



Dispelling the \sqrt{L} myth of the HL-LHC

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Theory Seminar
ETH and University Zurich
17th Dec, 2024

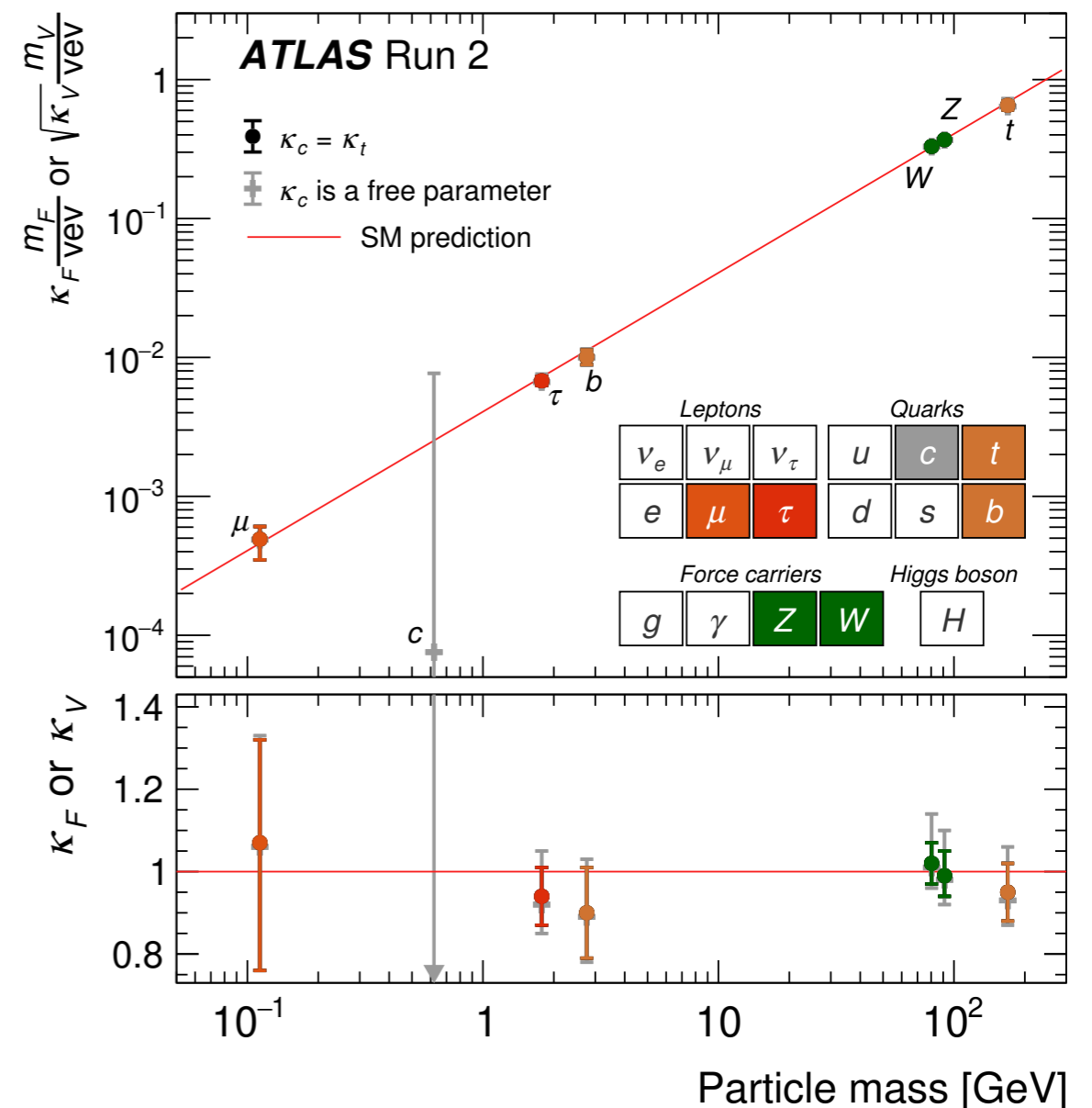


LHC Collider Physics

Many breakthroughs in the last ~15 years

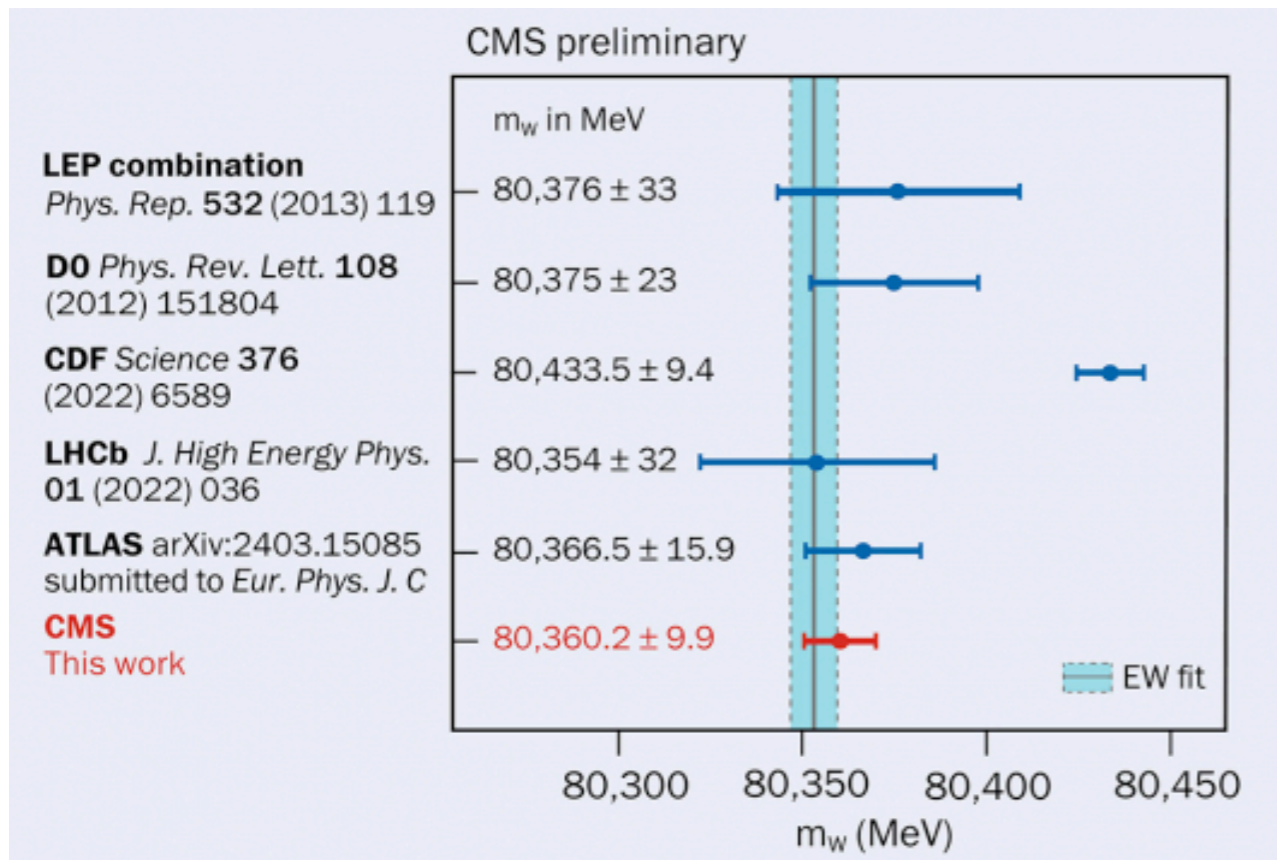
- ▶ Higgs boson discovery
- ▶ Fermion-H couplings: ttH and $H \rightarrow \tau\tau, bb$
- ▶ EW precision measurements
 - $\sin^2\theta_{\text{eff}}$ and M_W
- ▶ Top quark mass and α_s
- ▶ Observation of rare processes
 - $pp \rightarrow B_s, t\gamma q, tWZ, tttt, \dots$
- ▶ Approaching $H \rightarrow \mu\mu, cc, \text{di-Higgs}$
- ▶ Huge number of BSM searches

[ATLAS, [Nature 607 52 \(2022\)](#)]

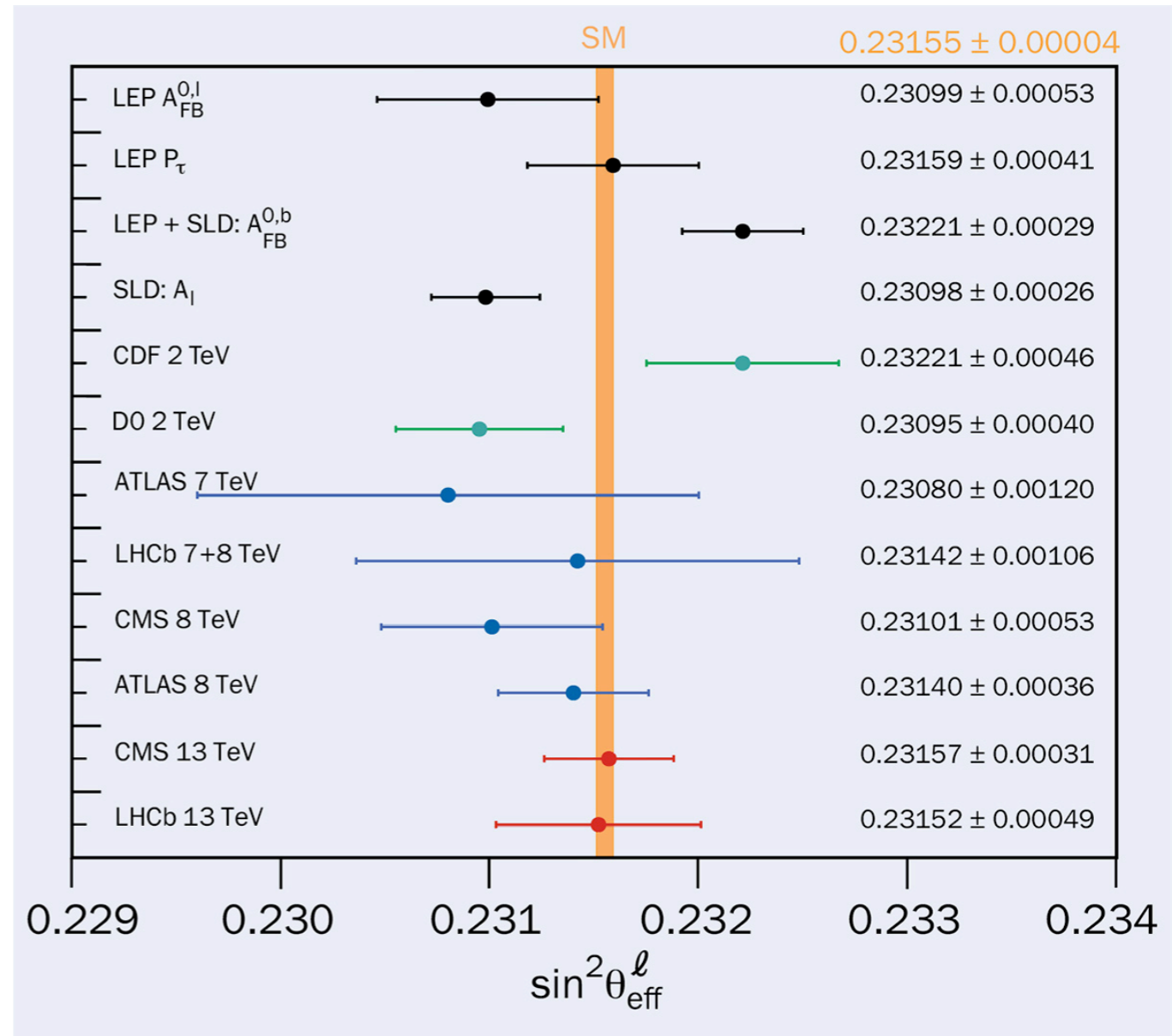


LHC Collider Physics

Many precision results



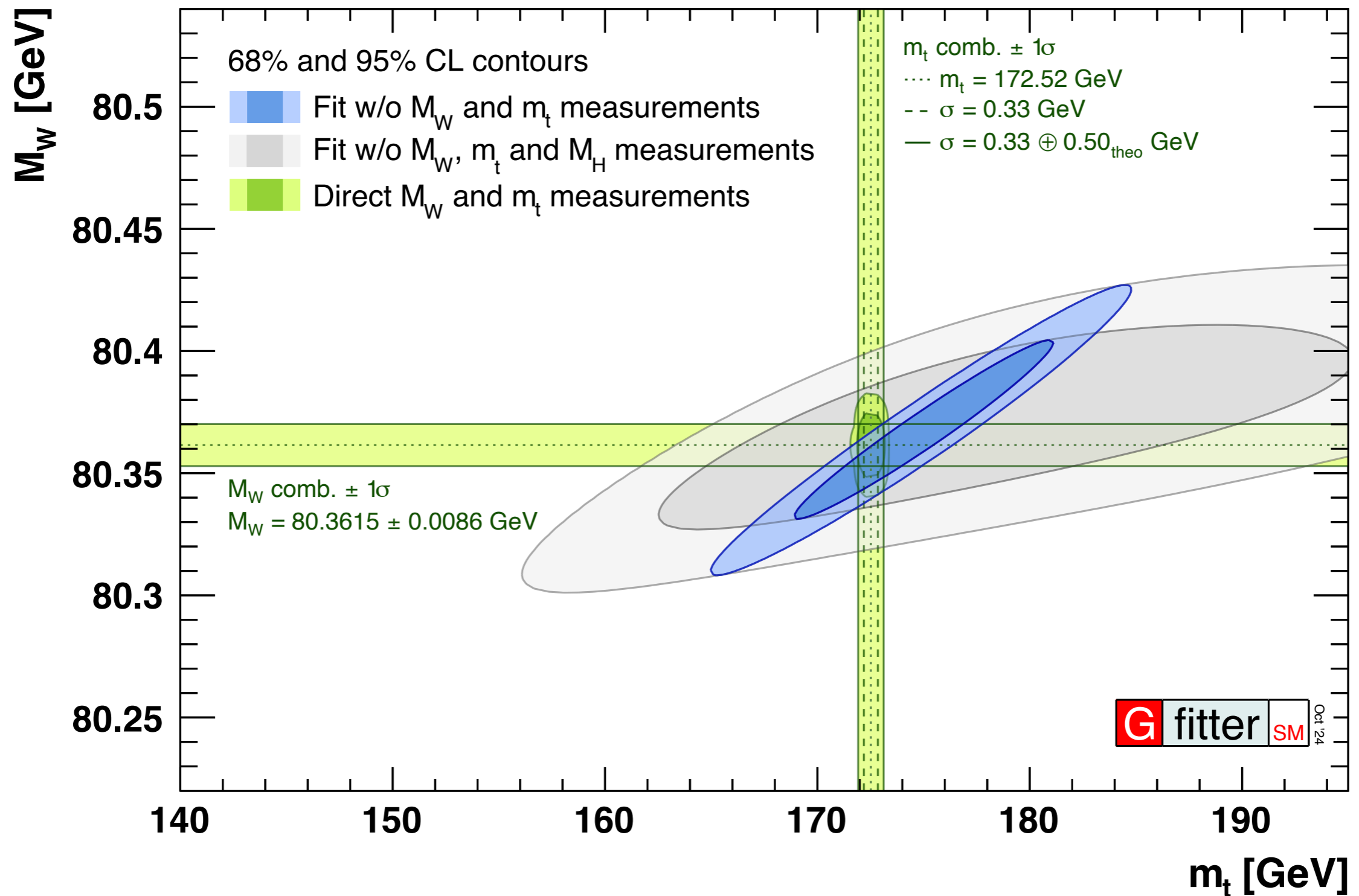
[CERN Courier, Nov 20 (2024)]



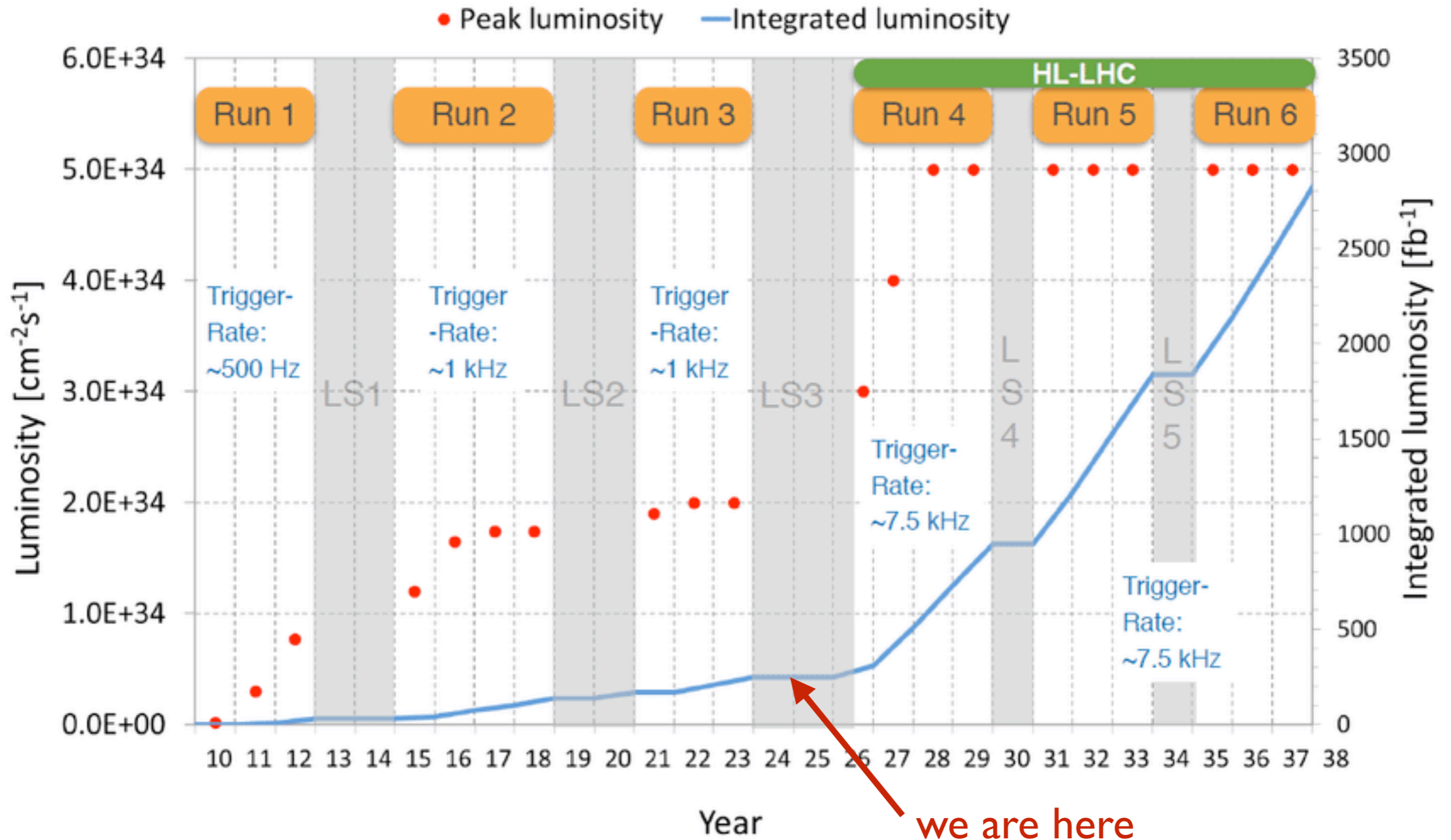
[CERN Courier, Sep 9 (2024)]

