Measuring top quarks with the highest precision and at new and record energies using the ATLAS detector at the LHC

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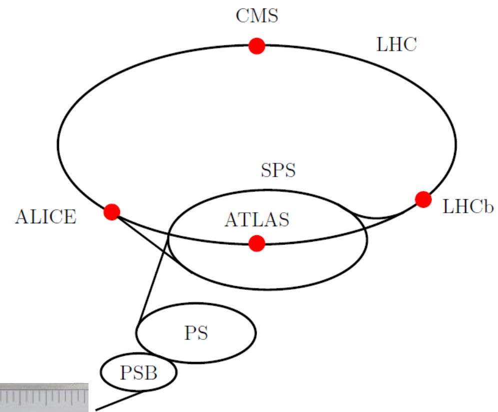
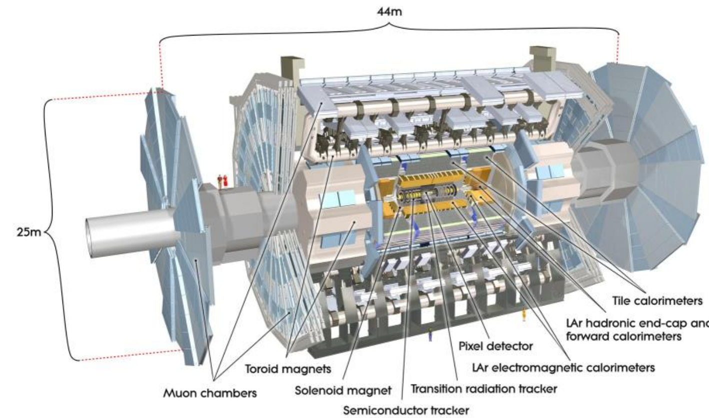
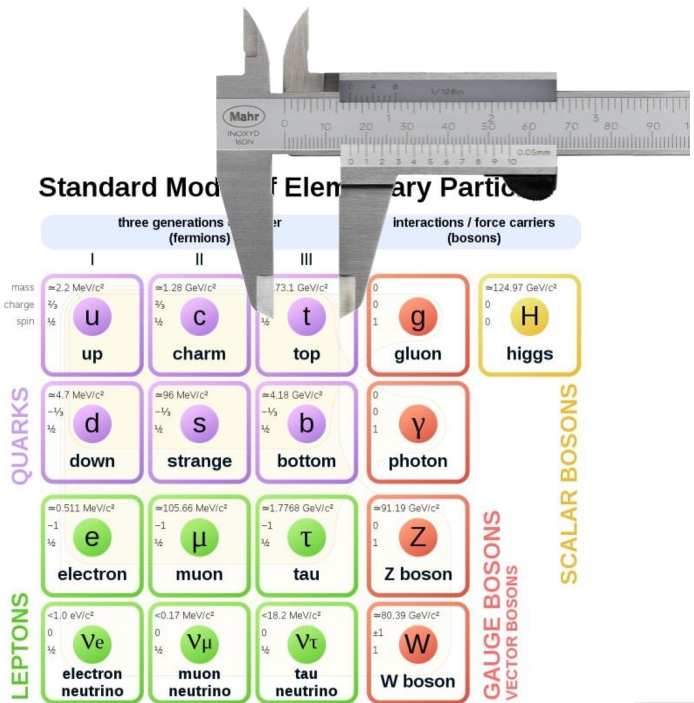
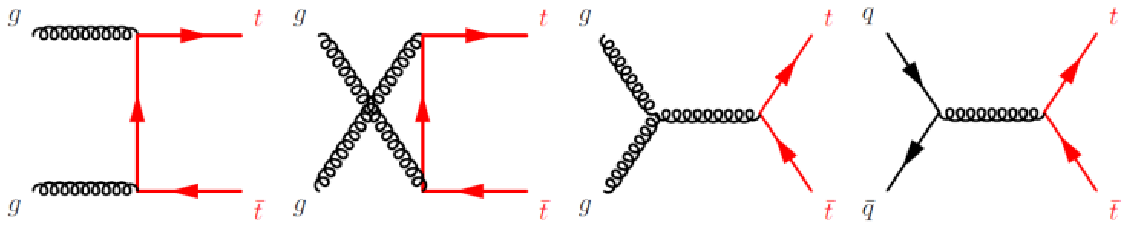


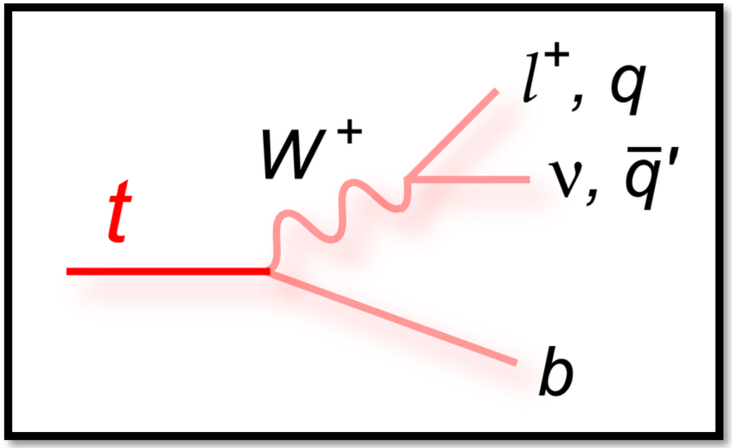




The top quark production and decay

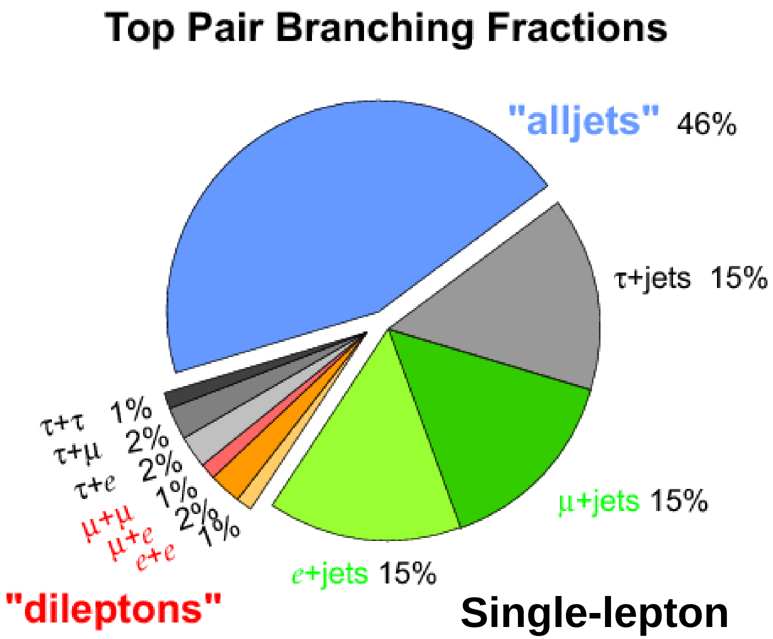
- Top quark pair production governed by strong interaction:





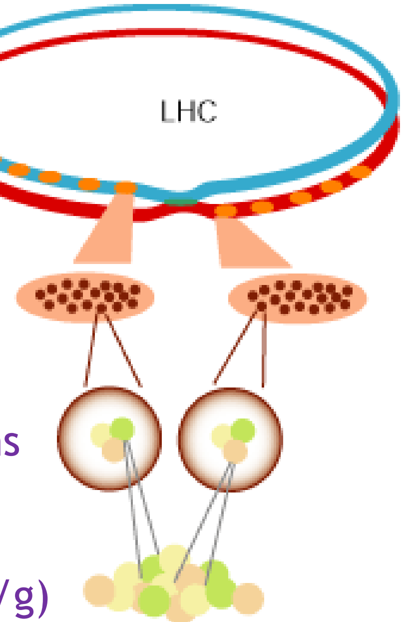
- The top quark decays almost 100% to a W-boson and b-quark (V_{tb} ~ 1), and the final state topology is given W-boson decays:

Decay mode	Branching fraction [%]
$W \to q\bar{q}$	67.41 ± 0.27 (6/9)
$W \to e\bar{\nu}_e$	10.71 ± 0.16 (1/9)
$W \to \mu\bar{\nu}_\mu$	10.63 ± 0.15 (1/9)
$W \to \tau\bar{\nu}_\tau$	11.38 ± 0.21 (1/9)



Producing top quarks at the LHC

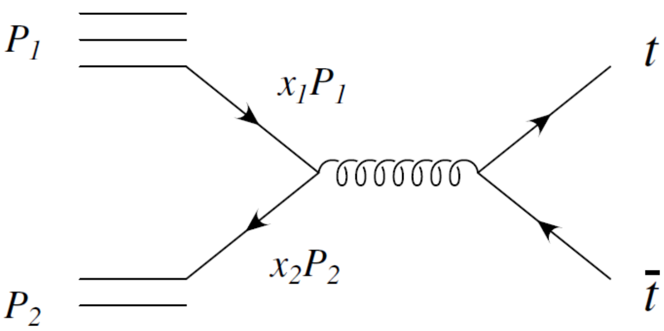
The ATLAS and CMS experiments at the LHC have accumulated millions of top quark events (~ 500 top quark pairs per minute), sustained by data from the LHCb experiment in forward regions



bunches

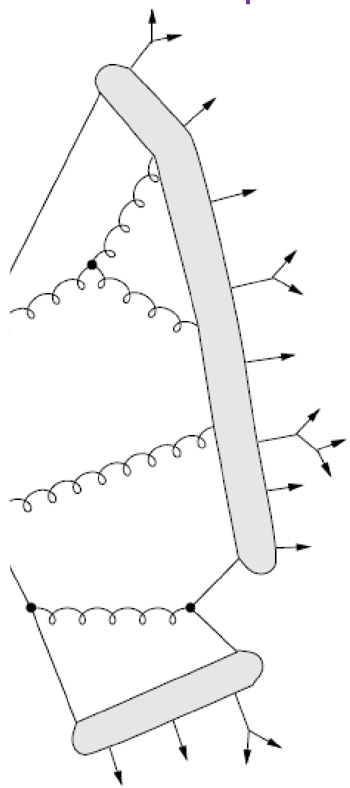
10^{11} protons

partons (q/g)

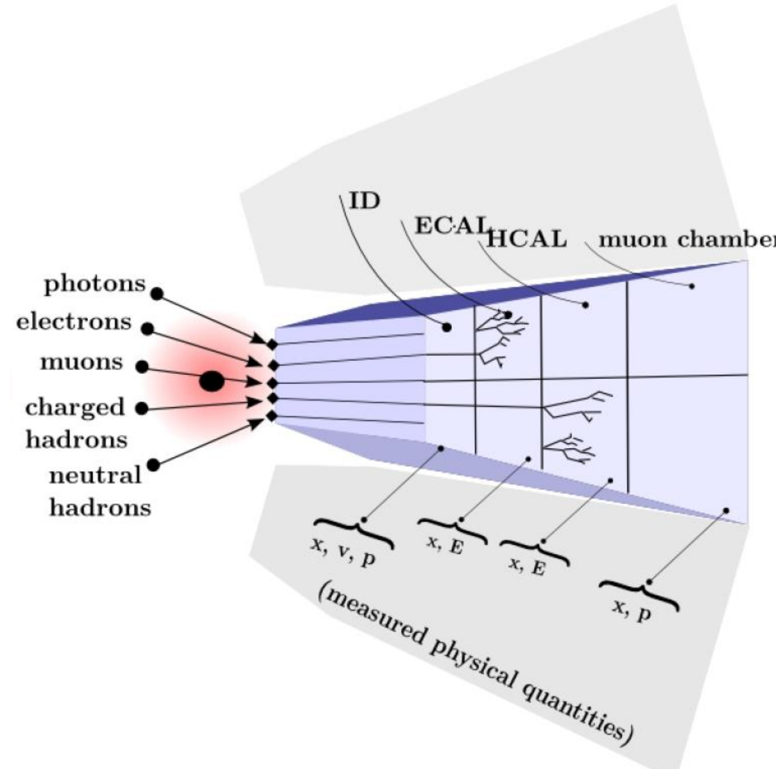


The hard interaction is described in terms of **cross-section (σ)**

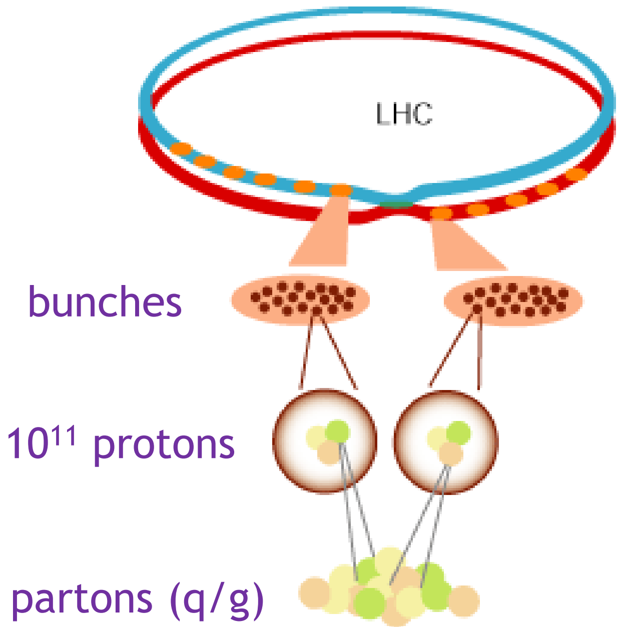
Hadronisation process



Final states are measured by different detectors



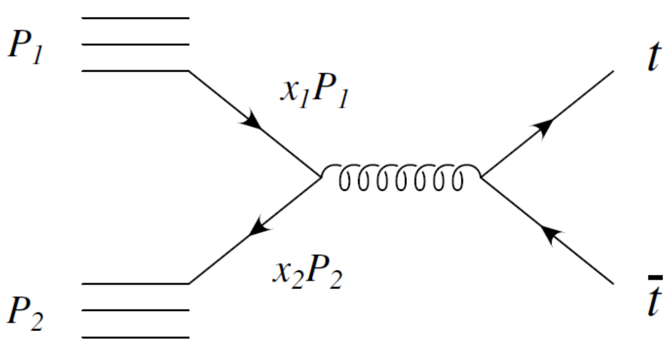
Counting top quarks at the LHC

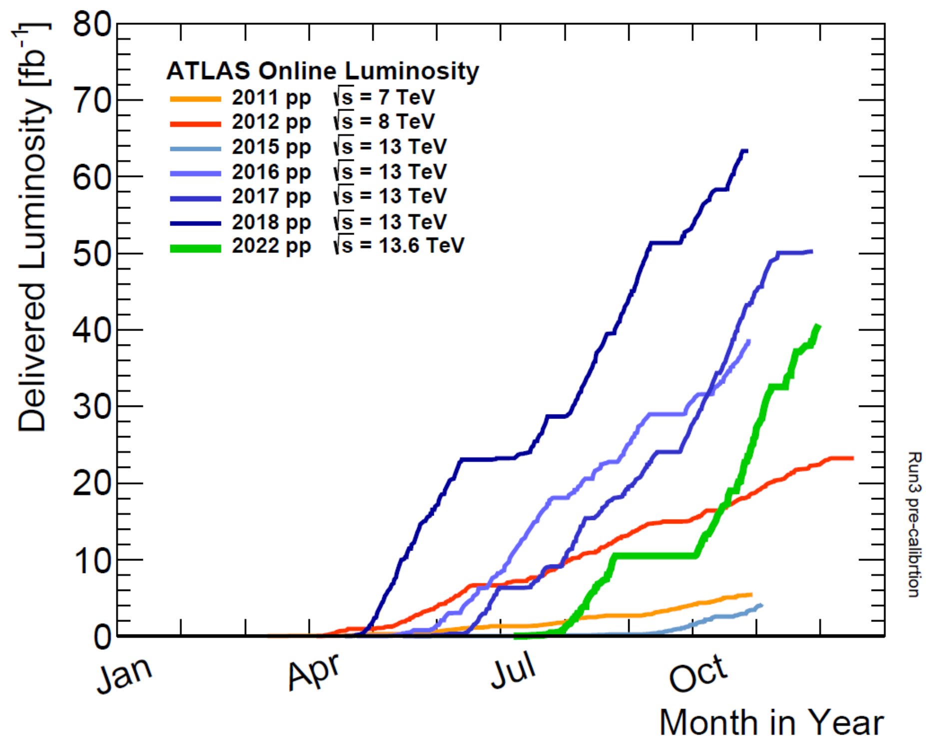


For a given process, the number of events that occur per second at the LHC is:

$$N = L\sigma$$

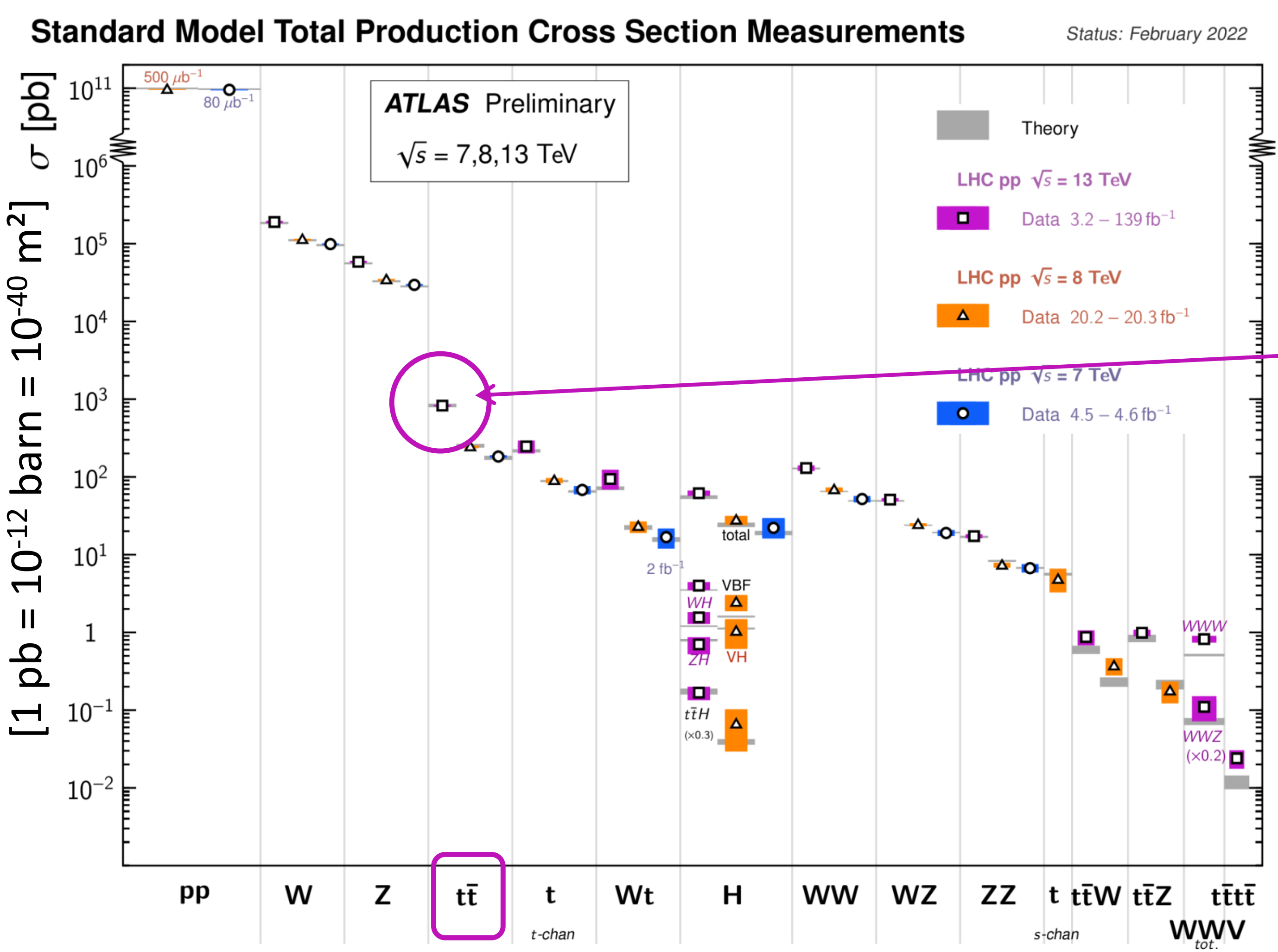
where L is the instant. luminosity (# of collisions per unit of time and transverse section of the beams)



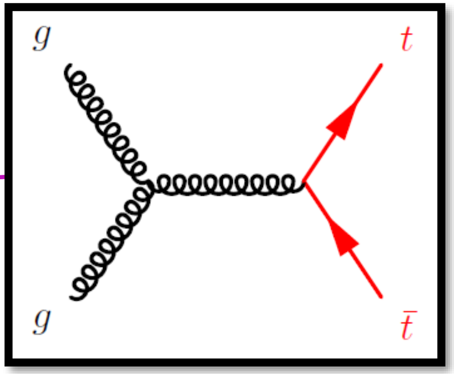


The hard interaction is described in terms of **cross-section (σ)**

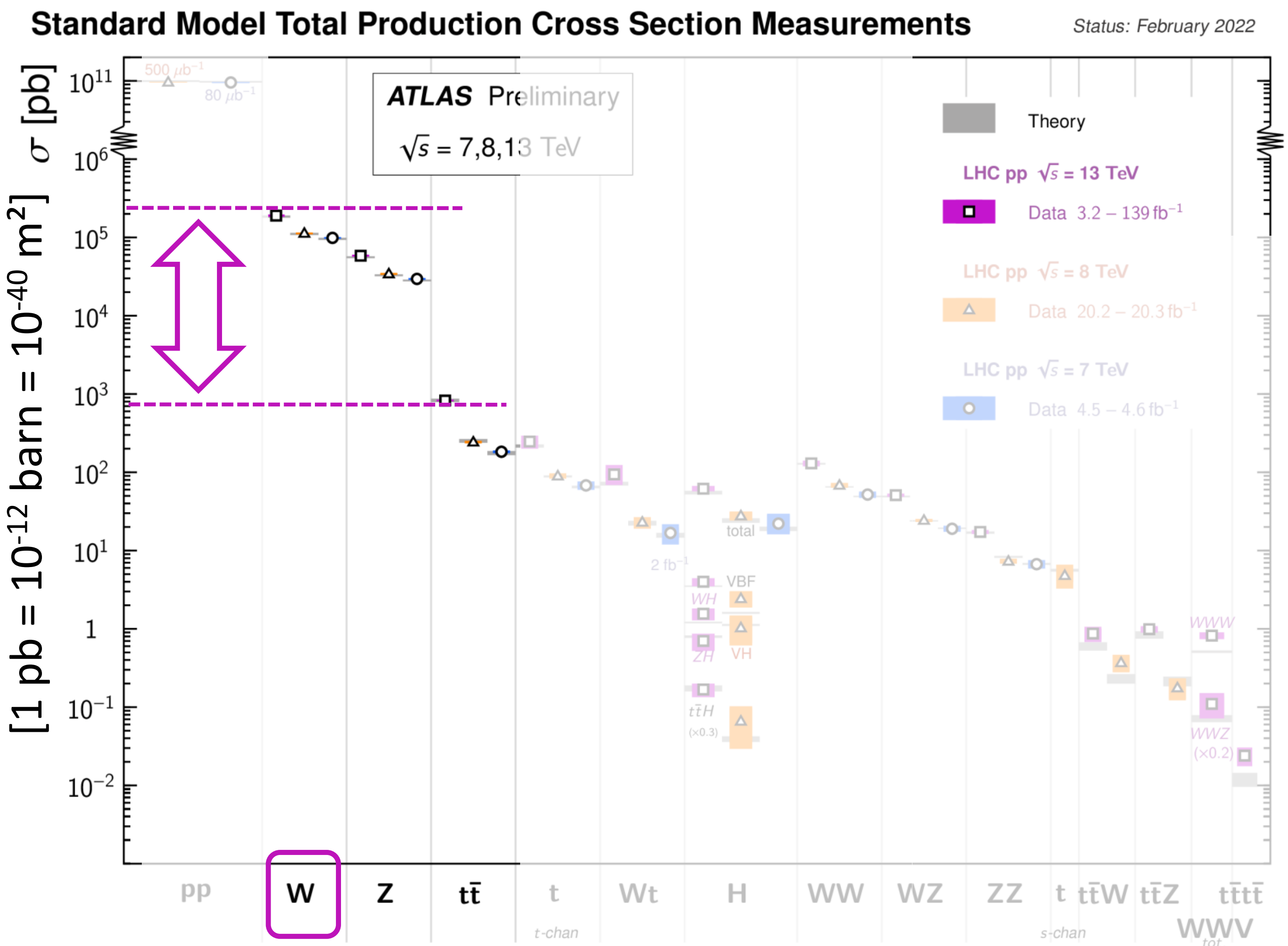
Top quark production cross-section at the LHC



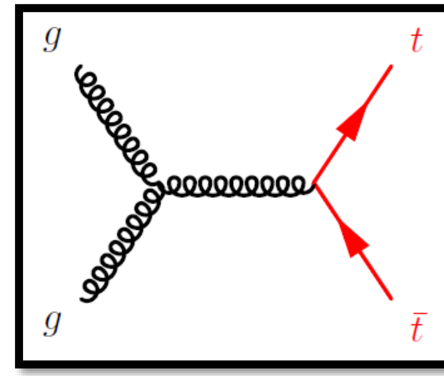
Top-quark-pair production cross-section @ 13 TeV ~800 pb

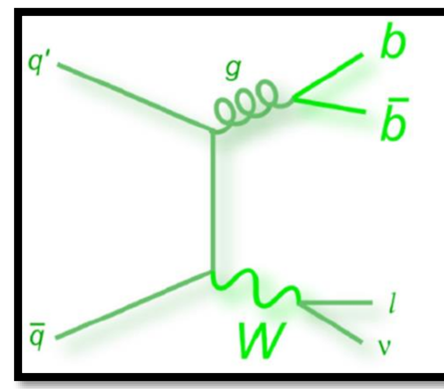


Production cross-section of the backgrounds at the LHC



Top-quark-pair production cross-section @ 13 TeV ~800 pb





The production of a W boson in association with jets has a similar final state but a cross-section which is two orders of magnitude higher than that of top quark pairs!

Measuring σ(ttbar) at √s=5.02 TeV with ATLAS

July 2022: [arXiv:2207.01354]

[CERN Courier Sep/Oct 2022]

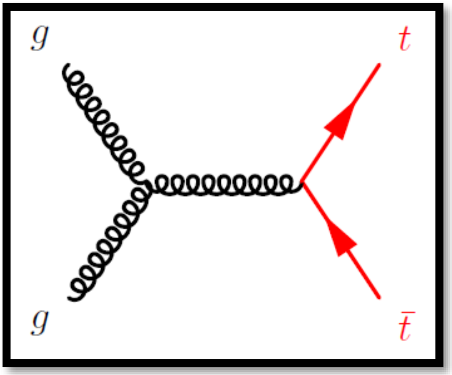
ATLAS

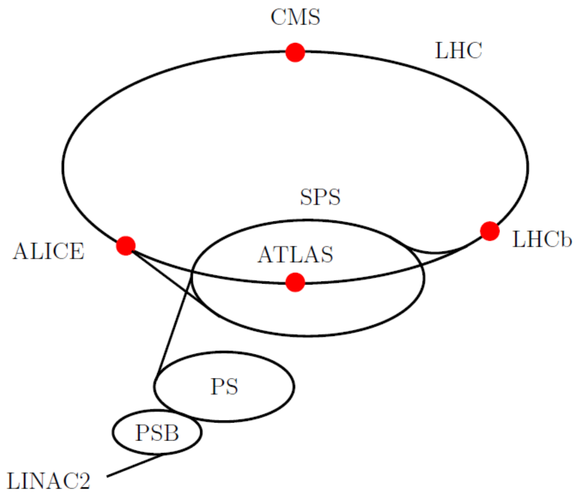
Low-pileup data pin down top-quark production

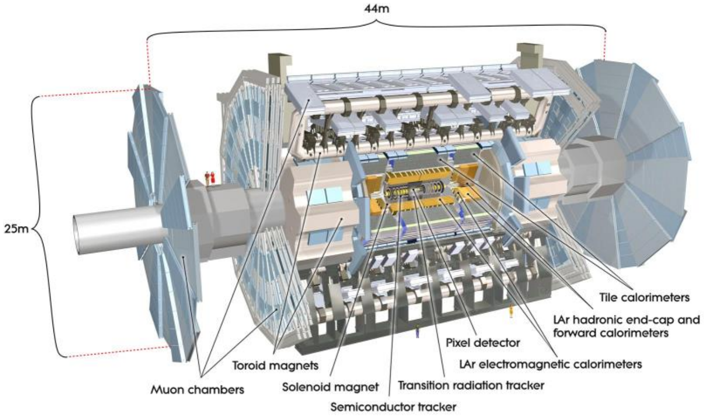
The top quark – the heaviest known elementary particle – differs from the other quarks by its much larger mass and a lifetime that is shorter than the time needed to form hadronic bound states. Within the Standard Model (SM), the top quark decays almost exclusively into a W boson and a b quark, and the dominant production mechanism in proton–proton (pp) collisions is top-quark pair ($t\bar{t}$) production.

Measurements of $t\bar{t}$ production at various pp centre-of-mass energies at the LHC probe different values of Bjorken-x, the fraction of the proton's longitudinal momentum carried by the parton participating in the initial interaction. In particular, the fraction of $t\bar{t}$ events produced through quark–antiquark annihilation increases from 11% at 13 TeV to 25% at 5.02 TeV. A measurement of the $t\bar{t}$ production cross-section thus places additional constraints on the proton's parton distribution functions (PDFs), which describe the probabilities of finding quarks and gluons at particular x values.

√s=5.02 TeV

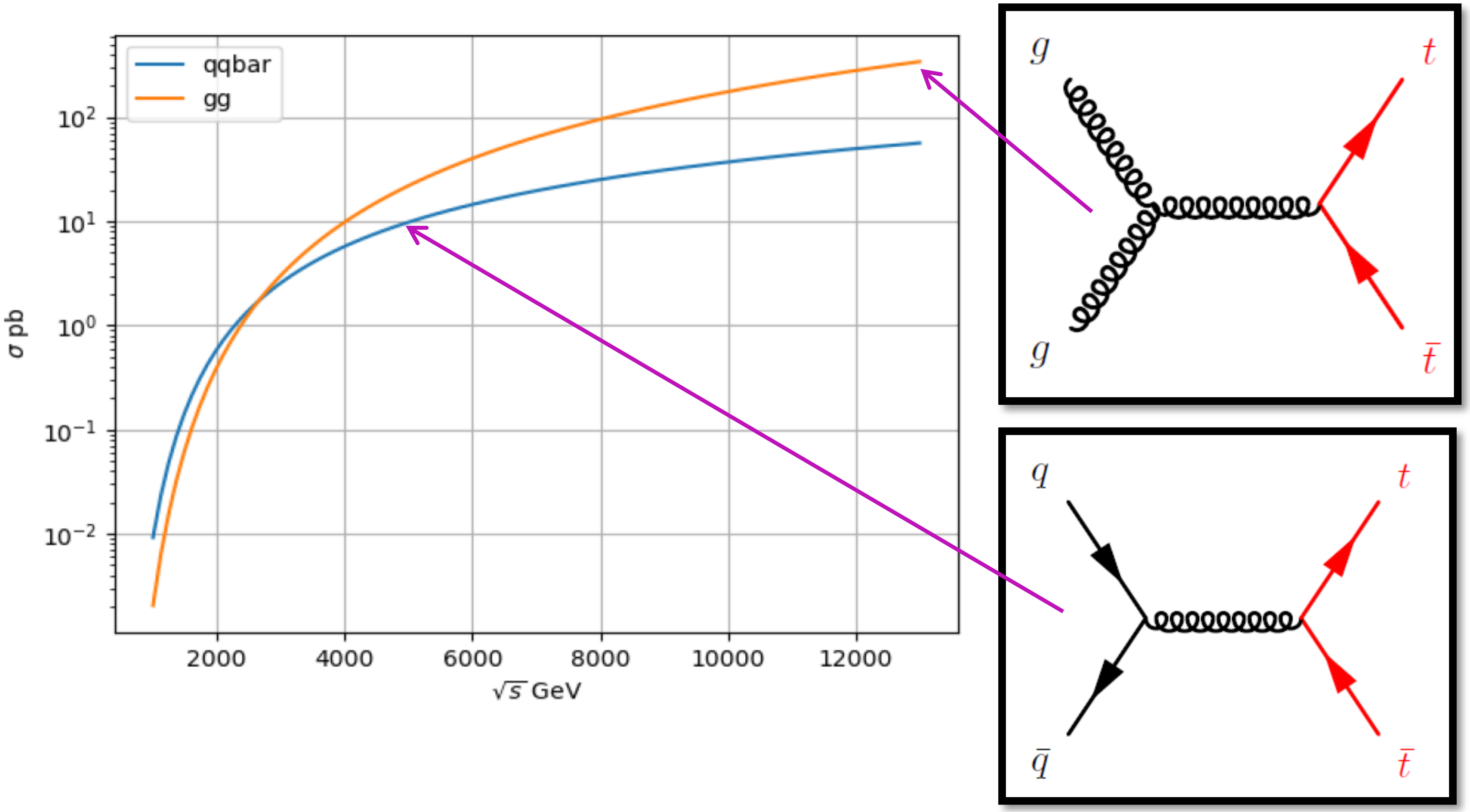




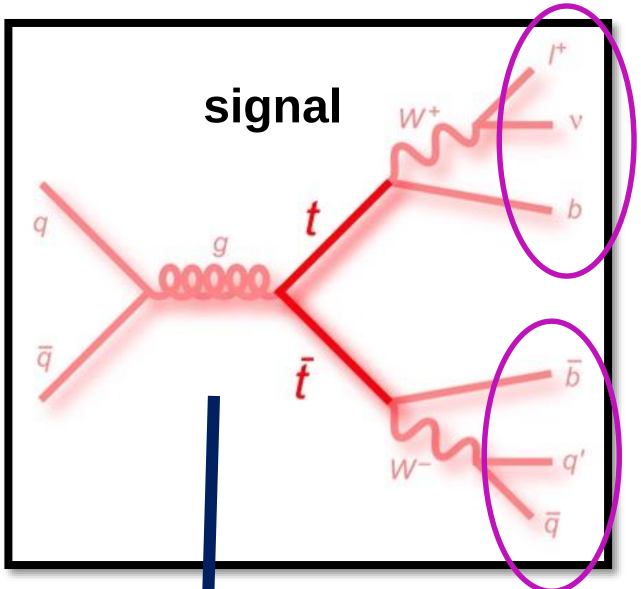


ttbar at √s=5.02 TeV: event selection

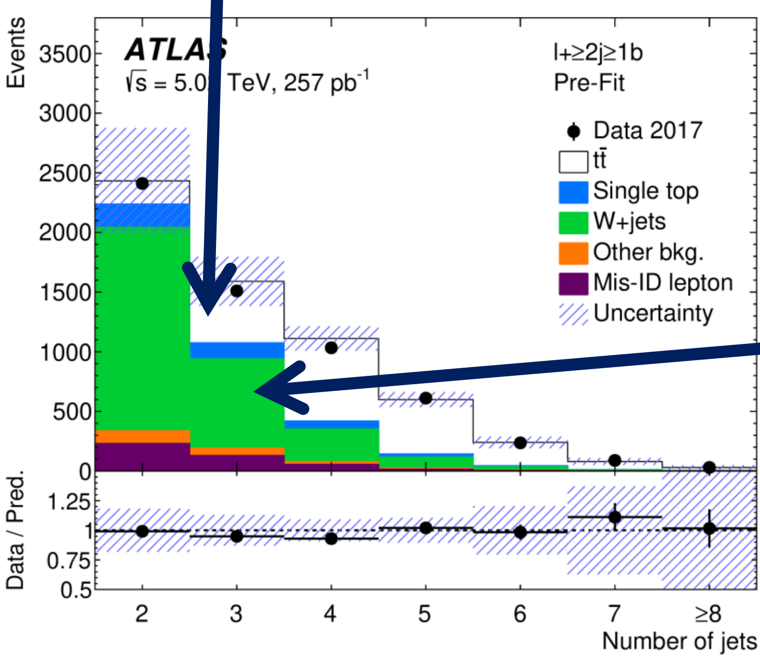
- In Nov. 2017, ATLAS recorded one week of pp collisions at √s=5.02 TeV, with the main motivation of providing a proton reference sample for the heavy-ion analyses
- Also provided a unique opportunity to study top-quark production at a previously unexplored energy in ATLAS:
  - ✓ 25% of qqbar-initiated events, compared to 11% at 13 TeV



