FACULTY OF SCIENCES

Dispelling the $\sqrt{\mathcal{L}}$ myth for the High-Luminosity LHC

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Amber Cauwels / Journal Club / 28-Feb-2025

GHENT UNIVERSITY

About the paper

- Title: Dispelling the $\sqrt{\mathcal{L}}$ myth for the High-Luminosity LHC
- Authors: Alberto Belvedere, Christoph Englert, Roman Kogler, Michael Spannowsky
- Published: Jul 20, 2024
- Journal: The European Physical Journal C

DESY.

Durham University

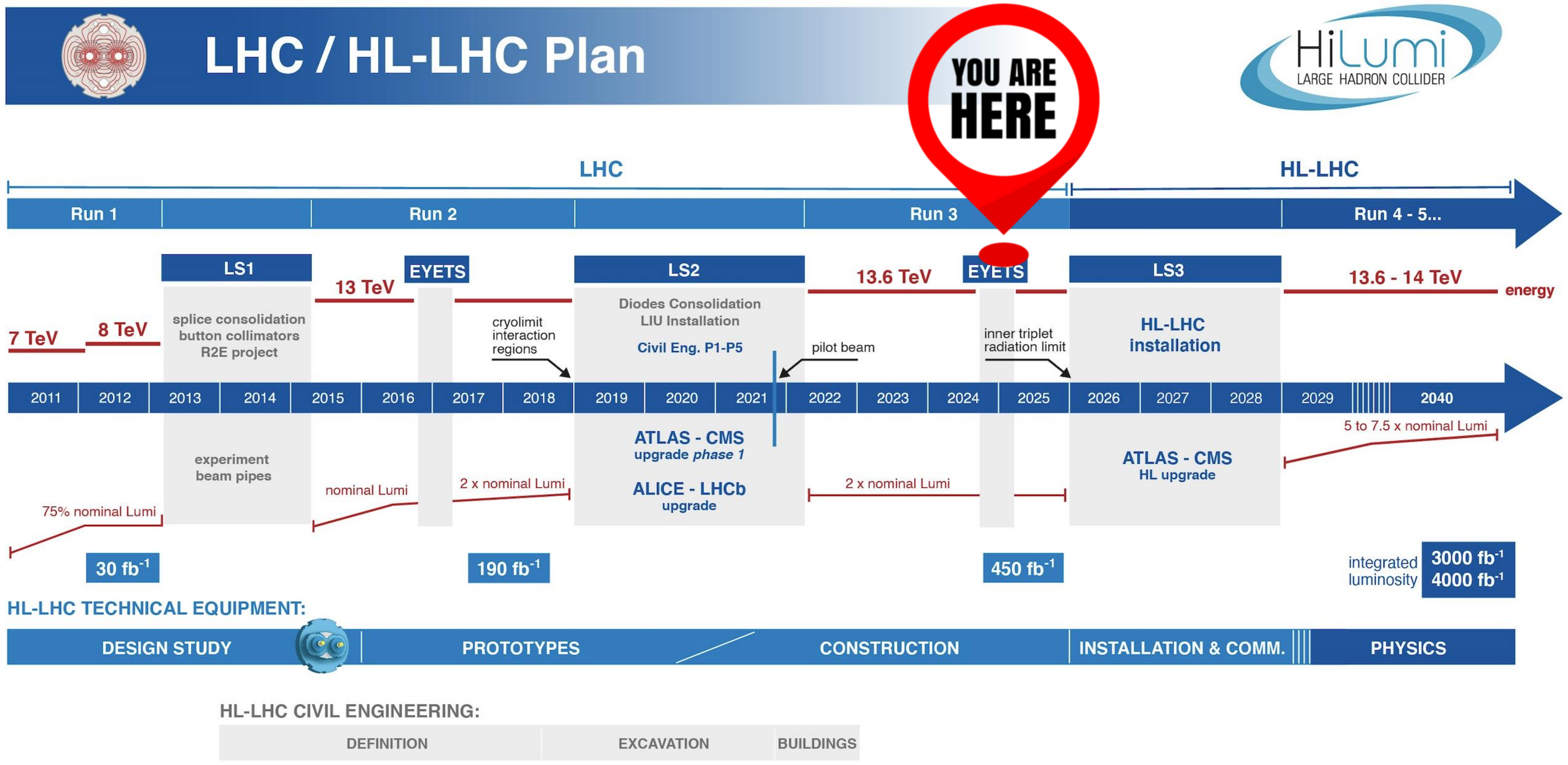
University of Glasgow

VIA VERITAS VITA

Their Claim :

"The assumption that the sensitivity in searches and measurement scales only with $\sqrt{\mathcal{L}}$ at the High-Luminosity LHC is overly conservative at best, and unrealistic in pratice"

High-Luminosity LHC



- $\mathcal{L}_{inst}$: describes the number of collisions happening in a unit of time
- $\mathcal{L} = \int \mathcal{L}_{inst}\, dt$
- HL-LHC:
  - $\mathcal{L}_{inst}$ x 5-7.5
  - $\mathcal{L}$ x 10
  - $\mathcal{L}_{tot} \approx 3000\, fb^{-1} = 3\, ab^{-1}$

How???

High-Luminosity LHC

Cutting-edge 11–12 Tesla superconducting magnets, compact superconducting cavities for beam rotation with ultra-precise phase control, new technology and physical processes for beam collimation, 100-meter-long high-power superconducting links with negligible energy dissipation, installation of 24 new quadrupole magnets made of niobium-tin (Nb_3Sn) superconductors, development of innovative crab cavities, reinforcement of machine protection systems, implementation of crystal collimators, upgraded beam optics with achromatic telescopic squeezing (ATS) scheme, expansion of cryogenic infrastructure, construction of new cooling circuits, replacement of 60 out of 118 existing collimators, addition of 15 to 20 new collimators, development of superconducting power transmission lines made of magnesium diboride (MgB_2), renovation of the injector accelerator chain, replacement of Linac2 with the new Linac4 linear accelerator, enhancements to the Proton Synchrotron Booster, upgrades to the Proton Synchrotron (PS), improvements to the Super Proton Synchrotron (SPS), excavation of two new 300-meter-long service tunnels, construction of two new shafts approximately 100 meters deep, relocation of power converters to new service tunnels, expansion of cryogenic facilities into new service tunnels, installation of innovative superconducting electrical transmission lines, capability to carry currents up to 100,000 amperes, implementation of new beam optics designs, installation of new instrumentation for beam parameter measurement, replacement of four 15-meter-long dipole magnets with eight 5.5-meter-long magnets, upgrade of dipole magnets to 11 Tesla strength, use of niobium-tin (Nb_3Sn) in new dipole magnets, generation of 11 Tesla magnetic fields in new dipole magnets, installation of 16 crab cavities near ATLAS and CMS experiments, enhancement of machine protection systems, replacement of 60 existing collimators with advanced designs, addition of 15 to 20 new collimators, development of crystal collimators, use of 4 mm-long bent crystals as primary collimators, implementation of innovative superconducting power lines, utilization of magnesium diboride (MgB_2) in power lines, capability of power lines to carry up to 100,000 amperes...

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How???

The $\sqrt{\mathcal{L}}$ myth

Physics projections for HL-LHC:

- Sensitivity $\mathcal{S}$ to new physics:

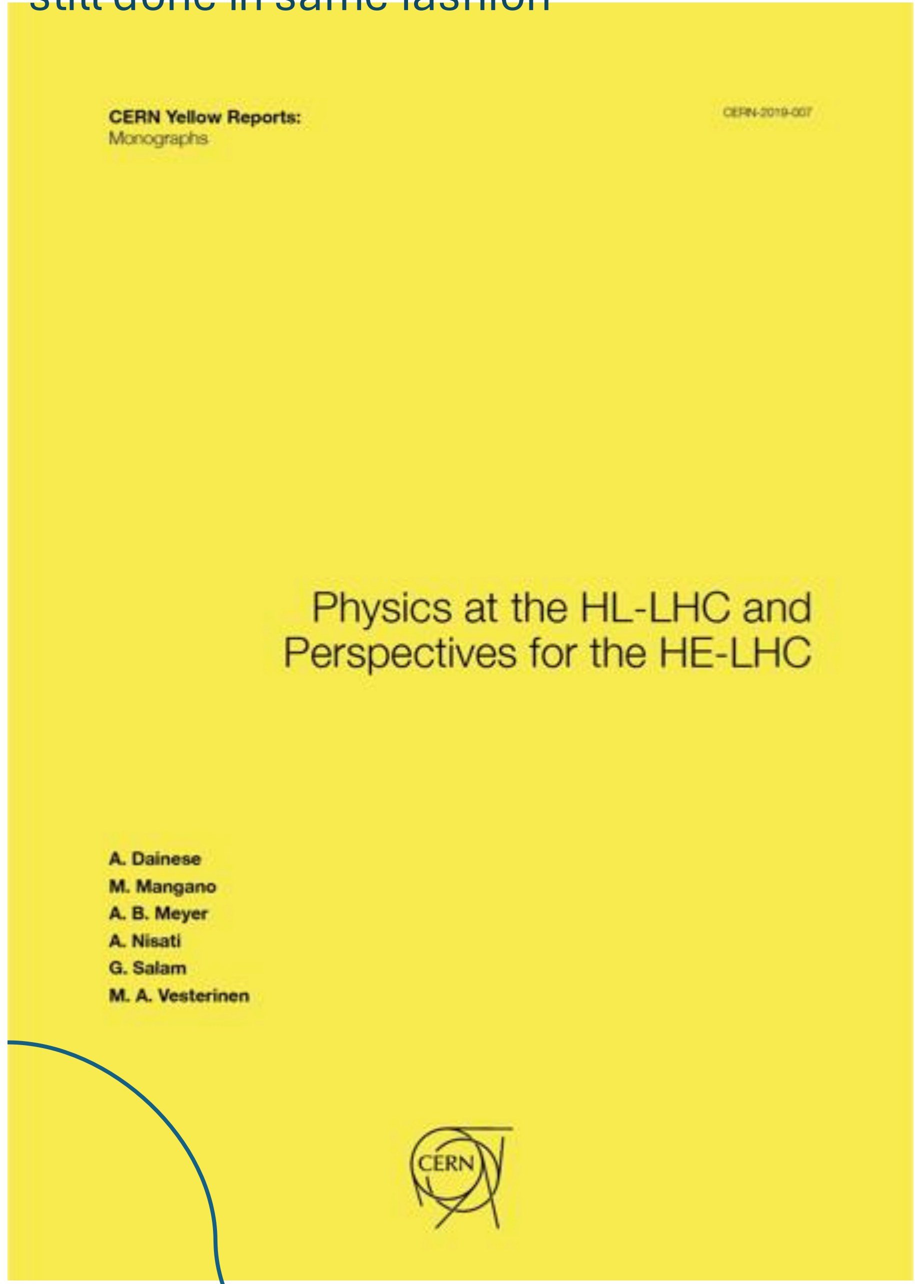
$$\mathcal{S} \simeq \frac{N_S}{\sqrt{N_B}} = \frac{\mathcal{L}\,\sigma_S}{\sqrt{\mathcal{L}\,\sigma_B}} = \sqrt{\mathcal{L}}\frac{\sigma_S}{\sqrt{\sigma_B}}$$

