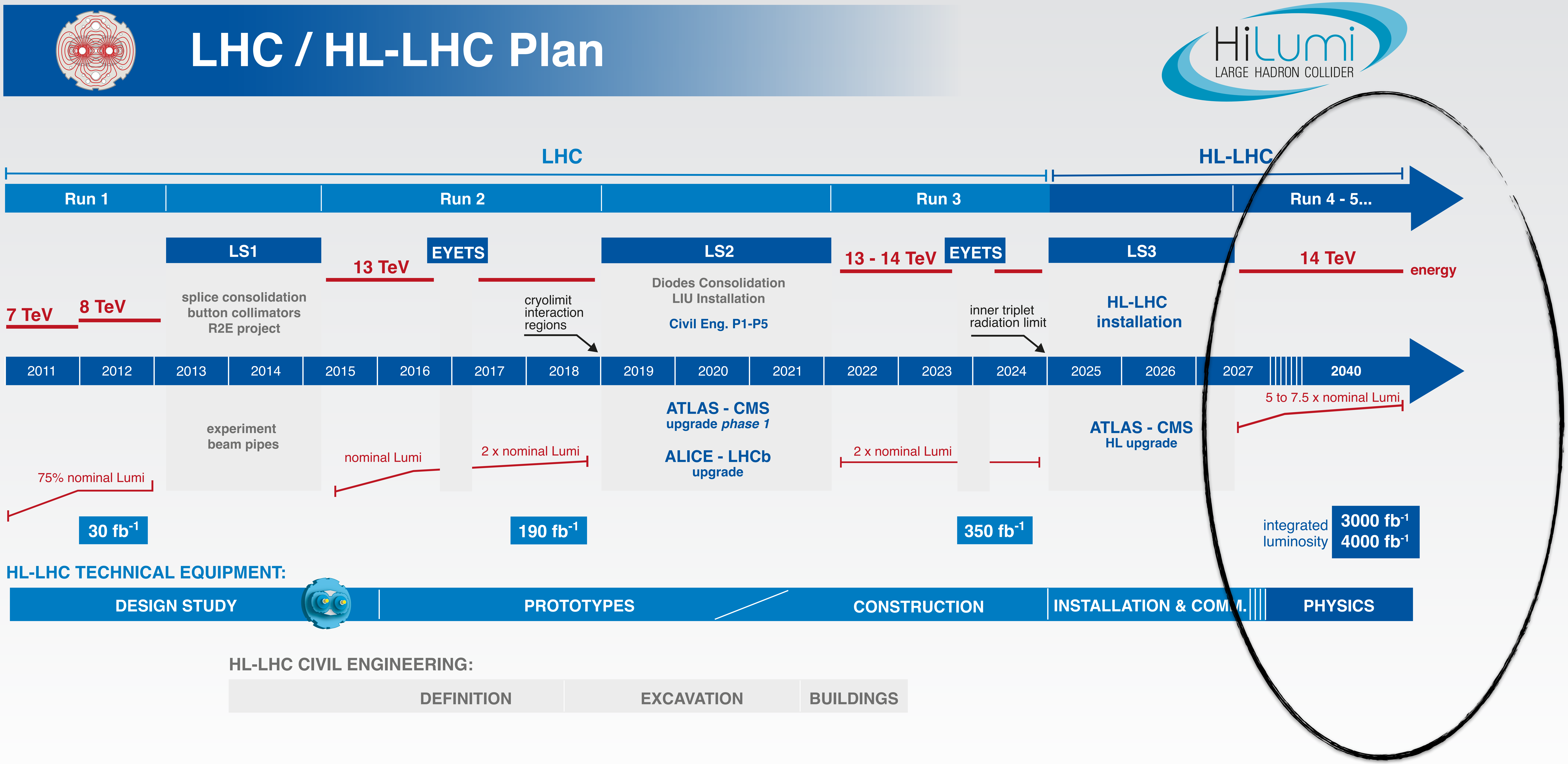
Top quarks beyond LHC run 3
- opportunities and challenges -

Jan Kieseler for CMS, ATLAS, and LHCb

15.9.2021

ATLAS help: Nedaa-Alexandra Asbah

HL-LHC timescale

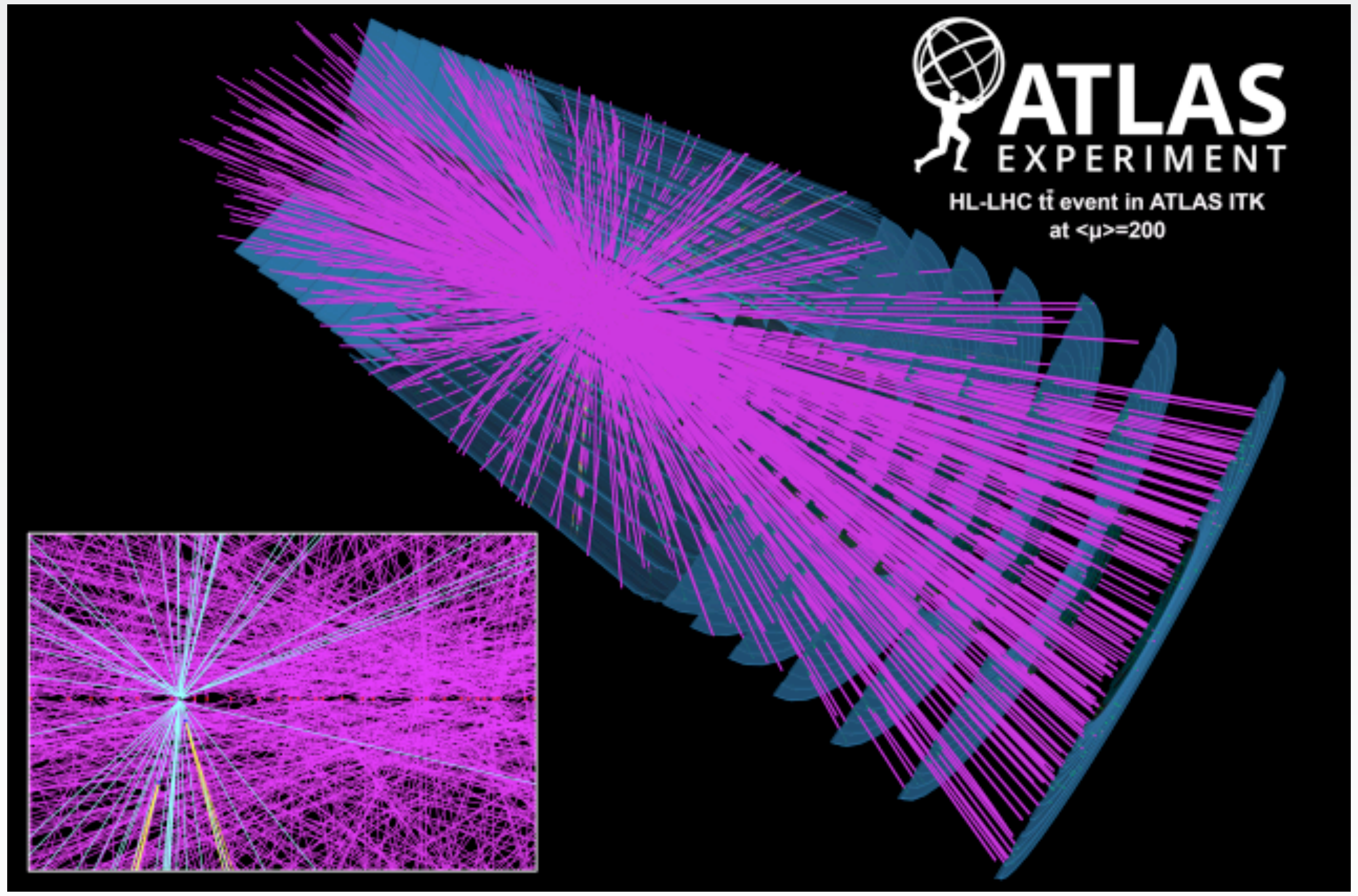


HL-LHC key parameters

HL-LHC
- 14 TeV → not a bump-hunt machine
- 3-4 ab-1
- 140-200 Pileup

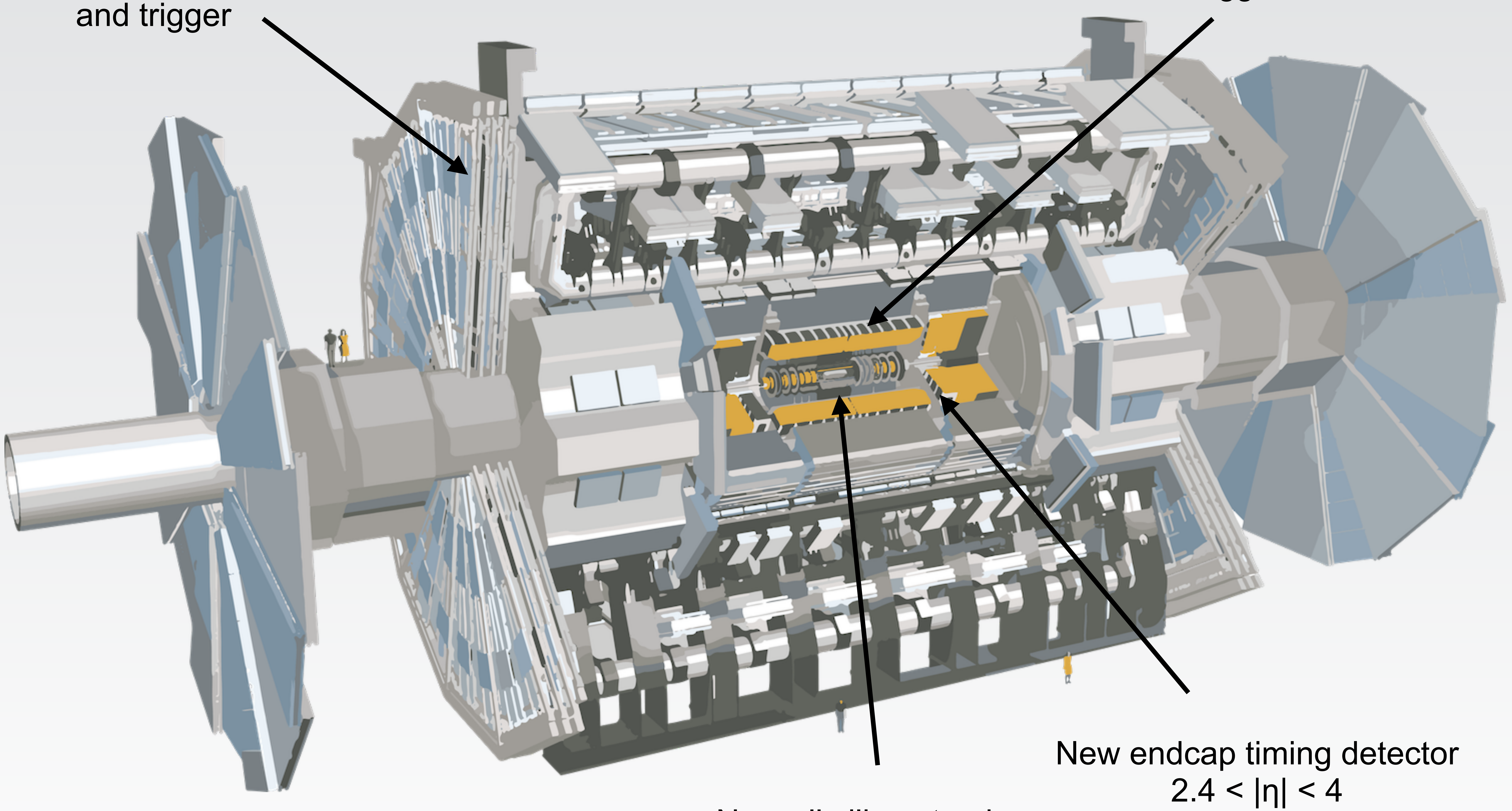
Huge yield (in terms of approx. top units)
- 3**B** ttbar events
- 300**M** tW
- 30**M** s-channel
- 3**M** ttV
- 30**k** 4 top

Unprecedented challenges for detectors and reconstruction
- Radiation
- Occupancy
- Particle density



ATLAS

- Improvements on trigger level to cope with 200 pileup
- Dedicated timing detector
- New all silicon tracker $|\eta| < 4$
- Increased trigger bandwidth

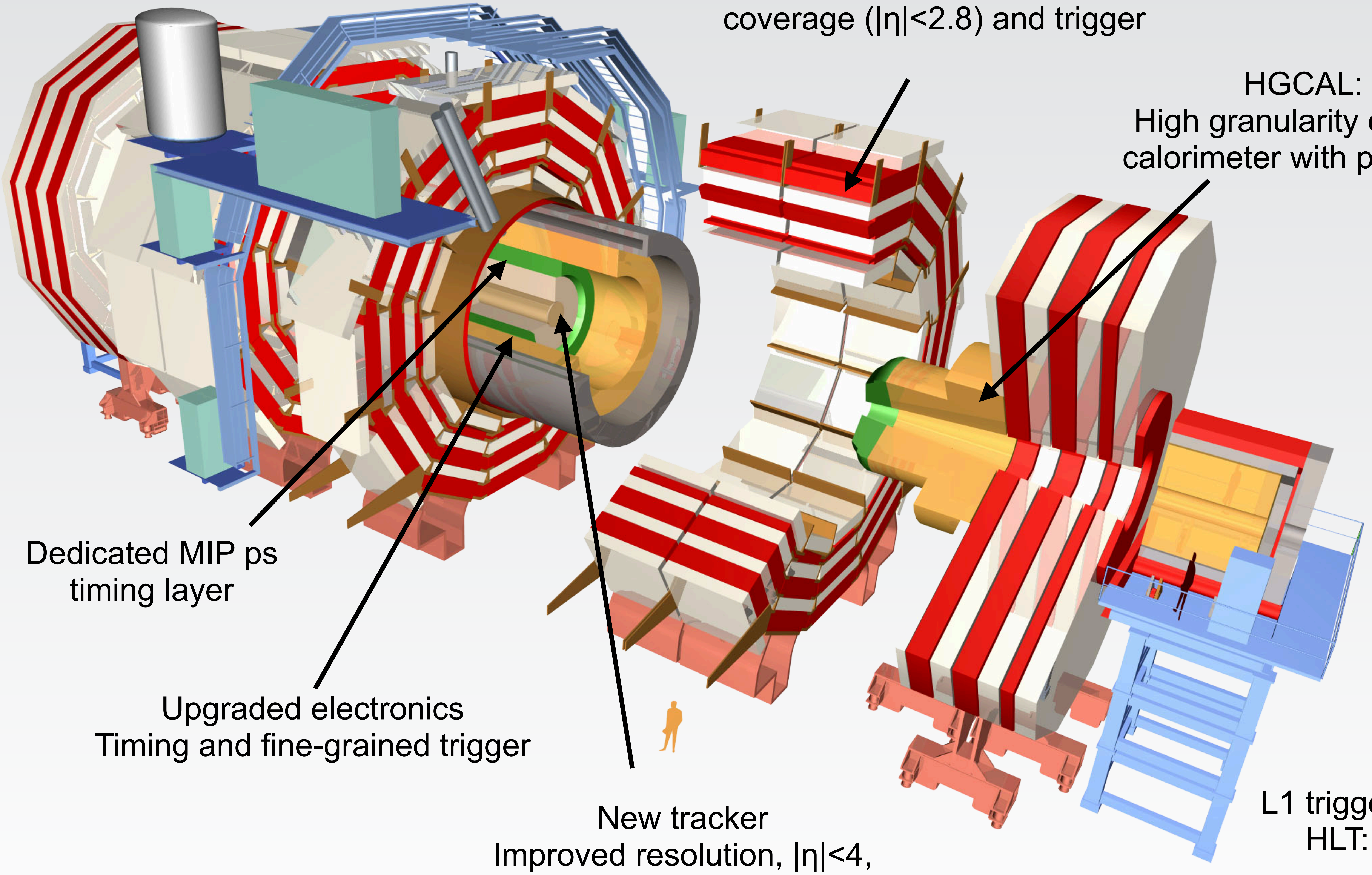


ATLAS TDRs

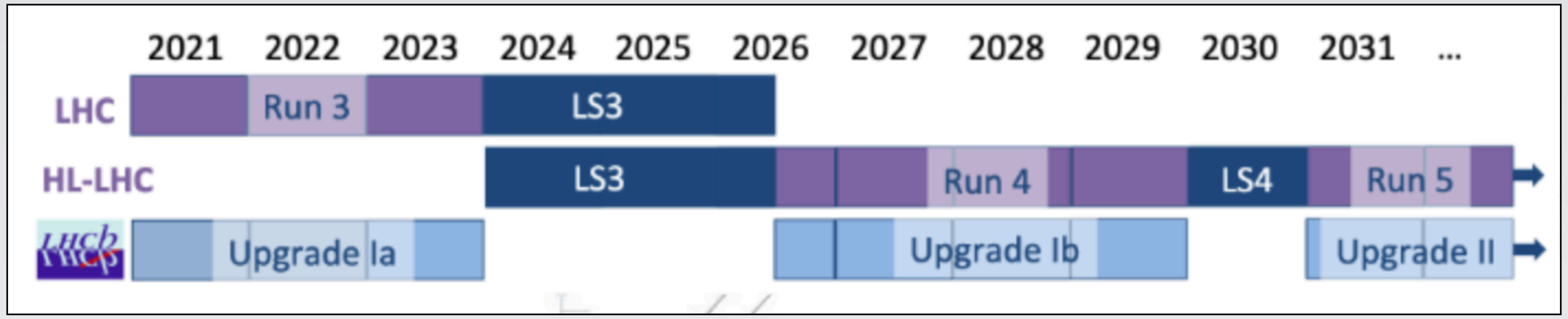
CMS

- Up to ps timing capabilities in many sub detectors
- Special MIP timing layer up to |η| < 3
- Tracker coverage up to |η| < 4
- First large scale high-granularity calorimeter in a running experiment (1.5 < |η| < 3)

