(Theory) Adventures with Wmass

Zhen Liu
University of Minnesota

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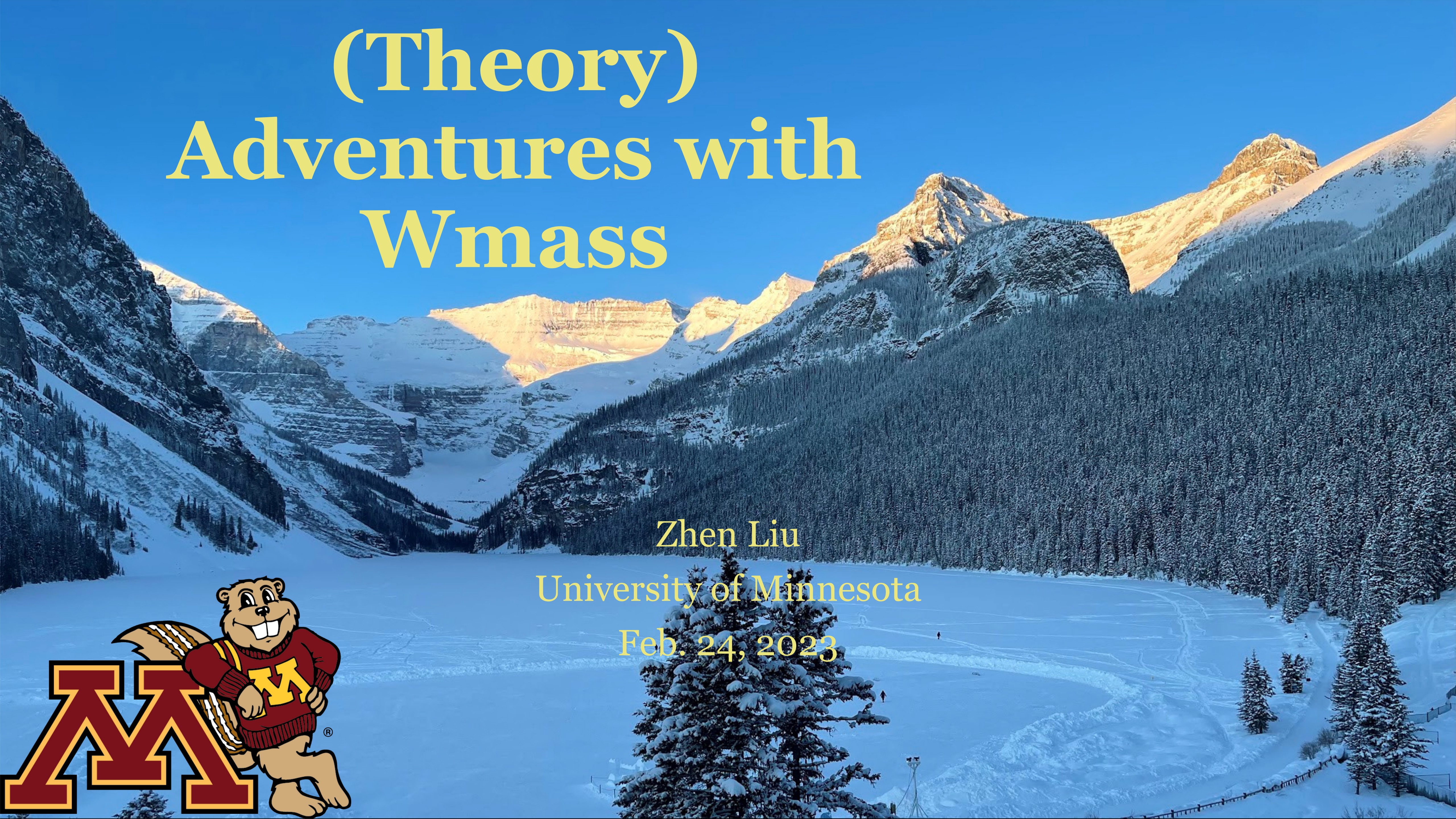
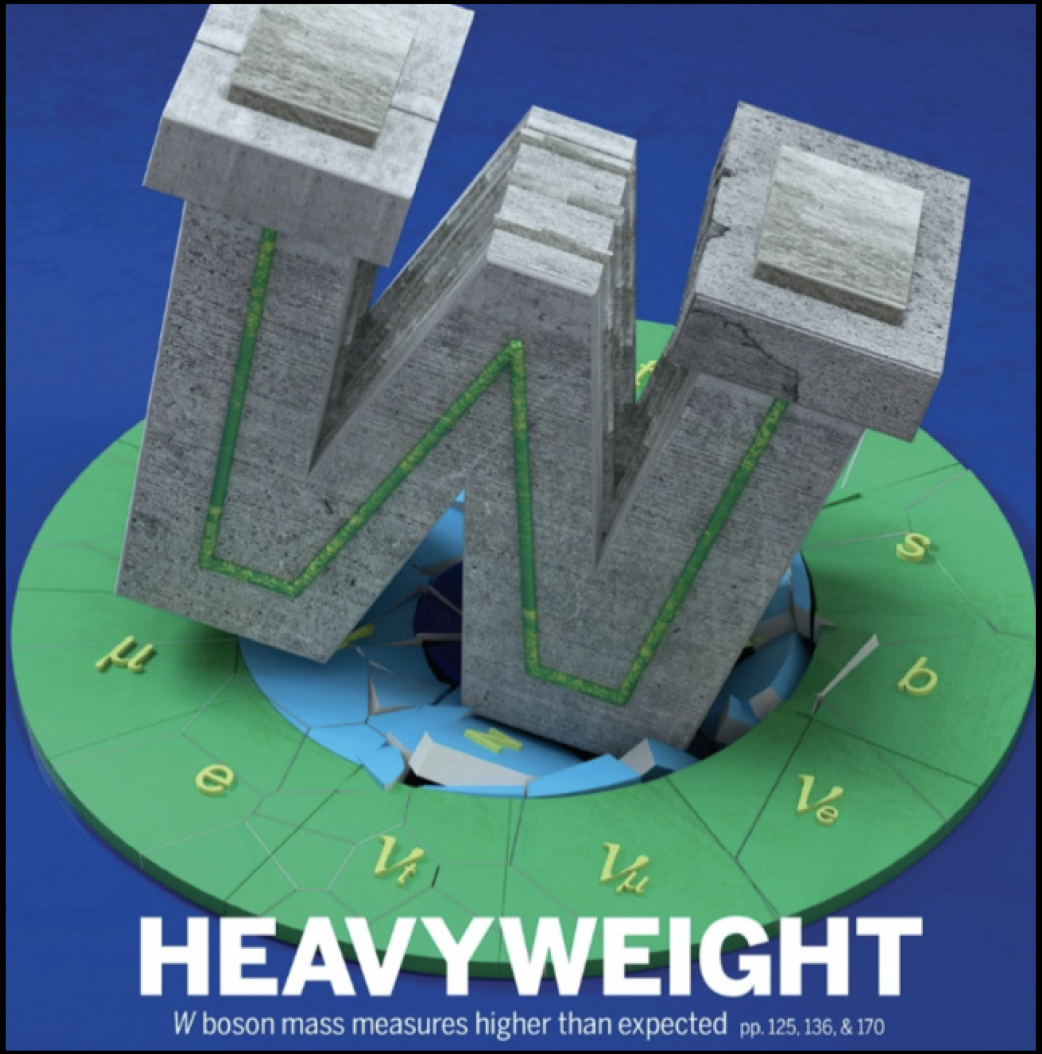


Outline

- CDF Measurement
- Theory Assessment
  - Tension with SM
  - What did we measure?
    - Various critics & updates
  - BSM interpretations
  - Future



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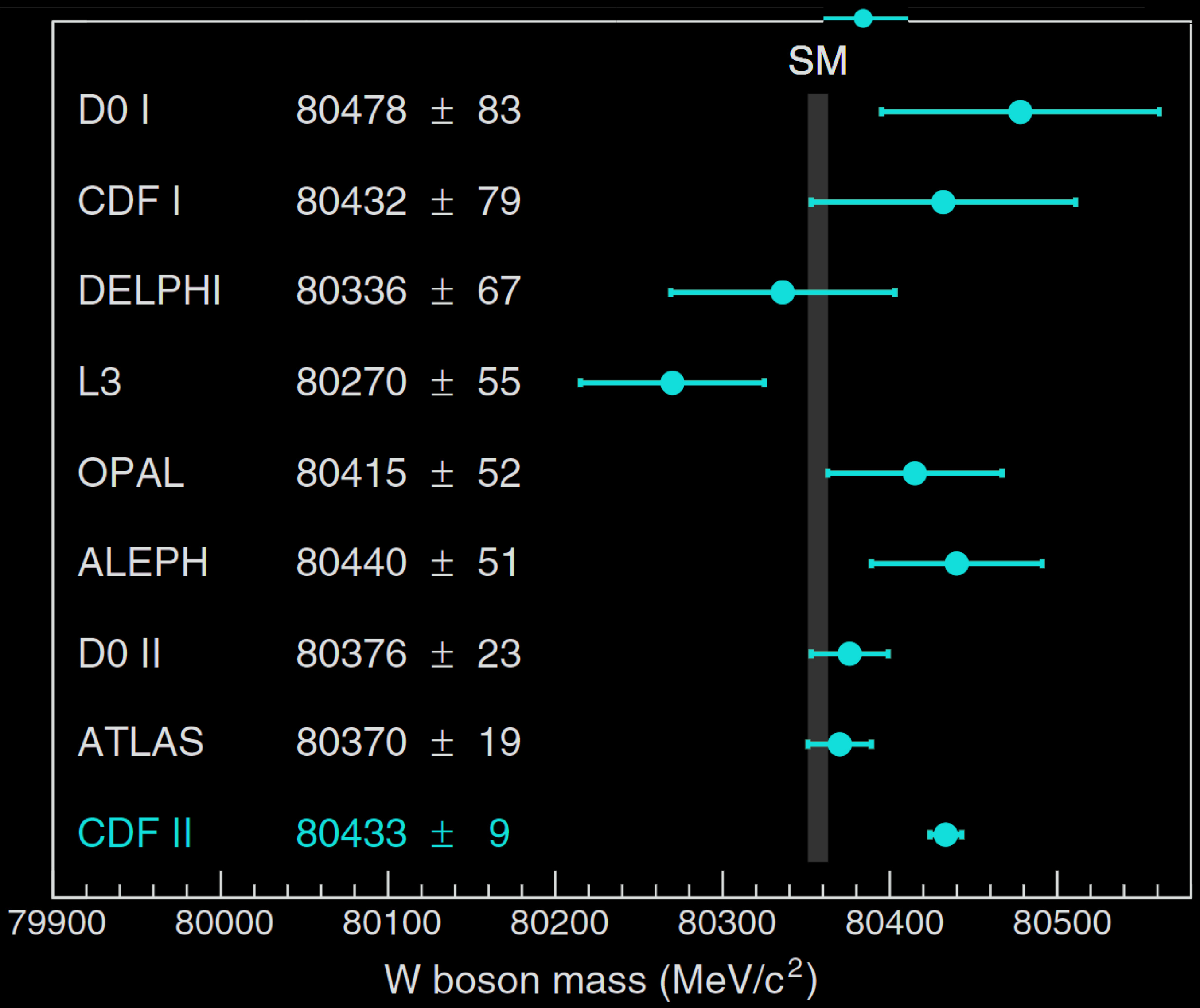
Tension with other experiments

