top quark measurements: What and how?

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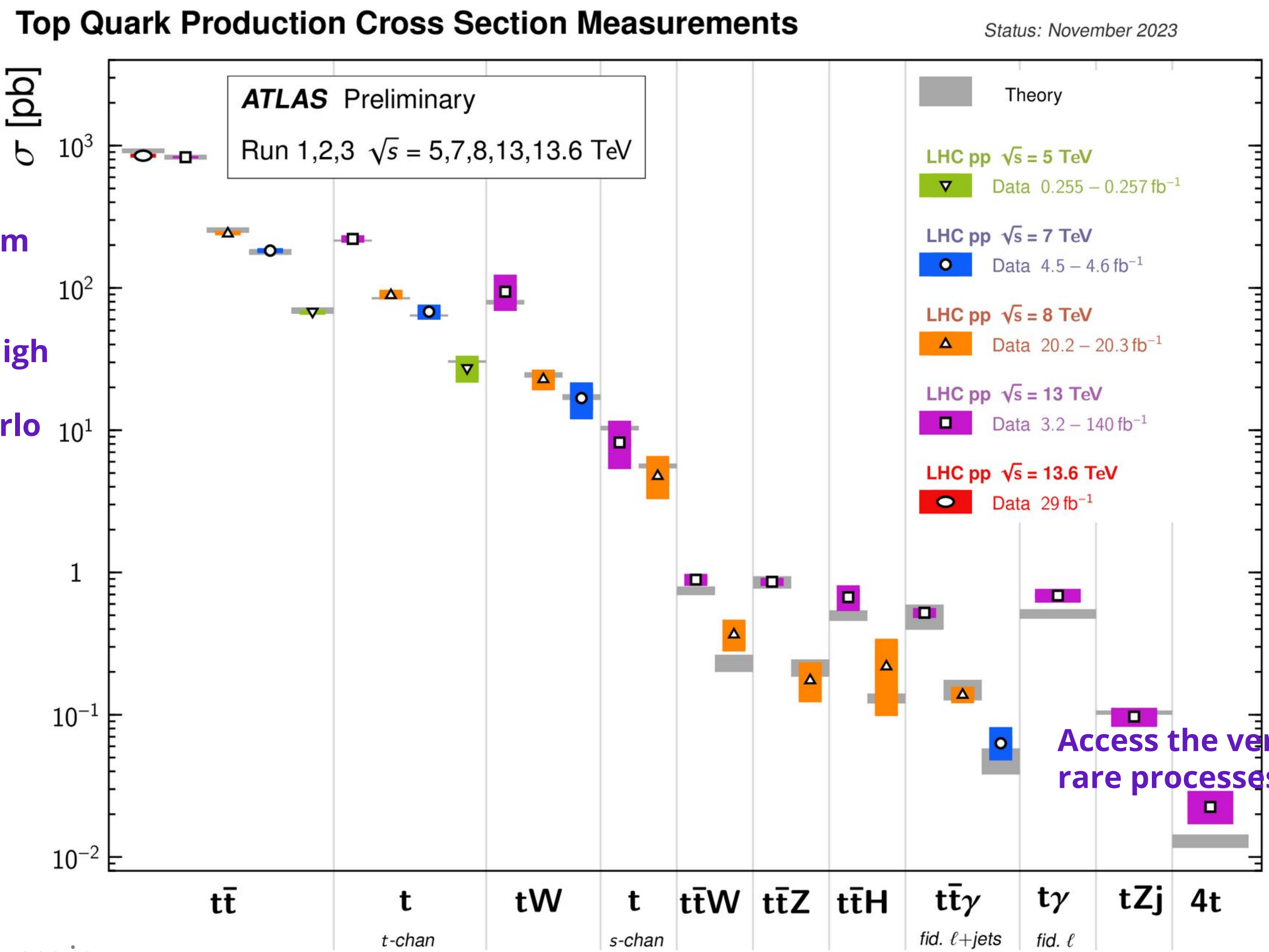
CPPS retreat - 14 –16 February 2024

What do we measure?

Extremely precise tt measurements to
- **find deviations from SM,**
- **measure SM parameters with high precision,**
- **improve Monte Carlo simulations,**
- **input to PDF fits...**



Access the very rare processes

→Details on particular analyses in the poster session!

Scrutinise production of top+X processes
- **EW, yukawa couplings**

What do we measure?

