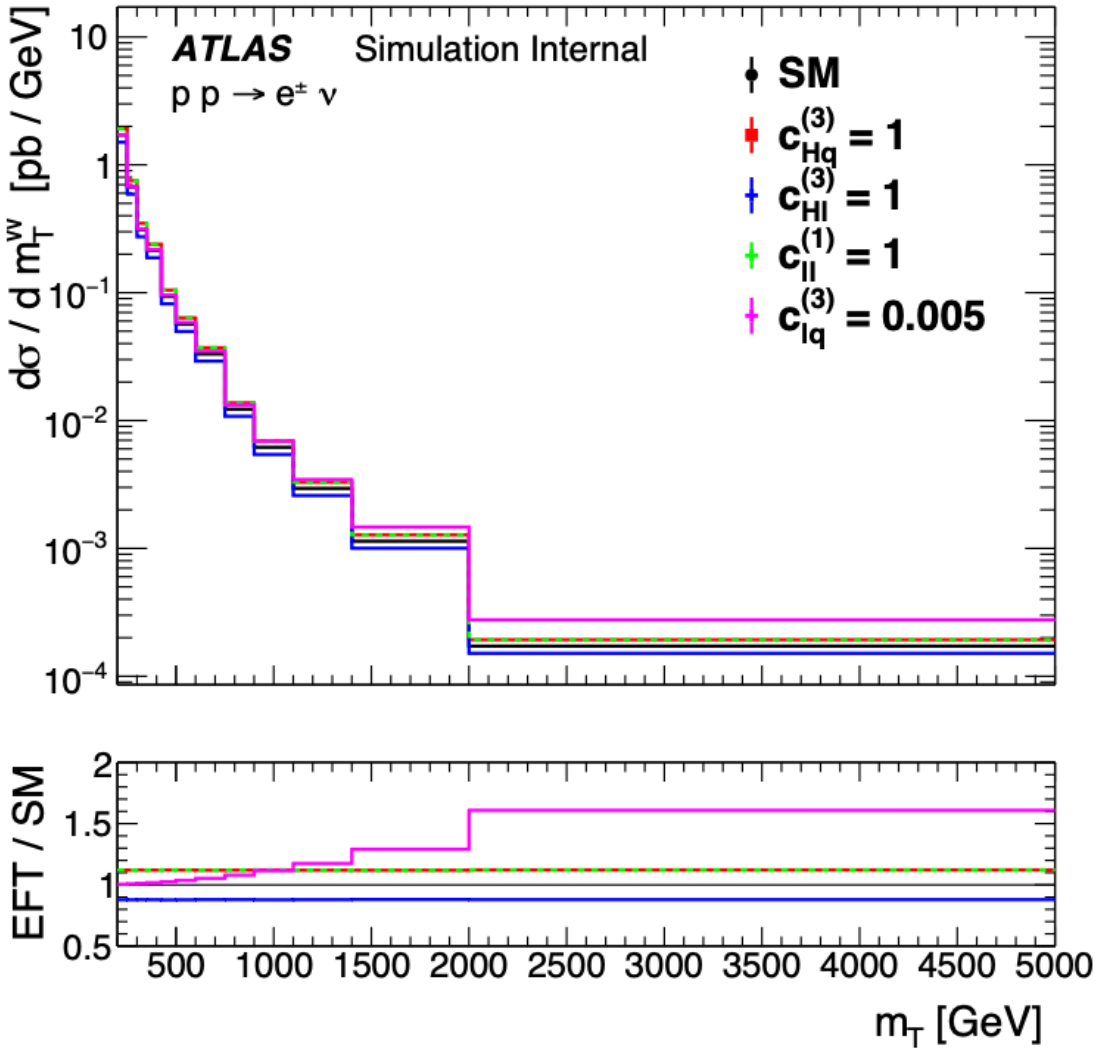
SMEFT Interpretation of Charged-Current Drell-Yan

- The charged-current Drell-Yan process is sensitive to **four** dimension-6 SMEFT operators:

Wilson Coefficient	Operator
$c_{Hq}^{(3)}$	$\mathcal{O}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$
$c_{H\ell}^{(3)}$	$\mathcal{O}_{H\ell}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{\ell}\tau^I\gamma^\mu \ell)$
$c_{\ell\ell}^{(1)}$	$\mathcal{O}_{\ell\ell}^{(1)} = (\bar{\ell}\gamma_\mu l)(\bar{\ell}\gamma^\mu l)$
$c_{\ell q}^{(3)}$	$\mathcal{O}_{\ell q}^{(3)} = (\bar{\ell}\tau^I\gamma_\mu \ell)(\bar{q}\tau^I\gamma^\mu q)$

→ $\mathcal{O}_{lq}^{(3)}$ gives significant enhancements at high-m_T^W !

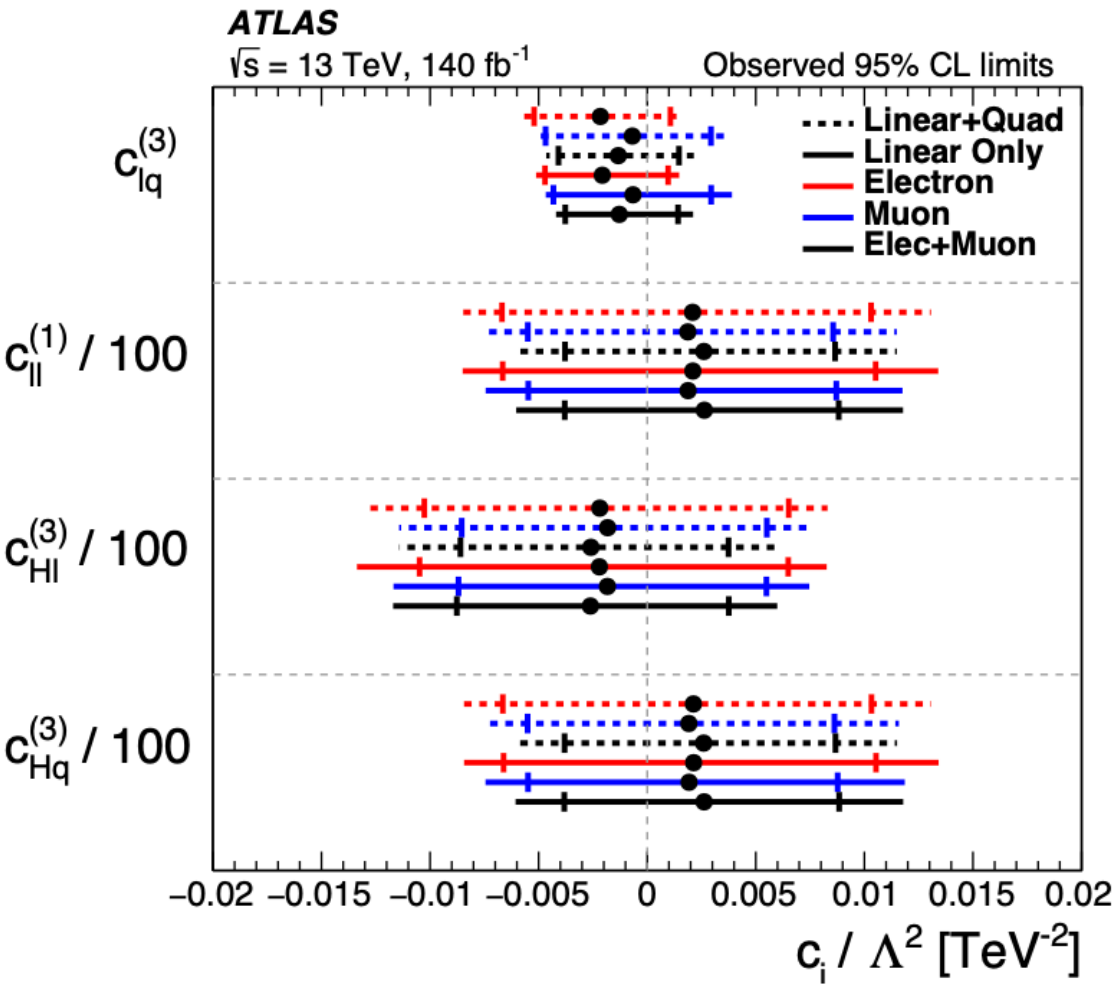
→ High-m_T^W CDDY measurement provides **strong** constraining power



