Top quark properties and searches in ATLAS and CMS

Sebastian Wuchterl
on behalf of the ATLAS and CMS collaborations

58th Rencontres de Moriond

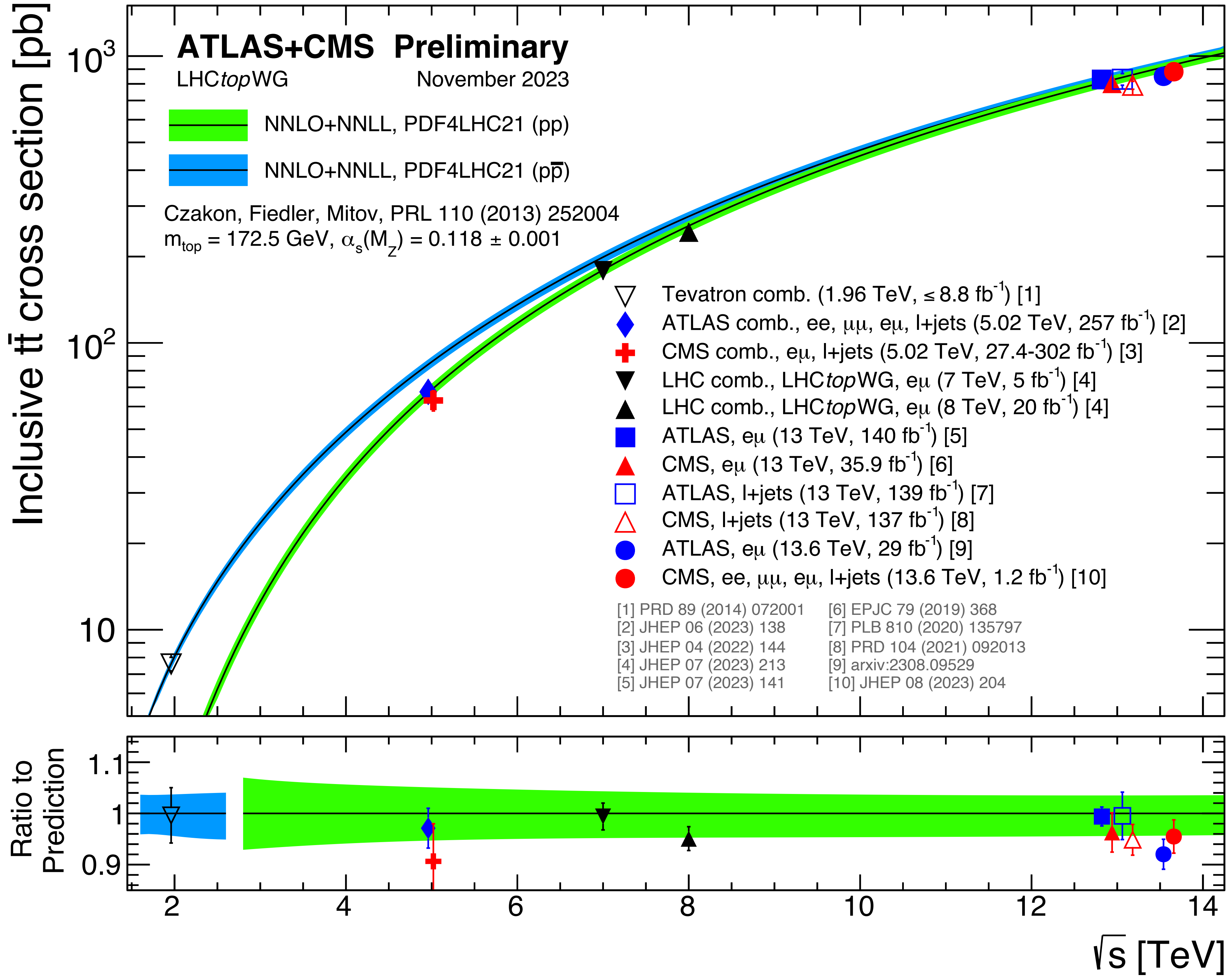
Electroweak Interactions & Unified Theories

26 March 2024

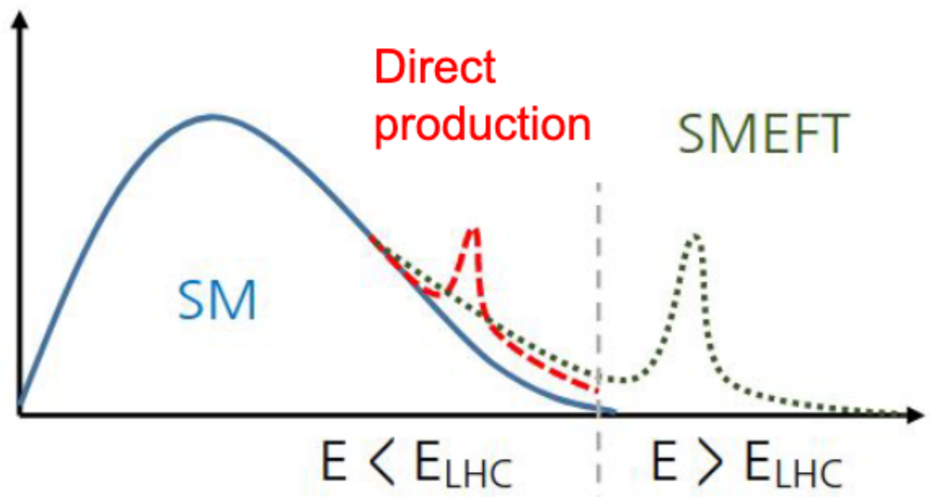
The top quark in the standard model (SM)

[LHC Top WG]

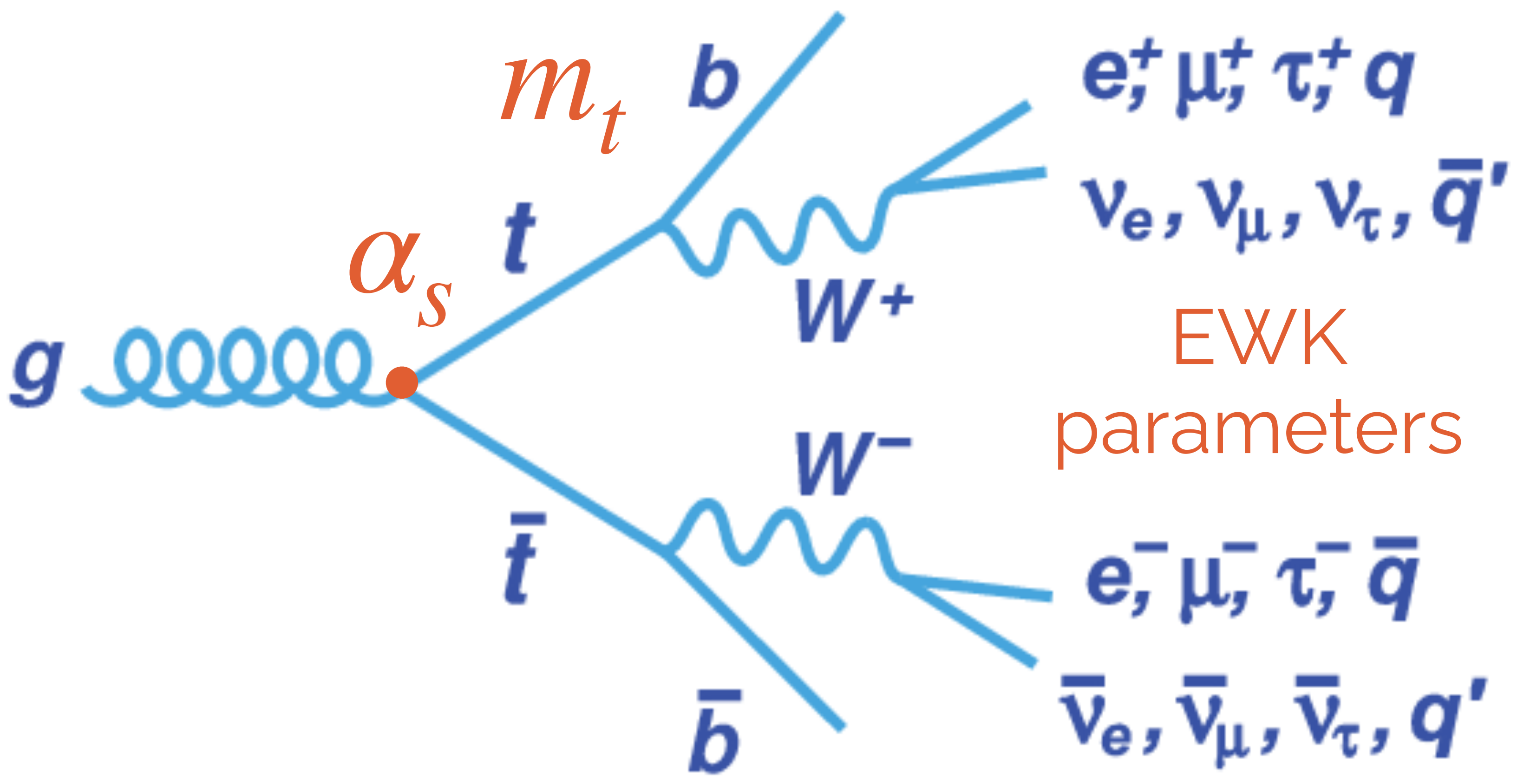
- Top quark is the most massive elementary particle
  - High relevance for EWK symmetry breaking (→BSM)
  - Short lifetime (~10^{-25}s) < $t_{had.}$ (~10^{-24}s) < t_{spin} (~10^{-21}s)
- Only quark that decays before forming bound states
  → Unique way to study 'bare' quark properties



- High production rate at LHC
  → High precision SM measurements, e.g. for $\sigma_{t\bar{t}}$
  → Study SM QCD + EWK parameters
  → Portal to beyond-the SM (BSM) physics



$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i$$



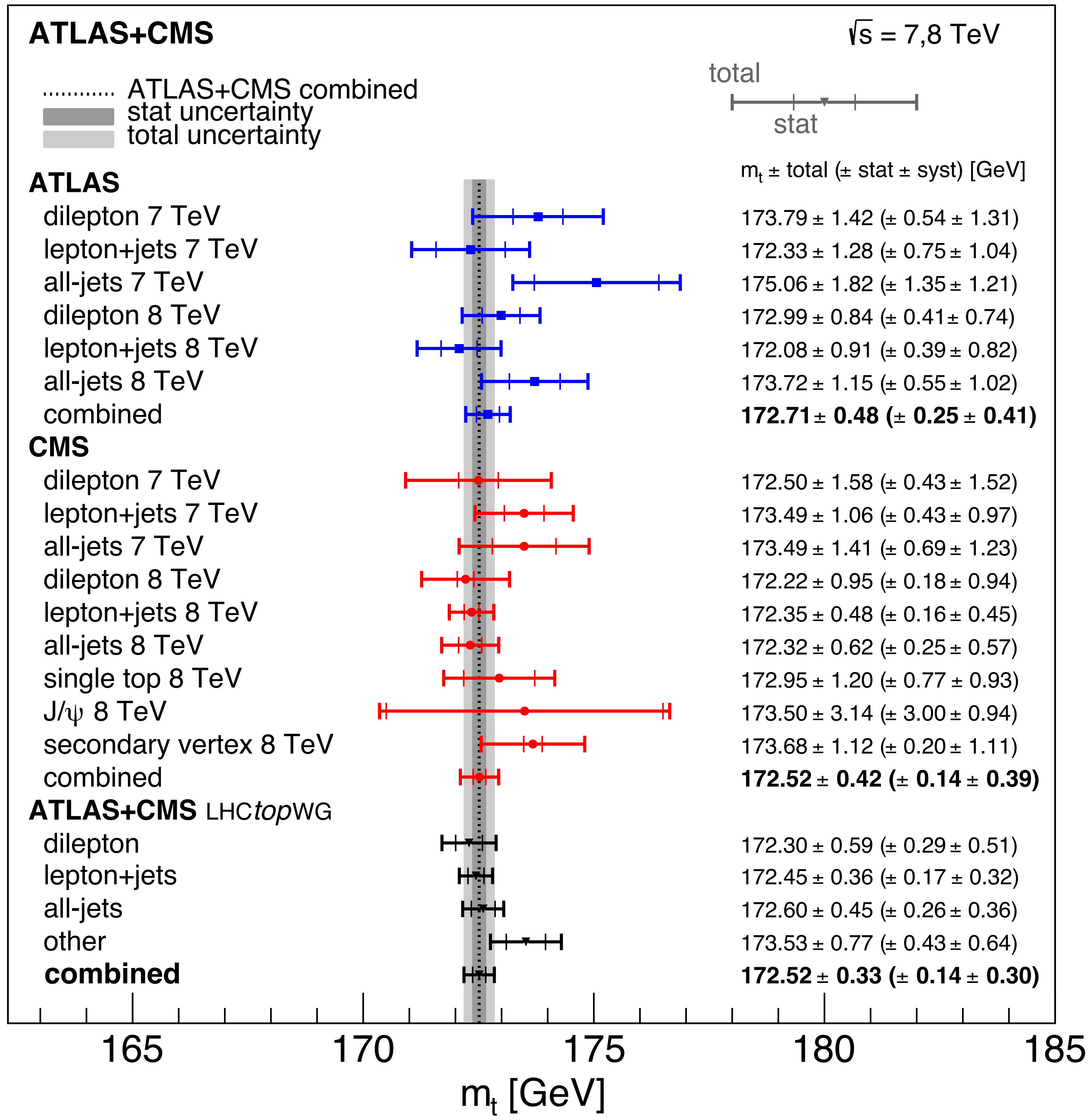
→ Selection of property measurements and fundamental searches

ATLAS + CMS mass combination [arXiv:2402.08713] NEW!

- **Legacy combination** of Run-1 ATLAS+CMS m_t measurements
  - 6 (ATLAS) + 9 (CMS) individual measurements
  - Wide range of final states and techniques: $t\bar{t}$ (dl, l+jets, all-jets), single-t, J/Psi, SV
  - Best Linear Unbiased Estimator (BLUE) combination

$$m_{top} = \sum_i w^i m^i_{top}$$

$$\sum_i w^i = 1$$



The "only correlation that matters"

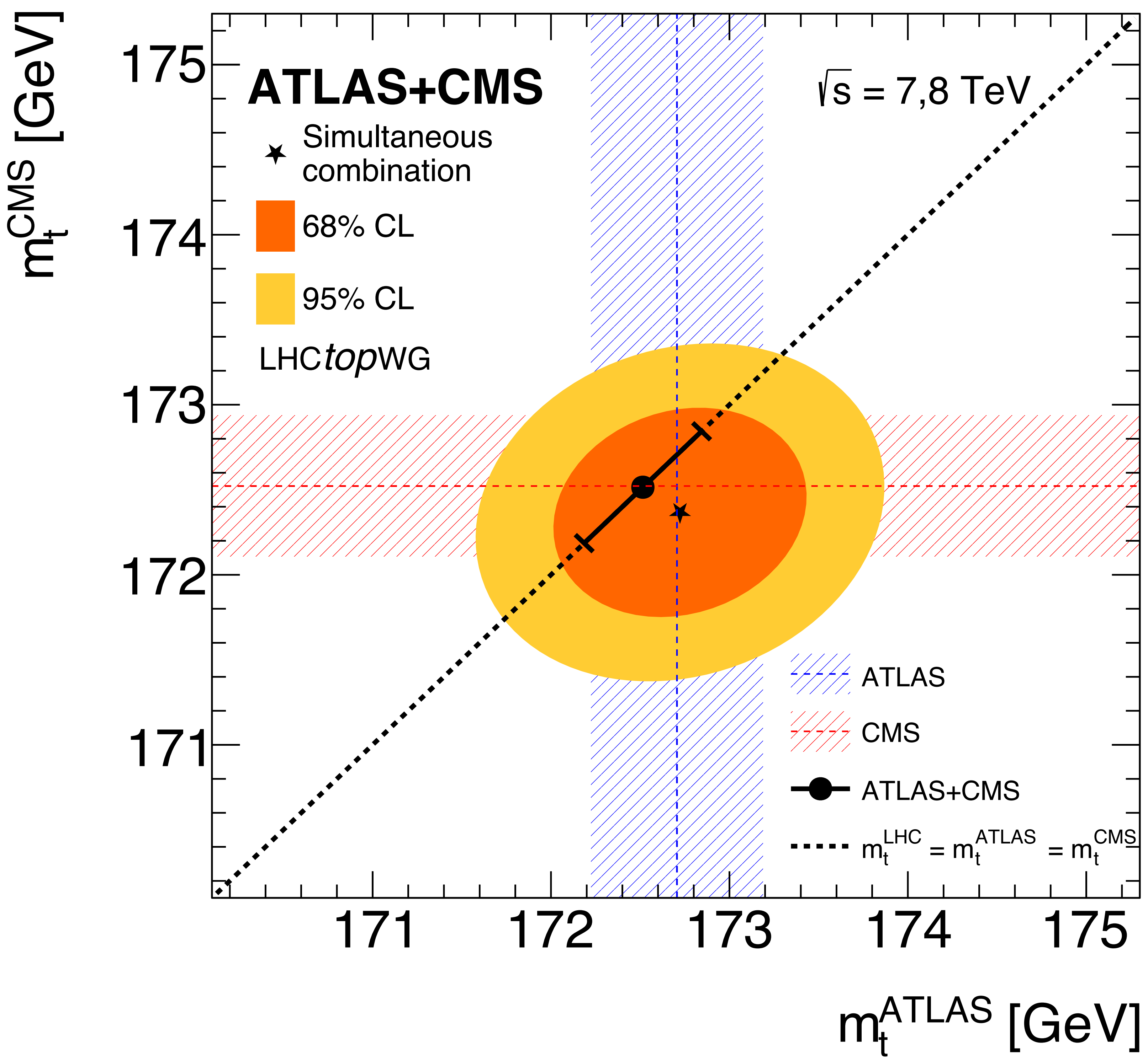
Uncertainty category	ρ	Scan range	$\Delta m_t/2$ [MeV]	$\Delta\sigma_{m_t}/2$ [MeV]
JES 1	0	—	—	—
JES 2	0	[−0.25, +0.25]	8	7
JES 3	0.5	[+0.25, +0.75]	1	<1
b-JES	0.85	[+0.5, +1]	26	5
g-JES	0.85	[+0.5, +1]	2	<1
l-JES	0	[−0.25, +0.25]	1	<1
CMS JES 1	—	—	—	—
JER	0	[−0.25, +0.25]	5	1
Leptons	0	[−0.25, +0.25]	2	2
b tagging	0.5	[+0.25, +0.75]	1	1
p_T^{miss}	0	[−0.25, +0.25]	<1	<1
Pileup	0.85	[+0.5, +1]	2	<1
Trigger	0	[−0.25, +0.25]	<1	<1
ME generator	0.5	[+0.25, +0.75]	<1	4
QCD radiation	0.5	[+0.25, +0.75]	7	1
Hadronization	0.5	[+0.25, +0.75]	1	<1
CMS b hadron $\mathcal{B}$	—	—	—	—
Color reconnection	0.5	[+0.25, +0.75]	3	1
Underlying event	0.5	[+0.25, +0.75]	1	<1
PDF	0.85	[+0.5, +1]	1	<1
CMS top quark p_T	—	—	—	—
Background (data)	0	[−0.25, +0.25]	8	2
Background (MC)	0.85	[+0.5, +1]	2	<1
Method	0	—	—	—
Other	0	—	—	—

Stable wrt. variations

- Very detailed study of systematics, their correlations, and impacts

ATLAS + CMS mass combination [arXiv:2402.08713]

NEW!



Uncertainties	Best result [GeV]	Combination [GeV]	Best / combined
ATLAS	0.84	0.48	1.8
CMS	0.48	0.42	1.1
LHC	0.48	0.33	**1.5**

- **Combinations are worth the effort!**
- Lower precision alternative results important for combinations
  - Most precise CMS 0.48 GeV → 0.42 GeV

Dominant in the LHC combination

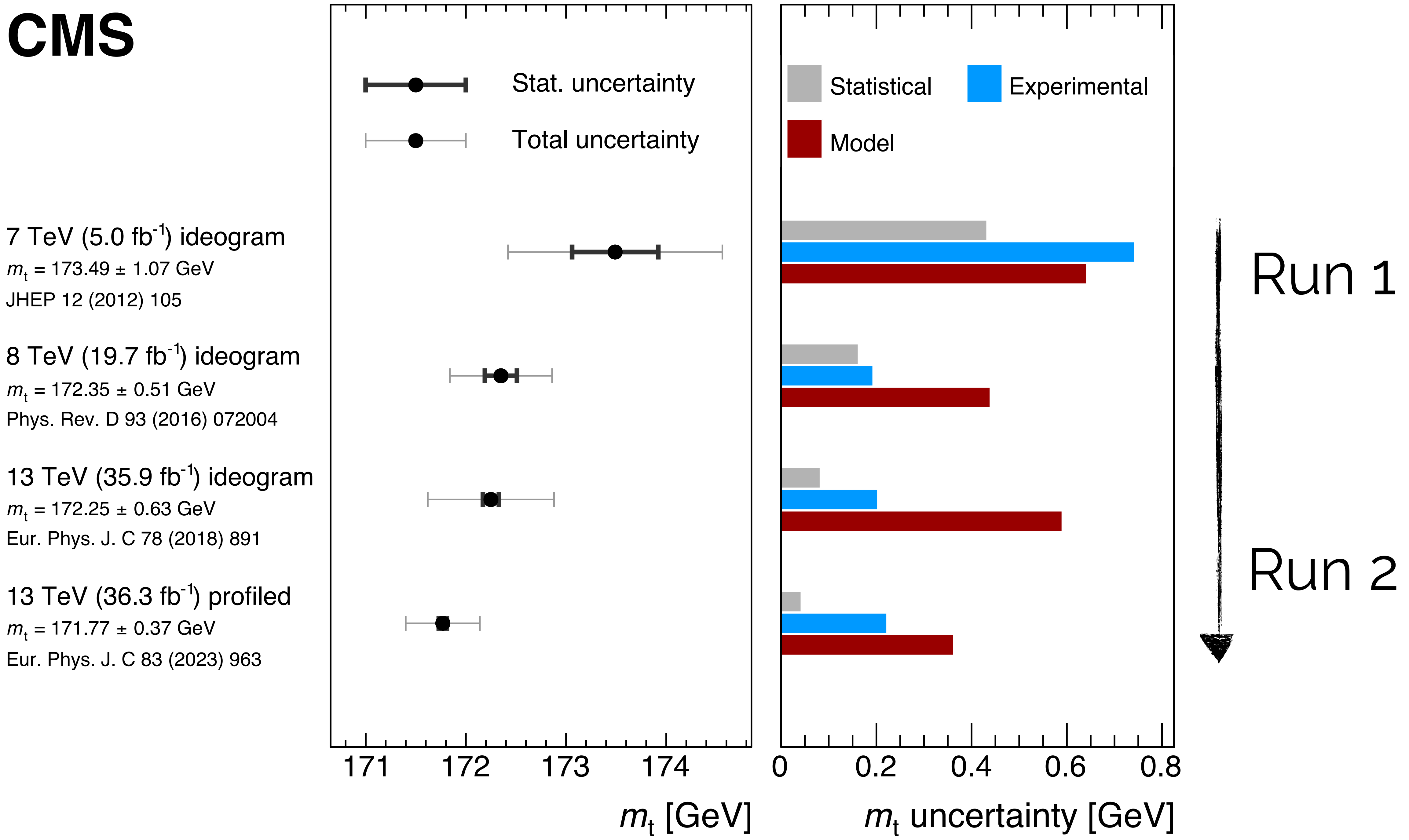
Dominant in individual combinations

Uncertainty category	Uncertainty impact [GeV] LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

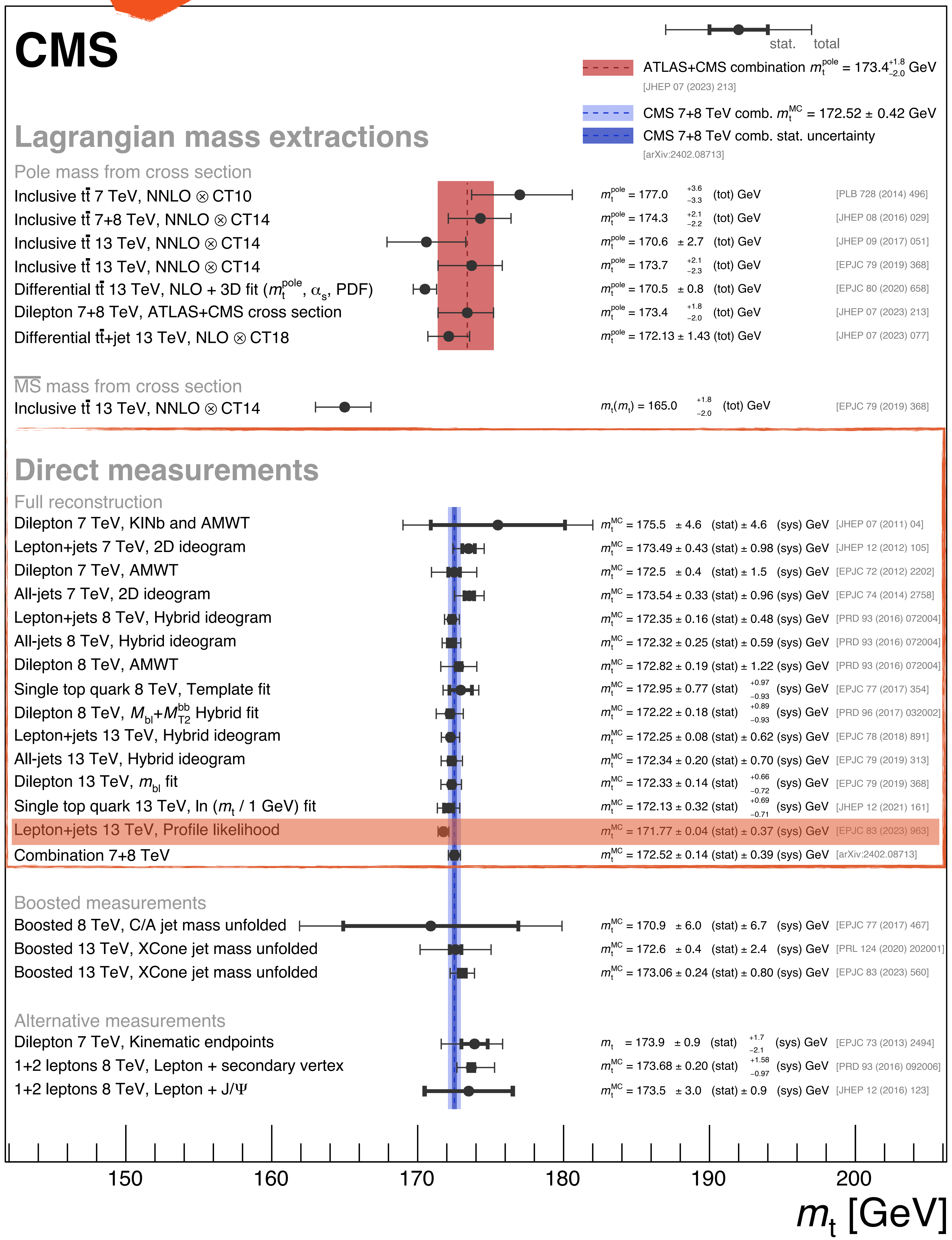
Review of m_t measurements [arXiv:2403.01313]

NEW!

- **Comprehensive review** of CMS m_t measurements
  - Evolvement over time!



