Faculty of Science

Palacký University Olomouc

Physics of the Top Quark: From Precision Tests of the Standard Model to Searches for New Physics

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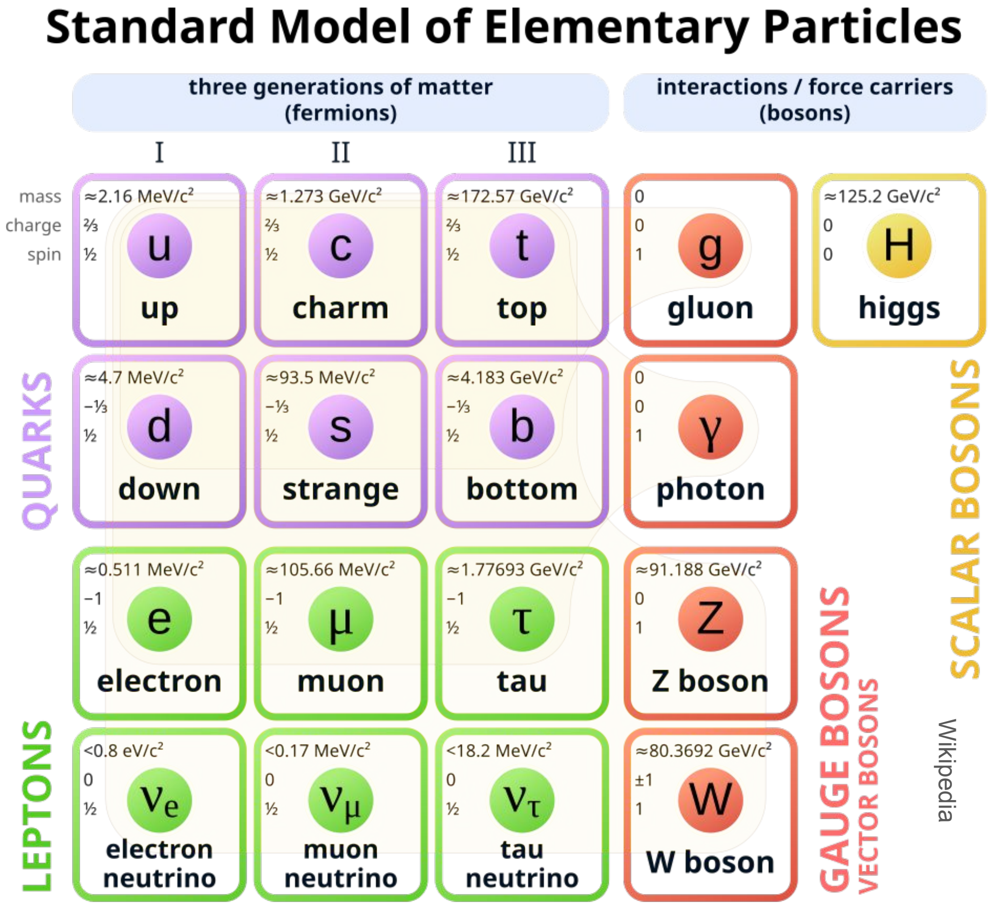
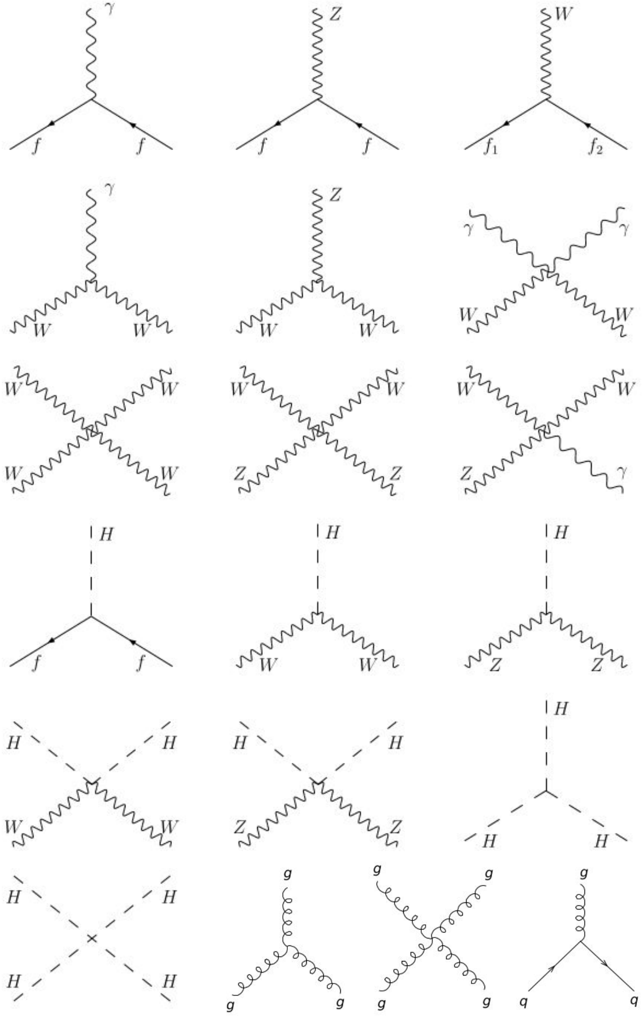
Faculty of Science

Top quark as an important signal at the Large Hadron Collider will be presented with focus on measuring its kinematic spectra in proton-proton collisions. From precision tests of the Standard Model and measurements challenging theoretical descriptions of its differential cross-sections we shall move to the search for top quark pairs production in proton-lead collisions with the ATLAS experiment at CERN, and will touch the top-quark role in searches for possible new physics.

Particles content of the Standard Model

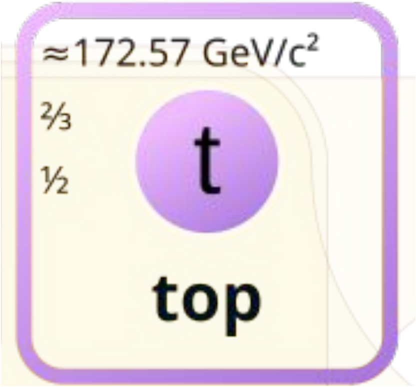




J. Hořejší, https://arxiv.org/pdf/2210.04526

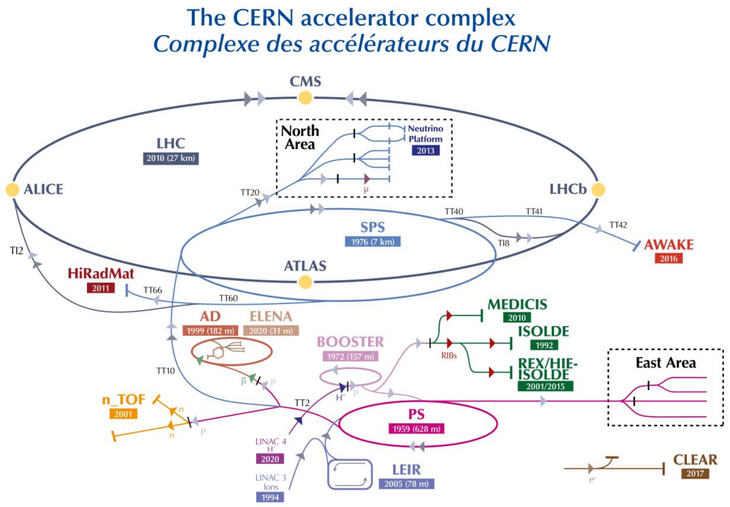
Top quark – properties and motivation

- Discovered in 1995 at Fermilab, Tevatron accelerator, experiments CDF and DZero.
- Top quark the only fermion with mass of the order of the Higgs boson vacuum expectation energy.
- Could it be special in some way?
- Decaying via weak interaction so fast as via the strong one.
- The only quark not forming a rich Zoo of mesons.
- Elementary, yet heavier than the gold nucleus.
- Top quark is
  - an interesting and important SM signal
  - a tool for precision physics and searchess.
  - background to some processes.
  - accompanying final state e.g. for the Higgs boson production
  - a background process for some SM as well as beyond the SM processes ⇒ It is important to understand its spectra.



LHC collider experiments

- The Large Hadron Collider and the ATLAS, ALICE, CMS and LHCb experiments at CERN.
- LHC: proton-proton but also ion-ion collider.
- 40 MHz collision rate.



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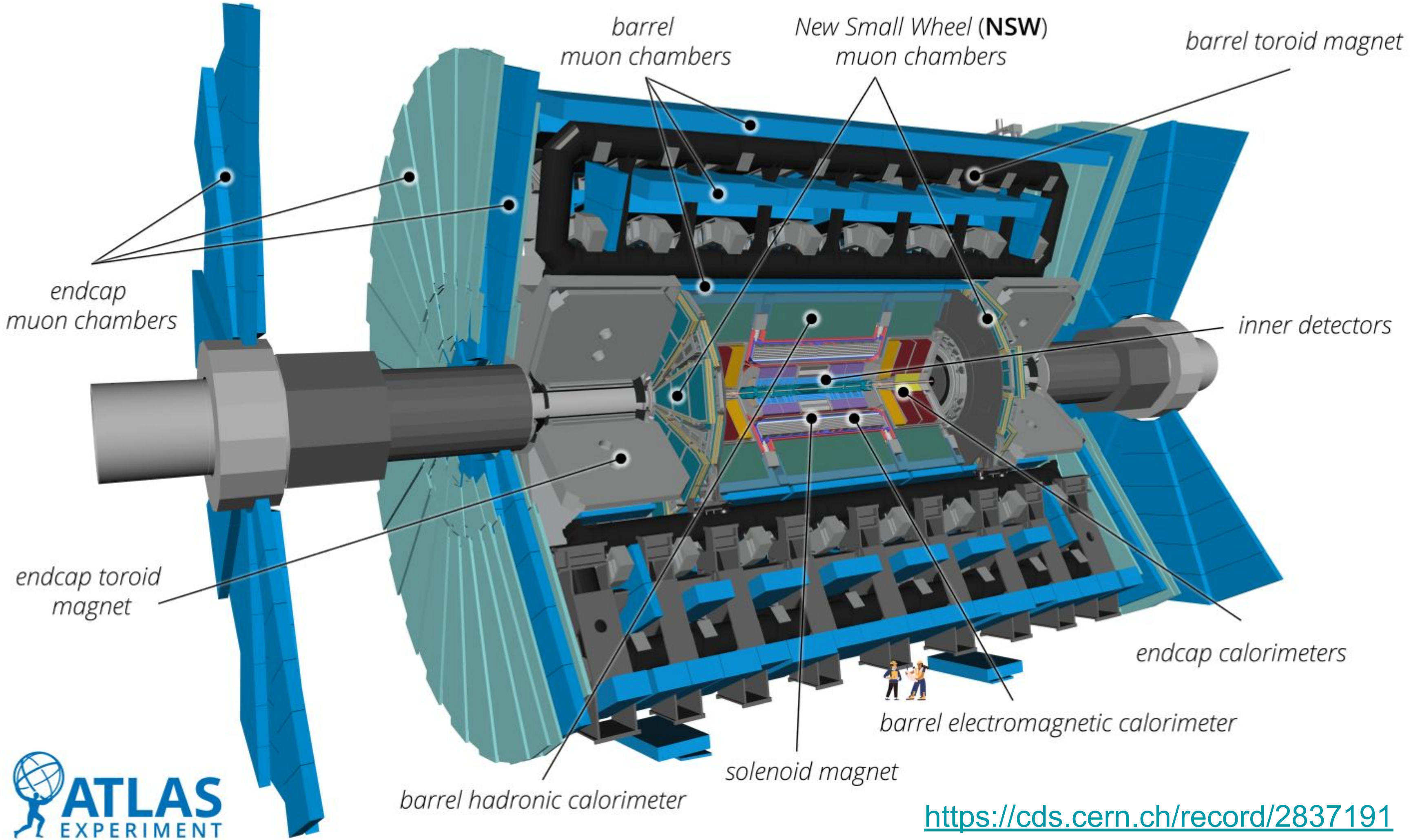
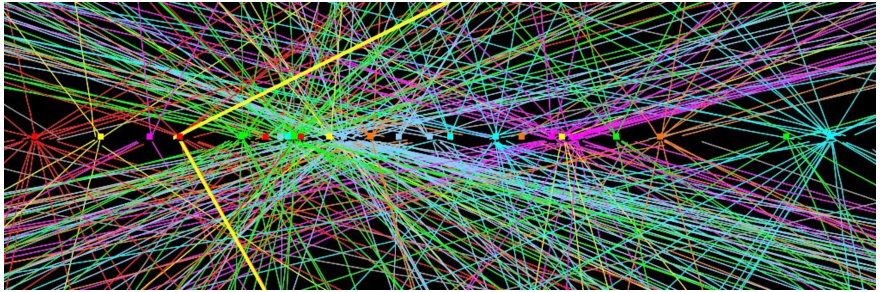


ATLAS EXPERIMENT

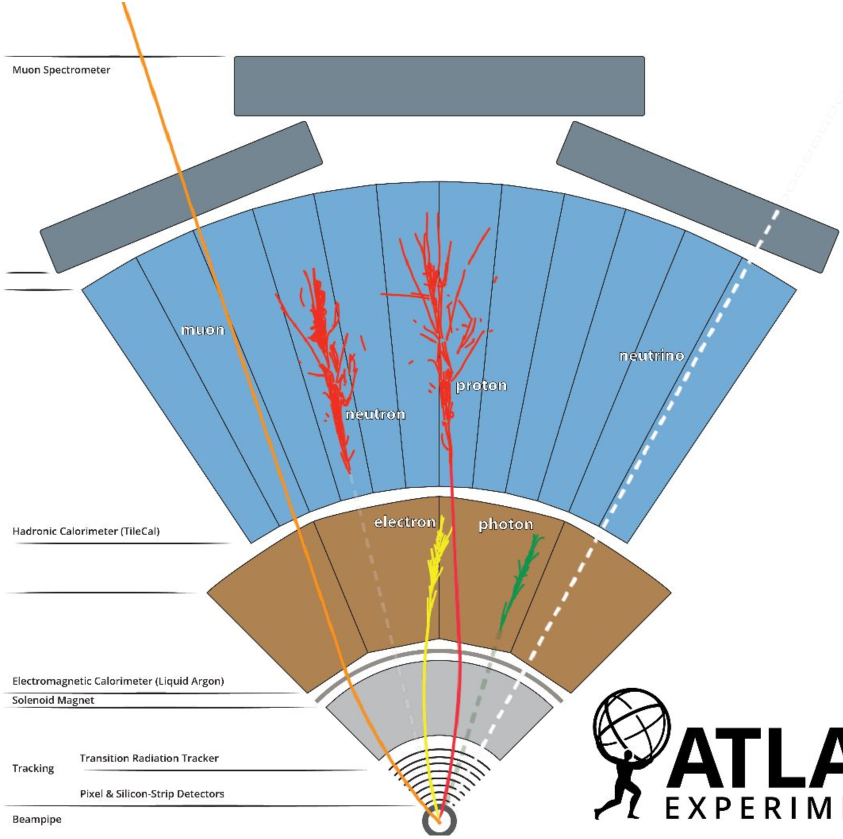
https://cds.cern.ch/record/2837191

The ATLAS Experiment at CERN

- A versatile particle detector aimed at Higgs boson discovery
  - but also at precision Standard Model physics and new physics searches.
- Precision **tracking** in solenoid magnetic field.
- **Calorimetry** of electrons and photons, calorimetry of hadrons.
- Dedicated **muons detectors** in a toroidal magnetic field.
- Many *pp* interactions per bunch crossing in a single event (pile-up), many “primary” vertices.



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayStandAlone#2012_Z_mu_mu_event_with_high_pil



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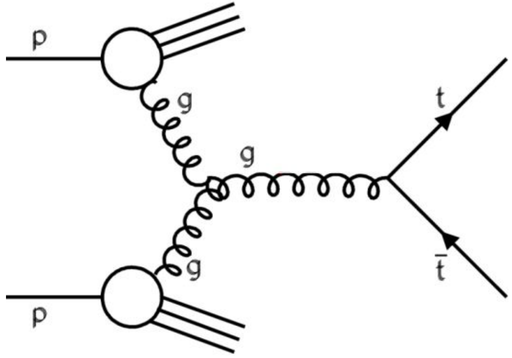
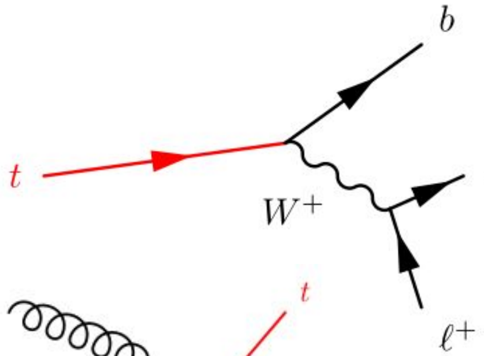
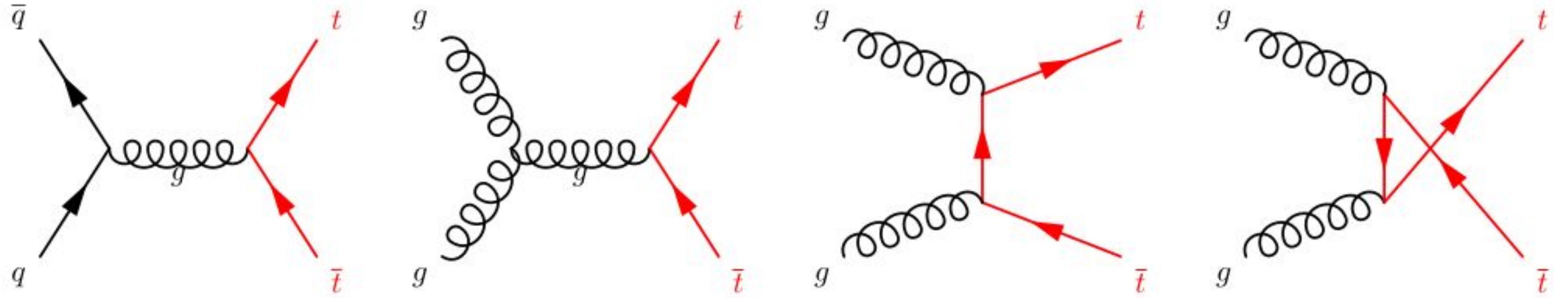
Top quark – production and decay

- LHC is a
  - gluon-gluon collider: gluons dominate the proton structure at the momentum fractions needed for production of heavy particles.
  - ‘top’ factory.
- Top quark
  - most abundantly produced in pairs, see the QCD Leading Order (LO) Feynman diagrams below.
  - decays into a W boson and a b-quark.
  - decays to a W boson and a *b*-quark.