ATLAS & CMS:
- Larger η acceptance
- Better momentum resolution
- Timing capabilities

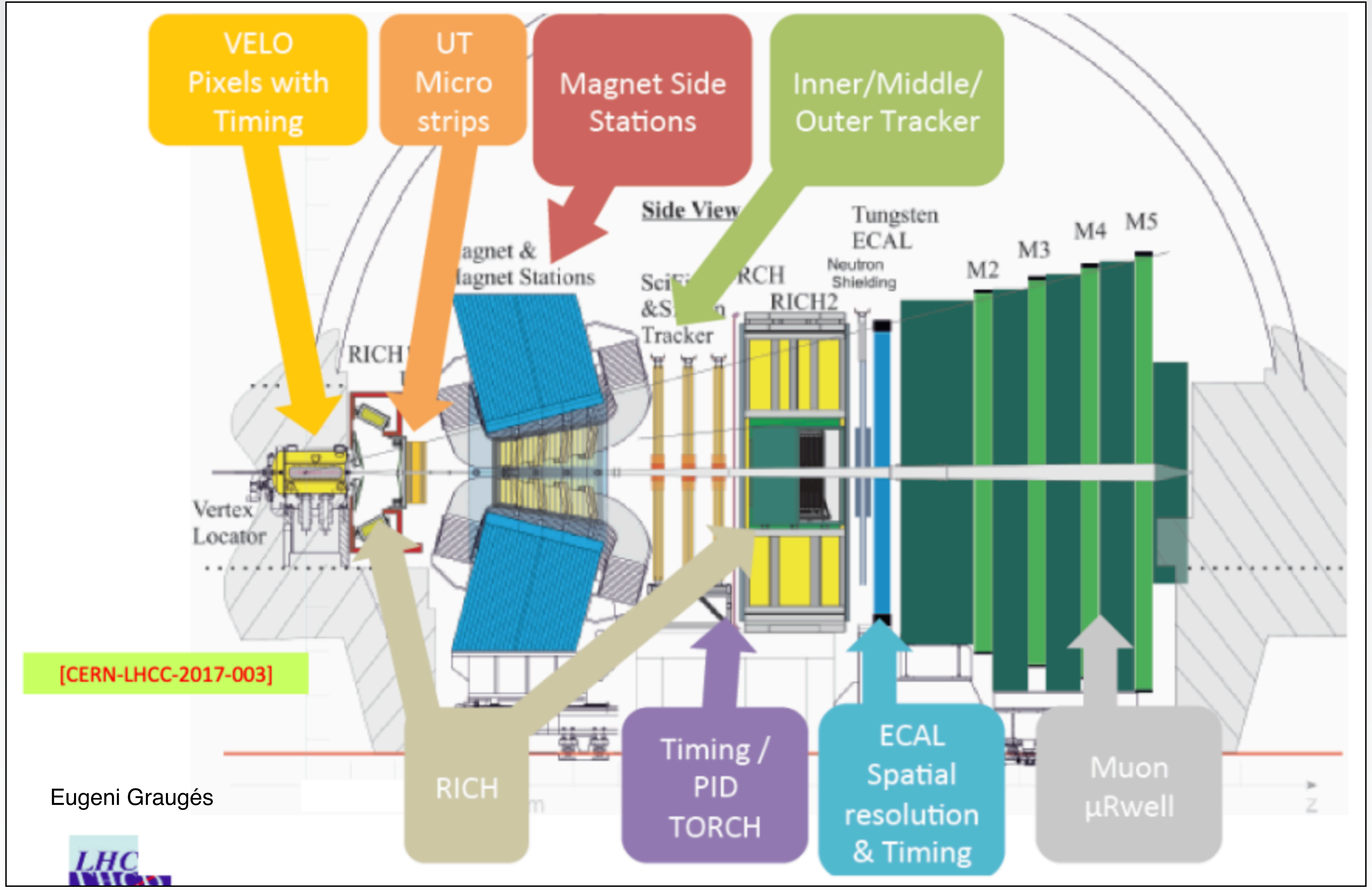


CMS TDRs



	LHC Run	Period of data taking	Maximum $\mathcal{L}$ $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Cumulative $\int \mathcal{L}\,dt$ $[\mathrm{fb}^{-1}]$
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	8
Phase-I Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50
Phase-II Upgrade	5 →	2031–2033, 2035 →	2×10^{34}	300

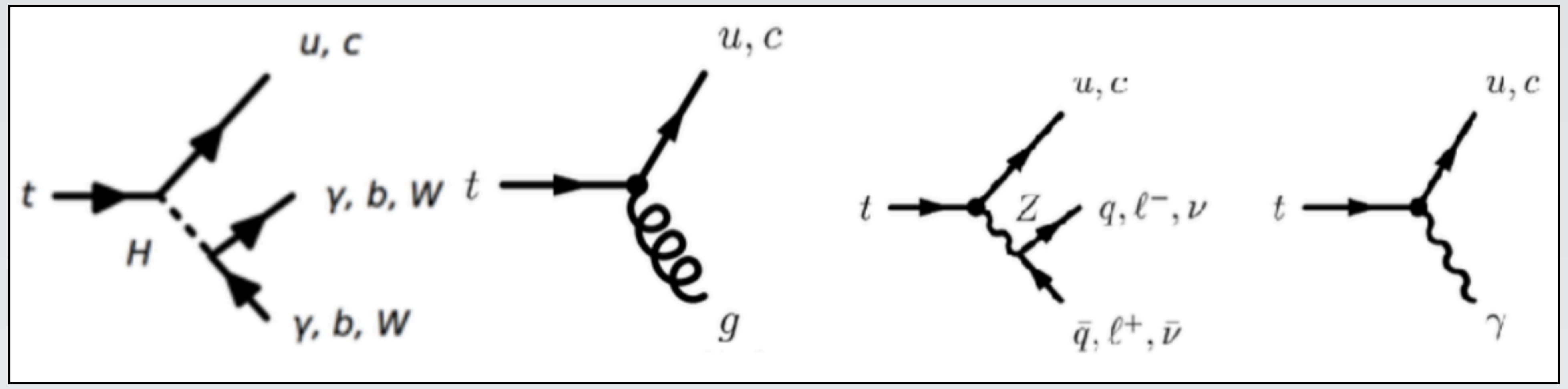
- LHCb has undergone big upgrade for Run 3 "trigger-less" readout
- Big "Phase-2" upgrade planned to be operational after LS4 → 300fb-1
- Instantaneous luminosity will increase accordingly
- Mostly better spatial resolution and precision timing in most sub detector systems

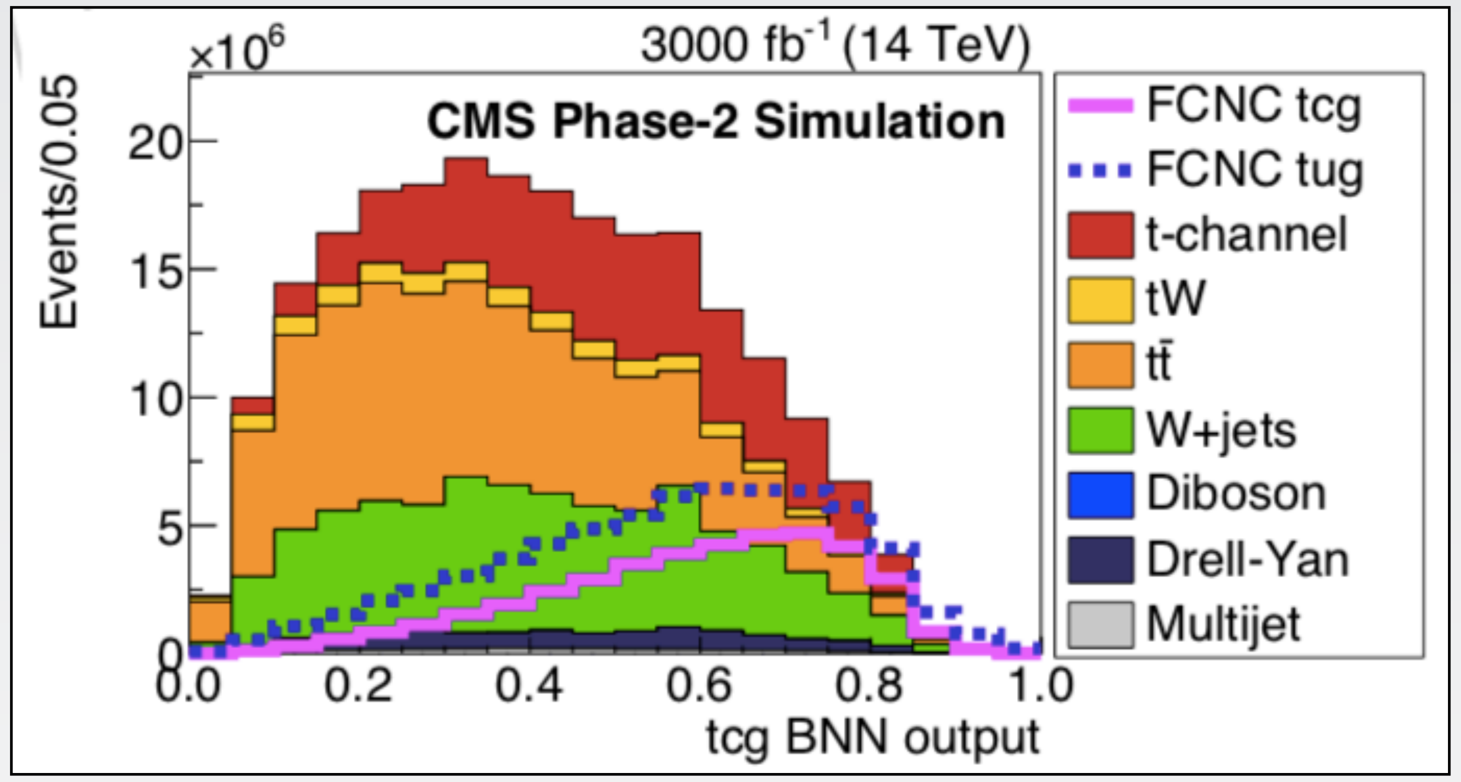


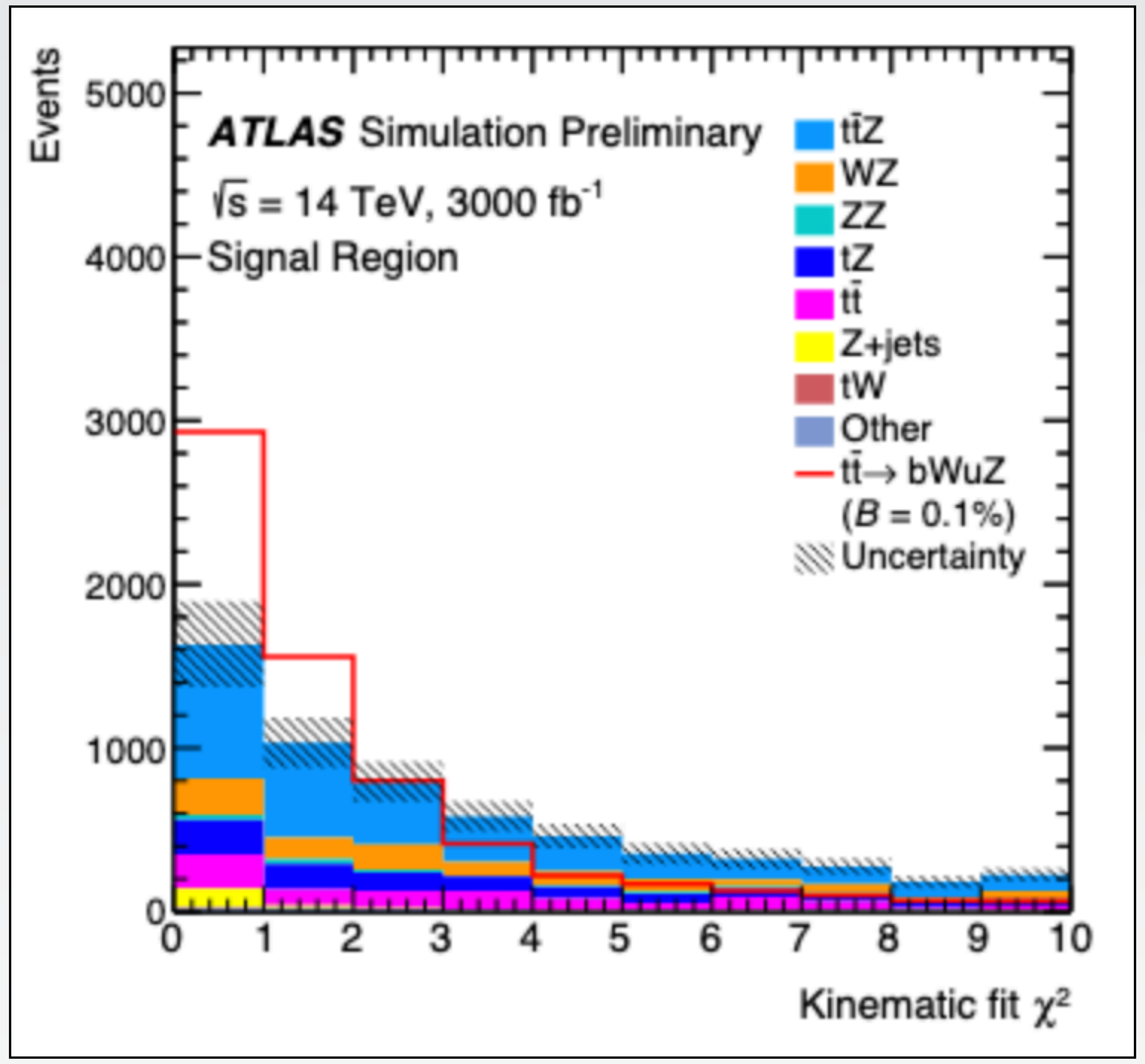
LHCb LoI,PC, etc.

