# Top quark physics at run 3 opportunities and new ideas

- **Participants:**
  - Nicolas Tonon: experimental EFT
  - Frédéric Derue: experimental precision measurement
  - Tamara Vazquez Schroeder: experimental ttH
  - Gauthier Durieux: theory EFT
  - Giacomo Cacciapaglia: theory BSM
  - Frédéric Déliot: chair
  - **you**

# new ideas in precision measurements

- improve systematics
  - perform specific measurements to constrain the modeling
  - combined/profile fit when when performing a precision measurement

# Precision, measurement, exploration

**Precision**

Top mass precision (< 0.5 GeV) - new record

W mass (19 MeV), $sin^2\theta_{eff}$ (1.5‰) approaching records

2-3% unc. for W/Z/$t\bar{t}$ inclusive σ, focus on multi-dim. differential

Lepton universality τ-μ (1%) - new record

Charge, forward-backward asymmetries, polarization, spin-correlation

**Measurement**

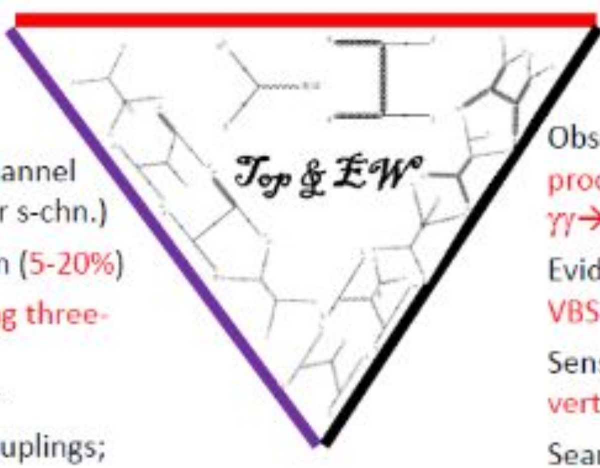
Diboson σ precision (5%)

Single top σ precision (t-channel 7%, Wt – 10%, evidence for s-chn.)

VBF V, tt+γ/W/Z σ precision (5-20%)

Record precision in studying three-body vertices

→ high energy behavior of anomalous triple-boson couplings; CKM $|V_{tb}|$ (5%)




**Exploration**

Observation of rare VBS processes (WW, WZ, ZZ, Wγ) γγ→WW, tZq, tri-bosons

Evidence for rare four-top, VBS Zγ processes

Sensitivity in four-body vertices

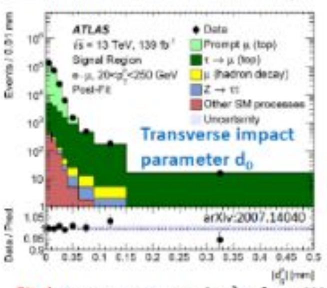
Searched for rare decays, top FCNCs

Y. Wu, La Thuile 2021

# Utilize $t\bar{t}$ precision

Large dataset, detailed work, and deployment of novel methods leads
to unprecedented precisionin both traditionaland explorationchannels

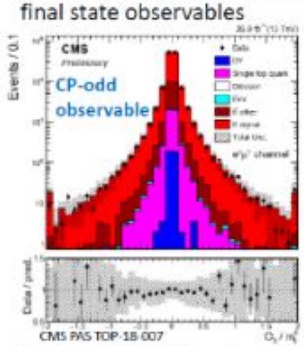
lepton universality meets standard candle and novelty ★




Fit $d_0$ to separate $\mu$ and $\tau \to \mu$ from Ws
→ $R(\tau/\mu)=0.992$ with 1% precision

Record precision surpassing LEP
(was 2% error, 2.7σ away from unity)

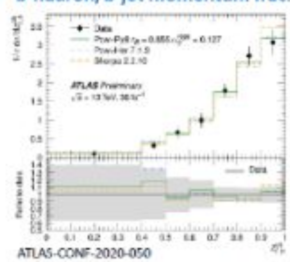
Probe CP violation in Top via final state observables




No sign of CP violation observed with per-mille precision, constraint on chromoelectric dipole moment

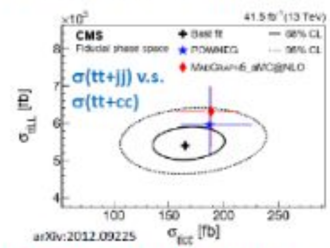
Ideal sample to study b-jet fragmentation

b-hadron/b-jet momentum frac.