Statistical Model

- The fit is performed one-by-one for each Wilson coefficient: vary one Wilson coefficent and set other three to zero
- The fit is performed six times for each Wilson coefficient:
  - Linear or Linear+quadratic effects
  - Electron, muon, or combined (electron+muon) channel measurement
- Likelihood: $$L(\vec{N} \mid \vec{\mu}, V) = \frac{1}{(2\pi)^{n/2}|V|^{1/2}} \exp\left(-\frac{1}{2}\left(\vec{N} - \vec{\mu}(c)\right)^{T} V^{-1}\left(\vec{N} - \vec{\mu}(c)\right)\right) \times \prod_{i}^{n_{syst}} \boldsymbol{f_i}(\boldsymbol{\theta_i})$$
  - Statistical uncertainties included in covariance matrix (diagonal → uncorrelated between bins)
  - Systematic uncertainties included as **nuisance parameters** (~ 150 nuisance parameters)
    - Additional model parameters with Gaussian PDF's constrained alongside Wilson coefficients
    - Experimental (affect measurement) or theoretical (affect prediction)

Observed Limits



- 6 limits shown for each coefficient (correspond to 6 different fits performed)
- All limits are consistent with the SM hypothesis at 95% CL (i.e. limits agree with $c_i = 0$ within 2 standard deviations)
- Most stringent constraints are shown using the electron + muon combined measurement (lowest statistical uncertainty)
- Constraint on $c_{lq}^{(3)}$ → strongest four-fermion constraint in the world!

Summary

- The SMEFT offers a broad and generalised way of quantifying SM deviations in terms of new physics
- The landscape of SMEFT Wilson coefficents are continually being constrained:
  - No signs of new physics so far…
  - What will HL-LHC have to offer?

Project 2: Fortuity in D1-D5 System

1. Black holes in string theory
2. Fortuity in D1D5 System
3. Summary

Black Holes

- Black holes first appeared as solutions to Einstein's field equations

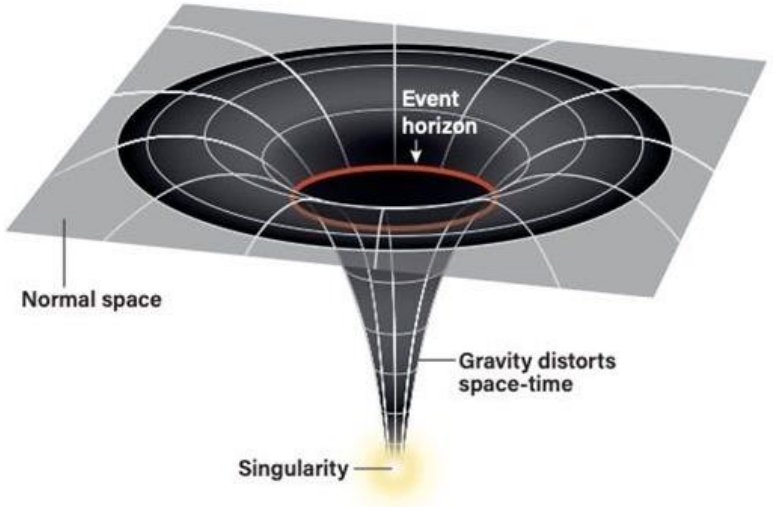
  → Now known to be very common throughout the universe

  → Spacetime singularity enclosed by an event horizon

- Black hole obey a set of thermodynamical laws:

  - Entropy $S_{BH} = \frac{k_B A_H}{4 l_p^2}$

  - Thermal radiation = Hawking radiation

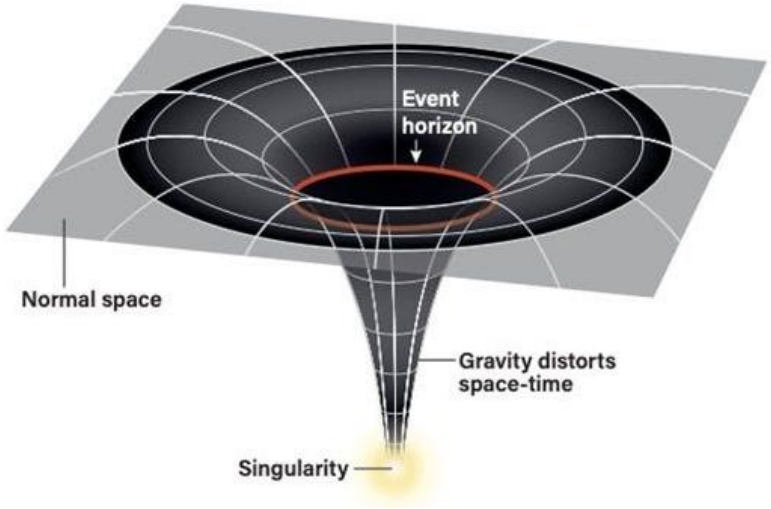


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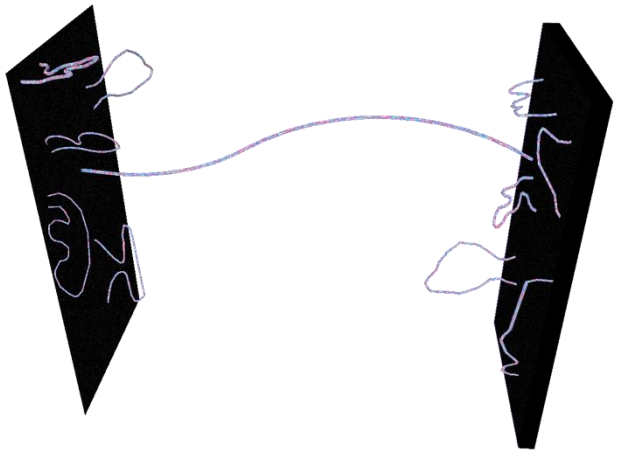
Statistical mechanics → there should exist BH microstates… what are they??

  - Thermal radiation = Hawking radiation

Many mysteries surrounding black holes!

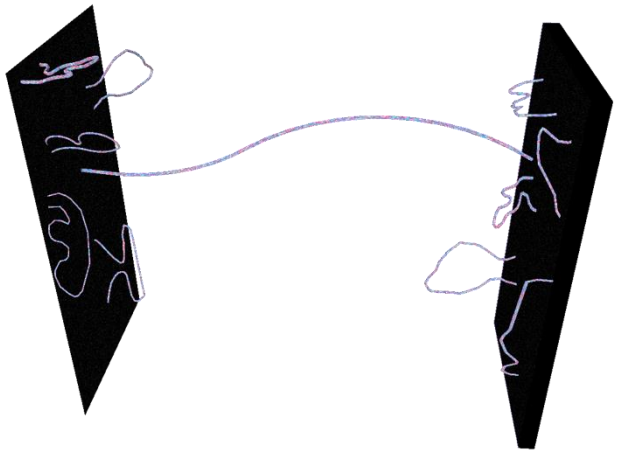
String Theory

- Quantum theory of gravity should explain the mysteries of black holes → **string theory** is a leading candidate
- Basic idea of string theory: point particles are replaced by very small one-dimensional **strings**
  - Strings appear as pointlike to distant observer, vibrational harmonics of the string determines the properties of the point particle
  - String theory contains other dynamial objects called **D-branes** → surfaces which strings attach to



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→ Can string theory describe black holes?

Black Holes in String Theory

- D-branes and strings can bind into a compact object, wrapping compact dimensions

  → Large number of strongly-interacting strings/D-branes → very heavy/dense object → black hole!