- Statistical Uncertainties δ for SM measurements:

$$\delta \sim \frac{1}{\sqrt{L}} \quad \text{with} \quad L = \frac{\mathcal{L}_{Run2}}{\mathcal{L}_{HL-LHC}}$$

- Systematic Uncertainties:
  - Unchange: eg. intrinsic detector limitations
  - ½ for theoretical uncertainties
  - MC uncertainties removed
  - $\sqrt{\mathcal{L}}$ rescaling for systematics limited by statistics
  - Often: YR18

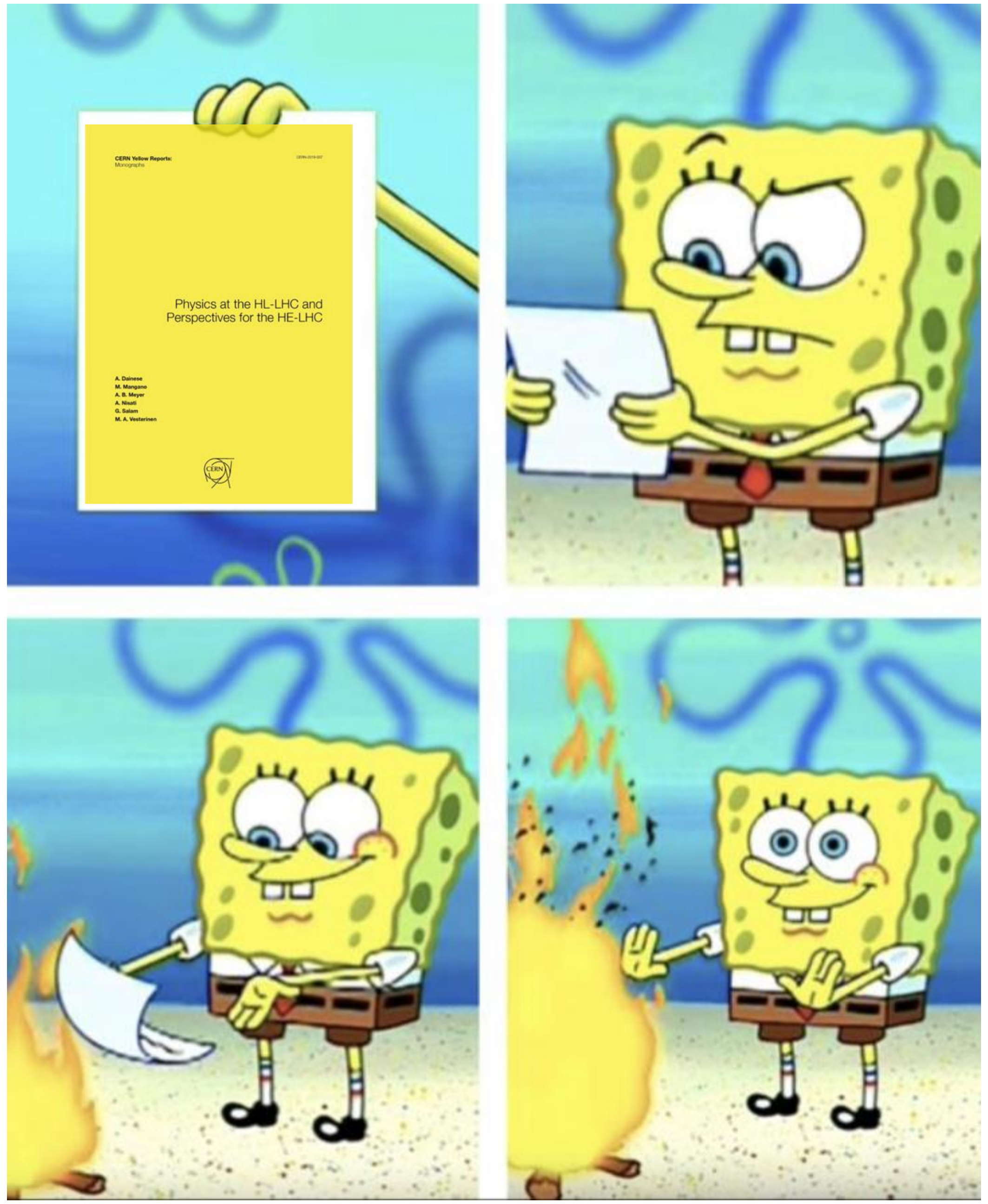
2019, but projection now are still done in same fashion


CERN Yellow Reports:
Monographs
CERN-2019-007
Physics at the HL-LHC and Perspectives for the HE-LHC
A. Dainese
M. Mangano
A. B. Meyer
A. Nisati
G. Salam
M. A. Vesterinen
CERN

Important imput to european strategy update

The myth dispelled

- $\sqrt{\mathcal{L}}$ scaling too conservative:
  - + New phase-space regions
  - + New observables
  - + New reconstruction techniques and calibrations
  - + …
  - ➢ Reducing systematic uncertainties
  - ➢ New measurement strategies

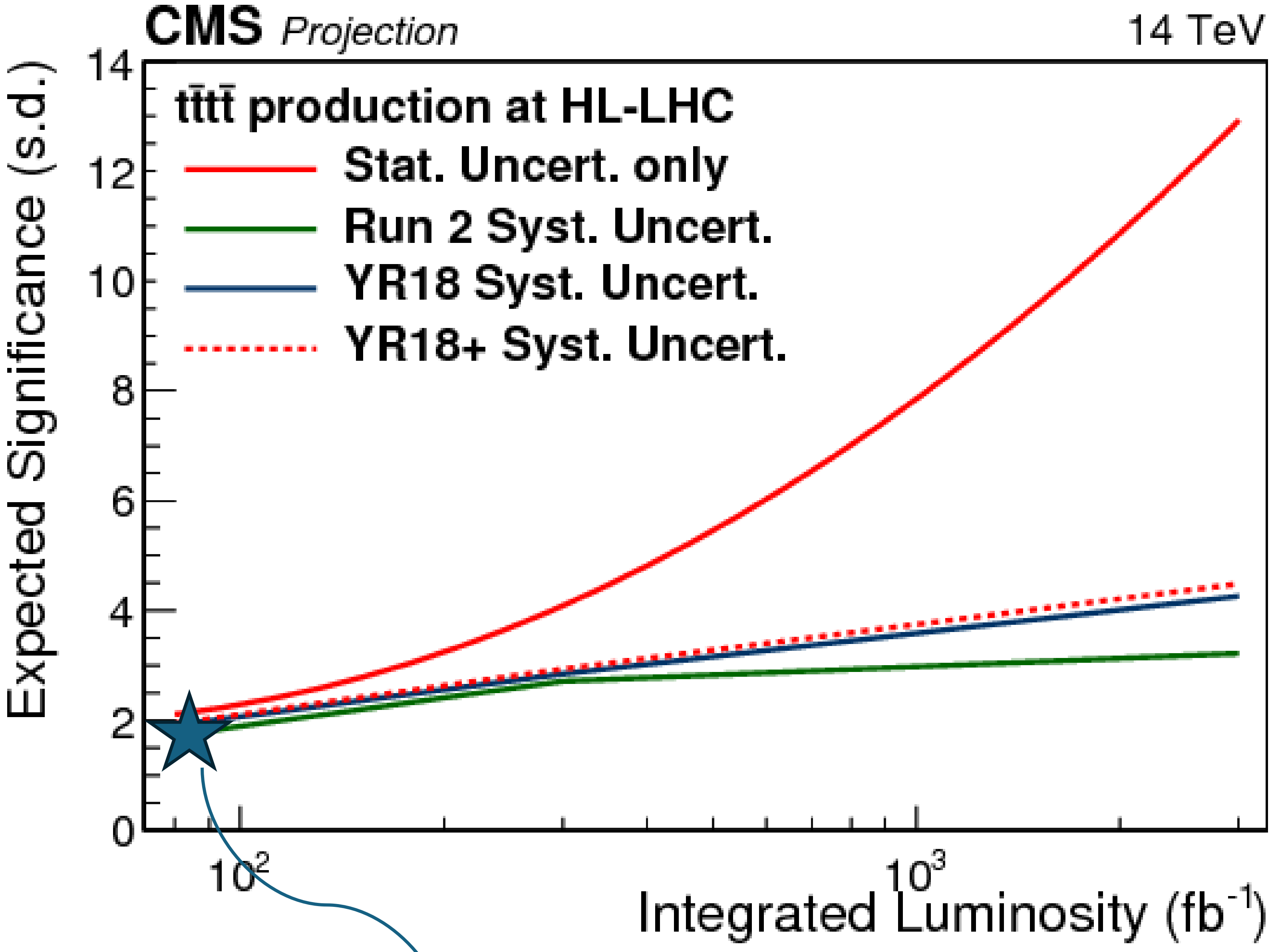


- They showcase their point with some examples
- Focus on (in my biased opinion) most interesting ones