Single most precise result

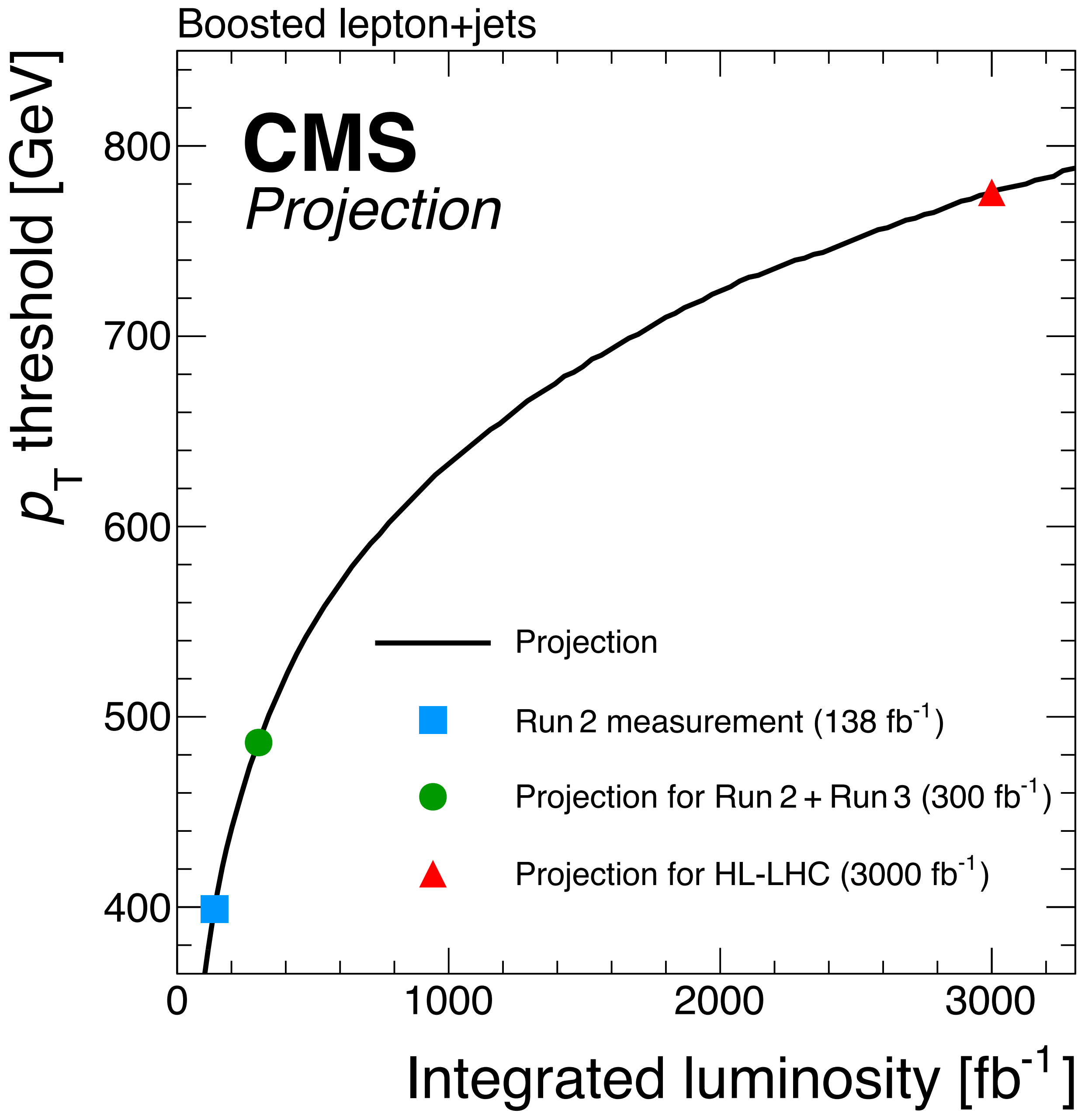


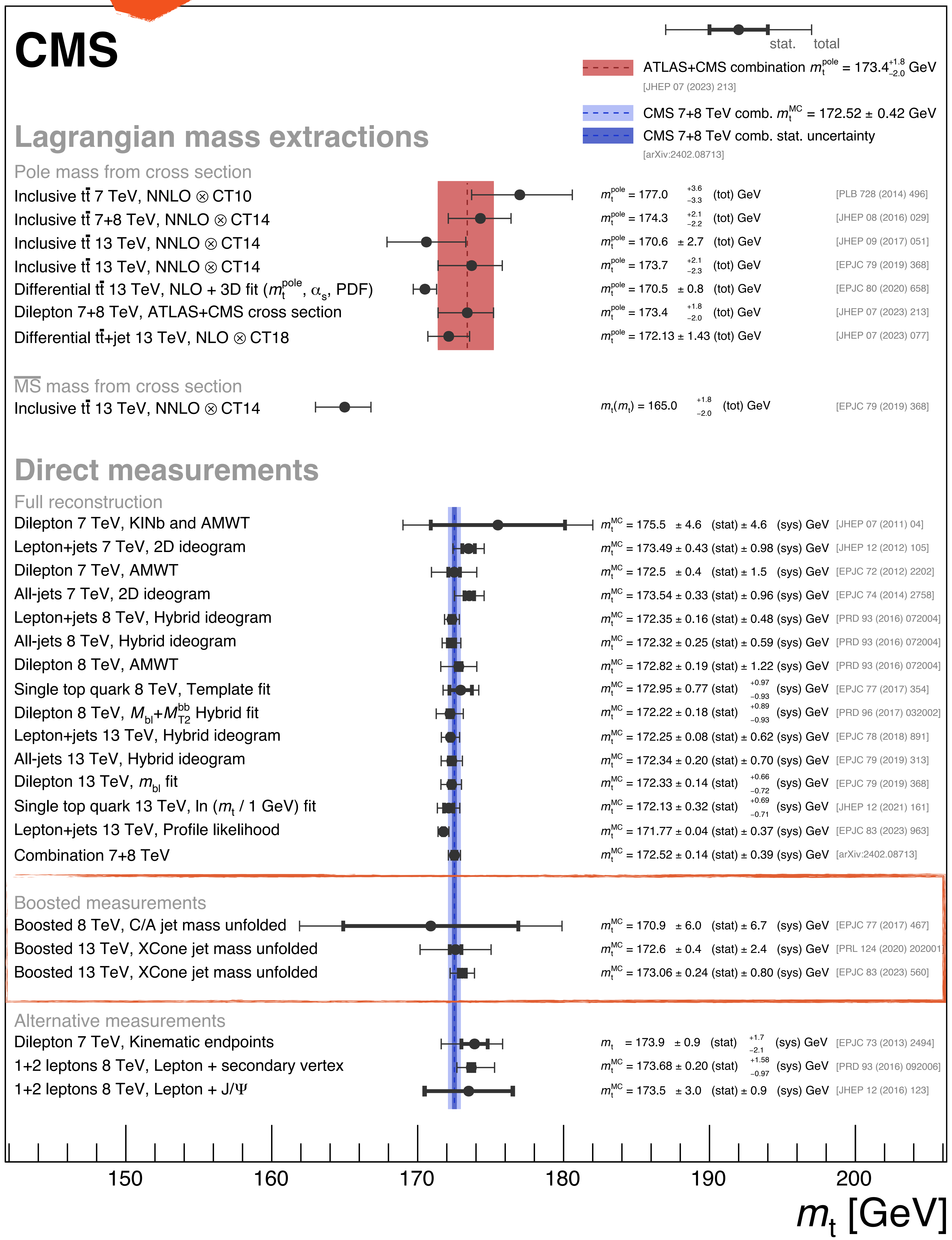
Review of m_t measurements [arXiv:2403.01313]

NEW!

- **Comprehensive review** of CMS m_t measurements
  - Boosted jet mass, bridging between direct / indirect m_t measurements
  - **Promising HL-LHC extrapolations!**

Theor. calculations for p_T > 750 GeV



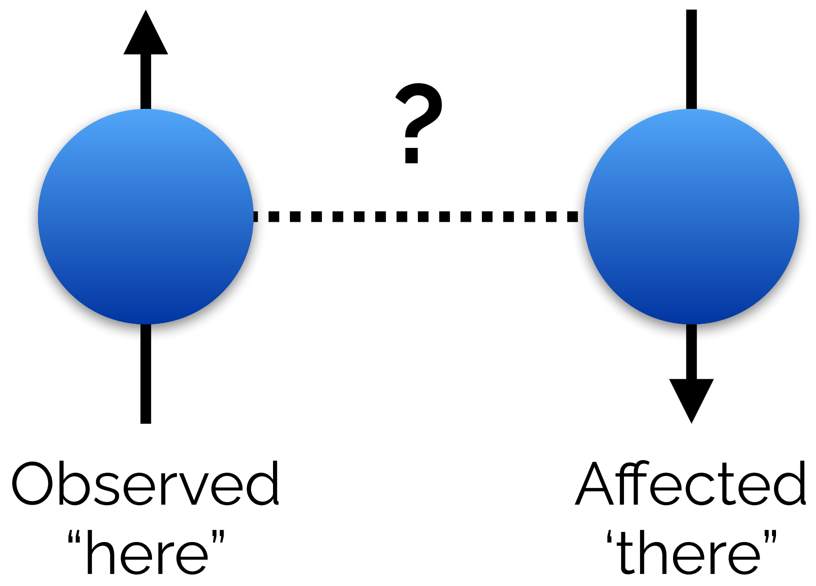


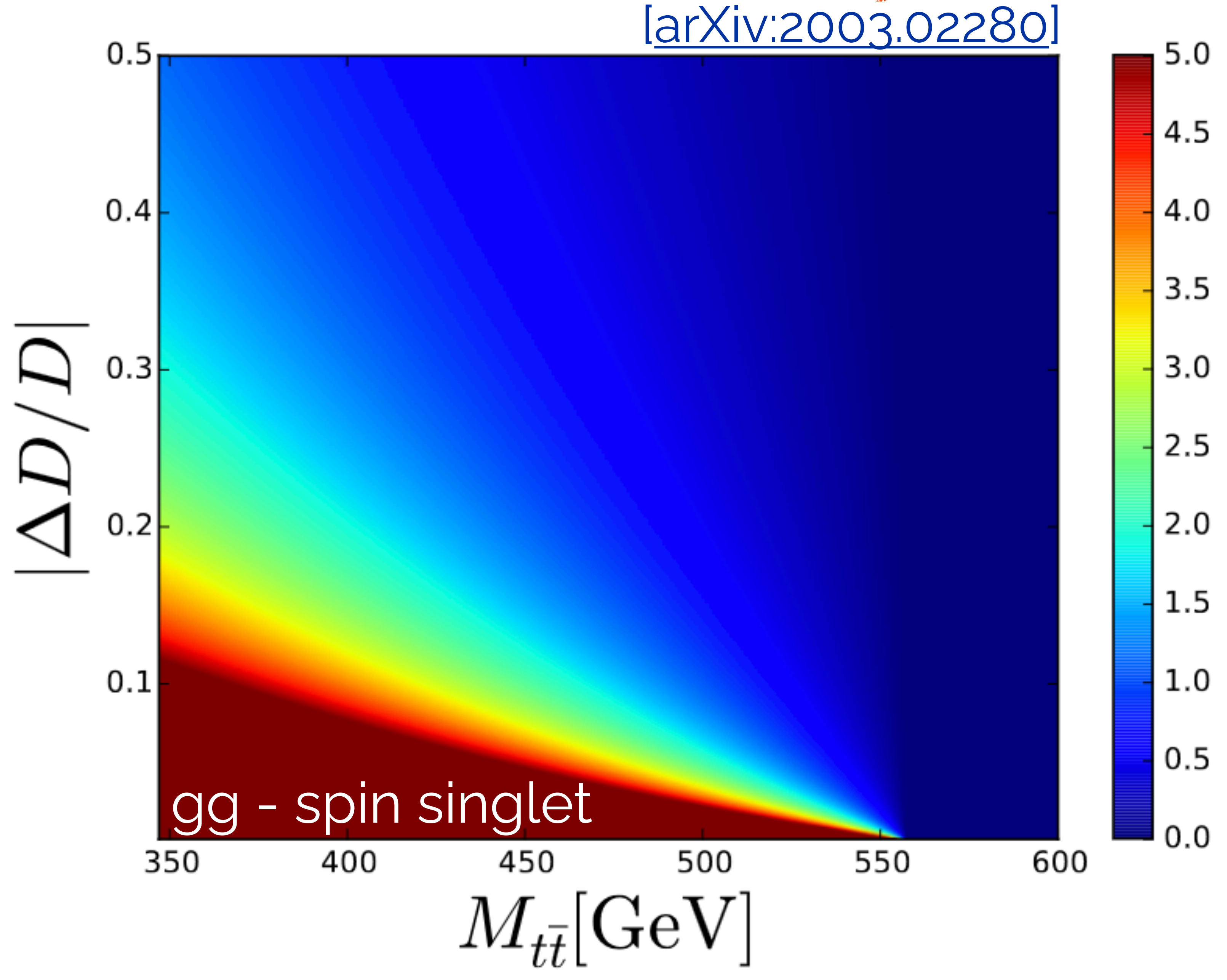
Observation of quantum entanglement in $t\bar{t}$

[arXiv:2311.07288] NEW!

ATLAS EXPERIMENT

Alain Aspect   John Clauser   Anton Zeilinger





- $t\bar{t}$ system described as two-qubit system
- Spin-density matrix already measured by ATLAS [1] + CMS [2]
- Cross section dependent on decay-lepton properties:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

Spin correlations

- Criterium for entanglement: $\mathbf{tr}[\mathbf{C}] + 1 < 0$

$$D = \frac{\mathrm{tr}[\mathbf{C}]}{3} \qquad D = -3 \cdot \langle \cos\varphi \rangle$$

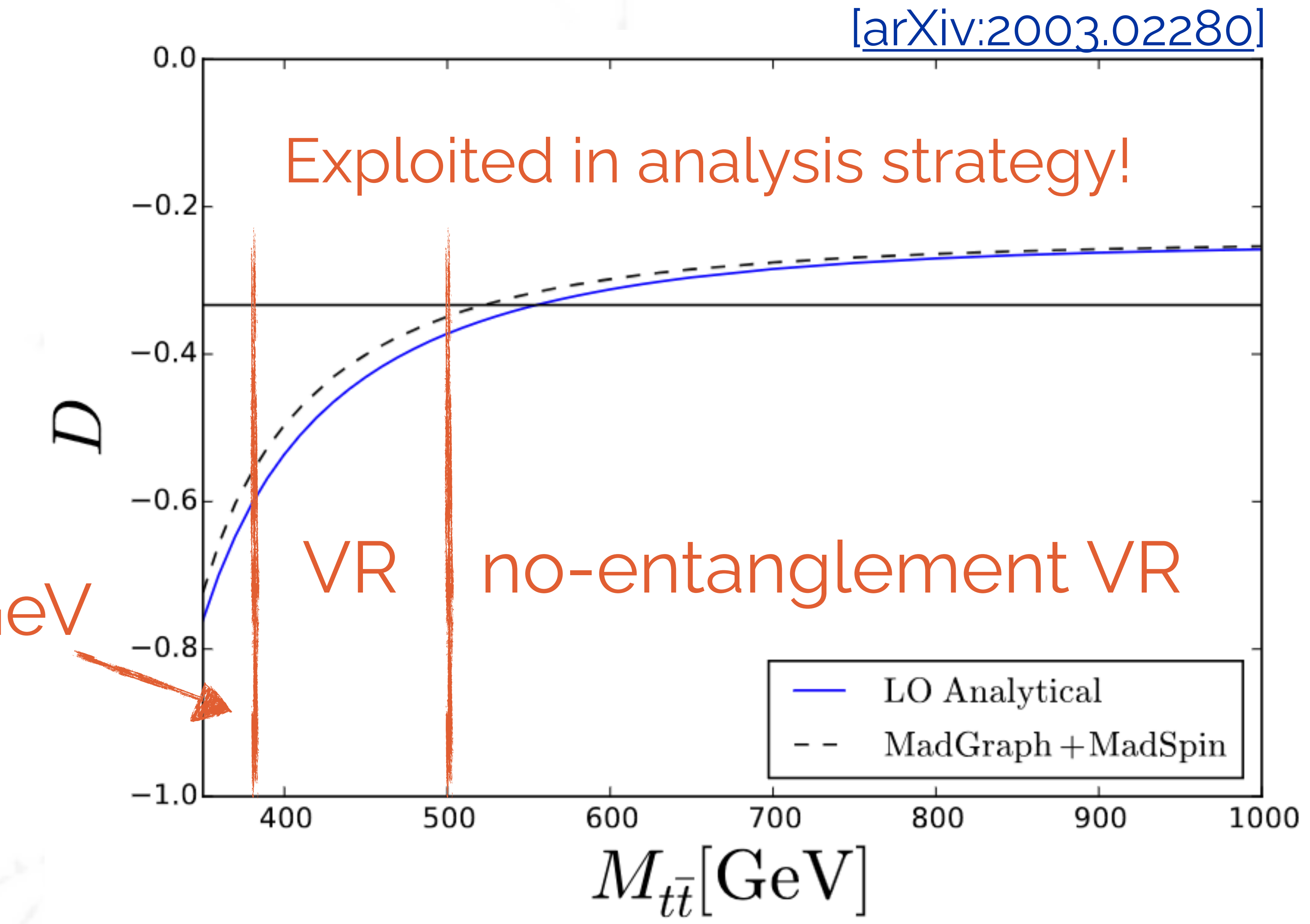
Can be measured from $\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi}$

φ: Angle between leptons in $t\bar{t}$ restframe

$$D < -1/3$$

Entanglement marker

SR: < 380 GeV

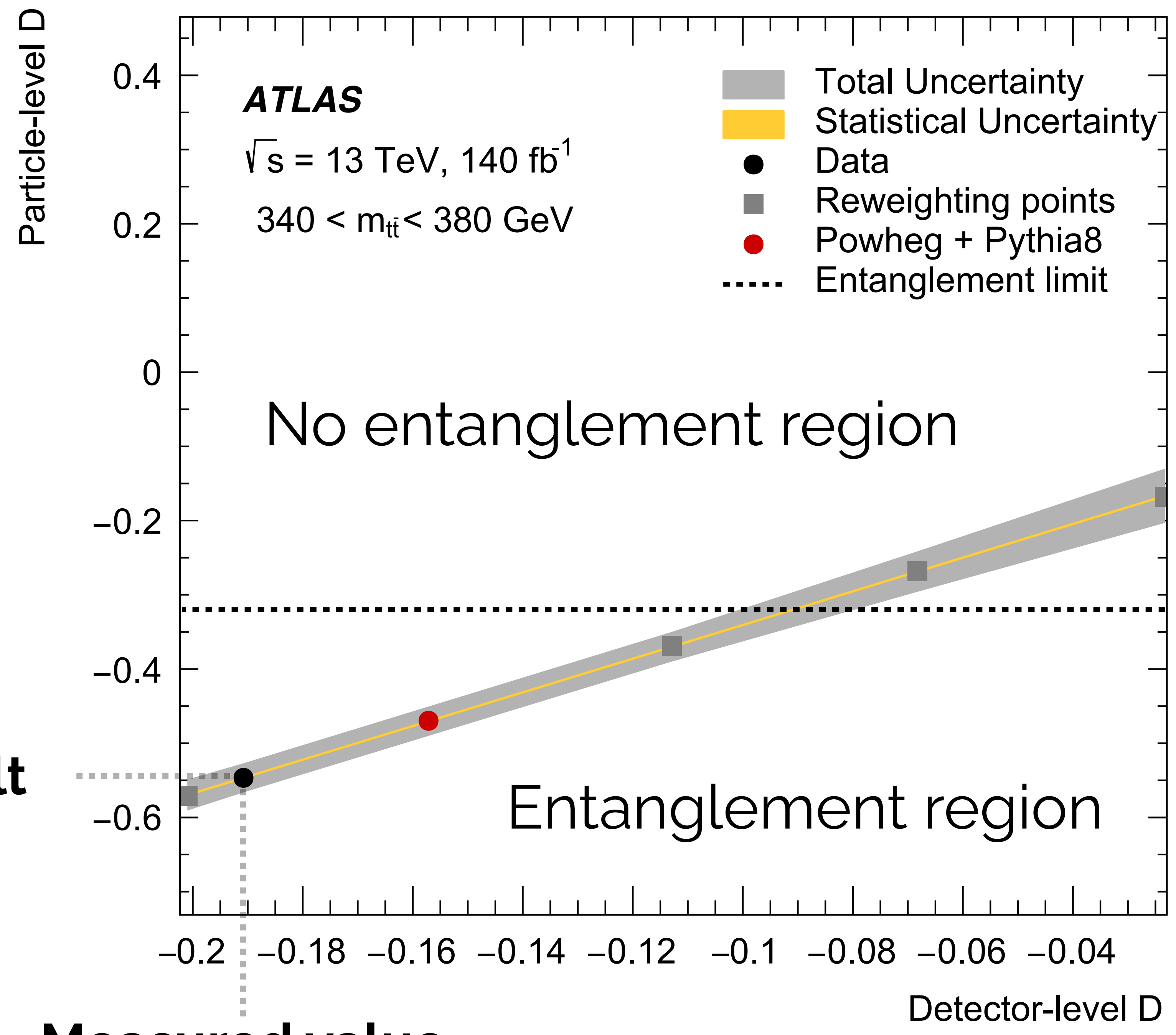


[1] [JHEP 03 (2017) 113] [2] [Phys. Rev. D 100, 072002]

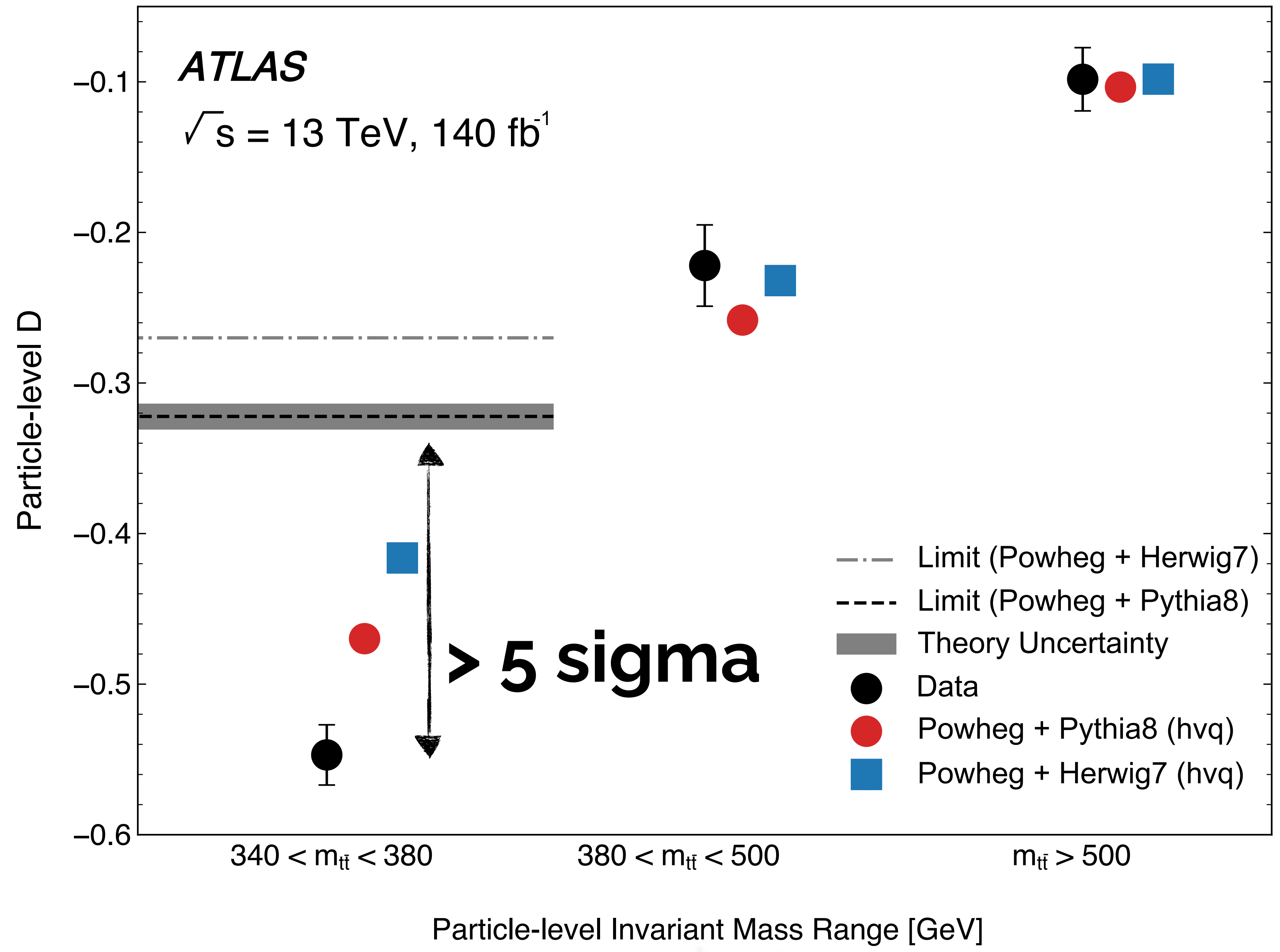
Observation of quantum entanglement in $t\bar{t}$ [arXiv:2311.07288] NEW!

ATLAS EXPERIMENT

- 1M high-purity electron-muon events
- **Calibrate from detector-level D to particle-level D**



- Calibrated for each region and systematic



$$D = -0.547 \pm 0.002\,(\text{stat.}) \pm 0.021\,(\text{syst.})$$

$$D = -0.470 \pm 0.002\,(\text{stat.}) \pm 0.018\,(\text{syst.})\,(\text{expected})$$

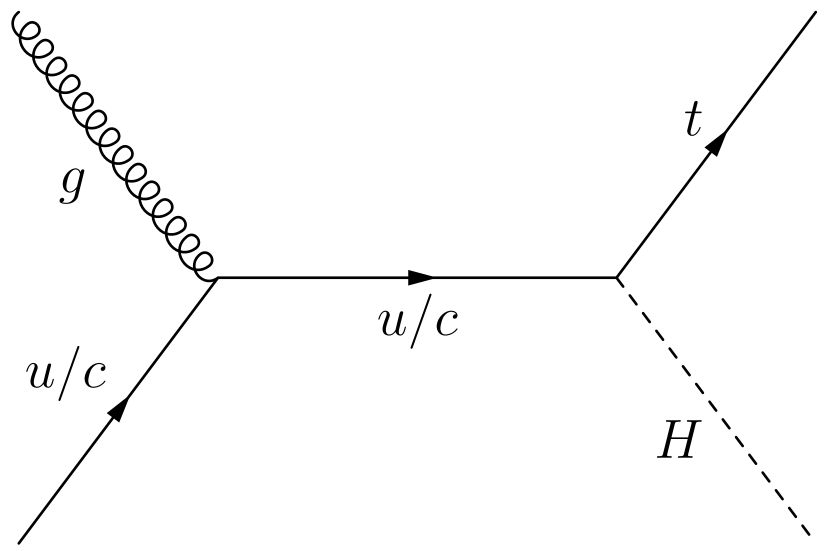
Dominant systematics

Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.547)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.1	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
E_T^{miss}	0.002	0.3	0.002	0.4
Backgrounds	0.010	1.8	0.009	1.8
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.021	3.8	0.018	3.9
Total uncertainty	0.021	3.8	0.018	3.9

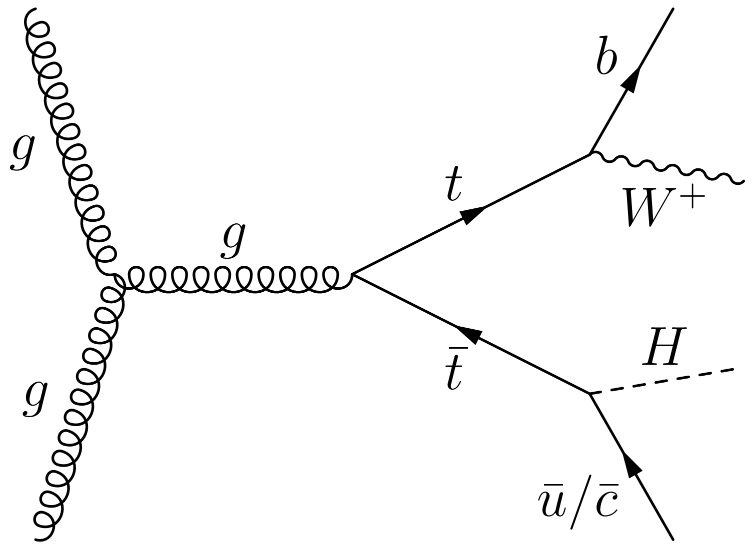
Searches for FCNC with top + Higgs

NEW!