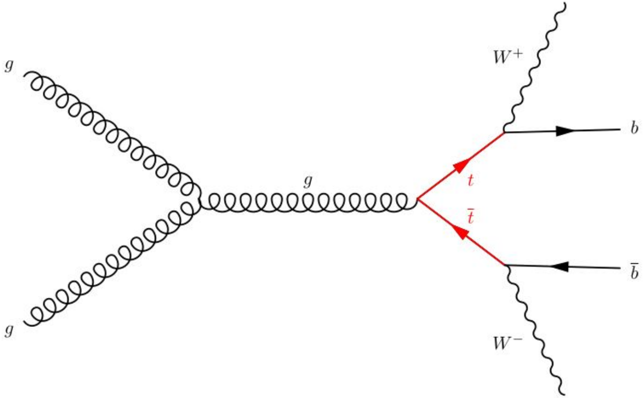
acc. to https://cms.cern/news/three-questions-top-quark-can-answer

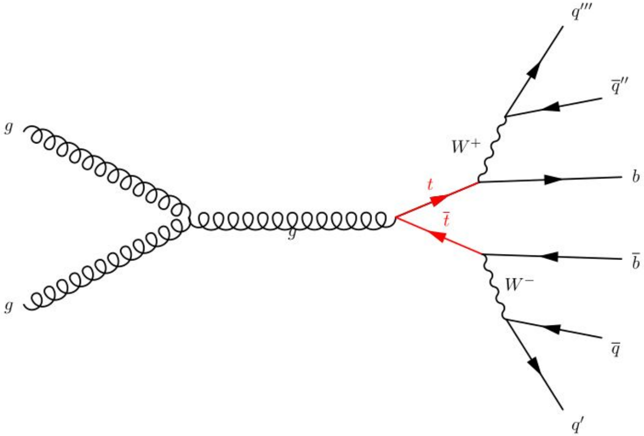


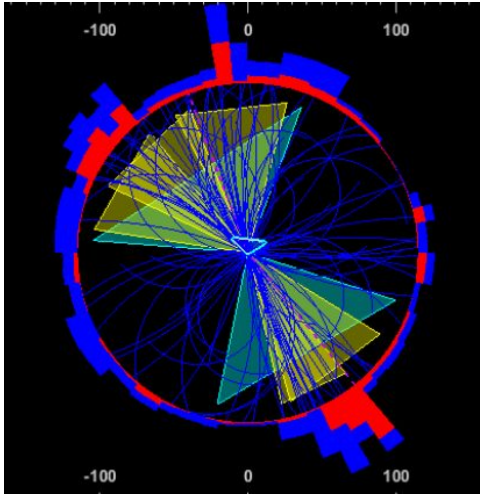


Top quark – production and decay

- The ttbar final states lead to two b-quarks and two W bosons which hadronice and decay further, respectively.
- Experiments observe the decay products.
- Four-momenta of W and top candidates formed from the detected particles.

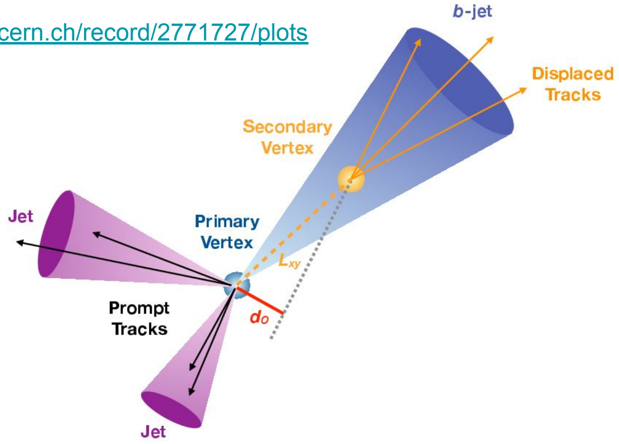






Top quark – technology driver

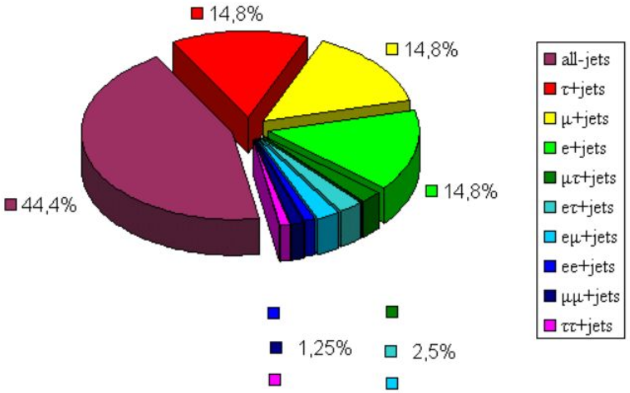
https://cds.cern.ch/record/2771727/plots



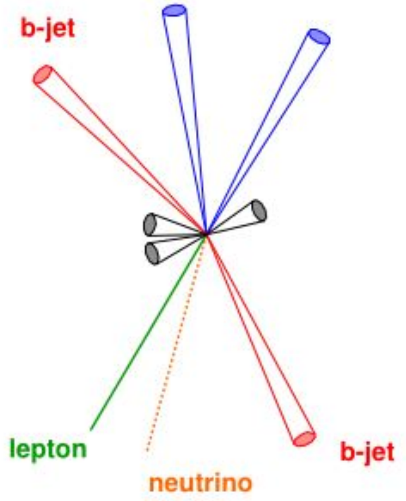
- The b-quark leads to long-lived B-mesons, tracks pointing to displaced vertices w.r.t. the collision point.
- Driver of experimental techniques for precision tracking and vertex reconstruction.

Top quark pairs decay modes

- Defined by the decay modes of the two W bosons: leptonic, **semileptonic**, hadronic.

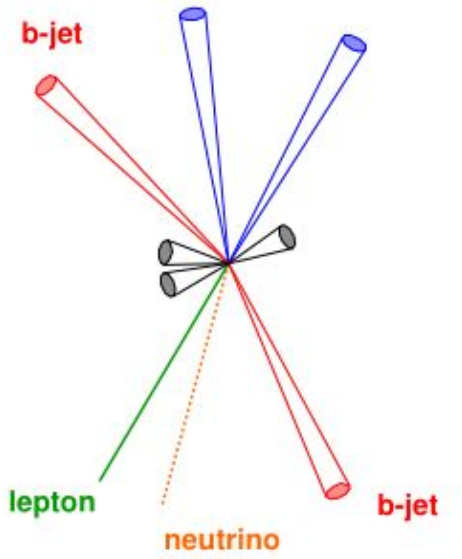


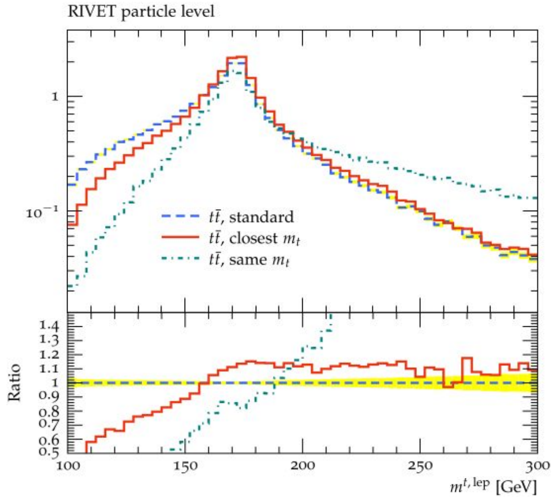
$t\bar{t}$ LO final state	channel name	branching frac
$b\bar{b}\ell\nu_\ell\ell'\nu_{\ell'}$	dilepton	10.6%
$b\bar{b}q\bar{q}'\ell\nu_\ell$	ℓ+jets	43.9%
$b\bar{b}q\bar{q}'q''\bar{q}'''$	all-hadronic	45.4%

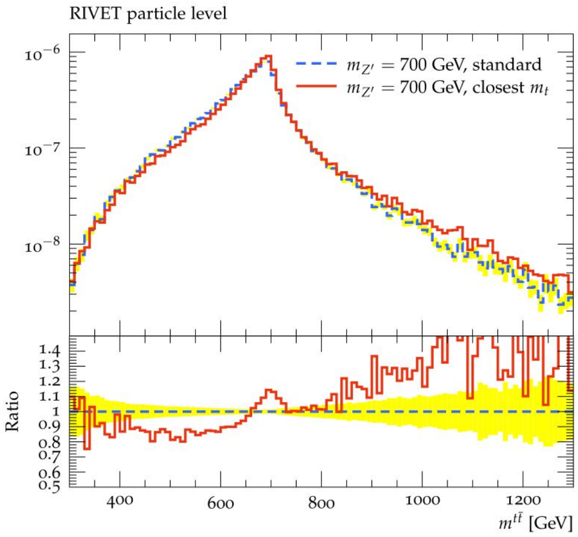


Top quark pairs – reconstruction of their kinematics

- Various algorithms to access the four-momenta of the top quarks from their decay products.
- Combinatorial issues from extra hadronic activity in the event (jets).
- Underconstraint kinematics due to escaping neutrinos in leptonic decays.
- Different algorithms lead to different resolution *e.g.* in the invariant mass of the ttbar system where resonances are searched for.

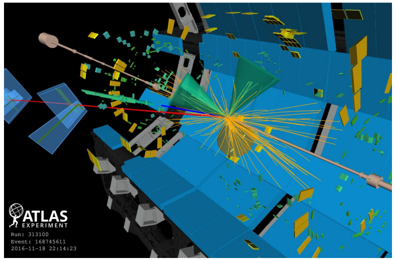




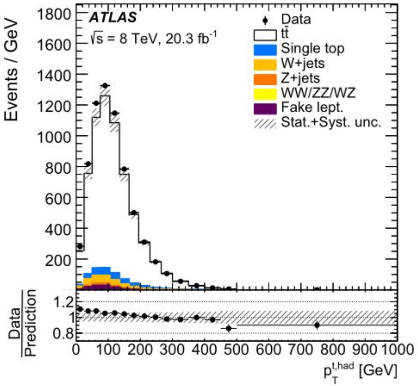


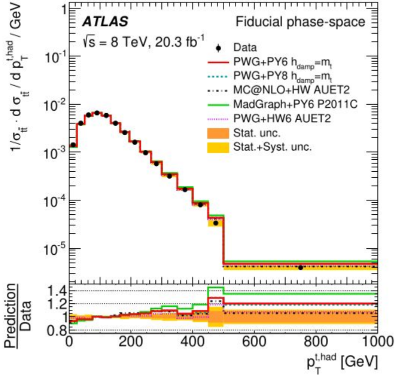
[Auth1] Kvita J. Study of methods of resolved top quark reconstruction in semileptonic $t\bar{t}$ decay. *Nucl. Instrum. Meth. A*, 900:84–100, 2018. [Erratum: Nucl. Instrum. Meth. A: 1040, 167172 (2022)].

Experimental high energy physics in general



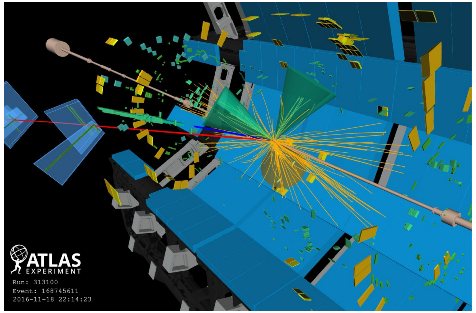
- Choice / **design of sensitive variables** for selection and measurement.
- **Objects** definitions and calibrations
  - electrons, muons, hadronic “jets”, …
- **Events**
  - selected based on expected objects in the final state.
  - ideally enriched in the desired signal process.
  - Such events are a composition of the desired signal and various **backgrounds mimicking the signal**.
- **Backgrounds**
  - estimated using simulation or data-driven techniques.
- **Statistical methods**
  - kinematics reconstruction, spectra unfolding;
  - signal strength fit, results combination.
- **A search** for a process
  - quantifies its **cross-section** or signal strength w.r.t. Standard Model expectations.
  - or sets **upper limits on the cross-section** if the process is not observed.
- **A measurement** corrects spectra of reconstructed objects for the detector resolution (unfolding).
- Design and evaluation of **systematics uncertainties**
  - objects calibrations, background and signal modelling.
- Results **comparison to theory predictions**
  - at various order of the perturbation theory: LO, NLO, NNLO…





Example analyses within the ATLAS experiment

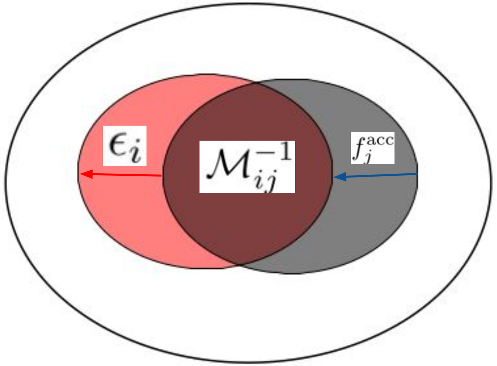
- **proton-proton collisions at centre-of-mass energies of**
  - **7 TeV** (2011, 5 fb^{-1})
  - **8 TeV** (2012, 20 fb^{-1})
  - **13 TeV** (2015–2018, 93 fb^{-1}).
  - 13.6 TeV (ongoing, 2022–2026, currently 300 fb^{-1})



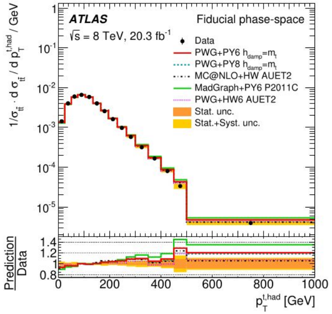
- **proton-lead collisions**
  - at the nucleon-nucleon centre-of mass energy of **8.16 TeV** (2016).
- **Measurements of spectra of the top quark**
  - **top quark transverse momentum (p_T)**
    - sensitive to higher orders of perturbative Quantum Chromodynamics
  - top-antitop (ttbar) pair invariant mass
    - sensitive to new physics resonances
  - angular and momentum-projection variables
    - sensitive to different modelling of the process and systematics uncertainties.

Spectra unfolding

- Restricting to a certain kinematic "fiducial" phase-space defined by objects selection criteria.
- Correcting for the detector resolution from the **detector** to the **particle** level.
- Fluctuations in measured objects energies and angles.
- Corrections evaluated using simulation.
- The **migration matrix** between the detector and particle level bins defined in the overlap region.
- Corrections needed to remove events outside of the phase-space.



$$\frac{\mathrm{d}\sigma}{\mathrm{d}X_i} \equiv \frac{1}{\epsilon_i \mathcal{L}\,\mathrm{BR}\,\Delta_i} \sum_j \mathcal{M}_{ij}^{-1} \left[f_j^{\mathrm{acc}} \left(D_j^{\mathrm{det}} - B_j^{\mathrm{det}} \right) \right]$$



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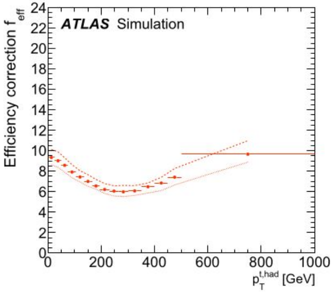
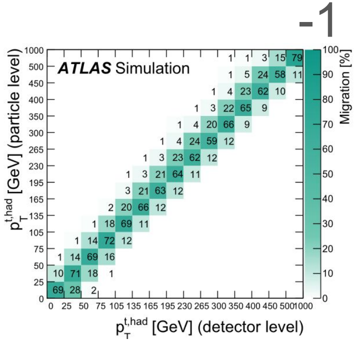
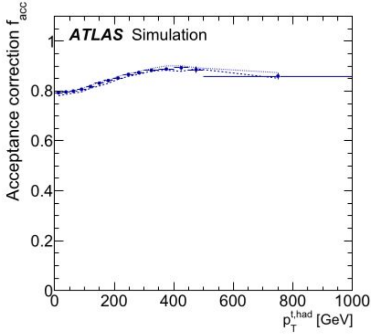
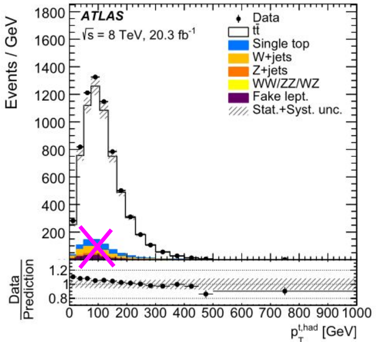


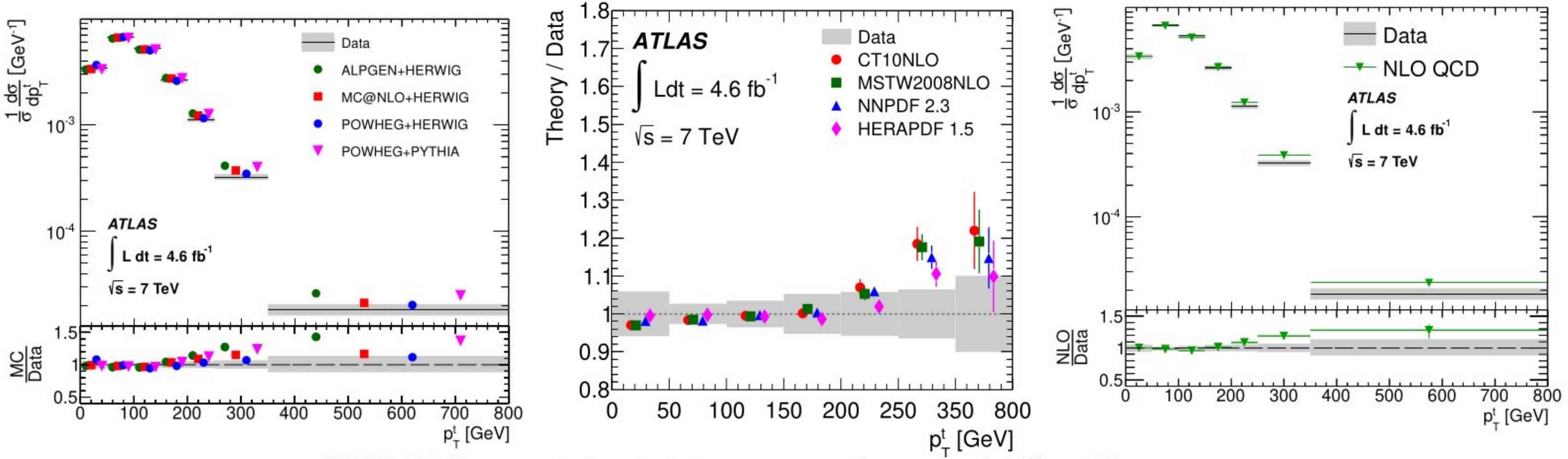






Top quark – a tool for precision physics measurements

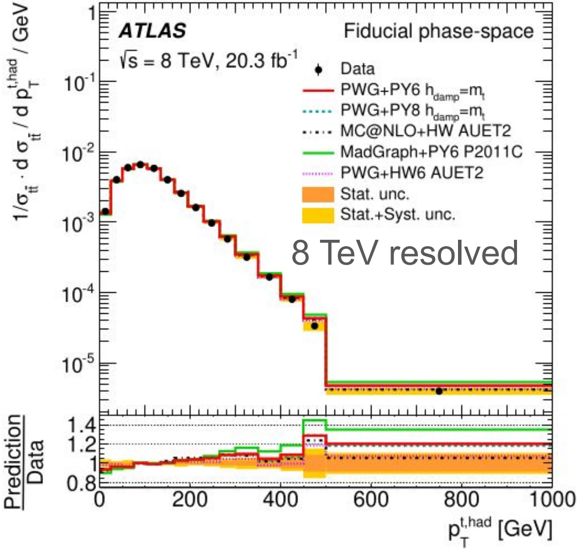
- A *pp* analysis at 7 TeV of c.m.s. energy.
- Observation: **a slope in top quark transverse momentum**
  - **NLO prediction/data ranging from -10% to +10%.**
  - top quark transverse momentum spectrum is softer in data.
  - this means less events in the so-called boosted regime.
- Also some preference for parton distribution functions (middle).
- Preference for NLO generators compared to older ones (left).

