

High p_T Physics at the LHC

Lecture 3:

Introductory Topics and SM Physics

Warwick Week 2026

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Lecture Outline

- Introduction to ATLAS and CMS detectors
- Low p_T processes
- Hadronic jets
- W_{\pm} and Z boson physics
- Top quark physics

*** Slides based on Andrew Chisholm's lecture ***

General Purpose Detector Overview

Most general purpose hadron collider detectors (GPDs) (e.g. ATLAS, CMS, CDF, DØ, UA1) share the same common components

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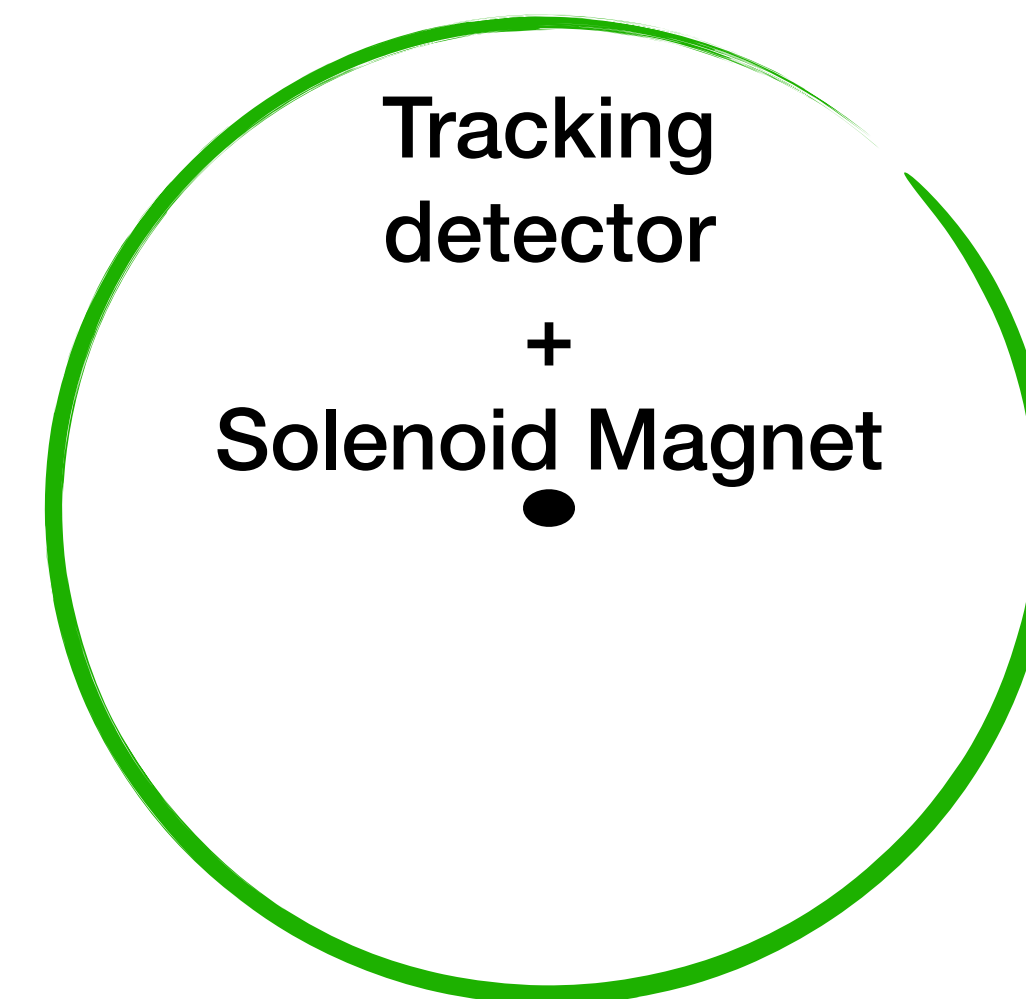


General Purpose Detector Overview

Most general purpose hadron collider detectors (GPDs) (e.g. ATLAS, CMS, CDF, DØ, UA1) share the same common components

Tracking detector + Solenoid Magnet

Measure trajectory of charged particles to infer momentum and charge, used to reconstruct primary interaction point



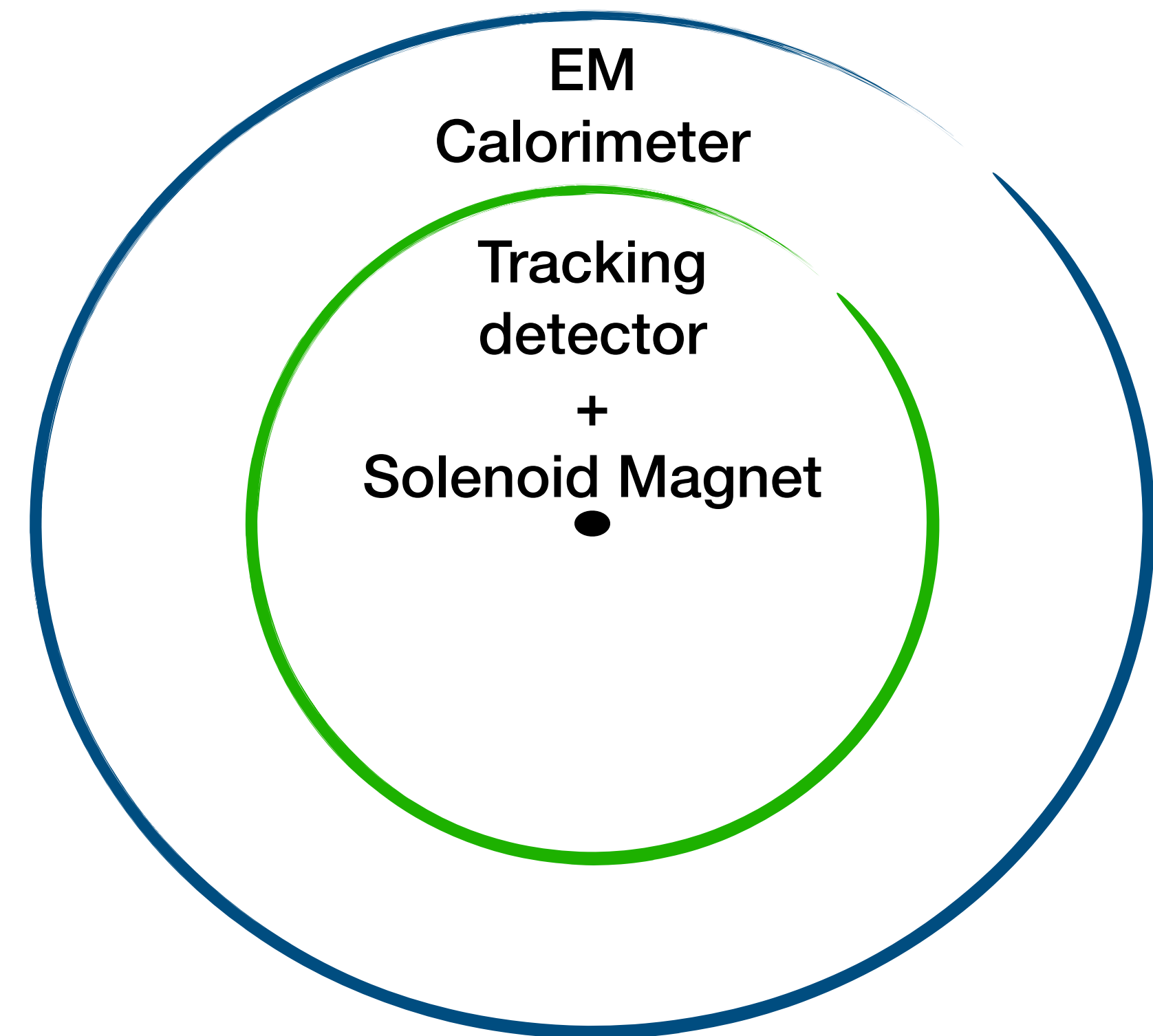
General Purpose Detector Overview

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Electromagnetic Calorimeter

Measure the energy of high energy[†] electrons, positrons and photons

[†] Typically $E_T > 100$ MeV



General Purpose Detector Overview

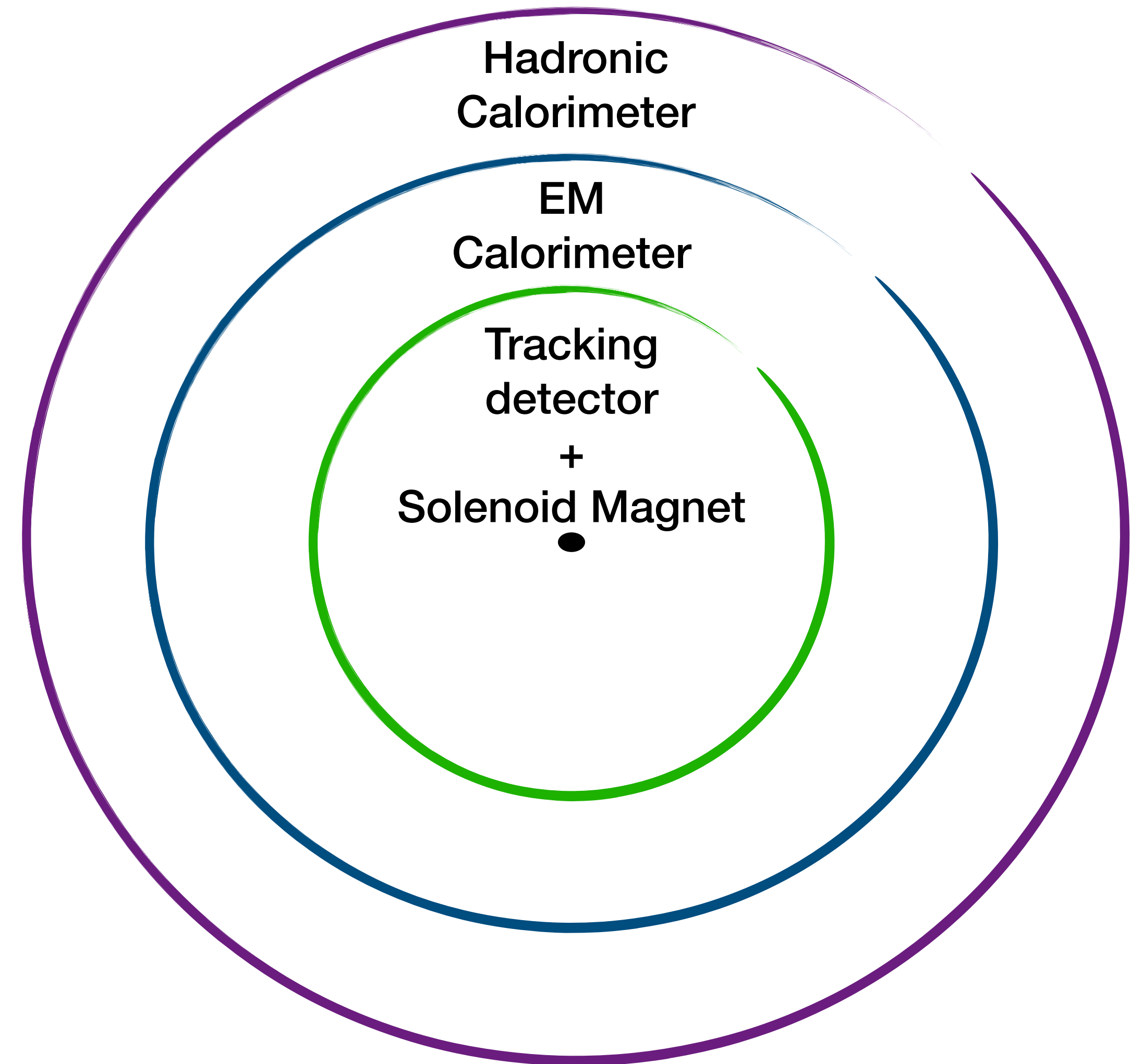
Most general purpose hadron collider detectors (GPDs) (e.g. ATLAS, CMS, CDF, DØ, UA1) share the same common components

Hadronic Calorimeter

Measure the energy of high energy[†] hadrons

(π^\pm , K^\pm , p/\bar{p}), used (with EM calo.) to build “jets”

[†] Typically $E_T > 100$ MeV

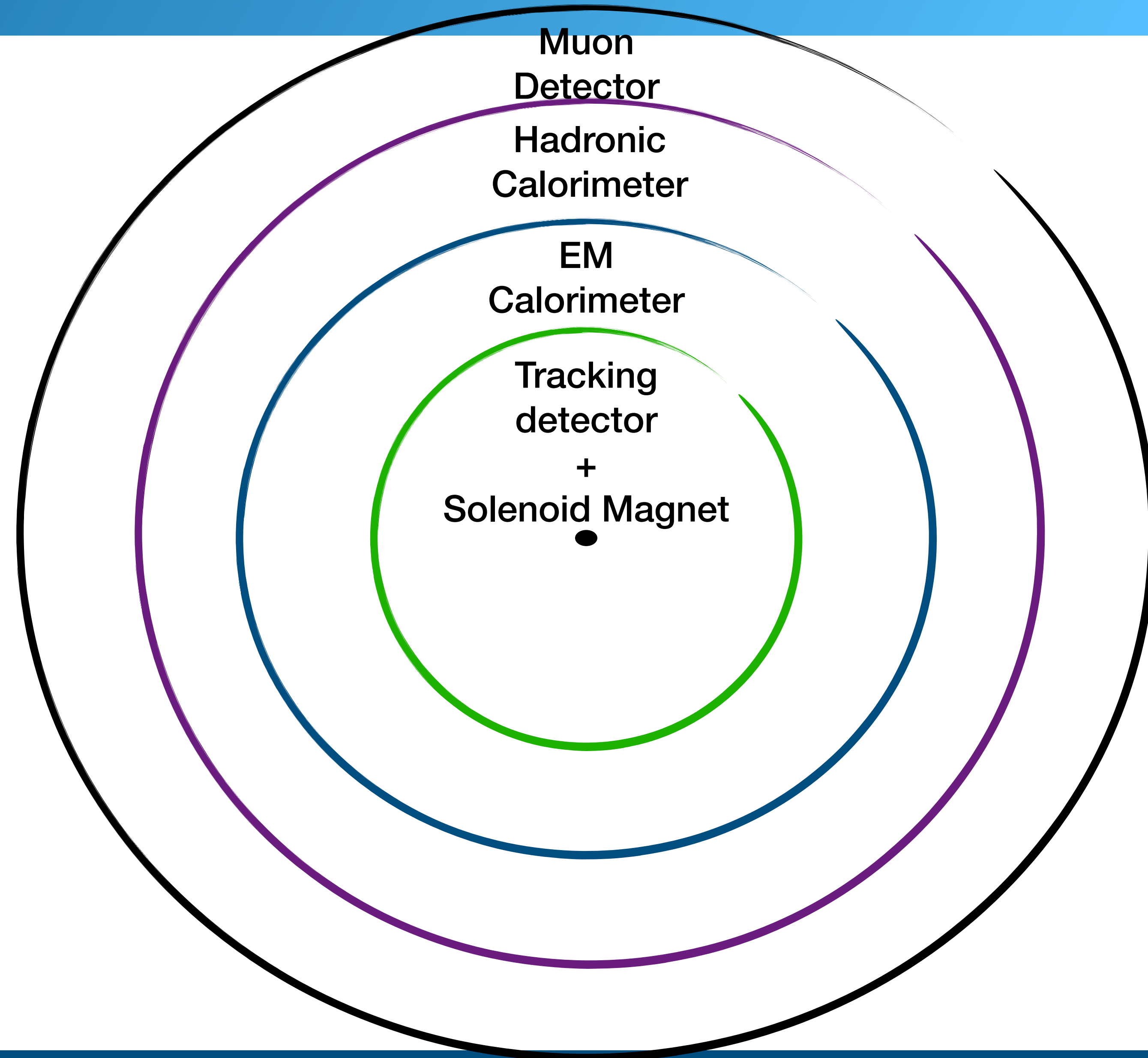


General Purpose Detector Overview

Most general purpose hadron collider detectors (GPDs) (e.g. ATLAS, CMS, CDF, DØ, UA1) share the same common components

Muon Detector

Detect muons with momentum sufficient to traverse calorimeters, sometimes a dedicated magnet system is present to measure momentum and charge

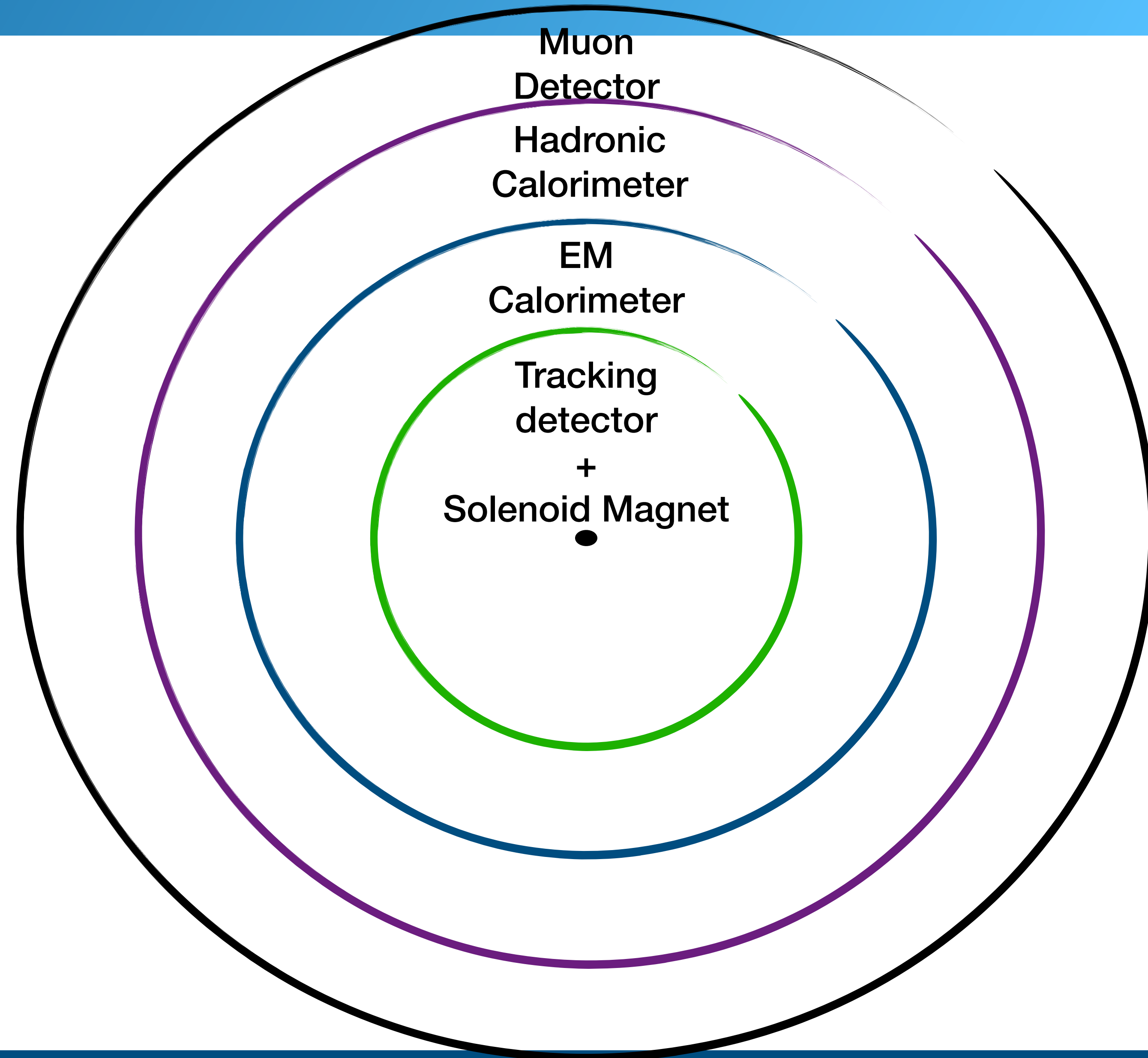


General Purpose Detector Overview

Most general purpose hadron collider detectors (GPDs) (e.g. ATLAS, CMS, CDF, DØ, UA1) share the same common components

+ **Trigger**

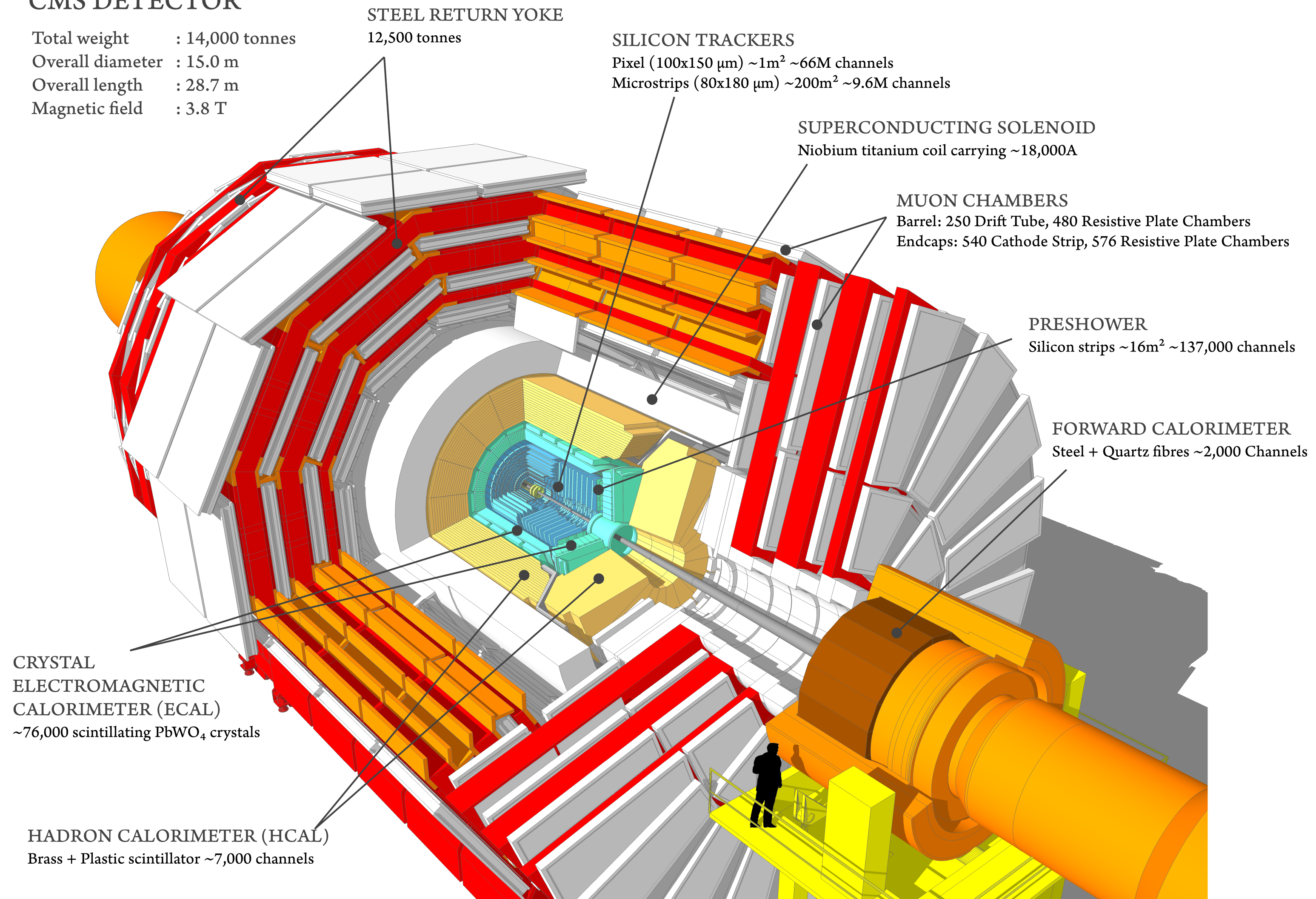
System to perform first coarse selection of “interesting” events to reduce raw collision data rate ($O(10 \text{ MHz})$ at LHC) to a manageable rate ($O(100\text{Hz})$ at LHC) for permanent storage and offline analysis



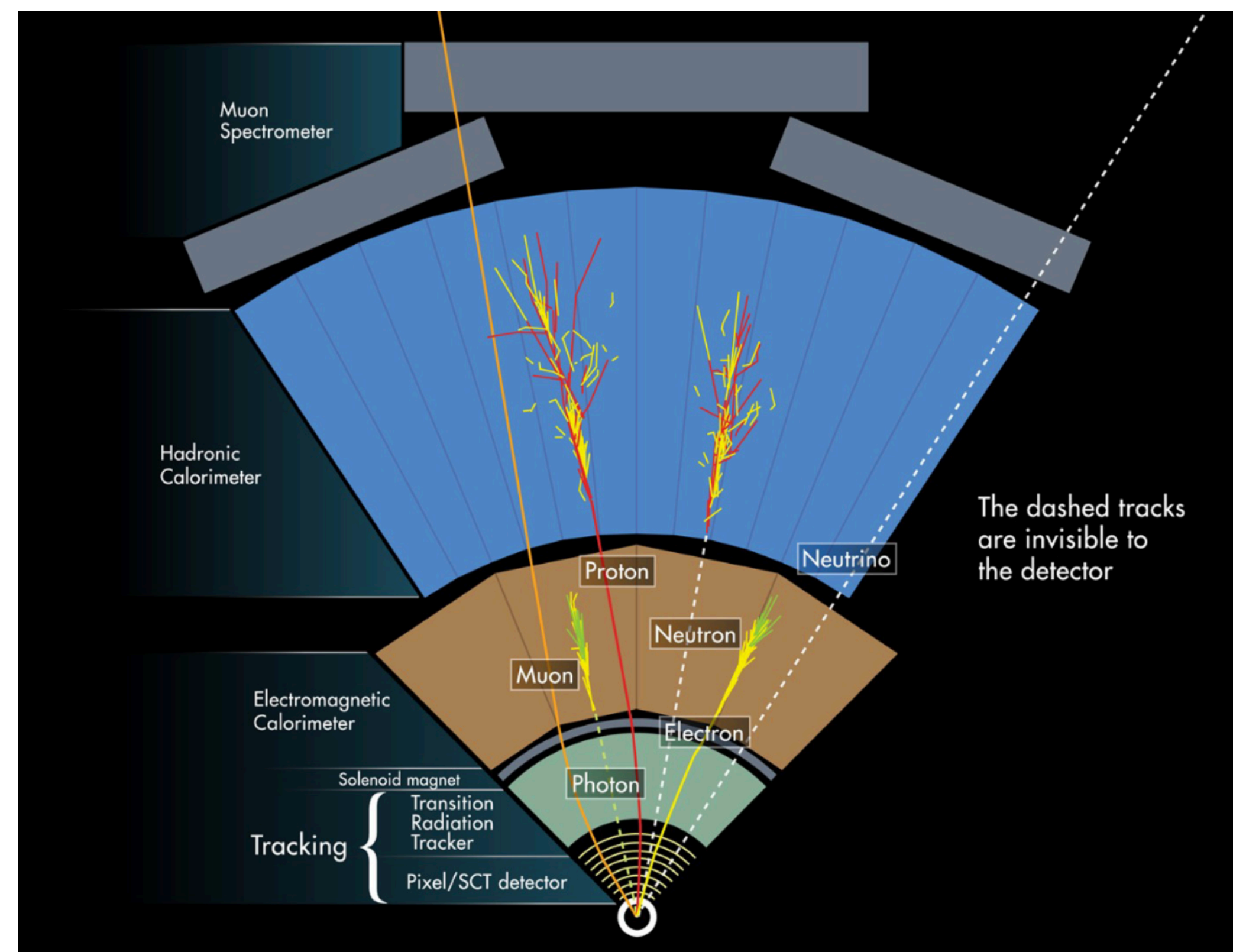
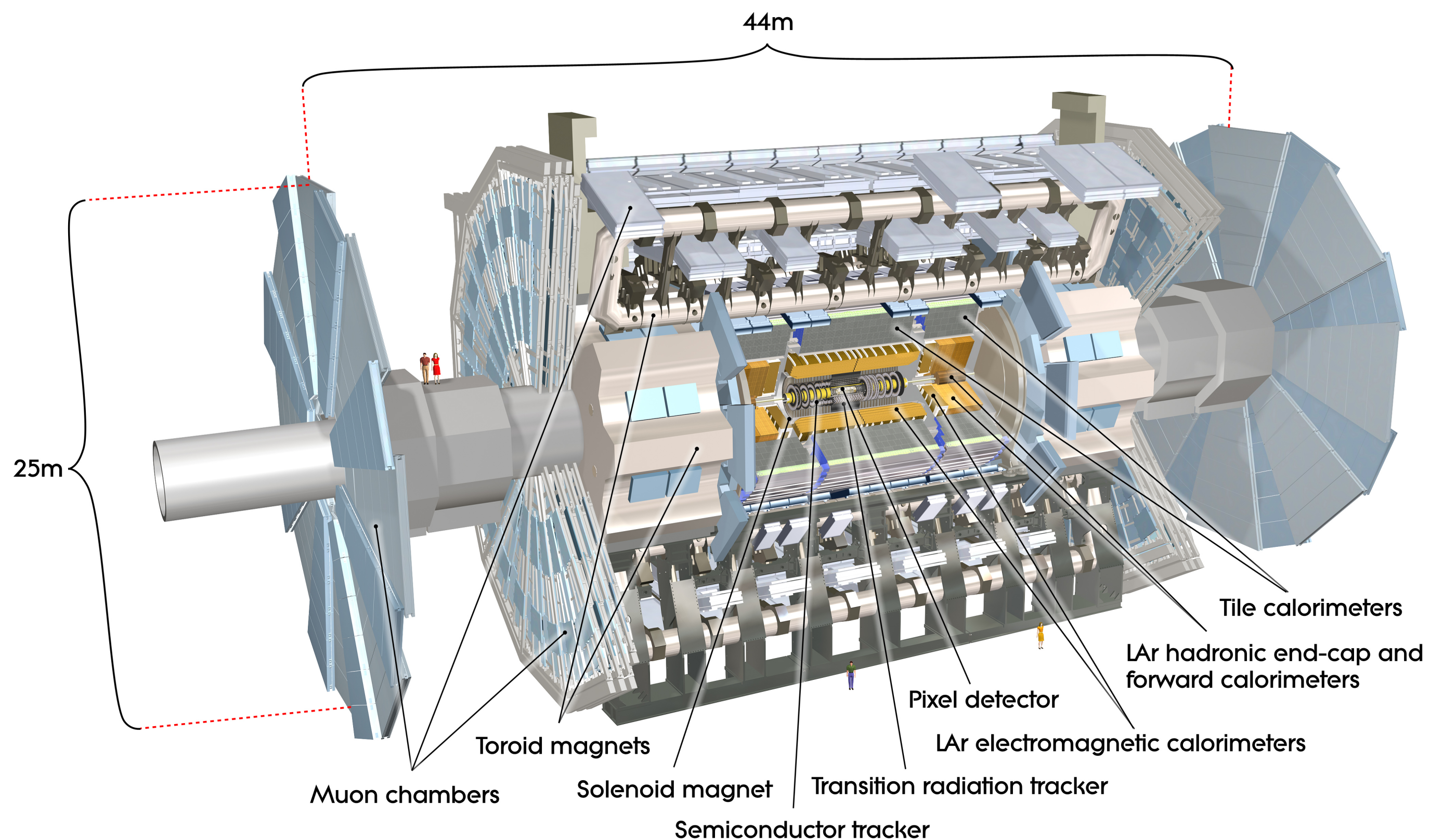
CMS detector

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



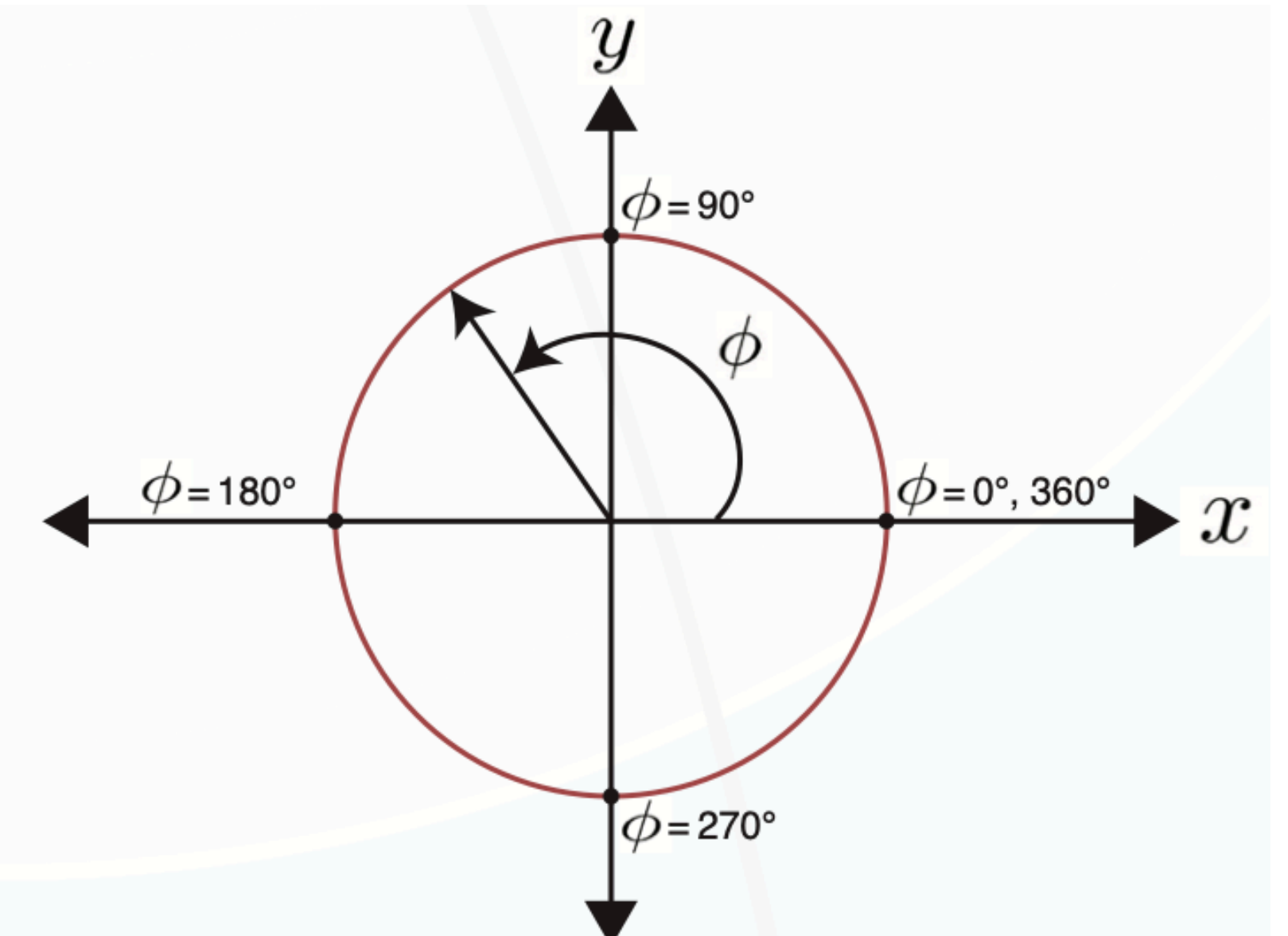
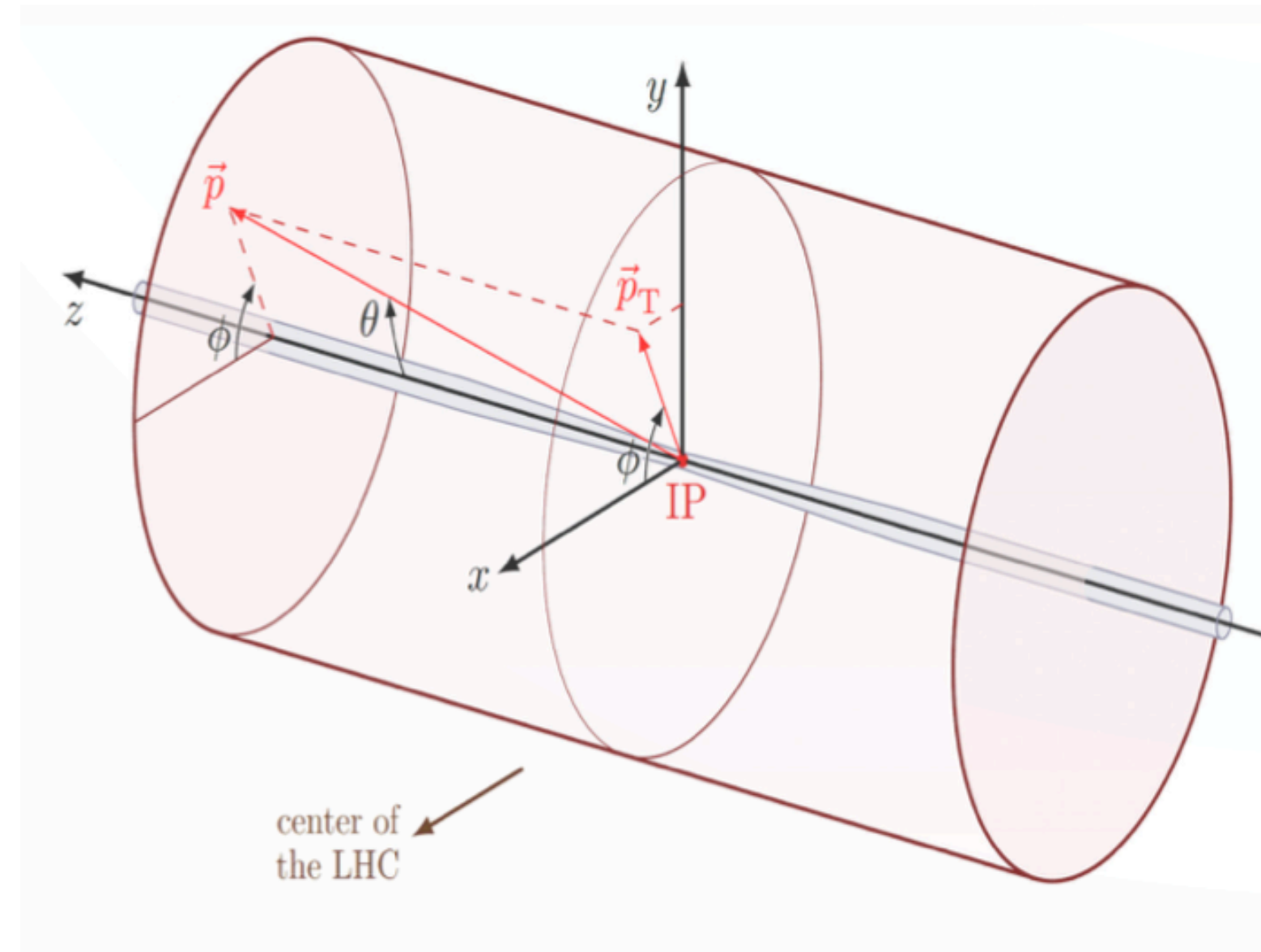
ATLAS detector



