LPC Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

BSM Searches with the Top Quark at the LHC

Romain Madar (CNRS/IN2P3/LPC)
on behalf of ATLAS and CMS collaborations

IRN Terascale – 06/11/2020

ATLAS EXPERIMENT

Motivations

$$y_t \sim 1$$

Motivations

$$y_t \sim 1$$

$\rightarrow$ **Heaviest known particle**

Motivations

$$y_t \sim 1$$

→ **Heaviest known particle**

→ **Key role in the naturalness "problem"**

Some people sees this more as matter of taste than a real problem.

Yet, probably the most dominant *leitmotiv* for BSM model building for the LHC.

Motivations

$$y_t \sim 1$$

→ **Heaviest known particle**

→ **Key role in the naturalness "problem"**

Some people sees this more as matter of taste than a real problem.

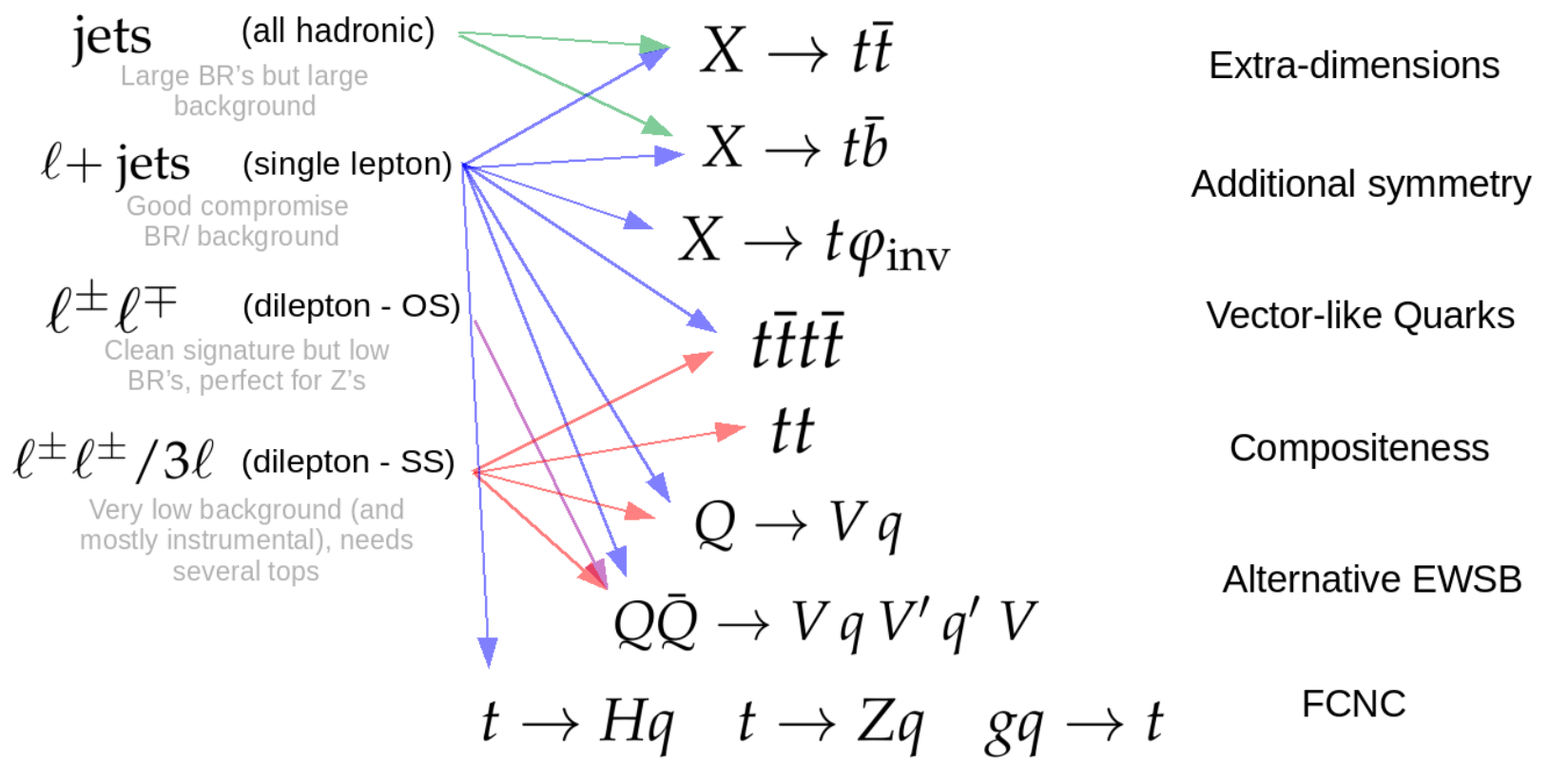
Yet, probably the most dominant *leitmotiv* for BSM model building for the LHC.

→ **Vacuum stability (Higgs field potential)**

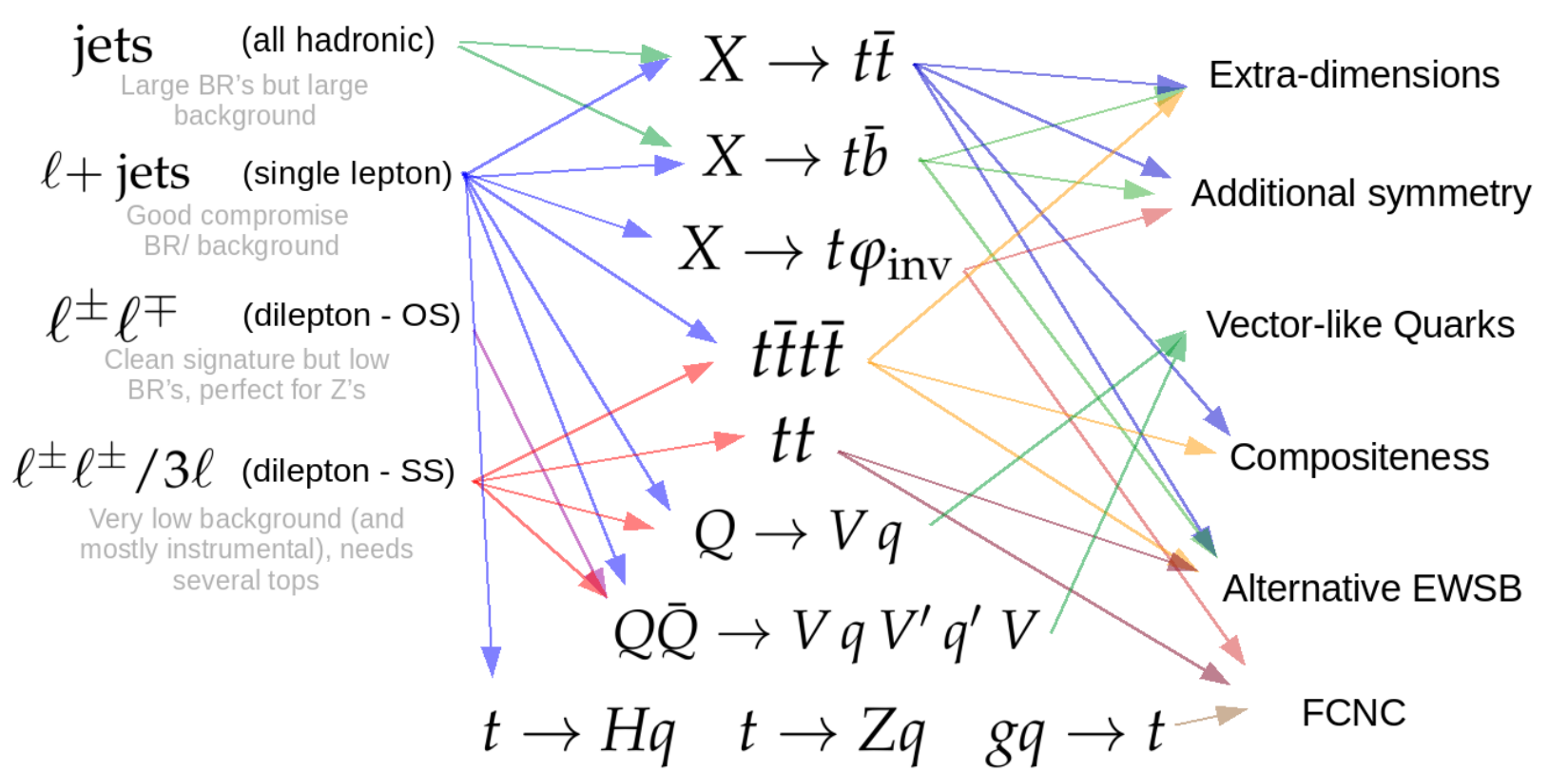
A Glimpse of BSM searches

Final state	Targeted process	Class of models
jets (all hadronic) Large BR's but large background	$X \to t\bar{t}$	Extra-dimensions
$\ell+\text{jets}$ (single lepton) Good compromise BR/ background	$X \to t\bar{b}$	Additional symmetry
$\ell^{\pm}\ell^{\mp}$ (dilepton - OS) Clean signature but low BR's, perfect for Z's	$X \to t\varphi_{\text{inv}}$	Vector-like Quarks
$\ell^{\pm}\ell^{\pm}/3\ell$ (dilepton - SS) Very low background (and mostly instrumental), needs several tops	$t\bar{t}t\bar{t}$	Compositeness
	tt	
	$Q \to V\,q$	Alternative EWSB
	$Q\bar{Q} \to V\,q\,V'\,q'\,V$	
	$t \to Hq \quad t \to Zq \quad gq \to t$	FCNC

