UNIVERSITY OF MARYLAND 1856
DEPARTMENT OF PHYSICS

A New Purpose for the W-mass Measurement: Searching for New Physics via $l{+}mET$

Particle Physics on the Plains at University of Kansas

[2310.xxxx] by Kaustubh Agashe, Sagar Airen, Roberto Franceschini, Doojin Kim, Ashutosh Kotwal, Lorenzo Ricci, DS

Deepak Sathyan

October 14, 2023

W-mass Measurement Results

High-precision measurement of the *W* boson mass with the CDF II detector

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Authors Info & Affiliations

April 2022

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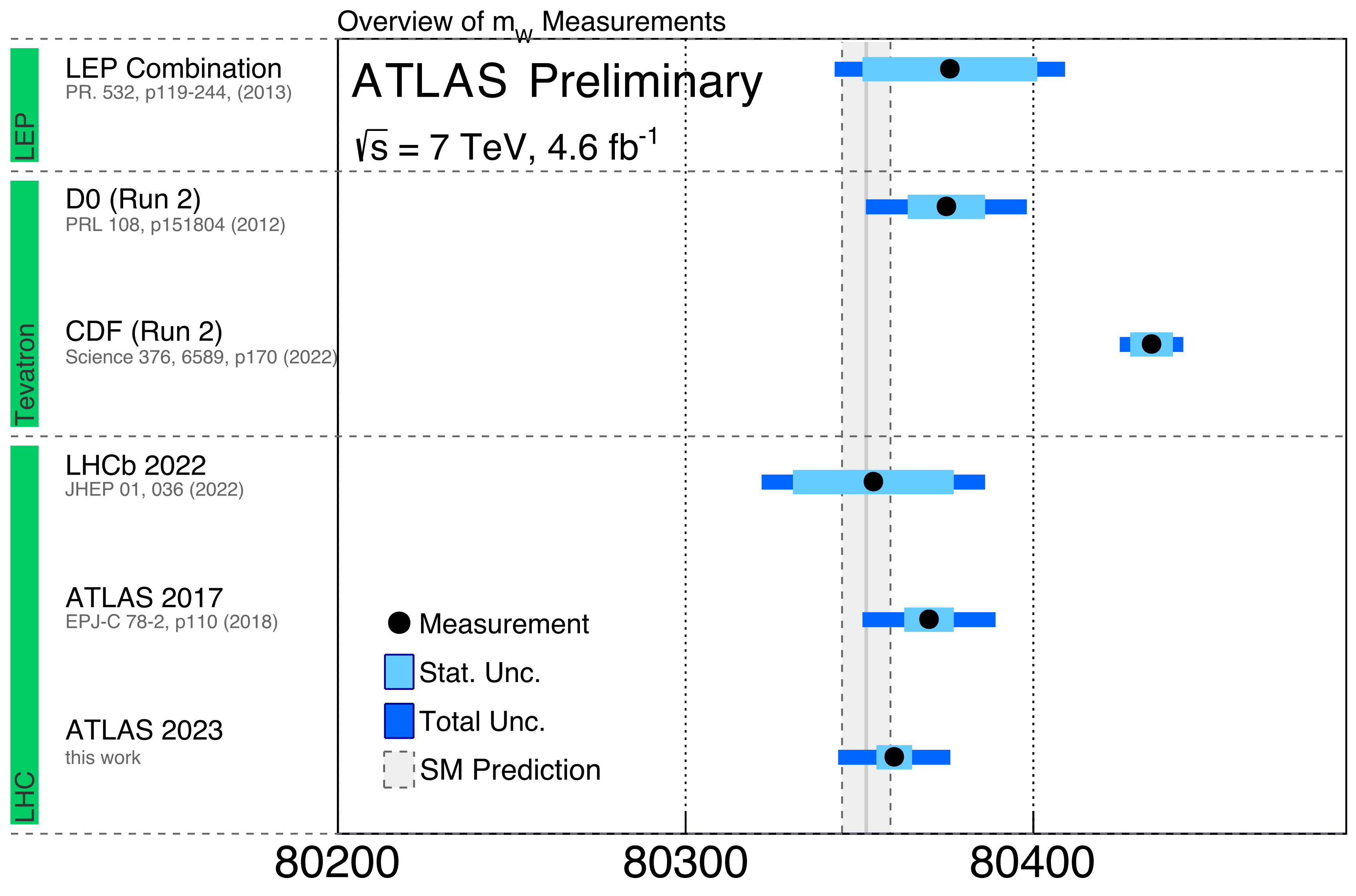
The ATLAS Collaboration

March 2023



ATLAS Improved W Mass Measurement

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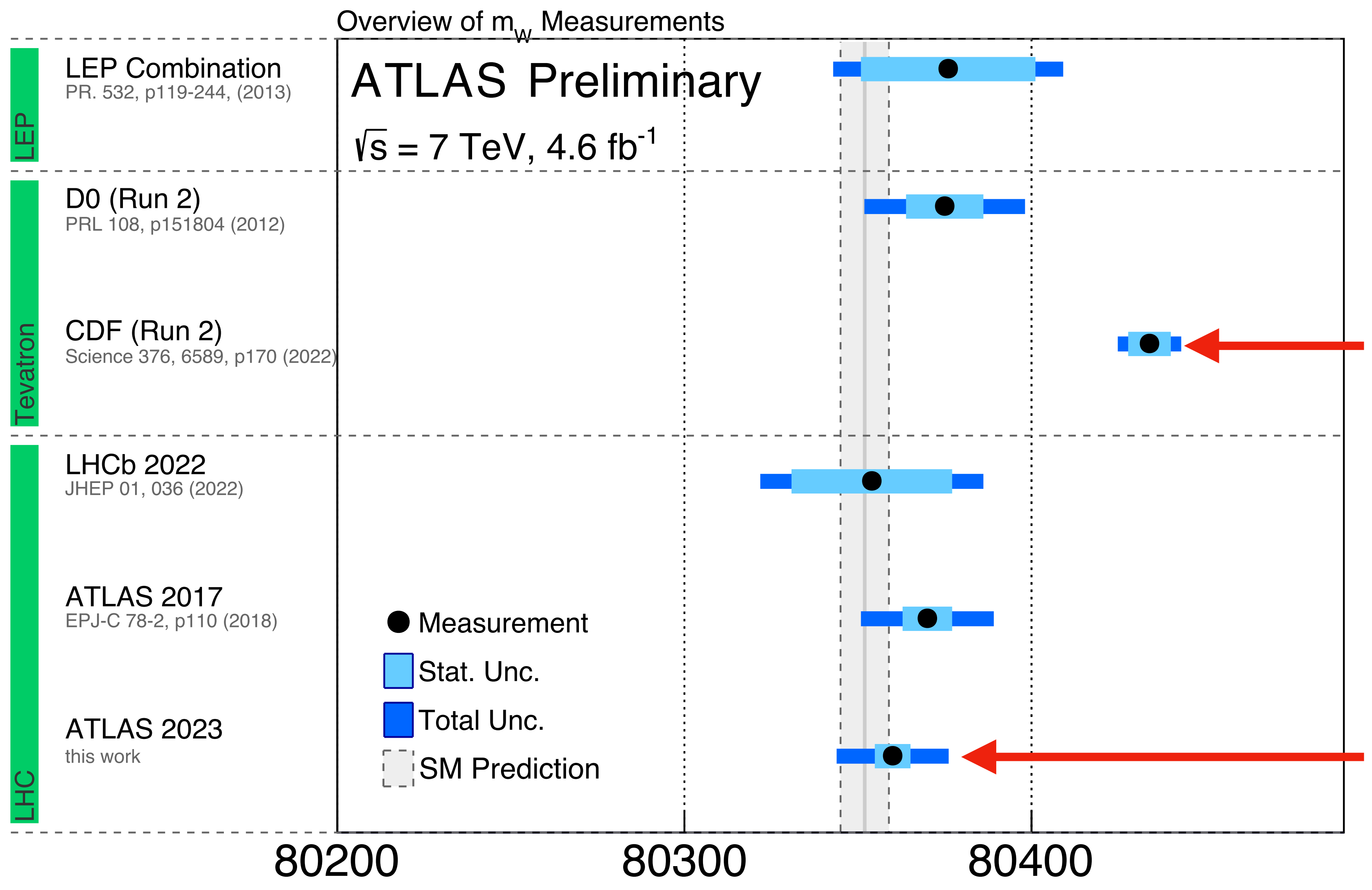

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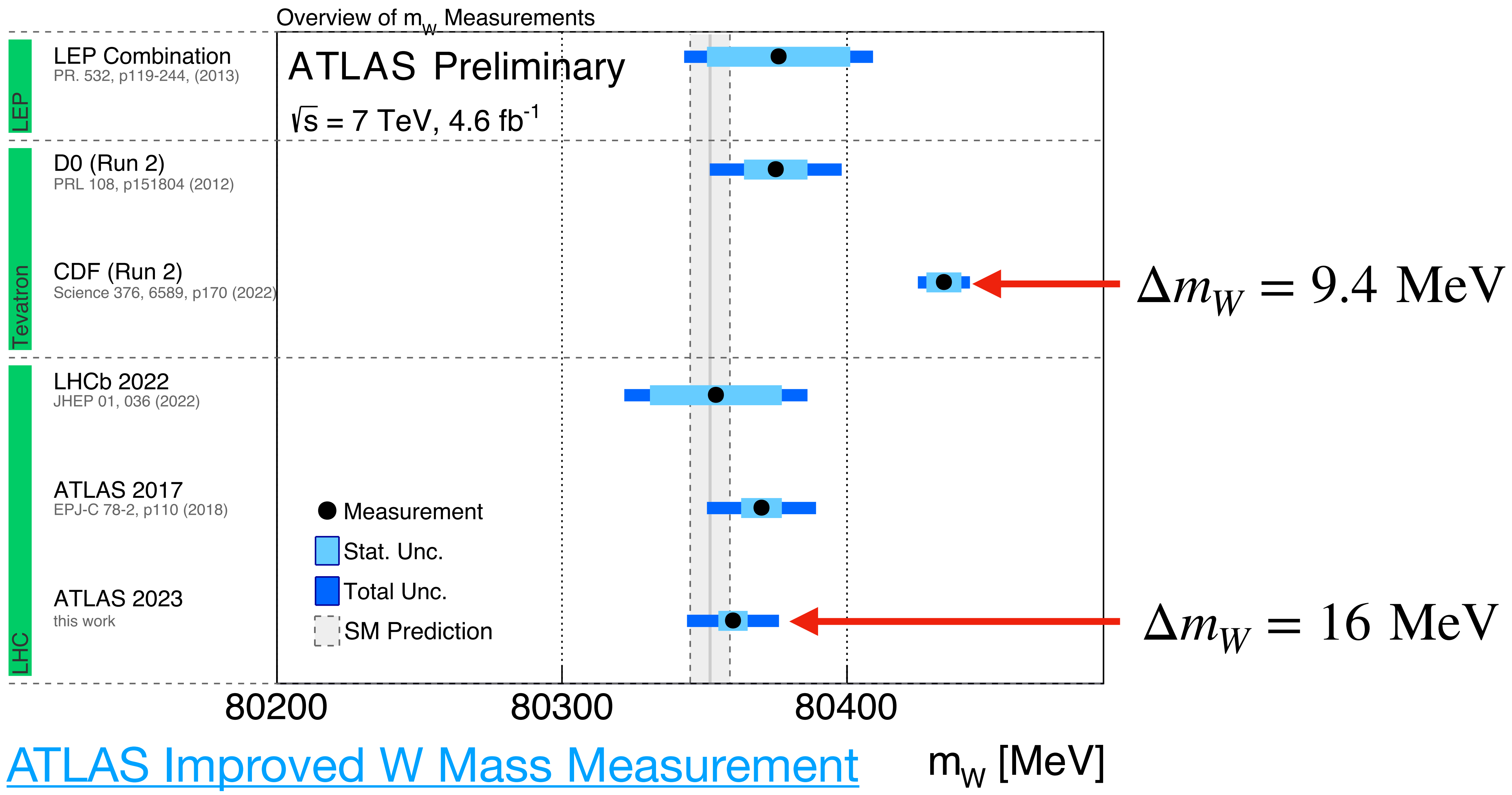

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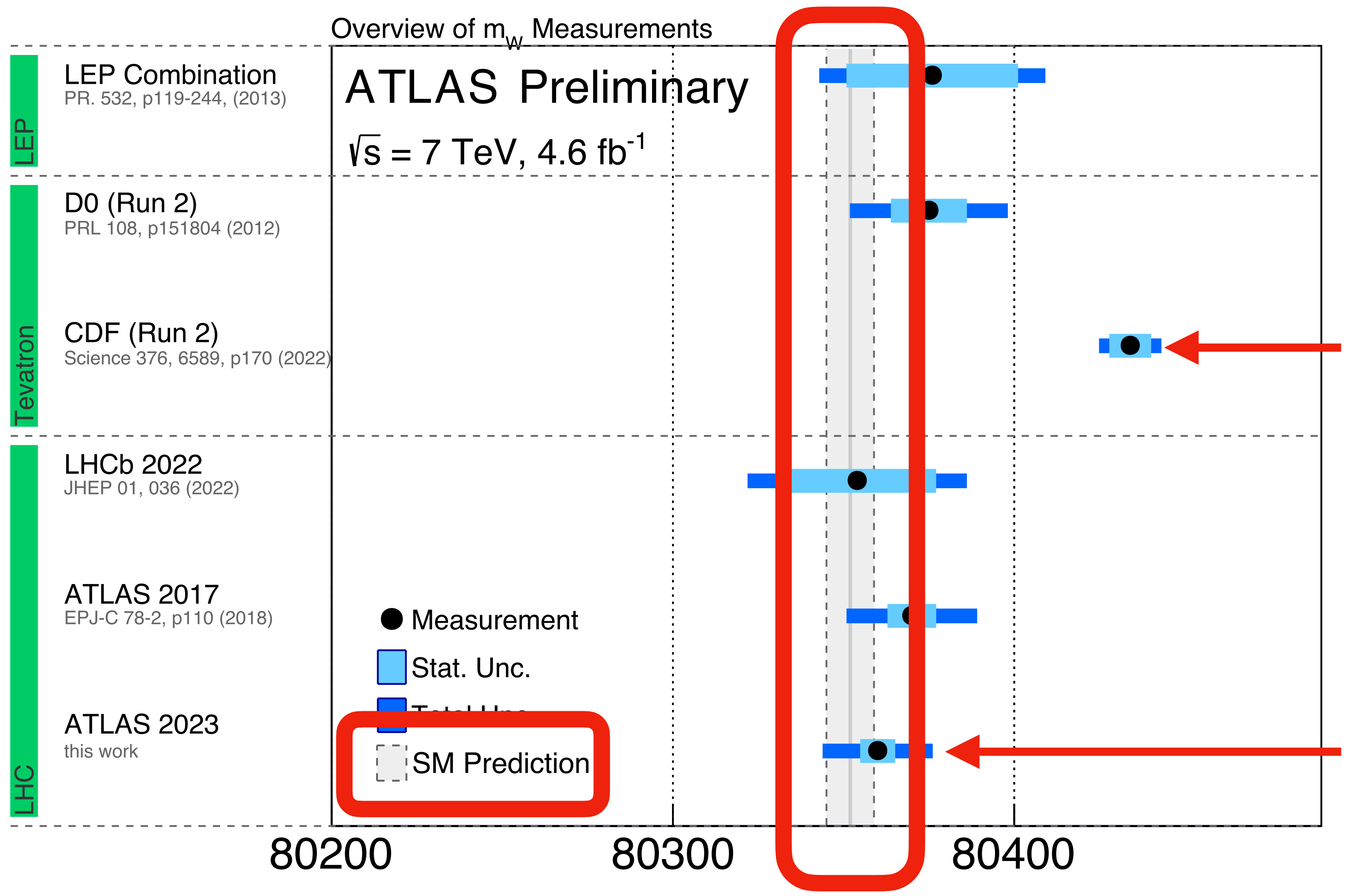

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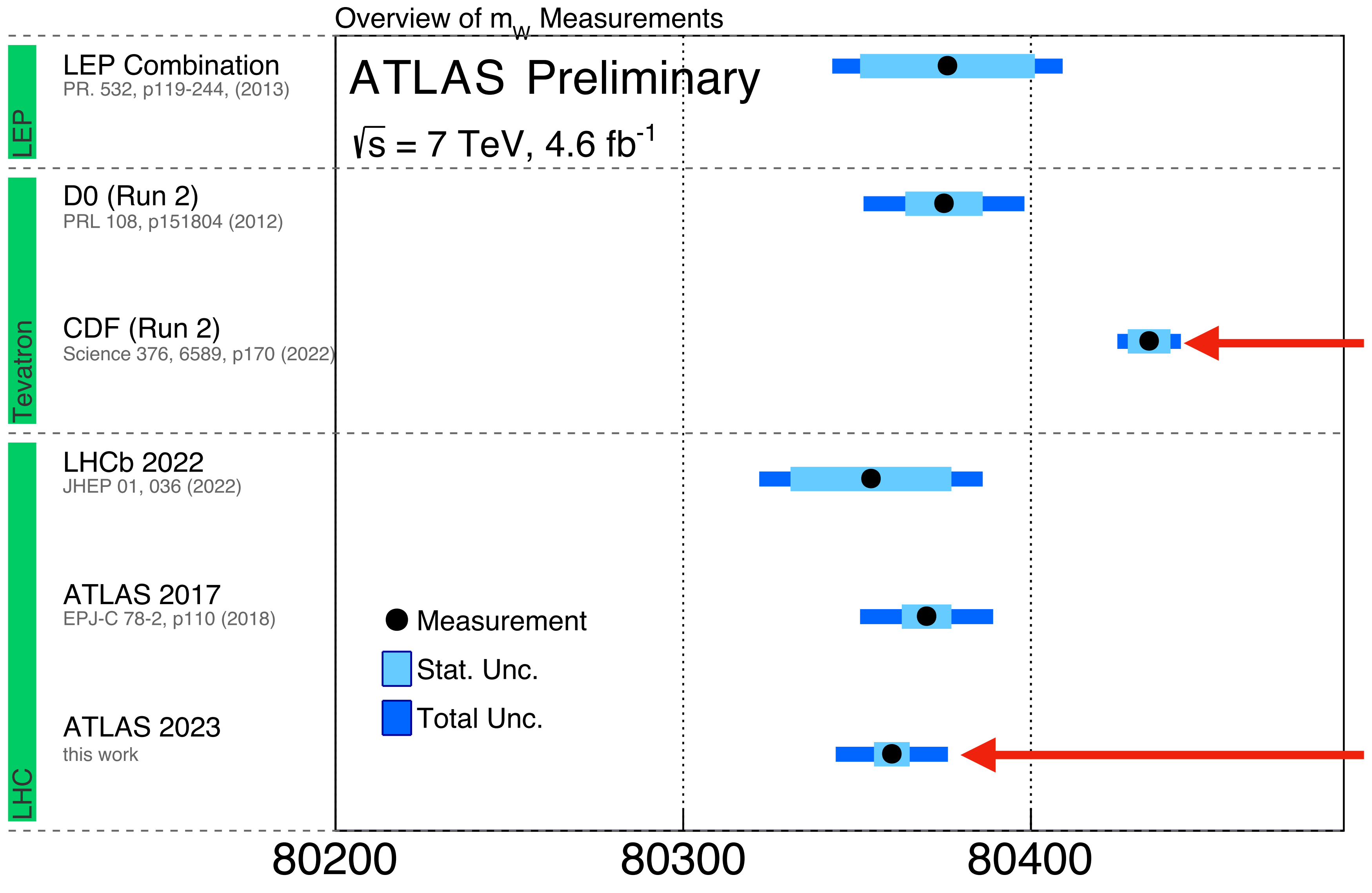
- Probe for new physics (NP):
    - Comparing measured m_W to prediction from EW fit tests indirect effects of heavy new physics (NP)
    - Can $m_W^{\text{meas.}}$ alone without EW fit probe direct effects of NP? (removing EW fit from the picture)



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ATLAS Improved W Mass Measurement

