Experimental summary

12^{th} International Workshop on Top Quark Physics

Beijing – 22^{nd} - 27^{th} September, 2019

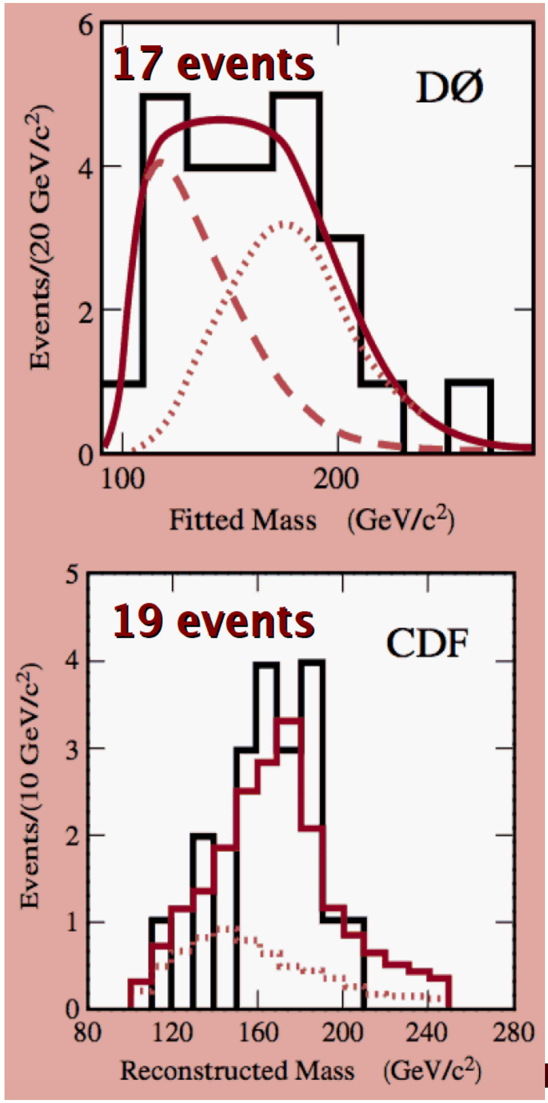
Disclaimer: Impossible to cover wealth of top physics, apologies in advance for having not shown your favorite result.

Andreas Jung (Purdue University)

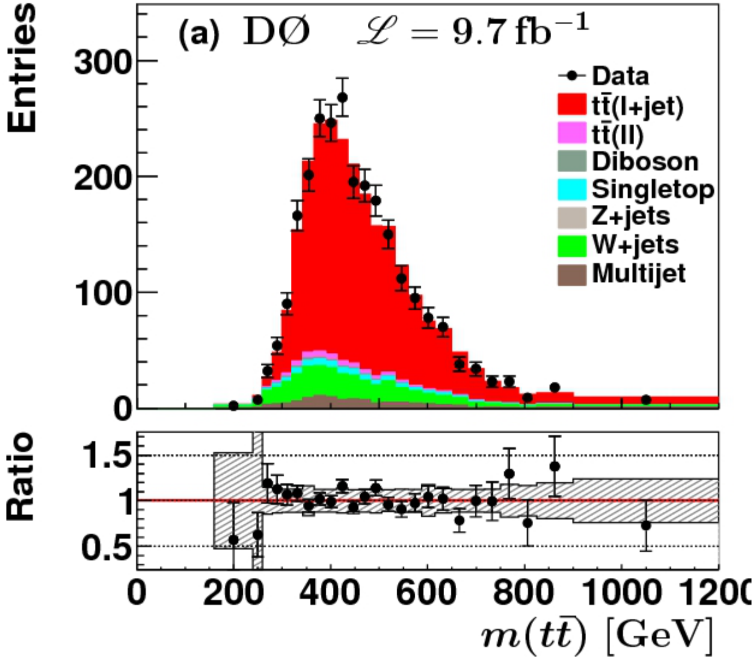
September 27^{th}, 2019

The past...

Discovery at Tevatron: 1995

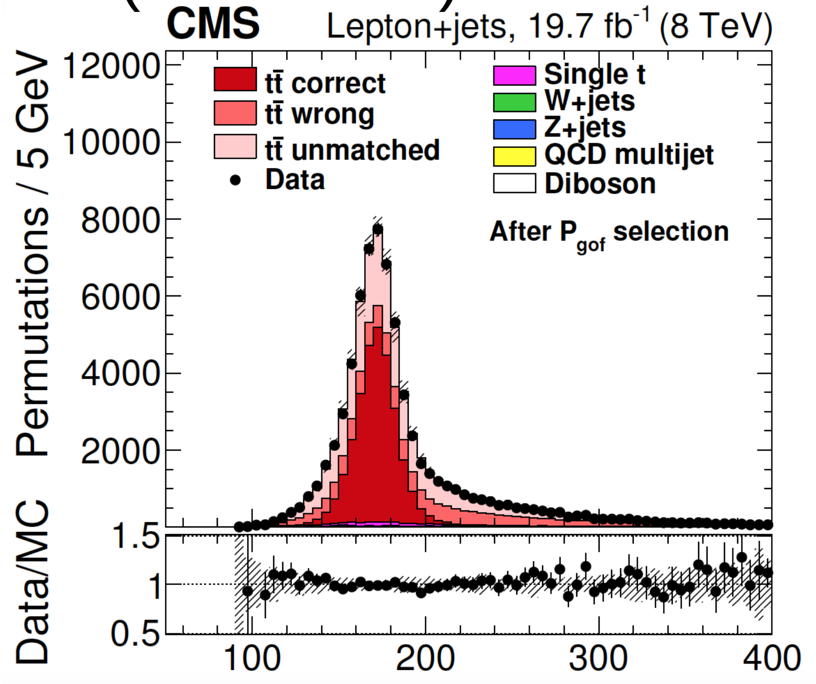


1000's events (Tevatron Run II)



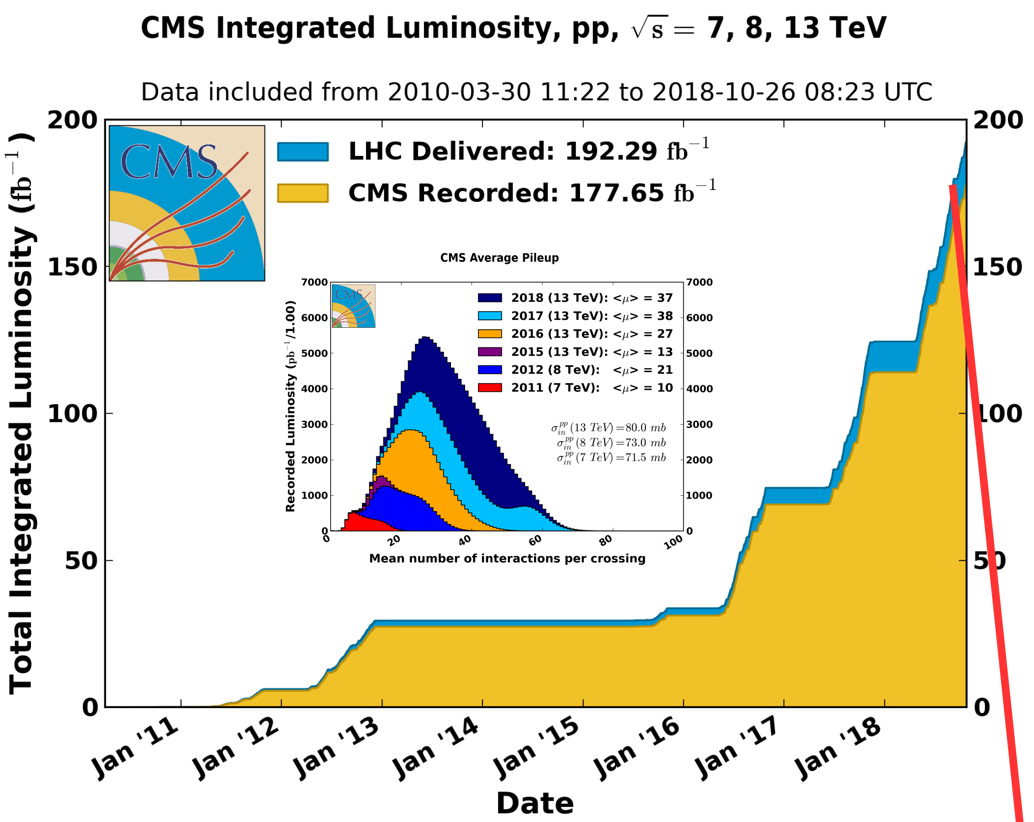
- Establish top quark SM
- First differential measurements
- Searches...

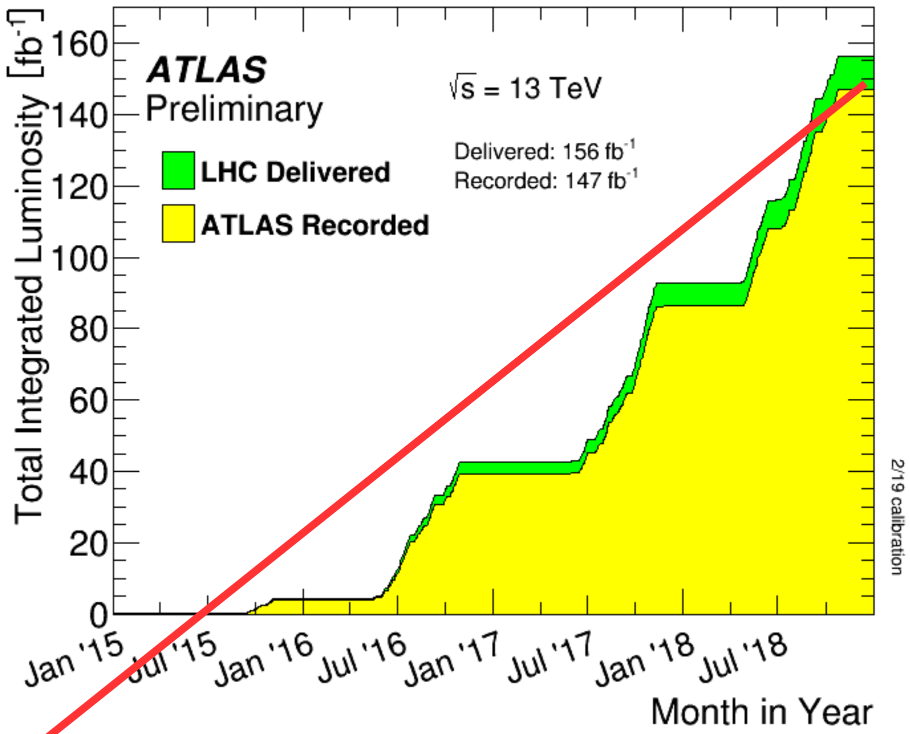
100,000's events (LHC Run I)



- SM top quark ?
- Multi-differential
- Precision measurements

The present…LHC Run II





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

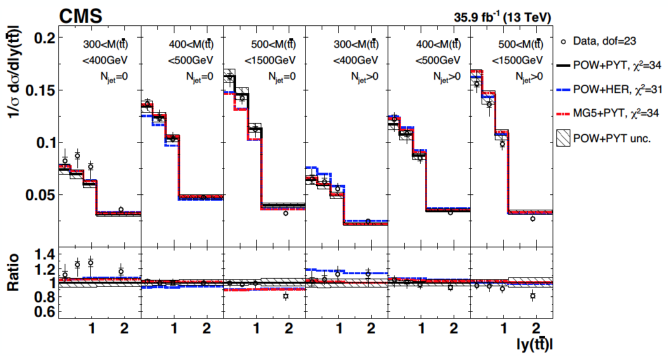
~ 120 million $t\bar{t}$ pairs

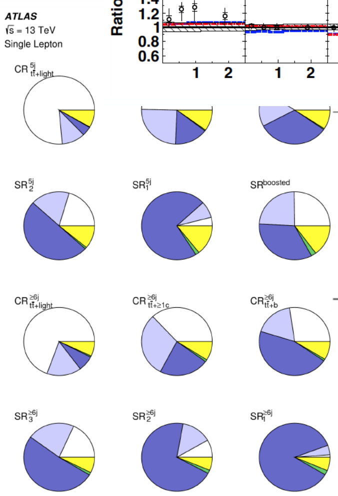
~ 30 million single top

~ 120k $t\bar{t}Z$, tZ

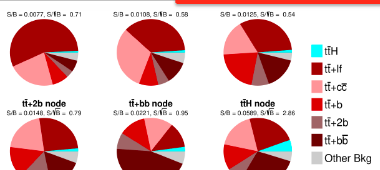
"Obstacles"...

- Vast amount of information – most intense week I had in quite a while
- Talks range anywhere between ~30 to up to 72 distributions shown in **a single talk**
- Also heard: "Apologies for being wordy here"





SigmaProcess:alphaSvalue	0.144	0.140	0.140	0.141
SpaceShower:pT0Ref	1.30	1.62	1.56	1.61
SpaceShower:pTmaxFudge	0.95	0.92	0.91	0.95
SpaceShower:pTdampFudge	1.21	1.14	1.05	1.10
SpaceShower:alphaSvalue	0.125	0.129	0.127	0.128
TimeShower:alphaSvalue	0.126	0.129	0.127	0.130
BeamRemnants:primordialKThard	1.72	1.82	1.88	1.83
MultipartonInteractions:pT0Ref	1.98	2.22	2.09	2.14
MultipartonInteractions:alphaSvalue	0.118	0.127	0.126	0.123
BeamRemnants:reconnectRange	2.08	1.87	1.71	1.78



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
Fitting UE observables at 1.96, 7 & 13 TeV, min bias at 1.96 & 7 TeV
CP1 & CP2 LO tune in backup

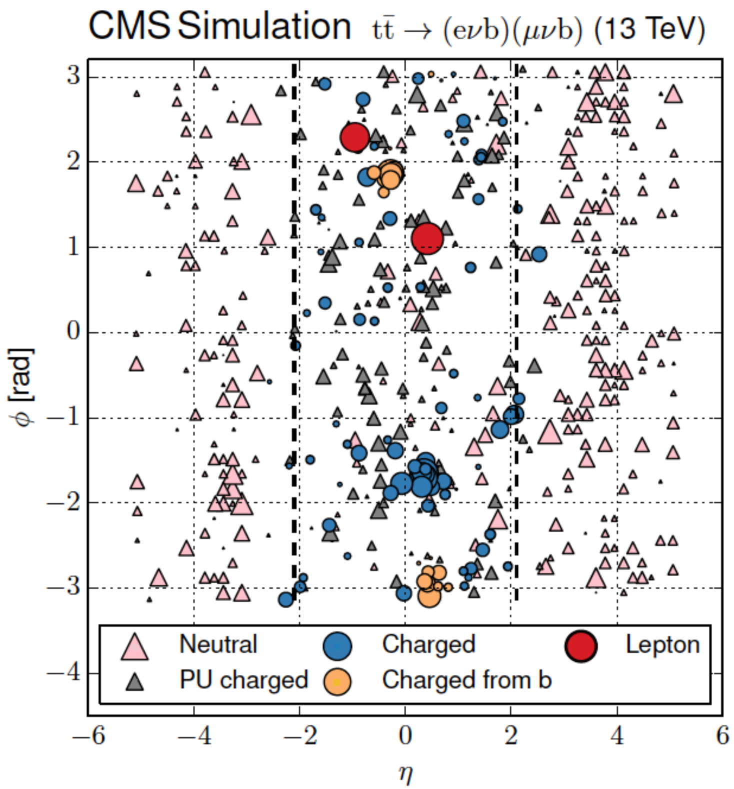
PYTHIA8 parameter	CP3	CP4	CP5
PDF Set	NNPDF3.1 NLO	NNPDF3.1 NNLO	NNPDF3.1 NNLO
$\alpha_S(m_Z)$	0.118	0.118	0.118
SpaceShower:rapidityOrder	off	off	on
MultipartonInteractions:EcmRef [GeV]	7000	7000	7000
$\alpha_S^{ISR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{FSR}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{MPI}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
$\alpha_S^{ME}(m_Z)$ value/order	0.118/NLO	0.118/NLO	0.118/NLO
MultipartonInteractions:pT0Ref [GeV]	1.52	1.48	1.41
MultipartonInteractions:ecmPow	0.02	0.02	0.03
MultipartonInteractions:coreRadius	0.54	0.60	0.76
MultipartonInteractions:coreFraction	0.39	0.30	0.63
ColorReconnection:range	4.73	5.61	5.18
χ^2/dof	0.76	0.80	1.04

*Hadronization and beam remnants fixed to Monash tune

Modeling & Tuning

Mackay

- 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	
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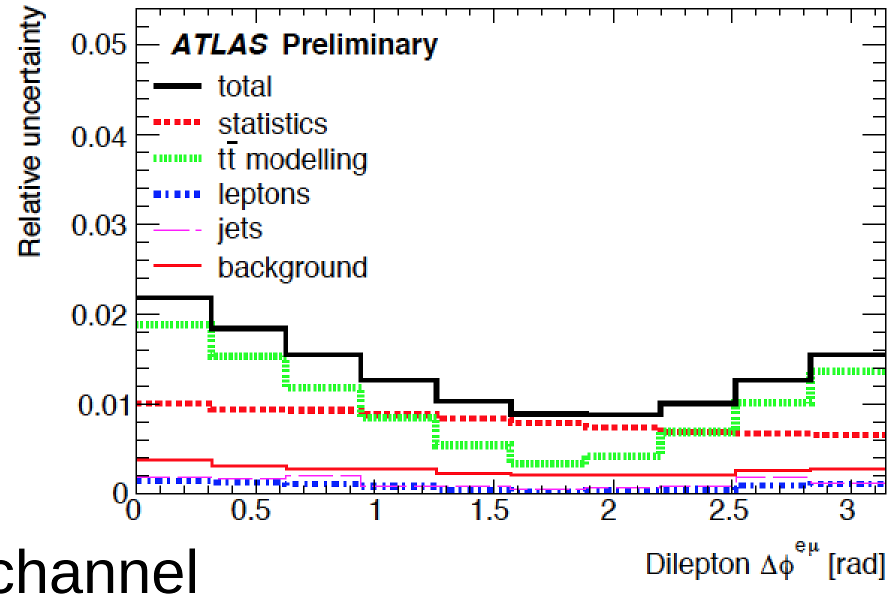
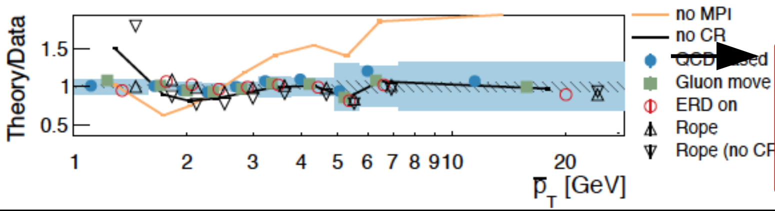
Extracted by varying 5 parameters



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

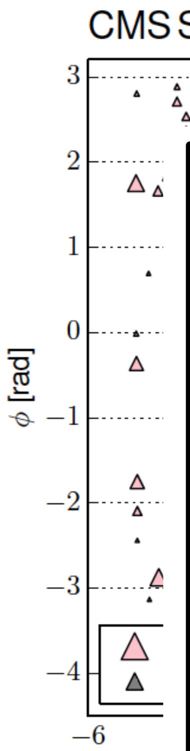


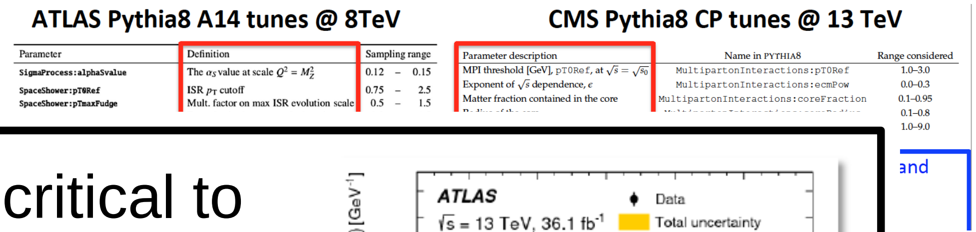
Towards a common MC setup in ATLAS & CMS
- 1st step: run settings in other experiment setup

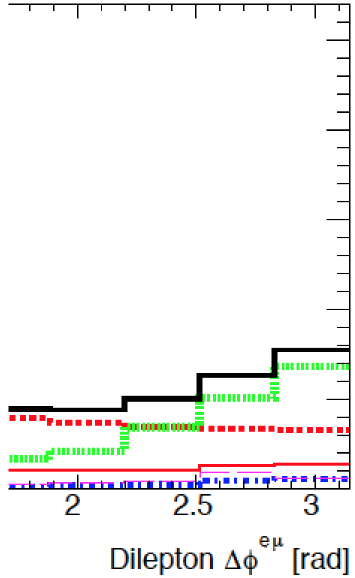
Modeling & Tuning

Mackay

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



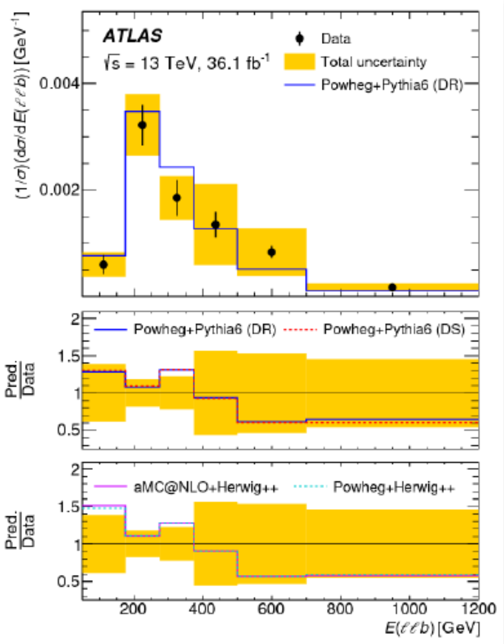




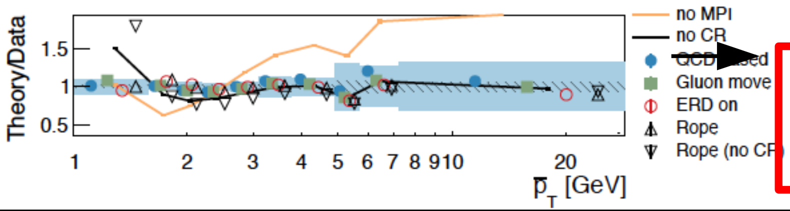
Modeling of tX, and ttX critical to further understand uncertainties

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

Berlendes



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



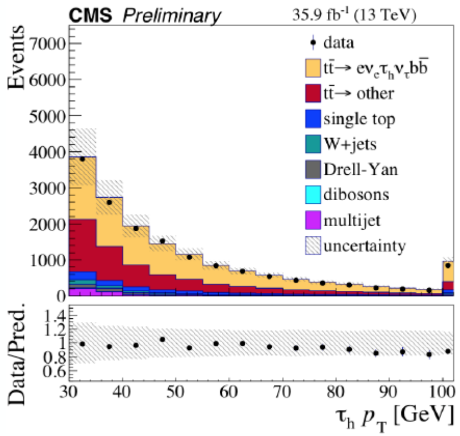
Towards a common MC setup in ATLAS & CMS
- 1st step: run settings in other experiment setup

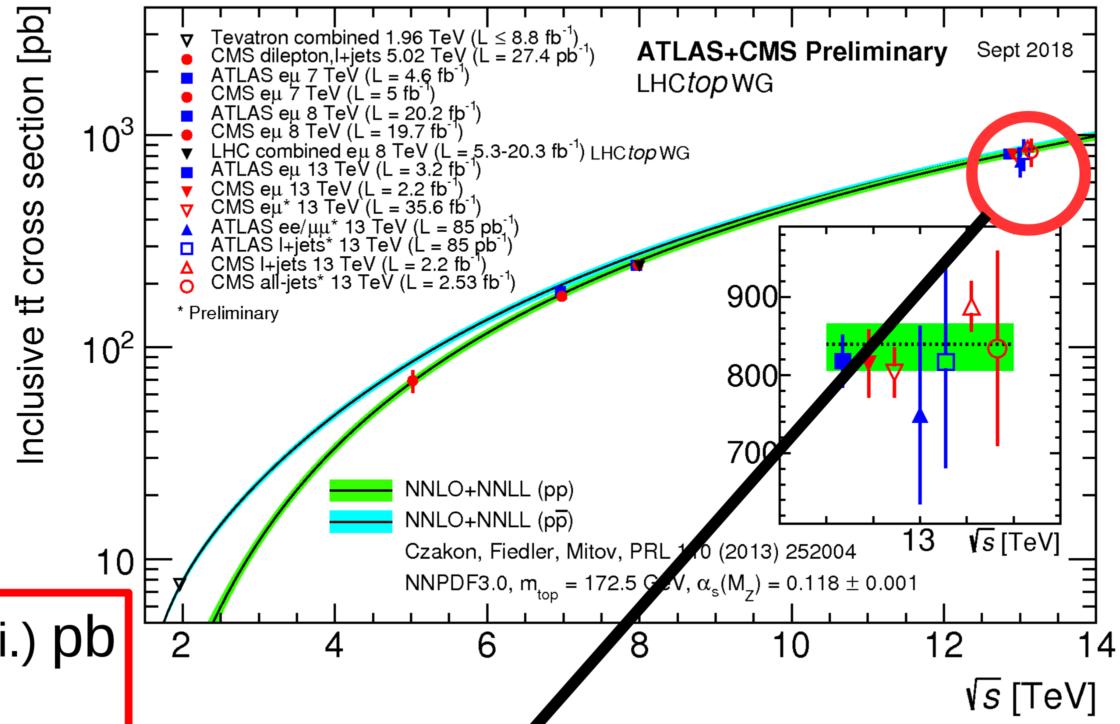
Inclusive cross sections

Escobar

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

CMS cross section at 13 TeV in lepton +τ(hadr.) channel





□ = 781 ± 7 (stat.) ± 62 (syst.) ± 20 (lumi.) pb

δ□/□= 8.4%

R = 0.973 ± 0.009 (stat.) ± 0.066 (syst.)