A Glimpse of BSM searches



A Glimpse of BSM searches



Recent Selected Highlights

ATLAS

- Search for $pp \to t\bar{t}t\bar{t}$ arXiv:2007.14858
- Search for $X \to t\bar{t}$ hadronic JHEP **10** (2020) 61
- Lepton universality in $W \to \ell\nu$ arXiv:2007.14040

CMS

- Search for $t\bar{t}t\bar{t}$ EPJC 80 (2020) 75
- Probing y_t with $pp \to t\bar{t}$ arXiv:2009.07123
- Measurement of $pp \to t\bar{t}$ at high p_T arXiv:2008.07860

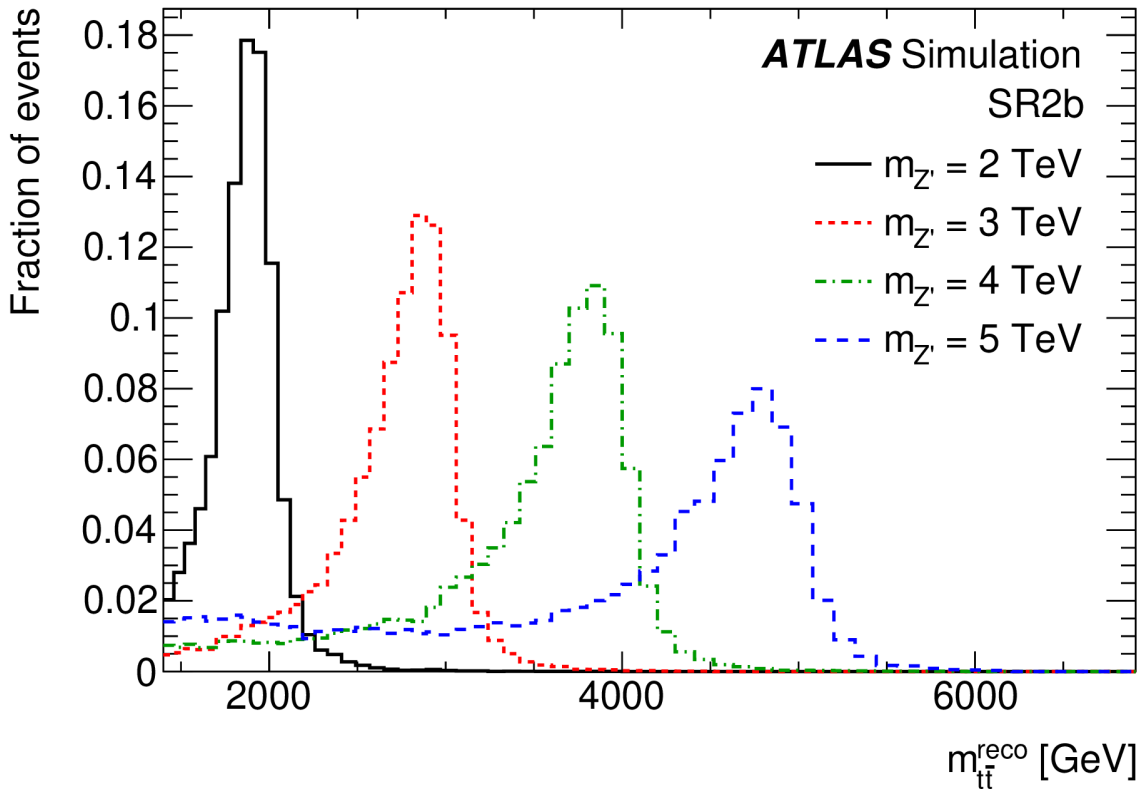
ATLAS + CMS

- Spin correlation in $t\bar{t}$ LHCtopWG: prelim

High p_T Top Quarks

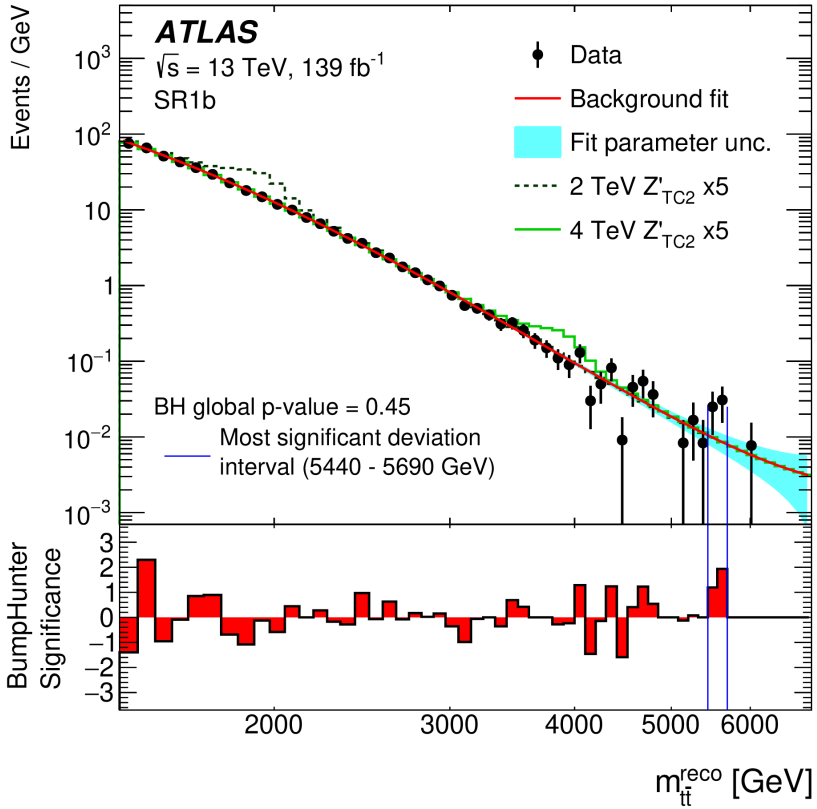
Motivations and strategy

- Exploit high $\mathcal{BR}$ of hadronic decay of $t\bar{t}$
- Exploit large-R jets sub-structure (boosted top quarks)



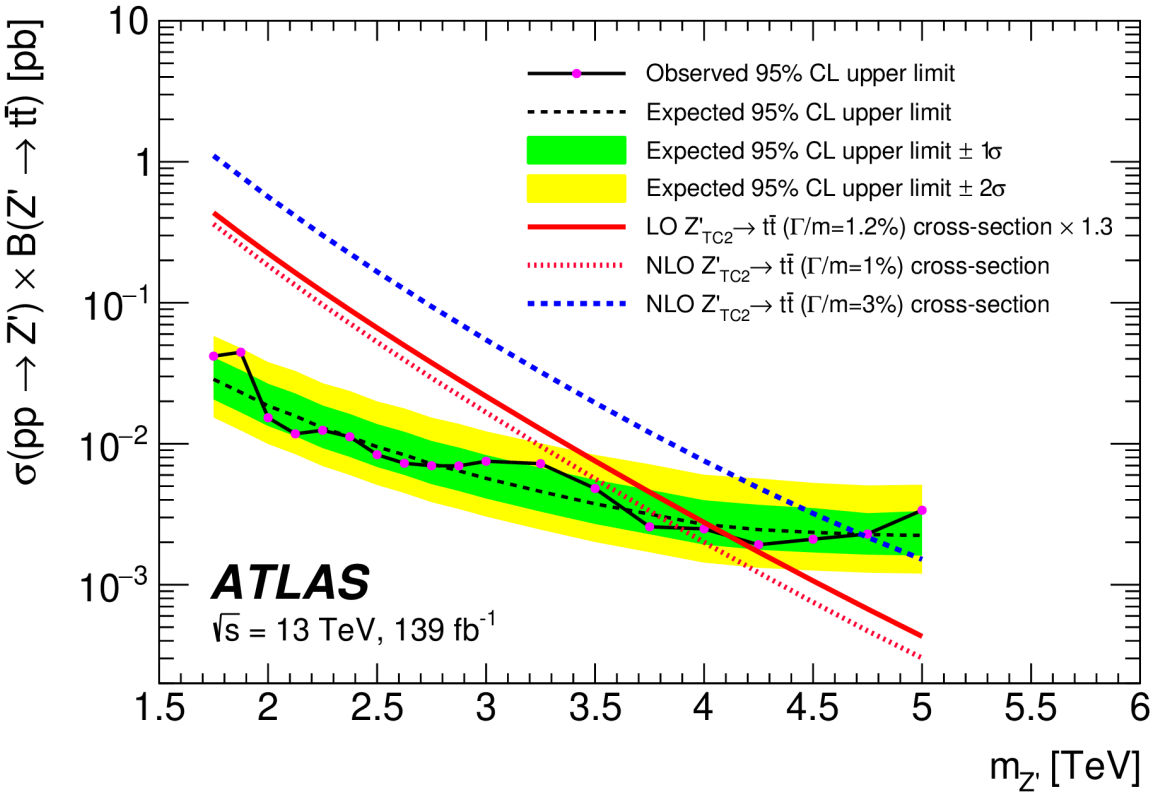
Motivations and strategy

- Exploit high $\mathcal{BR}$ of hadronic decay of $t\bar{t}$
- Exploit large-R jets sub-structure (boosted top quarks)
- Target $m_{t\bar{t}} > 1.4\,\text{TeV}$, data-driven background estimate