- FCNC suppressed in SM, enhancement would be a direct sign of BSM physics
- Higgs mediated FCNC increased in 2HDM-like scenarios



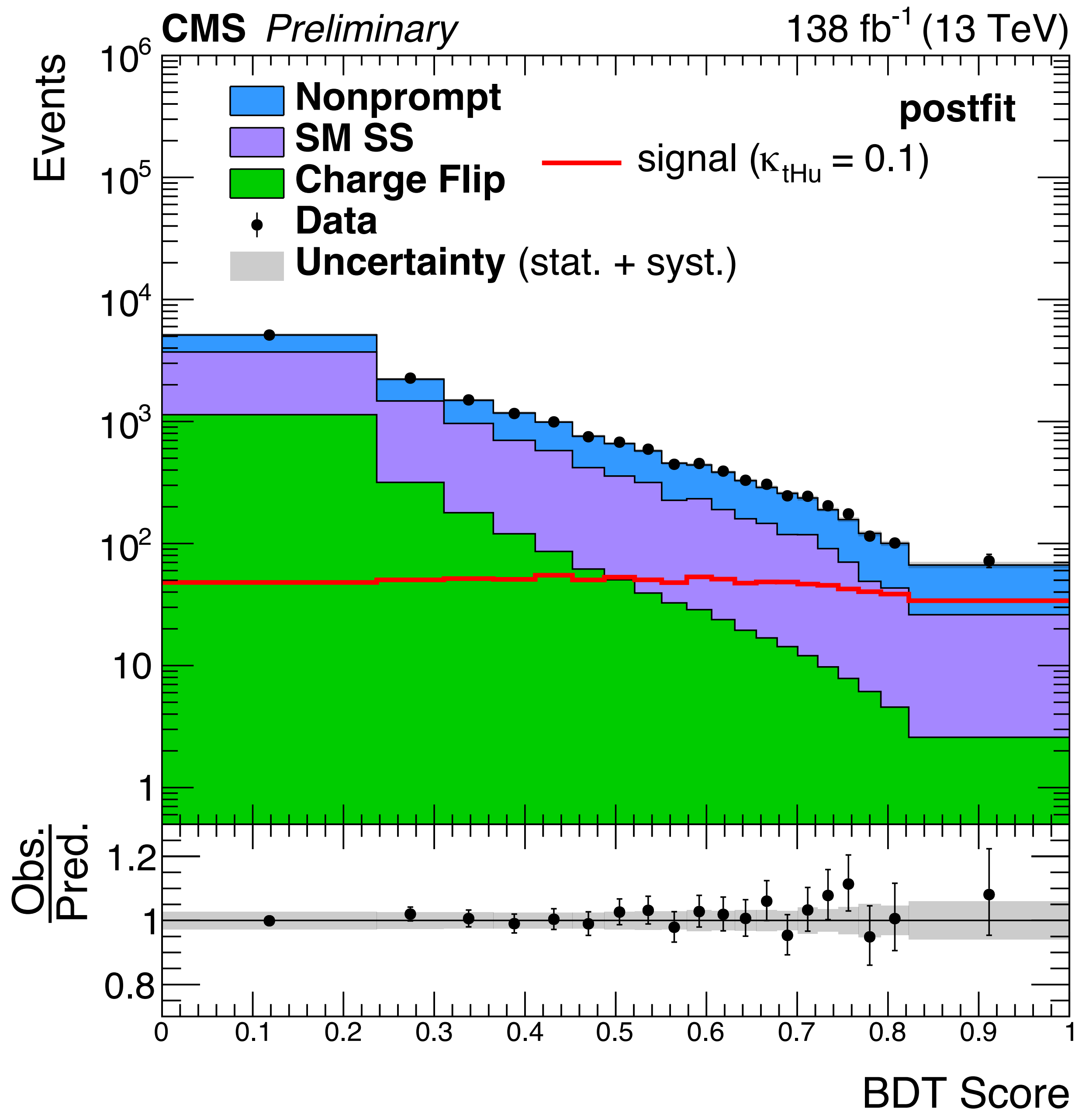
top-associated production



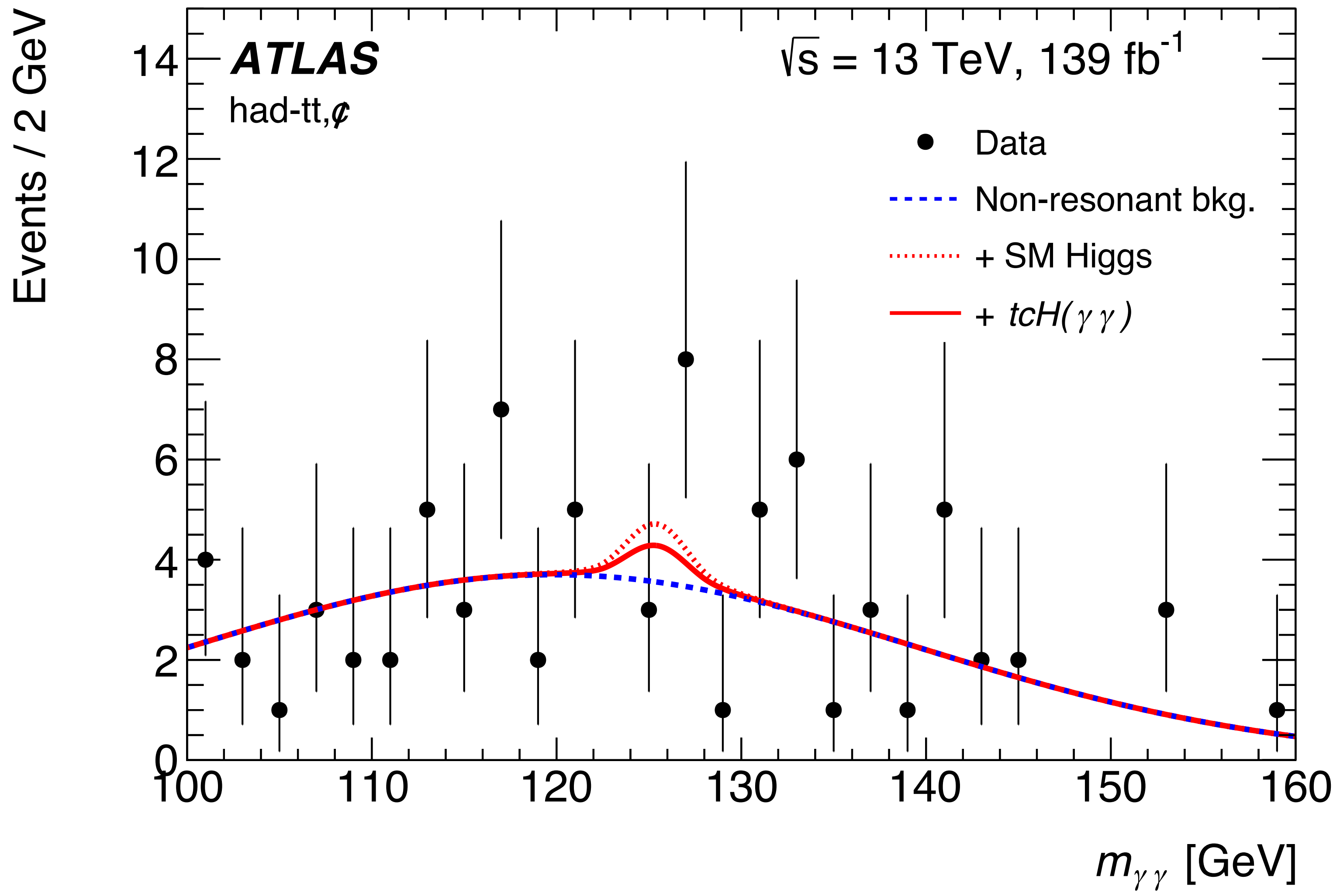
$t\bar{t}$ decay

- Analysis of **same-sign dilepton** final state events (e/muon)
- BDTs for tHc and tHu signals
  - Charm ID as input
- Limited by signal **modeling/ backgrounds**

[CMS-PAS-TOP-22-002]



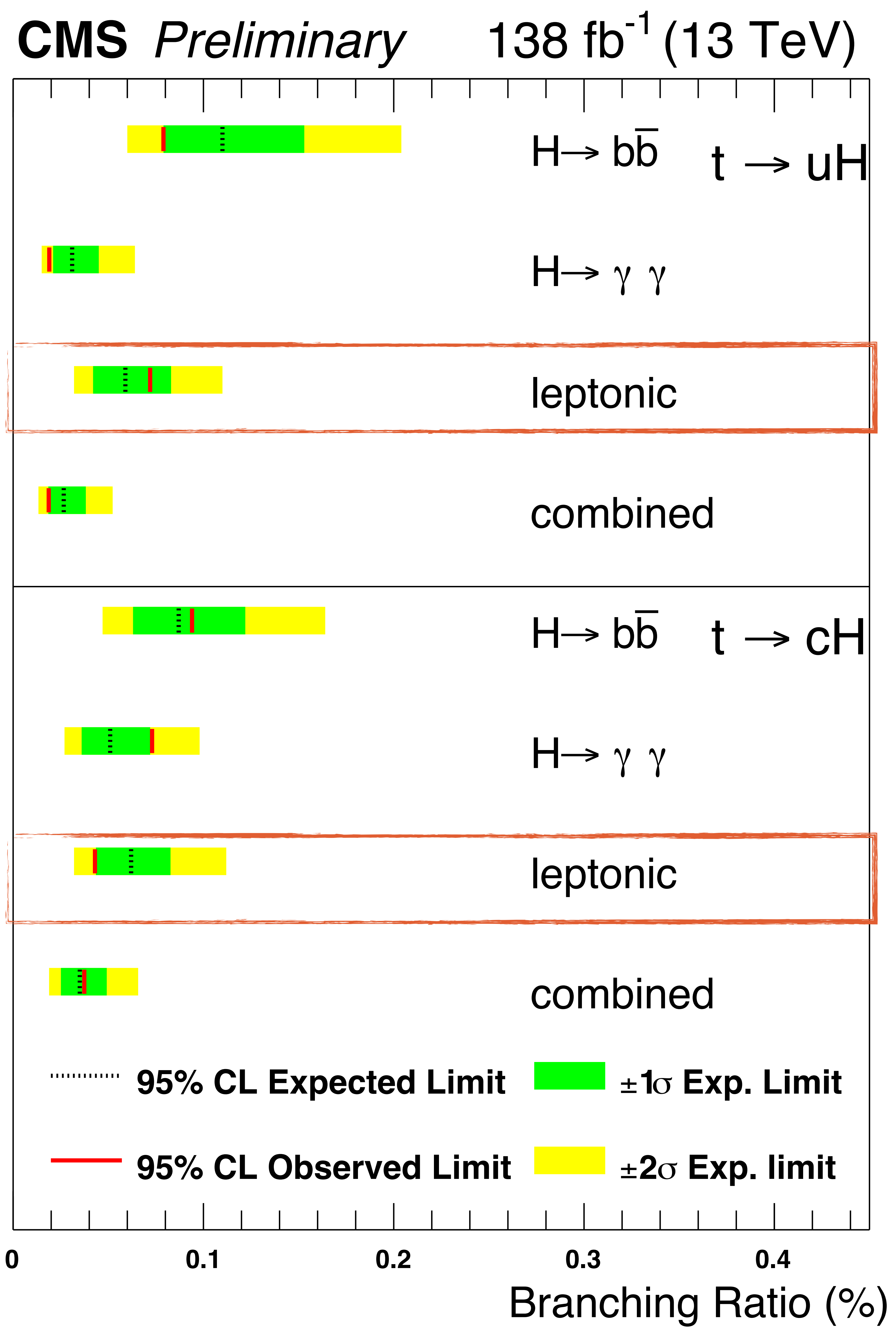
[JHEP 12 (2023) 195]



- Analysis of **diphoton** final state events
- BDTs for tHc and tHu signals
  - Charm ID as input
- **Statistically limited**

Searches for FCNC with top + Higgs + **Combinations!**

NEW!

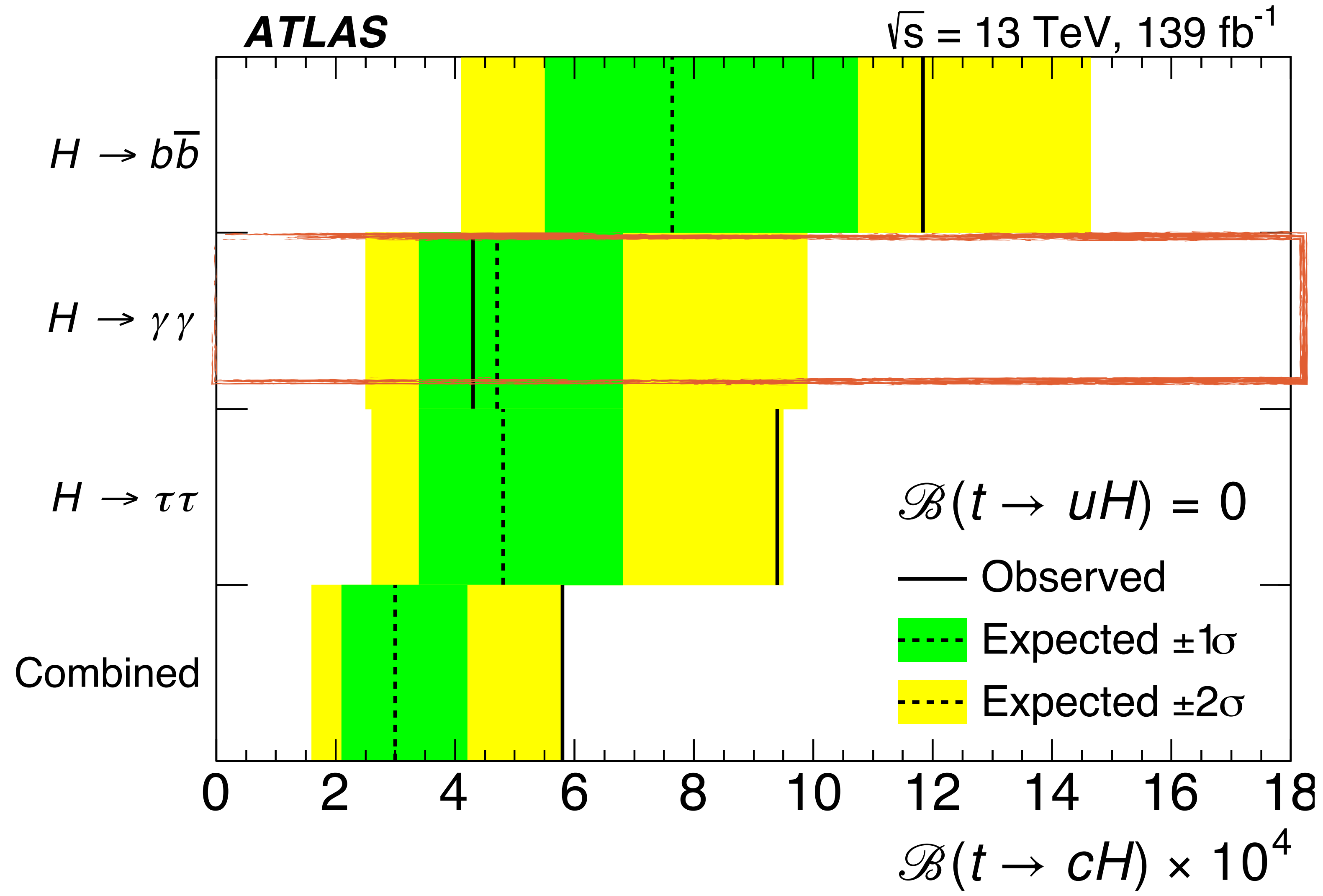


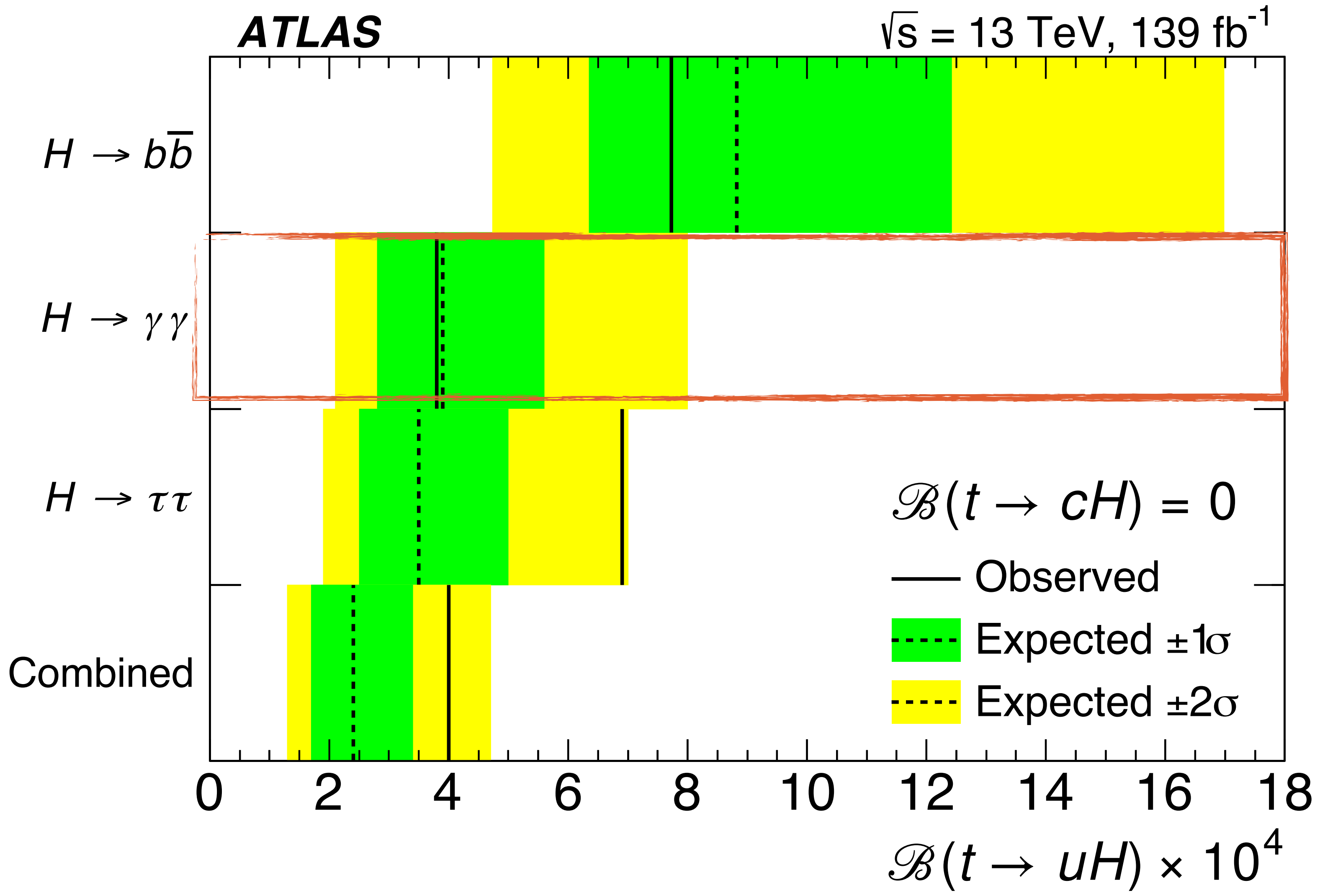
[CMS-PAS-TOP-22-002]

- CMS FCNC same-sign dilepton results combined with
  - H→b$\bar{b}$ [JHEP 02 (2022) 169]
  - H→γγ [Phys. Rev. Lett. 129 (2022)]
- Up to **factor 1.15 improvement** wrt. single best result!

Most stringent limits to date!

[JHEP 12 (2023) 195]



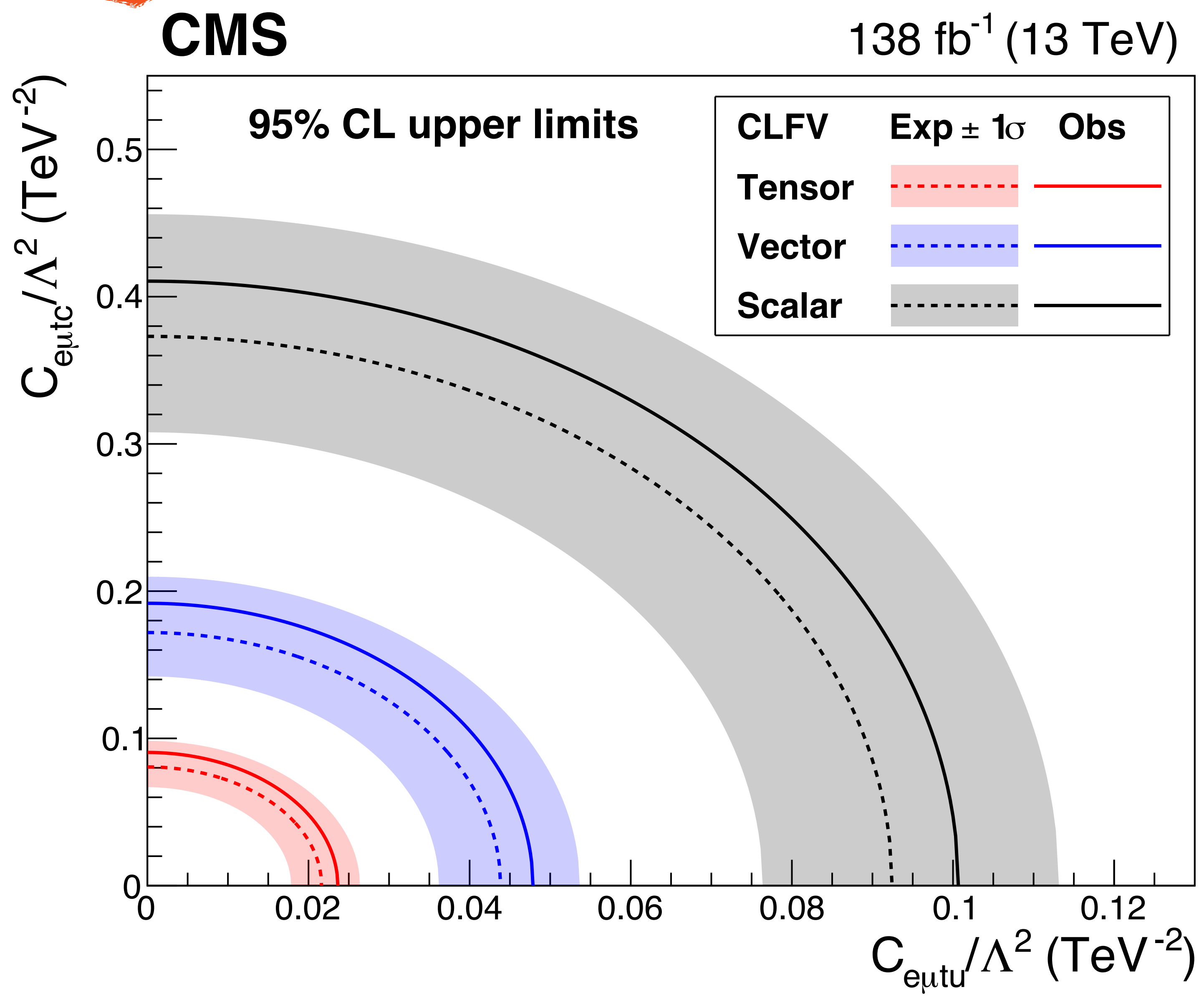


- ATLAS FCNC γγ results combined with
  - H→b$\bar{b}$ [JHEP 07 (2023) 199]
  - H→ττ [JHEP 06 (2023) 155]

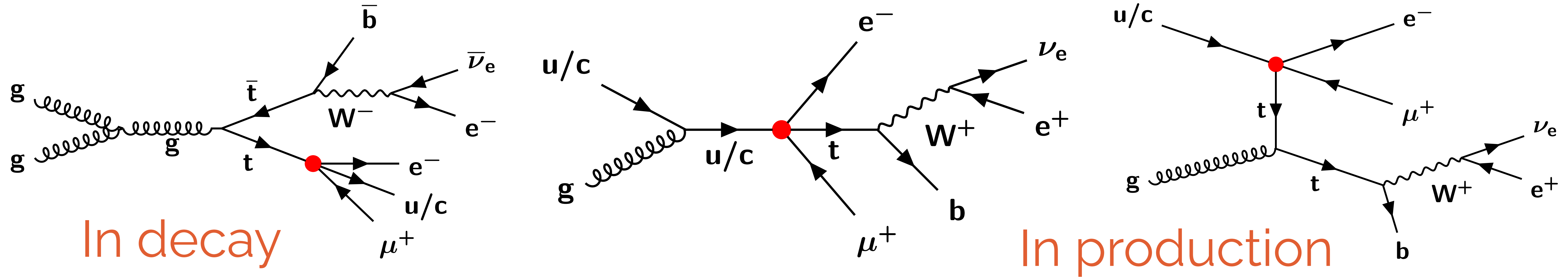
LFV in production and decay in CMS [arXiv:2312.03199]

NEW!

