Measurement of the differential cross section for top-quark pair production in the dilepton channel at $\sqrt{s}$ = 13 TeV with the CMS detector

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(DESY)

Motivation

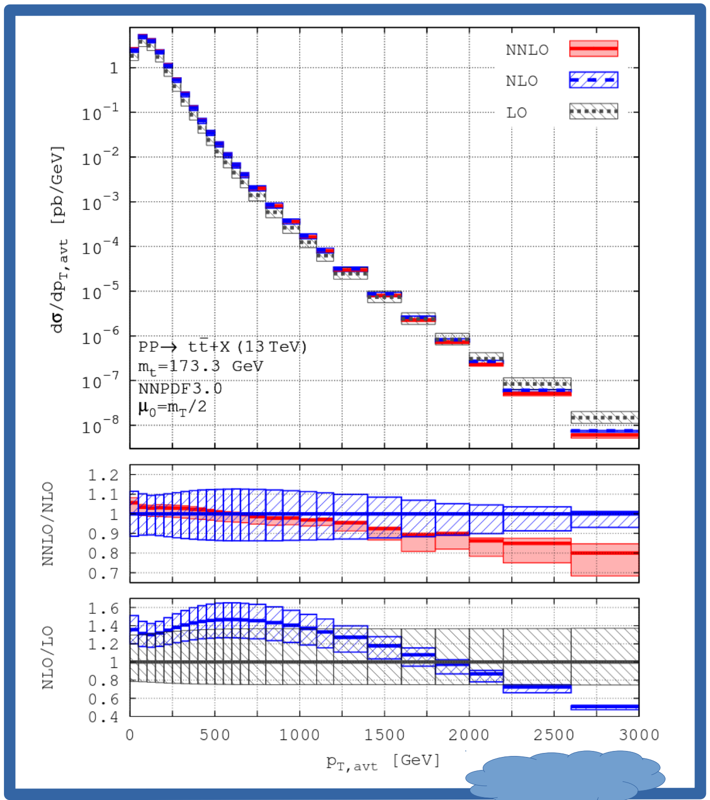
- **Precise understanding of top quark distributions is crucial:**

  > precision tests of perturbative QCD

  > validating Monte Carlo models
  and improving them via tuning

  > sensitive to new physics,
  e.g. SUSY, Z', Dark Matter

[arXiv:1606.03350]
M. Czakon, D. Heymes, A. Mitov



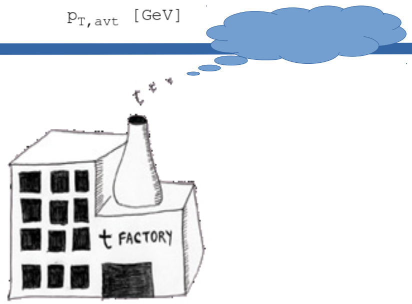
- **Goal**: measure $t\bar{t}$ differential cross sections in dilepton channel as a function of observables:

  → top quark or $t\bar{t}$ system

  → jet multplicity and other decay products

  > **parton** and **particle** (**new**) level

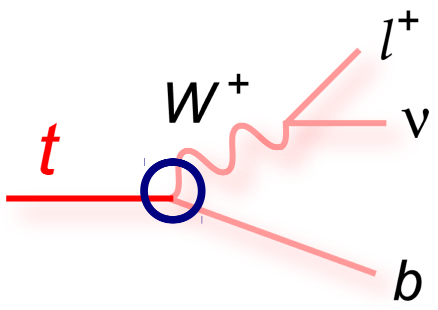
  > **normalized** and **absolute** (**new**) results



Why four types of cross sections?

- **Parton level** top quark in full phase space
  - after QCD radiation and before decay
  - mimics definition of the bare quark widely used in fixed order theory calculations

  → *can be used for extraction of SM parameters*



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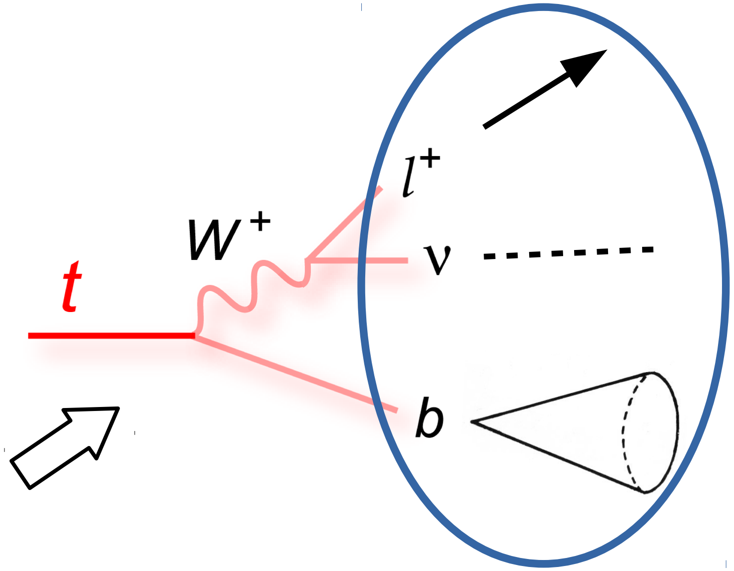

- **Particle level** top quark in fiducial phase space
  > based on the stable particles after hadronization

  > fiducial phase space defined closely to detector level

  > reduced effect from extrapolation of the results, MC generator choice and tuning