- Precision ttbar measurements as tests of the SM
  - Extract Yukawa coupling from mtt threshold or top quark width from invariant mass of lepton+b-jet, charge asymmetry in rapidity between top and antitop quark
- It all boils down to measure the total rate of the process or as a function of certain variables…
- However…

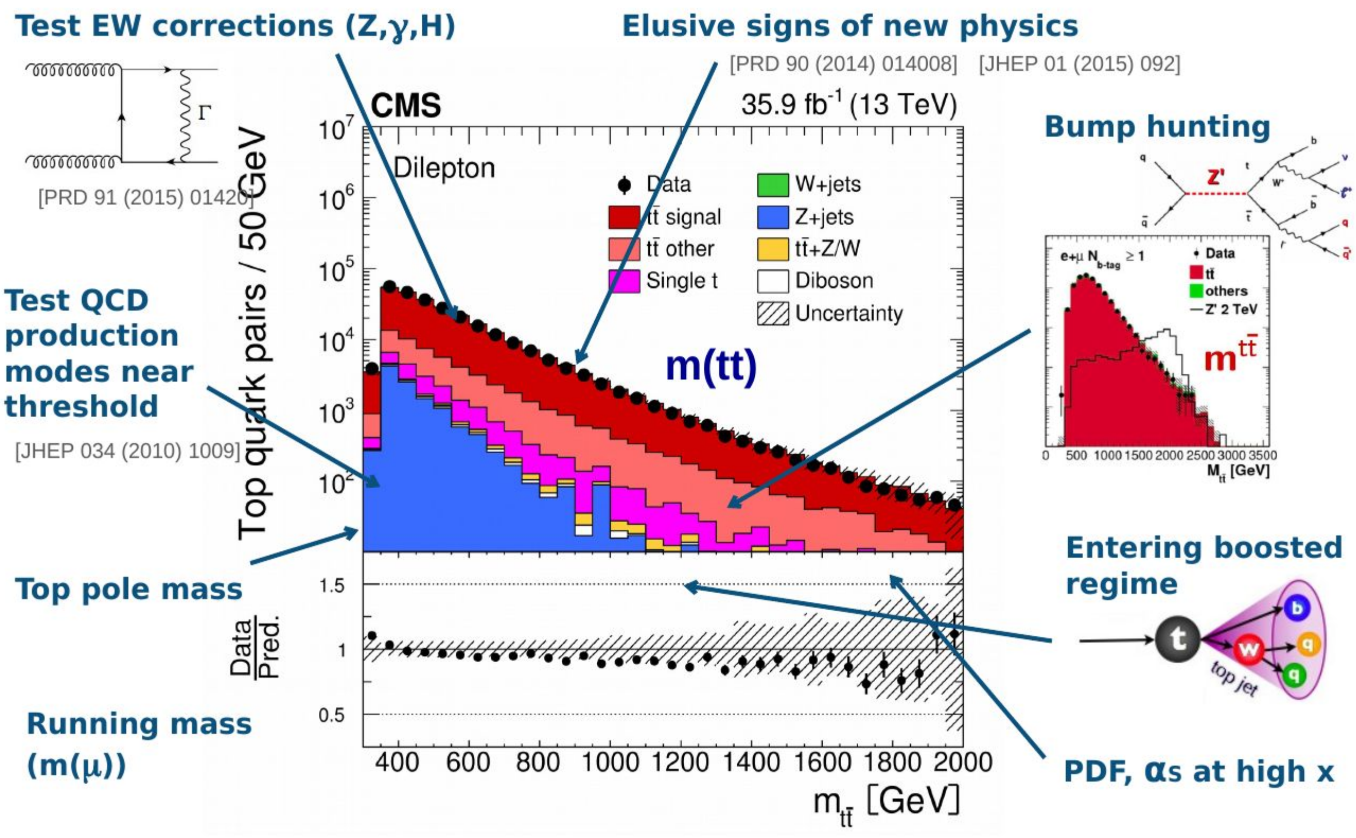
Number of observed events
just count …

Background
measured from data or calculated from theory

$$\sigma = \frac{N^{obs} - N^{bkg}}{\int \mathcal{L}\, dt \cdot \varepsilon}$$

Luminosity
determined by accelerator, triggers, …

Efficiency
many factors, optimized by experimentalist



Test EW corrections (Z,γ,H)

[PRD 91 (2015) 014020]

Elusive signs of new physics

[PRD 90 (2014) 014008] [JHEP 01 (2015) 092]

Test QCD production modes near threshold

[JHEP 034 (2010) 1009]

Top pole mass

Running mass (m(μ))

