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A Twisted Tale of the Transverse-mass Tail

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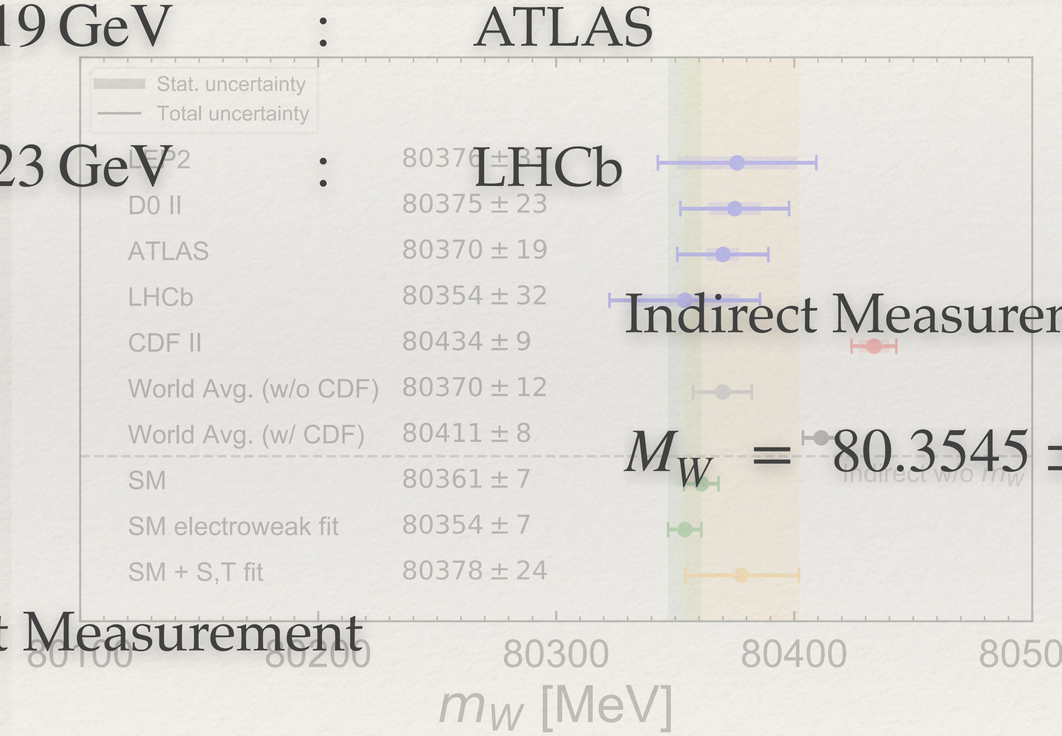
The punchline

This work is motivated to solve a puzzle

Direct Measurements

$$M_W \;=\; 80.370 \pm 0.019\,\text{GeV} \quad : \quad \text{ATLAS}$$

$$M_W \;=\; 80.354 \pm 0.023\,\text{GeV} \quad : \quad \text{LHCb}$$



Indirect Measurement : Precision Electroweak

$$M_W \;=\; 80.3545 \pm 0.0057\,\text{GeV}$$

Direct Measurement

$$M_W \;=\; 80.4335 \pm 0.0094\,\text{GeV} \quad : \quad \text{CDF}$$

An obvious conclusion: these sets of measurements are not compatible with each other.

The punchline

An obvious conclusion: these sets of measurements are not compatible with each other.

If you think a bit more, the picture seem to point to only two (slightly more nuanced) conclusions:

Either : CDF measurement is just plain wrong!

➡ (that's it no more information)

Or : CDF measurements (central value and error) are good

➡ ATLAS and LHCb made a mess of their measurements

➡ There must be BSM physics (since we love our precision EW fit)

Challenge : can one make all three compatible with each other

The punchline

Challenge : can one make all three compatible with each other

It turns out that you can !

