Introduction to the Large Hadron Collider and Standard Model measurements

Mario Campanelli

University College London

Atlas Collaboration

A word about myself

- 1994-1995 Master degree in Rome, on the L3 detector (CERN)
- 1995-1998 PhD ETH Zurich on L3
- 1998-2001 Researcher ETHZ on ICARUS
- 2001-2007 Researcher Geneva Uni on CDF (Chicago)
- 2007-now Academic staff (now Professor) UC London on ATLAS (CERN)

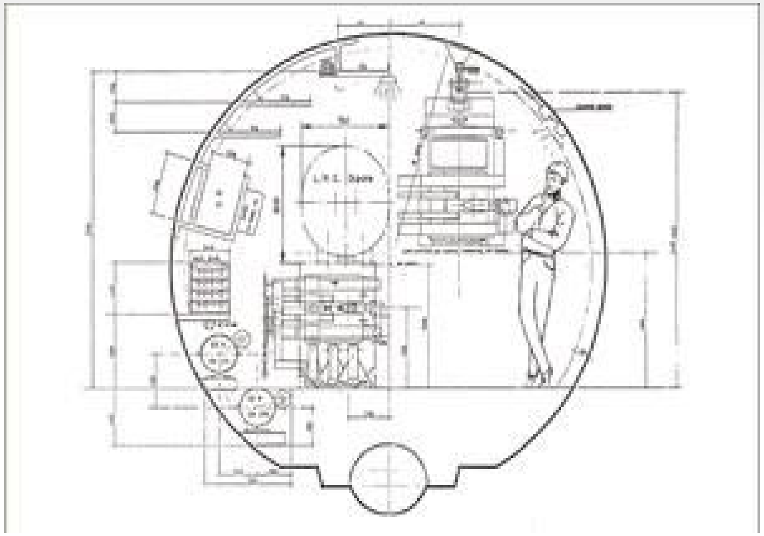
Outline

- The machine: why the LHC is a unique collider
- Present status
- Parton density functions and luminosity
- QCD physics
- Production of vector bosons

A bit of history…

In the eighties, CERN built LEP, the large electron-positron collider, in a 26.6 km tunnel at average depth of 100m.

It was the largest civil-engineering project in Europe at that time.



Already in spring 1984 (5 years before LEP started operations!) a workshop was held on the possibility of building ”a Large Hadron Collider” in the LEP tunnel

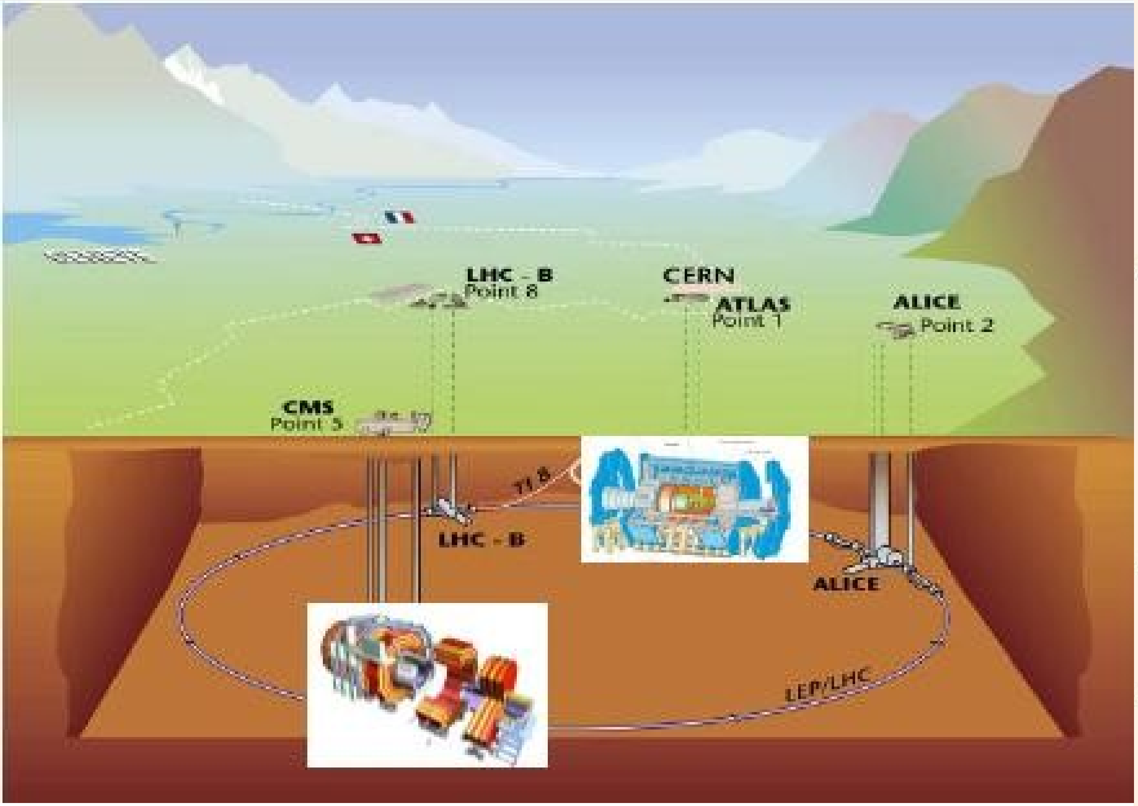
Towards the LHC

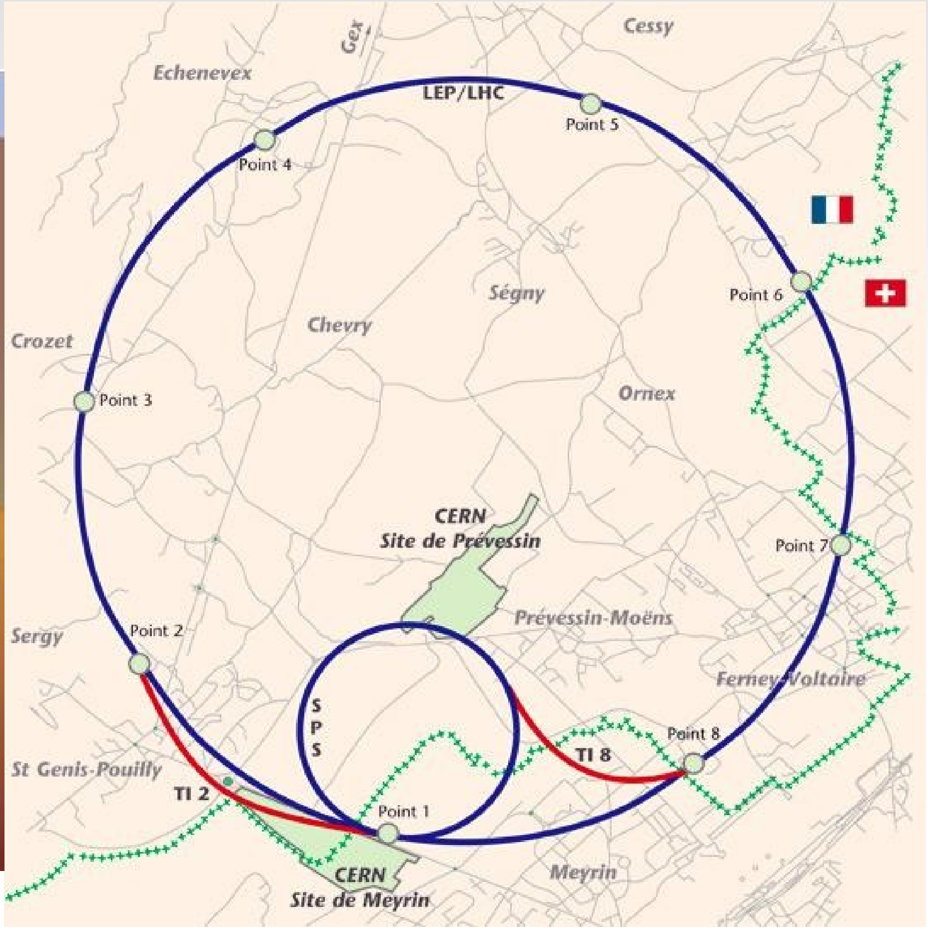
At that time, the US was building a very ambitious hadron collider, the SSC in Texas

In 1993 the US congress canceled the SSC project due to budget cuts, the LHC was the only viable project for the energy frontier (and approved in 1994)

The discussion on detectors was well under way, and after many merges ATLAS and CMS were approved in 1995.

LHC layout


LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
TI 8
LHC - B
ALICE
LEP/LHC


Cessy
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Site de Prévessin
Point 7
Prévessin-Moëns
Sergy
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Ferney-Voltaire
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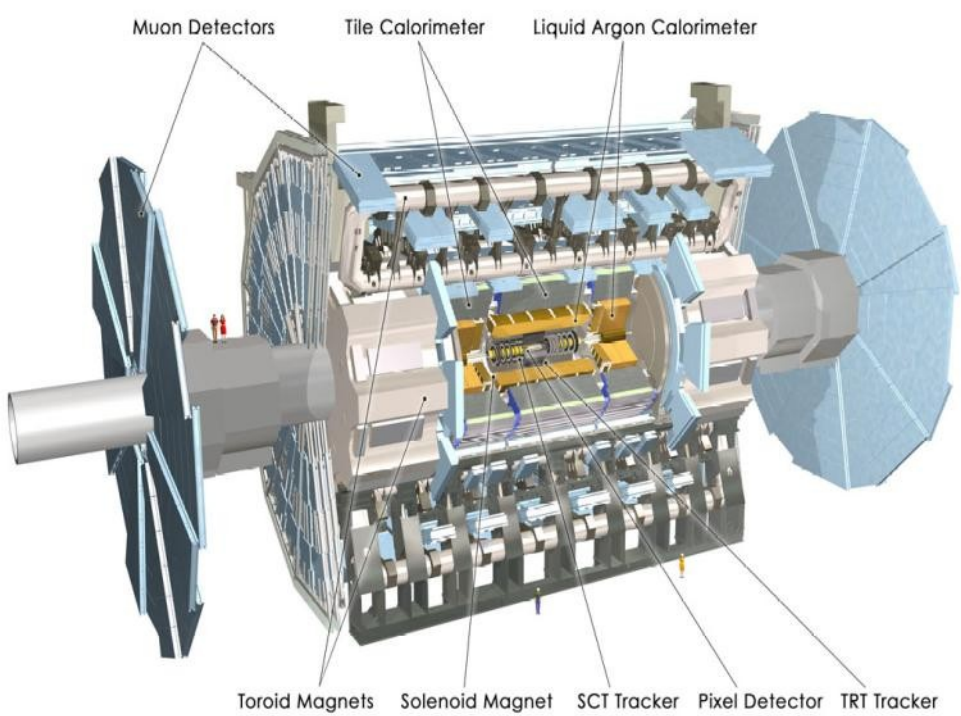
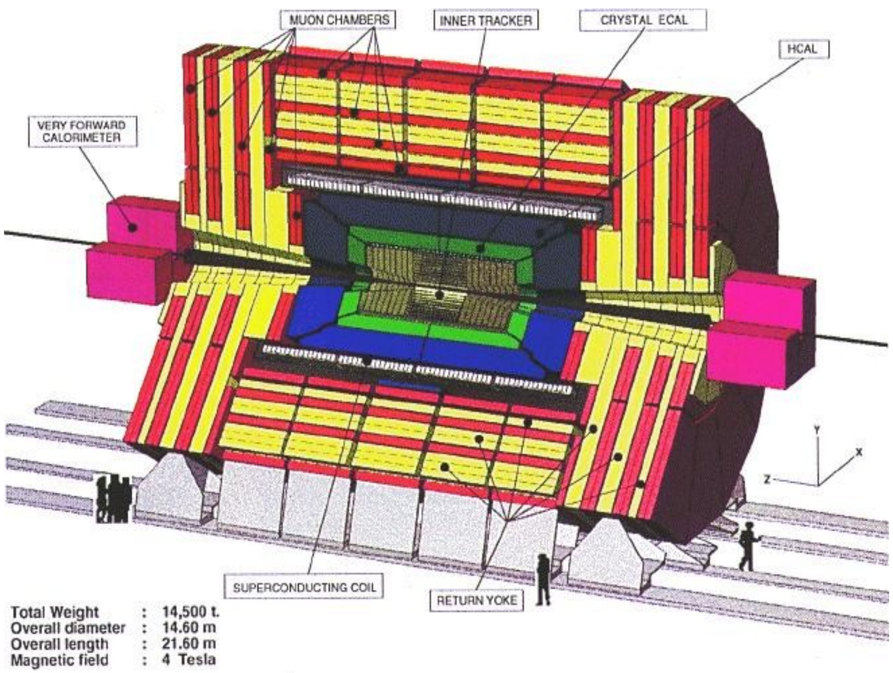
TI 2
Point 1
CERN
Site de Meyrin
Meyrin