- 7 σ tension with SM (discuss later)
- ~3 σ tension with other experiments

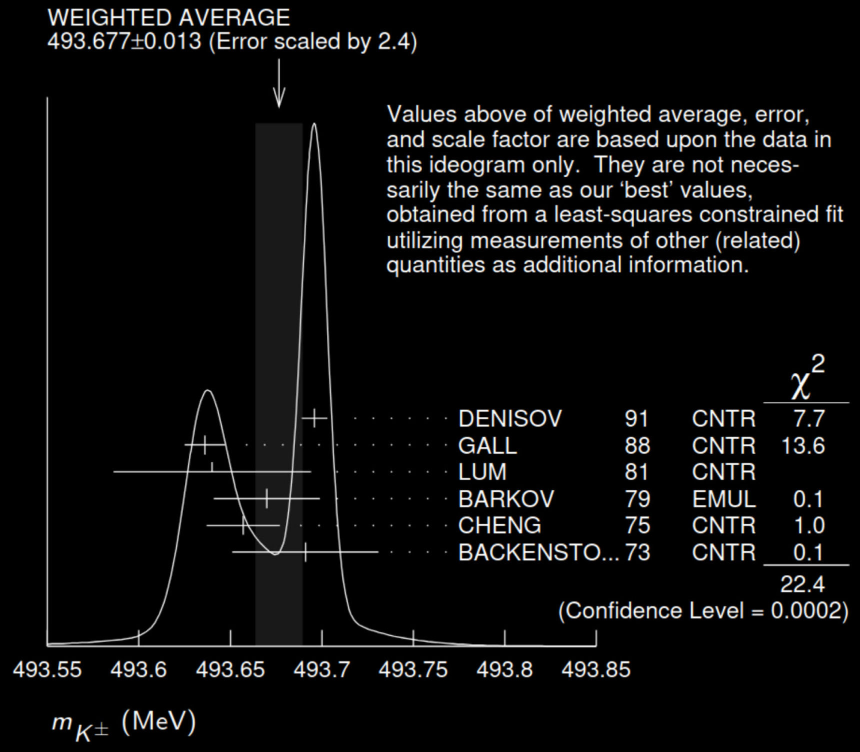
LHCb: 80,354 ± 32 MeV

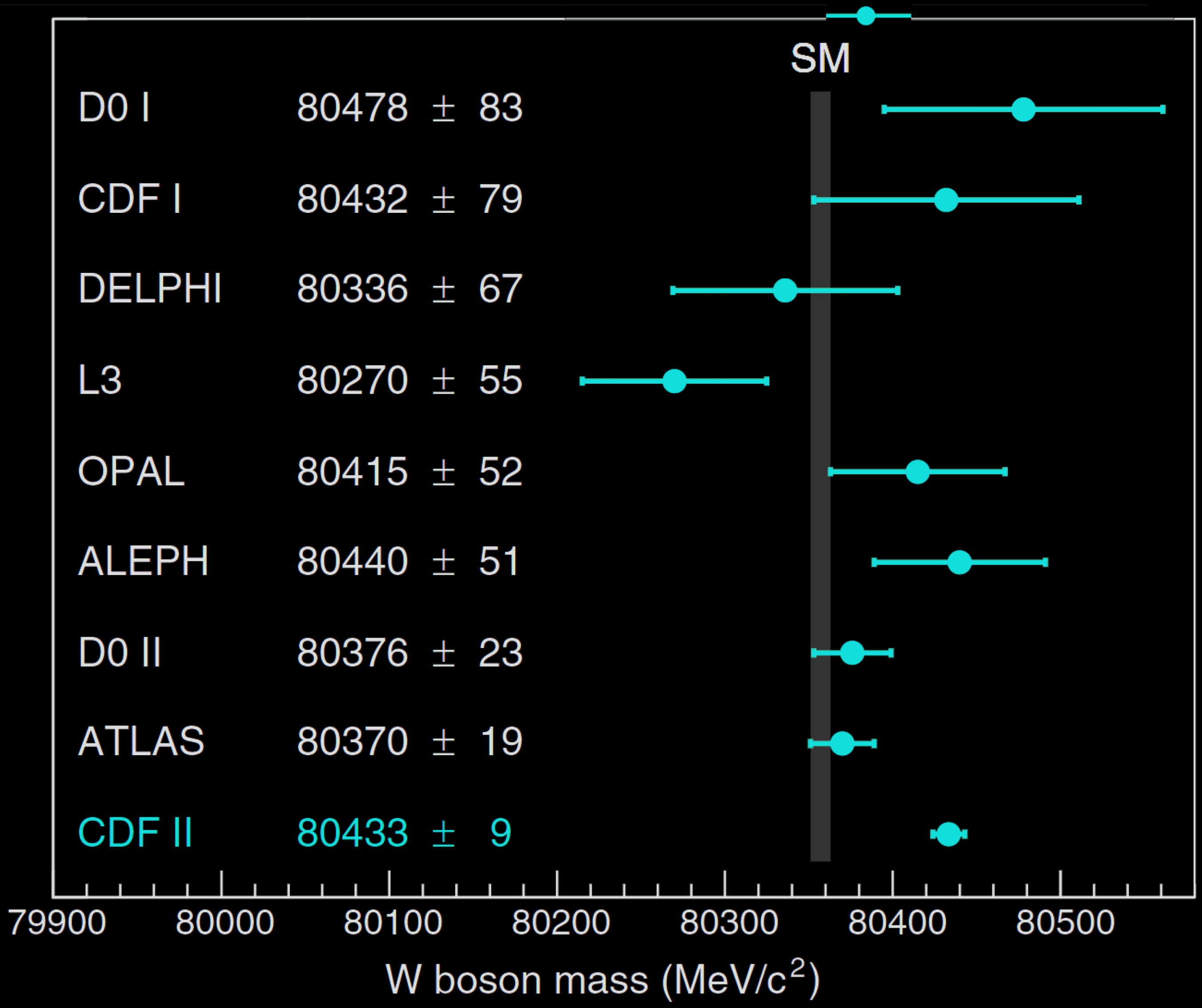


Tension with other experiments

also LHCb: 80,354 ± 32 MeV

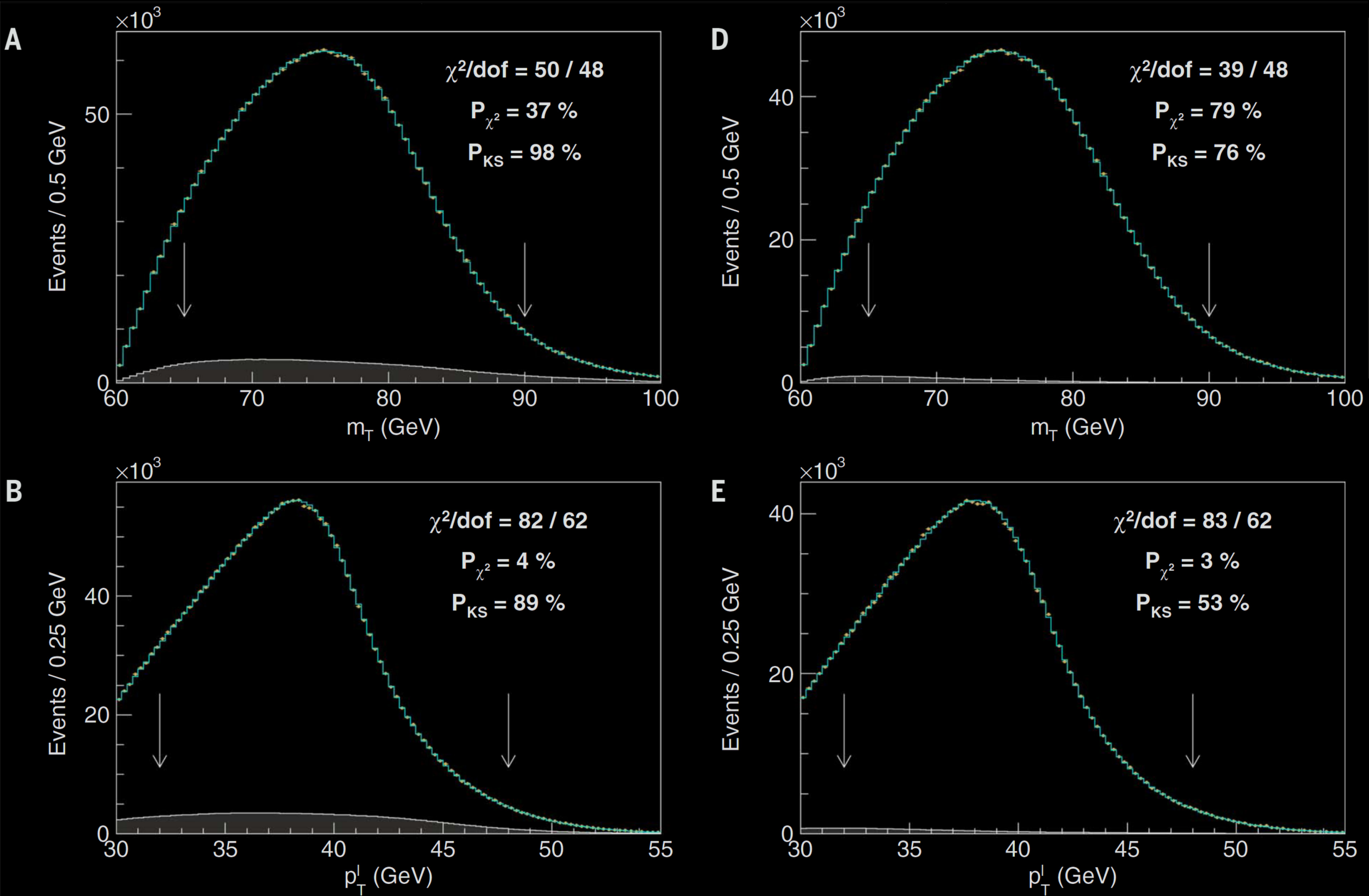
- (If we roughly combine, non-officially, 3 σ tension with SM)
- ~80,410 ± 15 MeV*
- Larger error bars as a result of incompatible measurements.





*Falkowski 22'

CDF Measurement



Distribution	W boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80{,}429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^\ell(e)$	$80{,}411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^\nu(e)$	$80{,}426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu,\nu)$	$80{,}446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^\ell(\mu)$	$80{,}428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^\nu(\mu)$	$80{,}428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

- $M_T = \sqrt{2\left(p_T^\ell p_T^\nu - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu}\right)}$
- p_T^ℓ
- p_T^ν with $(\vec{p}_T^{\,\nu} = -\vec{p}_T^{\,\ell} - \vec{u}_T)$

CDF II extracted the W mass with high precision energy measurements, via templates fits of various distributions, with fixed Γ_W (a SM single parameter fit).

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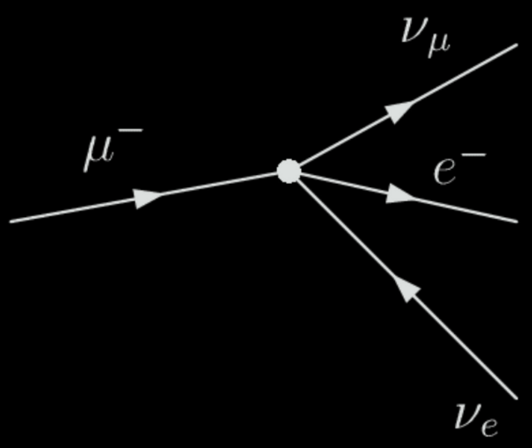
Tension with SM

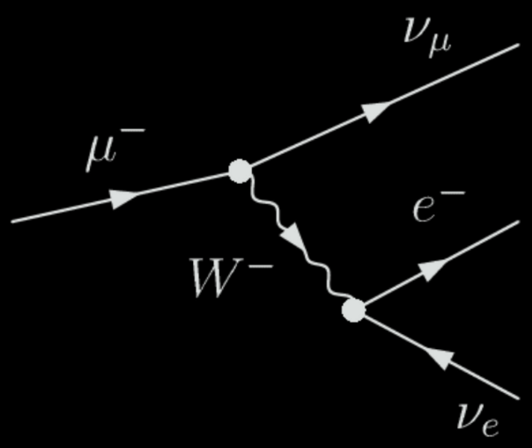
$M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

$\Updownarrow$

loop corrections





SM is over-constrained (hence highly predictive).
We are testing it from all angles!
Precision directly probes new physics.

Parameter	Fit Result
G_μ [GeV^{-2}]	1.1663787×10^{-5}
$\alpha(0)^{-1}$	137.035999139
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	0.027627 ± 0.000096
M_Z [GeV]	91.1883 ± 0.0021
M_H [GeV]	125.21 ± 0.12
m_t [GeV]	172.75 ± 0.44
M_W [GeV]	80.3591 ± 0.0052

Sven Heinemeyer – IDT-WG3-Phys Open Meeting on M_W, 12.05.2022

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What we want & what we measure?

The pole mass with a kinematic meaning.

A template fit to Monte Carlo event generator input parameter.

Good news: both are about kinematics.

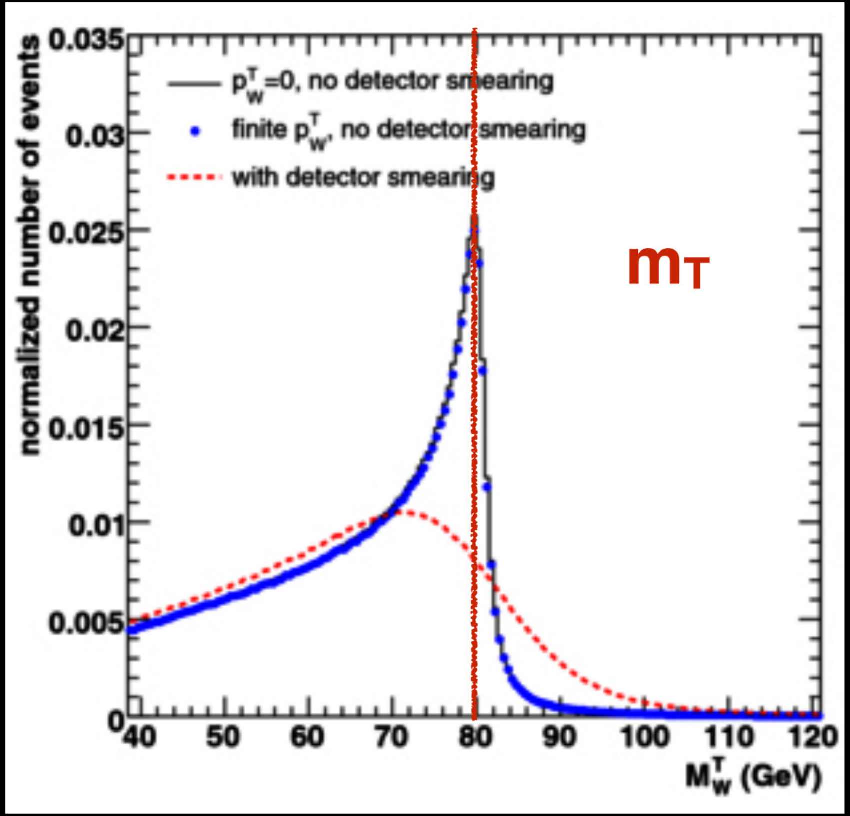
This is why mT & kinematics are important.

But physics is subtle… in particular, when hyper-precise

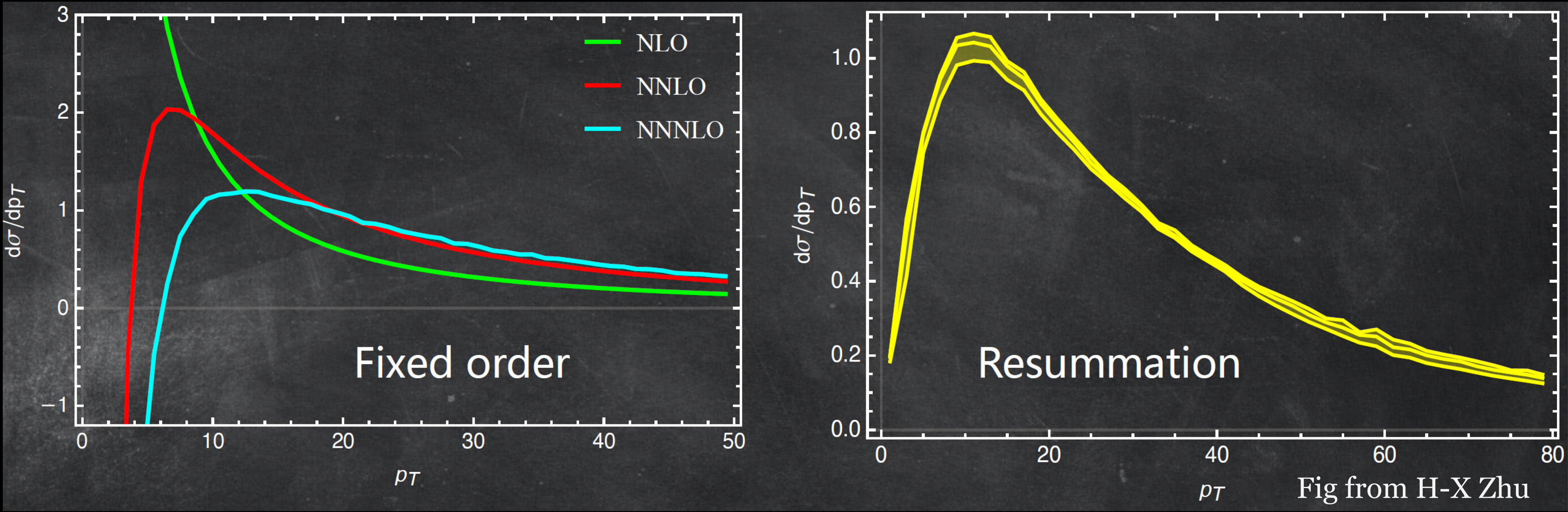
Let's take a closer look:

- Transverse mass has a Jacobian peak at mW in W-rest frame;
- Transverse mass is a boost (along beam direction) invariant quantity;
- The lab frame measurement is sensitive (& smeared by):
  - Resolution;
  - W-finite width;
  - PDF slope;
  - W-transverse momentum;
  - …

- $M_T = \sqrt{2\left(p_T^\ell p_T^\nu - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu}\right)}$
- p_T^ℓ
- p_T^ν with $(\vec{p}_T^{\,\nu} = -\vec{p}_T^{\,\ell} - \vec{u}_T)$



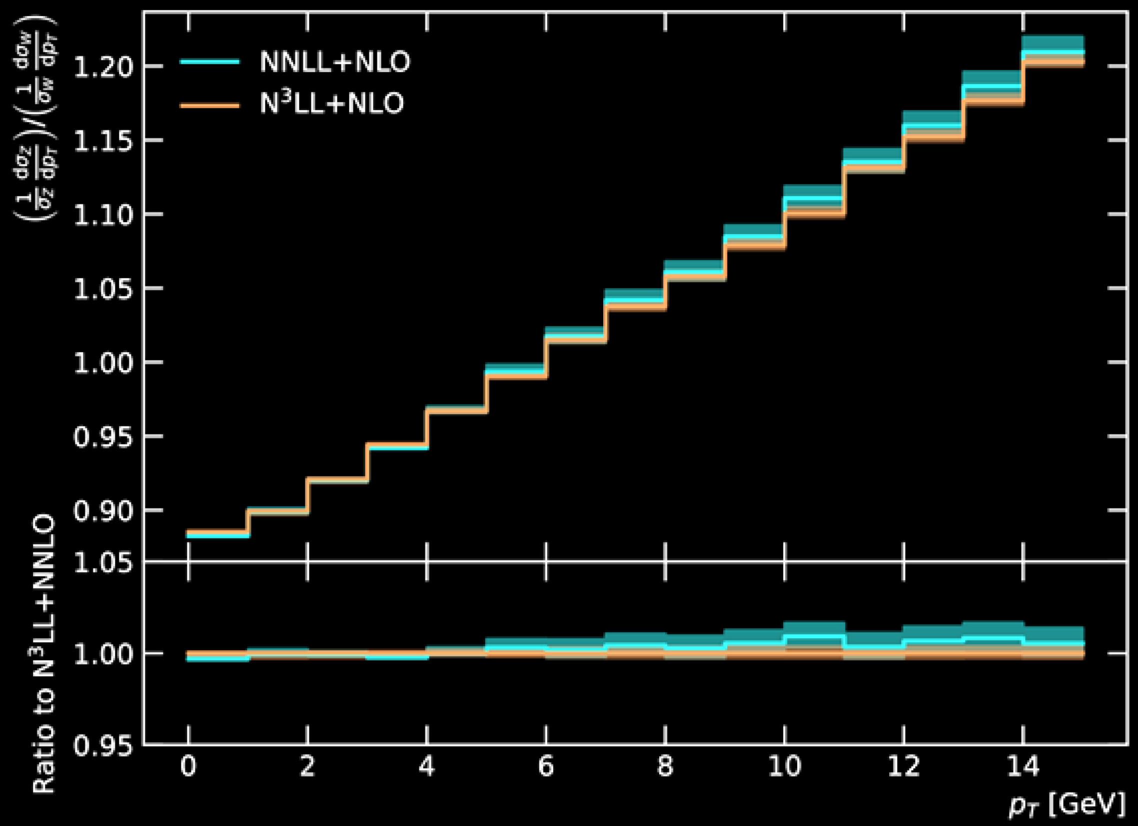
Necessary to Resum (schematical figure)



Fixed order calculation is good in large pT~Q
But small qT requires resummation to obtain physical results
pT_W is small.