It requires one to construct

curious extensions of the SM

In these scenarios

the "SM-measurement" of M_W

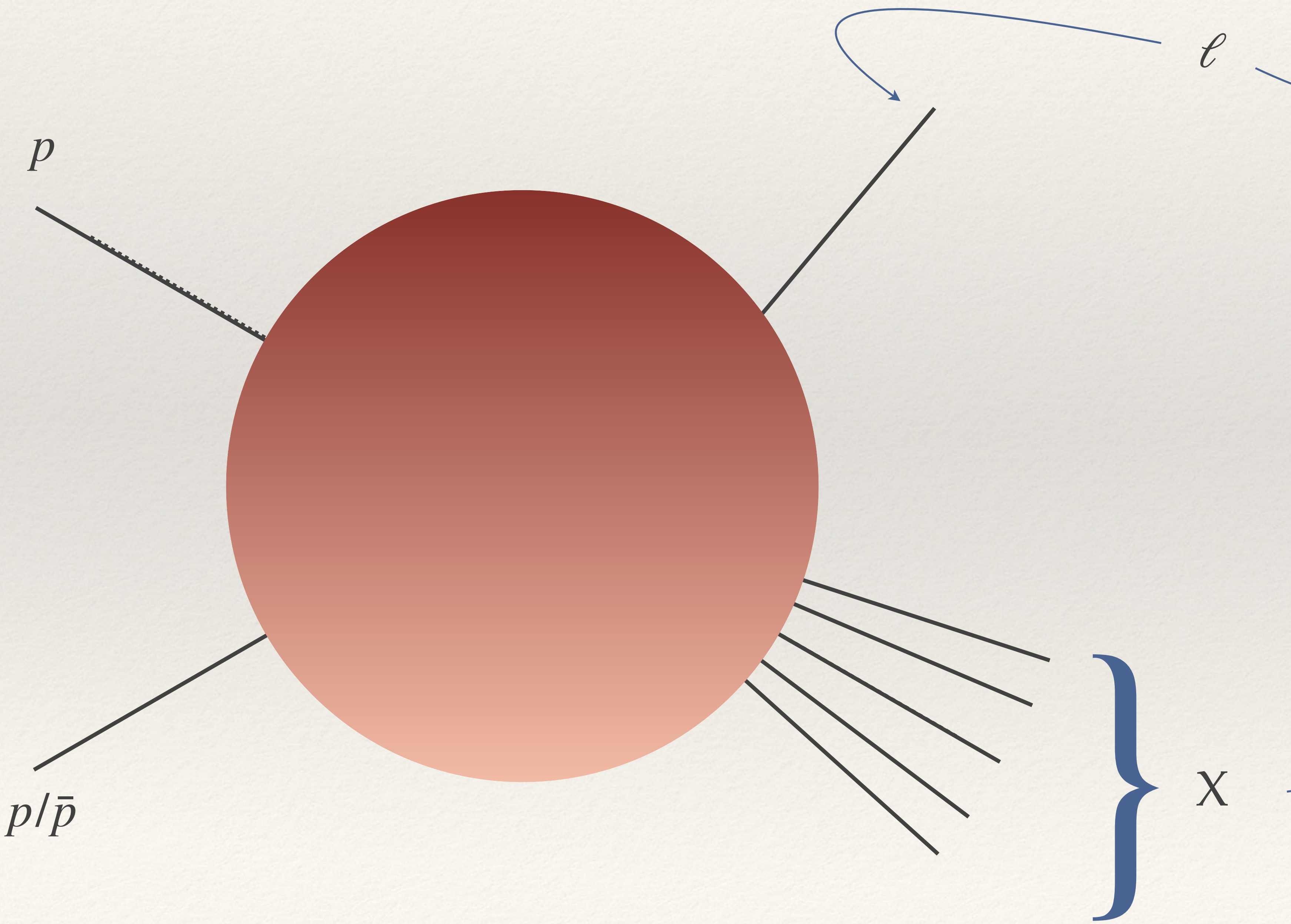
depends on types of

collider and collision energy!

Outline

- Anatomy of an “W-events”
    - from observables to the measurement & the role of interpretation
- Construction of a minimal scenario where W-mass measurement yields different answers based on “in-states” of a collider and energy of collisions.
- Constraintology
- Towards model building

Anatomy of a “W-event”



Observables:

Lepton 4-momentum
p_μ^ℓ

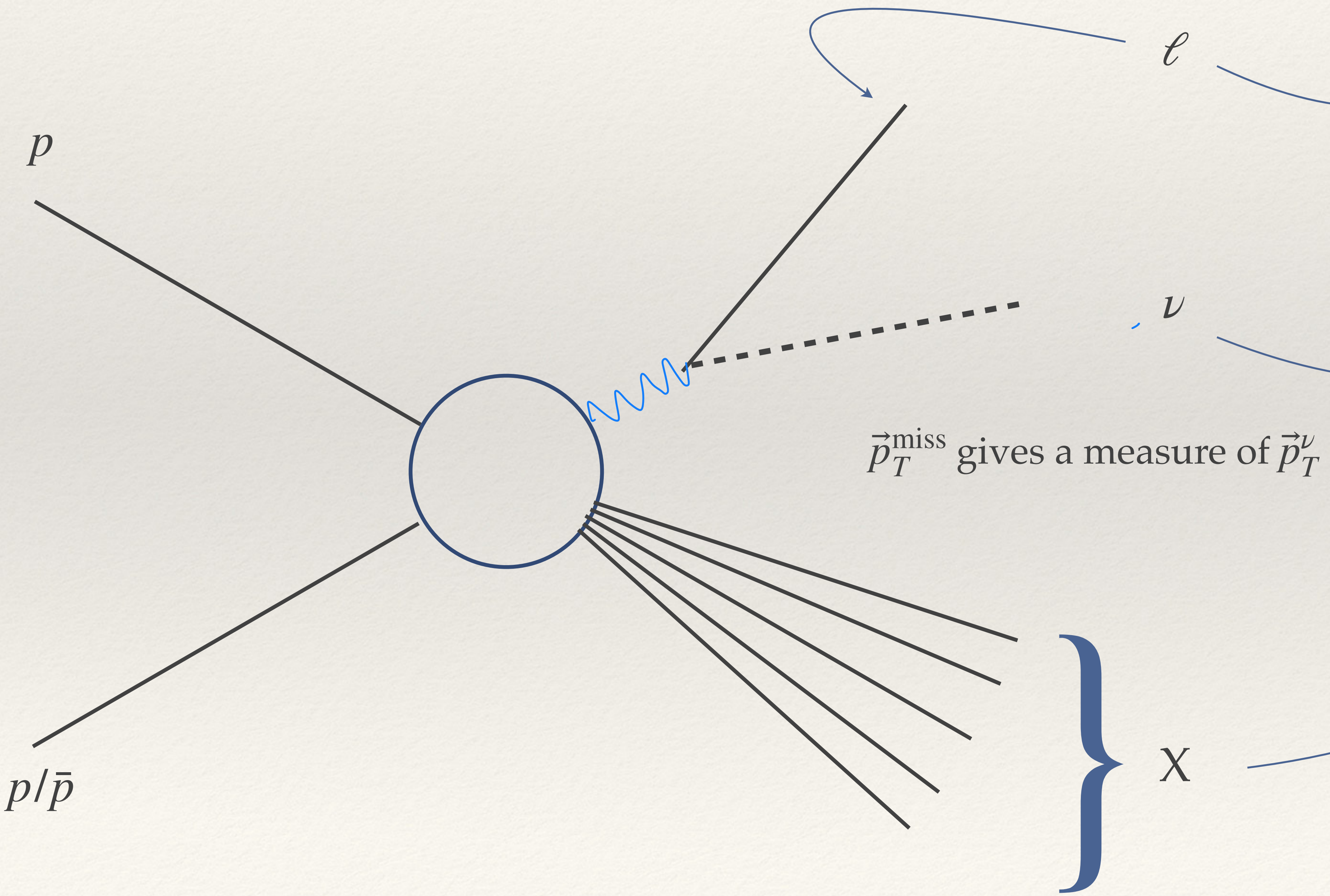
Missing transverse momentum
$\vec{p}^{\text{miss}}$

Hadronic recoil
u_T

Anatomy of a “W-event”

Interpretation : $\ell + X$ events are due to SM

$$W\left(\ell + \nu\right) + X$$



$\vec{p}_T^{\,\mathrm{miss}}$ gives a measure of $\vec{p}_T^{\,\nu}$

Observables:

Lepton 4-momentum

p_μ^ℓ

Missing transverse momentum

$\vec{p}^{\,\mathrm{miss}}$

Hadronic recoil

u_T

Anatomy of a “W-event”

Extracting W-mass - construct the Transverse mass

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

Where

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

Observables:

Lepton 4-momentum

p_μ^{ℓ}

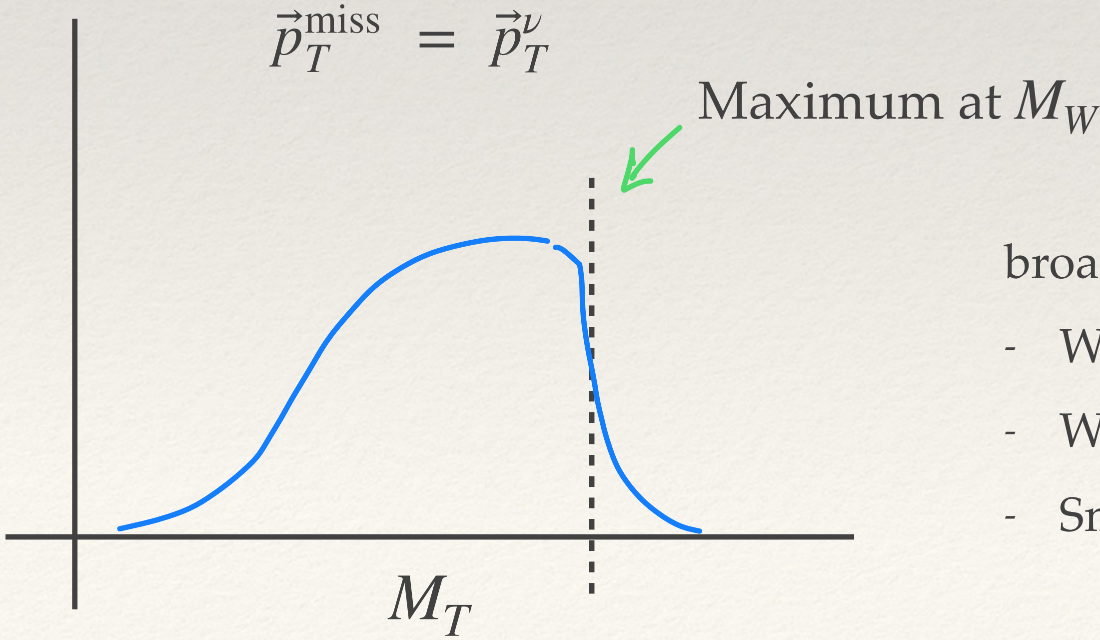
Missing transverse momentum

$\vec{p}^{\,\text{miss}}$

Hadronic recoil

u_T

$$\vec{p}_T^{\,\text{miss}} = \vec{p}_T^{\,\nu}$$



broadened because of

- W transverse momentum
- Width
- Smearing, resolution, etc.

Anatomy of a "W-event"

Extracting W-mass - construct the Transverse mass

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Observables:

Lepton 4-momentum

p_μ^ℓ

Missing transverse momentum

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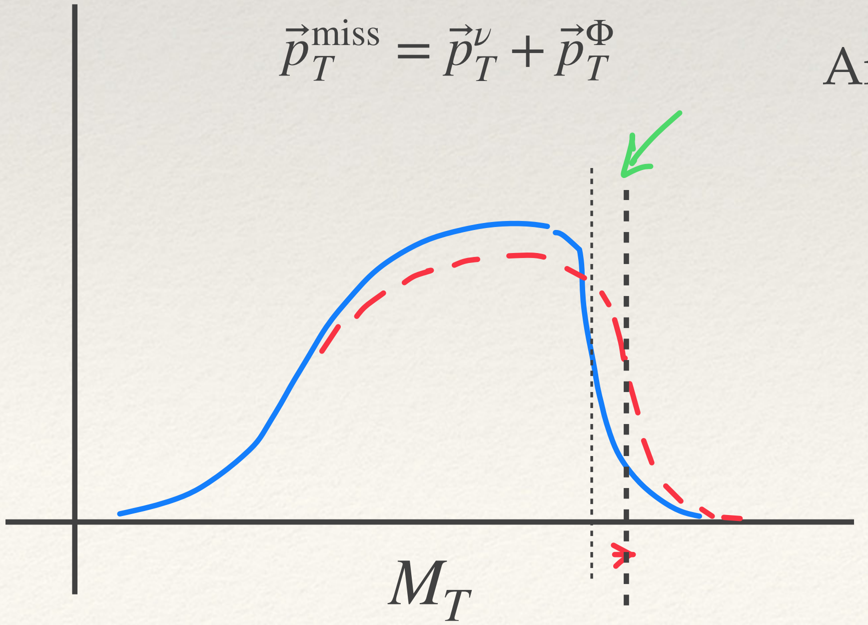
Hadronic recoil

u_T

$$\vec{p}_T^{\,\text{miss}} = \vec{p}_T^{\,\nu} + \vec{p}_T^{\,\Phi}$$



An extra contribution to MET

If you try to fit it with the ansatz $\vec{p}_T^{\,\text{miss}} = \vec{p}_T^{\,\nu}$ it would yield a larger M_W

Anatomy of a “W-event”

Extracting W-mass - construct the Transverse mass

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

Where

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

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

Observables:

Lepton 4-momentum
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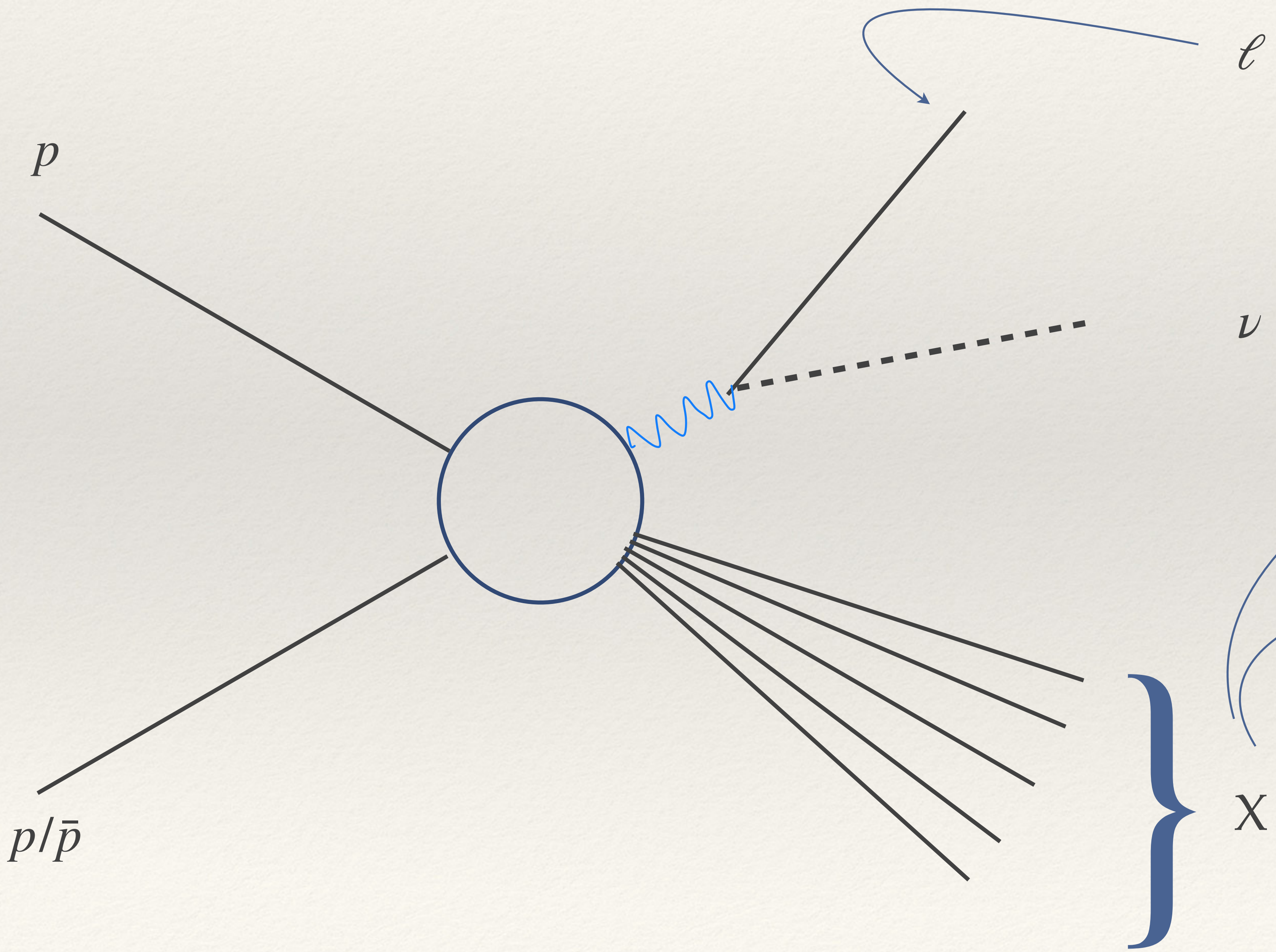
Anatomy of a “W-event”

Interpretation : $\ell + X$ events are due to SM

$$W\left(\ell + \nu\right) + X$$



Observables:

Lepton 4-momentum

p_μ^ℓ

Missing transverse momentum

$\vec{p}^{\rm miss}$

Hadronic recoil

u_T

Even here X contributes to

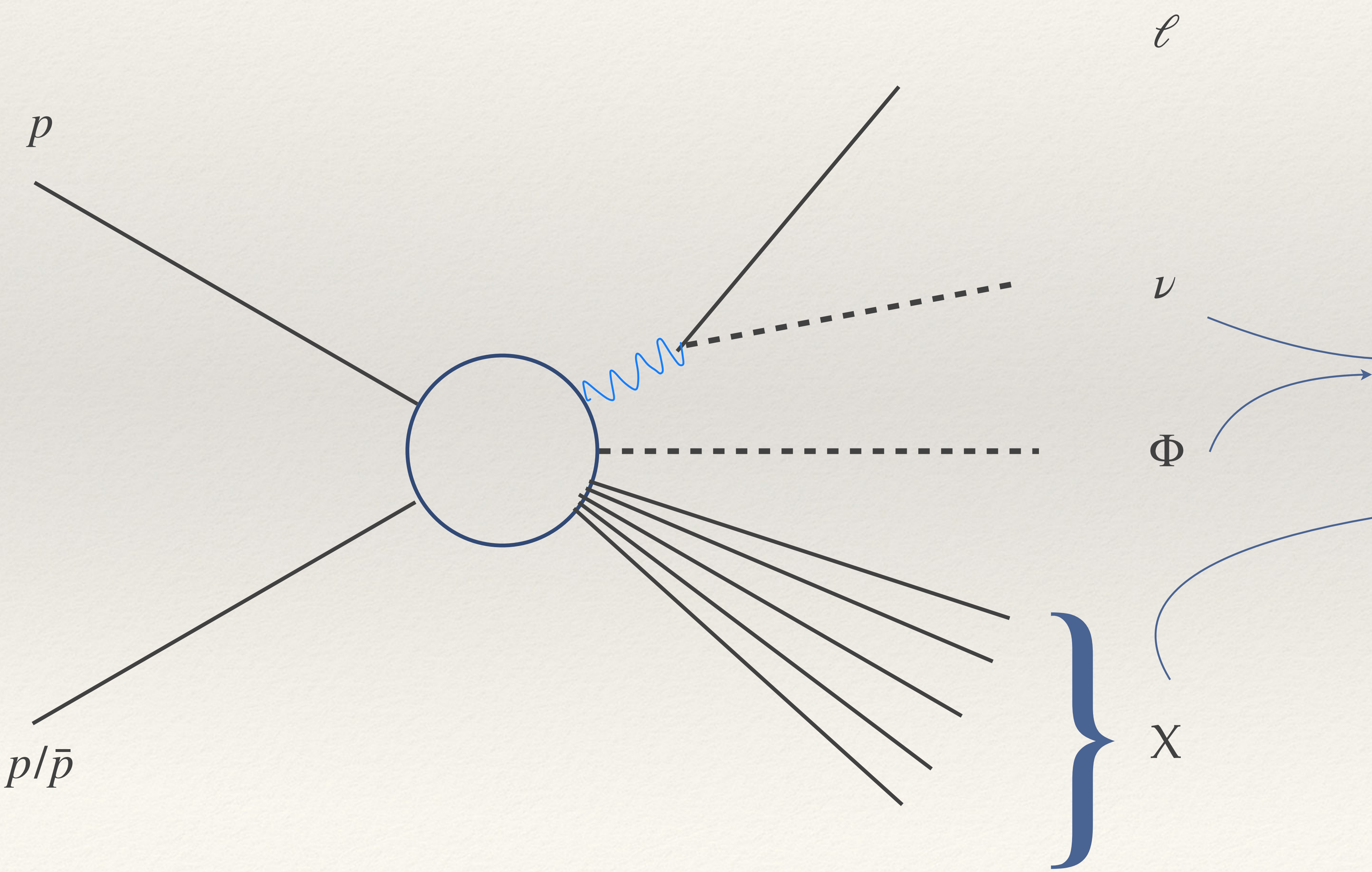
$\vec{p}_T^{\rm miss}$

A cut on $u_T < u_0$ is recommended

Anatomy of a “W-event”

Key Idea : some $\ell + X$ events are due to

$$W\left(\ell + \nu\right) + X + \Phi$$



Observables:

Lepton 4-momentum

p_μ^ℓ

Missing transverse momentum

$\vec{p}^{\text{miss}}$

Hadronic recoil

u_T

An extra source of MET

$$\vec{p}_T^{\text{miss}} = \vec{p}_T^{\nu} + \vec{p}_T^{\Phi}$$

A proof of principle

- Introduce a new BSM (scalar/pseudo scalar) state Φ that simply decays to the dark sector once produced
  - ➡ Contributes to the MET as far as collider physics is considered
- Consider a single visible sector irrelevant interaction (for now)

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

$$\Lambda_{\text{eff}} = \frac{\Lambda}{|\kappa|}$$

Details matter

Key Idea : Fitting with full set of SM events ($W(\ell + \nu) + X$) + few BSM events $W(\ell + \nu) + X + \Phi$ with SM interpretation will generate a larger fit for M_W

However, M_T is not the only distribution that affects M_W determination

A larger M_W also results in a harder lepton p_T^{ℓ} and a bigger p_T^{miss}

In fact, in LHCb the only distribution of relevance is p_T^{ℓ}

Algorithm

For a quantitative study:

- we take true M_W to be the precision EW measurement (say, M_W^0)
- Generate SM events for various $M_W(\Delta) = M_W^0 + \Delta$, and NP events for a given Λ_{eff}
- Finally, for each Δ we find the preferred value and the confidence belts in Λ_{eff} by minimizing

$$\mathscr{D}^2 = \sum_{x \in \mathscr{X}} \sum_b \left(\frac{X_b(\Delta) - X_b(0) - X_b^{\text{NP}}(\Lambda_{\text{eff}})}{\sigma_b^X} \right)^2$$

X_b : Bin count in bin b of Histogram x

σ_b^2 : variance in bin b

We also add a systematics component to the variance, which reflects the uncertainties due to scale, generator, detector elements, etc.

Selection Cuts

CDF	ATLAS	LHCb
$p+\bar{p}$ @ 1.96 TeV	$p+p$ @ 7 TeV	$p+p$ @ 13 TeV
$-1.0 < \eta^{\ell} < 1.0$	$-2.5 < \eta^{\ell} < 2.5$	$2.2 < \eta^{\ell} < 4.4$
$30 < p_T^{\ell}\,(\mathrm{GeV}) < 55$	$p_T^{\ell} > 30\,\mathrm{GeV}$	$28 < p_T^{\ell}\,(\mathrm{GeV}) < 52$
$30 < p_T^{\mathrm{miss}}\,(\mathrm{GeV}) < 55$	$p_T^{\mathrm{miss}} > 30\,\mathrm{GeV}$	
$60 < M_T\,(\mathrm{GeV}) < 100$	$M_T > 60\,\mathrm{GeV}$	
$u_T < 15\,\mathrm{GeV}$	$u_T < 30\,\mathrm{GeV}$	

Definition of u_T is collider specific:

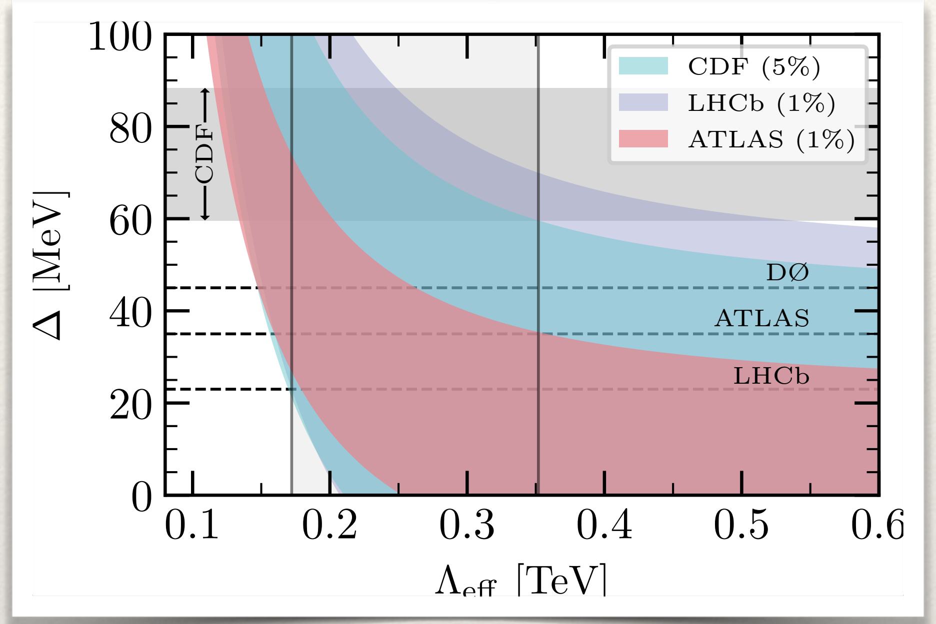
CDF : all hadrons and photons in $|\eta| < 3.6$