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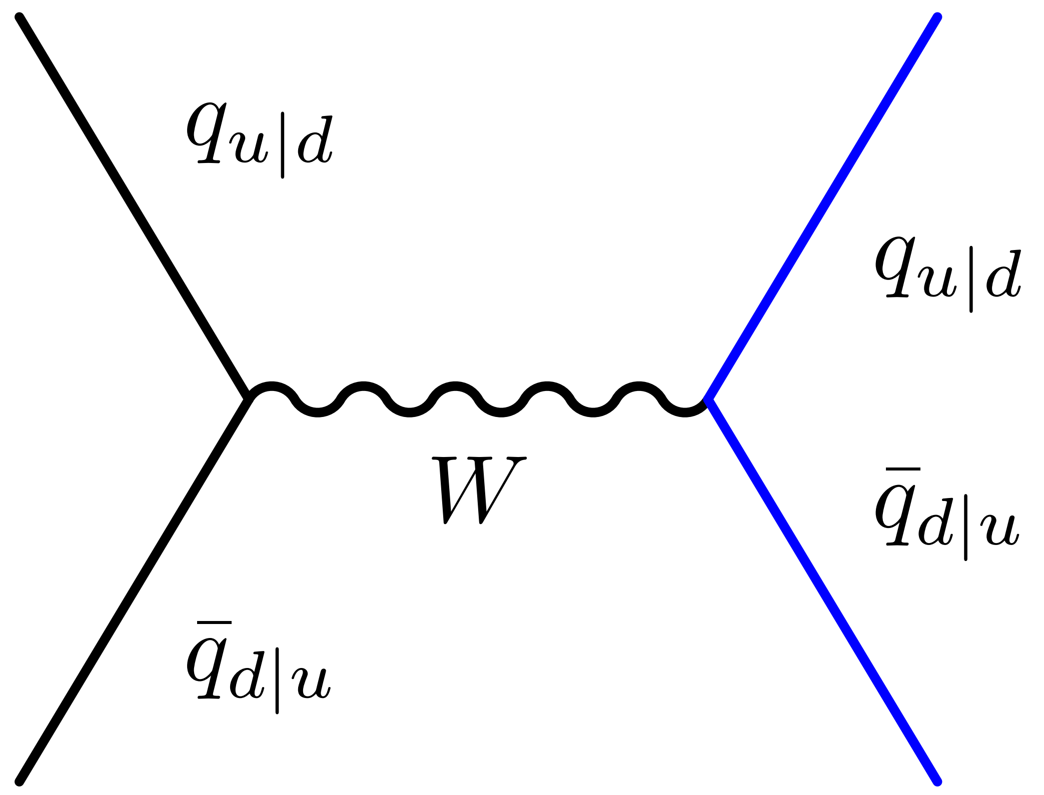
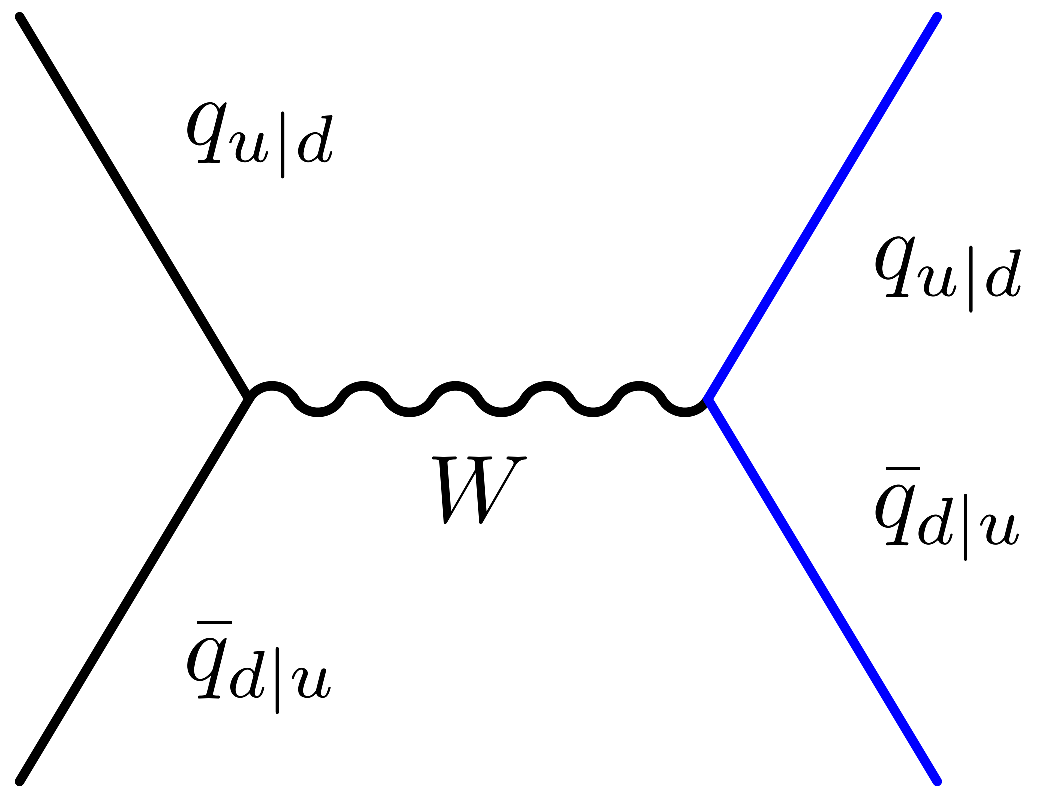
- hadronic: 2 jet final state
    - fully reconstructible, but…
    - jet energy scale uncertainty plagues reconstruction of invariant mass

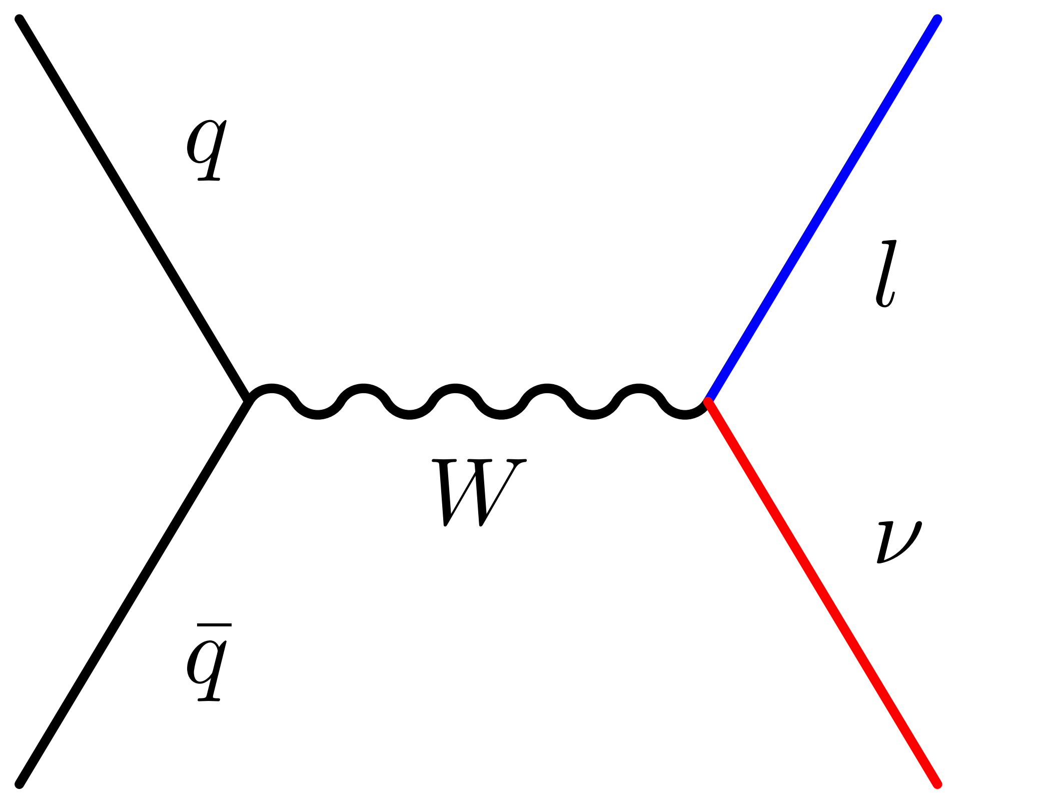


How is W-mass measured?

Two types of W decay:

- hadronic: 2 jet final state
  - fully reconstructible, but…
  - jet energy scale uncertainty plagues reconstruction of invariant mass
- leptonic: $\ell + mET$ final state
  - cleaner channel than hadronic decay, but…
  - ν is invisible → not fully reconstructible
  - good hideout for new physics





Blue: SM visible
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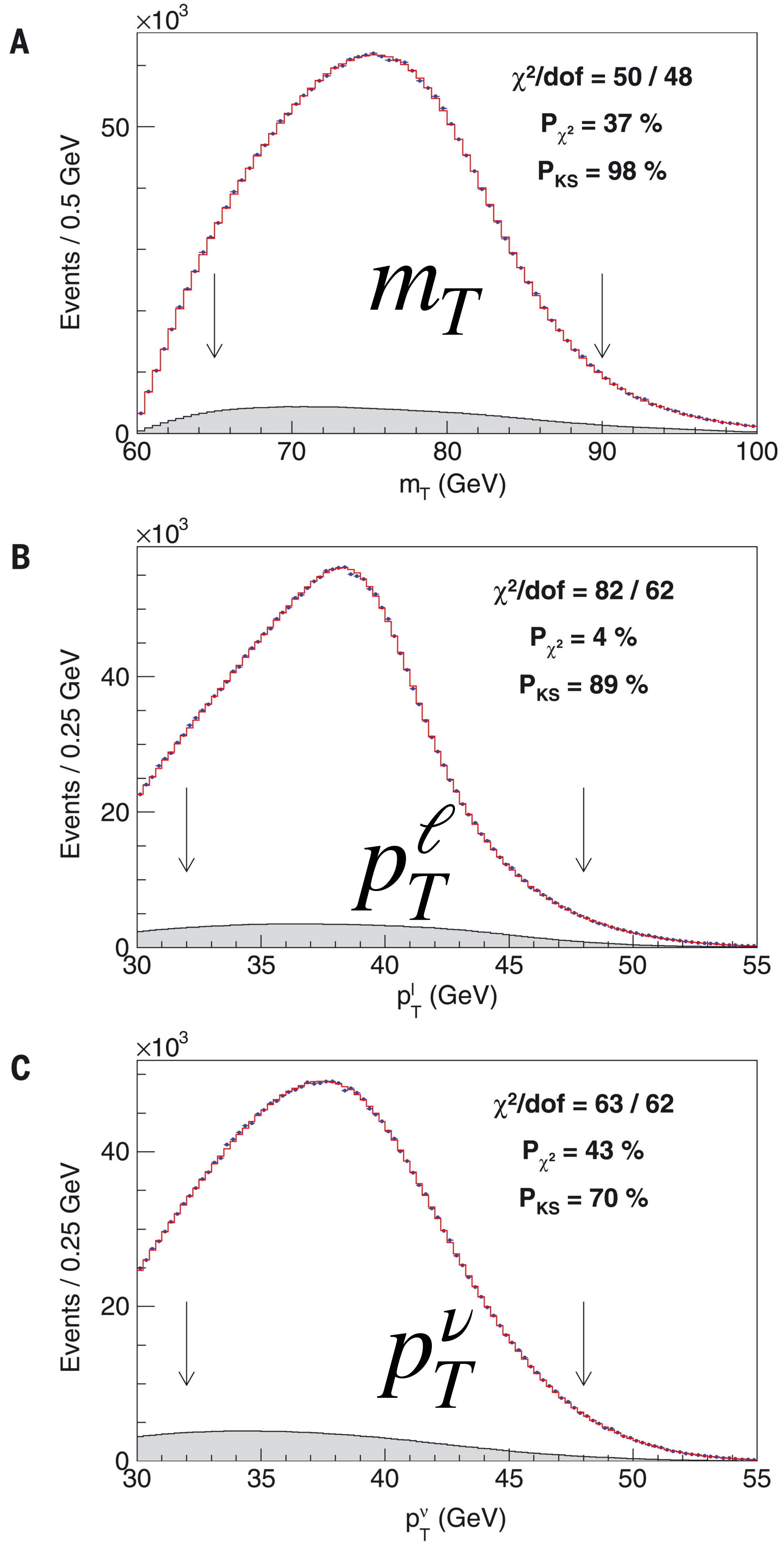
How is W-mass measured?

- ATLAS and CDF both use two kinematic observables to fit m_W:
  - lepton transverse momentum p_T^ℓ
    - clean measurement, but affected by nonzero p_T^W
  - transverse mass
    m_T, $m_T^2 = (E_T^\ell + E_T^{\rm miss})^2 - (\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\rm miss})^2$
    - Provides complementary systematics to p_T^ℓ

- CDF also includes p_T^ν

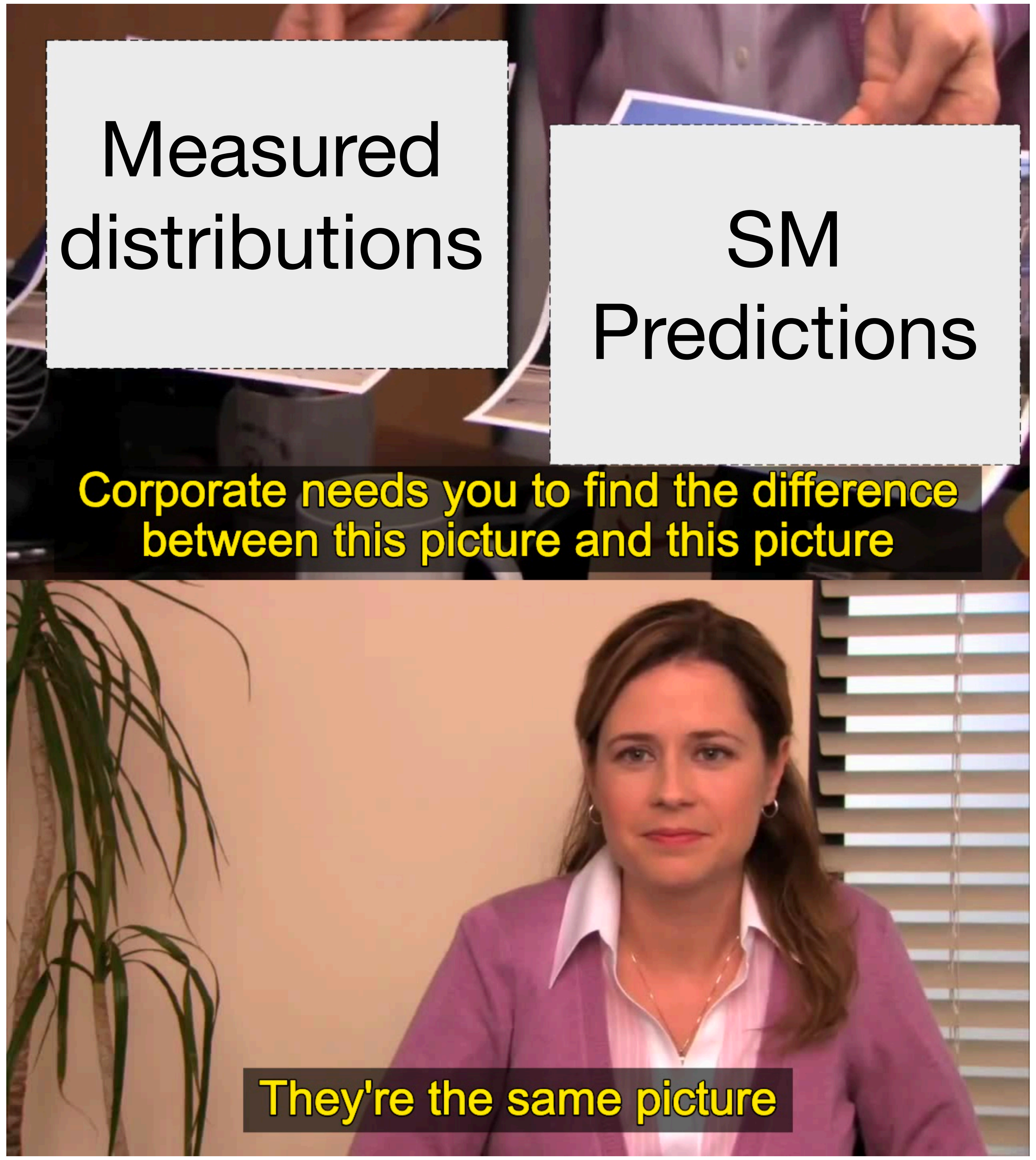
[High-precision measurement of the W boson mass with the CDF II detector | Science]



Probing New Physics

- How can a mass measurement alone probe NP?

  - new physics signals are an irreducible background to the measurement
  - measured kinematic distributions are in perfect agreement with SM predictions with great precision
  - exclude NP signals producing different kinematic distributions



Cartoon picture

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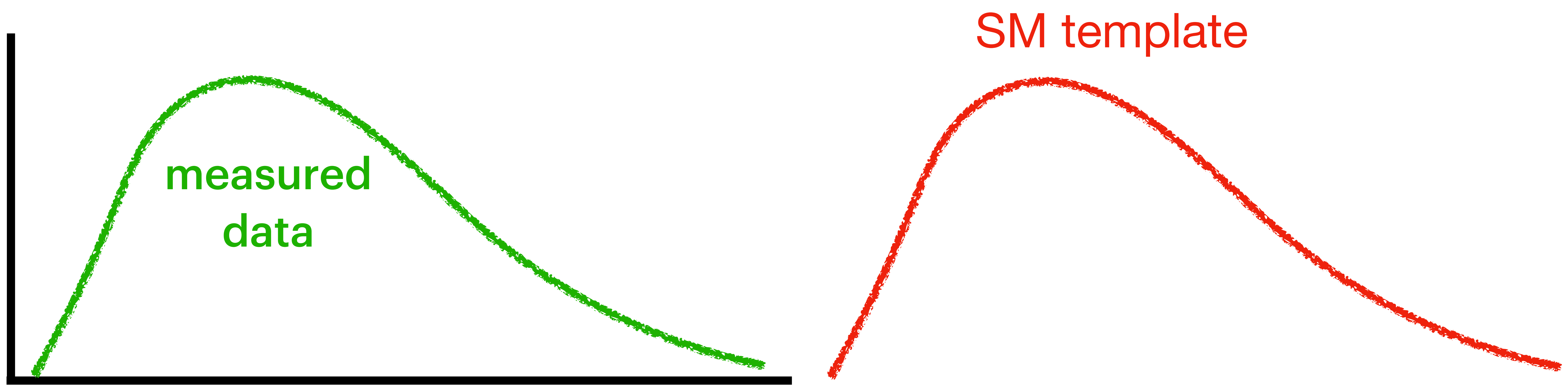

