A twisted tale of the transverse-mass tail for W-mass Anomaly

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Based on 2212.02534 [hep-ph]

with Triparno Bandyopadhyay, Ankita Budhraja and Tuhin S. Roy

Flow of the Discussion

- What happens when we find a Anomaly !!
- To take it seriously or not ?
- The CDF W-boson mass measurement
- New Physics Perspective
- Other W-mass results are important too
- Our Proposal and Analysis
- LHC Constraints
- More General EFT Operator
- Summary

"Anomaly" in High-Energy Physics

Quantum Anomaly

Measure in the path integral changed by quantum corrections.

Experimental Anomaly

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- “Discovery of $K_L^0 \to \pi^+\pi^-$” $\Rightarrow$ immediately leads to discovery of CP violation $\Rightarrow$ inconsistent with Weinberg-Salam theory $\Rightarrow$ Kobayashi and Maskawa predicted charm, bottom and top quarks in 1973 before their discoveries.

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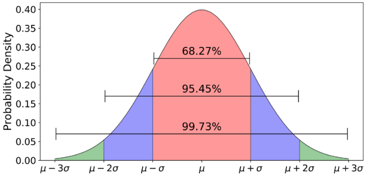
Contradiction

Even after the exp. paper was published, many theoretical researchers (except for Kobayashi and Maskawa) did not believe the experimental results, but believed CP-conserving theory.

Why / When does this happen?

Statistical Fluctuations



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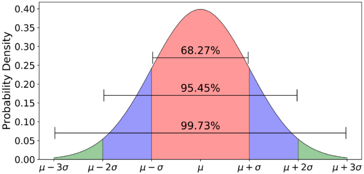

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Would-be better strategy is: 1. cross-checked by the second experiment 2. hidden theoretical correlation between several anomalies.

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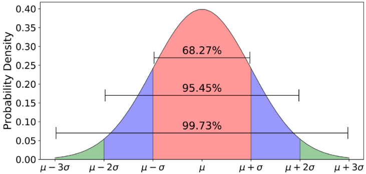

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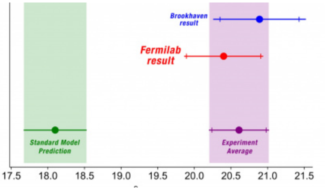
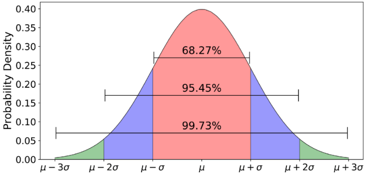
Muon g-2 anomaly

The previous data is checked.
The latest lattice result for HVP significantly reduces tension [BMW, Nature '21]. This leads to other tensions.





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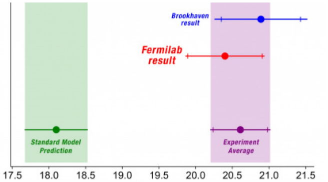

Other-examples! "750 GeV anomaly" had been observed by two different experiments. But, unfortunately, both were just fluctuations, and disappeared.


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Visualizing a key step in cytokine signaling pp. 139 & 163
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W boson mass measures higher than expected pp. 125, 136, & 170

Standard Model : W-mass

Status from different analyses

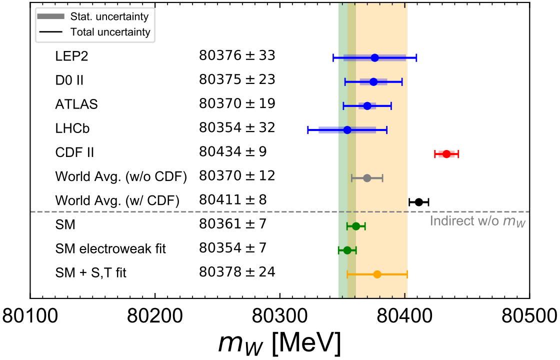
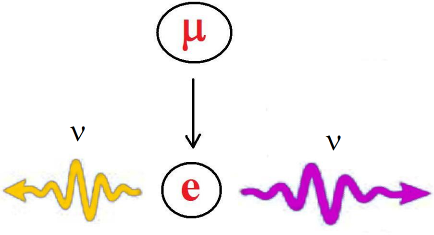
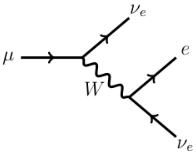


Figure Ref: 'SMEFT Analysis of m_W' 2204.05260

- CDF Run II result is the most precise one.
- 7σ tension with SM
- 3σ tension between CDF-II and ATLAS result.
- Can't measure invariant mass directly due to neutrino.
- Look at the sensitive observables
- $M_T^2 = 2\left(p_T^\ell\, p_T^\nu - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu}\right)$
- p_T^ℓ, p_T^ν with $\vec{p}_T^{\,\nu} = -\vec{p}_T^{\,\ell}$
- Requires precise theory calculation
- Fit theory templates with varying M_W.