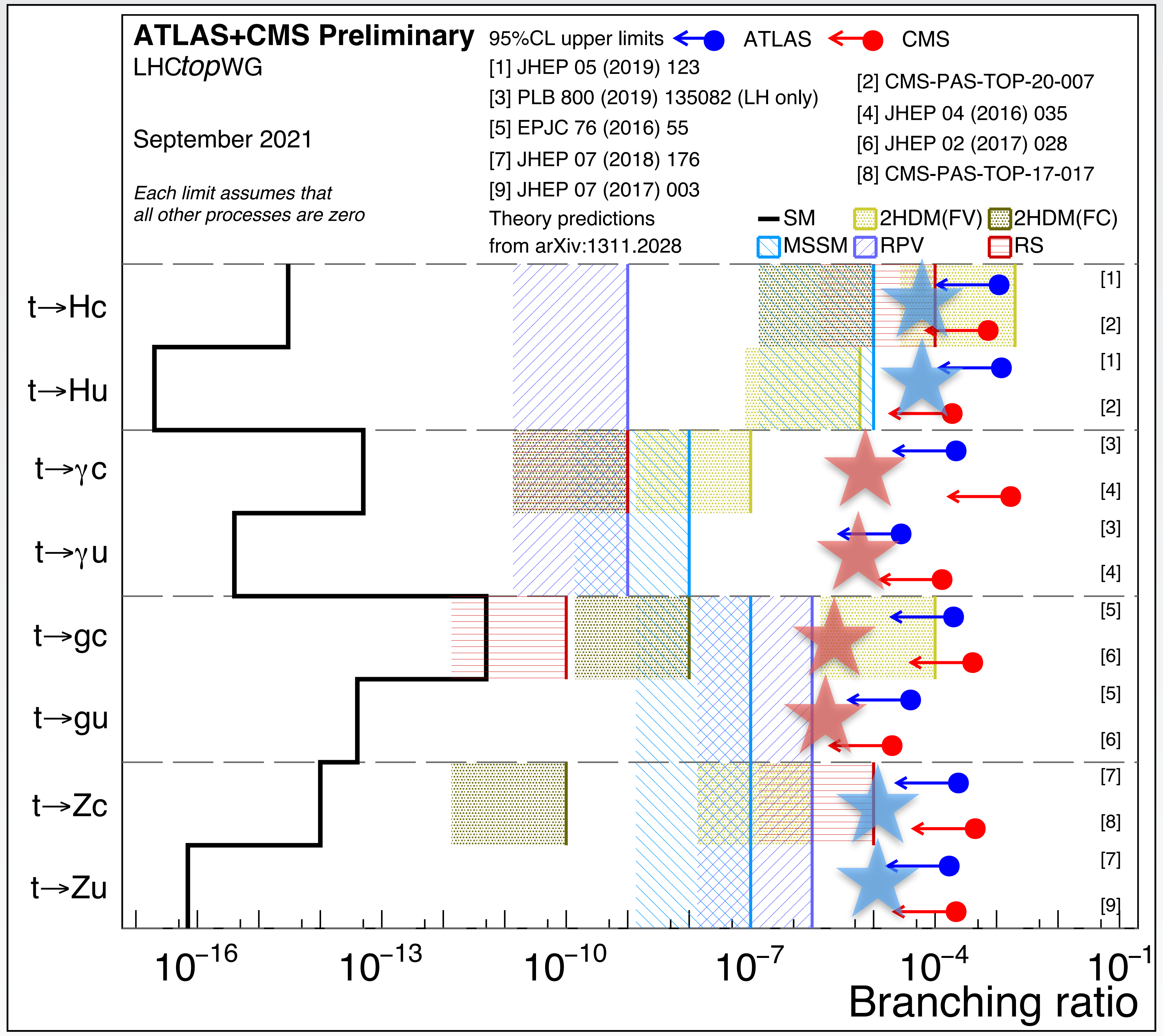
Rare processes: FCNC

- Forbidden at tree-level
- Only via loops, highly suppressed
- Potentially strong enhancement in BSM scenarios
- Statistics limited measurements









- FullSim (CMS) and smeared particle-level analyses (ATLAS)

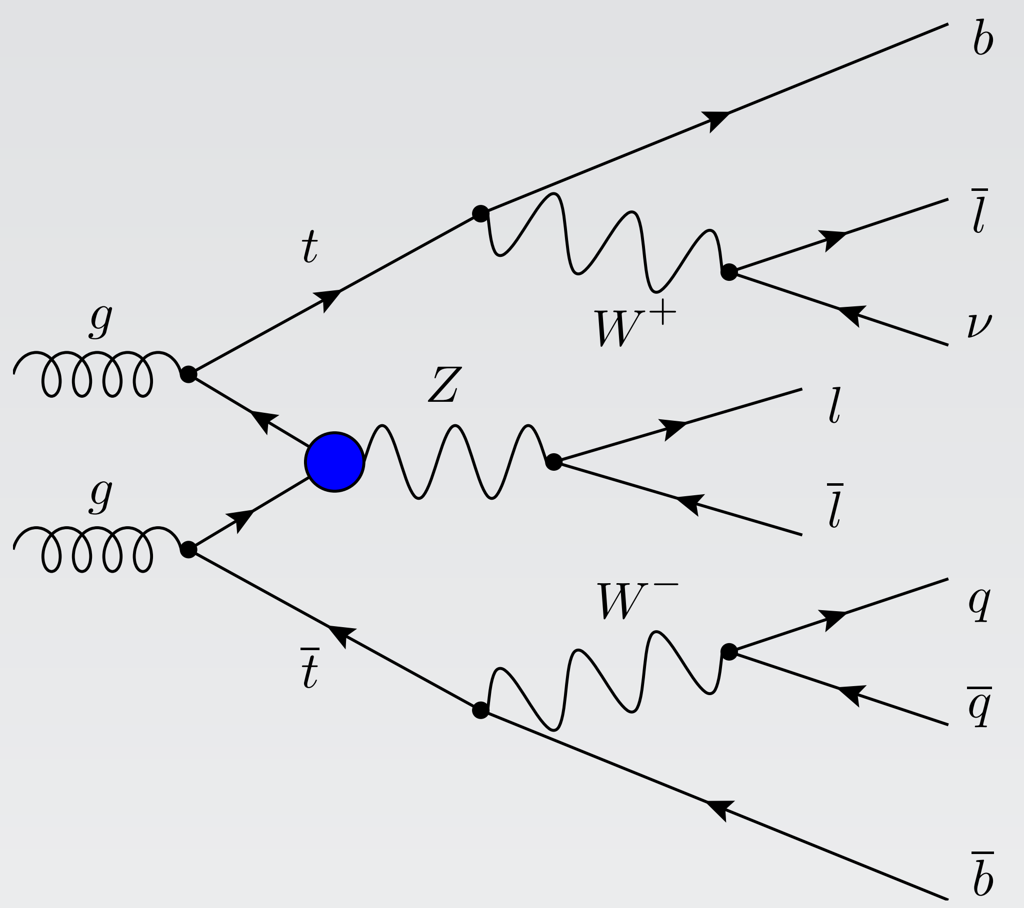
- Evaluated for different systematic uncertainty scenarios
  - Mostly synchronised between experiments (See Yellow Reports)
  - Most uncertainties are assumed to be reduced by a factor of two

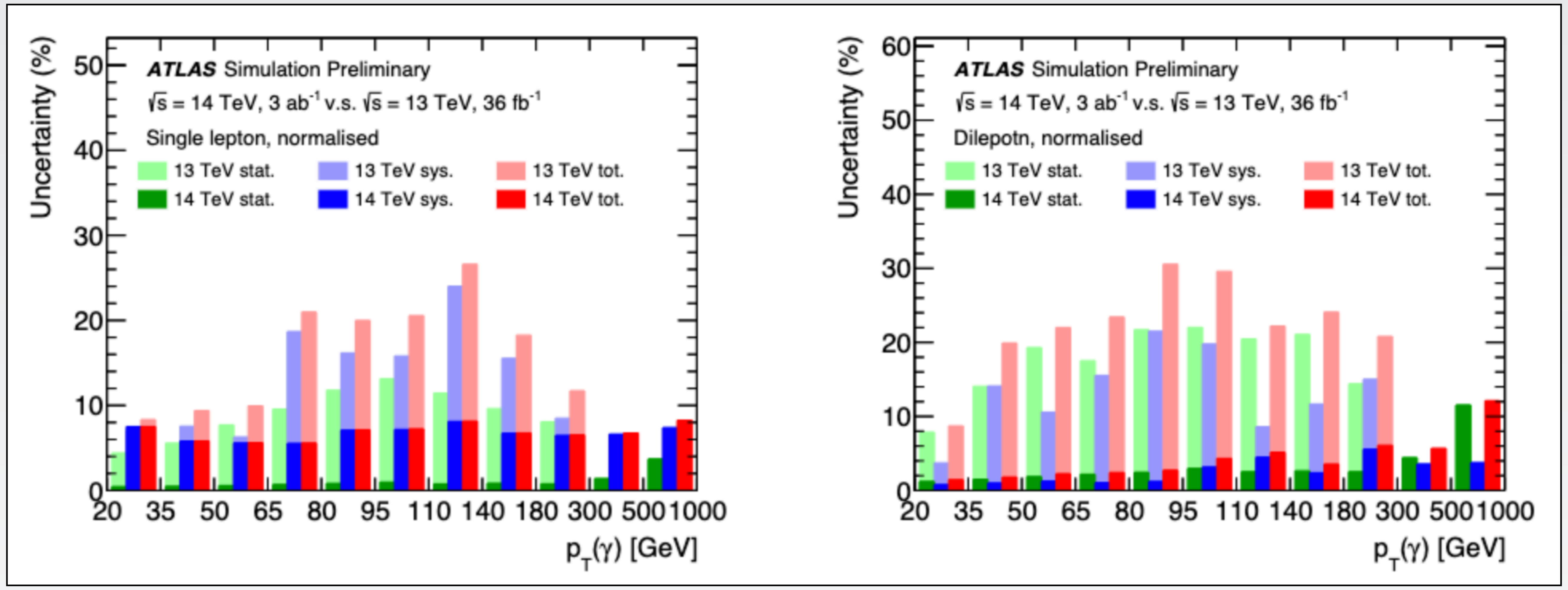
- Improvements of about an order of magnitude

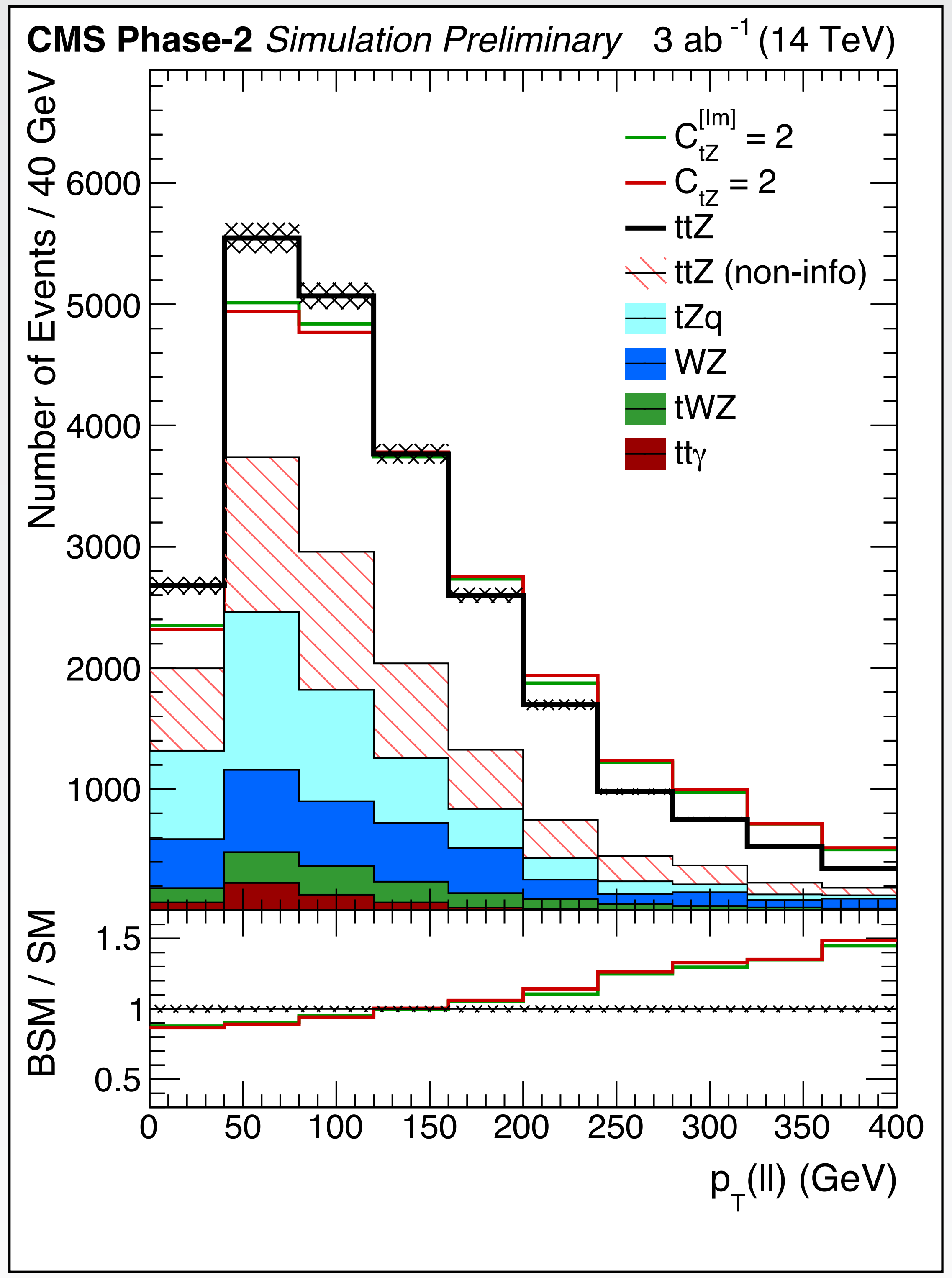
ATL-PHYS-PUB-2016-019, ATL-PHYS-PUB-2019-001, CMS-PAS-FTR-18-004, CMS-TDR-019

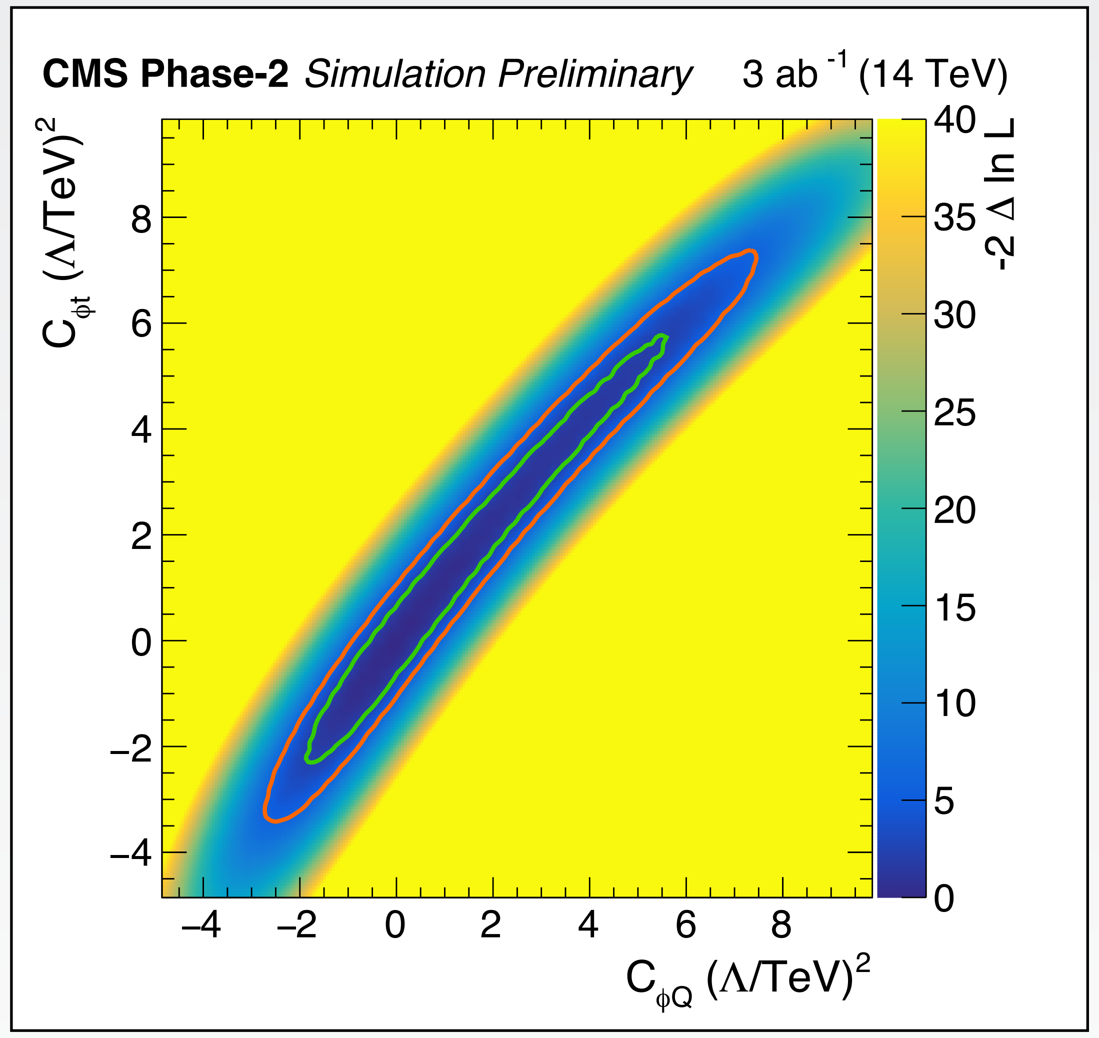
Rare processes: ttγ/ttZ(V)

- High scale process
- Sensitive to BSM propagators
- Cross section enhancements can be interpreted e.g. in EFT framework









- At HL-LHC precise differential measurements possible

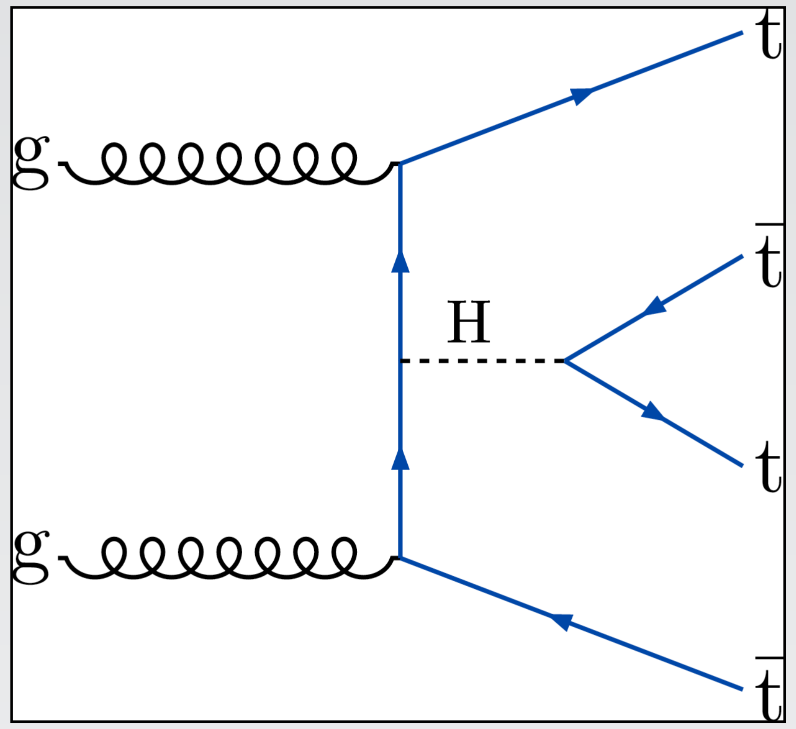
$$\mathcal{L}_{t\bar{t}Z} = e\bar{u}(p_t)\left[\gamma^\mu\left(C^Z_{1,V} + \gamma_5 C^Z_{1,A}\right) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C^Z_{2,V} + i\gamma_5 C^Z_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu,$$

