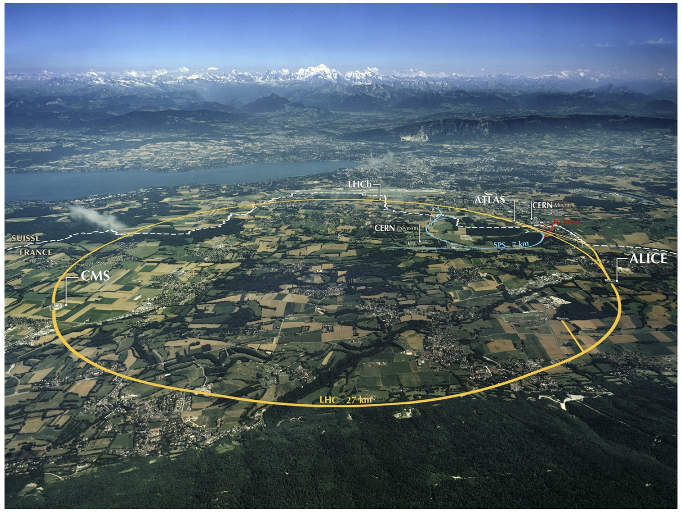
Top physics: Opportunities and Challenges



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

Andy Jung (Purdue University)

PITT PACC Workshop: LHC physics for Run 3

PURDUE UNIVERSITY

April 7th, 2021

The top quark

- Top is the heaviest fundamental particle discovered so far
  → $\boldsymbol{m_t}$ **= 173.34 ± 0.76 GeV** [arxiv:1403.4427]

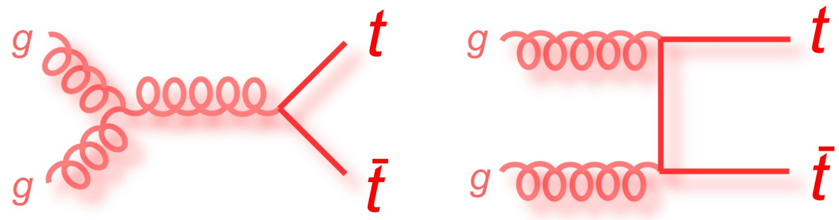
- Unique quark:

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

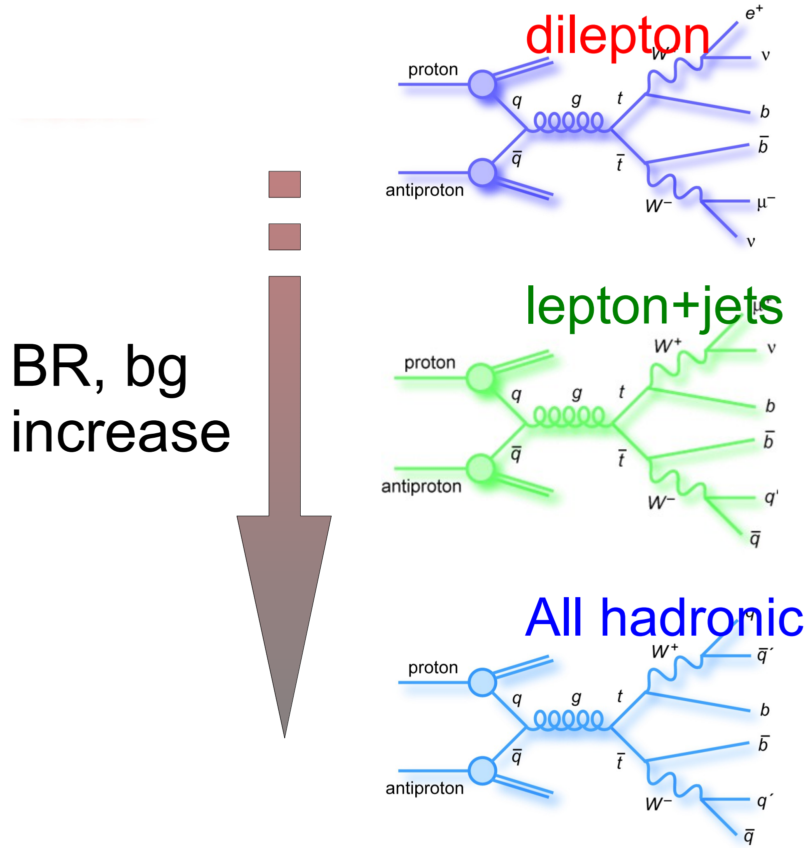
  → **Observe bare quark properties**

- Large Yukawa coupling to Higgs boson
  → $\lambda_t \sim 1$ **only m_t is natural mass**
  Special role in EW symmetry breaking ?

- Production dominated by gg fusion:

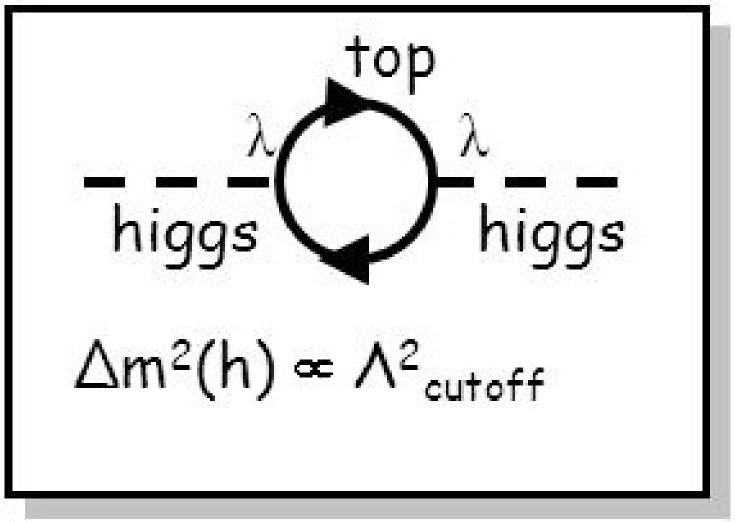


- Decay channels:

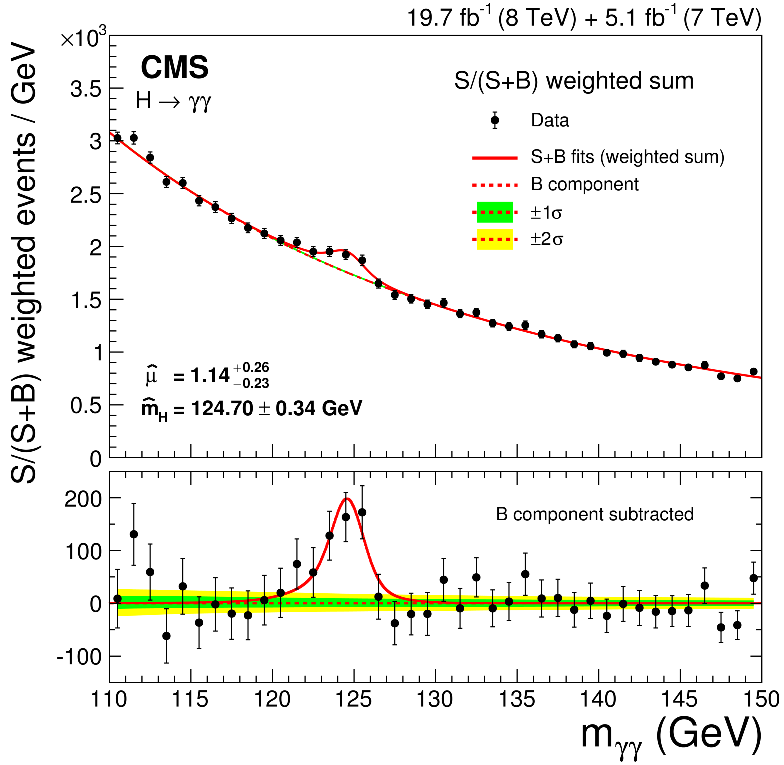


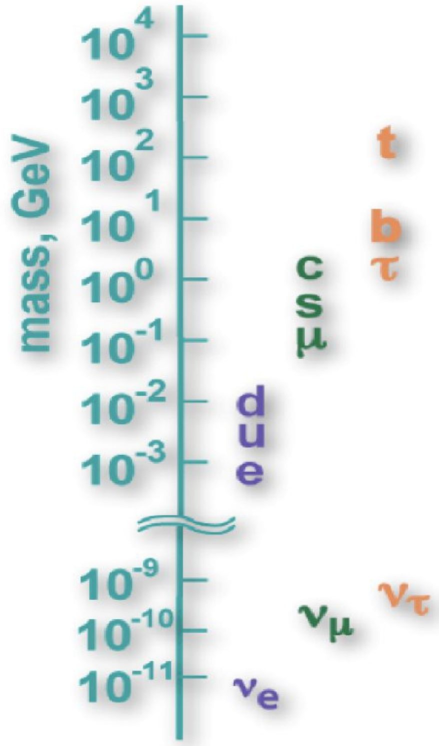
Why top (and Higgs) ?

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



Loops are dominated by top quarks





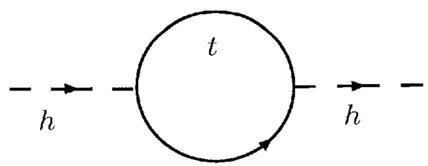
Natural Higgs mass close to Planck scale of 10^{19} GeV

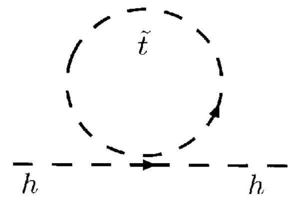
Higgs mass at ~ 125 GeV!

→ New physics in loops ?

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

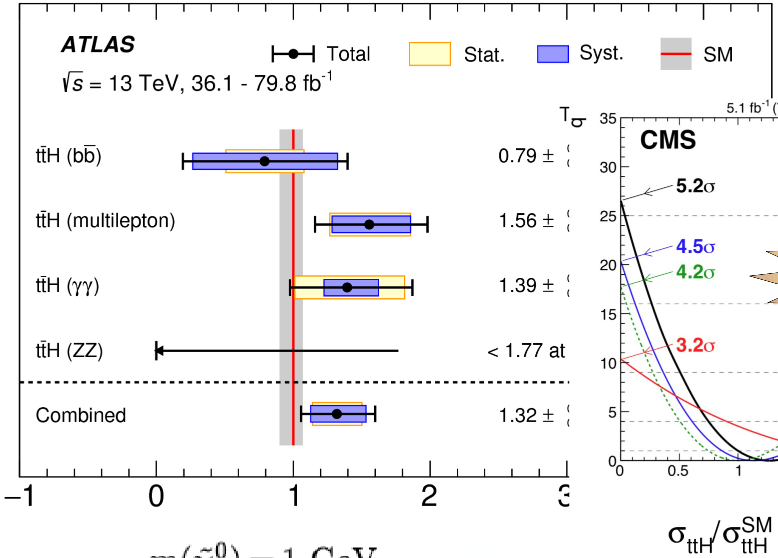
→ No fine-tuning if top quark partner exists

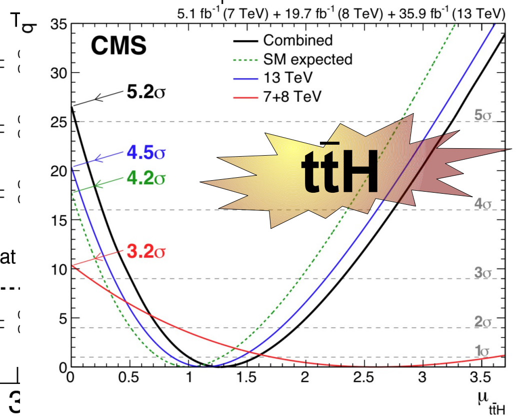




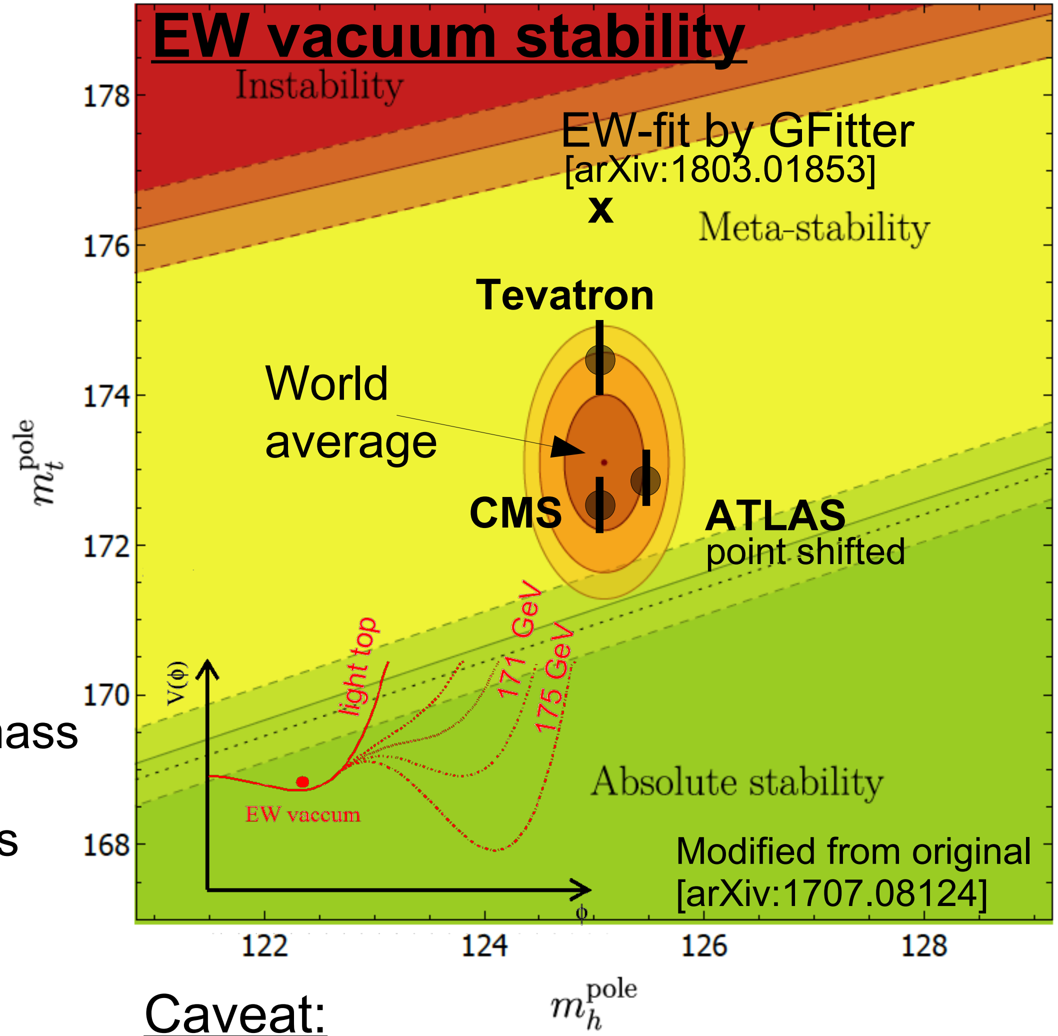
Beyond the SM ?

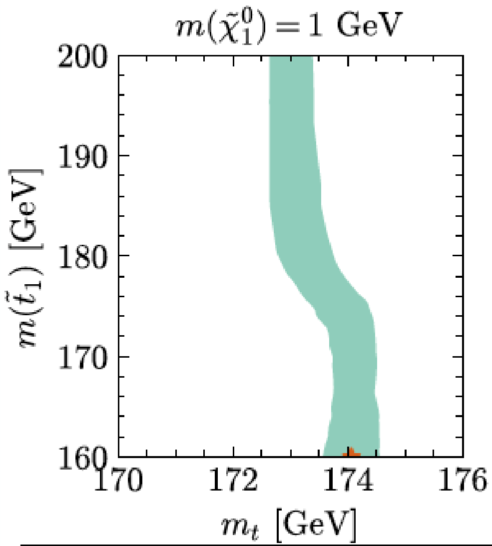
- Very subjective but illustrative, latest results from LHC & Tevatron – SM true
- ***ttH* observation:**



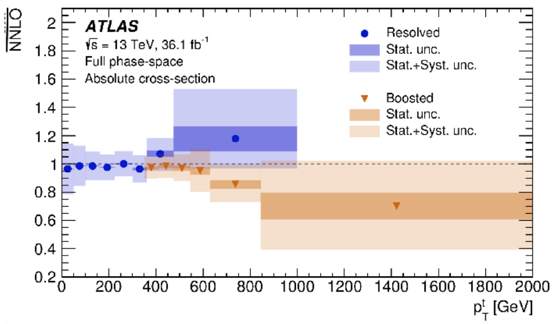


GFitter: $m_t = 176.4 \pm 2.1$ GeV





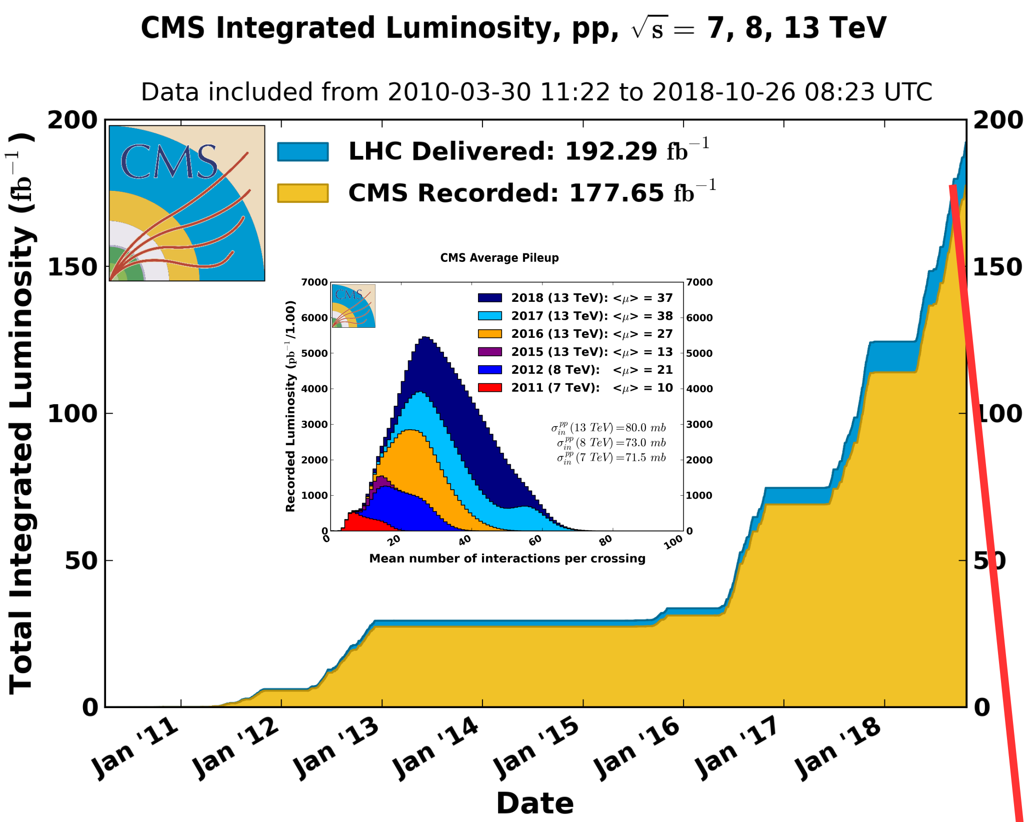
- Direct mass ↔ indirect mass
- Bias from a top partner ?
- top kinematics, spin corr's

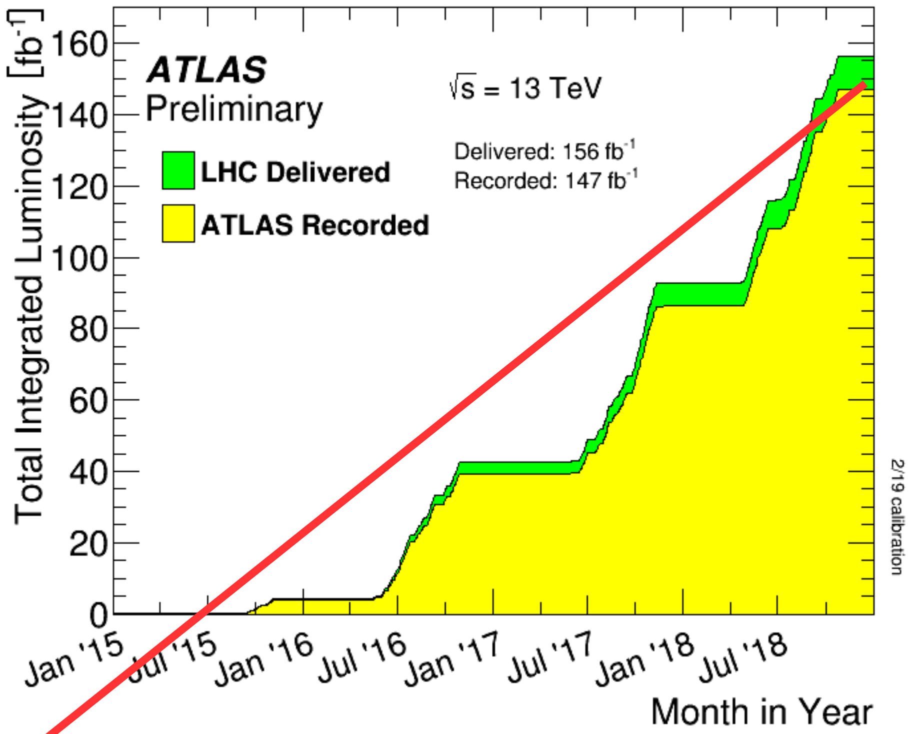


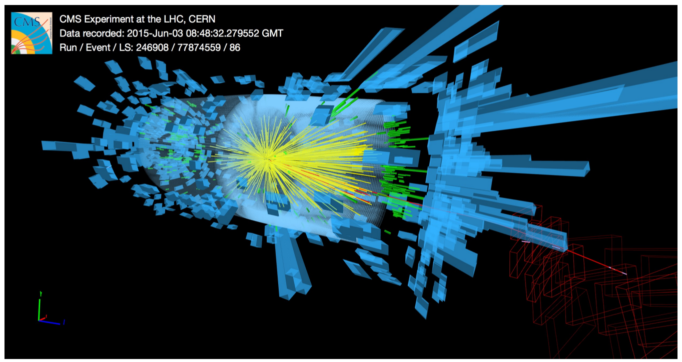
Caveat:

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

The present...LHC Run II



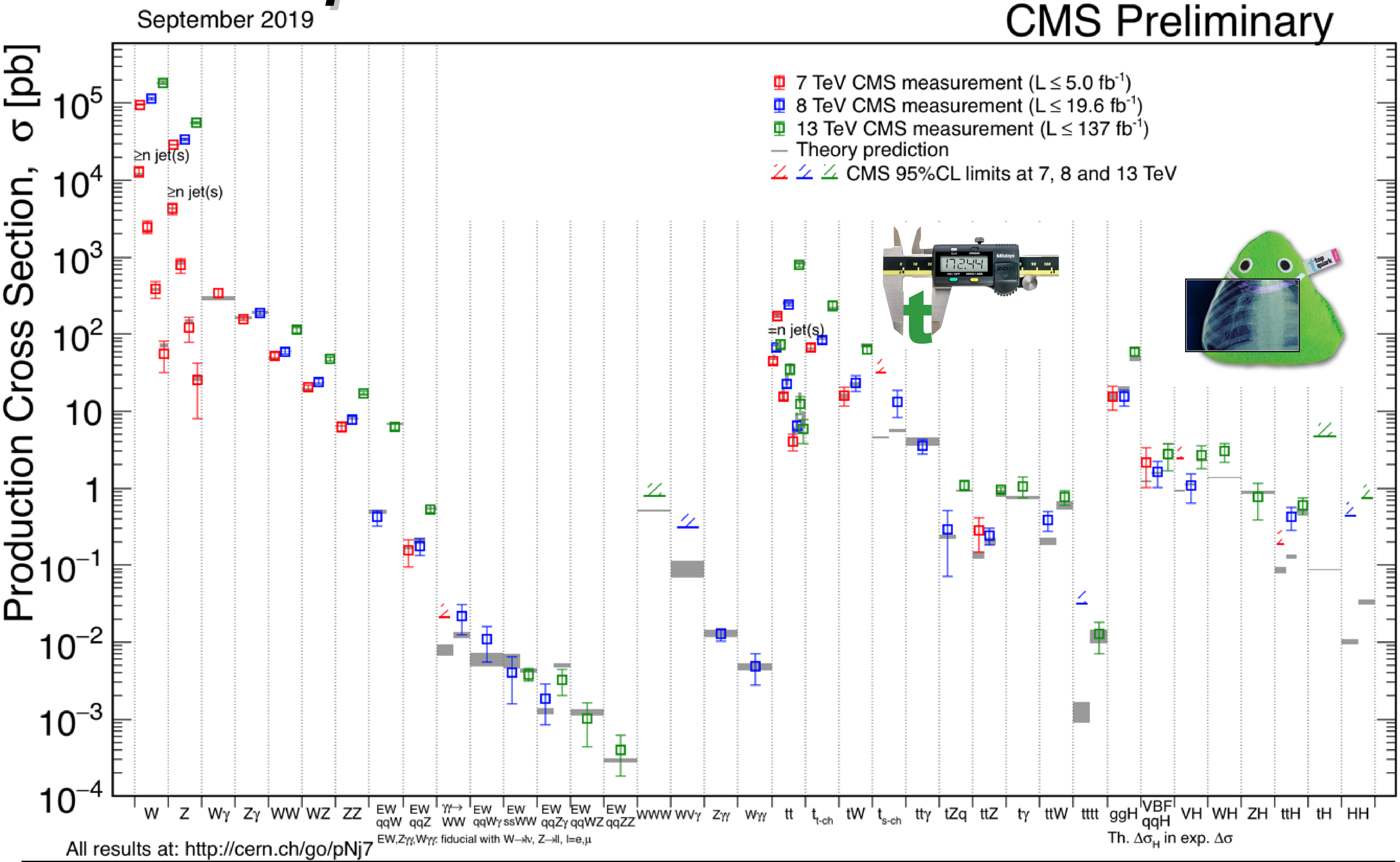




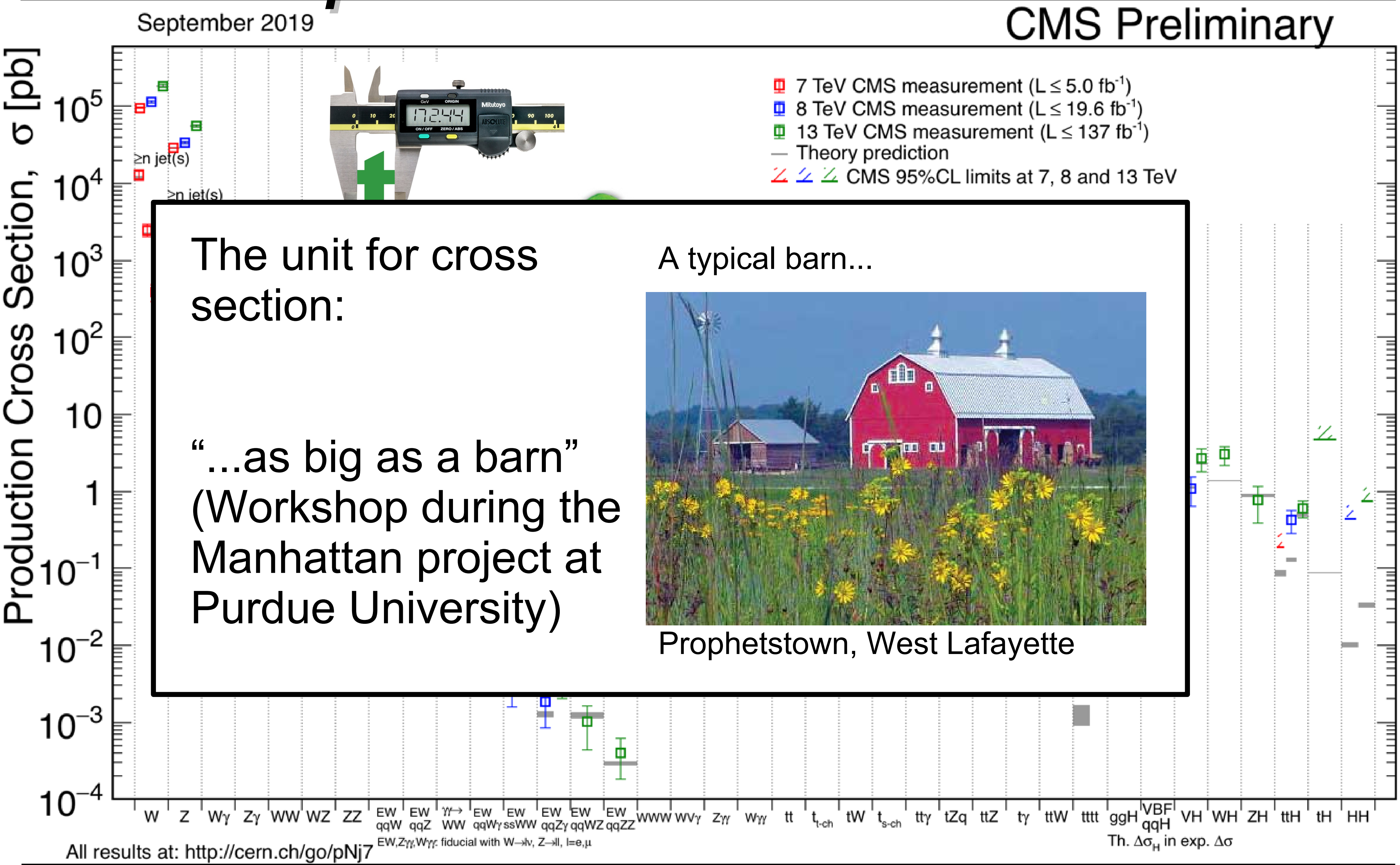
<u>Full Run II provides about</u>

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

The precision frontier



The precision frontier



The unit for cross section:

"...as big as a barn" (Workshop during the Manhattan project at Purdue University)

A typical barn...

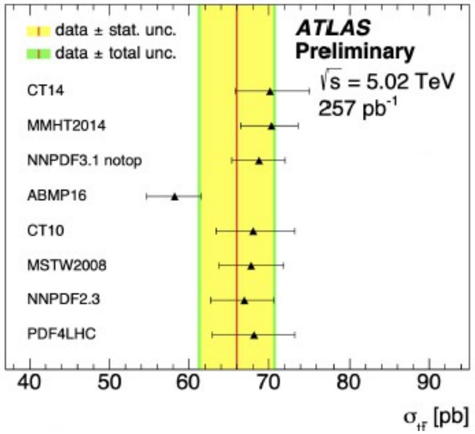
Prophetstown, West Lafayette

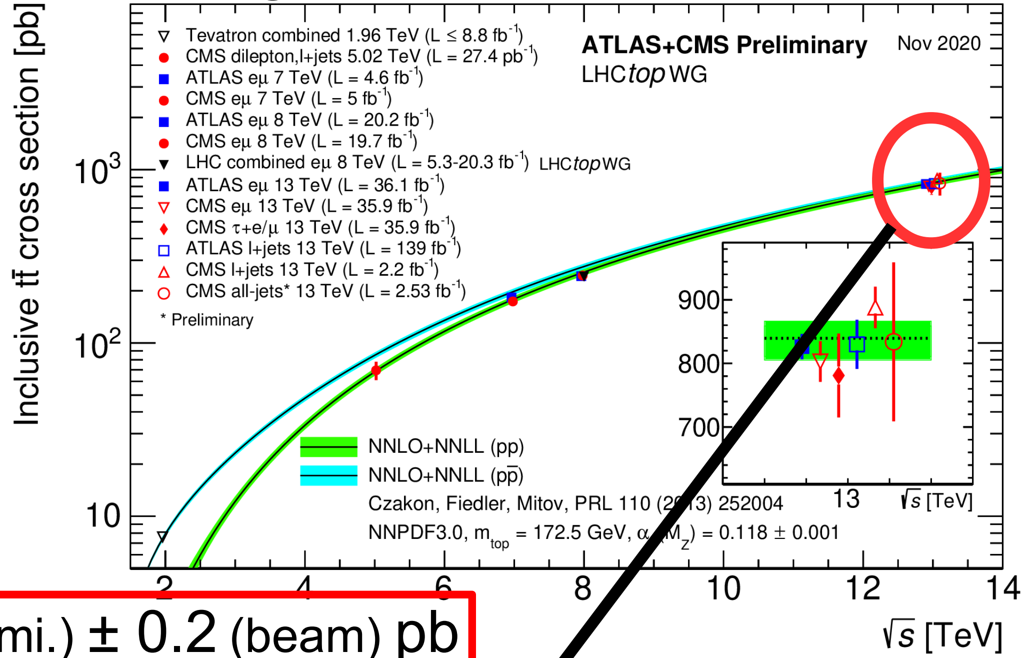
Inclusive cross sections

- 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

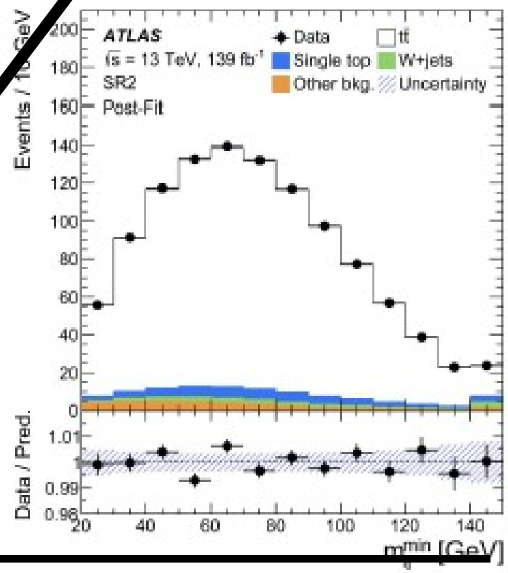
δσ/σ= 8.1% [CMS]

NEW

ATLAS cross section at 13 TeV

Full Run II data set

NEW

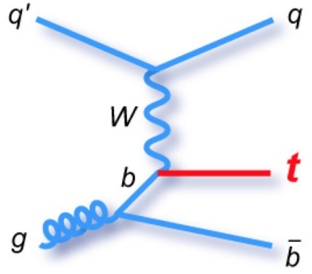


σ = 830 ± 0.4 (stat) ± 36 (syst) ± 14 (lumi) pb

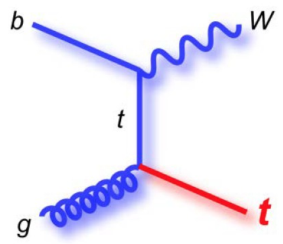
δσ/σ= 4.7% [PLB 810 (2020) 135797]

Single Top Quark Production

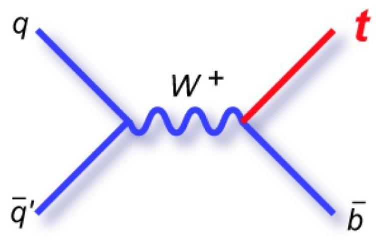
- **Single top cross section as high as $t\bar{t}$ at 8 TeV – large samples**
- Single top production: Test of EW interactions



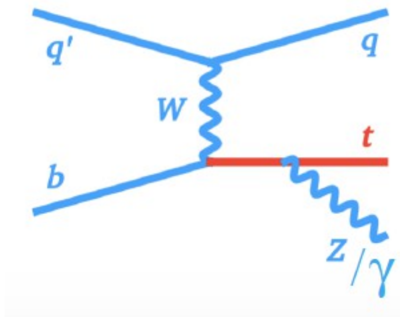
t-channel



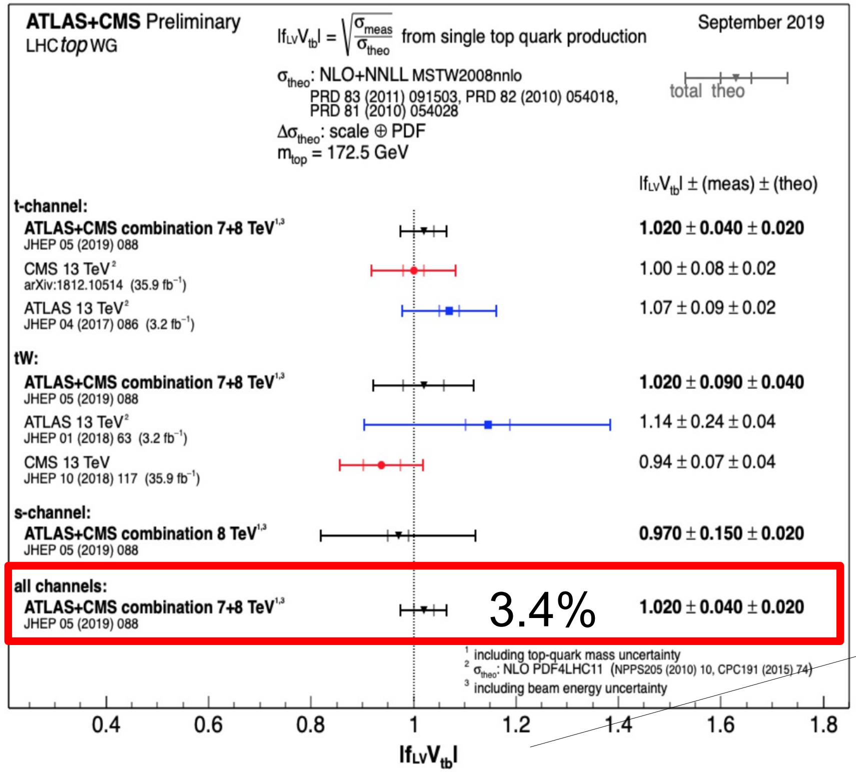
tW-channel



s-channel



tZ/γq-channel (rare process, < 1 pb)

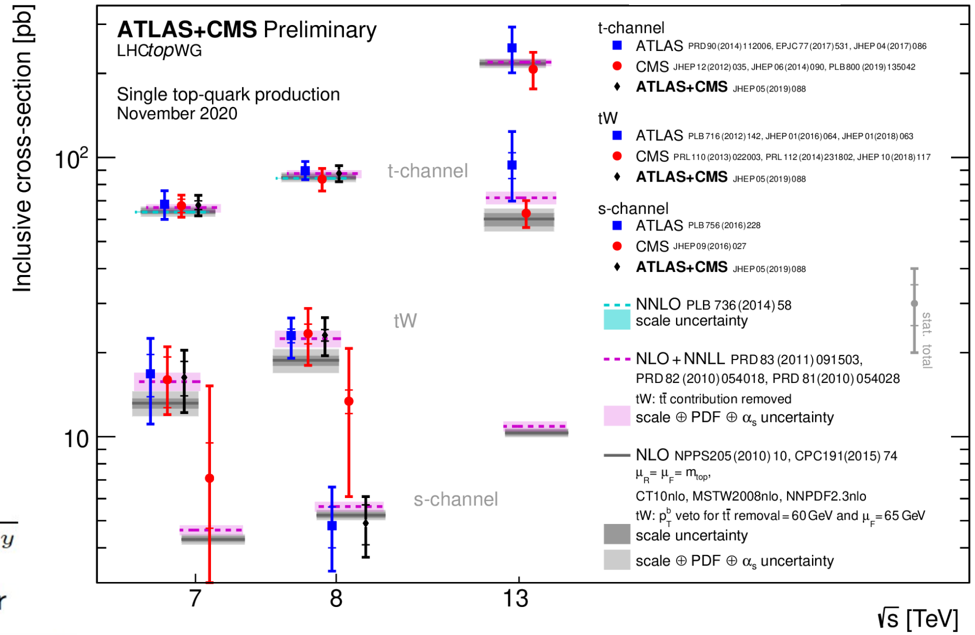


$$|V_{tb} \cdot f_{LV}|^2 = \frac{\sigma^{obs}}{\sigma^{theory}}$$

f_{LV}: BSM form factor

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

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



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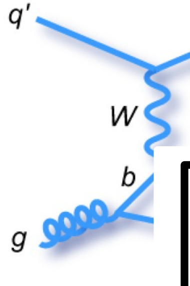
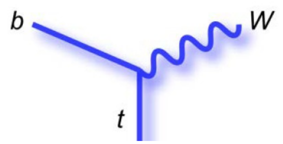
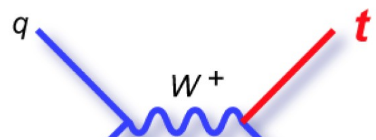
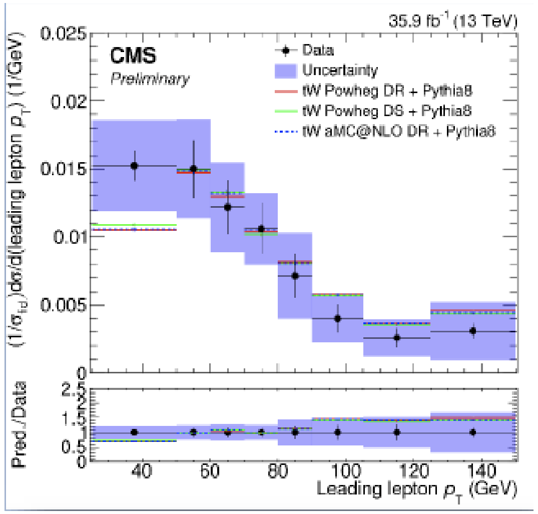


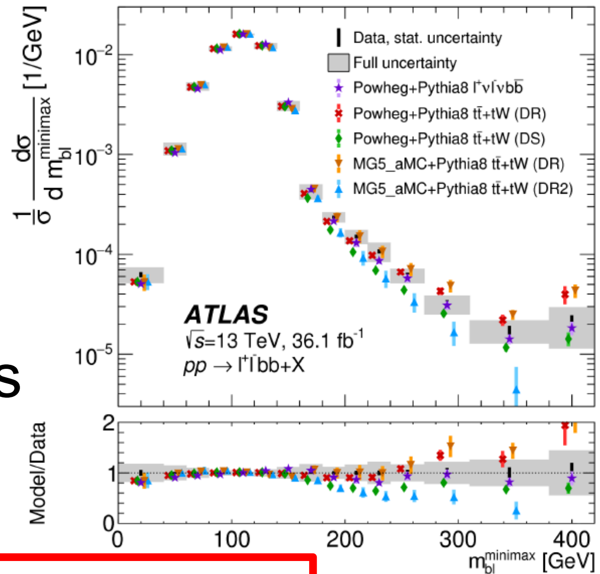




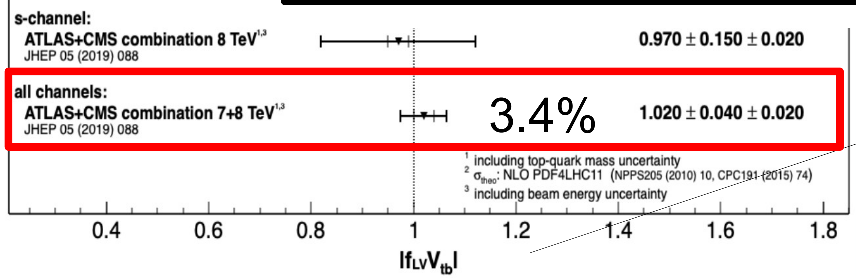


[CMS-PAS TOP-19-003]

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



Impressive amount of differential measurements in single top!



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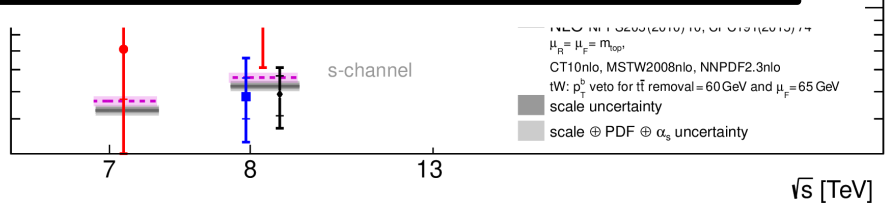
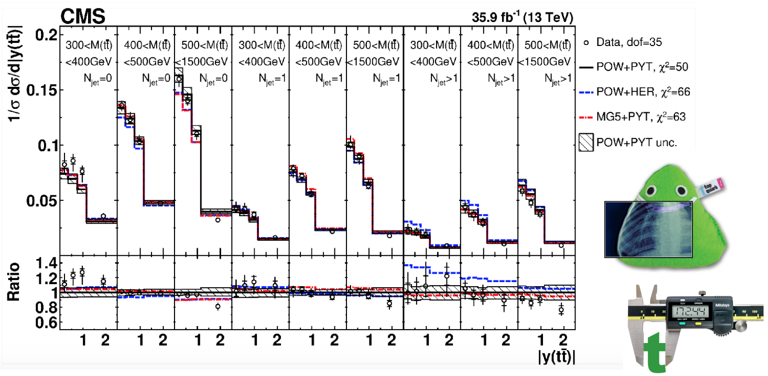
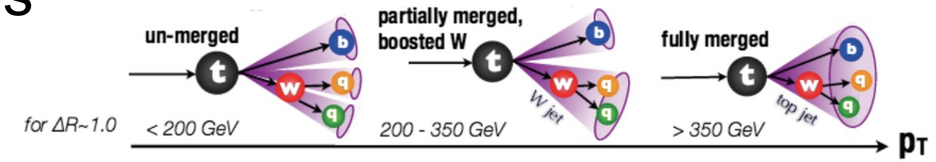


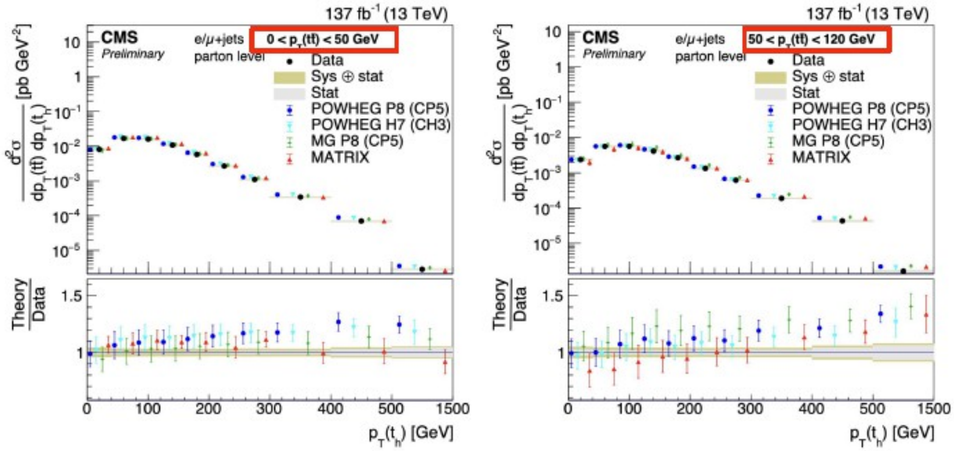
Differential cross sections

- 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]

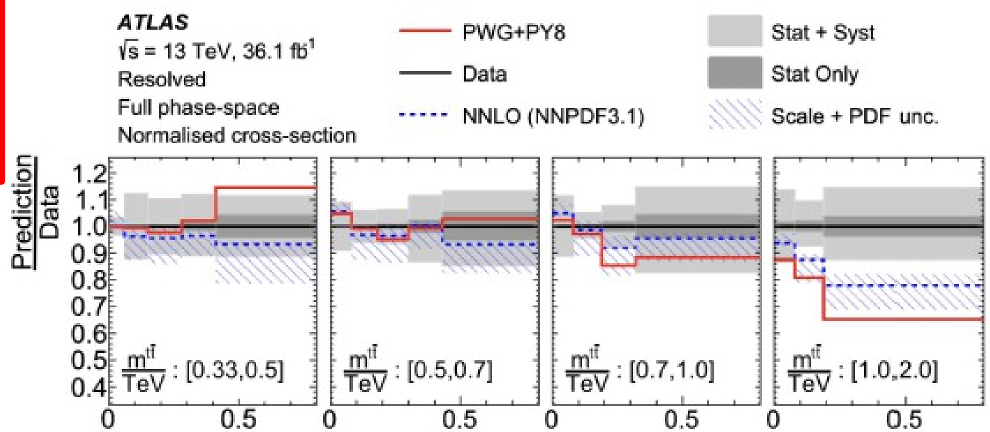






- Improve signal modeling, seen 1st triple and double differential measurements!
- Getting more precise in boosted regime
- On CMS site: 1st simultaneous measurement of resolved and boosted

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

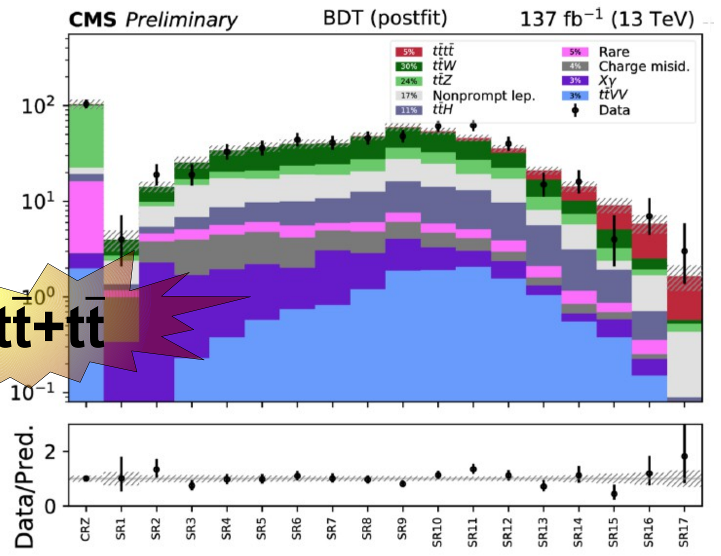


[EPJC 79 (2019) 1028]