Standard Model : W-mass





μ-lifetime : $\tau_\mu = f(M_W; \alpha, M_Z, ...)$ Invert $\Rightarrow$ Theory Prediction for M_W

Convenient to use G_F : effective matrix element/4-fermion coupling:

$$\boxed{\tau_\mu^{-1} = G_F^2 \frac{m_\mu^5}{192\pi^2}\left(1 + \mathcal{O}\left(\frac{m_e^2}{m_\mu^2}, \frac{m_{mu}^2}{M_W^2}\right) + \Delta_{QED}\right)}$$

$$\boxed{G_F = \frac{\alpha\pi}{\sqrt{2}M_W^2 \sin^2\theta_W}(1 + \Delta r)}$$

Δr = loop corrections (self-energies, vertex, box, counter-terms)

How Much We can trust CDF-II

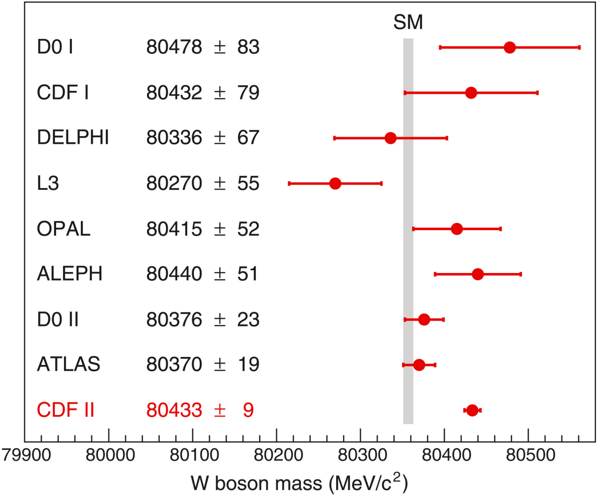


Figure Ref: 'Science 376 (2022)'

NEW PHYSICS MODELS

What kind of New Physics ?

$\mathcal{O}(xx)$ articles have been published discussing BSM perspectives.

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Explicit Models

- 2HDM [J. Kim et al. 2205.0170]
- Higgs Portal DM [Z. Liu et al. 2204.09024]
- Supersymmetry [Athron et al. 2204.05285]
- RH neutrinos [Blennow et 2204.04204]

EFT / Generic Analyses

- SMEFT [J. Ellis et al. 2204.05260]
- RGE Running Effect [R. S. Gupta 2204.13690]
- EW Fit [De Blas et al., 2204.04204; Strumia 2204.04191, Lu et al. 2204.03796...]
- Higgs Couplings

This Work

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- These particles decay mostly to the dark sector or can be long-lived.
- Contributes to the observed missing momentum in a detector.
- The best fit mass depends on the nature of the collider and the center-of-mass energy of collisions.
- Interestingly, we find that the nature of the new physics particle and its interactions appear as a variation of Axion Like Particles (ALP) after a field redefinition.

- The all-important observation which allows us to reconcile these different measurements is that the precise M_W measurements rely on leptonic decays of W which give rise to neutrinos in the final state.

- Exact reconstruction of the W four-vector is not possible, experimental collaborations use various kinematic variables sensitive to the W-boson mass.

- The most important of which is the transverse mass, M_T.

- It is defined using only the transverse components of the lepton momentum (p^ℓ) and the missing transverse momentum ($\vec{p}_T^{\text{miss}}$).

$$M_T^2 \equiv 2\left(p_T^\ell \, p_T^{\text{miss}} - \vec{p}_T^\ell \cdot \vec{p}_T^{\text{miss}}\right) ,$$

$$p_T^\ell = \sqrt{\vec{p}_T^\ell \cdot \vec{p}_T^\ell} \quad \text{and} \quad p_T^{\text{miss}} = \sqrt{\vec{p}_T^{\text{miss}} \cdot \vec{p}_T^{\text{miss}}} .$$

- If the missing momentum is entirely due to the missing neutrino from W decay, the transverse mass shows a kinetic endpoint at $M_T \leq M_W$.

- Smearing, energy mismeasurements, and hadronic activities in the event soften the kinematic edge.

- A precise extraction of M_W is possible after taking various systematics into consideration, with the assumption $p_T^{miss} = p_T^{\nu}$.

We find that breaking this assumption slightly gives the desired result.

W is produced along with a BSM invisible state, with the assumption $p_T^{miss} > p_T^{\nu}$.

$$M_T\Big|_{\vec{p}_T^{\,\mathrm{miss}}=\vec{p}_T^{\,\nu}+\vec{p}_T^{\,\Phi}} \geq M_T\Big|_{\vec{p}_T^{\,\mathrm{miss}}=\vec{p}_T^{\,\nu}} .$$

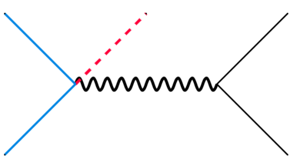
- one expects more events at the tail of the M_T distribution.