SM Internal Consistency

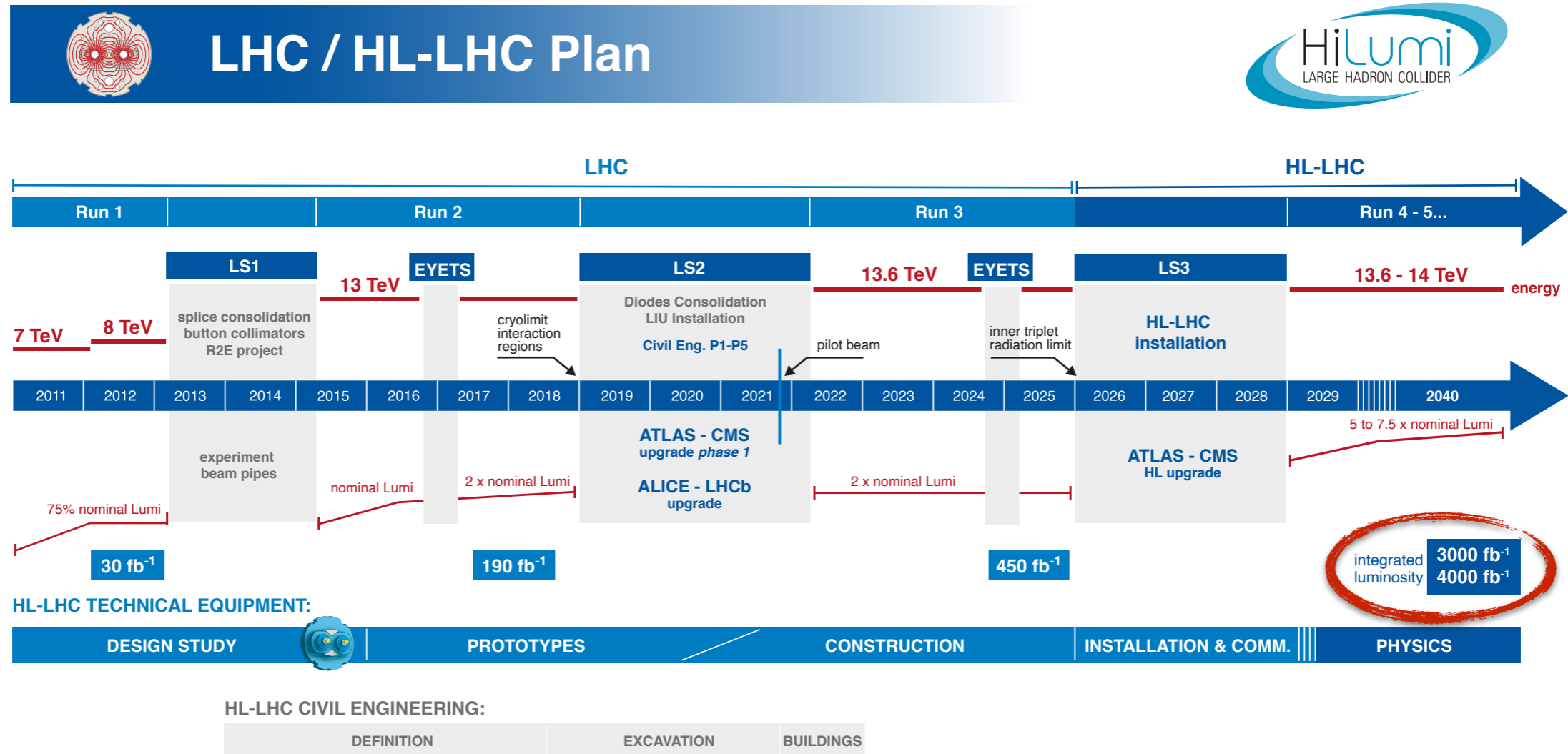
[Gfitter Preliminary, Nov (2024)]



LHC: Status and HL-LHC



Physics Potential of the HL-LHC



Sensitivity scales with luminosity:

$$\mathcal{S} \approx \frac{S}{\sqrt{B}} \approx \sqrt{L} \frac{\sigma_S}{\sqrt{\sigma_B}}$$

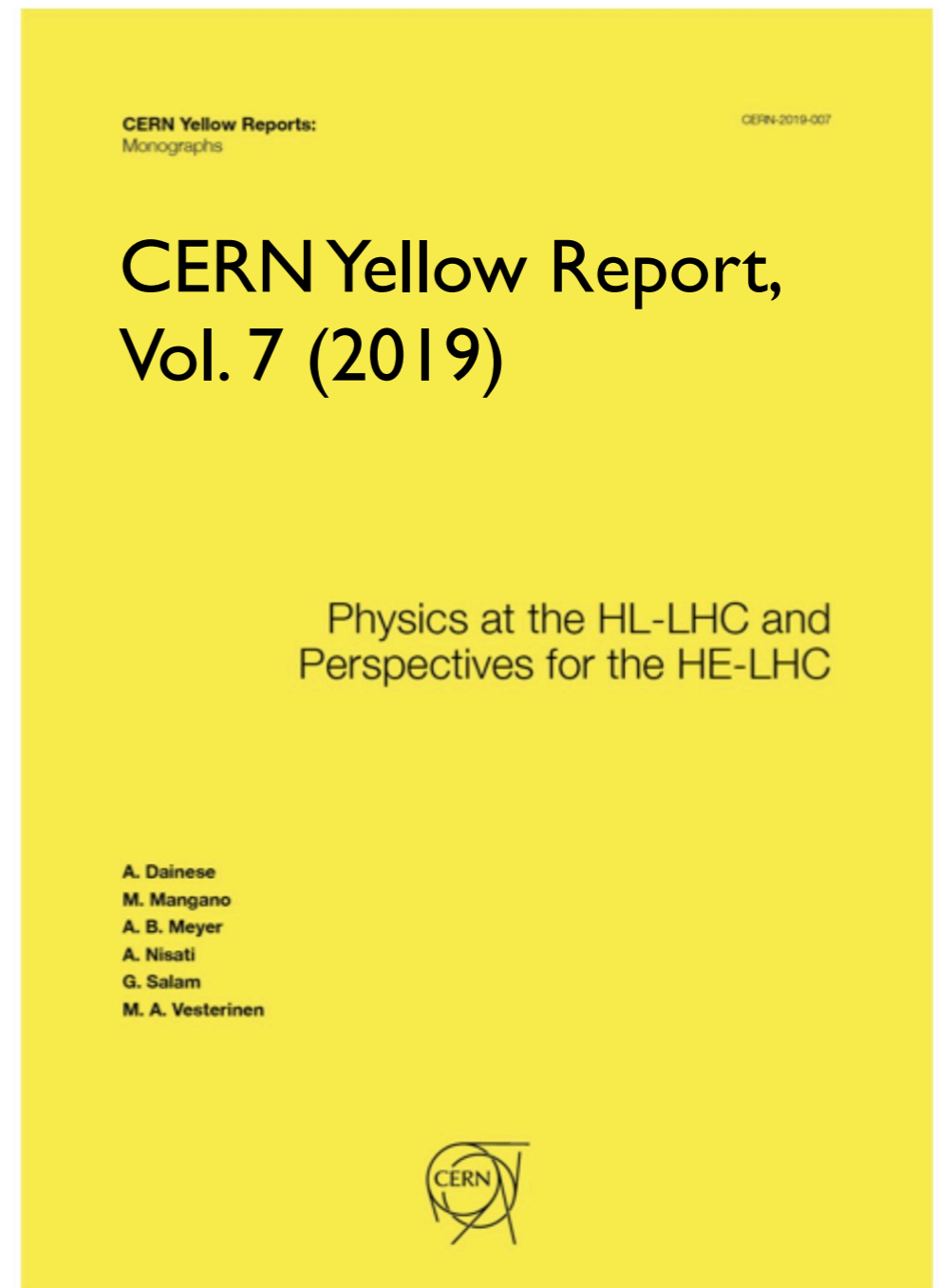
For measurements:

$$\delta \sim \sqrt{S} \sim \sqrt{L}$$

More realistic estimates

Huge effort by the LHC Collaborations + theory to estimate the physics potential

- ▶ Cumulated in CYRM-2019-007
 - Standard model
 - Higgs physics
 - BSM searches
 - Flavour physics
 - Heavy ions
- ▶ Existing analyses derived expected sensitivities
 - Higher luminosity
 - Better systematic uncertainties



Somewhat bleak outlook for collider physics

Content: Beyond the YR estimates

1. Experimental techniques

- Four top production

2. Novel methods

- Top quark mass from boosted jet mass

3. Going differential

- EFT constraints in the Higgs sector

4. Sensitivity from rare processes

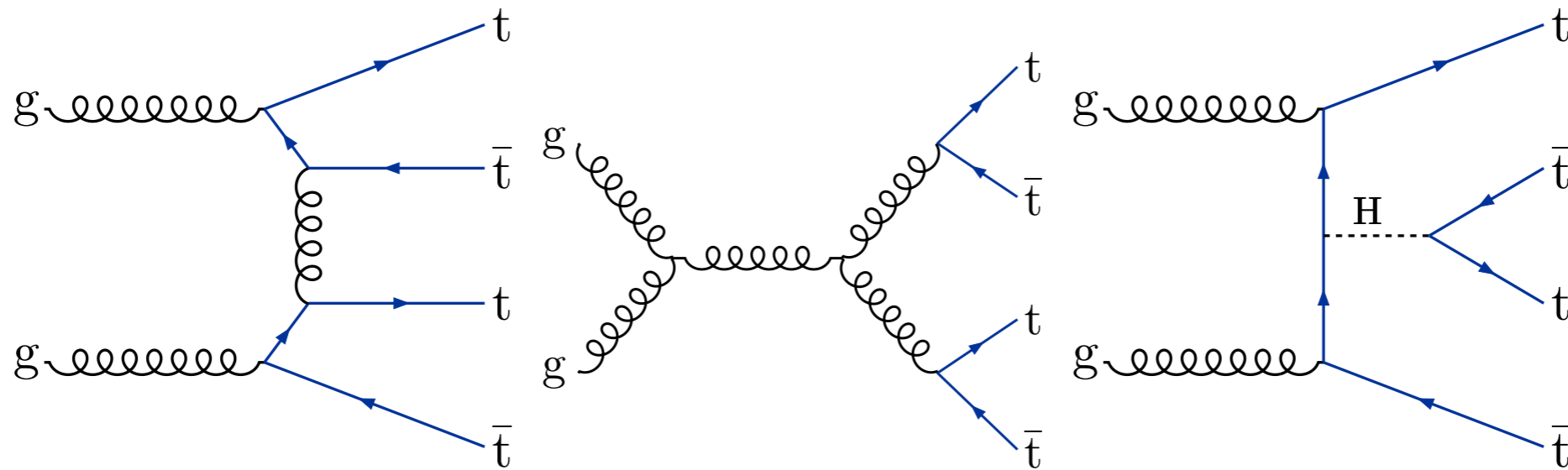
- tWZ production

5. Optimal analysis strategies

- Search for $t^* \rightarrow tg$

1st Example: Four Tops (Experimental Techniques)

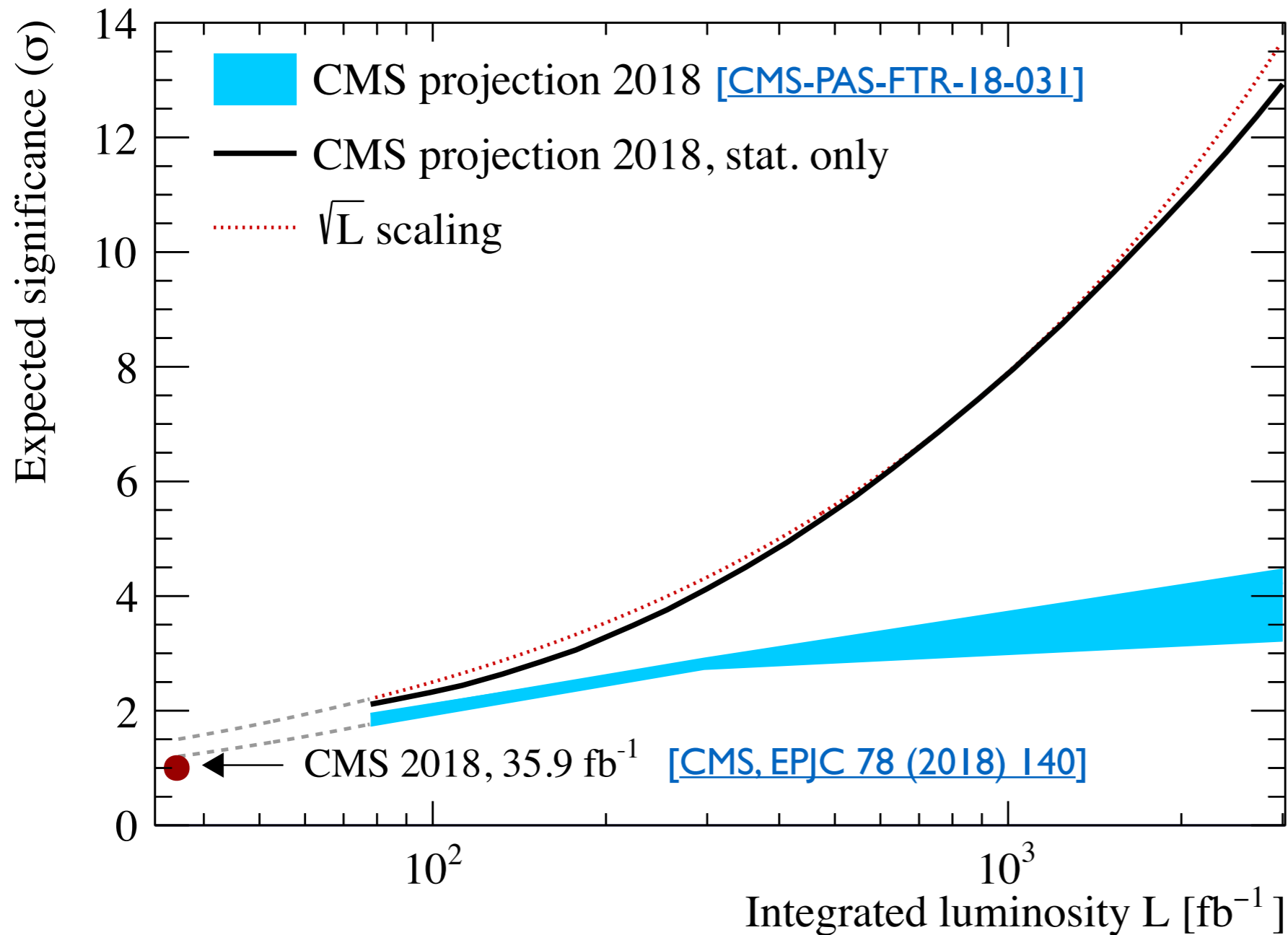
Four Top Quark Production



- ▶ $\sigma(tttt) \approx 13 \text{ fb}$
- ▶ Very sensitive to BSM effects
- ▶ Challenging from experimental and theoretical sides
- ▶ CMS analysis done in same-sign dileptons and multileptons
 - 35.9 fb^{-1}
 - Sensitivity reached: 10σ [\[CMS, EPJC 78 \(2018\) 140\]](#)

N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
	3	≥ 8	SR3
		5, 6	SR4
		≥ 7	SR5
≥ 3	≥ 4	≥ 5	SR6
	2	≥ 5	SR7
	≥ 3	≥ 4	SR8
Inverted Z veto			CRZ

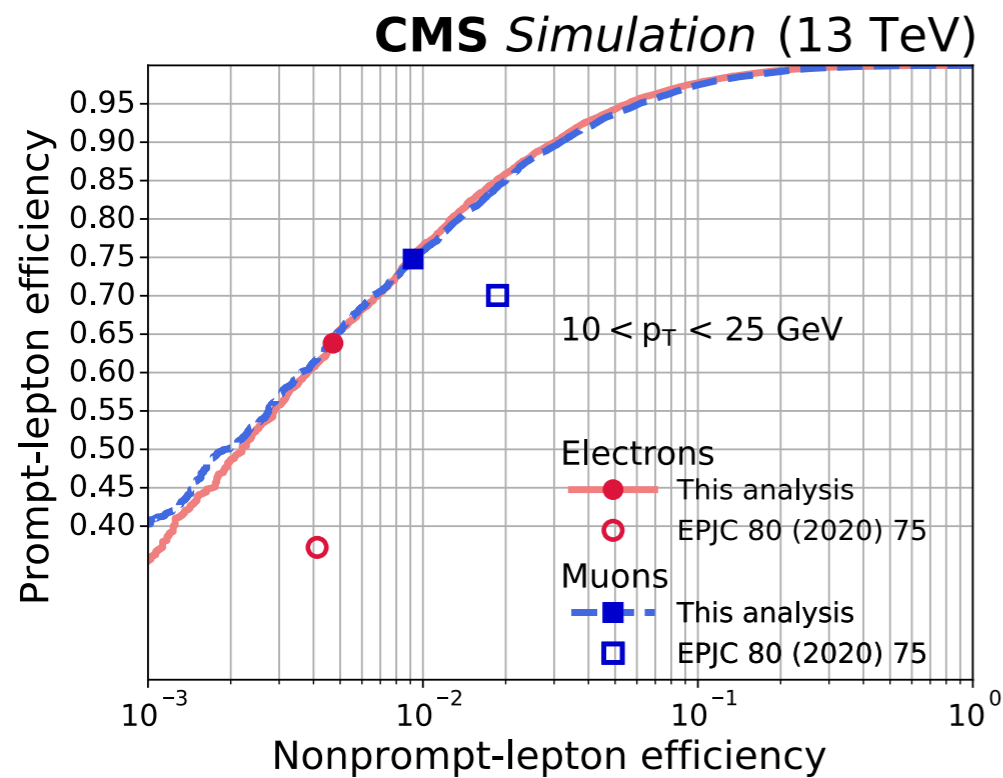
Four Tops: Expectations



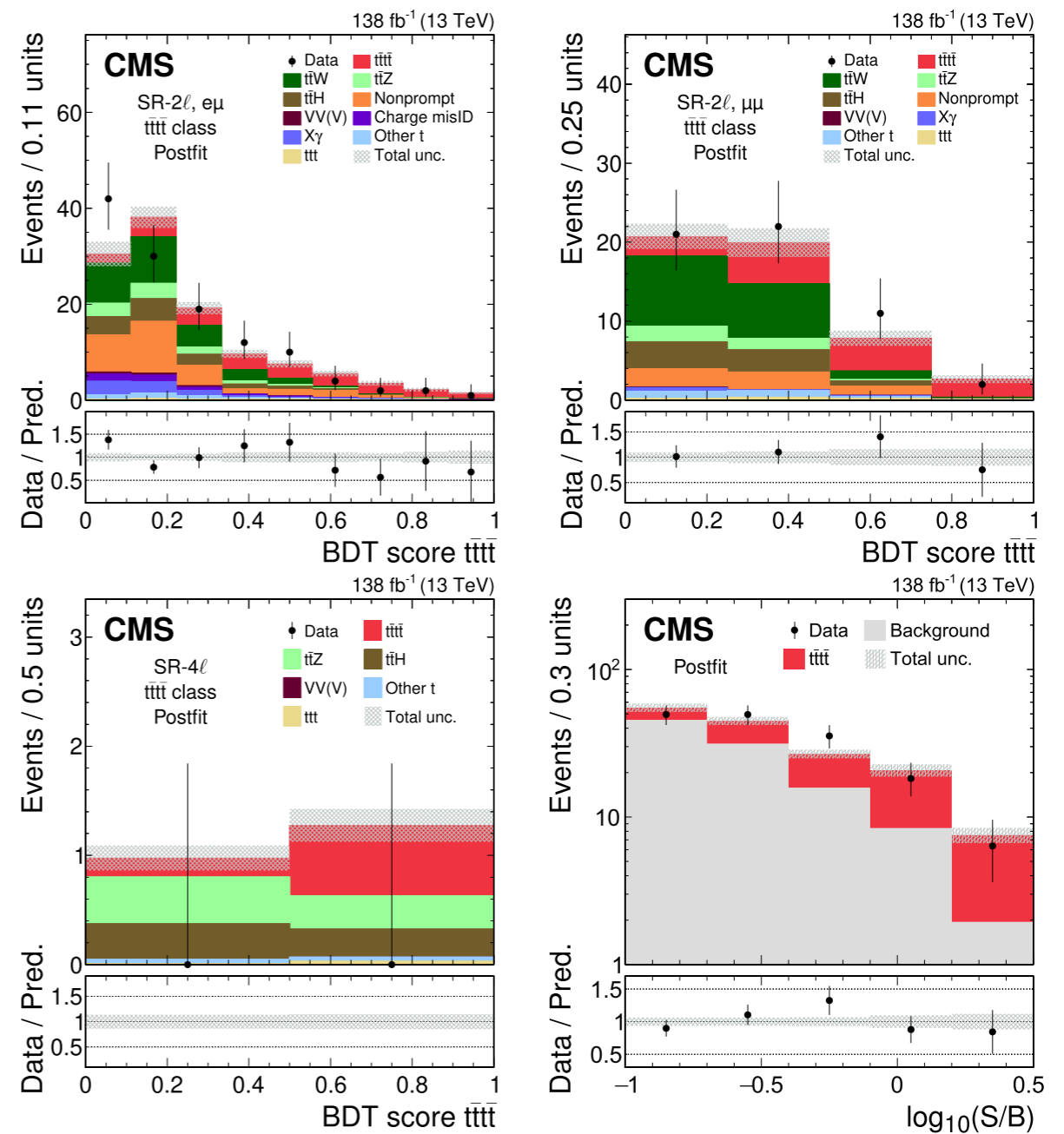
- ▶ Same-sign dileptons and multileptons
- ▶ Extrapolation to HL-LHC reaches 4.2σ for optimistic uncertainties

