Using $W \to \ell \nu_\ell$ Processes to Probe Sterile Neutrinos at Colliders

New-ν Physics: From Colliders to Cosmology

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Overview

What I'll cover:

- The model
- Effect of $W \to eN$ on W-boson mass
- Angular observables' sensitivity to sterile neutrinos

Formalism

- We work in νSMEFT.
  - Operators contributing to $W \to Ne$:

$$\Delta\mathcal{L} = \frac{c^i_{LNH}}{\Lambda^2}\bar{L}_i\nu_R\tilde{H}H^\dagger H + \frac{c^i_{HNe}}{\Lambda^2}\bar{\nu}_R\gamma^\mu e_{iR}H^\dagger iD_\mu H + \frac{c^i_{NW}}{\Lambda^2}\bar{L}_i\sigma^{\mu\nu}\nu_R\sigma_I\tilde{W}^I_{\mu\nu},$$

  - c^i_{LNH} and c^i_{NW} give rise to parity conserving interactions, while c^i_{HNe} gives rise to a parity-violating V+A interaction - only this operator changes the kinematics of the W decays
  - Thus we assume only $c^i_{HNe} \neq 0$ which gives rise to a W decay of width:

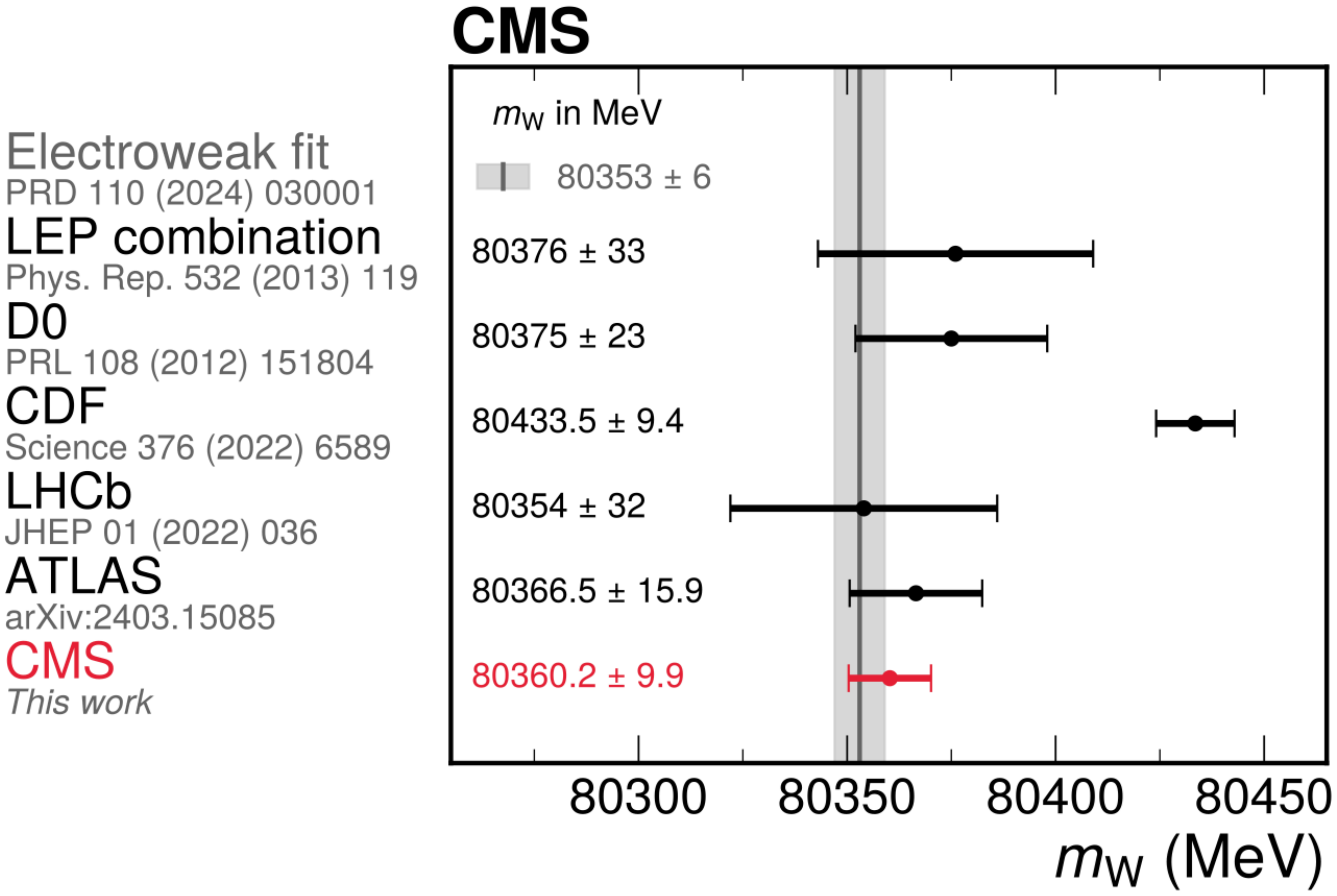
$$\Gamma(W \to e\nu_R) = \frac{m_w^3 v^2}{48\pi\Lambda^4}\left(c^e_{HNe}\right)^2$$

arXiv:1909.04665

Motivation

W Mass Discrepancy

- Most precise W mass measurement to date much higher than other measurements
- LHC measurements closer to EW SM prediction



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W Mass Measurement at Hadron Colliders

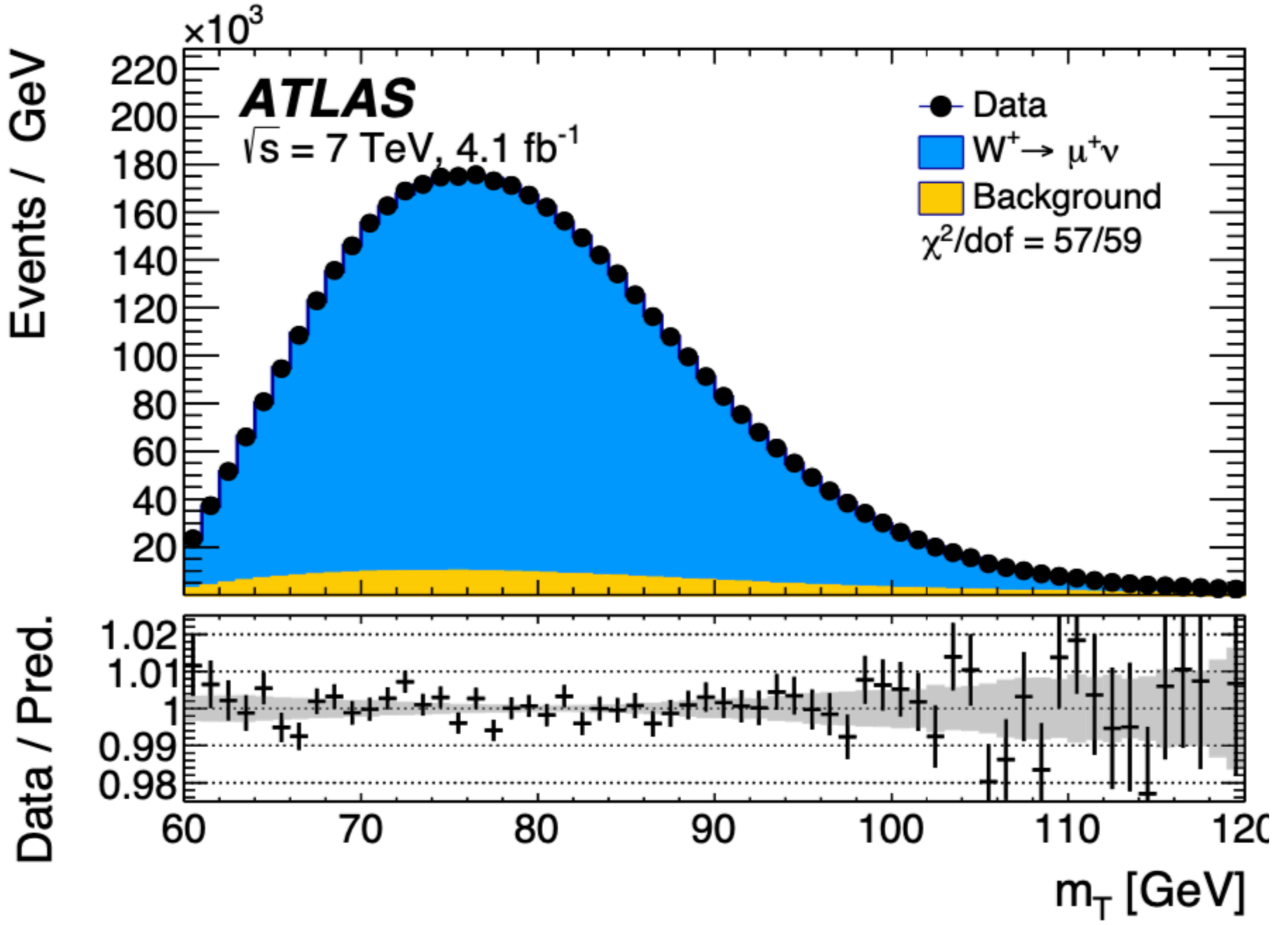
- W-mass measured in $W \to \ell \nu_\ell$ processes at colliders
- Observables used are p_T^ℓ, p_T^{miss} and m_T, where p_T^{miss} is an approximation of the neutrino momentum
  - Defined by $\vec{p}_T^{\text{miss}} = -(\vec{u}_T + \vec{p}_T^\ell)$ where the recoil $\vec{u}_T$ is the vector sum of the transverse energy of all other deposits in calorimeters
- Distributions of $p_T^\ell, p_T^{\text{miss}}$ have Jacobian endpoints at $m/2$ while m_T drops off at m
  - m is invariant mass of charged lepton-neutrino system.