The Working Principle & Framework

- SM single W-events + SM background events + NP events $\Rightarrow$ fitted with the SM hypothesis to find the W-mass $\Rightarrow$ best fit to be slightly larger than the true M_W.
- We need a light NP particle (say Φ) which decays mostly to the dark sector (or sufficiently long-lived).
- We need an irrelevant operator that allows for the production $p + \bar{p}(p) \to W + \Phi$.
- We show that such a naive set-up accommodates the CDF measurement of M_W, with the precision electroweak measurement on one hand, and with results from LEP, ATLAS, and from LHCb on the other.

In this paper, We take Φ to be an SM singlet and invoke the following interaction:

$$\mathcal{L} \supset \frac{\kappa}{\Lambda}\, g_w W_\mu^+ \Phi\, \overline{u}_L \gamma^\mu d_L \;+\; \text{h.c.}$$



κ = dimensionless complex coupling constant, Λ = the scale of the operator, and g_w = the weak coupling constant. $\Lambda_{\text{eff}} = \Lambda / |\kappa|$ is the *effective* scale of NP.

Analysis Flow

✓ We choose the true mass of the W-boson to be the one determined using precision electroweak observables.

$$\boxed{\widehat{M}_W \;=\; 80.3545 \pm 0.0057 \;\text{ GeV} \;.}$$

✓ We generate a large sample of matched $W(\ell\nu) + \text{jets}$ events at the parton level for which we utilize `MadGraph-v3.4.1`.

✓ Subsequently, all parton level events are passed through `PYTHIA-v8.306` for showering and hadronization.

✓ We use `Delphes-v3.5.0` to provide a realistic detector environment whenever we can.

Selection Cuts at different detector

CDF : $p+\bar{p}$: 1.96 TeV

- $-1.0 < \eta^{\ell} < 1.0$
- $30 < p_T^{\ell}\,(\mathrm{GeV}) < 55$
- $30 < p_T^{\mathrm{miss}}\,(\mathrm{GeV}) < 55$
- $60 < M_T\,(\mathrm{GeV}) < 100$
- $u_T < 15$ GeV

ATLAS : $p+p$: 7 TeV

- $-2.5 < \eta^{\ell} < 2.5$
- $p_T^{\ell}\,(\mathrm{GeV}) > 30$
- $p_T^{\mathrm{miss}}\,(\mathrm{GeV}) > 30$
- $M_T\,(\mathrm{GeV}) > 60$
- $u_T < 30$ GeV

LHCb : $p+p$: 13 TeV

- $2.0 < \eta^{\ell} < 5.0$
- $28 < p_T^{\ell}\,(\mathrm{GeV}) < 52$

We closely follow the cuts as given in the respective experimental reports. The working definition of transverse hadronic recoil u_T employed in this work is collider specific.

Fitting Ranges at different detector

CDF : $p + \bar{p}$: 1.96 TeV
$32 < p_T^\ell\,(\mathrm{GeV}) < 48$
$32 < p_T^{\mathrm{miss}}\,(\mathrm{GeV}) < 48$
$65 < M_T\,(\mathrm{GeV}) < 90$

ATLAS : $p + p$: 7 TeV
$32 < p_T^\ell\,(\mathrm{GeV}) < 45$
$32 < p_T^{\mathrm{miss}}\,(\mathrm{GeV}) < 45$
$66 < M_T\,(\mathrm{GeV}) < 99$

LHCb : $p + p$: 13 TeV
$28 < p_T^\ell\,(\mathrm{GeV}) < 52$

Fitting ranges are not simultaneous for $\mathcal{X} \in \{M_T, p_T^\ell, p_T^{\mathrm{miss}}\}$

The definition of transverse hadronic recoil u_T:

- For Tevatron, we use the sum of all momenta for all final state hadrons and photons within $|\eta| \leq 3.6$ to calculate the recoil.
- For ATLAS we use the sum of all jets and photons within $|\eta| \leq 4.9$.

CDF Result and Theory Perspective

CDF used `ResBos-v1` code at $NNLL + NLO$ accuracy

$\Rightarrow$ Boundary Conditions at α_s, Anomalous dimensions are at 2-loop (for γ) and at 3-loop for (β), Fixed order matching at α_s^2.

`ResBos-v2` is able to go to $N^3LL + NNLO$ accuracy

`ResBos-v2` corrected major criticism of incorrect angular functions in the `ResBos` code. **Ref: 2205.2788** mimics CDF analysis using pseudoexperiments at $N^3LL + NNLO$ accuracy by **J. Isaacson, Y. Fu, C.-P. Yuan**.

They determine that the data-driven techniques used by CDF capture most of the higher order corrections, and using higher order corrections would result in a decrease in the value reported by CDF by at most 10 MeV.