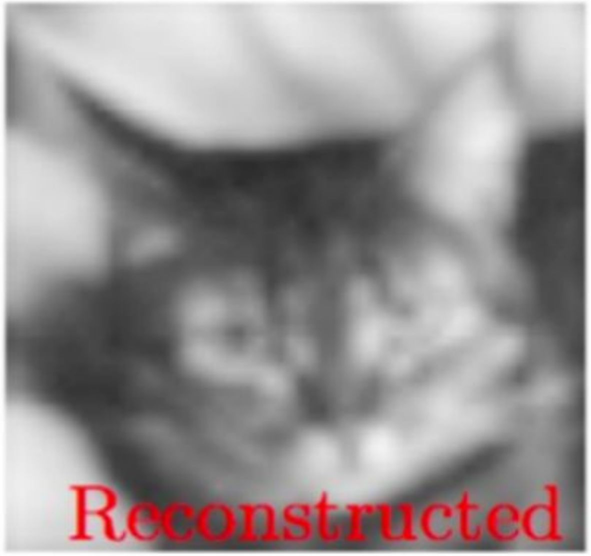
Bump hunting

Entering boosted regime

PDF, αs at high x

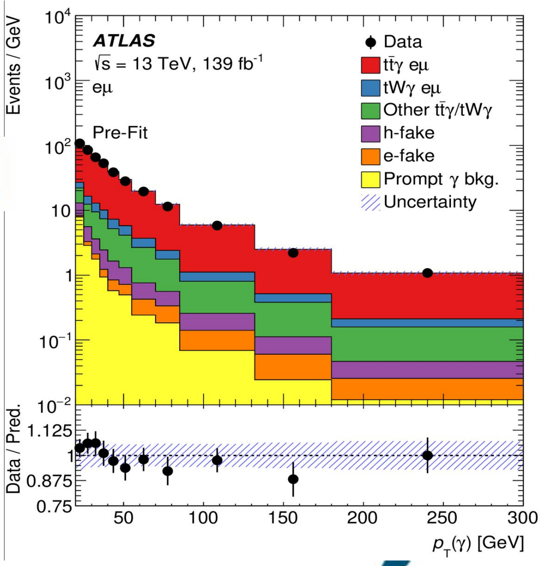
General strategy: unfold measurements

- Detector and resolution effects
  - Smearing of true info
  - No direct comparison between results of different experiments and to theory predictions possible
- Unfolding: correct for acceptance & resolution effects
- Requires knowledge of the acceptance and detector resolution

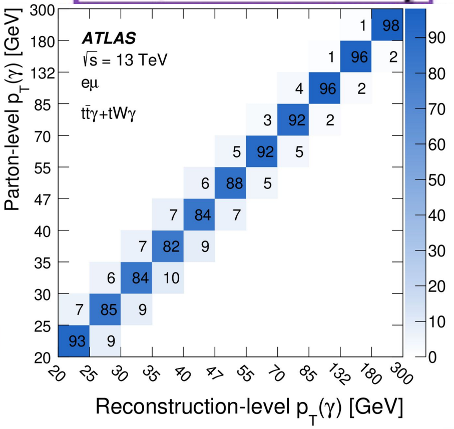


General strategy: unfold measurements

Reco level



Response matrix R_{ij}



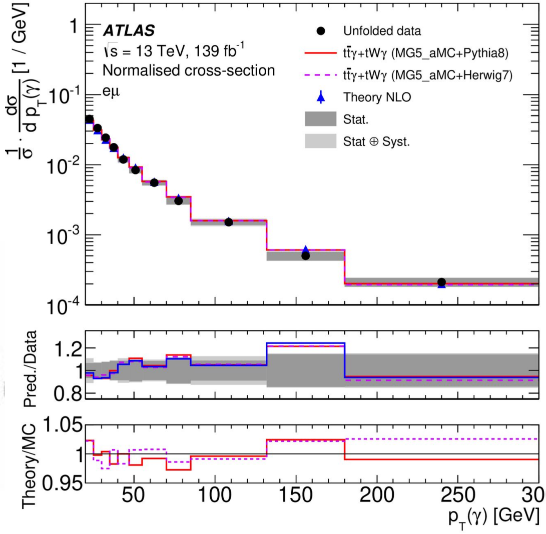
	20–25	25–30	30–35	35–40	40–47	47–55	55–70	70–85	85–132	132–180	180–300
180–300										1	98
132–180									1	96	2
85–132								4	96	2	
70–85							3	92	2		
55–70						5	92	5			
47–55					6	88	5				
40–47				7	84	7					
35–40			7	82	9						
30–35		6	84	10							
25–30	7	85	9								
20–25	93	9									

$$R_{ij} = \frac{N^{\text{gen in bin j}}_{\text{reco in bin i}}}{N^{\text{gen in bin j}}}$$

Δ^{i}_{X} = bin width for variable X

$$\frac{d\sigma}{dX_i} = \frac{\sum_j R_{ij}^{-1}\left[(N_{\text{data},j} - N_{\text{BG},j})\right]}{\Delta_{X_i} \cdot L}$$