Four Tops: Improvements

▶ Lepton identification



▶ Signal/bkg separation: BDTs



▶ b jet identification

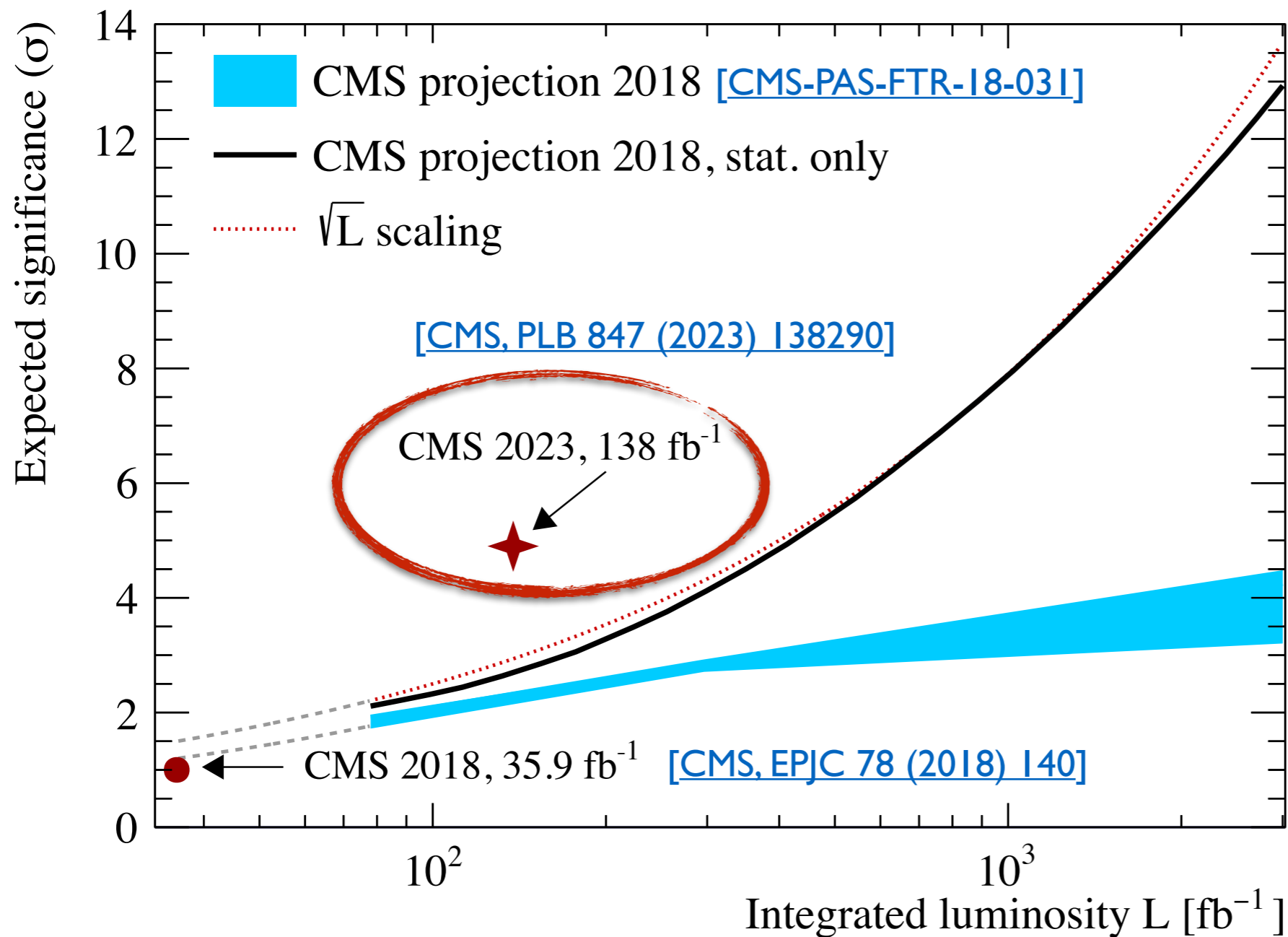
- DeepJet, improvement by 5-25%

▶ Signal extraction

- Likelihood fit

[CMS, PLB 847 (2023) 138290]

Four tops, 5 Years Later



- ▶ same-sign dileptons and multileptons
- ▶ extrapolation to HL-LHC reaches 4.2σ for optimistic uncertainties

2023: Updated methods and systematics: MVA lepton ID, BDTs to isolate signal

[[A. Belvedere, C. Englert, R. Kogler, M. Spannowsky, EPJC84, 715 \(2024\)](#)]

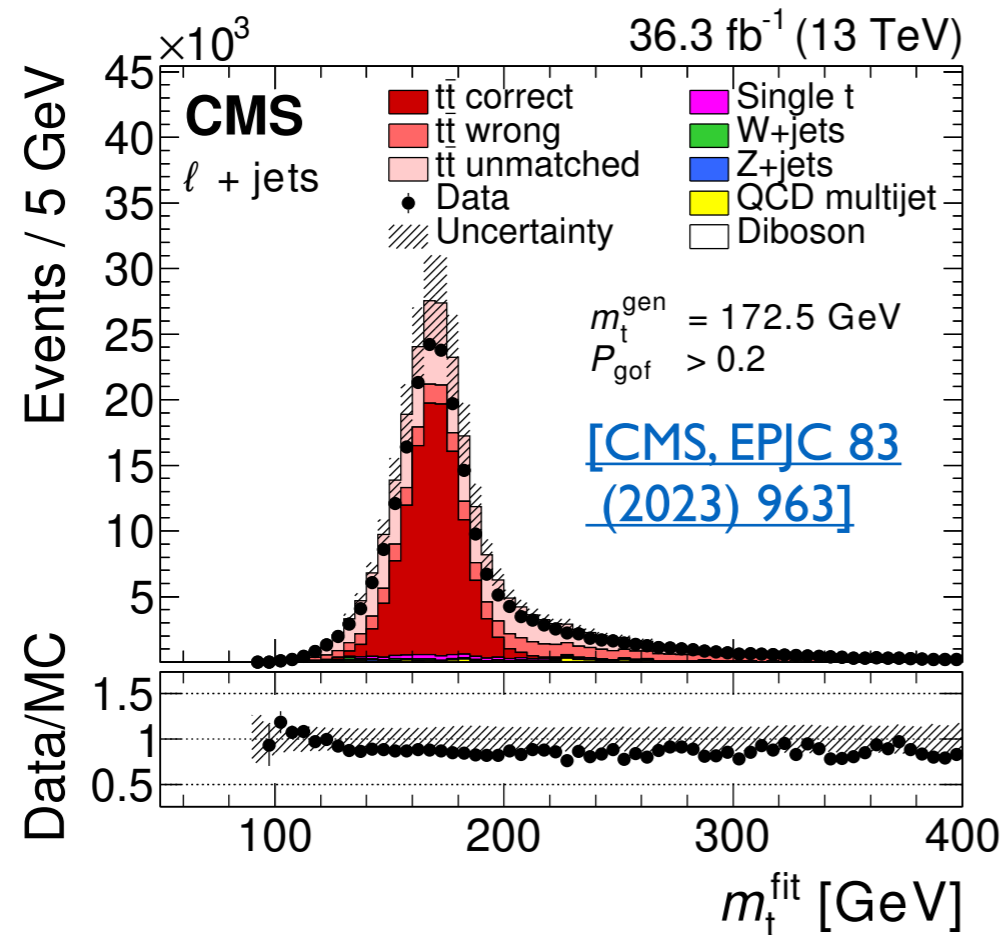
2nd Example: Top Quark Mass (Novel Methods)

The Top Quark Mass

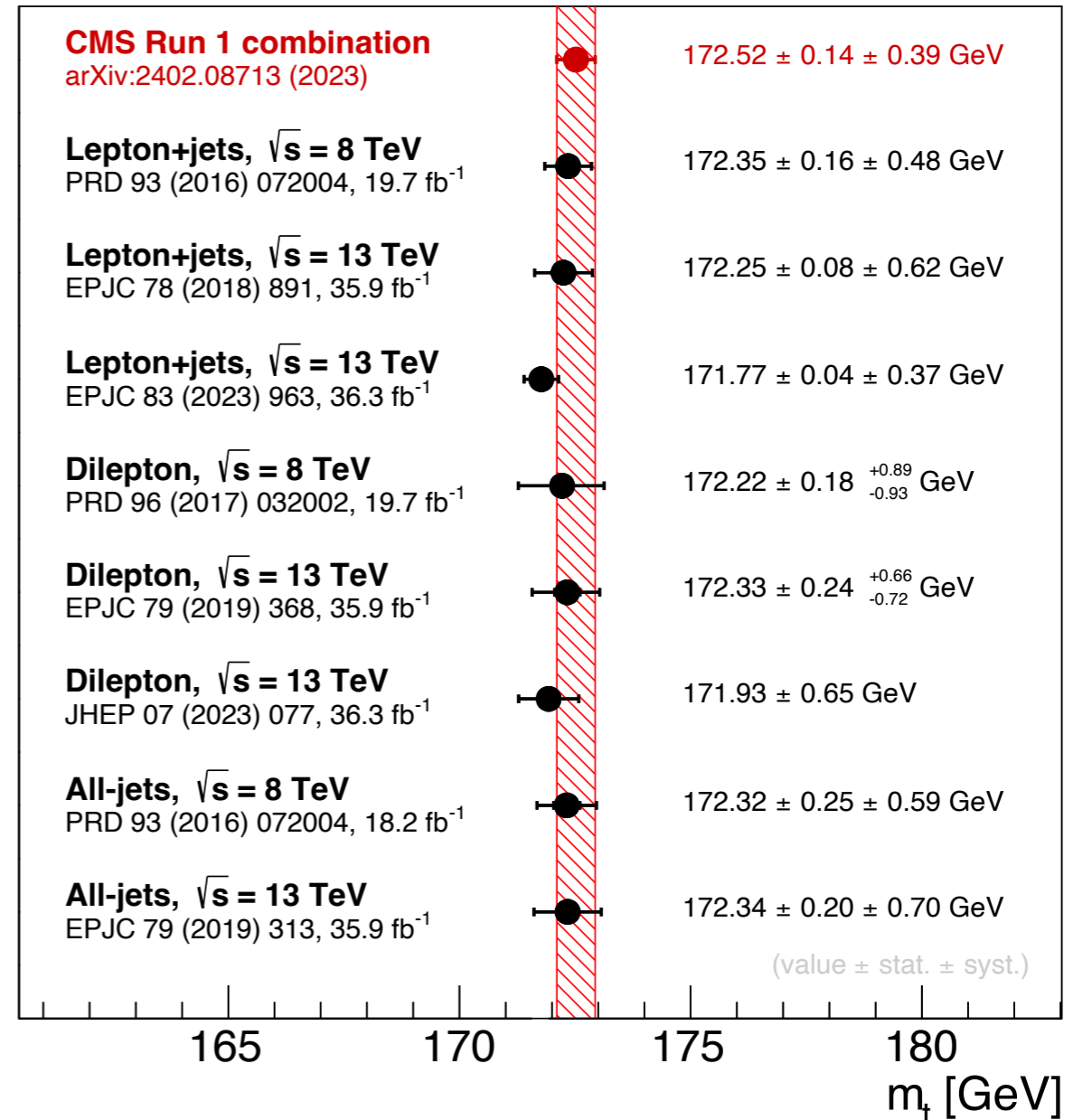
► Direct measurements

- Likelihood fits to constrain experimental systematic uncertainties

[\[CMS, arXiv:2403.01313\]](#)



CMS



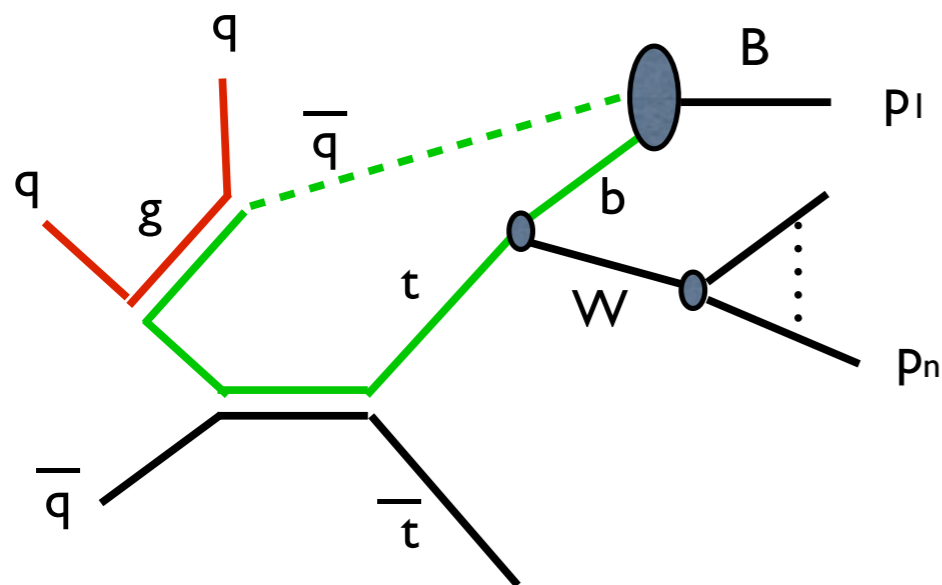
- Achieved precision:
about 400 MeV

m_t : Interpretation

- ▶ Direct determinations use event generators with PS, MPI, hadronization...

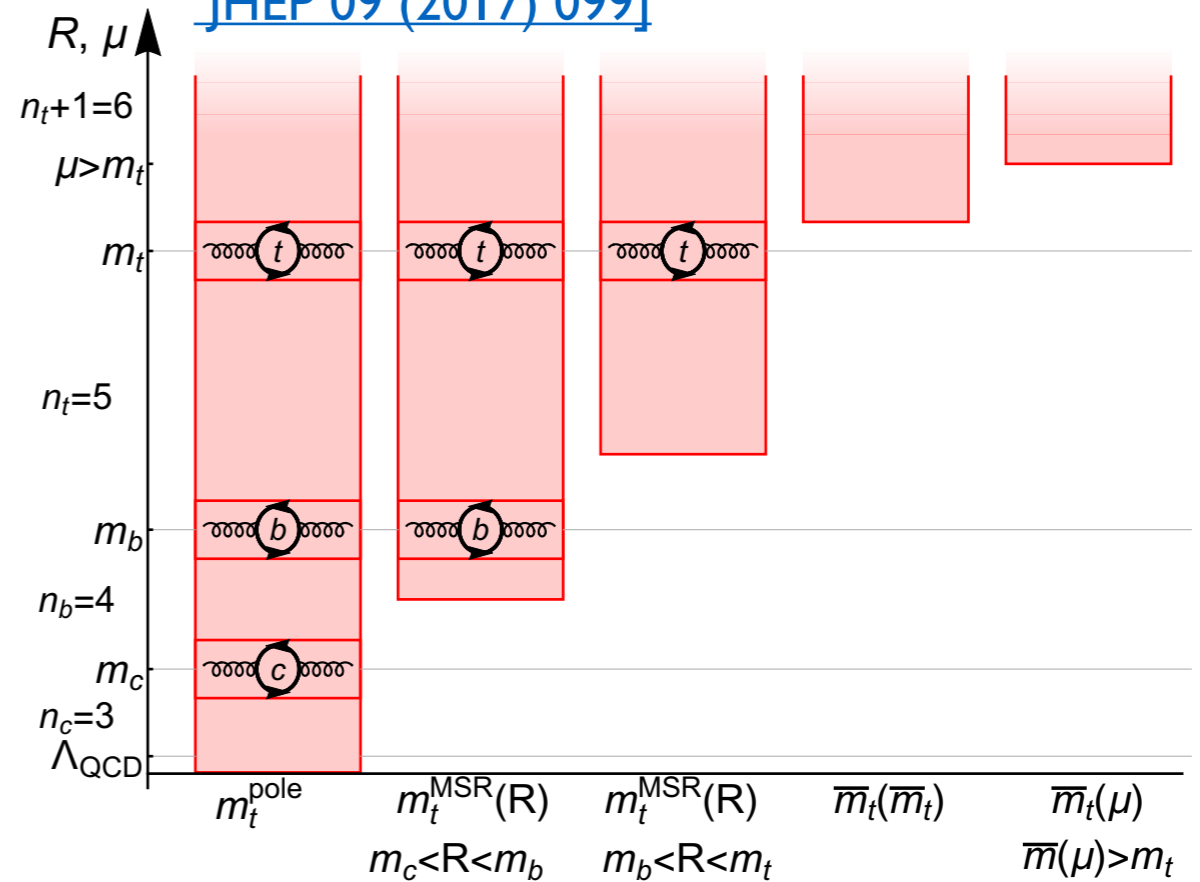
Translation to pole mass unclear

$$M_{exp}^2 = \left(\sum_{i=1, \dots, n} p_i \right)^2$$



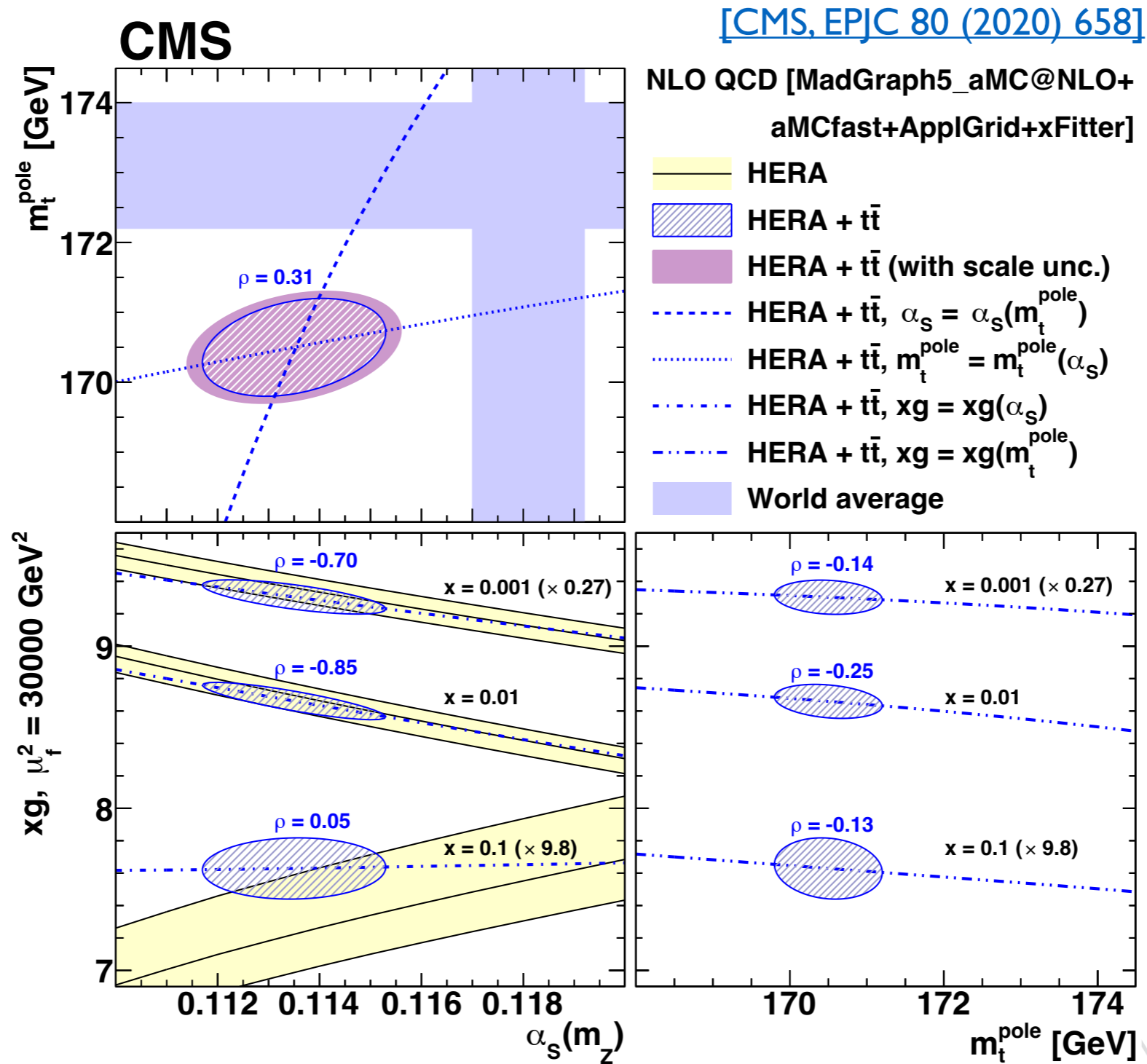
[A. H. Hoang, arXiv:1412.3649]

[A. H. Hoang, C. Lepenik, and M. Preisser, JHEP 09 (2017) 099]



Additional uncertainty
of 250-500 MeV

m_t : Indirect Determinations



m_t : Indirect Determinations

[CMS, arXiv:2403.01313]

CMS



--- ATLAS+CMS combination $m_t^{\text{pole}} = 173.4^{+1.8}_{-2.0}$ GeV
[JHEP 07 (2023) 213]