W Mass Measurement at Hadron Colliders

- Invariant mass m related to m_W via the Breit-Wigner resonance

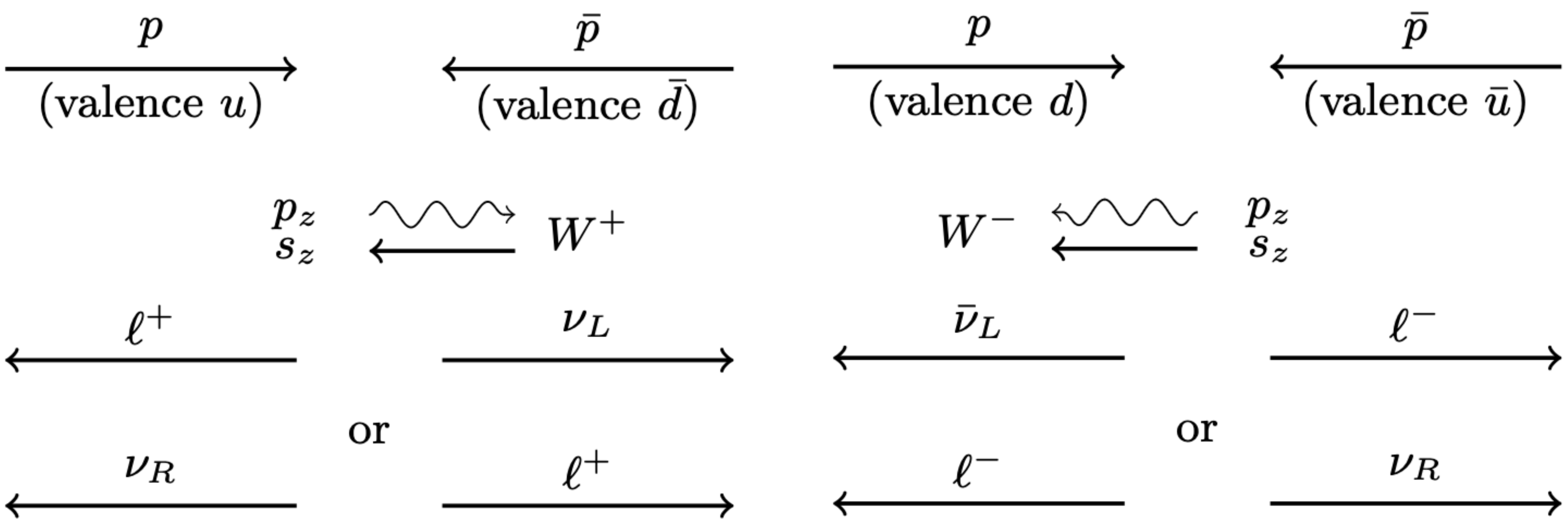
$$\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_W^2)^2 + m^4\Gamma_W^2/m_W^2}$$

- Simulate expected final state distributions for many m_W and then fit to experimental data using χ^2 test



Motivation

Kinematics at CDF



(a) W^+ production and decay at the Tevatron.

(b) W^- production and decay at the Tevatron.

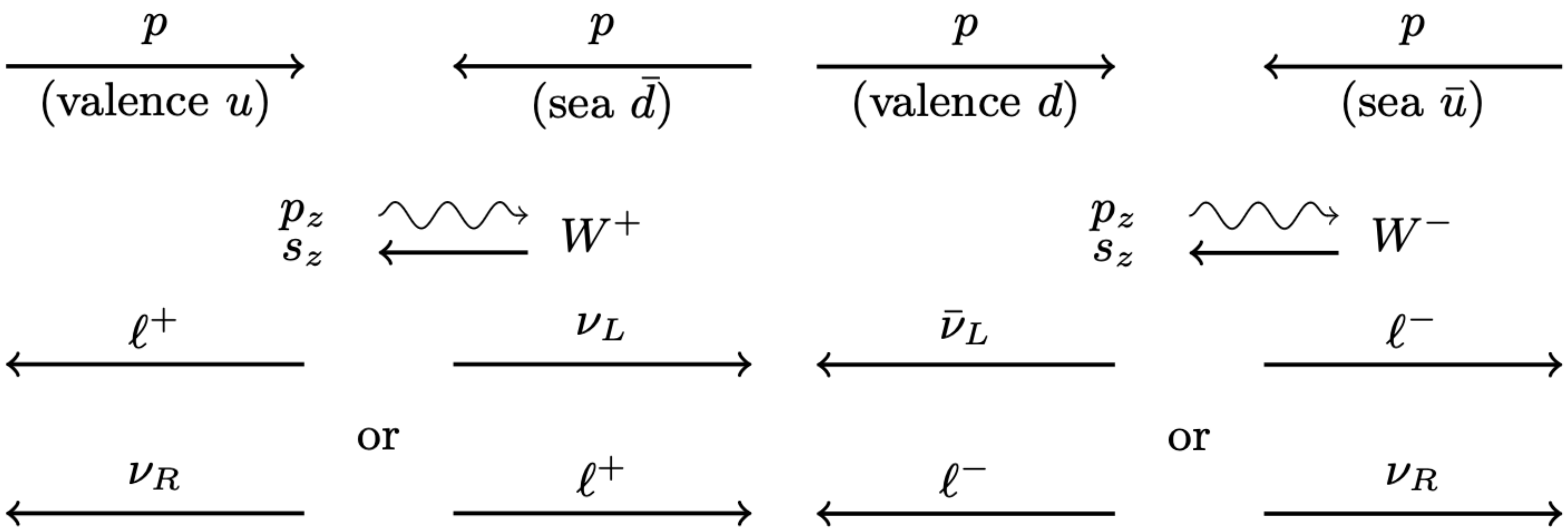
- $x_u > x_d \Rightarrow$ W boosted in direction of u or $\bar{u}$
- $\Rightarrow$ charged lepton more boosted in decays to RHN than SM decays

$\Rightarrow \nu_R$ decays must be more transverse to enter detector

$\Rightarrow$ W transverse decays lead to a harder p_T spectrum, leading to a higher m_W

Motivation

Kinematics at LHC



(a) W^+ production and decay at the LHC.

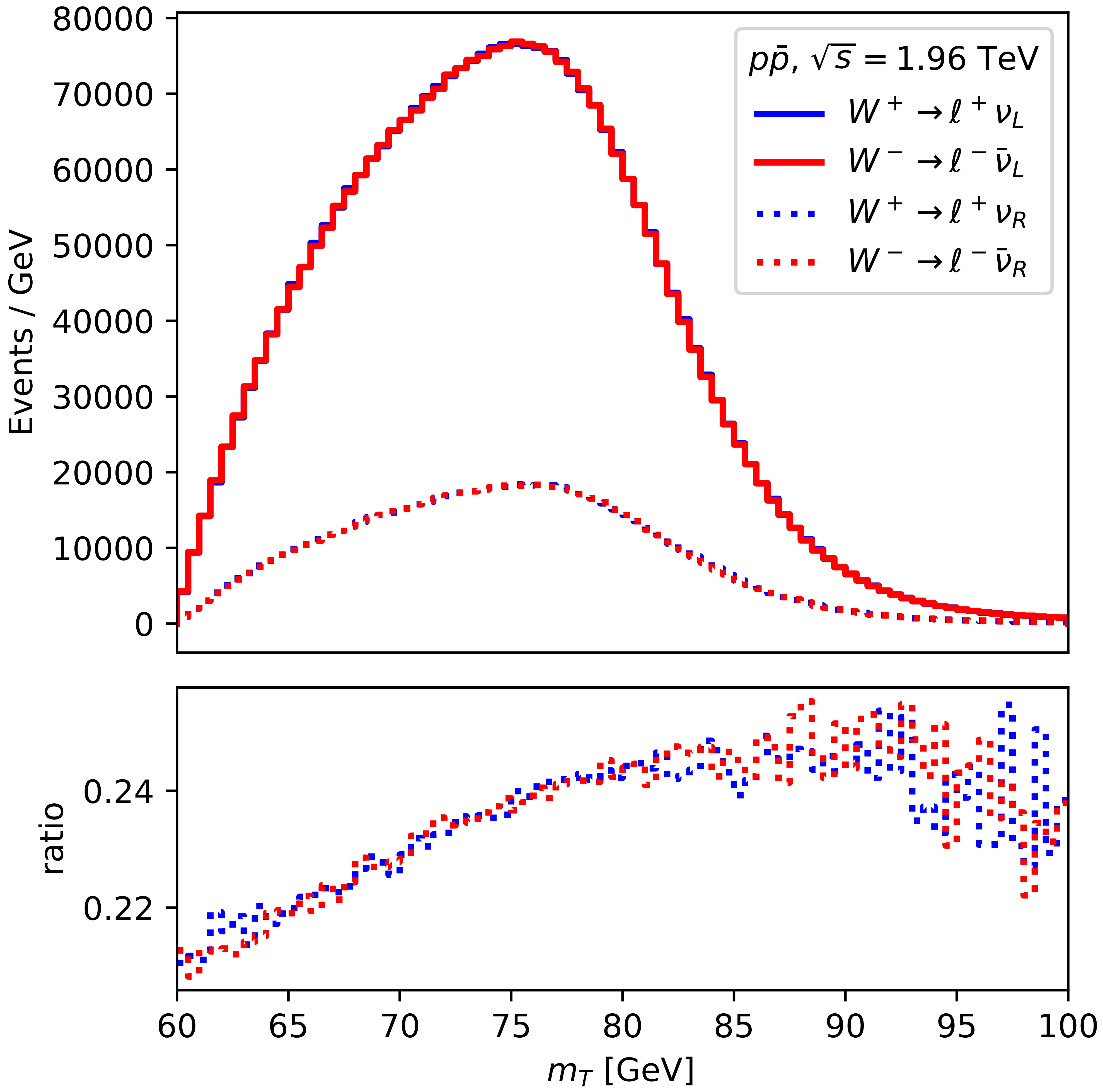
(b) W^- production and decay at the LHC.

