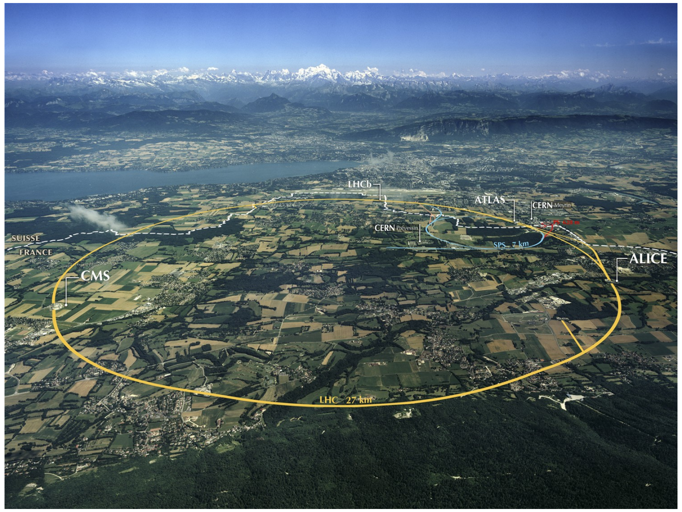
Top at the HL-LHC – ultimate reaches and challenges



- Overview (very short and selective)
- Challenges ahead
- Opportunities
- Conclusions & Outlook

Andy Jung (Purdue University)

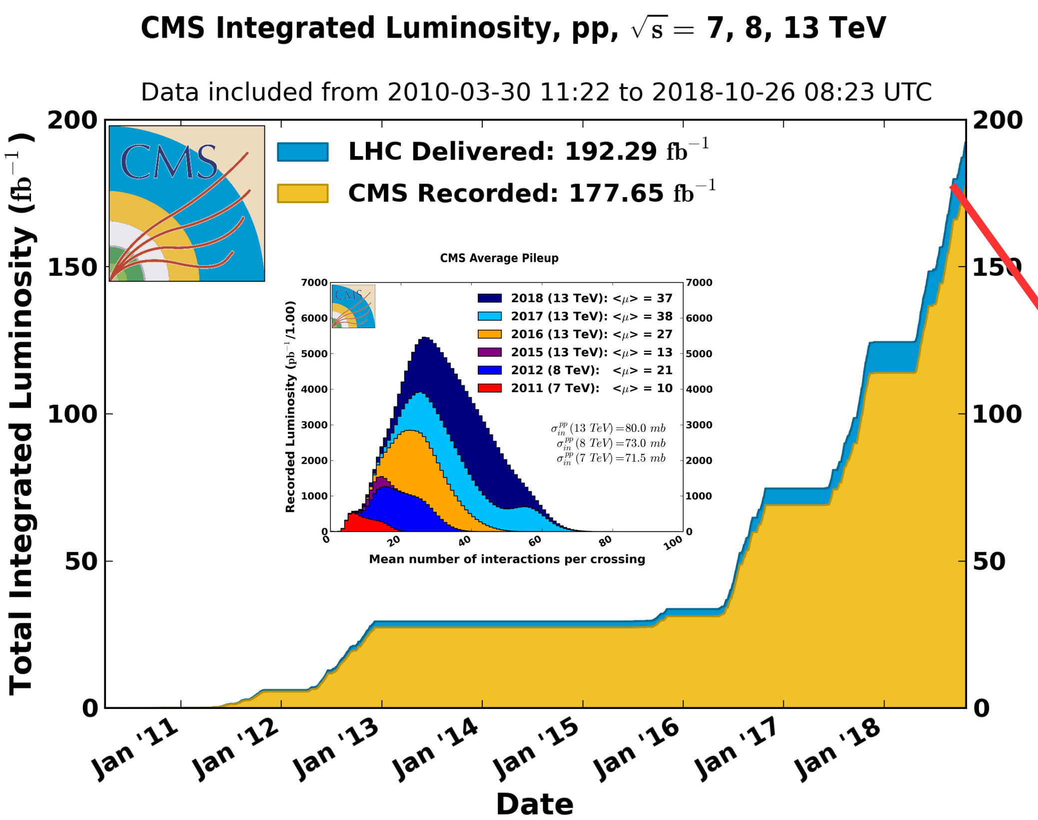
ECFA WHF WG1: 1st Workshop of the Higgs/Top/EW group

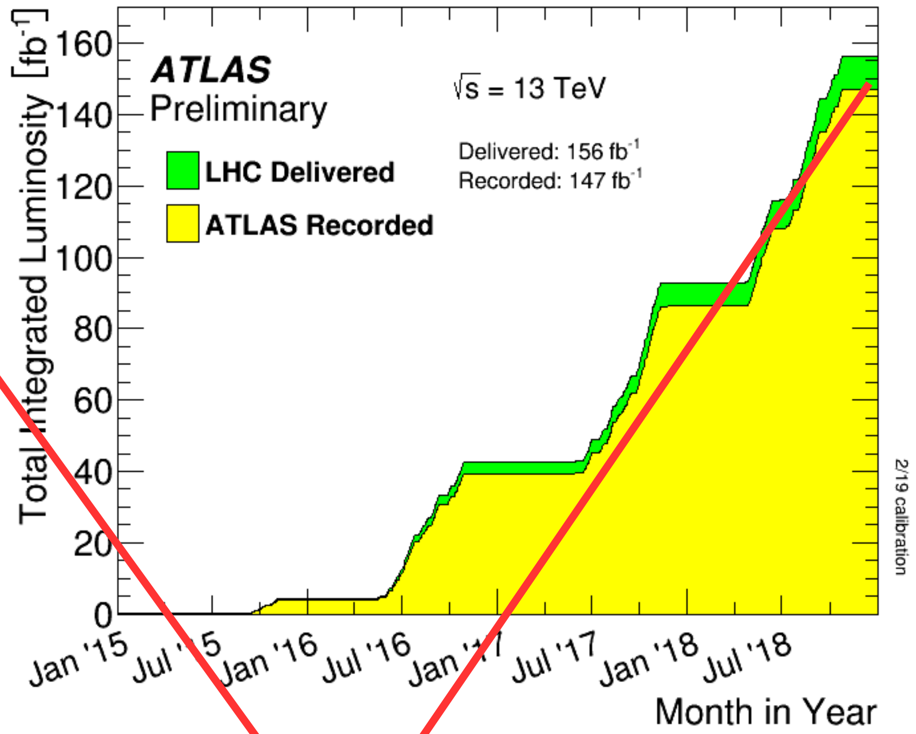
PURDUE UNIVERSITY

Caveat: biased selection of topics/results

April 21st, 2022

The present...LHC Run II





<u>Many new results @Moriond22</u>

- ATLAS: ATLAS-CONF-2021-013, ATLAS-CONF-2021-003
- ATLAS+CMS: ATL-PHYS-PUB-2021-16
- CMS: TOP-20-010, TOP-20-006, TOP-21-003, TOP-21-007, TOP-21-008, TOP-21-011, TOP-20-008

<u>Full Run II provides about</u>

~ 120 million $t\bar{t}$ pairs
~ 30 million single top
~ 120k $t\bar{t}Z$, tZ
~ 30k $t\bar{t}H$

Challenges & Opportunities

Disclaimer: Personal opinions!

Challenges ahead:

- Experimental systematic uncertainties
- More "global" approaches (kinematic ranges, EFT)
- Theory uncertainties

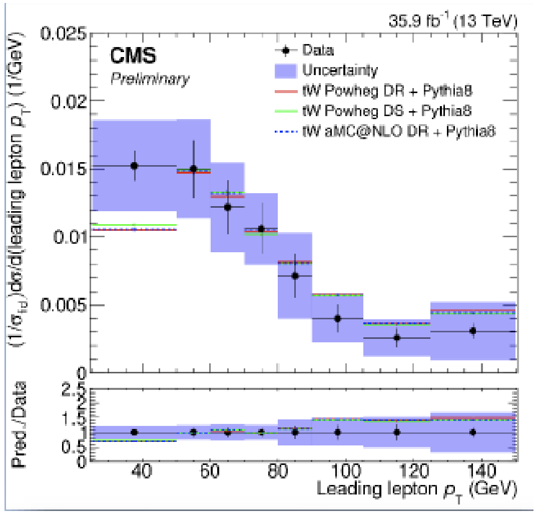
Opportunities

- Vast top quark sample...

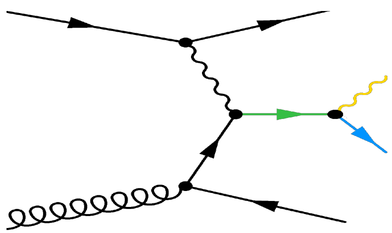
HL-LHC provides about
~ 3 billion $t\bar{t}$ pairs
~ 750 million single top
~ 3 million $t\bar{t}Z$, tZ
~ 36k $t\bar{t}$+$t\bar{t}$
(~ 750k $t\bar{t}H$)

Single Top Quark Production

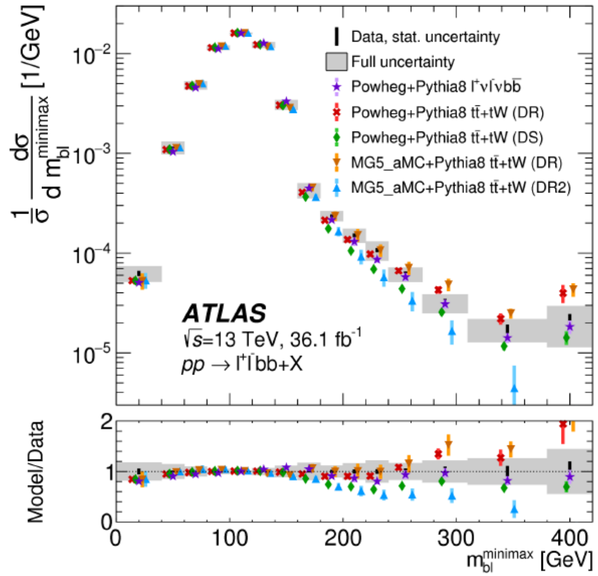
Challenges and Opportunities:

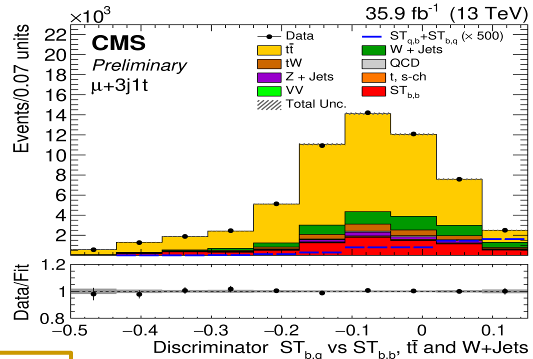


[CMS-PAS TOP-19-003]

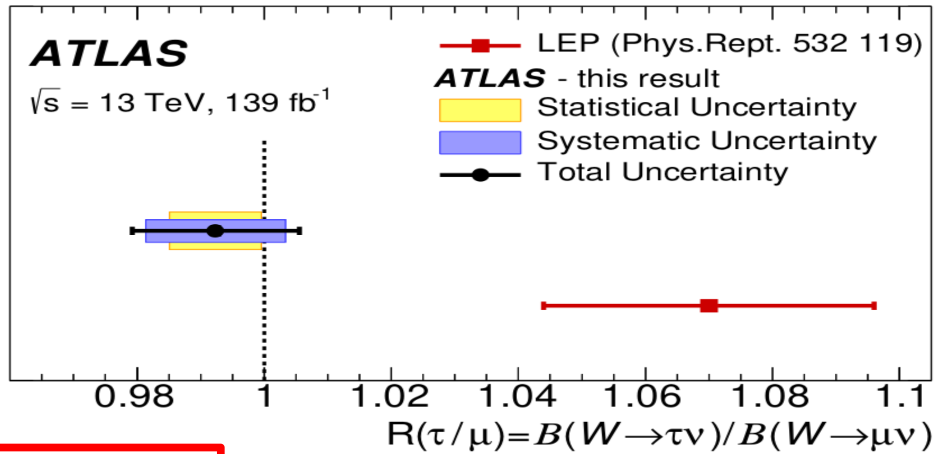


- CMS: differential ratio of t vs. $\bar{t}$ – sensitive to proton structure
- ATLAS: tW measurement requires tt + tW interference terms





arXiv:2007.14040 accepted by **Nature Physics**



$$|V_{td}|^2 + |V_{ts}|^2 \leq 0.17 \text{ at } 95\% \text{ CL.}$$

$$|V_{tb}| = 1.00 \pm 0.01\ (\text{stat} + \text{syst}) \pm 0.03\ (\text{nonprofiled})$$

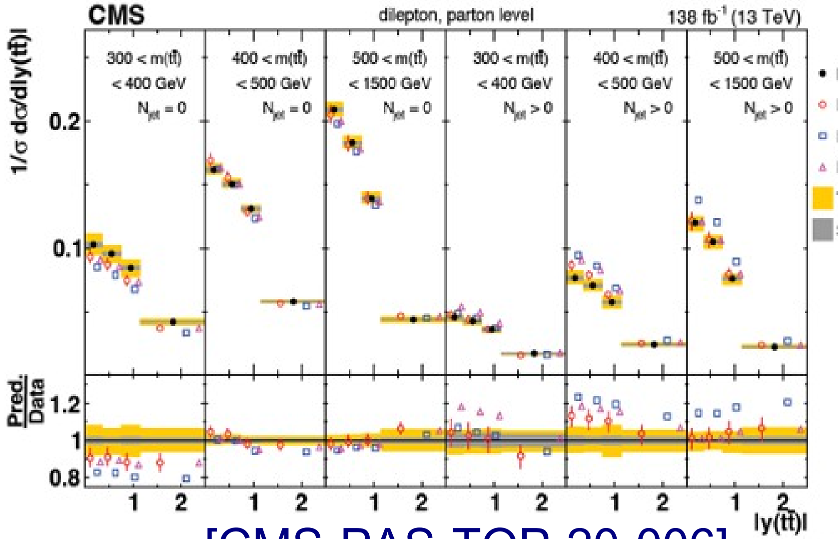
→ Impressive amount of differential measurements in single top! tt+tW interference terms become relevant to describe data!

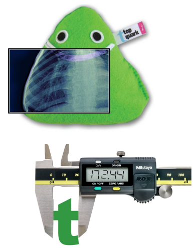
ATLAS: Lepton Universality

Differential cross sections

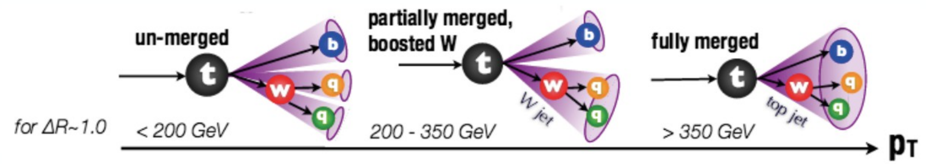
- Enormous amount of differential cross section measurements at ATLAS & CMS – impossible to summarize in 1 slide.
- Expect even more n-dimensional distributions

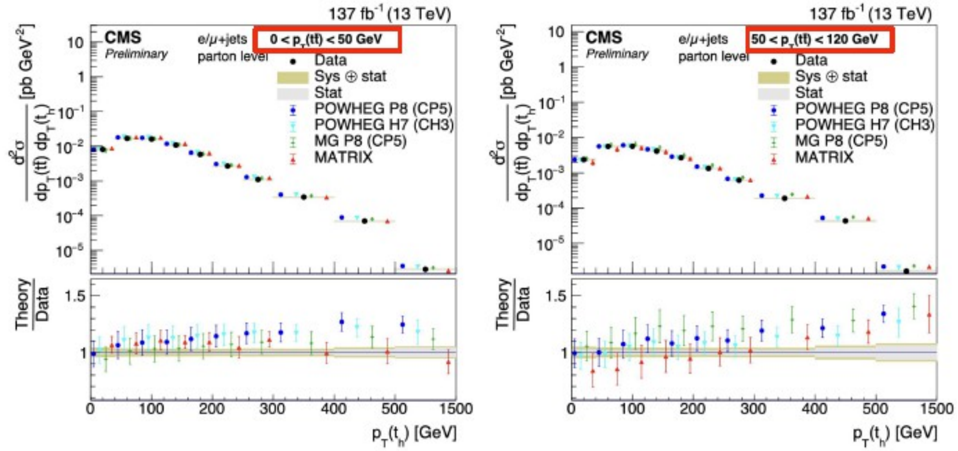
[CMS-PAS-TOP-20-001]





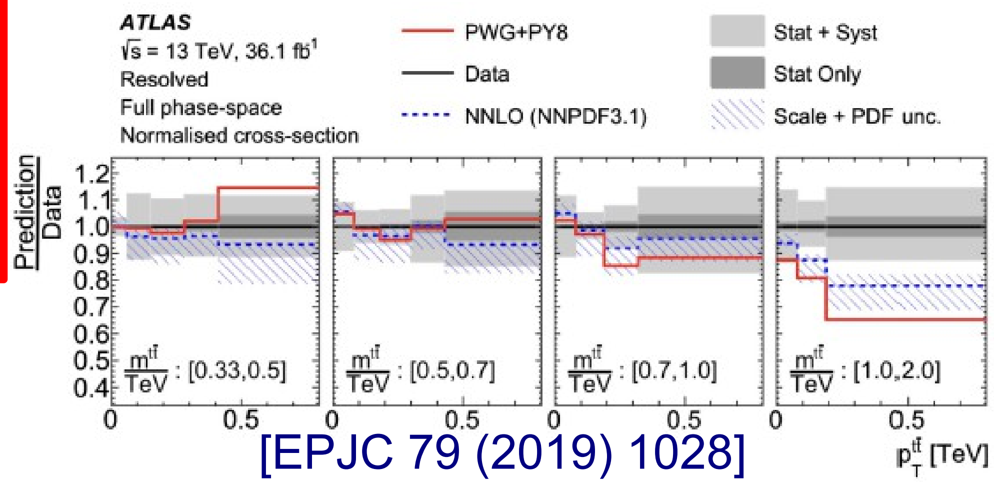
[CMS-PAS-TOP-20-006]





- Improve signal modeling, seen 1st triple and double differential measurements!
- Getting more precise in boosted regime
- On CMS site: 1st simultaneous measurement of resolved and boosted

