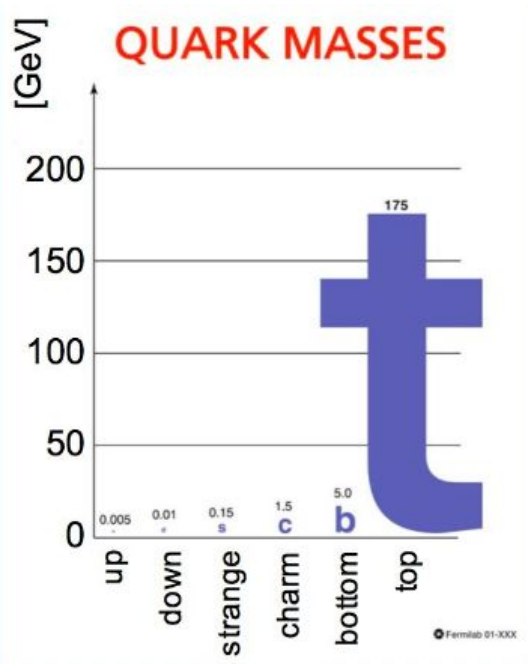
Overview on the top quark: between SM and BSM

COMPOSE-IT 28/01/2020

A.O.M.Iorio

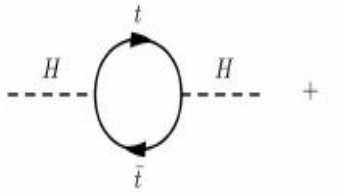
The top quark: why so important?



Heaviest particle known: top quark mass appears in most loops and corrections to SM and BSM

◦ **Strongest coupling with higgs:**
→ possibly related to EWK Symmetry Breaking
→ Leading contribution to Higgs mass corrections

$$m_f = \frac{\lambda_f v}{\sqrt{2}}$$



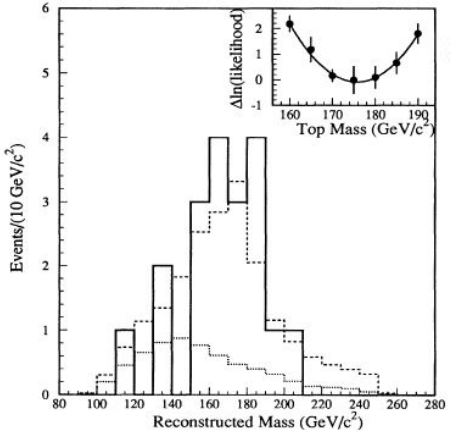
◦ **Only quark to decay before hadronisation**
→ Properties can be directly measured

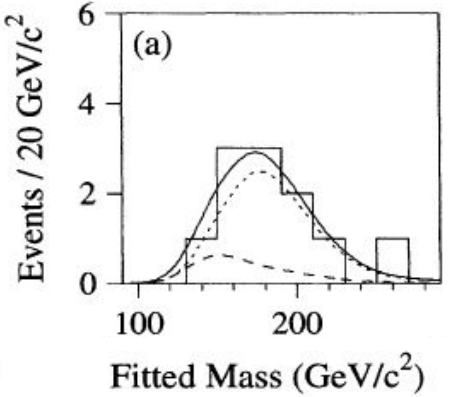
◦ **For new physics searches:**
→ Top BSM partners usually have the lowest mass
→ Least explored couplings

On top of all quarks since 25 years now!

We have gone a long way since first observation at TeVatron in ‘95!

→ Observation of pair (‘95) and single (2009!) production





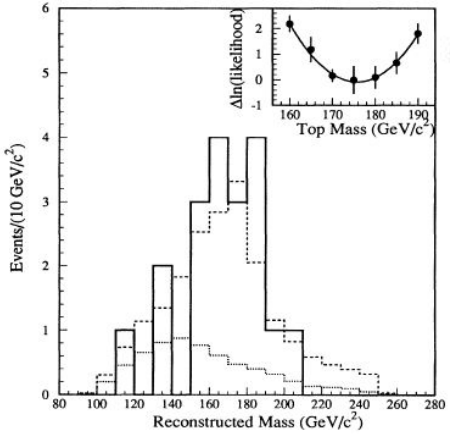
On top of all quarks since 25 years now!

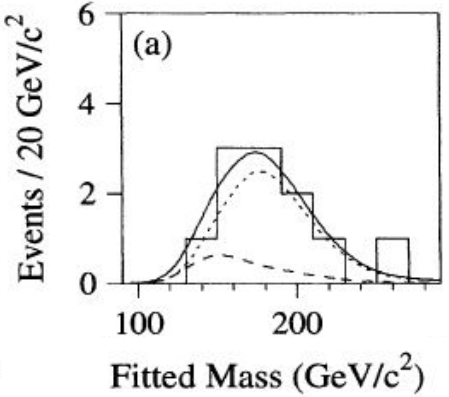
We have gone a long way since first observation at TeVatron in '95!

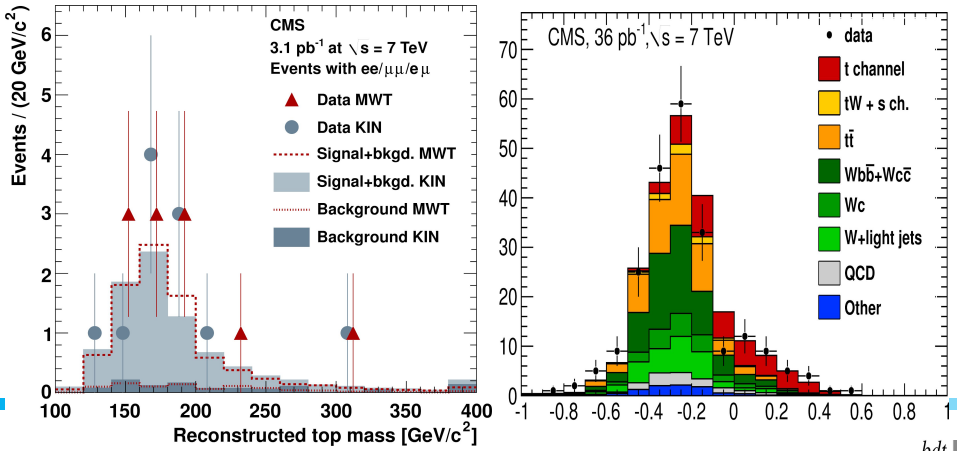
→ Observation of pair ('95) and single (2009!) production

15 years later at LHC: confirmed both its production modes!

What now? What does it mean living the top life nowadays?







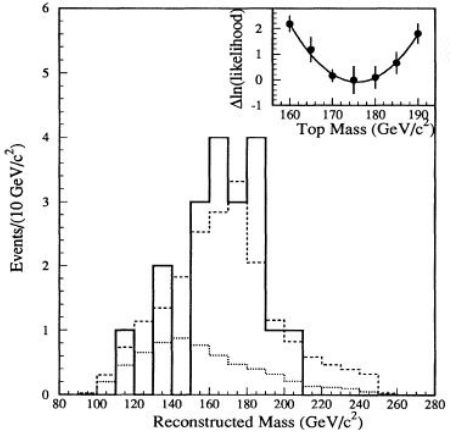
On top of all quarks since 25 years now!

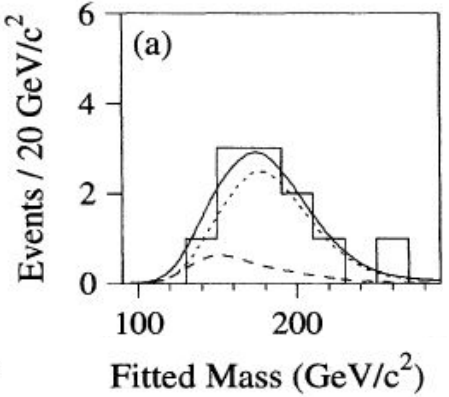
We have gone a long way since first observation at TeVatron in '95!

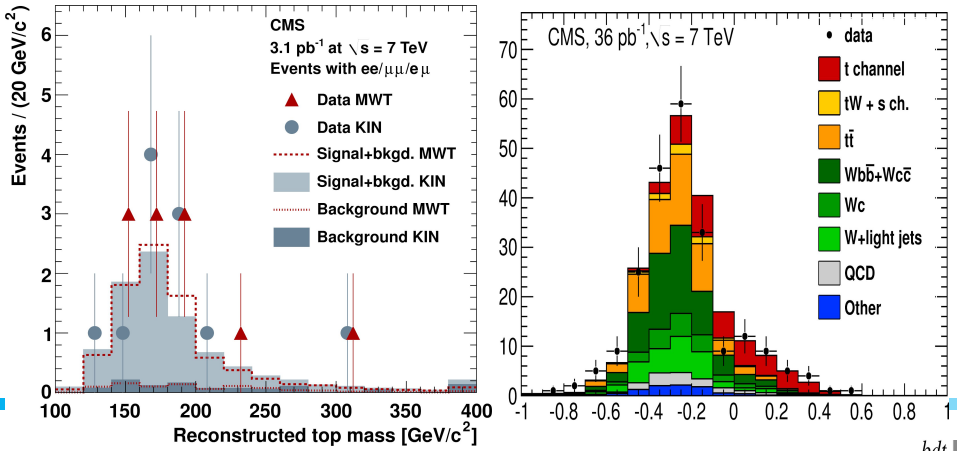
→ Observation of pair ('95) and single (2009!) production

15 years later at LHC: confirmed both its production modes!

What now? What does it mean living the top life nowadays?





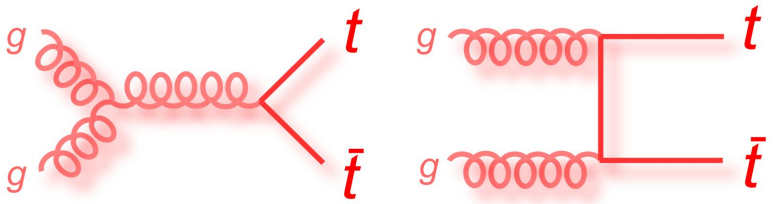


What now?

