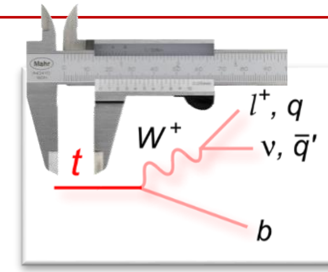
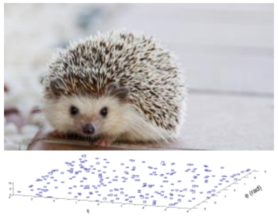
1.) Measuring top quarks with the highest precision and at record energies using the ATLAS detector at the LHC



2.) “Hedgehog” events at the LHC revisited



Leonid Serkin

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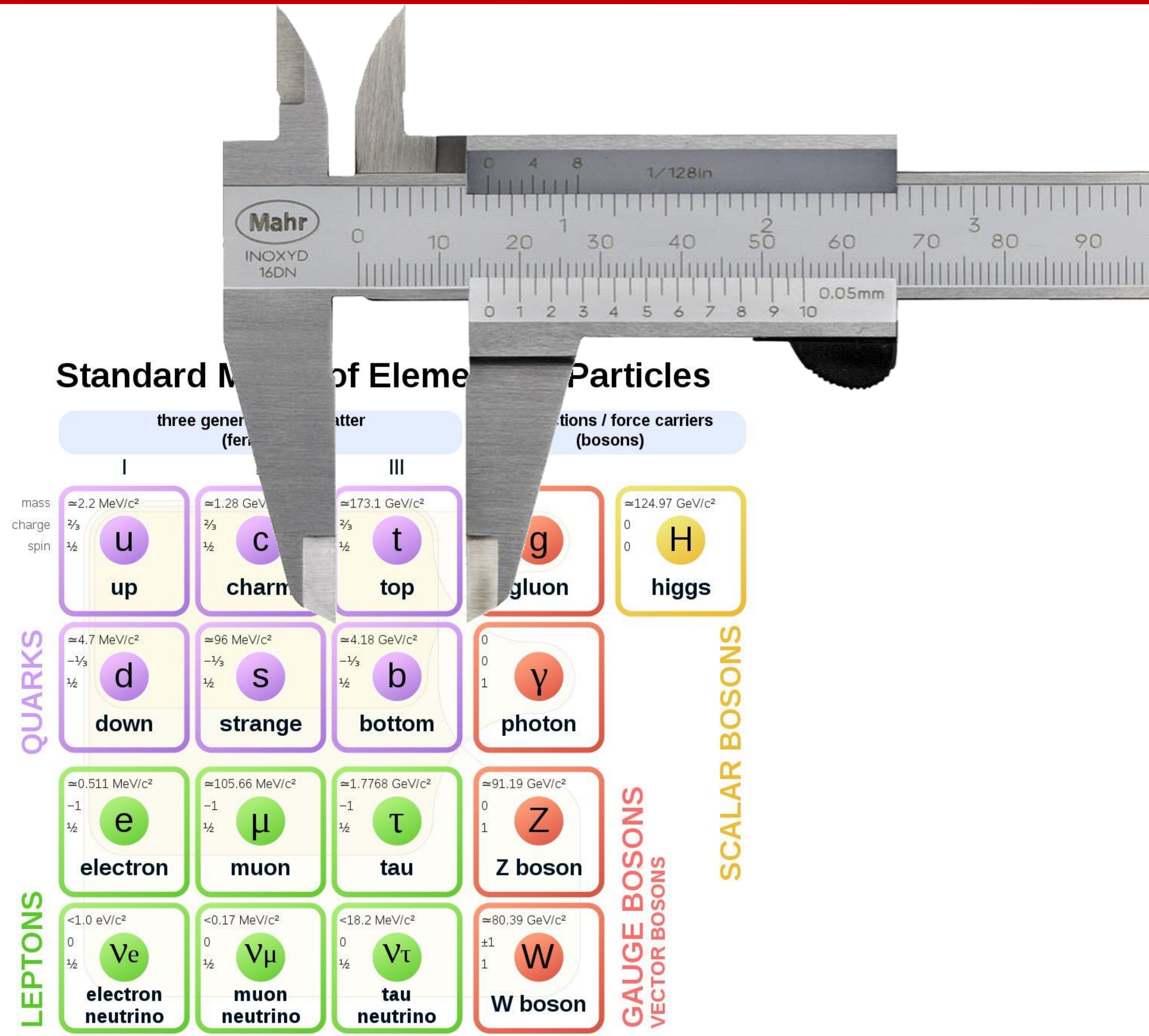
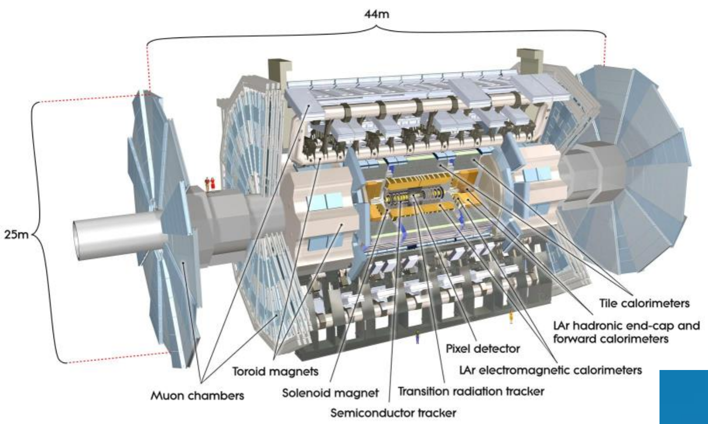
Instituto de Ciencias Nucleares (ICN-UNAM), México

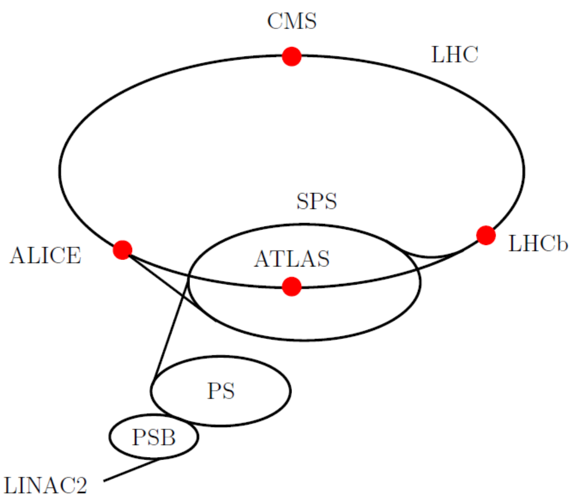
Seminario de Física de Altas Energías, ICN-UNAM, IF-UNAM, 22 Feb. 2023

Measuring top quarks





44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker



CMS
LHC
SPS
ALICE
ATLAS
LHCb
PS
PSB
LINAC2

Status: November 2018
Albania
Algeria
Argentina
Armenia
Australia
Austria
Azerbaijan
Bangladesh
Belarus
Belgium
Bosnia and Herzegovina
Botswana
Brazil
Bulgaria
Czech Republic
Denmark
Ecuador
Egypt
Finland
France
Georgia
Germany
Ghana
Greece
Honduras
Hong Kong
Hungary
Iceland
India
Indonesia
Iran
Iraq
Ireland
Israel
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Kyrgyzstan
Mongolia
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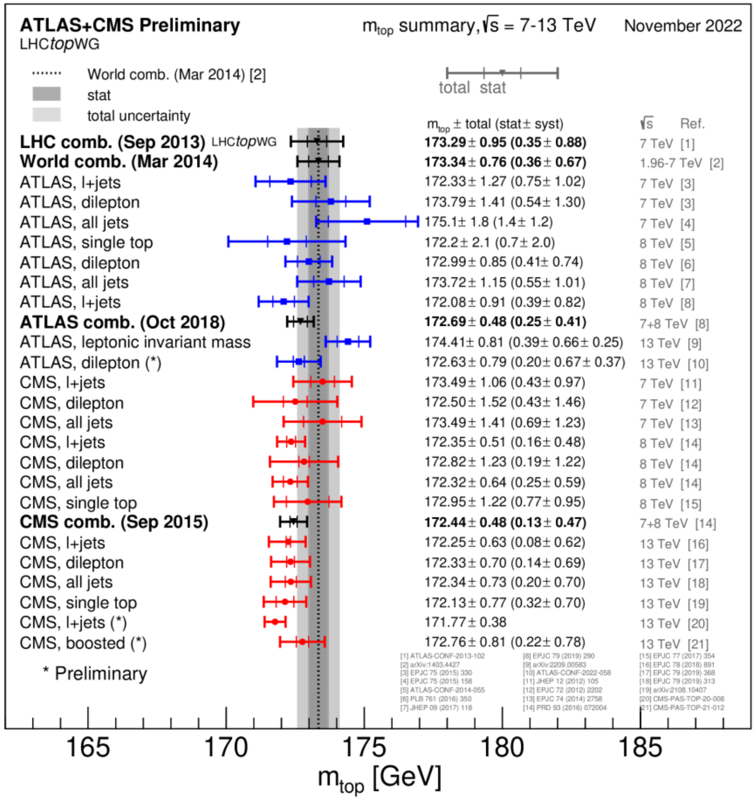
Palestine
Peru
Philippines
Poland
Portugal
Romania
Russia
Saudi Arabia
Senegal
Serbia
Slovakia
Slovenia
South Africa
South Korea
Spain
Sri Lanka
Ukraine
UAE
UK
USA
Uruguay
Uzbekistan
Venezuela
Vietnam
Zambia
Zimbabwe
Mexico
ATLAS Collaboration member nationalities
Over 5500 members of 103 nationalities
ATLAS EXPERIMENT

Introduction

- The top quark is the heaviest known elementary particle described by SM and has a mass of 172.5 GeV (similar to the mass of a gold nucleus, which contains 197 protons and neutrons)

- Due to its large mass, the predicted top quark lifetime (~ 5 x 10^{-25} s) implies that it decays before forming hadrons

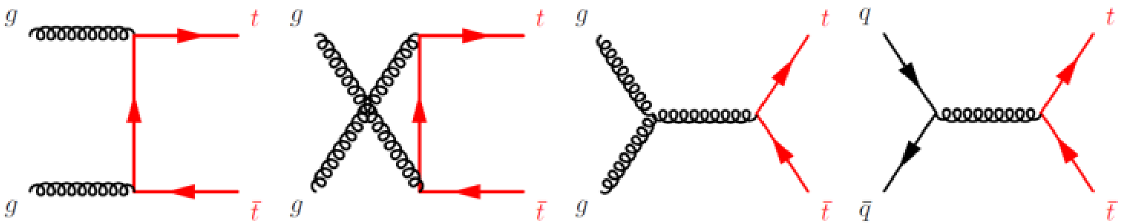
- Inclusive top-quark-pair production cross-section σ(tt) is a standard candle that allows us to test QCD predictions.

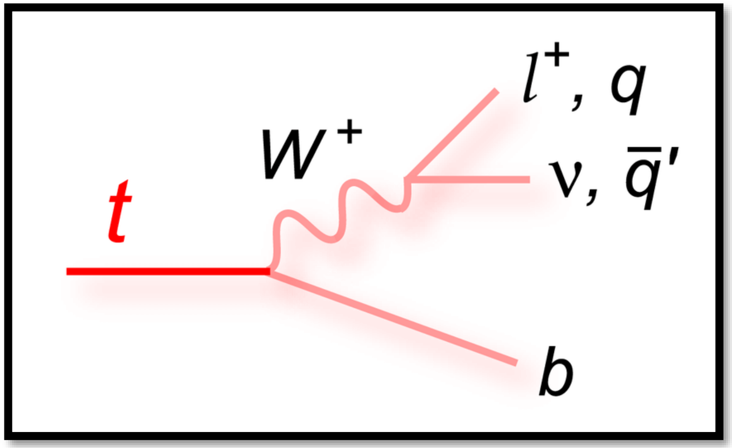


- Today will focus on two latest measurements with my direct and leading contribution as a member of the ATLAS Collaboration while **measuring the inclusive top-quark-pair production cross-section**:
  - ✓ highest precision measurement ever achieved in ATLAS
  - ✓ measurement at record centre-of-mass energy ever achieved at the LHC

The top quark production and decay

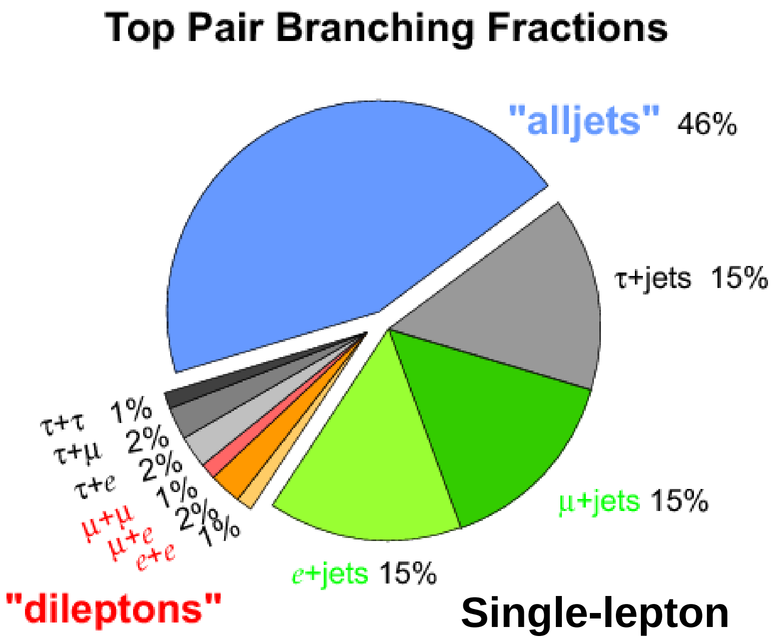
- Top quark pair production governed by strong interaction:



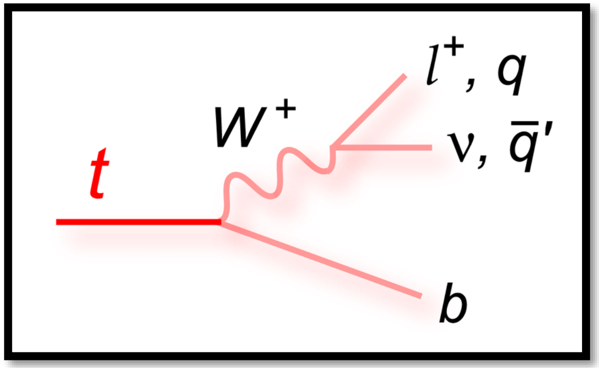


- The top quark decays almost 100% to a W-boson and b-quark (V_{tb} ~ 1), and the final state topology is given W-boson decays:

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)

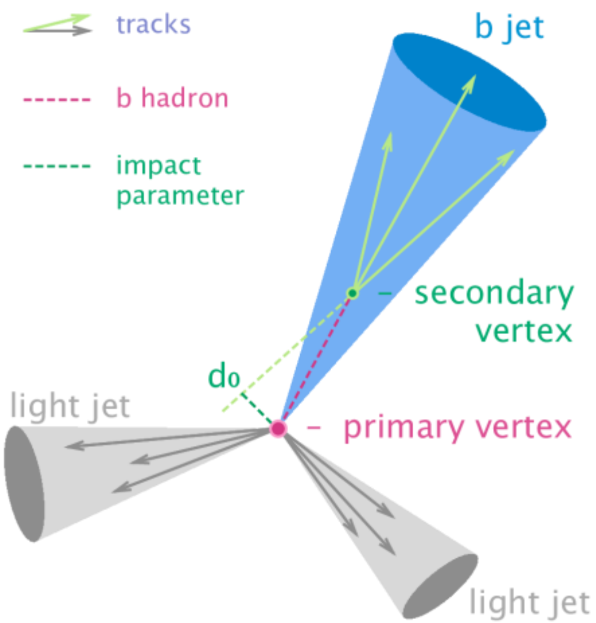


Experimental signatures of the top quark



- Very peculiar experimental signature:
  - collimated sprays of particles (jets)
  - charged leptons (electrons and muons)
  - missing transverse energy (associated to neutrinos)

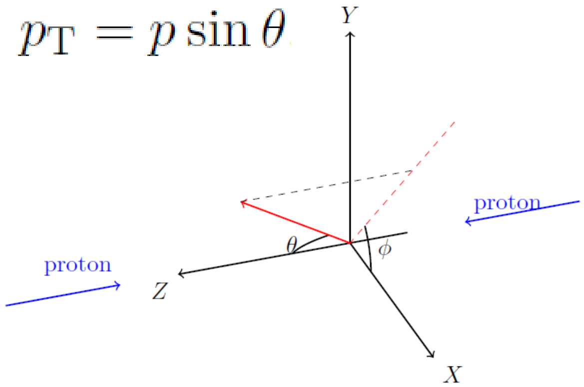
- Algorithms used to identify b-tagged jets (jets likely to contain a b-hadron)
  - The b-hadron has a long lifetime (1.5ps for B^0) and hence can travel few millimetres before decay
  - The algorithms are based on displaced vertex and jet shape information
  - Using multivariate discriminants to identify the origin of the jets: b-tagged, c-tagged and light-jets

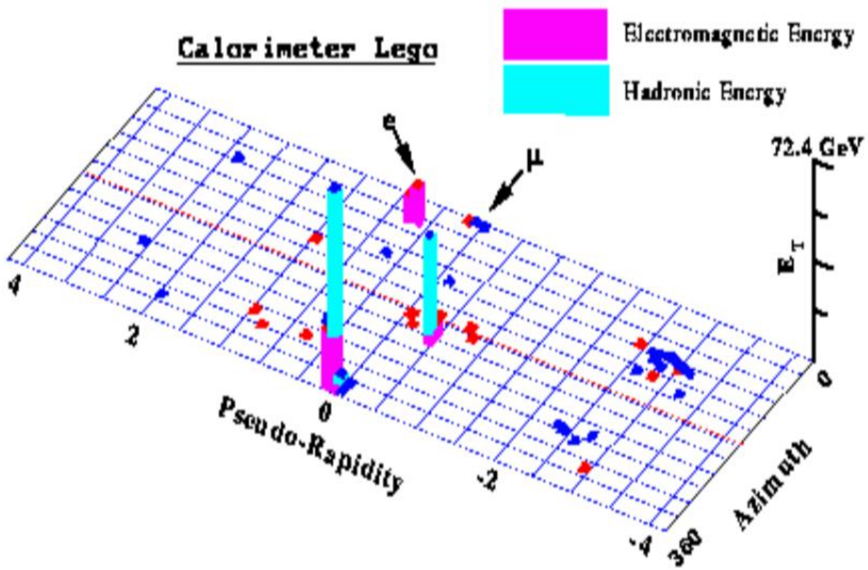


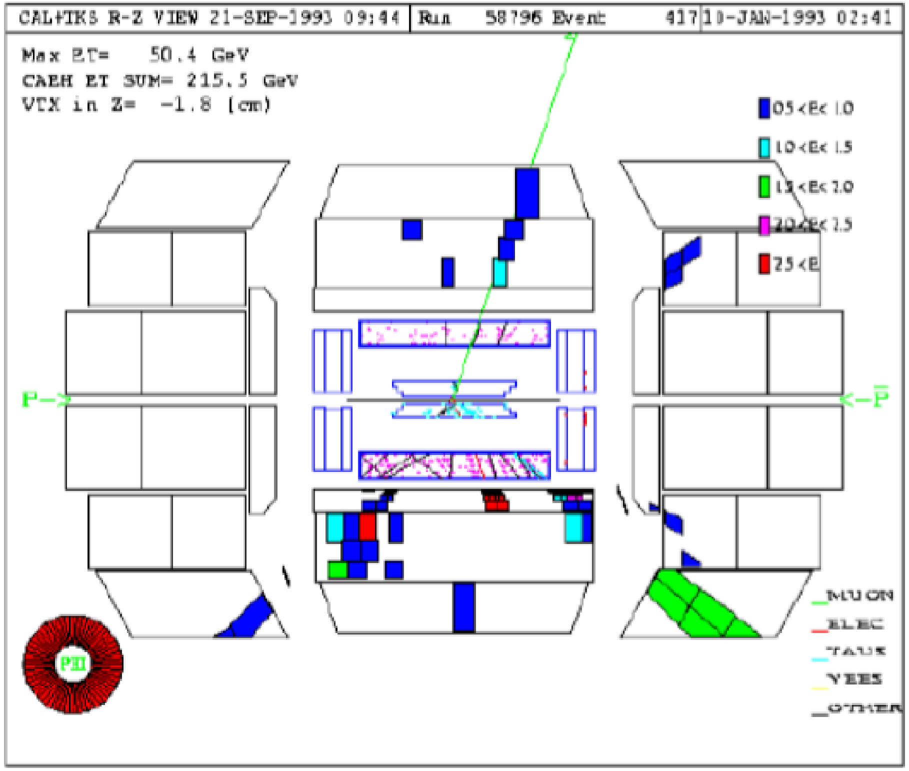
Top quark discovery at Tevatron

- 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

$$p_T = p \sin\theta$$



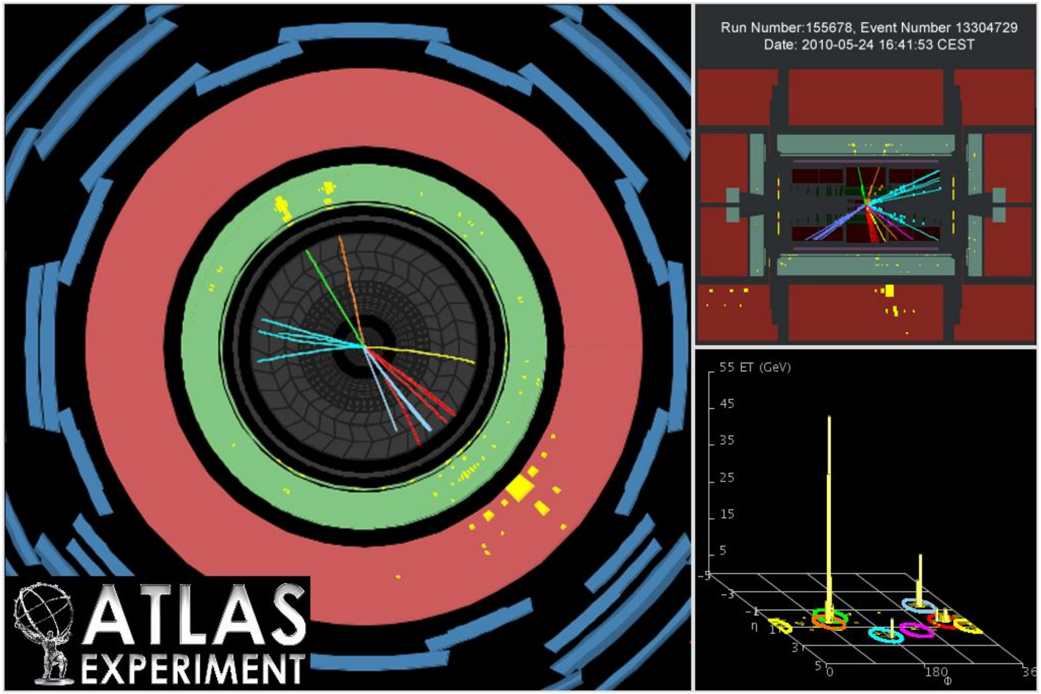


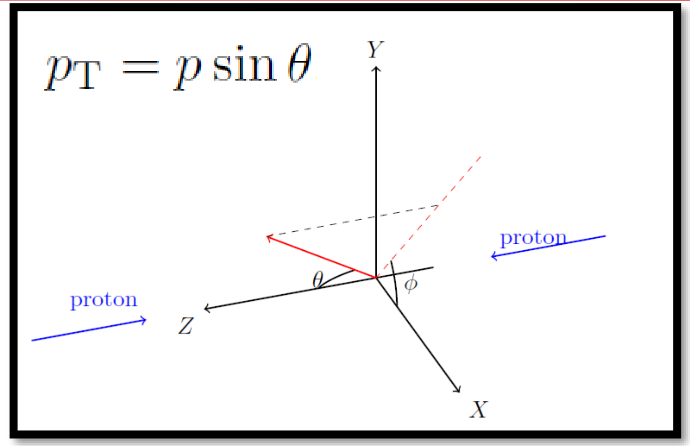


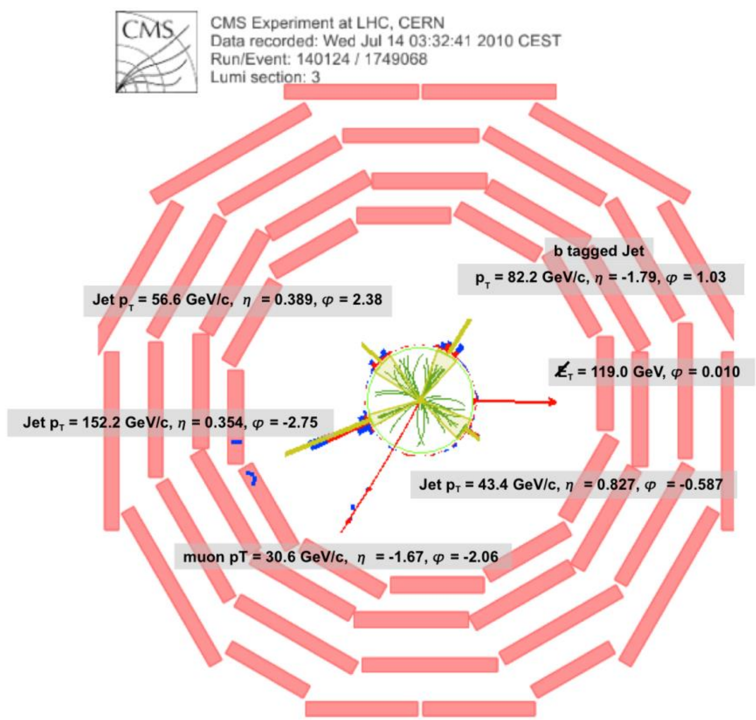
$$\eta = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = -\ln\tan\left(\frac{\theta}{2}\right)$$

Top quark re-discovery at the LHC

- First top quark pair production candidates were observed at the LHC in 2010 at √s = 7 TeV