- Valence quarks higher p_z $\Rightarrow$ W boosted in direction of valence quark
- $\Rightarrow$ in RHN decays, charged lepton more boosted in W^+ case
  less boosted in W^- case

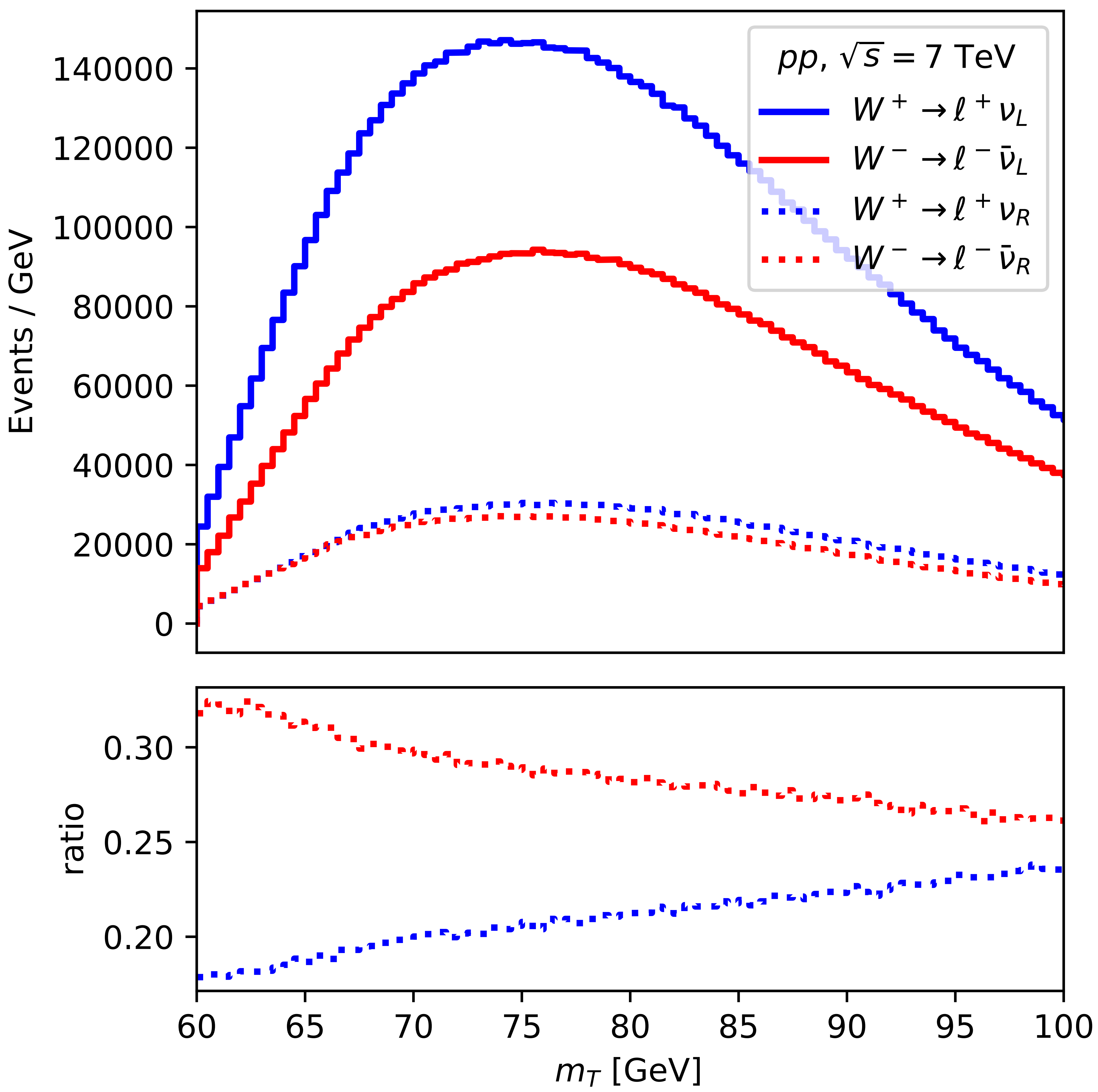
$\Rightarrow$in ν_R decays, ν_R decays more transverse to enter detector for W^+
less transverse to enter detector for W^-

$\Rightarrow$ W mass artificially raised in W^+ decays, artificially lowered in W^- decays

Motivation



m_T distribution at CDF



m_T distribution at ATLAS

Event Generation

- Given our assumptions, neutrino decays with width

$$\Gamma_{\nu_R} = \frac{m_N^5}{(2\pi)^3} \frac{G_F^2}{192} \frac{v^4 \sum_i (c^i_{HNe})^2}{\Lambda^4}.$$

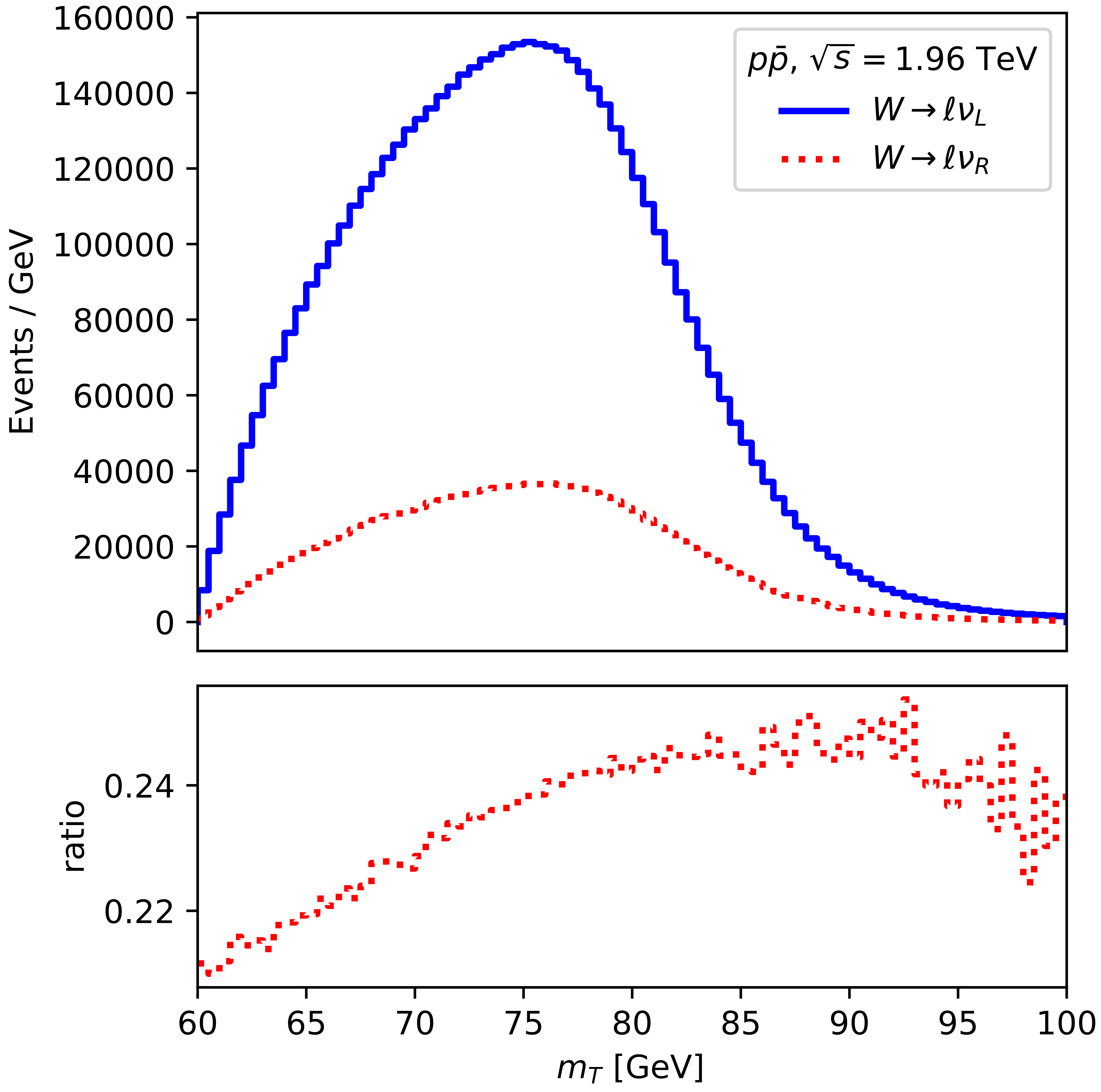
- Standard W selection requires ν_R to decay outside detector
  - With Λ at the lower bound of $v = 246\,\mathrm{GeV}$ and c^i_{HNe} of $\mathcal{O}(1)$ we find $m_N \lesssim 100\,\mathrm{MeV}$ for almost all events to decay outside fiducial volume of typical detector ($\gamma c\tau \approx 200\mathrm{m}$)
- We find existing W-boson measurements are sensitive to $c_{HNe}/\Lambda^2 \approx 0.1/v^2$ and masses $m_N \lesssim 1\,\mathrm{GeV}$.