EFT interpretation

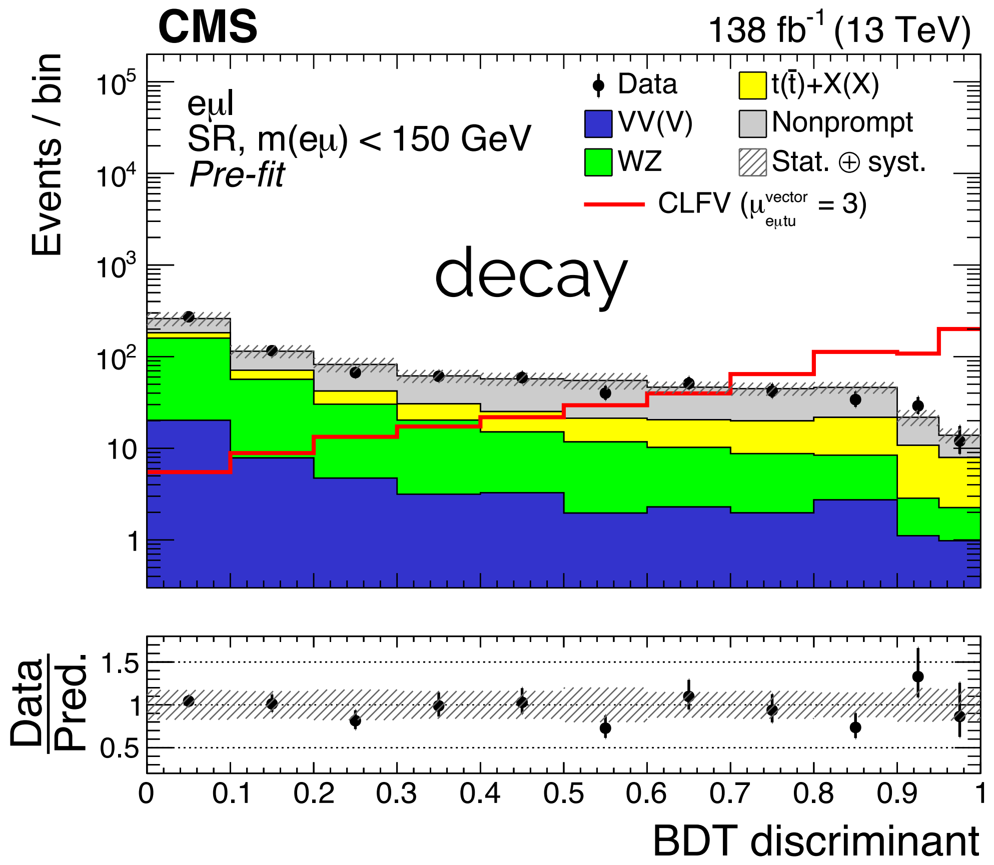


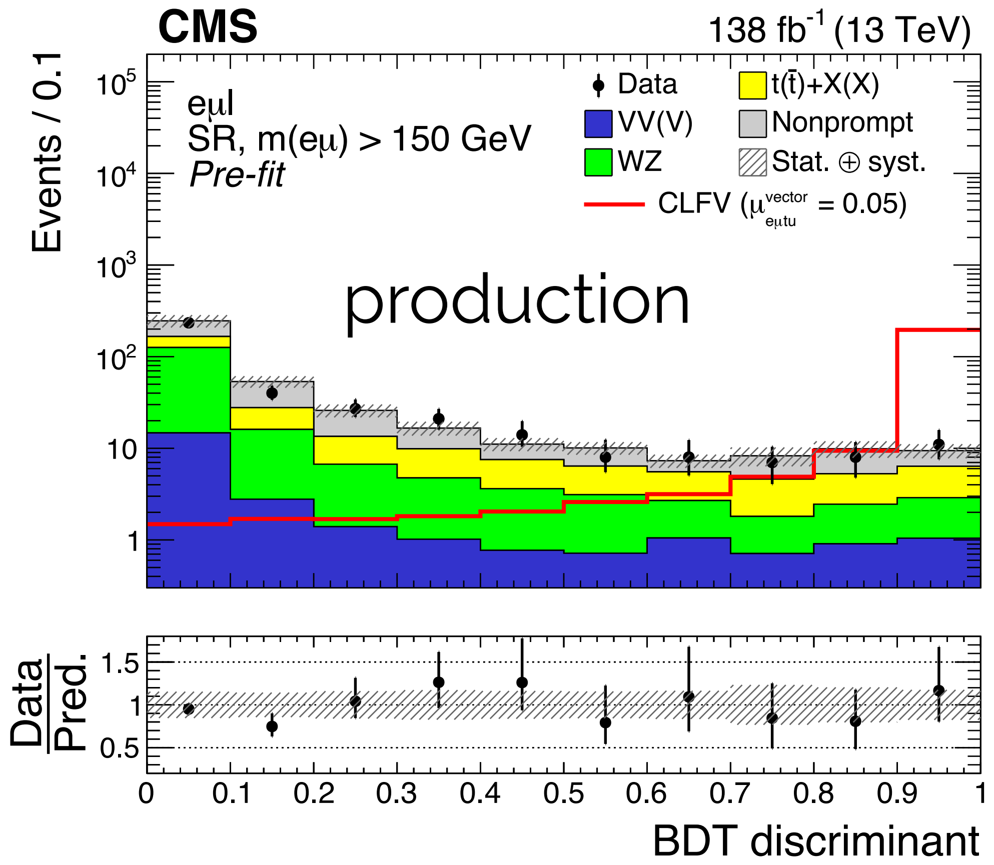
- Neutrino oscillations and flavour anomalies suggest charged lepton flavour violation (cLFV)
  - Some studies indicate within LHC reach [JHEP07(2019)025]
- Measurement in triple-lepton final state with electrons & muons

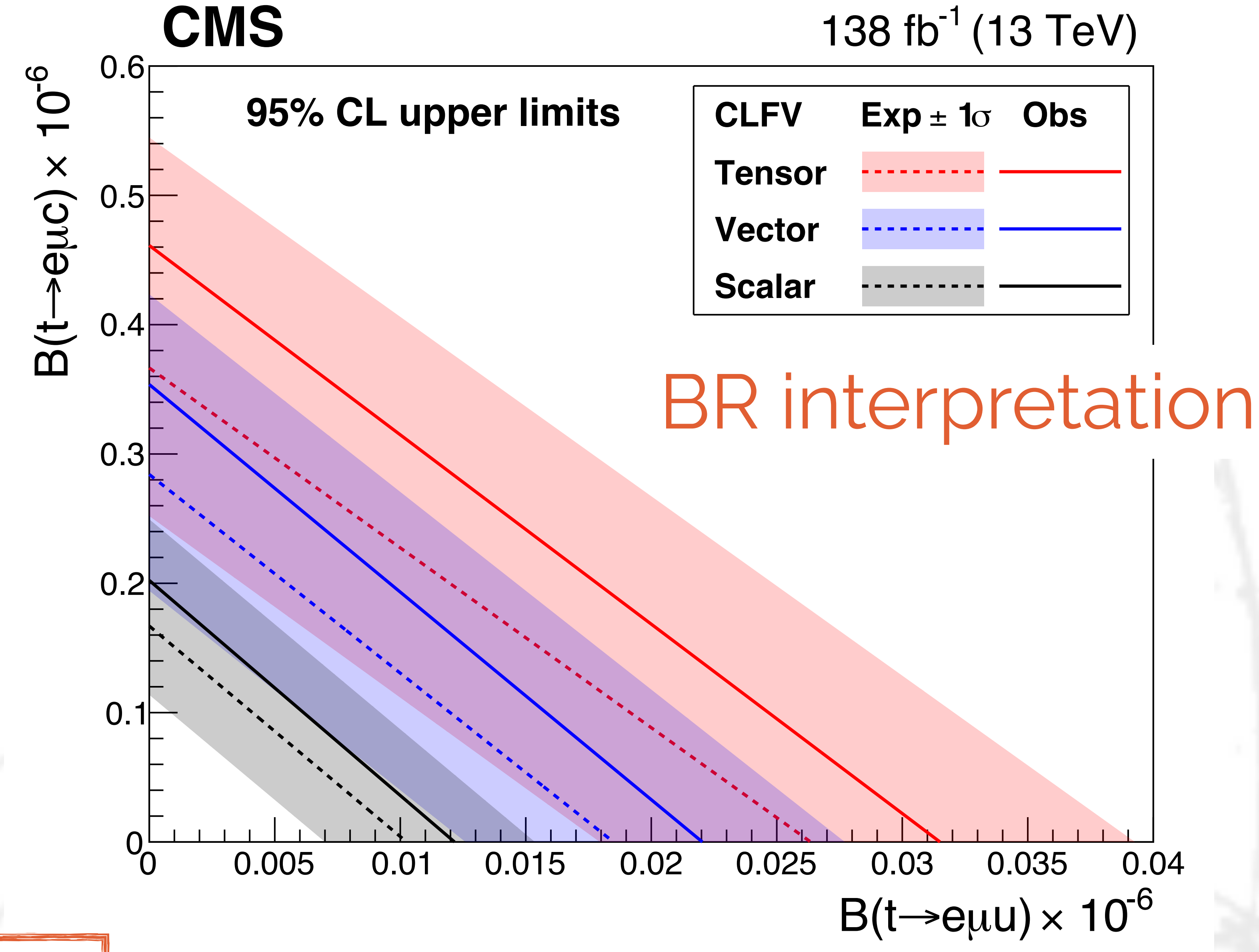


- Search in EFT context, probing several operators

- BDTs dedicated to production and decay signatures
- Limited by **nonprompt bkg. and jet radiation modelling**





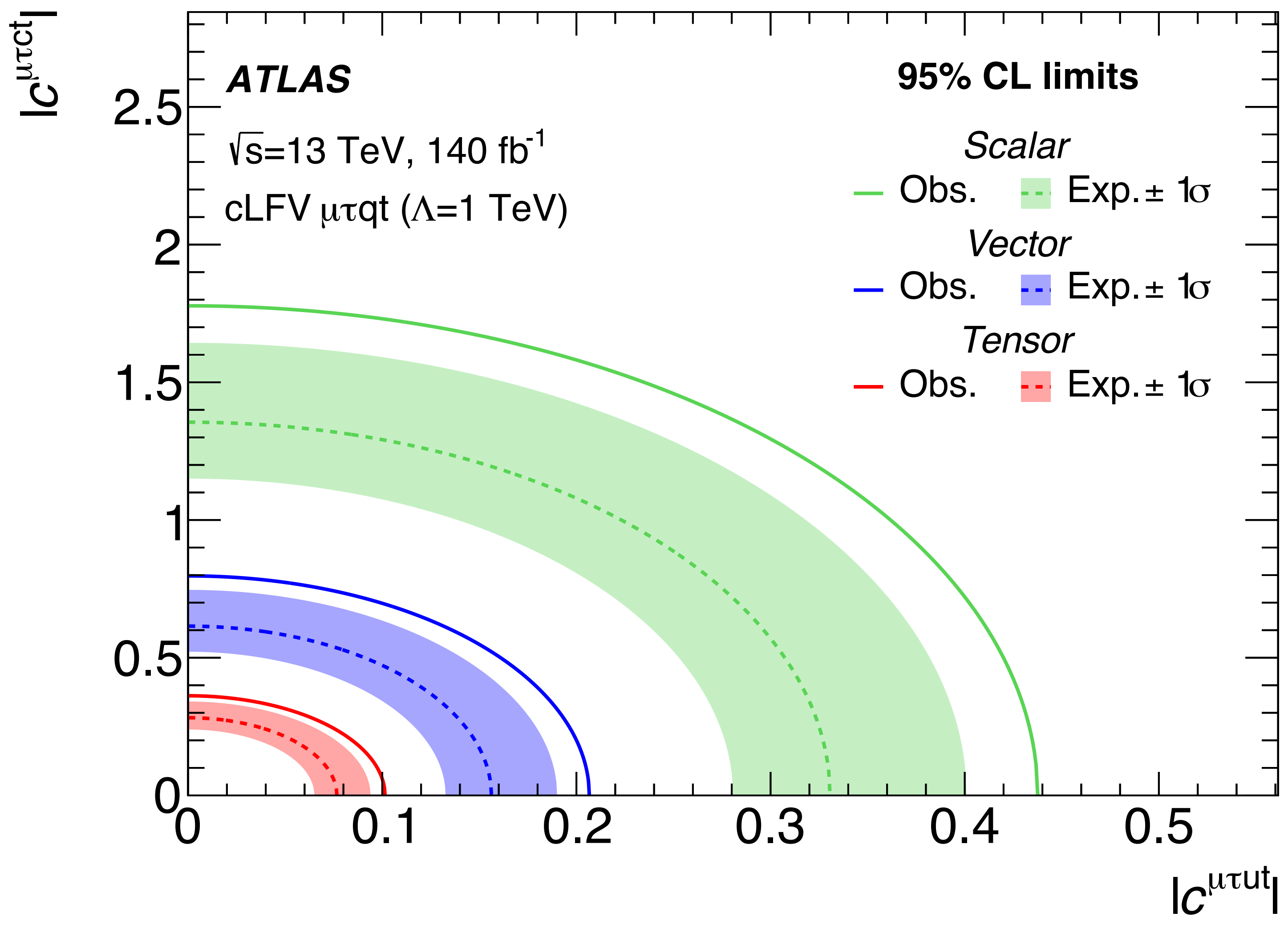


Most stringent to date, order of magnitude improvement!

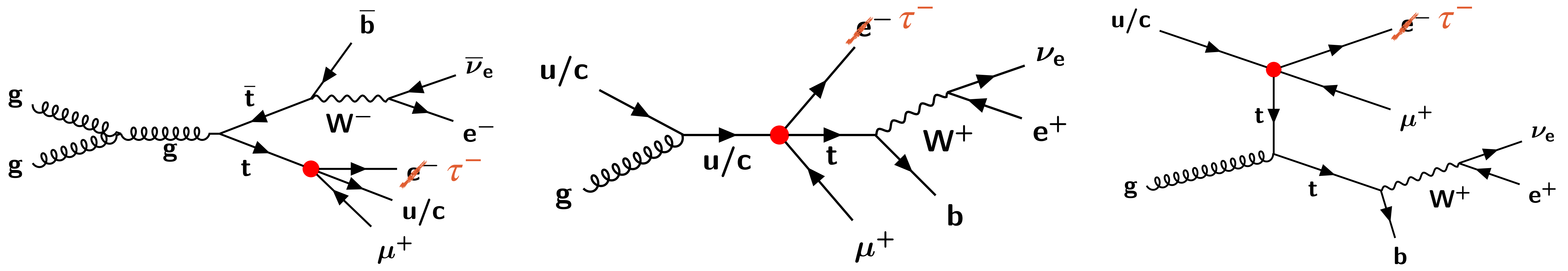
LFV in production and decay in ATLAS

NEW!

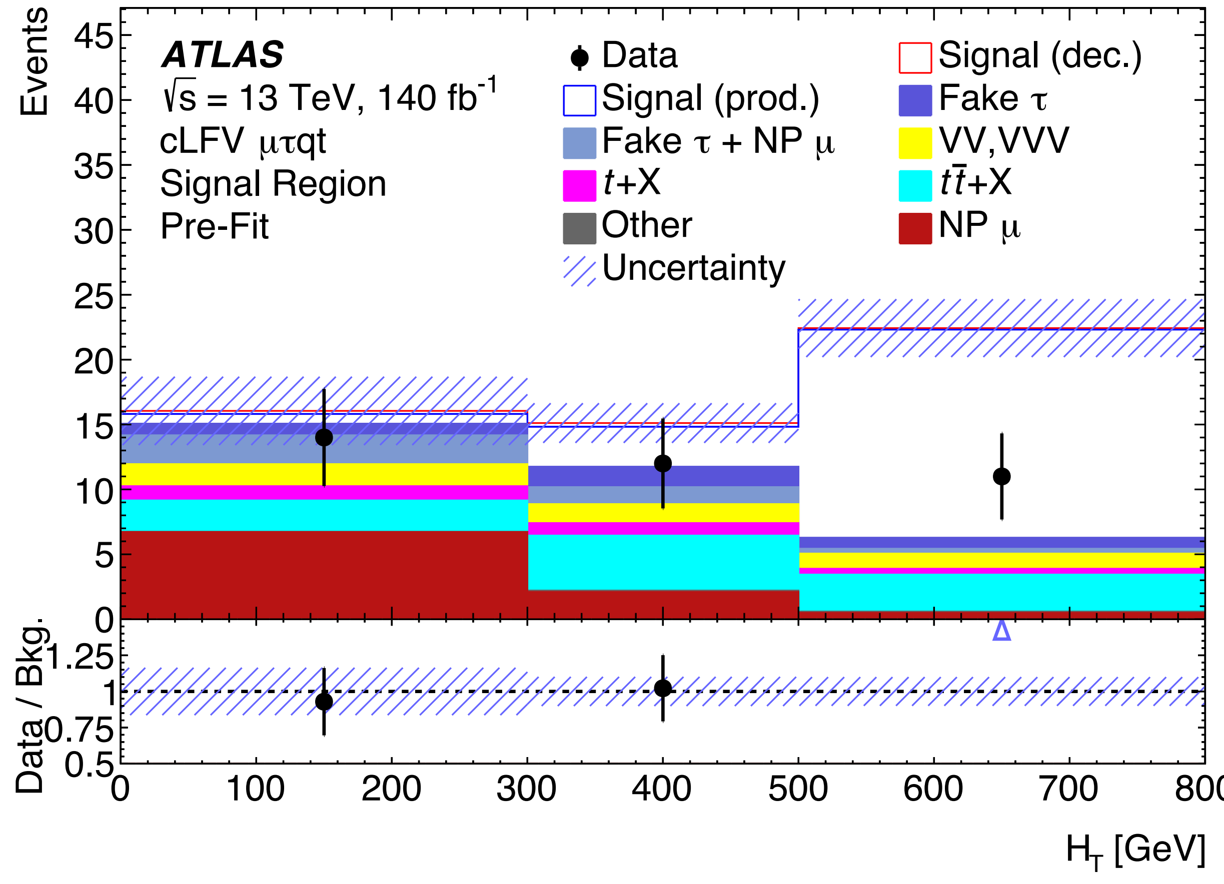
[arXiv:2403.06742] EFT interpretation

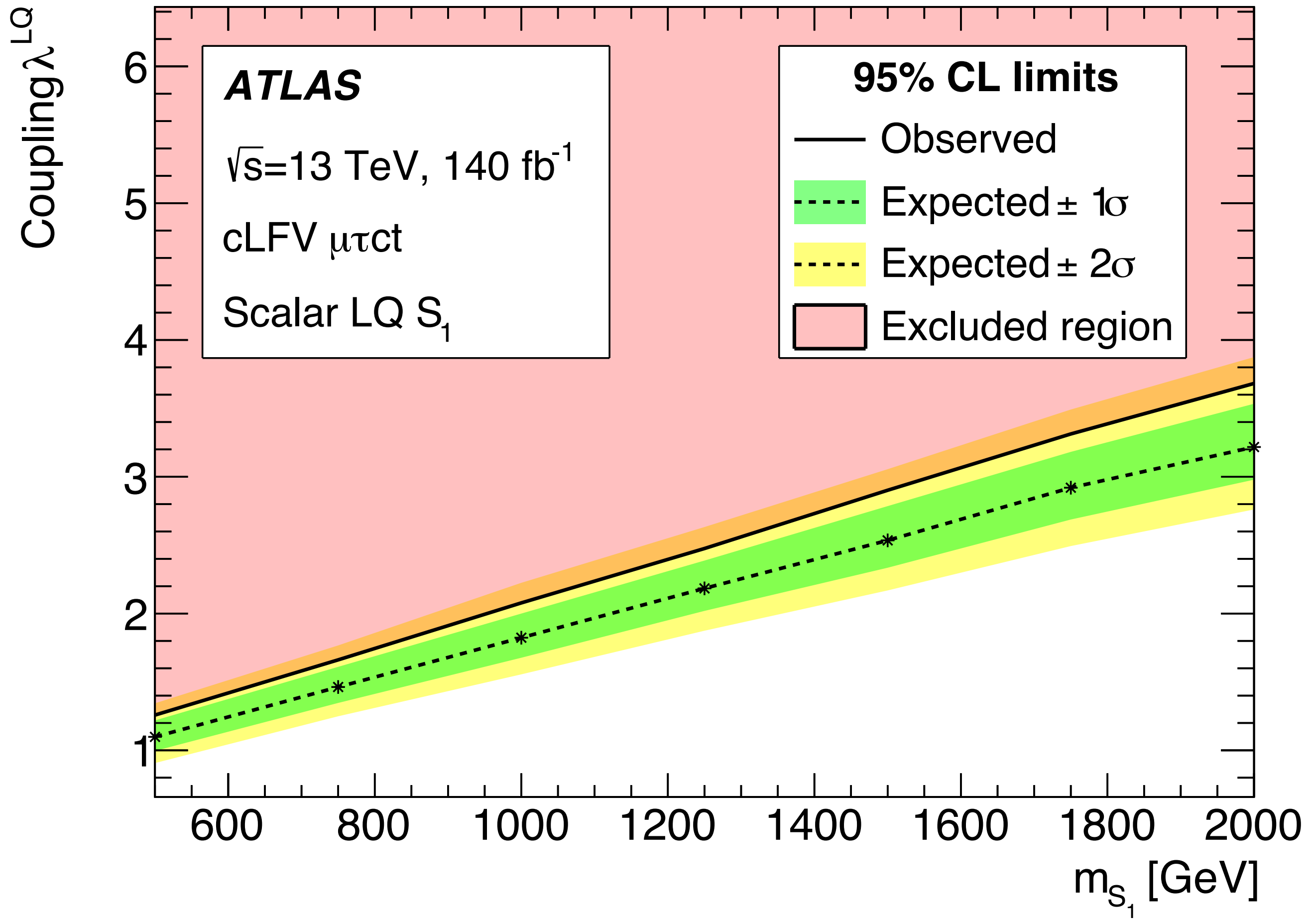


- Targeting same diagrams, but in (hadronic) tau & muon final state

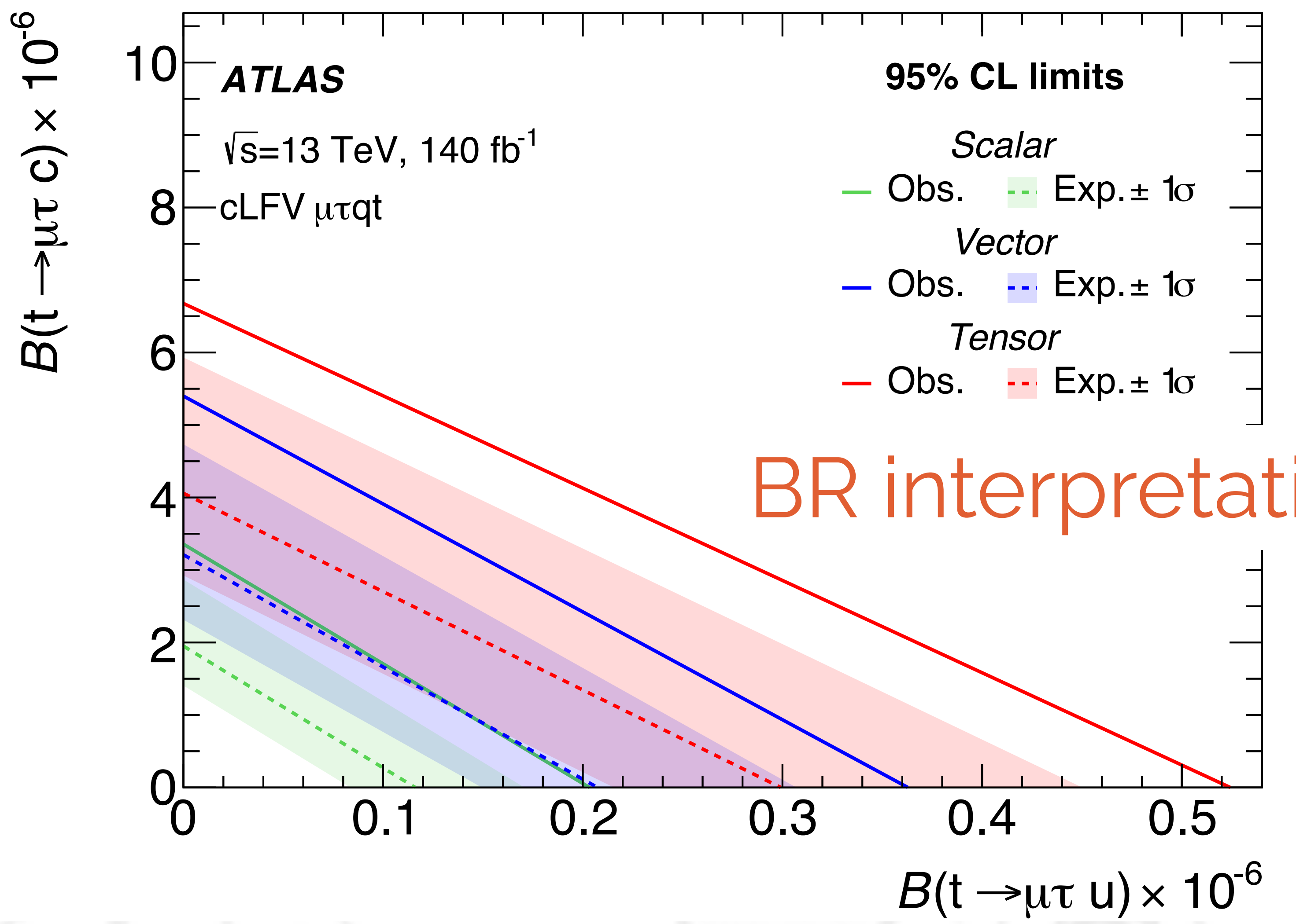


- First direct cLFV search with tau & muon final state
- **Limited by statistical uncertainty**
- Additional scalar leptoquark (S_1) interpretation:
  - Inter-generational couplings considered
  - λ^{LQ} steers SM—S_1 coupling





S_1 masses between 0.5-2 TeV excluded



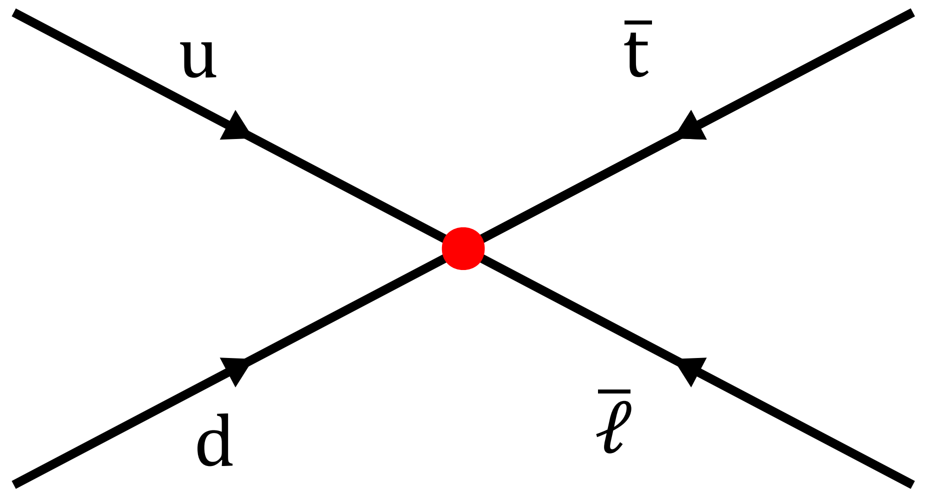
BR interpretation

Order of magnitude improvement!

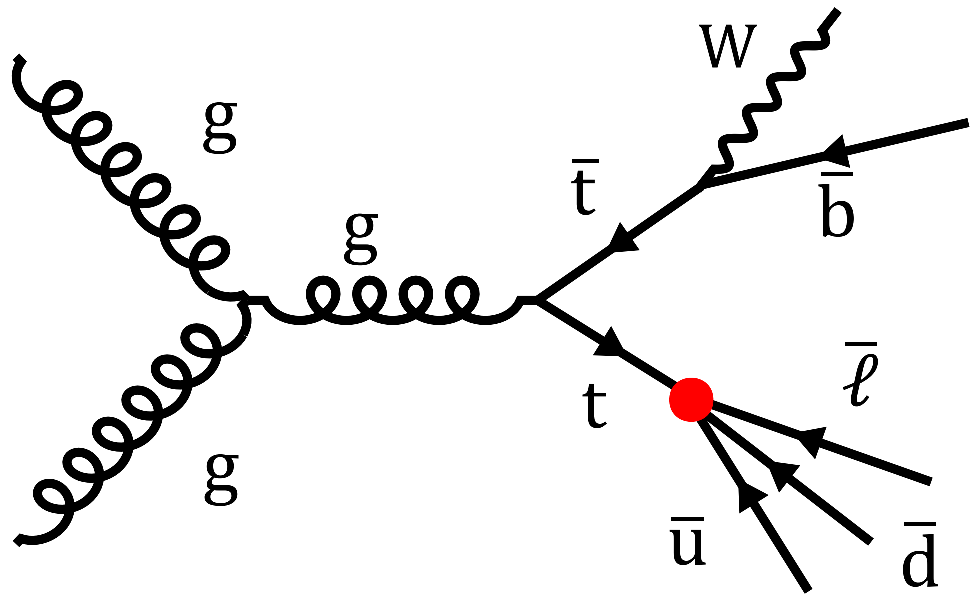
Search for baryon number violation (BNV) [arXiv:2402.18461]

NEW!