Unfolded



1. Event selection
2. (Top quark kinematic reconstruction)
3. Bin-wise cross section measurement:
   - ◊ Subtract background
   - ◊ Unfolding**: correct for detector effects & acceptance
4. Compare diff. cross section to theory predictions/calculations: Absolute or normalised to in-situ measured σ extrapolated to full or in fiducial phase space (parton/particle level)

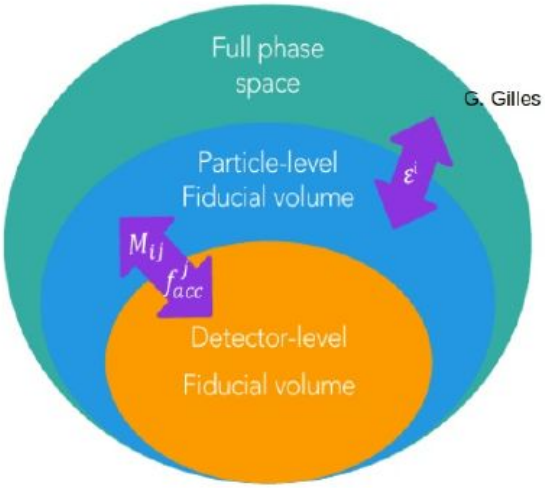
** If we can simulate the theory up to detector level we don't need it! We would just perform a fit to data to extract the best-fit value of the parameter of interest

What is parton level? What is particle level? … and why we use those definitions?

Parton level

- Defined using on-shell top quarks and including initial- and final-state radiation from quarks and gluons before the top-quark decay
  - Basically checking event history of the simulation chain!
  - No kinematic requirements (full phase space)
    - Not trivial at all to define jets in an unambiguous way

Why? Compare to high-order calculations, with stable top quarks



Particle level

- Constructed from the collection of stable particles from full matrix-element plus parton-shower generators, including top-quark decay and final-state radiation effects (QCD+EWK FSR effects).
  - Particles produced from interactions with the detector components or from pile-up of additional pp collisions are not considered

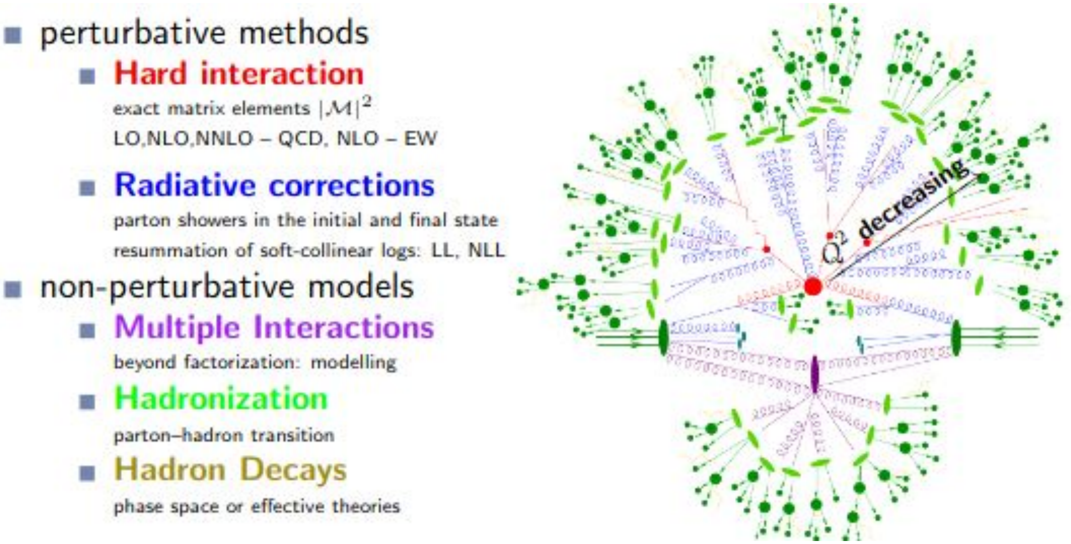
- **Dressed leptons**: Momenta of nearby photons, within a ΔR= 0.1 cone, are added to the lepton
- **Jets**: define with anti-k_t algorithm. Loop over all stable particles excluding the electrons, muons, neutrinos, and photons used in the definition of the selected leptons.
- **b-jets**: A jet is a b-jet if any rescaled B-hadron is included. A rescaled B-hadron is treated as a stable B-hadron for which the 4-momentum is scaled down to infinitesimal value and added to the list of particles. Only B-hadrons with an initial $p_T > 5$ GeV are considered.

