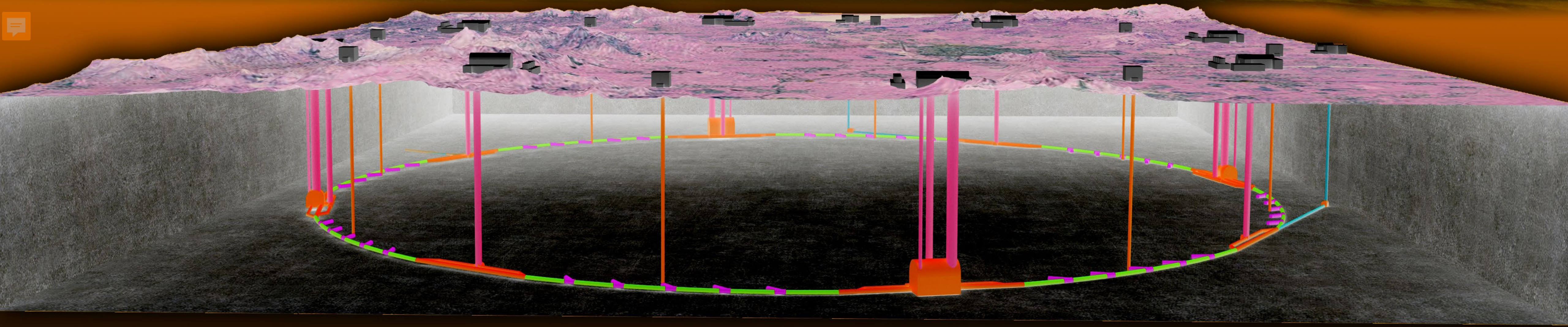
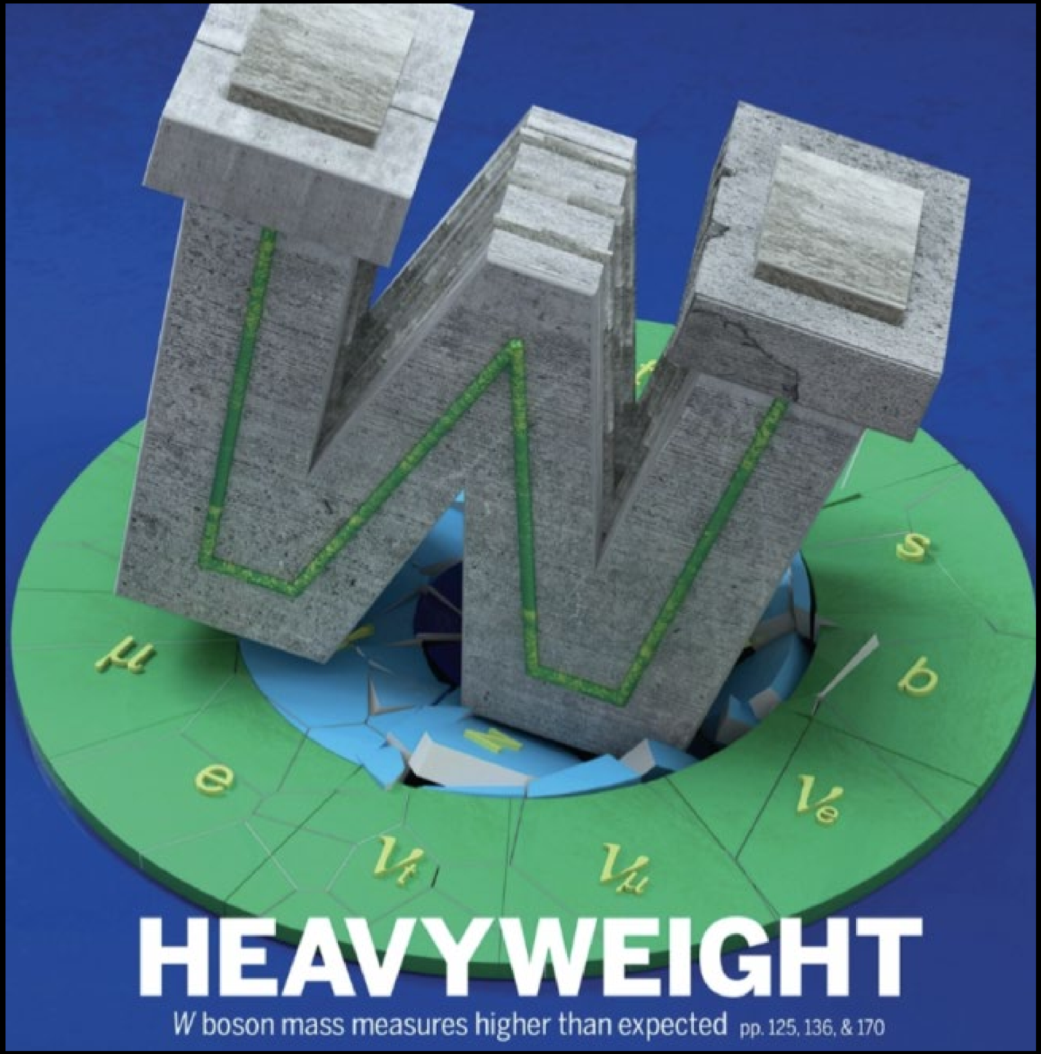


W mass and the Future

Zhen Liu
University of Minnesota
May. 25, 2022

Outline

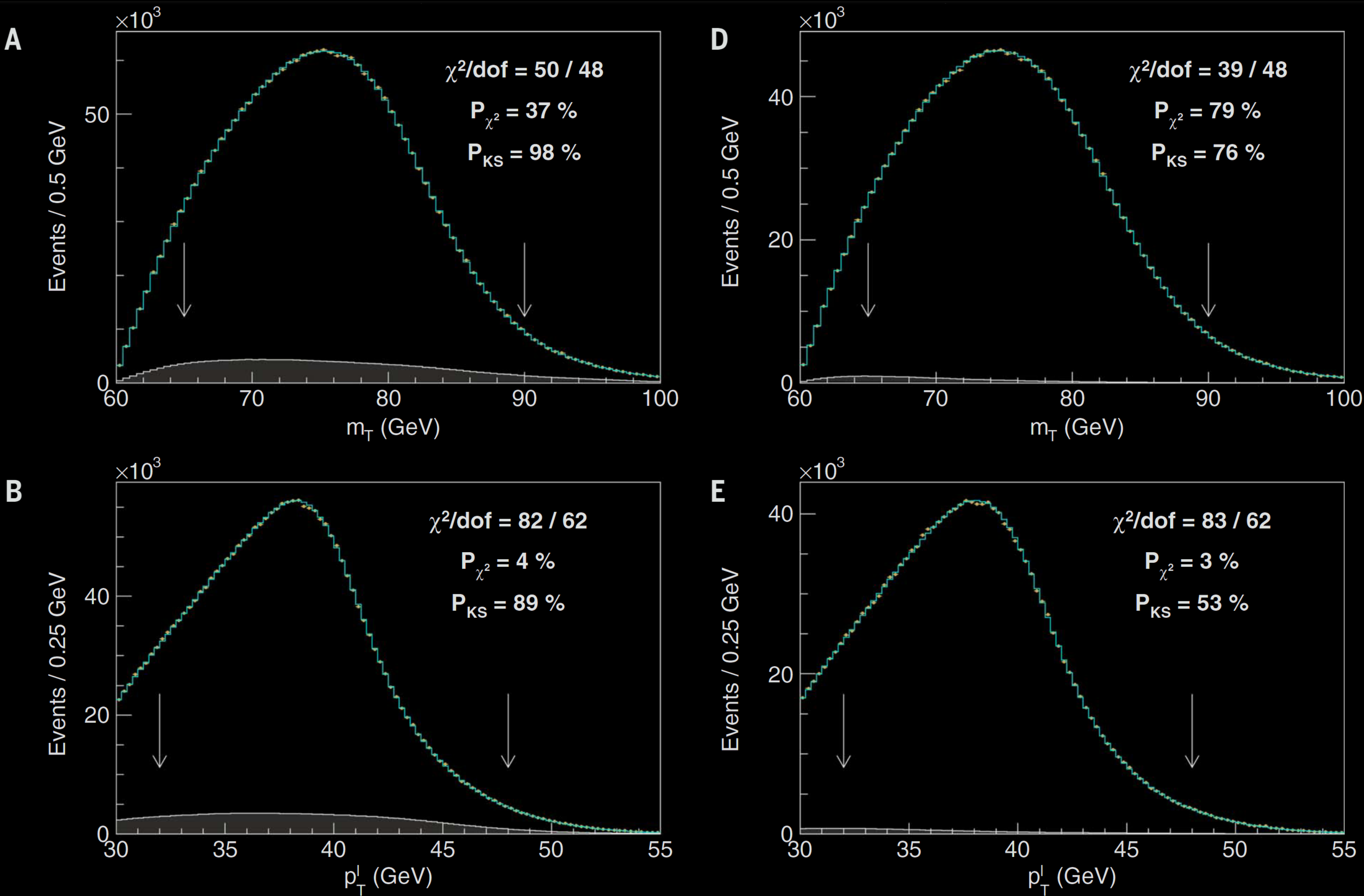
- CDF Measurement
- Theory Assessment
  - Tension with SM
  - Shifts and Uncertainties
  - BSM interpretations
  - mW @ CEPC



Outline

- CDF Measurement
- Theory Assessment
  - Tension with SM
  - Shifts and Uncertainties
  - BSM interpretations
  - mW @ CEPC

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

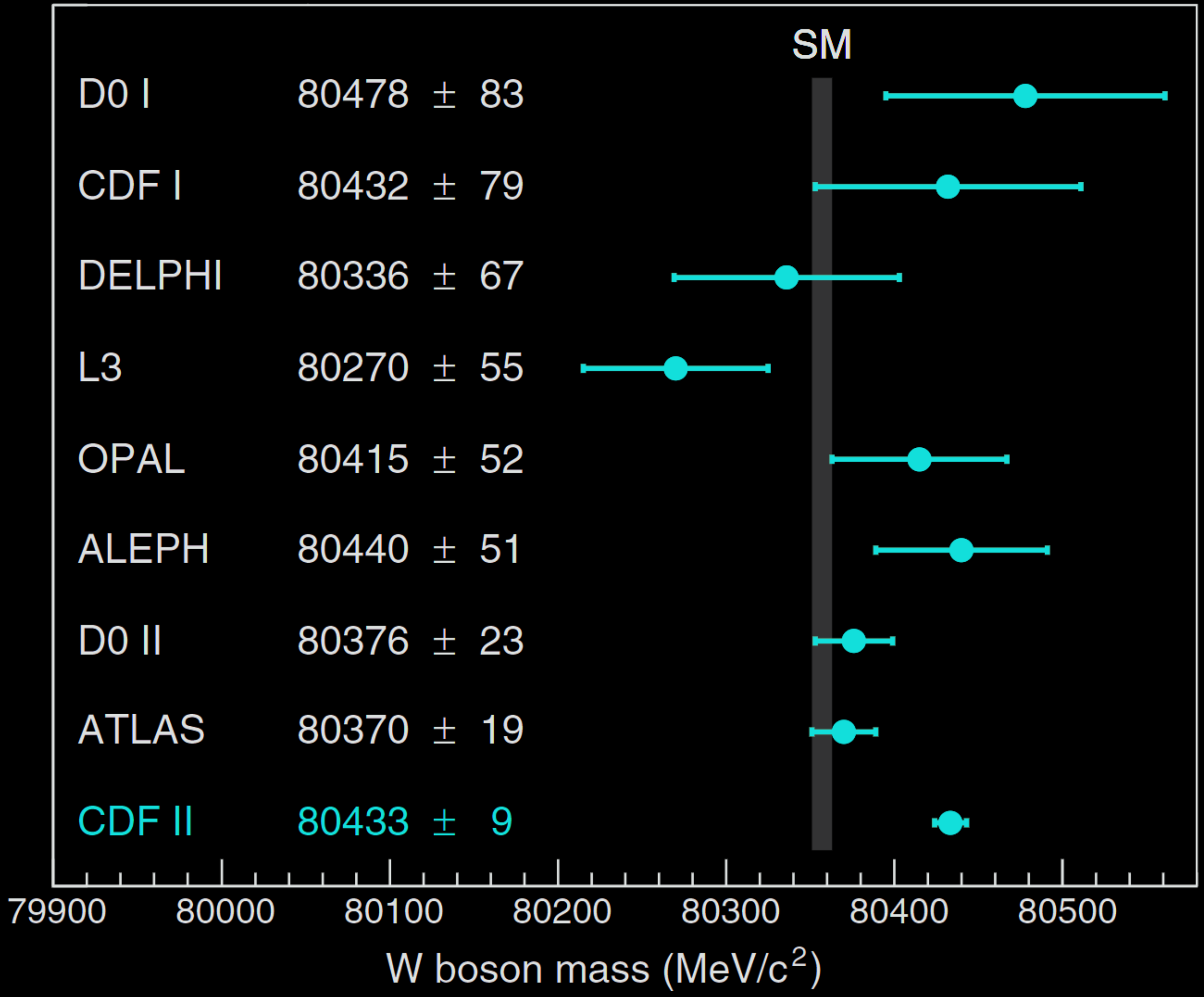
- $M_T = \sqrt{2\left(p_T^{\ell} p_T^{\nu} - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu}\right)}$
- p_T^{ℓ}
- p_T^{ν} with $(\vec{p}_T^{\,\nu} = -\vec{p}_T^{\,\ell} - \vec{u}_T)$

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).