- Needed to explain matter-antimatter asymmetry, included in many BSM extensions
- **Model-independent search** for high-energy BNV in dilepton final states

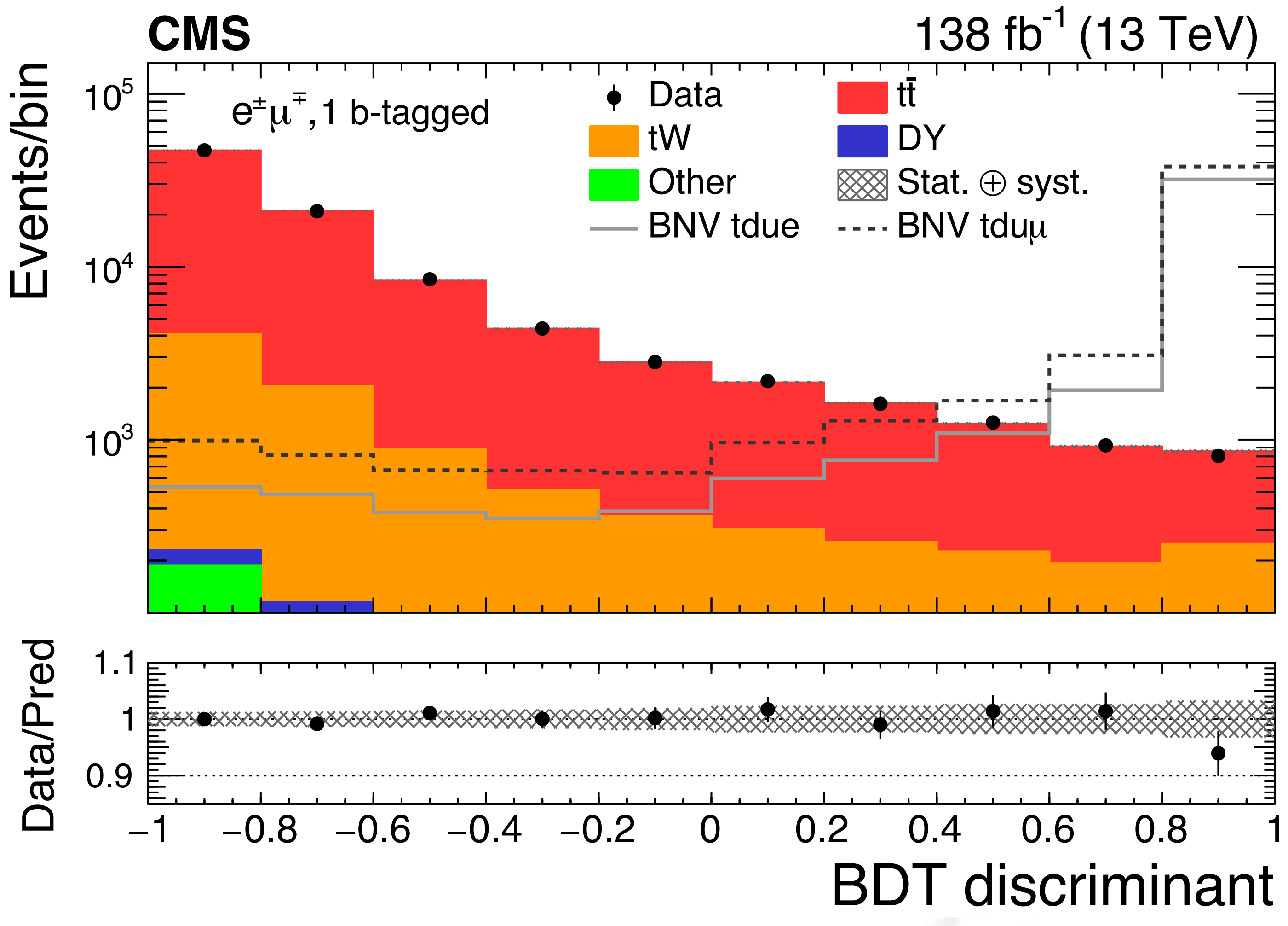


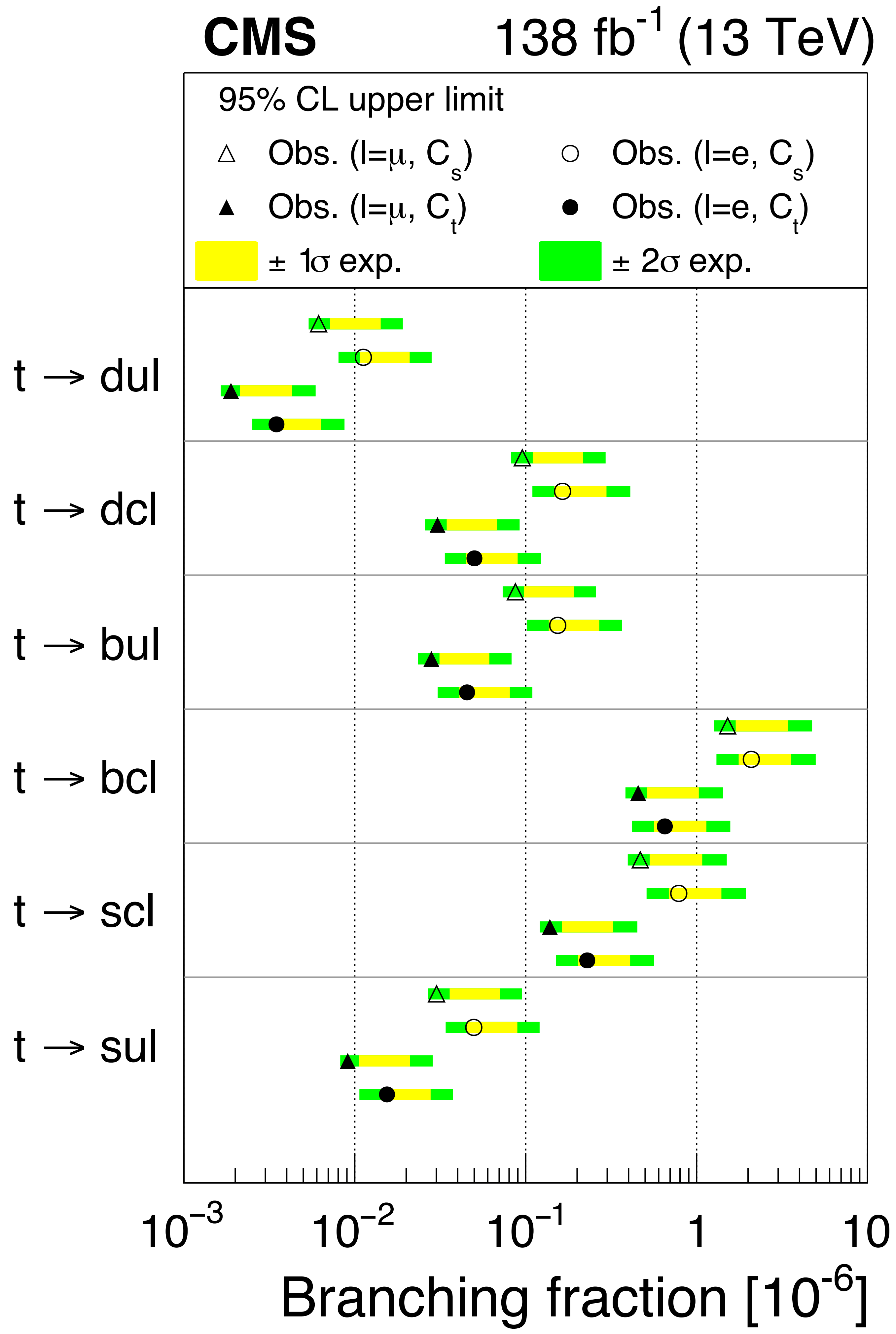
In single-top production,
for the first time



In tt̄ decay

- Combined BDT trained to enhance signal sensitivity
- Interpretation in EFT couplings for all lepton-quark combinations
- Limited by **background (tW/tt̄) modelling**

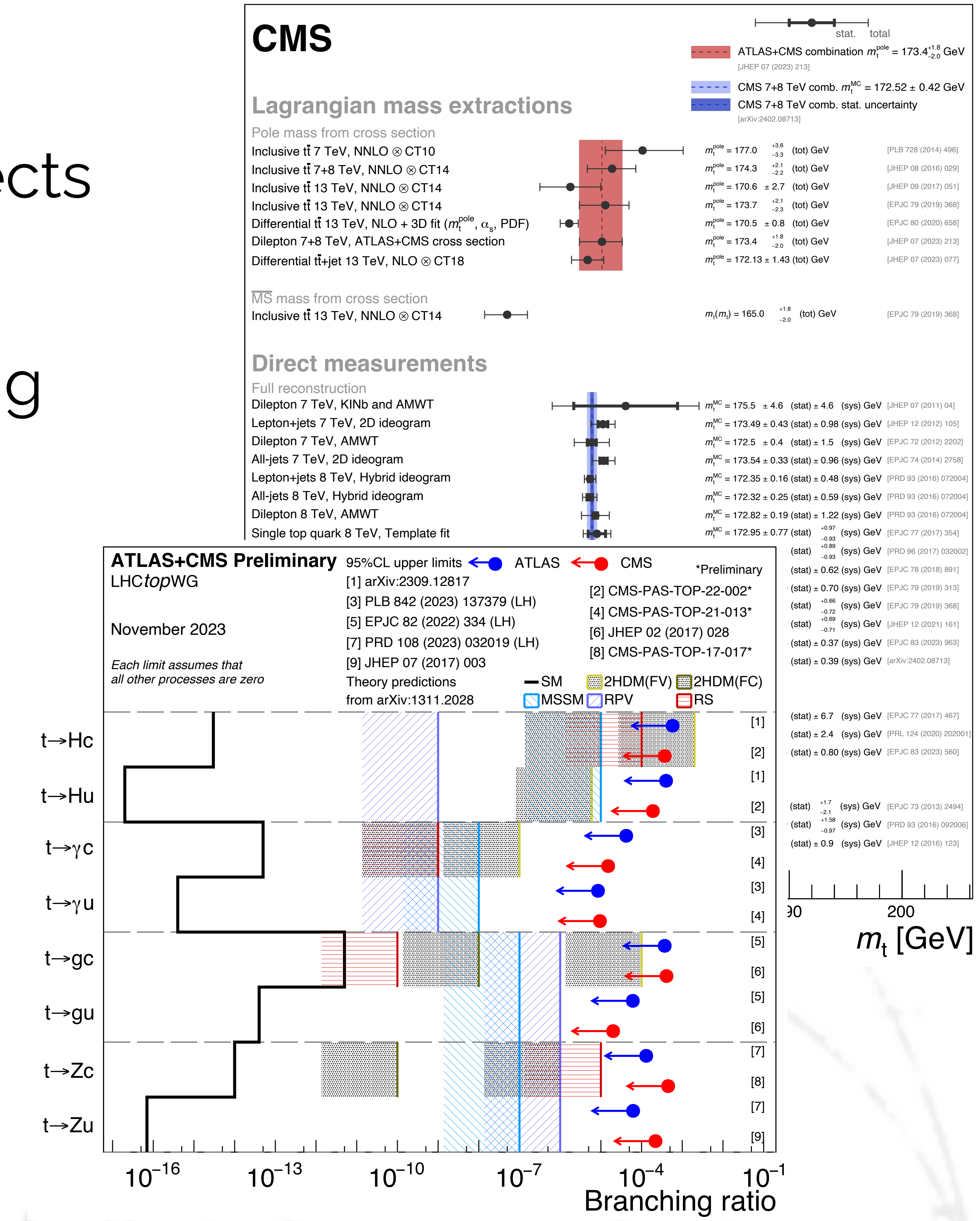




Order of magnitudes improvements for BR limits!

Summary

- Top quark is a key instrument to study standard model and look for BSM effects
- ATLAS and CMS have a many SM measurements and BSM searches involving top quarks:
  - Top quark mass combination / review (ATLAS+CMS)
  - Observation of quantum entanglement in $t\bar{t}$ (ATLAS)
  - Lepton flavour (ATLAS+CMS) and baryon number violation (CMS)
  - Updated results for FCNC searches involving Higgs bosons (ATLAS+CMS)
- Conclusions:
  - Combination of individual results are useful!
    - Top quark mass and FCNC searches
  - All results in good agreement with the SM & no new physics observed
  - Available LHC Run 3 data will give rise to more opportunities



Backup

Mass combination

ATLAS+CMS $\sqrt{s}$ = 7,8 TeV

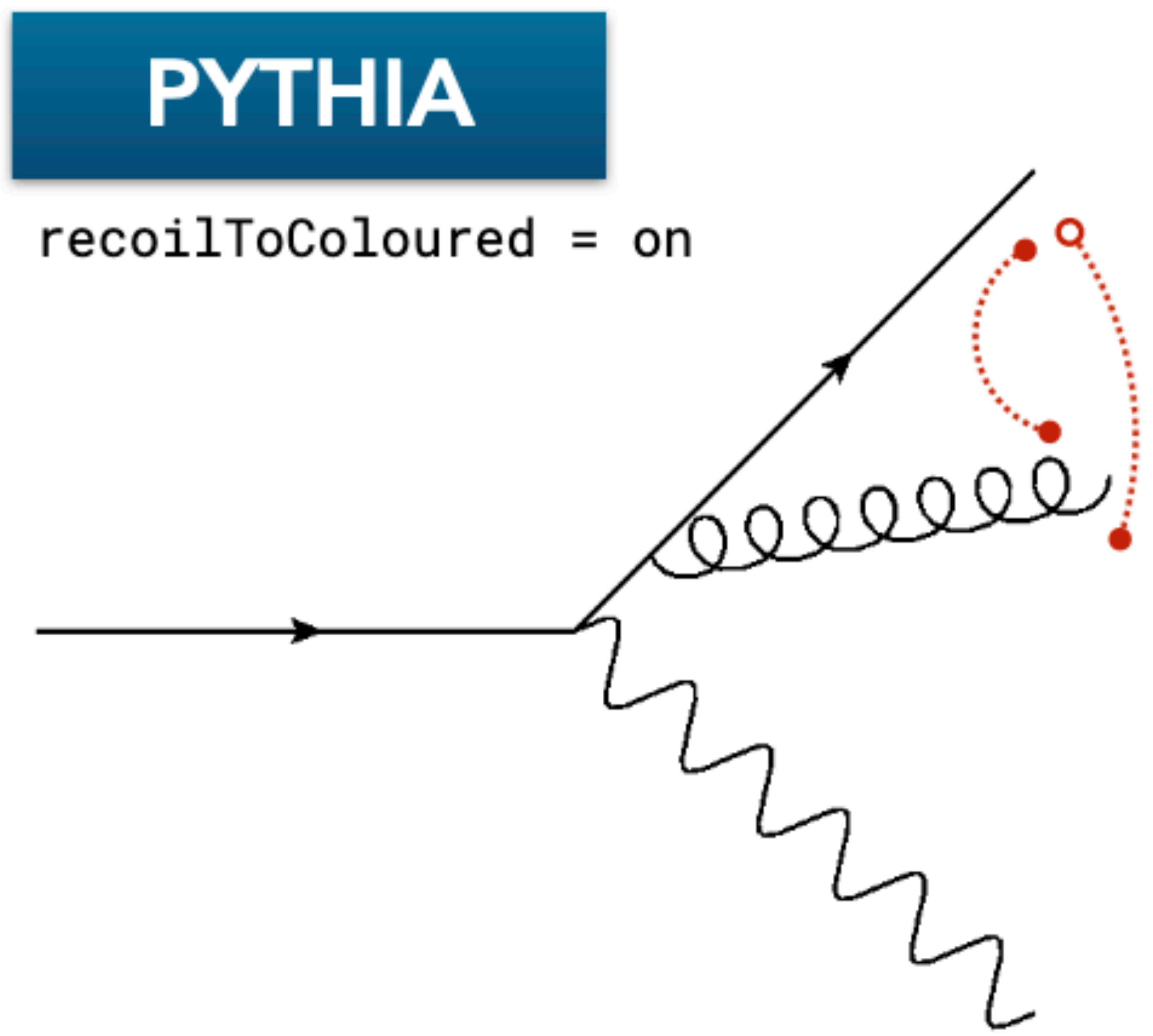
	ATLAS dil 7 TeV	ATLAS lj 7 TeV	ATLAS aj 7 TeV	ATLAS dil 8 TeV	ATLAS lj 8 TeV	ATLAS aj 8 TeV	CMS dil 7 TeV	CMS lj 7 TeV	CMS aj 7 TeV	CMS dil 8 TeV	CMS lj 8 TeV	CMS aj 8 TeV	CMS t 8 TeV	CMS J/Ψ 8 TeV	CMS vtx 8 TeV
ATLAS dil 7 TeV	1.00	-0.07	0.42	0.51	0.06	0.07	0.13	0.22	0.11	0.18	0.23	0.13	0.10	-0.06	-0.15
ATLAS lj 7 TeV	-0.07	1.00	-0.01	0.00	-0.07	-0.02	0.09	0.08	0.03	0.08	0.04	0.01	0.10	0.02	-0.04
ATLAS aj 7 TeV	0.42	-0.01	1.00	0.29	-0.06	0.00	0.11	0.19	0.11	0.13	0.21	0.16	0.09	-0.01	-0.04
ATLAS dil 8 TeV	0.51	0.00	0.29	1.00	-0.18	0.31	0.09	0.16	0.08	0.12	0.16	0.10	0.07	-0.04	-0.10
ATLAS lj 8 TeV	0.06	-0.07	-0.06	-0.18	1.00	-0.03	0.02	-0.00	-0.00	-0.04	0.05	-0.03	0.03	-0.01	0.00
ATLAS aj 8 TeV	0.07	-0.02	0.00	0.31	-0.03	1.00	0.10	0.11	0.06	-0.01	0.14	0.08	0.07	0.01	0.10
CMS dil 7 TeV	0.13	0.09	0.11	0.09	0.02	0.10	1.00	0.31	0.57	0.31	0.46	0.36	0.26	0.08	0.13
CMS lj 7 TeV	0.22	0.08	0.19	0.16	-0.00	0.11	0.31	1.00	0.53	0.10	0.41	0.45	0.29	-0.03	0.03
CMS aj 7 TeV	0.11	0.03	0.11	0.08	-0.00	0.06	0.57	0.53	1.00	0.12	0.34	0.35	0.21	-0.03	0.07
CMS dil 8 TeV	0.18	0.08	0.13	0.12	-0.04	-0.01	0.31	0.10	0.12	1.00	0.23	0.07	0.09	-0.04	-0.16
CMS lj 8 TeV	0.23	0.04	0.21	0.16	0.05	0.14	0.46	0.41	0.34	0.23	1.00	0.70	0.48	0.06	0.15
CMS aj 8 TeV	0.13	0.01	0.16	0.10	-0.03	0.08	0.36	0.45	0.35	0.07	0.70	1.00	0.47	0.05	0.22
CMS t 8 TeV	0.10	0.10	0.09	0.07	0.03	0.07	0.26	0.29	0.21	0.09	0.48	0.47	1.00	-0.01	0.08
CMS J/Ψ 8 TeV	-0.06	0.02	-0.01	-0.04	-0.01	0.01	0.08	-0.03	-0.03	-0.04	0.06	0.05	-0.01	1.00	0.12
CMS vtx 8 TeV	-0.15	-0.04	-0.04	-0.10	0.00	0.10	0.13	0.03	0.07	-0.16	0.15	0.22	0.08	0.12	1.00

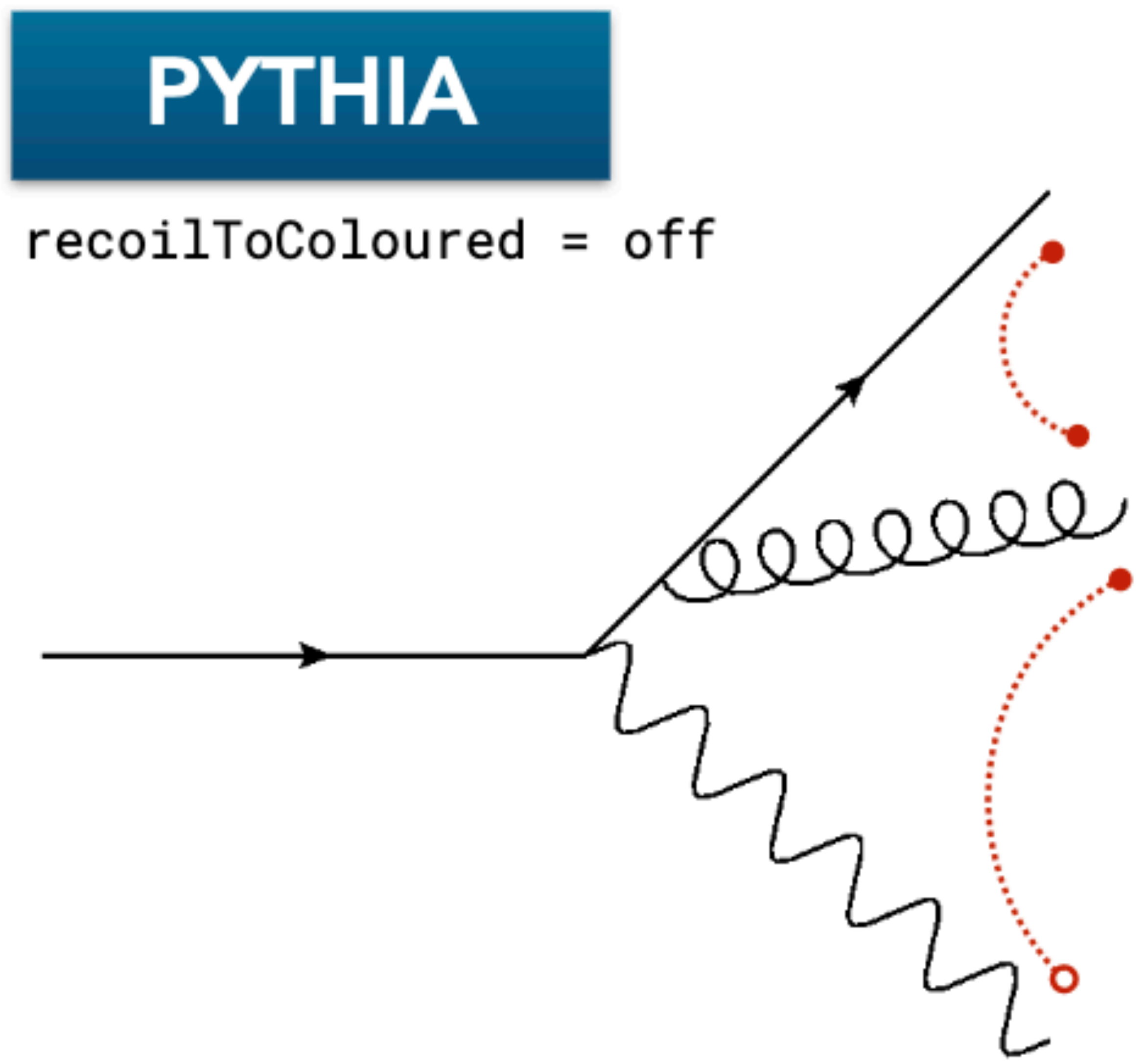
	ATLAS						CMS								
	2011 (7 TeV)			2012 (8 TeV)			2011 (7 TeV)			2012 (8 TeV)					
	dil	lj	aj	dil	lj	aj	dil	lj	aj	dil	lj	aj	t	J/ψ	vtx
Pull	+0.93	−0.15	+1.43	+0.61	−0.51	+1.09	−0.01	+0.96	+0.71	−0.33	−0.47	−0.37	+0.38	+0.31	+1.08
Weight	−0.02	+0.07	+0.00	+0.16	+0.17	+0.03	−0.08	−0.01	+0.03	+0.12	+0.34	+0.12	−0.03	+0.01	+0.08

Recoil for mass combination

- Improvement in understanding of modelling:
  - Off-shell effects
  - NNLO calculations
  - Top-quark radiation pattern and decay
    - Choice of recoiler in gluon radiation in top quark decay
    - Pythia specific setting

- Strongly correlated with b-JES
- Add. Uncertainty added on the order of 70% of b-JES
  - Change of 35 MeV in central value
  - 20 MeV in uncertainty





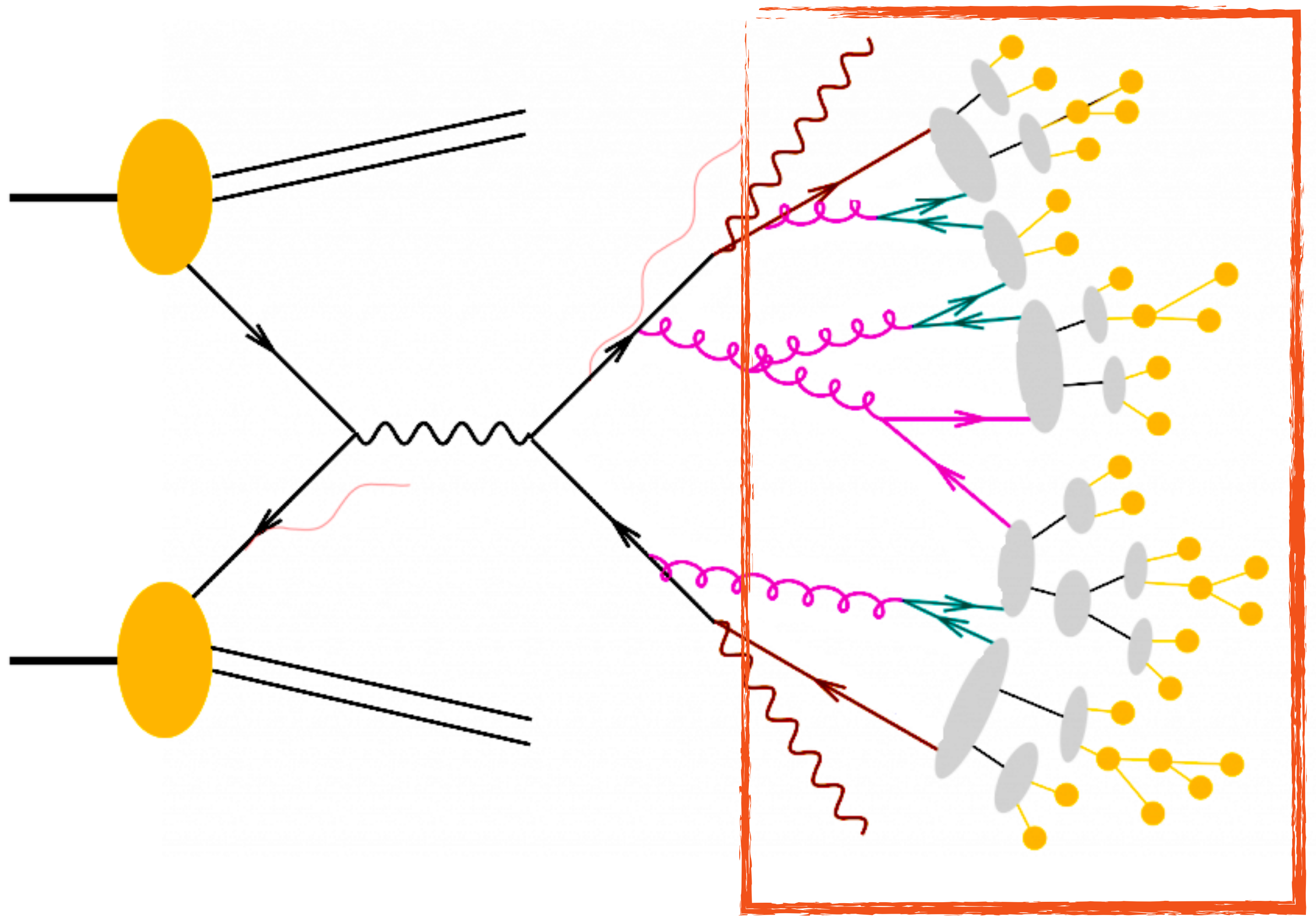
Measuring the top quark mass

Direct measurements

- Measuring m_t^{MC} using reconstructed decay products and Monte-Carlo templates
  - Very high experimental precision of ~**0.4 GeV**
  - Relies on details of simulation