Four tops in 2018

Source uncert.	*Stat. only*	*Run 2*	*YR18*	*YR18+*
Statistical	$(L/L_{ref})^{-0.5}$	$(L/L_{ref})^{-0.5}$	$(L/L_{ref})^{-0.5}$	$(L/L_{ref})^{-0.5}$
Experimental	None	Original	$\max(0.5, (L/L_{ref})^{-0.5})$	$(L/L_{ref})^{-0.5}$
Int. Luminosity	None	Original	0.4	0.4
Data-driven bckgrnd	None	Original	$\max(0.5, (L/L_{ref})^{-0.5})$	$(L/L_{ref})^{-0.5}$
Theory (shapes)	None	Original	0.5	0.5
Bckgrnd cross section	None	Original	0.5	0.5
Signal cross section	None	Original	0.5	0.5

Int. Luminosity	*Stat. only*	*Run 2*	*YR18*	*YR18+*
300 fb^{-1}	4.09	2.71	2.85	2.93
3 ab^{-1}	12.9	3.22	4.26	4.49



CMS PAS FTR-18-031

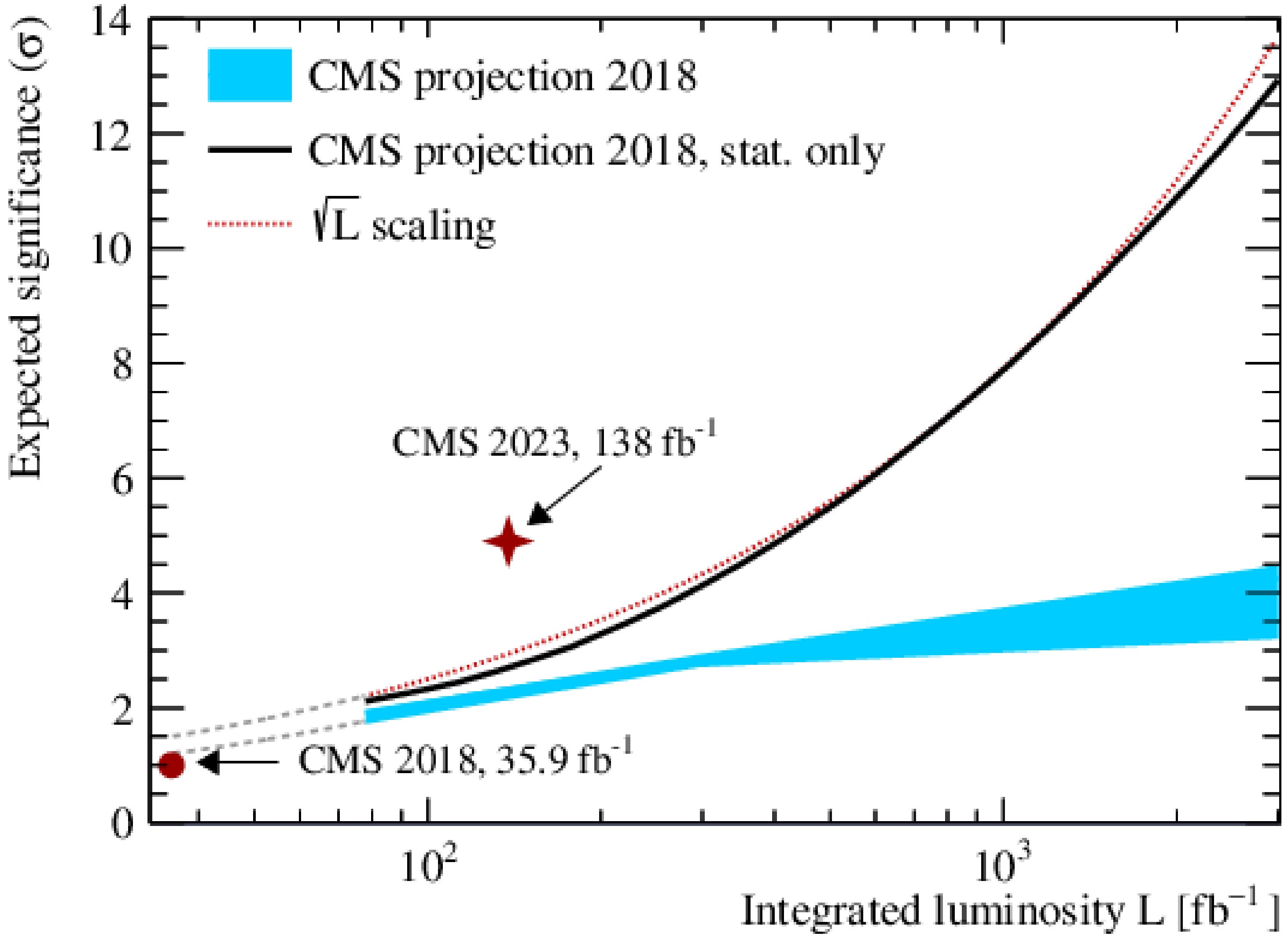
"Evidence for tttt will become possible with around 300 fb^{-1} of High-Luminosity LHC data at 14 TeV center-of-mass energy."

"With 3 ab^{-1} of High-Luminosity LHC data, the cross section can be constrained to 9% statistical uncertainty and 18 to 28% total uncertainty."

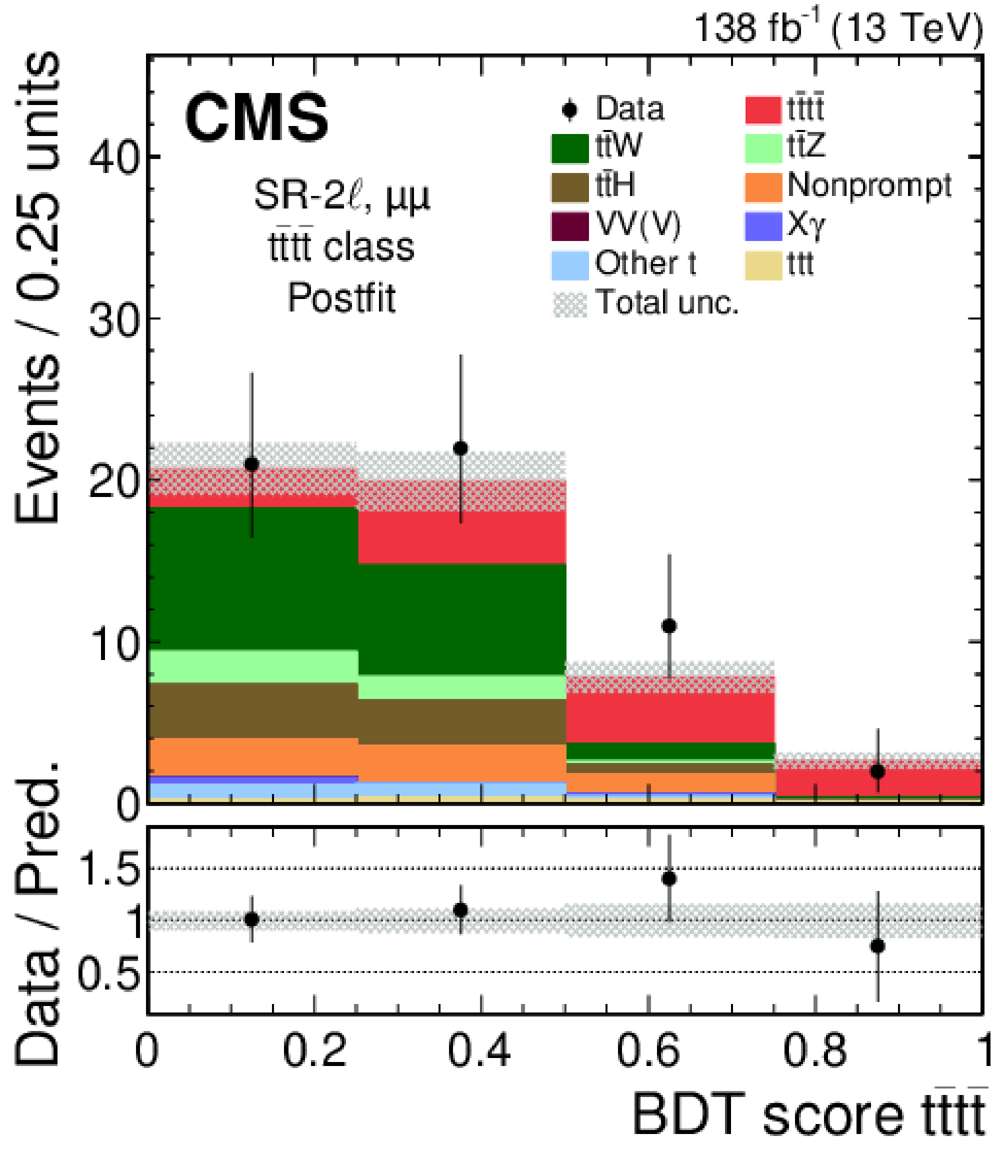
CMS-TOP-17-009: $1\sigma,\ \mathcal{L} = 36\, fb^{-1}$