Indirect mass extractions

Pole mass from cross section

Inclusive $t\bar{t}$ 7 TeV, NNLO \otimes CT10

Inclusive $t\bar{t}$ 7+8 TeV, NNLO \otimes CT14

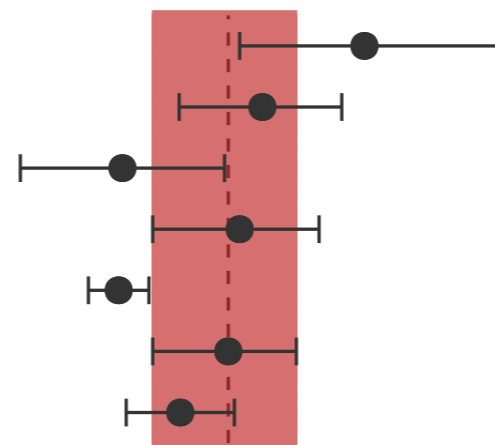
Inclusive $t\bar{t}$ 13 TeV, NNLO \otimes CT14

Inclusive $t\bar{t}$ 13 TeV, NNLO \otimes CT14

Differential $t\bar{t}$ 13 TeV, NLO + 3D fit ($m_t^{\text{pole}}, \alpha_s, \text{PDF}$)

Dilepton 7+8 TeV, ATLAS+CMS cross section

Differential $t\bar{t}$ +jet 13 TeV, NLO \otimes CT18



$m_t^{\text{pole}} = 177.0^{+3.6}_{-3.3}$ (tot) GeV [PLB 728 (2014) 496]

$m_t^{\text{pole}} = 174.3^{+2.1}_{-2.2}$ (tot) GeV [JHEP 08 (2016) 029]

$m_t^{\text{pole}} = 170.6 \pm 2.7$ (tot) GeV [JHEP 09 (2017) 051]

$m_t^{\text{pole}} = 173.7^{+2.1}_{-2.3}$ (tot) GeV [EPJC 79 (2019) 368]

$m_t^{\text{pole}} = 170.5 \pm 0.8$ (tot) GeV [EPJC 80 (2020) 658]

$m_t^{\text{pole}} = 173.4^{+1.8}_{-2.0}$ (tot) GeV [JHEP 07 (2023) 213]

$m_t^{\text{pole}} = 172.13 \pm 1.43$ (tot) GeV [JHEP 07 (2023) 077]

$\overline{\text{MS}}$ mass from cross section

Inclusive $t\bar{t}$ 13 TeV, NNLO \otimes CT14



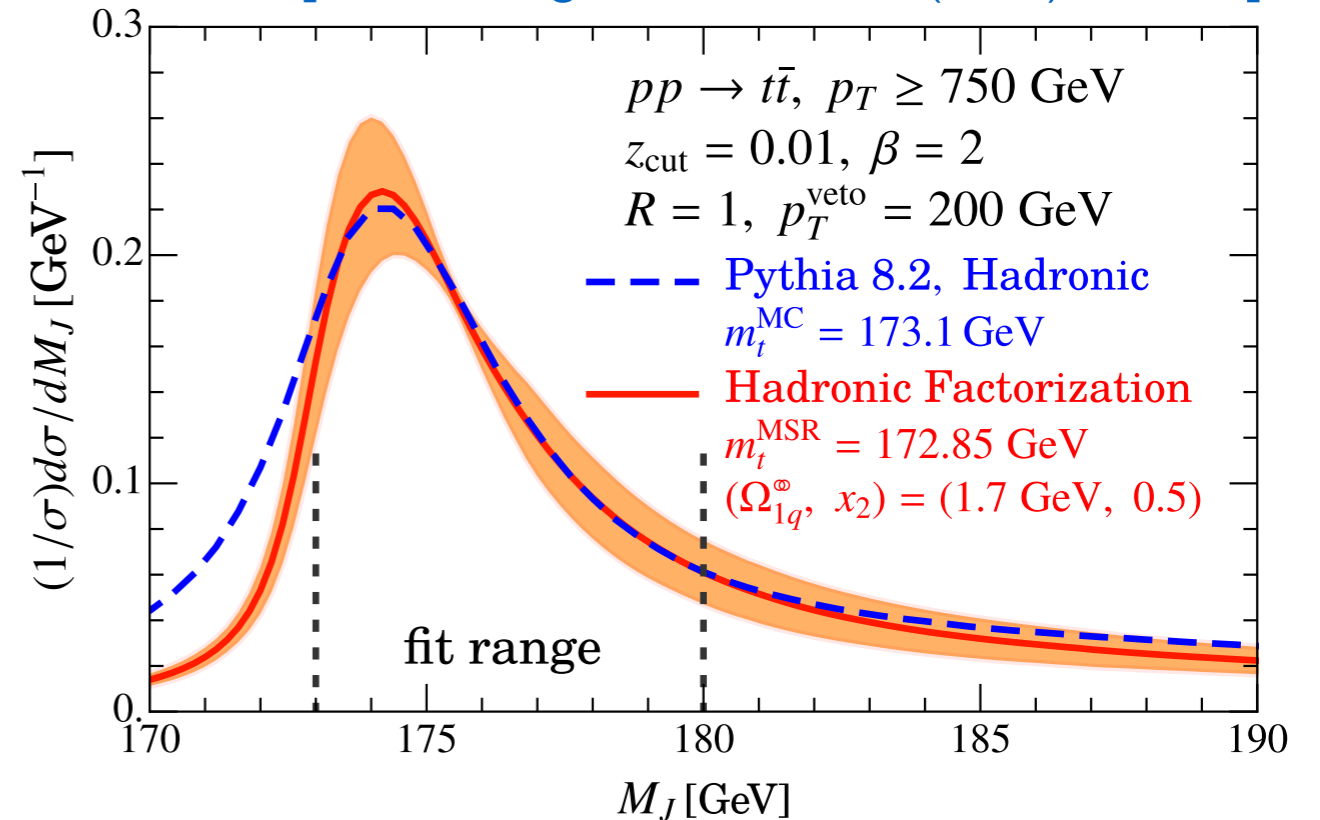
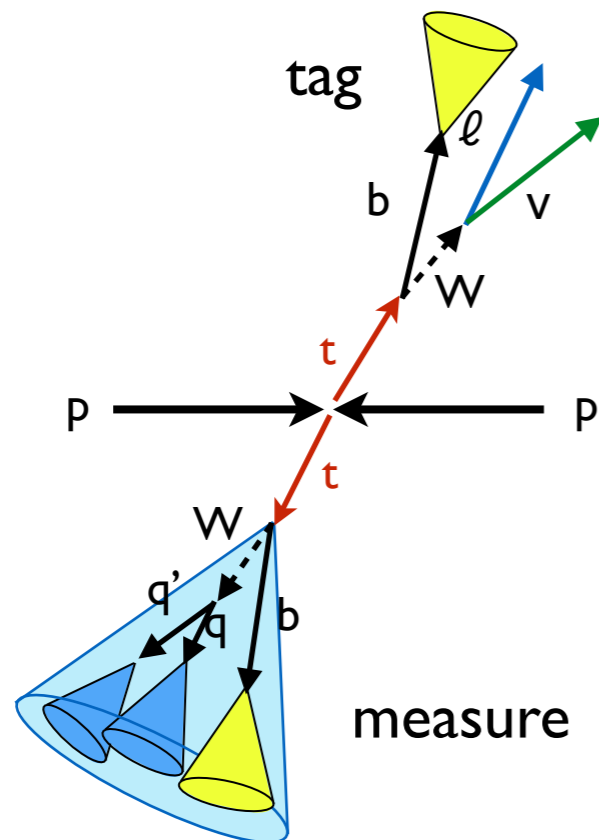
$m_t(m_t) = 165.0^{+1.8}_{-2.0}$ (tot) GeV [EPJC 79 (2019) 368]

- ▶ Achieved precision: Between 1.4-2.2 GeV in m_t

Jet Mass in pp

[A. H. Hoang et al., PRD 100 (2019), 074021]

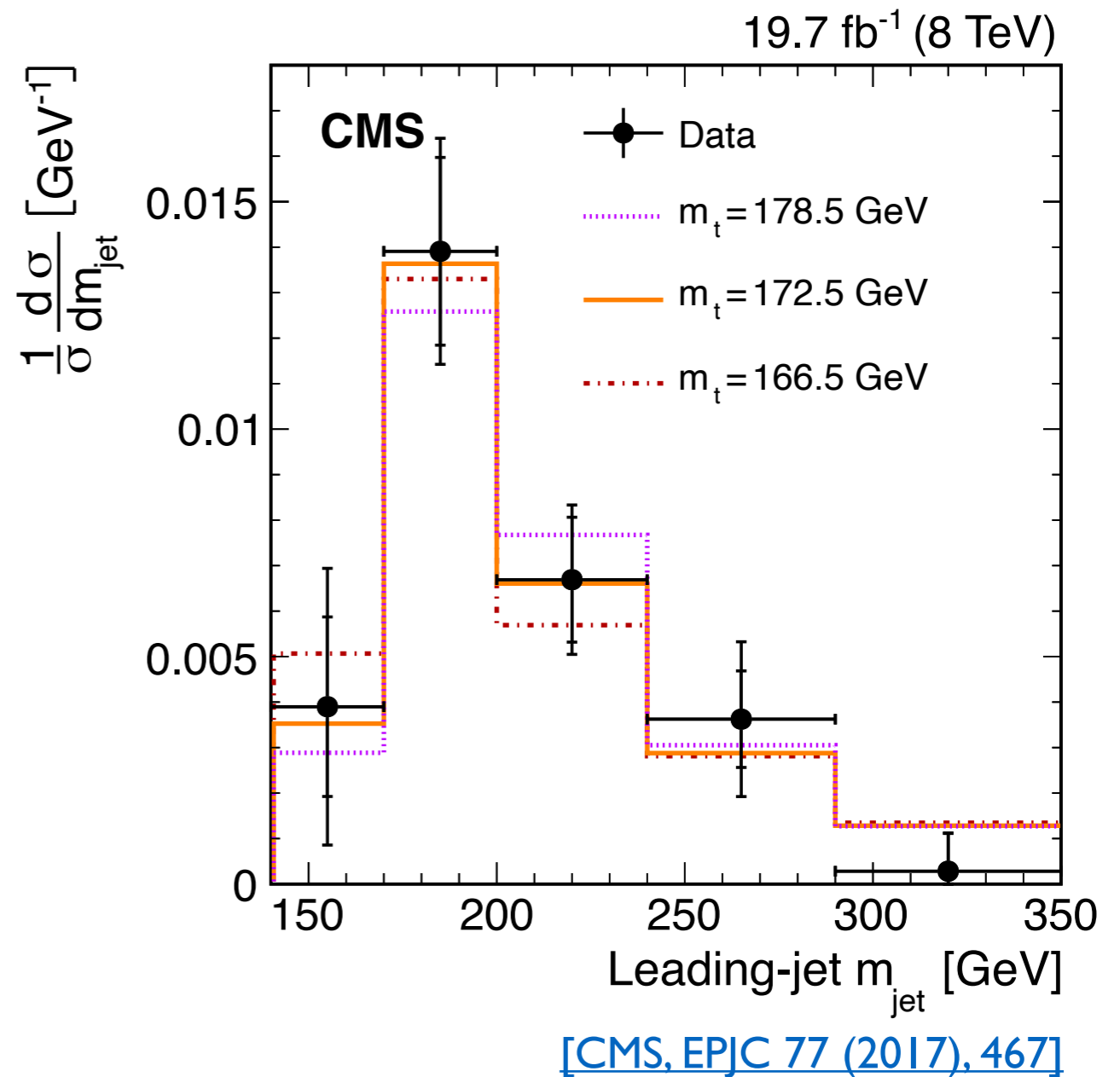
- ▶ Analytical calculation possible for fully-merged final states (SCET)
- ▶ Current calculations
 - Soft drop mass for $R=1.0$
 - $p_T > 750$ GeV



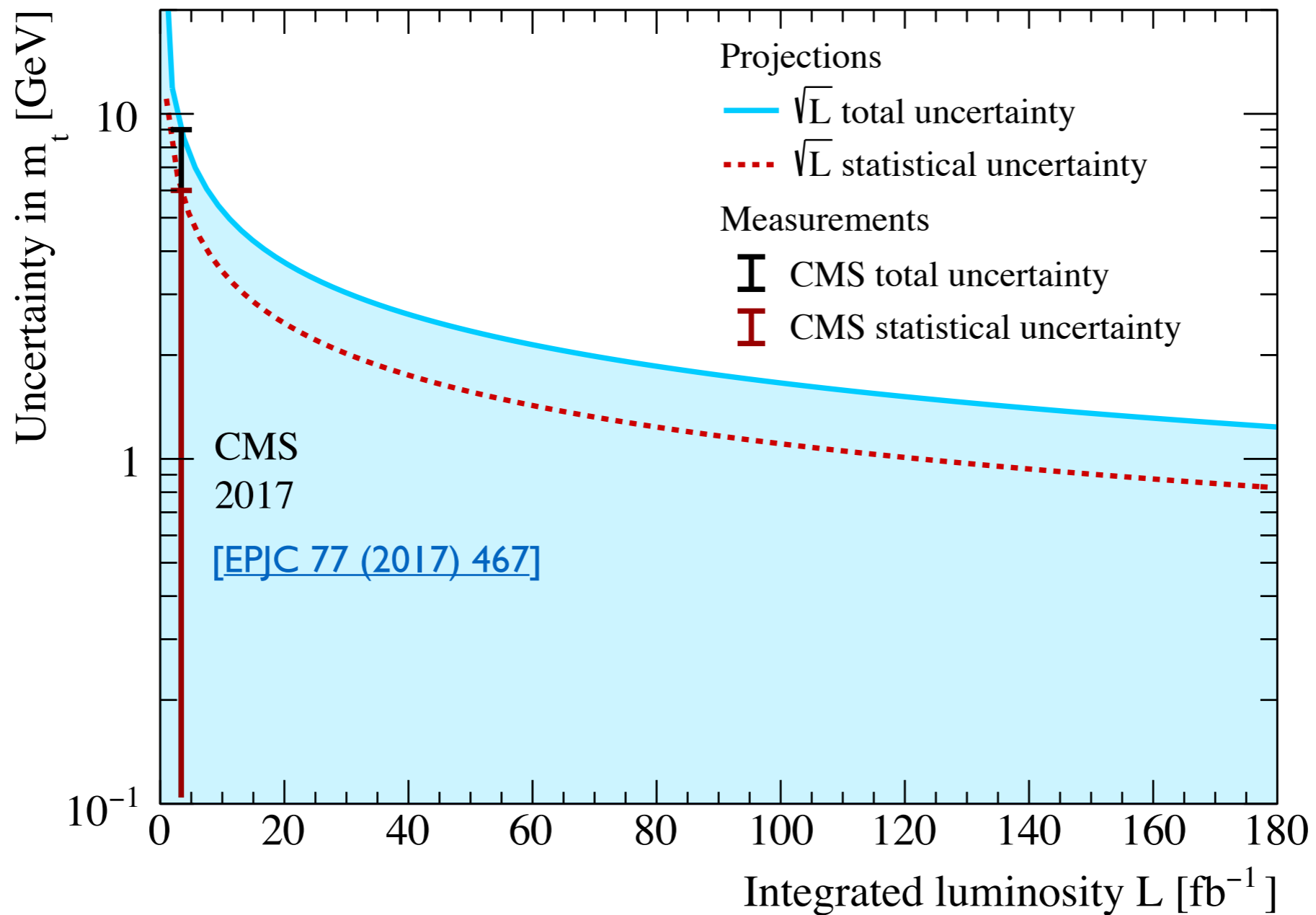
- ▶ Distribution in m_{jet}
 - Direct sensitivity to m_t
 - Can be measured at the LHC, at the level of stable particles

First measurement of m_{jet}

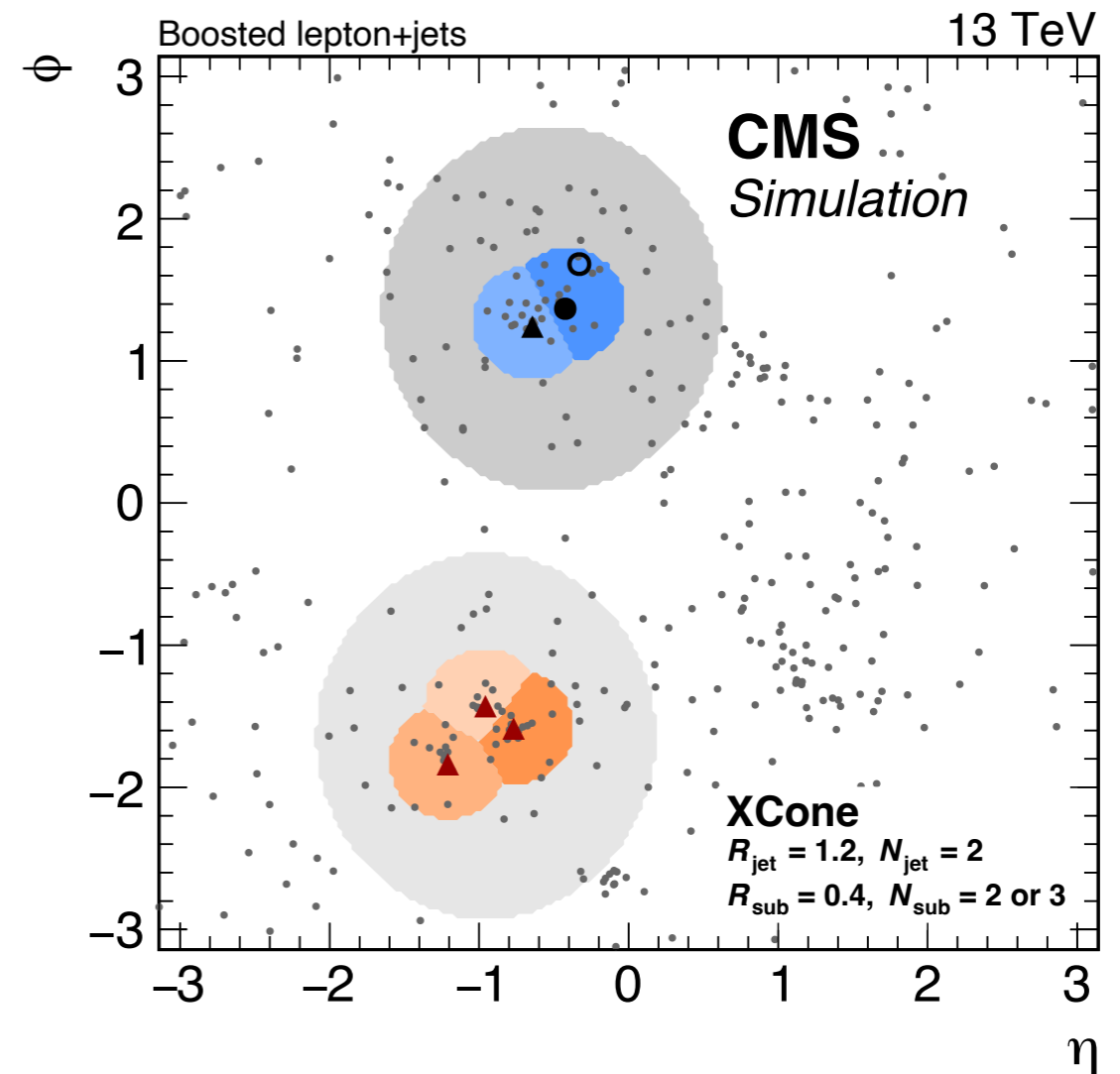
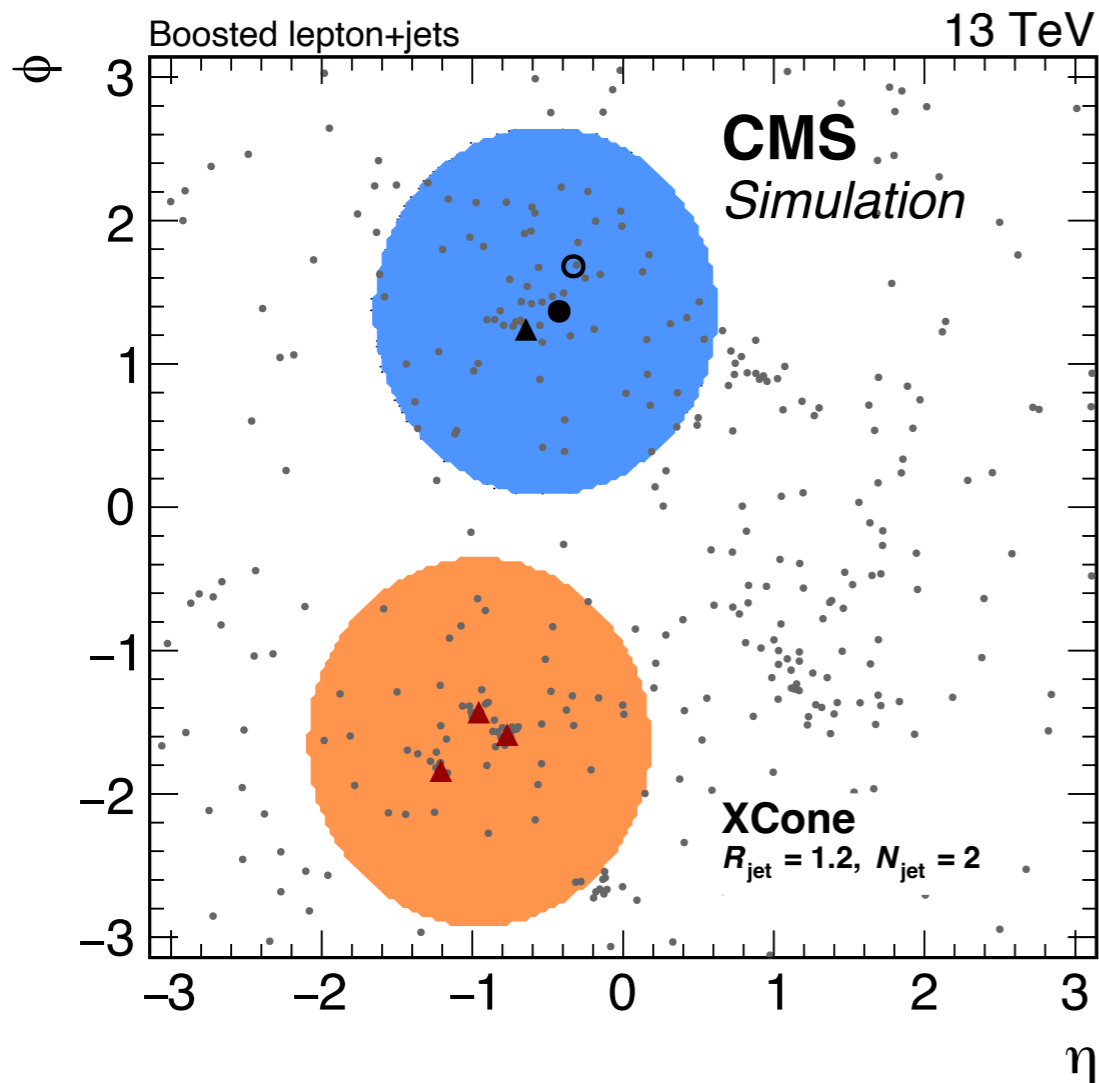
- ▶ Measurement at 8 TeV (2012 data)
 - ▶ Ungroomed jet mass for $R=1.2$
 - $p_T > 400$ GeV
 - Uncertainties on m_t :
 - ± 6 (stat)
 - ± 2.8 (syst)
 - ± 6 (theo)
-
- ± 9 (tot)



What do we expect?