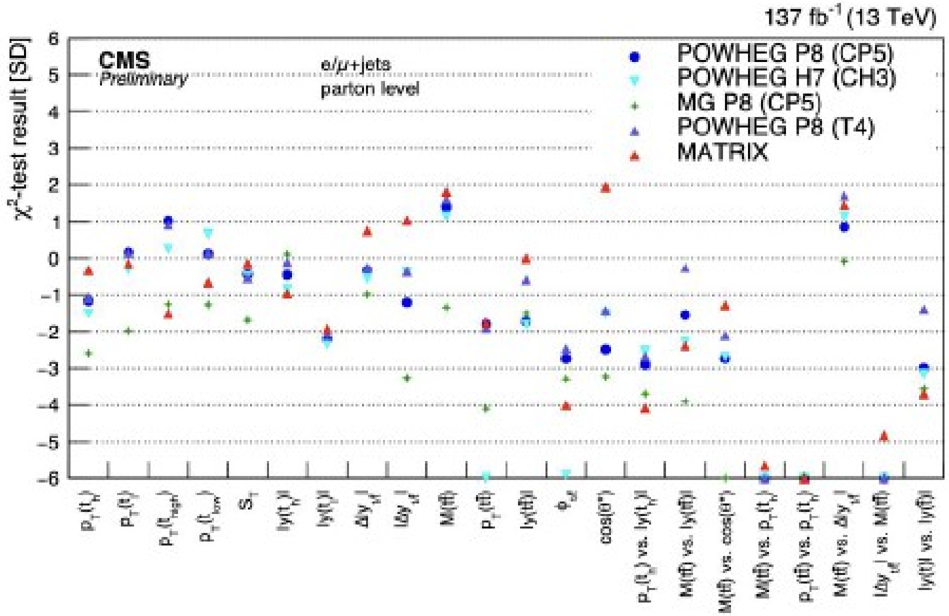
(particle level ok @1D, deviations in 2D ↔ NNLO predictions improve descriptions at parton level compared to NLO+PS)



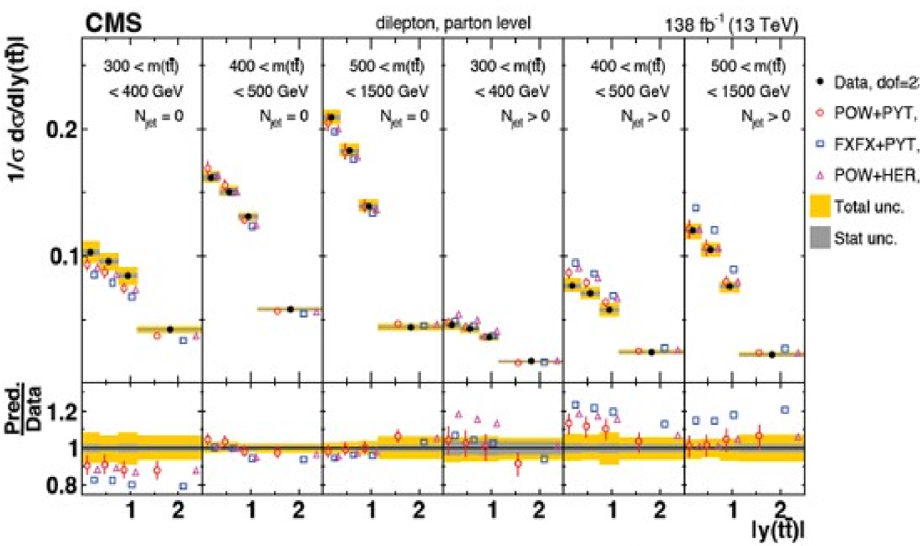
[EPJC 79 (2019) 1028]

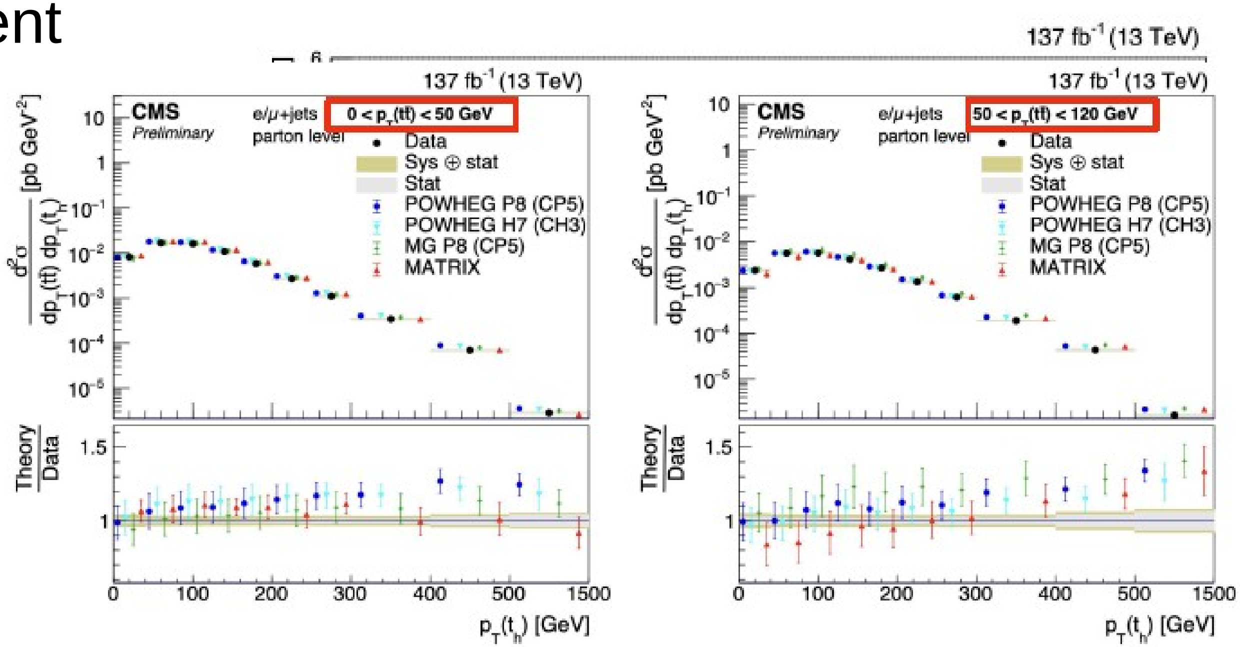
Challenges in multi-D x-sec's

- More global approach is needed to fully harvest the wealth of top data
  - Theory setup & uncertainties critical
  - As an example: MATRIX
    - Great tool, excellent to have
    - CPU time/demands is non-negligible, e.g. 10k jobs on lxplus → 2% stat in n-dim results, 10x not doable as normal user. Even more of troubling for uncertainties



- Recent CMS multi-D measurement
  - Top pT spectra up to 1.5 TeV, 3D xsec'



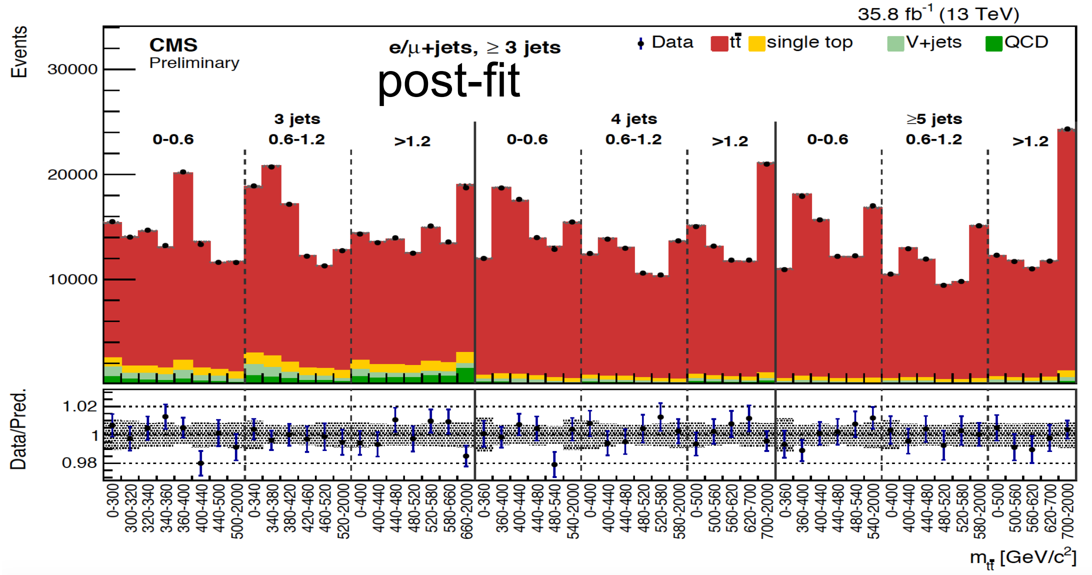


Top quark threshold region

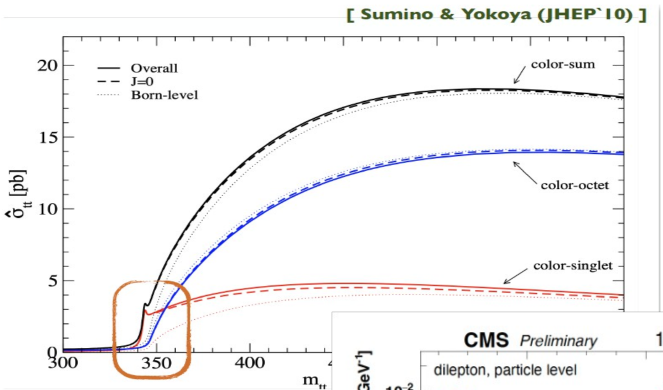
Extract y_t from template fit:

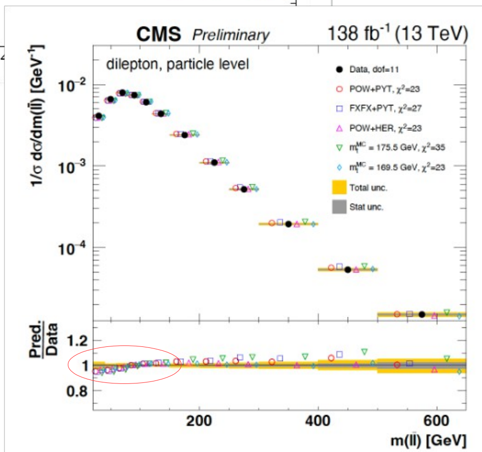
- CMS 13 TeV data, l+jets
- **Relies on threshold region**

- Also relevant to search for toponium as presented at a joint LHCtopWG seminar by Fuks et al.



y_t^{com} = 1.07 + 0.34-0.43 (obs) [1.00 +0.35-0.48 (exp)]





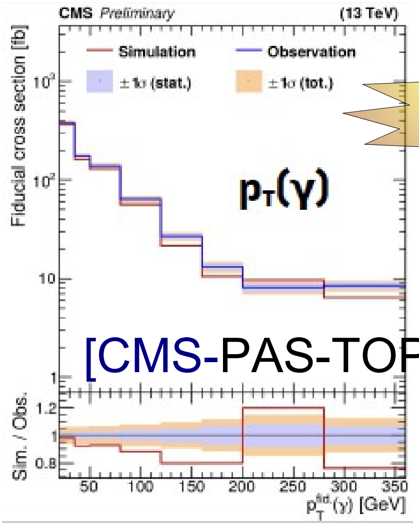
- Threshold region is challenging for:
  - Experimental measurements & theory calc's
- Modeling has impact on parameter extraction
- Exciting opportunities at HL-LHC (and Run 3) in this region

t̄t+X production

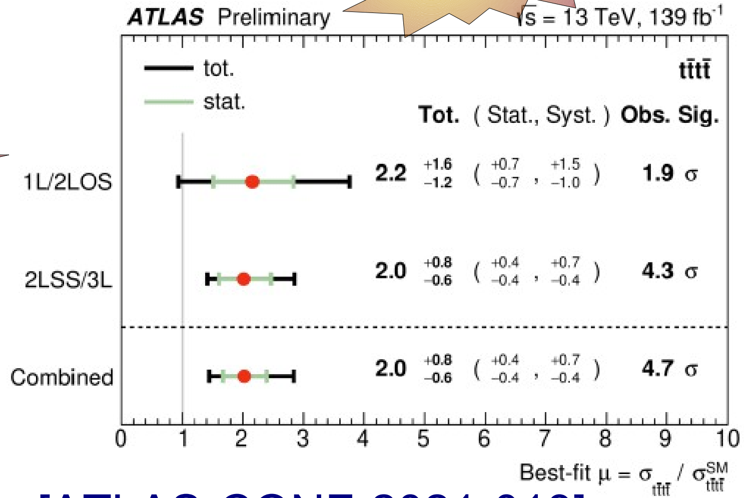
- **tt̄Z/W:** Most precise measurement, allowed for 1st differential cross sections
- **tt̄γ** : Differential tt̄γ by CMS
- **tt̄+tt̄:** Full Run 2 evidence at ATLAS
- **tt̄+cc̄:** 1st by CMS

tt̄+tt̄

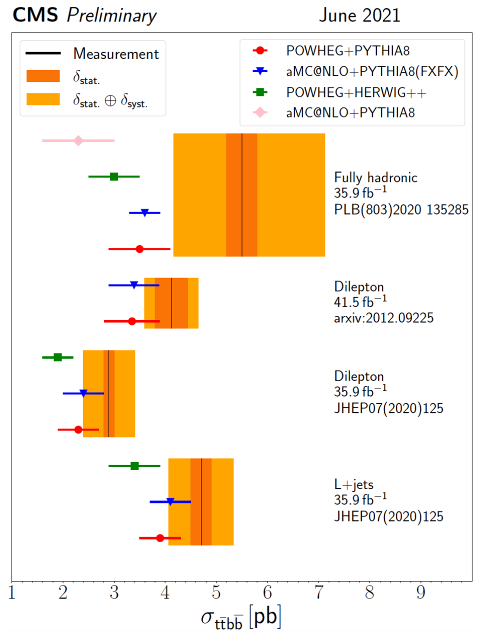
tt̄γ



[CMS-PAS-TOP-18-010]



[ATLAS-CONF-2021-013]



[CMS-PAS-TOP-20-003]

HL-LHC prospects:

- Differential measurements

~ 3 million tt̄Z, tZ
~ 36k tt̄+tt̄
(~ 750k tt̄H)

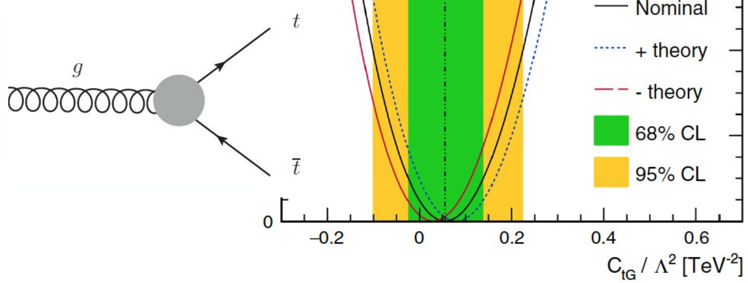
- Details matter: SF's for ttZ, ttW and ttbb are not easily comparable (mind phase space & uncertainties)
- Picture emerging: tt+X enters precision, poses demands on higher order corrections for theory predictions
- Signal modeling often limiting systematic

Effective field theory...

- EFT is now widely used to search for off-resonance effects
- Challenging on "inputs": Ideally want all correlations...

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} \mathcal{O}_i^{(6)}}{\Lambda^2}$$

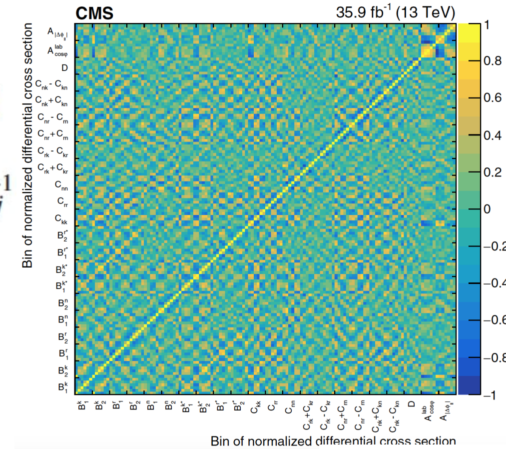
$$O_{\rm tG} = y_{\rm t} g_{\rm s} (\overline{Q} \sigma^{\mu\nu} T^a t) \tilde{\phi} G^a_{\mu\nu}$$



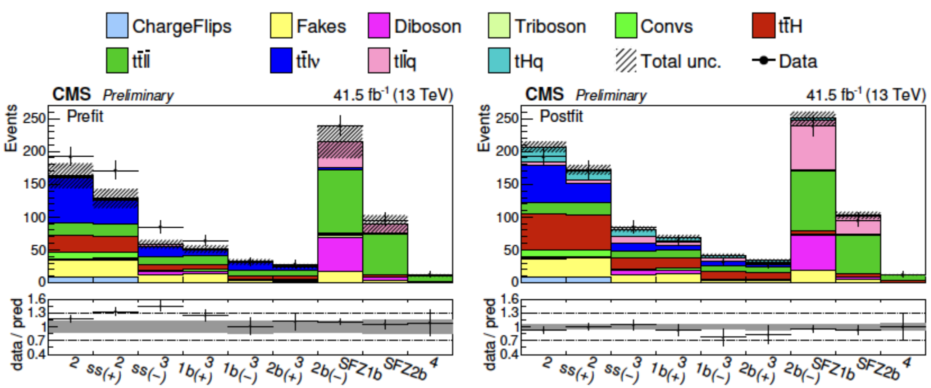
e.g. CMS Spin correlations employs systematic correlation matrix used in 120-bin fit:

$$\chi^2(C_{\rm tG}/\Lambda^2) = \sum_{i=1}^{N} \sum_{j=1}^{N} [\mathrm{data}_i - \mathrm{pred}_i(C_{\rm tG}/\Lambda^2)] \times [\mathrm{data}_j - \mathrm{pred}_j(C_{\rm tG}/\Lambda^2)] \mathrm{Cov}^{-1}_{ij}$$

PRD 100 (2019) 072002

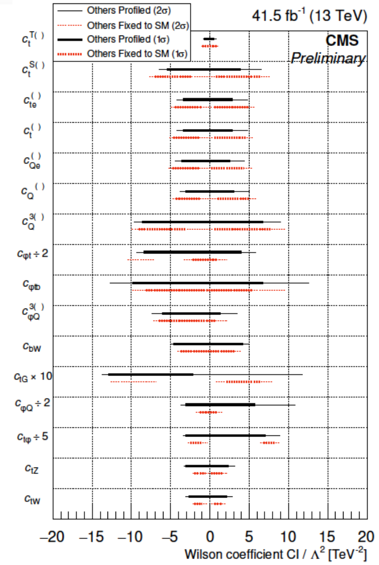


- More global approaches to capture experimental correlations, EFT at particle level to boost sensitivities



- Associated top production to probe for BSM effects
- Consistent treatment of experimental correlations
- Multi-process applications

[CMS-PAS-TOP-19-001]

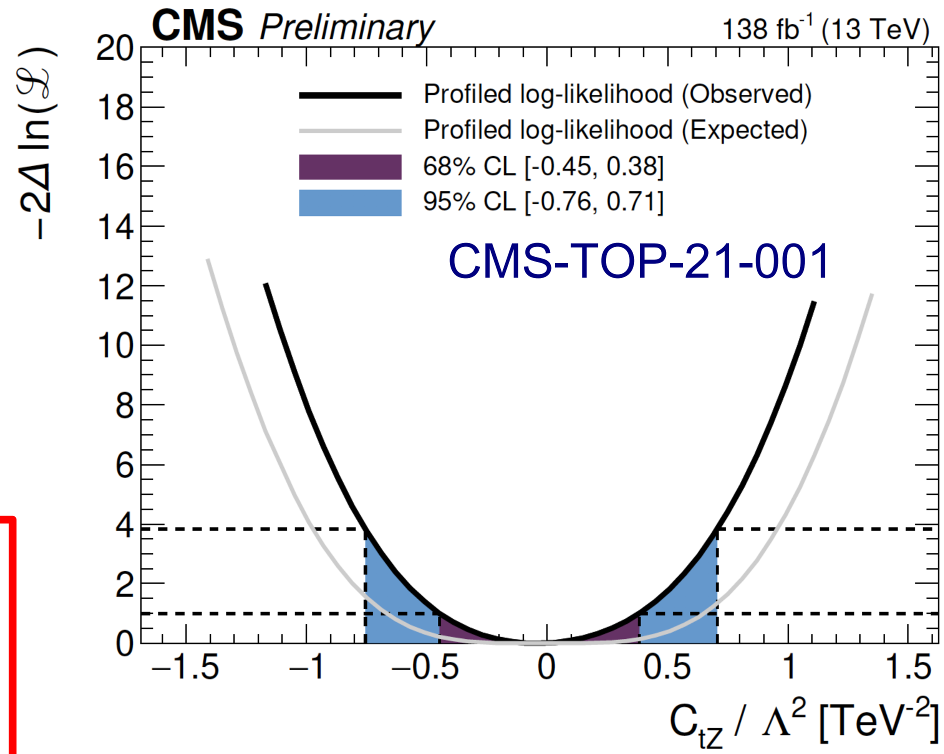


Effective field theory...

