Top physics at the HL-LHC and beyond

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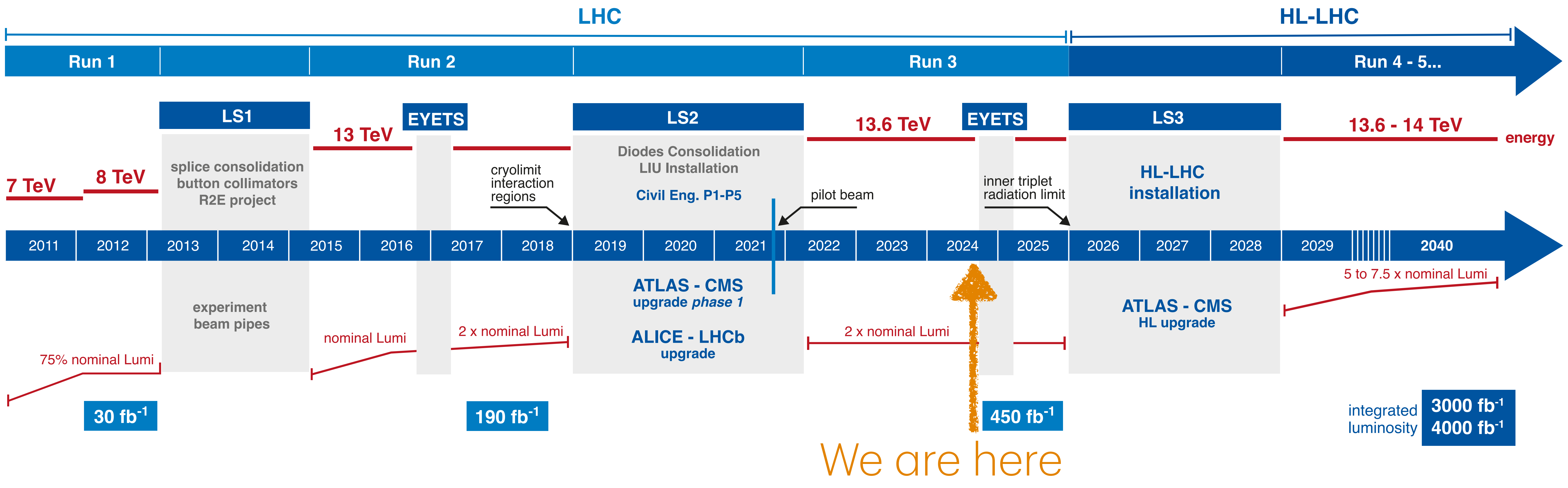
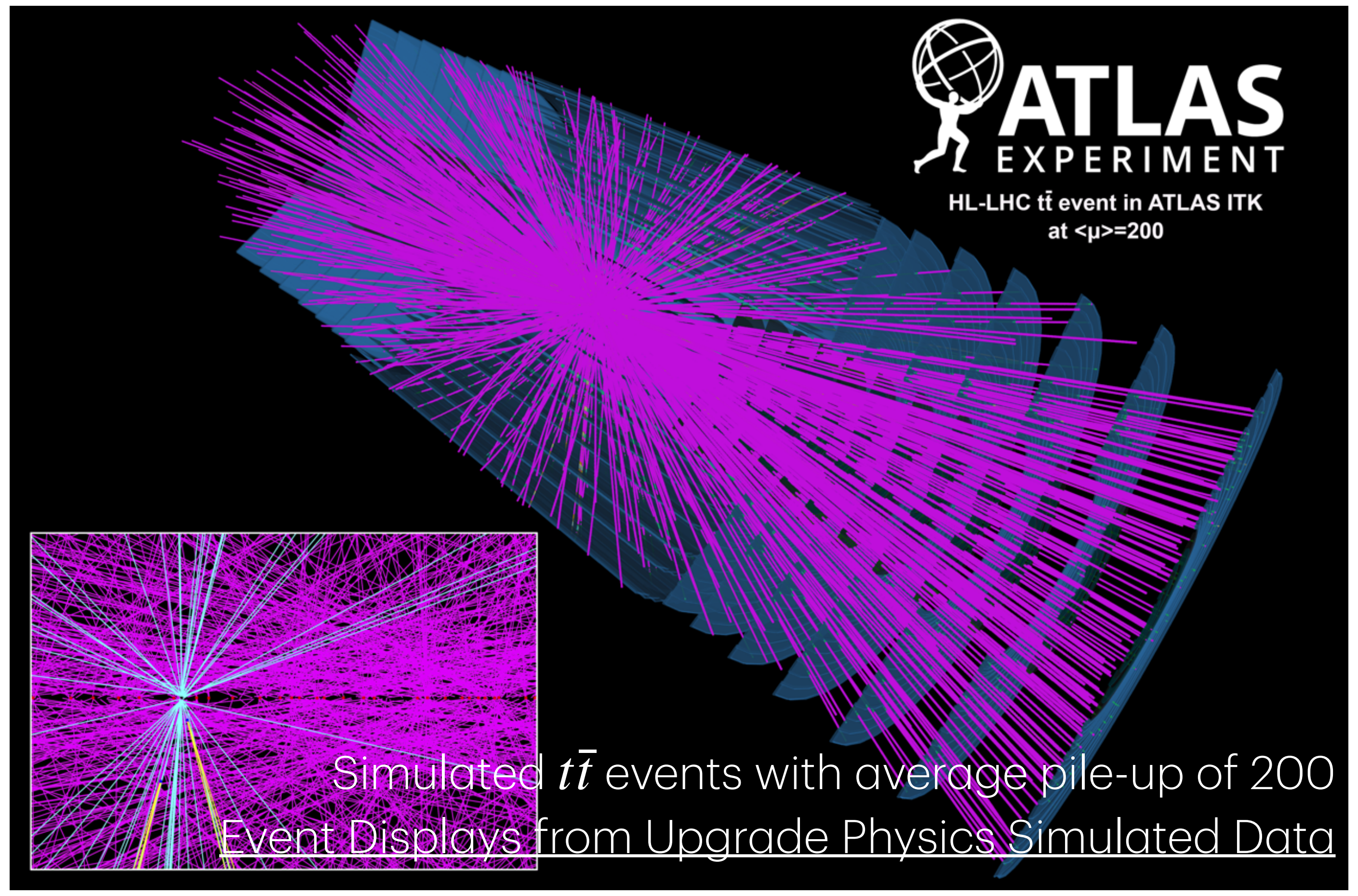
Physics Potential of Future Colliders
2024 September 18 - 20, TRIUMF

Outline

- **Future facilities**
  - HL-LHC
  - e^+e^- colliders
- **Top mass measurements**
  - Direct measurement from top decay
  - Indirect measurement from top production
  - Top pair production threshold scan
- **Top Flavour Changing Neutral Current**
  - top-Higgs, top-γ, top-g, top-Z
- **Top couplings in the SMEFT framework**

HL-LHC



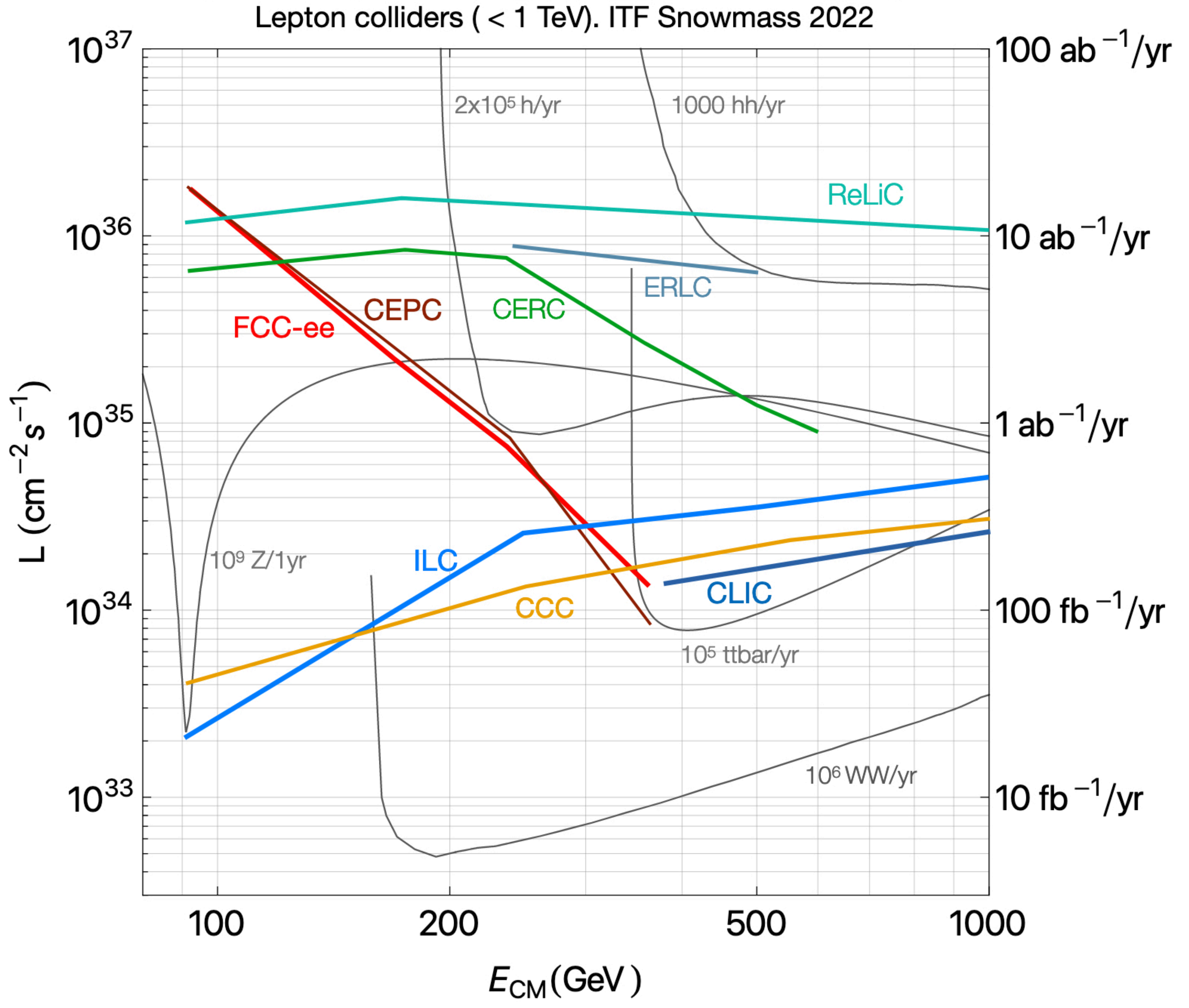


- **High Luminosity LHC**
  - 14 TeV centre-of-mass energy
  - Integrated luminosity: 3000~4000 fb^{-1}
  - Instantaneous luminosity up to 7.5×10^{34} cm^{-2}s^{-1}
    - Average pile-up up to 200
- **ATLAS and CMS Phase-2 upgrades**
  - Extended angular coverage
  - Increased trigger and readout rate
  - Timing detectors for improved track and vertex reconstruction
  - Improved pile-up mitigation techniques

Future Lepton Colliders

- Circular e^+e^- colliders
  - **FCC-ee**, **CEPC**
  - Higher luminosity at low energy
  - High collision rate, multiple interaction points
  - Unpolarized beams
- Linear e^+e^- colliders
  - **ILC**, **CLIC**, **CCC**
  - Luminosity increases as energy increases
  - Lower collision rate, but allow a high-granularity detector with pulsed operations
- Energy recovery e^+e^- colliders (**ERLC**, **ReLiC**, **CERC**), muon colliders, wakefield colliders, …

arXiv:2208.06030



arXiv:2209.03472

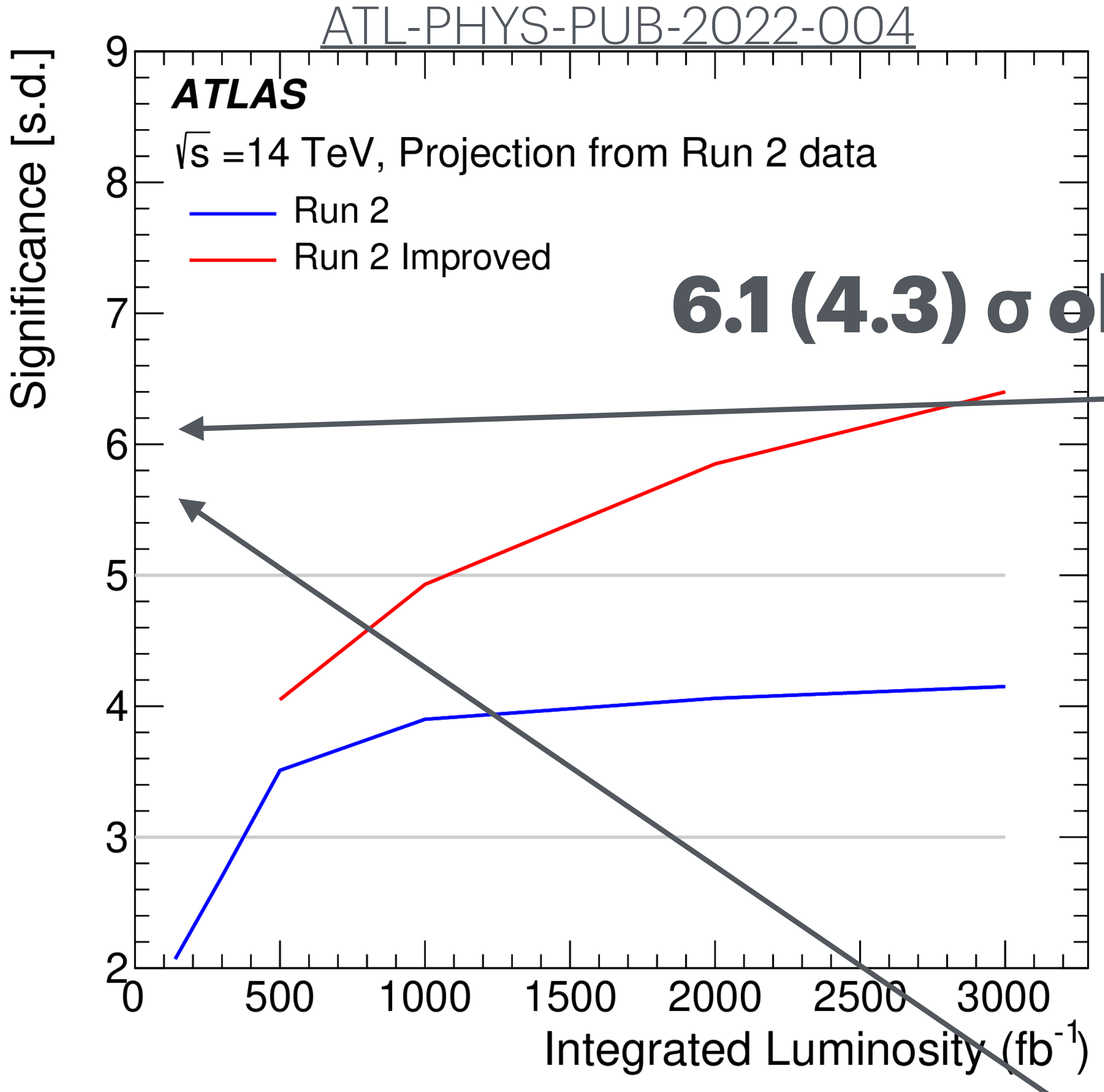
Collider	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
ILC	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8
ILC-GigaZ	m_Z	$\pm80/\pm30$	0.1
CLiC	380 GeV 500 GeV 1 TeV	$\pm80/0$ $\pm80/0$ $\pm80/0$	1 2.5 5
CEPC	m_Z $2m_W$ 240 GeV $2m_t$		60 / 100 3.6 / 6 12 / 20 – / 1
FCC-ee	m_Z $2m_W$ 240 GeV $2m_t$		150 10 5 1.5

> *The scientific choice is essentially Z-pole vs. energy upgrade, the rest is "just" politics*
>
> *— Marcel Vos @ Top2023*

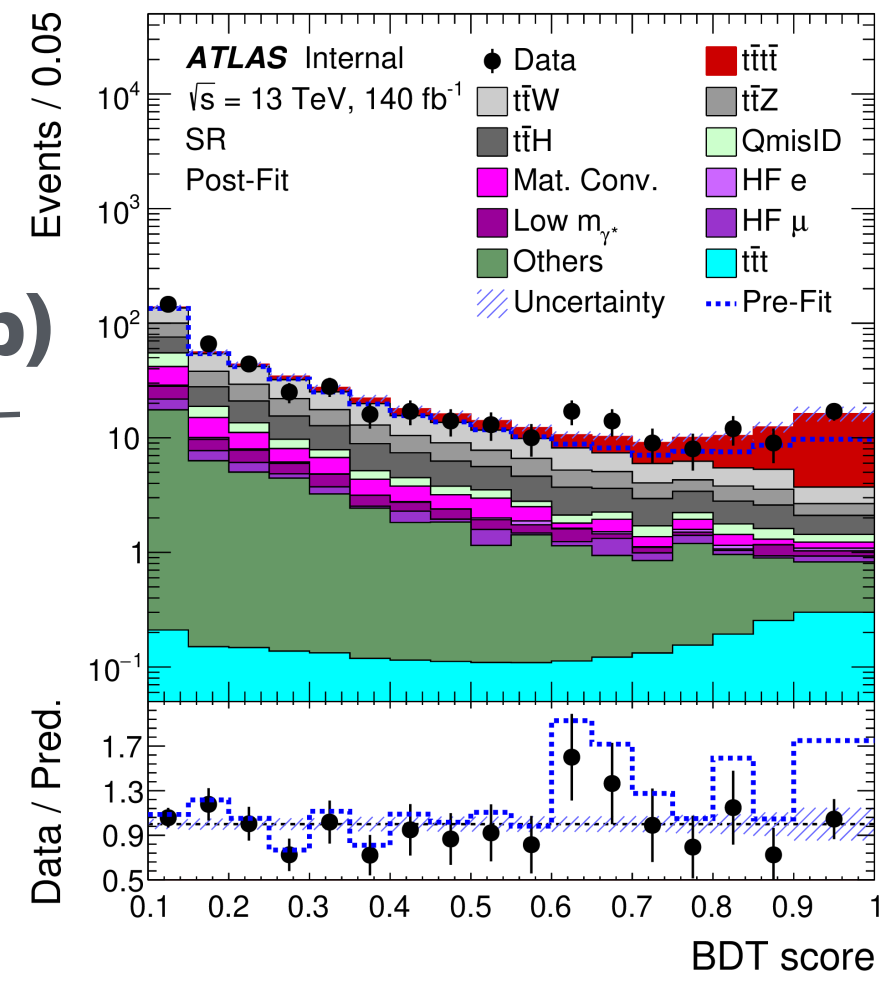
Projections are often conservative

- Example: $t\bar{t}t\bar{t}$
- ATLAS $t\bar{t}t\bar{t}$ projection (ATL-PHYS-PUB-2022-004) expected 5σ with 1000 fb^{-1}
  - "Run 2 Improved":
    - Some uncertainties reduced by a factor of 2: theory, signal and some backgrounds modelling, jet tagging
    - Some scaled down by luminosity: additional jet modelling, non-prompt lepton
    - Instrumental uncertainties are kept the same
  - Fit on H_T
- ATLAS and CMS already observed $t\bar{t}t\bar{t}$ in 2lSS and 3l channels with the LHC Run 2 data!
  - Improved background estimates
  - More sophisticated signal-background separation using ML techniques