Coordinate System and kinematic variables

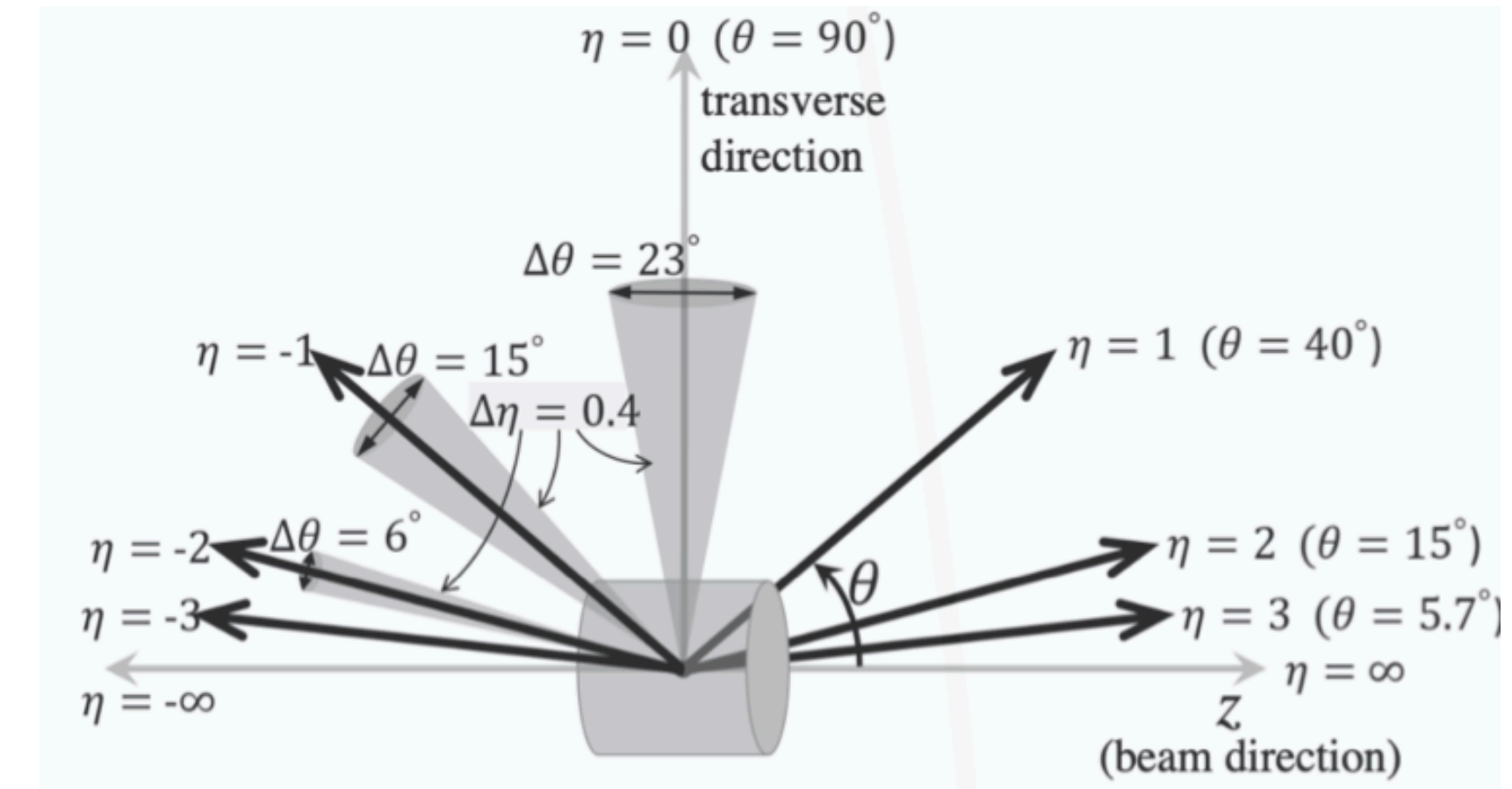
Figures Source: ATLAS Coordinate System - ATLAS Cheat Sheet

- Due to proton's composite nature, p_z and total energy, E , are not very useful
- Transverse momentum
 $p_T = \sqrt{p_x^2 + p_y^2}$, in the initial pp system is $\simeq 0$, so for the produced particles we can assume $\sum_i p_T^i = 0$
- Polar angle, θ , is not Lorentz invariant, so we instead use rapidity, y , and pseudo-rapidity, η , because Δy , $\Delta \eta$ are Lorentz invariant

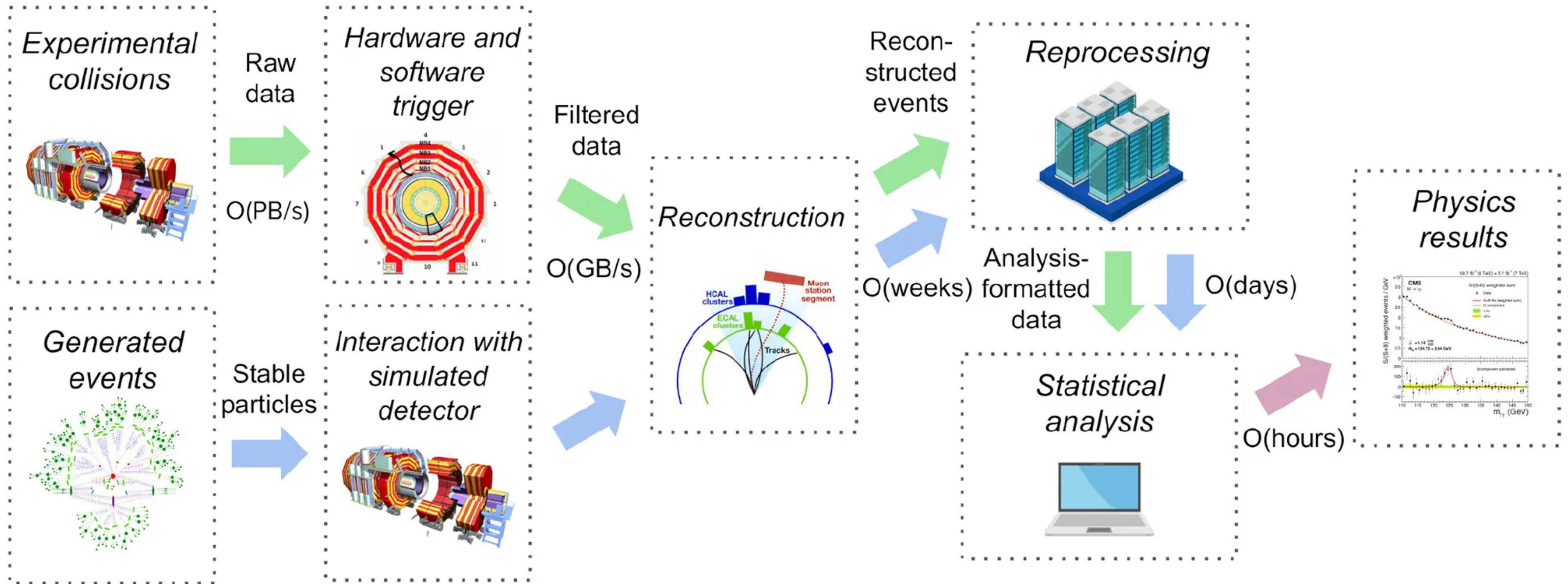


$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

$$\eta = \frac{1}{2} \ln \left(\frac{|p| + p_z}{|p| - p_z} \right) = -\ln \left[\tan \frac{\theta}{2} \right]$$



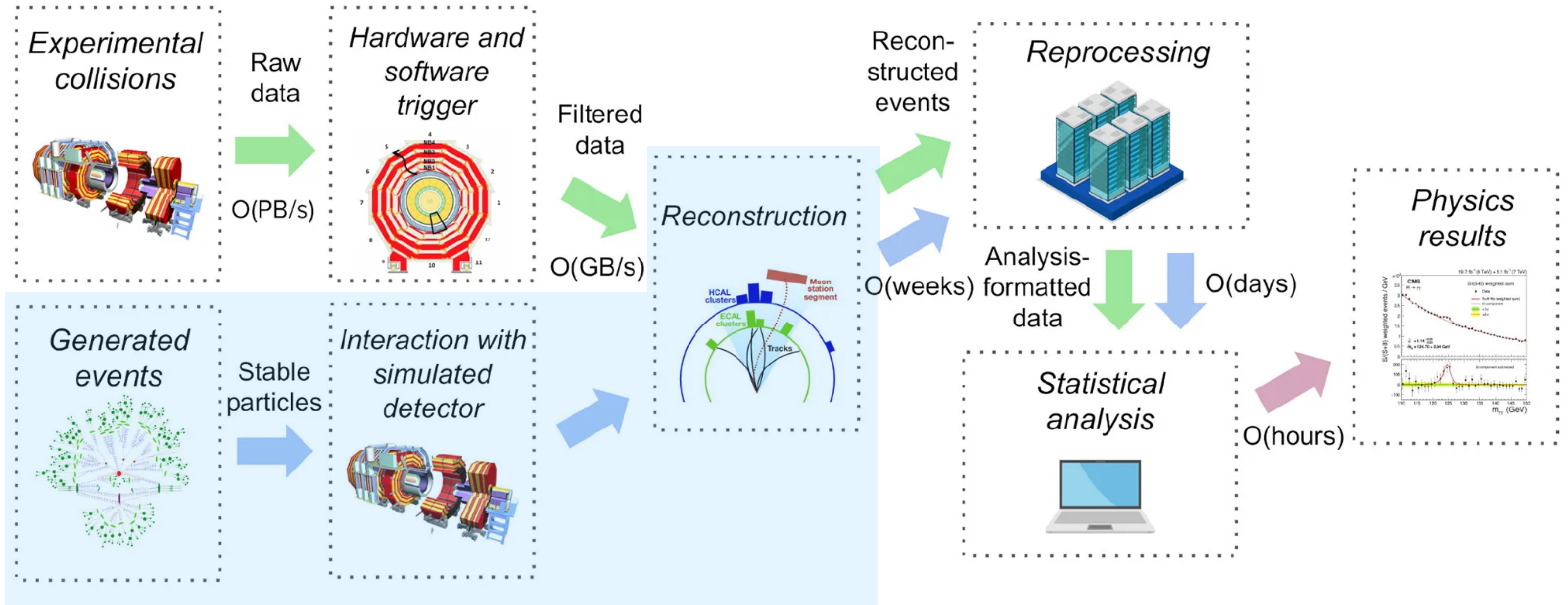
Steps in HEP analysis



Source: Scalable Declarative HEP Analysis Workflows for Containerised Compute Clouds

DOI: [10.3389/fdata.2021.661501](https://doi.org/10.3389/fdata.2021.661501)

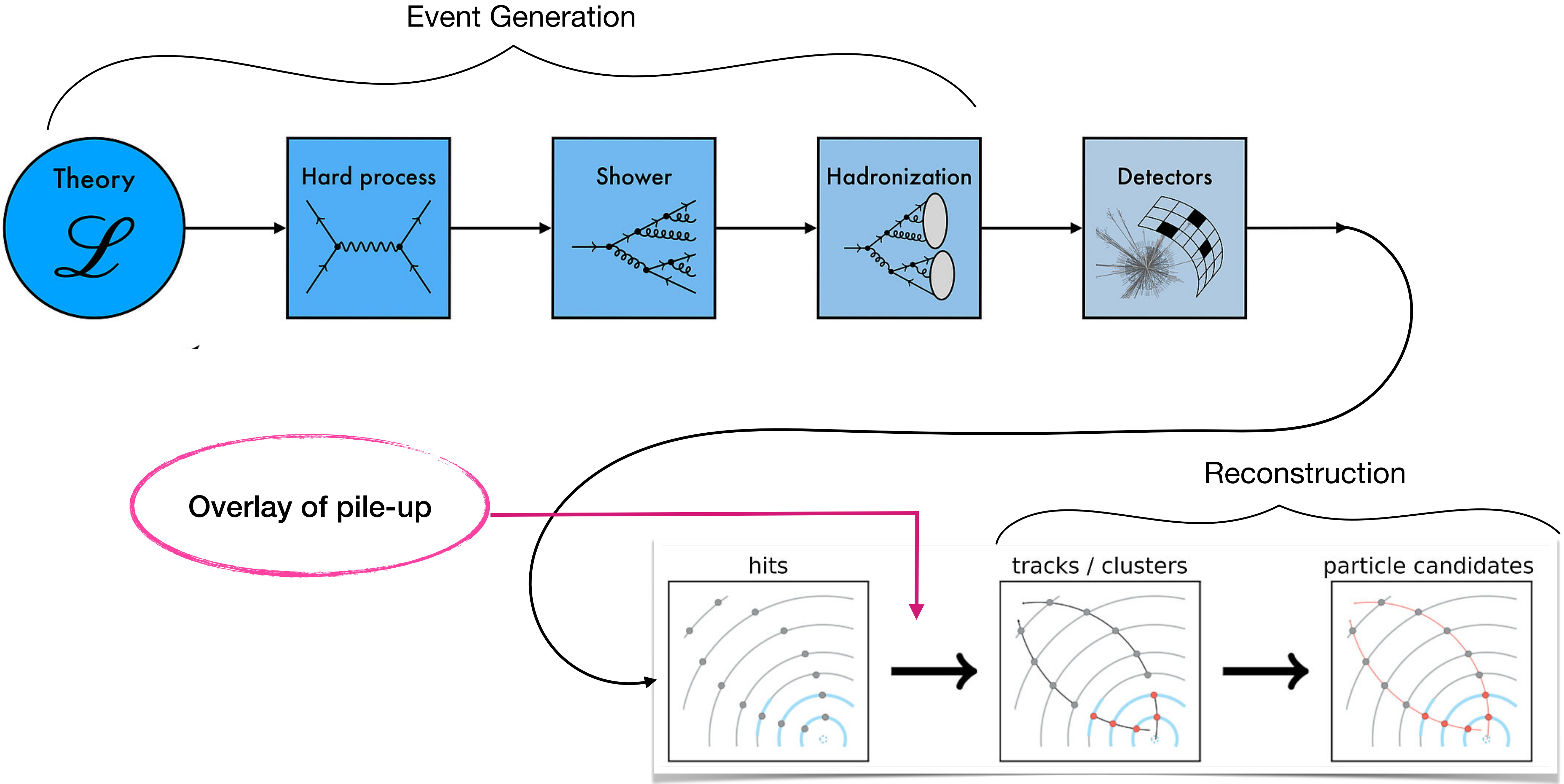
Steps in HEP analysis



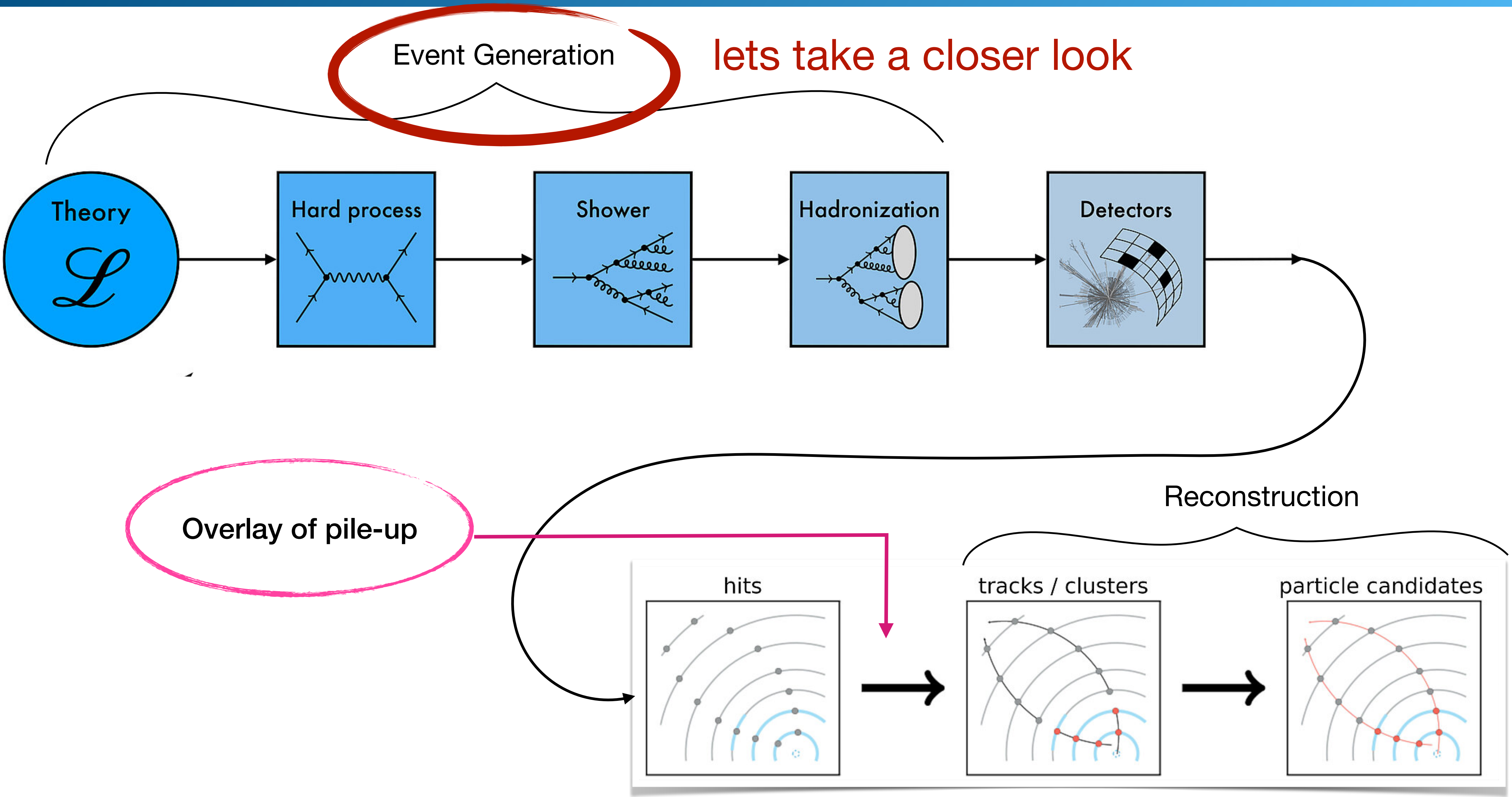
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Zoom-in in the MC production chain



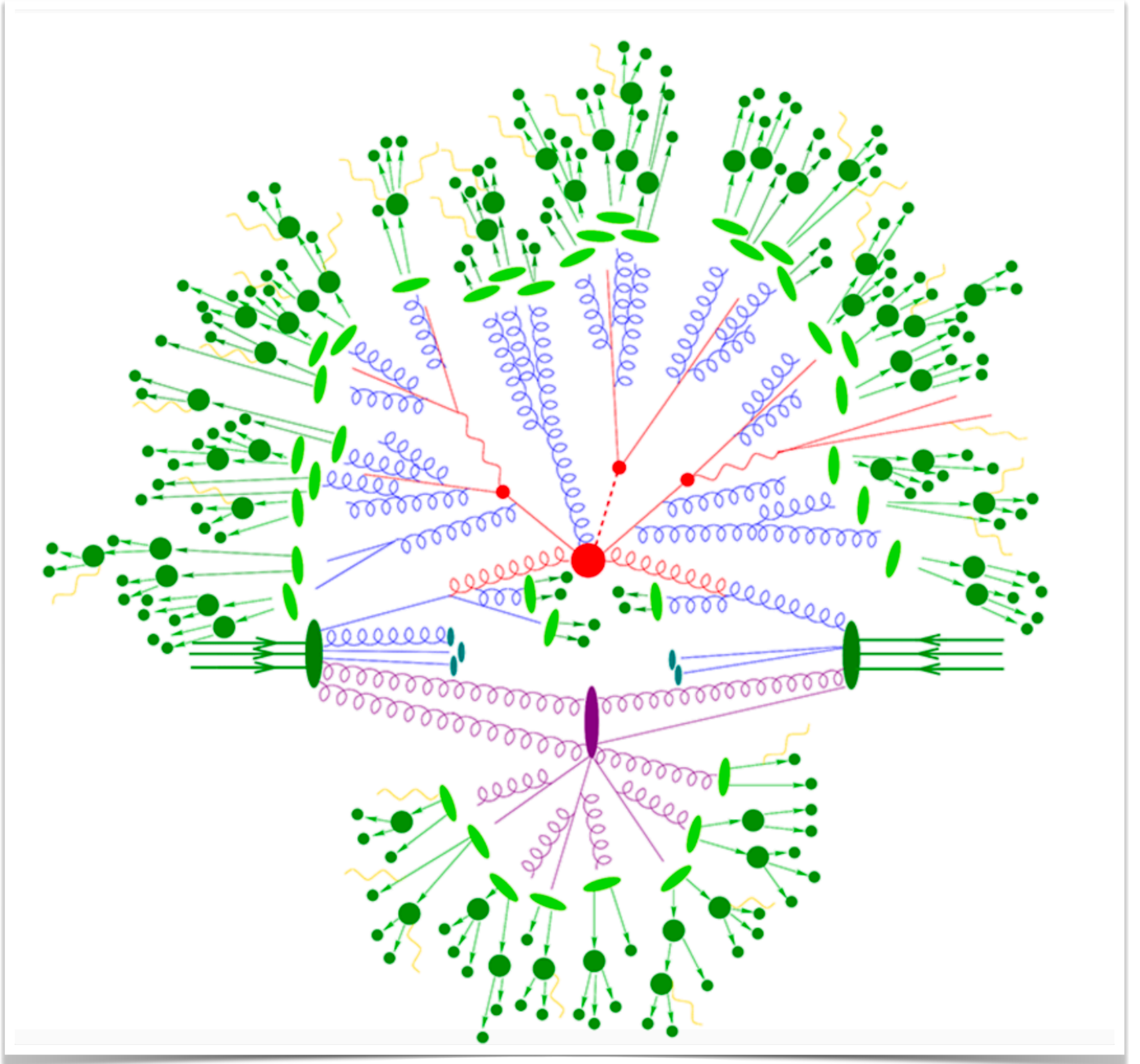
Zoom-in in the MC production chain



Event generation: a closer look

Listed in order of decreasing momentum transfer

- Hard scatter (red)
- Parton Shower (blue for ISR, red for FSR)
- Hadronisation (light green)
- Underlying event (purple)
- The yellow wavy lines represent electromagnetic radiation, which can be emitted at any stage by electrically charged particles.



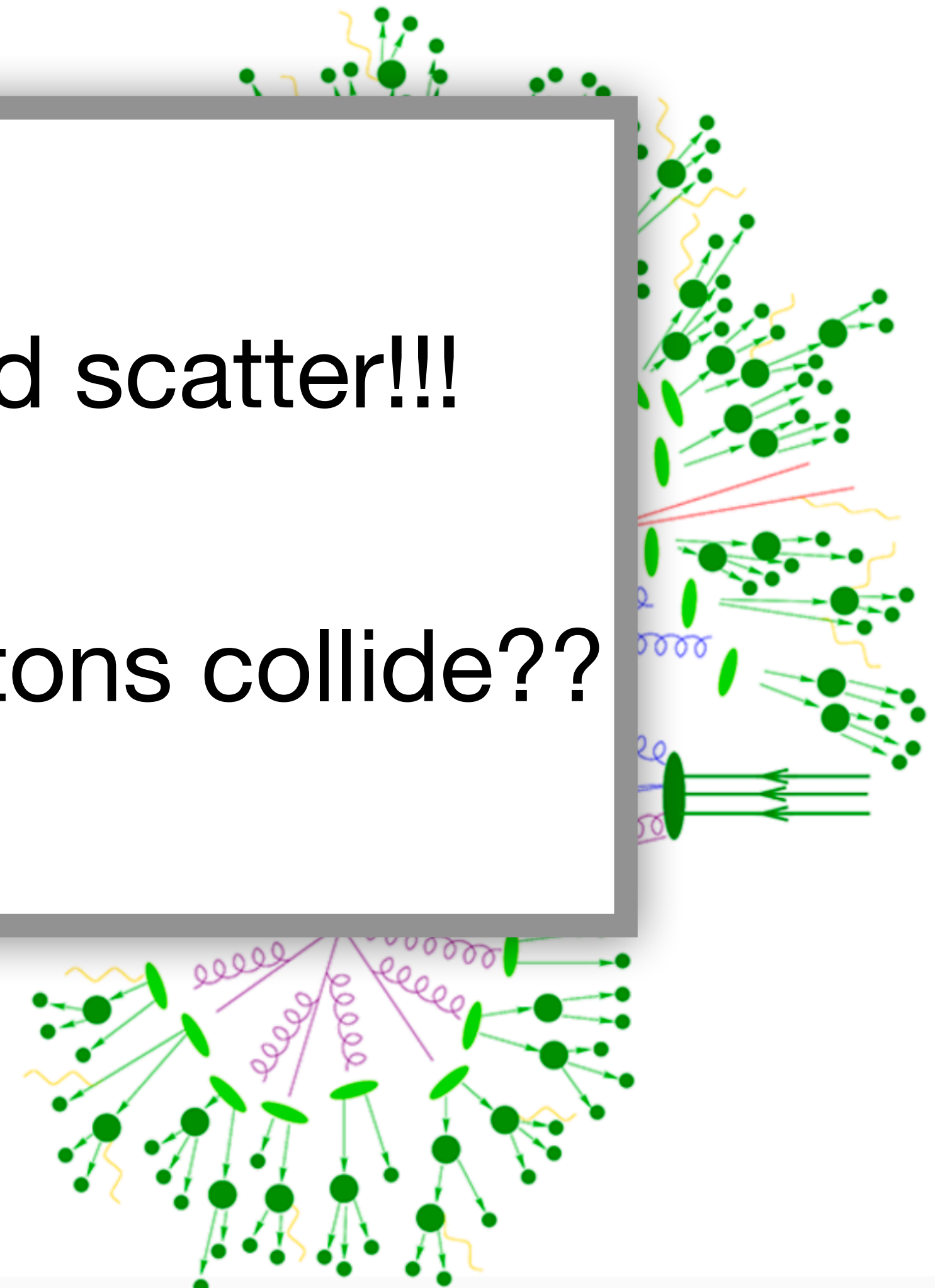
Event generation: a closer look

Listed in order of decreasing momentum transfer

- Hard scatter
- Parton Shower
- Hadronisation
- Underlying event
- The yellow electromagnetic emitted at any stage by electrically charged particles.

Not all pp collisions result in hard scatter!!!

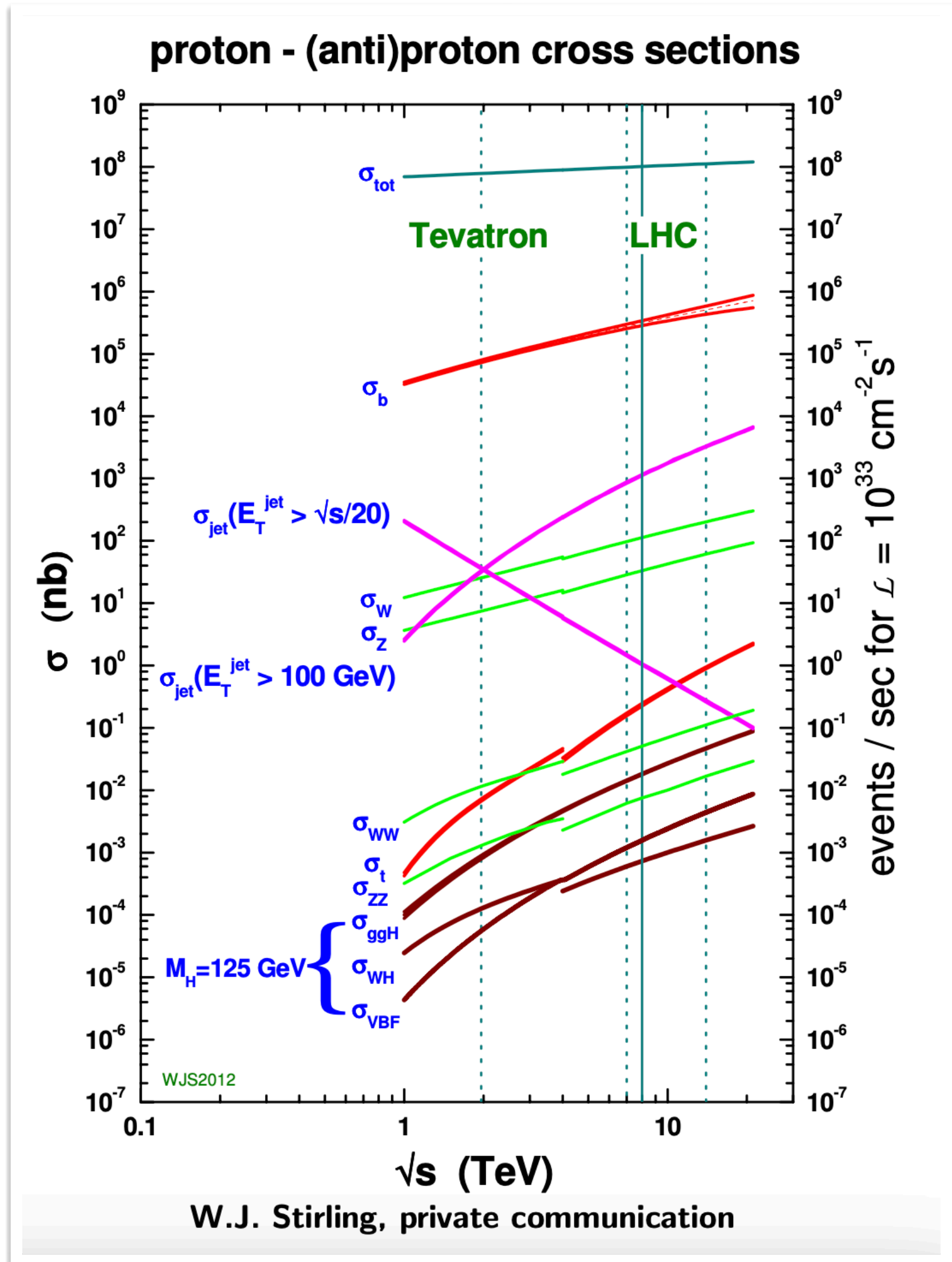
So what is happening when protons collide??



Event rates in pp collisions

- Total cross section varies slowly with the \sqrt{s} , @10TeV $\sigma_{tot} \approx 100$ mb
- Elastic pp collisions: $\sim 25\%$ of σ_{tot} —no new particles
- Inelastic collisions
 - $\sim 75\%$ of σ_{tot}
 - Can produce new particles
 - One or both protons break
- Cross-sections for “interesting” physics events (e.g. $X = H, W, Z, \gamma$) many orders of magnitude lower, but raise rapidly with \sqrt{s}

Figures Source: K. Jakobs, [arXiv:1206.7024](https://arxiv.org/abs/1206.7024)

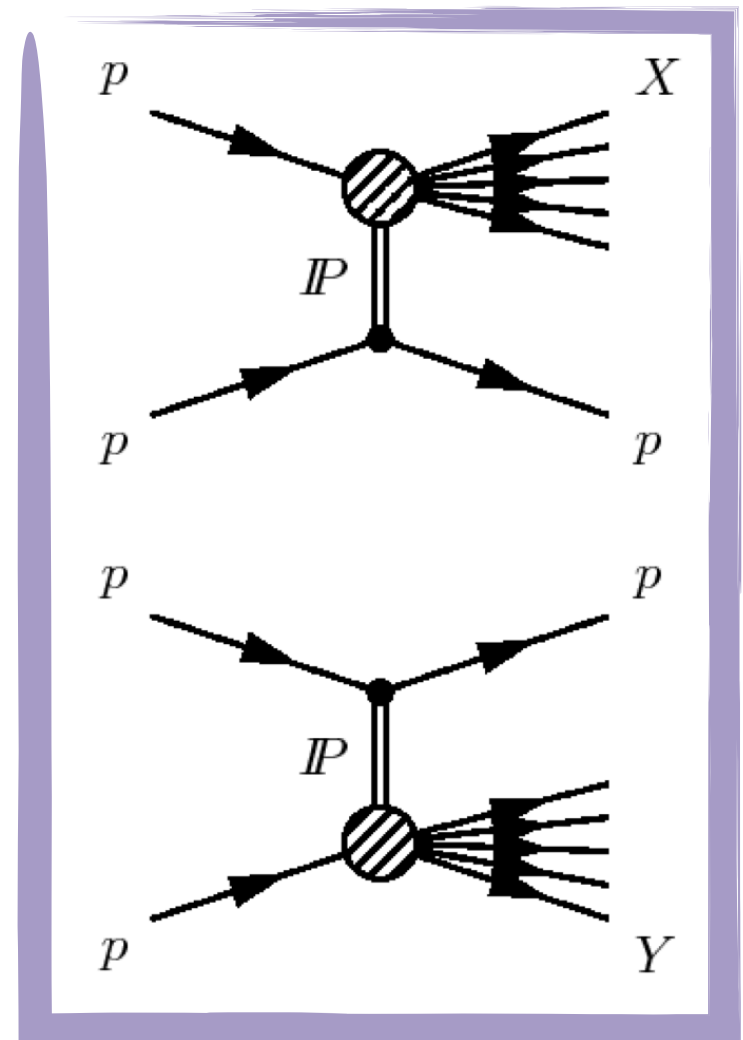


Inelastic pp collisions

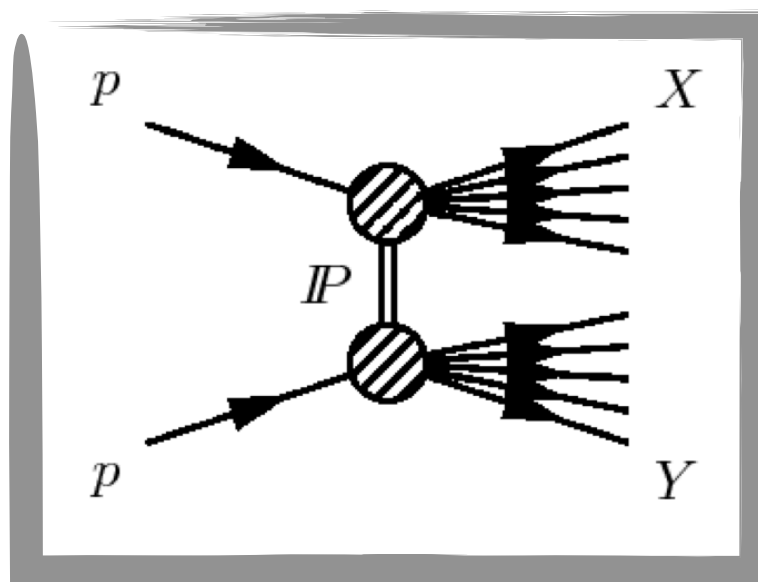
Diffractive events

- excitation of one or both protons into a high mass colour singlet state which decays to system X/Y
- no colour is exchanged
- localised (in y) production of new particles