  → *useful for testing of theory models and MC tuning*

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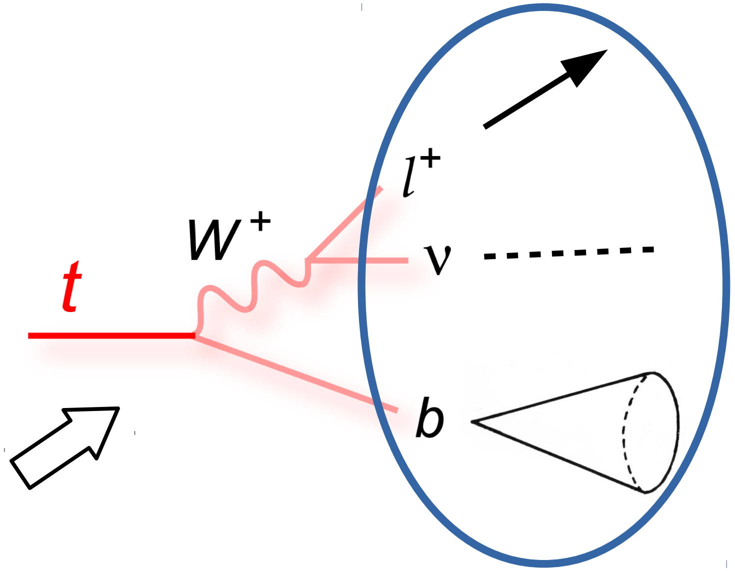

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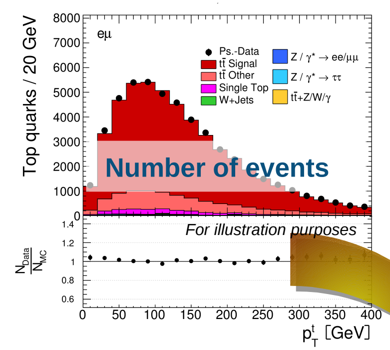
  - → *useful for testing of theory models and MC tuning*

- **Normalized** cross sections: mostly shape uncertainties contribute
  - → *minimized total uncertainty of the measurement*

- **Absolute** cross sections: contain rate info
  - → *useful for constraining theories sensitive to rate*

General analysis strategy

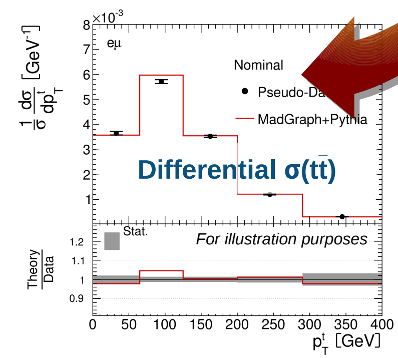
- **Main analysis ingredients**
  - > Event selection
  - > $t\bar{t}$ kinematic reconstruction (algebraic method)
  - > Bin-wise cross section measurement
  - > Unfolding: correct for detector effects & acceptance to parton or particle level after background subtraction



Δ^i_X = bin width for variable X

$$\frac{1}{\sigma}\frac{d\sigma}{dX_i} = \frac{1}{\sigma}\frac{unfold\left(N^X_{data,i} - N^X_{BG,i}\right)}{\Delta^i_X \cdot \int \mathscr{L}\, dt}$$

- **Differential $t\bar{t}$ cross sections**
  - > full phase space for parton level
  - > fiducial phase space for particle level



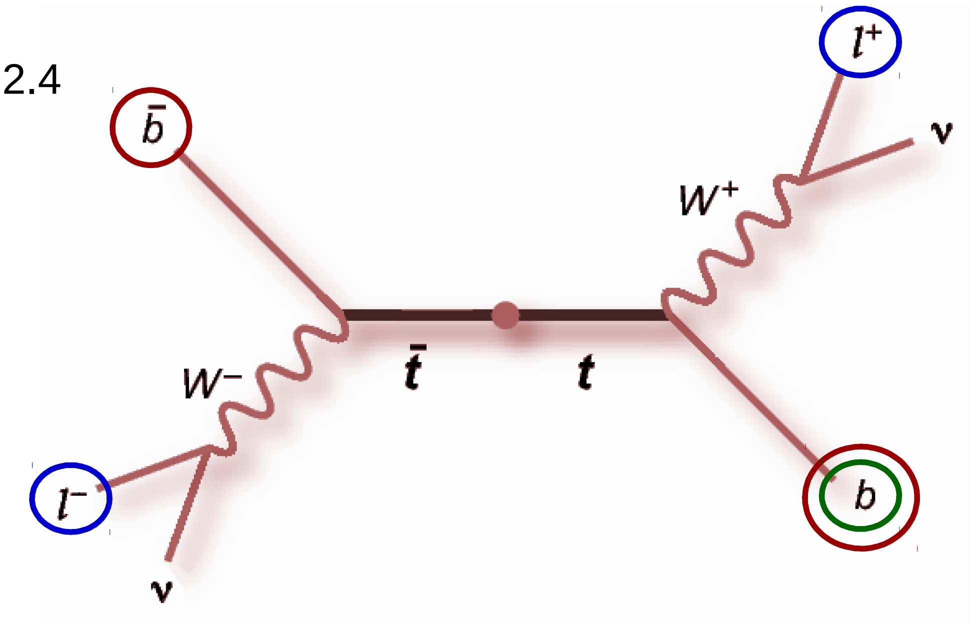
- **Results in this talk:** based on full dataset recorded by CMS in 2016 (L_{int} = 35.7 fb^{-1})

  → disclaimer: work is still in progress

Following similar analysis strategy as public results by CMS:
at **13 TeV** → PAS TOP-16-011 (dilepton)

Event selection in dilepton channel

- **Trigger selection** (also see talk by T. Arndt (T 4.4) on inclusive $t\bar{t}$ cross section)
- **2 high-p_T leptons (ee, μμ, eμ)**
  - $p_{T,1} > 25$ GeV, $p_{T,2} > 20$ GeV, $|\eta| < 2.4$
  - opposite charge
  - isolation criteria
- **QCD veto**: $m_{ll} > 20$ GeV
- **≥ 2 jets**: anti-k_T R = 0.4
  - $p_T > 30$ GeV, $|\eta| < 2.4$
  - Jet cleaning: ΔR(l, jet) > 0.4 against selected leptons
- **≥ 1 b-tagged jets**
- **ee, μμ channels**: $E_T^{miss} > 40$ GeV
  Z veto: $|m_Z - m_{ll}| > 15$ GeV