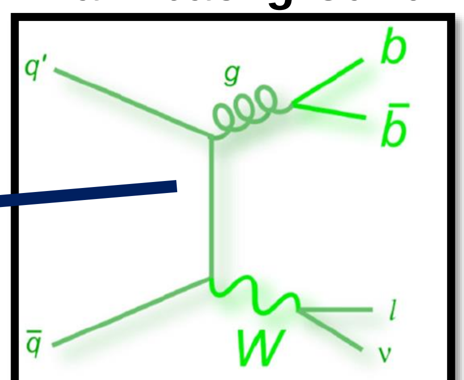
Finding top quarks in the single-lepton channel



- The single-lepton final state arising from ttbar decay is characterised by a charged lepton, a neutrino, and at least four jets, out of which two are b-tagged jets.
- First, define a trigger to remove different overwhelming background, i.e. select events that pass either a single-electron or a single-muon trigger.
- Select events that contain exactly one electron or muon candidate with pT > 25 GeV, ≥ 2 jets, 1 or 2 b-jets with pT > 20 GeV, and MET > 30 GeV



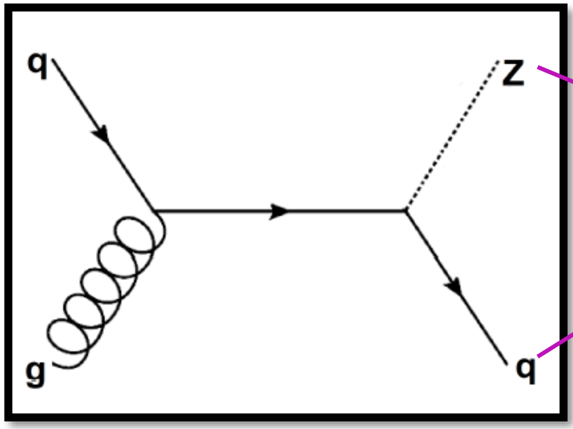
main background

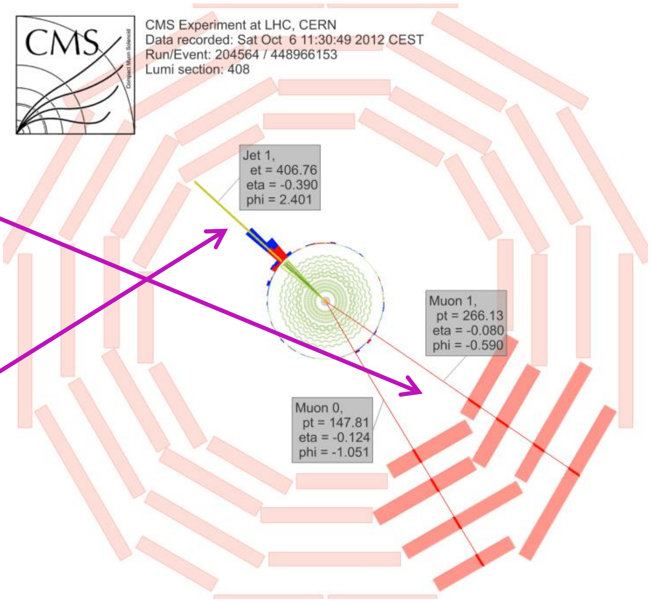


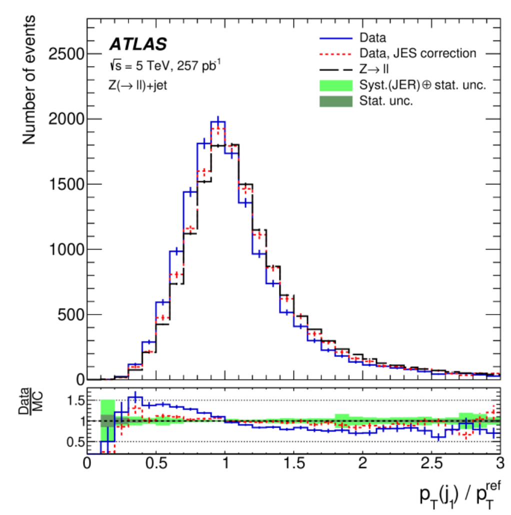
- Monte Carlo (MC) simulated event samples are used to develop the analysis procedures, evaluate signal and background contributions, and compare the predicted distributions with data.

Jet re-calibration at √s=5.02 TeV

- Due to much lower pileup conditions and lower underlying event, the ATLAS calorimeter cluster noise thresholds were adjusted accordingly, and a dedicated jet-energy scale and resolution calibration had to be performed.
- The technique called “Z+jet balance” exploits the transverse momentum balance between the jet recoiling a Z-boson (that decays to electrons or muons)
- To first order, the sum of all transverse momenta in an event at ATLAS should be zero. A non-zero sum of pT in an event from a process containing jets could indicate a flaw with the jet energy calibration.

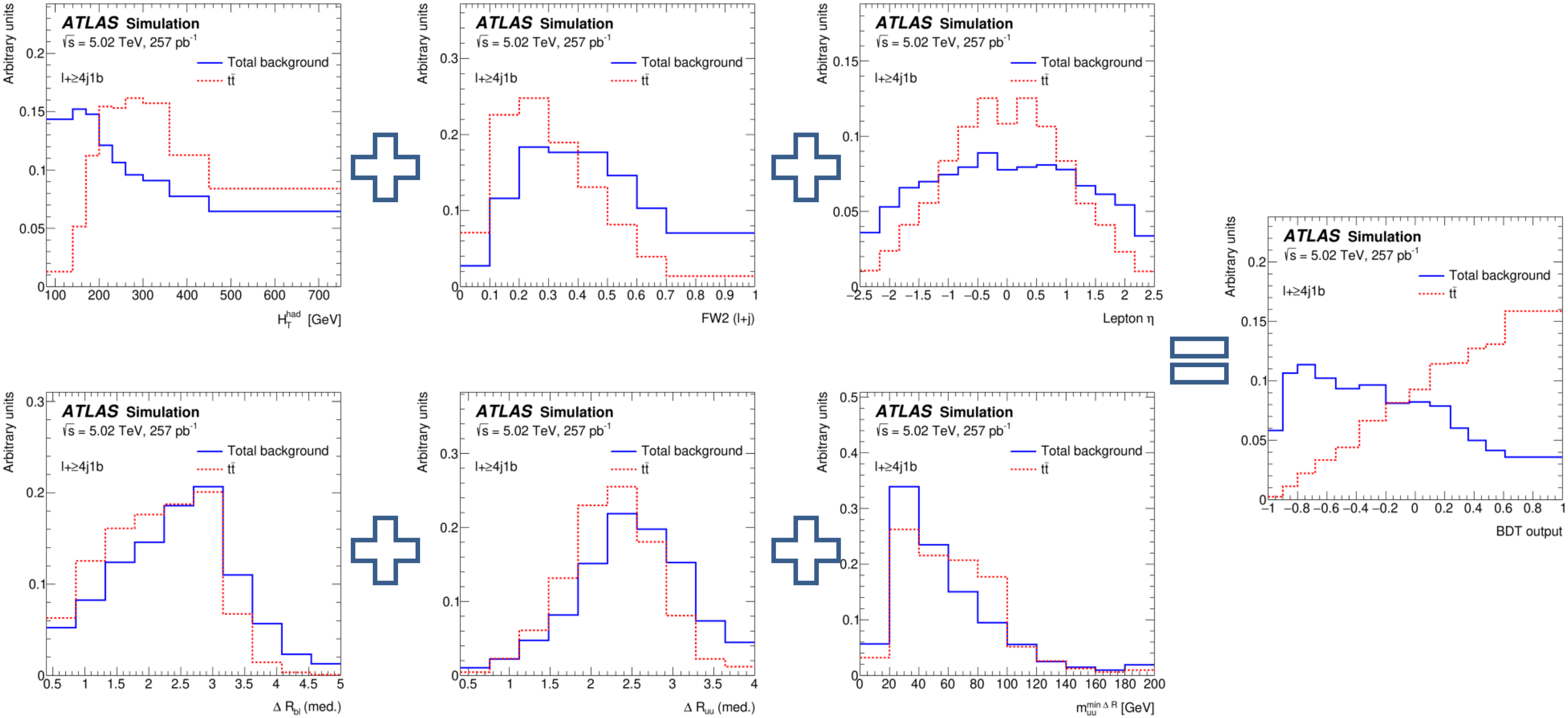






ttbar at √s=5.02 TeV: signal vs background

- Boosted Decision Trees (BDT) are used to separate the signal events from background events and extract the ttbar production cross-section
- 6 variables chosen to have good signal-to-background separation and in combination provided greater separation than other choices

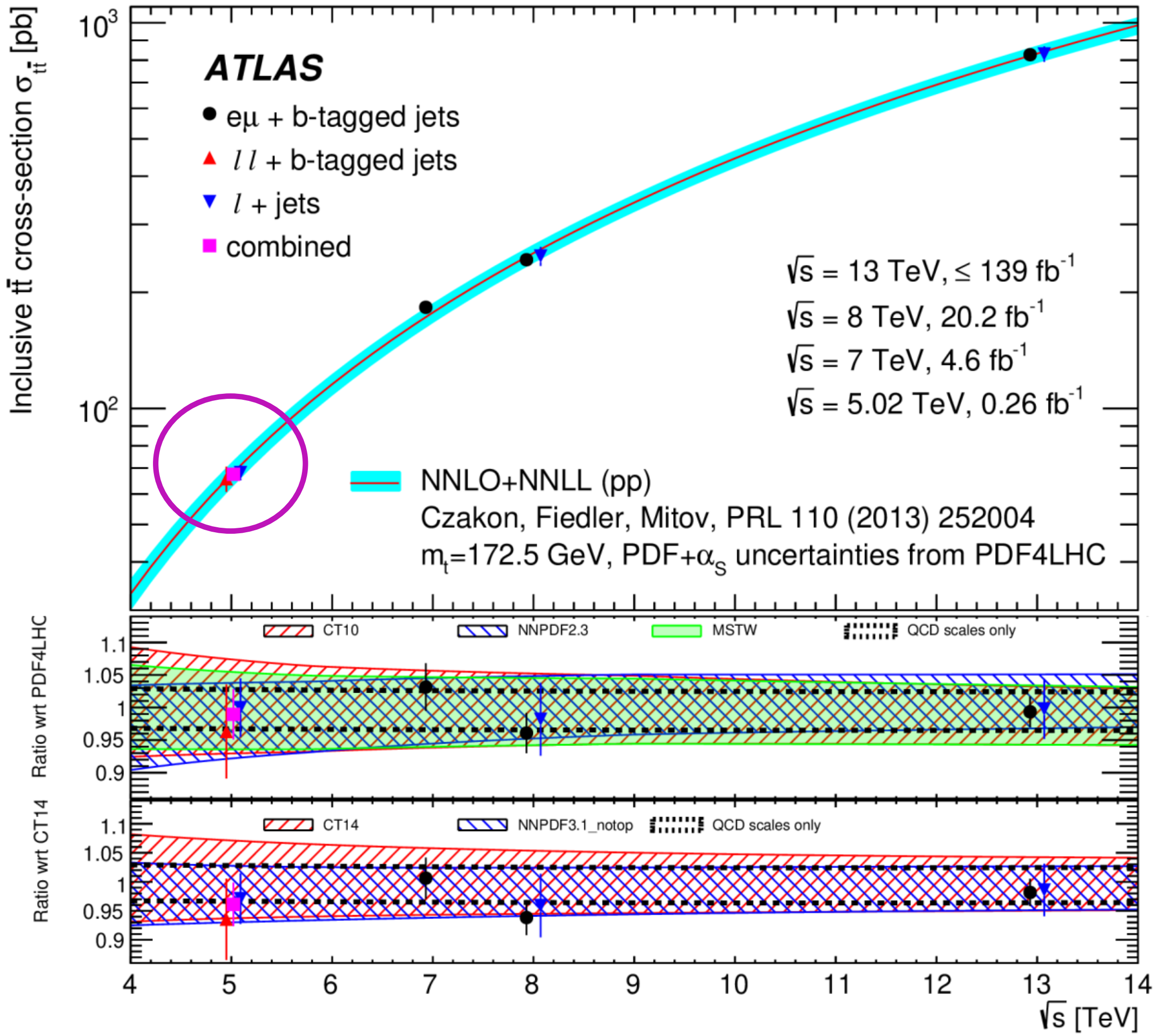


ttbar at √s=5.02 TeV: result

$$\sigma_{t\bar{t}} = 67.5 \pm 0.9(\text{stat.}) \pm 2.3(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.2(\text{beam})\ \text{pb}$$

(3.9% precision)