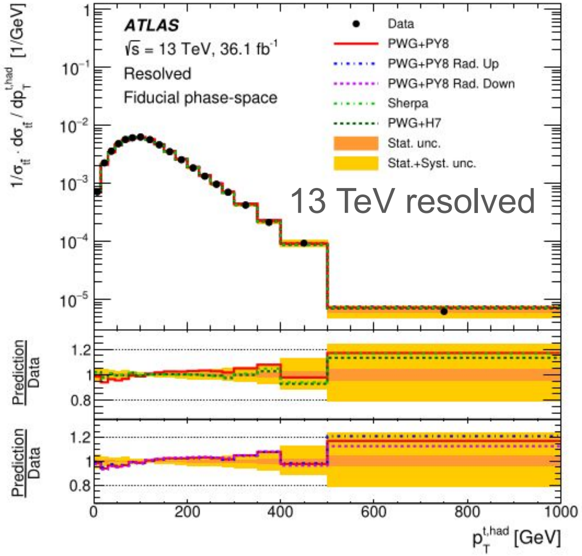


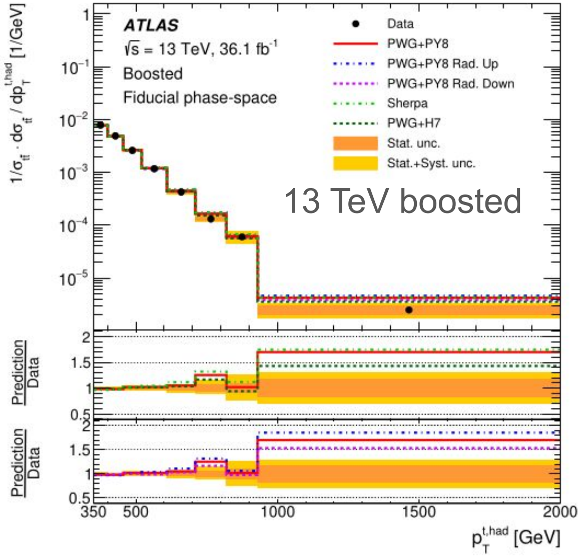
[ATLAS2] Georges Aad et al. Measurements of normalized differential cross sections for $t\bar{t}$ production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector. *Phys. Rev. D*, 90(7):072004, 2014.

Top quark – a tool for precision physics measurements

- Similar transverse momentum disagreement found in analyses at 8 and 13 TeV in resolved as well as boosted regimes.
- here normalized spectra; comparison to various NLO generators with different systematics settings.





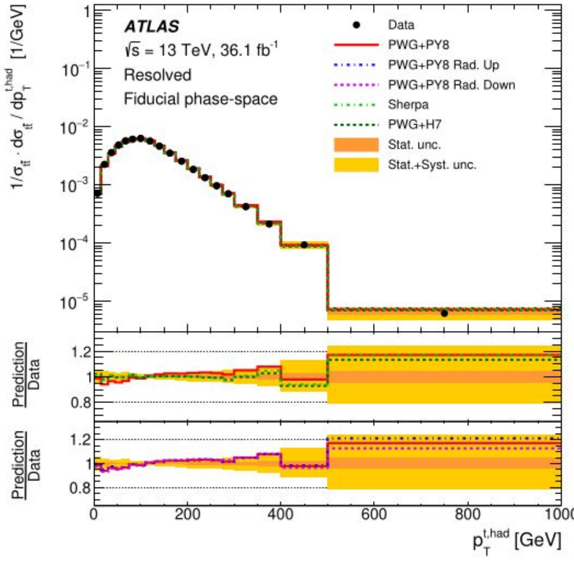


[ATLAS4] Georges Aad et al. Measurement of the differential cross-section of highly boosted top quarks as a function of their transverse momentum in $\sqrt{s}$ = 8 TeV proton-proton collisions using the ATLAS detector. *Phys. Rev. D*, 93(3):032009, 2016.

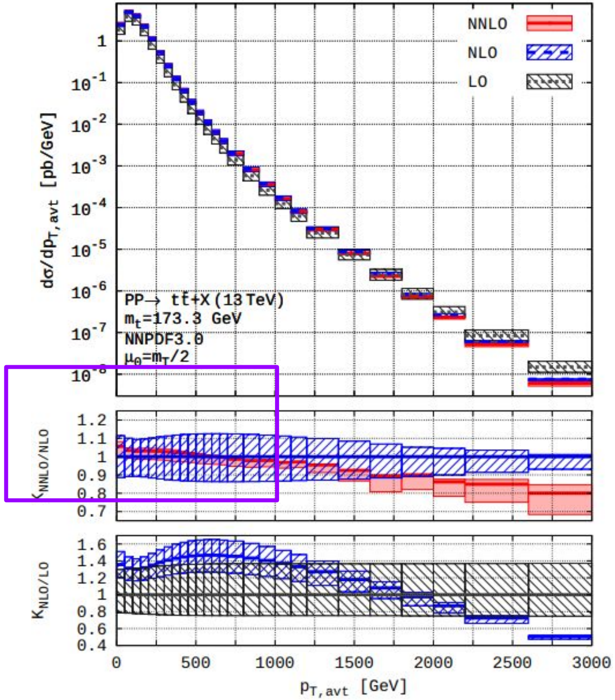
[ATLAS5] M. Aaboud et al. Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector. *JHEP*, 11:191, 2017.

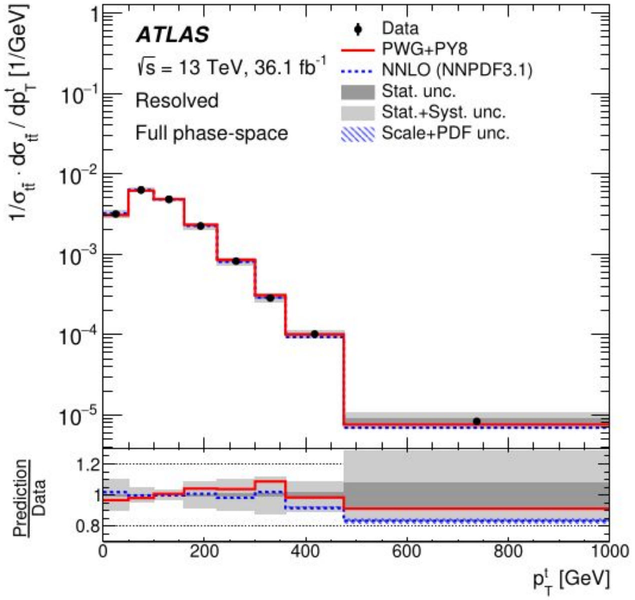
Top quark – a tool for precision physics measurements

- A slope in top quark transverse momentum compared to NLO – at the edge of systematics.
- Explained and described by a new NNLO prediction – within statistical uncertainties.
- A triumph of the theory, an important moment for top physics at the LHC.



NLO/data



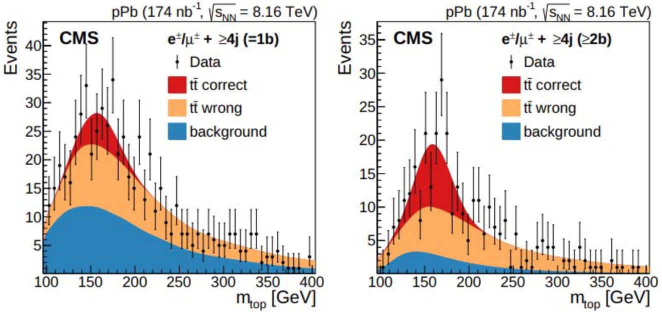


NNLO/data

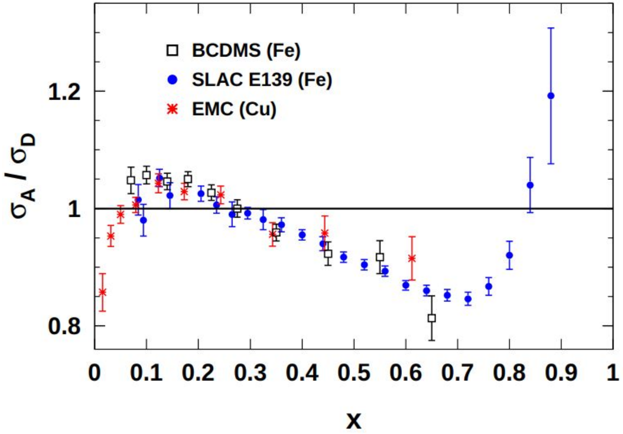
https://arxiv.org/abs/1606.03350

Top quark in heavy ion collisions

- Motivation:
  - are parton distribution functions the same inside bound nucleons as in a free proton?
    - nuclear modification factors
  - what are the strongly-interacting medium effects on various final states?
  - CMS observed in l+jets; ATLAS: included also the dilepton channel.
- Challenges:
  - a different environment of collision remnants
  - need for dedicated objects energy scale and other calibrations
  - need to validate background estimation in dedicated control regions.



https://arxiv.org/abs/1709.07411



https://arxiv.org/abs/1207.0131

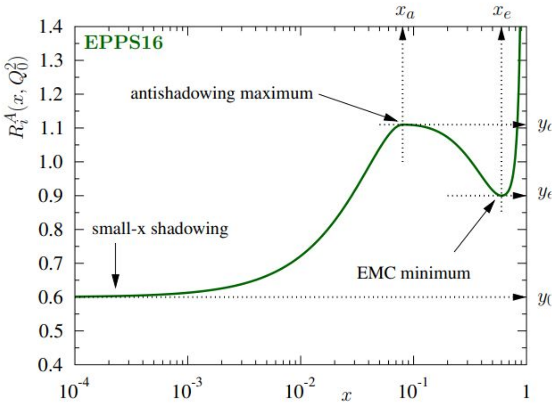


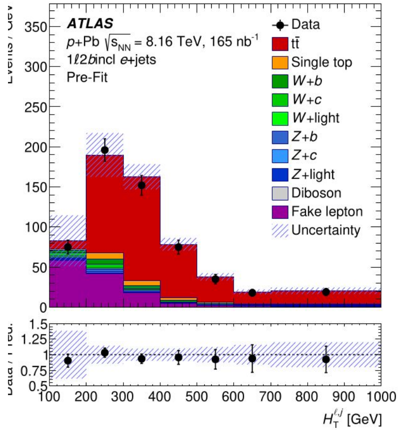
Fig. 1 Illustration of the EPPS16 fit function $R_i^A(x, Q_0^2)$.

https://arxiv.org/abs/1612.05741

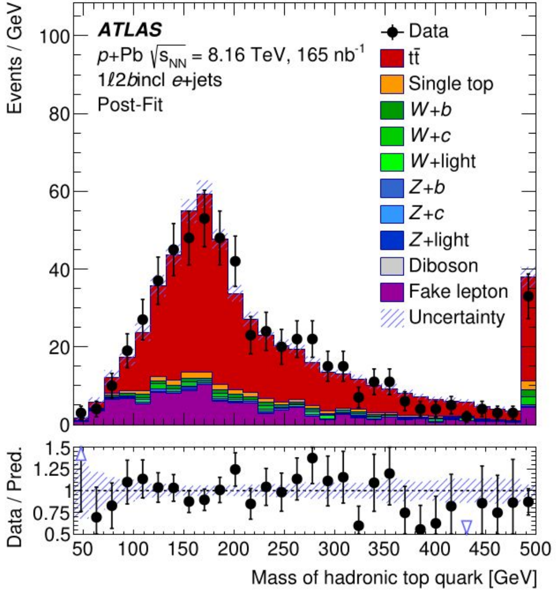
Statistical analysis: signal fit

$$\mathcal{L}(\mu, \boldsymbol{\theta}, \boldsymbol{\sigma}, \boldsymbol{\gamma}, \mathbf{d}, \mathbf{S}, \mathbf{B}) \equiv \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(d_i | \mu S_i + B_i) \cdot \mathcal{P}(h_i | \gamma_i h_i) \cdot \prod_{j=0}^{N_{\theta}} \mathcal{G}(\theta_j | 0, \sigma_j)$$

- $\mu = \frac{\sigma_{\text{observed}}}{\sigma_{\text{theory}}}$ is the signal strength;
- $\boldsymbol{\theta}$ and $\boldsymbol{\sigma}$ are vectors of additional ("nuisance") parameters (NPs, representing systematic uncertainties shifts) and their uncertainties;
- γ are bin-by-bin scaling factors allowing to let the total prediction $S_i + B_i$ in each bin fluctuate according to the Poisson distribution with the statistical uncertainty modified by the γ factor;
- $\mathbf{d}$; $\mathbf{S}$ and $\mathbf{B}$ are the binned data; and signal and background binned prediction templates; and $h_i = S_i + B_i$;
- $\mathcal{P}(k|\nu)$ and $\mathcal{G}(x|x_0, \sigma)$ are the Poisson and Gauss probability distribution functions, respectively.



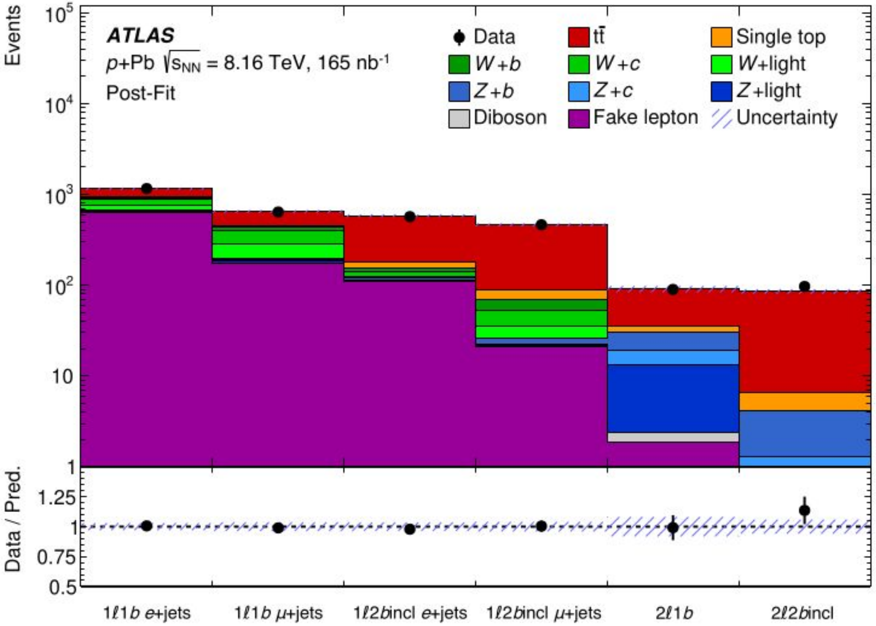
- Confirmation of the top quark mass peak:

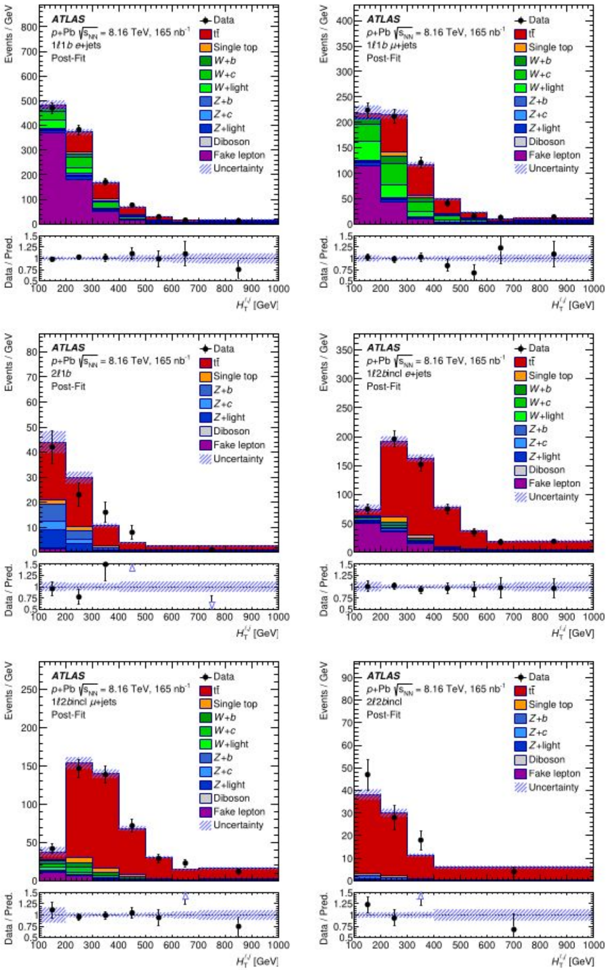


Validation, pre-fit and post-fit data/prediction agreement

- Simultaneous fit of the signal and background templates to a sensitive variable.
  - **6 regions** based on lepton flavour and number of *b*-jets.
    - one signal strength.