Tension with other experiments

also LHCb: 80,354 $\pm$ 32 MeV

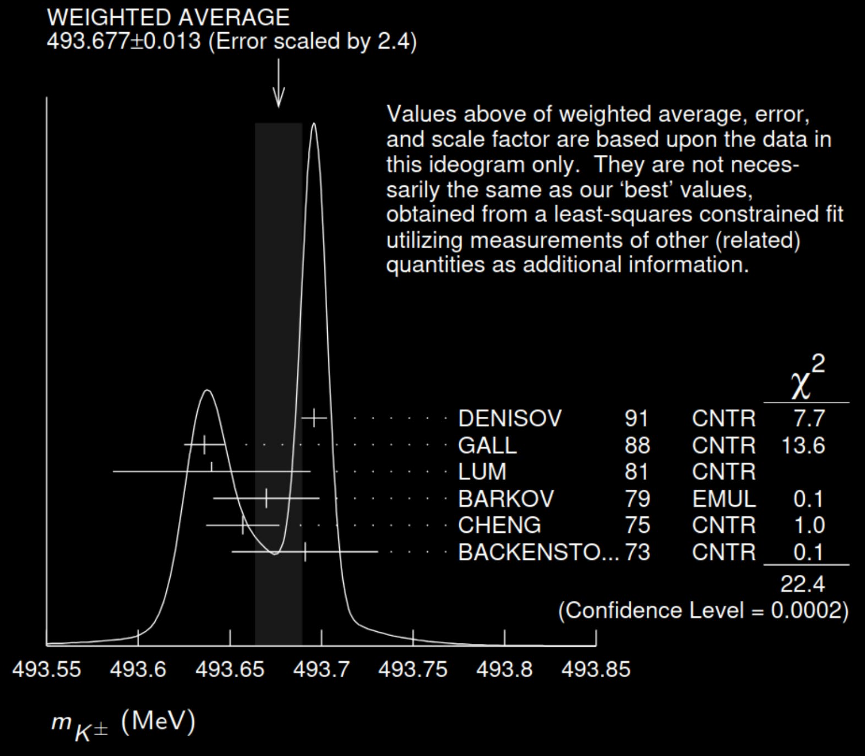
- $7\,\sigma$ tension with SM (discuss later)
- $\sim 3\,\sigma$ tension with other experiments

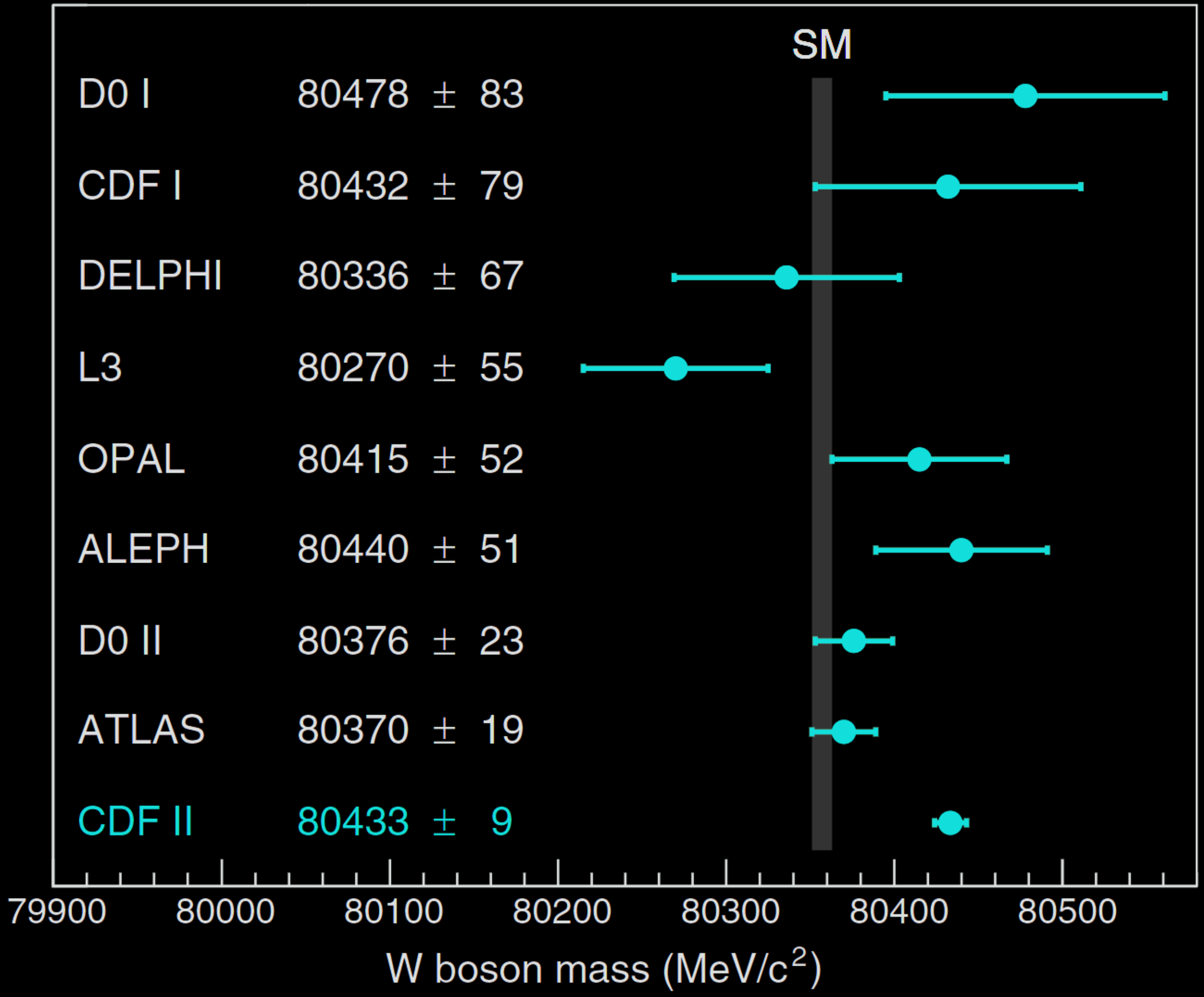


Tension with other experiments

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.





Outline

- CDF Measurement
- Theory Assessment
  - Tension with SM
  - Shifts and Uncertainties
  - BSM interpretations
  - mW @ CEPC

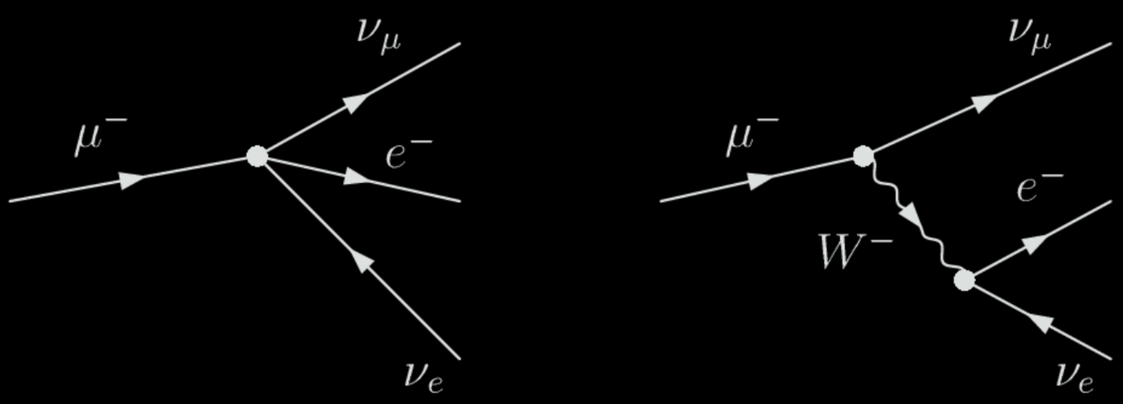
Tension with SM

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

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

$\Updownarrow$

loop corrections



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

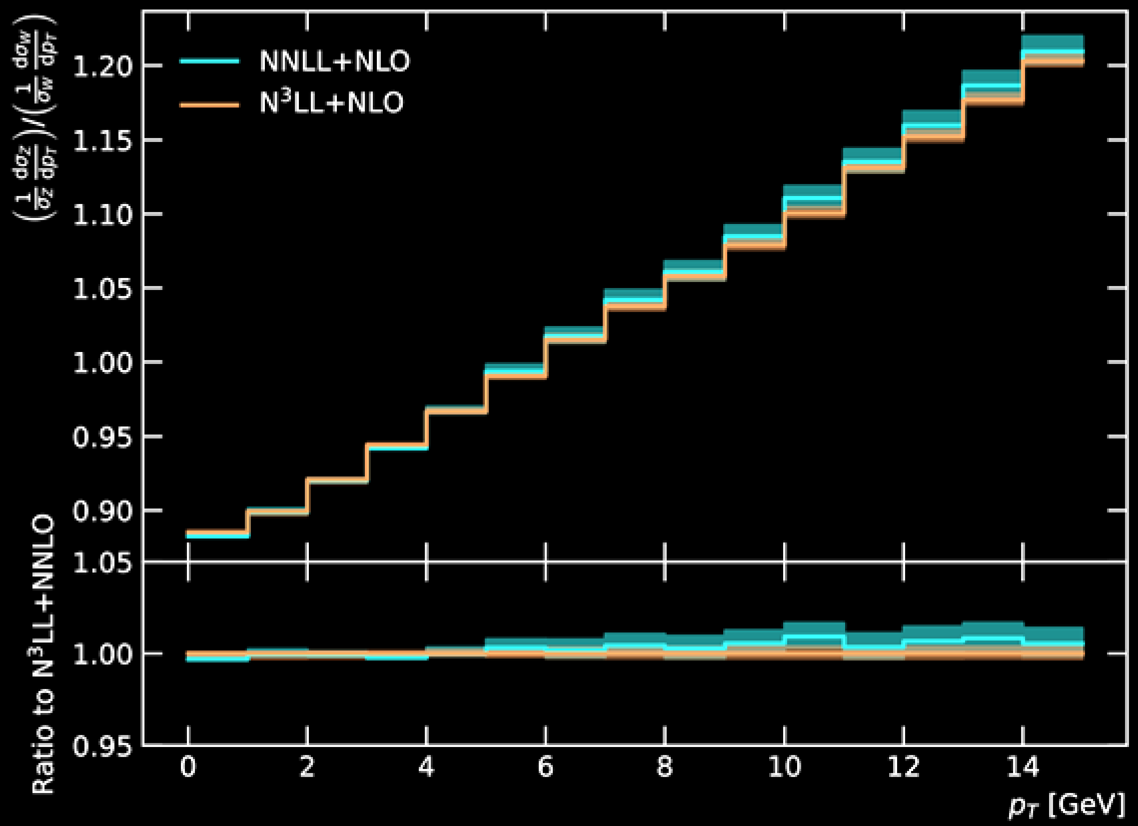
Parameter	Fit Result
G_μ [GeV^{-2}]	1.1663787×10^{-5}
$\alpha(0)^{-1}$	137.035999139
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$	0.027627 ± 0.000096
M_Z [GeV]	91.1883 ± 0.0021
M_H [GeV]	125.21 ± 0.12
m_t [GeV]	172.75 ± 0.44
M_W [GeV]	80.3591 ± 0.0052

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

Outline

- CDF Measurement
- Theory Assessment
  - Tension with SM
  - Shifts and Uncertainties
  - BSM interpretations
  - mW @ CEPC