Why? Avoid large dependence from simulations

Monte Carlo simulations

Fundamental for most measurements…

- Estimate background processes
- Correct the data (after detector reconstruction) to parton/particle level
- Assign uncertainties related to the model/simulations used (PDFs, renormalisation/factorisation scales)
- Compare with the results → tune the simulations



- perturbative methods
  - **Hard interaction**
    exact matrix elements $|\mathcal{M}|^2$
    LO,NLO,NNLO – QCD, NLO – EW
  - **Radiative corrections**
    parton showers in the initial and final state
    resummation of soft-collinear logs: LL, NLL
- non-perturbative models
  - **Multiple Interactions**
    beyond factorization: modelling
  - **Hadronization**
    parton–hadron transition
  - **Hadron Decays**
    phase space or effective theories

\+ detector simulation!

Most used MC: Madgraph_aMCatnlo or Powheg +Pythia/Herwig, Sherpa
Typically NLO+PS
Many assumptions to estimate uncertainties

A glimpse on Monte Carlo simulations
(Matrix element + parton shower)

More on K. Voss' talk!

- **tt**: Powheg + Pythia or Herwig, NLO (now also NNLO+PS)
  - Parton distribution function: NNPDF3.0 NLO
  - renormalization and factorization scale: $\sqrt{m2 + p2T}$
  - mt = 172.5 GeV, value of αS(mZ) = 0.118.
  - width of the top quark is set to the SM expectation of 1.31 GeV, and
  - top quark decays simulated at leading-order precision

All this info is needed to properly compare MCs and results!

Parton shower tunes!

A glimpse on Monte Carlo simulations
(Matrix element + parton shower)

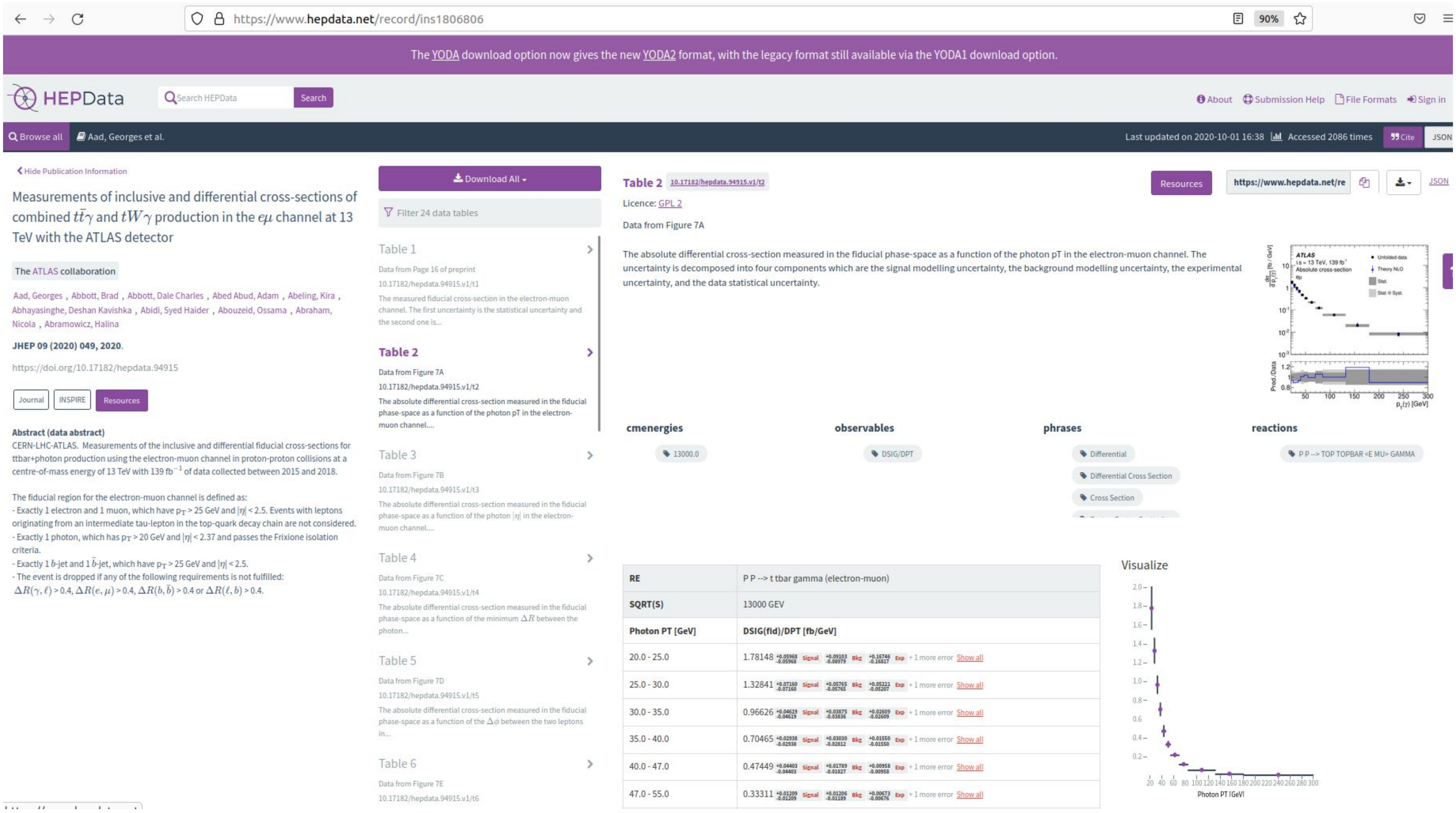
More on K. Voss' talk!