The “classics”: pair and single production

A great laboratory for top@ high precision:

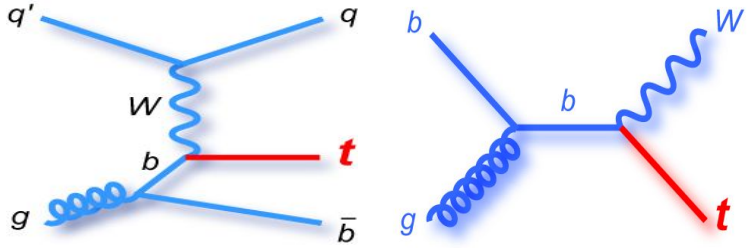
- **Coupling properites:** inclusive and differential xSection
- Top quark-related **parameters:** mass, width, CKM elements etc.
- **Modeling of QCD** (perturbative and non-pert.) and **PDF**



- **tt pairs** via strong interaction:

  - dominant at the LHC and Tevatron
  - depends on α_s
  - sensitive to pdf

- **σ at LO $\propto (\alpha_s/m_{top})^2$**

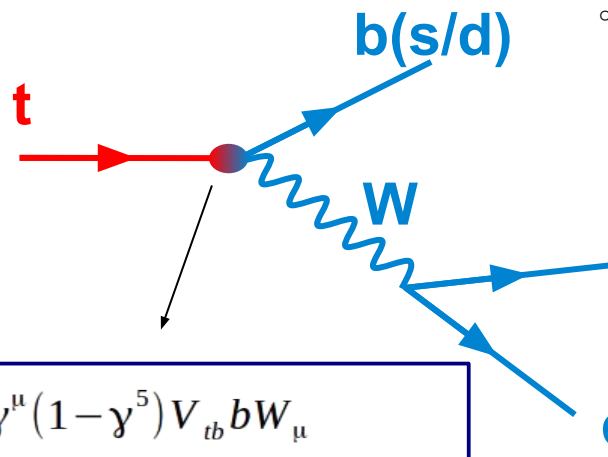


- **single-top quarks:**

- weak charged current interactions
  - *t*-, *s*-channel and W-associated
  - tWb vertex in production
  - Sensitive to Vtb

- **σ at LO $\propto (\alpha \cdot |V_{tb}|)^2$**

Top-quark decays vademecum



$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}bW_{\mu}$$

- Main mechanism is **electroweak: no hadronisation**

W decay:	Branching Ratio
W → lν (any)	0.32
W → qq' (any)	0.68

- Electroweak **tWb vertex:**
  - V-A: **polarization** of the products and defined **W-helicity**
  - CKM matrix element $|V_{tb}| \sim 1 \rightarrow \Gamma(t \rightarrow b) >> \Gamma(t \rightarrow s,d)$

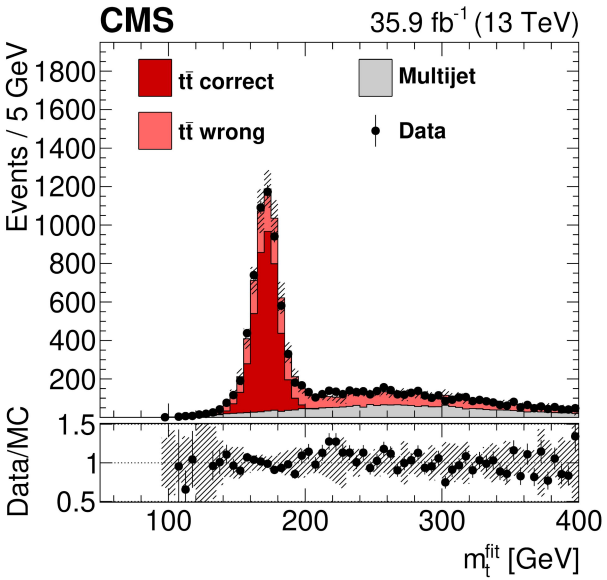
$1/m_{toq}$ < $1/\Gamma_t$ < $1/\Lambda$ < m_t/Λ^2

production lifetime hadronization spin decorrelation

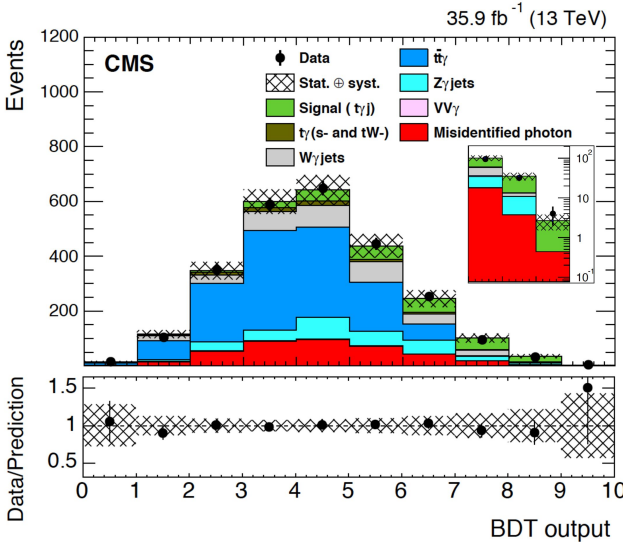
What's the kind of measurements we do with it?

… our results are usually a mix of three:

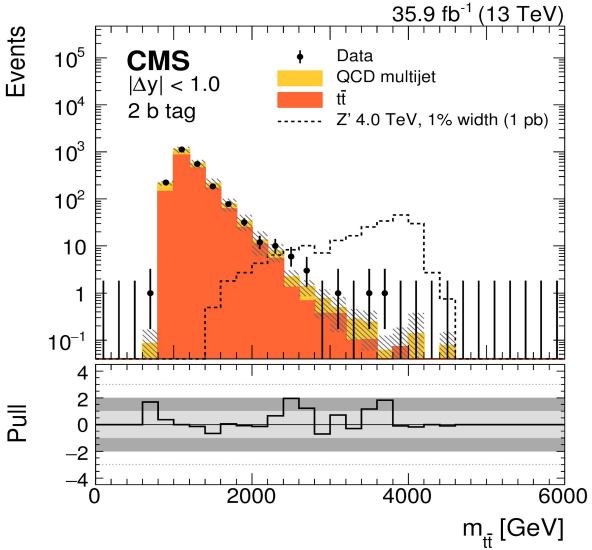
X: High precision
→ SM Measurements!



Y: Rare SM processes
→ Exploration!



Z: New physics signals
→ Searches!



→ Often as time goes one turns into the others

A further binding thread: EFT in top quarks

Effective lagrangians: taylor expansion of the unknown new physics lagrangian, truncated at X=...6

$$L = L_{SM}^{(4)} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \dots$$

→ define a reduced number of operators for top quarks

→ See also https://arxiv.org/pdf/1802.07237.pdf

Operators

Wilson coefficients

A further binding thread: EFT in top quarks

Effective lagrangians: taylor expansion of the unknown new physics lagrangian, truncated at X=...6

$$L = L_{SM}^{(4)} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \dots$$

→ define a reduced number of operators for top quarks

→ See also https://arxiv.org/pdf/1802.07237.pdf

Two quark operators:

$$
\begin{aligned}
{}^{\ddagger}O_{u\varphi}^{(ij)} &= \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger \varphi),\\
O_{\varphi q}^{1(ij)} &= (\varphi^\dagger \overleftrightarrow{iD}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j),\\
O_{\varphi q}^{3(ij)} &= (\varphi^\dagger \overleftrightarrow{iD}^I_\mu \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j),\\
O_{\varphi u}^{(ij)} &= (\varphi^\dagger \overleftrightarrow{iD}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j),\\
{}^{\ddagger}O_{\varphi ud}^{(ij)} &= (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_i \gamma^\mu d_j),\\
{}^{\ddagger}O_{uW}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\,\tilde{\varphi} W^I_{\mu\nu},\\
{}^{\ddagger}O_{dW}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} \tau^I d_j)\,\varphi W^I_{\mu\nu},\\
{}^{\ddagger}O_{uB}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} u_j) \quad \tilde{\varphi} B_{\mu\nu},\\
{}^{\ddagger}O_{uG}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} T^A u_j)\,\tilde{\varphi} G^A_{\mu\nu},
\end{aligned}
$$

Four quark operators:

$$
\begin{aligned}
O_{qq}^{1(ijkl)} &= (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l),\\
O_{qq}^{3(ijkl)} &= (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l),\\
O_{qu}^{1(ijkl)} &= (\bar{q}_i \gamma^\mu q_j)(\bar{u}_k \gamma_\mu u_l),\\
O_{qu}^{8(ijkl)} &= (\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l),\\
O_{qd}^{1(ijkl)} &= (\bar{q}_i \gamma^\mu q_j)(\bar{d}_k \gamma_\mu d_l),\\
O_{qd}^{8(ijkl)} &= (\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_k \gamma_\mu T^A d_l),\\
O_{uu}^{(ijkl)} &= (\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma_\mu u_l),\\
O_{ud}^{1(ijkl)} &= (\bar{u}_i \gamma^\mu u_j)(\bar{d}_k \gamma_\mu d_l),\\
O_{ud}^{8(ijkl)} &= (\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_k \gamma_\mu T^A d_l),\\
{}^{\ddagger}O_{quqd}^{1(ijkl)} &= (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),\\
{}^{\ddagger}O_{quqd}^{8(ijkl)} &= (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),
\end{aligned}
$$

Two quark, **two leptons** operators:

$$
\begin{aligned}
O_{lq}^{1(ijkl)} &= (\bar{l}_i \gamma^\mu l_j)(\bar{q}_k \gamma^\mu q_l),\\
O_{lq}^{3(ijkl)} &= (\bar{l}_i \gamma^\mu \tau^I l_j)(\bar{q}_k \gamma^\mu \tau^I q_l),\\
O_{lu}^{(ijkl)} &= (\bar{l}_i \gamma^\mu l_j)(\bar{u}_k \gamma^\mu u_l),\\
O_{eq}^{(ijkl)} &= (\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l),\\
O_{eu}^{(ijkl)} &= (\bar{e}_i \gamma^\mu e_j)(\bar{u}_k \gamma^\mu u_l),\\
{}^{\ddagger}O_{lequ}^{1(ijkl)} &= (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),\\
{}^{\ddagger}O_{lequ}^{3(ijkl)} &= (\bar{l}_i \sigma^{\mu\nu} e_j)\,\varepsilon\,(\bar{q}_k \sigma_{\mu\nu} u_l),\\
{}^{\ddagger}O_{ledq}^{(ijkl)} &= (\bar{l}_i e_j)(\bar{d}_k q_l),
\end{aligned}
$$

Some EFT example contributions:

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

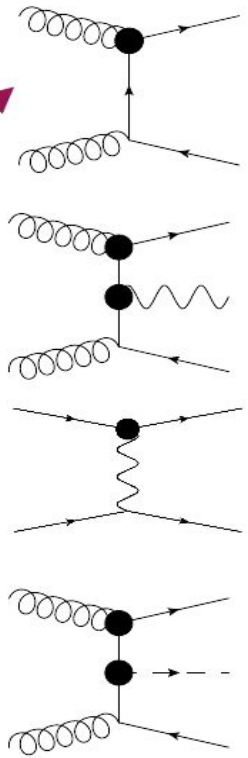
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu},$$

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}$$



top quark pair

top pair + Z

single top quark

top pair + scalar

Cartoon taken from [this talk](#) of Eleni Vryonidou

EFT in top quarks in practice

In top quark sector means:

◦ Re-interpret existing unfolded measurements.

◦ Design analyses to be explicitly sensitive EFT

→ Effort in the LHCTopWG across Atlas and CMS to define common benchmarks and language

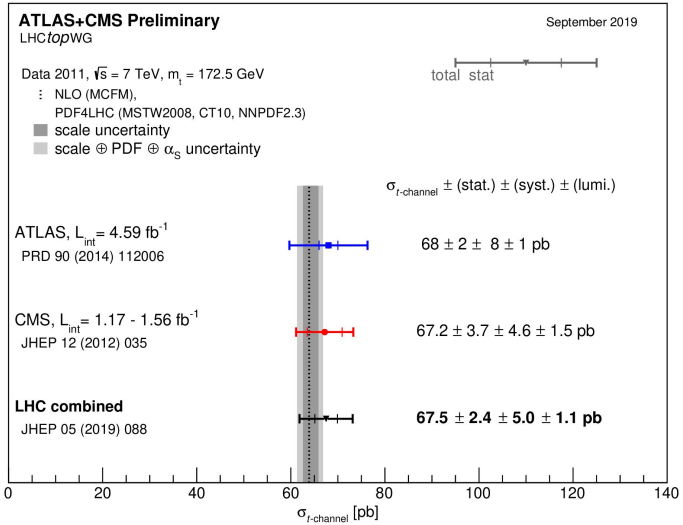
→ Effort also across communities (W/Z measurements, top quark, Higgs)

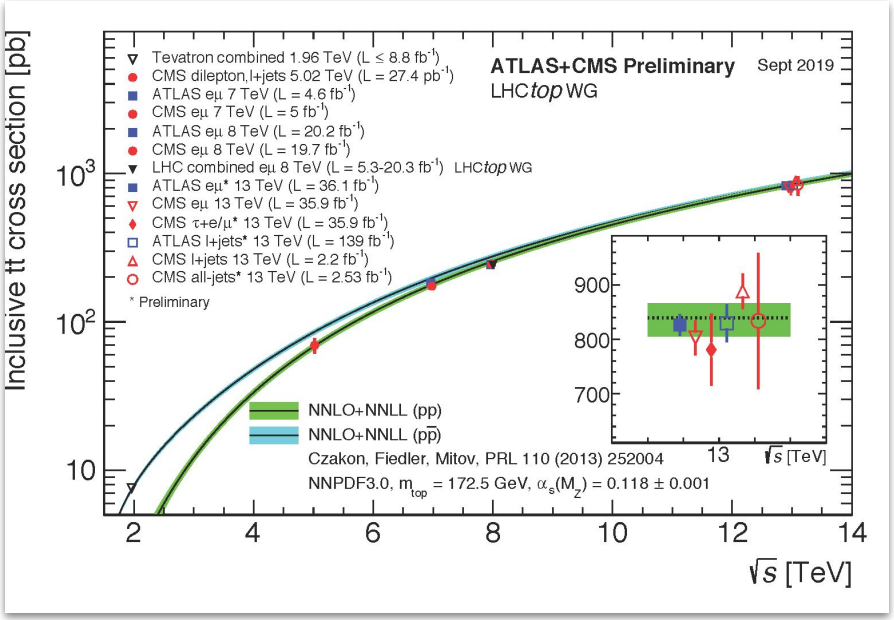
In the following we will highlight: high impact measurements that have possible EFT implications / are designed to do so.