- Machine Learning pushes limits beyond of whats established as standard, e.g. tZq and C(tZ) coefficient.
- Improvements compared to associated top production with additional leptons

JHEP 03 (2021) 095

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} \mathcal{O}_i^{(6)}}{\Lambda^2}$$



Challenges & Opportunities at HL-LHC

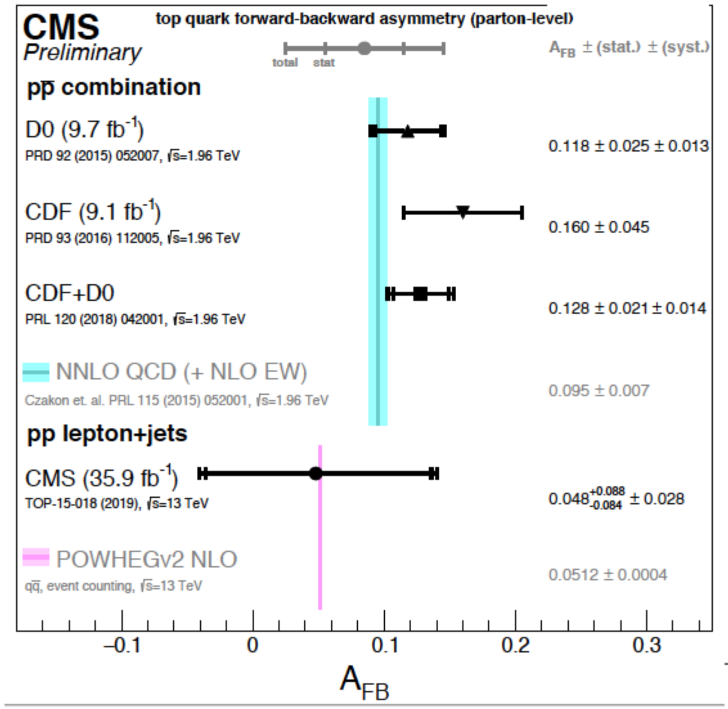
- More global approaches to capture experimental correlations, EFT at particle level and ML to boost sensitivities
- Transitioning to NLO where possible
- Joined effort by experimentalists and theorists to advance and squeeze out all information
- Clearly, this is a talk in its own...

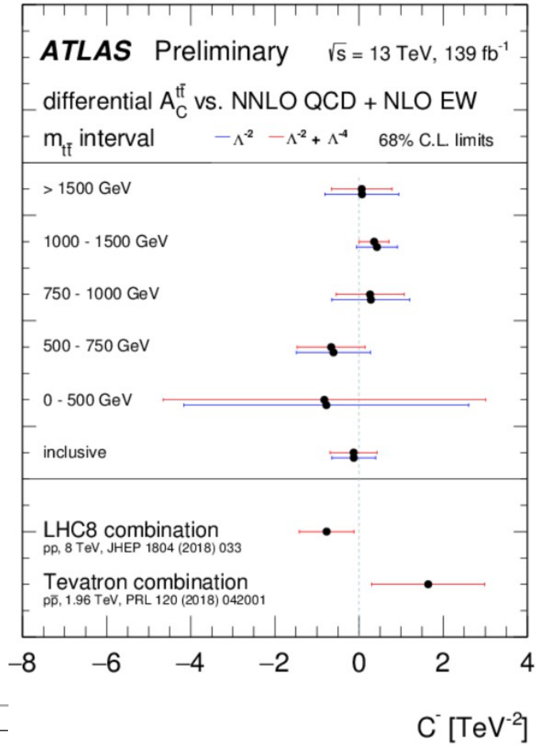
- Associated single top and Z (tZq) production to probe for BSM effects
- Exploits Machine Learning

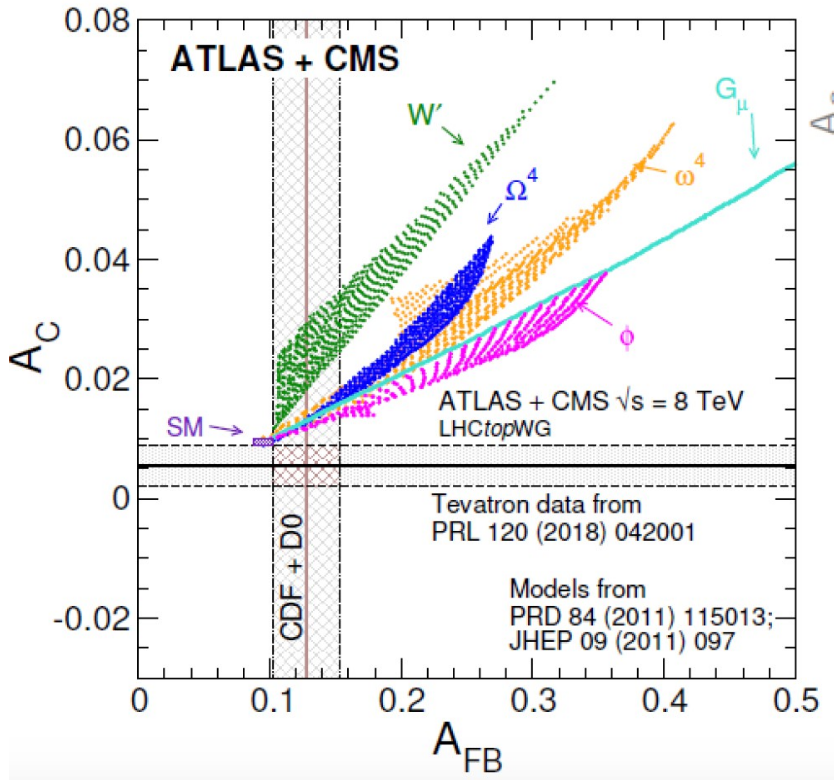
Caveat: Refer to LHC EFT forums for more comprehensive information

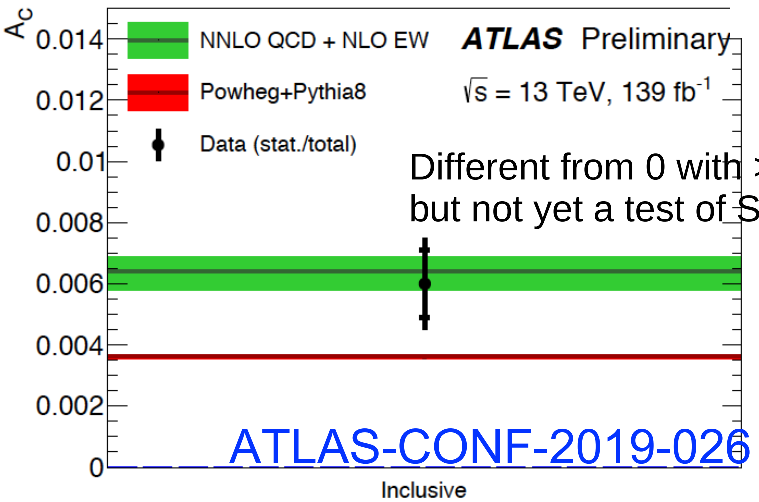
Top Quark Properties...

- Production asymmetry due to NLO interferences









Different from 0 with > 4 SD,
but not yet a test of SM

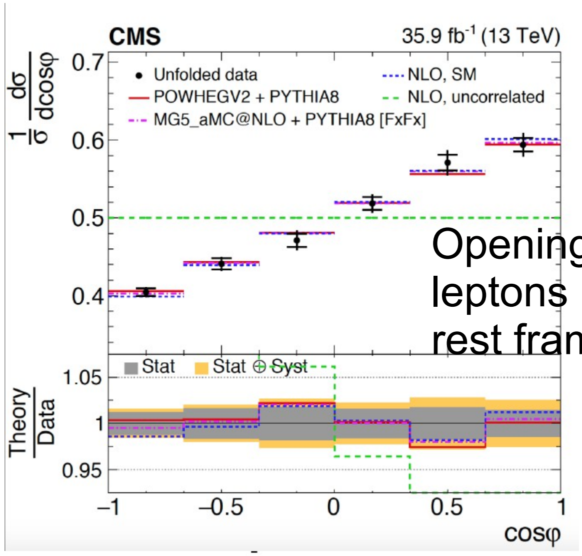
ATLAS-CONF-2019-026

→ ATLAS measures A_C not 0 with 4SD
→ Measurements of A_C difficult, new channels help
→ CMS 1st measurement of A_{FB} at LHC
→ **SM measurement relies on HL-LHC data set**

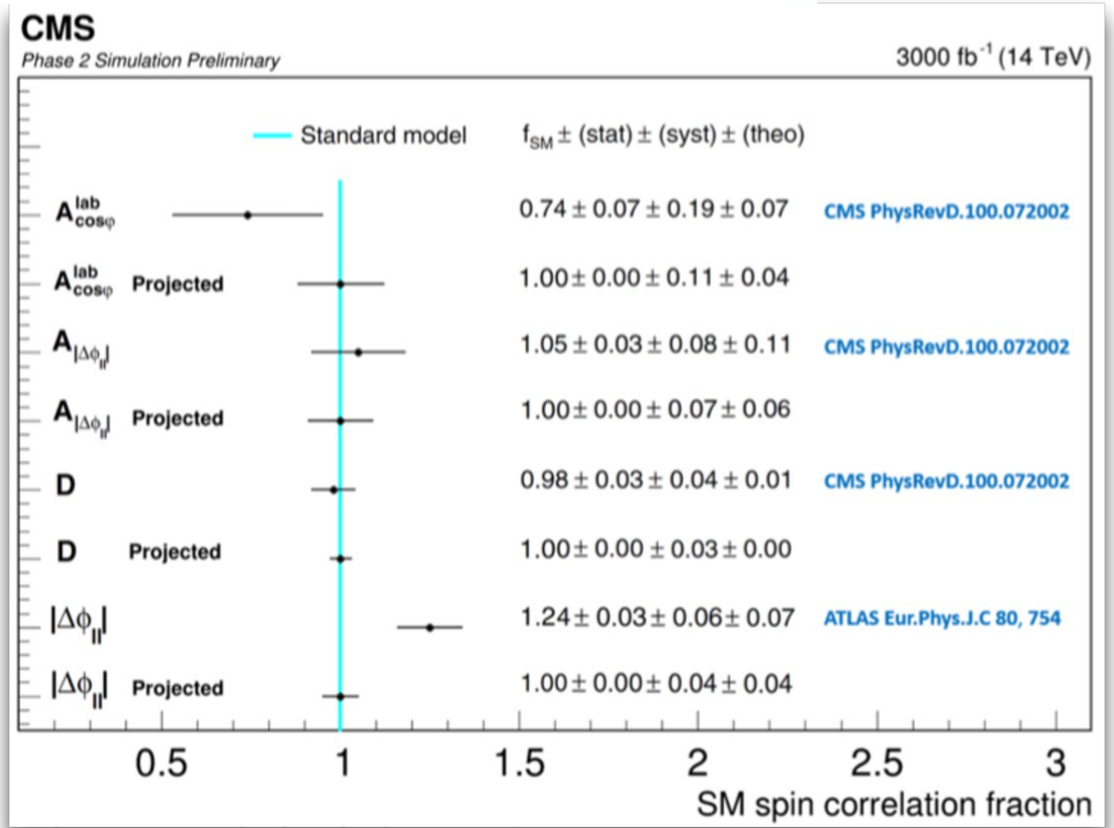
Using top quark properties

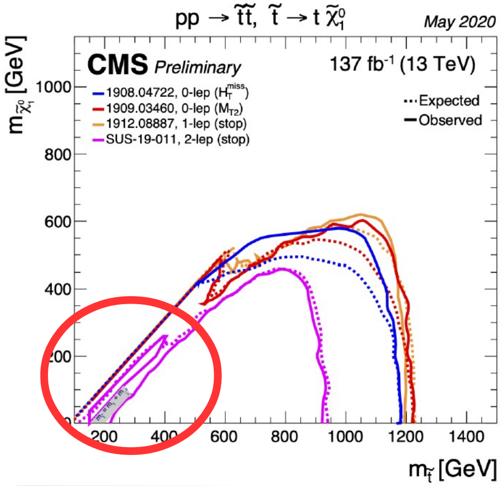
Double diff. xsec — **Polarisation (0 in SM)** — **Spin Correlation**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a\, d\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b)\cos\theta_+^a \cos\theta_-^b)$$



Opening angle between leptons in top parent rest frame

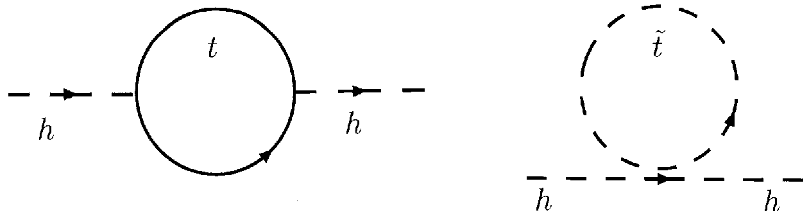


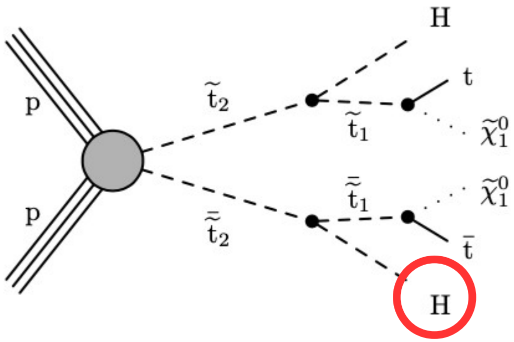


- Assumes better control of theory and exp uncertainties
- Contributed to Snowmass [CMS-PAS-FTR-18-034]

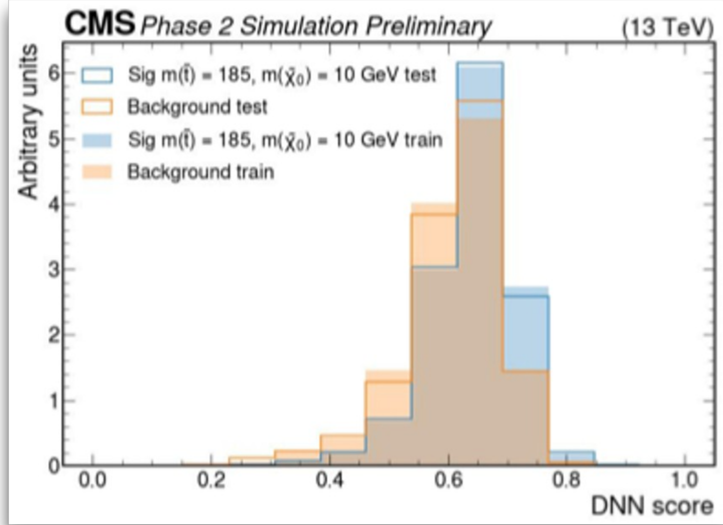
Using top quark properties

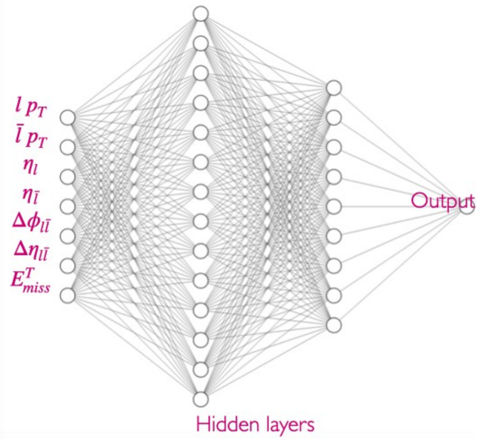
Reminder: Solve the hierarchy problem
→ need a top quark partner



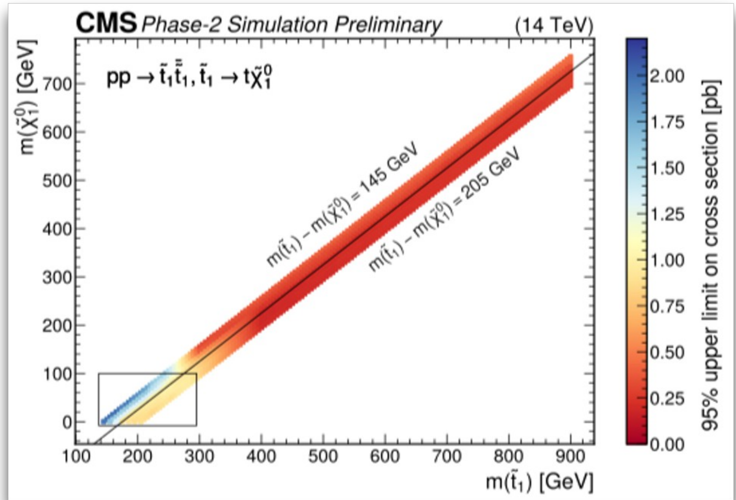


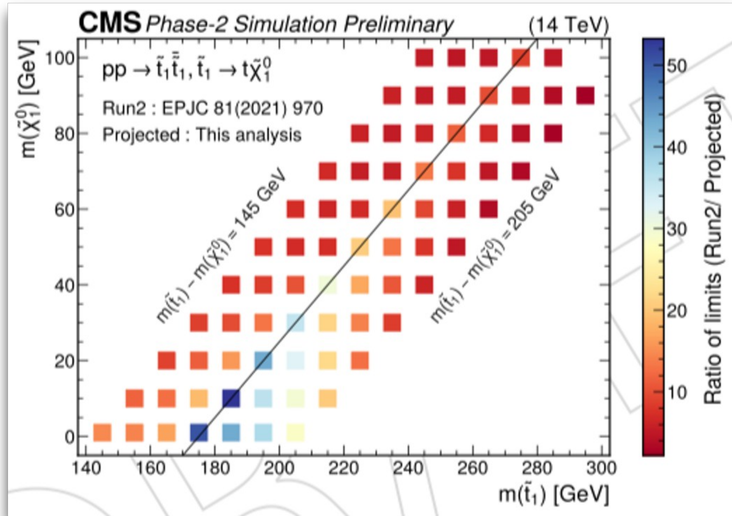
Signal to bg separation at 185 GeV





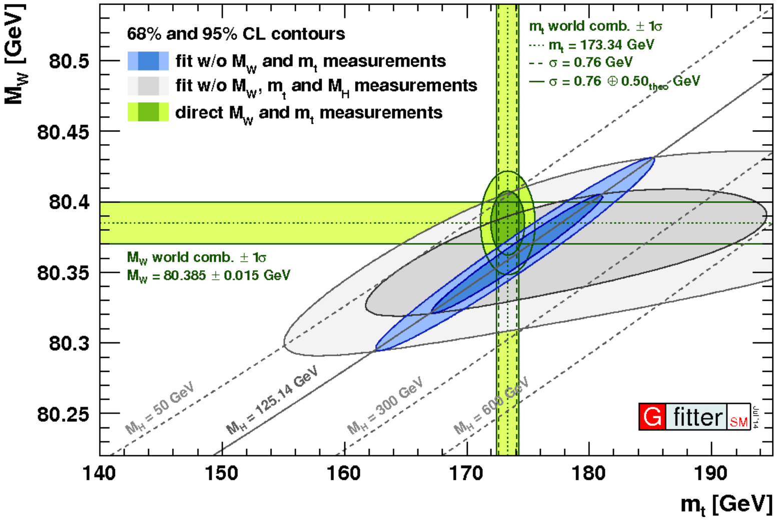
Employ Machine learning to construct a more powerful discriminant based on top quark properties