Indirect measurements

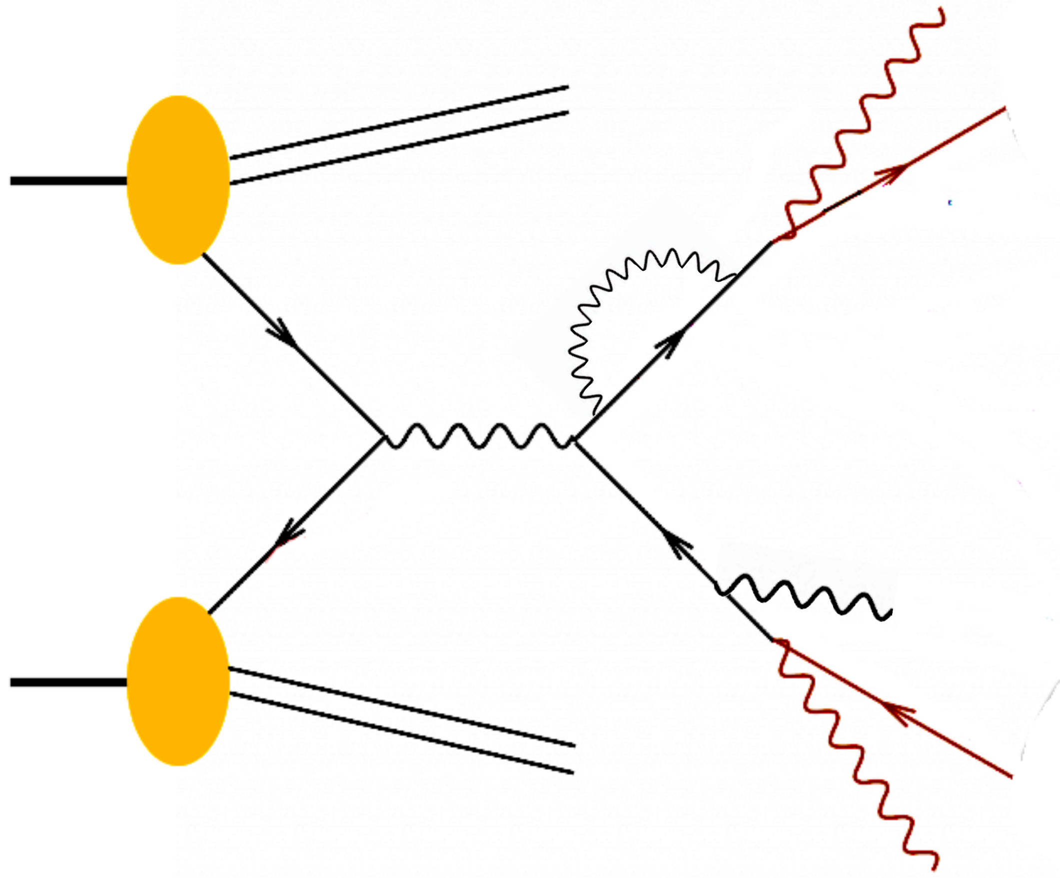
- Measuring observable with direct sensitivity to m_t
  - e.g. either inclusive or differential cross section
- Compare measured observable to fixed-order predictions



vs.

m_t^{MC} ⟷ m_t

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} \pm \Delta_{\mathrm{MC}} \; \mathcal{O}(1\,\mathrm{GeV})$$



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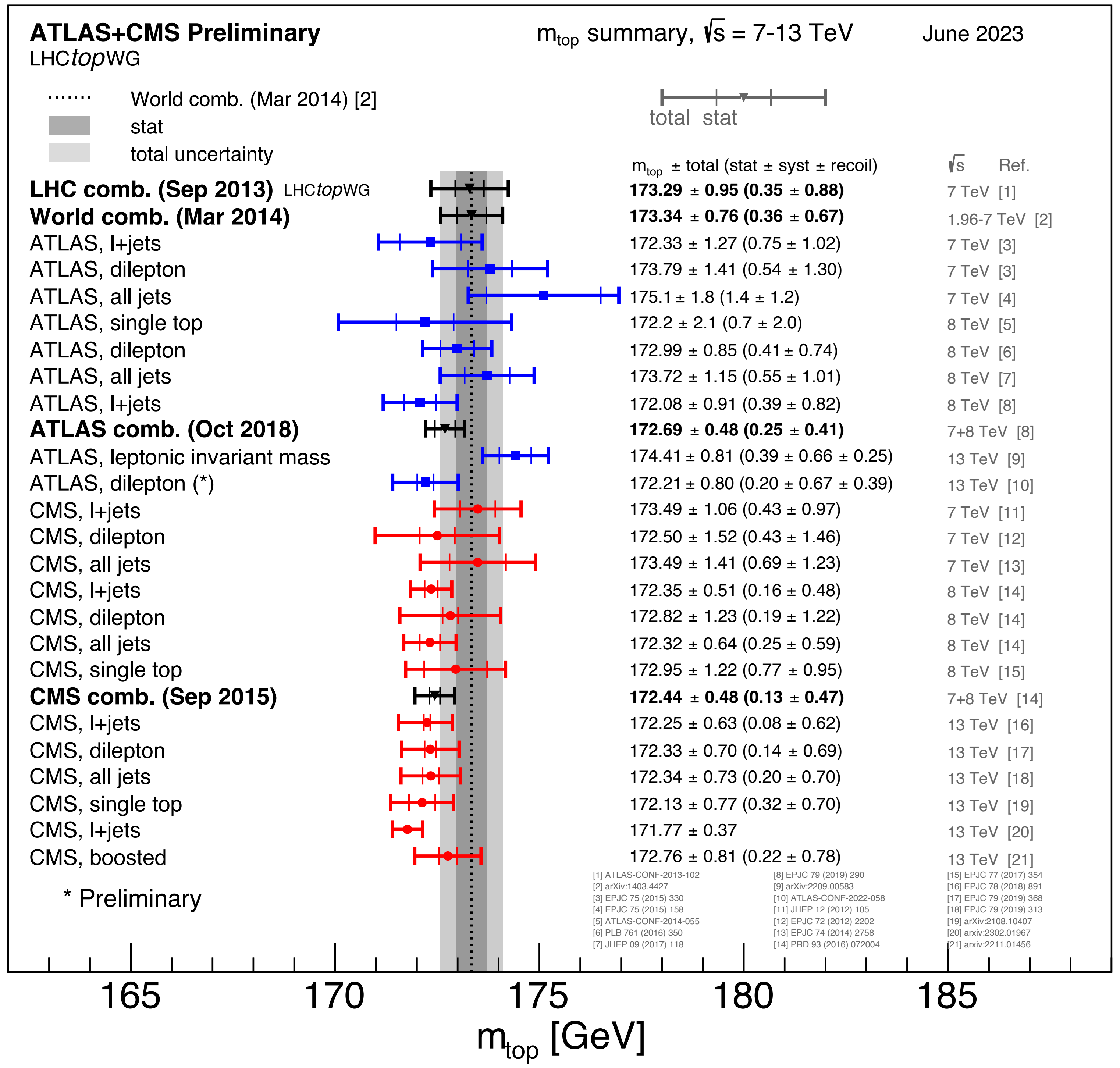

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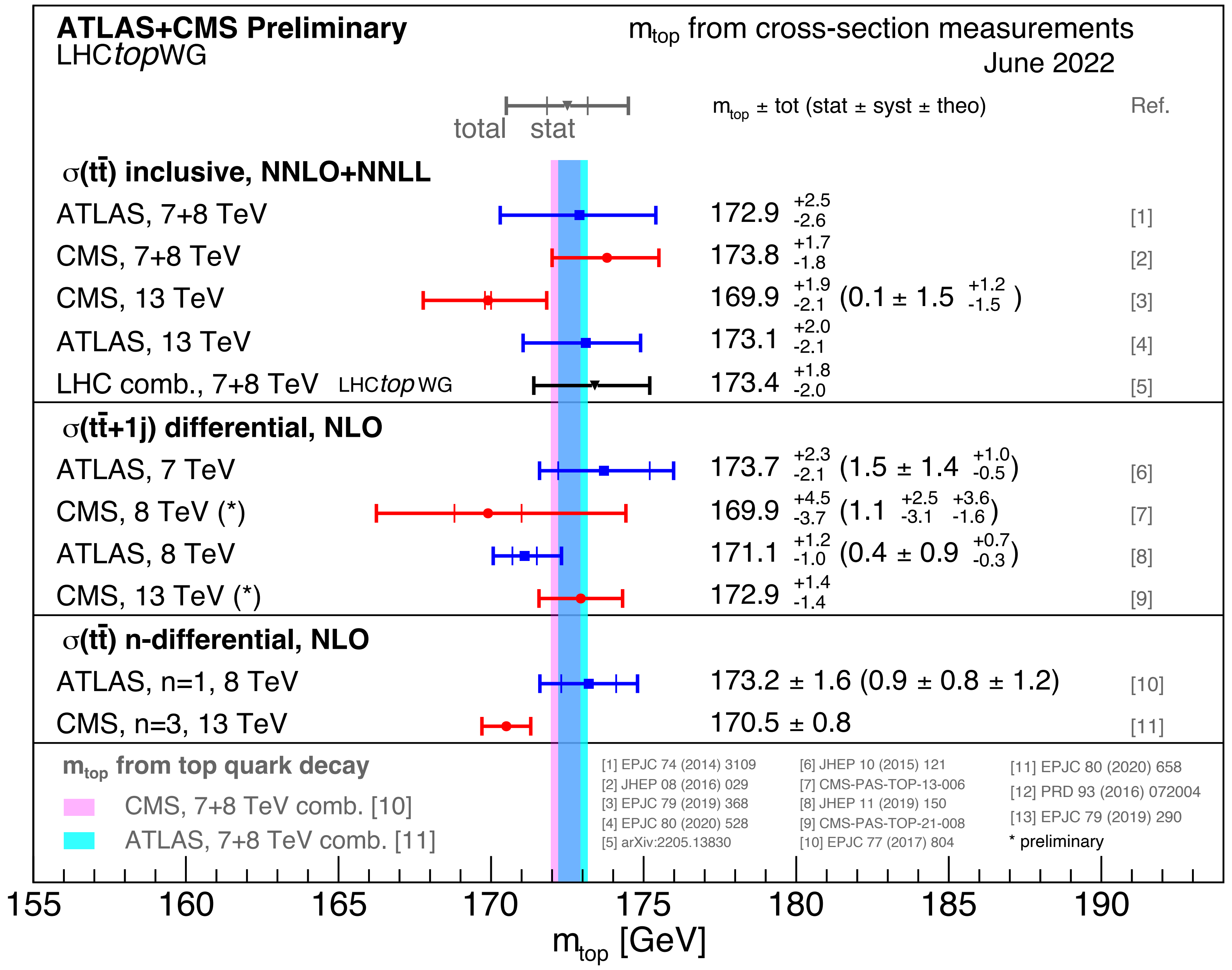
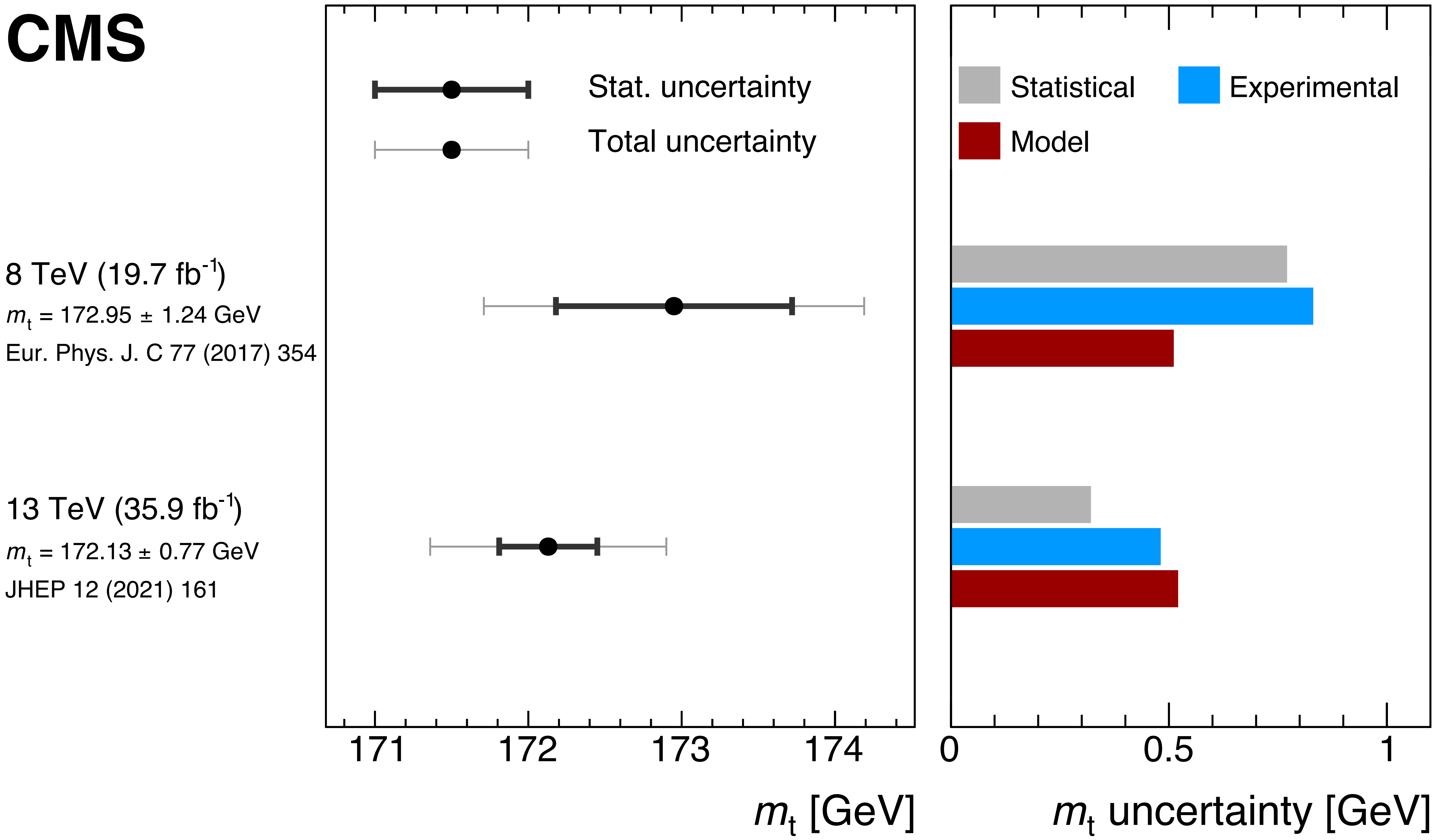


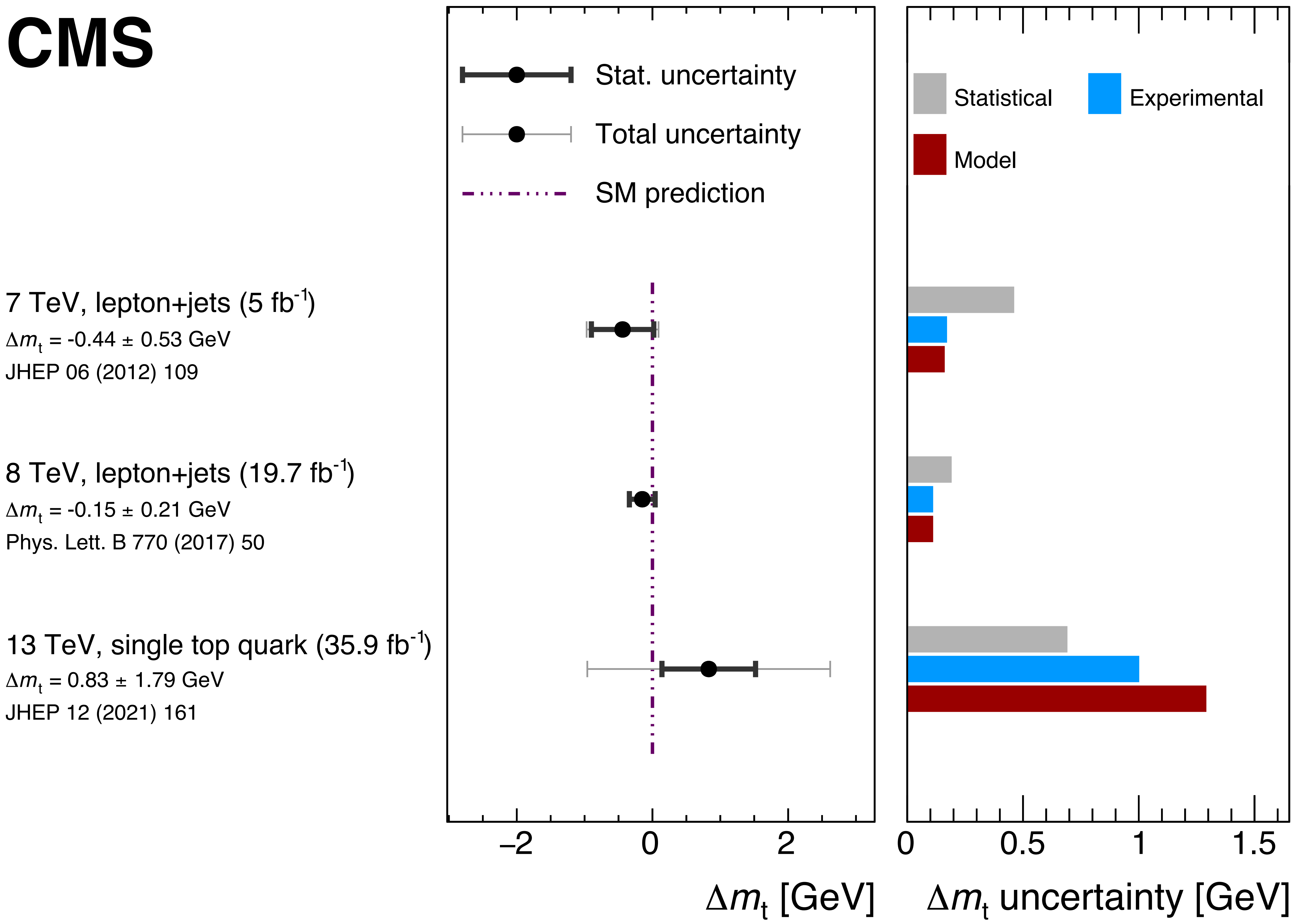
Need methods to extract well understood parameter with reasonable precision!

Mass review

Single top quark

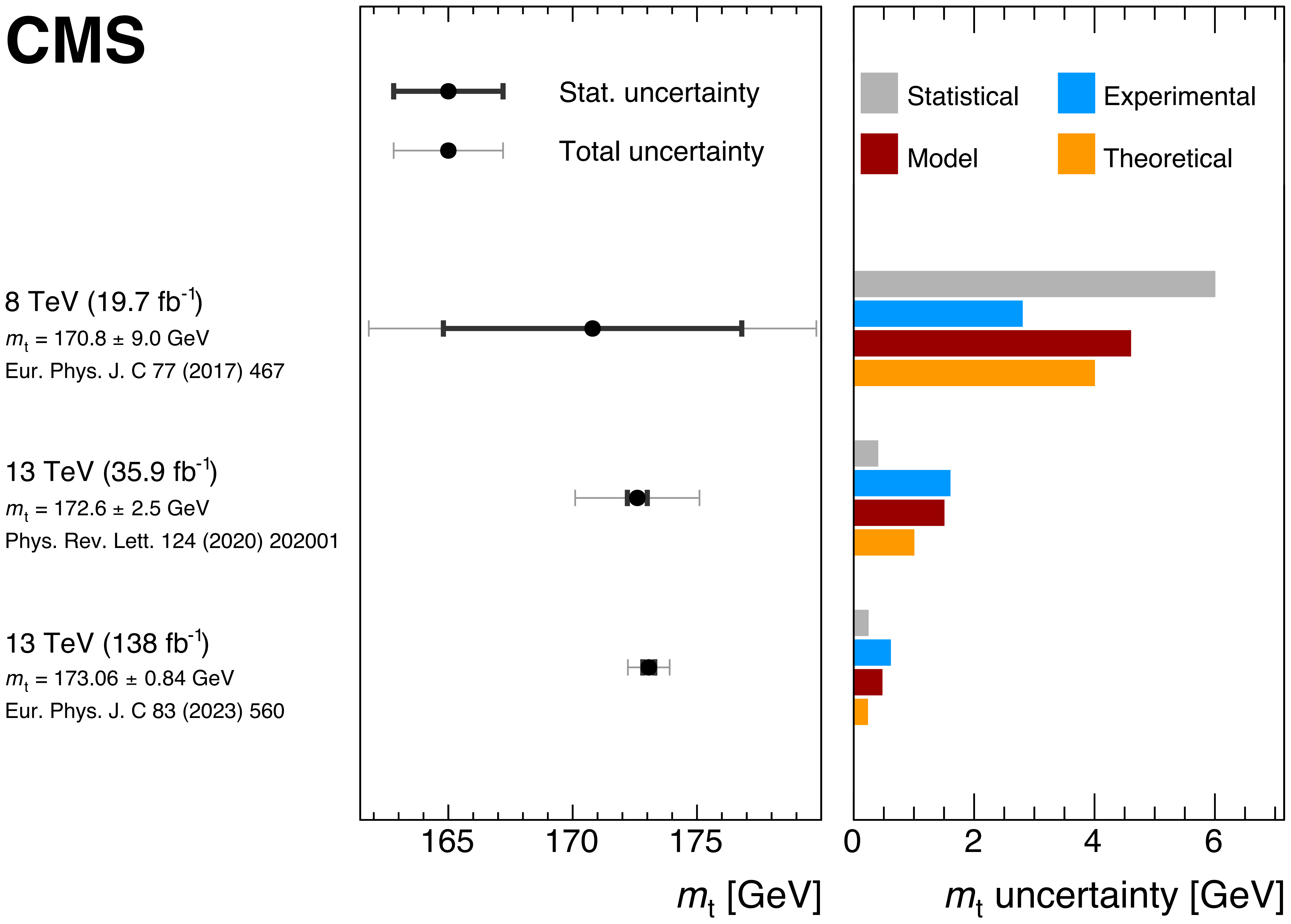


Mass difference

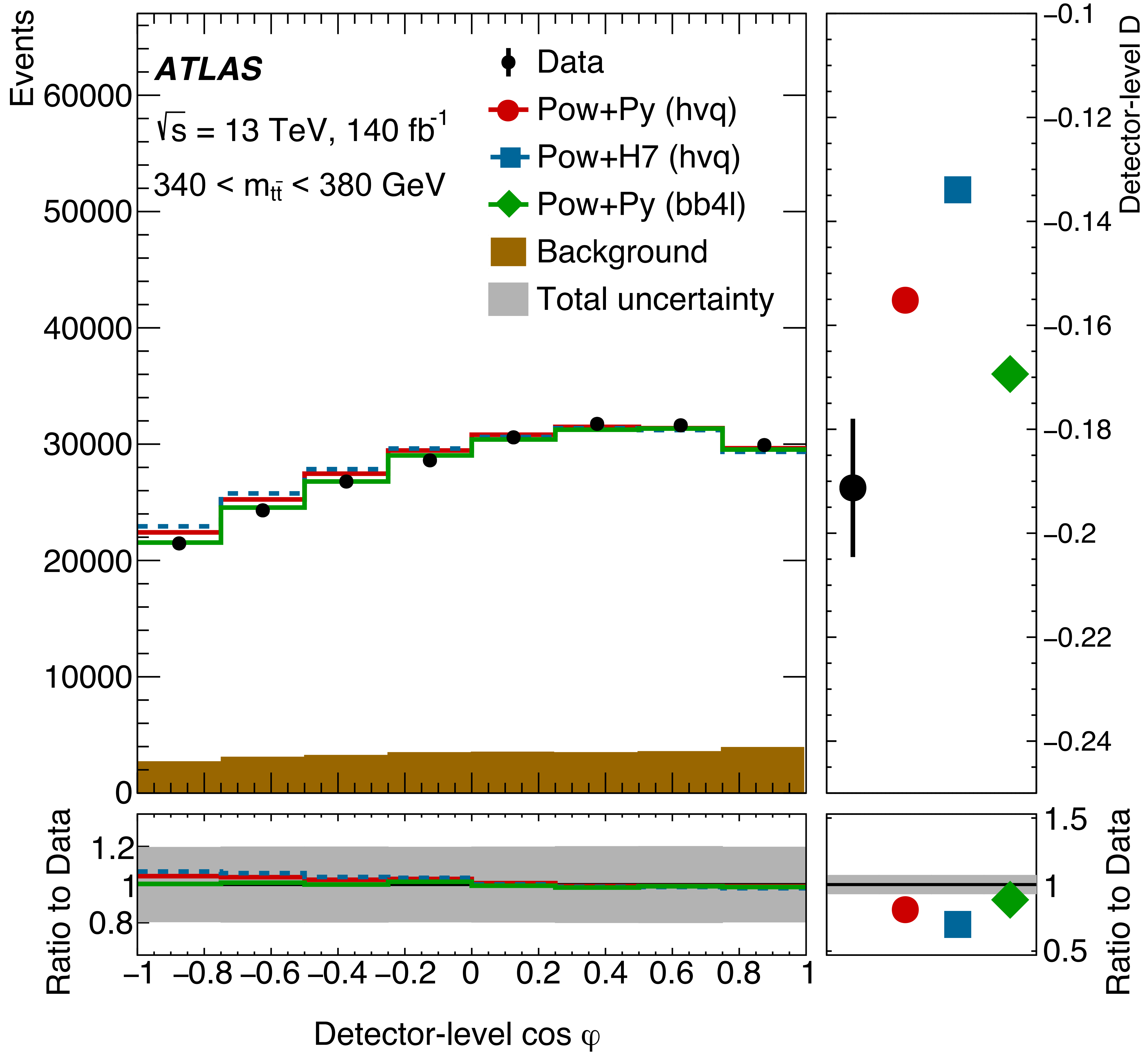


Mass review

Boosted jet mass



Entanglement

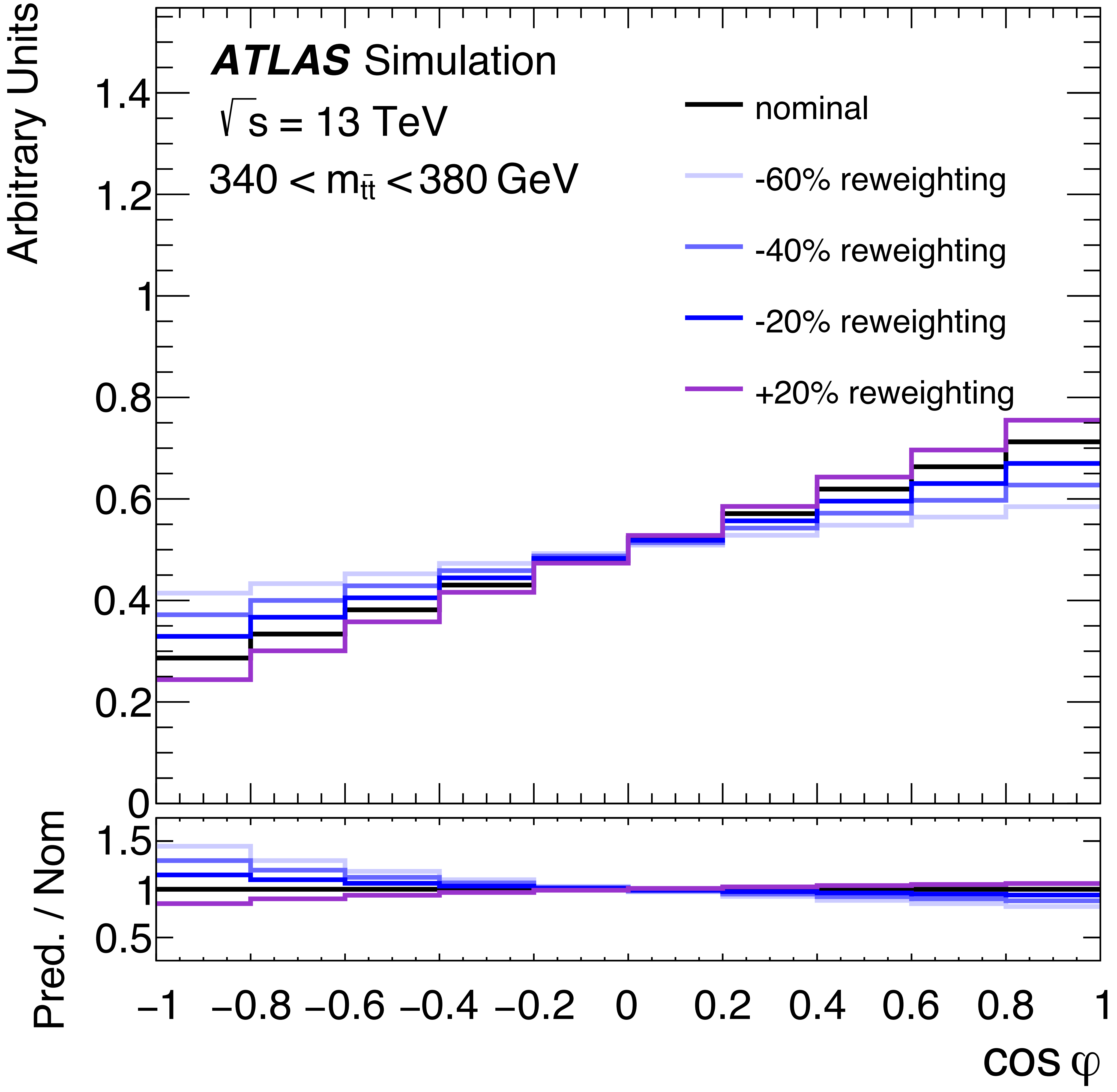


Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization	0.2%
h_{damp} setting	0.1%