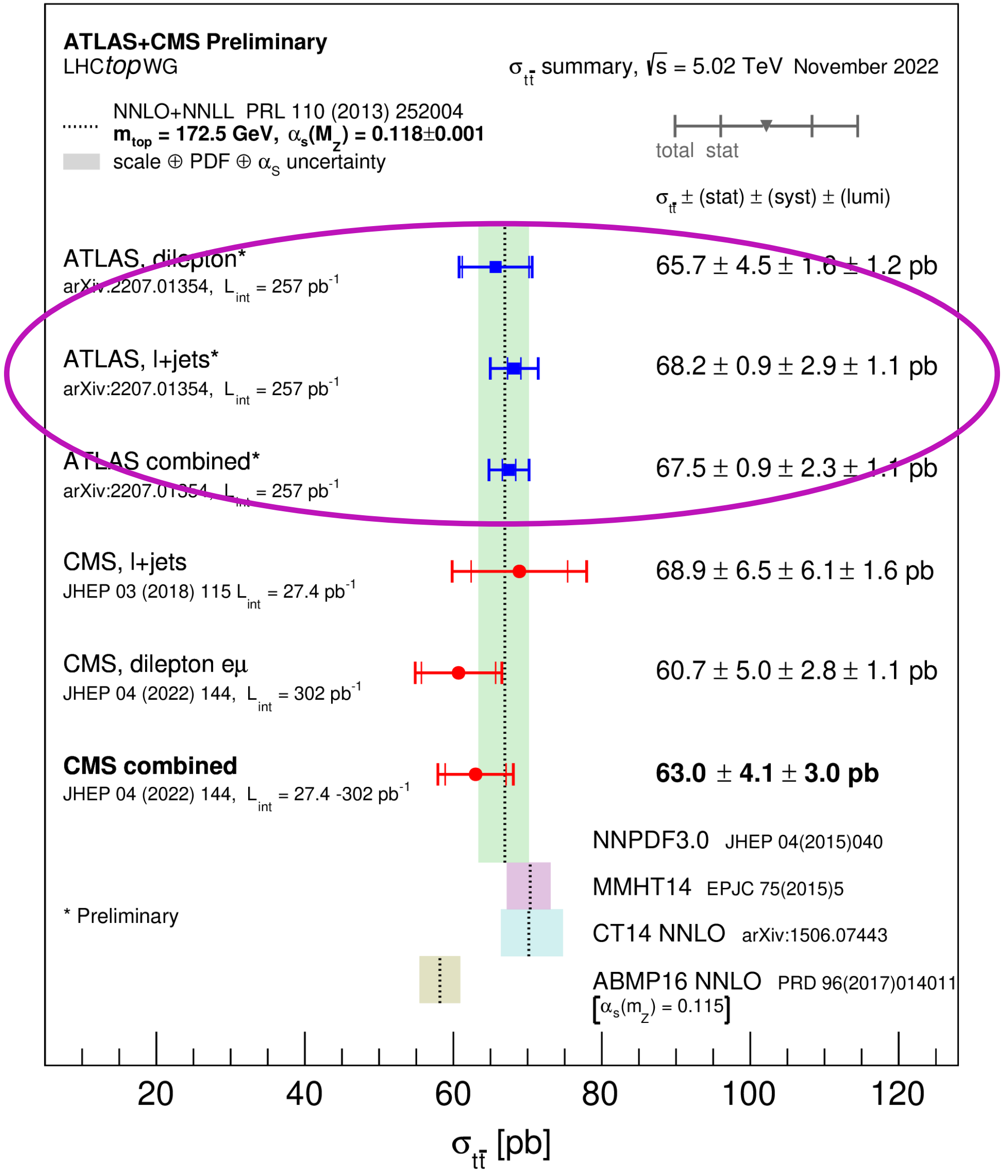
- Result is consistent with the NNLO+NNLL QCD prediction of 68.2 ± 5.2 pb, and exceed the relative precision of theoretical calculations (7.6%)
- Most precise single-lepton result in ATLAS, even more precise than the 13 TeV result that used ~500 more data



ttbar at √s=5.02 TeV: comparison with CMS

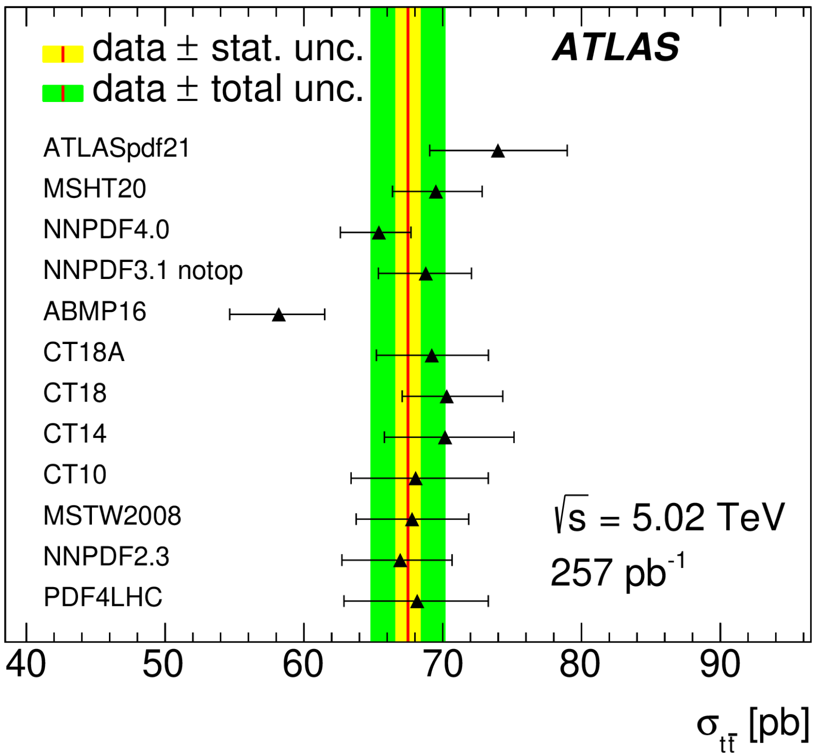
- Consistent with CMS result from combined single-lepton result using 2015 data (27.4 pb^{-1}) and dilepton using 2017 data (304 pb^{-1}) with 8% precision: σ(tt) = 63.0 ± 5.1 pb

- Total uncertainty reduced by almost a factor of two in the ATLAS measurement

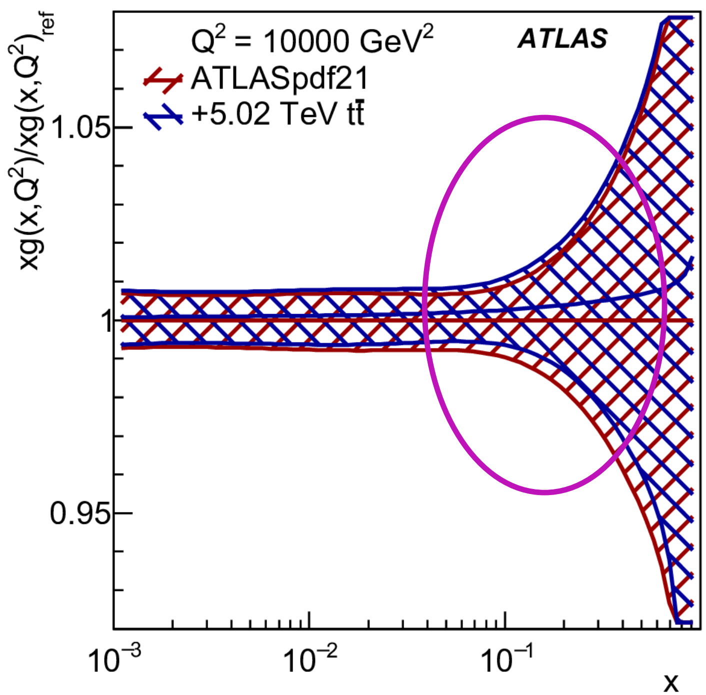


ttbar at √s=5.02 TeV: PDF reduction

- The measured value is compatible with the predictions of several parton distribution functions (PDF) considered, except ABMP16 (expected since has softer gluon PDF and predicts lower cross-section)

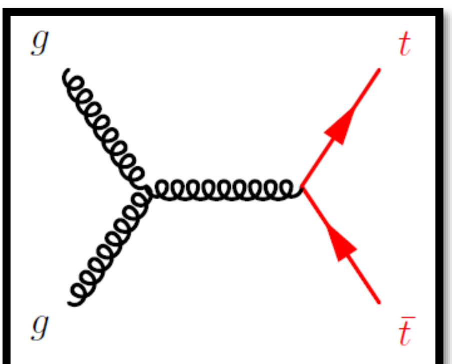


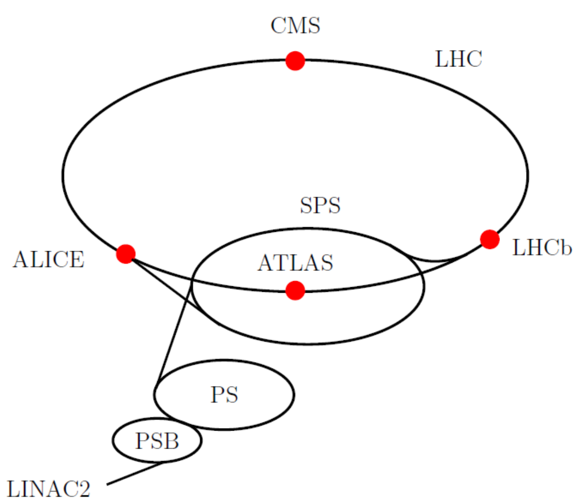
- Addition of new data shows a 5% reduction in the gluon PDF uncert. in the region of Bjorken-x of 0.1

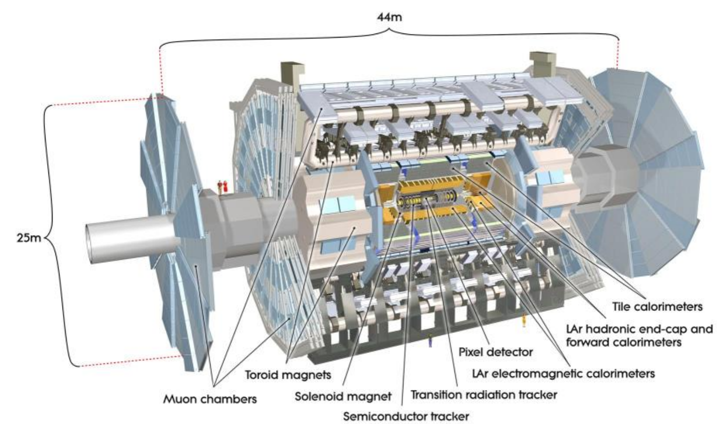


Mar. 2023: ATLAS-CONF-2023-006

√s=13.6 TeV

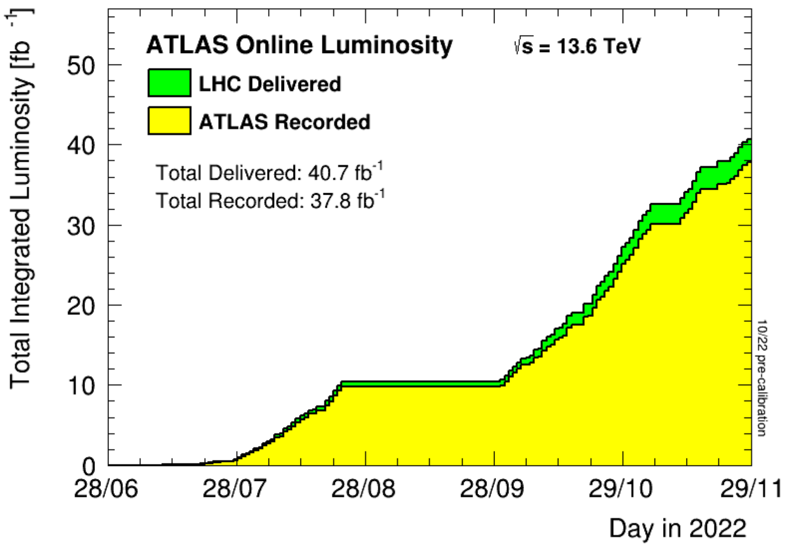


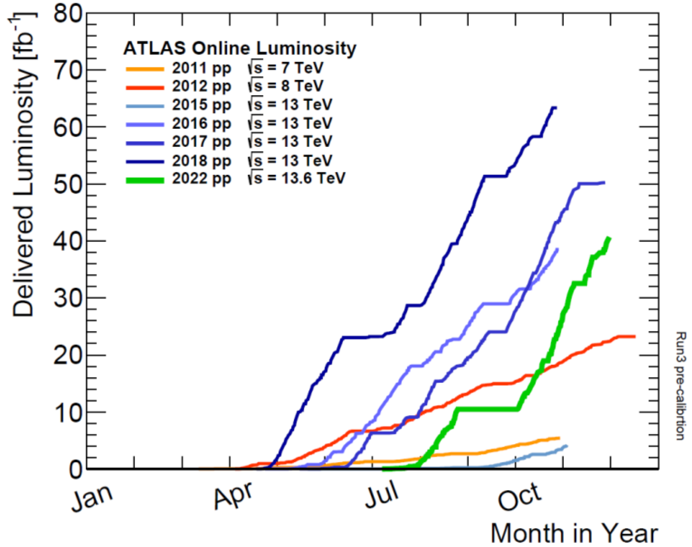




Measuring σ(Z) and σ(ttbar) at √s=13.6 TeV with ATLAS

- After over three years of upgrade and maintenance work, the LHC began its third operation period of operation (Run 3) in July 2022, colliding protons at a record-breaking energy of 13.6 TeV.





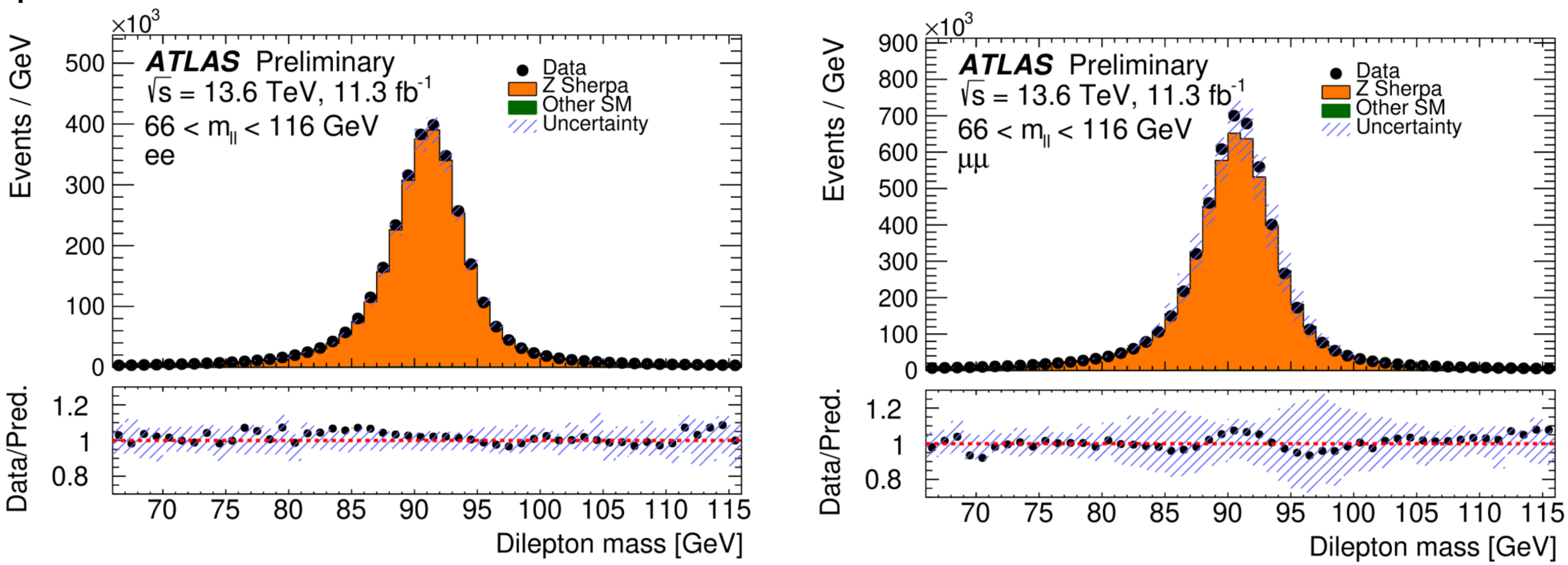
- New analysis with fresh data and noisy detector requires new strategy!

- Measure the cross-section of two well-known processes: the production of a pair of top quarks in the dilepton channel and the production of a Z boson, which decays to electron and muon pairs at a new centre-of-mass energy, assessing the consistency of the data acquired with the Standard Model prediction.

Measuring σ(Z) and σ(ttbar) at √s=13.6 TeV with ATLAS

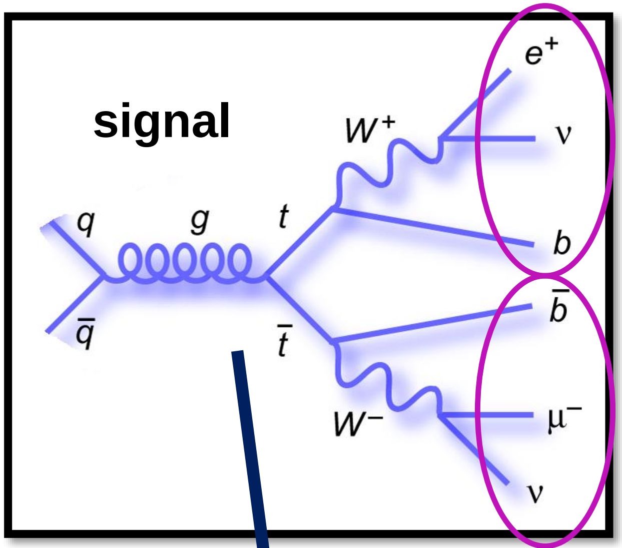
- The analysis uses early Run 3 data (11.3 fb^{-1}) and relies on "preliminary" calibrations of the leptons, jets and luminosity - derived quickly after the first data became available.

- Early measurements provide an opportunity to validate the functionality of the ATLAS detector and its reconstruction software, which underwent a number of improvements.

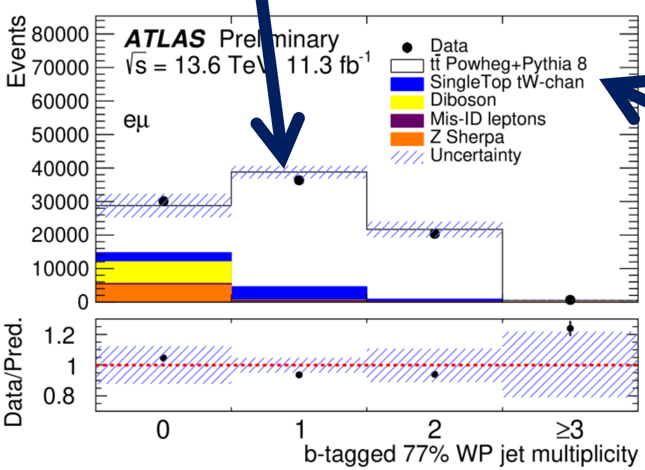


- The calibration, and corresponding uncertainties, will be improved as more data are processed - future updates will allow us to measure the cross-sections with greater precision.