Top quark cross sections

Event counting - inclusive or differential:

- Allows to access production properties, e.g. m_t, Vtb, α_S, etc.
- Inclusive cross section: first measurements, usually soon becoming systematics limited
- Allow to easily check the √s dependency across years

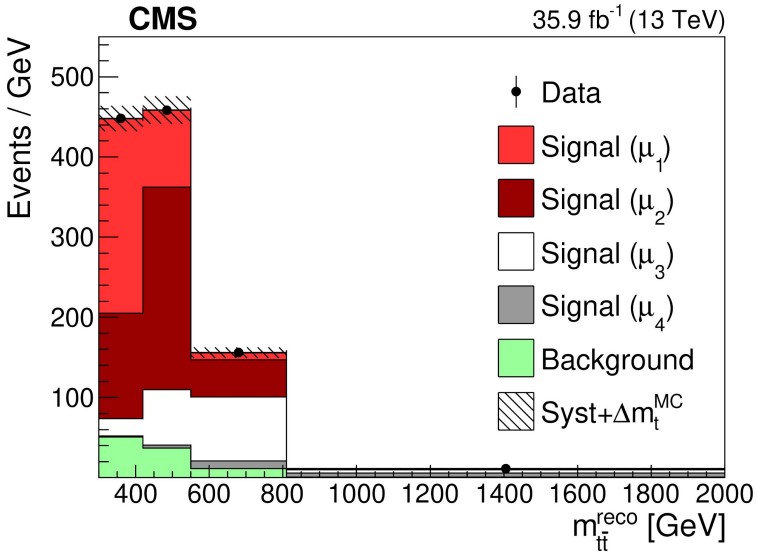


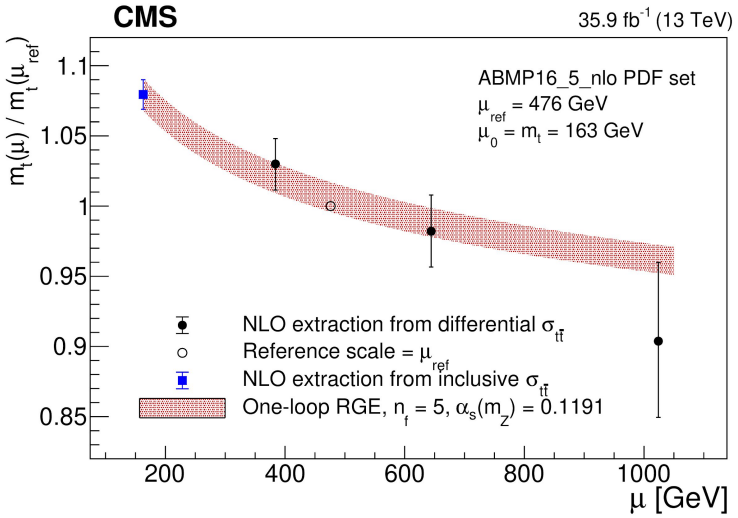


Differential spectra vs SM: top quark mass

- **Running top quark mass**

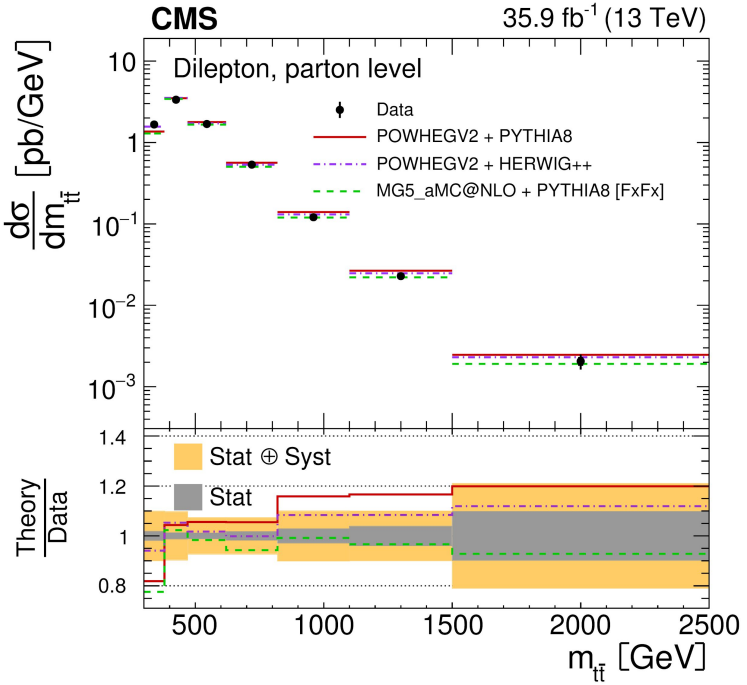
- Dileptonic event selection: opposite-sign muon/electron
- Cross section in bins of reconstructed top quark mass
- Sut signal split as function of generator-level mass

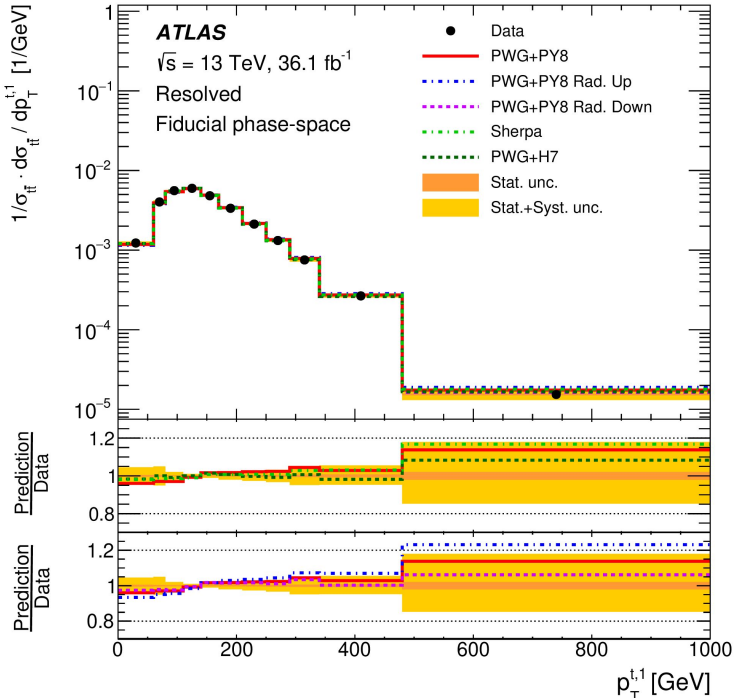




mtt spectrum vs QCD modelling

◦ **Pt spectra of the top quark pairs:** discrepancy coming from the transverse momentum spectra of the top quarks: prediction harder spectrum than data! Still under investigation where this effect comes from.
→ Work ongoint with full Run-II !



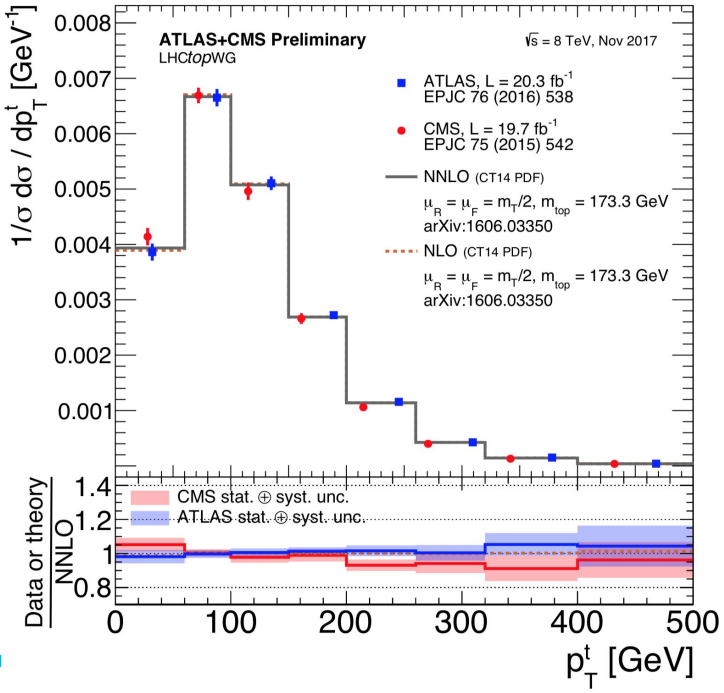


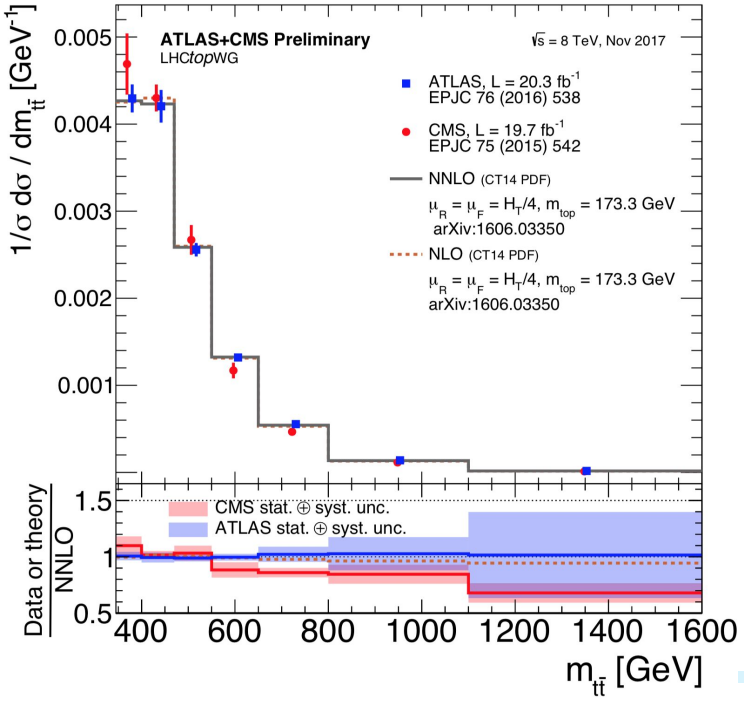
[TOP-17-014 Web page](#) / *JHEP 02 (2019) 149*

[TOPQ-2018-17 Web page](#) / arxiv1910.08819

An “historical” view on differential mtt

Discrepancies seen since long time: in Run-I data at 7-8 TeV discrepancywas already present
→ Not unambiguous interpretation.