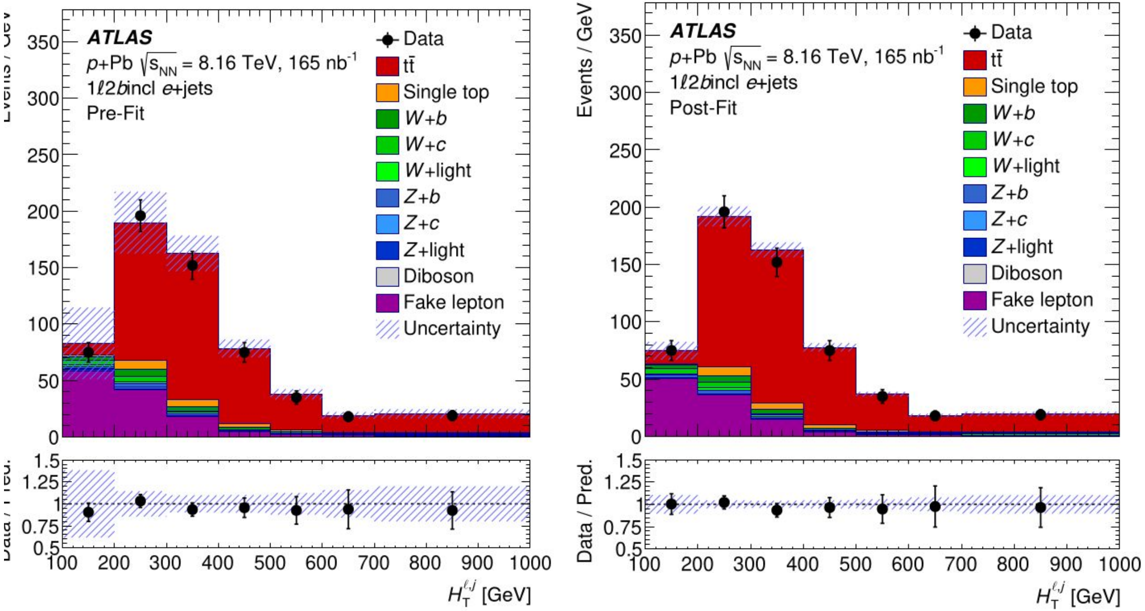
$$\mathcal{L}(\mu, \boldsymbol{\theta}, \sigma, \gamma, \mathbf{d}, \mathbf{S}, \mathbf{B}) \equiv \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(d_i|\mu S_i + B_i) \cdot \mathcal{P}(h_i|\gamma_i h_i) \cdot \prod_{j=0}^{N_\theta} \mathcal{G}(\theta_j|0, \sigma_j)$$





Validation, pre-fit and post-fit data/prediction agreement

- Backgrounds shape and normalization modified during the fit.
  - better data/prediction agreement.
- Systematics are constraint after the fit.



[ATLAS8] Georges Aad et al. Observation of $t\bar{t}$ production in the lepton+jets and dilepton channels in p+Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with the ATLAS detector. *JHEP*, 11:101, 2024.

Top quark in heavy ion collisions

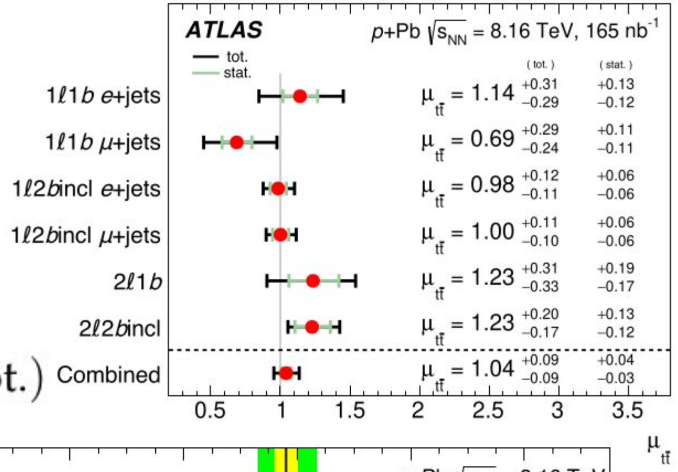
- Measure the cross-section ratio to the proton-proton case:

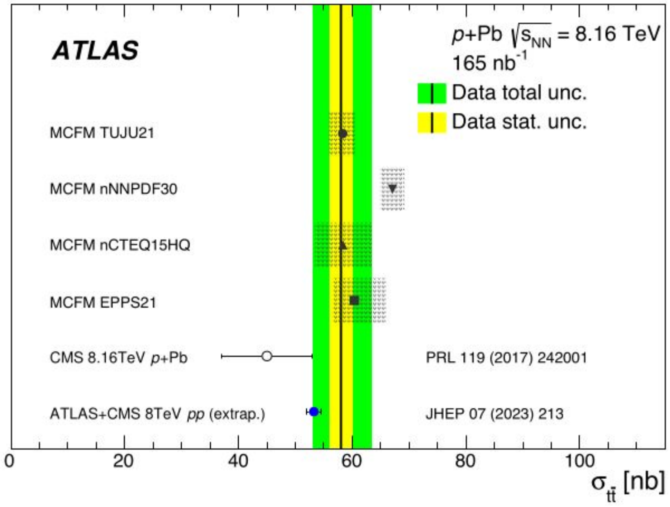
$$R_{pA} = \frac{\sigma_{t\bar{t}}^{p+\text{Pb}}}{A_{\text{Pb}} \cdot \sigma_{t\bar{t}}^{pp}}$$

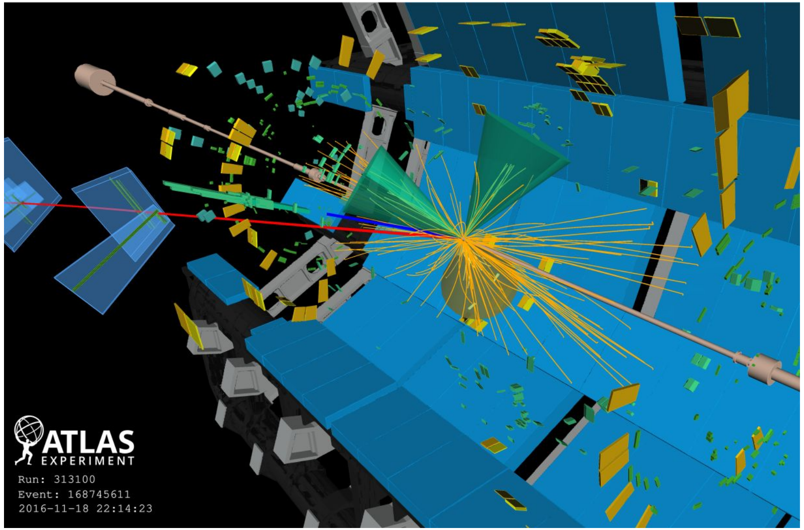
- ~2x better precision than CMS:

$$R_{pA} = 1.090 \pm 0.039\,(\text{stat.})\,^{+0.094}_{-0.087}\,(\text{syst.}) = 1.090 \pm 0.100\,(\text{tot.})$$

$$\sigma_{t\bar{t}} = 58.1 \pm 2.0\,(\text{stat.})\,^{+4.8}_{-4.4}\,(\text{syst.})\text{ nb}$$



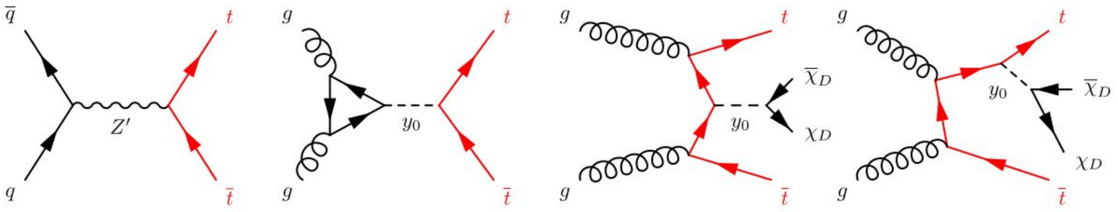




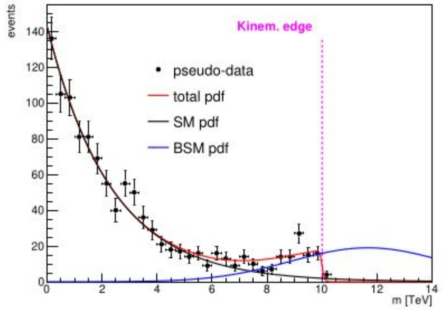
CMS: $\sigma_{t\bar{t}} = 45 \pm 8\,(\text{total})\text{ nb}.$

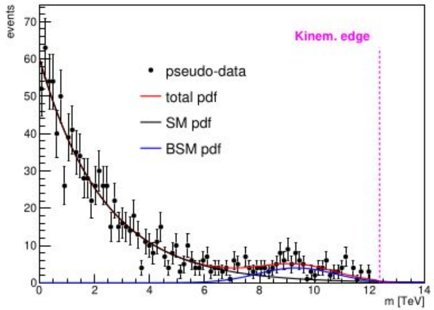
Top quark – a tool for searching new physics

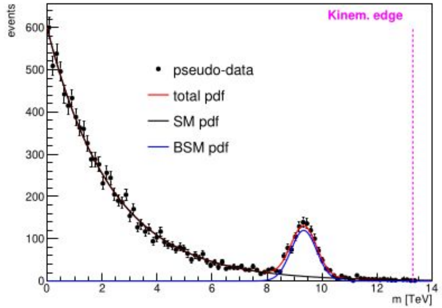
- Possible new physics processes involving the top quark



- Three general new physics scenarios:
  a. new physics is out of energy reach of the collider, hints can be observed at the very kinematic edge, direct resonance mass not possible
  b. new physics is within kinematic reach, but at the edge of the statistical power.
  c. new physics is within reach both kinematically and statistically.
- ⇒ check spectra of top quarks modified by the new physics!

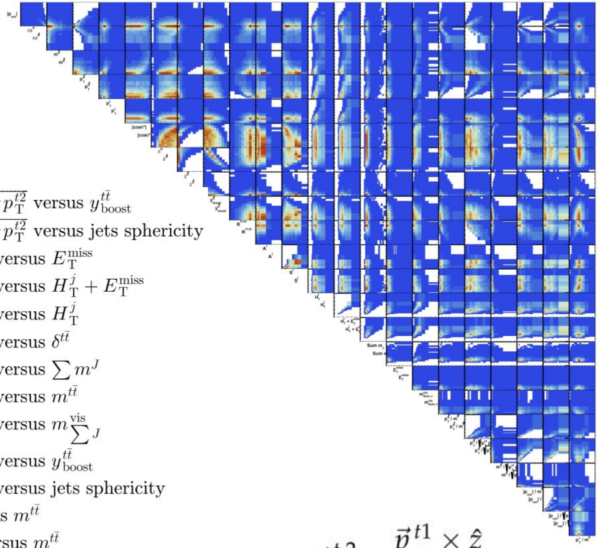






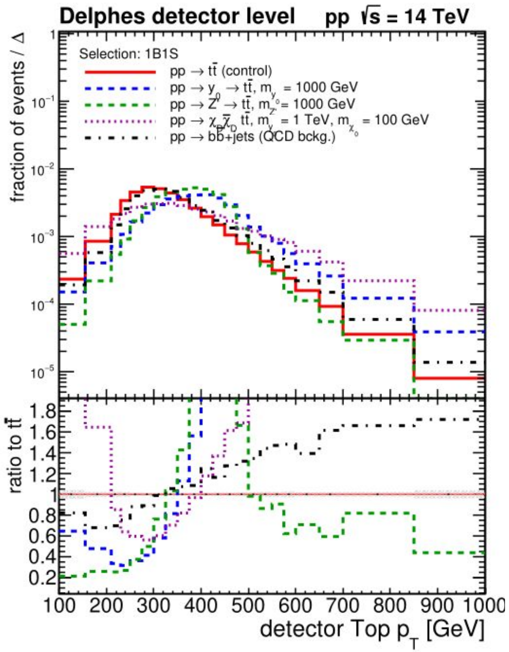
Top quark – a tool for searching new physics

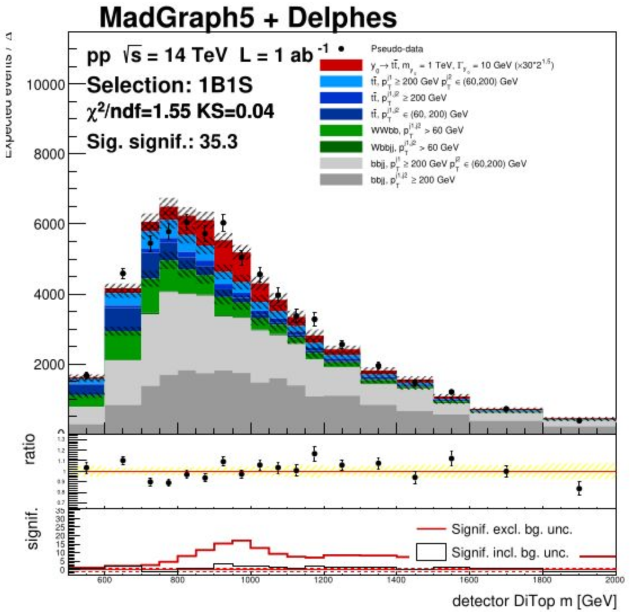
- Simulation of the top quark transverse momentum and the peak in the ttbar invariant mass for various cases of possible new physics scenarios.
- Design of new sensitive kinematic variables and robust to systematic uncertainties.
- Search for simulated excess due to the presence of new physics.



$p_T^{t\bar{t}}/\sqrt{p_T^{t1}p_T^{t2}}$ versus $y_{\text{boost}}^{t\bar{t}}$
$p_T^{t\bar{t}}/\sqrt{p_T^{t1}p_T^{t2}}$ versus jets sphericity
$p_T^{t\bar{t}}/m^{t\bar{t}}$ versus E_T^{miss}
$p_T^{t\bar{t}}/m^{t\bar{t}}$ versus $H_T^j + E_T^{\text{miss}}$
$p_T^{t\bar{t}}/m^{t\bar{t}}$ versus H_T^j
$p_T^{t\bar{t}}/m^{t\bar{t}}$ versus $\delta^{t\bar{t}}$
$p_T^{t\bar{t}}/m^{t\bar{t}}$ versus $\sum m^J$
$p_T^{t\bar{t}}/m^{t\bar{t}}$ versus $m^{t\bar{t}}$
$p_T^{t\bar{t}}/m^{t\bar{t}}$ versus $m_{\sum J}^{\text{vis}}$
$p_T^{t\bar{t}}/m^{t\bar{t}}$ versus $y_{\text{boost}}^{t\bar{t}}$
$p_T^{t\bar{t}}/m^{t\bar{t}}$ versus jets sphericity
$p_T^{t\bar{t}}$ versus $m^{t\bar{t}}$
$y_{\text{boost}}^{t\bar{t}}$ versus $m^{t\bar{t}}$
$y_{\text{boost}}^{t\bar{t}}$ versus $p_T^{t\bar{t}}$
$|p_{\text{out}}|/m^{t\bar{t}}$ versus E_T^{miss}
$|p_{\text{out}}|/m^{t\bar{t}}$ versus $H_T^j + E_T^{\text{miss}}$

$$p_{\text{out}} \equiv \vec{p}^{\,t,2} \cdot \frac{\vec{p}^{\,t1} \times \hat{z}}{|\vec{p}^{\,t,1} \times \hat{z}|}$$



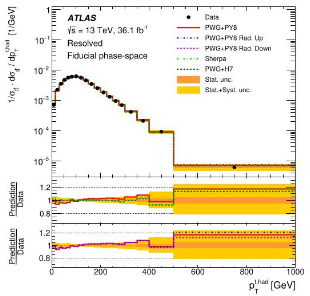


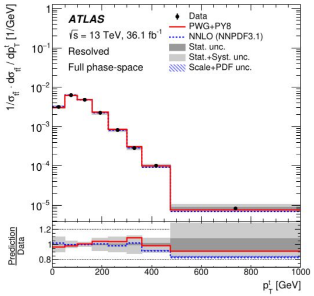
$y_0 \to t\bar{t}$

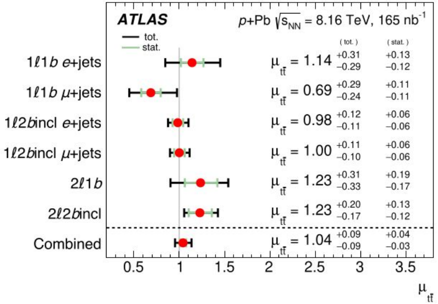
[Auth4] Kvita J. Boosted and semi-boosted all-hadronic $t\bar{t}$ reconstruction performance on kinematic variables for selected BSM models using a 2D extension of the BumpHunter algorithm. *International Journal of Modern Physics A*, 39(11n12):2430002, 2024.

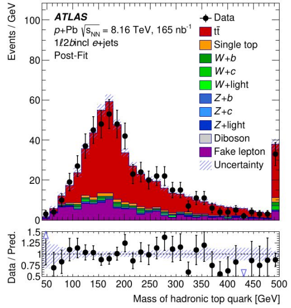
Top quark physics – conclusions

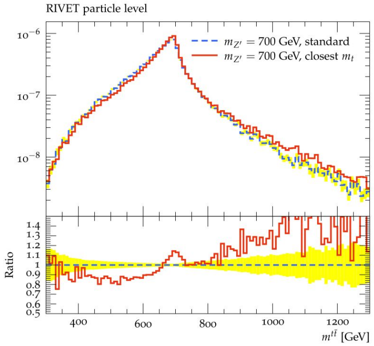
- Top quark spectra measured at the LHC have been an uncharted territory and required higher orders of the theory calculations
    - example of interplay between experiment and theory.
- Top quarks in heavy ion collisions explore a complementary environment and probe nuclear structure.
- Top quark final states remain attractive candidates for a connection to possible physics beyond the Standard Model.

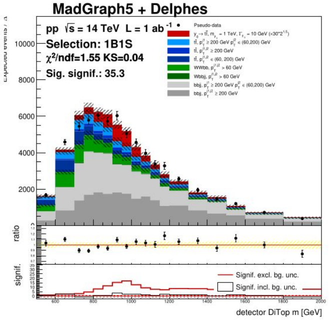












Outlook

- A production of 4 top quarks was observed recently.
  - a spectacular process mediated by the strong interaction at a threshold of ~700 GeV!
  - opens doors for observing 3 top quarks (both strong and weak interaction in play)
- Hints of top-antitop bound states near their production threshold.
- Well established ttbar + Higgs production opens ways for other interesting electroweak final states involving the top quark like ttV, ttVV
- Recent ATLAS observation of ttbar in lead-lead collisions
  - opens way to measuring top quark spectra in ion collisions environment
- New NNLO + parton shower generators for better theory precision.
- Study of interference effects with other processes.
- A ground for searching for new physics via resonances or associated production.