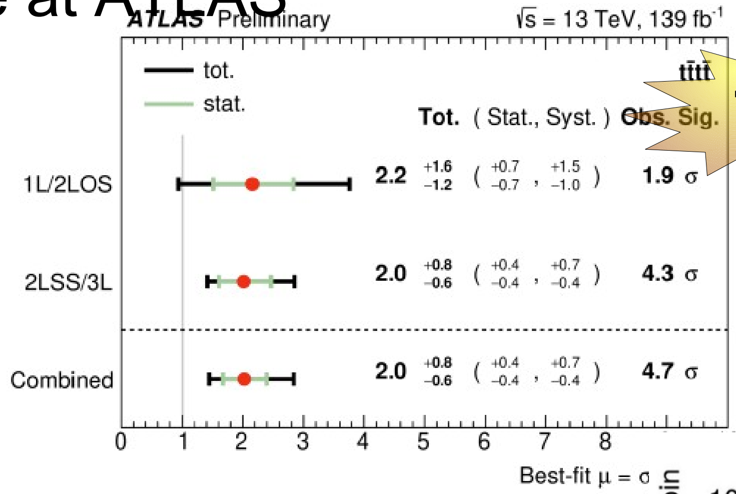
$t\bar{t}$+X: Highlights

- **$t\bar{t}$Z/W:** Most precise measurement, allowed for 1st differential cross sections
- **$t\bar{t}\gamma$** : Differential $t\bar{t}\gamma$ by CMS
- **$t\bar{t}$+$t\bar{t}$:** Full Run 2 evidence at ATLAS
- **$t\bar{t}$+$c\bar{c}$:** 1st by CMS

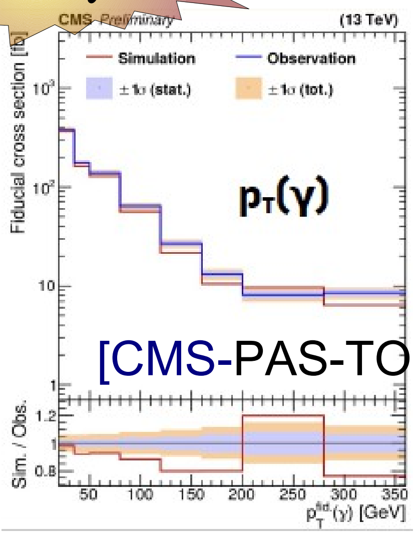
Details matter: SF's for ttZ, ttW and ttbb are not easily comparable (mind phase space & uncertainties)



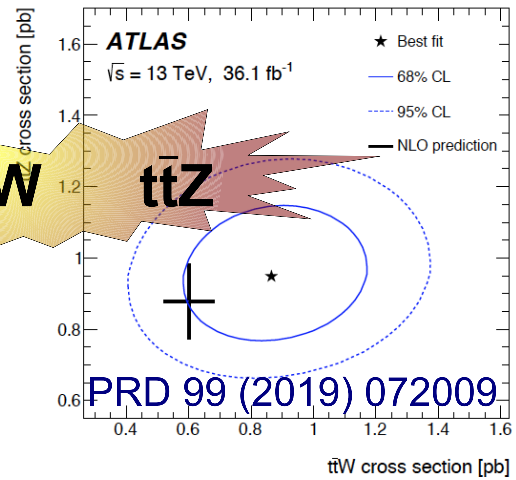
CMS-PAS-TOP-18-003



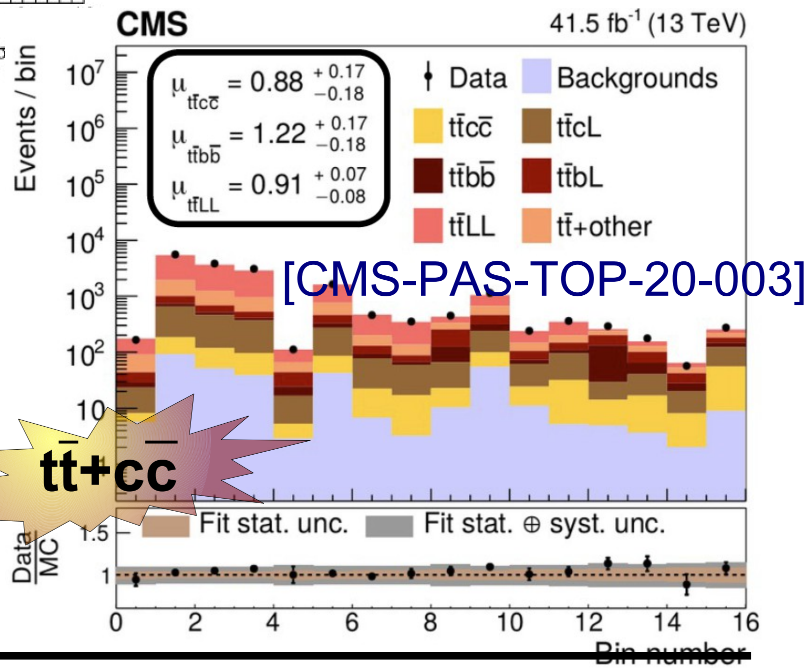
[ATLAS-CONF-2021-013]



[CMS-PAS-TOP-18-010



PRD 99 (2019) 072009



[CMS-PAS-TOP-20-003]

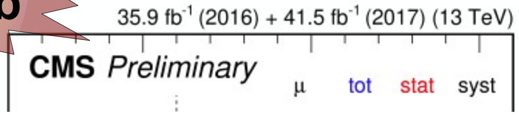
$t\bar{t}H$, Top Yukawa coupling

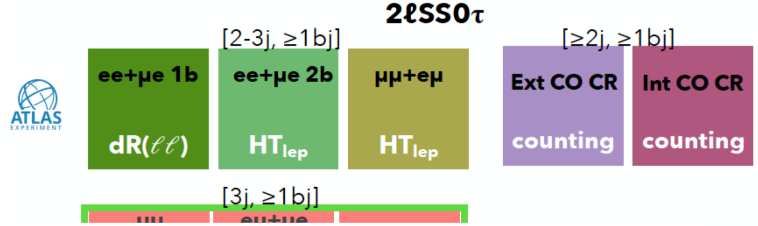
- Associated Higgs production only direct access to Yukawa coupling
  - Complex final state

CMS:
  - Evidence for bb

ATLAS:
  - Obs

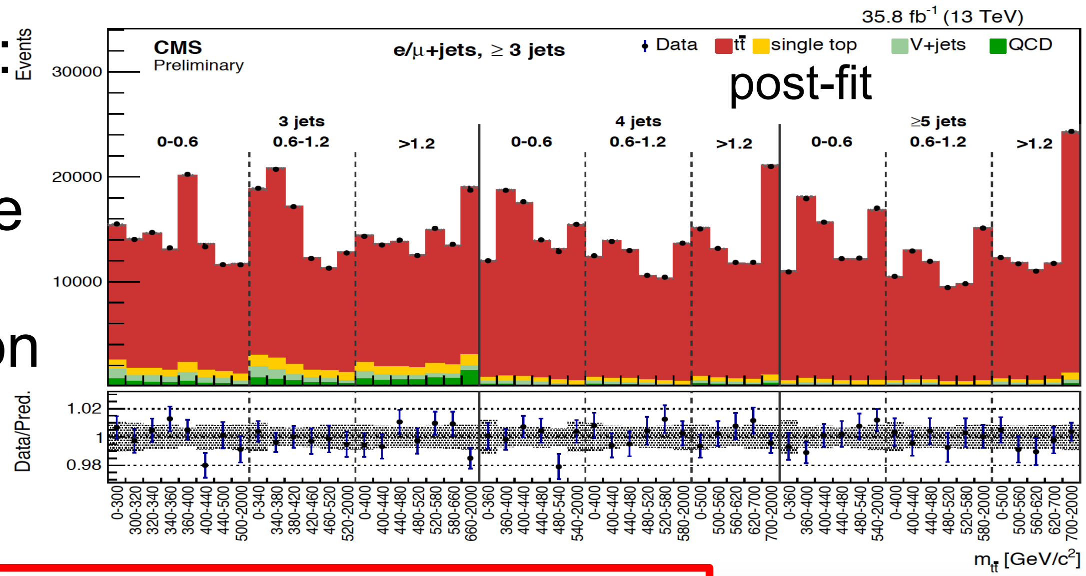
$t\bar{t}H \rightarrow b\bar{b}$





Details
and ttbb
compara
& uncert

Extract y_t from template fit:
- CMS 13 TeV data, l+jets
- Recover 3 jet bin and use 57 bins to fit
- Relies on threshold region

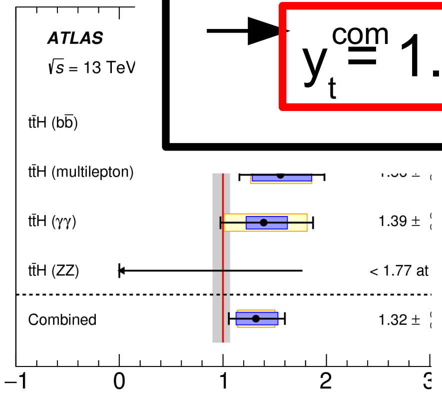


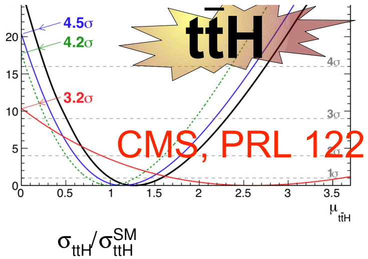
$y_t^{com} = 1.07 + 0.34\text{-}0.43$ (obs) [1.00 +0.35-0.48 (exp)]

er

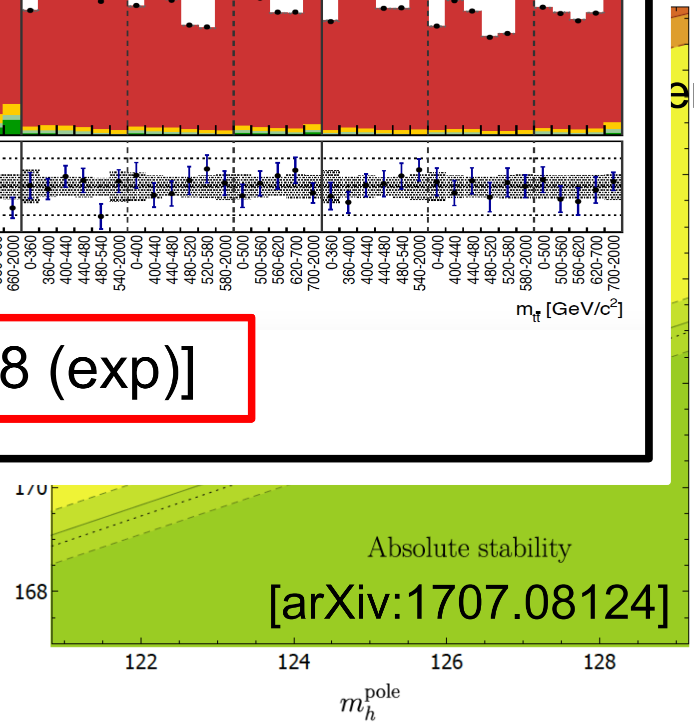
- $t\bar{t}H$ obs

ATLAS





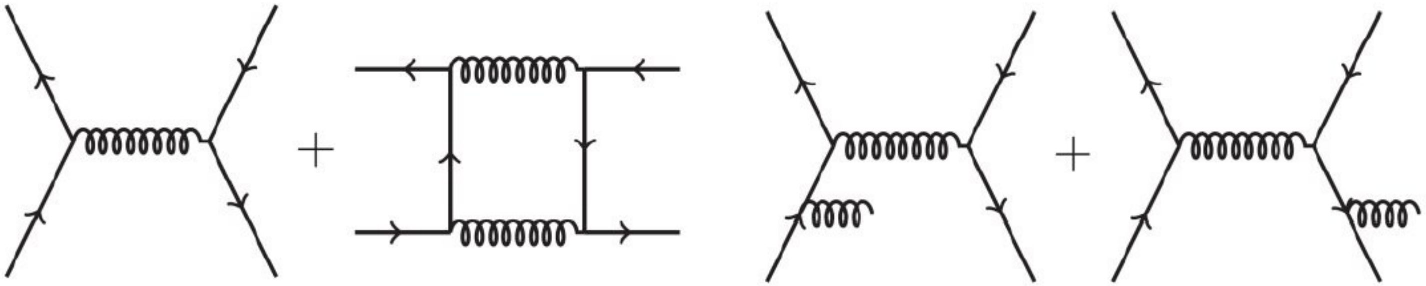
CMS, PRL 122 (2019) 132003



[arXiv:1707.08124]

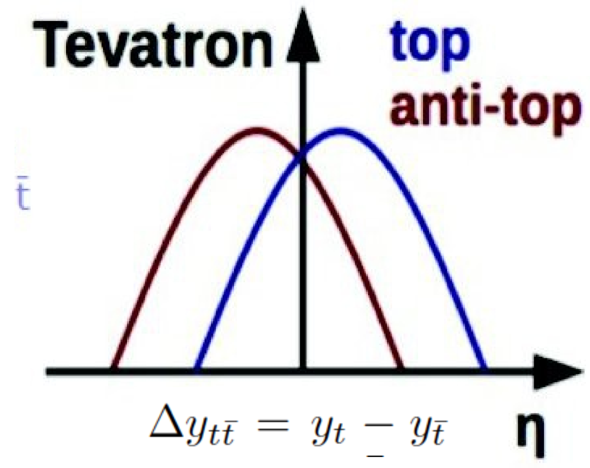
Top Quark Asymmetries

- Interference appears at NLO QCD:



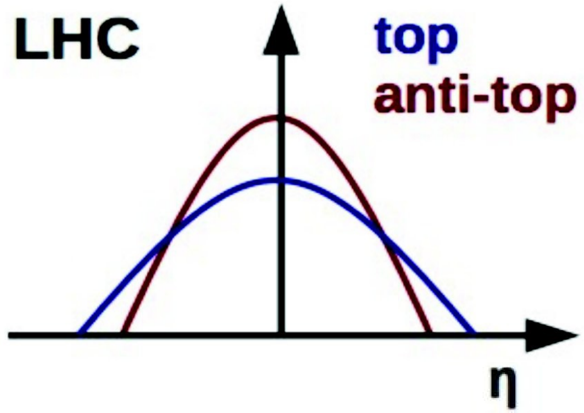
Positive asymmetry — Negative asymmetry

→ Only occurs in qq initial state; gg is fwd-bwd symmetric



$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}$$

- This is a forward-backward asymmetry at Tevatron
- No valence anti-quarks at LHC → t more central



- SM predictions at NLO (QCD+EWK)
  → Tevatron: AFB ~ 10 % vs. LHC: AC ~ 1 %
  (These are NNLO pQCD predictions, there is also the PMC approach)

- Experimentally: Asymmetries based on decay leptons "easier"
  or fully reconstructed top quarks "harder"

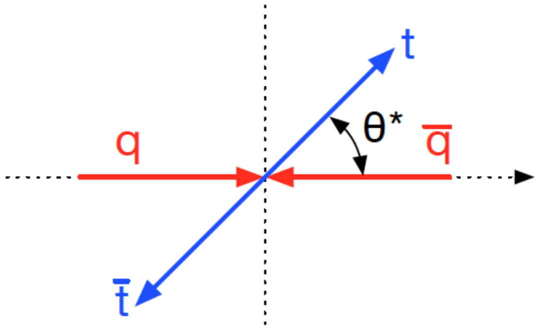
$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$

$$A_C^{lep} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)}$$

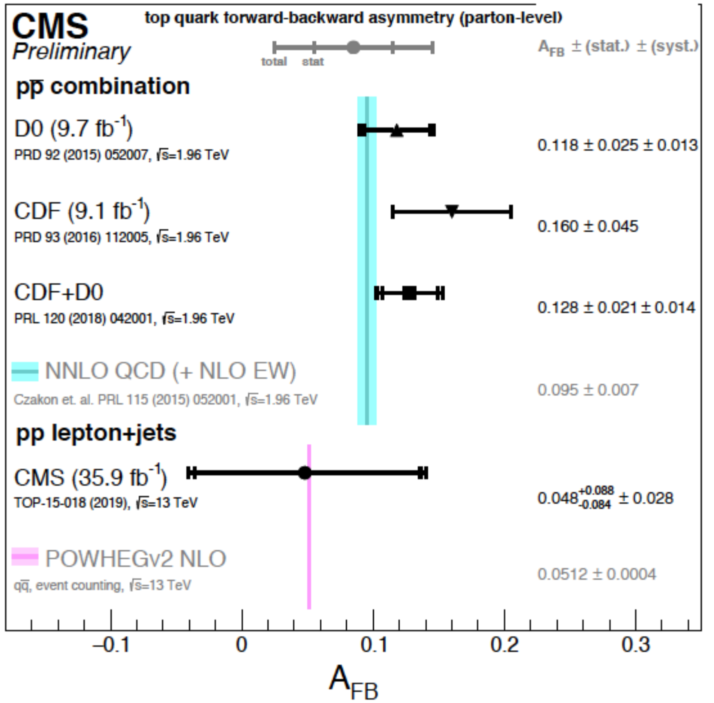
Top Quark Properties...

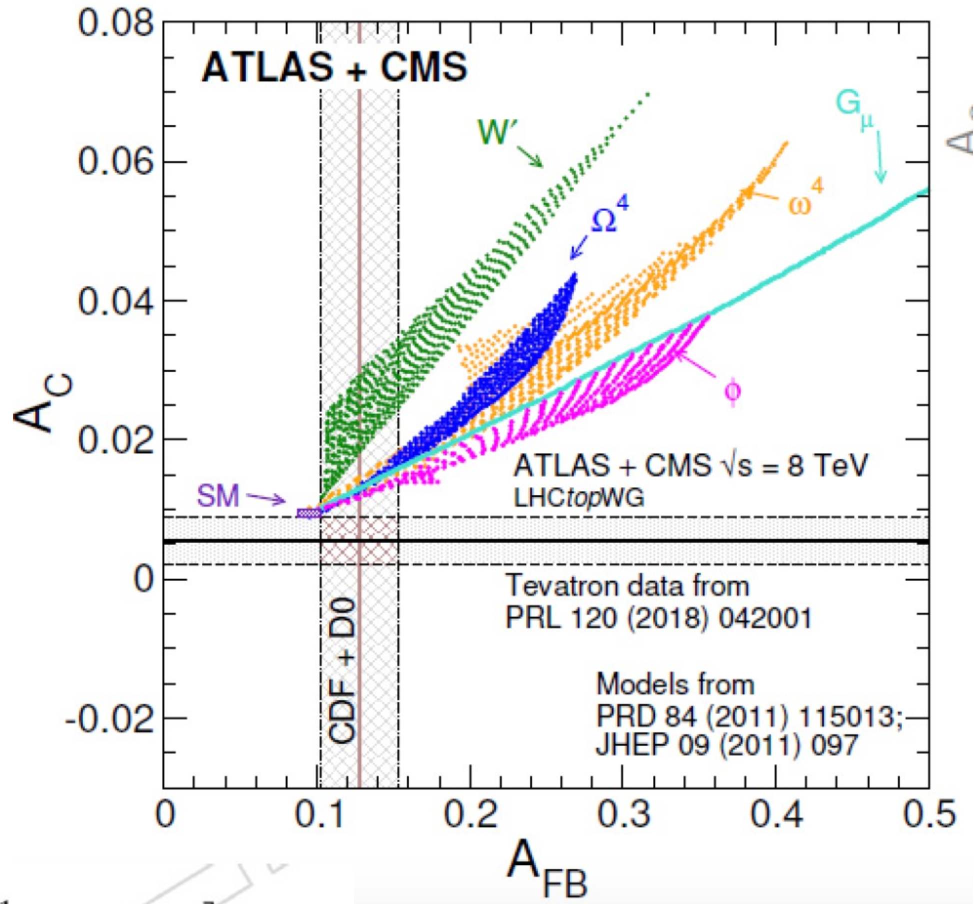
- <u>Production asymmetry due to NLO interferences</u>
- Measure production angle $c^* = \cos(\theta^*)$ to access asymmetry

arXiv:1912.09540



$$A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}$$



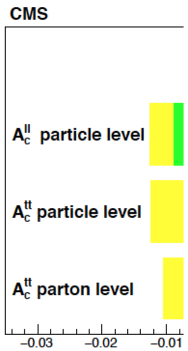


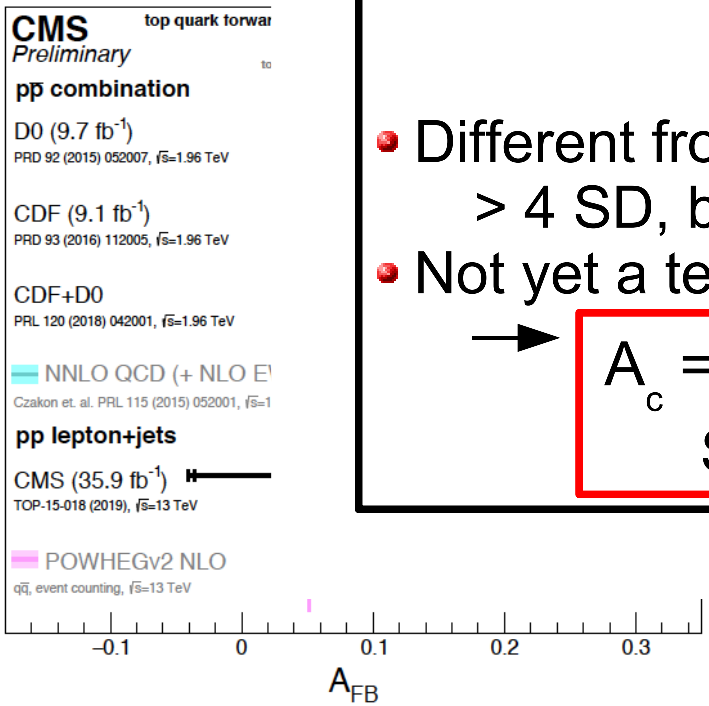
$$\frac{d\sigma}{dc^*}(q\bar{q}) \simeq f_{\text{sym}}(c^*) + \left[\int_{-1}^{1} f_{\text{sym}}(x)dx\right] c^* A_{FB}^{(1)}$$

→ Measurements of A_C difficult, new channels help
→ CMS 1st measurement of A_{FB} at LHC (!)

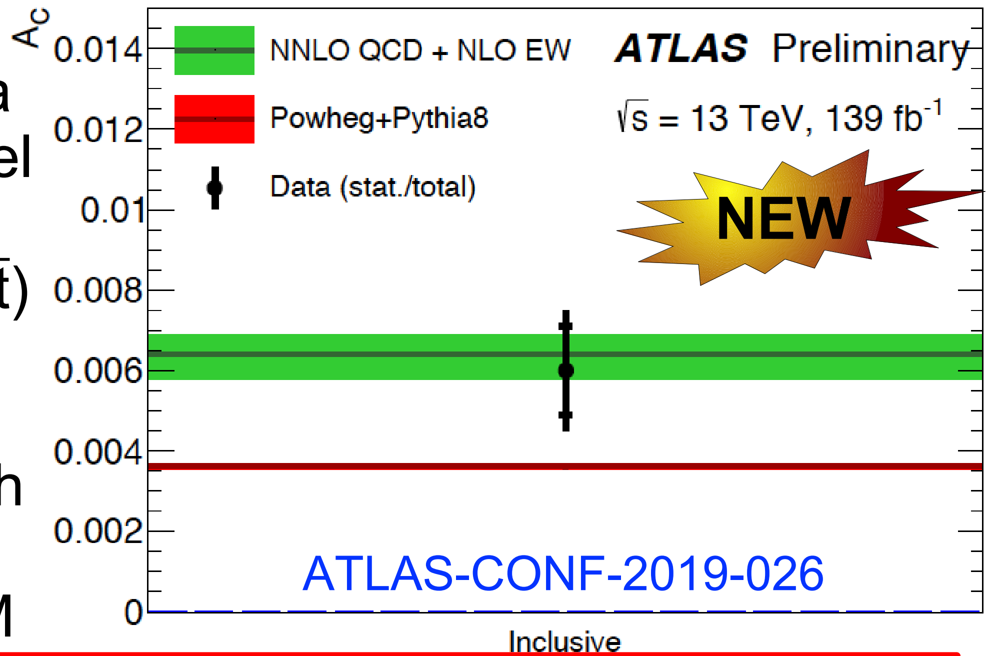
Top Quark Properties...