(tests lepton universality)

NEW

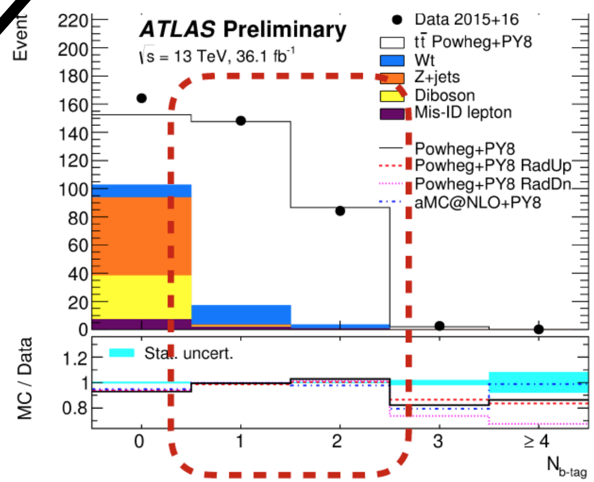
ATLAS cross section at 13 TeV in ∫μ channel

<u>Relative precision:</u> δσ/σ = 2.4%

NEW

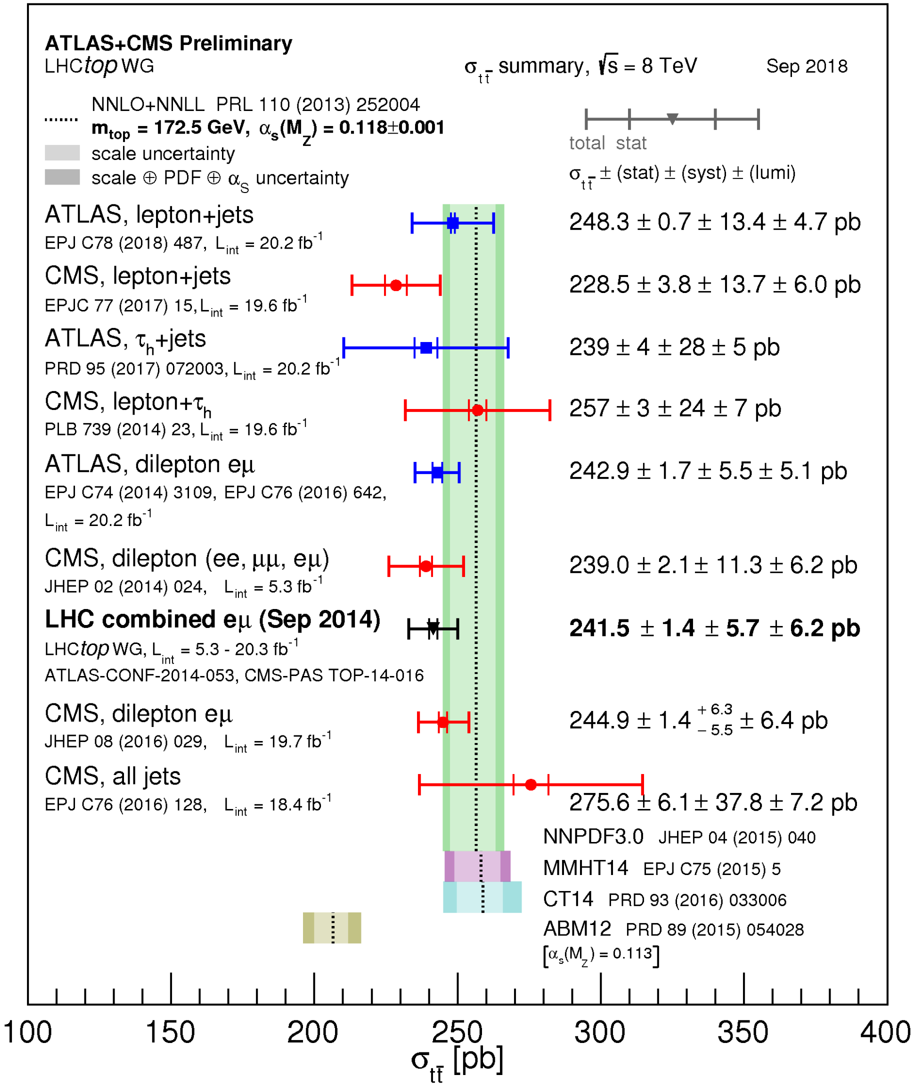
σ = 826.4± 3.6 (stat) ± 11.5 (syst) ± 15.7 (lumi) ± 1.9 (beam) pb

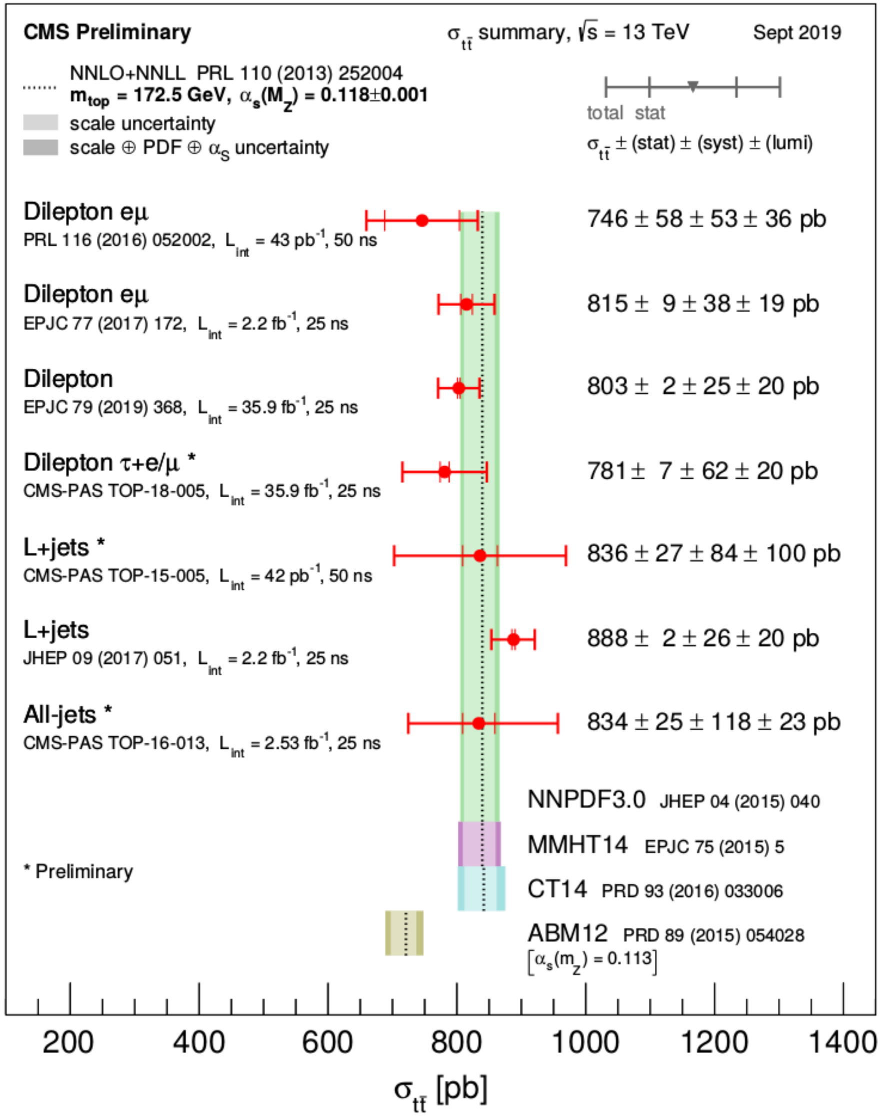
ATLAS-CONF-2019-041



Inclusive cross sections

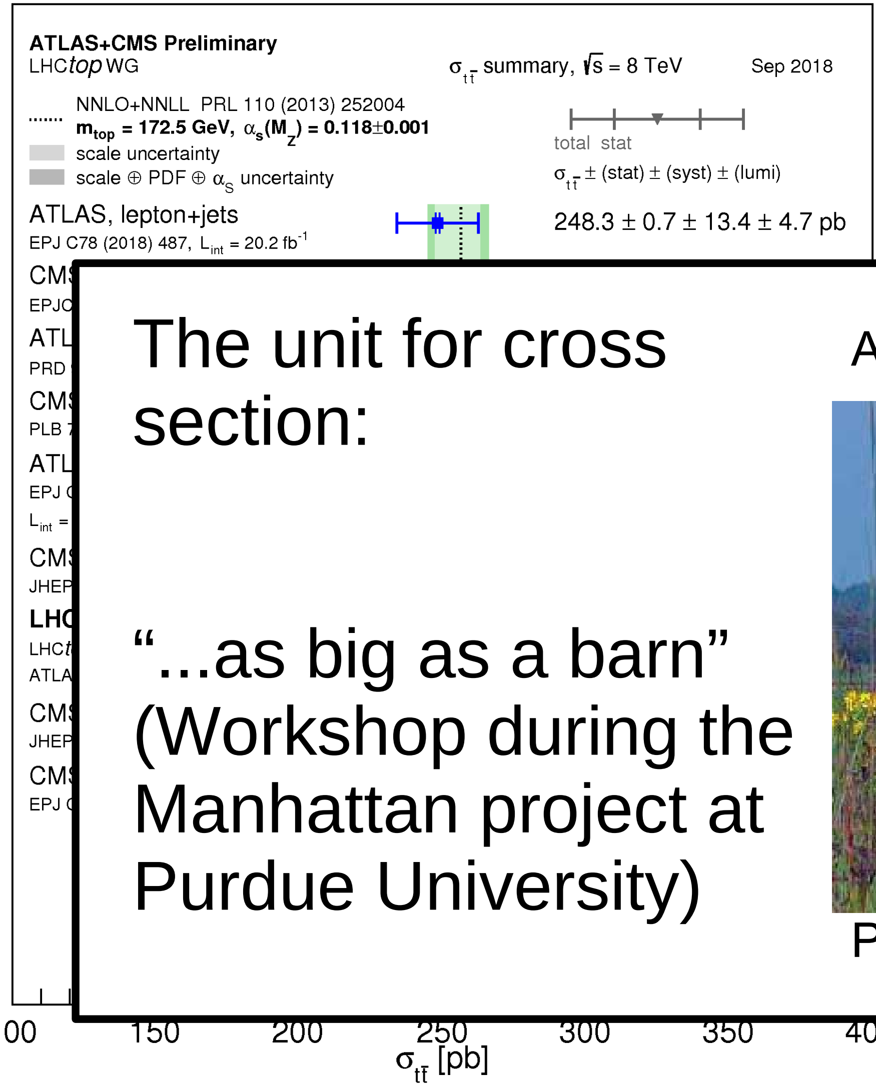
Escobar

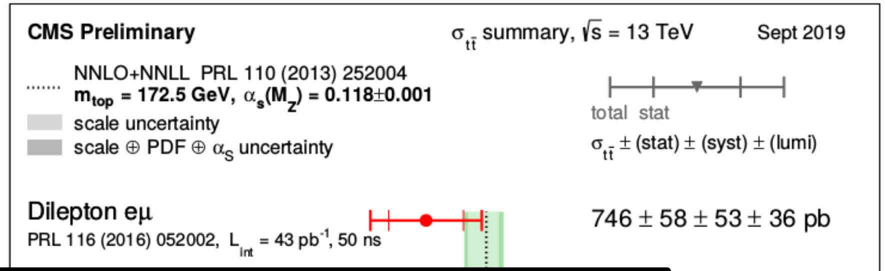




- Experimental uncertainty: 2.4% (!) – need **a lot** more discussion to benefit !
- Results indicate lower top mass...

Inclusive cross sections





The unit for cross section:

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

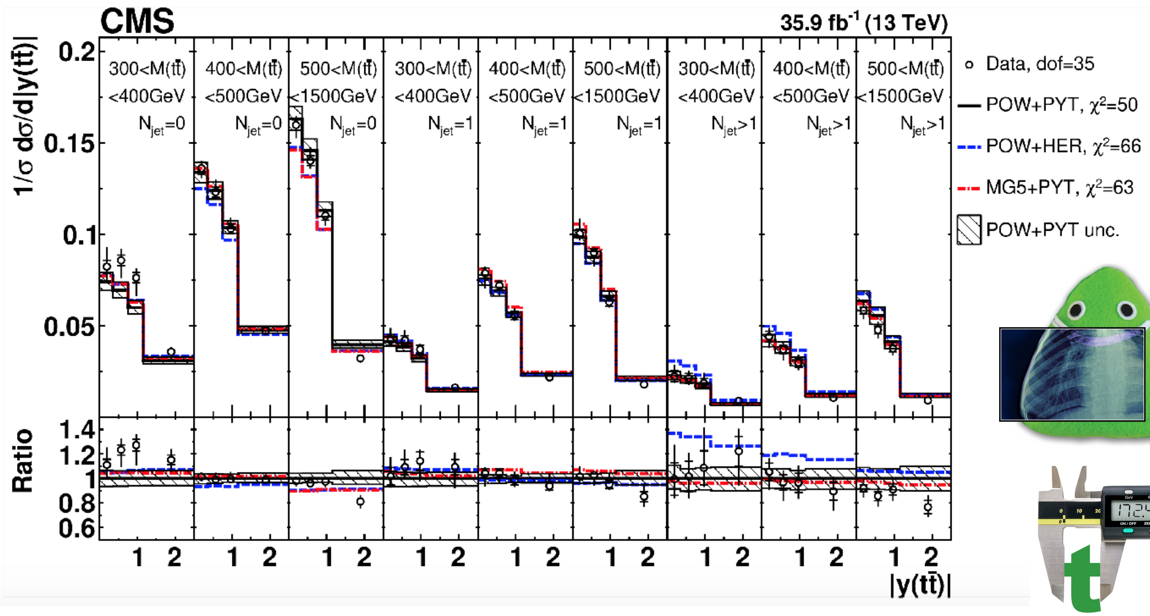
A typical barn...

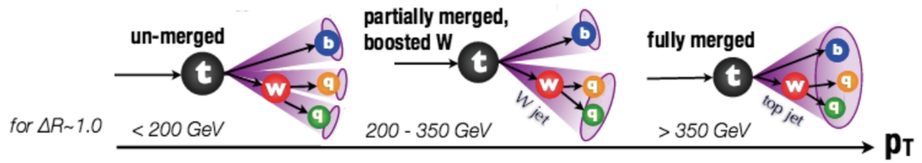
Prophetstown, West Lafayette

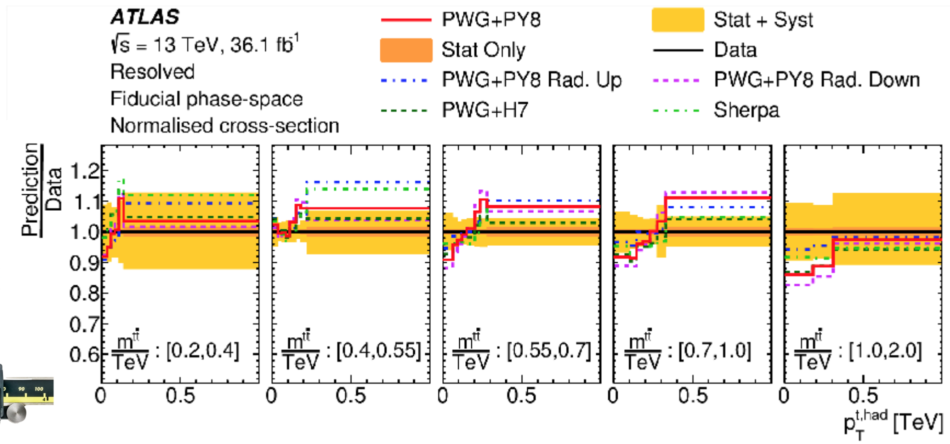
Differential cross sections

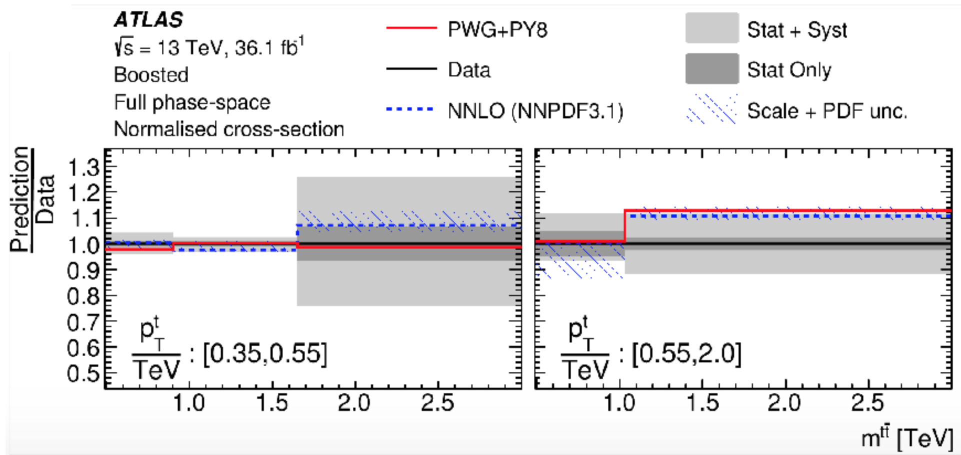
Boisvert

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







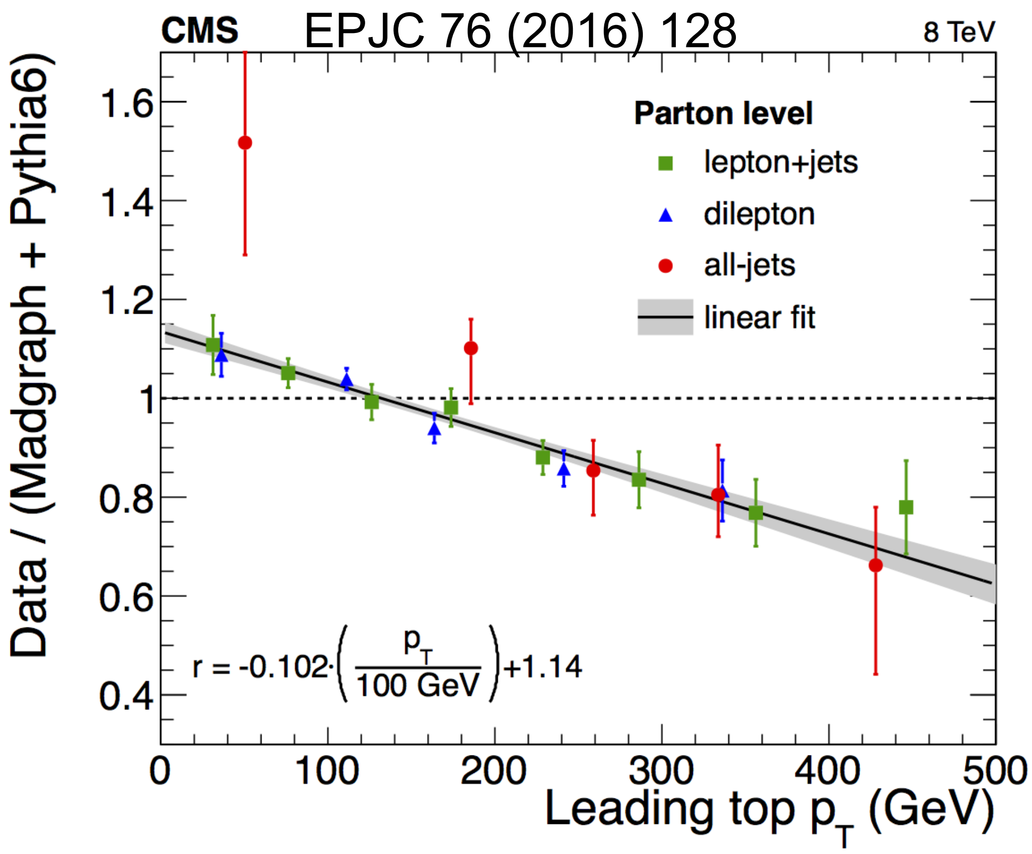


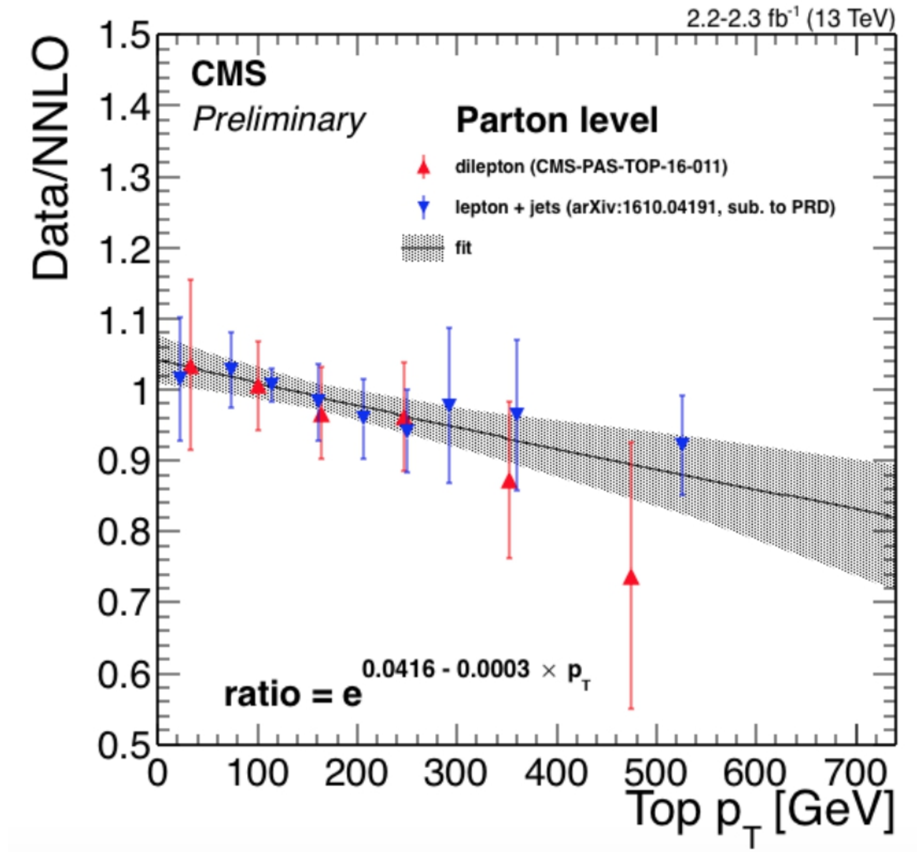
→ **Improve signal modeling, seen 1st triple and double differential measurements!**

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

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**

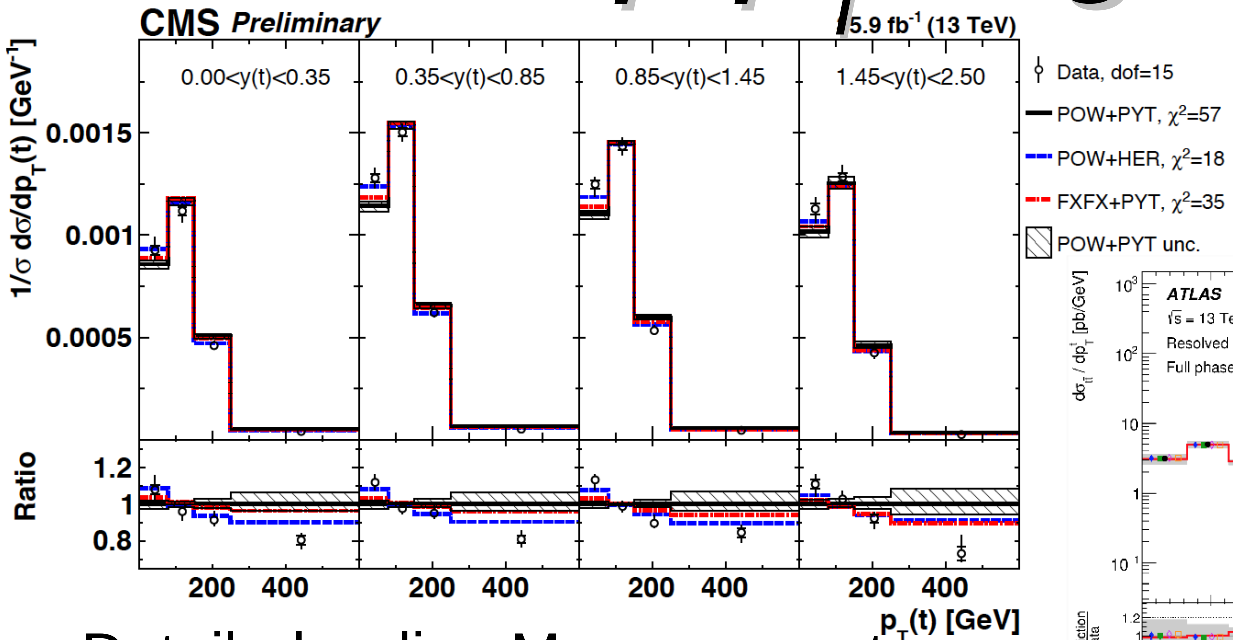


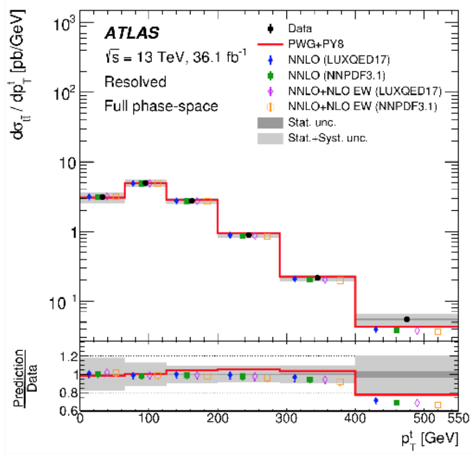


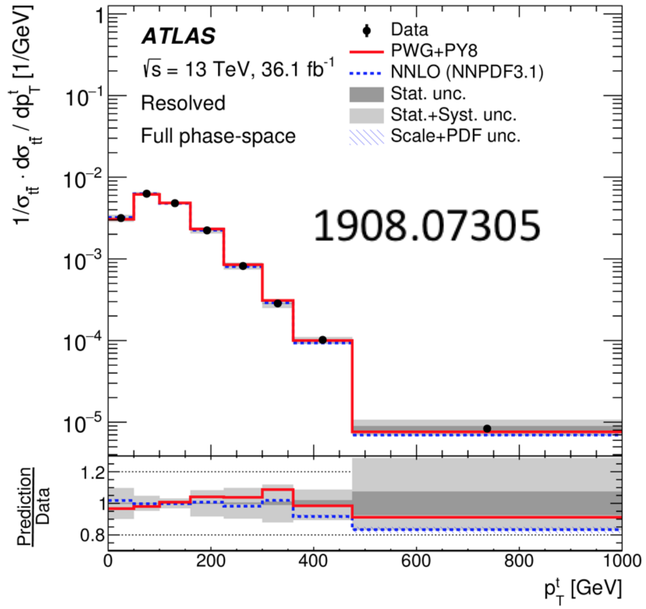
→ The pT spectra in 8 TeV are described by pQCD NNLO calculations, **but**

→ Indications of a slope wrt NNLO in 13 TeV data

The top p_T saga...continued Boisvert



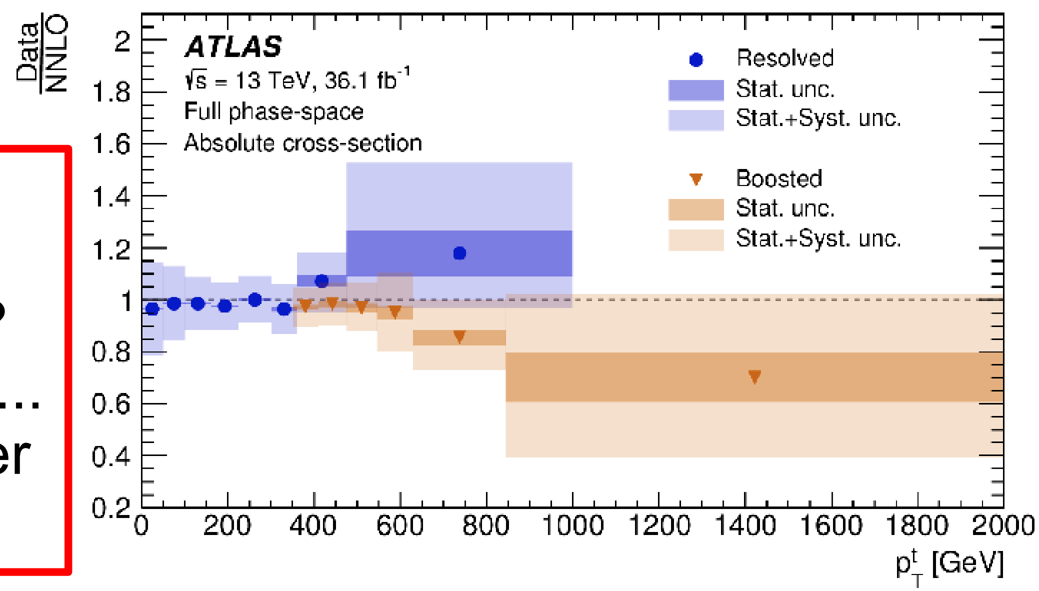




- Detailed *n*-dim. Measurements
- Common binning – study EW corrs.