Theory uncertainties



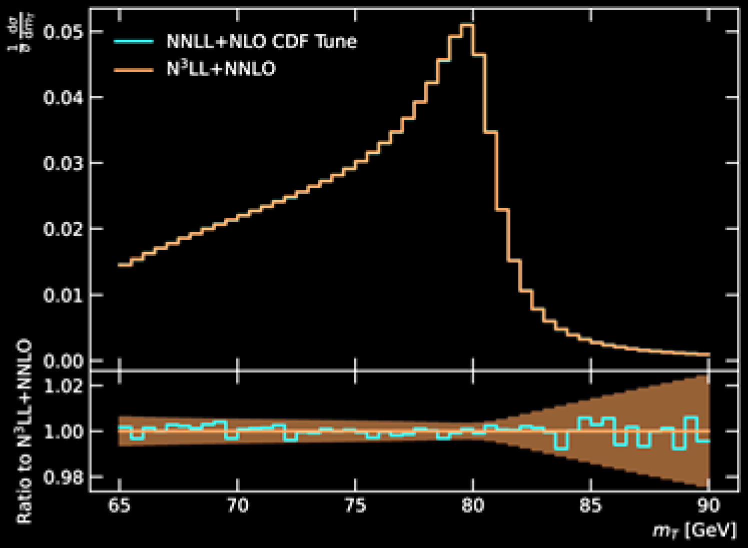
Rescaling W pT using Z pT

- 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

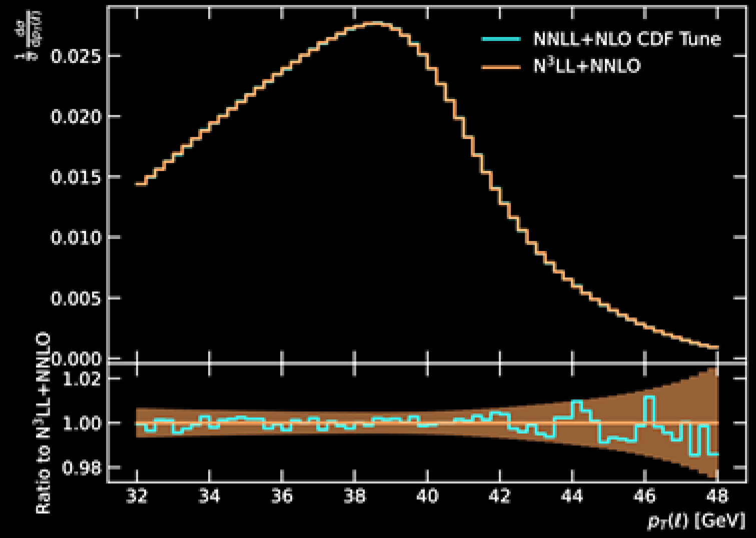
Issacson, Fu, Yuan, 2205.02788

Theory uncertainties

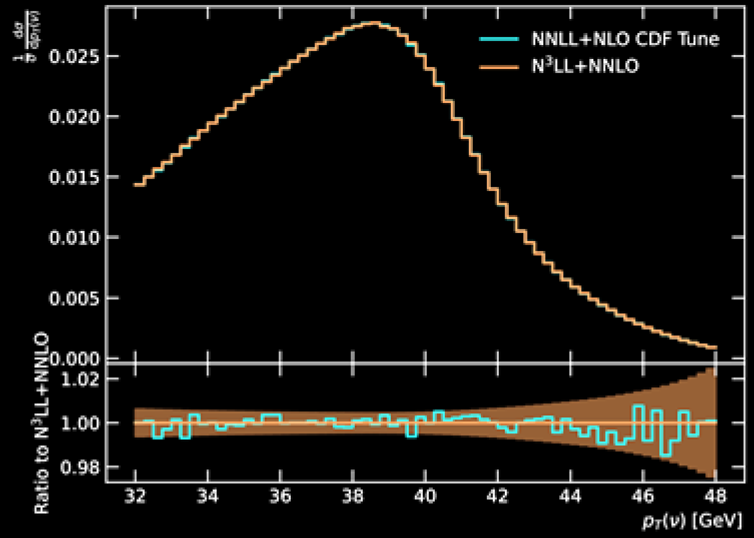
Issacson, Fu, Yuan, 2205.02788



Best Fit: $M_W = 80,386$ MeV



Best Fit: $M_W = 80,388$ MeV



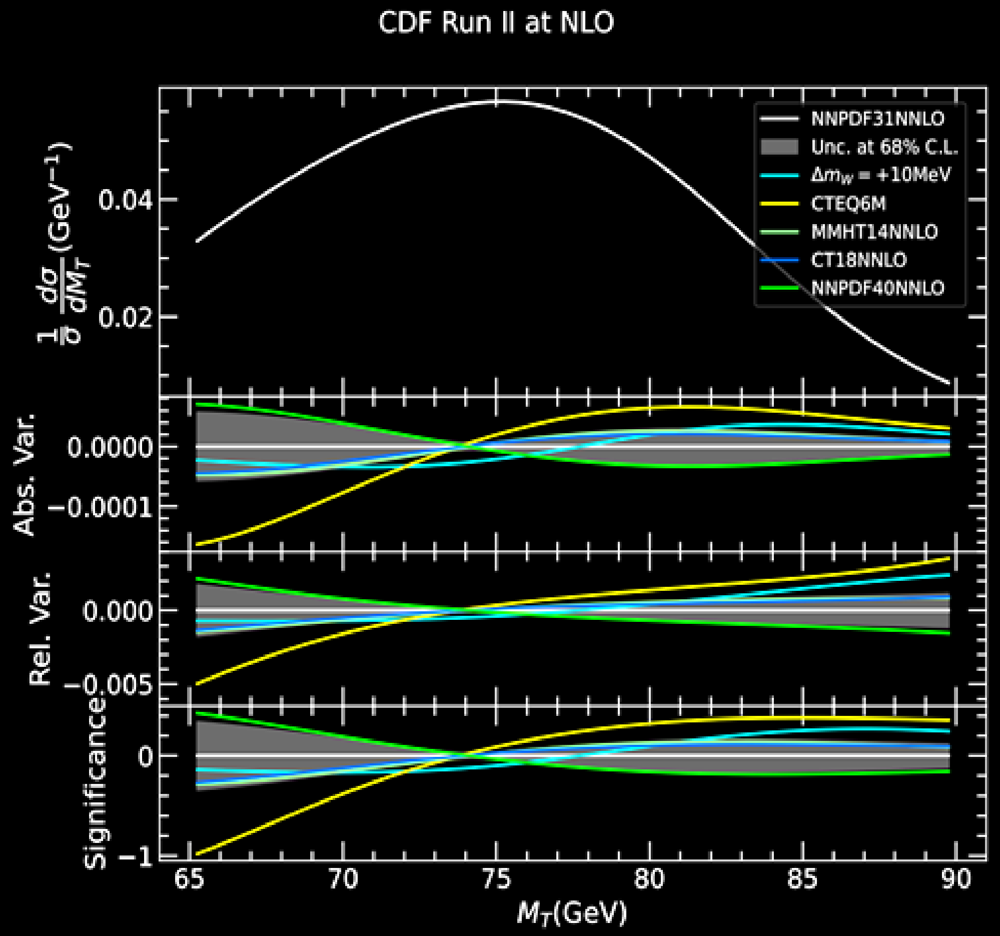
Best Fit: $M_W = 80,389$ MeV

	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	$3.0 \pm 3.4 \pm 2.2$

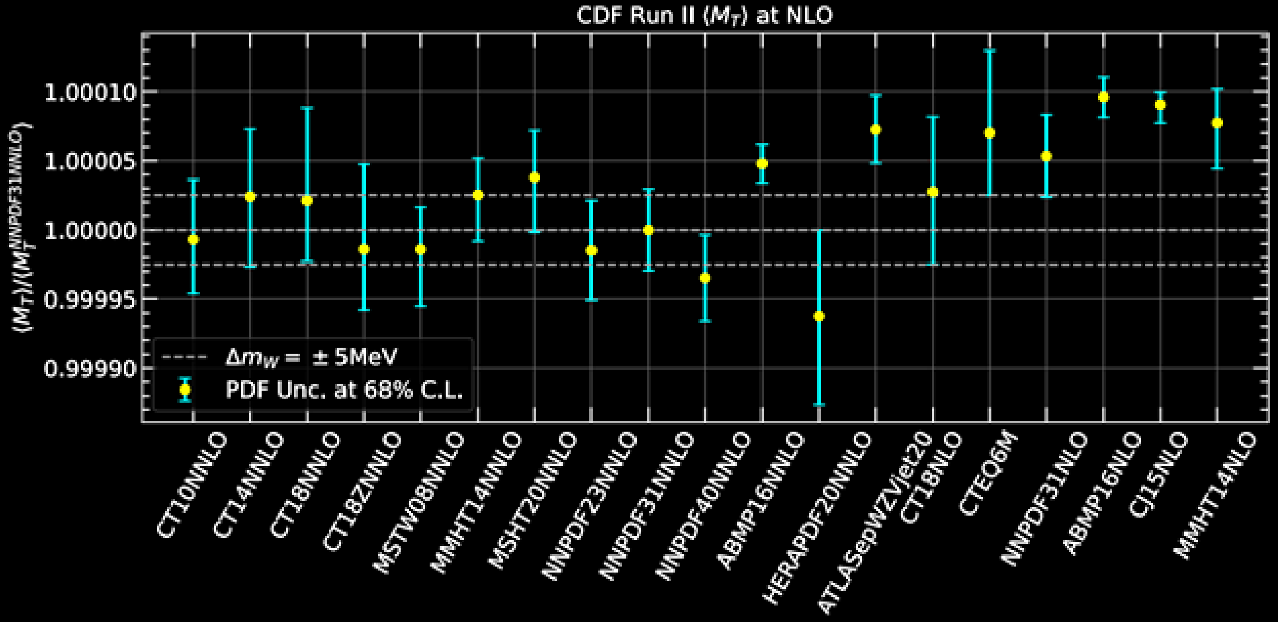
PDF Uncertainties

Gao, Liu, Xie, 2205.03942

normalized m_T distribution
PDF var. vs. M_W var.



mean value of m_T



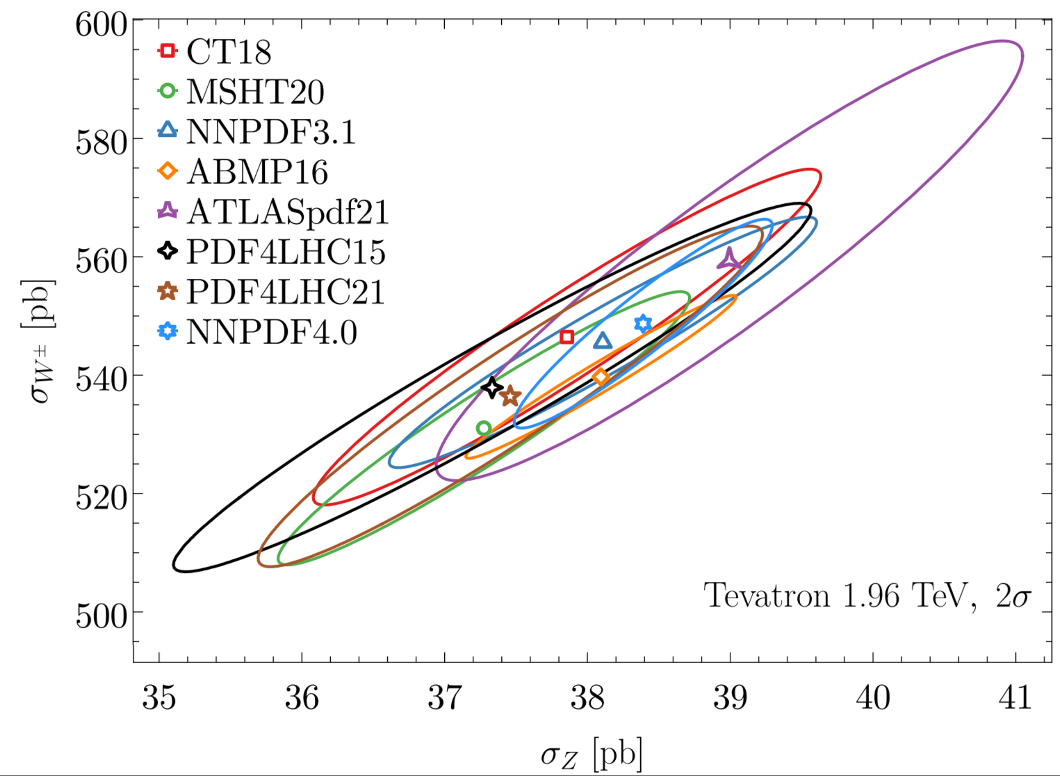
estimate shift and PDF unc. of W mass

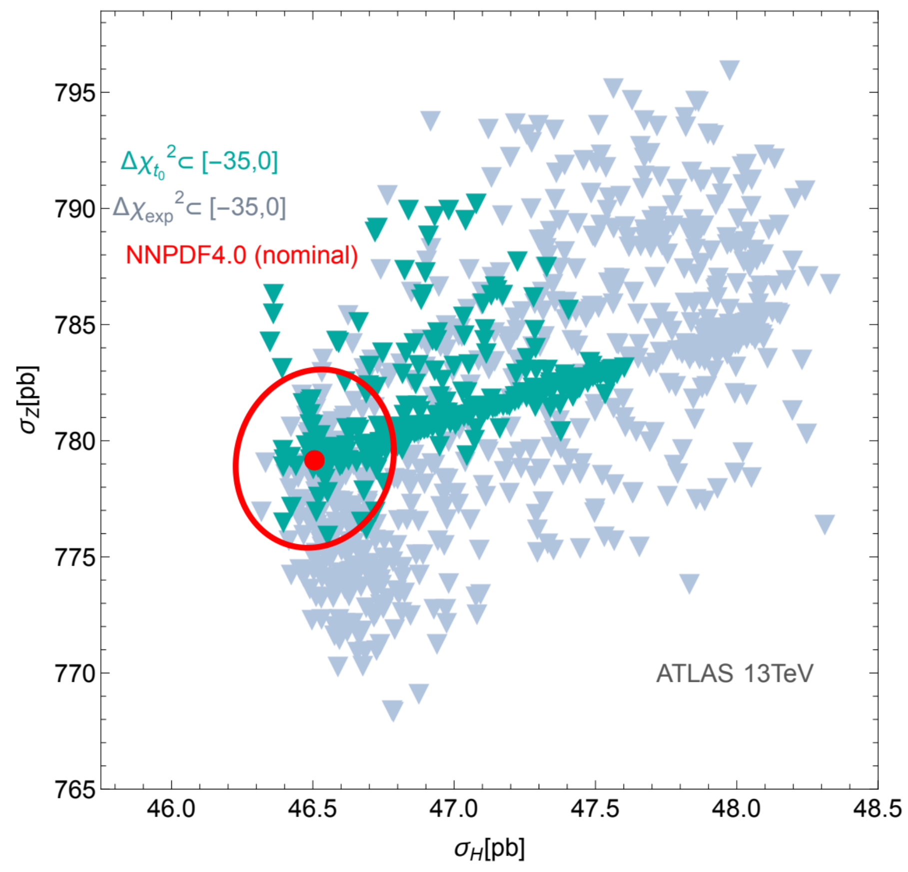
δM_W in MeV	sta.	NNPDF3.1	CT18	MMHT2014	NNPDF4.0	MSHT2020
$\langle M_T\rangle$(LO)	–	$0^{+8.3}_{-8.3}$	$-1.0^{+8.3}_{-11.4}$	$-3.3^{+7.4}_{-4.2}$	$+7.8^{+5.1}_{-5.1}$	$-3.1^{+6.7}_{-5.7}$
χ^2 fit (LO)	8.0	$0^{+7.6}_{-7.6}$	$-1.0^{+5.4}_{-8.6}$	$-3.3^{+6.1}_{-3.0}$	$+8.0^{+3.7}_{-3.7}$	$-3.0^{+5.0}_{-4.0}$
$\langle M_T\rangle$(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	$0^{+3.9}_{-3.9}$	–	–	–	–

PDF Uncertainties (continued)

Parton distributions need representative sampling

Aurore Courtoy,[1,*] Joey Huston,[2,†] Pavel Nadolsky,[3,‡] Keping Xie,[4,§] Mengshi Yan,[5,¶] and C.-P. Yuan[2,





Outline

- CDF Measurement
- Theory Assessment
  - Tension with SM
  - Shifts and Uncertainties
  - BSM interpretations
  - mW @ CEPC

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

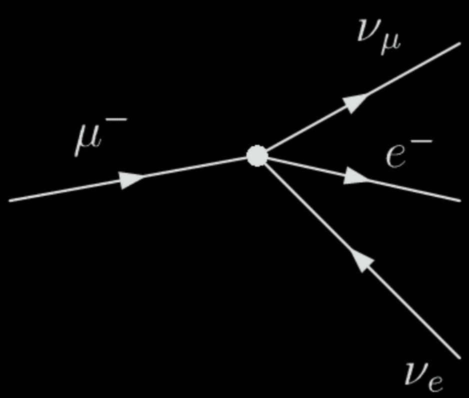
Tension with SM

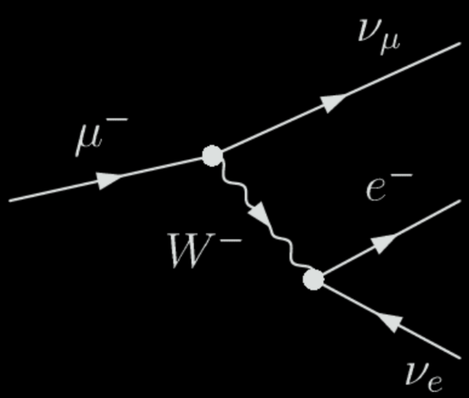
$M_Z, \alpha, G_\mu, \Delta r$:

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

$\Updownarrow$

loop corrections

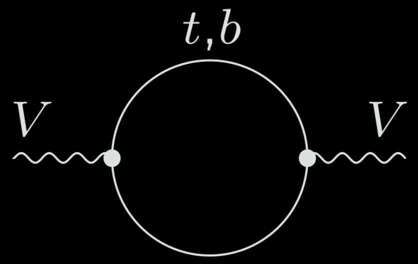




$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

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

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



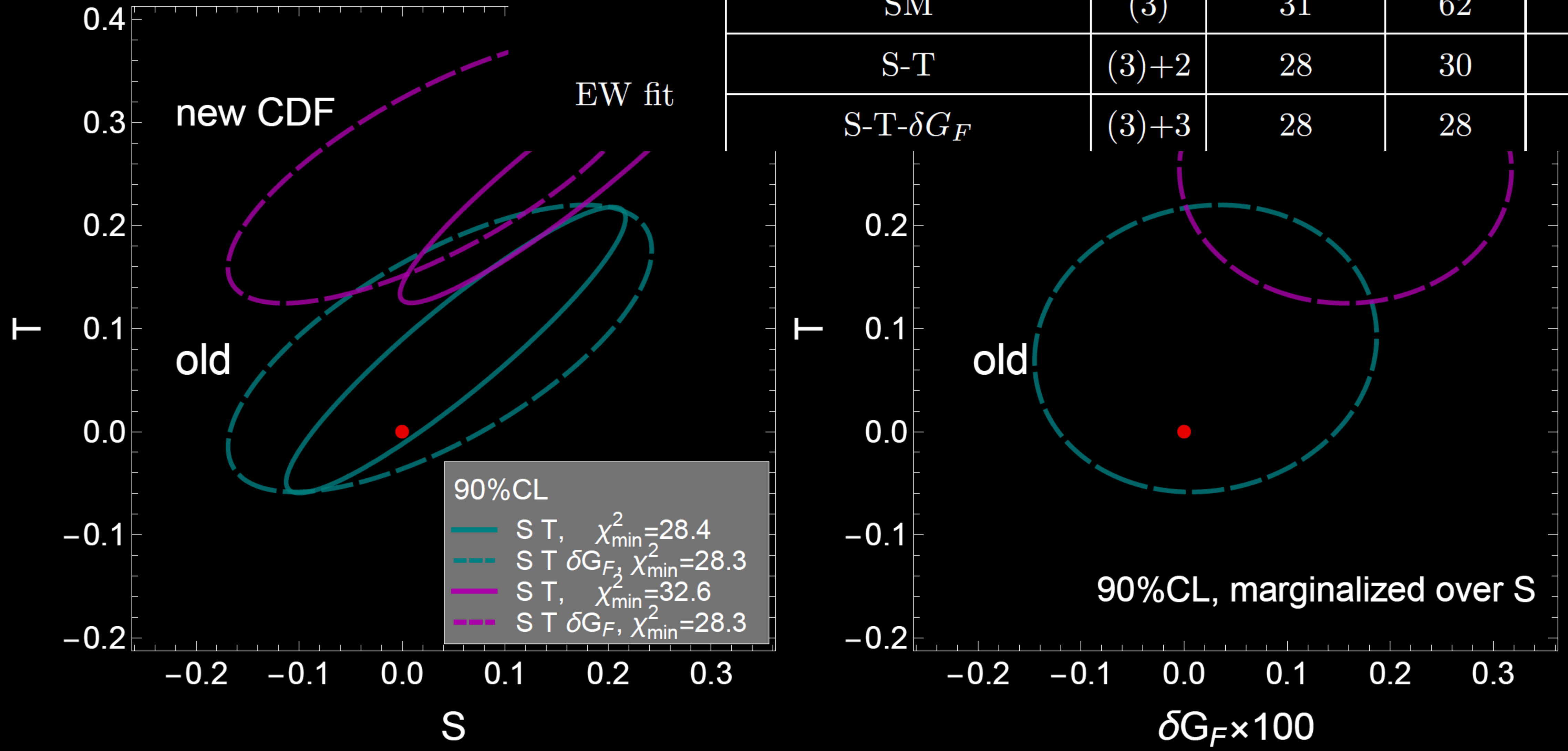
$$\delta m_W = \frac{1}{2c_{2w}}\left[c_w^2\,\hat{T} - s_w^2\left(\delta G_F + 2\hat{S}\right)\right]$$