- Production asymmetry due to NLO interferences





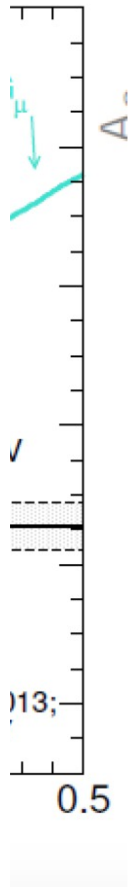
- Update by ATLAS
- Used 139\fb of data
- l+jets decay channel
- Inclusive and differential in m(tt̄)



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

→ A_c = 0.006 ± 0.0015 (stat+syst)

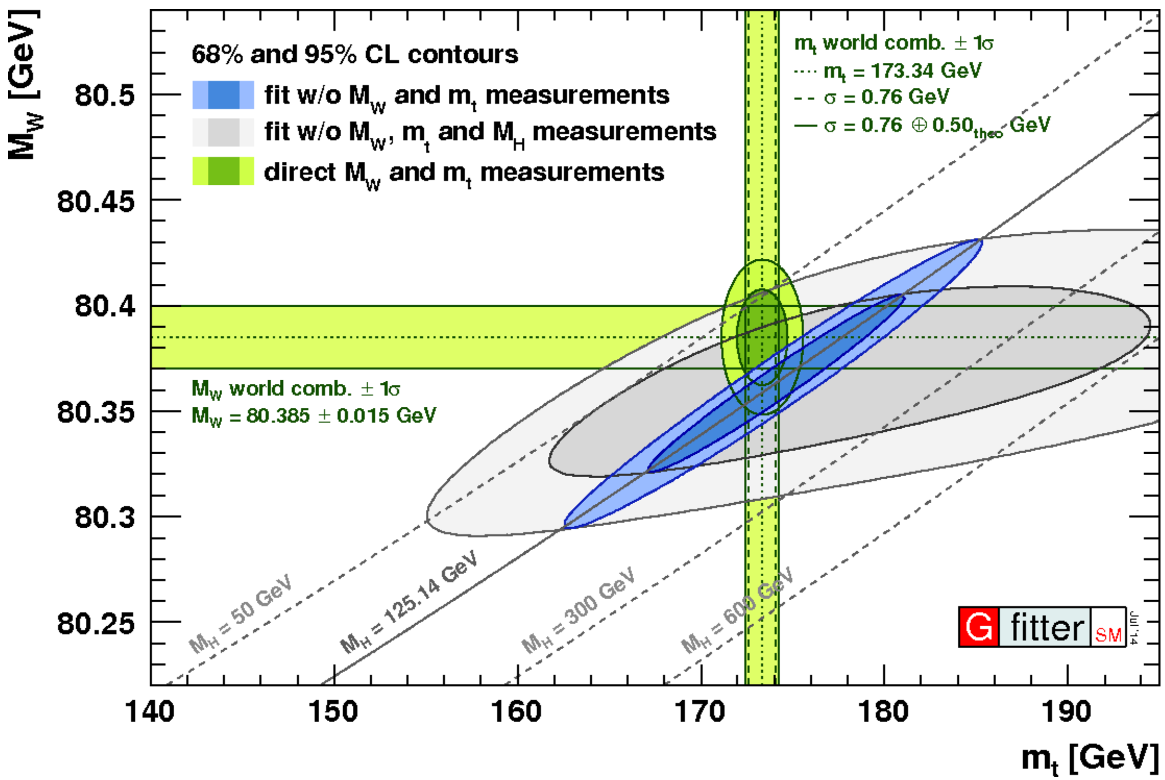
SM measurement soon ?



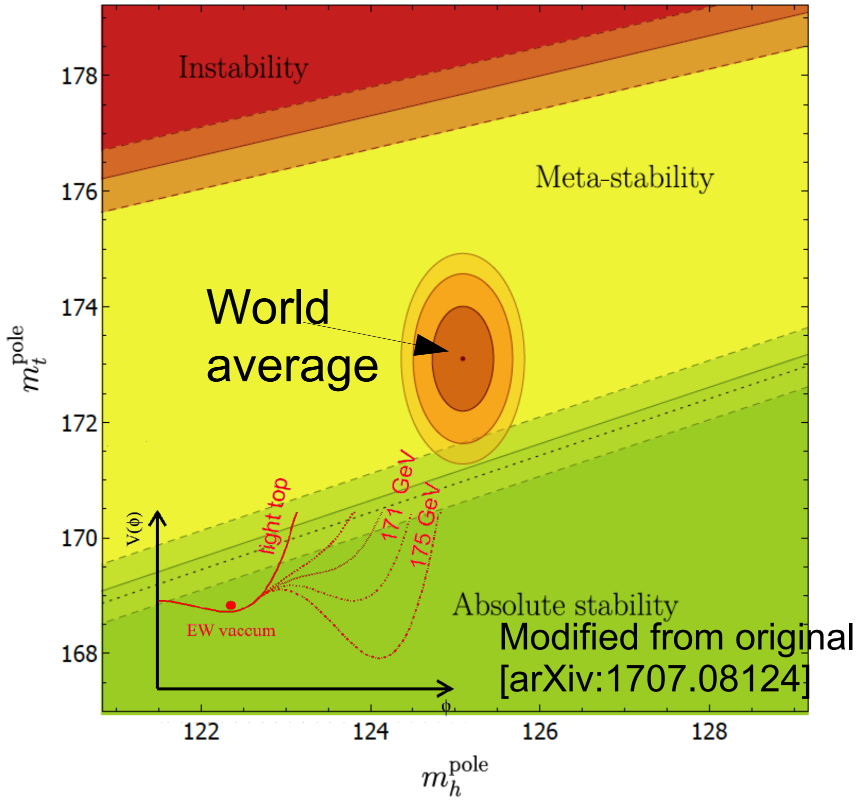
→ Measurements of A_C difficult, new channels help

→ CMS 1st measurement of A_{FB} at LHC (!)

Latest weighing…



EW vacuum stability



- 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 from e.g. cross section, end point, J/psi method → top quark pole mass
  - Direct methods e.g. template, matrix element, likelihood, ideogram → “MC” mass, close to pole mass

Top mass – direct methods

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

- CMS: all-jets + l+jets

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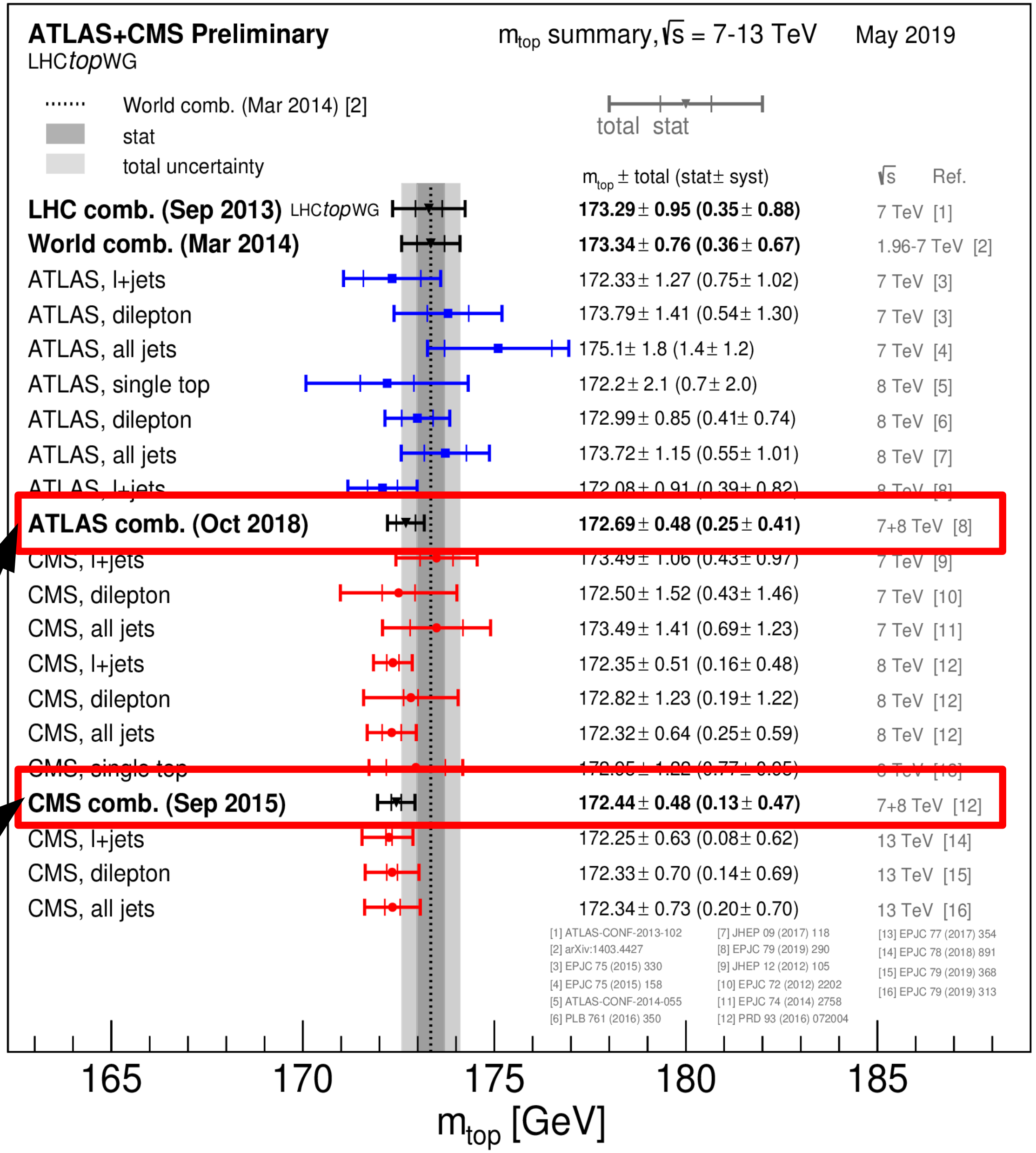
→ m_{top} = 172.26 ± 0.61 GeV
$\delta m_t/m_t$ = 0.36% (!)

- ATLAS: soft muon tag + displaced vertex, 13 TeV

ATLAS-CONF-2019-046

→ m_{top} = 174.48 ± 0.78 GeV
$\delta m_t/m_t$ = 0.45% (!)



In context of LHCtopWG

- Time for another LHC combination ?

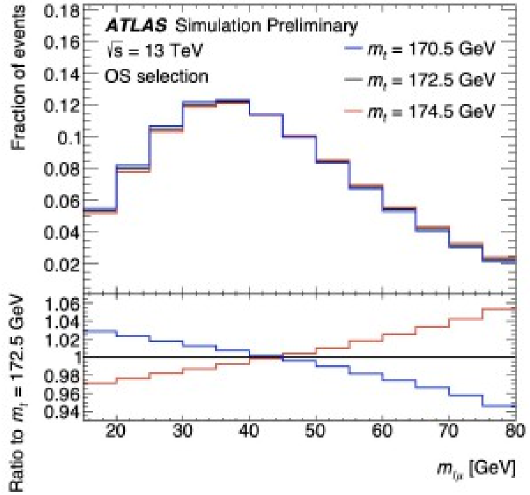
World combination ?

Top mass – alternative

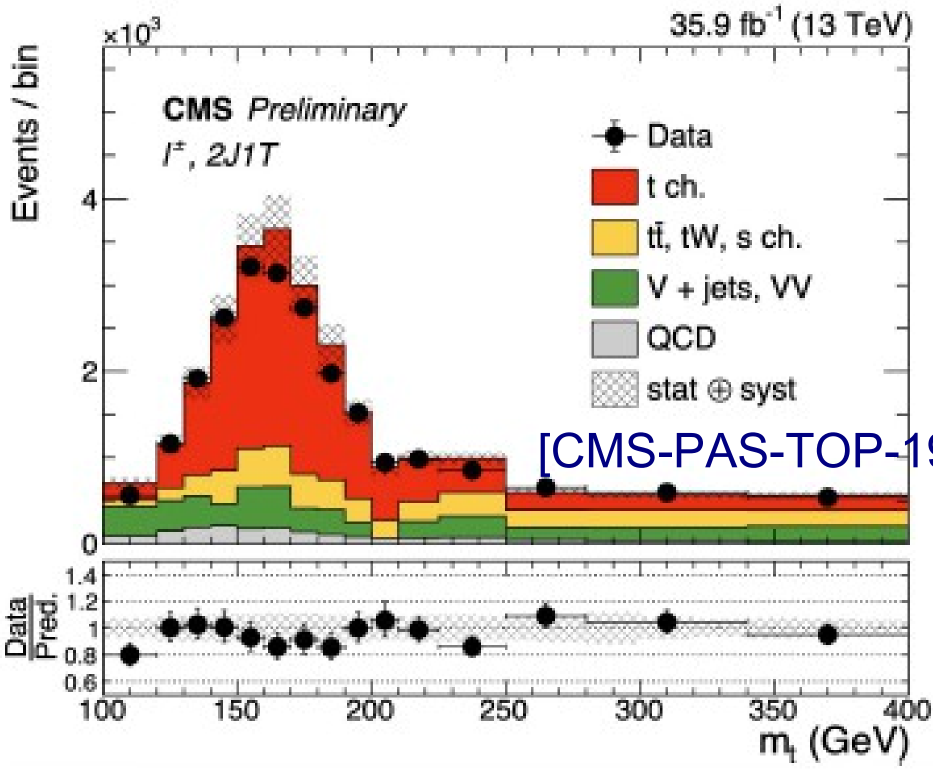
Latest top mass measurements:

- ATLAS 13 TeV data, leptonic invariant mass
  - Limited by B hadron branching [ATLAS-CONF-2019-046]
- CMS mass in the t-channel
  - Combined and separate lepton categories, CPT

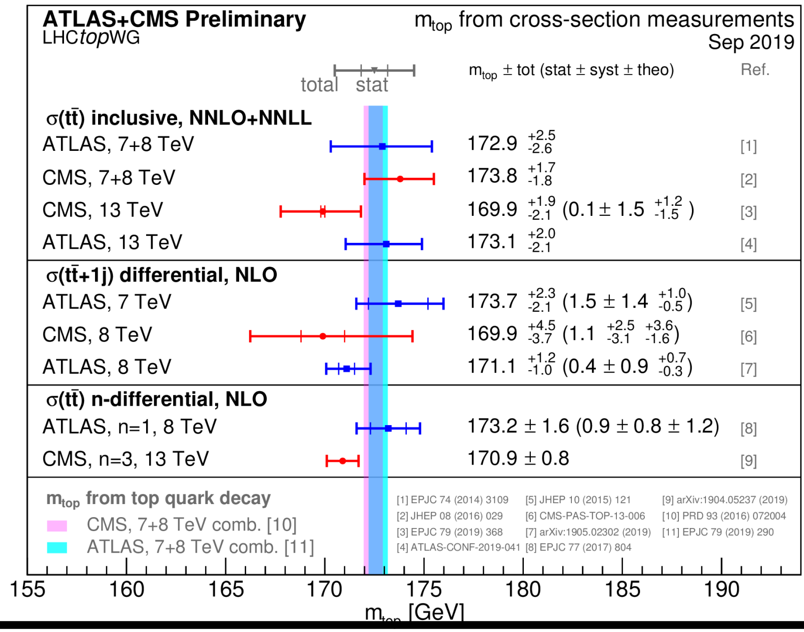
m_{top} = 172.1 ± 0.8 (total) GeV $\delta m_t/m_t$ = 0.47% (!)



m_{top} = 174.5 ± 0.8 (total) GeV
$\delta m_t/m_t$ = 0.45% (!)



[CMS-PAS-TOP-19-009]



Challenges & Opportunities

Disclaimer: My personal opinions!

Challenges ahead:

- Differences in MC setups
- More “global” approaches (kinematic ranges, EFT)
- Systematic uncertainties

Opportunities

- Vast top quark sample...

Challenges/Perspectives

Direct methods:

- Most precise results, $\delta m_t/m_t = 0.28\%$ (!)
- Does not include theoretical "scheme" uncertainty
- No single large uncertainty left:

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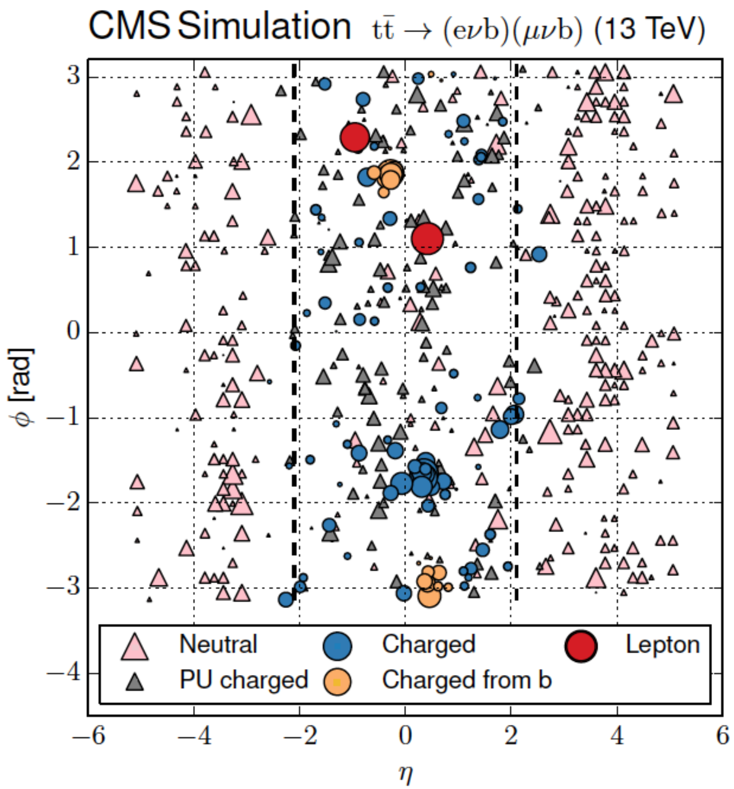
	2D		1D	Hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.03	0.0	0.03	0.03	0.0
JEC (quad. sum)	0.12	0.2	0.82	0.17	0.3
Intercalibration	−0.01	0.0	+0.16	+0.04	+0.1
MPFInSitu	−0.01	0.0	+0.23	+0.07	+0.1
Uncorrelated	−0.12	−0.2	+0.77	+0.15	+0.3
Jet energy resolution	−0.18	+0.3	+0.09	−0.10	+0.2
b tagging	0.03	0.0	0.01	0.02	0.0
Pileup	−0.07	+0.1	+0.02	−0.05	+0.1
All-jets background	0.01	0.0	0.00	0.01	0.0
All-jets trigger	+0.01	0.0	0.00	+0.01	0.0
ℓ+jets Background	−0.02	0.0	+0.01	−0.01	0.0
ℓ+jets Trigger	0.00	0.0	0.00	0.00	0.0
Lepton isolation	0.00	0.0	0.00	0.00	0.0
Lepton identification	0.00	0.0	0.00	0.00	0.0
Modeling uncertainties					
JEC flavor (linear sum)	−0.39	+0.1	−0.31	−0.37	+0.1
Light quarks (uds)	+0.11	−0.1	−0.01	+0.07	−0.1
Charm	+0.03	0.0	−0.01	+0.02	0.0
Bottom	−0.31	0.0	−0.31	−0.31	0.0
Gluon	−0.22	+0.3	+0.02	−0.15	+0.2
b jet modeling (quad. sum)	0.08	0.1	0.04	0.06	0.1
b frag. Bowler–Lund	−0.06	+0.1	−0.01	−0.05	0.0
b frag. Peterson	−0.03	0.0	0.00	−0.02	0.0
semileptonic b hadron decays	−0.04	0.0	−0.04	−0.04	0.0
PDF	0.01	0.0	0.01	0.01	0.0
Ren. and fact. scales	0.01	0.0	0.02	0.01	0.0
ME/PS matching	−0.10 ± 0.08	+0.1	+0.02 ± 0.05	+0.07 ± 0.07	+0.1
ME generator	+0.16 ± 0.21	+0.2	+0.32 ± 0.13	+0.21 ± 0.18	+0.1
ISR PS scale	+0.07 ± 0.08	+0.1	+0.10 ± 0.05	+0.07 ± 0.07	0.1
FSR PS scale	+0.23 ± 0.07	−0.4	−0.19 ± 0.04	+0.12 ± 0.06	−0.3
Top quark p_T	+0.01	−0.1	−0.06	−0.01	−0.1
Underlying event	−0.06 ± 0.07	+0.1	+0.00 ± 0.05	−0.04 ± 0.06	+0.1
Early resonance decays	−0.20 ± 0.08	+0.7	+0.42 ± 0.05	−0.01 ± 0.07	+0.5
CR modeling (max. shift)	+0.37 ± 0.09	−0.2	+0.22 ± 0.06	+0.33 ± 0.07	−0.1
"gluon move" (ERD on)	+0.37 ± 0.09	−0.2	+0.22 ± 0.06	+0.33 ± 0.07	−0.1
"QCD inspired" (ERD on)	−0.11 ± 0.09	−0.1	−0.21 ± 0.06	−0.14 ± 0.07	−0.1
Total systematic	0.71	1.0	1.07	0.61	0.7
Statistical (expected)	0.08	0.1	0.05	0.07	0.1
Total (expected)	0.72	1.0	1.08	0.61	0.7

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

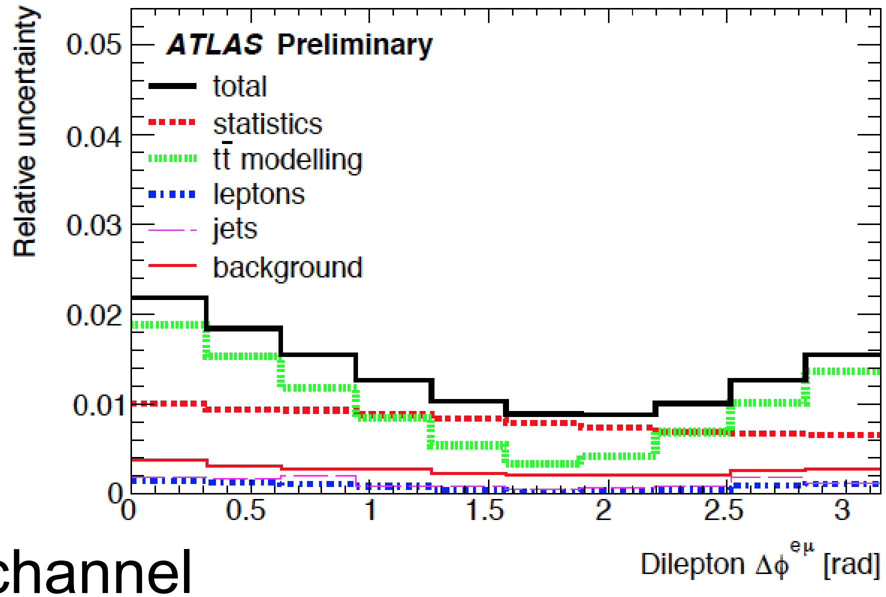
CTEQ, MSTW, NNPDF, HERA LO PDF
Extracted by varying 10 parameters
Fitting UE and min bias at 7 TeV

Param	CTEQ	MSTW	N
SigmaProcess:alphaSvalue	0.144	0.140	
SpaceShower:pT0Ref	1.30	1.62	
SpaceShower:pTmaxFudge	0.95	0.92	
SpaceShower:pTdampFudge	1.21	1.14	
SpaceShower:alphaSvalue	0.125	0.129	
TimeShower:alphaSvalue	0.126	0.129	
BeamRemnants:primordialKThard	1.72	1.82	
MultipartonInteractions:pT0Ref	1.98	2.22	
MultipartonInteractions:alphaSvalue	0.118	0.127	
BeamRemnants:reconnectRange	2.08	1.87	

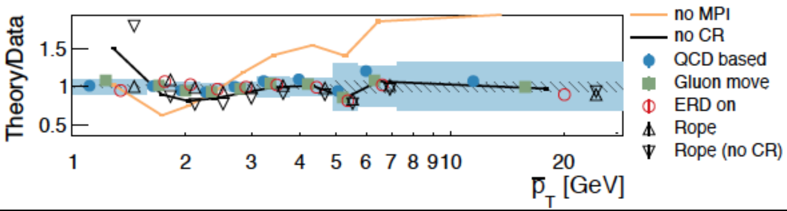
CMS Pythia8 CP tunes @ 13 TeV

Parameter description	Name in PYTHIA8	Range considered
MPI threshold [GeV], pT0Ref, at $\sqrt{s} = \sqrt{s_0}$	MultipartonInteractions:pT0Ref	1.0–3.0
Exponent of $\sqrt{s}$ dependence, ϵ	MultipartonInteractions:ecmPow	0.0–0.3
Matter fraction contained in the core	MultipartonInteractions:coreFraction	0.1–0.95
Radius of the core	MultipartonInteractions:coreRadius	0.1–0.8
Range of color reconnection probability	ColorReconnection:range	1.0–9.0

NNPDF3.1 LO/NLO/NNLO PDF sets and α_s for ME and shower as inputs
Extracted by varying 5 parameters