Motivations and strategy

- Exploit high $\mathcal{BR}$ of hadronic decay of $t\bar{t}$
- Exploit large-R jets sub-structure (boosted top quarks)
- Target $m_{t\bar{t}} > 1.4\,\text{TeV}$, data-driven background estimate



Top Yukawa Coupling from $t\bar{t}$ Events

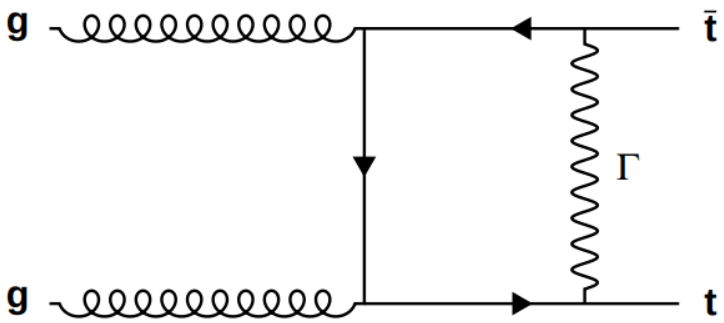
Motivations and strategy

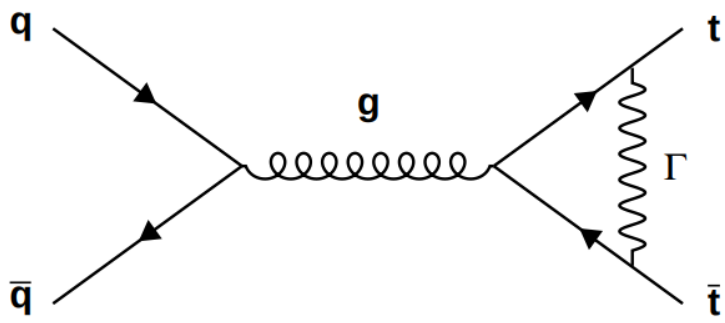
- Independent from H decay modes (as opposed to $pp \to t\bar{t}H$)

Top Yukawa Coupling from $t\bar{t}$ Events

Motivations and strategy

- Independent from H decay modes (as opposed to $pp \to t\bar{t}H$)
- Sensitive to any top-coupled scalar field, denoted Γ
- Additional amplitudes modifying $m_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ spectrum

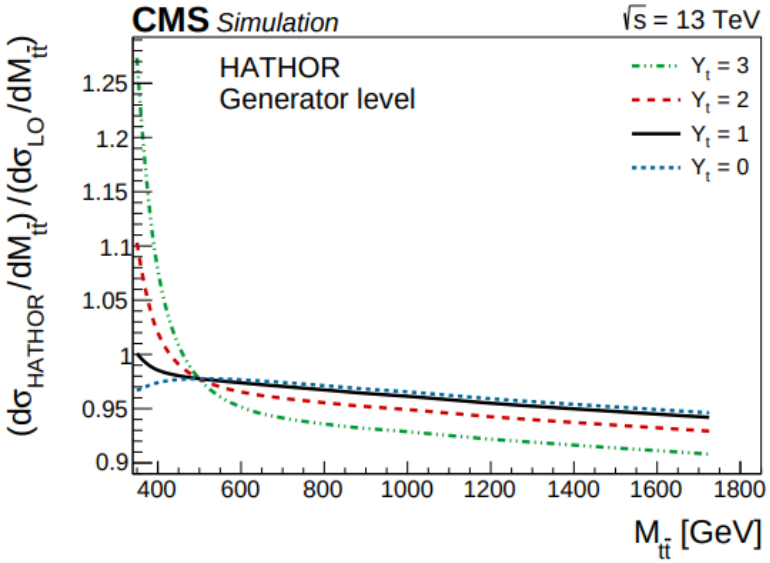


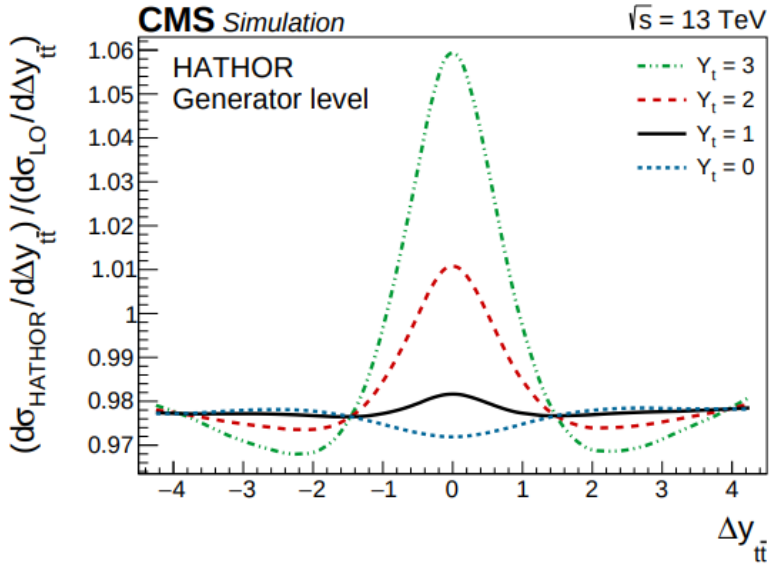


Top Yukawa Coupling from $t\bar{t}$ Events

Motivations and strategy

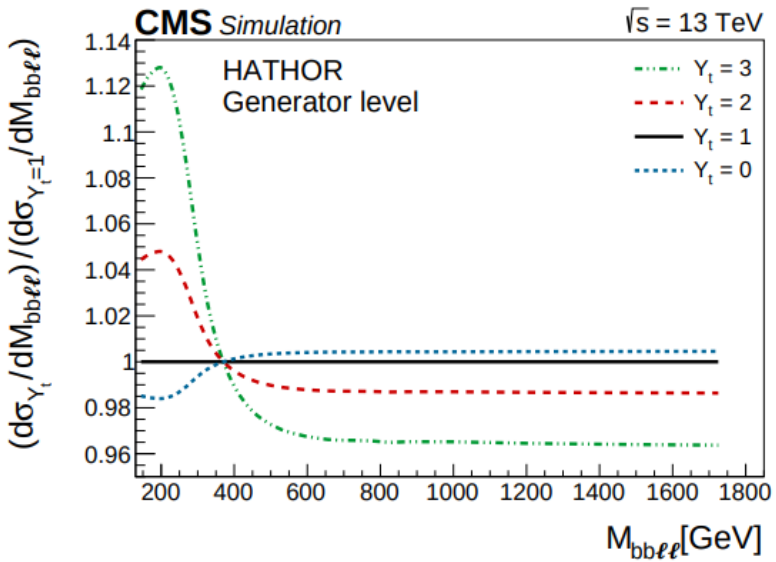
- Independent from H decay modes (as opposed to $pp \to t\bar{t}H$)
- Sensitive to any top-coupled scalar field, denoted Γ
- Additional amplitudes modifying $m_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ spectrum
- Measure distribution shape *v.s* $(m_{t\bar{t}}, \Delta y_{t\bar{t}})$ ...

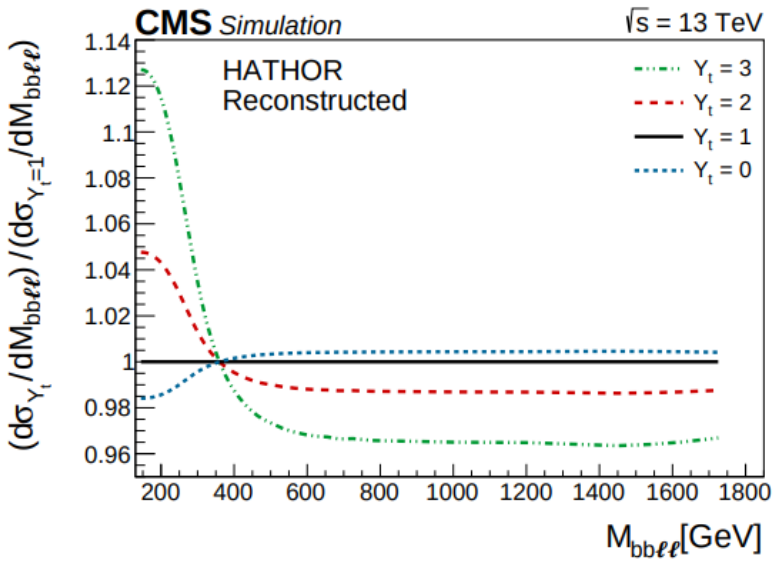




Motivations and strategy

- Independent from H decay modes (as opposed to $pp \to t\bar{t}H$)
- Sensitive to any top-coupled scalar field, denoted Γ
- Additional amplitudes modifying $m_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ spectrum
- Measure distribution shape *v.s* $(m_{t\bar{t}}, \Delta y_{t\bar{t}})$ ...
- ... or an more experimental-friendly variables, $m_{\ell\ell bb}$ and $\Delta y_{\ell\ell bb}$