The bin-by-bin correction factors are available in the fitting region.

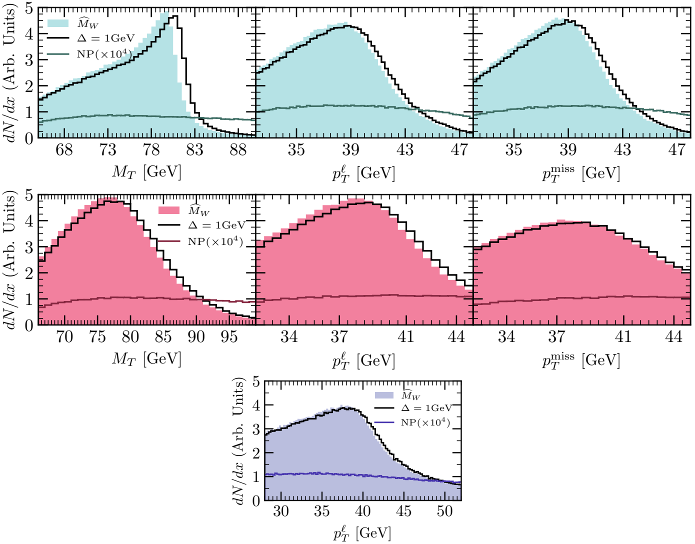
We take advantage of that for $\{M_T, p_T^{\ell}, p_T^{\rm miss}\}$

Minimization Procedure

- ✓ We *repeat* all the steps above after setting $M_W = \widehat{M}_W + \Delta$, where Δ represents the shift in the mass parameter.
- ✓ Finally, for each Δ we find the preferred value of $\Lambda_{\rm eff}$ by minimizing the function $\mathcal{D}^2$

$$\boxed{\mathcal{D}^2 = \sum_{x\in\mathcal{X}} \sum_{b\in\text{fit range}} \left(\frac{X_b(\Delta) - X_b(0) - X_b^{\rm NP}(\Lambda_{\rm eff})}{\sigma^X_{b,stat} + \sigma^X_{b,syst}} \right)^2}$$

  $X_b =$ the number of events in the bin b of the histogram X, and $\left(\sigma_b^X\right)^2 =$ is the variance of the same bin.
- ✓ We work with $W \to e\nu_e$ for Tevatron and ATLAS, whereas we use $W \to \mu\nu_\mu$ for LHCb.
- ✓ We employ semi-realistic detector environments as implemented in `Delphes` for our ATLAS study.
- ✓ For Tevatron and for LHCb, we simply proceed directly to the analysis stage skipping the detector-simulation step.
- ✓ Since muons at the LHCb are well reconstructed with high efficiency and the muon p_T is the only observable, we expect our results for LHCb to be realistic.
- ✓ For Tevatron, however, the results are sensitive to details.



Different kinematic variables corresponding to CDF (top), ATLAS (middle) and LHCb (bottom). In each panel, the different histograms correspond to SM with $\Delta = 0$ (shaded), $\Delta = 1$ GeV (black line) (large Δ chosen for demonstration), and the NP process with $\Lambda_{\rm eff} = 1$ TeV (colored line). For legibility, we scale the NP numbers by 10^4.

- Following the recipe described above, we can determine the confidence belts in Λ_{eff} for each value of Δ.
- The location of the minimum of $\mathcal{D}^2$, as well as the width of the confidence belt depends on the assigned variance in each bin of the histogram.
- The statistical component of the variance is rather straightforward. Using the notation established above, we take $\left(\sigma_b^X\right)^2|_{\text{stat}} = X_b(\Delta)$.
- We also need to add a systematics component to the variance, which reflects the uncertainties due to scale, generator, detector elements, etc.

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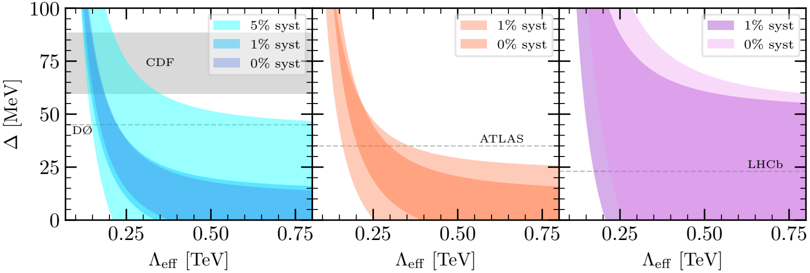