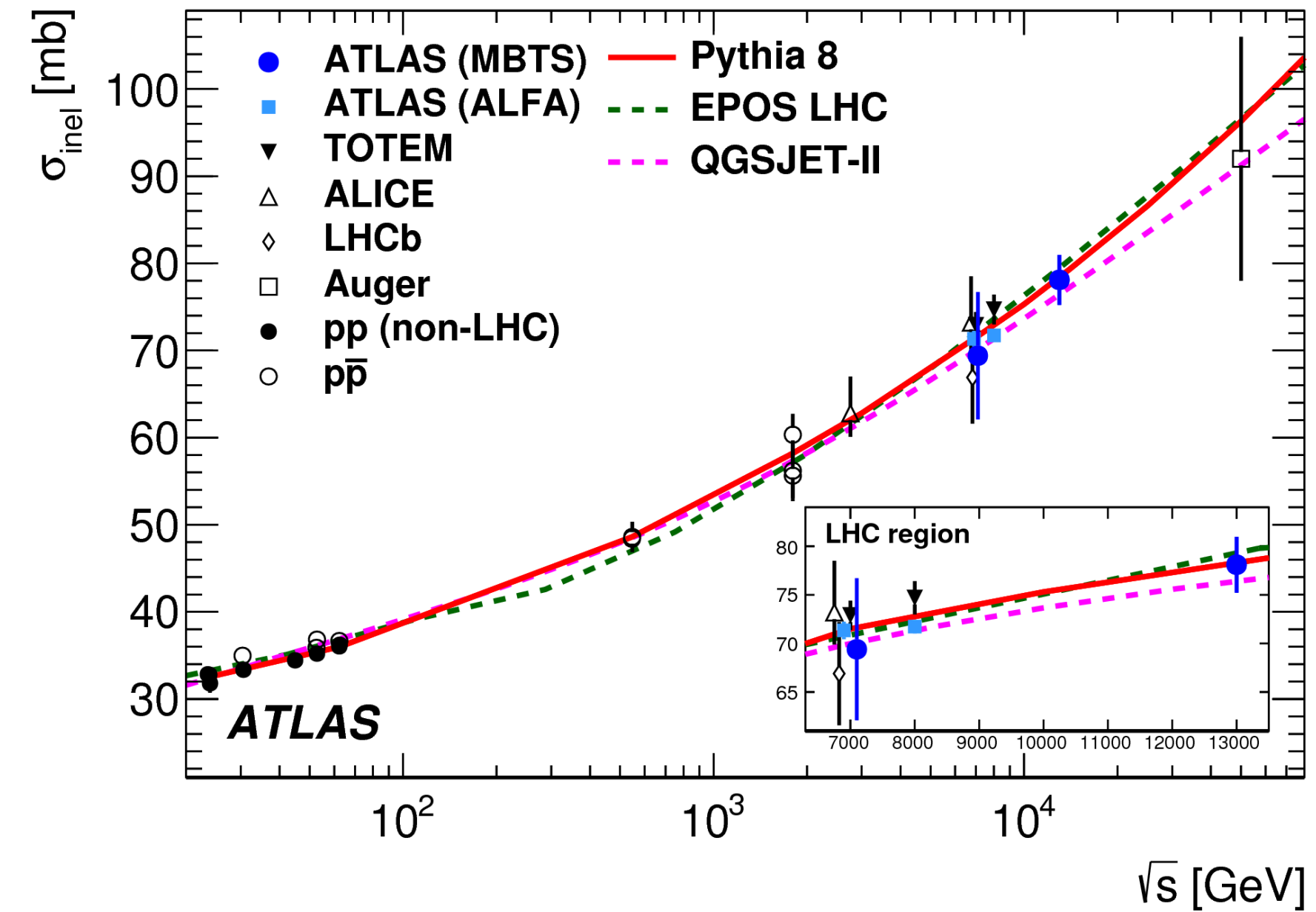
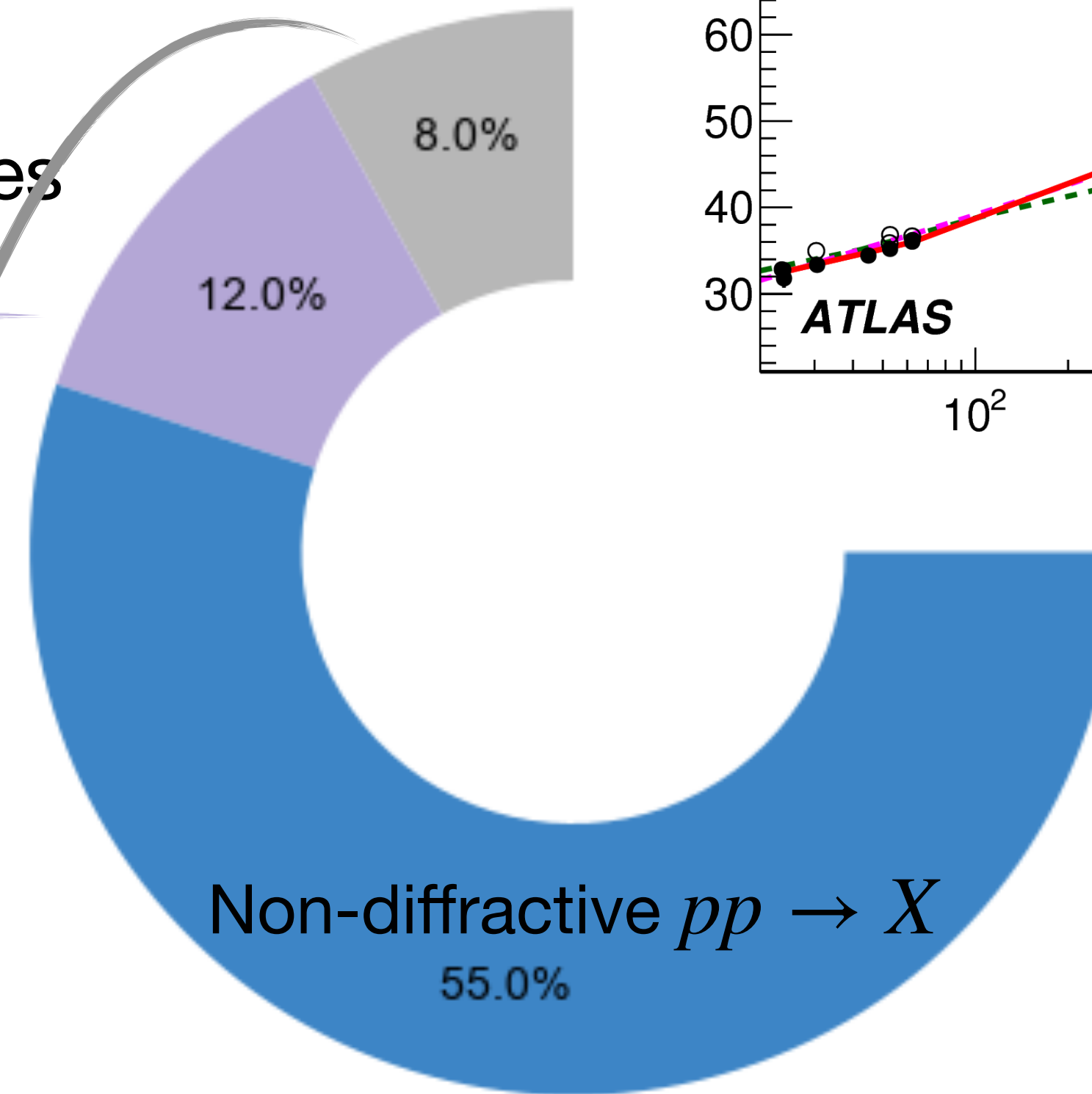
Single-diffractive



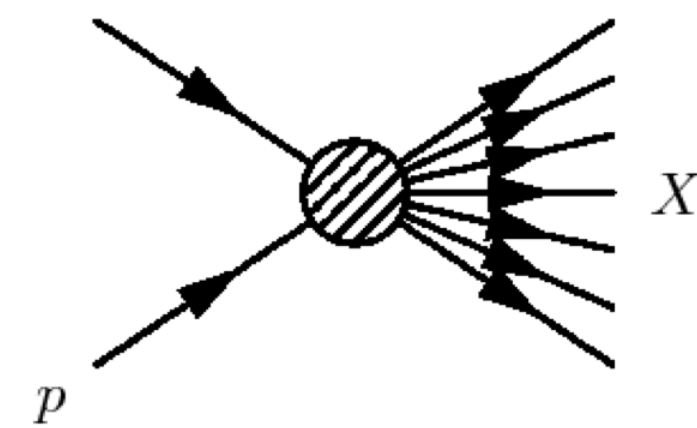
Double-diffractive



Images: ATLAS, STDM-2015-05



Non-diffractive

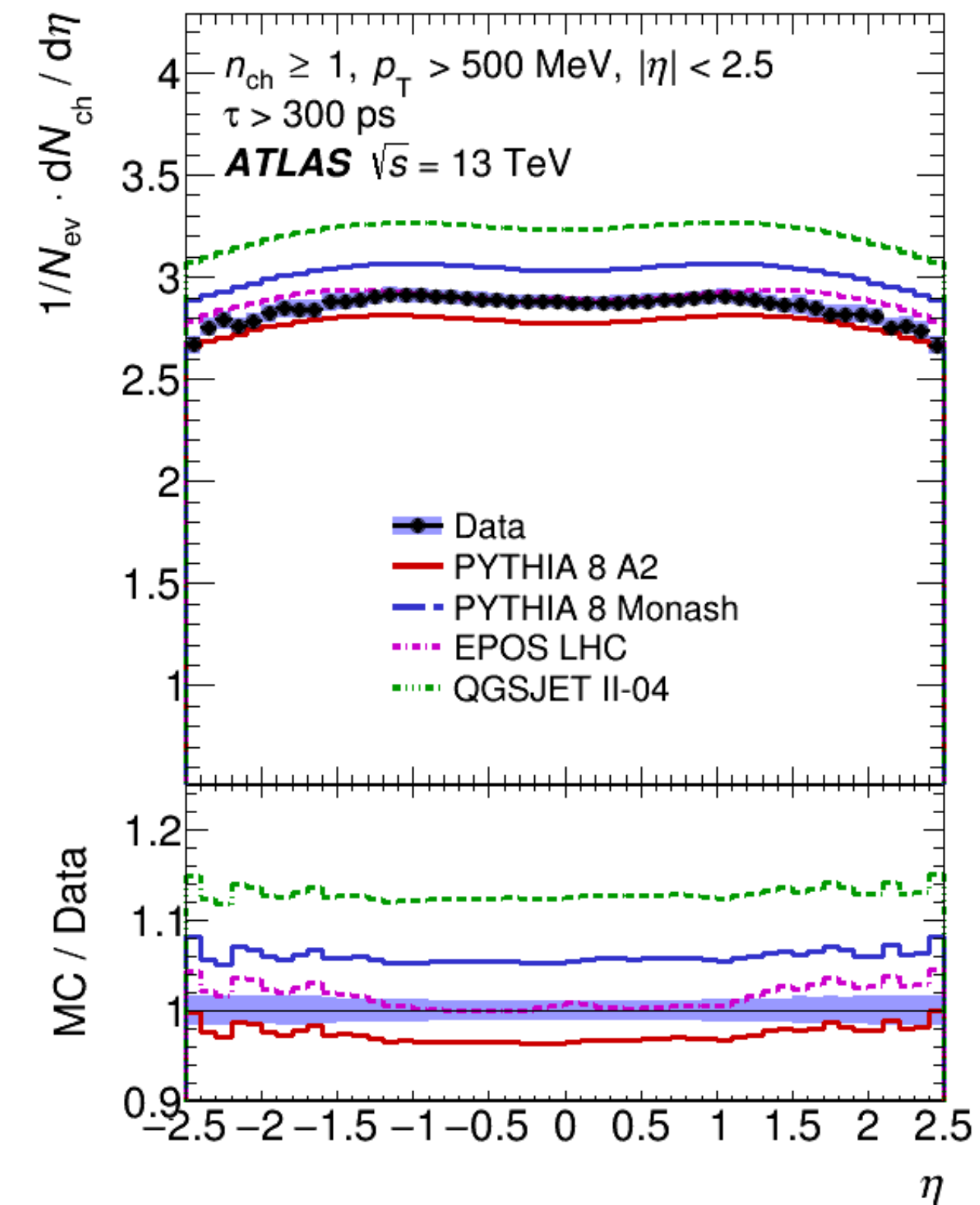
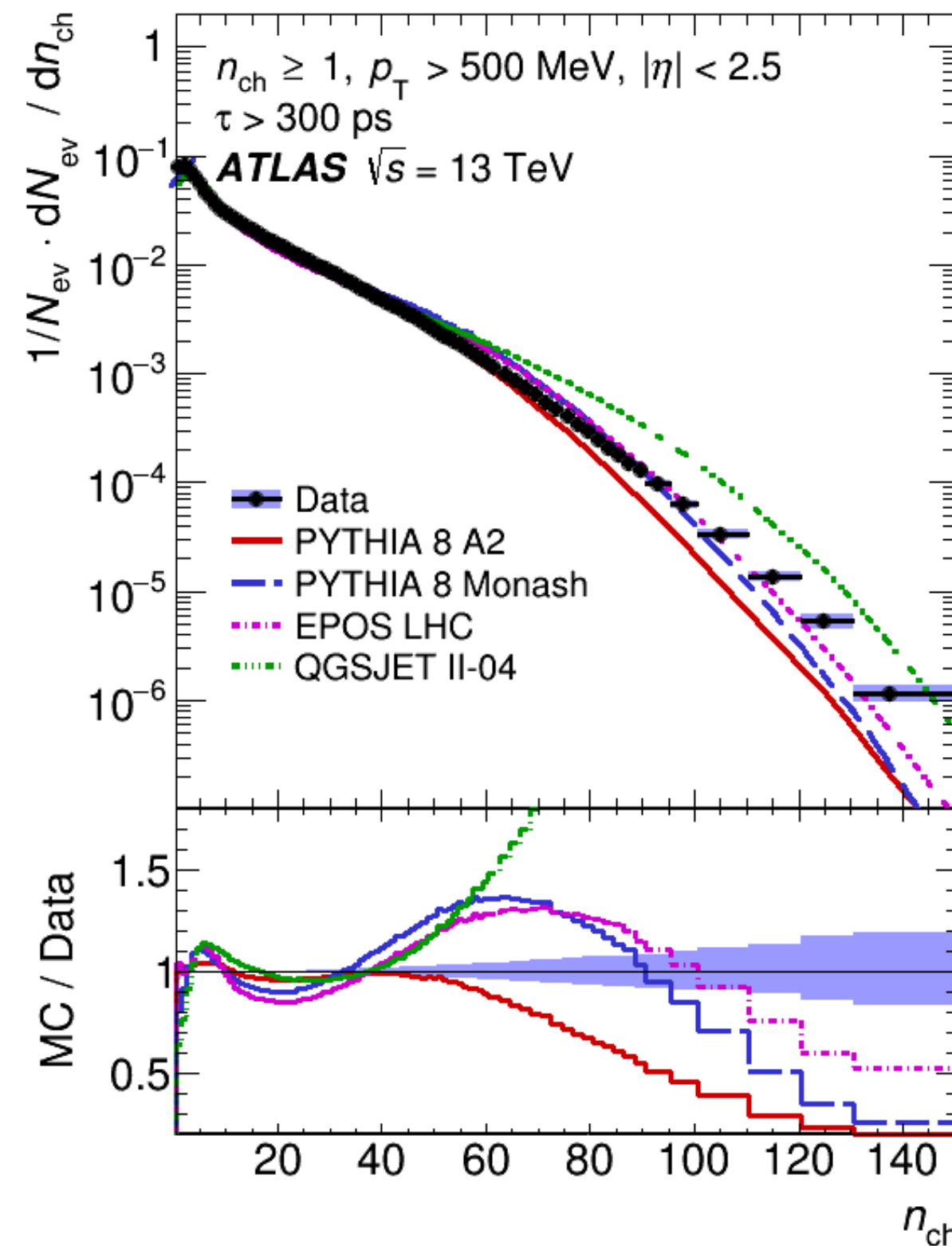
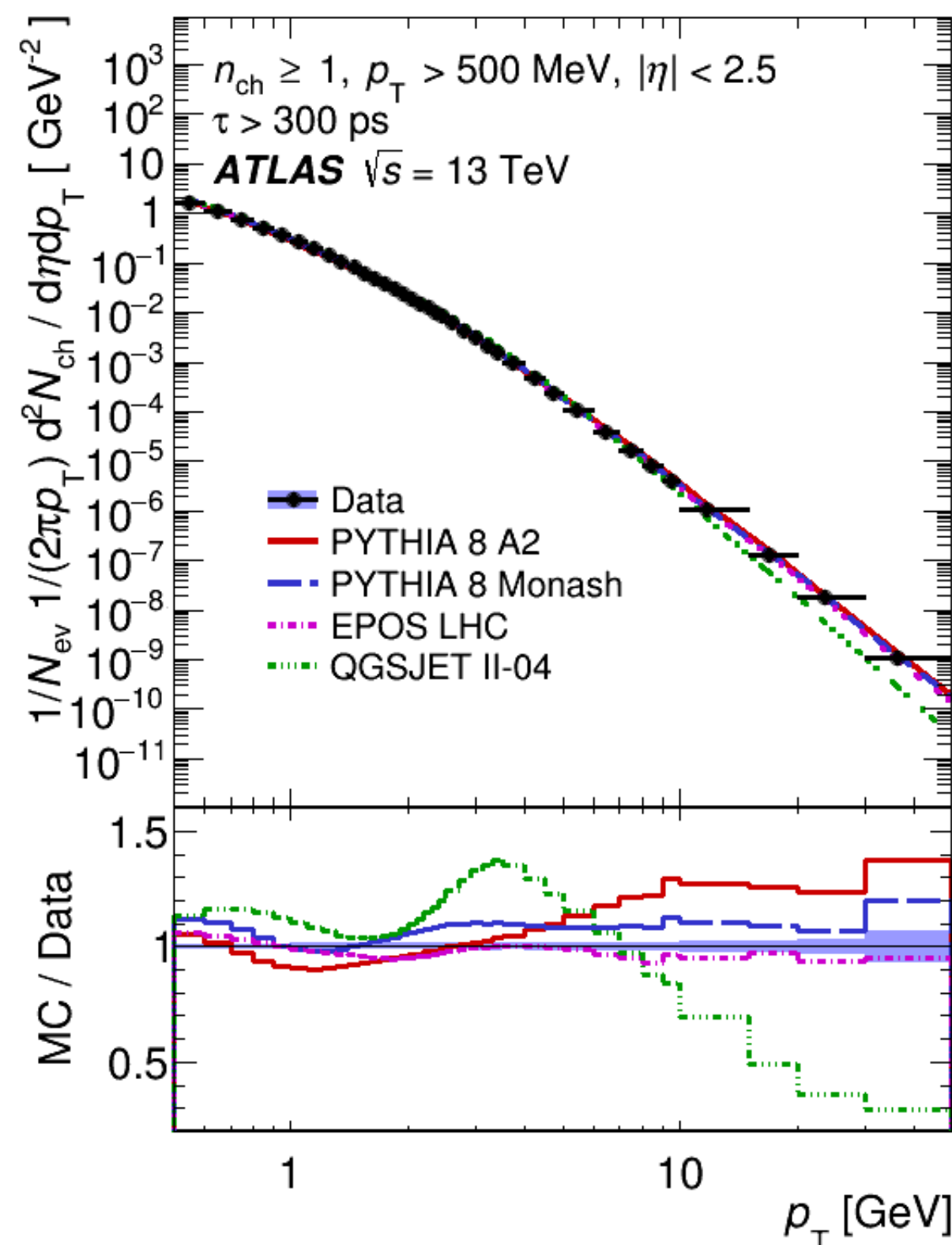


- colour exchange
- more uniform production of particles in y

Soft pp interactions

The majority of pp events @ LHC energies: soft non-diffractive processes, low particle multiplicity with low p_T hadronic activity

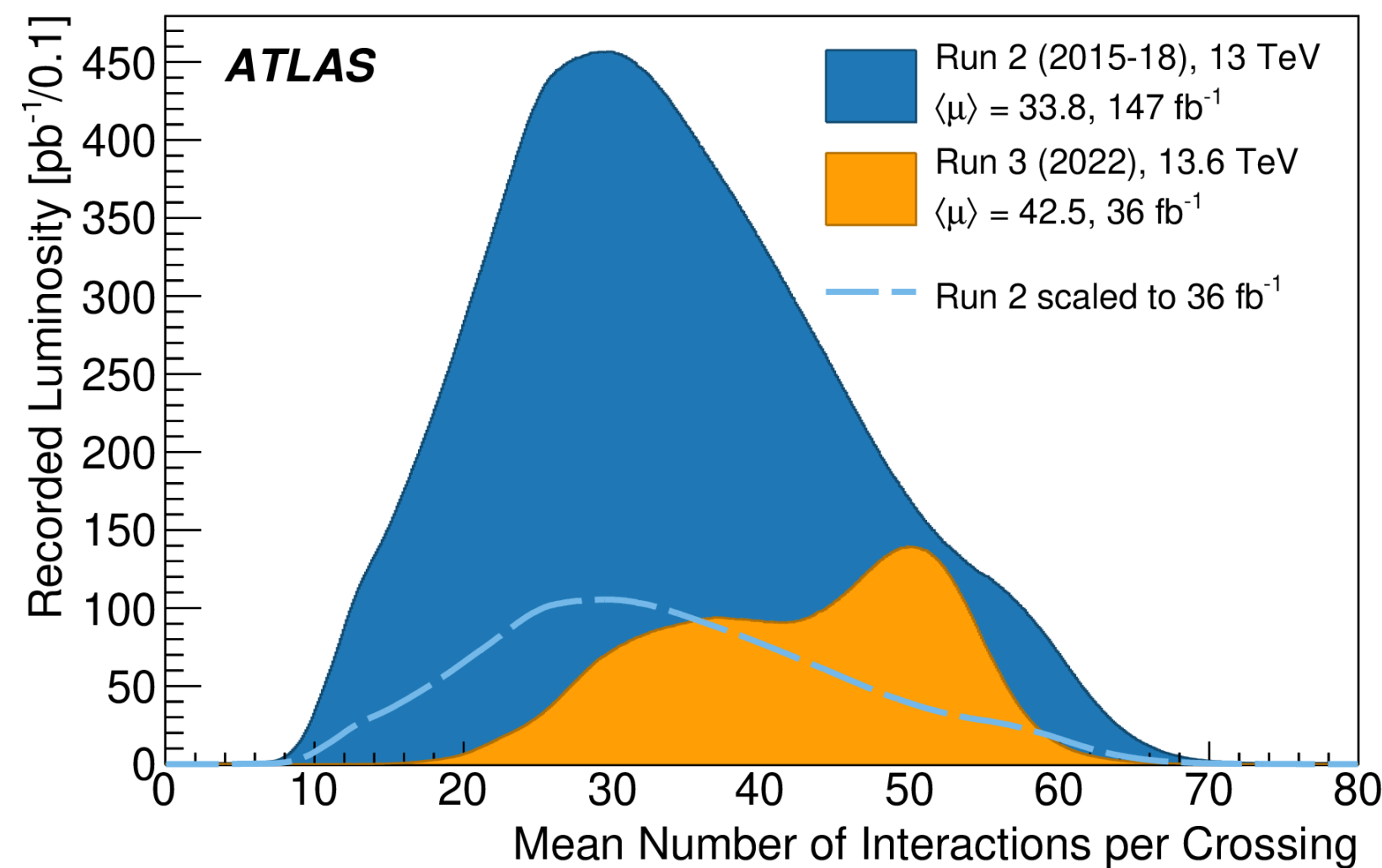
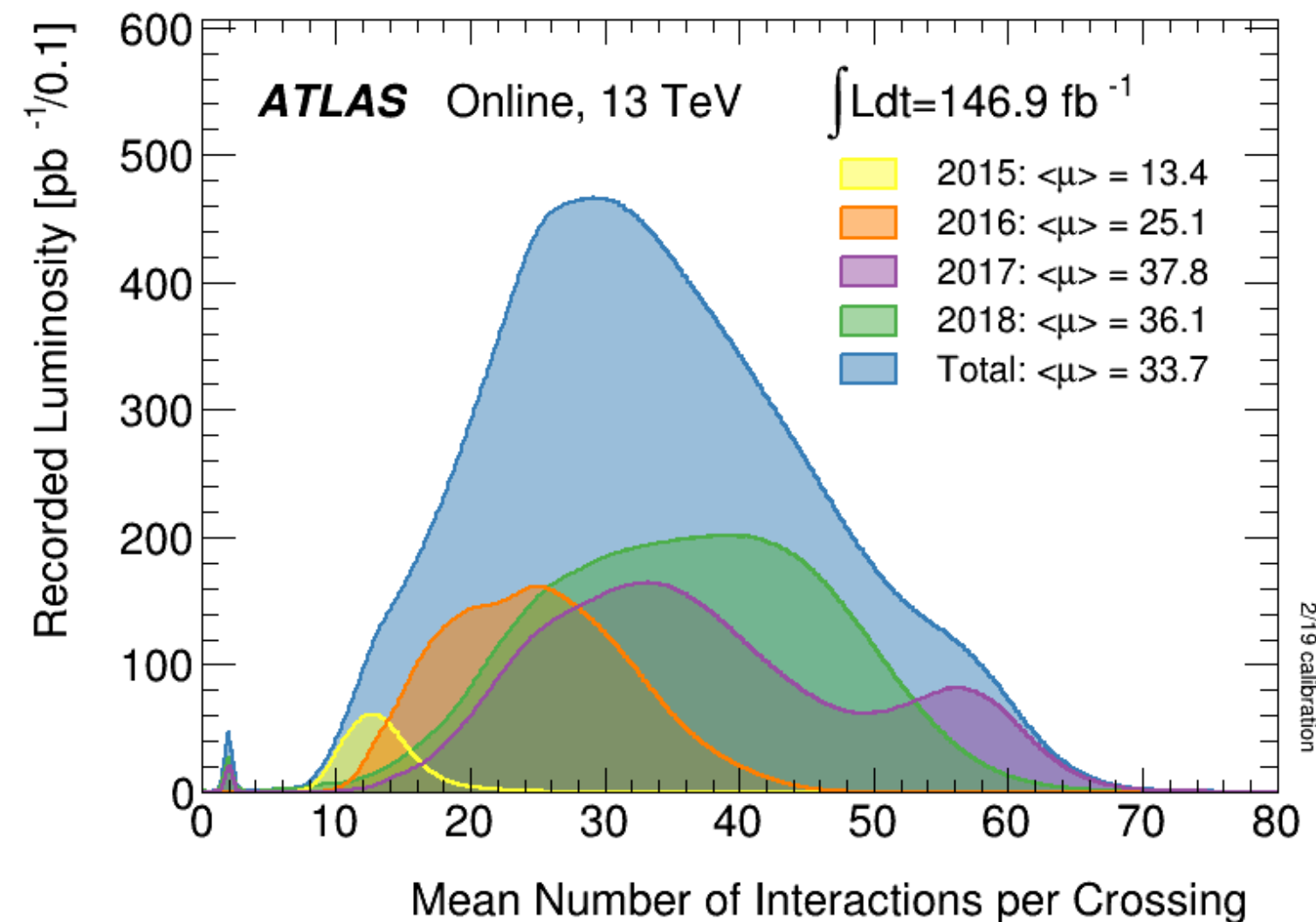
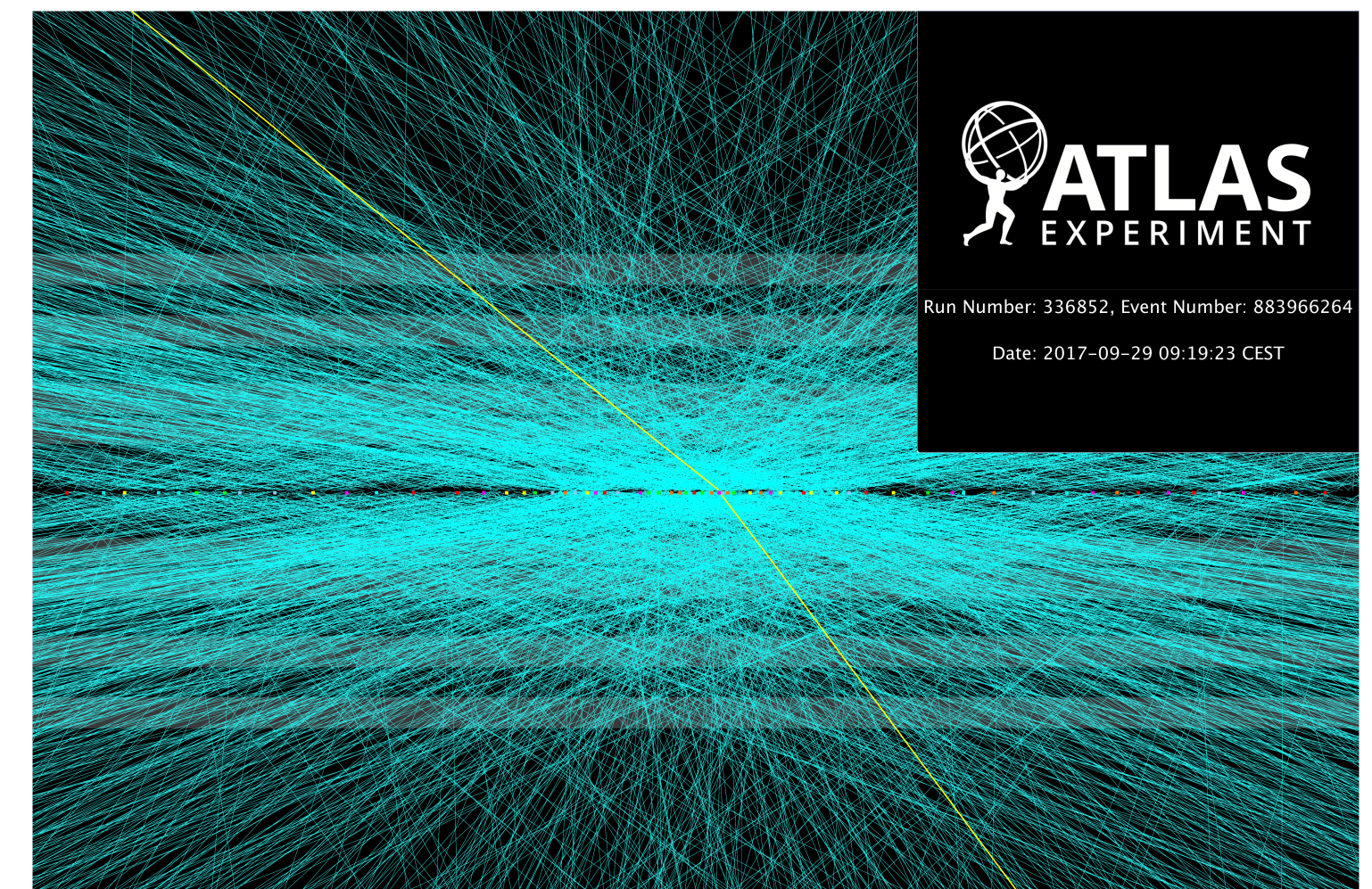
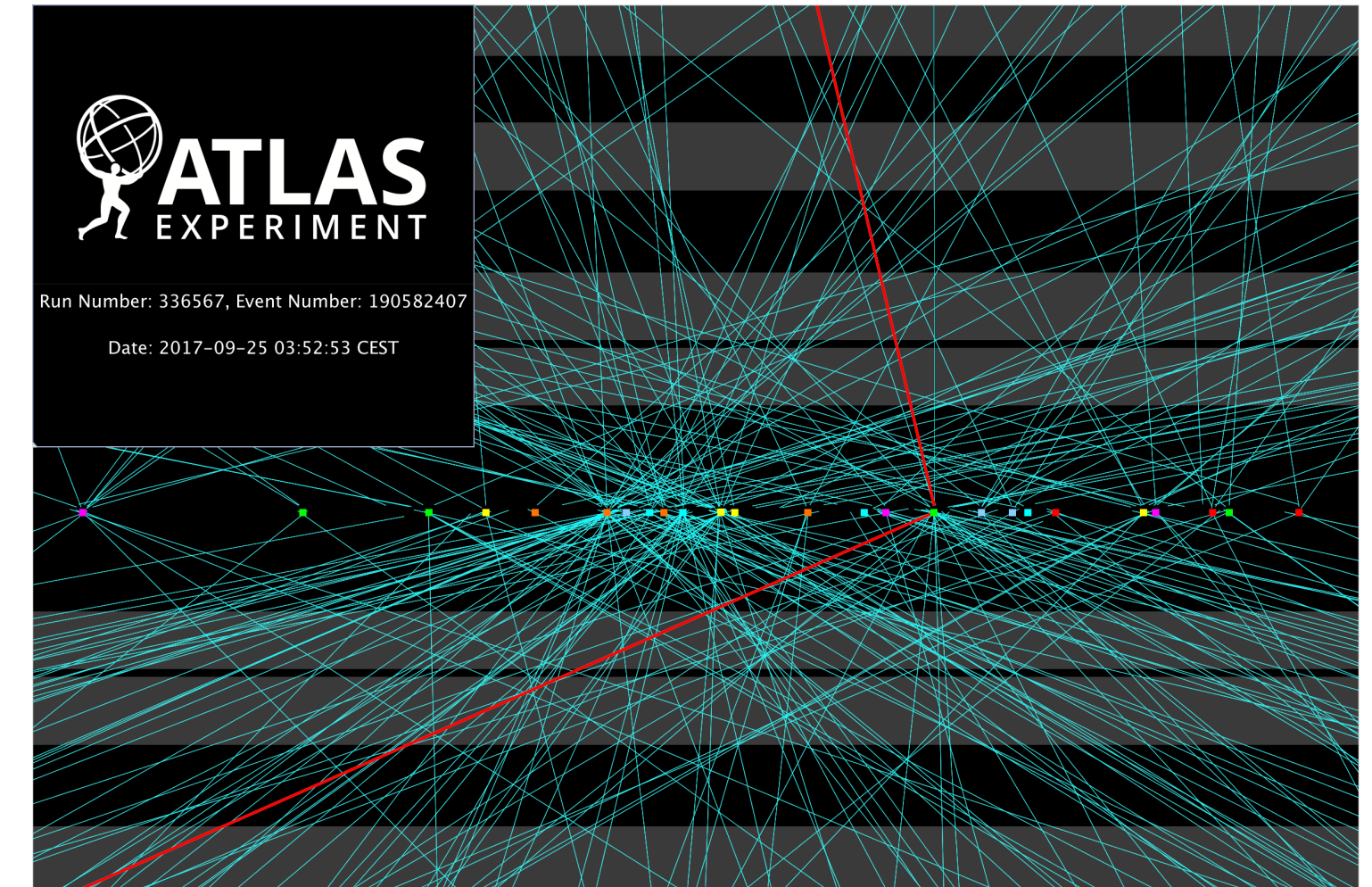
- “minimum bias” events: trigger requires minimal activity in the detector, such as a single low p_T track / calo. deposit
- Modelled semi-empirically with MC generators which are “tuned” to data, predictions can vary quite a bit among generators / data used for tunes



Events with multiple pp collisions

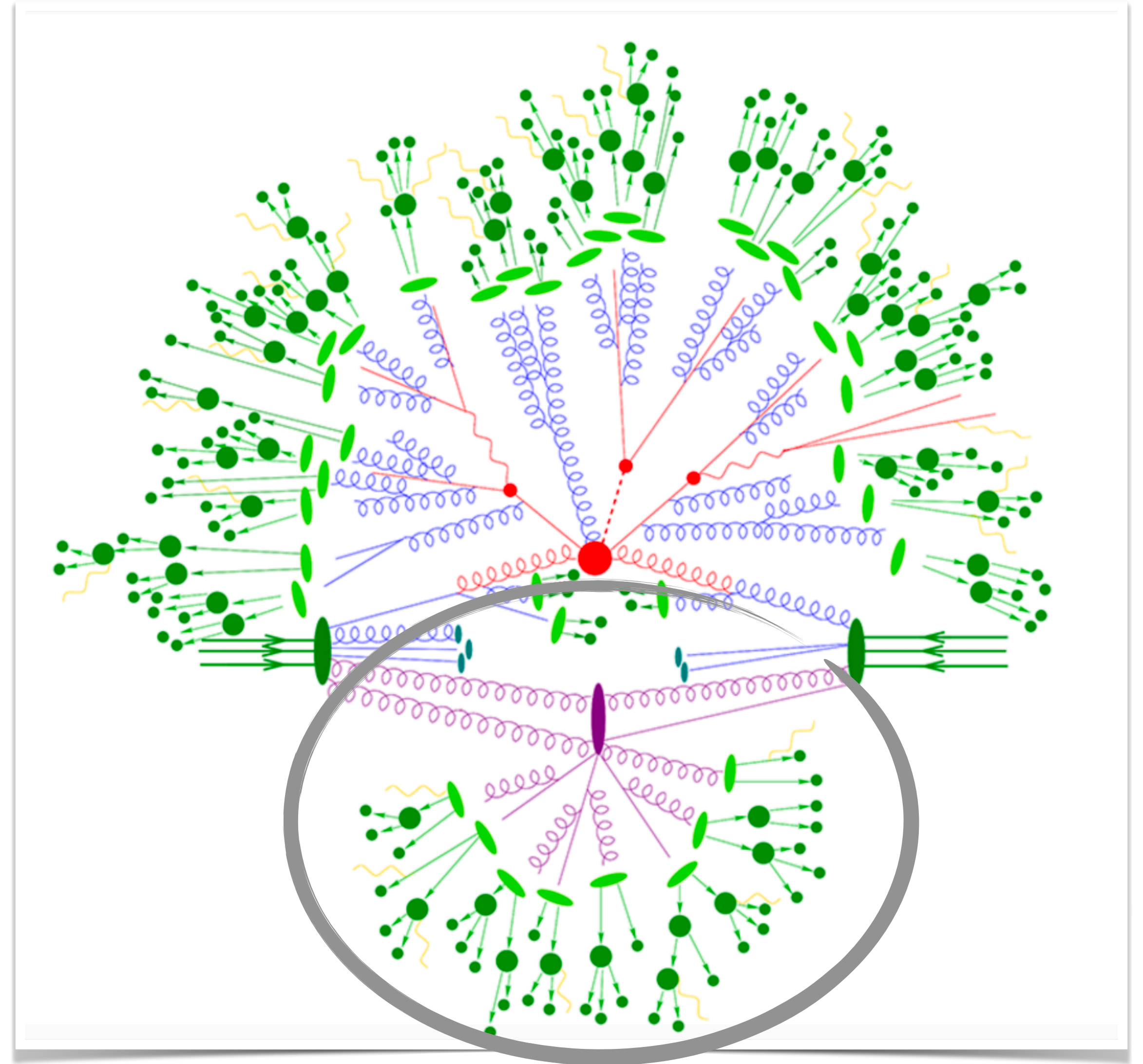
- Given the high density of nominal LHC bunches (1011 protons/bunch), multiple independent pp interactions in a single bunch crossing (“pile-up”) are common
 - Most of these interactions are soft non-diffractive collision events, critical to understand their behaviour!
 - This phenomenon presents a wide variety of challenges for triggering, event reconstruction and physics analysis...