- **tt+X**: MadGraph5_aMC@NLO + parton shower, Sherpa
  - Typically include higher order effects both in QCD and electroweak EW using NLO inclusive and multileg merged setups
    - NNLO MCs not expected soon…
  - **BUT top quark + photon processes not even available at NLO!**
    - Only tty 2->3 can be generated at NLO (e.g. tty with a photon coming from the ttbar decay products can only be simulated at LO!)
    - Additional complications: photon definition - minimal pt and isolation requirements to avoid divergences

- Systematic uncertainties: Signal & background modeling
  - MC generators (MC@NLO, Powheg, MadGraph, ...)
  - hadronization (Pythia/Herwig)
  - Initial and final state radiation
  - PDFs (PDF4LHC recommendations: https://arxiv.org/pdf/1510.03865.pdf)

Preserving measurements

… so that you can compare your future models to our results or use the results in your fits



The YODA download option now gives the new YODA2 format, with the legacy format still available via the YODA1 download option.

Aad, Georges et al.

Last updated on 2020-10-01 16:38 Accessed 2086 times

Hide Publication Information

Measurements of inclusive and differential cross-sections of combined $t\bar{t}\gamma$ and $tW\gamma$ production in the $e\mu$ channel at 13 TeV with the ATLAS detector

The ATLAS collaboration

Aad, Georges , Abbott, Brad , Abbott, Dale Charles , Abed Abud, Adam , Abeling, Kira , Abhayasinghe, Deshan Kavishka , Abidi, Syed Haider , Abouzeid, Ossama , Abraham, Nicola , Abramowicz, Halina

JHEP 09 (2020) 049, 2020.

https://doi.org/10.17182/hepdata.94915

Abstract (data abstract)

CERN-LHC-ATLAS. Measurements of the inclusive and differential fiducial cross-sections for ttbar+photon production using the electron-muon channel in proton-proton collisions at a centre-of-mass energy of 13 TeV with 139 fb^{-1} of data collected between 2015 and 2018.

The fiducial region for the electron-muon channel is defined as:
- Exactly 1 electron and 1 muon, which have $p_T > 25$ GeV and $|\eta| < 2.5$. Events with leptons originating from an intermediate tau-lepton in the top-quark decay chain are not considered.
- Exactly 1 photon, which has $p_T > 20$ GeV and $|\eta| < 2.37$ and passes the Frixione isolation criteria.
- Exactly 1 b-jet and 1 $\bar{b}$-jet, which have $p_T > 25$ GeV and $|\eta| < 2.5$.
- The event is dropped if any of the following requirements is not fulfilled: $\Delta R(\gamma,\ell) > 0.4$, $\Delta R(e,\mu) > 0.4$, $\Delta R(b,\bar{b}) > 0.4$ or $\Delta R(\ell,b) > 0.4$.

Table 1

Data from Page 16 of preprint

10.17182/hepdata.94915.v1/t1

The measured fiducial cross-section in the electron-muon channel. The first uncertainty is the statistical uncertainty and the second one is...

Table 2

Data from Figure 7A

10.17182/hepdata.94915.v1/t2

The absolute differential cross-section measured in the fiducial phase-space as a function of the photon pT in the electron-muon channel....

Table 3

Data from Figure 7B

10.17182/hepdata.94915.v1/t3

The absolute differential cross-section measured in the fiducial phase-space as a function of the photon $|\eta|$ in the electron-muon channel....

Table 4

Data from Figure 7C

10.17182/hepdata.94915.v1/t4

The absolute differential cross-section measured in the fiducial phase-space as a function of the minimum ΔR between the photon...

Table 5

Data from Figure 7D

10.17182/hepdata.94915.v1/t5

The absolute differential cross-section measured in the fiducial phase-space as a function of the $\Delta\phi$ between the two leptons in...