ATL-PHYS-PUB-2022-004



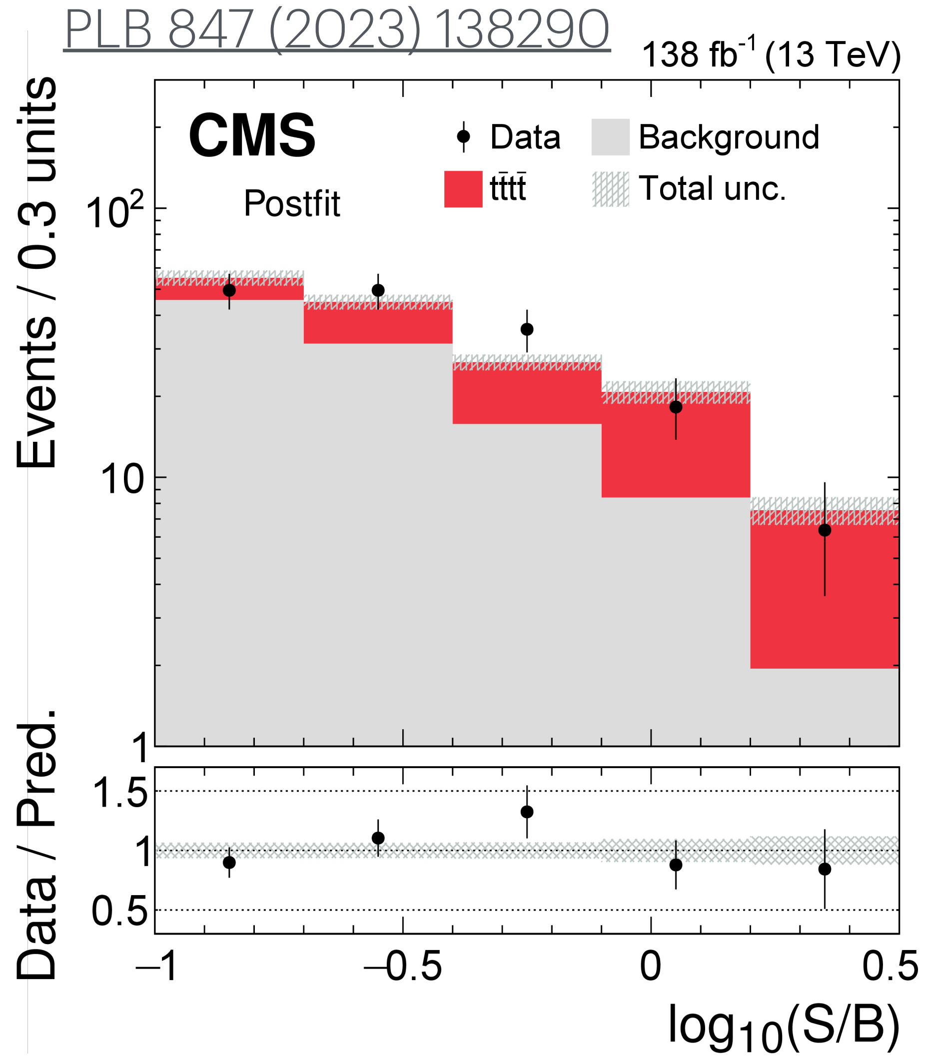
EPJC 83 (2023) 496



6.1 (4.3) σ obs (exp)

5.6 (4.9) σ obs (exp)

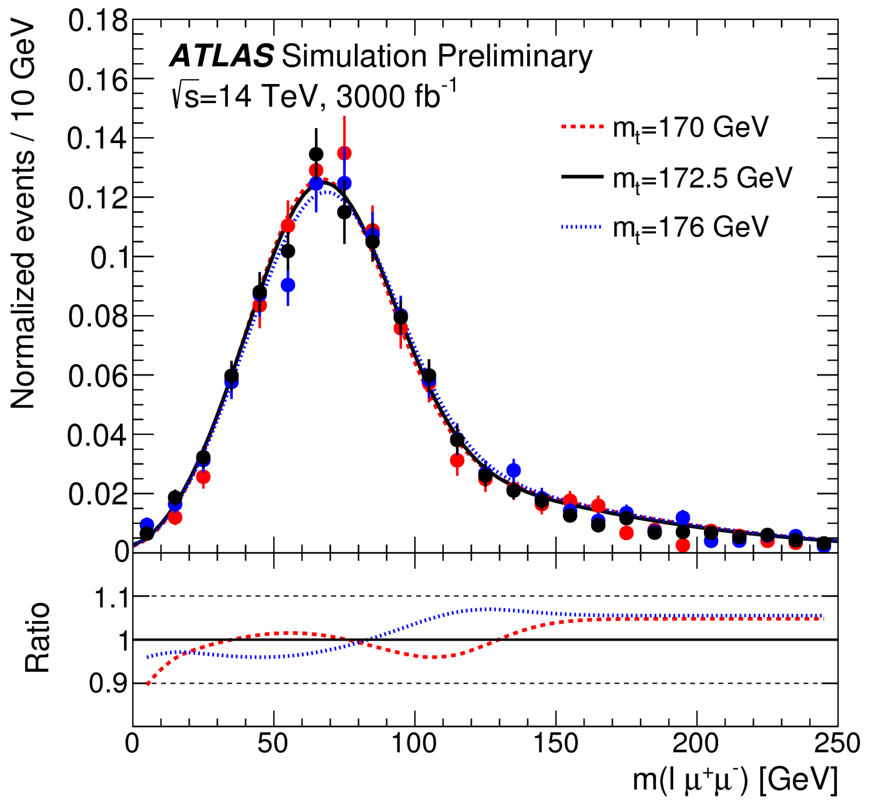
PLB 847 (2023) 138290



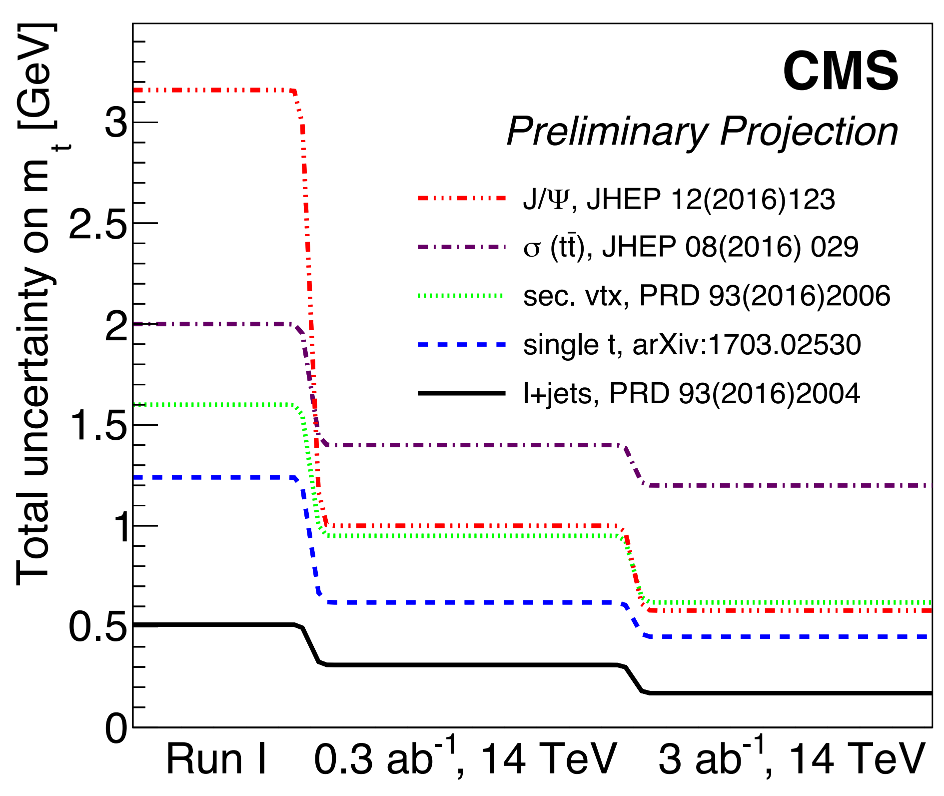
Top mass @ (HL-)LHC

- **Direct measurement** from top decay
  - Reconstruct top mass from decay products in $t\bar{t}$ or single top events
  - Measure the "MC mass" m_t^{MC}
    - More precise experimentally
    - Subject to additional uncertainty when translating to a theoretically well-defined mass
  - Dominant systematic uncertainties: **J**et **E**nergy **S**cales
    - Constrain from simultaneous fit together with m_t^{MC}
    - Or build top mass sensitive observables without jets
      - lepton + secondary vertex tracks in b-jet
      - lepton + soft $\mu^+\mu^-$ from J/ψ in B meson (e.g. ATLAS HL-LHC projection)
  - LHC Run 3 and HL-LHC projections based on the CMS analysis
  - Lepton collider projection from top threshold scans (see later slides)

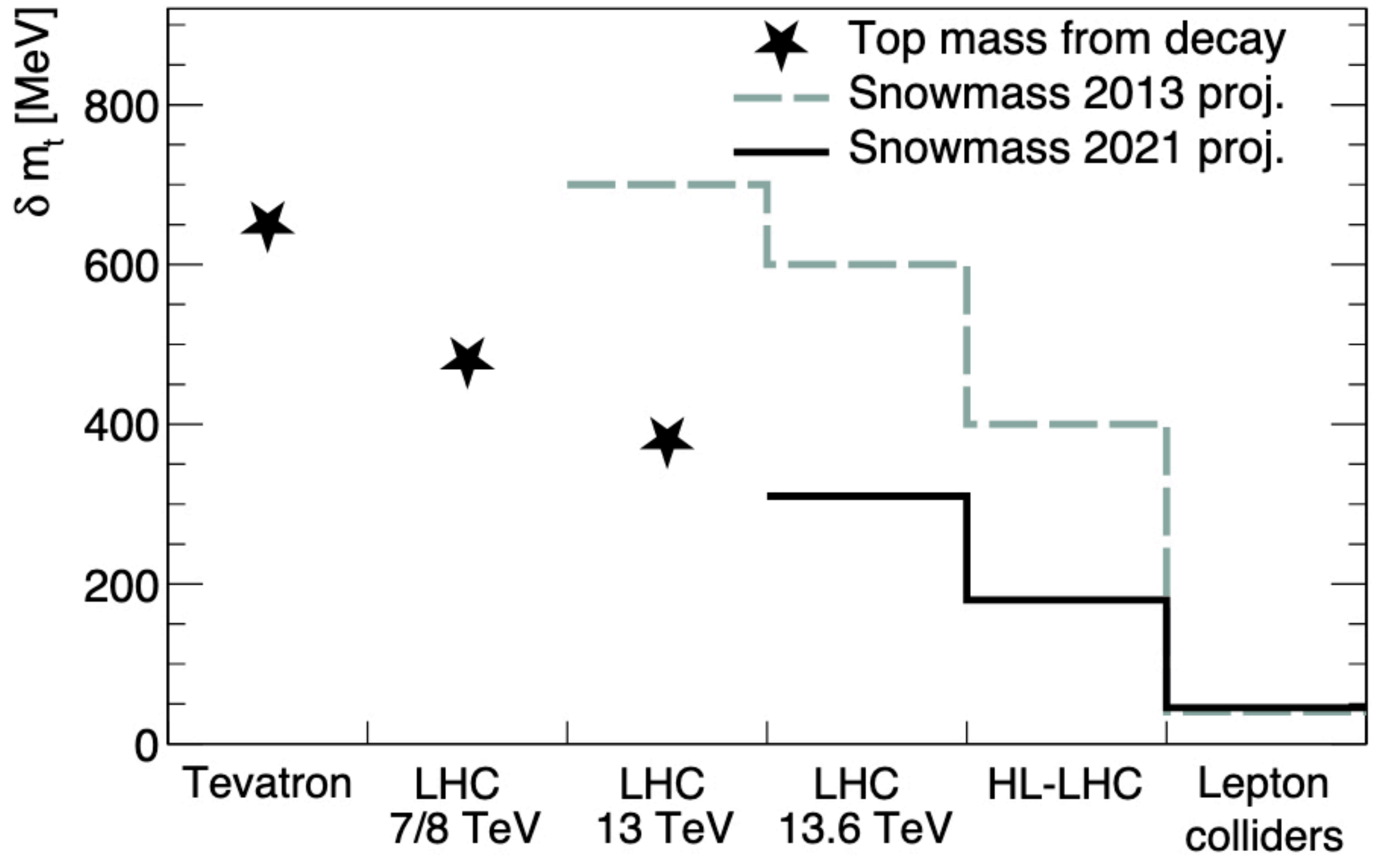
ATL-PHYS-PUB-2018-042



CMS-PAS-FTR-16-006



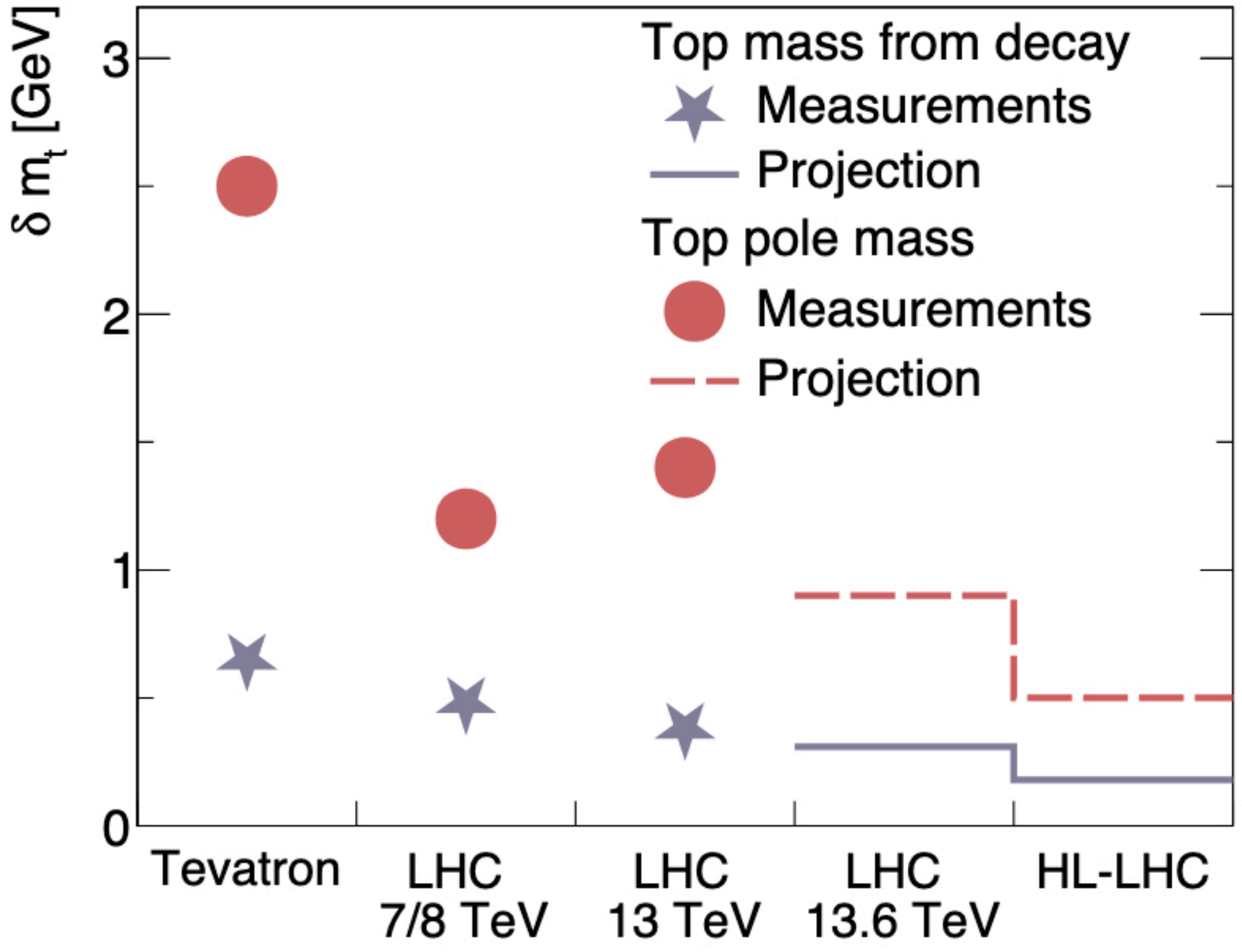
arXiv:2209.11267



Top mass @ (HL-)LHC

- **Indirect measurement** from top production
  - Extract from total or differential cross-section measurements
    - $t\bar{t}$ or $t\bar{t}$+jets events usually in the di-leptonic channel
  - Top mass in a well-defined renormalization scheme, e.g. m_t^{pole}, $m_t^{\overline{MS}}$
  - Dominant uncertainty: theory (PDF, α_s, QCD scale variations)
    - Can still benefit from better differential cross-section measurements
  - Snowmass 2021 projection for HL-LHC:
    - Combine ATLAS and CMS measurements in $t\bar{t}$ and $t\bar{t}$+jets
    - Experimental uncertainty: 0.4 GeV
      - Reduce by a factor of 2 from LHC Run 2 to LHC Run 3, and another factor of 2 from Run 3 to HL-LHC
    - Theoretical uncertainty: 0.25 GeV
      - Run 3 same as Run 2; reduce by a factor of 2 at HL-LHC