$Z \rightarrow \mu\mu$ events, Run2, 25 and 65 pile up interactions



The underlying event

- In hard pp scattering events, the underlying event (UE) consists of the “beam remnant” and particles produced in multiple parton interactions (MPI) and initial/final state radiation
- Not simply a “minimum bias” event overlaid on the hard scattering, activity is correlated with hard process due to colour and momentum conservation
- As with soft non-diffractive events, modelled with effective descriptions within MC generators tuned to data

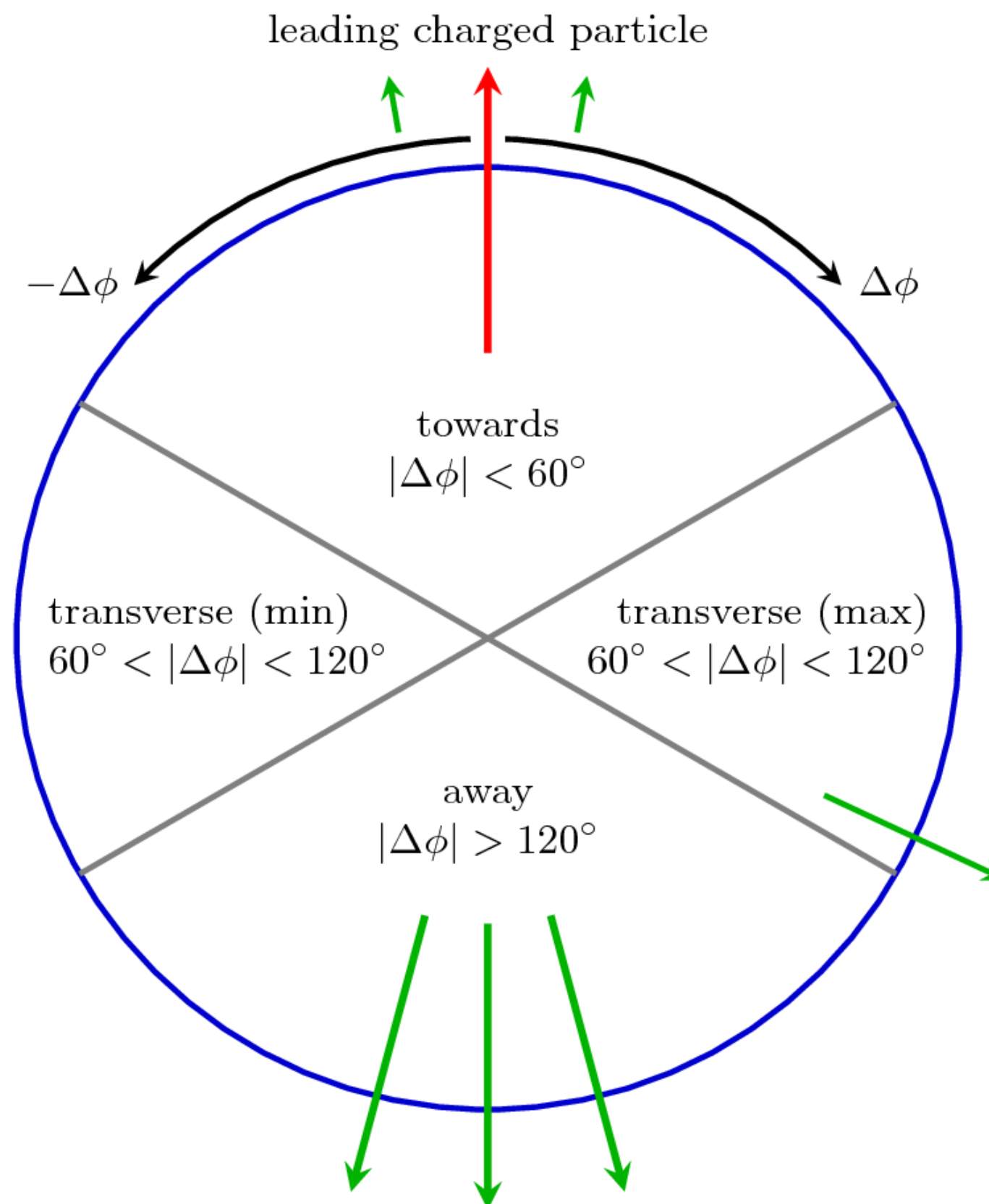


How to measure the underlying event

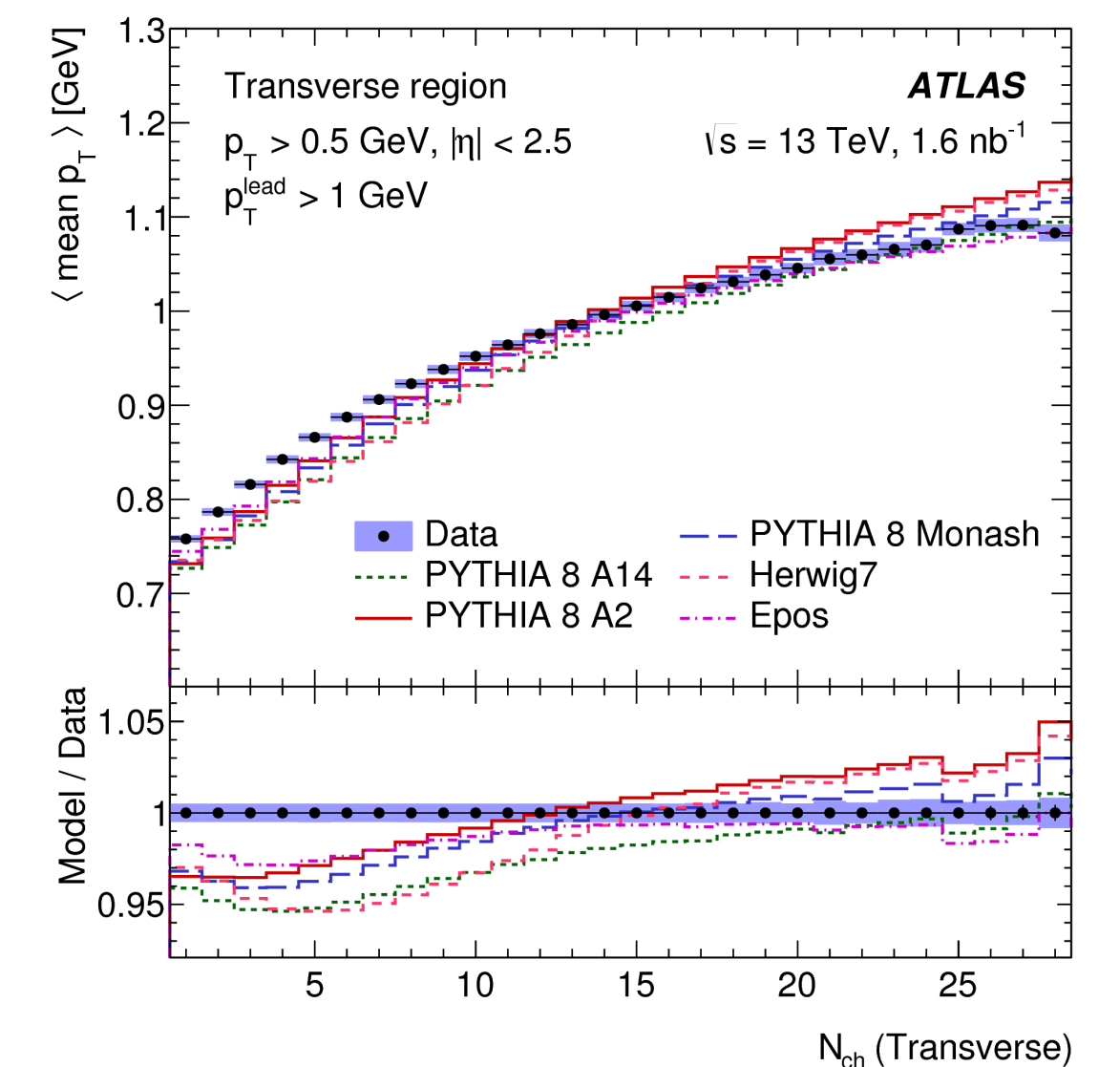
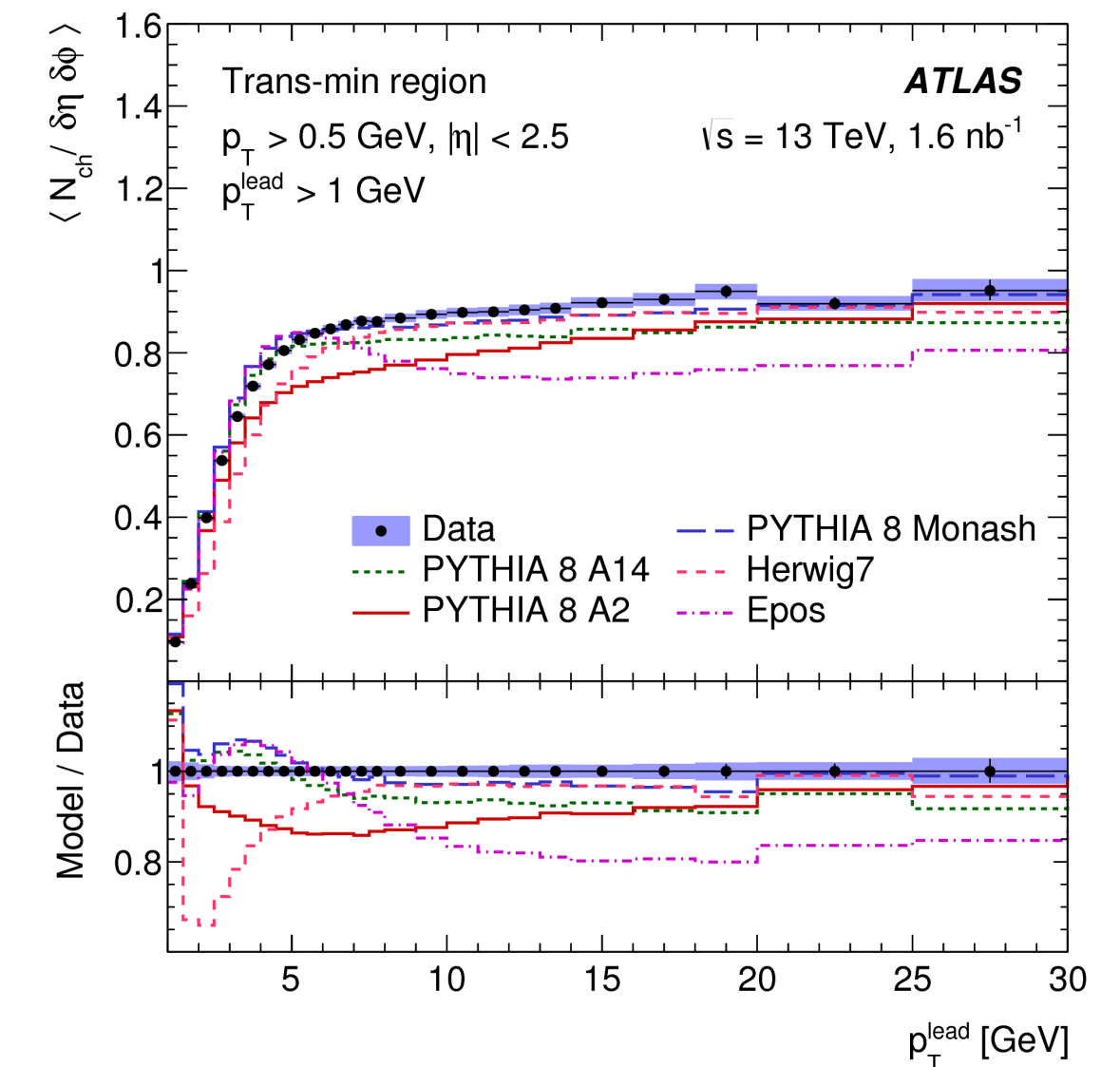
Since it accompanies every “interesting” pp event, we need to understand the UE, but how can one disentangle the “hard process” from the underlying event in order to measure it?

- Divide azimuthal plane w.r.t. direction of leading p_T track into four regions
- Towards and away regions sensitive to hard process;
- Transverse region is more sensitive to the UE

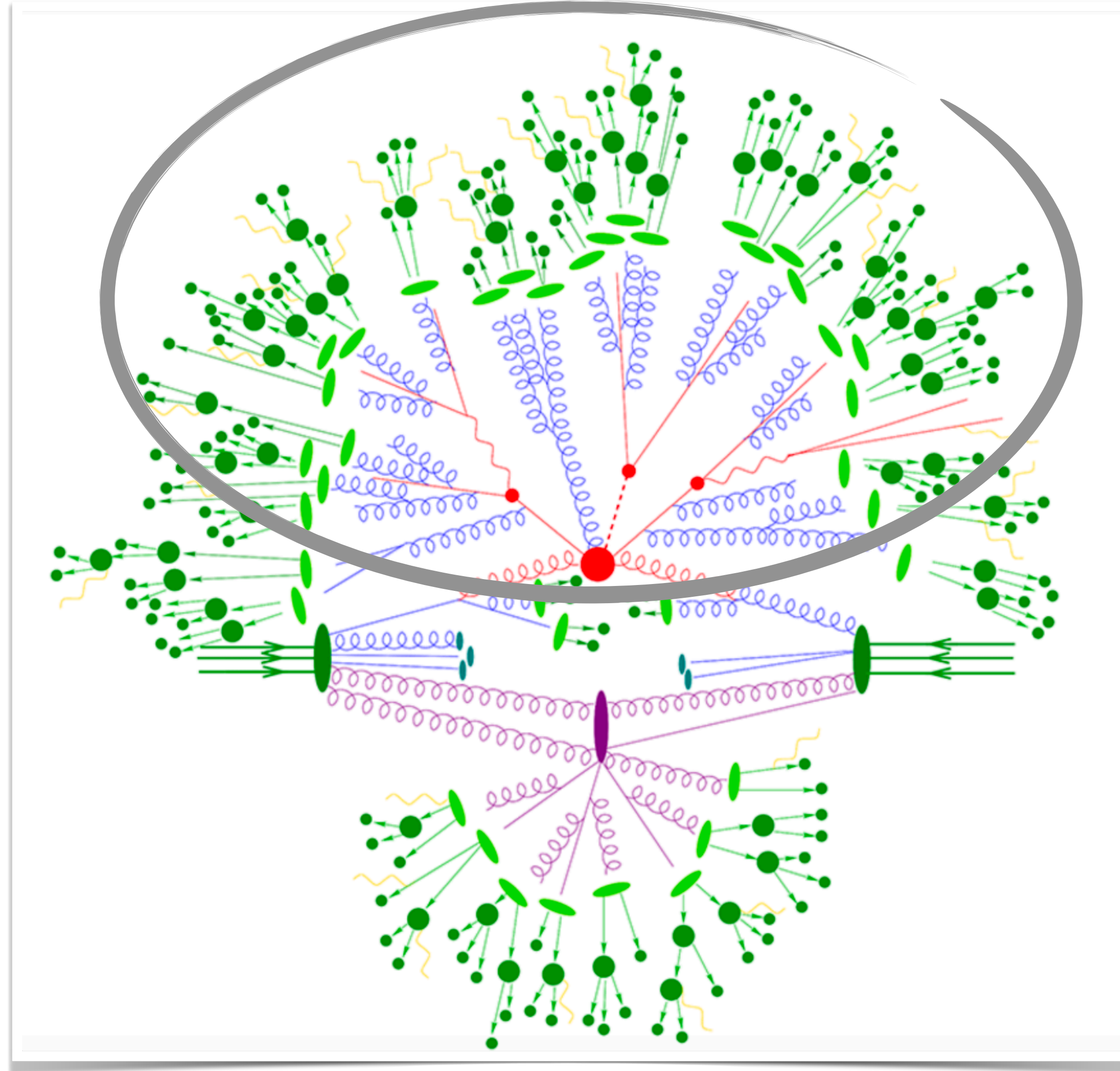
Use observables such as mean charged-particle p_T and multiplicity in transverse region to “tune” predictions of UE models in MC generators



Figures from [STDM-2016-17](#)



Next up: hard scatter and tests of QCD



Any questions
so far ??

Hard parton – parton scattering in QCD

The “QCD Collinear Factorisation” method is the basis of all pp scattering calculations and MC simulations, cross-section calculation separated into two parts

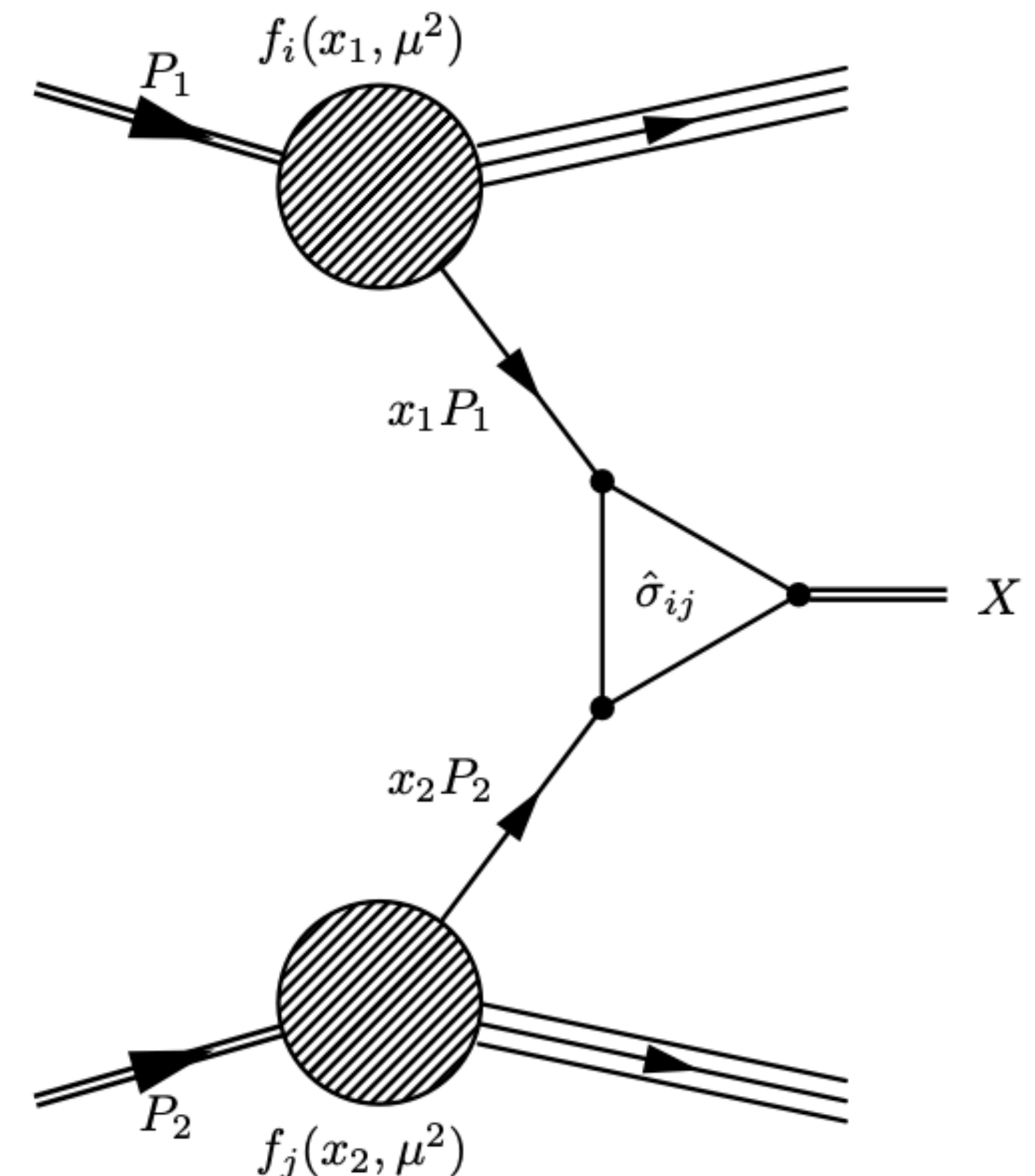
The “hard scattering” partonic cross-section for two partons (i.e. quarks and gluons) $i, j \rightarrow X$

- Calculable with perturbative QCD, often systematically improvable with higher order corrections to perturbative series

$$\sigma(P_1, P_2) = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu^2) \cdot f_j(x_2, \mu^2) \cdot \hat{\sigma}_{ij}(p_1, p_2, a_S(\mu^2), Q^2/\mu^2)$$

Description of the probability (density) f to find a parton with (longitudinal) momentum fraction x within a proton, known as a **parton density function**

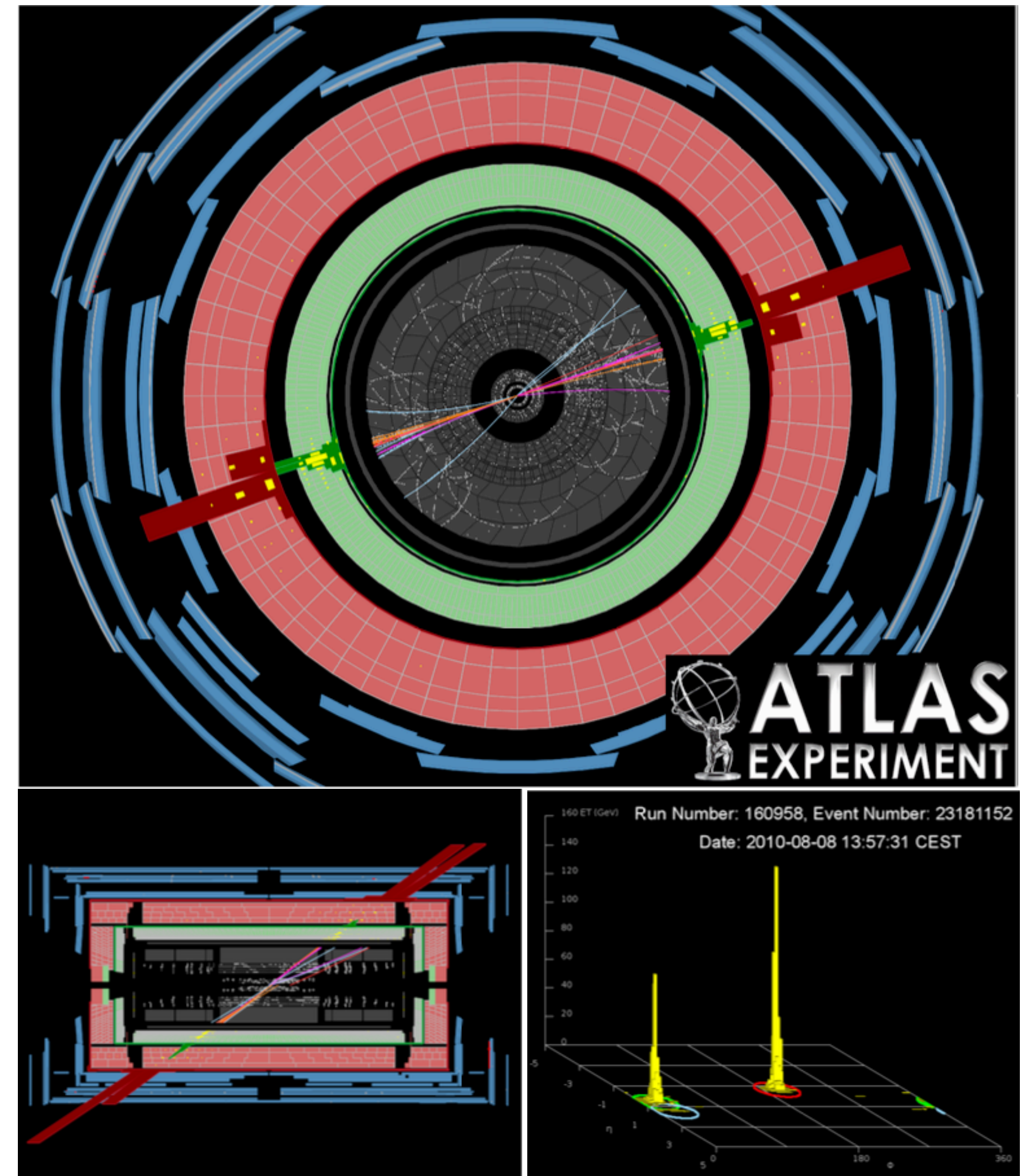
- Non-perturbative quantity, obtained by fitting to data (typically ep DIS measurements)



Jets

The fragmentation of a high energy quark/ gluons into a collimated hadronic final state is known as a “jet”

- Hard pp interactions are dominated by jet production initiated hard qq, gg, qg scattering, jets are ubiquitous at the LHC!
- The hard scattering processes (e.g. $gg \rightarrow q\bar{q}$) are calculable in perturbative QCD
- The soft fragmentation/hadronisation process (i.e. $qg \rightarrow$ hadrons) is a non-perturbative, rely on physically motivated MC models (e.g. Lund string)



Jet definitions

- Jets are defined with an algorithm which clusters constituents within an event (usually calorimeter energy deposits/tracks) into a single entity

The Rules

- For jets to make sense in the context of perturbative QCD to make sense, the (hard) jets should not change when:
 - IR Safety: There is soft emission (i.e. add a very soft gluon)
 - Collinear Safety: There is a collinear splitting (i.e. one parton is replaced by two such as $g \rightarrow q\bar{q}$)

“Infrared unsafety is a serious issue, not just because it makes impossible to carry out meaningful (finite) perturbative calculations, but also because it breaks the whole relation between the (Born or low-order) partonic structure of the event and the jets that one observes, and it is precisely this relation that a jet algorithm is supposed to codify: it makes no sense for the structure of multi-hundred GeV jets to change radically just because hadronisation, the underlying event or pileup threw a 1 GeV particle in between them.” (arXiv:0704.0292)

Jet definitions

- Which particles we should put together in a one jet ?
- How do we combine their momenta?
 - How we choose which we should combine?
 - How/When we stop the combination?

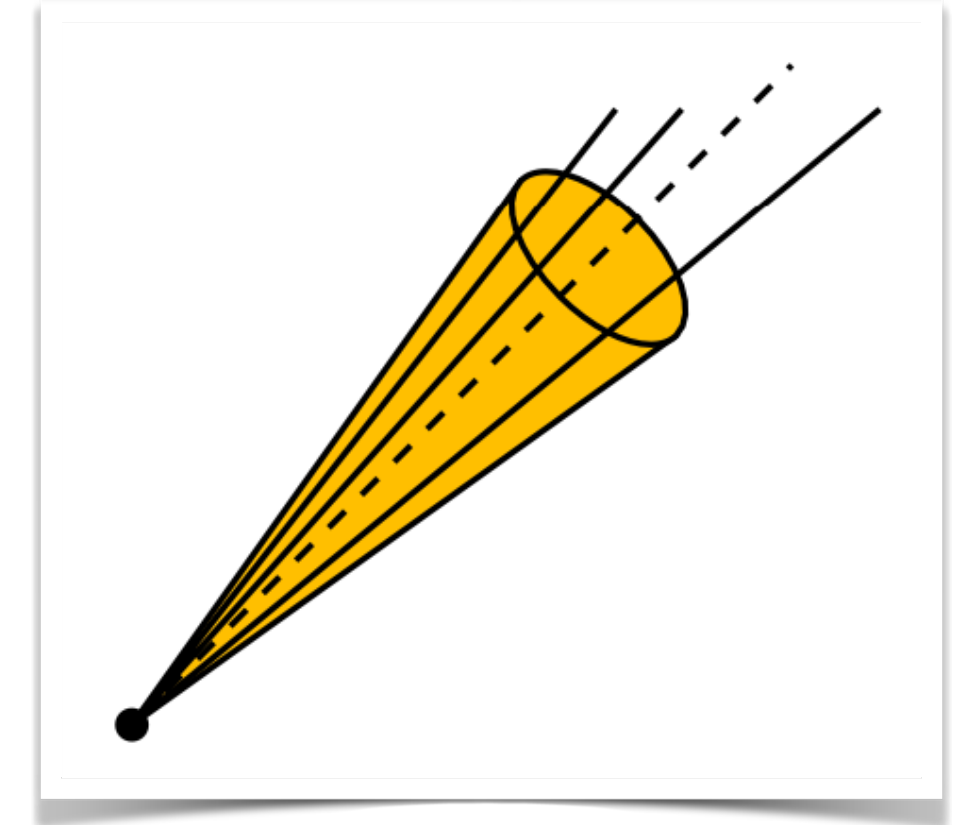
Jet definitions II

Cone Algorithms:

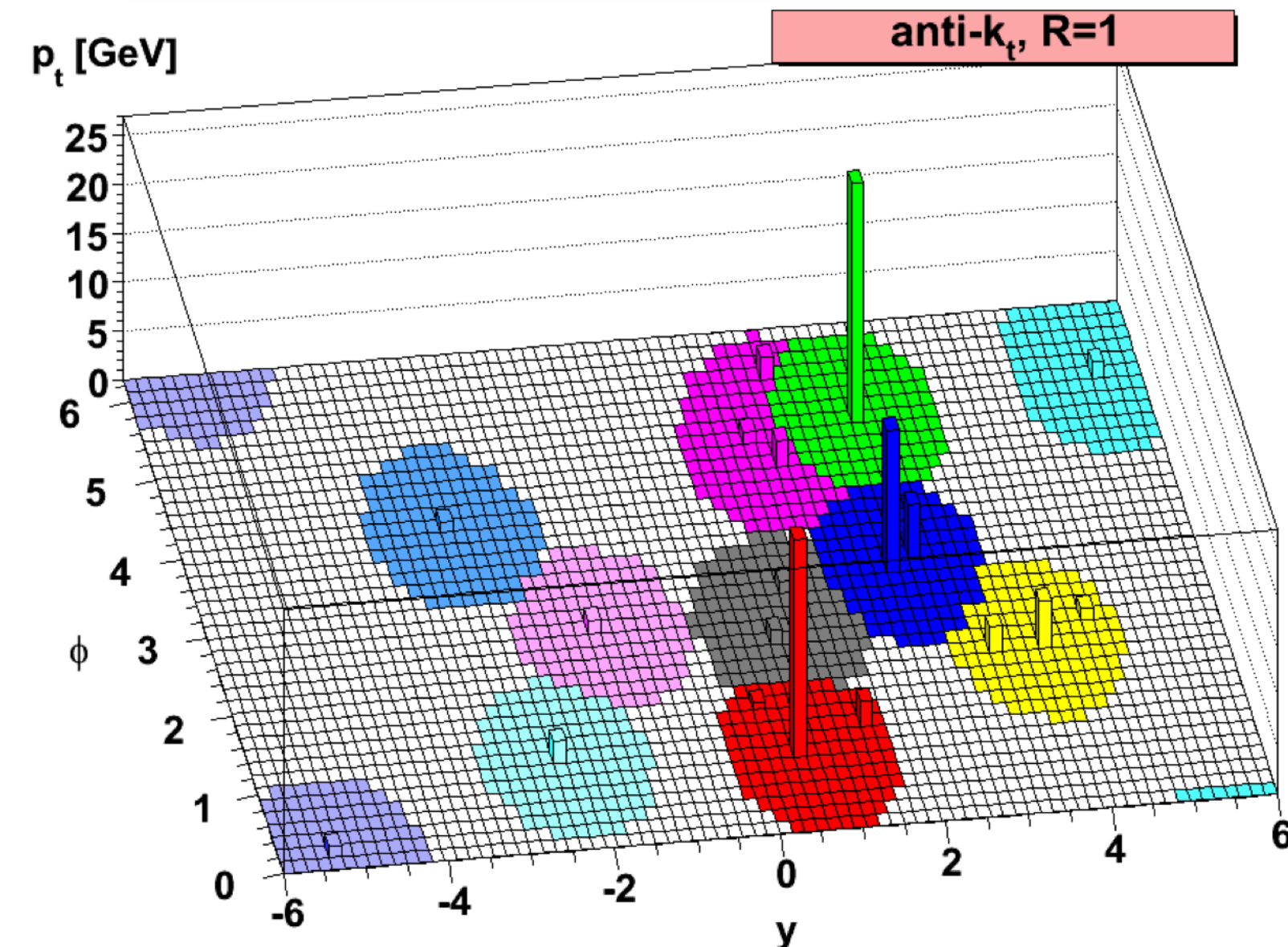
- Cluster all constituents within a given geometric cone, defined by

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

- X Features:** behaviour very susceptible to additional soft gluon radiation (e.g. number of jets in event)
- Generally considered obsolete (exception of SIScone)



DOI: [10.1088/1126-6708/2008/04/063](https://doi.org/10.1088/1126-6708/2008/04/063)



Sequential Recombination Algorithms

- Successively combine the “closest” pair of particles according to distance measure

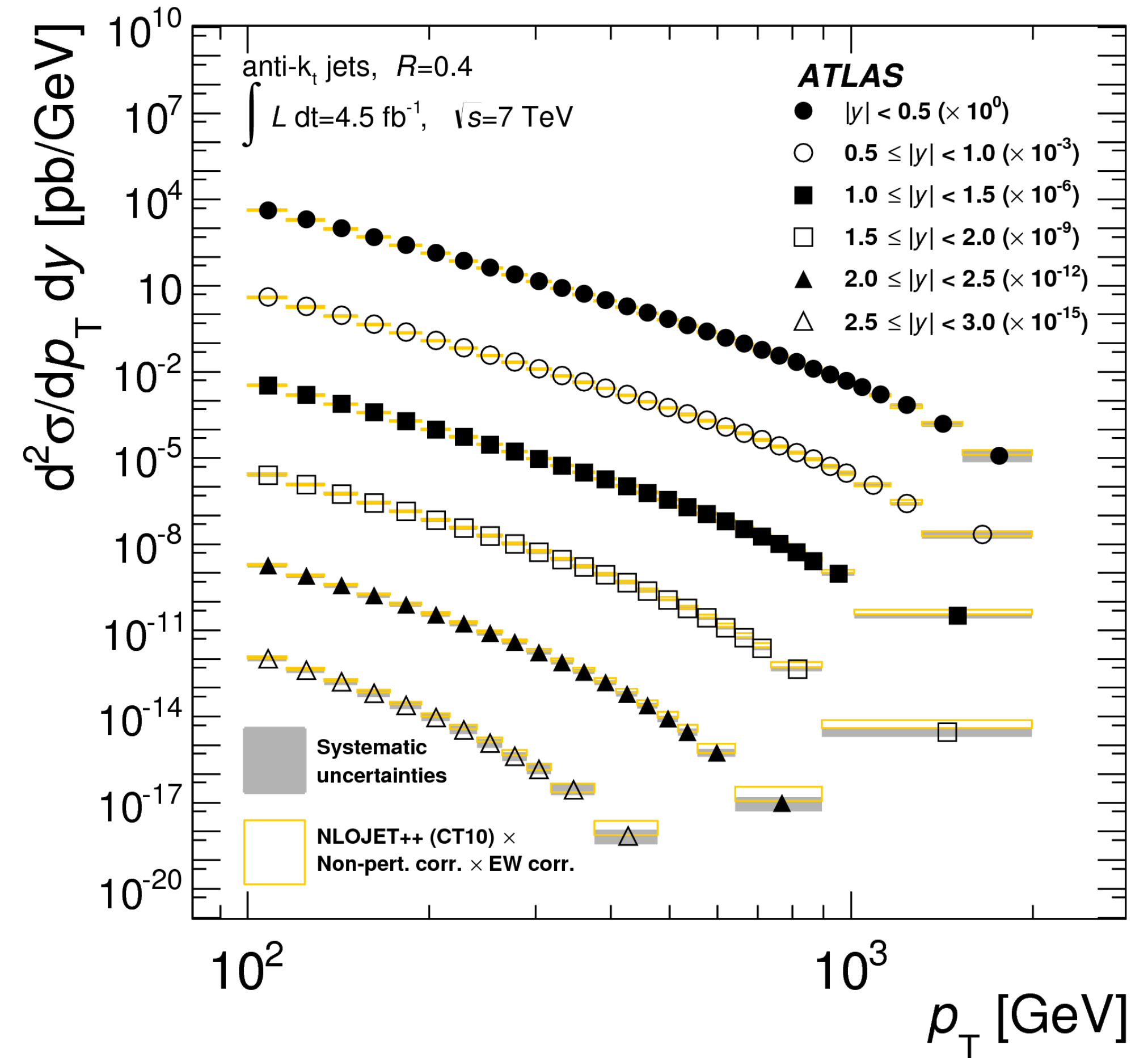
$$d_{ij} = \min(k_{T,i}^{2p}, k_{T,j}^{2p}) \frac{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}{R^2}$$

- Stop at a cut-off scale R, final clustering of particles defines the jet
- ✓ Features:** IR + Collinear safe, Version with $p = -1$ known as “anti-kT”
- widely used at ATLAS/CMS

Inclusive Jet Cross-sections

Jets are everywhere at the LHC, note y-axis units, $\approx 10^4$ pb / GeV at $p_T = 100$ GeV, very high rate! (c.f. total Higgs cross-section ≈ 20 pb at $\sqrt{s} = 7$ TeV)