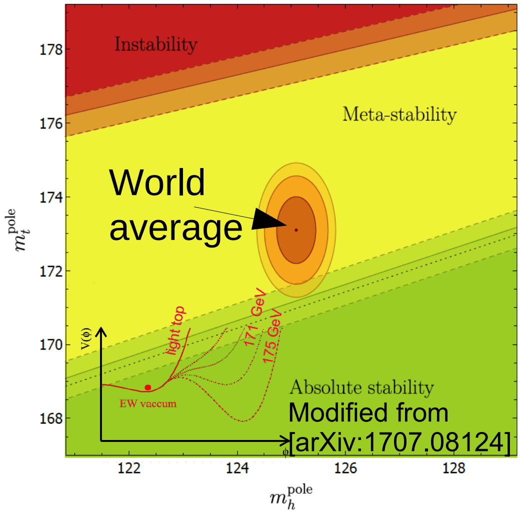


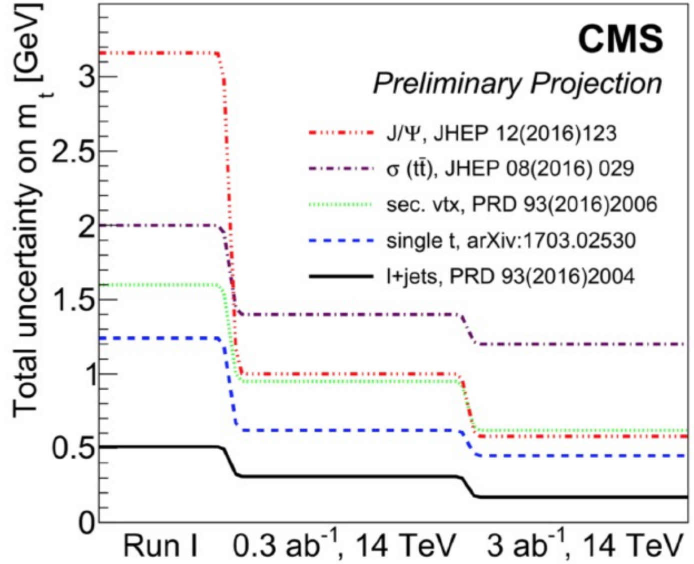
Significantly better sensitivity, excellent prospects for applications of top properties at HL-LHC

Latest weighing...



EW vacuum stability





Beyond projections already (as usual), e.g. triple differential cross sections

- Self-consistency test of the SM & stability of the EW vacuum both rely/use pole mass – what we measure depends on the method
  - Indirect extractions → top quark pole mass
  - Direct methods → "MC" mass, close to pole mass
- Precise top mass from cross sections (CMS) or leptonic variables (ATLAS): [arXiv:1904.05237] [ATLAS-CONF-2019-046]
  - → both at the level of 0.5%
  - → Limited by B-hadron & Color reconnection
  - → Exciting activities by theory community (parton showers, b jets/modeling)

Top mass – direct methods

- Direct measurements combined using BLUE – consistent among methods/channels
- CMS & ATLAS reach $\delta m_t/m_t$ = 0.28%

- CMS: Profile Likelihood

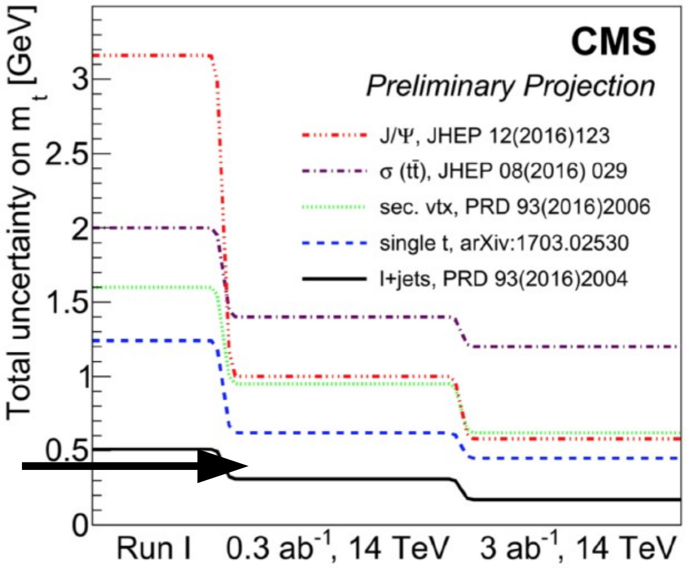
[CMS-PAS-TOP-20-008]

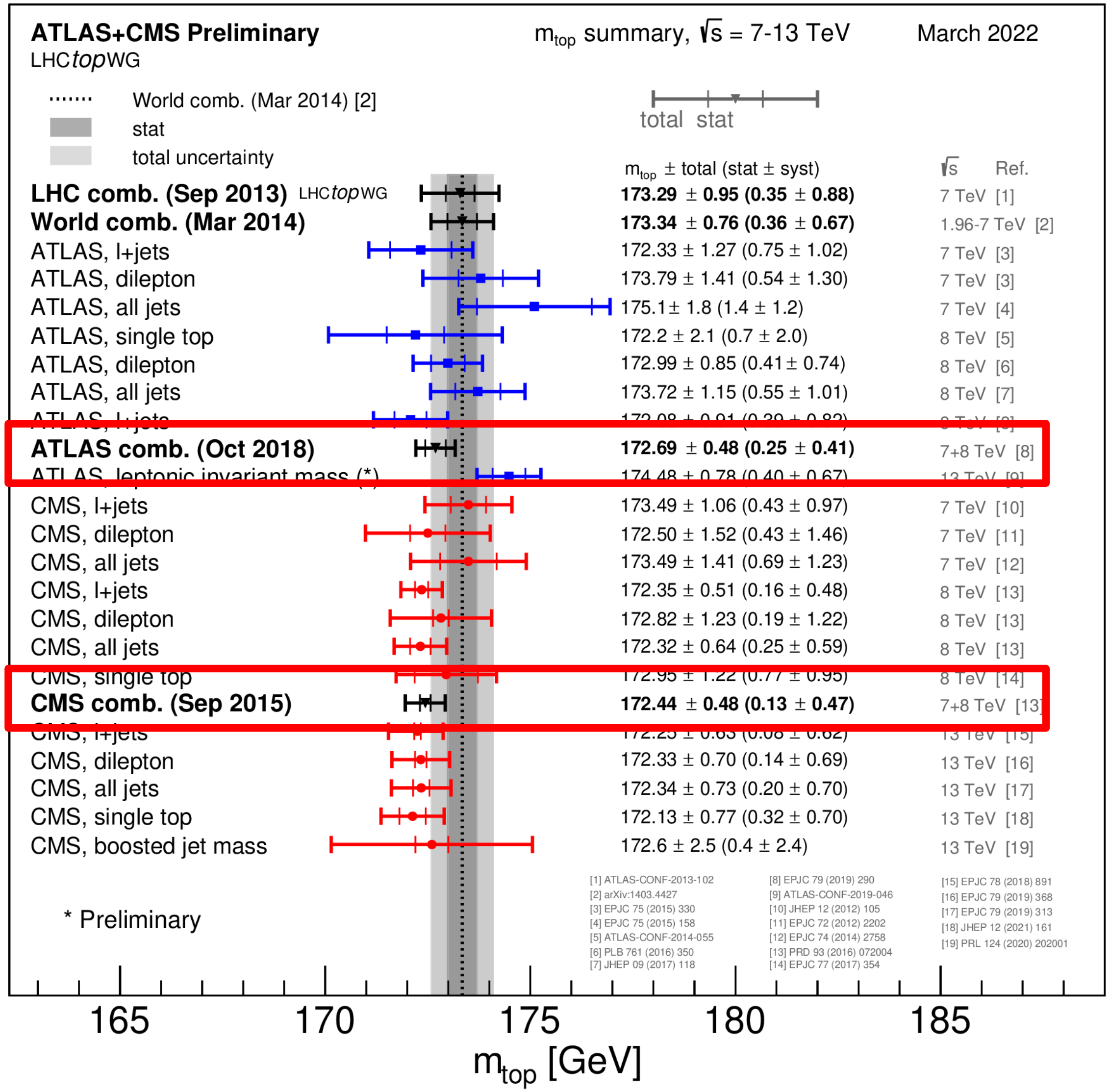
NEW

m_{top} = 171.77 ± 0.38 GeV

$\delta m_t/m_t$ = 0.22% (!)

Current most precise single measurement by CMS

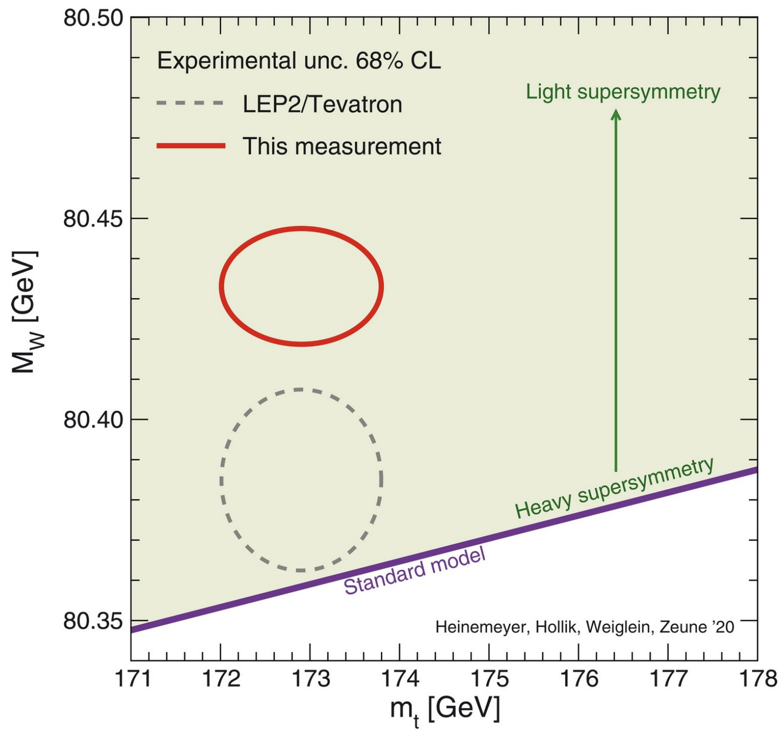




- Expect another drop at HL-LHC
  - Tremendous amount of work

Beyond the SM ?

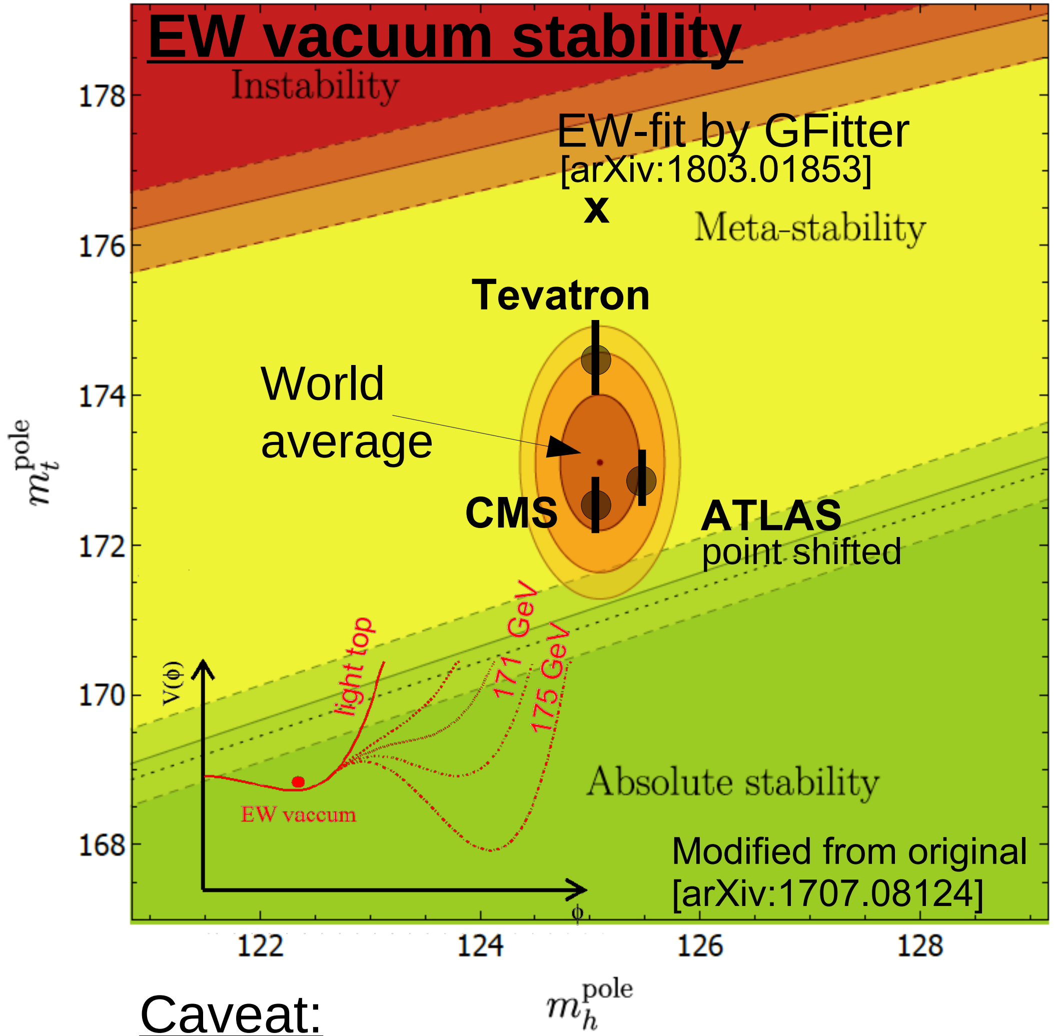
- Very subjective but illustrative, latest results from LHC & Tevatron – SM true
- Latest from Tevatron (CDF): [Science, Vol 376, No 6589]



- Direct mass ↔ indirect mass
- Bias from a top partner ?
- top kinematics, spin corr's show deviations...

HL-LHC (& Run 3) will provide answers

GFitter: $m_t = 176.4 \pm 2.1$ GeV

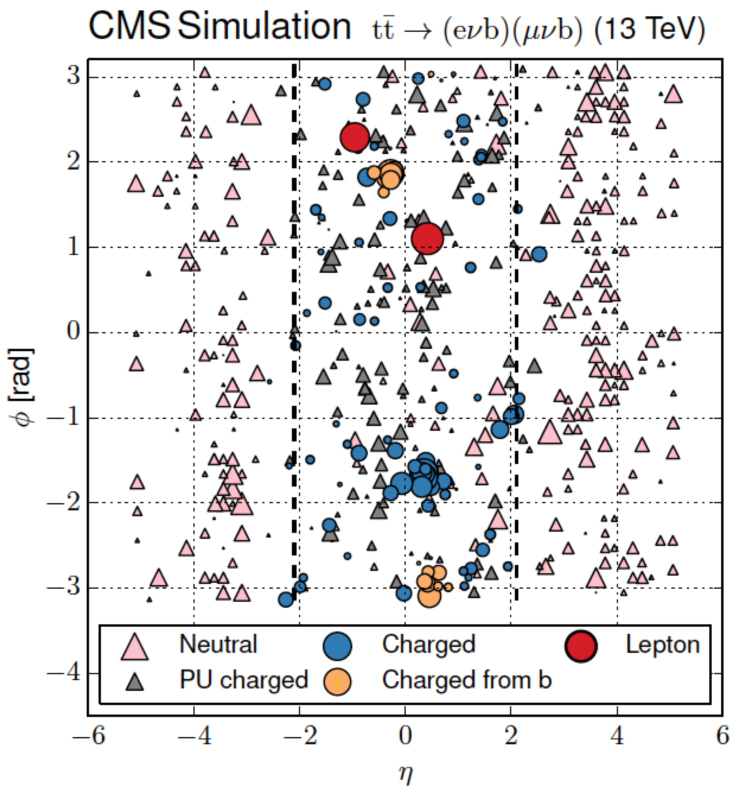


Caveat:

- New physics changes the vacuum stability, even if at Planck scale
- Theoretical uncertainties apply!