  → Microstates correspond to the different distinct arrangements of strings and D-branes

Black Holes in String Theory

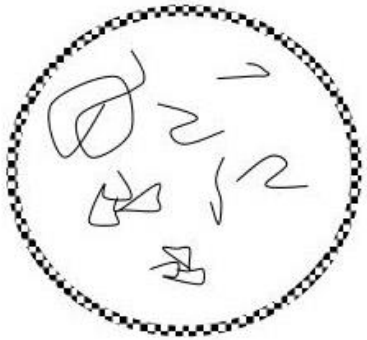
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- **Fuzzball proposal**: black hole is a quantum horizonless object

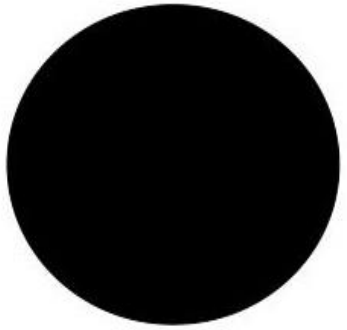
Microscopic picture



"Fuzzball"

Coarse-graining

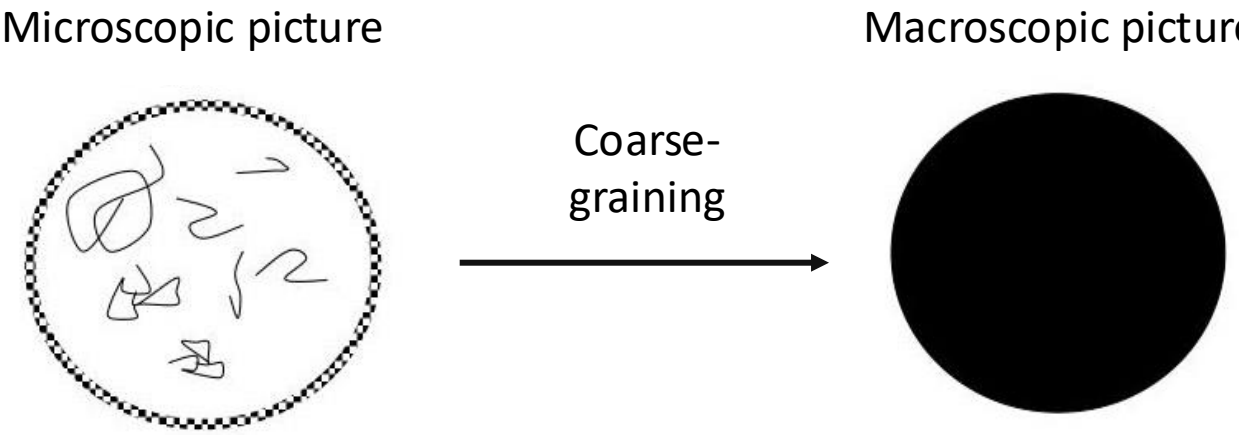
Macroscopic picture



Classical black hole

- Horizon arises as a result of coarse-graining over many microstates
- General relativity is just an effective description of the true nature of black holes

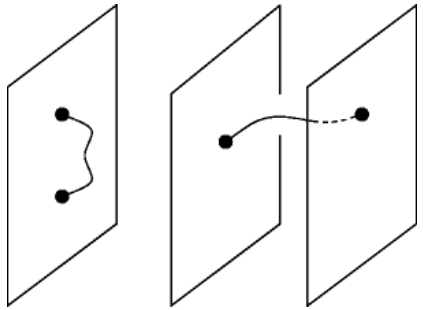
Black Holes in String Theory



- Want to compute and compare physical/observable quantities (e.g. entropy) on both sides – they should agree!
- **Microscopic picture:** can only be described using perturbative string theory (weakly-interacting strings)
- **Macroscopic picture:** black holes are described using general relativity (need strongly-interacting strings to make the black hole)
- Weakly-coupled and strongly-coupled regimes are not the same → no expectation that physical quantities should agree in both regimes

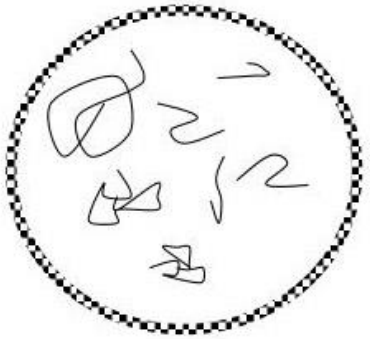
Black Holes in String Theory

Microscopic picture
(perturbative string theory)



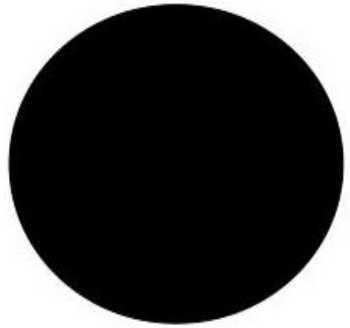
Increase string coupling

Fuzzball



Coarse-graining

Macroscopic picture



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D1-D5 System

- **Supersymmetry** allows quantities to be compared in the weakly-coupled and strongly-coupled regimes

  → Symmetry ”protects” measured quantities as one moves between the two regimes

- One well-studied example is the **D1-D5 system:**

  - **Microscopic:** very large number of D1-branes, D5-branes, and strings carrying momentum

    → Described by a **conformal field theory** (a QFT with an additional conformal symmetry)

  - **Macroscopic:** a 5-dimensional 3-charge supersymmetric black hole

    → Described by **supergravity** (supersymmetry + general relativity)

  - Originally developed in the late 90s, where it was shown that the microscopic entropy (calculated in the CFT) agrees with the black hole entropy!

D1-D5 System

- Over the decades, a dictionary has been established between the macroscopic and microscopic regimes:

Supergravity (macroscopic)	**D1-D5 CFT (microscopic)**
Empty space	Vacuum state
Single-particle excitation in empty space	**Supergraviton** state (preserves 1/4 of the total symmetry)
Supergraviton "gas" – a smooth wave-like geometry	Coherent superpostition of supergraviton states
Superstrata (a black hole microstate)	Very heavy coherent superpostition of supergraviton states

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Useful analogy with wave-particle duality and electromagnetism:

- Electromagnetic wave: coherent superposition of photons
- Photons ↔ supergravitons ↔ 1/4-BPS states
- Superstrata ↔ heavy electromagnetic waves

D1-D5 System

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Entropy scaling with N (no. of D-branes),

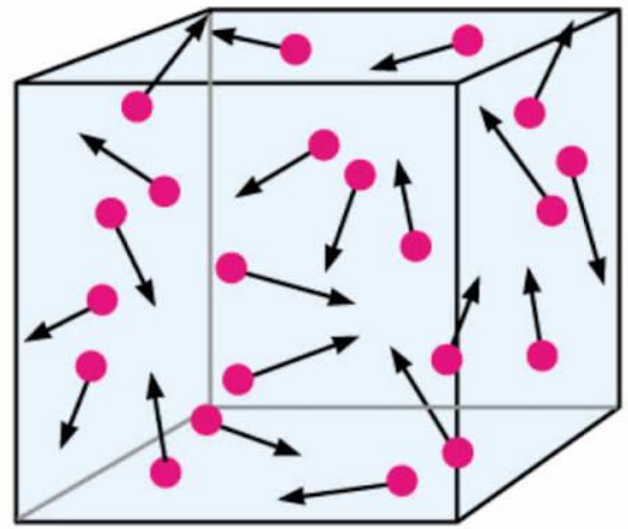
- Superstrata entropy $S \sim N^{3/4}$
- Total entropy $S \sim N$

Black hole occurs at very large N:

- The vast majority of black hole microstates are not superstrata!

Analogy with Gas

- Superstrata are not “typical” black hole microstates → analogy with **box of gas**:



Consider a gas of N particles in a box:

- Many, many different possible configurations of the N particles
- A small number of which are where all particles are equidistant away from the centre of the box
  - Simpler to describe thereoretically, but not representative of the full ensemble

  → Analogous to superstrata

Fortuity

- In 2023, it was proposed that **fortuity** offers a framework for categorising the typicality of a BH microstate

  1. **Montone** (atypical black hole microstate, like superstrata/supergravitons):

     → States remain supersymmetric (1/4-BPS) as N increases

  2. **Fortuitous** (typical black hole microstate):

     → States **do not** remain supersymmetric (1/4-BPS) as N increases

- Questions:

  - Can we find explicit forms of monotone and fortuitous states in the CFT?
  - Do they have different dynamical properties? Do they interact with each other?