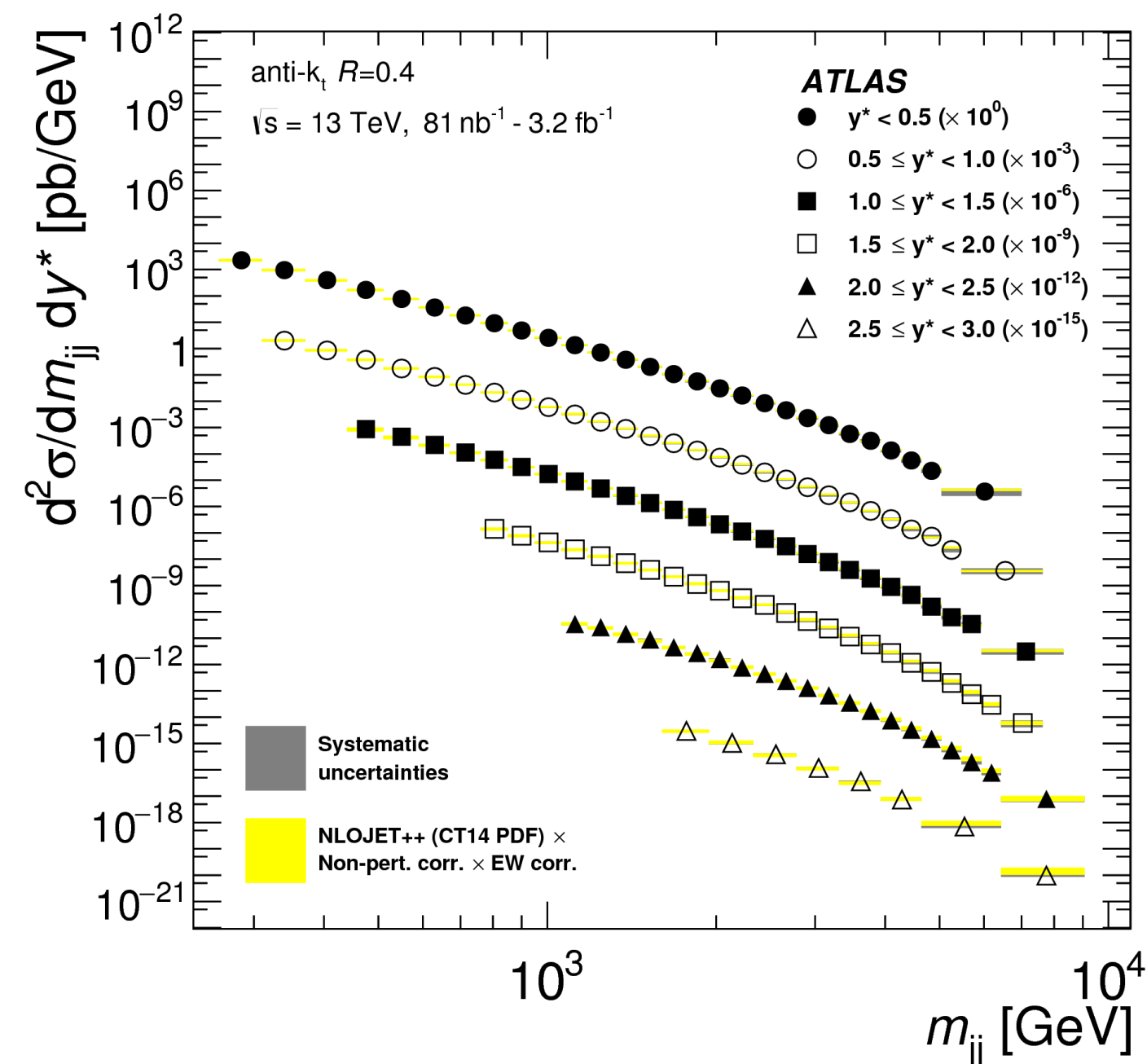
- Cross-section for anti-kT $R = 0.4$ jet production as a function of jet p_T , for different rapidity (y) ranges (note y-axis scaling on plot)
- Jet p_T distribution spans many orders of magnitude, drops towards maximum $\sqrt{\hat{s}}$ kinematically allowed (few TeV here)
- Good agreement with NLO perturbative QCD predictions within experimental and theoretical uncertainties



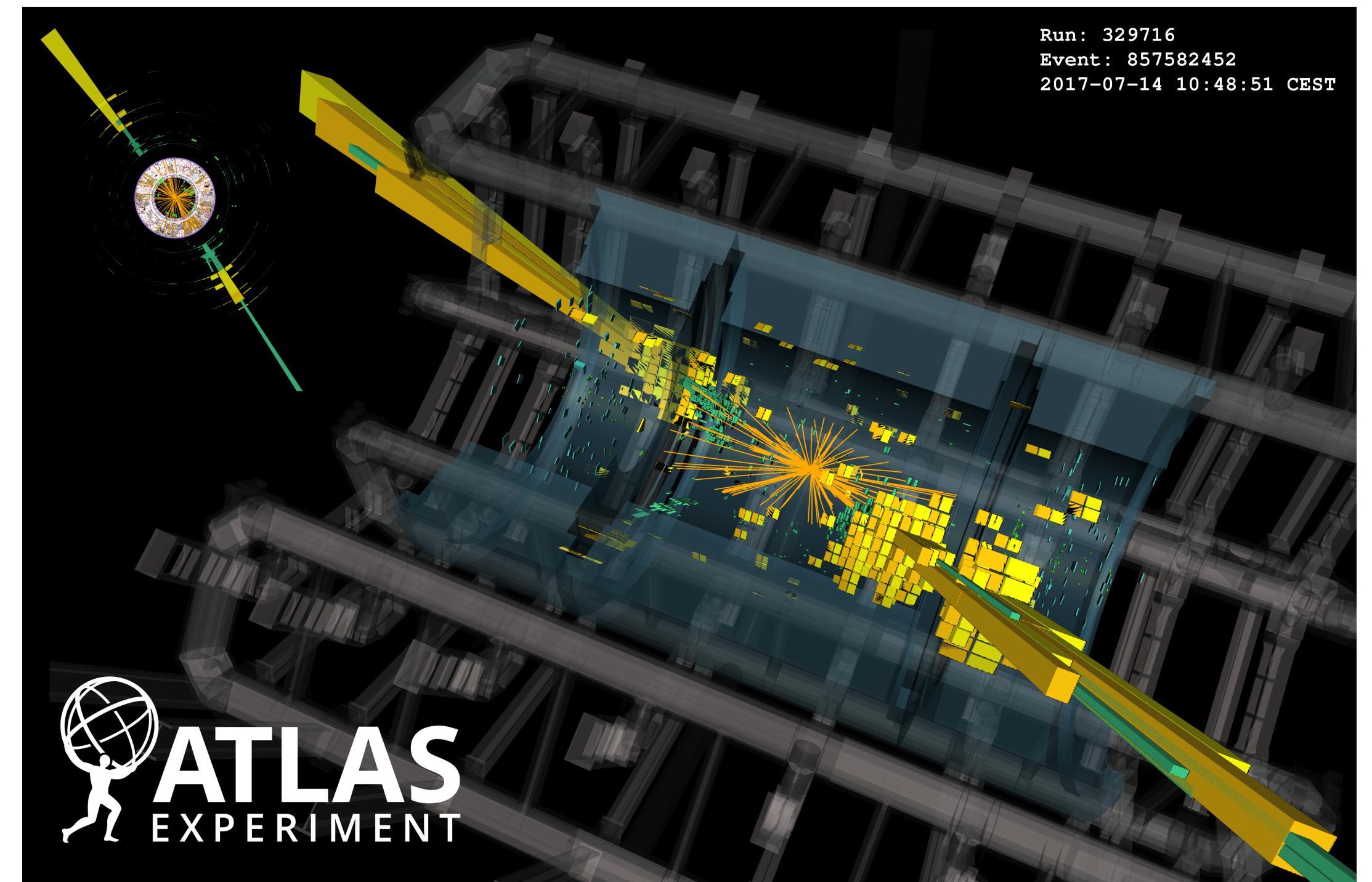
DOI: [10.1007/JHEP02\(2015\)153](https://doi.org/10.1007/JHEP02(2015)153),

Di-jet Cross-sections

- Di-jet production is another critical test of perturbative QCD
- Good agreement with NLO perturbative QCD predictions within experimental and theoretical uncertainties
- Also **important as a search channel for new resonances (e.g. $Z' \rightarrow q\bar{q}$)**
- Di-jet events with m_{jj} up to 9 TeV measured at the LHC ($\sqrt{s} = 13$ TeV)

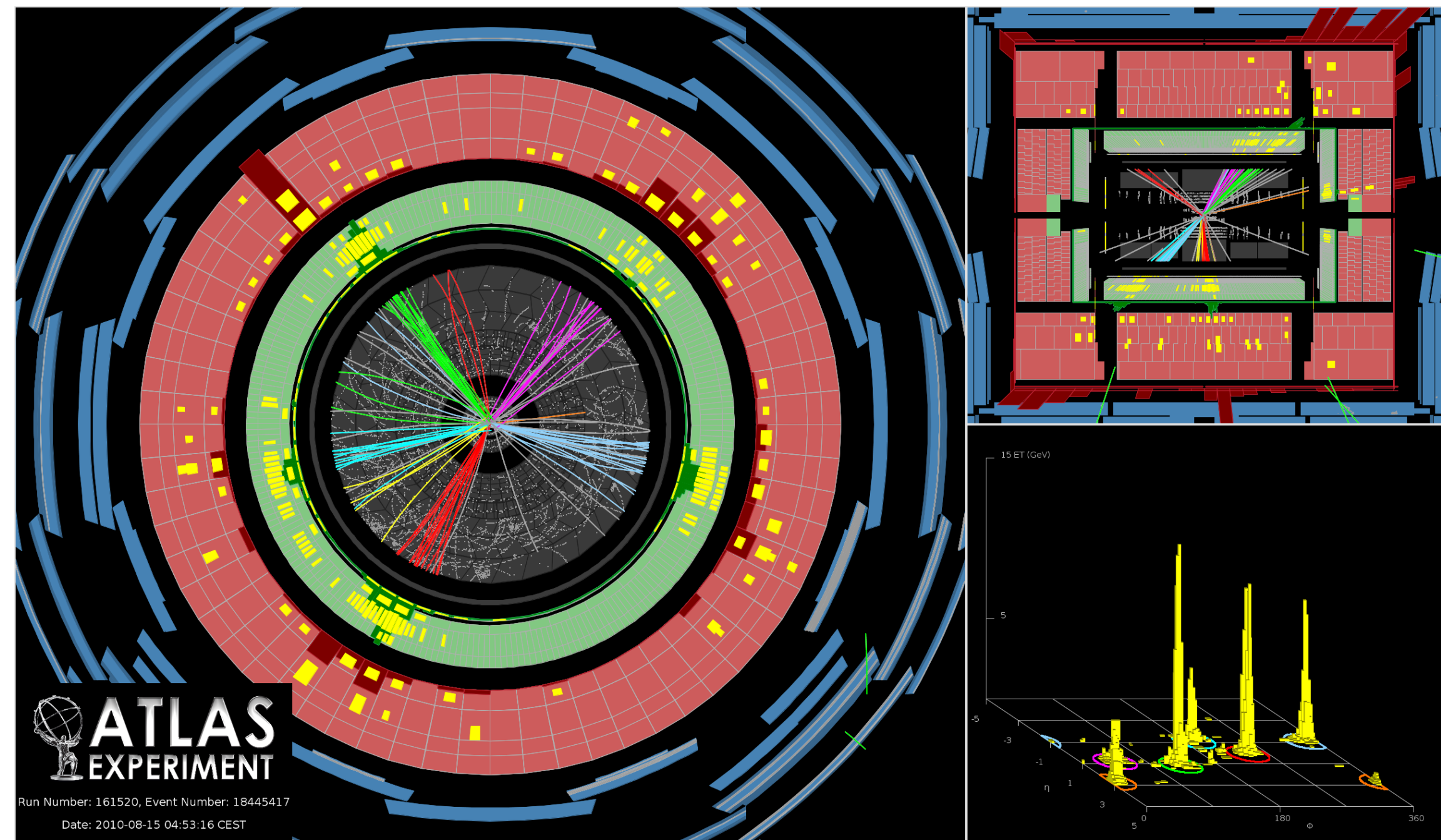
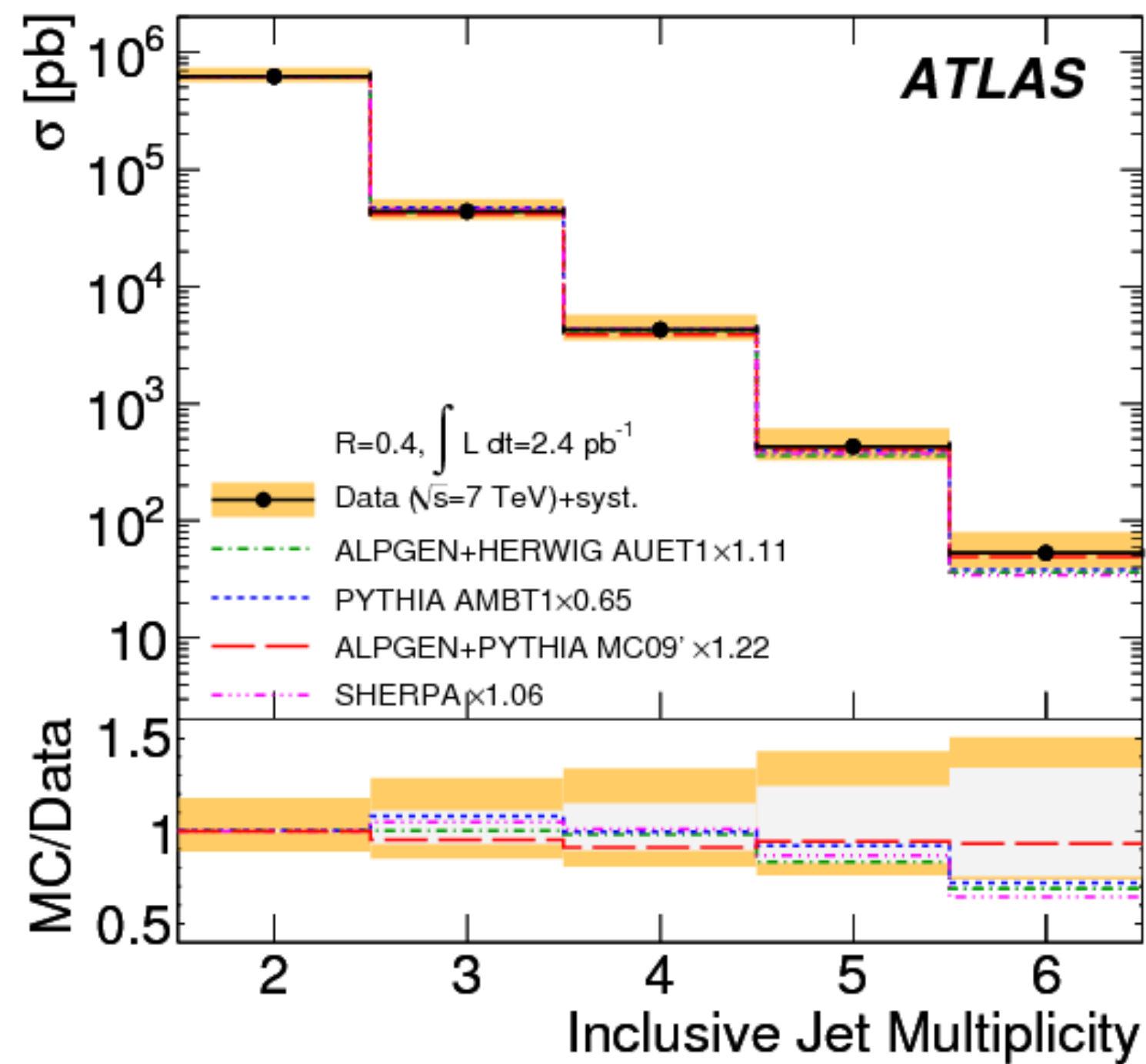


[DOI:10.1007/JHEP05\(2018\)195](https://doi.org/10.1007/JHEP05(2018)195)



Multi-jet Cross-sections

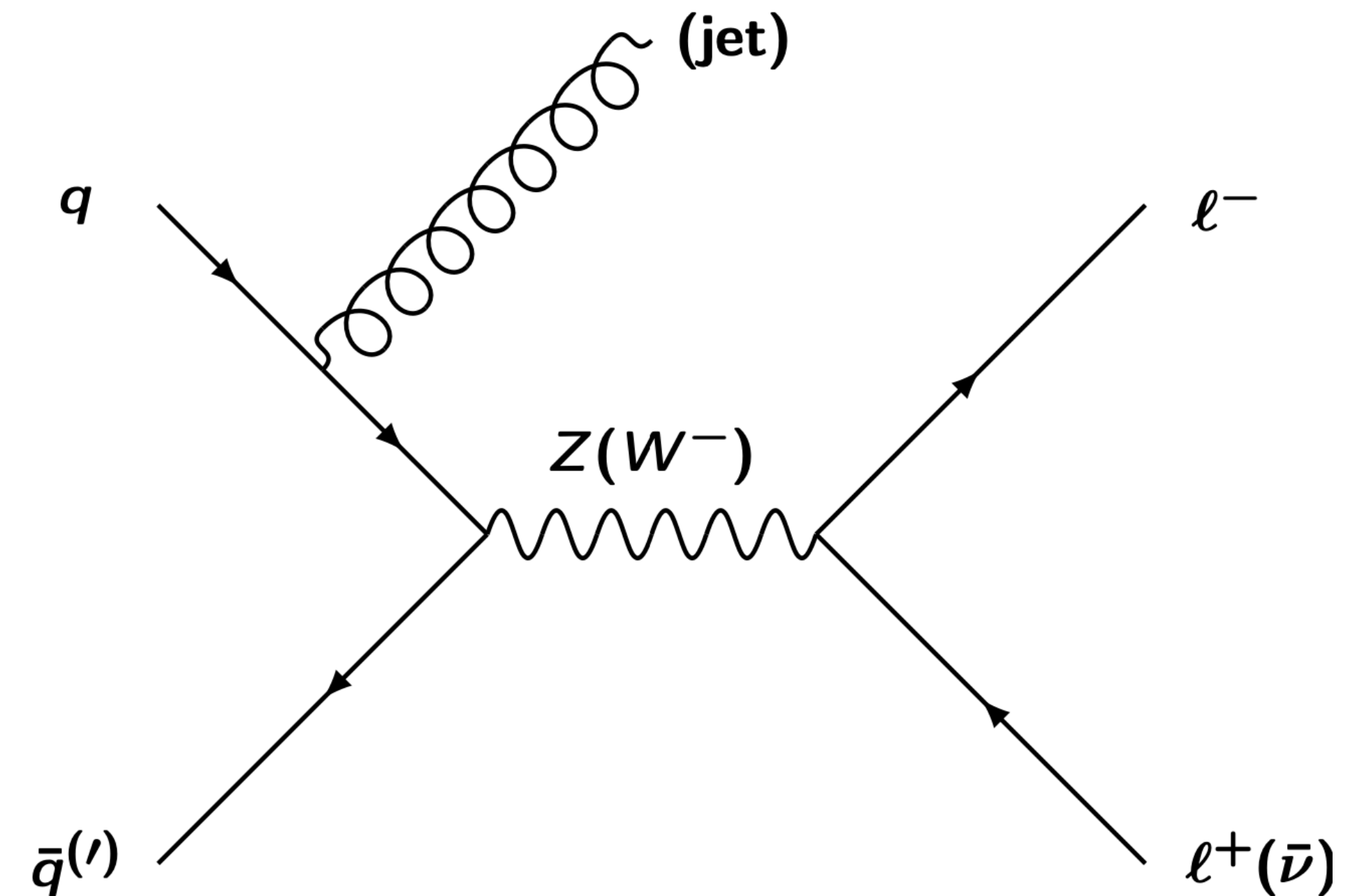
- Multi-TeV pp collisions provide a huge phase space for multi-jet production
- Another important test for QCD and MC generator predictions, critical background for general searches for new physics



[DOI: 10.1140/epjc/s10052-011-1763-6](https://doi.org/10.1140/epjc/s10052-011-1763-6)

W, Z bosons

- W and Z boson production in pp collisions proceeds primarily through $q\bar{q}$ annihilation (Drell-Yan), inclusive production often involves additional high p_T jets
- Leptonic W and Z boson decays are the primary source of isolated high p_T leptons at the LHC
- $B(Z \rightarrow \ell\ell) \approx 3\%$, $B(W \rightarrow \ell\nu) \approx 11\%$
- Useful as probes of parton densities and for precise tests of the SM
- Present in decays of H, top-quark and particles beyond the SM
- Very useful as a calibration source for lepton efficiency, energy scale / resolution measurements
- Important background for many search channels (e.g. SUSY)



W and Z boson mass distribution

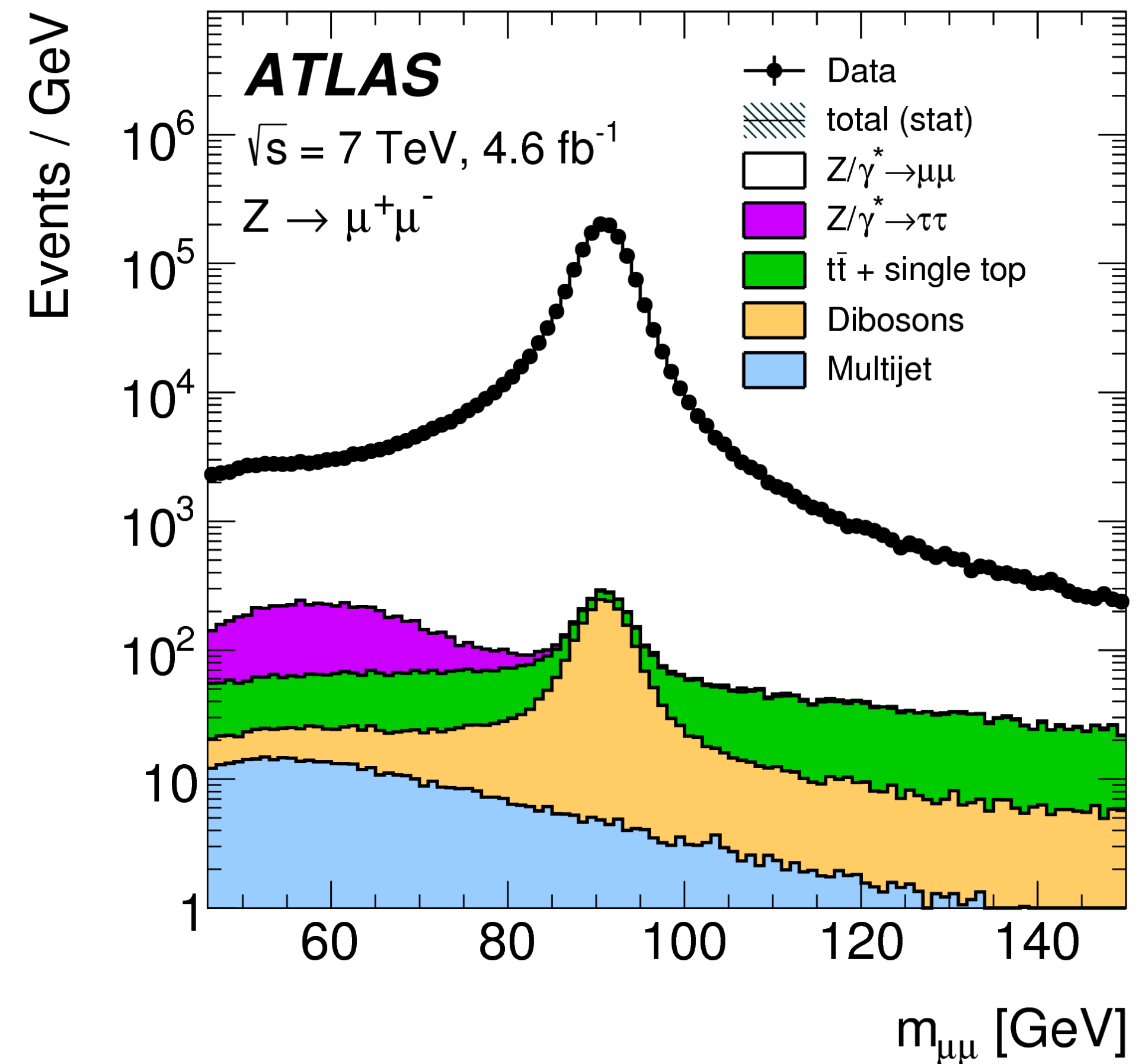
DOI: [10.1140/epjc/s10052-017-4911-9](https://doi.org/10.1140/epjc/s10052-017-4911-9)

Experimental Signature:

- Pair of isolated high p_T oppositely charged leptons

$Z \rightarrow \ell\ell$ candidates

- Di-lepton invariant mass distribution is the primary means by which Z boson candidates can be identified
- Mass resolution (at ATLAS/CMS) is typically smaller than $\Gamma_Z \approx 2.5$ GeV
- Reminder: $m_Z = 91.2$ GeV and $m_W = 80.4$ GeV



W and Z boson mass distribution

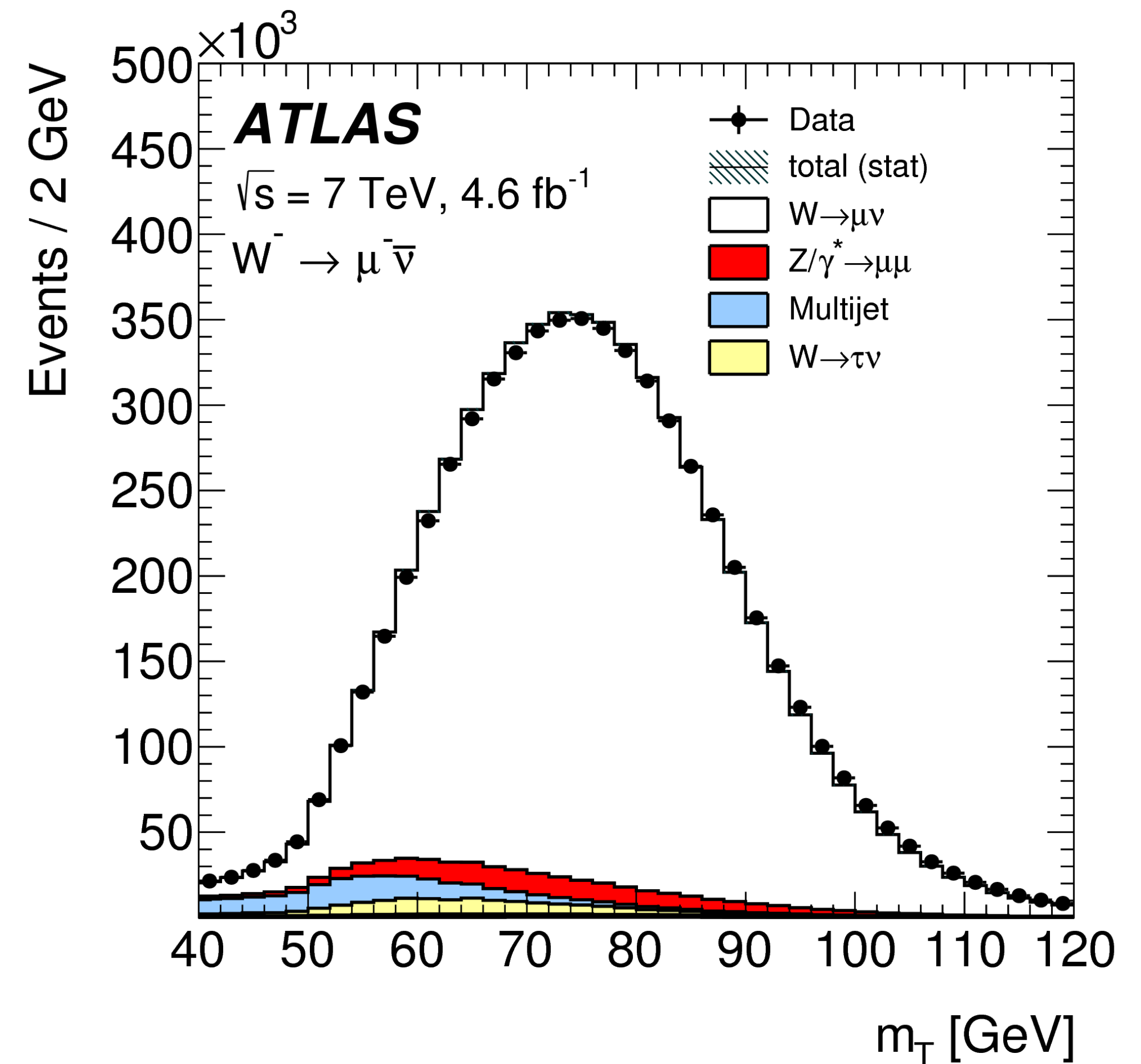
Experimental Signature:

Single isolated high p_T lepton and large missing transverse energy

$W^\pm \rightarrow \ell^\pm \nu$ candidates

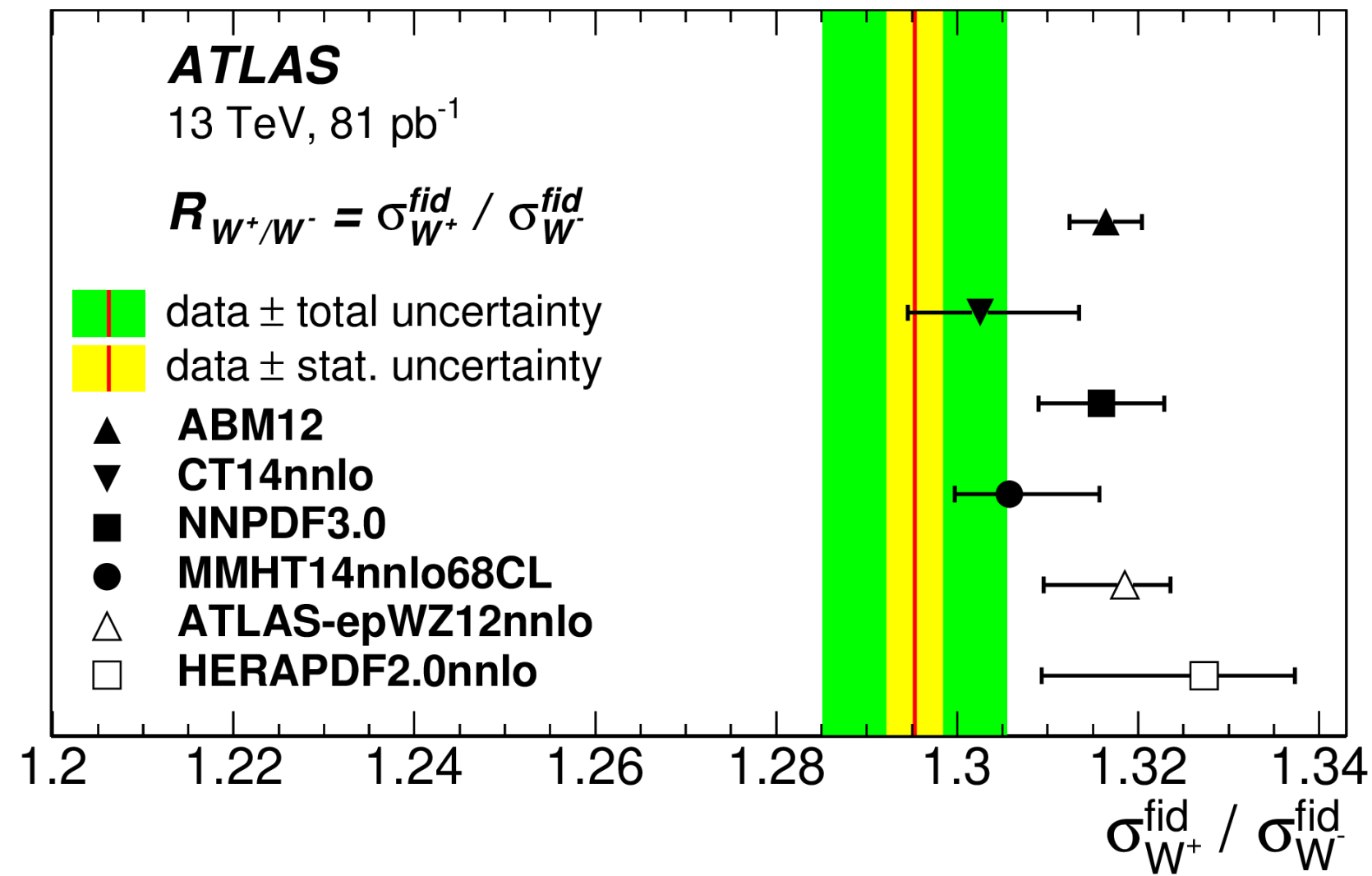
- Neutrino not detected, only its transverse momentum can be inferred from E_T^{miss}
- Can only reconstruct “transverse mass” m_T
- Peaking structure observed, though peak below m_W and much broader than $\Gamma_W \approx 2.1$ GeV

$$m_T = \sqrt{2p_T^\ell E_T^{miss} (1 - \Delta\phi_{\ell,\nu})}$$

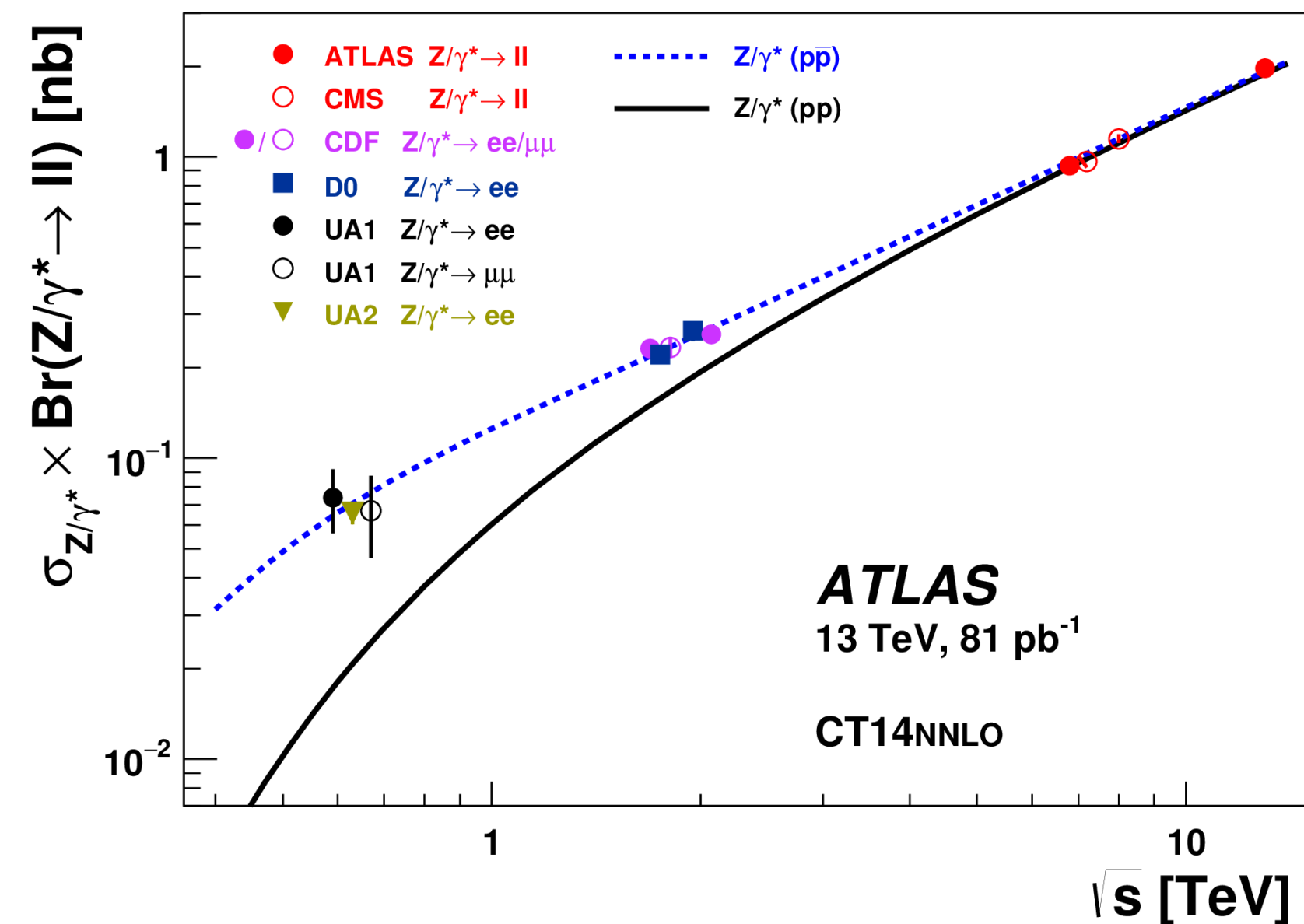
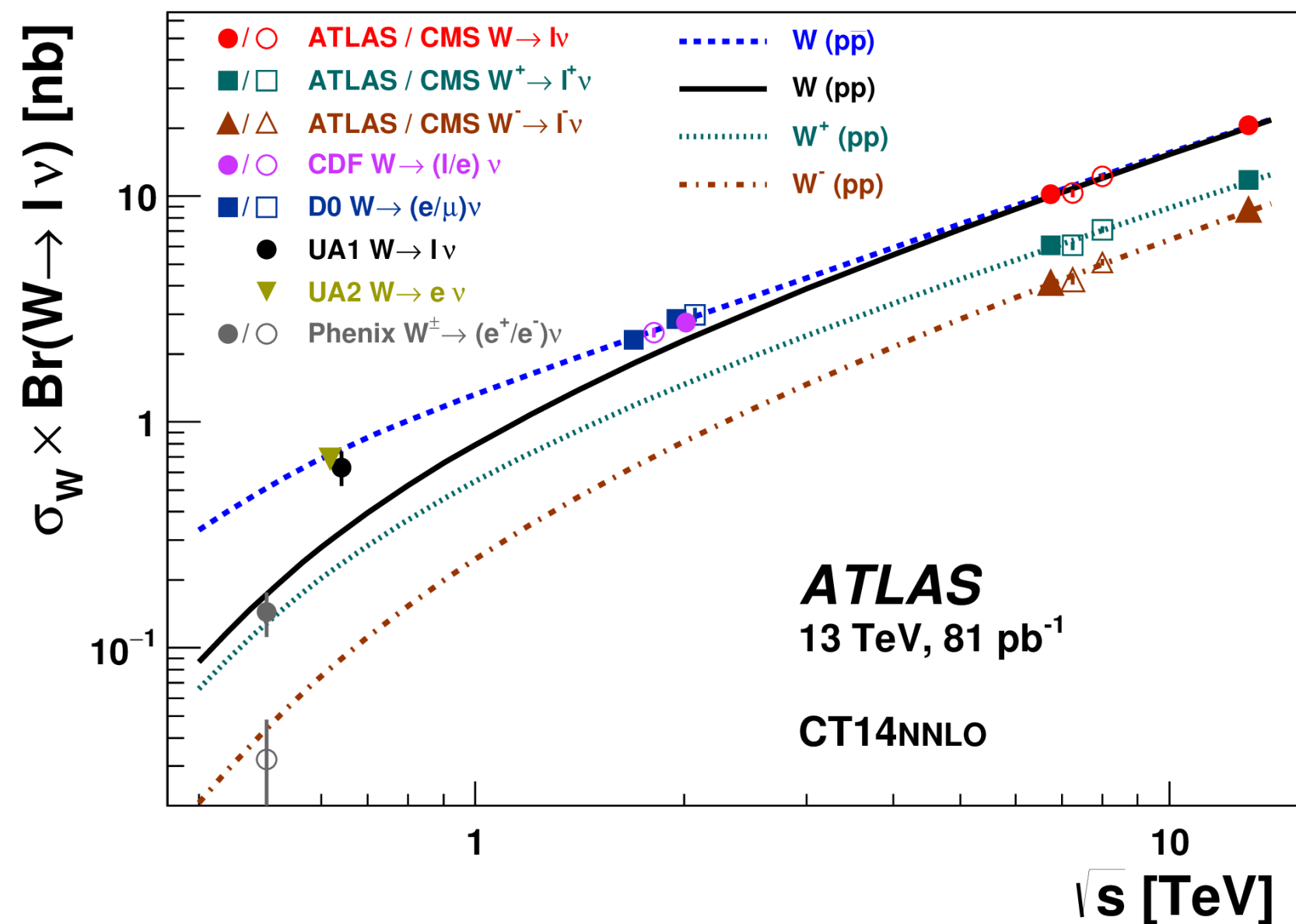
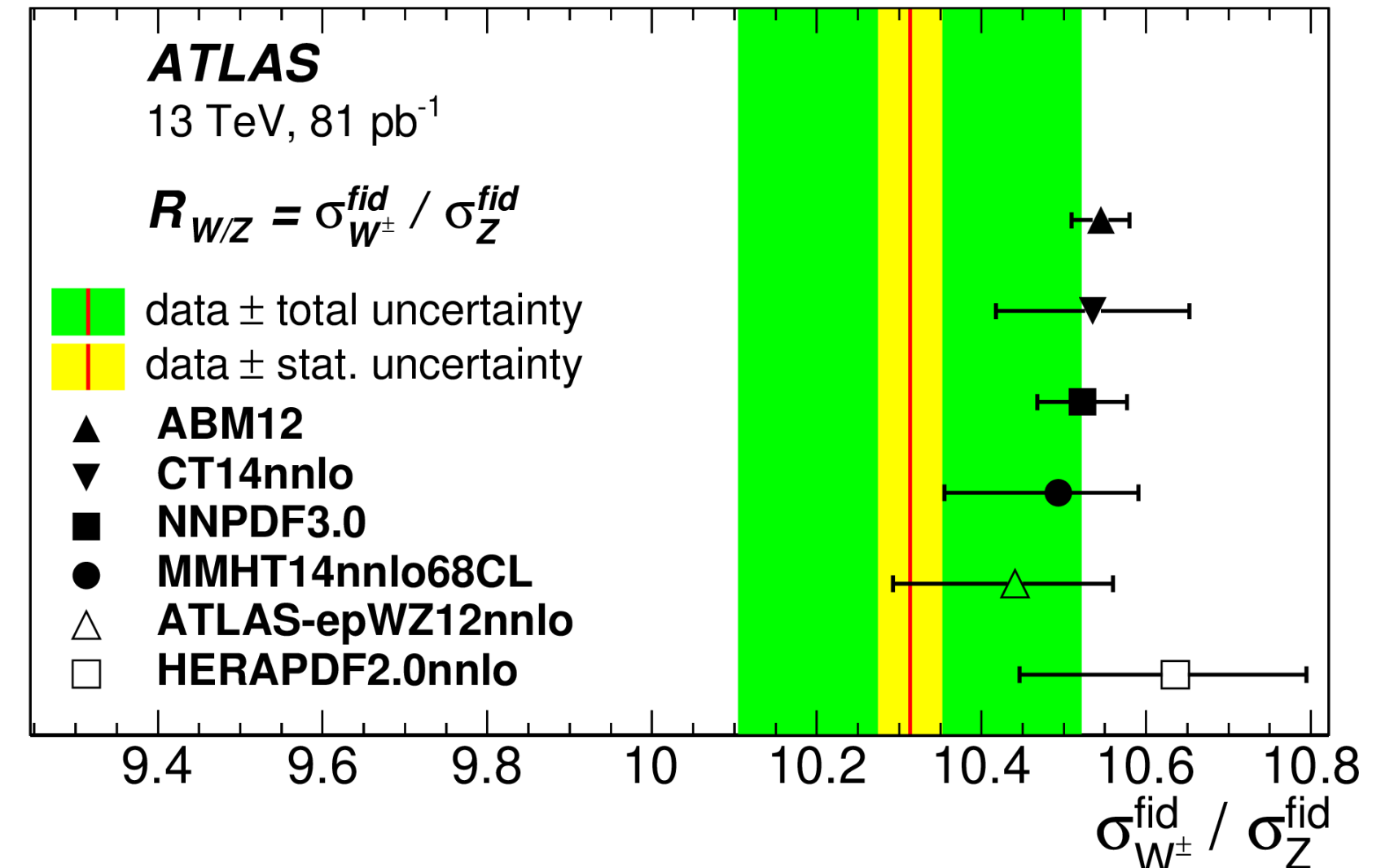