Question by doc. Michal Šumbera

Rád bych však okomentoval samotnou práci, která mi na mnoha místech připadá až příliš lakonická. Jejím hlavním tématem je implementace výpočtů poruchové teorie kvantové chromodynamiky pro popis spekter příčných hybností *t-kvarků*. Analýza modelových výpočtů kulminuje výsledkem, že teprve po započtení vyšších řádů poruchové teorie (tzv. next-to-next-to-leading order, NNLO) kvantové chromodynamiky (QCD) je získán uspokojivý popis experimentálních dat. Pojem NNLO je však krátce a bez vysvětlení zmíněn v 2. kapitole odstavci *2.2.4 Evolution of parton distribution functions*. Další popis metod a použití poruchové teorie v QCD (pQCD) v práci zcela chybí. Z tohoto důvodu je pak až poněkud překvapivé najít fyzikální argumenty pro použití vyšších řádů pQCD pro zlepšení popisu p_T spekter *t-kvarků*. Postrádám též zmínku o použití NNLO aproximace pro jiné QCD procesy jako je produkce tří jetů v elektron-pozitronové anihilaci, Drell-Yanovská produkce leptonů či hluboce neelastický rozptyl elektronů na polarizovaných protonech. Očekávám proto, že habilitant tato témata během obhajoby zmíní či nejlépe více rozvede to co mohl napsat v podkapitole *3.7 Higher order processes*.

Answer 1

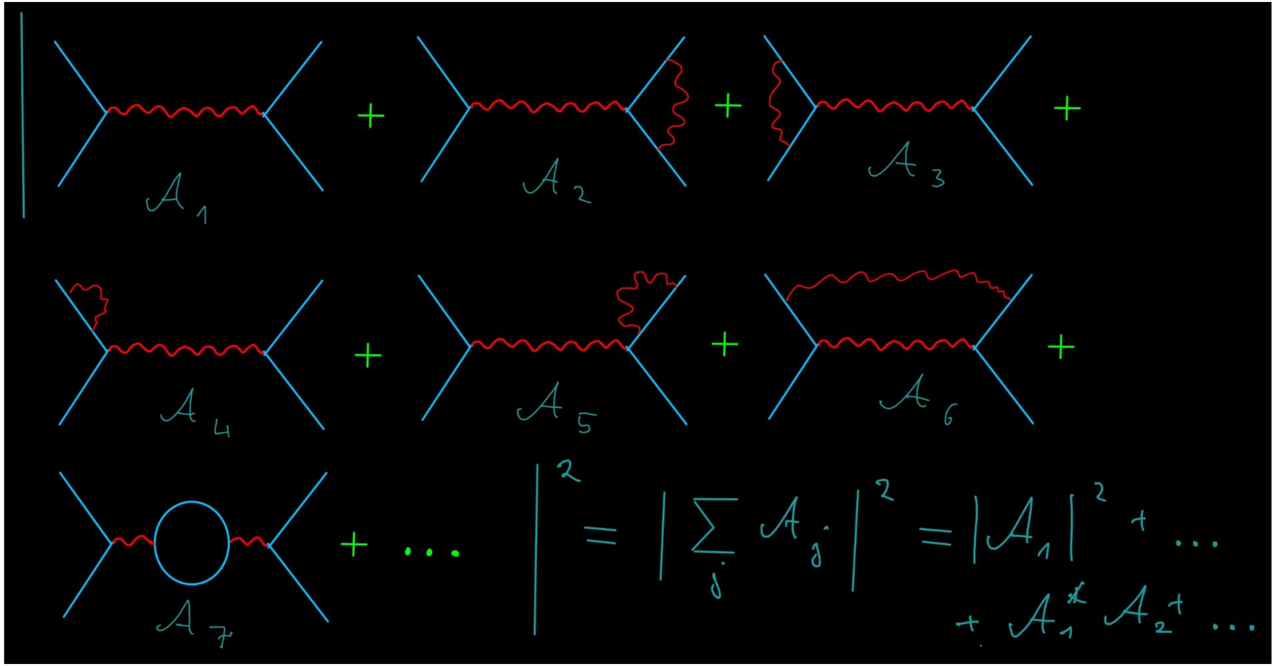
- I have been considering the level of details, to avoid the thesis becoming a textbook, and I am not a theorist.
- I have tried to support the experimental, statistical and data analysis parts with a reasonable introduction, context and a level of detail, supported by references.
- Indeed, the story of the measurement of the transverse momentum of the top quark is an example of an interplay between experiment and theory.
- The data disagreement to NLO QCD calculations paired with a parton shower was a surprise and had been a long standing problem.
- Theory at the NNLO level seems to address the discrepancy with experiment.

Answer 2: Perturbative QCD and higher orders

$$\hat{\sigma}_{ij}(\beta) = \frac{\alpha_S^2}{m^2}\left(\sigma_{ij}^{(0)} + \alpha_S \sigma_{ij}^{(1)} + \alpha_S^2 \sigma_{ij}^{(2)} + \mathcal{O}(\alpha_S^3)\right)$$

https://arxiv.org/pdf/1303.6254

- Including higher-order Feynman diagrams (virtual and real emissions)



Answer 2: Perturbative QCD and higher orders

$$\hat{\sigma}_{ij}(\beta) = \frac{\alpha_S^2}{m^2}\left(\sigma_{ij}^{(0)} + \alpha_S \sigma_{ij}^{(1)} + \alpha_S^2 \sigma_{ij}^{(2)} + \mathcal{O}(\alpha_S^3)\right)$$

https://arxiv.org/pdf/1303.6254

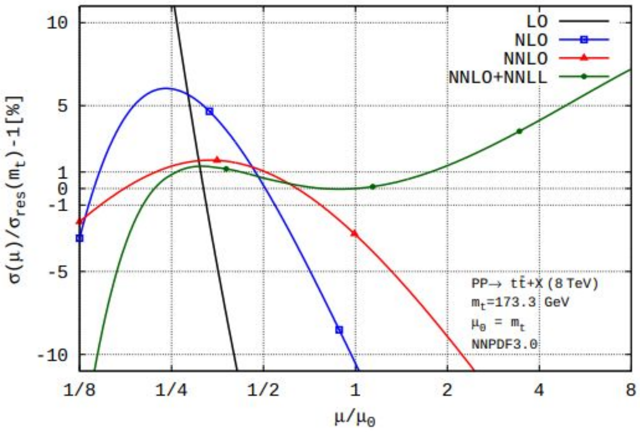
- Leading order (LO), next-to-leading order (NLO), NNLO, …
  - a regularization scale μ is needed to tame divergences in the individual terms in the perturbation series in powers of the strong coupling constant α_S.
  - summed to all orders, the result would be μ-independent
  - calculations to a fixed order of the series depend on μ which needs to be selected.
  - this dependence usually diminishes as the order increases.
  - general approach is to make the result less sensitive to the choice of μ
  - terms in the results typically involve log(μ/Q).
  - the idea is to have a result not largely sensitive to the scale choice, though this may be subjective
  - motivated choices use the typical energy or momentum transfer of the process Q

$$\sigma_{ij,\mathbf{I}}(\beta,\mu,m) = \sigma_{ij,\mathbf{I}}^{(0)}\left\{1 + \frac{\alpha_s(\mu^2)}{4\pi}\left[\sigma_{ij,\mathbf{I}}^{(1,0)} + \sigma_{ij,\mathbf{I}}^{(1,1)}\ln\left(\frac{\mu^2}{m^2}\right)\right] + \left(\frac{\alpha_s(\mu^2)}{4\pi}\right)^2\left[\sigma_{ij,\mathbf{I}}^{(2,0)} + \sigma_{ij,\mathbf{I}}^{(2,1)}\ln\left(\frac{\mu^2}{m^2}\right) + \sigma_{ij,\mathbf{I}}^{(2,2)}\ln^2\left(\frac{\mu^2}{m^2}\right)\right] + \mathcal{O}(\alpha_s^3)\right\}$$

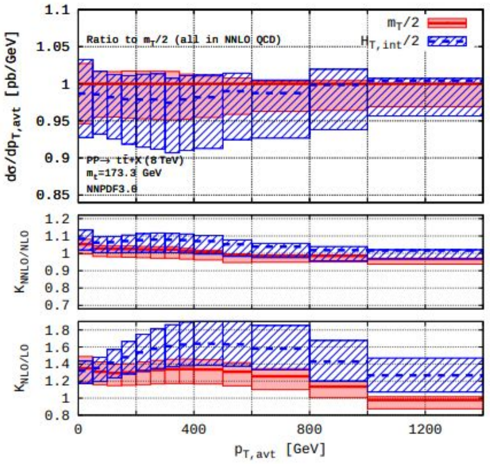
https://arxiv.org/pdf/0911.5166

Answer 3: Perturbative QCD and higher orders

- In contrast to Drell-Yann production of leptons in hadronic collision, the scales involved in the process of top quark production are two:
  - the momentum transfer (dynamic scale)
  - the mass of the top quark m_t (fixed scale)
  - and usually a combination of the above, e.g. $(Q^2 + m_t^2)^{1/2}$, is used.
- I cite the paper dedicated to different scale choices for different spectra.
  - Dynamical scales for multi-TeV top-pair production at the LHC, https://arxiv.org/abs/1606.03350:



$$\mu_0 \sim m_t \,,$$
$$\mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2} \,,$$
$$\mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} \,,$$
$$\mu_0 \sim H_T' = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + \sum_i p_{T,i} \,,$$
$$\mu_0 \sim E_T = \sqrt{\sqrt{m_t^2 + p_{T,t}^2}\sqrt{m_t^2 + p_{T,\bar{t}}^2}} \,,$$
$$\mu_0 \sim H_{T,\text{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2} \,,$$
$$\mu_0 \sim m_{t\bar{t}} \,,$$

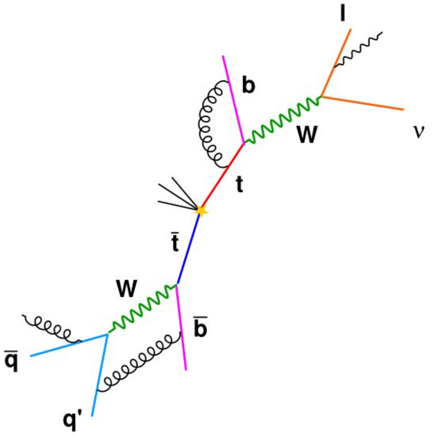


Overview of the theoretical developments

- NNLO ttbar
  - qq → ttbar + X: https://arxiv.org/abs/1204.5201
  - qq → ttbar + qq: https://arxiv.org/abs/1207.0236
  - gg → ttbar threshold expansion: https://arxiv.org/abs/0911.5166
  - gg → ttbar: https://arxiv.org/abs/1303.6254
- additional soft gluon resummation (NNLL)
  - https://arxiv.org/abs/1111.5869
- NNLO correction to leptonic observables
  - https://arxiv.org/abs/2008.11133
- Monte Carlo generators:
  - NLO + Parton Shower + non-resonant: https://arxiv.org/pdf/1607.04538
  - NNLO + Parton Shower: https://arxiv.org/abs/1908.06987
- 3 jets production at NNLO
  - https://arxiv.org/abs/2106.05331

Backup slides

Top quark pairs – the way they can be observed

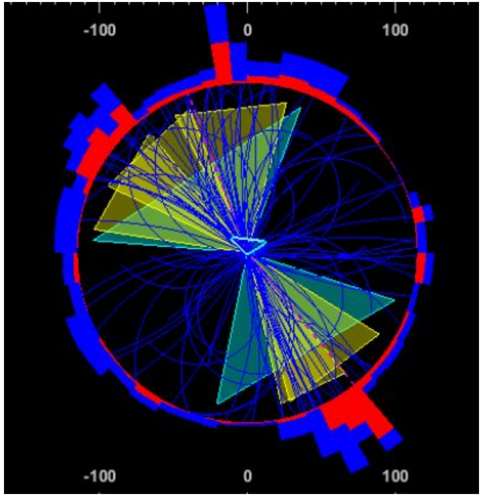


- We observe top quark decay products from which the decay mode, mass, and spectra can be inferred.
- Bosonic and fermionic propagators corrected for some higher order contributions lead resonant-shape Breit-Wigner distributions.

$$|S|^2 \sim \frac{1}{(p^2 - m^2)^2 + m^2\Gamma^2}$$

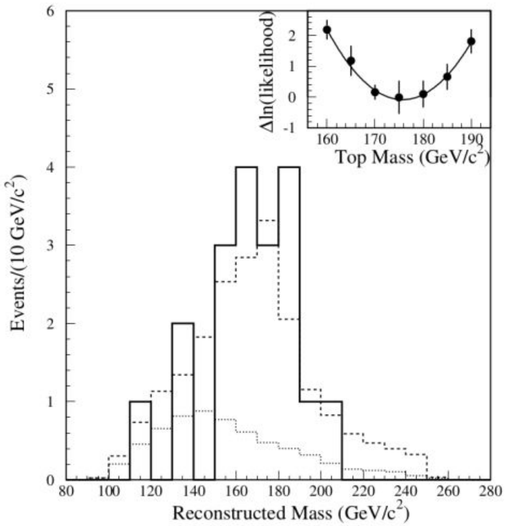
https://arxiv.org/pdf/2203.11056

- Hence we see enhancements of the cross section near the resonance pole.
- Also, mass of a particle can be inferred from the invariant mass of the four-vectors making up the assumed particle four-vector.



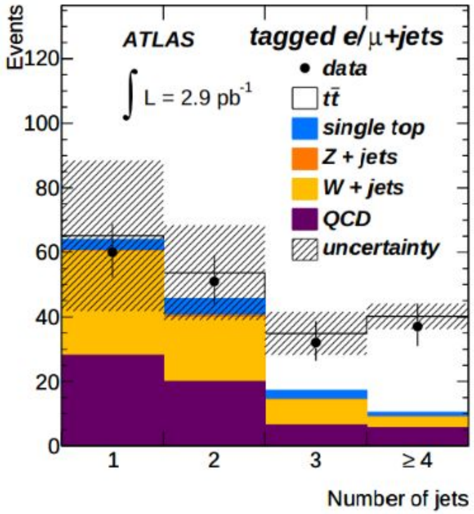
Top quark – discovery at Tevatron, 1995

- Proton-antiproton collisions of at almost 2 TeV in the central-mass-system.
- Experiment CDF (pioneered silicon tracking detectors)
- Experiment DZero (precise calorimetry and muon detectors).

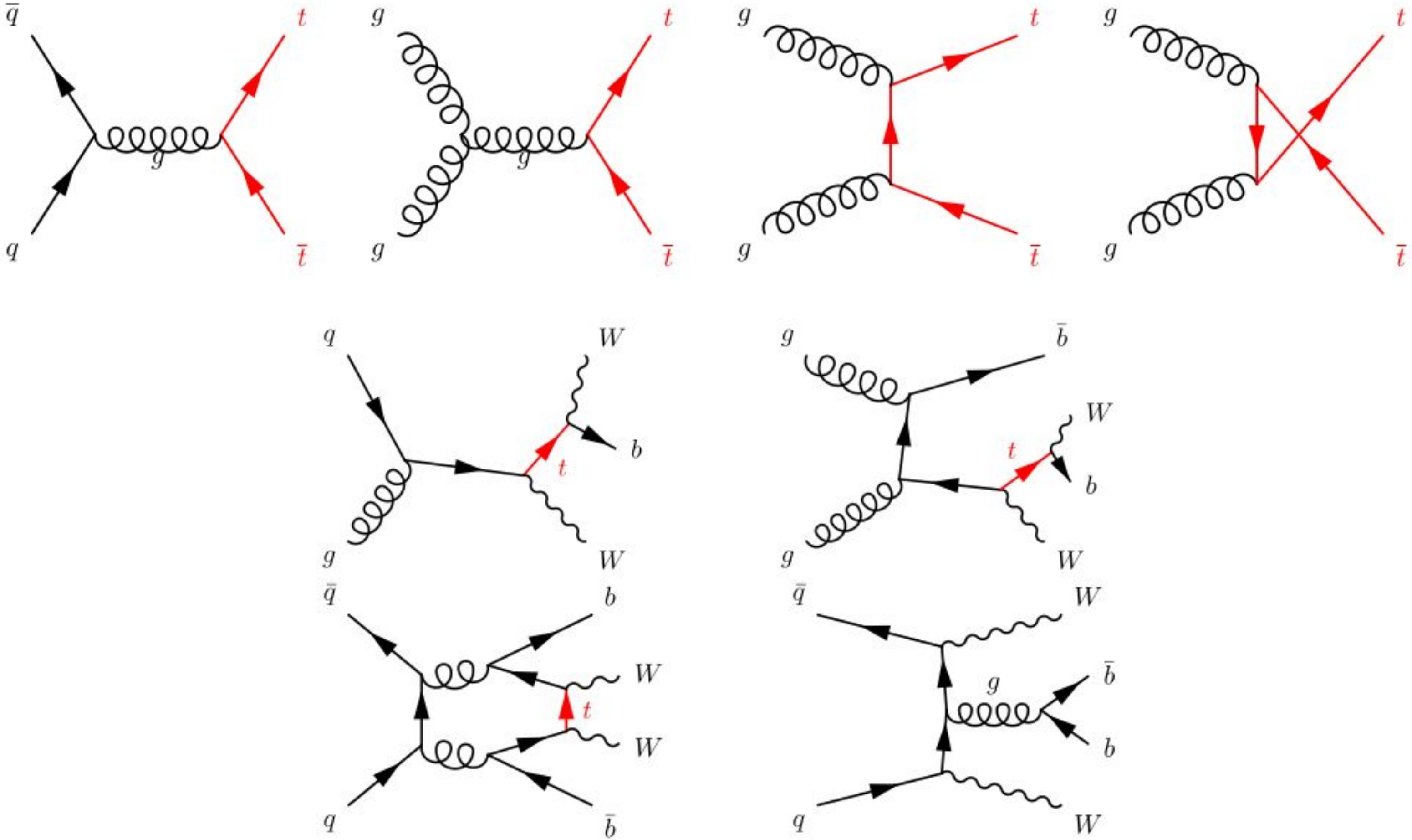


Top quark – rediscovery at the LHC, 2011.

- In the beginning, a counting experiment
- Verification of the new larger detectors at a new accelerator at a 4x higher energy, in different collisions.