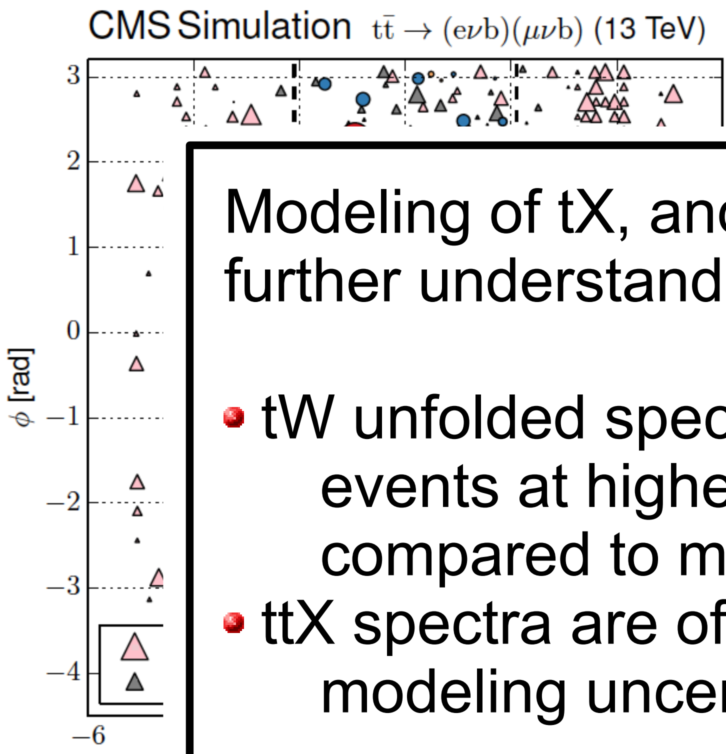
- 1st measurement of UE modeling in dilepton channel
  - MPI effects visible, **CR not quite yet**



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

Modeling & Tuning

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

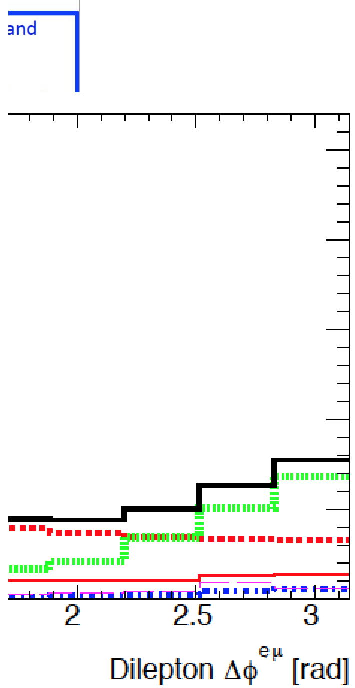


ATLAS Pythia8 A14 tunes @ 8TeV

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

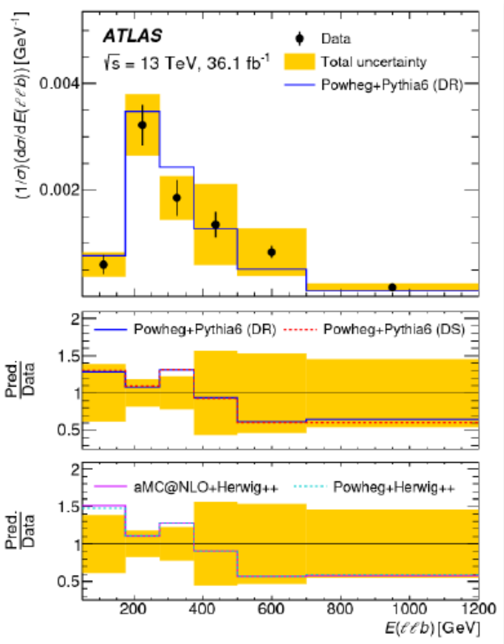
CMS Pythia8 CP tunes @ 13 TeV

Parameter description	Name in PYTHIA8	Range considered
MPI threshold [GeV], pT0Ref, at $\sqrt{s} = \sqrt{s_0}$	MultipartonInteractions:pT0Ref	1.0–3.0
Exponent of $\sqrt{s}$ dependence, ϵ	MultipartonInteractions:ecmPow	0.0–0.3
Matter fraction contained in the core	MultipartonInteractions:coreFraction	0.1–0.95
		0.1–0.8
		1.0–9.0

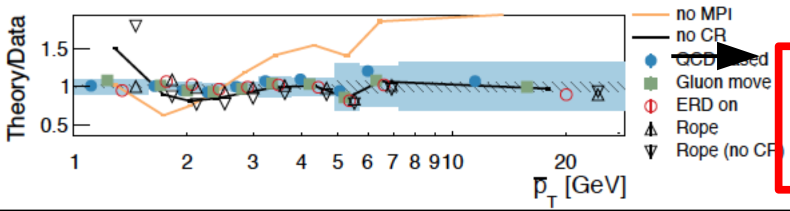


Modeling of tX, and ttX critical to further understand uncertainties

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

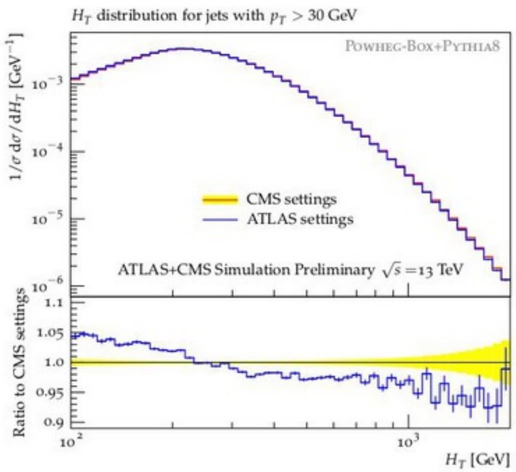


- 1st me…
  - MPI effects visible, CR not quite yet

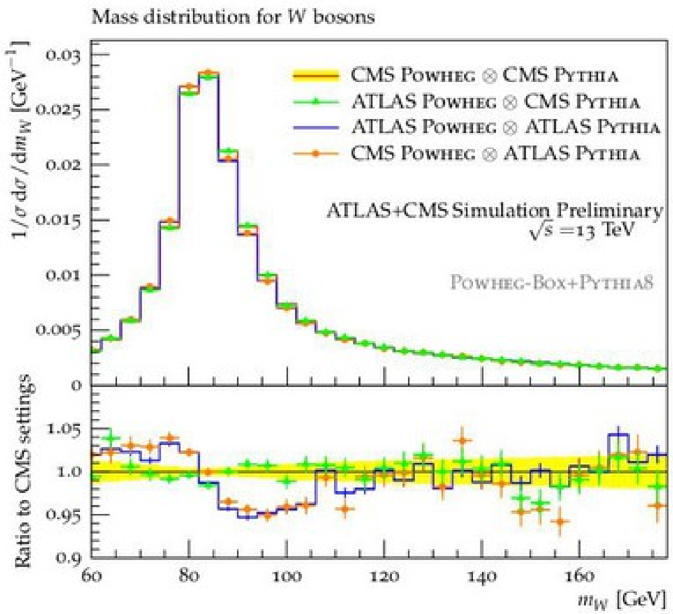


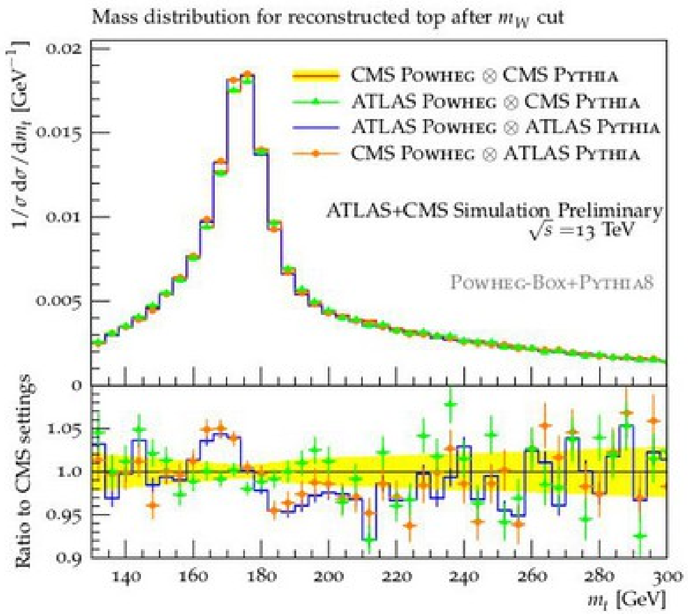
Towards a common MC setup in ATLAS & CMS - 1st step: run settings in other experiment setup

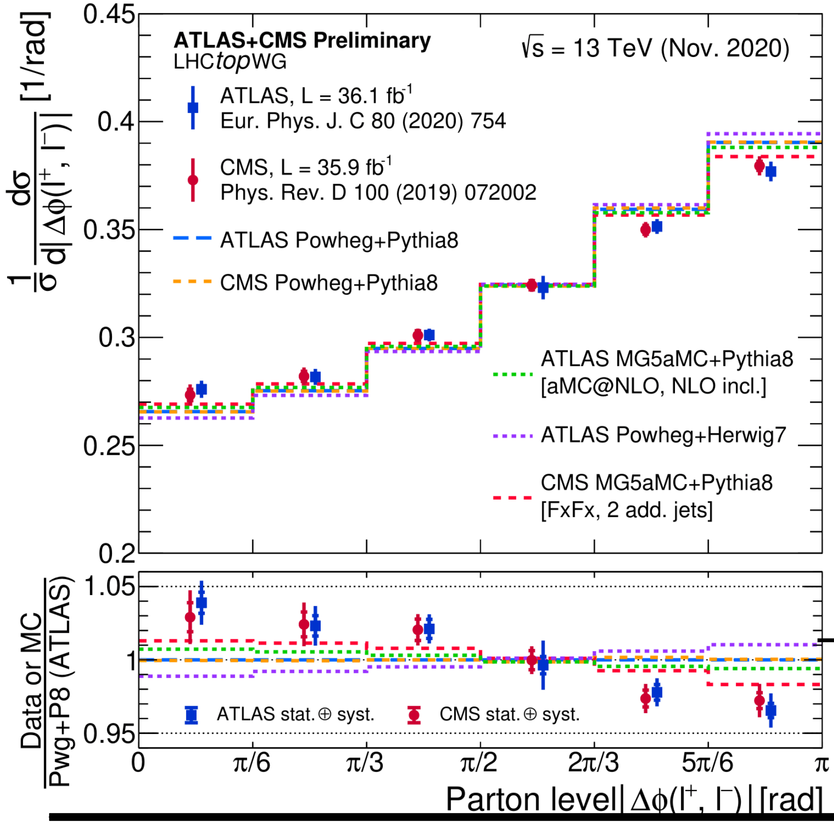
Common MC



- Complex issue of mixed setup in ATLAS & CMS





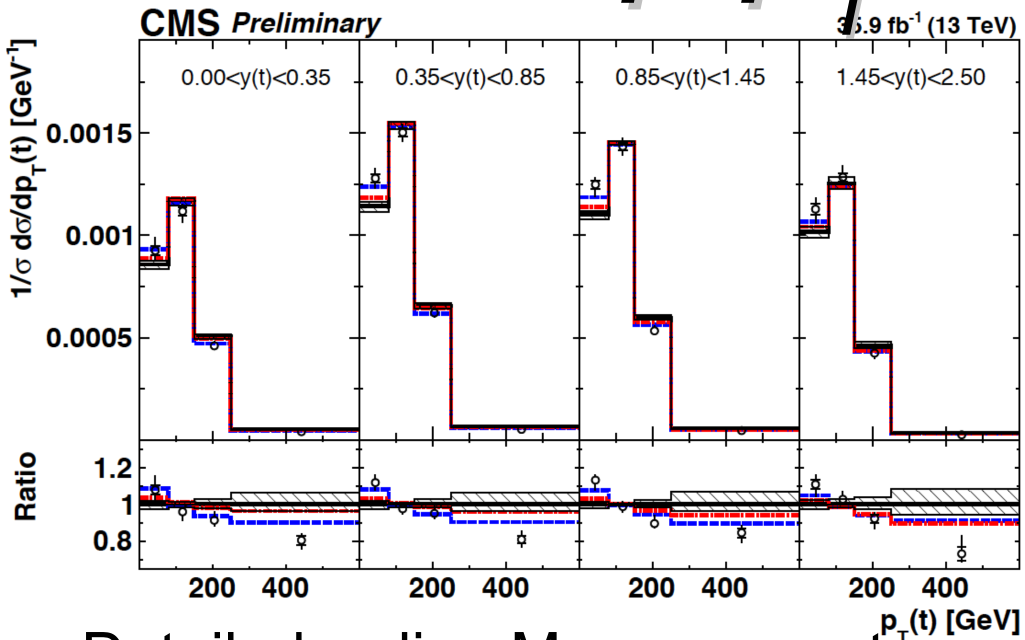


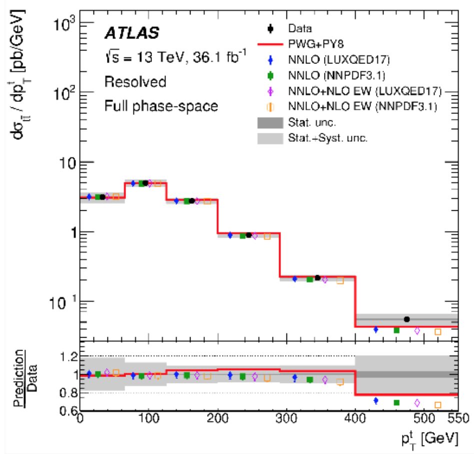
- Facilitate future combinations, studies on systematic uncertainties, etc.
- Vital and critical for success of Run 3 (and beyond)
- Many details, please check:

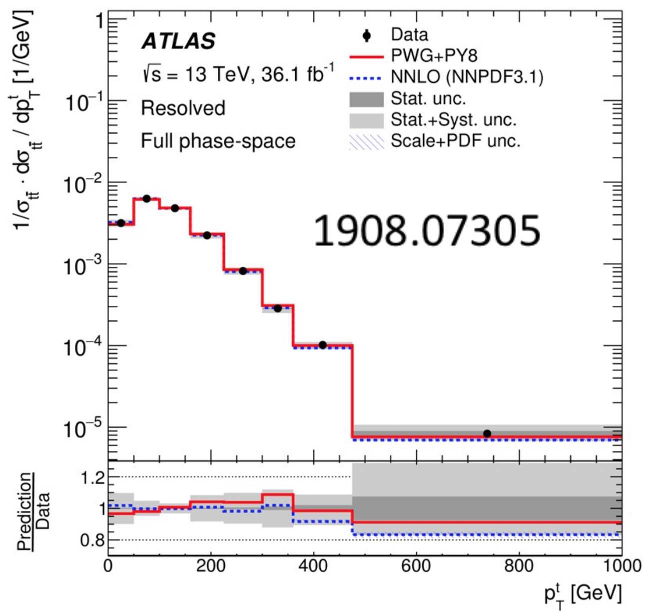
[LHCtopWG: Common samples]

Towards a common MC setup in ATLAS & CMS: Gained momentum, hopeful for TOP21

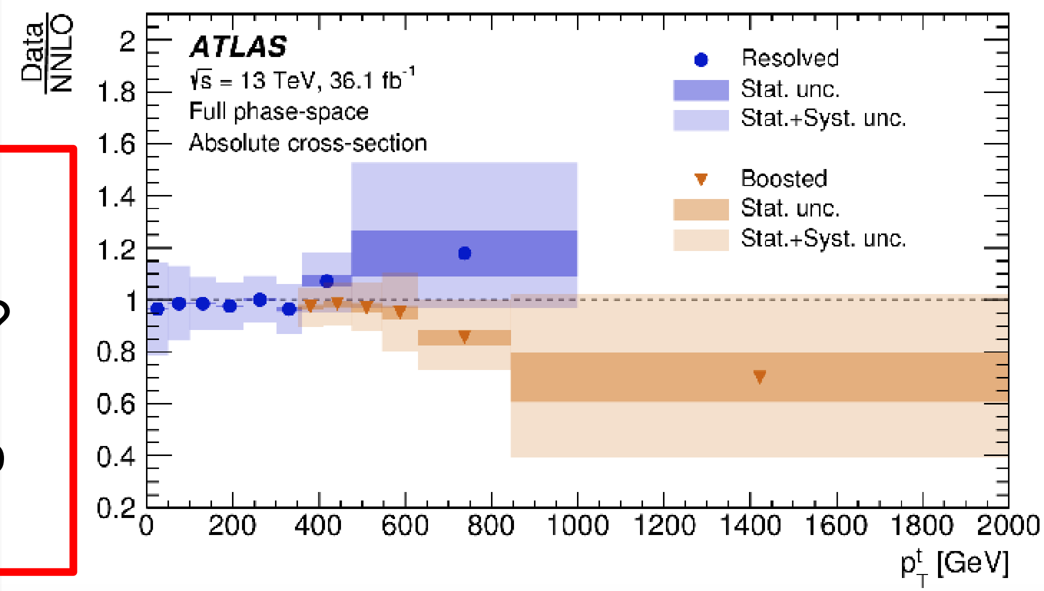
The top p_T saga...continues







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

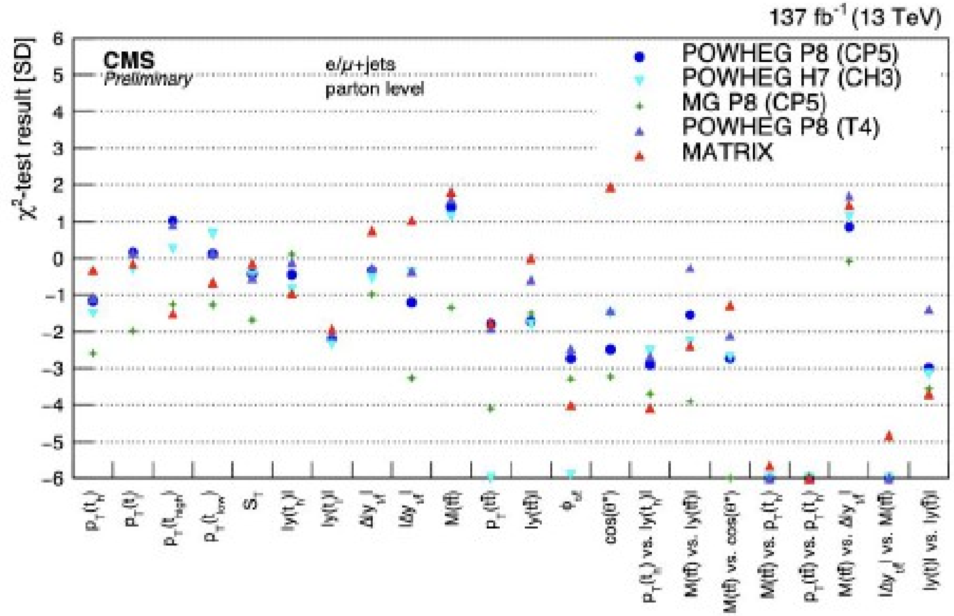


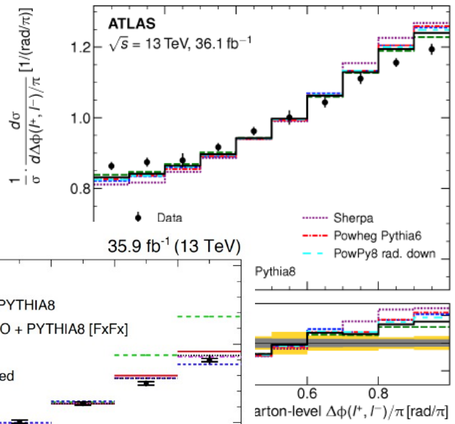
→

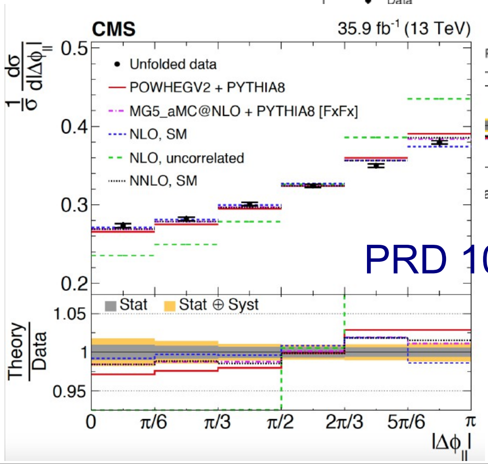
- Slopes in 13 TeV ATLAS & CMS data
- Large systematic uncertainty – further understanding, common procedure ?
  - Common MC clearly helps...
- Theory input: experiments are eager to use an "NNLO MC"

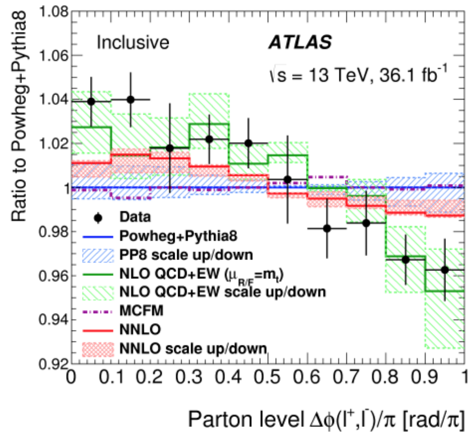
Challenges in multi-D x-sec's

- More global approach is needed to fully harvest the wealth of top data
  - LHCtopWG is the proper forum, could be a “fitter” forum a la PDF groups
  - Dedicated discussion on systematic uncertainties
  - Combinations in the full kinematic spectra
  - Theory setup & uncertainties critical









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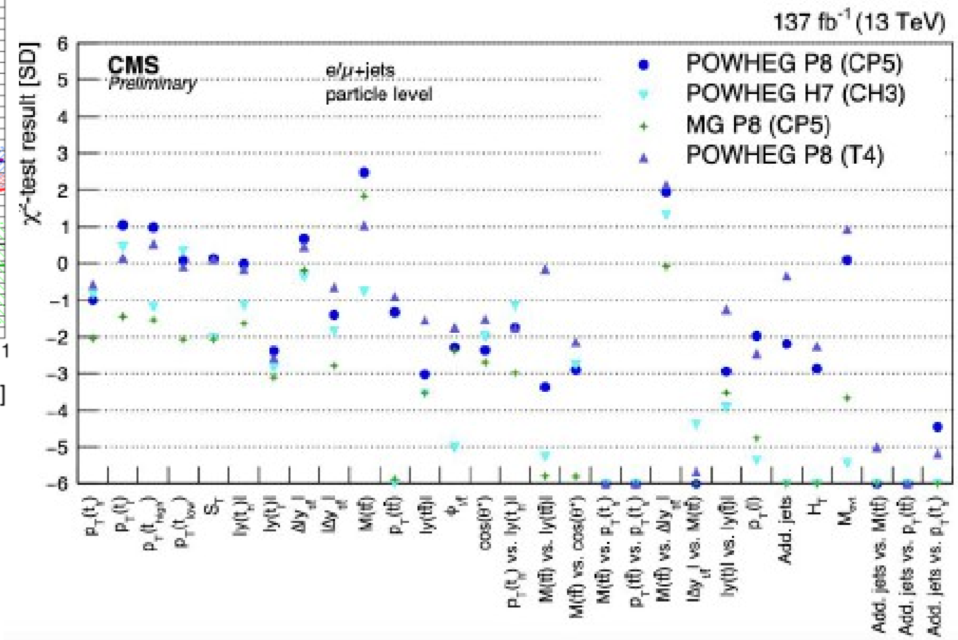


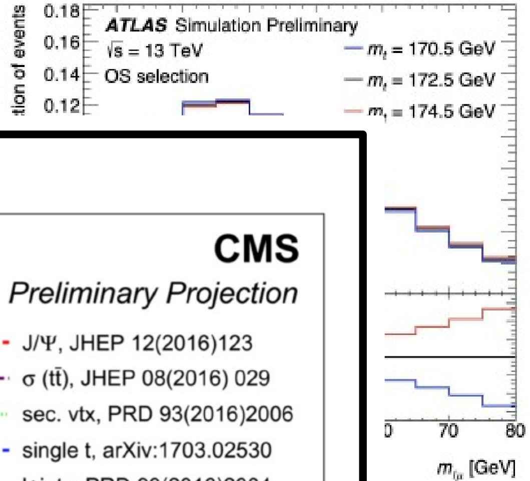
Top mass – alternative

Latest top mass measurements:

- ATL
  - L
- CM
  - C

m_{top}

GeV (!)