Results

CDF Mass Fit

- Simulated at CDF, 1.96TeV

- Likelihood fit for m_W gives $|c_{HNe}| = 1.2 \pm 0.2$ to account for CDF theory-experiment discrepancy of $m_{W,\mathrm{CDF}} - m_{W,\mathrm{SM}} = 76\,\mathrm{MeV}$, $(\Lambda = v)$



Results

ATLAS Mass Fits

- Simulated at ATLAS, 7TeV: compared MC to ATLAS measurement
- $m_{W^+} - m_{W^-} = -29.2 \pm 28.0\,\mathrm{MeV}$
- Fit for $p_T^{\ell}, p_T^{\mathrm{miss}}$ and m_T in ranges used in ATLAS measurements

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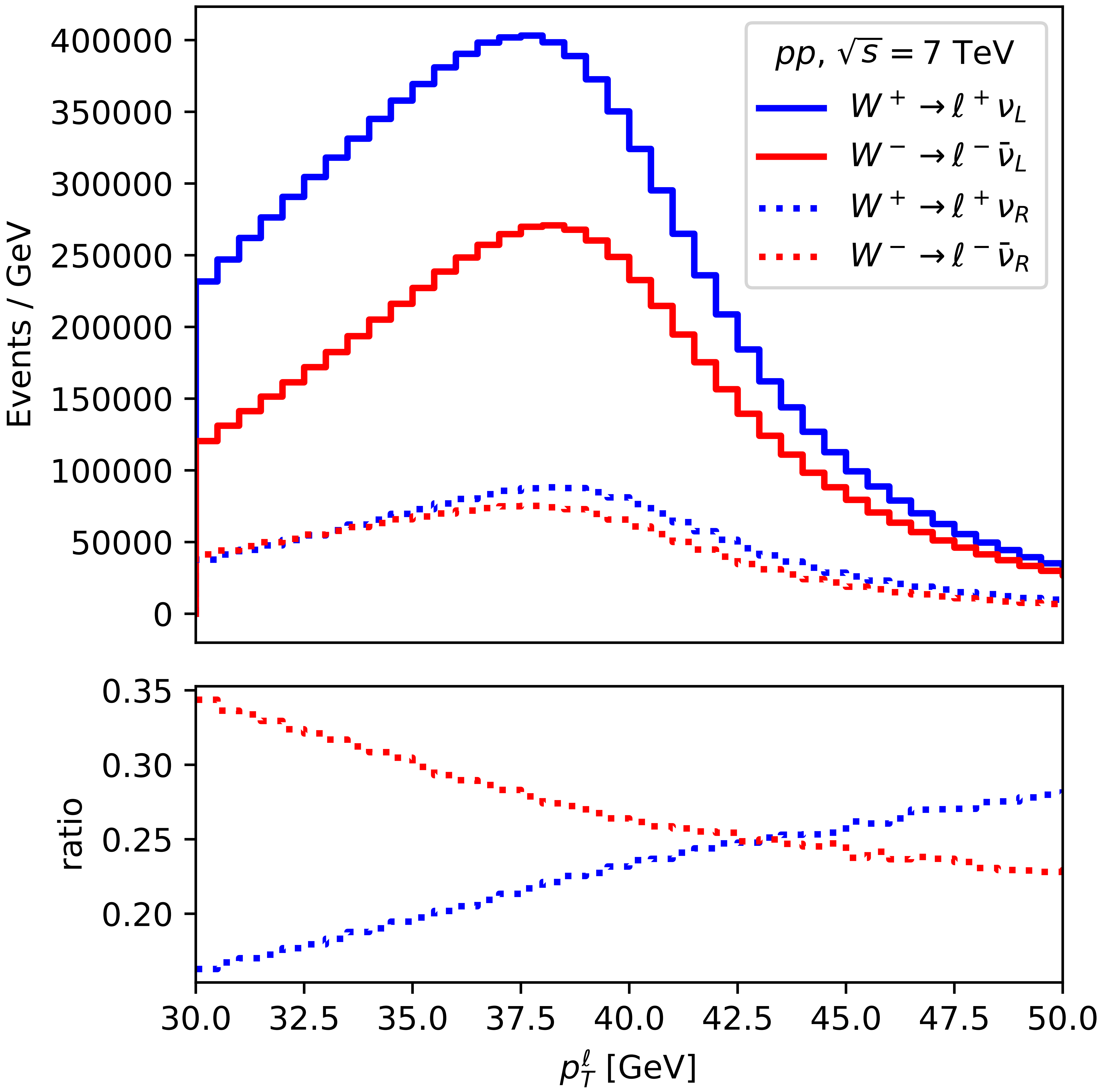
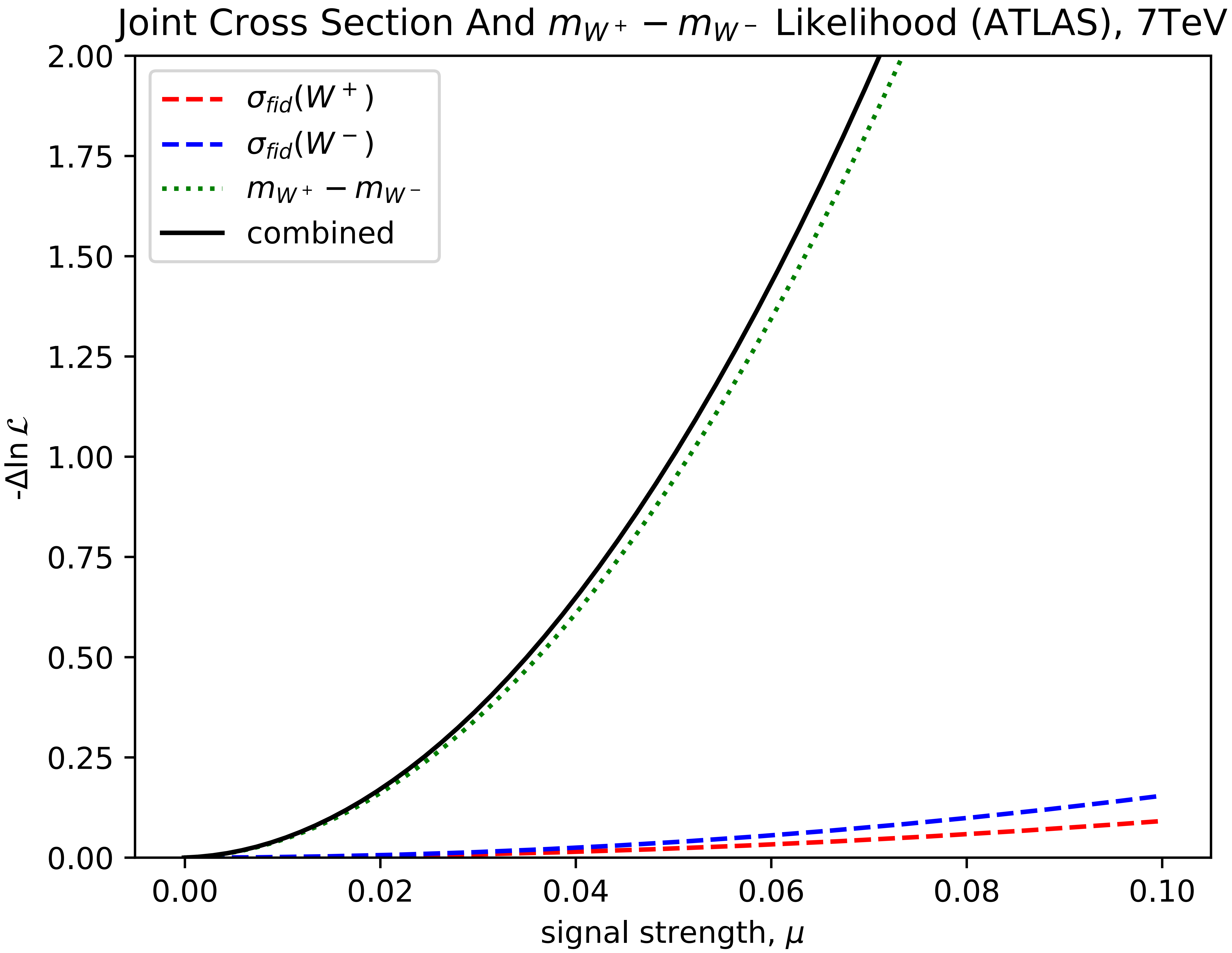


p_T^{ℓ} simulated at ATLAS corresponding to 4.7fb^{-1} of integrated luminosity at 7TeV