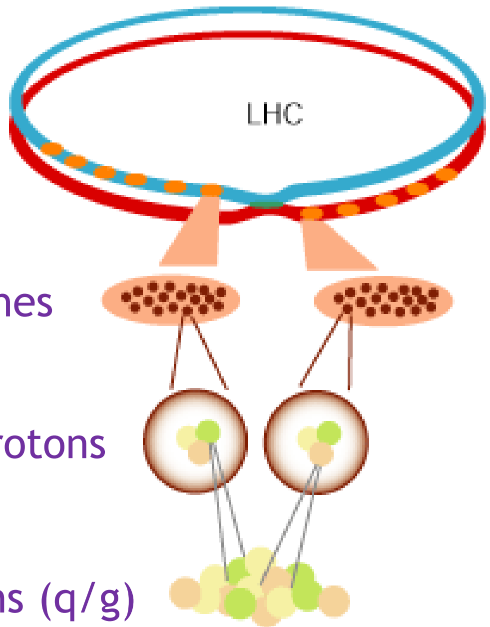




$$\eta = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = -\ln\tan\left(\frac{\theta}{2}\right)$$

Producing top quarks at the LHC

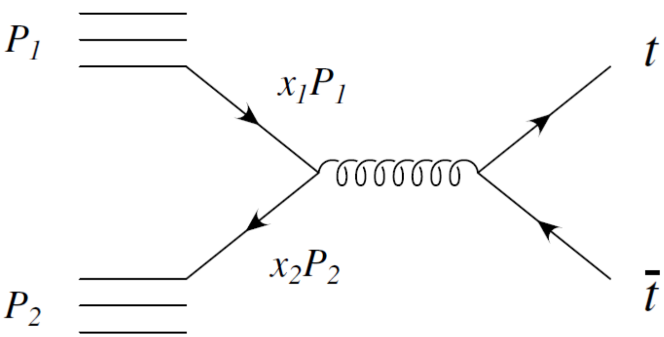
The ATLAS and CMS experiments at the LHC have accumulated millions of top quark events (~ 500 top quark pairs per minute), sustained by data from the LHCb experiment in forward regions



bunches

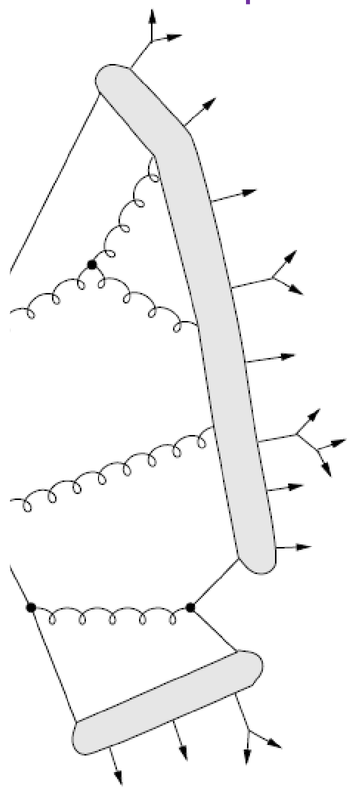
10^{11} protons

partons (q/g)

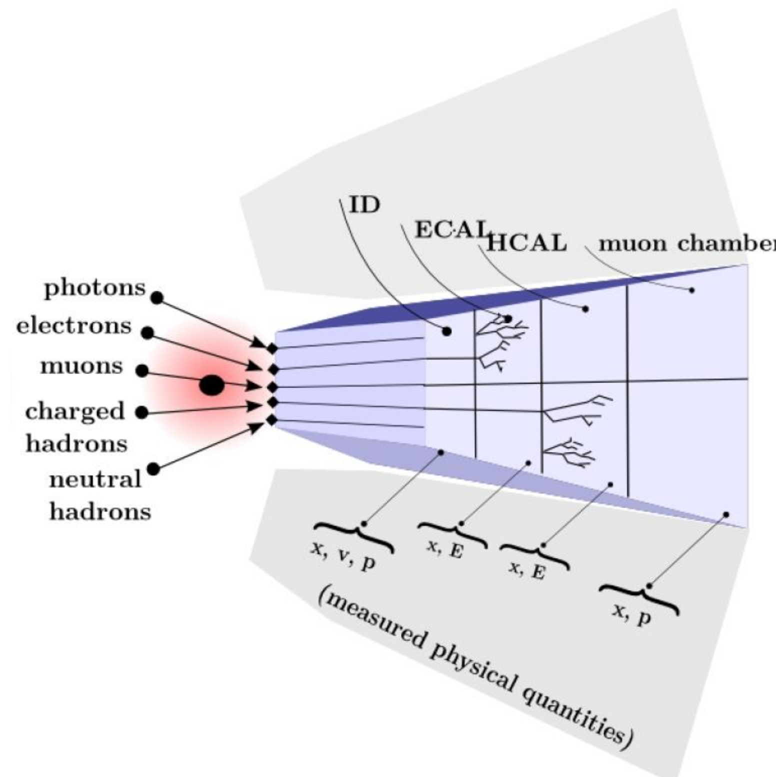


The hard interaction is described in terms of **cross-section (σ)**

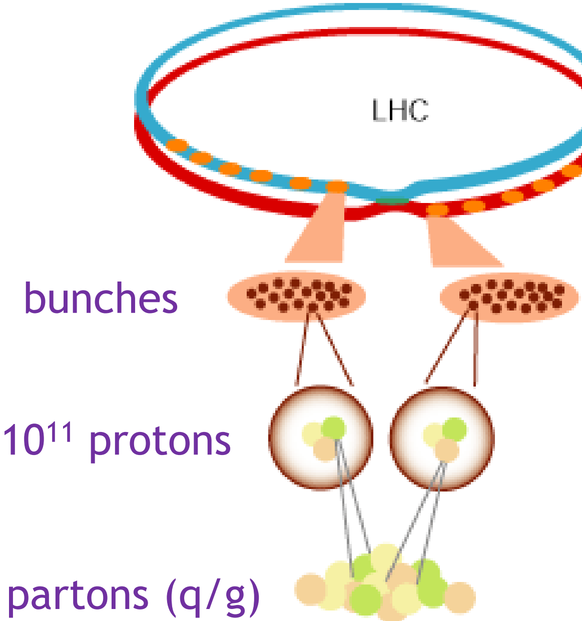
Hadronisation process

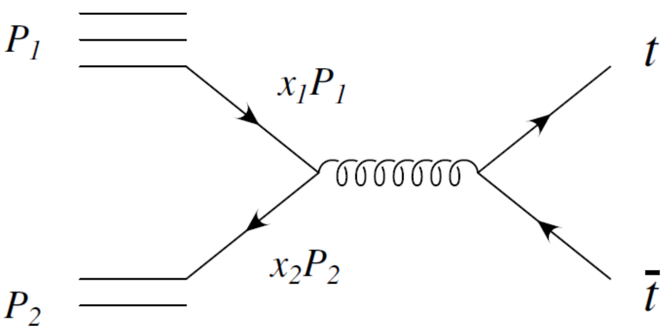


Final states are measured by different detectors



Counting top quarks at the LHC



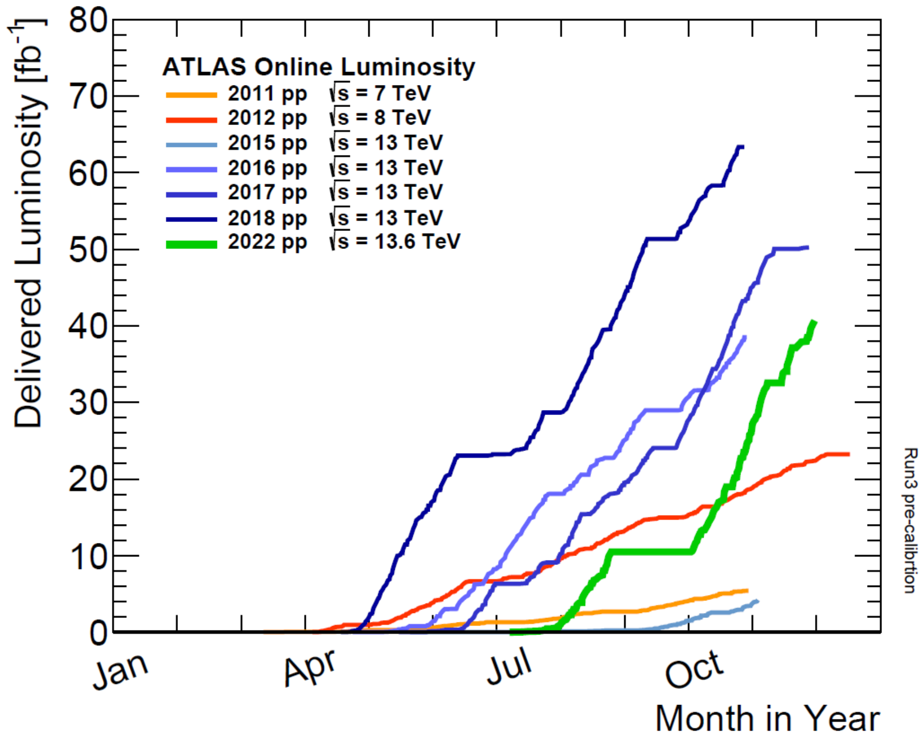


The hard interaction is described in terms of **cross-section (σ)**

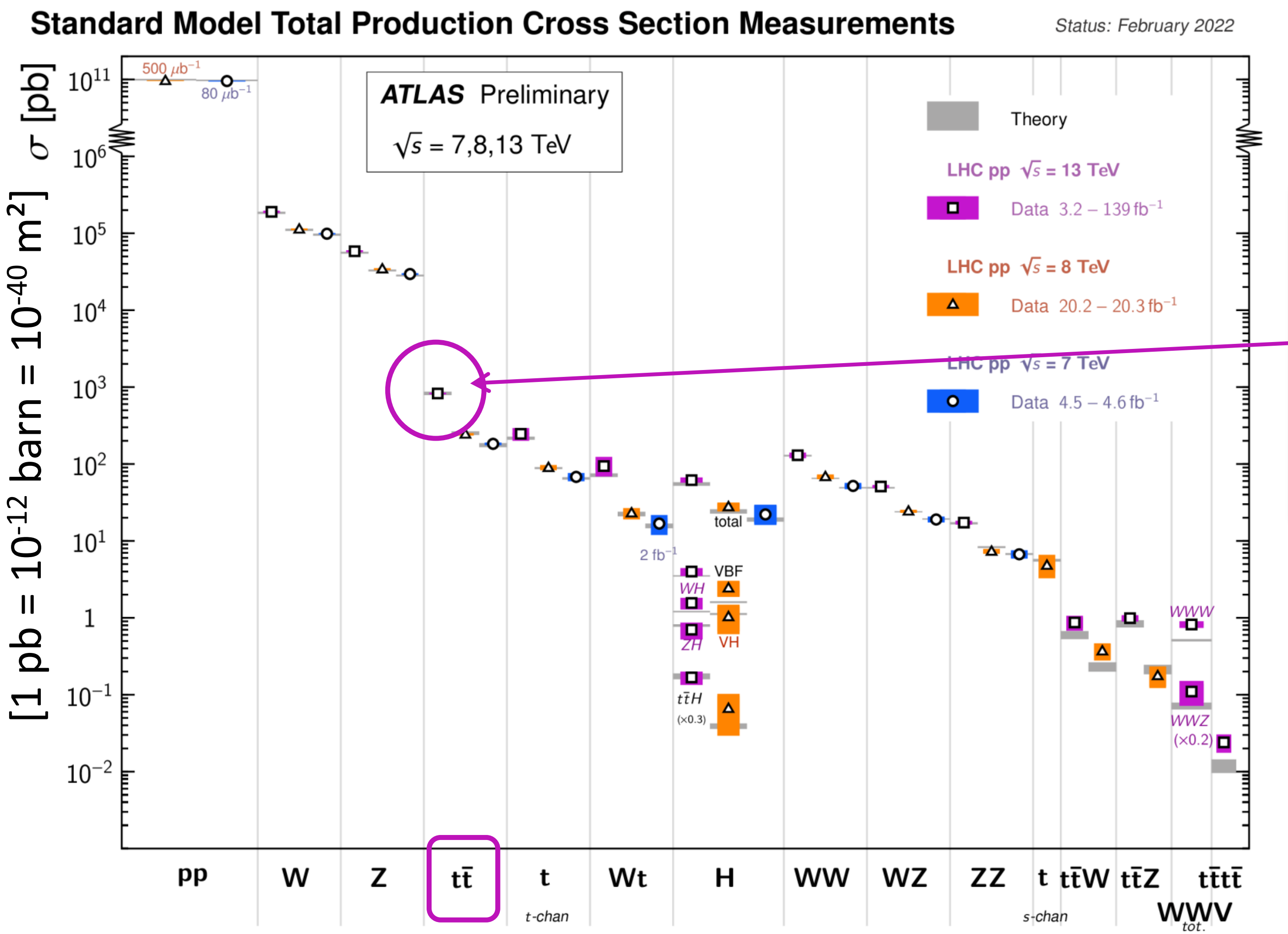
For a given process, the number of events that occur per second at the LHC is:

$$N = L\sigma$$

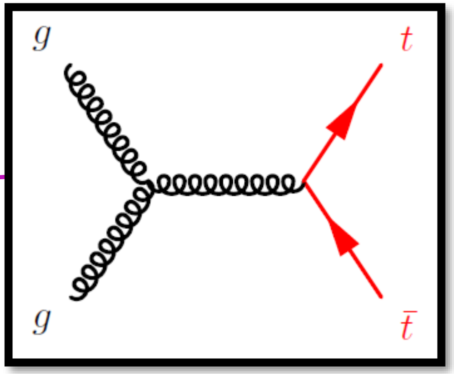
where L is the instant. luminosity (# of collisions per unit of time and transverse section of the beams)



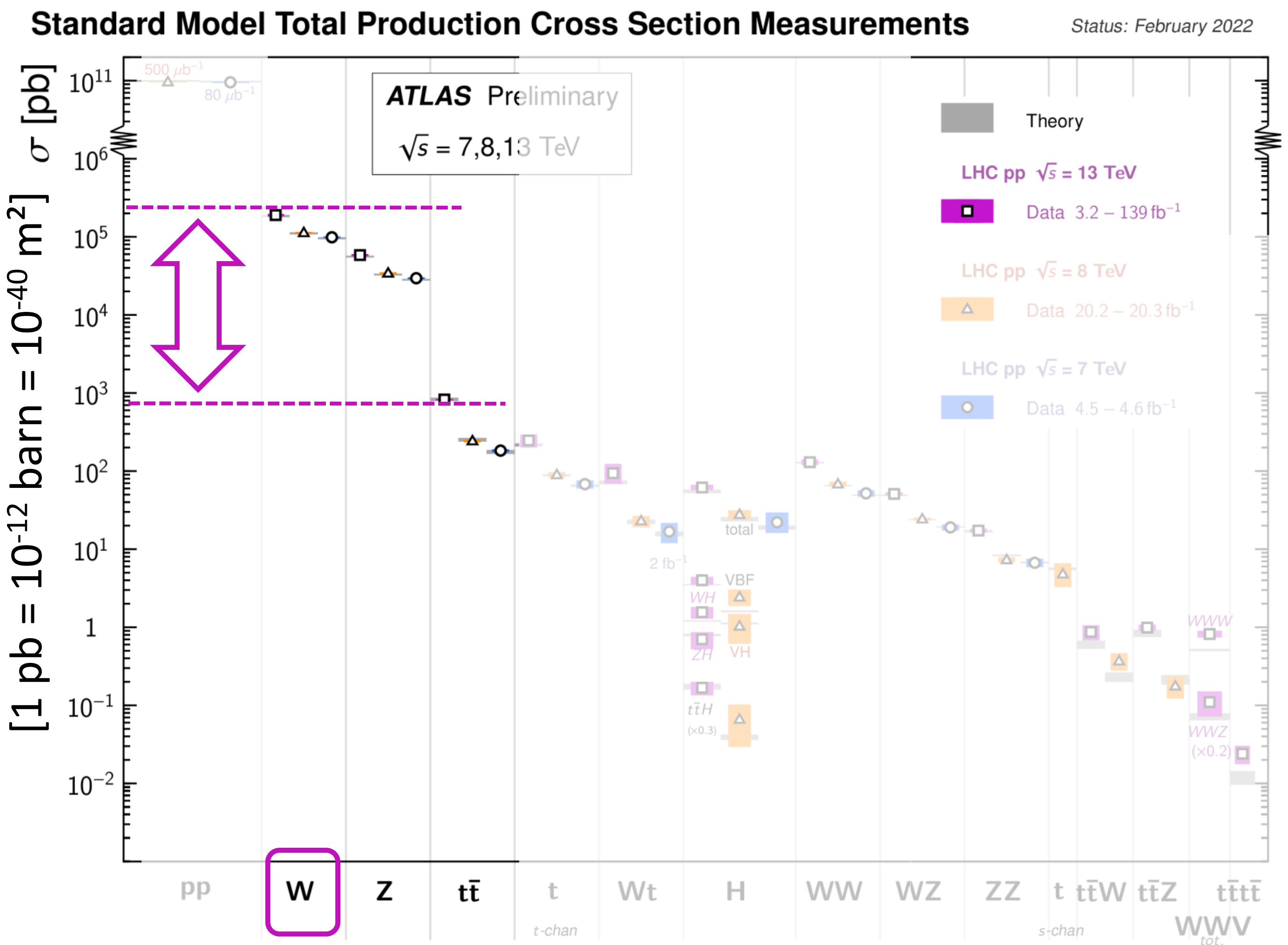
Top quark production cross-section at the LHC



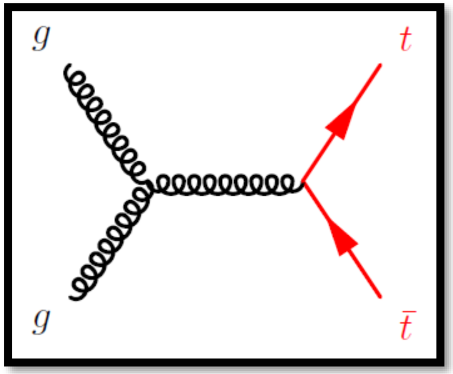
Top-quark-pair production cross-section @ 13 TeV ~800 pb

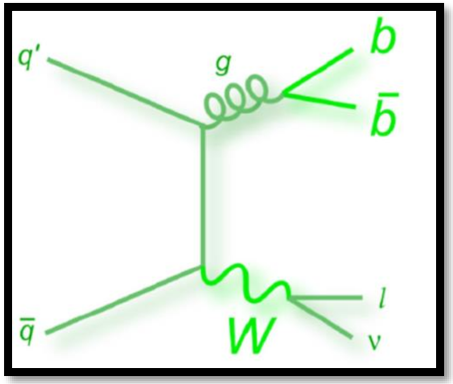


Production cross-section of the backgrounds at the LHC



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

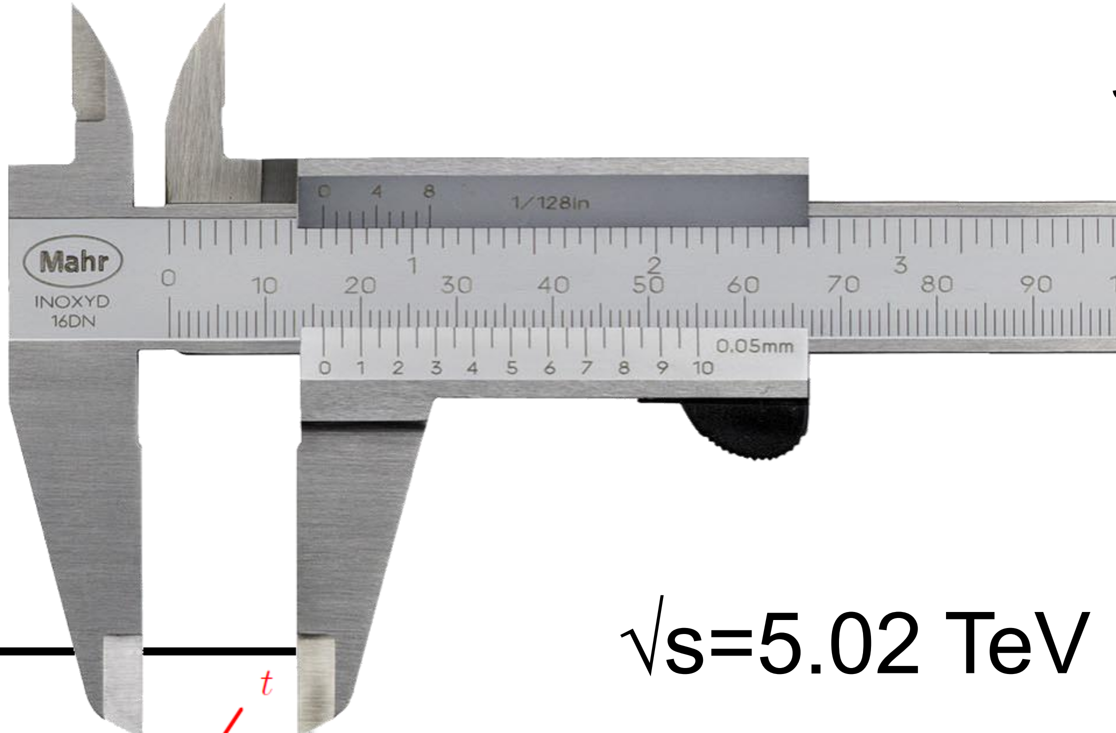


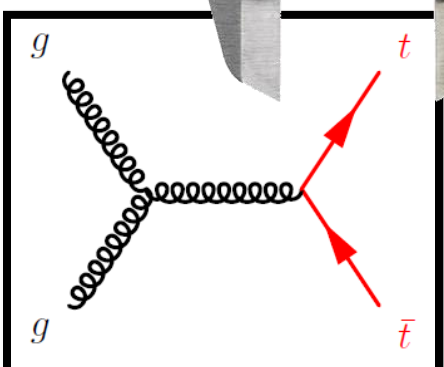


The production of a W boson in association with jets has a similar final state but a cross-section which is two orders of magnitude higher than that of top quark pairs!

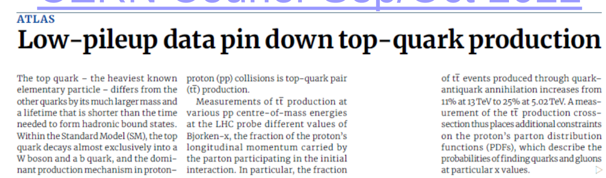
Measuring σ(ttbar) at √s=5.02 TeV with ATLAS

July 2022: arXiv:2207.01354





CERN Courier Sep/Oct 2022



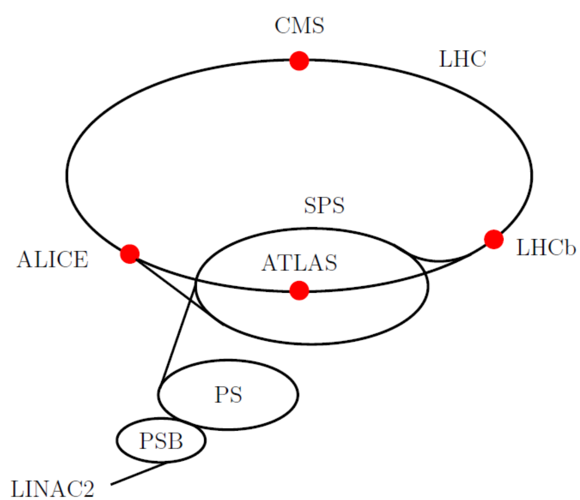
ATLAS

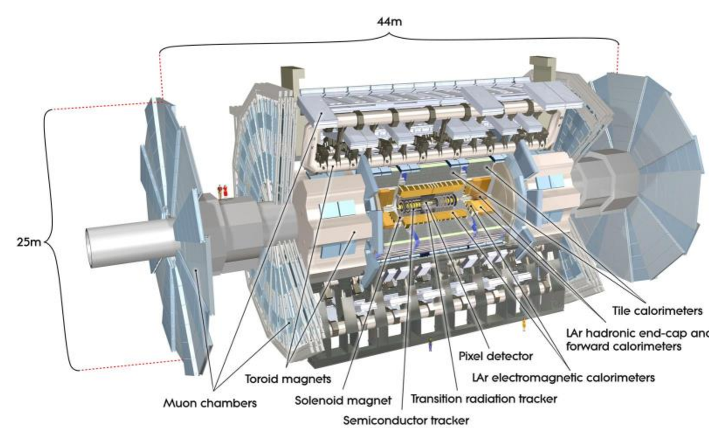
Low-pileup data pin down top-quark production

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.