The four top observation

- $\mathcal{L} = 138\ fb^{-1}$
- 13 TeV
- $\mathcal{S}\ =\ \ 5.6\ \sigma\ \leftrightarrow\ 2.7\ \sigma$
- $\sigma\ = 17.7^{+3.7}_{-3.5}\ (stat)\ ^{+2.3}_{-1.9}\ (syst)$ fb $\rightarrow\ \pm 25/28\%$



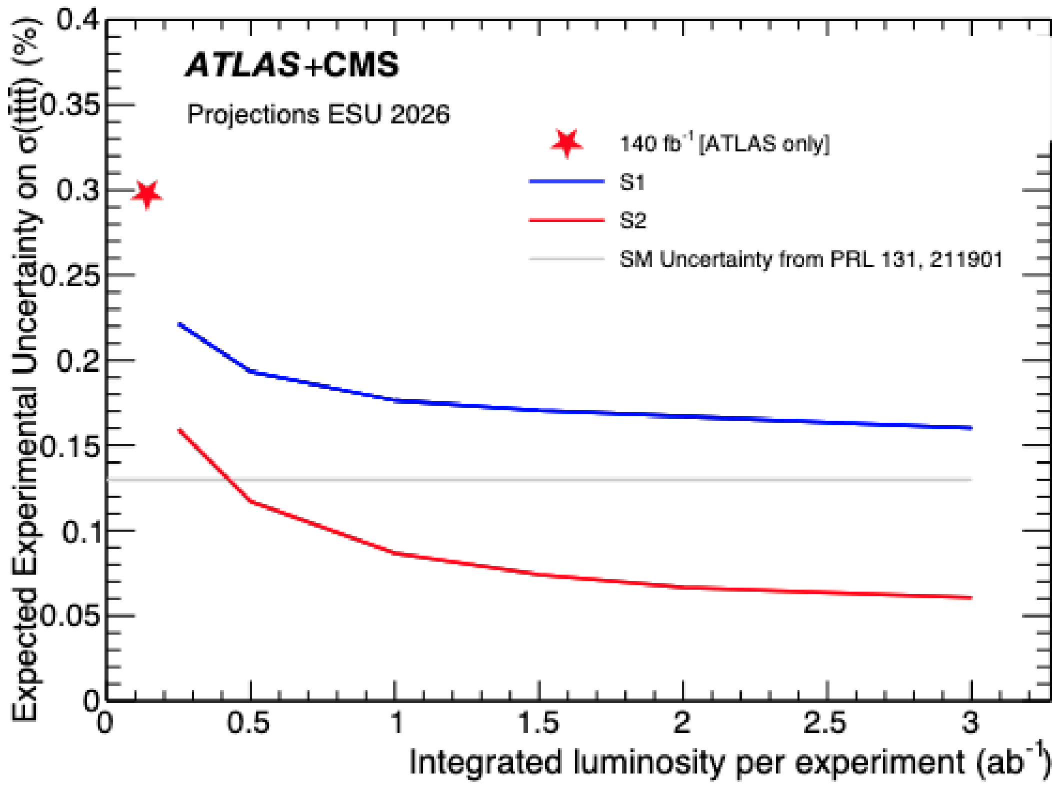
IPPP/23/76, DESY-24-016

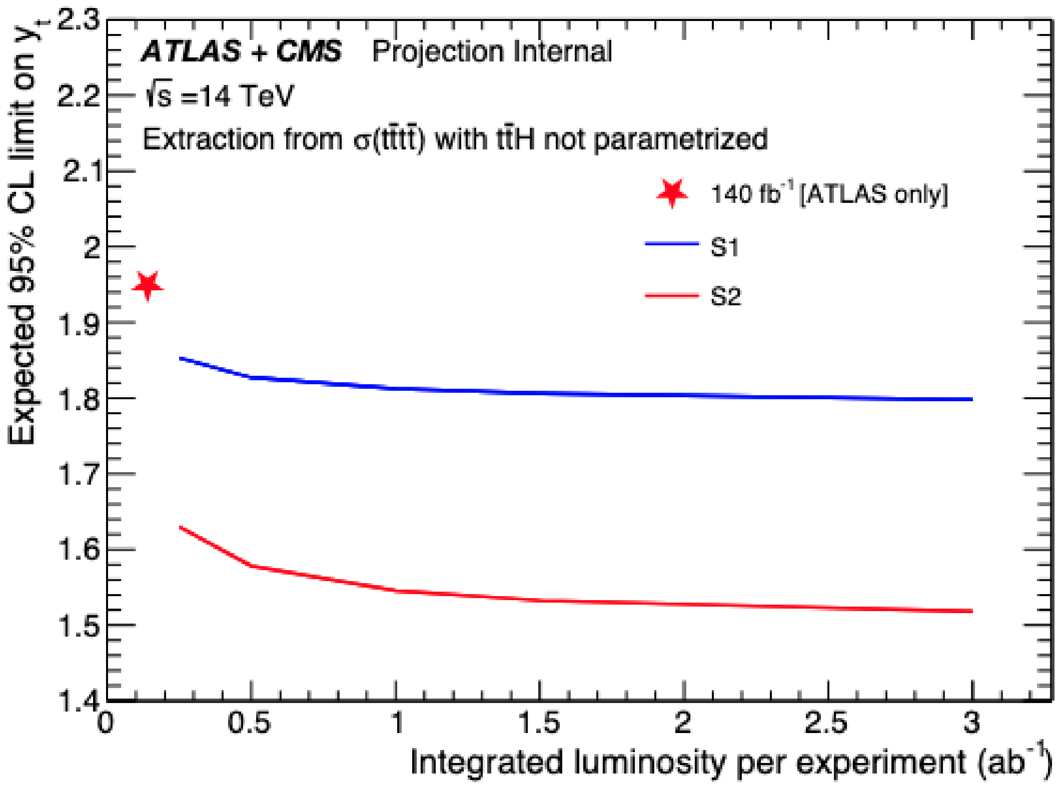


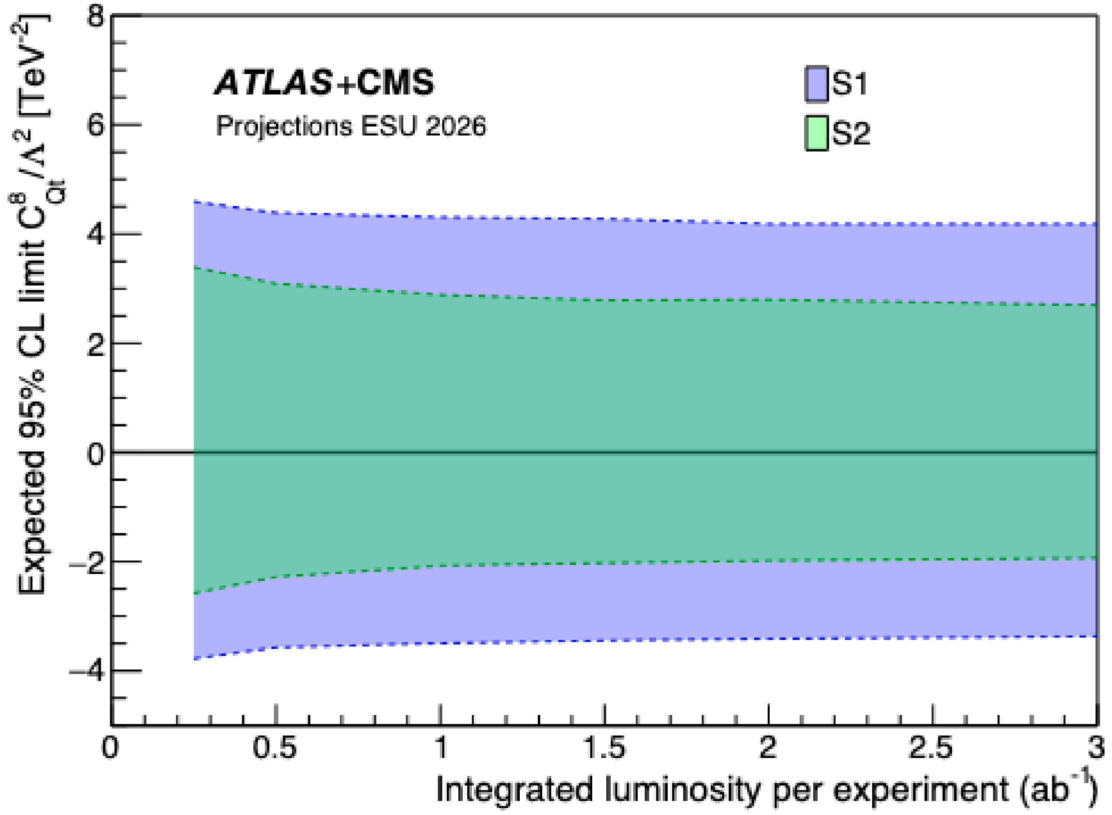
CMS-TOP-22-013

Four tops in the future