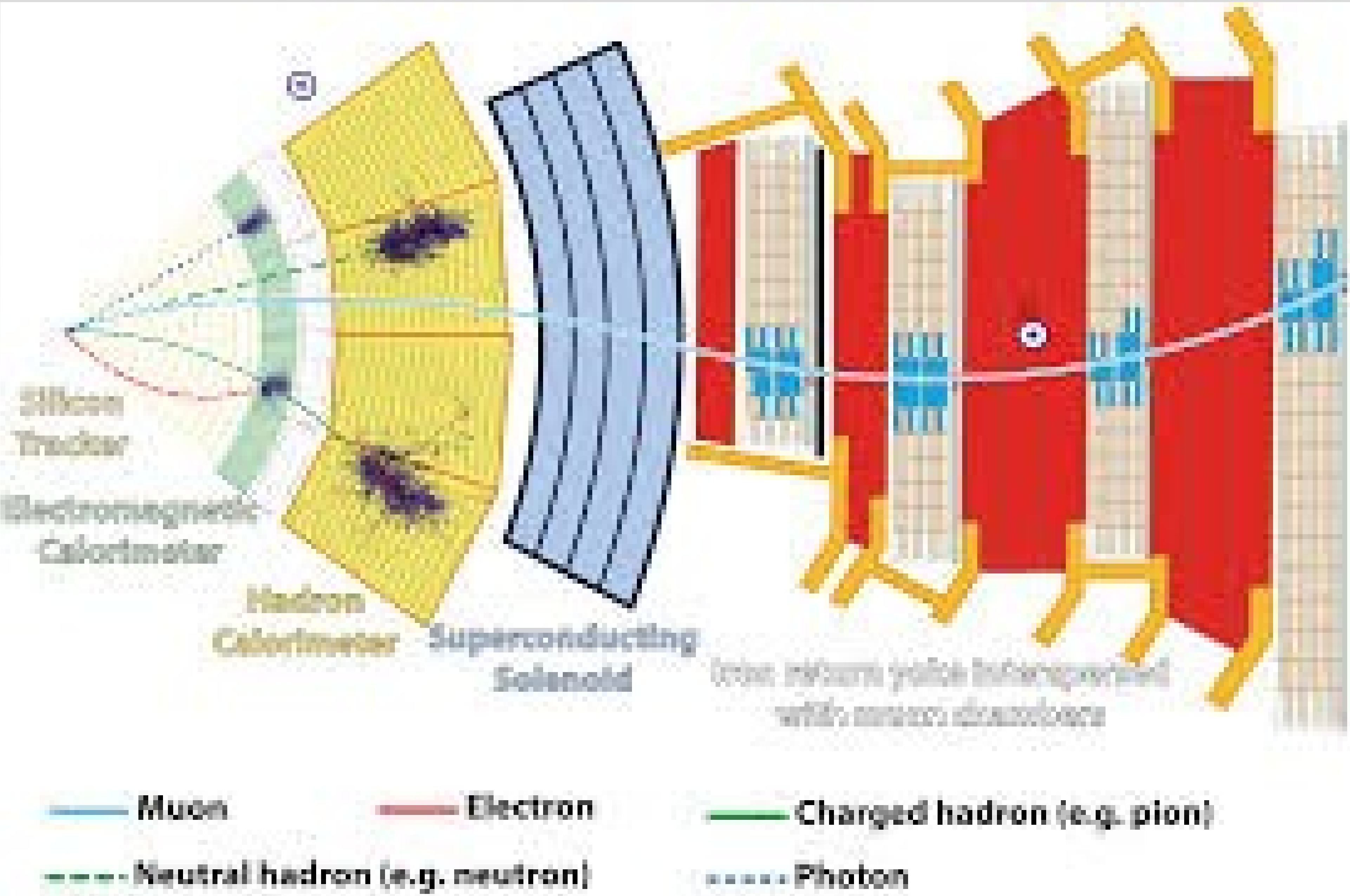
Two general-purpose detectors



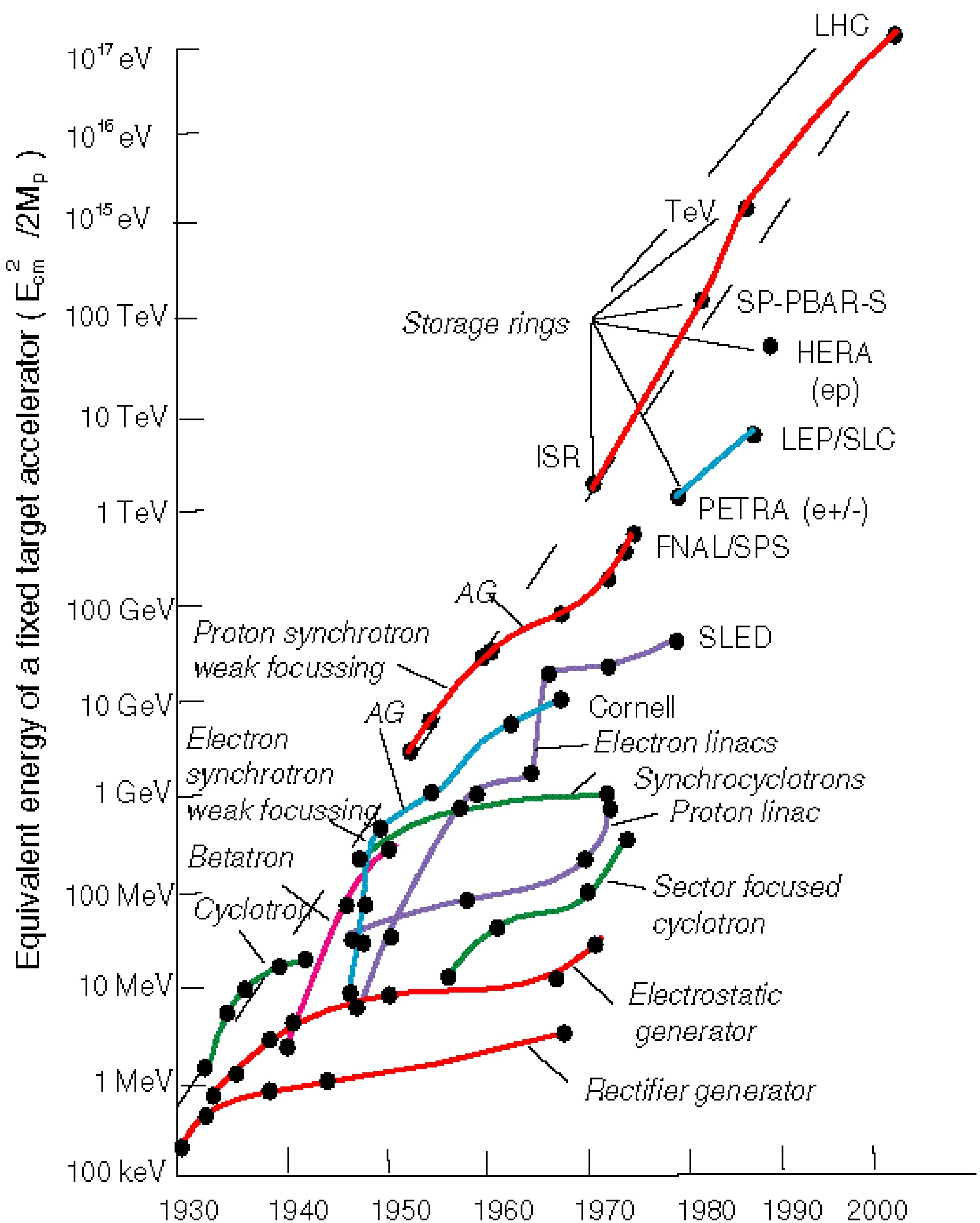


- Atlas: 1 solenoid (2T) and 8 + 2 toroid magnets (!)
- Air-core muon chambers (good stand-alone muons)
- Liquid Argon e.m. Calorimeter
- CMS: 1 solenoid magnet (4T) creates field inside and outside
- Muon chambers in return yoke
- 80000 $PbWO_4$ crystals as e.m. calorimeter

Subdetectors and particles



Why CMS stands for 'compact'



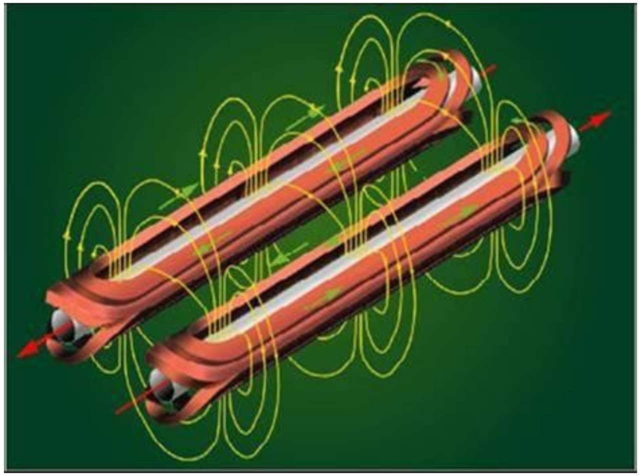
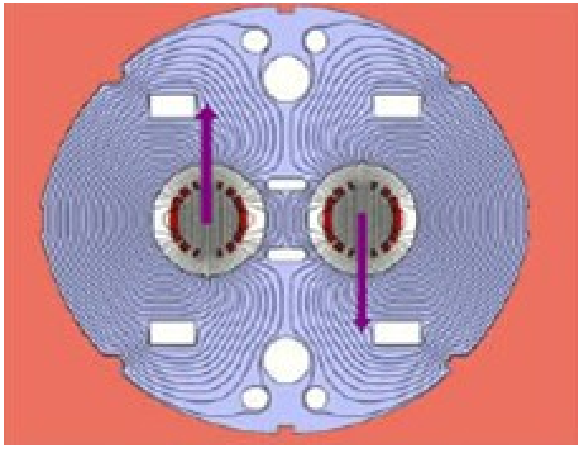
Lepton colliders provide cleaner events, and all energy is available in the final state. But:

a hadron collider is not limited by synchrotron radiation, and can go to much higher energy.

For a given ring size, the only limitation comes from the magnetic field of the bending magnets:

2-in-1 configuration

- Unlike LEP or the Tevatron, the LHC is a proton-proton (matter-matter) machine
- Why? Not possible to produce enough antiprotons to have the large luminosities needed for rare processes
- Most of interactions will be gluon-gluon (see later)
- Technical difficulty: get a very accurately opposite magnetic field

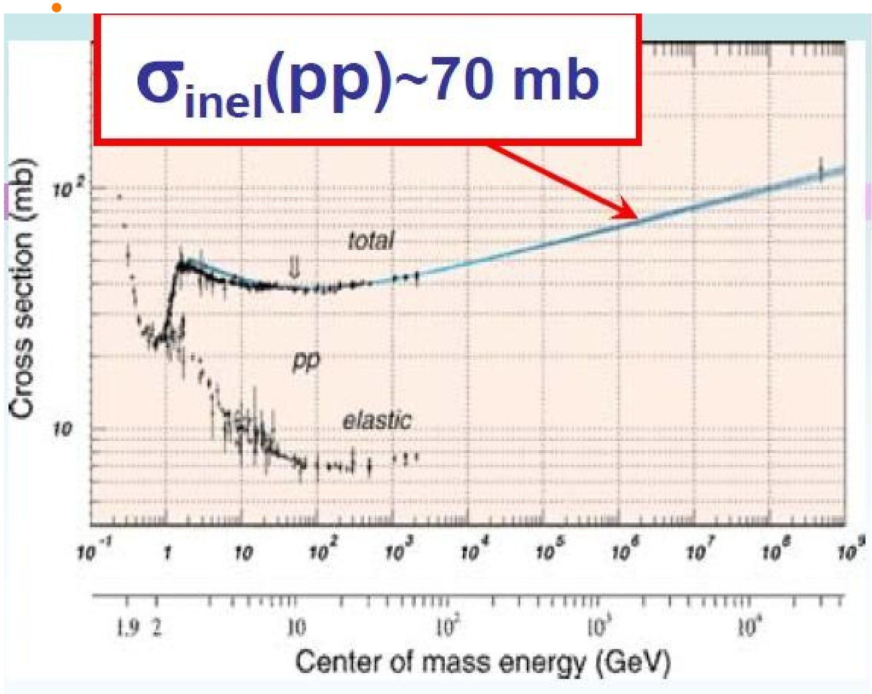




Event rate and luminosity

- Rate: number of collisions/s for a given process:
- $R = \sigma L$
- where luminosity L is given by
- $L = f\, n_1\, n_2 / A$
- $n_1\, n_2$ number of particles per beam ($O(10^{11})$)
- f crossing frequency (40 Mhz, with 2835/3564 bunches occupied)
- A = crossing area = πr^2 where $r = 16\ \mu m$ (rms of transverse beam profile)

Integrated luminosity and pileup

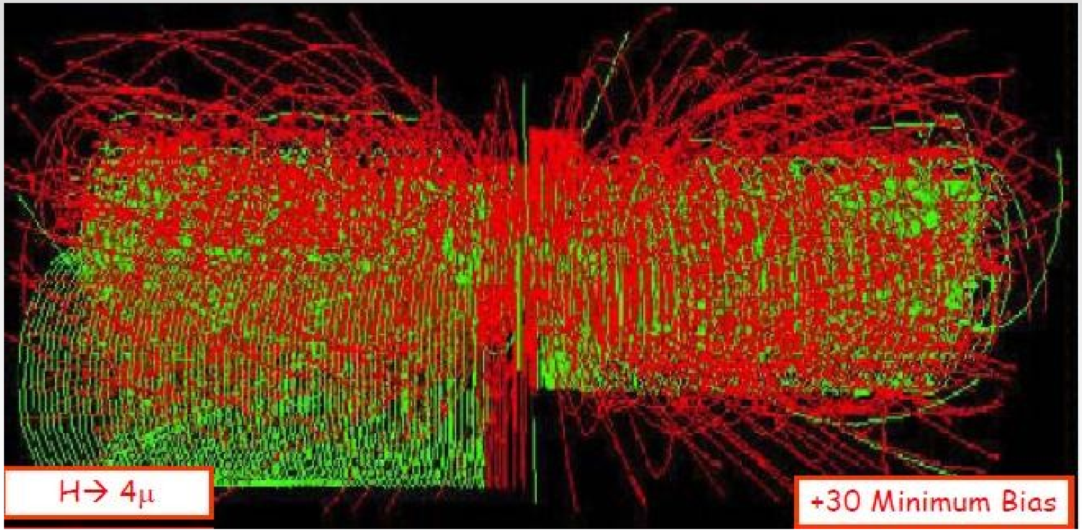
- These numbers correspond to a range between
- 10^{33} and 10^{34} cm^2/s (10^6-10^7 mb^{-1}) Hz
- And in one year (8-9 months of data taking) to 10-100 fb^{-1}
- The total pp cross section is about 70 mb:
-



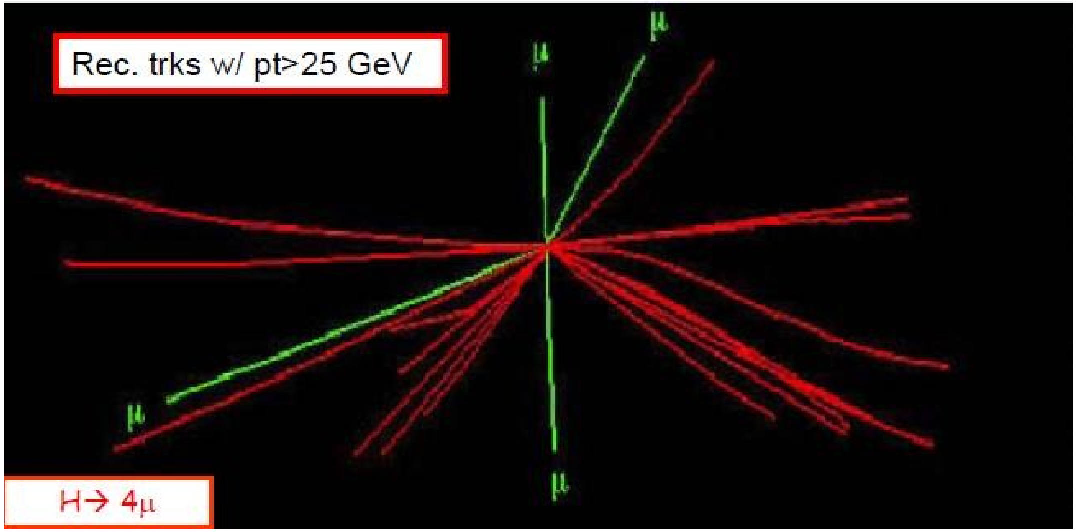
So, rate can go up to 700MHz! Divided by 40MHz bunch crossing rate, and accounting for empty bunches, we can have > 20 collisions/bunch crossing (pileup)

Pileup

Can you find four muons coming from a Higgs boson from this event?