Highly precise cross sections (CMS) or leptonic variables (ATLAS):

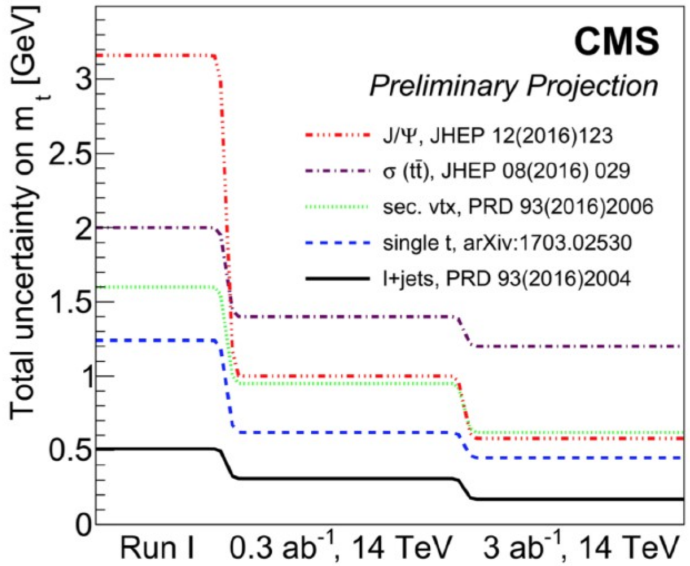
→ both at the level of 0.5%

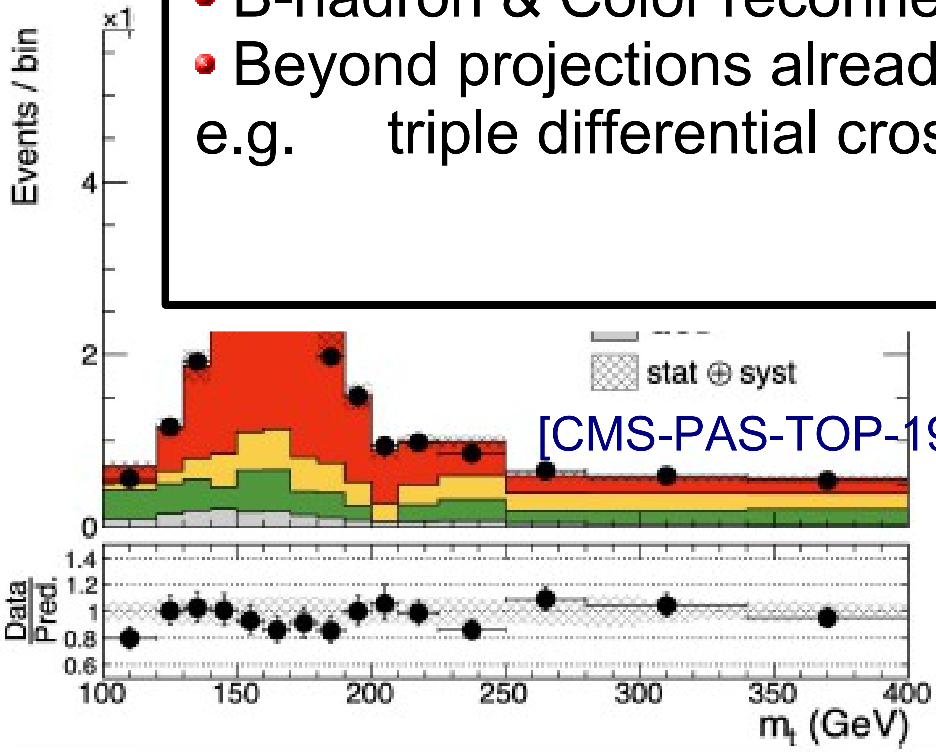
[ATLAS-CONF-2019-046]

[arXiv:1904.05237 sub. to EPJ-C]

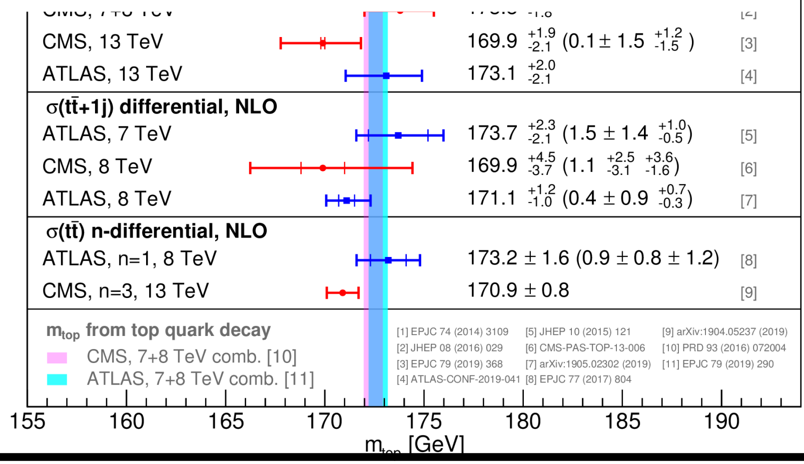
- B-hadron & Color reconnection
- Beyond projections already (as usual),

e.g. triple differential cross sections





[CMS-PAS-TOP-19-009]

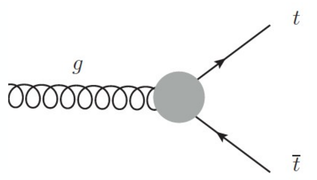


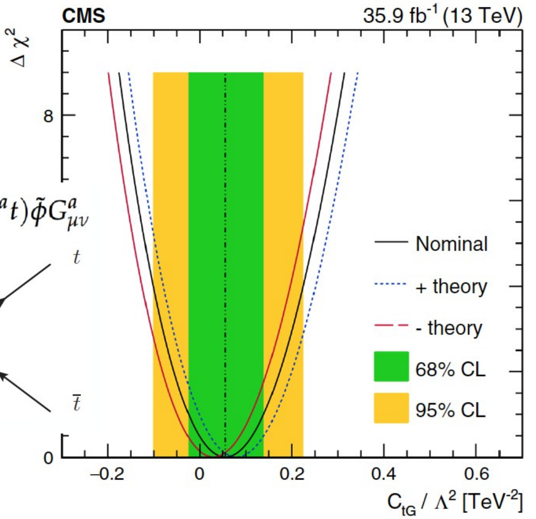
Effective field theory...

- EFT is now widely used to search for off-resonance effects due to BSM contributions

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

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{\phi}G^a_{\mu\nu}$$

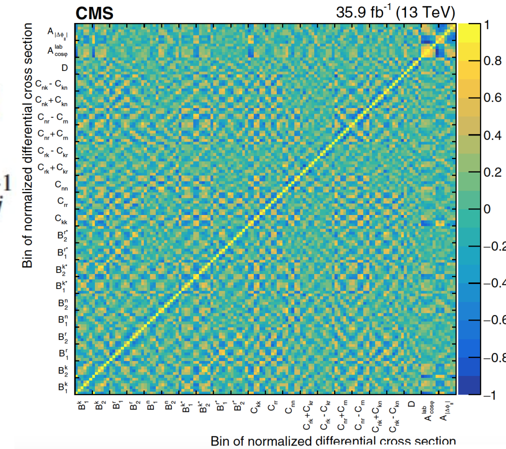




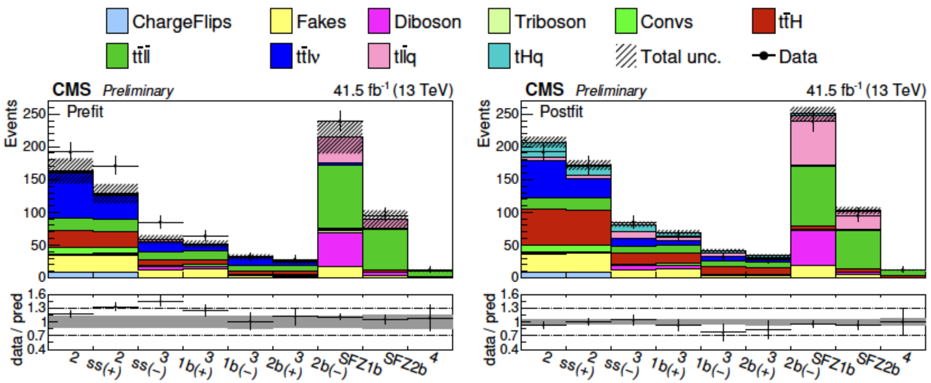
e.g. Spin correlations employs systematic correlation matrix used in 120-bin fit:

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

PRD 100 (2019) 072002

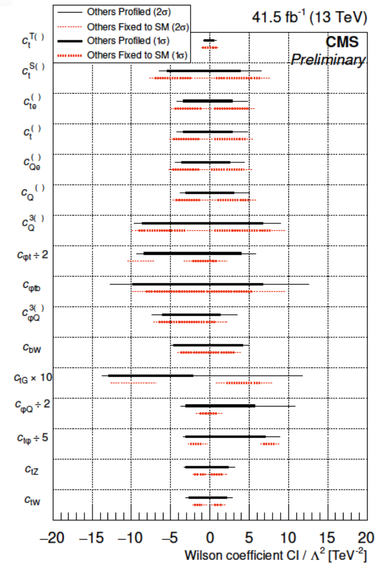


- More global approaches to capture experimental correlations, EFT at particle level to boost sensitivities

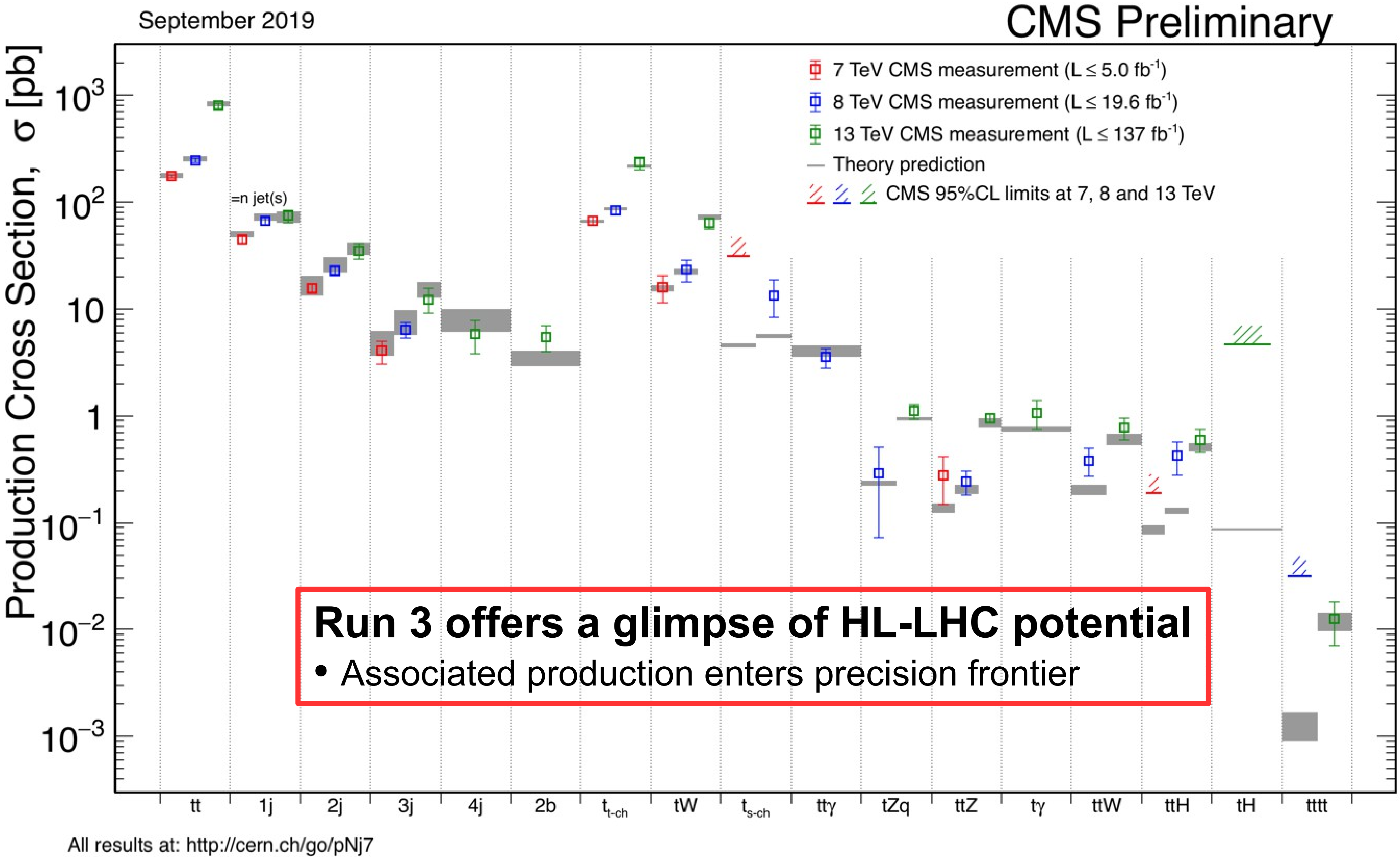


- Associated top production to probe for BSM effects
- Consistent treatment of experimental correlations

[CMS-PAS-TOP-19-001]



A bright top quark future ahead

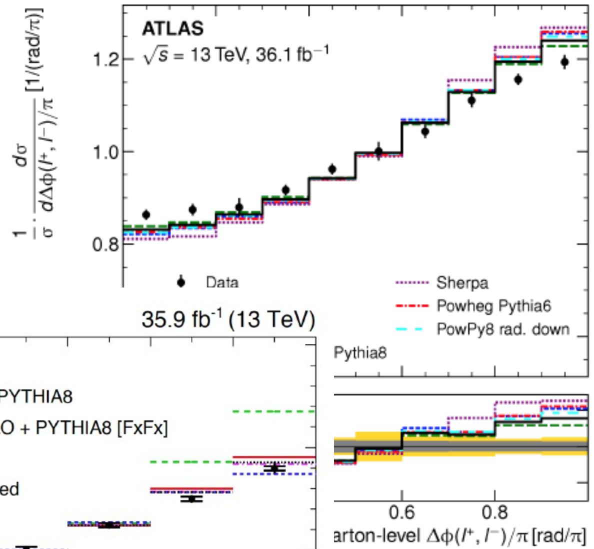


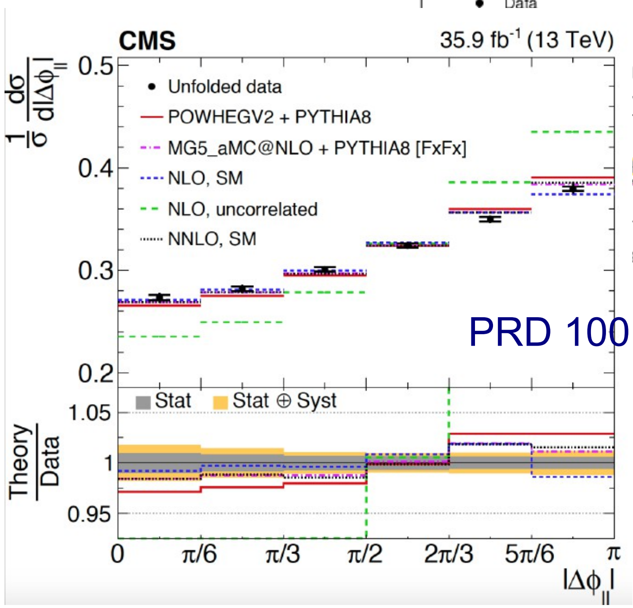
Run 3 offers a glimpse of HL-LHC potential

- Associated production enters precision frontier

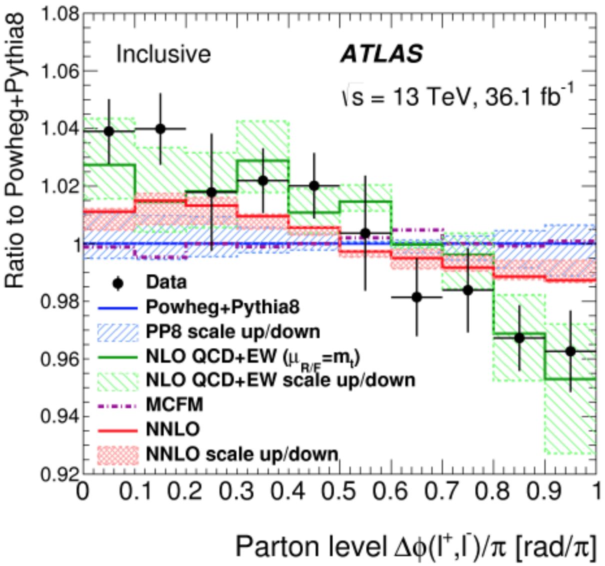
Opportunities

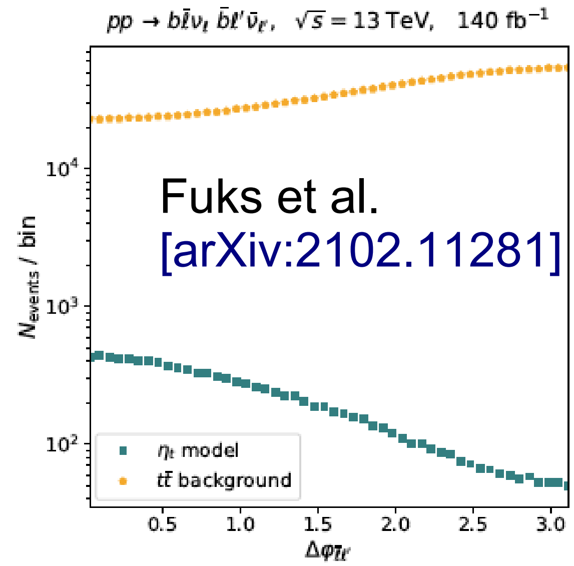
- Are a plenty...
- Biased selection: Toponium (!)
- LHCtopWG Joint Seminar, 13th April 2021
  - 9am eastern, indico
    https://indico.cern.ch/event/1017911/



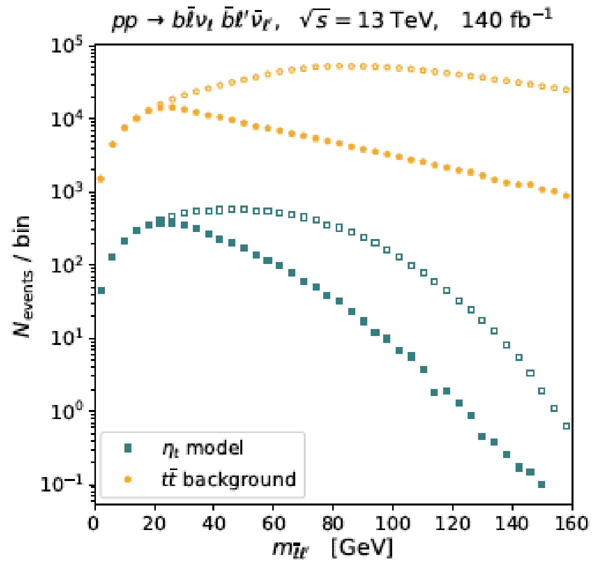


PRD 100 (2019) 072002





Fuks et al. [arXiv:2102.11281]



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

→ FCNCs and other statistically limited processes improve

Need all avenues to pin down BSM, challenges ahead:

→ Common MC samples

→ More global aproaches (kinematic distributions, EFT)

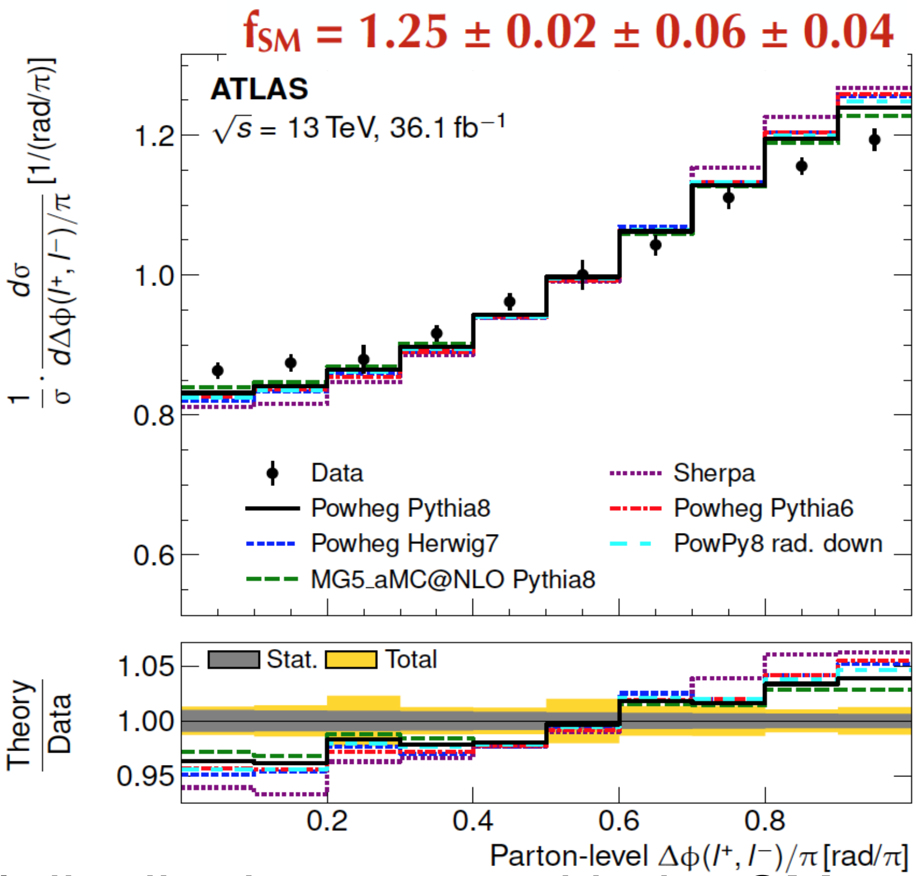
→ Use vast top sample as b-physics lab

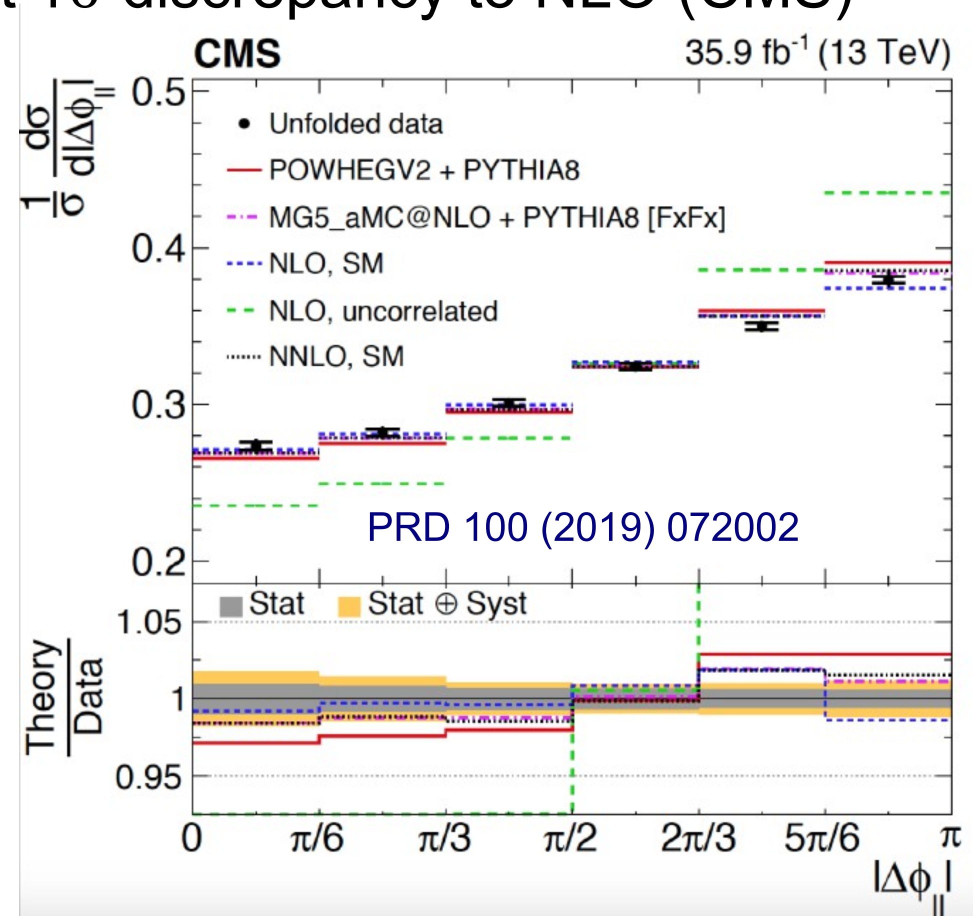
Backup...

...even more distributions than shown so far...

