LHC Top+SM

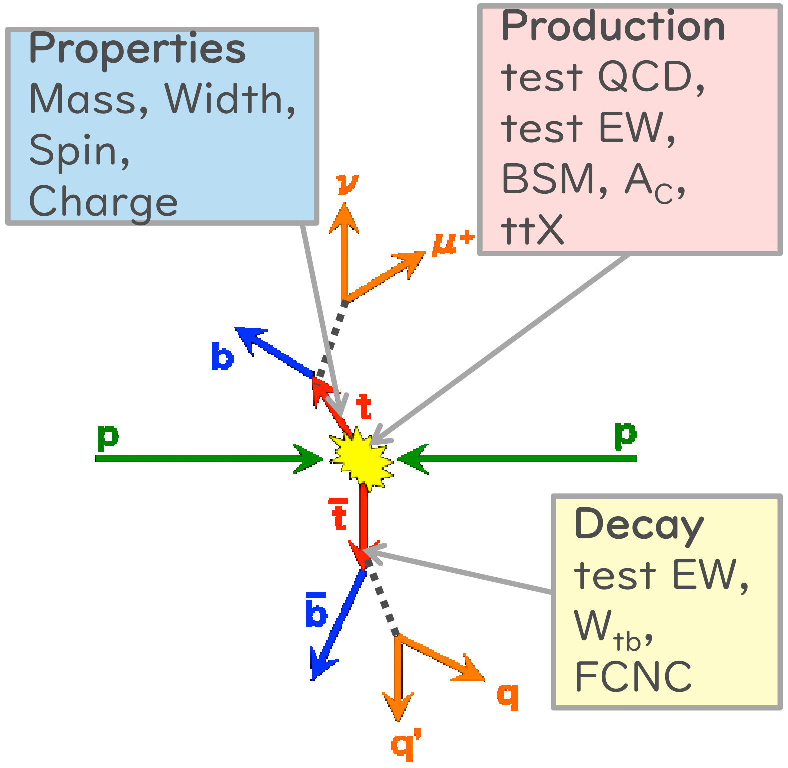
Kentaro Kawade
Shinshu University

Top

Interests in the Top quark physics

- Top quark?
  - Most massive elementary particle so far discovered
    - with a mass ~173 GeV
    - strong coupling to Higgs boson
    - many BSM particles strongly couple with top quark

- Studying top quark
  - Precision test of pQCD, EWK
  - Many BSM searches from top production, properties and decay
  - Important background for a lot of LHC searches

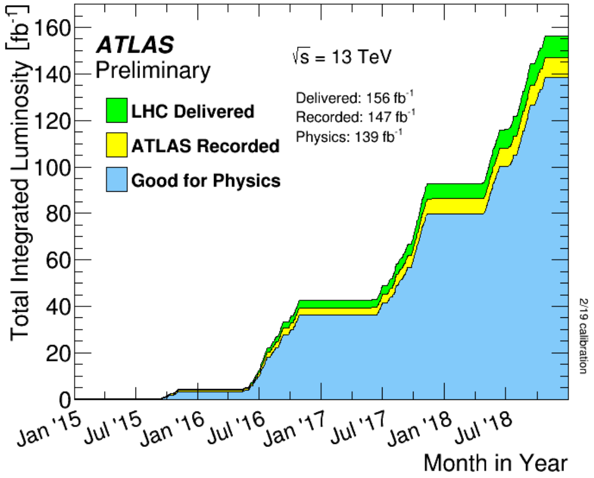


LHC is a Top-factory

- In the LHC-Run2 (2015-2018)
  - 140 fb^{-1} × 832 pb ~ 1.2 x 10^8 $t\bar{t}$ pairs were already produced

$\int L\,dt$ $\sigma_{t\bar{t}}$

~120M $t\bar{t}$



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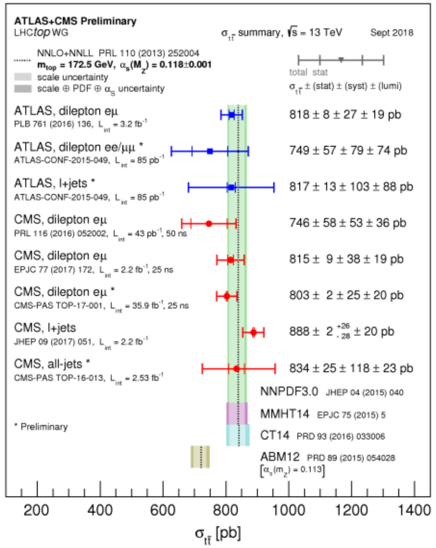

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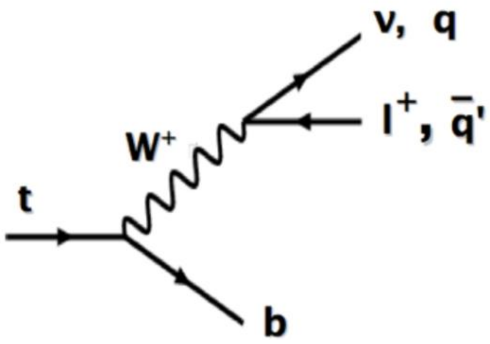
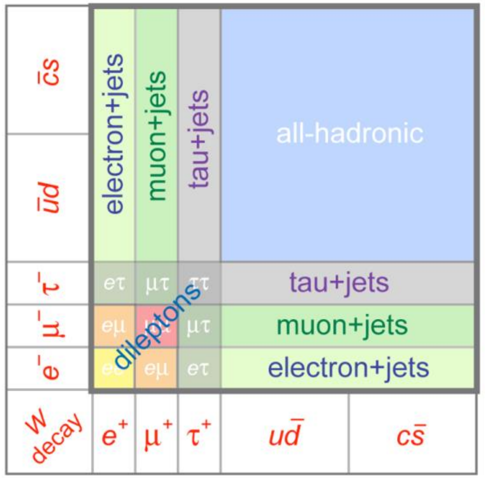
  - The goal: precision test of SM and BSM searches using huge $t\bar{t}$ sample
    - allow to measure very **rare SM** processes

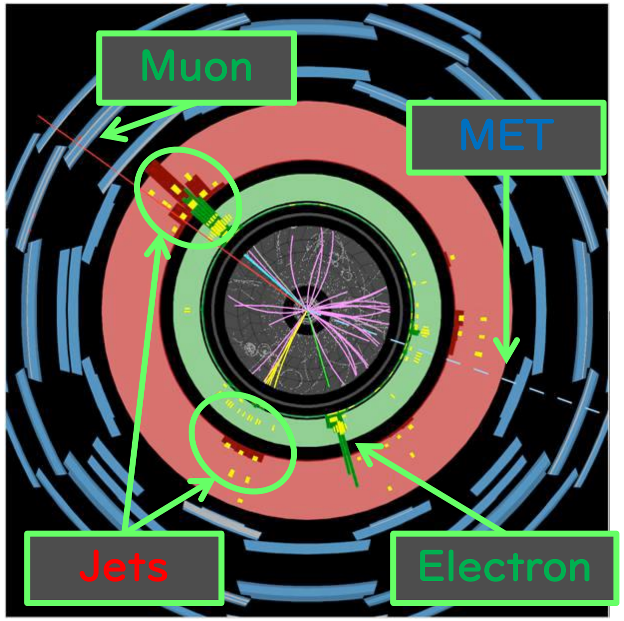
Top quark signal

- Top quark decay to W+b ($V_{tb} \sim 1$)

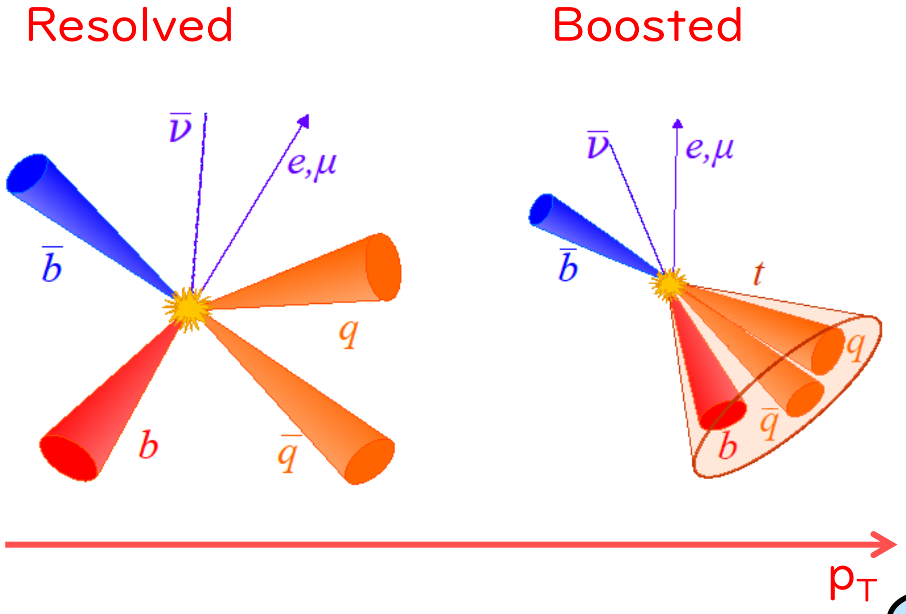


can be categorized by W-boson decay





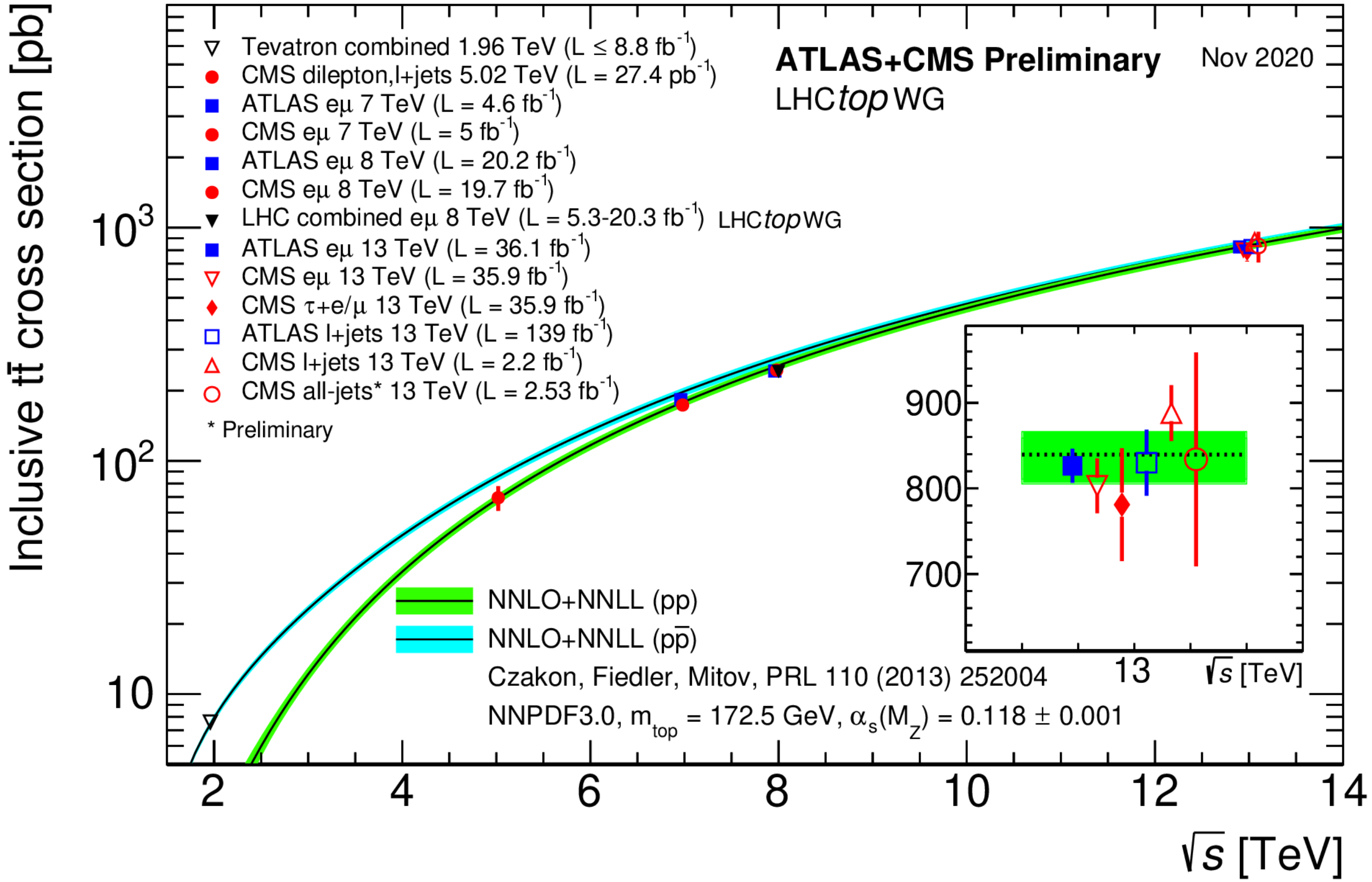
- **Final state objects**
  - High-p_T leptons or/and quark jets
  - Neutrino
    ⇒ Can be detected as large Missing E_T (MET)
  - b-jets
    - b-tagging
  - Top jet (boosted top)
    - top tagging