It gets much better if you just look at the energetic particles:



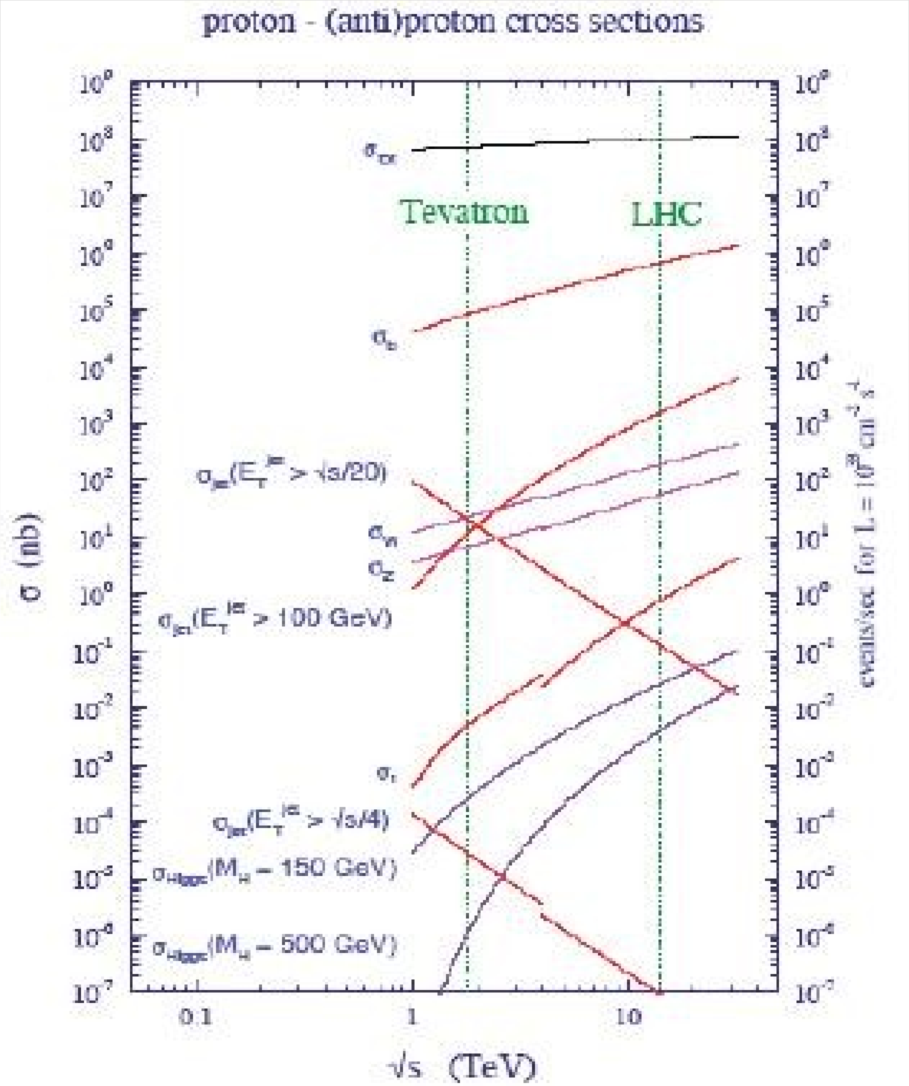
Measurements vs searches

- When protons collide, we do not know which process will be produced, only their cross-sections (probabilities)
- Some processes are very common (production of jets, vector bosons, top) other much more rare
- Also common processes can be rare in some kinematical configurations (e.g. very high-energy jets)
- High-precision measurements of common processes allow to test our theories and look for deviations that could indicate new physics
- In parallel, many analyses are explicitely looking for new processes in final states where new physics is expected to show up

Cross sections in pp interactions

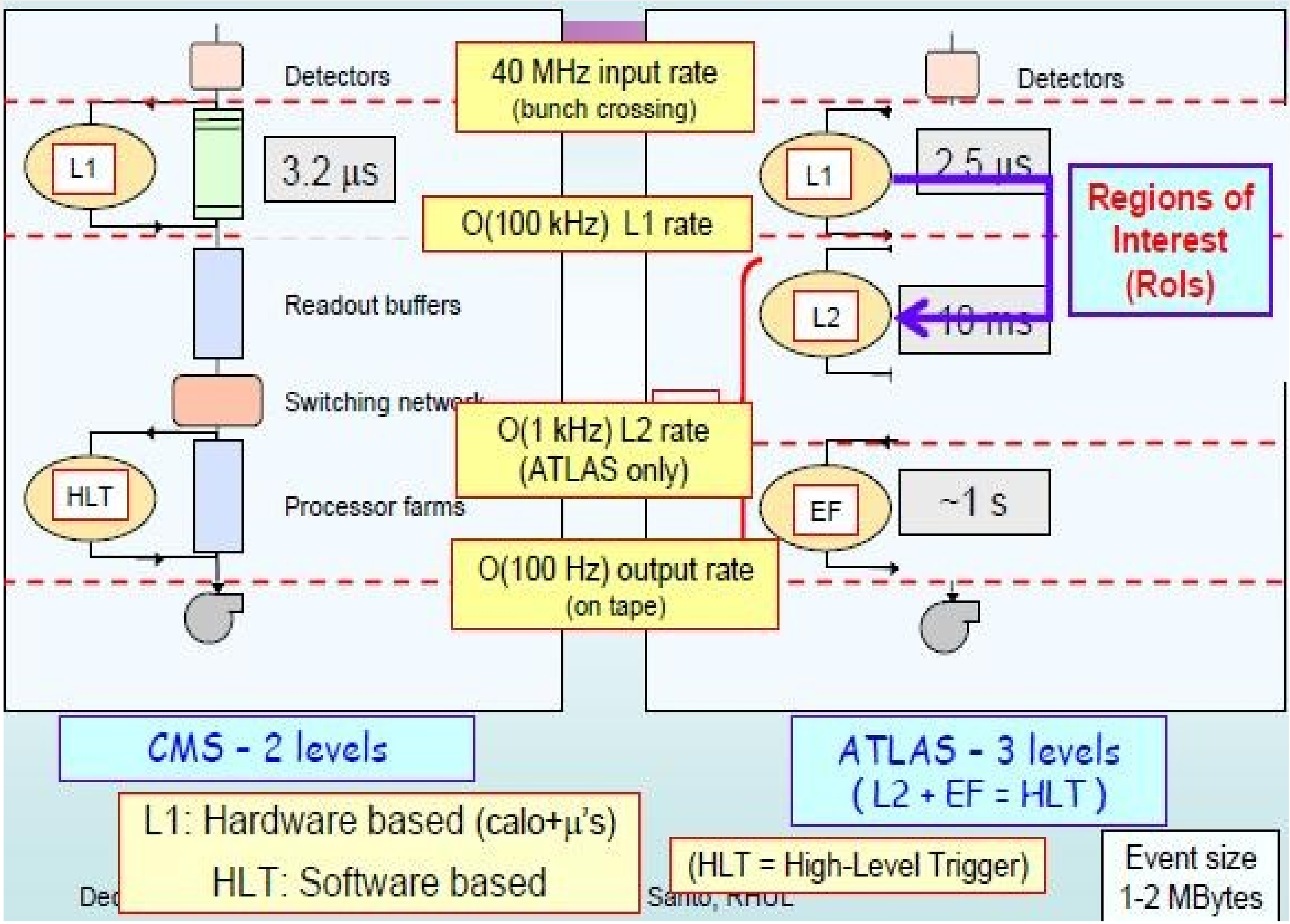
- No real thresholds
- Total cross section (including elastic) almost constant
- Some lines 'broken' going from Tevatron to LHC due

  to antiprotons vs protons
- Several orders of magnitude between discoveries and background



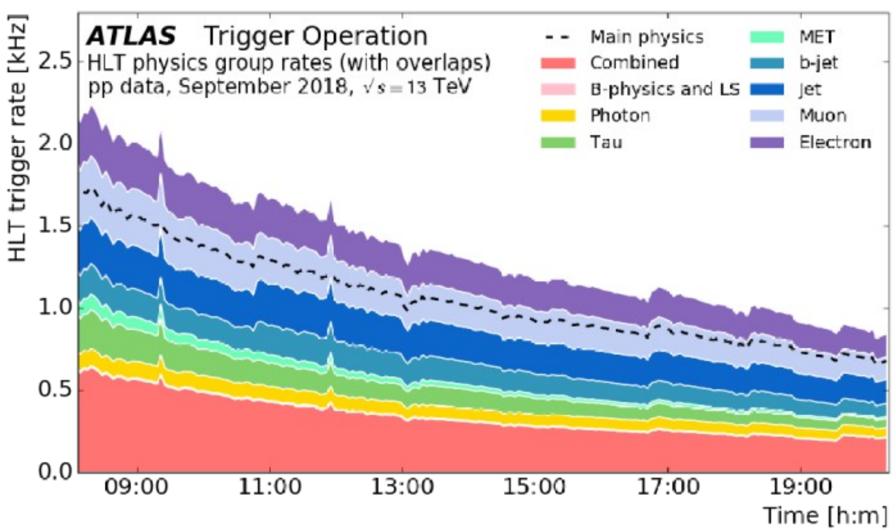
Triggering

- DAQ can only take O(1 kHz), so rejection factors on BG of order 1M are needed, while keeping high efficiency on rare signal events. Different stategies:



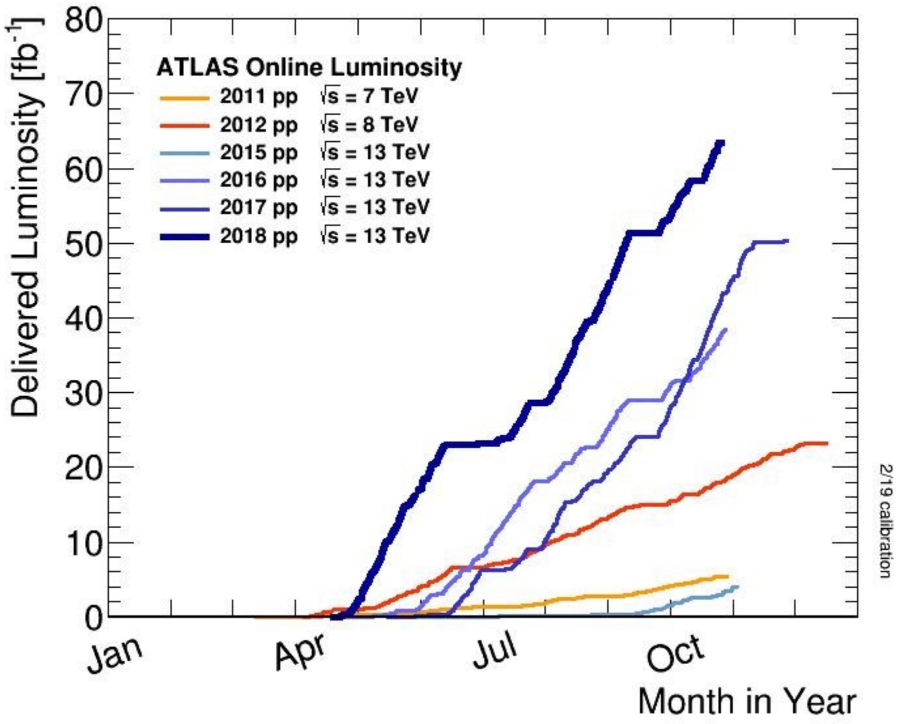
Triggering in practice

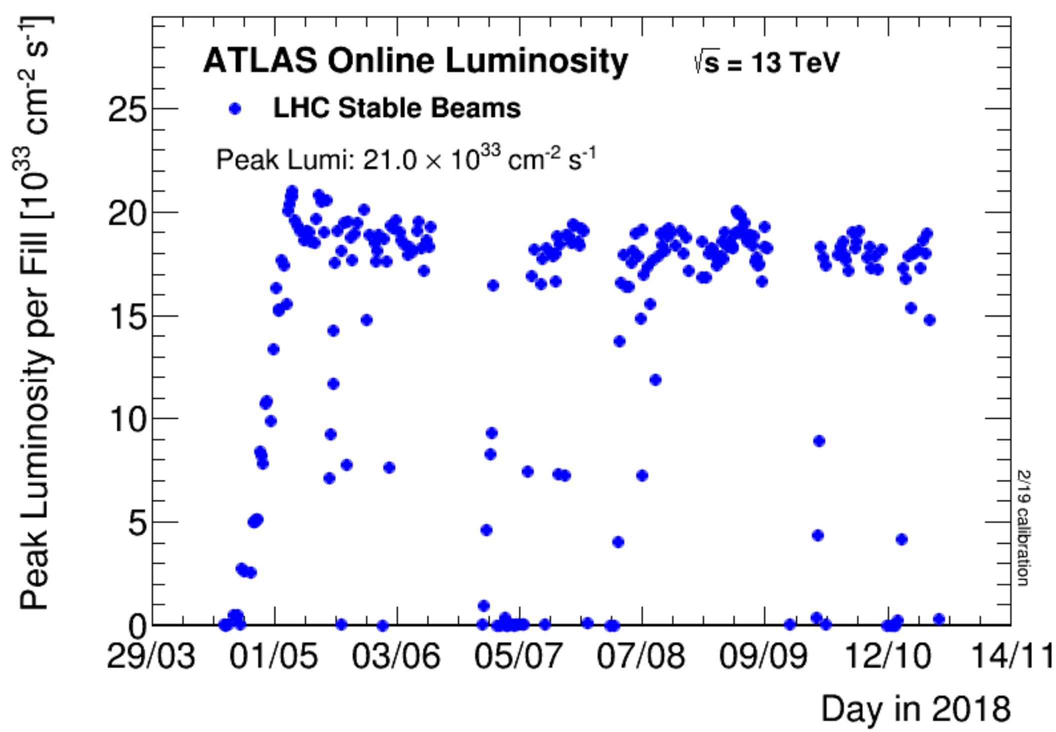
- The trigger hardware and software classifies events into categories according to the particles produced and their pT
- All events from the most rare and interesting categories are taken
- For all other categories, a (small) fraction of the events is selected, according to a known scale factor, that will be used as an event weight in the analysis
- Algorithms for event classifications and scale factors are constantly improved