Fortuity in the D1-D5 CFT

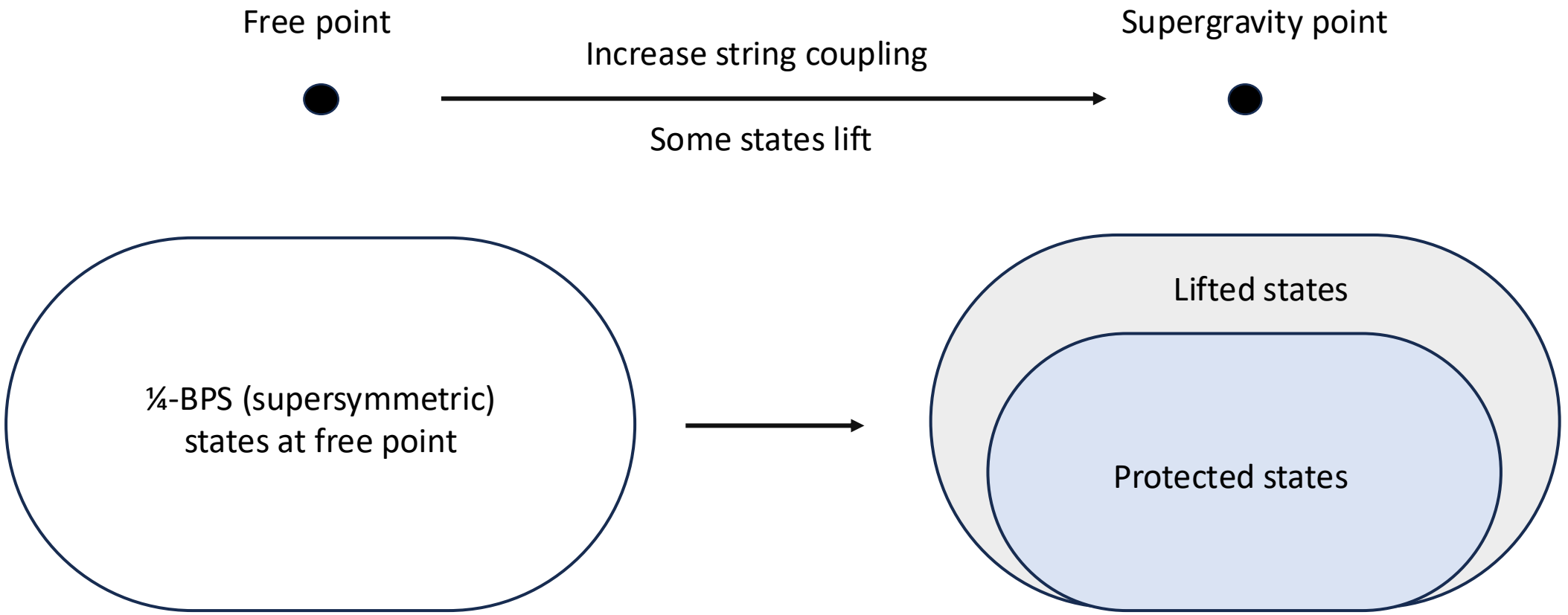
- **Goal:** Find explicit forms of monotone and fortuitous states in the D1-D5 CFT
- This CFT is very complicated! Black hole occurs when the states are very strongly-interacting, but we work in a special regime where there are no interactions **(free point)**
- At the free point, for small values of N, it is it is possible to to write down all the supersymmetric CFT states and all supergraviton states:

  → {**supersymmetric CFT states**} – {**supergraviton states**} = {**fortuitous states**}**?** Not exactly…

  - We are interested in classifying the states at **supergravity point** rather than the **free point**, where the strings are strongly interacting
  - When moving from the free point to the supergravity point, states may **lift** and lose their supersymmetry → lifted states should not be considered as black hole microstates!

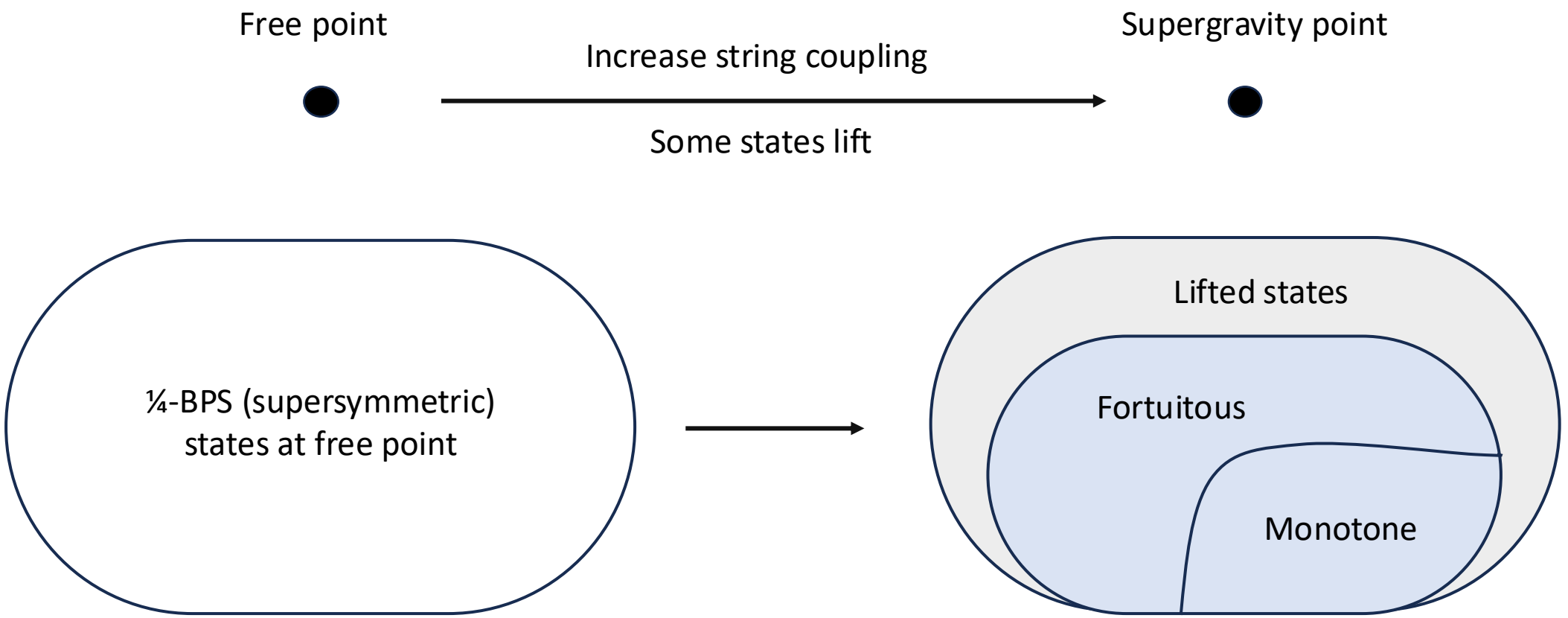
Fortuity in the D1-D5 CFT

Goal: Find explicit forms of monotone and fortuitous states in the D1-D5 CFT



Fortuity in the D1-D5 CFT

Goal: Find explicit forms of monotone and fortuitous states in the D1-D5 CFT



Fortuity in the D1-D5 CFT

- We look at performing lifting calculations in a specific sector of states, and then classifying the remaining protected states in terms of fortuitous and monotone states

- **Expectation:** supergravitons = monotone, some non-supergravitons states lift, and the rest are fortuitous

Fortuity in the D1-D5 CFT

- We look at performing lifting calculations in a specific sector of states, and then classifying the remaining protected states in terms of fortuitous and monotone states
- **Expectation:** supergravitons = monotone, some non-supergravitons states lift, and the rest are fortuitous
- We find explicit forms for lifted, monotone, and fortutous states
- **Unexpected result:** Lifted/protected states are linear combinations of both supergravitons and non-supergravitons, with coefficients depending on N:

Lifted

$$\|1,\text{top}\rangle^i = \sqrt{N(N-1)}\left(\sqrt{2}\,|1,\text{g.g.}\rangle_1^i + \sqrt{N-1}\,|1,1\rangle_1^i + |1,2\rangle_1^i - \sqrt{3(N-2)}|1,1\rangle_3^i\right).$$

$$\|1,\text{bottom}_1\rangle^i = \sqrt{N(N-1)}\left[\sqrt{2}|1,\text{g.g.}\rangle_1^i - \sqrt{(N-1)}\,|1,1\rangle_1^i + |1,2\rangle_1^i - \frac{N-4}{\sqrt{3(N-2)}}\,|1,1\rangle_3^i\right],$$

$$\|1,\text{bottom}_2\rangle^i = \sqrt{N(N-1)}\left[\sqrt{2}|1,\text{g.g.}\rangle_1^i - \sqrt{(N-1)}\,|1,1\rangle_1^i + (3-2N)\,|1,2\rangle_1^i - \sqrt{3(N-2)}\,|1,1\rangle_3^i\right].$$

Protected $\longrightarrow$

$$\|1,\text{singlet}\rangle^i = \sqrt{N(N-1)}\left[\sqrt{2}\,|1,\text{g.g.}\rangle_1^i + \frac{\sqrt{N-1}}{N-2}\,|1,1\rangle_1^i - \frac{1}{N-2}\,|1,2\rangle_1^i + \frac{\sqrt{3}}{\sqrt{N-2}}\,|1,1\rangle_3^i\right],$$

States with $(h, j) = (1, 0)$ at $N > 2$

- In the large-N limit, original expectation is recovered:
  - Protected state → supergraviton
  - Lifted states → non-supergravitons