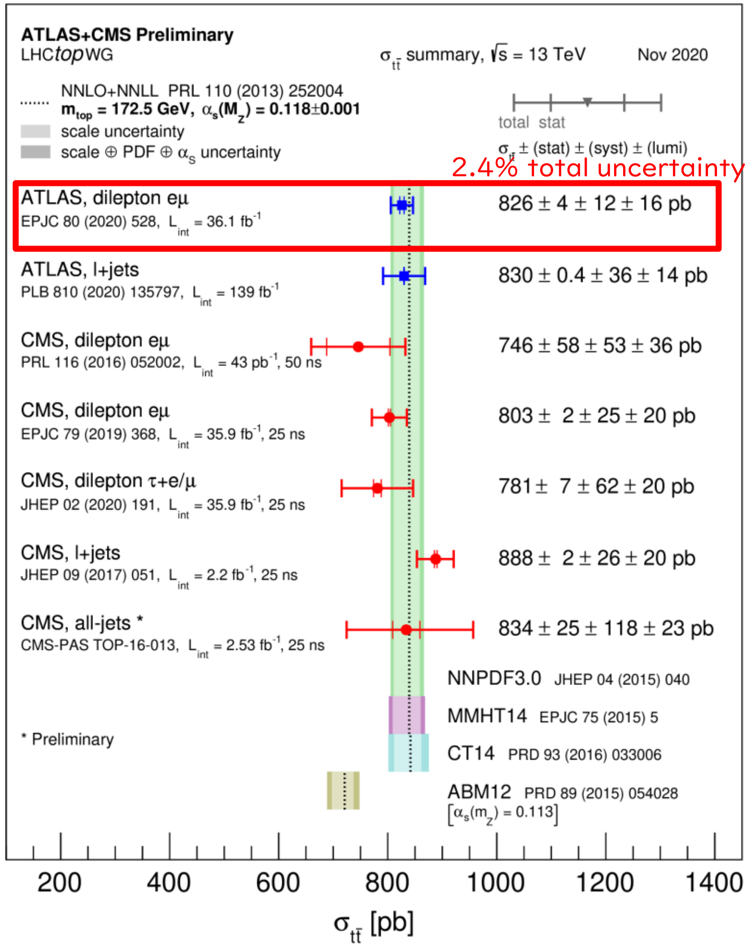


production cross-section measurements

$t\bar{t}$ production cross-section measurements

- Can precisely test pQCD
- Measurements have been performed in the various CMS-energy/final-state

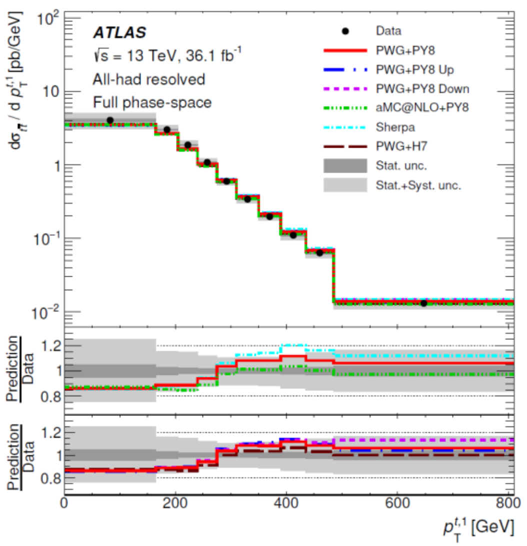


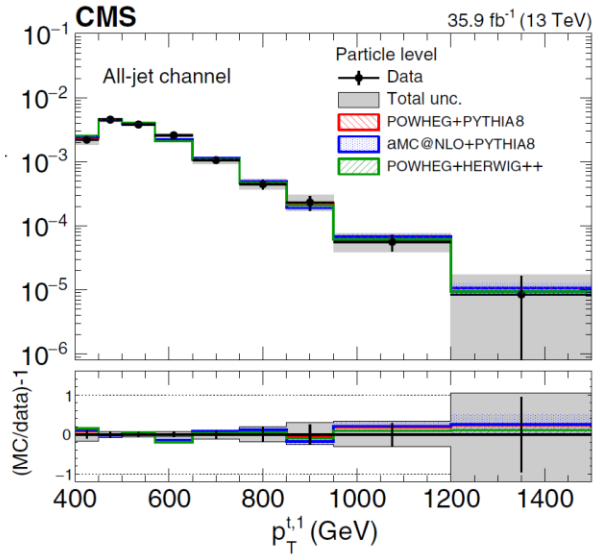


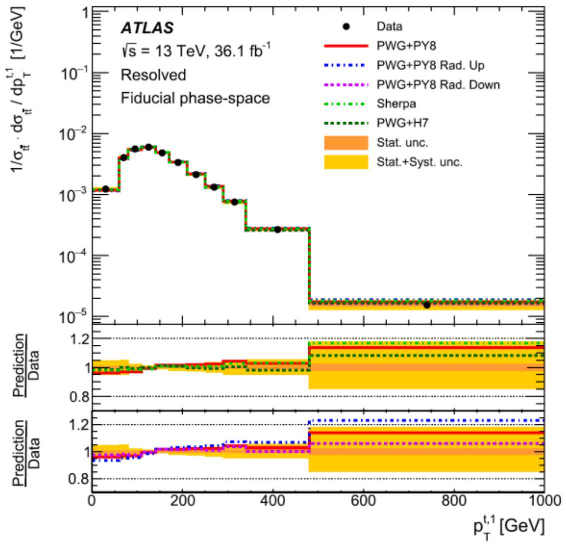
Differential cross-sections

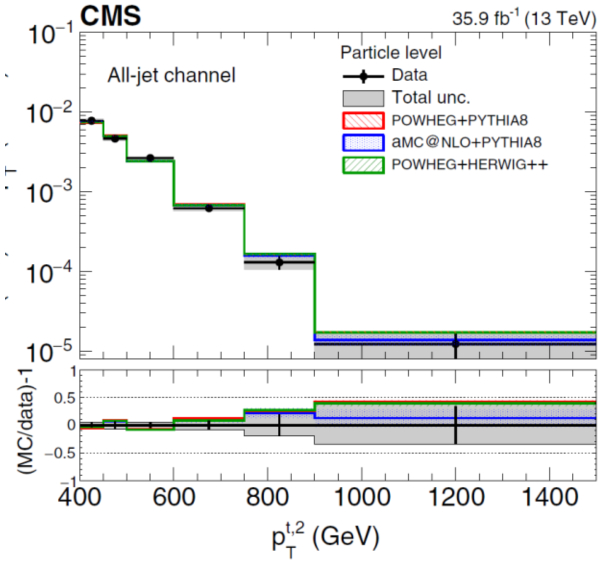
PHYS. REV. D 103, 052008 (2021)
Eur. Phys. J. C (2019) 79:1028
JHEP01(2021)033

- Differential cross sections can be used to test SM predictions and MC generators
  - Precision measurements are sensitive to new physics
- A lot of measurement have been performed
- Some tension between data and MC are observed
  - Significant over-prediction of $\sigma_{t\bar{t}}$ at higher p_T^t (also N_{jets} and $p_{T,tt}$)
  - Better models are needed to reproduce the data well





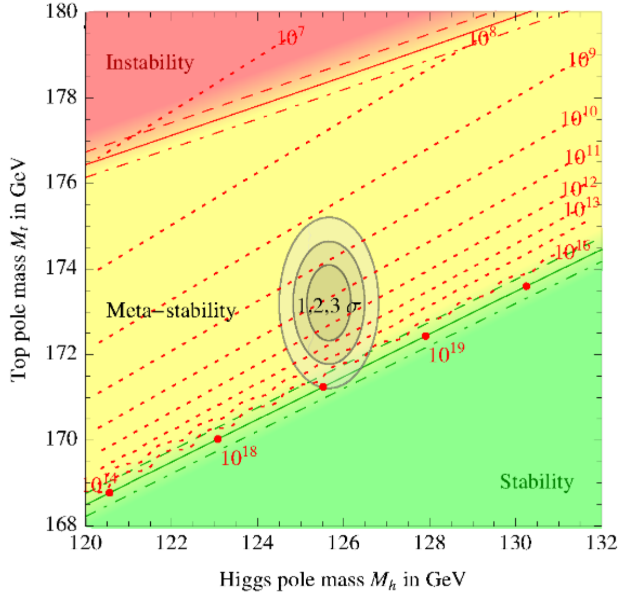




top mass and properties

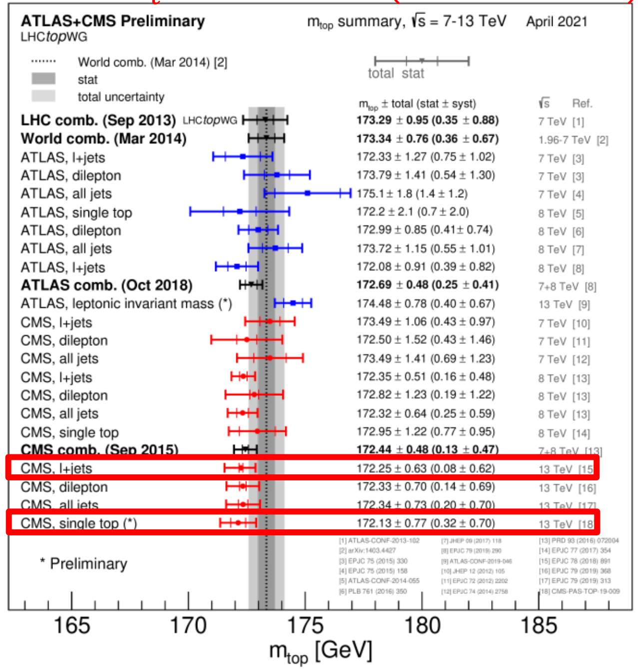
Mass of the top quark

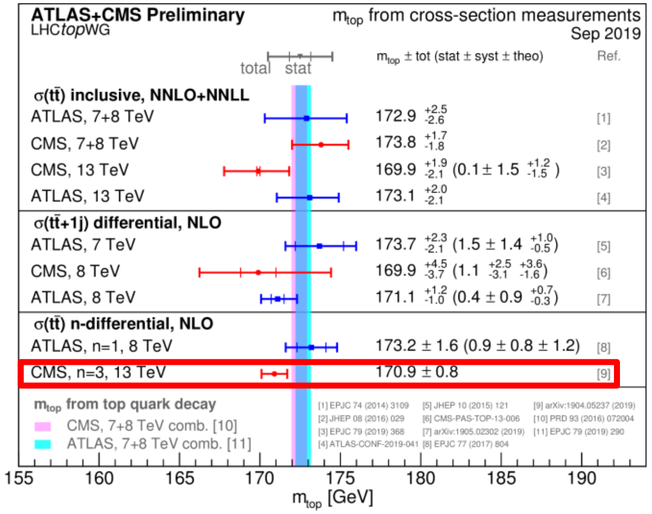
- The measured m_h and m_t are at the boundary between stable and metastable
  $\Rightarrow$ $\delta m_h \approx$ 0.2 GeV (Recent LHC status)
  - m_t measurement is becoming more important



- What is the mass of top quark?
  - MC mass？ m_t^{MC}
  - Pole mass？ m_t^{pole}
- How to measure them?
  - Direct measurement; m_t^{MC}
    - Reconstruct from top decay objects
  - Indirect measurement; m_t^{pole}
    - Extract from measured cross-section

Best $\delta m_t^{\mathrm{MC}} \sim$ 0.5GeV (Run-I comb.)