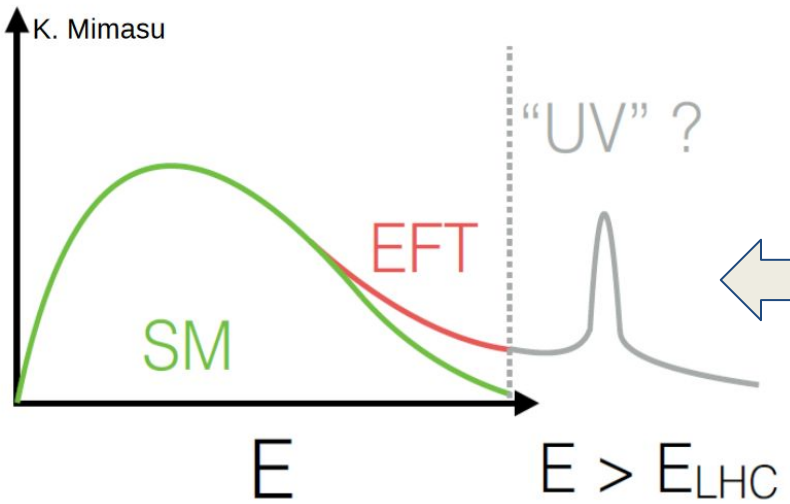


[LHC Top WG summary page]

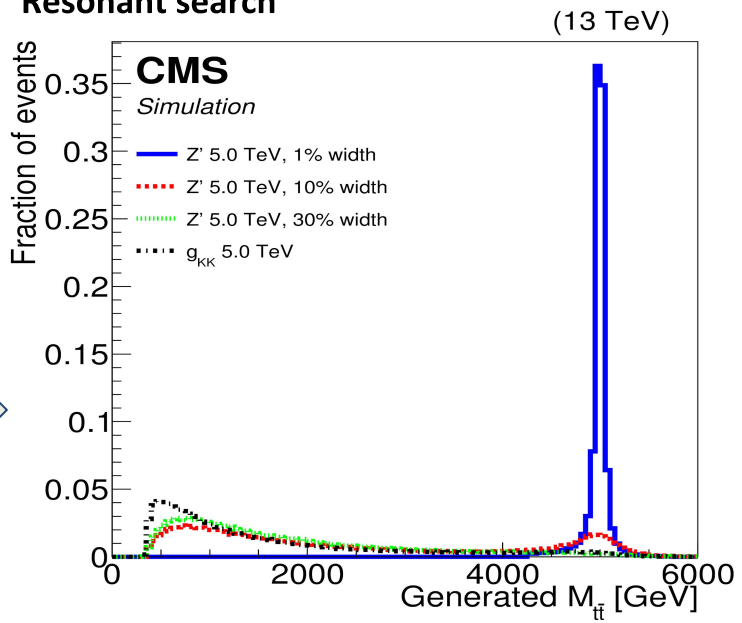
mtt beyond the SM, from EFT to resonances

Differential spectra at high-energy become key for **small anomaly detection** or traditional **bump-hunting**

EFT - type analysis



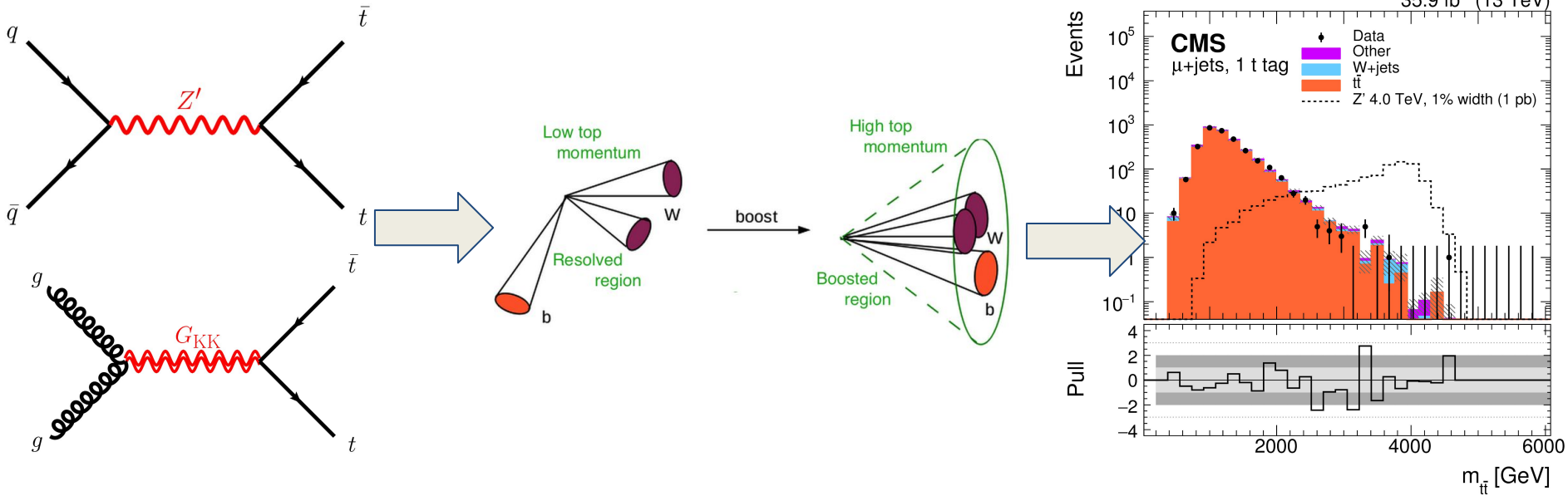
Resonant search



Nota bene: high-end tails will be extremely important for EFT analyses!

At high mtt: new physics searches

Search for a resonance → top quark pairs: boosted final states!

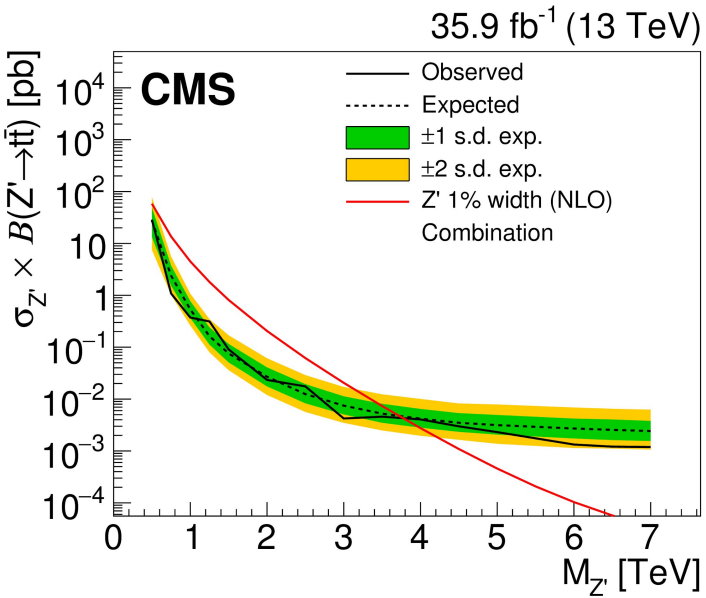


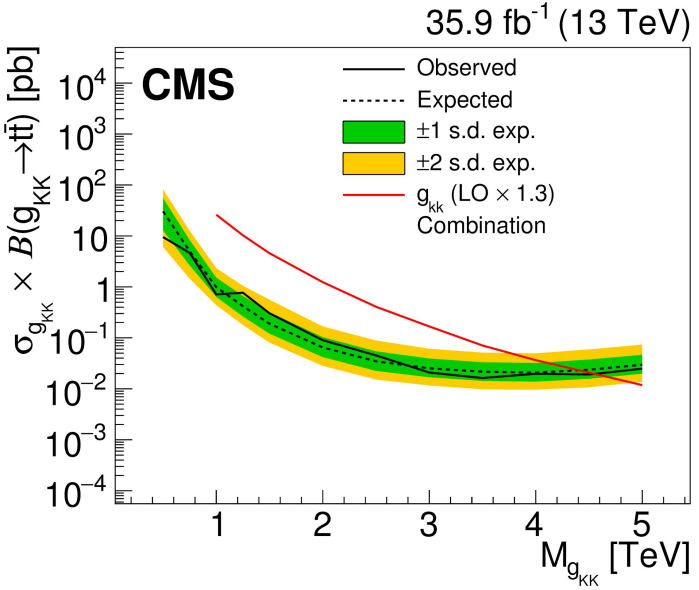
Boosted technologies: allow for probes of highest masses collecting top decay products in one fat jet

B2G-17-017 Web page/*JHEP 04 (2019) 031*

At high mtt: results and going forward

Limits go up: the mass shape does degenerate!
drawing from low x of the Parton Density Function → searches will become “EFT-like”





Probing couplings in tt: angular properties

Angular properties for ttbar pairs :

1) Define appropriate basis for tt events:

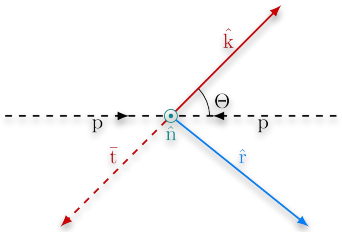
k = top direction; ***n***= normal to scattering plane; ***r*** orthogonal to other two

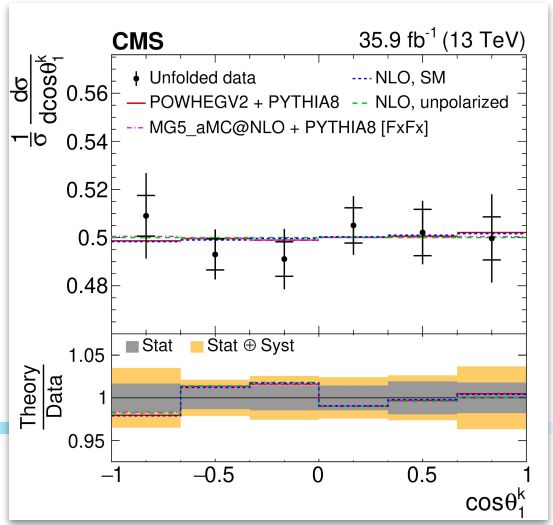
2) Decompose top polarisation $\boldsymbol{B}_1$, $\boldsymbol{B}_2$ and correlation matrix *C* in new basis

3) Define decay products: their distribution depends on top spin axis:

$$\frac{1}{\sigma}\frac{\mathrm{d}^4\sigma}{\mathrm{d}\Omega_1\,\mathrm{d}\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B_1}\cdot\hat{\ell}_1 + \mathbf{B_2}\cdot\hat{\ell}_2 - \hat{\ell}_1\cdot C\cdot\hat{\ell}_2\right)$$