Multiple sensitive variables unfolded, complementary to $e^+e^-$ measurements

Extremity test of QCD and Importance to Higgs physics with $t\bar{t}$ and jets




$t\bar{t}$+cc measured for the first time with dilepton, key is success tagging of all jet flavors

$t\bar{t}$+jj/bb was measured with record precision 10%

JHEP 07 (2020) 125

Y. Wu, La Thuile 2021

LHC = precision laboratory for top quark (and decay products)

- measurements of top properties → investigation of SM & BSM
- several results still stat-limited → can improve easily already in Run-3 !
- bottleneck systematics from jets and signal modelling
- lots of work needed
  - to extract the maximum from our data
  - to refine our techniques towards HL-LHC

# Modelling uncertainties

- MC event generators are ubiquitous in LHC physics

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)

- And MC modelling uncertainties already a limiting factor for most measurement and searches involving top-quarks

| *Modeling uncertainties* | | | | | |
|---|---|---|---|---|---|
| JEC flavor (linear sum) | −0.35 | +0.1 | −0.31 | −0.34 | 0.0 |
| – light quarks (uds) | +0.10 | −0.1 | −0.01 | +0.07 | −0.1 |
| – charm | +0.03 | 0.0 | −0.01 | +0.02 | 0.0 |
| – bottom | −0.29 | 0.0 | −0.29 | −0.29 | 0.0 |
| – gluon | −0.19 | +0.2 | +0.03 | −0.13 | +0.2 |
| b jet modeling (quad. sum) | 0.09 | 0.0 | 0.09 | 0.09 | 0.0 |
| – b frag. Bowler–Lund | −0.07 | 0.0 | −0.07 | −0.07 | 0.0 |
| – b frag. Peterson | −0.05 | 0.0 | −0.04 | −0.05 | 0.0 |
| – semileptonic b hadron decays | −0.03 | 0.0 | −0.03 | −0.03 | 0.0 |
| PDF | 0.01 | 0.0 | 0.01 | 0.01 | 0.0 |
| Ren. and fact. scales | 0.05 | 0.0 | 0.04 | 0.04 | 0.0 |
| ME/PS matching | $+0.32 \pm 0.20$ | −0.3 | $-0.05 \pm 0.14$ | $+0.24 \pm 0.18$ | −0.2 |
| ISR PS scale | $+0.17 \pm 0.17$ | −0.2 | $+0.13 \pm 0.12$ | $+0.12 \pm 0.14$ | −0.1 |
| FSR PS scale | $+0.22 \pm 0.12$ | −0.2 | $+0.11 \pm 0.08$ | $+0.18 \pm 0.11$ | −0.1 |
| Top quark $p_T$ | +0.03 | 0.0 | +0.02 | +0.03 | 0.0 |
| Underlying event | $+0.16 \pm 0.19$ | −0.3 | $-0.07 \pm 0.14$ | $+0.10 \pm 0.17$ | −0.2 |
| Early resonance decays | $+0.02 \pm 0.28$ | +0.4 | $+0.38 \pm 0.19$ | $+0.13 \pm 0.24$ | +0.3 |
| CR modeling (max. shift) | $+0.41 \pm 0.29$ | −0.4 | $-0.43 \pm 0.20$ | $-0.36 \pm 0.25$ | −0.3 |
| – "gluon move" (ERD on) | $+0.41 \pm 0.29$ | −0.4 | $+0.10 \pm 0.20$ | $+0.32 \pm 0.25$ | −0.3 |
| – "QCD inspired" (ERD on) | $-0.32 \pm 0.29$ | −0.1 | $-0.43 \pm 0.20$ | $-0.36 \pm 0.25$ | −0.1 |
| Total systematic | 0.81 | 0.9 | 1.03 | 0.70 | 0.7 |
| Statistical (expected) | 0.21 | 0.2 | 0.16 | 0.20 | 0.1 |
| Total (expected) | 0.83 | 0.9 | 1.04 | 0.72 | 0.7 |