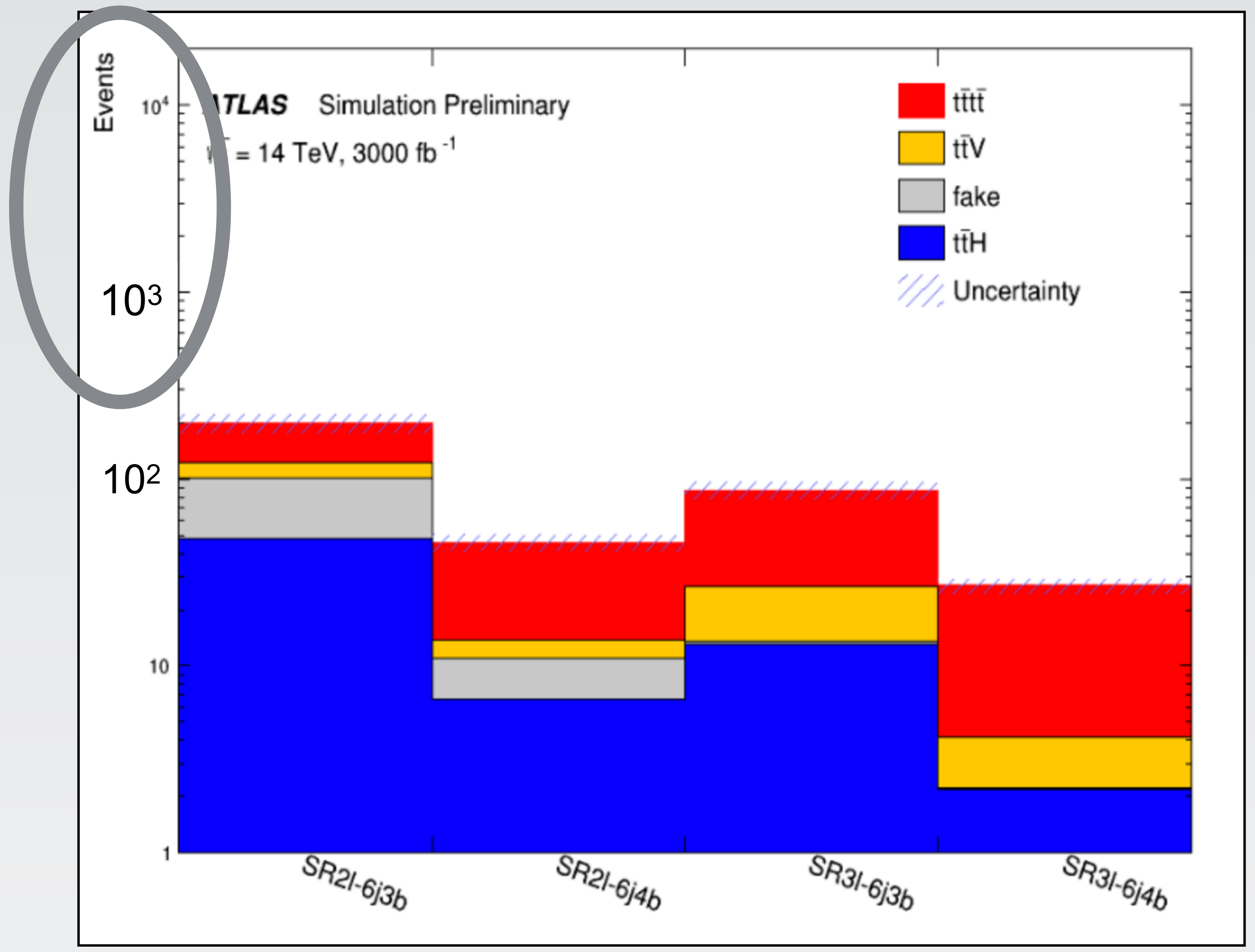
- Stringent constraints, e.g. on anomalous dipole moments possible
- *Correlations* with tVV, tZq

ATL-PHYS-PUB-2018-049, CMS-PAS-FTR-18-036

Rare processes: 4 top

- Very high scale process (4 m_t)
- High sensitivity to new physics
  - New resonances
  - Top compositeness → e.g. Andrea's talk
  - EFT





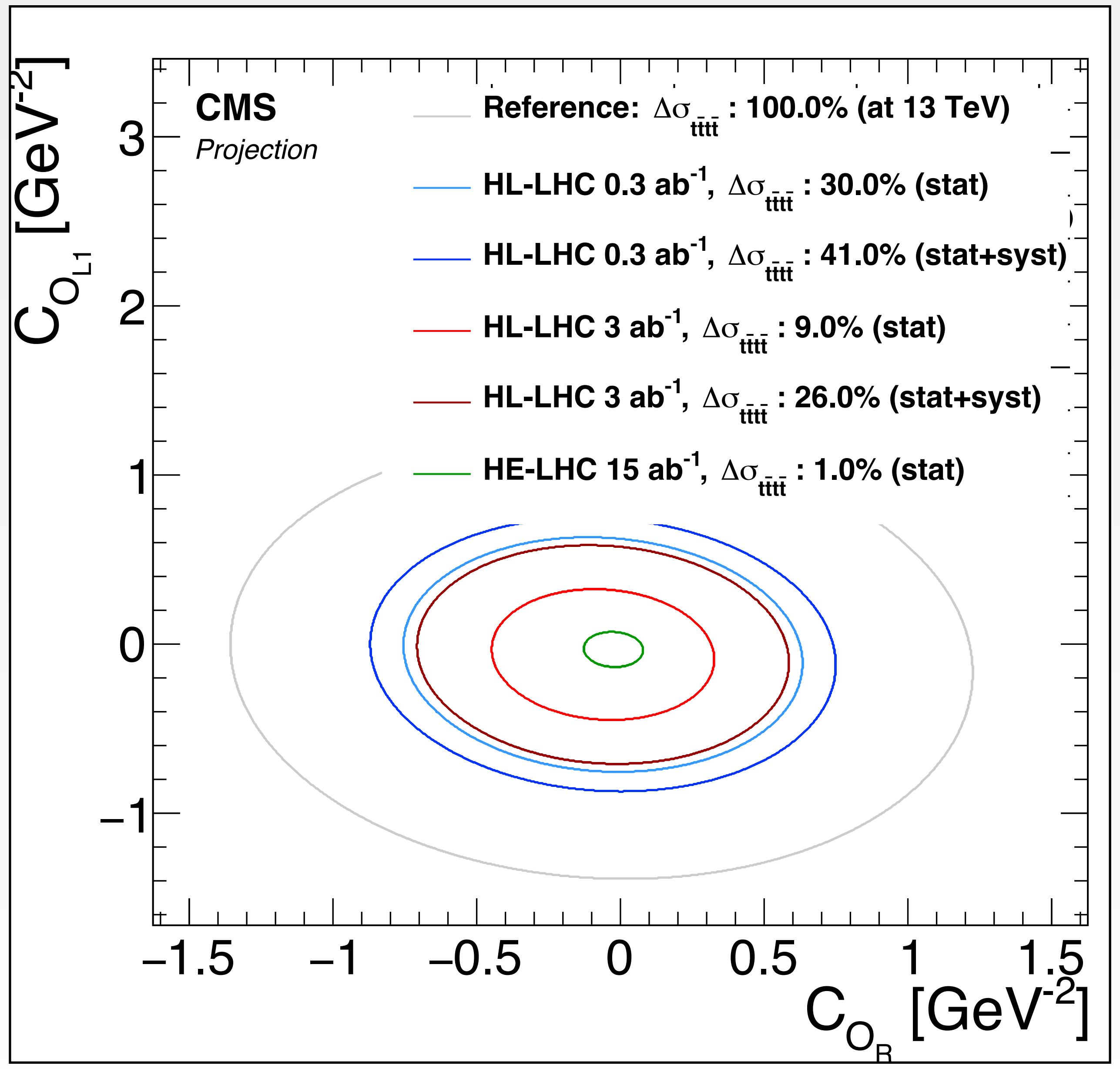
- A lot of events for analysis even after selections
- Important to understand ttV/ɣ tt+HF and ttH well

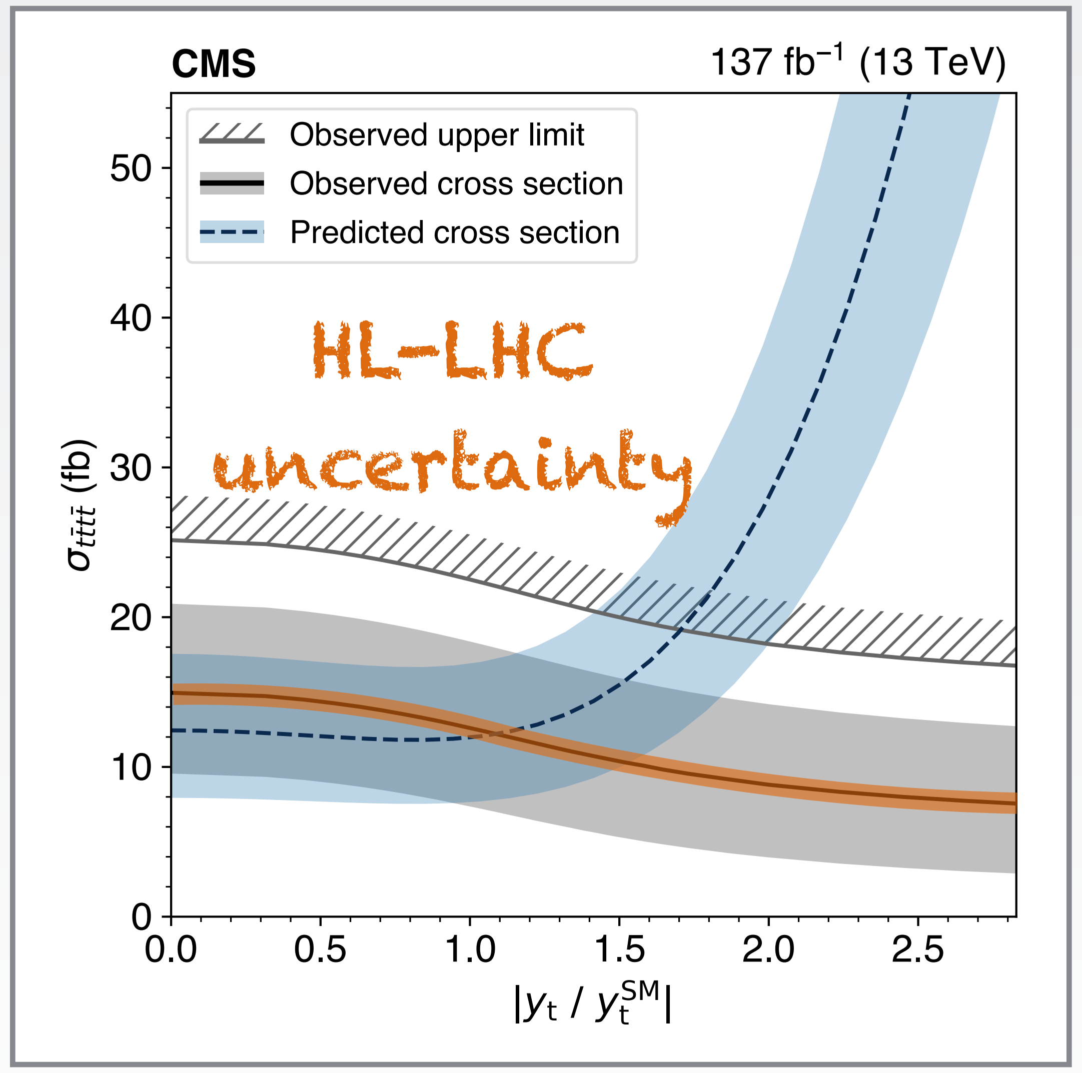
- HL-LHC (or even before) should become an *era of simultaneous multi-process analyses*

- Constraints on 4-fermion operators

- Precision up to 11% possible

- Rich interplay with Higgs, access to top Yukawa
  - Will need theory improvements





EPJC, 80 (2020) 75
not HL-LHC

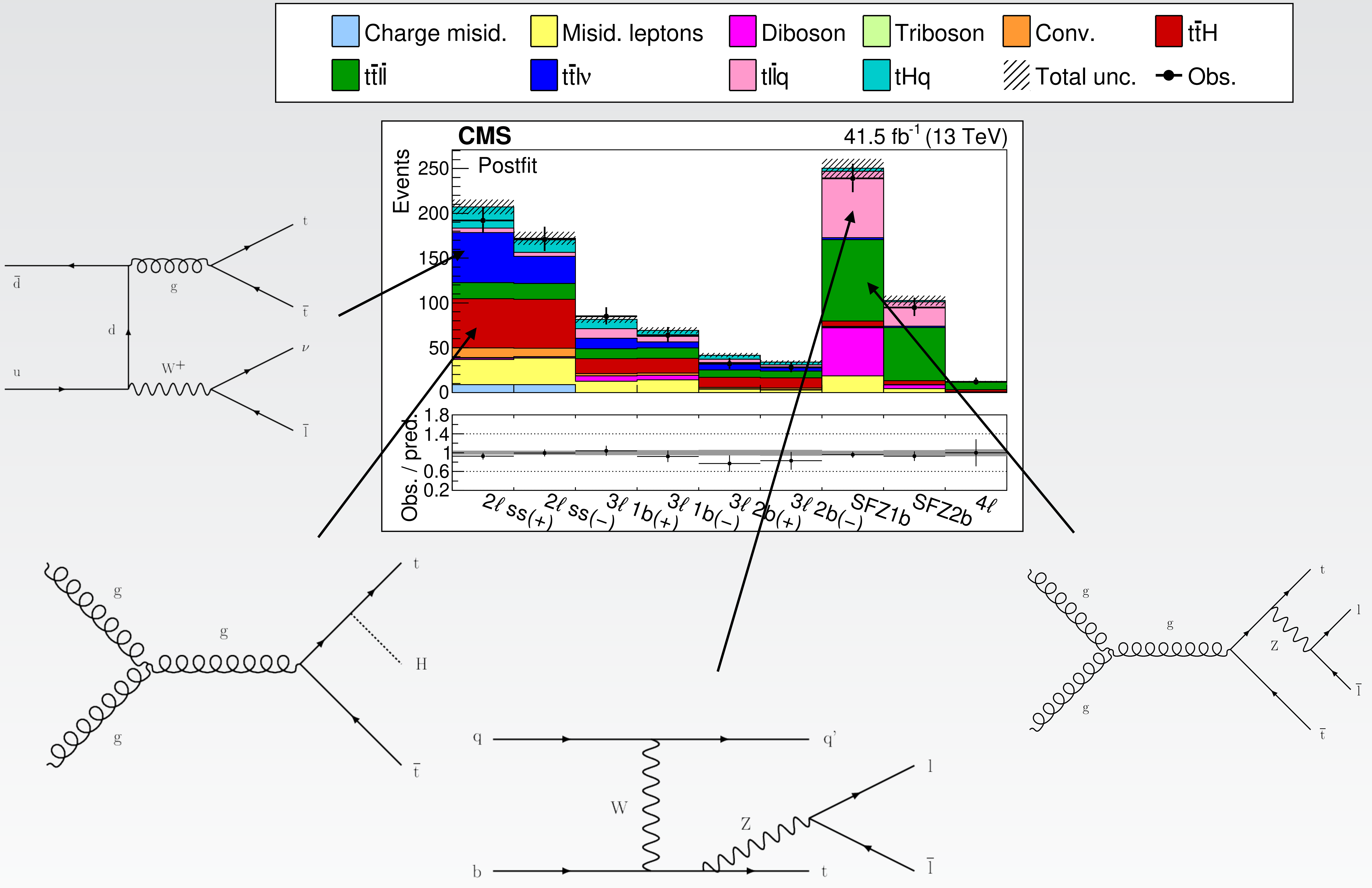
Theory band uses R. Frederix et al. arXiv:1711.02116

→ Run2 Timothee's talk

CMS-PAS-FTR-18-031, ATL-PHYS-PUB-2018-047

Rare multi-process analyses

- ttV, ttH, tHq, … 4 top backgrounds to each other
  - All high scale processes
  - Effective couplings potentially affected by non-resonant BSM loops
- Possible to make this challenge a strength in multi-process analyses and more global fits
- If we want to exploit the HL-LHC we need to get into that mode
- Work now on understanding technical and conceptual obstacles