Lifted

$$\|1, \text{top}\rangle^i_{N\to\infty} \sim N\left(|1,1\rangle^i_1 - \sqrt{3}\,|1,1\rangle^i_3\right) + \mathcal{O}(\sqrt{N})\,,$$

$$\|1, \text{bottom}_1\rangle^i_{N\to\infty} \sim -N\left(|1,1\rangle^i_1 + \tfrac{1}{\sqrt{3}}\,|1,1\rangle^i_3\right) + \mathcal{O}(\sqrt{N})\,,$$

$$\|1, \text{bottom}_2\rangle^i_{N\to\infty} \sim -2N\sqrt{N(N-1)}\,|1,2\rangle^i_1 + \mathcal{O}\left(N^{3/2}\right),$$

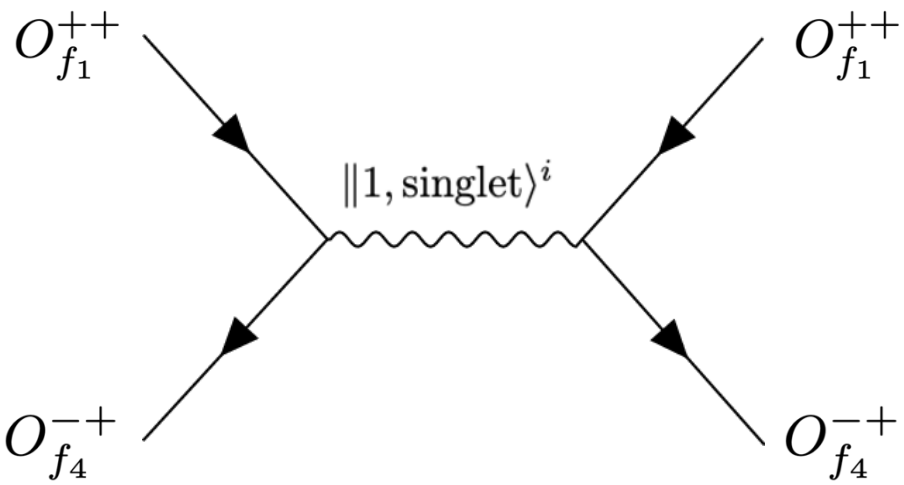
Protected →

$$\|1, \text{singlet}\rangle^i_{N\to\infty} \sim \sqrt{2N(N-1)}\,|1, \text{g.g.}\rangle^i_1 + \mathcal{O}(\sqrt{N})\,.$$

→ Having identified the explicit forms of monotone/fortutitous states, can we test these forms are correct?

Computing correlation functions

- Consider interaction between monotone states:





- Both calculations give the same value:

$$\langle O_{f_1}^{++} O_{f_4}^{-+} | 1, \text{singlet} \rangle^i = 1 - \frac{1}{N}$$

- Corresponding correlation function (physical observable) can be computed at the free point and the supergravity point

→ Agreement provides evidence that the form of the protected state $|1, \text{singlet}\rangle^i$ is correct

Computing correlation functions

- Do monotone and fortuitous states interact? → Compute correlation function between monotone and fortuitous state:

$$O_{F_U}(z,\bar{z})\Sigma^{+-}(0,0) \sim \frac{1}{z\bar{z}} \sum_r \psi_{(r)}^{+\dot{A}} \tilde{\psi}_{(r)}^{+\dot{B}} + \dots$$

Fortuitous state

Monotone state

Nonzero!

→ **Nonzero value**: no selection rule ruling out interactions between monotone and fortuitous states

→ Would be interesting to see how this calculation changes at $N > 2$!

Summary

- Fortuity offers a framework for characterising black hole microstates
- In the D1-D5 system, protected and lifted states can be linear combinations of supergravitons and non-supergravitons
  - Various correlation functions support these results
- We have only looked at a very simple sector of states in the D1-D5 system, what about more copmplicated sectors?
- Fortuity is restricted to supersymmetric black holes
  - It is natural to wonder whether a similar notion applies for more realistic non-supersymmetric black holes

Cross Section Dependence

- Expected number of event counts has four contributions:

$$\mu(c) = \mu_{SM} + \sum_i c_i\, \mu^i_{lin} + \sum_i c_i^2\, \mu^i_{quad} + \sum_{i\neq j} c_i c_j\, \mu^{ij}_{cross}$$

SM | Linear | Quadratic | Cross-terms

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

$$|\mathcal{A}^2| = |\mathcal{A}_{SM}|^2 + \sum_i \frac{c_i}{\Lambda^2}\mathcal{A}^\dagger_{SM}\mathcal{A}_i + \sum_i \frac{|c_i|^2}{\Lambda^4}|\mathcal{A}_i|^2 + \sum_{i,j,i\neq j} \frac{c_i c_j}{\Lambda^4}\mathcal{A}^\dagger_i\mathcal{A}_j$$

$$\mathcal{A} = \mathcal{A}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{A}_i$$

Cross Section Dependence

- Expected number of event counts has four contributions:

$$\mu(c) = \underbrace{\mu_{SM}}_{\text{SM}} + \underbrace{\sum_i c_i\, \mu^i_{lin}}_{\text{Linear}} + \underbrace{\sum_i c_i^2\, \mu^i_{quad}}_{\text{Quadratic}} + \underbrace{\sum_{i \neq j} c_i c_j\, \mu^{ij}_{cross}}_{\text{Cross-terms}}$$

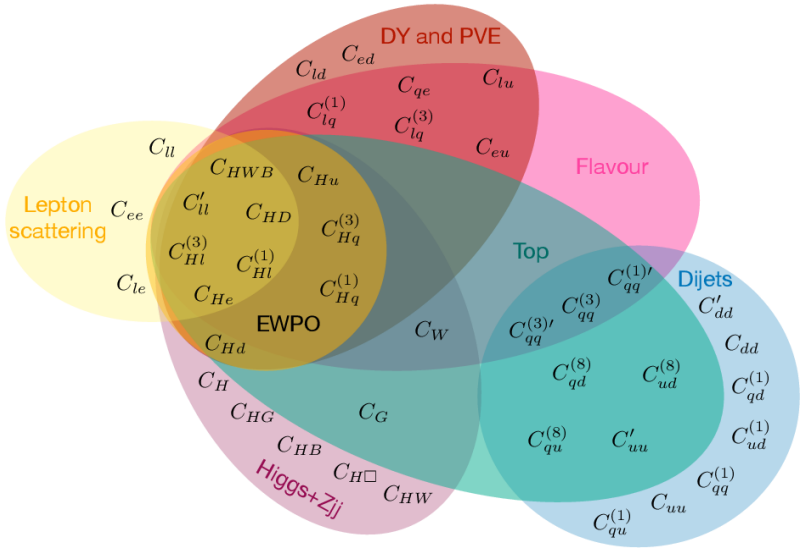
- We want the Wilson coefficients c_i to be the only unknown parameters of the prediction $\mu(c)$:
  - μ_{SM}, μ^i_{lin}, μ^i_{quad}, and μ^{ij}_{cross} need to be determined from Monte-Carlo simulation (SMEFTsim package in MadGraph)
  - Simulate processes in the SMEFT with a known value of c_i (e.g. $c_i = 1$)

Global SMEFT Fit

Different measurements are senstive to different combinations of Wilson coefficients

→ Combining multiple measurments in a SMEFT fit provides cosntraints on an enlarged set of Wilson coefficents

→ Multiple measurements provide complimentary information



Challenges:

- Large number of Wilson coefficients and nuisance parameters → fit instabilities
- Systematic uncertainties can be treated differently across measurments

ATLAS Global SMEFT Fit

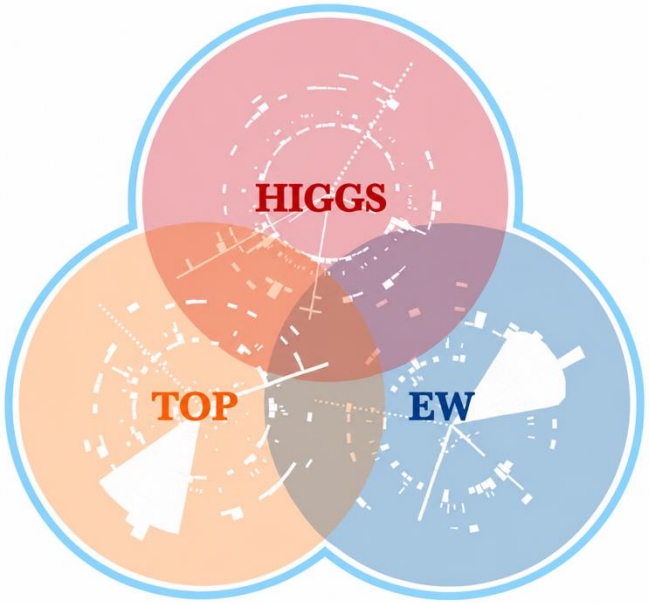
ATLAS global SMEFT fit:

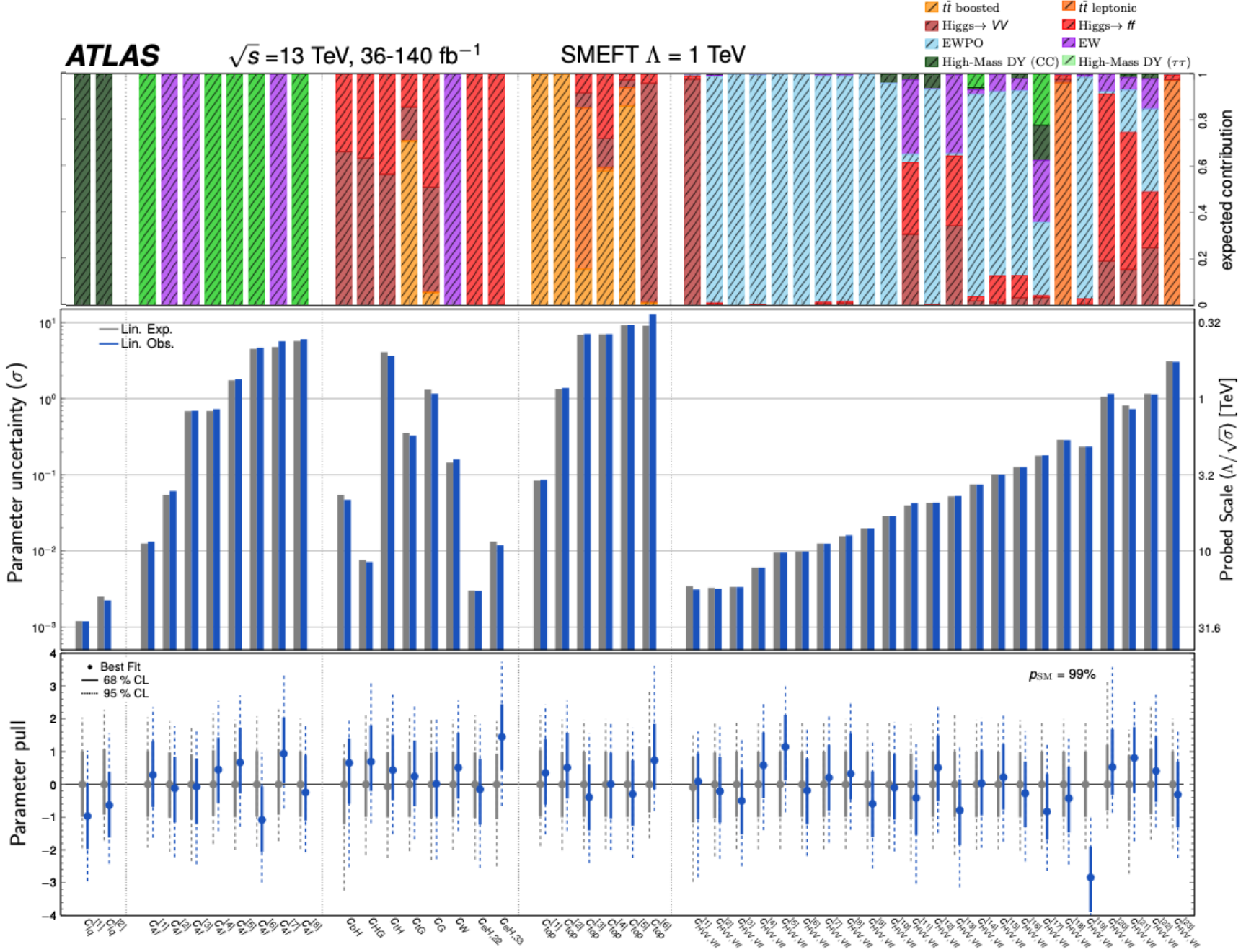
- Input dataset combines ATLAS + LEP (Large Electron Positron) collider data:
  - ATLAS: 7 Higgs decay channels, 2 di-Higgs channels, $t\bar{t}$, diboson (WW, WZ, Zjj), High-mass Drell-Yan (NC + CC)
  - LEP: 28 EW precision observables, measured at the Z resonance

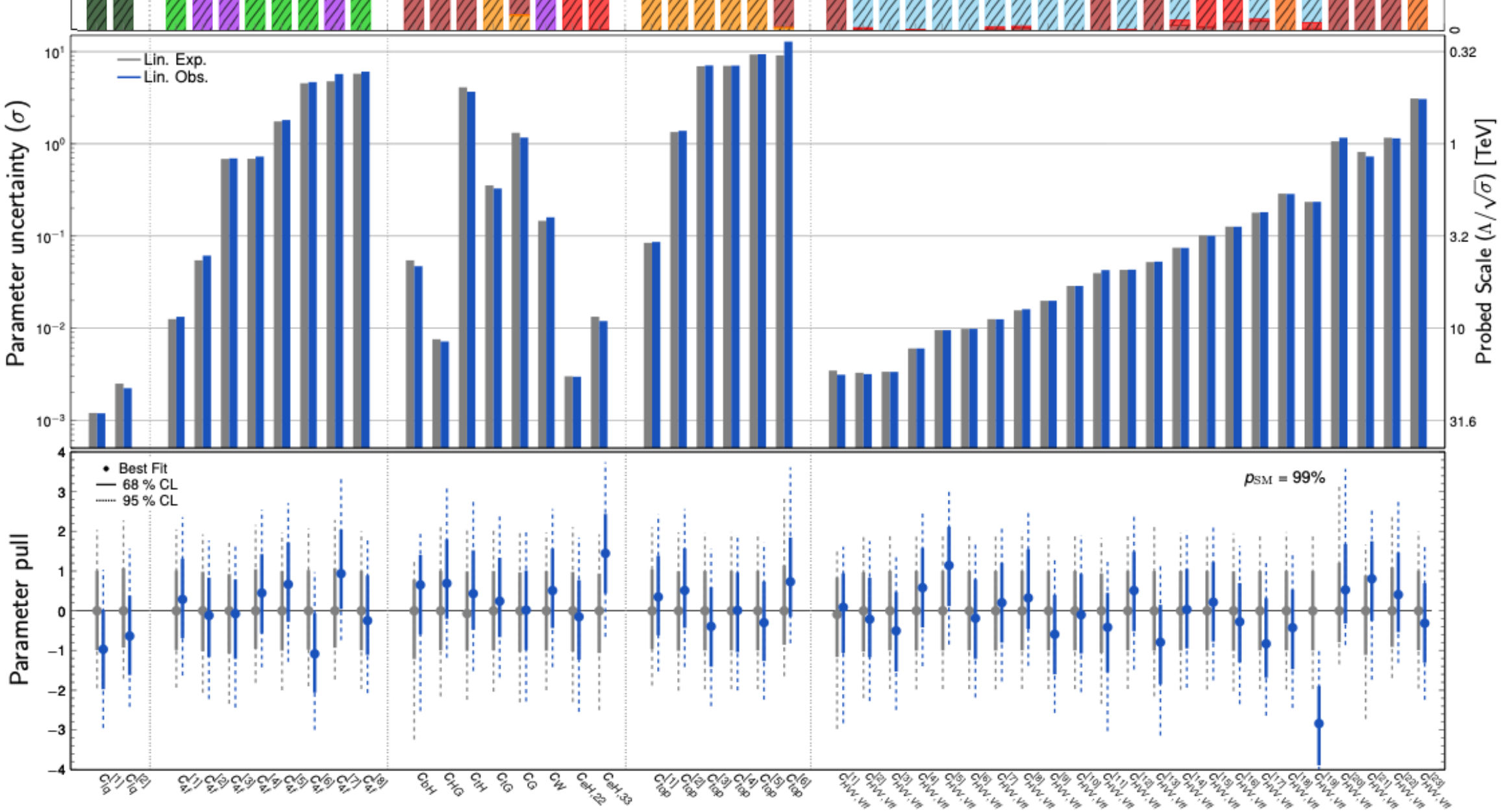
→ **Largest** fit combination to date at the LHC

→ Fit contains ≈ **4000 total nuisance parameters**!