| Source | Unc. on $m_t$ [GeV] | Stat. precision [GeV] |
|---|---|---|
| Data statistics | 0.40 | |
| Signal and background model statistics | 0.16 | |
| Monte Carlo generator | 0.04 | ±0.07 |
| Parton shower and hadronisation | 0.07 | ±0.07 |
| Initial-state QCD radiation | 0.17 | ±0.07 |
| Parton shower $\alpha_s^{FSR}$ | 0.09 | ±0.04 |
| *b*-quark fragmentation | 0.19 | ±0.02 |
| HF-hadron production fractions | 0.11 | ±0.01 |
| HF-hadron decay modelling | 0.39 | ±0.01 |
| Underlying event | < 0.01 | ±0.02 |
| Colour reconnection | < 0.01 | ±0.02 |
| Choice of PDFs | 0.06 | ±0.01 |
| Total systematic uncertainty | 0.67 | ±0.04 |
| Total uncertainty | 0.78 | ±0.03 |

Need a long-term strategy to reduce them

S. Amoroso, Top 2020

# Modelling uncertainties

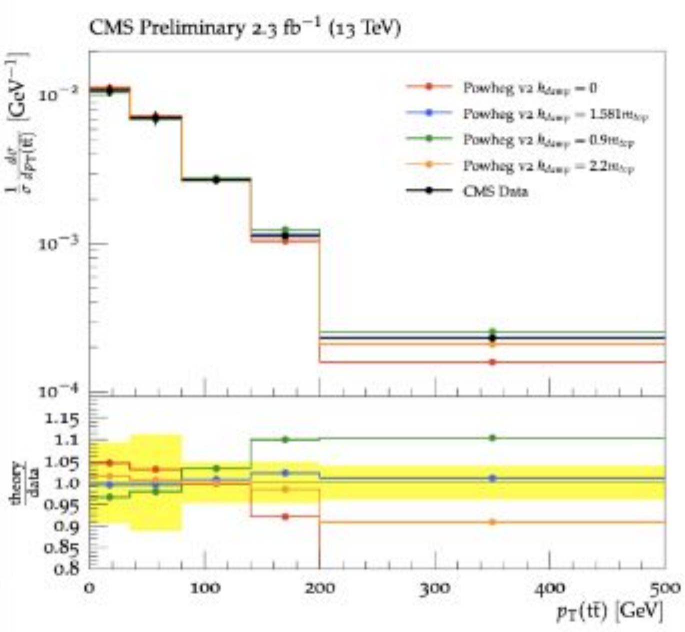
**CMS**

- Compared unfolded data to different hdamp values, tuned hdamp = 1.581$m_{top}$
- Uncertainty obtained by varying hdamp within $0.996m_{top} < hdamp < 2.239m_{top}$

**ATLAS***

The ISR uncertainty is decorrelated into different components:

1. Split in scale variations and alternative *hdamp* parameters
   - Tuned value of hdamp = 1.5$m_{top}$
   - Symmetrisation of hdamp = 3.0 $m_{top}$
2. Studied effect of correlating the HS scale variations with the PS tune
   - Envelope of the HS and PS independent variations gives larger uncertainty