ATLAS : all jets and photons in $|\eta| < 4.9$

Fitting Range

CDF	ATLAS	LHCb
$p+\bar{p}$ @ 1.96 TeV	$p+p$ @ 7 TeV	$p+p$ @ 13 TeV
$\mathcal{X} = \{M_T, p_T^\ell, p_T^{\text{miss}}\}$	$\mathcal{X} = \{M_T, p_T^\ell, p_T^{\text{miss}}\}$	$\mathcal{X} = \{p_T^\ell\}$
$32 \leq p_T^\ell\,(\text{GeV}) \leq 48$	$32 \leq p_T^\ell\,(\text{GeV}) \leq 45$	$28 < p_T^\ell\,(\text{GeV}) < 52$
$32 \leq p_T^{\text{miss}}\,(\text{GeV}) \leq 48$	$32 \leq p_T^{\text{miss}}(\text{GeV}) \leq 45$	
$65 \leq M_T\,(\text{GeV}) \leq 90$	$66 \leq M_T\,(\text{GeV}) \leq 99$	

Put everything together



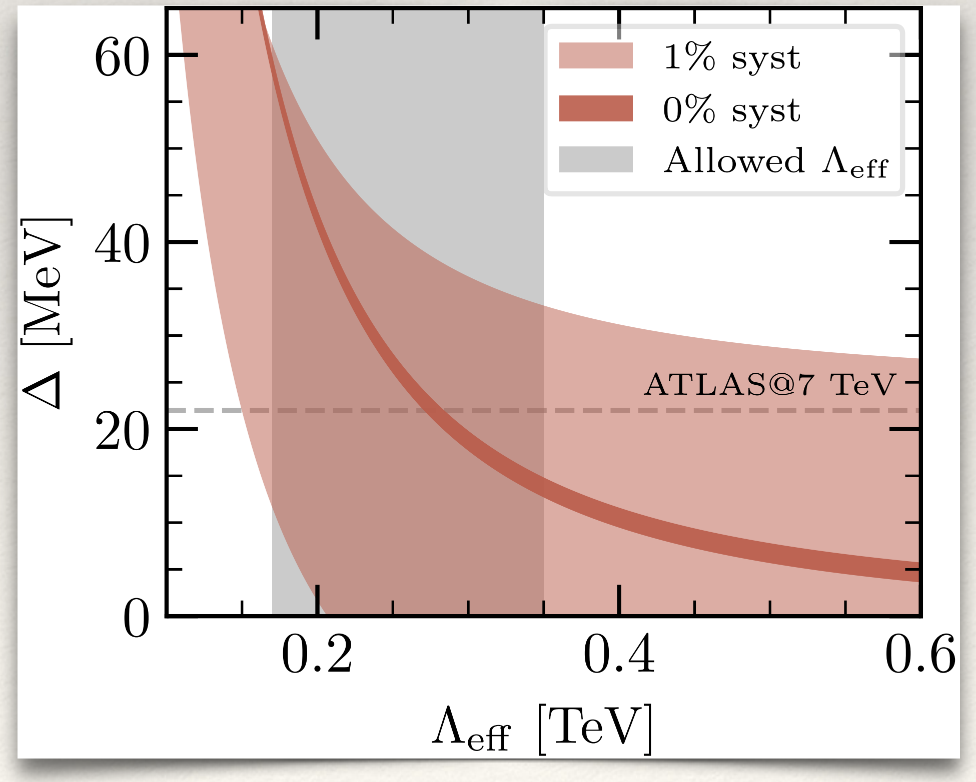
- Simultaneous plot of the results obtained from the simulations corresponding to CDF, ATLAS@7 TeV, and LHCb.
- The different bands, overlaid on the measurements, clearly convey the message that there is an overlap between the observations at CDF, ATLAS, and LHCb.
- This region of overlap (at 1σ) and is given by: 017 TeV $< \Lambda_{\text{eff}} <$ 0.35 TeV

Prediction for ATLAS@13 TeV

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

$$13\,\mathrm{MeV} < \Delta < 60\,\mathrm{MeV} \qquad @\,0\,\%\ \text{Systematics}$$

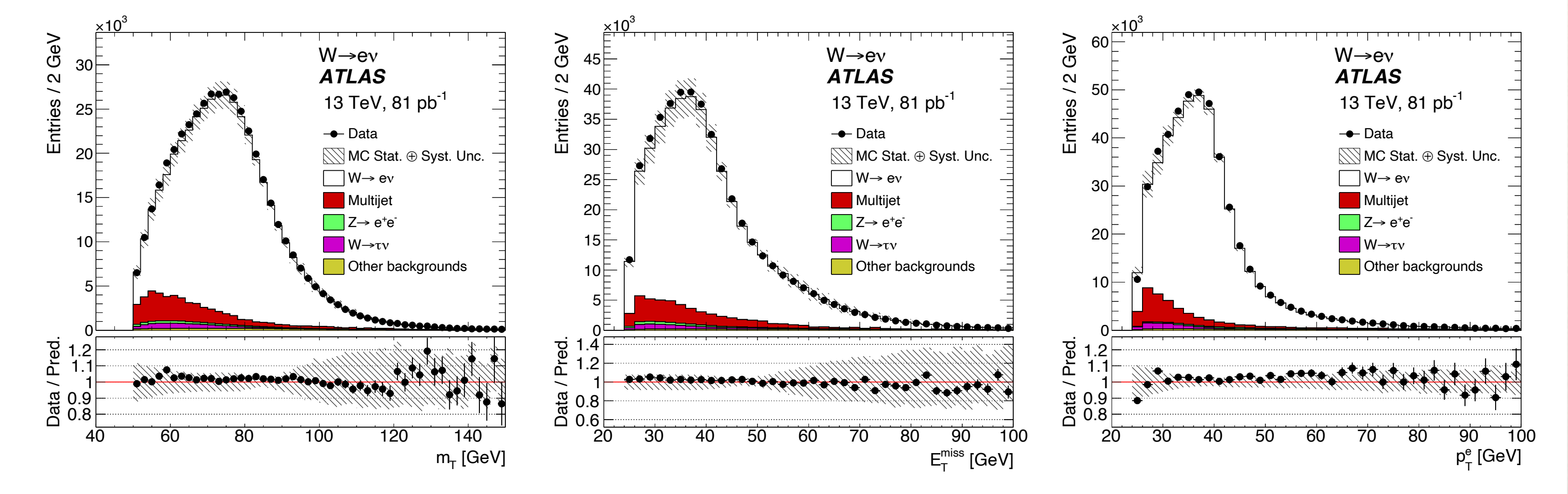
$$0\,\mathrm{MeV} < \Delta < 61\,\mathrm{MeV} \qquad @\,1\,\%\ \text{Systematics}$$