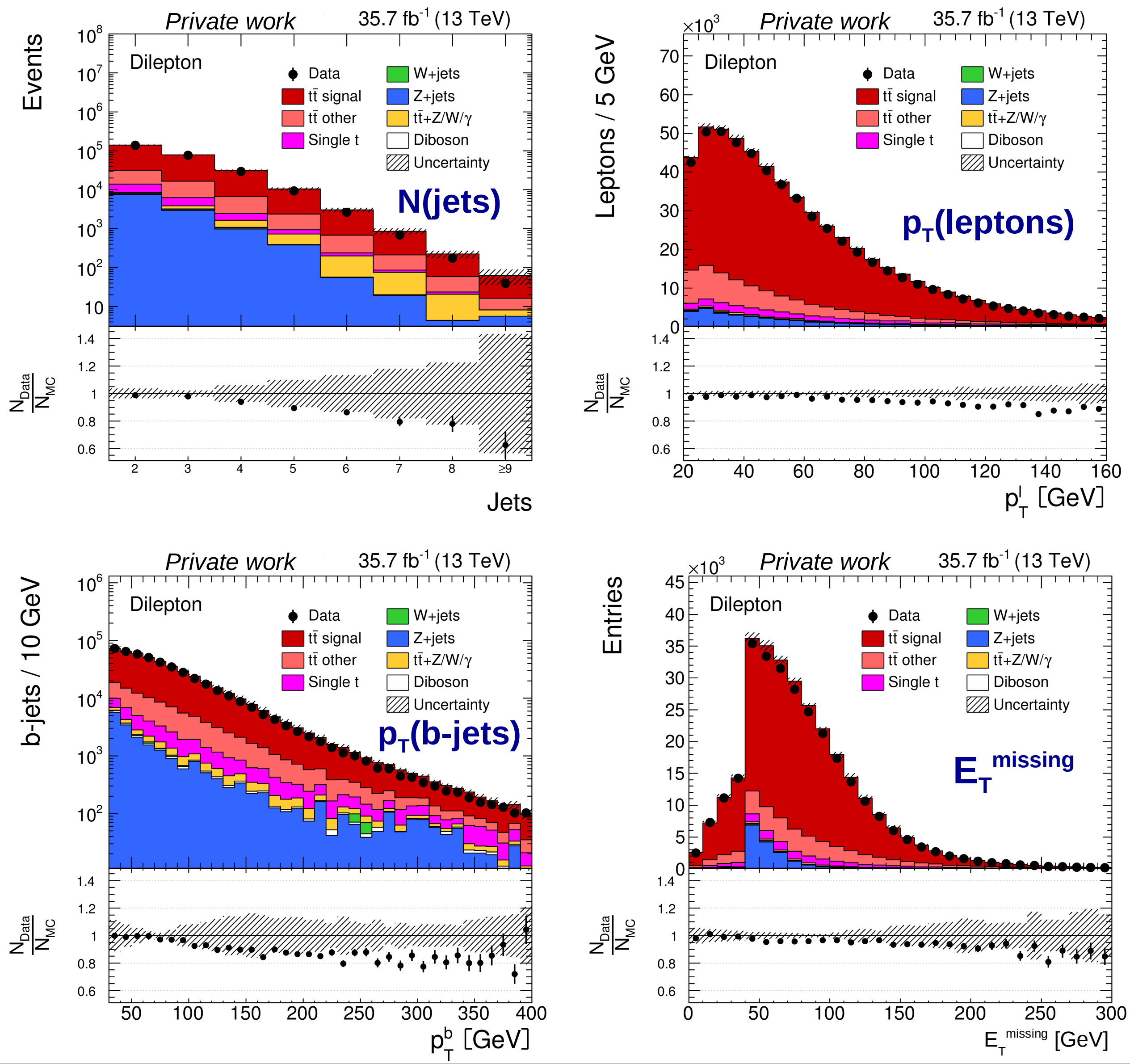


- **In addition**: <u>kinematic reconstruction</u> of $t\bar{t}$ system → event excluded, if no solution found