*More details about this in Simone Amoroso's talk

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

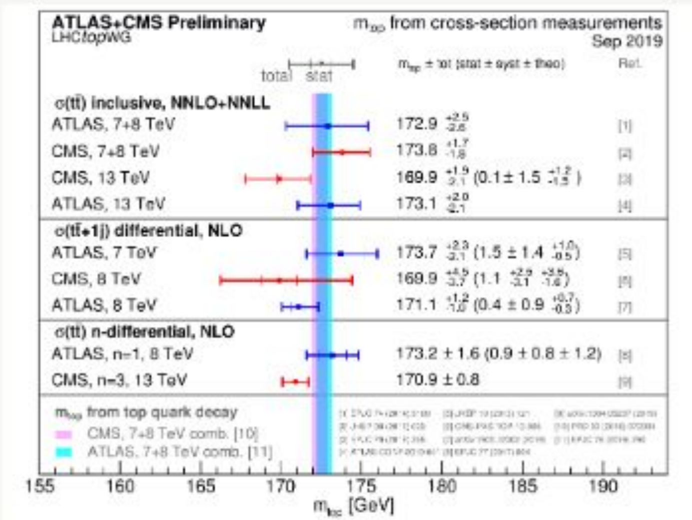
CMS parton shower tuning CMS PAS TOP-16-021

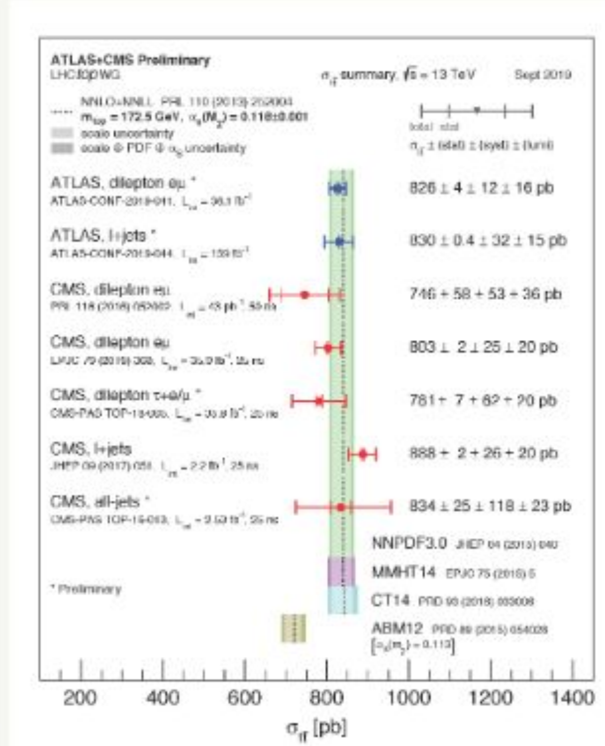
V. Vecchio, Top 2020

# To profile or not to profile

**Top precision measurements:**

- Differential and inclusive cross sections
  - Fiducial and full phase space
- SM parameters measurements




Also informations on the systematic uncertainties can be extracted from data (profiled) with the aim of reducing them. However, a general recipe for when to profile or not does not exist.

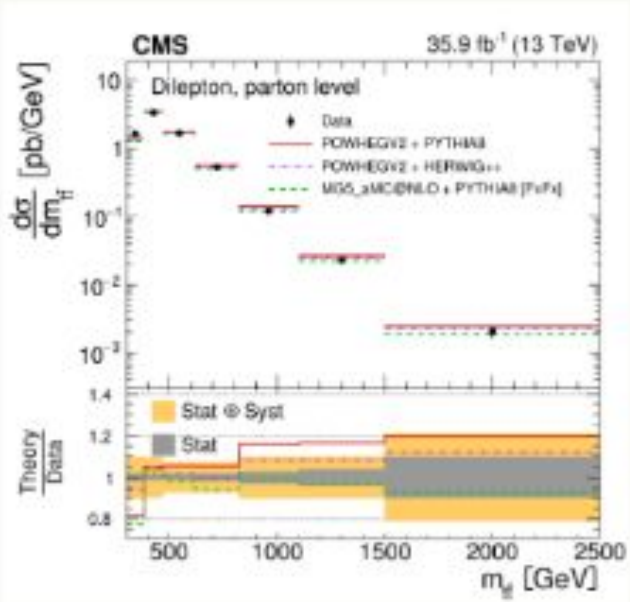
Uncertainties are **profiled** in:

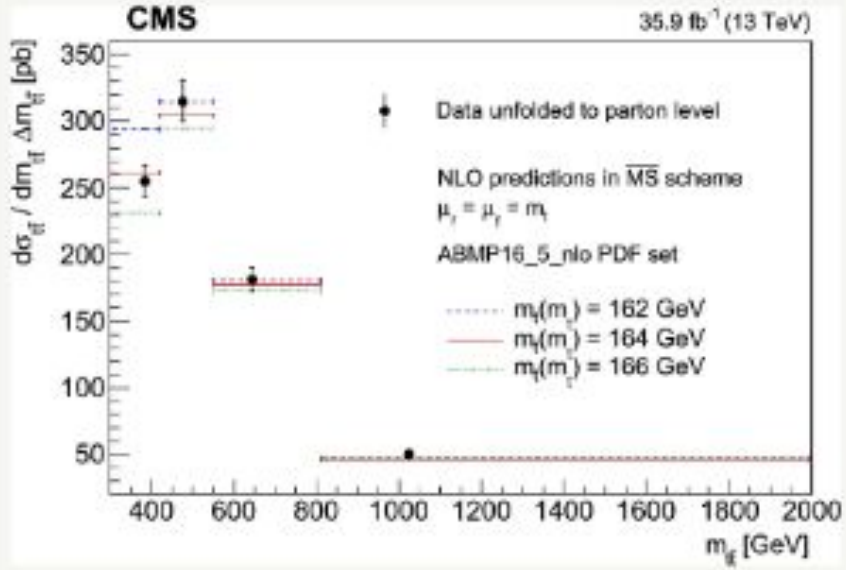
- **Inclusive** cross section measurements (see Olga Bessidskaia Bylund's talk)
- Rare processes and **properties** measurements

**Differential** cross section measurements usually **don't profile** their uncertainties

- First unfolded measurements with profiled uncertainties

# Combining profiling and unfolding




**CMS Maximum Likelihood Unfolding**

- The unfolding problem was found to be well-conditioned, and therefore no regularisation is needed
- Acceptance and efficiencies not free parameters
- Improved uncertainty on unfolded m(tt) thanks uncertainty profiling

**Profiling results**

| M(tt) bin | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Total Uncert | +4.7 -4.4 | +5.0 - 4.8 | +5.0 - 4.8 | +7.2 -6.9 |

CMS dilepton differential + running mass Phys. Lett. B 803 (2020) 135263

CMS dilepton differential JHEP 02 (2019) 149

# new ideas in EFT/BSM

From Nicolas' talk:

- EFT interpretations are becoming frequent in t(t)+X analyses
- Shifting from reinterpretations of inclusive → differential measurements Expect more and more direct EFT measurements in future
- Rares top quark processes (tX, tttt, ... ) a crucial component of EFT searches

- More studies needed : include EFT effects in top decay, validate/use new NLO models, etc.
- Simultaneous fits to multiple processes & operators ↔ Physics-driven approach. Simulation & fits more challenging ! Important to gain experience now
- Make maximal use of available information (→ differential, machine-learning, MEM, etc.)
- Ambitious objective : global fit in the top quark sector through combinations between…
  - analyses → orthogonal event selections, unified statistical framework, etc.
  - experiments → common procedures/assumptions (cf.TopLHCWG), etc.

# new ideas in EFT/BSM

- From Giaccomo’s talk:
    - Top decays to non-SM light states.
    - Can SM cross sections constrain top partners? tt+XX...
    - Multi-top production interpretations: are we being complete and inclusive?
    - Any connection between top and lepton universality violation? (RK)

# new ideas in ttH

- From Tamara's talk:
  - improving ttbb background modelling: joint Atlas/CMS theory effort, replace 2 points systematics, learning from SM measurements, making ttH more robust against ttbb
  - improving ttW measurement at high jet multiplicity: EFT measurements of $t\bar{t}$+X in multilepton final states
  - Future of STXS $t\bar{t}$H measurement: combination intra/inter collaboration
  - Other ways of measuring the top Yukawa coupling: 4top (no assumptions on total Higgs width), ttbar cross section