Critics 1: CDF only used an old version of DY generator; available higher-order corrections were not taken into account.

Theory uncertainties



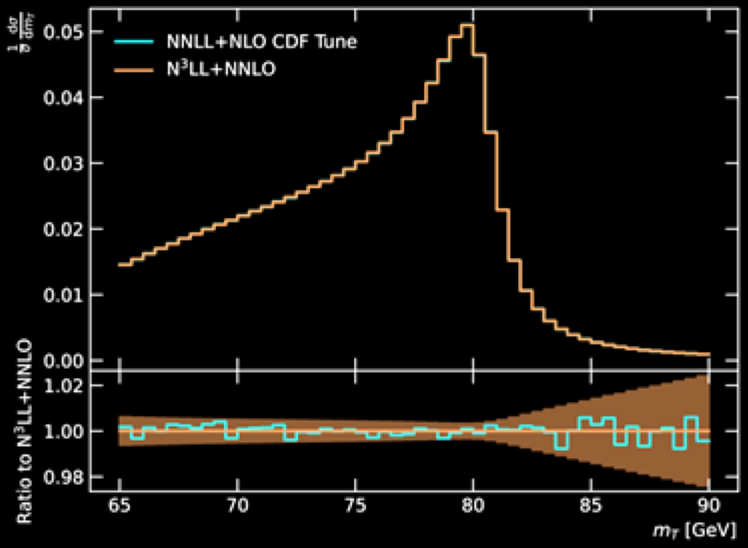
Rescaling W pT using Z pT

- Ratio is stable to higher order corrections at small p_T
- Scale uncertainty only using correlated prediction
- Need to investigate the CDF estimated uncertainty from this ratio

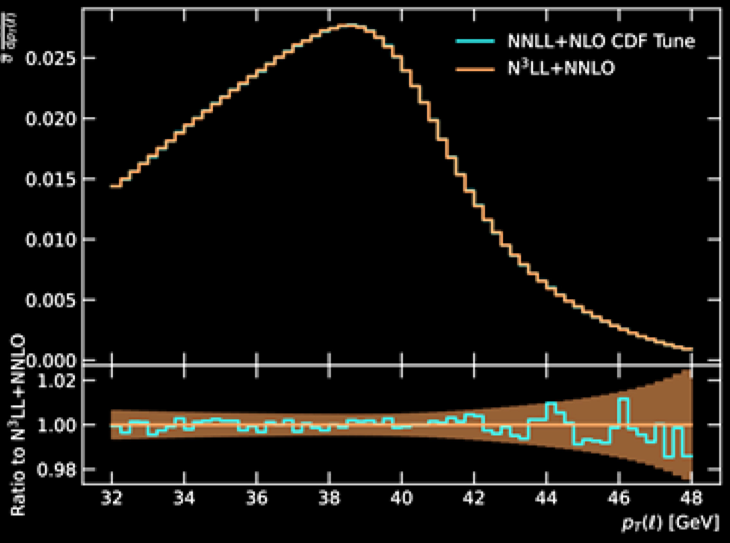
Issacson, Fu, Yuan, 2205.02788

Theory uncertainties

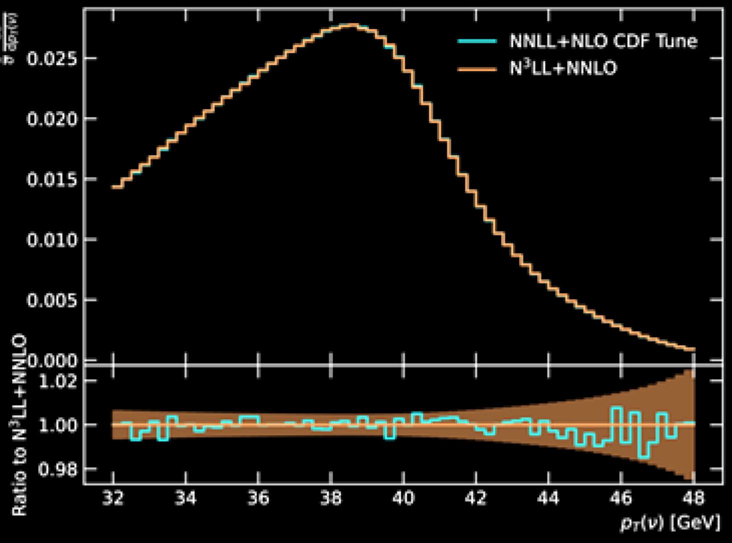
Issacson, Fu, Yuan, 2205.02788



Best Fit: $M_W = 80,386$ MeV



Best Fit: $M_W = 80,388$ MeV



Best Fit: $M_W = 80,389$ MeV

	Mass Shift [MeV]	
Observable	ResBos2	+Detector Effect+FSR
m_T	1.5 ± 0.5	$0.2 \pm 1.8 \pm 1.0$
$p_T(\ell)$	3.1 ± 2.1	$4.3 \pm 2.7 \pm 1.3$
$p_T(\nu)$	4.5 ± 2.1	$3.0 \pm 3.4 \pm 2.2$

But resummation is enough

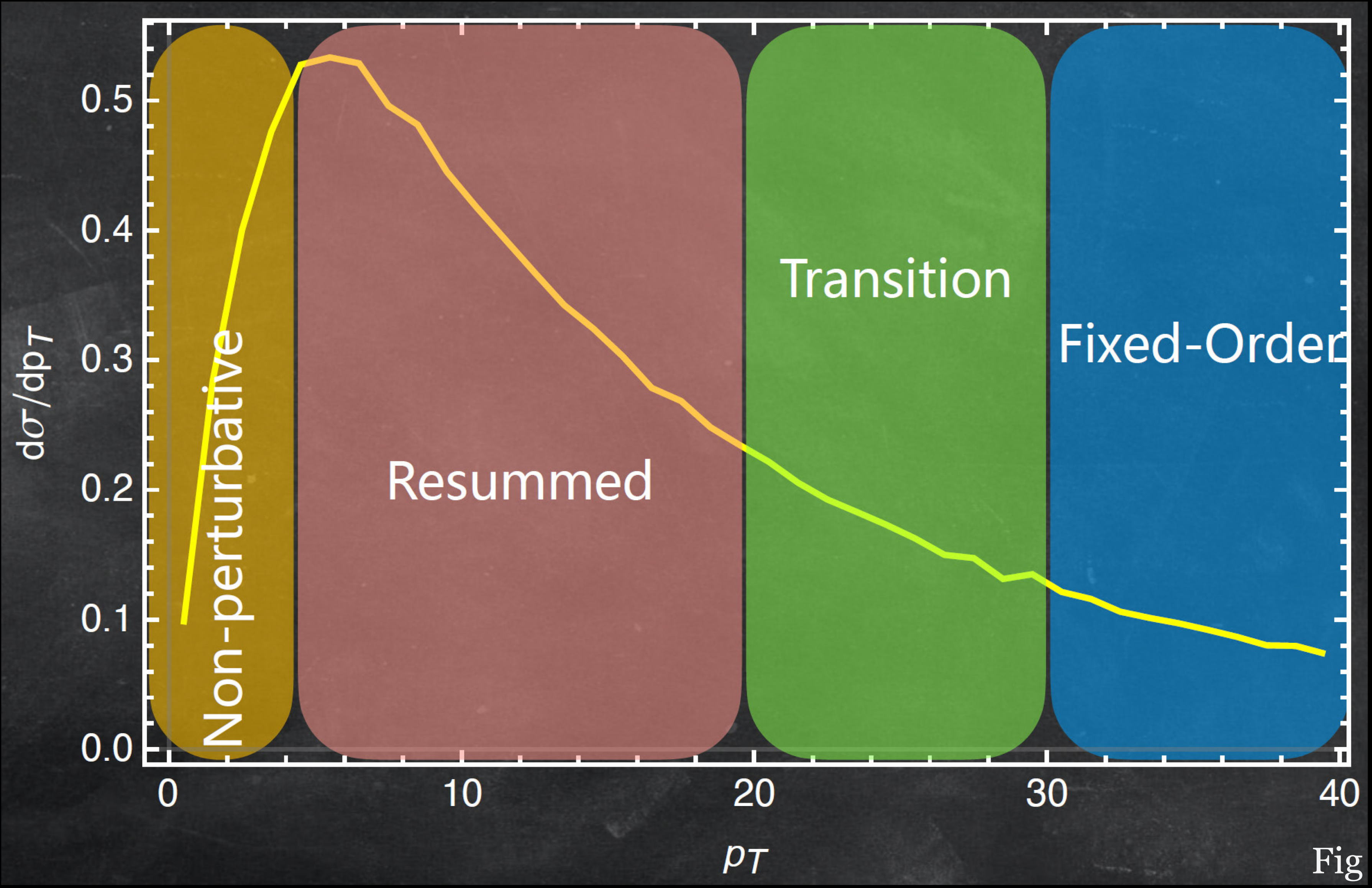


Fig from H-X Zhu

Not a critic: non-perturbative effects makes it hard to predict the shapes. We uses the Z-boson to calibrate.

Critics 2: CDF only used an old PDF set to generate templates. They “rescaled” to newer PDFs have a very small assigned PDF uncertainty.

PDF uncertainty

PDFs are key inputs for precision programs at hadron colliders, e.g., precision electroweak measurements, searches for new physics beyond the SM, especially non-resonance signatures hiding in high mass tails

PDF unc. at LHCb, NNPDF3.1, CT18, MSHT20

$$m_W = 80362 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV},$$
$$m_W = 80350 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 12_{\text{PDF}}\ \text{MeV},$$
$$m_W = 80351 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 7_{\text{PDF}}\ \text{MeV},$$

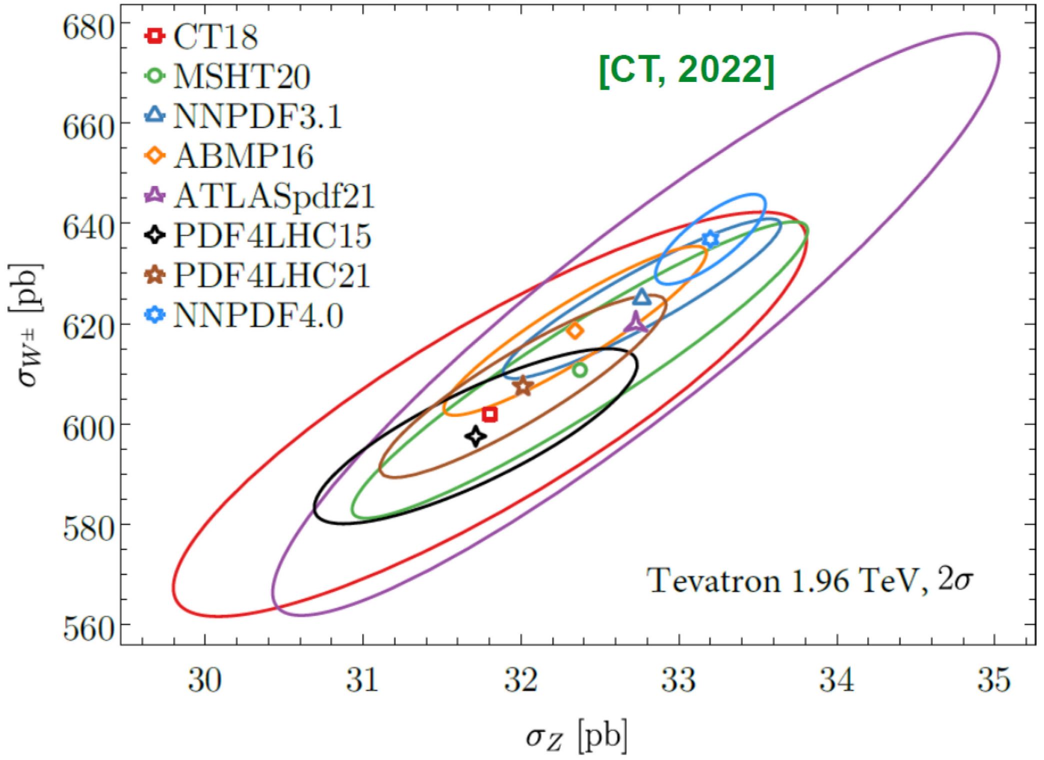
ATLAS, CT10 + 3.8 MeV (MMHT14-CT14)

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5

CDF, NNPDF3.1 only (3.9 MeV)

(other tested, CT18, MMHT14, +-2.1 MeV)

W/Z fiducial cross sections at Tevatron (95% C.L.)

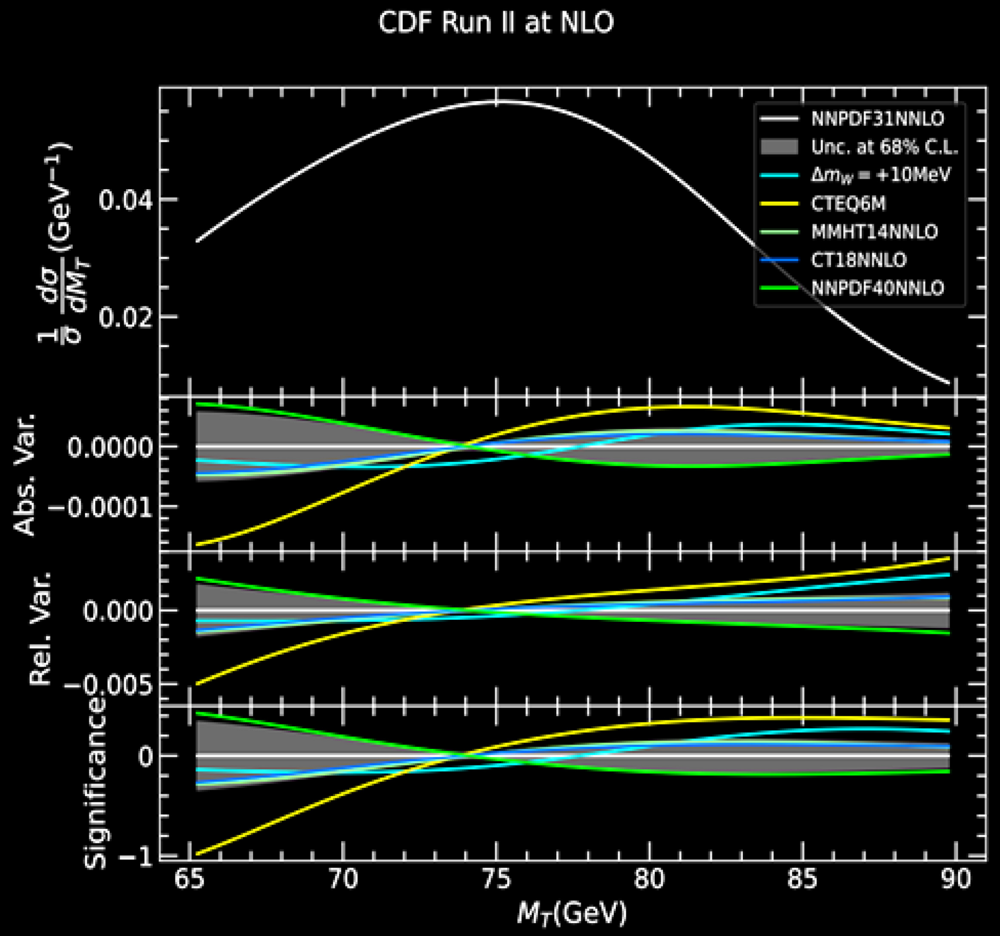


spread of predictions from different PDFs could be much larger than the PDF unc. of a specific set
even for the same group the PDF unc. not necessarily decrease with time