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

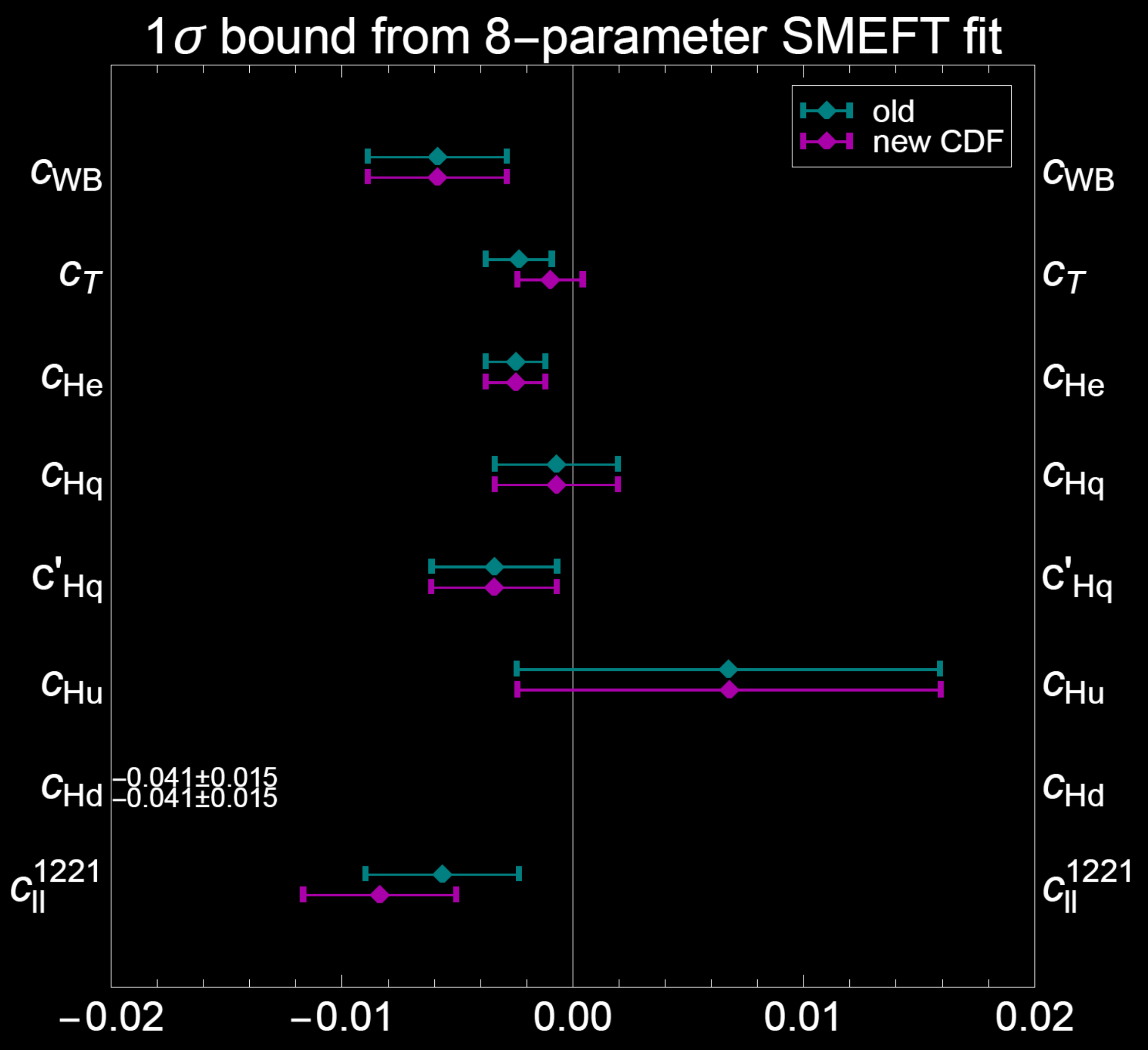
Sven Heinemeyer – IDT-WG3-Phys Open Meeting on M_W, 12.05.2022

SMEFT results

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



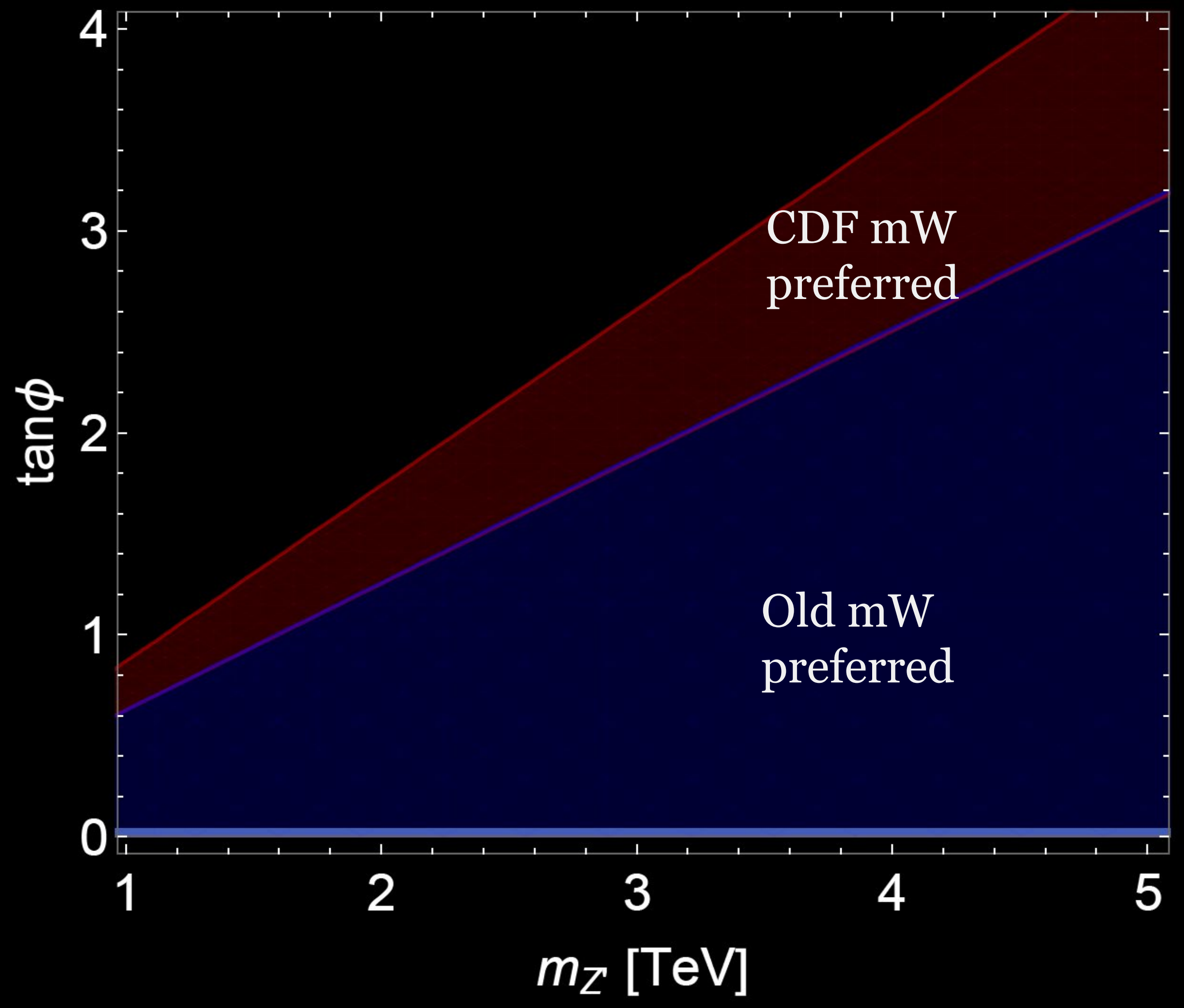
8-parameter “Global” SMEFT results



- 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

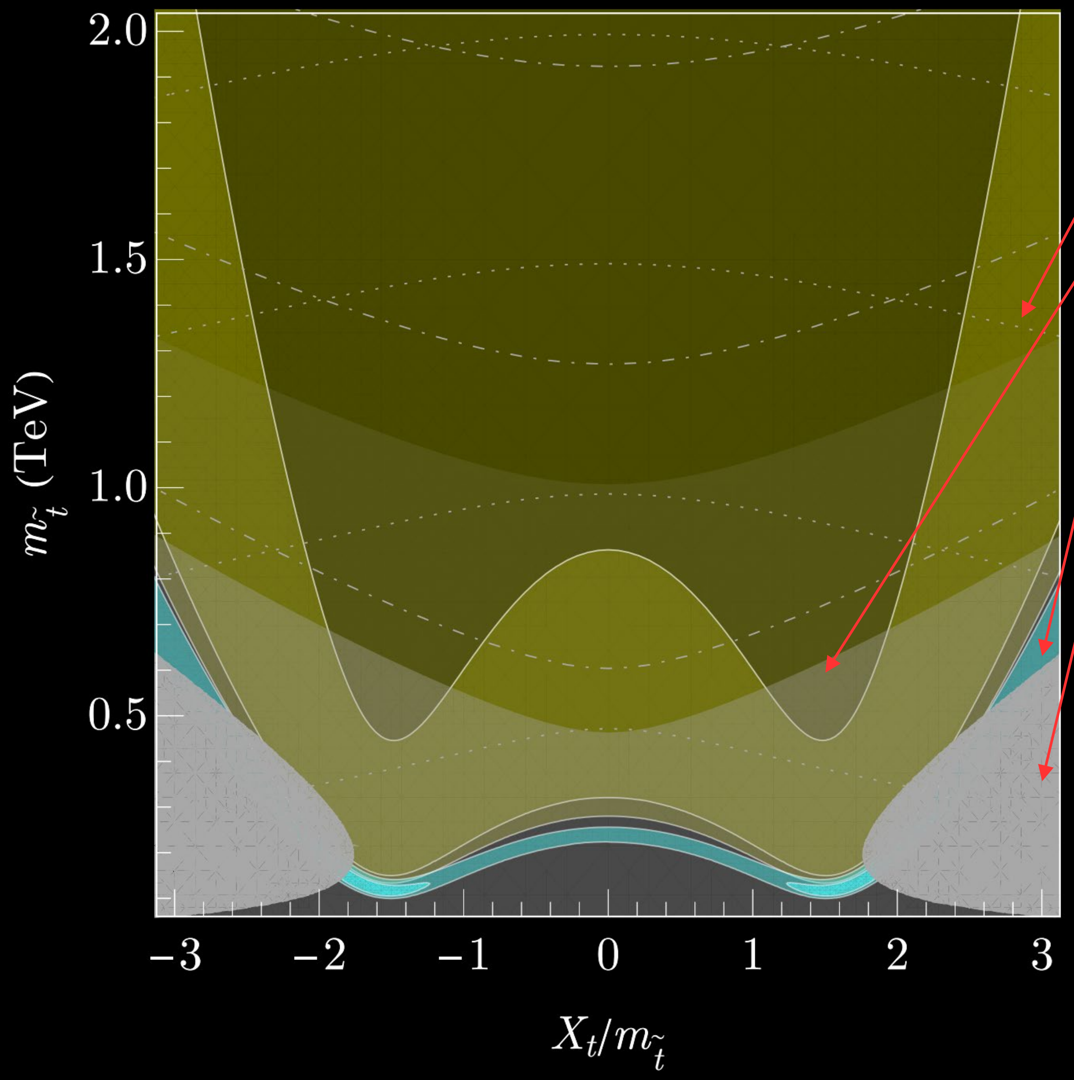
Tree-level new bosons



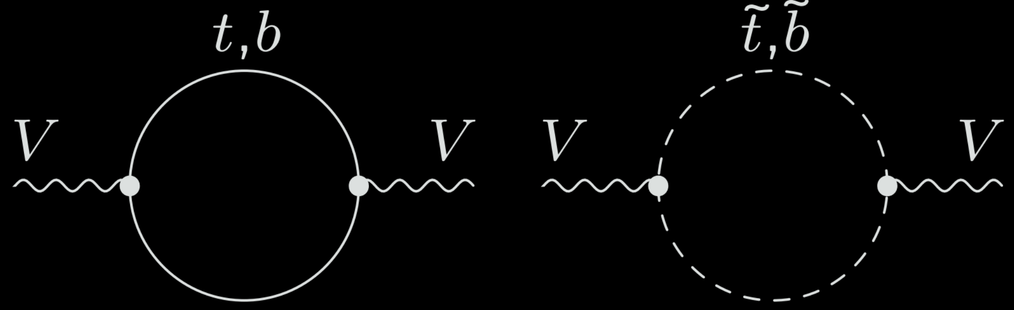
$SU(2)_L \times SU(2)_R \times U(1)_X$
$\rightarrow SU(2)_L \times U(1)_Y$