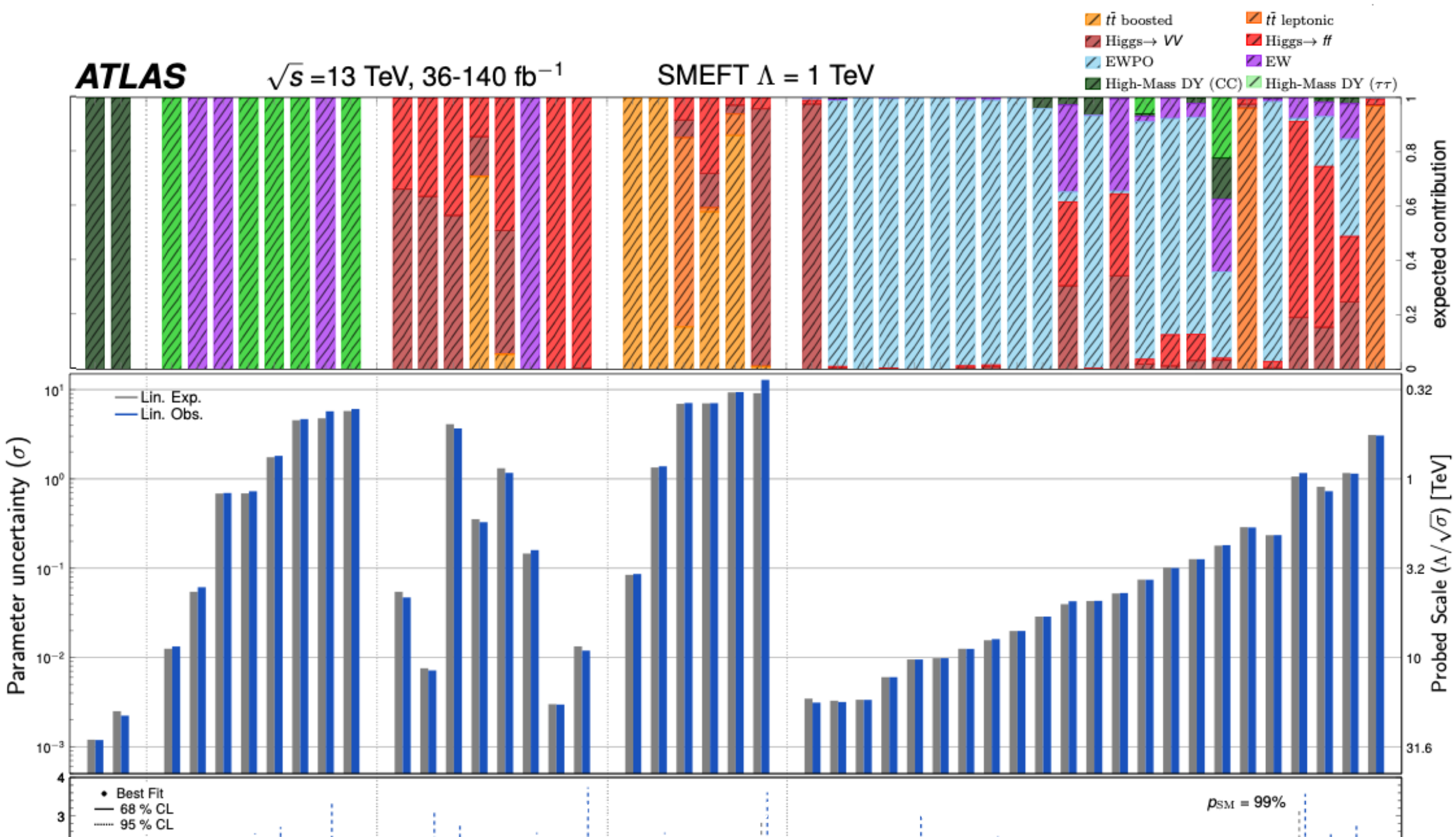
→ Sensitive to **86 SMEFT operators**




ATLAS
$\sqrt{s}$ =13 TeV, 36-140 fb^{-1}
SMEFT Λ = 1 TeV
$t\bar{t}$ boosted
$t\bar{t}$ leptonic
Higgs→ VV
Higgs→ ff
EWPO
EW
High-Mass DY (CC)
High-Mass DY (ττ)
expected contribution
Lin. Exp.
Lin. Obs.
Parameter uncertainty (σ)
Probed Scale (Λ/√σ) [TeV]
Best Fit
68 % CL
95 % CL
p_{SM} = 99%
Parameter pull


Lin. Exp.
Lin. Obs.
Parameter uncertainty (σ)
Probed Scale (Λ/√σ) [TeV]
0.32
1
3.2
10
31.6
Best Fit
68 % CL
95 % CL
Parameter pull
p_{SM} = 99%

Global Fit Results



Standard Model Effective Field Theory

- Taking a closer look at the SMEFT Lagrangian:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3} \mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots$$

$c_i^{(5)}/\Lambda \to 0$, $c_i^{(7)}/\Lambda^3 \to 0$, $c_i^{(8)}/\Lambda^4 \to 0$

  - Odd-dimensional operators violate baryon/lepton number conservation
  - For $d \geq 8$, the Λ^4 suppression strongly reduces the impact of the term

- The SMEFT is commonly truncated to dimension-6 only.

--> The Warsaw basis provides a complete basis for dimension-6 operators: 2499 operators

→ too many Wilson coefficients to constrain, even when truncating to dimension-6 only!

Standard Model Effective Field Theory

- Number of operators can be reduced by imposing a symmetry amongst the fermion flavours:

  2499 -> 59 operators -> much more manageable!

1–4: Bosonic Operators			
1: X^3	**2:** H^6	**3:** H^4D^2	**4:** X^2H^2
$Q_G = f^{ABC}G^{A\mu\nu}G^{B}_{\nu\rho}G^{C\rho}_{\mu}$	$Q_H = (H^\dagger H)^3$	$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$	$Q_{HG} = (H^\dagger H)G^{A\mu\nu}G^{A}_{\mu\nu}$
$Q_{\tilde{G}} = f^{ABC}\tilde{G}^{A\mu\nu}G^{B}_{\nu\rho}G^{C\rho}_{\mu}$		$Q_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$	$Q_{H\tilde{G}} = (H^\dagger H)\tilde{G}^{A\mu\nu}G^{A}_{\mu\nu}$
$Q_W = \epsilon^{IJK}W^{I\mu\nu}W^{J}_{\nu\rho}W^{K\rho}_{\mu}$			$Q_{HW} = (H^\dagger H)W^{I\mu\nu}W^{I}_{\mu\nu}$
$Q_{\tilde{W}} = \epsilon^{IJK}\tilde{W}^{I\mu\nu}W^{J}_{\nu\rho}W^{K\rho}_{\mu}$			$Q_{H\tilde{W}} = (H^\dagger H)\tilde{W}^{I\mu\nu}W^{I}_{\mu\nu}$
			$Q_{HB} = (H^\dagger H)B^{\mu\nu}B_{\mu\nu}$
			$Q_{H\tilde{B}} = (H^\dagger H)\tilde{B}^{\mu\nu}B_{\mu\nu}$
			$Q_{HWB} = (H^\dagger \tau^I H)W^{I\mu\nu}B_{\mu\nu}$
			$Q_{H\tilde{W}B} = (H^\dagger \tau^I H)\tilde{W}^{I\mu\nu}B_{\mu\nu}$