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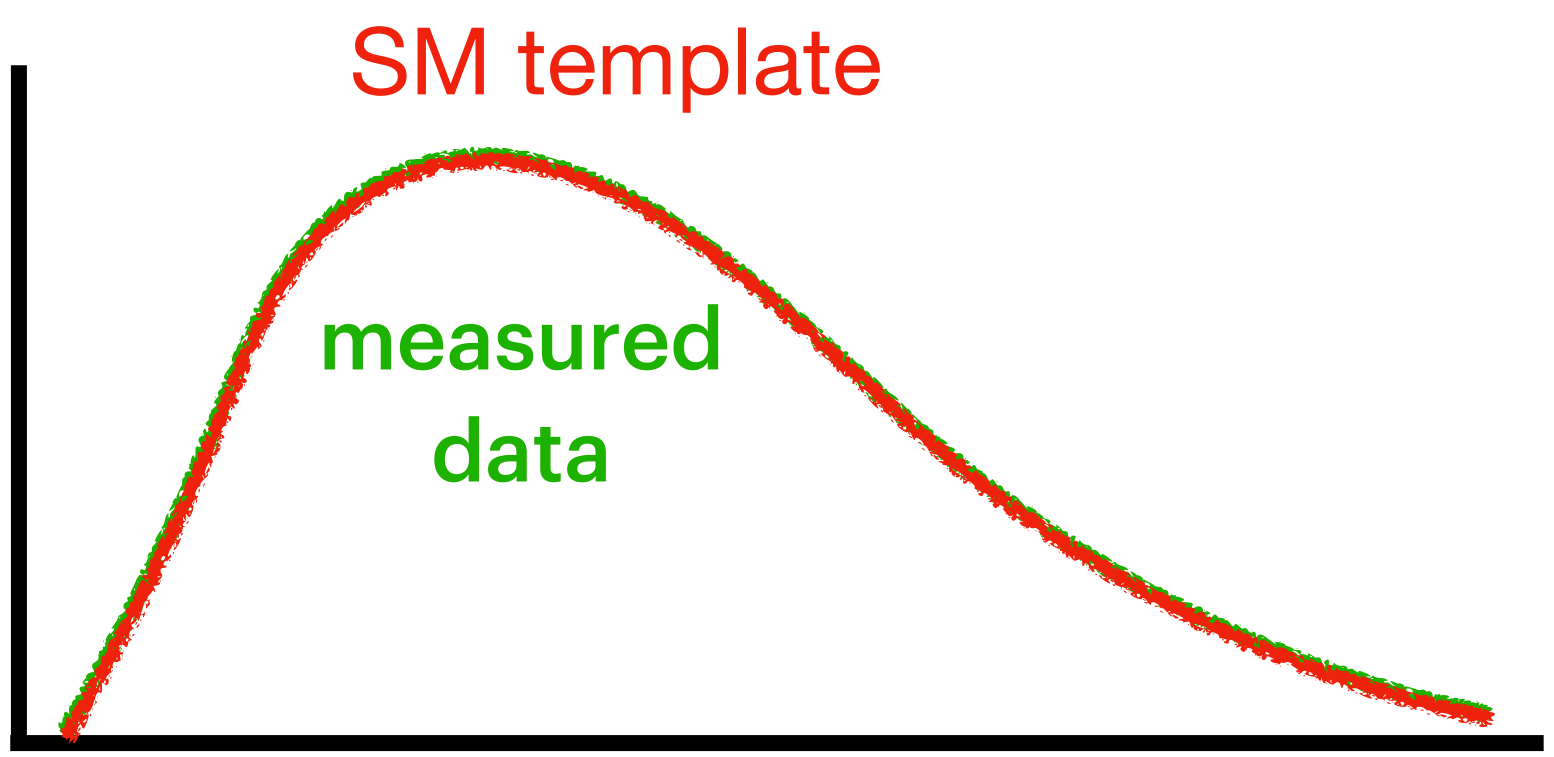

perfect agreement! obtain SM parameter from fit

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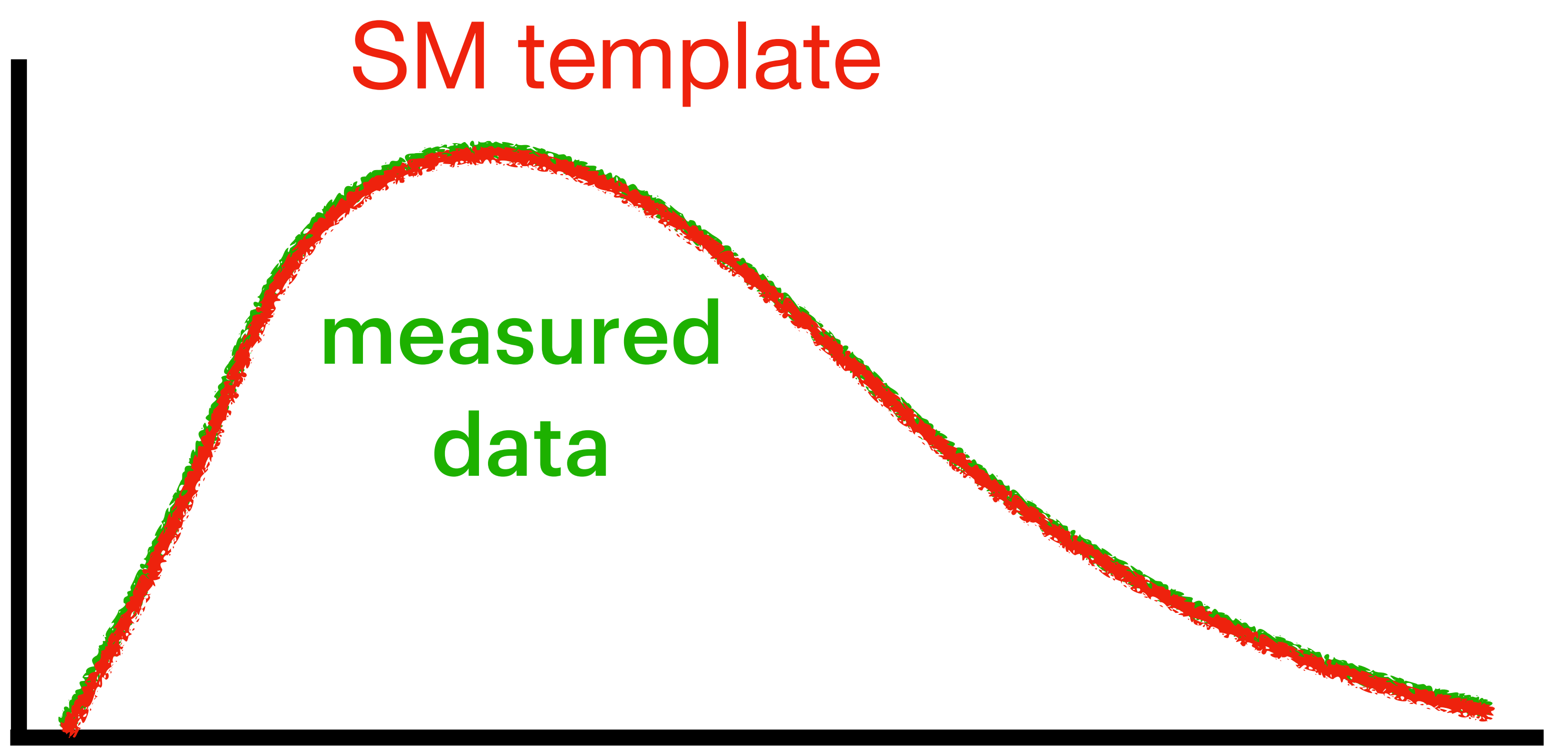

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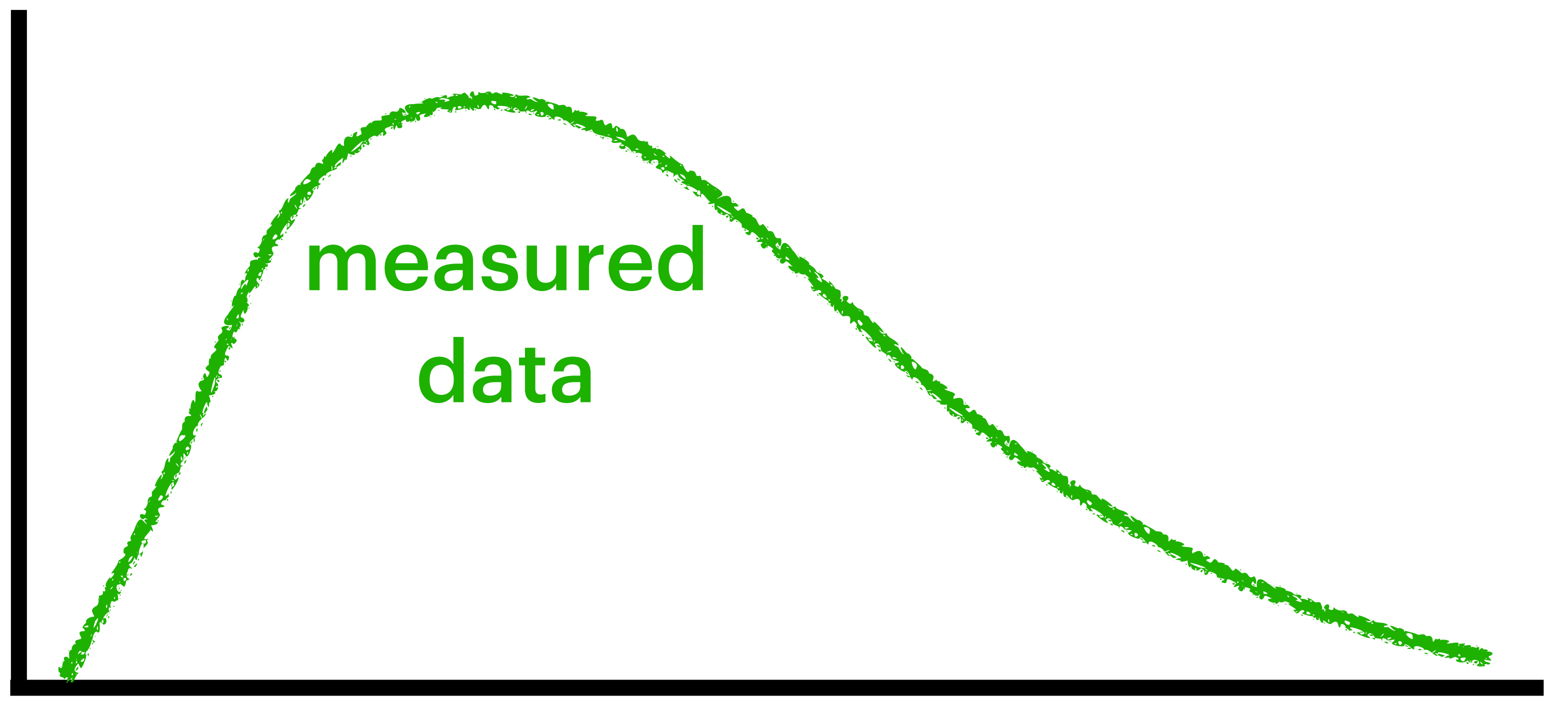

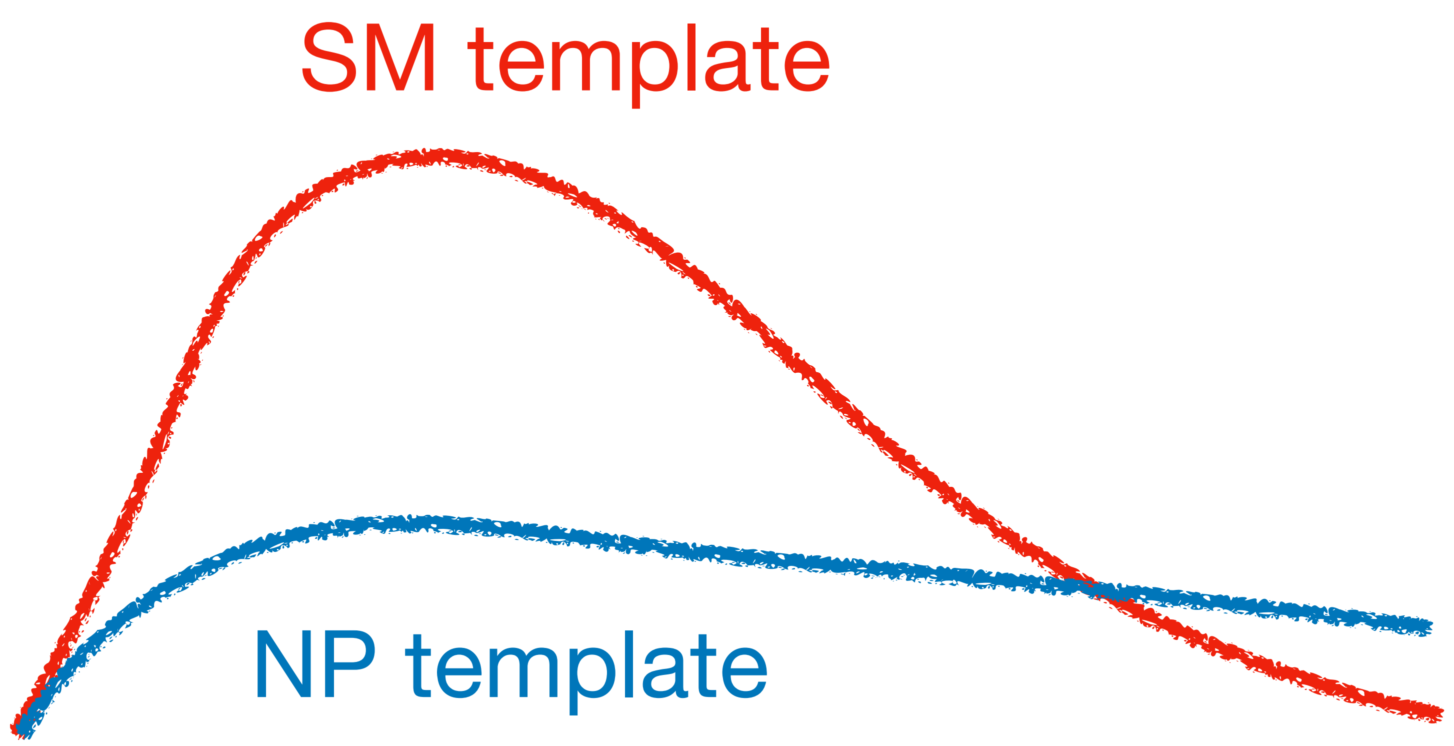

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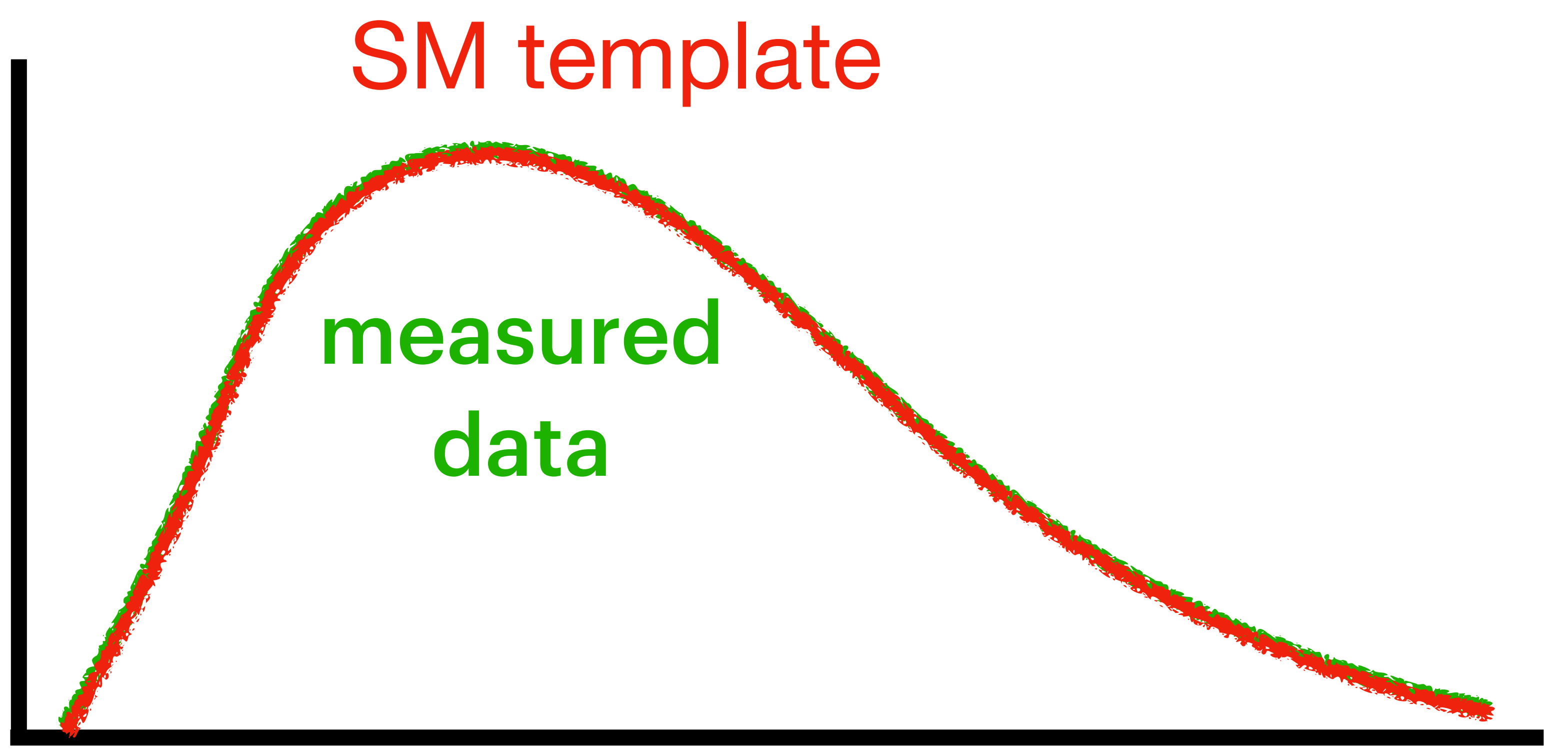

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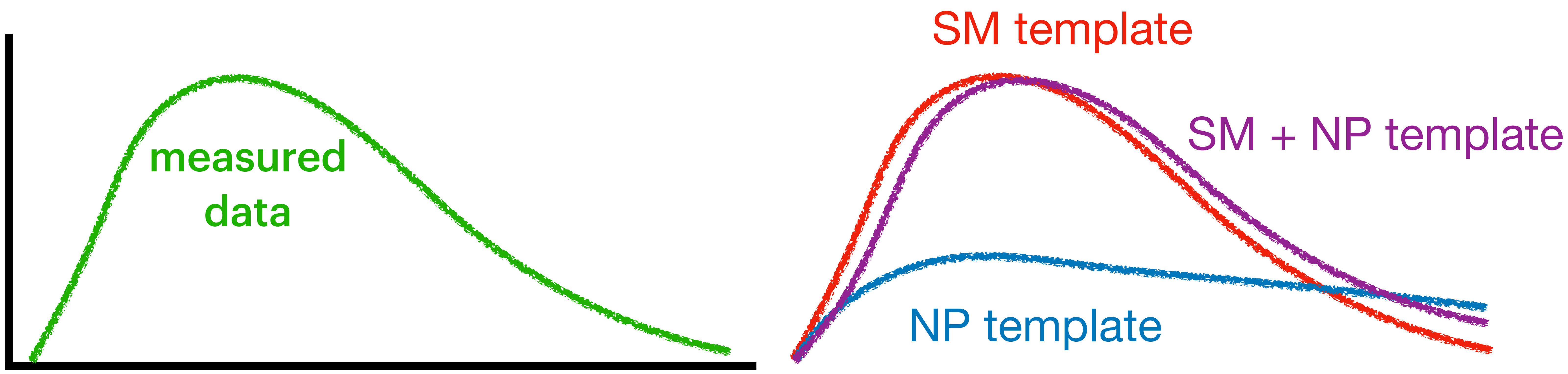

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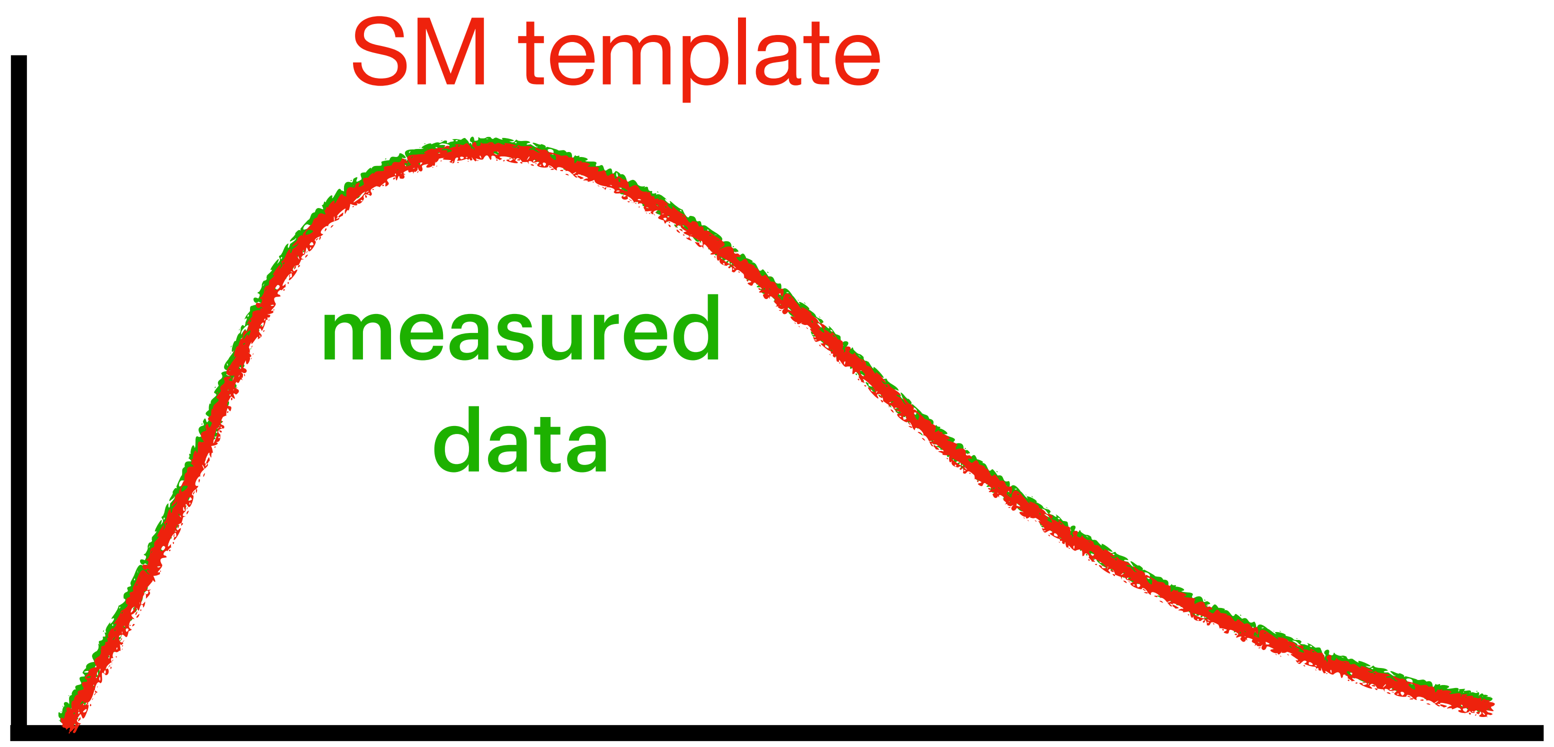