Modeling & Tuning

- Enormous amount of parameters to compare
- Modeling of ttbar system is the **limiting uncertainty**



ATLAS Pythia8 A14 tunes @ 8TeV

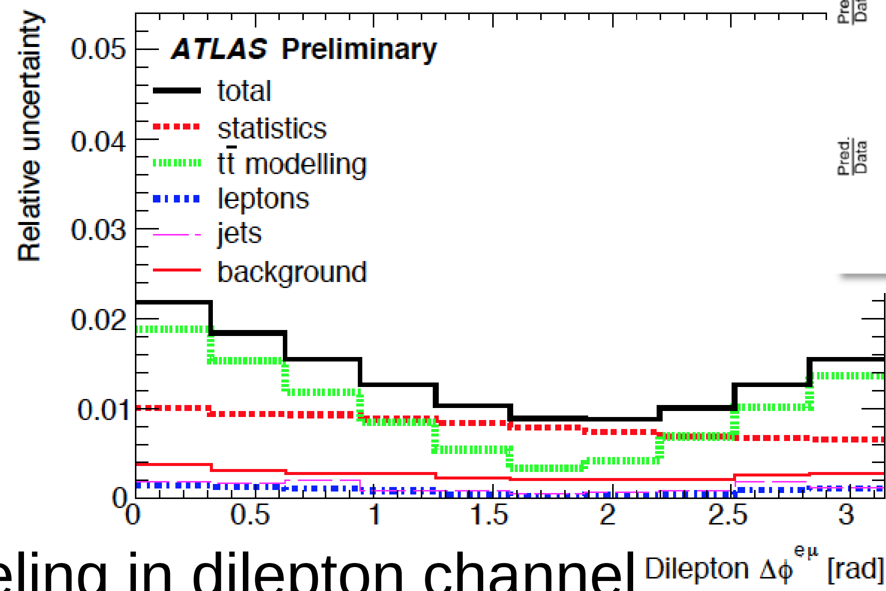
Parameter	Definition	Sampling range
SigmaProcess:alphaSvalue	The α_S value at scale $Q^2 = M_Z^2$	0.12 – 0.15
SpaceShower:pT0Ref	ISR p_T cutoff	0.75 – 2.5
SpaceShower:pTmaxFudge	Mult. factor on max ISR evolution scale	0.5 – 1.5
SpaceShower:pTdampFudge	Factorisation/renorm scale damping	1.0 – 1.5
SpaceShower:alphaSvalue	ISR α_S	0.10 – 0.15
TimeShower:alphaSvalue	FSR α_S	0.10 – 0.15
BeamRemnants:primordialKThard	Hard interaction primordial $k_\perp$	1.5 – 2.0
MultipartonInteractions:pT0Ref	MPI p_T cutoff	1.5 – 3.0
MultipartonInteractions:alphaSvalue	MPI α_S	0.10 – 0.15
BeamRemnants:reconnectRange	CR strength	1.0 – 10.0

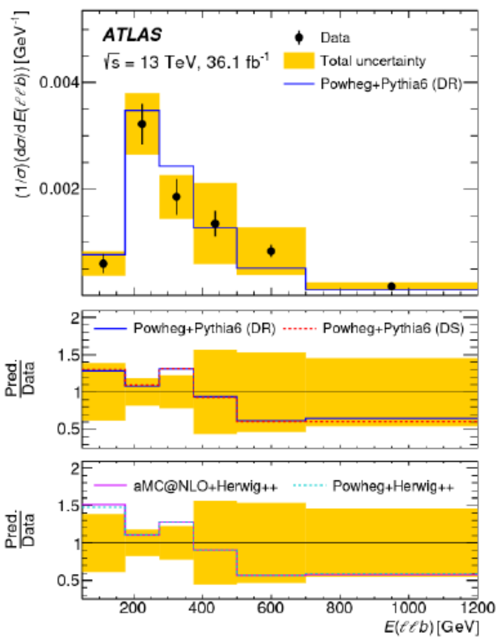
CTEQ, MSTW, NNPDF, HERA LO PDF sets
Extrac
Fitting

CMS Pythia8 CP tunes @ 13 TeV

Parameter description	Name in PYTHIA8	Range cor
MPI threshold [GeV], pT0Ref, at $\sqrt{s} = \sqrt{s_0}$	MultipartonInteractions:pT0Ref	1.0–
Exponent of $\sqrt{s}$ dependence, ϵ	MultipartonInteractions:ecmPow	0.0–
Matter fraction contained in the core	MultipartonInteractions:coreFraction	0.1–
Radius of the core	MultipartonInteractions:coreRadius	0.1–
Range of color reconnection probability	ColorReconnection:range	1.0–

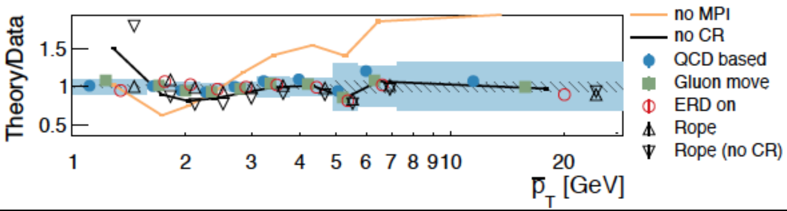
NNPDF3.1 LO/NLO/NNLO PDF sets and α_s for ME an shower as inputs
Extracted by varying 5 parameters
Fitting UE observables at 1.96, 7 & 13 TeV, min bias





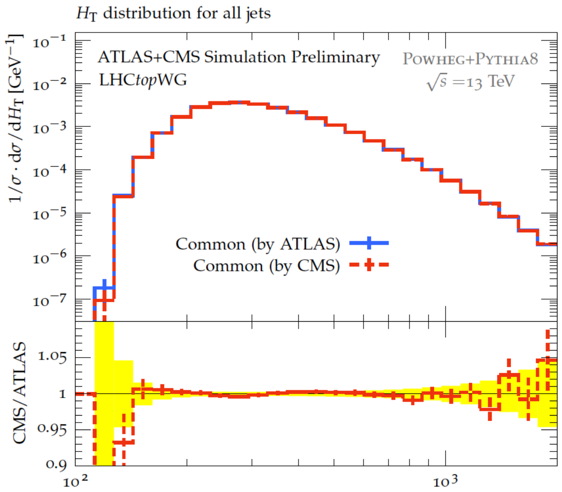
- tW unfolded spectra: More data events at higher scales compared to models ?
- ttX spectra are often limited by modeling unc.

- 1st measurement of UE modeling in dilepton channel
  - MPI effects visible, **CR not quite yet**

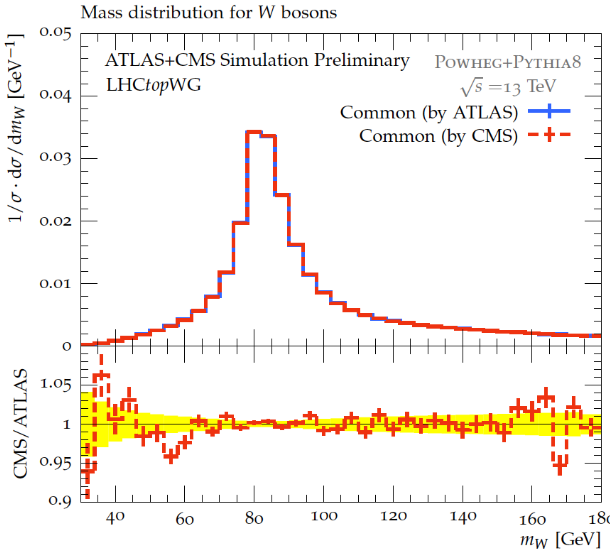


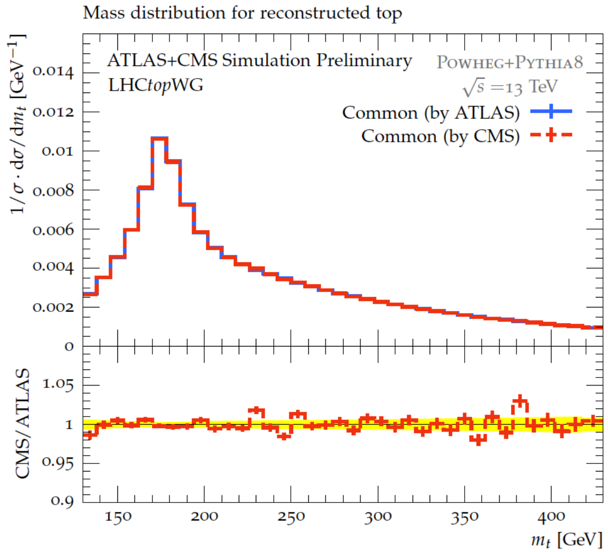
Enormous wealth of data available for studies
- Are we squeezing out all information ?

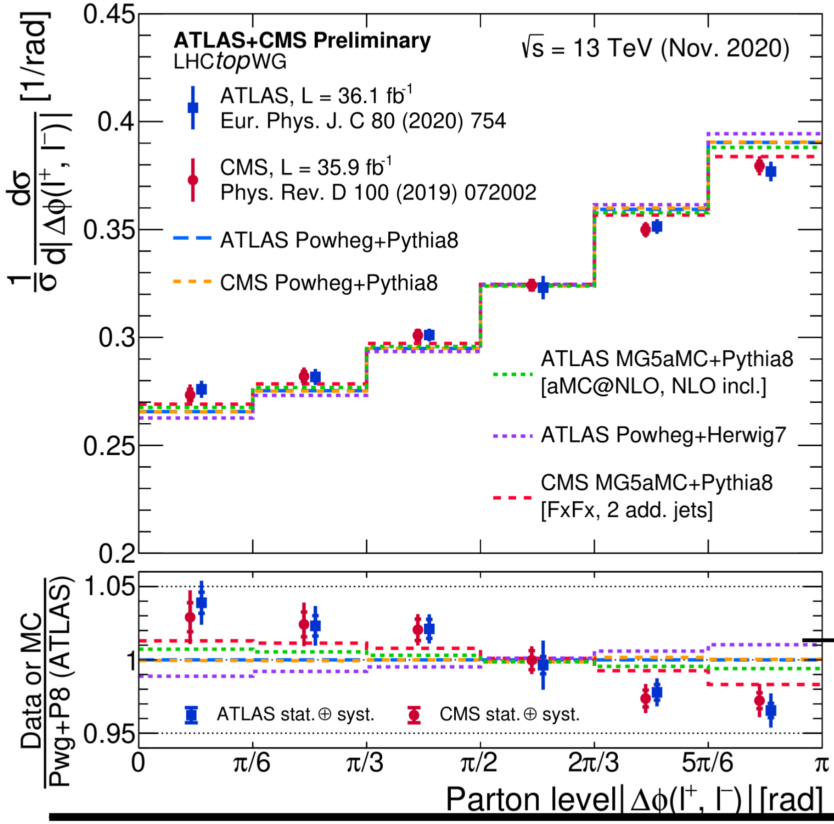
Tools, Common MC, etc.



- Complex issue of different setups in ATLAS & CMS





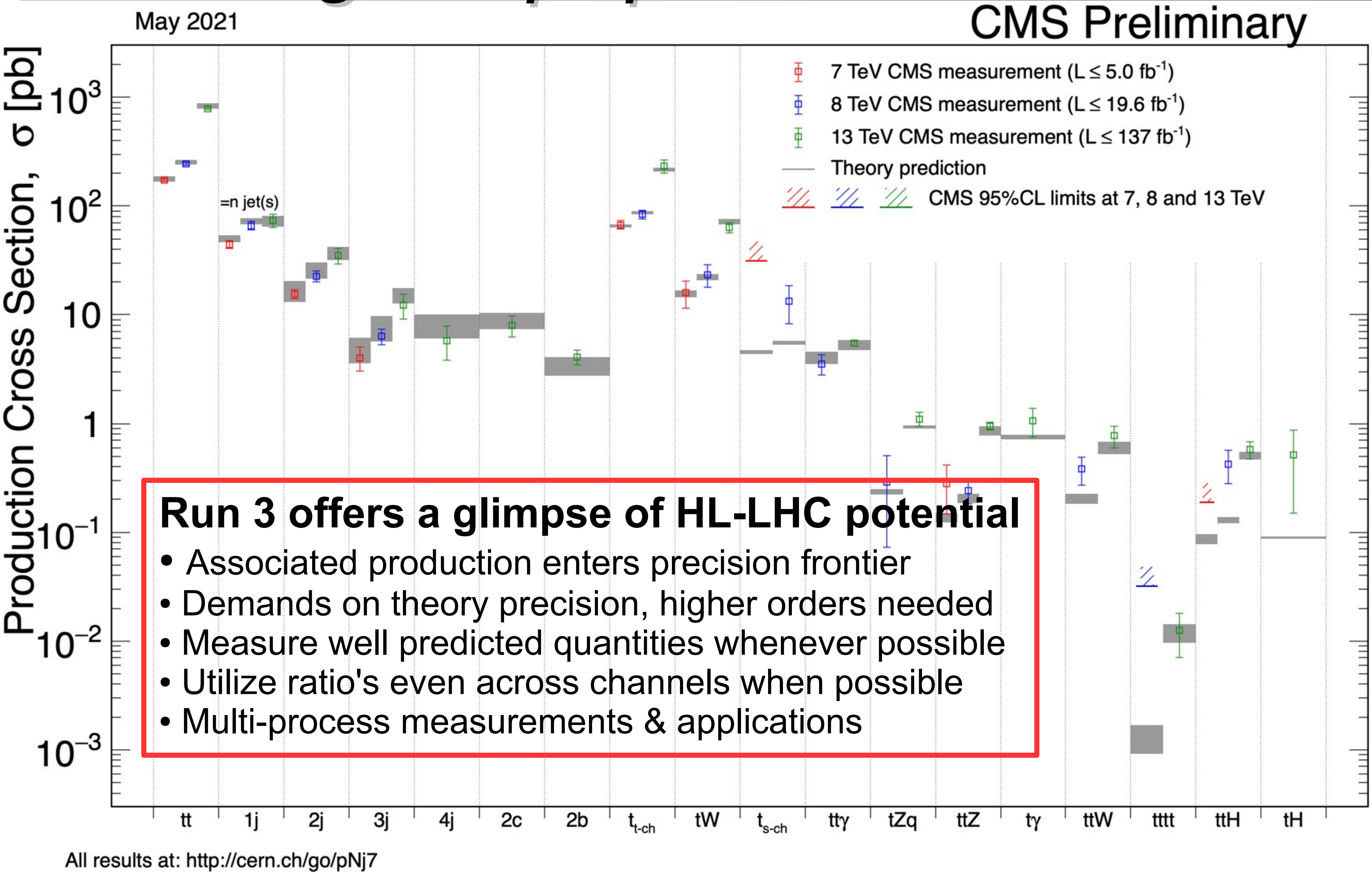


- Facilitate future combinations, studies on systematic uncertainties, etc.
- Vital and critical for success of Run 3 (and beyond)
- Many details, please check:

[LHCtopWG: Common samples]

Towards common MC settings in ATLAS & CMS:
ATL-PHYS-PUB-2021-016 & CMS NOTE-2021/005

A bright top quark future ahead



Run 3 offers a glimpse of HL-LHC potential

- Associated production enters precision frontier
- Demands on theory precision, higher orders needed
- Measure well predicted quantities whenever possible
- Utilize ratio's even across channels when possible
- Multi-process measurements & applications

Conclusions

- Next year(s) will show what ~150 million $t\bar{t}$ events tell us
  - Precision frontier of top quark physics

→ Run 3: Center of mass energy + more tops to come

Exciting times! Only seen 5% of the LHC data

→ Allows for multi-dimensional measurements of σ, α_S, PDFs and any properties, associated production as well

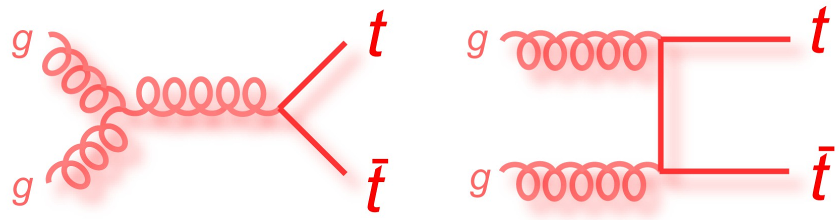
Need all avenues to pin down BSM, challenges ahead:
→ Theory uncertainties, Parton showers, common MC samples
→ More global approaches (kinematic distributions, EFT)
→ Use vast top sample as b-physics lab
→ Close collaborative effort to discuss progress and needs, LHCtopWG highly useful too

Backup...

The top quark

- Top is the heaviest fundamental particle discovered so far
  → m_t = 173.34 ± 0.76 GeV [arxiv:1403.4427]

- Production dominated by gg fusion:



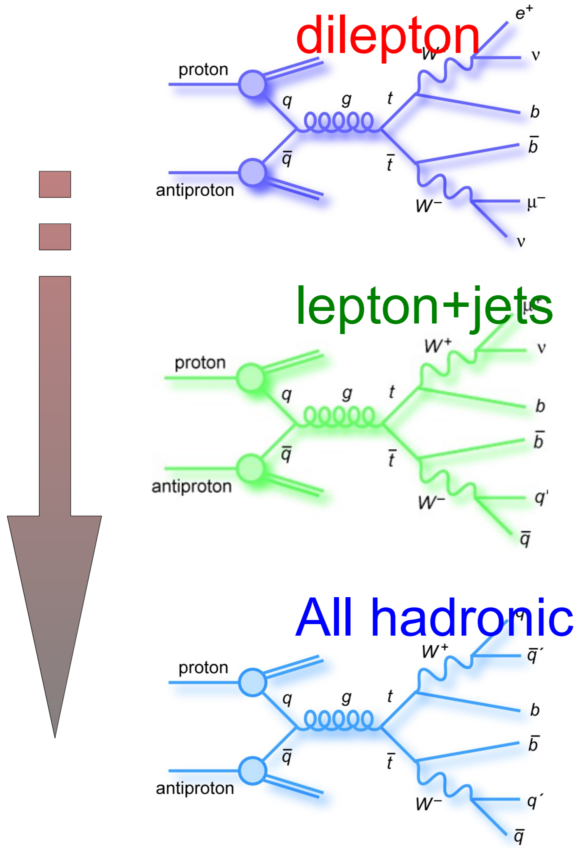
- Unique quark:

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

  → **Observe bare quark properties**

- Decay channels:

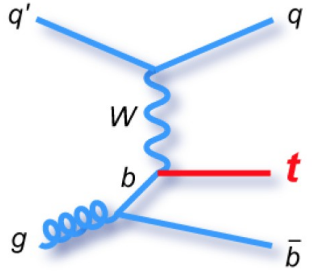
BR, bg increase



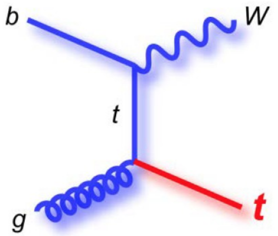
- Large Yukawa coupling to Higgs boson
  → λ_t ~ 1 **only m_t is natural mass**
  Special role in EW symmetry breaking ?

