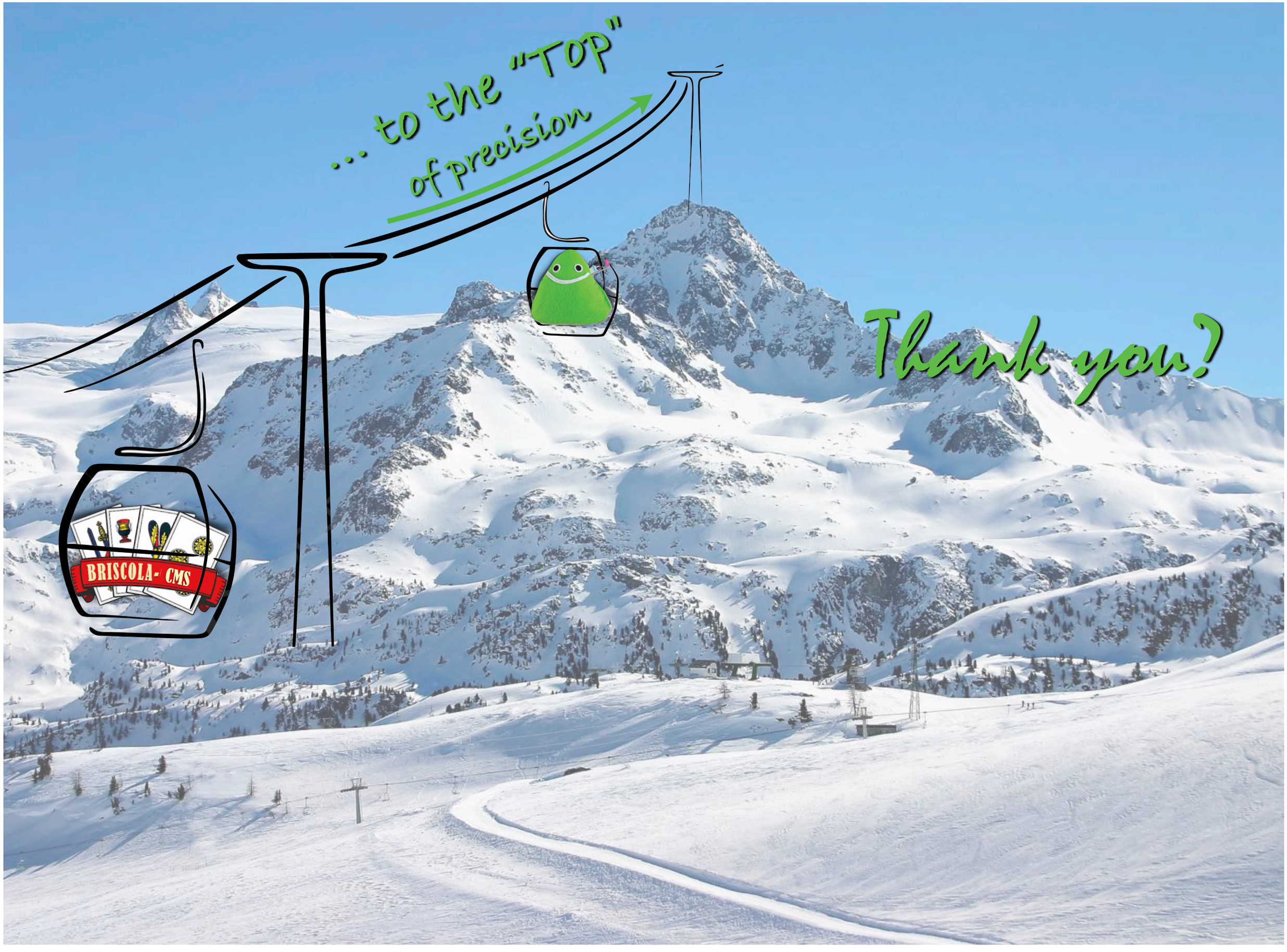
t(t)+X cross section measurements at ATLAS and CMS

Deborah Pinna

on behalf of the *ATLAS and CMS Collaborations*

Moriond EWK 2025

La Thuile, 23-30 March


... to the "Top"
of precision
Thank you?
BRISCOLA - CMS

The "Top" of precision measurements at LHC

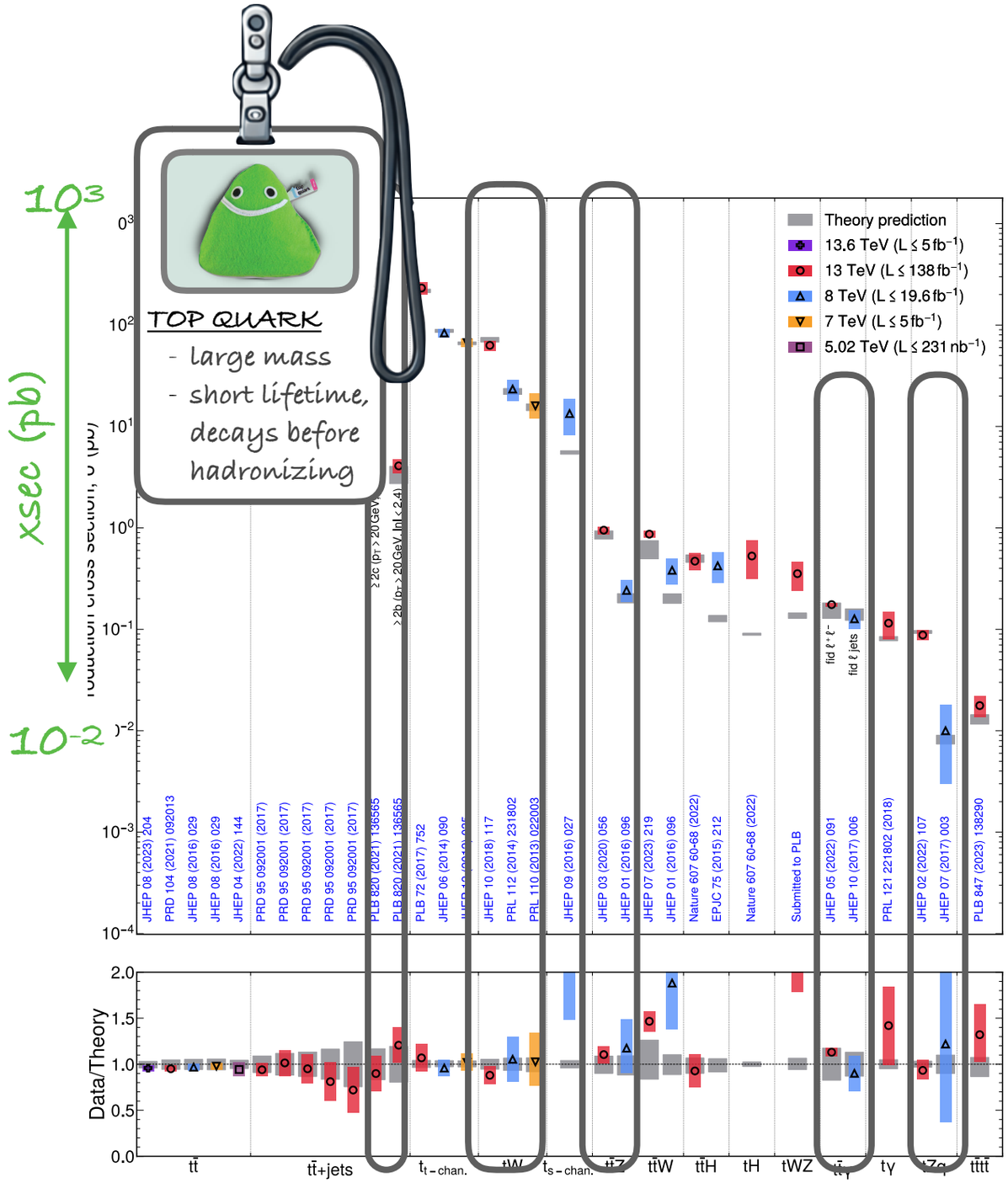
t(t)+X rare processes

- accessible with larger data samples from Run2 → entering the precision era

- Direct probe for SM precision measurements
  - powerful probes of EW and QCD sectors

- Probe for BSM physics
  - differential distributions enhance sensitivity to BSM

- Significant bkg for several SM and BSM studies



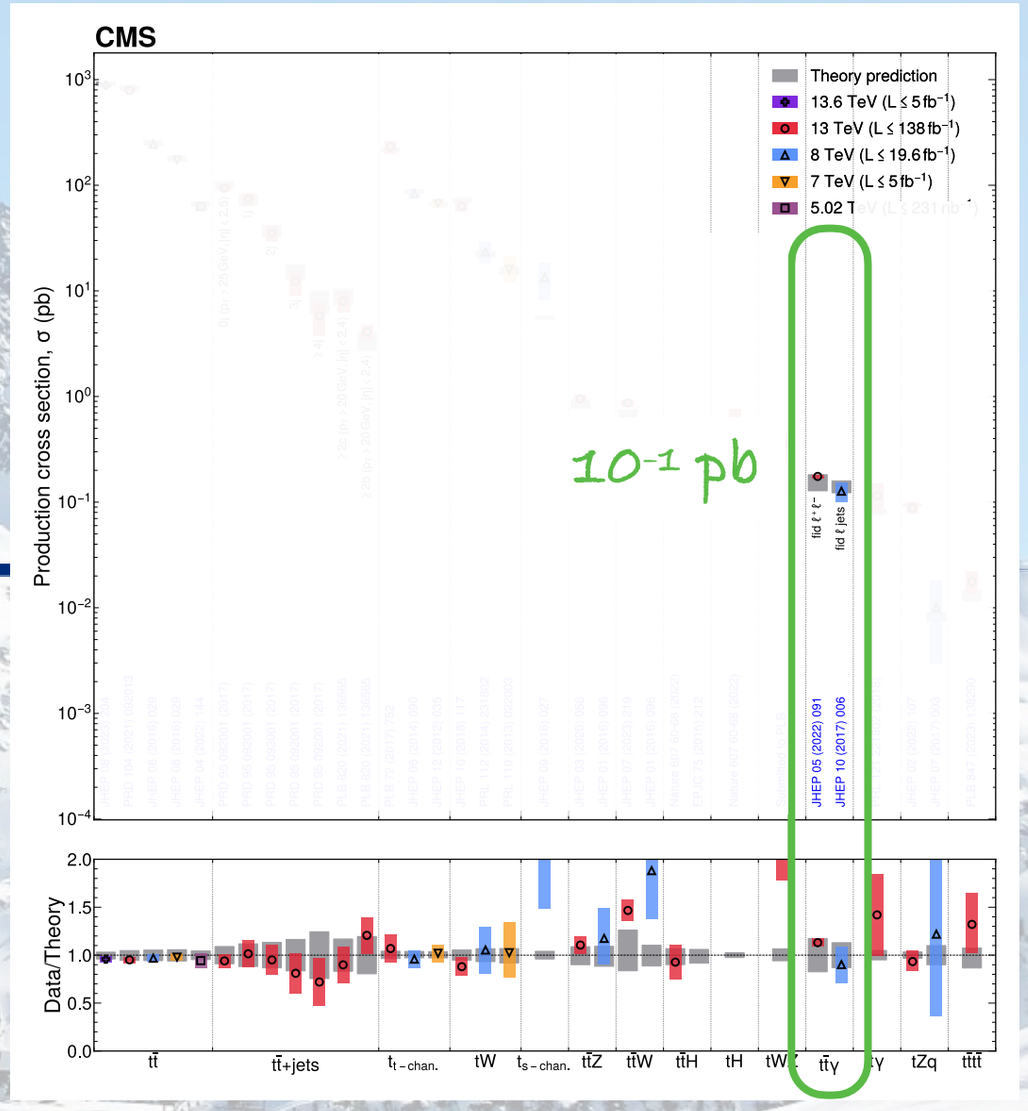
NEW ITEM

tt+W differential xsec measurement at CMS in YSF (David Marcus)

$tt+\gamma$

* Direct probe for SM precision measurements:
  - improving precision of inclusive and differential xsec measurements
  - predictions of t-γ EWK coupling

* Indirect probe for BSM physics:
  - sensitive to top anomalous dipole moments couplings
  - EFT interpretations



ATLAS EXPERIMENT JHEP 10 (2024) 191

CMS CMS-PAS-TOP-23-002

* selected most recent results

$tt+\gamma$: inclusive and differential cross sections

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CMS-PAS-TOP-23-002

1. Selection:

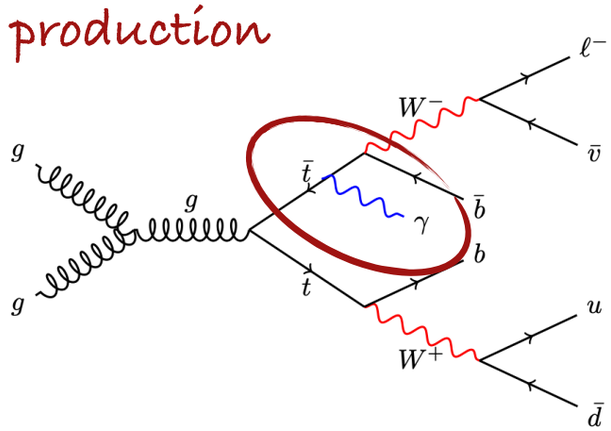
1l

- 1 photon
- 1 leptons: e or μ
- ≥ 4 jets
- ≥ 1 b-tagged jets

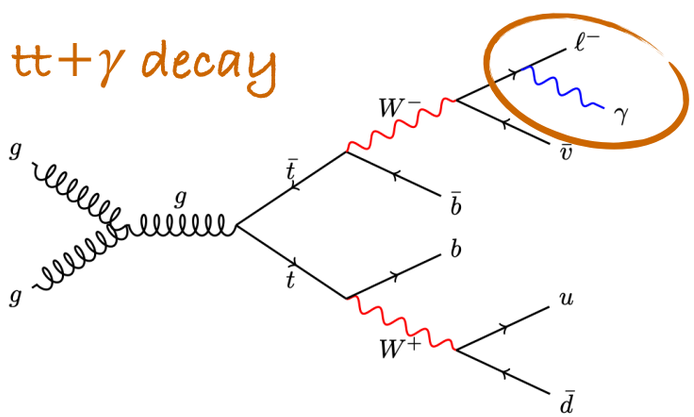
2l

- 1 photon
- 2 leptons: opp. charge e,μ
- ≥ 1 jet or ≥ 2 jets
- ≥ 1 b-tagged jets

$tt+\gamma$ production



$tt+\gamma$ decay



2. Bkg:

- main bkg from **$tt+\gamma$ decay**
- **fake photons** contribution from data-driven method
- **NN classification:** multi-class in 1l and binary in 2l