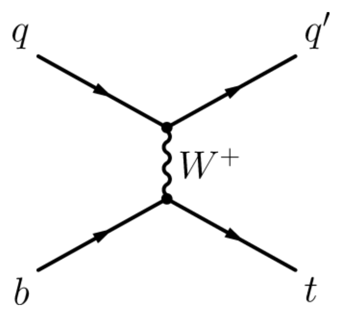




m_t in single top events

m_t in single top:

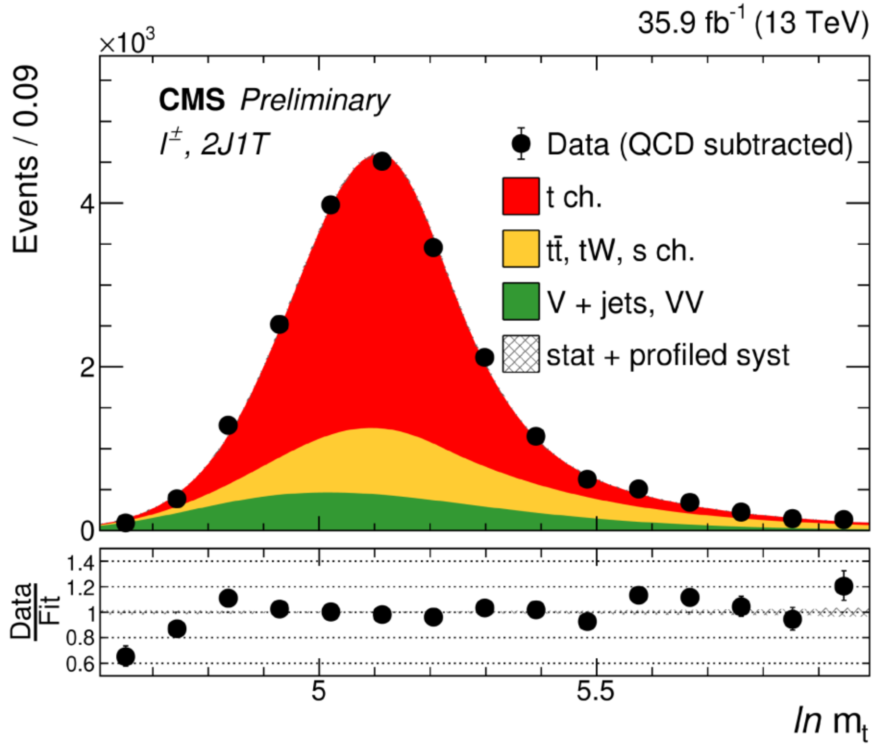
- Unique measurement in an independent process
- (partially) Uncorrelated systematics w.r.t. tt measurements
- lepton + jets final state
  - QCD/tt/W+jets background
    → BDT discriminant
- Extraction of top mass
  - m_t distribution highly skewed
    → difficult to model accurately
    using parametric shapes
  - ✓ Use $\ln m_t$ distribution
- Results



$$m_t = 172.13 \pm 0.32\,(\text{stat}+\text{prof})\,{}^{+0.69}_{-0.70}\,(\text{syst})\ \text{GeV} = 172.13^{+0.76}_{-0.77}\ \text{GeV}$$

$$m_t = 172.62 \pm 0.37\,(\text{stat}+\text{prof})\,{}^{+0.97}_{-0.65}\,(\text{syst})\ \text{GeV} = 172.62^{+1.04}_{-0.75}\ \text{GeV}$$

$$m_{\bar{t}} = 171.79 \pm 0.58\,(\text{stat}+\text{prof})\,{}^{+1.32}_{-1.39}\,(\text{syst})\ \text{GeV} = 171.79^{+1.44}_{-1.51}\ \text{GeV}$$



Running of the top quark mass

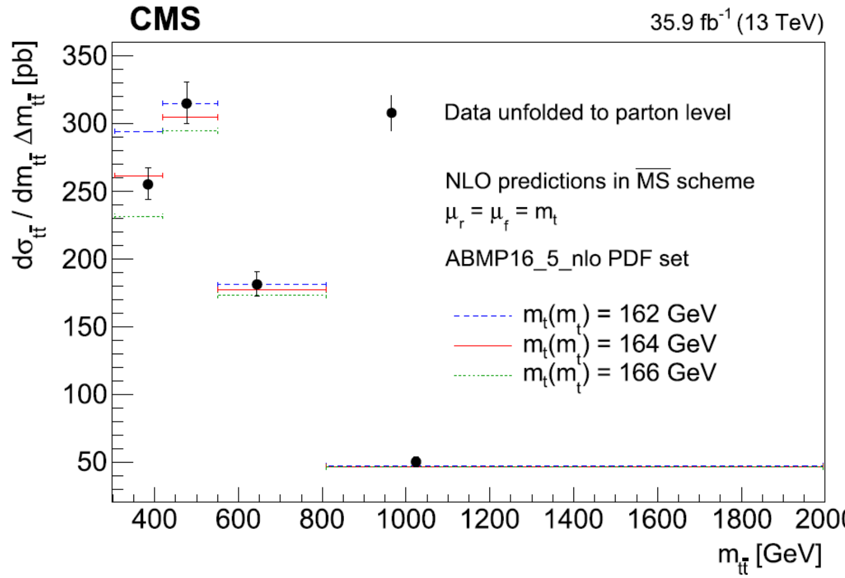
PLB 803 (2020) 135263

In $\overline{\mathrm{MS}}$ scheme, the value of m_t depends on energy scale ($\propto m_{tt}$)

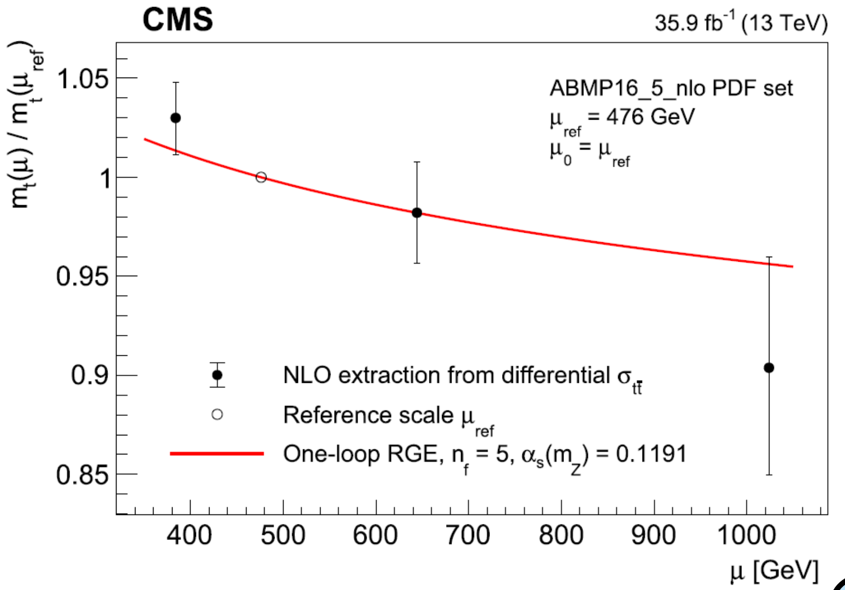
- Like α_s

→ **running of $m_t(\mu_m)$**

$$\mu^2 \frac{\mathrm{d}m(\mu)}{\mathrm{d}\mu^2} = -\gamma(\alpha_S(\mu))\, m(\mu),$$



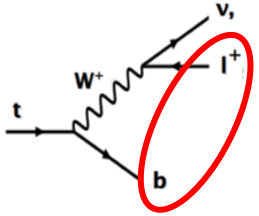
- Differential cross section as a function of m_{tt}
- Running factor extracted by comparing to NLO predictions

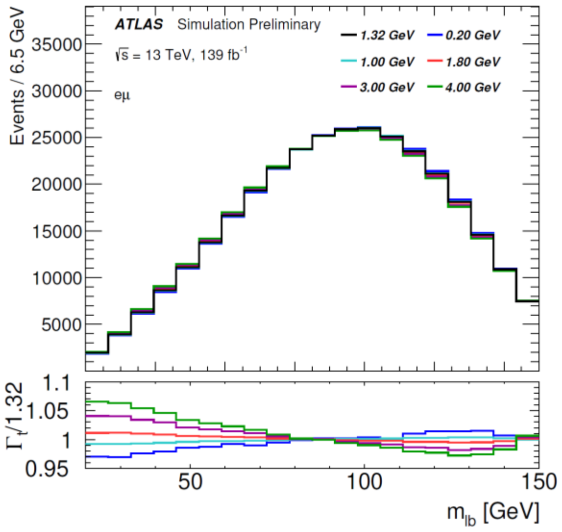


- The extracted running is found to be compatible with the scale dependence
  - no-running hypothesis is excluded at 95% C.L.
- The running is probed up to ~1 TeV

Top decay width

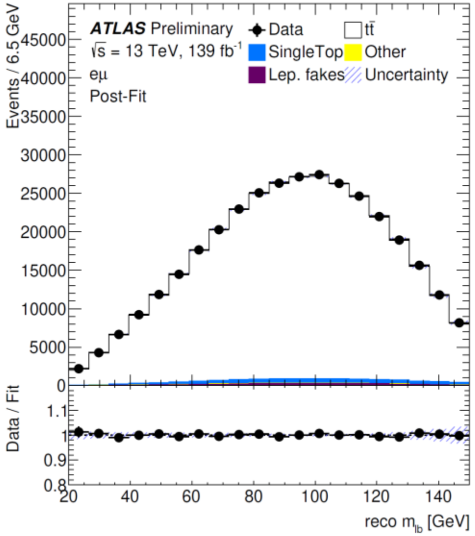
- Top decay width; One of the fundamental properties of the top quark
  - Direct measurement from m_{lb}
    m_{lb}: Invariant mass of charged lepton and bottom quark in top decays

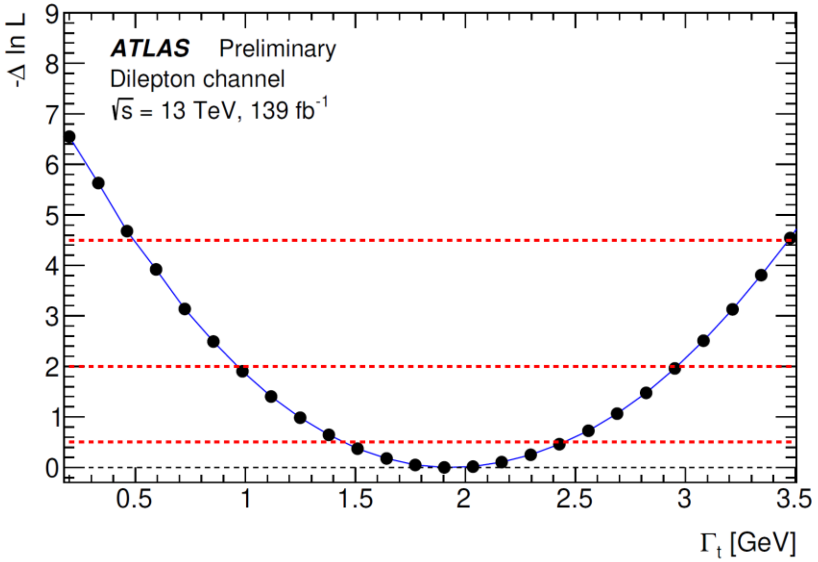




  ⇔ Indirect measurement: $\Gamma_t = 1.36 \pm 0.02(\mathrm{stat})^{+0.14}_{-0.11}(\mathrm{syst})\ \mathrm{GeV}$