Single Top Quark Production

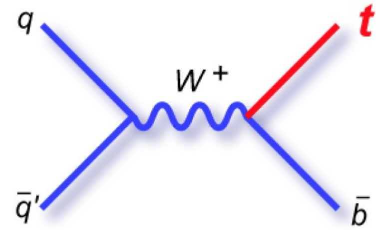
- **Single top cross section as high as $t\bar{t}$ at 8 TeV – large samples**
- Single top production: Test of EW interactions



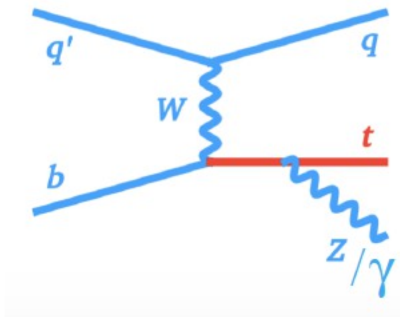
t-channel



tW-channel

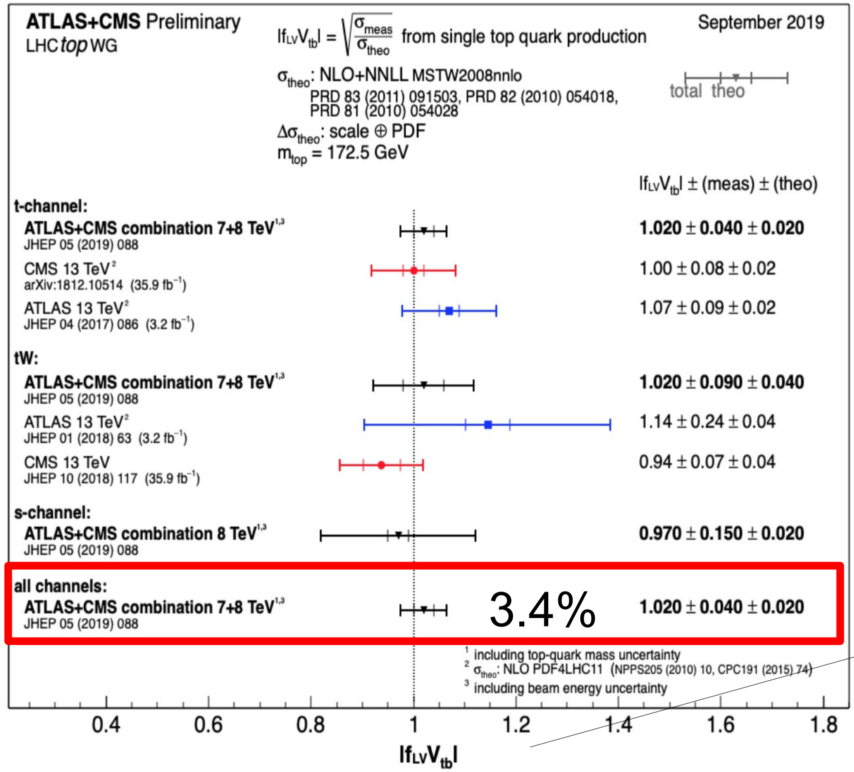


s-channel



tZ/γq-channel (rare process, < 1 pb)

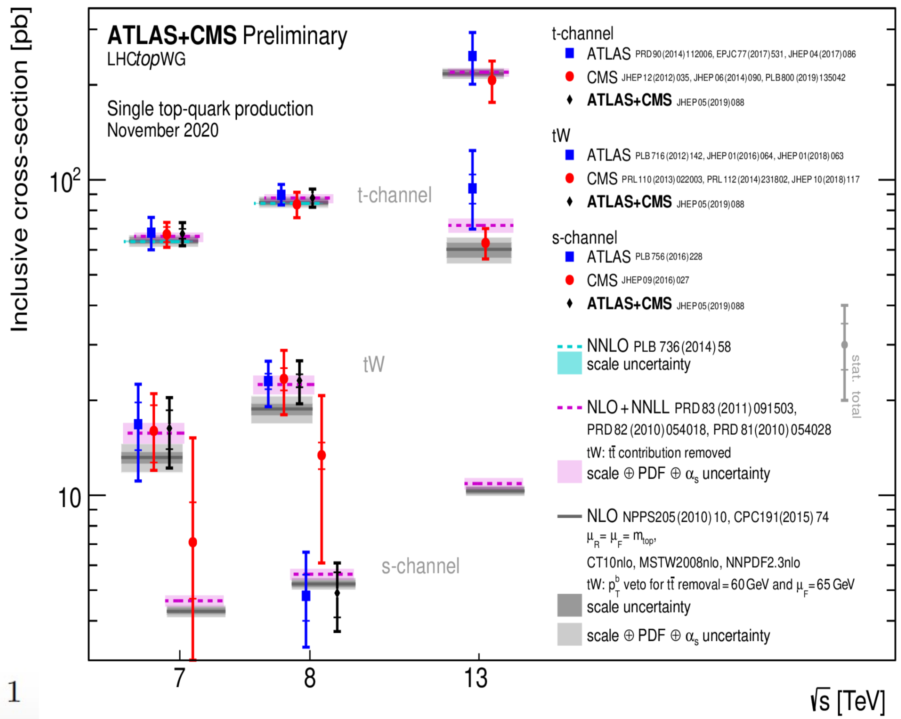
$$\cos\theta^{*}_{pol} = \frac{\vec{p}^{*}_{q'} \cdot \vec{p}^{*}_{\ell}}{|\vec{p}^{*}_{q'}||\vec{p}^{*}_{\ell}|}$$



$$|V_{tb} \cdot f_{LV}|^2 = \frac{\sigma^{obs}}{\sigma^{theory}}$$

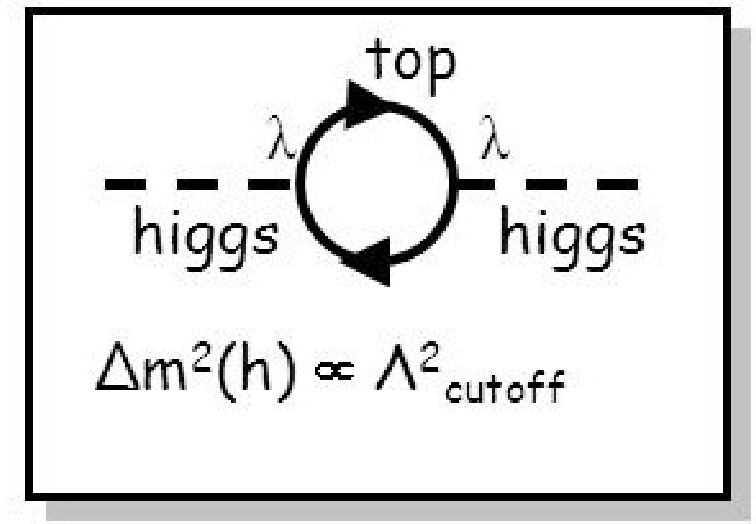
f_{LV}: BSM form factor

Consistent with $f_{LV} \cdot V_{tb} = 1$

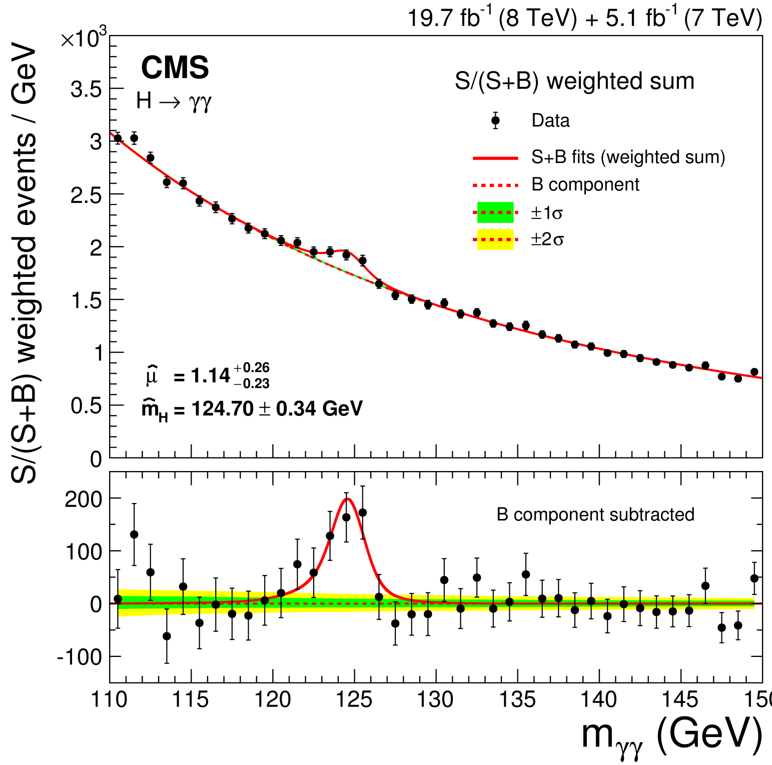


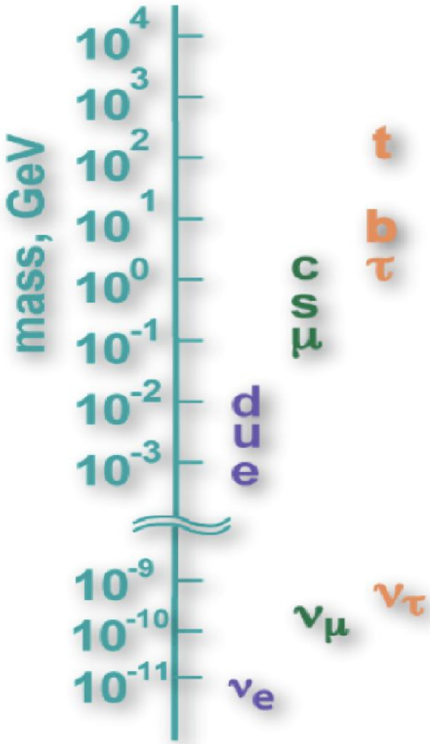
Why top (and Higgs) ?

- If we could calculate the Higgs mass:
  → Large corrections to the Higgs mass from top quark "loops"



Loops are dominated by top quarks





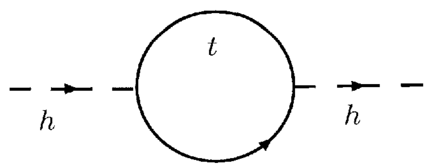
Natural Higgs mass close to Planck scale of 10^{19} GeV

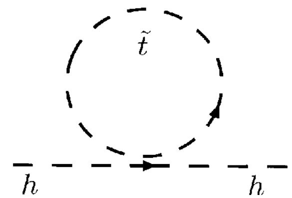
Higgs mass at ~ 125 GeV!

→ New physics in loops ?

→ Many BSM extensions include a **top quark partner**

→ No fine-tuning if top quark partner exists



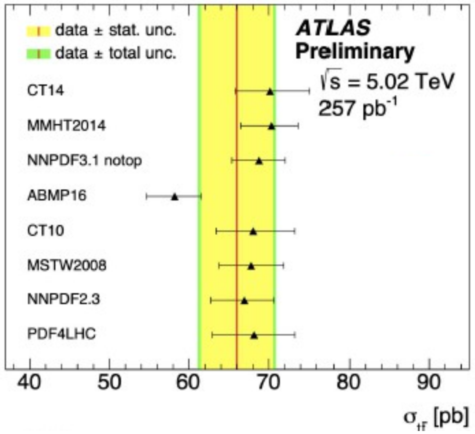


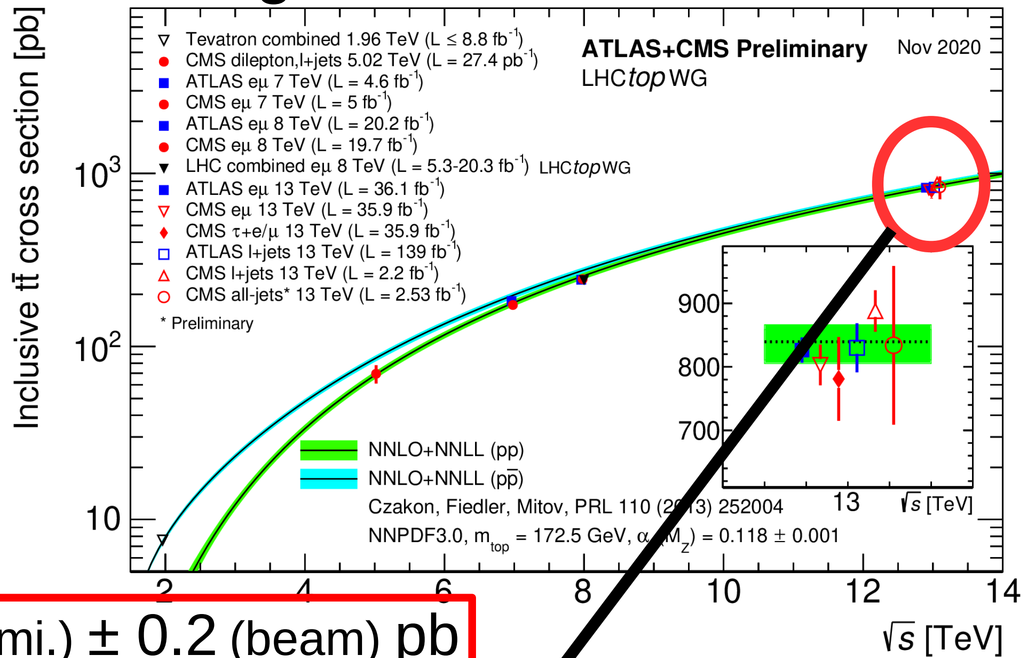
Inclusive cross sections

- Measurements cover 2, 5, 8 and 13 TeV – agreement with the SM

ATLAS & CMS cross section at 5.02 TeV

[CMS-PAS-TOP-20-004] [ATLAS-CONF-2021-003]





σ = 66.0 ± 4.5 (stat.) ± 1.6 (syst.) ± 1.2 (lumi.) ± 0.2 (beam) pb

δσ/σ= 7.5% [ATLAS]

σ = 62.6 ± 4.1 (stat.) ± 3.0 (syst.+lumi.) pb

δσ/σ= 8.1% [CMS]

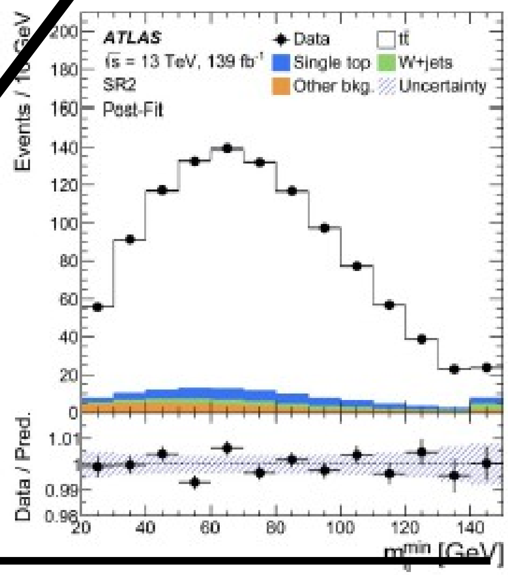
NEW

ATLAS cross section at 13 TeV
Full Run II data set

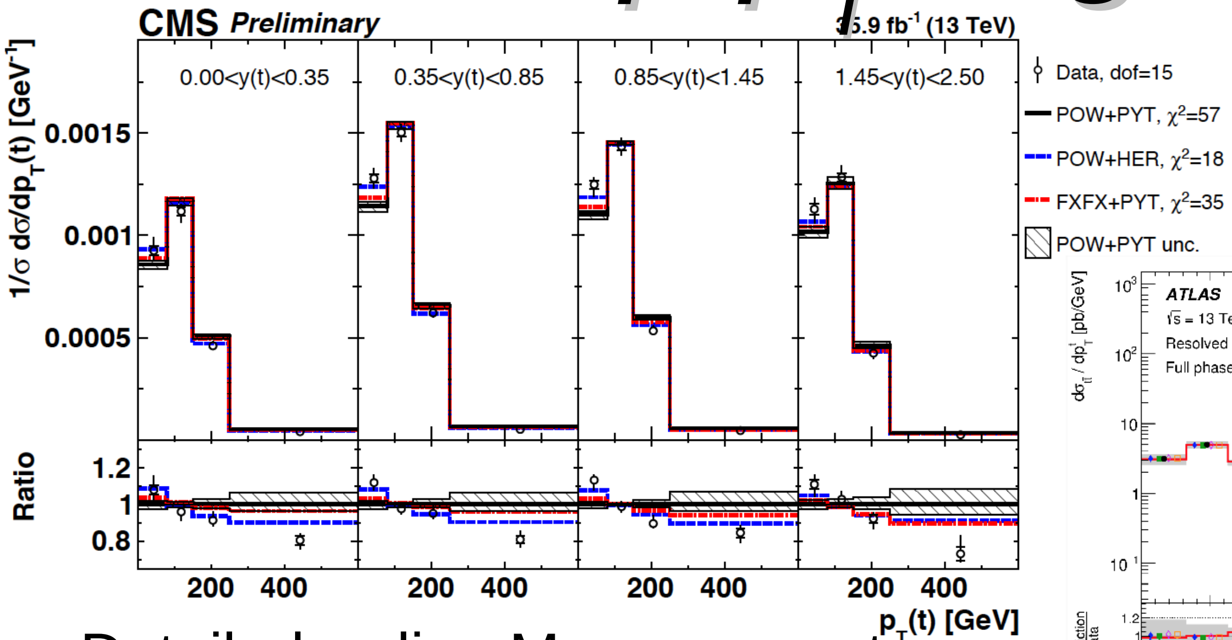
NEW

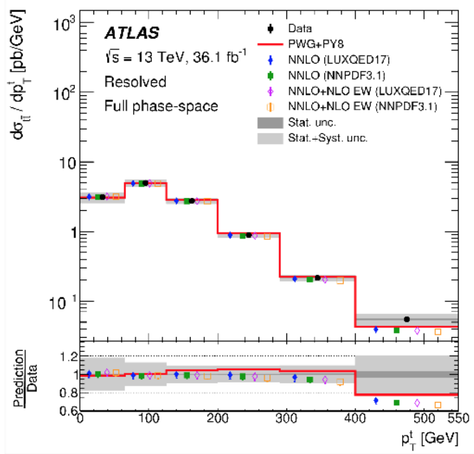
σ = 830 ± 0.4 (stat) ± 36 (syst) ± 14 (lumi) pb

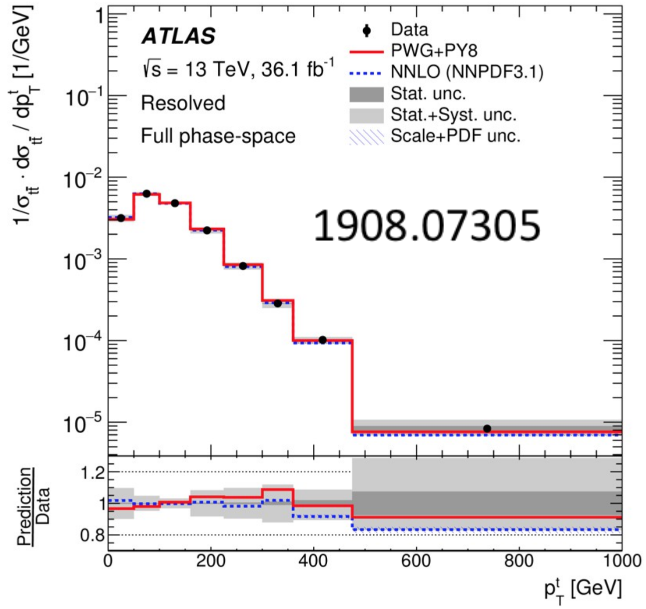
δσ/σ= 4.7% [PLB 810 (2020) 135797]



The top p_T saga...continues



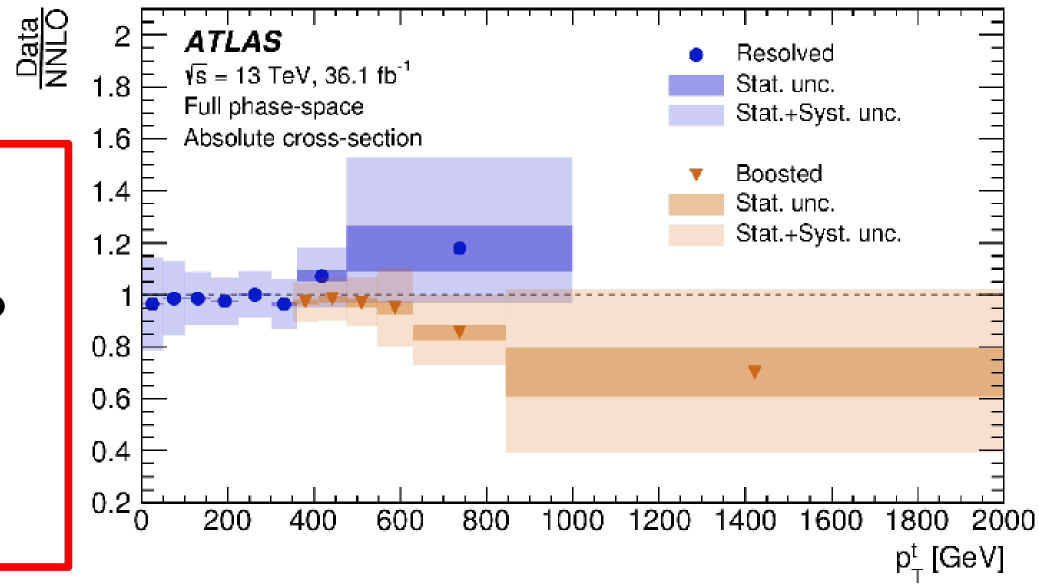




- Detailed *n*-dim. Measurements
- Common binning – study EW corrs.