$tt+\gamma$: inclusive and differential cross sections

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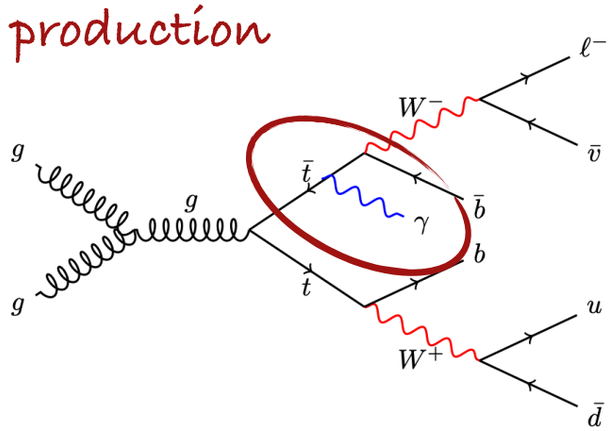
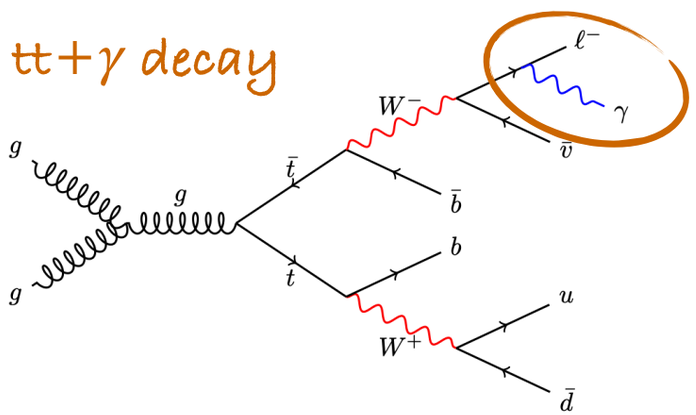
$tt+\gamma$ production



$tt+\gamma$ decay



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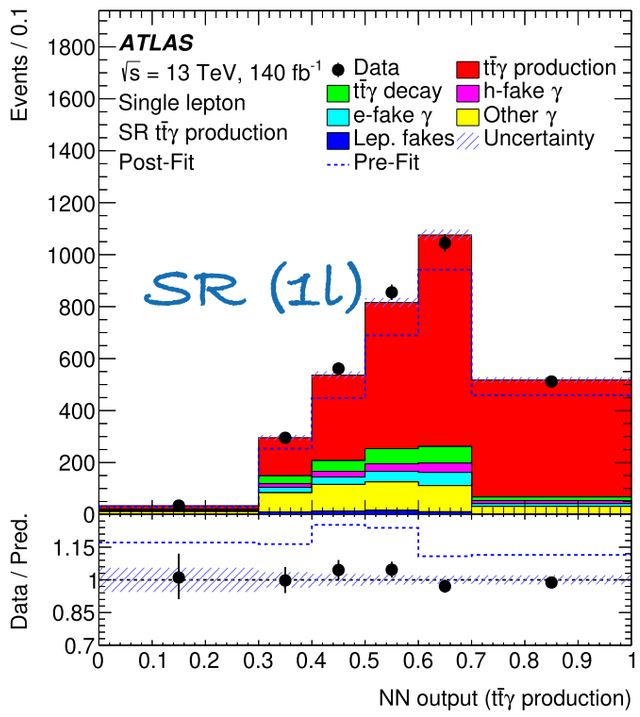

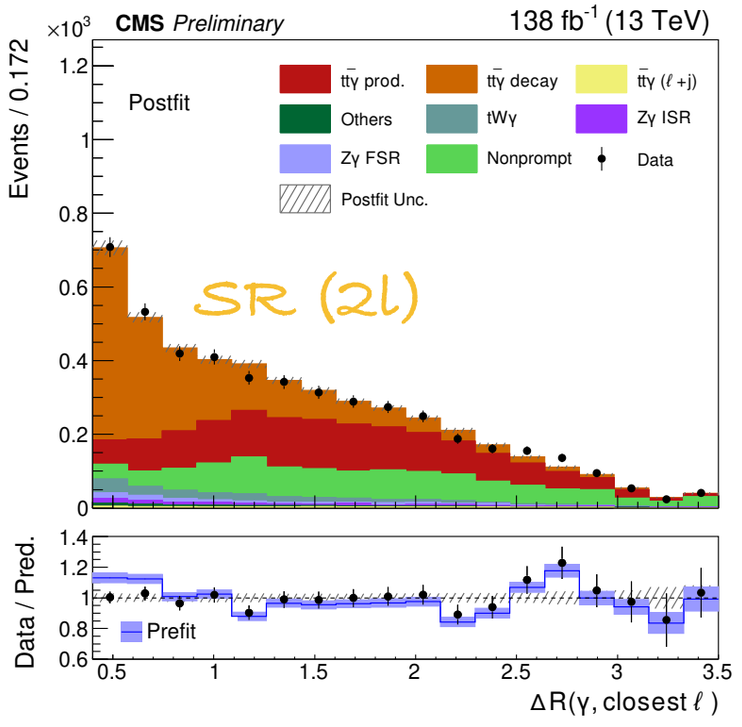

$tt+\gamma$: inclusive and differential cross sections

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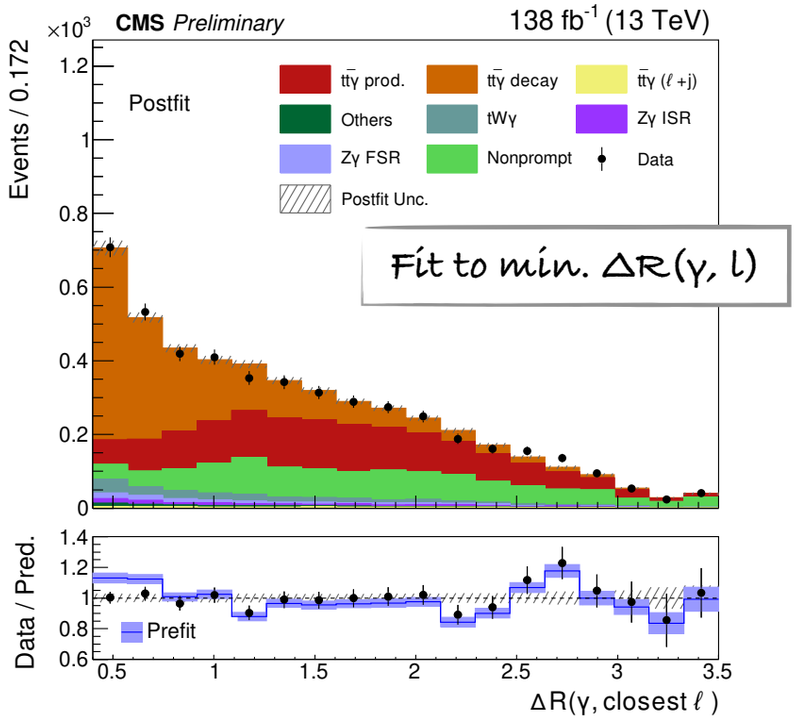
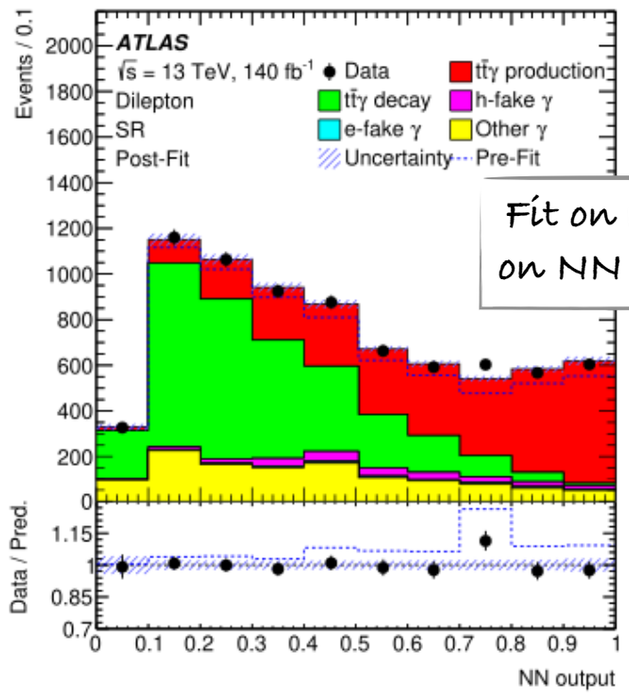
3. Results: $tt+\gamma$ cross sections for production and decay

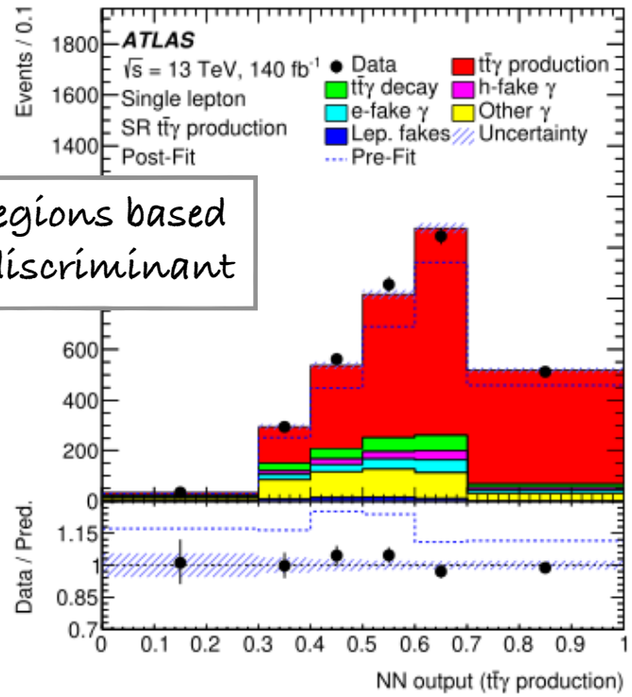


Fit to min. $\Delta R(\gamma, l)$

2l



1l



Fit on regions based on NN discriminant

	2l	1l
*prod+decay	134±7(syst)±3(stat) fb	704±49(syst)±5(stat) fb	116.1±8(syst)±1.7(stat) fb
*prod	54±4(syst)±2(stat) fb	288±20(syst)±5(stat) fb	45.7±3(syst)±1.4(stat) fb

- First measurements of $tt+\gamma$ production separate from $tt+\gamma$ decay
- In agreement within unc with NLO predictions
- Reaching precisions of current best theoretical predictions

$tt+\gamma$: inclusive and differential cross sections

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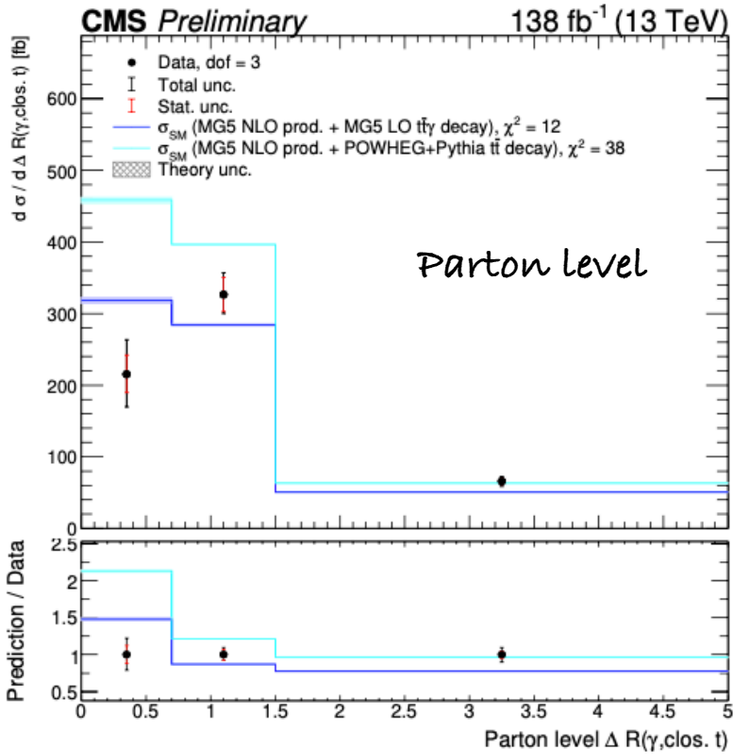
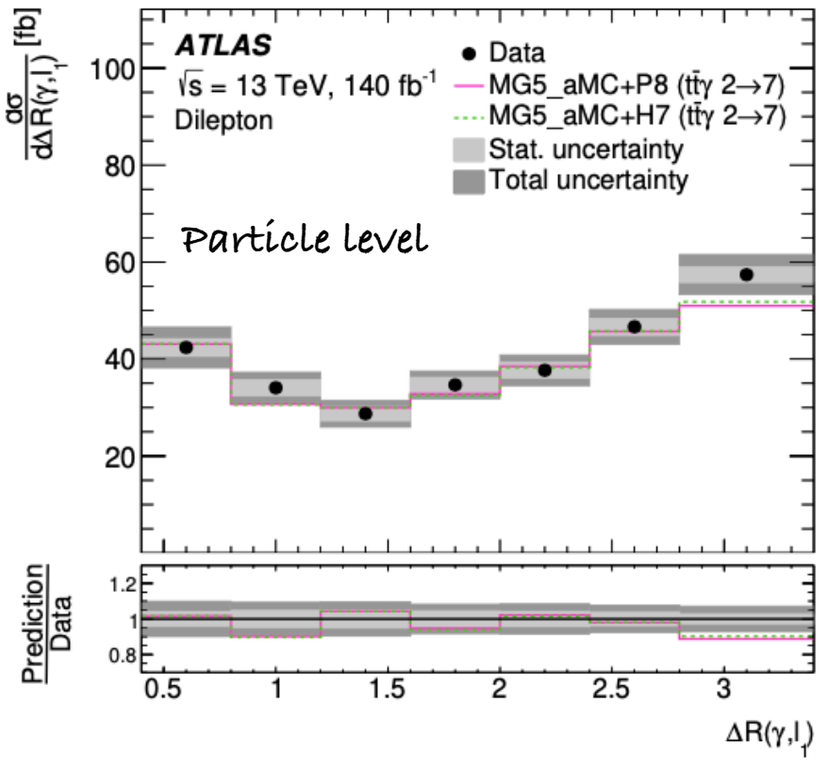
- **3. Results:** $tt+\gamma$ normalized and absolute differential cross sections for production+decay for various variables

top/tt var measured for first time in $tt+\gamma$



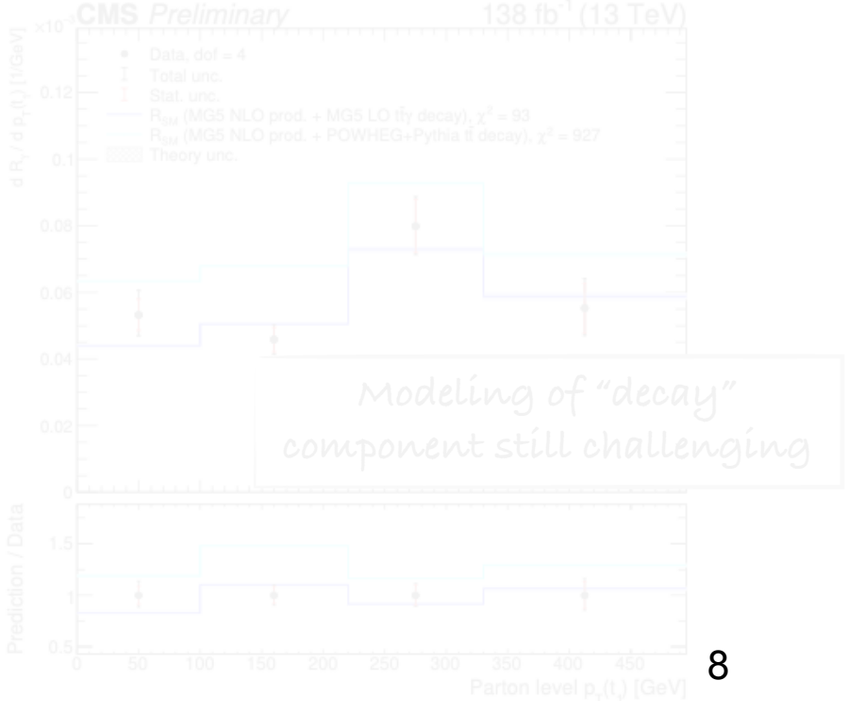


- $tt+\gamma/tt$ xsec ratio, allows achieving higher precision

$$R = \frac{\sigma_{t\bar{t},1\gamma}}{\sigma_{t\bar{t},0\gamma} + \sigma_{t\bar{t},1\gamma}}$$