HIG-25-002, talk at WGM 688







S1: systematics unchanged wrt. run2

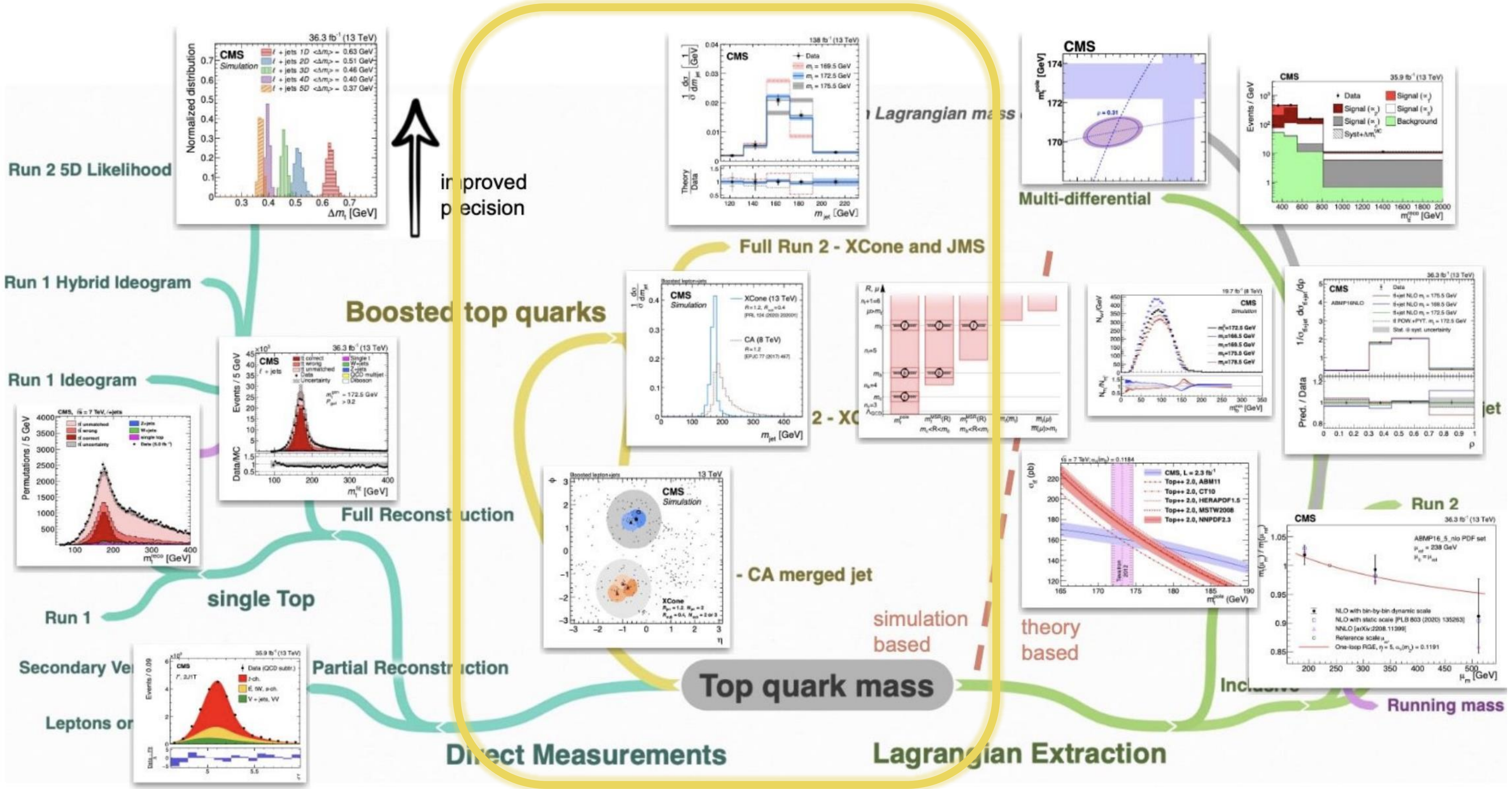
S2:

- ½ for theoretical uncertainties
- MC uncertainties removed
- $\sqrt{\mathcal{L}}$ rescaling for systematics with stat. origin

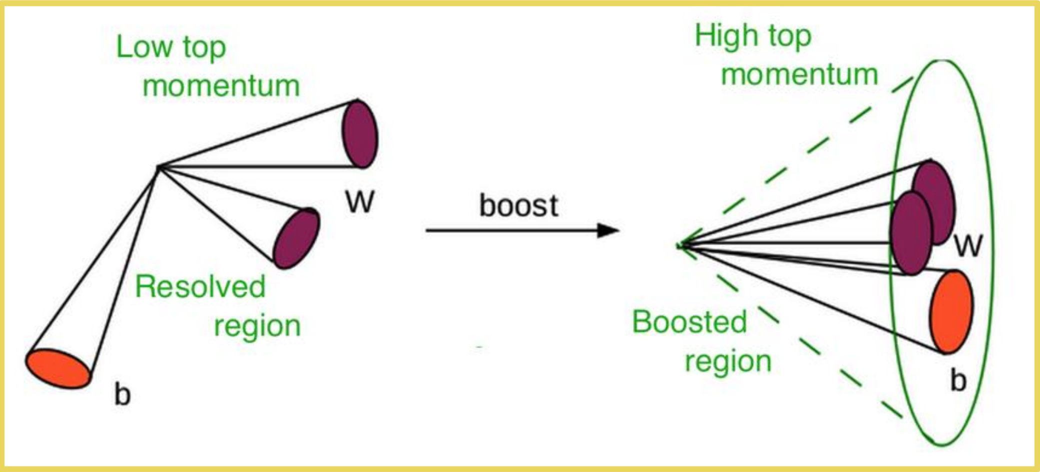
BUT disclaimer on summary slide:

All of those results produced with very conservative assumptions
Be prepared and ready to catch more results!