Results

ATLAS Mass Fits

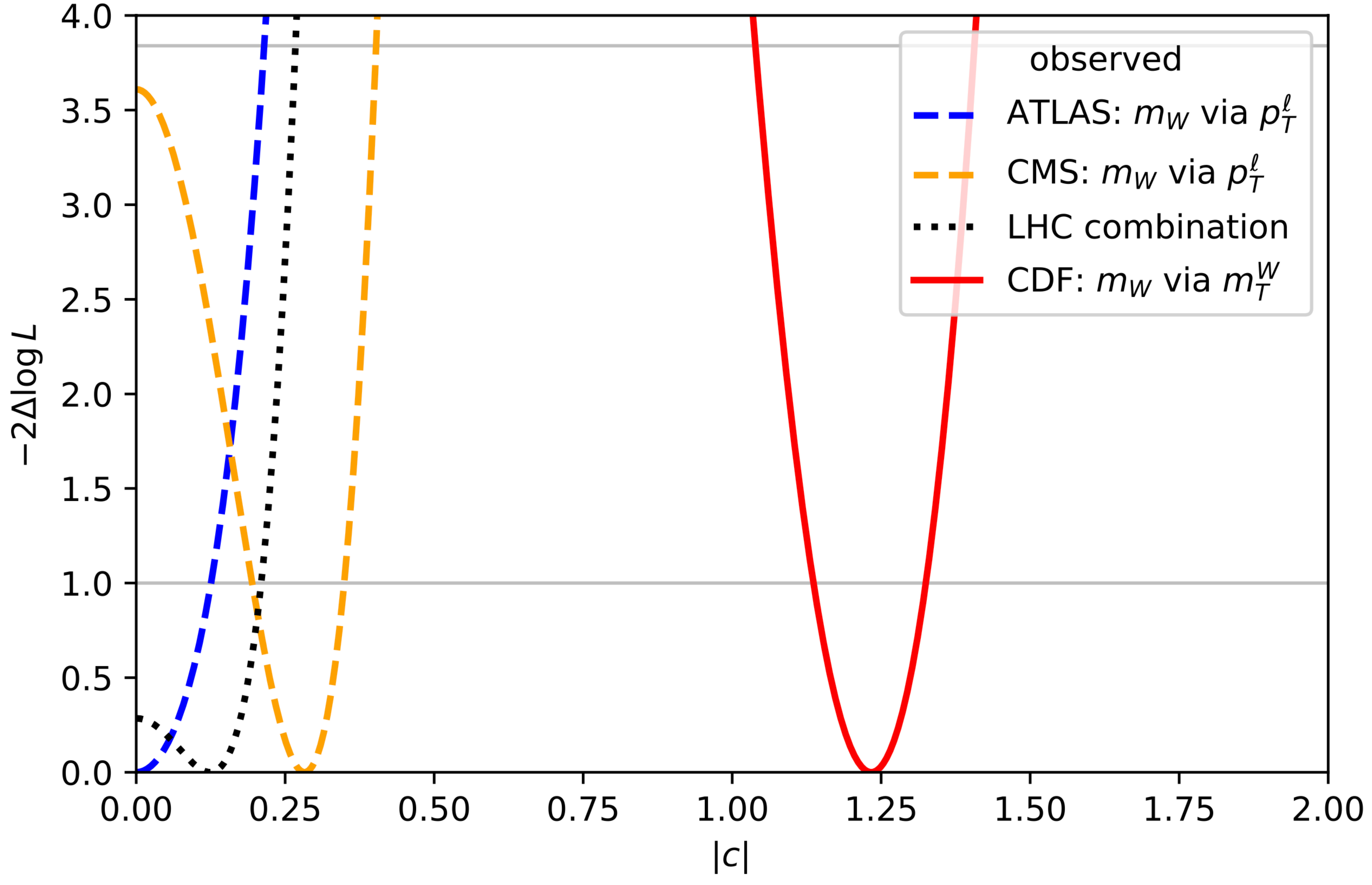
- Best constraint given by p_T^{ℓ} fit to $m_{W^+} - m_{W^-}$, which corresponds to $|c_{HNe}|v^2/\Lambda^2 < 0.13$ at 68% CL
- Additional constraints from cross-sections are small.



Results

CMS Mass Fits

- Compare to 2024 CMS measurement
- Equivalent value at CMS is $m_{W^+} - m_{W^-} = 57 \pm 30.3\,\mathrm{MeV}$
    - Corresponds to $|c_{HNe}|v^2/\Lambda^2 = 0.28 \pm 0.09$
- Combining ATLAS and CMS gives $|c_{HNe}| \in [0{,}0.27]$, 95% CL assuming $\Lambda = v$



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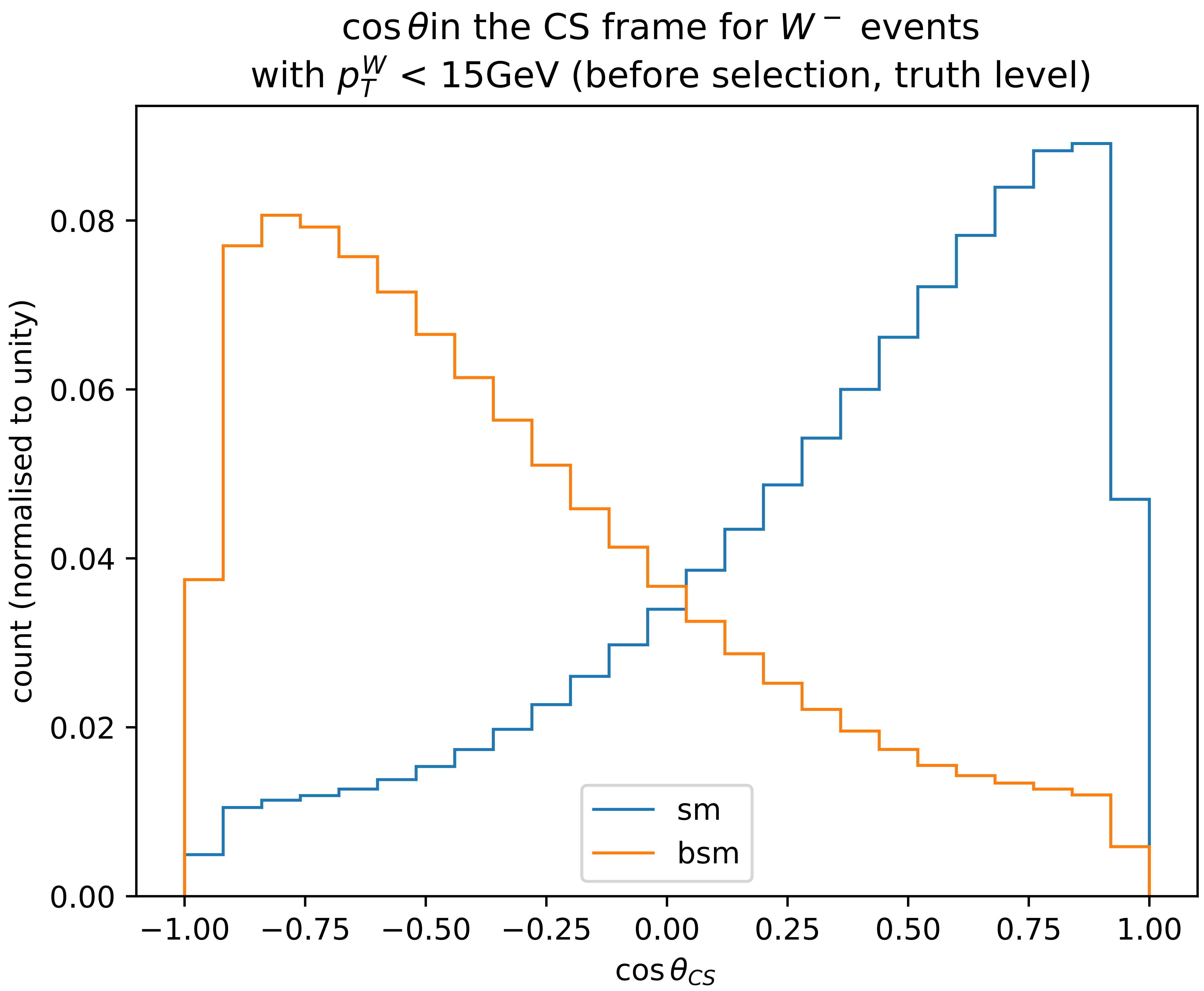
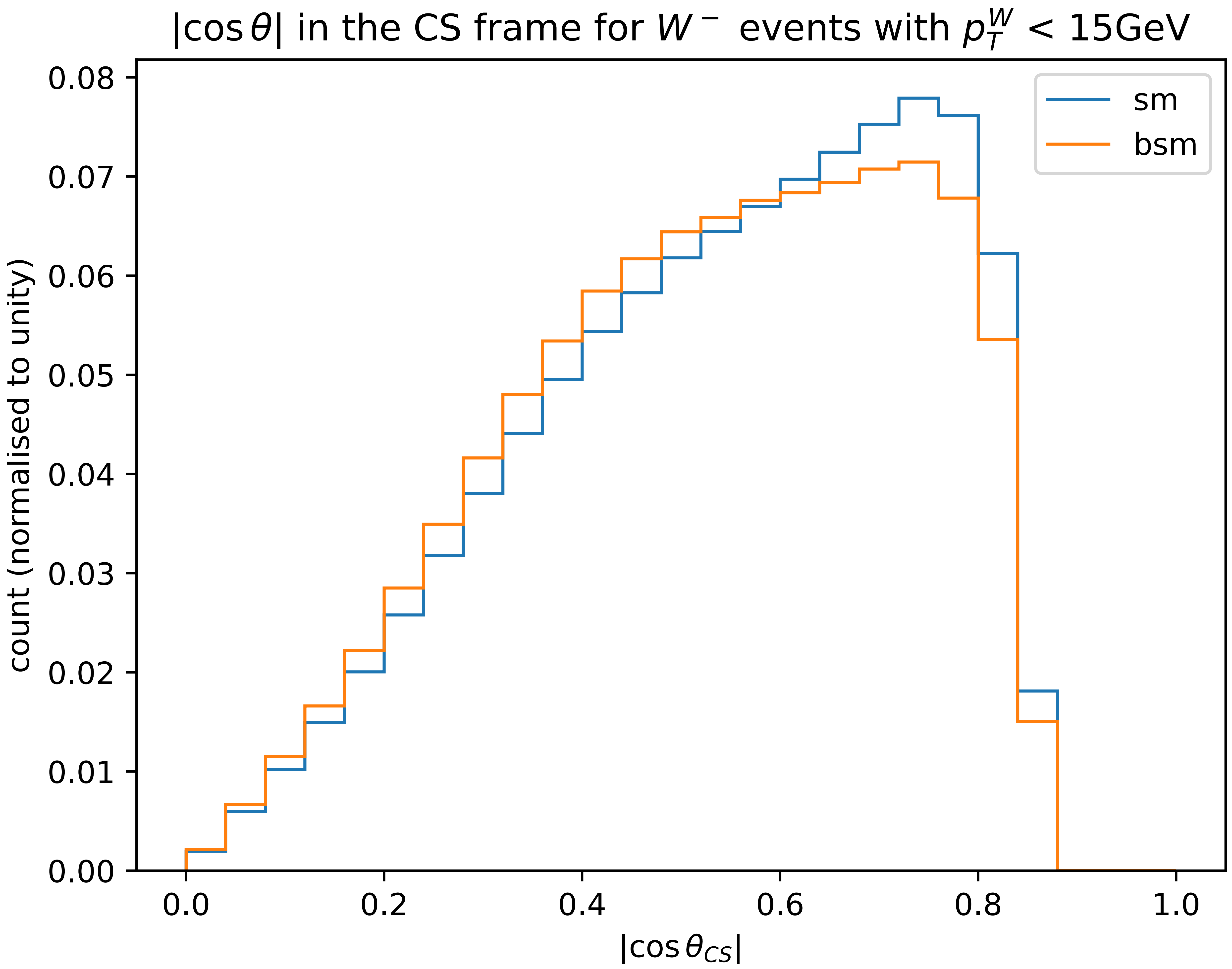
Angular Observables (CDF)