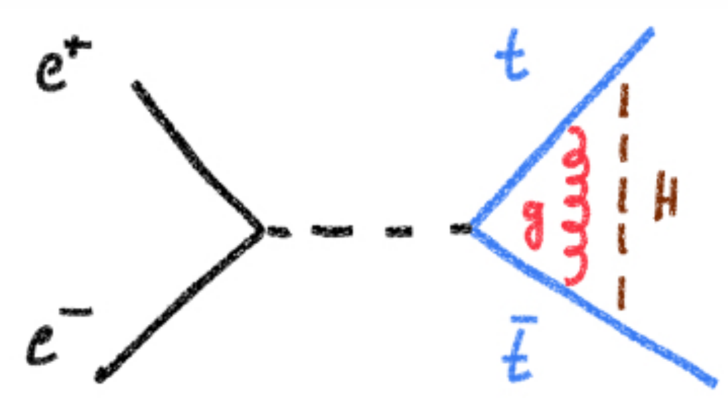
arXiv:2209.11267

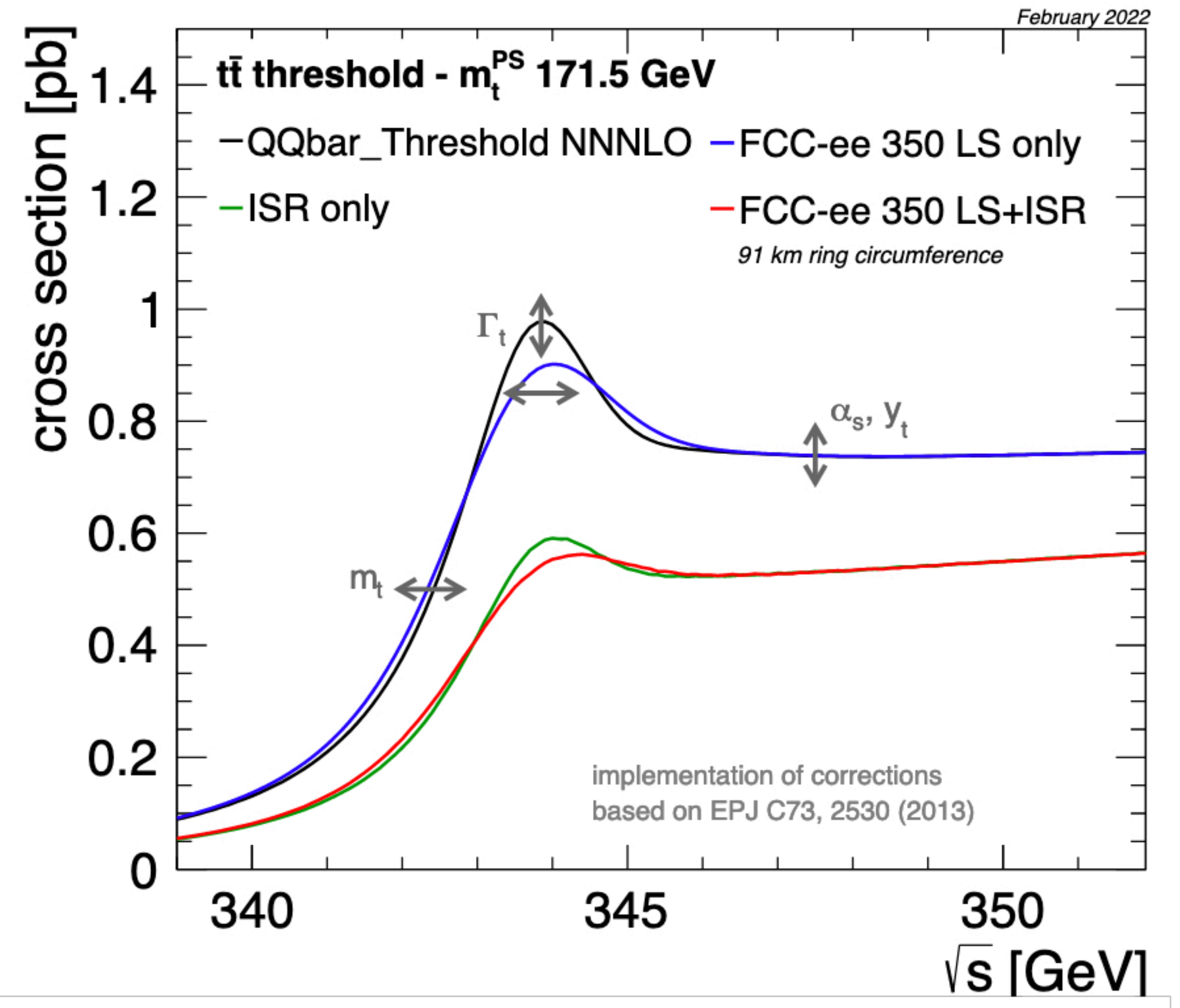


Top mass @ Lepton Colliders

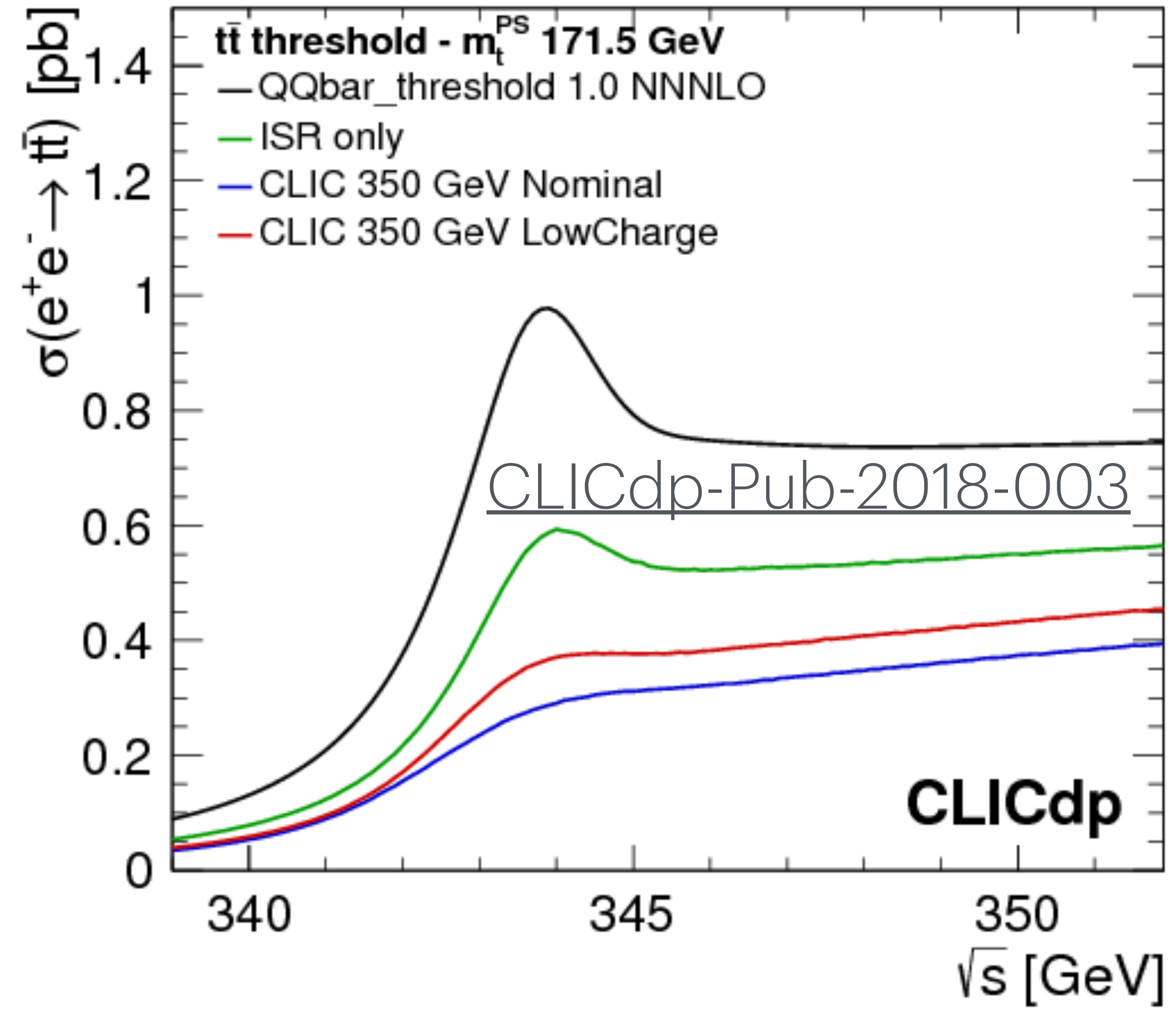
Seminar talk by Frank Simon

- The $t\bar{t}$ production threshold is sensitive to the top mass
  - The threshold mass m_t^{PS}
    - Conversion to $m_t^{\overline{MS}}$ known to $\mathcal{O}(\alpha_s^4)$
  - The peak shape is sensitive to the top width Γ_t
  - The tail is sensitive to top Yukawa y_t, and strong coupling α_s





- The luminosity spectrum affects the threshold curve shape
  - Linear colliders: characterized by a beamstrahlung tail
  - FCC-ee: Gaussian
  - Precise measurement of the luminosity spectrum is required

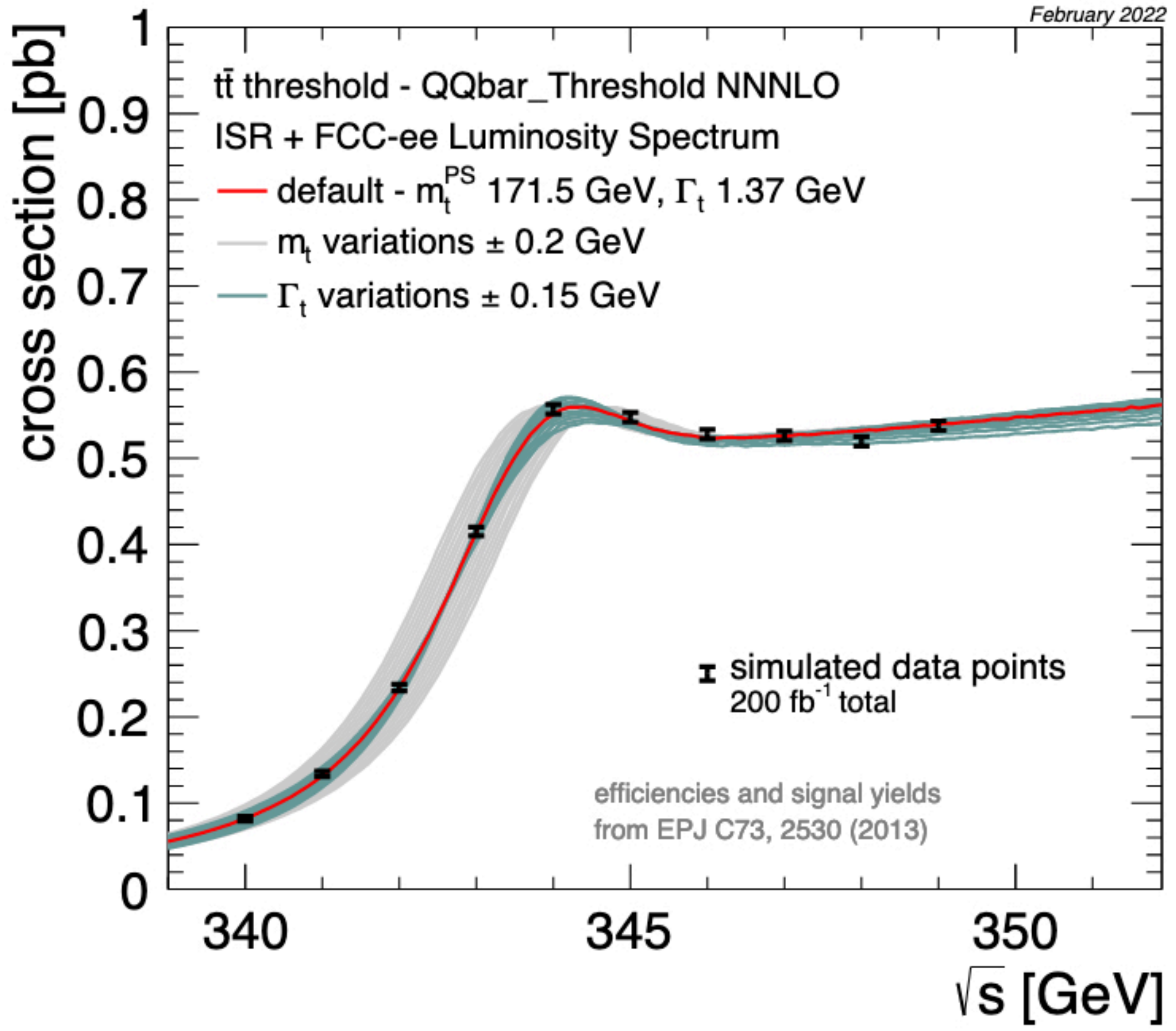


CLICdp-Pub-2018-003

Top mass @ Lepton Colliders

Seminar talk by Frank Simon

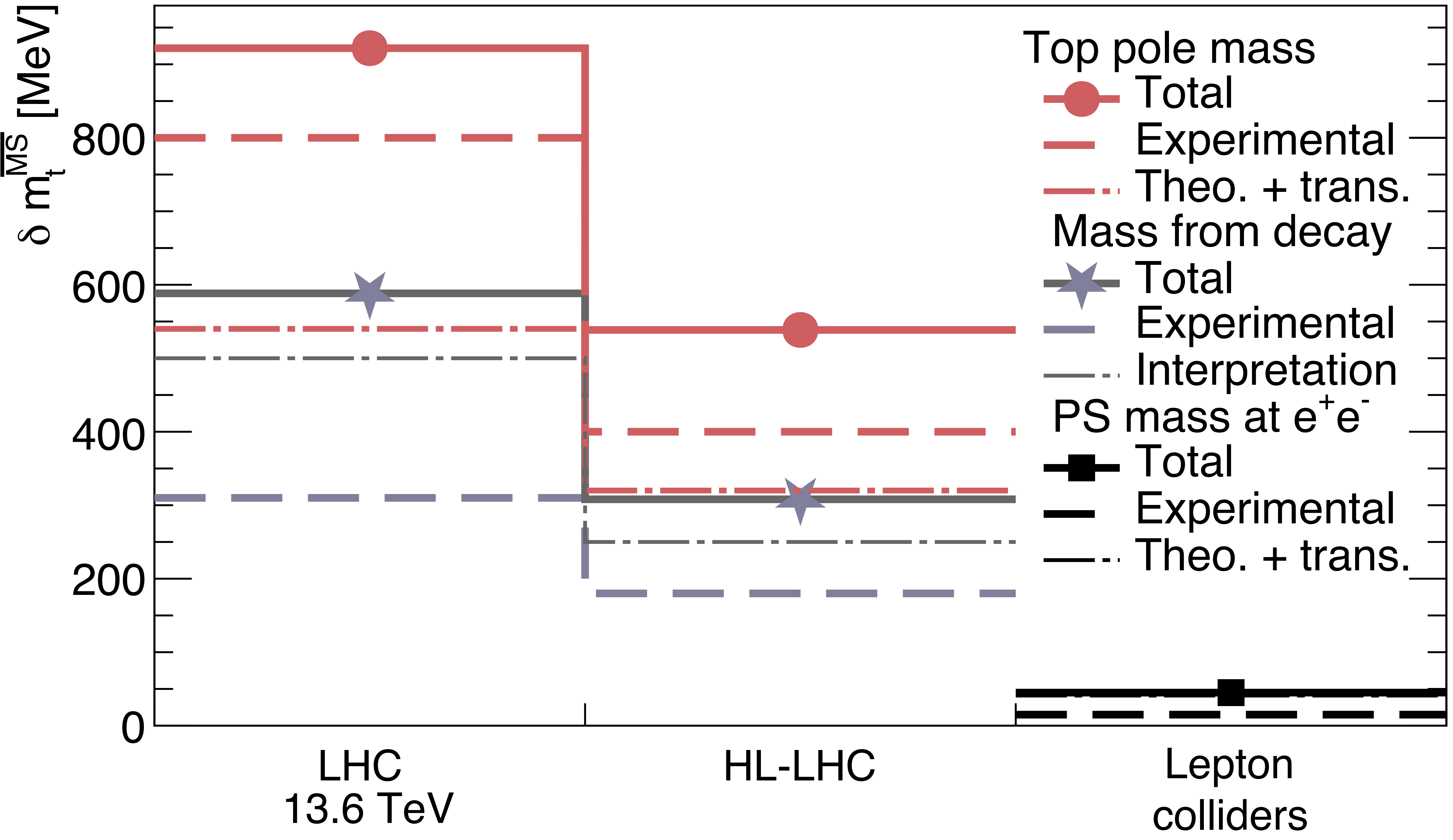
- Threshold scan around 350 GeV
  - Can extract m_t^{PS} with Γ_t, y_t, and α_s from template fits
  - Sizeable contribution from non-resonant backgrounds
  - The leading uncertainties: QCD scales
    - Need NNNLO QCD prediction
- Snowmass 2021 projection arXiv:2209.11267
  - Assumes other parameters Γ_t, y_t, and α_s are fixed
  - Smaller uncertainty on α_s for FCC-ee
    - Thanks to the high-statistics Z-pole run
  - Slightly larger experimental uncertainty for ILC/CLIC due to more complex luminosity spectrum shape corrections



δm_t^{PS} [MeV]	ILC	CLIC	FCC-ee
$\mathcal{L}$[fb^{-1}]	200	100 [200]	200
Statistical uncertainty	10	20 [13]	9
Theoretical uncertainty (QCD)	40 – 45		
Parametric uncertainty α_s	26	26	3.2
Parametric uncertainty y_t (HL-LHC)	5		
Non-resonant contributions	< 40		
Experimental systematic uncertainty	15 – 30		11 – 20
Total uncertainty	40 – 75		

Top mass summary

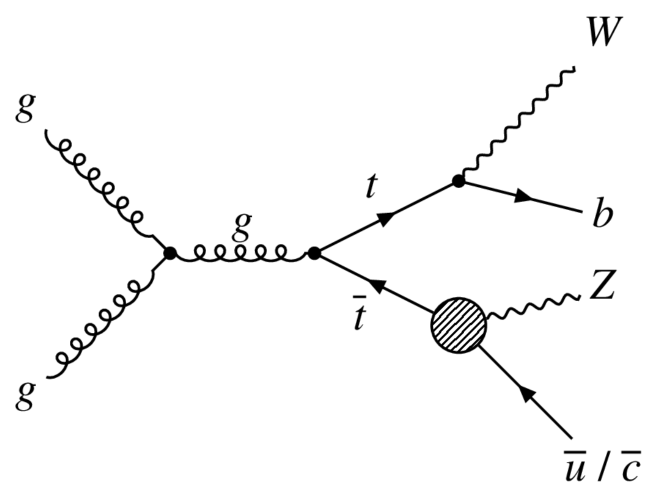
- For comparisons, translate mass measurements and projections all to $m_t^{\overline{MS}}$
- Additional uncertainty assumed when translating: 250~500 MeV from m_t^{MC} and 10~20 MeV from m_t^{PS}