New Techniques: XCone

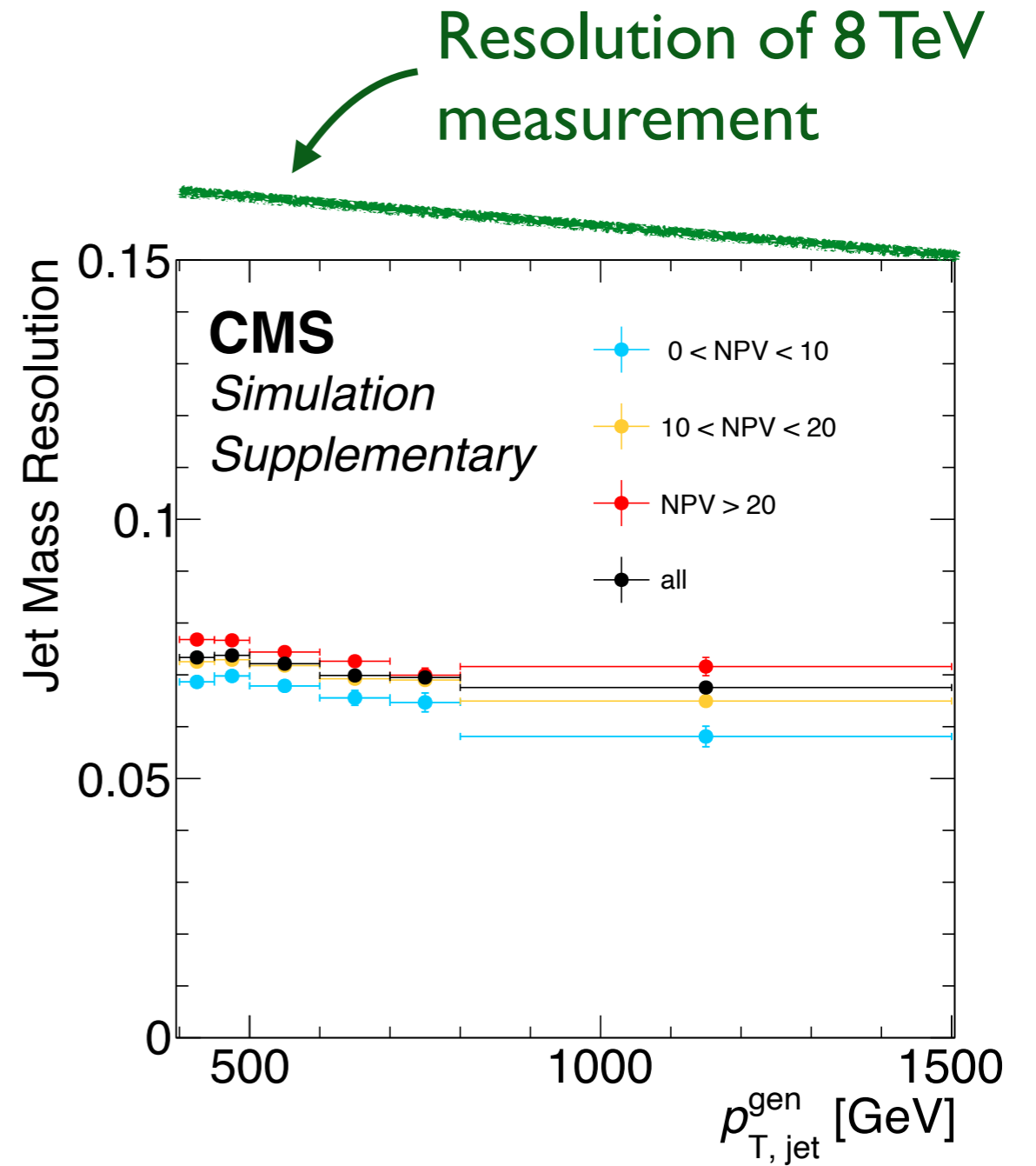
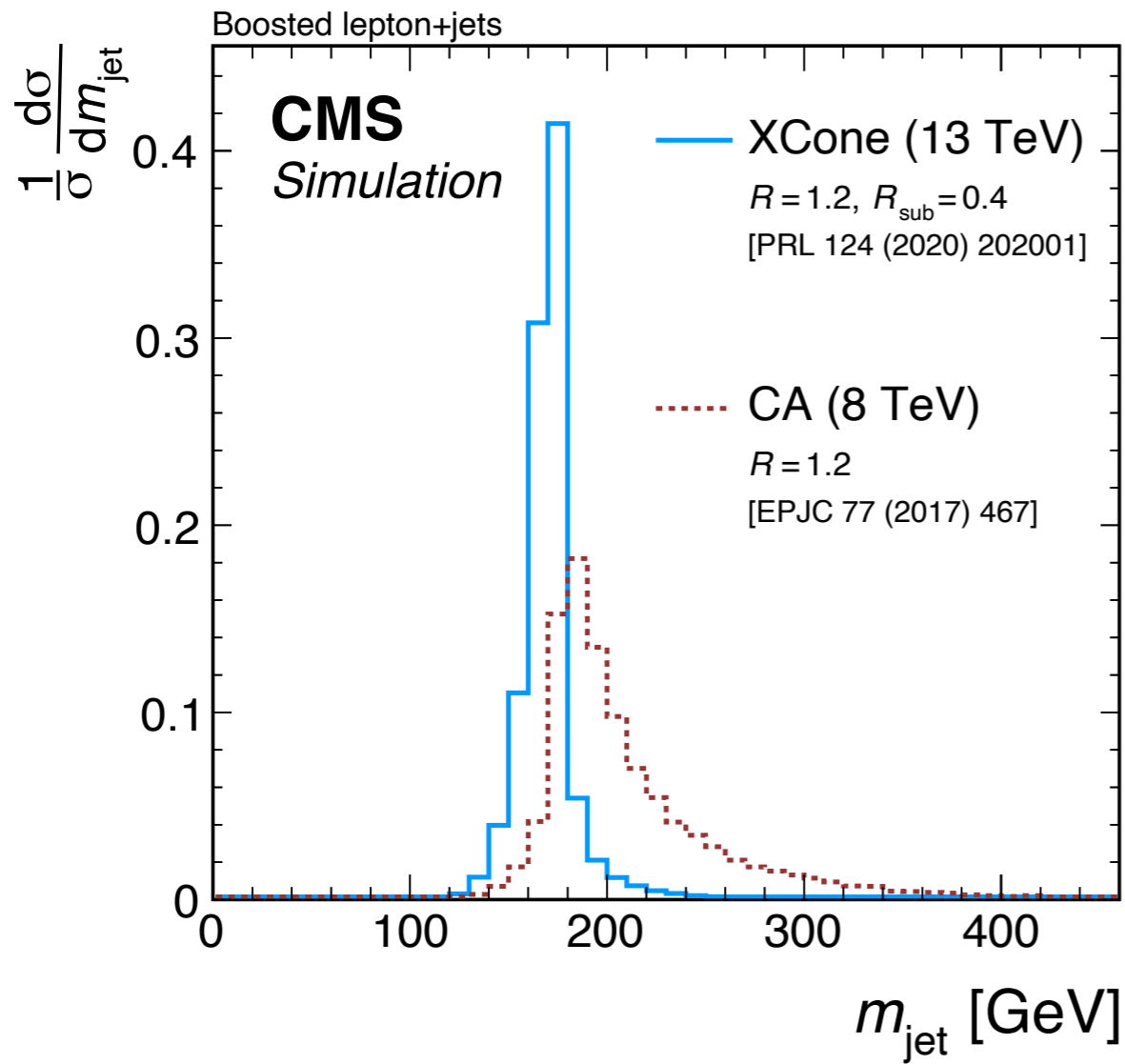


2-step jet clustering

- ▶ Inherent grooming
- ▶ Dynamical effective radius

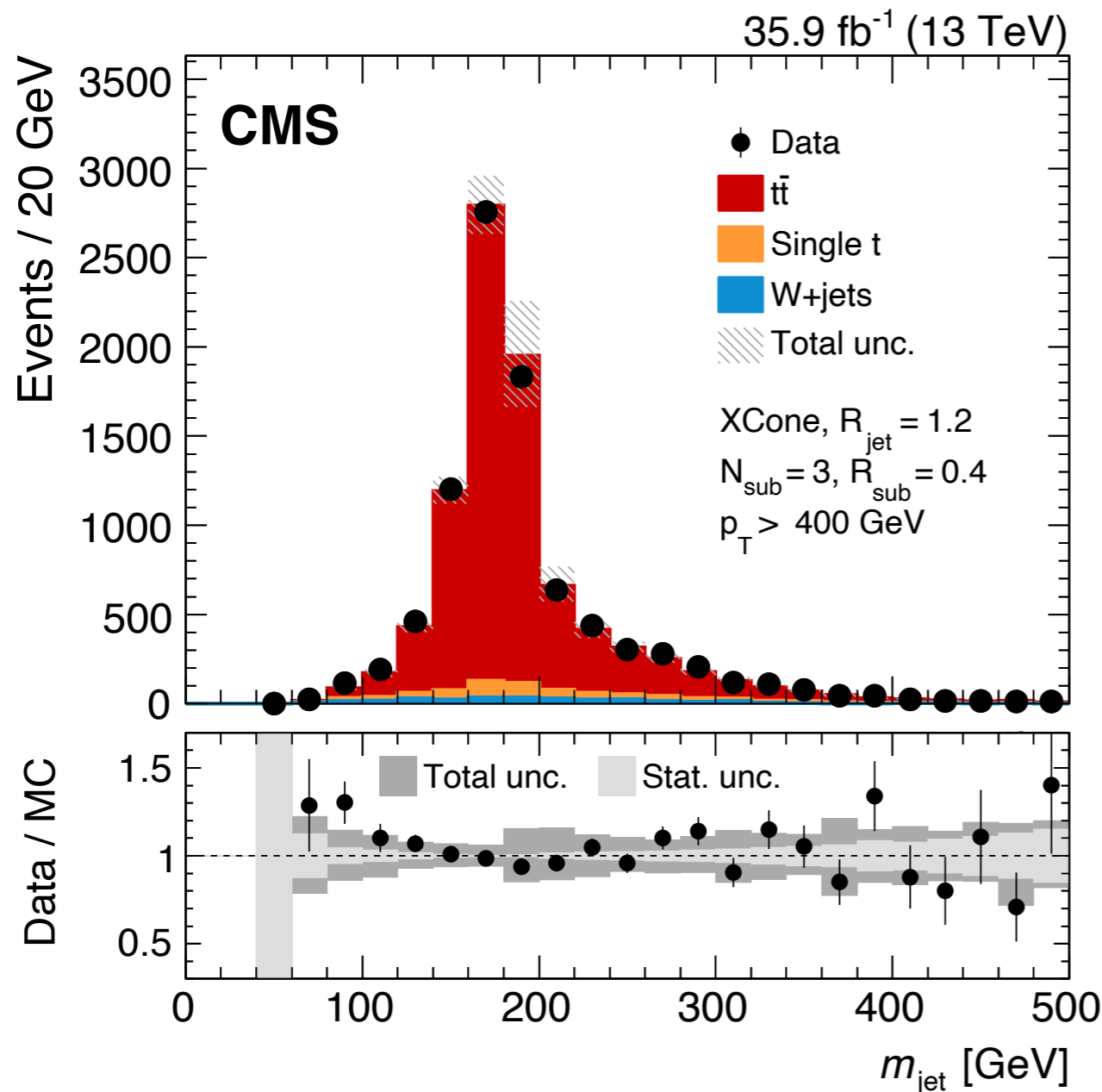
[[CMS, PRL 124, 202001 \(2020\)](#)]

Lineshape and Resolution



[CMS, TOP-19-005]

Jet mass with XCone

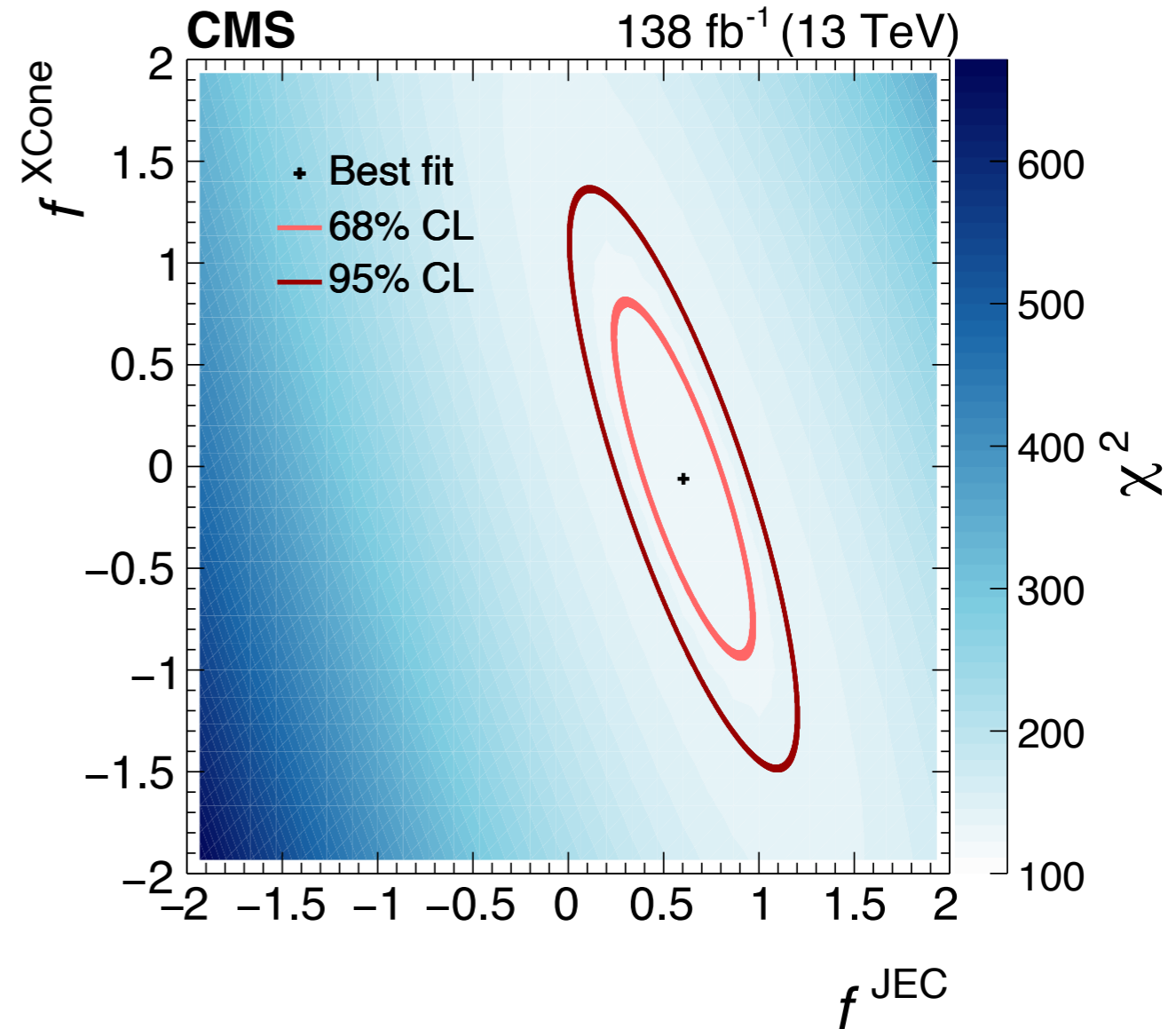
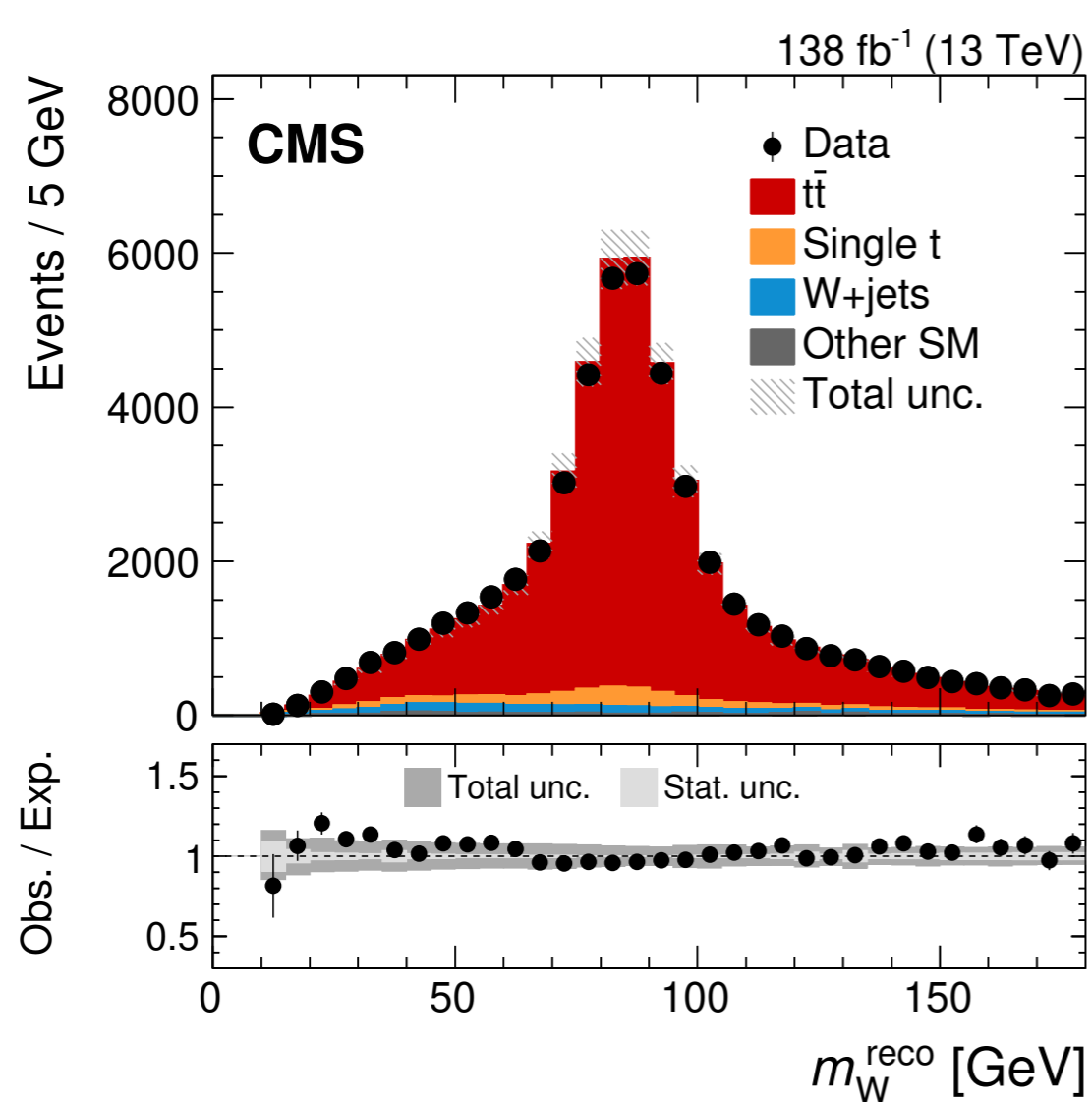