Kinematic distributions: final state objects

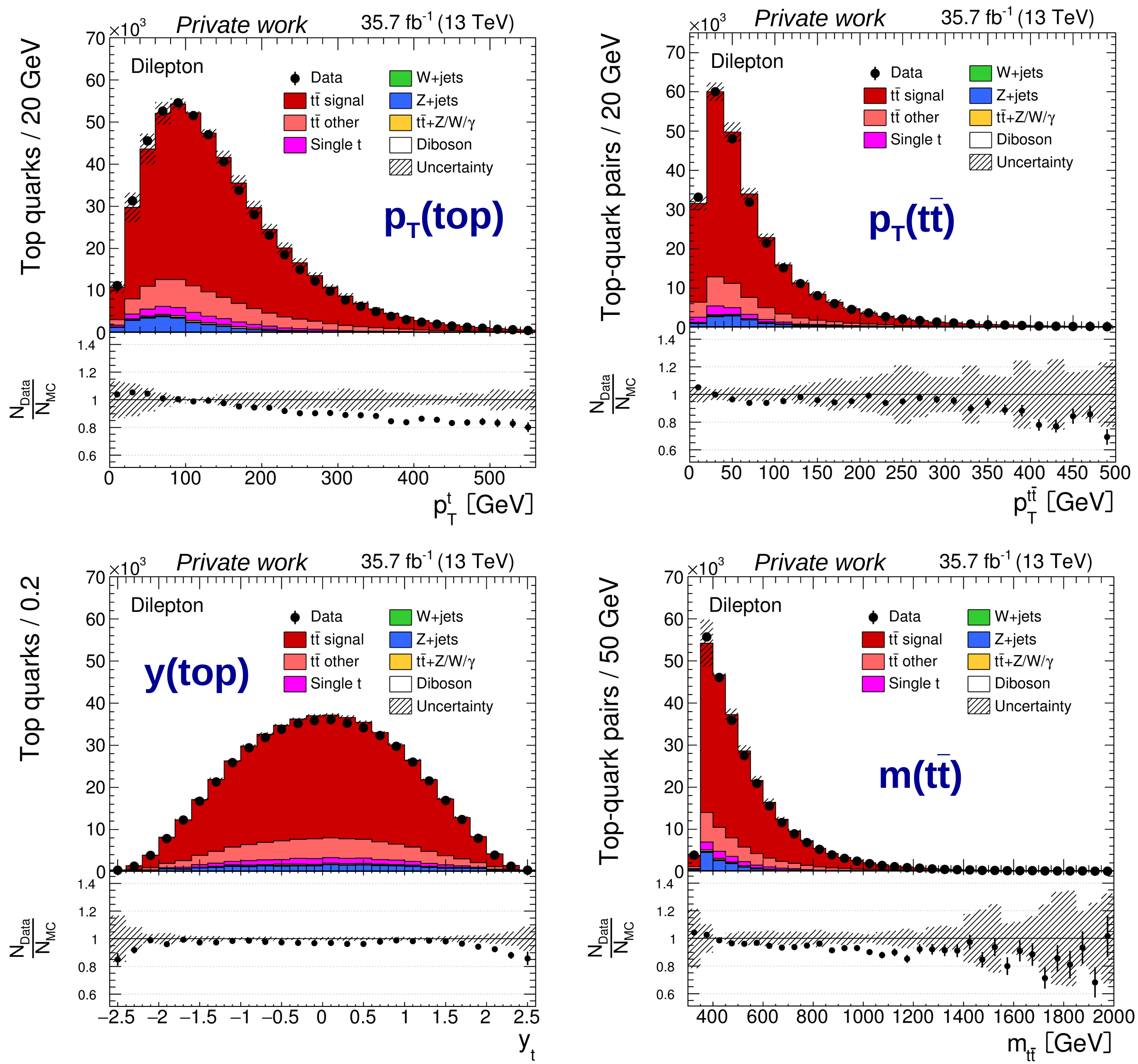
- After b-tagging requirement
- Reference $t\bar{t}$ prediction: **Powheg+Pythia8**
- Hatched area: systematic shape uncertainties

In general, good data-to-MC agreement



Kinematic distributions: top & $t\bar{t}$ system

- Very pure **$t\bar{t}$ signal** after full event selection & kinematic reconstruction (~80%)
- Reference $t\bar{t}$ prediction: **Powheg+Pythia8**
- **Softer data in p_T (top)**
  → consistent with Run-I



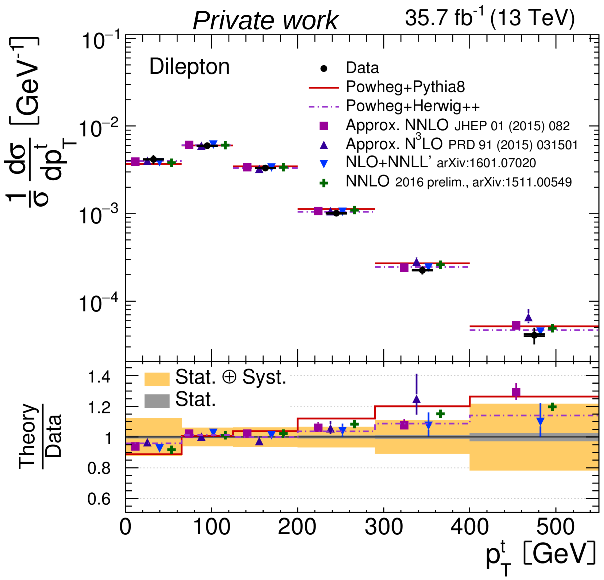
Agreement in most variables with the exception of p_T(top)

Results: p_T(top)

Upper: normalized

- Reference $t\bar{t}$ prediction used for unfolding: **PowhegV2+Pythia8**
- **Parton level top quark:**
  → compared with modern beyond-NLO QCD predictions

Parton level



Results: p_T(top)

Upper: normalized

Lower: absolute

new

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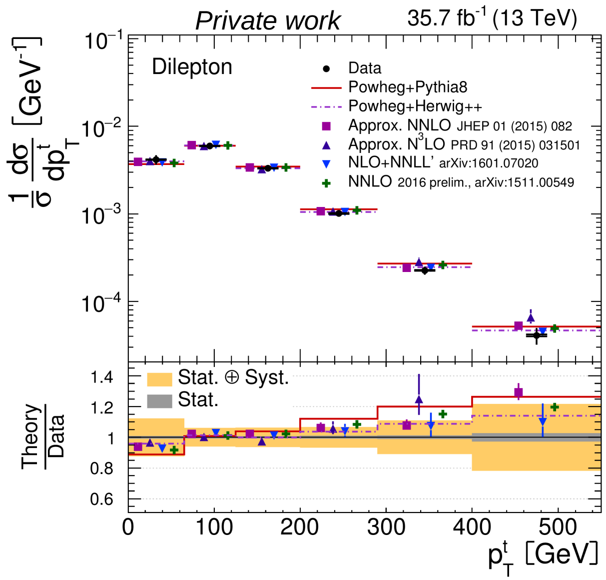
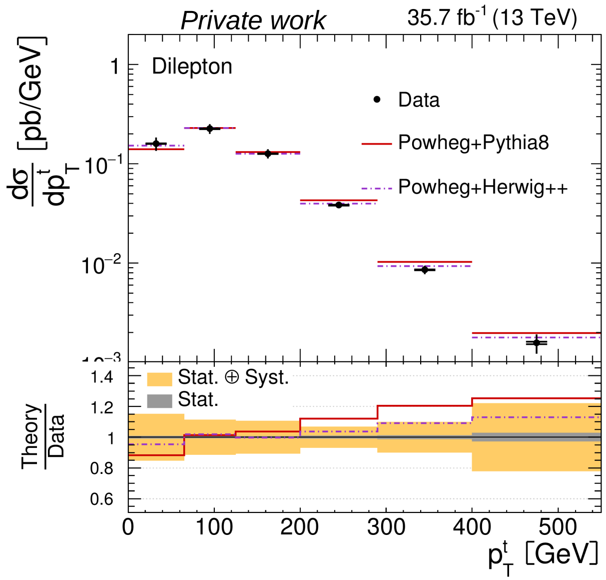
Parton level