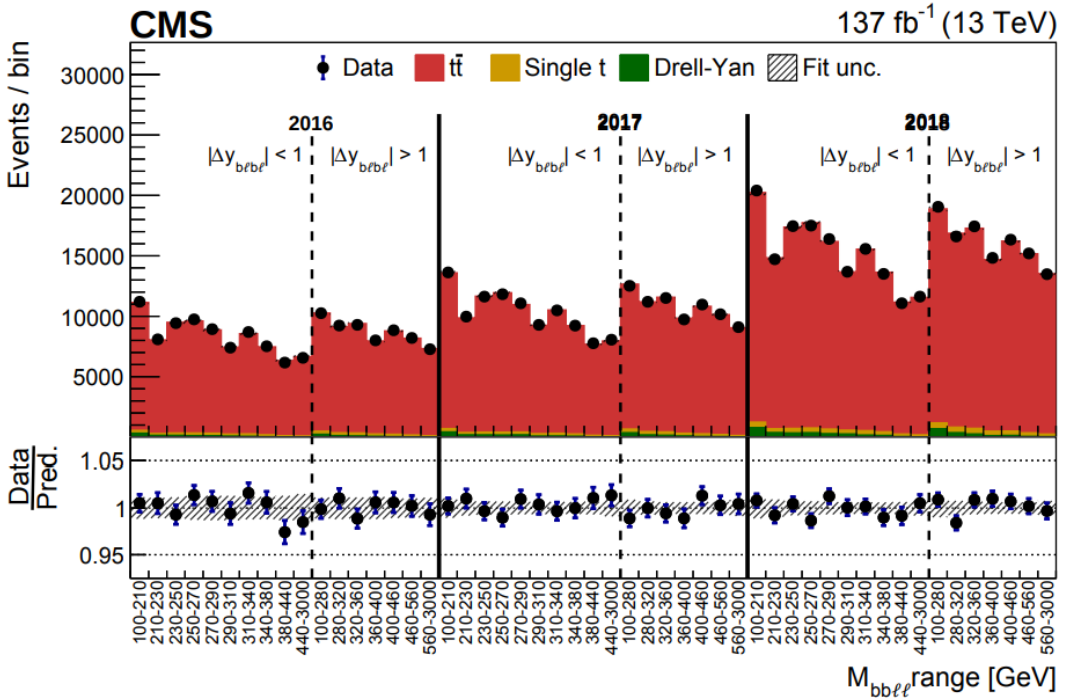




Top Yukawa Coupling from $t\bar{t}$ Events

Motivations and strategy

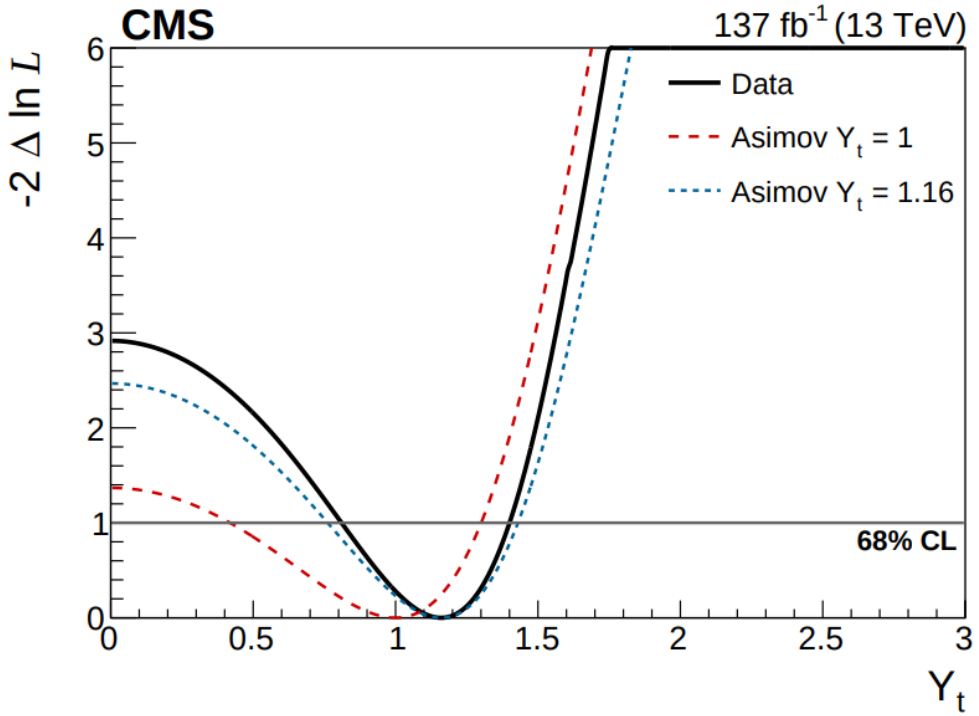
- Independent from H decay modes (as opposed to $pp \to t\bar{t}H$)
- Sensitive to any top-coupled scalar field, denoted Γ
- Additional amplitudes modifying $m_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ spectrum
- Measure distribution shape *v.s* $(m_{t\bar{t}}, \Delta y_{t\bar{t}})$ ...
- ... or an more experimental-friendly variables, $m_{\ell\ell bb}$ and $\Delta y_{\ell\ell bb}$



Top Yukawa Coupling from $t\bar{t}$ Events

Motivations and strategy

- Independent from H decay modes (as opposed to $pp \to t\bar{t}H$)
- Sensitive to any top-coupled scalar field, denoted Γ
- Additional amplitudes modifying $m_{t\bar{t}}$ and $\Delta y_{t\bar{t}}$ spectrum
- Measure distribution shape *v.s* $(m_{t\bar{t}}, \Delta y_{t\bar{t}})$ ...
- ... or an more experimental-friendly variables, $m_{\ell\ell bb}$ and $\Delta y_{\ell\ell bb}$



This measurement

$\to \; y_t \; = \; 1.16 \, {}^{+0.24}_{-0.35}$

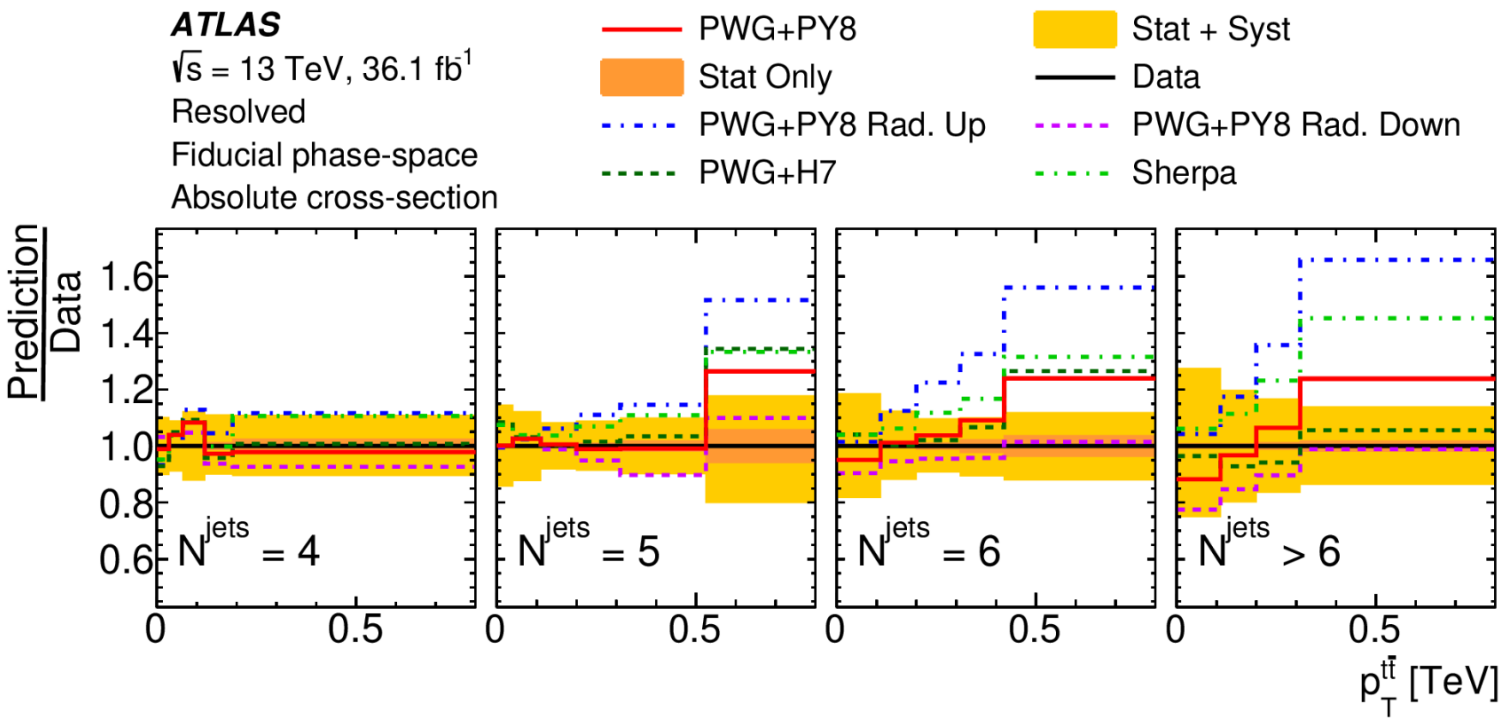
From Higgs comb.