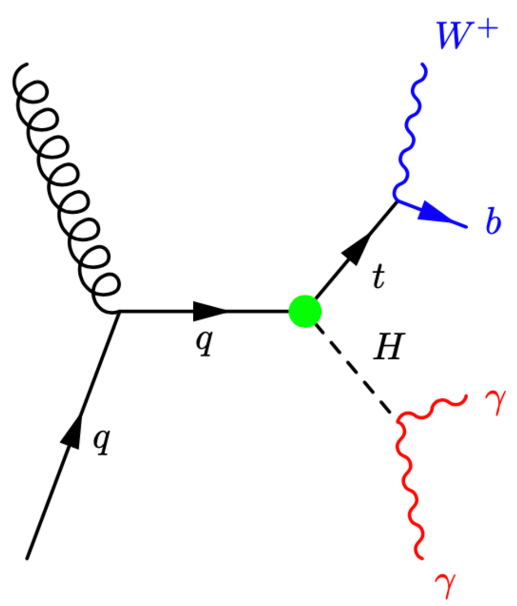
arXiv:2209.11267

Top FCNC @ (HL-)LHC

- **Probe from top decay**
  - From $t\bar{t}$ events in which one top decays as usual (W+b) and the other top decays via the FCNC coupling (t → u/c + H/Z/γ/g)
  - Need charm tagging to differentiate u and c



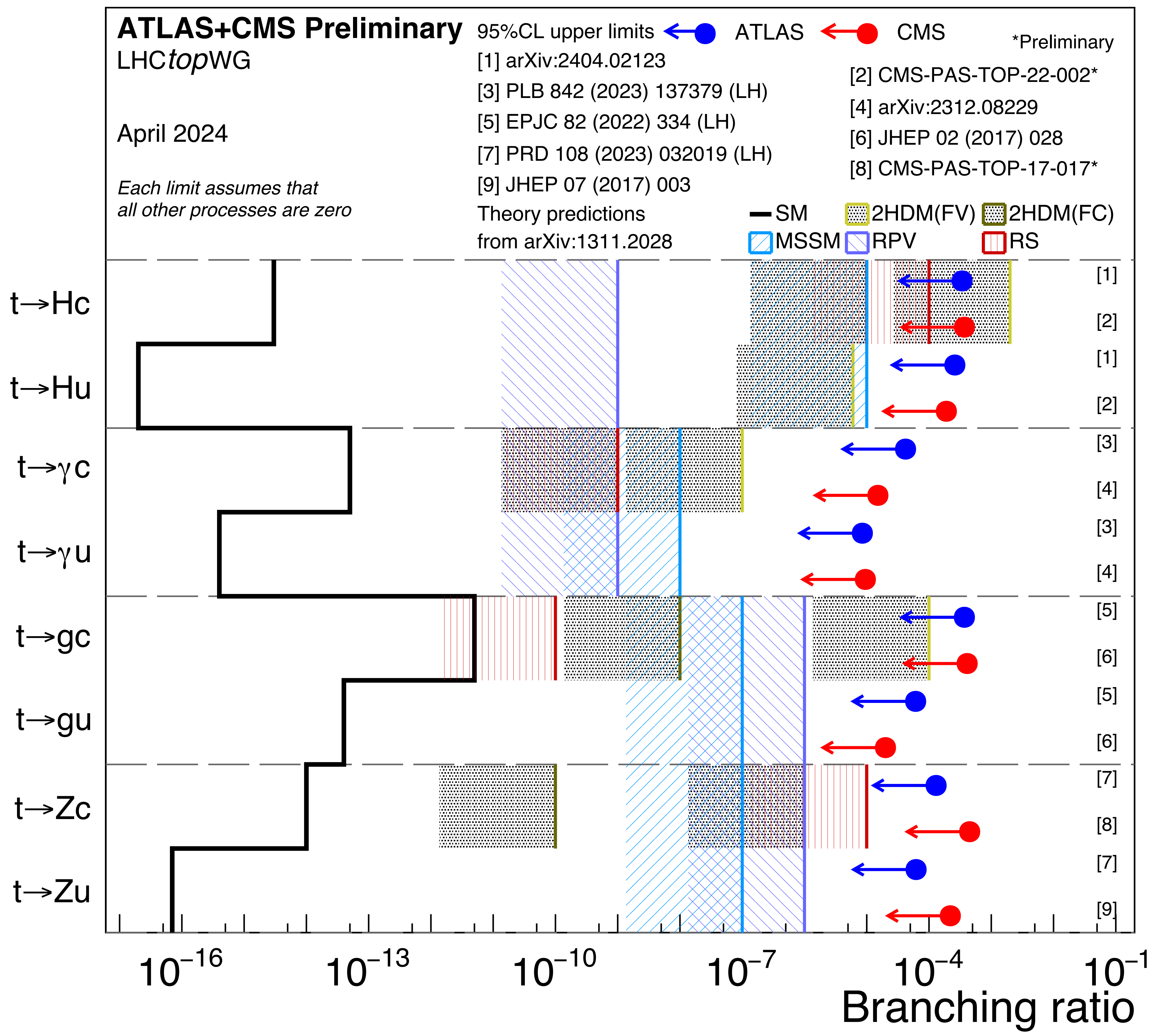
- **Probe from top production**
  - From s- or t-channel single top production (u/c → t + H/Z/γ/g)
  - Higher rate for the process initiated from a valance quark (u) than from a sea quark (c)



- Usually limits are set assuming only one FCNC coupling (tuX or tcX) is non-zero at a time

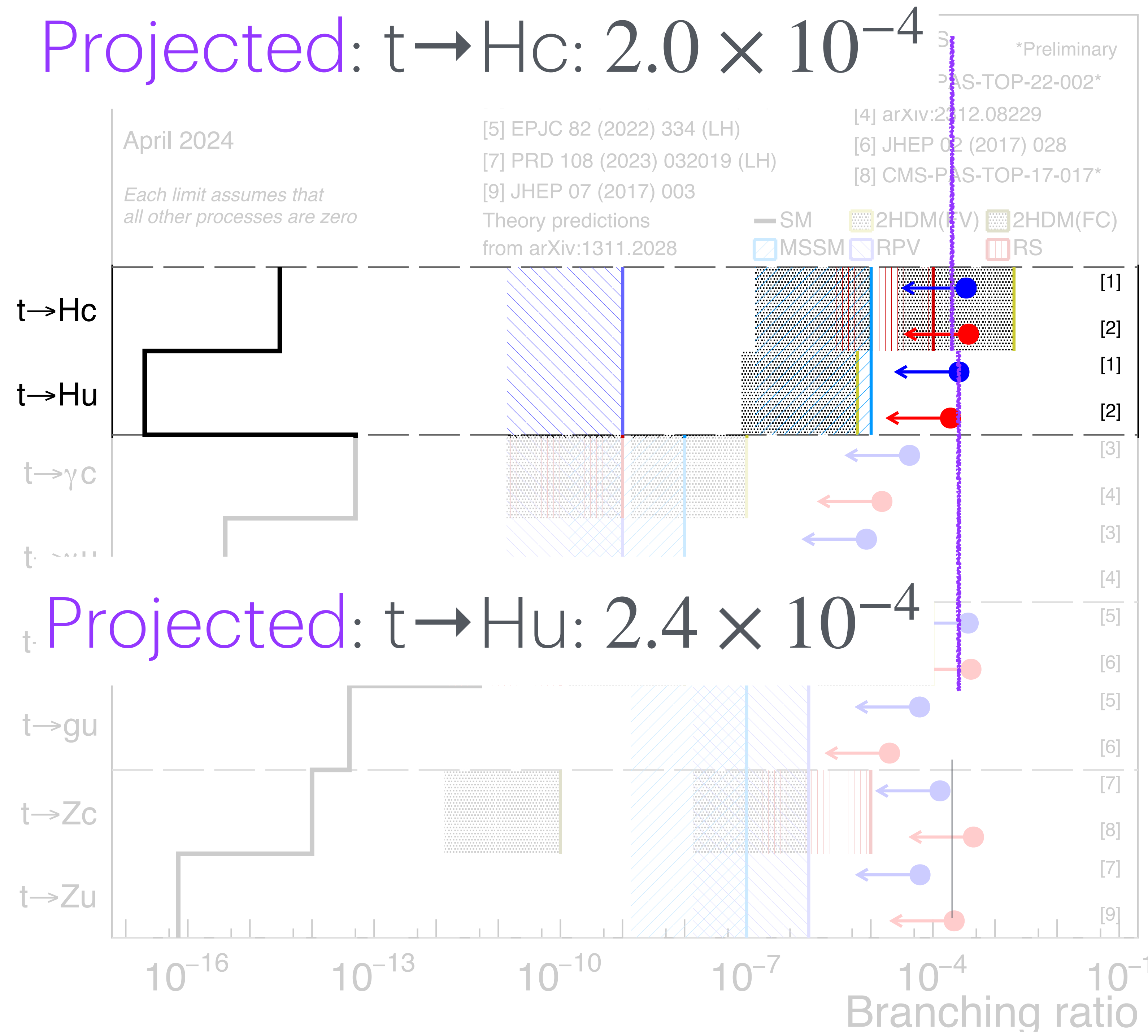
Blue: current ATLAS 95% CL upper limits
Red: current CMS 95% CL upper limits
Black: SM prediction

LHCTopWG



Top FCNC @ (HL-)LHC

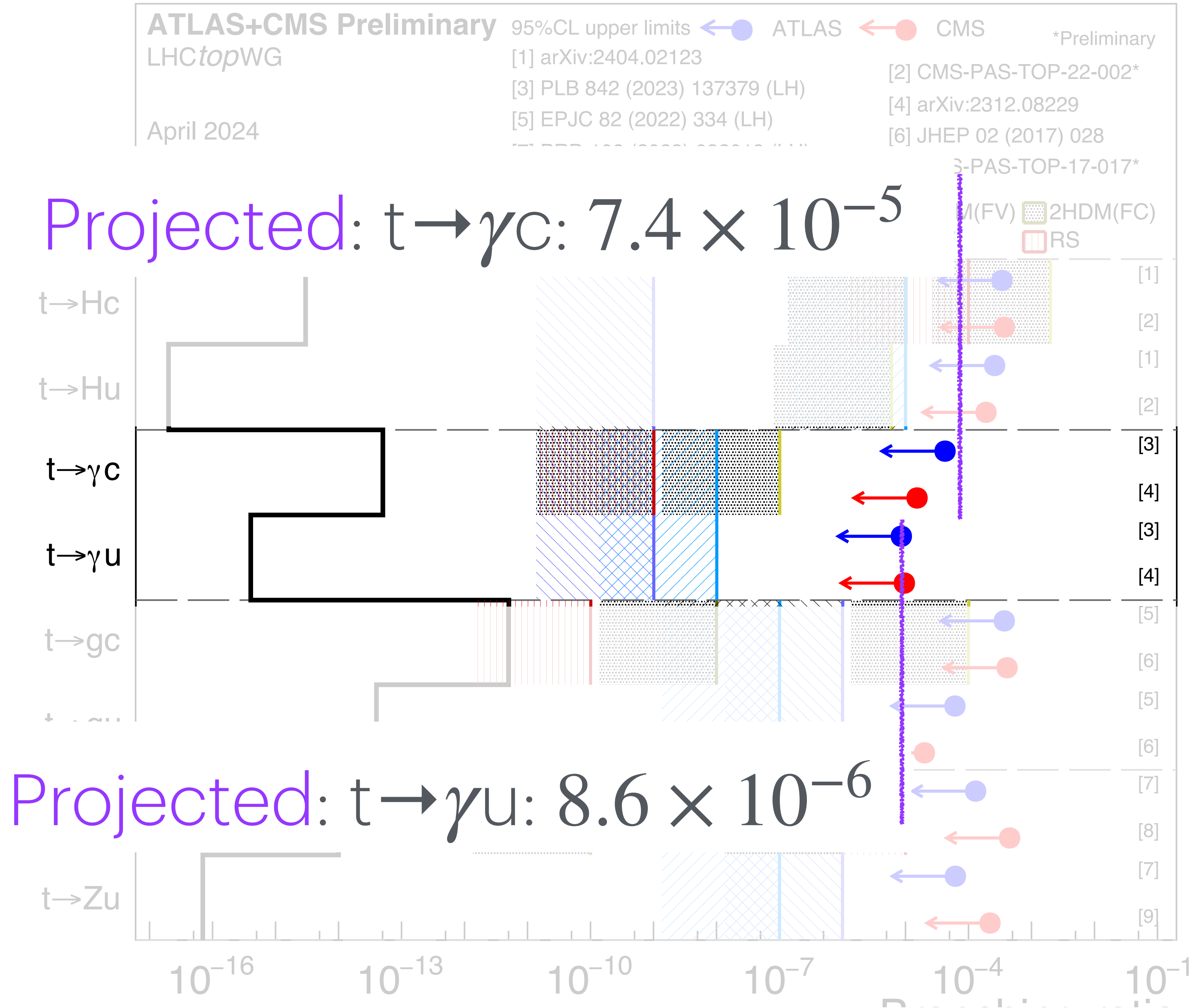
- **top-Higgs**
  - **HL-LHC projection** by ATLAS (ATL-PHYS-PUB-2016-019)
    - Via top decay (tHq) $t\bar{t} \rightarrow WbHq$ with $W \rightarrow \ell\nu$ and $H \rightarrow b\bar{b}$
    - Discriminate the signal and $t\bar{t}$ based on the estimated probability of jet origins (Higgs or W)
    - Systematics extrapolated based on ATLAS 8 TeV estimates
  - **LHC Run 2** limits: EPJC 84 (2024) 757 (ATLAS), CMS-PAS-TOP-22-002 (CMS)
    - Use both tHq and tH events
    - Discriminate signal and backgrounds using DNN or BDT
    - Combining multiple Higgs decay channels
      - $\gamma\gamma/\tau\tau$/VV* channels are statistically limited



- *Latest LHC Run 2 limits are already close to or better than the projections!*

Top FCNC @ (HL-)LHC

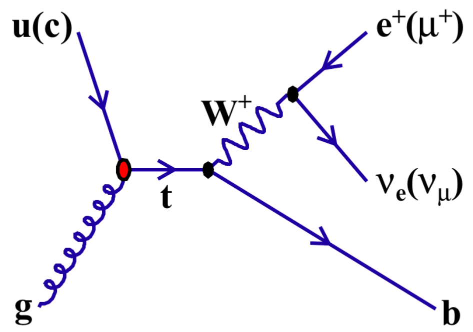
- **top-γ**
  - **HL-LHC projection** by CMS (CMS-TDR-019)
    - Use single top production associated with a photon
      - Target leptonic top decay
    - Discriminate the signal and backgrounds ($W\gamma$+jets, SM $t\gamma$, $t\bar{t}\gamma$, mis-identified photons) based on photon p_T or energy
  - **LHC Run 2** limits: PLB 842 (2023) 137379 (ATLAS), PRD 109 (2024) 072004 (CMS)
    - Use both $t\bar{t}$ and single top events
    - Use DNN or BDT to discriminate signal and backgrounds

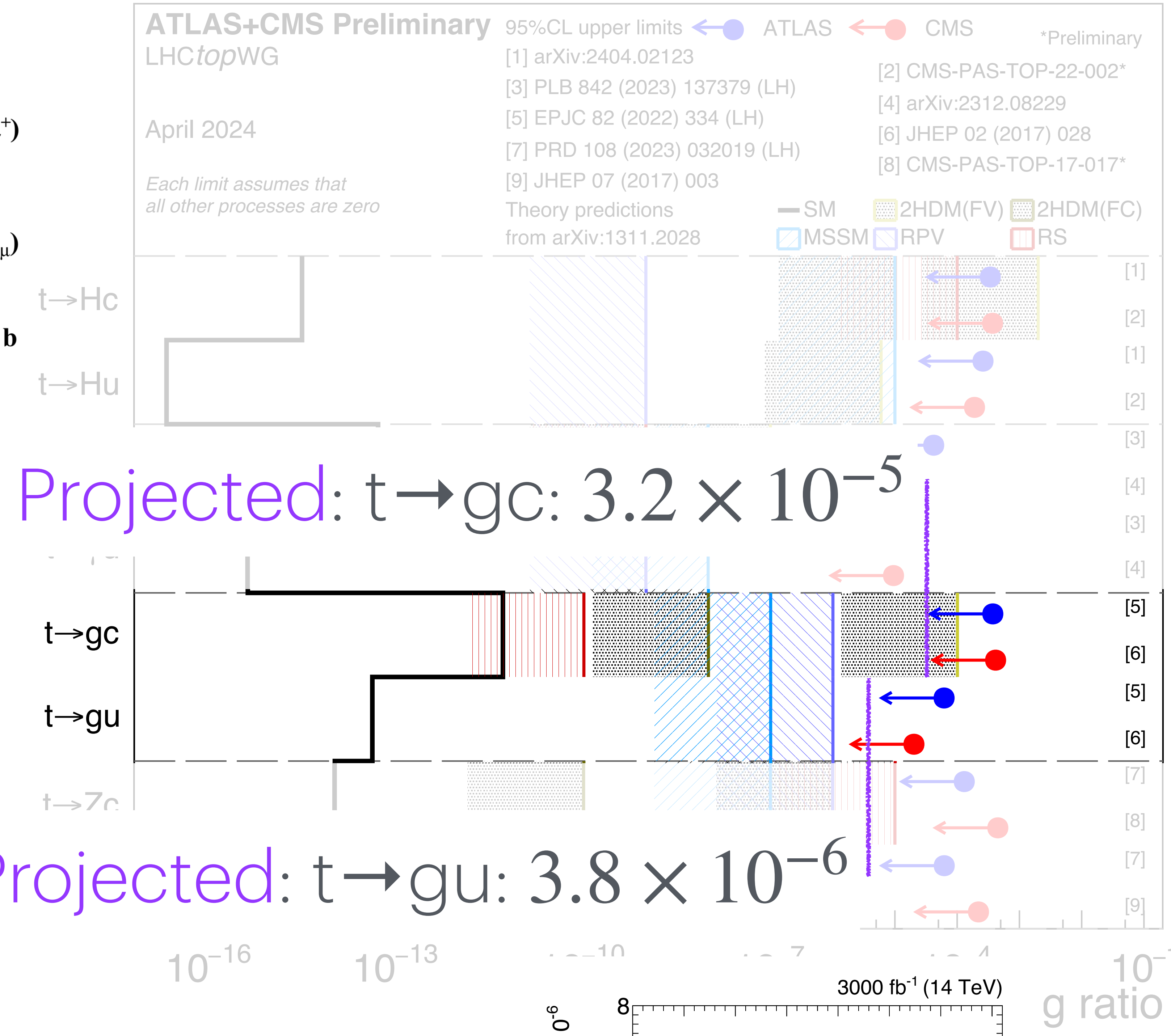


- *Latest LHC Run 2 limits are already better than the projections!*

Top FCNC @ (HL-)LHC

- **top-g**
  - **LHC Run 2** limits from EPJC 82 (2022) 334 (ATLAS), JHEP 02 (2017) 028 (CMS)
    - ATLAS targets s-channel single top without extra jets
    - CMS targets t-channel single top production
      - Higher rate, but more similar to SM single top
    - Both use NN to discriminate signal and backgrounds
  - **HL-LHC projection** by CMS (CMS-PAS-FTR-18-004)
    - Select t-channel single top events
    - Use Bayesian NN for signal-background discrimination
    - Systematic uncertainty limited
    - Dominant systematics: background cross sections (multi-jet QCD and $t\bar{t}$)