Exclusive m_t measurements

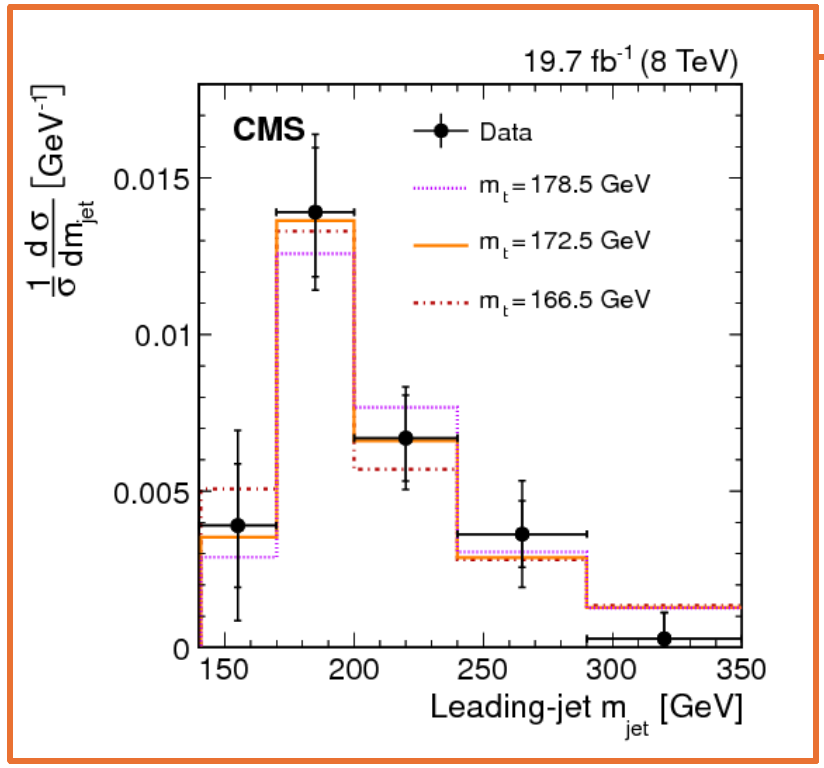


Each measurement is a piece of the puzzle…

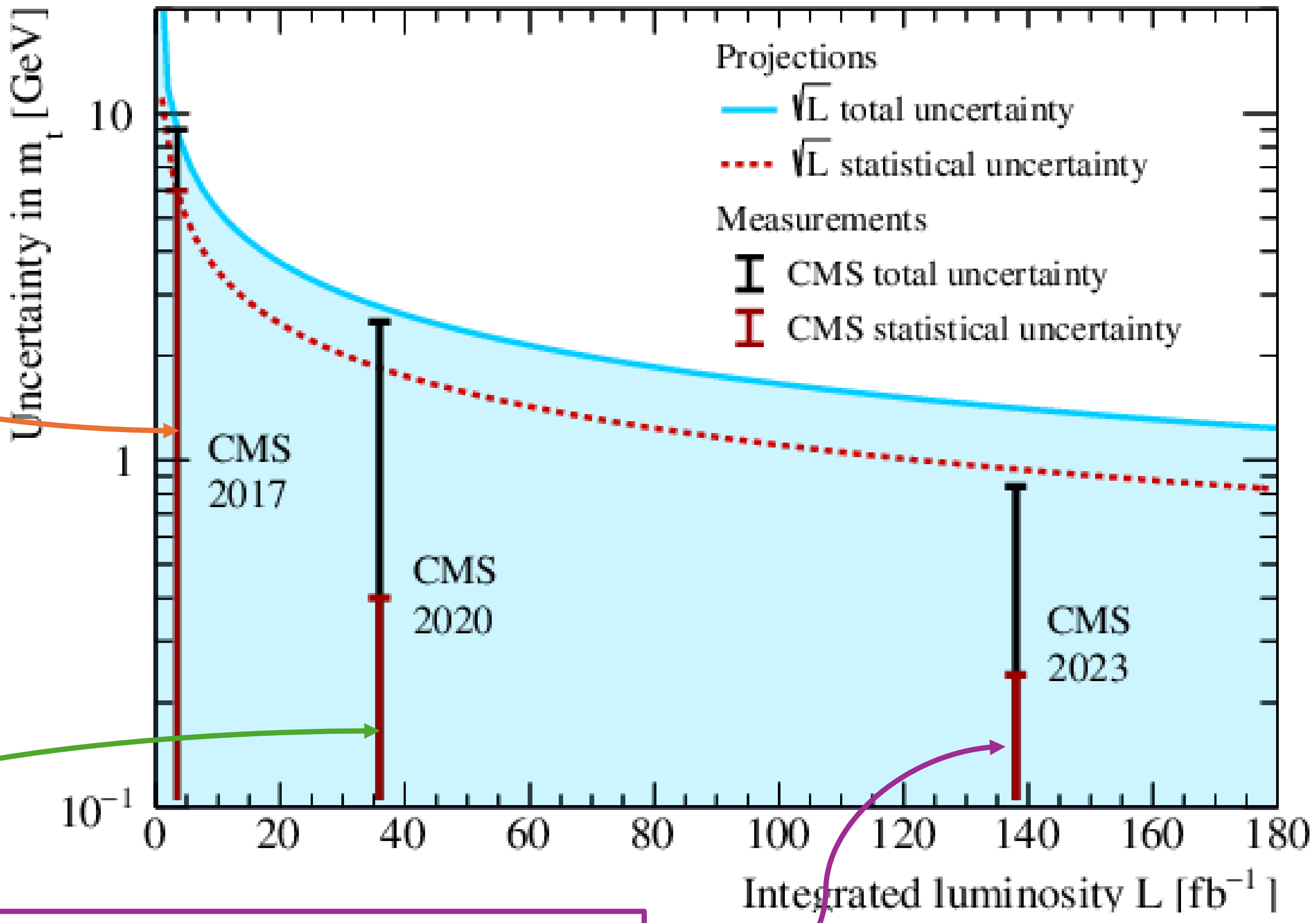


Exclusive m_t measurements

CMS-TOP-15-015

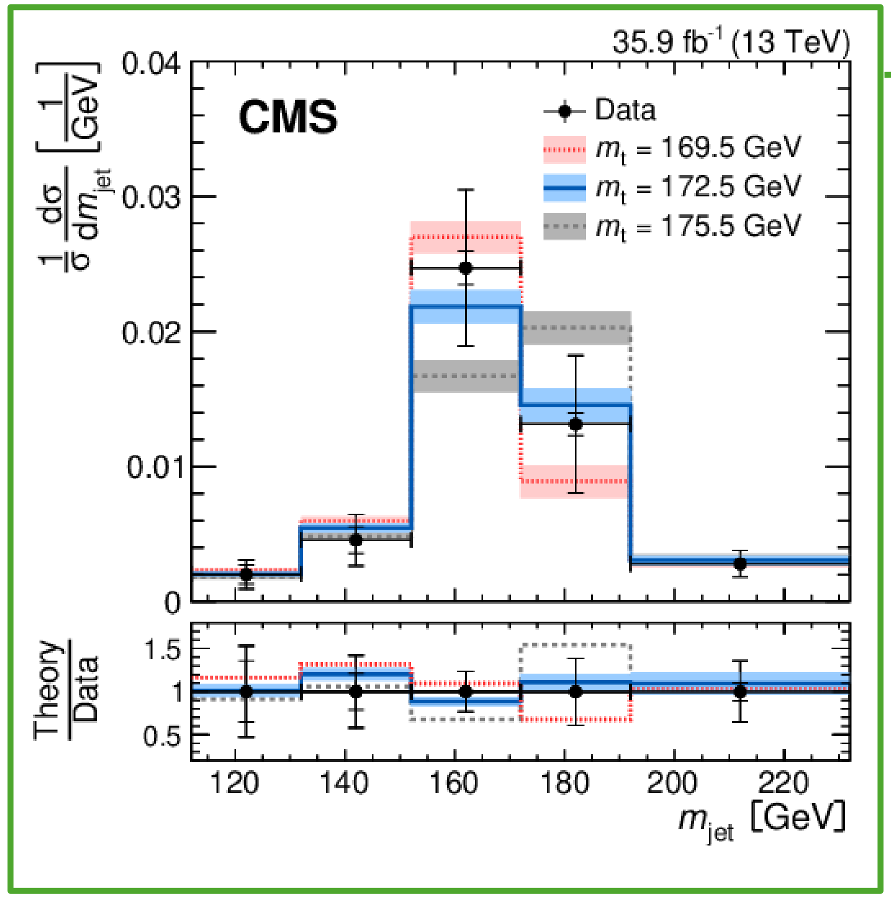


C/A clustering algo



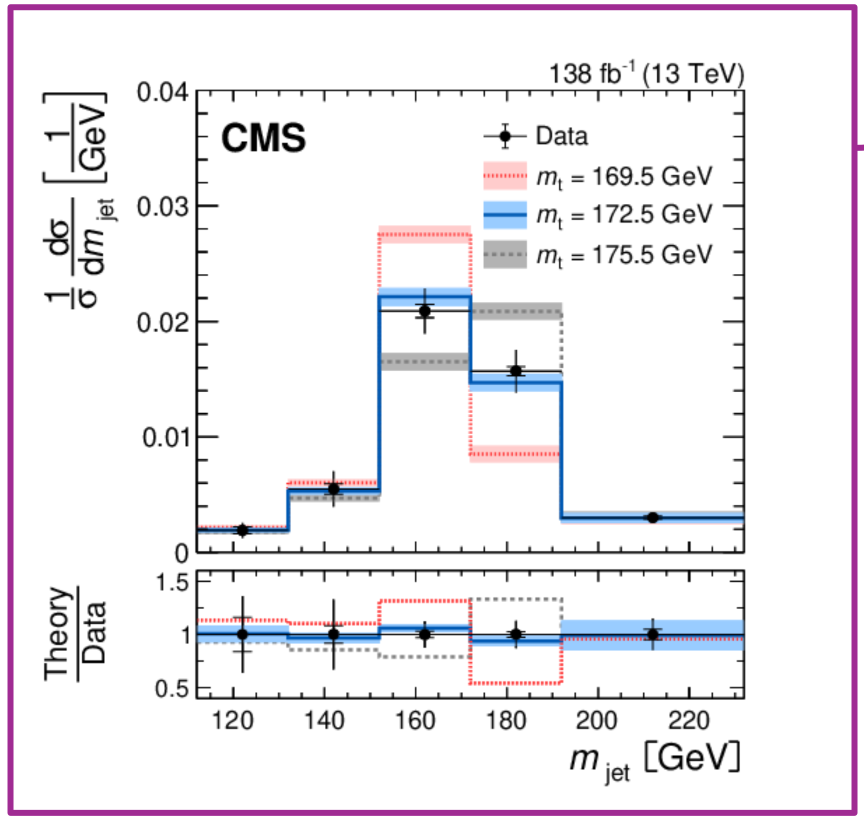
IPPP/23/76, DESY-24-016

CMS-TOP-19-005



XCone clustering algo

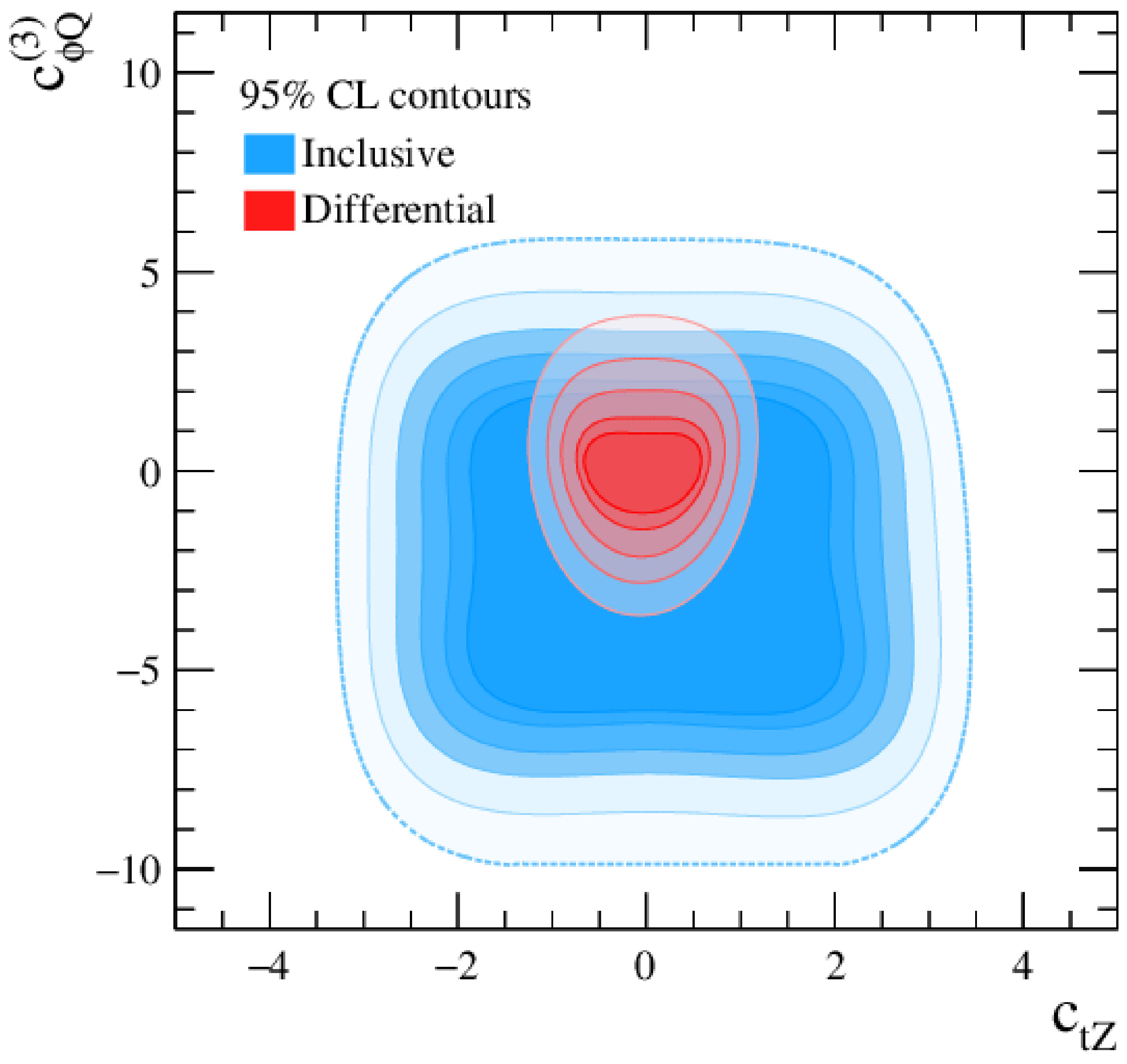
CMS-TOP-21-012