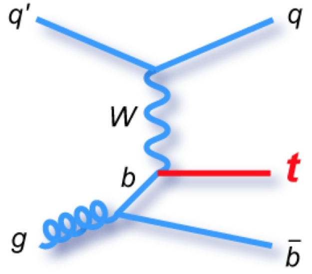
→

- Slopes in 13 TeV ATLAS & CMS data
- Large systematic uncertainty – further understanding, common procedure ?
- To be continued in LHCtopWG context...
- Theory can help: experiments are eager to use an “NNLO MC”

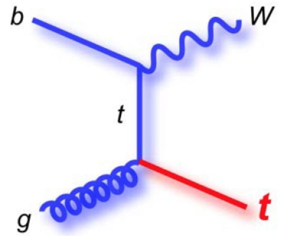


Single Top Quark Production Escobar

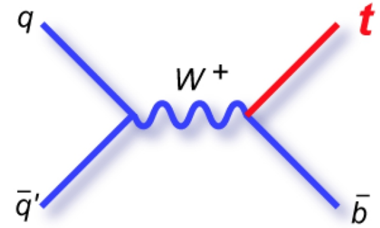
- **Single top cross section as high as $t\bar{t}$ at 8 TeV – large samples**
- Single top production: Test of EW interactions



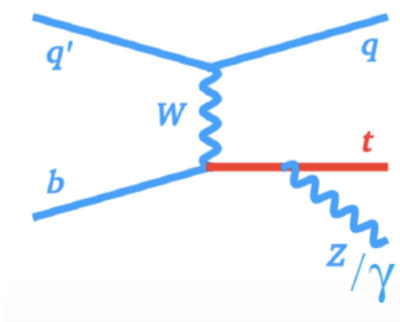
t-channel



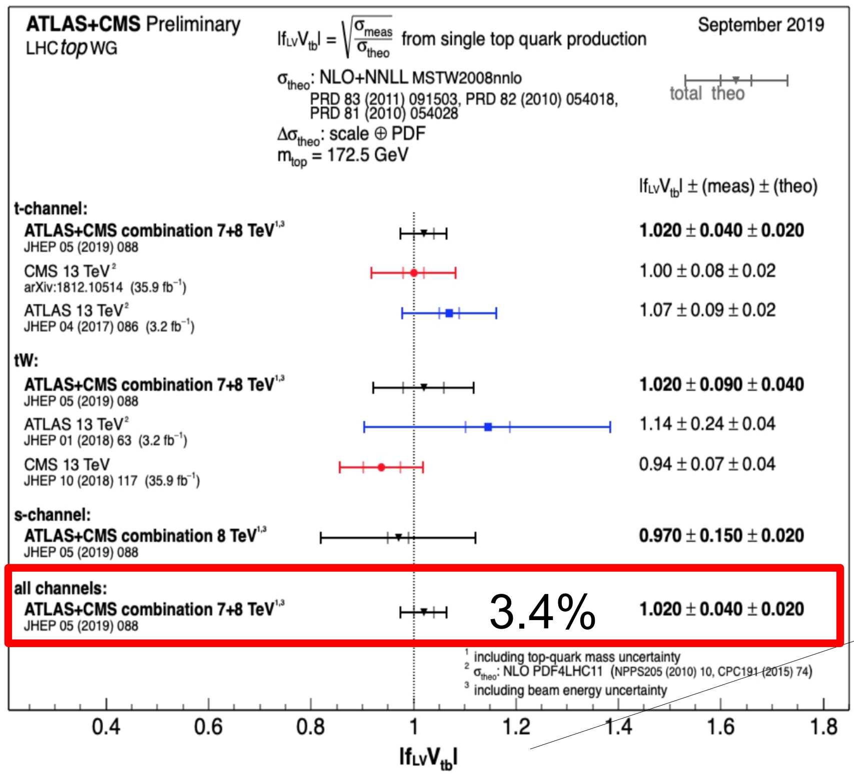
tW-channel



s-channel



tZ/γq-channel (rare process, < 1 pb)

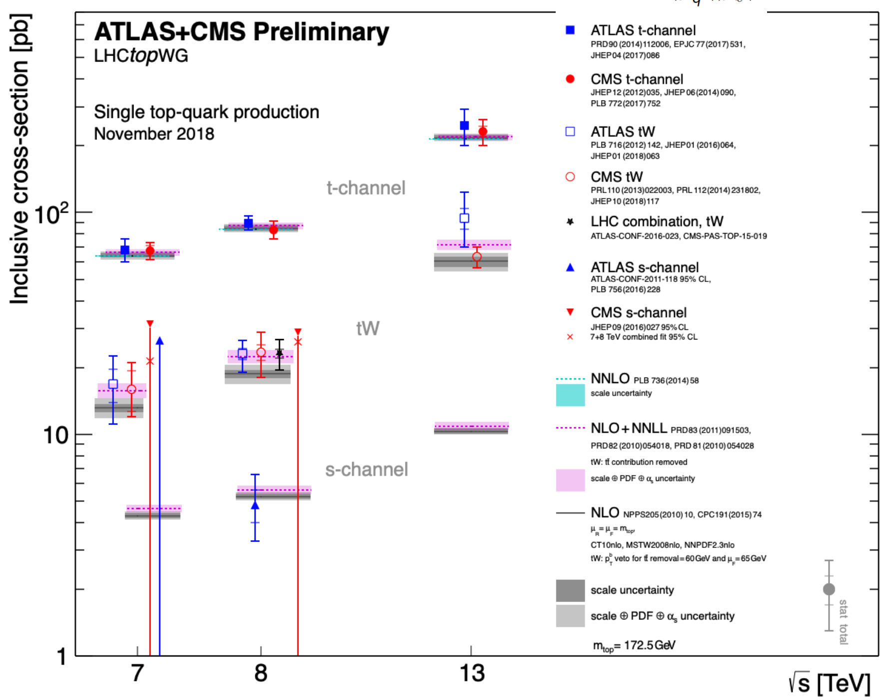


$$|V_{tb} \cdot f_{LV}|^2 = \frac{\sigma^{obs}}{\sigma^{theory}}$$

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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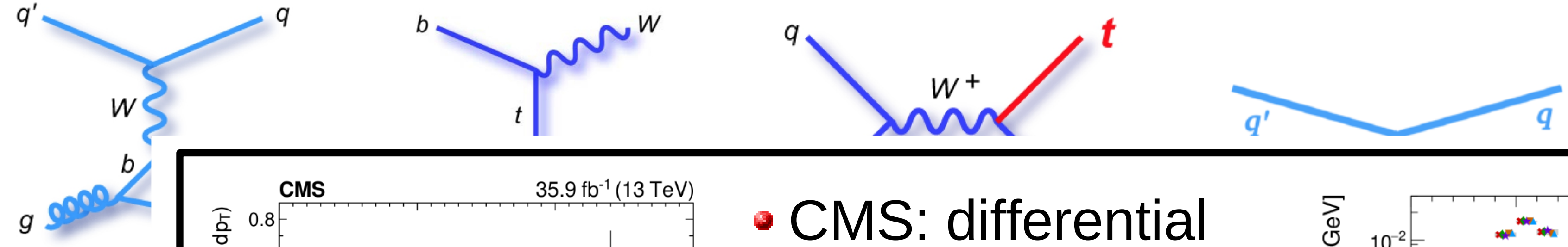
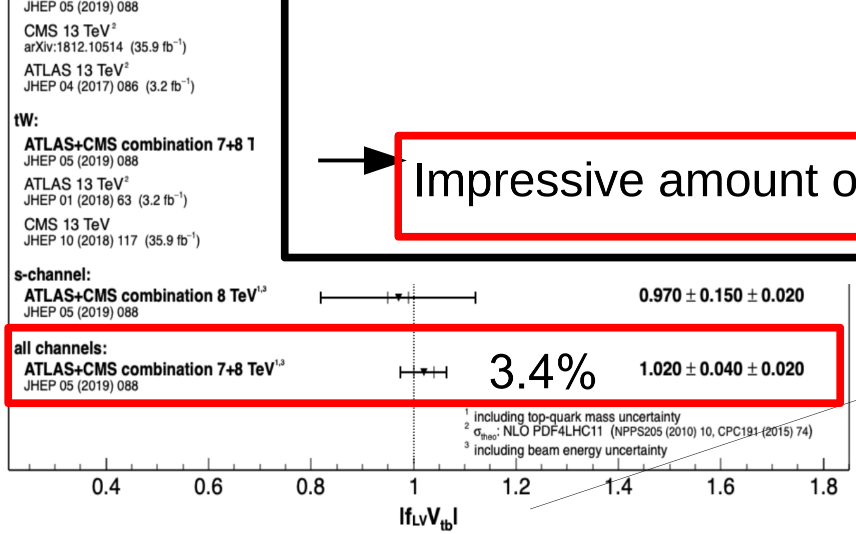
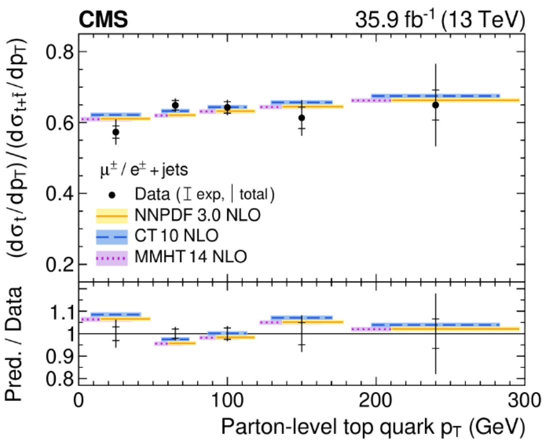
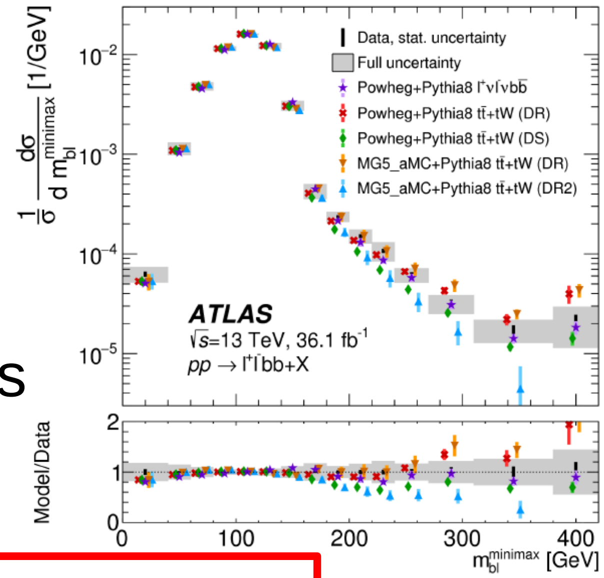






- CMS: differential ratio of t vs. $\bar{t}$ – sensitive to proton structure
- ATLAS: tW measurement requires tt + tW interference terms



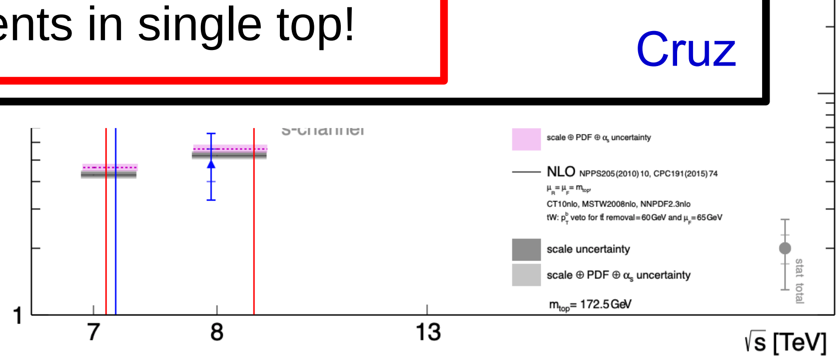
Impressive amount of differential measurements in single top!

Cruz

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

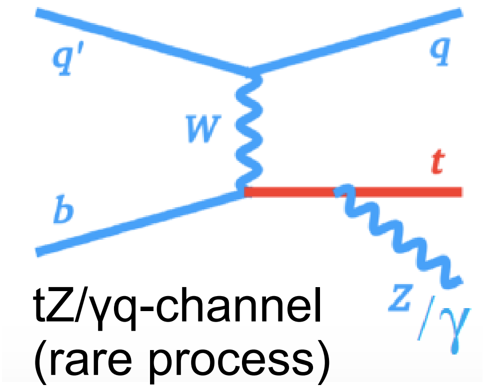
f_{LV}: BSM form factor

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

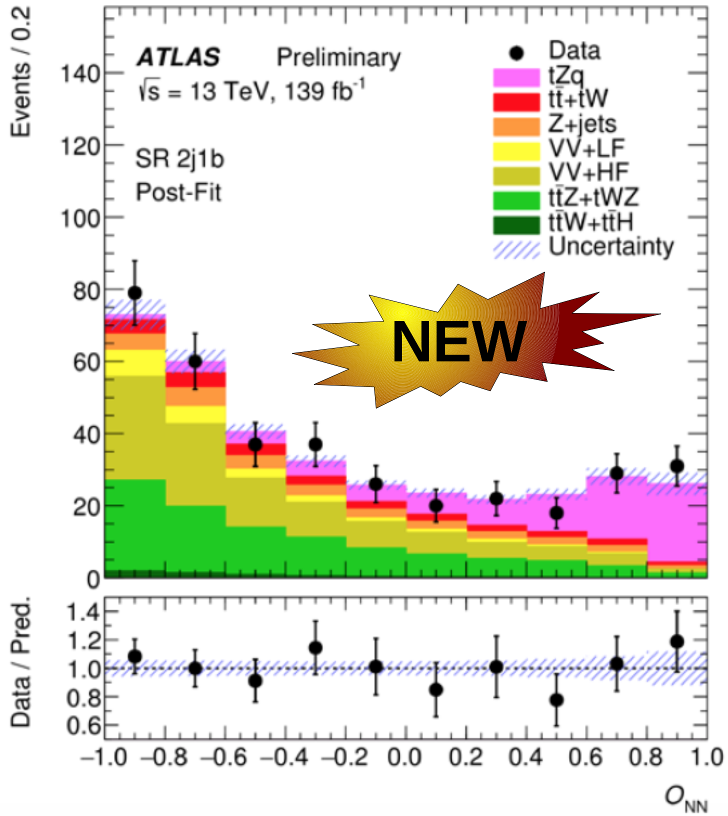


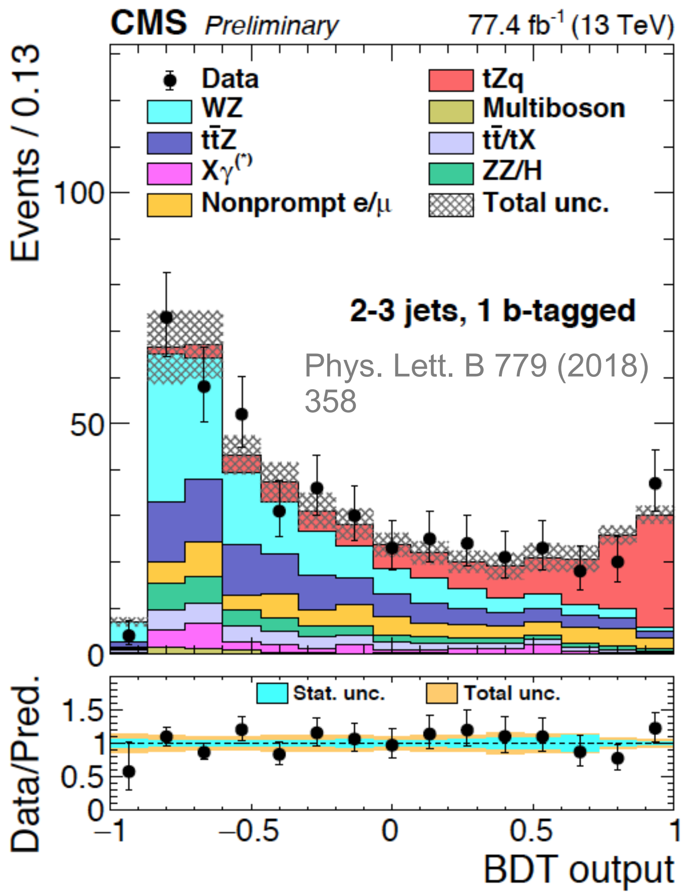
Rare single top quark

Choi



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

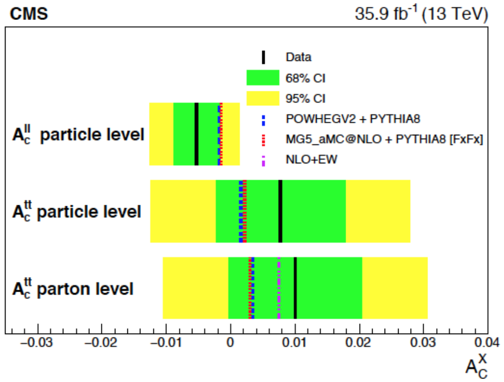
→ σ = 111 ± 13 (stat) ± 10 (syst) pb PRL122(2019)132003
obs. (exp.) significance: 8.2 (7.7) SD

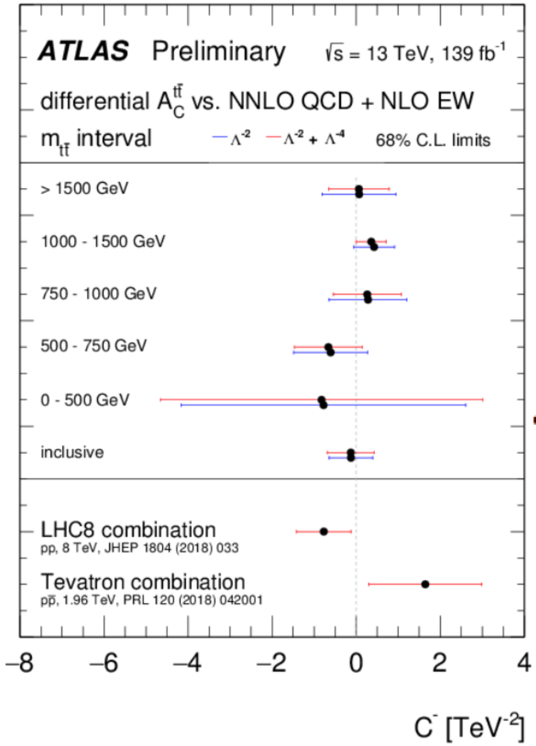
- Observation of tZq

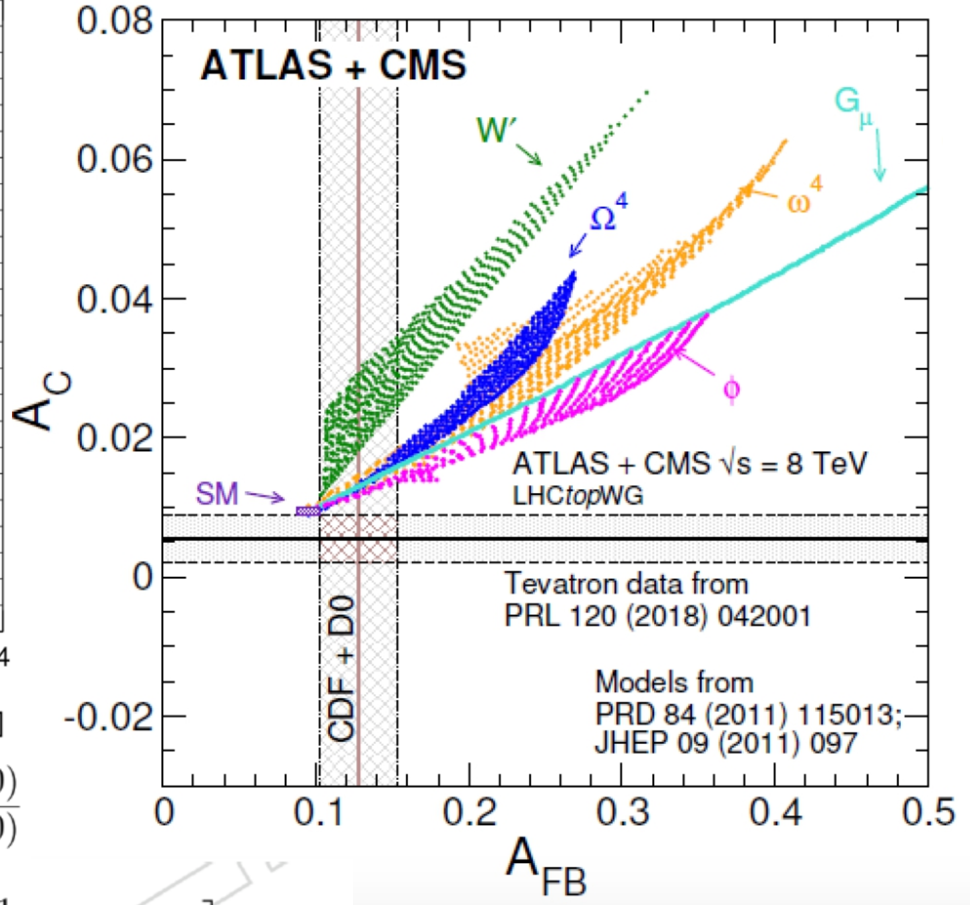
Top Quark Properties...

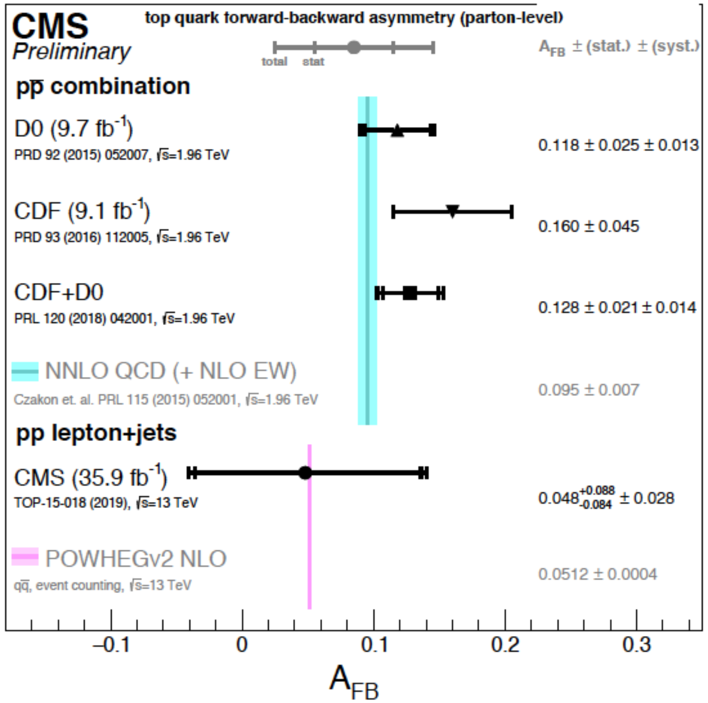
Goldouzian

- Production asymmetry due to NLO interferences









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

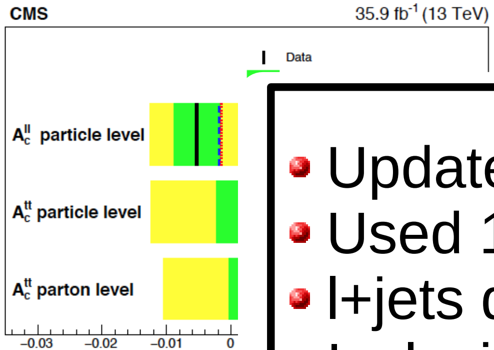
$$\frac{d\sigma}{dc^*}(q\bar{q}) \simeq f_{sym}(c^*) + \left[\int_{-1}^{1} f_{sym}(x)dx\right] c^* A_{FB}^{(1)}$$

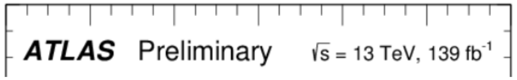
→ Measurements of A_C difficult, new channels help
→ Access A_{FB} at LHC (!)

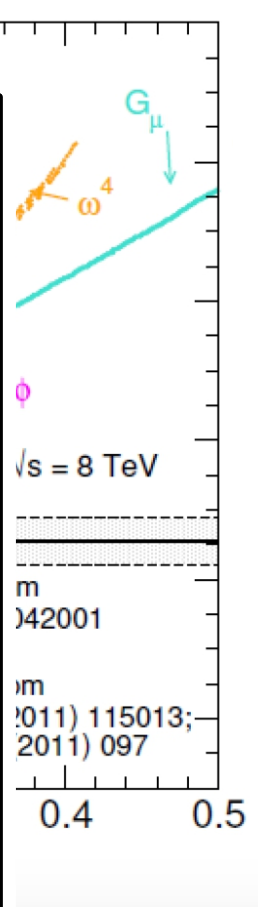
Top Quark Properties...

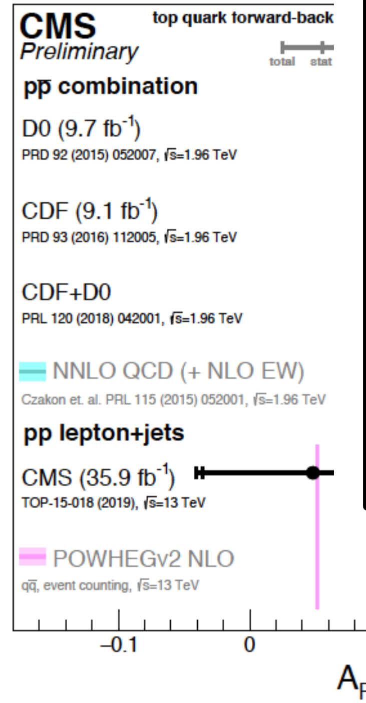
Goldouzian

- Production asymmetry due to NLO interferences

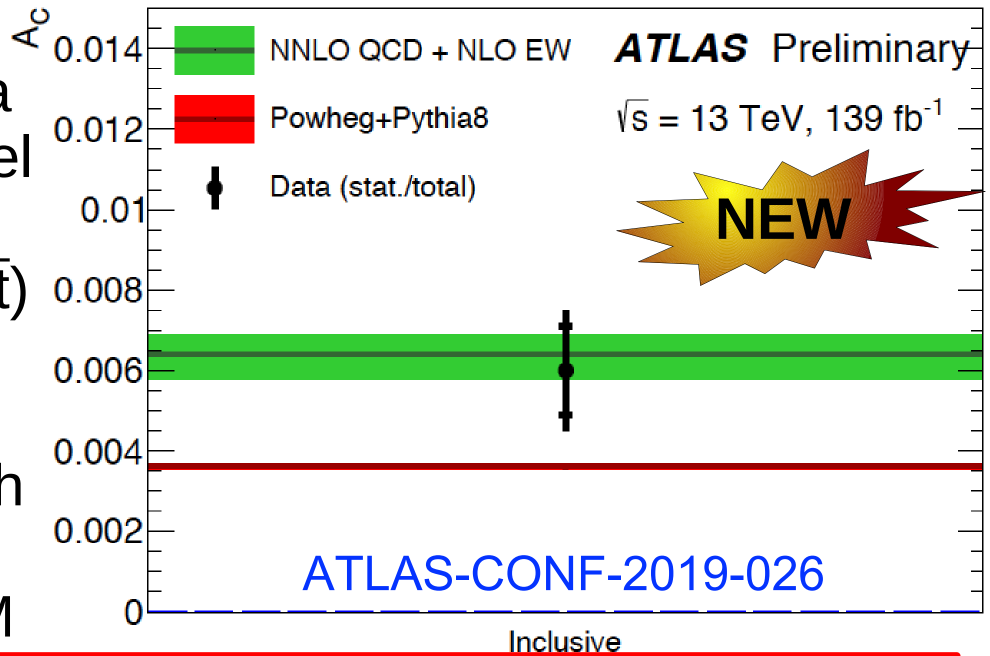








- Update by ATLAS
- Used 139\fb of data
- l+jets decay channel
- Inclusive and differential in $m(t\bar{t})$



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

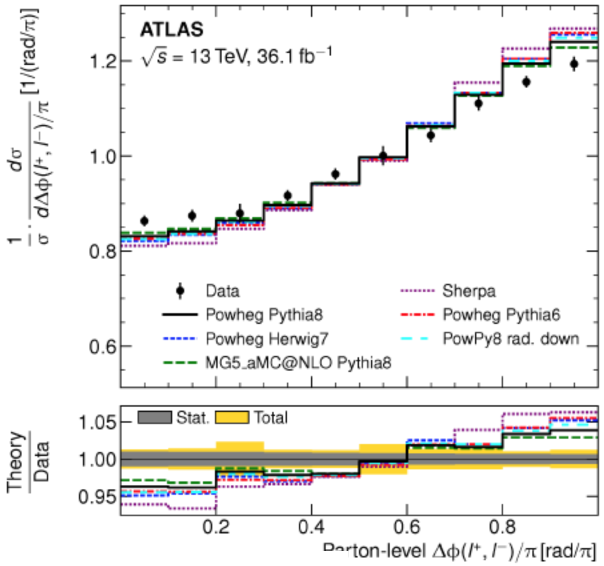
→ $A_c = 0.006 \pm 0.0015$ (stat+syst)

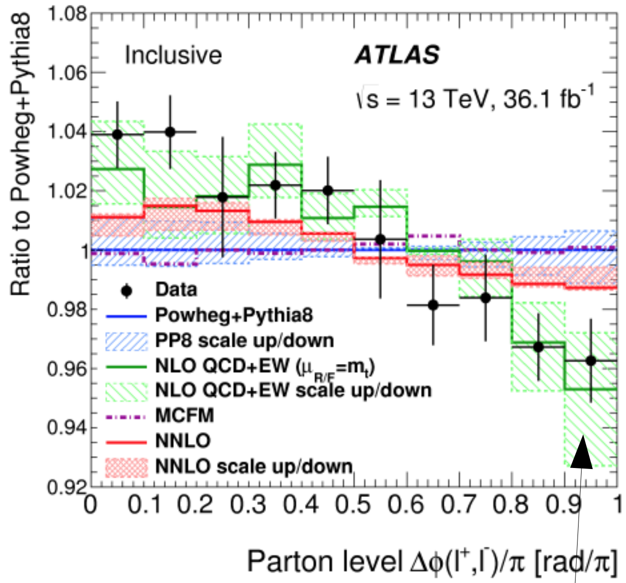
SM measurement in Run 2 ?

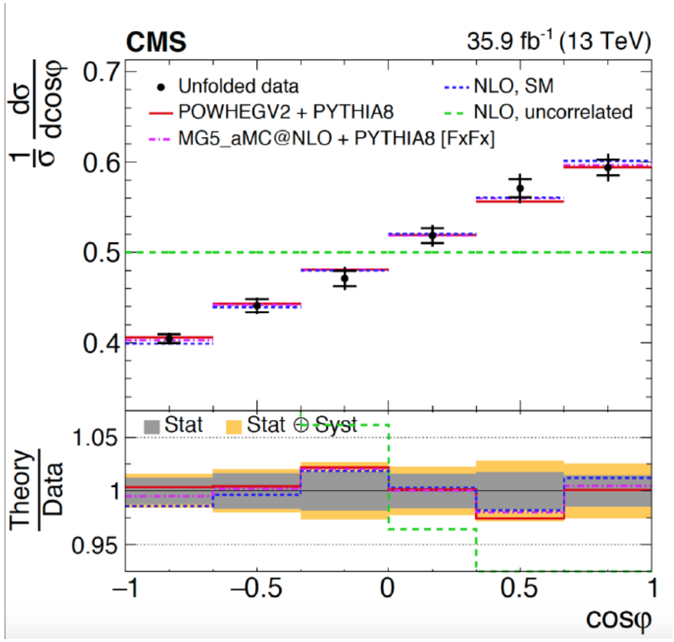
Top Quark Properties...