$\to y_t \; = \; 0.98 \pm 0.14$

Bottleneck: state-of-the-art SM predictions

Issue and current methodology

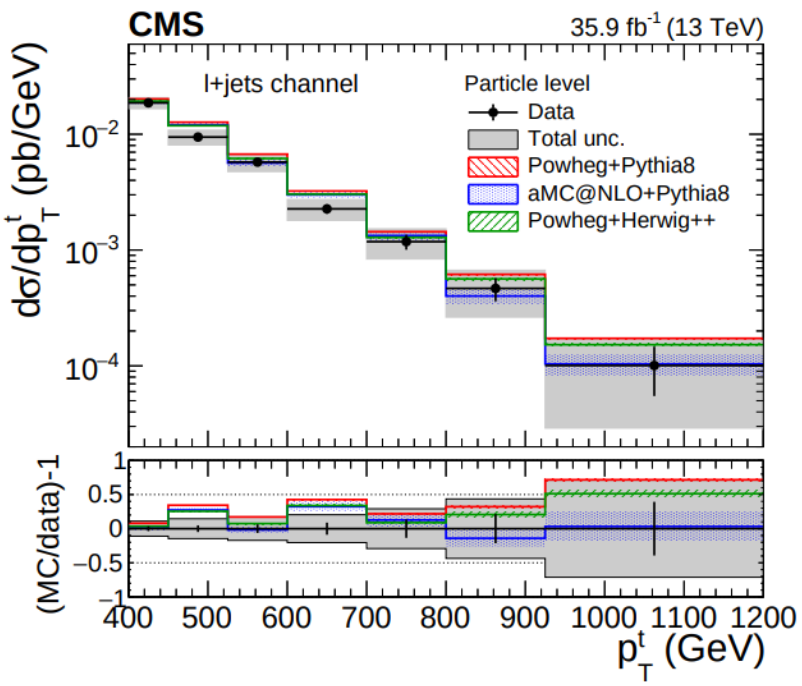
- High transverse momentum regime

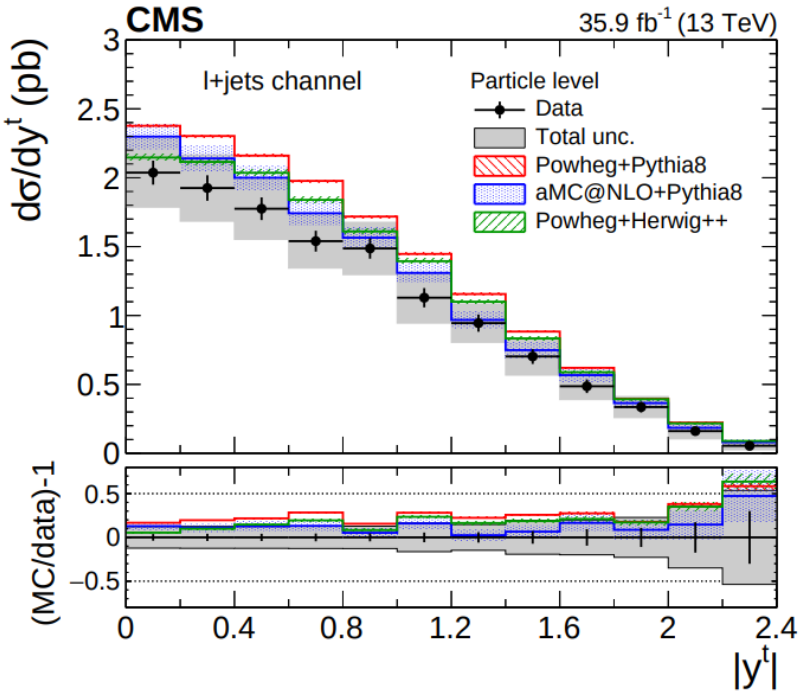


Bottleneck: state-of-the-art SM predictions

Issue and current methodology

- High transverse momentum regime

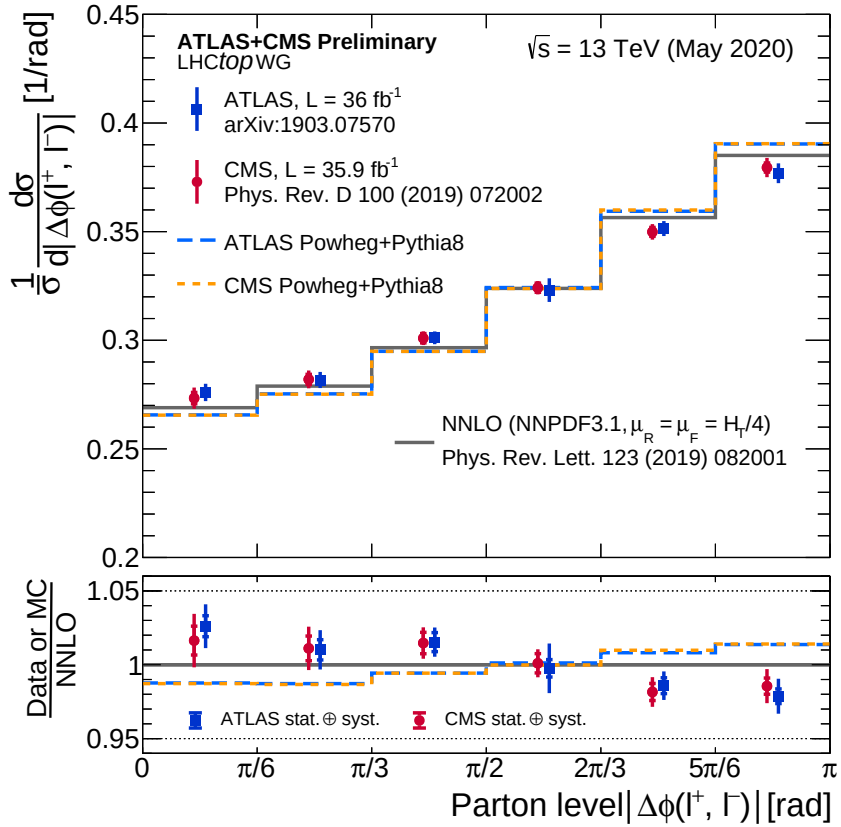




Bottleneck: state-of-the-art SM predictions

Issue and current methodology

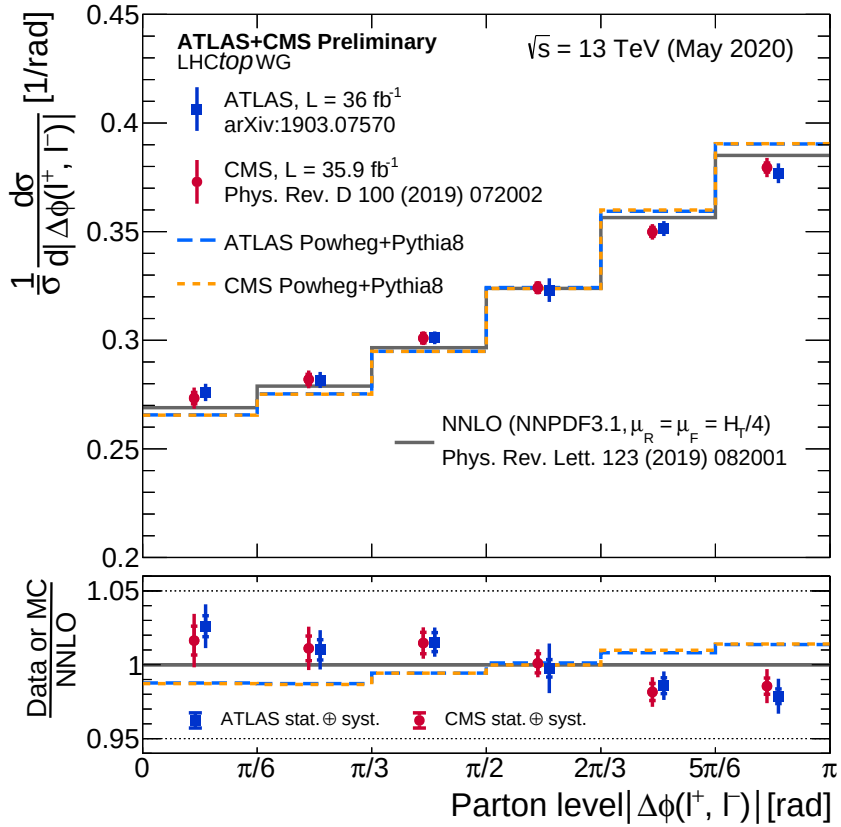
- High transverse momentum regime
- Opening angle between leptons (probing spin correlation and additional radiations)



Bottleneck: state-of-the-art SM predictions

Issue and current methodology

- High transverse momentum regime
- Opening angle between leptons (probing spin correlation and additional radiations)
- Large (over-estimated?) uncertainties together with *profiling*