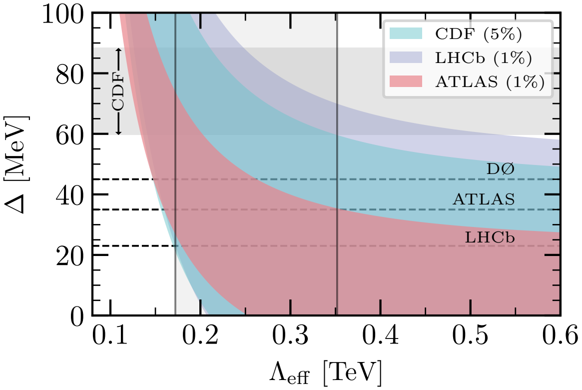
Left: 68% CL bands corresponding to 0%, 1%, and 5% systematic uncertainties for the CDF experiment overlaid on the CDF (+ResBos2) and D0 measurements of M_W at 1σ. *Centre:* 68% bands corresponding to ATLAS, overlaid on the ATLAS M_W measurement at 1σ. *Right:* 68% band for LHCb overlaid on the LHCb M_W measurement using p_T^{ℓ} only.

- We are more prone to systematics in the context of Tevatron analyses, because of which we show the 68% confidence level (CL) contours for 5% systematics, in addition to the 0% and 1% ones.
- Our first observation is that $\Lambda_{\text{eff}} \to \infty$, which corresponds to $\kappa \to 0$ for any finite Λ, is inconsistent with CDF (even when we include 5% systematics in our analysis).

In particular, we find that one needs to use $0.12\,\text{TeV} < \Lambda_{\text{eff}} < 0.35\,\text{TeV}$ (68% CL using 5% systematics) in order to predict the right shift of M_W at CDF.

$\Rightarrow$ Of this, $0.15\,\text{TeV} < \Lambda_{\text{eff}} < 0.35\,\text{TeV}$ is simultaneously allowed by the D0 and CDF measurements.

- Opposed to Tevatron, for ATLAS@7 TeV and LHCb we expect the systematics to be much more in control.
- For both these experiments, we find that there is a wide range of Λ_{eff} for which the NP hypothesis is allowed by the corresponding measurements of M_W, namely, $\Lambda_{\text{eff}} > 0.16\,\text{TeV}$ for ATLAS and $\Lambda_{\text{eff}} > 0.17\,\text{TeV}$ for LHCb. As expected, the bands are consistent with $\Delta = 0$ for $\Lambda_{\text{eff}} \to \infty$.



- Simultaneous plot of the results obtained from the simulations corresponding to CDF, ATLAS@7 TeV, and LHCb.
- The different bands, overlaid on the measurements, clearly convey the message that there is an overlap between the observations at CDF, ATLAS, and LHCb.
- This region of overlap (at 1σ) and is given by:

$$0.17\,\text{TeV} < \Lambda_{\rm eff} < 0.35\,\text{TeV}\ .$$

NEXT

- Various Constraints on this opeartor !!

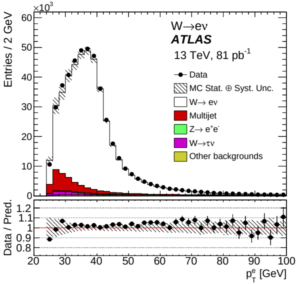
Constraints from LHC

- With the range of consistent Λ_{eff} values in hand, it would be remiss of us to not check for additional constraints on this range of interest.

The obvious measurements that should constrain the operator are the following:

✓ $pp \rightarrow W \rightarrow \ell + p_T^{\text{miss}}$ differential cross-section

[Ref : ATLAS Phys. Lett. B 759 (2016) 601]



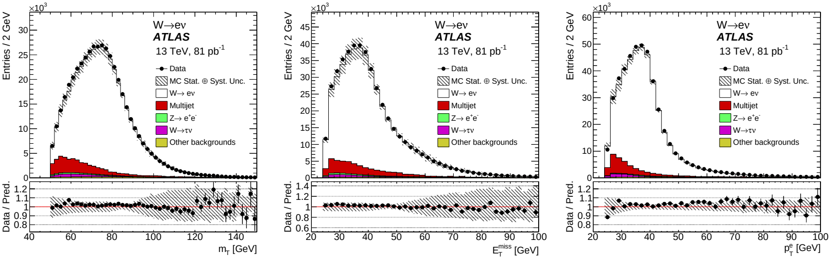
- The underlying processes corresponding to the W cross-section measurement and the W mass measurement are identical, the two analyses are essentially distinct by virtue of the somewhat different cuts imposed on the kinematic variables.
- While the mass measurement analysis uses the data in the bins defined by the fitting-ranges the cross section measurement includes data in the high momentum ranges as well. In fact, it is the events in these high momentum bins ($\gg M_W$) that we use to derive the bounds from the W cross section data.

Constraints from $\sigma(pp \to W \to \ell\nu)$

Variables	N_ℓ	N_J	p_T^ℓ	p_T^{miss}	M_T	$\lvert\eta^\ell\rvert$
Cuts	1	0	> 25 GeV	> 25 GeV	> 50 GeV	< 2.47

Table: Event selection criteria for W and $W\Phi$ production at $\sqrt{s} = 13$ TeV.