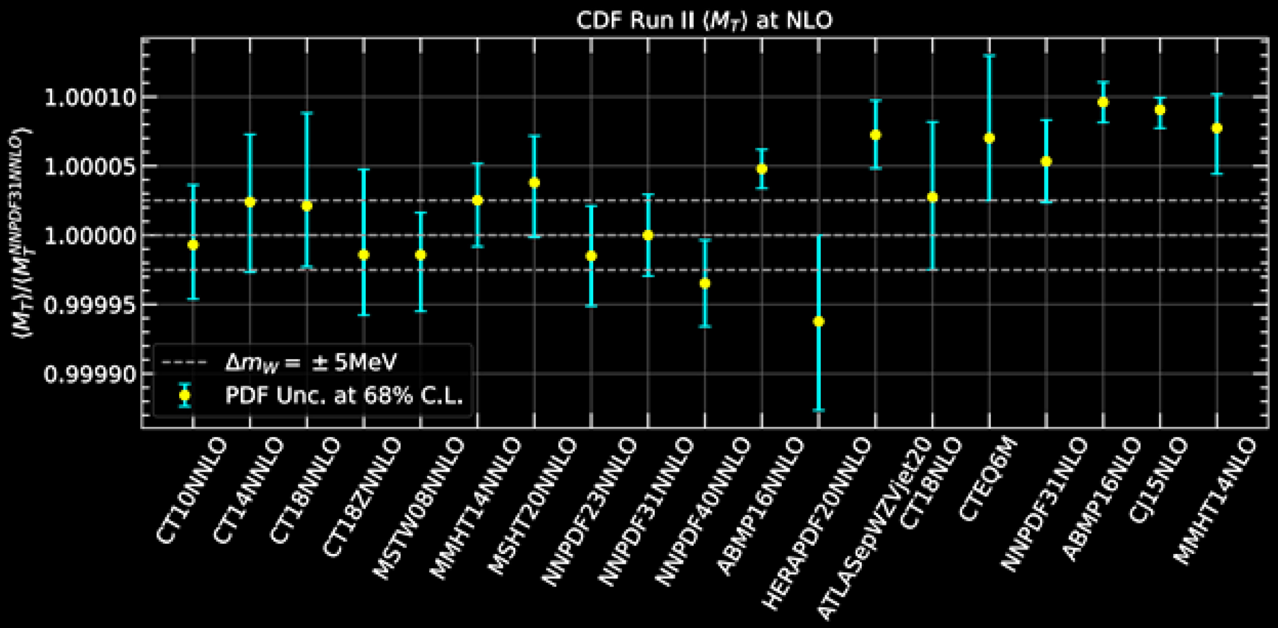
PDF Uncertainties

Gao, Liu, Xie, 2205.03942

normalized m_T distribution
PDF var. vs. M_W var.



mean value of m_T



estimate shift and PDF unc. of W mass

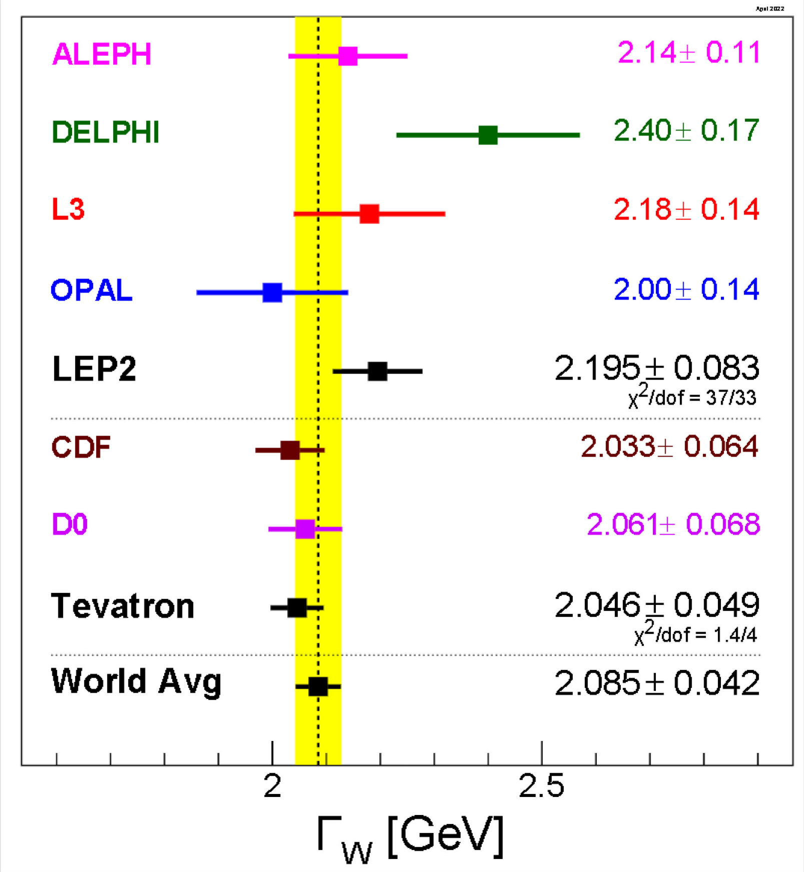
δM_W in MeV	sta.	NNPDF3.1	CT18	MMHT2014	NNPDF4.0	MSHT2020
$\langle M_T \rangle$(LO)	–	$0^{+8.3}_{-8.3}$	$-1.0^{+8.3}_{-11.4}$	$-3.3^{+7.4}_{-4.2}$	$+7.8^{+5.1}_{-5.1}$	$-3.1^{+6.7}_{-5.7}$
χ^2 fit (LO)	8.0	$0^{+7.6}_{-7.6}$	$-1.0^{+5.4}_{-8.6}$	$-3.3^{+6.1}_{-3.0}$	$+8.0^{+3.7}_{-3.7}$	$-3.0^{+5.0}_{-4.0}$
$\langle M_T \rangle$(NLO)	–	$0^{+5.9}_{-5.9}$	$-4.2^{+8.8}_{-13.3}$	$-5.0^{+6.7}_{-5.3}$	$+6.9^{+6.2}_{-6.2}$	$-7.6^{+7.9}_{-6.7}$
χ^2 fit (NLO)	8.0	$0^{+4.2}_{-4.2}$	$-4.3^{+5.4}_{-10.1}$	$-5.1^{+4.8}_{-3.4}$	$+7.1^{+4.5}_{-4.5}$	$-7.8^{+5.7}_{-4.5}$
CDF	9.2	$0^{+3.9}_{-3.9}$	–	–	–	–

Finite Width

Finite width will further distort the shape of distributions.

Current precision is dominated by prior CDF measurements.

In the CDF mW determination, it was fixed.



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SMEFT interpretations

Specifications/models		d.o.f.	χ^2		
			pre CDF-II	m_W^{combine}	$m_W^{\text{CDF-II}}$
	SM	(3)	31	62	76
EW fit	S-T	(3)+2	28	30	33
	S-T-δG_F	(3)+3	28	28	28
	Universal EW	(3)+8	17	17	17
BSM Models	Z'/W' ($\Delta S = 0.1$)[a]	(3)+1[b]	29 (28)	38 (33)	34 (31)
	VLQ Top I ($\Delta S = 0.1$)	(3)+2[c]	29 (29)	34 (32)	38 (34)
	VLQ Top II ($\Delta S = 0.1$)	(3)+2	28 (53)	33 (31)	37 (33)
	Top Squark	(3)+2[d]	28	31	34

Gu, ZL, Ma, Shu, 2204.05296

Tension with SM

$M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

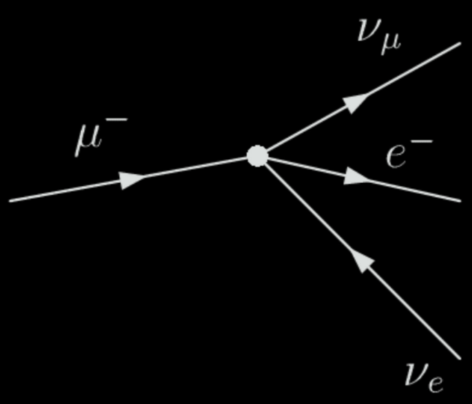
$\Updownarrow$

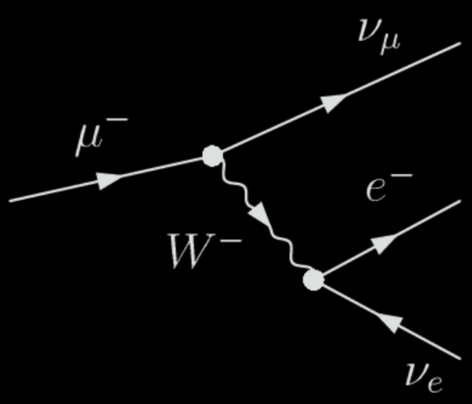
loop corrections

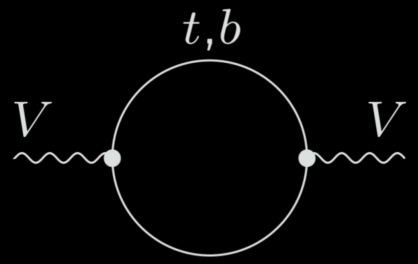
$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2 \qquad \log(M_H/M_W)$$

$$\sim 6\% \qquad \sim 3.3\% \qquad \sim 1\%$$





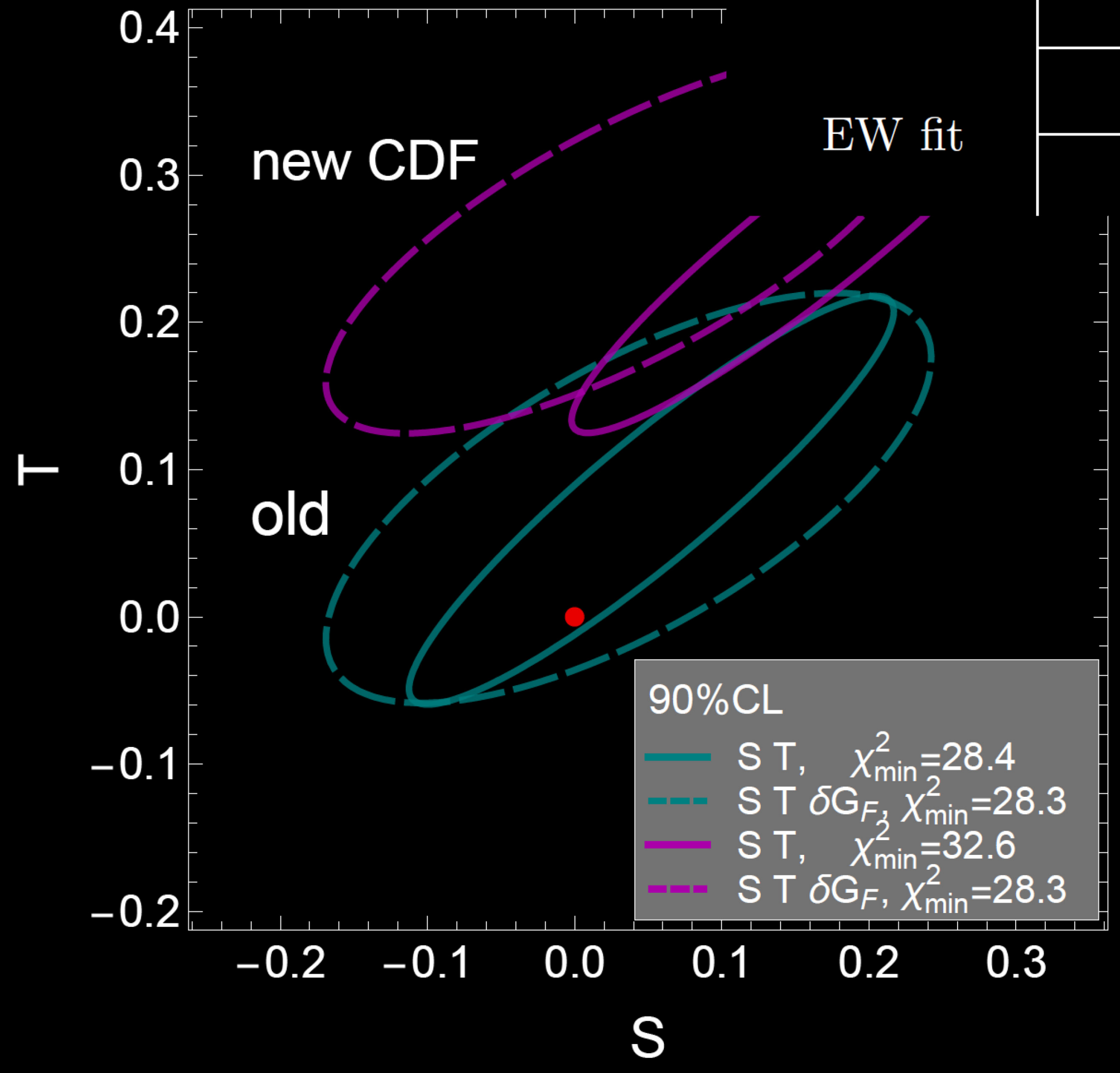


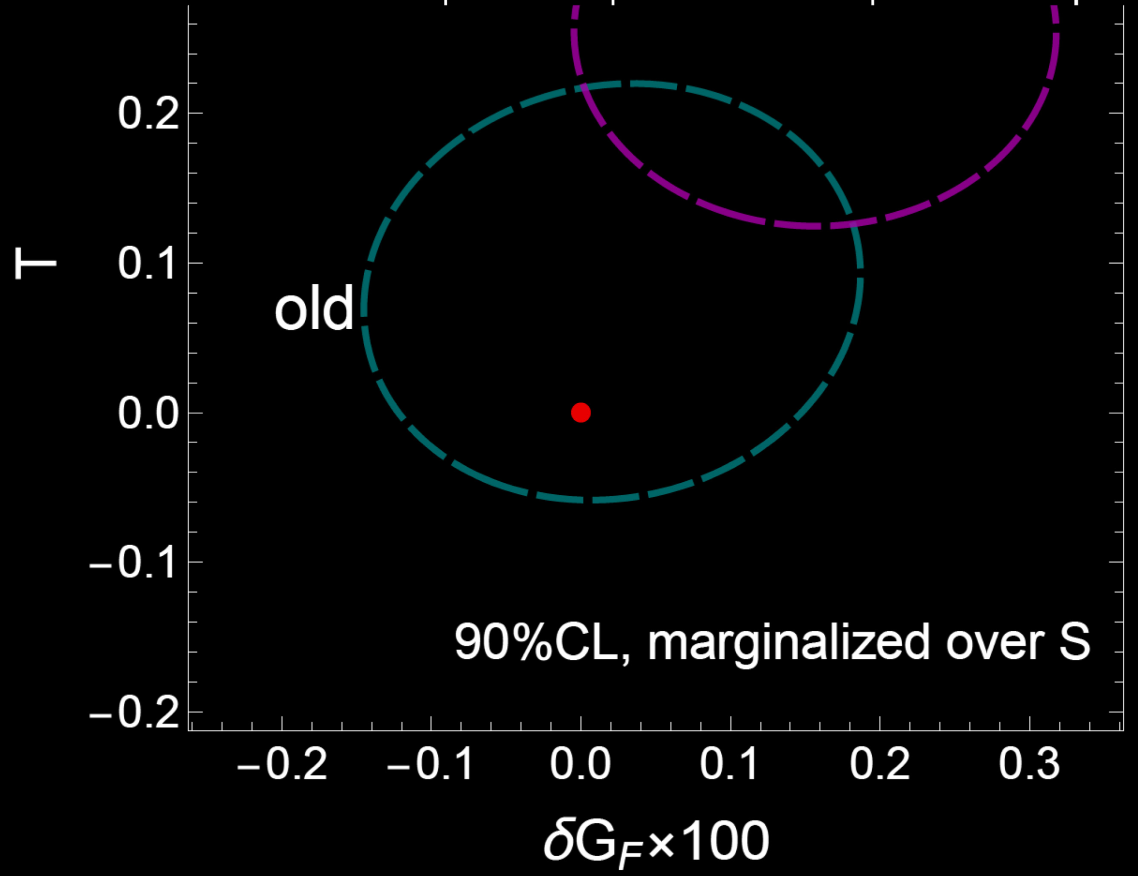
$$\delta m_W = \frac{1}{2c_{2w}}\left[c_w^2\,\hat{T} - s_w^2\left(\delta G_F + 2\hat{S}\right)\right]$$