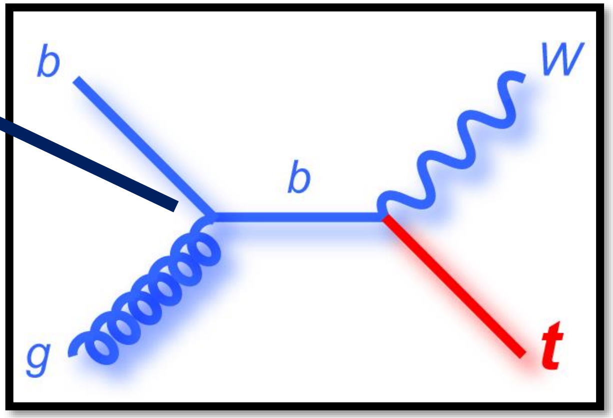
Finding top quarks in the dilepton channel



- The dilepton final state arising from ttbar decay is characterised by two charged leptons, two neutrinos and two b-tagged jets
- To remove different backgrounds, select events that have exactly two leptons (electrons or muons) of opposite electric charge.
- Then select events that contain exactly one electron and one muon with pT > 27 GeV, and select events with exactly 0, exactly 1 or exactly 2 b-jets.



very small background



- MC simulated samples are used to predict contributions from various background processes.

σ(Z) and σ(ttbar) at √s=13.6 TeV and their ratio

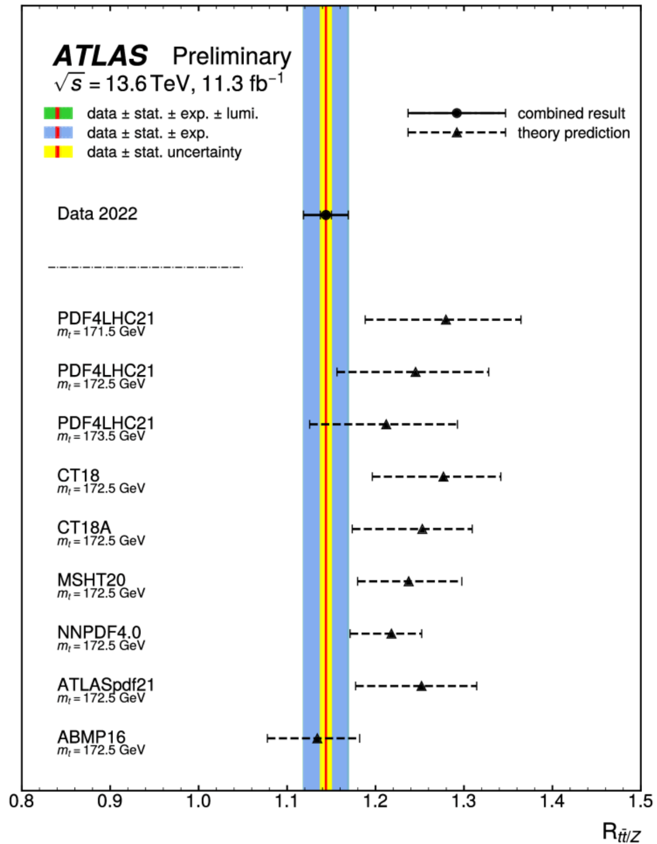
$$\sigma_{t\bar{t}} = 859 \pm 4(\text{stat.}) \pm 22(\text{syst.}) \pm 19(\text{lumi.})\text{pb}$$

(3.5% precision)

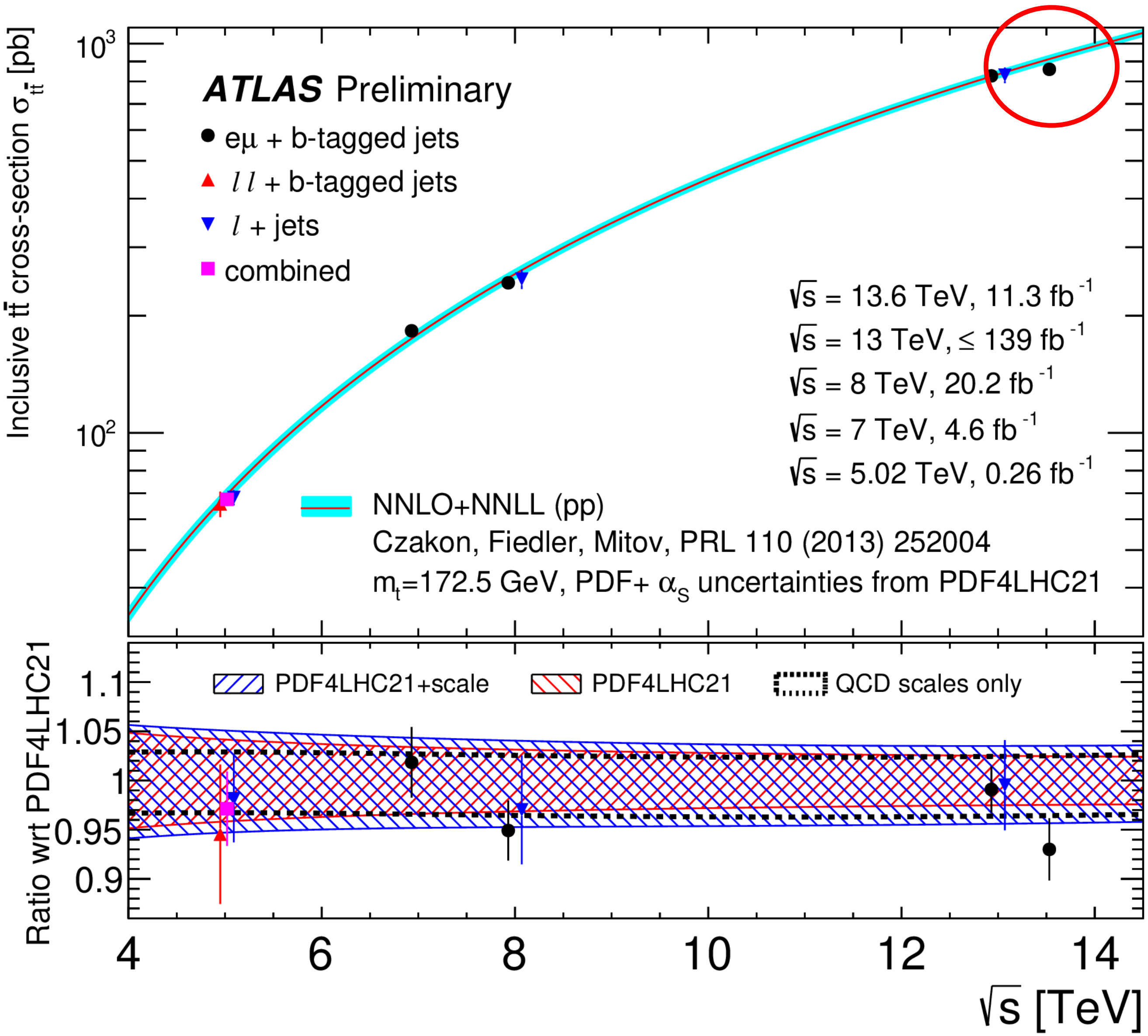
$$\sigma^{\text{fid.}}_{Z\to\ell\ell} = 751 \pm 0.3(\text{stat.}) \pm 15(\text{syst.}) \pm 17(\text{lumi.})\text{pb}$$

(3.0% precision)

- Given that the top-quark-pair and Z-boson production dynamics are driven to a large extent by different PDFs, the ratio of these cross-sections at a given centre-of-mass energy has a significant sensitivity to the gluon-to-quark PDF ratio.
- Many systematic uncertainties, especially the uncertainty on luminosity, partially cancel out in the ratio.



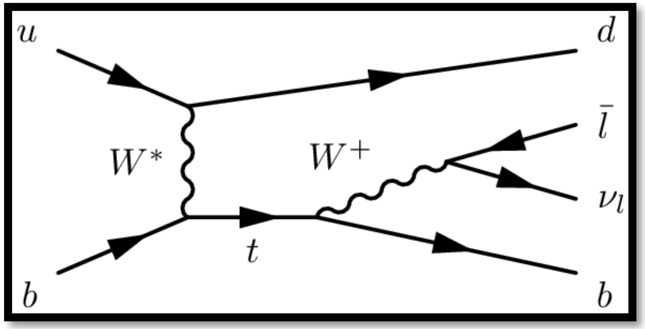
σ(Z) and σ(ttbar) at √s=13.6 TeV and their ratio

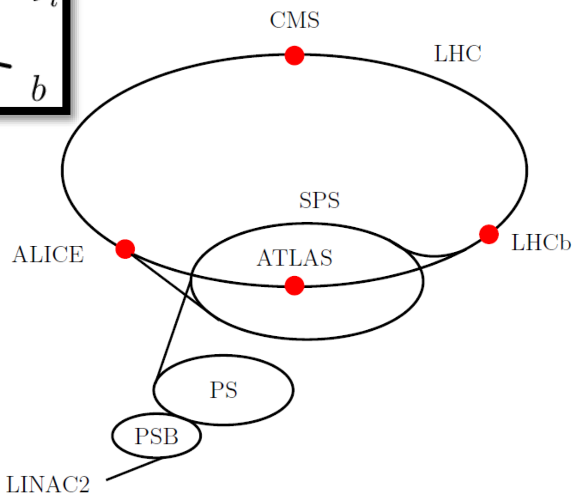


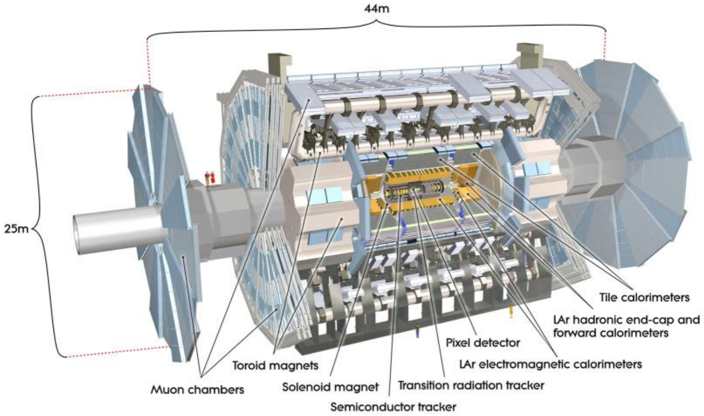
Measuring σ(single top) at √s=5.02 TeV with ATLAS

May 2023: ATLAS-CONF-2023-033

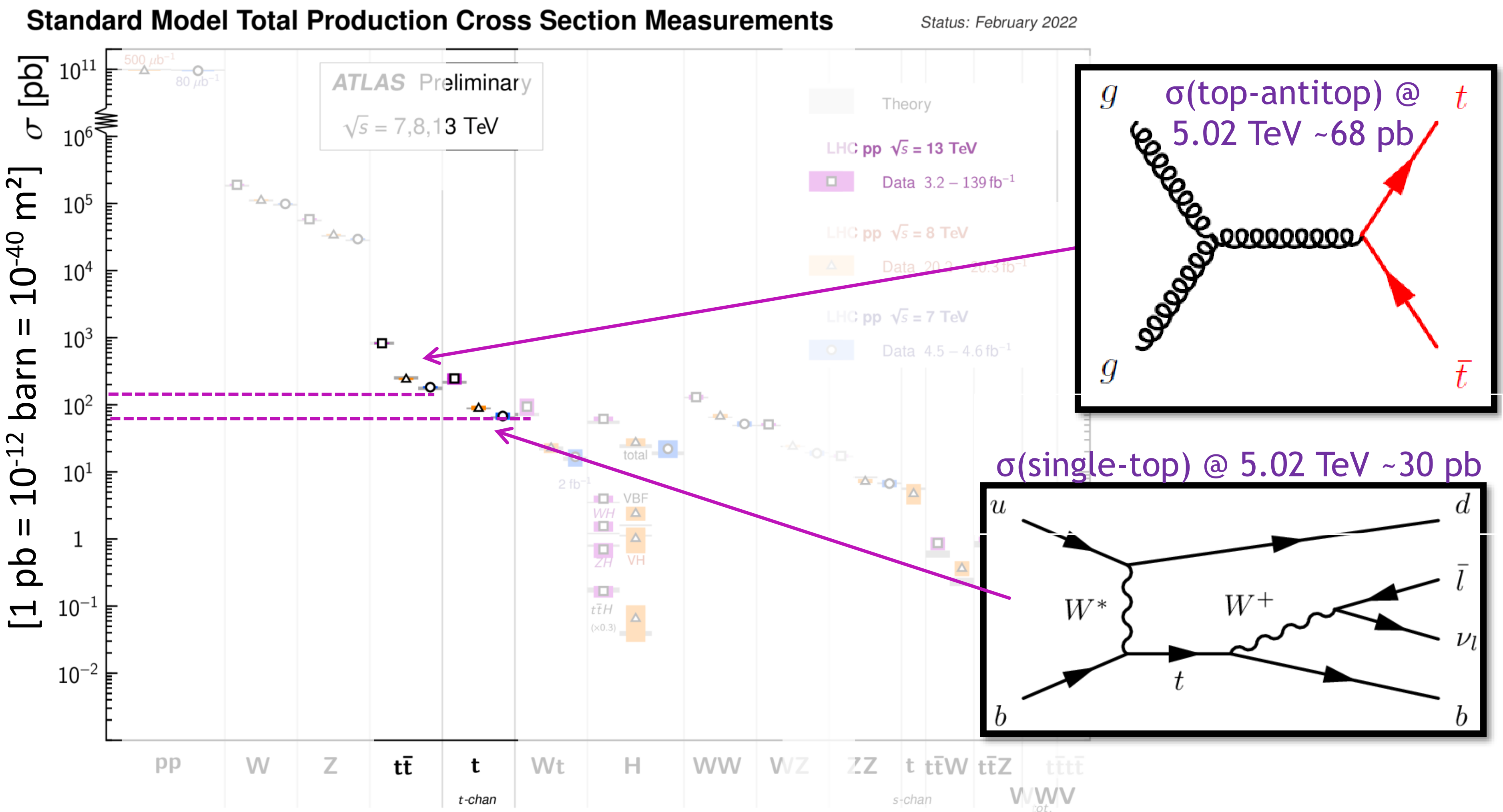
√s=5.02 TeV





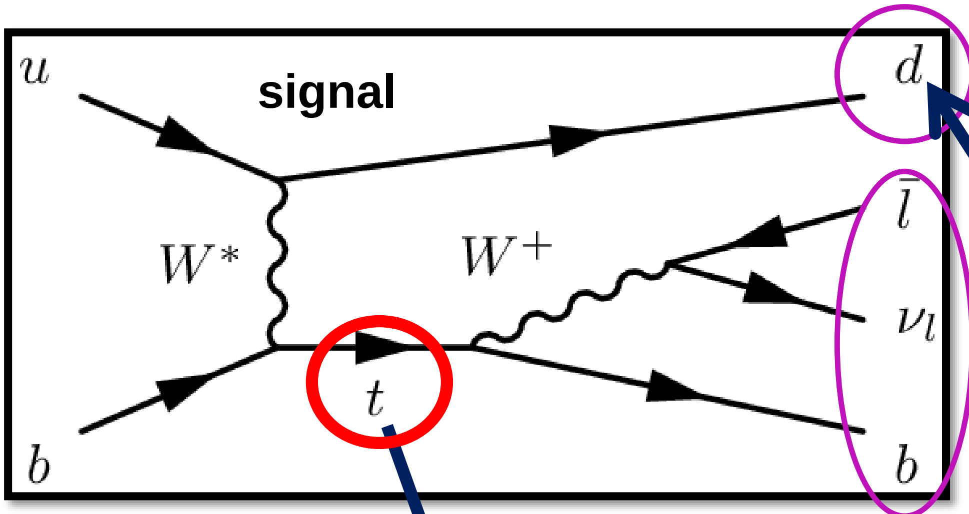


Top quark production cross-section at the LHC

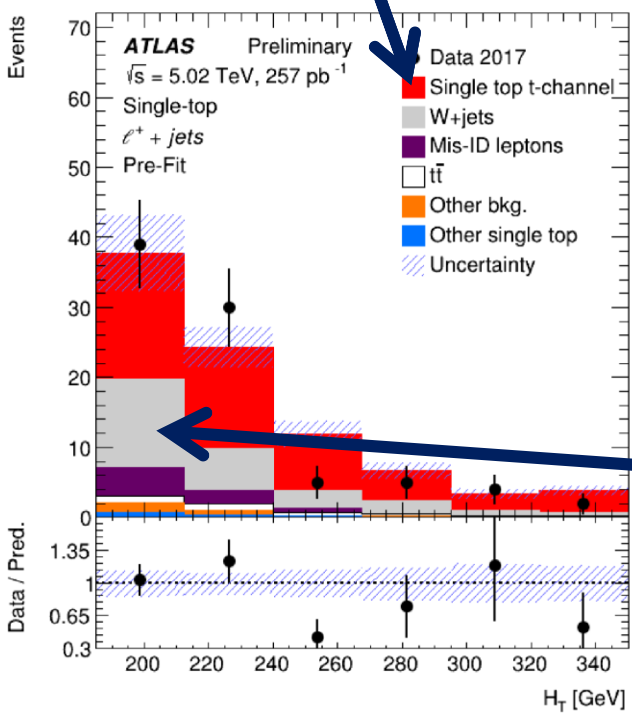


Single top quark via Electro-Weak production!