- For background (SM single W + SM background), we use the data provided by the collaboration in ATLAS Analysis.
- We simulate the NP contribution, $pp \to W\Phi + \text{jets}$, using `MadGraph` followed by `PYTHIA` for showering and `Delphes` for detector simulations. We use the anti-k_t algorithm with $p_T^{\text{min}} = 20\,\text{GeV}$, $R = 0.6$ to cluster calorimeter elements within $|\eta| < 5$.
- For subsequent analyses, we impose the same cuts on the kinematic variables in $\mathcal{X}$ and the same selection criteria on the number of final state particles as done by the collaboration in their analysis.



[Ref : ATLAS Phys. Lett. B 759 (2016) 601]

- We use the differential distributions for M_T, p_T^ℓ and $p_T^{\rm miss}$ variables.
- Lower bins for all these observables, are background-dominated, therefore, we concentrate on the high energy tails and impose analysis level cuts on the variables as follows:

$$M_T \ > \ 100 \ \text{GeV}\, ; \quad p_T^\ell \ > \ 65 \ \text{GeV}\, ; \quad p_T^{\rm miss} \ > \ 65 \ \text{GeV}\, .$$

For the three distinct variables $(M_T, p_T^\ell, p_T^{\rm miss})$, we get three different limits at 95% CL :

$$\Lambda_{\rm eff} > \begin{cases} 0.09 \ \text{TeV} & : \quad \text{from } M_T, \\ 0.15 \ \text{TeV} & : \quad \text{from } p_T^\ell, \\ 0.08 \ \text{TeV} & : \quad \text{from } p_T^{\rm miss}. \end{cases}$$

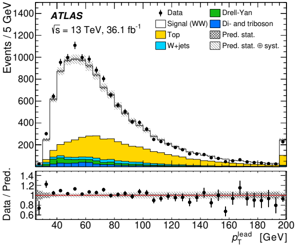
p_T^ℓ provides the most stringent constraint. This is essentially because the lepton transverse momentum can be the most precisely measured and is the least sensitive to systematics.

Constraints from $\sigma(pp \to WW \to e\mu + p_T^{\text{MISS}})$

Ref: ATLAS Eur. Phys. J. C 79 (2019) 884

The ATLAS analysis selects events with exactly one hard electron and one hard muon. The important kinematic variables are:

$$
\begin{aligned}
p_T^{\text{lead},\ell} &: \quad \text{momentum of the hardest } \ell \text{ in the event}\,, \\
p_T^{e\mu} &: \quad \text{transverse momentum of the } e\mu \text{ system}\,, \\
m_{e\mu} &: \quad \text{invariant mass of the } e\mu \text{ system}\,, \\
p_{T,\text{track}}^{\text{miss}} &: \quad \text{transverse momentum of all tracks}\,.
\end{aligned}
$$



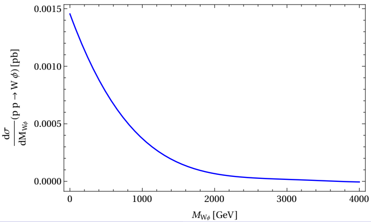
We focus on $p_T^{\text{lead},\ell}$ as the other available distributions (e.g., $p_T^{e\mu}$, $m_{e\mu}$, and angular variables) are less sensitive.

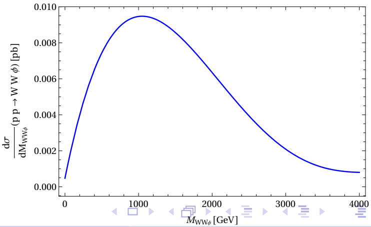
Variables	N_e	N_μ	N_J	p_T^ℓ	$\lvert\eta^\ell\rvert$	$p_{T,\text{miss}}^{\text{track}}$	$p_T^{e\mu}$	$m_{e\mu}$
Cuts	1	1	0	> 27 GeV	< 2.5	> 20 GeV	> 30 GeV	> 55 GeV

In addition, a veto on b-tagged jets with $p_T > 20$ GeV and $|\eta| < 2.5$. For unflavored jets, the veto is for $p_T > 35$ GeV and $|\eta| < 4.5$.

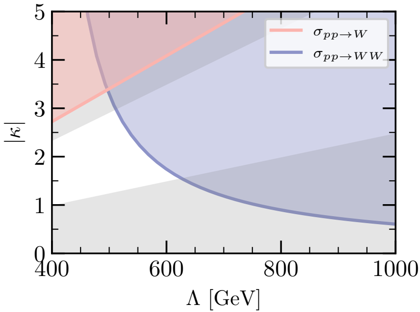
Constraints from $\sigma(pp \to WW \to e\mu + p_T^{\rm MISS})$

- In the $pp \to WW\Phi$ cross-section, the amplitude shows a power-law growth with the partonic center-of-mass energy, $\sqrt{\hat{s}}$, up to energies much higher than the suppression scale Λ of the EFT operator.
- This growth, beyond the UV cut-off of the theory, is clearly due to the amplitude picking up unphysical modes.
- This implies that we are extending the amplitude to energies beyond the range of computability of the effective theory.
- In order to regulate our result and force it to be in the regime of trustable computability, we impose a cut-off on the energy of the NP events. **Ref. A. Pomarol et al [2017]**.
- We include NP events for which the invariant mass of the $WW\Phi$ system (namely, $M_{WW\Phi}$) is less than Λ.