$$\hat{S} = \frac{\alpha}{4s_w^2}S\,, \qquad \hat{T} = \alpha T\,.$$

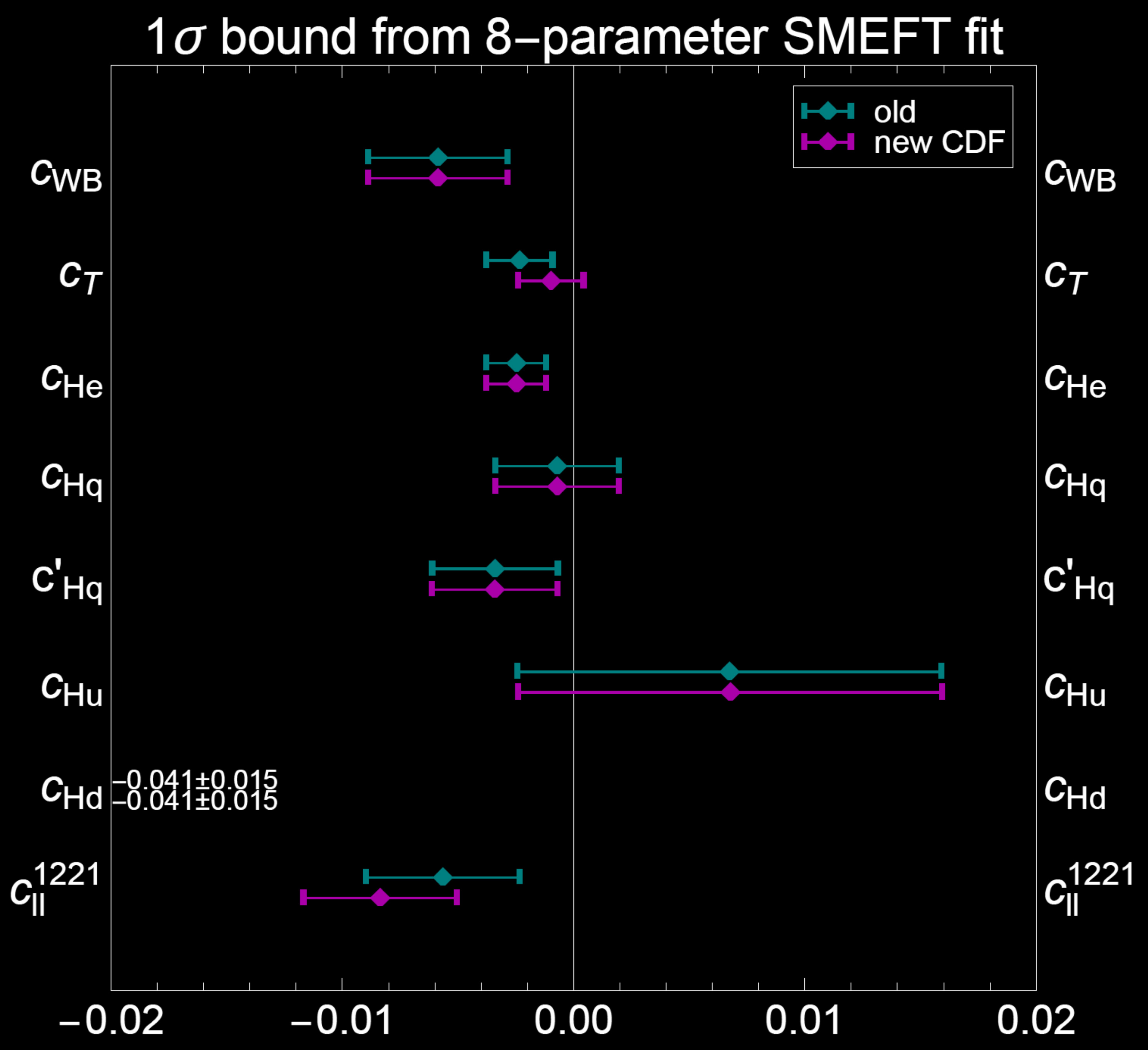
SMEFT results

	Specifications/models	d.o.f.	χ^2		
			pre CDF-II	m_W^{combine}	$m_W^{\text{CDF-II}}$
EW fit	SM	(3)	31	62	76
	S-T	(3)+2	28	30	33
	S-T-δG_F	(3)+3	28	28	28





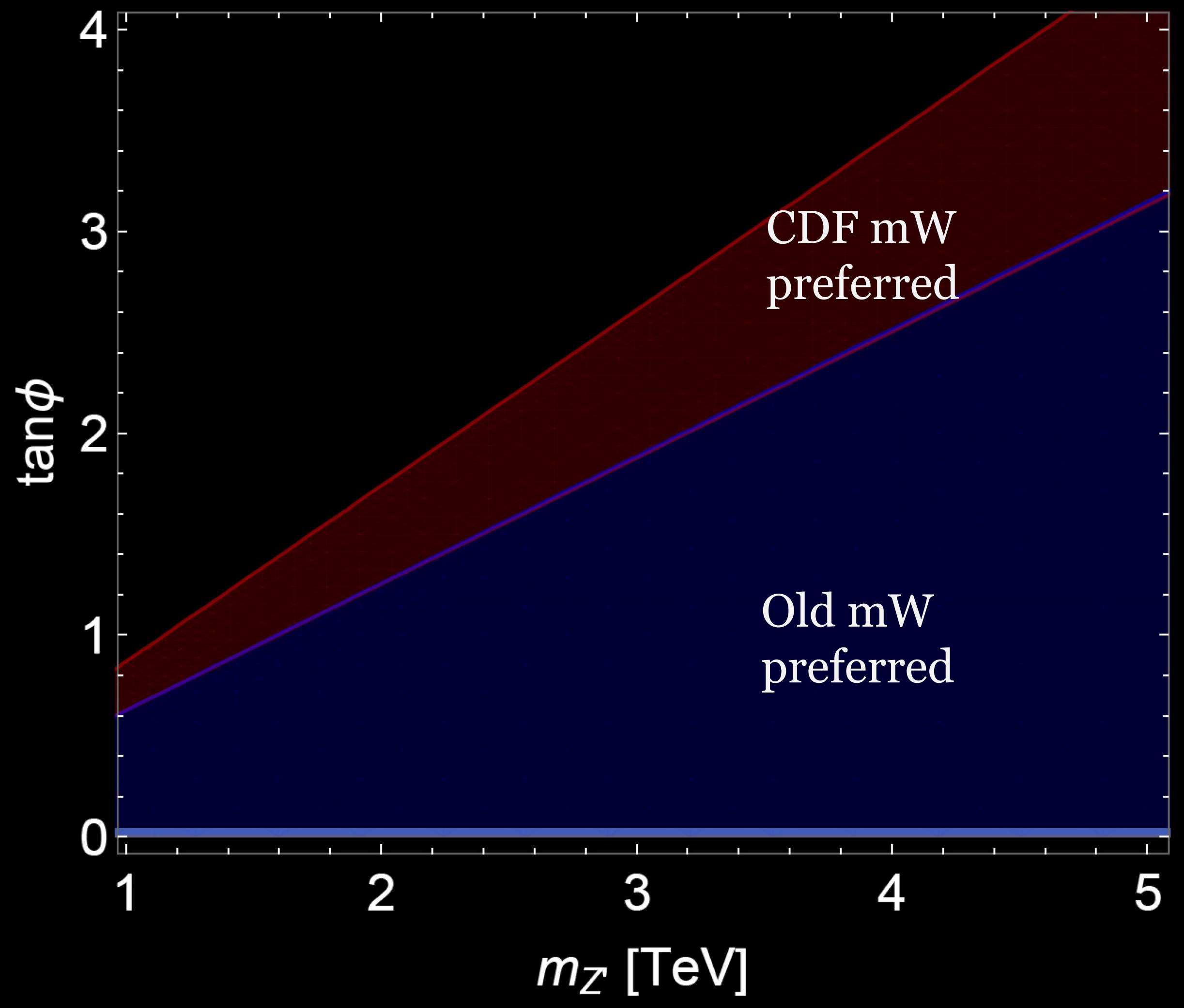
8-parameter "Global" SMEFT results



- Assuming flavor universality, SILH-like basis ($\mathcal{O}_{Hl}$ and $\mathcal{O}'_{Hl}$ are eliminated)
- Still prefers the same shift, but the 7σ is diluted... (Strong correlations among c_{WB}, c_T, c_{He} and $c_{\ell\ell}^{1221}$)
- Large deviation in c_{Hd} from the good-old LEP $A_{\rm FB}^b$ anomaly...

	1σ bounds (in %)		correlation matrix							
	old	new CDF	c_{WB}	c_T	c_{He}	c_{Hq}	c'_{Hq}	c_{Hu}	c_{Hd}	$c_{\ell\ell}^{1221}$
c_{WB}	-0.59 ± 0.30	-0.59 ± 0.30	1	0.96 (0.97)	0.96	-0.091	-0.25	-0.16	0.11	0.91
c_T	-0.23 ± 0.14	-0.10 ± 0.14		1	0.93	-0.07	-0.20	-0.16	0.15	0.78 (0.80)
c_{He}	-0.25 ± 0.13	-0.25 ± 0.13			1	-0.12	-0.29	-0.14	0.05	0.85
c_{Hq}	-0.07 ± 0.27	-0.07 ± 0.27				1	-0.30	0.60	0.38	-0.13
c'_{Hq}	-0.34 ± 0.27	-0.34 ± 0.27					1	-0.69	0.58	-0.33
c_{Hu}	0.67 ± 0.92	0.68 ± 0.92						1	-0.07	-0.11
c_{Hd}	-4.1 ± 1.5	-4.1 ± 1.5							1	-0.02
$c_{\ell\ell}^{1221}$	-0.56 ± 0.33	-0.84 ± 0.33								1

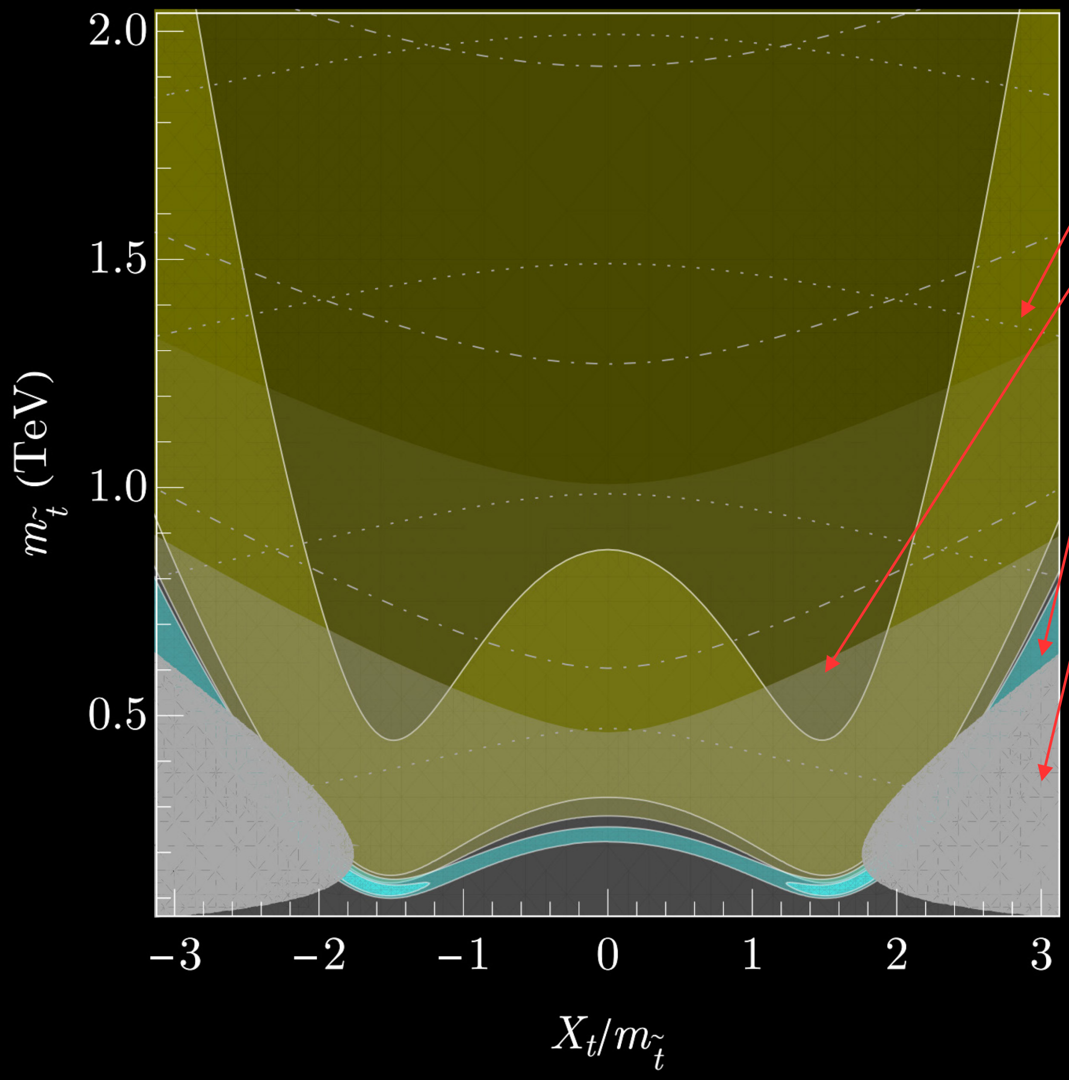
Tree-level new bosons



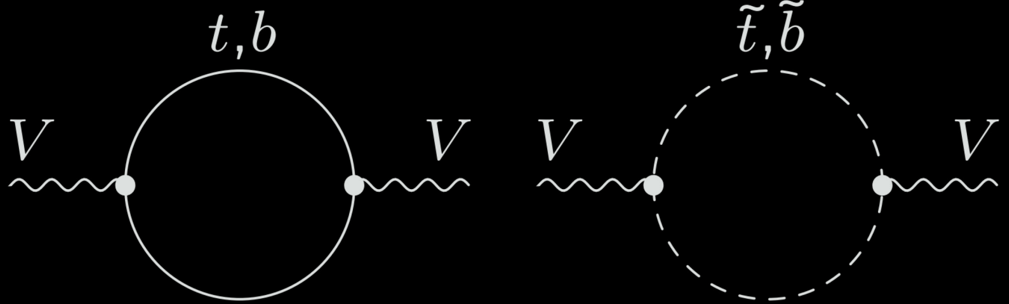
$SU(2)_L \times SU(2)_R \times U(1)_X$
$\to SU(2)_L \times U(1)_Y$

Z', W' generates T at tree-level.
One needs to avoid direct resonance searches by engineering partially mixed leptons to suppress leptonic searches.

Top squarks (degenerate)



Preferred by CDF
Preferred by old mW
Stop1 less than 400 GeV (current bound; more later)
Tachyonic Stop

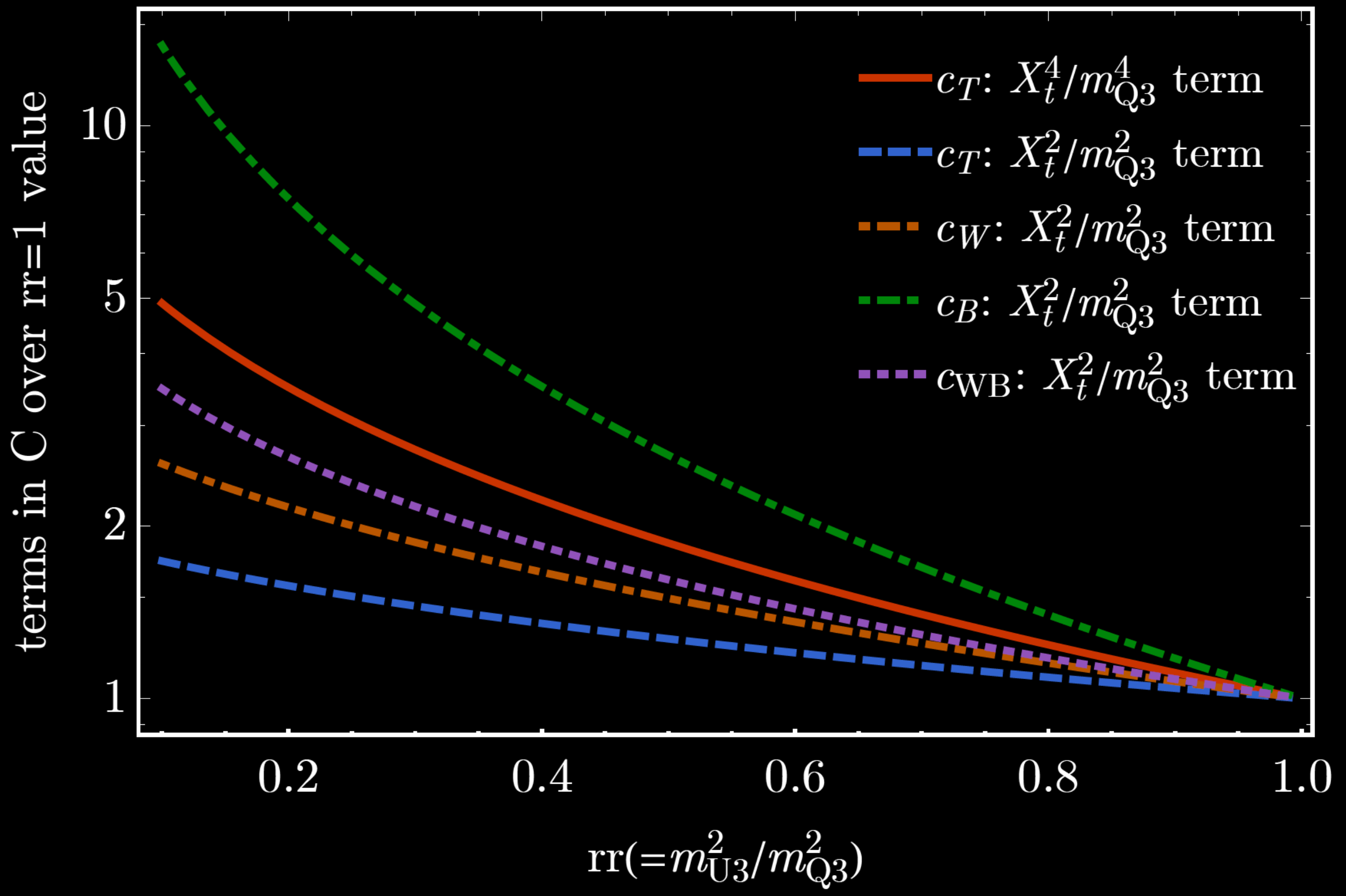


$$c_T = \frac{h_t^4}{64\pi^2 m_{\tilde{t}}^2}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)^2 - \frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right) + \frac{1}{10}\frac{X_t^4}{m_{\tilde{t}}^4}\right]$$

$$c_W = \frac{h_t^2}{640\pi^2 m_{\tilde{t}}^2}\frac{X_t^2}{m_{\tilde{t}}^2}, \quad c_B = \frac{h_t^2}{640\pi^2 m_{\tilde{t}}^2}\frac{X_t^2}{m_{\tilde{t}}^2}$$

$$c_{WB} = -\frac{h_t^2}{384\pi^2 m_{\tilde{t}}^2}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right) - \frac{4}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\right]$$