- measured $R = 0.0125 \pm 0.0005(\text{syst}) \pm 0.0002(\text{stat})$

- Measured for first time, inclusively and differentially!
- In agreement with nominal predictions from simulation



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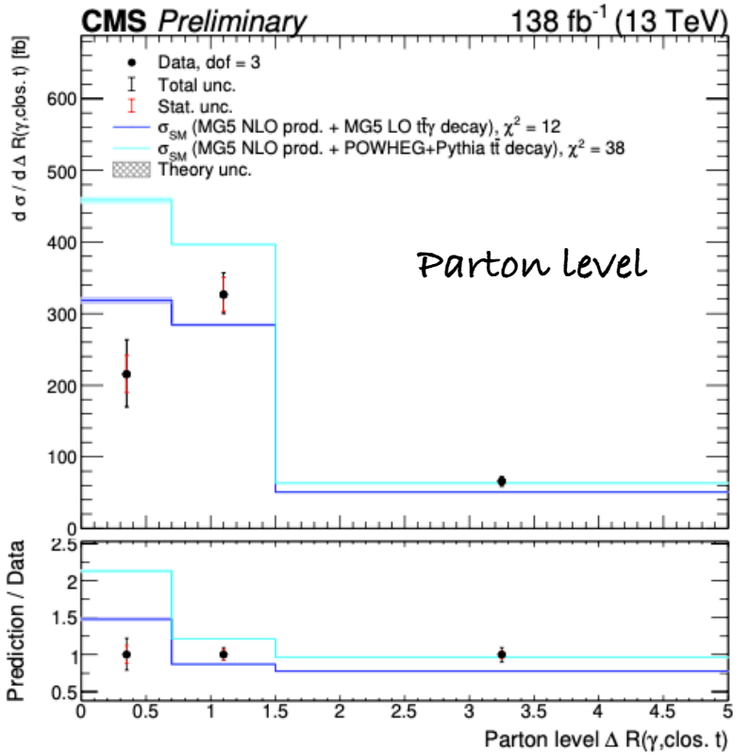

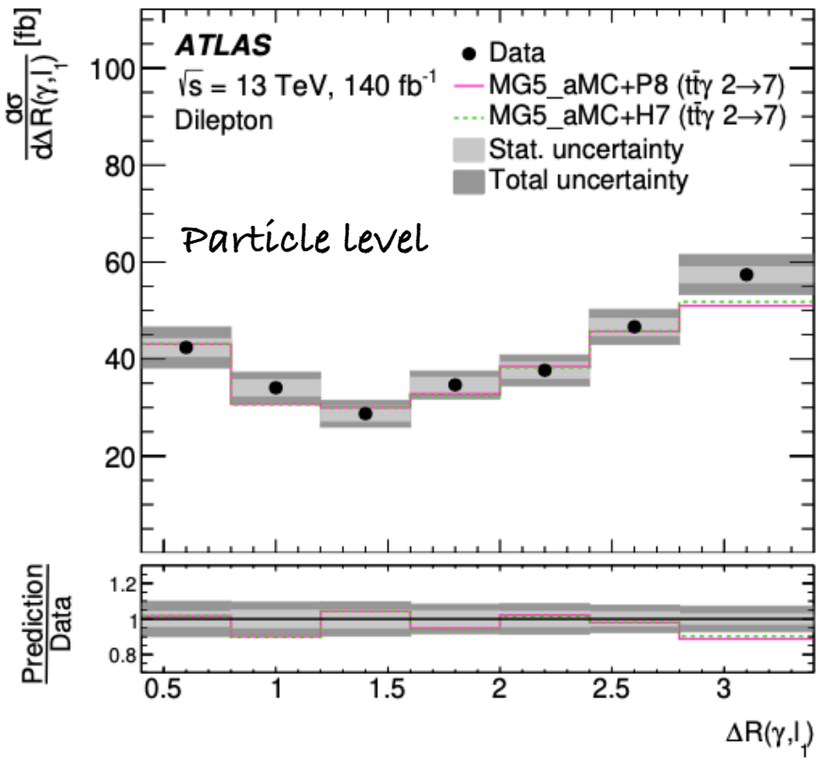

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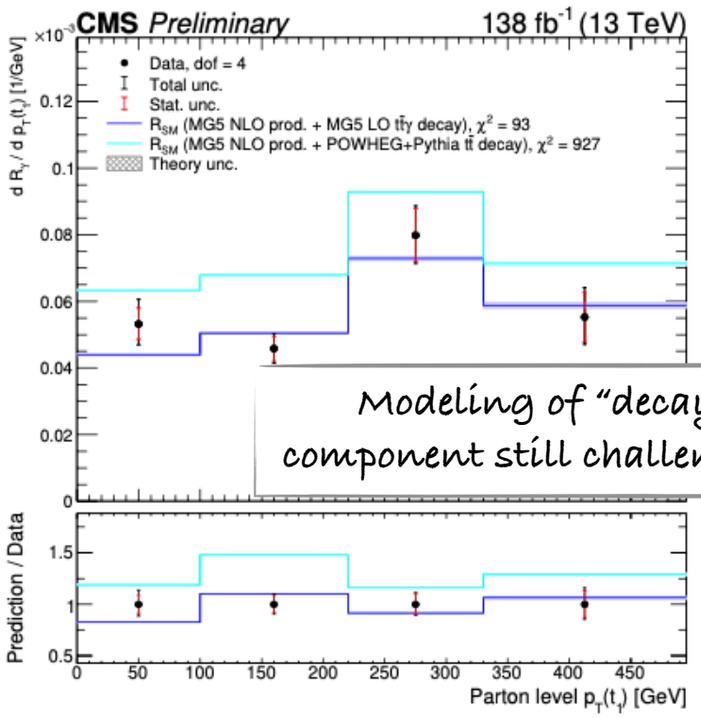

Modeling of "decay" component still challenging

$tt+\gamma$: inclusive and differential cross sections

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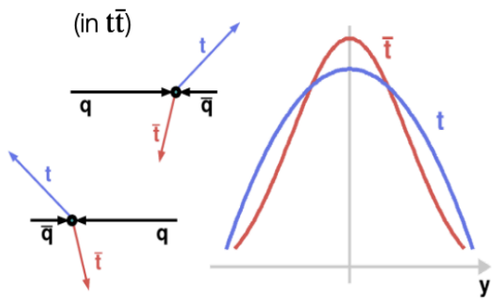
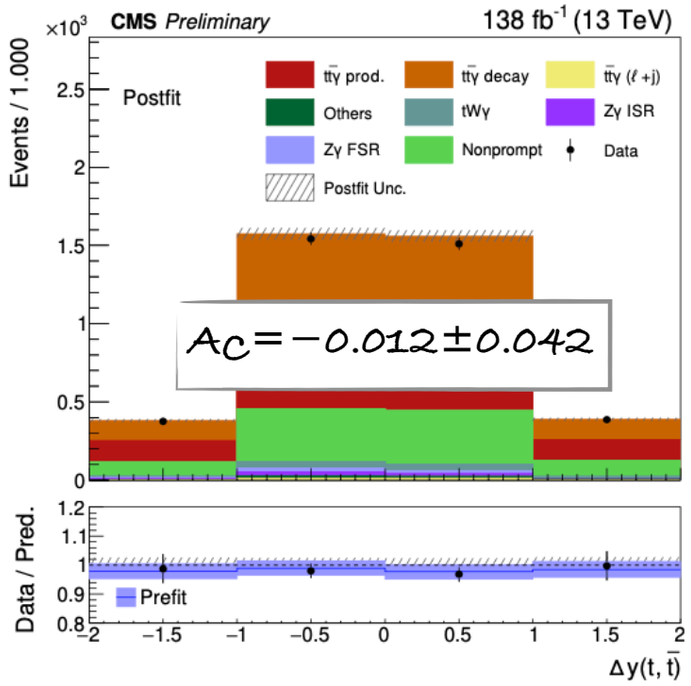
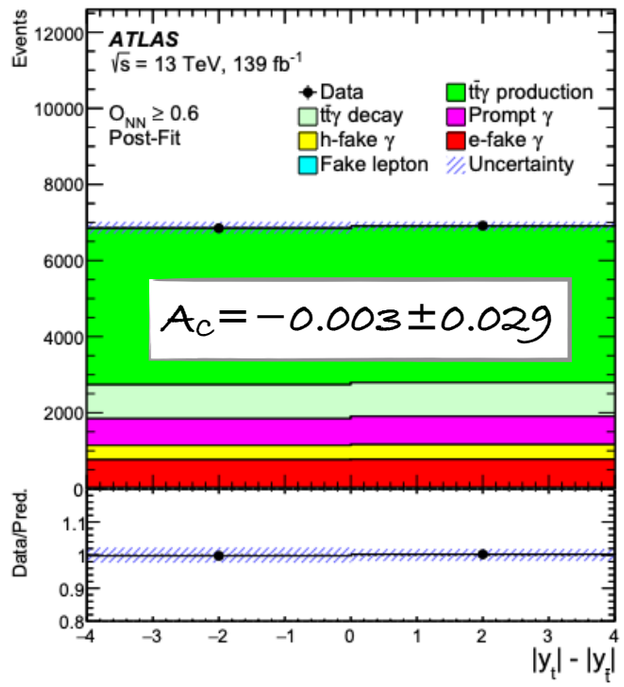
- Top quark charge asymmetry A_C:
  - V^0 introduces additional intrinsic asymmetry in tt system at LO
    → BSM clean probe







- Results compatible with SM and no-asymmetry
- statistically limited, more data needed for BSM sensitivity

- EFT interpretation:
  - BSM physics virtual effects parameterized by dim-6 operators added to SM Lagrangian
  - $tt+\gamma$ sensitivity to several EFT operators (eg dipole operators C_{tB}, C_{tW})
  - combined with tt+Z measurement

- Measured values in good agreement with SM

$tt+\gamma$: inclusive and differential cross sections

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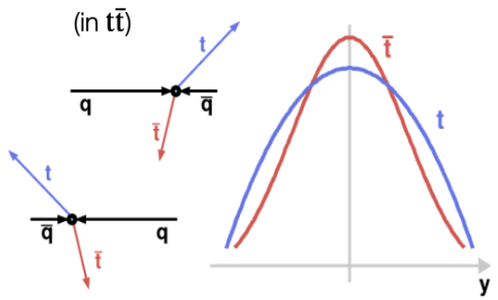