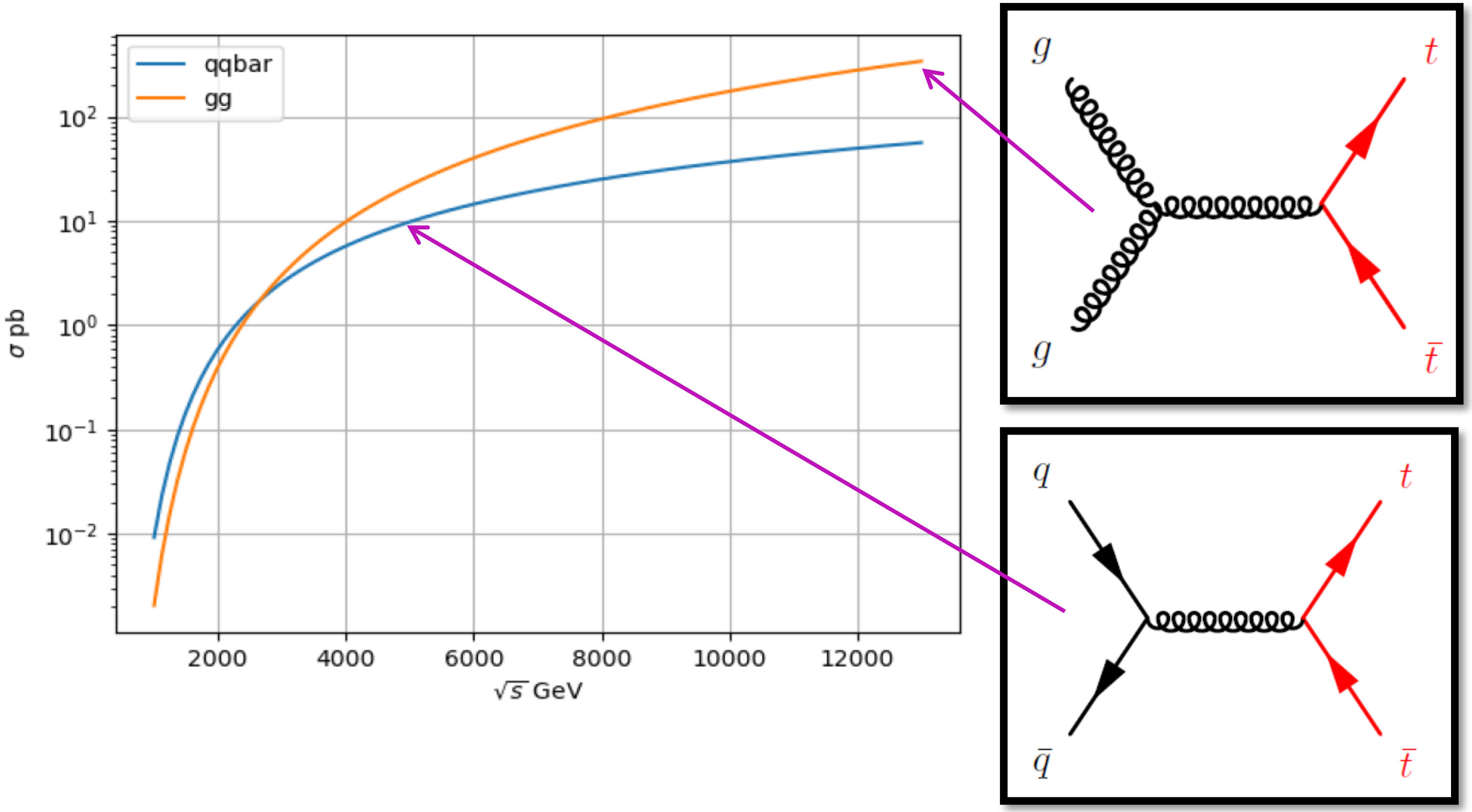
√s=5.02 TeV



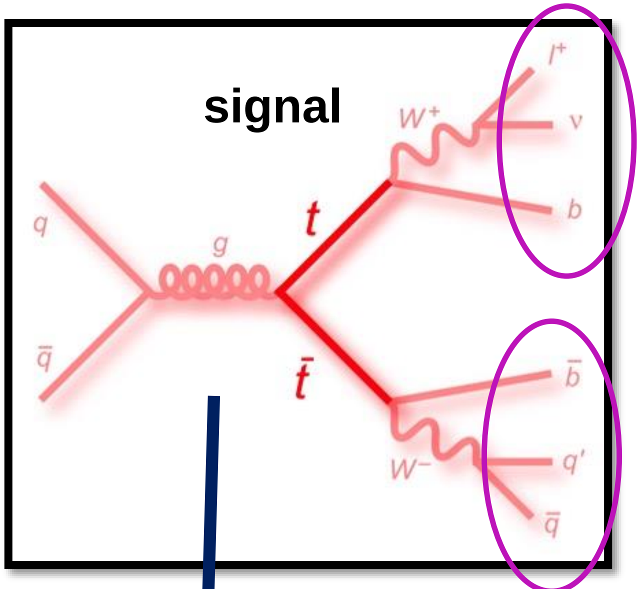


ttbar at √s=5.02 TeV: event selection

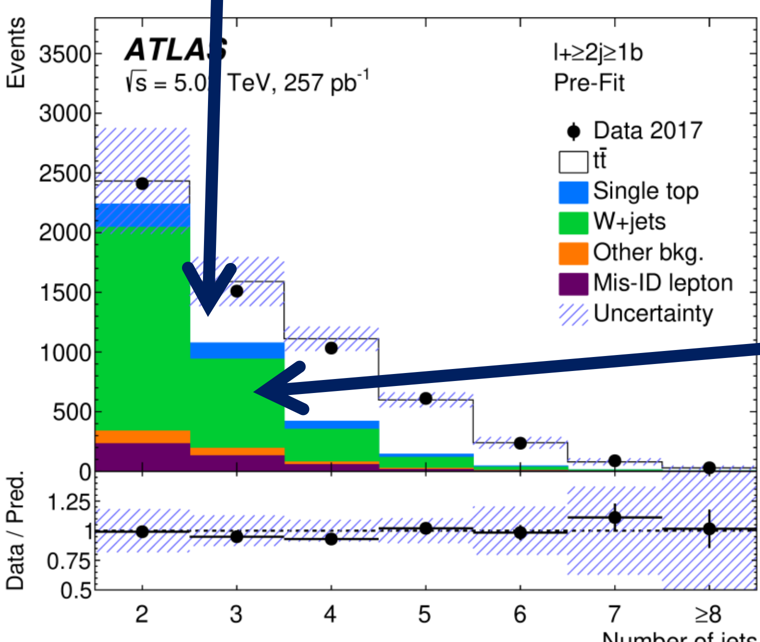
- In Nov. 2017, ATLAS recorded one week of pp collisions at √s=5.02 TeV, with the main motivation of providing a proton reference sample for the heavy-ion analyses
- Also provided a unique opportunity to study top-quark production at a previously unexplored energy in ATLAS:
  - ✓ 25% of qqbar-initiated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



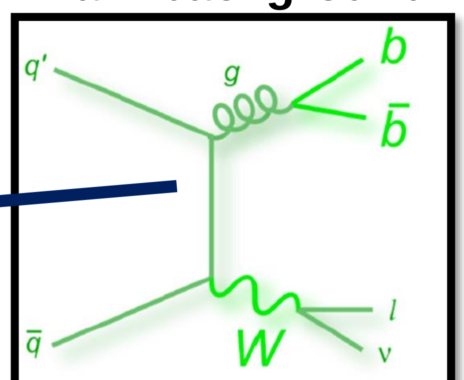
Finding top quarks in the single-lepton channel



- 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.

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

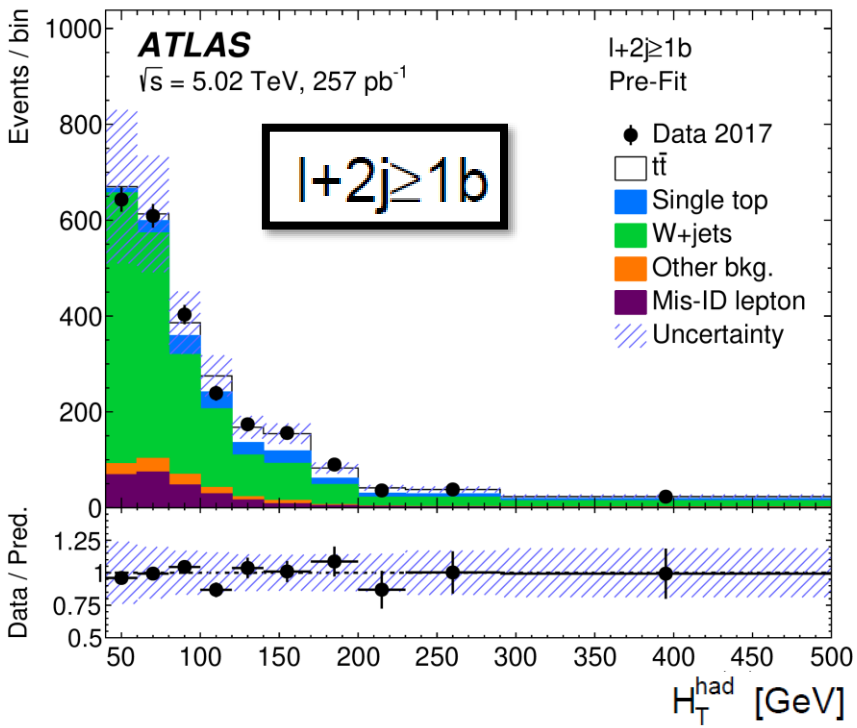
	$\ell + 2j \geq 1b$	$\ell + 3j\ 1b$	$\ell + 3j\ 2b$	$\ell + \geq 4j\ 1b$	$\ell + 4j\ 2b$	$\ell + \geq 5j\ 2b$
$t\bar{t}$	194 ± 27	310 ± 33	199 ± 24	690 ± 60	318 ± 32	380 ± 60
Single top	195 ± 22	98 ± 12	38 ± 5	67 ± 9	22 ± 4	15.9 ± 2.7
W+ jets	1700 ± 400	690 ± 210	58 ± 23	350 ± 120	30 ± 14	19 ± 10
Other 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

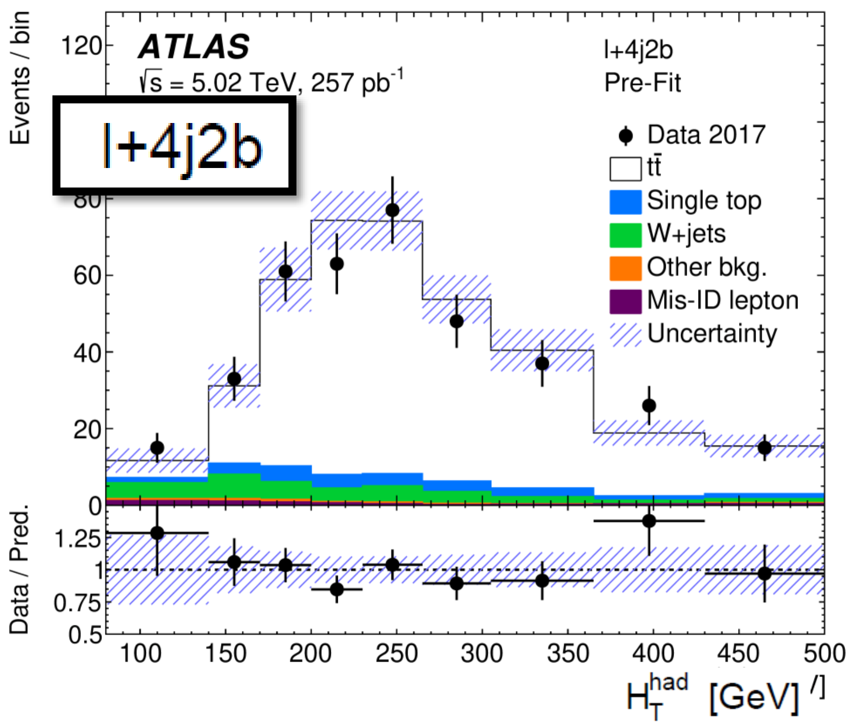
ttbar at √s=5.02 TeV: single-lepton channel

- 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

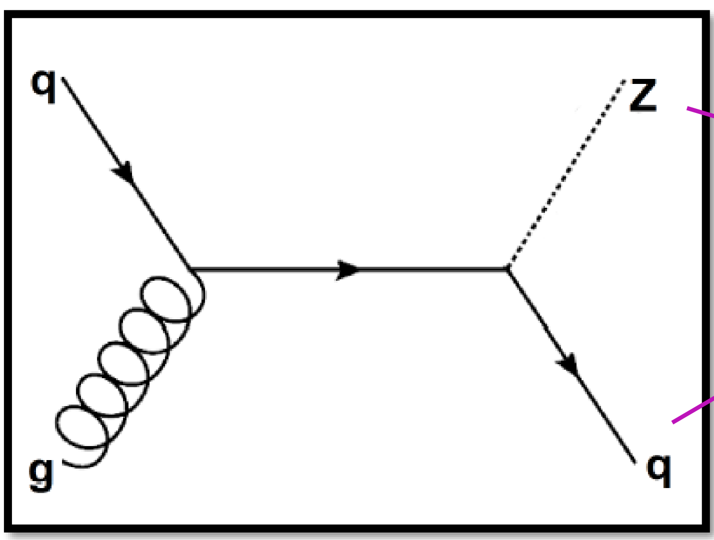
Region name	Jet multiplicity	b-jet multiplicity
ℓ+2j≥1b	2	≥ 1
ℓ+3j 1b	3	1
ℓ+3j 2b	3	2
ℓ+≥4j 1b	≥ 4	1
ℓ+4j 2b	4	2
ℓ+≥5j 2b	≥ 5	2

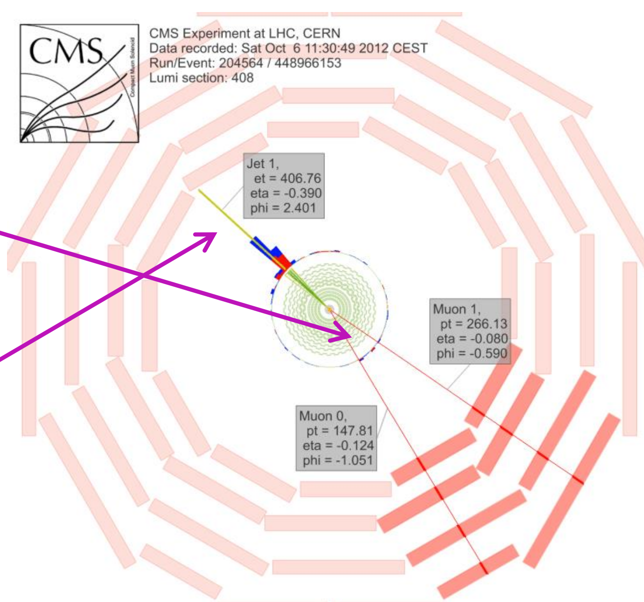




Jet re-calibration at √s=5.02 TeV

- The majority of the data was recorded with a mean number of two inelastic pp collisions per bunch crossing compared to roughly 35 collisions during 13 TeV runs.
- 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.

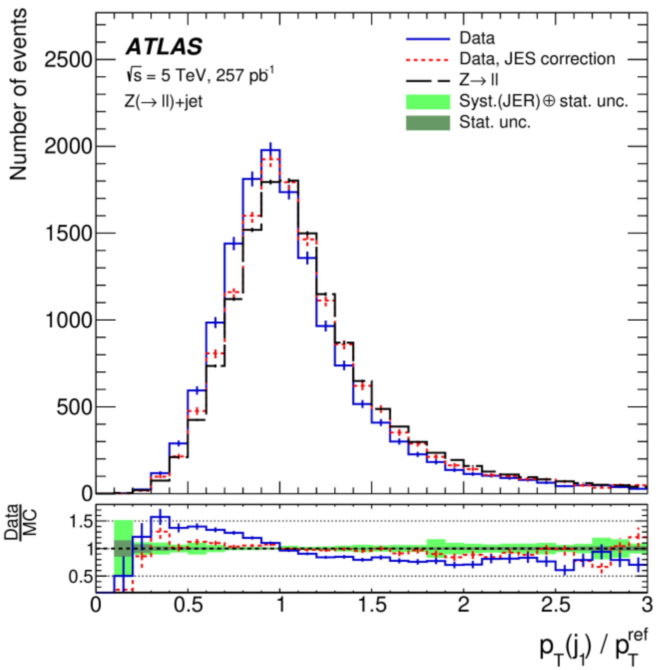


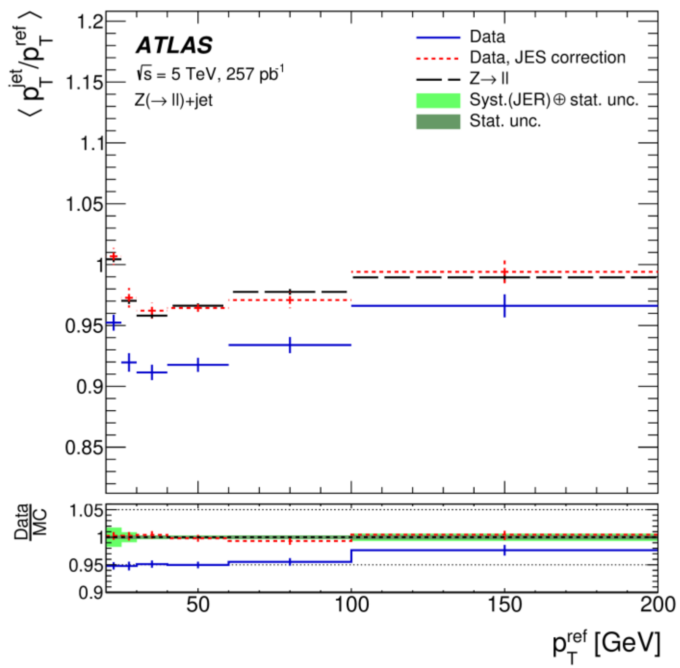


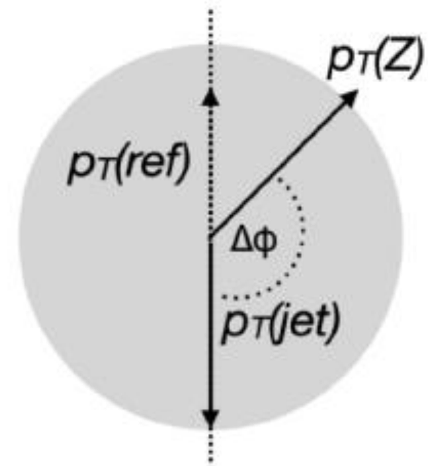
Jet re-calibration at √s=5.02 TeV

- 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 $\Delta\varphi > 2.8$)





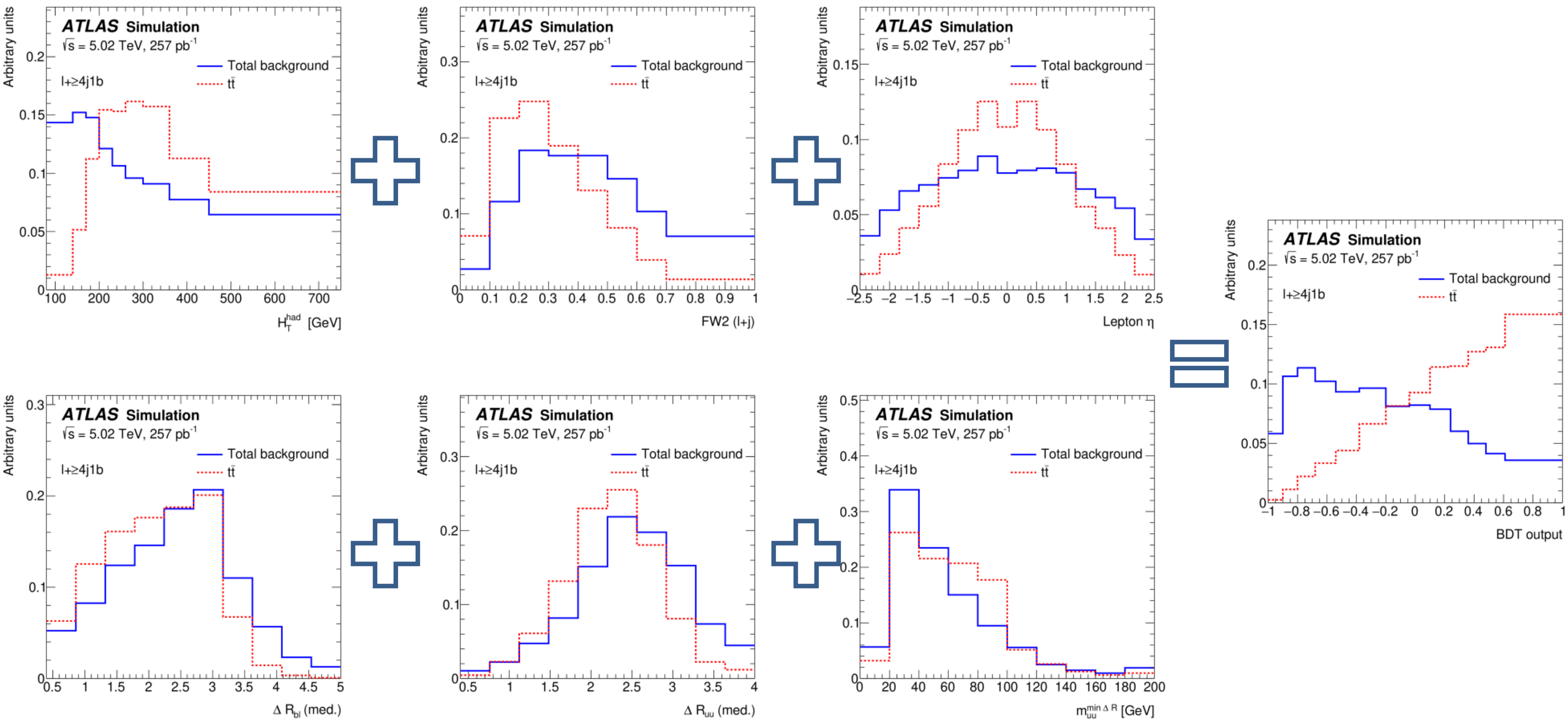


$$p_T^{ref} = p_T(Z) * |\cos \Delta\varphi(Z, j_1)|$$

- 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!

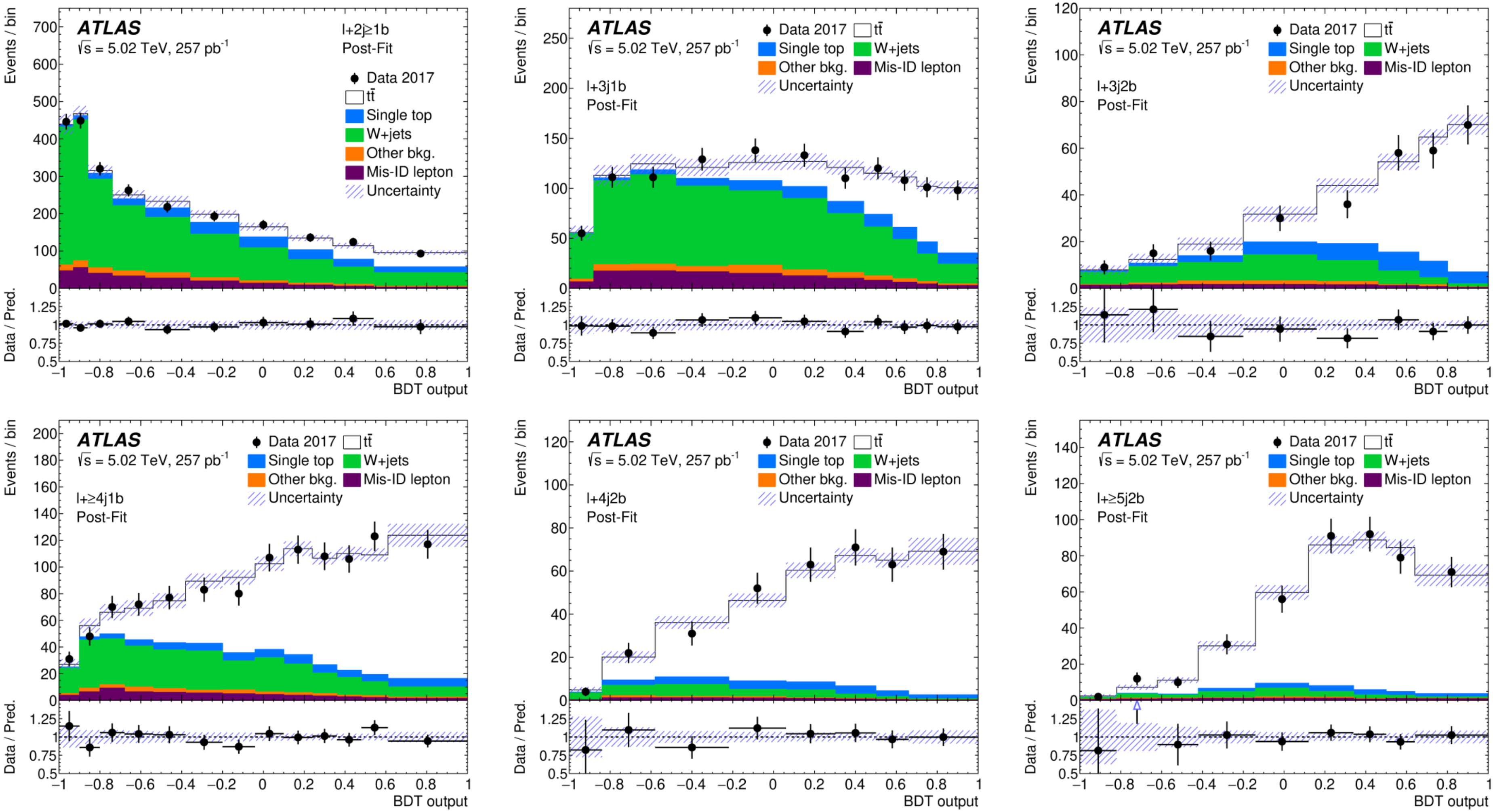
ttbar at √s=5.02 TeV: signal vs background

- 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: 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.



ttbar at √s=5.02 TeV: uncertainties

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_T^{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

- Largest uncertainties: luminosity (1.6%), signal and background modelling, object reconstruction
- Single-lepton: 4.2% total systematic uncertainty and 1.3% data statistical
- Dilepton measurement: 6.8% data statistical uncertainty
- **Combination** of both single-lepton and dilepton channels leads to a final uncertainty of just 3.9%.