- An ideal observable for detecting the difference between the SM and BSM decays would be $\cos\theta_{CS}$
- θ_{CS} is the final angle of one of the leptons in the Collins-Soper frame - a proxy for the W rest frame.
- However, our lack of knowledge of p_Z of the W means we may only reconstruct $\cos\theta_{CS}$ up to a sign.

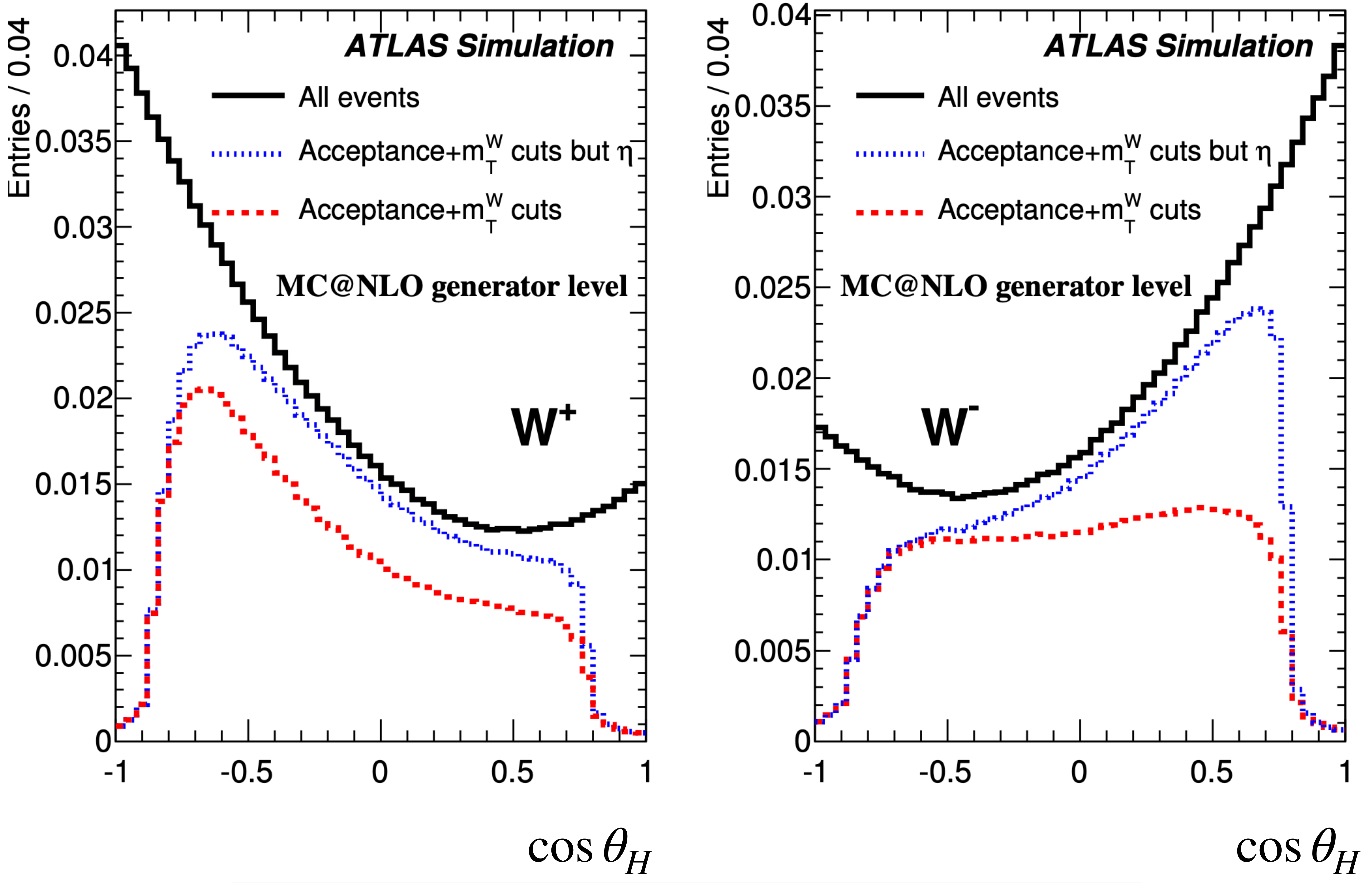


Angular Observables (CDF)

- After reconstruction the stark difference between these distributions goes away, as we can only plot $|\cos\theta_{CS}|$.
- e^+e^- measurements would allow full reconstruction.



Angular Observables (Atlas)



Above: $\cos\theta_H$ in $W \to \nu e$ decays

- An alternative reference frame is the helicity frame, a different proxy for the W rest frame corresponding to a rotation of axes, in which we define $\cos\theta_H$ in a similar manner to the CS frame.
- Although this is a different frame, the principles which motivated the use of the CS frame still apply.

A Sparrow (2012), PhD thesis; arXiv:1203.2165

Angular Observables (Atlas)

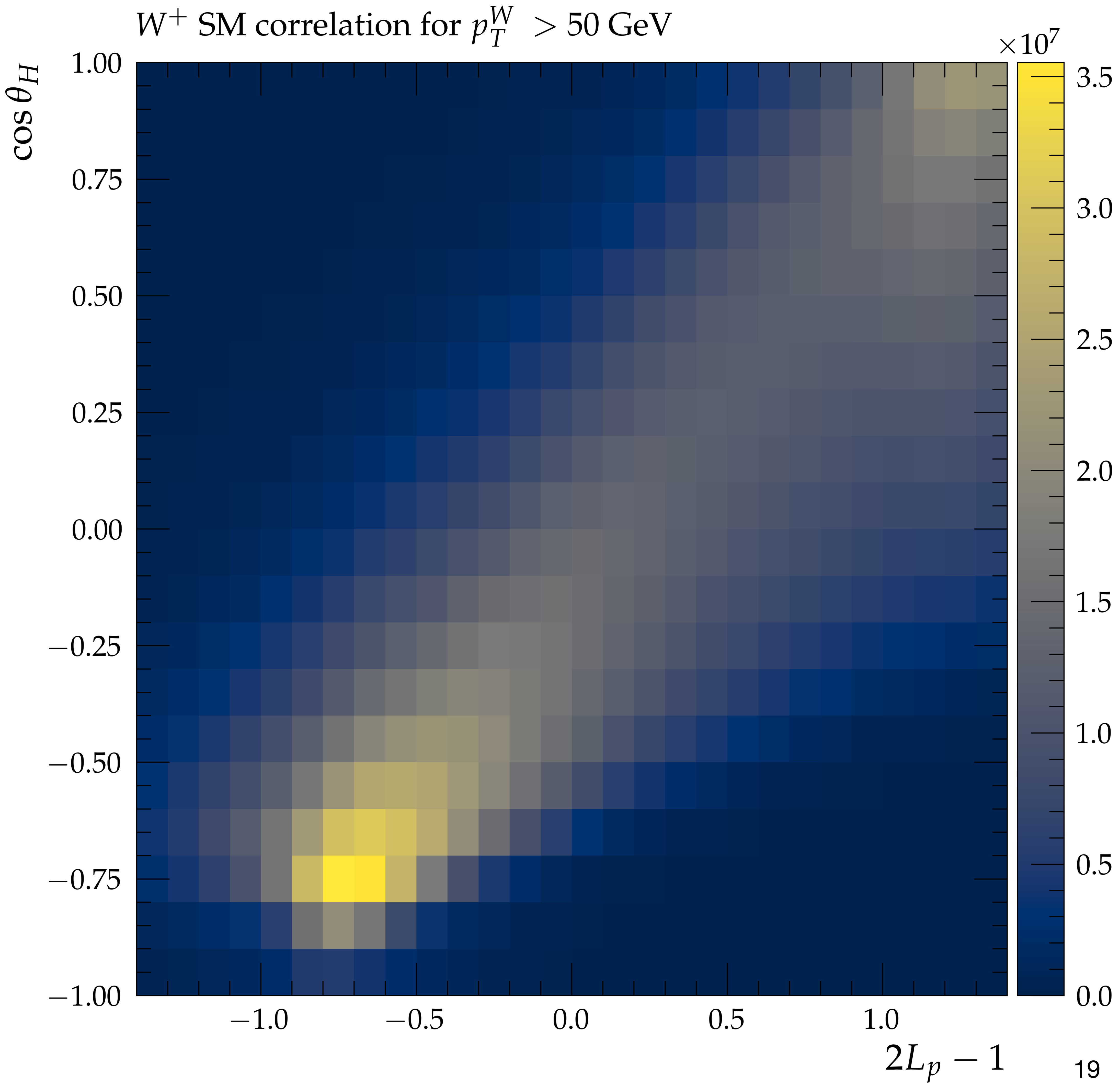
$$L_p = \frac{\vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,W}}{|\vec{p}_T^{\,W}|^2}$$