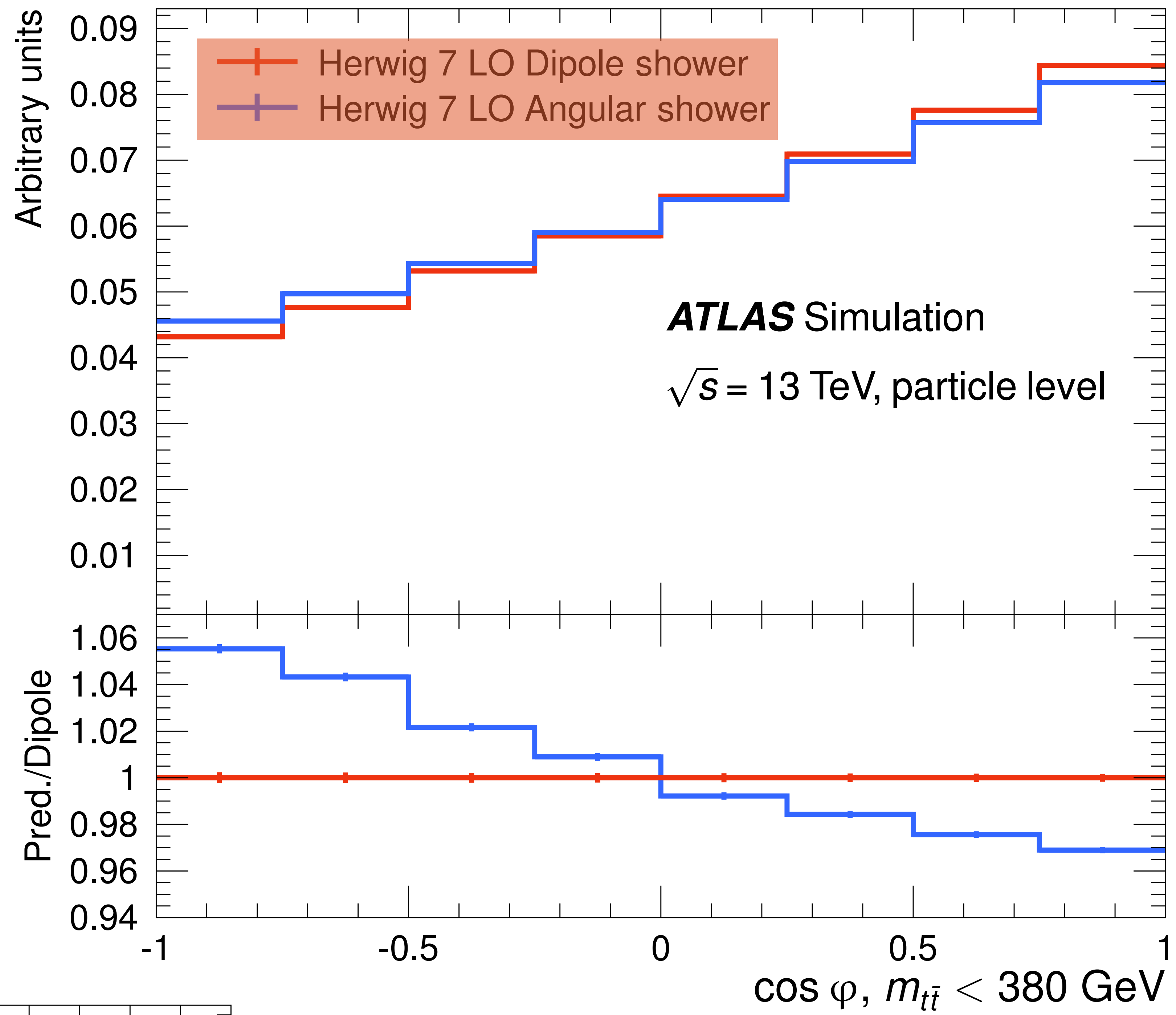
Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.547)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.1	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.3	0.002	0.4
Backgrounds	0.010	1.8	0.009	1.8
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.021	3.8	0.018	3.9
Total uncertainty	0.021	3.8	0.018	3.9

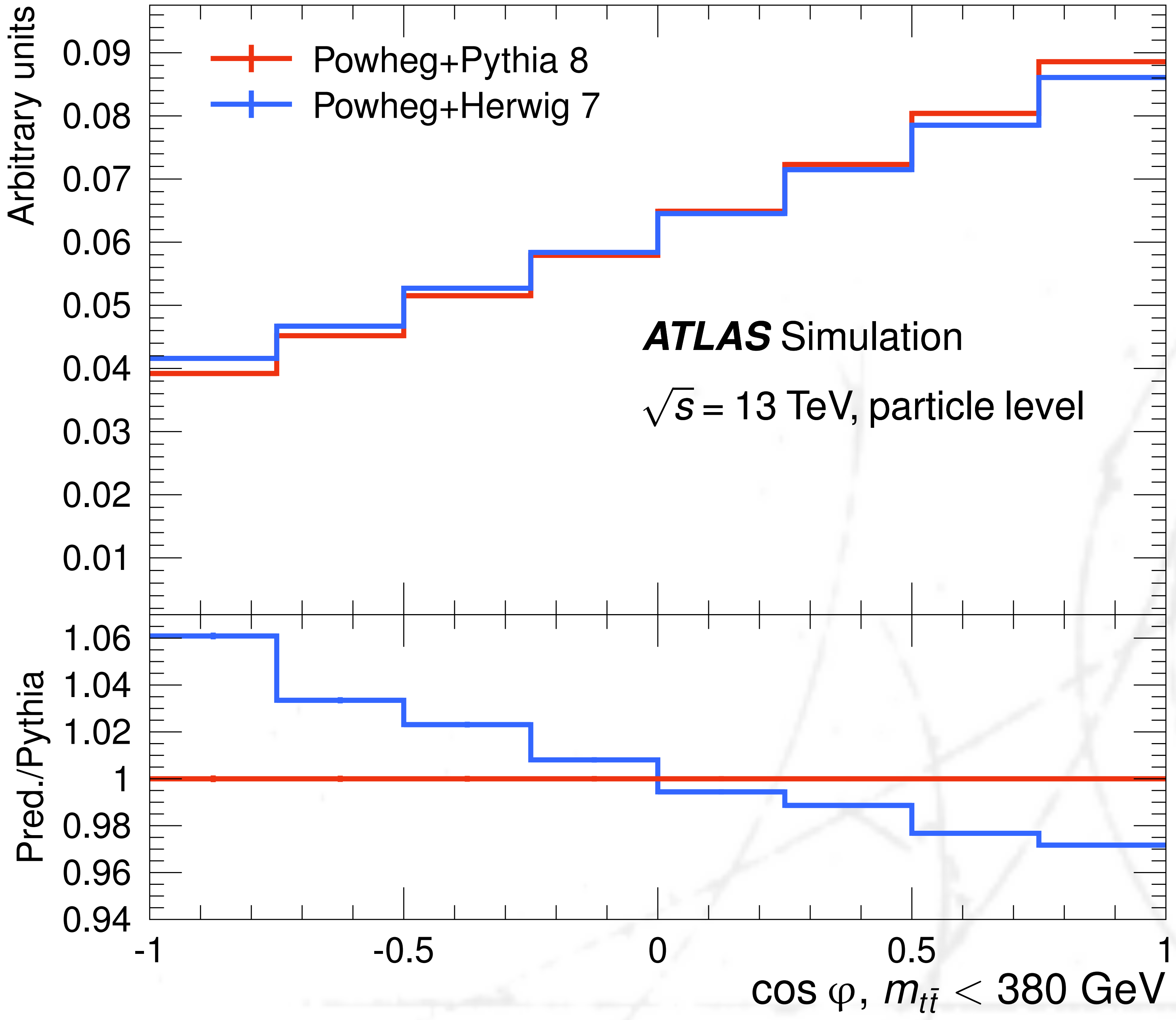
Entanglement

Parton-level weighting



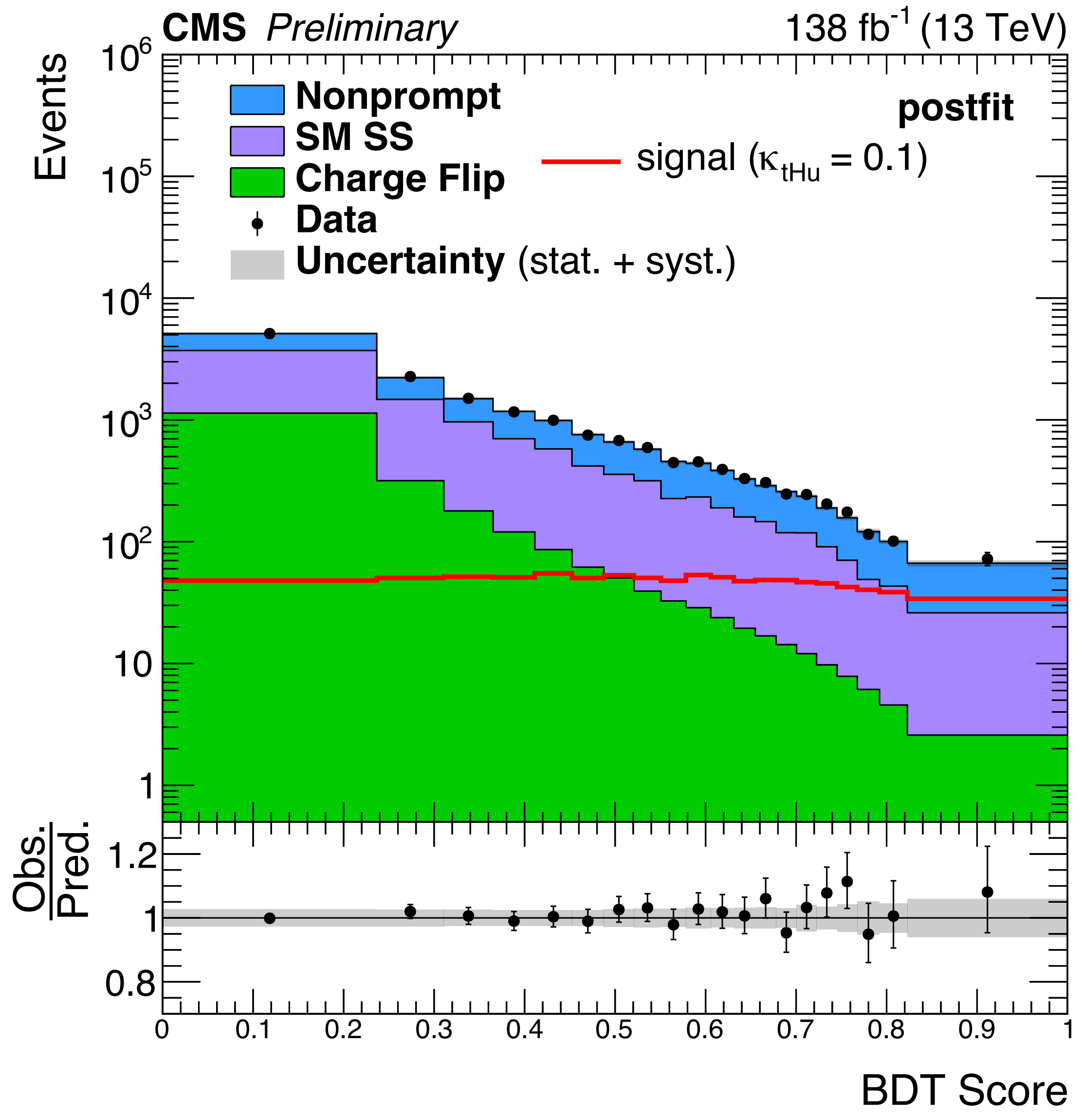
Parton to particle level effects

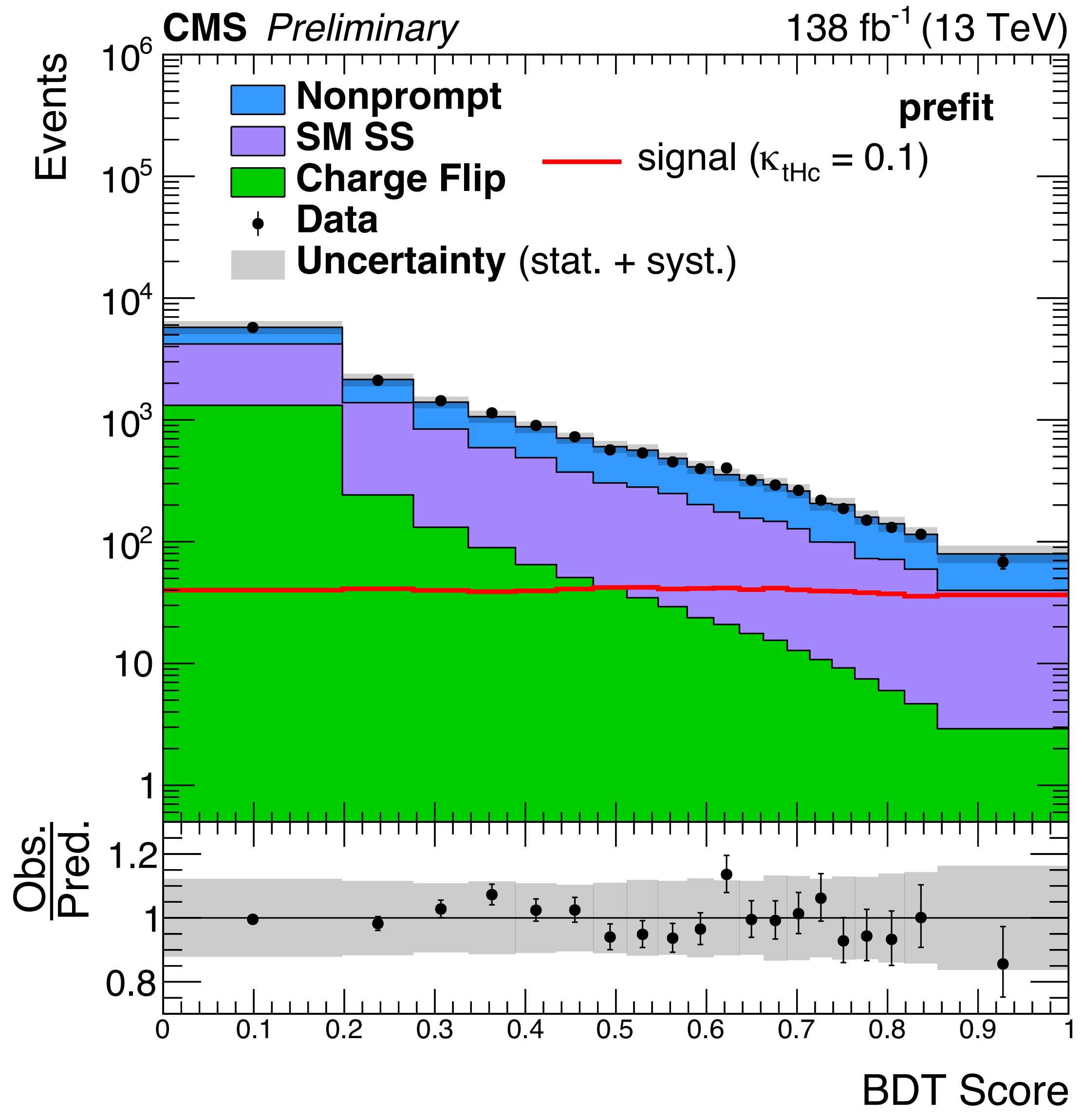


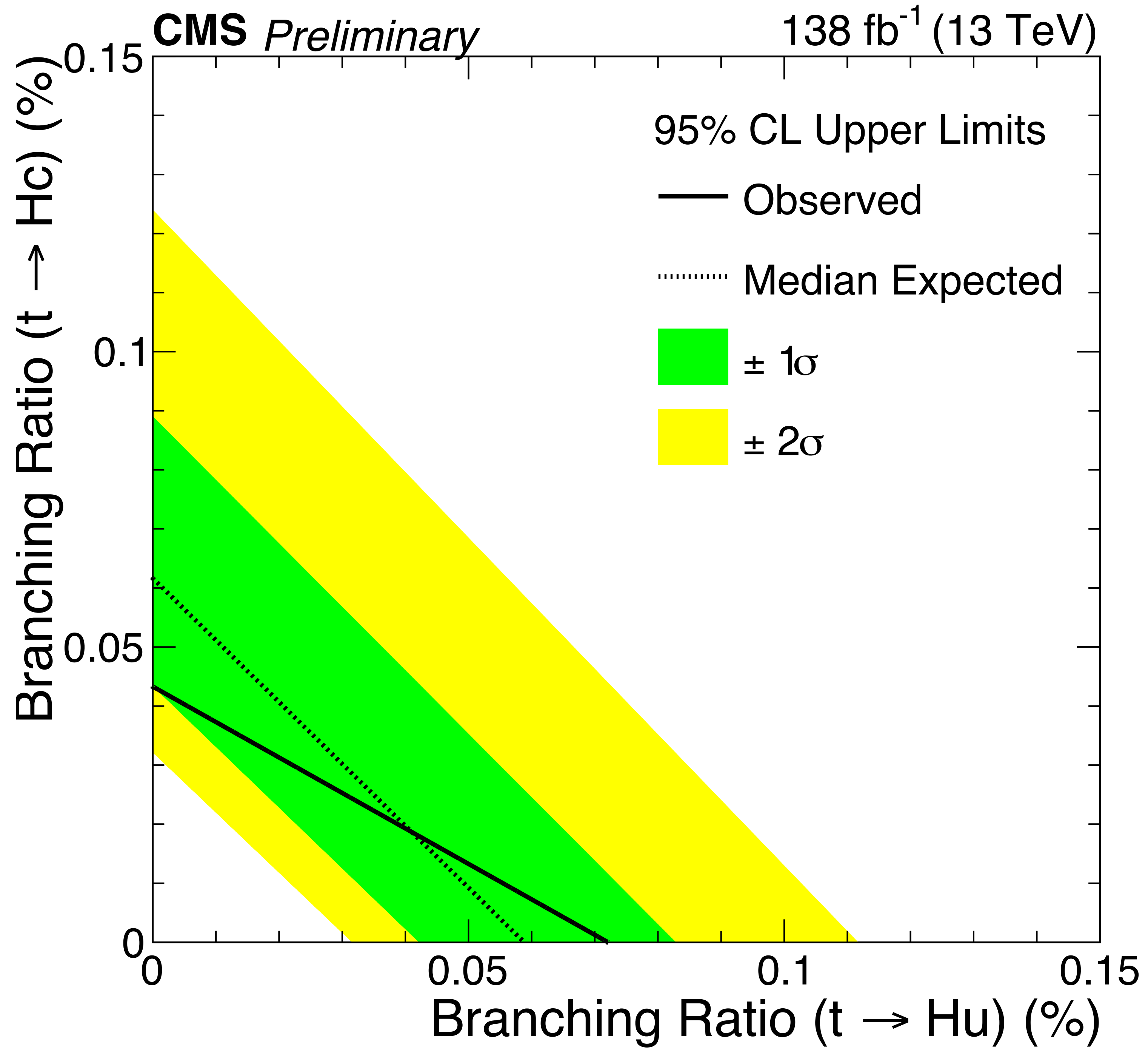


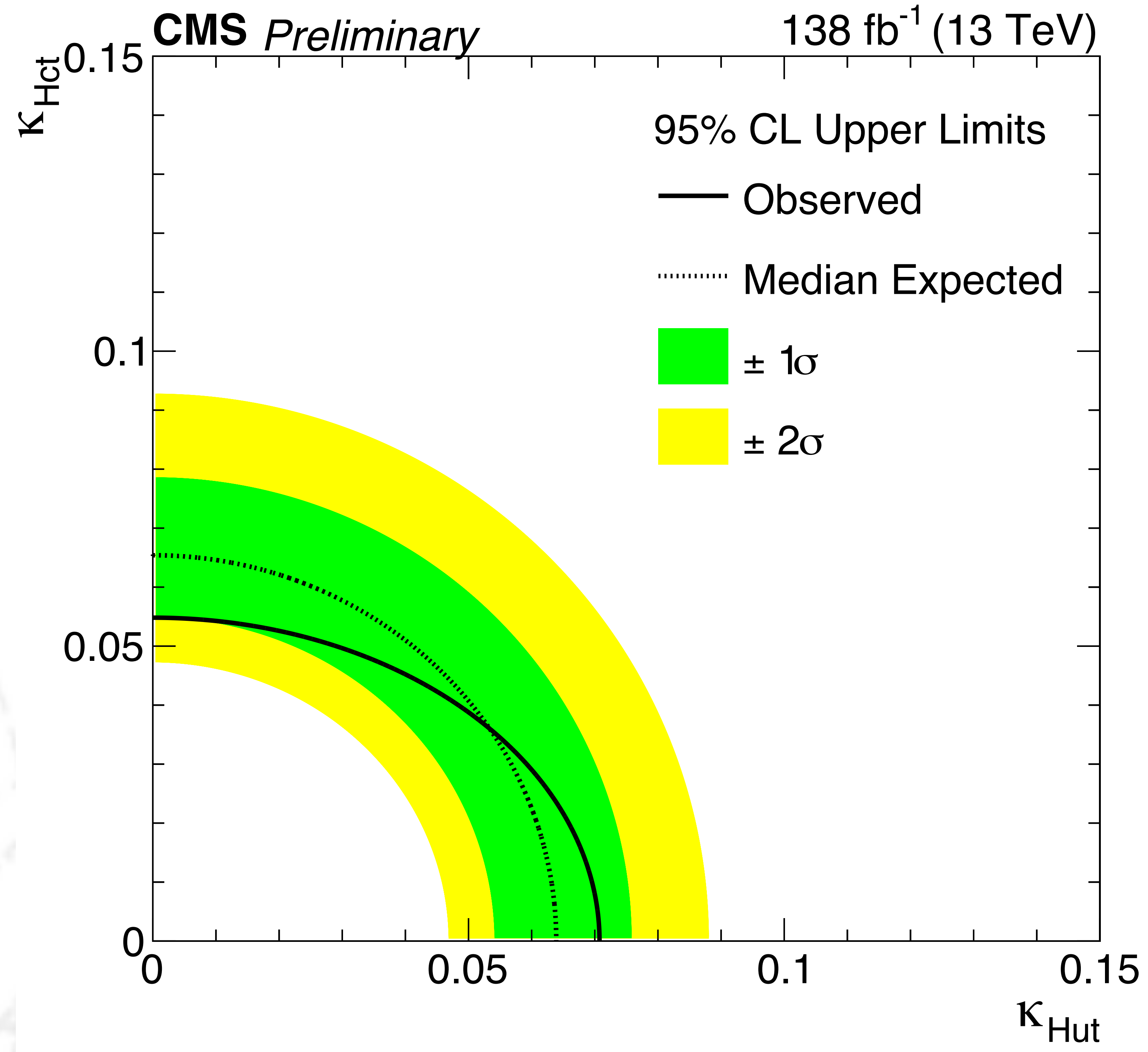
PS variations
Pythia (dipole) vs Herwig (angular)