4) One can write the products in 3) as angles in frame 1) and measure them

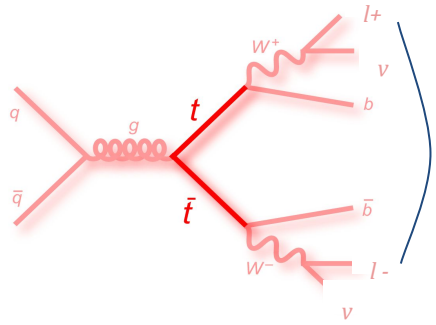


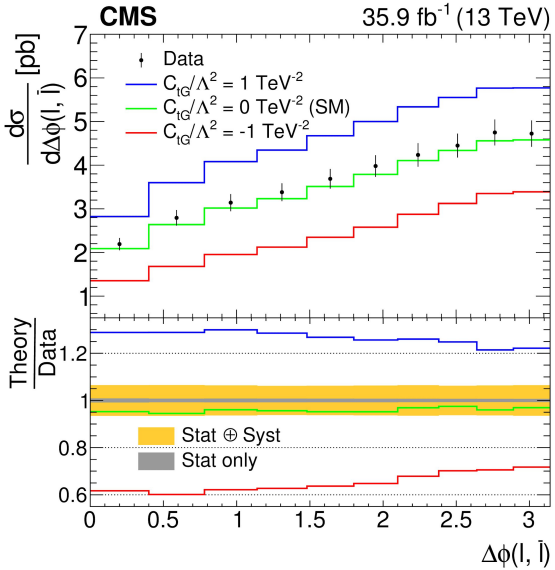


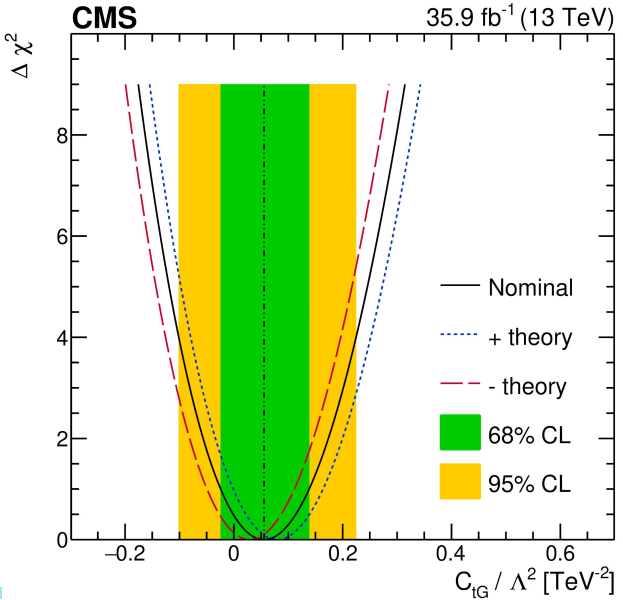
Probing EFT in tt: direct measurement

Angular properties: operators affecting the spin of tt, e.g. chromomagnetic dipole momentum $O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$

Angle between leptons: sensitive to operator OtG







Single top quark cross section

All single top quarks: cross section depends on $|Vtb|^2$

→ sensitive to models that deviate from CKM = unitary

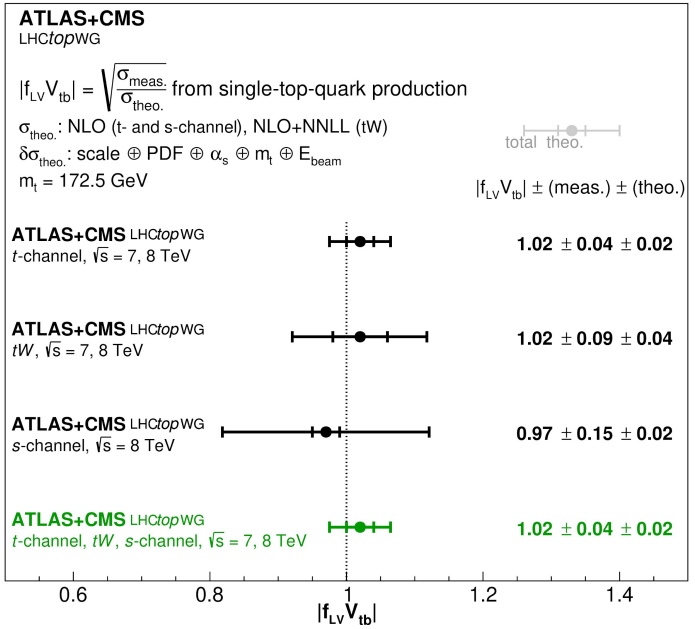
→ Sensitive to enhancements to Vtd/Vts from BSM.

Combination at LHC for Run-I:

10.1007/JHEP05(2019)088

New measurement at 13 TeV under different assumptions: **|Vtb| = 1.00 ± 0.03**

TOP-17-012 Web page / CDS record



Note: this measurement is also constraint on left-handed type operators:

$$\mathcal{L}_{Wtb}^{\text{dim}-6} = -\frac{g}{\sqrt{2}}\bar{b}(x)\gamma^{\mu}P_L t(x)\,W_{\mu}(x)\left(1+\frac{C_{\varphi Q}^{(3)}y_t^2 v^2}{2\Lambda^2}\right) + \frac{2\,g\,v\,y_t\,C_{tW}}{\Lambda^2}\bar{b}(x)\sigma^{\mu\nu}P_R t(x)\,\partial_{\nu}W_{\mu}(x) + \text{h. c.},$$

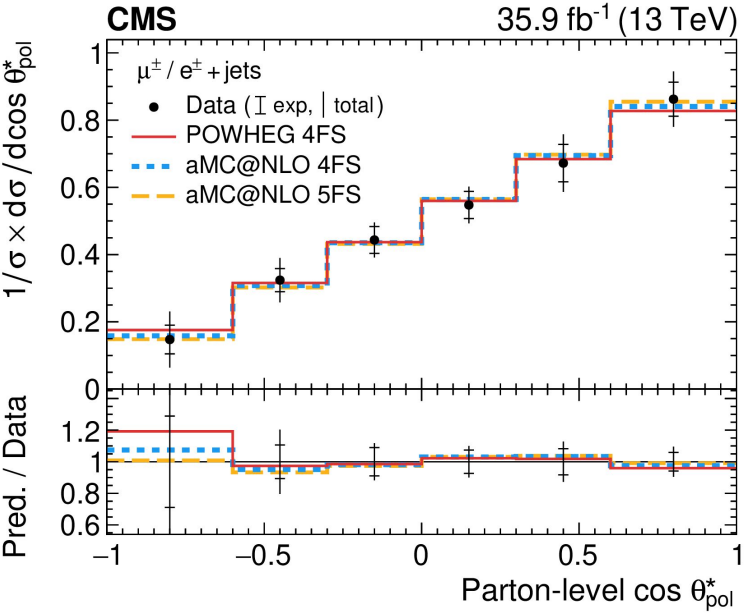
Going differential: spectrum and polarisation

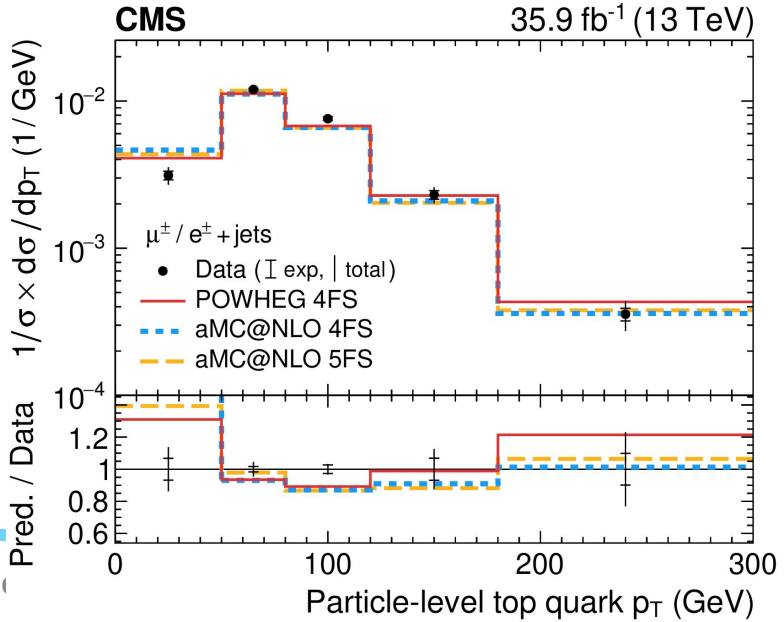
Single top quark: different degrees of polarisation w.r.t. tt events: electroweak production.

→ cos θ*: lepton in the top rest frame vs spin axis, taken from the recoil jet

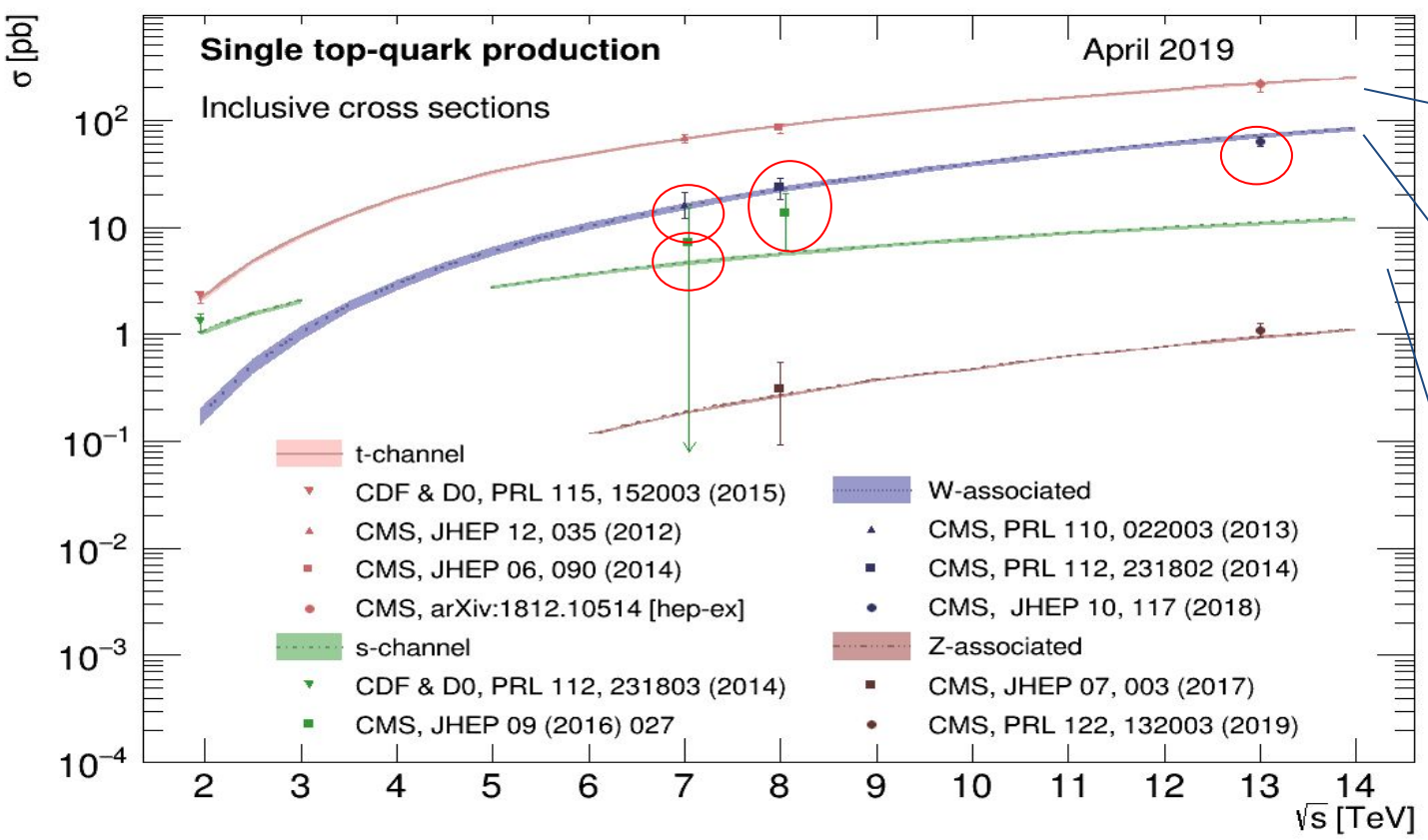
→ pt- spectrum entirely different from tt