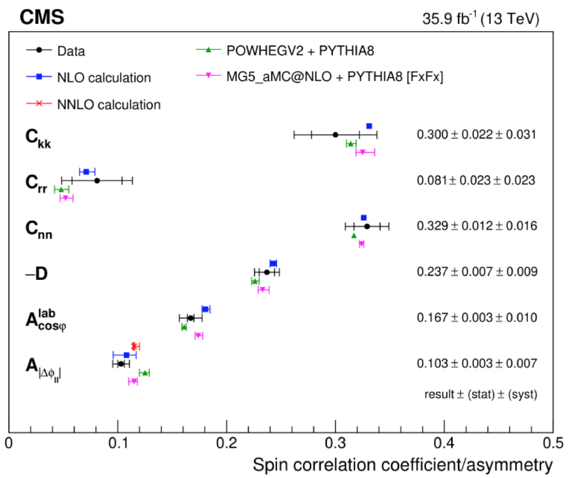
Goldouzian

- 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} ± (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) – Solve puzzle till TOP2020...

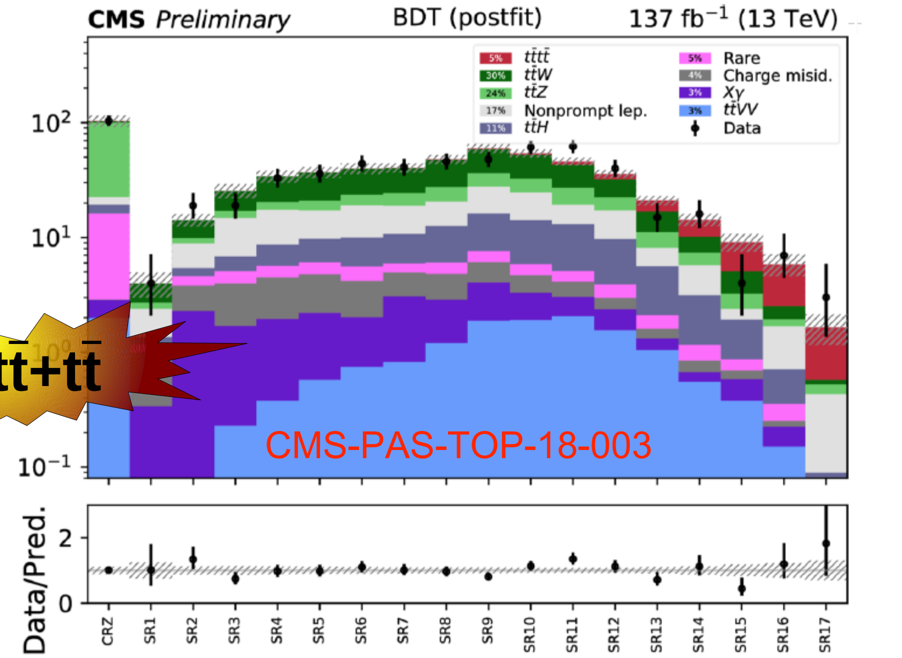
$t\bar{t}$+*X*: *Highlights*

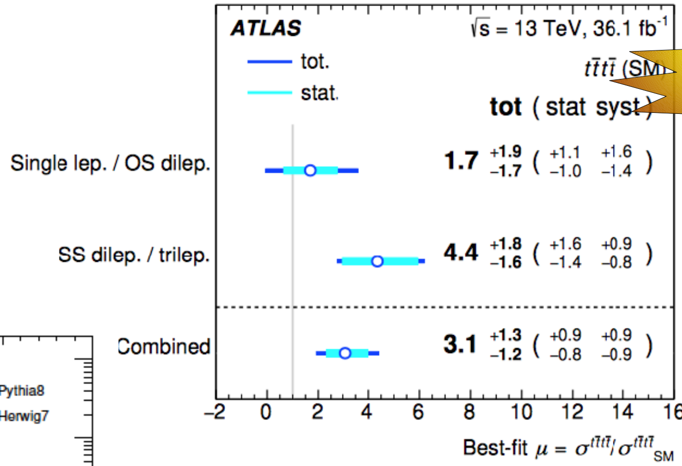
Li, Yumiceva, Quin

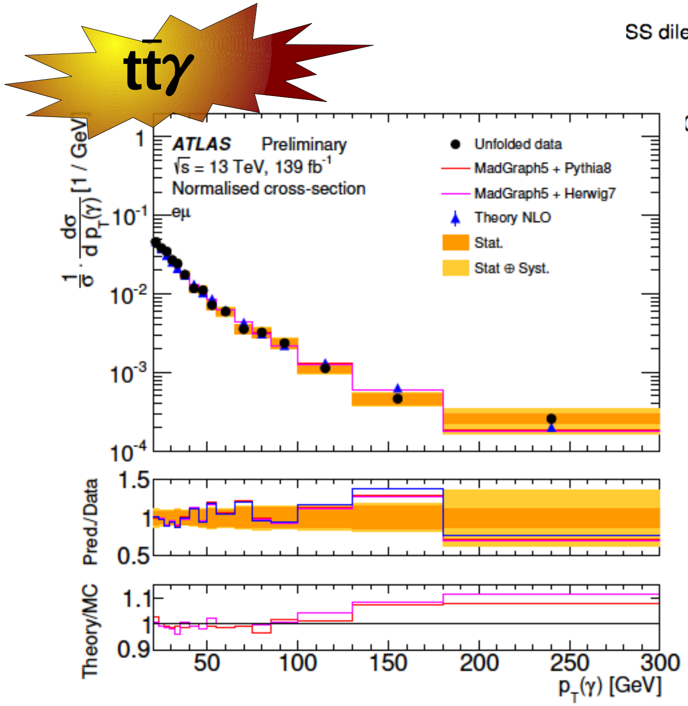
- **$t\bar{t}$Z/W:** Most precise measurement, allowed for 1st differential cross sections
- **$t\bar{t}\gamma$** : First evidence for $t\bar{t}\gamma$ by ATLAS

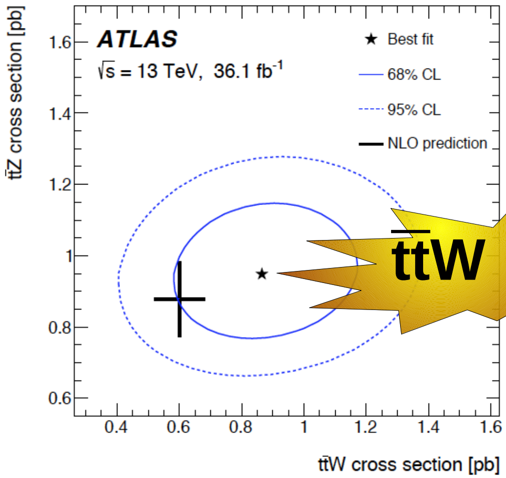
EPJC 79 (2019) 382

- **$t\bar{t}$+$t\bar{t}$:** Full Run 2 close to evidence at CMS

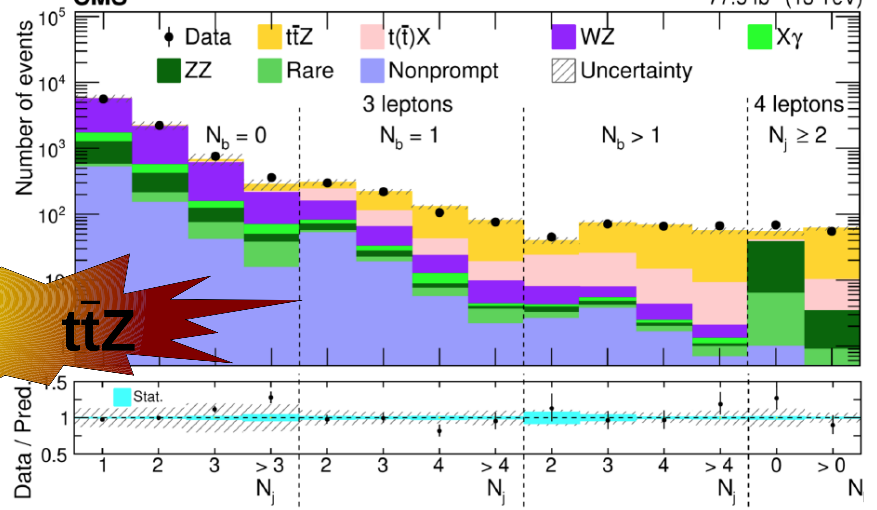








arXiv:1907.11270



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

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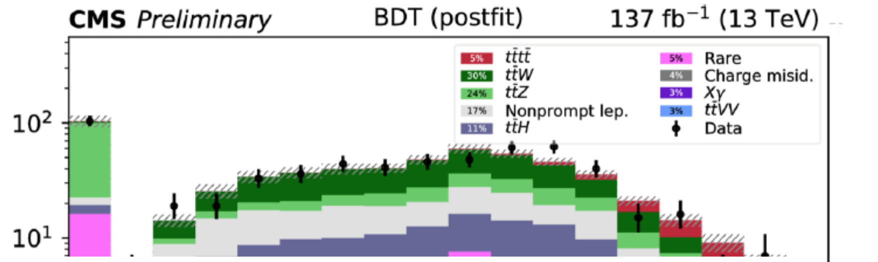
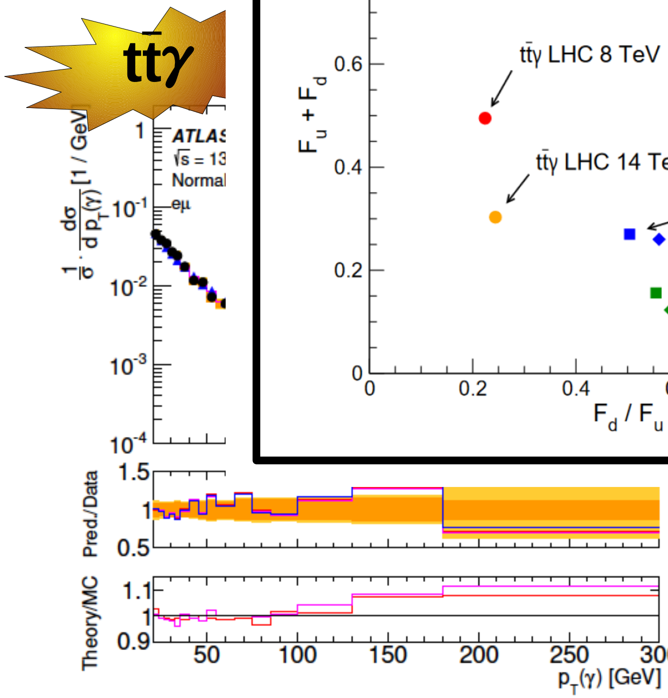
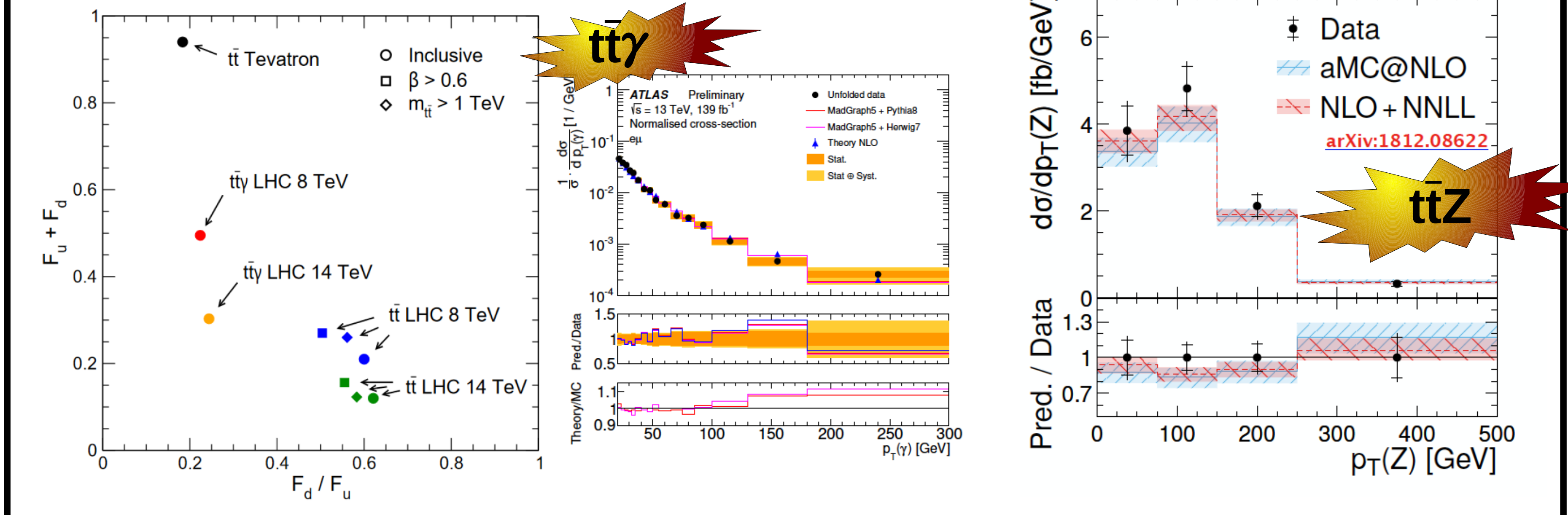
EPJC 79 (2019) 382

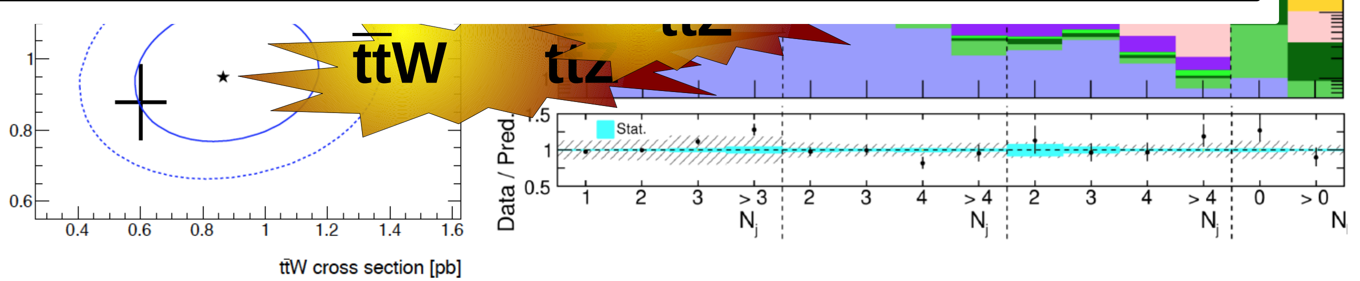
- **$t\bar{t}$+$t\bar{t}$:** F





Differential distributions:





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

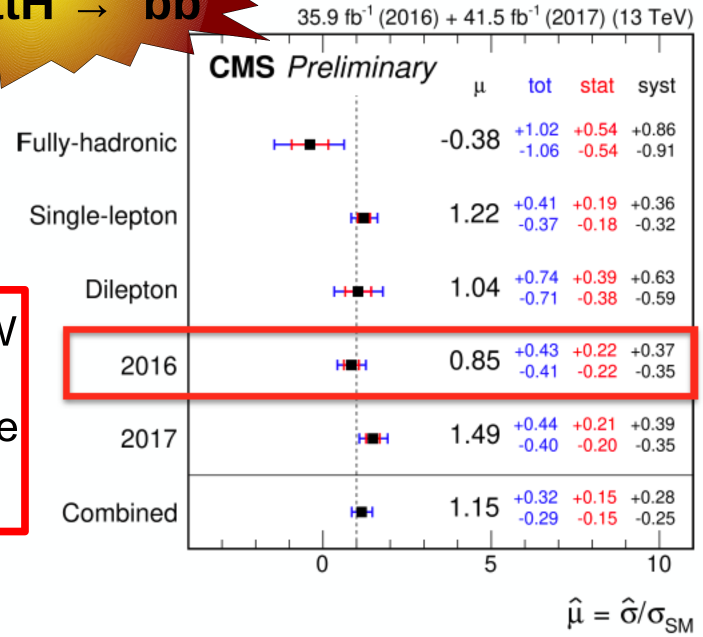
Vasquez Schroeder

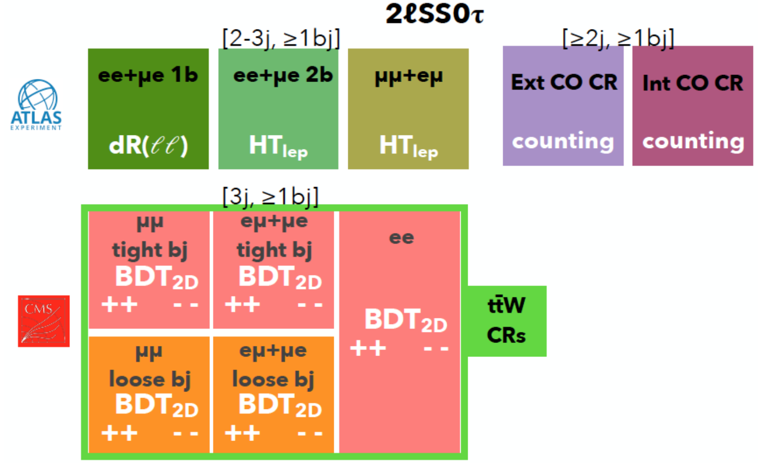
- Associated Higgs production only direct access to Yukawa coupling
  - Complex final state

CMS:
  - Evidence for bb

ATLAS:
  - Observe γγ channel

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

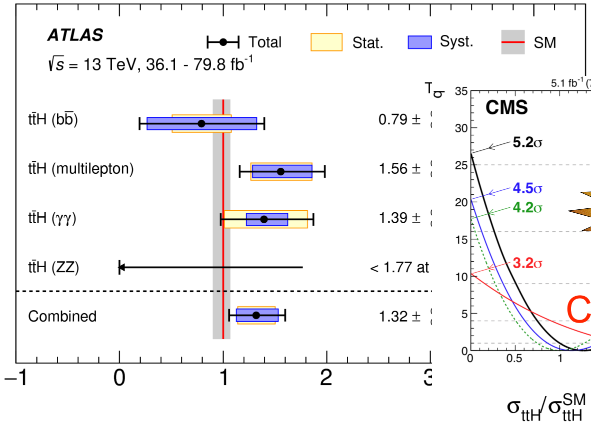


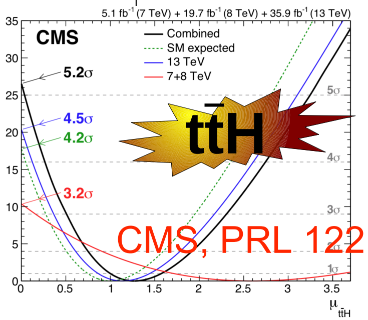


Details matter: SF's for ttZ, ttW and ttbb are not easily comparable (mind phase space & uncertainties)

- $t\bar{t}$H observed in both

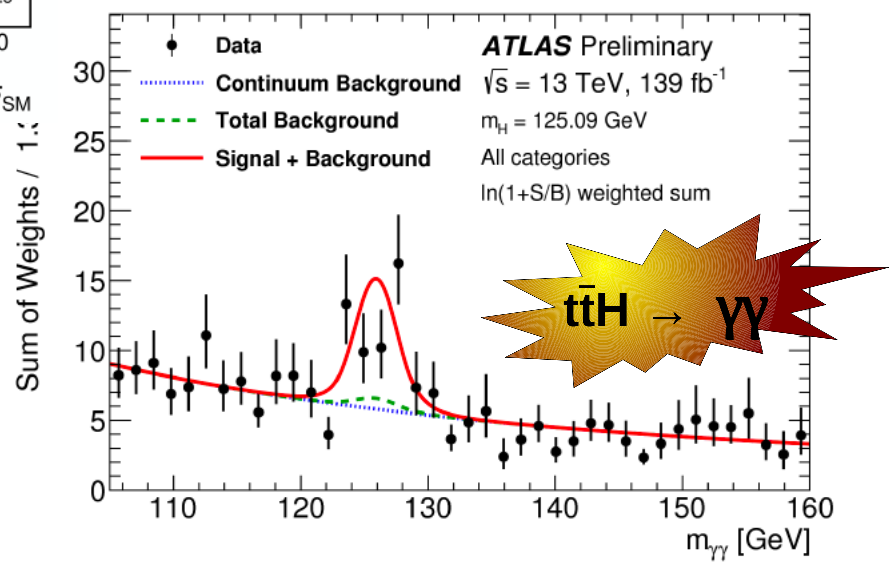
ATLAS, PLB 780 (2018) 557





CMS, PRL 122 (2019) 132003

$\mu_{t\bar{t}H} = 1.38\ ^{+0.41}_{-0.36} = 1.38\ ^{+0.33}_{-0.31}\ \text{(stat.)}\ ^{+0.13}_{-0.11}\ \text{(exp.)}\ ^{+0.22}_{-0.14}\ \text{(theo.)}$



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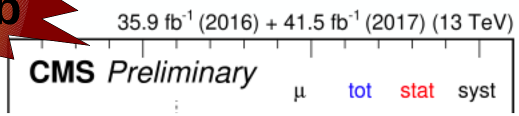
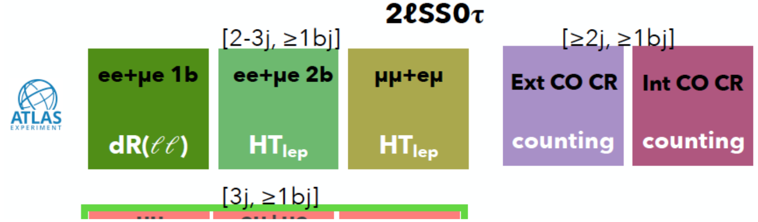
  - Complex final state

CMS:

- Evidence for bb

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





ATLAS:

- Obs

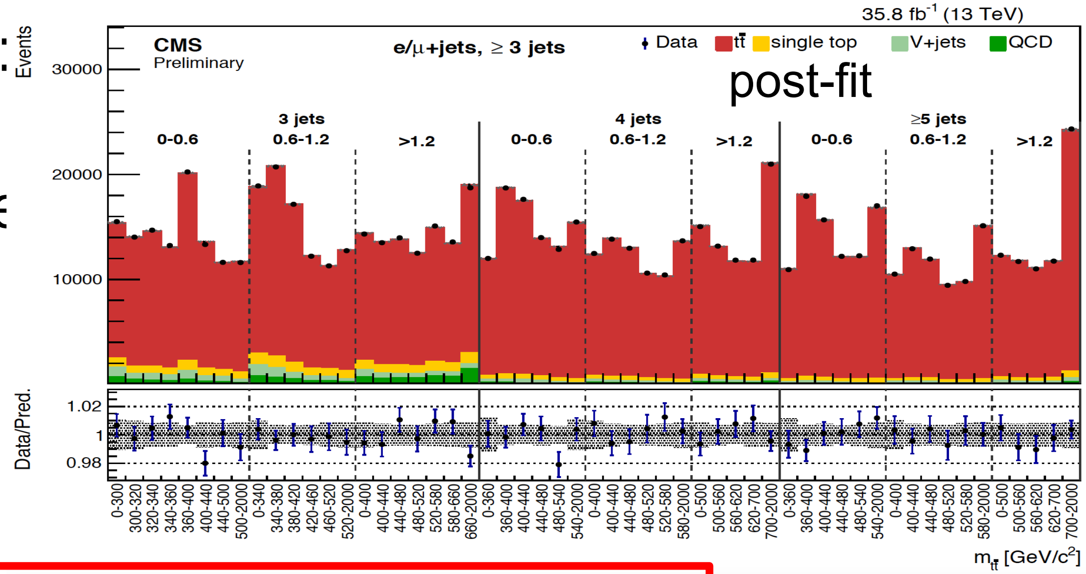
Details ... and ttbb ... compara... & uncert...

- $t\bar{t}H$ obs...

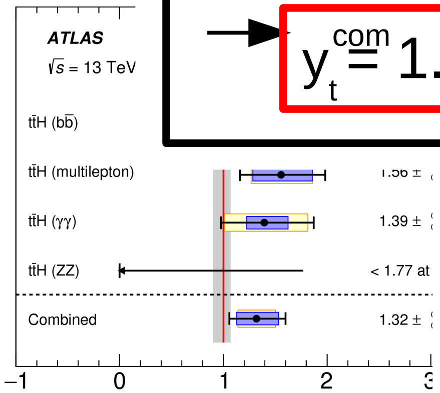
ATLA...

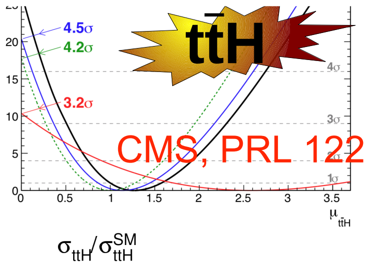
Extract y_t from template fit:

- CMS 13 TeV data, l+jets
- Recover 3 jet bin and use 57 bins to fit
- Precision of < 0.5% (!)

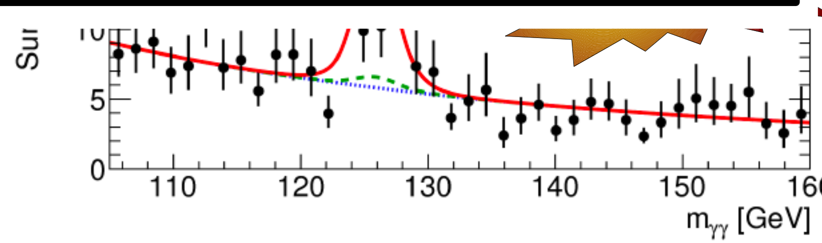


$y_t^{com} = 1.07 + 0.34 - 0.43$ (obs) [1.00 +0.35-0.48 (exp)]





CMS, PRL 122 (2019) 132003



Half time...

...made it through ~54 distributions

Breakfast burrito

Chinese food is great
but will be back to US tomorrow:
the “top quark diet”...