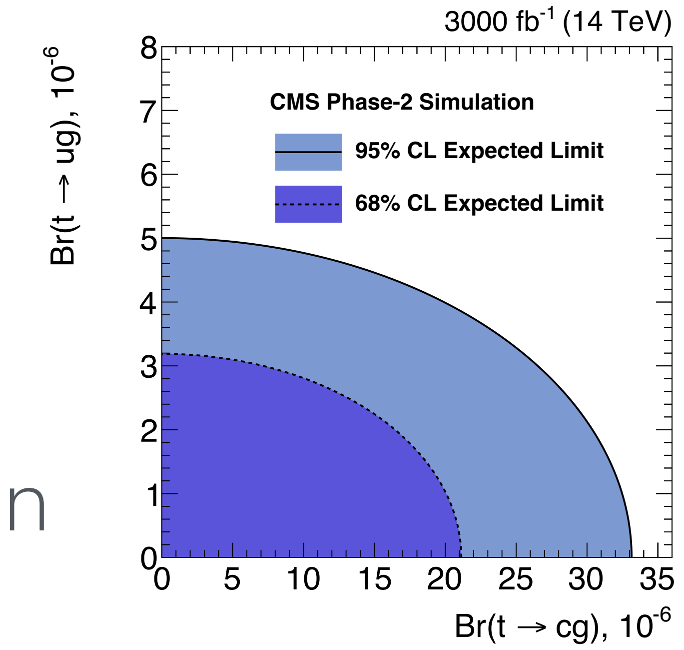




Projected: t→gc: 3.2×10^{-5}

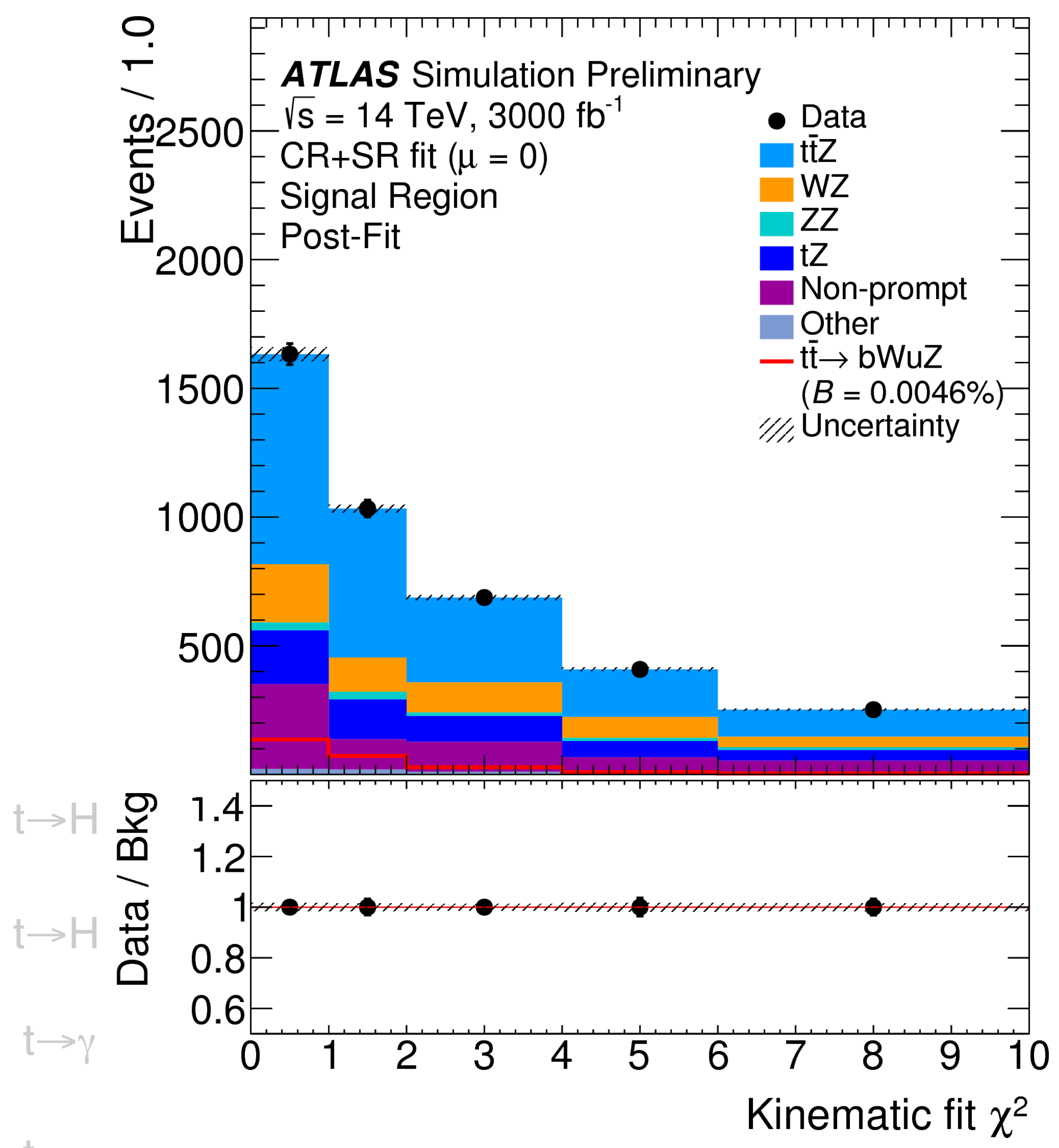
Projected: t→gu: 3.8×10^{-6}

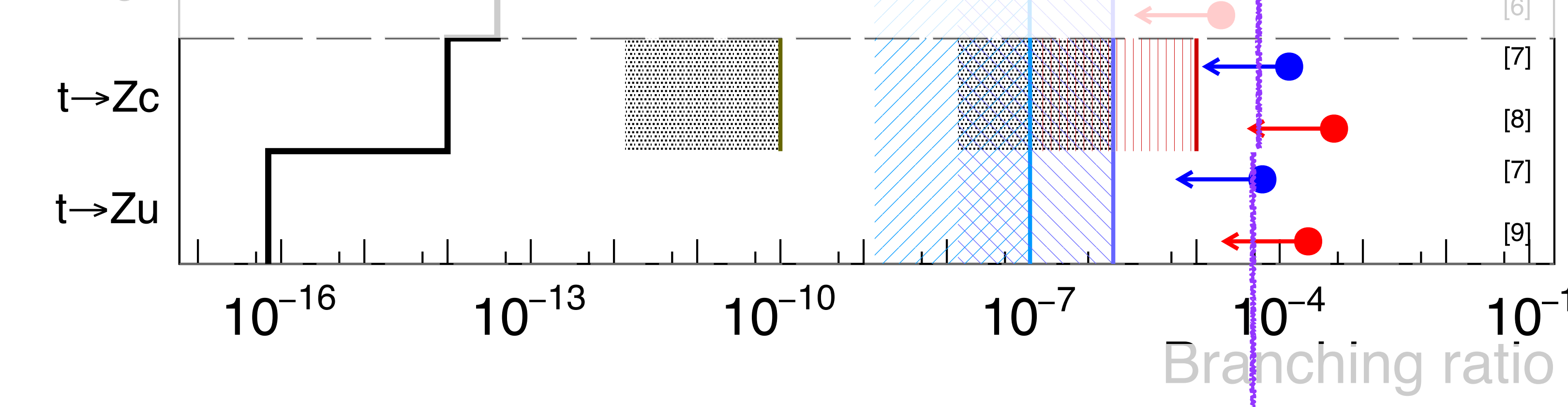
Bonus: 2D contours assuming both FCNC couplings are switched on



Top FCNC @ (HL-)LHC

- **top-Z**
  - **HL-LHC projection** by ATLAS (ATL-PHYS-PUB-2019-001)
    - Target $t\bar{t}$ three lepton final states: $t\bar{t} \to bWqZ \to b\ell\nu q\ell\ell$
    - Event reconstruction using a χ^2 kinematic fit
    - Dominant uncertainties: cross-sections and background modelling
      - Reduce by a factor of 2 from the partial Run 2 analysis
  - **LHC Run 2** limits: PRD 108 (2023) 032019 (ATLAS), CMS-PAS-TOP-17-017, JHEP 07 (2017) 003 (CMS)
    - Two signal regions dedicated for $t\bar{t}$ and single top
    - BDTs for signal-background discrimination
    - Statistically limited





Projected: t→Zc: 5.5×10^{-5}

(MC statistical uncertainty not considered)

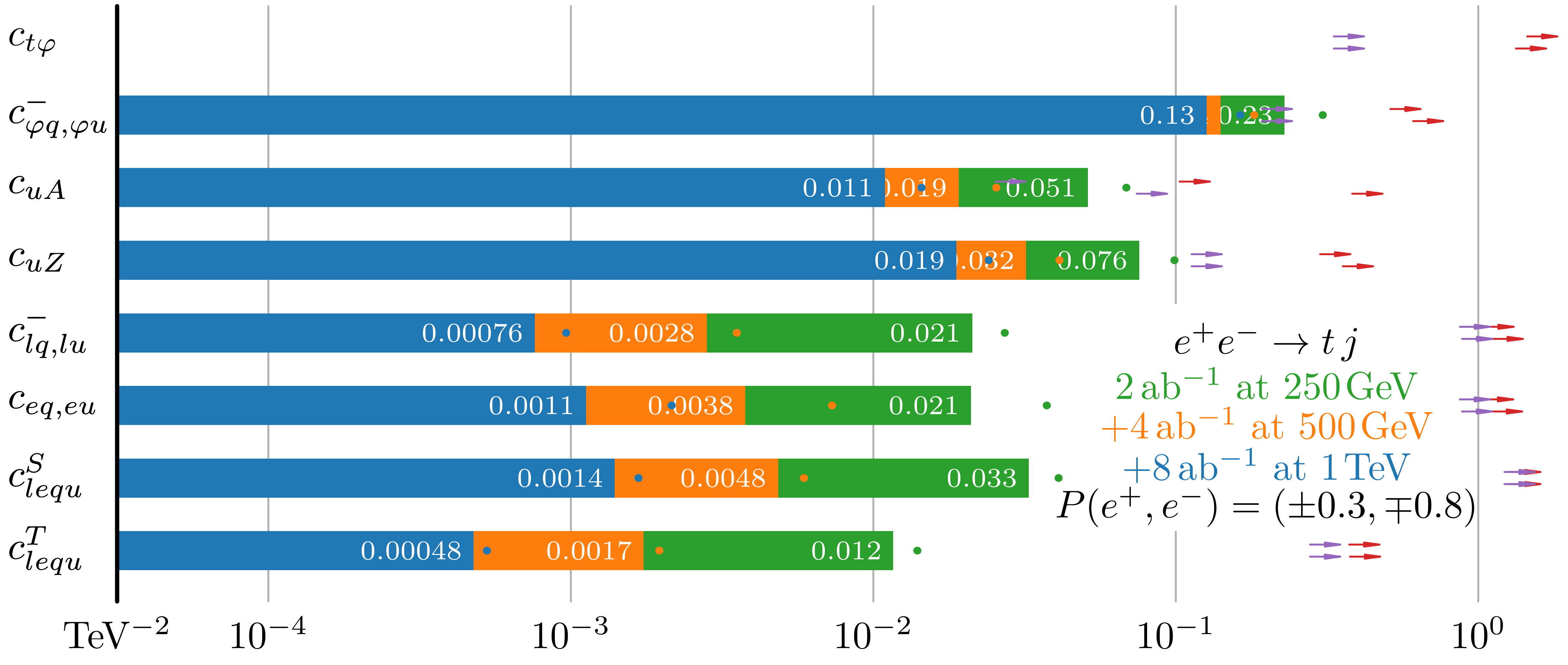
Projected: t→Zu: 4.6×10^{-5}

(MC statistical uncertainty not considered)

Top FCNC @ Lepton Colliders

- Top FCNC couplings can be probed at a lepton collider below the $t\bar{t}$ threshold
  - Sensitive to **top-Z** and **top-γ** couplings
    - $e^+e^- \to Z/\gamma \to t + u/c$
  - Top physics already at 240 GeV!
- Above $t\bar{t}$ threshold, can also probe via top decay
  - Fewer events compared to HL-LHC but cleaner
- Complementary to the hadron collider search and also competitive results:
  - Order of 10^{-5} limit on top-Z/γ BR (FCC-ee Snowmass 2021 report)
- Global fit on FCNC EFT operators benefits greatly from the clean final states at lepton colliders

ILC Snowmass 2021 report



PRD 91, 074017 (2015)

CERN Yellow Rep. Monogr. Vol. 3 (2018)

SMEFT Operators relevant to top

arXiv:2205.02140

	Coefficient	Operator	Coefficient	Operator
2-quark	$C^1_{\varphi Q}$	$(\bar{Q}\gamma^\mu Q)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)$	$C^3_{\varphi Q}$	$(\bar{Q}\tau^I\gamma^\mu Q)\left(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi\right)$
	$C_{\varphi t}$	$(\bar{t}\gamma^\mu t)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)$	$C_{\varphi b}$	$(\bar{b}\gamma^\mu b)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)$
	$C_{t\varphi}$	$(\bar{Q}t)\left(\epsilon\varphi^*\ \varphi^\dagger\varphi\right)$	C_{tG}	$(\bar{t}\sigma^{\mu\nu}T^At)\left(\epsilon\varphi^* G^A_{\mu\nu}\right)$
	C_{tW}	$(\bar{Q}\tau^I\sigma^{\mu\nu}t)\left(\epsilon\varphi^* W^I_{\mu\nu}\right)$	C_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\left(\epsilon\varphi^* B_{\mu\nu}\right)$
4-quark	$C^{1(ijkl)}_{qq}$	$(\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l)$	$C^{3(ijkl)}_{qq}$	$(\bar{q}_i\tau^I\gamma^\mu q_j)(\bar{q}_k\tau^I\gamma_\mu q_l)$
	$C^{(ijkl)}_{uu}$	$(\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l)$	$C^{8(ijkl)}_{ud}$	$(\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l)$
	$C^{8(ijkl)}_{qu}$	$(\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l)$	$C^{8(ijkl)}_{qd}$	$(\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l)$
2-quark 2-lepton	C^1_{lQ}	$(\bar{Q}\gamma_\mu Q)\ (\bar{l}\gamma^\mu l)$	C^3_{lQ}	$(\bar{Q}\tau^I\gamma_\mu Q)\ (\bar{l}\tau^I\gamma^\mu l)$
	C_{lt}	$(\bar{t}\gamma_\mu t)\ (\bar{l}\gamma^\mu l)$	C_{lb}	$(\bar{b}\gamma_\mu b)\ (\bar{l}\gamma^\mu l)$
	C_{eQ}	$(\bar{Q}\gamma_\mu Q)\ (\bar{e}\gamma^\mu e)$	C_{et}	$(\bar{t}\gamma_\mu t)\ (\bar{e}\gamma^\mu e)$
	C_{eb}	$(\bar{b}\gamma_\mu b)\ (\bar{e}\gamma^\mu e)$	–	–