Constraints: W cross section

$$pp \to W \to \ell \ + \ \mathrm{MET}$$

@ 13 TeV in ATLAS



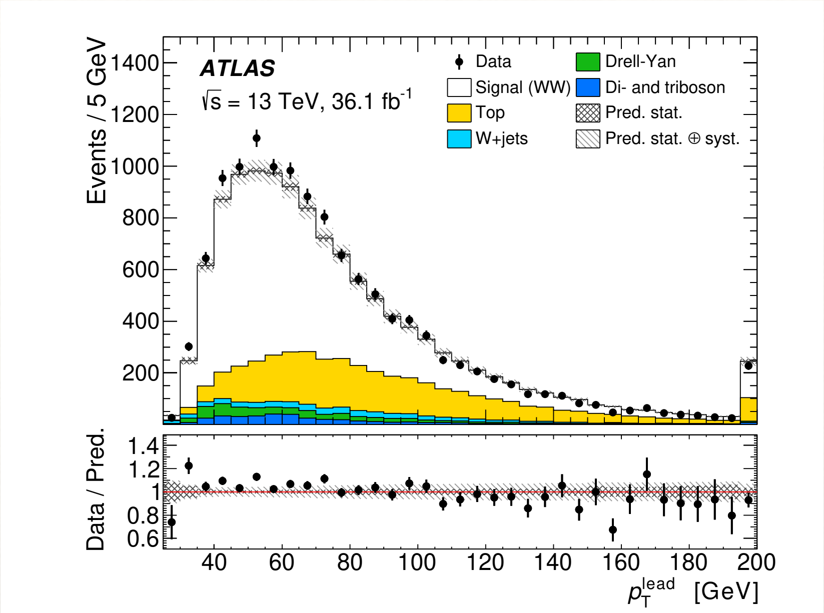
- The underlying processes corresponding to the W cross-section measurement and the W mass measurement are identical, the two analyses are essentially distinct by virtue of the somewhat different cuts imposed on the kinematic variables.

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

$$\Lambda_{\text{eff}} \ > \ \begin{array}{lcl} 0.09\ \text{TeV} & : & \text{from } \mathrm{M_T} \\ 0.15\ \text{TeV} & : & \text{from } \mathrm{p_T^\ell} \\ 0.08\ \text{TeV} & : & \text{from } \mathrm{p_T^{miss}} \end{array} \quad @\,95\ \%\ \text{CL}$$

Constraints: WW cross section

$pp \to WW \to e\mu \;+\;$ MET @ 13 TeV in ATLAS



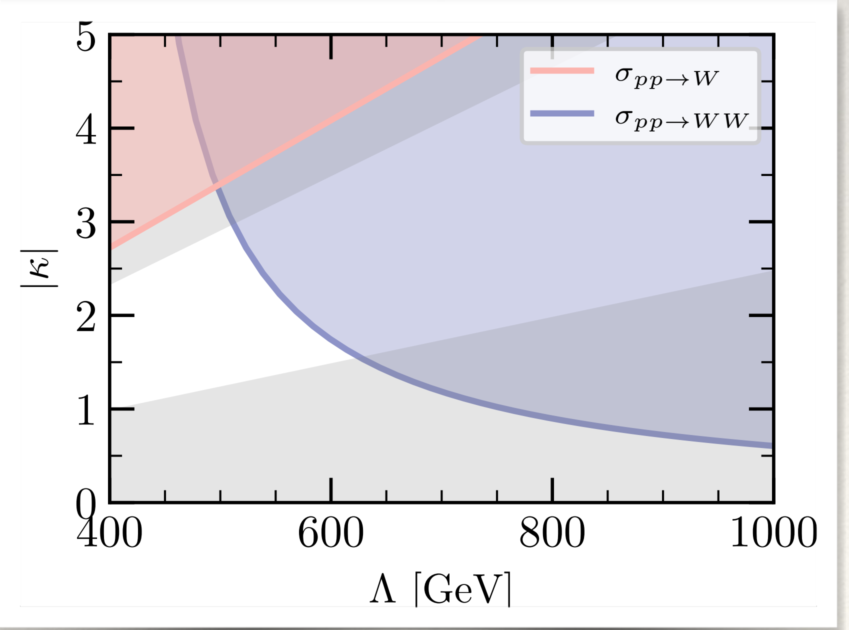
$p_T^{\text{lead},\ell}$: momentum of the hardest lepton in the event