→ for details, see talk by Dennis

Not HL-LHC
JHEP03 (2021) 095

Rare: very forward top

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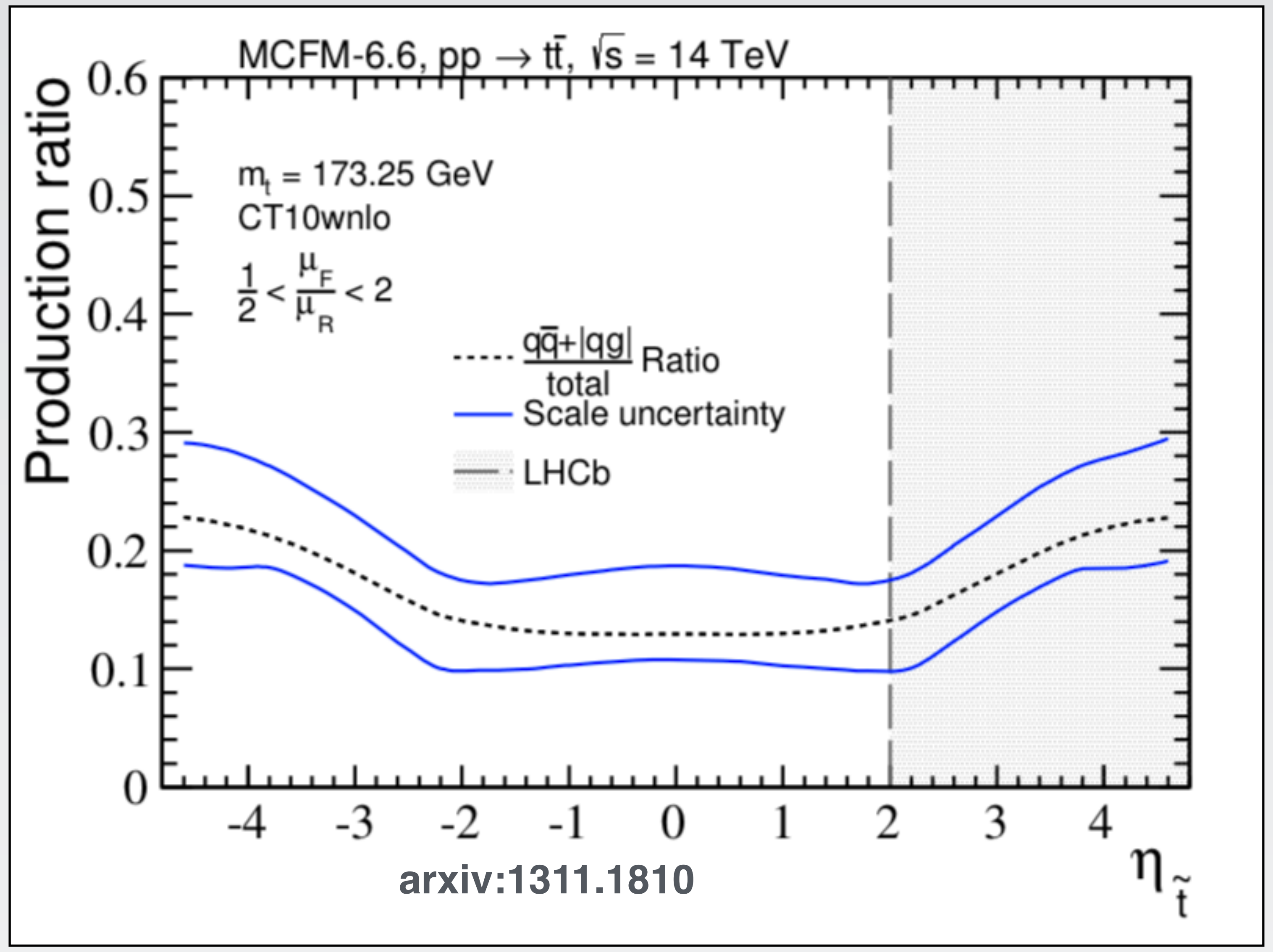
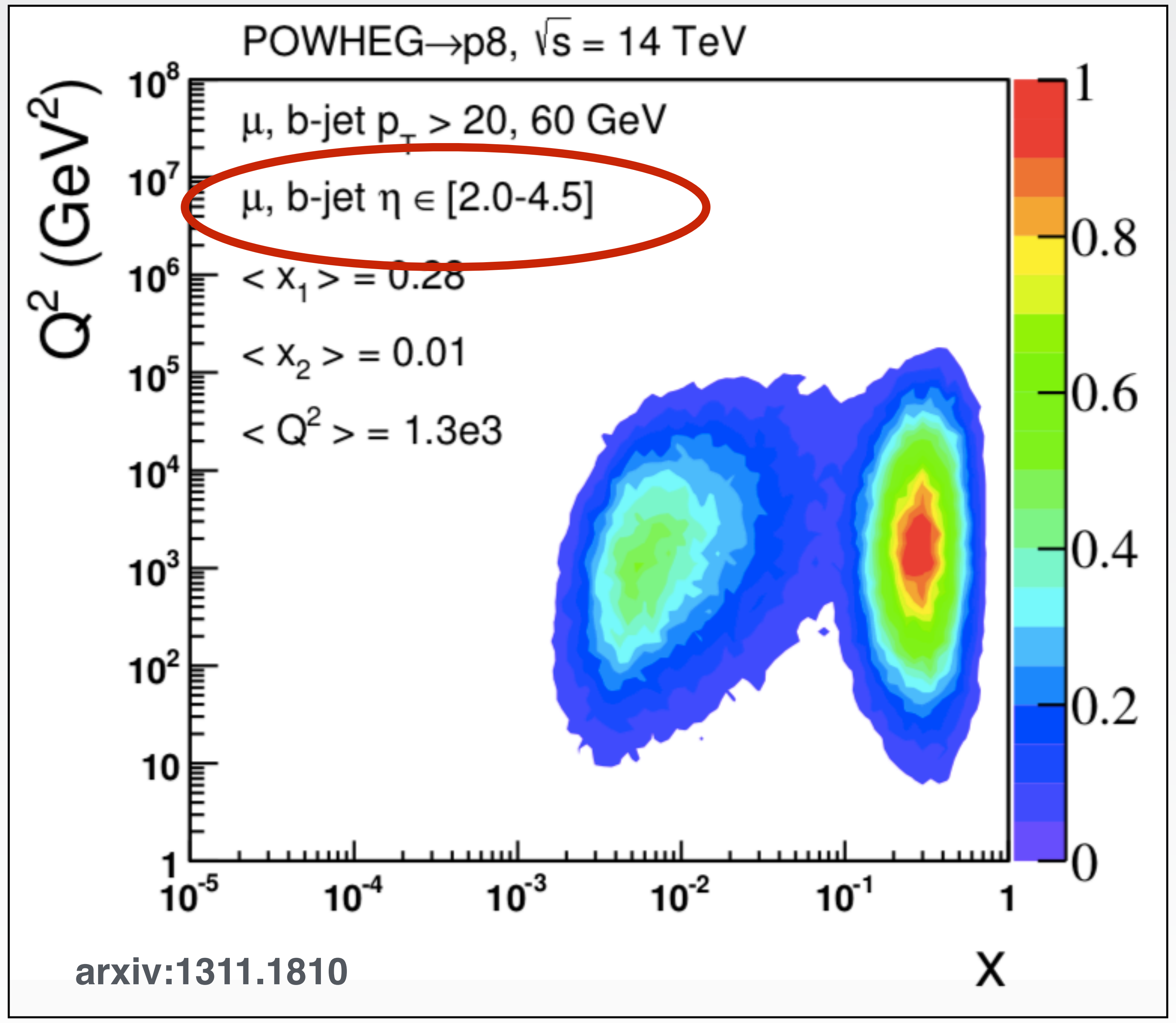
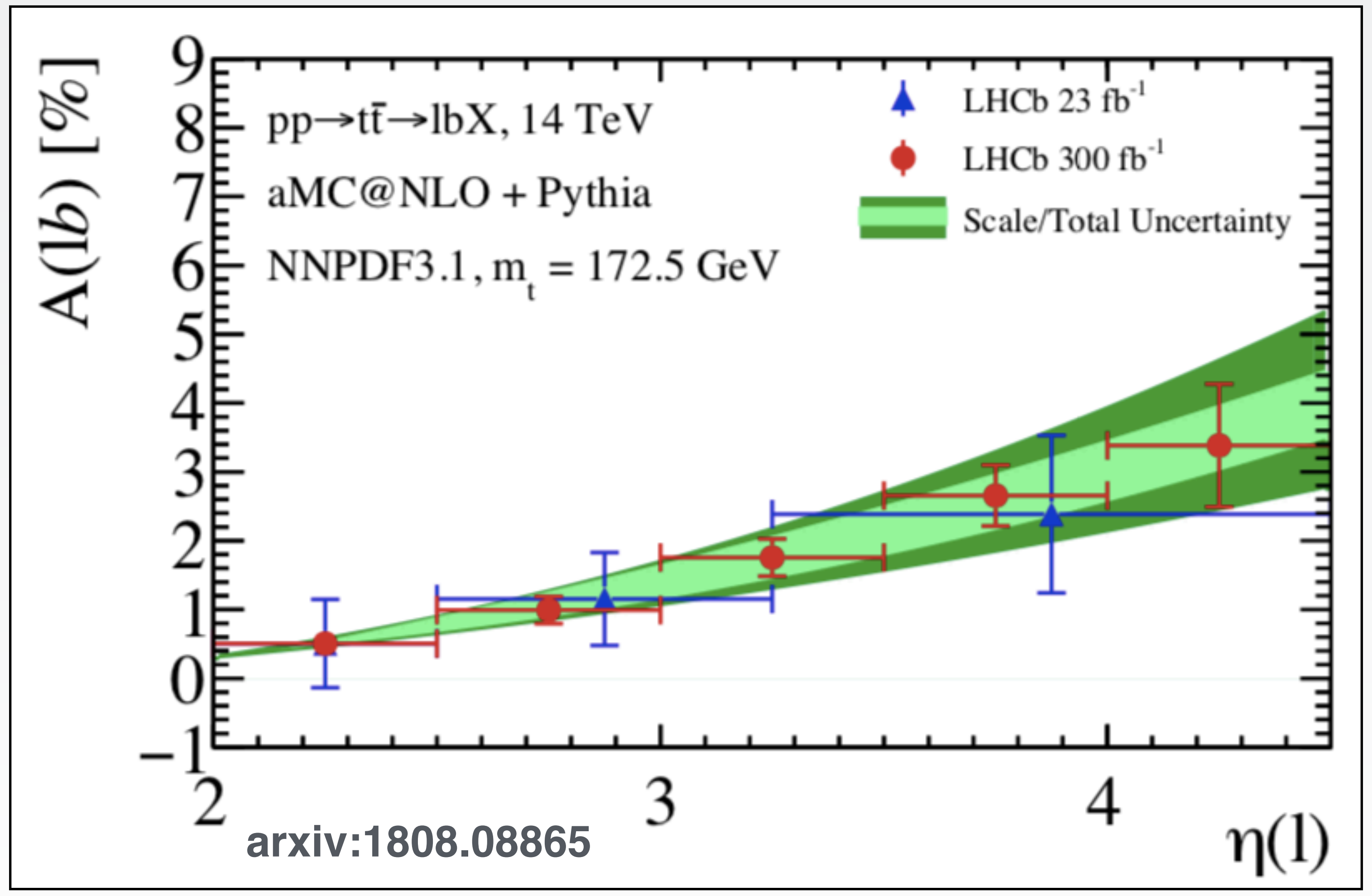


- Measurements at 13 TeV still statistics limited (fiducial):

  $\sigma_{t\bar{t}} = 126 \pm 19\,(\mathrm{stat}) \pm 16\,(\mathrm{syst}) \pm 5\,(\mathrm{lumi})\ \mathrm{fb}$ arxiv:1803.05188
  - Dominated by jet tagging uncertainties
  - New calibrations and detector will help reduce them
  - Statistics will be even more dominant

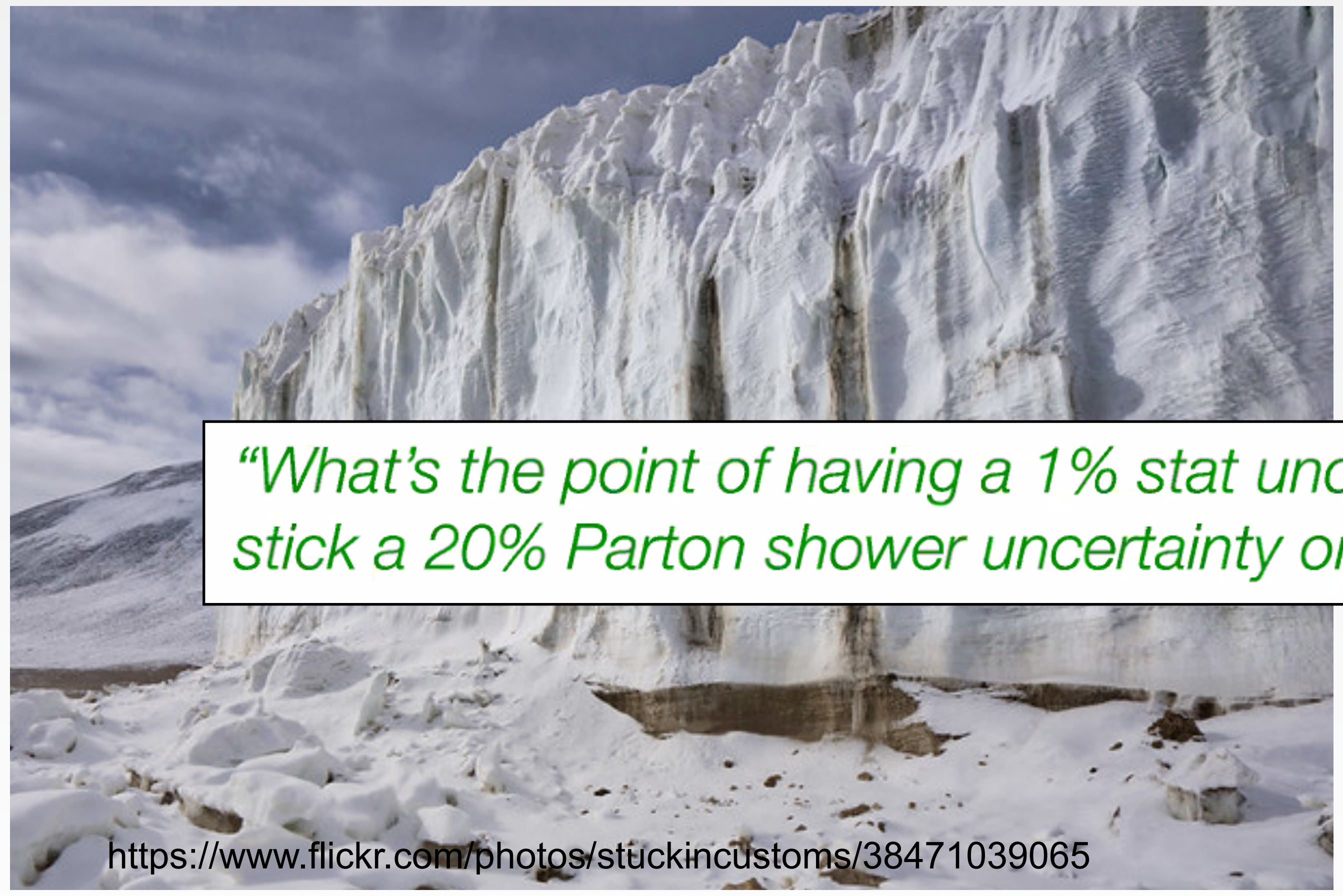


- Fiducial cross section increases more than total cross section from 13 to 14 TeV
- Differential measurements at very high y
- High x PDF essential to understand potential signs for new heavy states
- Non-zero asymmetry expected to be observable