  - Could hint
    - non-SM decay channels of the top quark
    - modification of top-quark couplings





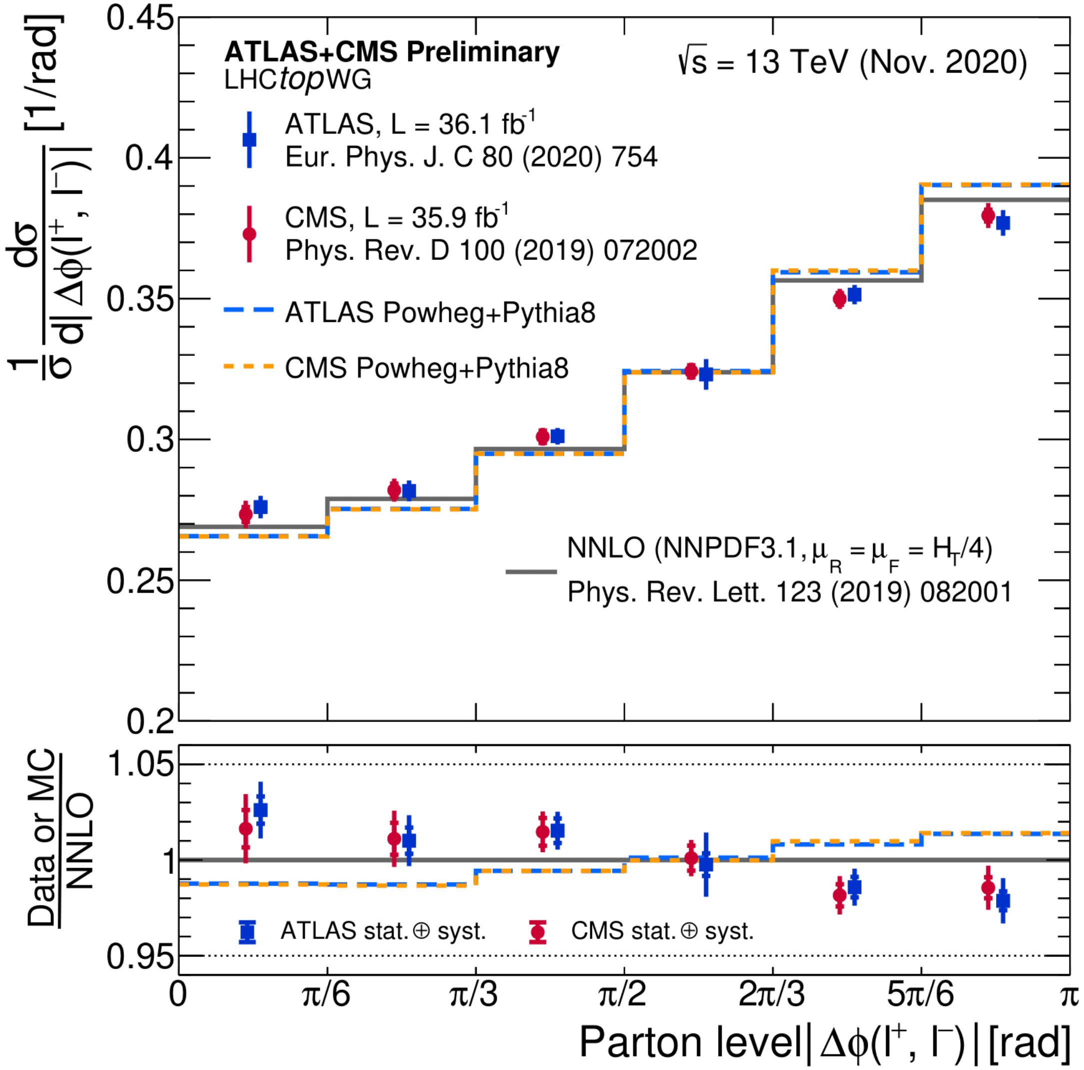
Γ_{top} = 1.9 ± 0.5 GeV

SM: 1.32 GeV @ m_{top} = 172.5 GeV

$t\bar{t}$ spin correlations

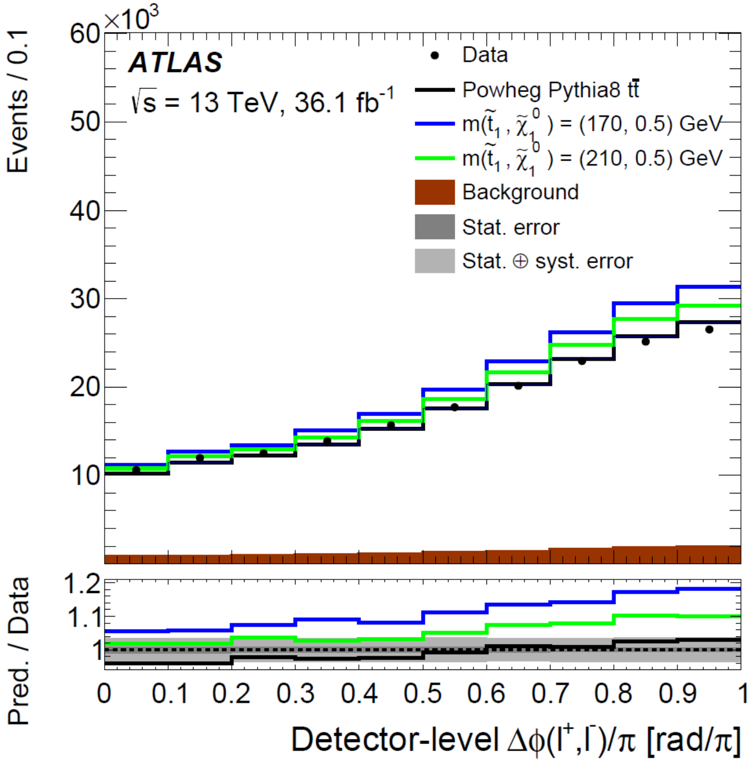
EPJC 80 (2020) 754
PRD 100 (2019) 0720002

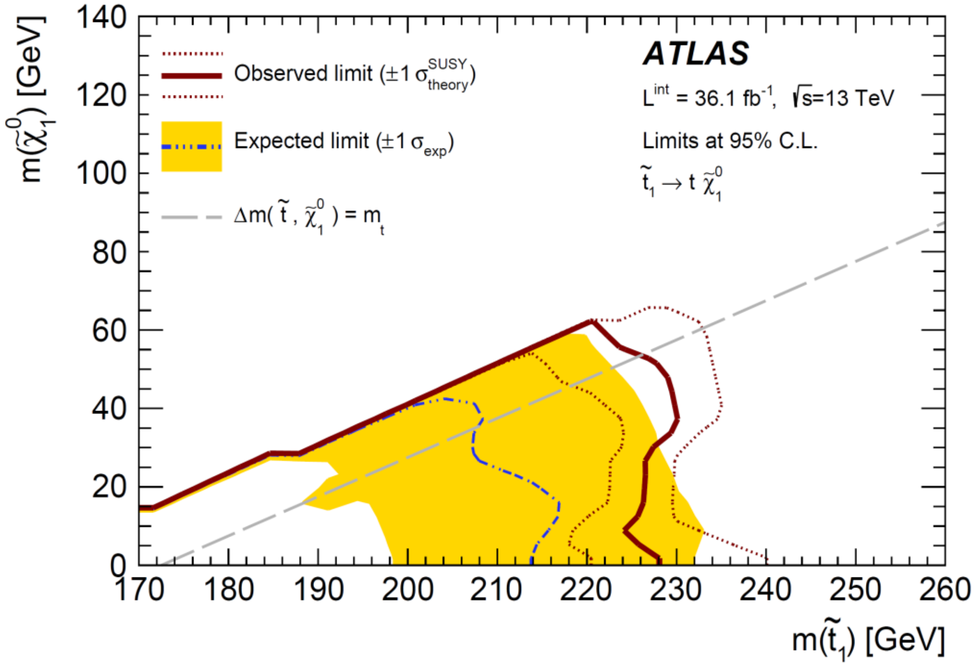
- top-quark pairs should be produced without polarization, while spin of t and $\bar{t}$ are correlated
  → Charged leptons carry full spin information ($a_\ell \sim 1$)
- dilepton ($e\mu$ or $e\mu$ / $\mu\mu$ / ee) channel is used
  - Angle between the leptons is sensitive to spin correlations
- Results are unfolded to both the parton-level
- MC and NNLO predictions does not much to the data



SUSY interpretation: $t\bar{t}$ spin correlations

- A search is performed for stop pair decaying into SM top quarks and light neutralinos
- Top squarks with masses between 170 and 230 GeV are excluded for most kinematically allowed neutralino mass





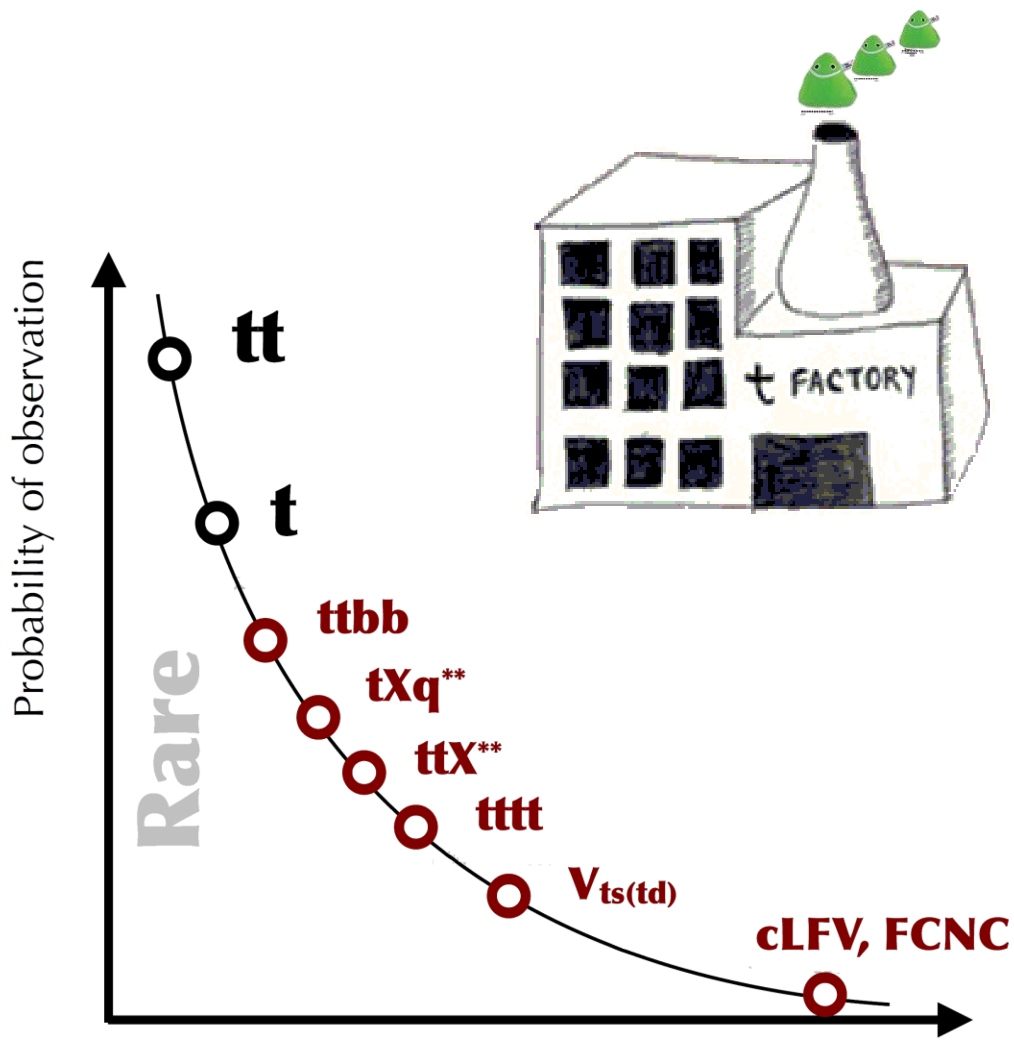
Rare top quark processes

SM rare process

- Is the SM still correct in extreme phase space?
  - Can be tested in rare SM process