- jet mass scale is calibrated using the hadronic W boson decay
- FSR unc. reduced by studying angular correlations in the jet substructure

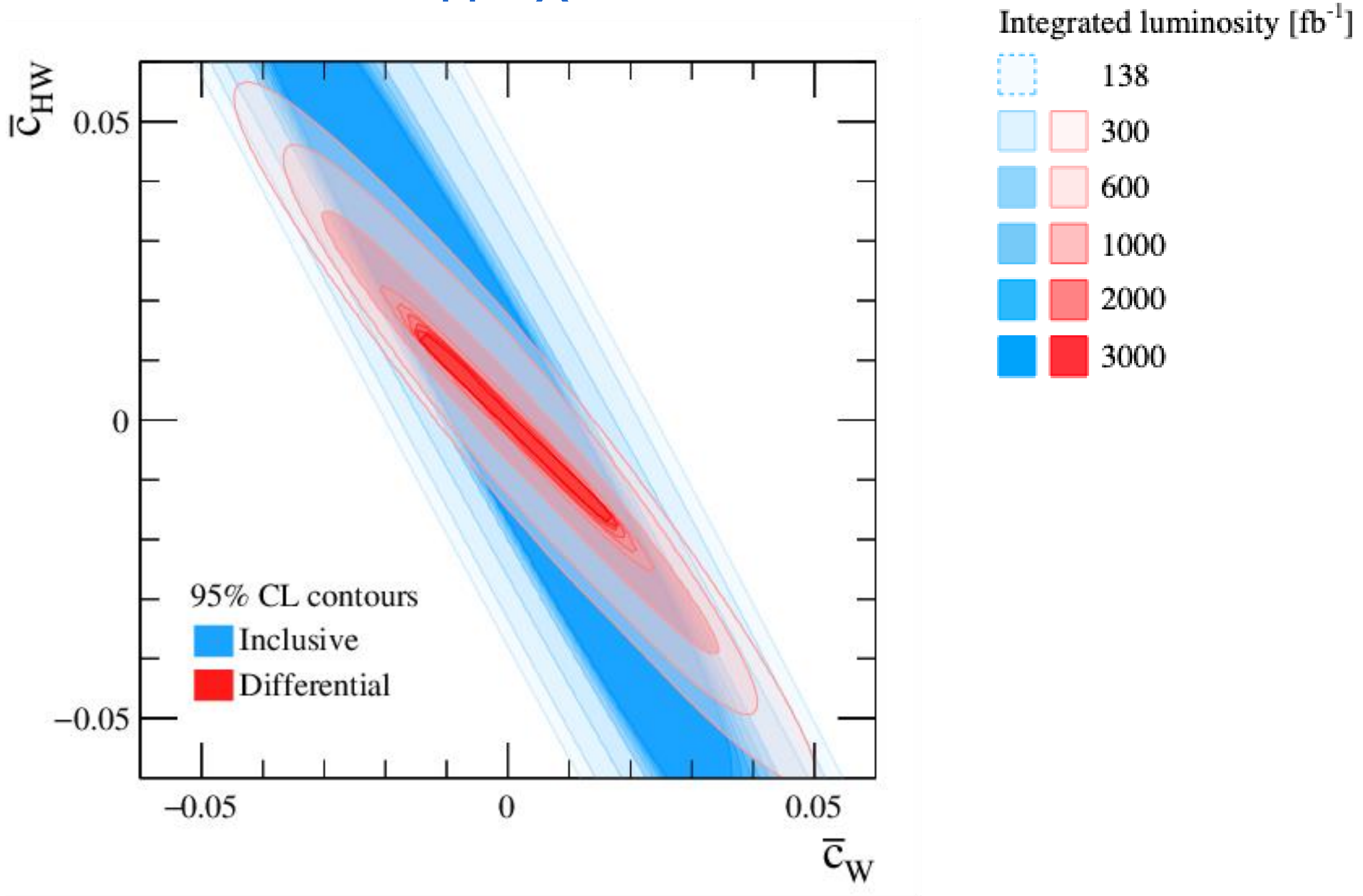
Constraints on EFT operators

tWZ + ttZ



Differential in $p_{T,Z}$

H + X



Differential in $p_{T,H}$ → needed to resolve degeneracy in WC

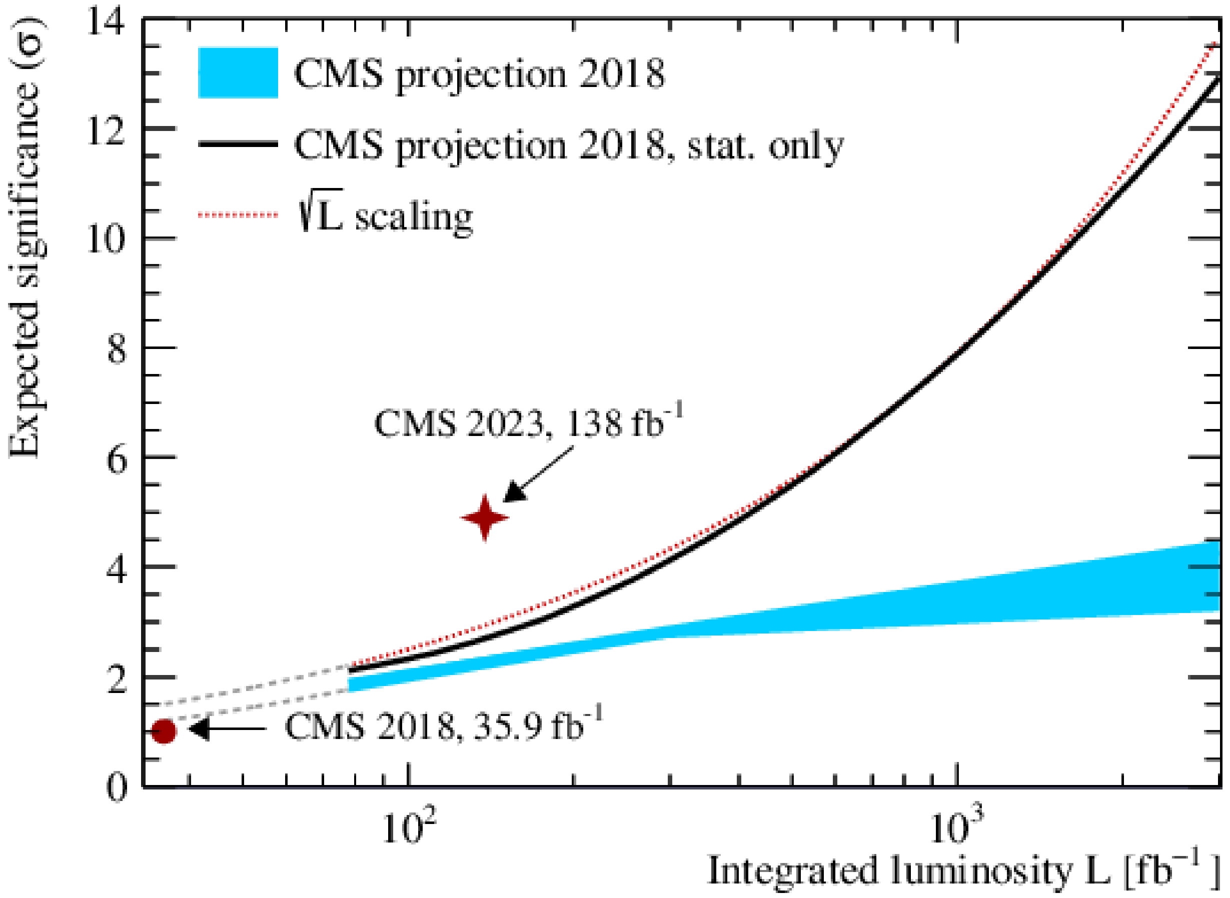
But then, how to make projections in the right way?