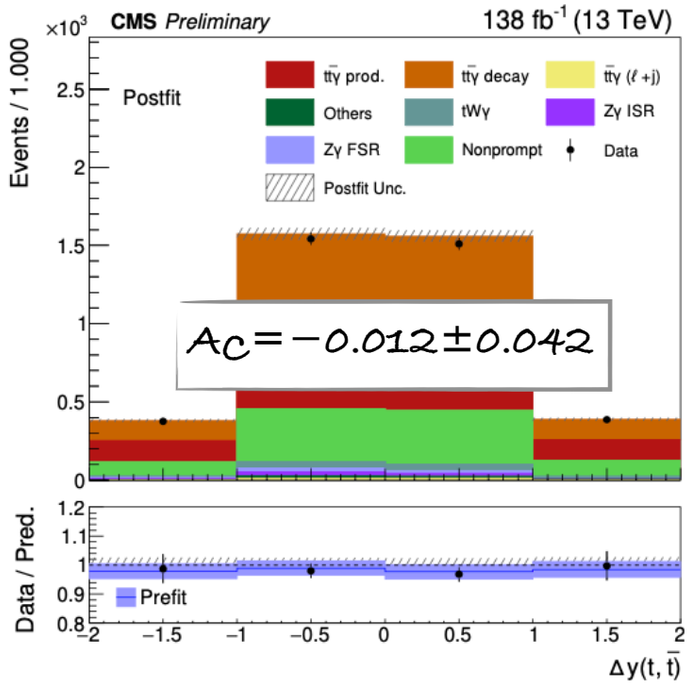

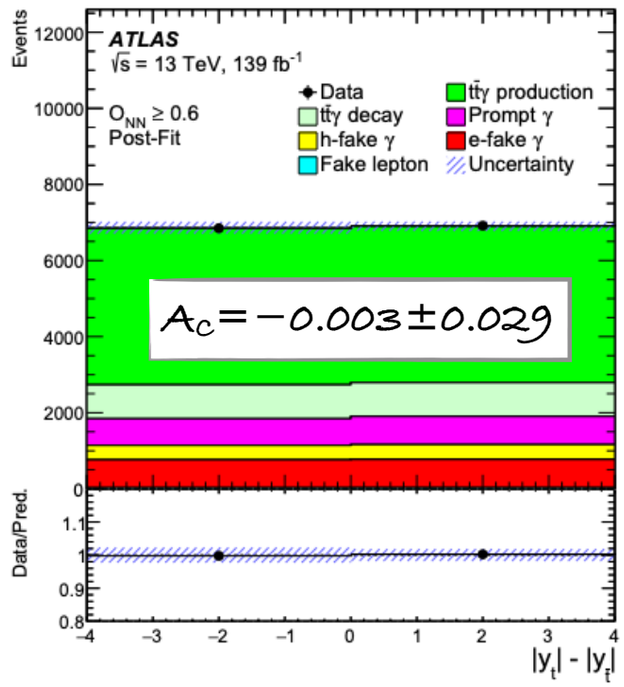

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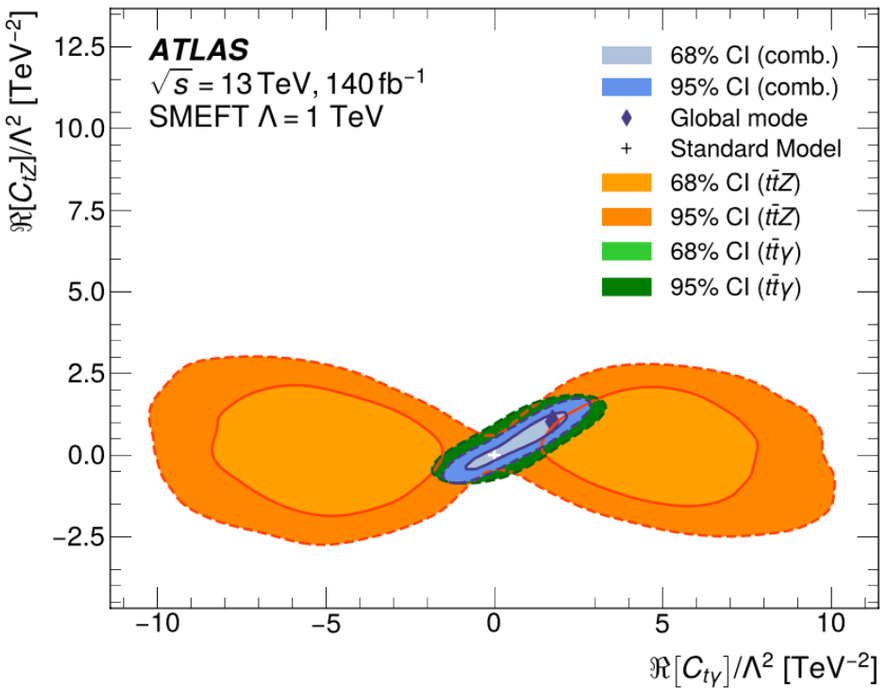
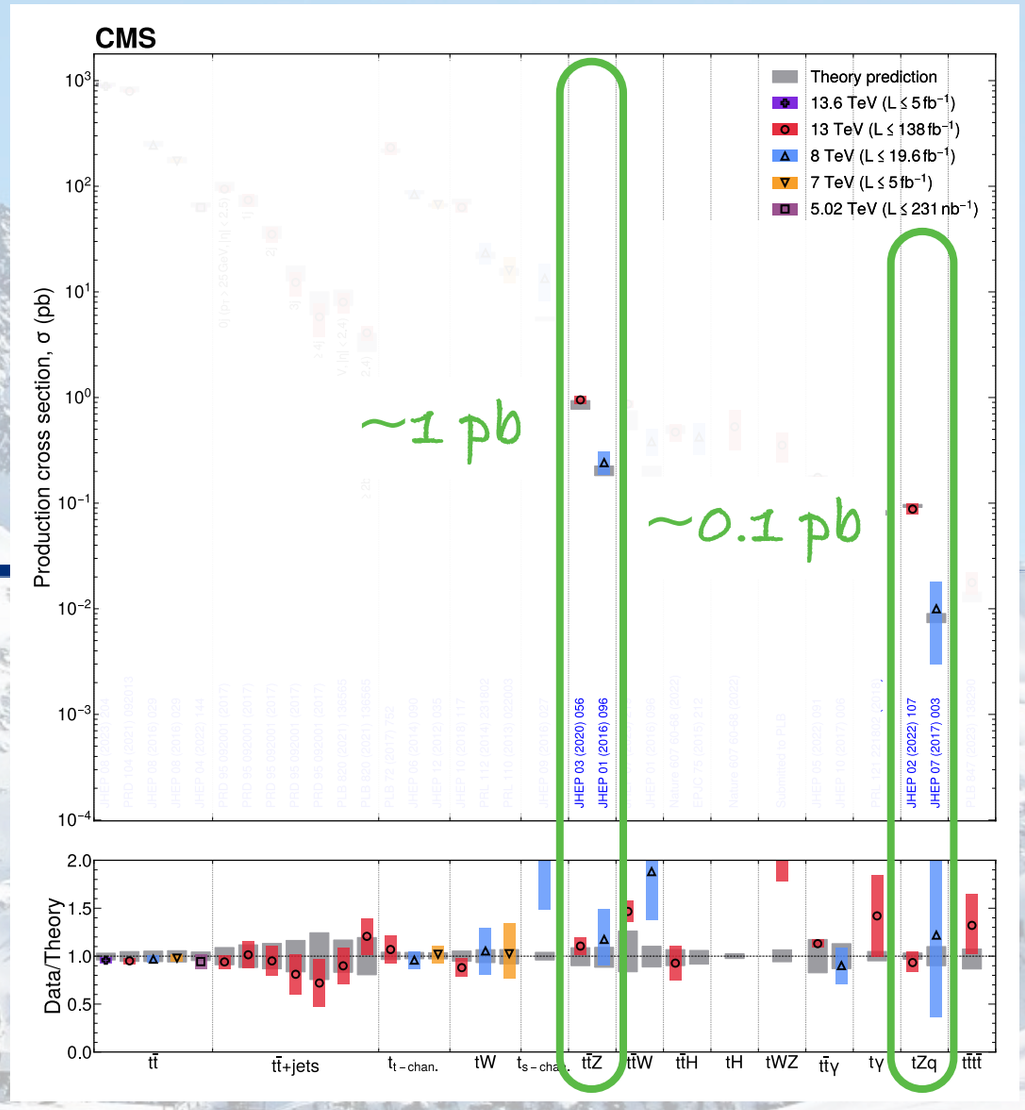


$tt+Z$ and $t+Zq$

* Not enough CP violation to explain baryon asymmetry observed
  - motivates searches for additional CP violation sources from new physics
* NP can be parameterized by EFT
  - CP-odd operators c'_{tW} and c'_{tZ} modify t-V(Z,W) interactions
  - SM-BSM interference proportional to $1/\Lambda^2$ (linear), gives rise to *CP*-odd contributions



ATLAS TOPQ-2023-02

CMS CMS-PAS-TOP-24-012

* selected most recent results

tt+Z, t+Zq: CP violation

CMS-PAS-TOP-24-012

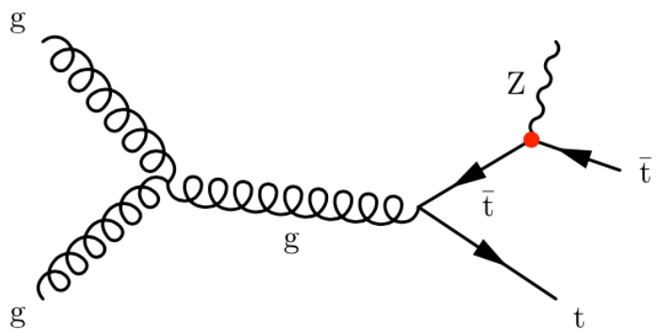
Run2+Run3

NEW ITEM

1. Selection:

- 3 leptons: e or μ
- 1 lep pair opp-sign same-flavor
- ≥ 1 jet
- ≥ 1 b-tagged jets

tt+Z, c'_{tZ}



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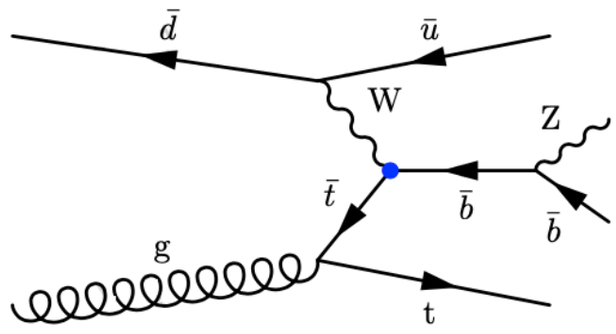
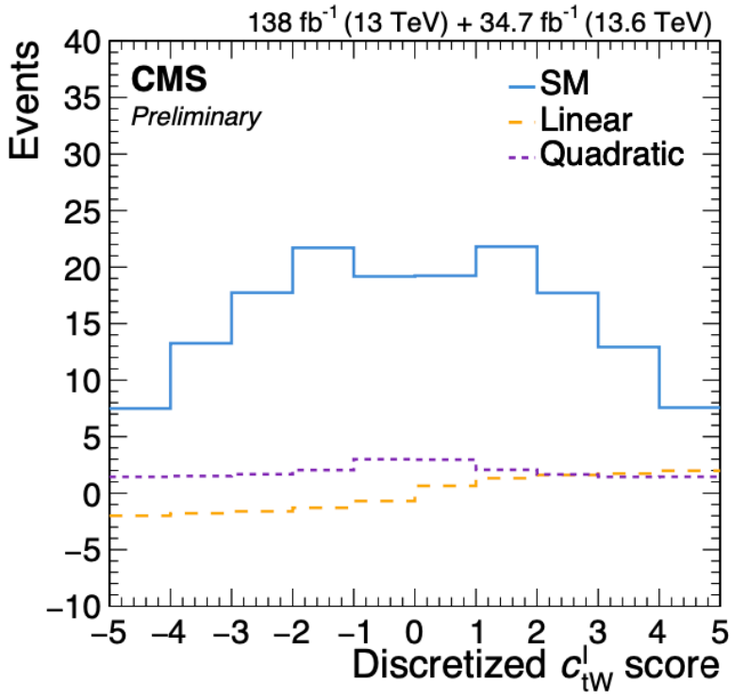
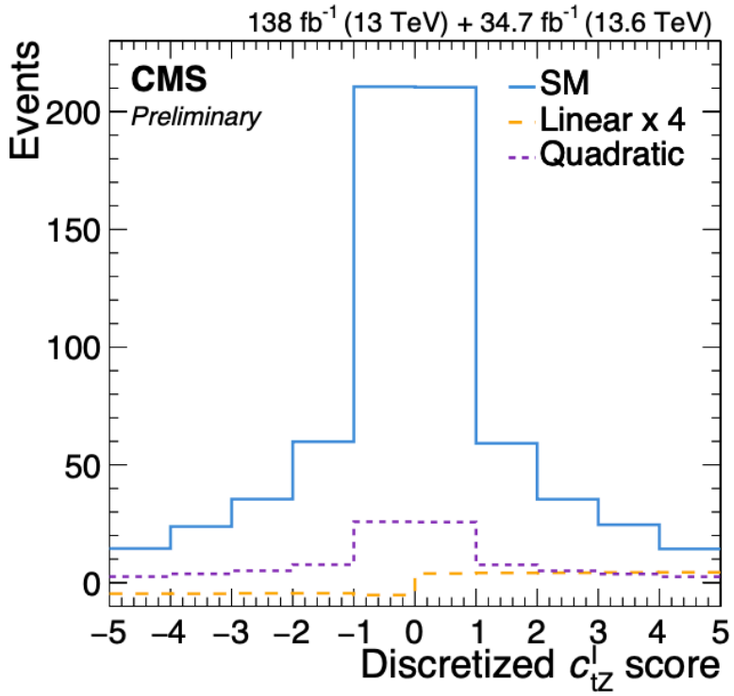


CP-odd observables using physics-informed ML

- SM contribution CP-invariant
- pure BSM contribution CP-invariant (quadratic)
- SM-BSM interference CP-odd (linear)





tt+Z, t+Zq: CP violation

CMS-PAS-TOP-24-012

Run2+Run3

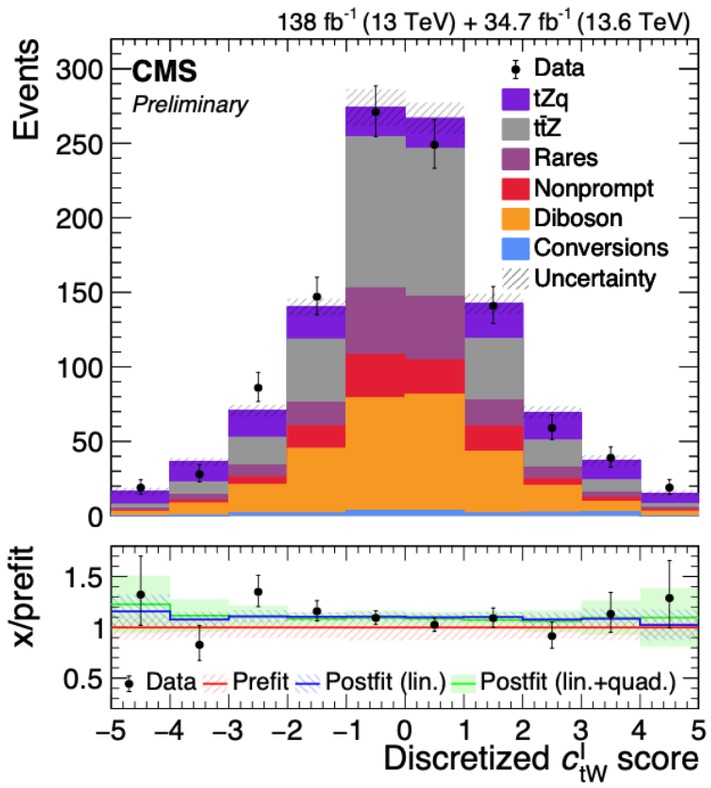
NEW ITEM

3. Results:

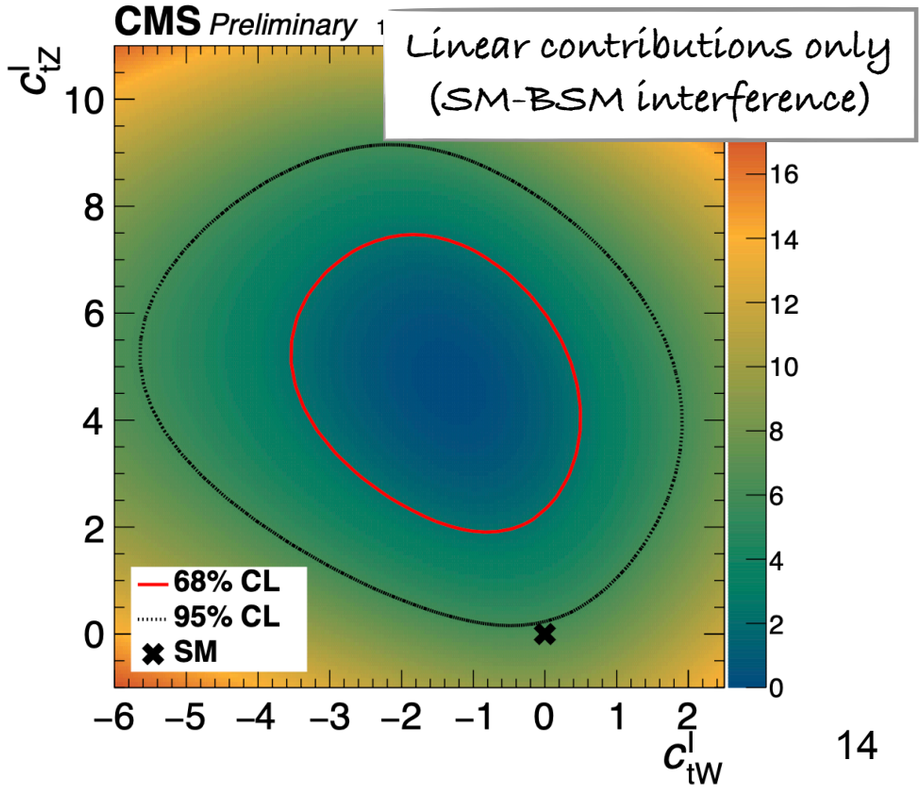
- CP-odd observables constructed using physics-informed ML techniques employed for first time in tt+Z and t+Zq events