Ex)

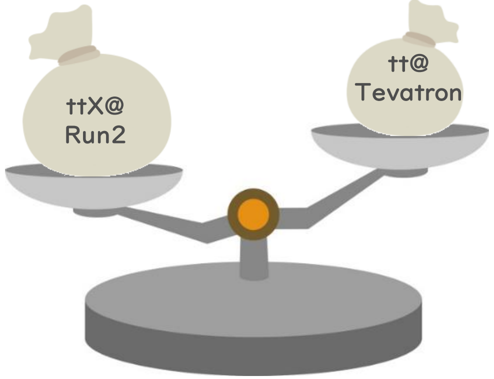
- $t\bar{t}bb,\ t\bar{t}X,\ t\bar{t}t\bar{t}$
  - Very rare SM processes
  - Can be measured thanks to huge LHC data
  - Important backgrounds for future BSM searches
- FCNC
  - Not sensitive at the LHC
  - If BSM exist, possible enhance

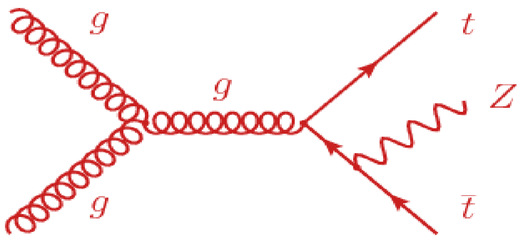


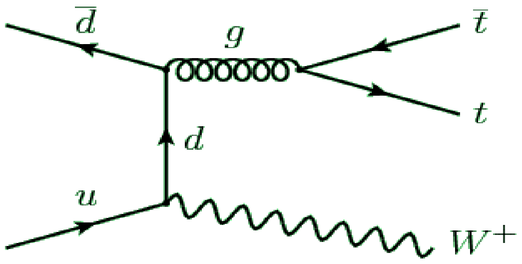
tt+X production

Phys. Rev. D 99, 072009

- Associate production with Vector bosons or photon
  - very rare $\sigma_{ttX}{}^{SM} < 1\ \mathrm{pb}$ $(\Leftrightarrow \sigma_{tt}{}^{SM} \sim 1\ \mathrm{nb})$
  - LHC has more ttX than tt at Tevatron
  - important to ttH, VLQ, SUSY searches







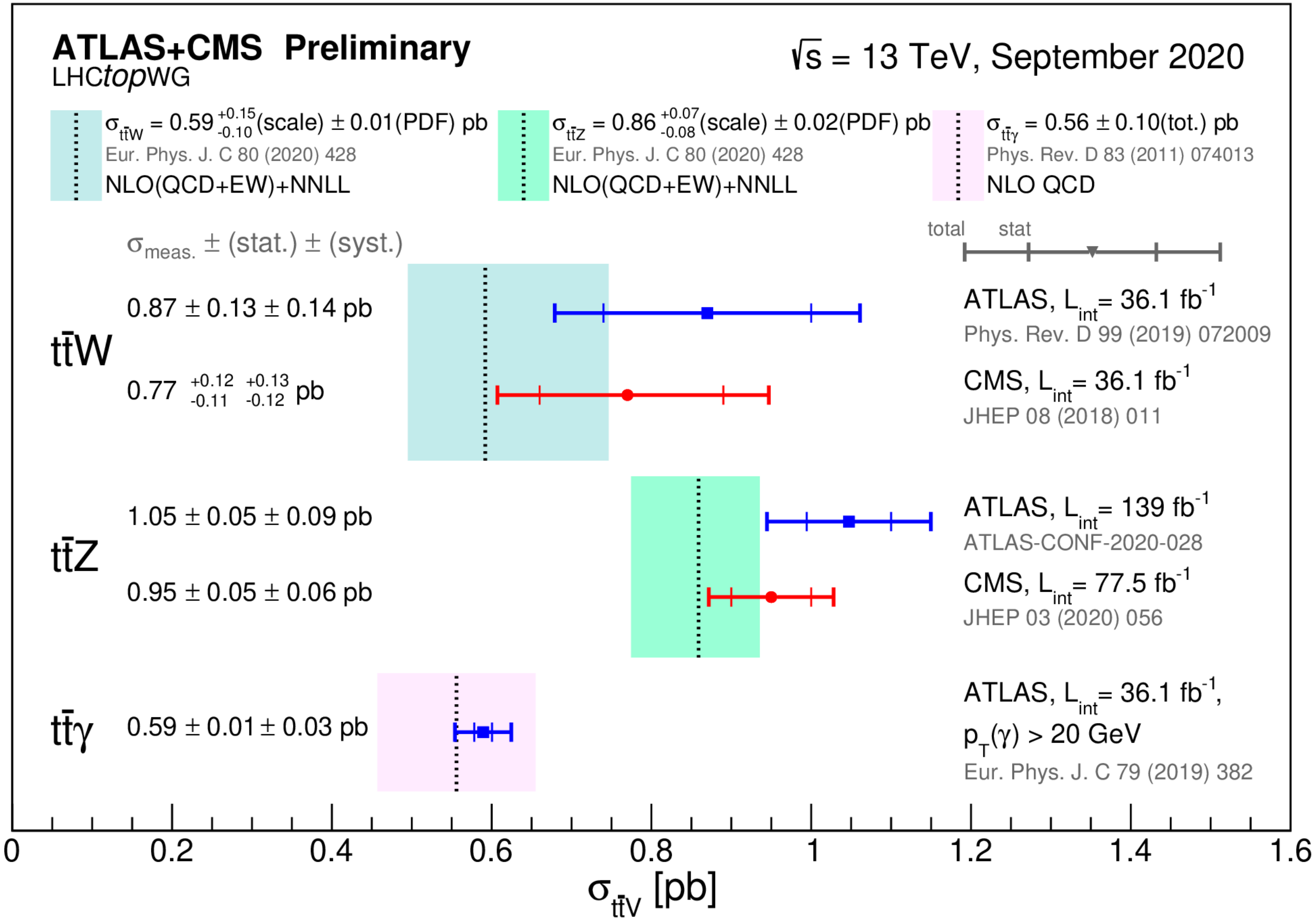
- tt+Z
  - Sensitive neutral current coupling between t and Z
  - Sensitive EFT operator related to tZ coupling
  - BSM can alter cross-section
- tt+γ
  - Sensitive to tγ electroweak coupling
- tt+W
  - Having Same sign lepton pair final state
    - Very rare for SM processes
  - Important final state in the many BSM searches

$$C_V^{SM} = T^3 - 2Q_t sin^2(\theta_W)$$

$$\gamma^\mu (C_V^{SM} - \gamma_5 C_A^{SM})$$

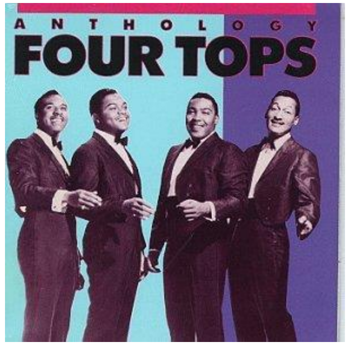
$$C_A^{SM} = T^3$$

Status of tt+X

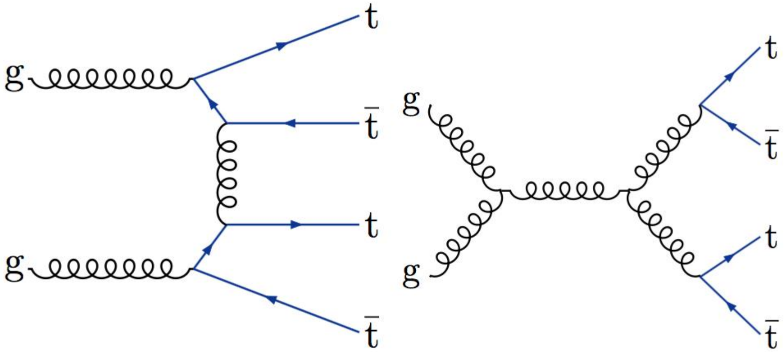


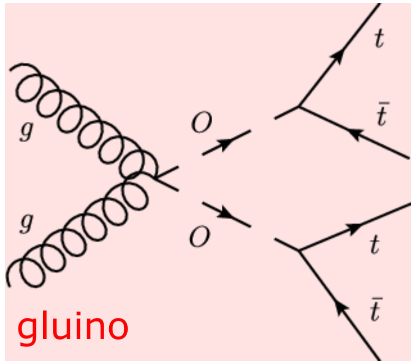
Eur. Phys. J. C (2020) 80:1085
ATLAS-CONF-2021-013

Four tops; $t\bar{t}t\bar{t}$

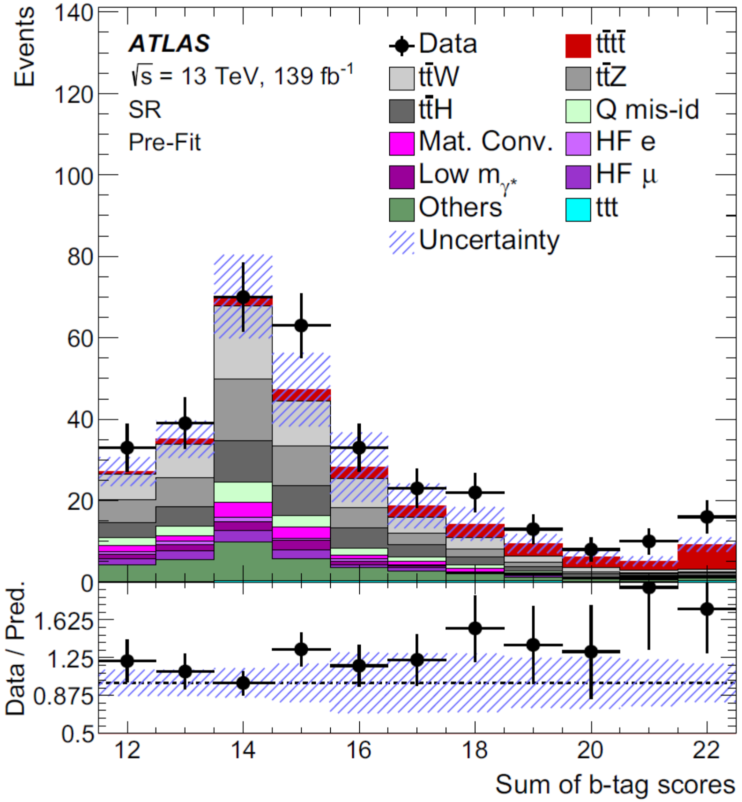


- $\sigma_{\mathrm{SM}}^{t\bar{t}t\bar{t}} \sim 12$ fb → Extremely rare process
  - CP properties of the Yukawa coupling
  - Many BSM enhance four tops





- Event selection
  - **Same-sign lepton pair and at least three leptons**
  - Single lepton and opposite-sign dilepton
  - Look for many jets and b-jets signal
  - BDT employed to separate signal and backgrounds
    - ex) Jet multiplicity, jet flavor and event kinematics