Burger meal, fried cheese
Nuggets

Pizza triple Cheese +
Meat lover + Bacon

Breakfast burrito (1900 cals)

Burger meal, fried cheese Nuggets (2000 cals)

Pizza triple Cheese + Meat lover + Bacon (2000 cals)

Breakfast burrito (1900 cals)

Burger meal, fried cheese Nuggets (2000 cals)

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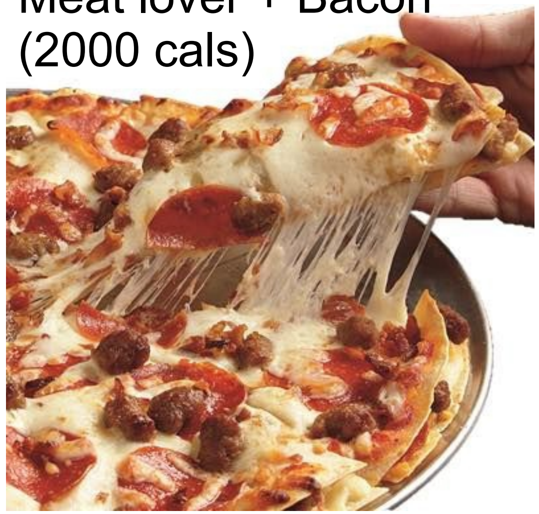


Nachos+Dip, Olive Garden (2000 cals)

Dessert: Milk shake, (1800 cals)

No Soda, no Latte, …

Top mass – direct methods

Castro

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

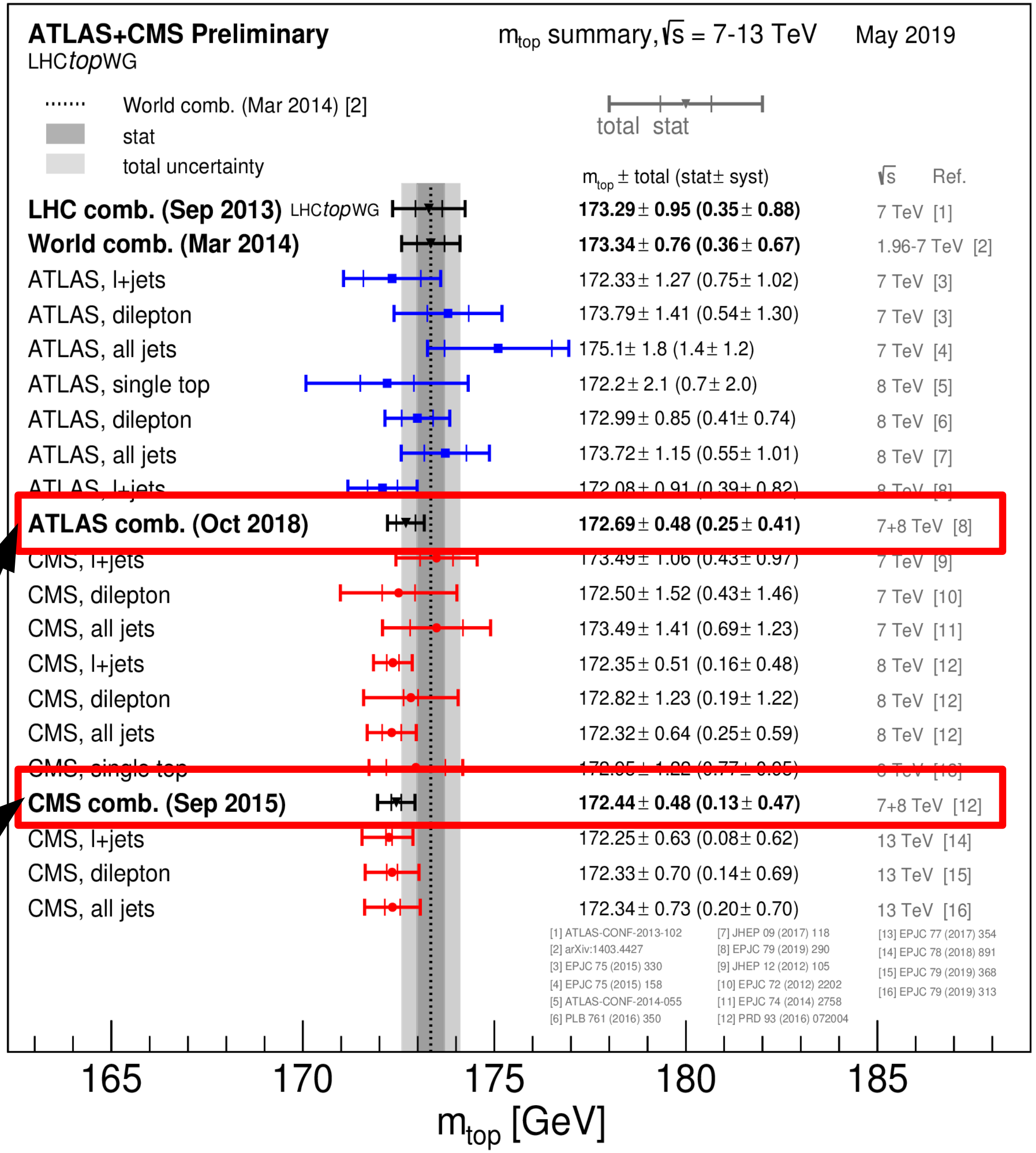
- CMS: all-jets + l+jets

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

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

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

NEW



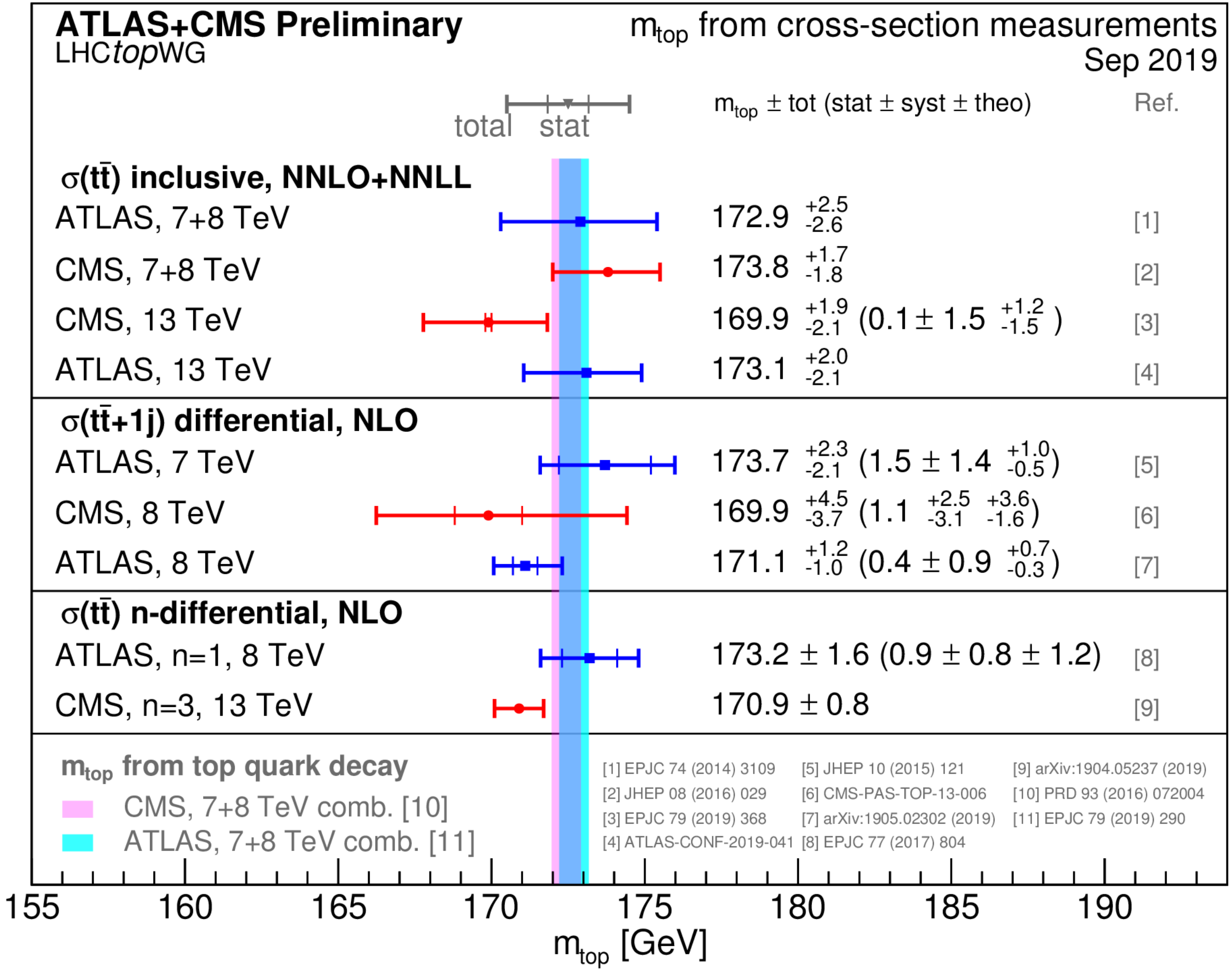
In context of LHCtopWG

- Time for another LHC combination ?

World combination ?

Top mass – alternative

Castro



Top mass – alternative

Castro

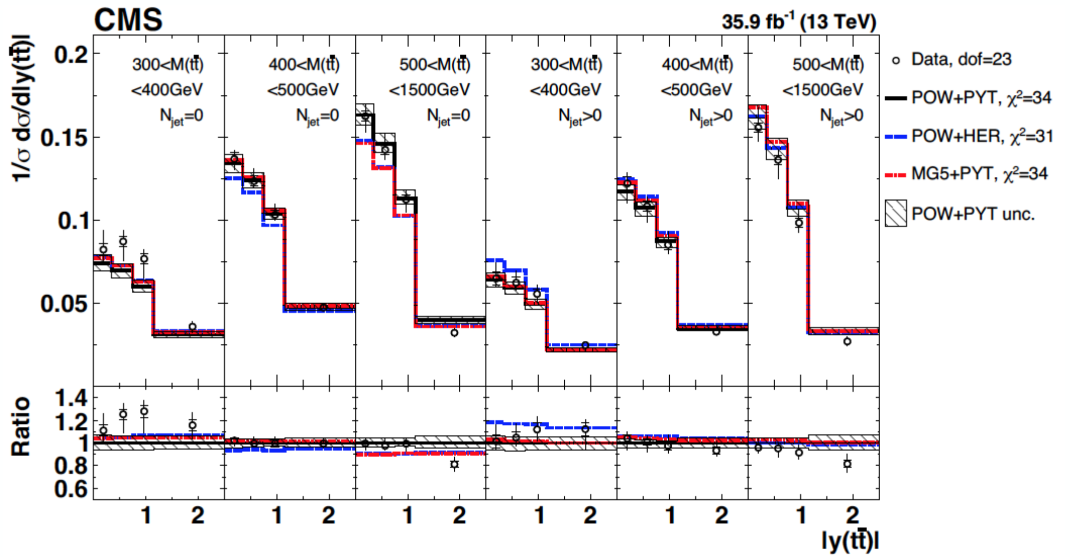
ATLAS+CMS Preliminary
LHC*top*WG

m_{top} from cross-section measurements
Sep 2019

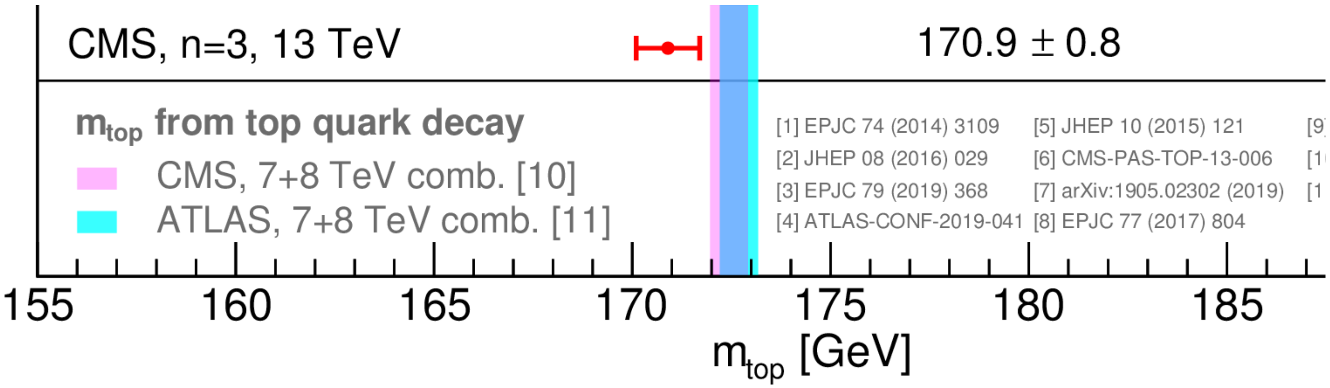
Triple-differential cross section measurement:

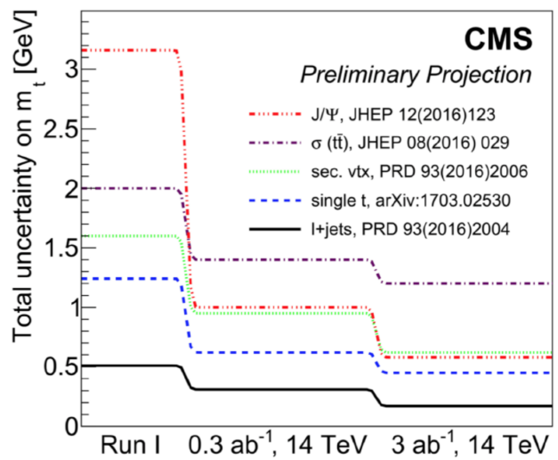
- CMS 13 TeV data, dilepto
- Discussed earlier...
- Precision of < 0.5% (!)

[arXiv:1904.05237 sub. to EPJ-C]



m^{pole}_{top} = 170.5 ± 0.8 (total) GeV $\delta m_t/m_t$ = 0.47% (!)

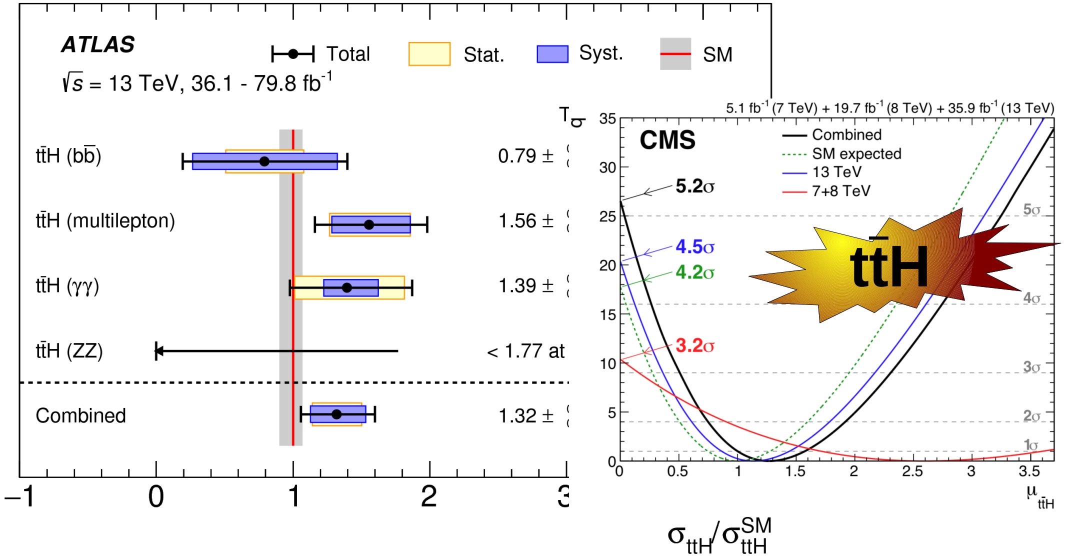


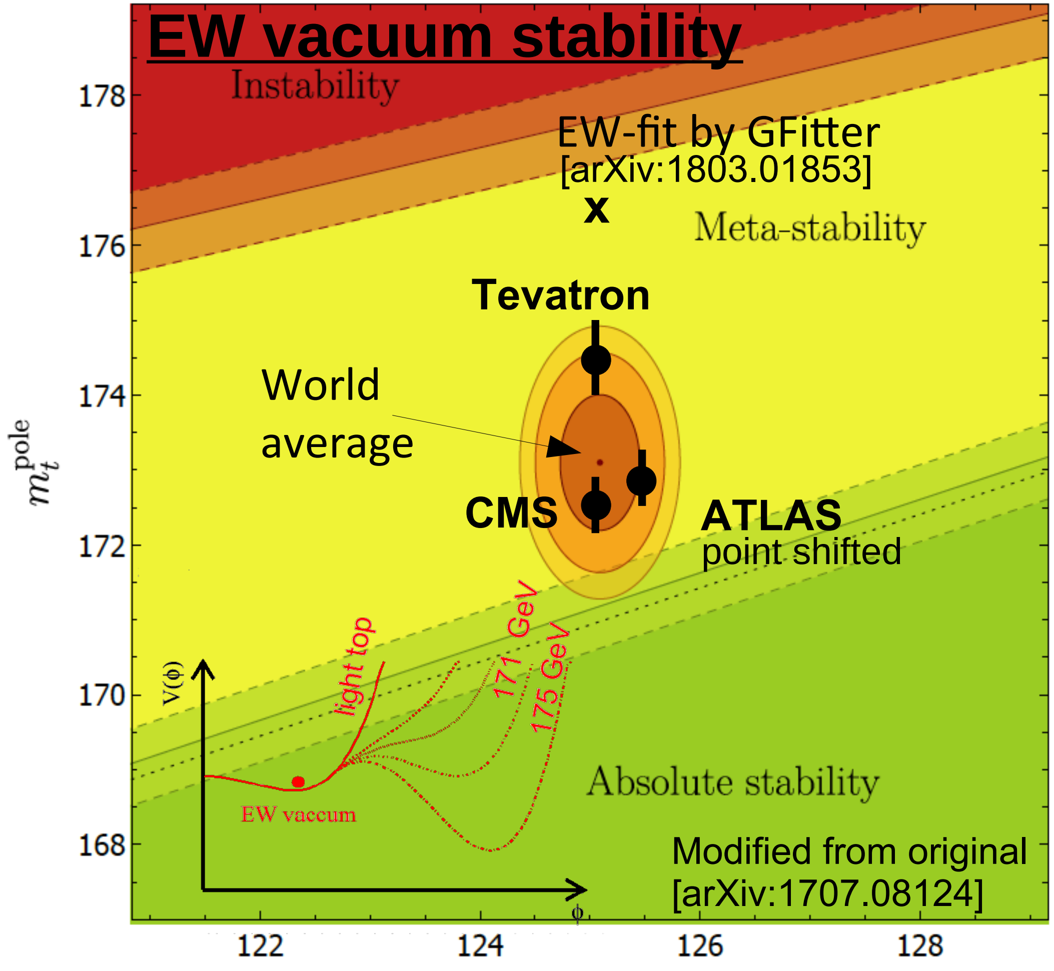


Beyond the SM ?

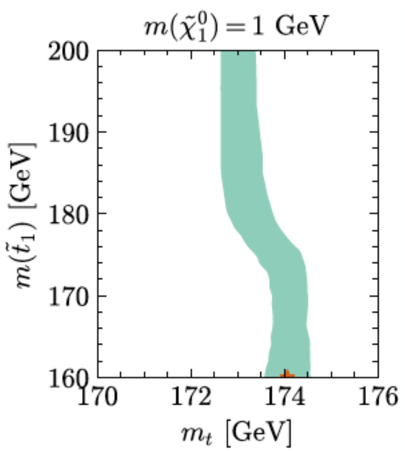
- Very subjective but illustrative, latest results from LHC & Tevatron – SM true
- ***ttH* observation:**

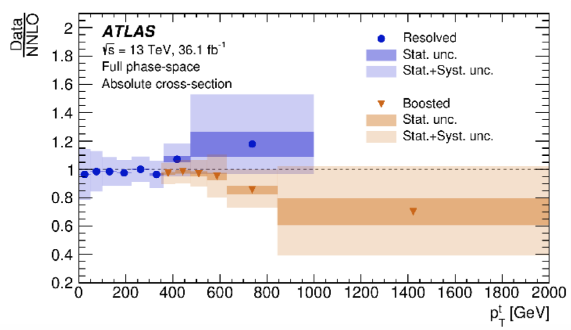
GFitter: $m_t = 176.4 \pm 2.1$ GeV





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



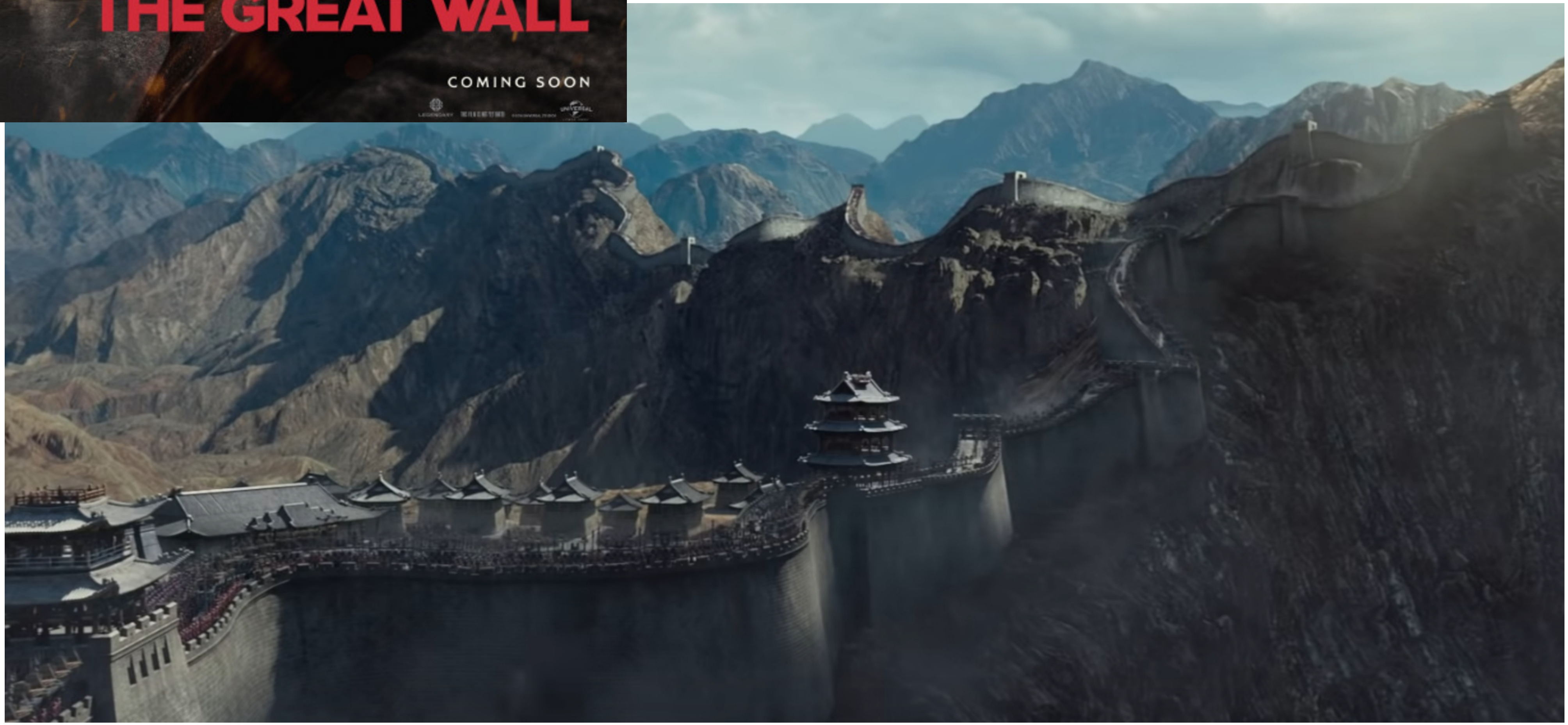


m_h^{pole}

<u>Caveat:</u>

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

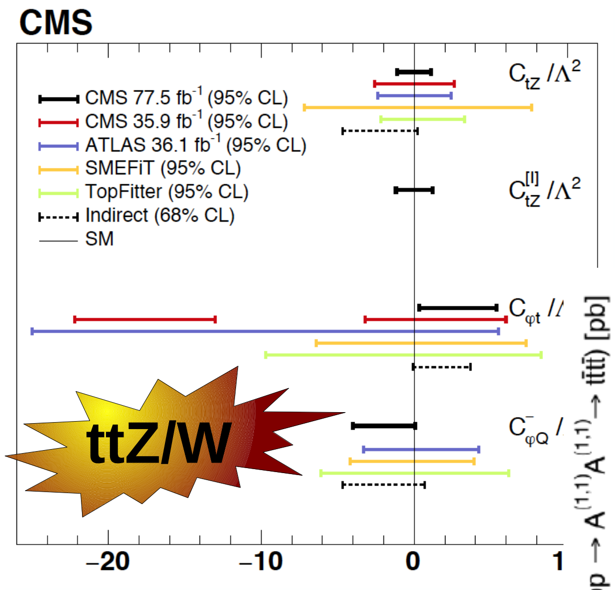
New friends for the top ?



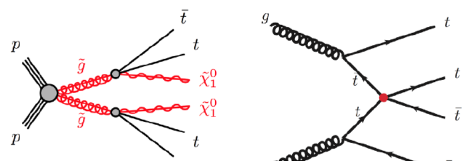
Effective field theory... ...many

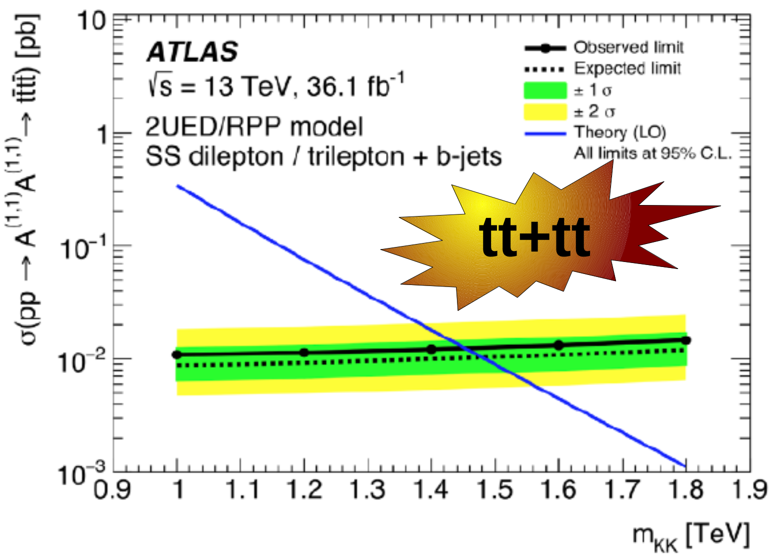
- EFT is now widely used to search for off-resonance effects due to BSM contributions

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

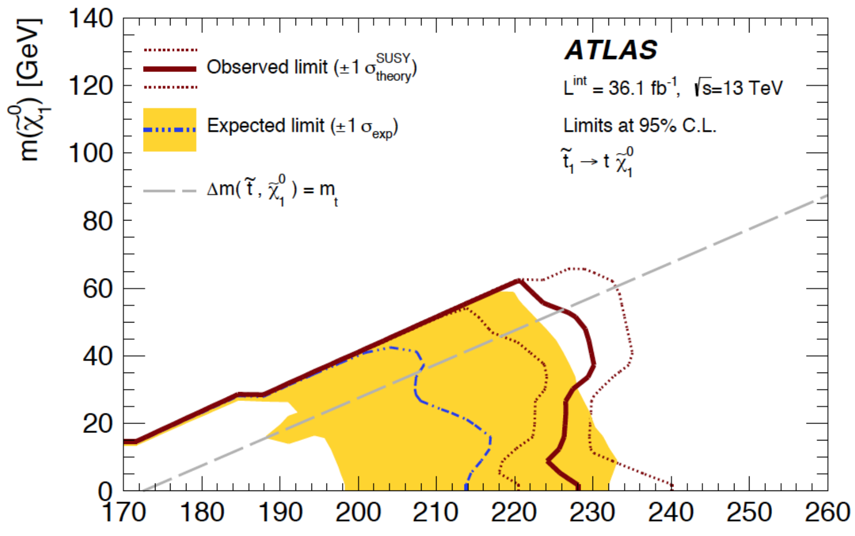


ttZ/W

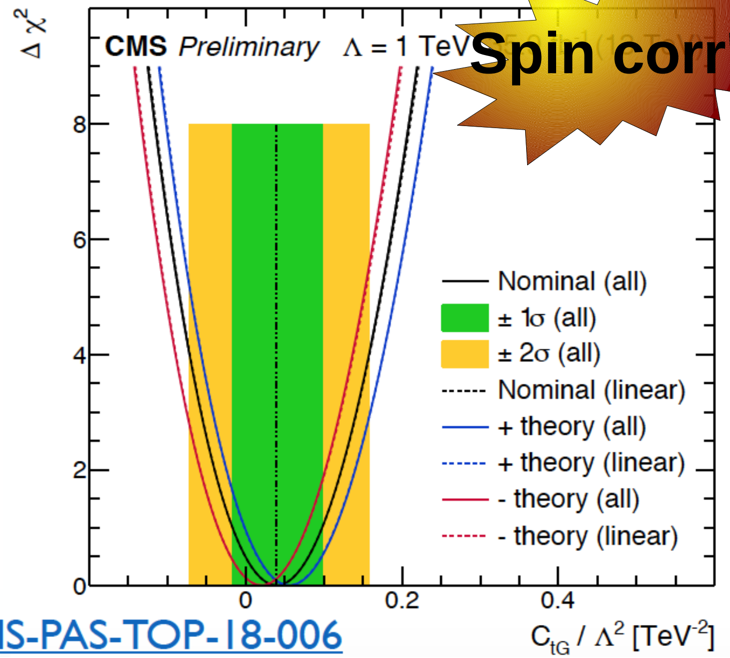




tt+tt



CERN-EP-2019-034



Spin corr's

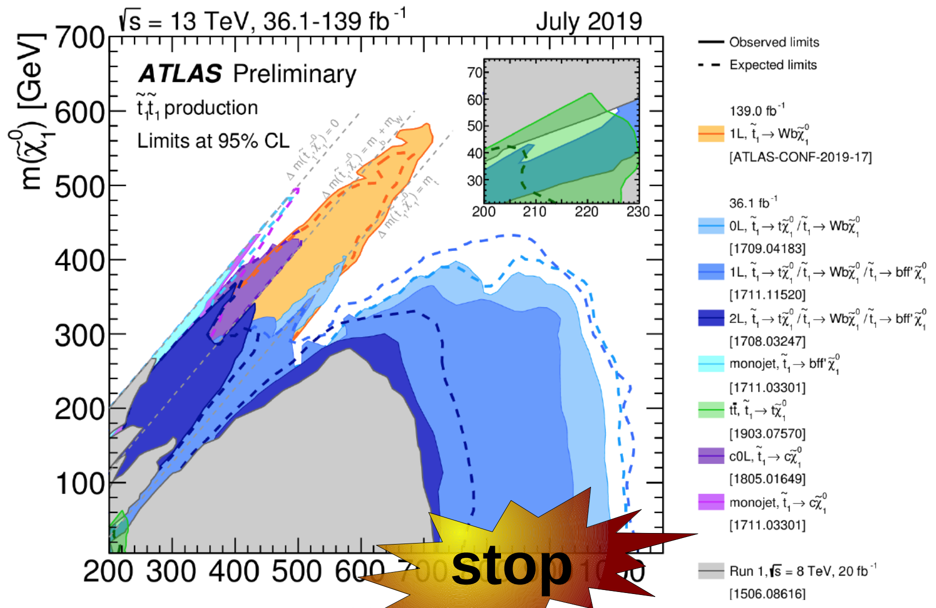
CMS-PAS-TOP-18-006

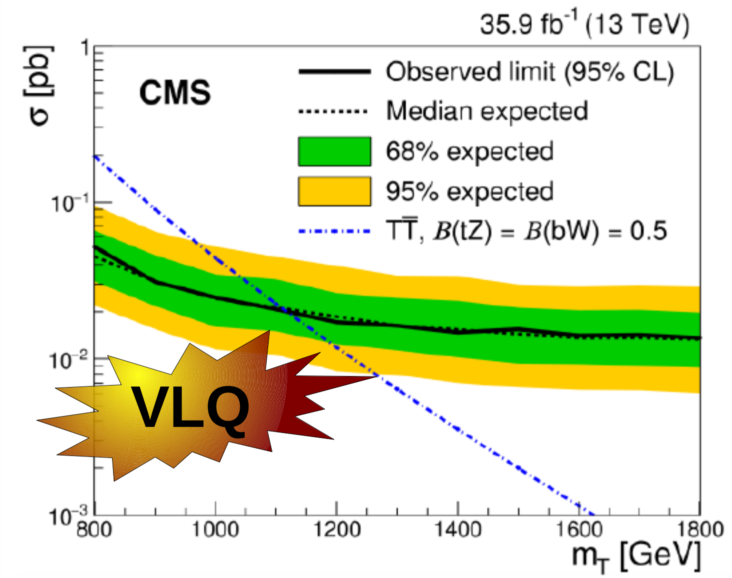
...apologies for being short here!