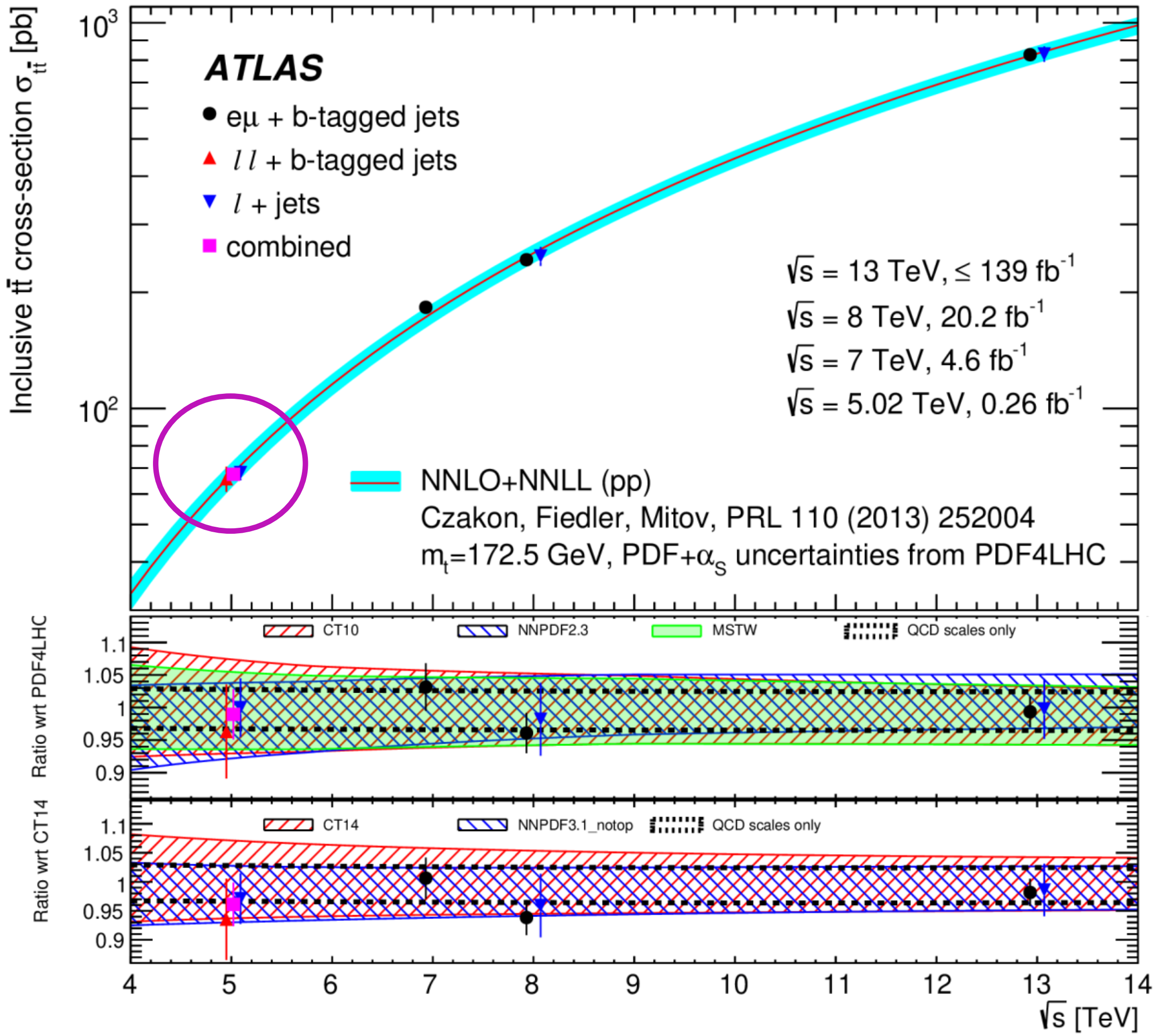
ttbar at √s=5.02 TeV: result

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

(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%)

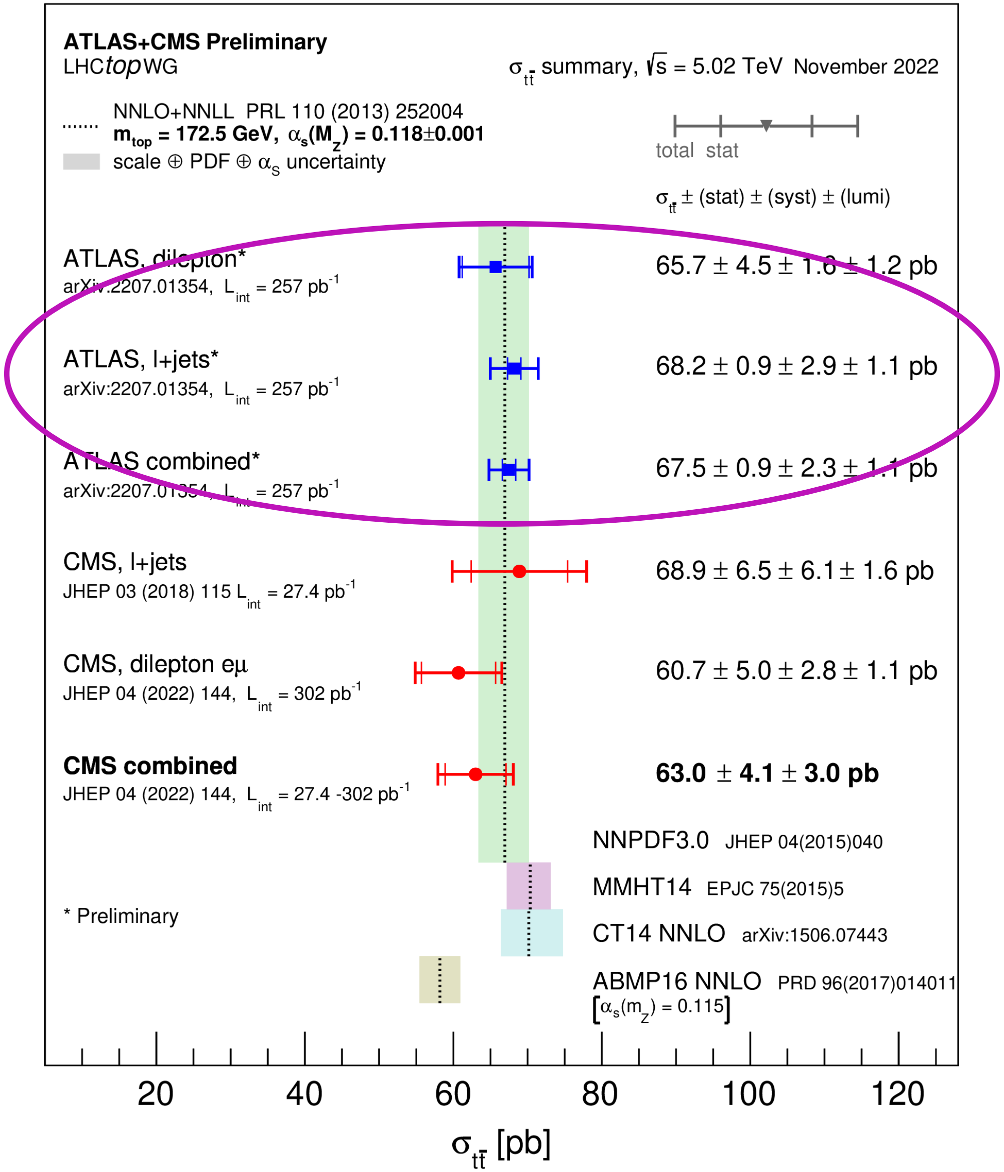
- Most precise single-lepton result in ATLAS, even more precise than the 13 TeV result that used ~500 more data



ttbar at √s=5.02 TeV: comparison with CMS

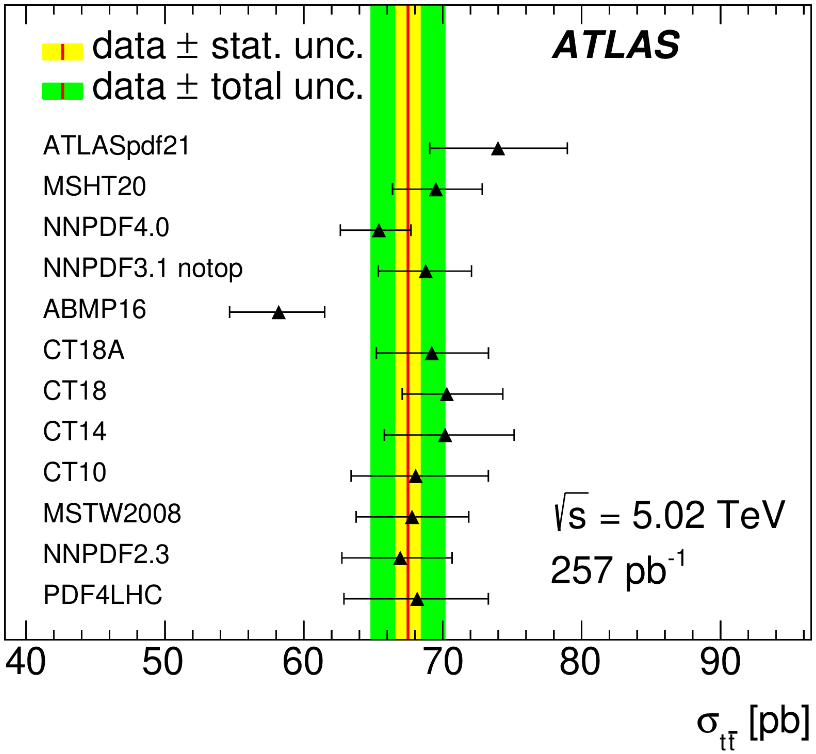
- Consistent with CMS result from combined single-lepton result using 2015 data (27.4 pb^{-1}) and dilepton using 2017 data (304 pb^{-1}) with 8% precision: σ(tt) = 63.0 ± 5.1 pb

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

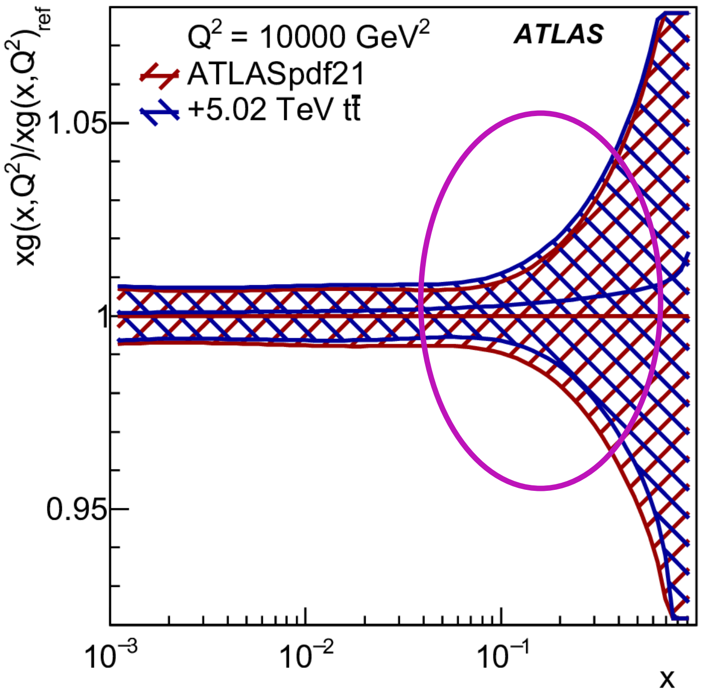


ttbar at √s=5.02 TeV: PDF reduction

- 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)

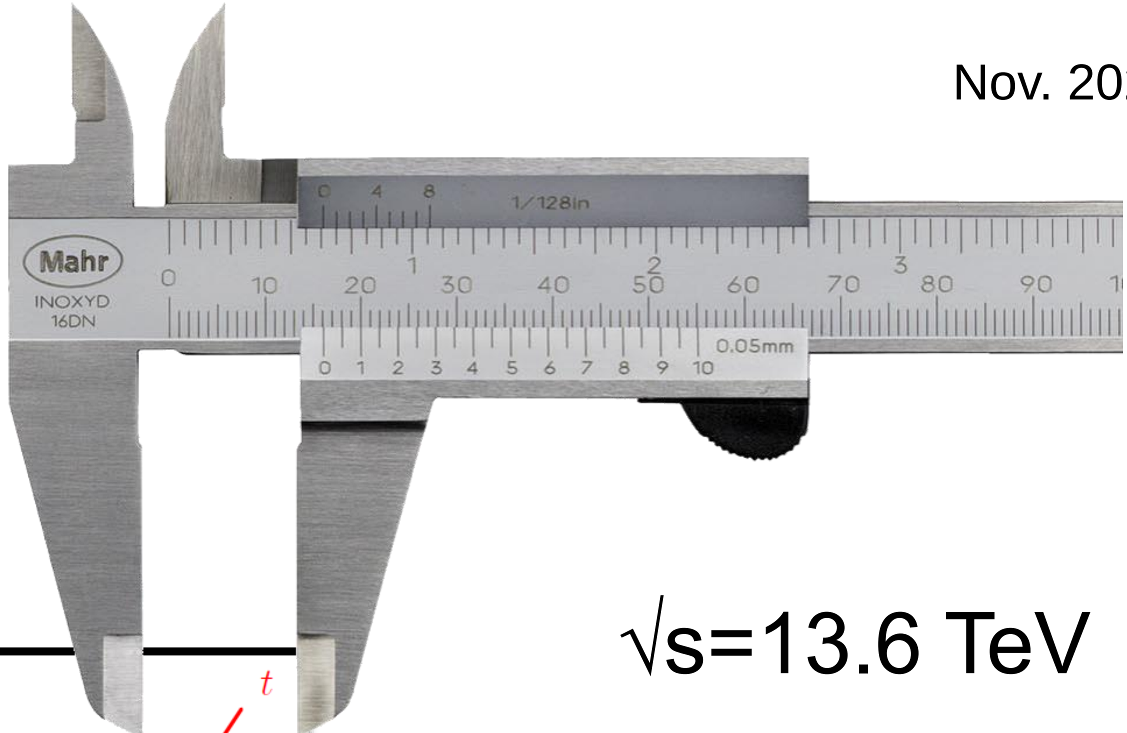


- Addition of new data shows a 5% reduction in the gluon PDF uncert. in the region of Bjorken-x of 0.1

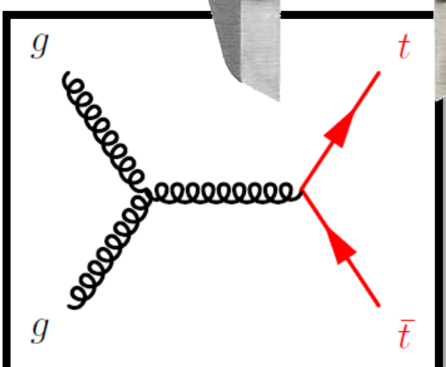


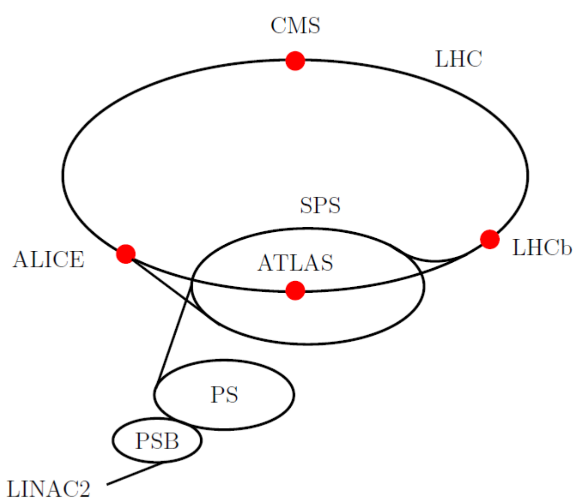
Measuring σ(Z) and σ(ttbar) at √s=13.6 TeV with ATLAS

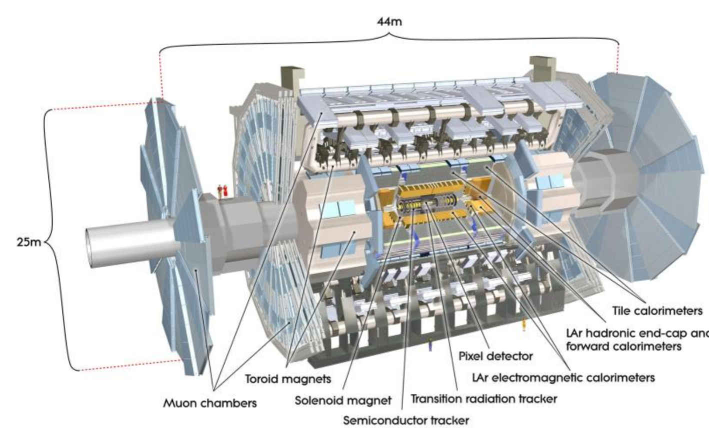
Nov. 2022: ATLAS-CONF-2022-070



√s=13.6 TeV

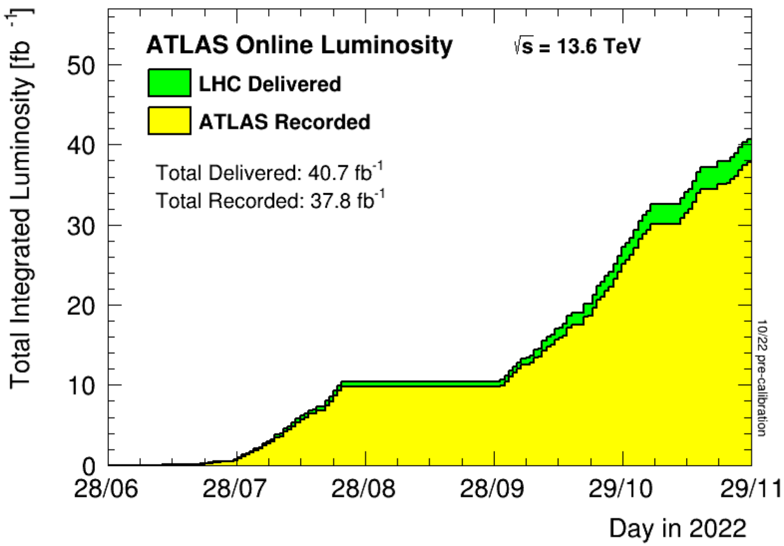


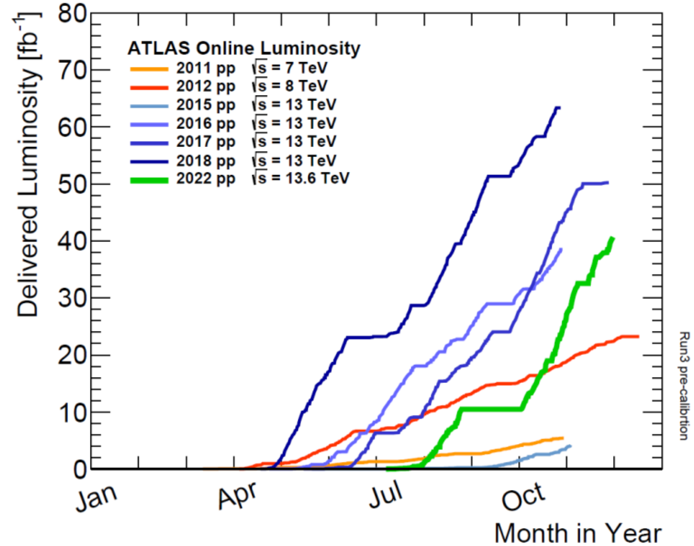




Measuring σ(Z) and σ(ttbar) at √s=13.6 TeV with ATLAS

- 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.





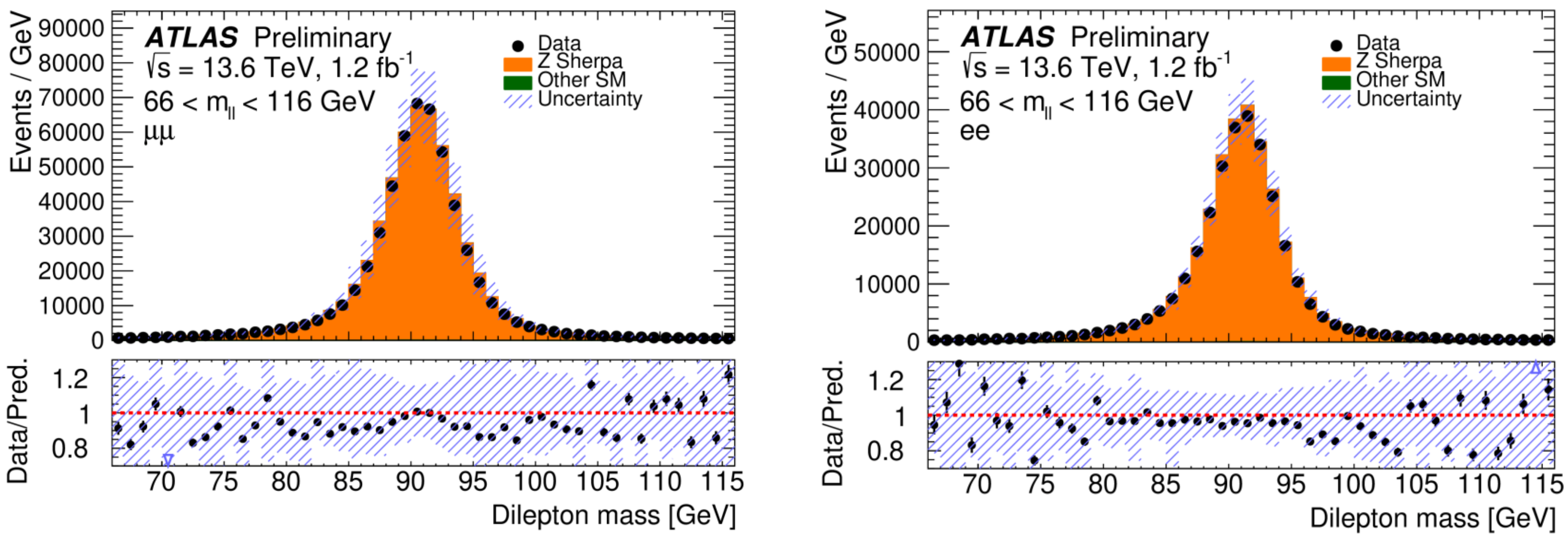
- New analysis with fresh data and noisy detector requires new strategy!

- 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

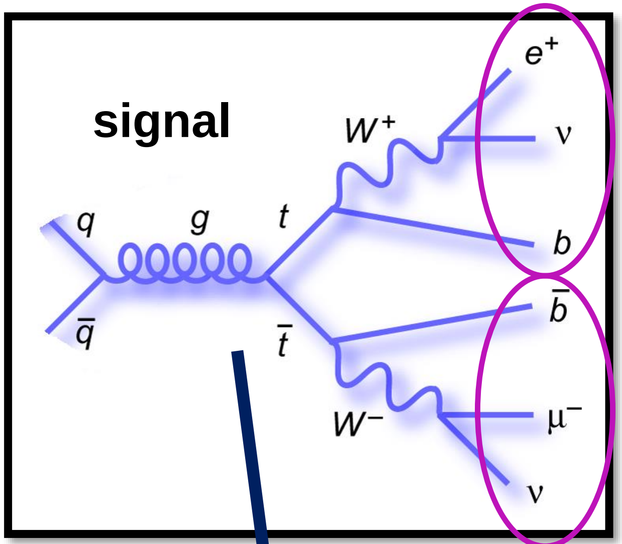
- The analysis uses very early Run 3 data (1.2 fb^{-1}) and relies on "preliminary" calibrations of the leptons, jets and luminosity - derived quickly after the first data became available.

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

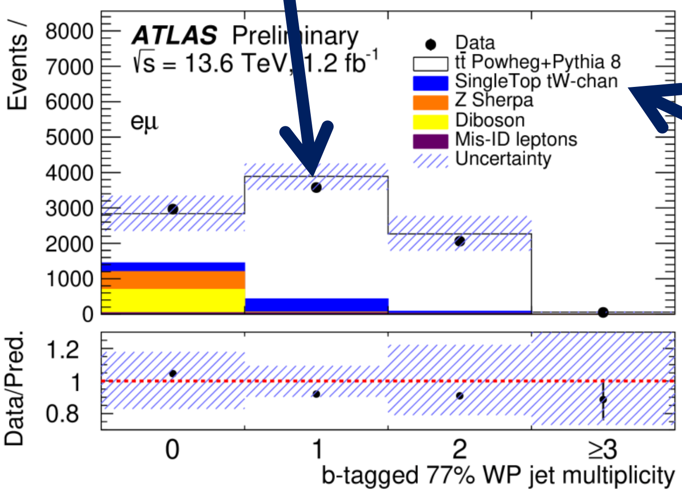


- The calibration, and corresponding uncertainties, will be improved as more data are processed - future updates will allow us to measure the cross-sections with greater precision.

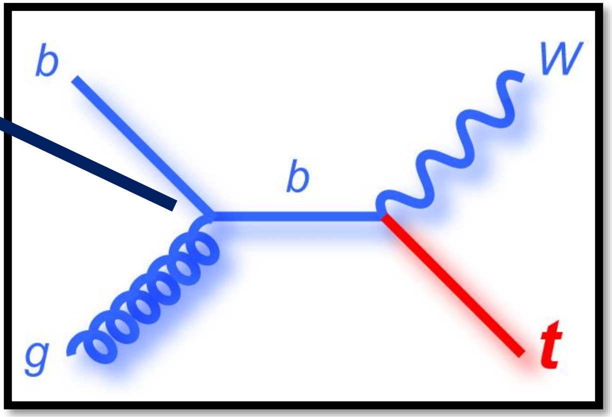
Finding top quarks in the dilepton channel



- 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.

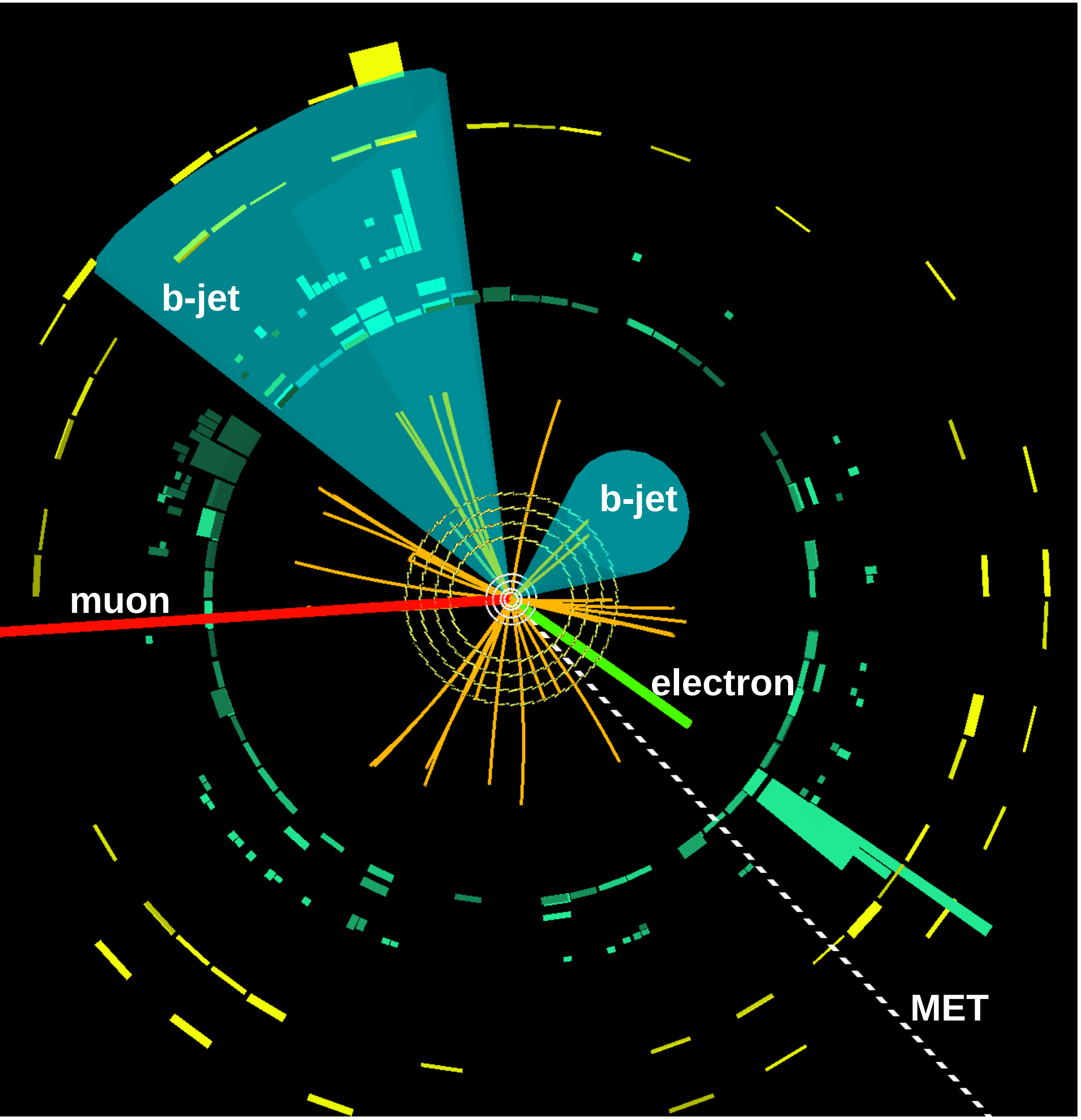


very small background



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

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.