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

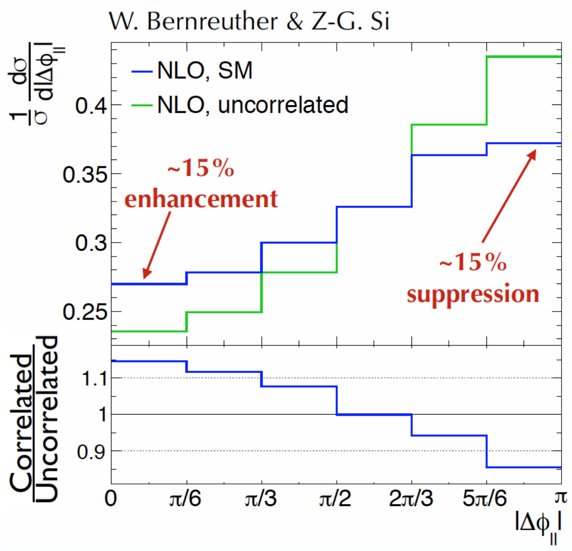
Spin Correlations

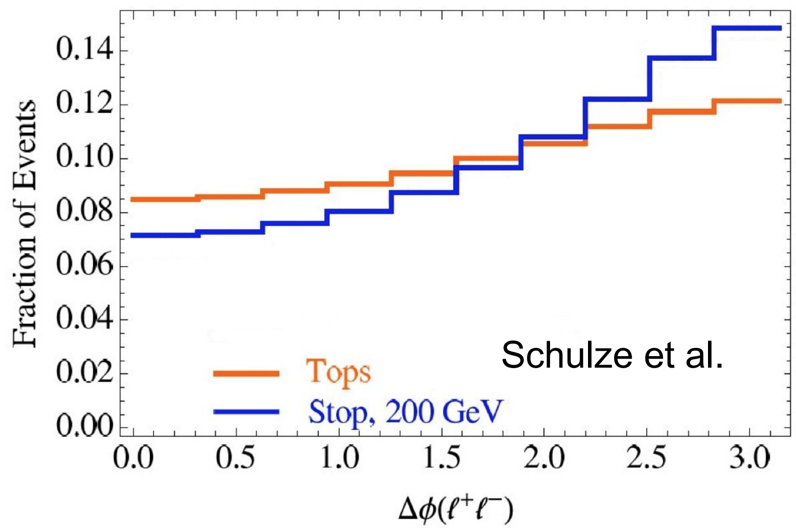
- Double-differential cross section allows to access spin correlation and polarization information in top quark events

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

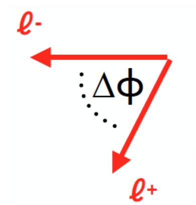
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a\, d\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a\cos\theta_+^a + B_-^b\cos\theta_-^b - C(a,b)\cos\theta_+^a\cos\theta_-^b)$$

- 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)

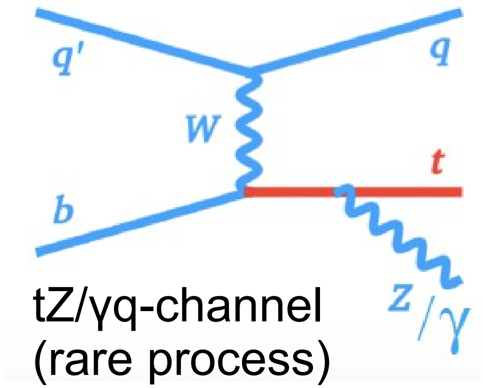




Angle between leptons in transverse plane



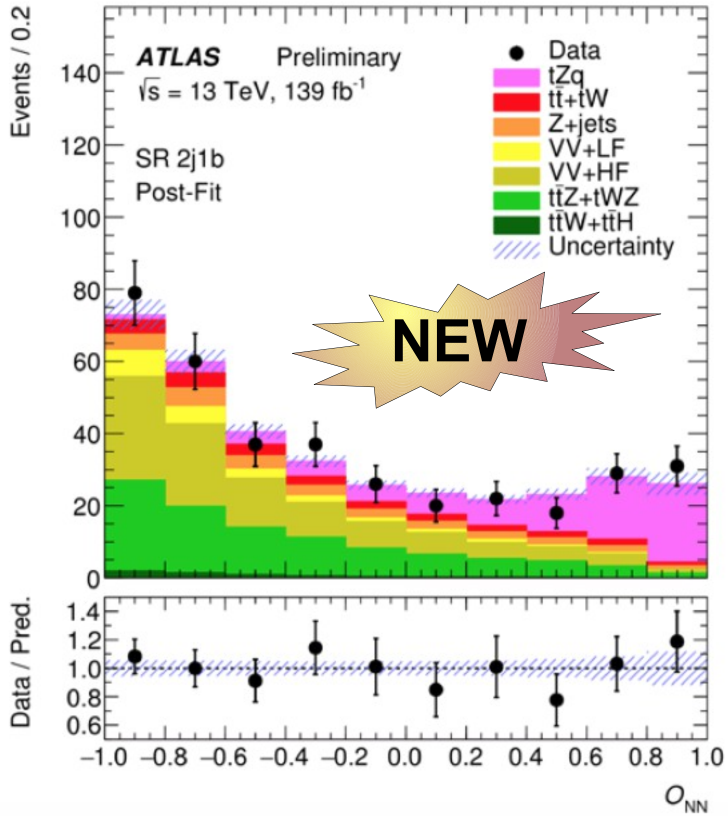
Rare single top quark

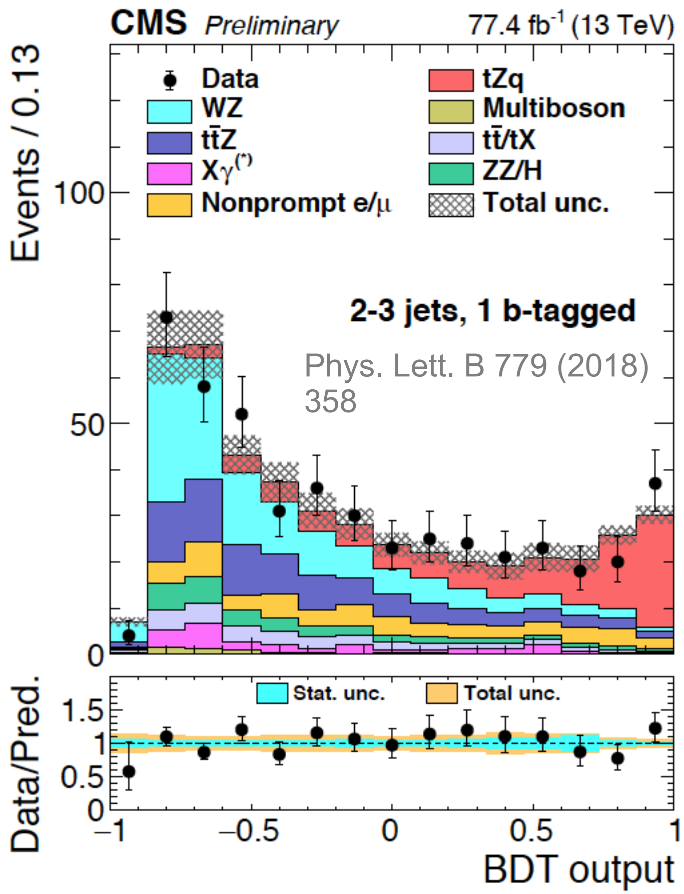


SM NLO prediction:

$\sigma = 94.2 \pm 3.1$ 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

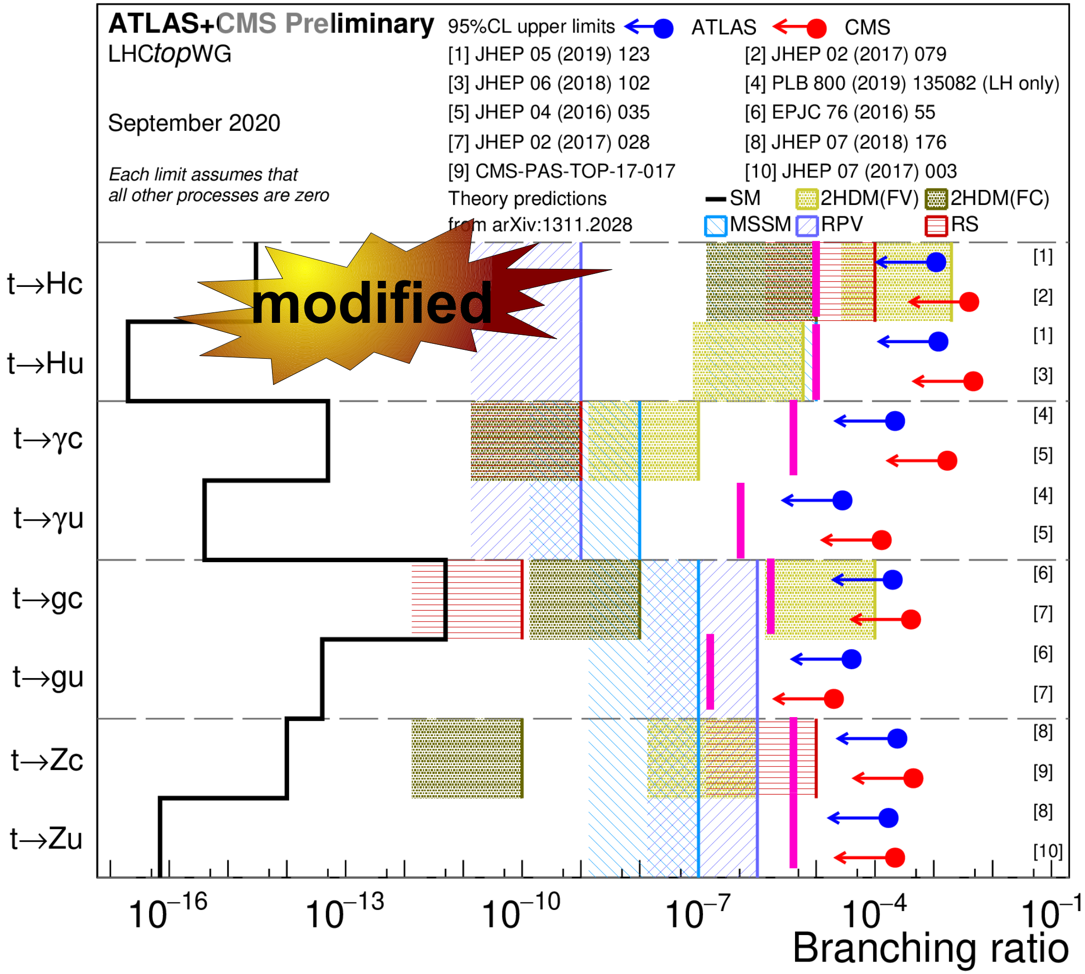
- Observation of tZq

Rare top quark decays – Prospects

Flavor-changing neutral currents (FCNCs)

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

Caveats: 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

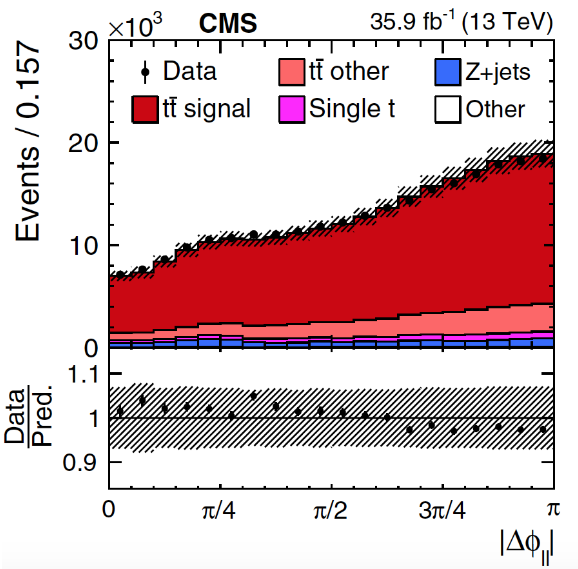
Challenges in multi-D x-sec's

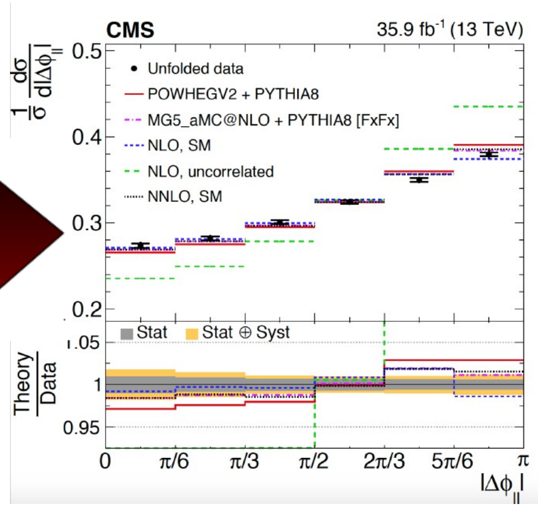
"To fully correct the data or not" → always do both!

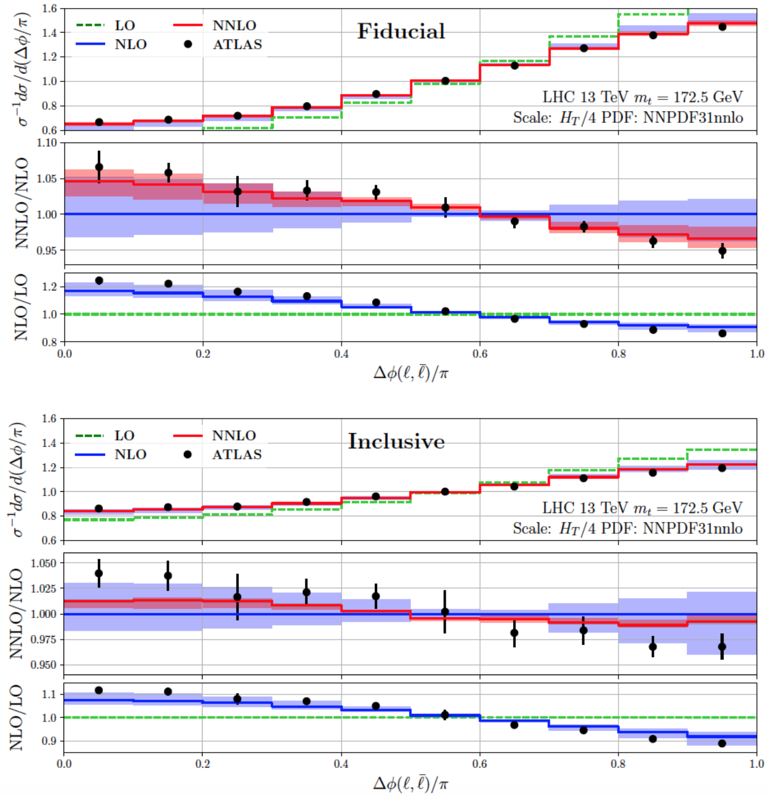
- Parton level correction:
  - More precise theoretical predictions ↔ larger extrapolation uncertainties
  - Global fits, any comparison, combinations
- Particle level: more precise

arxiv:1901.05407

- Likelihood-based unfolding, including nuisance fit
- Rely on particle level to feed into effective field theories



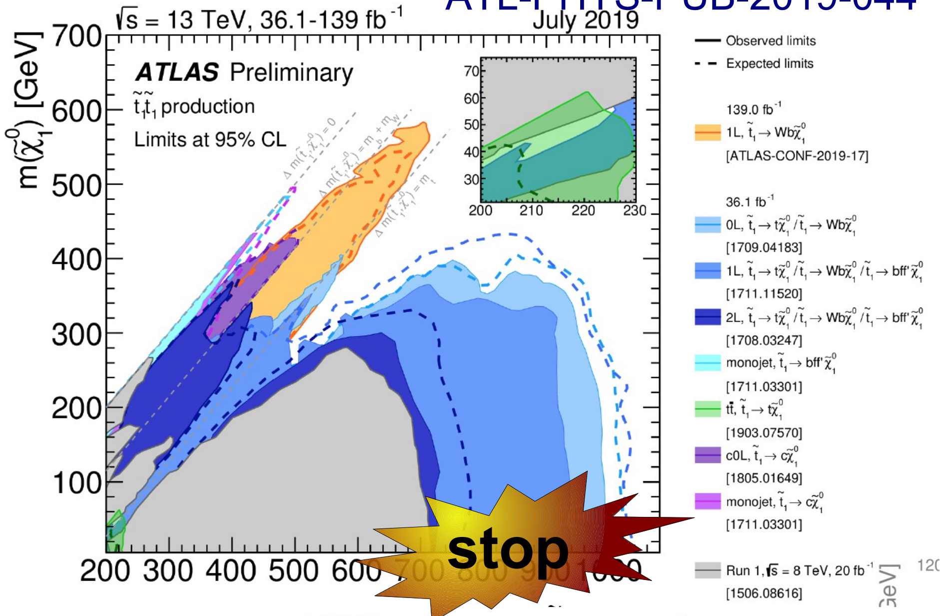


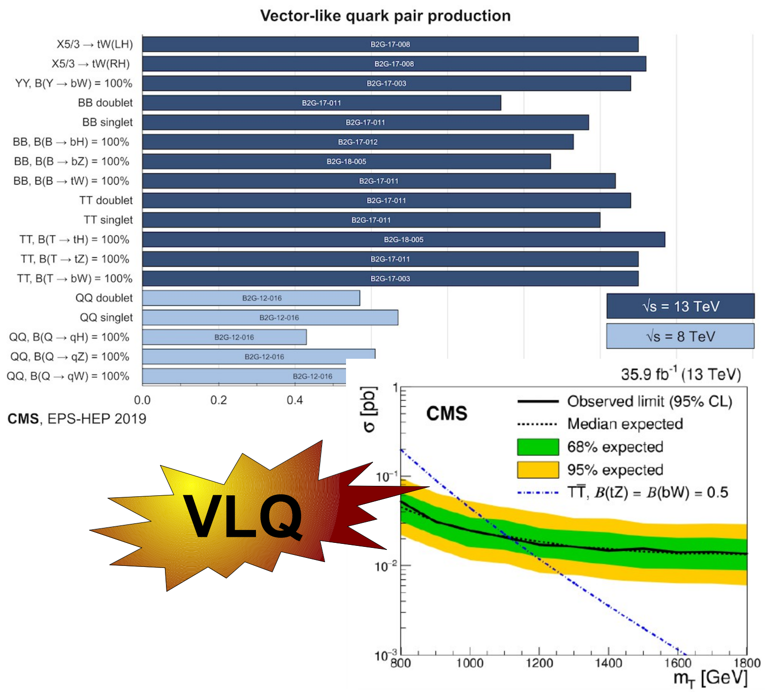


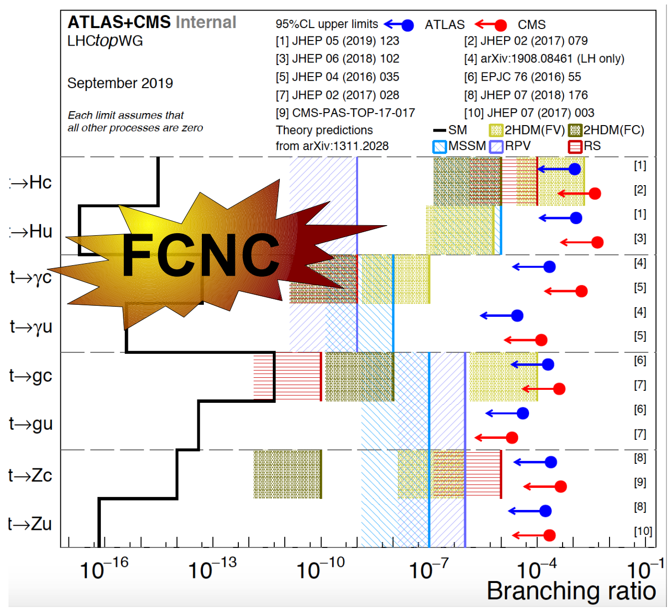
New friends for the top ?

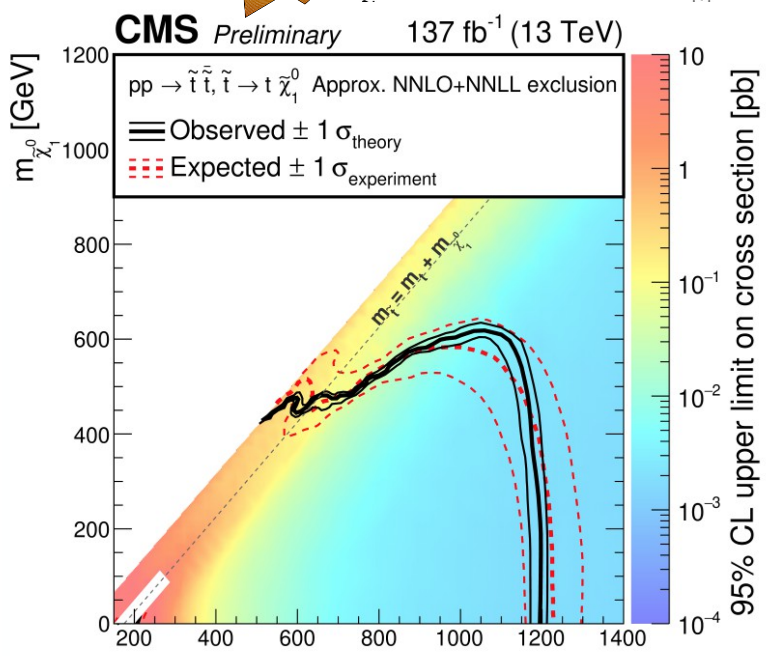
- “stealth” top region not yet fully excluded (mind BR of stop → top+neutralino)
- $t\bar{t}$ modeling uncertainties dominate searches
  - Danger of “over-tuning” ? Minimized by specific phase space / control regions
  - SM measurements biased by stealthy top quark partner ?