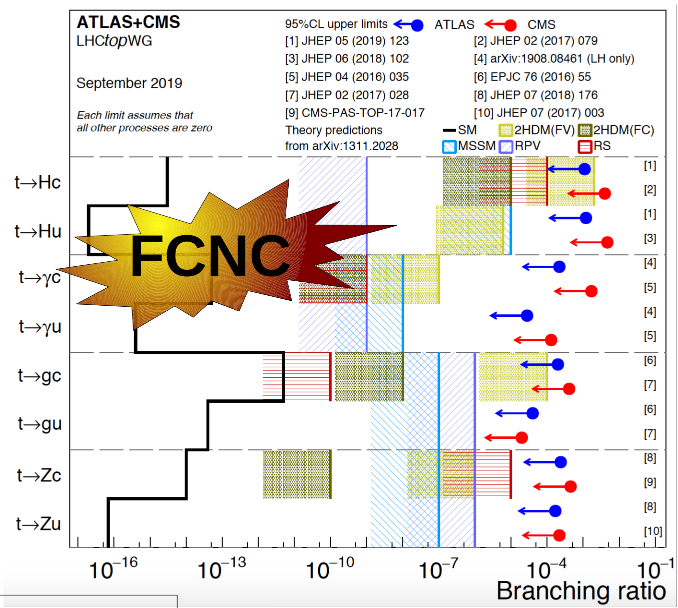
New friends for the top ?

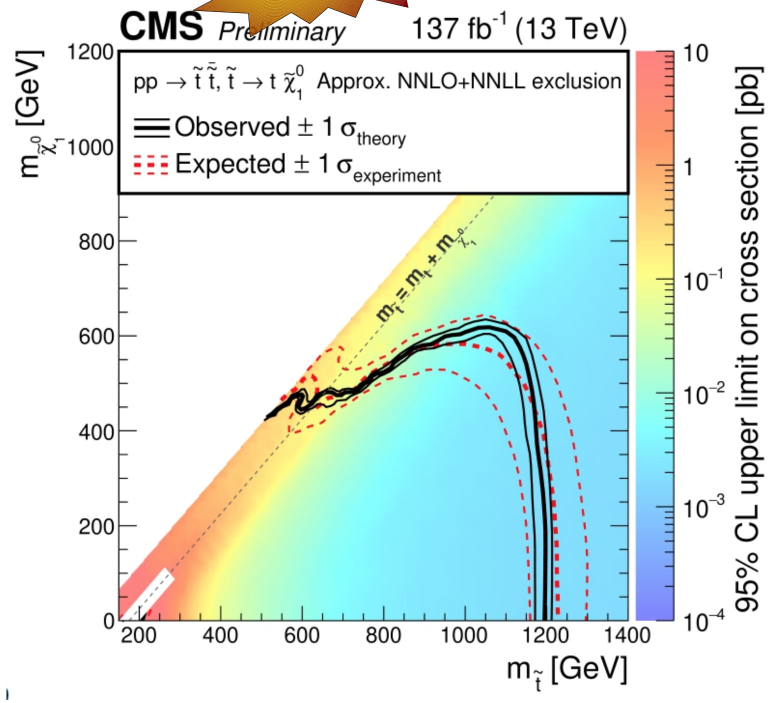
Majewski
Nikiforou

- “stealth” top region not yet fully excluded
- $t\bar{t}$ modeling uncertainties dominate searches
  - Danger of “over-tuning” ? Minimized by specific phase space / control regions







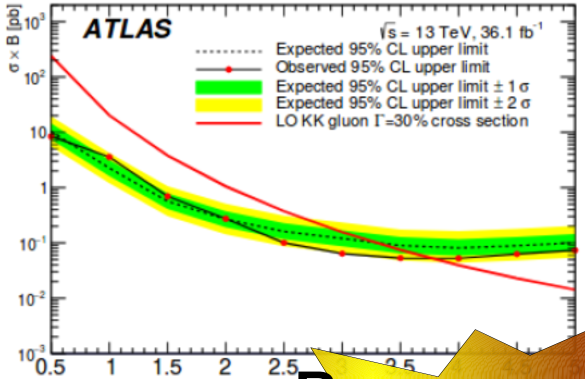


...apologies for being even shorter here!

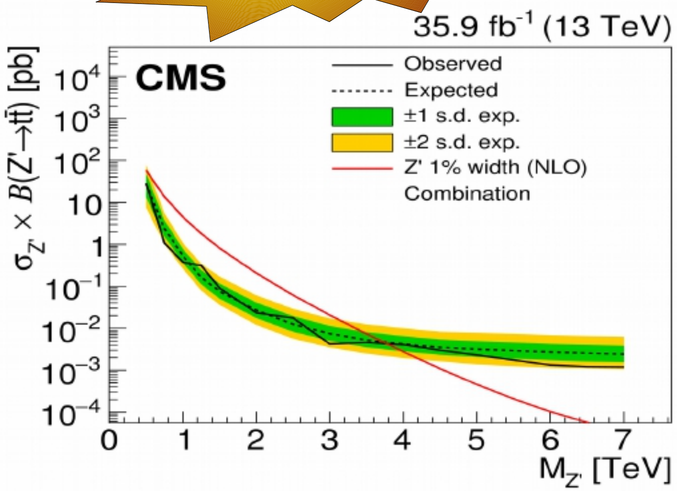
New friends for the top ?

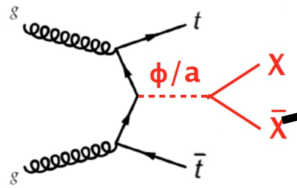
Schwanenberger
Chatterjeen

- DM + Resonances, Impossible to summarize: 32 vs. 71 (!)
  - Broader resonances hard to model
  - Differential top quark cross section to search for DM

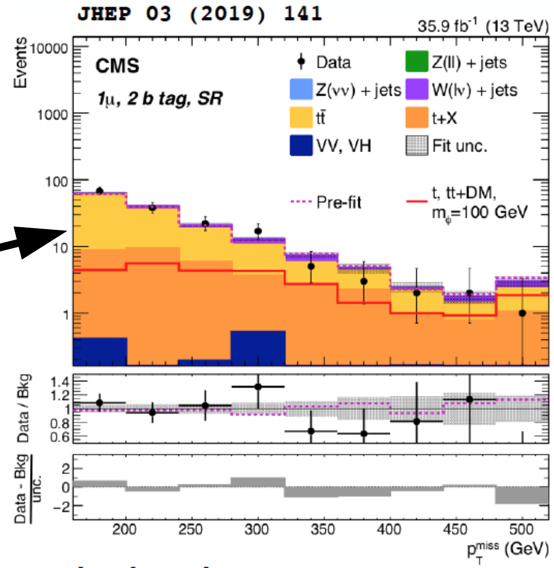


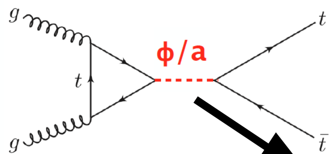
Resonances: KK, Z'



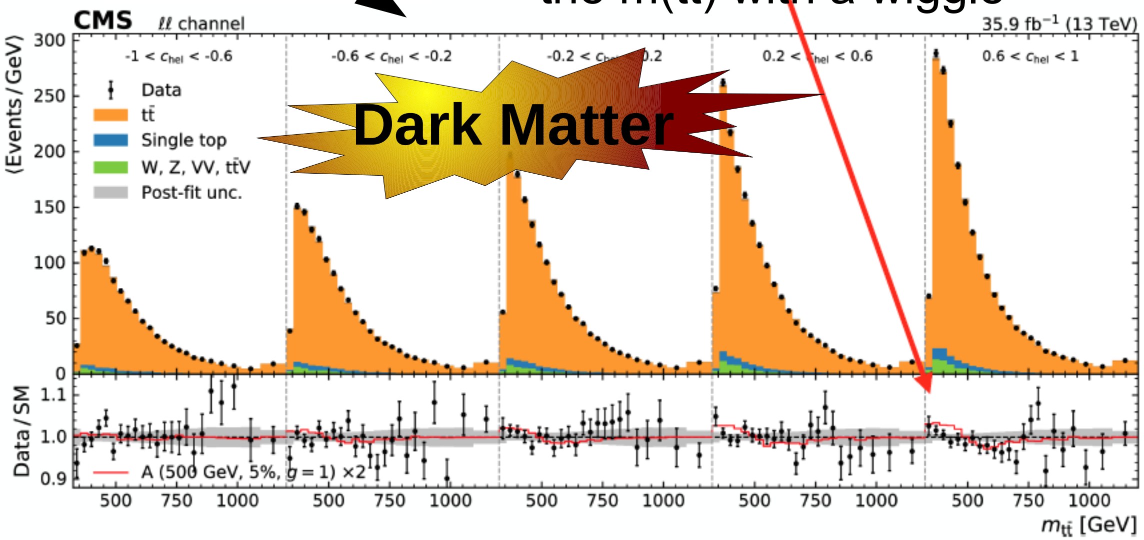


Direct DM production
vs.
DM mediater





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



Dark Matter

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

No BSM found (yet)...

But how to celebrate...:

- No alcohol sale on Sundays, but...

Indiana Looks to Finally End Prohibition-Era Restriction on Sunday Alcohol Sales

By Jim Vorel | January 12, 2018 | 10:53am

Photo via Getty Images, Hannah Foslien

DRINK > NEWS > INDIANA SUNDAY ALCOHOL SALES

1918

Indiana goes dry as a state.

2018

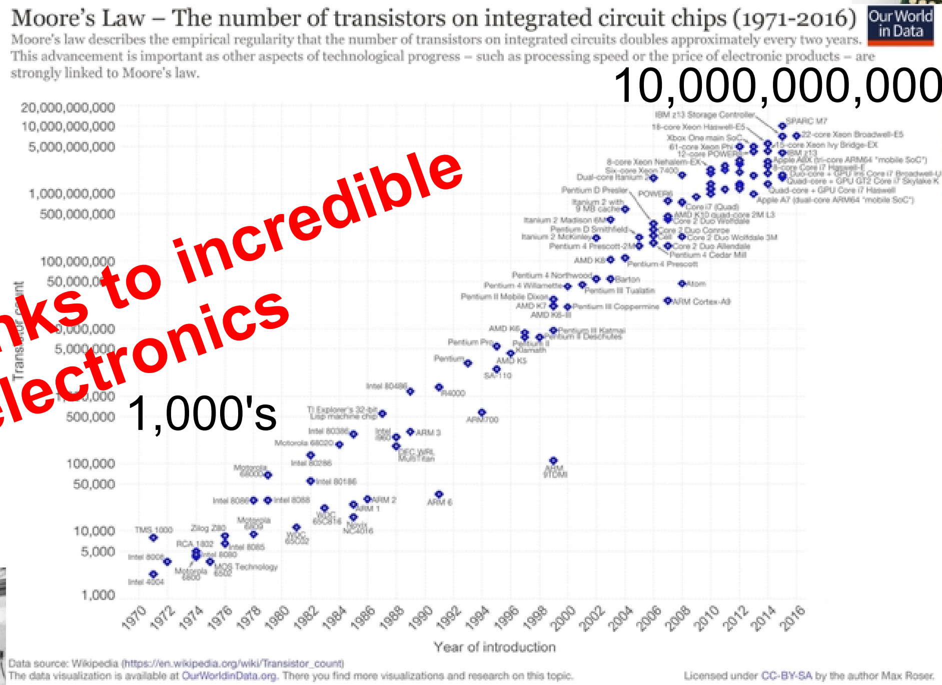
On Wednesday, Feb. 28, Gov. Eric Holcomb signs Senate Bill 1, which allows Sunday carryout sales between noon and 8 p.m. by grocers, convenience stores and liquor stores.

- ...after about 86 years can buy alcohol again on Sundays

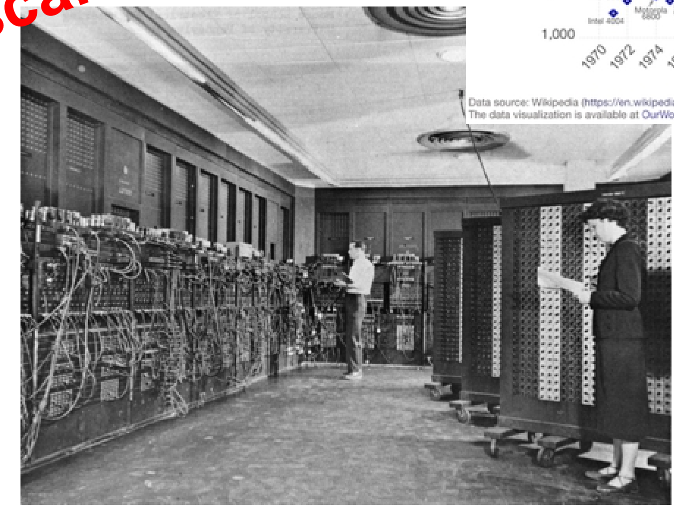
Future upgrade plans

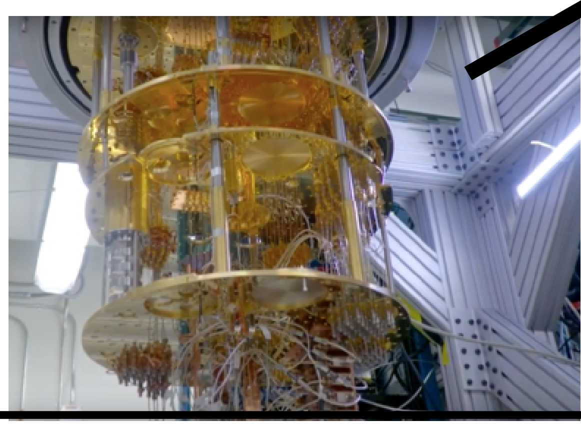
Exciting times...

Computing is a critical resource for progress in experiments and theory...



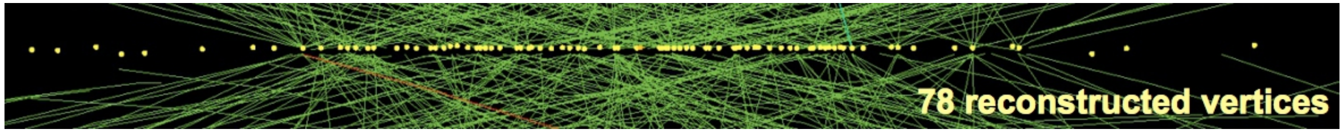
Moore's law – thanks to incredible scaling of microelectronics





IBM Quantum Computer
~< 100 bits

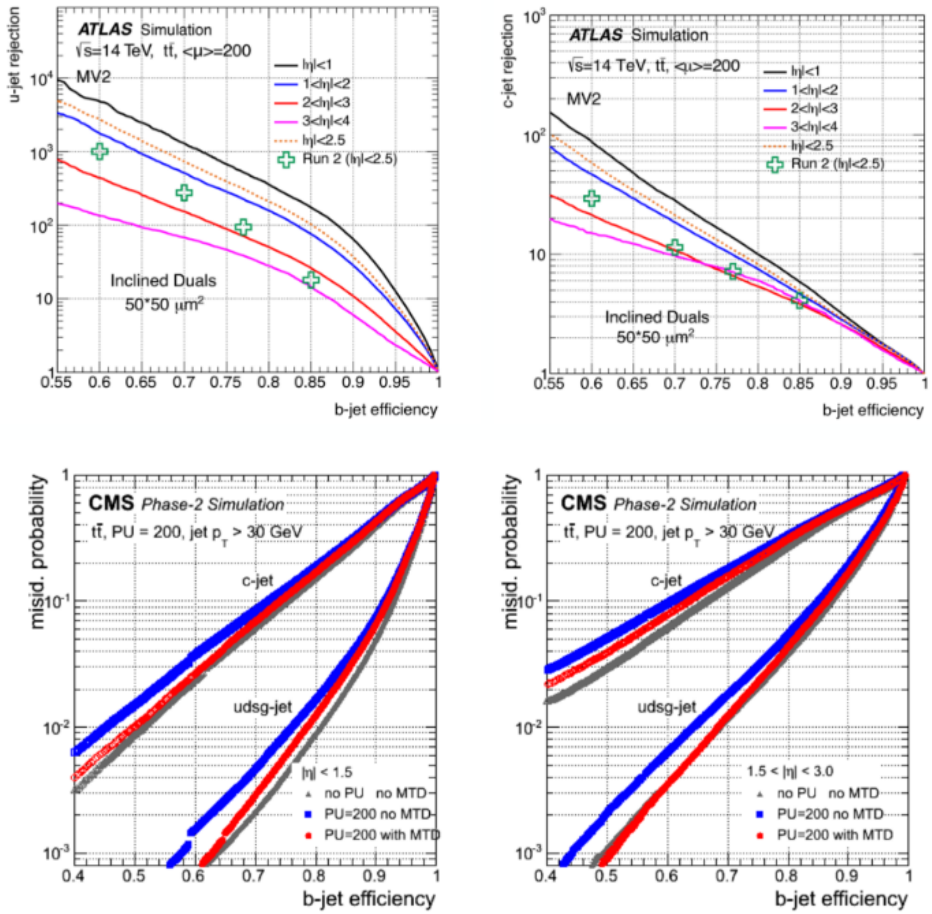
- QC/QA for better understanding top quark physics ?
- Maybe one of the next TOP's will tell



Special thanks for sending me input

- **Flavour tagging (example)**
  - Important for many top quark selections
  - Track and secondary vertex bases taggers (default)
    - benefits mostly from improved tracker resolution/coverage
  - Good performance compared to run 2 and high PU
  - Performance at high η worse than for central jets

flavour tagging performance



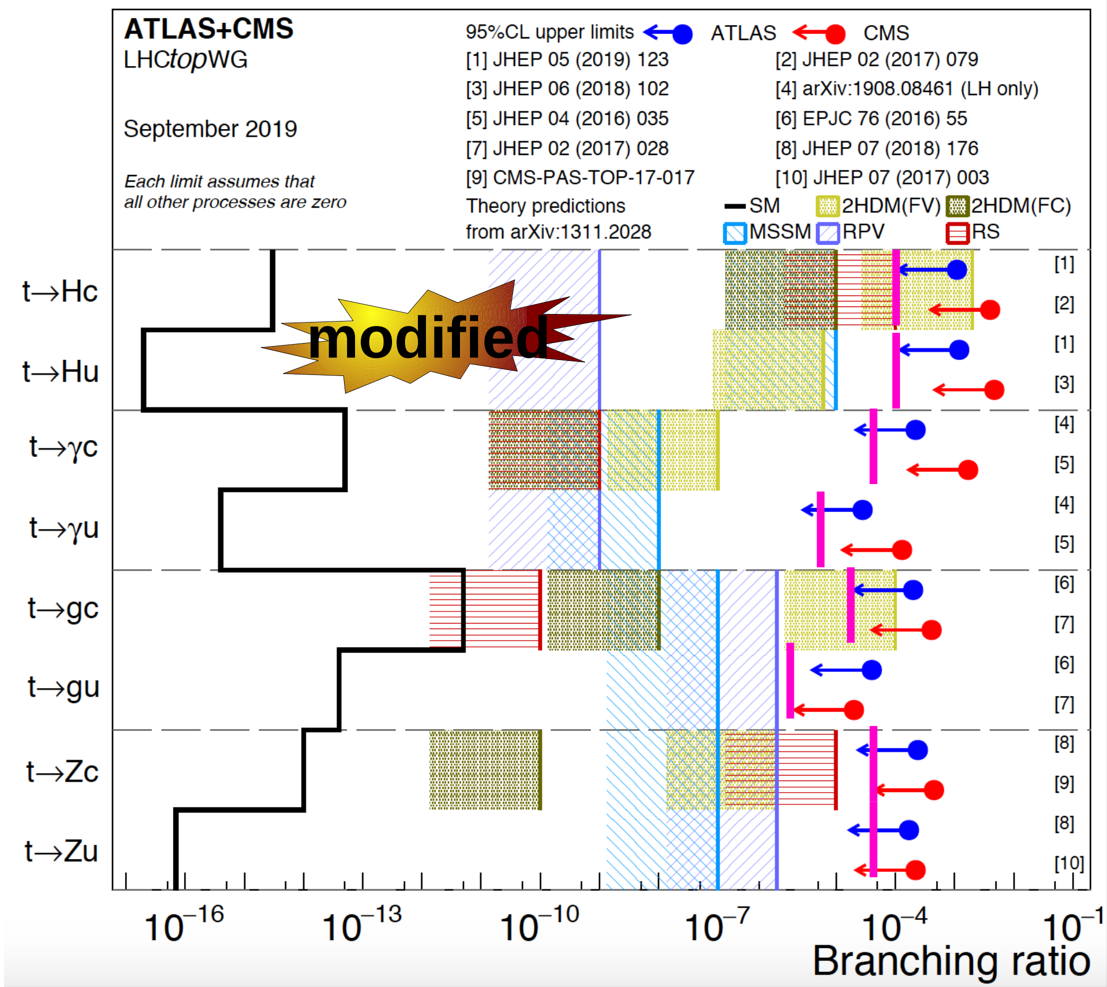
→ Well prepared for the challenges of top quark physics at the HL-LHC experiments

The future...FCNC prospects

Updates included:
→ presented by Castro

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 exclude more phase space



$t \to gu$	$t \to gc$	$t \to qZ$	$t \to \gamma u$	$t \to \gamma c$	$t \to Hq$
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}

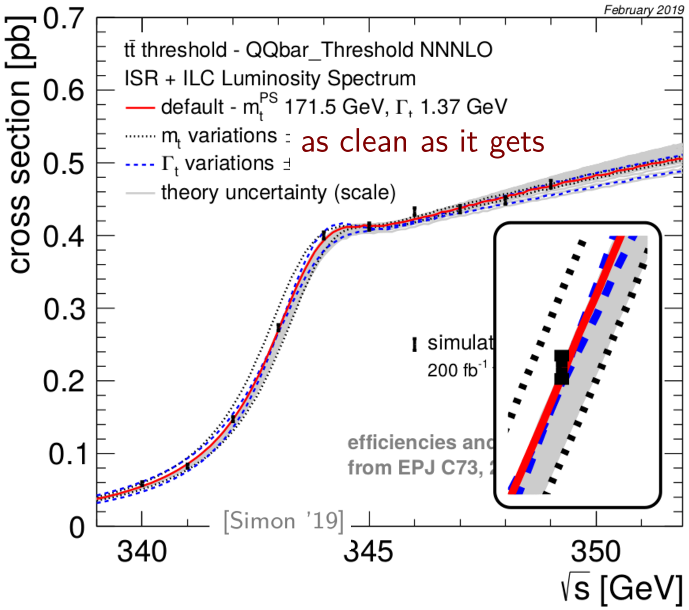
CERN-LPCC-2018-03

Future colliders

Durieux

Special thanks for sending me input

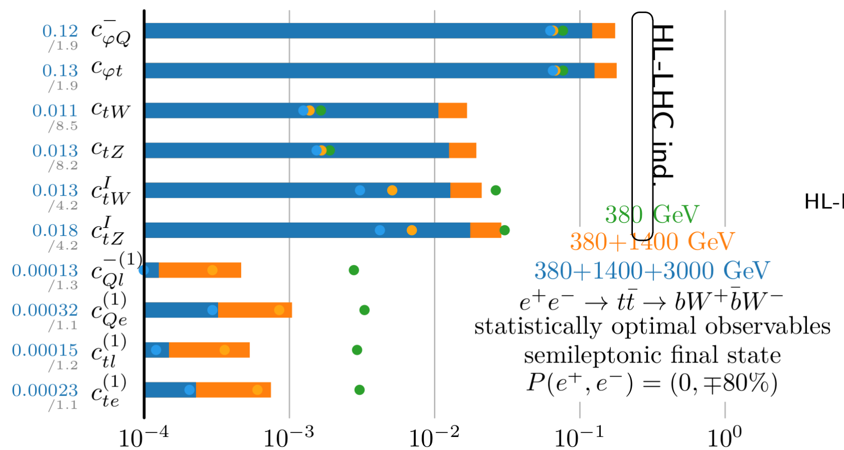
Mass extraction



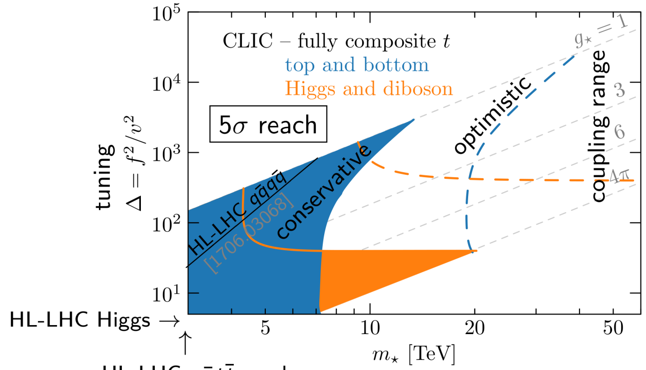
as clean as it gets

Electroweak couplings

precise, global and robust



high-energy top measurements are very sensitive to compositeness



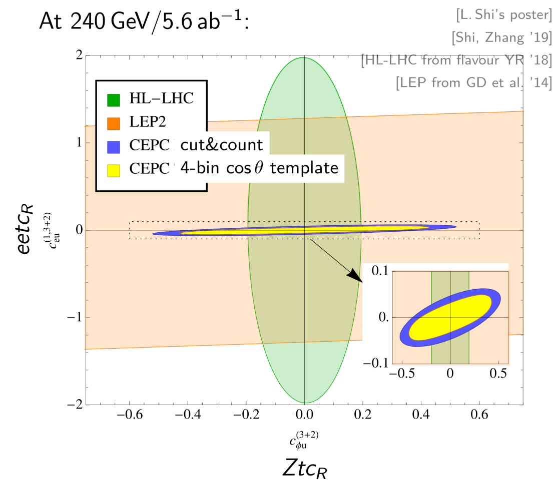
Farina et al. [1811.04084]

next-generation lepton colliders

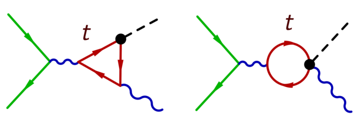
$e^+e^- \to t\,j$ FCNC

below the $t\bar{t}$ theshold

At 240 GeV/5.6 ab^{-1}:

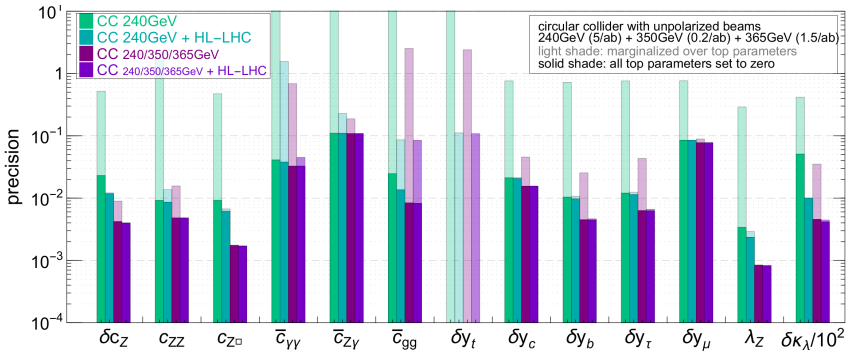


Top electroweak loops



Uncertainties on the top have a big effect on the Higgs

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. → 0



Conclusions

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

→ HL-LHC: We will get about 3 billion $t\bar{t}$ events
→ Allows for multi-dimensional measurements of σ, α_S, PDFs and any properties, associated production as well
→ FCNCs and other statistically limited processes improve
Maybe even a 100 TeV collider, it's not that big...

Deep-neural-network based b-tagging as basis for improvements in top analyses — *Manuel Guth*
Main Building 214 — 17:50 - 17:55

Measurement of the forward-backward asymmetry in l+jets — *Pu-Sheng Chen*
Main Building 214 — 18:00 - 18:05

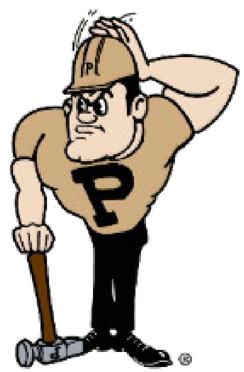
Measurements of inclusive and differential cross-sections of ttgam production in the e+mu final state at 13 TeV with the ATLAS detector — *Knut Zoch*

Differential measurement of tZ production in CMS — *Joscha Knolle*
Main Building 214 — 18:20 - 18:25

Observation of the associated production of a top quark and a Z boson at sqrt(s)=13 TeV with the ATLAS detector — *Dylan Frizzell*

The first measurement of the running of the top quark mass — *Matteo Defranchis*
Main Building 214 — 18:40 - 18:45

YSF session – excellent speakers
Exciting results, new methods



BOILER UP

Thanks to local organizers !

- YSF session, Poster session, Great dinner
- Impressive great wall excursion...





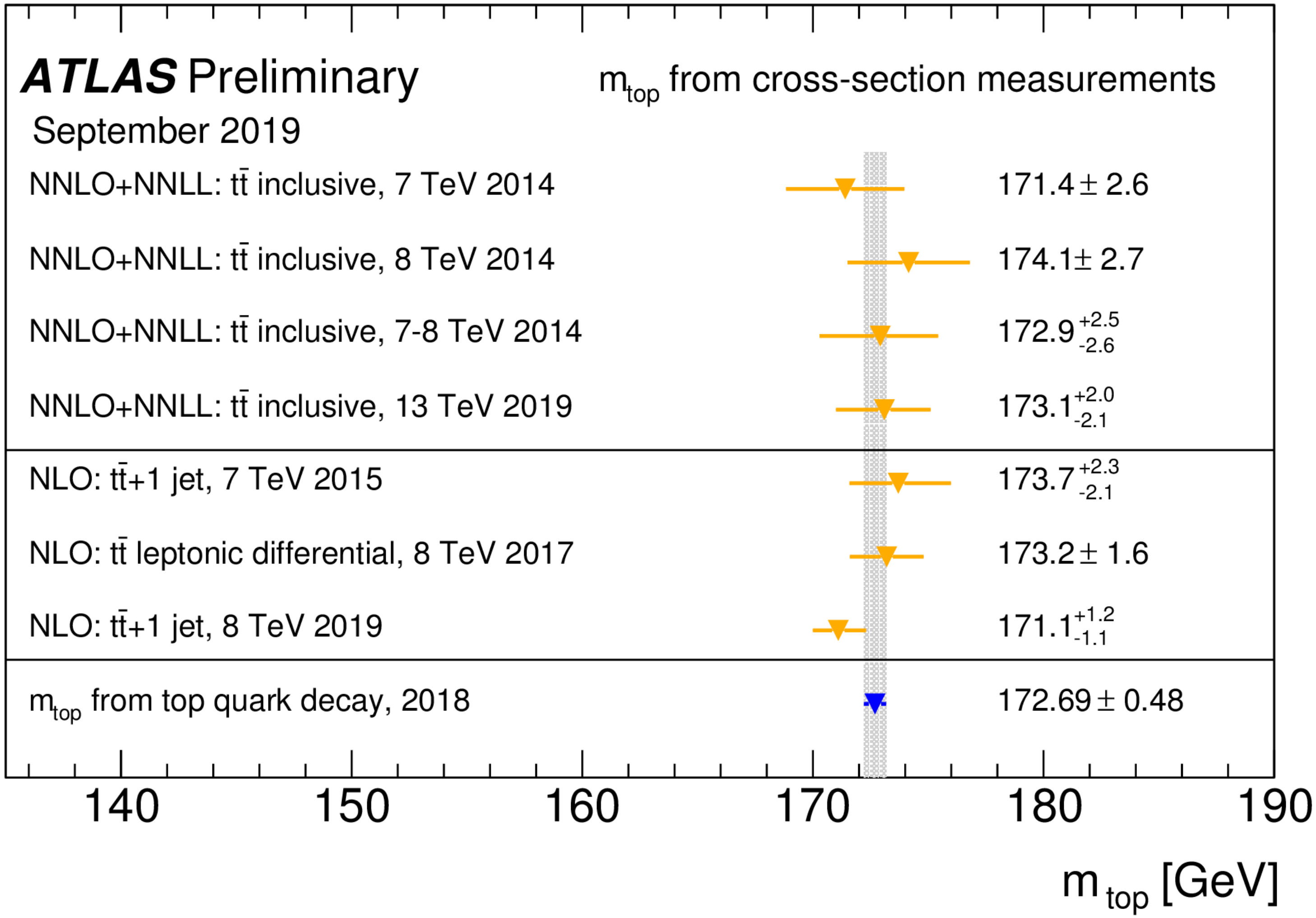


Thanks to Hongbo and local organizing committee
for a great workshop in a fantastic location!

Backup...

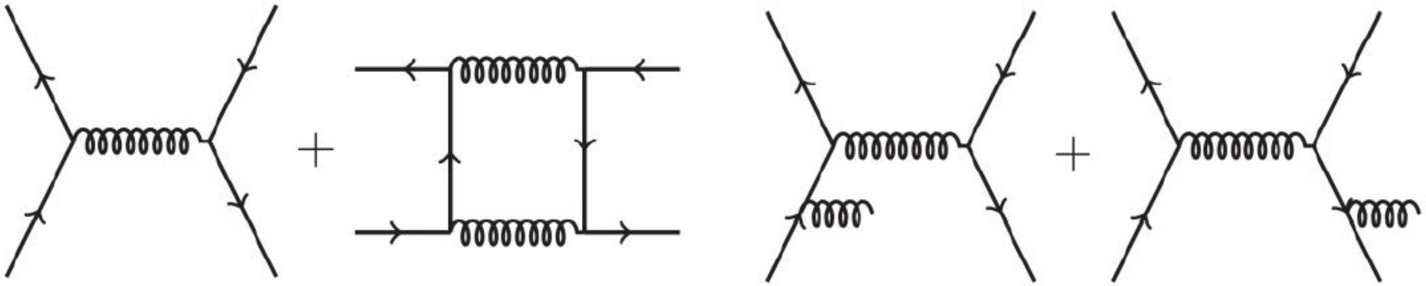
...in case you need more than ~80 distributions shown so far...

Mass from cross section



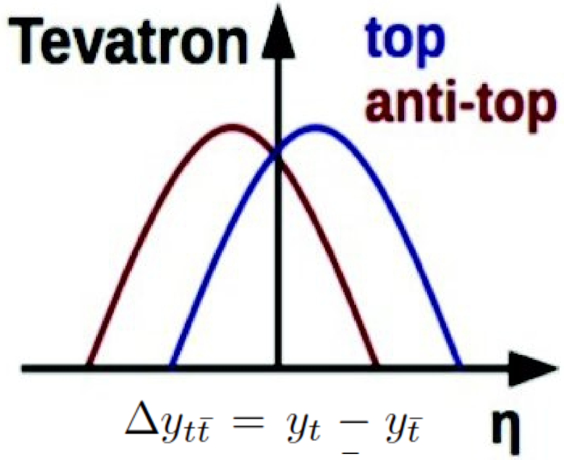
Top Quark Asymmetries

- Interference appears at NLO QCD:



Positive asymmetry — Negative asymmetry

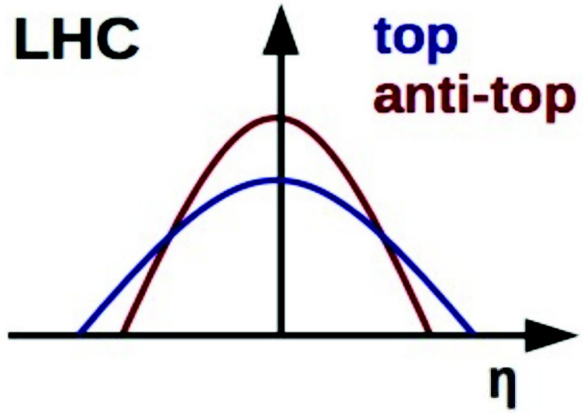
→ Only occurs in qq initial state; gg is fwd-bwd symmetric



$$\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$$

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

- 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"

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

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

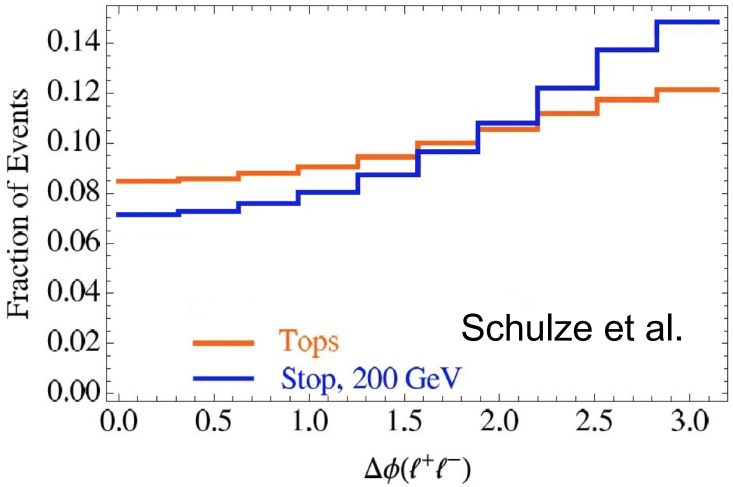
Spin correlations

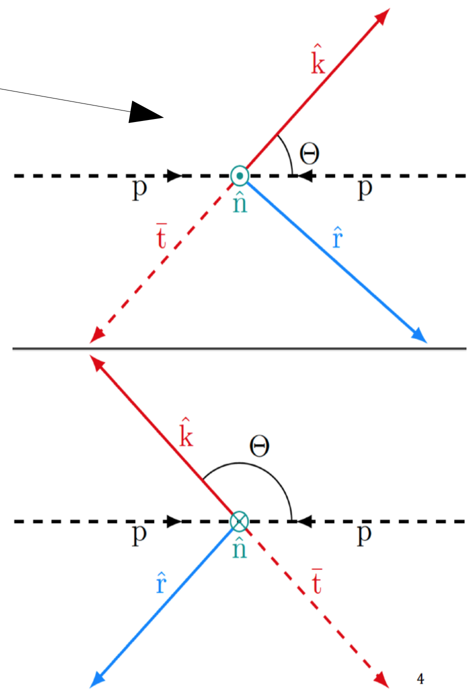
- Double-differential cross section allows to access spin correlation and polarization information in top quark events

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

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta^a_+ d\cos\theta^b_-} = \frac{1}{4}(1 + B^a_+\cos\theta^a_+ + B^b_-\cos\theta^b_- - C(a,b)\cos\theta^a_+\cos\theta^b_-)$$

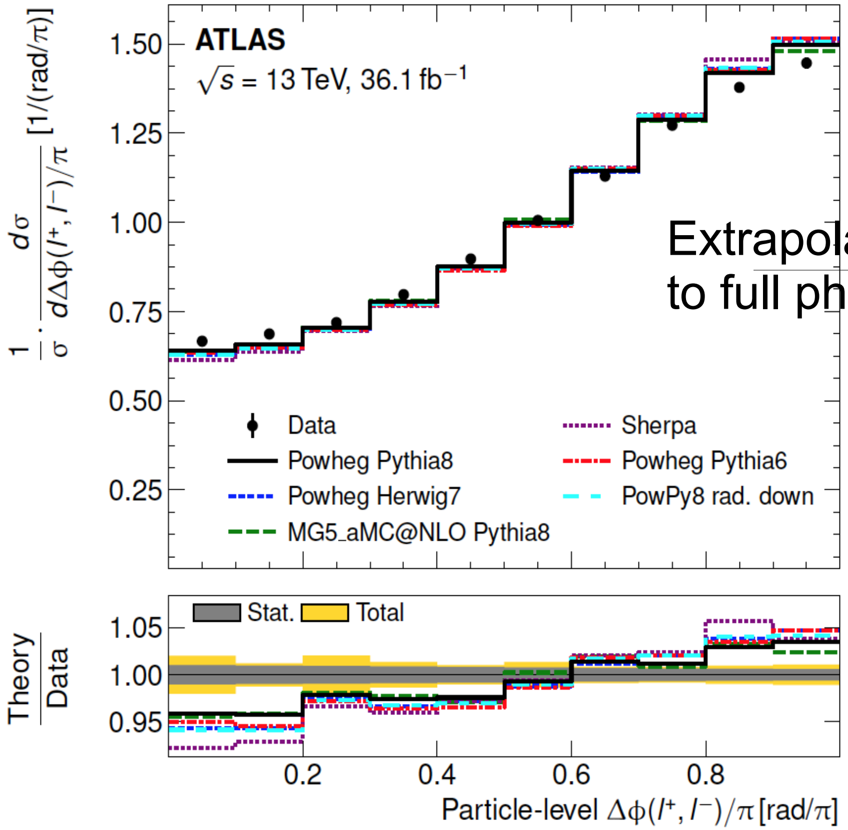
- Charged lepton is perfect spin analyzer, well reconstructed as well
- Can probe top quark spin in 3 dimensions
- Sensitive to BSM physics (more spin corr's = s-channel dark matter; less spin corr's = new scalars)



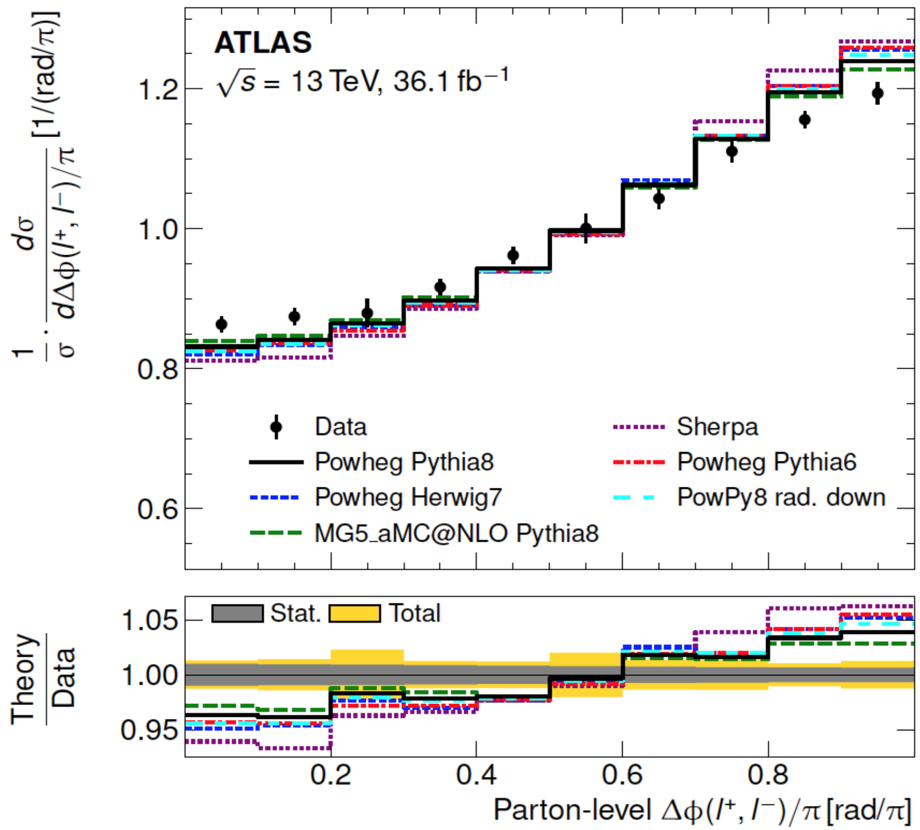


Spin correlations

- ATLAS measures dPhi in 1D and as a function of mttbar, B and C as well as cross correlations
- Discrepancy between NLO simulations and data at the 3σ level in dPhi at particle **and** parton level, also seen in differential in mttbar bins:
  - f_{SM} of 1 agrees with NLO SM, **observe** $f_{SM} = 1.25 \pm 0.02 \pm 0.06 \pm 0.04$



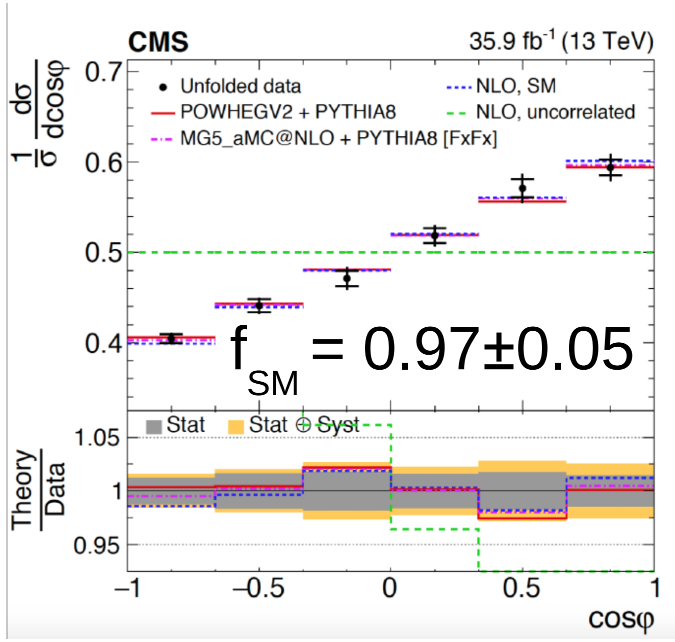
Extrapolate from particle to full phase space

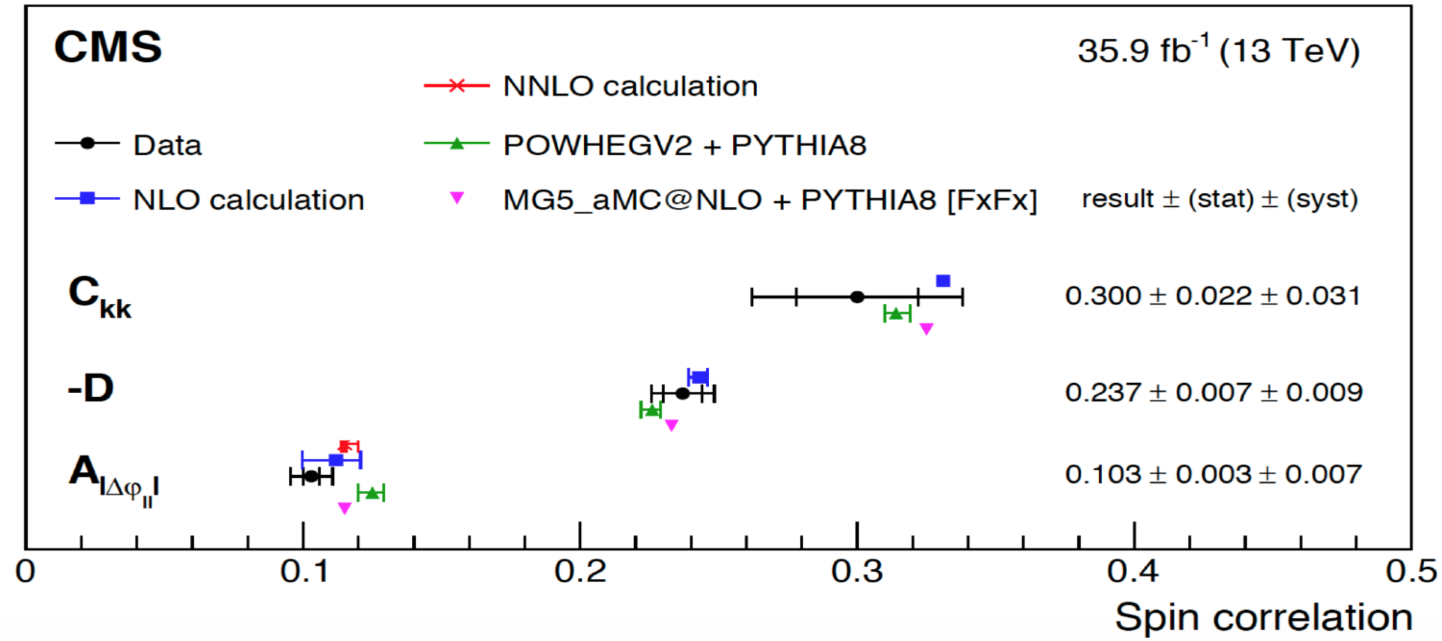


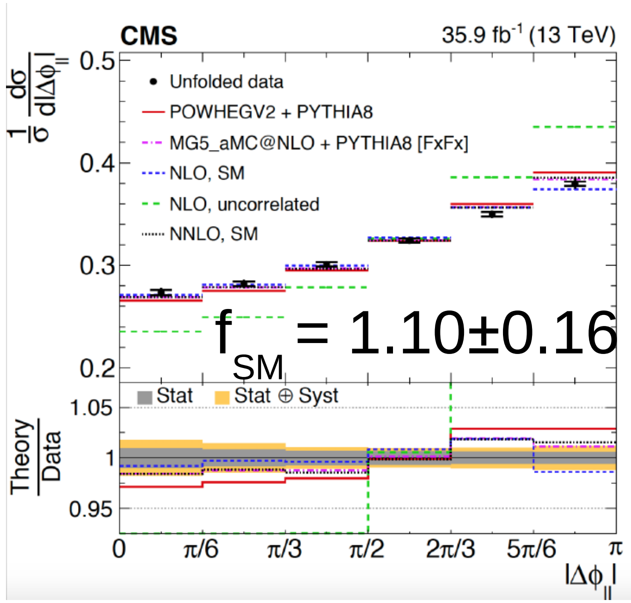
Spin correlations

NEW

- CMS employs 13 TeV dilepton data
- Opening angle maximally sensitive to alignment of top quark spins
- Most precise direct measurement via cosφ
  - Systematic: p_T and BG modeling
- Indirect measurement via dPhi shows about 1σ discrepancy to NLO simulations

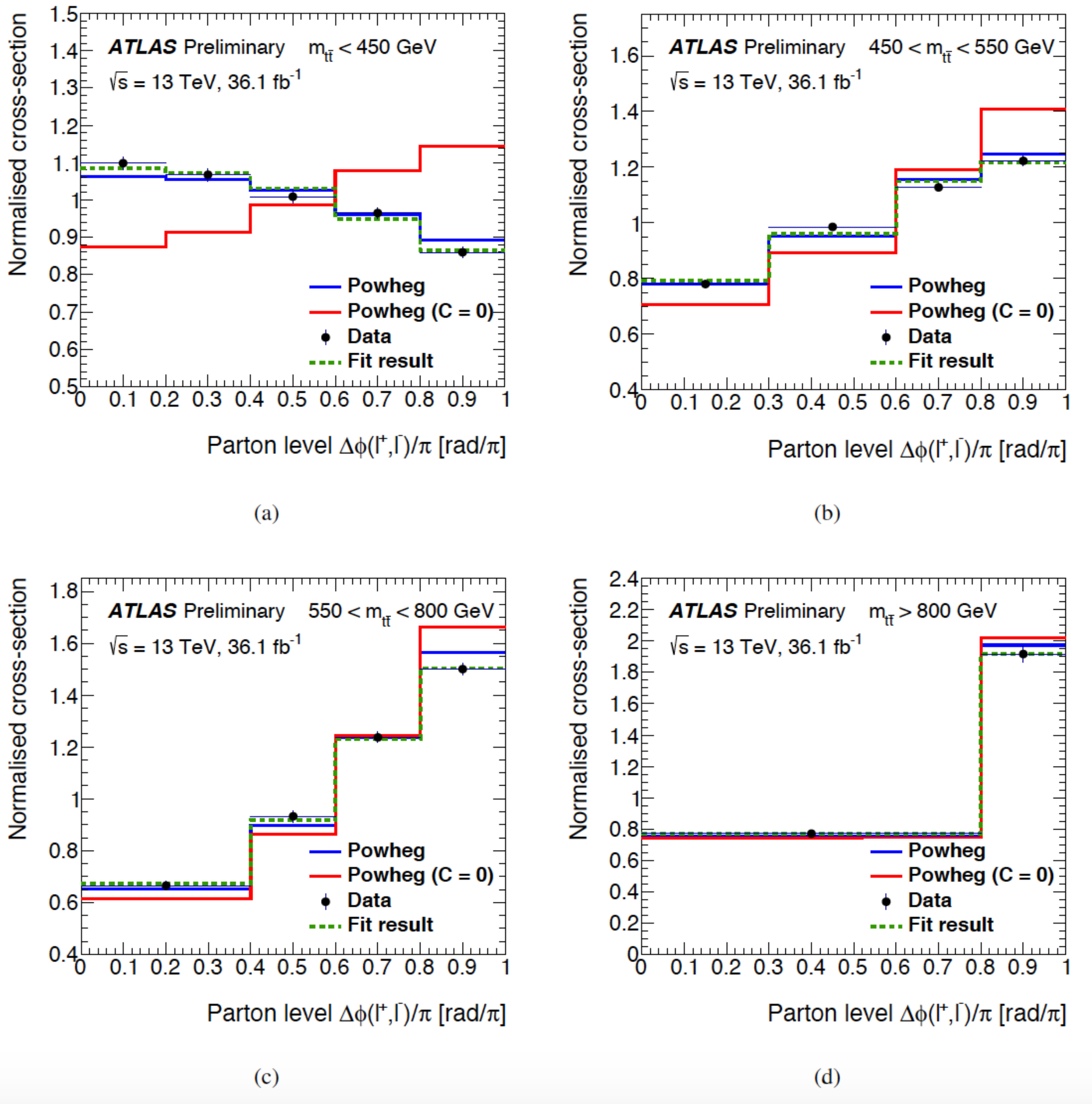






Spin correlations

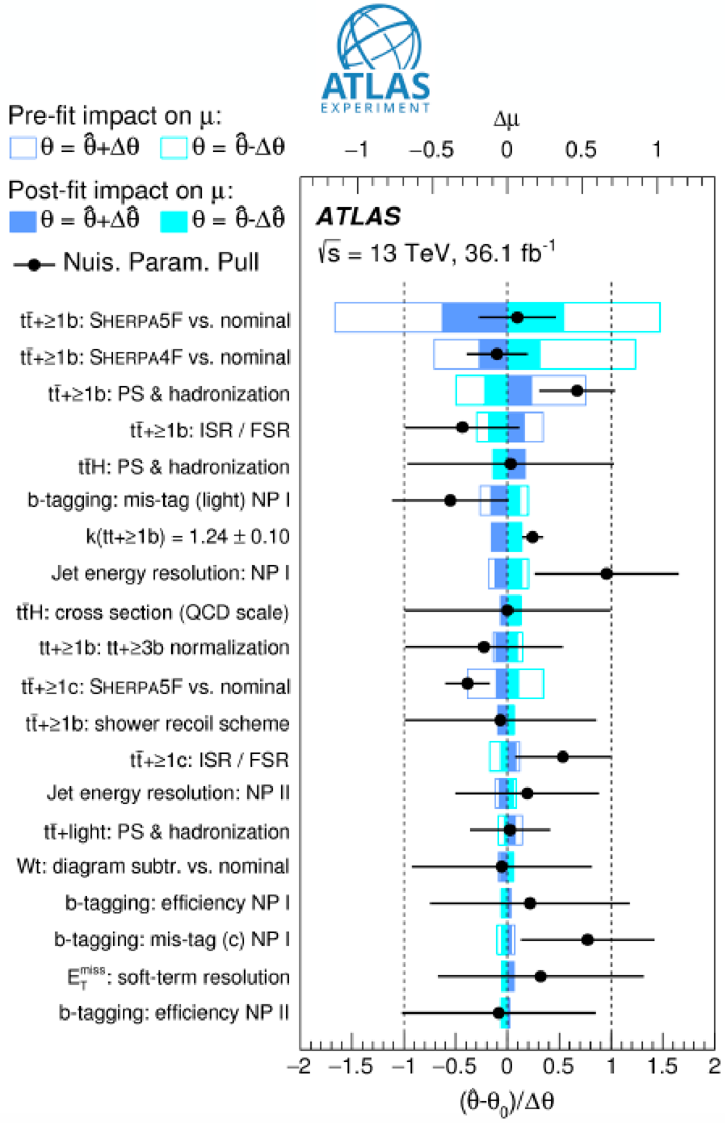
- 2D as well:



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

T. Vasquez Schroeder

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

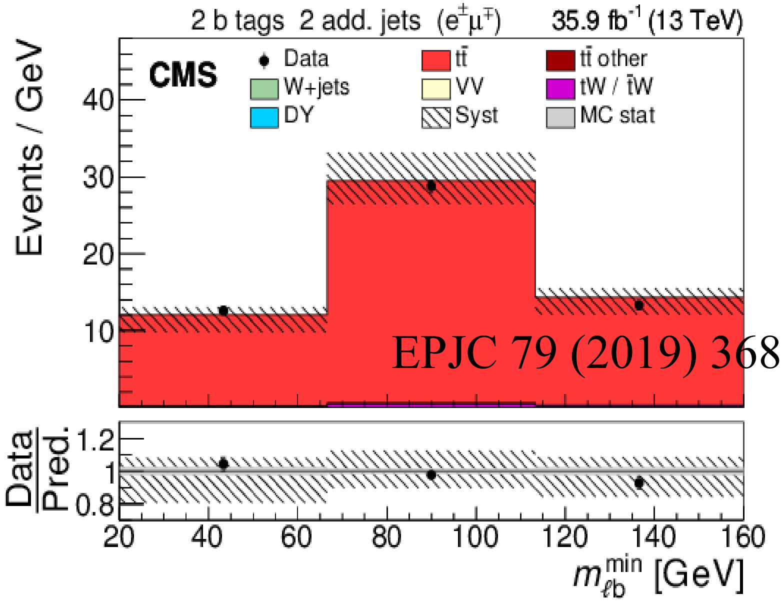


Indirect methods: incl. σ

- CMS measurement at 13 TeV, dilepton
- 12 categories based on N(b-jets), N(light jets)
- Employ m_{lb}^{min}, p_T, event yield
- Simultaneous fit to measure cross section and top mass
  - 888 ± 2 (stat.) ± 27 (syst.) ± 20 (theo.) pb
  - Extract MC mass from cross section:

m_{top}^{MC} = 172.33 ± 0.14 (stat.) ± 0.66/0.72 (syst.) GeV

$\delta m_t/m_t$ = 0.42%



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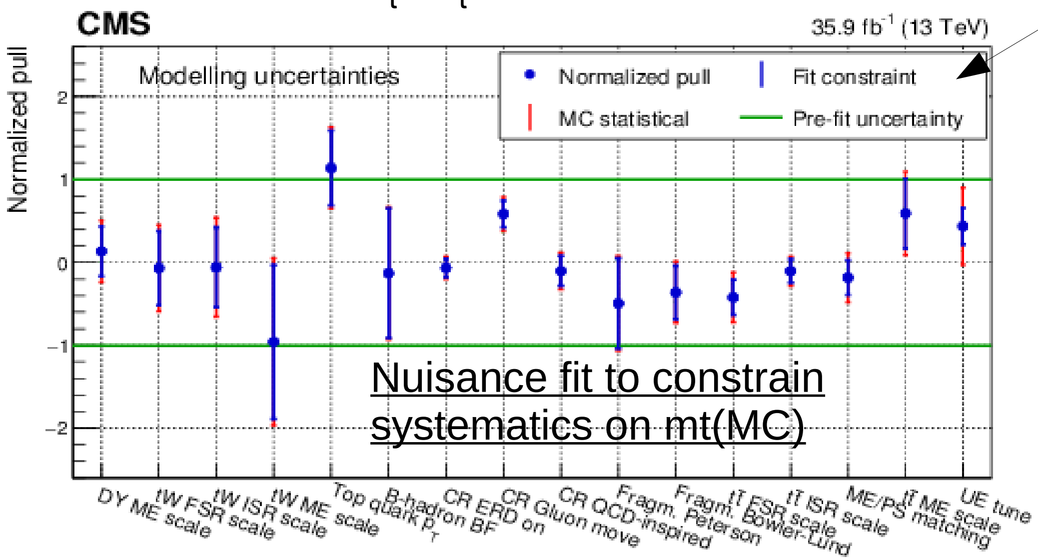


Nuisance fit to constrain systematics on mt(MC)

Dominant systematics:

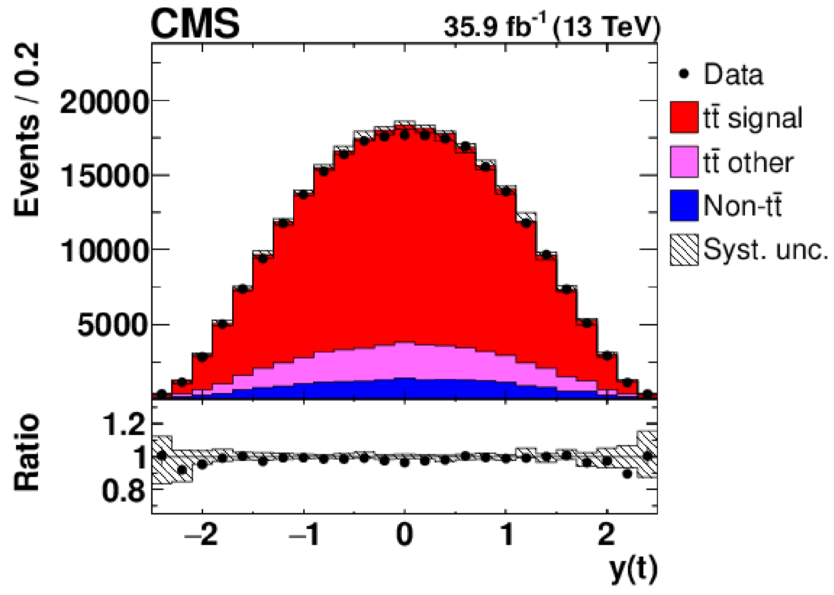
→ Jet energy (0.57 GeV)
→ MC statistics (0.36 GeV)
→ Background (0.28 GeV)

Extract most precise MS mass:

PDF set	$m_t(m_t)$ [GeV]
ABMP16	161.6 ± 1.6 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
NNPDF3.1	164.5 ± 1.6 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
CT14	165.0 ± 1.8 (fit + PDF + α_S) $^{+0.1}_{-1.0}$ (scale)
MMHT14	164.9 ± 1.8 (fit + PDF + α_S) $^{+0.1}_{-1.1}$ (scale)

Indirect methods: diff. σ

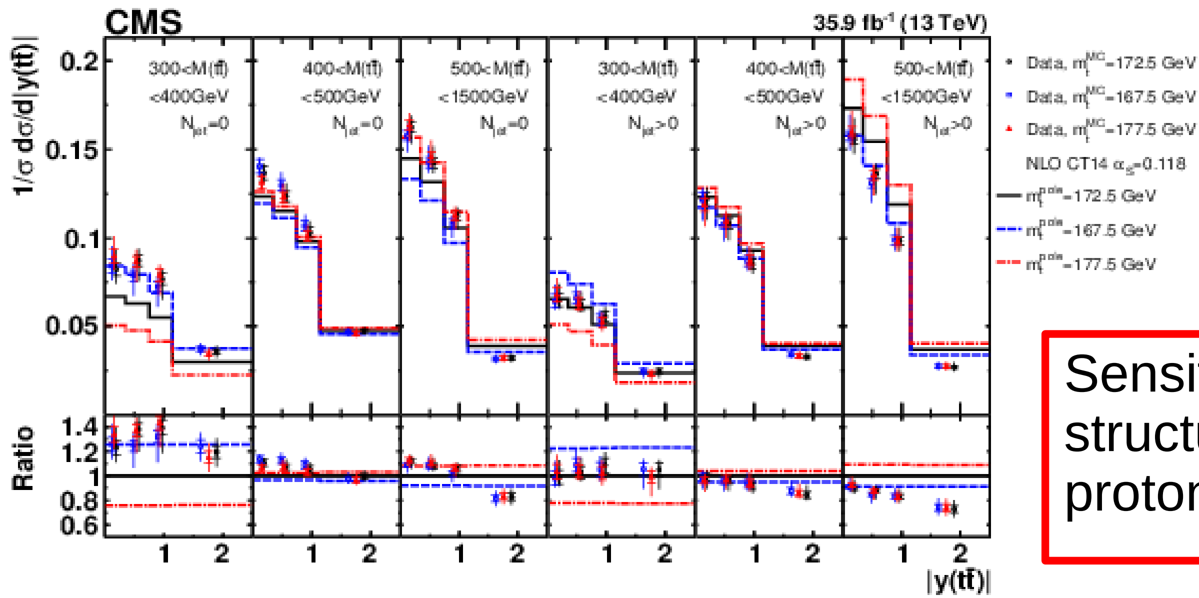
- CMS measurement at 13 TeV, dilepton
- Use $y(t\bar{t})$, $M(t\bar{t})$, N(add. jet)
- Unfolded to parton level & NLO fixed order, 7 PDF sets in simultaneous fit PDF, a_S, m_t
- Weak correlation of 0.3 a_S and m_t^{pole}



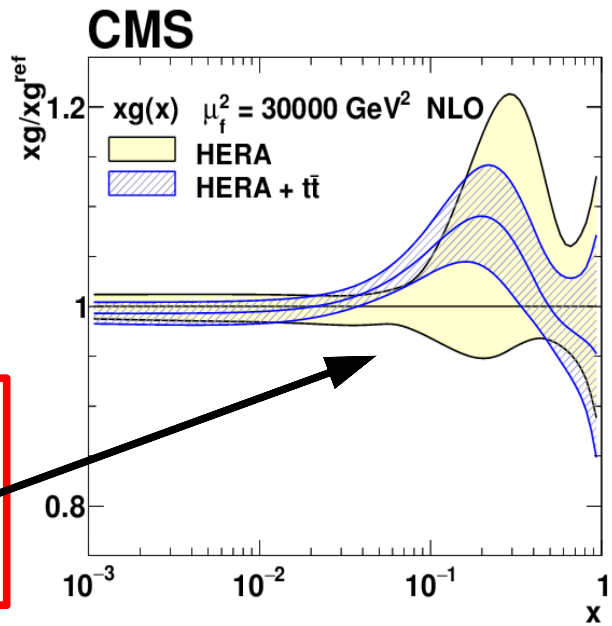
m_{top}^{pole} = 170.5 ± 0.7 (fit) ± 0.1 (mod) ± 0.1 (scale) GeV

$\delta m_t/m_t$ = 0.47%

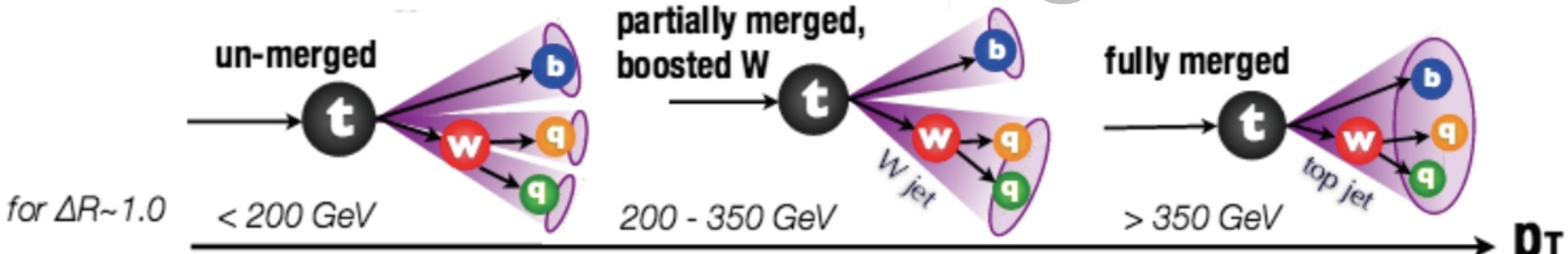
CMS-TOP-18-004



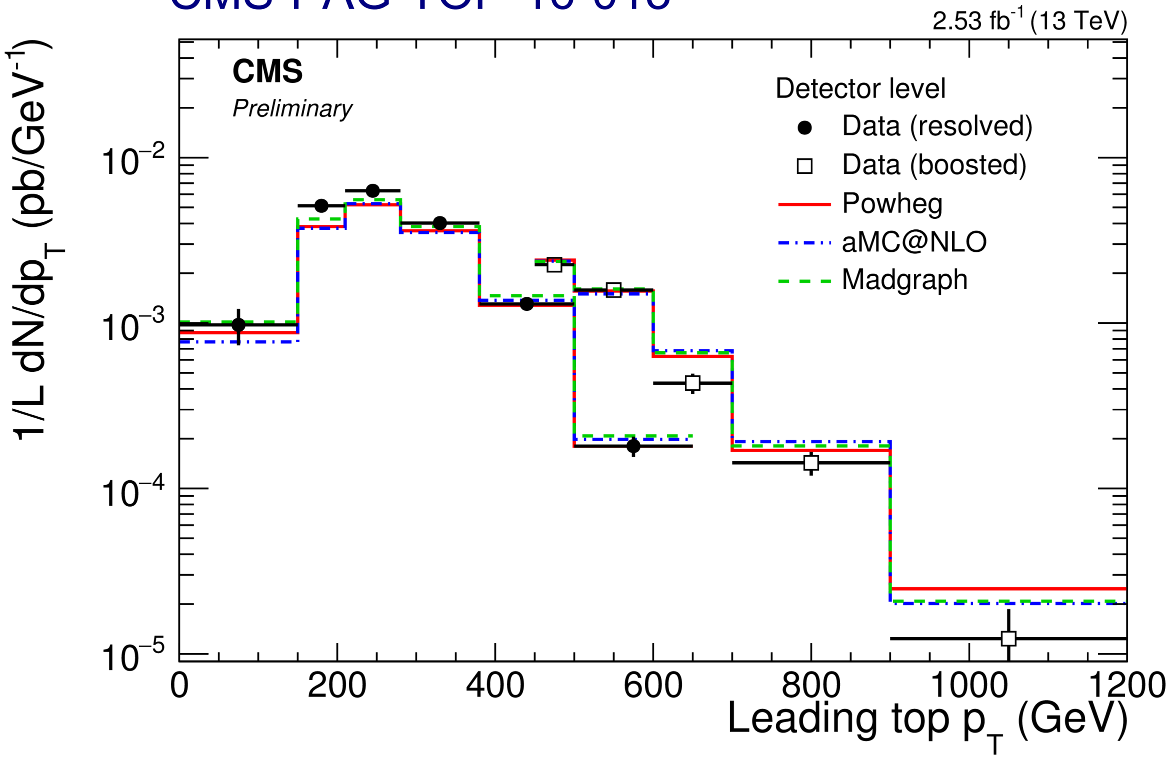
Sensitive to gluon structure of the proton, xg(x)

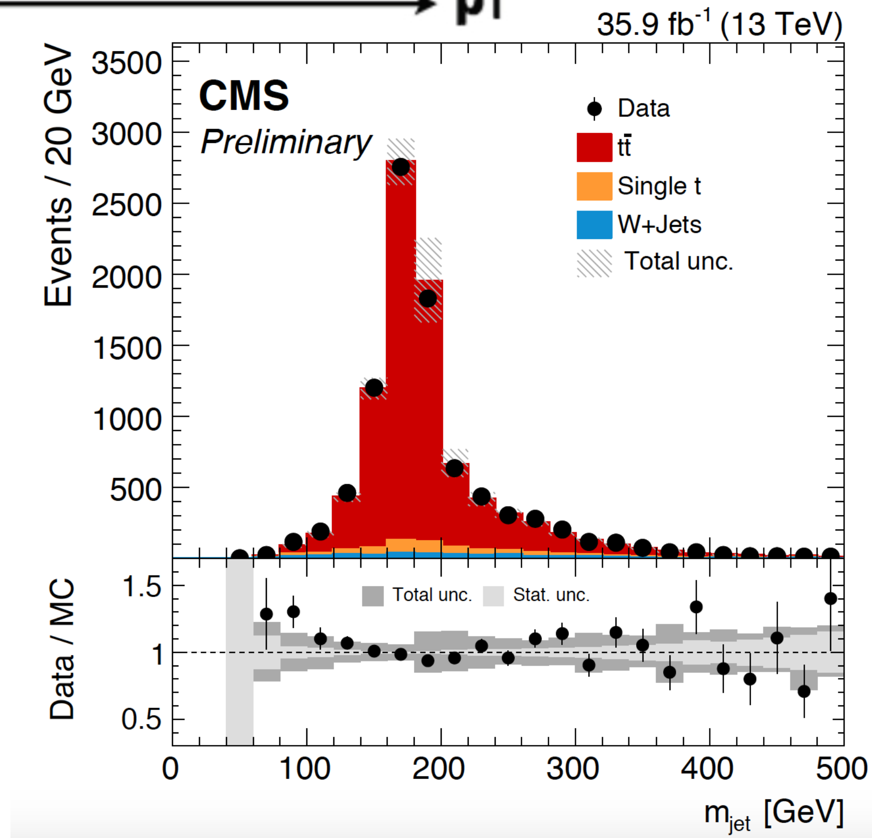


Boosted Regime



CMS-PAG-TOP-16-013

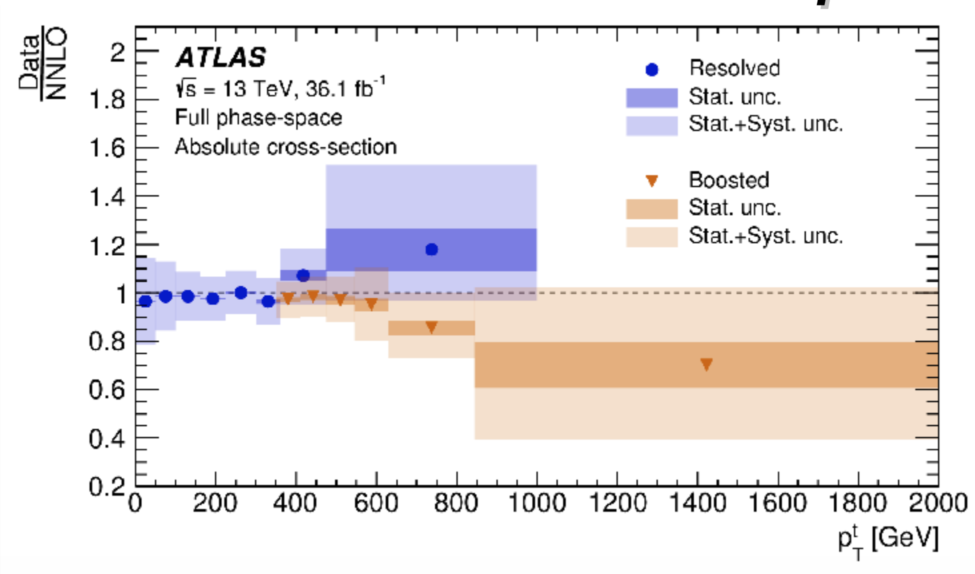


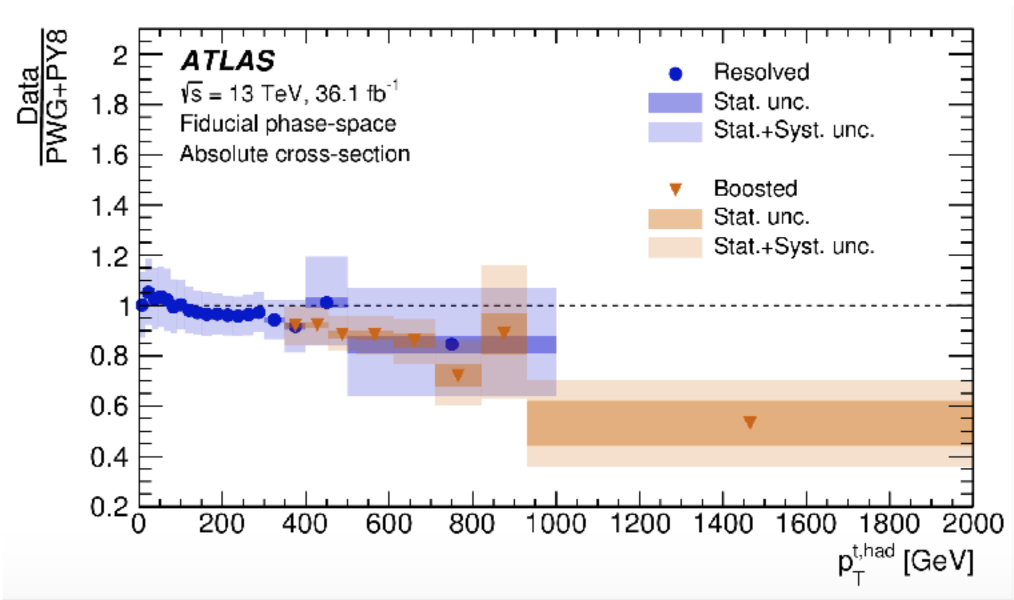


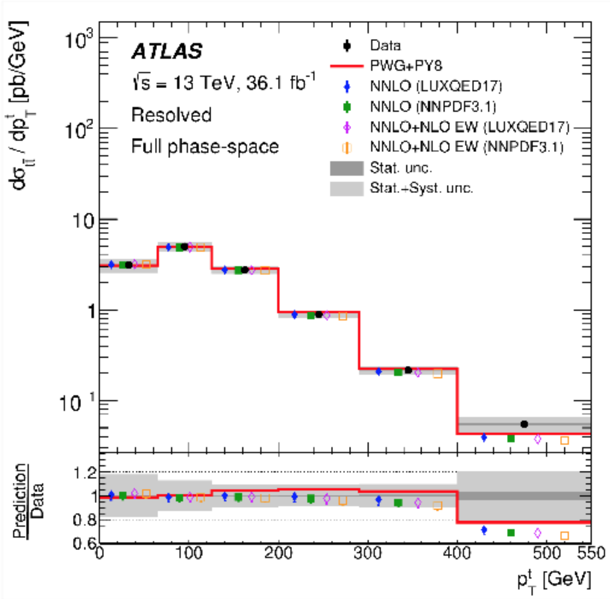
- Consistent picture in boosted and resolved phase space CMS-PAS-TOP-19-005
- Parton/Particle level results receive larger/reduced systematic uncertainties
- CMS 13 TeV all-hadronic combined resolved and boosted analysis

The top p_T saga…continued

V.Boisvert







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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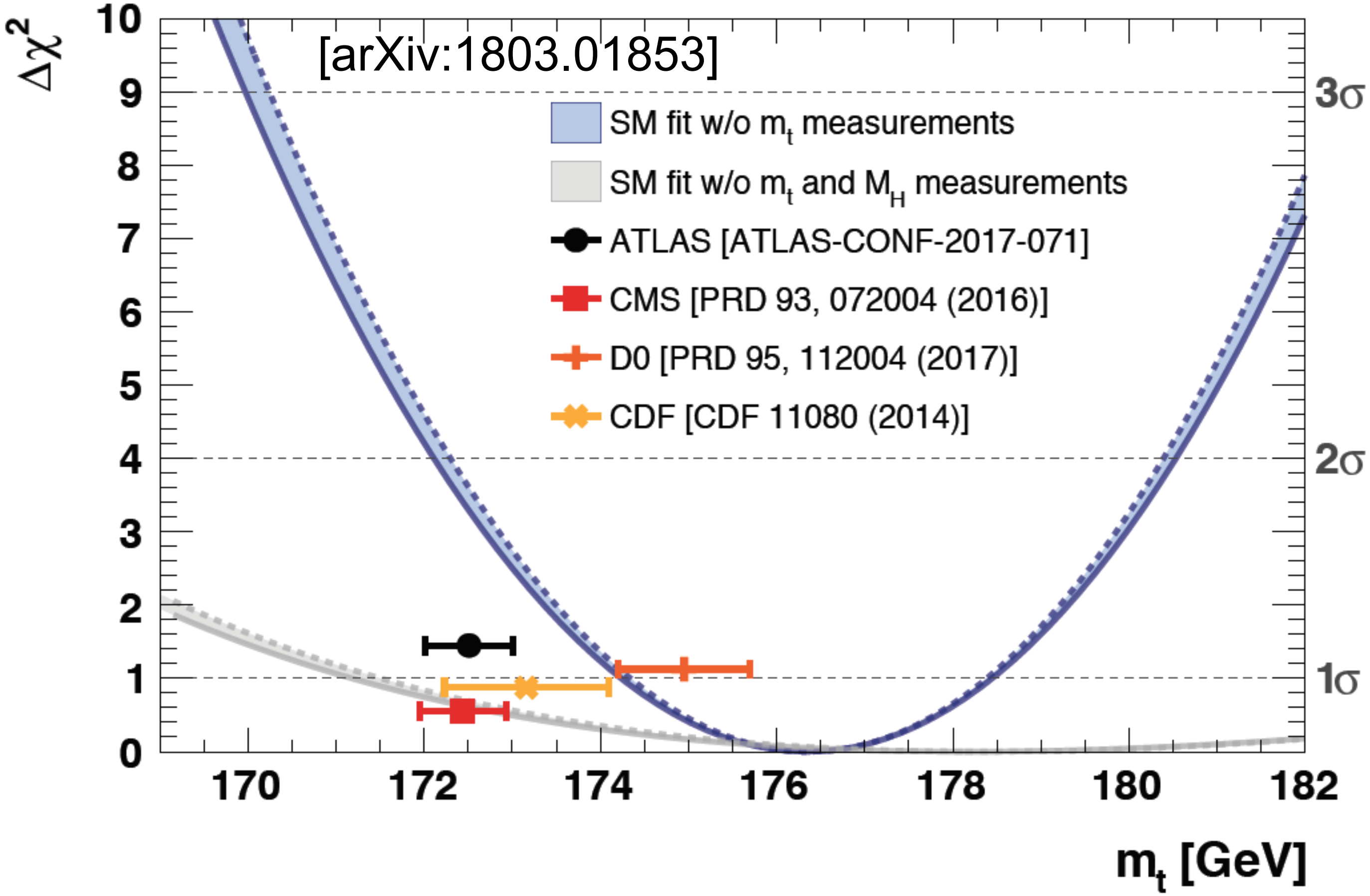
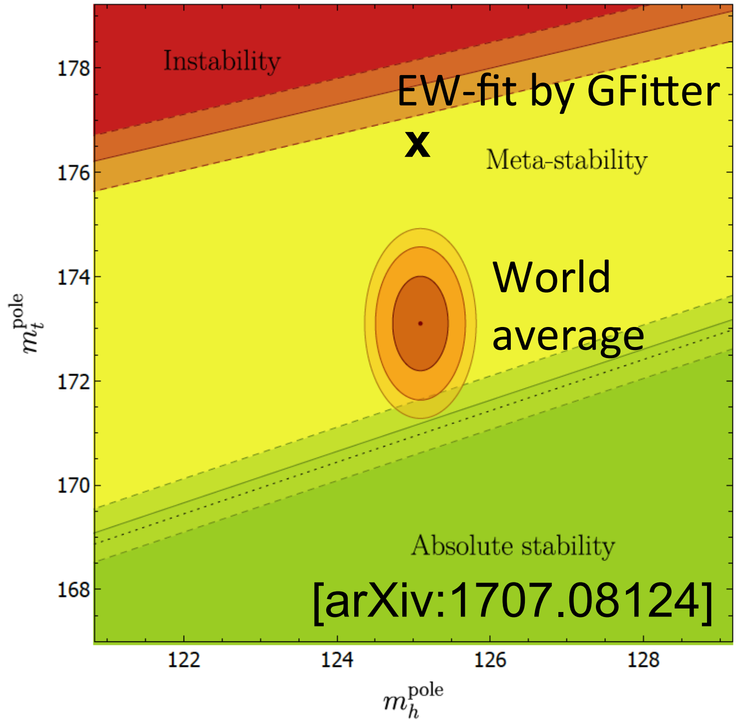
	2D		1D	Hybrid	
	δm_t^{2D} [GeV]	δJSF^{2D} [%]	δm_t^{1D} [GeV]	δm_t^{hyb} [GeV]	δJSF^{hyb} [%]
Experimental uncertainties					
Method calibration	0.03	0.0	0.03	0.03	0.0
JEC (quad. sum)	0.12	0.2	0.82	0.17	0.3
Intercalibration	−0.01	0.0	+0.16	+0.04	+0.1
MPFInSitu	−0.01	0.0	+0.23	+0.07	+0.1
Uncorrelated	−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

SM vacuum stability & EW fit

- Latest EW-fit by GFitter $m_t = 176.4 \pm 2.1\,\mathrm{GeV}$





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

→ SM EW fit closer to the unstable boundary ? Beware of uncertainties...but could indicate SM is not enough to describe nature

→ **Need more data!**