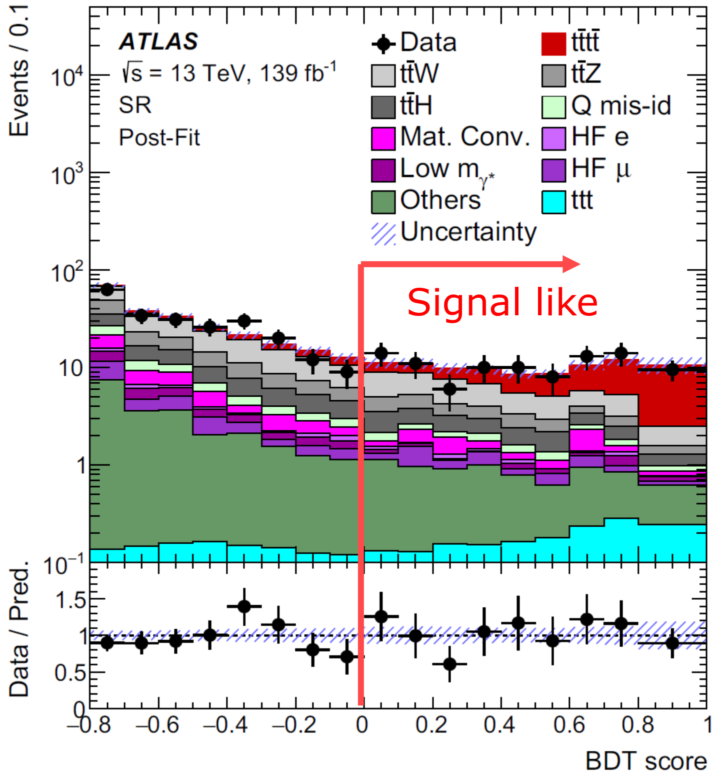
Results; $t\bar{t}t\bar{t}$

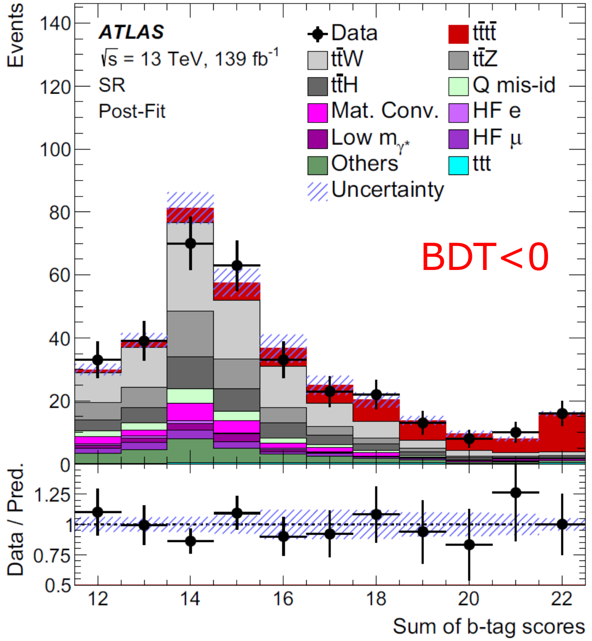
Eur. Phys. J. C (2020) 80:1085

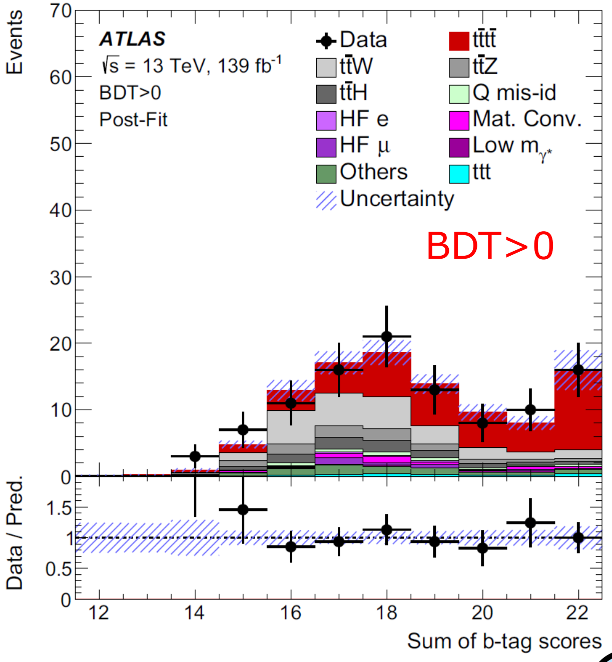
- Signal and backgrounds normalizations are determined by likelihood fit
  - to the BDT
- Uncertainties
  - Signal modelling
    - cross-section
    - modelling
  - ttW modelling
  - Statistical unc.
- Measured cross-section is

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5(\text{stat})\ ^{+5}_{-4}(\text{syst})\ \text{fb} = 24\ ^{+7}_{-6}\ \text{fb}.$$

Standard Model expectation of $\sigma_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4$ fb.

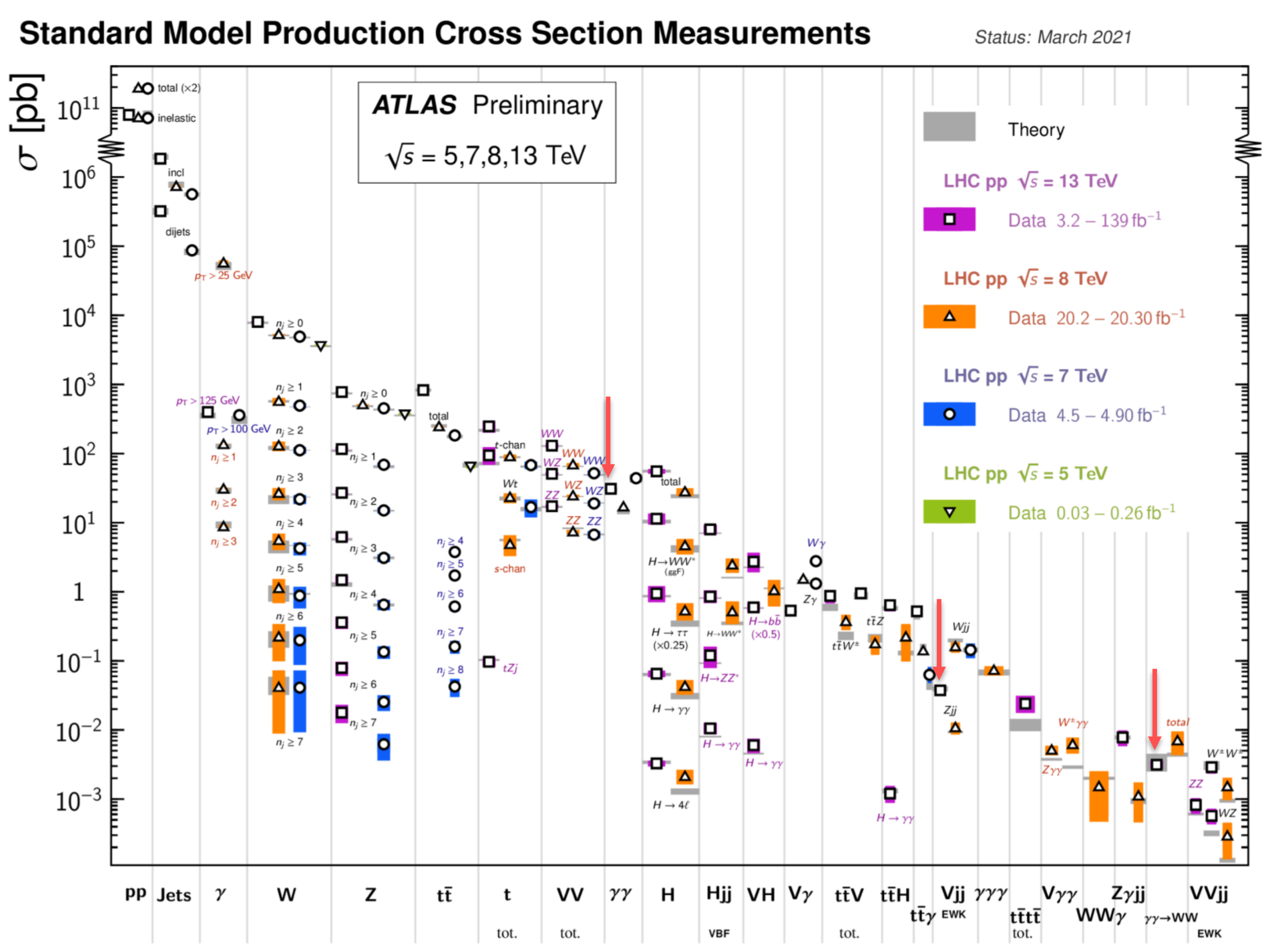




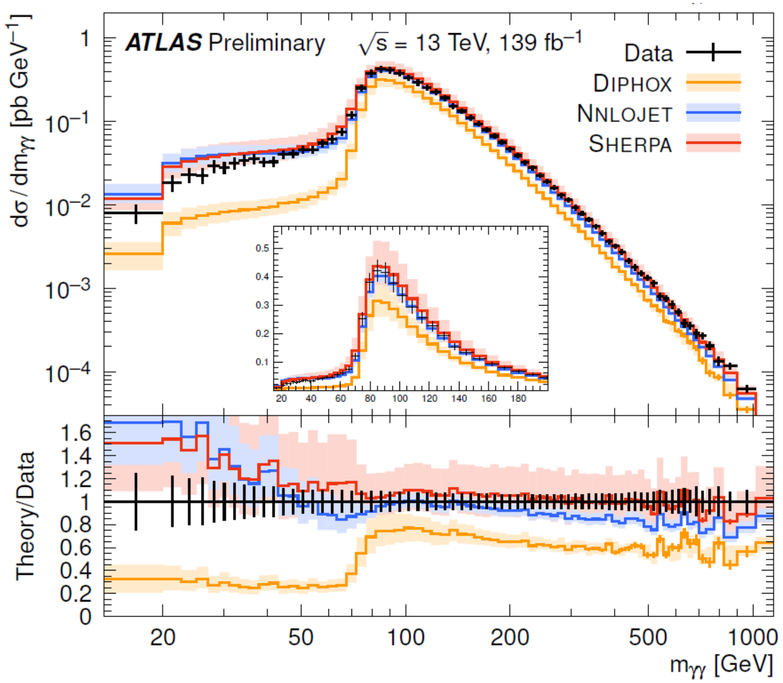


Standard model

Standard model measurements

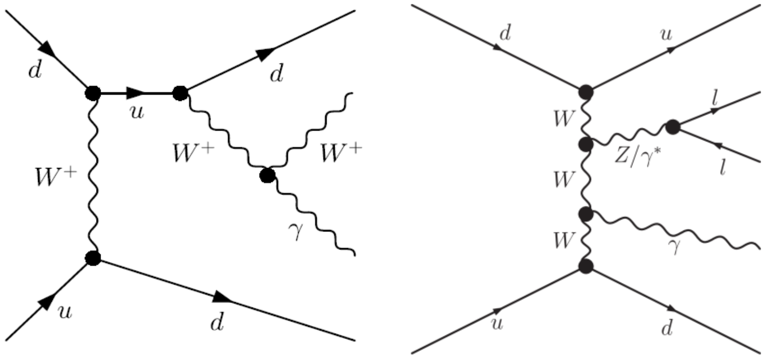


- Various SM cross-section measurement have been performed
- SM can describe the experimental results in the wider region !
- Differential cross-sections