$$C^-_{\varphi Q} = C^1_{\varphi Q} - C^3_{\varphi Q}$$

$$C_{tZ} = c_W C_{tW} - s_W C_{tB}$$

$$C^+_{lQ} = C^1_{lQ} + C^3_{lQ}$$

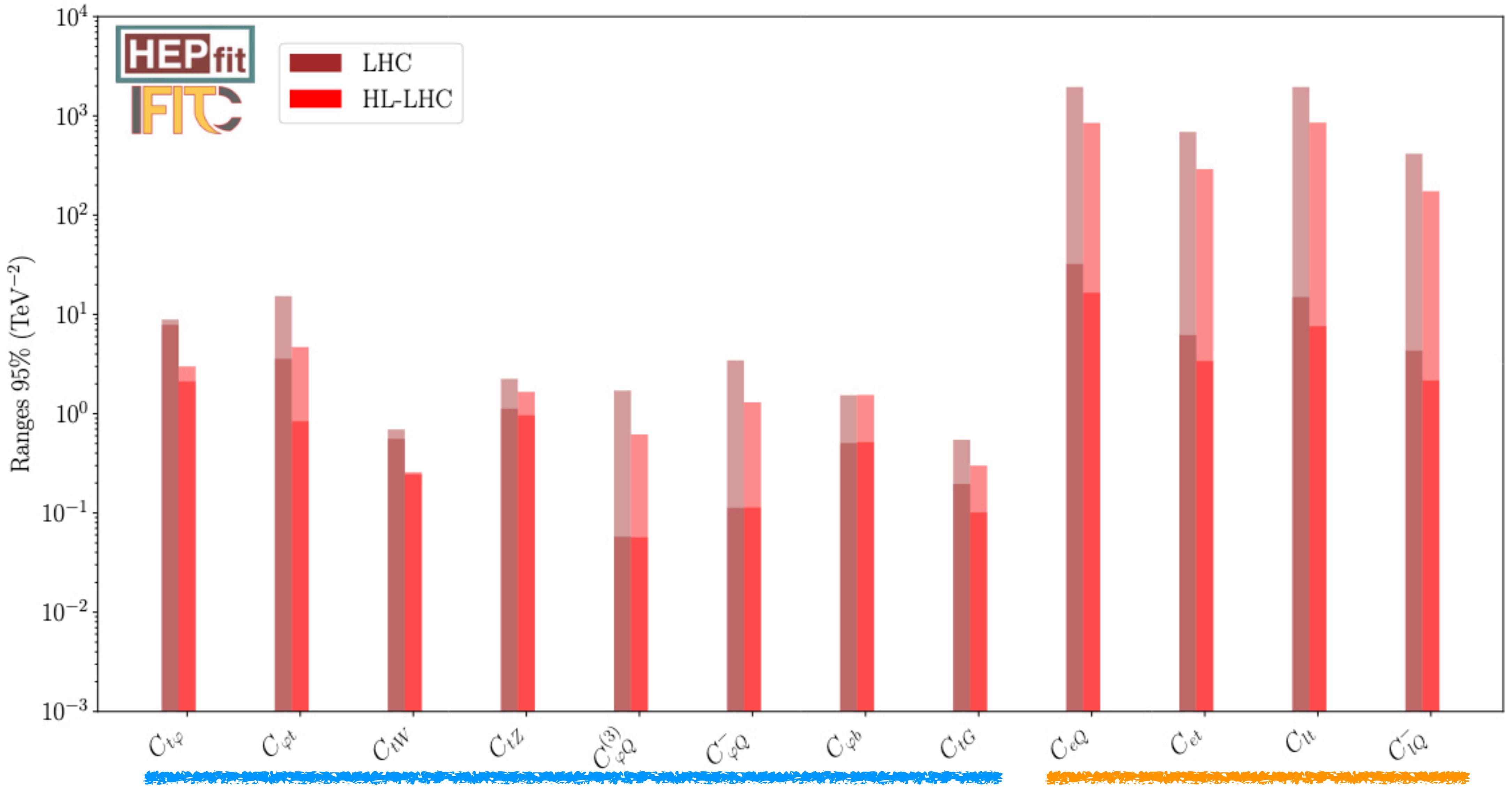
$$C^-_{lQ} = C^1_{lQ} - C^3_{lQ}$$

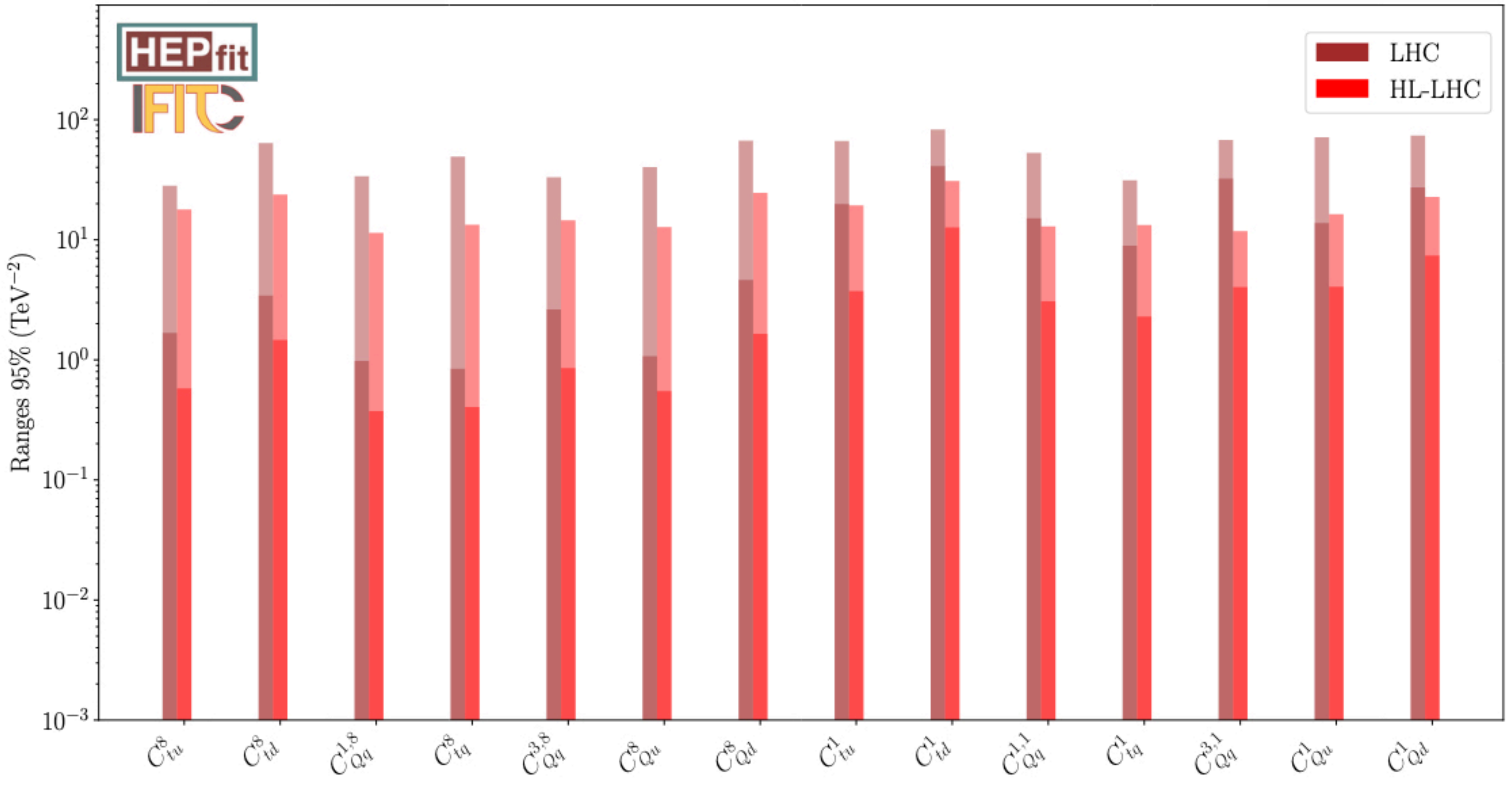
- Some of the coefficients used in the fit are linear combinations of the ones listed below

Top EFT @ HL-LHC

arXiv:2205.02140 and
Talk by Víctor Miralles @ ICHEP2024

- Use observables in $t\bar{t}$, single top, top+X measurements from both ATLAS and CMS
  - Most measurements limited by theory and modelling uncertainties
- Project to HL-LHC from LHC
  - Theory and modelling uncertainties reduced by a factor of 2
  - Experimental systematic uncertainties scaled by luminosity: $1/\sqrt{\mathscr{L}}$
  - Improve by a factor of ~3
- Solid bar from the individual fit; shaded from the global fit
  - Worse limit in global fit due to unresolved correlation between WCs

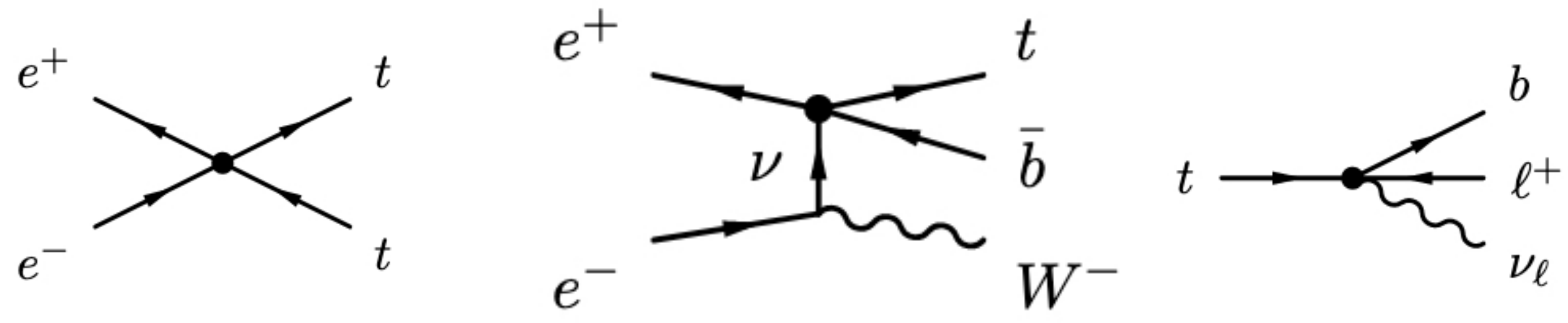


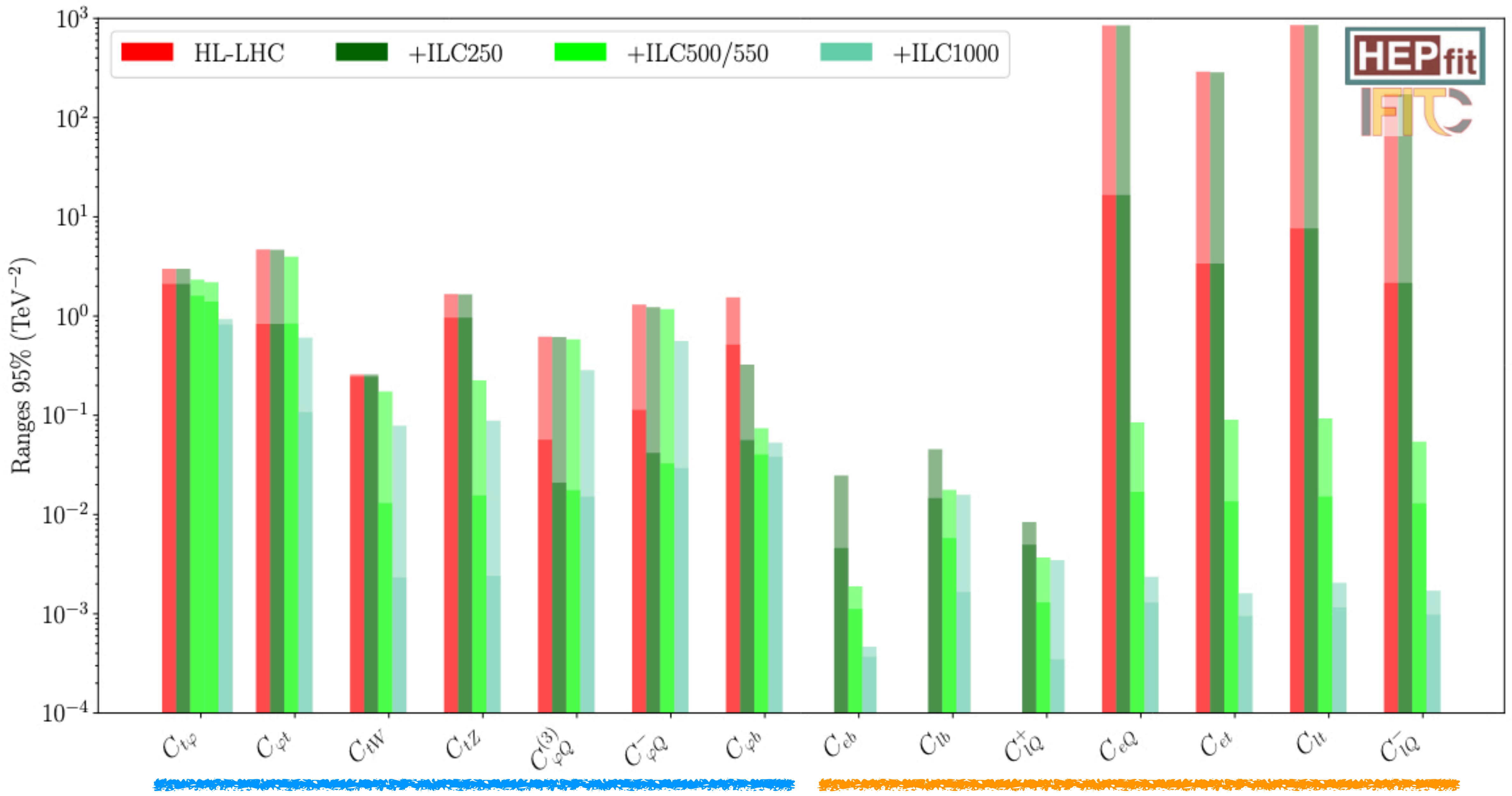


Top EFT @ Lepton colliders

arXiv:1807.02121
arXiv:2205.02140
Talk by Víctor Miralles @ ICHEP2024

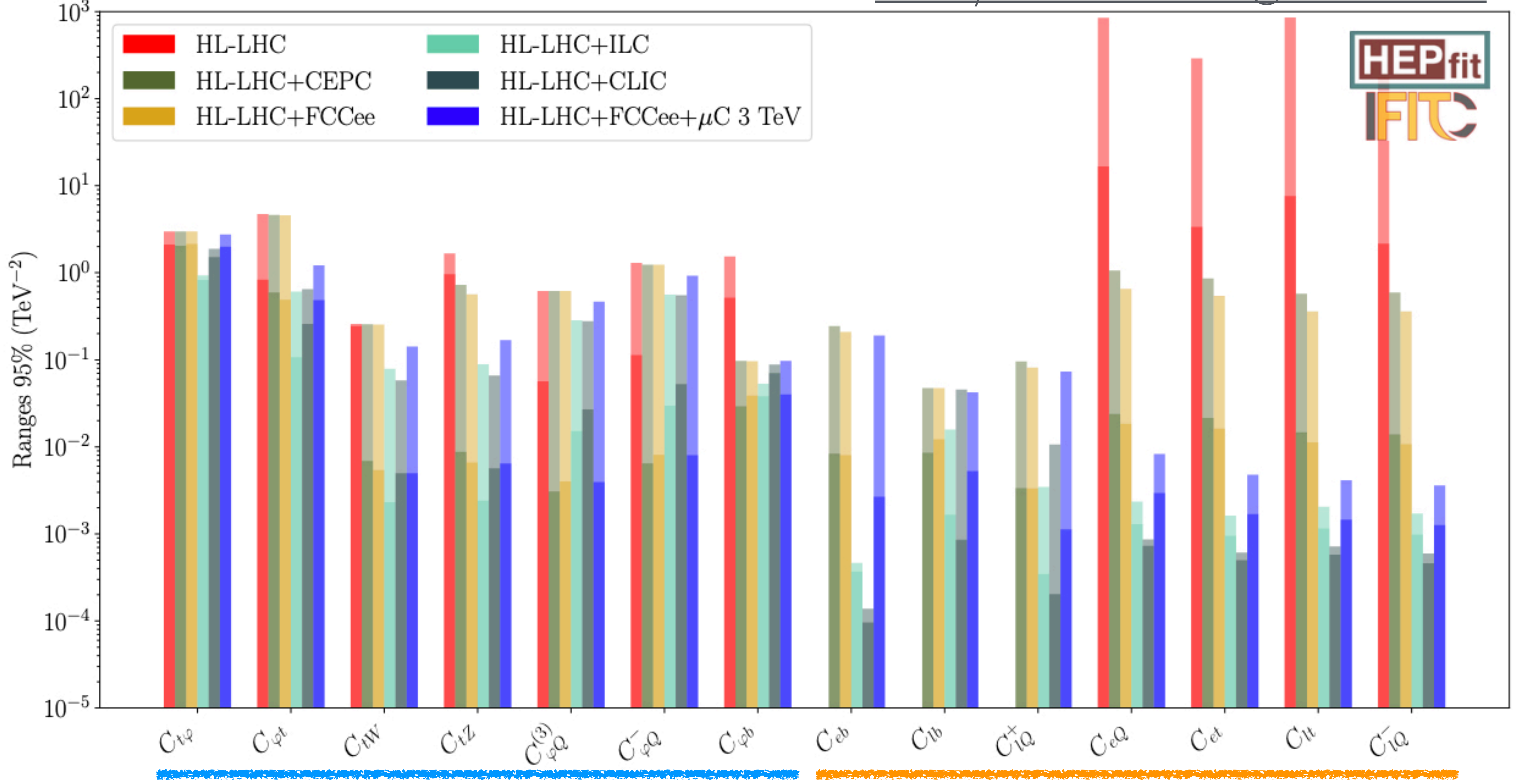
- $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$
  - Sensitive to 2-quark and 2-quark 2-lepton WCs
  - Not sensitive to 4-quark operators
- Use statistically optimal observables defined at leading order on the $e^+e^- \to bW^+\bar{b}W^-$ differential distribution (arXiv:1807.02121)
  - Combine information from σ, A_{FB}, as well as top polarization
- Need two runs **at different energies above the $t\bar{t}$ threshold** to disentangle the 2-quark WCs and the 2-lepton 2-quark WCs
  - Scale differently with energy





Combine HL-LHC and Lepton Collider

From the talk by Víctor Miralles @ ICHEP2024



Lepton collider configurations considered

arXiv:2205.02140

Machine	Polarisation	Energy	Luminosity
ILC	$P(e^+, e^-)$:(±30%, ∓80%)	250 GeV	2 ab^{-1}
		500 GeV	4 ab^{-1}
		1 TeV	8 ab^{-1}
CLIC	$P(e^+, e^-)$:(0%, ±80%)	380 GeV	1 ab^{-1}
		1.4 TeV	2.5 ab^{-1}
		3 TeV	5 ab^{-1}
FCC-ee	Unpolarised	Z-pole	150 ab^{-1}
		240 GeV	5 ab^{-1}
		350 GeV	0.2 ab^{-1}
		365 GeV	1.5 ab^{-1}
CEPC	Unpolarised	Z-pole	57.5 ab^{-1}
		240 GeV	20 ab^{-1}
		350 GeV	0.2 ab^{-1}
		360 GeV	1 ab^{-1}

- **FCC-ee**/**CEPC** can constrain 2-fermion operators quite well. Additional runs above the top threshold help to constrain the 4-fermion operators, but still hard to disentangle the 2-fermion and 4-fermion operators.
- **ILC**/**CLIC** can set very tight bounds on the 4-fermion operators due to the higher energy reach.

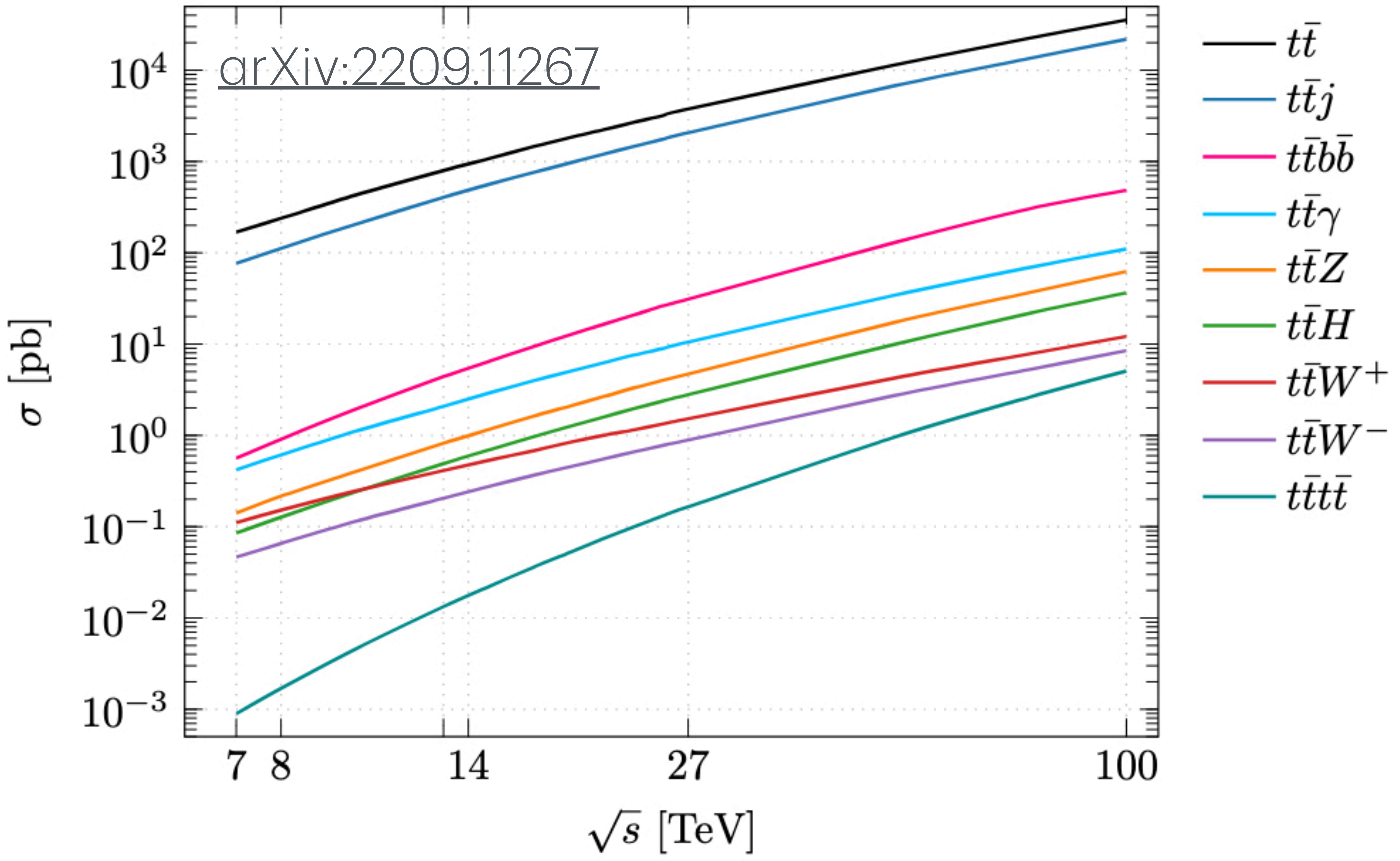
Summary

- **HL-LHC** and future **lepton colliders** provide great opportunities for **top physics**
- **Top mass**:
  - Direct measurement of the top mass at the HL-LHC is expected to reach a precision of ~170 MeV
    - Additional ~250 MeV uncertainty when translating to $\overline{MS}$ mass
  - Indirect measurement via cross-sections is projected to reach a precision of ~500 MeV
  - The $t\bar{t}$ threshold scan at a lepton collider can measure the top mass to a precision of 40~75 MeV
- **Top FCNC**:
  - HL-LHC can set top FCNC branching ratio upper limit to the order of
    - 10^{-4} for $t \to Hq$; 10^{-5} for $t \to Zq$; 10^{-6} (10^{-5}) for $t \to \gamma u$ ($t \to \gamma c$); 10^{-6} (10^{-5}) for $t \to gu$ ($t \to gc$)
  - Some recent LHC Run 2 analyses already set limits close to or better than the (old) projections
  - Lepton colliders can probe top-Z/γ FCNC couplings even before $t\bar{t}$ threshold
- **Top EFT**:
  - HL-LHC is expected to improve the bounds on 2-fermion and 4-fermion Wilson coefficients by a factor of ~3
  - The bounds on 2-quark and 2-lepton 2-quark Wilson coefficients can be further improved at lepton colliders operating at and above the $t\bar{t}$ threshold.