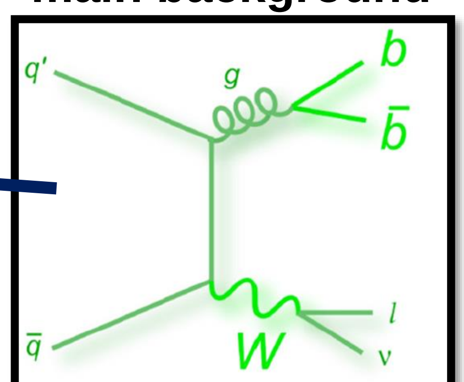
Finding single-top quarks in the single-lepton channel



- The single-lepton final state arising from single-top decay is characterised by a charged lepton, a neutrino, one b-tagged jet
- The spectator-quark jet tends to be produced in the forward direction!
- Select events that contain exactly one electron or muon candidate with pT > 18 GeV, exactly 2 jets, with b-jet with pT > 23 GeV and one forward light jet



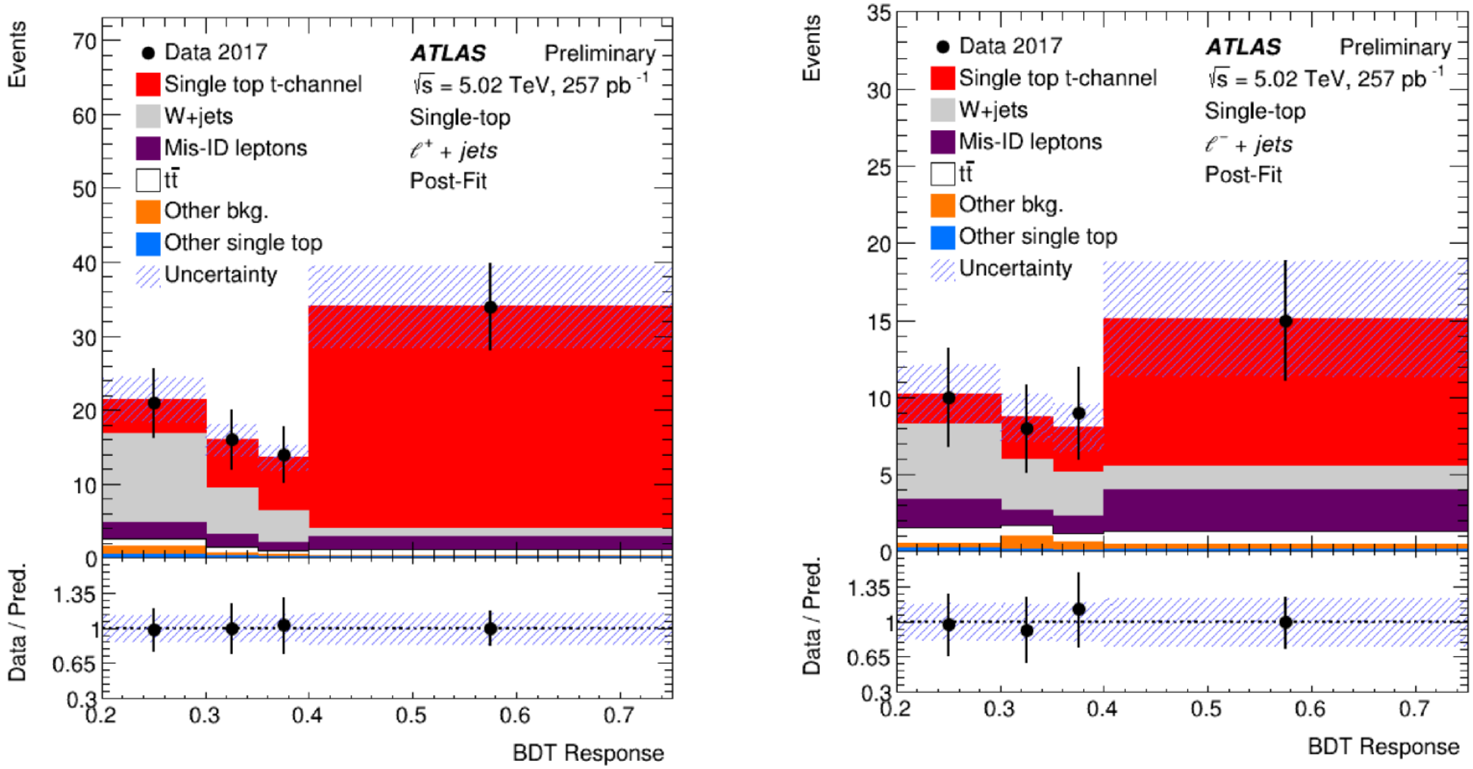
main background



- Apply the same jet energy re-calibration as described previously, and port the systematic and fitting machinery from the ttbar analysis!

single top quark at √s=5.02 TeV: BDT

- Profile maximum-likelihood fit to the BDT discriminant distributions in two channels: lepton with positive and negative charges (single-top-quark and single-top-antiquark).



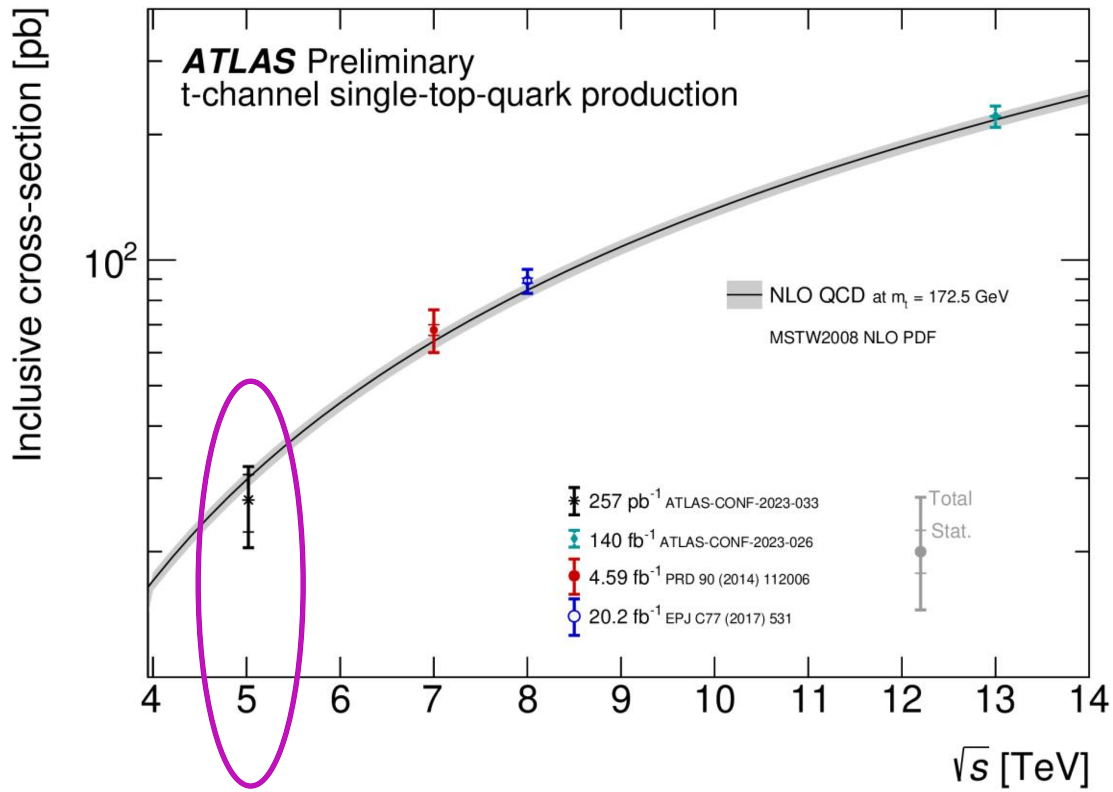
- We are observing the single-top production with a **6.1σ significance**!

single top quark at √s=5.02 TeV: result

$$\sigma(tq+\bar{t}q) = 26.6^{+4.3}_{-4.0}\ (\text{stat})\ ^{+4.4}_{-3.6}\ (\text{syst})\ \text{pb}$$

(22% precision)

- Result is consistent with the NNLO QCD prediction of 30.3 ± 0.6 pb
- First ever measurement of the single-top production at this energy!
- Provides another independent test of the SM predictions!



Summary

✓ The LHC is a top-quark-factory with millions of top quark events accumulated (~500 top-quark-pairs produced per minute).

✓ Large statistics is not a guarantee of high precision - we are limited by systematic uncertainties, both experimental and theoretical.

✓ With just a single week of data, one can obtain results even more precise than those using 3 years of data!

✓ The first ATLAS Run 3 result probed the top-pair and Z-boson production cross-sections at a new centre-of-mass energy – and proved a valuable tool for validating the detector's many upgrades.

✓ The first ATLAS 5.02 TeV single-top-quark measurement provides another independent test of SM and will be used to constrain CKM matrix elements.

✓ The good (or bad depending on your opinion): so far all the measurements are consistent with the SM prediction.

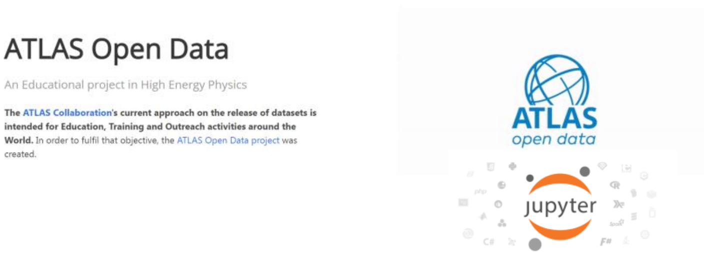
❑ Ask me for more details about "[ATLAS Open Data]" project for science education: it allows you to measure the top quarks, find the Higgs or test the SM in different corners.

Muchas gracias por su atención!

BACK-UP

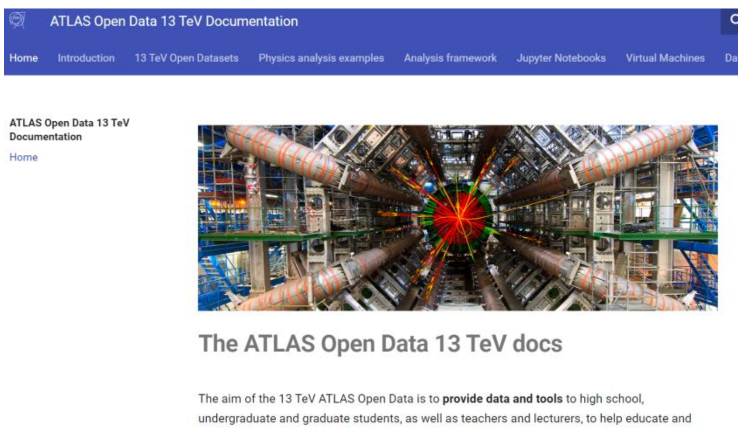
ATLAS Open Data: data and tool for education

[Sitio web: http://opendata.atlas.cern/](http://opendata.atlas.cern/)

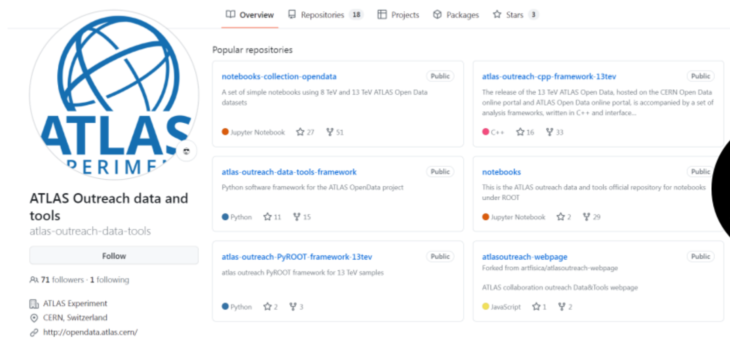


[Documentación](http://opendata.atlas.cern/release/2020/documentation/index.html)

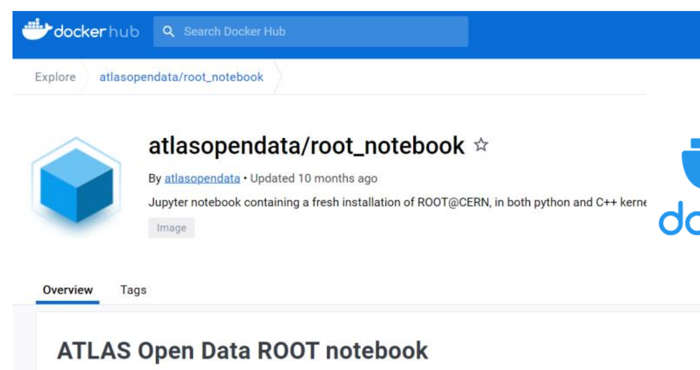
http://opendata.atlas.cern/release/2020/documentation/index.html



[GitHub]()



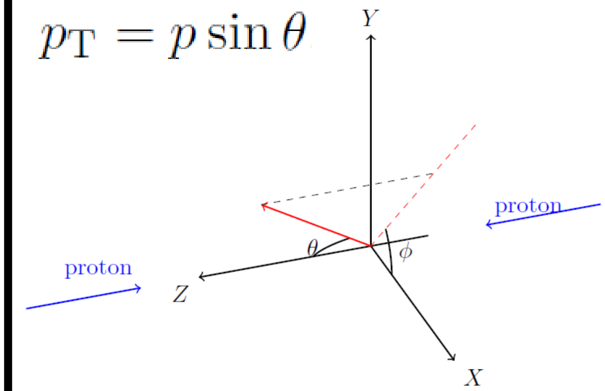
[Docker]()

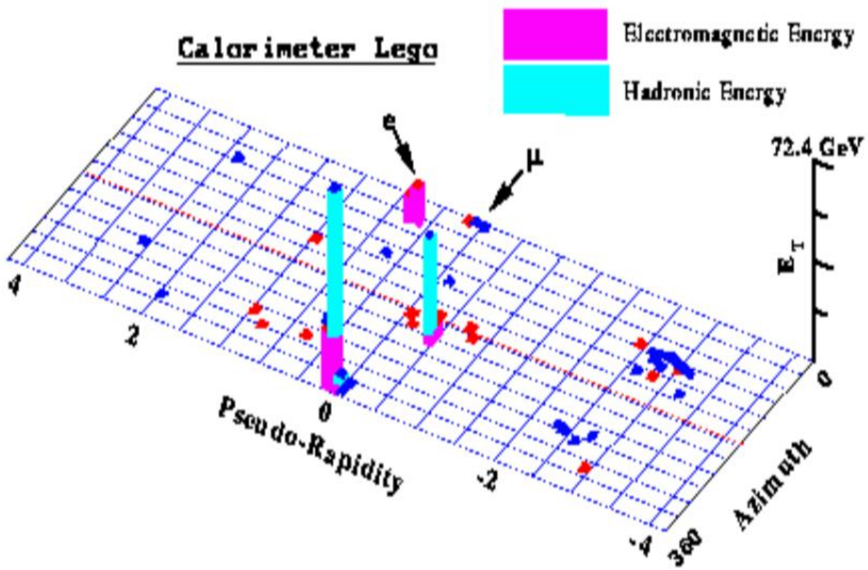


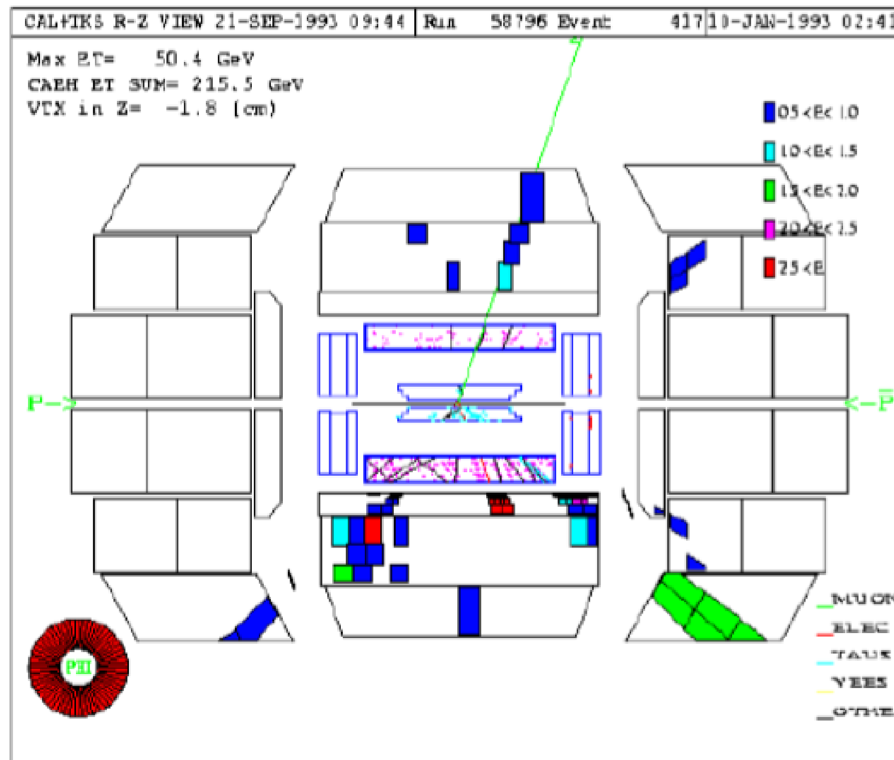
Top quark discovery at Tevatron

- The first top quarks were observed in CDF and D0 detectors in 1995 at Fermilab proton-antiproton collider at a center-of-mass energy ($\sqrt{s}$) of 1.8 TeV