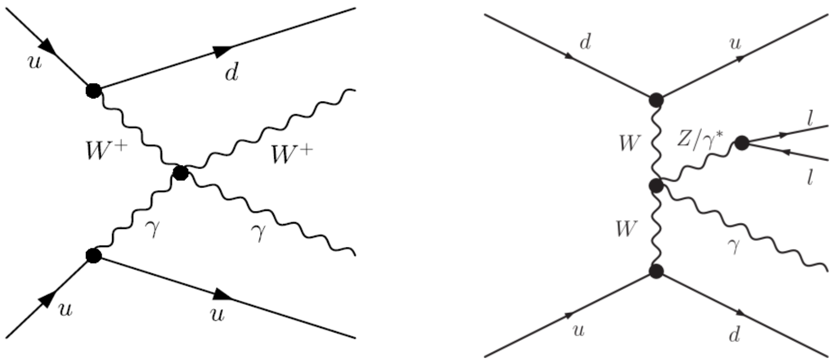


Phys. Lett. B 811 (2020) 135988
CMS-PAS-SMP-20-016

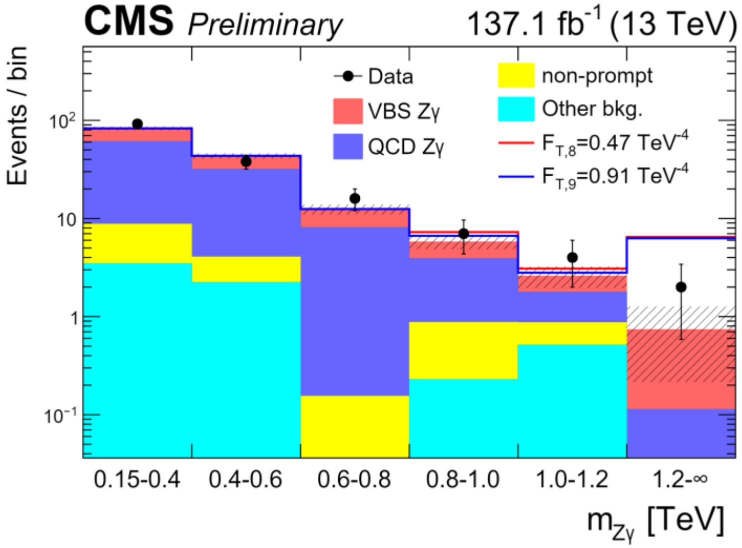
Vγ scattering

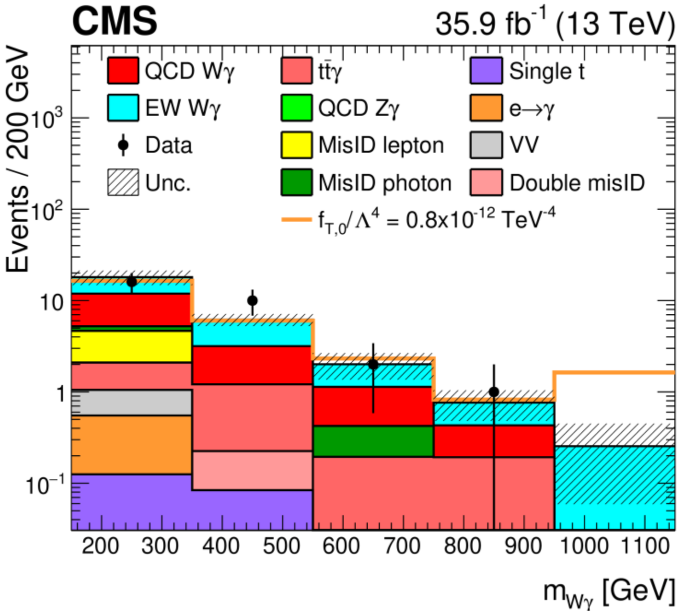


Triple gauge coupling



Quartic gauge coupling



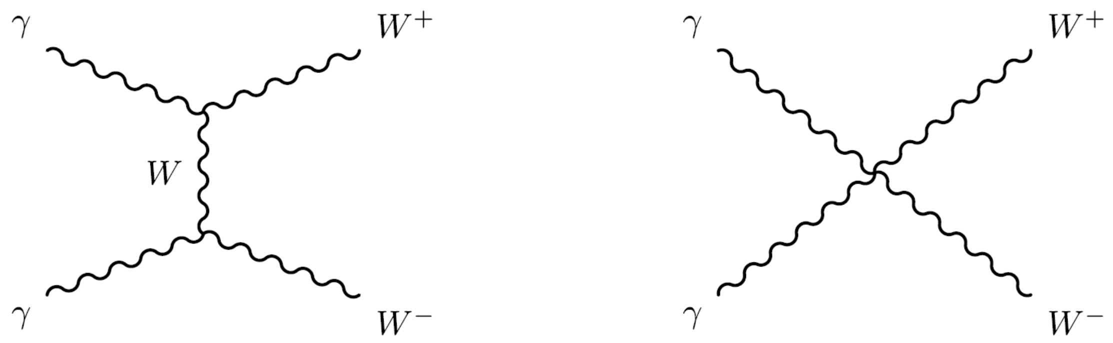


- Sensitive to QGCs pr aQCGs
  - VV and H more sensitive to TGCs
- In good agreement with recent theoretical predictions
- Constraints on anomalous couplings

Phys.Lett.B816(2021)136190

Large Photon Collider : $\gamma\gamma \rightarrow WW$ process

- LHC is also the "Large Photon Collider"



- $\gamma\gamma \rightarrow WW$
  - Sensitive to trilinear and quartic γ+W couplings
  - Also sensitive to the BSM
- Keys
  - Separation from QCD events (incl. pp→WW production)
    → **Charged track multiplicity**
  - Initial parton interaction not included in the simulation
  - Only elastic scattering is modeled
    → Data driven correction

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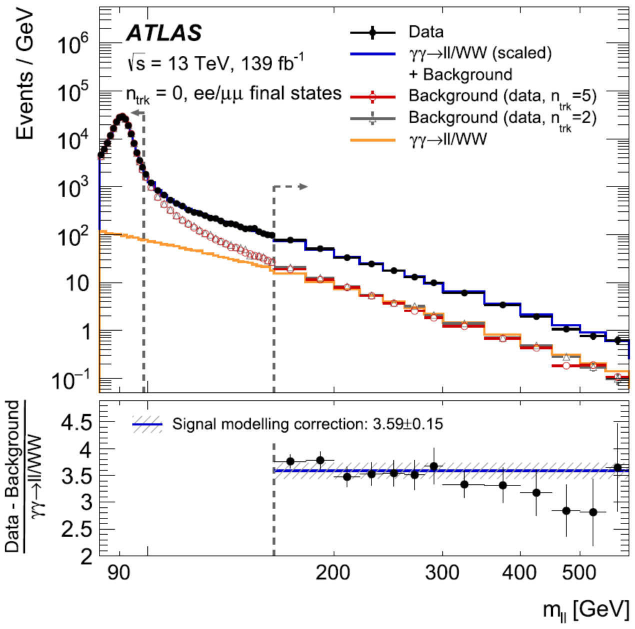
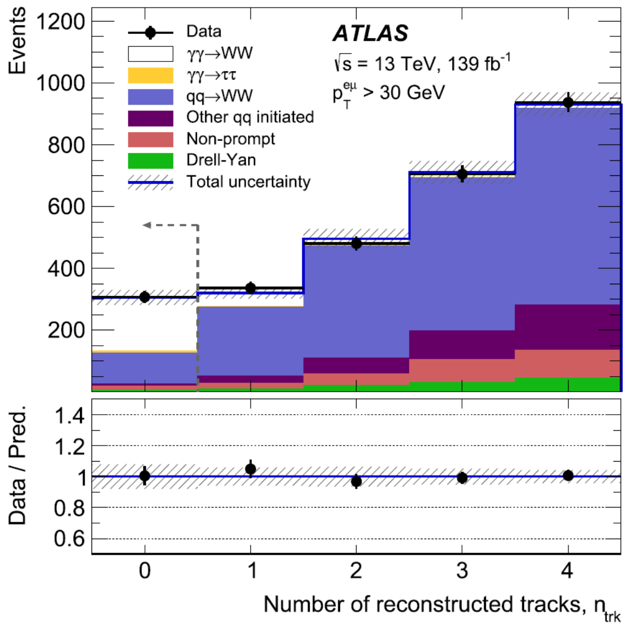
Cross-section measurement

- Data/MC correction using "Same Flavour CRs"
  - $\gamma\gamma \rightarrow \ell\ell$: Independent to $\gamma\gamma \rightarrow WW$ (~1%)
  - Derived correction factor

    $3.59 \pm 0.15\,(\mathrm{exp.}) \pm 0.39\,(\mathrm{trans.})$
  - Background templates from higher n_{trk} regions
- Separated by number of tracks
  - 0 track: Signal region
  - 1 or more tracks: Control region



	Signal region		Control regions	
n_{trk}	$n_{\mathrm{trk}} = 0$		$1 \leq n_{\mathrm{trk}} \leq 4$	
$p_{\mathrm{T}}^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \rightarrow WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \rightarrow \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell–Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \rightarrow WW$ (incl. gg and VBS)	101 ± 17	55 ± 10	1700 ± 270	970 ± 150
Non-prompt	14 ± 14	36 ± 35	220 ± 220	500 ± 400
Other backgrounds	7.1 ± 1.7	1.9 ± 0.4	311 ± 76	81 ± 15
Total	305 ± 18	459 ± 19	2460 ± 60	6320 ± 130
Data	307	449	2458	6332



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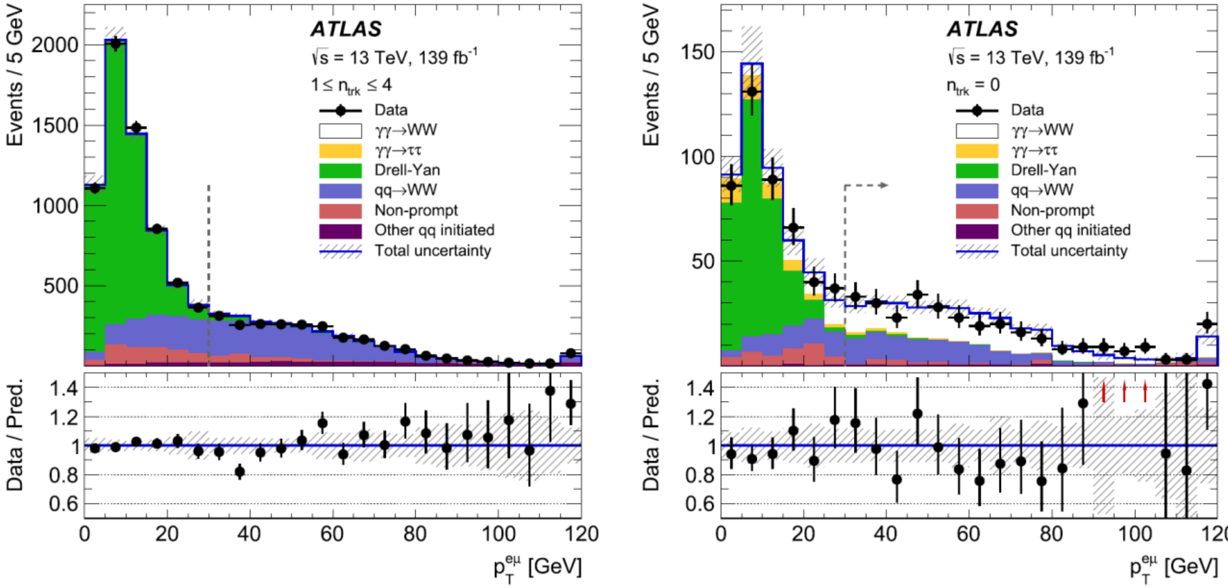
Results

- $p_{\mathrm{T}}^{e\mu}$ distributions in good agreement with observed data
  - 8.4 σ observation



- Measured cross section

$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$

$$\sigma_{\text{theo}} \times (3.59 \pm 0.15\,(\text{exp.}) \pm 0.39\,(\text{trans.})) = 2.34 \pm 0.27\ \text{fb}$$