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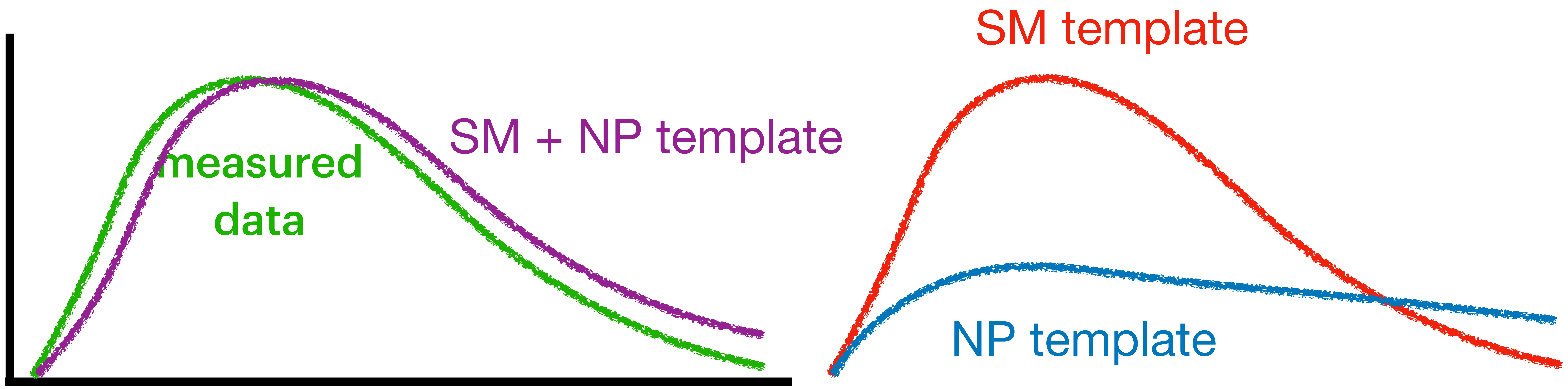


bad fit! NP can be excluded

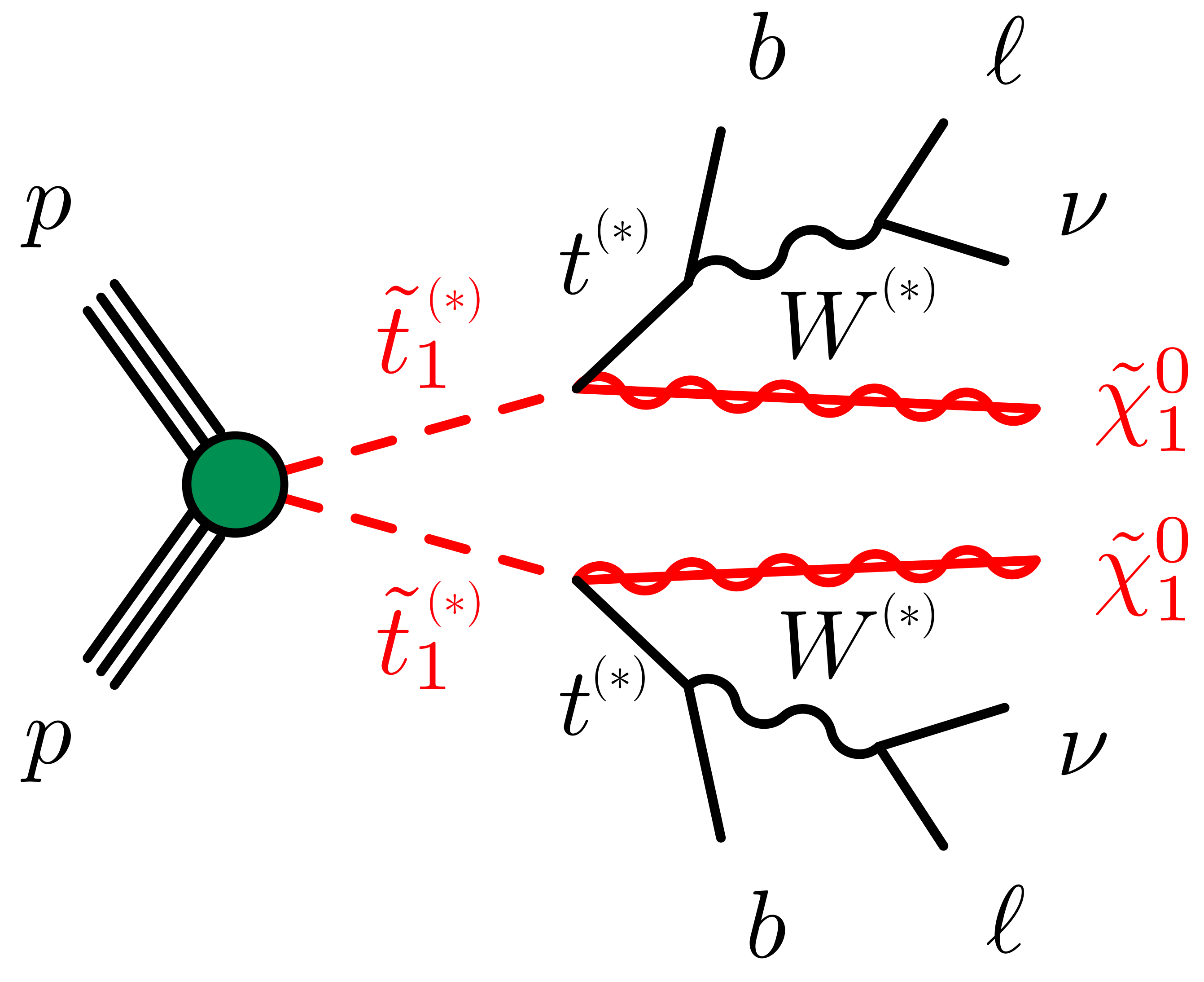
Examples of Probing NP

- Idea is general to any precision measurement
  - searching for SUSY stop production using top quark mass

$$\Delta m_t / m_t \sim 10^{-2} - 10^{-3}$$

$$\Delta m_W / m_W \sim \mathcal{O}(10^{-4})$$

  - not yet implemented for $\ell + mET$ final state
    - higher precision allows probing of fainter NP signals
    - sensitive to NP charged only under EW interactions

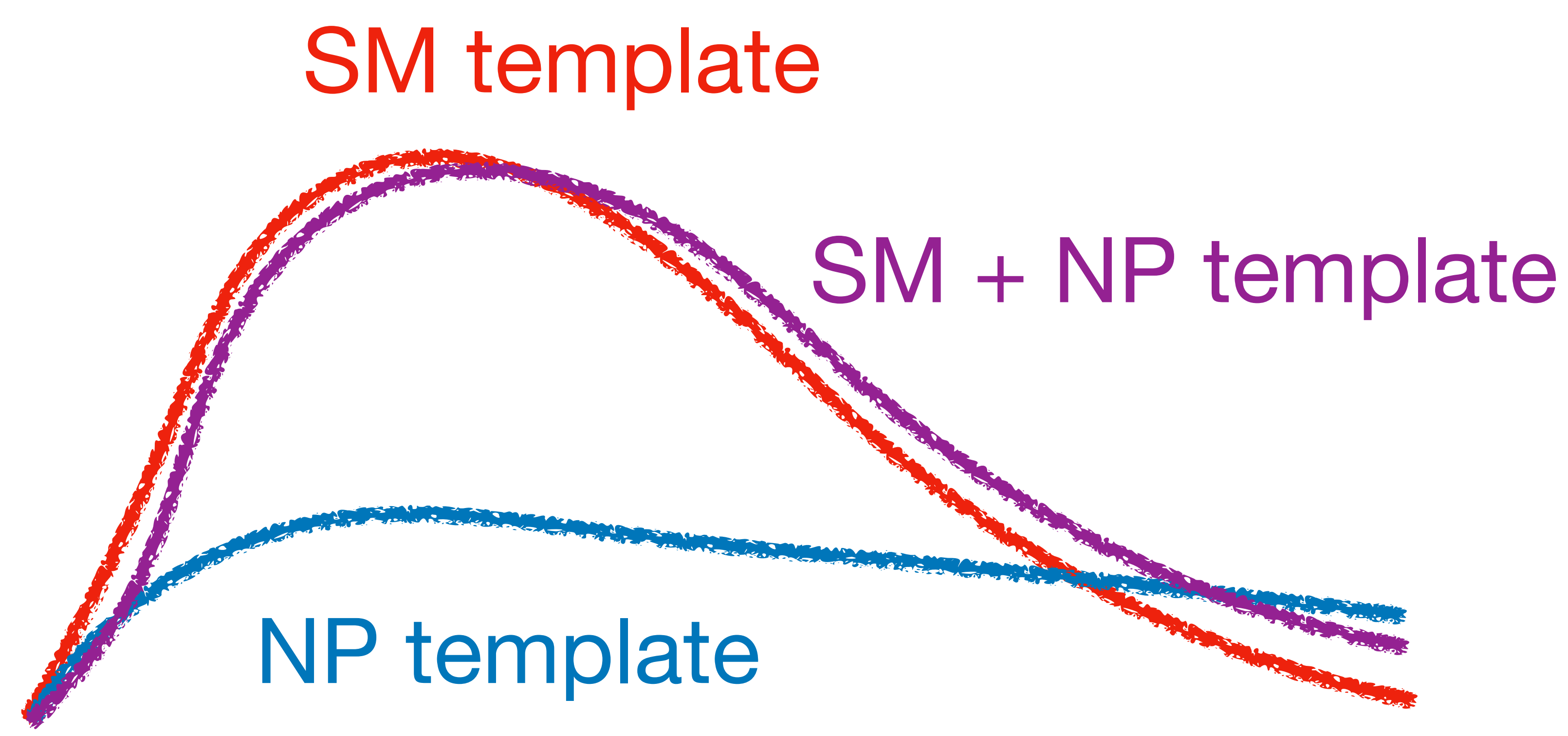


Cohen, Majewski, Ostdiek, Zheng [1909.09670]
Eifert, Nachman [1410.7025]
Franceschini [1601.02684]
Agashe, Airen, Franceschini, Incandela, Kim, DS [2212.03929]

New Purpose for Precision W-mass Data

- Use these precise measurements to probe NP signals that contaminate W-mass data

  - Fit templates of kinematic observables to data
    - templates now should include NP + SM W compared to what ATLAS and CDF do
    - Sensitive to regions of parameter space where NP distributions differ noticeably from SM templates



New Purpose for Precision W-mass Data

- Use these precise measurements to probe NP signals that contaminate W-mass data
  - Since the measurement is probing NP parameters *and* m_W, must perform a global fit to both
    - NP contamination could add shift in m_W and add additional uncertainty in the measurement
- independent of electroweak fit

- What kinds of new physics can be probed?

Types of NP Contamination

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Three categories to populate SM W region, requiring final state of $\ell + mET$:

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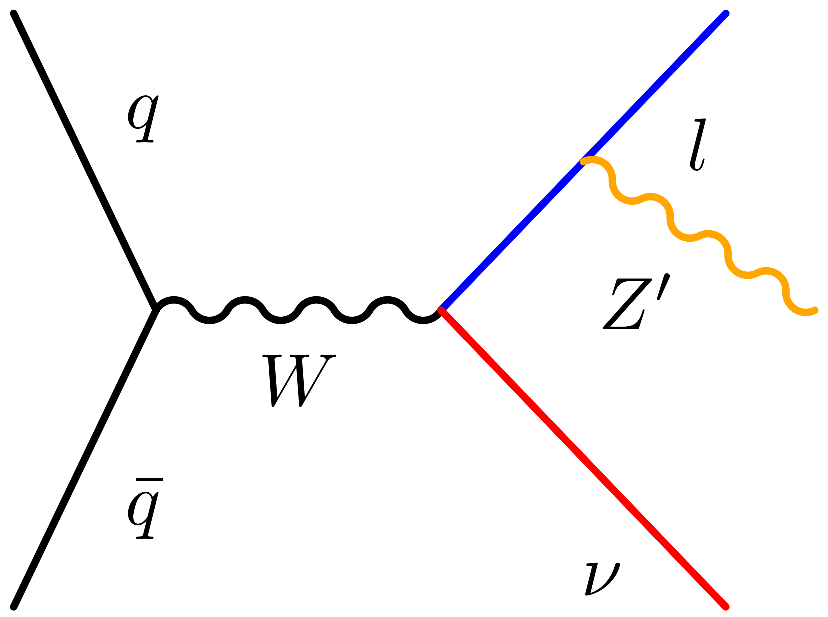
- Modify decay of SM W



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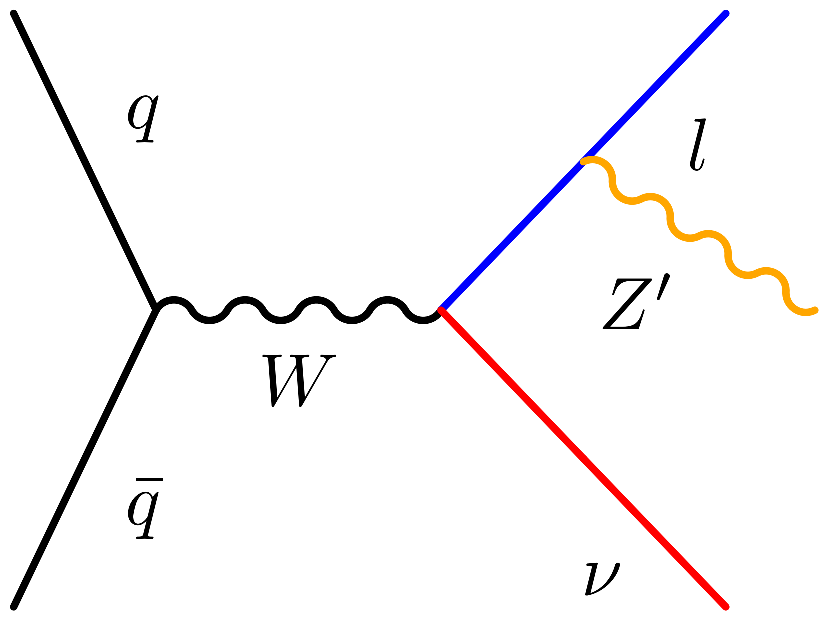

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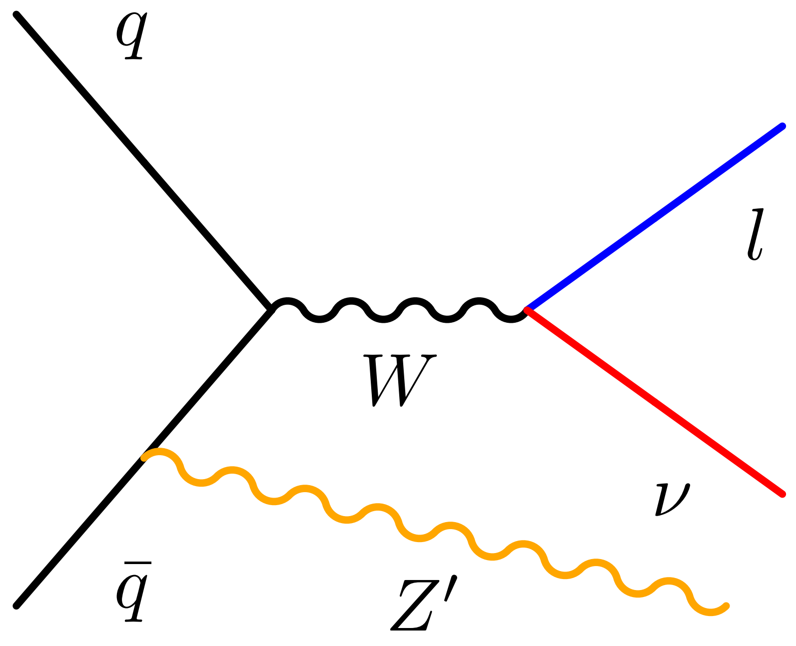

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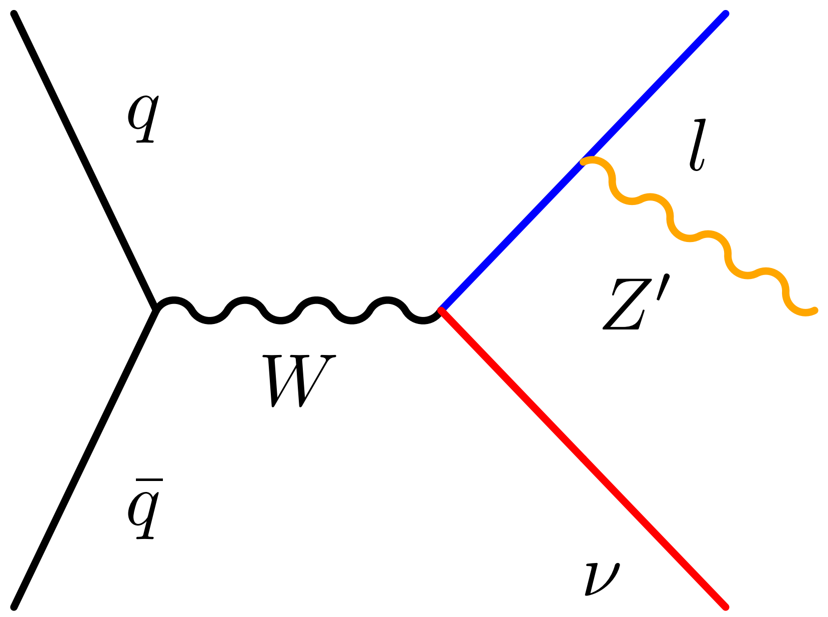