Resonant and non-resonant WbWb production

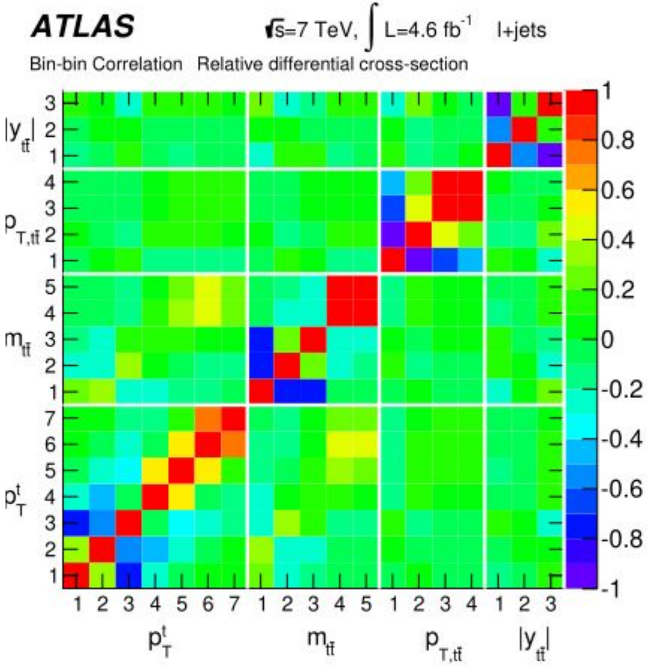


Top quark – a tool for precision physics measurements

- Evaluation of correlations over bins for all variables.
  - necessary to compare multiple spectra from a single model to data.
  - evaluated using the bootstrap method.

4.4.6 Statistically correlated spectra

A technique of bootstrapping has been actively applied at the ATLAS experiment according to [83] in order to construct statistically-varied versions (replicas) of histograms of any dimension, by repeatedly filling an arbitrary number (typically 100–1000) of replicas by the same events but weighted by random weights drawn from the Poisson distribution of mean of 1, *i.e.* as $w \sim \text{Poisson}(1)$. This means that each event is used on average once in each replica, but allows for a multiple, yet weighted, spectra be generated, in order to study effects of statistical fluctuations based directly on the measured data spectra, without the need for extensive MC simulations. Setting the initial random seed to a defined combination of the run and event number of the collision event, one can create statistically correlated replicas over the replica number, over spectra, or even across analyses. Similarly, the bootstrap technique applied to MC events allows to determine the statistical significance of systematic uncertainties and allow one to possibly drop or smoothen them.



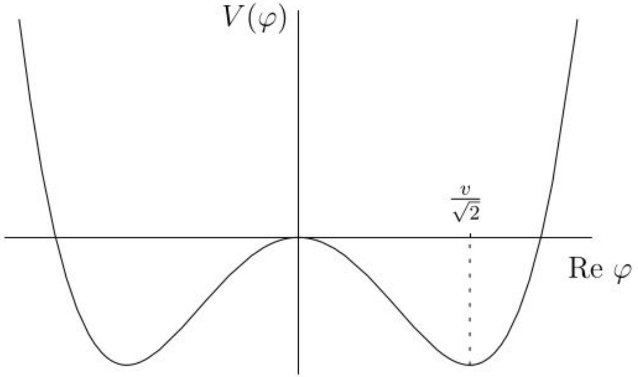
[ATLAS2] Georges Aad et al. Measurements of normalized differential cross sections for $t\bar{t}$ production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector. *Phys. Rev. D*, 90(7):072004, 2014.

Top quark – the last of the "tiniest"

- Higgs potential $V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$
- Higgs field in unitary gauge

$$\Phi_U(x) = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + H(x)) \end{pmatrix}$$

- Resulting mass terms and the Higgs field expectation value.



$$\mathscr{L}_{mass}^{(IVB)} = \frac{1}{4} g^2 v^2 W_\mu^- W^{+\mu} + \frac{1}{8}\left(g^2 + g'^2\right) v^2 Z_\mu Z^\mu$$

$$m_W = \frac{1}{2} g v \quad G_F/\sqrt{2} = g^2/\left(8 m_W^2\right)$$

$$v = \left(G_F \sqrt{2}\right)^{-1/2} \doteq 246 \text{ GeV}$$

J. Hořejší, https://arxiv.org/pdf/2210.04526

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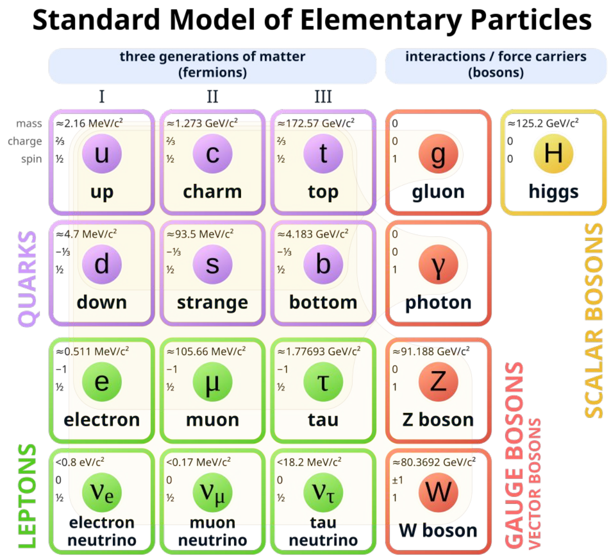
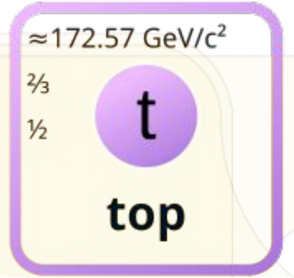


Symbol	Name	Interaction	Mass
γ	photon	electromagnetic	0
$W^\pm$	charged vector bosons	weak (charged currents)	80.37 GeV
Z	neutral vector boson	weak (neutral currents)	91.19 GeV
g	gluons	strong	0
H	BEH boson (scalar)	Yukawa	125.2 GeV

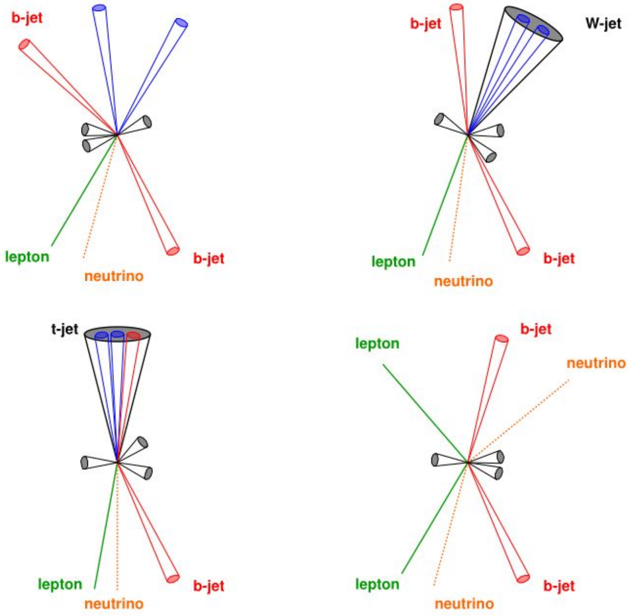
Top quark the only fermion with mass of the order of v.

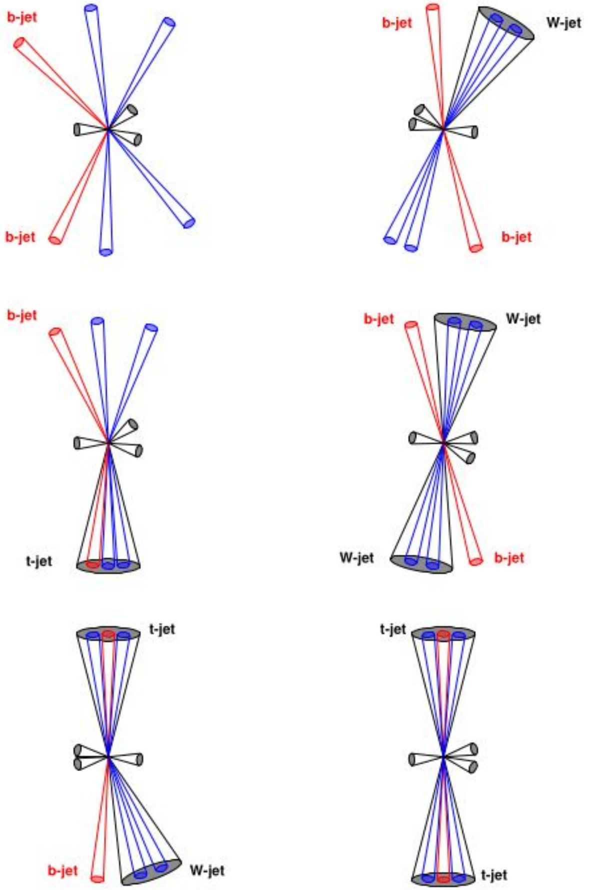


J. Hořejší, https://arxiv.org/pdf/2210.04526

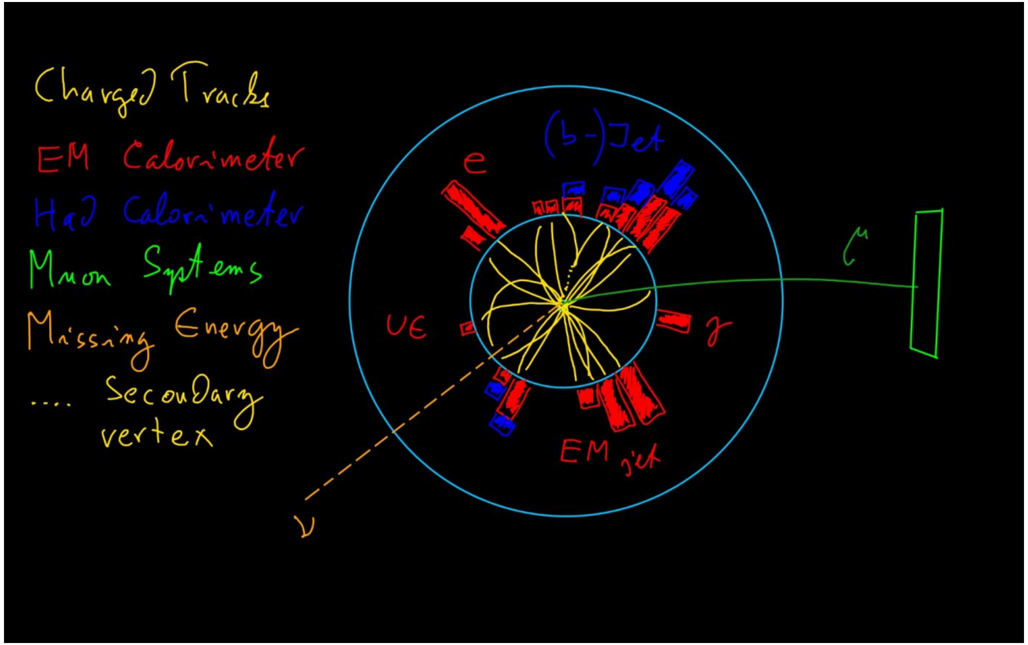
Resolved and boosted top quarks

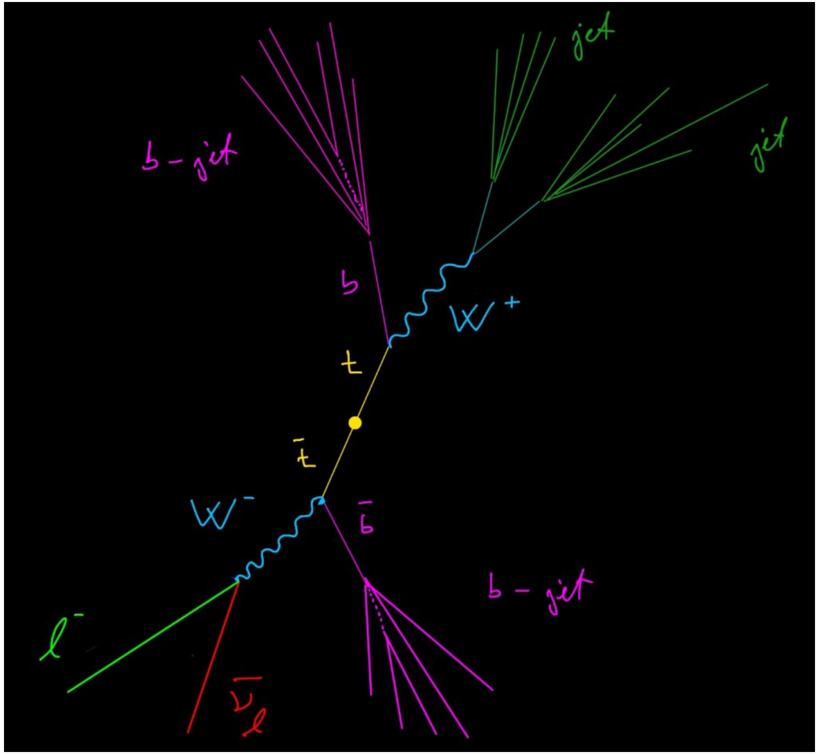
- different degree of the transverse boost
- various final states requiring different experimental reconstruction techniques
- access to different energy transfer testing different regimes of the perturbative QCD





The semileptonic channel





Resolved and Boosted regimes

- the consistency of the resolved and boosted regimes

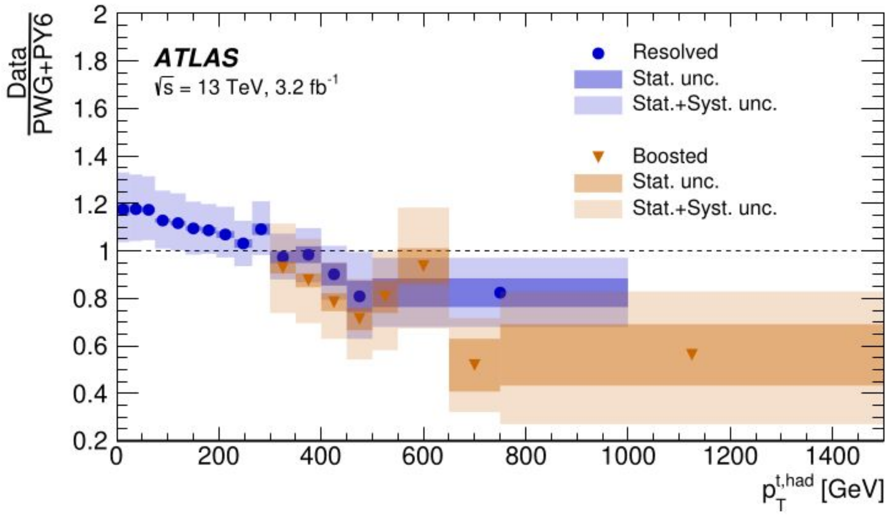
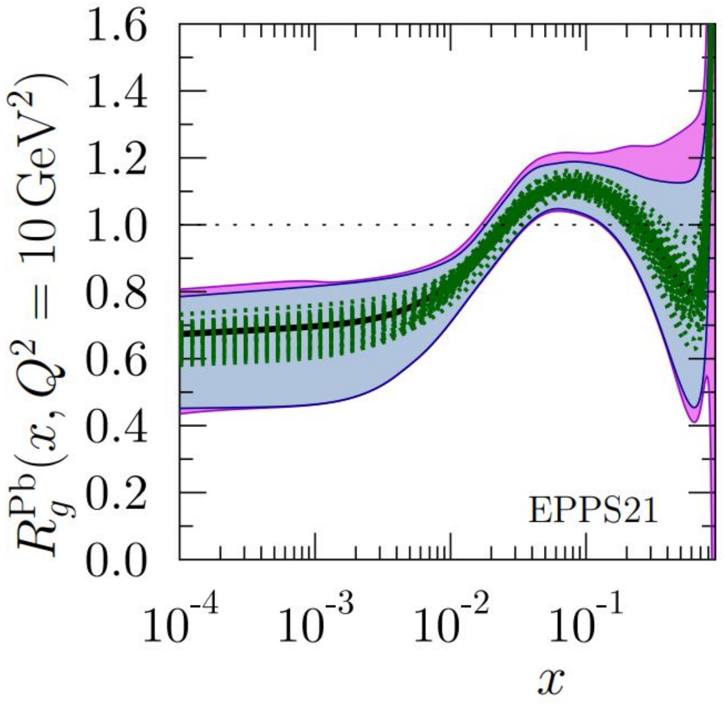


FIGURE 7.5: The first ATLAS analysis of the top quark differential spectra in both resolved (left) and boosted (right) regimes [ATLAS5] at the energy of $\sqrt{s} = 13\,\text{TeV}$ showing the results for the top quark p_{T} at the detector (top) and unfolded the particle (middle) levels. In the bottom plot, the consistency between the two regimes is checked in terms of the ratio to the same NLO generator prediction.