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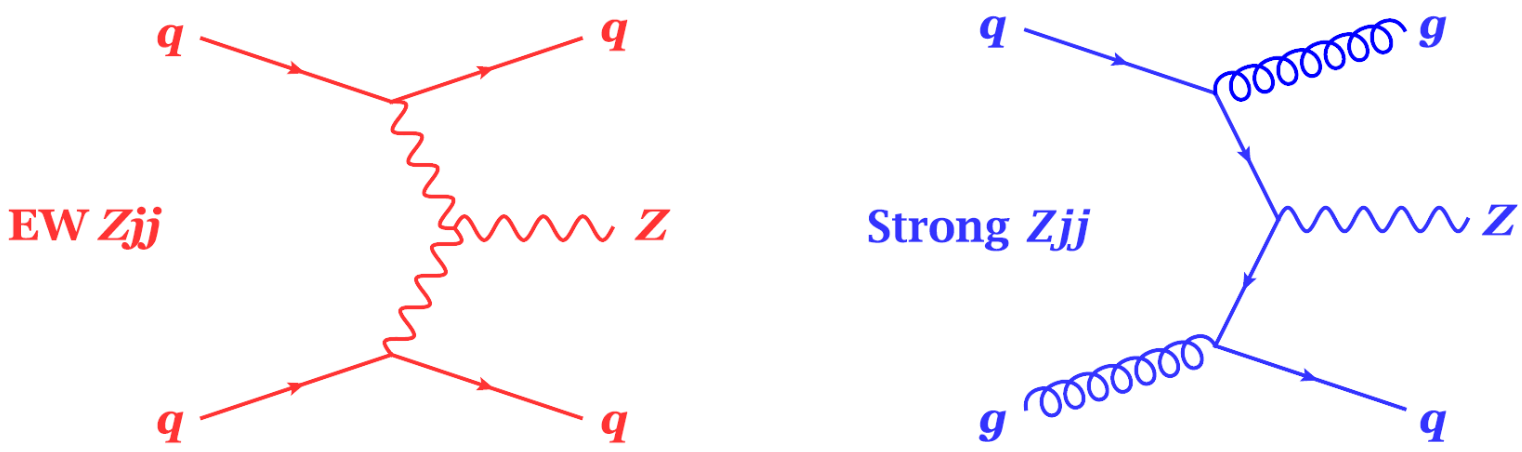
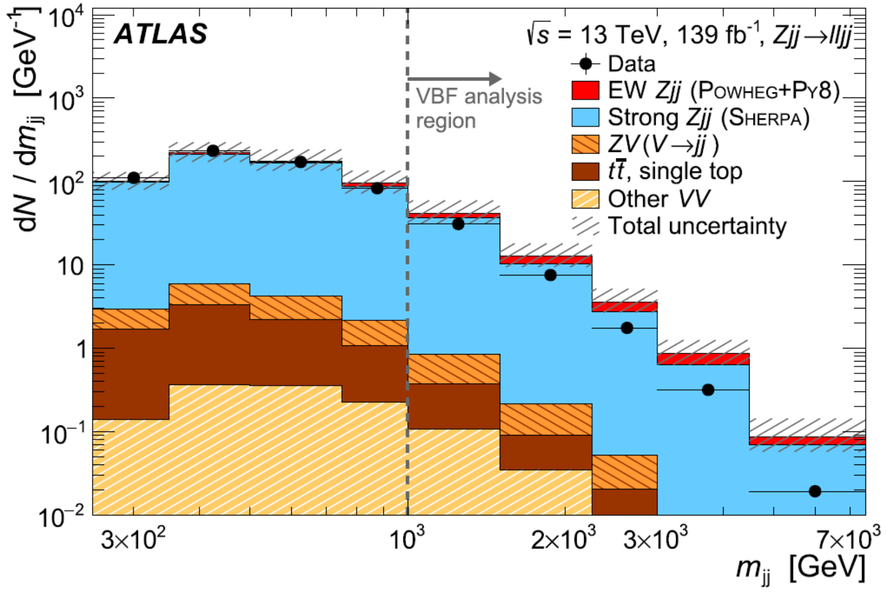
EW Z+jj

- Very sensitive to the VBF production mechanism



- Separation from strong Zjj production
  - m_{jj}: Invariant mass of two reading jets
  - N_{jets}^{Gap}: Jets in the rapidity interval between the 1st and 2nd jets
  - $\xi_Z = |y_{\ell\ell} - 0.5(y_{j1} + y_{j2})| \,/\, |\Delta y_{jj}|$: Z-boson centrally produced wrt dijet



Extraction of EW Zjj production

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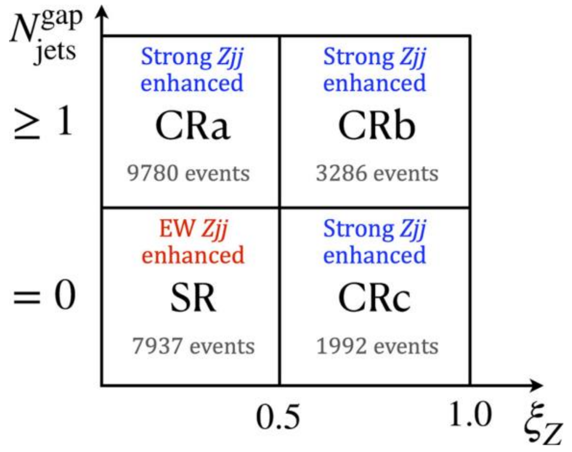
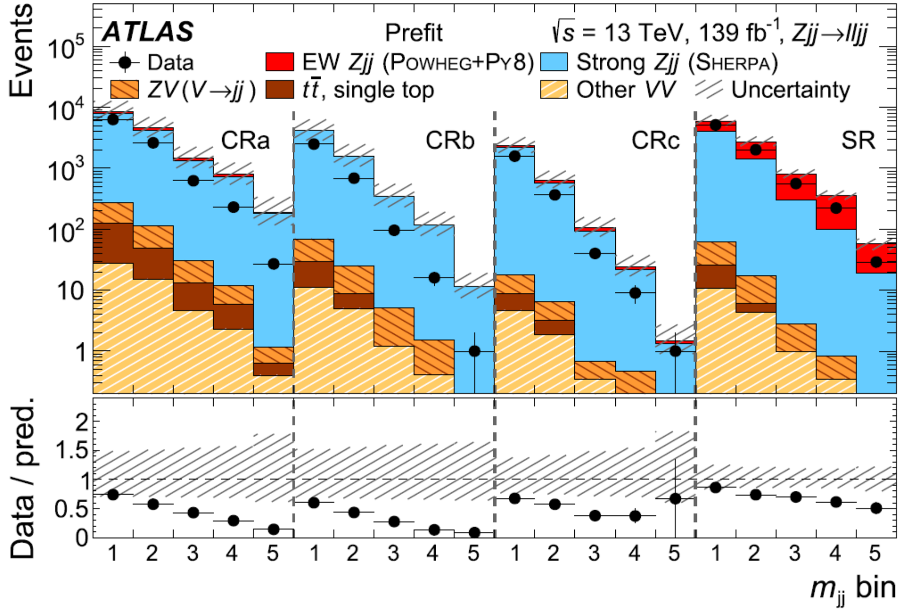
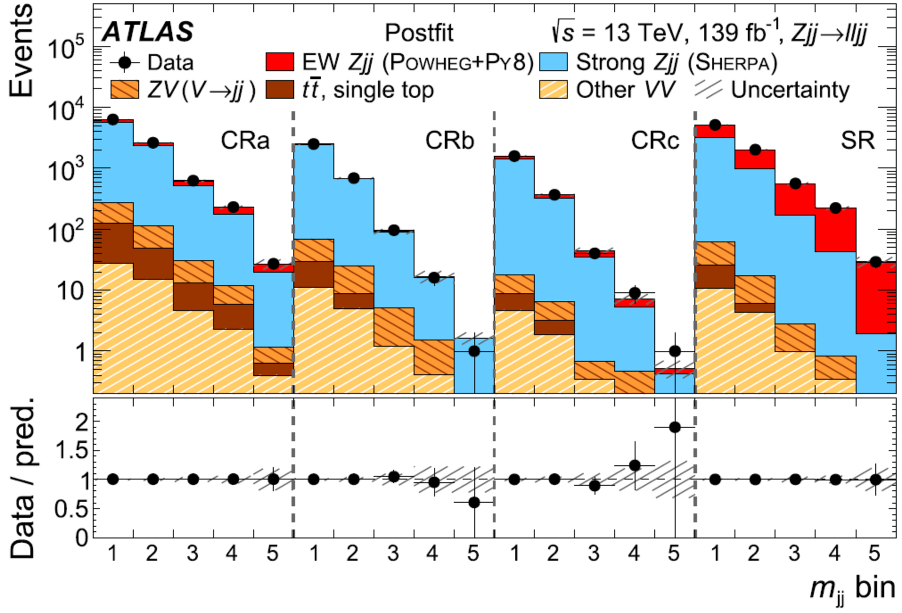
- Poor agreement between data and simulation
  → Data driven background estimation (Shape + Normalization)
- Unfold to particle level
  - Iterative Bayesian unfolding
- Fiducial cross-sections are measured to be

$$\sigma_{\mathrm{EW}} = 37.4 \pm 3.5\,(\mathrm{stat}) \pm 5.5\,(\mathrm{syst})\ \mathrm{fb}.$$

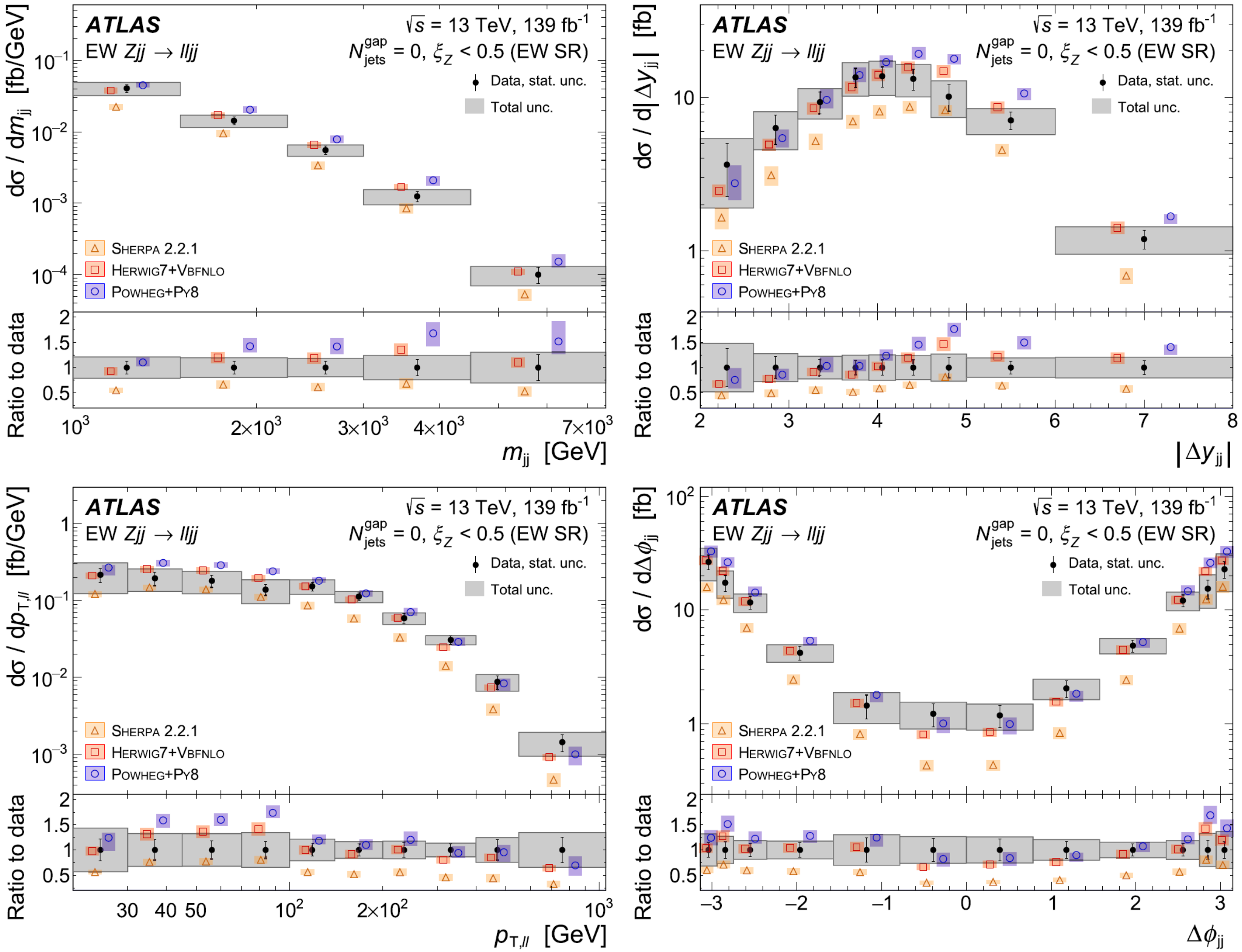






Differential cross sections

- HERWIG7+VBFNLO
  - reasonable agreement with the data
- POWHEG+PY8
  - overestimation at high m_{jj}, high $|\Delta y_{jj}|$, and intermediate $p_{T,ll}$
- SHERPA
  - Significant underestimate



Summary

- Various SM+top quark measurements have been performed
  - Only small part are showed in this talk…
- SM still powerful to describe production in the wider range
- Systematics already became dominant uncertainties
  - Improve modellings
  - Improve analysis
- A lot of ongoing analyses
  → Stay tuned !!