W and Z boson cross-sections

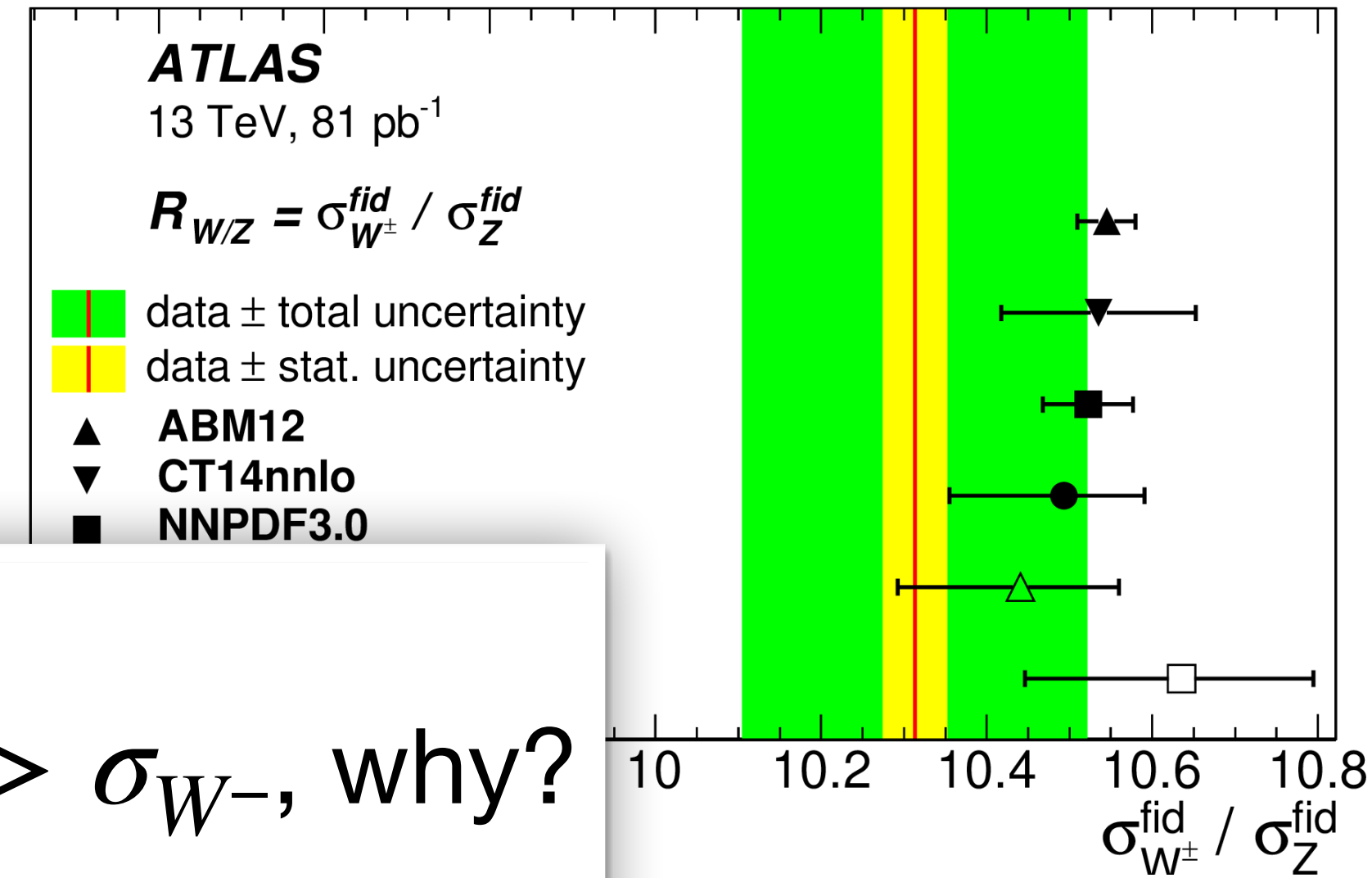
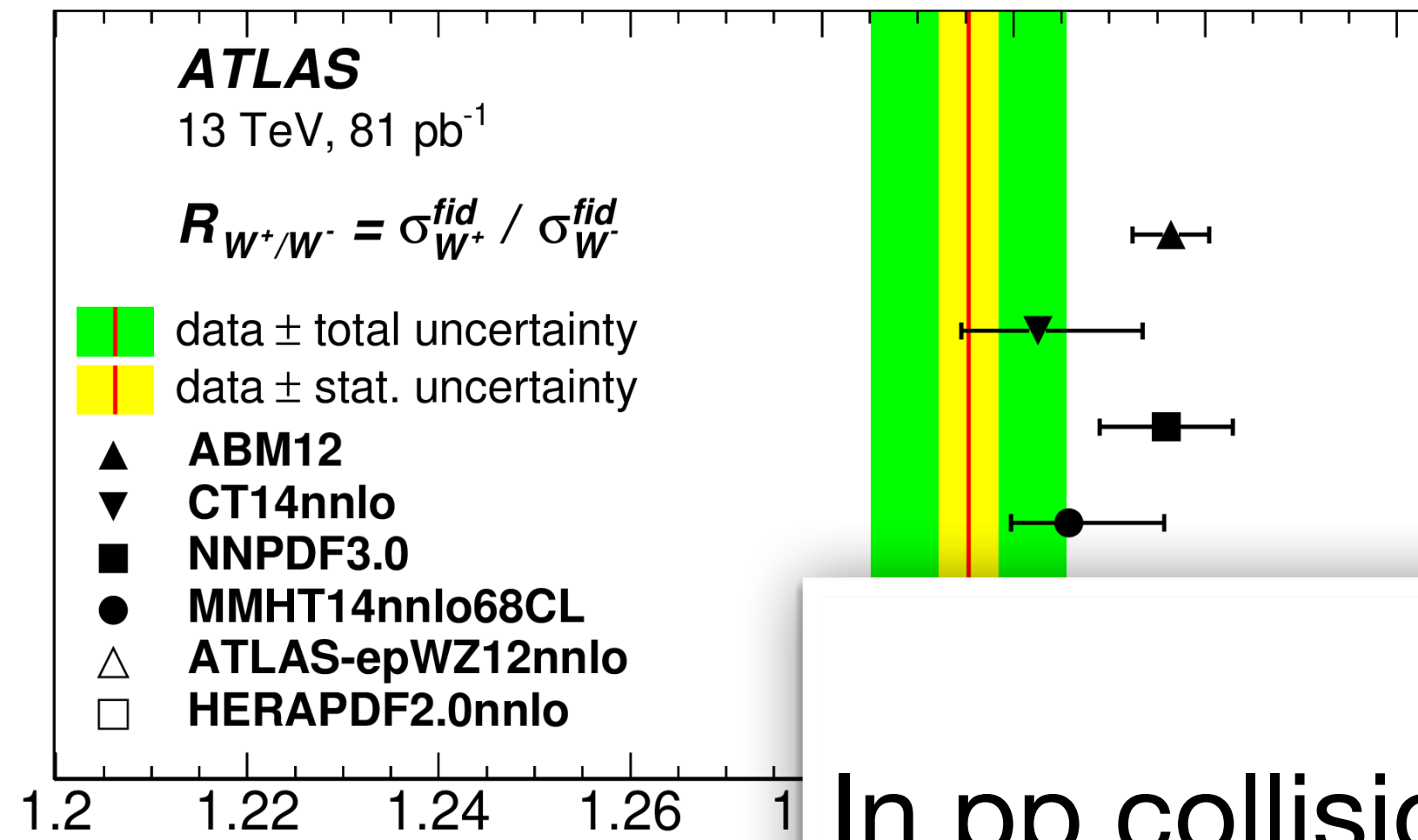
$\sigma_{W^+}/\sigma_{W^-}$



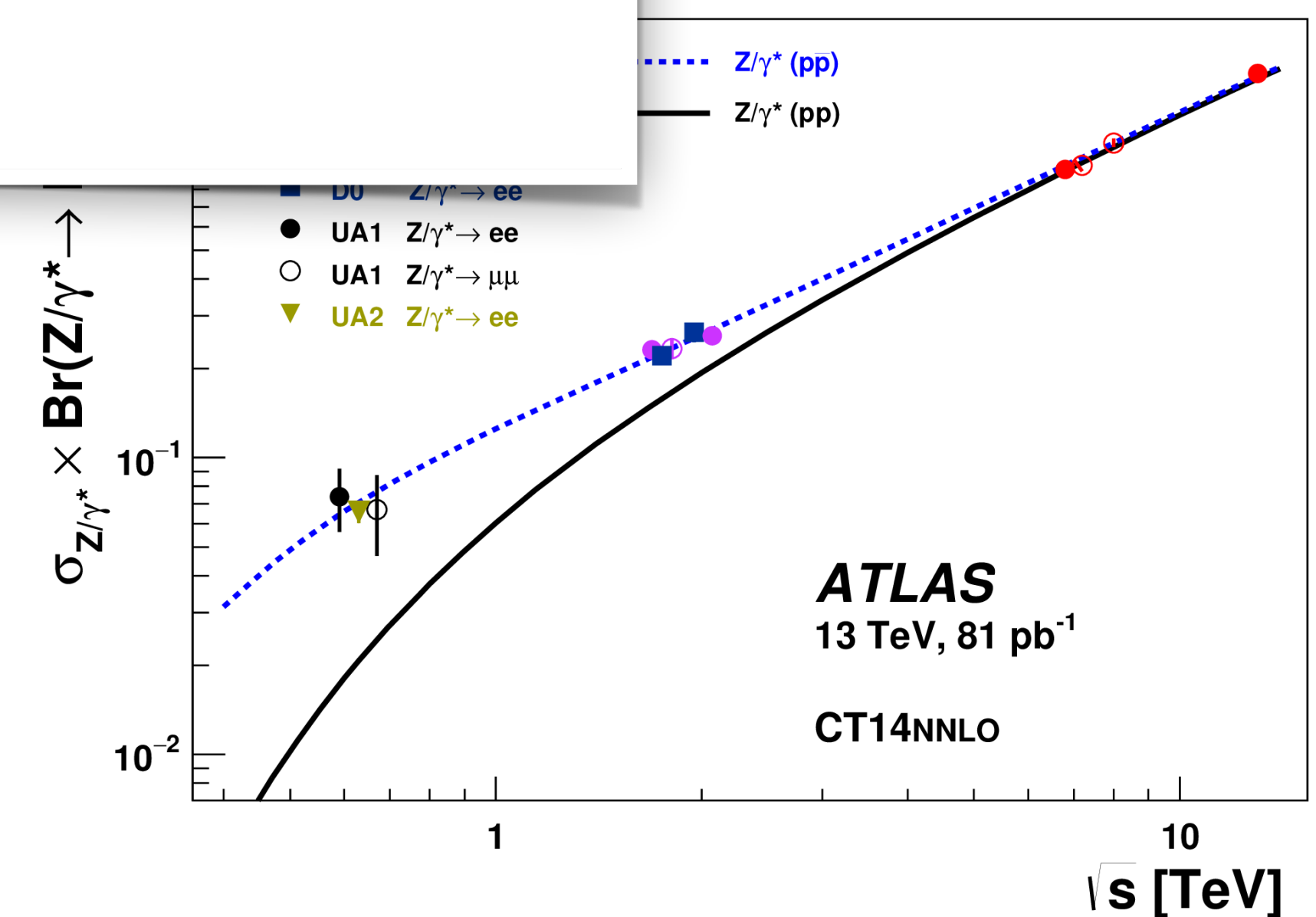
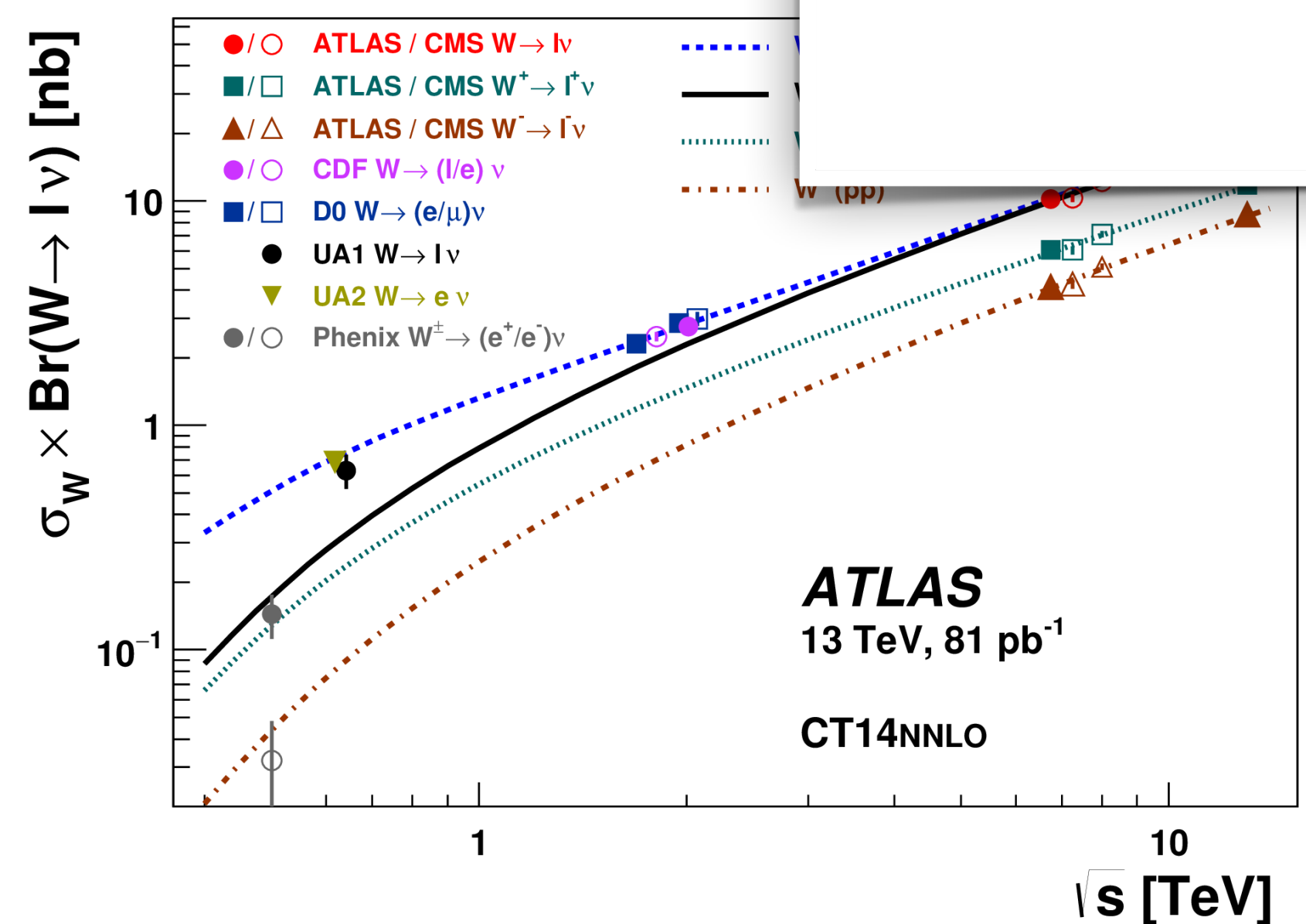
σ_{W^\pm}/σ_Z



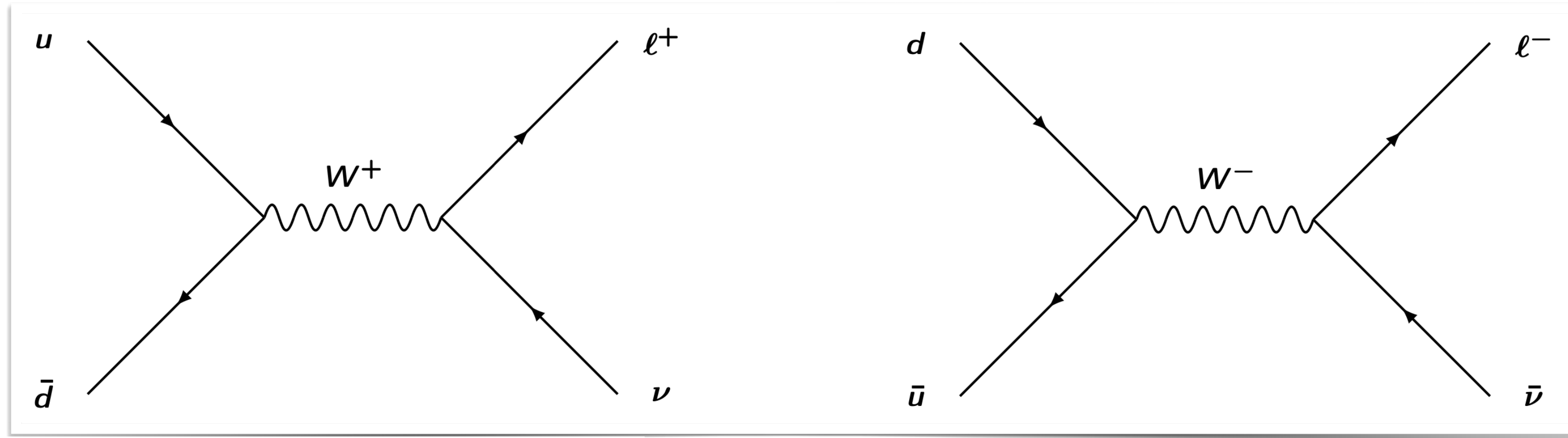
W and Z boson cross-sections



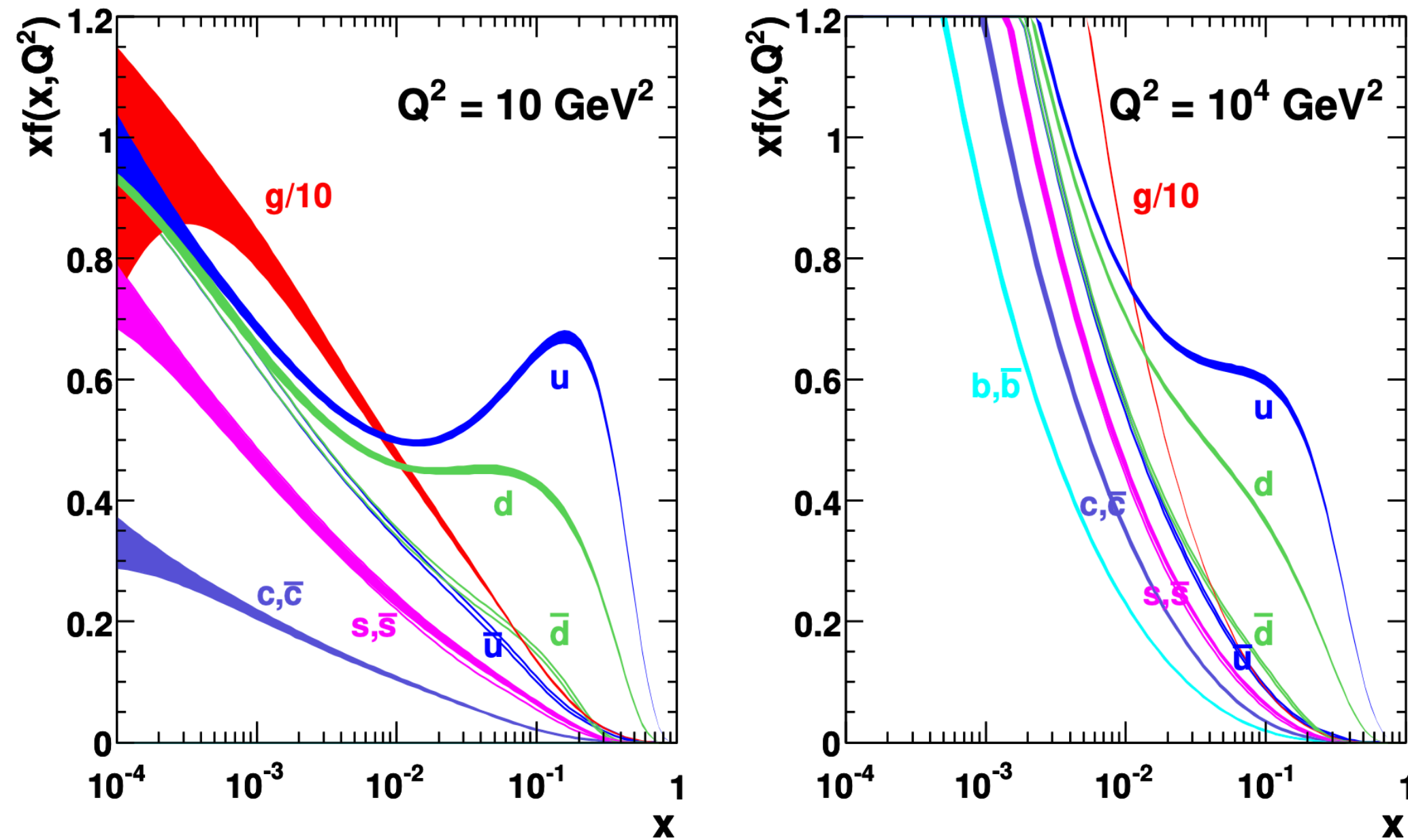
In pp collisions, $\sigma_{W^+} > \sigma_{W^-}$, why?



W^+ and W^- cross section



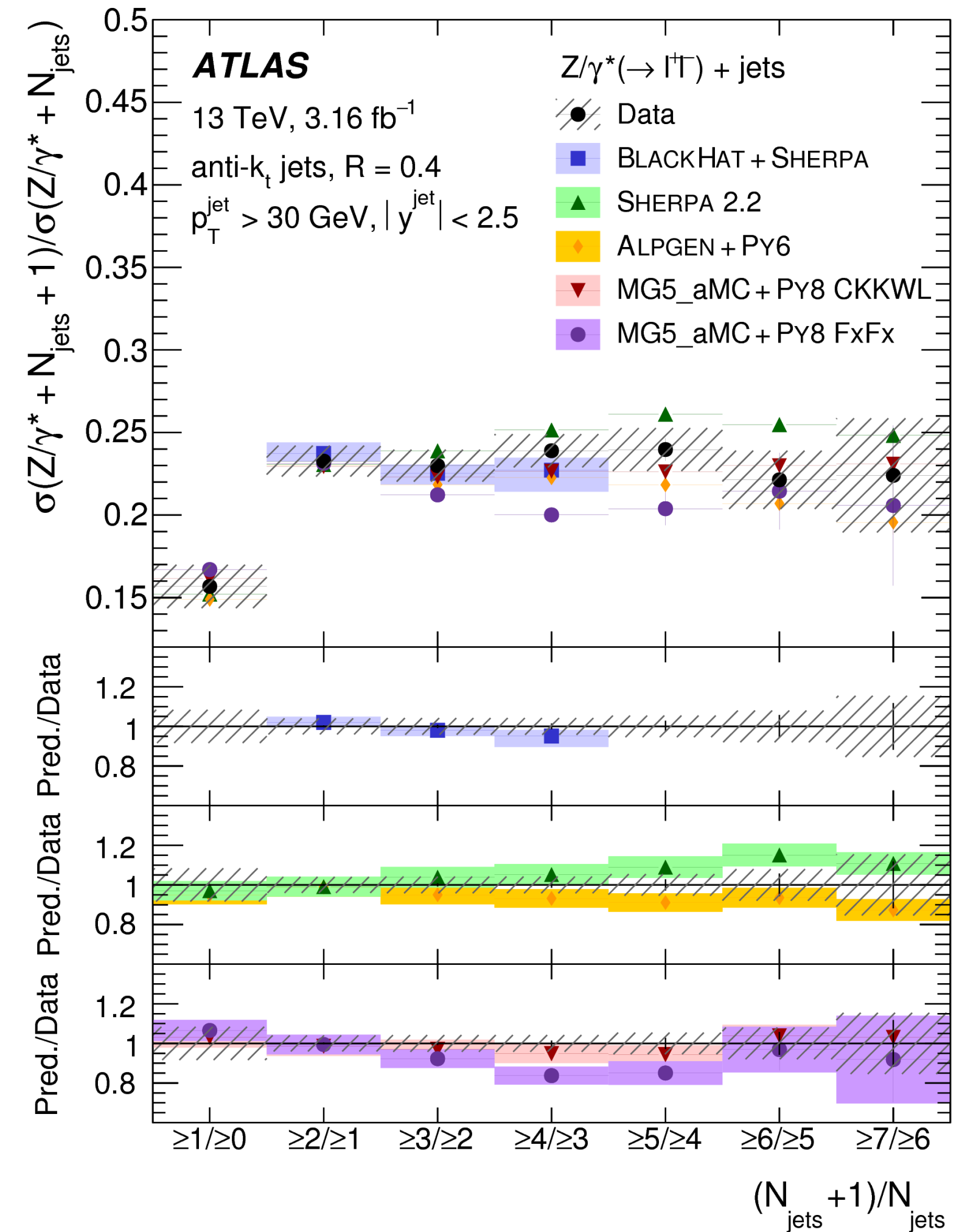
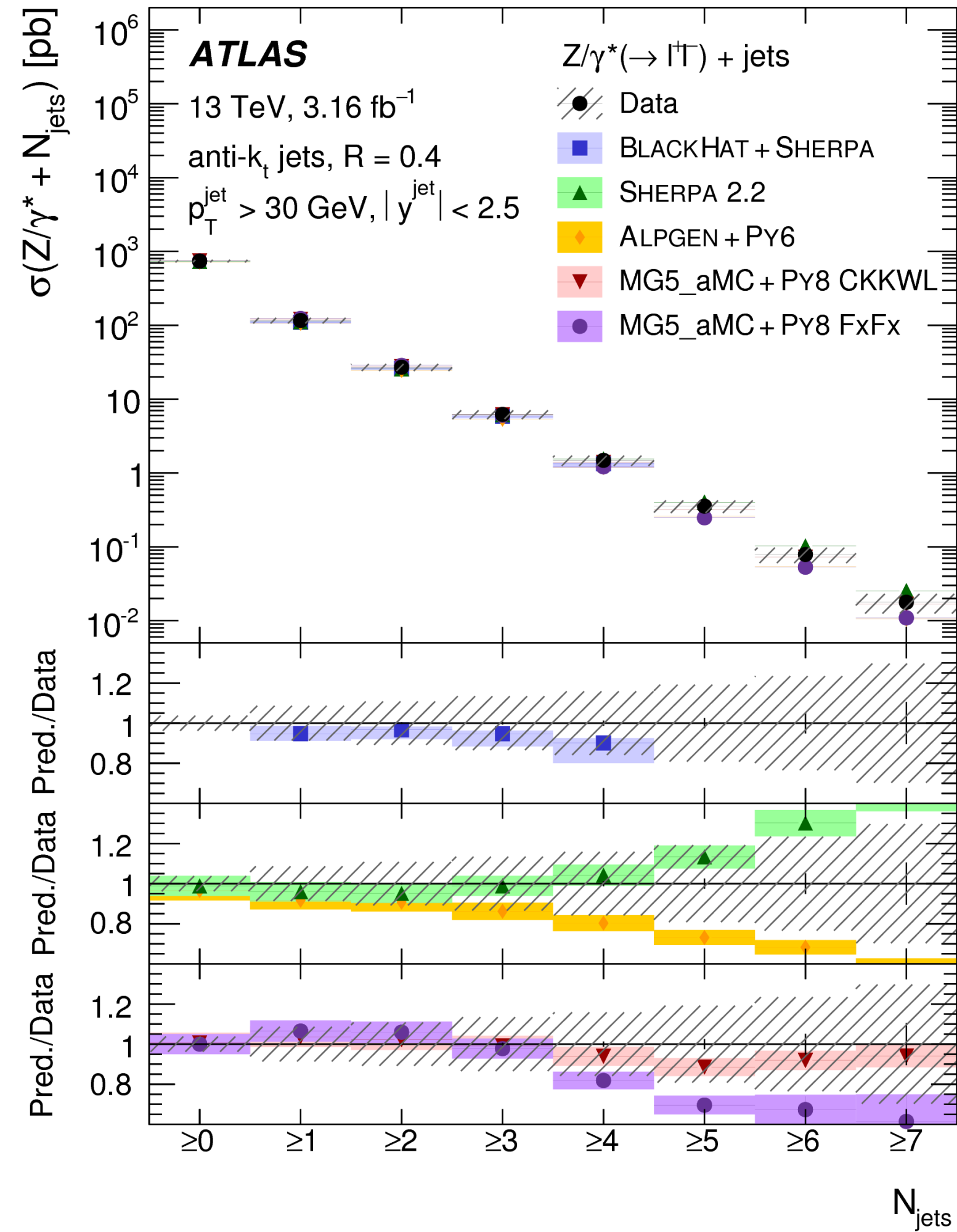
MSTW 2008 NNLO PDFs (68% C.L.)