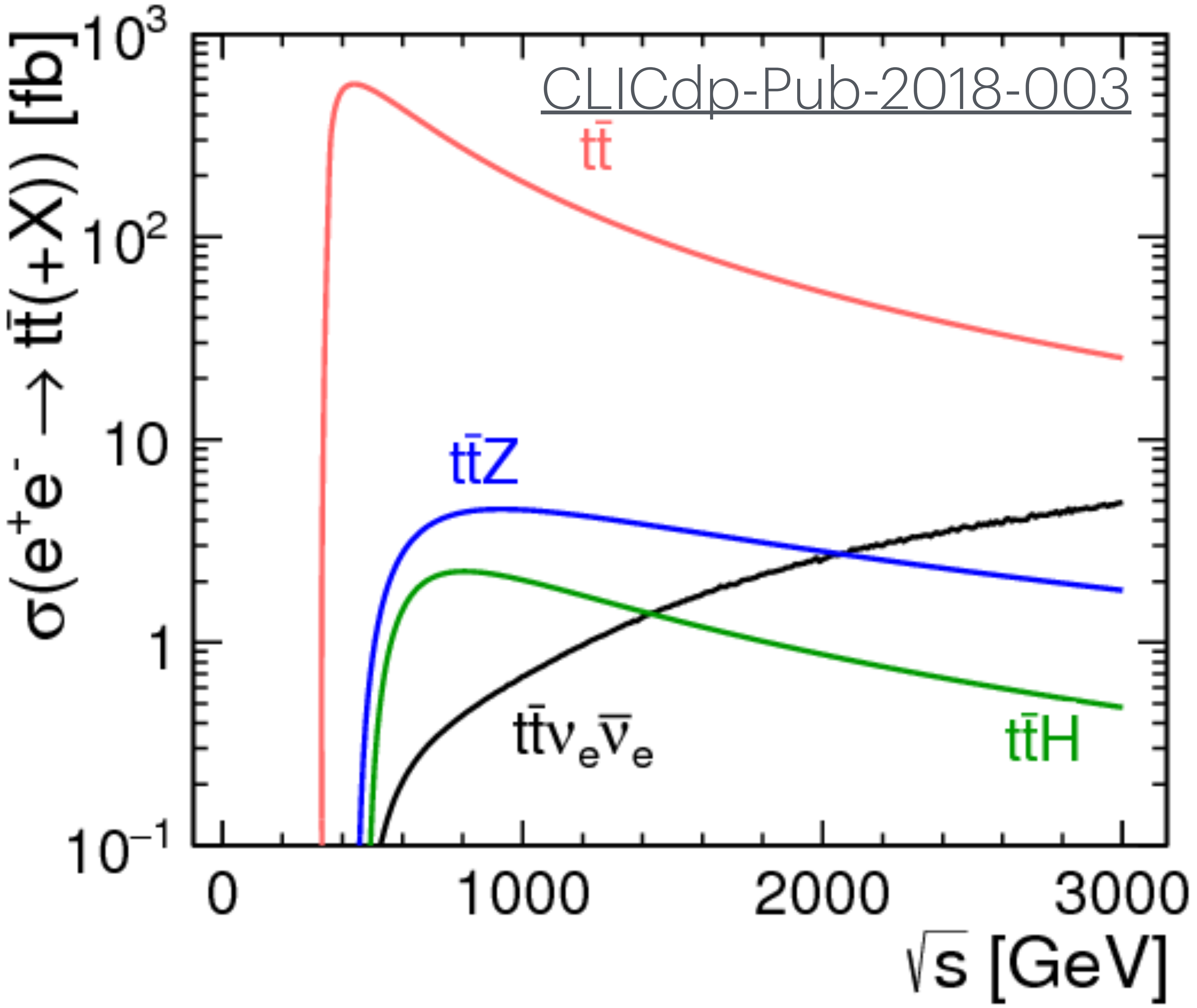
Backup

Top cross-sections

pp



e+e-



Top mass projection assumptions

- CMS-PAS-FTR-16-006

Table 1: Summary of the systematic uncertainties on m_t for the reference measurement in lepton+jets channel. Experimental uncertainties are separated from theoretical ones.

Source	Value (GeV) 8 TeV, $19.7\,fb^{-1}$	14 TeV, $0.3\,ab^{-1}$	14 TeV $3\,ab^{-1}$	Comment
Method calibration	±0.04	±0.02	±0.02	MC stat. $\times4$
Lepton energy scale	$+0.01$	±0.01	±0.01	unchanged
Global JES	±0.13	±0.12	±0.04	3D fit, differential
Flavor-dependent JES	±0.19	±0.17	±0.06	3D fit, differential
Jet energy resolution	-0.03	±0.02	< 0.01	differential
E_T^{miss} scale	$+0.04$	±0.04	±0.04	unchanged
b tagging efficiency	$+0.06$	±0.03	±0.03	improved with data
Pileup	-0.04	±0.04	±0.04	unchanged
Backgrounds	$+0.03$	±0.01	±0.01	cross sections
ME generator	-0.12 ± 0.08	–	–	NLO ME generator
Ren. and fact. scales	-0.09 ± 0.07	±0.06	±0.06	NLO ME generator, MC stat.
ME-PS matching	$+0.03 \pm 0.07$	±0.06	±0.06	MC stat.
Top quark p_T	$+0.02$	< 0.01	< 0.01	improved with data
b fragmentation	< 0.01	< 0.01	< 0.01	unchanged
Semileptonic b hadron decays	-0.16	±0.11	±0.06	improved with data
Underlying event	$+0.08 \pm 0.11$	±0.14	±0.09	improved with data, MC stat.
Color reconnection	$+0.01 \pm 0.09$	±0.05	< 0.01	improved with data
PDF	±0.04	±0.03	±0.02	improved with data
Systematic uncertainty	±0.48	±0.30	±0.17	
Statistical uncertainty	±0.16	±0.04	±0.02	
Total	±0.51	±0.31	±0.17	

Table 2: Summary of the systematic uncertainties on m_t for the measurements in the single-top quark t-channel. Experimental uncertainties are separated from theoretical ones.

Source	Value (GeV) 8 TeV, $19.7\,fb^{-1}$	14 TeV, $0.3\,ab^{-1}$	14 TeV $3\,ab^{-1}$	Comment
Fit Calibration	±0.38	±0.15	±0.15	MC stat. $\times4$, improved method
Lepton energy scale	< 0.05	< 0.05	< 0.05	unchanged
Global JES	$+0.55, -0.46$	±0.35	±0.23	benefits from lepton+jets
Flavor-dependent JES	±0.40	±0.28	±0.19	benefits from lepton+jets
Jet energy resolution	< 0.05	< 0.04	< 0.03	benefits from lepton+jets
E_T^{miss}	±0.15	±0.15	±0.15	unchanged
b tagging efficiency	±0.10	±0.08	±0.05	improved with data
Pileup	±0.10	±0.10	±0.10	unchanged
Backgrounds	±0.39	±0.20	±0.20	cross sections
ME generator	±0.10	–	–	NLO ME generator
Ren. and fact. scales	±0.23	±0.07	±0.07	MC stat.
b quark hadronization	±0.14	±0.10	±0.06	improved with data
Underlying event	±0.20	±0.15	±0.10	improved with data
Color reconnection	< 0.05	< 0.04	< 0.02	improved with data
PDF	< 0.05	< 0.04	< 0.02	improved with data
Systematic uncertainty	$+0.97, -0.93$	±0.59	±0.45	
Statistical uncertainty	±0.77	±0.20	±0.06	
Total	$+1.24, -1.21$	±0.62	±0.45	

Top mass projection assumptions (2)

- CMS-PAS-FTR-16-006

Table 3: Summary of the systematic uncertainties on m_t for the measurement from $m_{sv\ell}$. Experimental uncertainties are separated from theoretical ones.

Source	Value (GeV) 8 TeV, 19.7 fb^{-1}	14 TeV, 0.3 ab^{-1}	14 TeV 3 ab^{-1}	Comment
Lepton energy scale	$+0.22, -0.26$	±0.26	±0.26	unchanged
Sec. vertex track multiplicity	-0.06	±0.06	±0.06	unchanged
Sec. vertex mass modeling	-0.29	±0.22	±0.15	upgraded tracker and decay tables
Jet energy scale	$+0.19, -0.17$	±0.14	±0.10	benefits from lepton+jets
Jet energy resolution	±0.05	±0.05	±0.05	unchanged
Unclustered energy	$+0.07$	±0.07	±0.07	unchanged
b tagging efficiency	-0.02	±0.02	±0.01	improved with data
Pileup	$+0.07, -0.05$	±0.07	±0.07	unchanged
Lepton selection efficiency	$+0.01$	±0.01	±0.01	unchanged
Backgrounds	< 0.03	±0.01	±0.01	cross sections
$\sigma(t\bar{t}$ + heavy flavor)	$+0.46, -0.36$	±0.33	±0.20	improved with data
ME generator	-0.42	–	–	NLO ME generator
Single t fraction	±0.07	±0.06	±0.06	cross sections
Single t diagram interference	$+0.24$	±0.06	< 0.01	NLO ME generator
Ren. and fact. scales	$+0.30, -0.20$	±0.10	±0.10	NLO ME generator
ME-PS matching	$+0.06, -0.04$	±0.06	±0.06	unchanged
Top quark p_T	$+0.82$	±0.14	±0.14	improved with data and NNLO k-factors
Top quark decay width	-0.05	±0.04	±0.02	improved with data
b quark fragmentation	$+1.00, -0.54$	±0.70	±0.40	improved with data
Semileptonic B decays	±0.16	±0.11	±0.06	improved with data
b hadron composition	-0.09	±0.07	±0.04	improved with data
Underlying event	$+0.19$	±0.15	±0.10	improved with data
Color reconnection	$+0.08$	±0.05	±0.02	improved with data
PDF	$+0.06, -0.04$	±0.04	±0.02	improved with data
Systematic uncertainty	$+1.58, -0.97$	±0.95	±0.62	
Statistical uncertainty	±0.20	±0.05	±0.02	
Total	$+1.59, -0.99$	±0.95	±0.62	

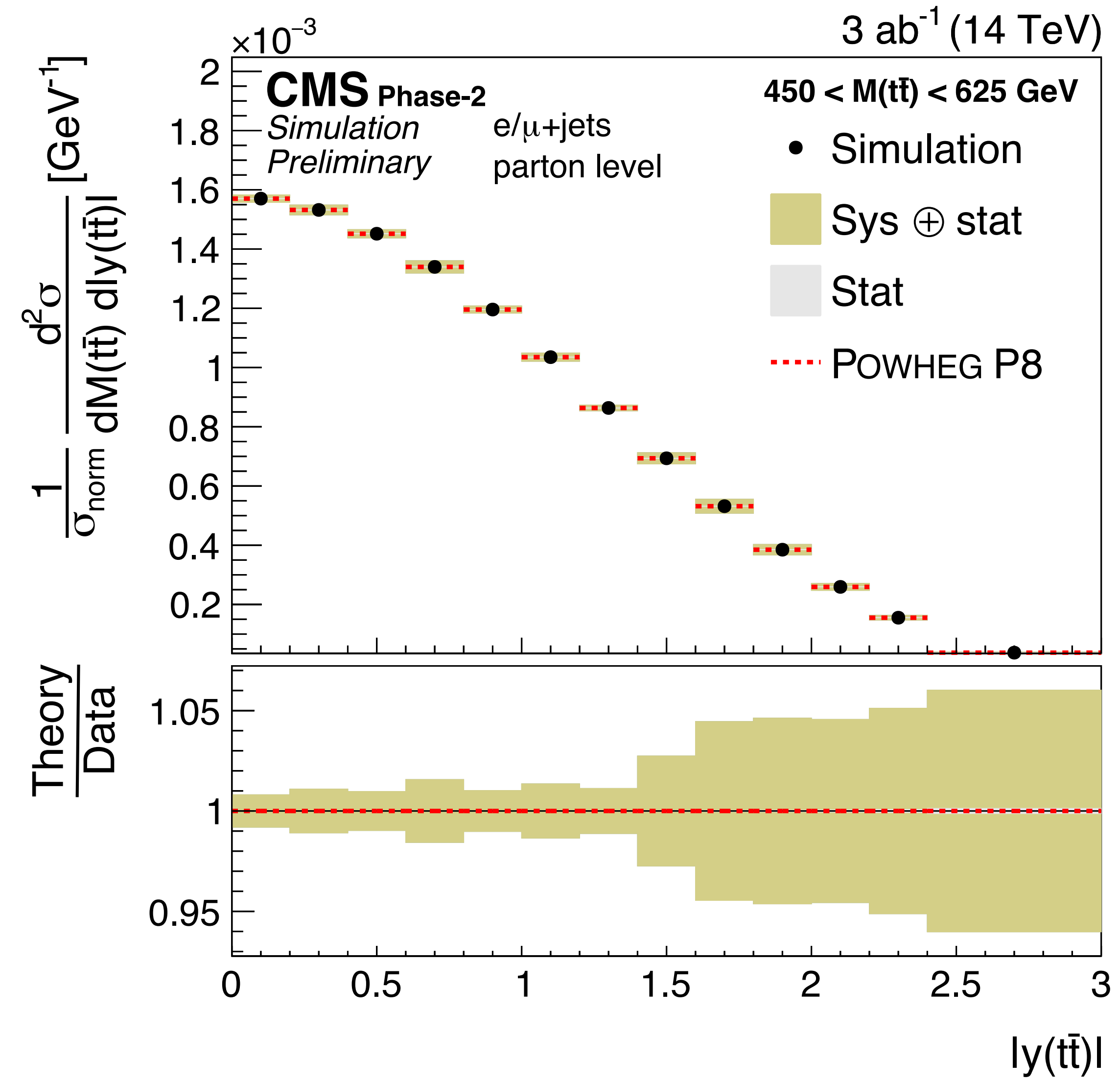
Table 4: Summary of the systematic uncertainties on m_t for the measurement from $m_{J/\psi+\ell}$. Experimental uncertainties are separated from theoretical ones.