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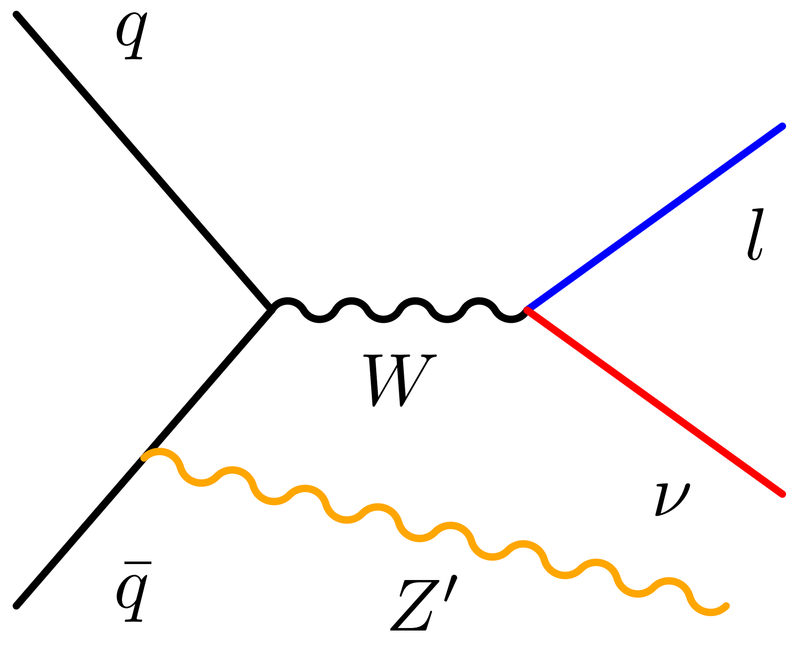
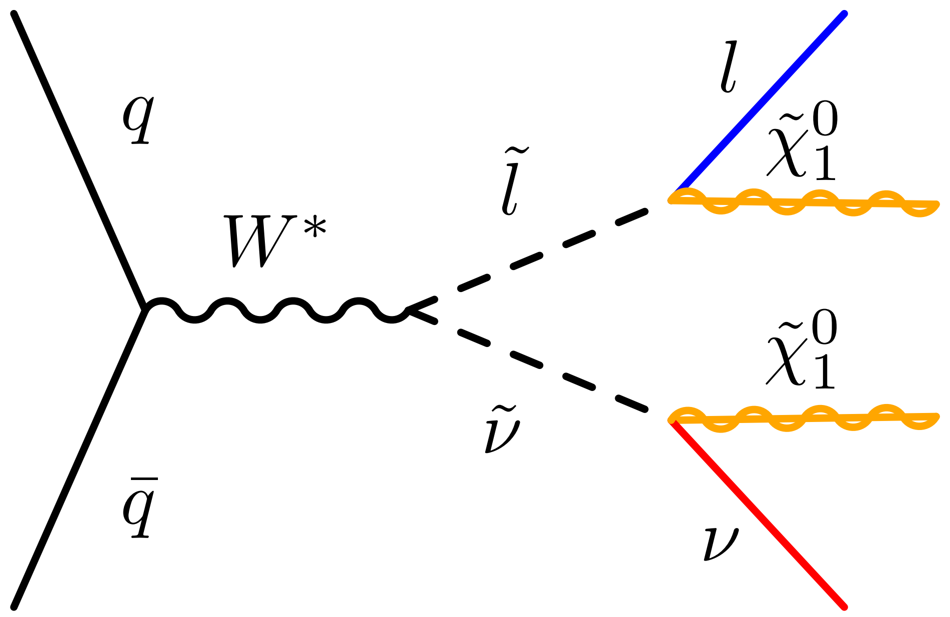


- Without on-shell W



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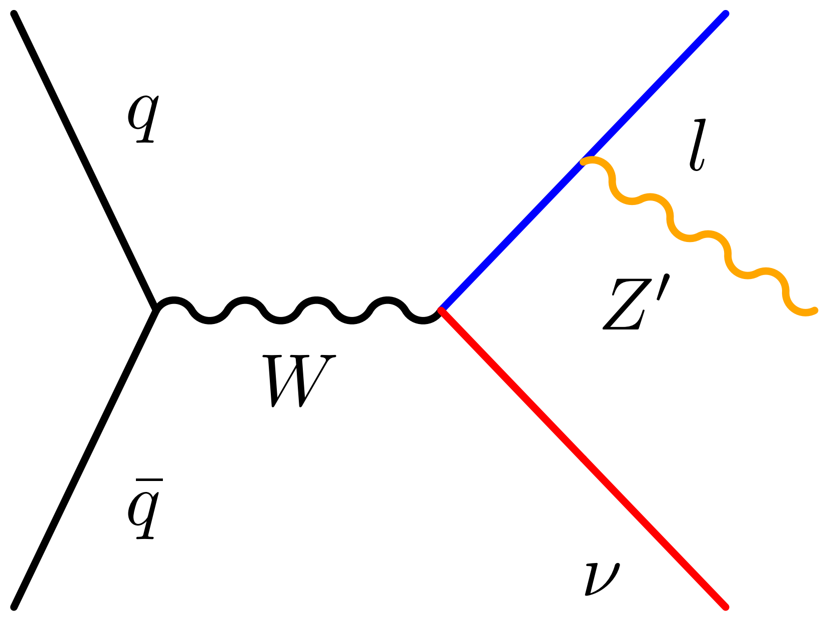

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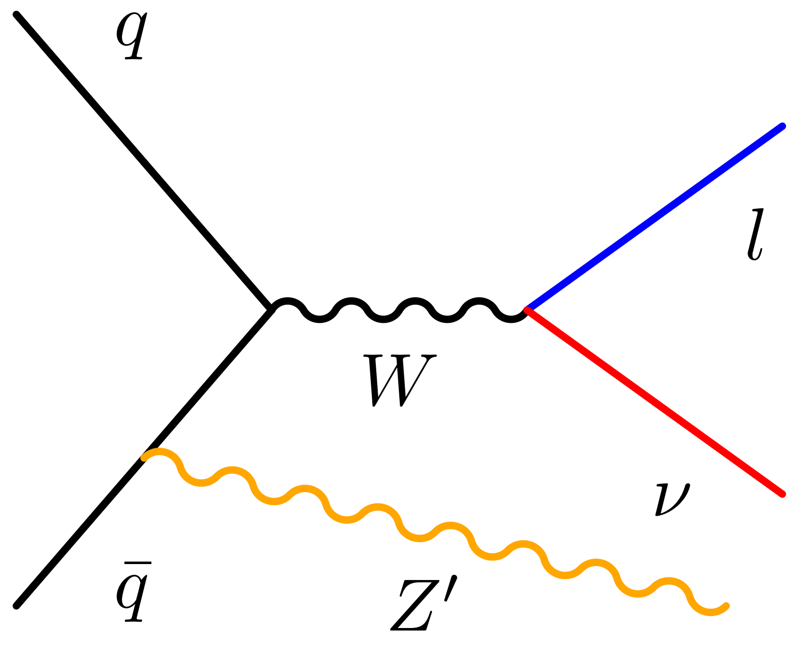

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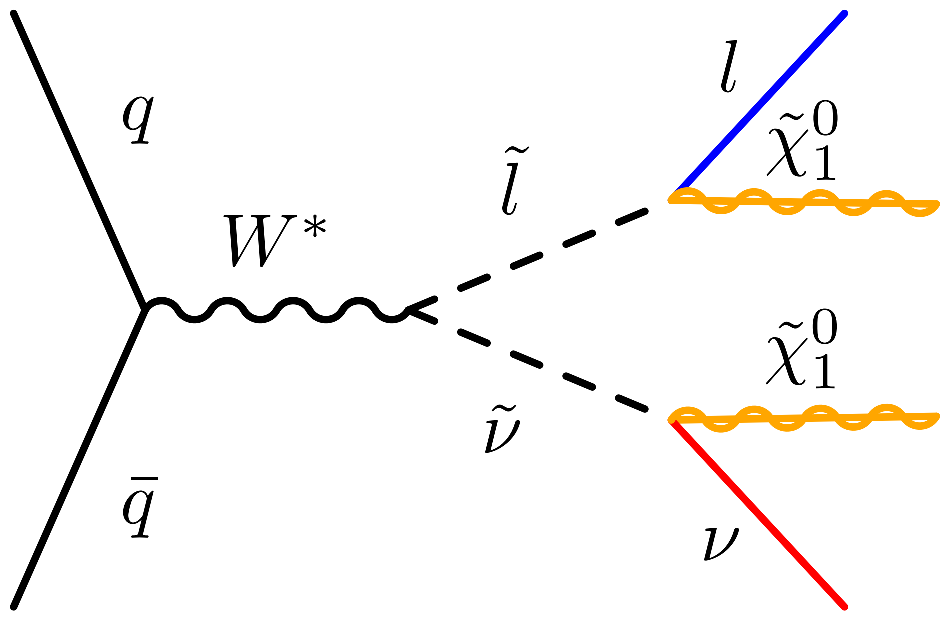

Focus of today's talk

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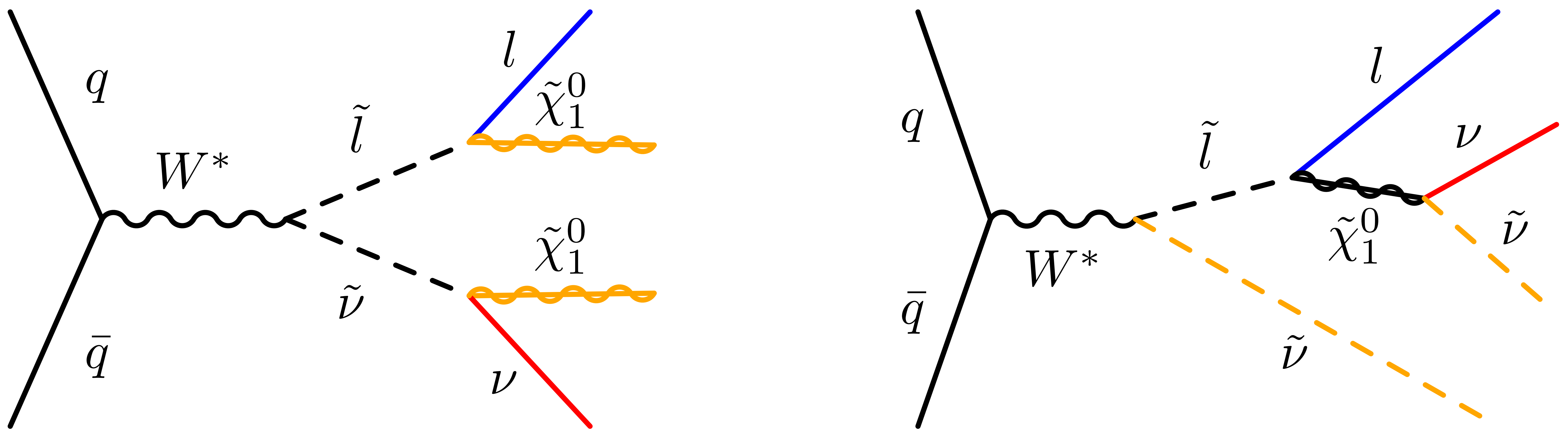
NP without on-shell W

MSSM Slepton-Sneutrino Production



$\ell + mET$ in MSSM

NP without on-shell W

- Supersymmetry is well-known and well-studied
- Simple production mechanism for $\ell + mET$:

$$pp \to \tilde{\ell}(\to l\tilde{\chi}_1^0)\,\tilde{\nu}$$

- Assume all other superpartners are heavy
    - light sleptons are motivated in Sleptonic SUSY

Agashe, Ekhterachian, Liu, Sundrum [2203.01796]

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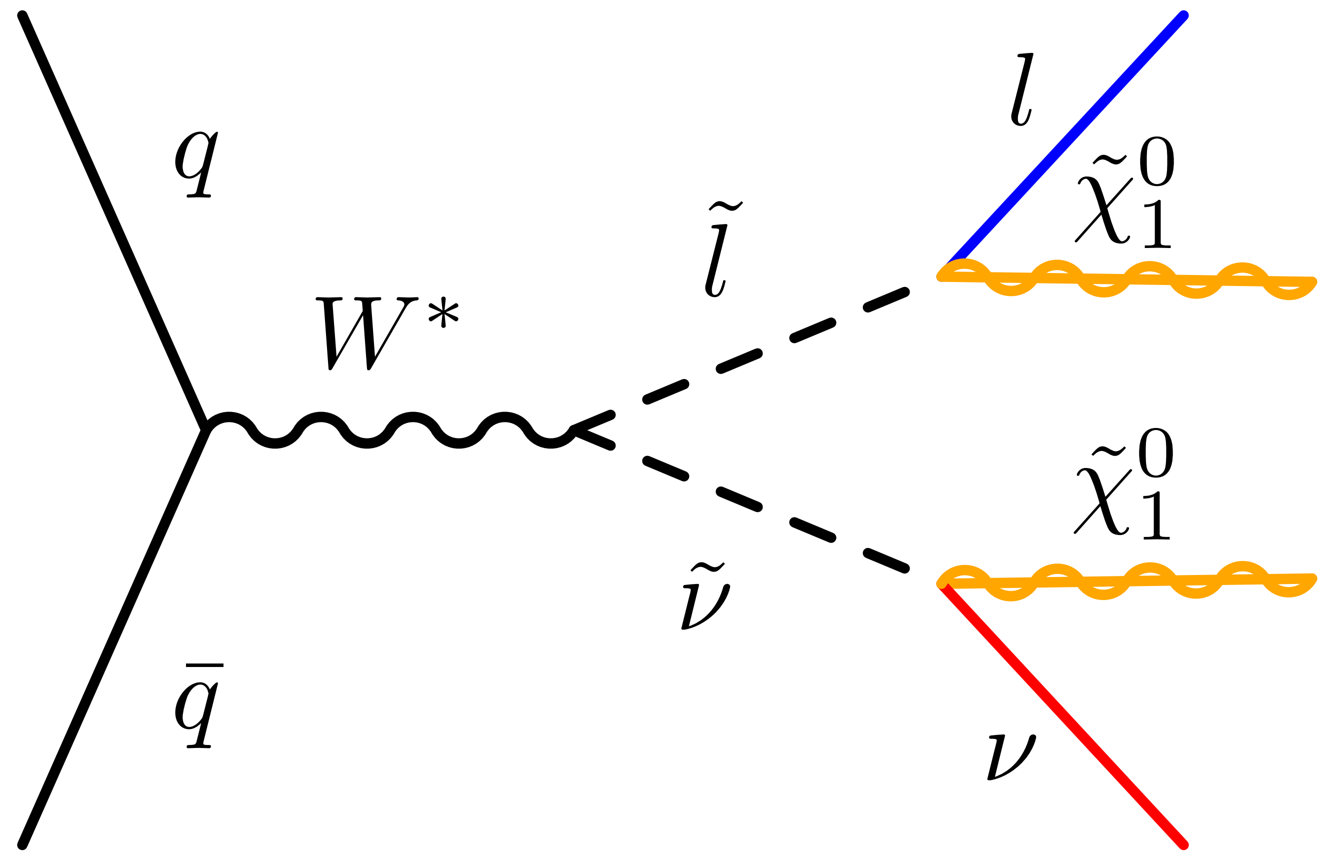

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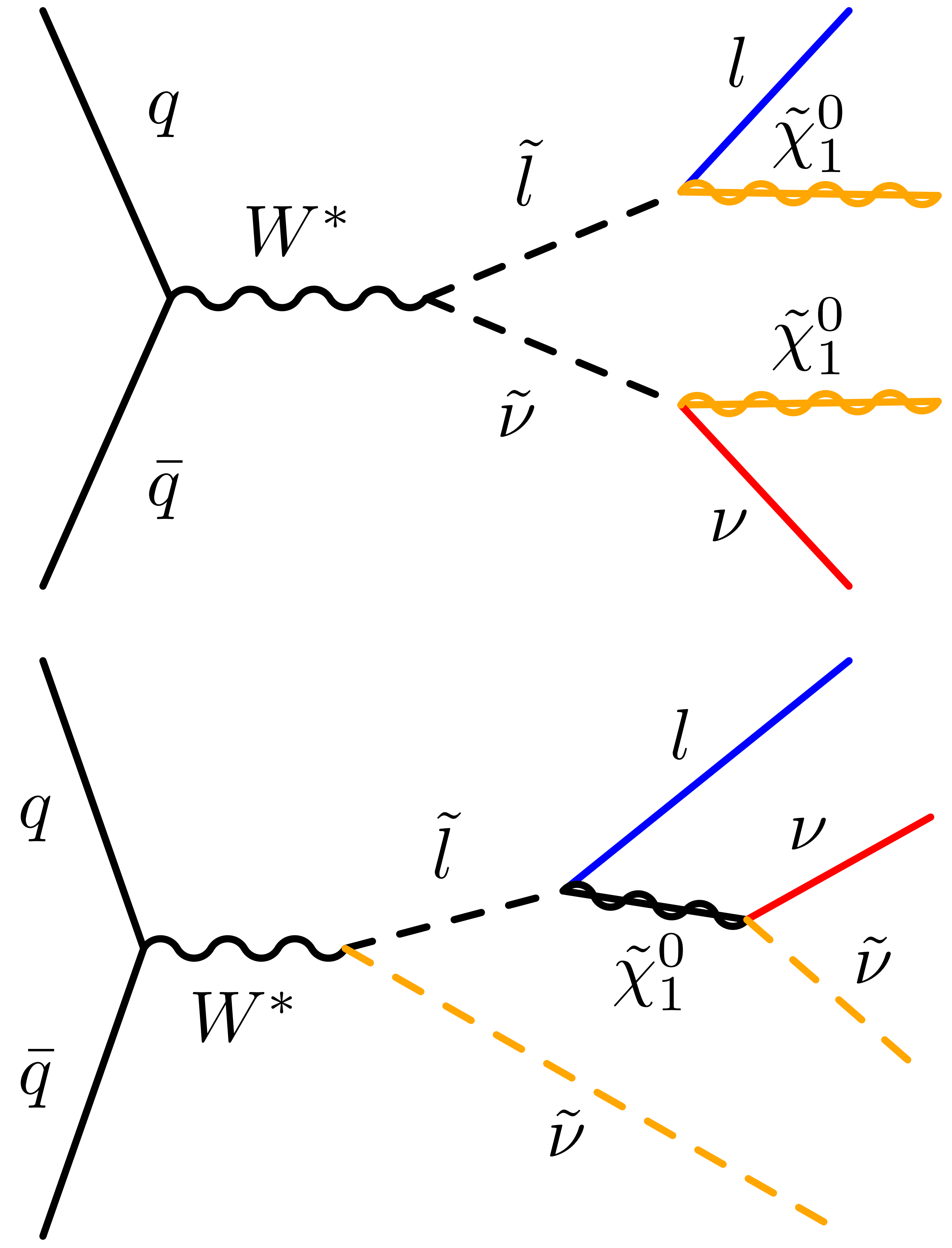
  - sneutrino is LSP: $\tilde{\chi}_1^0 \to \tilde{\nu}\,\nu$



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MSSM Masses

NP without on-shell W

- slepton-sneutrino process contains 3 NP masses: $m_{\tilde{l}}, m_{\tilde{\nu}}, m_{\tilde{\chi}_1^0}$
  - slepton-sneutrino mass splitting relation fixed by D-term:

$$m_{\tilde{\nu}_\ell}^2 = m_{\tilde{\ell}}^2 + \cos(2\beta)\, m_W^2$$

  - setting $\tan\beta \to \infty$ ensures lightest sneutrinos

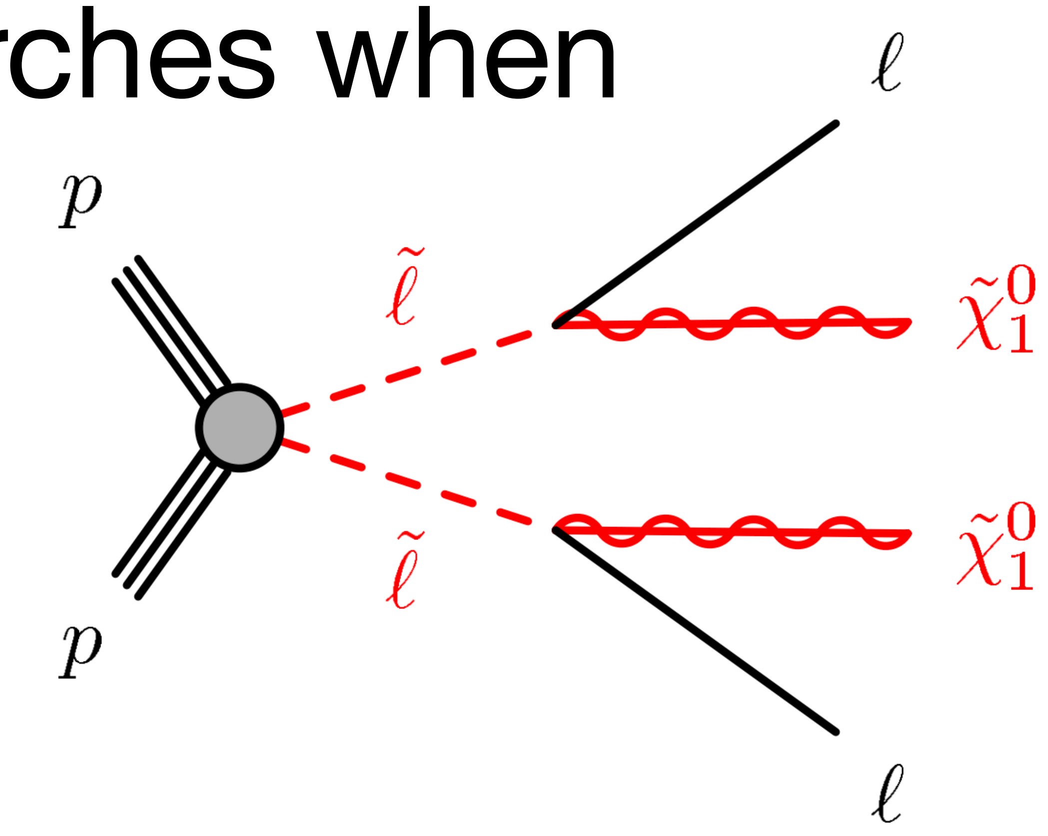
$$m_{\tilde{\nu}_\ell}^2 = m_{\tilde{\ell}}^2 - m_W^2$$