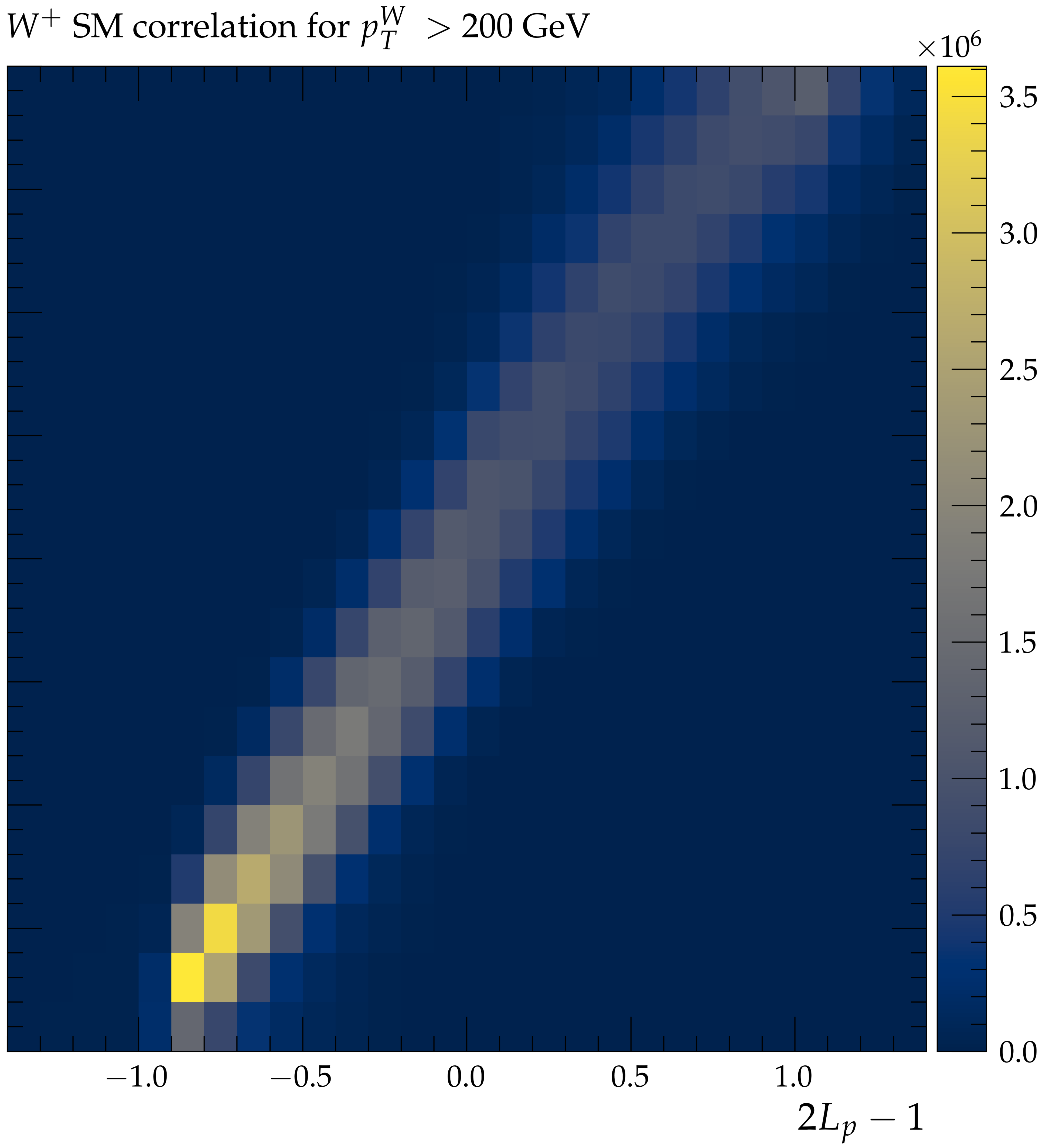
- There is a well documented variable, L_p, such that $2L_p - 1$ is highly correlated to $\cos\theta_H$ at high p_T^W.
- This allows us to observe the decay angle in the W rest frame at high p_T^W using only transverse, lab frame quantities.
- Can be shown that $\cos\theta_H = \dfrac{2|\vec{p}_\ell| - E_W}{|\vec{p}_W|} \approx 2L_p - 1$ at high p_T^W

A Sparrow (2012), PhD thesis

Angular Observables (Atlas)

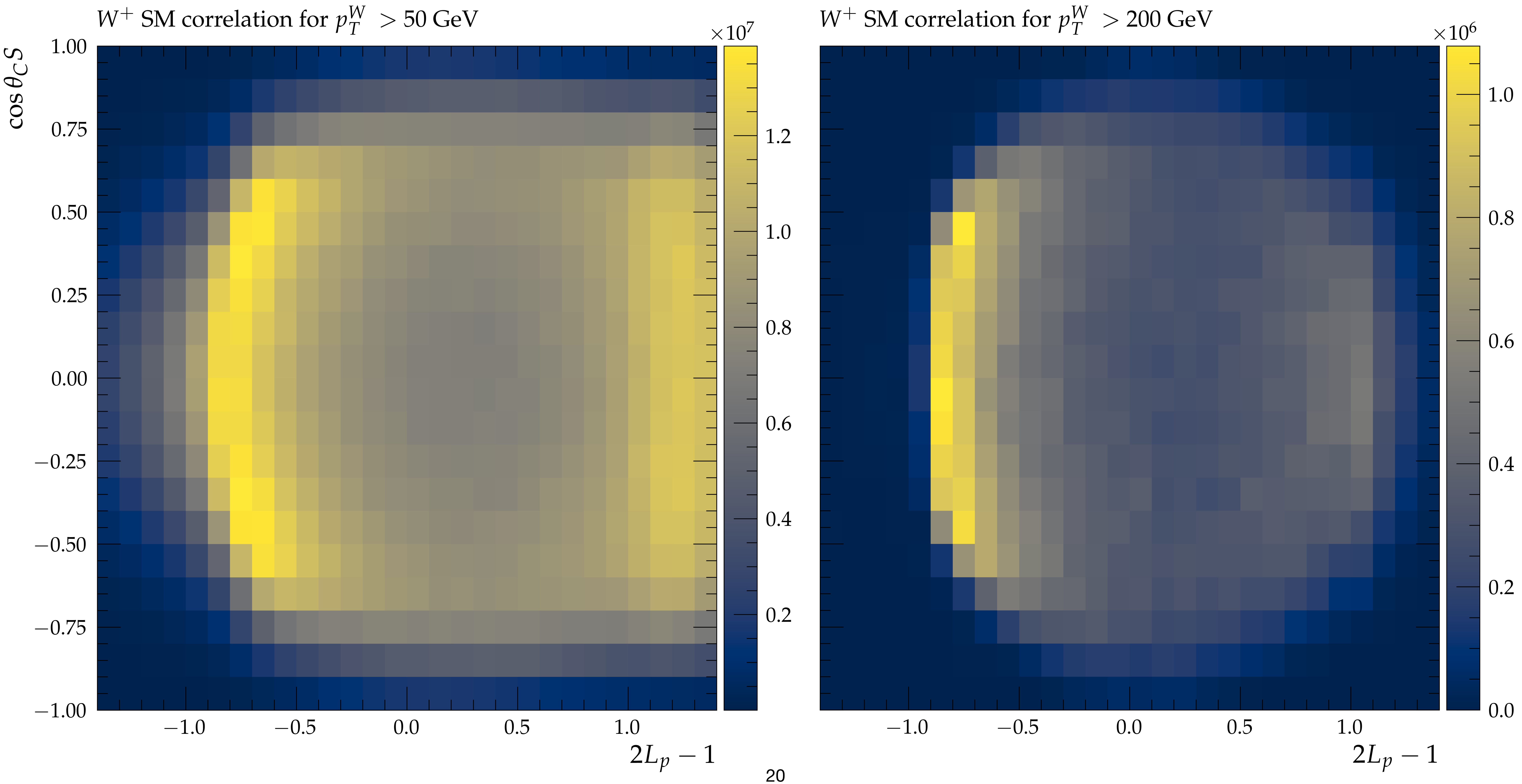
W+, SM





Angular Observables (Atlas)