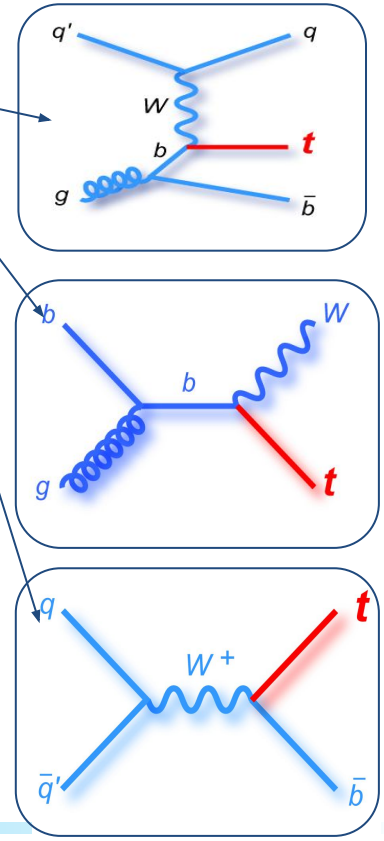
TOP-17-023 Web page / arxiv:1907.08330



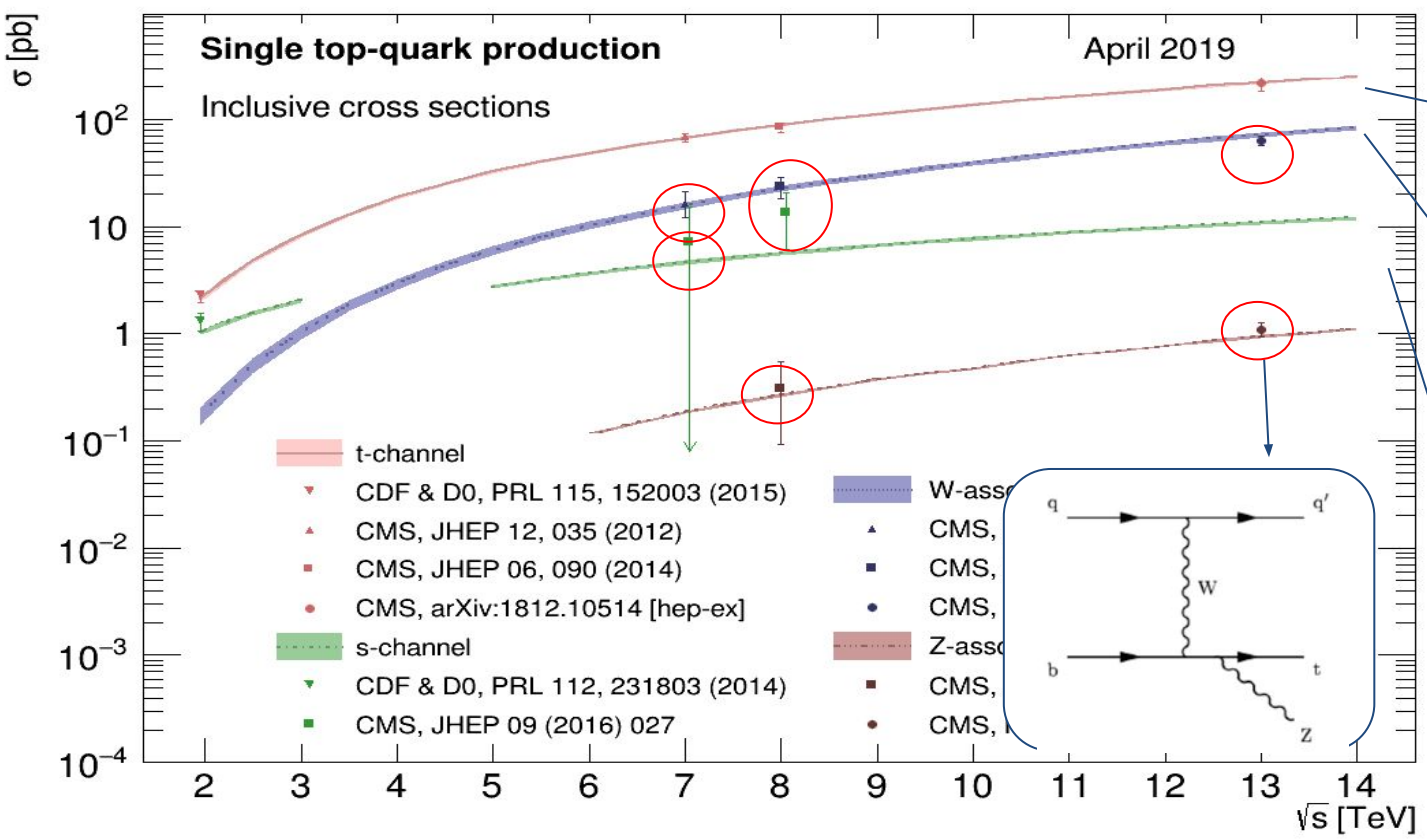


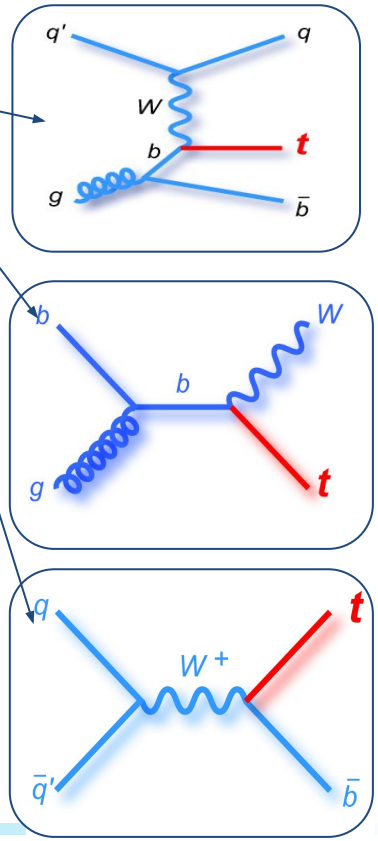
Lower cross-section channels





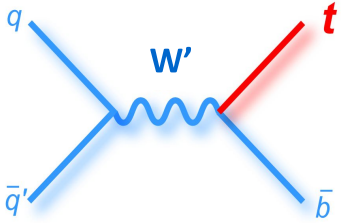
Lower cross-section channels

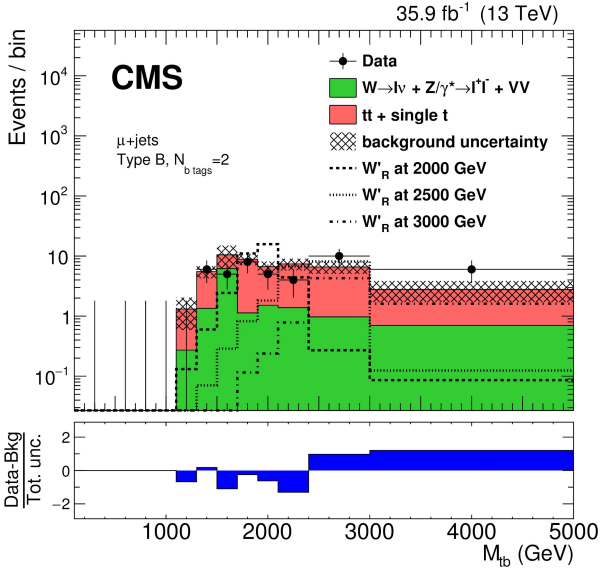


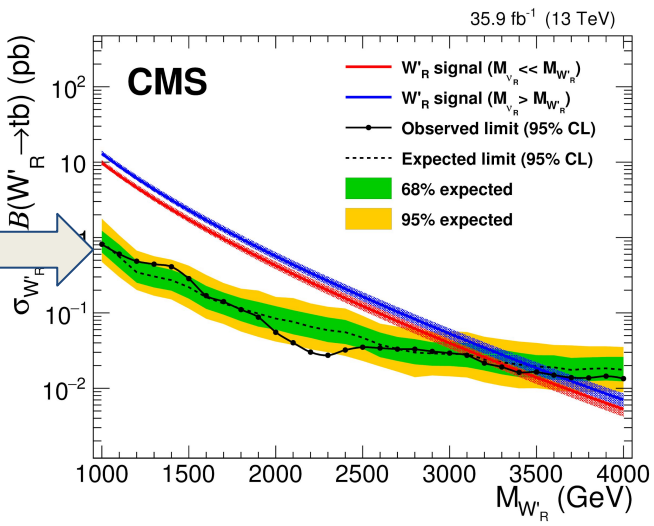


Single-top quark at high-pt / BSM

Single-top s-channel: in the SM it is strongly suppressed due to pdf effects and to the W being virtual.
→ In case of a new resonance, W' , this can be searched!
→ events with one lepton, one neutrino, one or two b-tagged jets:

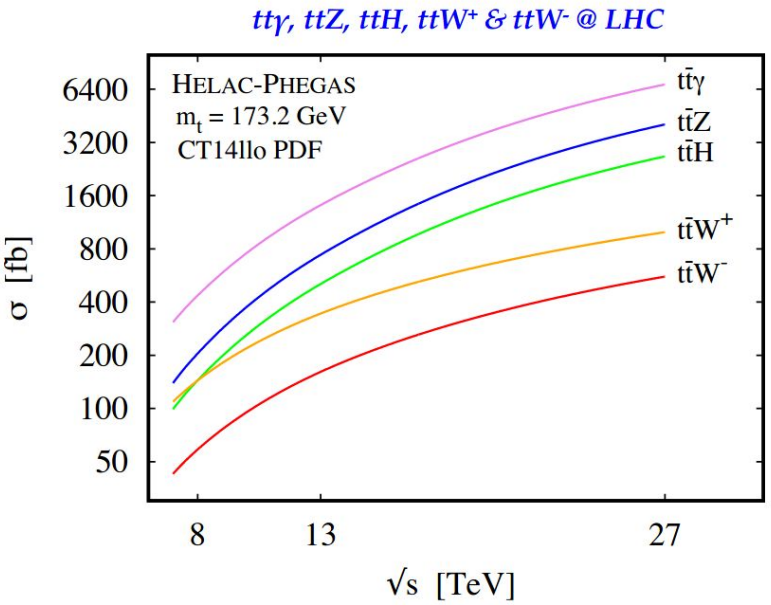






Different Right-handed vs Left handed: can be inferred from angular quantities!

New goldmine of Run-II: ttX/tXj productions!



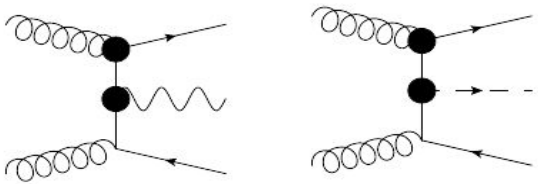
Plus 4-top production , single top+X channels etc

Evidence already!

Solid observation, several possibilities open:

→ Can use precision measurements to constrain top operators

→ Similar to what done for “classic” tt and t productions!