$-2.7\ (-2.0) < c_{tW}^{I} < 2.5\ (2.0)$

$-0.2\ (-1.5) < c_{tZ}^{I} < 2.0\ (1.5)$



- Good agreement with SM
- Pre-fit vs post-fit deviations: slight c'_{tZ} asymmetry, mild excess of obs events (consistent with previous ttZ measurements)



tt+ll: production and LFU violation

TOPQ-2023-02

NEW ITEM

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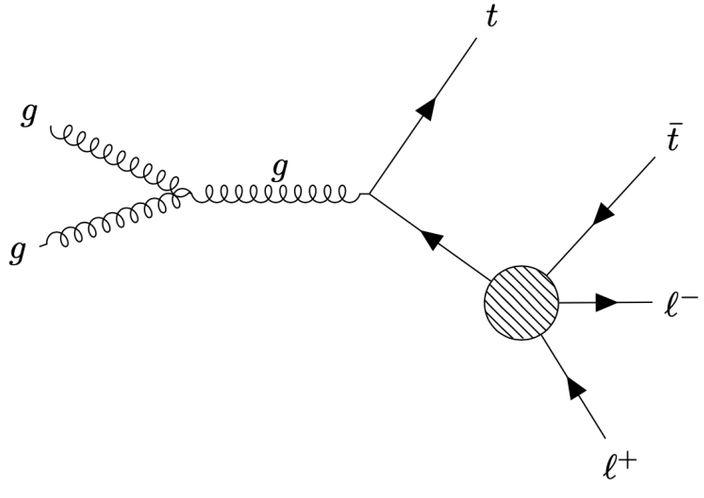
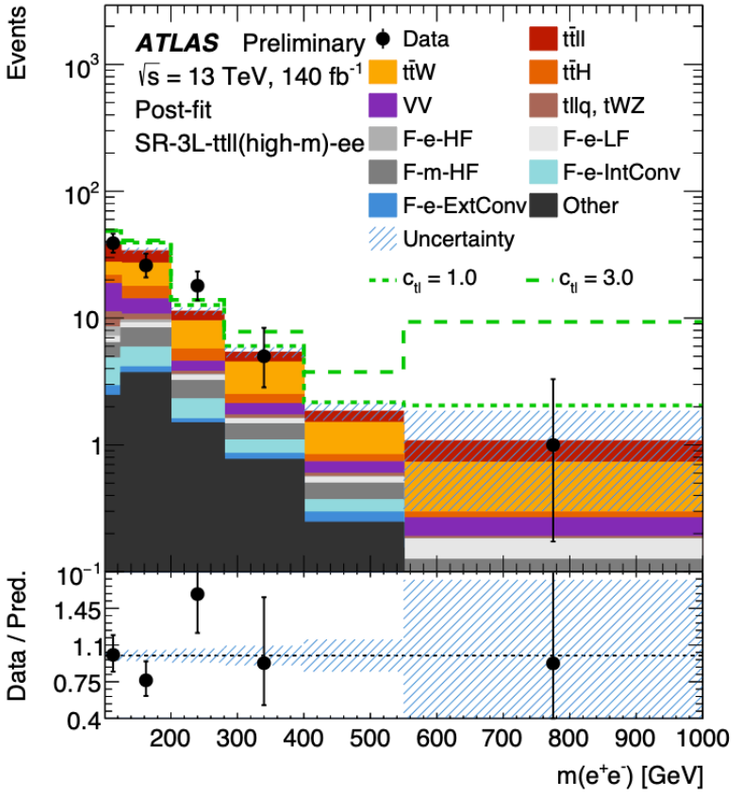
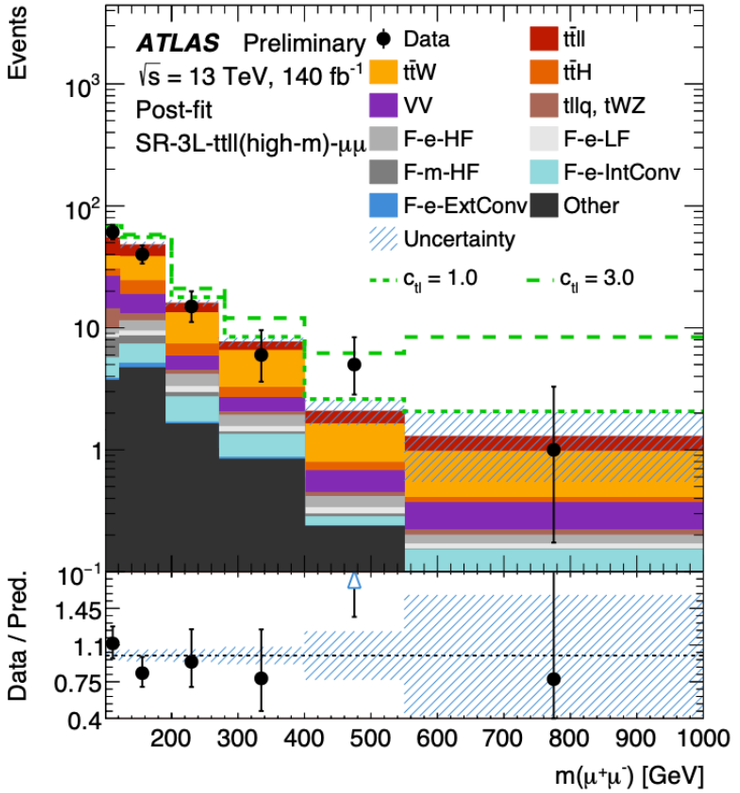


tt+ll to search for BSM physics

- probe of ttll interaction vertex
- translates in unique sensitivity to four-fermion EFT operators
- considering di-leptons high-invariant mass phase space





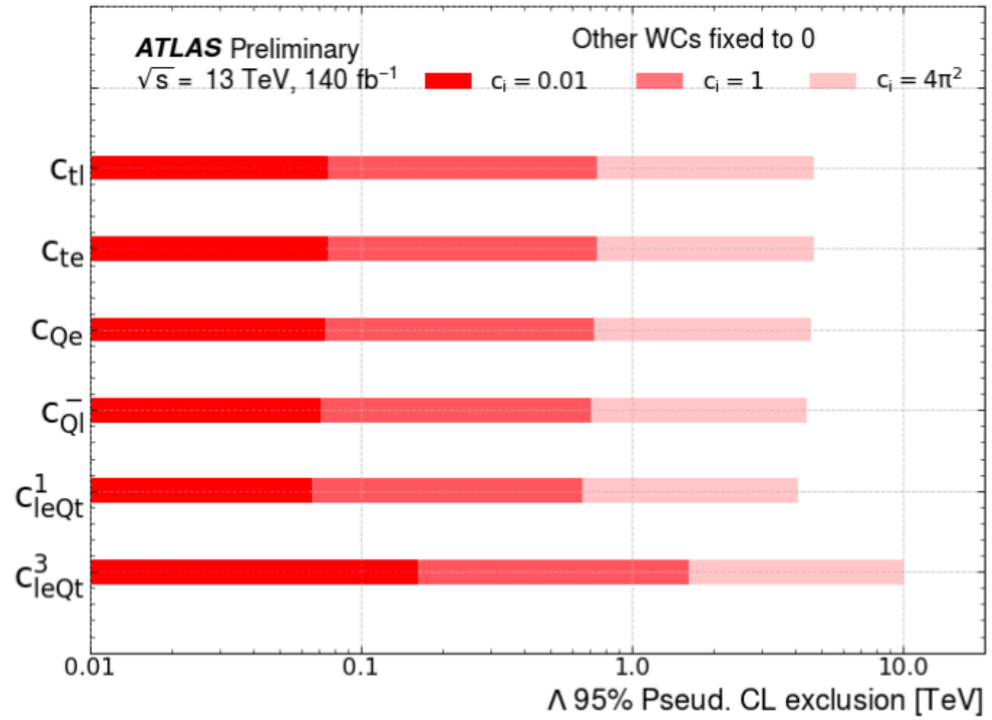
tt+ll: production and LFU violation

TOPQ-2023-02

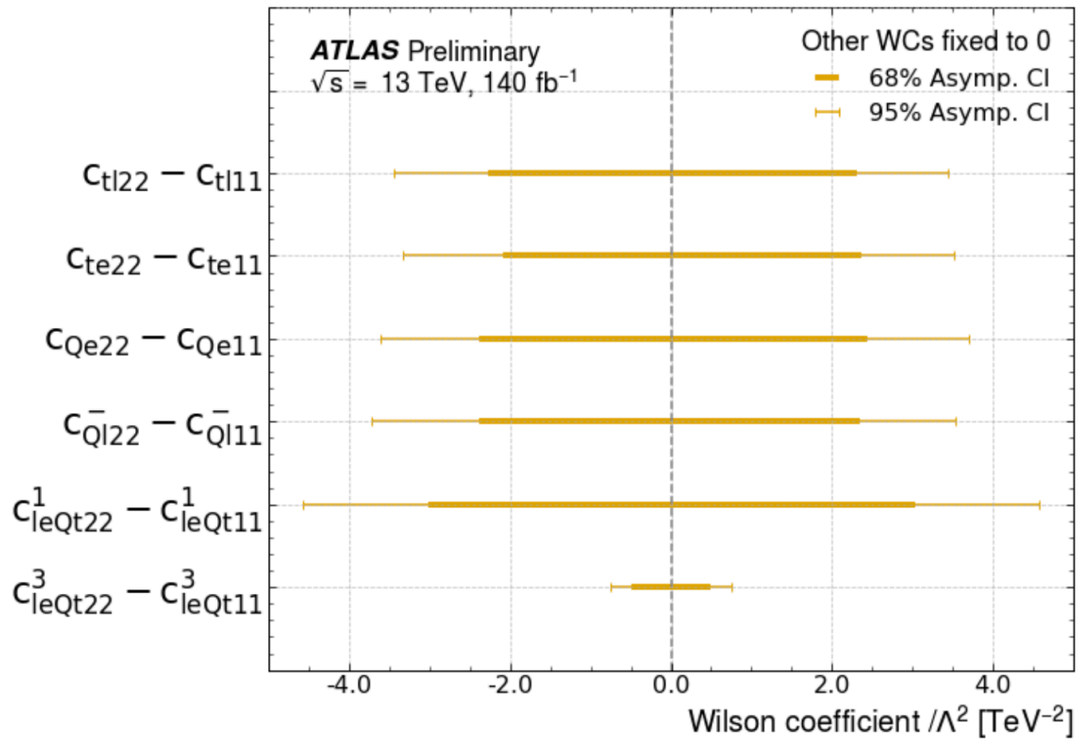
NEW ITEM

3. Results: several interpretations

- EFT coefficient: flavour-inclusive, for first time also flavour-split
- configurations to test lepton flavour universality-violating signals



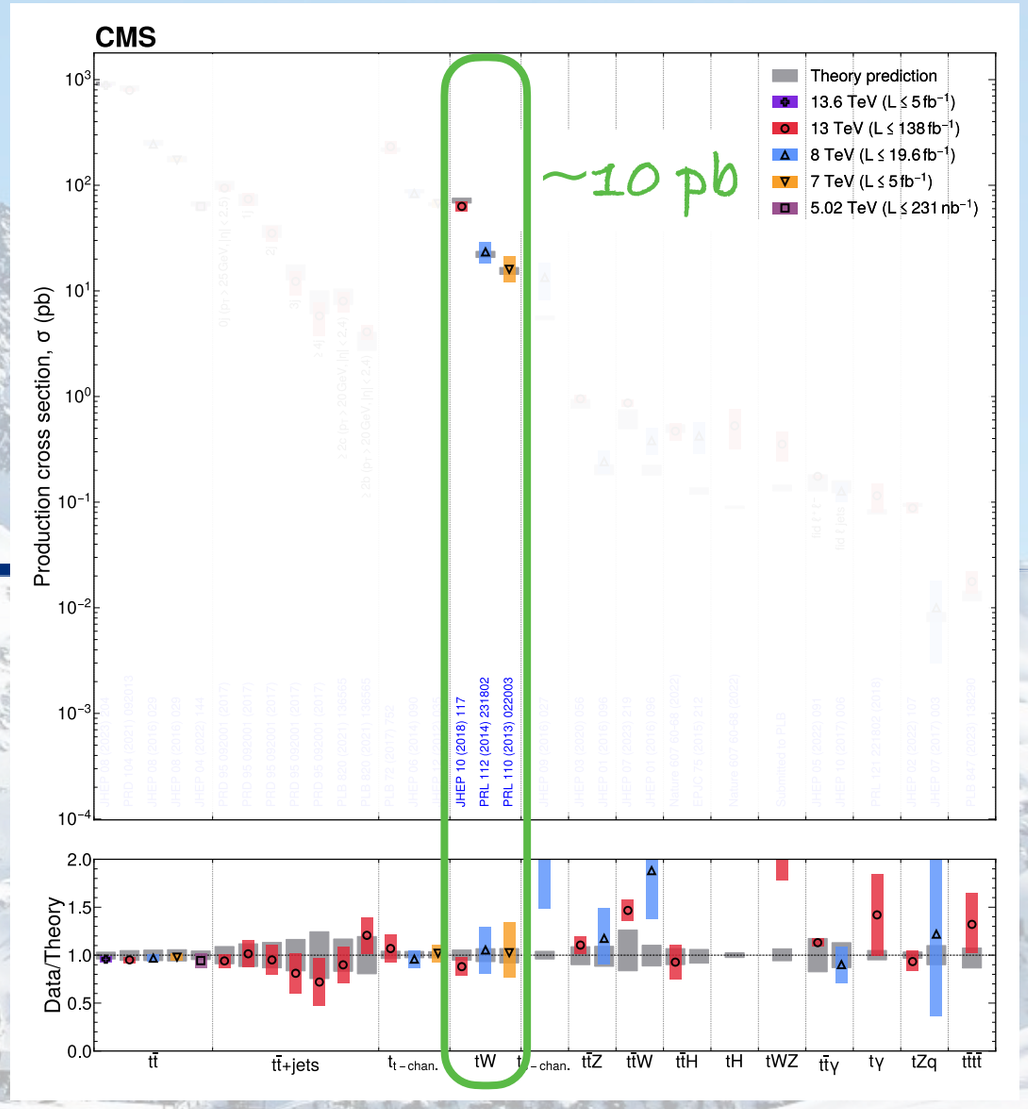
- Good agreement with SM
  - Limits on EFT coefficient improving previous LHC constraints
  - Lepton flavour universality-violating EFT effects:
    - no deviations observed
    - currently statistically limited



t+W

* Single-top production involve Wtb EWK vertex:
  - important test of 3rd-generation quarks EWK interactions
  - sensitive to W_{tb} vertex corrections $|f_{LV}V_{tb}|^2$ from BSM physics