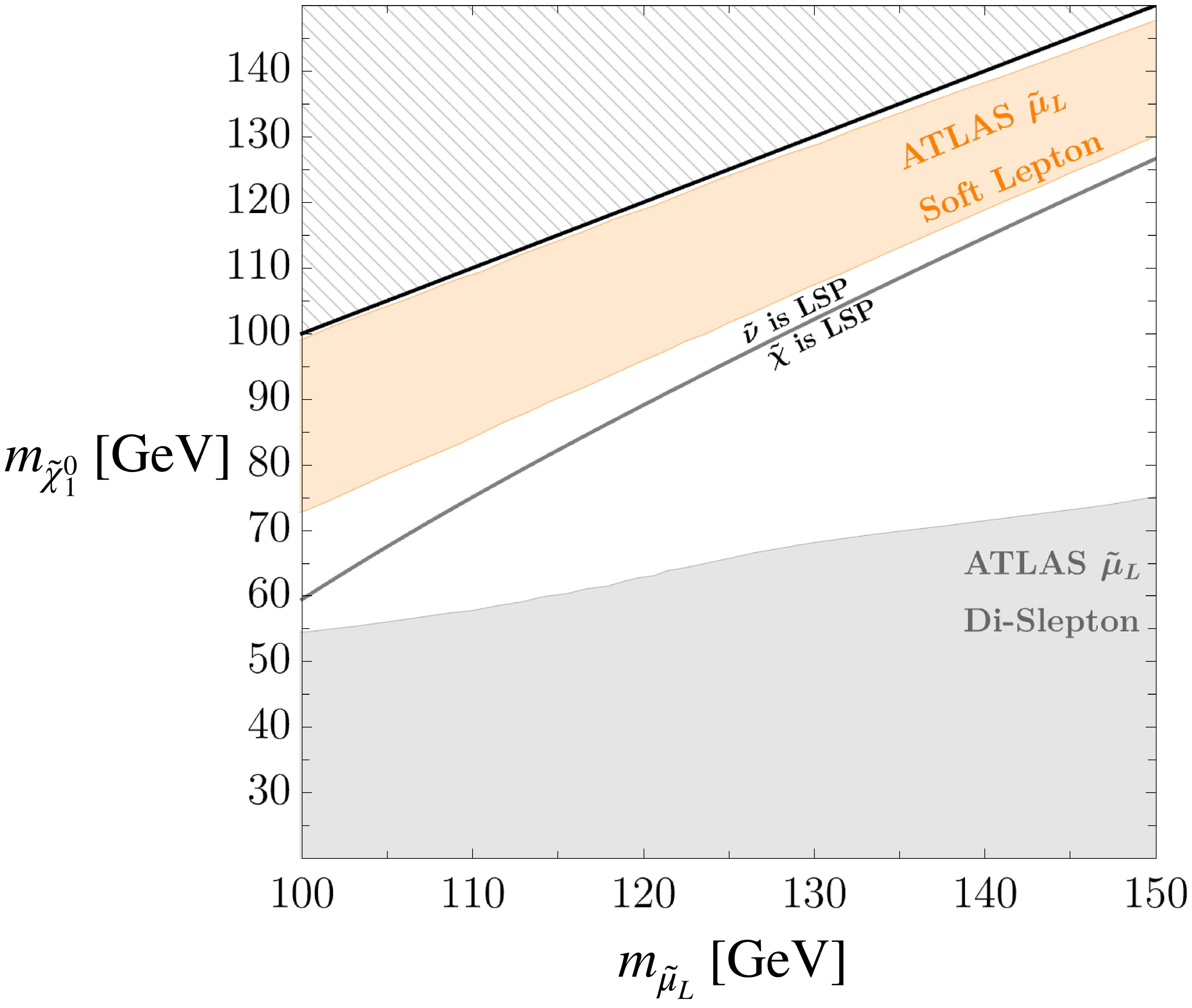
Martin [hep-ph/9709356]

MSSM Masses

NP without on-shell W

- LEP rules out $m_{\tilde{l}} < 100$ GeV
- Heavier sleptons have negligible cross sections at Tevatron
- LHC searches for di-slepton production using ML techniques
  - Gap in the searches when $m_{\tilde{l}} \sim m_{\tilde{\chi}_1^0}$





LEP2 SUSY WORKING GROUP Sleptons (cern.ch)

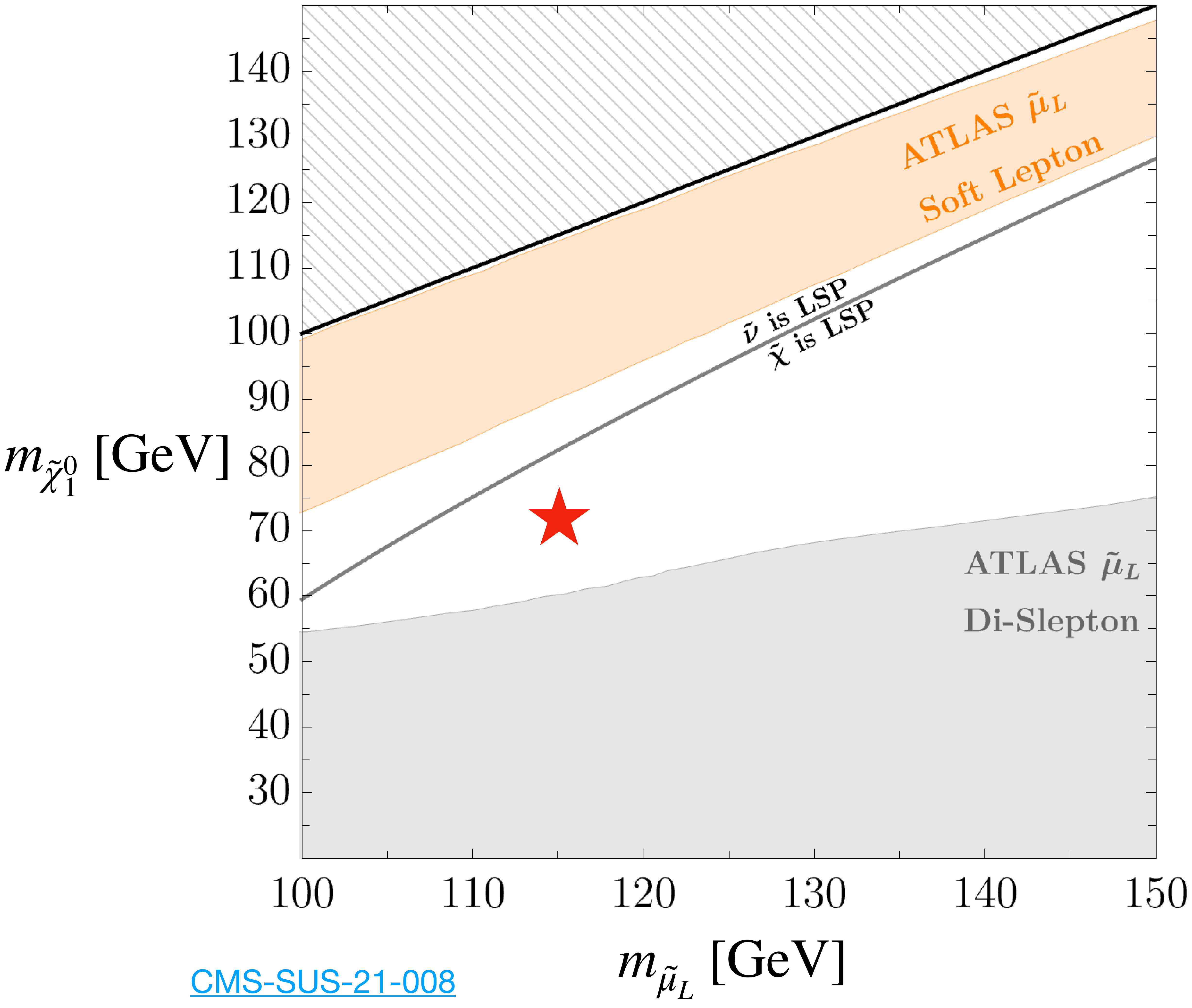
[2209.13935] ATLAS dislepton search (arxiv.org)

CMS-SUS-21-008

MSSM Masses

NP without on-shell W

- Proposals to use precision WW data to disentangle dislepton events
    - gap still exists
    - 1D fit: assumes m_W from independent measurements, whereas we float m_W



Curtin, Jaiswal, Meade [1206.6888]
Curtin, Jaiswal, Meade, Tien [1304.7011]

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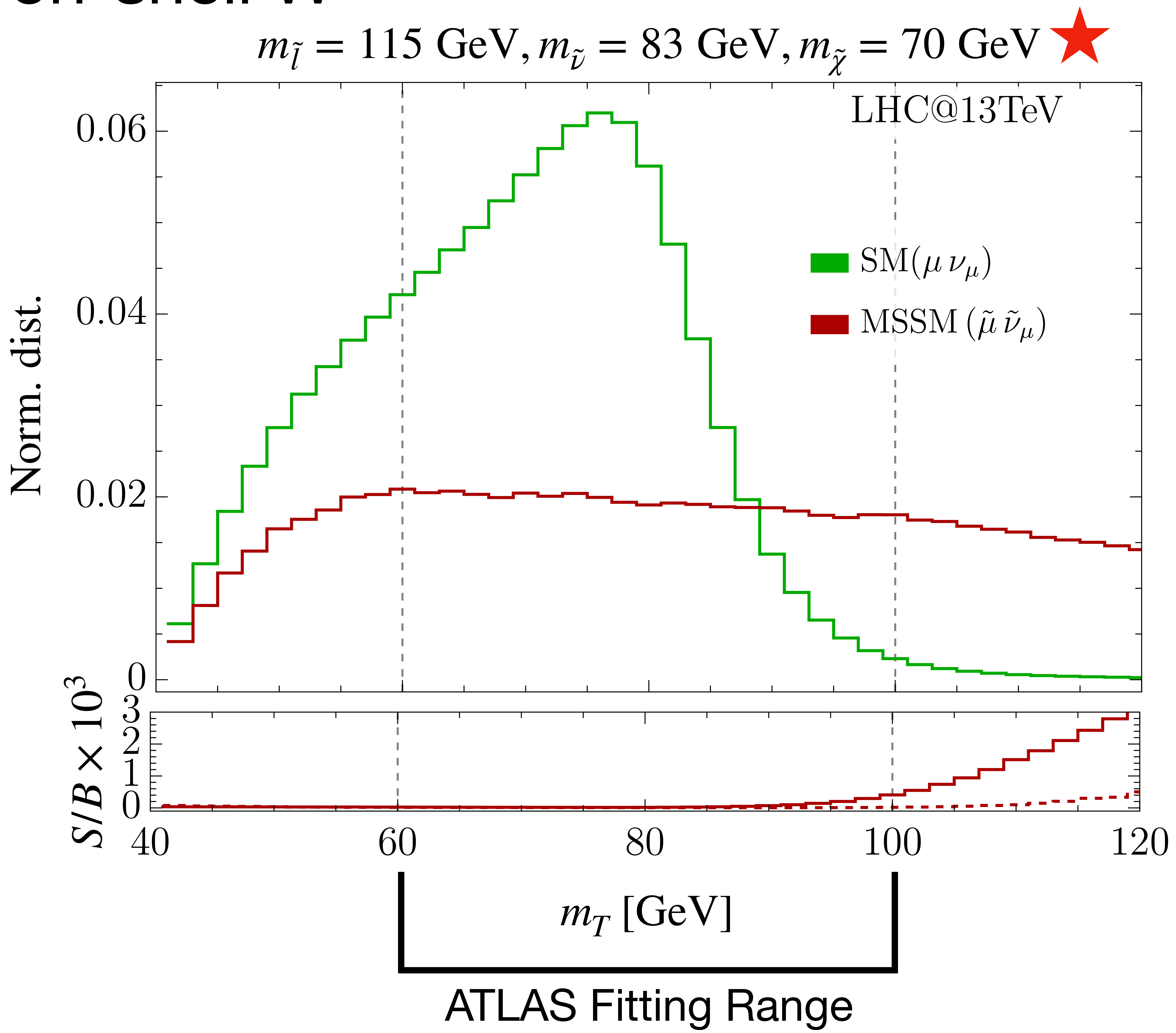
Slepton-Sneutrino Kinematic Distributions

NP without on-shell W

- SUSY slepton m_T (red) vs SM W (green)
- SUSY distributions are flat
  - These distributions don't shift m_W:
    - Marginalize over m_W obtained from min. χ^2, but we find negligible shift
    - for simplicity, fix $\Delta_{m_W} = 0$, focus on sensitivity to NP



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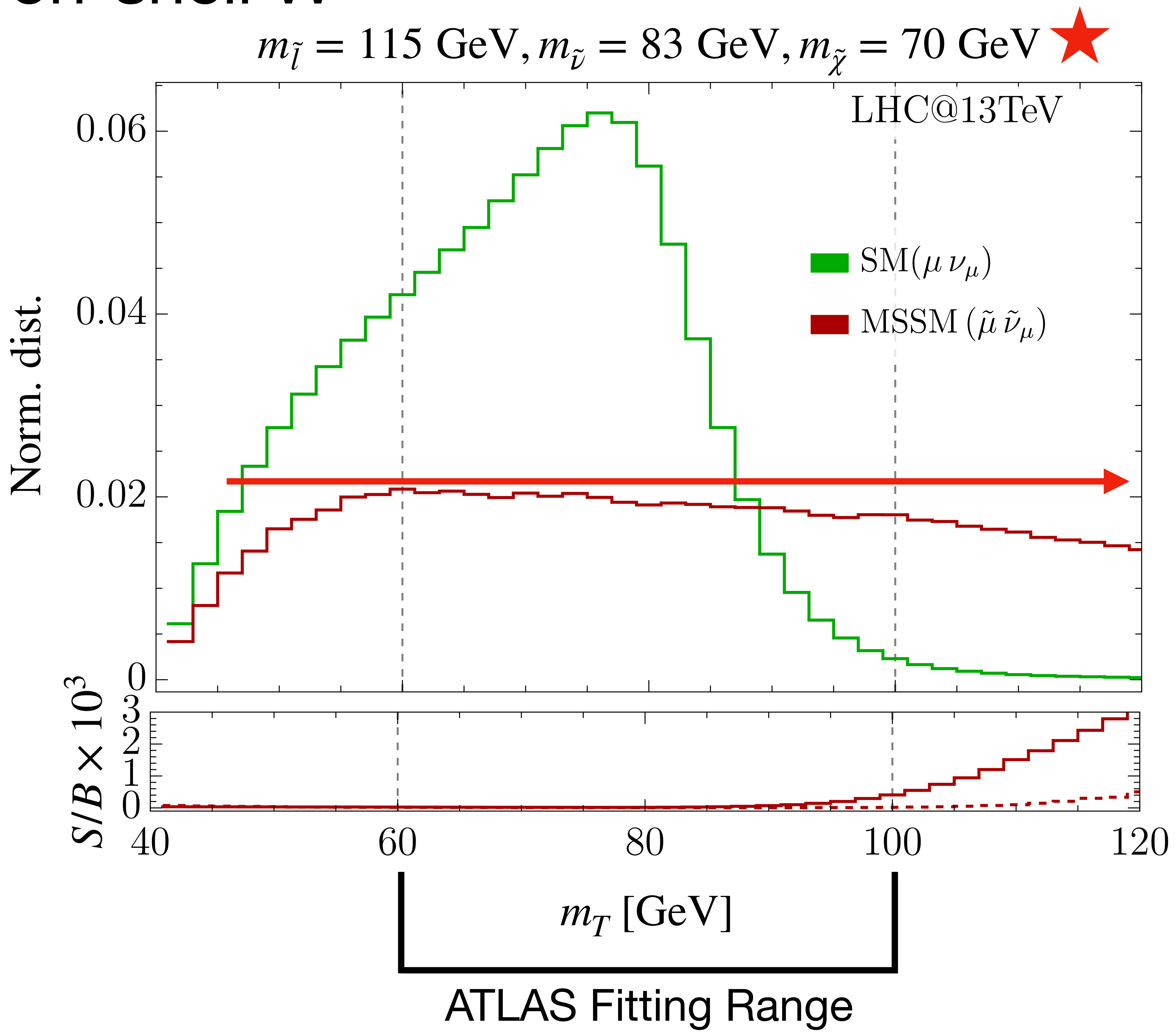
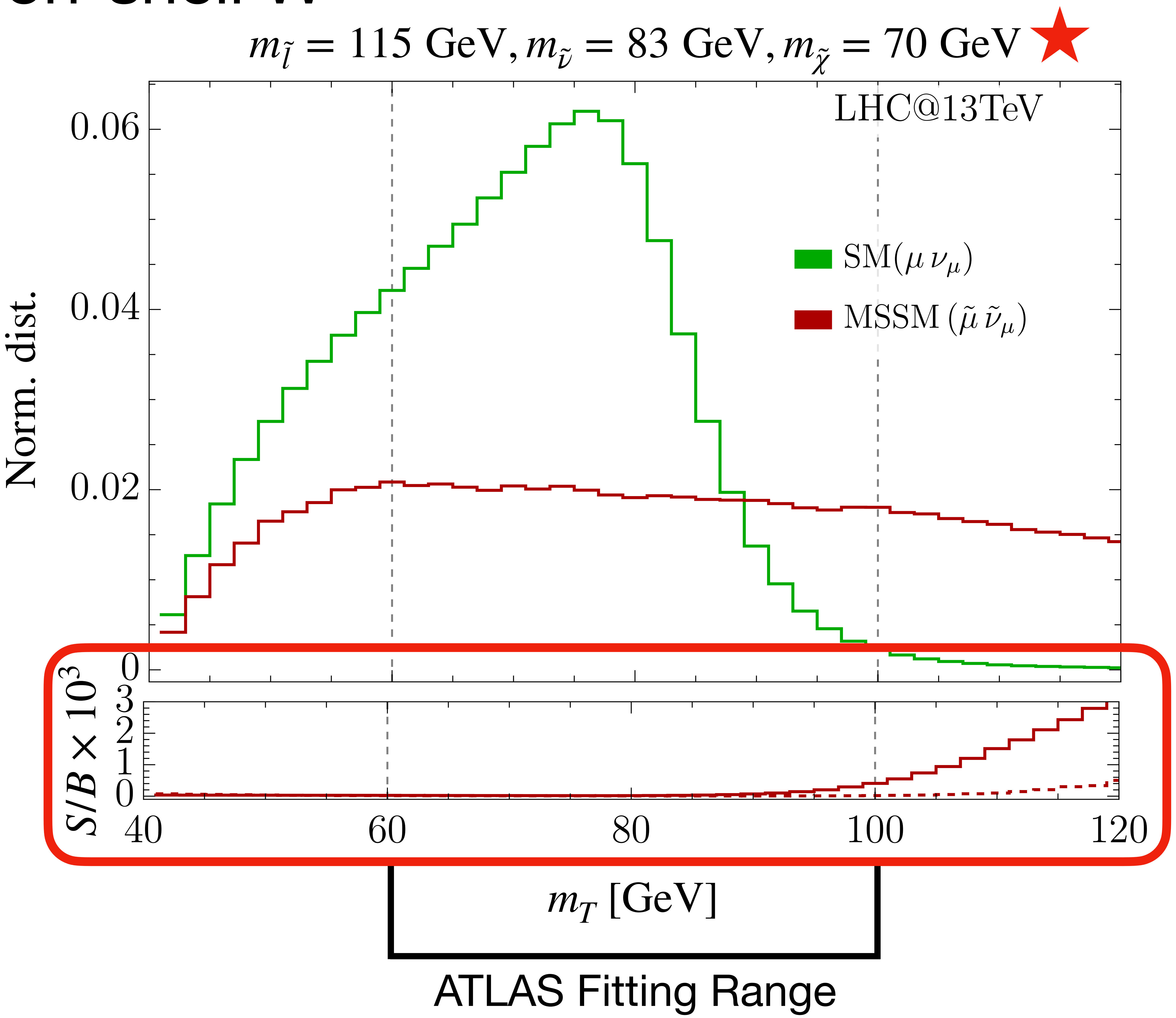