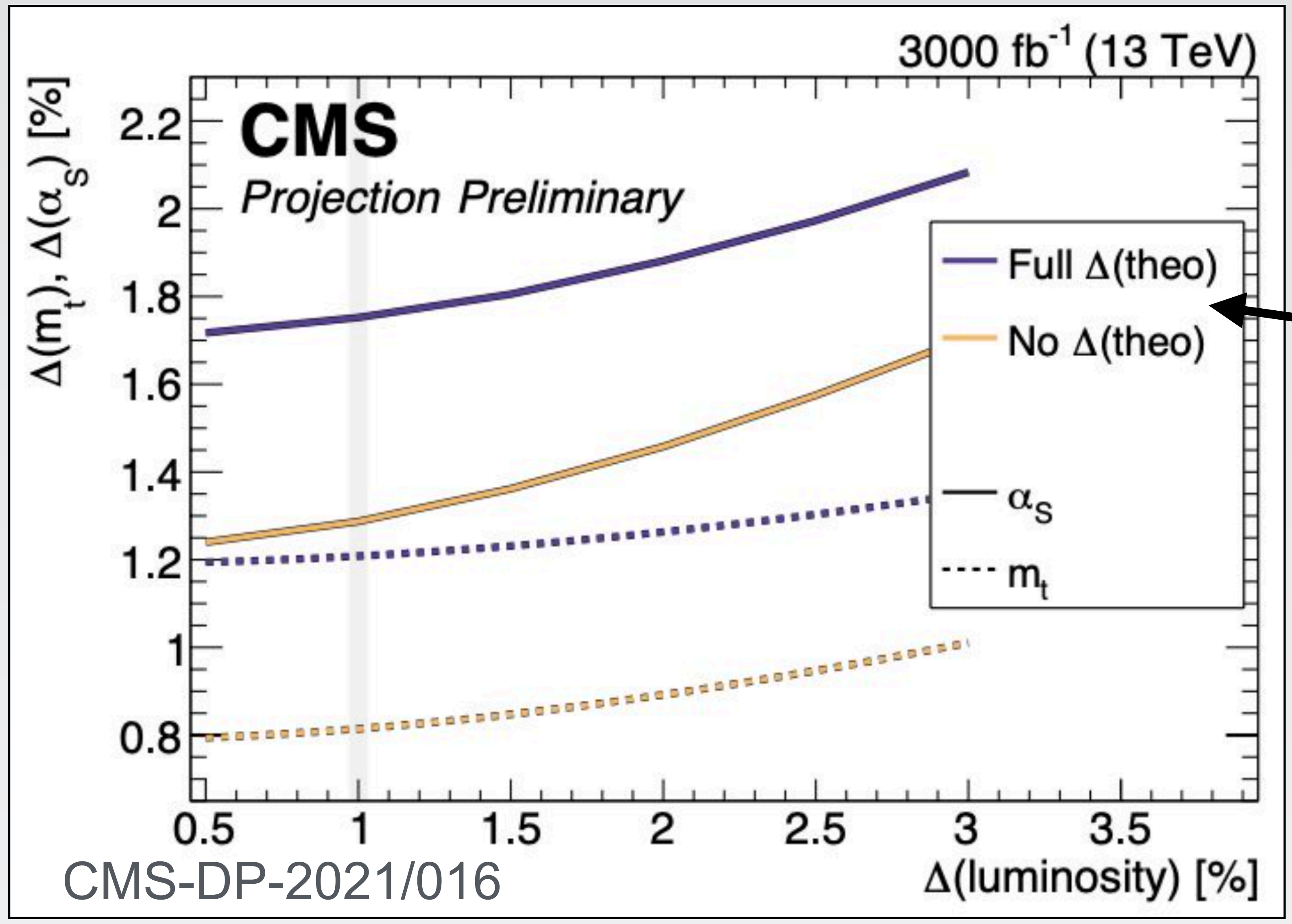


Precision: top-quark pair

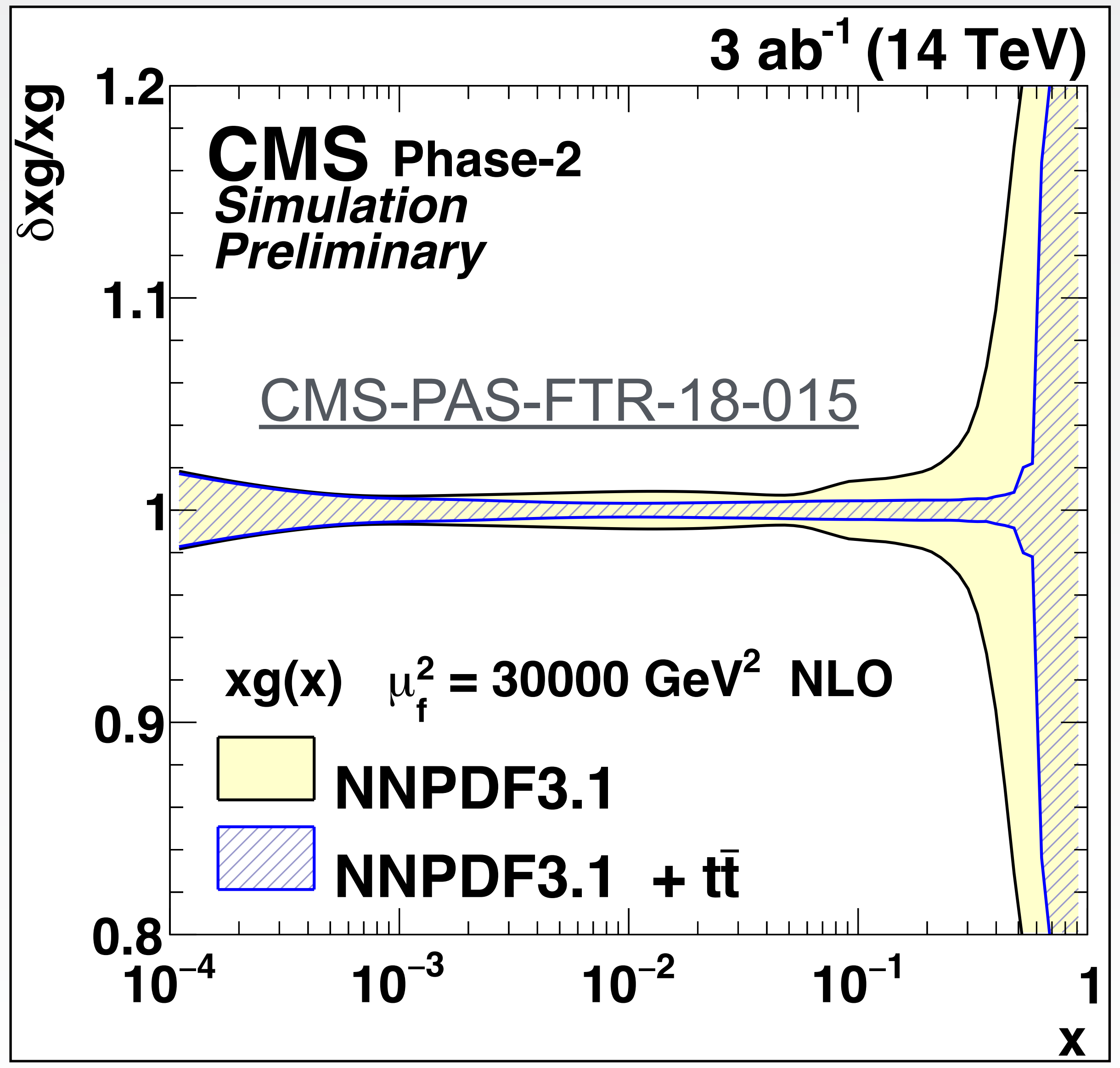
- Precision access to physics at very different scales
- Precise measurements as input to SM parameter extractions, e.g.
  - Top mass, alpha_s from cross section
  - High x PDF from differential distributions
- Statistics won't at all be a limiting factor, systematics and theory uncertainties will be
- Without changing techniques, we will hit a wall



"What's the point of having a 1% stat uncertainty if you're gonna stick a 20% Parton shower uncertainty on it…" ***Jay, ranting in a pub***