- ▶ Improved statistical uncertainty
- ▶ Less susceptibility to UE and hadronization
- ▶ Unfolding to particle level:
 - Reduction of all uncertainties
- ▶ $m_t = 172.6 \pm 2.5$ GeV

[CMS, PRL 124, 202001 (2020)]

Jetmass: Further Improvements

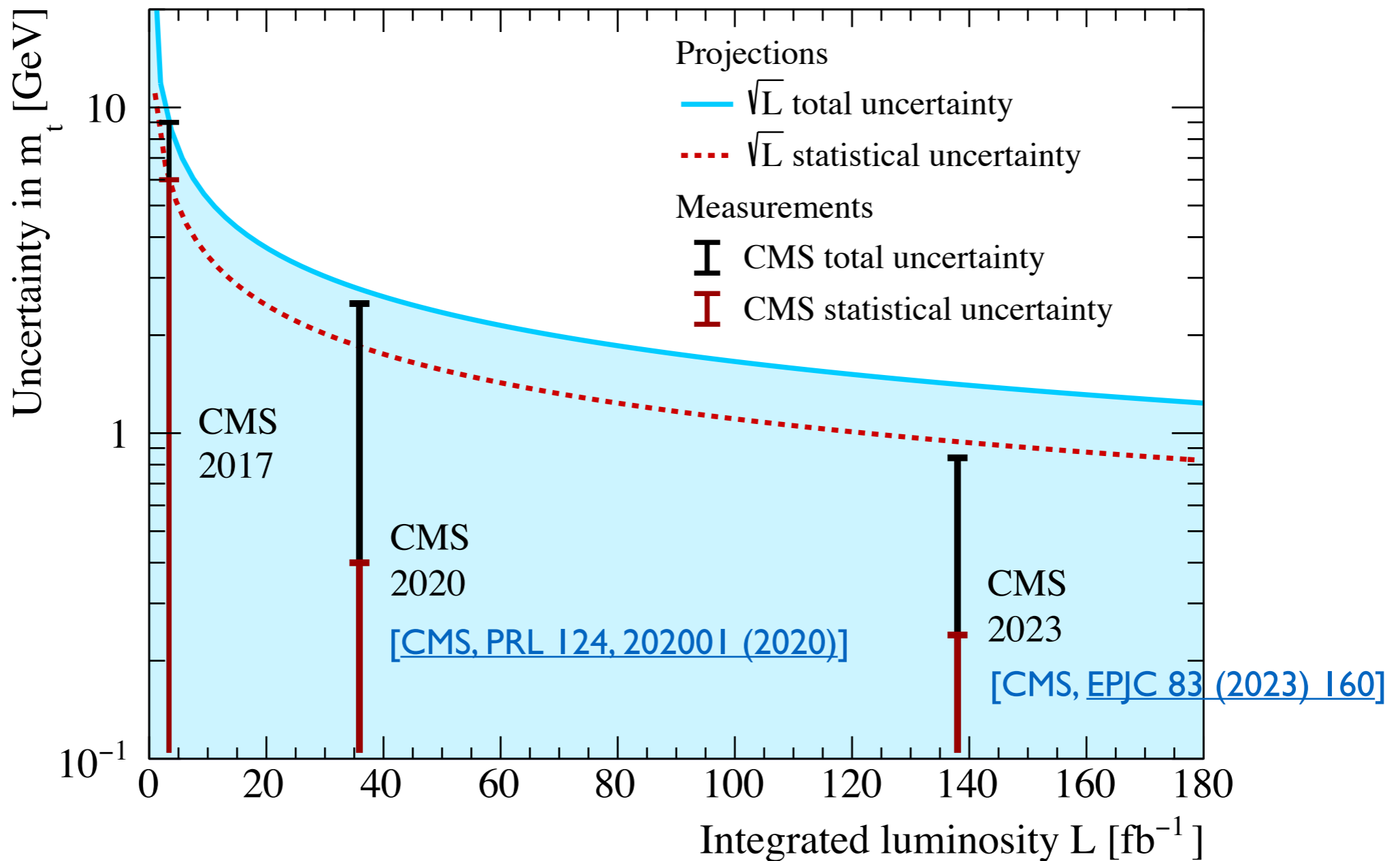
- ▶ XCone method allows for calibration of jet mass scale using m_W



- ▶ Additionally:
FSR modelling constrained through jet substructure

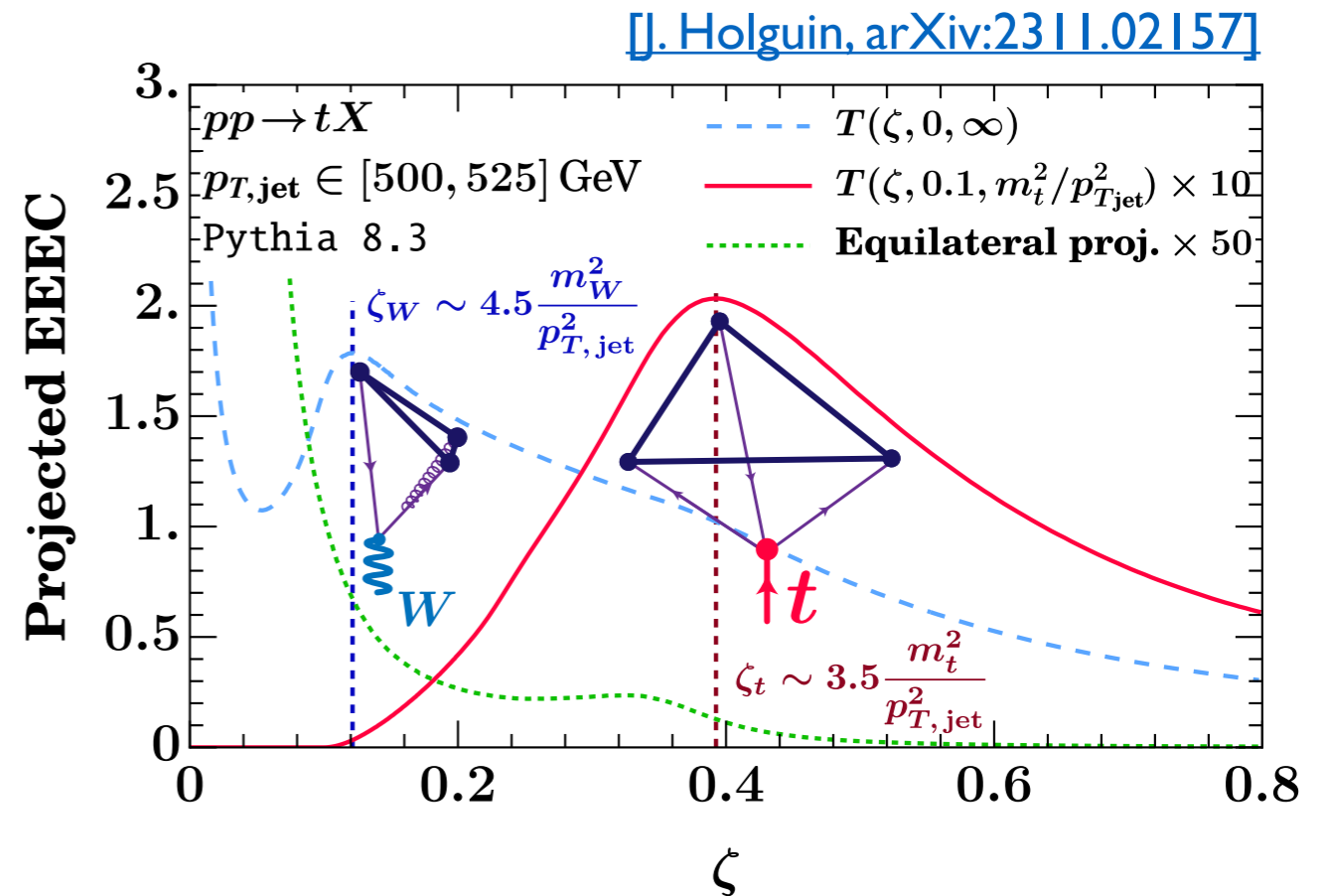
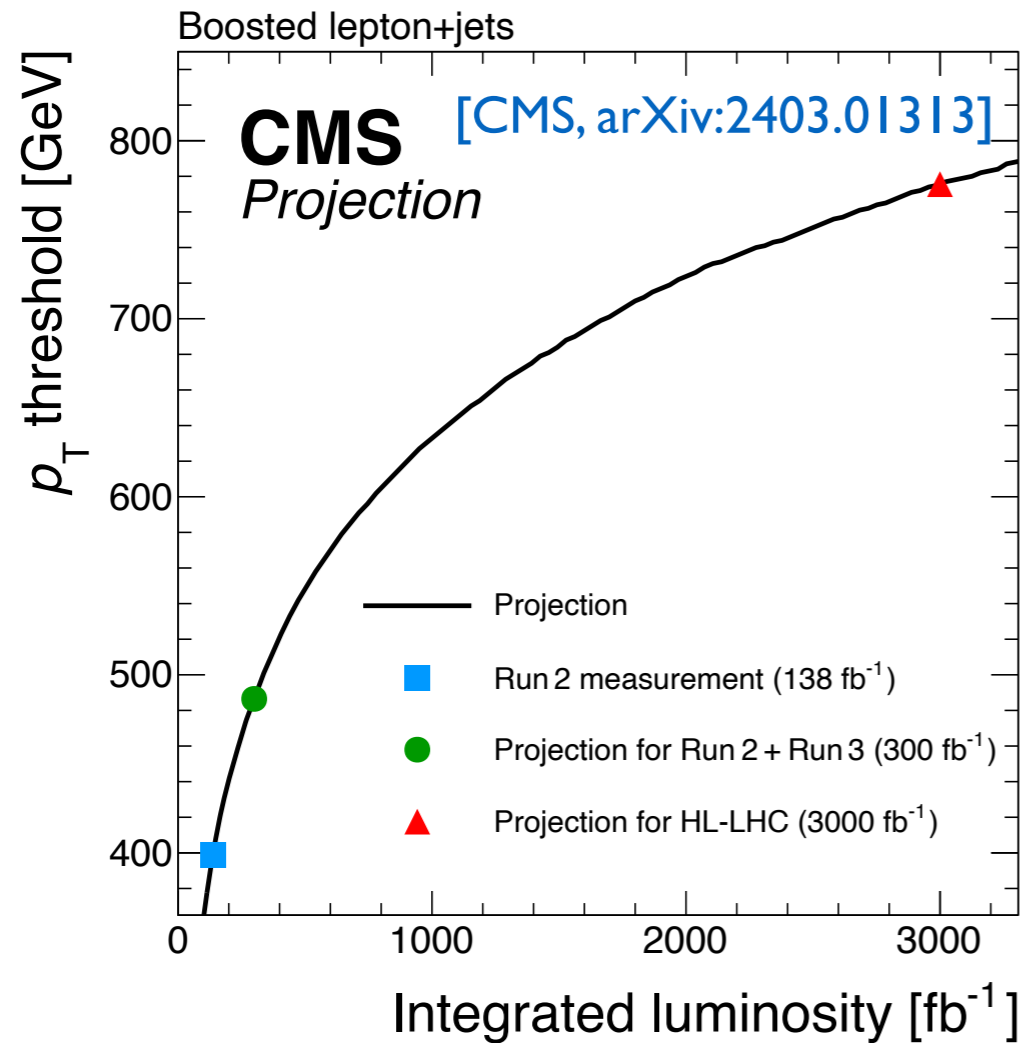
[CMS, EPJC 83 (2023) 160]

Summary on m_t from m_{jet}



[A. Belvedere, C. Englert, R. Kogler, M. Spannowsky, EPJ C84, 715 (2024)]

Future of m_t from Jetmass



Measuring top/W ratio turns

$$\zeta^{\text{peak}} \sim \left(\frac{m_t^2}{p_{T,\text{jet}}^2} \right) \rightarrow \left(\frac{m_t^2}{p_{T,\text{jet}}^2} \frac{p_{T,\text{jet}}^2}{m_W^2} \right) = \left(\frac{m_t^2}{m_W^2} \right)$$

- ▶ New techniques in development, more data coming

3rd Example: Higgs Physics (Going Differential)

Higgs Physics

Study sensitivity of measurements in EFT framework

- ▶ Focus on operators with Higgs involvement
- ▶ Do not consider operators constrained by EWPO
- ▶ 8 operators of interest left

$$\begin{aligned}
 \mathcal{L}_{\text{SILH}} = & \frac{\bar{c}_H}{2v^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{\bar{c}_T}{2v^2} \left(H^\dagger \overleftrightarrow{D}^\mu H \right) \left(H^\dagger \overleftrightarrow{D}_\mu H \right) - \frac{\bar{c}_6 \lambda}{v^2} (H^\dagger H)^3 \\
 & + \left(\frac{\bar{c}_{u,i} y_{u,i}}{v^2} H^\dagger H \bar{u}_L^{(i)} H^c u_R^{(i)} + \text{h.c.} \right) + \left(\frac{\bar{c}_{d,i} y_{d,i}}{v^2} H^\dagger H \bar{d}_L^{(i)} H d_R^{(i)} + \text{h.c.} \right) \\
 & + \frac{i\bar{c}_W g}{2m_W^2} \left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H \right) (D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B g'}{2m_W^2} \left(H^\dagger \overleftrightarrow{D}^\mu H \right) (\partial^\nu B_{\mu\nu}) \\
 & + \frac{i\bar{c}_{HW} g}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{i\bar{c}_{HB} g'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
 & + \frac{\bar{c}_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}.
 \end{aligned}$$

Focus on linear contribution: $\mathcal{M} = \mathcal{M}_{\text{SM}} + \mathcal{M}_{d=6}$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2 \text{Re}\{\mathcal{M}_{\text{SM}} \mathcal{M}_{d=6}^*\} + \mathcal{O}(1/\Lambda^4)$$

[C. Englert et al., EPJC 76 (2016), 393]

Sensitivity Estimate

Results from Run 1+2

- ▶ Include all available Higgs measurements from ATLAS and CMS
- ▶ 77 signal strength measurements included

Future Prospects

- ▶ Generate pseudo-data using realistic assumptions for efficiencies and systematic uncertainties

Included production
and decay modes
(including theory unc.)

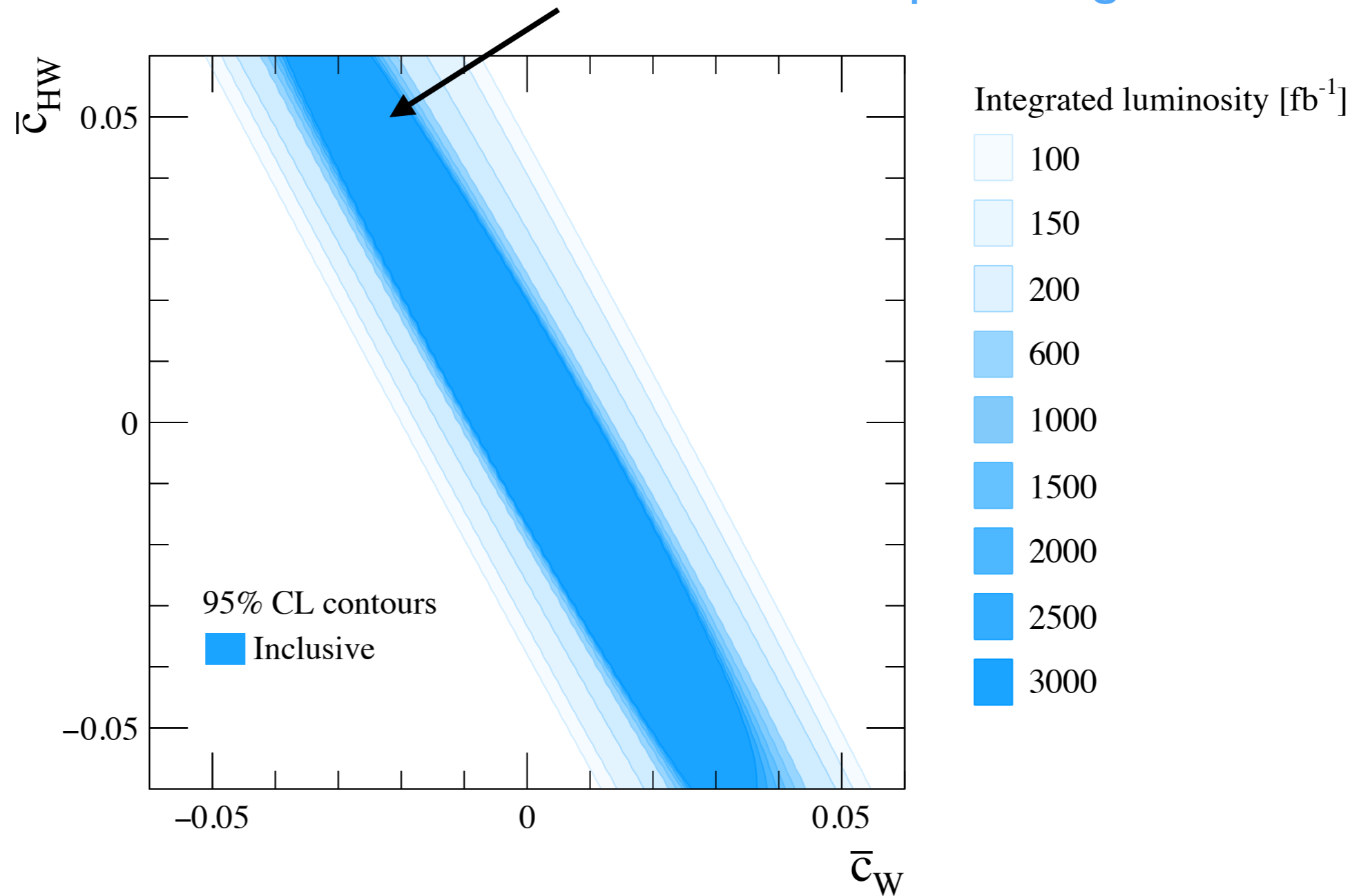
production process		decay process	
$pp \rightarrow H$	14.7	$H \rightarrow bb$	6.1
$pp \rightarrow H + j$	15	$H \rightarrow \gamma\gamma$	5.4
$pp \rightarrow H + 2j$	15	$H \rightarrow \tau^+\tau^-$	2.8
$pp \rightarrow HZ$	5.1	$H \rightarrow 4l$	4.8
$pp \rightarrow HW$	3.7	$H \rightarrow 2l2\nu$	4.8
$pp \rightarrow t\bar{t}H$	12	$H \rightarrow \mu^+\mu^-$	2.8

Number of predicted events:
$$N_{\text{th}} = \sigma(H + X) \times \text{BR}(H \rightarrow YY) \times \mathcal{L} \times \text{BR}(X, Y \rightarrow \text{final state})$$

Each channel has own prod. and decay efficiencies:
$$N_{\text{ev}} = \epsilon_p \epsilon_d N_{\text{th}}$$

EFT Constraints: Inclusive

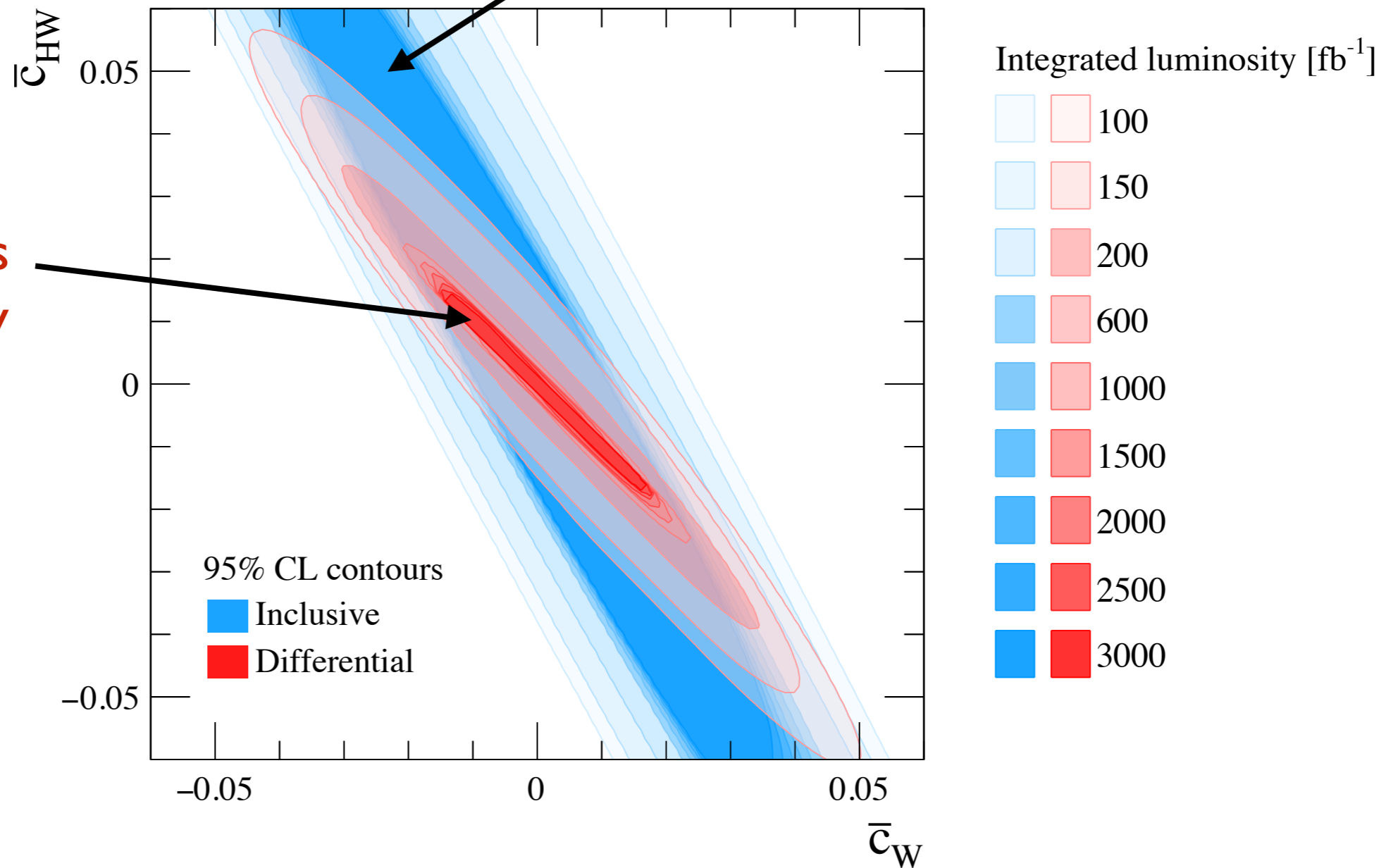
Blind directions in SMEFT fits: compensating effects



EFT Constraints: Differential

Blind directions in SMEFT fits: compensating effects

Differential measurements lift degeneracy

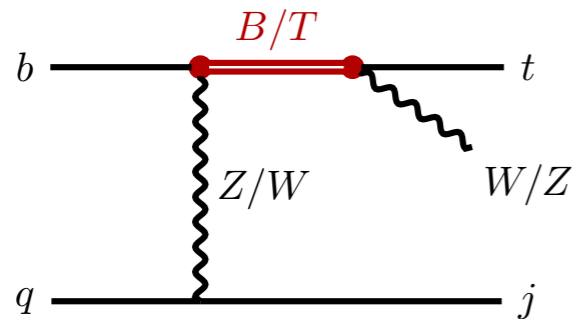


Major improvement in sensitivity with same data!