Slepton-Sneutrino Kinematic Distributions

NP without on-shell W

- Bottom figure:
  - S/B (solid) increases considerably beyond Jacobian peak
    - motivates extending fitting range to increase sensitivity to NP
  - Z contamination (dashed, bottom figure) negligible, even beyond fitting range
    - Important to consider, as Z sample is used in data-driven approach



SUSY Slepton-Sneutrino Search

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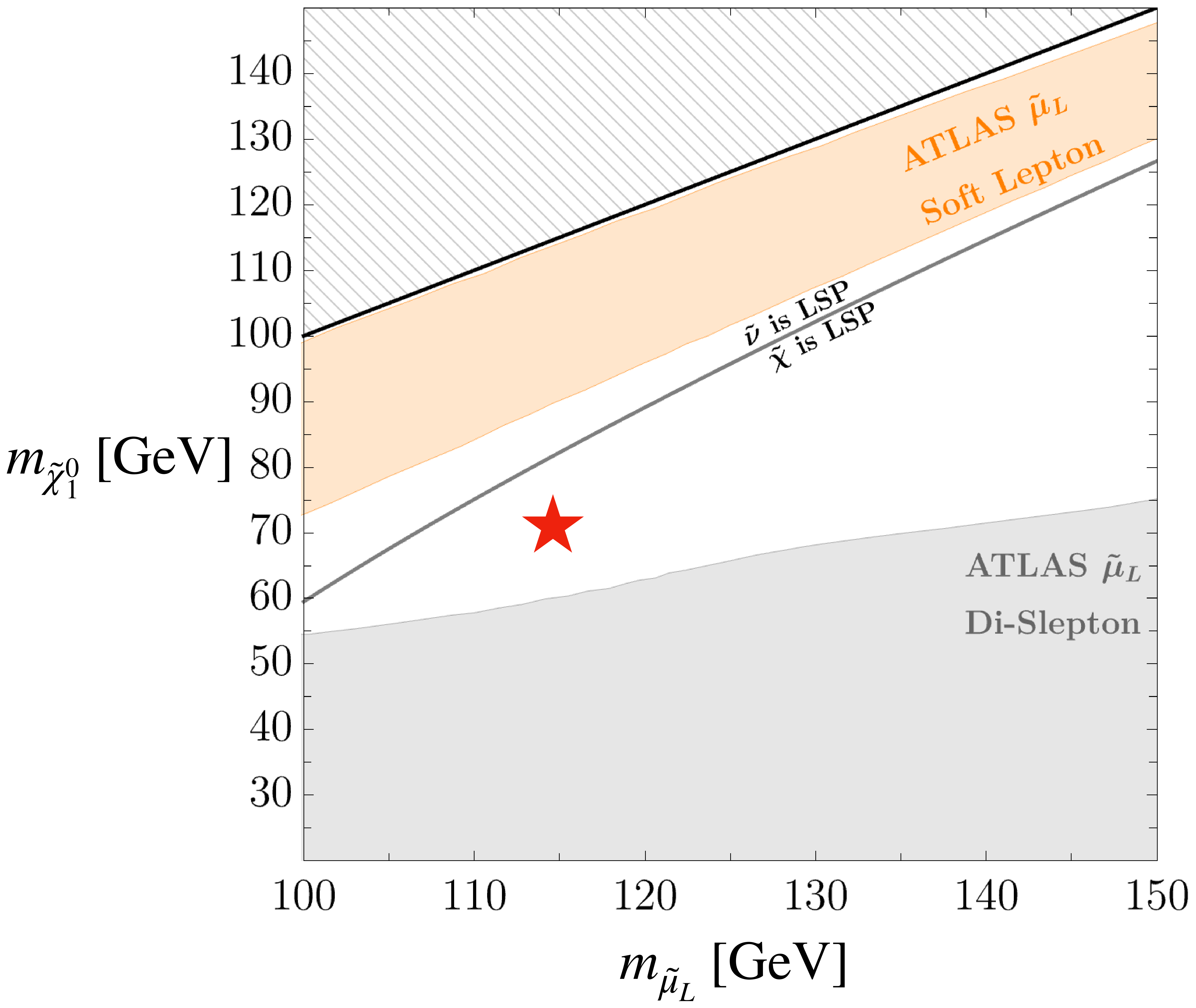

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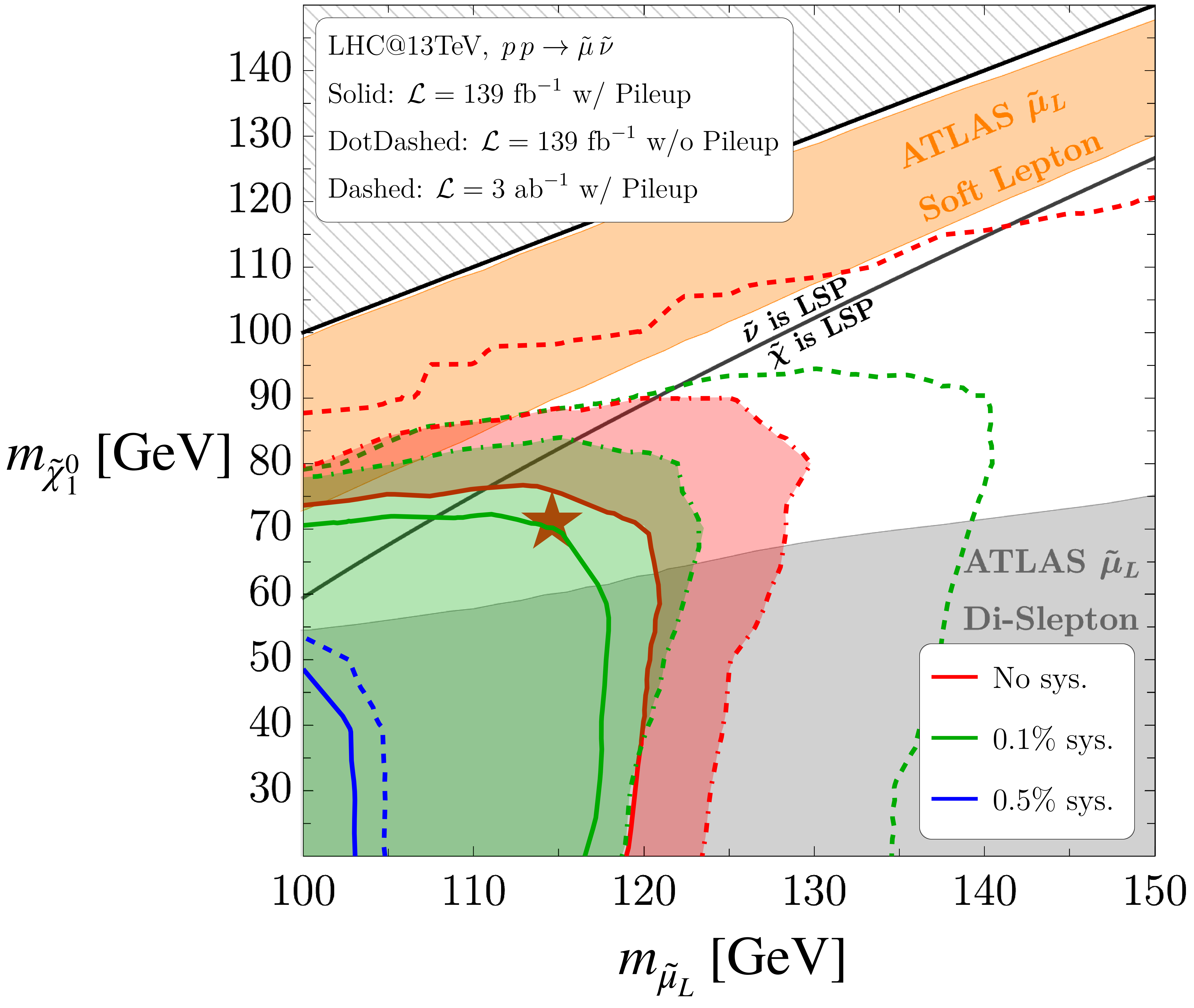

- With slepton-sneutrino search, we can probe that unexplored space!

SUSY Slepton-Sneutrino Search

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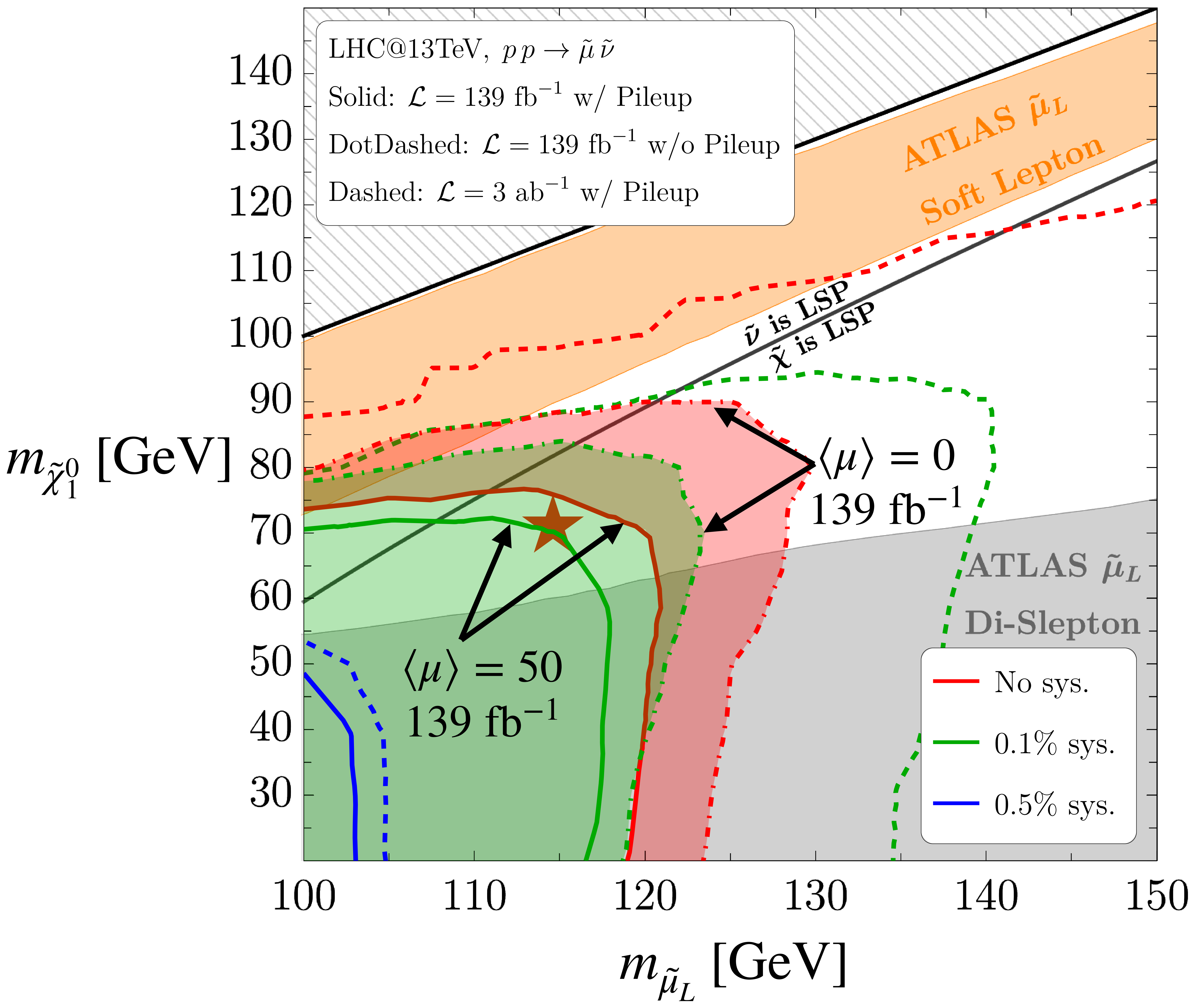

- With slepton-sneutrino search, we can probe that unexplored space!
- Run-2 projections shown
  - with pileup (solid)
  - without pileup (dot-dashed)
    - No-pileup exclusions reached with smaller extension beyond ATLAS fitting range

SUSY Slepton-Sneutrino Search

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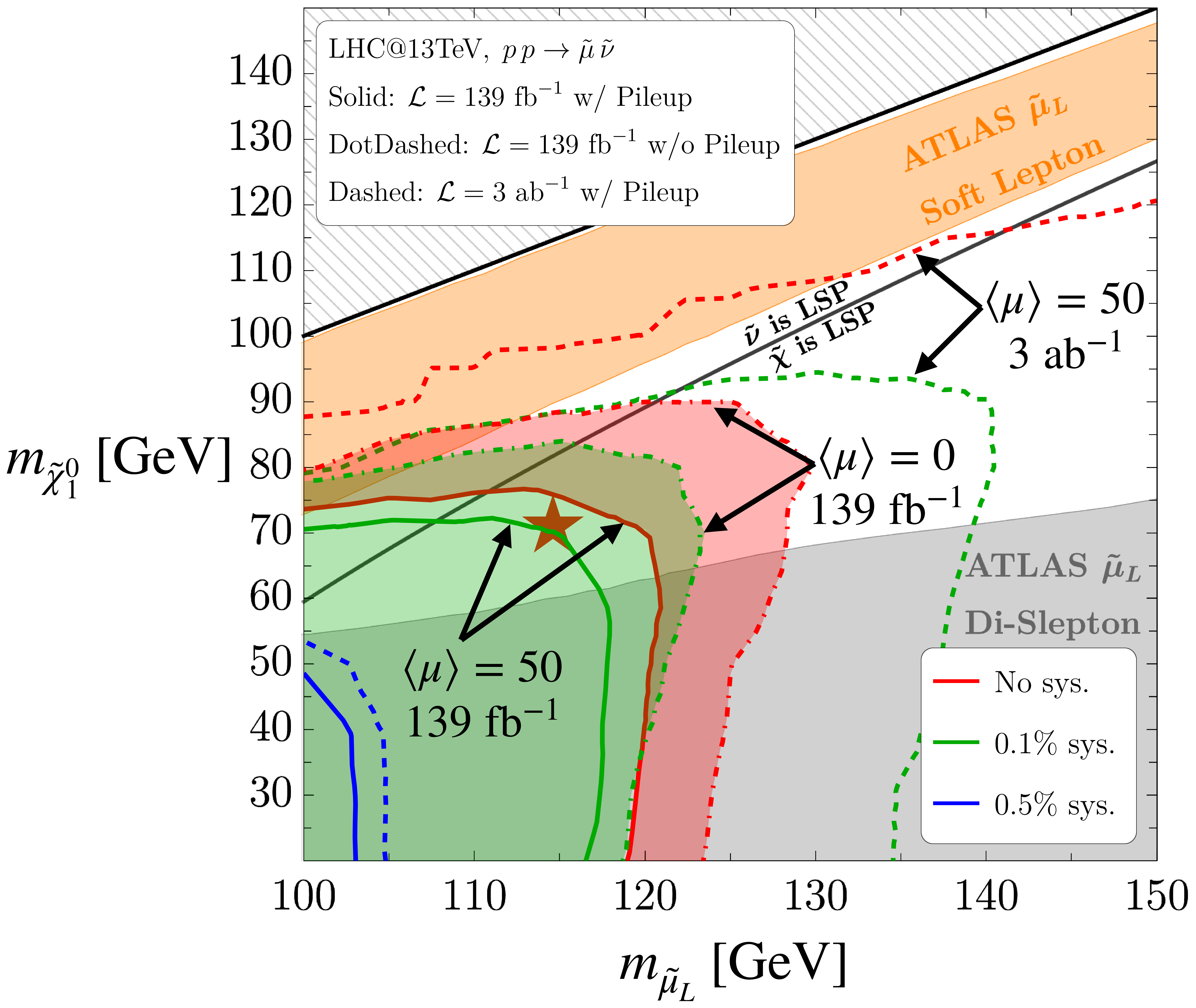

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- Run-2 projections shown
  - with pileup (solid)
  - without pileup (dot-dashed)
    - No-pileup exclusions reached with smaller extension beyond ATLAS fitting range
- HL-LHC projections shown (dashed) with pileup
  - saturated at larger systematics

Extending the fitting range

NP without on-shell W

	ATLAS (μ)	$\tilde{\ell}_\mu \tilde{\nu}_\mu$
p_T^ℓ (GeV)	> 30 (analysis) > 18 (trigger)	> 30
m_T (GeV)	> 60	> 60
$\lvert\vec{u}_T\rvert$ (GeV)	< 30	< 30
m_T range (GeV)	$[60, 100]$	$[60, 120]^*$ $[60, 140]$
p_T^ℓ range (GeV)	$[30, 50]$	$[30, 60]^*$ $[30, 70]$

*without pileup

[ATLAS Improved W Mass Measurement]

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ATLAS Improved W Mass Measurement

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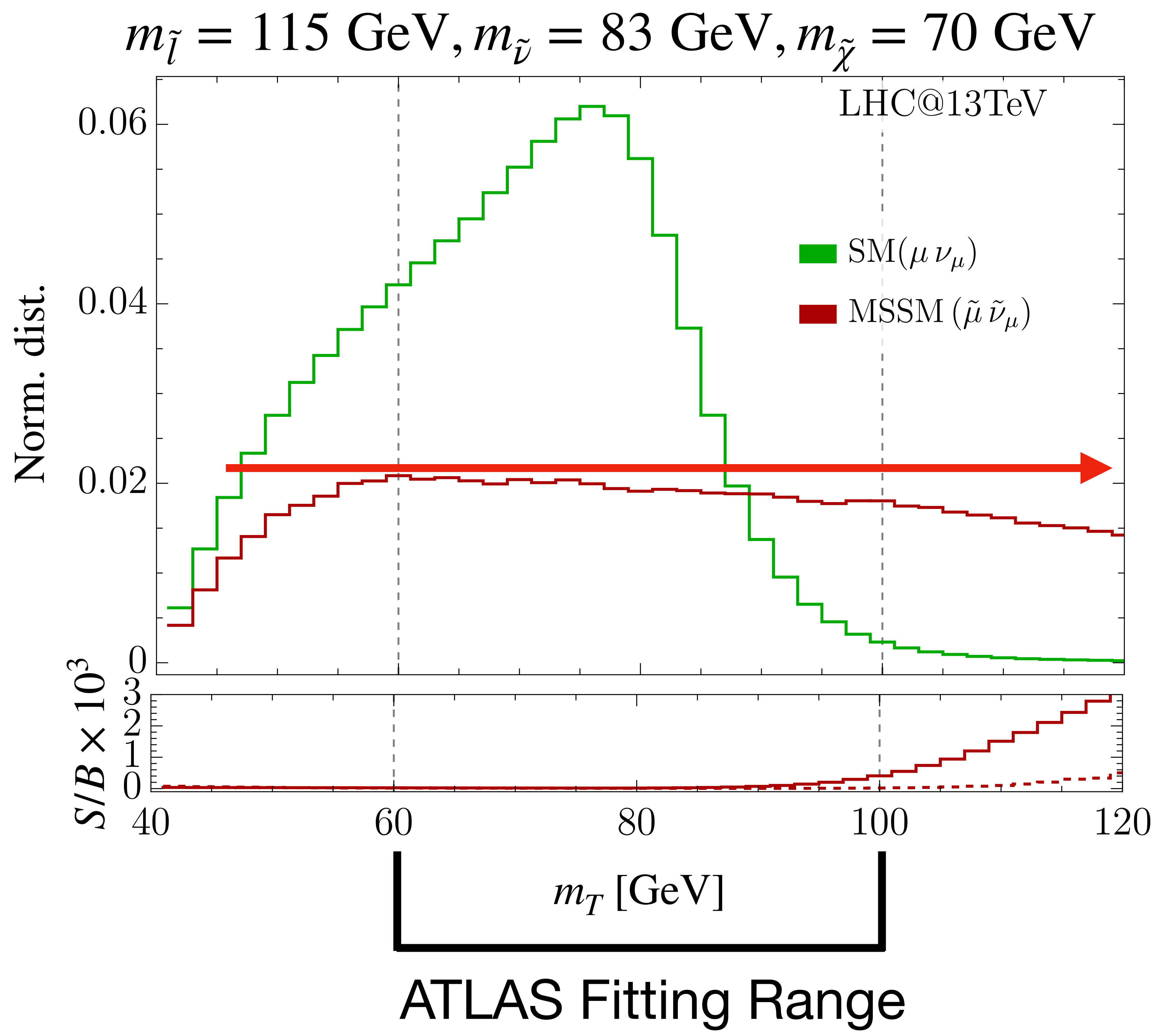
ATLAS Improved W Mass Measurement

- Added sensitivity extending to ~ 250 GeV p_T, 500 GeV m_T?