Degenerate Top Squark not working…



$$c_T = \frac{h_t^4}{64\pi^2 m_{\tilde t}^2}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)^2 - \frac{1}{2}\frac{X_t^2}{m_{\tilde t}^2}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right) + \frac{1}{10}\frac{X_t^4}{m_{\tilde t}^4}\right]$$

$$c_W = \frac{h_t^2}{640\pi^2 m_{\tilde t}^2}\frac{X_t^2}{m_{\tilde t}^2}, \quad c_B = \frac{h_t^2}{640\pi^2 m_{\tilde t}^2}\frac{X_t^2}{m_{\tilde t}^2}$$

$$c_{WB} = -\frac{h_t^2}{384\pi^2 m_{\tilde t}^2}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right) - \frac{4}{5}\frac{X_t^2}{m_{\tilde t}^2}\right]$$

Use non-degenerate soft-masses to enhance the loops

$$rr \equiv \frac{m_{U_3}^2}{m_{Q_3}^2}$$

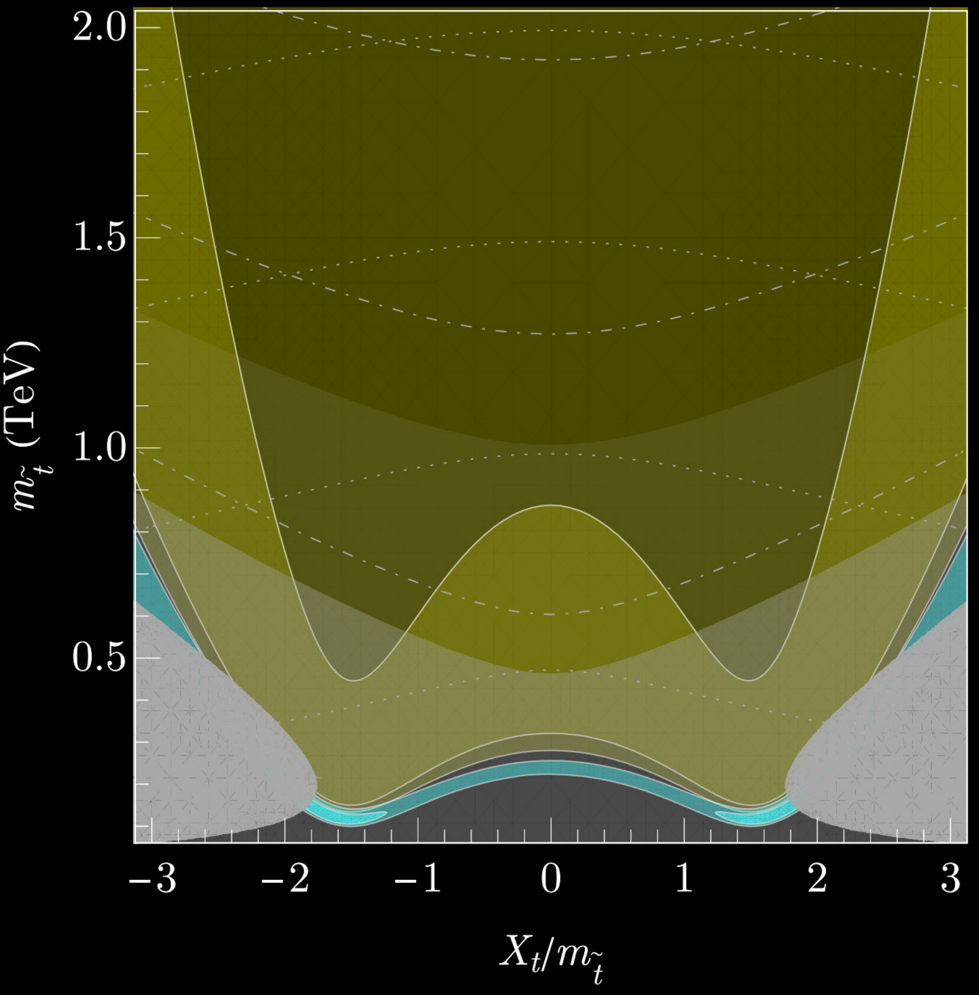
$$c_T = \frac{h_t^4}{16\pi^2 m_{\tilde Q_3}^2}\left[\frac{1}{4}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)^2 + 2\frac{X_t^2}{m_{\tilde Q_3}^2}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)\left(-\frac{1-5rr-2rr^2}{8(1-rr)^3} + \frac{3rr^2}{4(1-rr)^4}\log(rr)\right) + \frac{X_t^4}{m_{\tilde Q_3}^4}\left(\frac{1+10rr+rr^2}{4(1-rr)^4} + \frac{3rr(1+rr)}{2(1-rr)^5}\log(rr)\right)\right]$$

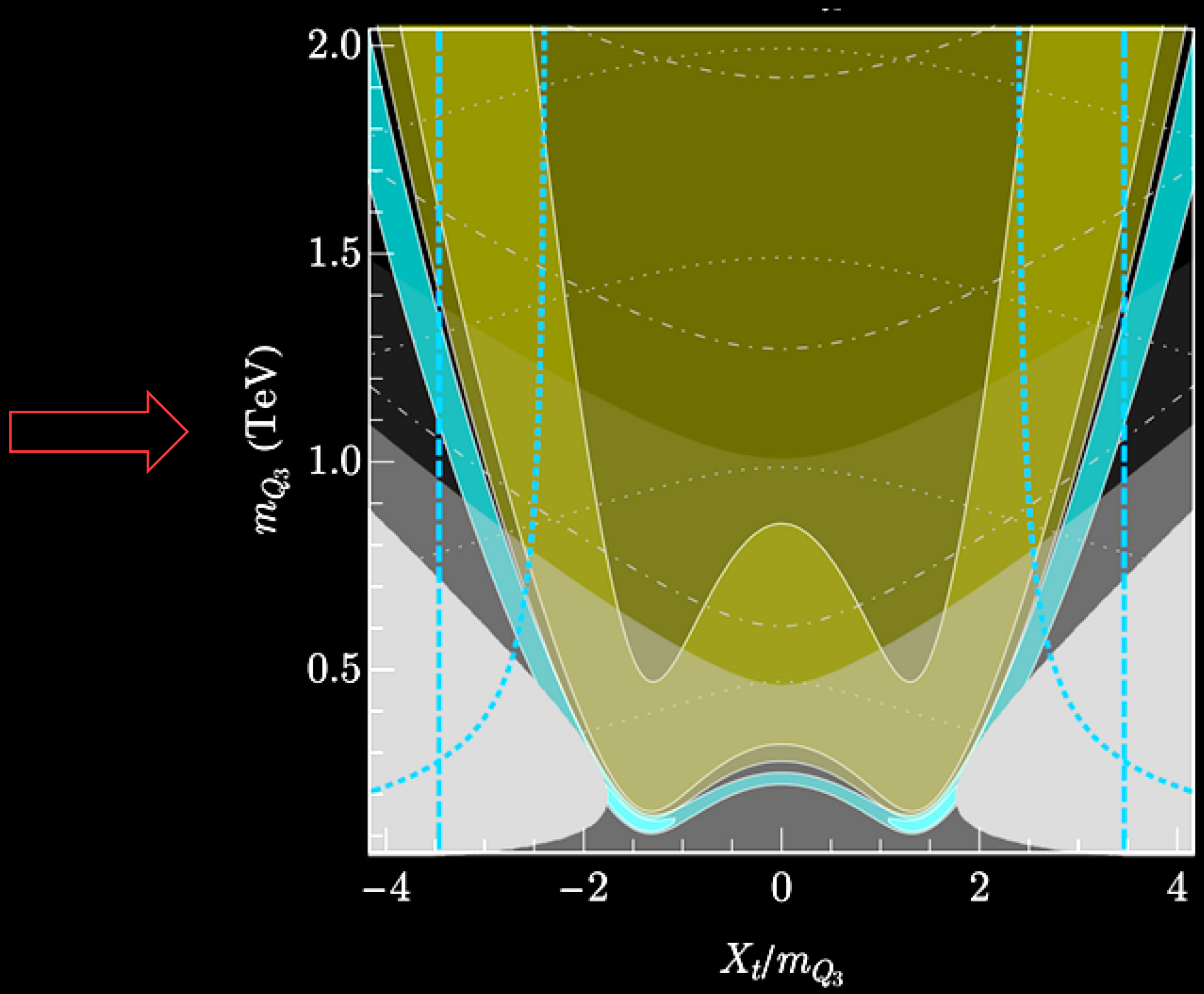
$$c_W = \frac{h_t^2}{16\pi^2 m_{\tilde Q_3}^2}\frac{X_t^2}{m_{\tilde Q_3}^2}\left(\frac{1-8rr-17rr^2}{12(1-rr)^4} + \frac{3rr^2+rr^3}{2(1-rr)^5}\log(rr)\right)$$

$$c_B = \frac{h_t^2}{16\pi^2 m_{\tilde Q_3}^2}\frac{X_t^2}{m_{\tilde Q_3}^2}\left(\frac{-23-8rr+7rr^2}{12(1-rr)^4} + \frac{-4-12rr+3rr^2+rr^3}{6(1-rr)^5}\log(rr)\right)$$

$$c_{WB} = \frac{h_t^2}{16\pi^2 m_{\tilde Q_3}^2}\left[-\frac{1}{24}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right) + \frac{X_t^2}{m_{\tilde Q_3}^2}\left(\frac{5+33rr-3rr^2+rr^3}{24(1-r)^4} + \frac{2rr+rr^2}{2(1-rr)^5}\log(rr)\right)\right]$$

Top squarks (non-degenerate)

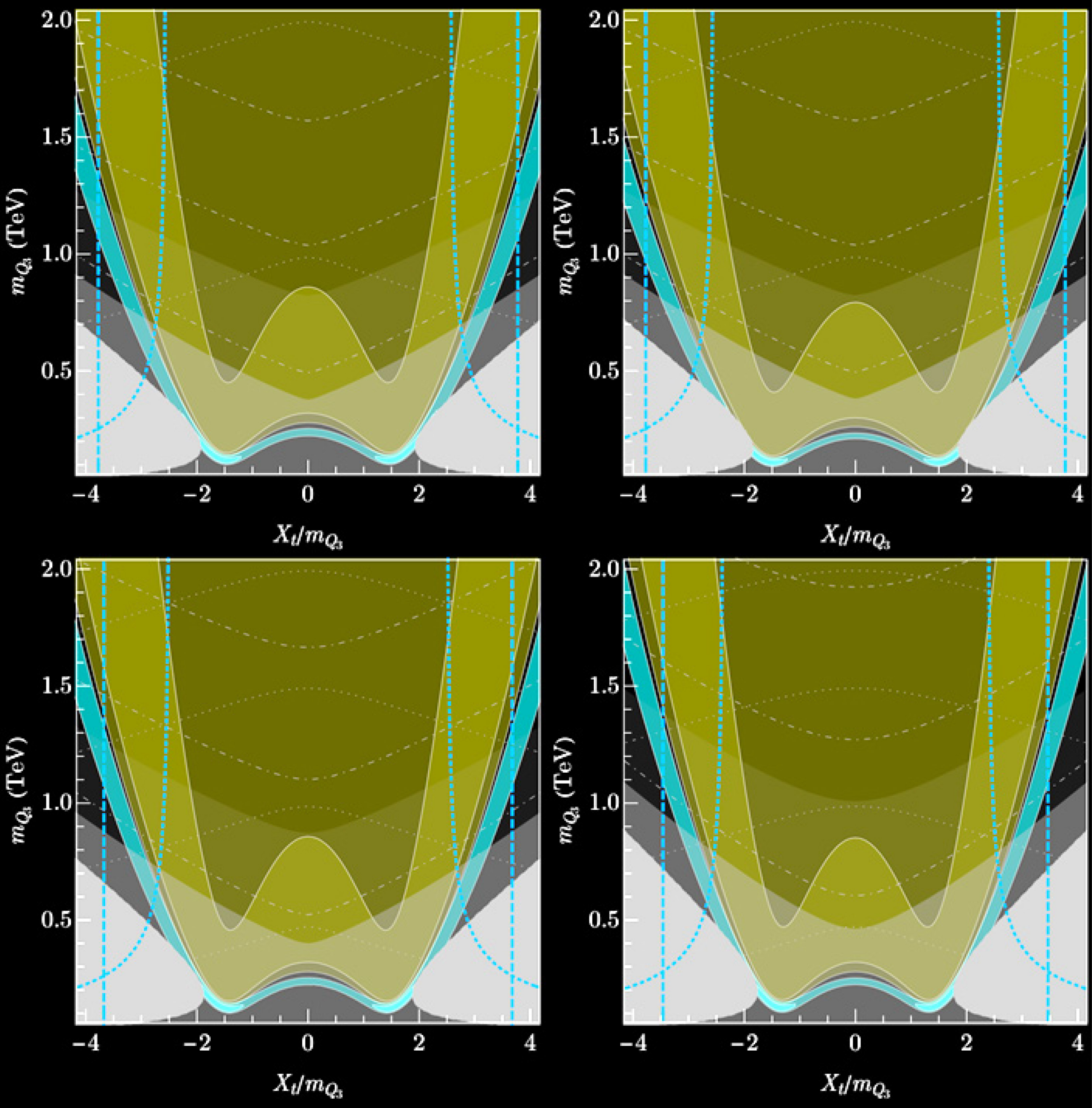




Top squarks

A few more directions could help further enhance or constrain:

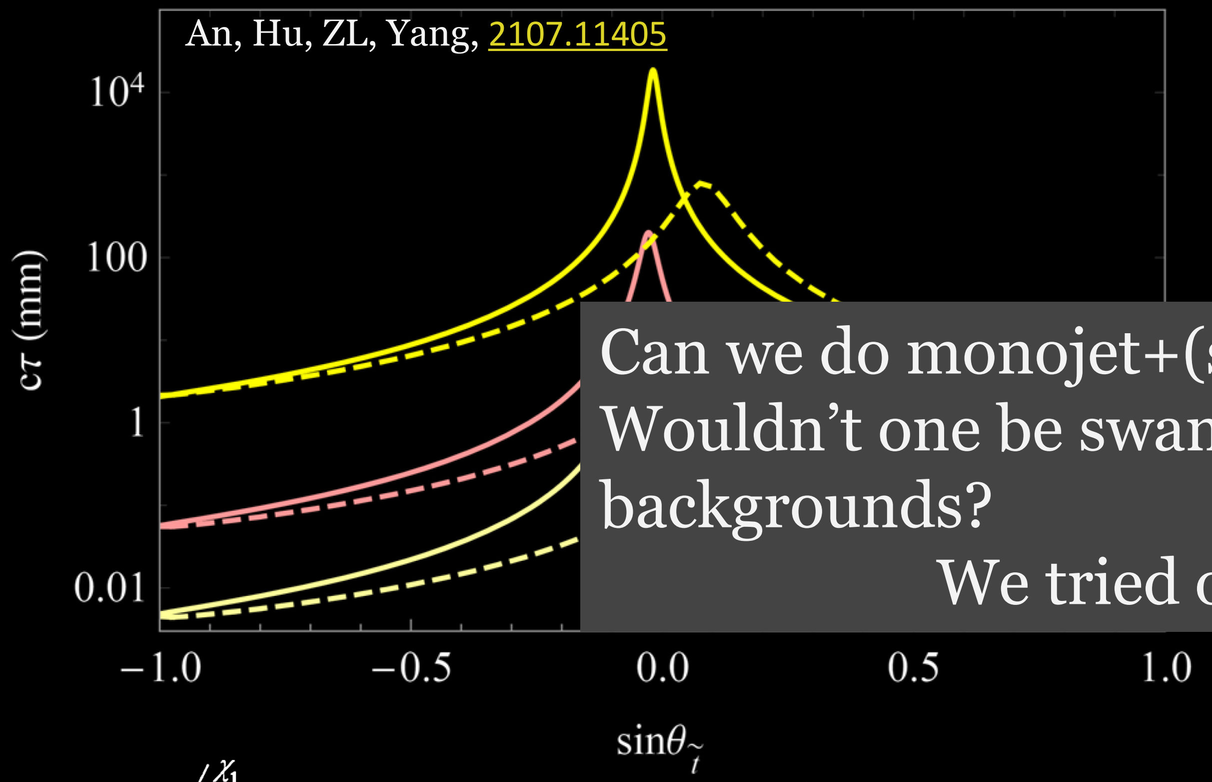
- rr (soft mass ratios)
- right-handed sbottom mass
- $tan\beta$
- Addition of slepton contributions (also accommodates muon g-2)*

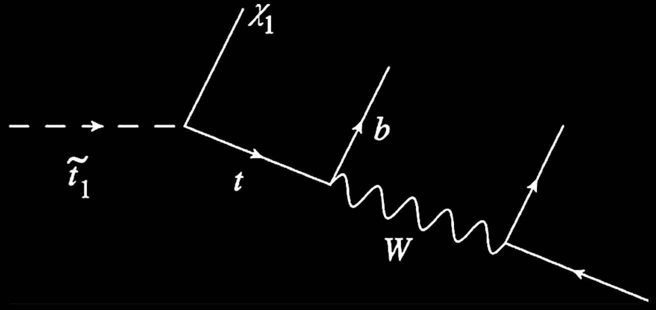


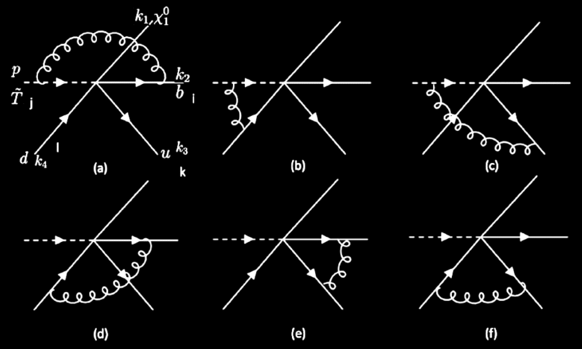
*Agashe, M, ZL, Sundrum, 2203.01796
Heinemeyer et al, 2203.15710

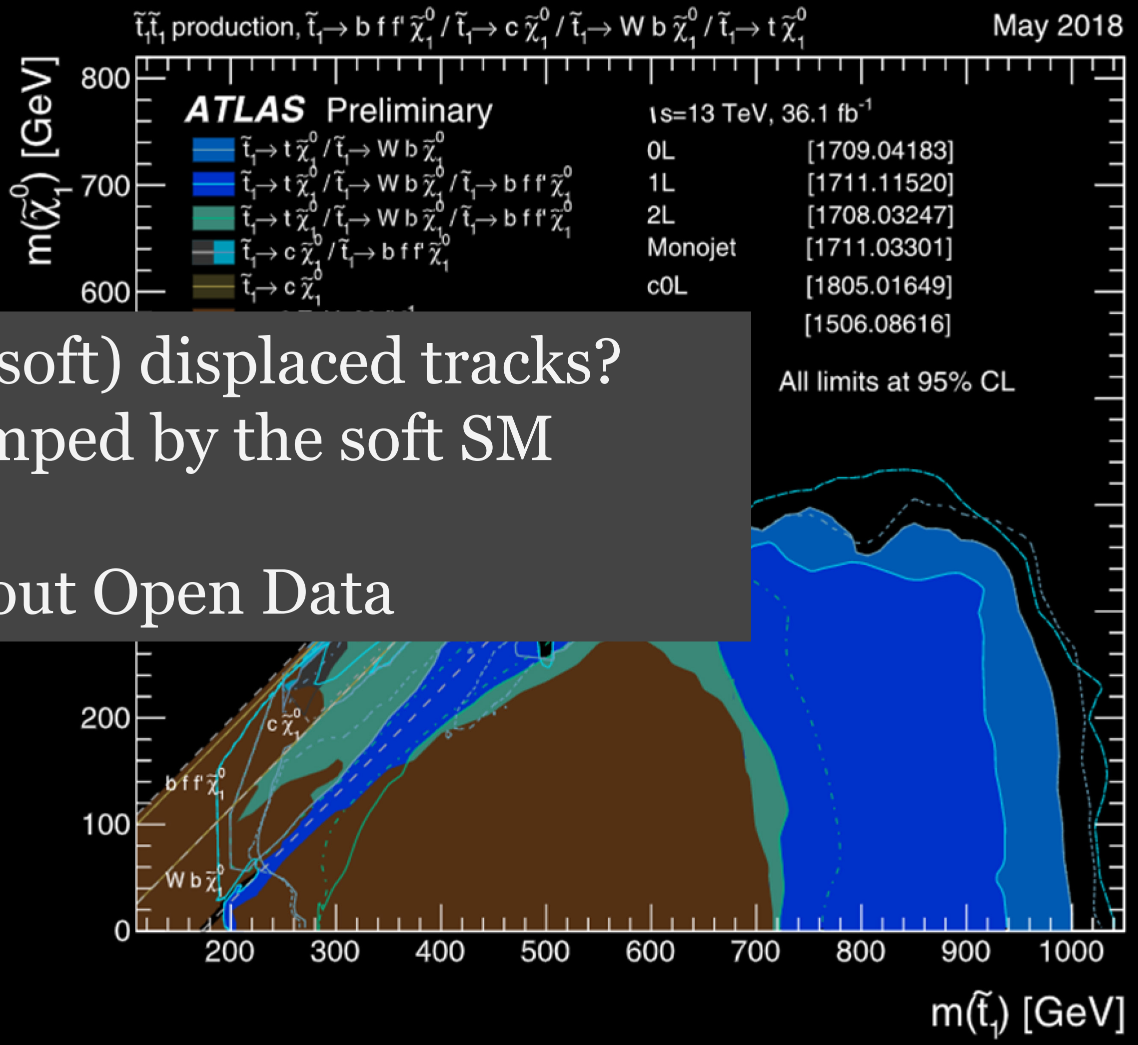
Coannihilation and LLP

Mono-jet + (soft) displaced tracks





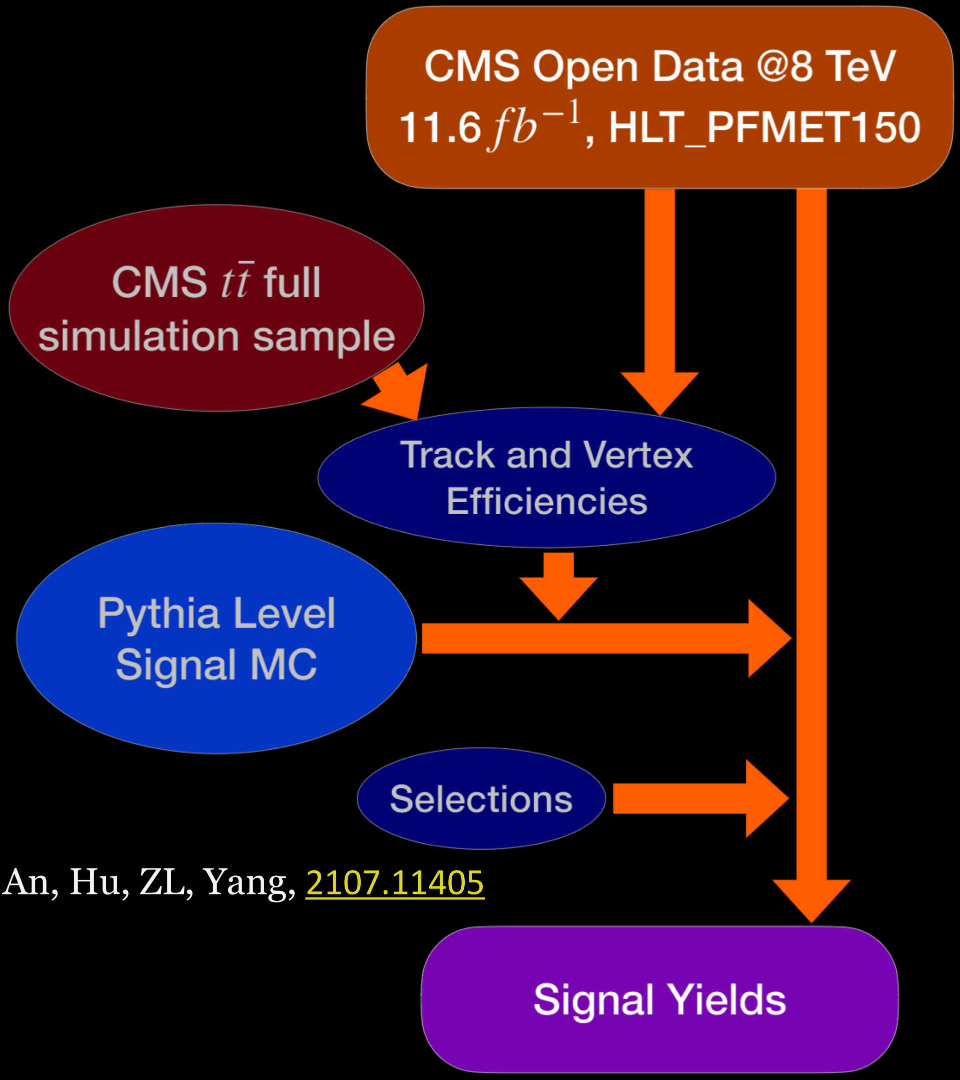




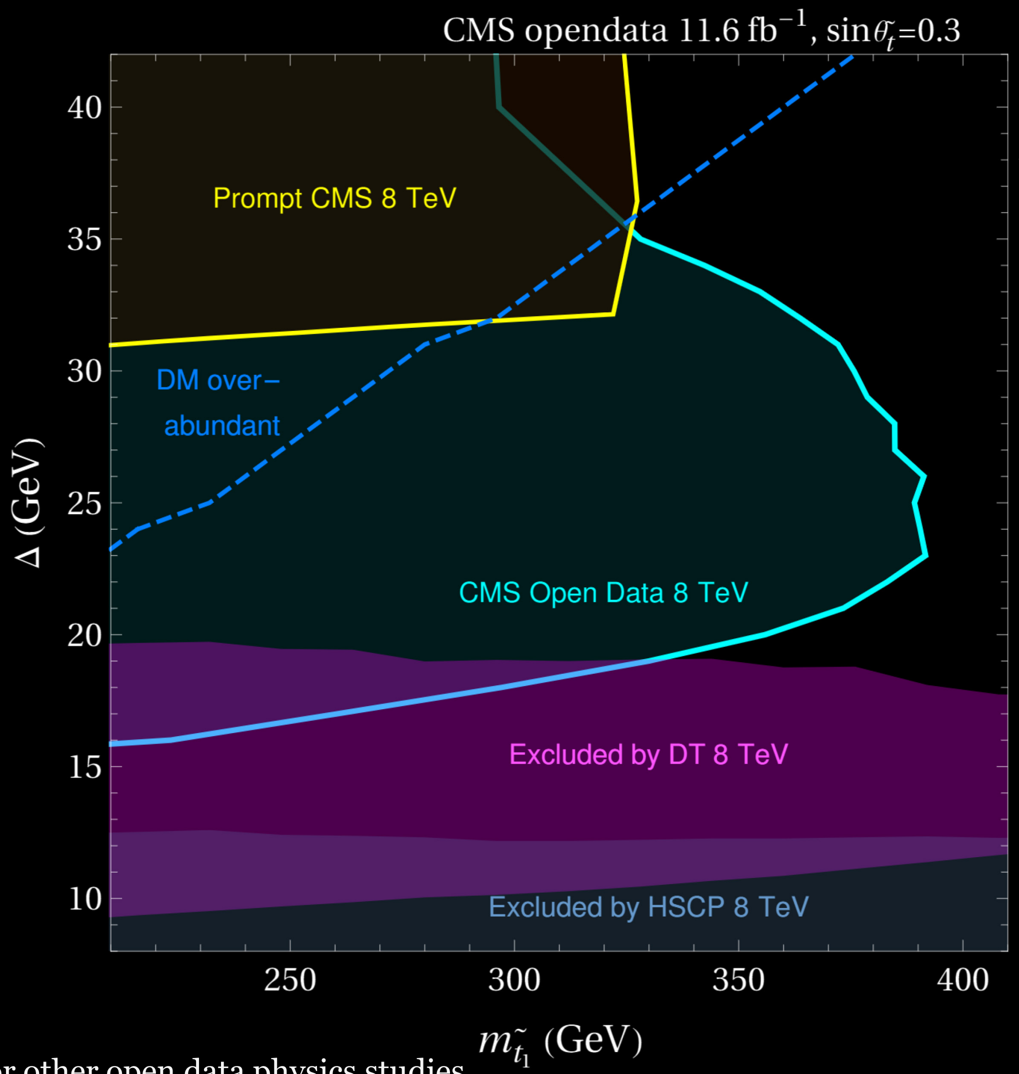
Can we do monojet+(soft) displaced tracks?
Wouldn't one be swamped by the soft SM backgrounds?

We tried out Open Data

400 GeV Stop alive



An, Hu, ZL, Yang, 2107.11405

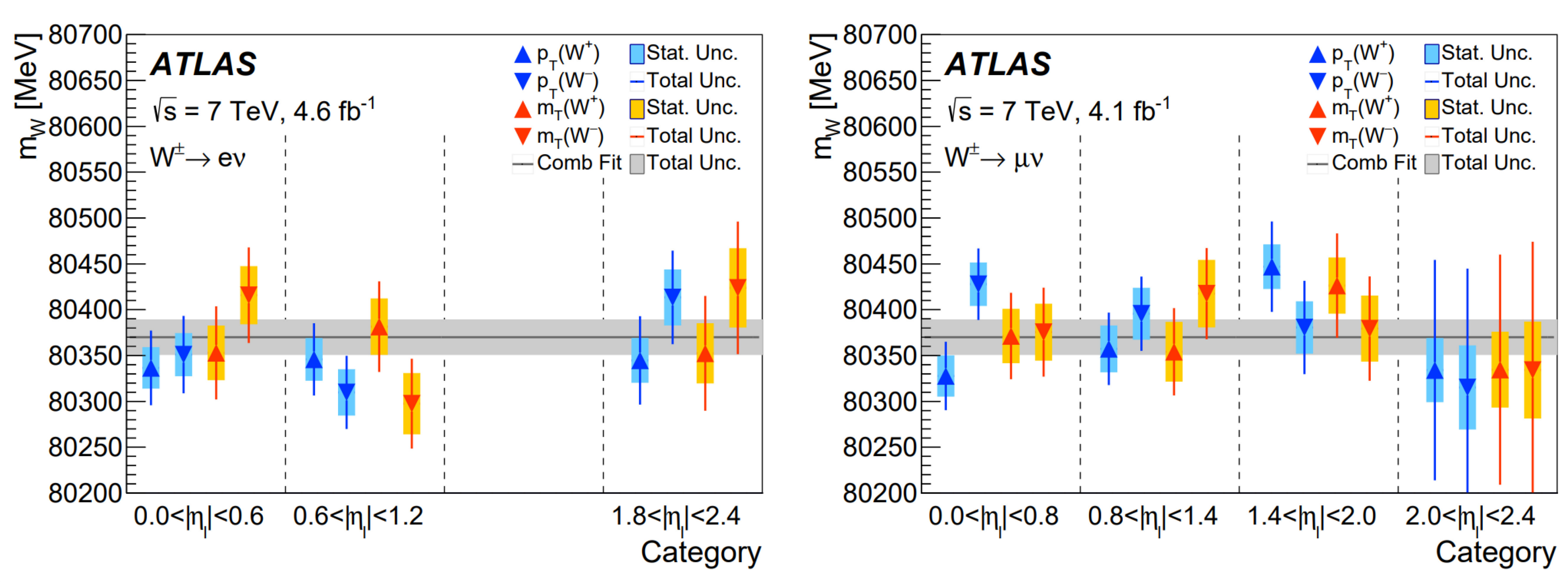


See also for other open data physics studies,
A. Larkoski, S. Marzani, J. Thaler, A. Tripathee, and W. Xue 1704.05066,
A. Tripathee, W. Xue, A. Larkoski, S. Marzani, and J. Thaler 1704.05842,
M. Andrews, J. Alison, S. An, P. Bryant, B. Burkle,S. Gleyzer, M. Narain, M. Paulini, B. Poczos, and E. Usai 1902.08276,
P. T. Komiske, R. Mastandrea, E. M. Metodiev,P. Naik, and J. Thaler 1908.08542,
C. Cesarotti, Y. Soreq, M. J. Strassler, J. Thaler, and W. Xue 1902.04222.