* t+W
  - 26% of total single-top production at 13 TeV
  - dilepton channel: clean signature, lower bkg



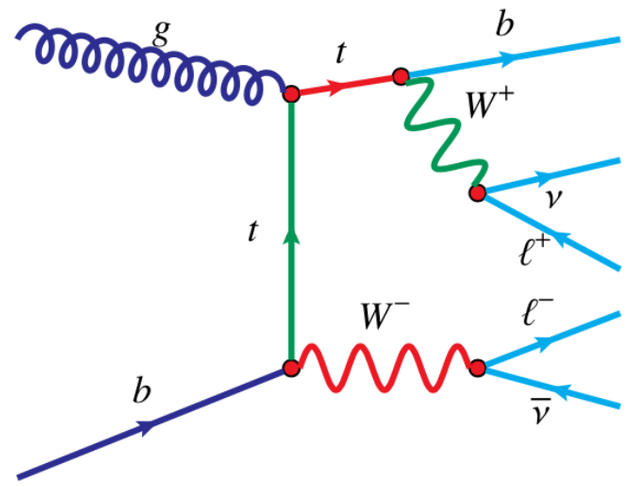
Phys. Rev. D 110 072010

* selected most recent results

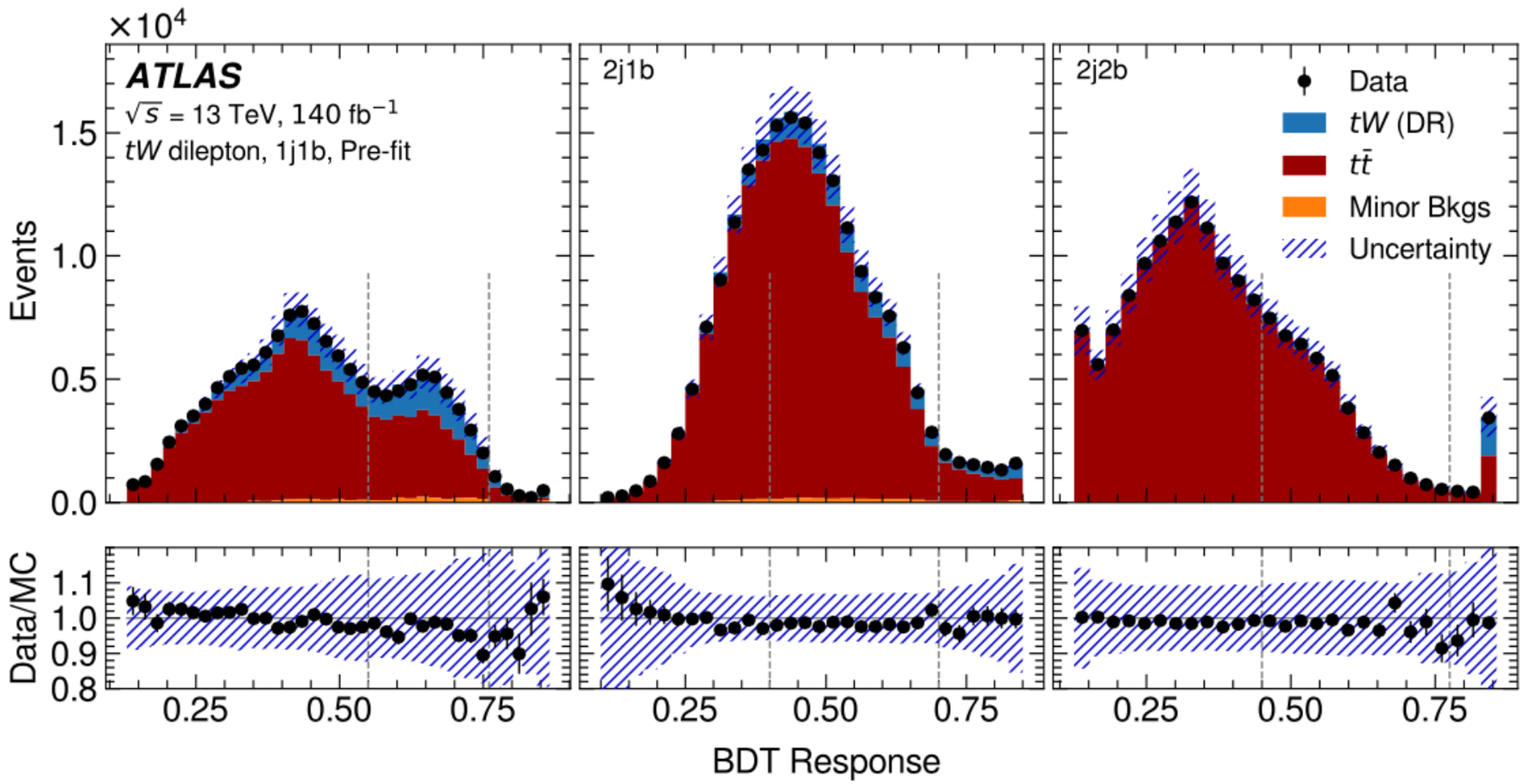
t+W: inclusive cross section

Phys. Rev. D 110 072010

- 1. Selection:
  - 2 leptons: e, μ opp-charge
  - ≥ 1 jet, ≥ 1 b-tagged jet
  - categorization based on jets and b-tagged jets multiplicity
  - MVA techniques



- 2. Bkg:
  - main bkg from **tt**
  - minor bkg from **Z+jets, W+jets, VV**



t+W: inclusive cross section

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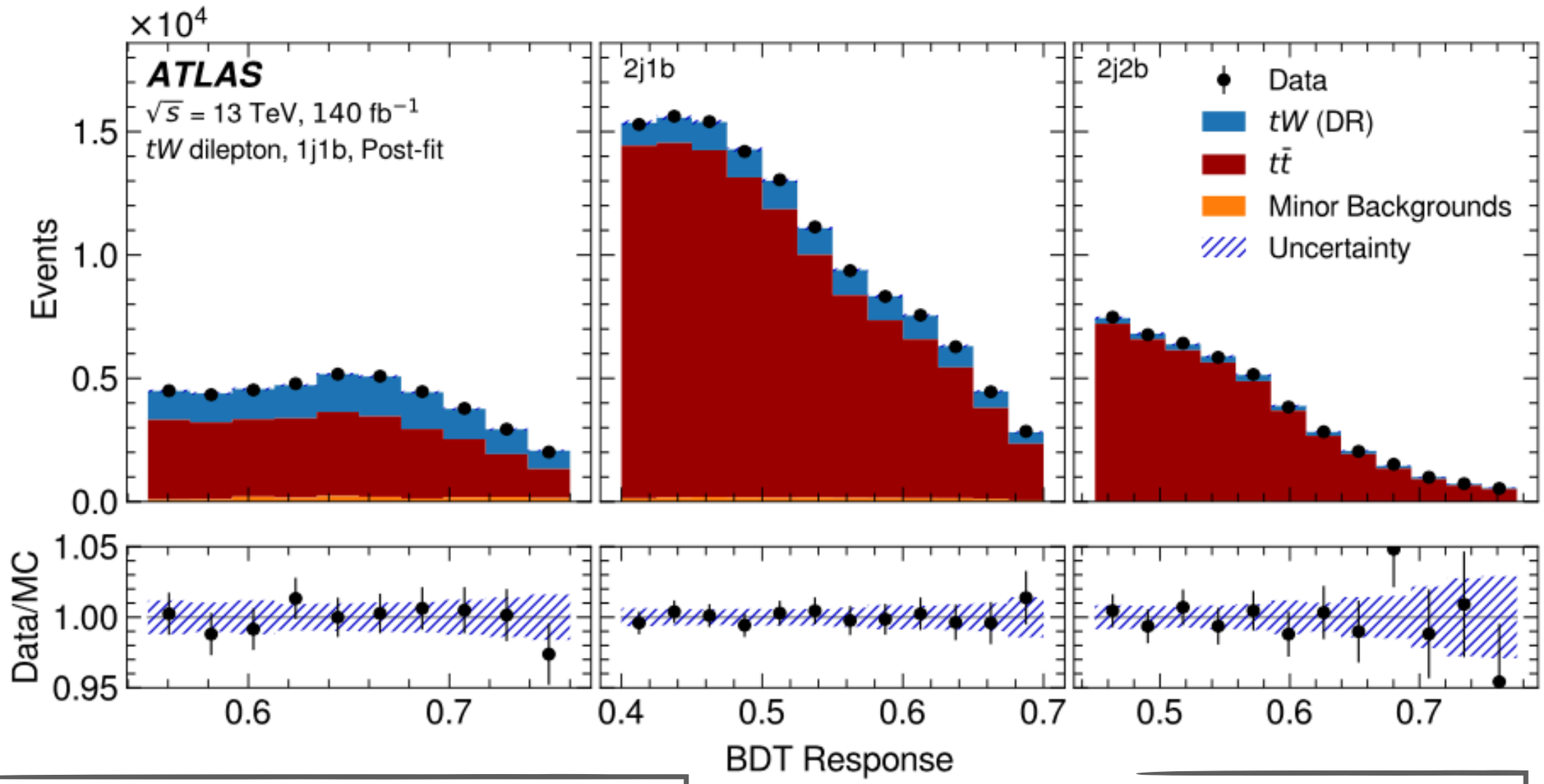
- 3. Results: combined fit to jet, b-jet categories. Syst unc. included as nuisance parameters



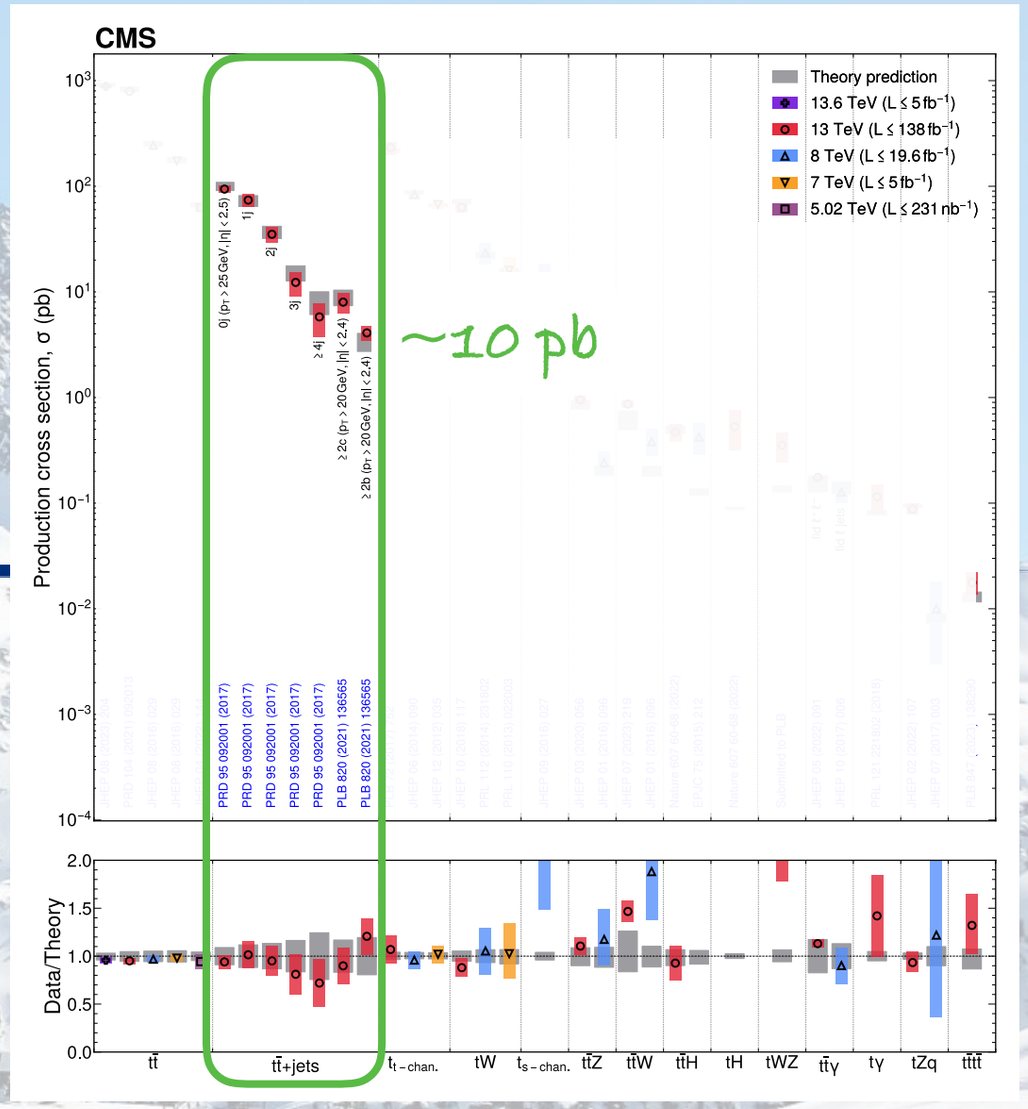
σ_{tW} = 75 ± 1(stat) ± 15 (syst) ± 1 (lumi) pb

$|f_{LV}V_{tb}|^2$ = 0.97 ± 0.10

– Xsec and form factor times the CKM matrix element in agreement within SM predictions

tt+cc

* tt+cc processes:
  - modeling challenging
  - leading background for searches and other measurements, such at ttH(bb), tttt which provide direct access to top Yukawa coupling
  - recent measurements of tt+bb and ttH(bb) show tt+≥1c normalization larger than simulation value