Table 6

Data from Figure 7E

10.17182/hepdata.94915.v1/t6

Table 2 10.17182/hepdata.94915.v1/t2

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Data from Figure 7A

The absolute differential cross-section measured in the fiducial phase-space as a function of the photon pT in the electron-muon channel. The uncertainty is decomposed into four components which are the signal modelling uncertainty, the background modelling uncertainty, the experimental uncertainty, and the data statistical uncertainty.

cmenergies
- 13000.0

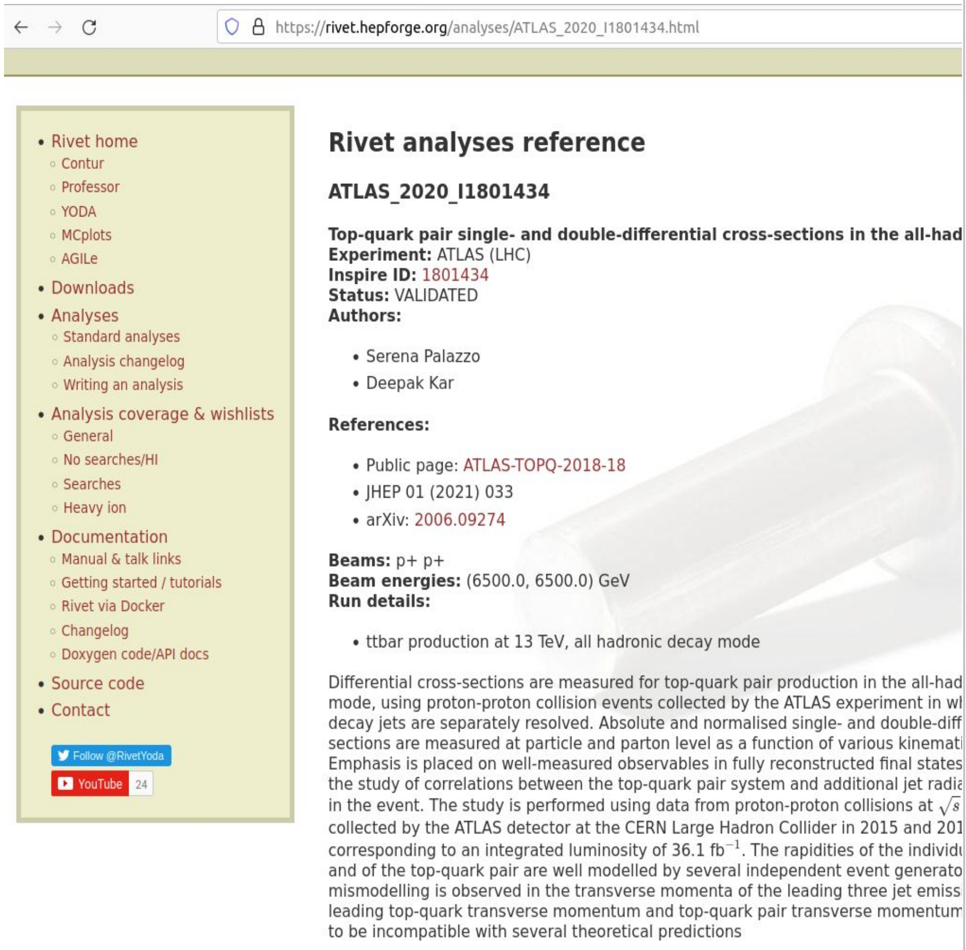
observables
- DSIG/DPT

phrases
- Differential
- Differential Cross Section
- Cross Section

reactions
- P P --> TOP TOPBAR <E MU> GAMMA

RE	P P --> t tbar gamma (electron-muon)
SQRT(S)	13000 GEV
Photon PT [GeV]	**DSIG(fid)/DPT [fb/GeV]**
20.0 - 25.0	$1.78148\ ^{+0.05968}_{-0.05968}$ Signal $^{+0.09103}_{-0.08979}$ Bkg $^{+0.16746}_{-0.16817}$ Exp + 1 more error Show all
25.0 - 30.0	$1.32841\ ^{+0.07160}_{-0.07160}$ Signal $^{+0.05765}_{-0.05765}$ Bkg $^{+0.05221}_{-0.05207}$ Exp + 1 more error Show all
30.0 - 35.0	$0.96626\ ^{+0.04619}_{-0.04619}$ Signal $^{+0.03875}_{-0.03836}$ Bkg $^{+0.02609}_{-0.02609}$ Exp + 1 more error Show all
35.0 - 40.0	$0.70465\ ^{+0.02938}_{-0.02938}$ Signal $^{+0.03030}_{-0.02812}$ Bkg $^{+0.01550}_{-0.01550}$ Exp + 1 more error Show all
40.0 - 47.0	$0.47449\ ^{+0.04403}_{-0.04403}$ Signal $^{+0.01789}_{-0.01827}$ Bkg $^{+0.00958}_{-0.00958}$ Exp + 1 more error Show all
47.0 - 55.0	$0.33311\ ^{+0.01209}_{-0.01209}$ Signal $^{+0.01206}_{-0.01189}$ Bkg $^{+0.00673}_{-0.00676}$ Exp + 1 more error Show all