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

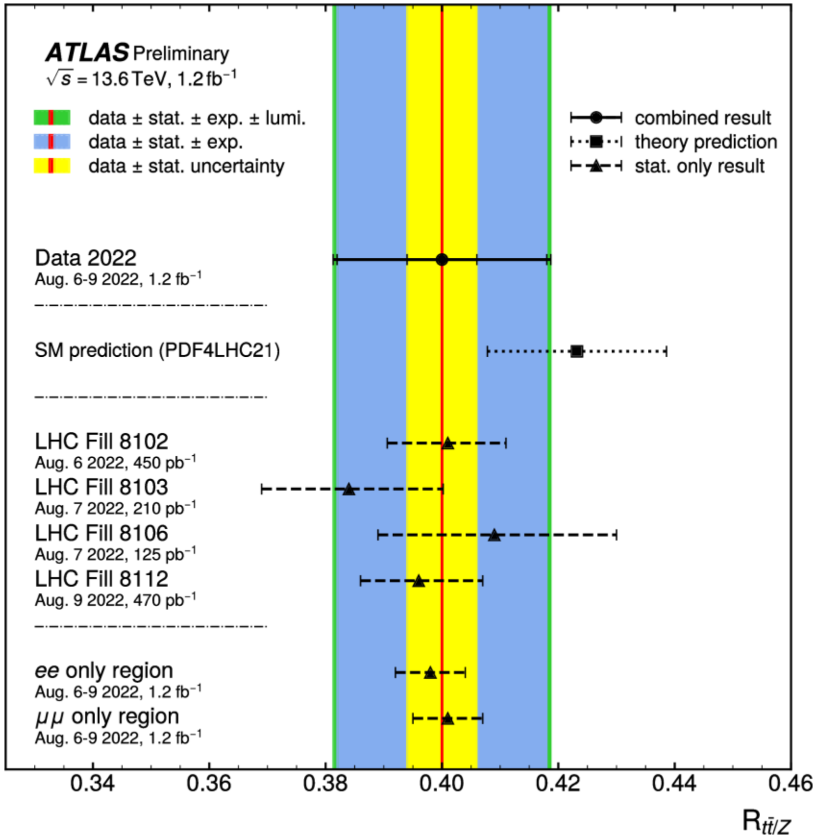
$$\sigma_{t\bar{t}} = 830 \pm 12(\text{stat.}) \pm 27(\text{syst.}) \pm 86(\text{lumi.})\text{pb}$$

(11% precision, out of which 10% uncert. on lumi)

$$\sigma_{Z\to\ell\ell}^{m_{\ell\ell}>40} = 2075 \pm 2(\text{stat.}) \pm 98(\text{syst.}) \pm 199(\text{lumi.})\text{pb}$$

(10.7% precision, out of which 10% uncert. on lumi)

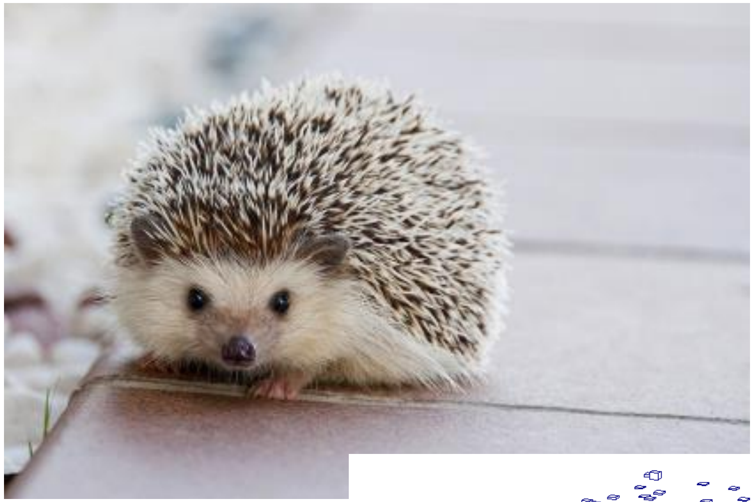
- Given that the top-quark-pair and Z-boson production dynamics are driven to a large extent by different PDFs, the ratio of these cross-sections at a given centre-of-mass energy has a significant sensitivity to the gluon-to-quark PDF ratio.
- Many systematic uncertainties, especially the uncertainty on luminosity, partially cancel out in the ratio.
- Total uncert of 4.7% for the ratio of the cross-sections, consistent with the SM.

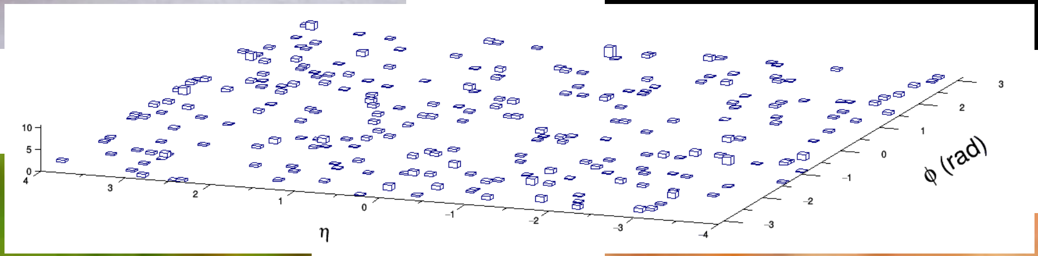


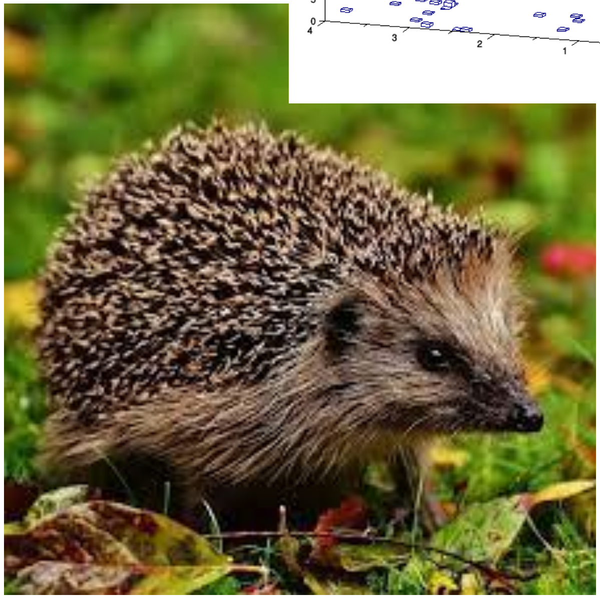
Take-home from the first part of the talk

- The LHC is a top-quark-factory with millions of top quark events accumulated (~500 top-quark-pairs produced per minute).
- Inclusive σ(tt): a standard candle at LHC, allows us to test QCD predictions and constrain parameters such as top mass, α_S and PDFs.
- Large statistics is not a guarantee of high precision - we are limited by systematic uncertainties, both experimental and theoretical.
- High precision measurements require the use of different decay channels, optimisation of the analysis strategy, application of multivariate techniques and careful assessment of systematic uncertainties through detected object calibration.
- With just a single week of data, one can obtain results even more precise than those using 3 years of data, and twice as precise as in CMS;)
- 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 good (or bad depending on your opinion): so far all the measurements are consistent with the SM prediction.

“Hedgehogs (erizos)” events at the LHC revisited







Introduction to “hedgehog” events

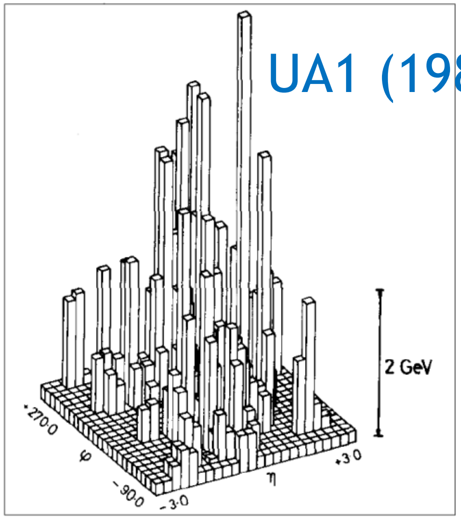
- First dedicated analysis of highest transverse energy (E_T) events seen in the UA1 detector at the SppS collider at CERN in proton-antiproton collisions at √s = 630 GeV looking for the presence of events with a very extended structure of low momentum tracks filling in a uniform way the pseudorapidity-azimuth (η-φ) phase space.

- Several isotropic events with E_T ~210 GeV in UA1 observed (even tested for top quark production), no evidence for non-QCD mechanism for these events.

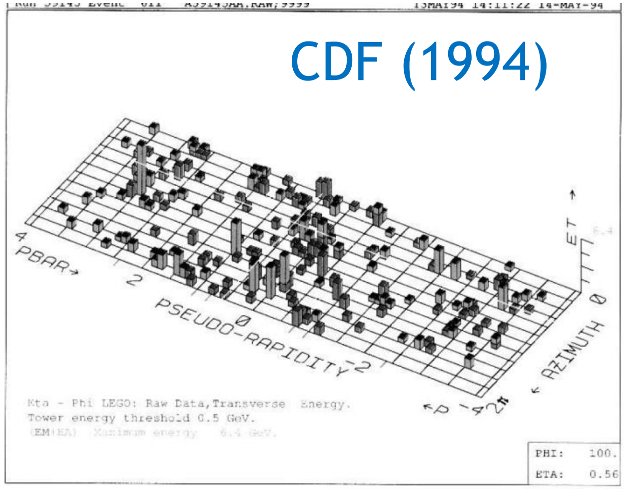
- Similar unusual events observed in p-pbar collisions at √s = 1.8 TeV by CDF’s Run 1 detector with more than 60 charged particles and E_T ~320 GeV

- Called “**hedgehog**” events by C. Quigg.

- Recently, a new event shape parameter, **flattenicity**, was proposed [A. Ortiz, G. Paic, Rev. Mex. Fis. Suppl. 3 (2022) 4, 040911] that allows one to identify and characterise these events.



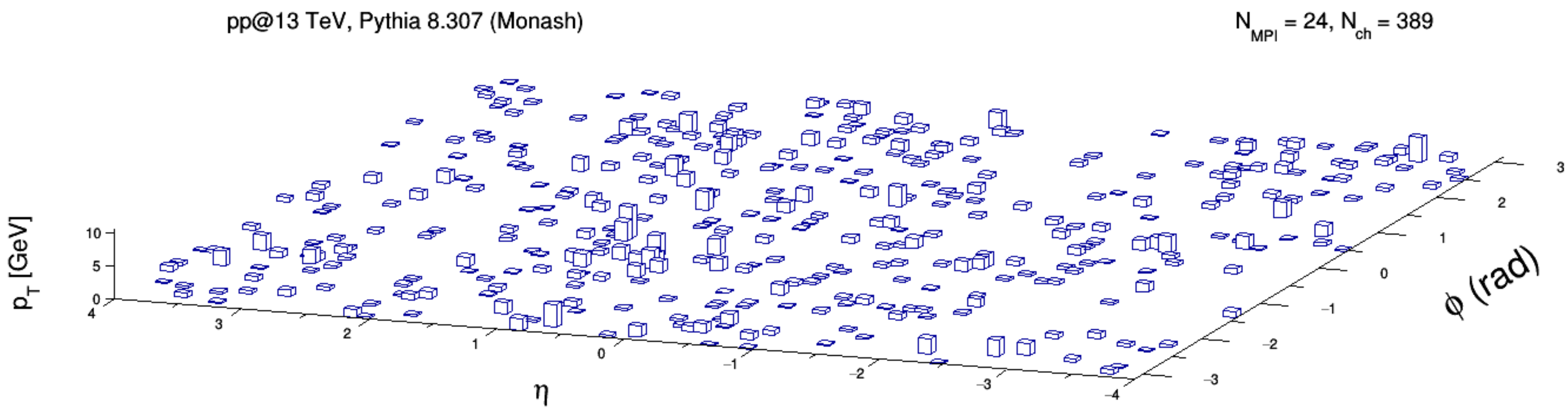
UA1 Collaboration, Zeit. für Phys. C, V. 36, p. 33 (1987)



C. Quigg, Il Nuovo Cimento, V. 33C, N. 5 p. 327 (2010)

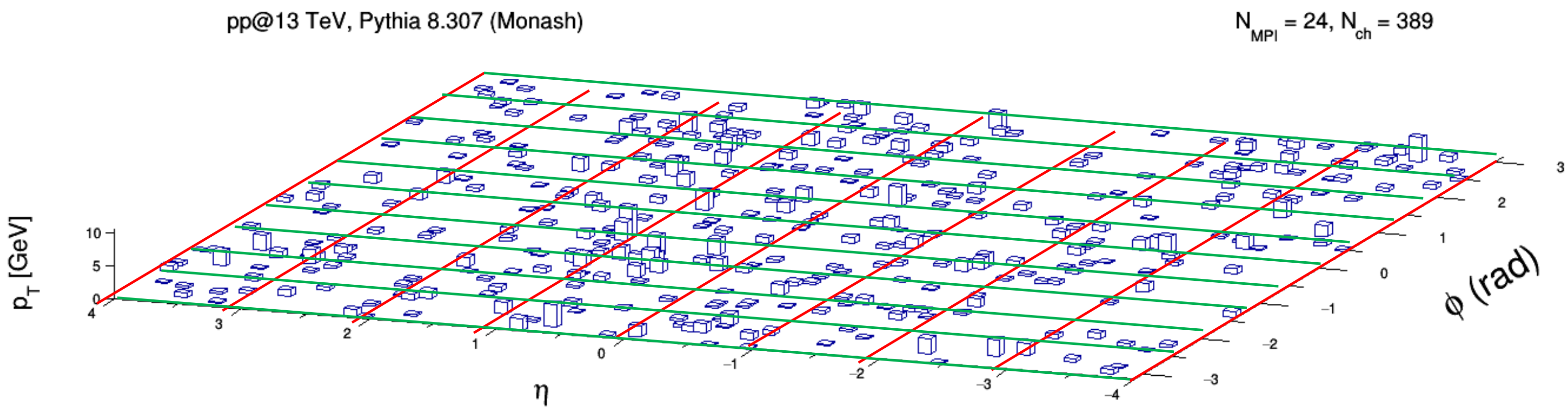
Calculating flattenicity

- The idea: find out how uniform the p_T of tracks is distributed in a given event!



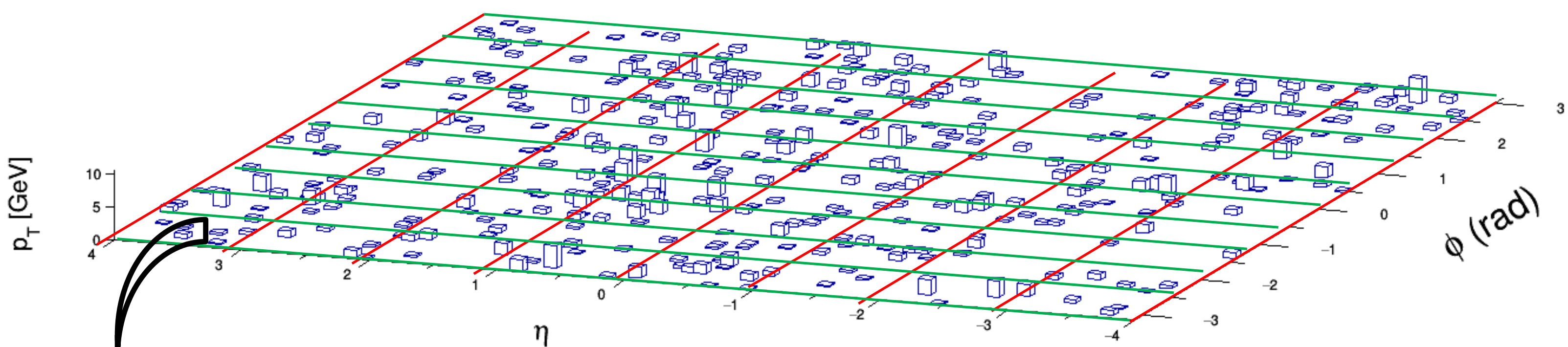
Calculating flattenicity

- Build 8 x 10 grid in (η-φ) space:

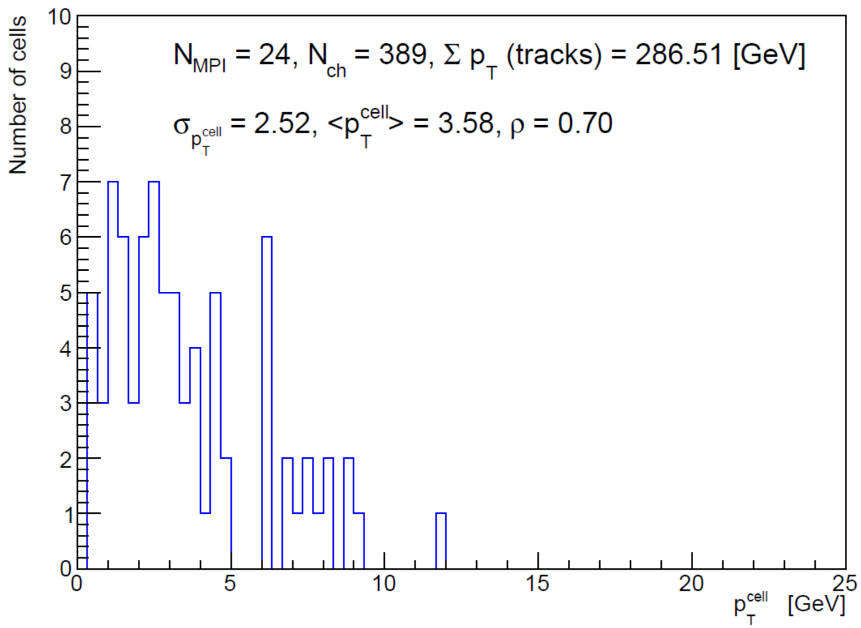


Calculating flattenicity

- Build **8** x **10** grid in (η-φ) space:

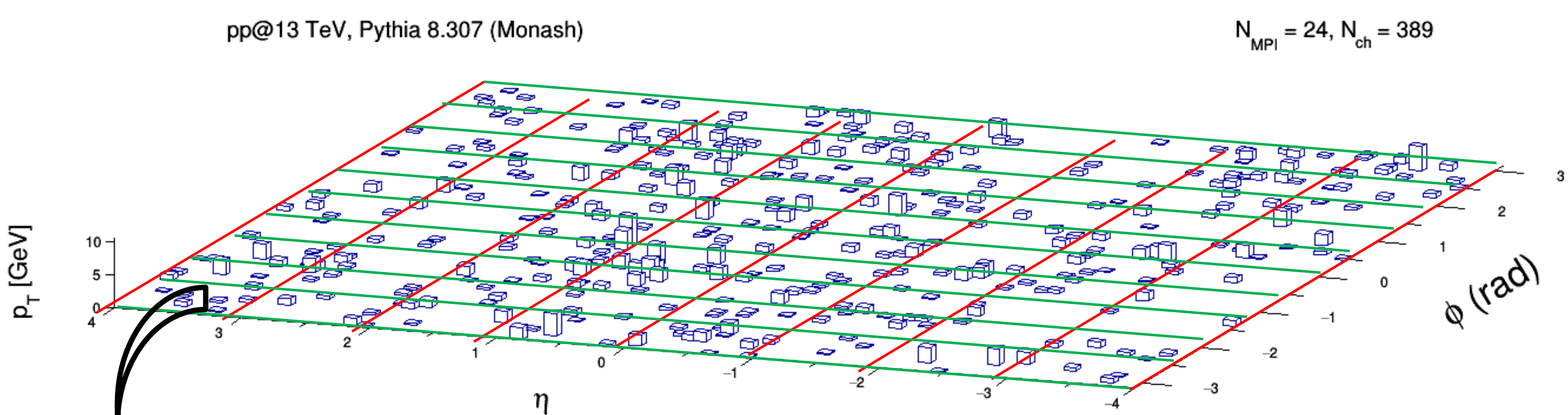


In each cell, the average transverse momentum is calculated: $p_{\mathrm{T}}^{\mathrm{cell}}$



Calculating flattenicity

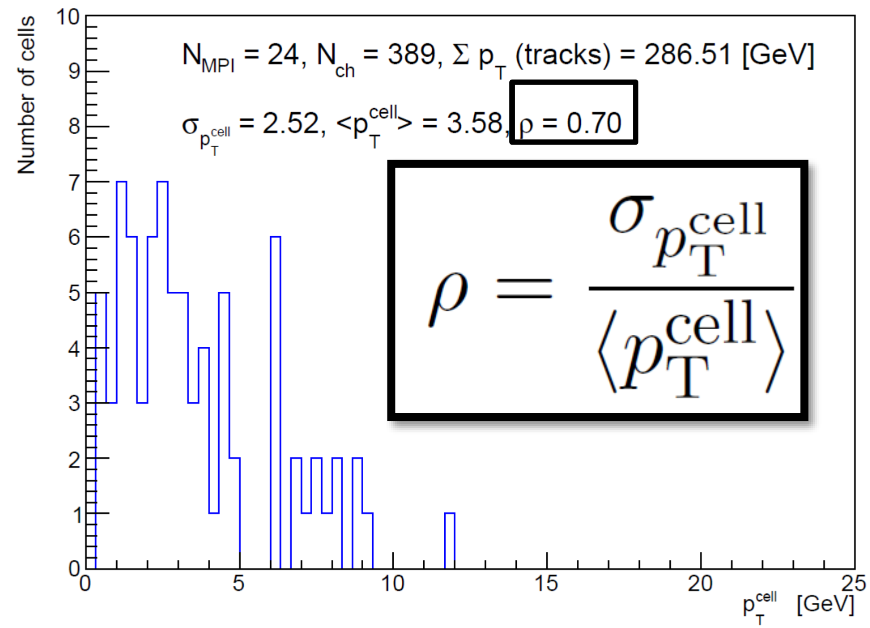
- Build **8** x **10** grid in (η-φ) space:



In each cell, the average transverse momentum is calculated: $p_{\mathrm{T}}^{\mathrm{cell}}$

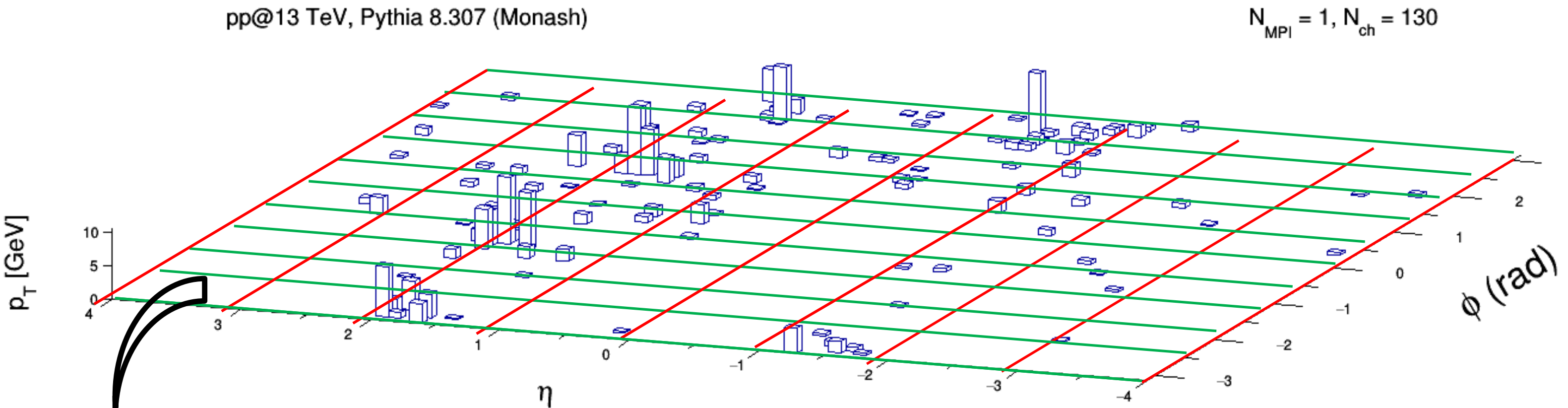
- Event-by-event, the relative standard deviation of the $p_{\mathrm{T}}^{\mathrm{cell}}$ distribution is obtained – flattenicity.

- Events with isotropic distribution of particles (“**hedgehogs**”) are expected to have **a small value of flattenicity** (ρ < 1).