Modified nuclear parton distribution functions

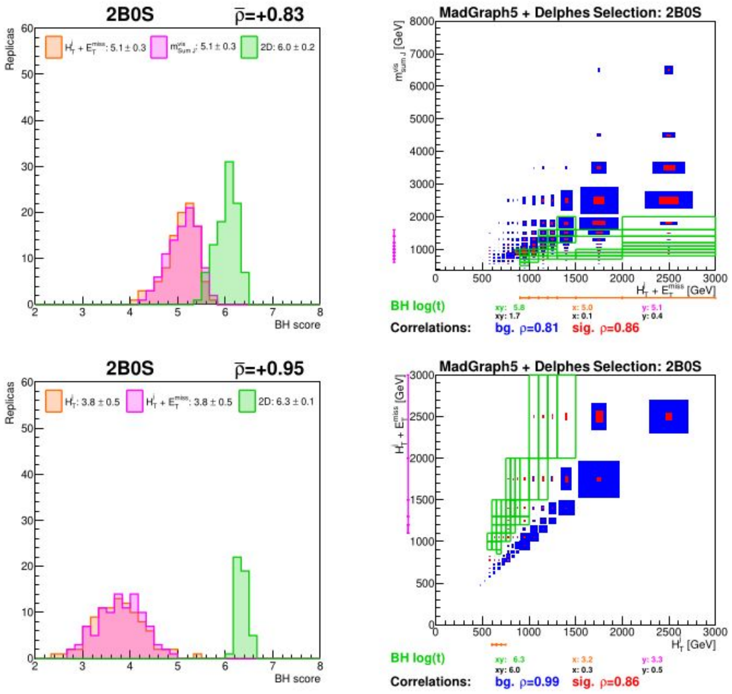


https://arxiv.org/abs/2112.12462

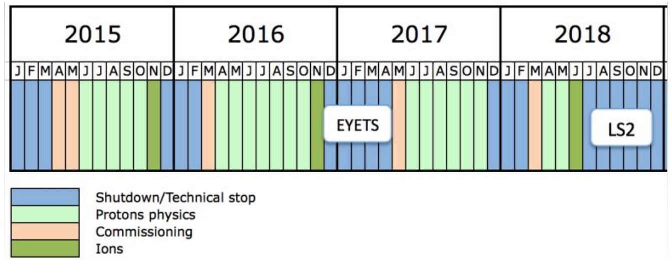
New physics: 2D variables

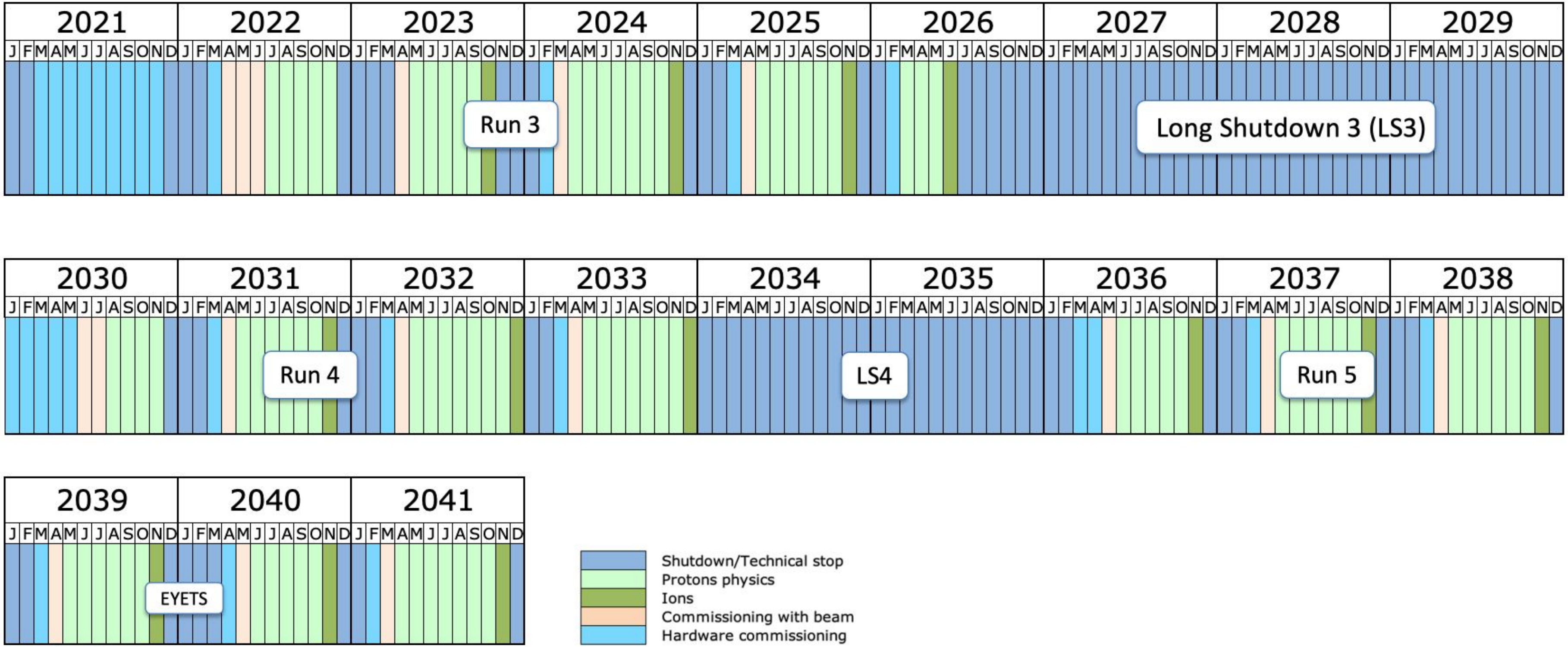
FIGURE 8.10: Left: a histogram of 1D (orange, purple) and 2D (green) BUMPHUNTER scores over pseudo-experiments for the visible mass of the sum of large jets and $H_T^j + E_T^{miss}$ variables using the y_0 signal model (top) and for the H_T^j and $H_T^j + E_T^{miss}$ variables using the $t\bar{t} + y_0$, $y_0 \to \chi_D \bar{\chi}_D$ (bottom) signal model. Right: The green boxes indicate the best 2D (xy) BUMPHUNTER area while the vertical purple and horizontal orange bars indicate the bin ranges of the best 1D BUMPHUNTER areas for variables on the y and x axes, respectively. The blue (red) boxes area is proportional to the number of total signal+background (signal) events. The 2D approach clearly identifies an area where a higher significance is found compared to the individual 1D variables. The colored xy, x and y labels indicate the BUMPHUNTER 1D and 2D results scores. The black xy, x and y labels indicate the simple and less powerful 1D and 2D χ^2 scores of compatibility to the background-only hypothesis. [Auth4]

[Auth4] Kvita J. Boosted and semi-boosted all-hadronic $t\bar{t}$ reconstruction performance on kinematic variables for selected BSM models using a 2D extension of the BumpHunter algorithm. *International Journal of Modern Physics A*, 39(11n12):2430002, 2024.



LHC Run Periods





Last update: November 24

Publications and Contributions

Author's private contributions

[Auth1] Kvita J. Study of methods of resolved top quark reconstruction in semileptonic $t\bar{t}$ decay. *Nucl. Instrum. Meth. A*, 900:84–100, 2018. [Erratum: Nucl. Instrum. Meth. A: 1040, 167172 (2022)].

[Auth2] Baron P. and Kvita J. Extending the Fully Bayesian Unfolding with Regularization Using a Combined Sampling Method. *Symmetry*, 12:2100, 2020.

[Auth3] Pácalt J. and Kvita J. Study of semi-boosted top quark reconstruction performance on the line shape of a $t\bar{t}$ resonance. *Int. J. Mod. Phys. A*, 37(16):2250110, 2022.

[Auth4] Kvita J. Boosted and semi-boosted all-hadronic $t\bar{t}$ reconstruction performance on kinematic variables for selected BSM models using a 2D extension of the BumpHunter algorithm. *International Journal of Modern Physics A*, 39(11n12):2430002, 2024.

Author's selected ATLAS publications

[ATLAS1] Georges Aad et al. Measurements of top quark pair relative differential cross-sections with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV. *Eur. Phys. J. C*, 73(1):2261, 2013.

[ATLAS2] Georges Aad et al. Measurements of normalized differential cross sections for $t\bar{t}$ production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector. *Phys. Rev. D*, 90(7):072004, 2014.

[ATLAS3] Georges Aad et al. Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector. *Eur. Phys. J. C*, 76(10):538, 2016.

[ATLAS4] Georges Aad et al. Measurement of the differential cross-section of highly boosted top quarks as a function of their transverse momentum in $\sqrt{s} =$ 8 TeV proton-proton collisions using the ATLAS detector. *Phys. Rev. D*, 93(3):032009, 2016.

[ATLAS5] M. Aaboud et al. Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector. *JHEP*, 11:191, 2017.

[ATLAS6] Morad Aaboud et al. Measurements of differential cross sections of top quark pair production in association with jets in pp collisions at $\sqrt{s} =$ 13 TeV using the ATLAS detector. *JHEP*, 10:159, 2018.

[ATLAS7] Georges Aad et al. Measurements of top-quark pair differential and double-differential cross-sections in the ℓ+jets channel with pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector. *Eur. Phys. J. C*, 79(12):1028, 2019. [Erratum: Eur.Phys.J.C 80, 1092 (2020)].

[ATLAS8] Georges Aad et al. Observation of $t\bar{t}$ production in the lepton+jets and dilepton channels in p+Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with the ATLAS detector. *JHEP*, 11:101, 2024.

Eur. Phys. J. C (2013) 73:2261
DOI 10.1140/epjc/s10052-012-2261-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Measurements of top quark pair relative differential cross-sections with ATLAS in *pp* collisions at $\sqrt{s} = 7$ TeV

The ATLAS Collaboration*
CERN, 1211 Geneva 23, Switzerland

[ATLAS1] Georges Aad et al. Measurements of top quark pair relative differential cross-sections with ATLAS in *pp* collisions at $\sqrt{s} = 7$ TeV. *Eur. Phys. J. C*, 73(1):2261, 2013.

Abstract Measurements are presented of differential cross-sections for top quark pair production in *pp* collisions at $\sqrt{s} = 7$ TeV relative to the total inclusive top quark pair production cross-section. A data sample of 2.05 fb^{-1} recorded by the ATLAS detector at the Large Hadron Collider is used. Relative differential cross-sections are derived as a function of the invariant mass, the transverse momentum and the rapidity of the top quark pair system. Events are selected in the lepton (electron or muon) + jets channel. The background-subtracted differential distributions are corrected for detector effects, normalized to the total inclusive top quark pair production cross-section and compared to theoretical predictions. The measurement uncertainties range typically between 10 % and 20 % and are generally dominated by systematic effects. No significant deviations from the Standard Model expectations are observed.

PHYSICAL REVIEW D **90**, 072004 (2014)

Measurements of normalized differential cross sections for $t\bar{t}$ production in *pp* collisions at $\sqrt{(s)} = 7$ TeV using the ATLAS detector

G. Aad *et al.**
(ATLAS Collaboration)

(Received 1 July 2014; revised manuscript received 3 September 2014; published 13 October 2014)

Measurements of normalized differential cross sections for top-quark pair production are presented as a function of the top-quark transverse momentum, and of the mass, transverse momentum, and rapidity of the $t\bar{t}$ system, in proton–proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV. The data set corresponds to an integrated luminosity of 4.6 fb^{-1}, recorded in 2011 with the ATLAS detector at the CERN Large Hadron Collider. Events are selected in the lepton + jets channel, requiring exactly one lepton and at least four jets with at least one of the jets tagged as originating from a *b*-quark. The measured spectra are corrected for detector efficiency and resolution effects and are compared to several Monte Carlo simulations and theory calculations. The results are in fair agreement with the predictions in a wide kinematic range. Nevertheless, data distributions are softer than predicted for higher values of the mass of the $t\bar{t}$ system and of the top-quark transverse momentum. The measurements can also discriminate among different sets of parton distribution functions.

Author's contributions

The author contributed to the development of the analysis framework for the first publication with early LHC data [ATLAS1]. He then became one of the two responsible contact editors (together with dr. Lorenzo Bellagamba) and member of the analysis team of the paper of the full dataset at 7 TeV, the analysis [ATLAS2]. He contributed to the core analysis SW, wrote the core statistical code to combine the e+jets and μ+jets channels using the BLUE method, worked on the unfolding stress tests with an artificially injected bump at the parton level of the spectra, supervised MSc. student Peter Berta, evaluated the efficiency and acceptance corrections, binned the approximate NNL predictions to the analysis bins, worked on unfolding closure tests, the summation of systematic uncertainties, plotting, running the analysis SW. A summary of the pseudo-top concept is presented and also further extended in study by the author of this thesis [Auth1].

[ATLAS2] Georges Aad et al. Measurements of normalized differential cross sections for $t\bar{t}$ production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector. *Phys. Rev. D*, 90(7):072004, 2014.

Eur. Phys. J. C (2016) 76:538
DOI 10.1140/epjc/s10052-016-4366-4

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector

ATLAS Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 18 November 2015 / Accepted: 30 August 2016 / Published online: 3 October 2016

[ATLAS3] Georges Aad et al. Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector. *Eur. Phys. J. C*, 76(10):538, 2016.

Author's contributions

Author of this thesis was a member of the analysis core team of the analysis [ATLAS3] He worked on corrections to particle and parton level (efficiency, acceptance, matching), binning optimization, development of the core analysis framework and unfolding. He introduced the p_{out}, $y^{t\bar{t}}_{\mathrm{boost}}$, $z_{t\bar{t}}$ and $\chi^{t\bar{t}}$ variables as new ATLAS observables. He ran the analysis framework, optimized the pseudo-top algorithm, evaluated the migration matrices. He provided students supervision, also to his PhD student Josef

Pácalt who worked on corrections to particle and parton levels and binning optimization. The author of this thesis also contributed to the boosted analysis [ATLAS4] via the supervision of PhD student Peter Berta.

Abstract Measurements of normalized differential cross-sections of top-quark pair production are presented as a function of the top-quark, $t\bar{t}$ system and event-level kinematic observables in proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV. The observables have been chosen to emphasize the $t\bar{t}$ production process and to be sensitive to effects of initial- and final-state radiation, to the different parton distribution functions, and to non-resonant processes and higher-order corrections. The dataset corresponds to an integrated luminosity of 20.3 fb^{-1}, recorded in 2012 with the ATLAS detector at the CERN Large Hadron Collider. Events are selected in the lepton+jets channel, requiring exactly one charged lepton and at least four jets with at least two of the jets tagged as originating from a b-quark. The measured spectra are corrected for detector effects and are compared to several Monte Carlo simulations. The results are in fair agreement with the predictions over a wide kinematic range. Nevertheless, most generators predict a harder top-quark transverse momentum distribution at high values than what is observed in the data. Predictions beyond NLO accuracy improve the agreement with data at high top-quark transverse momenta. Using the current settings and parton distribution functions, the rapidity distributions are not well modelled by any generator under consideration. However, the level of agreement is improved when more recent sets of parton distribution func-

PHYSICAL REVIEW D **93,** 032009 (2016)

Measurement of the differential cross-section of highly boosted top quarks as a function of their transverse momentum in $\sqrt{s} = 8$ TeV proton-proton collisions using the ATLAS detector

G. Aad *et al.**
(ATLAS Collaboration)

(Received 14 October 2015; published 26 February 2016)

The differential cross-section for pair production of top quarks with high transverse momentum is measured in 20.3 fb^{-1} of proton-proton collisions at a center-of-mass energy of 8 TeV. The measurement is performed for $t\bar{t}$ events in the lepton + jets channel. The cross-section is reported as a function of the hadronically decaying top quark transverse momentum for values above 300 GeV. The hadronically decaying top quark is reconstructed as an anti-k_t jet with radius parameter $R = 1.0$ and identified with jet substructure techniques. The observed yield is corrected for detector effects to obtain a cross-section at particle level in a fiducial region close to the event selection. A parton-level cross-section extrapolated to the full phase space is also reported for top quarks with transverse momentum above 300 GeV. The predictions of a majority of next-to-leading-order and leading-order matrix-element Monte Carlo generators are found to agree with the measured cross-sections.

DOI: 10.1103/PhysRevD.93.032009

[ATLAS4] Georges Aad et al. Measurement of the differential cross-section of highly boosted top quarks as a function of their transverse momentum in $\sqrt{s}$ = 8 TeV proton-proton collisions using the ATLAS detector. *Phys. Rev. D*, 93(3):032009, 2016.

…student supervision, learning the concept of the boosted top quarks for the ATLAS 13 TeV analysis.

mization. The author of this thesis also contributed to the boosted analysis [ATLAS4] via the supervision of PhD student Peter Berta.

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Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

The ATLAS collaboration

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Abstract: Measurements of differential cross-sections of top-quark pair production in fiducial phase-spaces are presented as a function of top-quark and $t\bar{t}$ system kinematic observables in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The data set corresponds to an integrated luminosity of $3.2\,\mathrm{fb}^{-1}$, recorded in 2015 with the ATLAS detector at the CERN Large Hadron Collider. Events with exactly one electron or muon and at least two jets in the final state are used for the measurement. Two separate selections are applied that each focus on different top-quark momentum regions, referred to as resolved and boosted topologies of the $t\bar{t}$ final state. The measured spectra are corrected for detector effects and are compared to several Monte Carlo simulations by means of calculated χ^2 and p-values.

Author's contributions

The author of this thesis was one of the contact editors and member of the analysis team of the paper [ATLAS5]. He contributed to efficiencies extraction and their $t\bar{t}$ modelling systematics; he was responsible for differential corrections evaluation and their model dependence study. He served as one of the two responsibles and co-editors (together with dr. Véronique Boisvert) of the two internal notes and of the publication. As for the analysis published as [ATLAS6], this analysis was enabled by the previous analysis [ATLAS5] and the author was the analysis team member, contact person for the inclusive analysis; and provided supervision and contributed to the internal note.

[ATLAS5] M. Aaboud et al. Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector. *JHEP*, 11:191, 2017.

publication. As for the analysis published as [ATLAS6], this analysis was enabled by the previous analysis [ATLAS5] and the author was the analysis team member, contact person for the inclusive analysis; and provided supervision and contributed

… a sequel analysis with spectra measured for various extra jest multiplicities.

[ATLAS6] Morad Aaboud et al. Measurements of differential cross sections of top quark pair production in association with jets in pp collisions at $\sqrt{s}$ = 13 TeV using the ATLAS detector. *JHEP*, 10:159, 2018.

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Measurements of differential cross sections of top quark pair production in association with jets in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

ATLAS EXPERIMENT

The ATLAS collaboration

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Abstract: Measurements of differential cross sections of top quark pair production in association with jets by the ATLAS experiment at the LHC are presented. The measurements are performed as functions of the top quark transverse momentum, the transverse momentum of the top quark-antitop quark system and the out-of-plane transverse momentum using data from pp collisions at $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the LHC in 2015 and corresponding to an integrated luminosity of 3.2 fb^{-1}. The top quark pair events are selected in the lepton (electron or muon) + jets channel. The measured cross sections, which are compared to several predictions, allow a detailed study of top quark production.

Eur. Phys. J. C (2019) 79:1028
https://doi.org/10.1140/epjc/s10052-019-7525-6

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Measurements of top-quark pair differential and double-differential cross-sections in the ℓ+jets channel with pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

ATLAS Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 21 August 2019 / Accepted: 2 December 2019 / Published online: 24 December 2019

Author's contributions

Author of this thesis was a member of the analysis core team of [ATLAS7]. He contributed to the implementation of the bootstrap method preserving statistical correlations between various spectra. He evaluated the efficiency and acceptance corrections and the migration matrices for both 1D and 2D spectra, and their model dependence. He supervised the PhD student Petr Baroň who was granted the exceptional ATLAS co-authorship of the paper, contributing to studies of systematic uncertainties in modelling the single-top and Wt backgrounds.

[ATLAS7] Georges Aad et al. Measurements of top-quark pair differential and double-differential cross-sections in the ℓ+jets channel with pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector. *Eur. Phys. J. C*, 79(12):1028, 2019. [Erratum: Eur.Phys.J.C 80, 1092 (2020)].

Abstract Single- and double-differential cross-section measurements are presented for the production of top-quark pairs, in the lepton + jets channel at particle and parton level. Two topologies, resolved and boosted, are considered and the results are presented as a function of several kinematic variables characterising the top and $t\bar{t}$ system and jet multiplicities. The study was performed using data from pp collisions at centre-of-mass energy of 13 TeV collected in 2015 and 2016 by the ATLAS detector at the CERN Large Hadron Collider (LHC), corresponding to an integrated luminosity of 36 fb^{-1}. Due to the large $t\bar{t}$ cross-section at the LHC, such measurements allow a detailed study of the properties of top-quark production and decay, enabling precision tests of several Monte Carlo generators and fixed-order Standard Model predictions. Overall, there is good agreement between the theoretical predictions and the data.

…a small team (~5 people), initiated the analysis, leading role, first observation of the process with the ATLAS experiment, double the precision of the CMS experiment, and in additional dilepton channels.