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

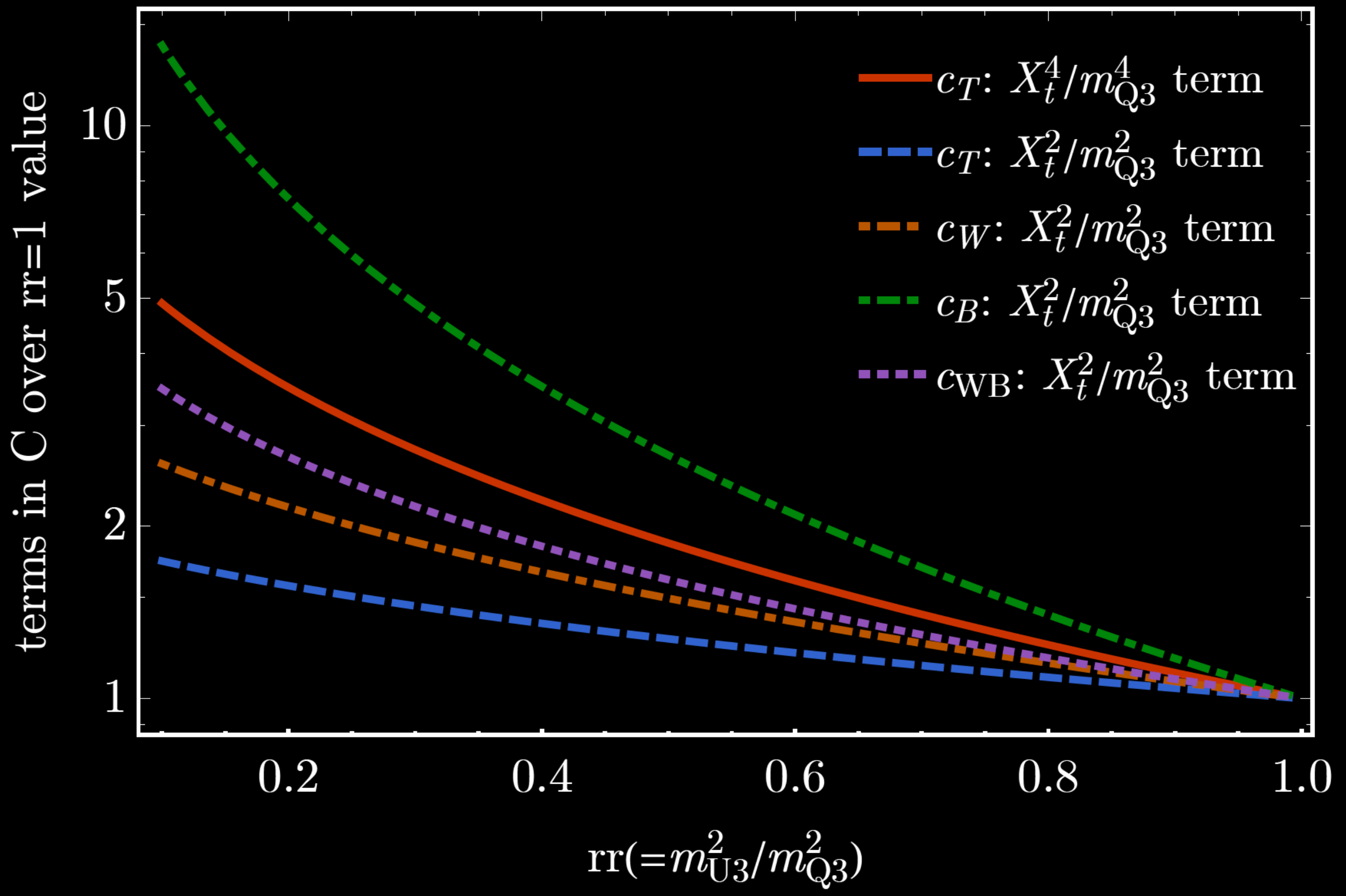


$$c_T = \frac{h_t^4}{64\pi^2 m_{\tilde t}^2}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)^2 - \frac{1}{2}\frac{X_t^2}{m_{\tilde t}^2}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right) + \frac{1}{10}\frac{X_t^4}{m_{\tilde t}^4}\right]$$

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

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

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

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

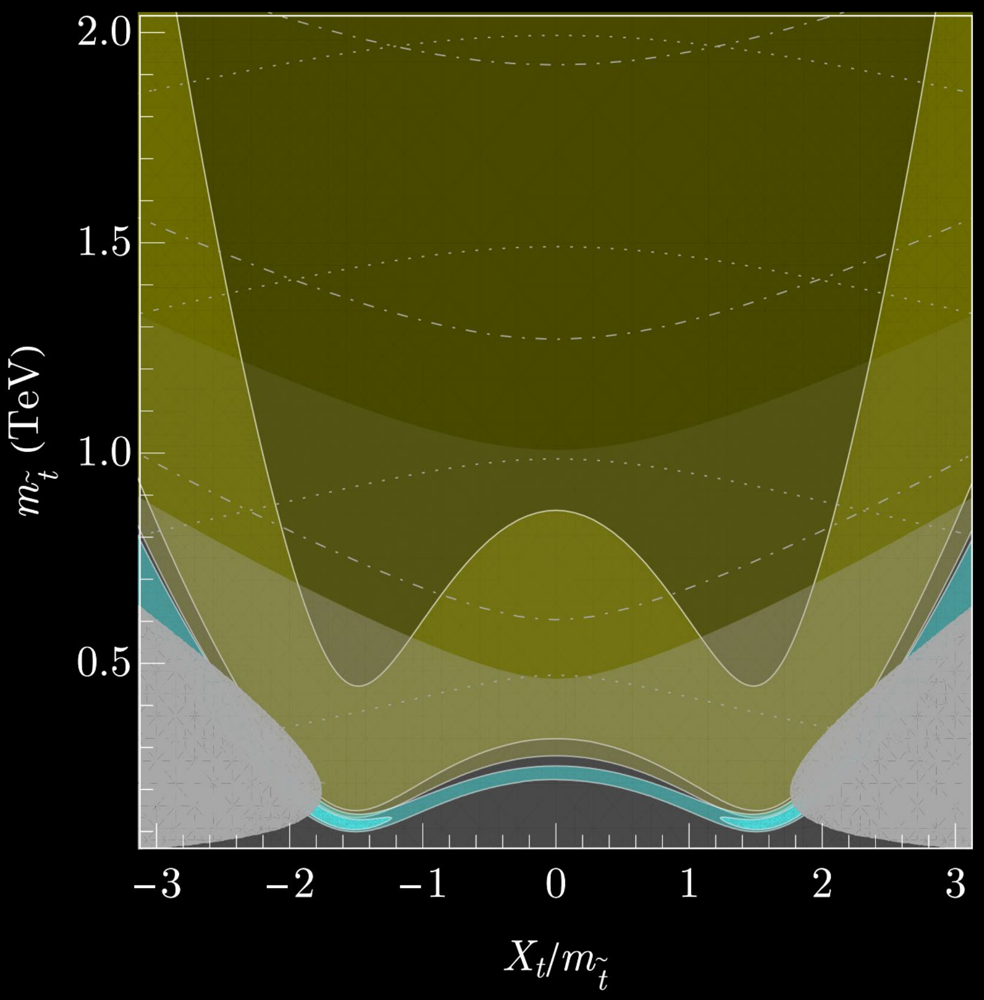
$$c_T = \frac{h_t^4}{16\pi^2 m_{\tilde{Q}3}^2}\left[\frac{1}{4}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)^2 + 2\frac{X_t^2}{m_{\tilde{Q}3}^2}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{h_t^2}\right)\left(-\frac{1-5rr-2rr^2}{8(1-rr)^3} + \frac{3rr^2}{4(1-rr)^4}\log(rr)\right) + \frac{X_t^4}{m_{\tilde{Q}3}^4}\left(\frac{1+10rr+rr^2}{4(1-rr)^4}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

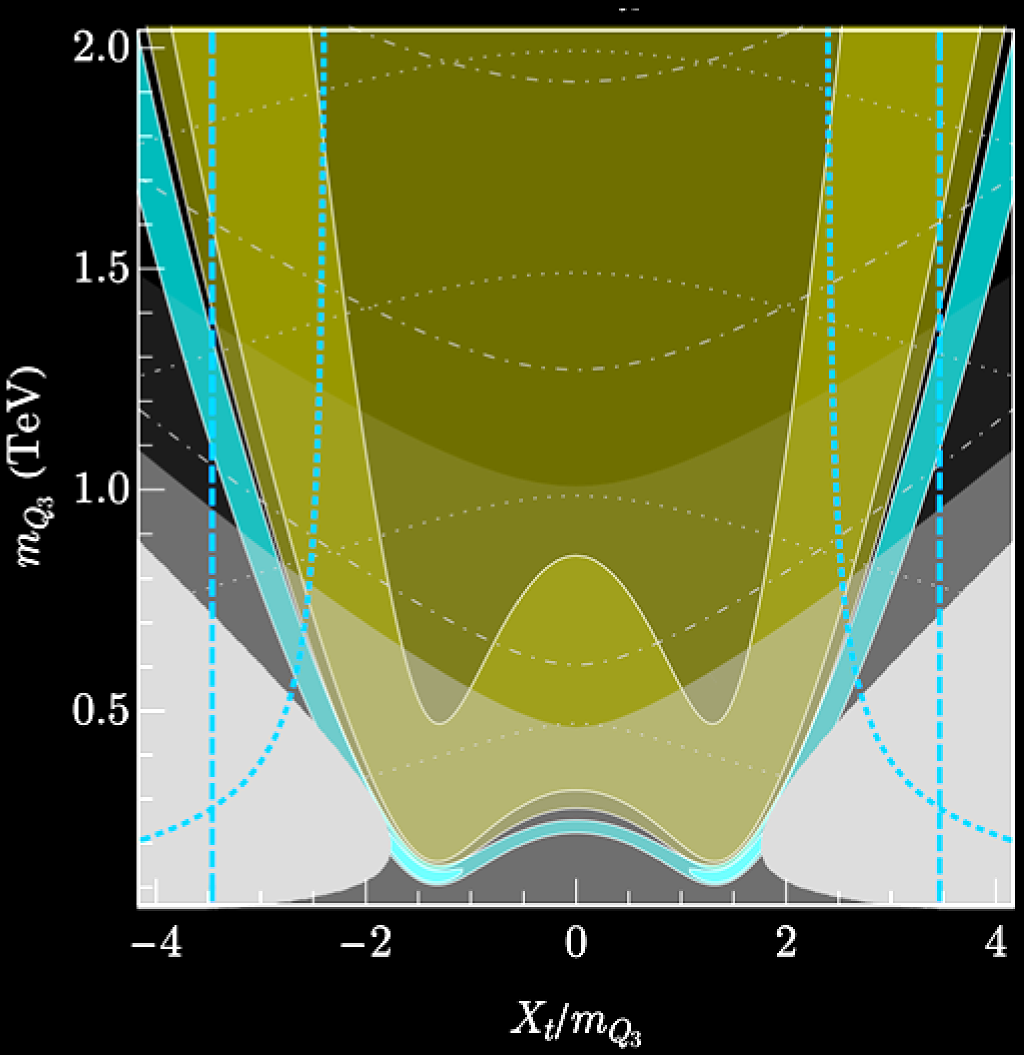
$$c_W = \frac{h_t^2}{16\pi^2 m_{\tilde{Q}3}^2}\frac{X_t^2}{m_{\tilde{Q}3}^2}\left(\frac{1-8rr-17rr^2}{12(1-rr)^4} + \frac{3rr^2+rr^3}{2(1-rr)^5}\log(rr)\right)$$

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

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

Top squarks (non-degenerate)



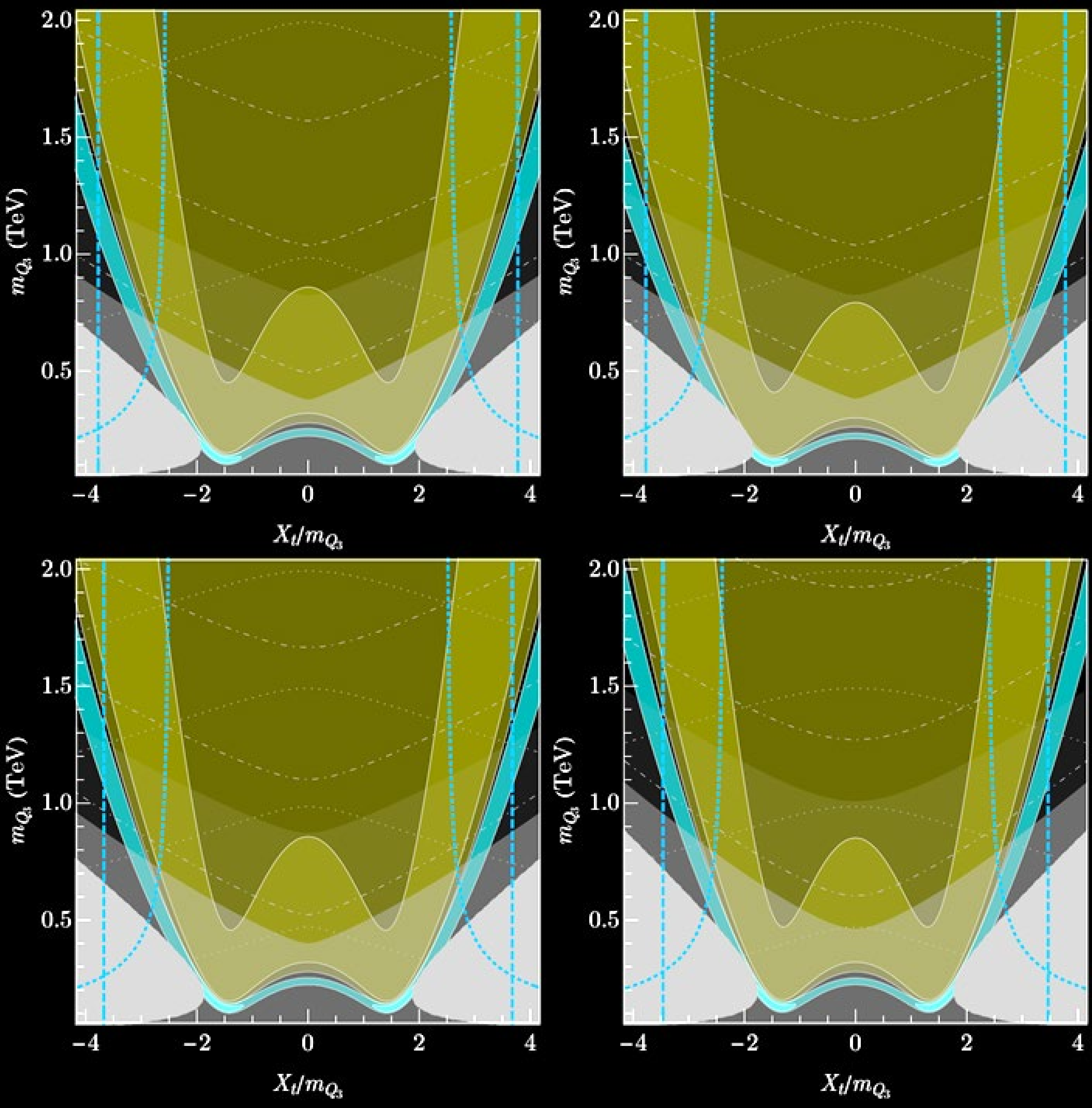


Top squarks

A few more directions could help further enhance or constrain:

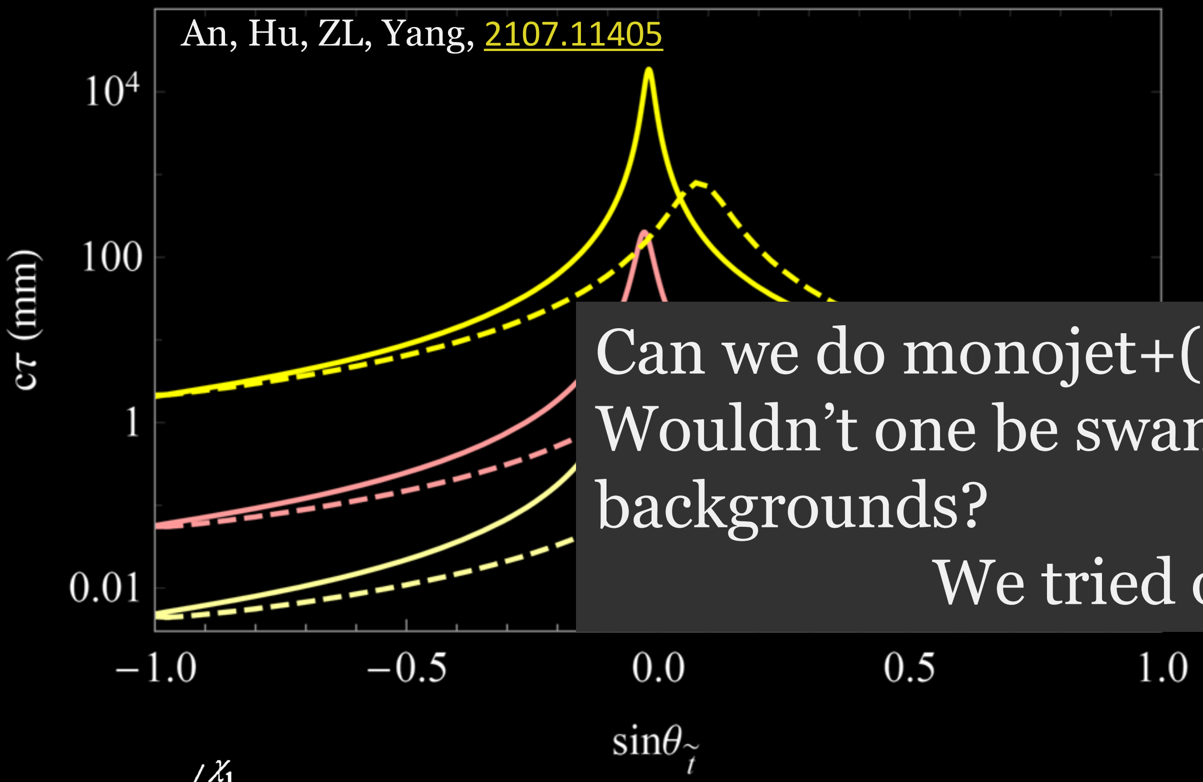
- rr (soft mass ratios)
- right-handed sbottom mass
- $tan\beta$
- Addition of slepton contributions (also accommodates muon g-2)*

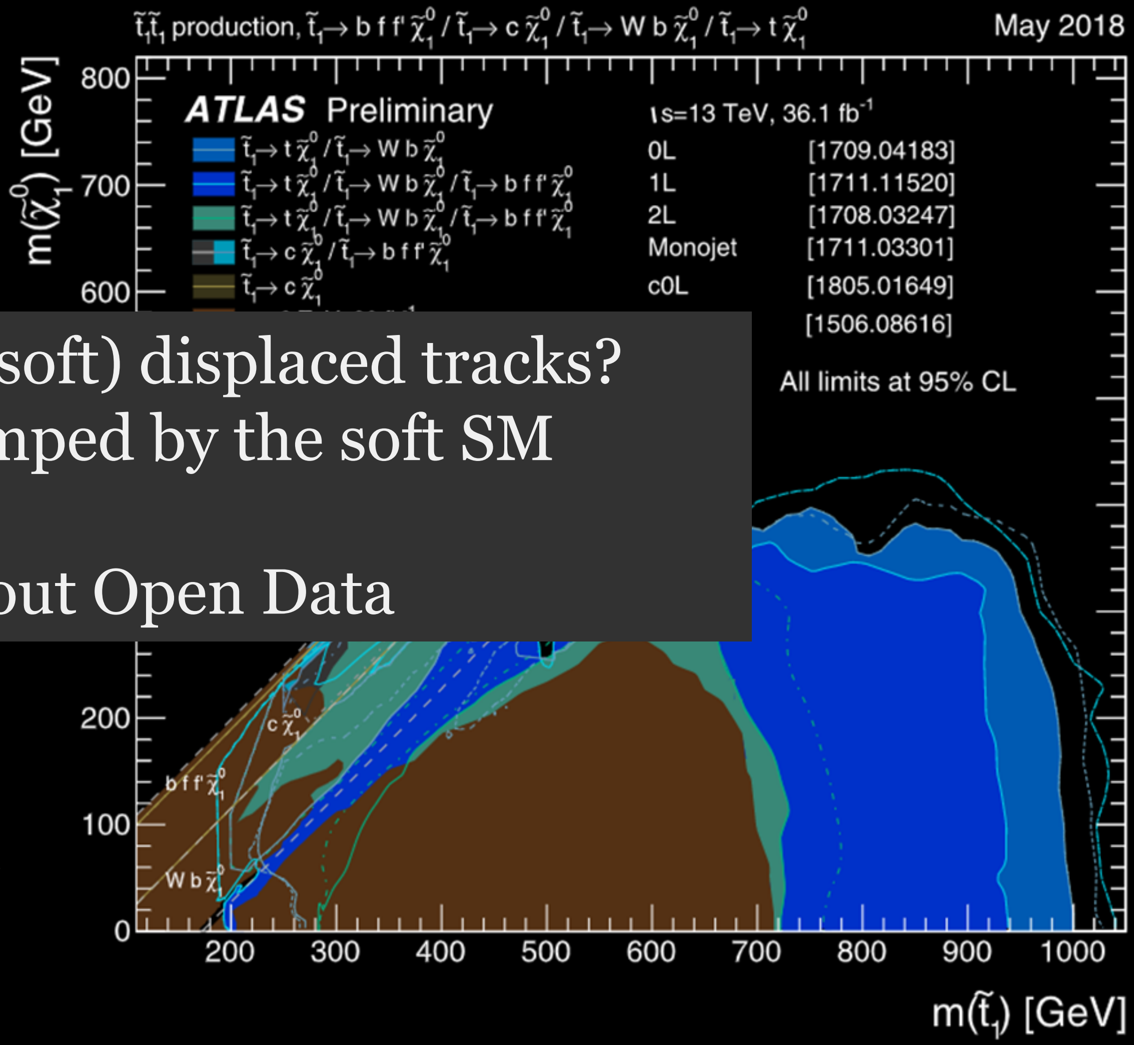
*Agashe, M, ZL, Sundrum, 2203.01796
Heinemeyer et al, 2203.15710



Coannihilation and LLP

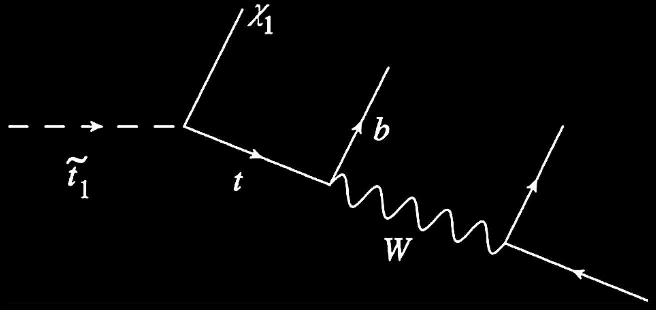
Mono-jet + (soft) displaced tracks

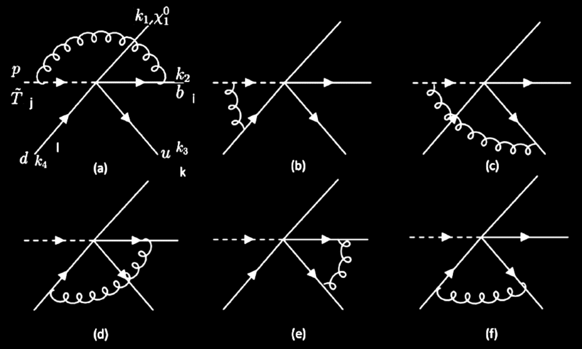




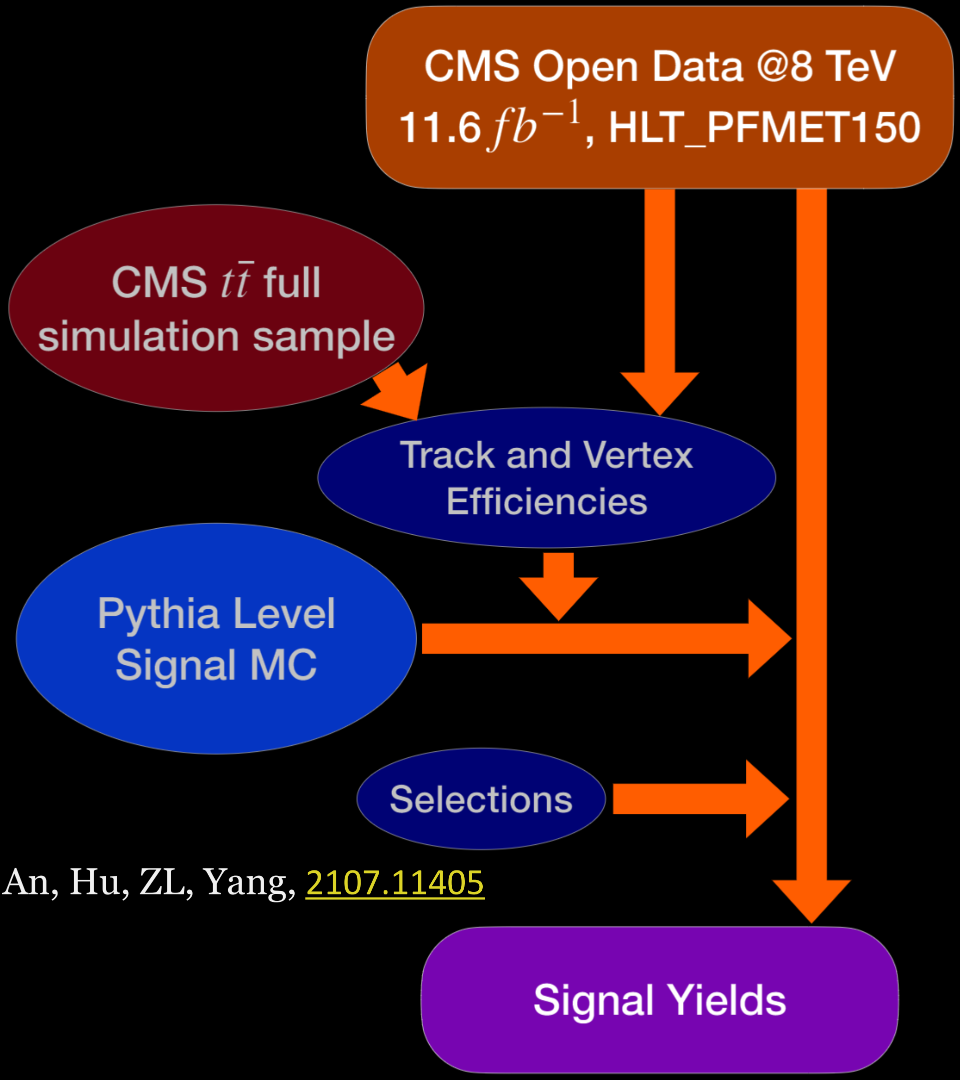
Can we do monojet+(soft) displaced tracks? Wouldn't one be swamped by the soft SM backgrounds?