Results: p_T(top)

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- **Parton level top quark:**
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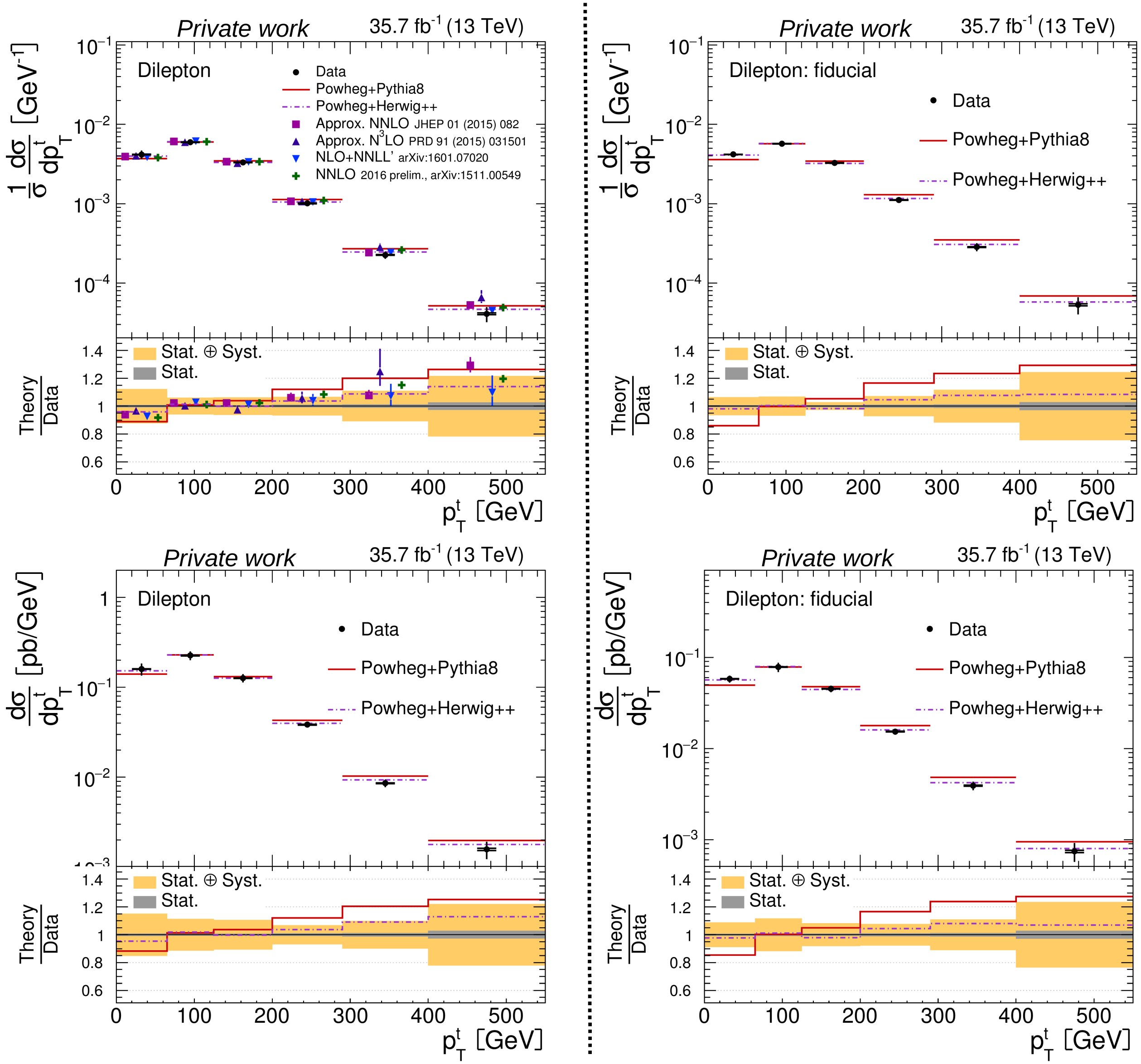
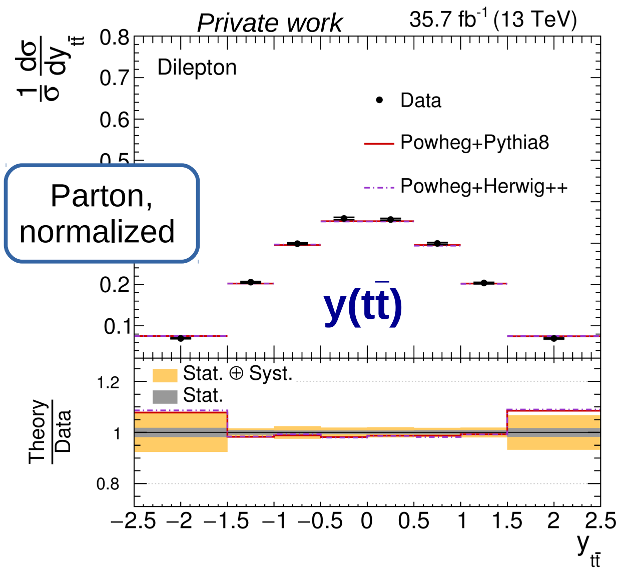
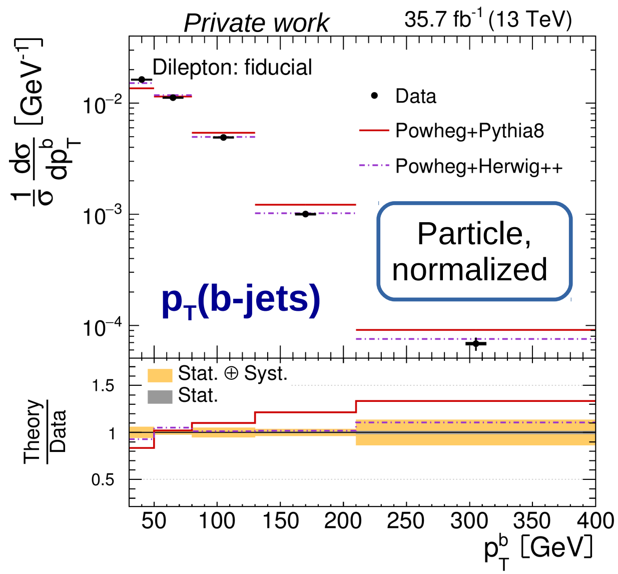
- **Particle level top quark**:
  → following definitions by LHCTopWG for Run-II
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions
- Slope in p_T(top) observed at both levels
- Treatment of systematic uncertainties is not finalized