Exclusion Plot



Allowed (white) region consistent with all the measurements of M_W along with the 95% CL exclusions obtained from ATLAS measurements of $W \to \ell + p_T^{\text{miss}}$ (red) and $WW \to e\mu + p_T^{\text{miss}}$ (blue) cross sections.

Earlier, physics was insensitive to the simultaneous scaling of $\kappa \to a\kappa$ and $\Lambda \to a\Lambda$, since ultimately $\Lambda_{\text{eff}} = |\kappa|/\Lambda$ remained invariant. However, the 'elevation' of Λ to the role of the explicit cut-off introduces scale dependence. Hence, the constraint obtained from the WW analysis is *essentially* on the coefficient $|\kappa|$ for a varying Λ.

NEXT

➳ In future M_W measurements !!

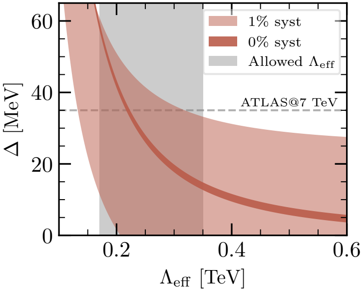
Tentative Future Prediction

With the allowed range of $\Lambda_{\rm eff}$, we use our NP hypothesis to predict the M_W extraction expected from the 13 TeV LHC data.

- We simulate for the ATLAS detector assuming an integrated luminosity of 500 fb^{-1}.
- Although we do not explicitly simulate for CMS, the predictions for ATLAS should act as a proxy for the former as well.

From this exercise, we predict (at 68% CL) for LHC@13 TeV the following ranges of Δ for two different systematics:

$$
\begin{aligned}
13\,\text{MeV} &\lesssim \Delta \lesssim 60\,\text{MeV} \qquad (0\%\ \text{systematics})\,, \\
0\,\text{MeV} &\lesssim \Delta \lesssim 61\,\text{MeV} \qquad (1\%\ \text{systematics})\,.
\end{aligned}
$$



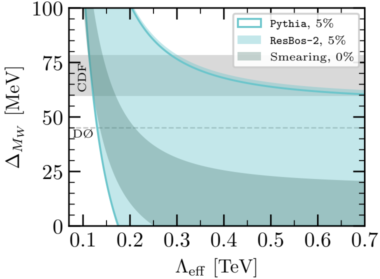
Some Subtleties related to CDF Analyses

✗ We are unable to incorporate some aspects of **detector simulations and statistical nuances**, we perform additional checks to establish the robustness of our results.

✓ M_T variable is the most peaked, it is this histogram for which the effect of smearing is the starkest.

✓ The analysis by Isaacson, C.P. Yuan et al [2022] mitigates this issue by modelling the detector smearing using Gaussian templates. We use it.

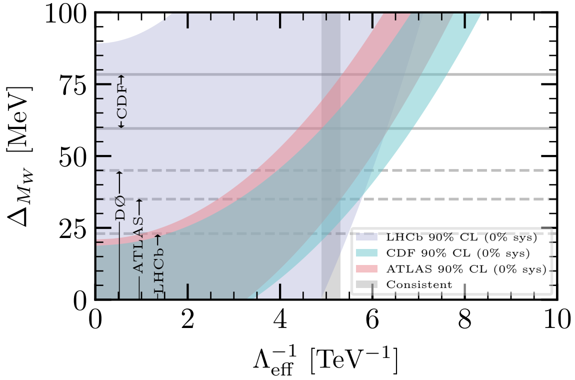
✓ We can clearly see that the band with 5% systematics completely covers the band with 0% systematics and without smearing. Therefore, any effect of smearing that we do not explicitly include are taken care of by systematics.



What if one ignores all systematics?

Even if we ignore all systematics for all the experiments and work with only statistical errors, we find that there is a non-zero range which satisfies all experimental measurements.

$$0.2\,\text{TeV} < \Lambda_{\text{eff}} < 0.22\,\text{TeV at } 90\%\text{ CL.}$$



NEXT

➳ Possible Motivation to have this operator !!

Possibility behind our EFT Operator

If the complex parameter κ is purely imaginary (*i.e.*, $\kappa = ik$), the theory described here is equivalent to more familiar constructions of Axion Like Particles (ALPs).