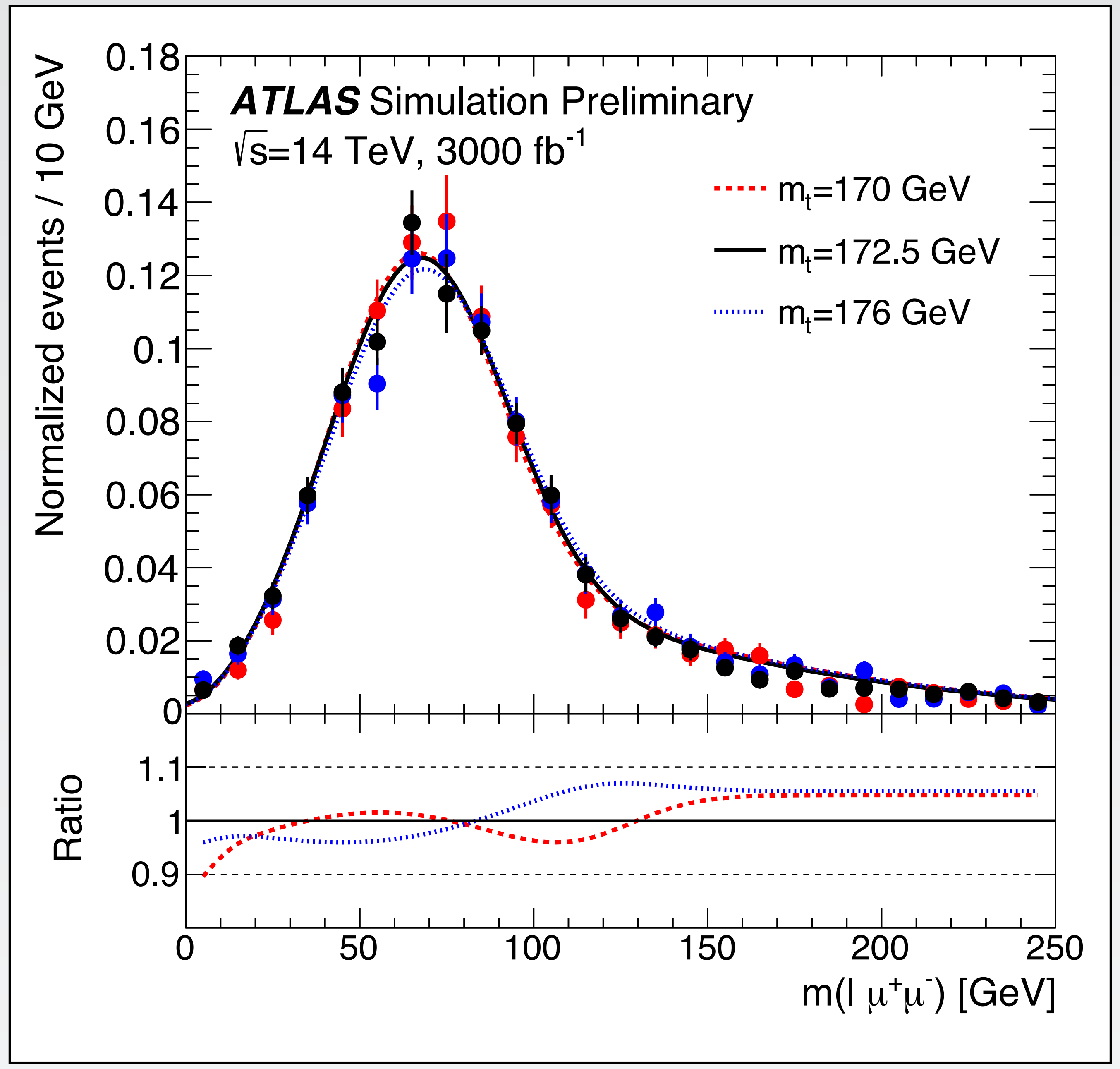
N3LO would help a lot

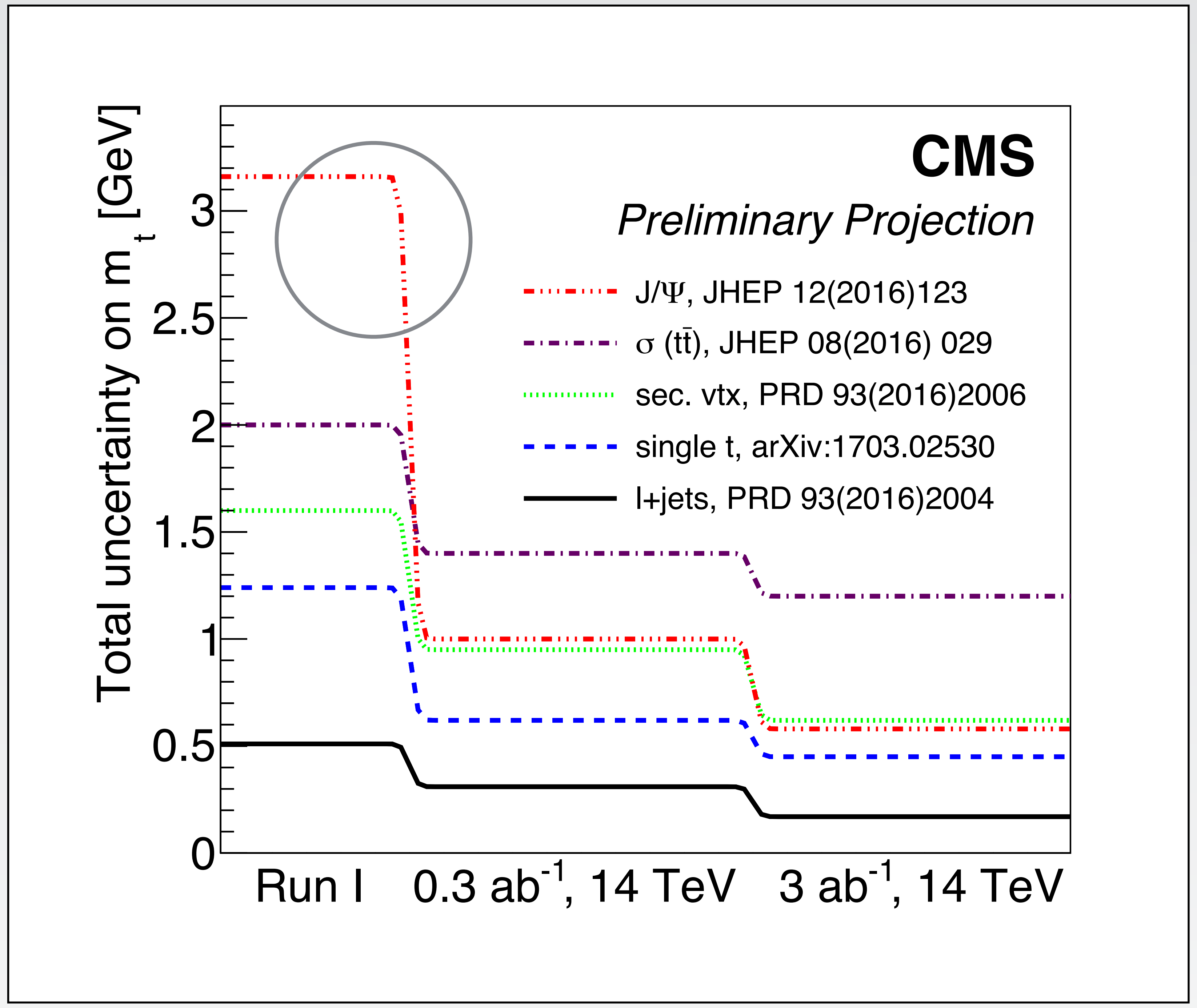


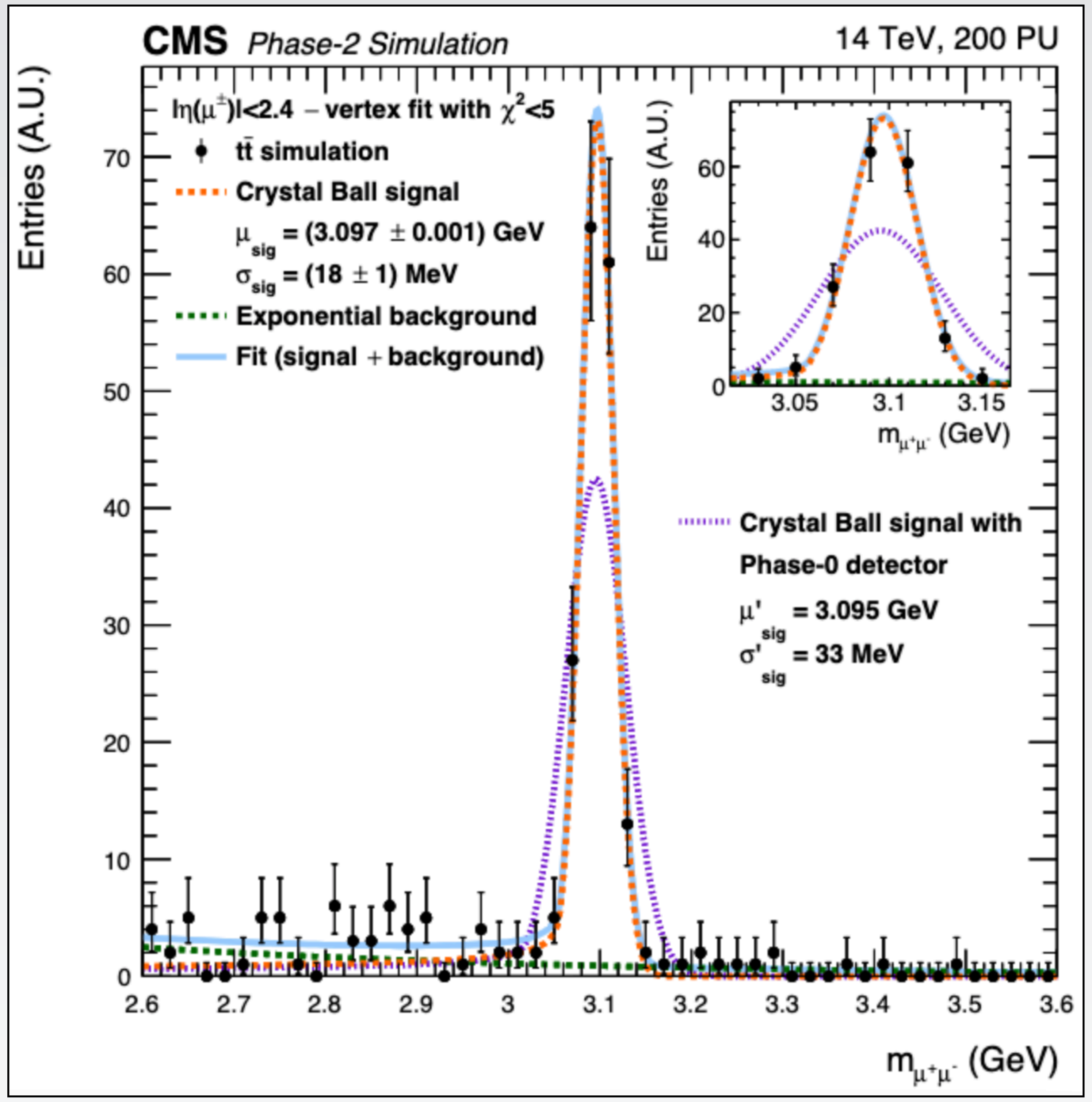
Also due to eta coverage

Take less affected observables

- Experimentally: e.g. using J/Psi + lepton to determine m_t : clear correlation







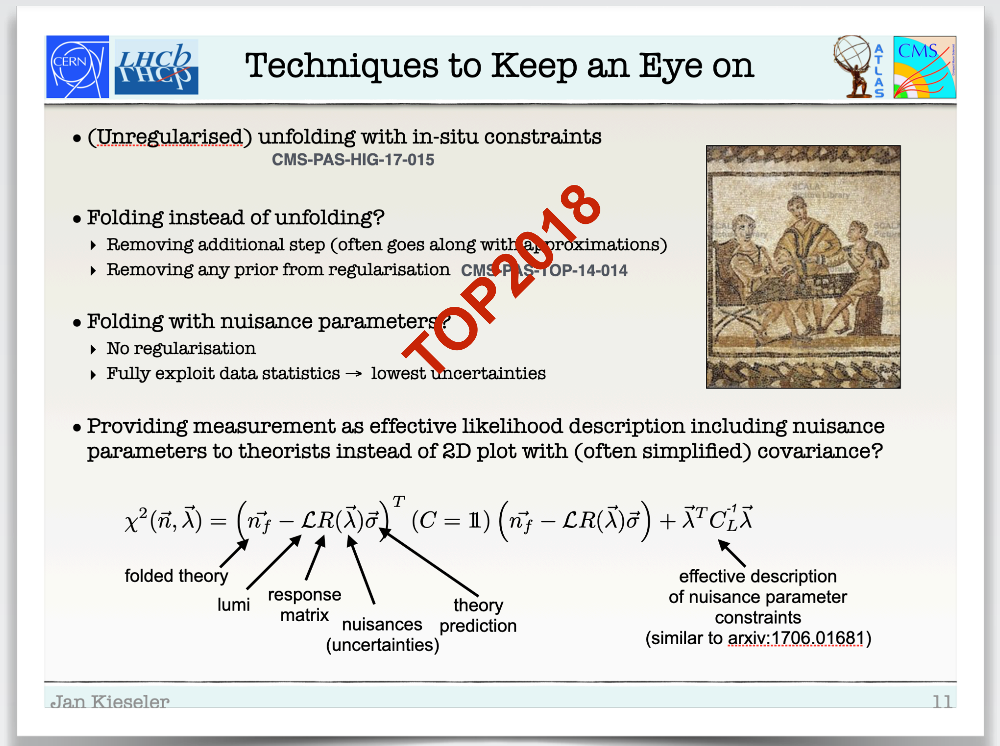
Profit from improved tracker resolution

- Extraction from J/Psi needs the most statistics
- Less affected by jet related uncertainties, final observable only built from leptons
- Also other top mass measurements will profit, mostly assuming *ancillary measurements* of modelling parameters

- Theory: focus on observables already precisely predicted: charge asymmetry/W helicity/ratios

ATL-PHYS-PUB-2018-042,
CMS-TDR-014,
CMS-PAS-FTR-16-006

- Unfolding with in-situ constraints / uncertainty marginalisation



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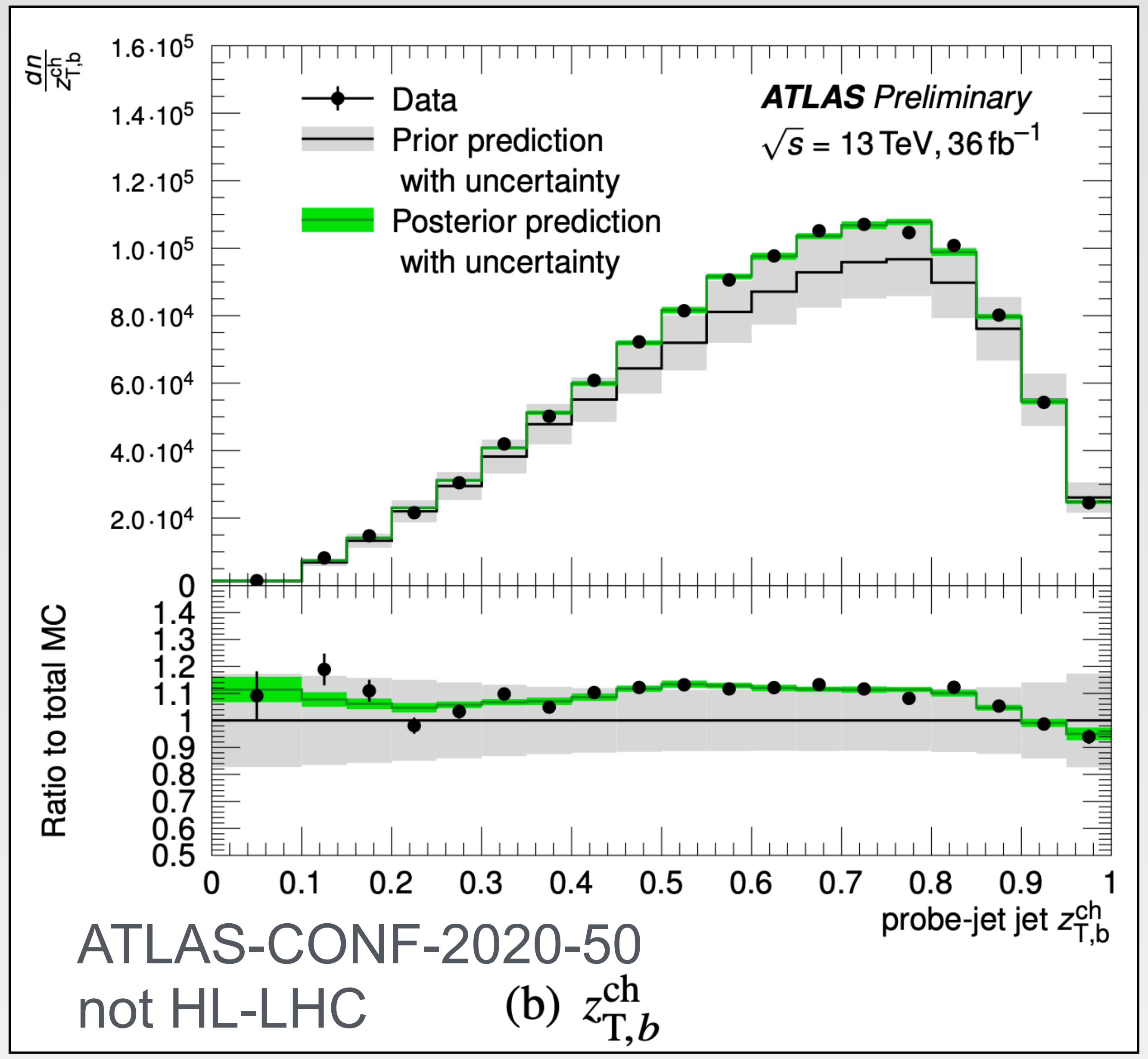
01/14/21 | By Stephanie Melchor

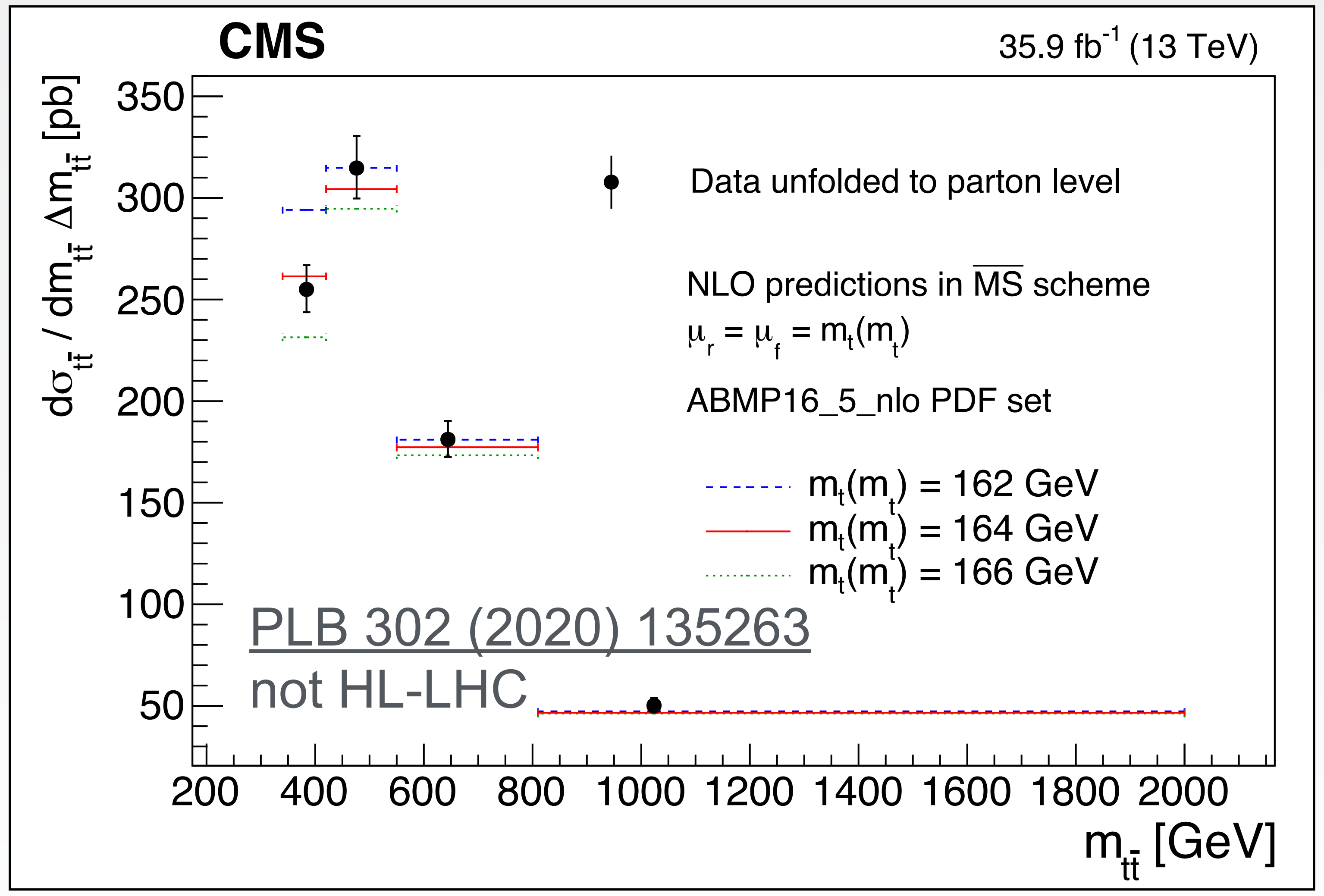
The ATLAS collaboration has begun to publish likelihood functions, information that will allow researchers to better understand and use their experiment's data in future analyses.



- We are on a good path, let's keep climbing

- Use *differentiable programming* to find optimal analysis working points
  - Code written using differentiable programming tools allows **optimising free parameters automatically** with powerful gradient descent methods
  - Optimise not only for best Signal/Background but also to find **best classifier to constrain systematics** [1,2]
  - Direct simulation based inference [3]
  - These also offer direct access for ***multi-process optimisations***

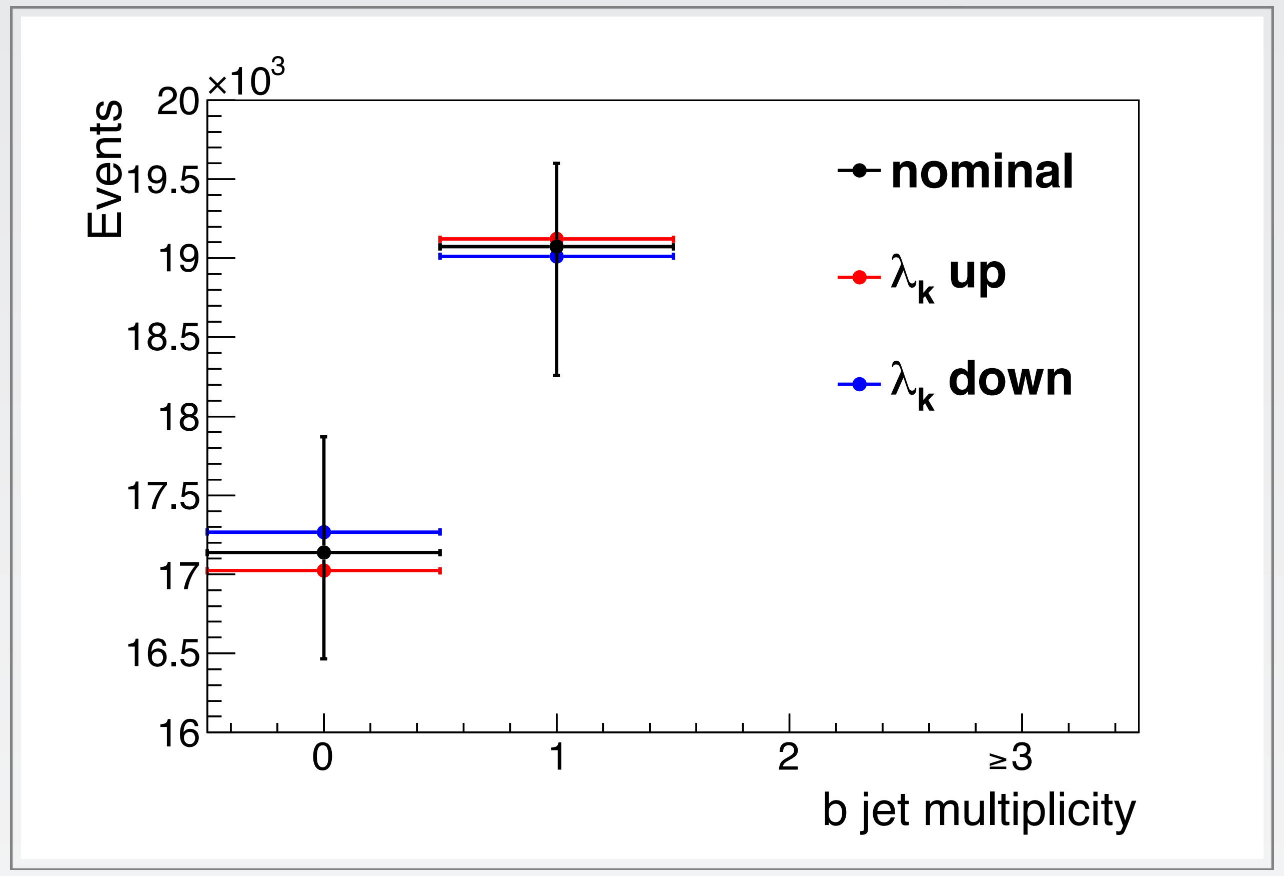
→ possibly Clara's talk

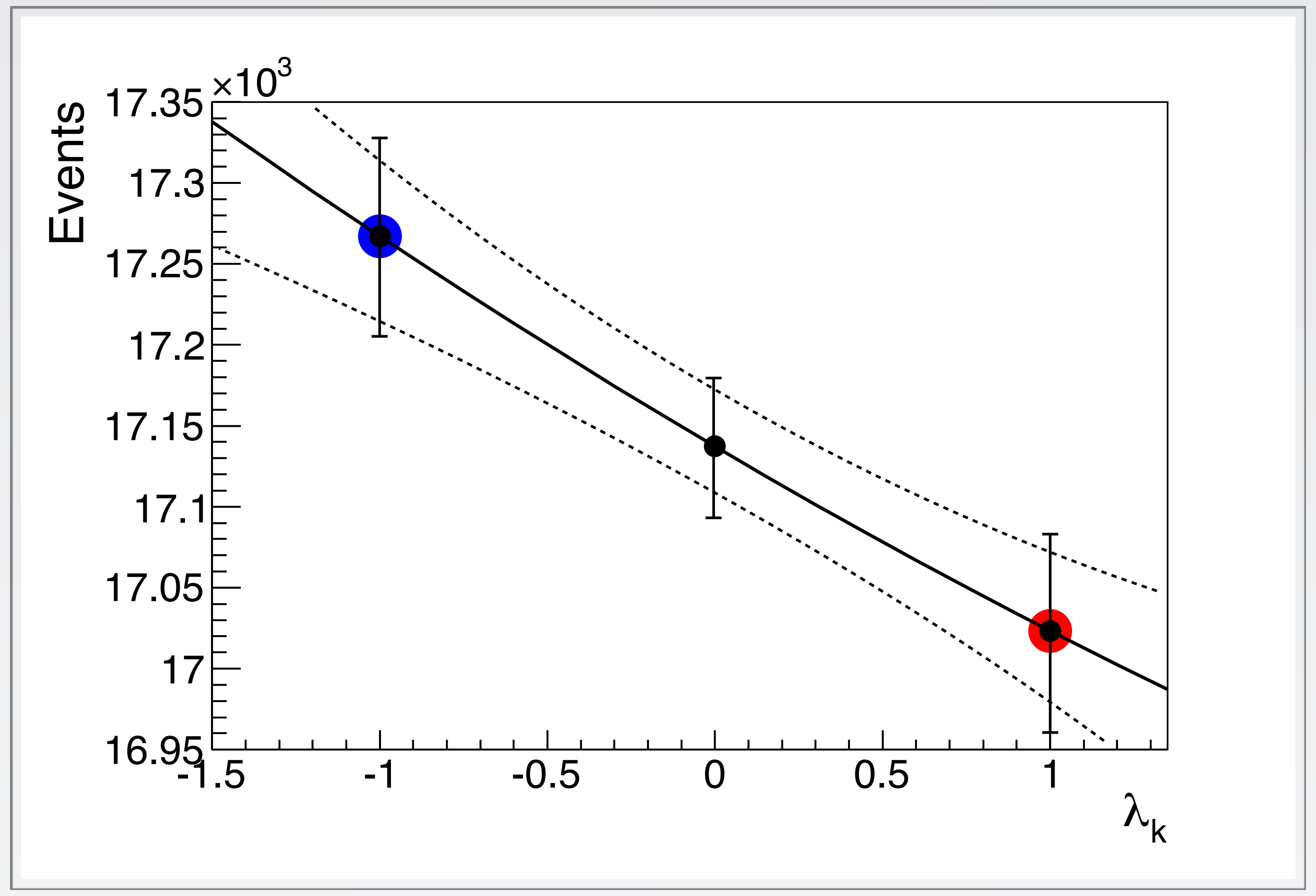


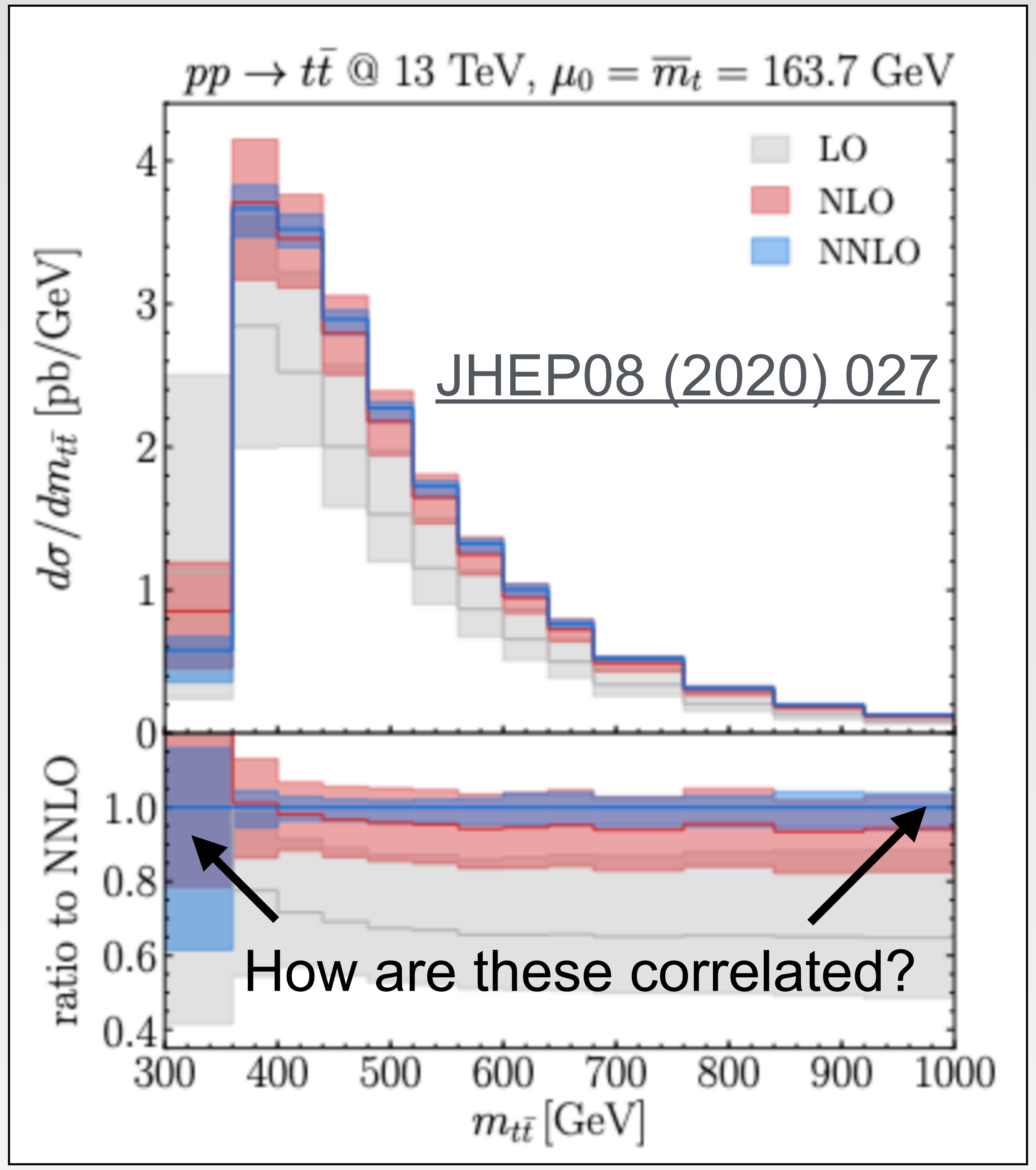
[1] Inferno ,[2] Neos, [3] Cranmer et al. and therein

Challenges

- 3 ab-1 of data will have enormous constraining power
- Make sure constrains are physically meaningful
  - Precise understanding of uncertainty correlations: systematic orthogonal variations of modelling parameters (e.g. as for PDFs)
  - Understand and model impact of statistical fluctuations







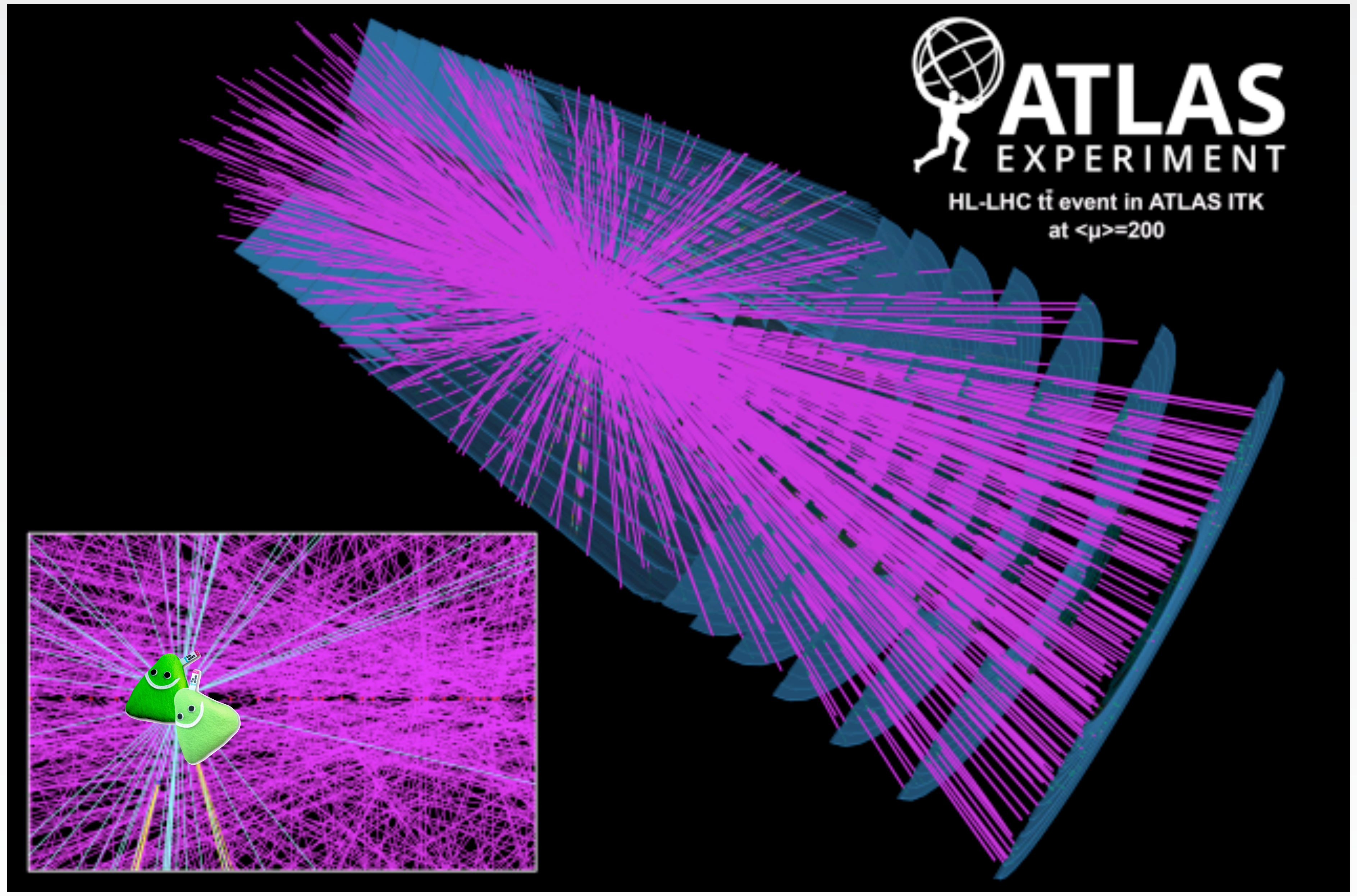
Total Stat+Syst	$\pm^{0.57}_{0.64}$
MC Statistical	0.36
Total	$\pm^{0.68}_{0.73}$
m_t^{MC}	172.33

CMS-PAS-TOP-17-001

- Have the person power to do all that, ***otherwise we'll have a big problem.***
- **Dire need of a paradigm change** from by-eye optimisations of many, many parameters, e.g. working points, cuts, … reconstruction algorithms to *differentiable implementations* that allow to use modern optimisation tools
  - Really find an optimum: *end-to-end* optimisation
  - More time for new developments/analysis, less maintenance work
  - Chance to solve computing challenges too

Summary

- The HL-LHC is not a bump-hunt machine, it's more a precision-at-high-scales environment
- This will bring a lot of unique opportunities for a plethora of top quark (related) measurements t(t)+X, tttt, …
- The focus will hopefully be to measure multiple processes and their interplay consistently with high precision
- There are many challenges ahead, many requiring detailed understanding of and improving experimental and theoretical uncertainties
- We need a change of paradigms to remove technical obstacles that would keep us from exploiting this unique potential
- Reminder: snowmass 2021 effort

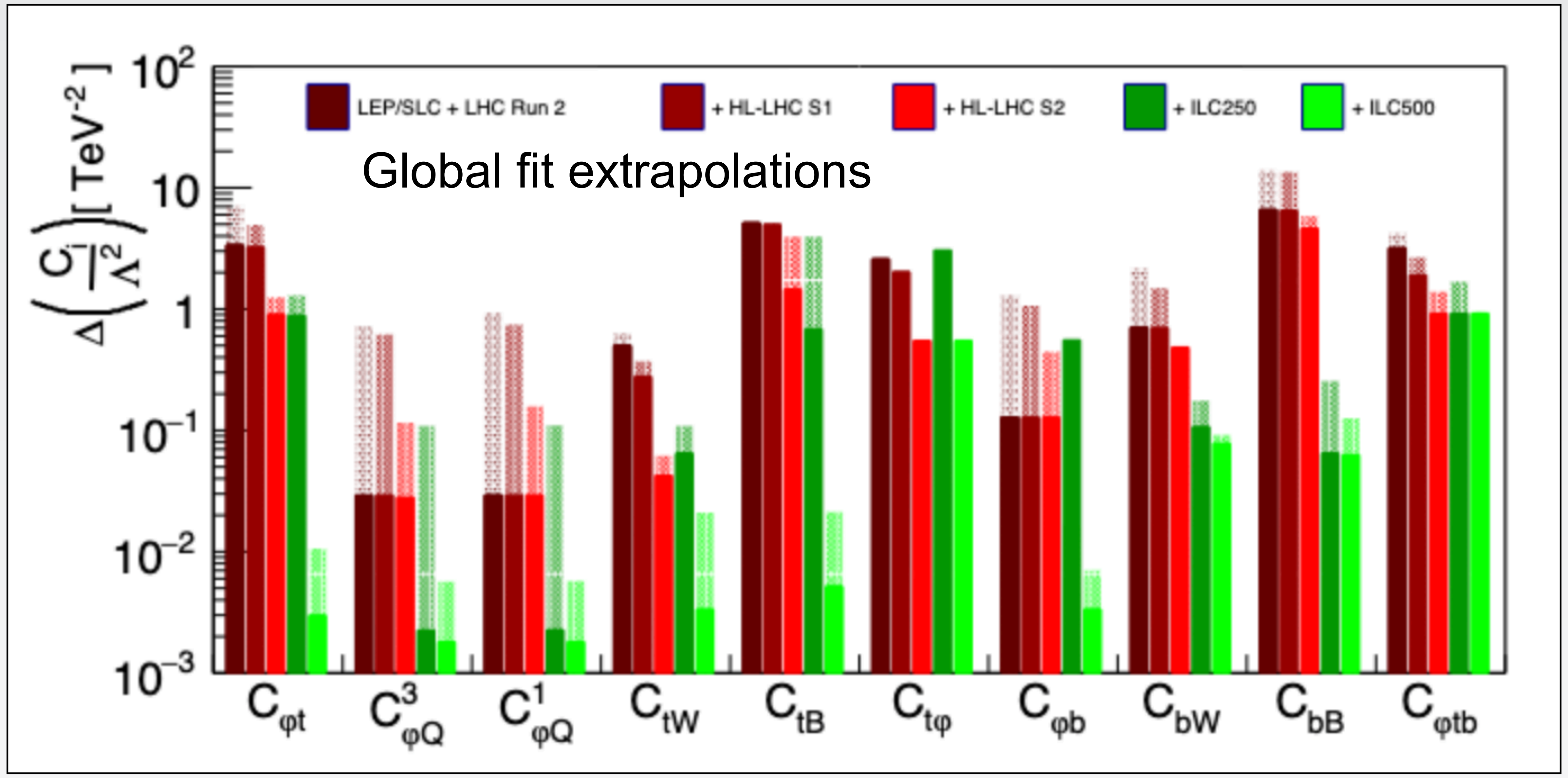


Additional material

Comparison of EFT extrapolations

ttγ ATLAS

Operator	O_{tB}	O_{tG}	O_{tW}
Single lepton	[-0.5,0.3]	[-0.1,0.1]	[-0.3,0.5]
Dilepton	[-0.6,0.4]	[-0.1,0.1]	[-0.4,0.3]
Current limit	[-7.1,4.7]	[-0.2,0.5]	[-2.5,2.5]



ttZ CMS

Table 5: Expected 68 % and 95 % CL intervals, where one Wilson coefficient at a time is considered non-zero.

Wilson coefficient	68 % CL $(\Lambda/\text{TeV})^2$	95 % CL $(\Lambda/\text{TeV})^2$
$C_{\phi t}$	[-0.47, 0.47]	[-0.89, 0.89]
$C_{\phi Q}$	[-0.38, 0.38]	[-0.75, 0.73]
C_{tZ}	[-0.37, 0.36]	[-0.52, 0.51]
$C_{tZ}^{[Im]}$	[-0.38, 0.36]	[-0.54, 0.51]

Table 6: Expected 68 % and 95 % CL intervals for the selected Wilson coefficients in a profiled scan over the 2D parameter planes $C^-_{\phi Q}/C_{\phi t}$ and $C_{tZ}/C^{[Im]}_{tZ}$. The respective second parameter of the scan is left free.

Wilson coefficient	68 % CL $(\Lambda/\text{TeV})^2$	95 % CL $(\Lambda/\text{TeV})^2$
$C_{\phi t}$	[-1.65, 3.37]	[-2.89, 6.76]
$C_{\phi Q}$	[-1.35, 2.92]	[-2.33, 6.69]
C_{tZ}	[-0.37, 0.36]	[-0.52, 0.51]
$C_{tZ}^{[Im]}$	[-0.38, 0.36]	[-0.54, 0.51]

- Not quite direct comparison
- Sometimes individual analysis extrapolations turn out to be more powerful than extrapolations of global fits

ATL-PHYS-PUB-2018-049, CMS-PAS-FTR-18-036, G. Durieux et al.