We tried out Open Data

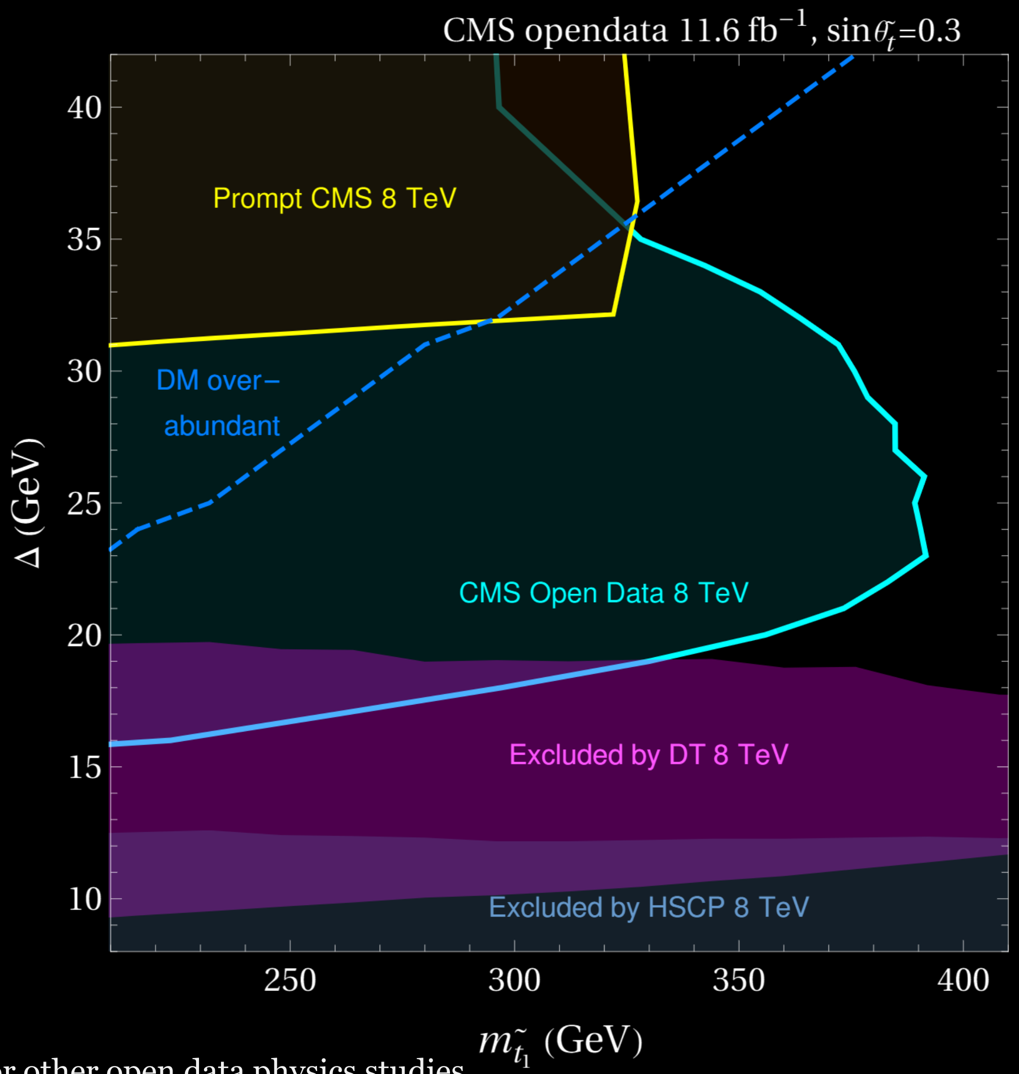




400 GeV Stop alive



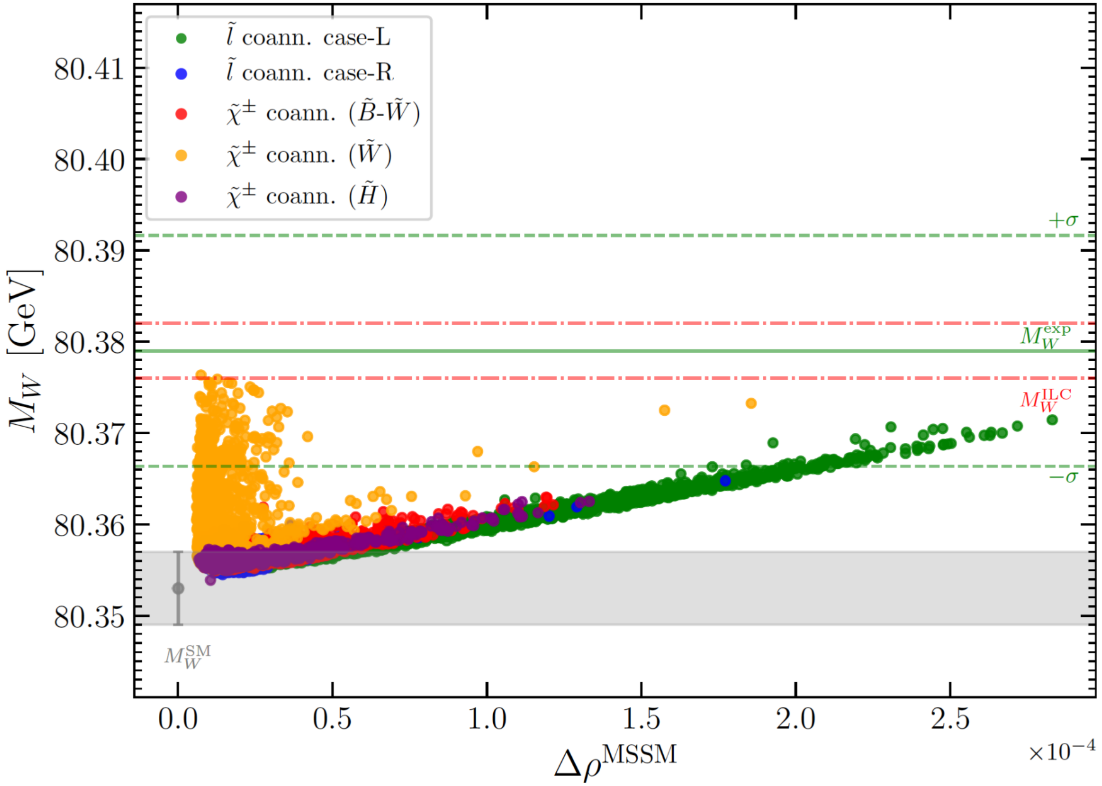
An, Hu, ZL, Yang, 2107.11405



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.

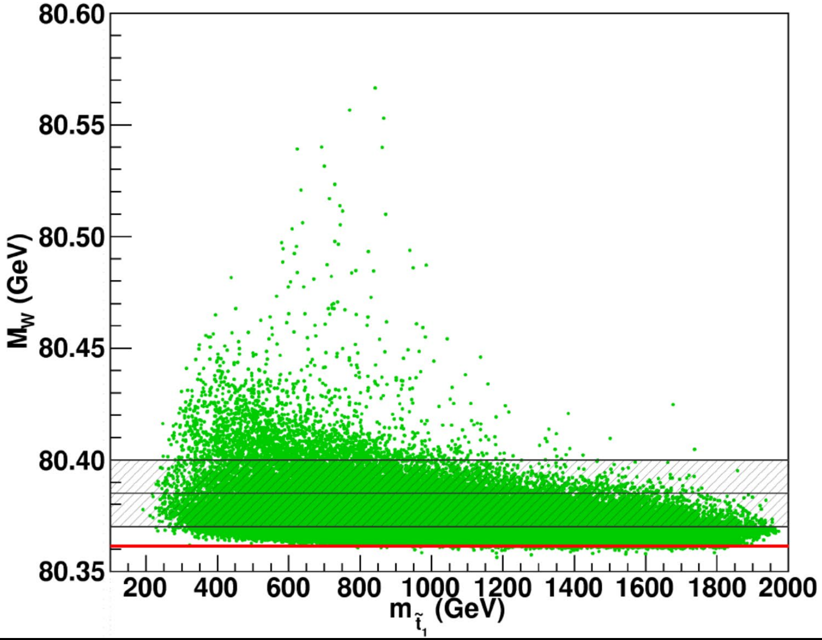
mW and g-2

Prediction for M_W: [E. Bagnaschi, M. Chakraborti, S.H., I. Saha, G. Weiglein '20-'22]



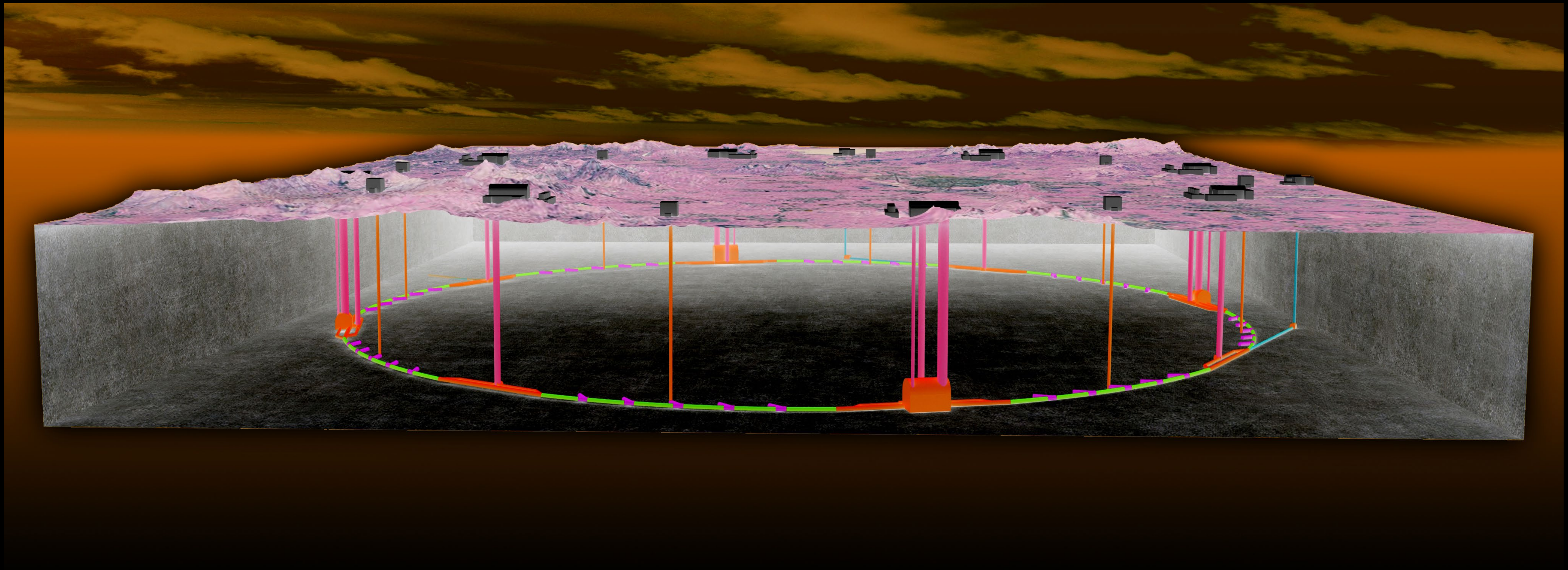
Effects of stops: [S.H., G. Weiglein, L. Zeune '13]

$\Rightarrow$ larger M_W without $(2/5 \leq m_{\tilde{t}_i}/m_{\tilde{b}_j} \leq 5/2)$

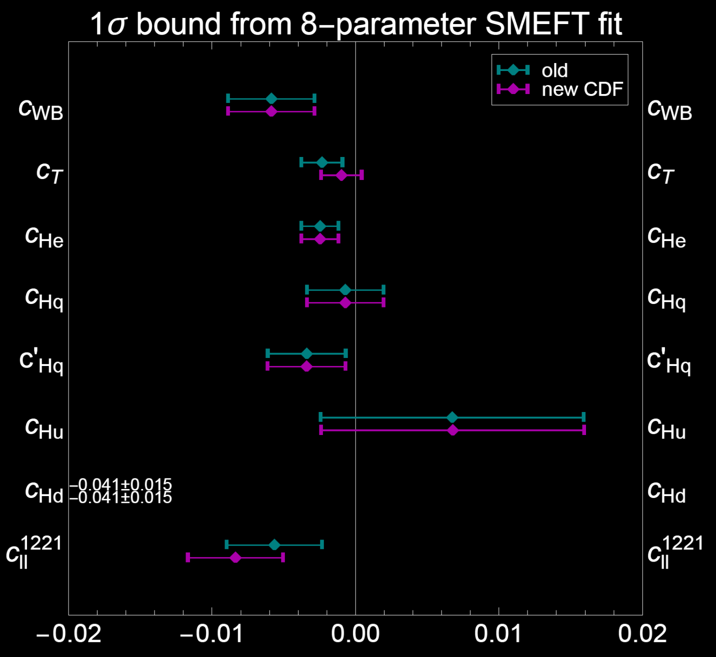


Outline

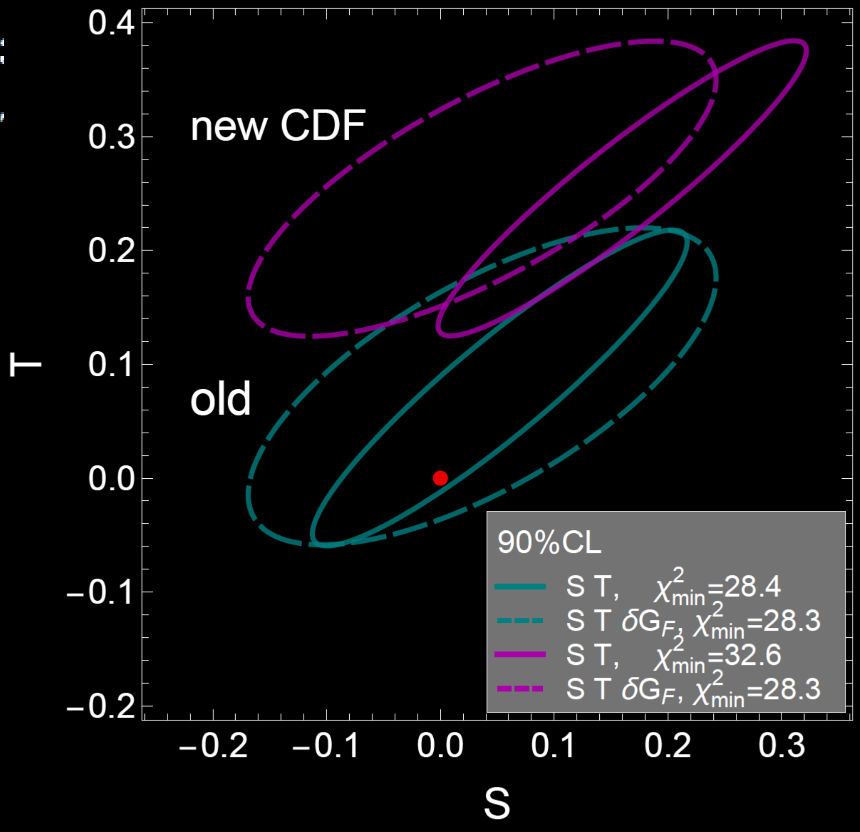
- CDF Measurement
- Theory Assessment
  - Tension with SM
  - Shifts and Errors
  - BSM interpretations
  - mW @ CEPC



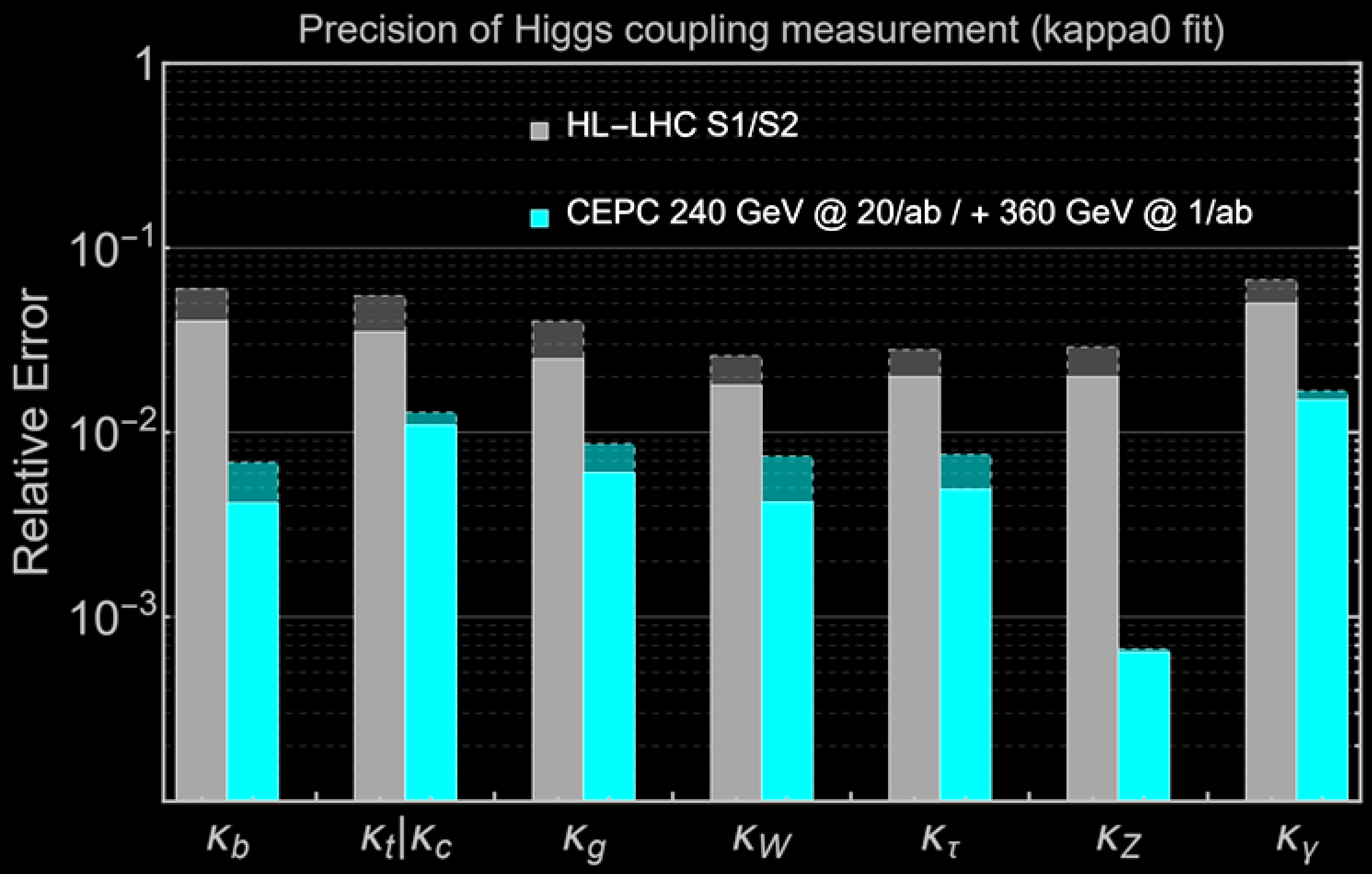
W mass Precision

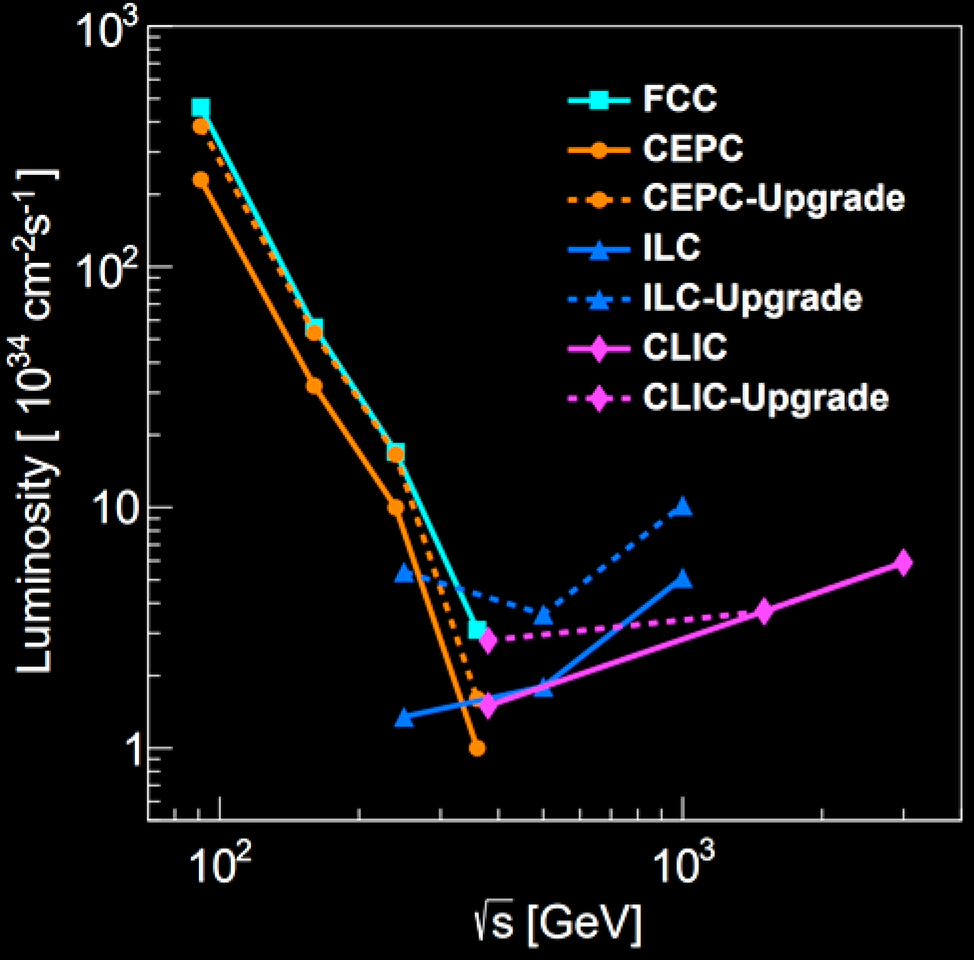


Observable	current precision	CEPC precision (Stat. Unc.)	CEPC runs	main systematic
Δm_Z	2.1 MeV [37–41]	0.1 MeV (0.005 MeV)	Z threshold	E_{beam}
$\Delta \Gamma_Z$	2.3 MeV [37–41]	0.025 MeV (0.005 MeV)	Z threshold	E_{beam}
Δm_W	9 MeV [42–46]	0.5 MeV (0.35 MeV)	WW threshold	E_{beam}
$\Delta \Gamma_W$	49 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



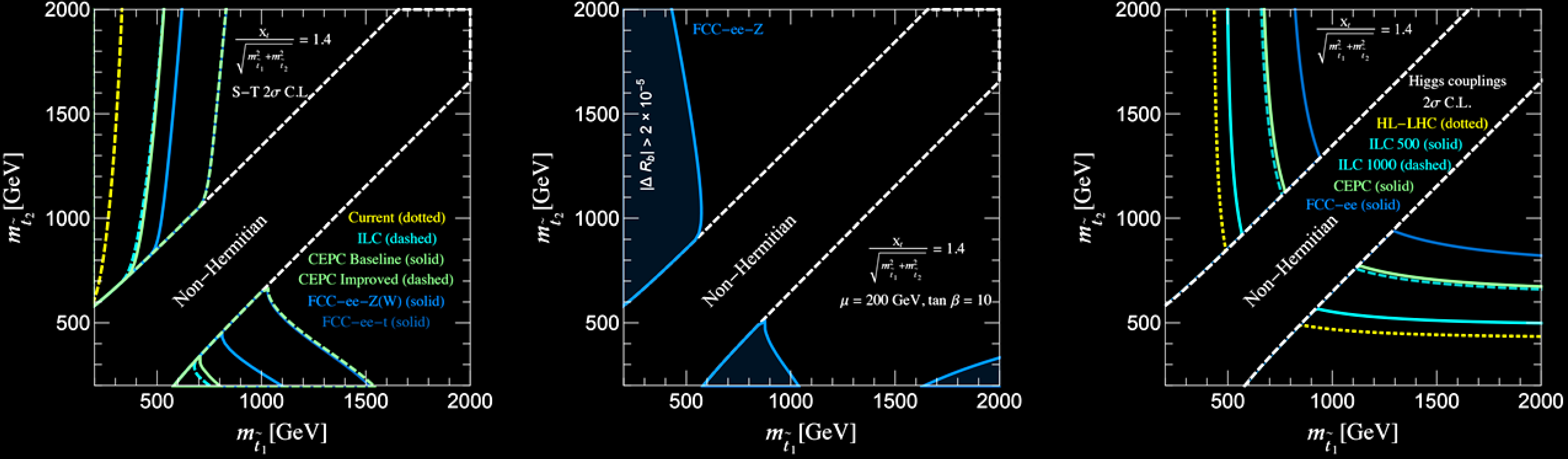
(in)Direct Probes of Loop Particles





New CEPC Snowmass paper: 2205.08553

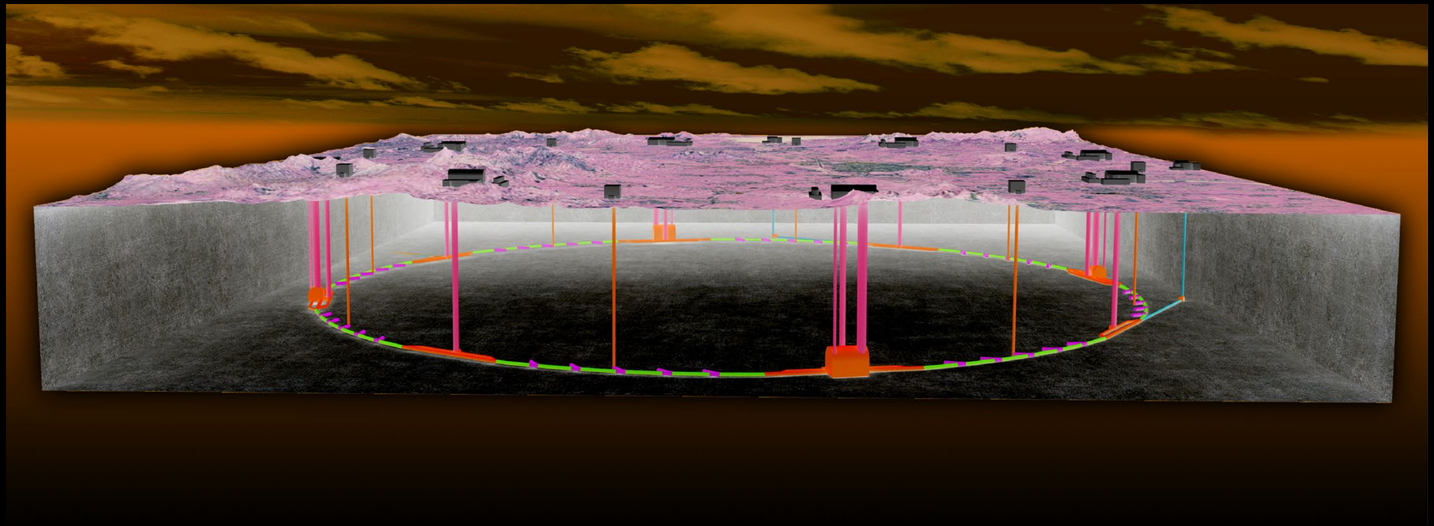
Probing Stop via loop (Z-pole, Higgs precision)



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

Summary and Outlook

- CDF Measurement
- Theory Assessment
  - Tension with SM
  - Shifts and Uncertainties
  - BSM interpretations
  - **mW @ CEPC**



There are many nice and interesting work by our colleagues
(sorry for not covering them here for sake of time).
We are excited to explore further!

W mass Precision

Updated Prospects Tables

1: Polarized threshold scan

ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	161	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480	500
$P(e^-)$ [%]	0	90	90	80
$P(e^+)$ [%]	0	60	60	30
statistics	200	2.4	1.1	
background		2.0	0.9	
efficiency		1.2	0.9	
luminosity		1.8	1.2	
polarization		0.9	0.4	
systematics	70	3.0	1.6	
experimental total	210	3.9	1.9	3.0
beam energy	13	0.4	0.4	0.4
theory	-	1.0	1.0	1.0
total	210	4.0	2.2	3.2

Table 10: Current and preliminary anticipated uncertainties in the measurement of M_W at e^+e^- colliders close to WW threshold.

- Changes wrt Snowmass 2013
- Update with current ILC run plan integrated luminosities
- Halve beam energy uncertainty (10 ppm $\rightarrow$ 5 ppm)
- Include guessed theory uncertainty in threshold total

2: $q\bar{q}\ell\nu_\ell$

ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	172-209	250	350	500
$\mathcal{L}$ [fb^{-1}]	3.0	2000	200	4000
$P(e^-)$ [%]	0	80	80	80
$P(e^+)$ [%]	0	30	30	30
beam energy	9	0.4	0.55	0.8
luminosity spectrum	N/A	1.0	1.4	2.0
hadronization	13	1.3	1.3	1.3
radiative corrections	8	1.2	1.5	1.8
detector effects	10	1.0	1.0	1.0
other systematics	3	0.3	0.3	0.3
total systematics	21	2.3	2.7	3.3
statistical	30	0.75	2.8	0.9
total	36	2.4	3.9	3.4

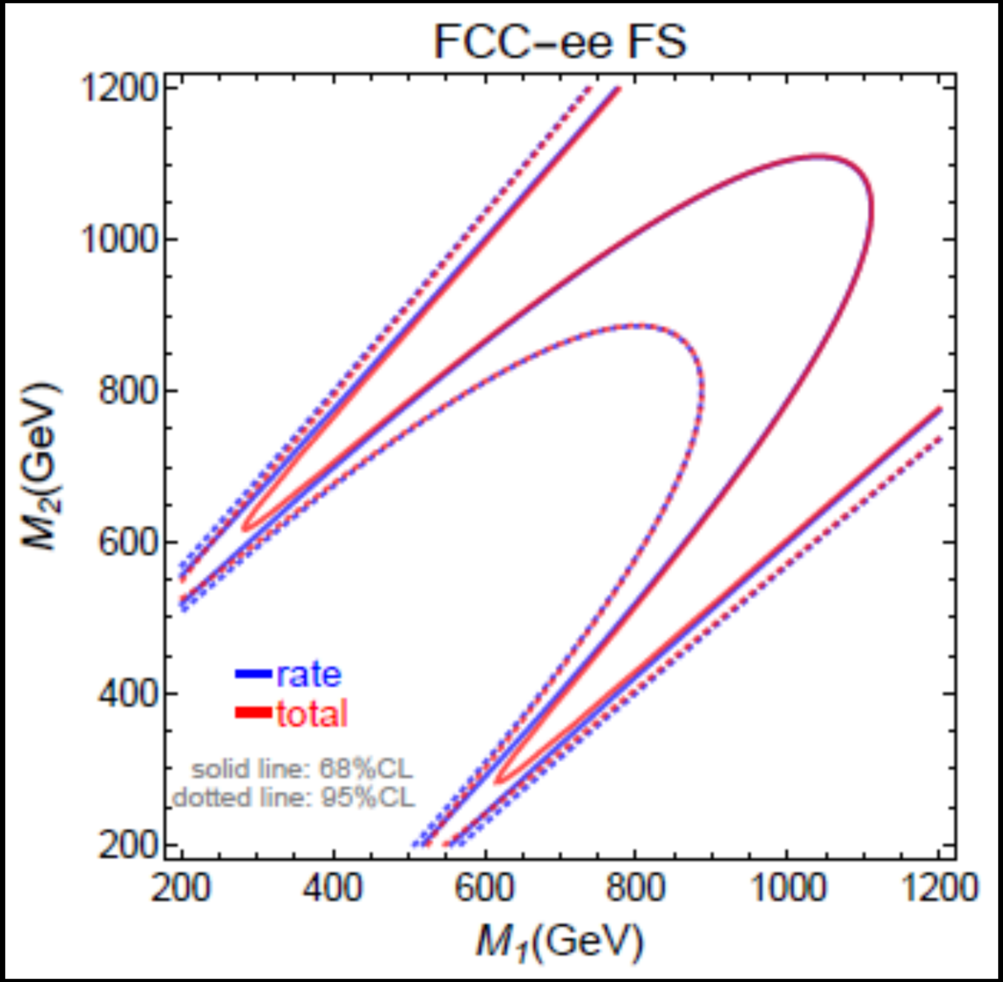
Table 6: Current and preliminary estimated experimental uncertainties in the measurement of M_W at e^+e^- colliders from kinematic reconstruction in the $q\bar{q}\ell\nu_\ell$ channel with $\ell = e, \mu$.

3: Hadronic mass

ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	2000	200	4000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	0.75	2.0	0.5	0.5
total	3.5	4.0	3.5	3.9

Table 8: Preliminary estimated experimental uncertainties in the measurement of M_W at e^+e^- colliders from direct reconstruction of the hadronic mass in single-W and WW events where one W decays hadronically. Does not include WW with $q\bar{q}\ell\nu_\ell$ where $\ell = e, \mu$.

DIAGNOSTIC POWER: CASE OF TOP SQUARK



Blue: cross section alone
Red: with asymmetries

Asymmetries could cover the region where stop contribution to rates being zero, shining lights on the "blind spot".

Sensitivity is low because of all effects are loop-induced and operators are of similar strength. BSM models inducing different tensorial structure of interactions will be best application (for future work).

Asymmetry breaks the flat direction of inclusive rate measurement, and provides novel information about the underlying operator structures.