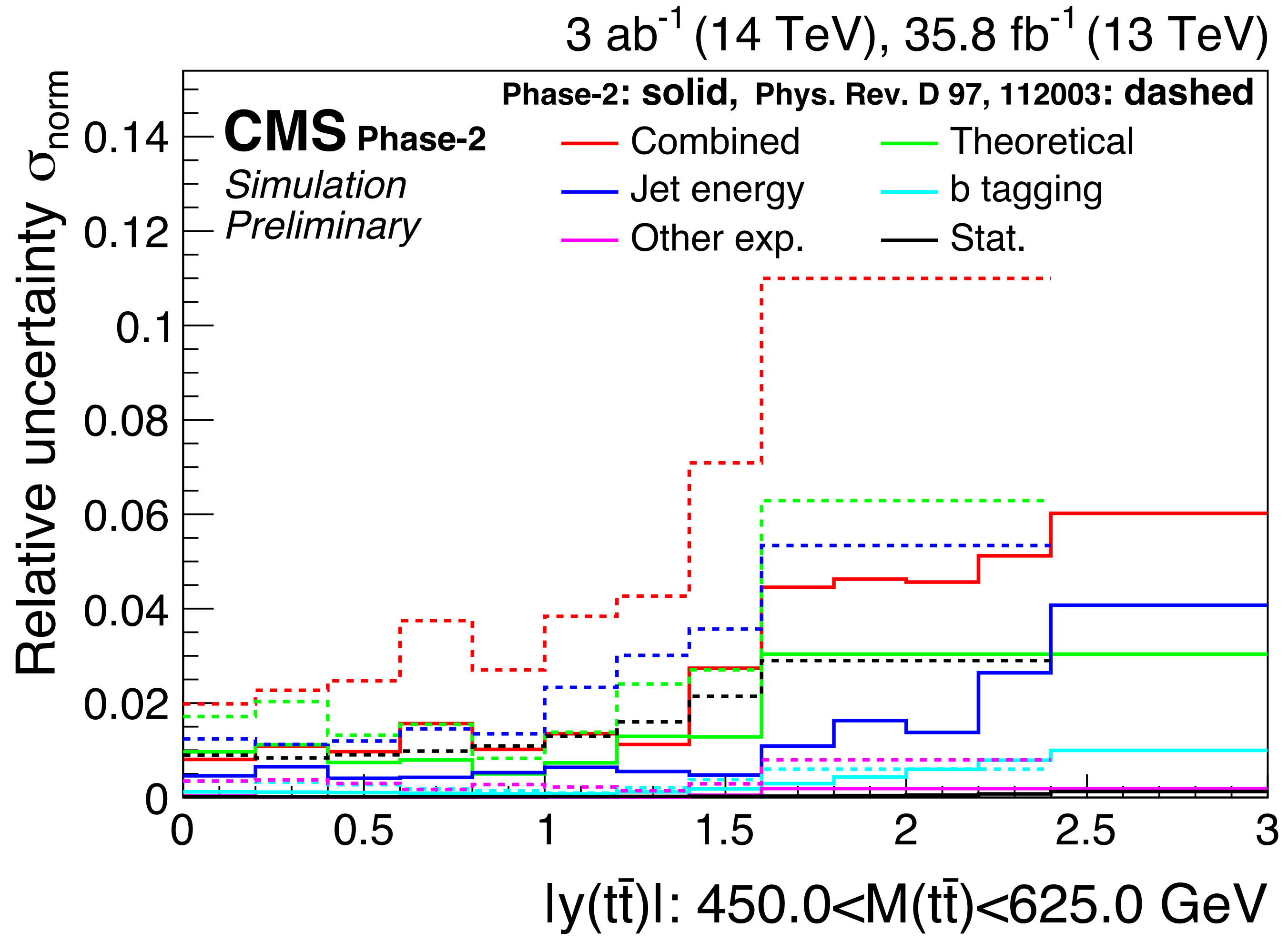
Source	Value (GeV) 8 TeV, 19.7 fb^{-1}	14 TeV, 0.3 ab^{-1}	14 TeV 3 ab^{-1}	Comment
Size of the simulation samples	±0.22	±0.07	±0.07	MC stat. $\times10$
Muon momentum scale	±0.09	±0.09	±0.09	unchanged
Electron momentum scale	±0.11	±0.11	±0.11	unchanged
Modeling of $m_{J/\psi}$	$+0.09$	< 0.01	< 0.01	constrained J/ψ vertex fit
Jet energy scale	< 0.01	< 0.01	< 0.01	unchanged
Jet energy resolution	< 0.01	< 0.01	< 0.01	unchanged
Trigger efficiencies	±0.02	±0.01	±0.01	improved method
Pileup	±0.07	±0.07	±0.07	unchanged
Backgrounds	±0.01	±0.01	±0.01	unchanged
ME generator	-0.37	–	–	NLO ME generator
Ren. and fact. scales	$+0.12, -0.46$	±0.08	±0.04	NLO ME generator, MC stat.
ME-PS matching	$+0.12, -0.58$	±0.50	±0.43	MC stat.
Top quark p_T	$+0.64$	±0.12	±0.12	improved with data and NNLO k-factors
b quark hadronization	±0.30	±0.21	±0.12	improved with data
Underlying event	±0.13	±0.10	±0.07	improved with data
Color reconnection	$+0.12$	±0.09	±0.06	improved with data
PDF	$+0.39, -0.11$	±0.27	±0.15	improved with data
Systematic uncertainty	$+0.89, -0.94$	±0.66	±0.53	
Statistical uncertainty	±3.0	±0.77	±0.24	
Total	$+3.13, -3.14$	±1.00	±0.58	

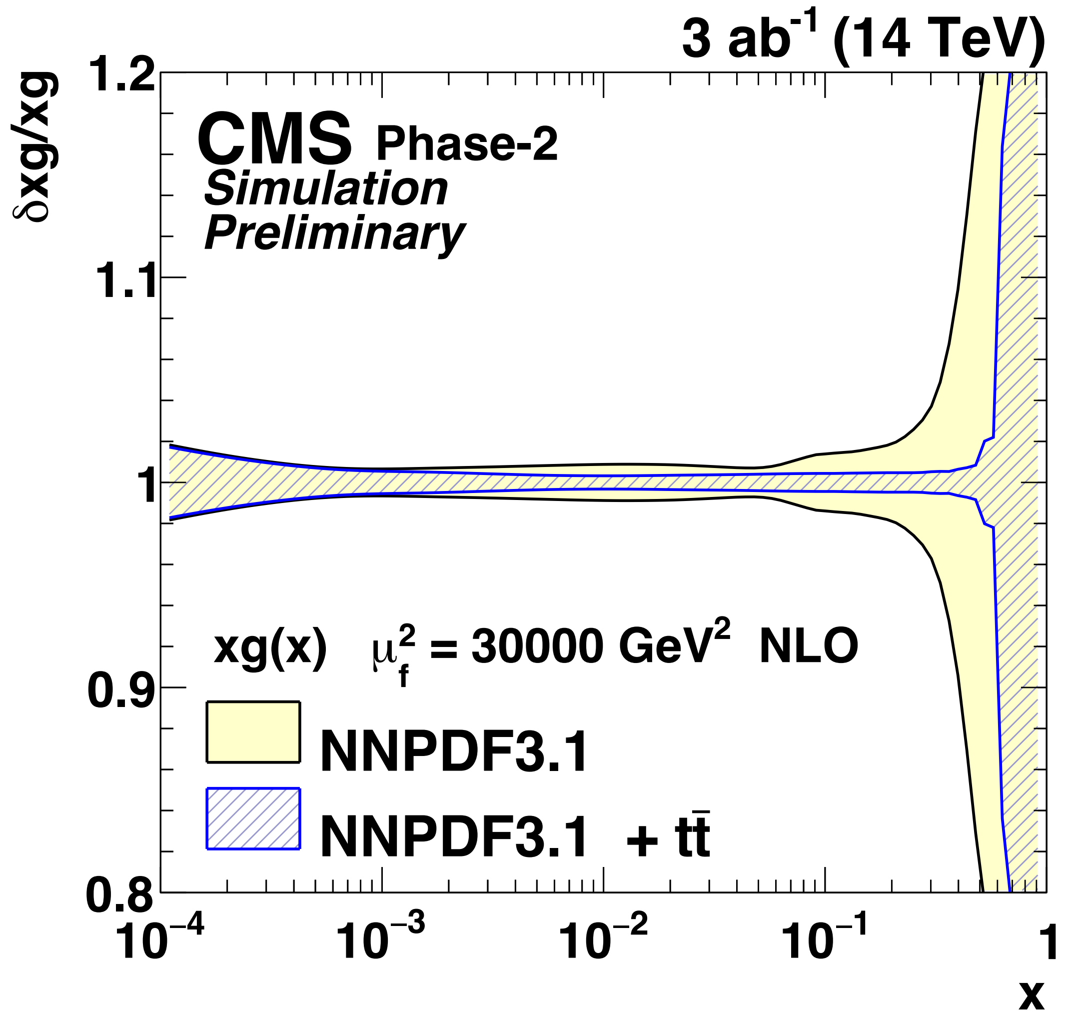
TTbar Cross-section @ HL-LHC

CMS-PAS-FTR-18-015

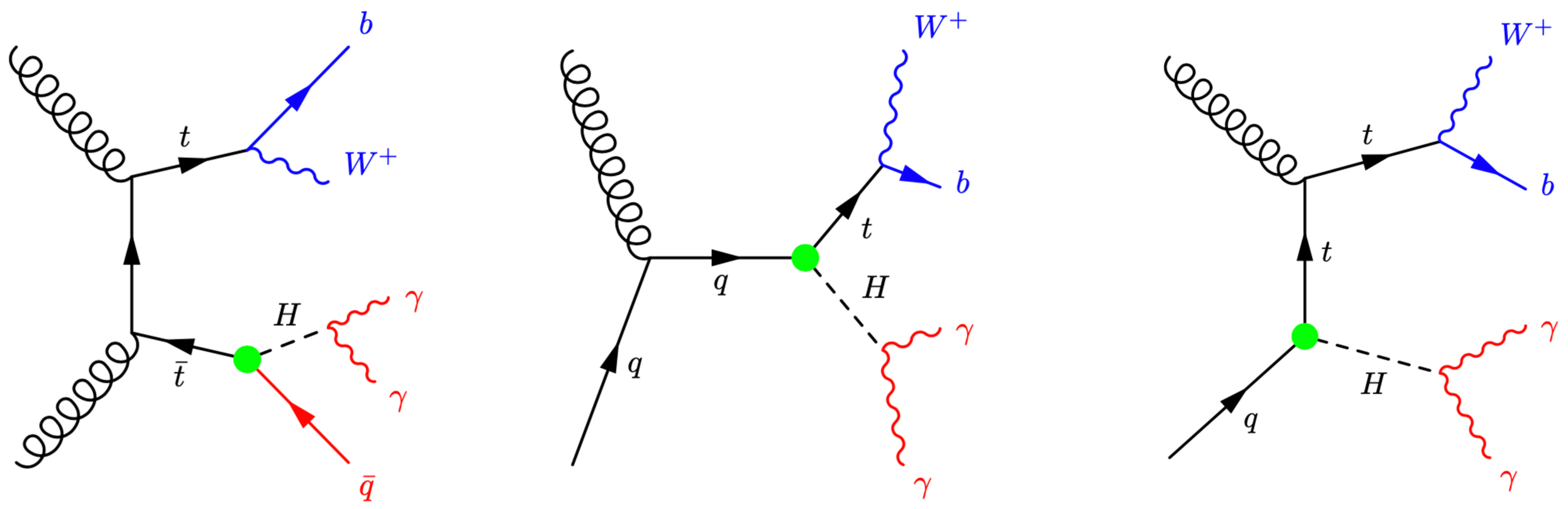
- A projection of differential $t\bar{t}$ cross-section measurement in the resolved lepton+jets channel by CMS
  - 3 ab-1 @ 14 TeV
  - Phase-2 CMS detector simulated by DELPHES
  - require 4 jets, 2 b-tags, and exactly 1 electron or muon
  - PUPPI algorithm essential for mitigating pileup
  - reconstruct ttbar by kinematic fit
- Projected normalized differential cross-sections:
  - 1D: p_T, $|y|$ of individual top; p_T, $|y|$, and m of $t\bar{t}$
  - 2D: $m(t\bar{t})$ vs $|y(t\bar{t})|$
- Uncertainties
  - Detector systematics estimated based on simulation: e/mu ID, b-tagging, jet energy scale and resolution, met, luminosity
  - Theoretical and modelling uncertainties are reduced by half wrt the analysis using 2016 LHC data
  - < 5% (10&) uncertainties in most bins in the single (double) differential cross-sections
    - Benefit from the large amount of data and improved jet calibration
- Constrain the gluon distribution in PDF from the double differential cross-sections

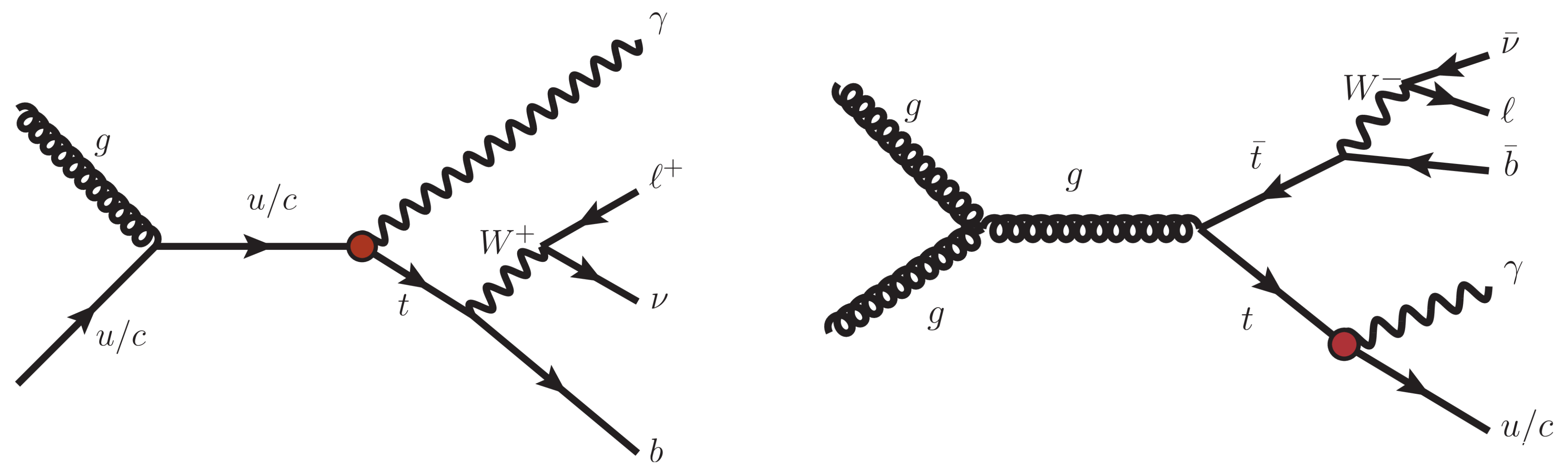


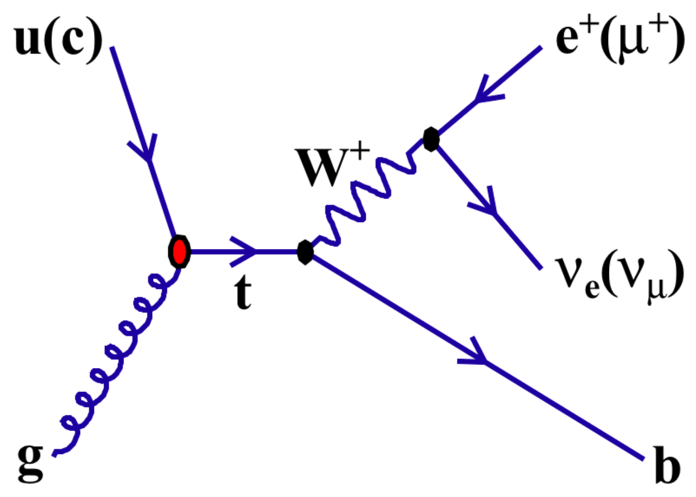


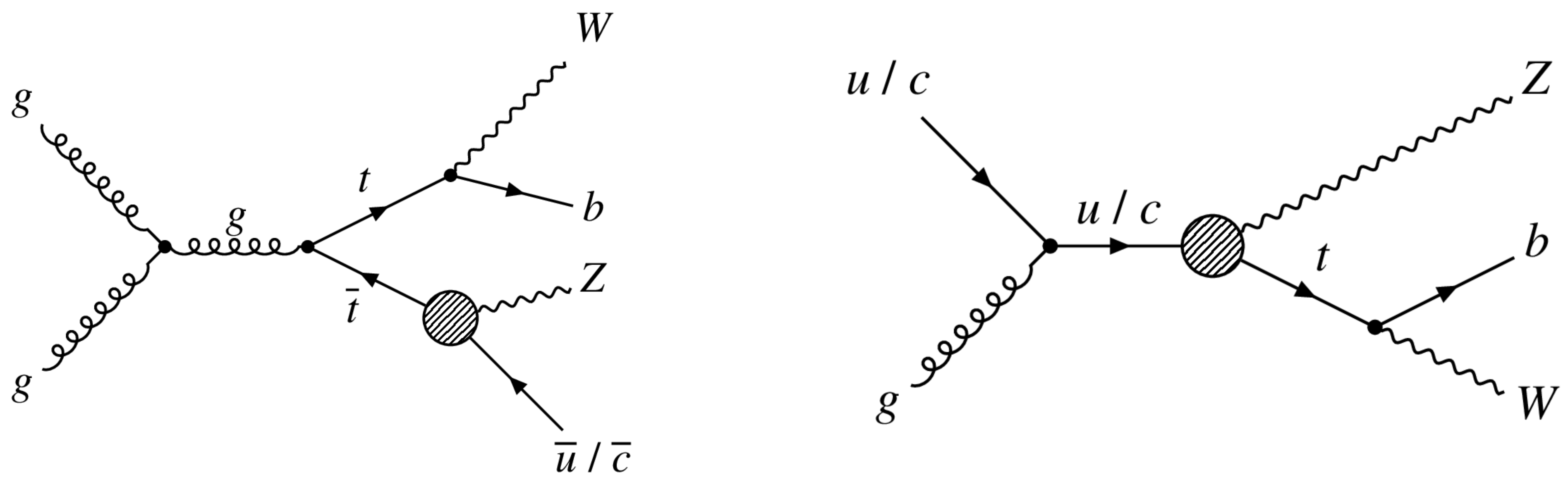


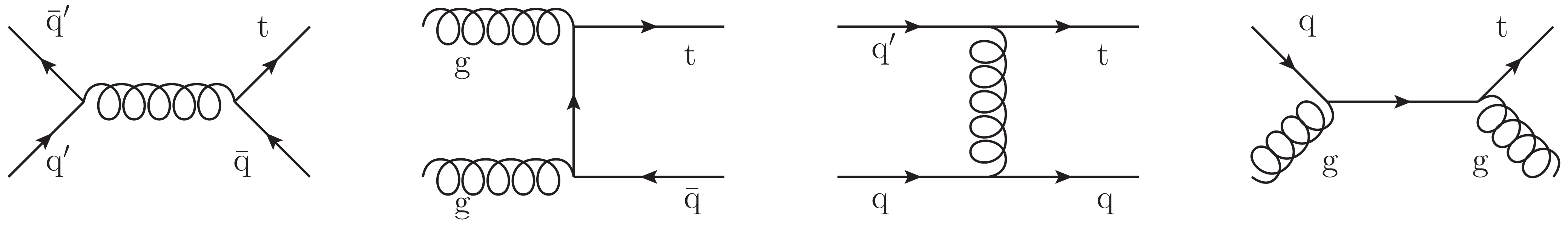
Some top FCNC Feynman diagrams











Observables used in EFT fit at LHC

Process	Observable	$\sqrt{s}$	L_{int}	Experiment
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	140 fb^{-1}	CMS
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (4+2 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC
$t \to Wb$	F_0, F_L	8 TeV	20 fb^{-1}	LHC
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^-e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD

arXiv.2205.02140

Wilson Coefficients used in fit

arXiv.2205.02140

Coefficients fitted			
2-quark	C_{tG} $C_{\varphi t}$ –	$C^3_{\varphi Q}$ $C_{\varphi b}$ $C_{t\varphi}$	$C^-_{\varphi Q} = C^1_{\varphi Q} - C^3_{\varphi Q}$ $C_{tZ} = c_W C_{tW} - s_W C_{tB}$ C_{tW}
4-quark	$C^8_{tu} = \sum_{i=1,2} 2C^{(i33i)}_{uu}$ $C^8_{Qu} = \sum_{i=1,2} C^{8(33ii)}_{qu}$ –	$C^8_{td} = \sum_{i=1,2,3} C^{8(33ii)}_{ud}$ $C^8_{Qd} = \sum_{i=1,2,3} C^{8(33ii)}_{qd}$ –	$C^{1,8}_{Qq} = \sum_{i=1,2} C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$ $C^{3,8}_{Qq} = \sum_{i=1,2} C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$ $C^8_{tq} = \sum_{i=1,2} C^{8(ii33)}_{uq}$
2-quark 2-lepton	C_{eb} C_{lb} –	C_{et} C_{lt} –	$C^+_{lQ} = C^1_{lQ} + C^3_{lQ}$ $C^-_{lQ} = C^1_{lQ} - C^3_{lQ}$ C_{eQ}