SUSY Tail Analysis

NP without on-shell W

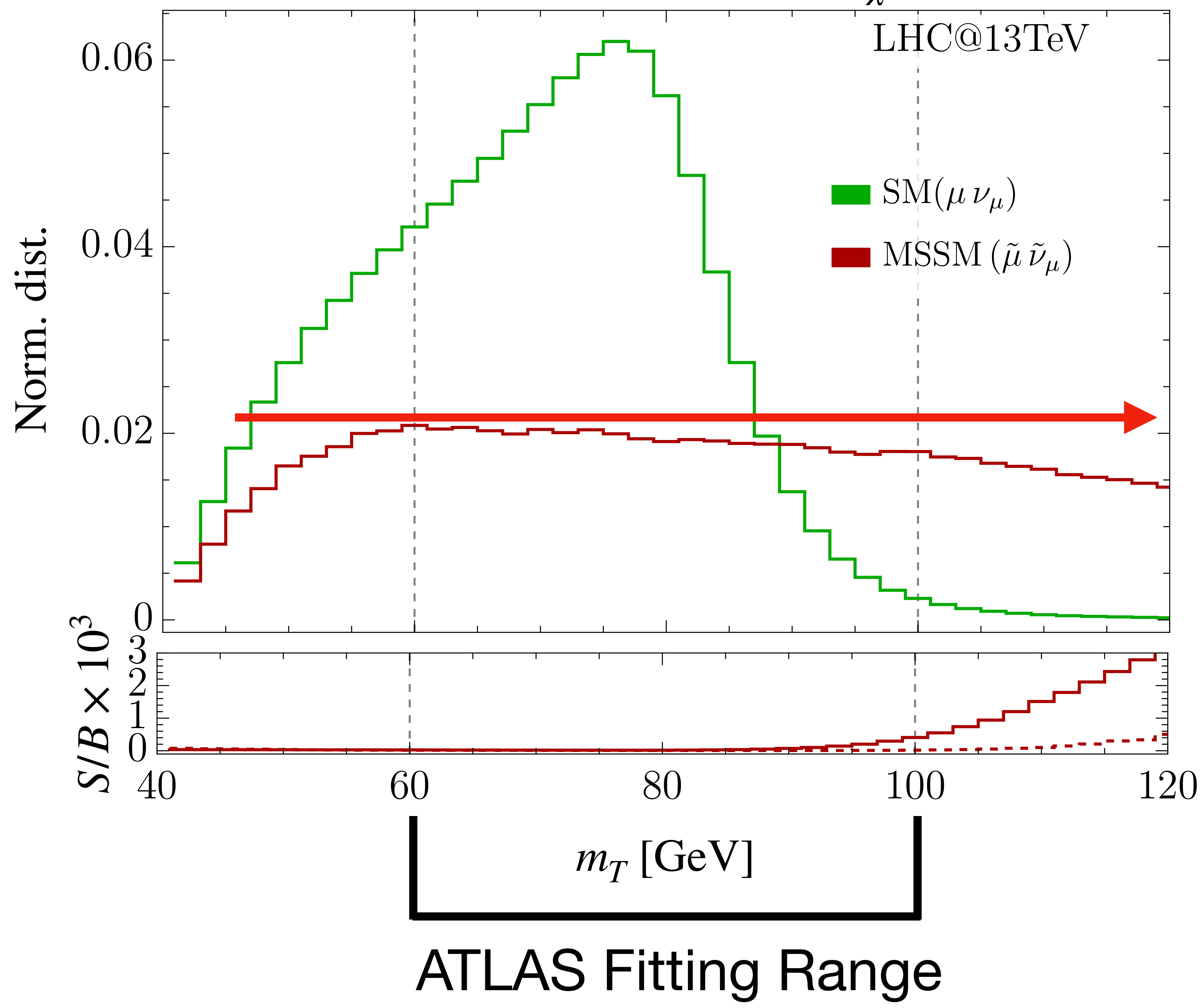


SUSY Tail Analysis

NP without on-shell W

- Extending to the tails of p_T^{ℓ}, m_T
  - background is now dominantly Drell-Yan (off-shell W) to lepton + neutrino
  - No longer normalizing the data

$m_{\tilde{l}} = 115$ GeV, $m_{\tilde{\nu}} = 83$ GeV, $m_{\tilde{\chi}} = 70$ GeV



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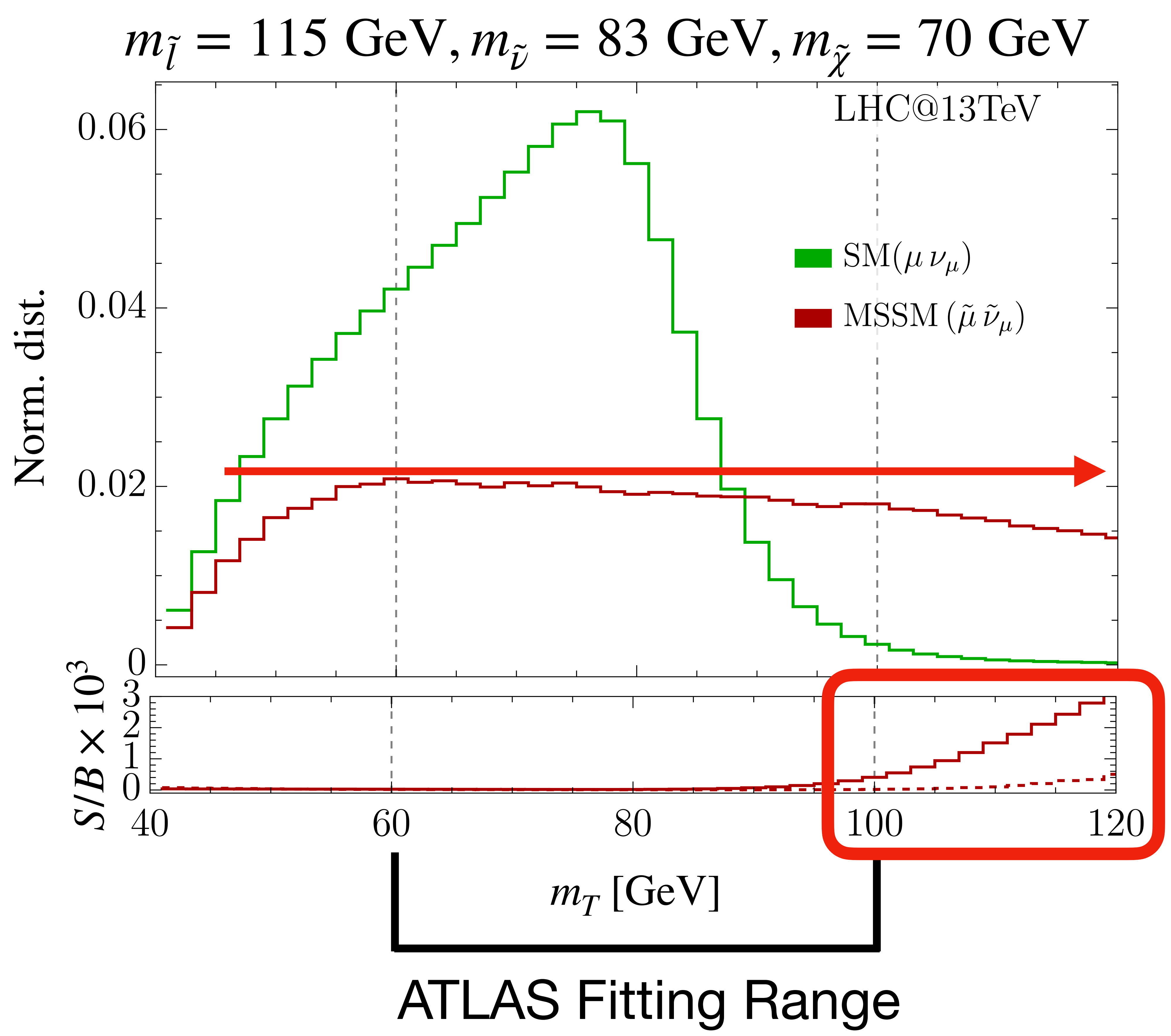
  - backgrounds are not as under control as in SM W analysis region
  - larger per-bin systematics
  - error on luminosity (correlated systematics)
  - other backgrounds



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- Sensitivity greatly improves since background is smaller, but…
  - backgrounds are not as under control as in SM W analysis region
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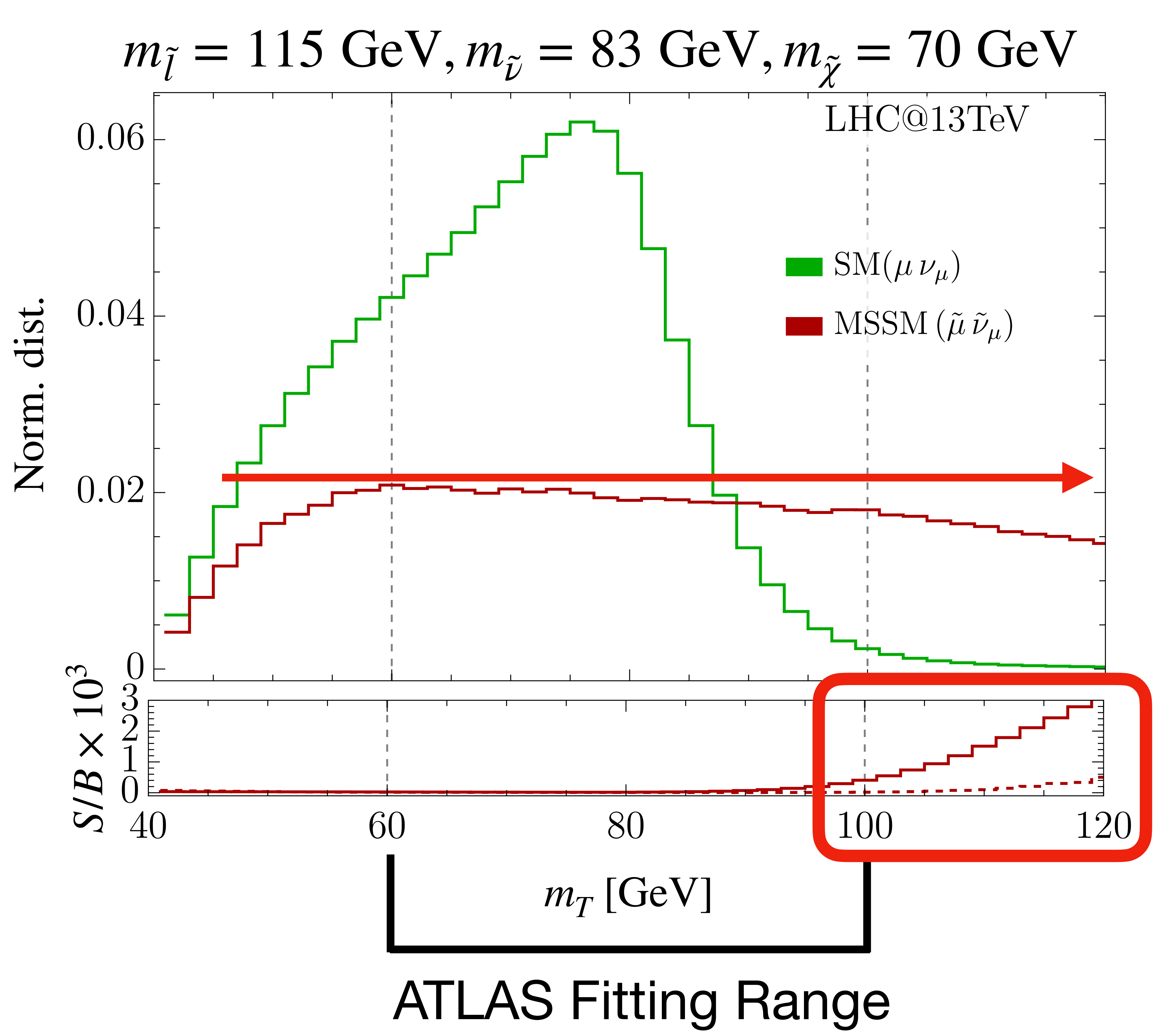
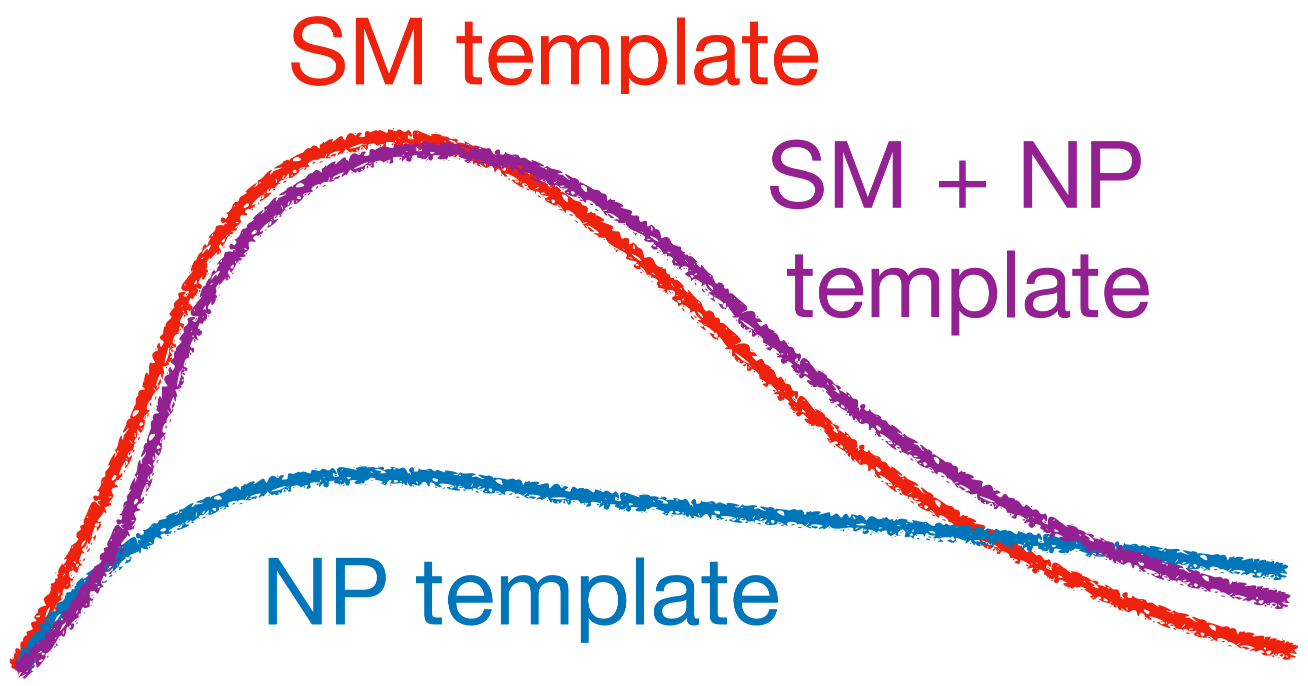
  - error on luminosity (correlated systematics)
  - other backgrounds
- Could a recasted W' search work for SUSY sleptons?
  - Still investigating



Brief summary of our idea

- Experiments performed precise measurements of m_W using kinematic observables p_T^ℓ, m_T
    - Measured distributions agree with SM templates
- Any NP producing $\ell + mET$ final state could contaminate the measured sample, and should be added to the template
- Sensitive to NP that produces different kinematics in p_T^ℓ, m_T compared to measured sample
- Adding NP requires a simultaneous fit to NP parameters and m_W
- 3 categories of NP contamination: anomalous W decay, anomalous W production, and $\ell + mET$ without on-shell W



Conclusions

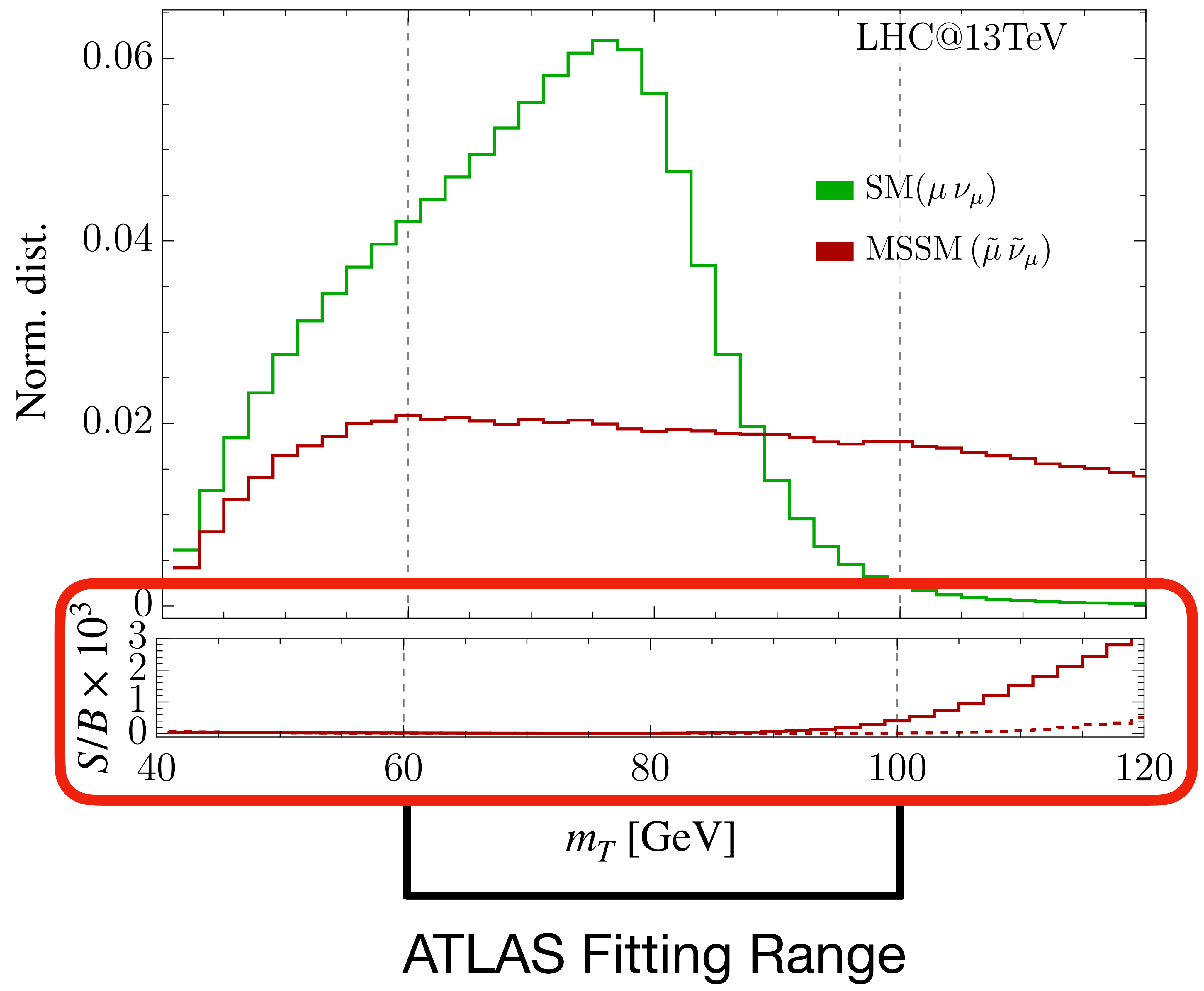
- A new purpose for precision W-mass measurements: constraining NP that produces the same $\ell + mET$ final state yet modifying the measured kinematic observables
- Sensitivity to unexplored parameter space for MSSM sleptons!!
- Ongoing work:
  - Further analysis on other models
  - Extending the range of p_T^{ℓ}, m_T beyond SM W possibly constrains SUSY sleptons further

Thank you!

Backup Slides

More details on Z contamination

- Estimating the Z contamination
  - toy model approach, not what experimentalists would actually do
  - Simulate NP in $Z \to l\bar{l}$ sample, then impose invariant mass cut $80 < m_{l\bar{l}}$ [GeV] < 100
    - cut kills most, but not always all of the signal
  - Treat one of the leptons as invisible, and compute m_T of that event
  - Show S/B of the m_T from contamination of $Z \to l\bar{l}$ to m_T of W



W Decay Width

- CDF fixed W decay width when measuring m_W
- ATLAS treats it as a nuisance parameter
  - reports uncertainty in m_W from Γ_W to be 2-7 MeV

Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3

- for simplicity, we fix the decay width like CDF, expecting any shift in gamma to be negligible