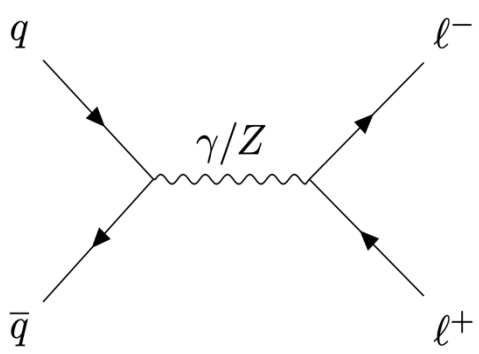
8: Four-Fermion Operators			
8b: $(\overline{R}R)(\overline{R}R)$	**8c:** $(\overline{L}L)(\overline{R}R)$	**8d:** $(\overline{L}R)(\overline{L}R)$ + h.c.	**8e:** $(\overline{L}R)(\overline{R}L)$ + h.c.
$Q_{ee} = (\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)$	$Q_{\ell u} = (\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u)$	$Q^{(1)}_{quqd} = (\bar{q}^j u)\epsilon_{jk}(\bar{q}^k d)$	$Q_{\ell edq} = (\bar{\ell}^j e)(\bar{d}q^j)$
$Q_{uu} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$	$Q_{\ell d} = (\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)$	$Q^{(8)}_{quqd} = (\bar{q}^j T^A u)\epsilon_{jk}(\bar{q}^k T^A d)$	
$Q_{dd} = (\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$	$Q_{qe} = (\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$	$Q^{(1)}_{\ell equ} = (\bar{\ell}^j e)(\bar{q}^j u)$	
$Q_{eu} = (\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$	$Q^{(1)}_{qu} = (\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$	$Q^{(3)}_{\ell equ} = (\bar{\ell}^j \sigma_{\mu\nu} e)(\bar{q}^j \sigma^{\mu\nu} u)$	
$Q_{ed} = (\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$	$Q^{(8)}_{qu} = (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$		
	$Q^{(1)}_{qd} = (\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$		
	$Q^{(8)}_{qd} = (\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$		

5–7: Fermion Bilinears			8: Four-Fermion Operators
5: ψ^2H^3 + h.c.	**6:** ψ^2XH + h.c.	**7:** ψ^2H^2D	**8a:** $(\overline{L}L)(\overline{L}L)$
$Q_{eH} = (H^\dagger H)(\bar{\ell}_p e_r H)$	$Q_{eW} = (\bar{\ell}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$	$Q^{(1)}_{H\ell} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}_p \gamma^\mu \ell_r)$	$Q_{\ell\ell} = (\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$
$Q_{uH} = (H^\dagger H)(\bar{q}_p u_r \tilde{H})$	$Q_{eB} = (\bar{\ell}_p \sigma^{\mu\nu} e_r)H B_{\mu\nu}$	$Q^{(3)}_{H\ell} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}_p \tau^I \gamma^\mu \ell_r)$	$Q^{(1)}_{qq} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$
$Q_{dH} = (H^\dagger H)(\bar{q}_p d_r H)$	$Q_{uG} = (\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{H} G^A_{\mu\nu}$	$Q^{(1)}_{Hq} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$Q^{(3)}_{qq} = (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$
	$Q_{uW} = (\bar{q}_p \sigma^{\mu\nu} \tau^I u_r)\tilde{H} W^I_{\mu\nu}$	$Q^{(3)}_{Hq} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$Q^{(1)}_{\ell q} = (\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma^\mu q)$
	$Q_{uB} = (\bar{q}_p \sigma^{\mu\nu} u_r)\tilde{H} B_{\mu\nu}$	$Q_{He} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	$Q^{(3)}_{\ell q} = (\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}\gamma^\mu \tau^I q)$
	$Q_{dG} = (\bar{q}_p \sigma^{\mu\nu} T^A d_r)H G^A_{\mu\nu}$	$Q_{Hu} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
	$Q_{dW} = (\bar{q}_p \sigma^{\mu\nu} \tau^I d_r)H W^I_{\mu\nu}$	$Q_{Hd} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	
	$Q_{dB} = (\bar{q}_p \sigma^{\mu\nu} d_r)H B_{\mu\nu}$	$Q_{Hud} = i(H^\dagger \tilde{D}_\mu H)(\bar{u}_p \gamma^\mu d_r)$	

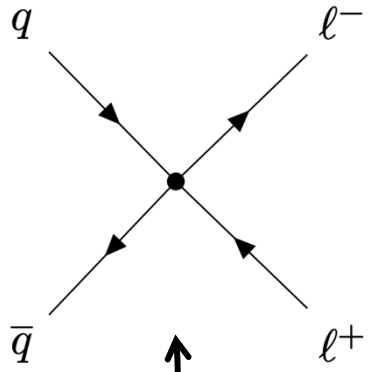
Effective Field Theory Example

- **Example:** Neutral-Current Drell-Yan process ($qq \to l^+l^-$)

Many BSM models can be represented in the SMEFT

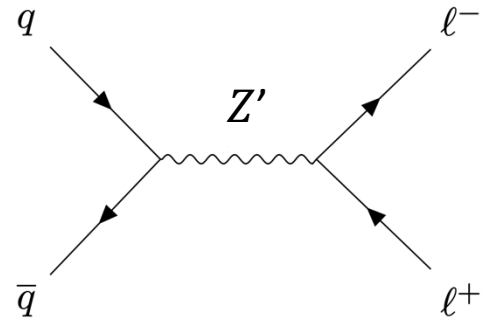


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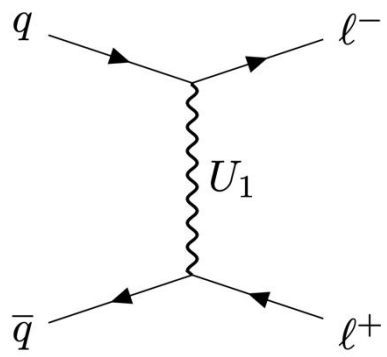
$E \ll m_{Z'}$

Z' = Heavy Z-boson



$E \ll m_U$

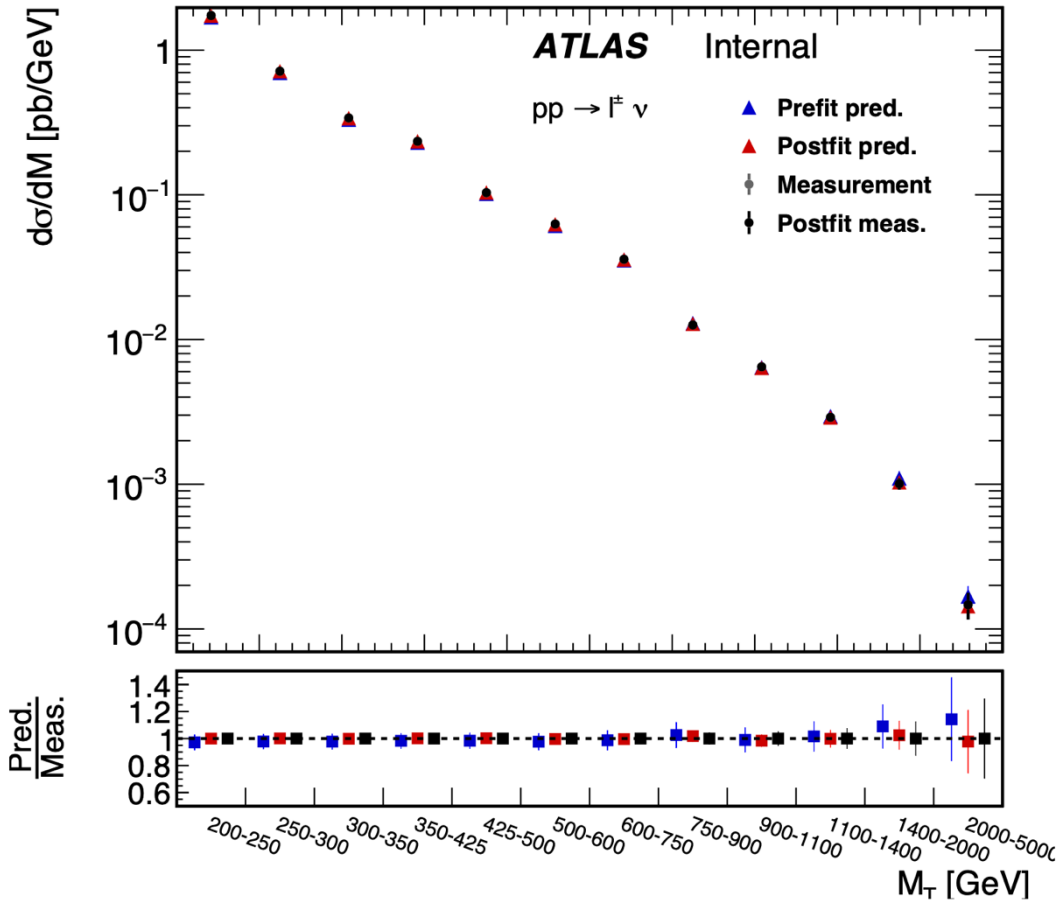
U_1 = Heavy leptoquark



If Z' or U_1 were real particles occurring in nature, $c_{lq}^{(1)}$ would deviate from 0

Expected and Observed Limits

What happens when the fit is performed?



Nusiance parameter pulls in combined fit:

