Experimental summary

Reinhard Schwienhorst, Michigan State

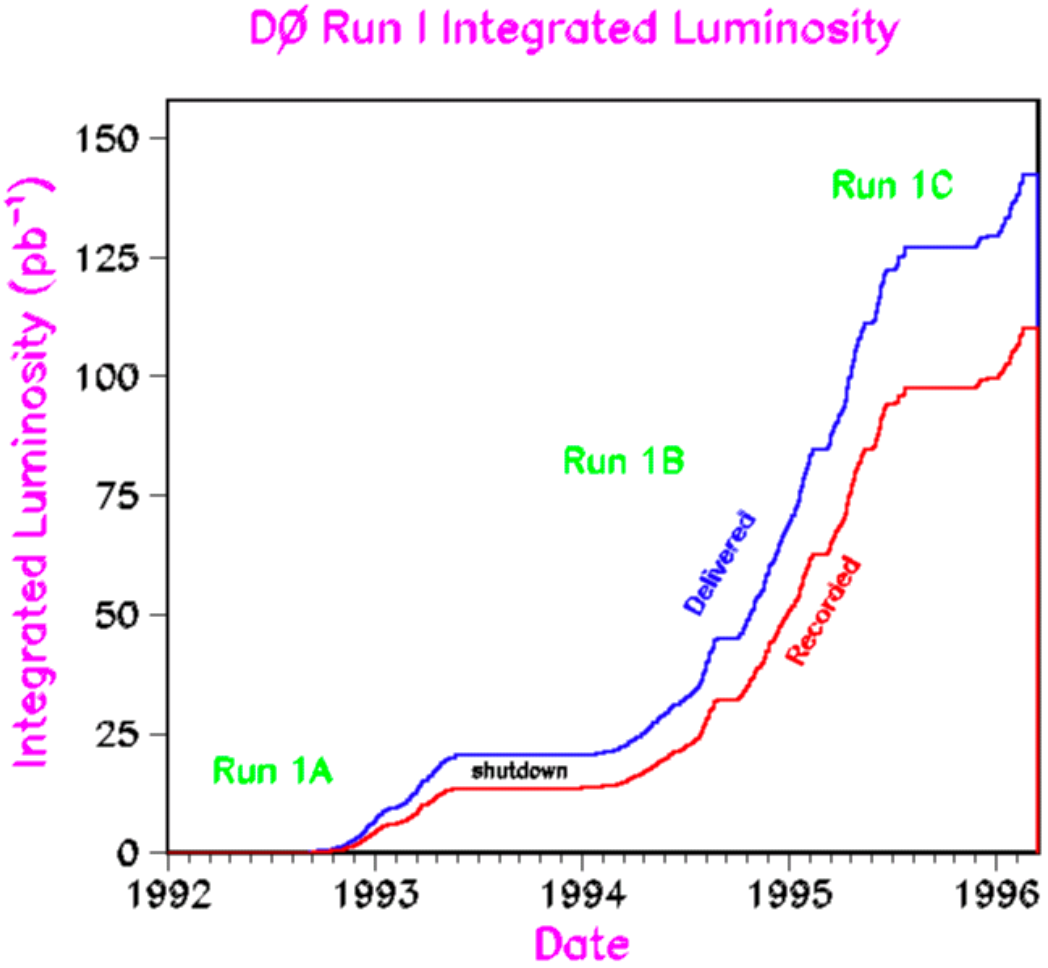
Top is a Millennial

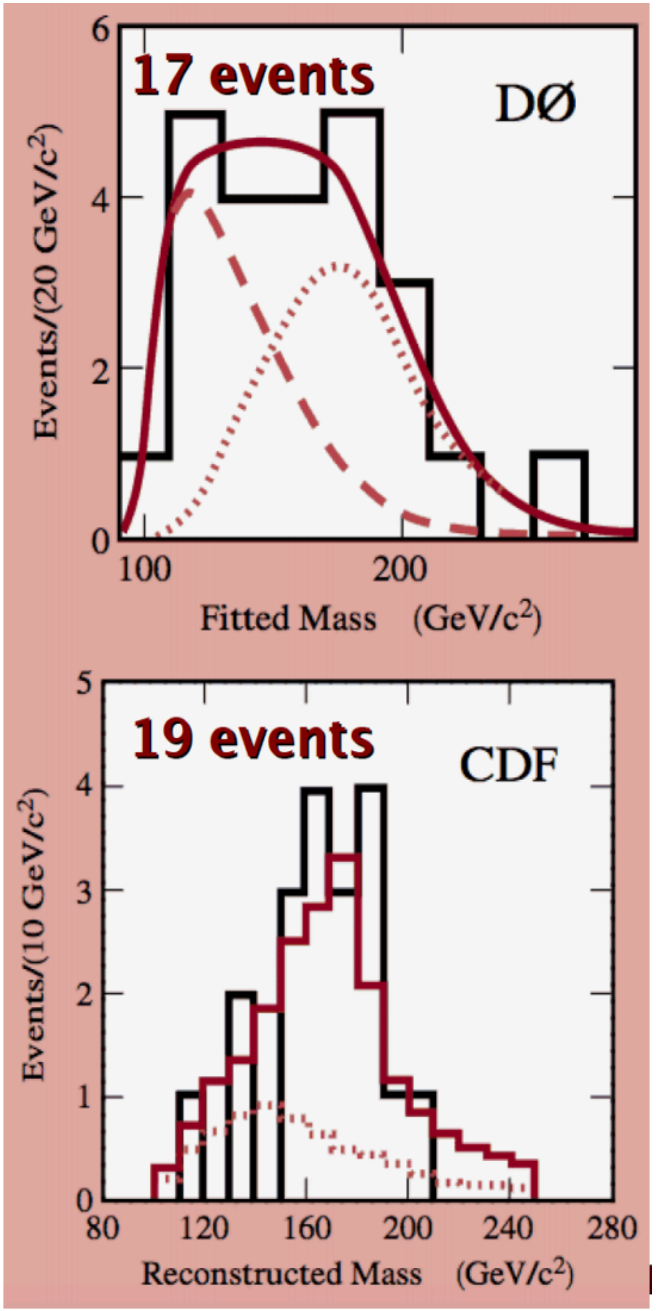
- Discovered 1995 - 25 year anniversary!
- Experienced Internet boom, 9/11 and the Great Recession

https://news.fnal.gov/2020/03/twenty-fifth-anniversary-of-the-discovery-of-the-top-quark-at-fermilab/

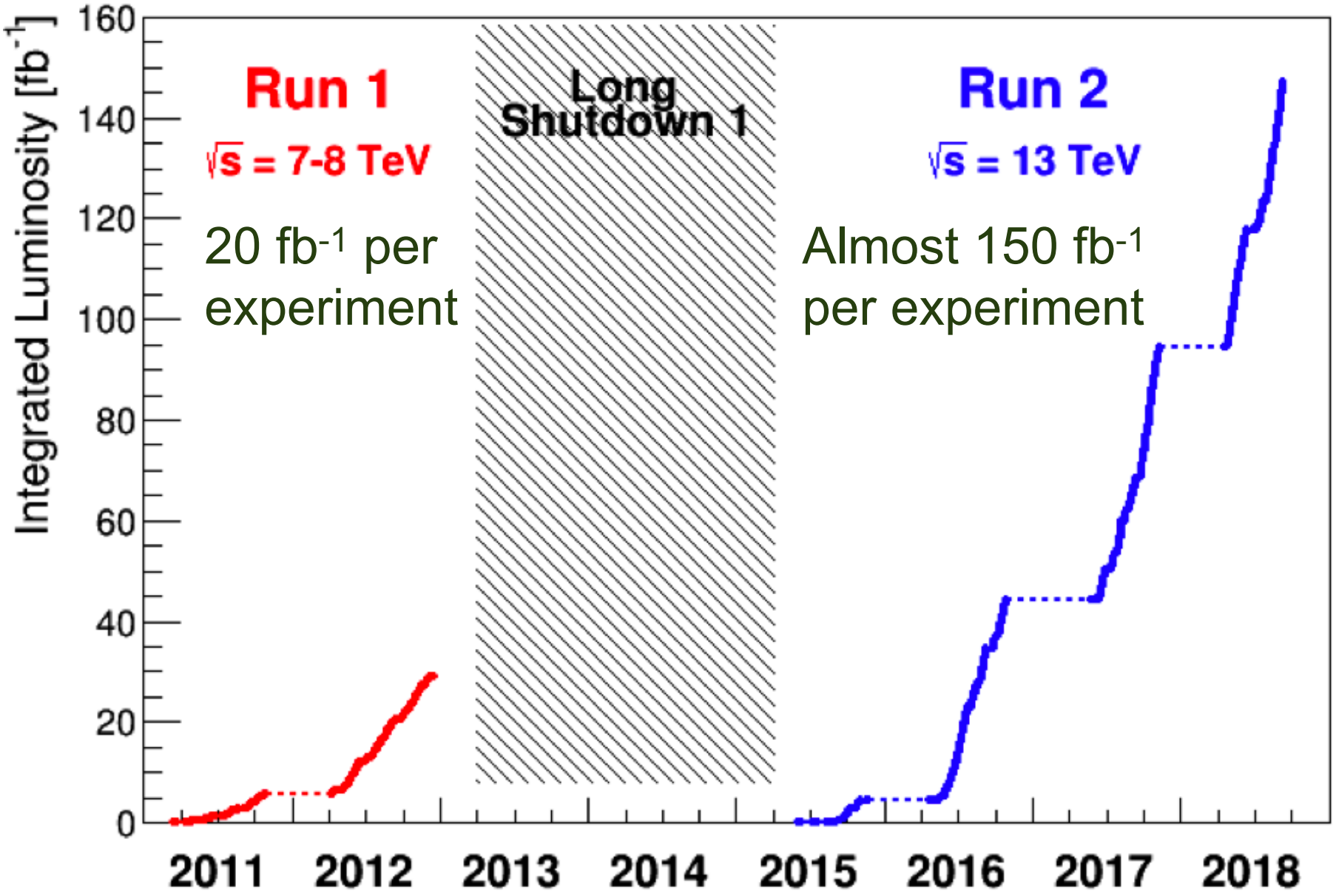
Fermilab CDF and D0 top-quark discovery

- Only a handful of events
- Already clear top mass peak at 175 GeV
- Based on 0.05 fb^{-1}





LHC collisions recorded



- About a million times more top-quarks than in top discovery

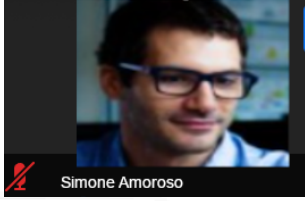
Introduction

- Too many results to show them all, apologies if I skipped your favorite result
- Many new results over the past year, most channels now have measurements from both ATLAS and CMS
  - First LHC*top*WG plot at 13 TeV now public
- Measurements from previous *n* years are still valuable
  - Persistence - many measurements will not be updated for a long time
  - Full Run-2 data results will be continue to be published for the next 3-5 years
- Virtual top-quark conference format works
  - No common meals, no excursion, no late-nite student sessions
  - But no travel, more access, more opportunities for creativity
  - Plenty of questions and discussion after talks and for posters
  - I counted 150/120/80/70/90 people connected each day
  - Thanks a lot to the organizers!

Theme: Precision measurements and their challenges

- Top pair modeling and uncertainties (Simone Amoroso)
  - PW+PY, Matching, Parton Shower, what next?
  - b-fragmentation, strange and charm in top events (Juan Gonzalez)
- Bottlenecks (Valentina Vecchio)
  - Profiling of uncertainties, unfolding
- Inclusive cross-sections (Olga Bessidskaia Bylund)
  - Top pair and single top
  - Elastic top production virtual poster by Jay Howarth
- Differential distributions (Otto Hindrichs)
  - State-of-the-art unfolding
  - CMS t-channel poster by Matthias Komm
  - CMS tW poster by Victor Bouza
  - YSF talk on ATLAS differential all-hadronic by Riccardo Poggi
- Interpretations (Matteo Defranchis)
  - Top mass, PDFs
  - YSF talk on CMS Yukawa coupling from ttbar XS by Evan Ranken

MC generators and their uncertainties



Unfolding, Bkg. subtraction, Selection Optimisation

Need good modelling of the data, and uncertainties not in tensions with it

Extrapolation, Interpretations

Need high accuracy predictions, and well-defined uncertainties (as small as possible too)

- ATLAS and CMS both use Powheg+Pythia as the main top-pair generator
  - Different tunes/shower settings
  - Outstanding agreement with data, well beyond expectations for an NLOPS generator (thanks to years of tuning)
  - But also plenty of regions with large mismodellings
- Differences also in systematic uncertainty treatment
  - NLO subtraction, PS, top pT, color reconnection
- Ambiguities in MC predictions likely to dominate top measurements also in the future
  Development of better models is essential

Parameter	CMS	ATLAS
POWHEG		
vetoCount	100	3
pTdef	1	2
pThard	0	0
pTemt	0	0
emitted.	0	0
MPIveto	0	0
SpaceShower		
alphaSorder	2	1
alphaSvalue	0.118	0.127
rapidityOrder	off	on
pT0Ref	2.0	1.56
TimeShower		
alphaSorder	2	1
alphaSvalue	0.118	0.127
MultipartonInteractions		
alphaSvalue	0.118	0.126
alphaSorder	2	1
pT0Ref	1.44	2.09
ecmPow	0.03344	0.215
bProfile	2	3
coreRadius	0.7634	-
coreFraction	0.63	-

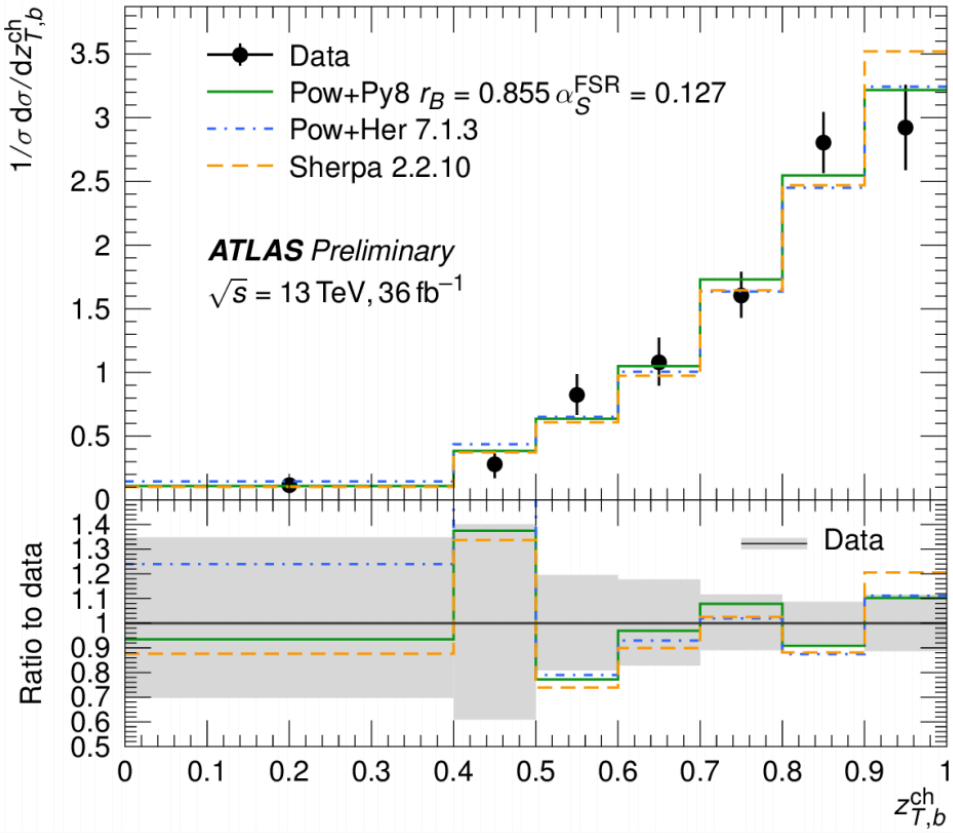
B-fragmentation

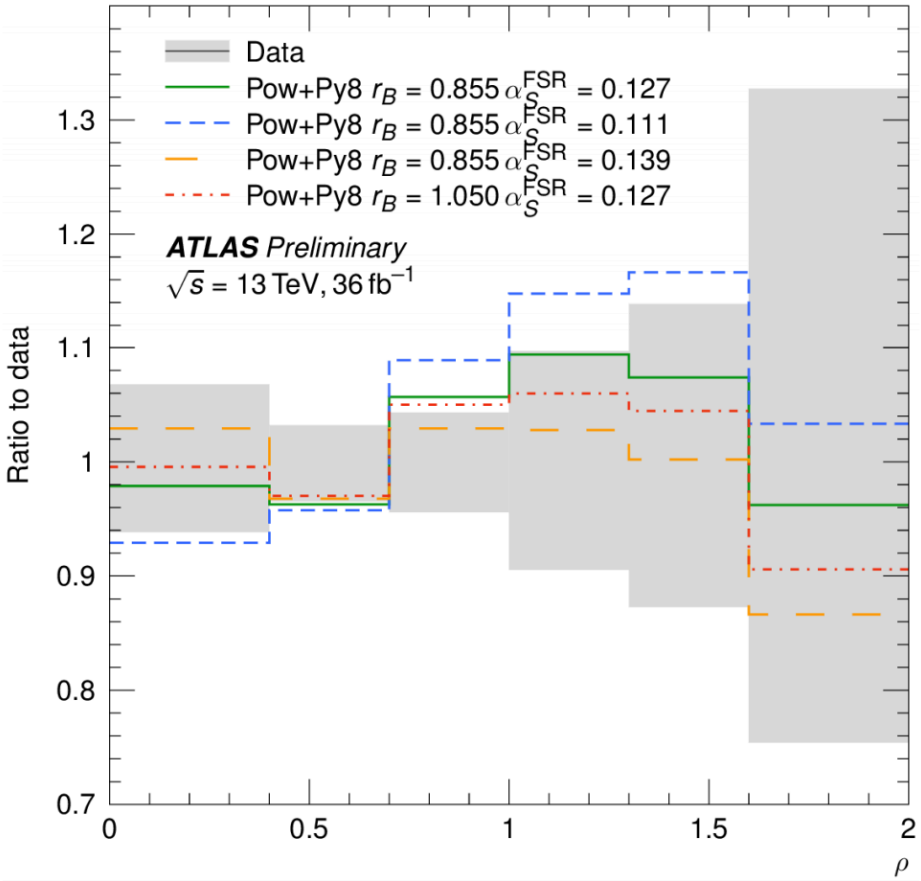
NEW

- New ATLAS analysis
- Isolate charged particles from b-decay from those from PV
  - Unfold to particle level and compare generators and tunes

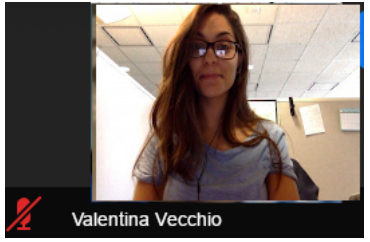
$$z_{\mathrm{T},b}^{\mathrm{ch}} = \frac{p_{\mathrm{T},b}^{\mathrm{ch}}}{p_{\mathrm{T,jet}}^{\mathrm{ch}}}$$

$$\rho = \frac{2p_{\mathrm{T},b}^{\mathrm{ch}}}{p_{\mathrm{T}}^{e} + p_{\mathrm{T}}^{\mu}}$$

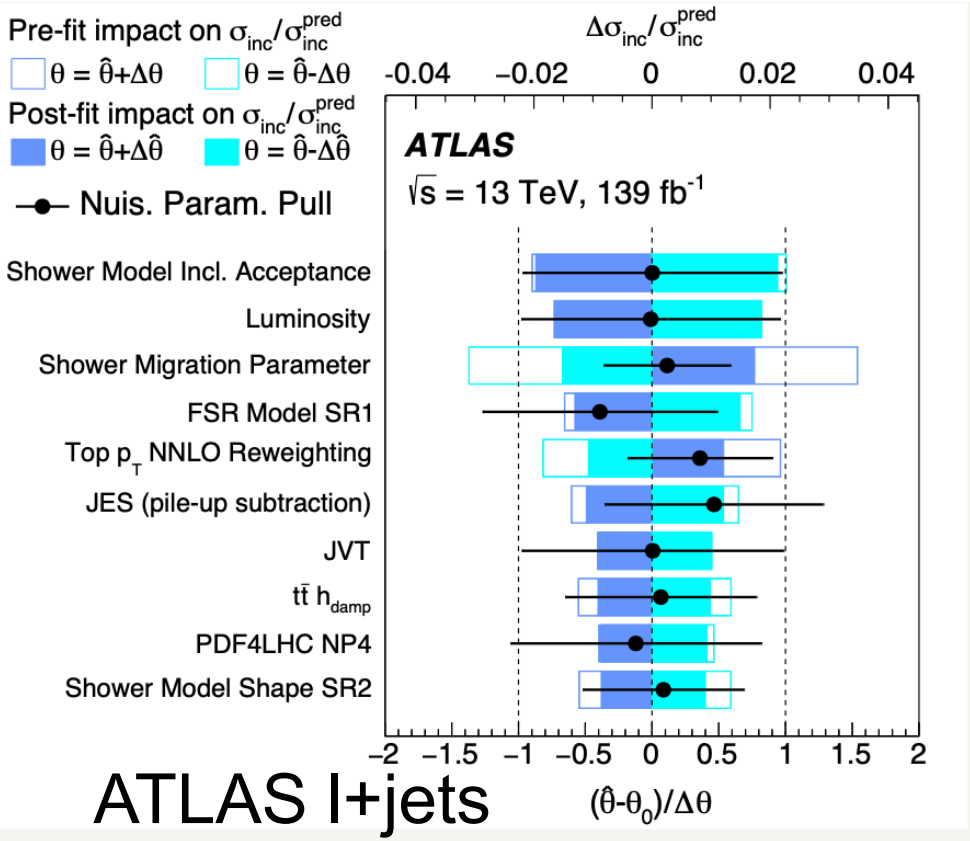




Profiling

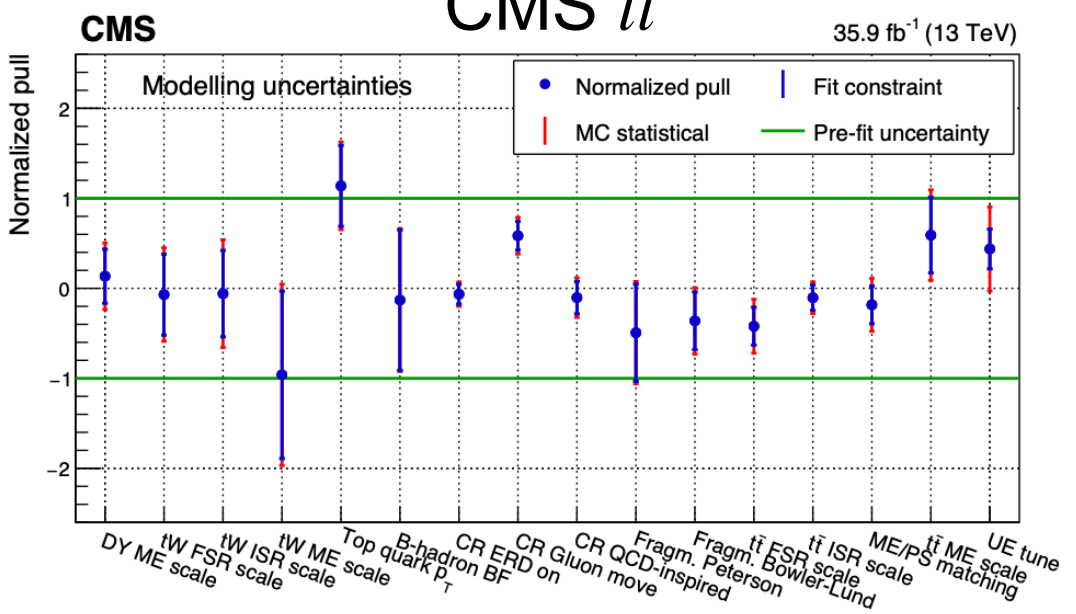


- Many analyses now rely on profiling of nuisance parameters in signal and control regions to correct for mis-modeling and reduce uncertainties
  - Important to prevent unphysical constraints and pulls of NPs
  - Challenging to use these results in global fits and combinations
  - *"Uncertainties are a matter of trust"*
- Still need a more unified approach in presenting profiled results



ATLAS l+jets

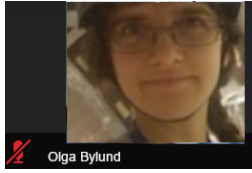
CMS ll



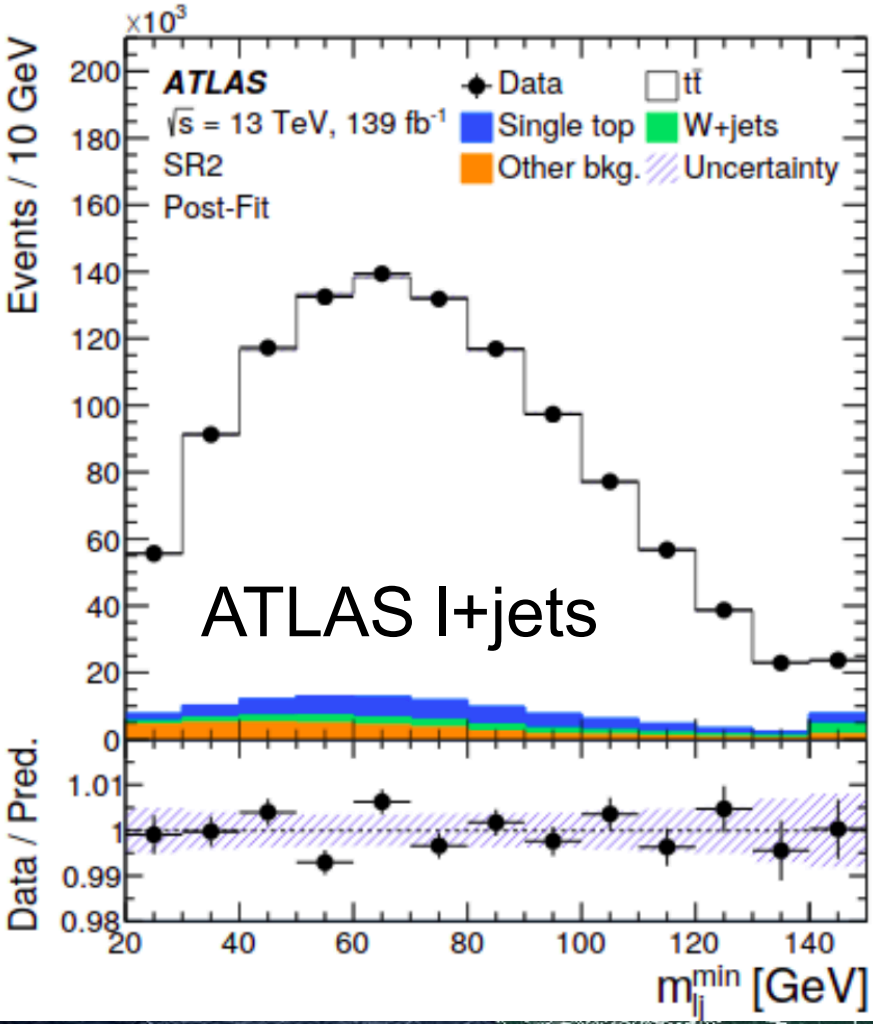
ATLAS ttbar(l+jets) inclusive cross-section arXiv:2006.13076

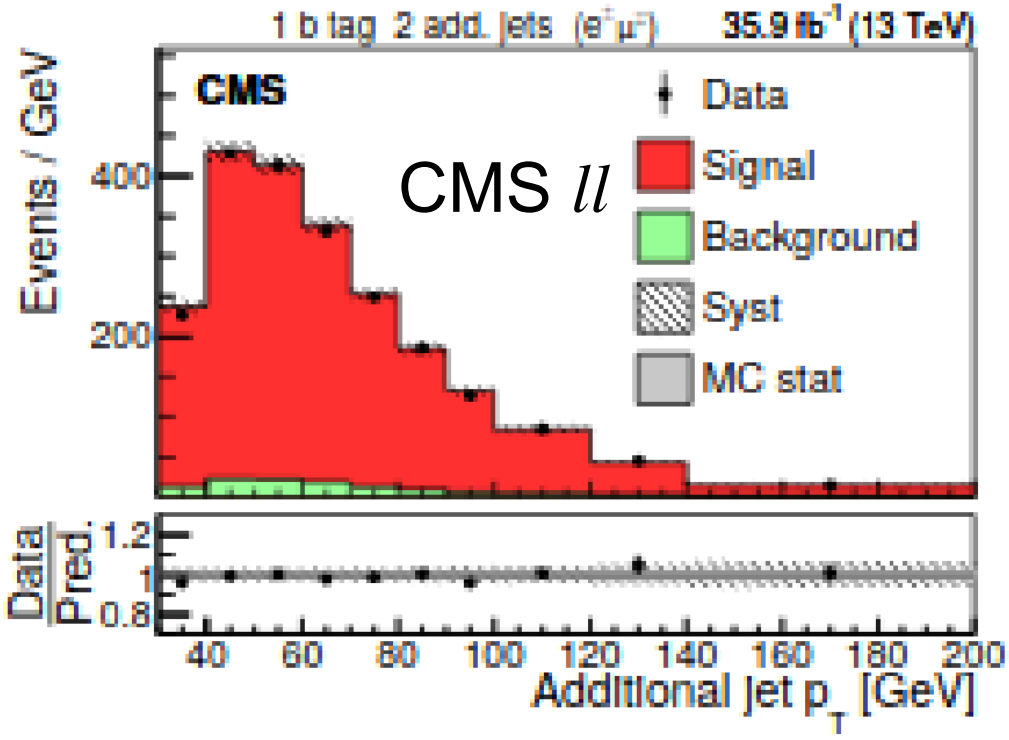
CMS ttbar(dilepton) inclusive cross-section Eur. Phys. J. C (2019) 79:368

Inclusive tt cross-section



- Dilepton channel most precise
  - ATLAS uncertainty 2.4%
    - 2l requirement, then fit ratio of 1-tag and 2-tag
  - CMS uncertainty 4% - profile likelihood fit to many distributions
- ATLAS lepton+jets uncertainty 4.6% - profile likelihood fit

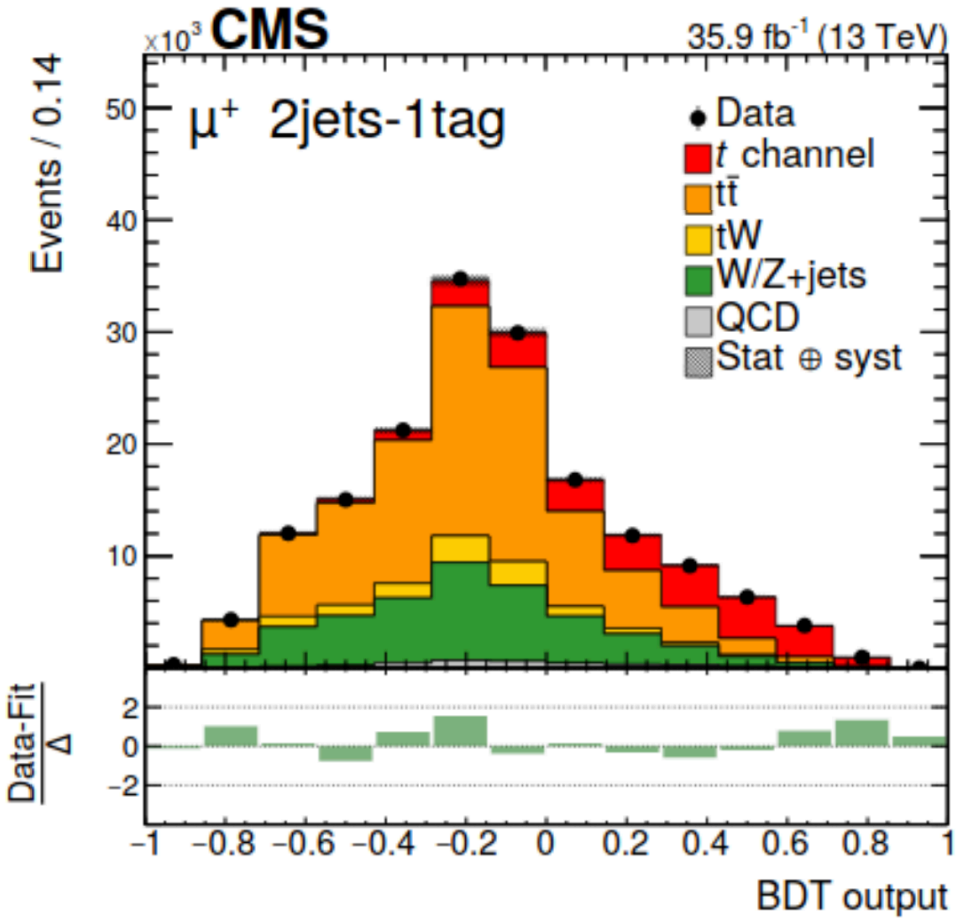


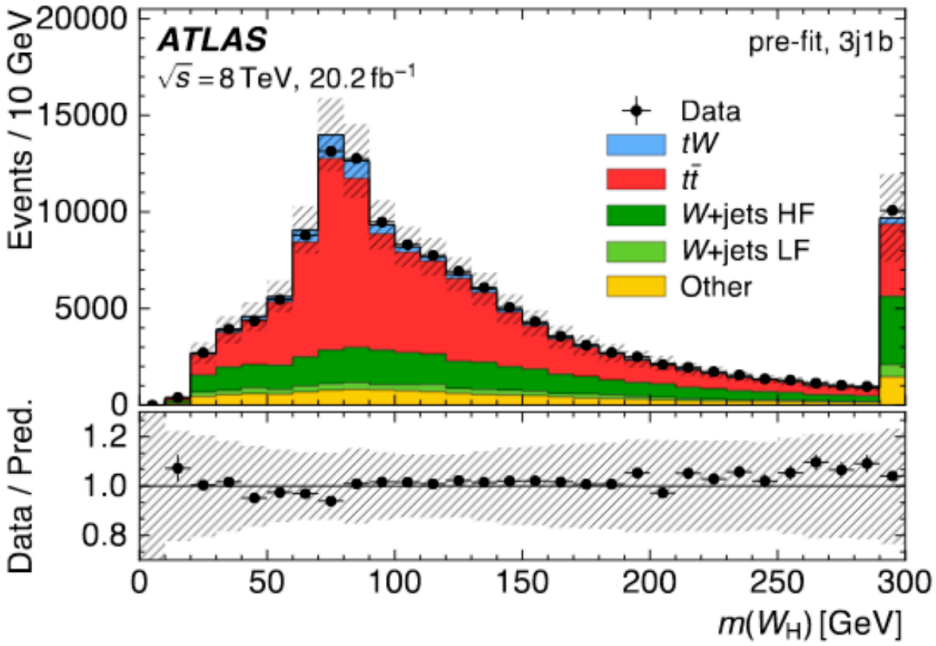


Inclusive single top cross-section

- CMS t-channel at 13 TeV
  - Profile only experimental and background uncertainties
  - Uncertainty 15%
  - Basis for differential measurements and interpretations
- ATLAS tW lj at 8 TeV
  - Not as sensitive as dilepton, but reconstruction of both W bosons

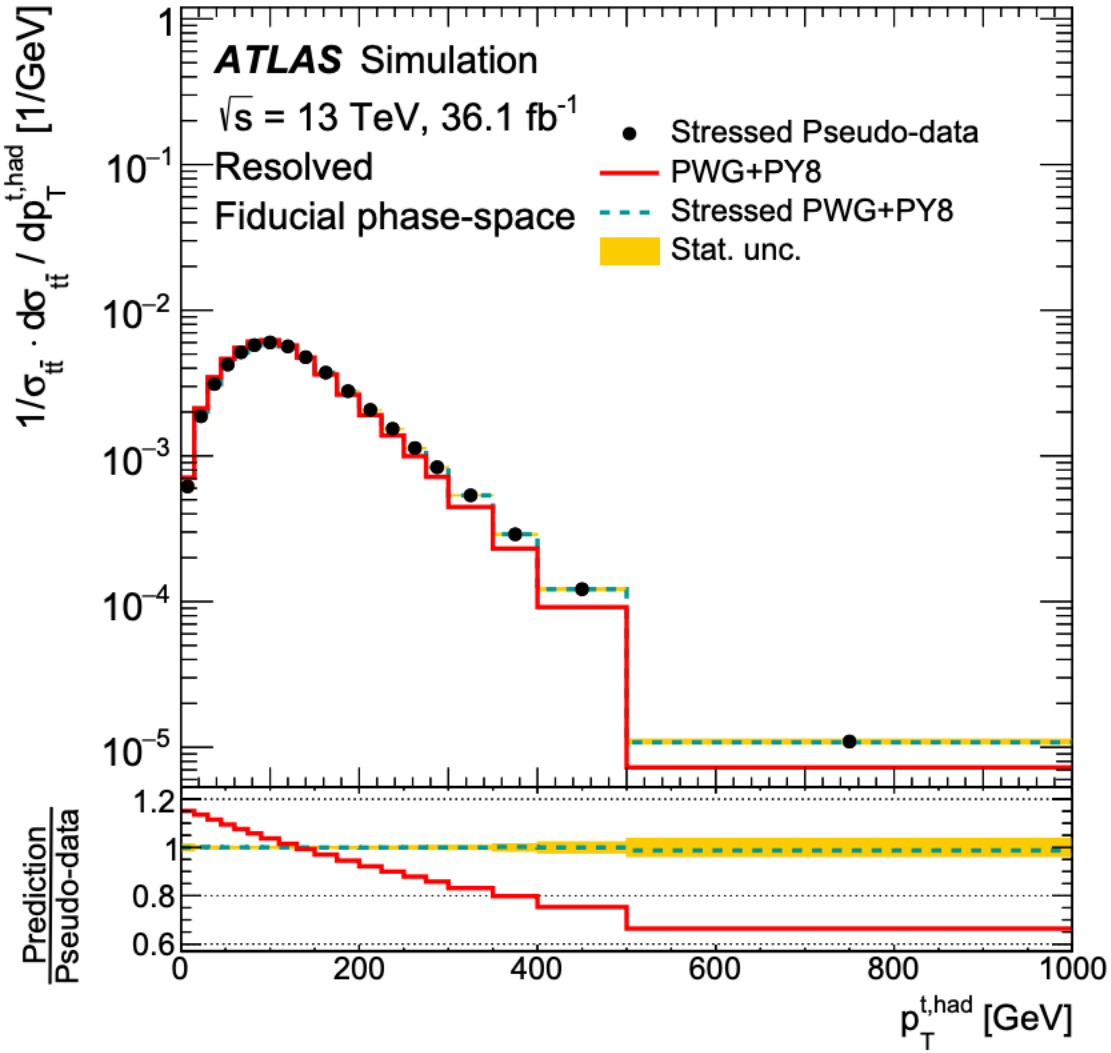
Uncertainty 27%





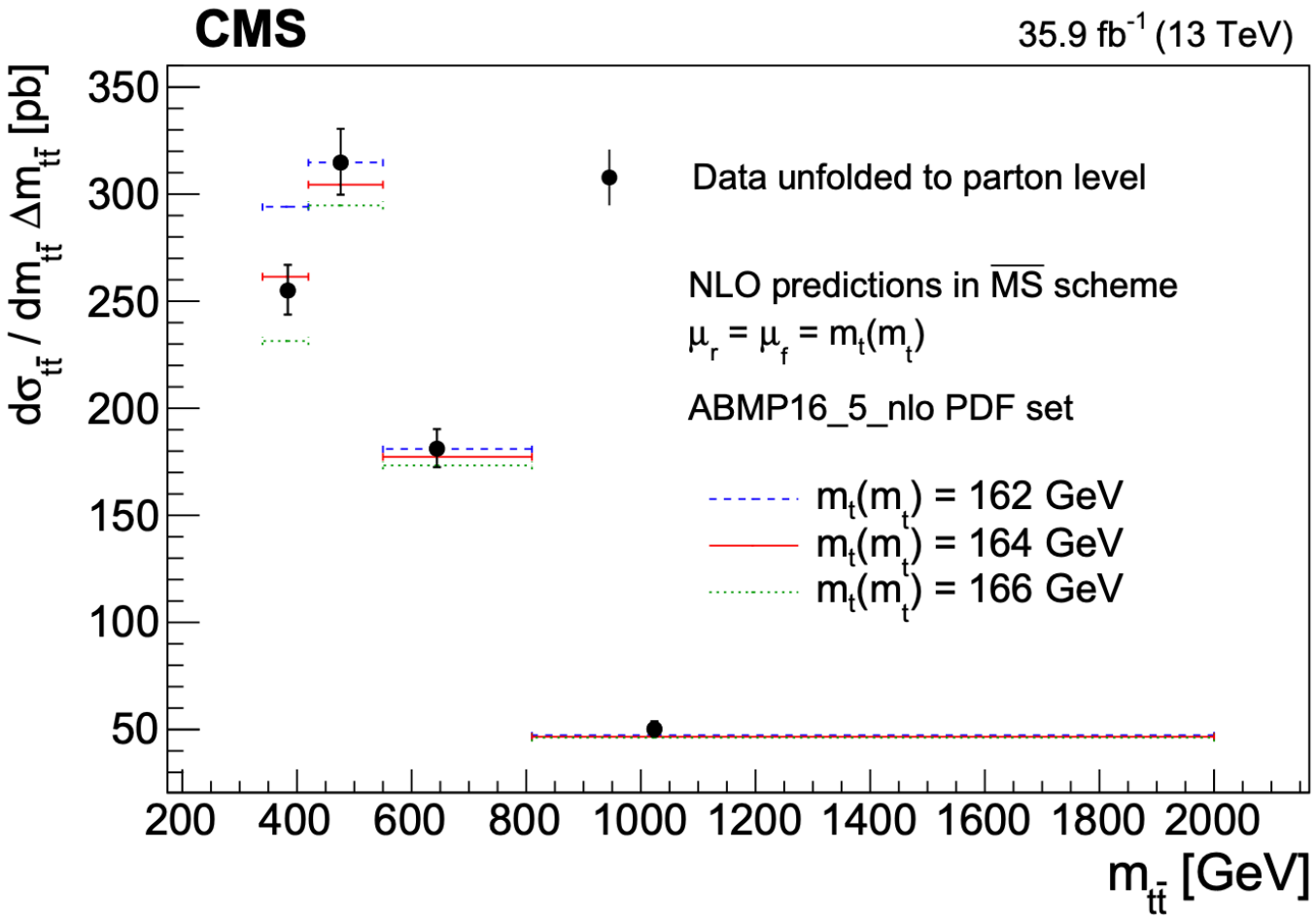
Unfolded differential cross sections

- Differential distributions are the pillars of top-quark physics
- Introduction in Otto's talk, and important issues in Valentina's
- Important unfolding checks:
  - Bottomline test - chi2 at detector level should be similar to unfolded level (CMS)
  - Stress test - unfolding reweighted MC should reproduce reweighting function (ATLAS)
- Thousands of bins in 1d, 2d, 3d
  - Including correlations and uncertainties
  - Assumptions and special treatments need to be clear
    - Profile likelihood or fully Bayesian unfolding



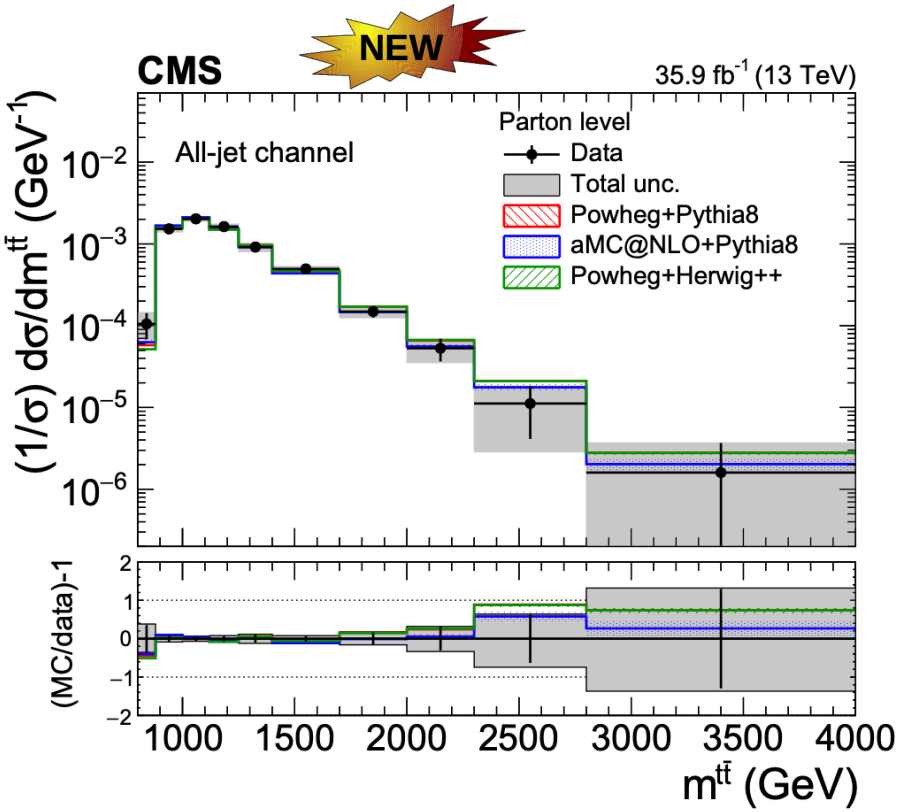
Unfolding with profiling of uncertainties

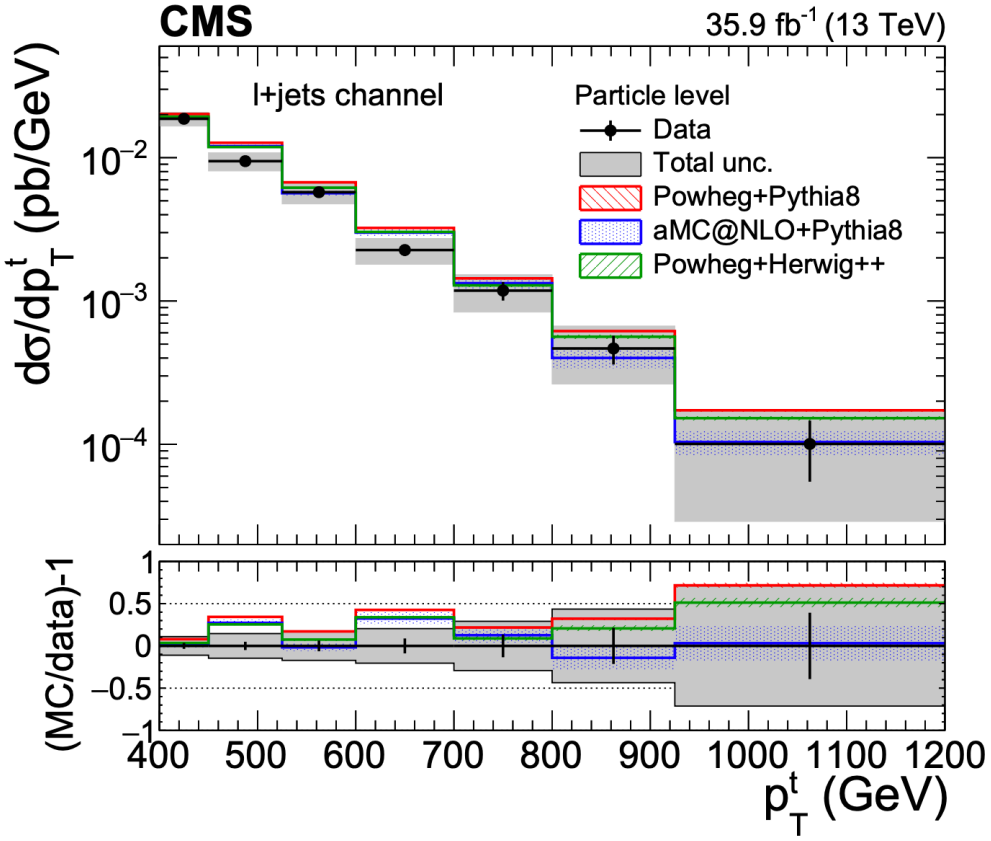
- Provide auxiliary distributions to constrain uncertainties
- ATLAS: eg ttbb, include distribution of b-tag discriminant in likelihood
- CMS: M(ttbar) distribution (CMS)
  - Include N_b, m_{lb}, jet p_T in likelihood



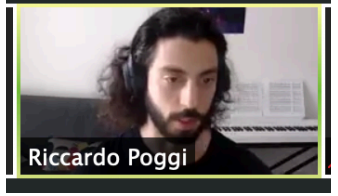
Unfolded differential cross sections

- New unfolded results: CMS boosted all-hadronic

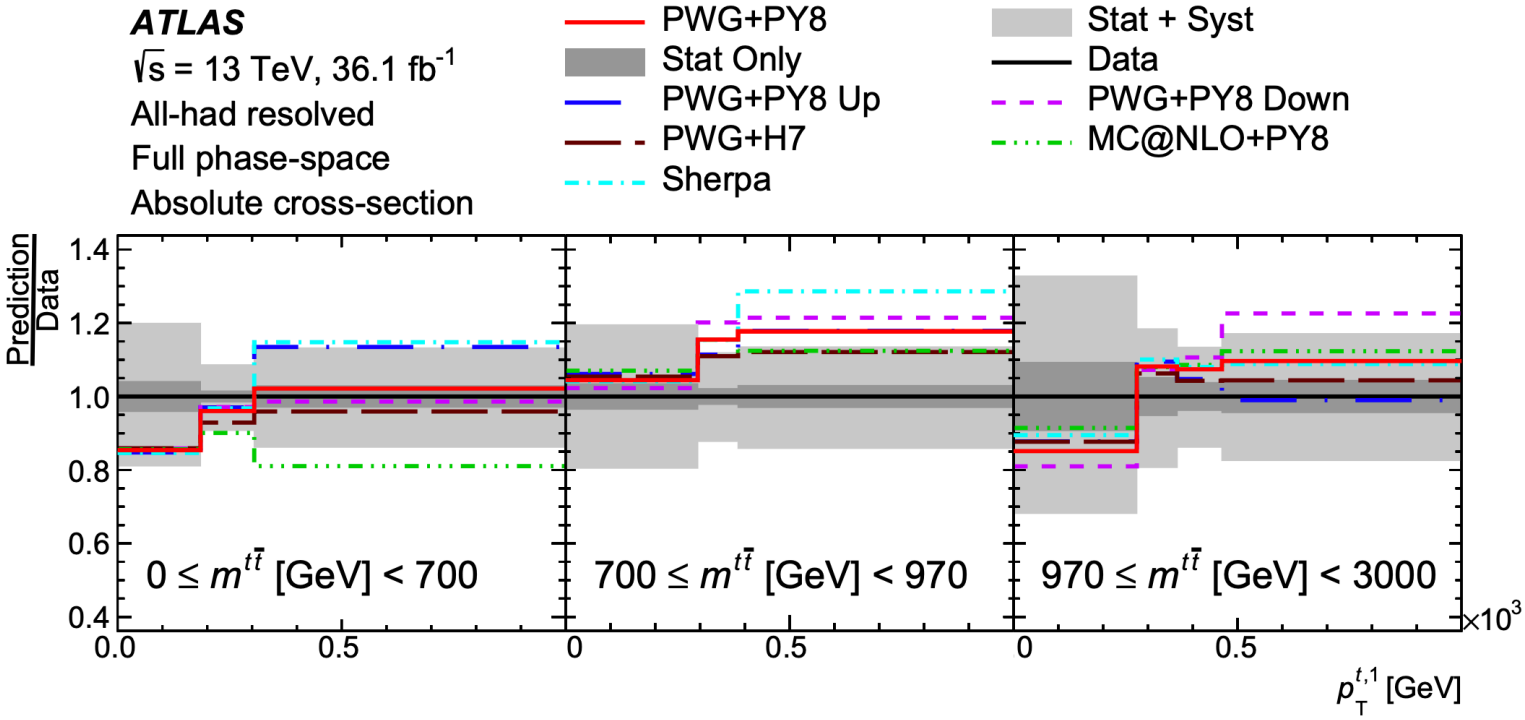


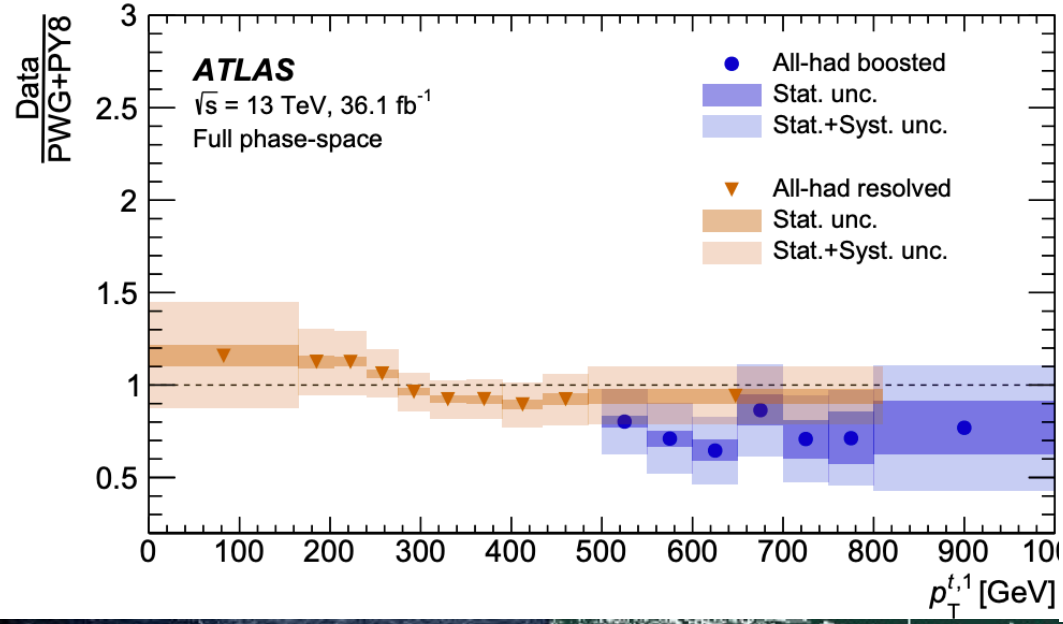


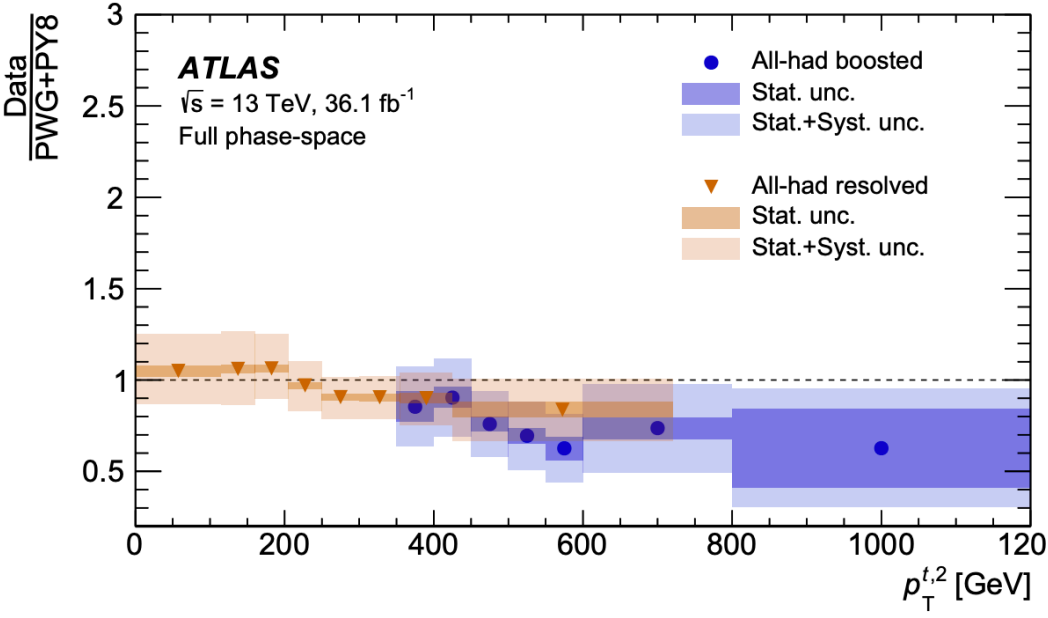
ATLAS all-hadronic resolved final state



- Slope in top-quark pT persists
- More visible for second-leading top quark

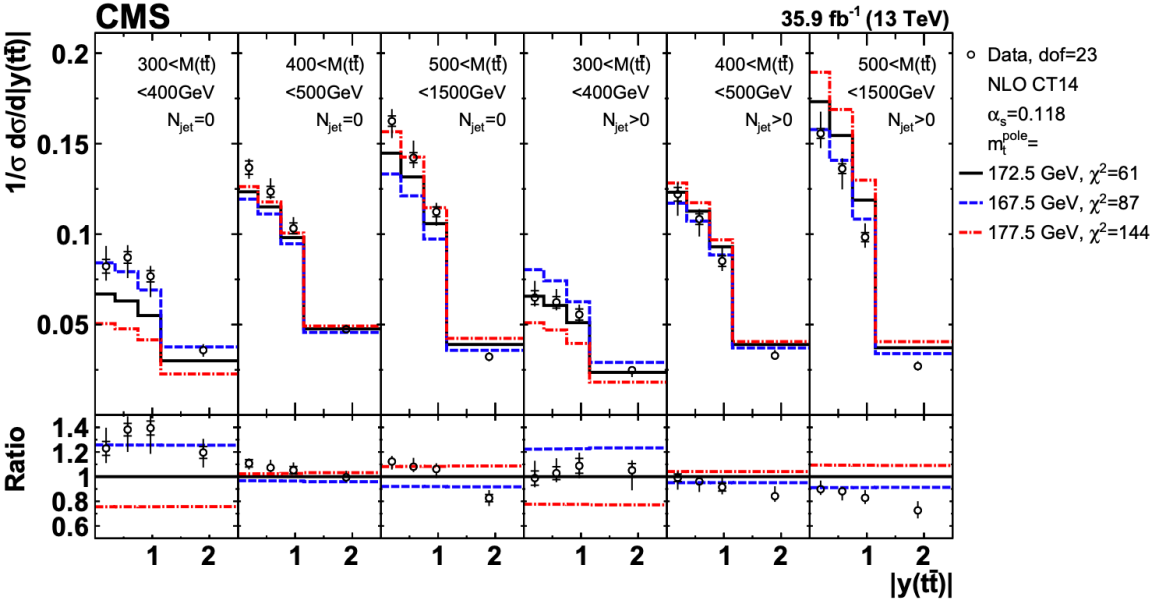


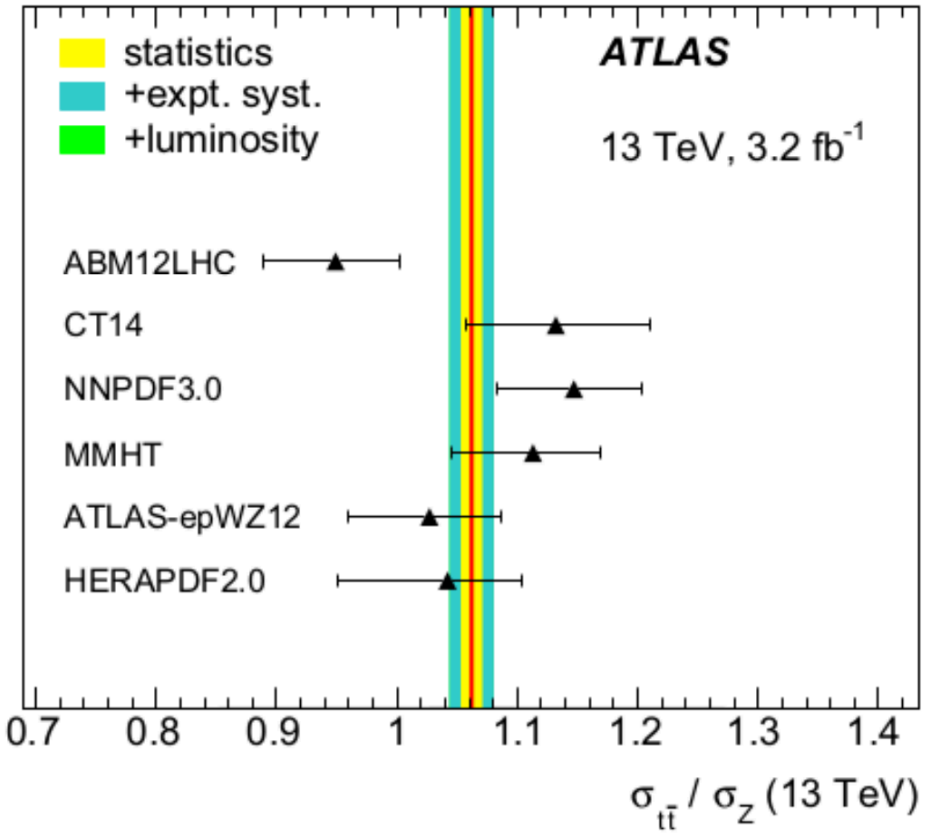


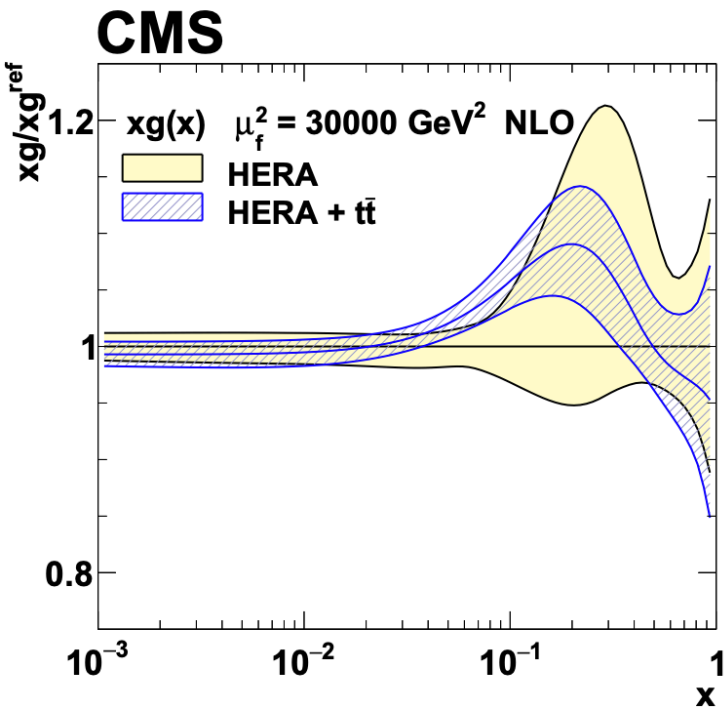


Differential cross sections - interpretation

- 3d cross-sections provide detailed physics information
  - PDF fits, generator tuning
- Ratios cancel many uncertainties

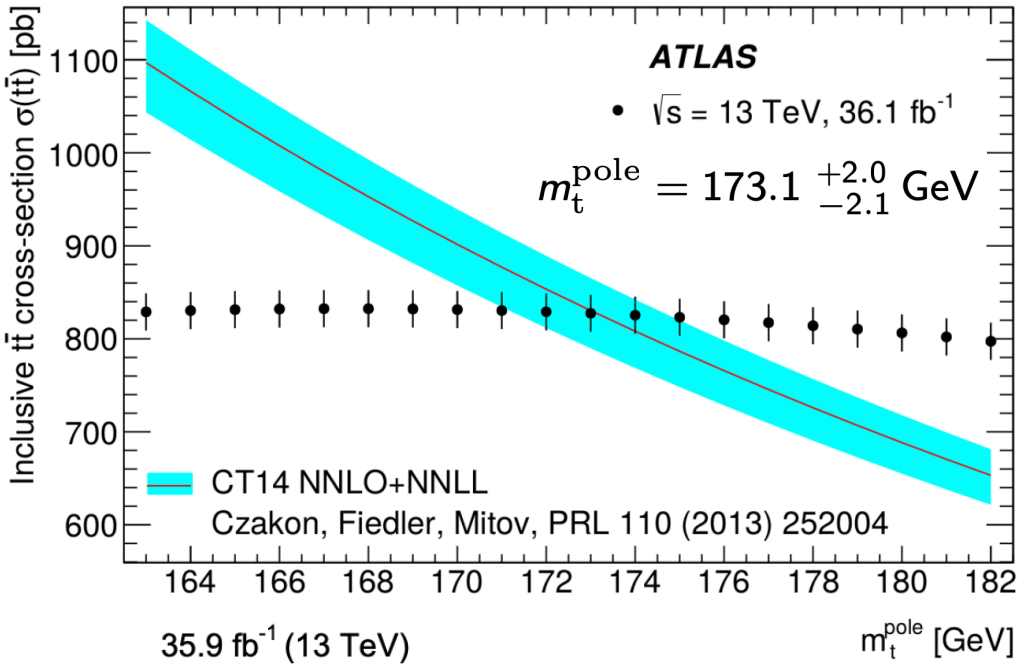


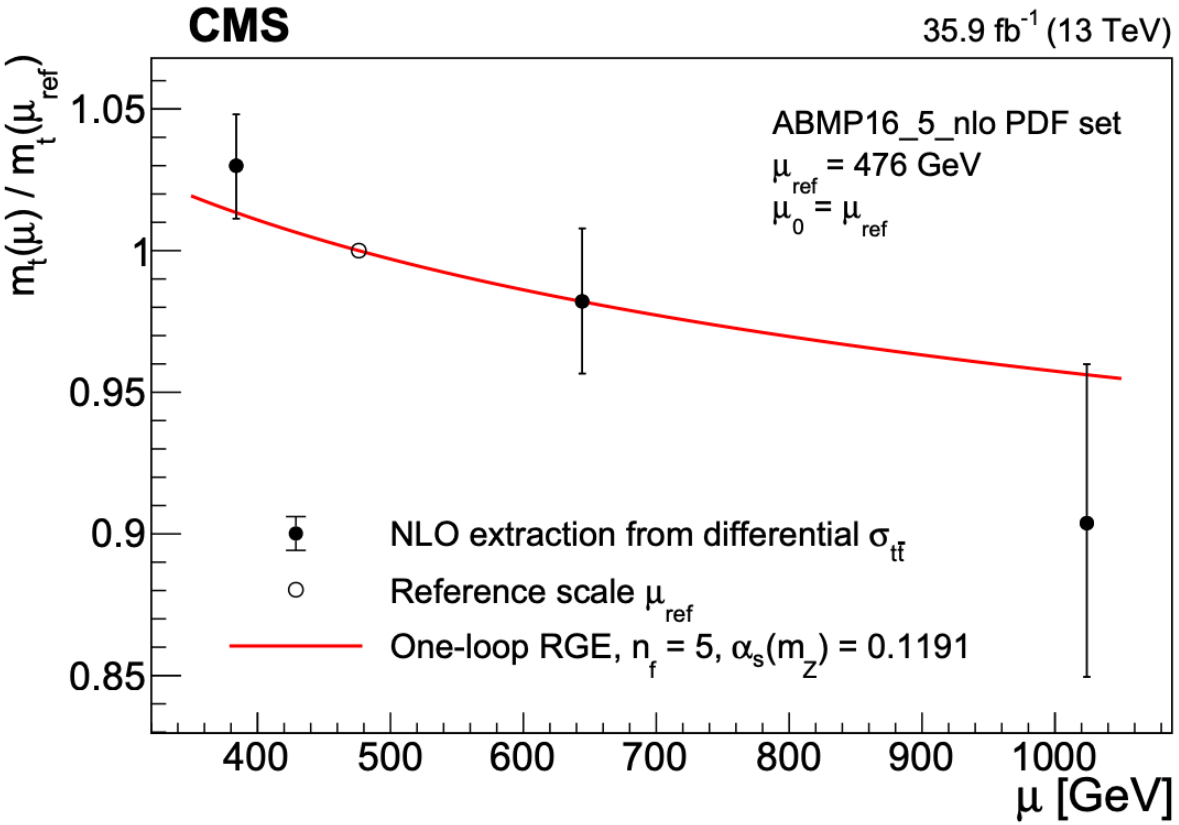




Top mass

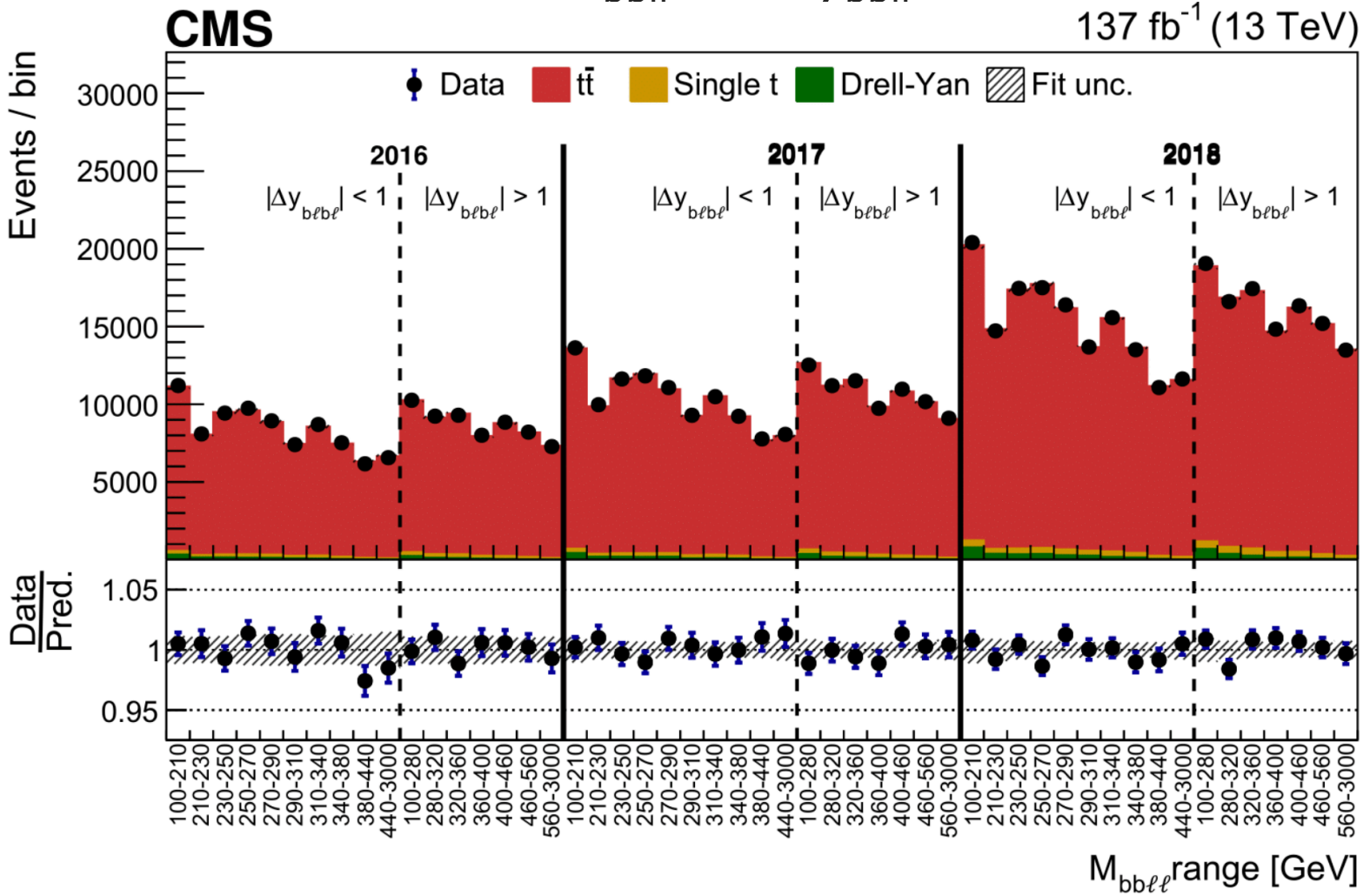
- Top mass from inclusive XS
  - Compare to NNLO prediction
  - Limited by theory uncertainties
- Running of the top mass from differential XS
  - M(tt)
  - Sensitive to threshold effects





Yukawa coupling from tt dilepton

- Develop multiplicative EW correction for signal sample
- Profile likelihood fit to 2d m_{bbll} and y_{bbll}



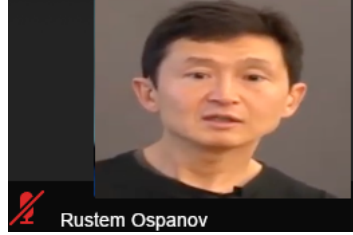
- $Y_t < 1.54$ at 95% CL
- Slightly better than 4-top

$$Y_t = 1.16^{+0.07}_{-0.08}(\text{stat})^{+0.17}_{-0.27}(\text{syst})$$

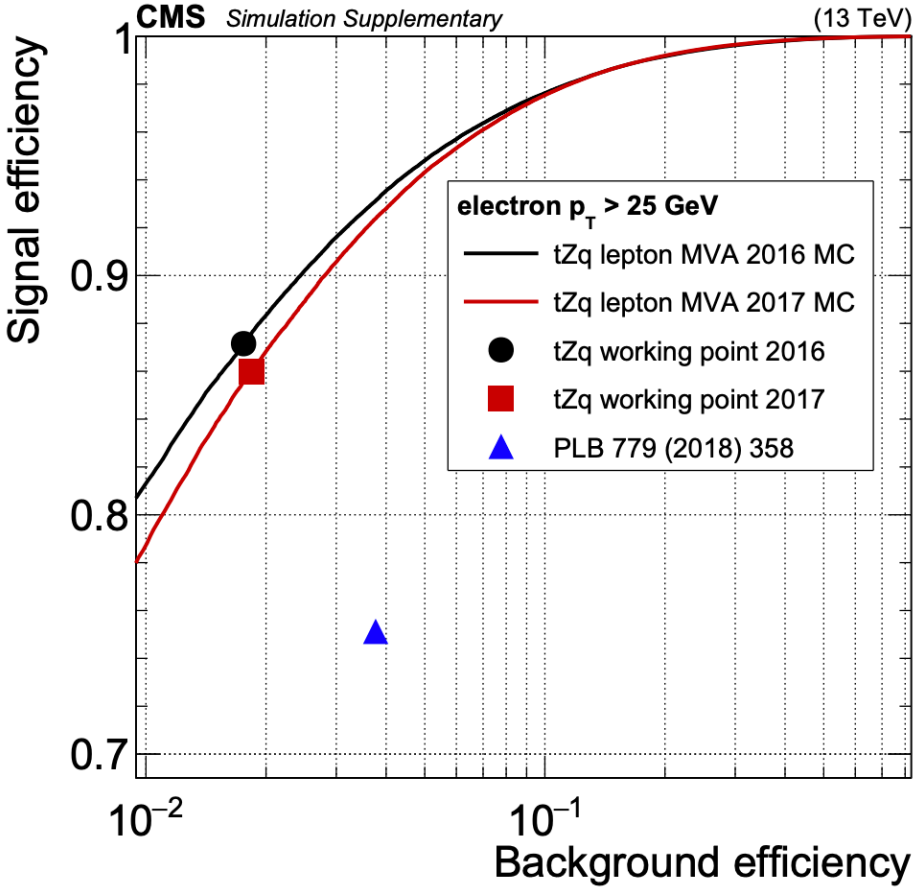
Theme: Top+X

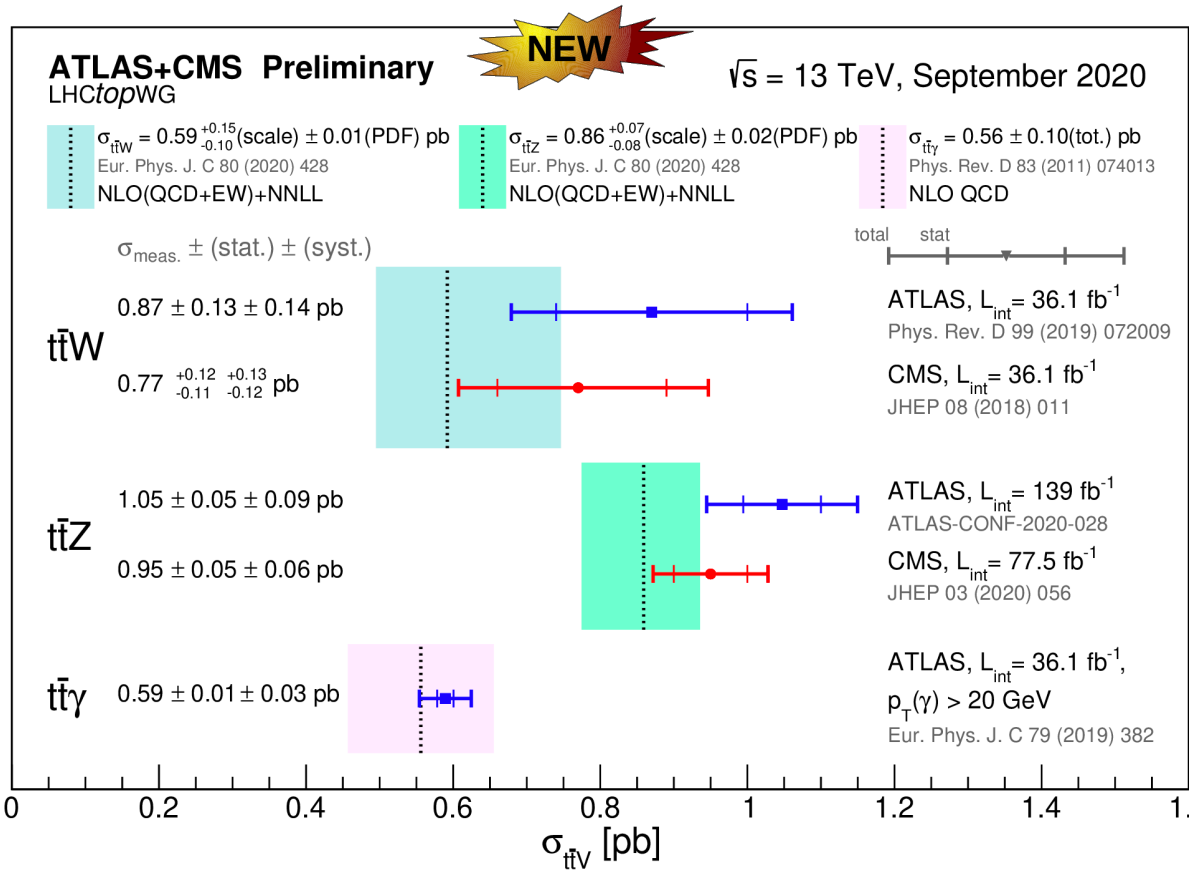
- Top-pair plus boson production (Rustem Ospanov)
  - Inclusive and differential tt + γ, W, Z
  - YSF talk on ATLAS ttZ by Florian Fisher
- TtH and tH and 4-top (Korbinian Schweiger)
  - And ATLAS 4-top joker talk by Erich Varnes
- Tt+HF (Sebastien Wertz)
  - And CMS ttcc joker talk by Seth Moortgat

tt+V



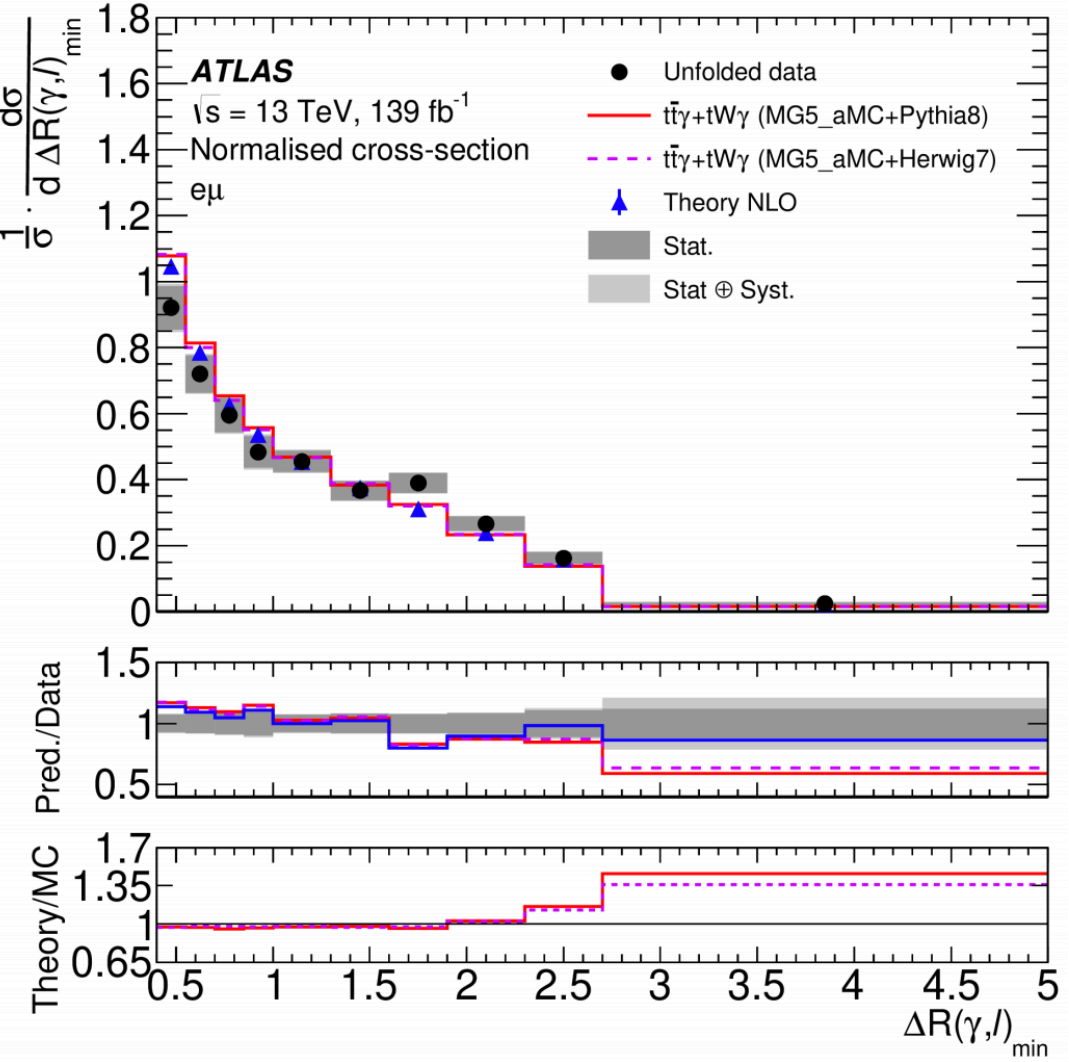
- New measurements of tt+W, Z, γ
  - Lepton isolation is key to ttW and ttZ

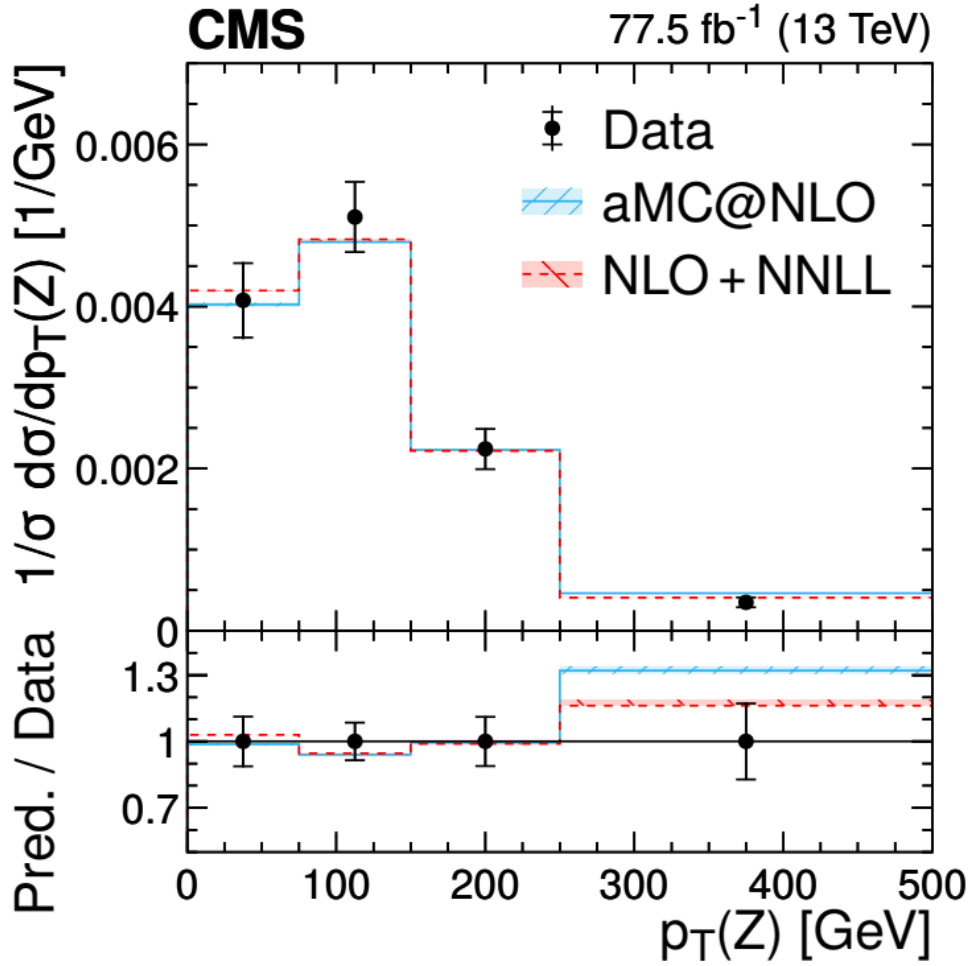




ttV differential

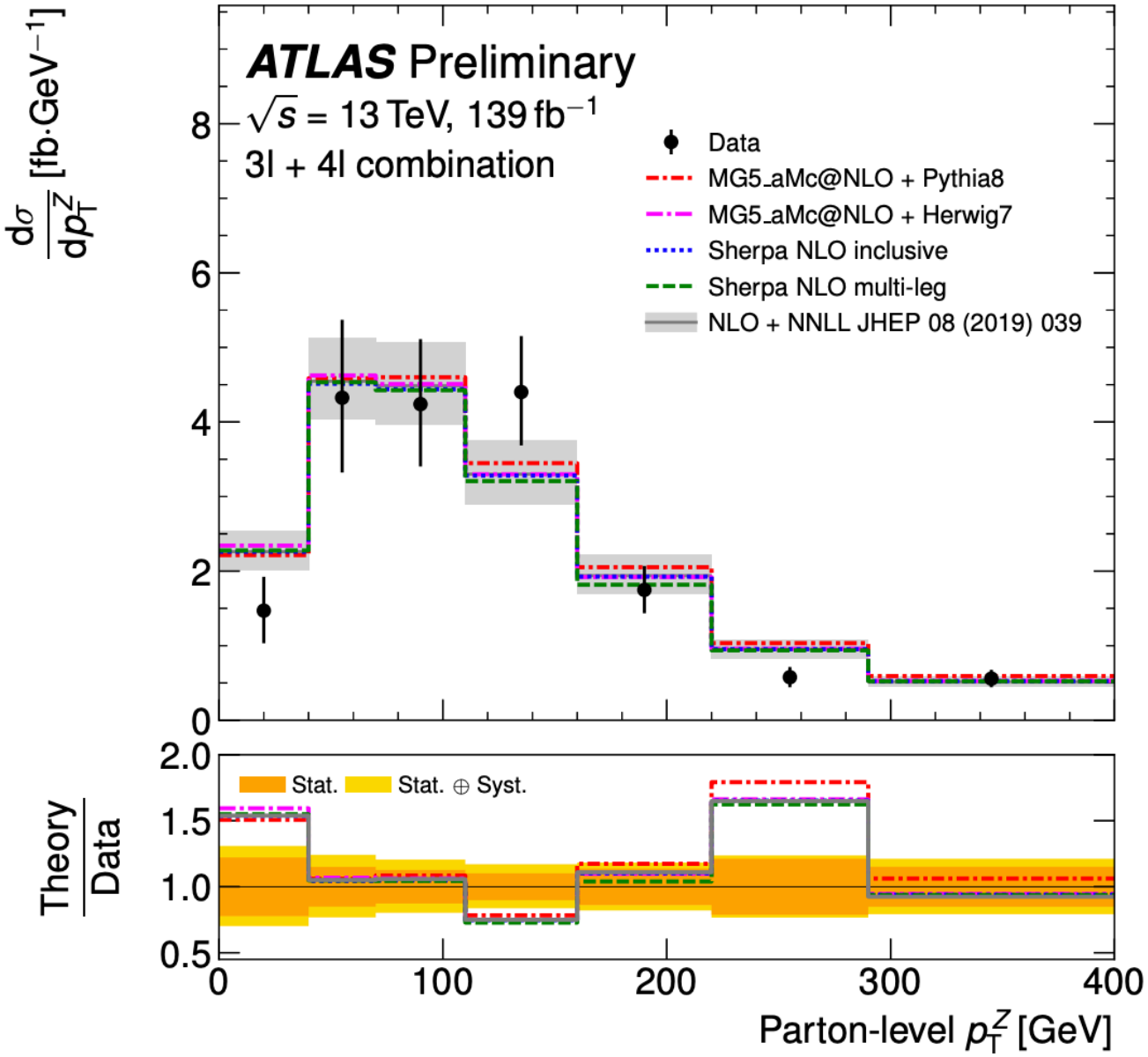
- ATLAS ttγ inclusive and differential in eμ final state with full Run 2 data
  - Not (yet) in new summary plot
- CMS ttZ differential





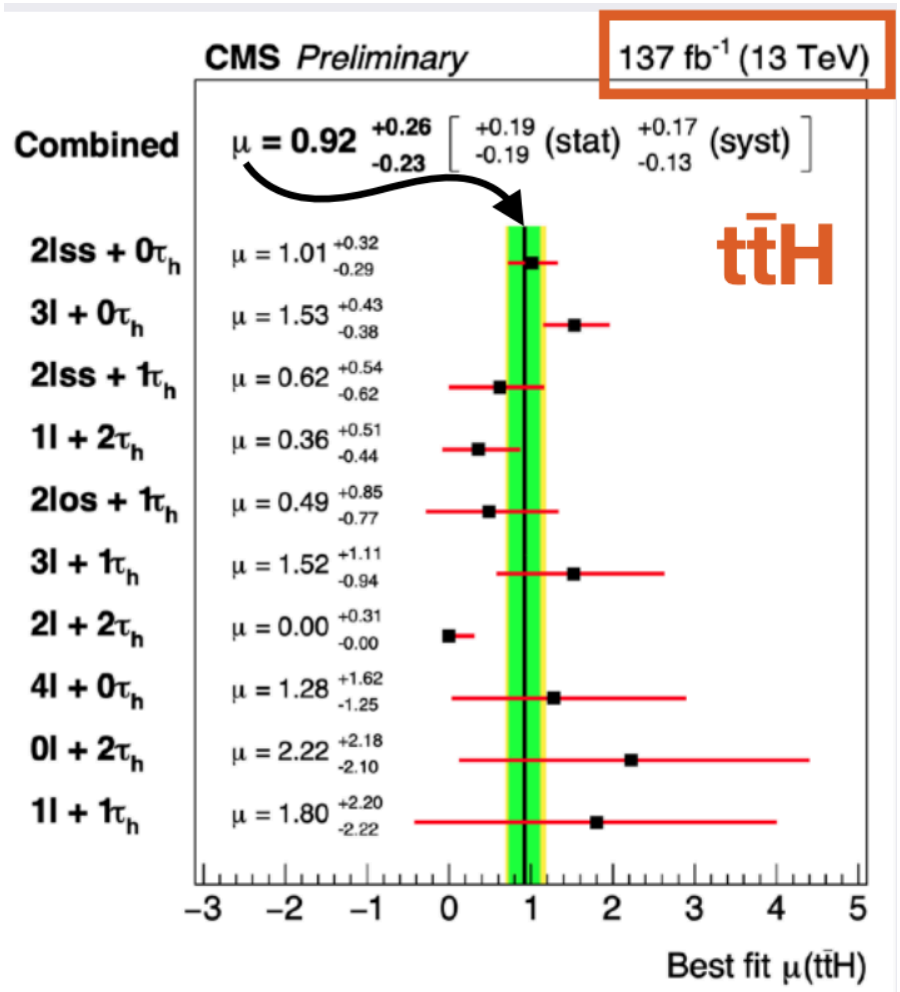
ATLAS ttZ

- Inclusive and differential ttZ measurement with 139 fb^{-1}

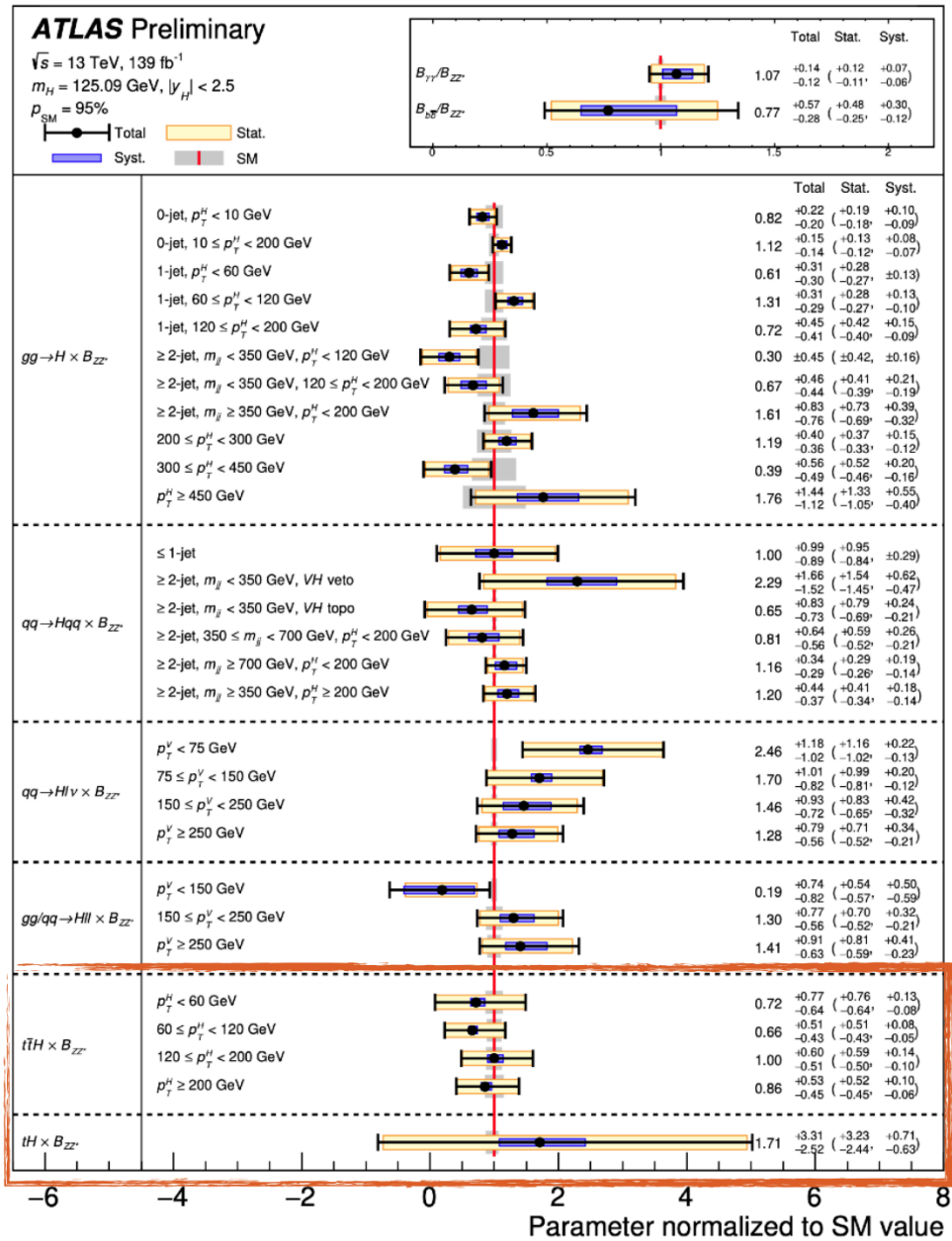


ttH and tH

- 6 measurements with full Run 2 dataset
- ATLAS combination in κ-framework
  - Exclude negative κ_t at 2.9σ
- CMS multilepton analysis
  - 35x3 distributions

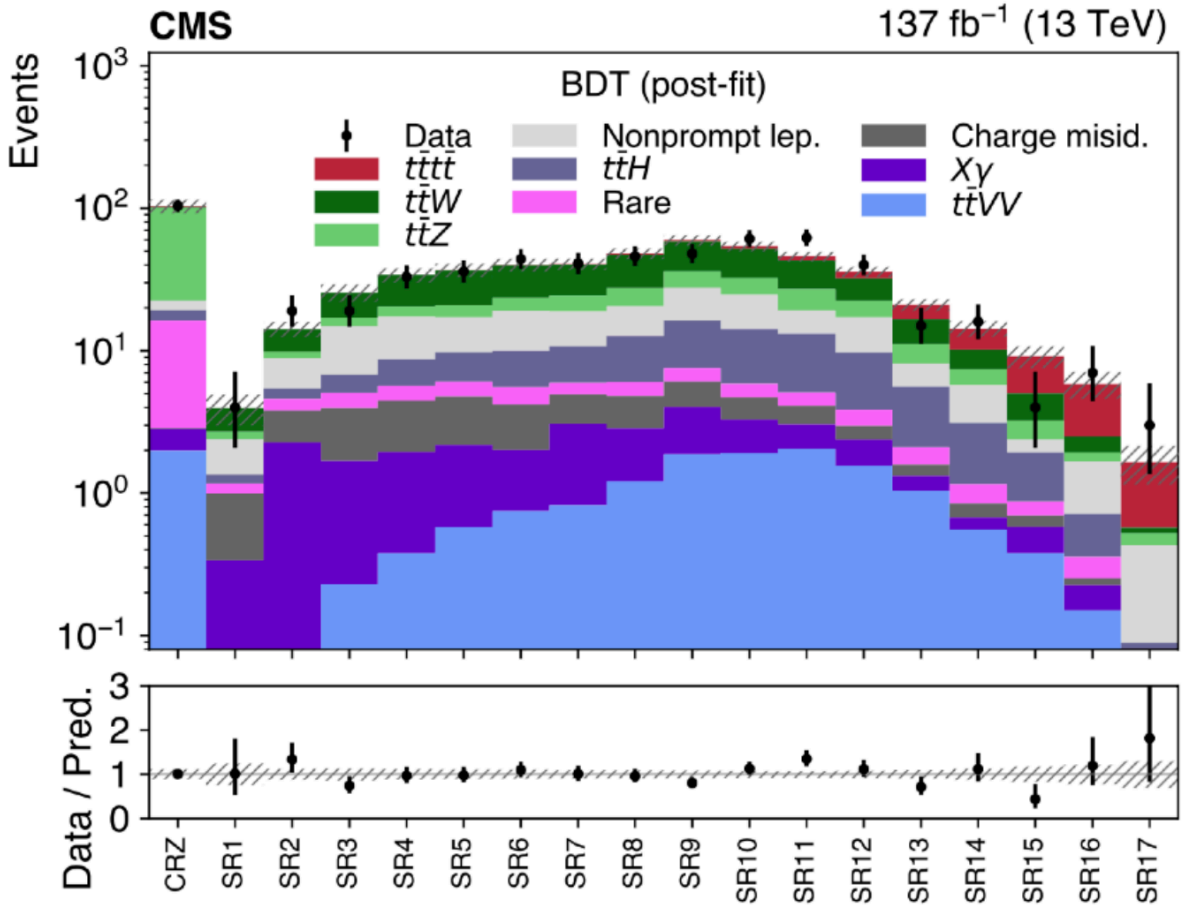


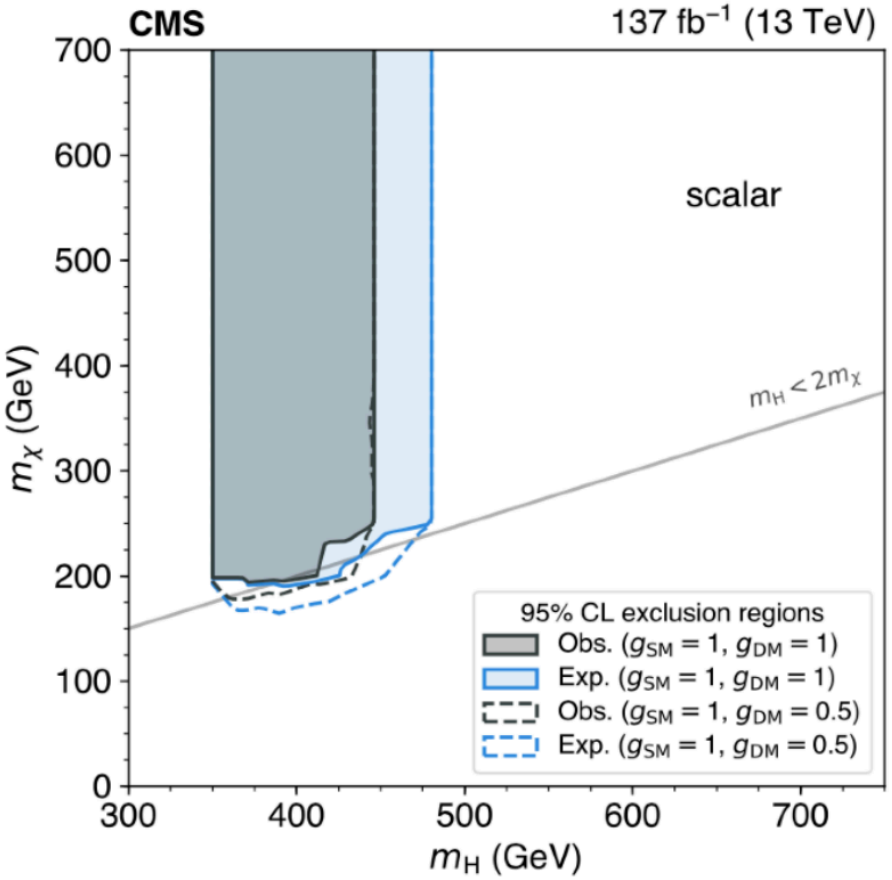
NEW



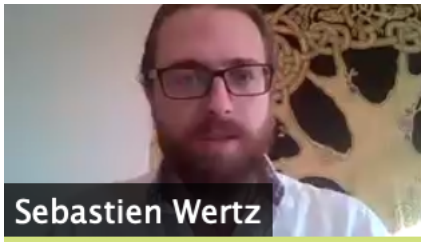
4-top

- No narrow resonances, many final-state jets, small XS
- Multilepton final states most sensitive
  - Build on ttH multilepton experience
  - ATLAS analysis based on full Run 2 data, obs (exp) sig 4.3 (2.4)σ
  - CMS analysis based on full Run 2 dataset and search for new scalar or vector particle

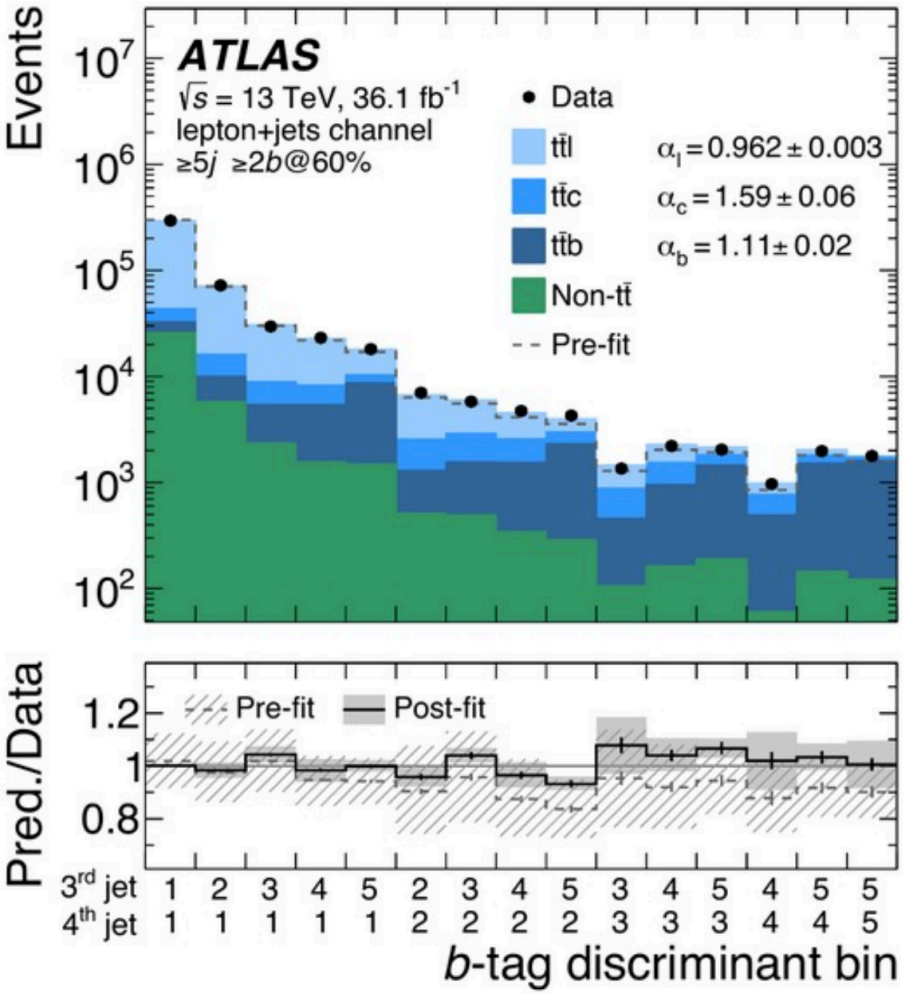


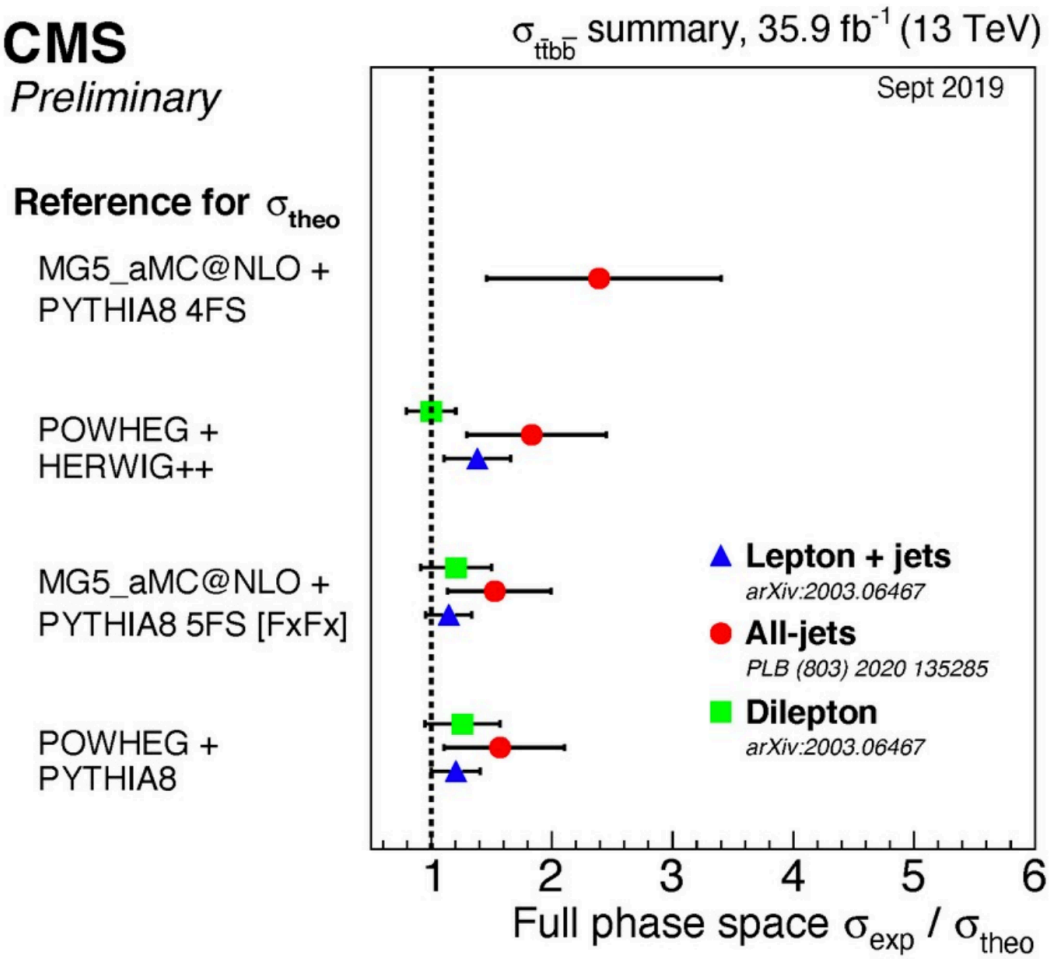


tt+bb



- Top+HF is an important background
  - For ttH(bb), 4-top
  - Test of ISR flavor composition at high scale
- B-tagging is key
- lepton+jets, dilepton and now also all-hadronic final state





Theme: EFT, asymmetries, CEDM, ee

- Flavor-Changing Neutral Currents and EFT (Mohammad Kareem)
- CMS EFT interpretations (Nicolas Tonon)
- Charge asymmetry, lepton universality (Nello Bruscino)
  - ATLAS first evidence for charge asymmetry
  - ATLAS lepton universality measurement in W boson decays
- Other interpretations
  - YSF talk on CMS CEDM limit by Seungkyu Ha
  - YSF talk on top mass in ee→tt+γ by Angelika Widl

EFT

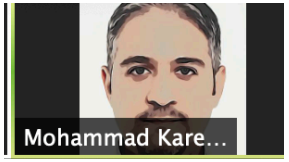
- ATLAS and CMS have started to publish papers top EFT operators in Warsaw basis - document produced for LHCtopWG

Interpreting top-quark LHC measurements
in the standard-model effective field theory

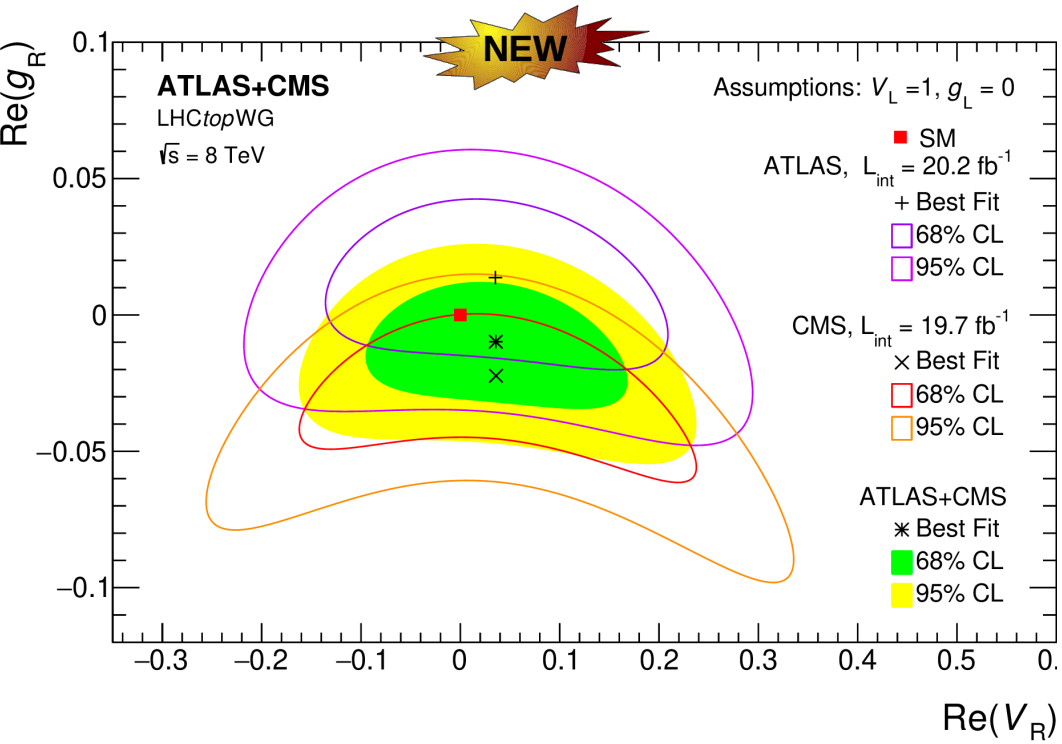
J. A. Aguilar Saavedra,[1] C. Degrande,[2] G. Durieux,[3]
F. Maltoni,[4] E. Vryonidou,[2] C. Zhang[5] (editors),
D. Barducci,[6] I. Brivio,[7] V. Cirigliano,[8] W. Dekens,[8,9] J. de Vries,[10] C. Englert,[11]
M. Fabbrichesi,[12] C. Grojean,[3,13] U. Haisch,[2,14] Y. Jiang,[7] J. Kamenik,[15,16]
M. Mangano,[2] D. Marzocca,[12] E. Mereghetti,[8] K. Mimasu,[4] L. Moore,[4] G. Perez,[17]
T. Plehn,[18] F. Riva,[2] M. Russell,[18] J. Santiago,[19] M. Schulze,[13] Y. Soreq,[20]
A. Tonero,[21] M. Trott,[7] S. Westhoff,[18] C. White,[22] A. Wulzer,[2,23,24] J. Zupan.[25]

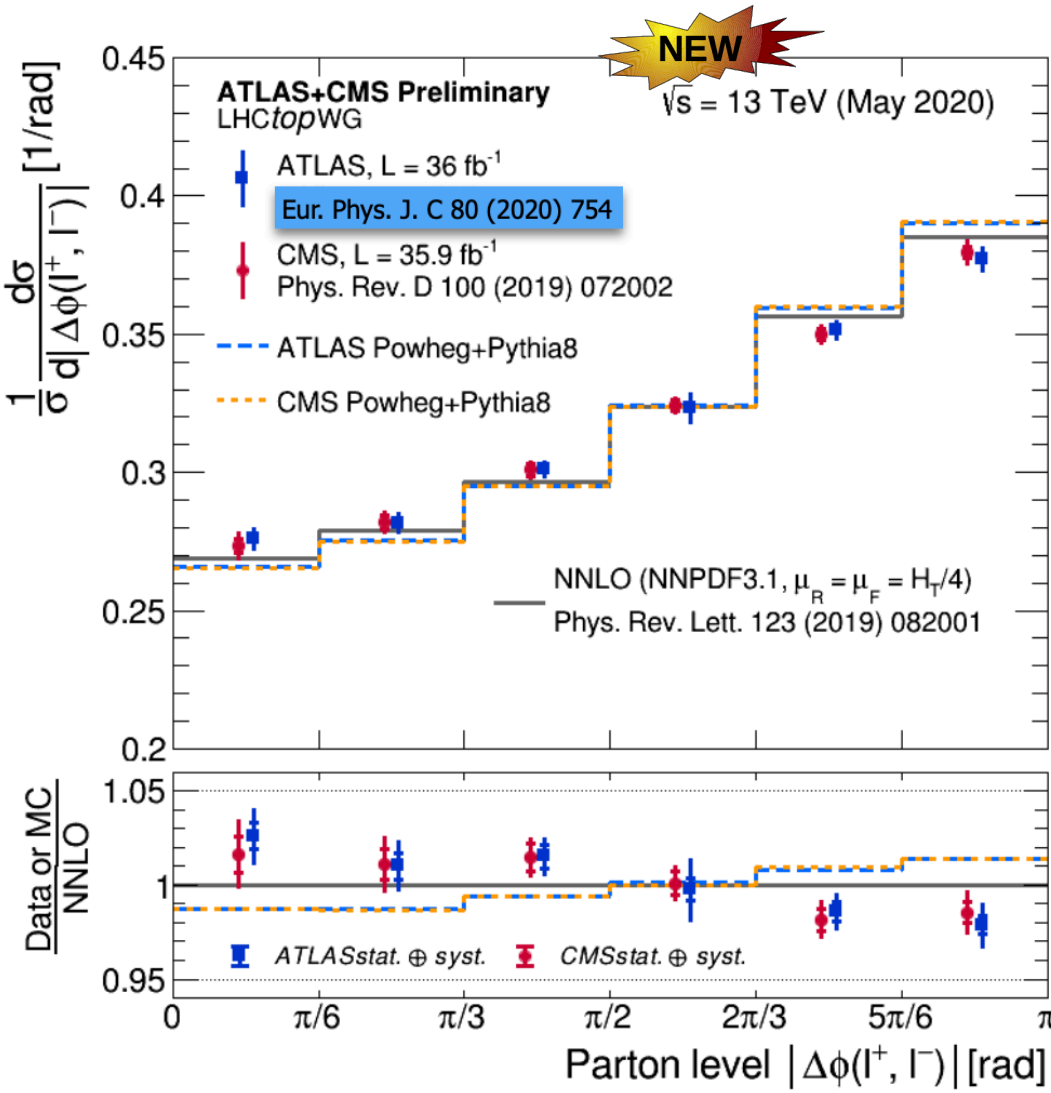
- Using data for EFT interpretations
  - Inclusive cross-section and other parameter measurements
  - Unfolded differential measurements
  - Impact of EFT on acceptance, background?
- Combinations are a challenge
  - Correlations of uncertainties between measurements, experiments
  - Modeling of modified signals, backgrounds
  - Which information to make available publicly?
- LHC EFT WG - open meeting in middle of October

EFT



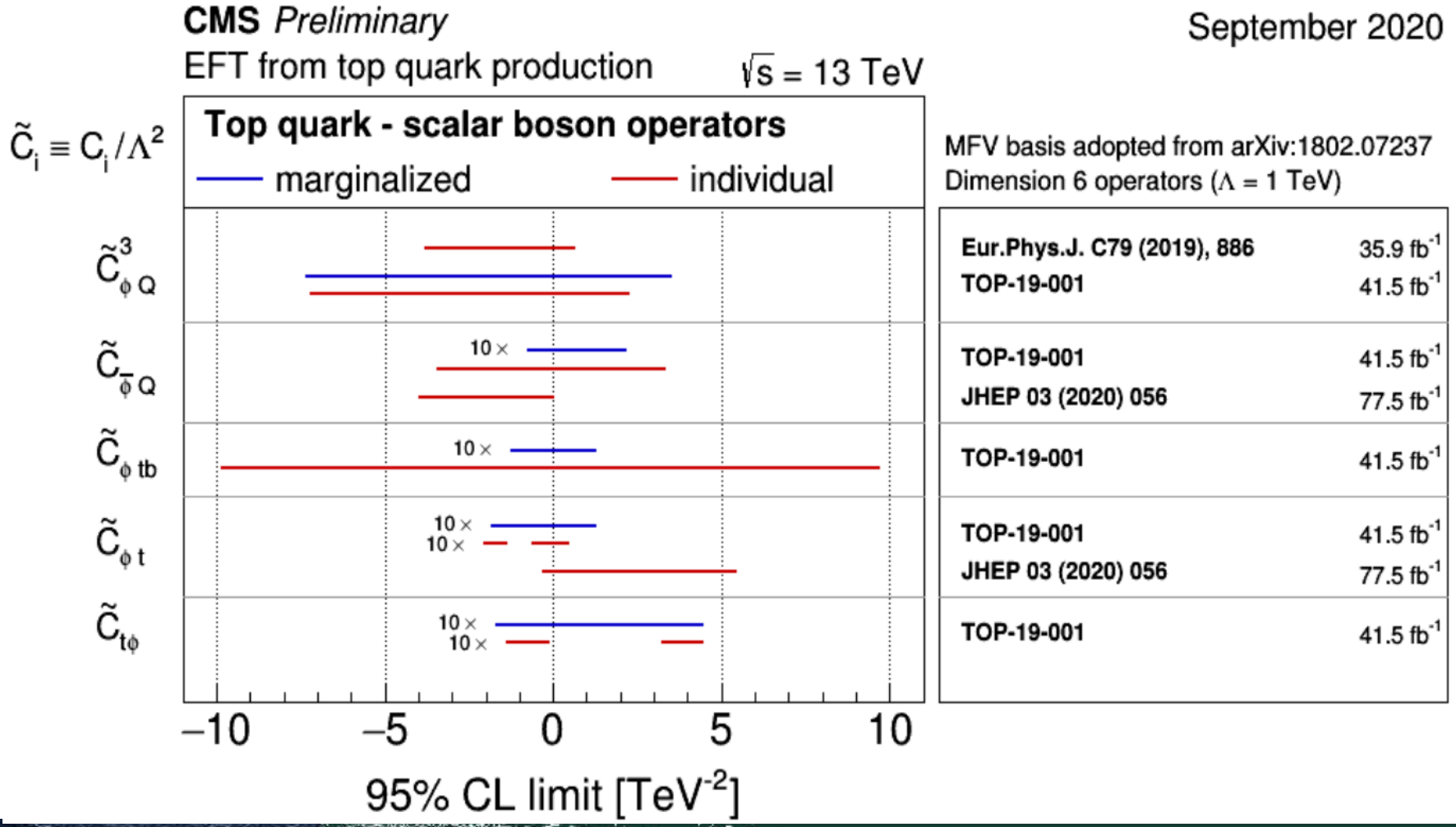
- W helicity combination of ATLAS and CMS measurements
  - And interpretation in terms of EFT coefficients
- Spin correlation LHCtopWG summary plot



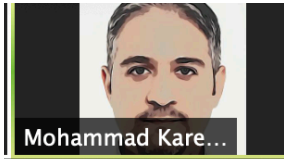


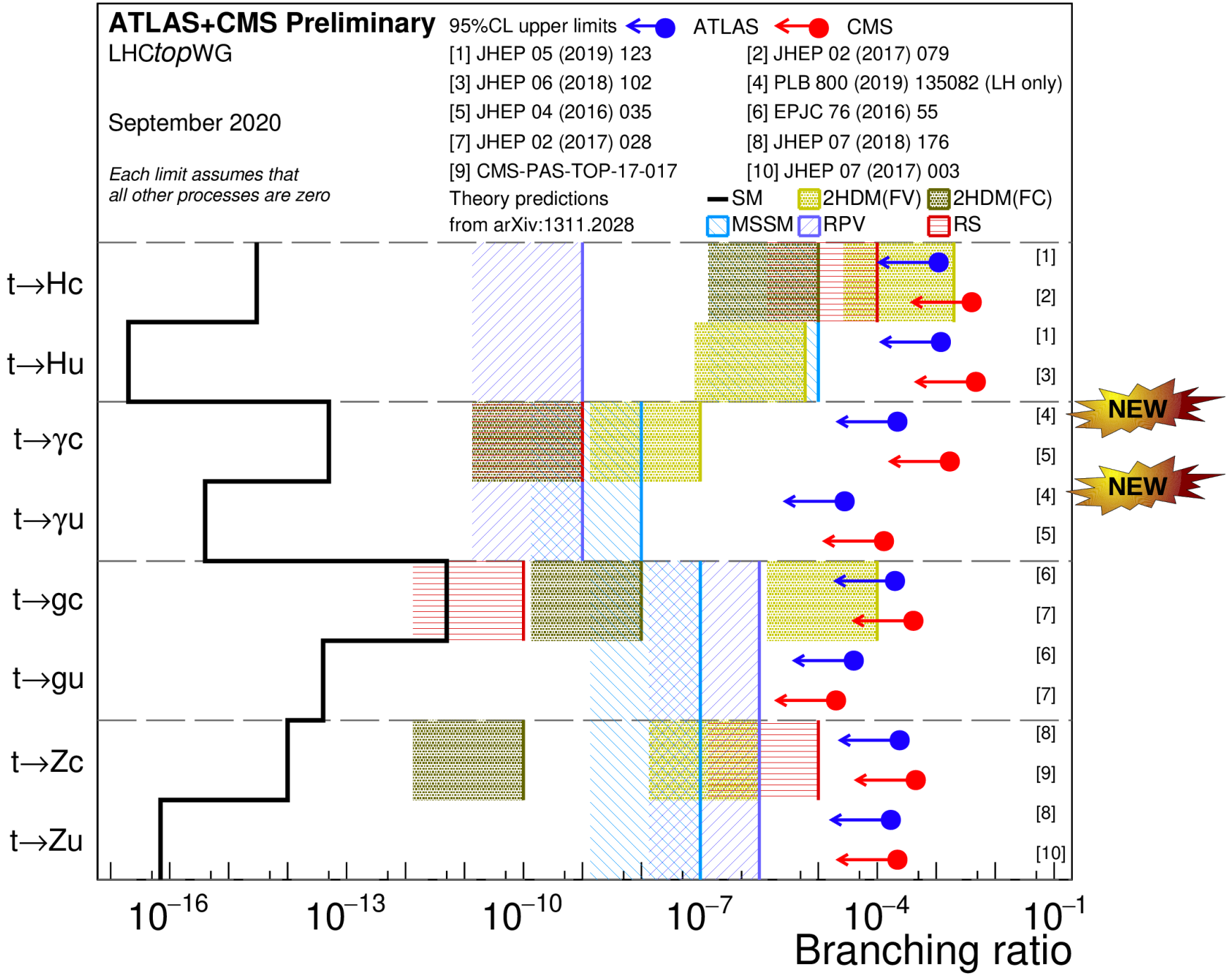
CMS EFT

- Use multiple approaches
  - EFT from cross-section
  - EFT from unfolded distributions
  - EFT from likelihood fits to detector-level data
  - Hybrid approach
  - Summary plots to summarize current status

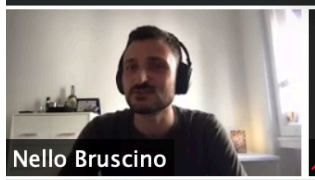


Flavor-Changing Neutral Currents



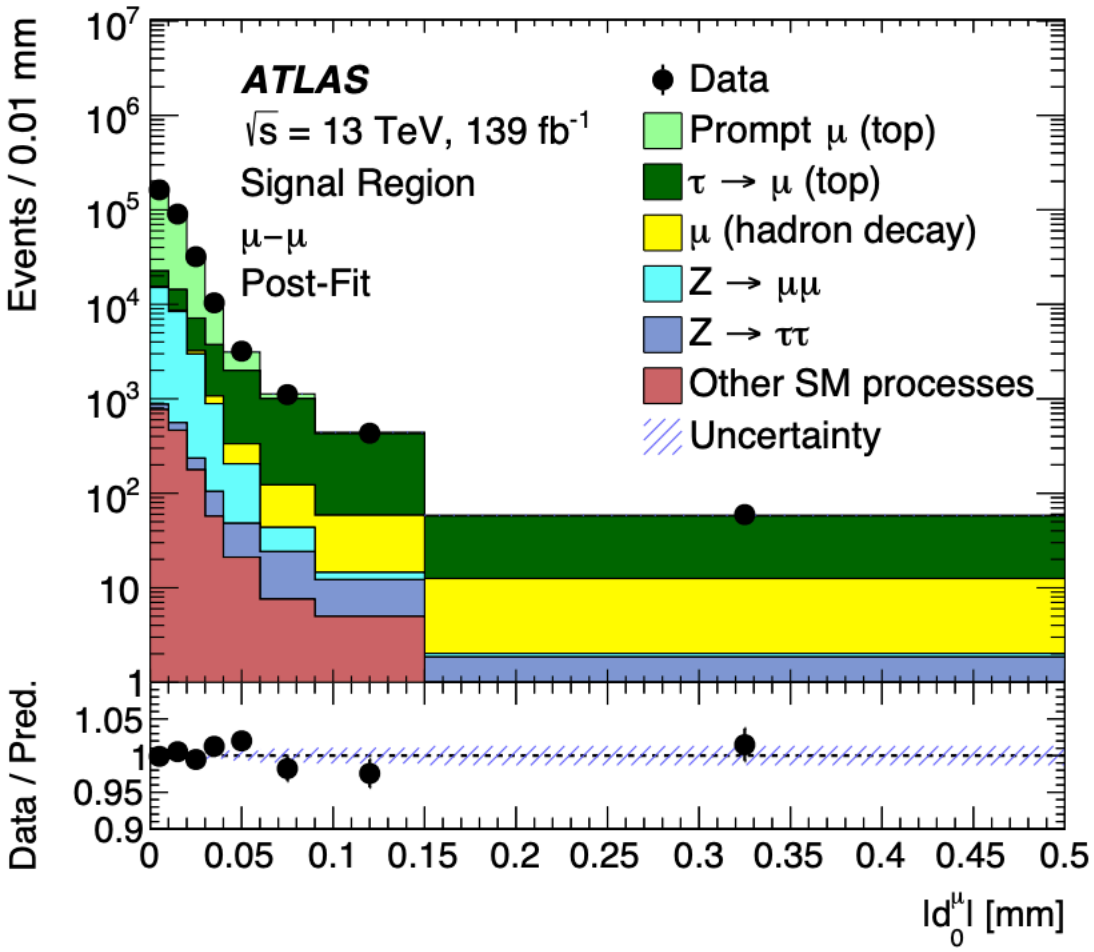


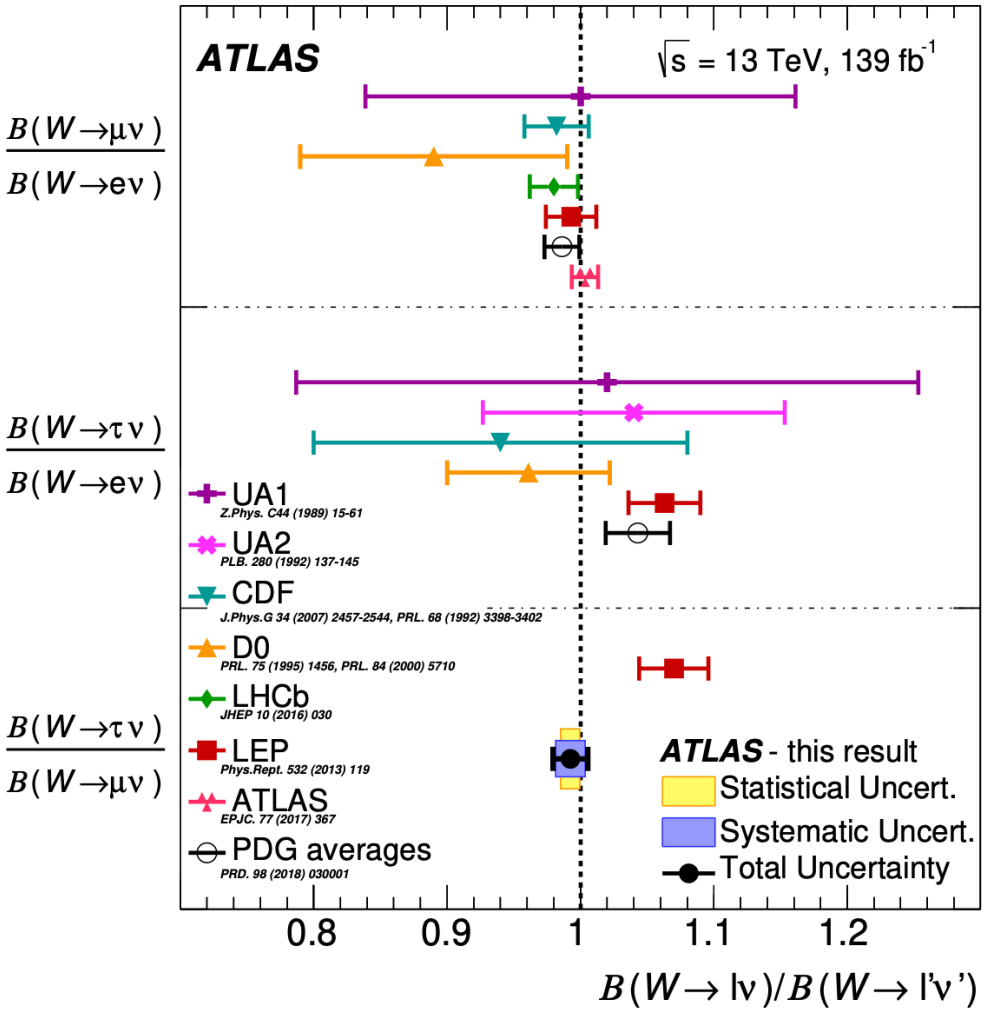
ATLAS charged lepton flavor universality



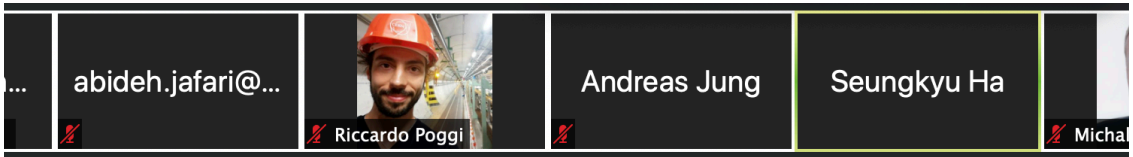
NEW

- Top quarks provide a pure sample of W bosons
- Resolve puzzle from LEP
- Separate W→tau and W W→e,mu decays





CMS top Charged Electric Dipole Moment



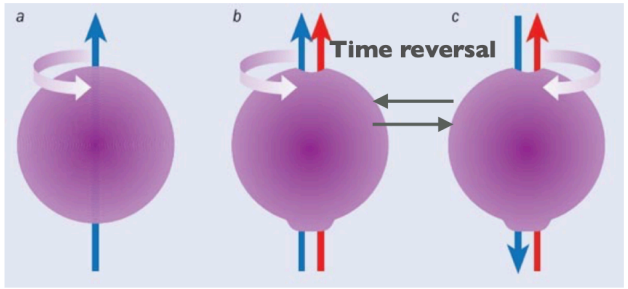
Search for CP violating anomalous top quark coupling in proton-proton collisions at $\sqrt{s}$ = 13 TeV

Seungkyu Ha[1,2]

on behalf of the **CMS Collaboration**

Sep. 16, 2020

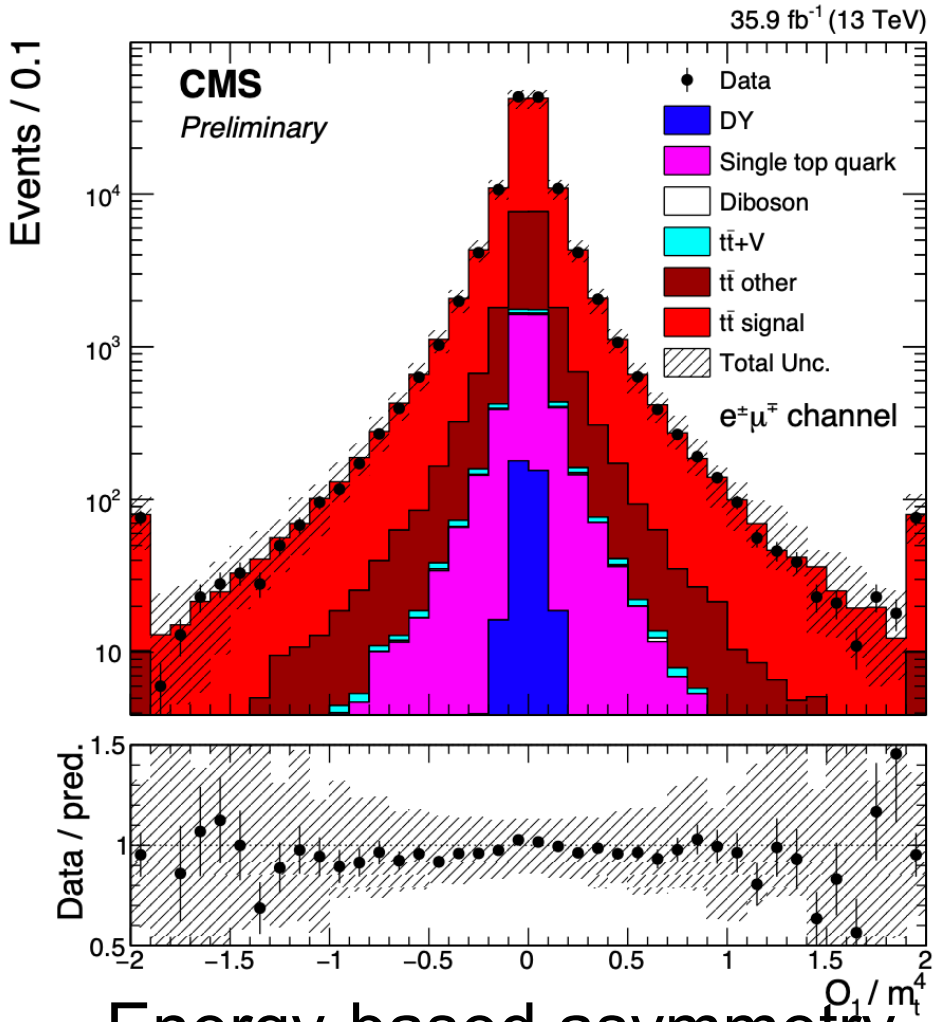
Korea University[1] , Yonsei University[2]



: Magnetic Dipole Moment

: Electric Dipole Moment

CEDM leads to CP violation

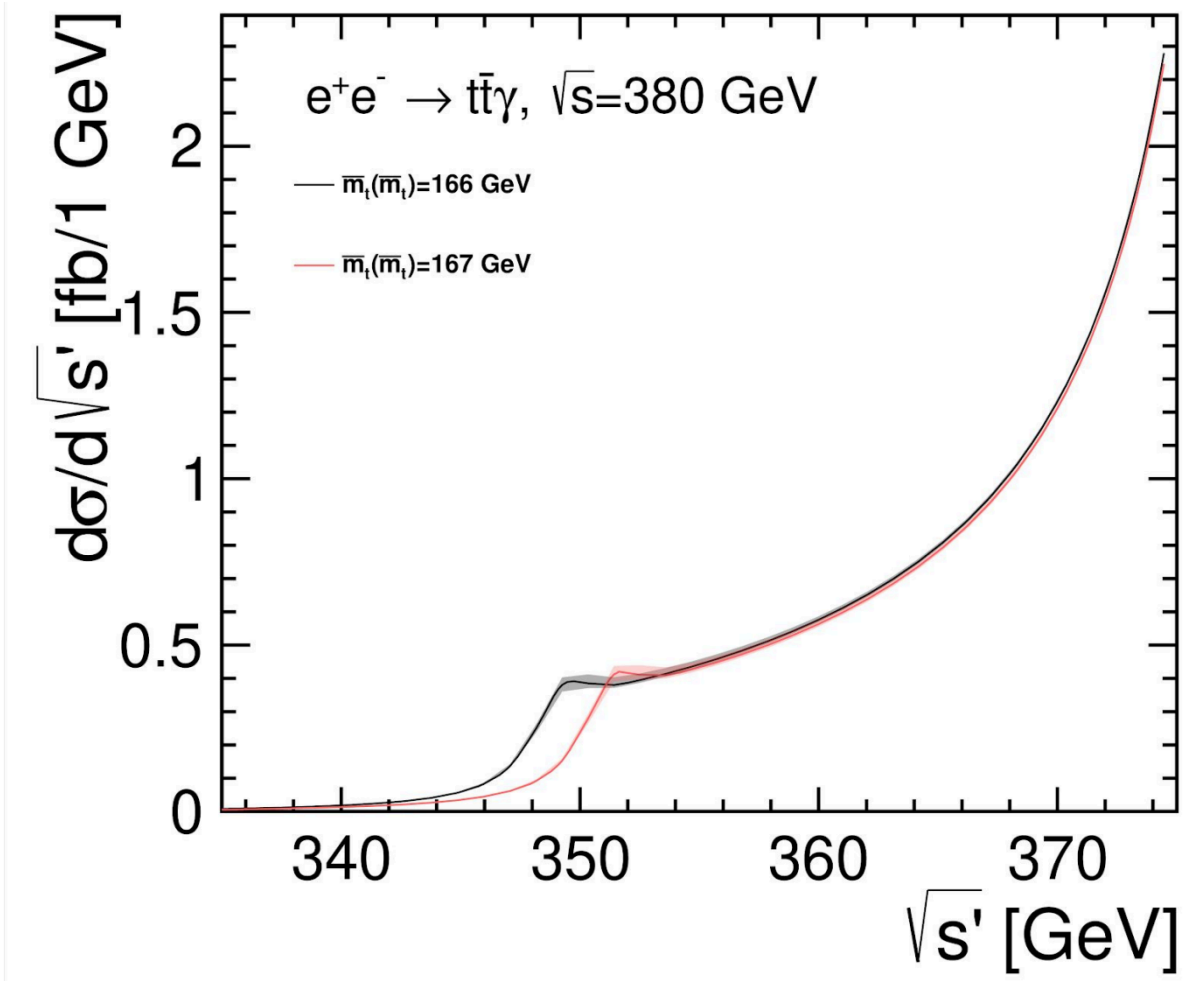


Energy-based asymmetry discriminant

Set 95% CL limit

Top mass from radiative events at lepton collider

- Precision top mass measurement at ee collider without top mass scan
  - Can measure mass with 150 MeV accuracy at 500 GeV
- Can measure running top mass



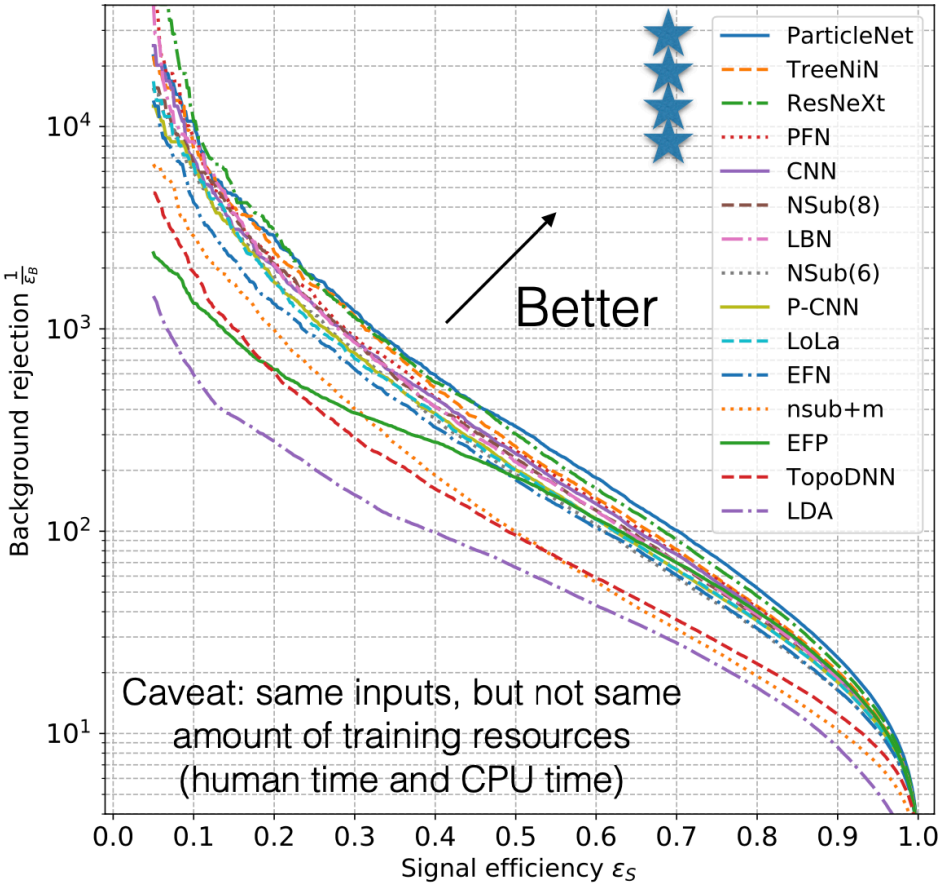
[Boronat, Fullana, Fuster, Gomis, Hoang, Mateu, Vos, AW 2019]

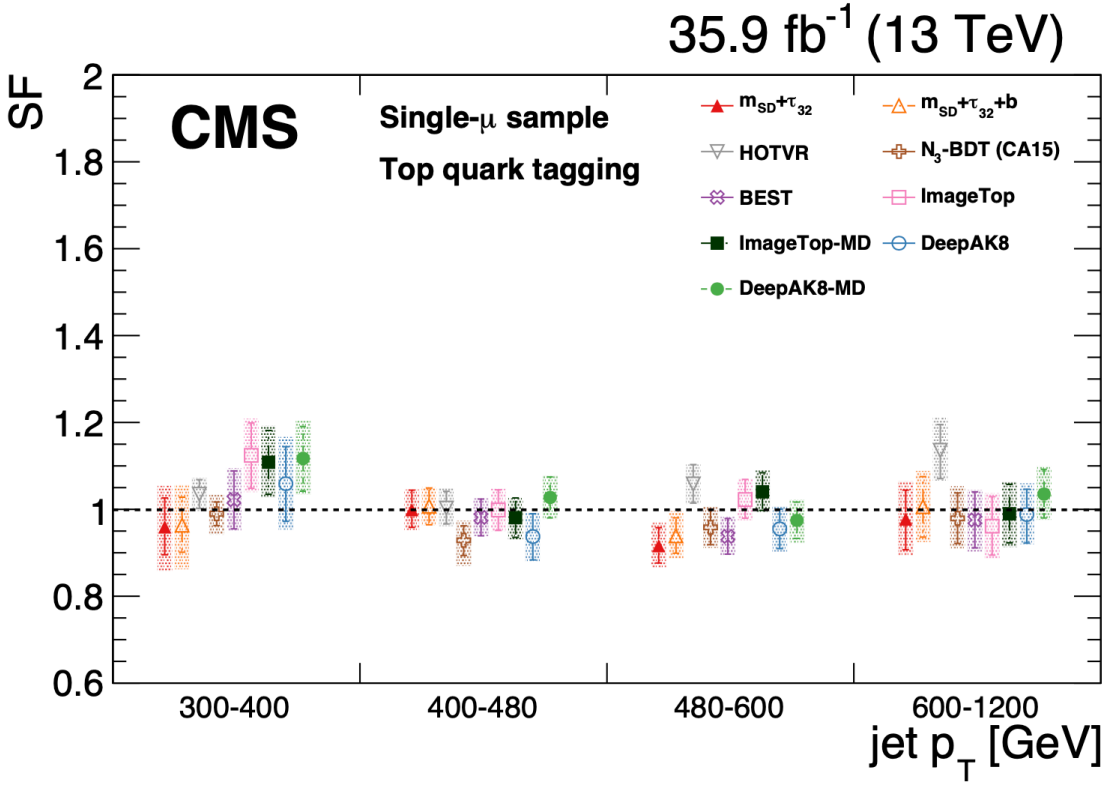
Theme: Machine learning is everywhere

- Overview of ML use by ATLAS and CMS (Ben Nachman)
  - Active area of developments
  - Wide range of application
- Jet substructure with latent algorithms (Jernej Kamenik)
  - Reveal physics of the algorithm
- Top mass and BSM and resolving it with ML (Bryan Ostdiek)
  - SUSY stop contamination in top mass measurements

Modern machine learning

G. Kasieczka and T. Plehn et al., SciPost Phys. 7, 014 (2019)

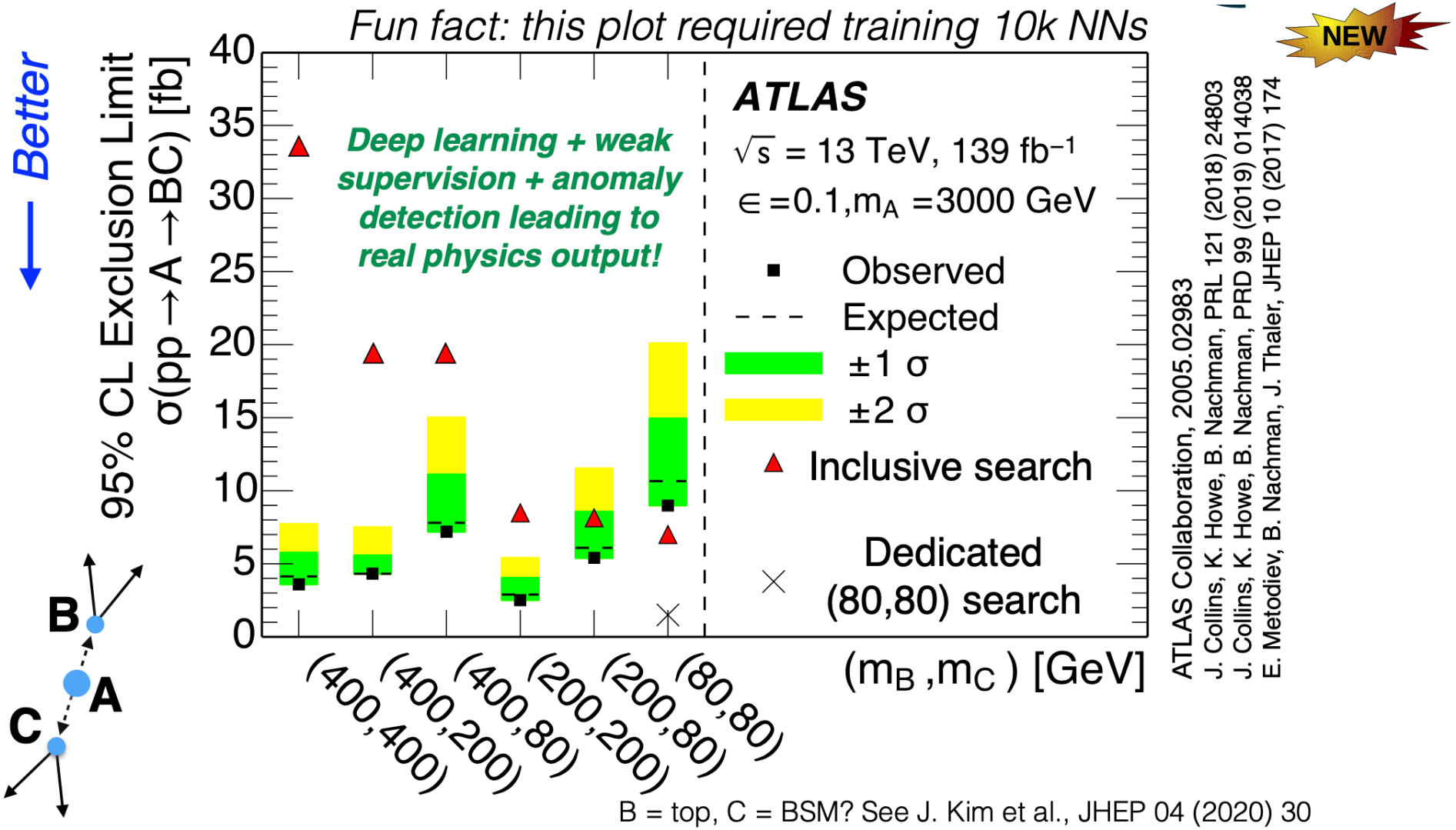




- Classifiers perform well when they are fully optimized on all of the available information
  - Image pixels (clusters, tracks, not high-level variables)
  - Sub-structure, flavor information

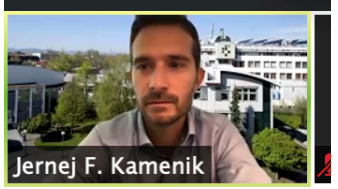
It's not all in the ROC curves

- Experimental challenges include hard-to-model backgrounds (eg multijet) and large systematic uncertainties
- Adapt learning approach to underlying physics problem



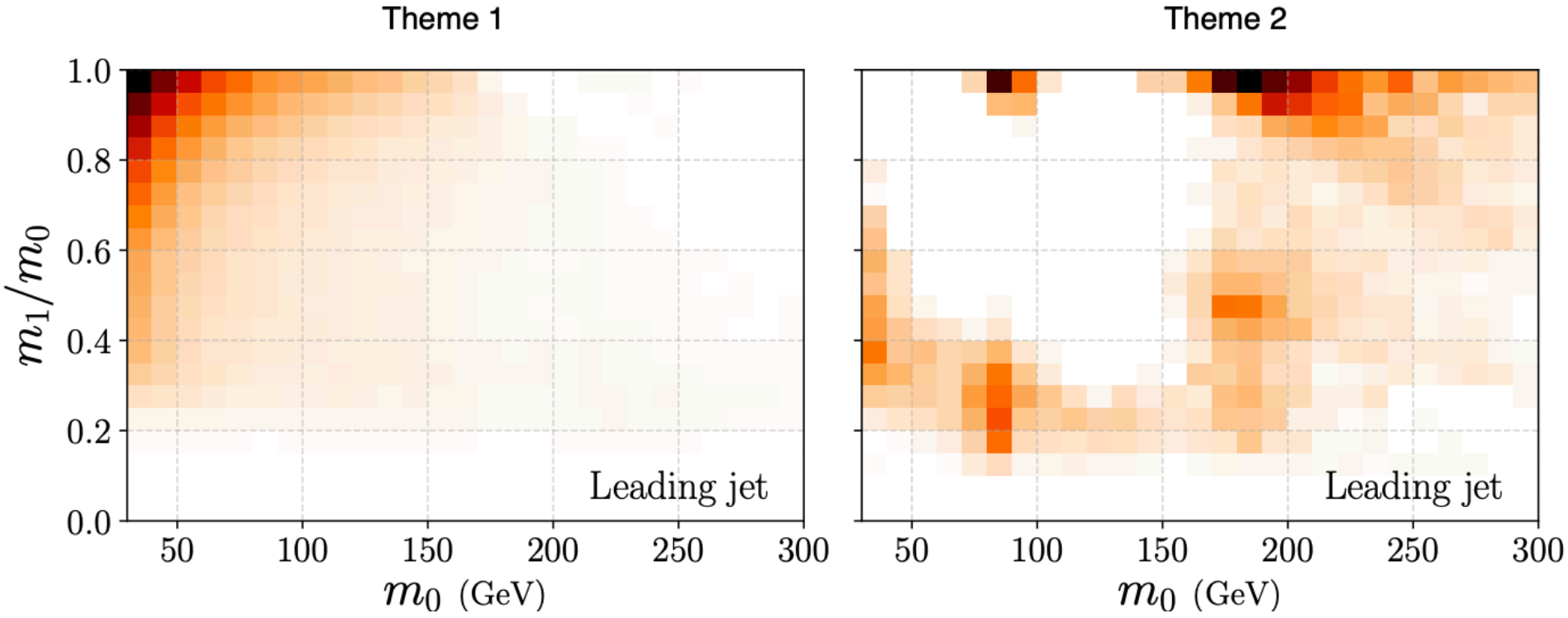
B = top, C = BSM? See J. Kim et al., JHEP 04 (2020) 30

Latent algorithms

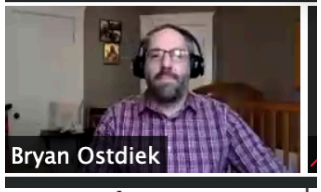


- "Where is the physics?" - ask the boosted-top ML algorithm directly
- 2 examples:
  - Variational Autoencoder
  - Latent Dirichlet Allocation - selects 2 themes
  - Both trained on a mixed sample: *B*: QCD (light quark & gluon) dijets

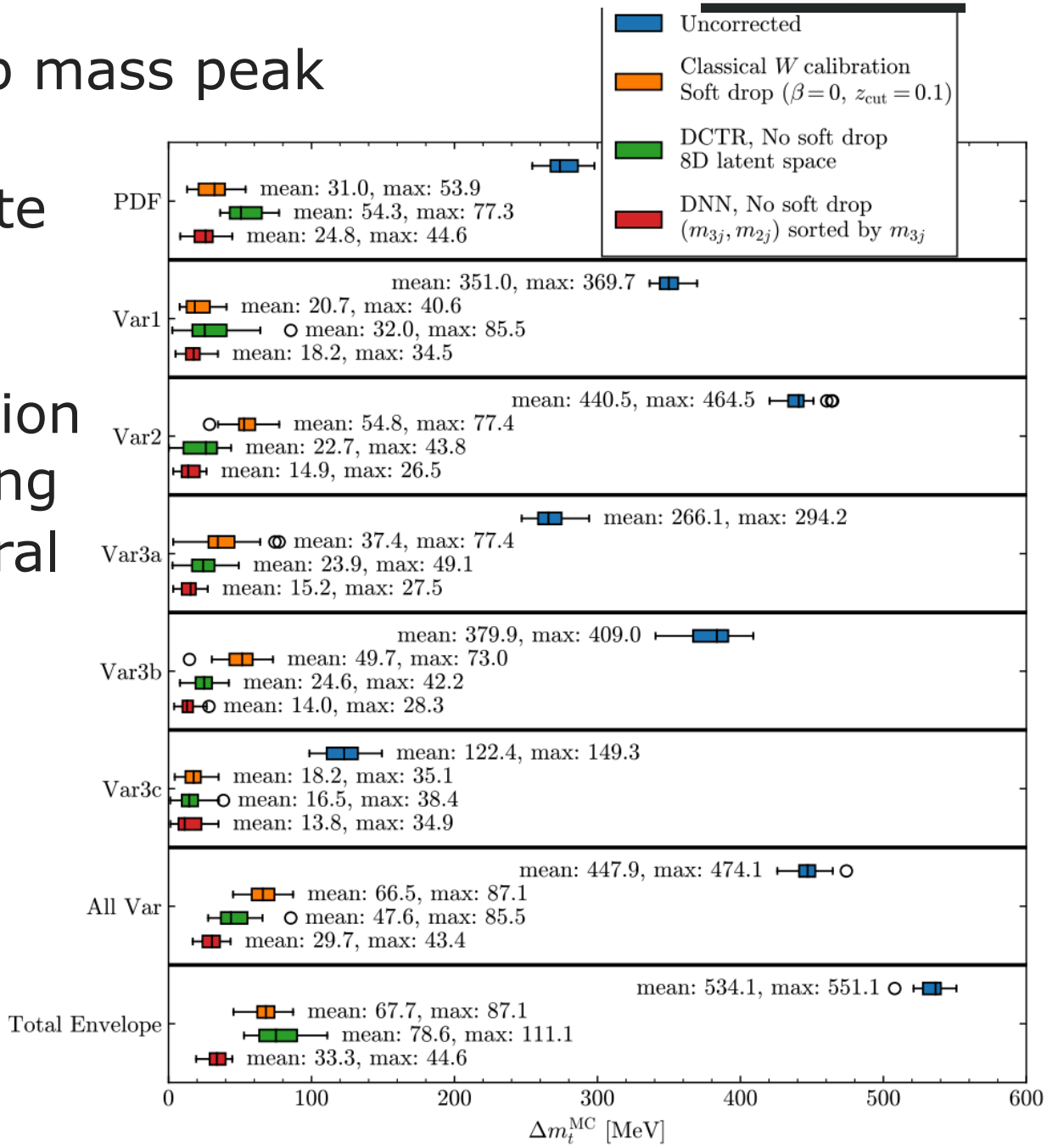
S: $pp \to t\bar{t} \to W^+W^-b\bar{b}, \quad S/B = 1$



Top mass, BSM, DCTR



- SUSY top noise under top mass peak
- Could affect top mass measurements in template fits
- DCTR: Deep neural networks usingClassification for Tuning and Reweighting
- DNN: Series of deep neural networks
- DNN recudes mass uncertainties more than W-based JES calibration



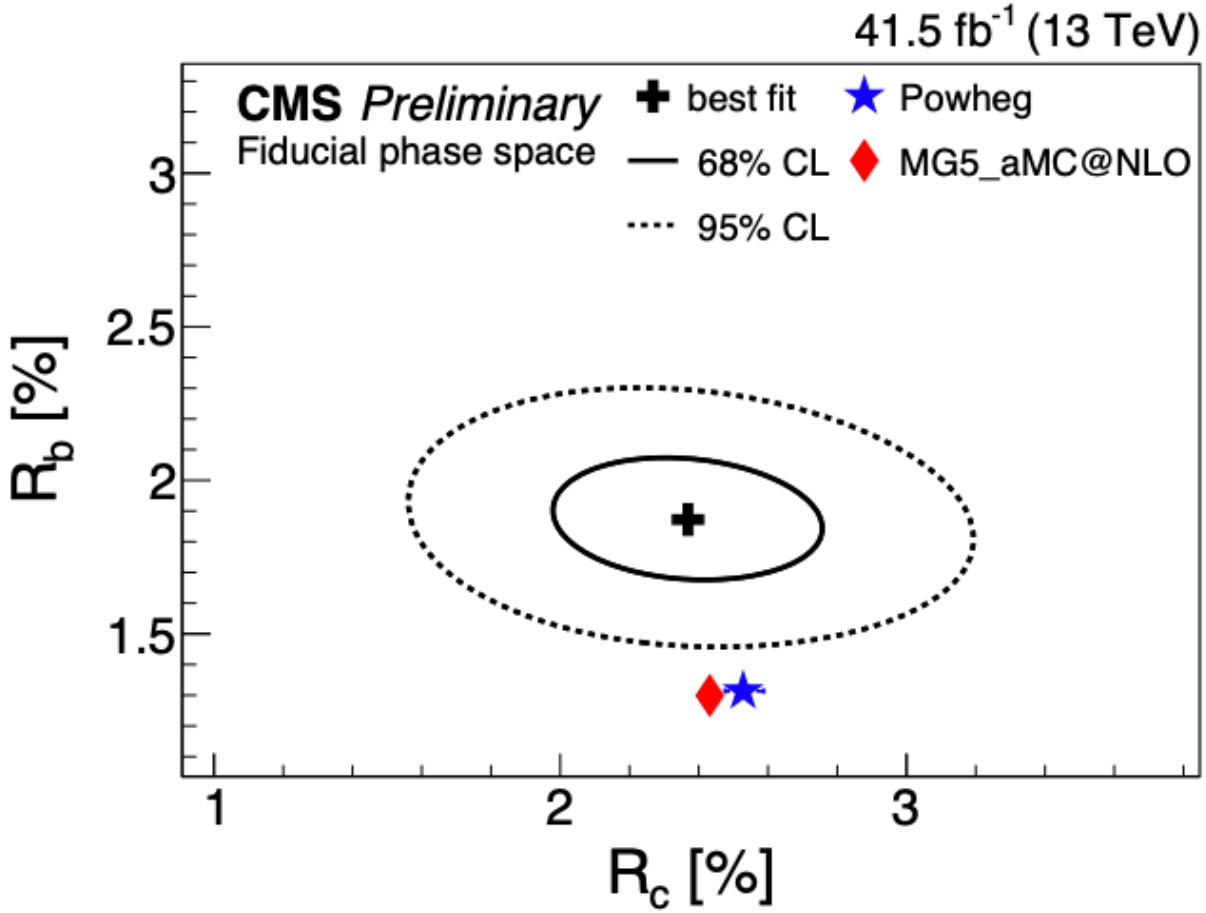
Theme: Jokers

- CMS ttcc (Seth Moortgat)
- CMS EFT fit to tt+X (Brent Yates)
- ATLAS 4-top (Erich Varnes)

ttcc and ttbb with CMS

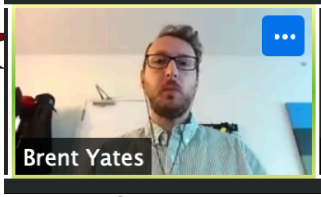
NEW

- Top+HF is an important background
  - For ttH, 4-top, searches
  - ttbb has been studied already by ATLAS and CMS, not yet ttcc
- ML for particle ID, b-tagging, charm tagging, event reconstruction, final template fit

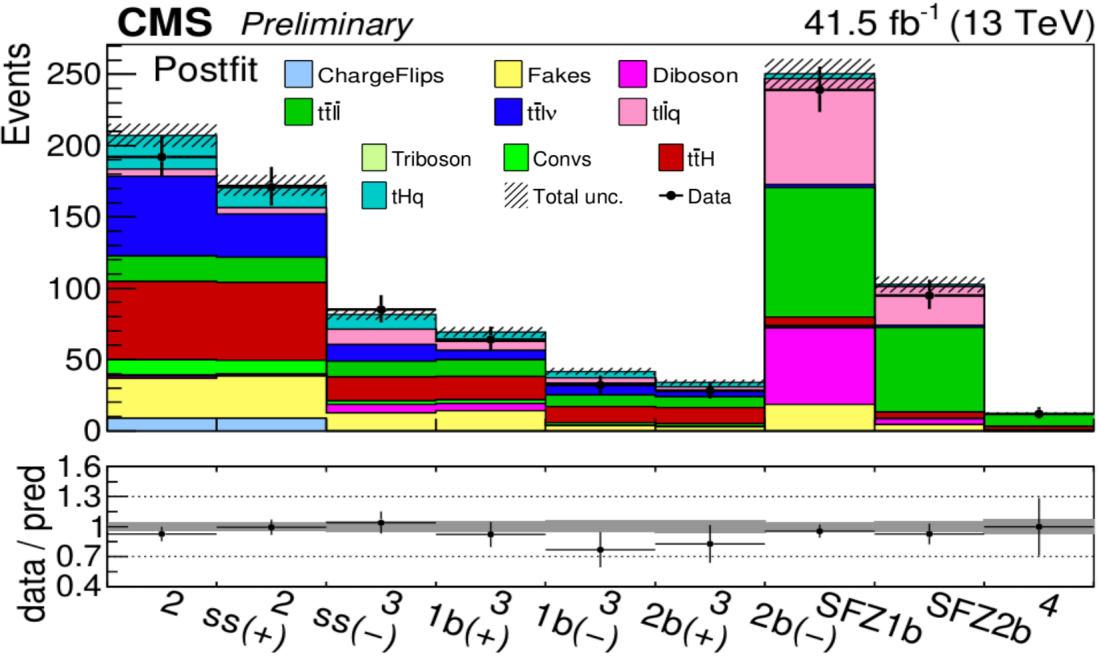


EFT interpretation of tt+X with CMS

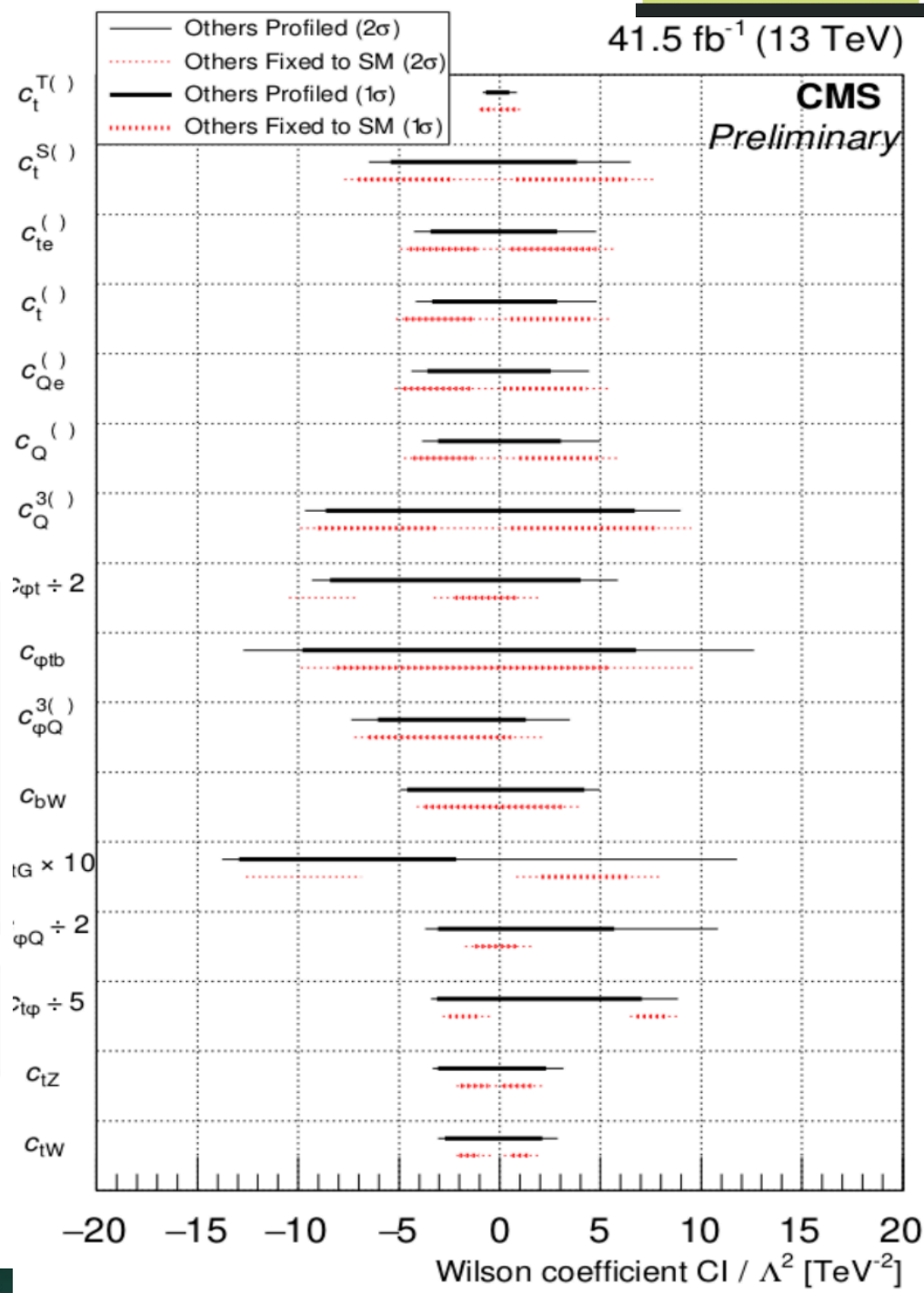
NEW



- ttll, ttlv, tllq, ttH, tHq
- 16 EFT operators, consider one-at-a-time
- Quadratic model for yields in each bin based on MC

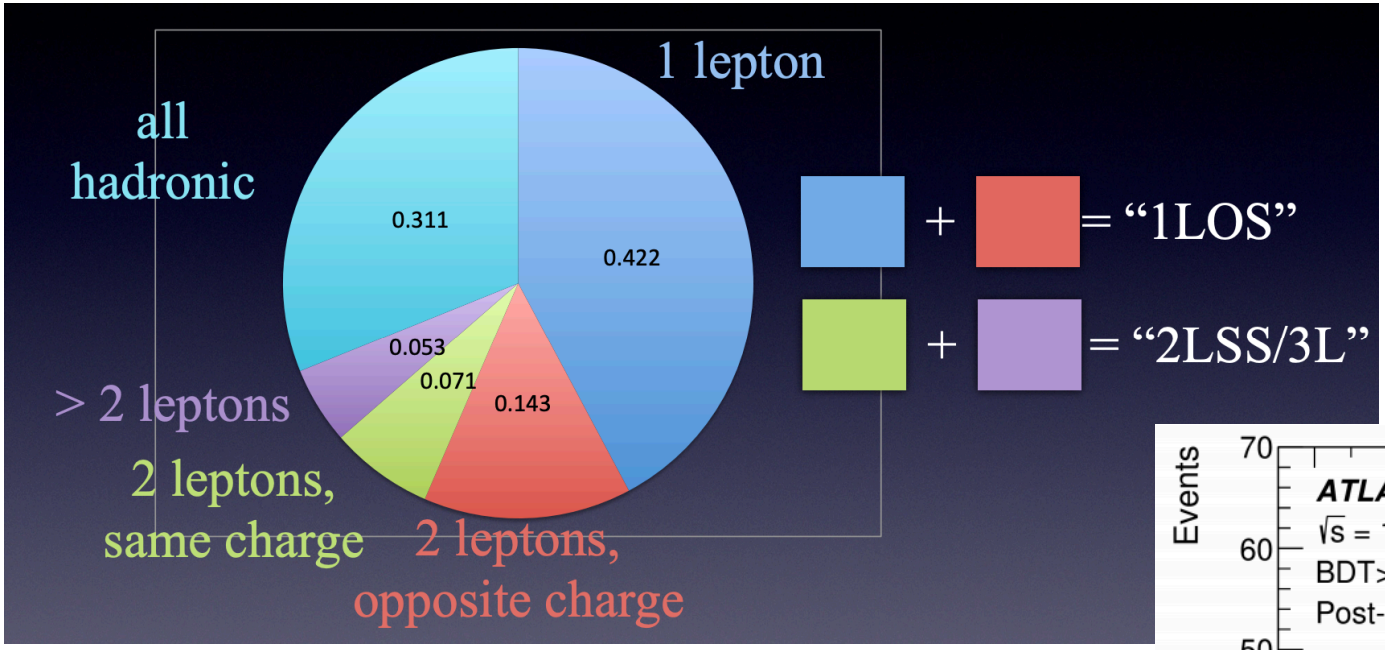


(jet bins integrated)



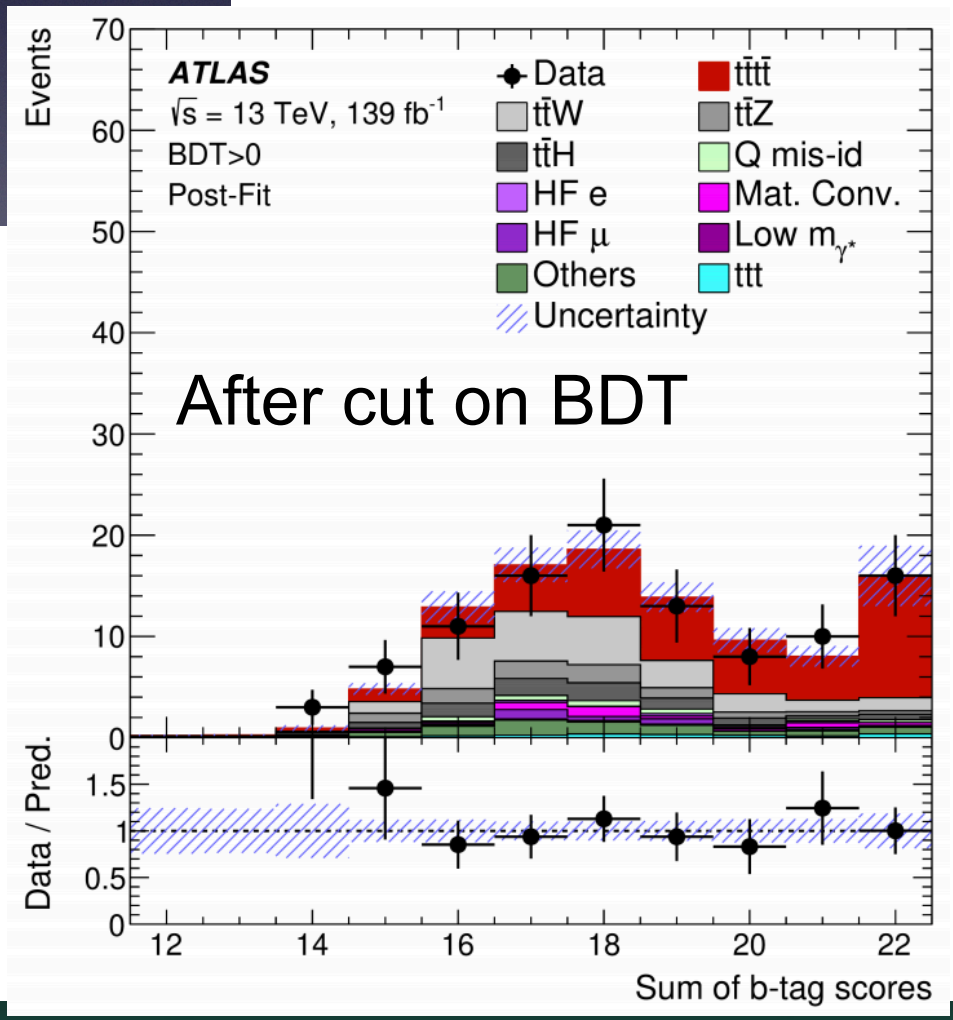
ATLAS 4-top evidence

NEW



- Challenges:
  - modelling of backgrounds, tt+ W+jets
  - up to 9 jets

4.3 s.d. from 0
(2.4 s.d. expected)
Evidence for $t\bar{t}t\bar{t}$ production



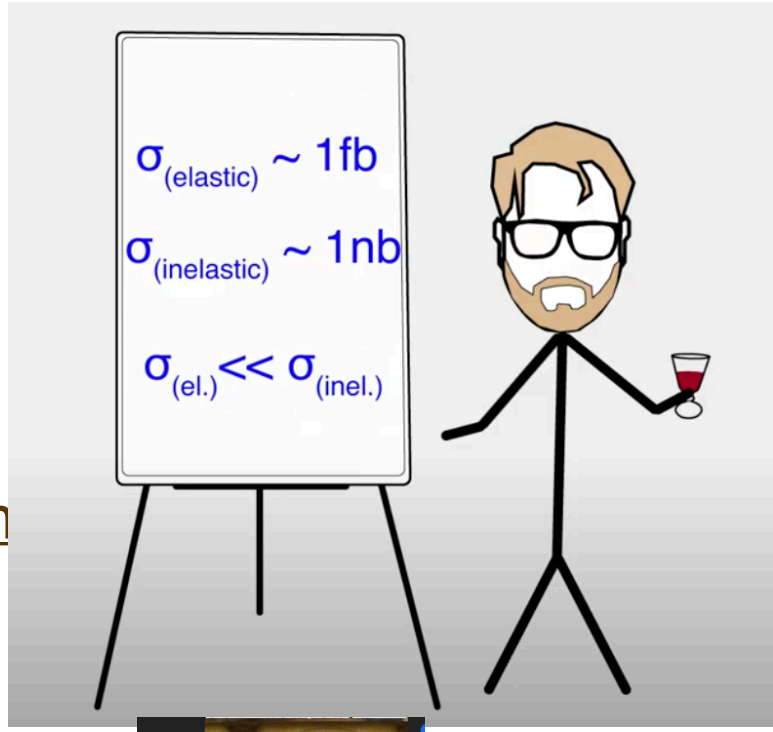
Theme: posters

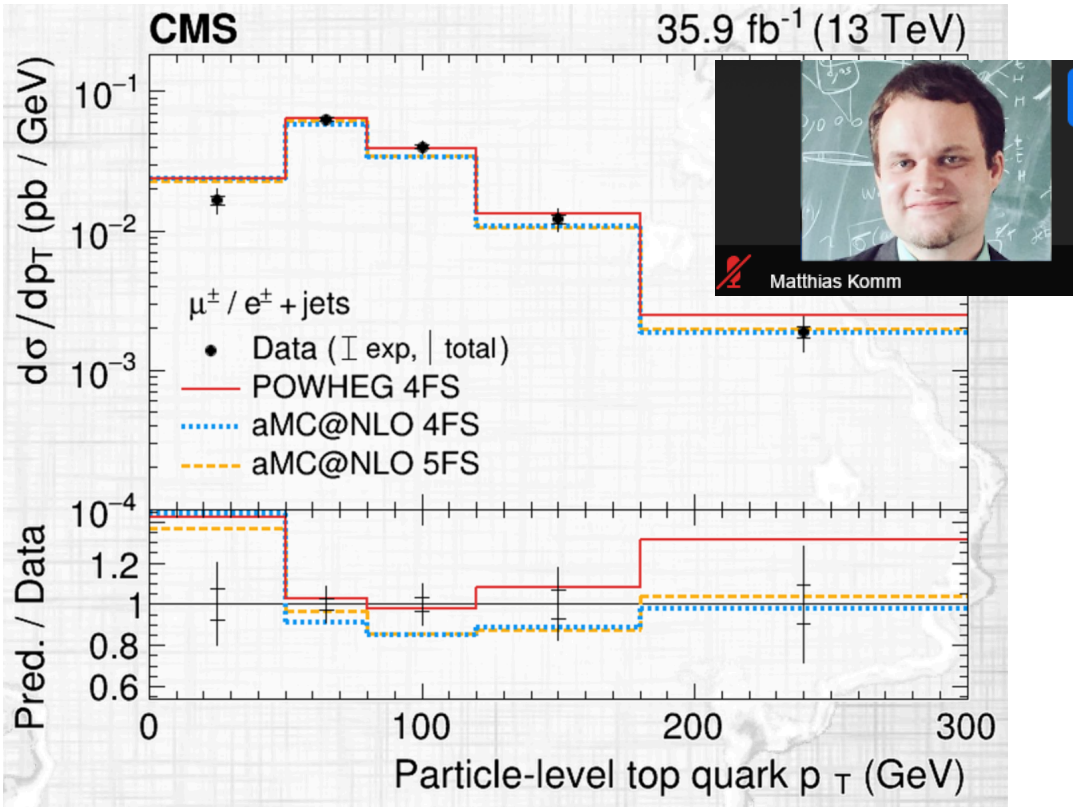
- Poster session had 9 posters (same # as last year)
  - All high-quality
  - If you haven't made a video yet, make one, then upload to youtube!
- Appetizers and drinks at home

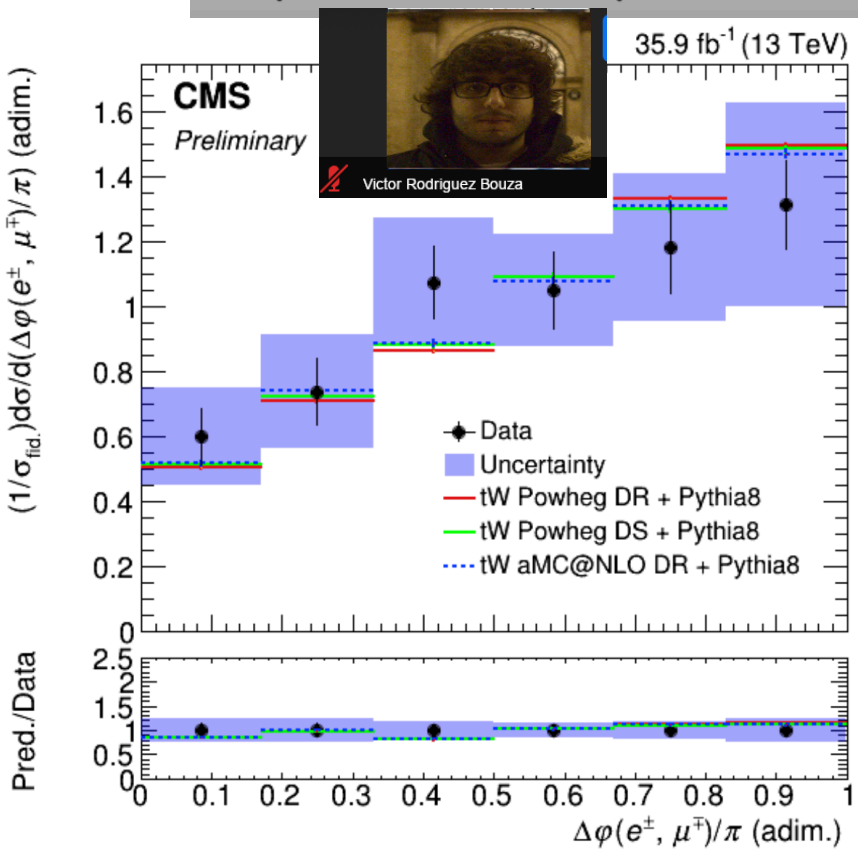
Posters

- Elastic top production virtual poster (Jay Howarth)

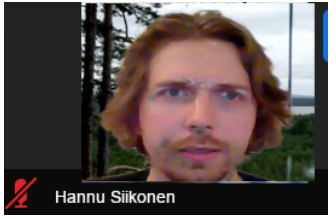
  https://www.youtube.com/watch?v=9VB4nFd7LRo
- Single top at CMS
  - T-channel (incl, diff, R) by Matthias Komm
  - tW by Victor Bouza





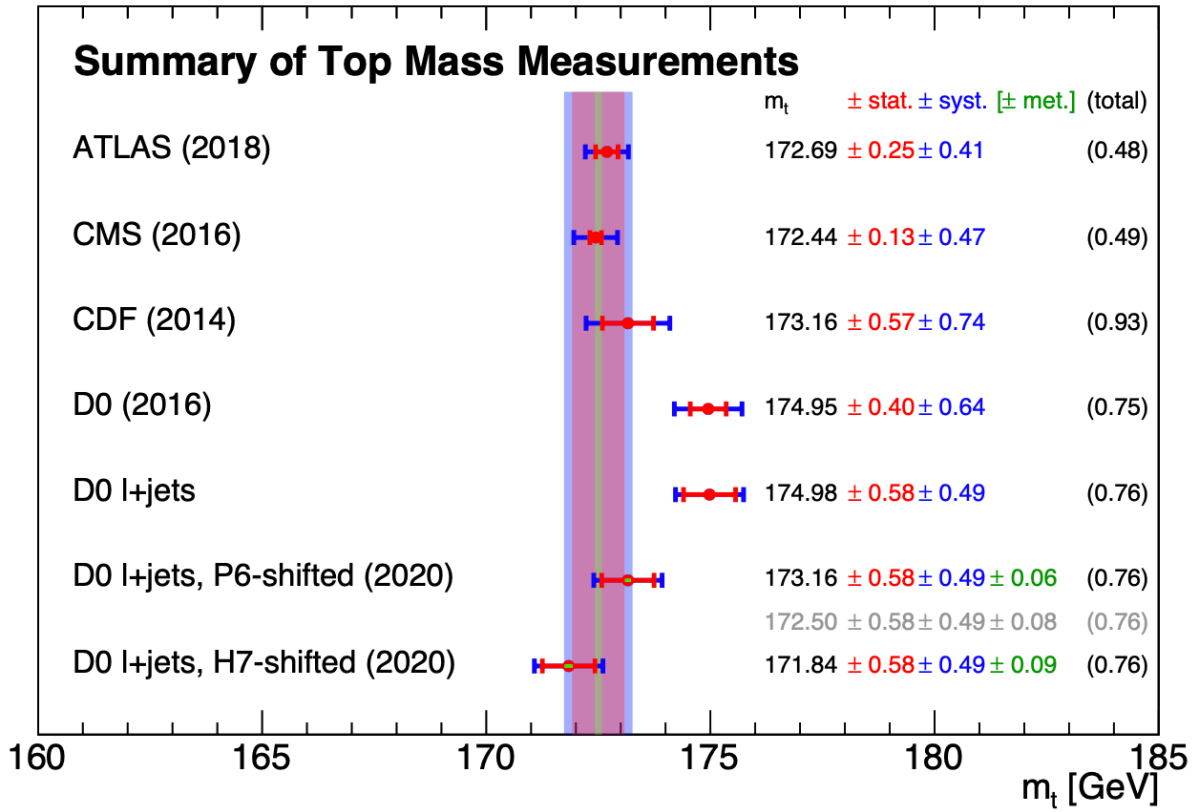


Posters



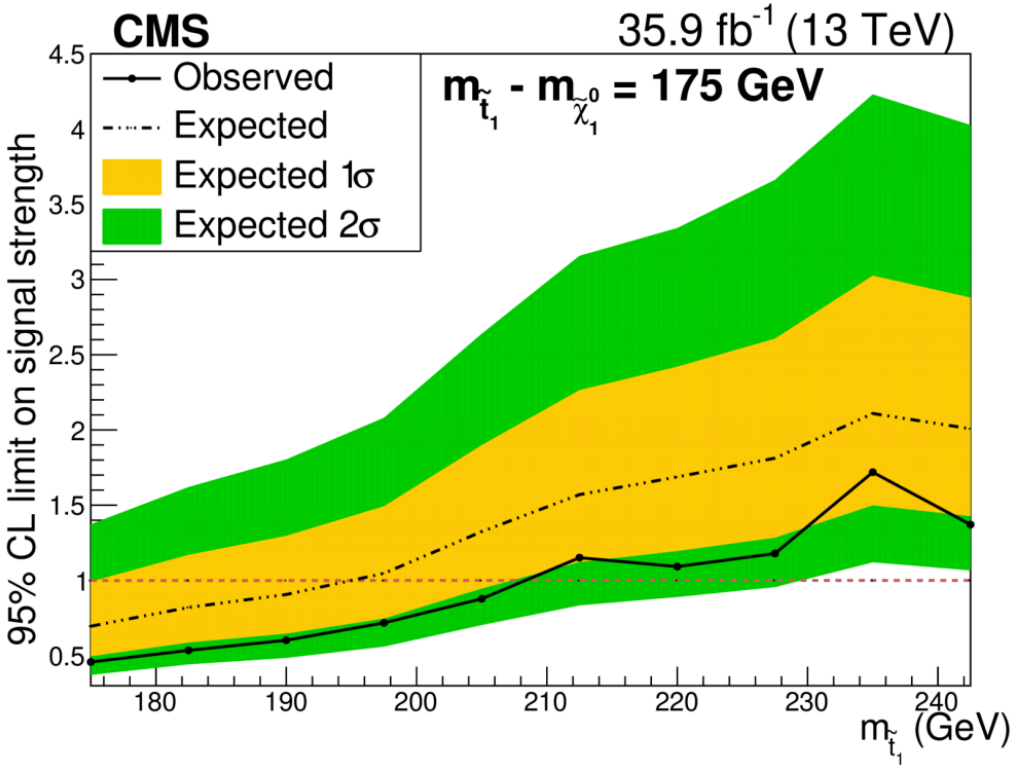
- Re-analysis of D0 JES and its impact on D0 top mass (Hannu Siikonen)
  - Tevatron top mass measurements are still important
  - Statement from D0 at

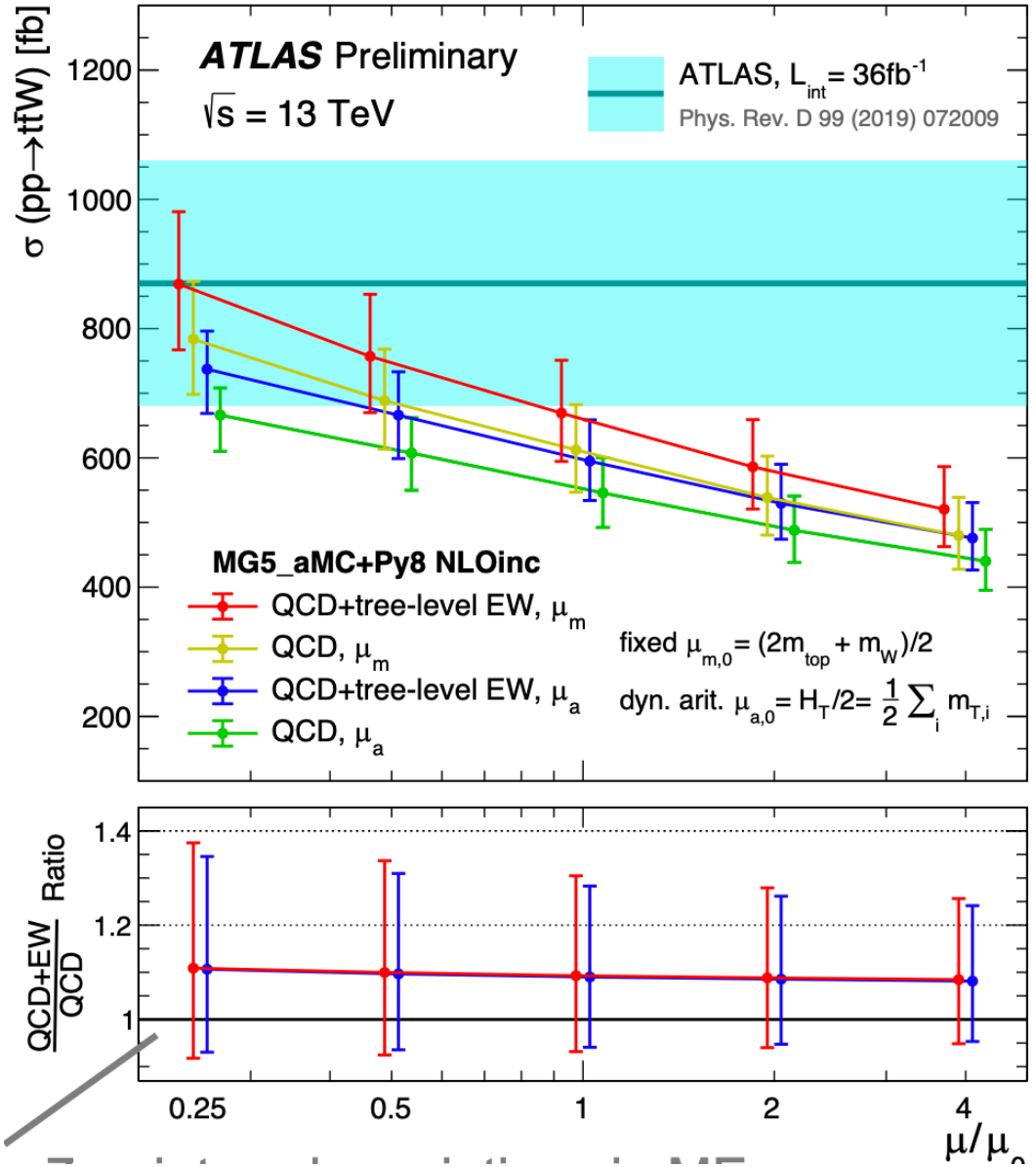
    https://www-d0.fnal.gov/Run2Physics/WWW/results/final/TOP/T14E/D0_statement_top_mass.pdf
    - "We do not confirm the conclusions"
    - Some differences in event selection, details of correction factors
    - Some cuts were hard-coded and not documented in each analysis internal note
    - JES plot that was used had work-in-progress central values



Posters

- ttW studies at ATLAS by Marcos Miralles Lopez
- Search for hidden stop with CMS by Andrea Fernandez





Top to the Extreme

- Top as a background in high-mass searches, Leonid Serkin
  - Top pT reweighting
  - Treat tt background uncorrelated bin-by-bin
- Searches with highly boosted tops, Titas Roy
  - B* search to tW all-hadronic

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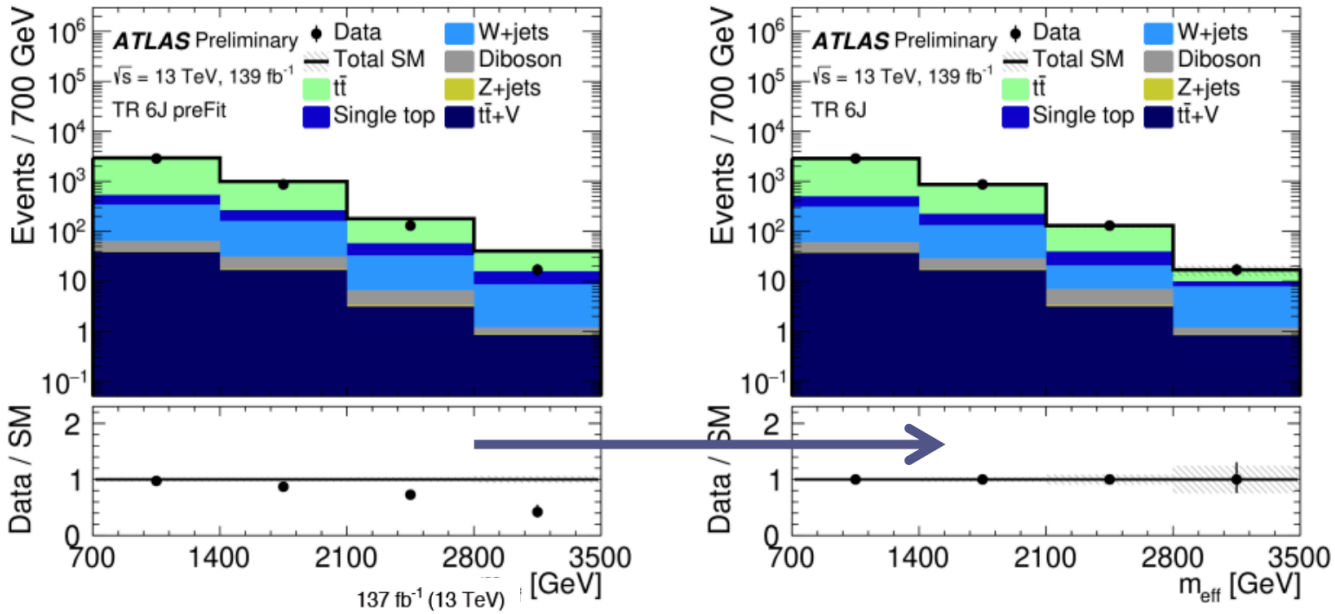