Outline

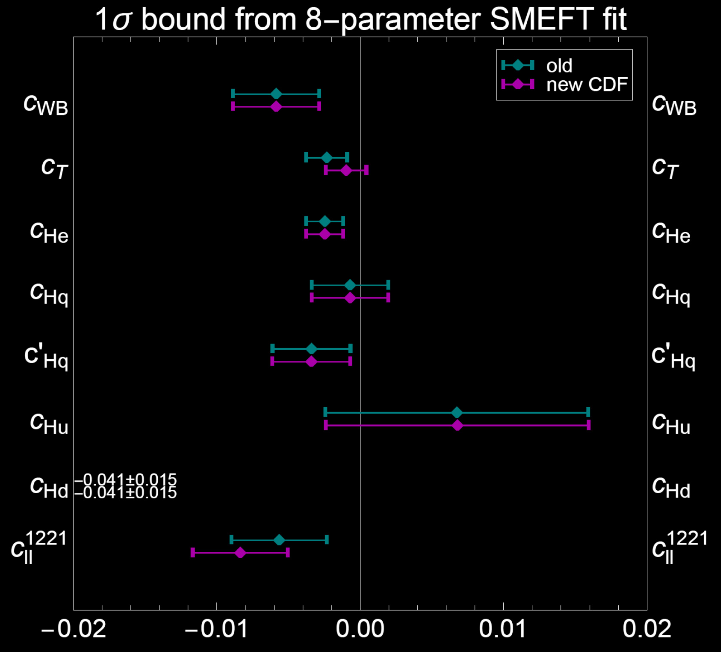
- CDF Measurement
- Theory Assessment
  - Tension with SM
  - What did we measure?
    - Various critics & updates
  - BSM interpretations
  - Future

ATLAS & CMS & LHCb

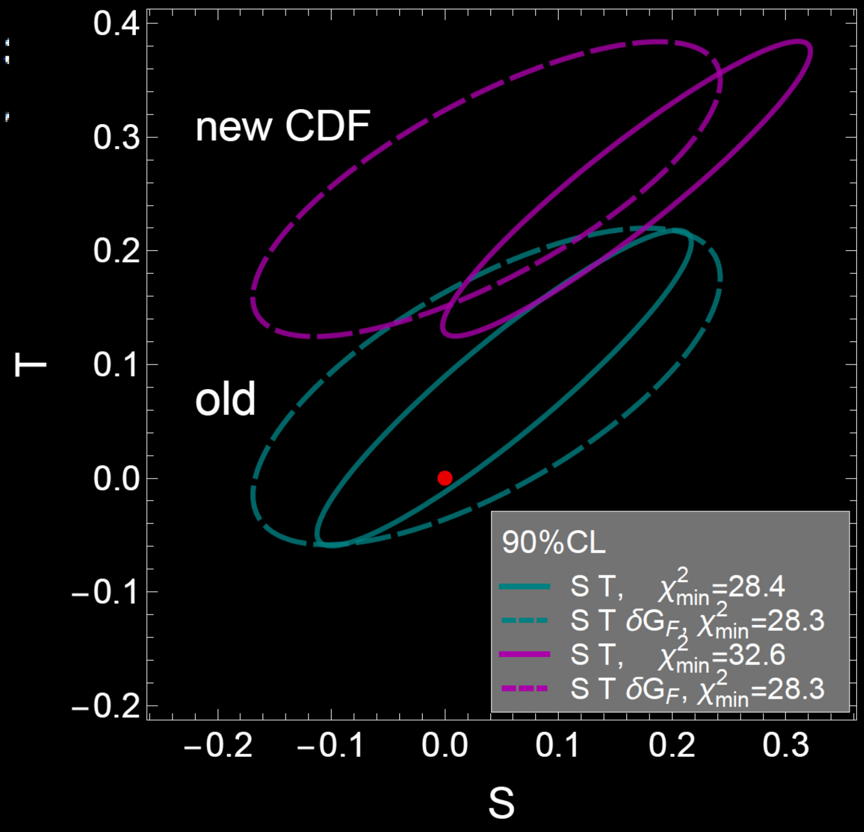


We have high hope for LHC to shed more light on mW.
Independent checks are always helpful and appreciated, even if the uncertainty budget is larger.
(My wish) We shall present mW-alone, mW&Width 2D results.

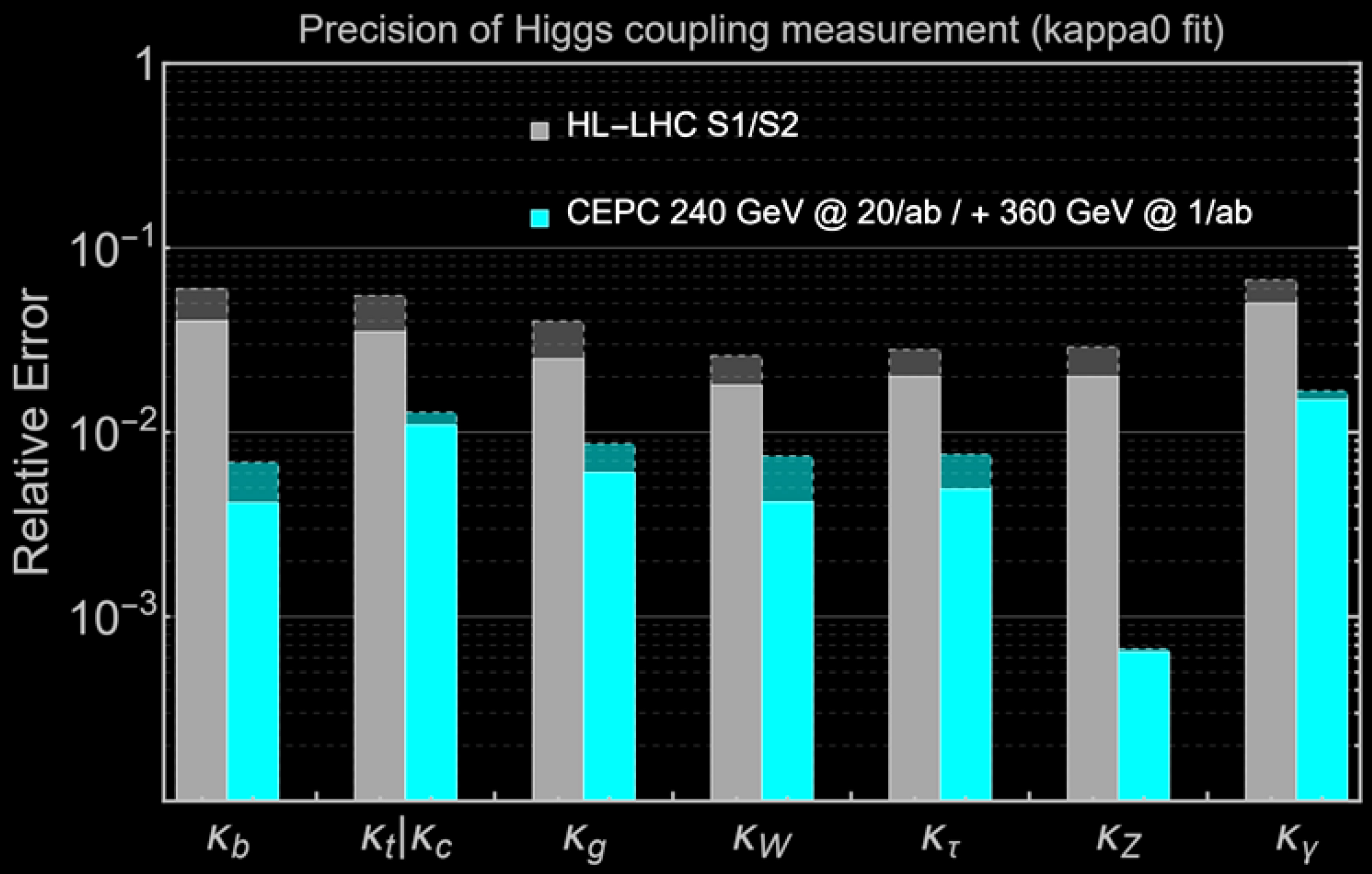
W mass Precision

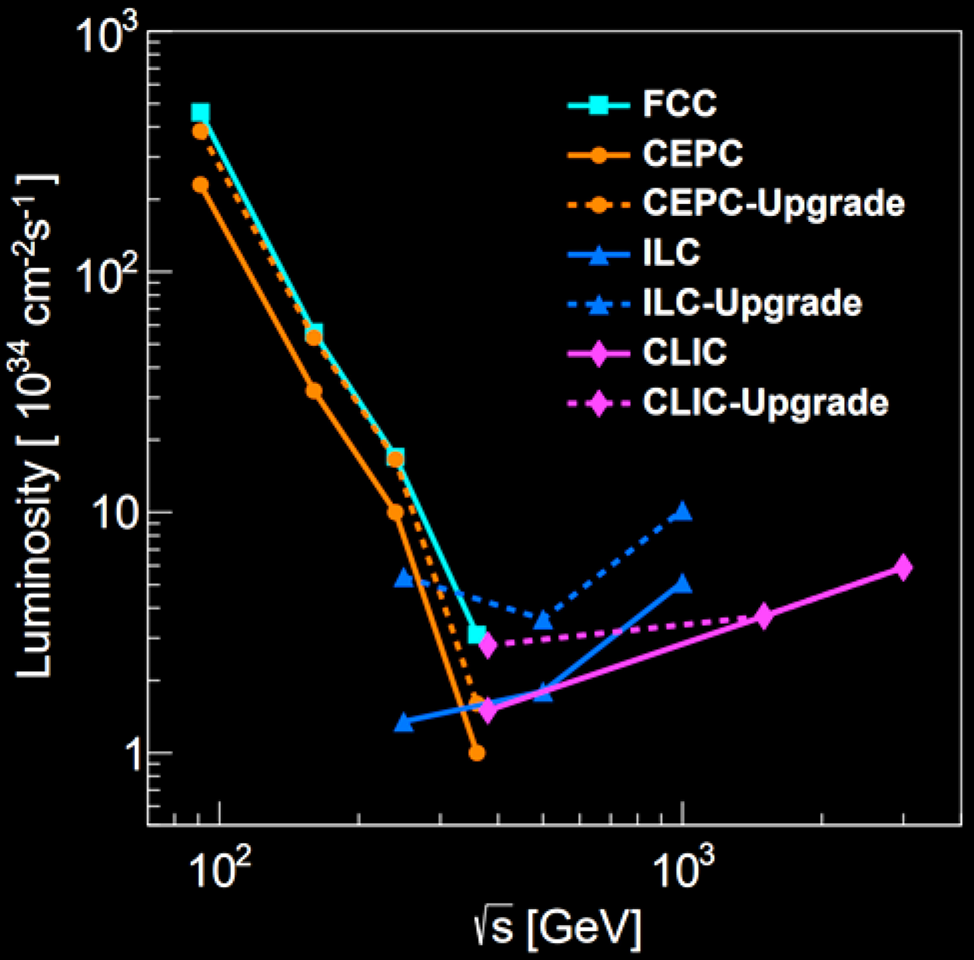


Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta\Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	WW threshold	E_{beam}
$\Delta\Gamma_W$	49 MeV [46–49]	2.0 MeV (1.8 MeV)	WW threshold	E_{beam}
Δm_t	0.76 GeV [50]	$\mathcal{O}(10)$ MeV[a]	$t\bar{t}$ threshold	
ΔA_e	4.9×10^{-3} [37, 51–55]	1.5×10^{-5} (1.5×10^{-5})	Z pole ($Z \to \tau\tau$)	Stat. Unc.
ΔA_μ	0.015 [37, 53]			to-point Unc.
ΔA_τ	4.3×10^{-3} [37, 51–55]			lecay model
ΔA_b	0.02 [37, 56]			CD effects
ΔA_c	0.027 [37, 56]			CD effects
$\Delta\sigma_{had}$	37 pb [37–41]			umiosity
δR_b^0	0.003 [37, 57–61]			on splitting
δR_c^0	0.017 [37, 57, 62–65]			on splitting
δR_e^0	0.0012 [37–41]			and t channel
δR_μ^0	0.002 [37–41]			E_{beam}
δR_τ^0	0.017 [37–41]			E_{beam}
δN_ν	0.0025 [37, 66]			energy scale

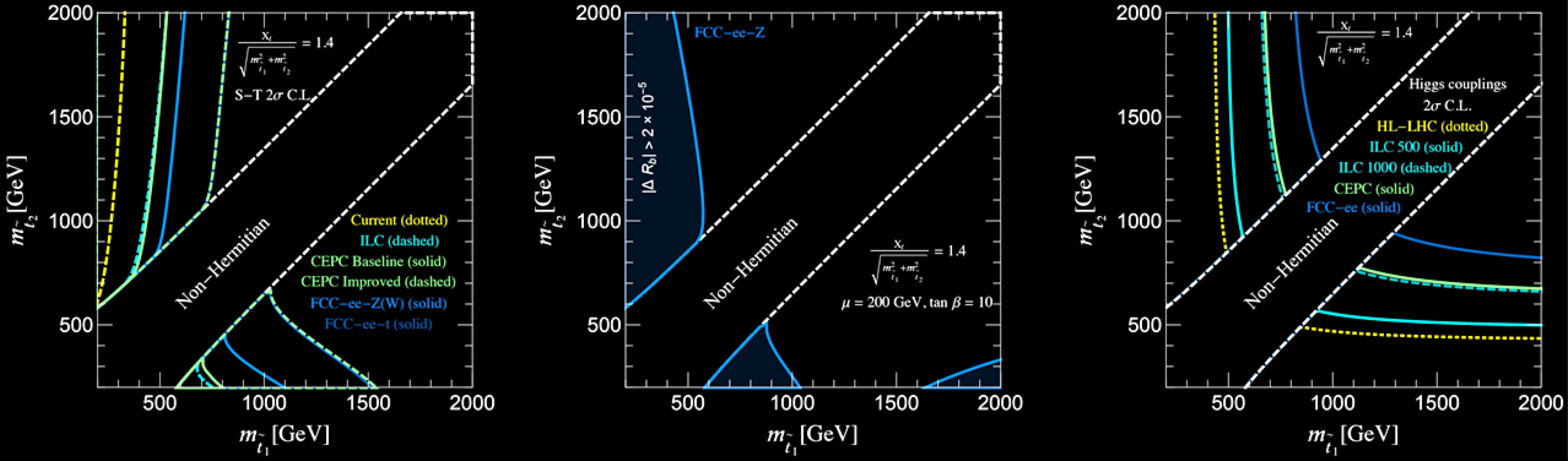


(in)Direct Probes of Loop Particles





Probing Stop via loop (Z-pole, Higgs precision)



Fan, Reece, Wang, 1412.3107
Gori, Gu, Wang, 1508.07010

Summary and Outlook

- CDF Measurement
- Theory Assessment
  - Tension with SM
  - What did we measure?
    - Various critics & updates
  - BSM interpretations
  - Future

I hope you enjoyed this adventure so far and that we did make progress in understanding physics. The future is in our hands.