[A. Belvedere, C. Englert, R. Kogler, M. Spannowsky, EPJC84, 715 (2024)]

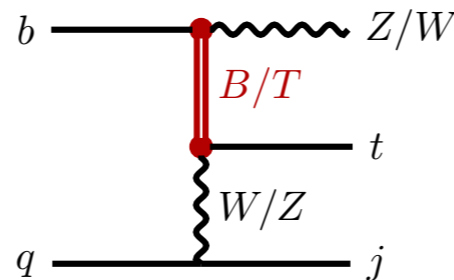
4th Example: $pp \rightarrow tWZ$ (Rare Processes)

Top-Electroweak Interactions



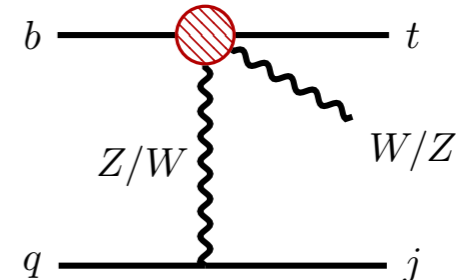
s-channel BSM

Sensitivity to narrow resonances



t-channel BSM

Access large width



Effective field theory

Generalisation of BSM effects

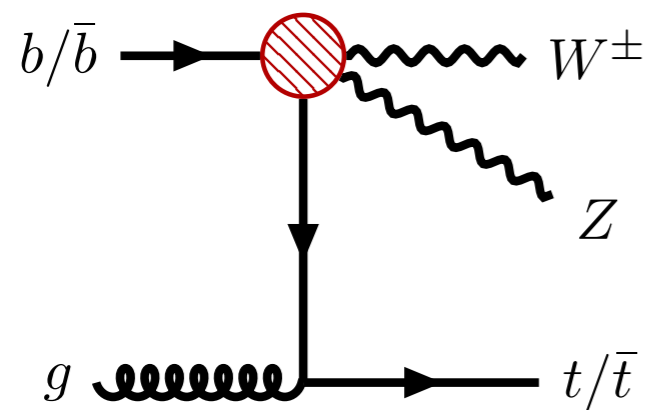
- ▶ Complement direct searches by SM measurements sensitive to dim-6 operators
 - Similar to BSM t-channel exchange for large mass/width resonances
 - Probe large uncharted parameter space
- ▶ Sensitivity to dim-6 operators increases $\sim E$ and $\sim E^2$
 - Differential measurements of very rare single-top associated production
- ▶ Constrain top-EW interactions with global fits in EFT parameter space
 - Better sensitivity than from $t\bar{t}Y$, $t\bar{t}W$, $t\bar{t}Z$ or $t\bar{t}H$ measurements
- ▶ Improve the physics potential of the (HL-)LHC

Top-Electroweak Interactions

BSM effects in top-EW section poorly constrained

- ▶ $pp \rightarrow tWZ$ powerful probe of BSM effects

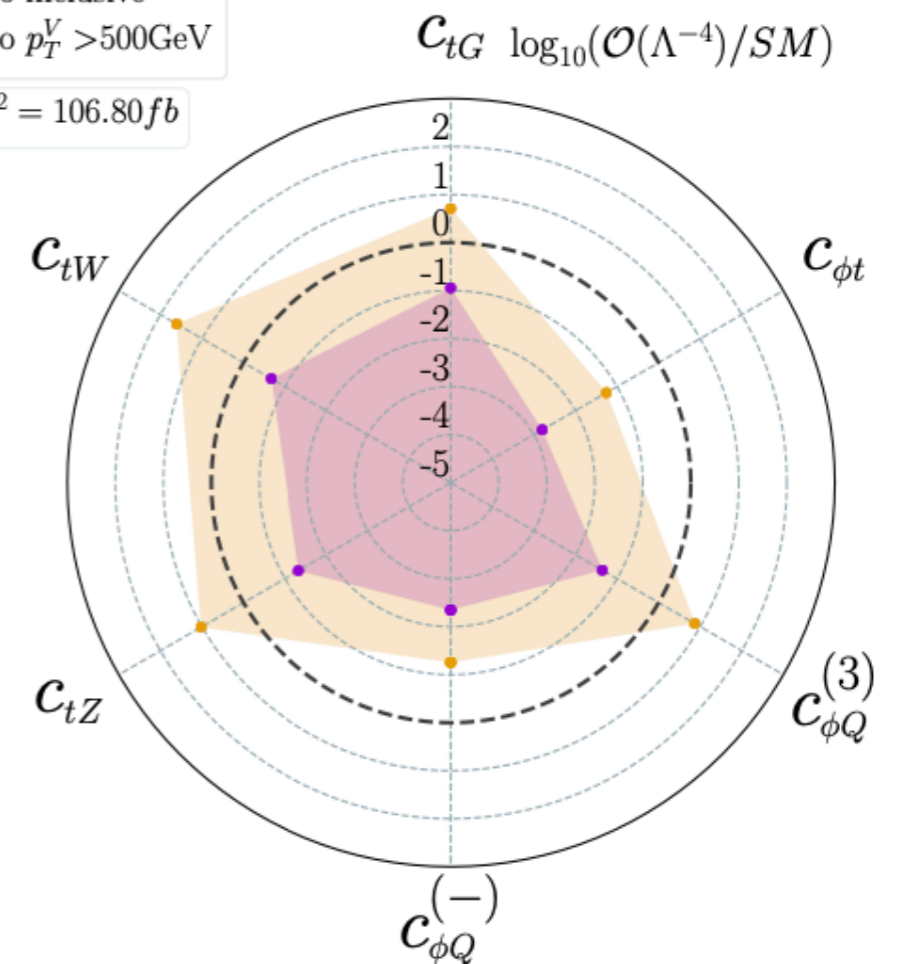
[F. Maltoni, L. Mantani, K. Mimasu, [JHEP 10 \(2019\) 004](#)]



Sensitivity to:

$$\begin{matrix} \mathcal{O}_{tW} & \mathcal{O}_{tZ} \\ \mathcal{O}_{\phi Q}^{(3)} & \mathcal{O}_{\phi tb} \end{matrix}$$

● b -veto inclusive
● b -veto $p_T^V > 500\text{GeV}$
 $\sigma_{SM}^{DR2} = 106.80\text{fb}$



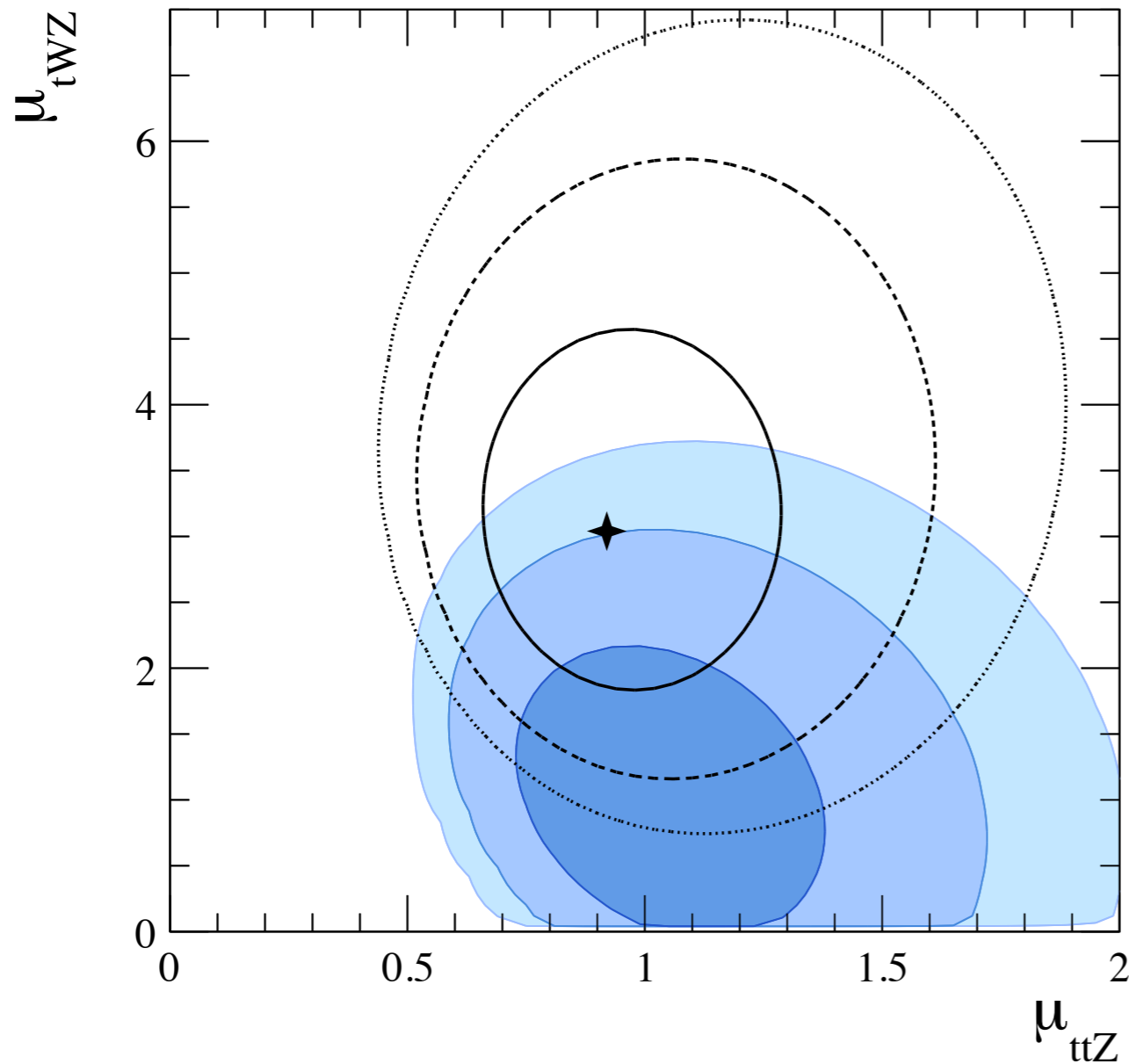
- ▶ Small cross section of 127 fb on top of large irreducible background: ttZ (and other reducible ones of same size)
- ▶ Recent evidence for tWZ production by CMS

[[CMS,PLB 855 \(2024\) 138815](#)]

- ▶ New physics could arise from $bW \rightarrow tZ$ vertices leading to anomalous energy growth

CMS Measurement (Recast)

Signal strengths in ttZ and tWZ



Expected signal strengths

■ 68% CL

■ 95% CL

■ 99% CL

Observed signal strengths

— 68% CL

- - - 95% CL

..... 99% CL

Observed

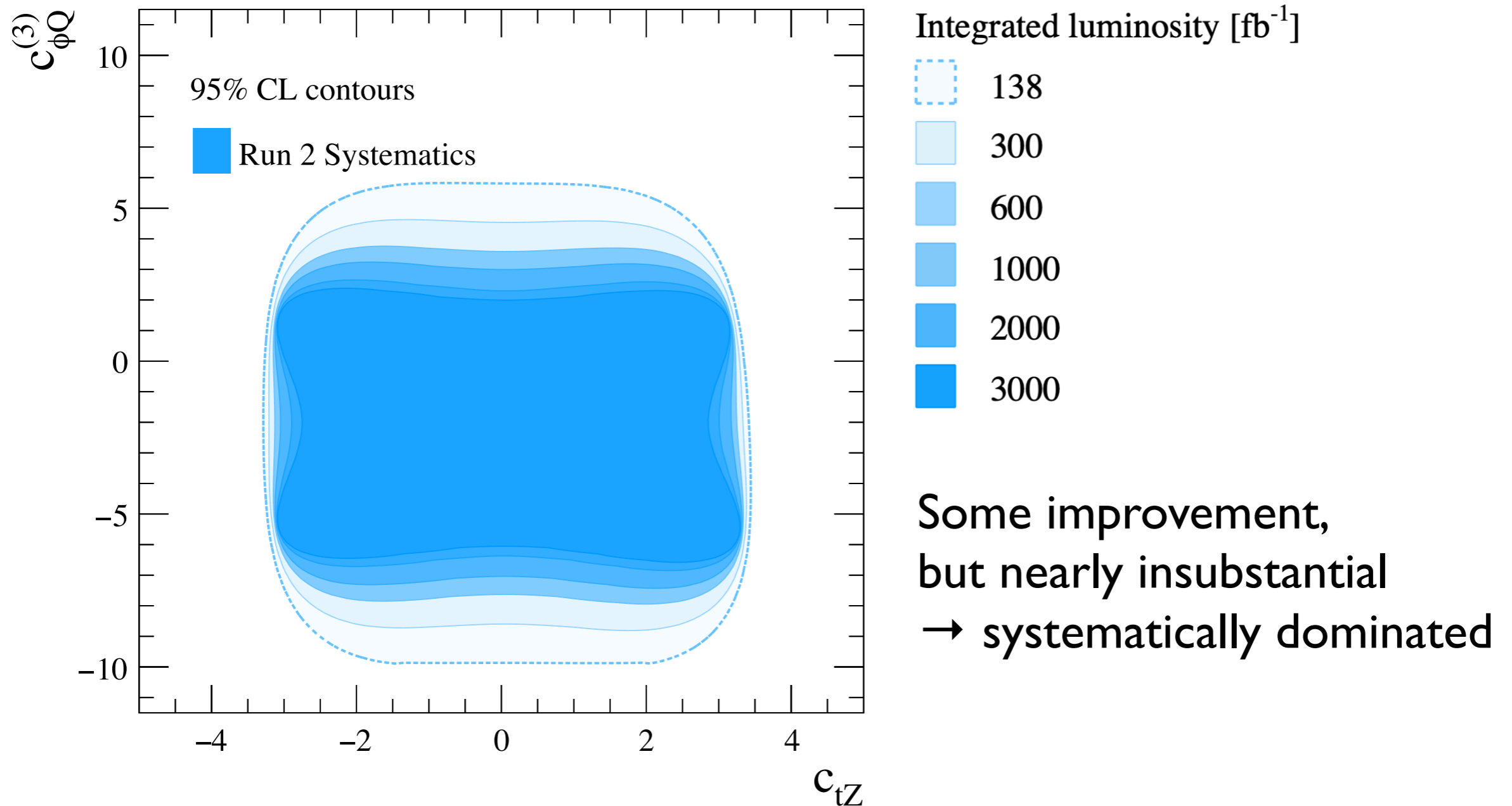
Best fit values: $\mu_{tWZ} = 3$, $\mu_{ttZ} = 0.92$

CMS values: $\mu_{tWZ} = 3.4$, $\mu_{ttZ} = 0.87$

Observed μ_{tWZ} is 2σ higher than SM.