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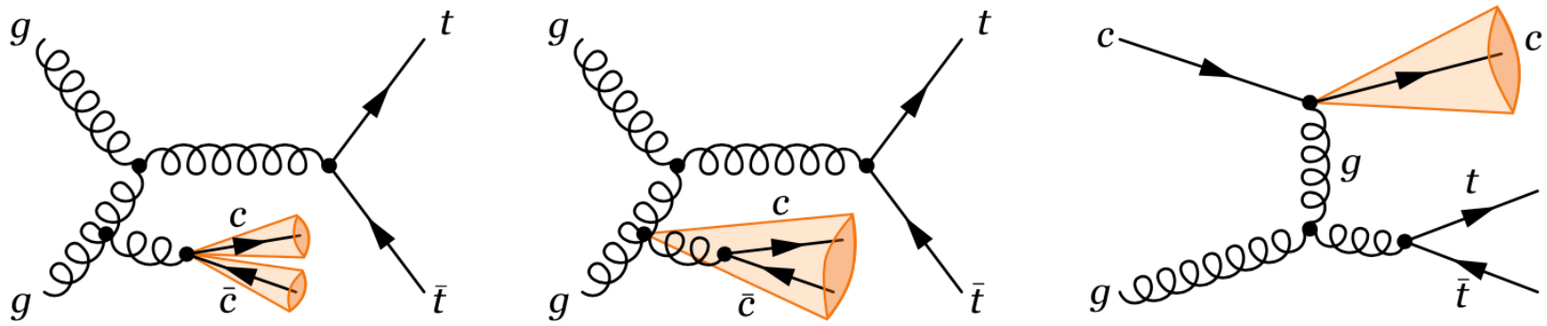
* selected most recent results

tt+cc: differential cross sections

JHEP 01 (2025) 068

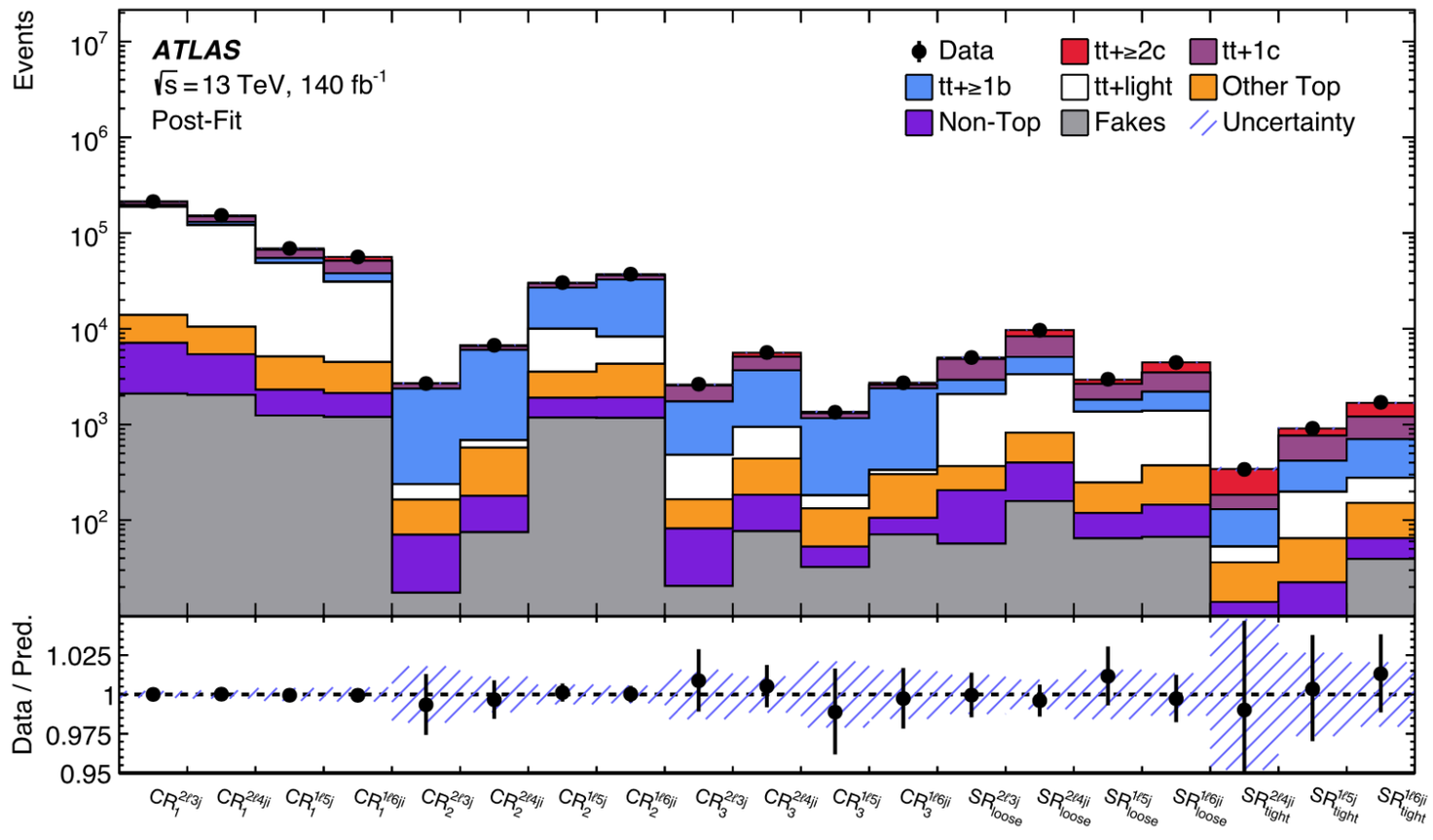
1. Selection:

- 1 or 2 (opp-charge) leptons
- ≥ 3 or 5 jets
- SRs and CRs categorized based on # of b-, c-tagged jets



2. Bkg:

- main bkg from **tt+≥ 1b, tt+light**
- normalization estimated from data



tt+cc: differential cross sections

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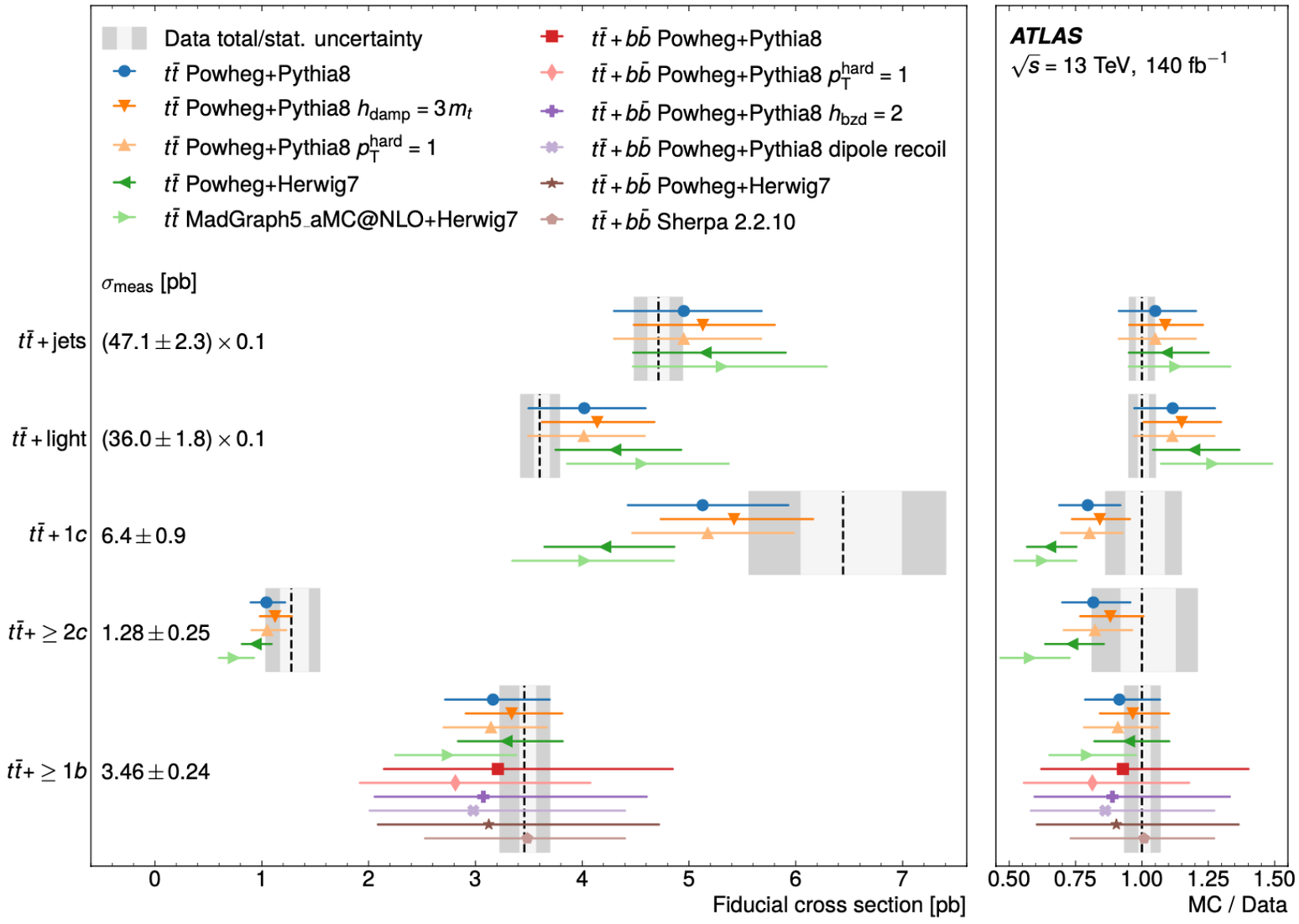
- 3. Results: fiducial differential cross-sections of tt+jets production

- Good agreement with predictions
- Precision limited by unc on tt+≥1c, tt+≥1b, tt+light, b/c-tagger, data statistics.
- First time of regions sensitive to tt+≥2c, tt+1c separately



Summary

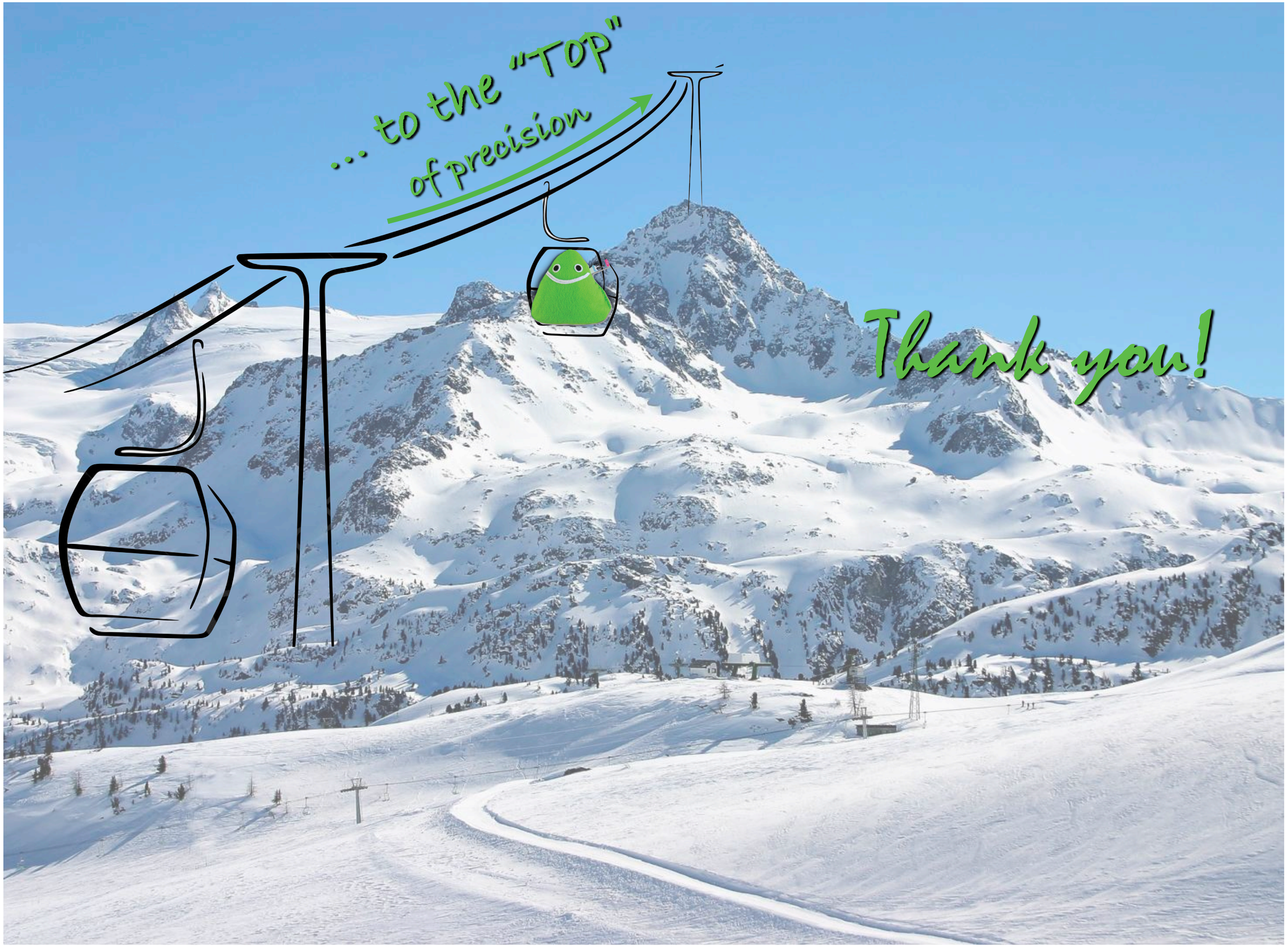
- Run 2 and Run 3 data give access to very rare top processes

- New results with increasing precision despite small xsec: thanks to optimized selections, improved analysis techniques

- Direct probe for SM precision measurements
  - putting SM to test with top quark rare processes, especially those involving top quark EW couplings

- Probe for BSM physics:
  - strengthening constraints on anomalous couplings, interpreted in EFT context