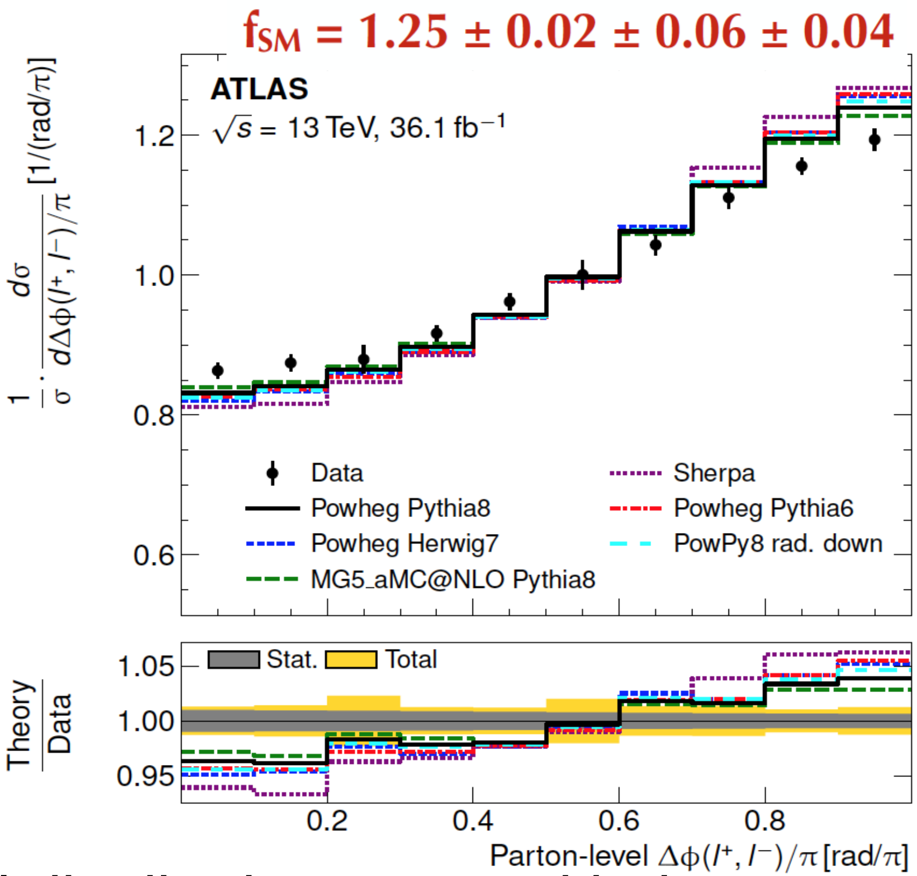
→

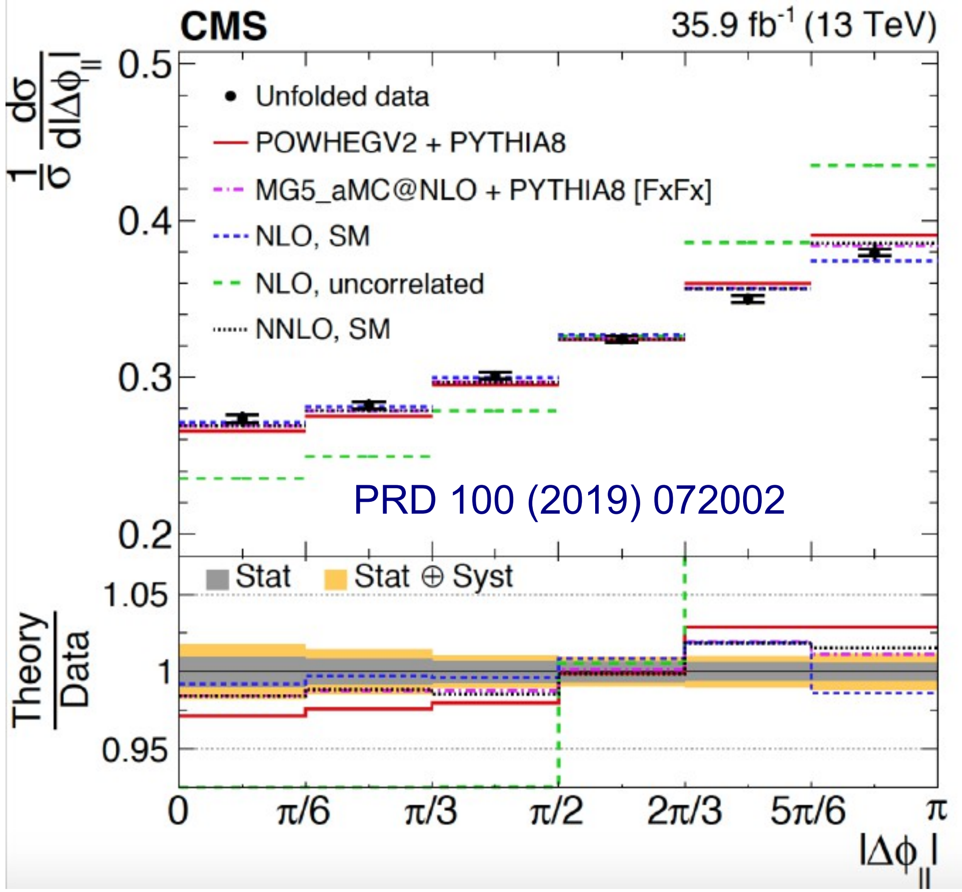
- Slopes in 13 TeV ATLAS & CMS data
- Large systematic uncertainty – further understanding, common procedure ?
  - Common MC clearly helps...
- Theory input: experiments are eager to use an “NNLO MC”



Spin Correlations

- Opening angle cosφ maximally sensitive to alignment of top quark spins
- **Most precise direct measurement** via cosφ ◄—— Opening angle between leptons in top parent rest frame: f_{SM} = 0.97±0.05
  - Systematic: p_T and BG modeling
- Indirect measurement via Δϕ shows about 1σ discrepancy to NLO (CMS)





- All distribution agree with the SM, no deviations observed

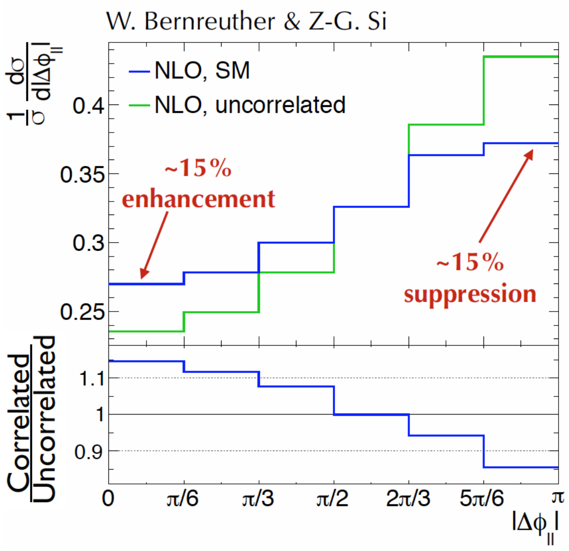
Spin Correlations

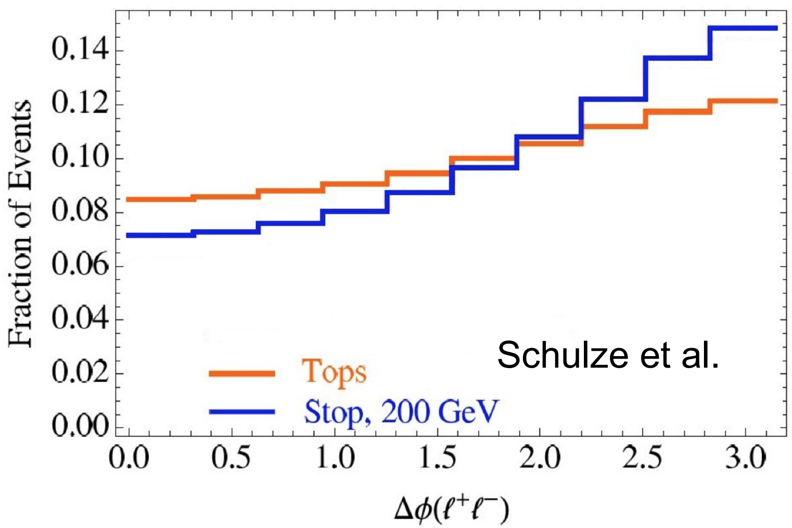
- Double-differential cross section allows to access spin correlation and polarization information in top quark events

Double diff. xsec — **Polarisation (0 in SM)** — **Spin Correlation**

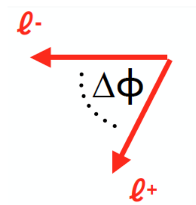
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a \, d\cos\theta_-^b} = \frac{1}{4}\left(1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b)\cos\theta_+^a \cos\theta_-^b\right)$$

- Charged lepton is perfect spin analyzer, well reconstructed
- Sensitive to BSM physics (more spin corr's = s-channel dark matter; less spin corr's = new scalars)

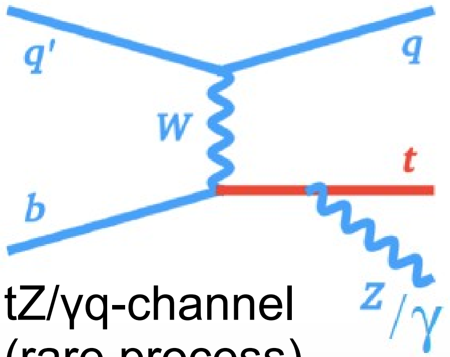




Angle between leptons in transverse plane

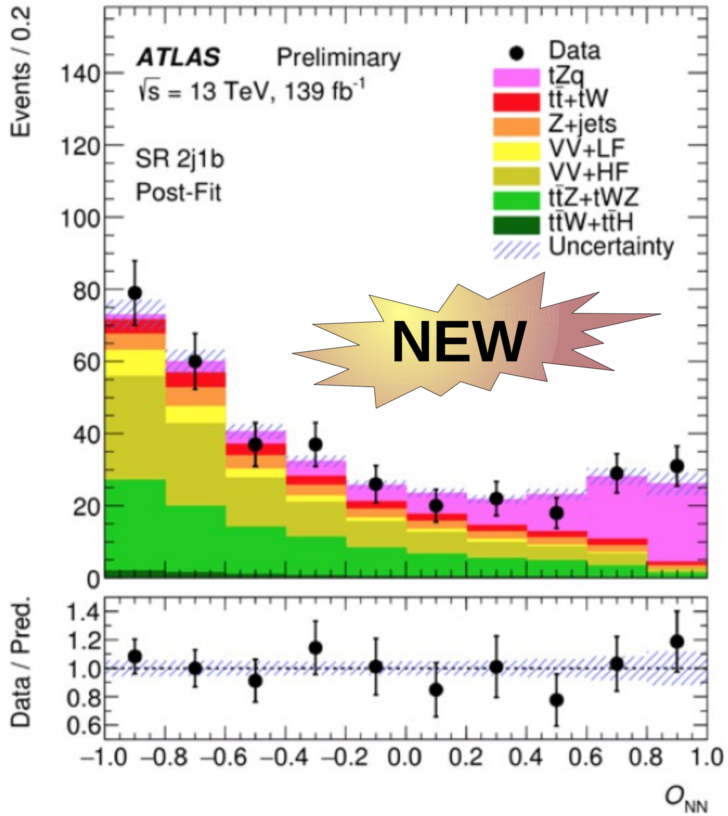


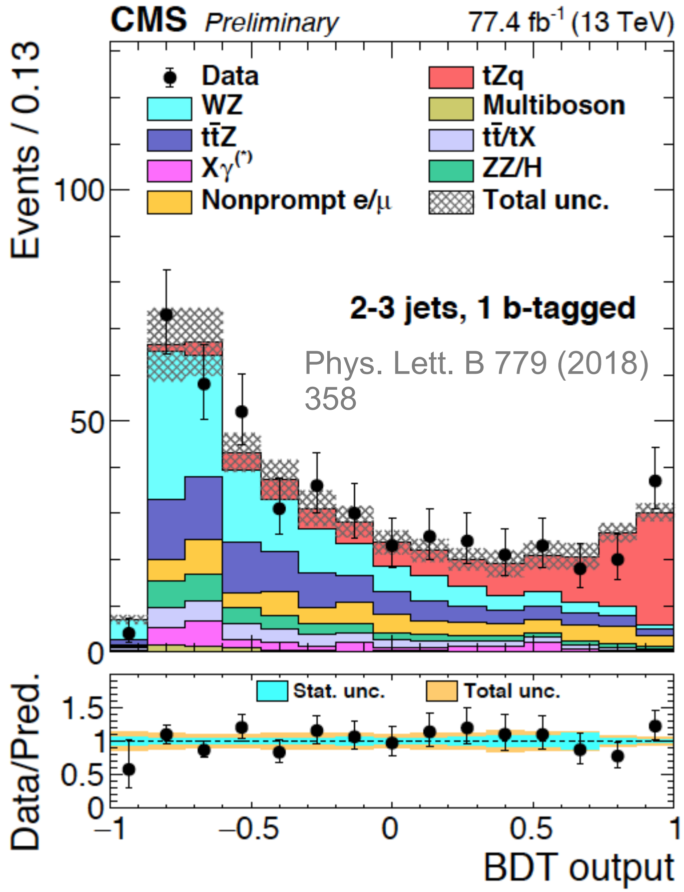
Rare single top quark



tZ/γq-channel
(rare process)

SM NLO prediction:
$\sigma = 94.2 \pm 3.1$ fb
Phys. Lett. B 779 (2018) 358





→ σ(tllq) = 98 ± 12 (stat) ± 8 (syst) pb, 9.2 SD
(SM: 102 +5-2 fb) ATLAS-CONF-2019-043

- **Heavy use of BDT** to enhance sensitivity – multiple signal regions
- ATLAS & CMS measurement of **tZq single top** production @13 TeV

→ σ = 111 ± 13 (stat) ± 10 (syst) pb PRL122(2019)132003
obs. (exp.) significance: 8.2 (7.7) SD

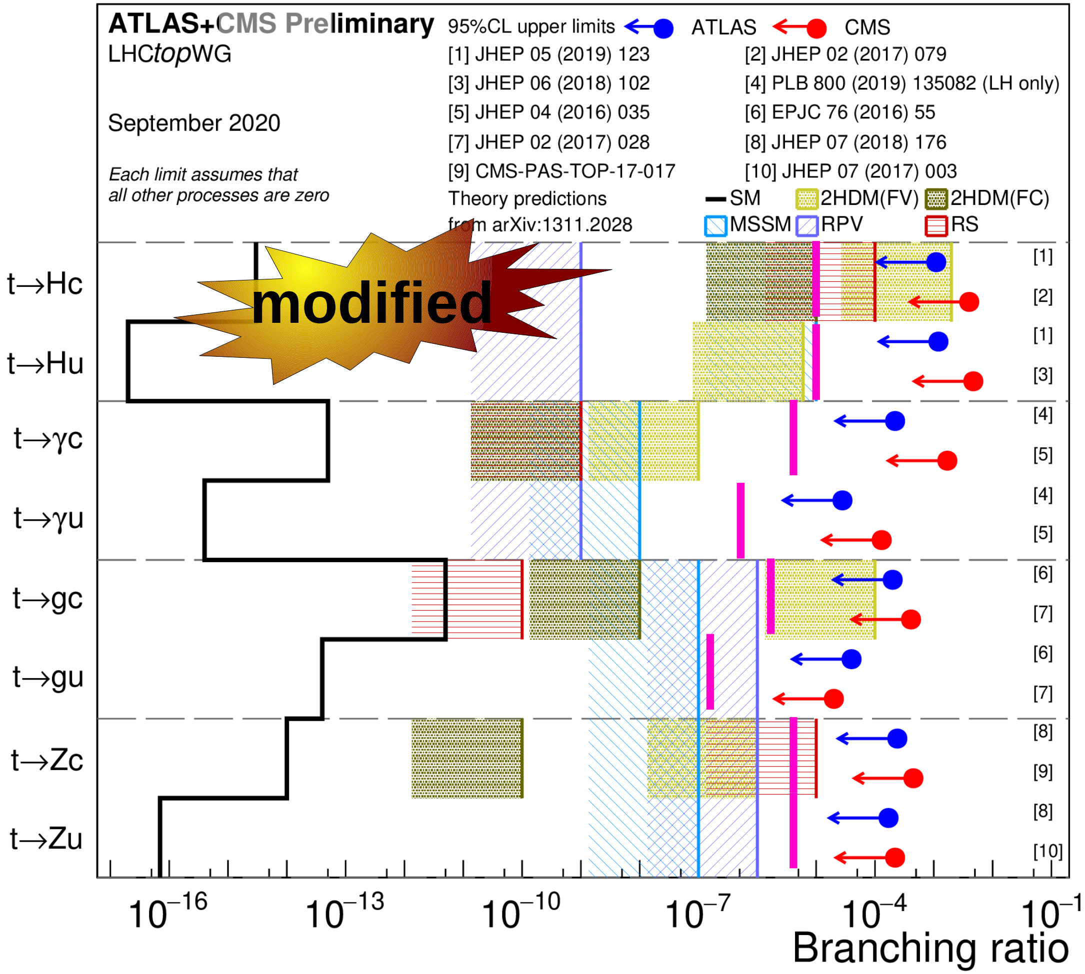
- Observation of tZq

Rare top quark decays – Prospects

Flavor-changing neutral currents (FCNCs)

Extrapolations to HL-LHC:
→ watch out for the bar: |

<u>Caveats:</u> Some are "inclusive"...and also, we tend to do (much) better than projections, so we can hope to challenge more of the potential SM extensions