Evolution of rates for the category classes in a typical ATLAS run

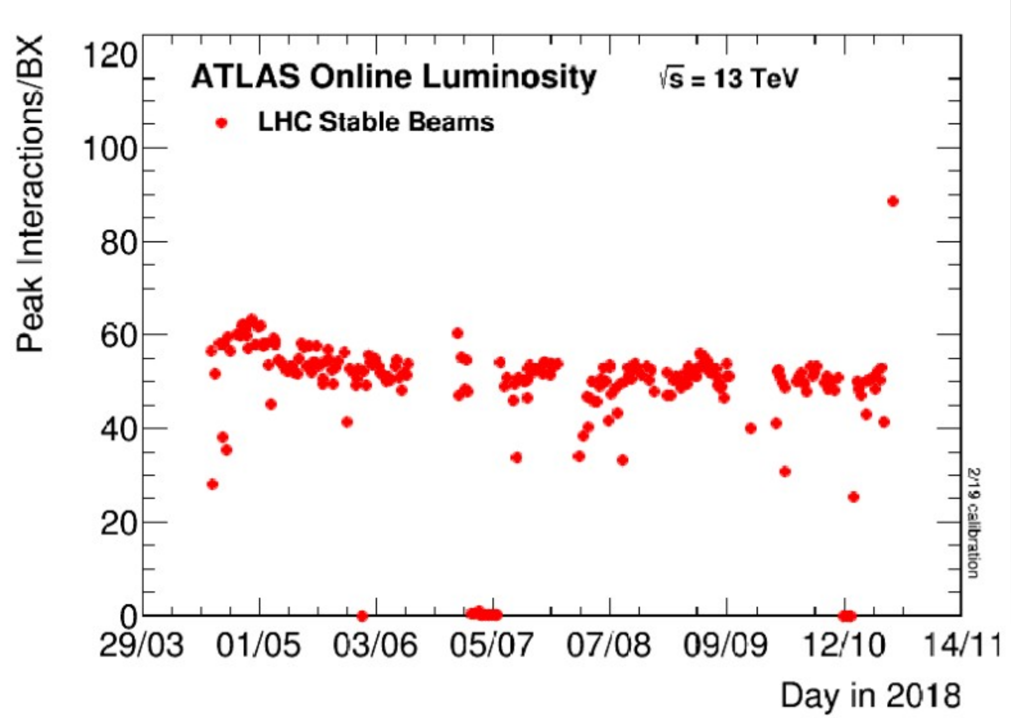
Run-2 luminosity

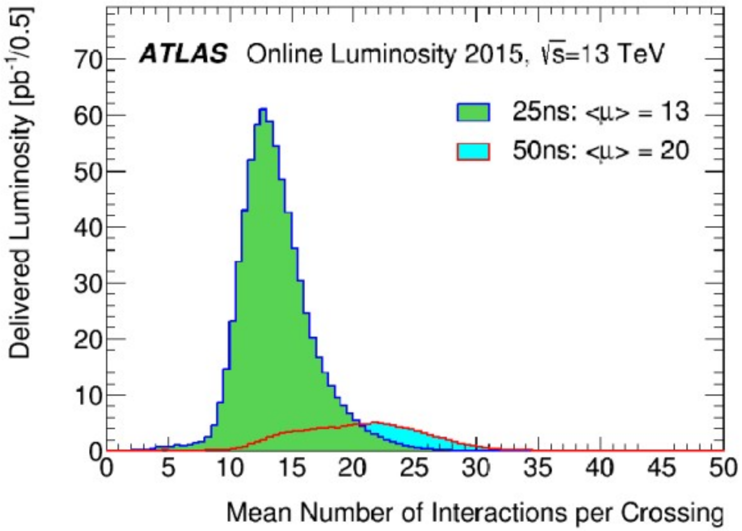


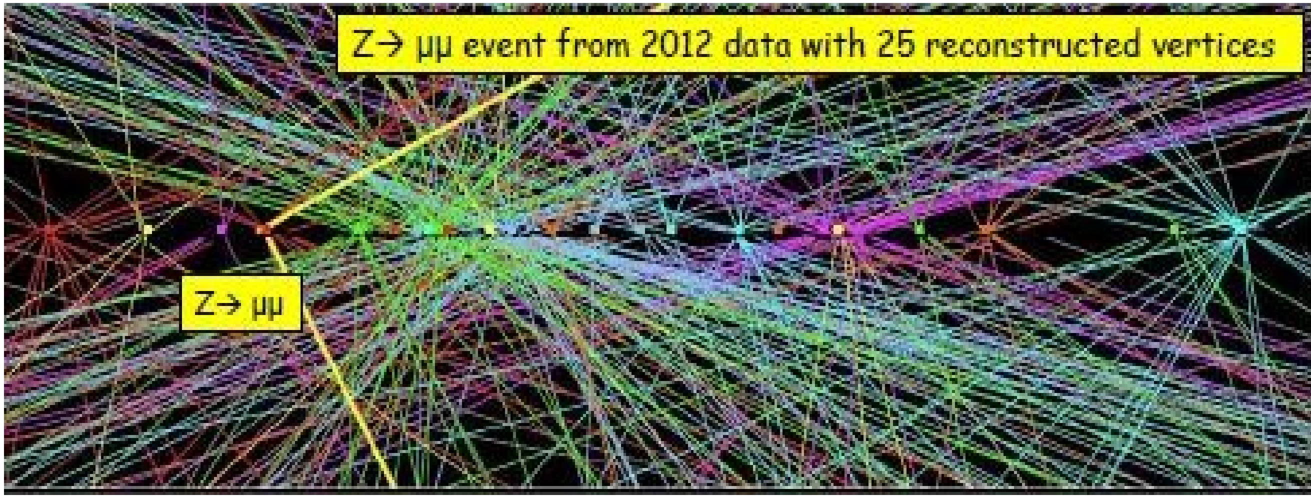


- Energy: 13 TeV (7-8 during Run1)
- Integrated luminosity improved every year
- Instantaneous luminosity very high throught 2018

Pileup evolution







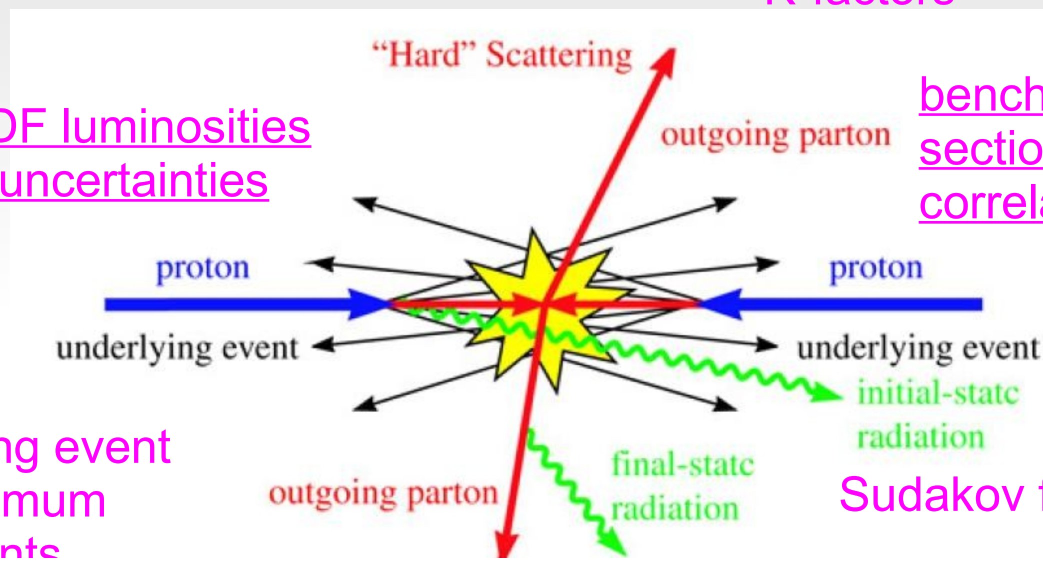
From August 2015, 25 ns operations reduced in-time pileup for same luminosity
However, next year luminosity will increase, and pileup conditions could be similar to Run 1

Collisions in a hadron collider

LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities and PDF uncertainties

benchmark cross sections and pdf correlations



underlying event and minimum bias events

Sudakov form factors

Parton distribution functions

The functions f_1, f_2 (PDF's) are fractional momentum distributions (x = Pp/Pbeam) of the partons inside a proton.

Gluons and quarks other than the valence (uud) are present, with steeply falling distributions

This is why for low-mass objects a pp or p-antip collider are almost the same

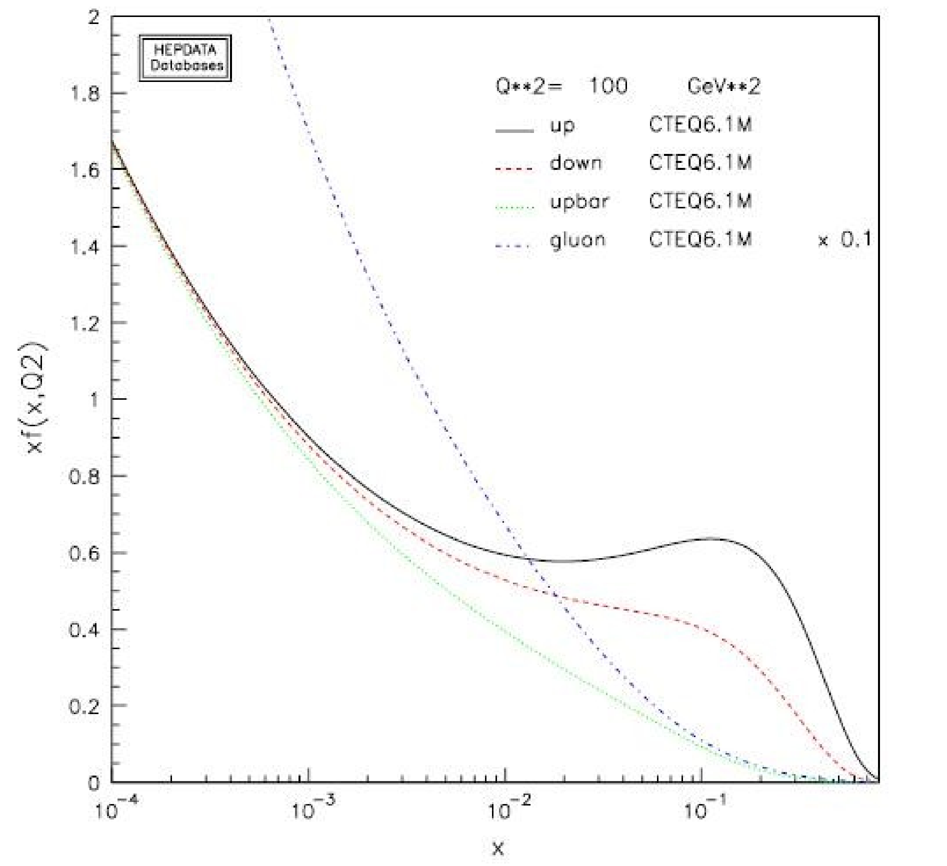


Figure 27. The CTEQ6.1 parton distribution functions evaluated at a Q of 10 GeV.

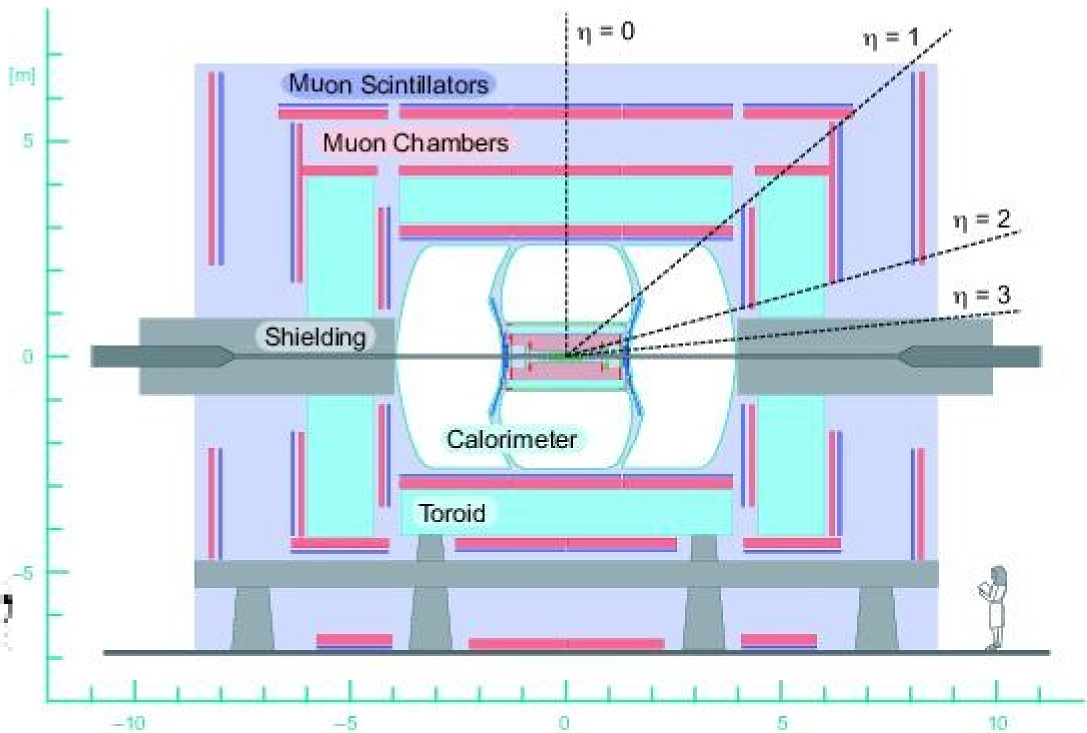
Typically the two colliding partons will have different x → event will be longitudinally unbalanced (Lorentz-boosted)

Relevant variables

- Only variables invariant under z-boost should be used.
- This is why cuts are expressed in terms of Et and not E, and instead of the angle ¯ we use rapidity
- $$\phi_z = \frac{1}{2}\log_e \frac{E + p_z c}{E - p_z c}$$

It depends on the mass of an object, so it cannot directly reference to a detector location; for that we use pseudorapidity, equal to rapidity for massless particles:

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

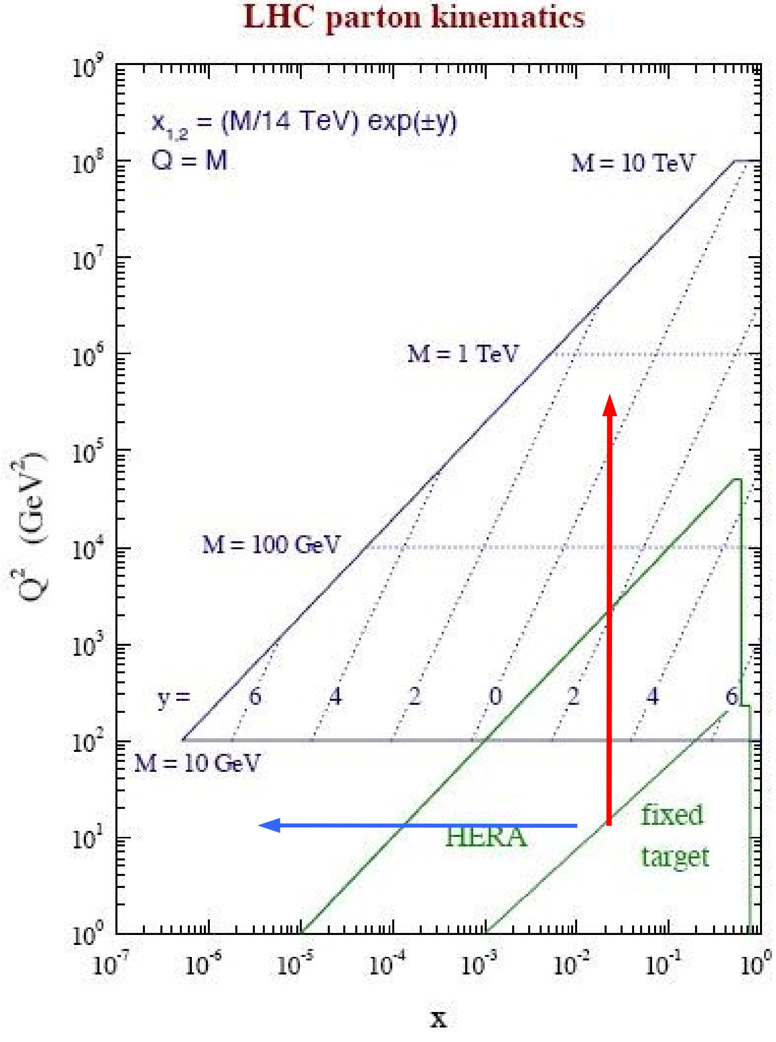


Kinematic region of the LHC

Every collision can be represented as a point in a (x, Q2) plane

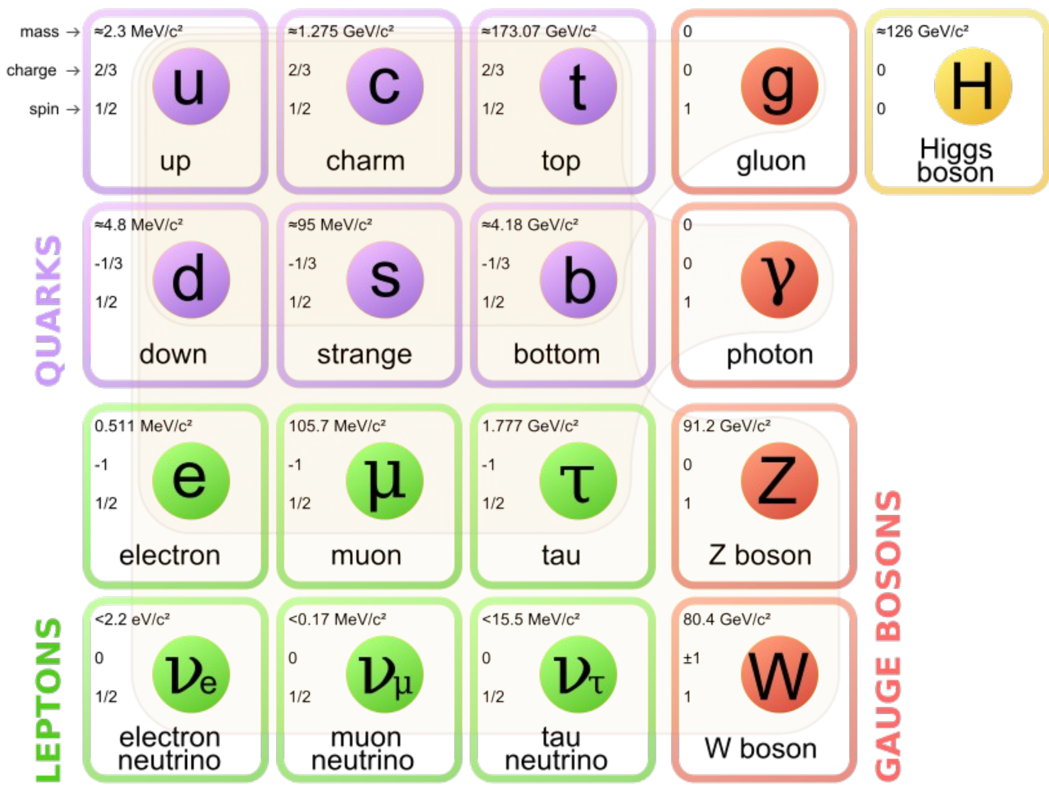
The LHC extends the kinematic region of old experiments, so a precision knowledge of the PDFs needed to ptoperly interpret all measurements

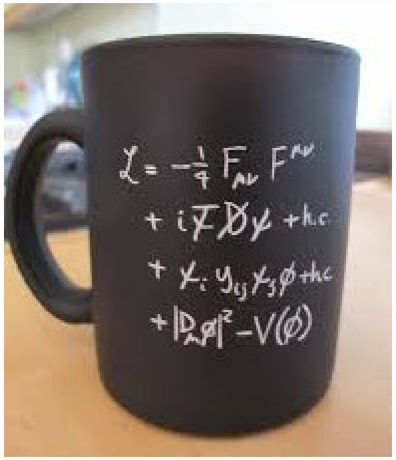
$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{Ns}\left[\sum_k Q_k^2 (q_k(x_1, M^2)\bar{q}_k(x_2, M^2) + [1 \leftrightarrow 2])\right]$$

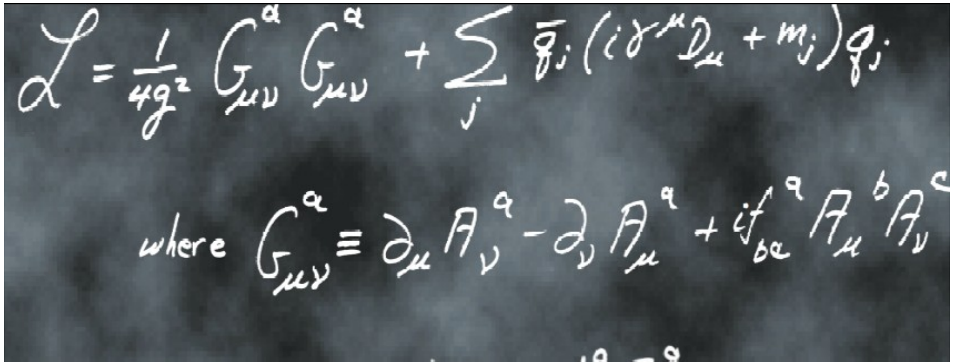


Measuring "the Standard Model"

- With SM we indicate a description of all known particles and their electroweak and strong interactions
- In practice, since measurements of heavy quarks (t,b) and Higgs are separately classified, a SM measurement refers to production of gluons and light quarks (hadrons and jets), W, Z and γ bosons

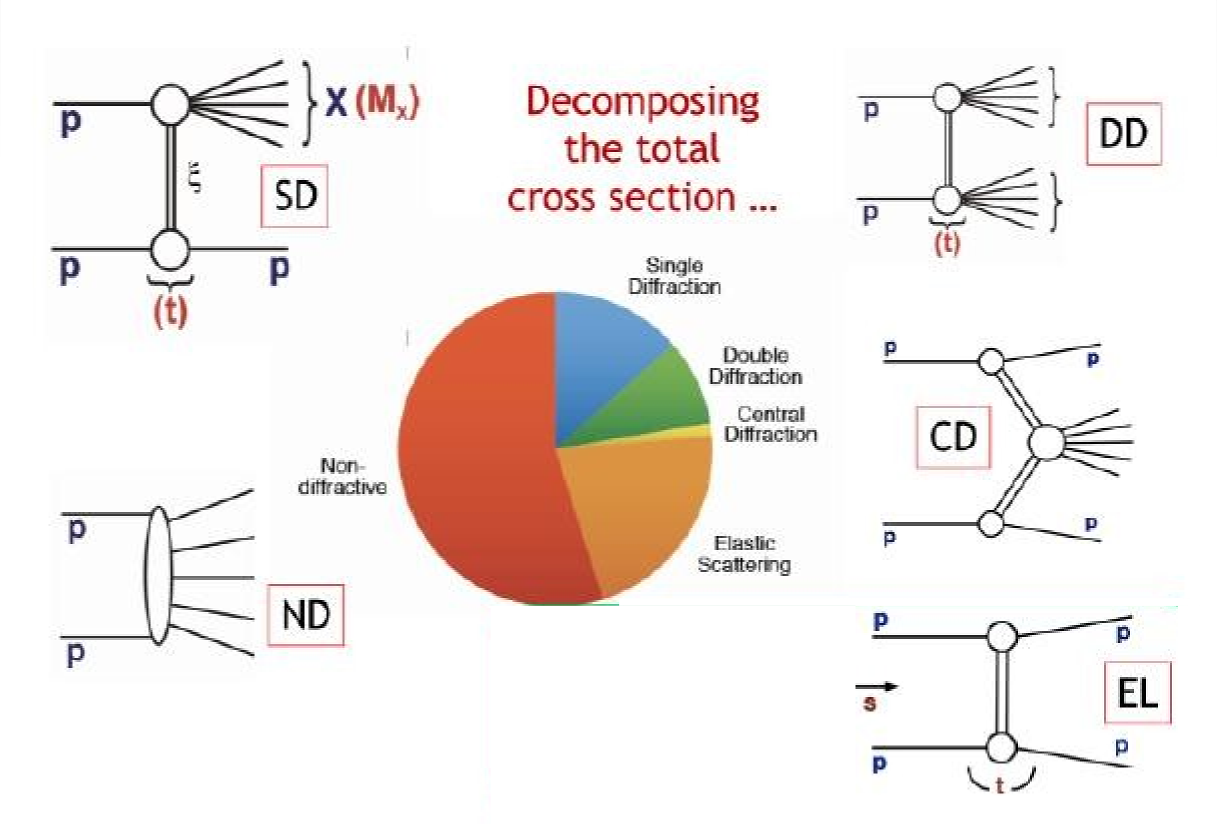






Low-energy measurements (soft-QCD)

- The most likely process at the LHC is production of low-energy hadrons (Minimum Bias), resulting from the exchange of soft gluons

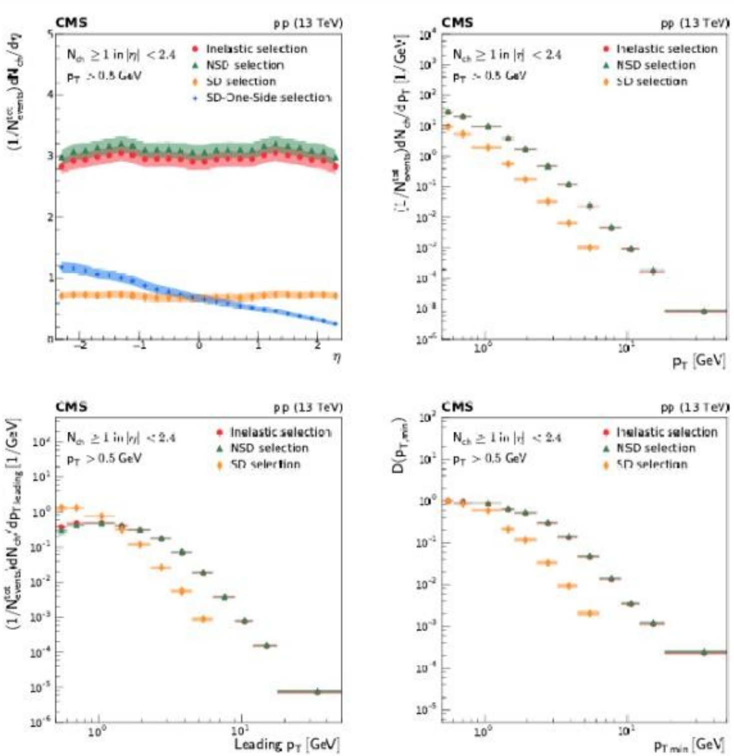


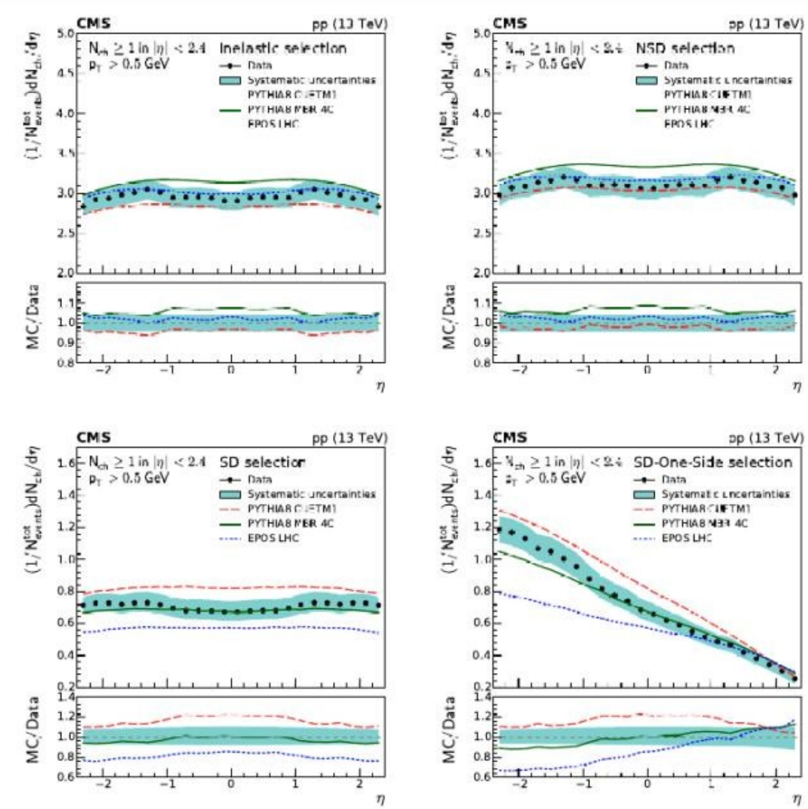
About half of all collisions at the LHC are diffractive, namely protons exchange does not carry quanta of the strong interactions.