- Primarily due to larger valance u quark proton parton density
- The cross-section ratio is thus a useful input to PDF fits

Z production in association with jets

- Important test of perturbative QCD and common background for many searches
- MC generators tend to struggle to describe multiplicity beyond 3 additional jets

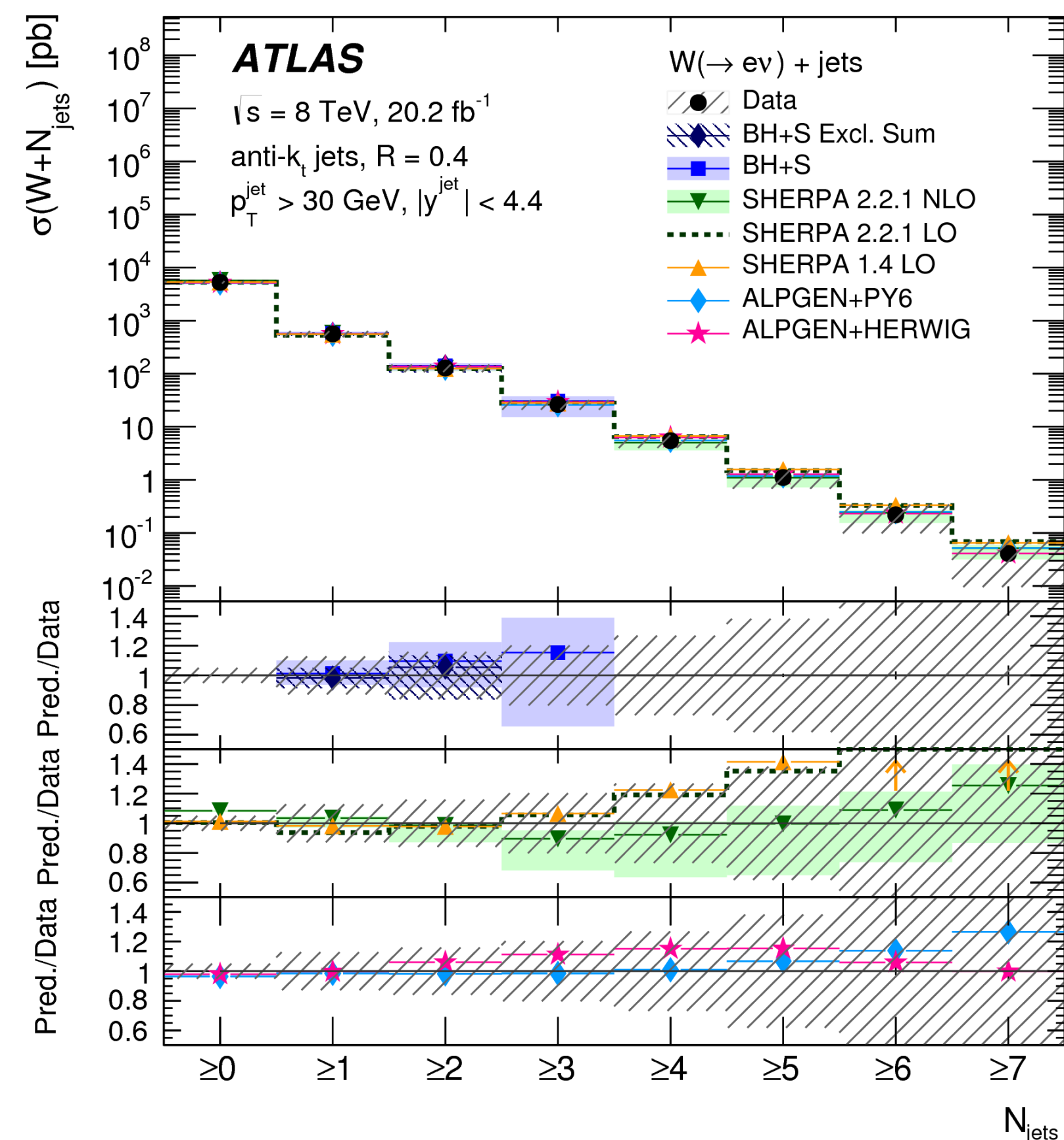
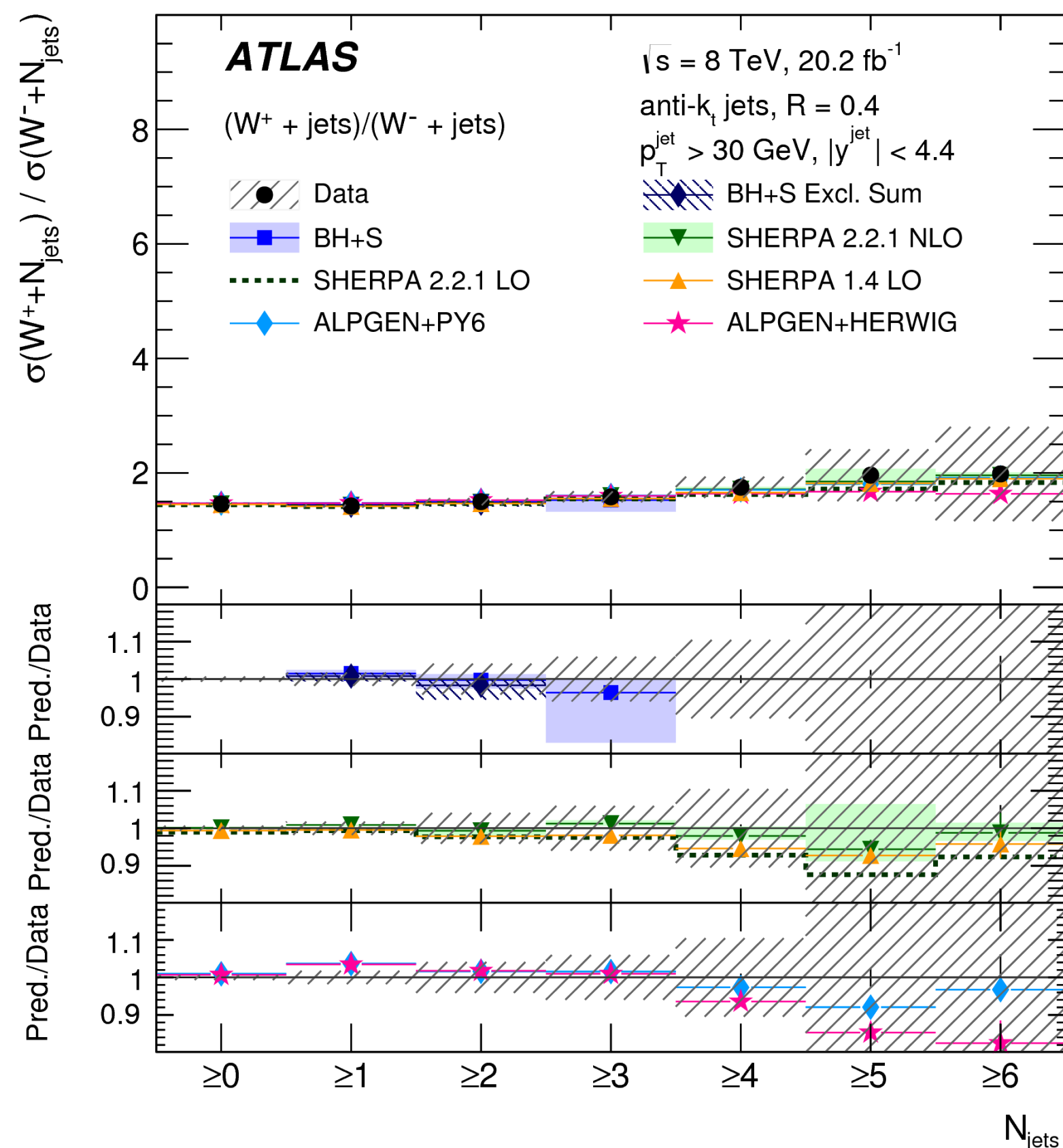


DOI: [10.1140/epjc/s10052-017-4900-z](https://doi.org/10.1140/epjc/s10052-017-4900-z)

W-boson production in association with jets

DOI: [10.1007/JHEP05\(2018\)077](https://doi.org/10.1007/JHEP05(2018)077)

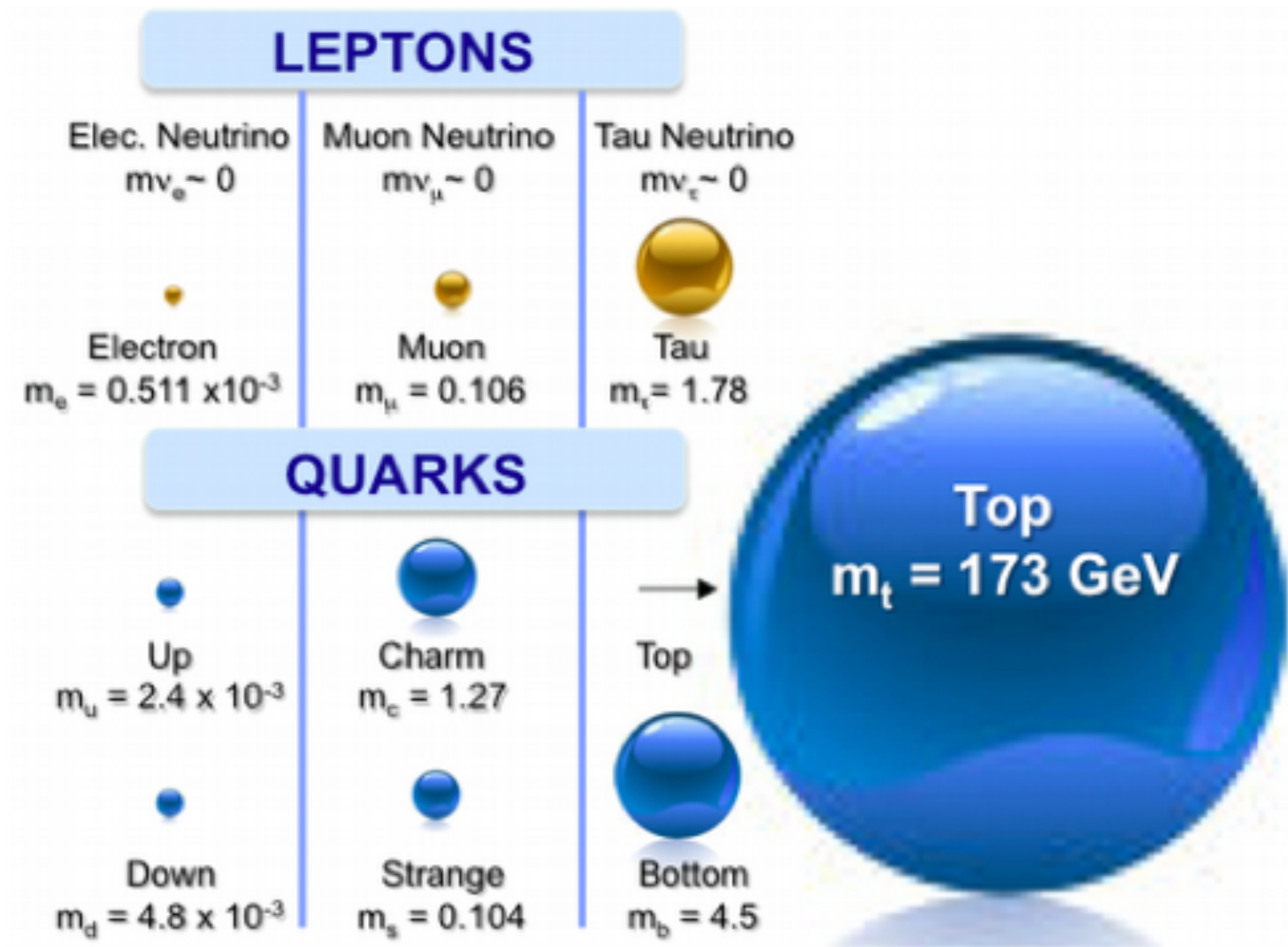
- Test for perturbative QCD and common background for many searches
- MC generators struggle to describe multiplicity beyond 3 additional jets
- Relative jet multiplicity very similar for W^+ and W^- until around 4 additional jets where pdf effects become more important



Introduction to top-quark physics

The top quark was discovered by the CDF and DØ experiments at the Fermilab Tevatron in 1995 and is unique among the other known quarks:

- Lifetime of $\approx 5 \times 10^{-25} s$ ($\Gamma_t \approx 1.3 \text{ GeV}$), shorter than timescale associated with hadronisation
- How about bound states (i.e. “toponium”) ??????
- Provides a unique opportunity to study the properties of a “bare” quark - e.g. spin is transferred to decay products (leptons, down-type quarks)



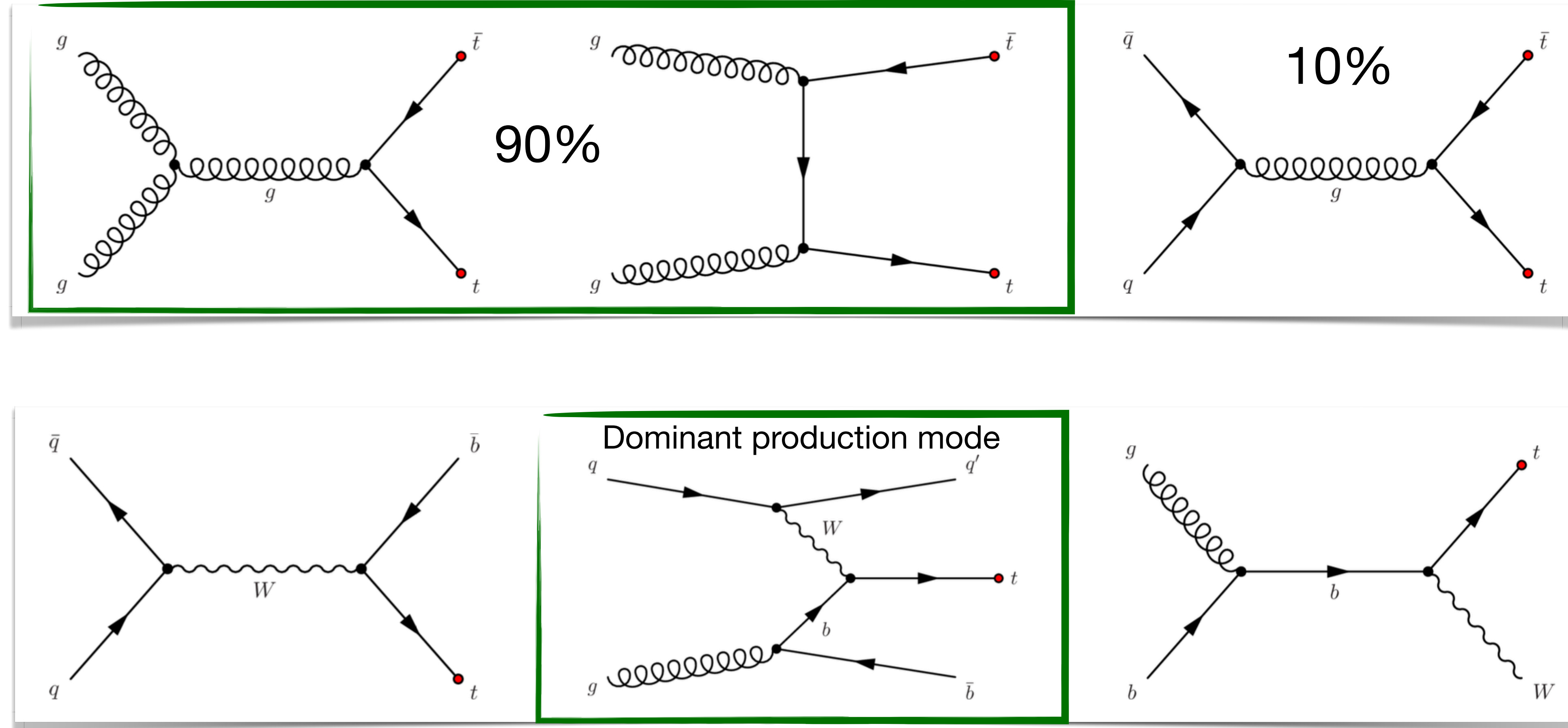
Many interesting properties to study:

- Mass - why is it so much larger than the other quarks?
- Spin - is it consistent with the SM hypothesis of spin 1/2 (fermion)?
- Width and decays - very large phase space open for decay products (e.g. BSM particles?)
- Couplings - in addition to gauge couplings, the top quark Yukawa coupling ($t\bar{t}H$) is expected to be ~ 1 (i.e. very large!)

Top Quark Production

- Top Pair Production: this is the dominant source of top quarks at the LHC, proceeds entirely via strong interactions
- Single top quark production: top quarks are also produced alone, in an electroweak process, in association with other quarks and W bosons

In pp collisions @ 13 TeV

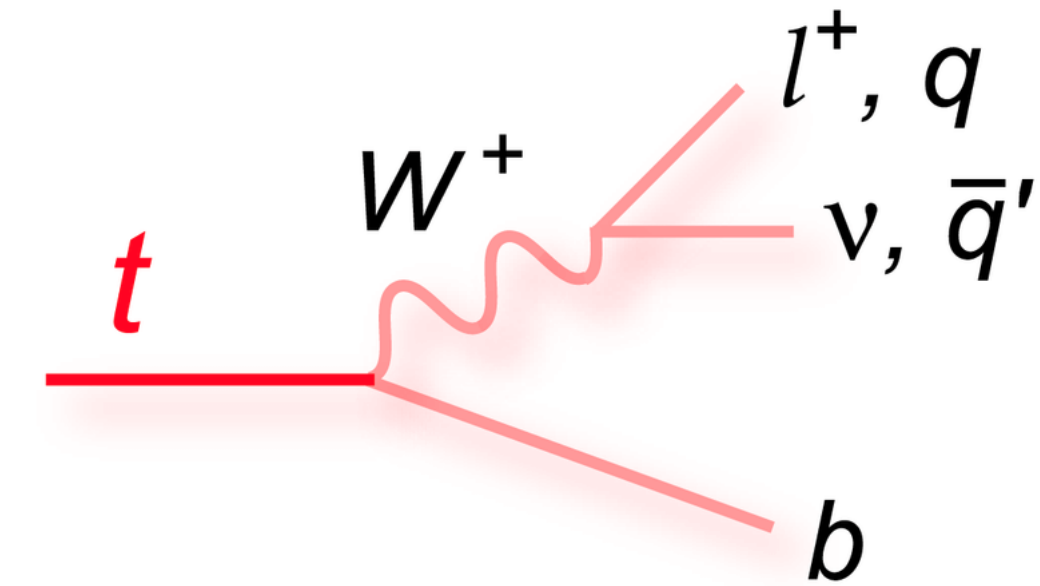


~ 200M top quarks @ LHC in Run 2

Top quark decays and $t\bar{t}$ final states

The decay $t \rightarrow Wb$ accounts almost the entire top quark decay width

- Other decays $t \rightarrow W\{s, b\}$ decays are suppressed by very small CKM elements and have not been observed directly
- Decays involving flavour changing neutral currents (e.g. $t \rightarrow q\{H, \gamma\}$) are very rare in the SM (loop suppressed) and highly susceptible to potential BSM contributions



From an experimental perspective, $t\bar{t}$ decays are categorised based on the W boson decays:

- all-hadronic: (46% of total) leading up to 6 jets
- Semi-leptonic: One hadronic and one leptonic, leading up to 4 jets, 1 lepton and 1 neutrino (45% of total)
- di-leptonic: two jets, two leptons and two neutrinos

Top Pair Decay Channels

$\bar{c}s$	electron+jets			all-hadronic	
$\bar{u}d$	muon+jets			all-hadronic	
τ^+	tau+jets			all-hadronic	
μ^-	tau+jets			all-hadronic	
e^-	muon+jets			all-hadronic	
e^-	electron+jets			all-hadronic	
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

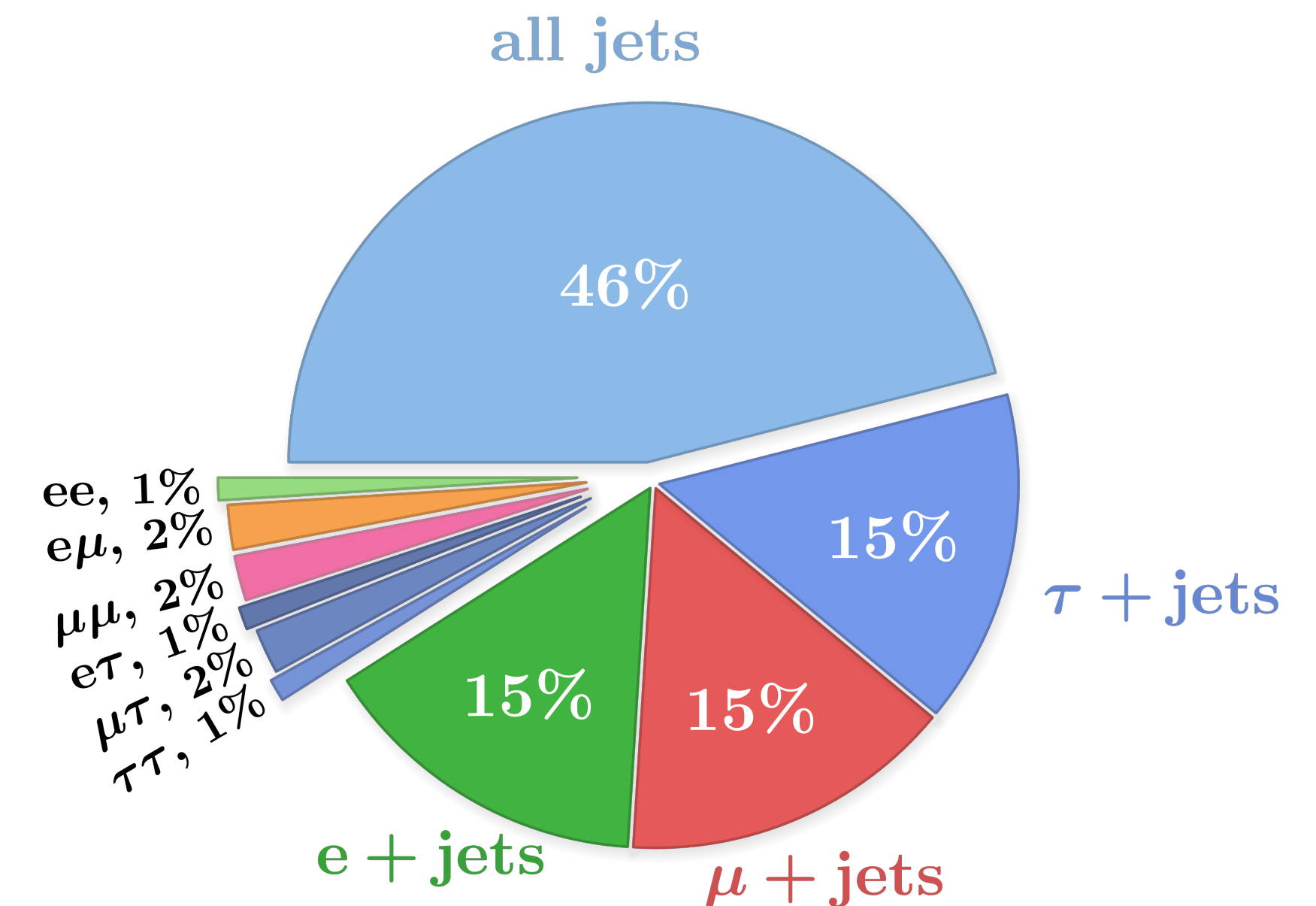
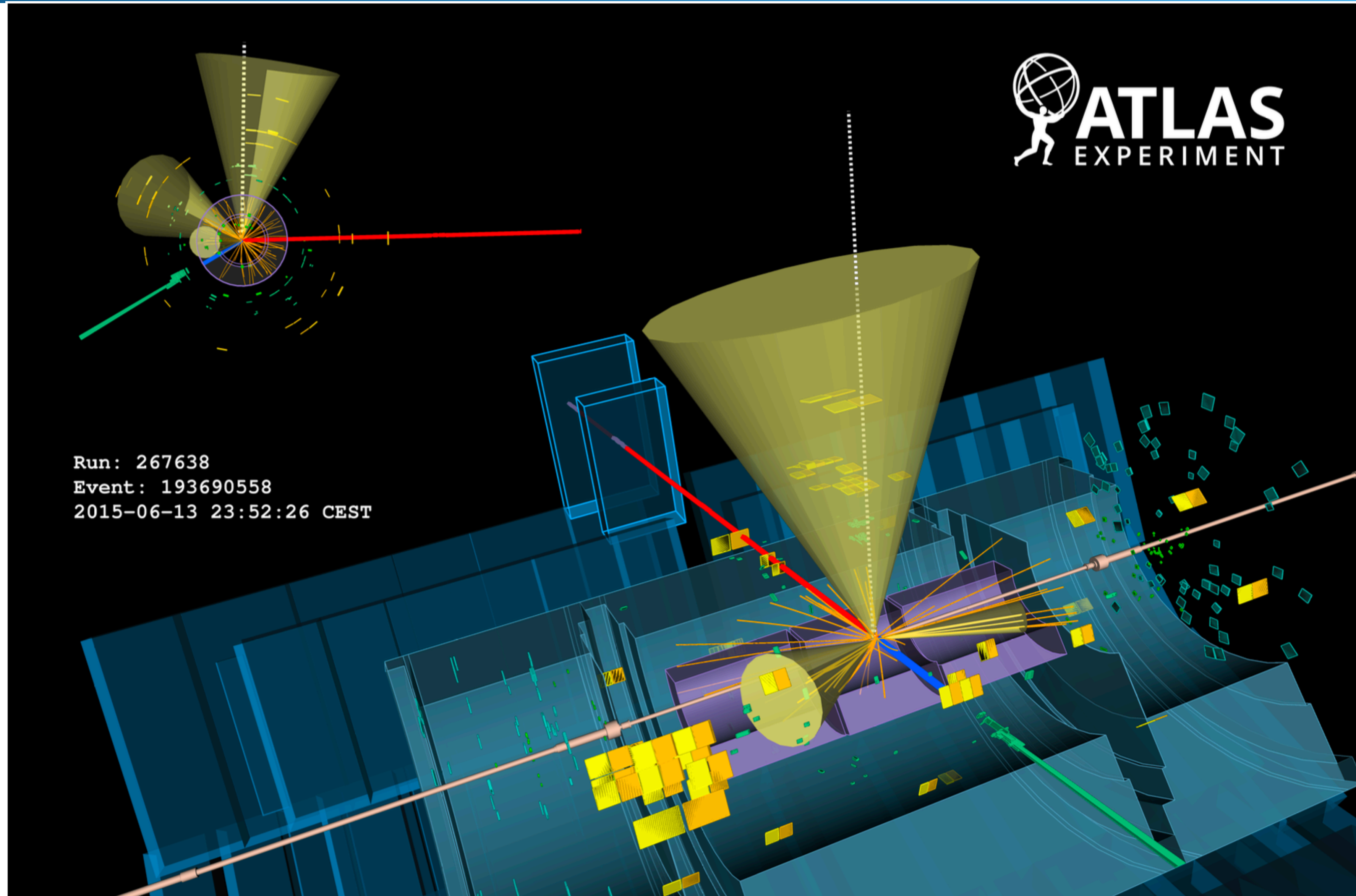
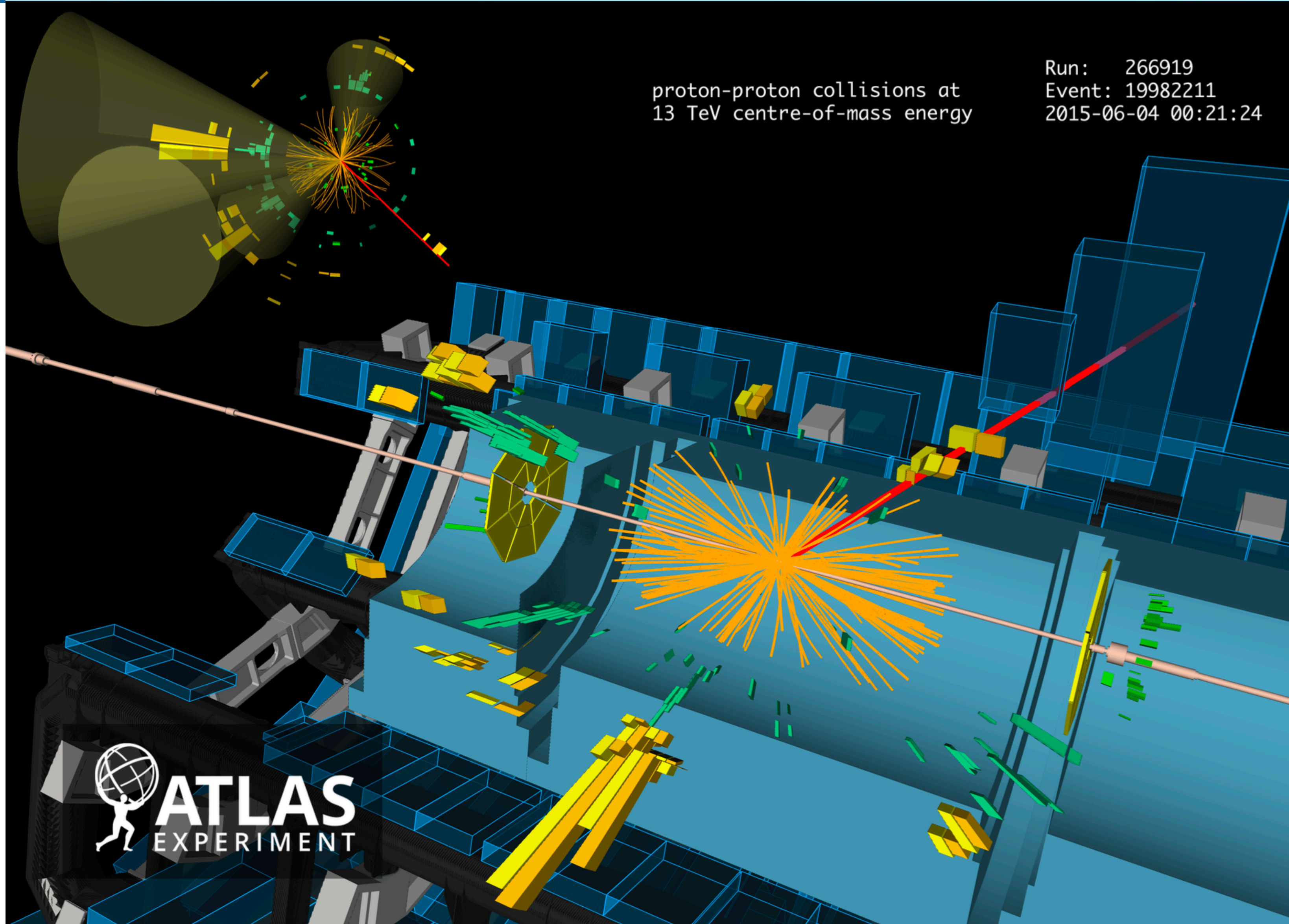


Image by Izzak Neutrings

Example of $t\bar{t}$ event

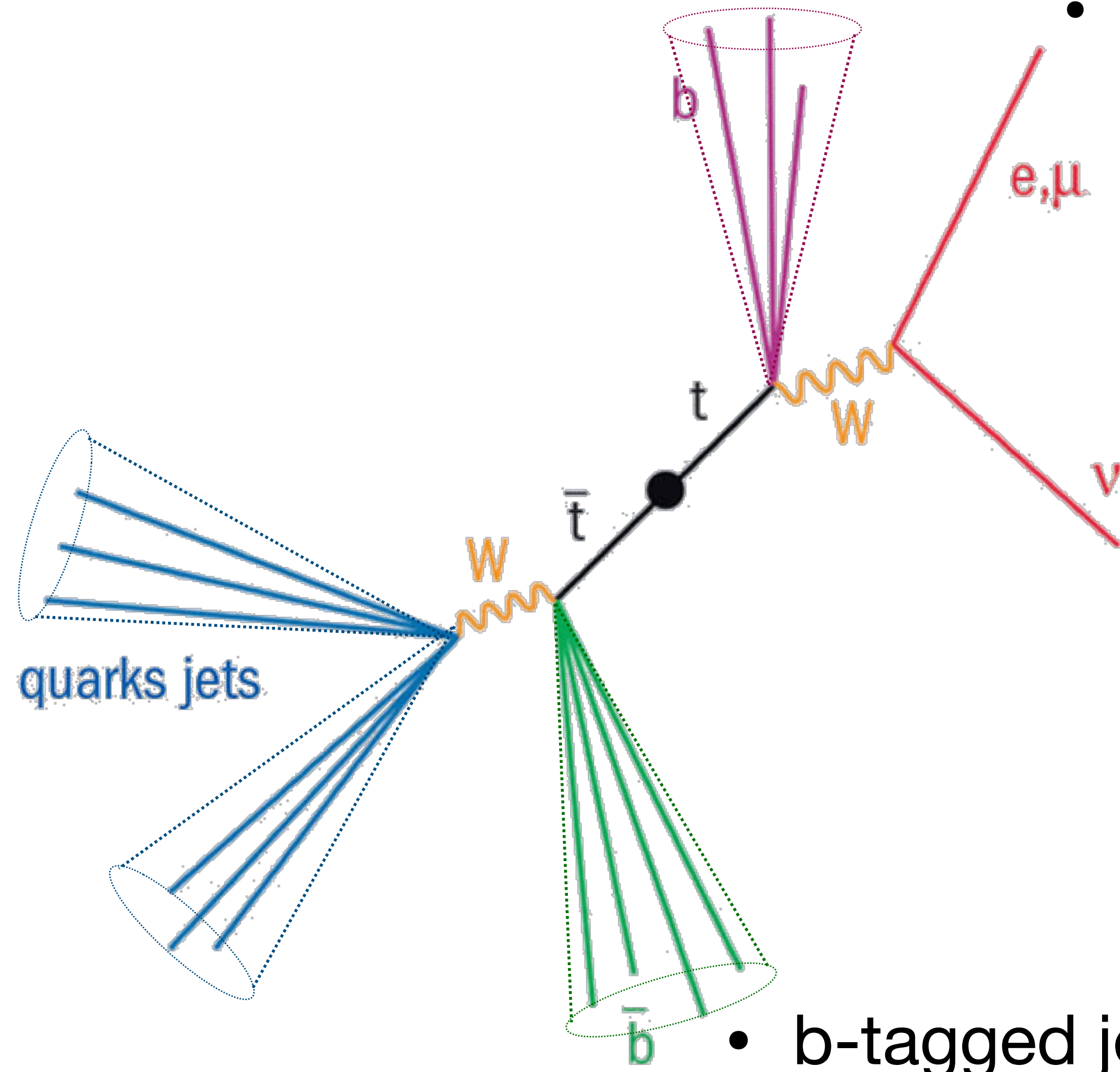


Example of $t\bar{t}$ event



Semi-leptonic $t\bar{t}b\bar{b}$ selection

- b-tagged jet



- Electron (muon): isolated object, with $E_T (p_T) > 20$ GeV and $|\eta| < 2.5$

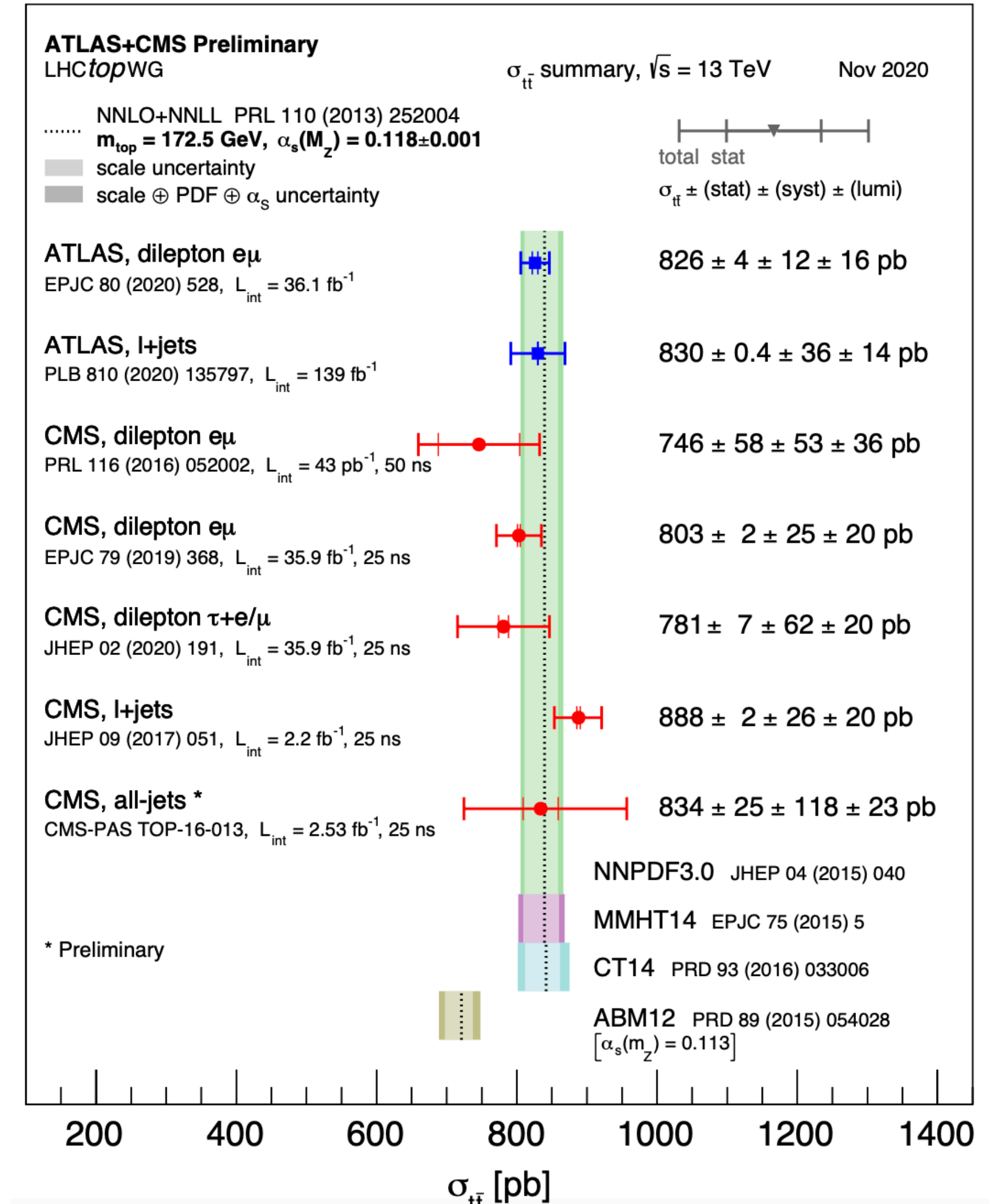
- Neutrino - p_T^{miss} , vector sum of energy deposits in the calorimeter

- Jets: Anti- k_T $R=0.4$, with $p_T > 20$ GeV, $|\eta| < 2.5$

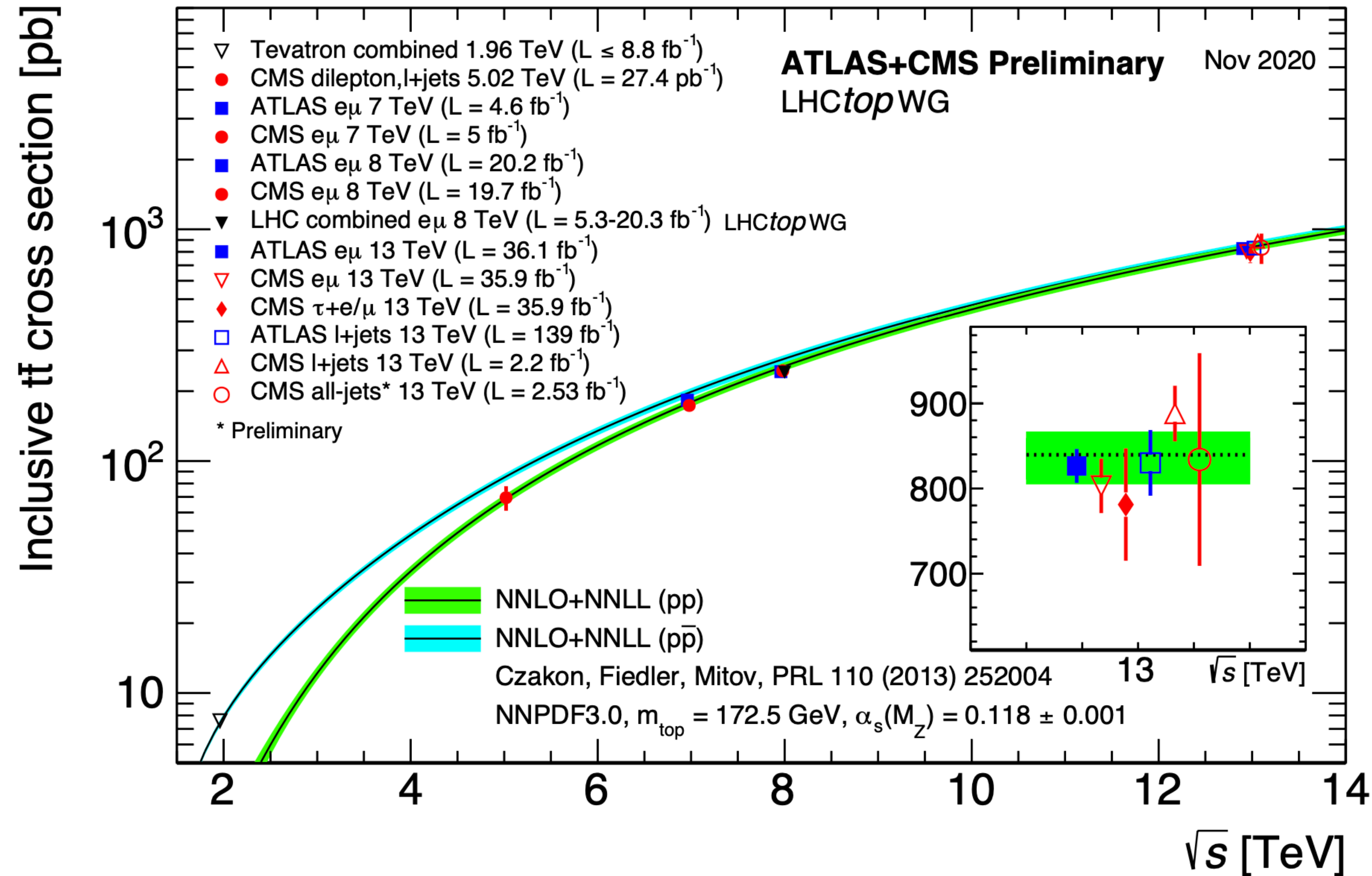
- b-tagged jet

Measurements of $t\bar{t}$ production I

- Most precise measurements made in the di-leptonic channel due to higher S/B ratio, lower susceptibility to experimental systematic uncertainties
- Precision of LHC Run 2 measurements typically limited by systematic and luminosity uncertainties
- $t\bar{t}$ cross-sections sensitive to different PDFs