Preserving measurements
… making life easier with ready-to-use code



https://rivet.hepforge.org/analyses/ATLAS_2020_I1801434.html

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Rivet analyses reference

ATLAS_2020_I1801434

Top-quark pair single- and double-differential cross-sections in the all-had
Experiment: ATLAS (LHC)
Inspire ID: 1801434
Status: VALIDATED
Authors:

- Serena Palazzo
- Deepak Kar

References:

- Public page: ATLAS-TOPQ-2018-18
- JHEP 01 (2021) 033
- arXiv: 2006.09274

Beams: p+ p+
Beam energies: (6500.0, 6500.0) GeV
Run details:

- ttbar production at 13 TeV, all hadronic decay mode

Differential cross-sections are measured for top-quark pair production in the all-had mode, using proton-proton collision events collected by the ATLAS experiment in wh decay jets are separately resolved. Absolute and normalised single- and double-diff sections are measured at particle and parton level as a function of various kinemati Emphasis is placed on well-measured observables in fully reconstructed final states the study of correlations between the top-quark pair system and additional jet radia in the event. The study is performed using data from proton-proton collisions at $\sqrt{s}$ collected by the ATLAS detector at the CERN Large Hadron Collider in 2015 and 201 corresponding to an integrated luminosity of 36.1 fb^{-1}. The rapidities of the individu and of the top-quark pair are well modelled by several independent event generato mismodelling is observed in the transverse momenta of the leading three jet emissi leading top-quark transverse momentum and top-quark pair transverse momentum to be incompatible with several theoretical predictions

Source code: `ATLAS_2020_I1801434.cc`

```
#include "Rivet/Analysis.hh"
#include "Rivet/Projections/FinalState.hh"
#include "Rivet/Projections/VetoedFinalState.hh"
#include "Rivet/Projections/PromptFinalState.hh"
#include "Rivet/Projections/DressedLeptons.hh"
#include "Rivet/Projections/FastJets.hh"
#include "Rivet/Projections/InvisibleFinalState.hh"

namespace Rivet {


  /// @brief All-hadronic ttbar cross-sections at 13 TeV
  class ATLAS_2020_I1801434 : public Analysis {
  public:

    /// Constructor
    RIVET_DEFAULT_ANALYSIS_CTOR(ATLAS_2020_I1801434);


    void init() {

      Cut eta_full =  Cuts::abseta < 5.0;
      Cut lep_cuts = Cuts::abseta < 2.5 && Cuts::pT > 15*GeV;

      FinalState fs(eta_full);
      FinalState fs_neutrino;

      const FinalState all_photons(eta_full && Cuts::abspid == PID::PHOTON);
      PromptFinalState photons(all_photons);
      photons.acceptTauDecays(false);
      declare(photons, "photons");


      PromptFinalState electrons(eta_full && Cuts::abspid == PID::ELECTRON);
      electrons.acceptTauDecays(true);
      declare(electrons, "electrons");

      DressedLeptons dressedelectrons(photons, electrons, 0.1, lep_cuts, true, true);
      declare(dressedelectrons, "dressedelectrons");

      DressedLeptons ewdressedelectrons(all_photons, electrons, 0.1, eta_full, true, true);
      declare(ewdressedelectrons, "ewdressedelectrons");

      PromptFinalState muons(eta_full && Cuts::abspid == PID::MUON);
      muons.acceptTauDecays(true);
      declare(muons, "muons");

      DressedLeptons dressedmuons(photons, muons, 0.1, lep_cuts, true, true);
      declare(dressedmuons, "dressedmuons");

      DressedLeptons ewdressedmuons(all_photons, muons, 0.1, eta_full, true, true);
      declare(ewdressedmuons, "ewdressedmuons");

      PromptFinalState taus(eta_full && Cuts::abspid == PID::TAU);
      declare(taus, "taus");

      VetoedFinalState vfs(fs);
      InvisibleFinalState prompt_invis(true, true); // require promptness & allow from prompt tau
      vfs.addVetoOnThisFinalState(dressedelectrons);
```