$$p_{\mathrm{T}} = p \sin\theta$$



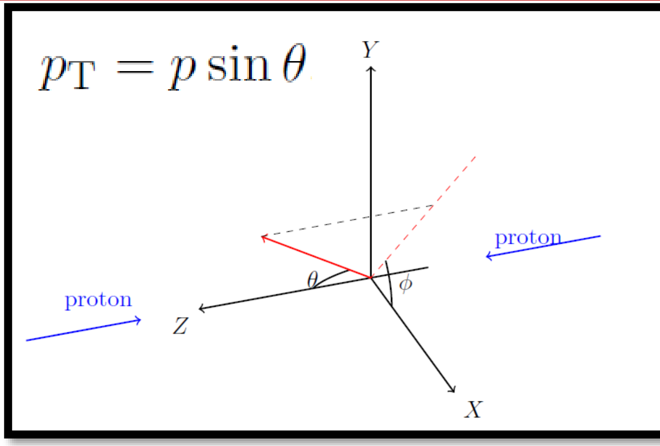


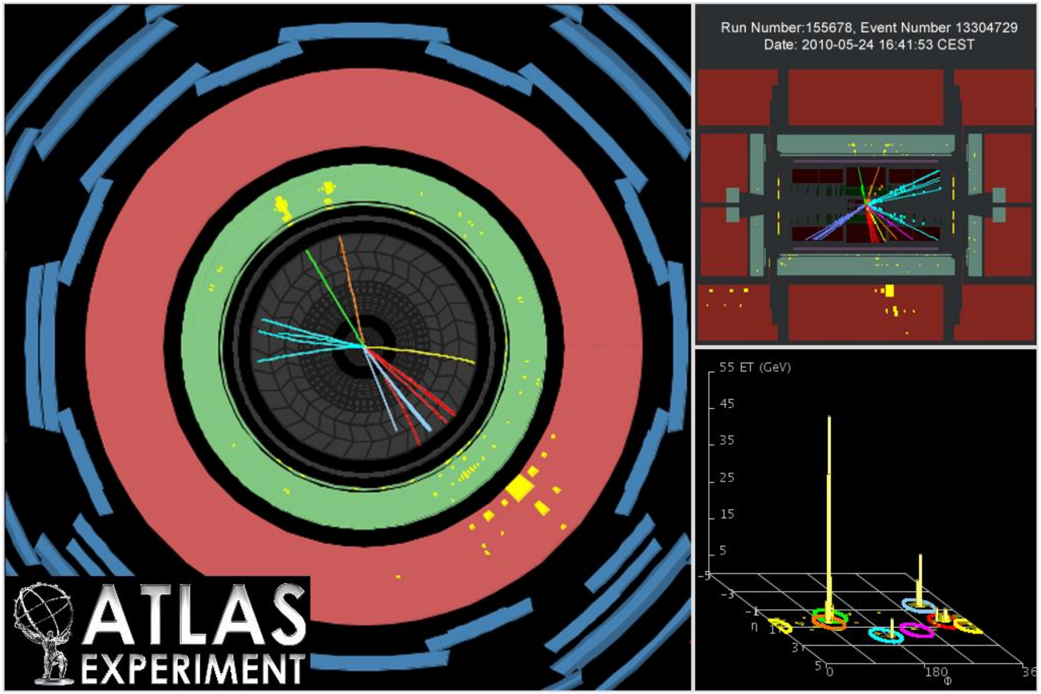


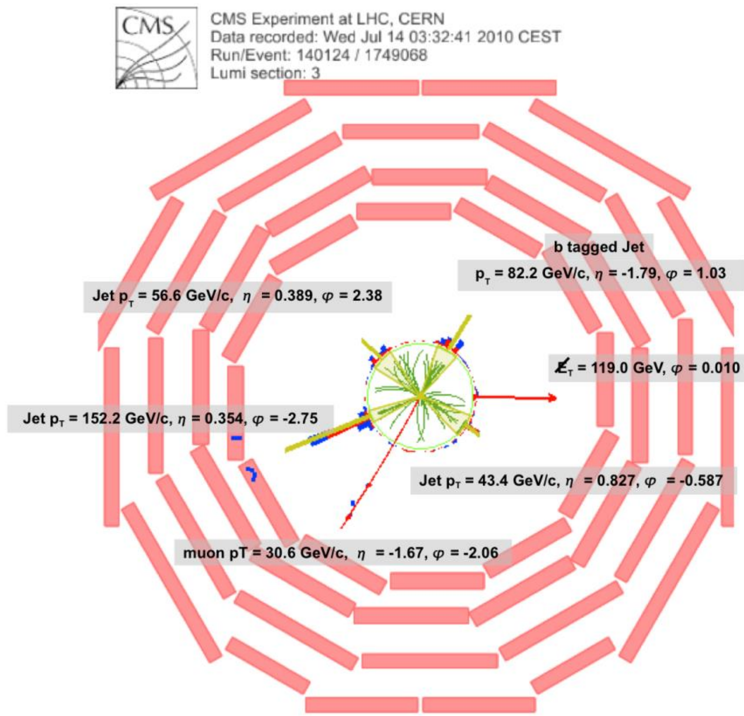
$$\eta = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = -\ln\tan\left(\frac{\theta}{2}\right)$$

Top quark re-discovery at the LHC

- First top quark pair production candidates were observed at the LHC in 2010 at $\sqrt{s}$ = 7 TeV

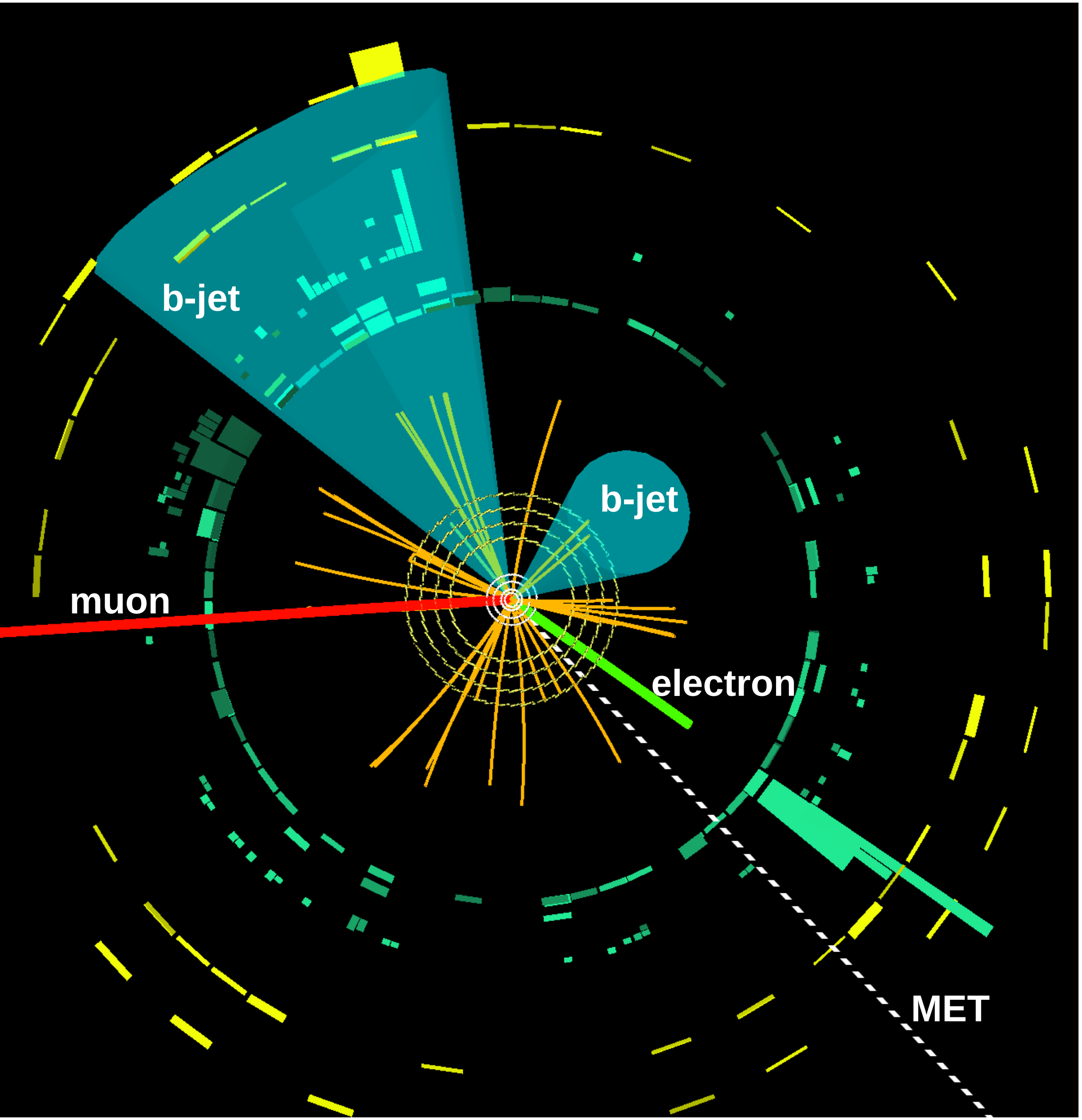






$$\eta = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = -\ln\tan\left(\frac{\theta}{2}\right)$$

Candidate ttbar events at √s=13.6 TeV in ATLAS



Charged particle tracks reconstructed in the inner detector (orange lines), an electron track (green line), a muon track (red line) as well as the energy deposits in the LAr (green and cyan blocks) and Tile (yellow/orange blocks) calorimeters.

The event contains two jets that have passed b-tagging requirements and these are delineated with cyan cones.

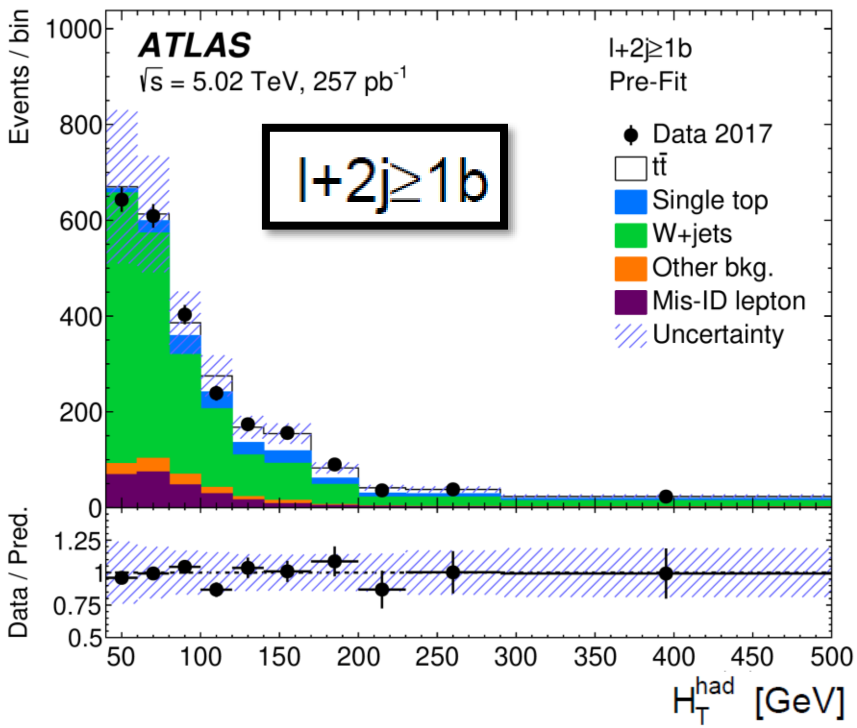
The direction of the missing transverse momentum is shown as dashed white line.

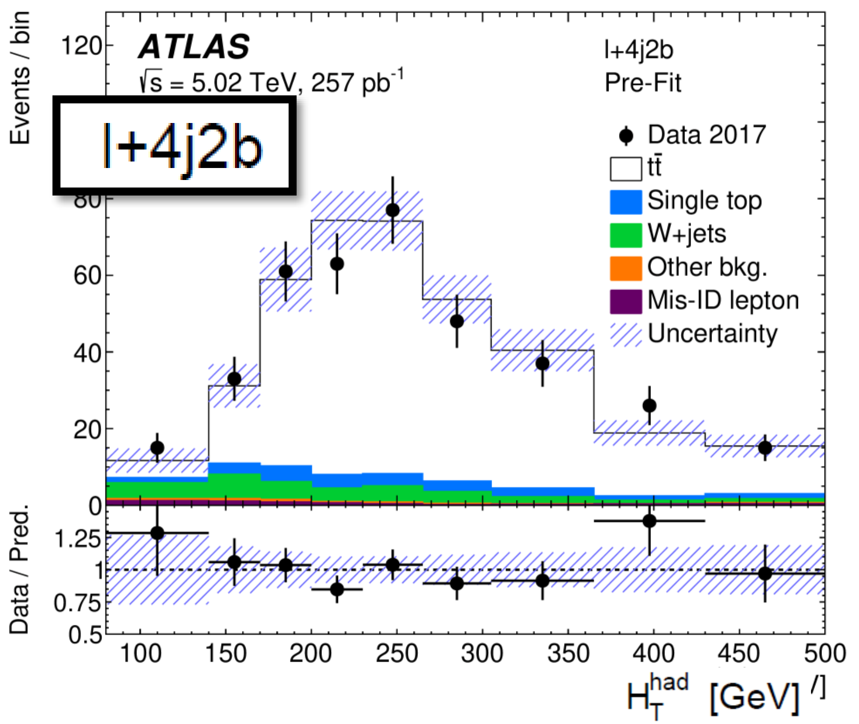
ttbar at √s=5.02 TeV: single-lepton channel

- Events passing the selection requirements were further split into six orthogonal regions based on number of jets and b-tagged jets

  ✓ This separation created subsamples with different levels of signal and background, each having an excellent agreement of rates and shapes

REGION NAME	JET MULTIPLICITY	b-JET MULTIPLICITY
ℓ+2j≥1b	2	≥ 1
ℓ+3j 1b	3	1
ℓ+3j 2b	3	2
ℓ+≥4j 1b	≥ 4	1
ℓ+4j 2b	4	2
ℓ+≥5j 2b	≥ 5	2





ttbar at √s=5.02 TeV: single-lepton channel

- Events passing the selection requirements were further split into six orthogonal regions based on number of jets and b-tagged jets

Region name	Jet multiplicity	b-jet multiplicity
ℓ+2j≥1b	2	≥ 1
ℓ+3j 1b	3	1
ℓ+3j 2b	3	2
ℓ+≥4j 1b	≥ 4	1
ℓ+4j 2b	4	2
ℓ+≥5j 2b	≥ 5	2

	$\ell + 2j \geq 1b$	$\ell + 3j\ 1b$	$\ell + 3j\ 2b$	$\ell + \geq 4j\ 1b$	$\ell + 4j\ 2b$	$\ell + \geq 5j\ 2b$
$t\bar{t}$	194 ± 27	310 ± 33	199 ± 24	690 ± 60	318 ± 32	380 ± 60
Single top	195 ± 22	98 ± 12	38 ± 5	67 ± 9	22 ± 4	15.9 ± 2.7
W+ jets	1700 ± 400	690 ± 210	58 ± 23	350 ± 120	30 ± 14	19 ± 10
Other bkg.	110 ± 40	55 ± 23	7.2 ± 3.0	29 ± 12	3.5 ± 1.5	3.7 ± 1.7
Misidentified leptons	250 ± 130	110 ± 60	10 ± 5	60 ± 30	6 ± 3	8 ± 5
Total	2500 ± 400	1260 ± 210	312 ± 34	1200 ± 160	380 ± 40	430 ± 70
Data	2411	1214	293	1135	375	444

ttbar at √s=5.02 TeV: BDT in single-lepton channel

- 2 boosted-decision trees using six input variables each trained to separate signal from background (mainly W+jets and single top)