FCNC - CMS



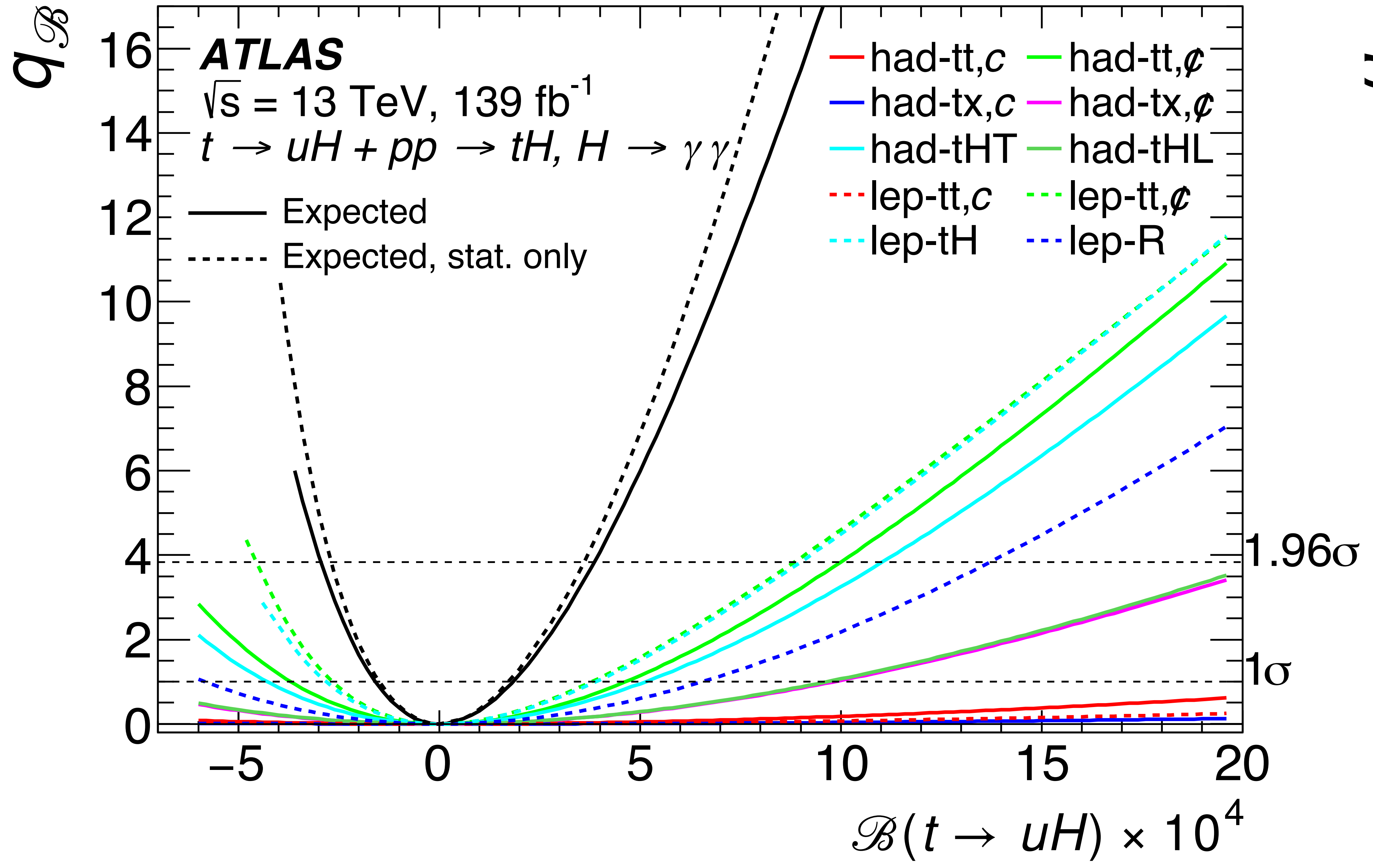


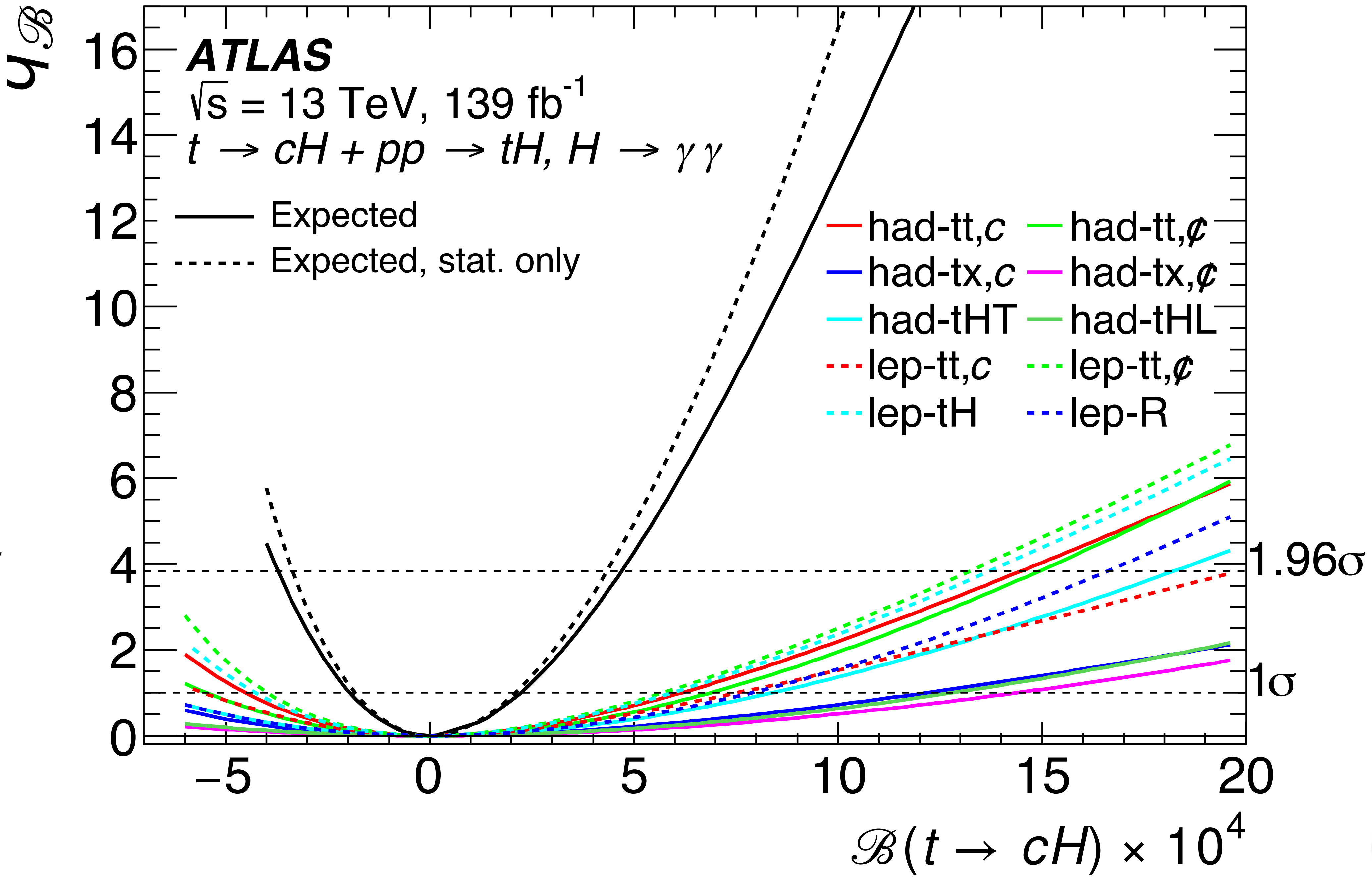




Source	Uncertainty in tcH Prediction	Uncertainty in tuH Prediction	Uncertainty in SM SS Prediction	Uncertainty in Nonprompt Estimate	Uncertainty in Charge Flip Estimate
Jet energy scale	1–6%	< 8%	< 5%	-	-
Theory normalization	6–10%	6–10%	5–25%	-	-
PDF shape	< 2%	< 2%	4–6%	-	-
Renormalization and factorization scale shape	7–9%	2–6%	10–15%	-	-
Pileup	< 2%	< 2%	< 2%	-	-
Trigger efficiency	2%	2%	2%	-	-
Lepton efficiency	2–3%	2–3%	2–3%	-	-
b/c tagging	10–16%	6–13%	7–14%	-	-
Estimate normalization	-	-	-	30%	30%
ϵ_{TL}/ϵ_q	-	-	-	7–10%	<5%
Total	14–16%	11–14%	20–28%	31–35%	29–31%

FCNC - ATLAS





Leptoquark model

$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{\mathrm{LQ}} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix},$$

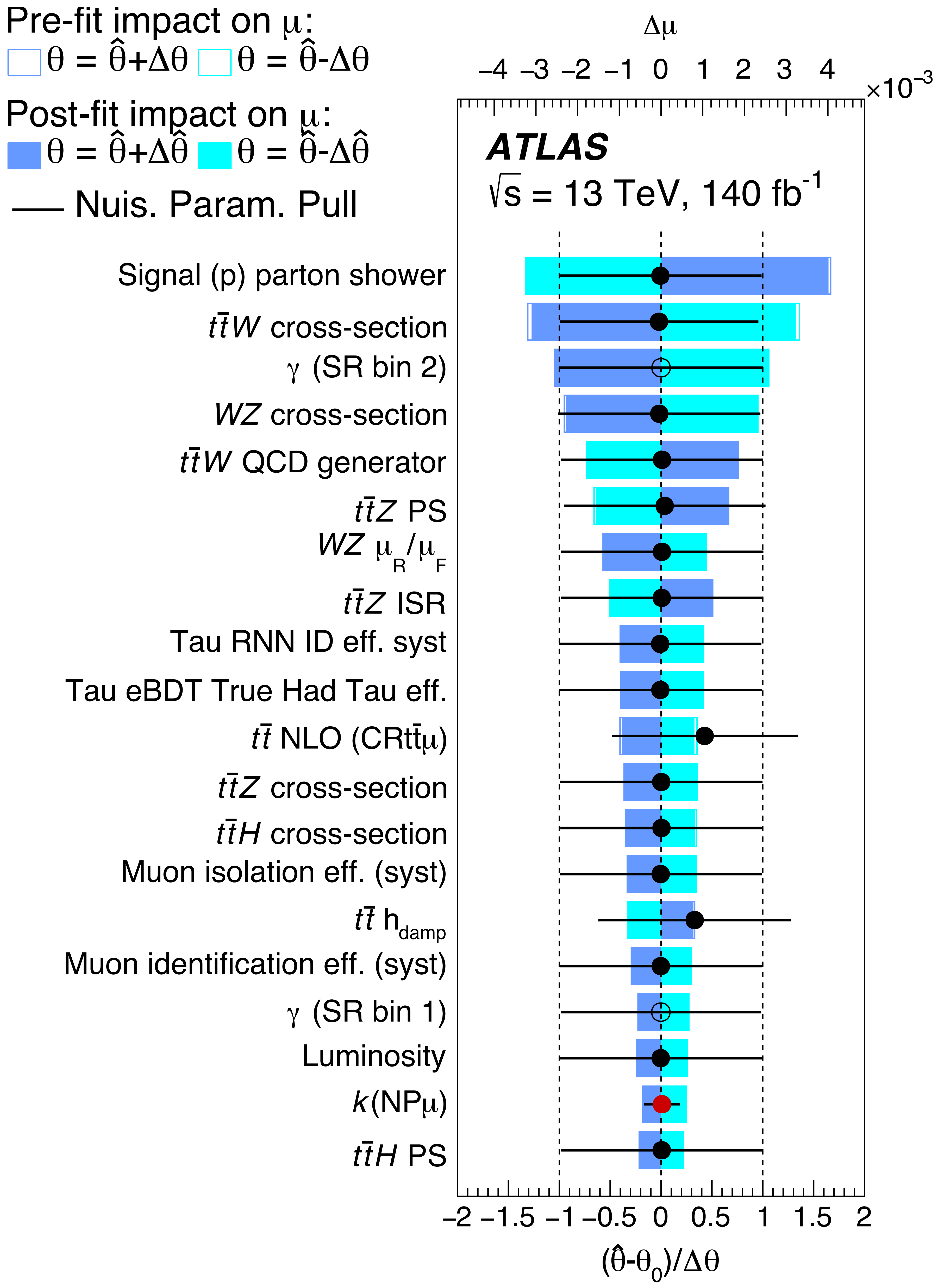
Source	relative impact (%)
Experimental	
Photon energy resolution	1.5
Photon identification	0.4
Luminosity, pile-up modelling	0.3
Jet energy scale and resolution, flavour tagging	< 0.2
Theoretical	
Normalisation ($\sigma(pp \to t\bar{t}, tH), \mathcal{B}(H \to \gamma\gamma)$)	1.1
Parton showering model	0.8
m_t value, NLO generator for $pp \to tH$	0.5
Resonant background	0.5
Non-resonant background	2.3

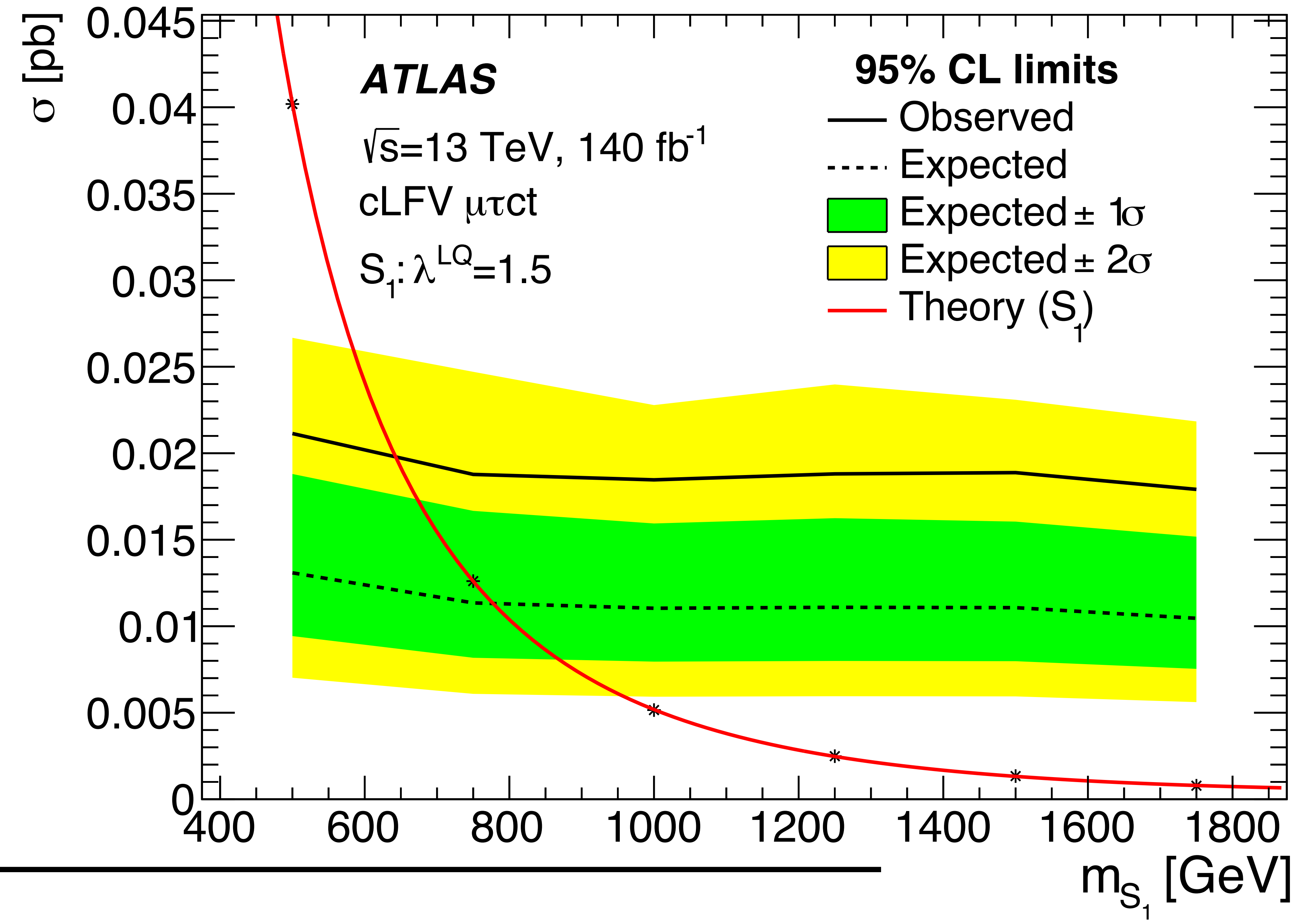
LFV - CMS

CLFV coupling	Lorentz structure	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp. (68% CL range)	**Obs.**	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp. (68% CL range)	**Obs.**
$e\mu tu$	Tensor	0.022 (0.018–0.026)	**0.024**	0.027 (0.018–0.040)	**0.032**
	Vector	0.044 (0.036–0.054)	**0.048**	0.019 (0.013–0.028)	**0.022**
	Scalar	0.093 (0.077–0.114)	**0.101**	0.010 (0.007–0.016)	**0.012**
$e\mu tc$	Tensor	0.084 (0.069–0.102)	**0.094**	0.396 (0.272–0.585)	**0.498**
	Vector	0.175 (0.145–0.214)	**0.196**	0.296 (0.203–0.440)	**0.369**
	Scalar	0.385 (0.318–0.471)	**0.424**	0.178 (0.122–0.266)	**0.216**

Systematic uncertainty	$m(e\mu) < 150$ GeV Background	Signal	$m(e\mu) > 150$ GeV Background	Signal
Pileup	<0.1%	0.4%	<0.1%	0.3%
Lepton reconstruction	<0.1%	0.6%	<0.1%	1.7%
Lepton identification and isolation	1.0%	1.4%	1.0%	1.3%
High-p_T lepton	<0.1%	0.2%	<0.1%	3.4%
Muon momentum scale and resolution	<0.1%	0.3%	<0.1%	0.1%
L1 prefiring	<0.1%	0.4%	<0.1%	0.4%
Jet energy scale and resolution	<0.1%	1.0%	1.0%	0.4%
b tagging	<0.1%	0.9%	1.0%	0.5%
Jet modeling	6.0%	—	7.0%	—
Nonprompt	11.0%	—	9.0%	—
PDF	<0.1%	2.3%	<0.1%	1.3%
QCD scale	4.0%	2.8%	5%	1.4%
Initial- and final-state radiation	—	7.6%	—	1.0%

LFV - ATLAS





	95% CL upper limits on $\mathcal{B}(t \to \mu\tau q)$	
	Stat. uncertainty	**Stat.+syst. uncertainties**
Expected	4.6×10^{-7}	5.0×10^{-7}
Observed	8.2×10^{-7}	8.7×10^{-7}

	95% CL upper limits on $\lvert c\rvert/\Lambda^2$ [TeV^{-2}]					
	$c_{\mathrm{lq}}^{-(ijk3)}$	$c_{\mathrm{eq}}^{(ijk3)}$	$c_{\mathrm{lu}}^{(ijk3)}$	$c_{\mathrm{eu}}^{(ijk3)}$	$c_{\mathrm{lequ}}^{1(ijk3)}$	$c_{\mathrm{lequ}}^{3(ijk3)}$
Previous (u)	12	12	12	12	18	2.4
Expected (u)	0.33	0.31	0.3	0.32	0.33	0.08
Observed (u)	0.43	0.41	0.4	0.42	0.44	0.10
Previous (c)	14	14	14	14	21	2.6
Expected (c)	1.3	1.2	1.2	1.2	1.4	0.28
Observed (c)	1.6	1.6	1.6	1.6	1.8	0.36

BNV

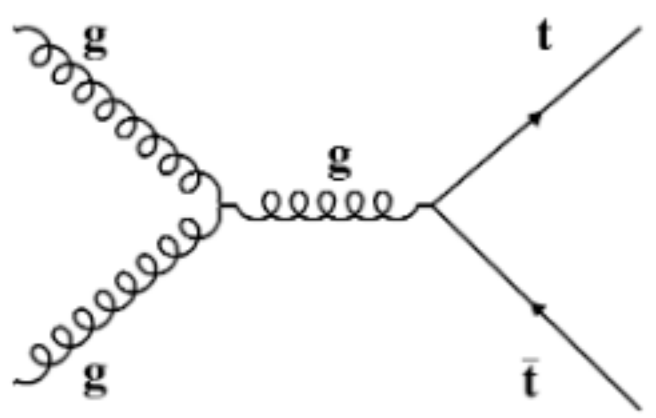
- Uncertainties:
  - tW normalisation
  - Mouse energy scale
  - Top quark p_T spectrum modeling

Vertex	C_x	C_x/Λ^2 [TeV^{-2}] Exp.	C_x/Λ^2 [TeV^{-2}] Obs.	$\mathcal{B}_x$ [10^{-6}] Exp.	$\mathcal{B}_x$ [10^{-6}] Obs.
teud	s	0.055	0.048	0.015	0.011
	t	0.031	0.027	0.005	0.003
tμud	s	0.046	0.036	0.010	0.006
	t	0.025	0.020	0.003	0.002
tecd	s	0.207	0.184	0.208	0.164
	t	0.114	0.102	0.063	0.050
tμcd	s	0.178	0.141	0.153	0.095
	t	0.100	0.080	0.048	0.030
teus	s	0.115	0.101	0.063	0.050
	t	0.064	0.056	0.019	0.015
tμus	s	0.102	0.079	0.050	0.030
	t	0.056	0.043	0.015	0.009
tecs	s	0.448	0.403	0.973	0.786
	t	0.243	0.218	0.286	0.229
tμcs	s	0.394	0.311	0.752	0.468
	t	0.217	0.169	0.228	0.138
teub	s	0.199	0.178	0.191	0.154
	t	0.109	0.097	0.057	0.045
tμub	s	0.168	0.134	0.136	0.087
	t	0.095	0.076	0.044	0.028
tecb	s	0.718	0.657	2.503	2.090
	t	0.405	0.367	0.795	0.652
tμcb	s	0.703	0.564	2.393	1.521
	t	0.386	0.307	0.722	0.455

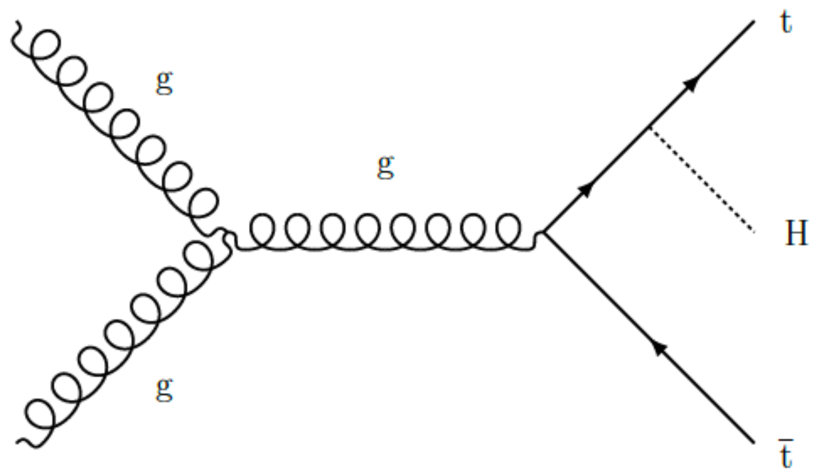
New physics via EFT

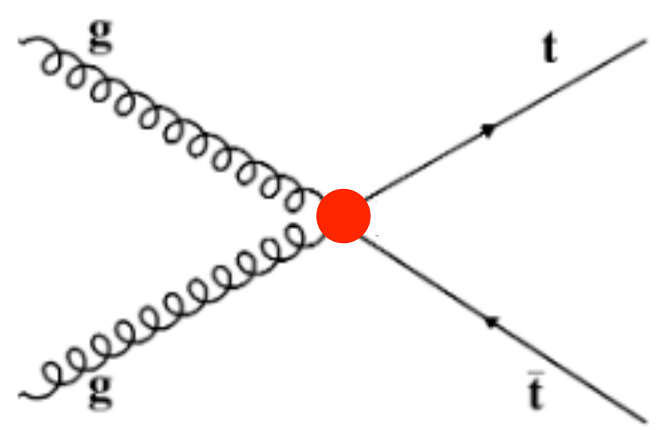
- Simplified description of the investigated system
- Robust within a limited region of validity
- Historical example: electroweak decay (Fermi)

- Standard Model effective field theory (SMEFT)
  - Dimension-6 operators parametrize new physics
  - 59 up to 2499 independent operators

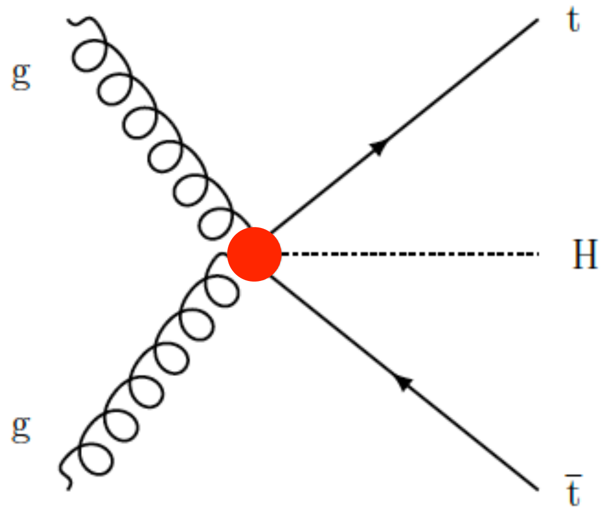


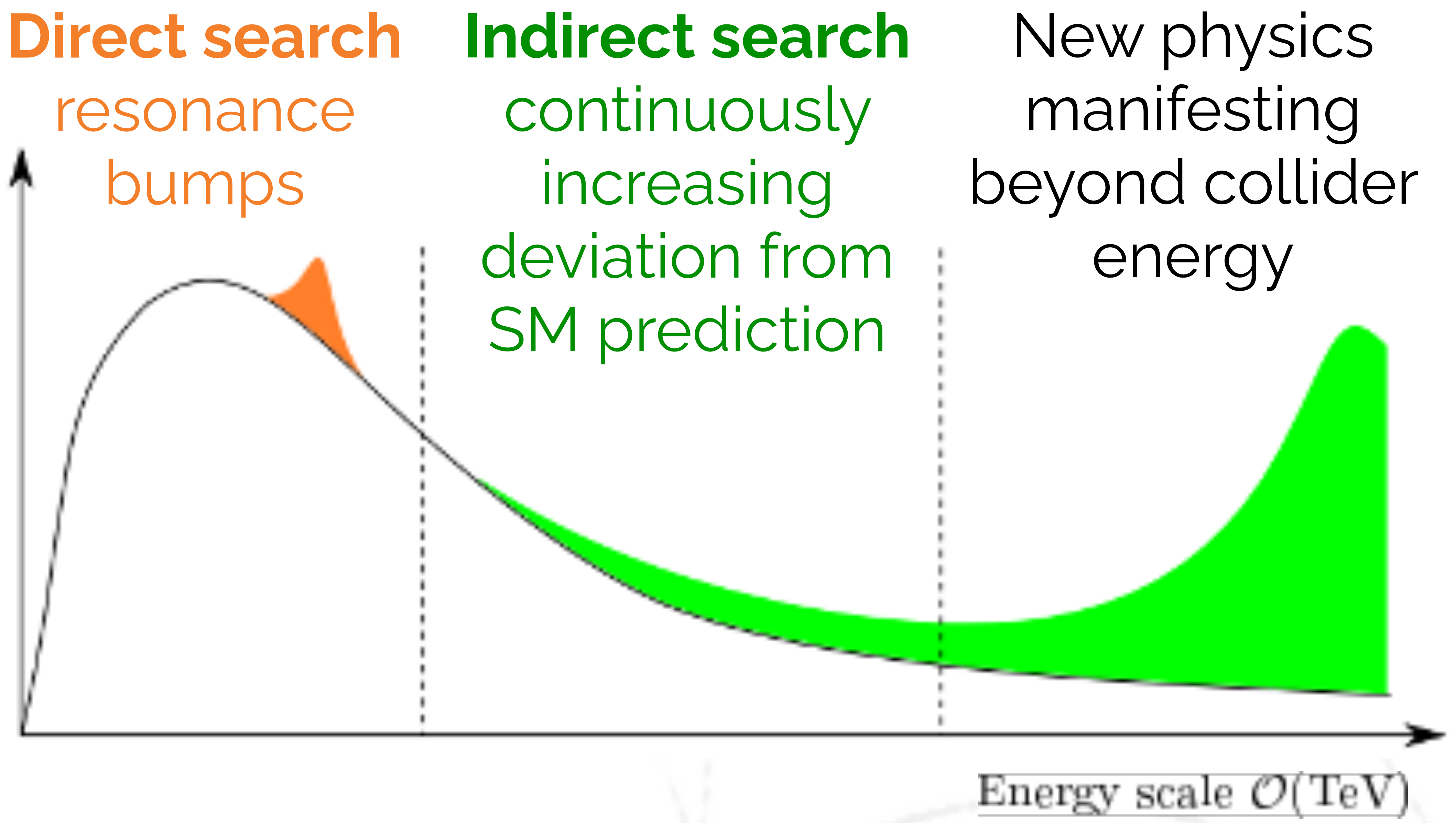
SM





EFT





Dimensionless Wilson coefficients

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i$$

New physics scale

Higher order EFT operators