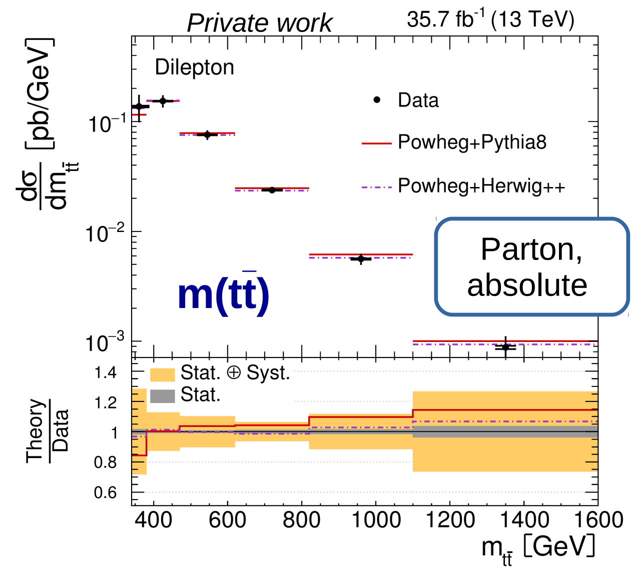
Parton level | new **Particle level**



More results to come…





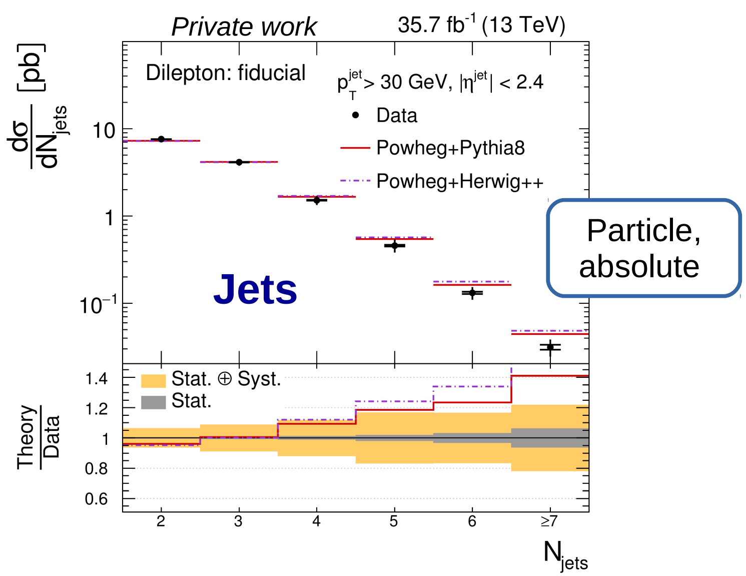


- Precision measurement in four different regimes:

  → parton -vs- particle levels
  → normalized -vs- absolute results

  … for top quarks and decay product observables (jets, b-jets, leptons)

- Measurements dominated by theory related uncertainty sources



Summary

Top quark pair differential cross section measurements:

- Essential for constraining the SM
- Ideal probe for looking for new physics beyond the SM

Results using $L = 35.7\ fb^{-1}$ of 13 TeV data recorded by CMS in 2016:

- Measuring absolute and normalized $t\bar{t}$ differential cross sections at both parton and particle levels

  → probing $t\bar{t}$ production in the greatest detail ever
- Measurement dominated by systematic uncertainties: ~ 5-20% precision