Author's contributions

Author of this thesis initiated this measurement [ATLAS8] within the ATLAS collaboration between the Top Quark and Heavy Ion physics groups. He acted as the analysis co-coordinator, under dr. Iwona Grabowska-Bołd, the main analysis framework developper, internal note co-editor. He designed the signal and control regions, contributed to the pseudo-top algorithm optimization, the selection and optimization of the fit variable and separation power between various H_{T} variables; he worked on systematics evaluation and studies including $t\bar{t}$ signal modelling and PDF uncertainties; checks of the signal efficiency, correlation among variables, lepton p_{T} reweighting studies, design of fake lepton background shape systematics binned in the W transverse mass; design of the single top background, post-fit control plots, yield tables, the idea of events matching between different jet collections, statistical studies for ratios and systematics cancellation; and to the write-up of both the internal note as well as the final publication.

[ATLAS8] Georges Aad et al. Observation of $t\bar{t}$ production in the lepton+jets and dilepton channels in p+Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV with the ATLAS detector. *JHEP*, 11:101, 2024.

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Observation of $t\bar{t}$ production in the lepton+jets and dilepton channels in p+Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with the ATLAS detector

ATLAS EXPERIMENT

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: This paper reports the observation of top-quark pair production in proton-lead collisions in the ATLAS experiment at the Large Hadron Collider. The measurement is performed using 165 nb^{-1} of p+Pb data collected at $\sqrt{s_{NN}} = 8.16$ TeV in 2016. Events are categorised in two analysis channels, consisting of either events with exactly one lepton (electron or muon) and at least four jets, or events with two opposite-charge leptons and at least two jets. In both channels at least one b-tagged jet is also required. Top-quark pair production is observed with a significance over five standard deviations in each channel. The top-quark pair production cross-section is measured to be $\sigma_{t\bar{t}} = 58.1 \pm 2.0\,(\text{stat.})\,^{+4.8}_{-4.4}\,(\text{syst.})$ nb, with a total uncertainty of 9%. In addition, the nuclear modification factor is measured to be $R_{pA} = 1.090 \pm 0.039$ (stat.) $^{+0.094}_{-0.087}$ (syst.). The measurements are found to be in good agreement with theory predictions involving nuclear parton distribution functions.

Nuclear Inst. and Methods in Physics Research, A 1040 (2022) 167172

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Study of methods of resolved top quark reconstruction in semileptonic $t\bar{t}$ decay: Erratum

J. Kvita

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Keywords:
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ABSTRACT

Study of methods of resolved top quarks kinematic reconstruction in the $t\bar{t} \to \ell$+jets channel is presented at the particle level as well as the fast-simulation detector level. Previous and current pseudo-top quark reconstruction algorithms are compared with suggestions presented on how to improve the reconstructed top-quark mass line shape, including the check of performance on physics observables in terms of correlations between detector, particle and parton levels, and in unfolding, with implications for current high energy physics experiments.

[Auth1] Kvita J. Study of methods of resolved top quark reconstruction in semileptonic $t\bar{t}$ decay. *Nucl. Instrum. Meth. A*, 900:84–100, 2018. [Erratum: Nucl. Instrum. Meth. A: 1040, 167172 (2022)].

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Boosted and semi-boosted all-hadronic $t\bar{t}$ reconstruction performance on kinematic variables for selected BSM models using a 2D extension of the BumpHunter algorithm

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In this paper, we explore the usage of boosted as well as semi-boosted topologies in all-hadronic $t\bar{t}$ final states in simulated pp collisions at $\sqrt{s} = 14\,\text{TeV}$, with top quarks decaying into a boosted hadronic top-jet or a W-jet and an isolated b-jet. Correlations between selected kinematic variables and their shapes are studied for scalar and vector resonances decaying to a pair of top quarks, and also for a models of $t\bar{t}$-associated production with an invisible dark matter particle pair. Stacked signal+background samples have been investigated in terms of the ability to resolve an excess of events over the Standard Model background in terms of the $t\bar{t}$ invariant mass, top quark transverse momentum and other 1D and 2D spectra using a parameterized detector simulation. A 2D extension of the BumpHunter algorithm is proposed, resulting in an improved signal sensitivity in specific 2D areas. We identify the most promising variables with the largest signal significance and smaller sensitivity to experimental uncertainties related to the jet energy calibration. We compare to statistical tests computing the background-only hypothesis compatibility and a likelihood fit of the signal strength.

[Auth4] Kvita J. Boosted and semi-boosted all-hadronic $t\bar{t}$ reconstruction performance on kinematic variables for selected BSM models using a 2D extension of the BumpHunter algorithm. *International Journal of Modern Physics A*, 39(11n12):2430002, 2024.

Open Access Article

Extending the Fully Bayesian Unfolding with Regularization Using a Combined Sampling Method

by Petr Baroň † and Jiří Kvita *,†

Joint Laboratory of Optics of Palacký University and Institute of Physics AS CR, Faculty of Science, Palacký University, 17. listopadu 12, 771 46 Olomouc, Czech Republic

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† These authors contributed equally to this work.

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(This article belongs to the Special Issue Particle Physics and Symmetry)

[Auth2] Baron P. and Kvita J. Extending the Fully Bayesian Unfolding with Regularization Using a Combined Sampling Method. *Symmetry*, 12:2100, 2020.

International Journal of Modern Physics A | Vol. 37, No. 16, 2250110 (2022) | Research Paper

Study of semi-boosted top quark reconstruction performance on the line shape of a $t\bar{t}$ resonance

Josef Pácalt and Jiri Kvita

https://doi.org/10.1142/S0217751X2250110X

Abstract

In this paper, we study the top quark pair events production in pp collisions in the $\ell +$ jets channel at the energy of $\sqrt{s} = 14$ TeV for Standard Model as well as new physics processes. We explore the usage of semi-boosted topologies where the top quark decays into a high-transverse momentum (boosted) hadronic W-jet and an isolated b-jet and study their performance in the $t\bar{t}$ events kinematic reconstruction. An important event fraction is recovered and the correlation of selected kinematic variables between the detector and particle level is studied. Quality of the reconstructed mass line shape of a hypothetical scalar resonance decaying into $t\bar{t}$ is evaluated and compared for regimes of a different degree of the transverse boost. Unfolding performance is checked in terms of comparing the excess of events in spectra before and after the unfolding, concluding with the proof of a signal significance loss after the unfolding procedure for both energy and angle related observables, with possible applications for current LHC experiments.

[Auth3] Pácalt J. and Kvita J. Study of semi-boosted top quark reconstruction performance on the line shape of a $t\bar{t}$ resonance. *Int. J. Mod. Phys. A*, 37(16):2250110, 2022.

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TOPQ-2023-31 2025-08-20	Run2 WbWb differ. cross sections l+jets — Editorial Board - Member Differential cross-section measurements of coherent production of singly and doubly resonant top-quark in $WWbb$ events with one lepton at $\sqrt{s} = 13$ TeV with the ATLAS detector	
TOPQ-2023-32 2024-02-01	Observation of top pair production in proton-lead collisions — Analysis Team - Member Observation of $t\bar{t}$ production in lepton+jets and dilepton channels in p+Pb collisions at $\sqrt{s_{NN}}=$ 8.16 TeV with the ATLAS detector	• Paper draft main analyser • INT Note Analysis coordination, main analyser, analysis framework, note editor. Pseudo-top optimization, systematics evaluation and studies, design of fake lepton background shape syst, events matching, statistical crosschecks.
HDBS-2020-16 2022-03-30	HBSM: t->qX, X->bb — Editorial Board - Member Search for a new scalar resonance in flavour-changing neutral-current top-quark decays $t \rightarrow qX$ ($q=u,c$), with $X \rightarrow b\bar{b}$, in proton-proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	
HDBS-2019-24 2021-07-07	HBSM Run2 t->H+ b -> cb b — Editorial Board - Member Search for a light charged Higgs boson in $t \rightarrow H^{\pm}b$ decays, with $H^{\pm} \rightarrow cb$, in the lepton+jets final state in proton-proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	
TOPQ-2018-15 2019-05-23	XS l+jets differential 36 fb-1 — Analysis Team - Member Measurements of top-quark pair differential and double-differential cross-sections in the ℓ+jets channel with pp collisions at $\sqrt{s}=13$ TeV using the ATLAS detector	• INT note Supervision, editing, corrections
TOPQ-2017-12 2017-06-19	XS 13 TeV ttbb — Editorial Board Chair - Chair Measurements of inclusive and differential fiducial cross-sections of $t\bar{t}$ production with additional heavy-flavour jets in proton-proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	

(Olomouc)

A Active Author
M Counted for M&O
O Counted for Operation Tasks

TOPQ-2017-01 2017-01-05	XS differential ttbar+jets 13 TeV Analysis Team - Member Measurements of differential cross sections of top quark pair production in association with jets in ${pp}$ collisions at $\sqrt{s}=13$ TeV using the ATLAS detector	• INT note Contact person for inclusive analysis, supervision
TOPQ-2017-02 2017-01-05	MS top width 8 TeV Editorial Board - Member Direct top-quark decay width measurement in the $t\bar{t}$ lepton+jets channel at $\sqrt{s}=8 \rm{TeV}$ with the ATLAS experiment	
TOPQ-2016-09 2016-11-23	XS differential all-had 13 TeV Analysis Team - Member Measurements of $t\bar{t}$ differential cross-sections of highly boosted top quarks decaying to all-hadronic final states in pp collisions at $\sqrt{s}=13\,$ TeV using the ATLAS detector	
TOPQ-2016-01 2016-01-02	XS differential ljets 13 TeV Analysis Team - Contact Editor Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s}=13$ TeV using the ATLAS detector	• Supporting note - boosted channel Contact person, supervision, editing • Supporting note - resolved channel Contact person, supervision, editing.
STDM-2015-17 2015-12-07	MinBias with low pT tracks 13 TeV Analysis Team - Member Charged-particle distributions at low transverse momentum in $\sqrt{s}=13$ TeV pp interactions measured with the ATLAS detector at the LHC	• Support Note secondary estimate
TOPQ-2015-17 2015-10-21	XS ttbar+jets 13 TeV 2015 Editorial Board - Member Measurement of jet activity produced in top-quark events with an electron, a muon and two b-tagged jets in the final state in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	
TOPQ-2015-06 2015-05-12	XS differential ljets 8 TeV Analysis Team - Member Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s}=8$ TeV using the ATLAS detector	• Supporting note Corrections to particle and parton level, binning optimization, development of the analysis framework, unfolding, supervised student of Palacky
STDM-2015-02 2015-03-31	Minimum Bias with tracks at 13 TeV Analysis Team - Member Charged-particle distributions in $\sqrt {s}=13$ TeV pp interactions measured with the ATLAS detector at the LHC	
TOPQ-2014-15 2014-09-30	XS ttbar differential XS boosted Analysis Team - Member Measurement of the differential cross-section of highly boosted top quarks as a function of their transverse momentum in $\sqrt{s}=8$ TeV proton$-$proton collisions using the ATLAS detector	

PERF-2014-03 2014-02-10	2012 Pileup Suppression	Analysis Team - Member Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s}=8$ TeV using the ATLAS detector
EXOT-2012-22 2012-11-09	JTX - Photon+jet resonance 8 TeV	Editorial Board - Member Search for new phenomena in photon+jet events collected in proton$-$proton collisions at $\sqrt{s}=8$ TeV with the ATLAS detector
TOPQ-2012-08 2011-12-09	XS differential resolved cross section 7 TeV	Analysis Team - Contact Editor Measurements of normalized differential cross sections for $t\bar{t}$ production in pp collisions at $\sqrt{(s)}$=7 TeV using the ATLAS detector
TOPQ-2011-07 2011-04-21	ttbar differential xs	Analysis Team - Member Measurements of top quark pair relative differential cross-sections with ATLAS in pp collisions at $\sqrt{s}=7$ TeV
STDM-2011-21 2011-03-22	W+b cross section	Analysis Team - Member Measurement of the cross section for the production of a W boson in association with b-jets in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector

Conference Notes

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Ref Code	Title	Contributions
ATLAS-CONF-2023-063 CONF-TOPQ-2018-43 2023-08-24	Observation of top pair production in proton-lead collisions Analysis Team - Member Observation of $t\bar{t}$ production in lepton+jets and dilepton channels in p+Pb collisions at $\sqrt{s_{NN}}=$ 8.16 TeV with the ATLAS detector	
ATLAS-CONF-2022-027 CONF-HDBS-2022-33 2022-04-21	HBSM: t->qX, X->bb (CONF) Editorial Board - Member Search for flavour-changing neutral currents in top-quark decays $t \to qX(q=u,c)$, with $X \to b\bar{b}$, in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector	

ATLAS-CONF-2021-037 CONF-HDBS-2021-21 2021-07-22	HBSM Run2 t->H+ b -> cb b CONF `Editorial Board - Member` Search for a light charged Higgs boson in $t \rightarrow H^{+}b$ decays, with $H^{+}\rightarrow cb$, in the lepton+jets final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector	
ATLAS-CONF-2018-029 CONF-TOPQ-2017-12 2018-06-30	XS 13 TeV ttbb `Editorial Board Chair - Chair` Measurements of fiducial and differential cross-sections of $t\bar{t}$ production with additional heavy-flavour jets in proton-proton collisions at $\sqrt{s}$=13 TeV with the ATLAS detector	
ATLAS-CONF-2017-056 CONF-TOPQ-2017-02 2017-06-28	MS top width 8 TeV `Editorial Board - Member` Direct Top-Quark Decay Width Measurement in the $t\bar{t}$ Lepton+Jets Channel at $\sqrt{s}$= 8 TeV with ATLAS	
ATLAS-CONF-2016-040 CONF-TOPQ-2016-02 2016-07-19	XS differential ljets 13 TeV ICHEP `Analysis Team - Contact Editor` Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s}=13$ TeV using the ATLAS detector	• Resolved supporting note Contact person, supervision, editing. • Boosted supporting note Contact person, supervision, editing
ATLAS-CONF-2016-100 CONF-TOPQ-2016-03 2016-07-19	XS differential all-had 13 TeV `Analysis Team - Member` Measurements of tt̄ differential cross-sections in the all-hadronic channel using highly boosted top quarks in pp collisions at √s = 13 TeV using the ATLAS detector	
ATLAS-CONF-2015-065 CONF-TOPQ-2015-11 2015-11-18	XS ttbar+jets 13 TeV 2015 `Editorial Board - Member` Measurement of jets produced in top quark events using the di-lepton final state with 2 b-tagged jets in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	
ATLAS-CONF-2015-028 CONF-STDM-2015-05 2015-07-09	Minimum Bias with tracks at 13 TeV `Analysis Team - Member` Charged-particle multiplicities in pp interactions at sqrt(s) = 13 TeV measured with the ATLAS detector at the LHC	
ATLAS-CONF-2013-099 CONF-TOPQ-2007-63 2013-08-19	XS differential resolved cross section 7 TeV `Analysis Team - Contact Editor` Measurement of top quark pair differential cross-sections in the l+jets channel in pp collisions at √s=7 TeV using the ATLAS detector	
ATLAS-CONF-2014-057 CONF-TOPQ-2013-08 2013-07-15	XS ttbar differential XS boosted 8 TeV `Analysis Team - Member` Measurement of the ttbar cross section as a function of the top transverse momentum in a boosted topology	

ATLAS-CONF-2013-059 CONF-EXOT-2007-57 2013-06-10	JTX - Photon+jet resonance 8 TeV Editorial Board - Member Search for new phenomena in the photon+jet events collected in proton-proton collisions at sqrt(s)= 8 TeV with the ATLAS detector	
ATLAS-CONF-2013-085 CONF-JETM-2007-43 2013-06-10	Pileup Subtraction for Jet Shapes Analysis Team - Member Performance of pile-up subtraction for jet shapes in pp collisions at √s=8 TeV	
ATLAS-CONF-2012-063 CONF-JETM-2007-31 2012-03-06	Gamma jet JES 2011 Analysis Team - Contact Editor Probing the measurement of jet energies with the ATLAS detector using photon+jet events in proton-proton collisions at sqrt(s) = 7 TeV	
ATLAS-CONF-2010-070 CONF-FTAG-2007-07 2010-07-14	Tracking Studies for b-tagging with 7 TeV Collision Data with the ATLAS Detector Analysis Team - Contact Editor Tracking Studies for b-tagging with 7 TeV Collision Data with the ATLAS Detector	
ATLAS-CONF-2010-040 CONF-FTAG-2007-04 2010-05-28	Tracking studies for b-tagging with 7 TeV collision data with the ATLAS detector Analysis Team - Member Tracking studies for b-tagging with 7 TeV collision data with the ATLAS detector	

PUB Notes

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Ref Code	Title	Contributions
ATL-PHYS-PUB-2018-017 PUB-TOPQ-2017-02 2017-11-03	XS PDF fit to W, Z, ttbar diff Analysis Team - Member Determination of the parton distribution functions of the proton from ATLAS measurements of differential W, Z and $t\overline{t}$ cross-sections	
ATL-PHYS-PUB-2013-005 PUB-MCGN-2013-02 2013-03-24	QCD radiation in ttbar Analysis Team - Contact Editor Monte Carlo generator comparisons to ATLAS measurements constraining QCD radiation in top anti-top final states	

Ongoing Analyses

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Ref Code	Title	Contributions
ANA-STDM-2021-22 2021-12-17	Minbias measurement at 13.6 TeV Analysis Team - Member	
ANA-TOPQ-2022-20 2022-10-19	ttbar differential x-sec - parton level Editorial Board - Member	

Personal look back: The story of the top quark pT and towards using top quark final states as a probe to new physics searches at the LHC

- I had the privilege to witness the revolution in precision of measuring top quark final states, and actually contribute and help drive the unfolding the differential spectra using the high statistics samples with the ATLAS experiment at the LHC using 1D and 2D variables, bringing in new ones sensitive to particular aspects of the ttbar modelling.
- Results have shaped the definition and constrained the systematic uncertainties concerning additional QCD radiation in ttbar samples, of top quark transverse momentum (in)description compared to pQCD predictions at various precision.
- I value
    - the opportunity to take part in the adventure of uncovering the top quark physics at high momenta, an uncharted territory before LHC, leading to surprise and resulting in the data requiring higher order QCD predictions
    - my contribution of bringing the top quark transverse momentum from Tevatron to LHC, introducing the pout variable at LHC which turned out to be valuable in tuning systematics in the ttbar modelling
    - the opportunity to supervise students who continue in the field and are able to find post-doc positions and obtain grants

Personal – where next

- Top quark spectra in ion collisions or in diffractive events.
  - private simulations / analysis within ATLAS.
- Astroparticle physics
  - unfolding, private simulations, possible new physics signatures in air showers.
- Neutrino physics
  - prototype experiment Water Cherenkov Test Experiment
    - data taking, particle identification, Cherenkov signal analysis, students supervision
  - member of the Hyper-Kamiokande experiment
    - testing photomultipliers for Hyper-K.