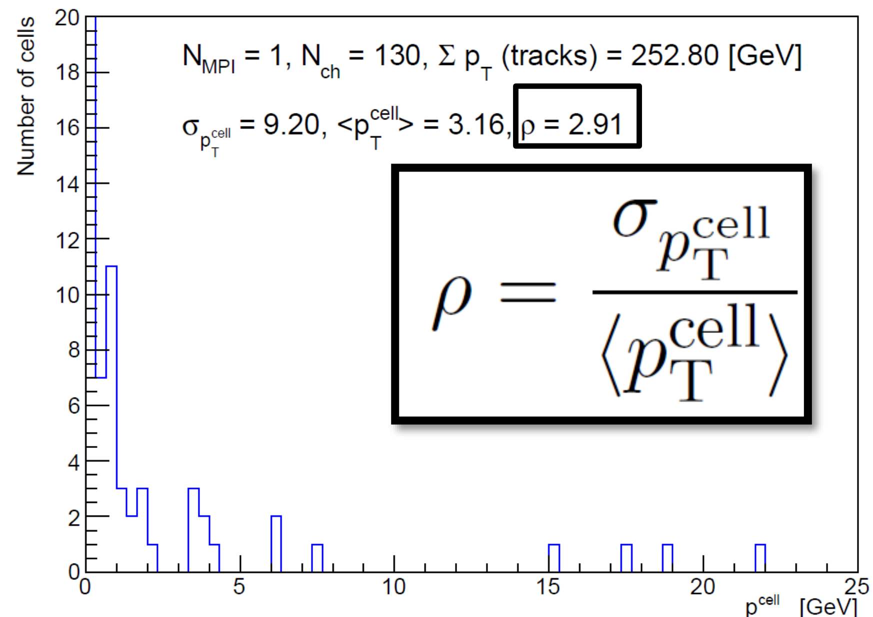
Calculating flattenicity

- Build 8 x 10 grid in (η-φ) space:



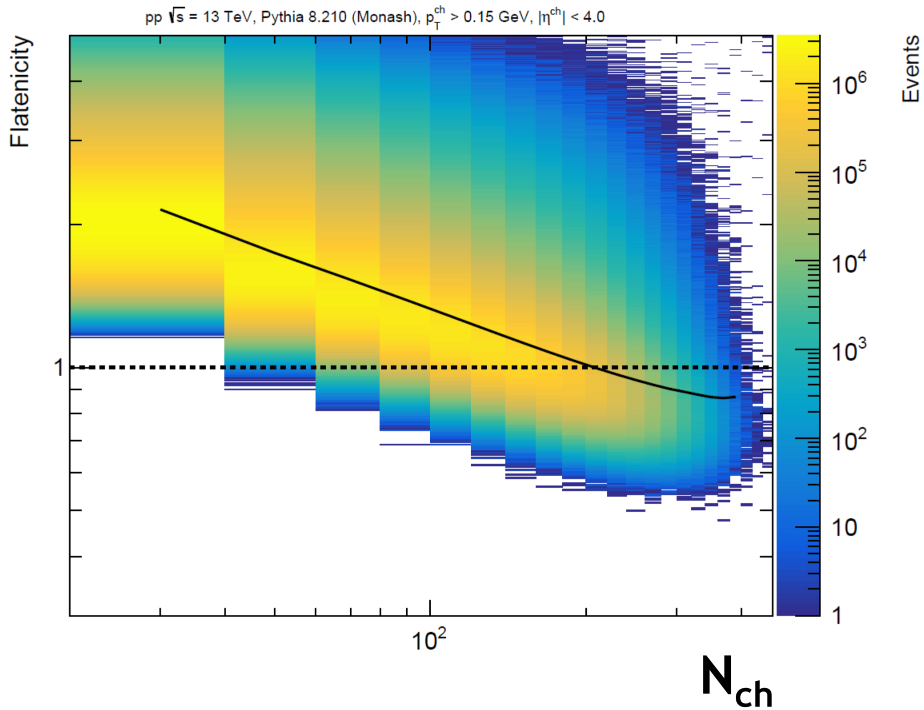
In each cell, the average transverse momentum is calculated: $p_{\mathrm{T}}^{\mathrm{cell}}$

- Event-by-event, the relative standard deviation of the $p_{\mathrm{T}}^{\mathrm{cell}}$ distribution is obtained – flattenicity.
- Events with **jet-like** structures are expected to have **larger values** of ρ.



$$\rho = \frac{\sigma_{p_{\mathrm{T}}^{\mathrm{cell}}}}{\langle p_{\mathrm{T}}^{\mathrm{cell}} \rangle}$$

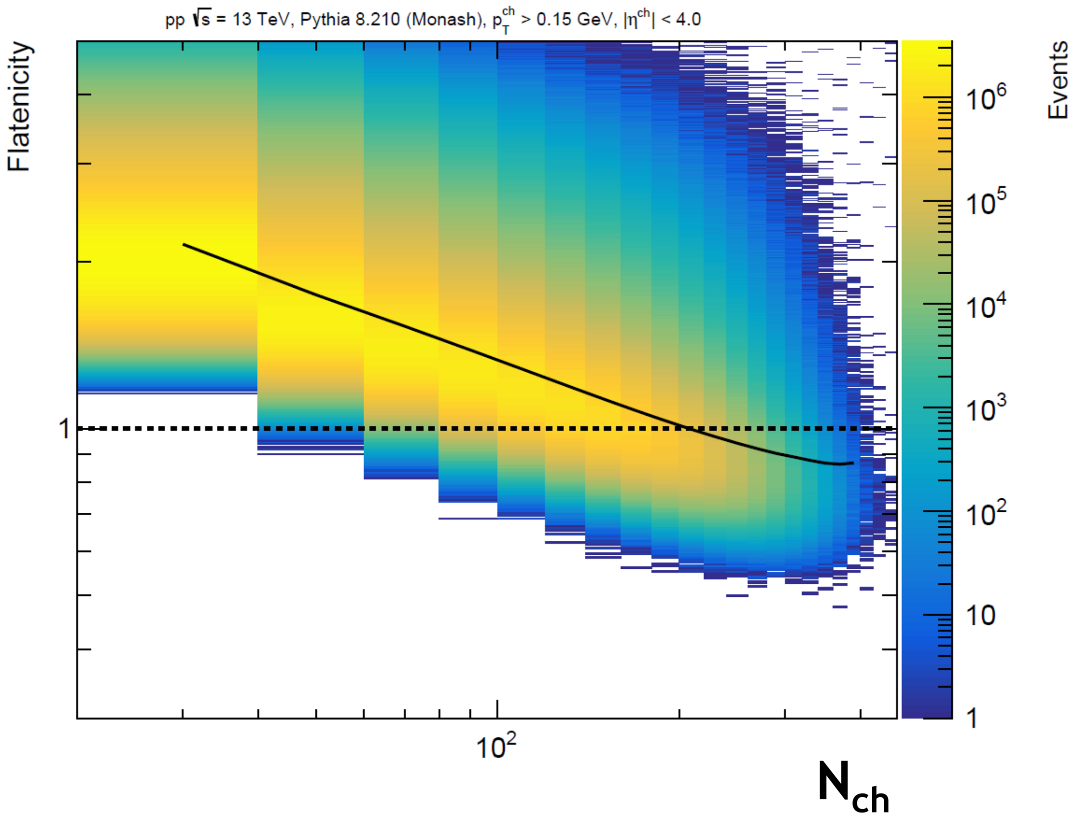
Analysing flattenicity vs number of charged particles



- MC event generators are able to model "hedgehog" events, which opens the possibility to study their properties and find a potential way to experimentally trigger these events.
- Use Pythia 8.3 MC, pp@13 TeV events with minimum-bias (SoftQCD:nonDiffractive) settings, Monash 2013 tune, with |η| < 4 and min p_T (chgd. particles) of 0.15 GeV.

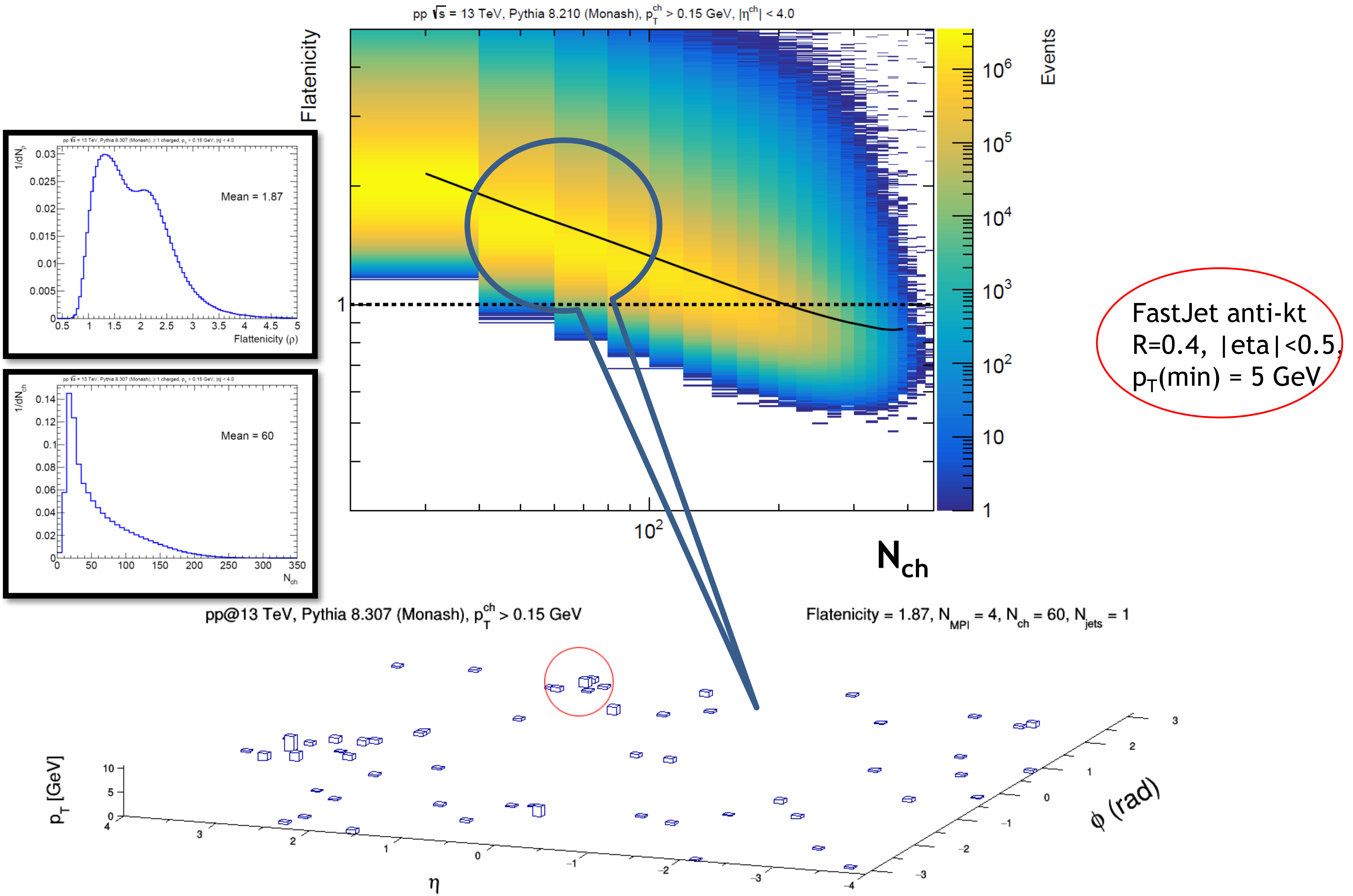
- At low number of charged particles (N_{ch}) the flattenicity distribution is very wide, <ρ> is signicantly above unity.
- <ρ> goes below unity with N_{ch} > 200, and for very high values of $N_{ch,}$ flattenicity approches 0.5 as the particles get to be quite uniformly distributed in the η-φ space.
- Events with isotropic distribution: ρ < 1
- Events with jet-like structures: large values of ρ.

Analysing flattenicity vs number of charged particles

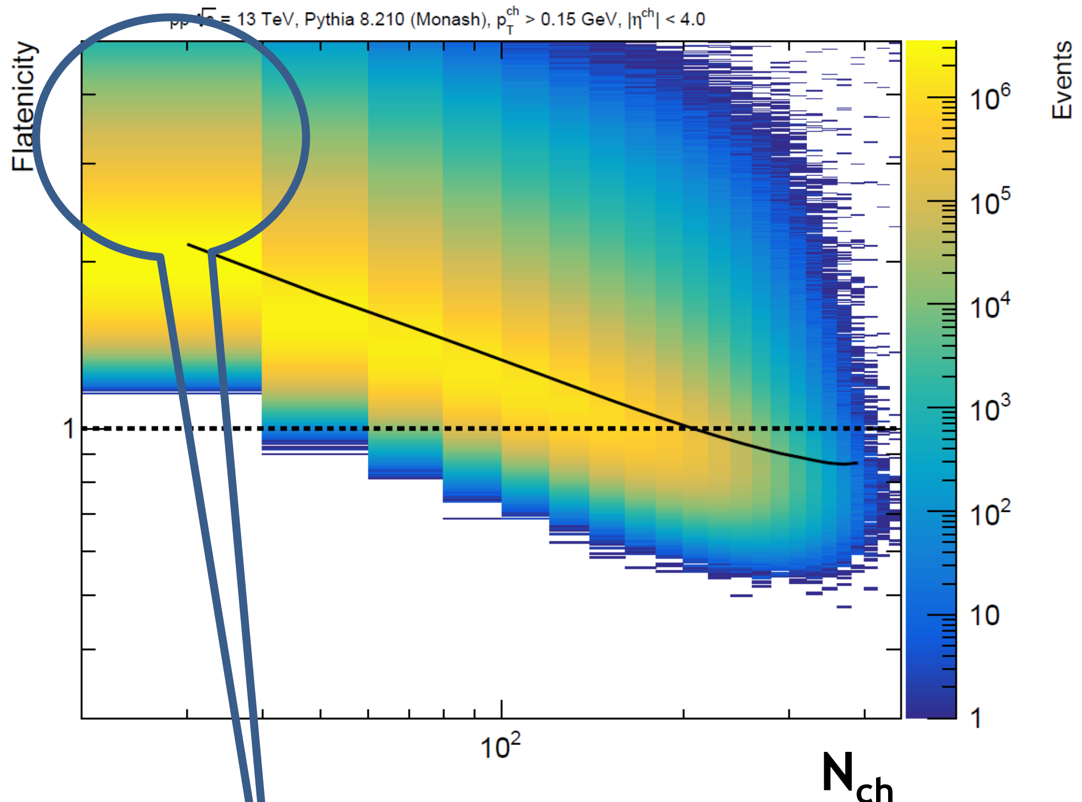


- Almost all of the results rely on "means" and "averages" of the distributions, yet the interesting (and by definition rare) effects lie on the "outliers"!
- Flattenicity opens a new way to study pp collisions and analyse those outliers: looking for **hedgehog events**!

Analysing flattenicity vs number of charged particles



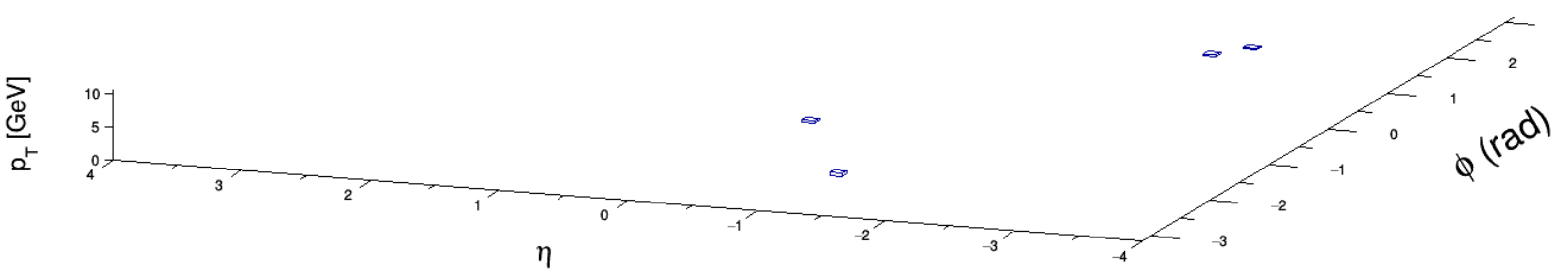
Analysing flattenicity vs number of charged particles



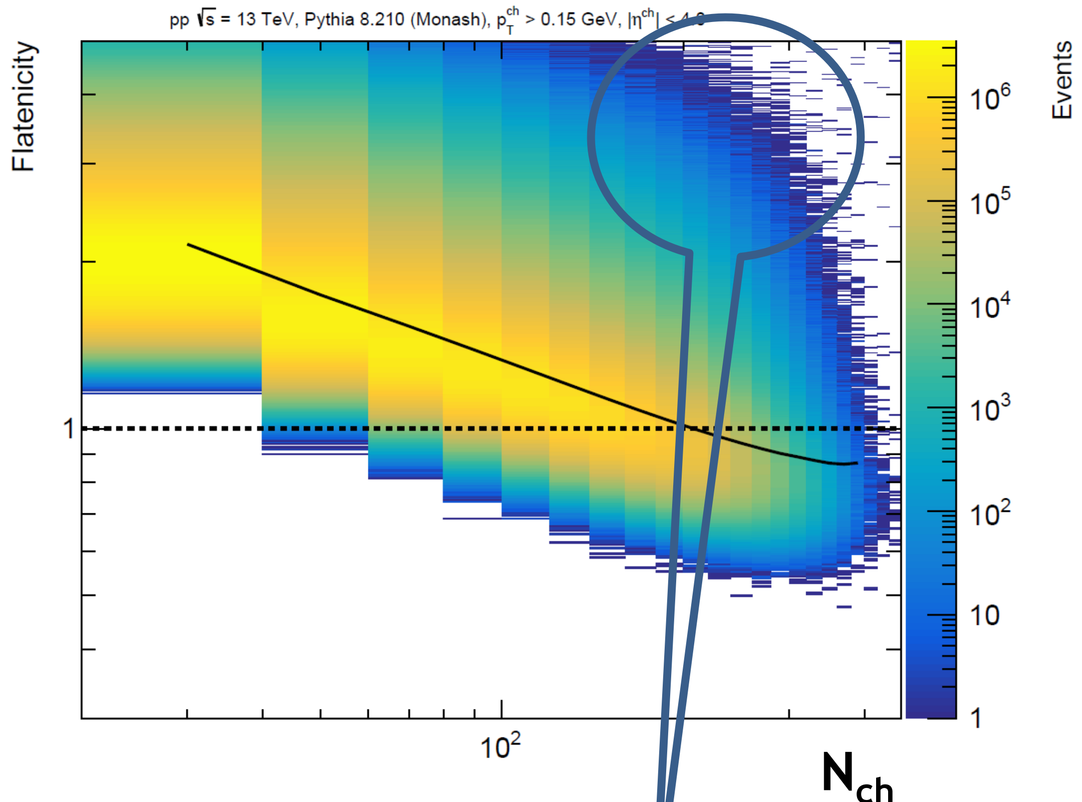
FastJet anti-kt
R=0.4, |eta|<0.5,
p_T(min) = 5 GeV

pp@13 TeV, Pythia 8.307 (Monash), p_T^{ch} > 0.15 GeV, $p_T^{\text{jet with R=0.4}}$ > 5 GeV

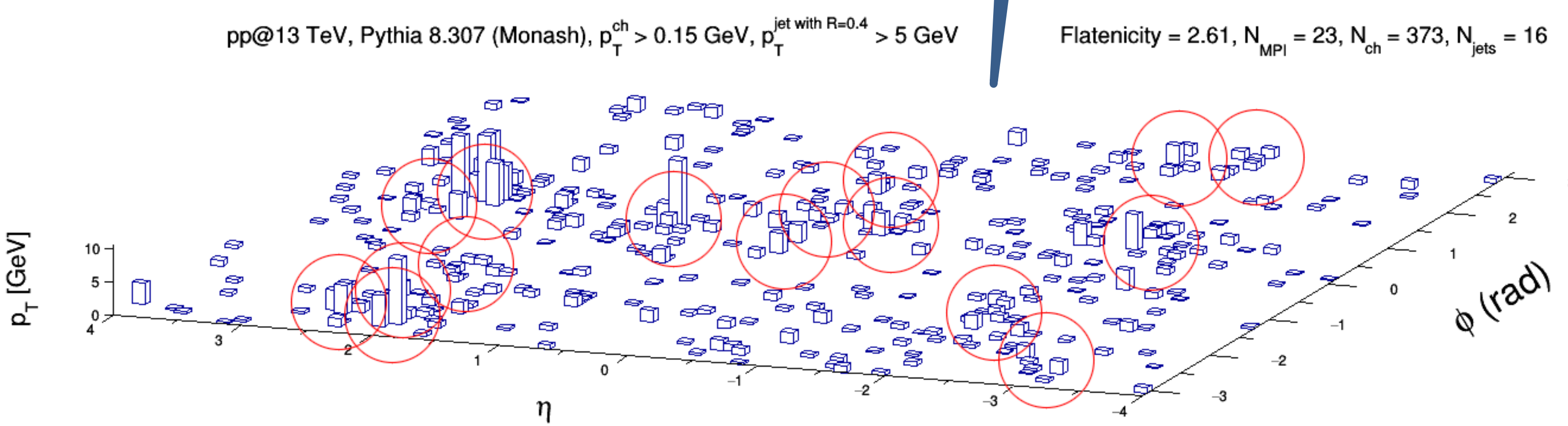
Flatenicity = 5.14, N_{MPI} = 1, N_{ch} = 4, N_{jets} = 0



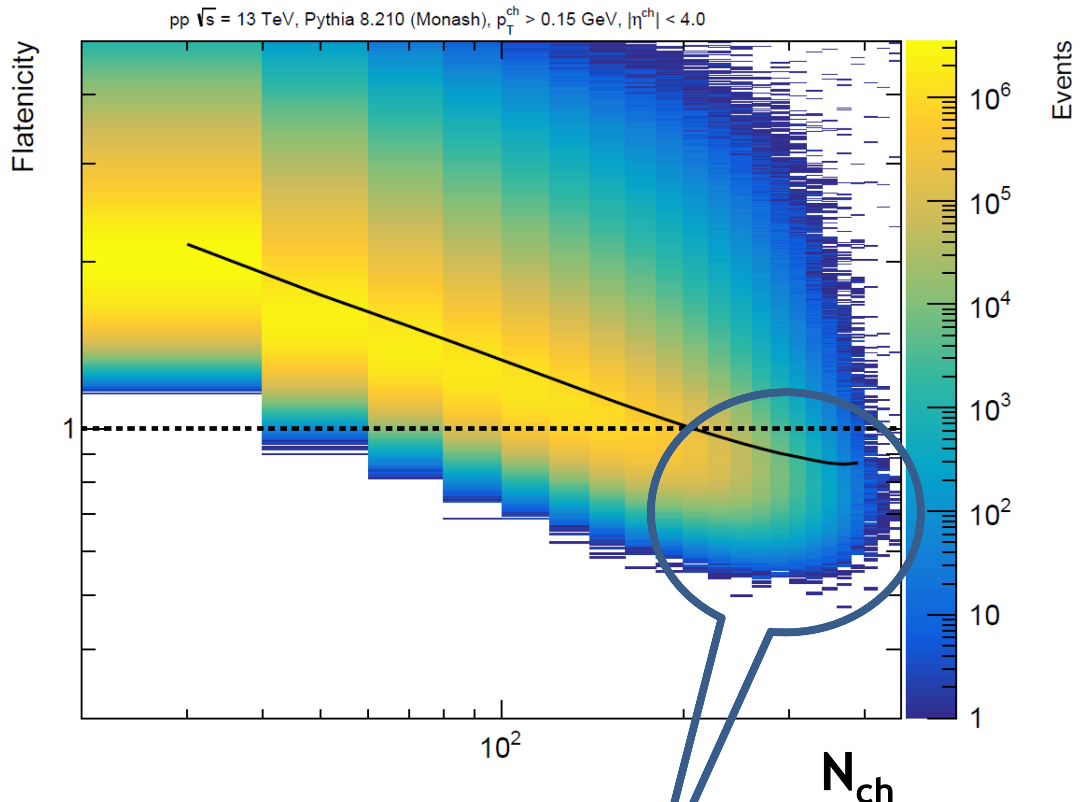
Analysing flattenicity vs number of charged particles



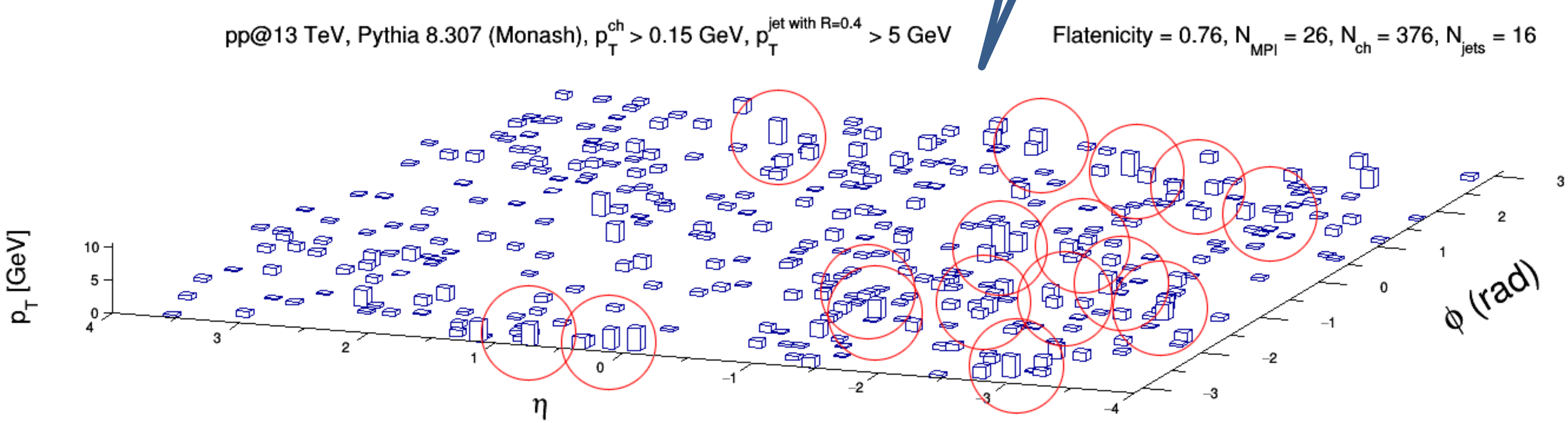
FastJet anti-kt R=0.4, |eta|<0.5, $p_T(min)$ = 5 GeV