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A redefinition of left-handed u and d quarks eliminates our operator but gives :

$$u_L \to \exp\left(+\frac{ik\Phi}{f_\Phi}\right) u_L \quad \text{and} \quad d_L \to \exp\left(-\frac{ik\Phi}{f_\Phi}\right) d_L \quad \text{where} \quad f_\Phi = 2\Lambda.$$

$$\delta\mathcal{L} = k\frac{i\partial_\mu\Phi}{f_\Phi}\left(\overline{u}_L\gamma^\mu u_L - \overline{d}_L\gamma^\mu d_L\right) + k\frac{i\Phi}{f_\Phi}\left(1+\frac{h}{v}\right)\left(m_u\,\overline{u}u - m_d\,\overline{d}d\right) + \cdots,$$

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$$\delta\mathcal{L} \;=\; k\frac{i\partial_\mu\Phi}{f_\Phi}\;\left(\overline{u}\gamma^\mu u \;-\; \overline{d}\gamma^\mu d\right)\;.$$

The guiding principle for building the UV model is straightforward $\Rightarrow$ the UV model must result in $\frac{\kappa}{\Lambda}\, g_w W^+_\mu \Phi\; \overline{u}_L\gamma^\mu d_L \;+\;$ h.c. and/or the derivative operator above in terms of left-handed quarks, but there should not be any quark field redefinitions that can eliminate both at the same time.

Generalizing the derivative operator in the flavor space:

$$\delta\mathcal{L} \; = \; \sum_{ij} k_{ij} \frac{i\partial_\mu \Phi}{f_\Phi} \, \overline{q}_{L_i} \gamma^\mu \sigma^3 q_{L_j} \; .$$

- Arbitrary k_{ij} is simply ruled out from large FCNCs.
- A safer ansatz is using $k_{ij} = k \, \delta_{ij}$.
- Given specific models, one might require small non-diagonal k_{ij} elements to counter loop-induced FCNCs.

✓ The left-handed quark doublets are also electroweak doublets and the operators may violate electroweak symmetry.

The simplest construct is to take k/f_Φ to be proportional to the Higgs vev. For example, the following electroweak operator yields :

$$\bar{k} \frac{1}{\bar{\Lambda}^3} \partial_\mu \Phi \sum_a H^\dagger t^a H \, \overline{q}_L \gamma^\mu t^a q_L \quad \Rightarrow \quad \frac{k}{f_\Phi} \; = \; \bar{k} \frac{1}{\bar{\Lambda}} \left(\frac{v/\sqrt{2}}{\bar{\Lambda}} \right)^2$$

This scheme finds the dimension $D = 5$ operator from a truly $D = 7$ operator. This seemingly low $\bar{\Lambda}$ may not necessarily mean the existence of additional new degrees of freedom at low energies [**Ref: Anson hook 2019 JHEP**].

Another model possibility

Triplet Extension

- A far more creative and attractive avenue.
- From an electroweak $D = 5$ operator.
- This requires an electroweak triplet $\Sigma \equiv \Sigma_a t^a \equiv \{\Sigma_\pm, \Sigma_3\}$.

$$\delta\mathcal{L} \;=\; \bar{k}\frac{1}{\bar{\Lambda}}\sum_a i\partial_\mu \Sigma_a \, \overline{q}_L \gamma^\mu \sigma^a q_L \;,$$

- Further model building is necessary to accommodate $\Sigma_\pm$, since these have to be heavier than the EW scale to avoid bounds from W/Z widths.
- The light neutral state (Φ) can be obtained by introducing another electroweak singlet (say Σ_0).

T-Parameter

One concern of adding an $SU(2)_w$ triplet to the spectrum of particles is the possible modification to the EW T-parameter. The triplet contributes only at one-loop level through the $\Sigma^\pm - \Sigma_0$ mass difference. The T-parameter is extremely sensitive to the mass difference for $M_{\Sigma^\pm} \geq M_W$. However, when both the charged and neutral components are lighter than the W mass, the contribution to T-parameter ~ 0.

NEXT

➳ Summary

Outlook

- The peculiarity of the CDF measurement of M_W lies not only in the fact that it deviates in a statistically significant way from the electroweak precision fits but also in the fact that it drifts away from measurements reported by other experimental collaborations.
- Any attempt from the theory side to explain the CDF 'anomaly' should not exist in a bubble where some new physics effect suitably increases M_W , but should strive to explain all the M W extractions simultaneously.
- In this work, we have gone some way in doing precisely this. We have proposed a simple extension of the Standard Model where the addition of a singular source of unaccounted for missed transverse energy can give rise to the discrepant measurements of M_W across different measurements.
- Of course, other classes of models may exist which, by leading to similar misinterpretations, could explain this discrepancy.
- It implies that before all these models are ruled out, one cannot simply take the disagreement between two experiments to indicate that one of the experiments must be wrong - in this regard, the M_W discrepancy might be a hint of a much broader and enriching theme.


Thank you!!