- Authors don't come with clear solution
- Any ideas on how Steven should do it?
- My proposal:
  - Customed Ghent projections
  - Learn from the past
  - Introducing the G-factor:

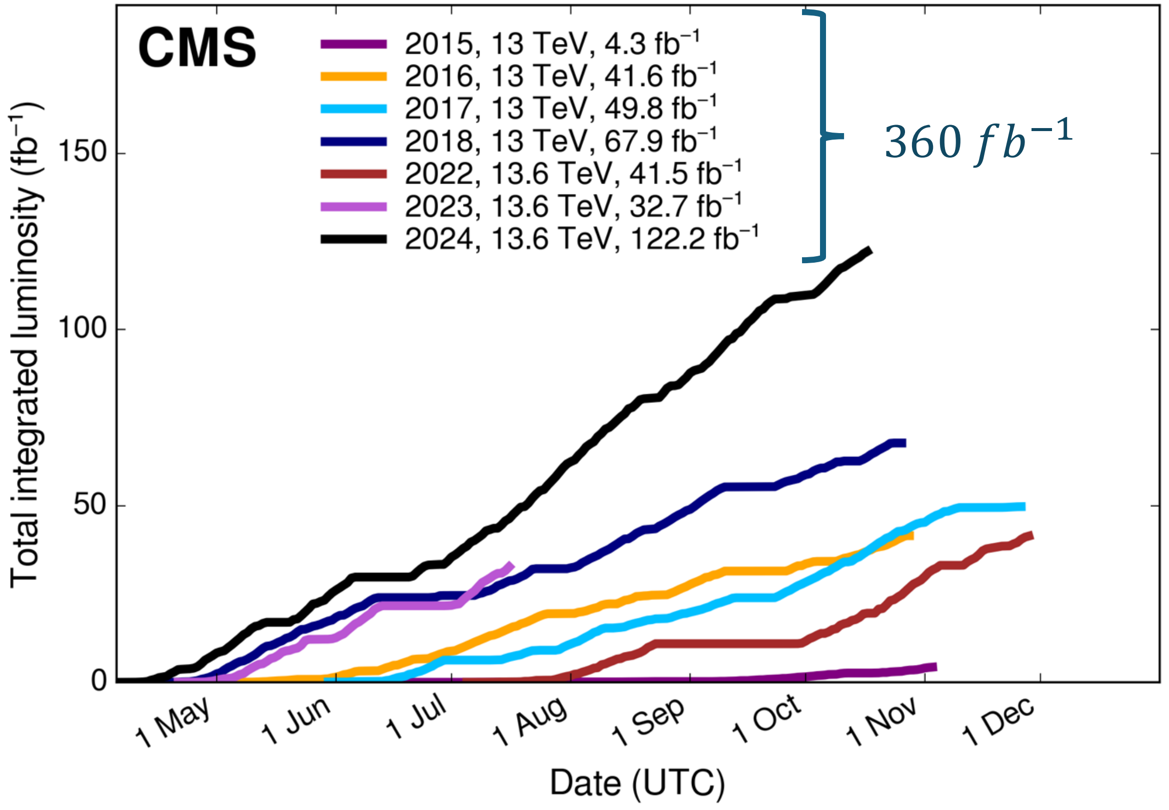
$$f_G = \frac{\sigma_{Ghent\ obs.\ 4tops}}{\sigma_{CMS\ proj.\ 4tops}} = \frac{5.6\sigma}{2.7\sigma} = 2.07$$

"The implications of these findings suggest a change in how sensitivity is estimated for future collider experiments, by broadening these studies with unexplored final states, more differential measurements, and modern analysis techniques as more data becomes available."

IPPP/23/76, DESY-24-016

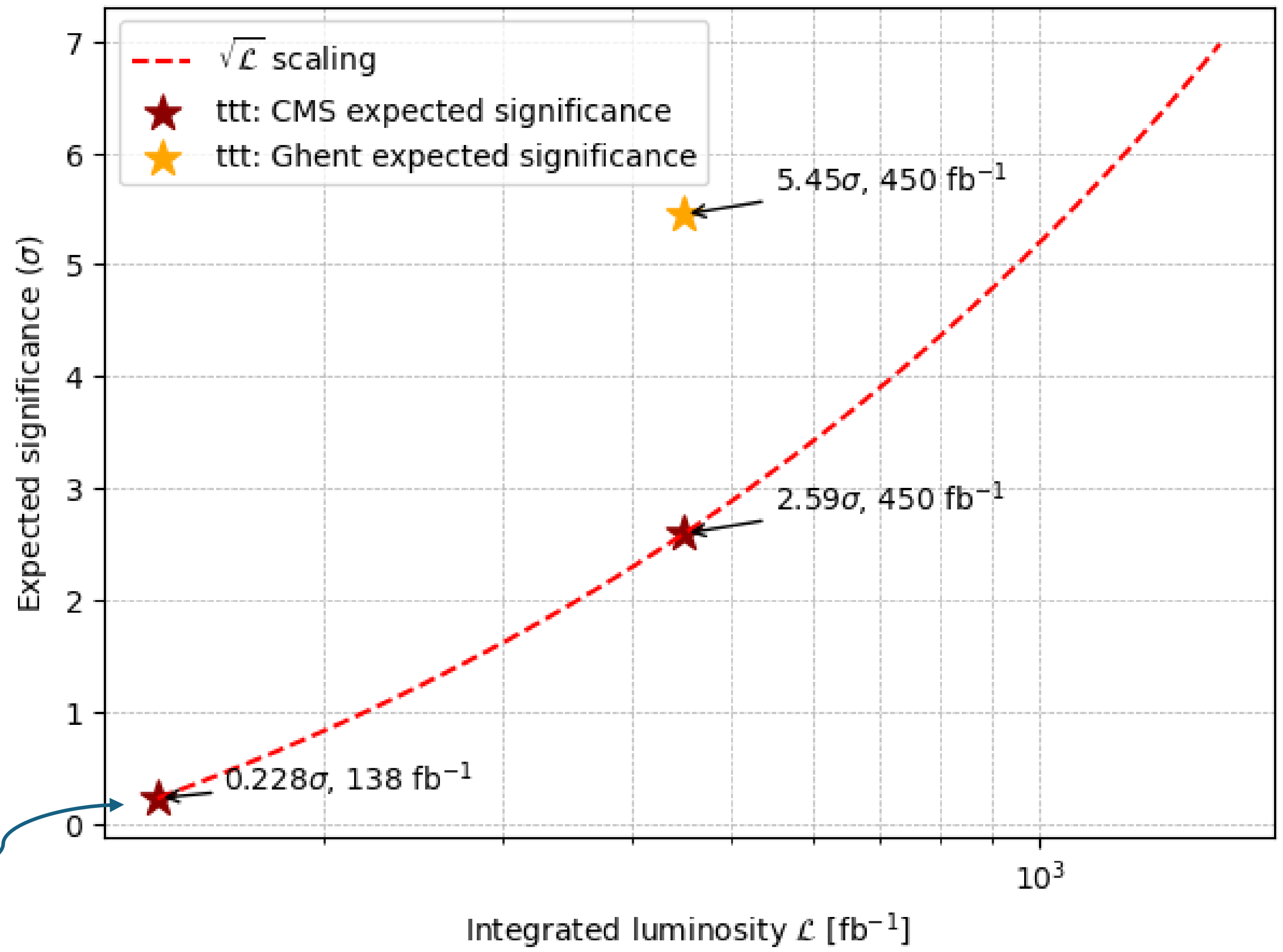


Expected 3top singificance



- Integrated Run2+Run3: $\mathcal{L} \approx 450\ fb^{-1}$
- More exciting observations!!
- IF: we keep looking beyond standard experimental strategies and data analysis techniques

AN-22-089



Concluding thoughts

Unsure what they want to achieve with this paper:

- A publication, stating the obvious?
- More awareness to take projections with a grain of salt?
- Better projections?

  -> poor yellow report people already went through a year long workshop

- Encourage phycisists to keep pushing the boundaries

  -> How can we continue breaking the $\sqrt{\mathcal{L}}$ scaling in our future analysis?

"Thus, the findings dispel the myth of $\sqrt{\mathcal{L}}$ scaling and call for reevaluating experimental strategies and data analysis techniques, encouraging the scientific community to look beyond conventional assumptions and explore the full potential of the HL-LHC."