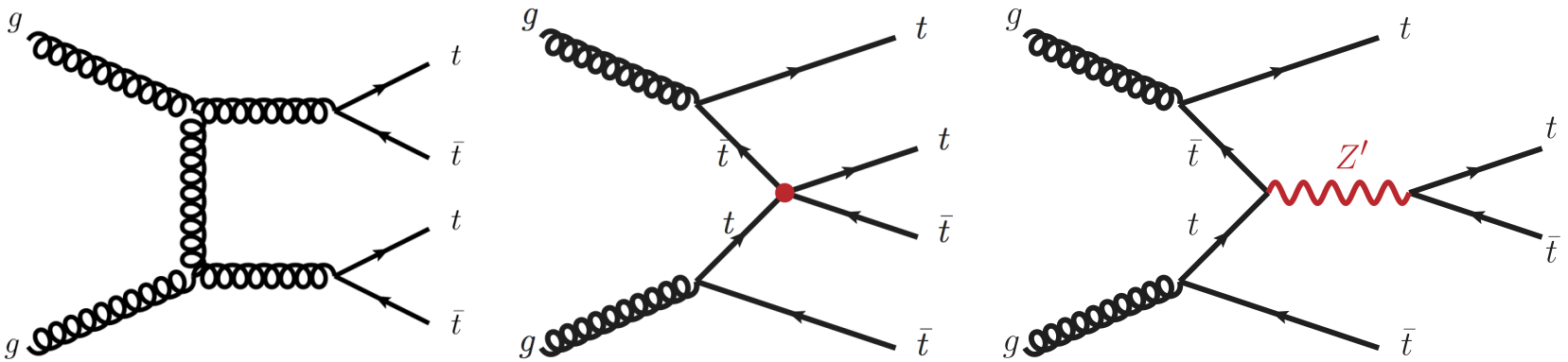


Four Top Quark Production

A bit of context

Motivations

- Small SM cross-section (12 fb), enhanced by **many** BSM scenarios

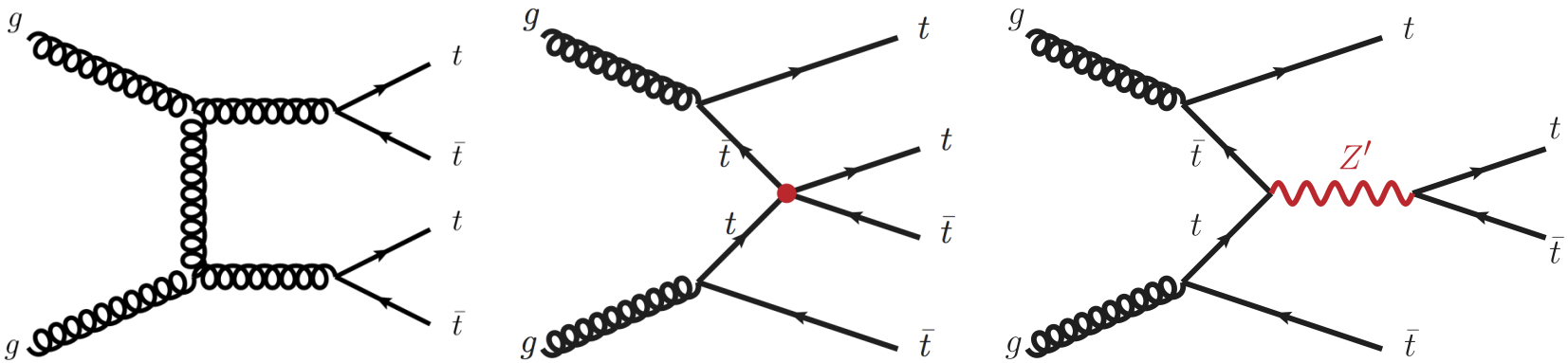


A bit of context

Motivations

- Small SM cross-section (12 fb), enhanced by **many** BSM scenarios
- Only way to detect spin-1 boson exclusively coupled to top quark

($gg \rightarrow Z'$ is forbidden for a spin-1 - Landau-Yang theorem)



A bit of context

Motivations

- Small SM cross-section (12 fb), enhanced by **many** BSM scenarios
- Only way to detect spin-1 boson exclusively coupled to top quark

  ($gg \rightarrow Z'$ is forbidden for a spin-1 - Landau-Yang theorem)
- Offers access to y_t, without any assumption on Γ_H value

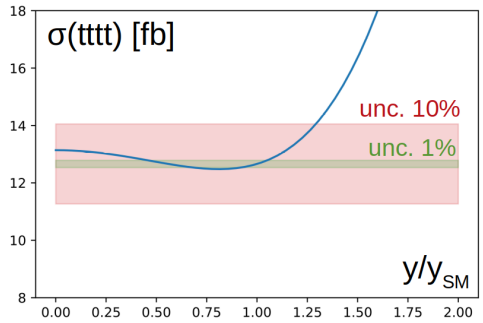
$$\mathcal{M}_H(q) \propto \frac{y_t}{(q^2 - m_H^2) + i m_H \Gamma_H}$$

off-shell

on-shell

$\propto y_t$

$\propto \frac{y_t}{\Gamma_H}$



A bit of context

Motivations

- Small SM cross-section (12 fb), enhanced by **many** BSM scenarios
- Only way to detect spin-1 boson exclusively coupled to top quark

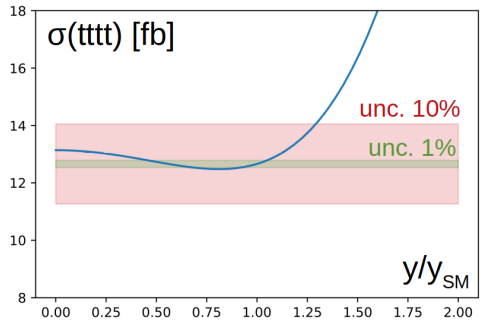
  ($gg \rightarrow Z'$ is forbidden for a spin-1 - Landau-Yang theorem)
- Offers access to y_t, without any assumption on Γ_H value

$$\mathcal{M}_H(q) \propto \frac{y_t}{(q^2 - m_H^2) + i m_H \Gamma_H}$$

off-shell on-shell

$\propto y_t$

$\propto \frac{y_t}{\Gamma_H}$

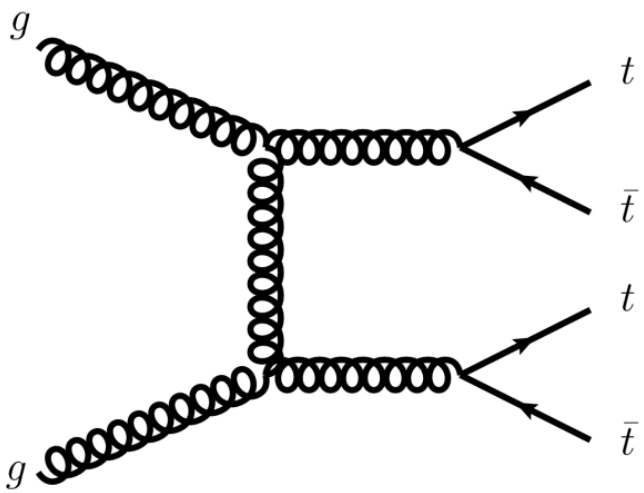


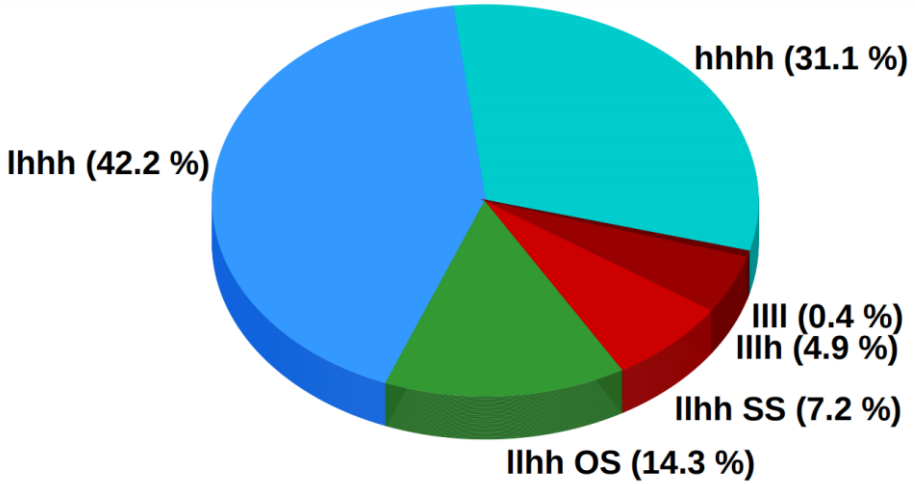
A long hunt ...

from ∼2010 (Les Houches 2011) to 2020 (ATLAS, CMS)

Strategy

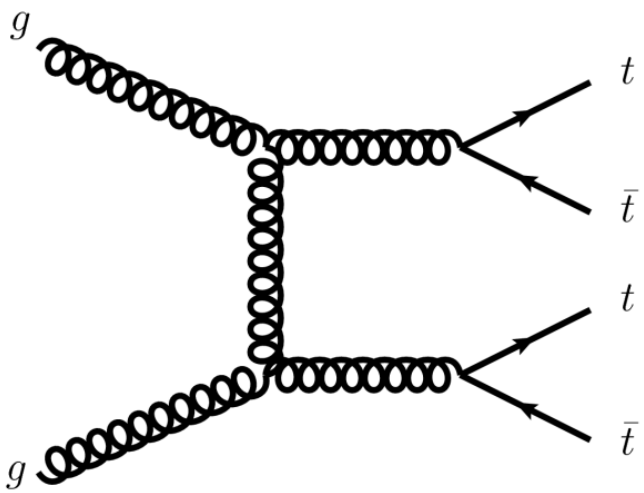
- Exploit final state with two leptons with the same electric charge (not heavily produced by other SM processes)