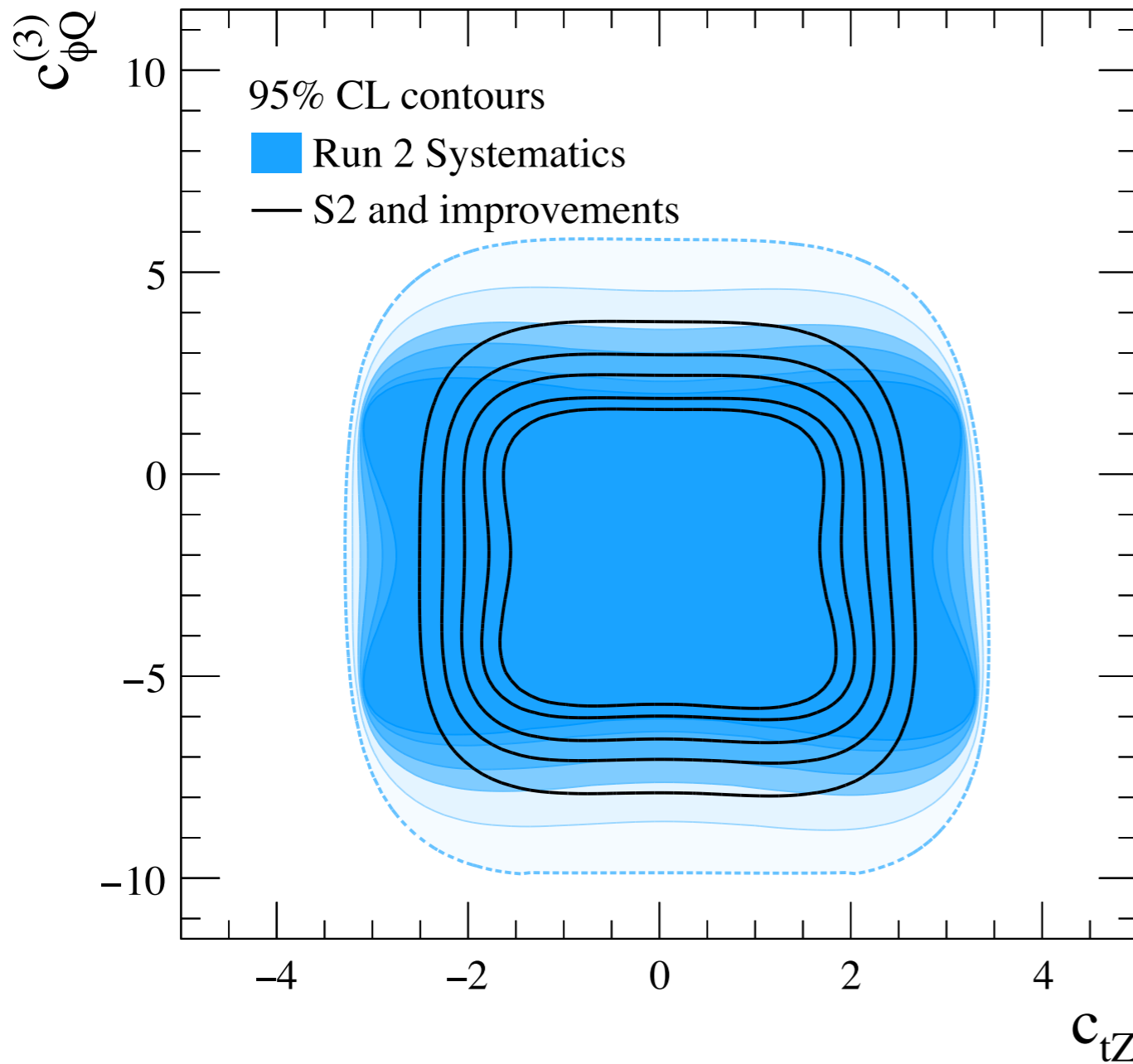
Extrapolation to HL-LHC

EFT constraints to probe sensitivity



Extrapolation to HL-LHC

EFT constraints to probe sensitivity



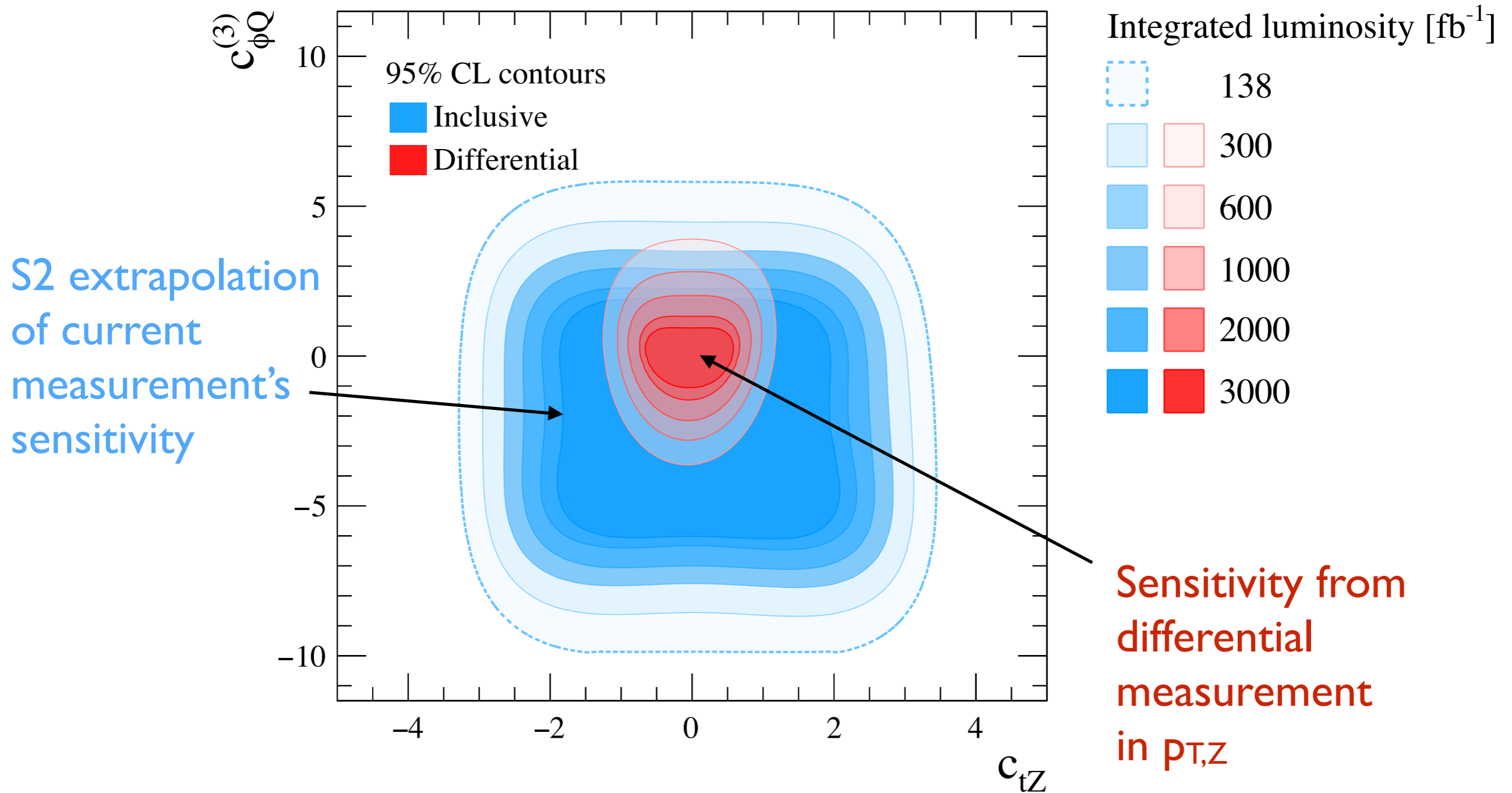
Integrated luminosity [fb^{-1}]



S2:

- ▶ Improve systematics to half the size at 3000 fb^{-1}
- ▶ Improve signal/background separation by 30%

Change Strategy: Differential



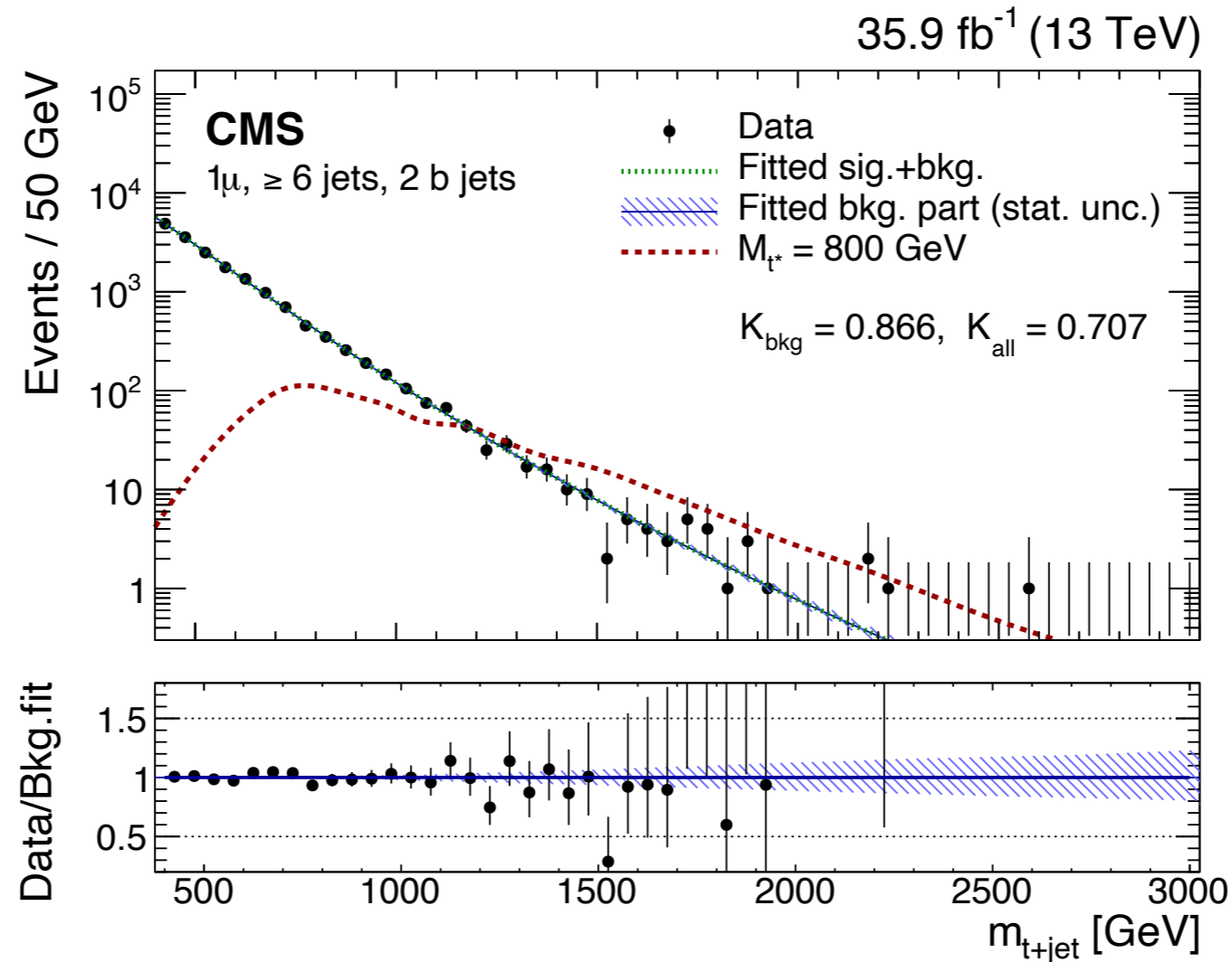
[A. Belvedere, C. Englert, R. Kogler, M. Spannowsky, EPJC84, 715 (2024)]

5th Example: Searches (Optimal Analysis Strategies)

$$t^* \rightarrow tg$$

CMS Result based on 36 fb^{-1} (2016 data)

- ▶ Search in reconstructed m_{t^*} spectrum
 - $1\mu, \geq 6$ jets, 2 b jets
 - Background: smoothly falling fit function

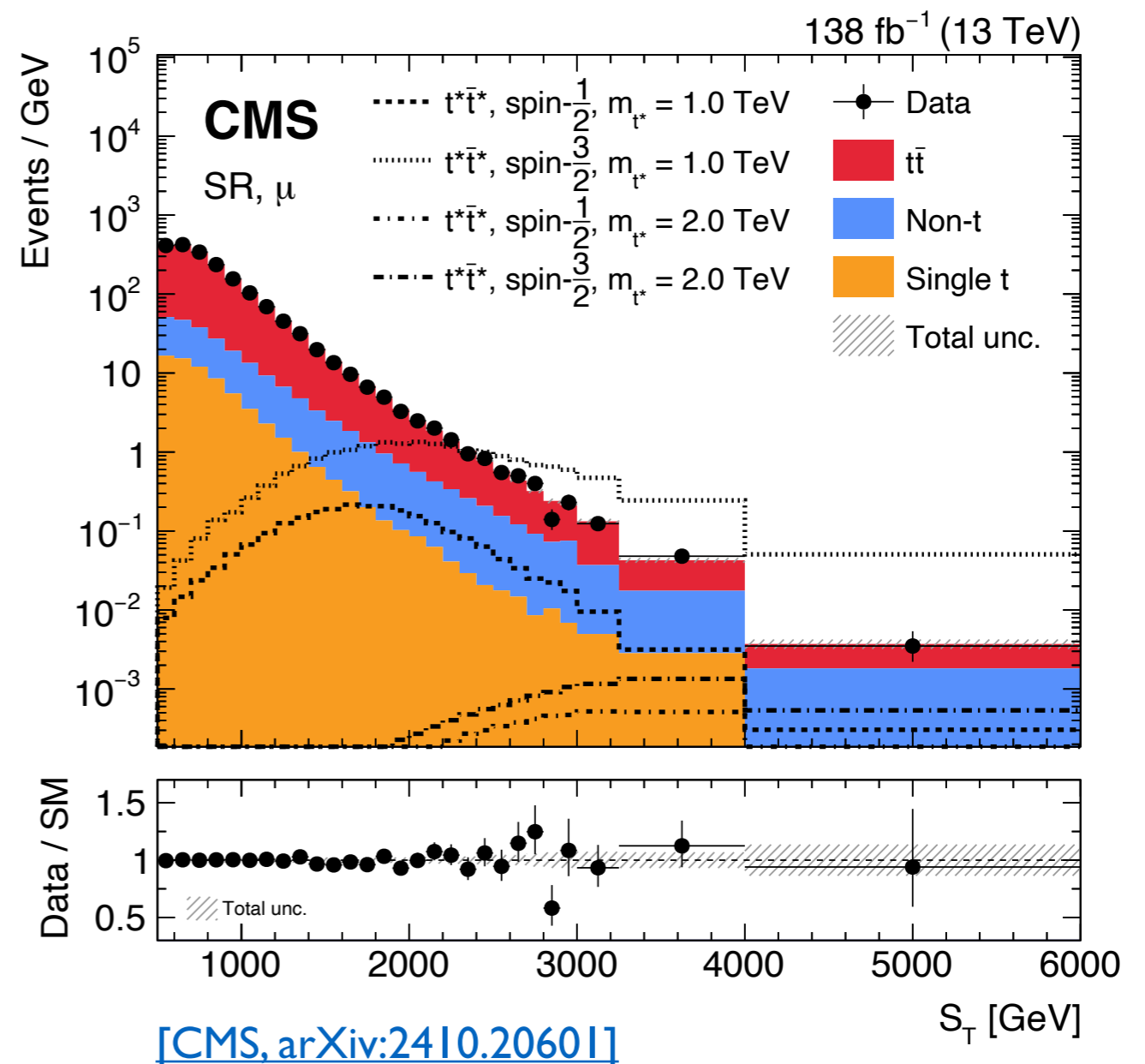


[CMS, PLB 778 (2018) 349]

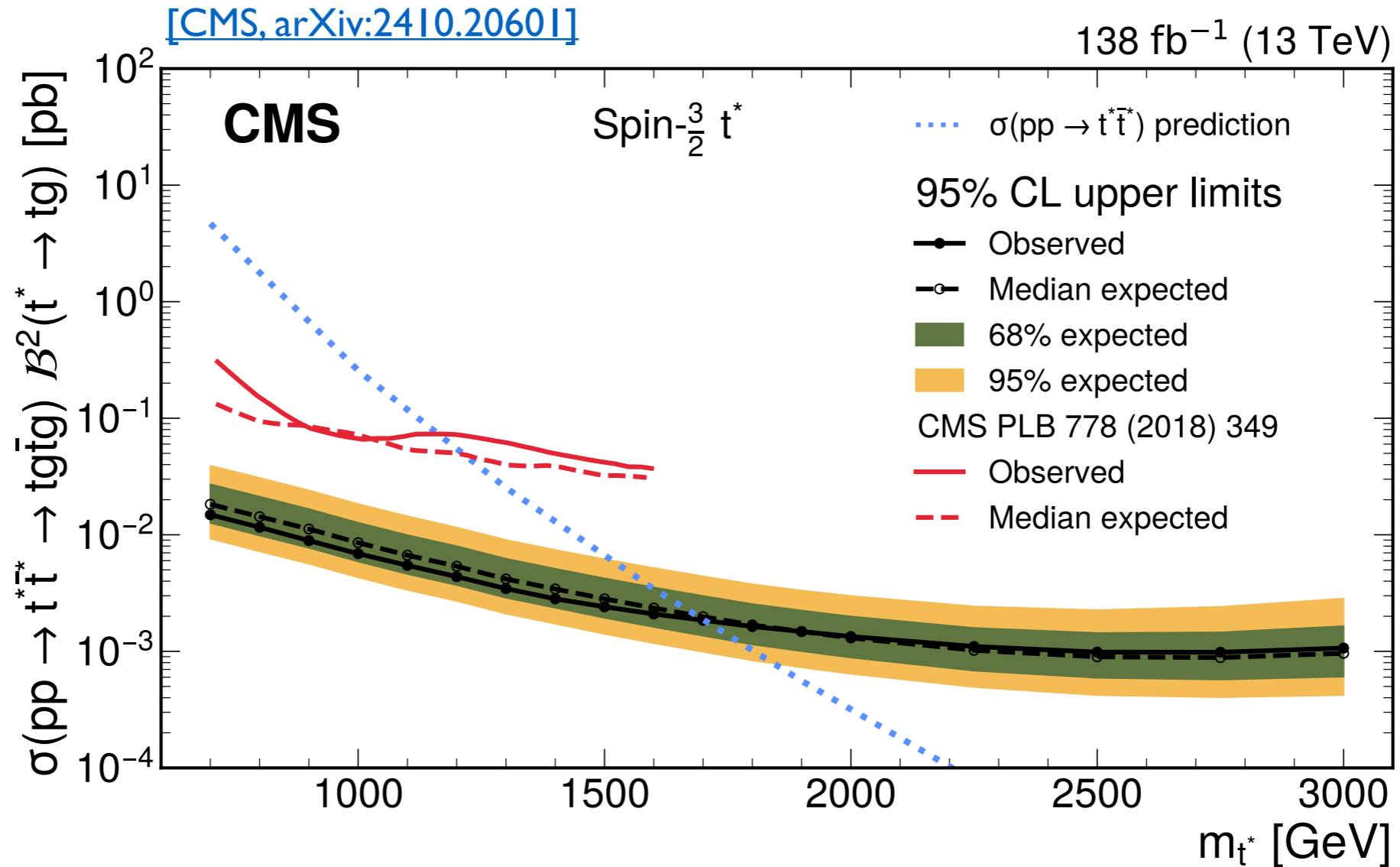
$t^* \rightarrow tg$: Run 2 Update

CMS Result based on full Run 2 data

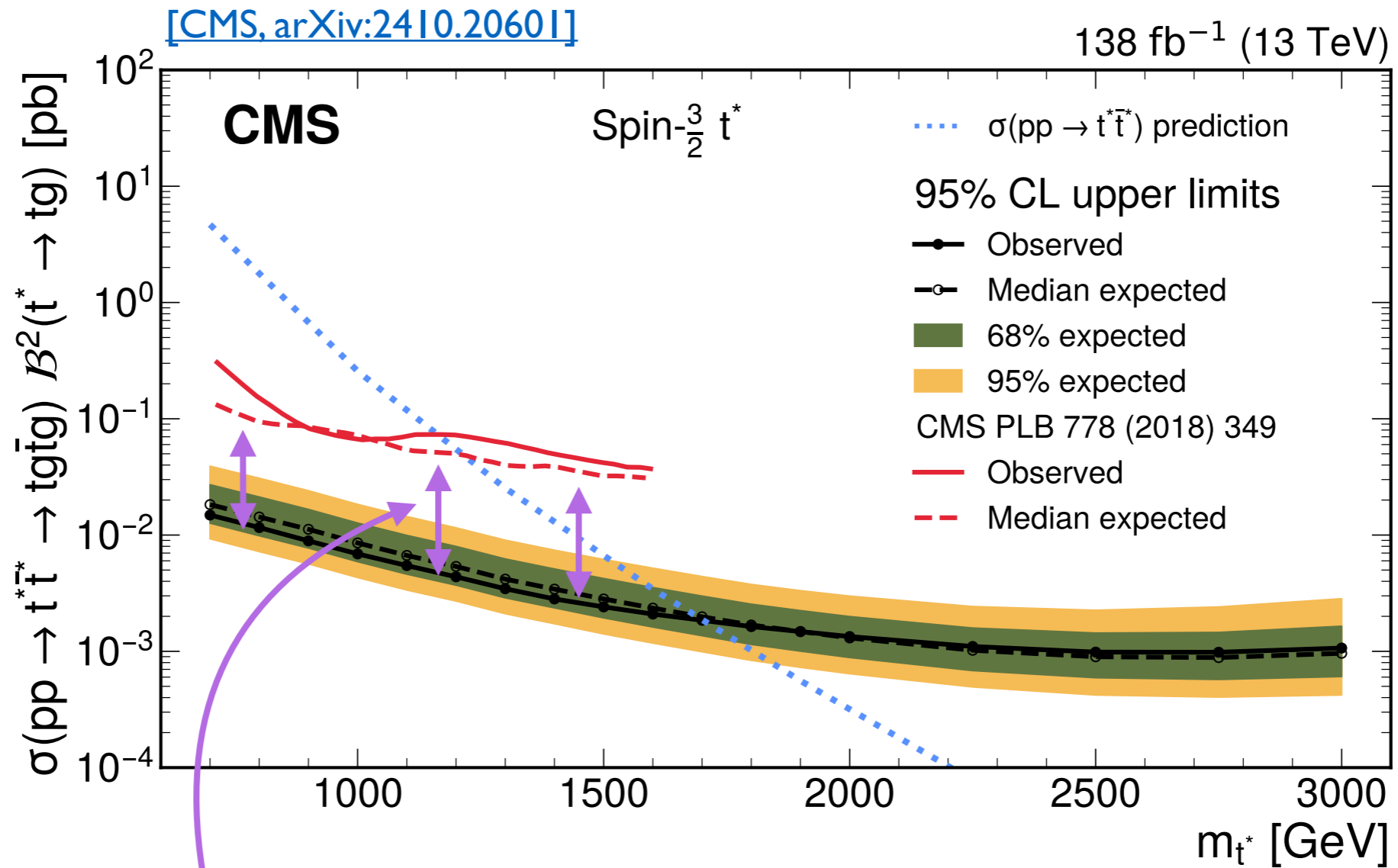
- ▶ Replaced reconstructed m_{t^*} by $S_T = p_T^\ell + p_T^{\text{miss}} + \sum p_T^{\text{jets}}$
- ▶ Include variable-radius jets
- ▶ ML to separate signal from background
- ▶ Background obtained from sideband region



Excited Top Quark Search



Excited Top Quark Search



Sensitivity improved by factor of 10!

Expected from \sqrt{s} scaling: factor 2

Conclusions

- ▶ We live in exciting times
 - Times will continue to be exciting

- ▶ Unprecedented physics potential of the HL-LHC

- Precision has been grossly underestimated, will improve **much better than \sqrt{L}**

- ▶ While we discuss the future in the context of the ESPP, the LHC will continue to deliver results with high precision / high sensitivity
- ▶ **New techniques, uncovered corners of phase space, theory developments and bright ideas will shape the field**