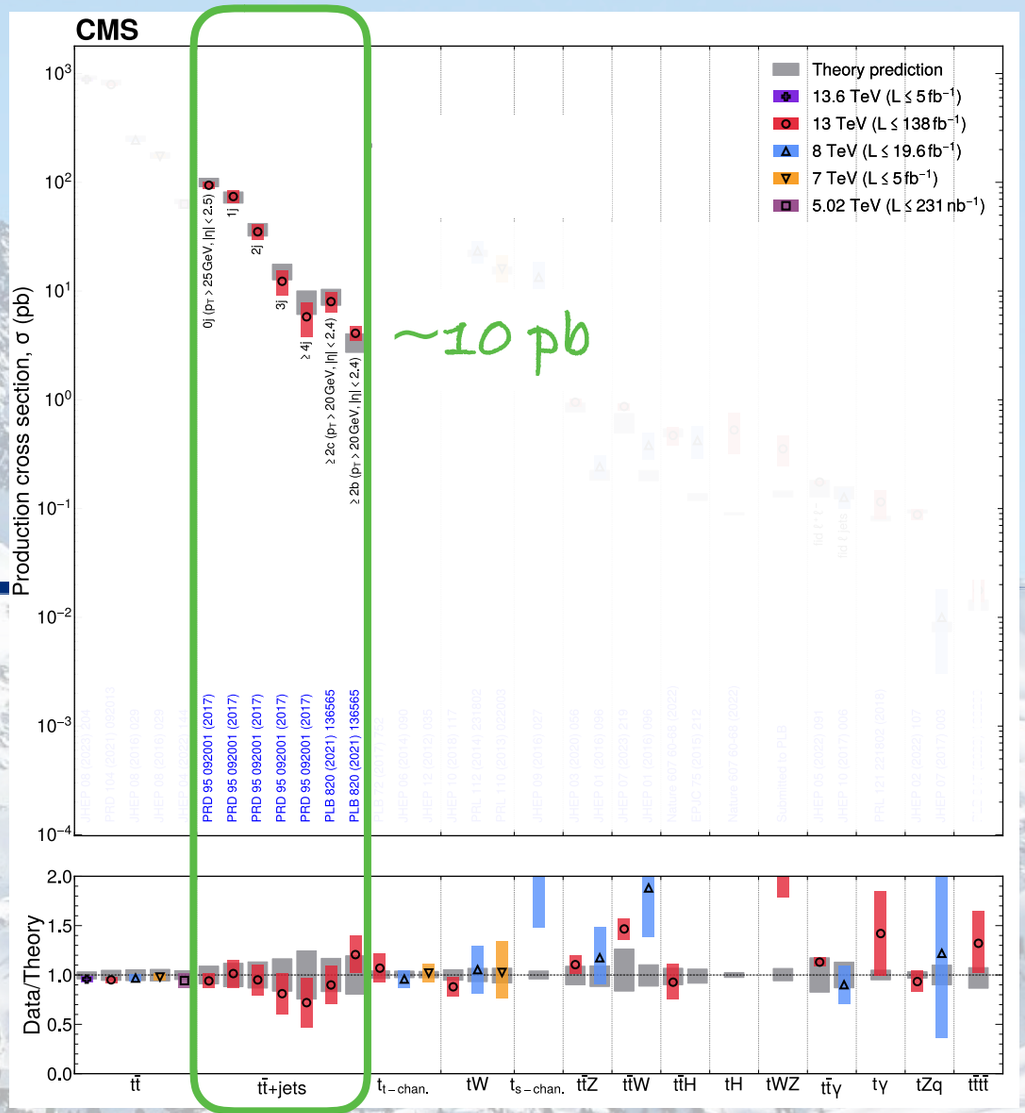
Stay tuned for more data !


... to the "Top"
of precision
Thank you!

Backup

tt+bb

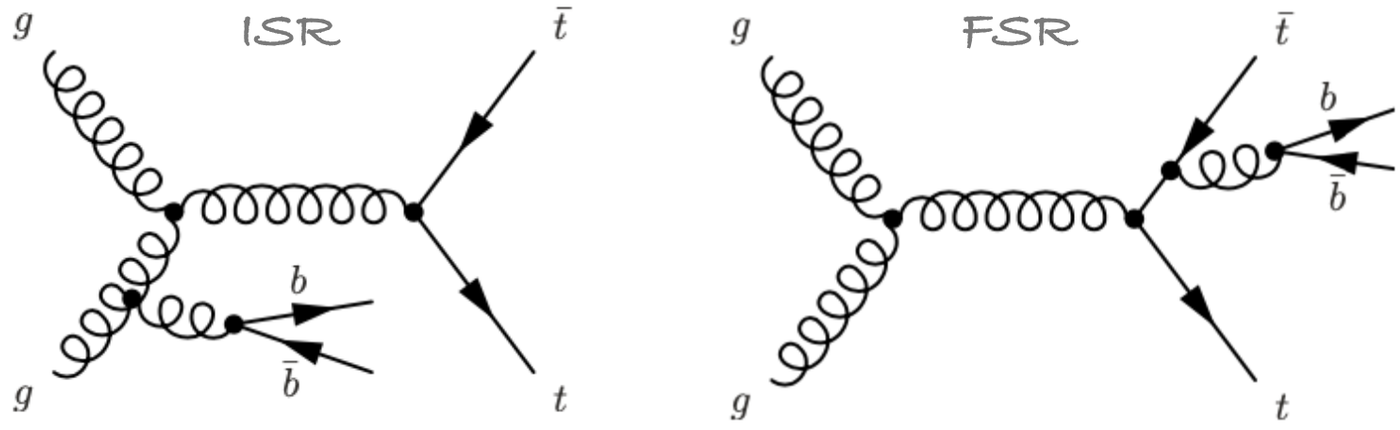
* tt+bb processes:
  - modeling challenging: difference in interactions energy scales with top and b quarks → different process scales (m_{top} vs m_b)
  - important test of perturbative QCD calculations
  - leading background for searches and other measurements, such at ttH(bb), tttt which provide direct access to top Yukawa coupling



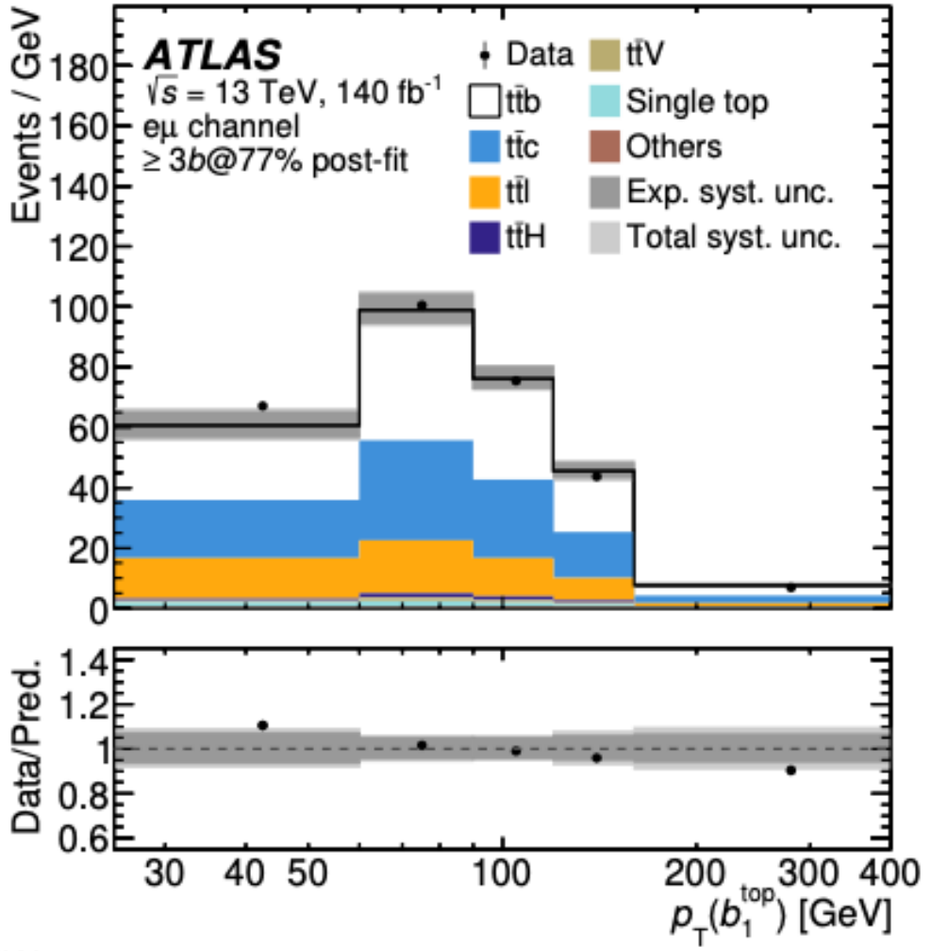
* selected most recent results

tt+bb: inclusive and differential cross sections

- 1. Selection:
  - 2 leptons: 1 e and 1 μ, opp-charge
  - ≥ 3 b-tagged jets

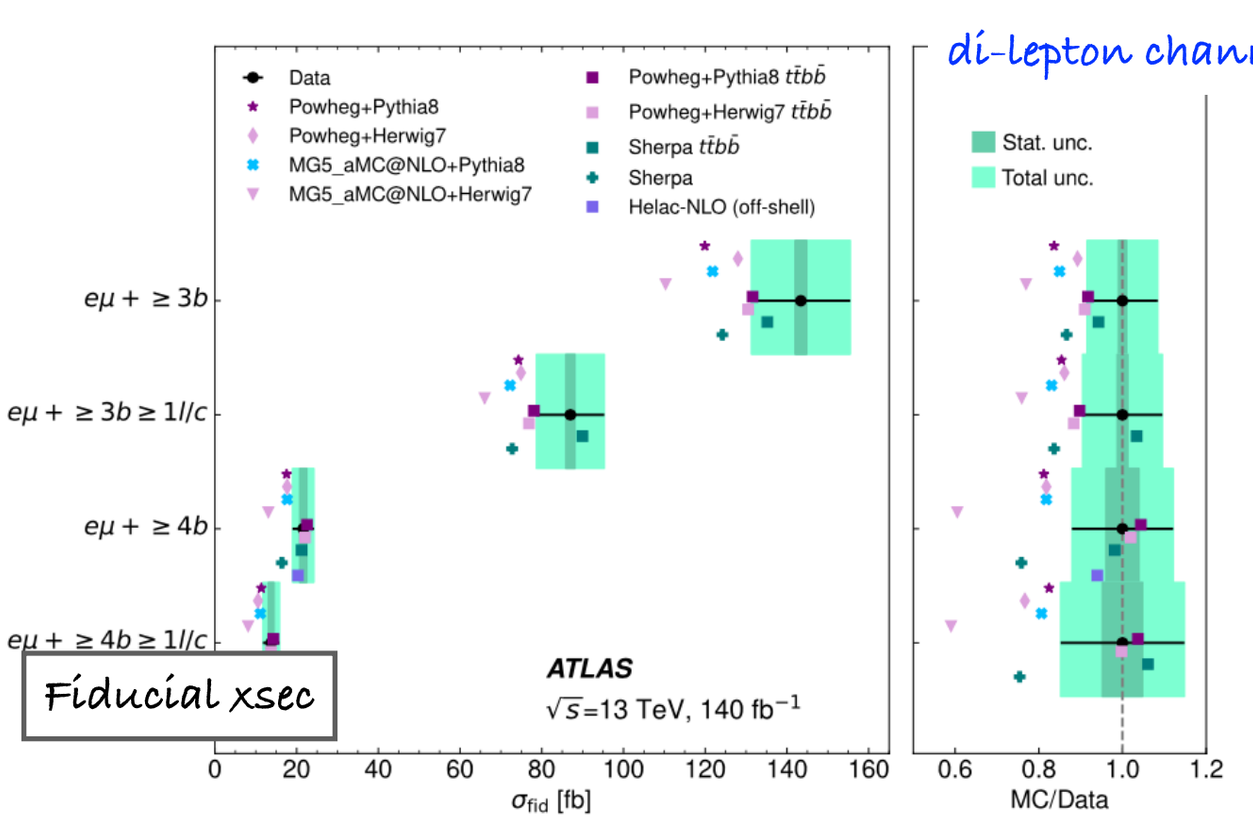


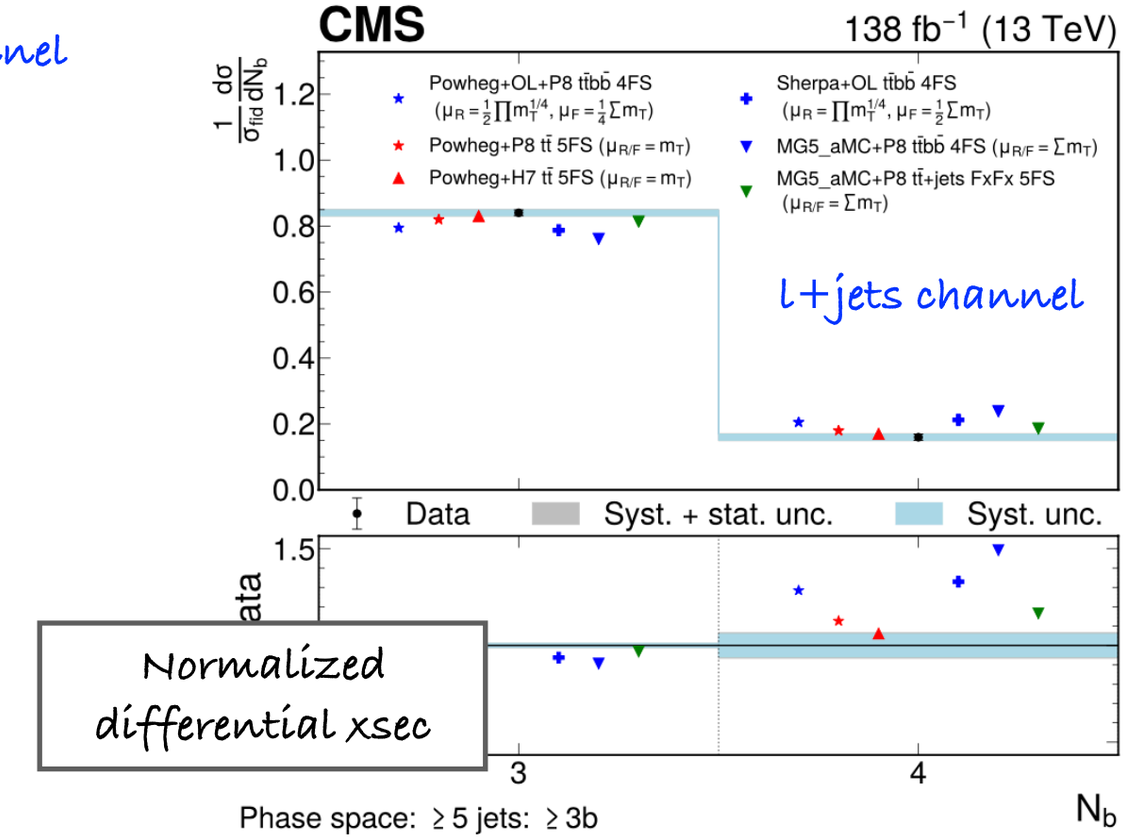
- 2. Bkg:
  - main bkg from **tt**
  - **mis-tag jets in tt-c, tt-l** data-driven scale factors to adjust composition in tt events
  - **non-prompt or mis-ID leptons** from data
  - minor bkg from simulation



tt+bb: inclusive and differential cross sections

- **3. Results:** fiducial and normalized differential cross-sections of tt+bb production in different phase spaces





- ATLAS (e-μ): tot unc 8.5-16% depending on phase space, best to date in eμ channel
- CMS (l+jets): tot unc 6-17%, depending on phase space, most precise ttbb xsec measurement
- Results more precise than current theoretical predictions unc at NLO