  → already a precision test of pQCD

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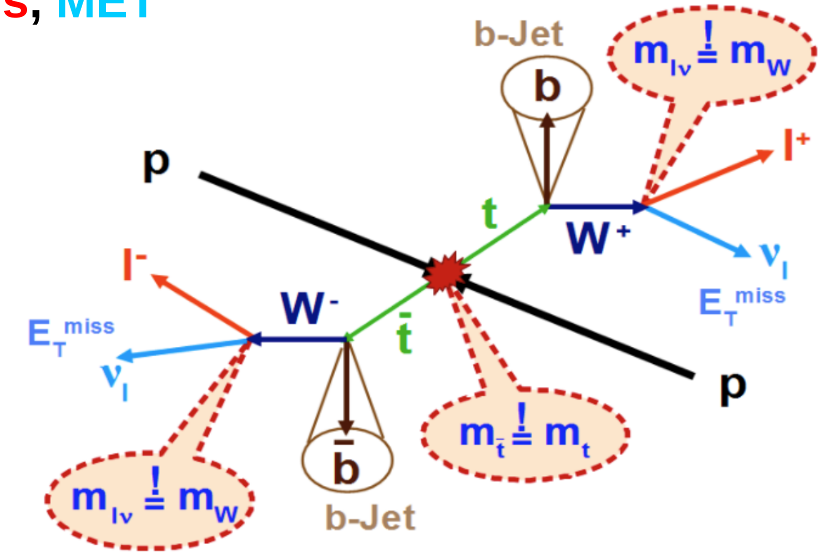
Thank you for your attention!

Backup

Kinematic reconstruction of $t\bar{t}$ system

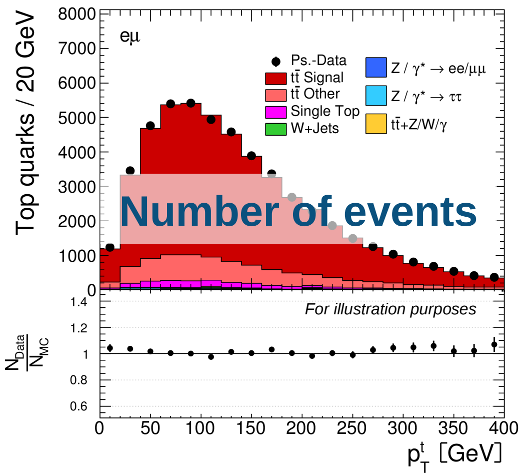
- **Measured input: 2 jets, 2 leptons, MET**
- **Unknowns:** $\vec{p}_\nu, \vec{p}_{\bar{\nu}} \rightarrow 6$
- **Constraints:**
  > $m_t, m_{\bar{t}} \rightarrow 2$
  > $m_{W(+)}, m_{W(-)} \rightarrow 2$
  > $(\vec{p}_\nu + \vec{p}_{\bar{\nu}})_T = \text{MET} \rightarrow 2$



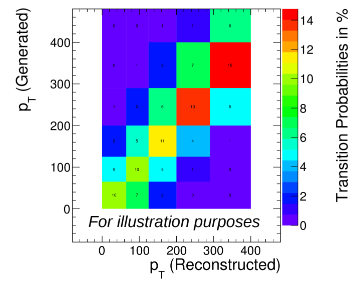
- Reconstructing each event 100 times and smearing inputs by their resolution:
  > top mass fixed to 172.5 GeV
  > W mass at RECO level smeared accordingly to W mass distribution
  > Jet and lepton energies are corrected for detector effects
- Consider weighted average of solutions for all smeared points:

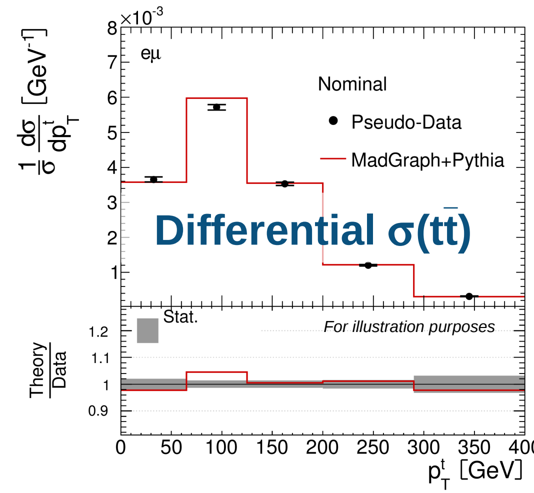
$$p_{x,y,z}^{top} = \frac{1}{w} \sum_{i=0}^{100} w_i \cdot (p_{x,y,z}^{top})_i$$

Differential cross section



Response matrix A_{ij}





$$\frac{1}{\sigma}\frac{d\sigma}{dX_i}=\frac{1}{\sigma}\frac{unfold\left(N^X_{data,i}-N^X_{BG,i}\right)}{\Delta^i_X\cdot\int \mathscr{L}\,dt}$$

Binning

Chosen to limit migration effects in and out of bins:

- purity (p_i) & stability (s_i): ≥ ~40%

$$p_i=\frac{N_i^{rec\,\&\,gen}}{N_i^{rec}}\qquad s_i=\frac{N_i^{rec\,\&\,gen}}{N_i^{gen}}$$

Regularized unfolding

- Basic unfolding - simple inversion of response matrix A_{ij}:

$$N_{i,unf}=A_{ij}^{-1}N_{j,measured}$$

- Regularization used to remove large statistical fluctuations (SVD)
- Optimized minimizing global bin correlation, done independently for parton and particle levels

Phase space

- Correct back to parton or particle level in full or fiducial phase space

Differential σ(tt̄)

- Normalized to in-situ measured σ(tt̄): mostly shape uncertainties contribute
- Absolute (no 1/σ in equation): rate & shape info

new

Binning and migrations

- **Migration effects** studied by:

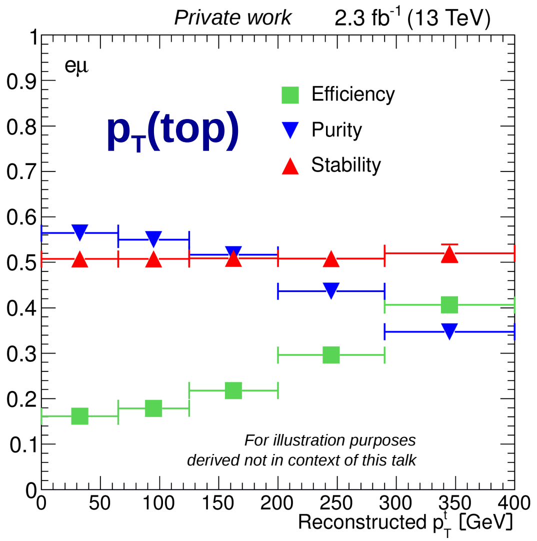
$$p_i = \frac{N_i^{rec\,\&\,gen}}{N_i^{rec}}$$ - **purity**: sensitive to migrations to i-th bin

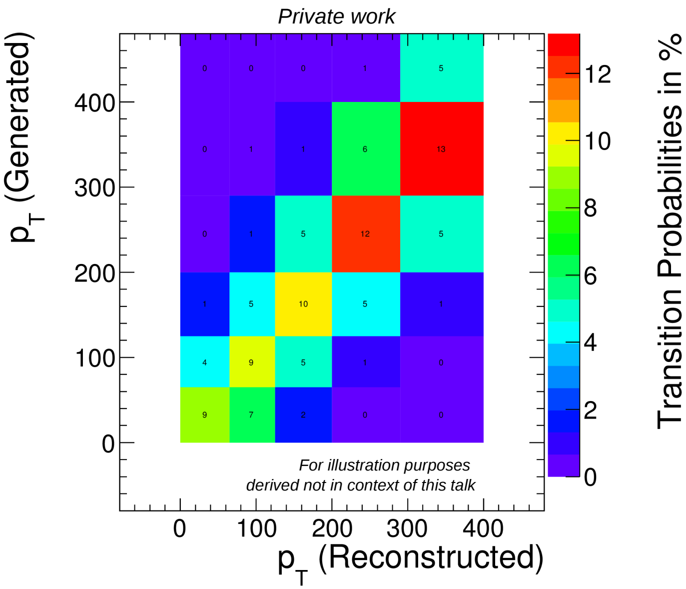
$$s_i = \frac{N_i^{rec\,\&\,gen}}{N_i^{gen}}$$ - **stability**: sensitive to migrations out of i-th bin

$$\varepsilon_i = \frac{N_i^{rec\,\&\,sel}}{N_i^{all\,generated}}$$ - **efficiency** in i-th bin

- **Binning criteria:**
  → stability or purity ≥ ~40%
  → diagonal response matrix

- Example for measurement in bins of p_T(top)





Unfolding

- **Unfolding** techniques correct migrations between bins
- **Response matrix (A):** represents bin-by-bin correlations
- Unfolding problem is transformed to χ^2 - minimization problem:

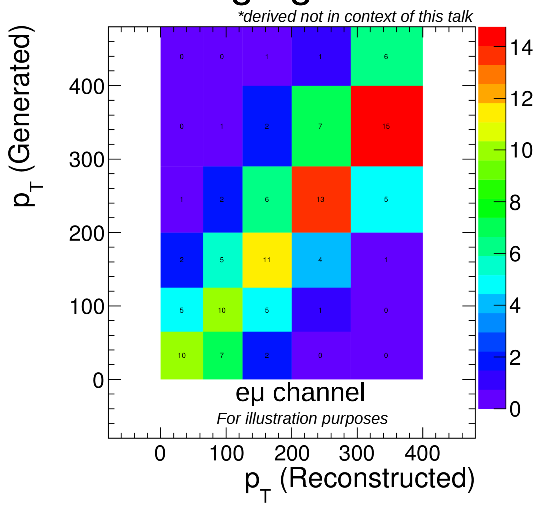
unfolding — regularization

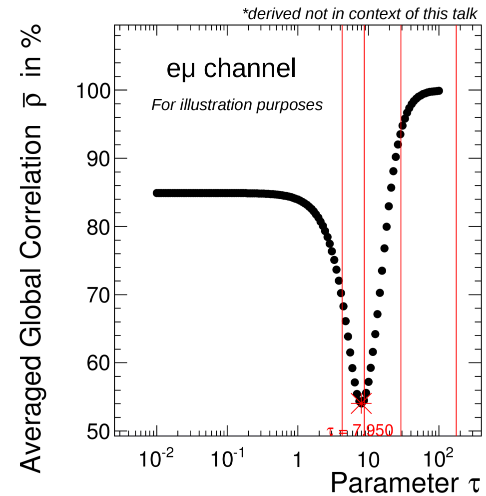
$$\chi^2 = (\vec{N} - A\cdot\vec{x})^T COV_{\vec{N}}^{-1} (\vec{N} - A\cdot\vec{x}) - \tau^2 \cdot K(\vec{x})$$

- **N:** BG corrected data
- **x:** unfolded result

- Non-physical fluctuations removed by means of the regularization:
  - > τ – continuous regularization parameter
  - > selected at minimum of average global correlation

- Signal $t\bar{t}$ reference sample used for unfolding: **PowhegV2+Pythia8**





Systematic uncertainties

Each uncertainty propagated through analysis chain individually

- For each source, the corresponding efficiency, resolution or scale is changed by its uncertainty or similar
- Systematic unc. per bin: difference of the changed result wrt nominal value

Experimental uncertainties

- Trigger efficiency, lepton ID/Iso, JES, JER, b-tagging, pile-up reweighting, background cross sections (30% variations for all samples), kinematic reconstruction efficiency

Signal model uncertainties

- Q^2 scale (variations in ME/ISR/FSR), UE tune, top mass, hadronization model, PDF (so far, only variation in α_s), matching uncertainty (not considered for now)