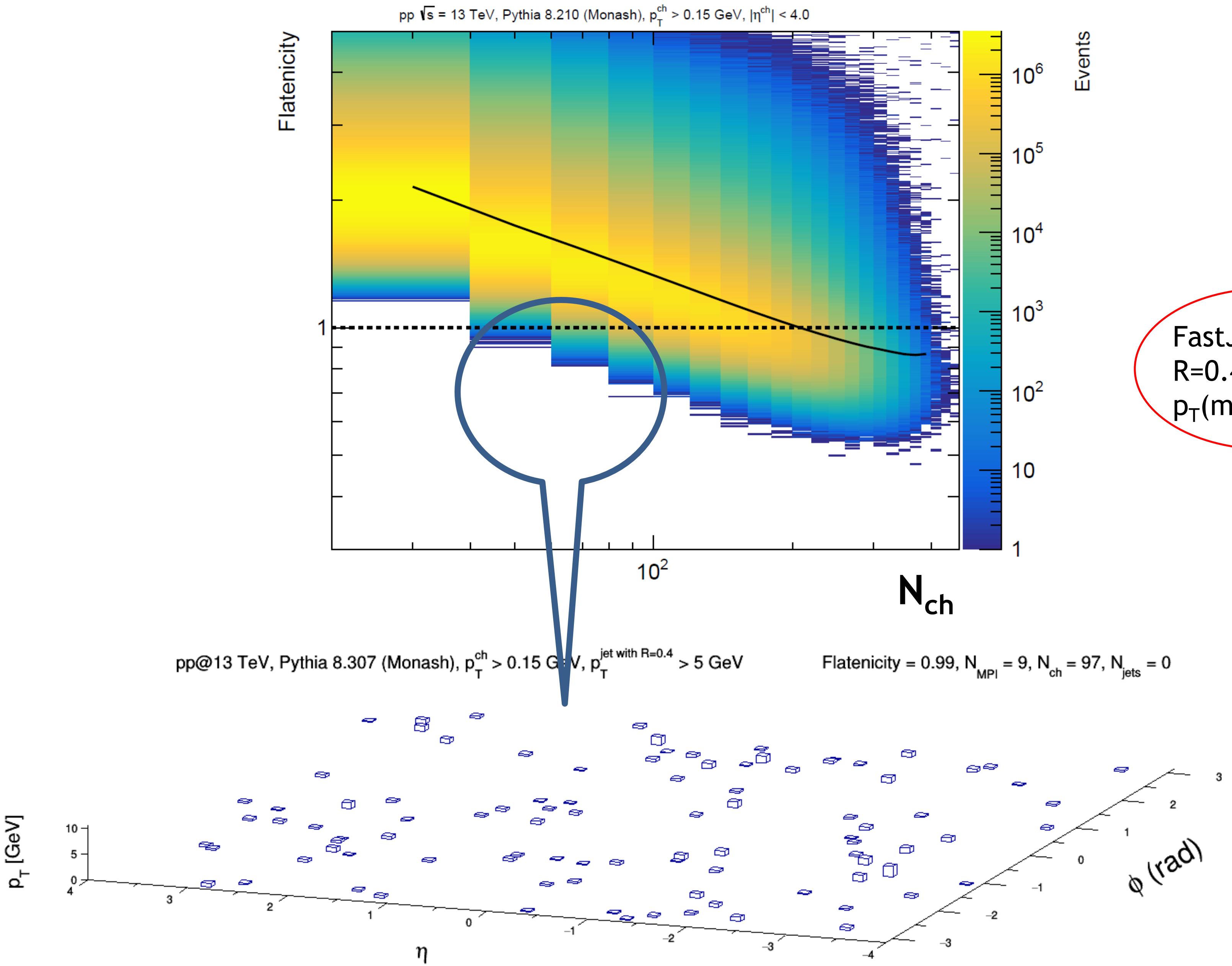
Analysing flattenicity vs number of charged particles



FastJet anti-kt
R=0.4, |eta|<0.5,
p_T(min) = 5 GeV

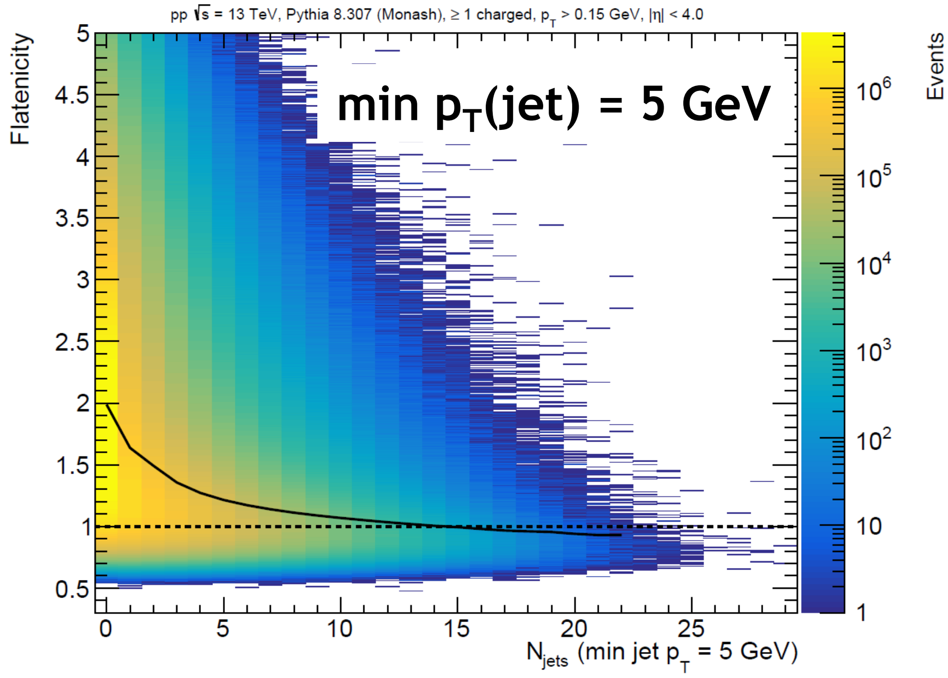


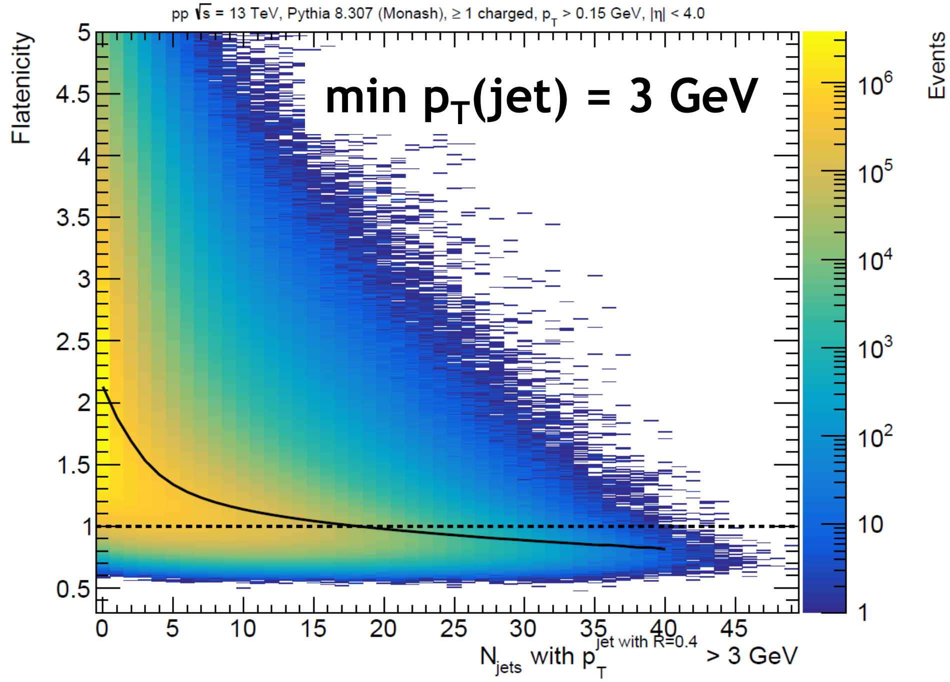
Analysing flattenicity vs number of charged particles



FastJet anti-kt
R=0.4, |eta|<0.5,
p_T(min) = 5 GeV

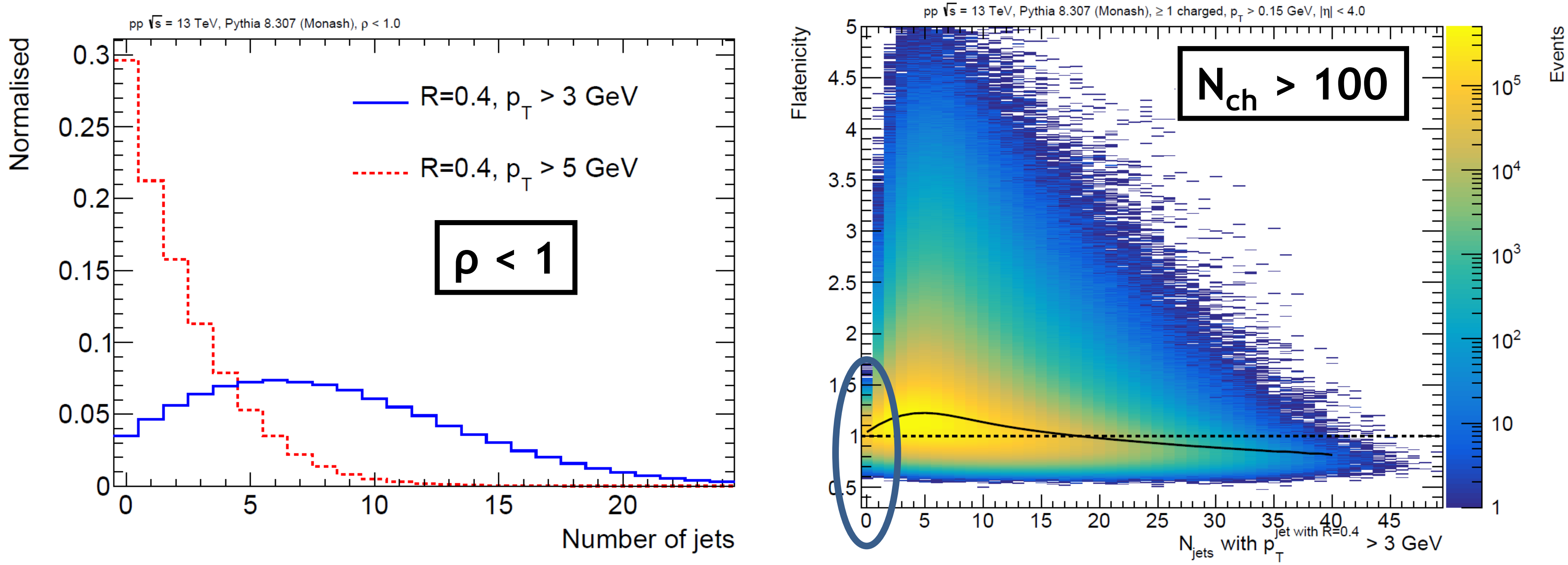
Analysing flattenicity vs number of jets





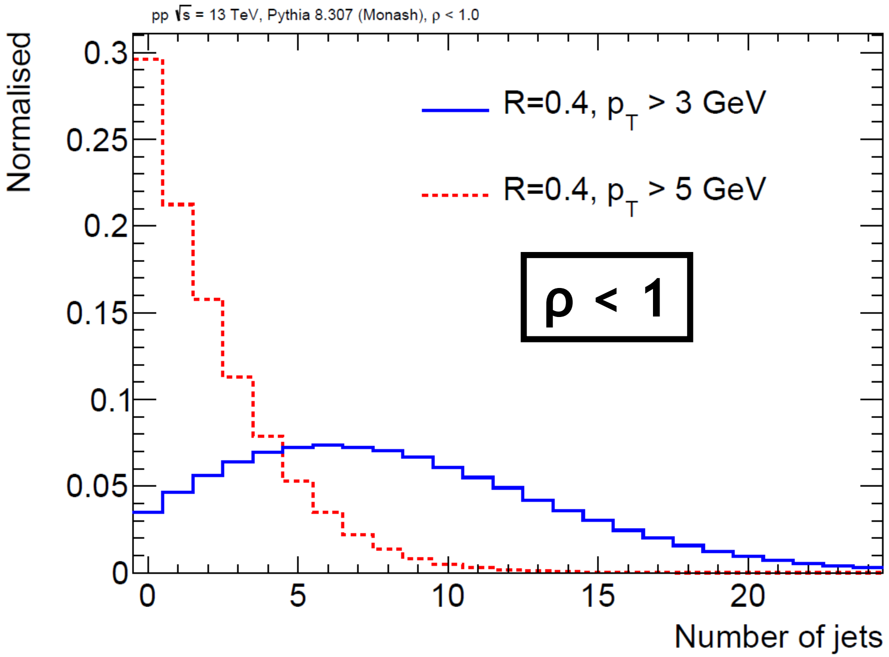
- As the jet energy decreases, the interpretation of the event topology becomes more difficult and the definition of a “jet” becomes arbitrary.
- Considering that events with high p_T are consistent with having a substantial component of QCD jets, the 3 GeV cut represents the lowest reasonable limit below which any attempt to separe experimentally soft production fluctuations from hard scattering would be unreliable.

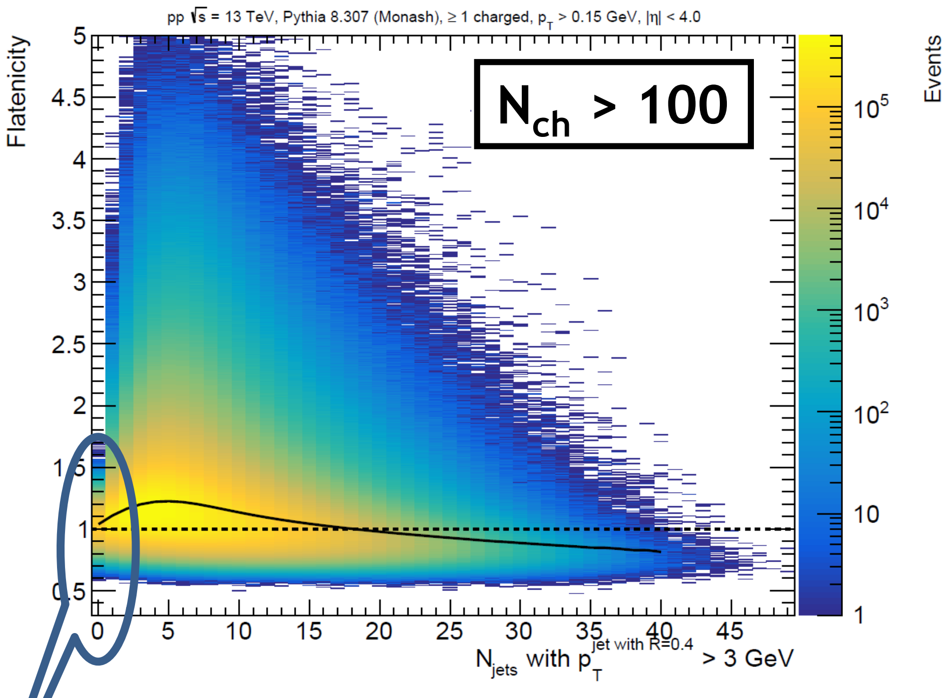
Analysing flattenicity vs number of jets

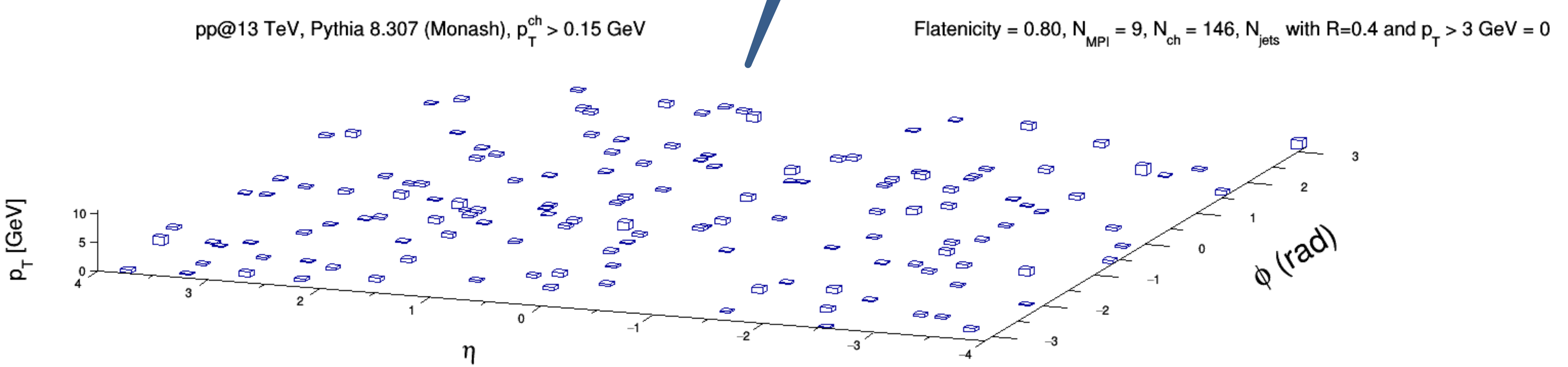


- As the jet energy decreases, the interpretation of the event topology becomes more difficult and the definition of a "jet" becomes arbitrary.
- Considering that events with high p_T are consistent with having a substantial component of QCD jets, the 3 GeV cut represents the lowest reasonable limit below which any attempt to separe experimentally soft production fluctuations from hard scattering would be unreliable.
- In the **low flattenicity regime**, we are able to select hedgehog events with **high multiplicity** and with **no jet production** (**~0.1% of all events**).

Analysing flattenicity vs number of jets

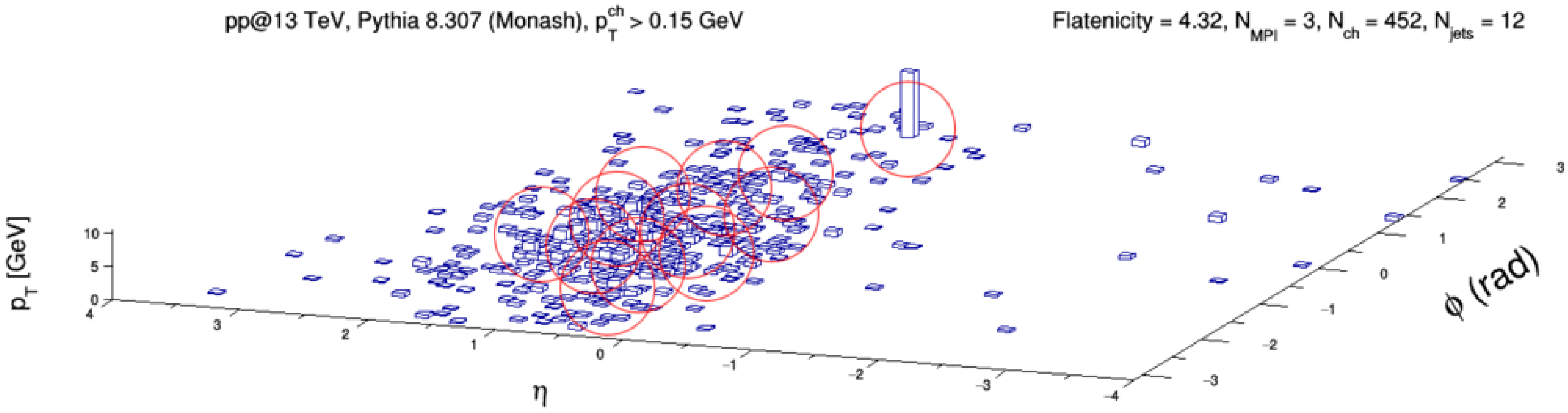






Analysing very atypical events

- Flattenicity allows one to find quite atypical (and rare 1/100M) events:
  - i.e. high chgd. multiplicities (>300) and low number of hard-scatterings (MPI=3)



- In some events we see one very high p_T charged particle (around which a jet is usually build, and particle p_T divided by jet p_T approaches unity!) .
- Recoil jets are usually produced opposite in φ, and fragment into several particles.
- Nor the partonic hard-scattering p_T , nor the additional multiparton interactions p_T are high enough nor match the reconstructed energy for these events.
- Are we looking at the limit of fragmentation and/or ISR/FSR emissions?
- We are identifying an experimental way to find these events, and it would be a perfect place to study data and tune our generators!

Take-home from the second part of the talk

- Hedgehog events have never been seriously studied in pp collisions at the LHC. These events are “rare” – but as rare as a top-quark–pair production!

Selection	Probability
$\rho < 1$	4×10^{-2}
$\rho < 0.75$, $N_{ch} > 100$, $N_{jets}=0$	2×10^{-6}
$\rho < 0.75$, $N_{ch} > 400$	6×10^{-8}

- Flattenicity - the new event structure parameter - allows one to identify the hedgehog events and observe the evolution of events from jetty to hedgehog type.
- We are able to identify different classes of hedgehog events: those with high jet multiplicity (jetty) and with no jet production.
- Studying these events may shed light to the search for the “energy re-distribution” effect in pp collisions.
- Next steps are to compare and count how many hedgehog events we observe in data from different LHC experiments! Stay tuned!

Muchas gracias por su atención!

BACK-UP

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	✓	–
$\mathrm{m(jj)}^{\min.\Delta R}$	Mass of the combination of any two jets with the smallest ΔR	✓	–
ΔR_{uu} (med.)	Median ΔR between any two untagged jets	–	✓
$\mathrm{m(uu)}^{\min.\Delta R}$	Mass of the combination of any two untagged jets with the smallest ΔR	–	✓

ttbar at √s=5.02 TeV: uncertainties

- Usual ATLAS recipe for signal modelling uncertainties: alternative samples for parton shower and generator, hdamp, scales, PDF
- Background modelling: W+jets scale and normalisation (4%+24% per extra jet) uncertainties split into W+light jet, W+≥1c and W+≥1b jet; single top: normalisation, parton shower, DR-DS and scales; Diboson norm. of 20%, Z+jets norm. of 50%; mis-ID: 50%-100% shape and normalisation
- Lepton uncertainties from dedicated CP studies for low-μ 5.02 TeV and 13 TeV data, i.e. isolation SFs from tag and probe dedicated 5.02 TeV Z→ll events
- b-tagging uncertainties from high-μ 13 TeV data, measured by the dilepton channel, efficiencies for low-μ 5.02 TeV and high-μ 13 TeV are consistent
- JES and JER uncertainties taken from high-μ 13 TeV data, additional uncertainty derived from the "in-situ" calibration called "JES correction"
- Integrated luminosity (1.6%) and LHC beam energy: 0.3% on σ(tt)
- Parametric dependence on top mass given separately

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
$E_{\mathrm{T}}^{\mathrm{miss}}$	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

- Simultaneous profile likelihood fit to several regions with systematic uncertainties implemented in the fit as additional terms in the binned likelihood:

$$\mathcal{L}(\mu,\theta) = \prod_{i=0}^{N} \frac{(\mu \cdot s_i(\theta) + b_i(\theta))^{n_i}}{n_i!} \exp\left(\mu \cdot s_i(\theta) + b_i(\theta)\right) \cdot \prod_{k=1}^{P} \rho(\theta_k)$$

ML en LHC

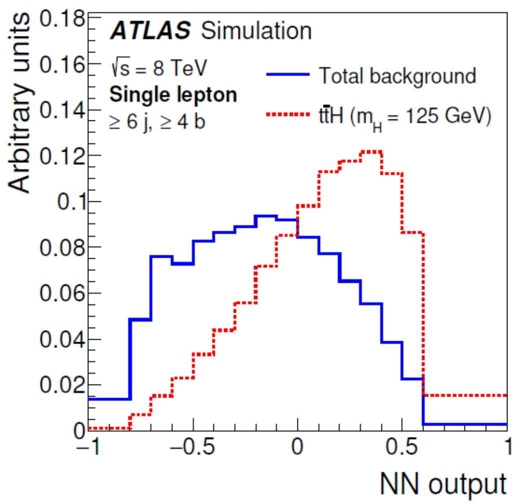
- ML juega un papel en diferentes rincones de los experimentos en el LHC

- En el análisis:
  - Clasificar entre eventos de señal y de fondo
  - Reconstruir partículas pesadas

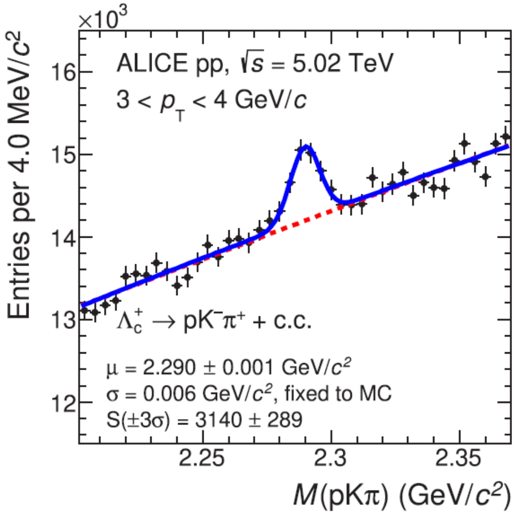
- En la reconstrucción de eventos:
  - Identificación y reconstrucción de partículas
  - Calibración de energía / dirección

- En el trigger:
  - Identificación rápida de estados finales complejos

- En la computación y grid:
  - Estimar la popularidad del conjunto de datos
  - Determinar la ubicación de las réplicas