These processes are only relevant at low-energy, since almost all high-Q processes are non-diffractive

Measuring Minimum Bias

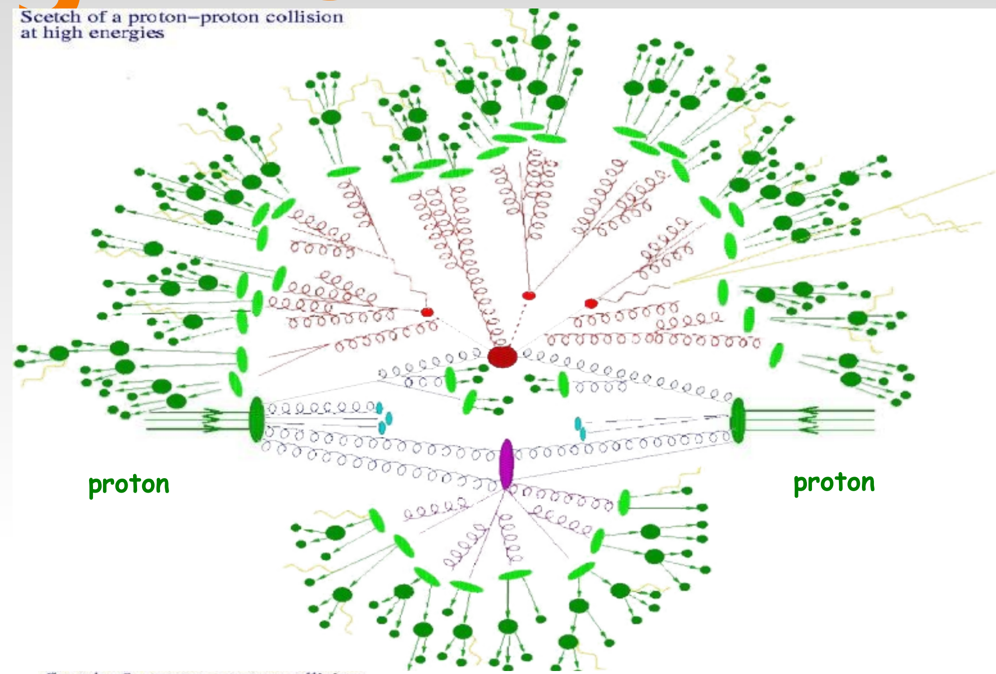
- Events have small multiplicity and low transverse momentum
- Typically measure individual tracks since resolution is good in this regime
- At low-Q2 QCD not perturbatively calculable
- → measurements help tuning MC models

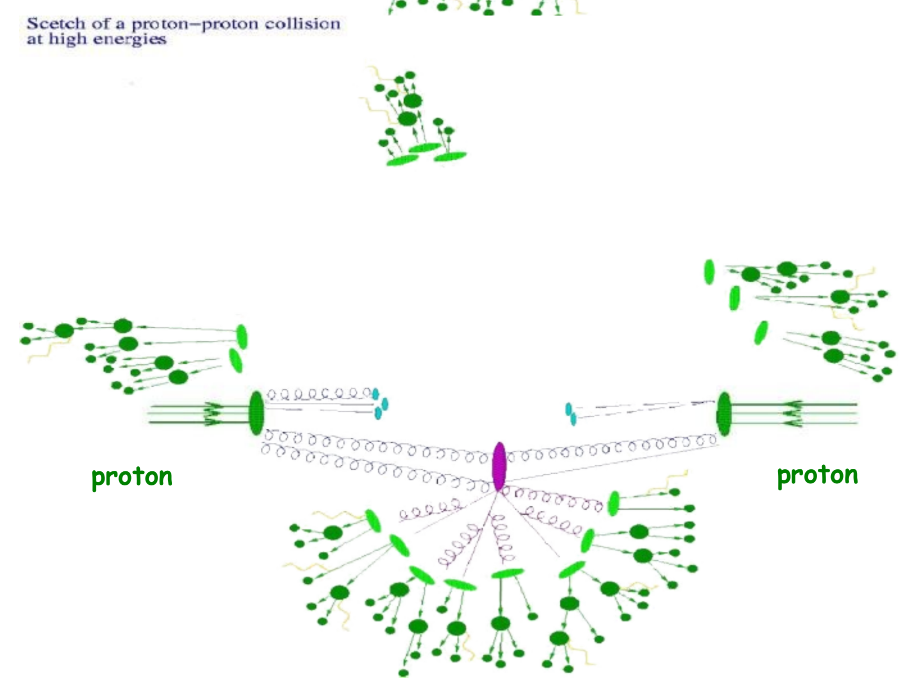




Minimum Bias vs the Underlying Event

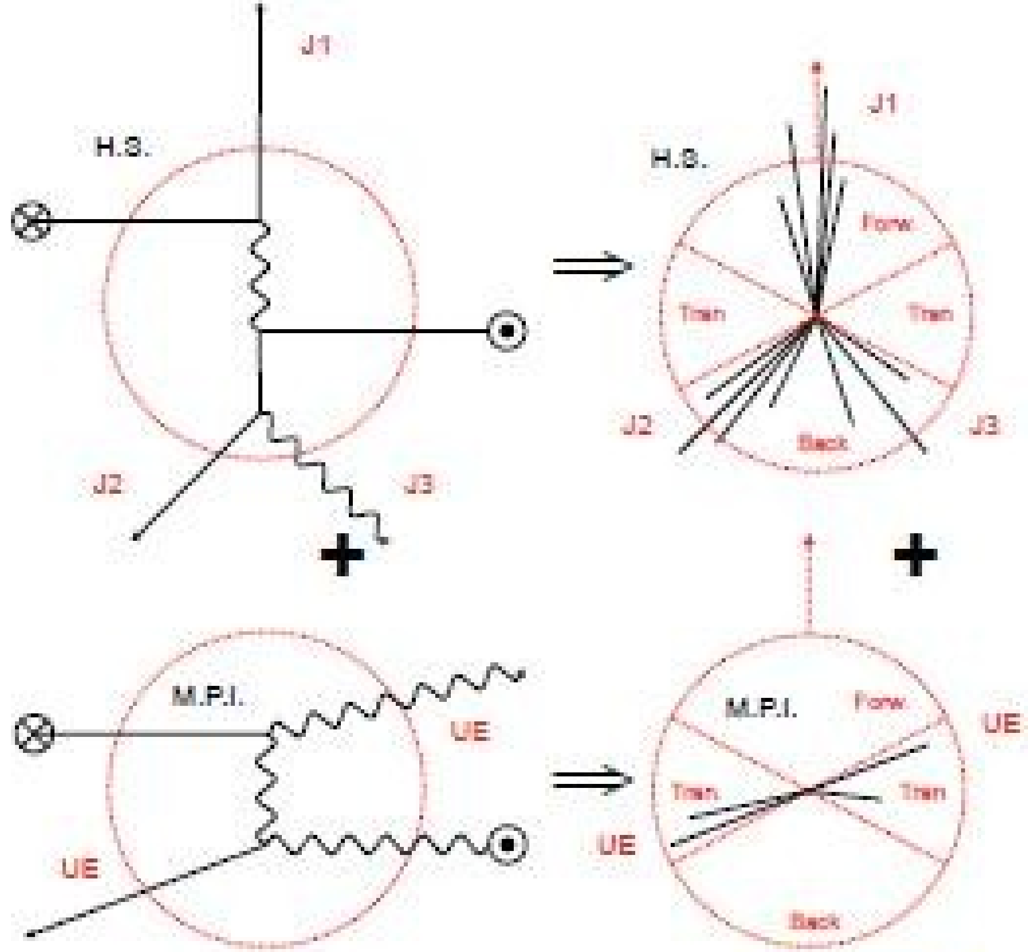
- Even a high-Q collision will have a soft component resulting from multiple partons and additional gluons
- Both MB and UE can be described by the same empyrical models, and a small number of tunable parameters
- Study MB helps understanding all other processes

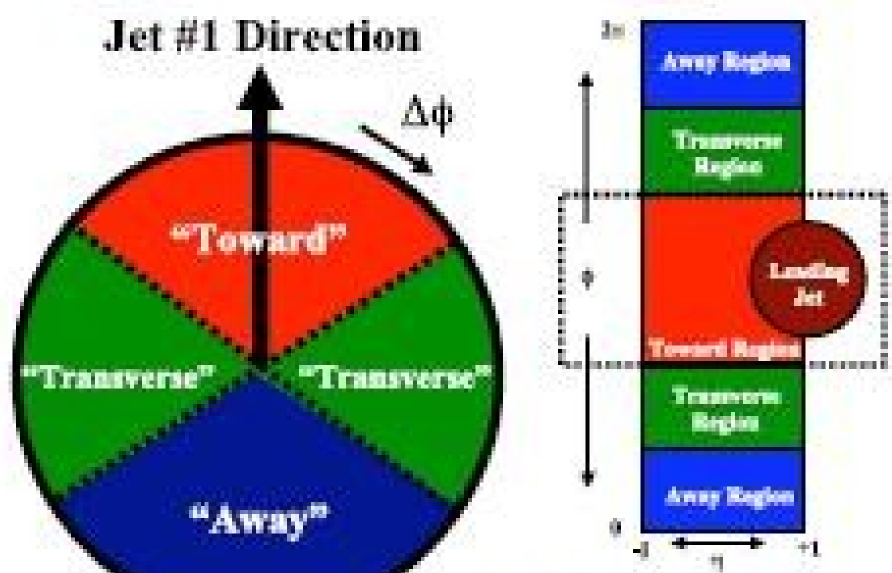




UE Characterization

- Hard Scatter yields* 2 or 3 hard jets.
  *Given sufficient qualifying statements...
- Two equally hard jets will be roughly back-to-back.
- Additional interactions yield softer particles whose directions are not correlated to the hard scatter axis.
- Fragmentation, especially due to connections to remnants, can yield additional particles.
- Three equally hard jets are roughly at 2π/3 intervals.
- $\pi/3 < |\Delta\varphi| < 2\pi/3$ and $|\eta| < 1$ defines the transverse region.
- For the third hardest jet to be in the transverse region it must be softened.

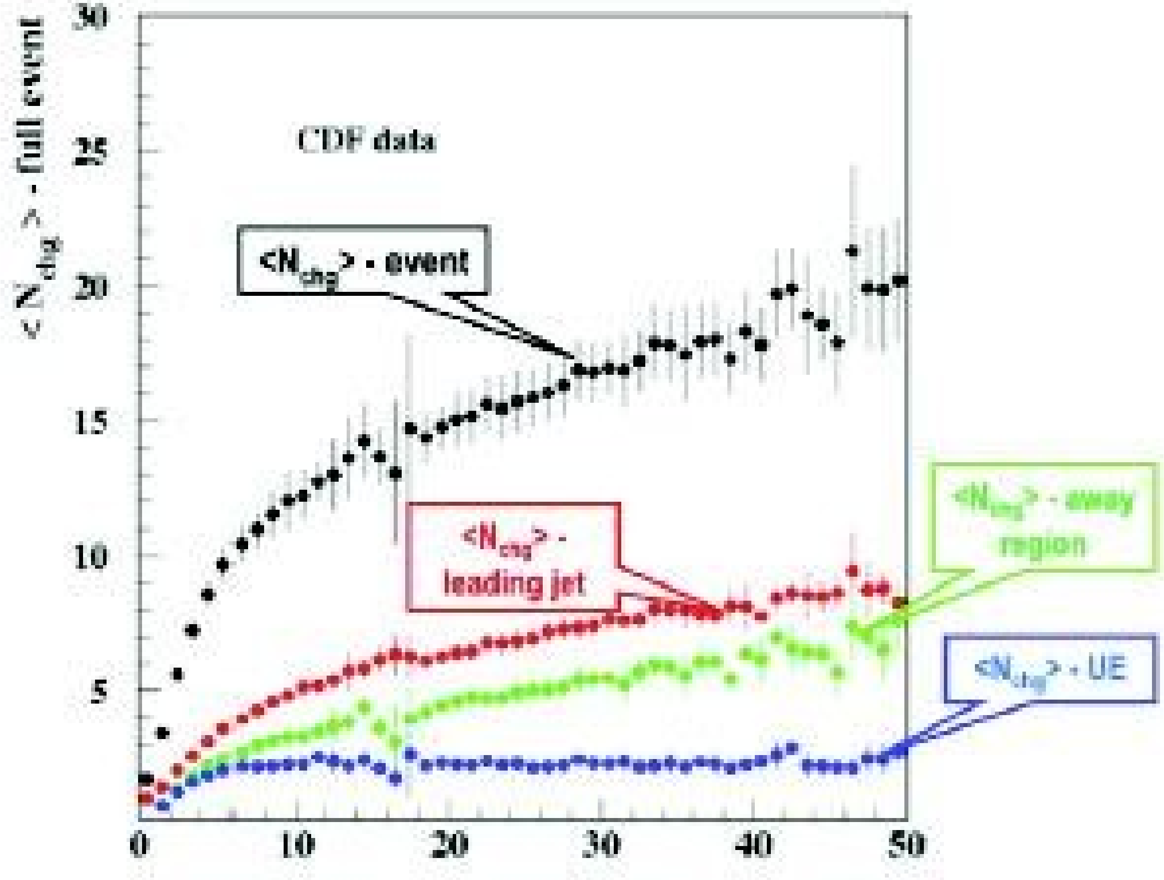




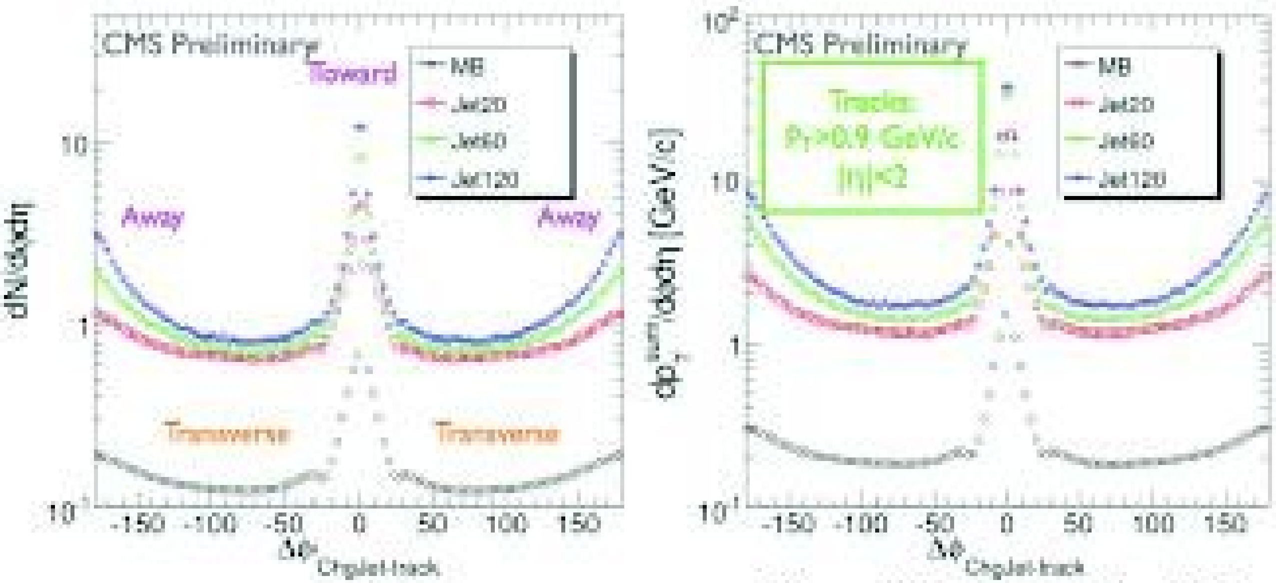
Images from R. Field.