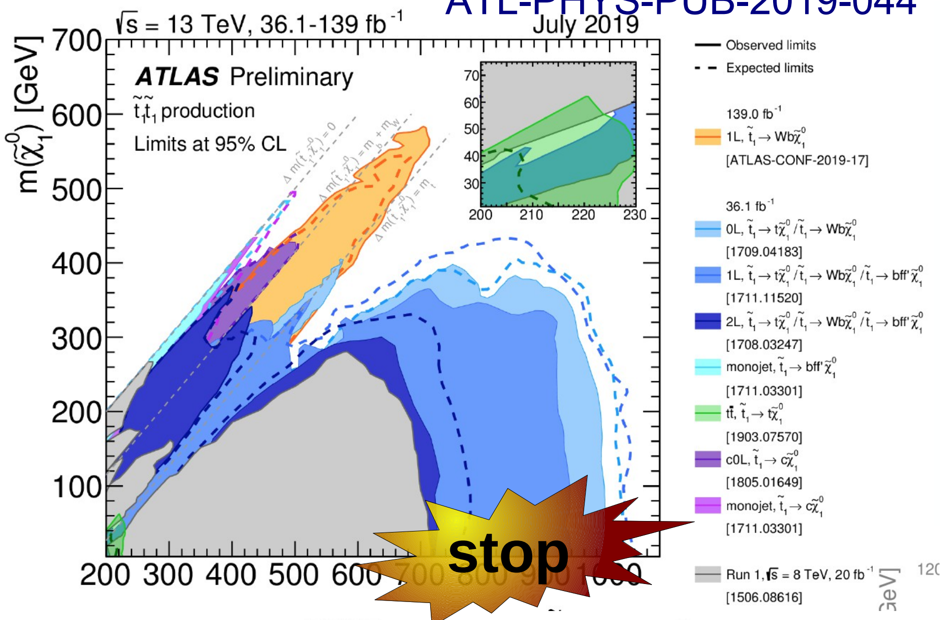
$t \to gu$	$t \to gc$	$t \to qZ$	$t \to \gamma u$	$t \to \gamma c$	$t \to Hq$
3.8×10^{-6}	3.2×10^{-5}	$2.4 - 5.8 \times 10^{-5}$	8.6×10^{-6}	7.4×10^{-5}	10^{-4}

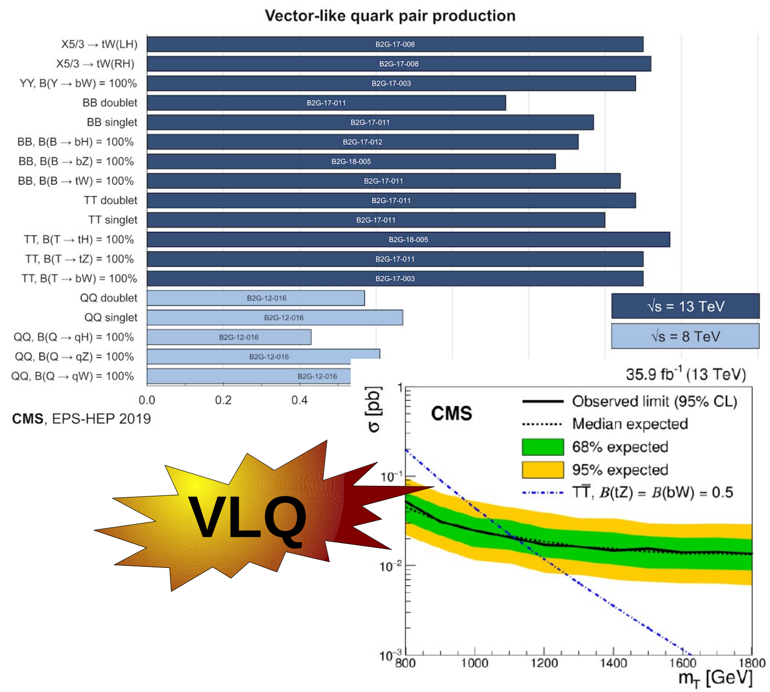
CERN-LPCC-2018-03

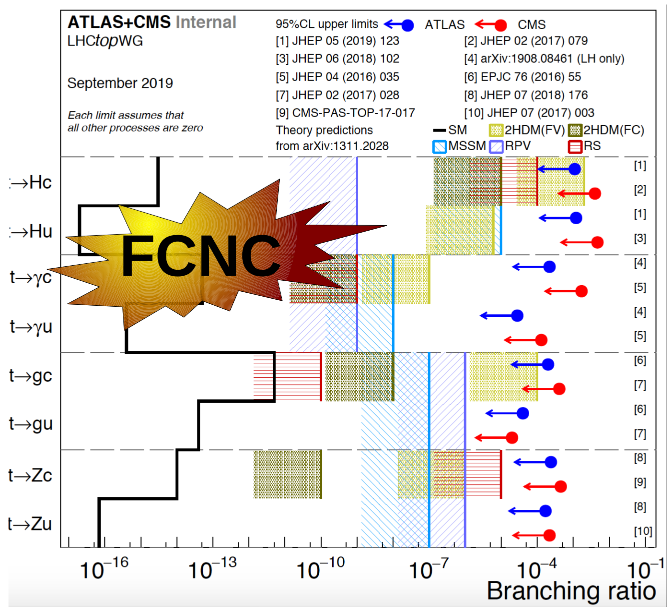
New friends for the top ?

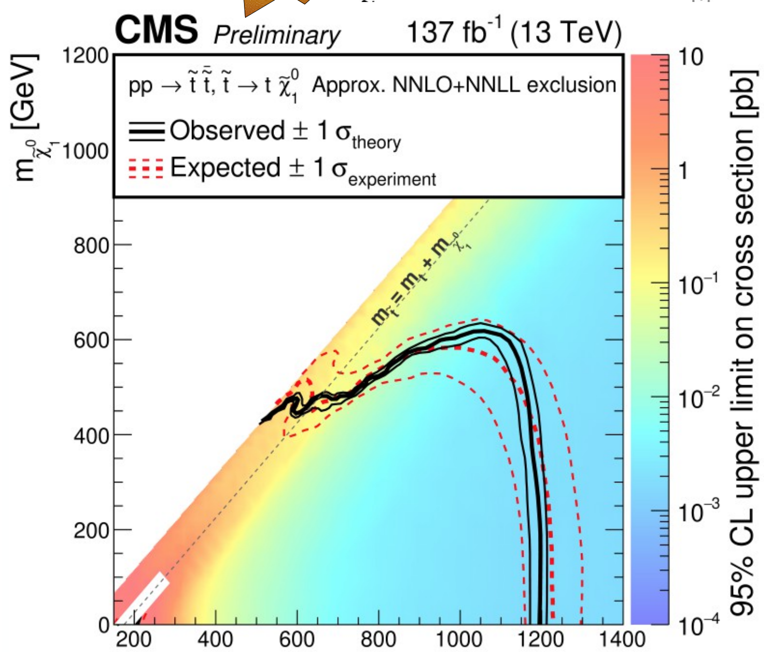
- “stealth” top region not yet fully excluded (mind BR of stop → top+neutralino)
- $t\bar{t}$ modeling uncertainties dominate searches
  - Danger of “over-tuning” ? Minimized by specific phase space / control regions
  - SM measurements biased by stealthy top quark partner ?

ATL-PHYS-PUB-2019-044





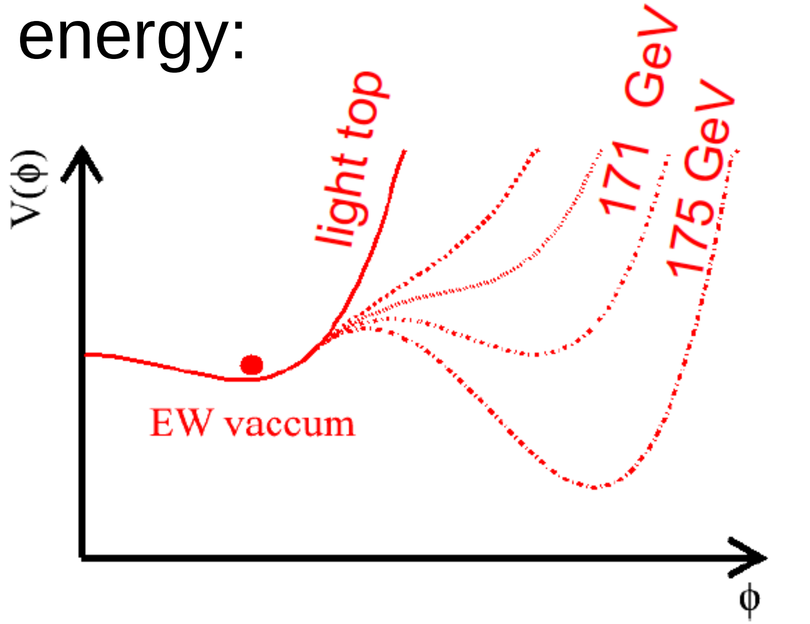


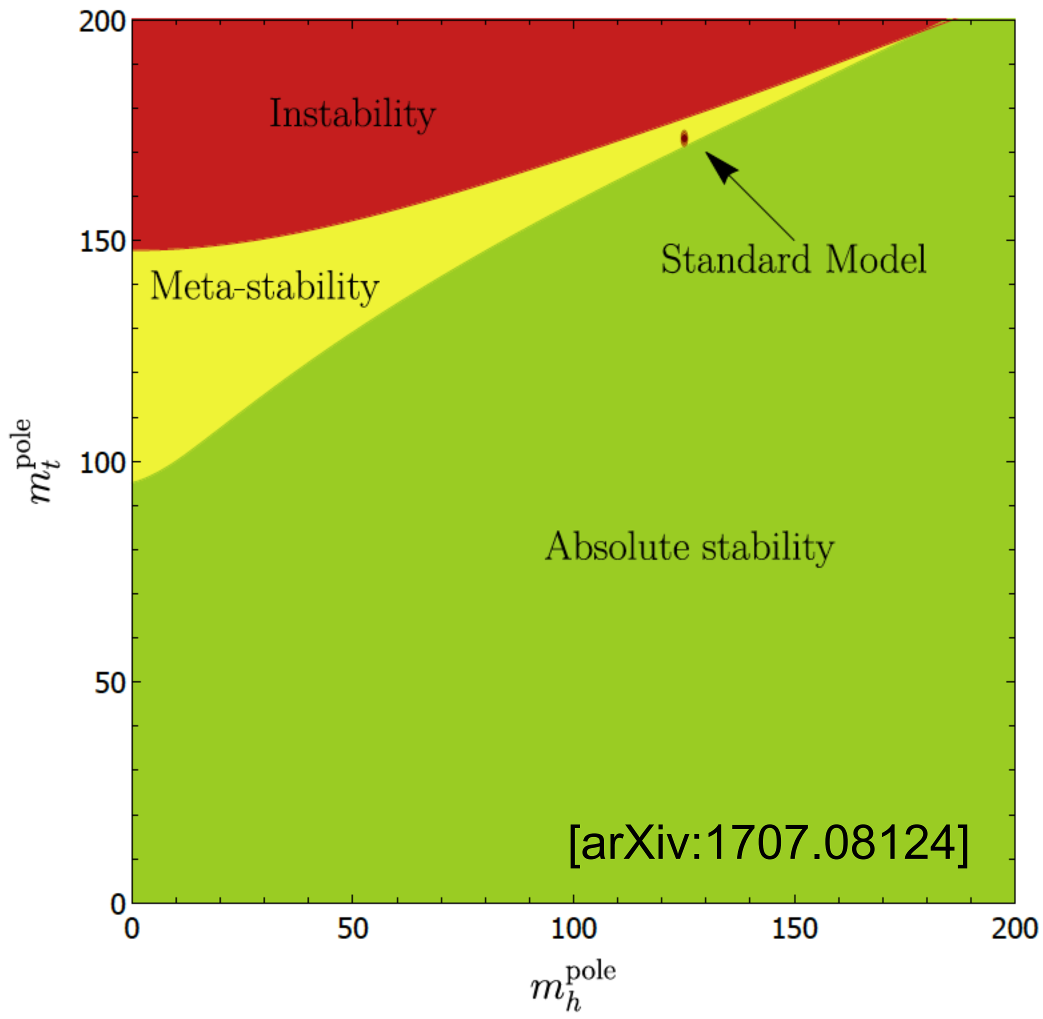


Acc. by JHEP [arXiv:1912.08887]

SM vacuum stability

- A very fundamental question: What happens with the SM theory at highest physically allowed scales ? → extrapolate to 10^{18} GeV
- In classical physics “stable” means minimum of potential energy:

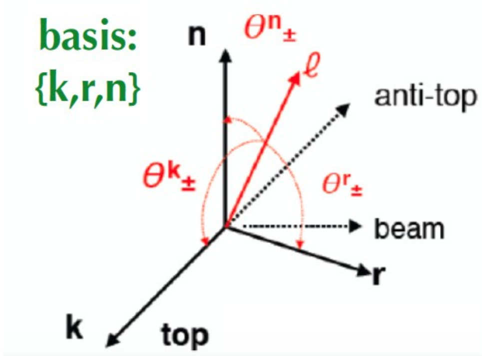




“Don't panic!” (D. Adams)
Lifetime is much much larger than current age of the universe: $10^{80} – 10^{320}\ t_{Universe}$

Spin Correlations

- 15 coefficients completely characterize spin dependence of top quark production, each probed by measuring a 1D differential distribution.
- Also measure opening angle of lepton in lab system
- Corrected to the parton level



Double diff. xsec **Polarisation (0 in SM)** **Spin Correlation**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a\, d\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b)\cos\theta_+^a \cos\theta_-^b)$$

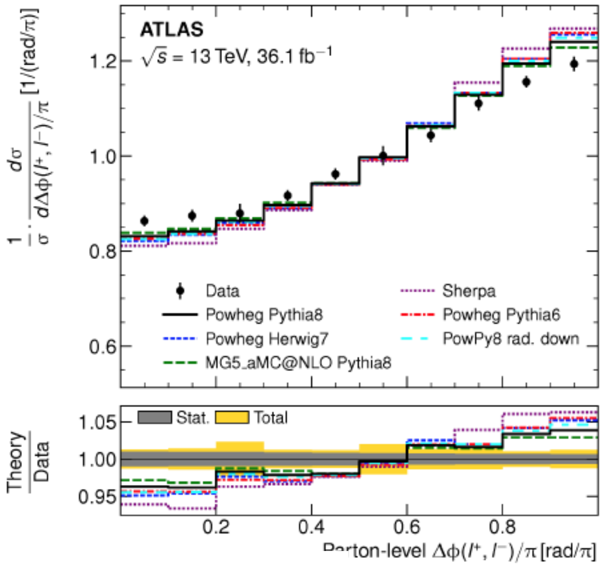
Dilepton distribution probes top spin in 3 dimensions

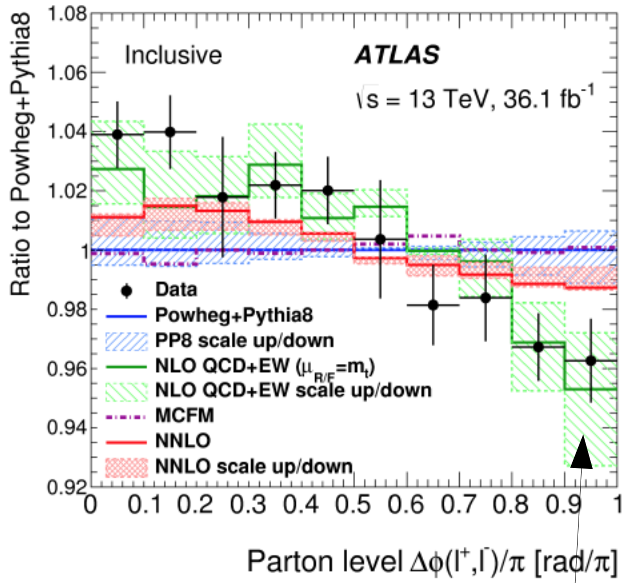
→ Leptons follow parent top spin (average polarisation given by 3-vectors B+/-)

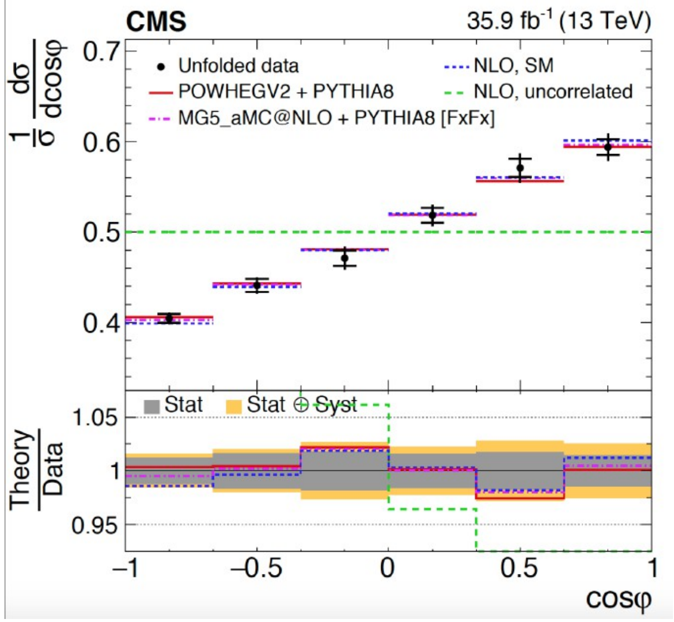
→ Relative lepton directions follow 3x3 matrix C of spin correlation coefficients

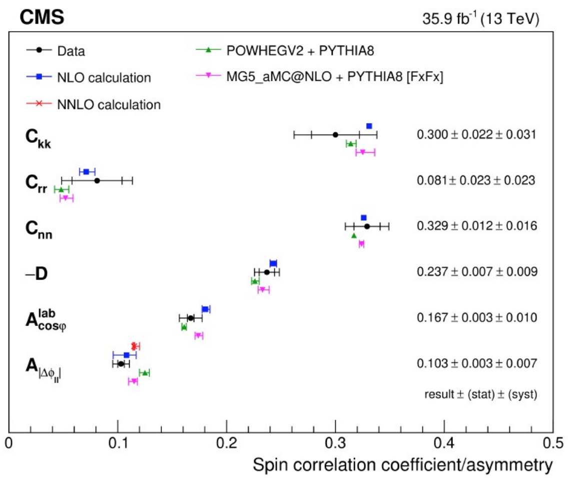
Top Quark Properties...

- ATLAS and CMS completed detailed studies of top quark's spin correlation, and polarization (CMS)
  - Initial deviations of > 3 SD seen by ATLAS, not confirmed by CMS (only ~ 1SD)
- Most precise variable cosφ









ATLAS

Region	$f_{SM} \pm$ (stat.,syst.,theory)
Inclusive	$1.249 \pm 0.024 \pm 0.061 \pm 0.040$
$m_{t\bar{t}} < 450$ GeV	$1.12 \pm 0.04\ ^{+0.12}_{-0.13} \pm 0.02$
$450 \leq m_{t\bar{t}} < 550$ GeV	$1.18 \pm 0.08\ ^{+0.13}_{-0.14} \pm 0.08$
$550 \leq m_{t\bar{t}} < 800$ GeV	$1.65 \pm 0.19\ ^{+0.31}_{-0.41} \pm 0.22$
$m_{t\bar{t}} \geq 800$ GeV	$2.2 \pm 0.9\ ^{+2.5}_{-1.7} \pm 0.7$

NLO theory slope and uncertainty appropriate ?

→ F_{SM} = 0.97 ± 0.05 (stat+syst)