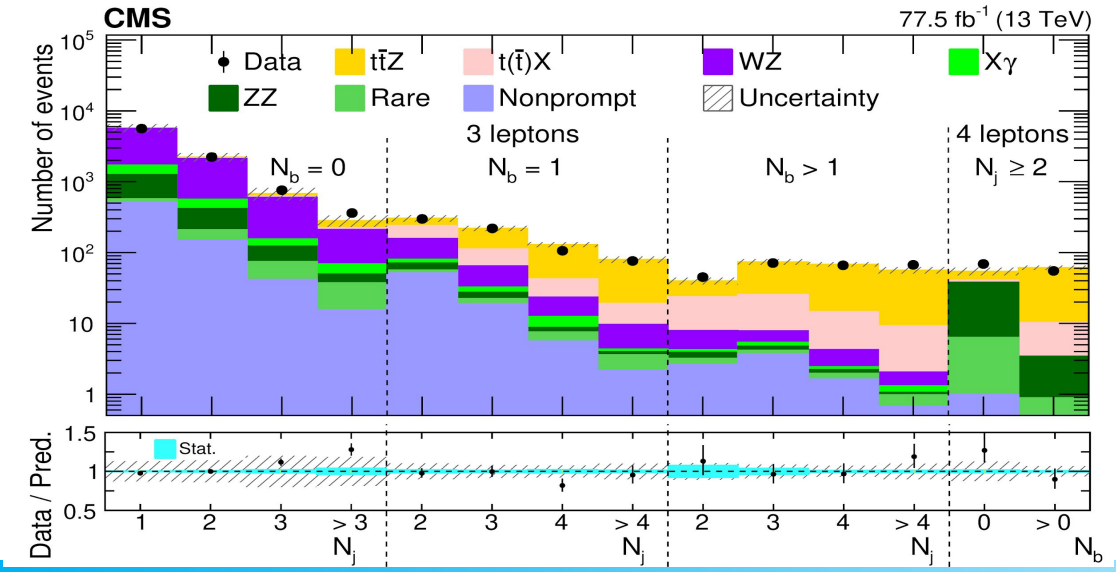


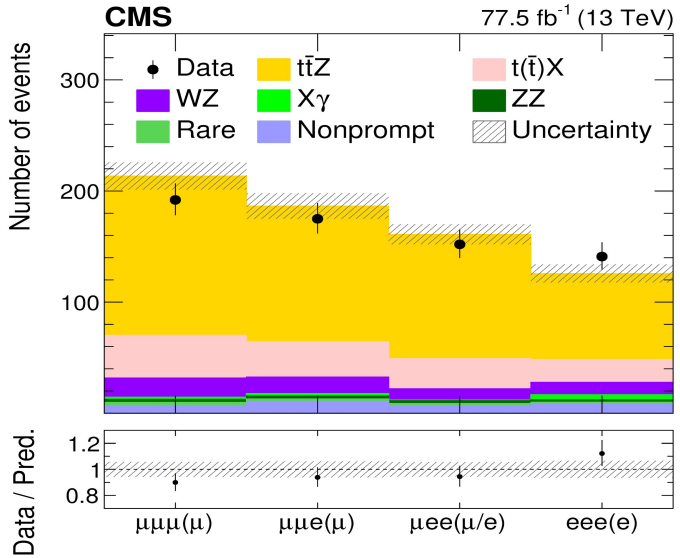
ttZ: from new channel to EFT probes

Very clean sample:

→ possible to have a lepton-antilepton pair + >= 1 b jet

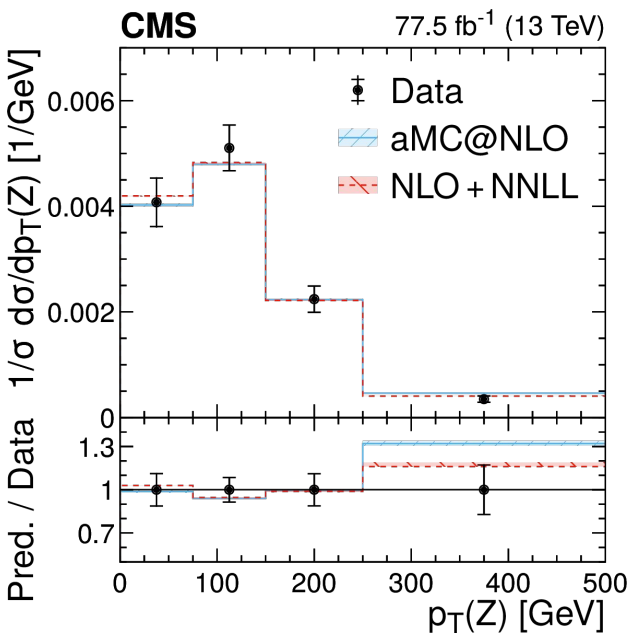
→ Signal enriched regions: differential distributions to probe EFT!

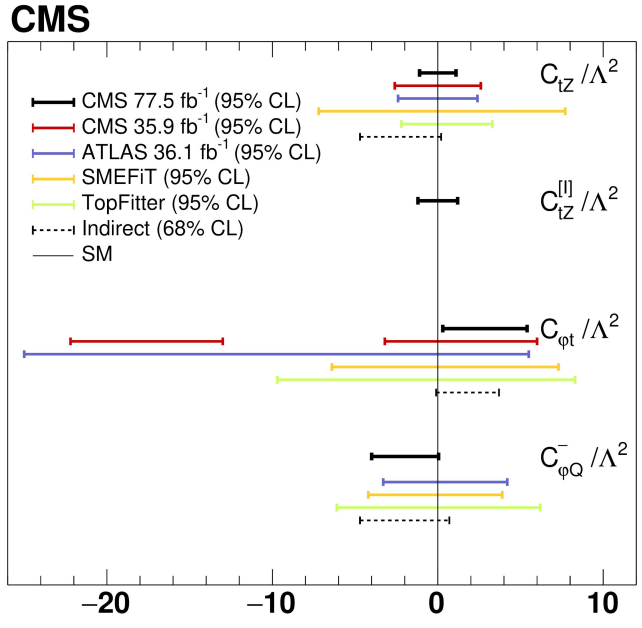




ttZ: from new channel to EFT probes

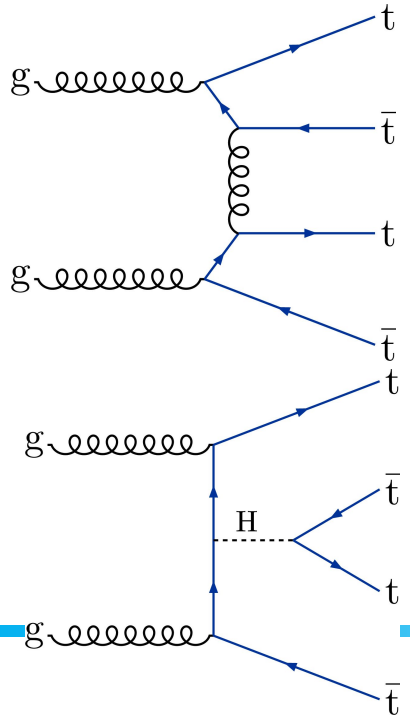
Contributions from EFT Can be seen in the Z angle and momentum:





4-top quark production

Very rare process: sensitive to:
→ 6-dimension operator involving top-higgs
→ top-higgs coupling y_t

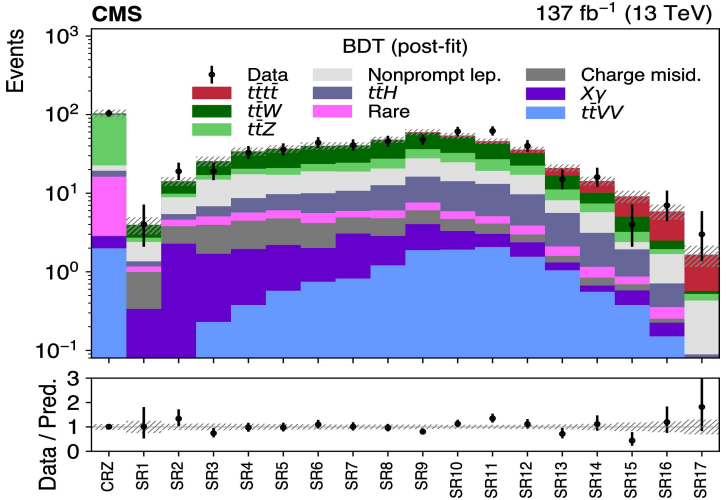


Complex analysis:
>= 2 leptons
high HT >300 GeV
>= 2 jets
>= 2 bjets

Multiple signal regions
depending on n leptons, jets,b

N_ℓ	N_b	N_{jets}	Region
2	2	≤5	CRW
		6	SR1
		7	SR2
		≥8	SR3
	3	5	SR4
		6	SR5
		7	SR6
		≥8	SR7
	≥ 4	≥5	SR8
≥ 3	2	5	SR9
		6	SR10
		≥7	SR11
	≥ 3	4	SR12
		5	SR13
		≥6	SR14
Inverted resonance veto			CRZ

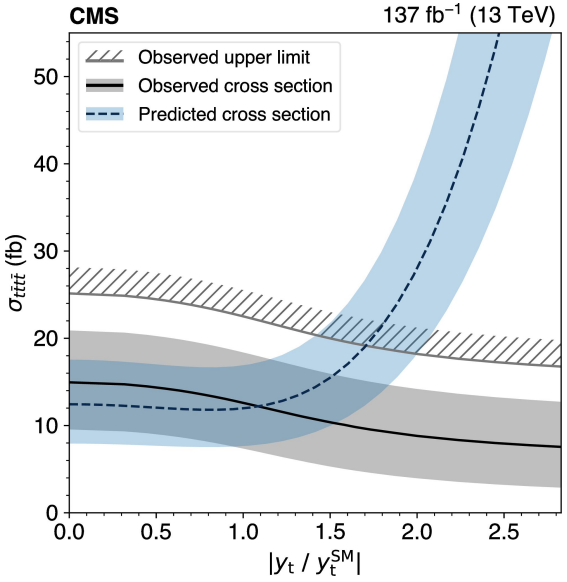
Simultaneous fit:
→ BDT in all channels
→ Cut and count analysis for cross-check

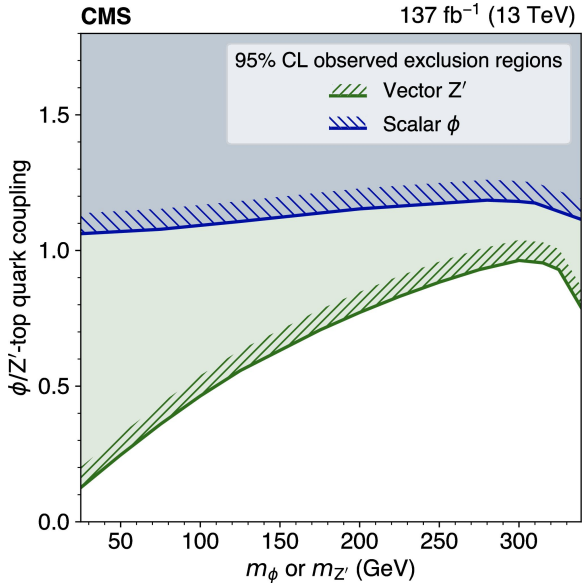


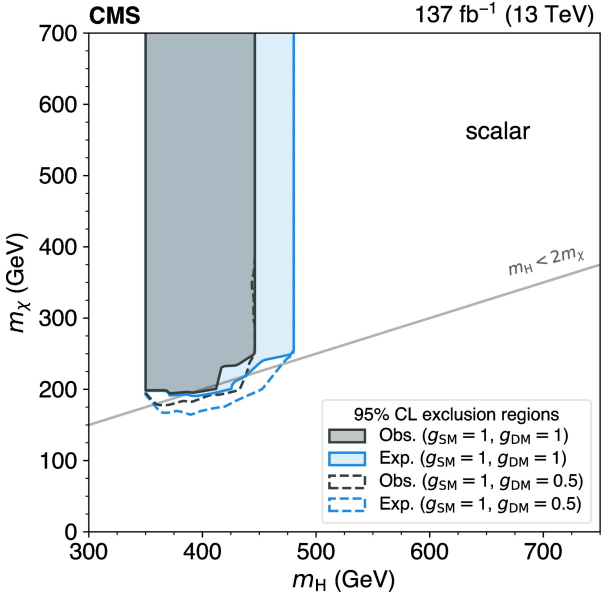
[TOP-18-003 Web page](#) / [arxiv:1908.06463](#)