UE Characterization

- The number of tracks in the transverse region is less correlated to the lead jet energy.
- Sources of transverse tracks:
  - MPI
  - Fragmentation of string connections to remnants.
- Track Jets are used, so that low energy calorimeter response is not involved.
  - Also simplifies comparison to models.
- Drell-Yan: Look for $\mu^+\mu^-$ there is no FSR associated with their production.
  - The entire φ range characterizes the UE.

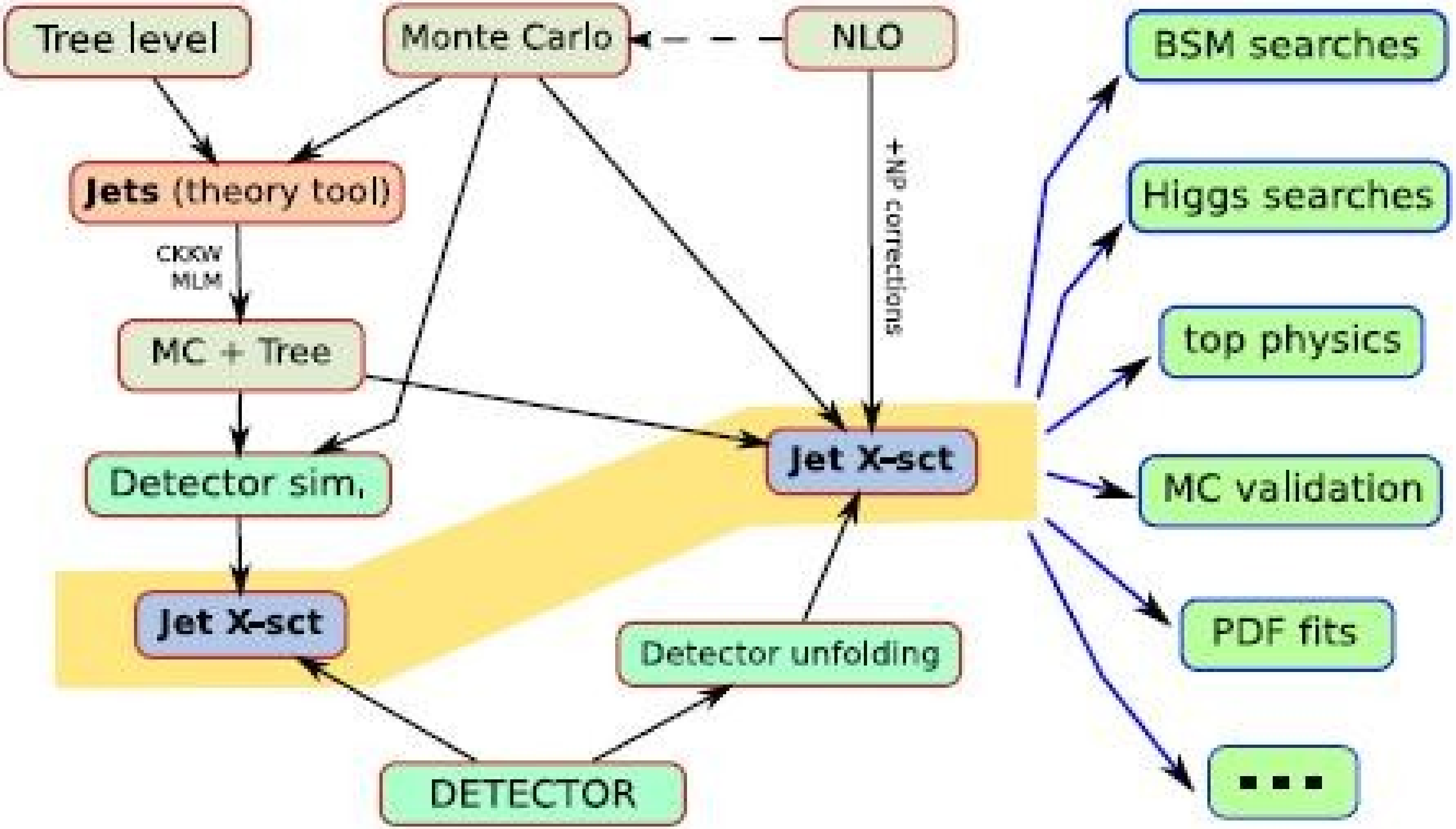


Above: Plot by Affolder at al. $P_{t\ leading\ jet}$ (GeV)



Above: Plots from F. Ambroglini

Hard QCD and Jets

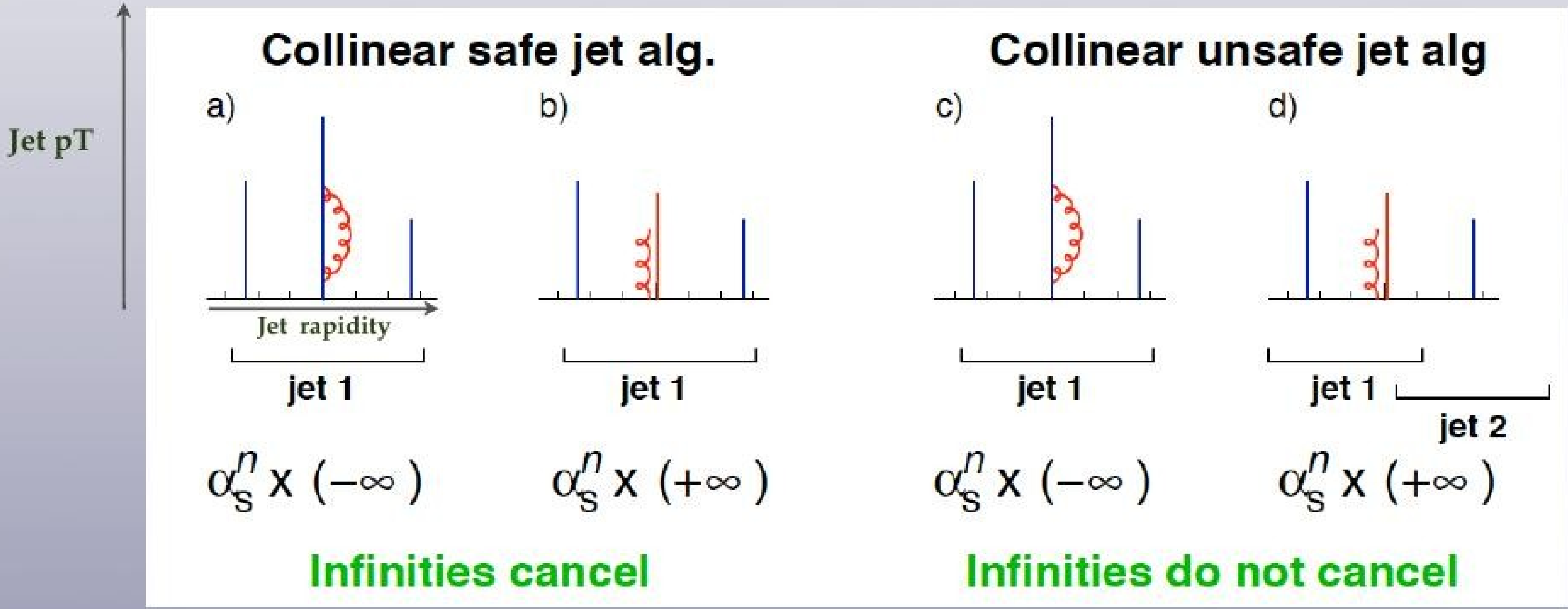


Jet (definitions) provide central link between expt., "theory" and theory

And jets are an input to almost all analyses

Jet algorithms

- In the particular case of jet algorithms, **infrared safety** can be formulated as the requirement that if the **final state particles** are modified by a **soft emission** or a **collinear splitting** then the set of hard jets found should be unchanged
- Failing this criterion, a jet definition will produce **infinite results** at some point in the perturbative expansion because of the **lack of cancellation** of infrared divergences



In the **IRC unsafe algorithm**, a **collinear splitting** leads to a **different set of final state jets** and thus to the lack of cancellation of soft and collinear divergences (KLN theorem)

Sequential recombination jet algorithms

It is possible to **generalize the kt algorithm** by introducing a modified distance as follows

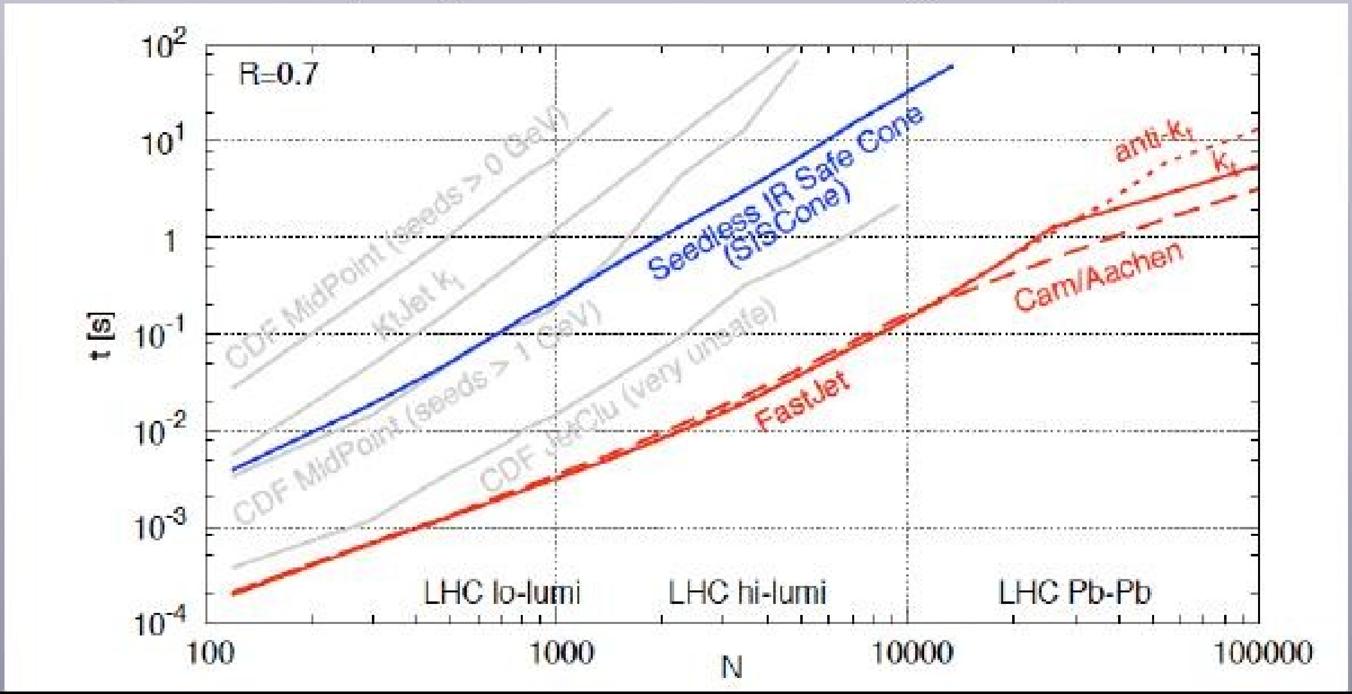
$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2,$$

$$d_{iB} = p_{ti}^{2p},$$

- **p = 1 ->** kt algorithm: follows QCD branching structure in pt and in angle
- **p = 0 -> Cambridge/Aachen:** follows QCD branching structure **only in angle**
- **p = -1 -> Anti-kT algorithm:** unrelated to QCD branching structure, with clustering measure favouring recombination of high-pT particles