ATL-PHYS-PUB-2019-044







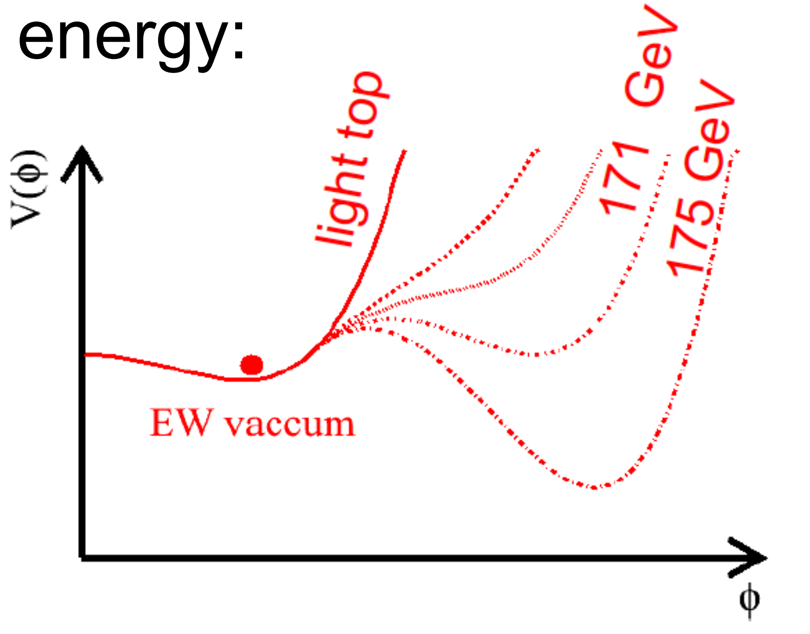


Acc. by JHEP [arXiv:1912.08887]

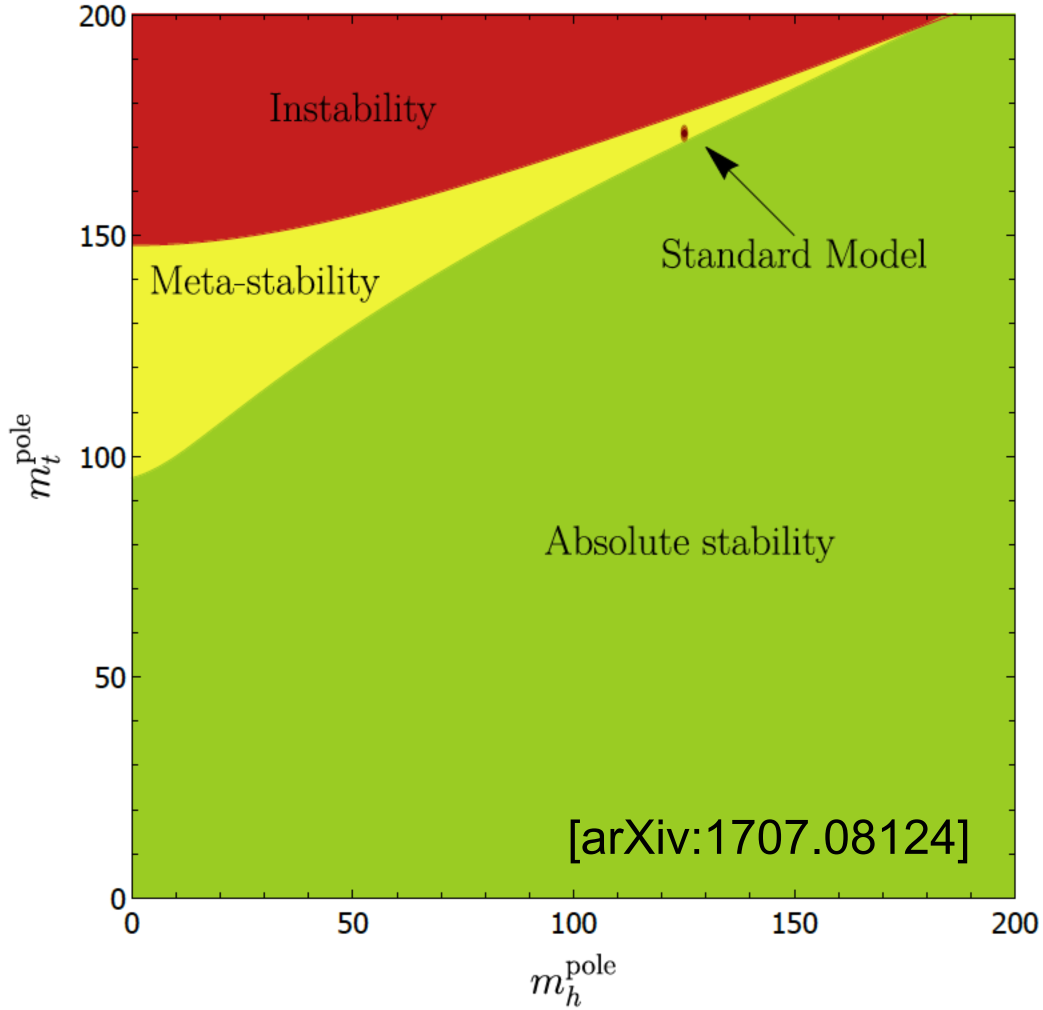
SM vacuum stability

- 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:

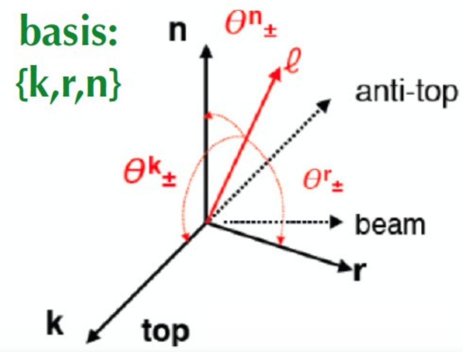


“Don't panic!” (D. Adams)
Lifetime is much much larger than current age of the universe: $10^{80} - 10^{320}\ t_{Universe}$



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**

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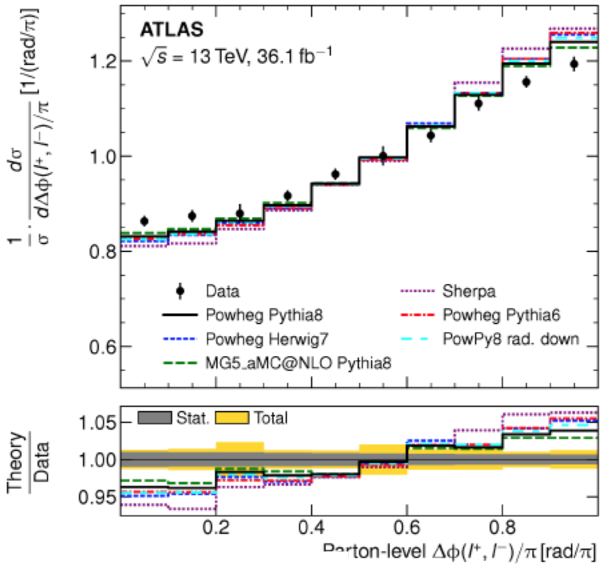
Dilepton distribution probes top spin in 3 dimensions

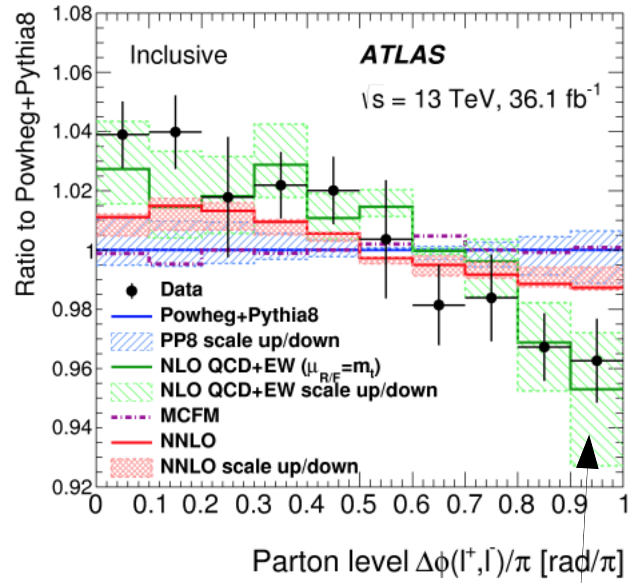
→ Leptons follow parent top spin (average polarisation given by 3-vectors B+/-)

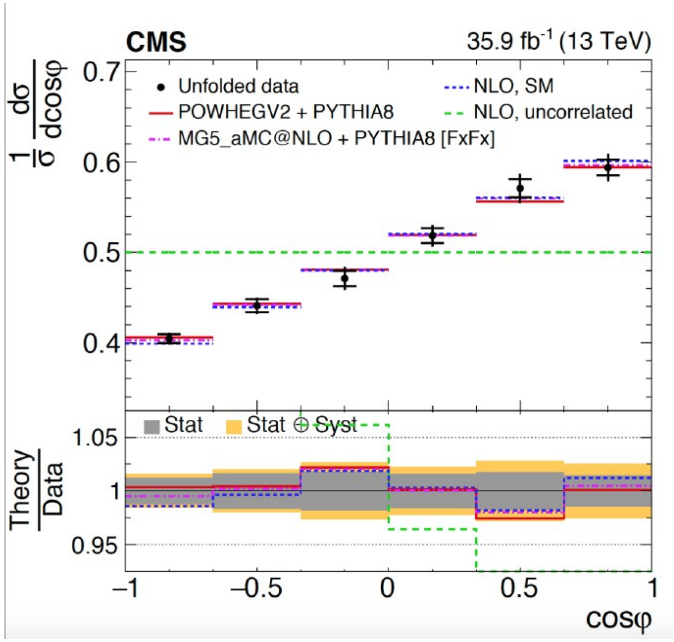
→ Relative lepton directions follow 3x3 matrix C of spin correlation coefficients

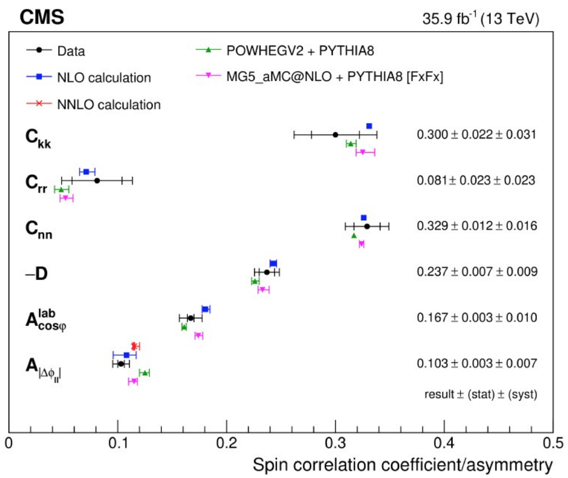
Top Quark Properties...

- 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	$2.2 \pm 0.9\ ^{+2.5}_{-1.7} \pm 0.7$

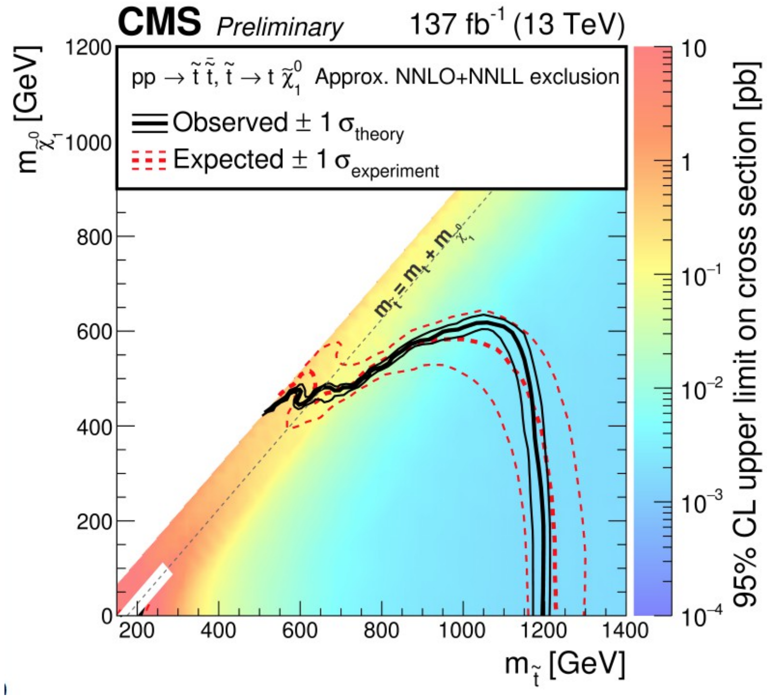
NLO theory slope and uncertainty appropriate ?

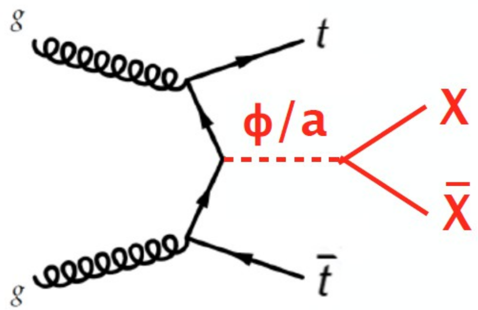
F_{SM} = 0.97 ± 0.05 (stat+syst)

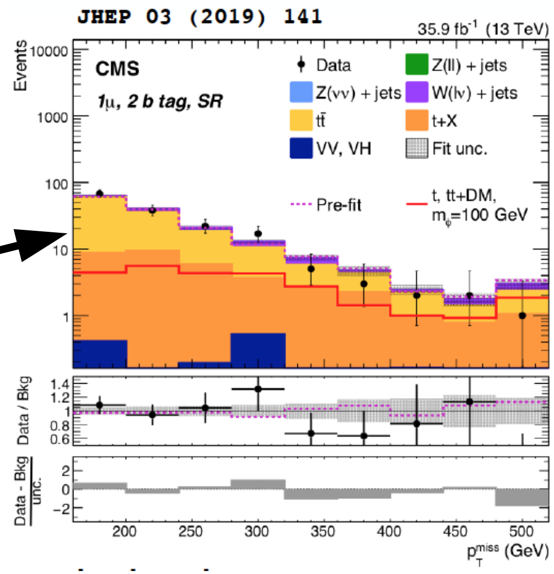
New friends for the top ?

Dark Matter

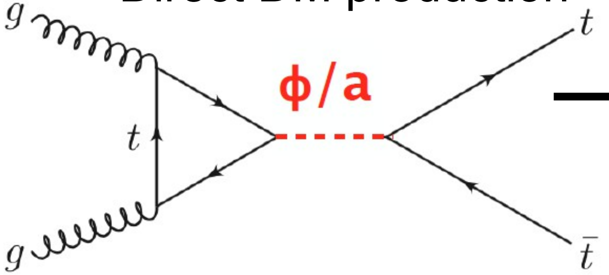
- Dark Matter searches
  - Differential top quark cross section to search for DM

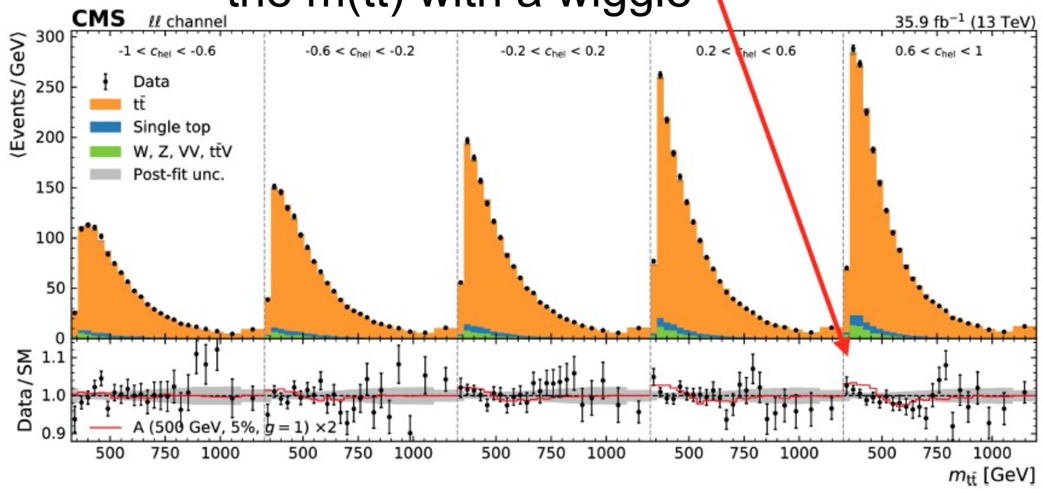






Pseudo-scalar particles alter the m(tt) with a wiggle





...apologies for being even (shorter)^2 here!

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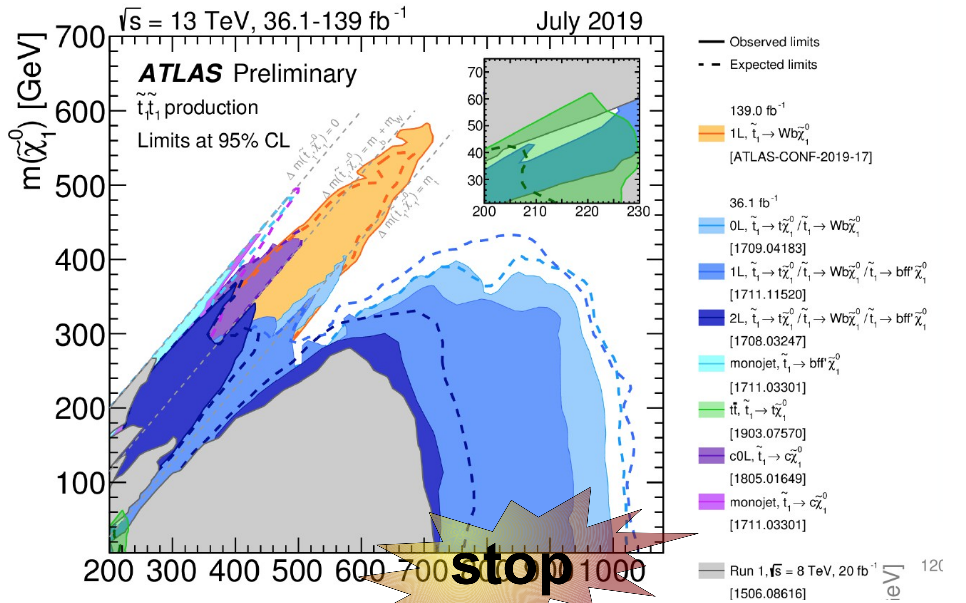
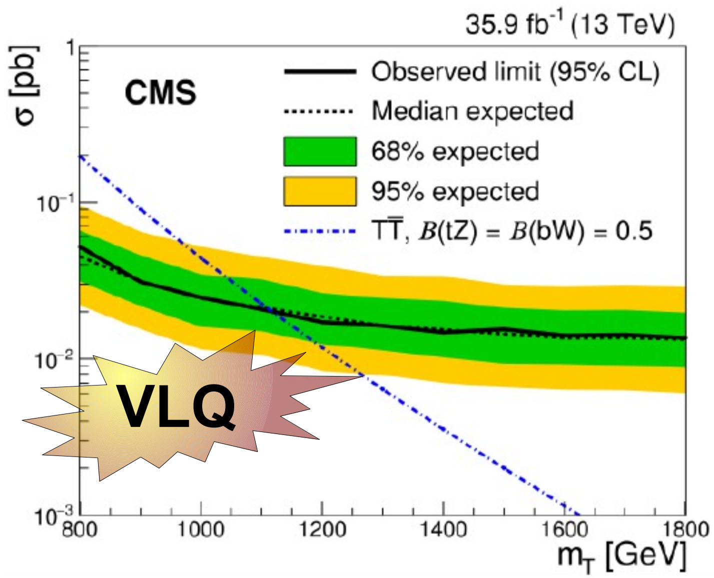
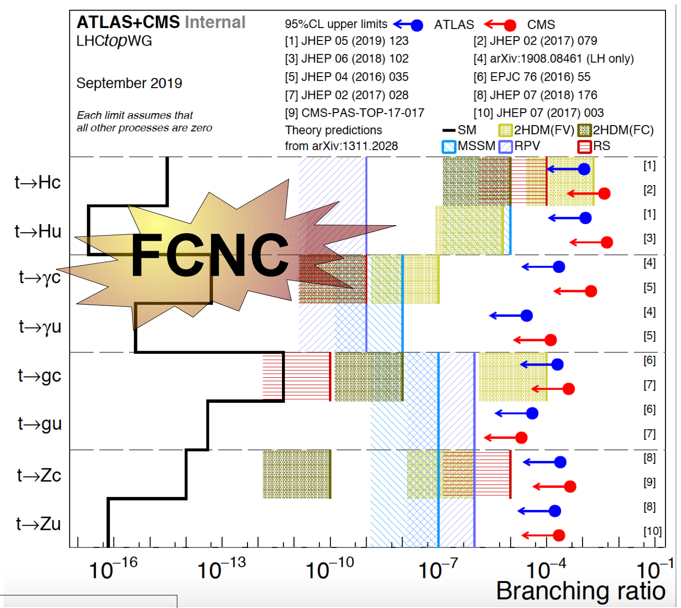
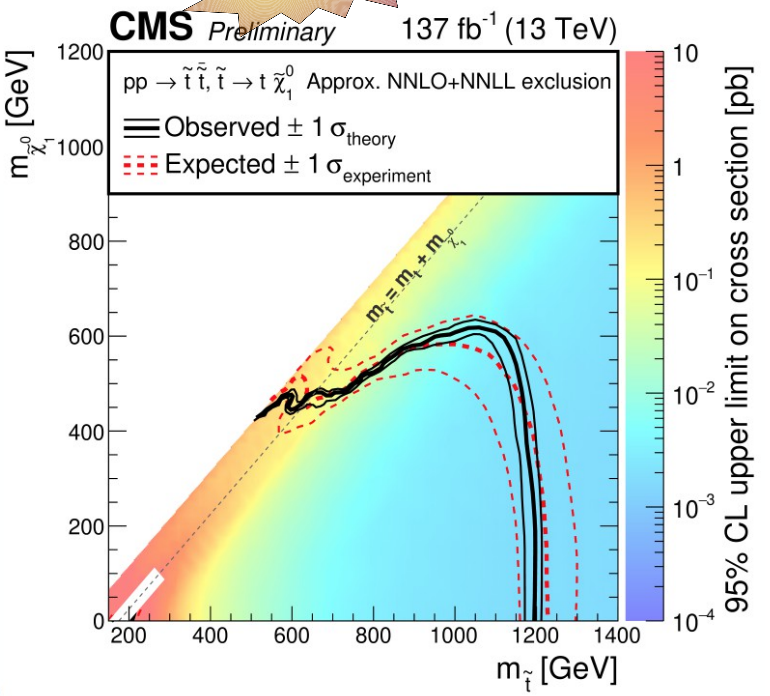




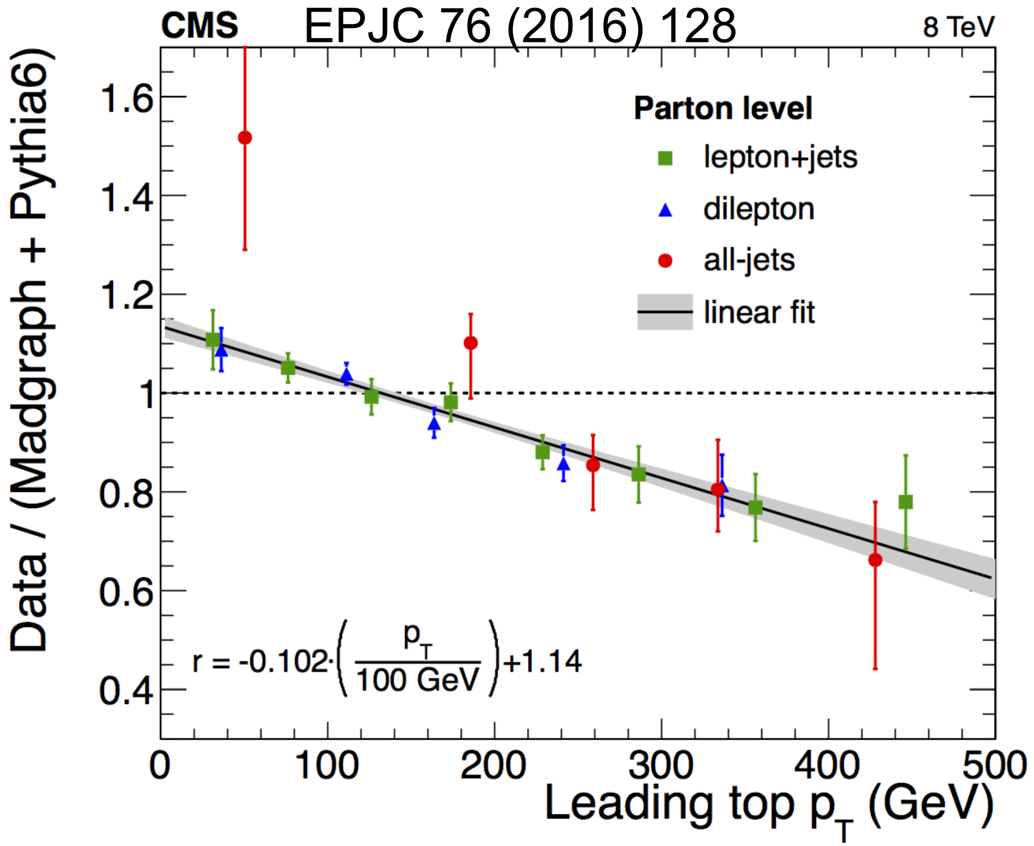


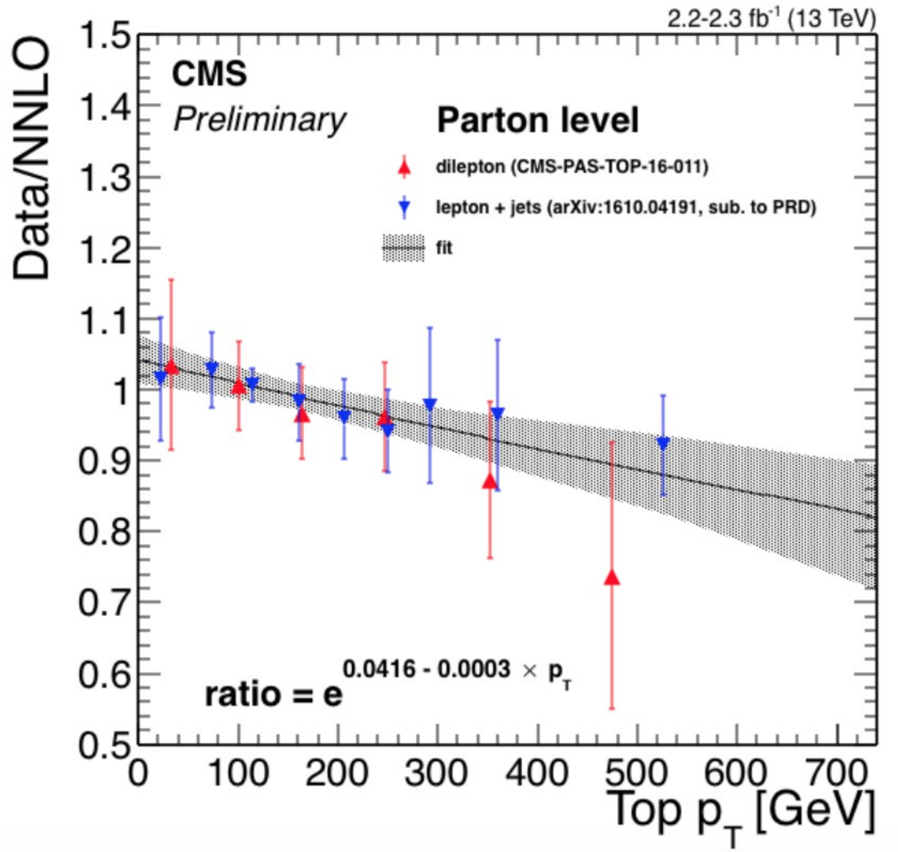


...apologies for being even shorter here!

The top p_T saga...

- Many Run I & Run II **top pT** measurements at ATLAS/CMS **not described** by NLO and most MCs – **pQCD calculation do a better job**
- Data is more soft: consistently seen in all decay channels, **also at 13 TeV**





→ The pT spectra in 8 TeV are described by pQCD NNLO calculations, **but**
→ Indications of a slope wrt NNLO in 13 TeV data