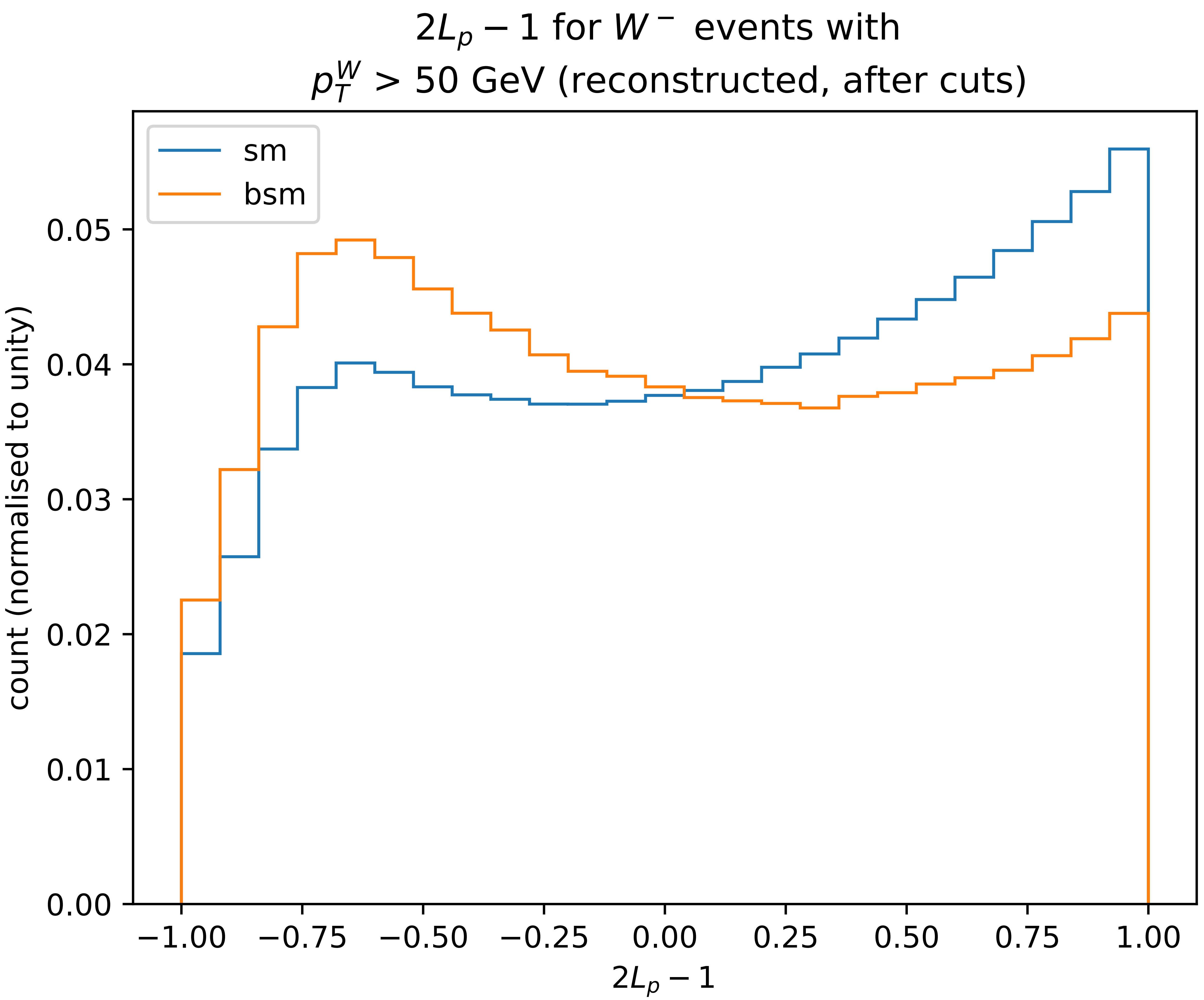
W+, SM



Angular Observables (Atlas)

Sensitivity

- Despite the looser correlation, the highest sensitivity is achieved for $p_T^W > 50\,\mathrm{GeV}$, which gives sensitivities of (for $\Lambda = v$)
  - $c_{HNe} = 0.090\,(0.072)$ for $W^-\,(W^+)$ at 95% CL
- Sensitivities are calculated by statistical uncertainty given by fitting SM pseudodata to SM+BSM simulations for different values of μ at integrated luminosity of 4.7 fb^{-1}.



Summary

- New constraints on sterile neutrinos from m_W measurements
  - Sensitivity to parity violating V+A interactions caused by c_{HNe} Wilson coefficient
  - Cases where standard W-boson selection may be employed
    - Masses $\sim \mathrm{MeV}$ up to $\approx 1\,\mathrm{GeV}$
  - Could obtain better sensitivity by directly fitting to W-mass data
- Angular variables like $\cos\theta_H$ can hold significant sensitivity

Back Up

Formalism

vSMEFT

$$\mathcal{L}^{d=4} = \mathcal{L}_{\mathrm{SM}} - \left[\lambda_i \overline{L_i} \tilde{H} N + \frac{1}{2} m_N \overline{N^c} N + \mathrm{h.c.}\right],$$

Mass Measurement Fits

- We performed a likelihood fit, reweighting m_T, p_T^{ℓ} and p_T^{miss} by a Breit-Wigner as in m_W measurements

$$\frac{\left(m^2 - m_W^2\right)^2 + m^4\Gamma_W^2 \big/ m_W^2}{\left(m^2 - {m_W^{ref}}^2\right)^2 + m^4\Gamma_W^2 \Big/ {m_W^{ref}}^2}$$

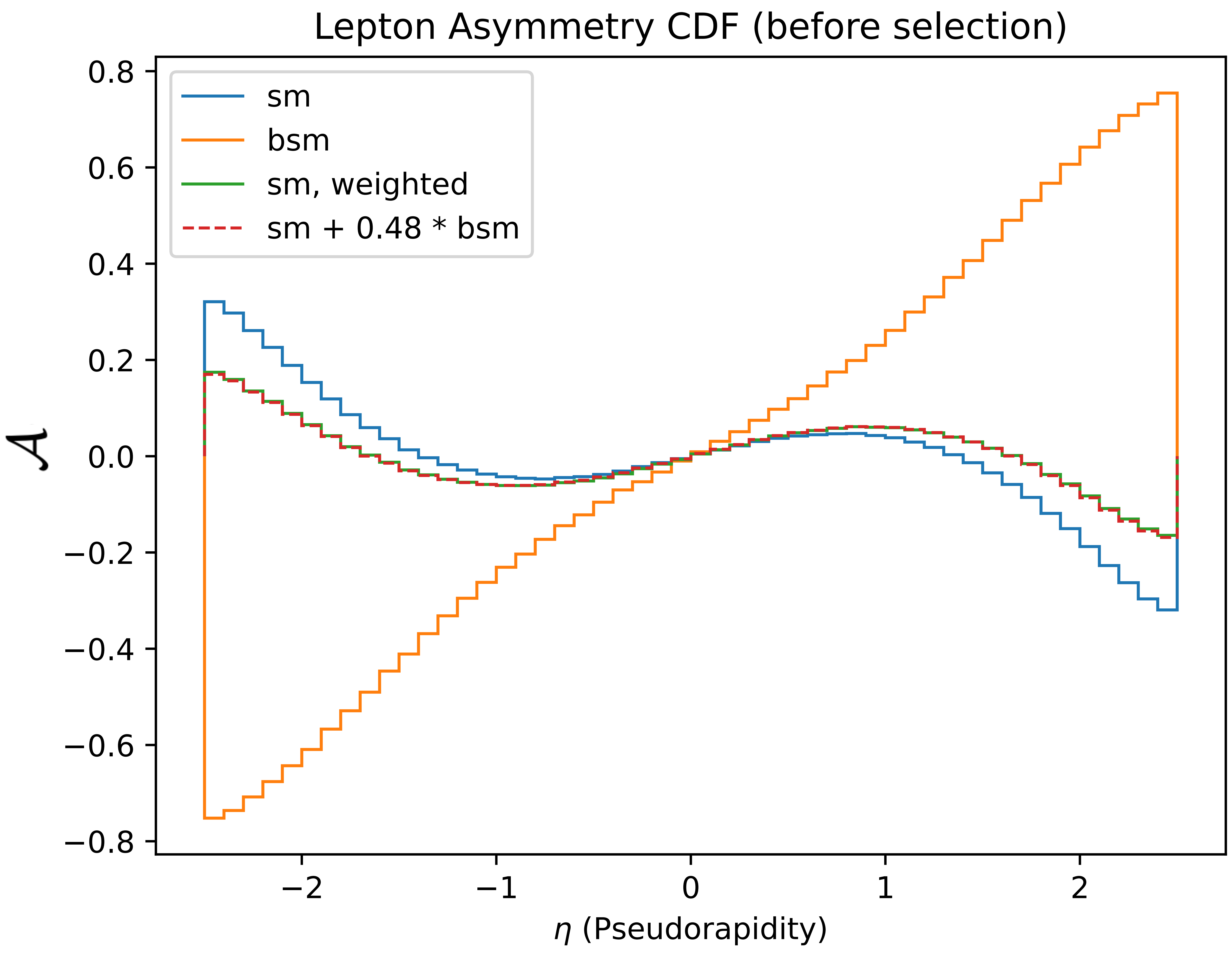
- Where m_W is a candidate mass, and $m_W^{ref} = 79.824\,\text{MeV}$ is the SM value.

Results

CDF PDF Reweighting

- Lepton Asymmetry affected by introduction of right-handed neutrino, which is used to set PDFs at CDF.

- Estimated impact of this by reweighting SM signal in order for A to match that of BSM model with signal strength μ.



$$\mathcal{A}(\eta_\ell) \equiv \frac{dN^+/d\eta_\ell - dN^-/d\eta_\ell}{dN^+/d\eta_\ell + dN^-/d\eta_\ell}$$

Results

CDF PDF Reweighting

- We find after reweighting, effect of sterile neutrinos on W mass reduced by $\sim 30\,\%$.