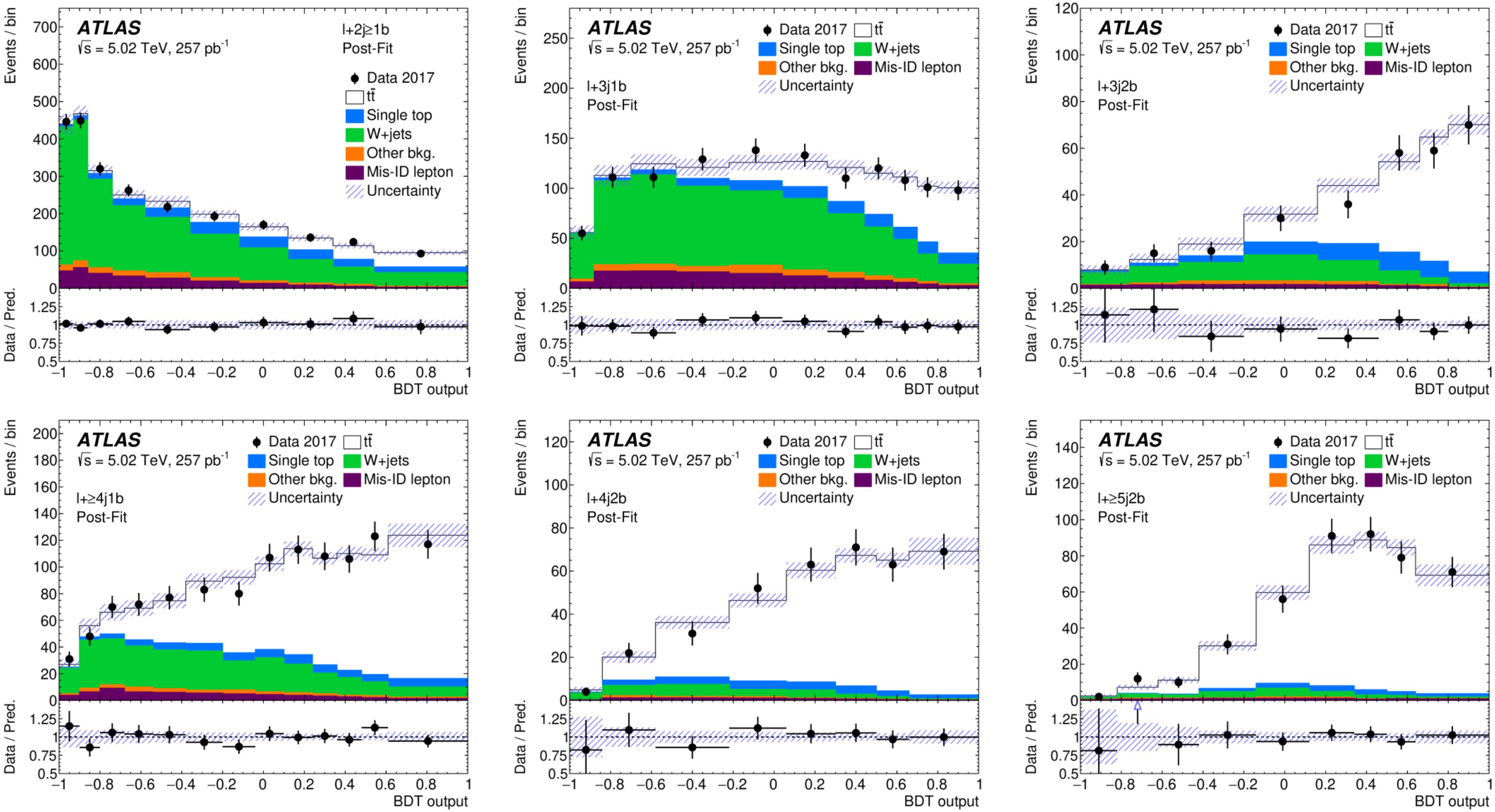
✓ One BDT trained in the two-jet and three-jet regions, whereas the second BDT was trained in the four-jet and five-jet regions

✓ Variables chosen to have good signal-to-background separation and in combination provided greater separation than other choices

VARIABLE	DEFINITION	$\ell + (2,3)$j, $(1,2)$b	$\ell + (4, \geq 5)$j, $(1,2)$b
$H_{\mathrm{T}}^{\mathrm{had}}$	Scalar sum of all jet transverse momenta	✓	✓
FW2 (l+j)	Second Fox-Wolfram moment computed using all jets and the lepton	✓	✓
Lepton η	Lepton pseudorapidity	✓	✓
ΔR_{bl} (med.)	Median ΔR between the lepton and b-jets	✓	✓
ΔR_{jj} (med.)	Median ΔR between any two jets	✓	–
$\mathrm{m(jj)}^{\mathrm{min.}\Delta R}$	Mass of the combination of any two jets with the smallest ΔR	✓	–
ΔR_{uu} (med.)	Median ΔR between any two untagged jets	–	✓
$\mathrm{m(uu)}^{\mathrm{min.}\Delta R}$	Mass of the combination of any two untagged jets with the smallest ΔR	–	✓

ttbar at √s=5.02 TeV: BDT in single-lepton channel

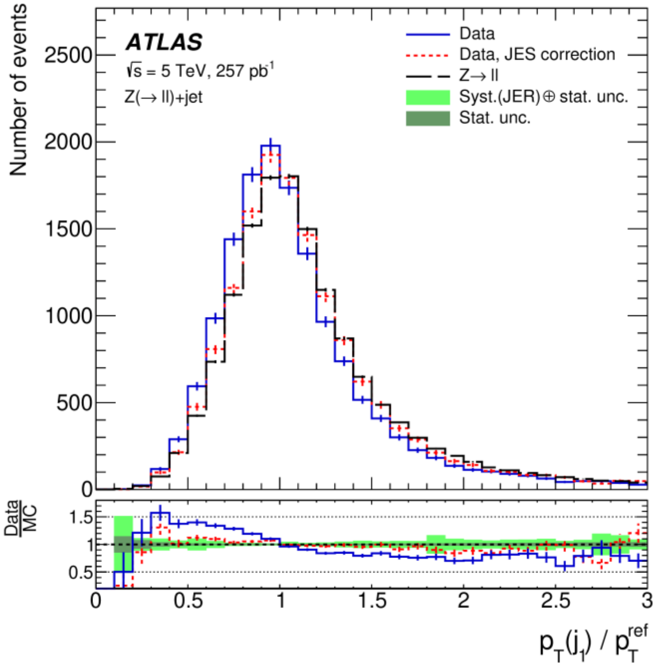
- Compare the shapes of the BDT outputs in each region with data
- Interpreted by a statistical model that employs the expected distributions for both the background and signal contributions in the six regions.

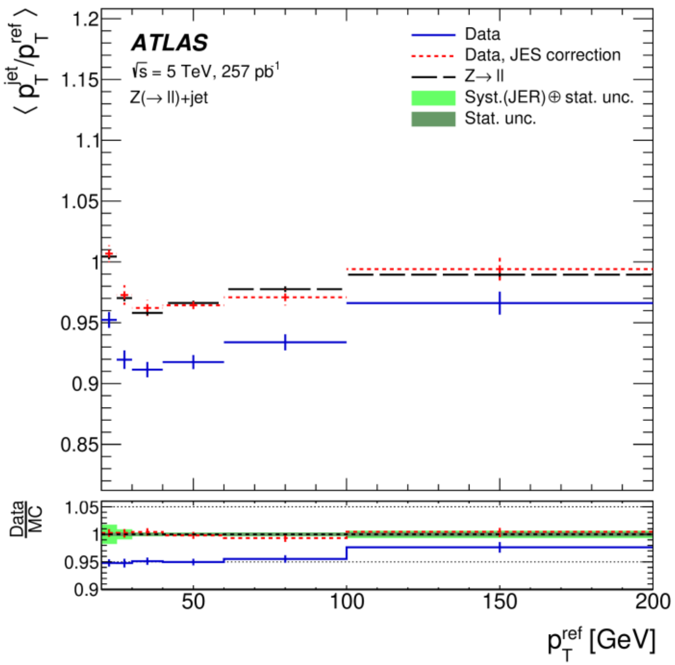


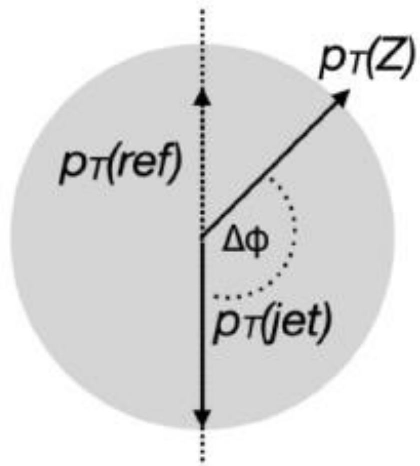
Jet re-calibration at √s=5.02 TeV

- Select same-flavour opposite-sign lepton pair such as the dilepton mass is between 81 < m(ll) < 101 GeV (the Z-boson candidates)

- Look for a recoiling jet, i.e. events with a back-to-back topology of jet wrt. to the Z-boson (azimuth $\Delta\varphi > 2.8$)







$$p_T^{ref} = p_T(Z) * |\cos \Delta\varphi(Z, j_1)|$$

- Measure pT(reference) and pT(jet) / pT(reference) in data and in MC simulations: must be balanced in the transverse plane! Then correct the jet energy scale and resolution of data events!

New inclusive ttbar cross-section at √s=5.02 TeV

Category	$\delta\sigma_{t\bar{t}}$ [%] Dilepton	Single lepton	Combination
$t\bar{t}$ generator†	1.2	1.0	0.8
$t\bar{t}$ hadronisation*,†	0.3	0.9	0.7
$t\bar{t}$ h_{damp} and scale variations†	1.0	1.1	0.8
$t\bar{t}$ parton-distribution functions†	0.2	0.2	0.2
Single-top background	1.1	0.8	0.6
W/Z+jets background*	0.8	2.4	1.8
Diboson background	0.3	0.1	< 0.1
Misidentified leptons*	0.7	0.3	0.3
Electron identification/isolation	0.8	1.2	0.8
Electron energy scale/resolution	0.1	0.1	< 0.1
Muon identification/isolation	0.6	0.2	0.3
Muon momentum scale/resolution	0.1	0.1	0.1
Lepton-trigger efficiency	0.2	0.9	0.7
Jet-energy scale/resolution	0.1	1.1	0.8
$\sqrt{s}$ = 5.02 TeV JES correction	0.1	0.6	0.5
Jet-vertex tagging	< 0.1	0.2	0.2
Flavour tagging	0.1	1.1	0.8
$E_{\text{T}}^{\text{miss}}$	0.1	0.4	0.3
Simulation statistical uncertainty*	0.2	0.6	0.5
Data statistical uncertainty*	6.8	1.3	1.3
Total systematic uncertainty	3.1	4.2	3.7
Integrated luminosity	1.8	1.6	1.6
Beam energy	0.3	0.3	0.3
Total uncertainty	7.5	4.5	3.9

- **Combination** of a cut-and-count dilepton result with a binned PLL fit in single-lepton channel:
  - ✓ Using Convino tool (Eur. Phys. J. C(2017) 77 792)
  - ✓ Minimising a χ^2 with 3 terms:

$$\chi^2 = \sum_{\alpha} \left(\chi^2_{s,\alpha} + \chi^2_{u,\alpha}\right) + \chi^2_p$$

$\chi^2_{s,\alpha}$ - the result of each measurement α and its statistical uncertainty

$\chi^2_{u,\alpha}$ - correlations between syst. uncert. and constraints on them from the data for each α

χ^2_p - correlation assumptions between uncertainties of two measurements

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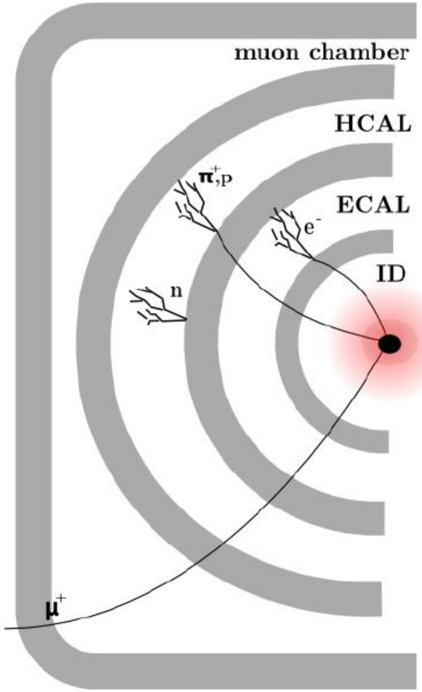
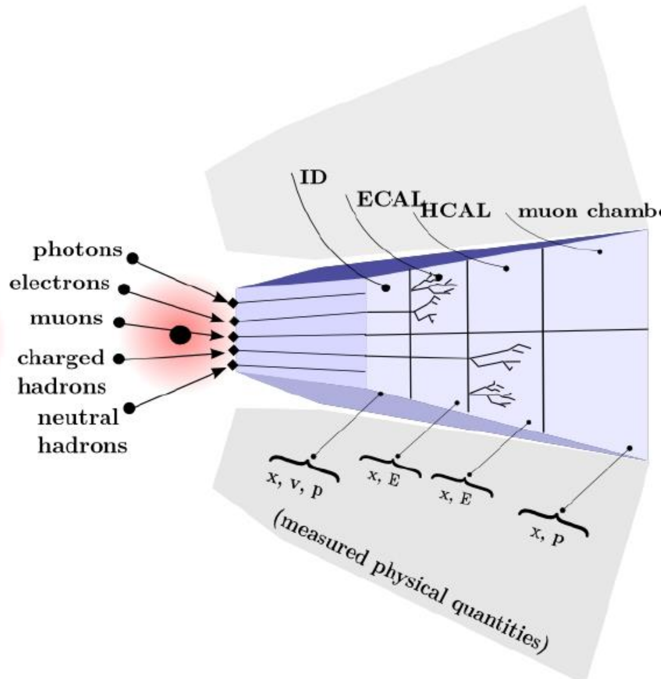
- Post-fit uncertainty correlations **accounted** for in the combination
- **Priors** for the correlations split in 3 categories:

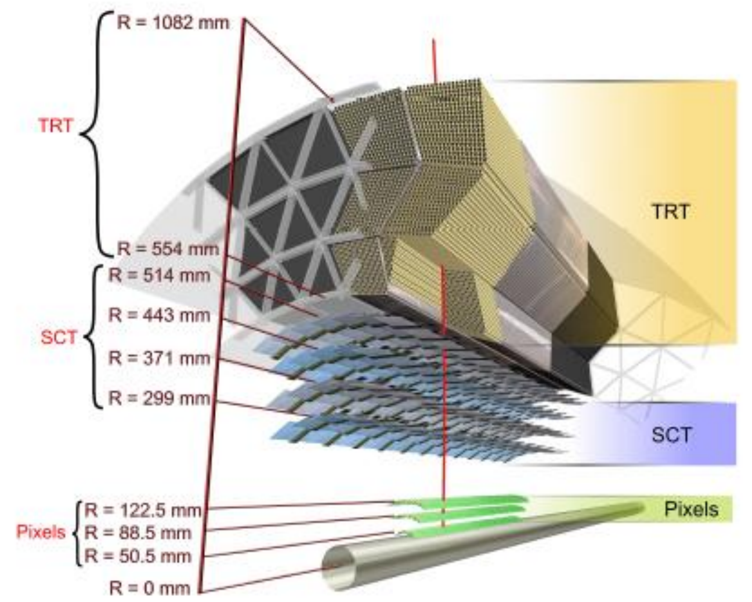
unique* (uncorrelated),

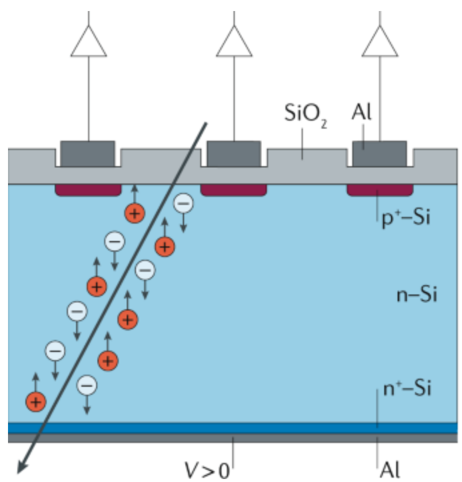
1-to-1 (fully correlated)

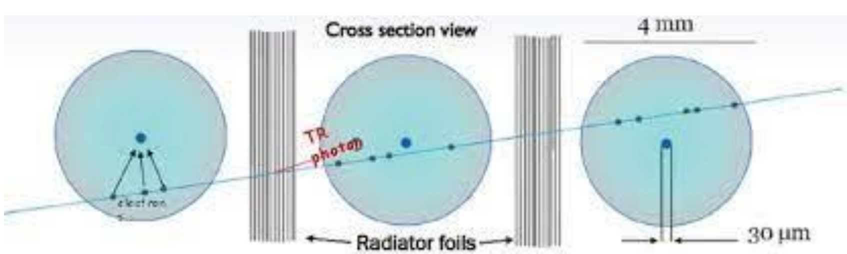
1-to-many† (i.e. separate NPs in one channel), investigated using different correlations


muon chamber
HCAL
ECAL
ID
π±,p
e-
n
μ+


photons
electrons
muons
charged hadrons
neutral hadrons
ID
ECAL
HCAL
x, v, p
x, E
x, E
x, p
(measured physical quantities)


R = 1082 mm
TRT
R = 554 mm
R = 514 mm
R = 443 mm
SCT
R = 371 mm
R = 299 mm
TRT
SCT
R = 122.5 mm
Pixels
R = 88.5 mm
R = 50.5 mm
R = 0 mm
Pixels


SiO2
Al
p+–Si
n–Si
n+–Si
V>0
Al


Cross section view
4 mm
TR photon
Radiator foils
30 μm

Parton Distribution Function