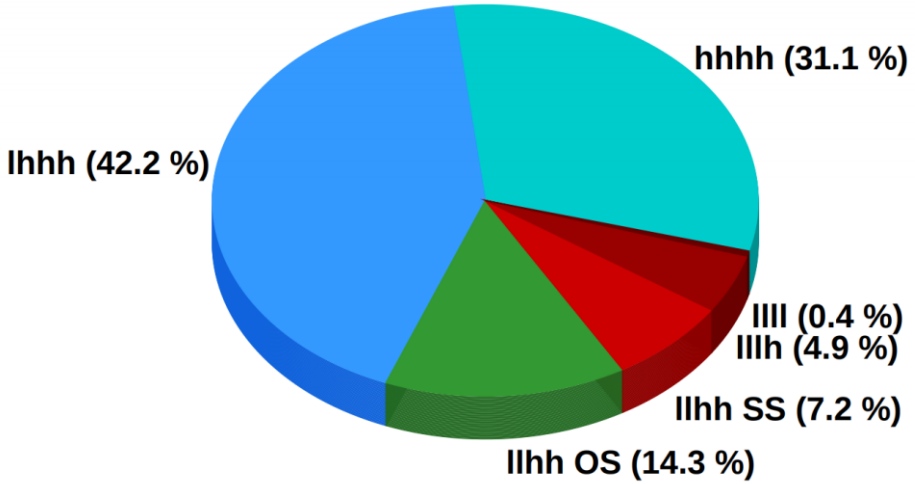




Strategy

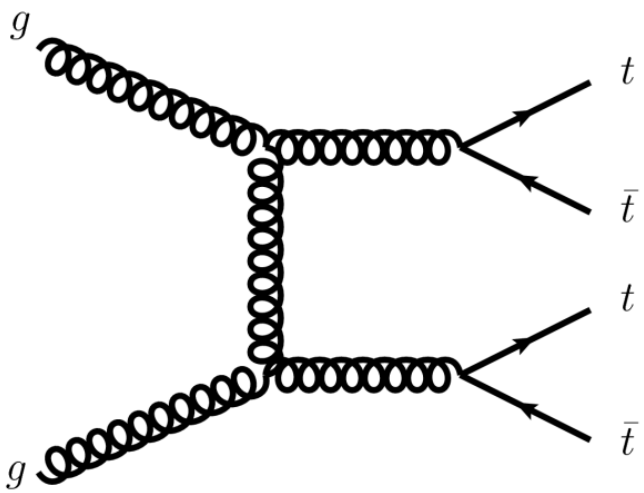
- Exploit final state with two leptons with the same electric charge (not heavily produced by other SM processes)
- Contamination from $t\bar{t} + W, Z, H$ with additionnal b-quarks

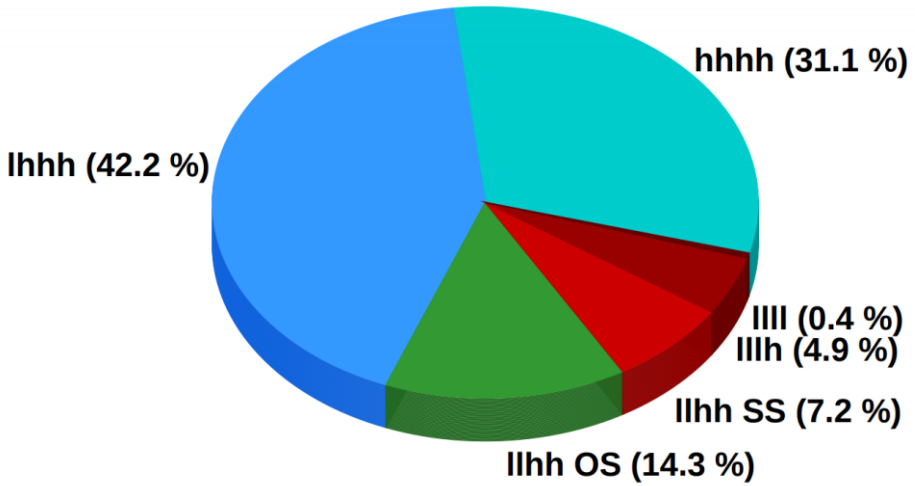




Strategy

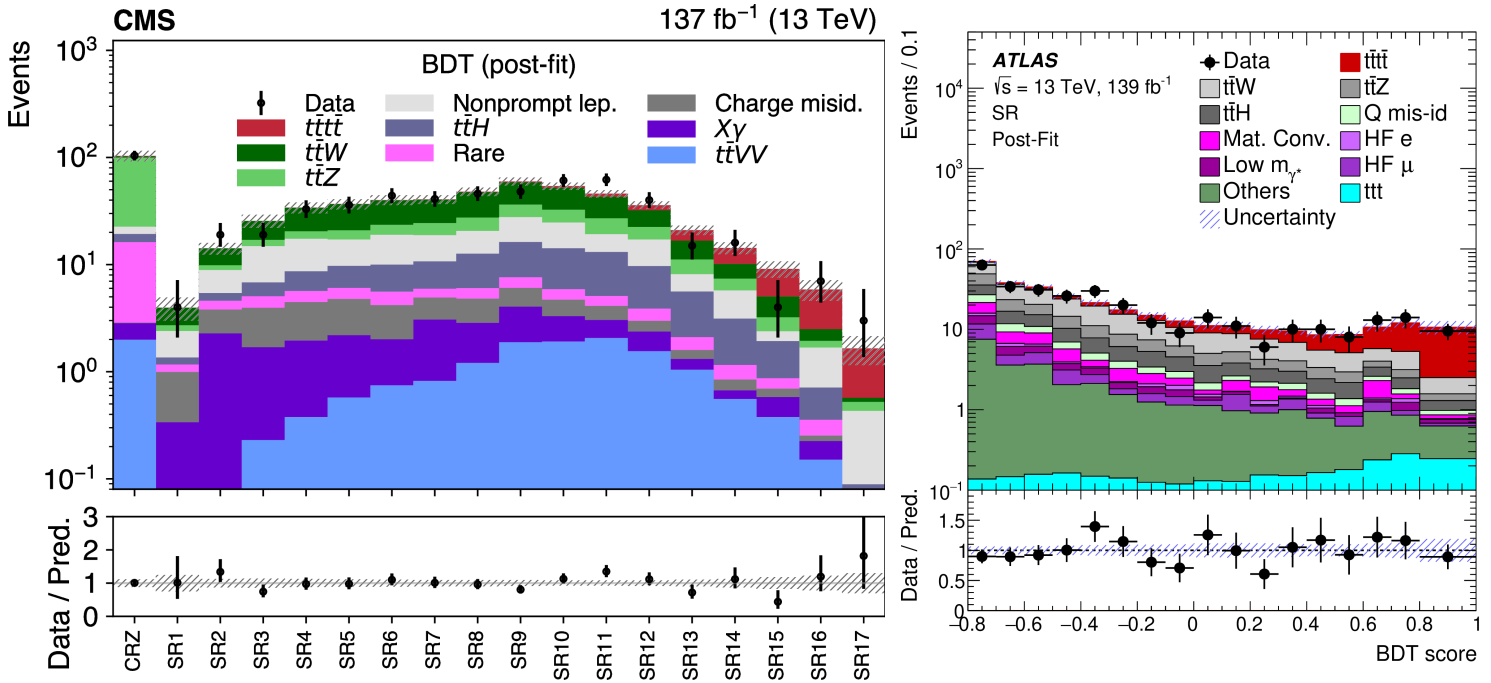
- Exploit final state with two leptons with the same electric charge (not heavily produced by other SM processes)
- Contamination from $t\bar{t} + W, Z, H$ with additionnal b-quarks
- Background is low but tricky to predict: data-driven estimate





Strategy

- Exploit final state with two leptons with the same electric charge (not heavily produced by other SM processes)
- Contamination from $t\bar{t} + W, Z, H$ with additionnal b-quarks
- Background is low but tricky to predict: data-driven estimate
- Use both cut-based and multivariate analysis to extract the signal



LHC Results

Strategy

- Exploit final state with two leptons with the same electric charge (not heavily produced by other SM processes)
- Contamination from $t\bar{t} + W, Z, H$ with additionnal b-quarks
- Background is low but tricky to predict: data-driven estimate
- Use both cut-based and multivariate analysis to extract the signal

ATLAS

$\rightarrow \sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6}$ fb (consistent with the SM prediction at 1.7 s.d.)