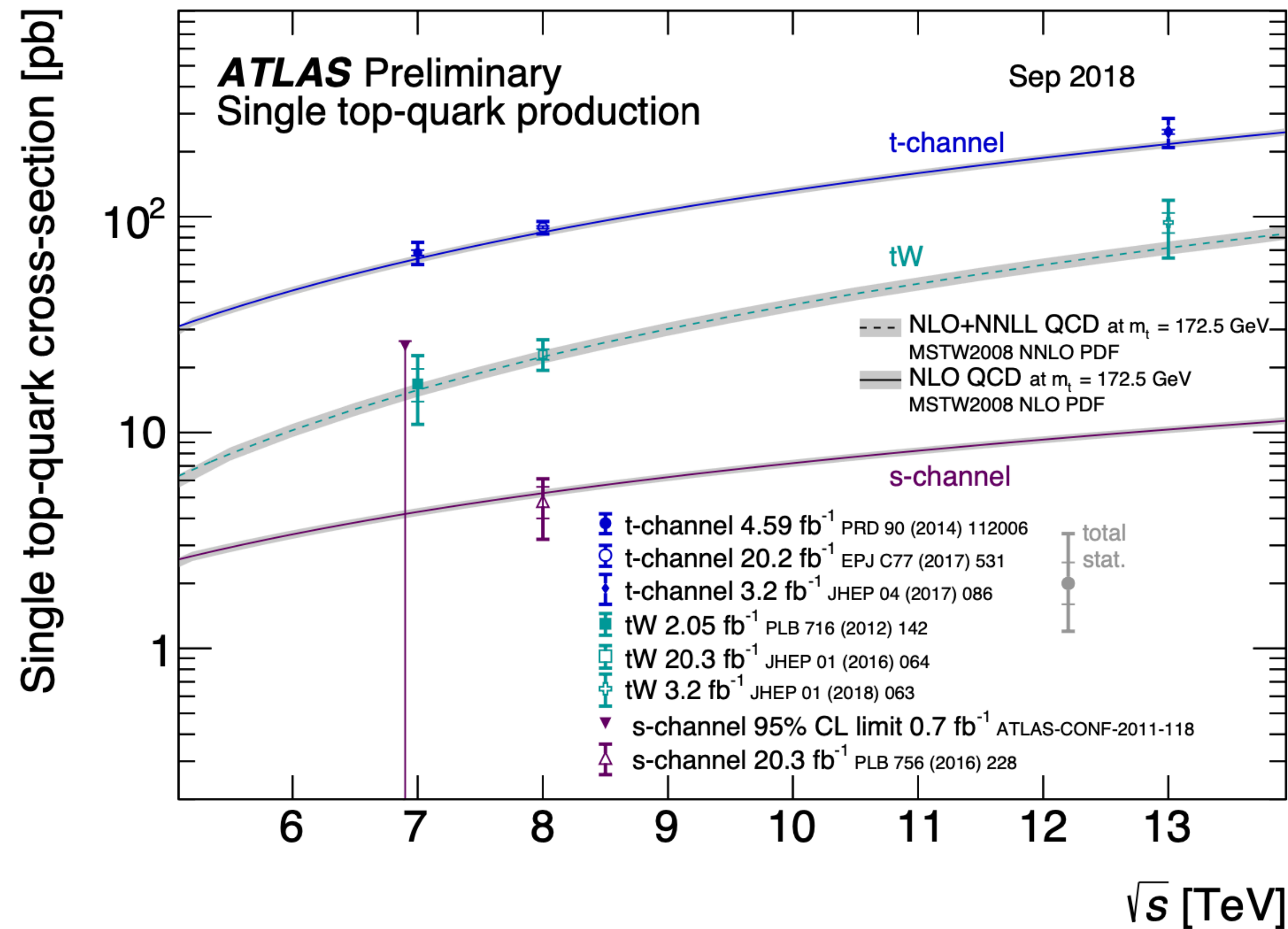


Measurements of $t\bar{t}$ production II



NNLO+NNLL QCD theoretical predictions for $t\bar{t}$ production in agreement with LHC and Tevatron measurements spanning order of magnitude in \sqrt{s}

Measurements of single top quark production

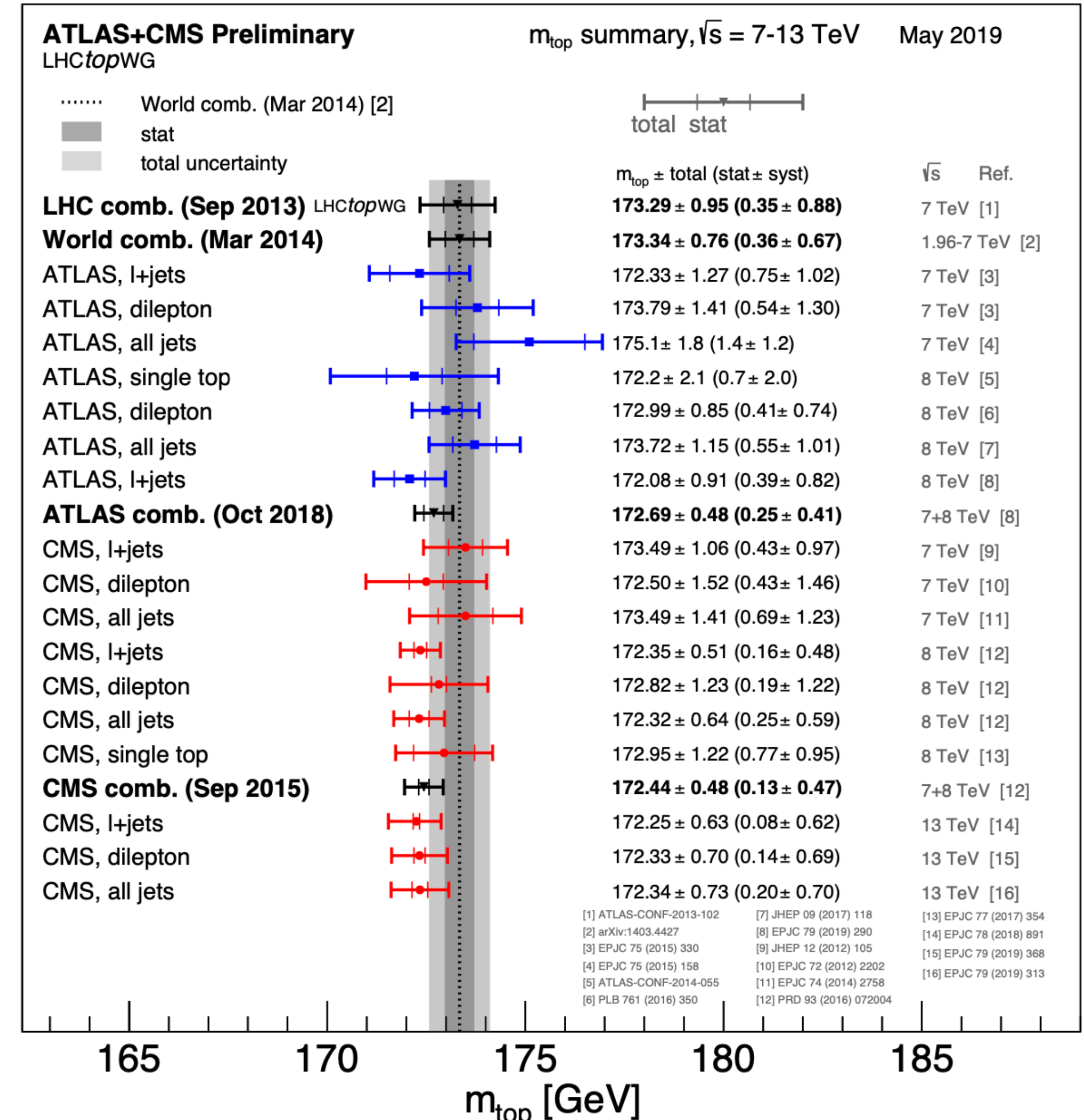


- The cross-sections for single top quark production are at least an order of magnitude lower than $t\bar{t}$, but now firmly established by LHC measurements
- Direct probe of $|V_{tb}|$ and sensitive to a variety of BSM models

Measurements of the top quark mass

The top quark mass is an important parameter of the SM and also has implications for our understanding of **SSB** and the **Higgs sector**

- Most precise measurements from the LHC offer $O(100 \text{ MeV})$ precision, now more precise than the Tevatron combination ($174.30 \pm 0.65 \text{ GeV}$)
- “Which top mass is being measured?” becomes a relevant question (i.e. soft QCD effects relevant at 100 MeV scale)



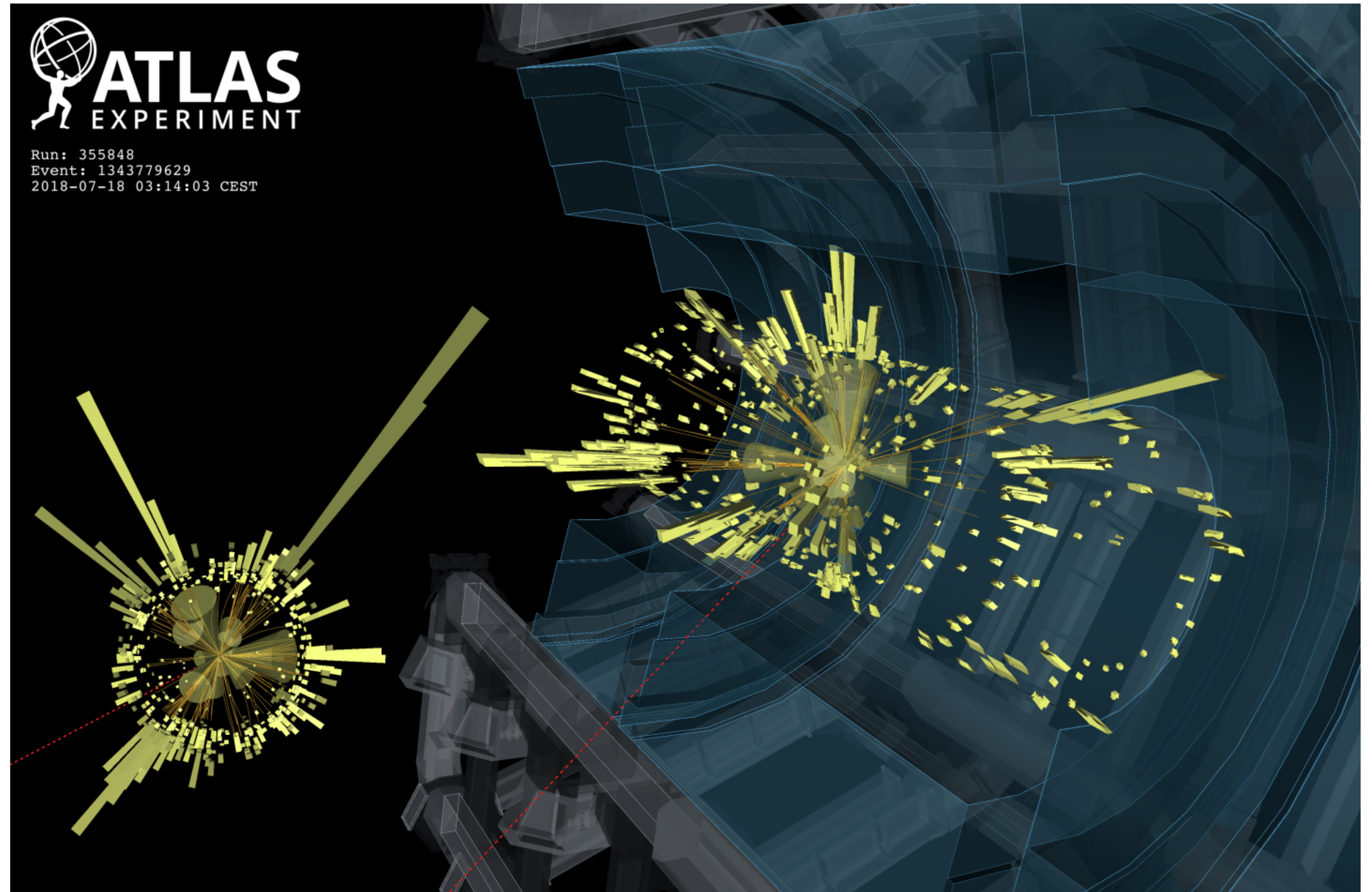
Summary

- The physics available to study at the LHC is broad and very rich, spanning orders of magnitude in terms of energy and coupling strength!
- Soft interactions at a hadron collider can never be ignored, it's essential that they are well understood
- Jets are everywhere at the LHC, important background to any measurement or search
- W and Z bosons are the primary source of isolated leptons
- The LHC produces a huge number of top quarks, now a major background to many Higgs / BSM searches

Additional Material

Event with the highest jet multiplicity ATLAS - Run2

- Visualisation of the highest jet multiplicity event selected in a control region used to make predictions of the background from multijet production.
- This event contains 19 jets, illustrated by cones.
- Yellow blocks: calorimeter energy
- Of the reconstructed jets, 16 (10) have transverse momenta above 50 GeV (80 GeV).
- No jets were b-tagged.
- The leading jet has a transverse momentum of 371 GeV,
- A value of 8 GeV missing transverse energy, whose direction is shown by the dashed red line



Toponium

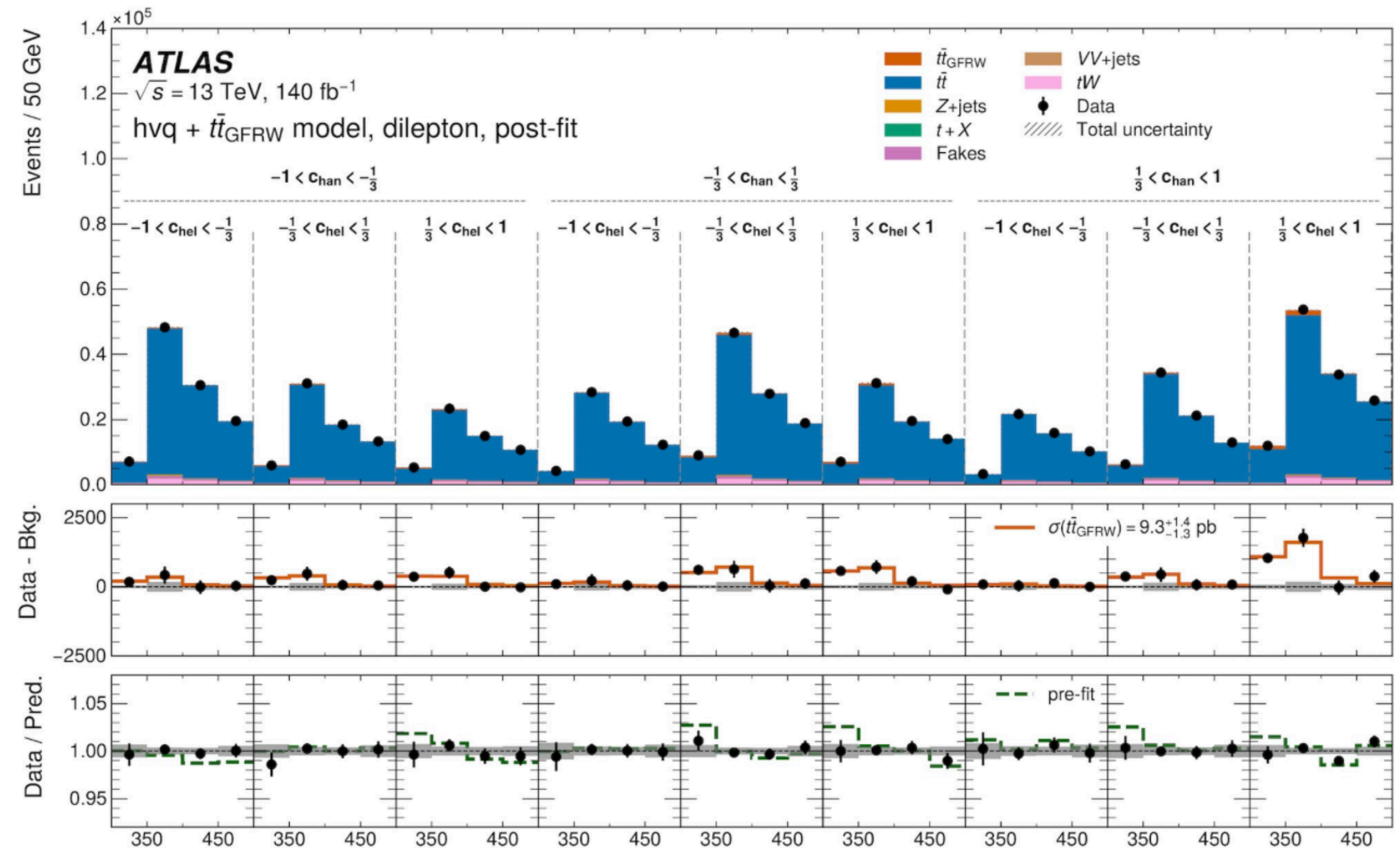
does the top quark – the heaviest of them all – form a similar bound state, a toponium?

- When top quarks are produced very slowly, close to the energy threshold for creating a pair, they “feel” each other’s presence through the strong force just before they decay.
- The signal manifests as a subtle distortion in the production rate of top-quark pairs ($t\bar{t}$) near the threshold.
- Analysis focused on the dilepton decay channel, $t\bar{t} \rightarrow e\mu, ee, \mu\mu + \text{neutrinos} + \text{jets}$.
- “gold standard” for cleanliness, allowing us to reconstruct the invariant mass of the top-quark system ($m_{t\bar{t}}$) with high precision.
- Standard perturbative QCD (pQCD) calculations break down when top quarks move slowly relative to one another. To describe this non-relativistic regime, we need a specialized framework known as Non-Relativistic QCD (NRQCD)

Toponium

Two hypotheses:

- The Standard Picture: A baseline pQCD model that assumes independent top quark production.
- The Toponium Picture: An extended model incorporating the NRQCD quasi-bound state effects.
- mass + the angular separation of the leptons in the laboratory frame.
quasi-bound state forms in a specific quantum spin state (a spin-singlet)



8 σ deviation

Toponium

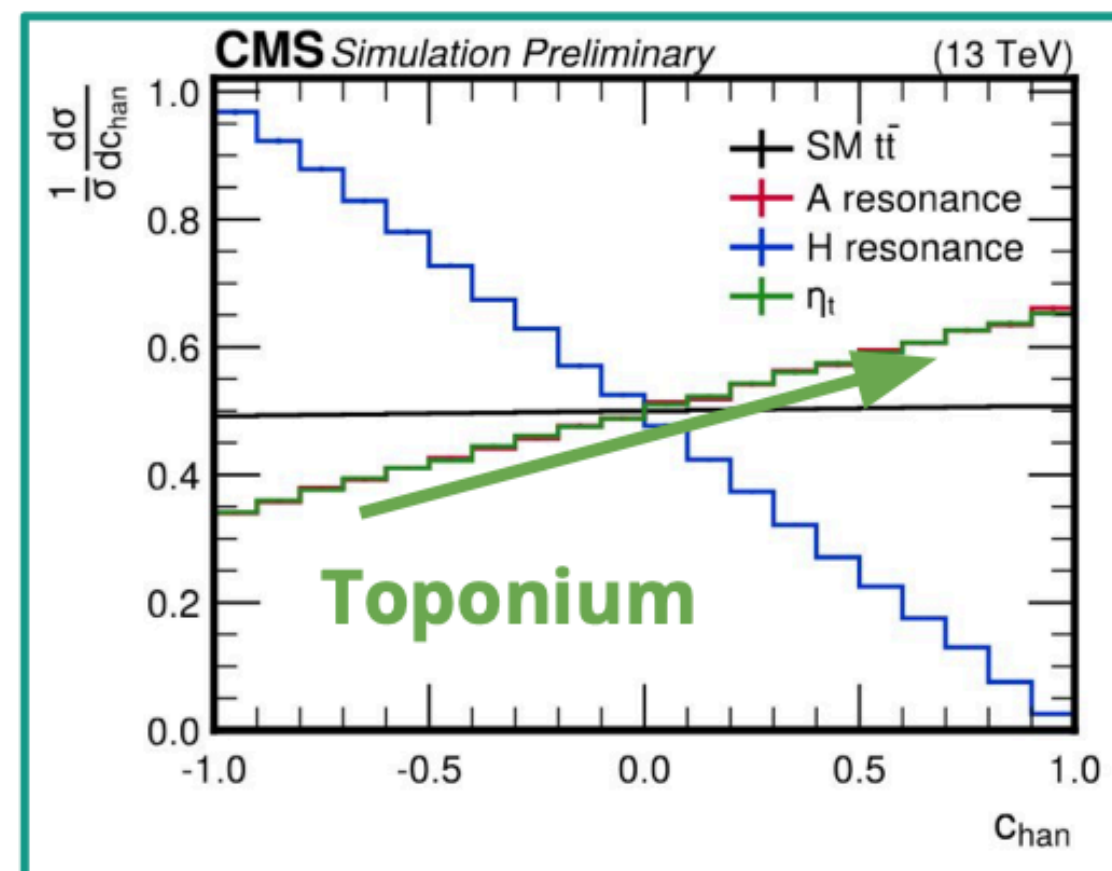
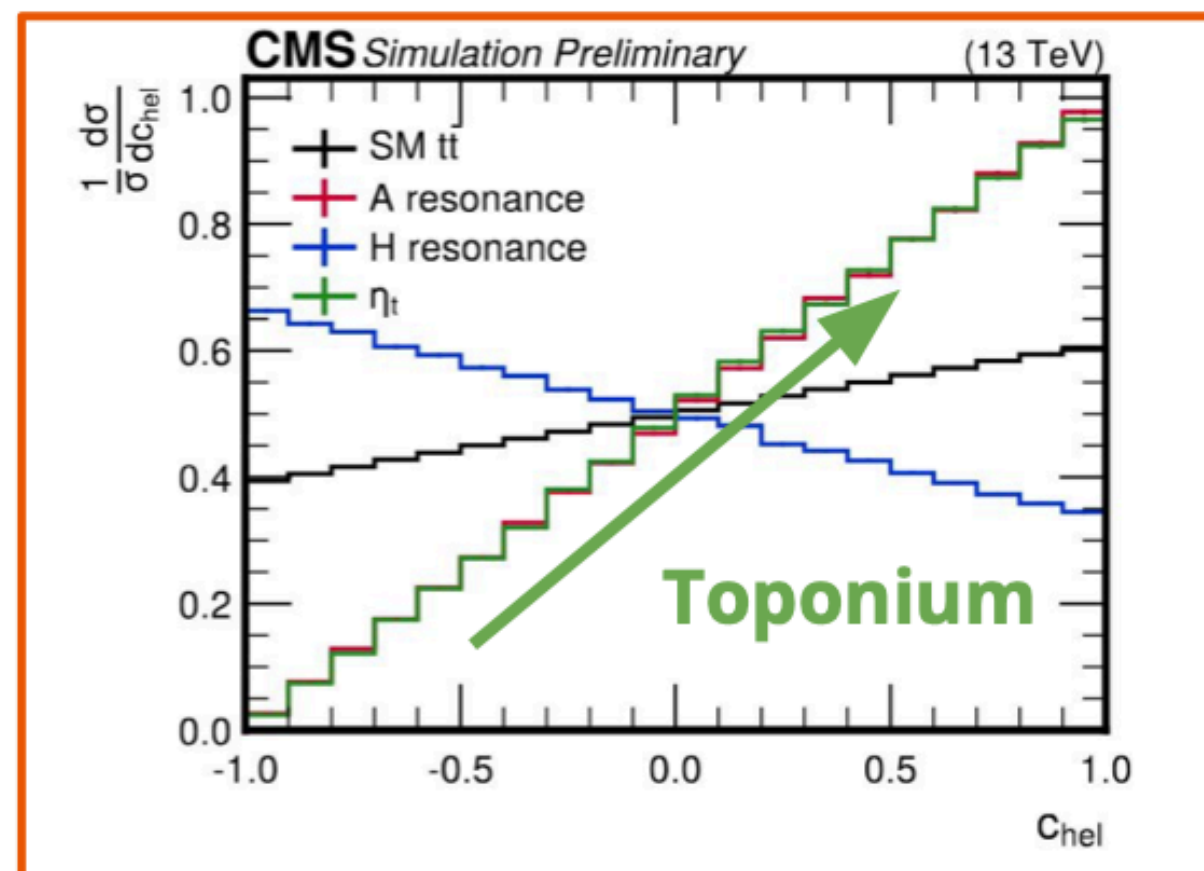
full Run 2 data: 140.1 fb⁻¹

[ATLAS-CONF-2025-008](#)

Observation of Xsection enhancement near $t\bar{t}$ threshold

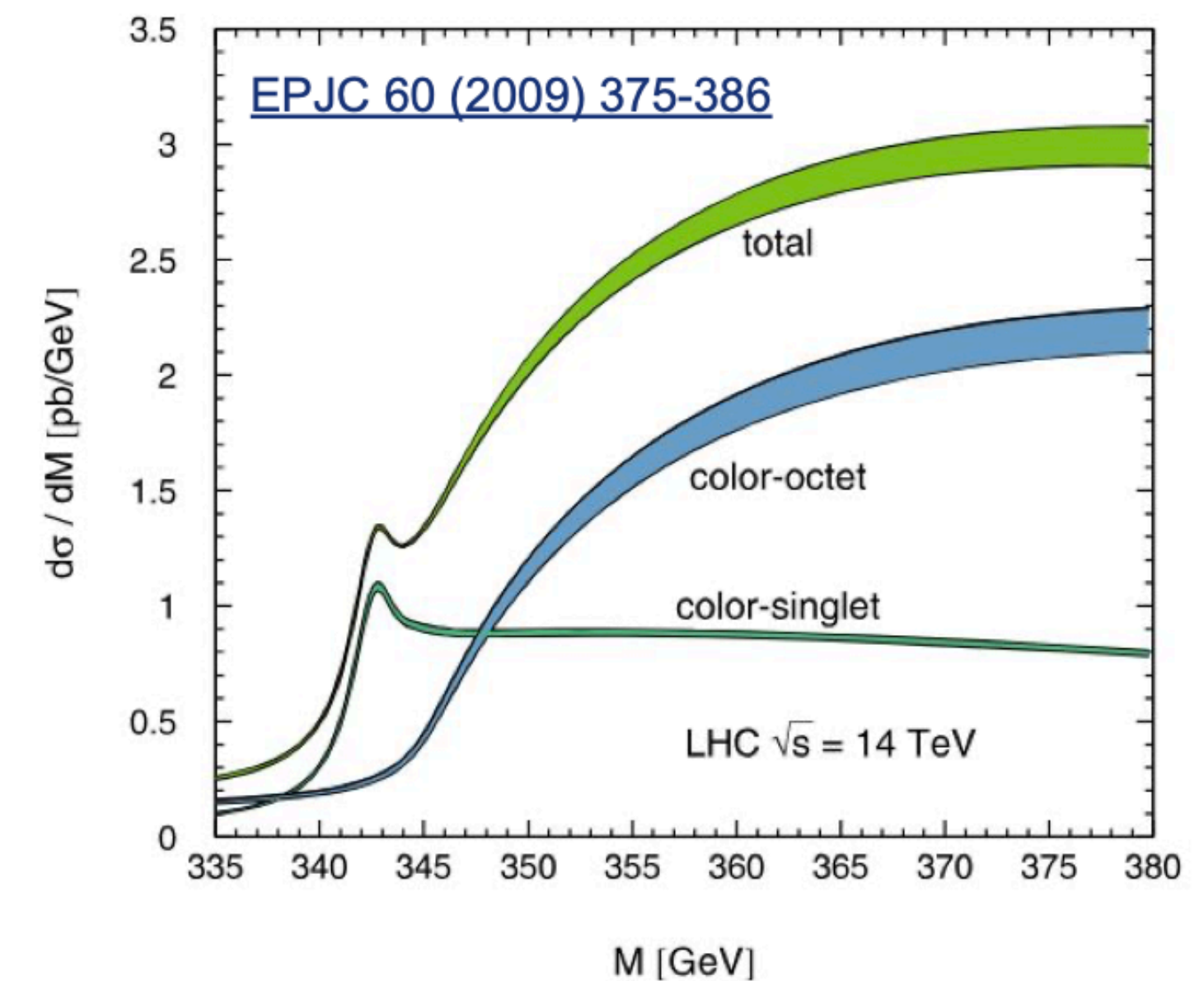
Toponium = Quasi-bound state of top quarks predicted by SM

- Not the same as $b\bar{b}/c\bar{c}$ (**not a s-channel resonance**)
 - one of top decays first, they do not annihilate themselves
- Pseudoscalar nature dominant - translated to angular properties of top decay products
- Not sensitive enough to be observed in $m_{t\bar{t}}$ spectrum
 - Use variables C_{hel} and C_{han} sensitive to spin-correlations



η_t = BSM-like pseudoscalar color-singlet resonance

[CMS-PAS-HIG-22-013](#)



Observed previously by CMS
[\[CMS-TOP-24-007, CMS-PAS-HIG-22-013\]](#)

Slide from Barbora Eckerova

Toponium

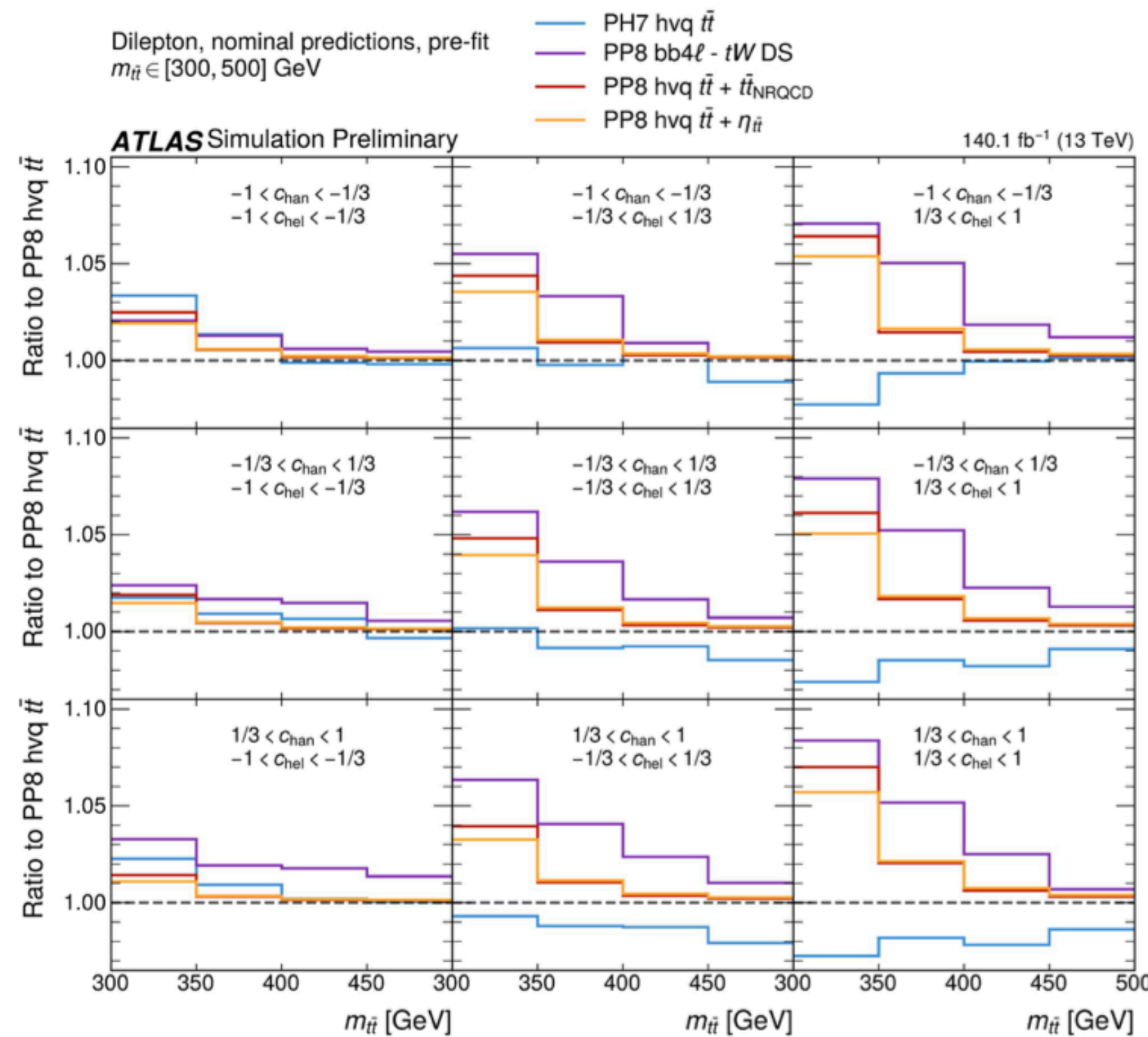
full Run 2 data: 140.1 fb⁻¹

ATLAS-CONF-2025-008

Observation of Xsection enhancement near $t\bar{t}$ threshold

Measured Xsection of $t\bar{t}$ quasi-bound state:

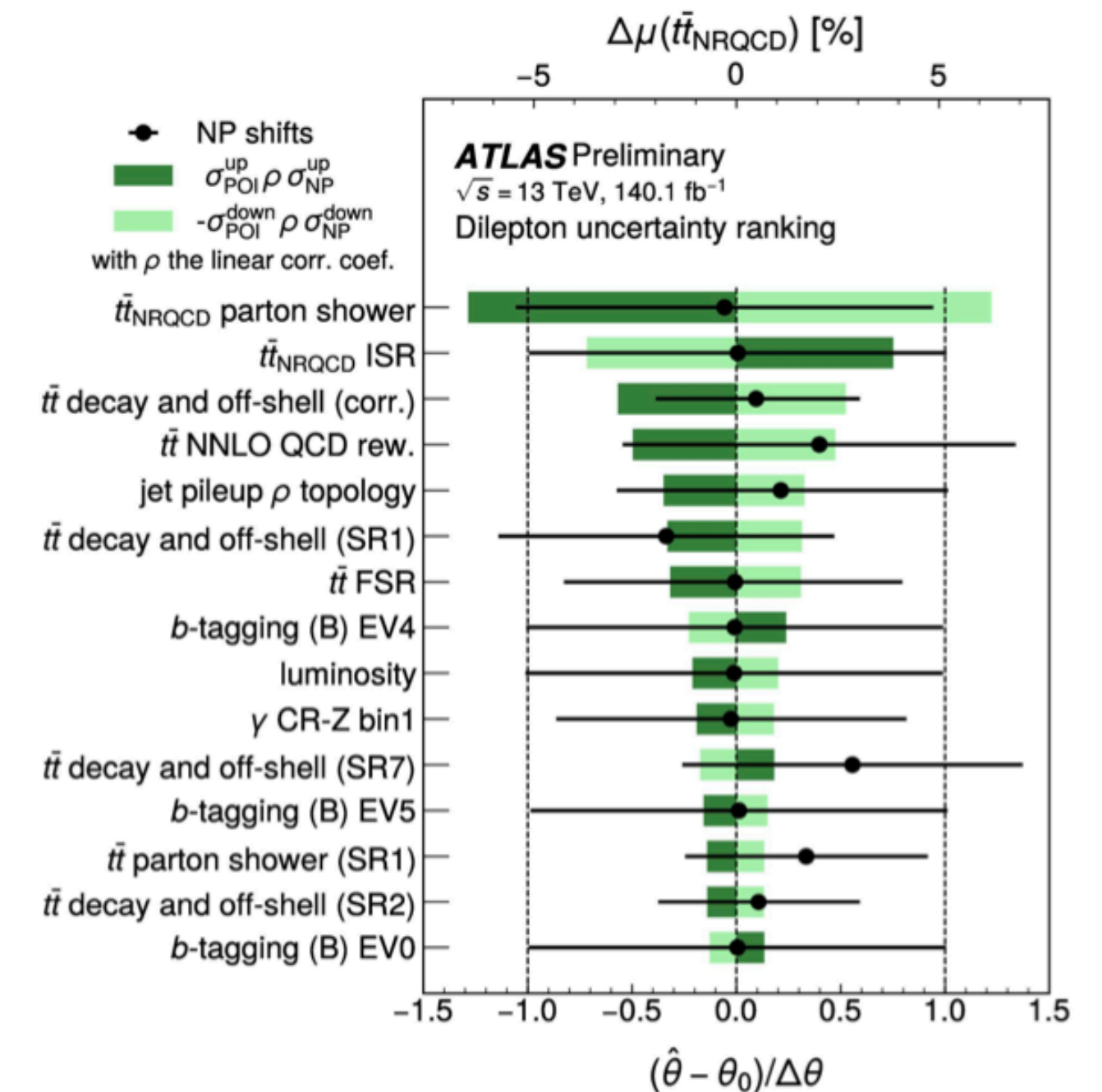
$$\sigma(t\bar{t}_{\text{NR-QCD}}) = 9.0 \pm 1.3 \text{ pb} = 9.0 \pm 1.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}$$



Extremely challenging measurement:

Need more precise models of the threshold region and toponium signal, understanding of NLO EW and NNLO QCD corrections to production
NLO and off-shell effects in decay, etc.

Further studies needed to investigate the nature of this excess



Measurement precision limited by signal and background modelling uncertainties.

Slide from Barbora Eckerova