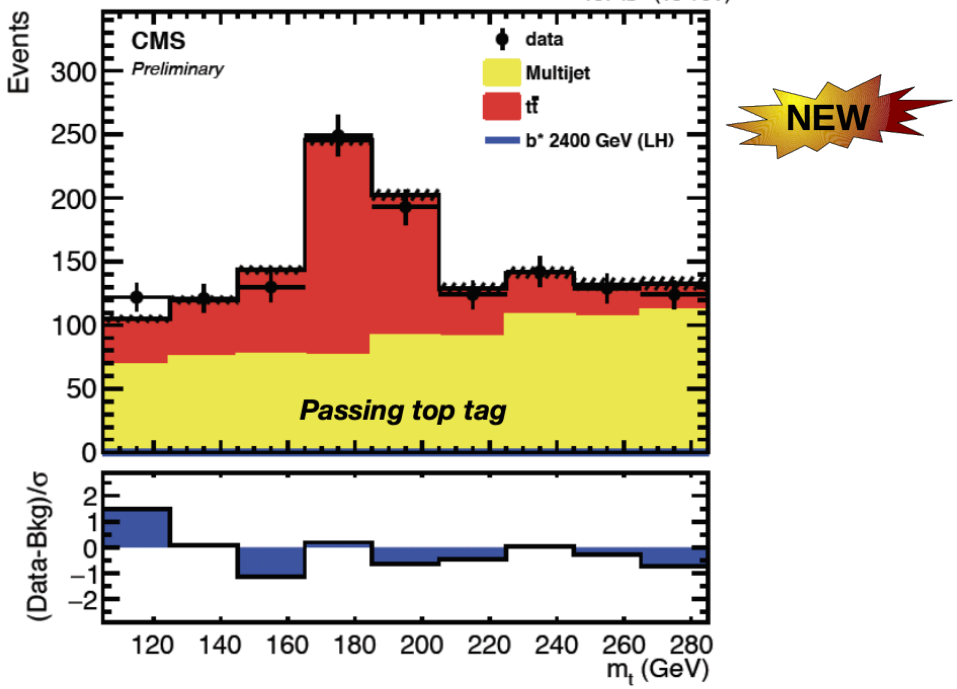

NEW

Conclusions

- Virtual top-quark workshop was a big success, over 150 people connected, lively discussions
  - Thanks for turning on video when talking and asking questions
  - Which of this year's features should we keep in future years?
- New ATLAS and CMS results, most with full Run 2 dataset
  - Still expect many more results with full Run 2 dataset
- Interpretations of measurements are just starting
  - By ATLAS and CMS, in global fits
  - EFT, BSM, SM parameters, PDFs, generator tuning, others
- Run 3 and HL-LHC are coming
  - Planning for future colliders (ee and hh)
  - Snowmass 21 EF03 https://snowmass21.org/energy/heavy_flavour

Conclusions

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  people connected, lively discussio
  - Thanks for turning on video when t
  - Which of this year's features should
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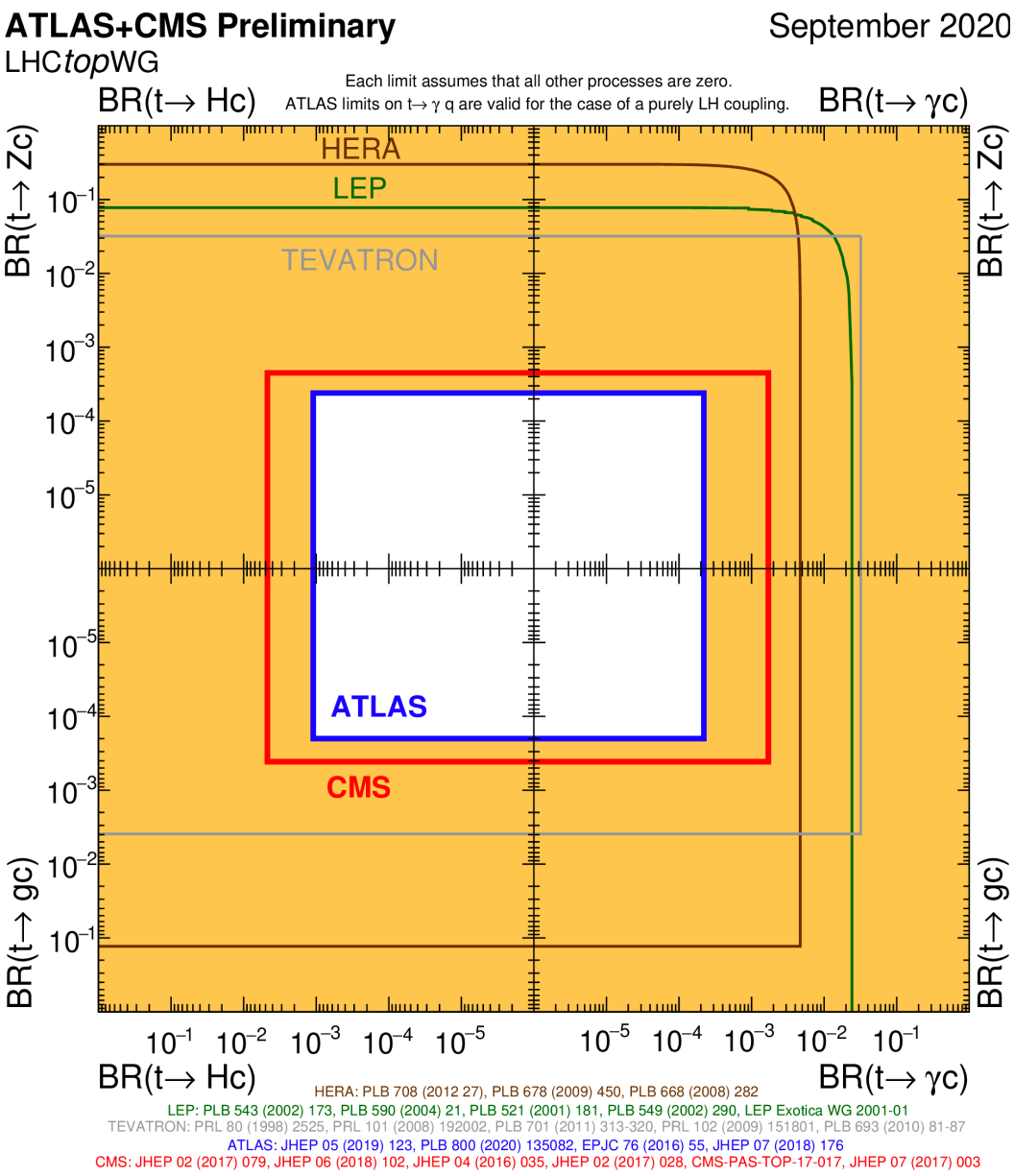
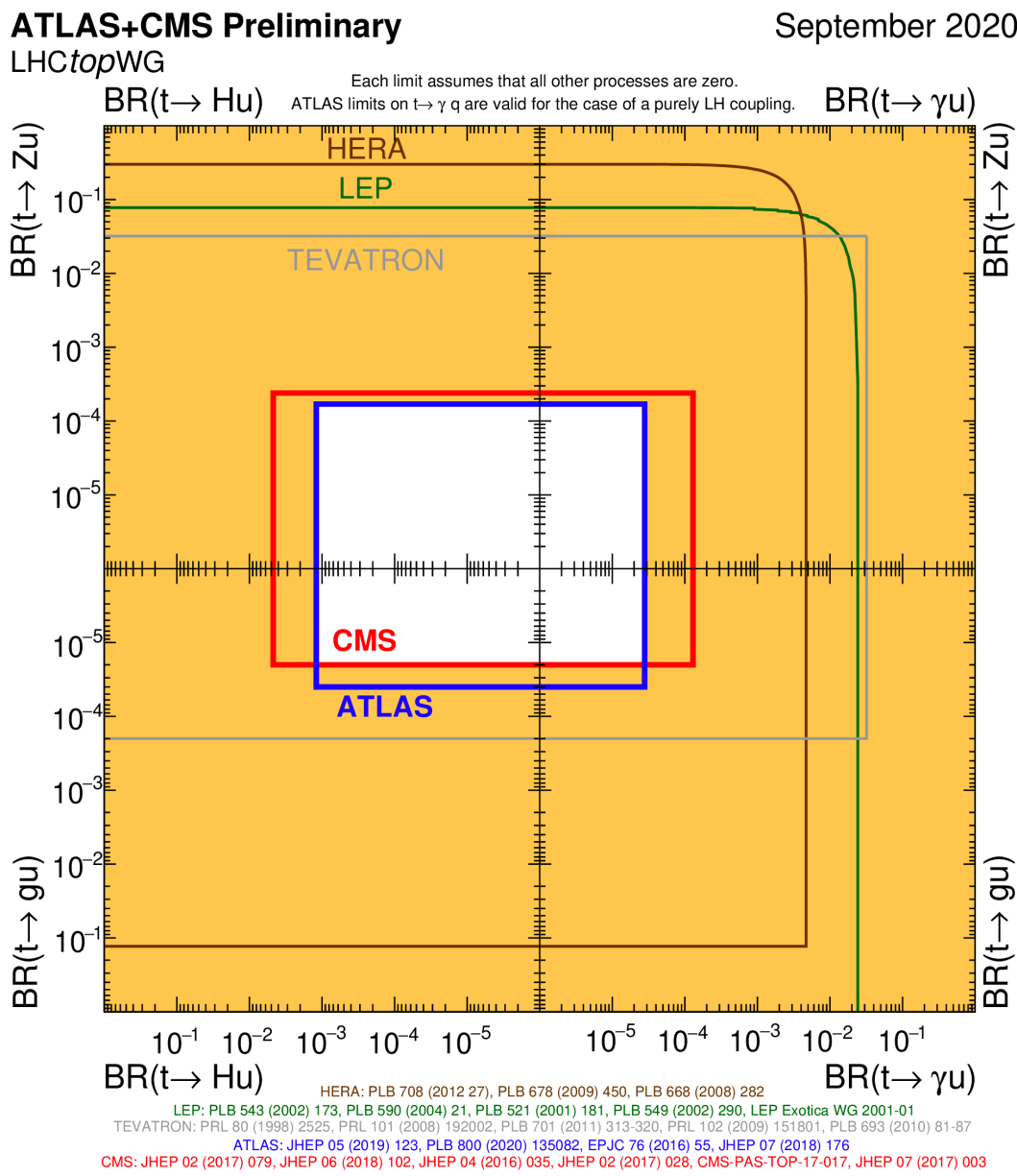
- Run 3 and HL-LHC are coming
  - Future colliders (ee and hh)
  - Snowmass 21

This is the golden age of top quark physics

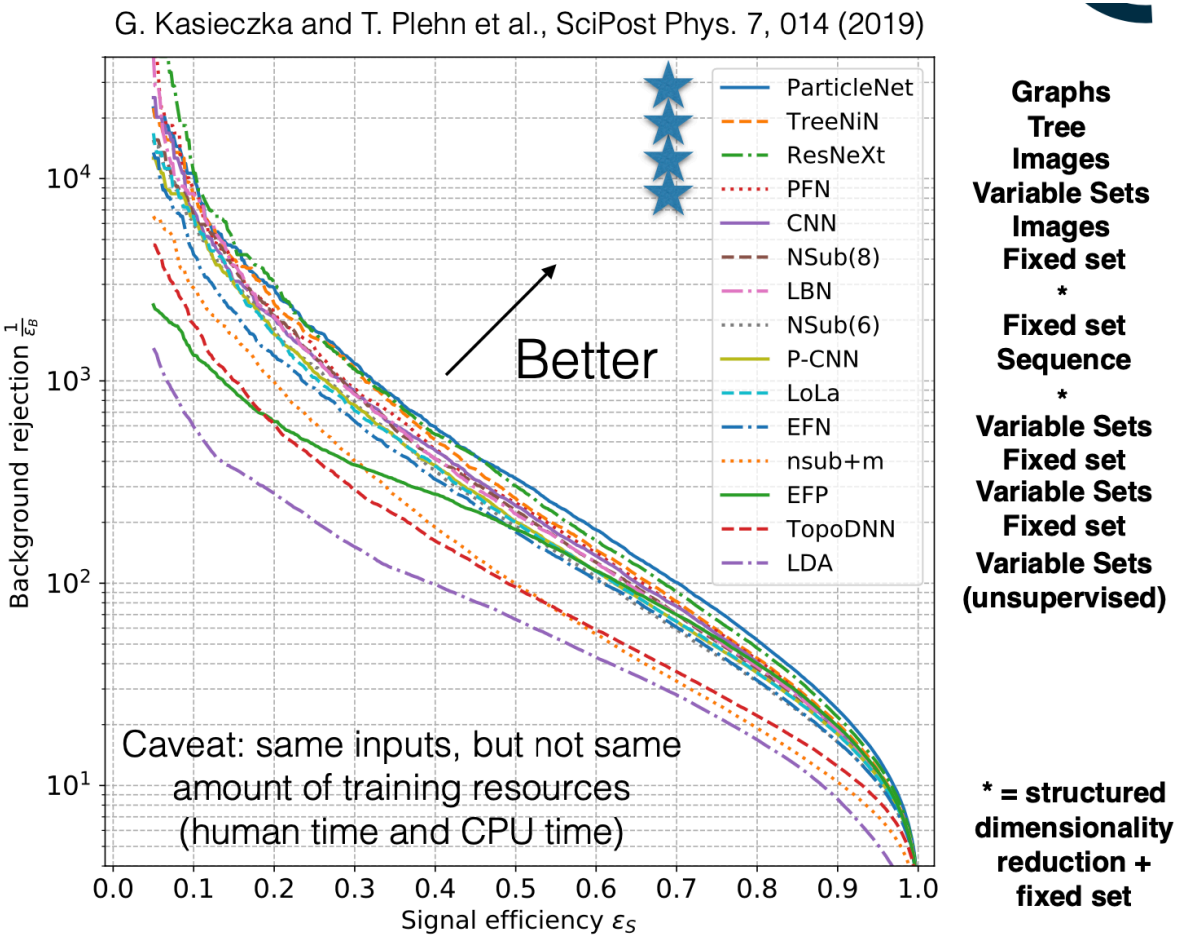
Additional material

Flavor-changing neutral currents



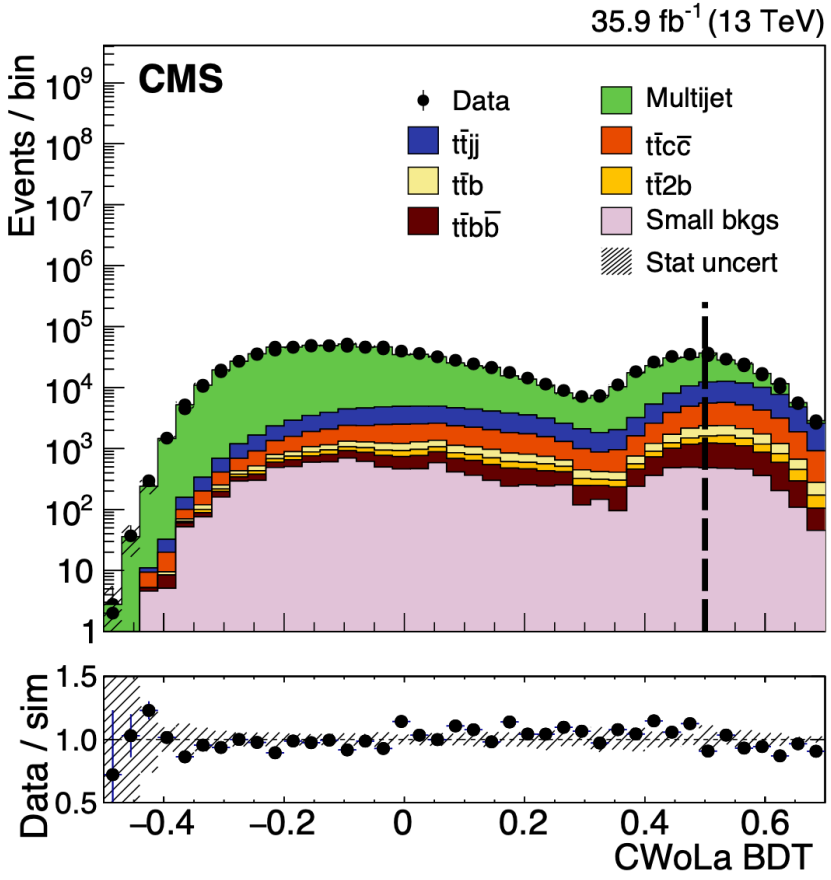


Modern machine learning



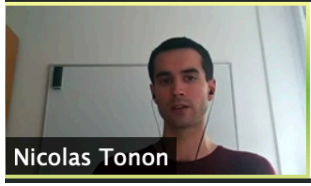
Graphs
Tree
Images
Variable Sets
Images
Fixed set
*
Fixed set
Sequence
*
Variable Sets
Fixed set
Variable Sets
Fixed set
Variable Sets
(unsupervised)

*** = structured dimensionality reduction + fixed set**



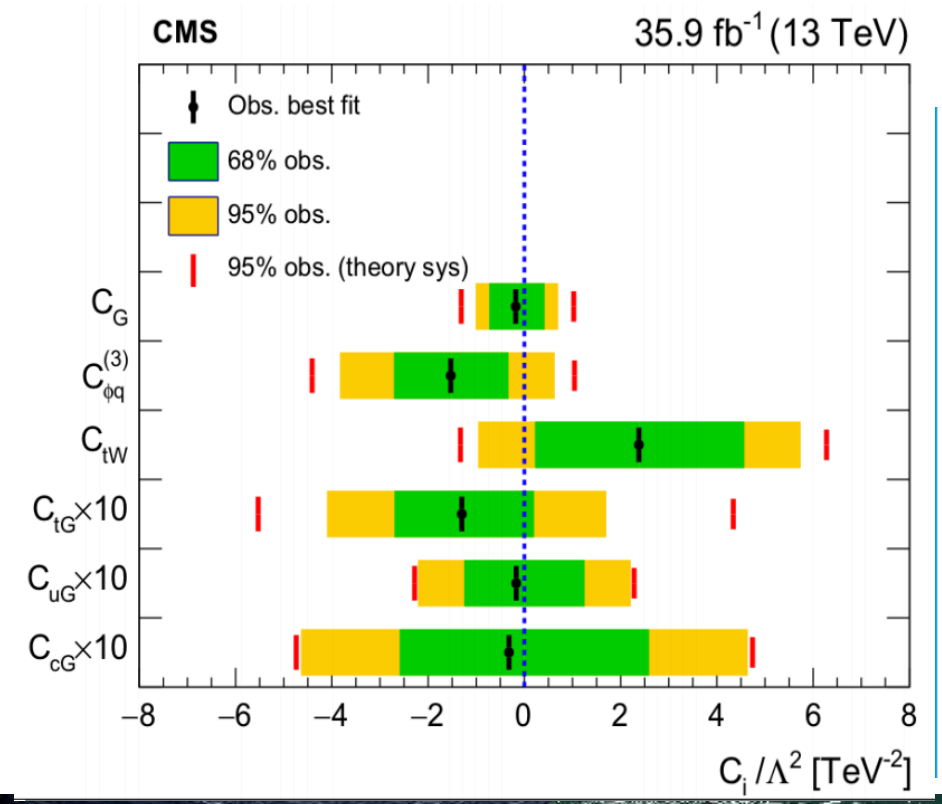
- Classifiers perform well when they are fully optimized on all of the available information
  - All calorimeter cells (pixels)
  - Sub-structure information

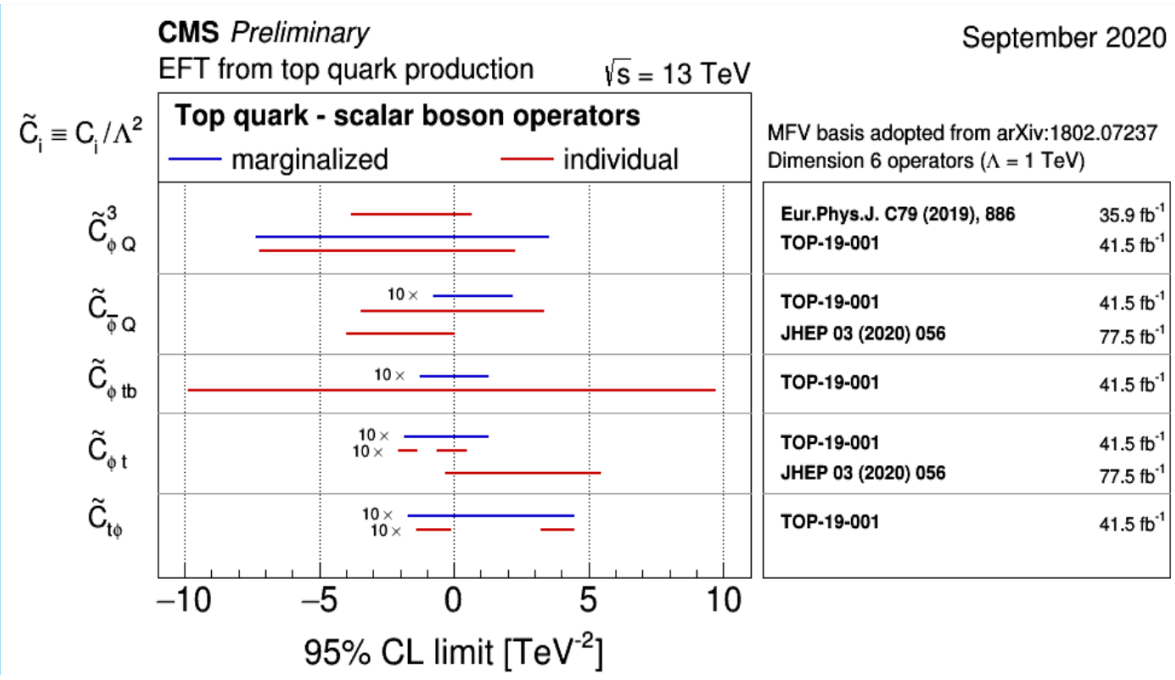
CMS EFT



- Use multiple approaches
  - EFT from cross-section
  - EFT from unfolded distributions
  - EFT from likelihood fits to detector-level data
  - Hybrid

Hybrid dilepton
Top pair and tW



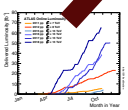


LHC collisions future

3,000 fb^{-1} by 2035
HL-LHC

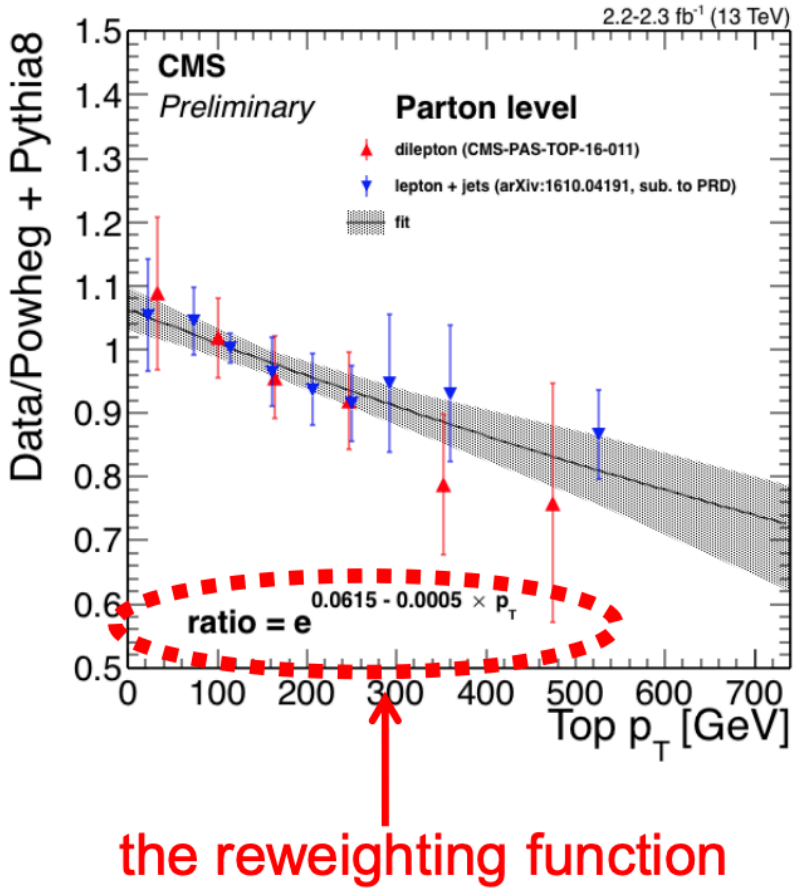
Twenty times the current dataset in 15 years

300 fb^{-1} by 2025



Top to the Extreme

- Top as a background in high-mass searches, Leonid Serkin
- Searches with highly boosted tops, Titas Roy



the reweighting function

Top p_T reweighting to data

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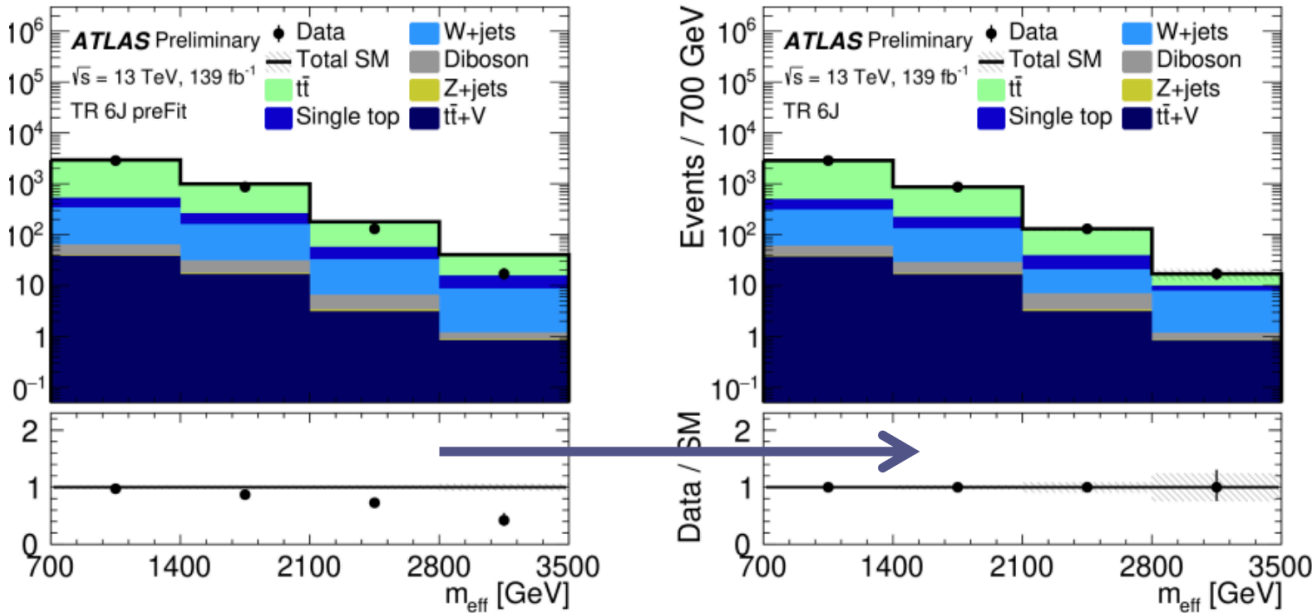

Treat top in each bin independently