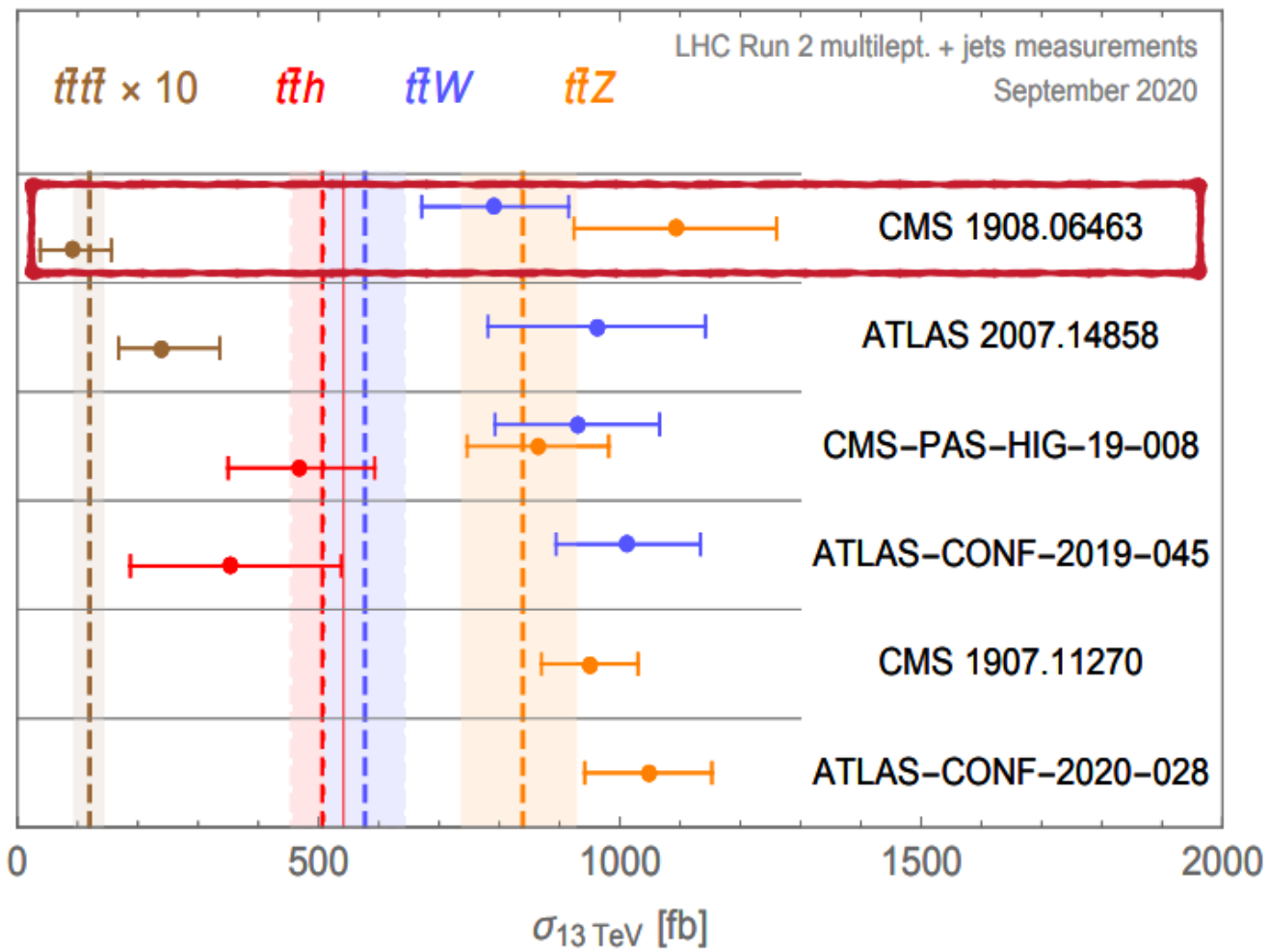
CMS

$\rightarrow \sigma_{t\bar{t}t\bar{t}} = 12^{+5.8}_{-5.2}$ fb

$\rightarrow |y_t| < 1.7 \times |y_t^{\mathrm{SM}}|$ at 95% C.L.

An interesting phase-space region to monitor...

Summary plot from T. Theil (TOP2020)



Lepton universality

Measuring R(W $\to \tau\nu$)/R(W $\to \mu\nu$) in $t\bar{t}$ events

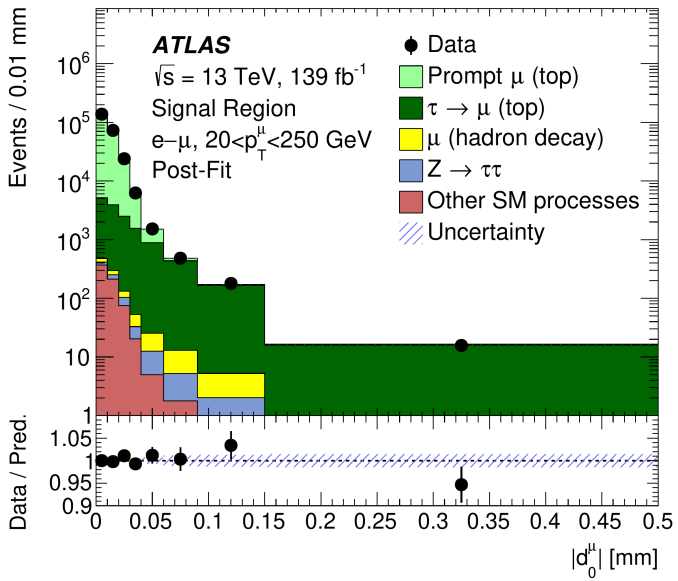
Motivation and strategy

- Lepton universality is an axiom of the SM, tension found at LEP
- Separate $W \to \mu\nu$ decay from $W \to \tau\nu \to \mu\nu's$, and compare them

Measuring R(W $\to \tau\nu$)/R(W $\to \mu\nu$) in $t\bar{t}$ events

Motivation and strategy

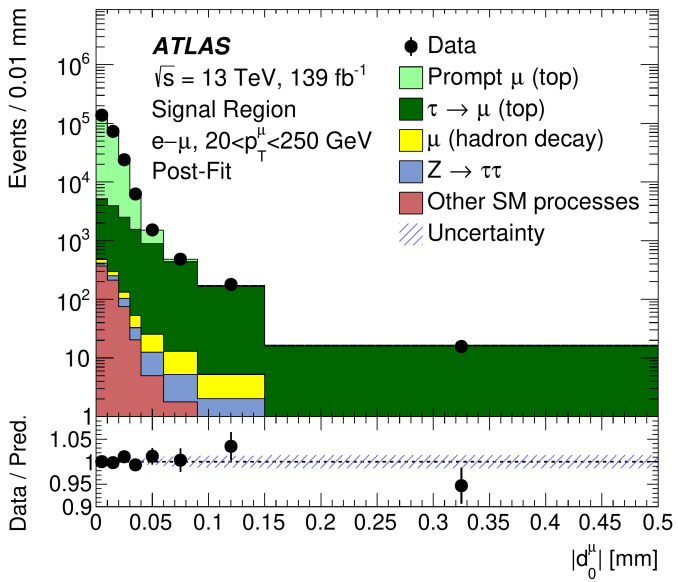
- Lepton universality is an axiom of the SM, tension found at LEP
- Separate $W \to \mu\nu$ decay from $W \to \tau\nu \to \mu\nu's$, and compare them
- Exploit τ time life, leading to a displaced vertex ($c\tau_{\text{life}} = 87\,\mu$m)
- Key observables: transverse impact parameter $|d_0^\mu|$, and p_T^μ

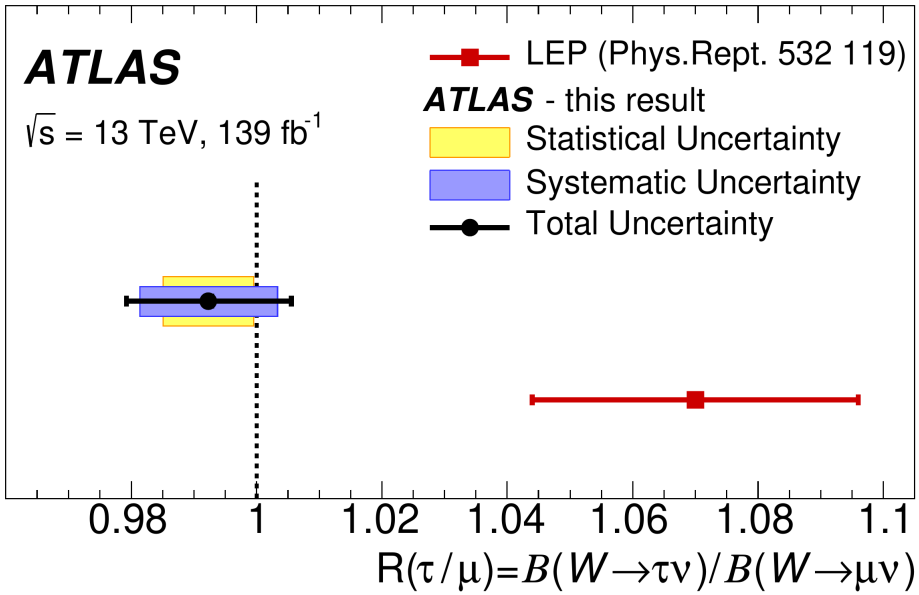


Measuring R(W $\to \tau\nu$)/R(W $\to \mu\nu$) in $t\bar{t}$ events

Motivation and strategy

- Lepton universality is an axiom of the SM, tension found at LEP
- Separate $W \to \mu\nu$ decay from $W \to \tau\nu \to \mu\nu's$, and compare them
- Exploit τ time life, leading to a displaced vertex ($c\tau_{\text{life}} = 87\,\mu$m)
- Key observables: transverse impact parameter $|d_0^\mu|$, and p_T^μ





Submitted to Nature Physics

Summary and outlook

Summary and outlook

Top quark sector is of particular interest to search for new phenomena

Summary and outlook

Top quark sector is of particular interest to search for new phenomena

Broad range of performed searches, both final state and BSM benchmark driven. No evidence for significant SM deviations so far.

Summary and outlook

Top quark sector is of particular interest to search for new phenomena

Broad range of performed searches, both final state and BSM benchmark driven. No evidence for significant SM deviations so far.

Newly observed rare processes (*e.g.* $t\bar{t}t\bar{t}$) and precision measurements (*e.g.* y_t from $t\bar{t}$) represent - according to me - the best way to move forward with the HL-LHC program.

Summary and outlook

Top quark sector is of particular interest to search for new phenomena

Broad range of performed searches, both final state and BSM benchmark driven. No evidence for significant SM deviations so far.

Newly observed rare processes (*e.g.* $t\bar{t}t\bar{t}$) and precision measurements (*e.g.* y_t from $t\bar{t}$) represent - according to me - the best way to move forward with the HL-LHC program.

Associated challenge: improve SM predictions for top-related processes (high p_T regime, additional heavy bosons and/or heavy flavour, etc ...)

Thanks for your attention!