4-top quark production

Depending on the mediator: can be interpreted as EFT **or** new physics direct search (extra Z'/DM mediators)







[TOP-18-003 Web page](#) / [arxiv:1908.06463](#)

Complex BSM final states → Vector Like Quarks

Vector-Like quarks: new fermions appearing in several composite models, coupled mostly to 3rd family

	SM	singlets	doublets	triplets
	$\begin{pmatrix}u\\d\end{pmatrix}$ $\begin{pmatrix}c\\s\end{pmatrix}$ $\begin{pmatrix}t\\b\end{pmatrix}$	T B	$\begin{pmatrix}X\\T\end{pmatrix}$ $\begin{pmatrix}T\\B\end{pmatrix}$ $\begin{pmatrix}B\\Y\end{pmatrix}$	$\begin{pmatrix}X\\T\\B\end{pmatrix}$ $\begin{pmatrix}T\\B\\Y\end{pmatrix}$
$SU(2)_L$	2	1	2	3
$U(1)_Y$	$q_L = 1/6$ $U_R = 2/3$ $d_R = -1/3$	2/3 -1/3	1/6 7/6 -5/6	2/3 -1/3

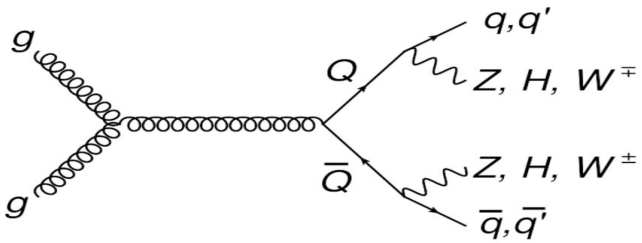
- Multiple representations
- $Q = I_3 + Y/2$

Appear in many SM extensions:

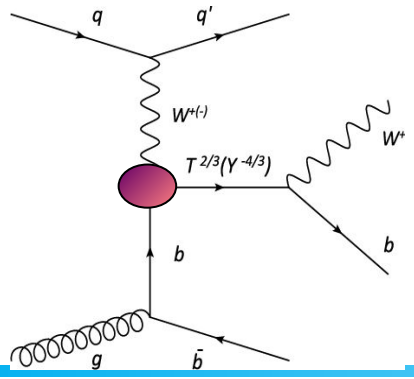
- **Little higgs, composite higgs**
- Warped **extra-dimensions**, Kaluza-Klein etc
- Some non-minimal **SUSY scenarios**

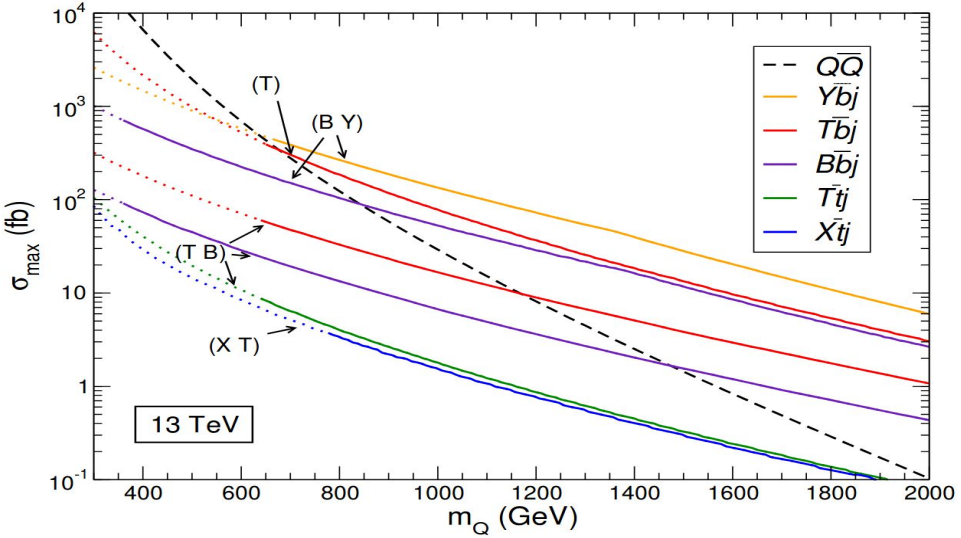
VLQ production

Pair-wise stong production: ***QQ***
- depends only on the Q mass



Single production: qQ
- depends on the Q mass and on the ***Qq*** coupling

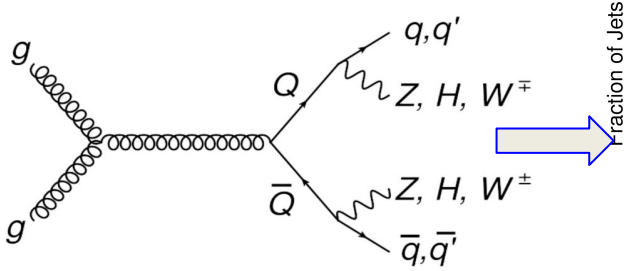


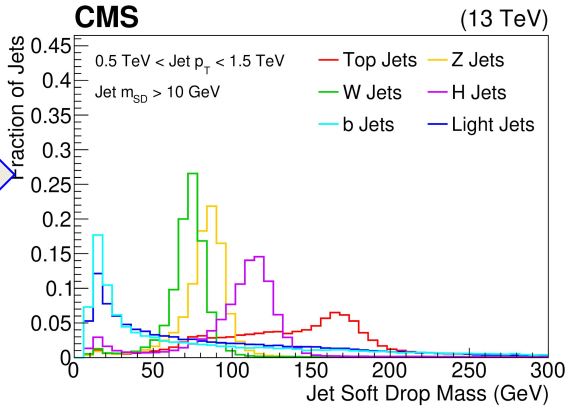


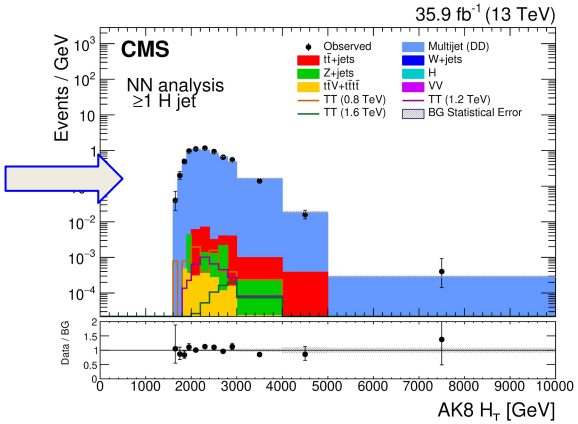
Both of them can reproduce the topologies we do measure in EFTs!

→ In particular single top quark ones!

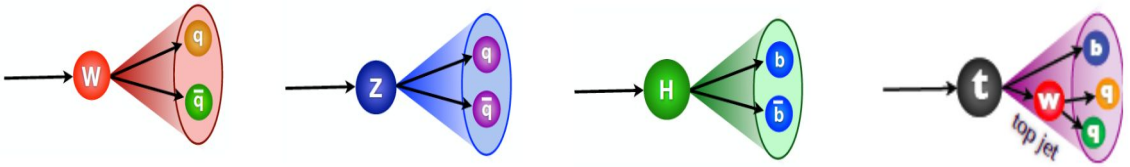
VLQ pairs: all-hadronic





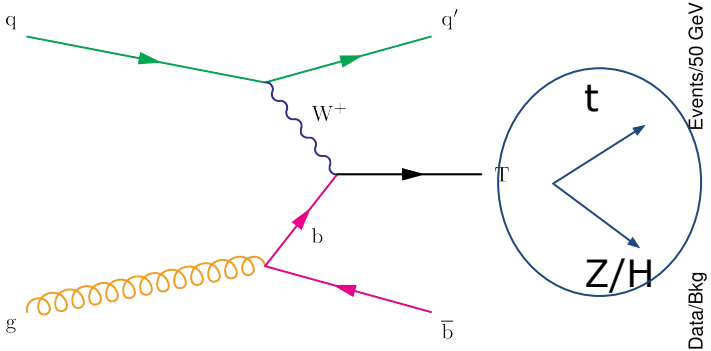


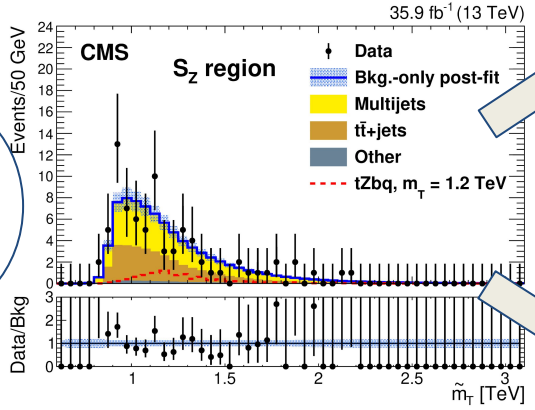
Inclusive search for TT → any combination of four: b,W, Z, H,t
→ a-specific search looking at high energy spectrum
→ Machine learning algorithm to separate different jets

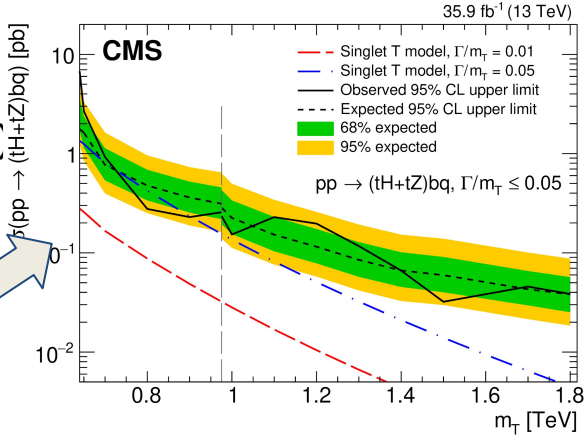


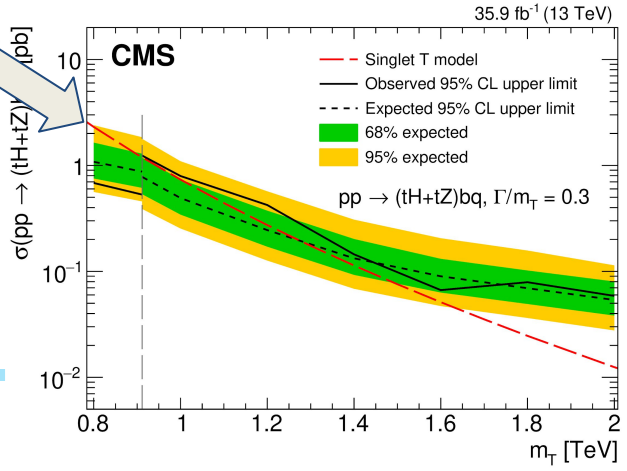
Single VLQs: T → tH/Z

More specific search (in this case): one top + H/Z
→ Possible enhancement to tH/tZ in EFT
→ two analyses: resolved (5 narrow jets) and boosted (2 fat jets)









Also in this case: very different behavior depending on width

[B2G-18-003 Web page](#) / [JHEP01(2020)036](#)

Some final considerations

EFT @ top quark:

- Common framework for interpreting top quark measurements as potential hints for new physics
- Still plenty of work, not all of the interpretations are model independent!
- “Rare” channels also start from there!

Differential and inclusive spectra:

- Measurements of two-fold nature: comparison with SM and with EFT benchmarks.

New physics scenarios:

- High mass resonant searches : can have interplay with SM and EFT extensions!
- In general using different technologies and problems, but having a common language would benefit greatly looking forward Run-III and HL-LHC → Still work in progress!