$p_T^{e\mu}$: transverse momentum of the eμ system

$m^{e\mu}$: invariant mass of the eμ system

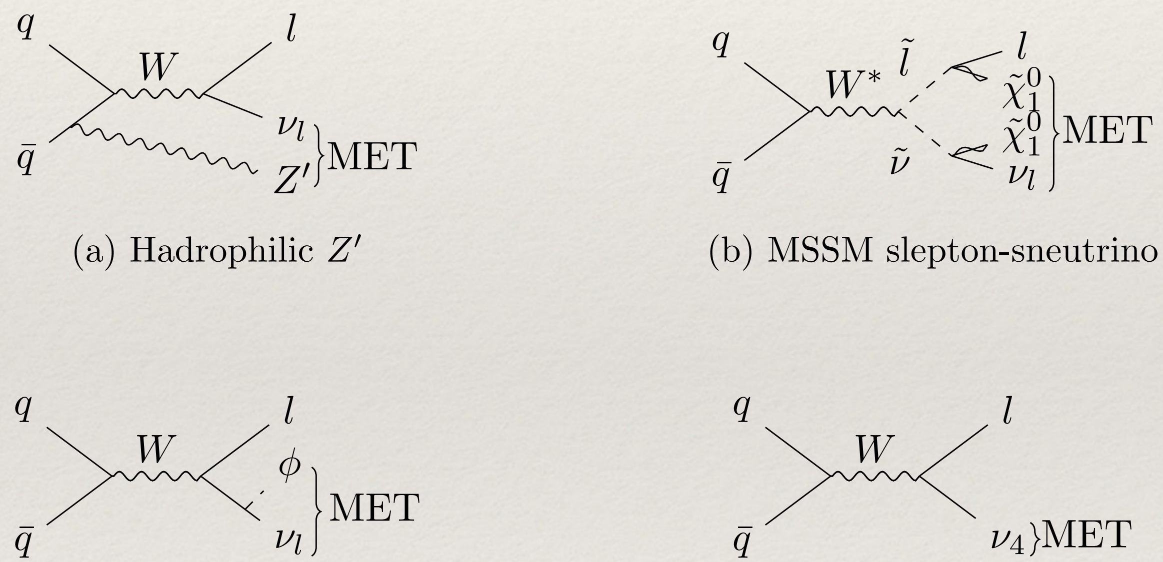
$p_{T,\text{Track}}^{\text{miss}}$: transverse momentum computed using jet and lepton tracks

Variables	N_e	N_μ	N_J, N_{J_b}	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



Towards model building

The key insight is that if there are extra New Physics events that contribute to $W(\ell\nu)$ + extra MET that pass M_W selection criteria — you will extract a higher M_W



(a) Hadrophilic Z'

(b) MSSM slepton-sneutrino

(c) Neutrinophilic scalar

(d) Heavy neutrino

Examples can be found in many places

See e-Print: 2404.17574 for a comprehensive discussion

Towards model building

Even the most minimal scenario described here can be mapped to ALP physics

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

Take Φ to be a pseudo scalar

$$u \;\to\; \exp\left(+\frac{ik\Phi}{f_\Phi}\right) u \quad \text{and} \quad d \;\to\; \exp\left(-\frac{ik\Phi}{f_\Phi}\right) d \quad \text{where} \quad f_\Phi \;=\; 2\Lambda \quad \text{and} \quad \kappa = ik$$

this redefinition eliminates the above operator and, in turn, gets you into the realm of an ALP

$$\delta\mathscr{L} \;=\; ik\frac{\partial_\mu \Phi}{f_\Phi}\;\left(\bar{u}\gamma^\mu u \;-\; \bar{d}\gamma^\mu d\right)$$

Conclusion

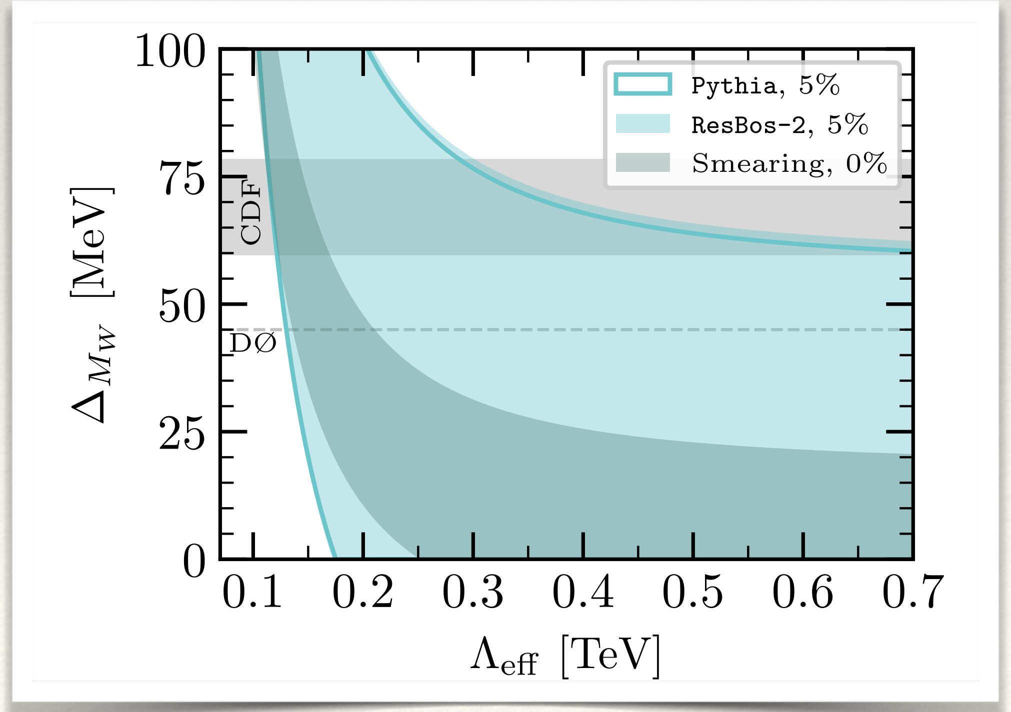
- We showed that, unlike the Z-boson or the Higgs scalar, measuring the mass of W-boson (in leptonic decays) can be tricky
    - The extracted value relies on interpreting ℓ + MET events as due to Standard Model W events and then fitting
    - A handful of new physics events passing these cuts can artificially give rise to the best fitted M_W that is larger than the true M_W.
        - Examples of such NP cases are plentiful.
    - Since the fraction of new physics events produced and passing the selection criteria depends crucially on the type of collider and the energy of the collider, one expects different results (M_W) from different experiments.

This is actually cool!

Backup slides

CDF-smearing

- 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 modeling 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.



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.

$$0.2\,\text{TeV} < \Lambda_{\text{eff}} < 0.22\,\text{TeV} \qquad @\,90\,\%\,\text{CL}$$