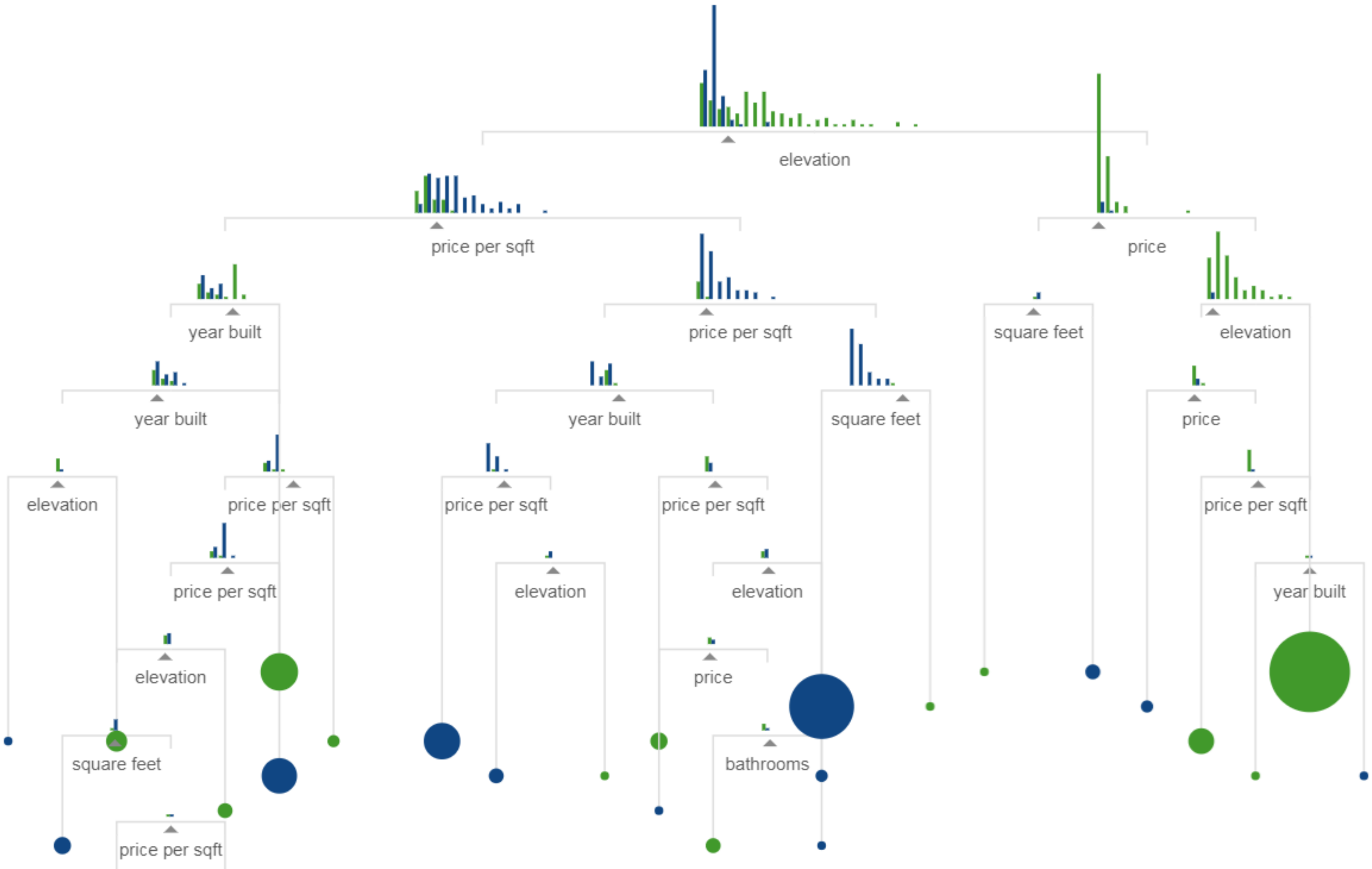


ATLAS Collaboration, Eur. Phys. J. C (2015) 75: 349

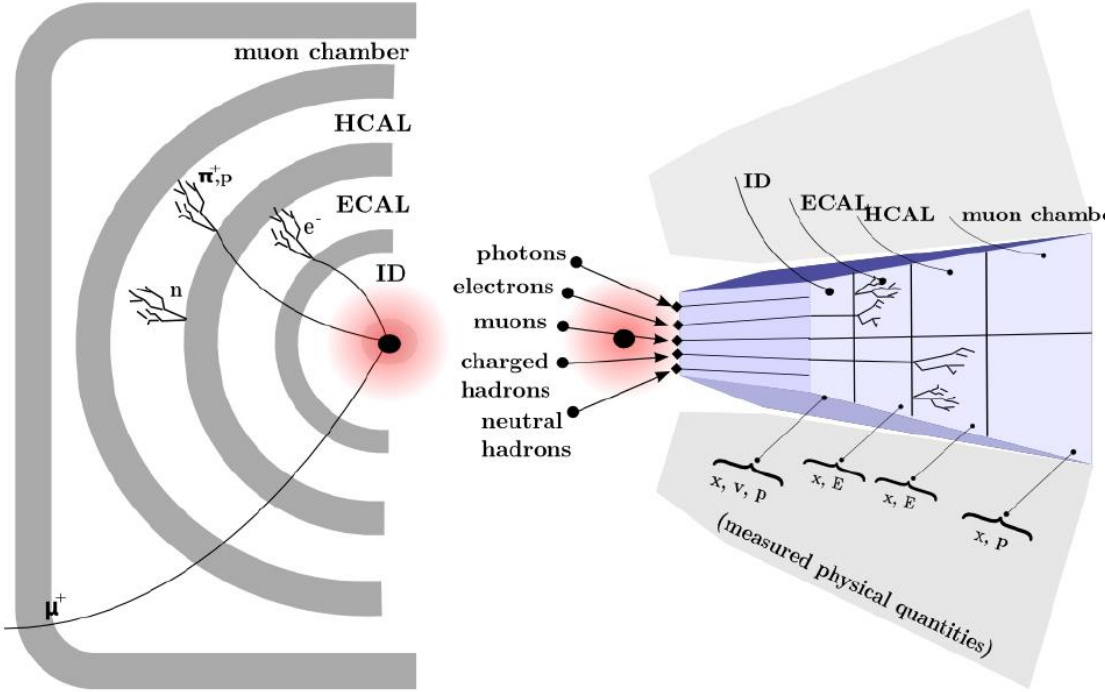


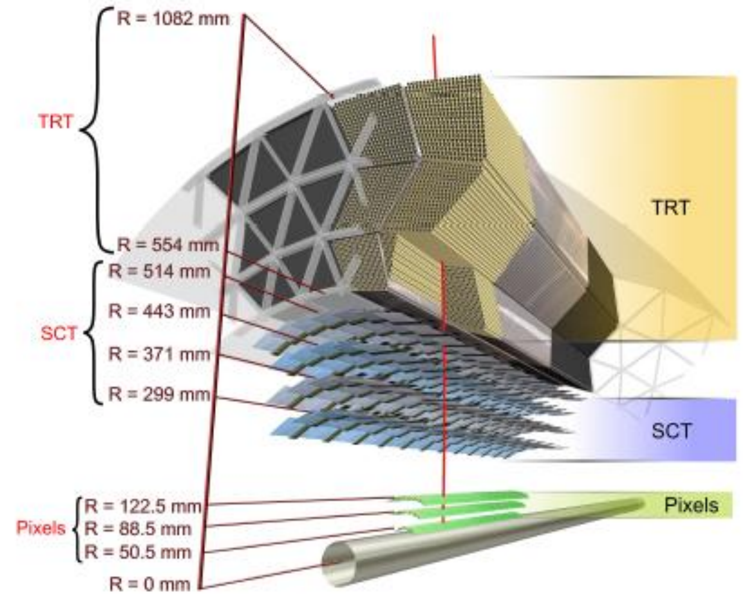
ALICE Collaboration, Phys. Rev. C 104, 054905

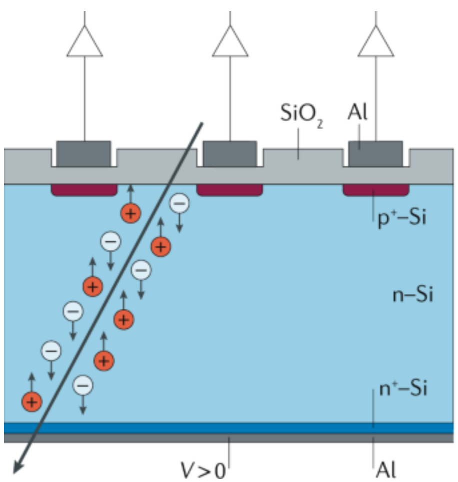
Decision trees

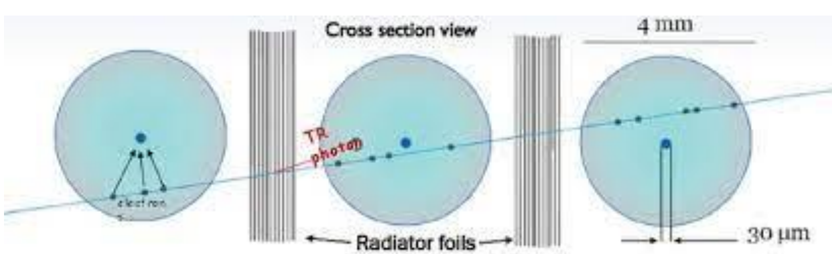


ATLAS


muon chamber
HCAL
ECAL
ID
π±,p
e-
n
μ+
photons
electrons
muons
charged
hadrons
neutral
hadrons
ID
ECAL
HCAL
muon chamb
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
Pixels
R = 122.5 mm
R = 88.5 mm
R = 50.5 mm
R = 0 mm
TRT
SCT
Pixels


SiO2
Al
p+–Si
n–Si
n+–Si
V>0
Al

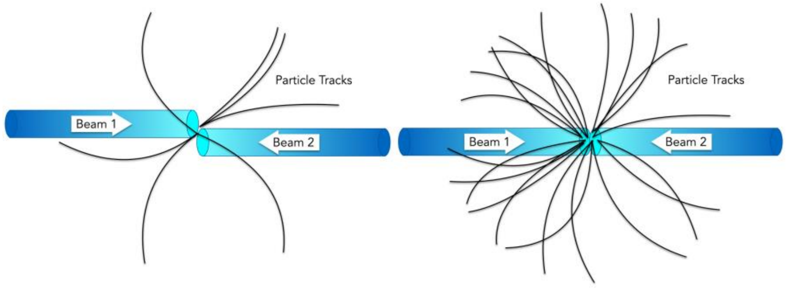

Cross section view
4 mm
TR photon
Radiator foils
30 μm

Luminosity uncertainty

Luminosity quantifies the total number of pp interactions in a given dataset. Assuming that two beams have N1 and N2 particles in each bunch and these bunches meet each other with a frequency fC, the luminosity is:

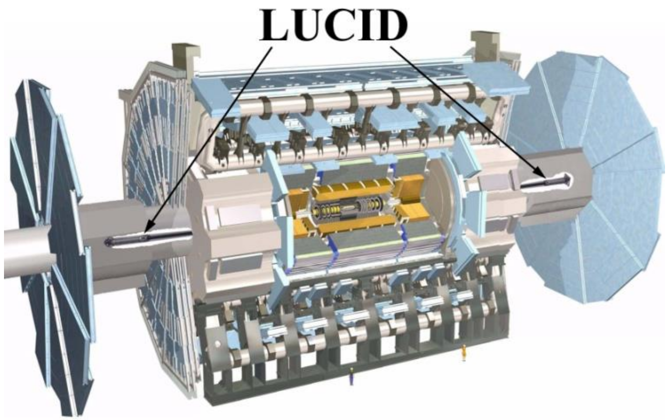
$$\mathcal{L} \propto f_C N_1 N_2 S_T^{-1}$$

where ST represents the transverse size of the beams at the interaction point.



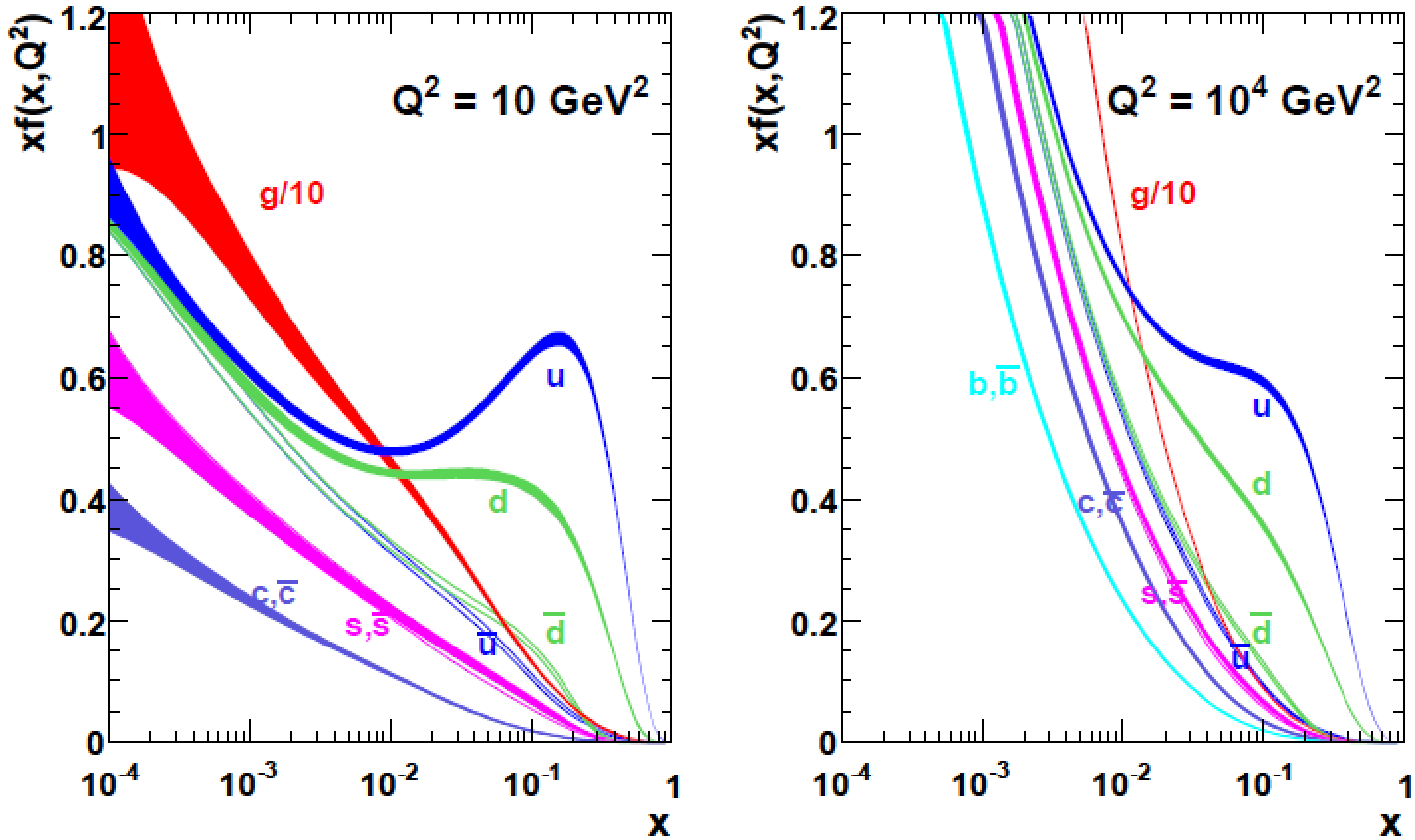
Once a year, LHC proton beams are displaced from their normal position in the horizontal and vertical planes: this method is called a van der Meer (vdM) beam separation scan, allows to map out the beam size and measure ST.

ATLAS has luminosity-sensitive detectors (LUCID-2) built specifically for such measurements. LUCID-2 consists of two sets of photomultiplier tubes (PMT) that surround the LHC beam pipe, 17 m on either side of the interaction point.



Parton Distribution Function

La función PDF describe la probabilidad de encontrar un parton de tipo i con un momento fracción x cuando se prueba un protón en la escala Q^2



Feynman Rules for QCD

Spin $\frac{1}{2}$

incoming quark	$c_i u(p)$
outgoing quark	$c_i^\dagger \bar{u}(p)$
incoming anti-quark	$c_i^\dagger \bar{v}(p)$
outgoing anti-quark	$c_i^\dagger v(p)$

Spin $\frac{1}{2}$

incoming gluon	$\varepsilon^\mu(p)$
outgoing gluon	$\varepsilon^\mu(p)^*$

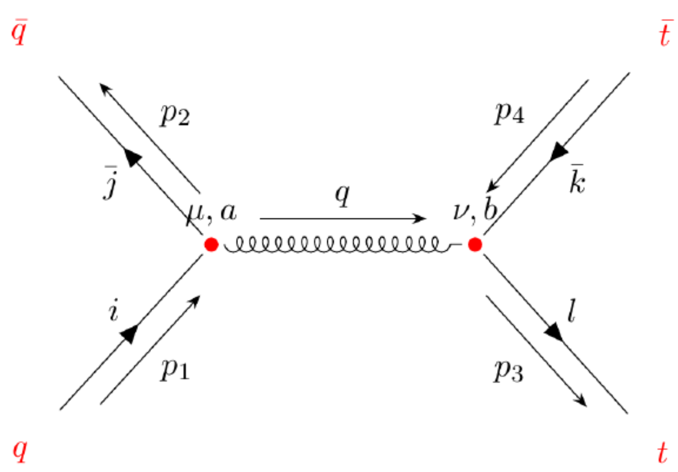
Internal Lines (propagators),

spin 1 gluon $\left\{ -i\frac{g_{\mu\nu}\delta^{ab}}{q^2} \right.$

Vertex Factors,

quark-gluon-quark vertex	$-ig_s t^a \gamma^\mu$
3-gluon vertex	$g_s f_{abc}\left(g_{\mu\nu}(p_1-p_2)_\lambda + g_{\nu\lambda}(p_2-p_3)_\mu + g_{\lambda\mu}(p_3-p_1)_\nu\right)$

where $t^a = \lambda^a/2$, $a = 1, 2, \ldots 8$, λ^a are the Gell-Mann $SU(3)$ matrices, and,



$$\mathcal{M}_{q\bar{q}} = \left[\bar{v}(p_2)\, c_j^\dagger \left(-ig_s\gamma^\mu t^a\right) u(p_1) c_i\right] \frac{g_{\mu\nu}\delta_{ab}}{(p_1+p_2)^2} \left[\bar{u}(p_3)\, c_k^\dagger \left(-ig_s\gamma^\nu t^b\right) v(p_4)\, c_l\right]$$

Como calcular la seccion eficaz de par de top quarks

Lorentz invariant Mandelstam variable:

$$s = (p_1 + p_2)^2 = p_1^2 + p_2^2 + 2p_1 \cdot p_2$$

$$t = (p_1 - p_3)^2 = p_1^2 + p_3^2 - 2p_1 \cdot p_3$$

$$u = (p_1 - p_4)^2 = p_1^2 + p_4^2 - 2p_1 \cdot p_4$$

$$t = m_t^2 - \frac{s}{2}\left(1 - \sqrt{1 - \frac{4m_t^2}{s}}\cos\theta\right)$$

$$u = m_t^2 - \frac{s}{2}\left(1 + \sqrt{1 - \frac{4m_t^2}{s}}\cos\theta\right)$$

$$\frac{d\sigma}{dt} = \frac{1}{16\pi s^2}|\mathcal{M}_{fi}|^2 \qquad \frac{d\hat{\sigma}}{dt}(q\bar{q} \to t\bar{t}) = \frac{4\pi\alpha_s^2}{9s^4}\left[\left(m^2 - t\right)^2 + \left(m^2 - u\right)^2 + 2m^2 s\right]$$

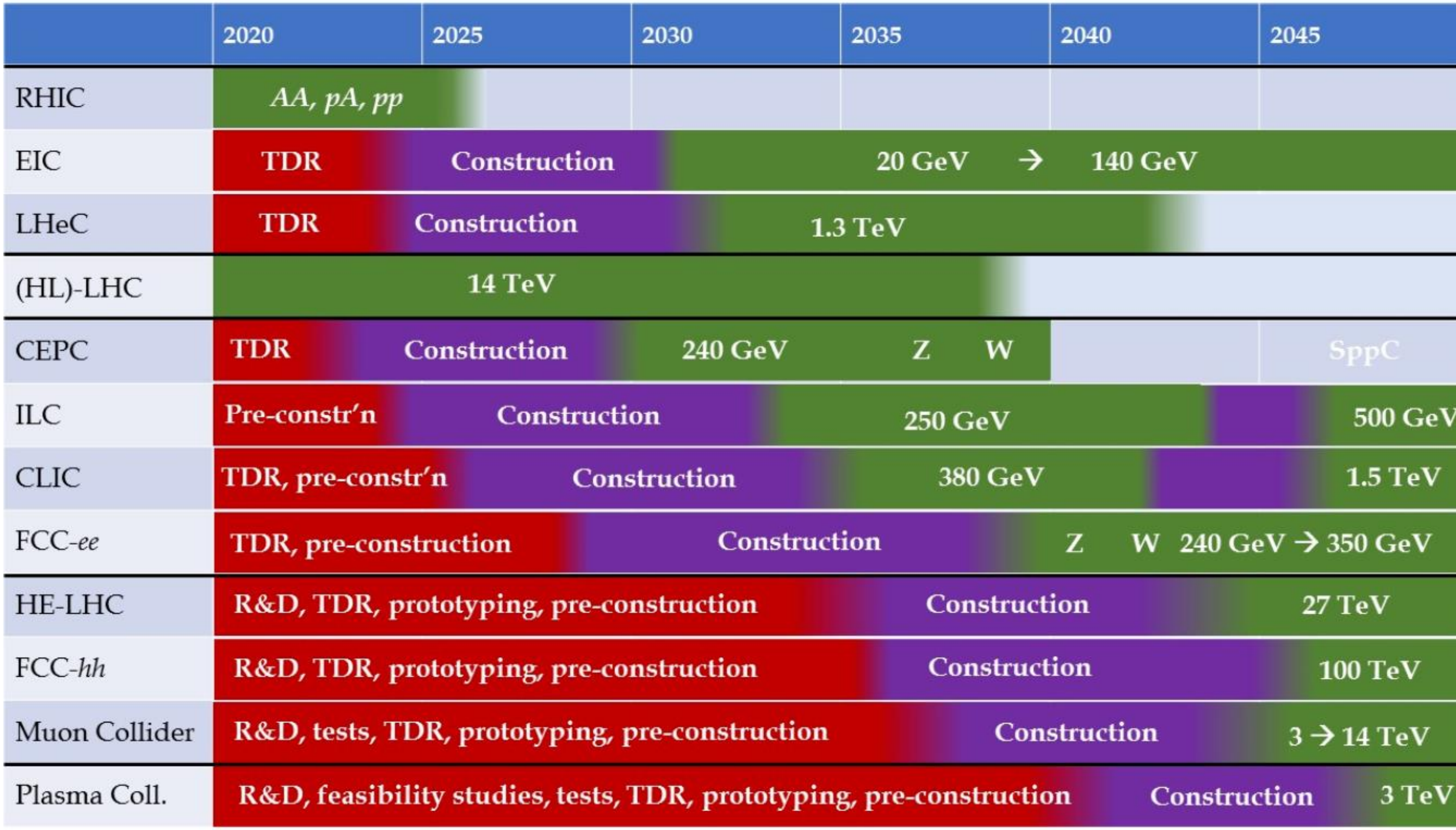
$$\sigma\left(q\bar{q} \to t\bar{t}\right) = \frac{4\pi\alpha_3^2}{27s}(2 + z)\sqrt{1 - z} \qquad z = 4m^2/\hat{s}.$$

The Factorization Theorem

$$\sigma_{pp\to N} = \sum_{1,2=q,\bar{q},g} \int dx_1 dx_2 \int f_1(x_1, Q^2) f_2(x_2, Q^2) \times \hat{\sigma}_{12\to N}(\mu_{\rm F}, \mu_{\rm R})$$

$$= \sum_{1,2=q,\bar{q},g} \int dx_1 dx_2 \int {\rm d}\Phi_X \times f_1(x_1, Q^2) f_2(x_2, Q^2) \frac{1}{2x_1 x_2 s}|\mathcal{M}_{12\to N}|^2(\Phi_N, \mu_{\rm F}, \mu_{\rm R}),$$

Futuros aceleradores



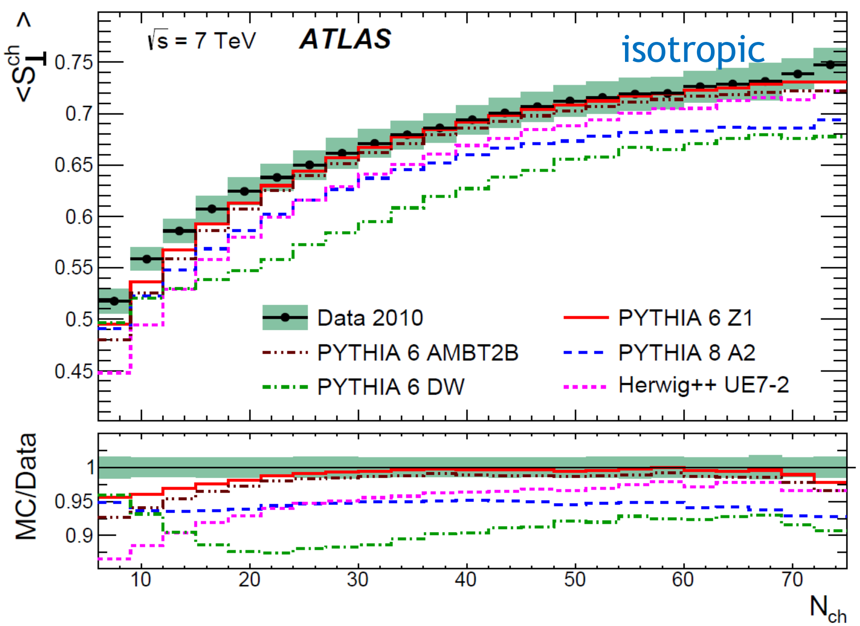
Characterisation of high-multiplicity events

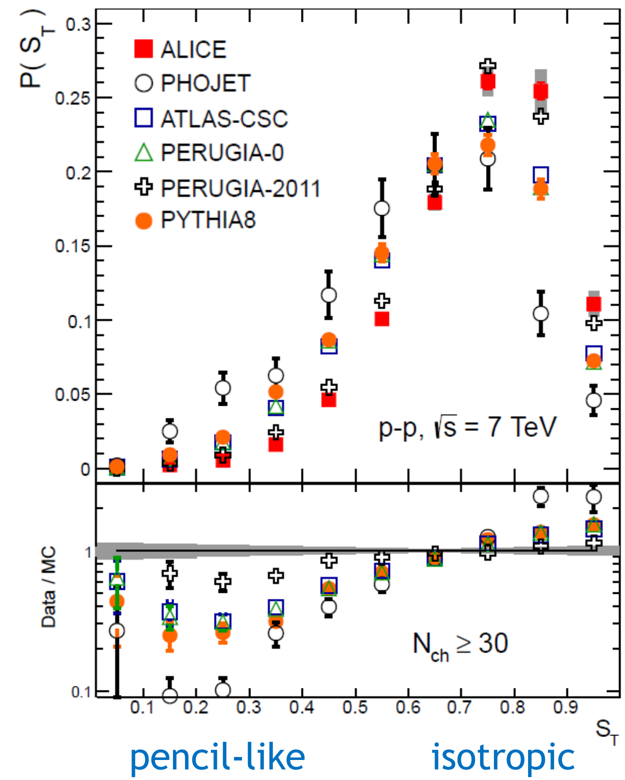
- Attempts to characterise these high-multiplicity events: use of event shapes, i.e. using transverse sphericity:

$$S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}\,, \quad S^{xy} = \sum_i \frac{1}{|\vec{p}_{T,i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i}\,p_{y,i} \\ p_{x,i}\,p_{y,i} & p_{y,i}^2 \end{bmatrix}$$

- Both ALICE and ATLAS observed an **under-estimation** of isotropic events by MC generators at high charged multiplicity ($N_{ch} \geq 30$)
    - ✓ Suggest that a very active underlying event (UE) is needed by the MC event generators in order to explain these high-multiplicity events

ATLAS Collaboration, Phys. Rev. D 88, 032004 (2013)





ALICE Collaboration, Eur. Phys. J. C 72 (2012) 2124

Characterisation of high-multiplicity events

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  ✓ Suggest that a very active underlying event (UE) is needed by the MC event generators in order to explain these high-multiplicity events

- ALICE measurement shows that <p_T> as a function of N_{ch} in isotropic events was found to be **smaller** than that measured in jet-like events, and that for jet-like events, the <p_T> is **over-estimated** by PYTHIA 6 and 8 models.

ALICE Collaboration, Eur. Phys. J. C 79 (2019) 857