By construction, these sequential recombination algorithms are **infrared safe**

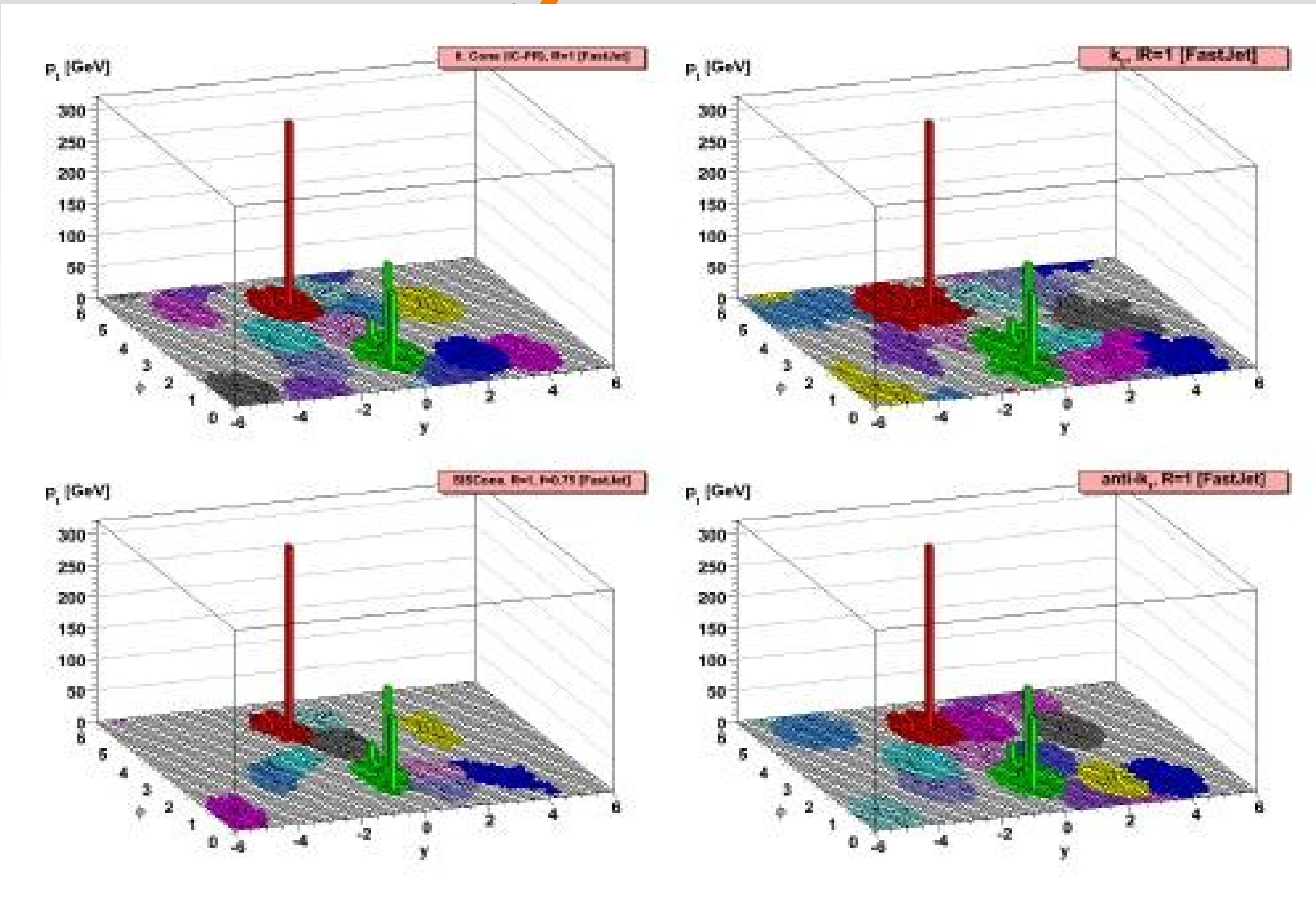
At the LHC, the default jet algorithm is the **Anti-KT** algorithm, for reasons that we discuss now



Original implementations of kt algorithm very **slow,** **T=O(N³)**, making it unpractical for high-multiplicity hadron collisions

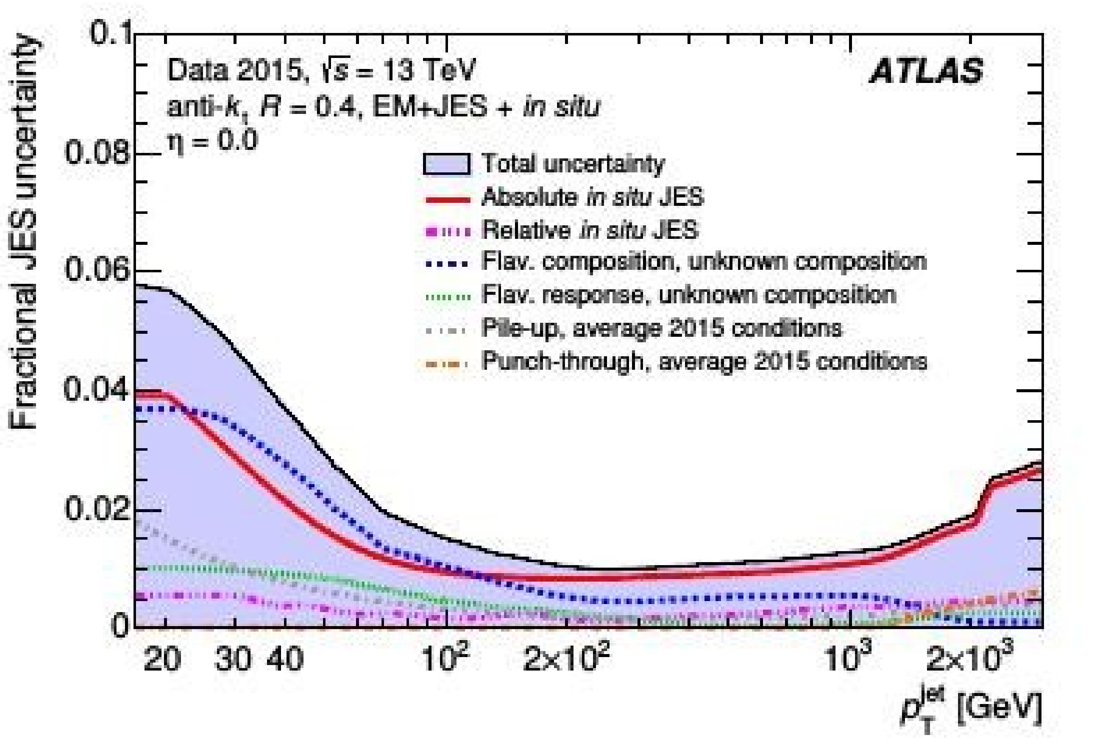
Modern implementations (**FastJet**) much more efficient using computational geometry, amd achieve **T=O(N log N)**

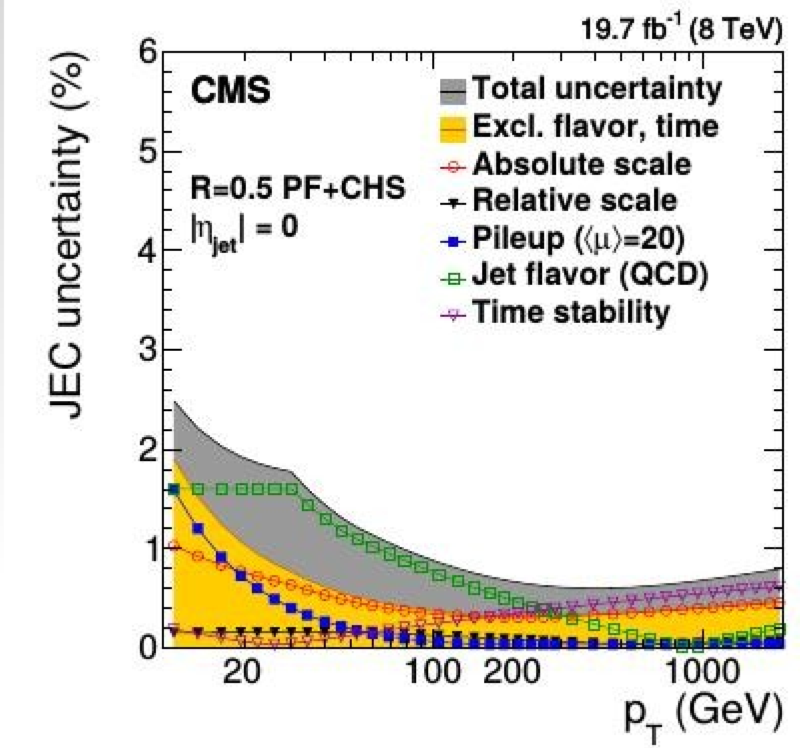
Comparing different jet algorithms



Anti-kt default algorithm in Atlas and CMS

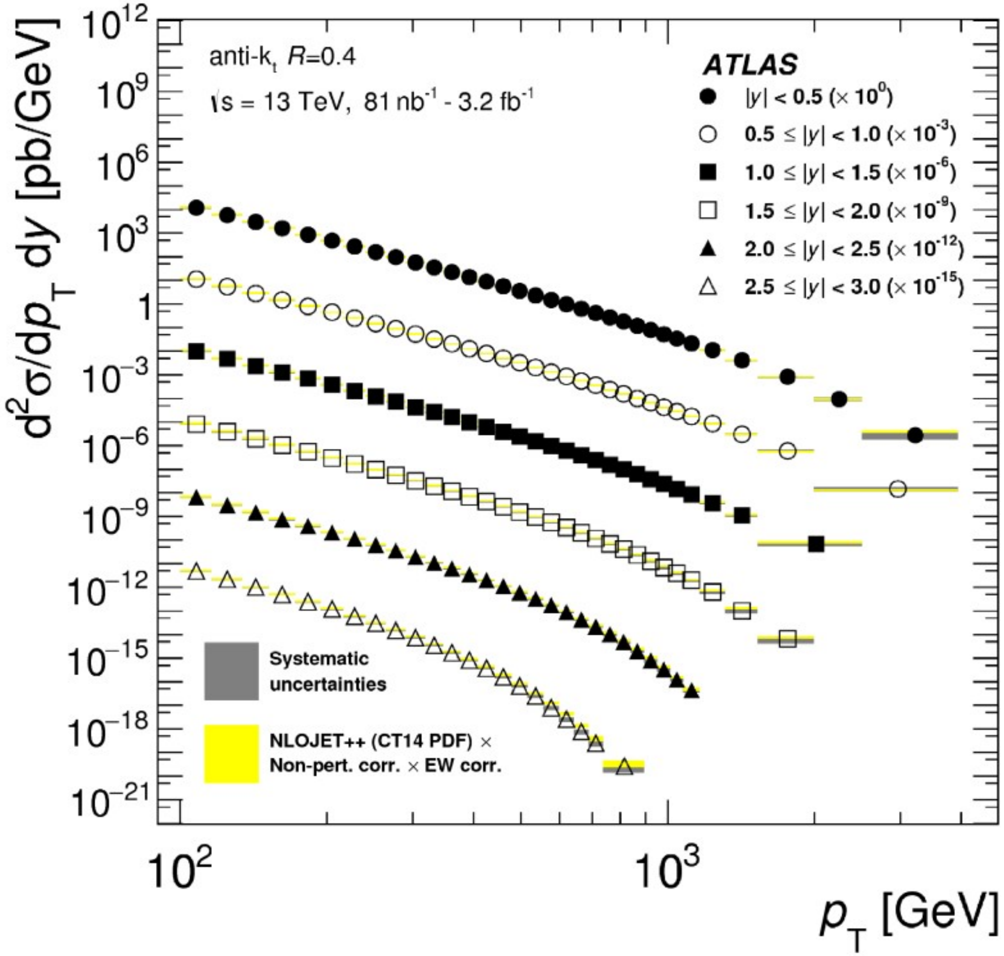
Jet Energy scale

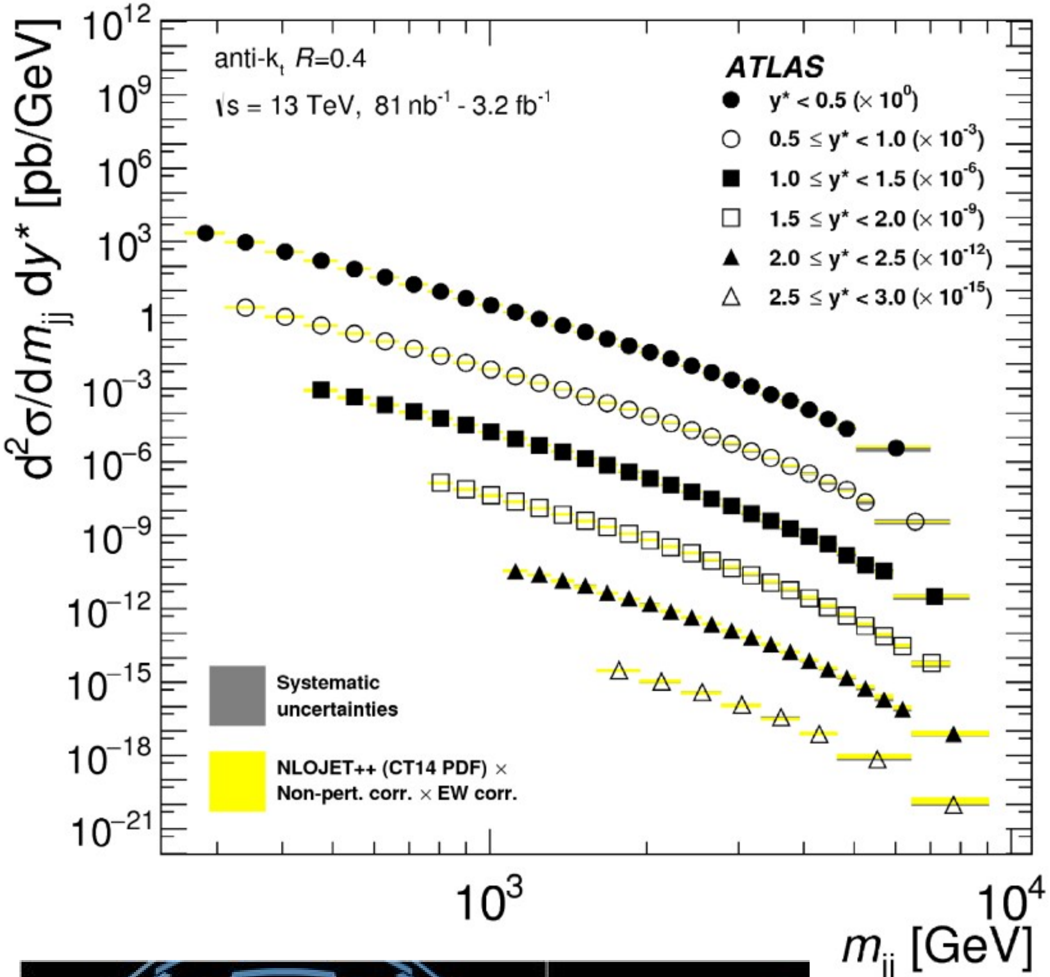


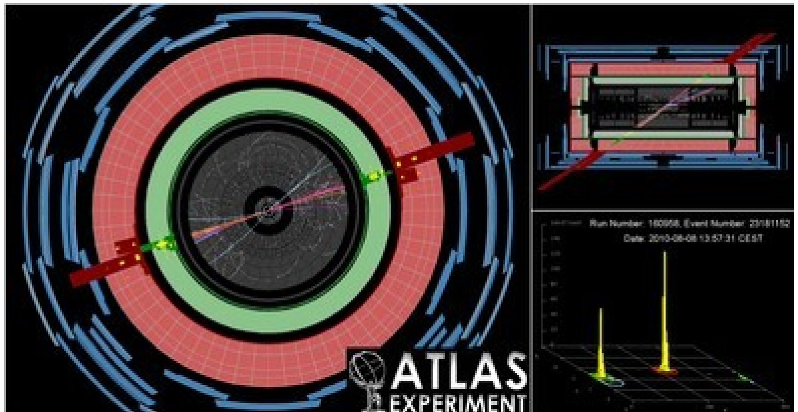


- Most important systematic uncertainty for jet measurements at the LHC
- Primary calibration from MC, using information from various calorimeter layers. Uncertainties from modelling, and from in-situ techniques (like photon-jet balance)

Jet and dijet cross-sections

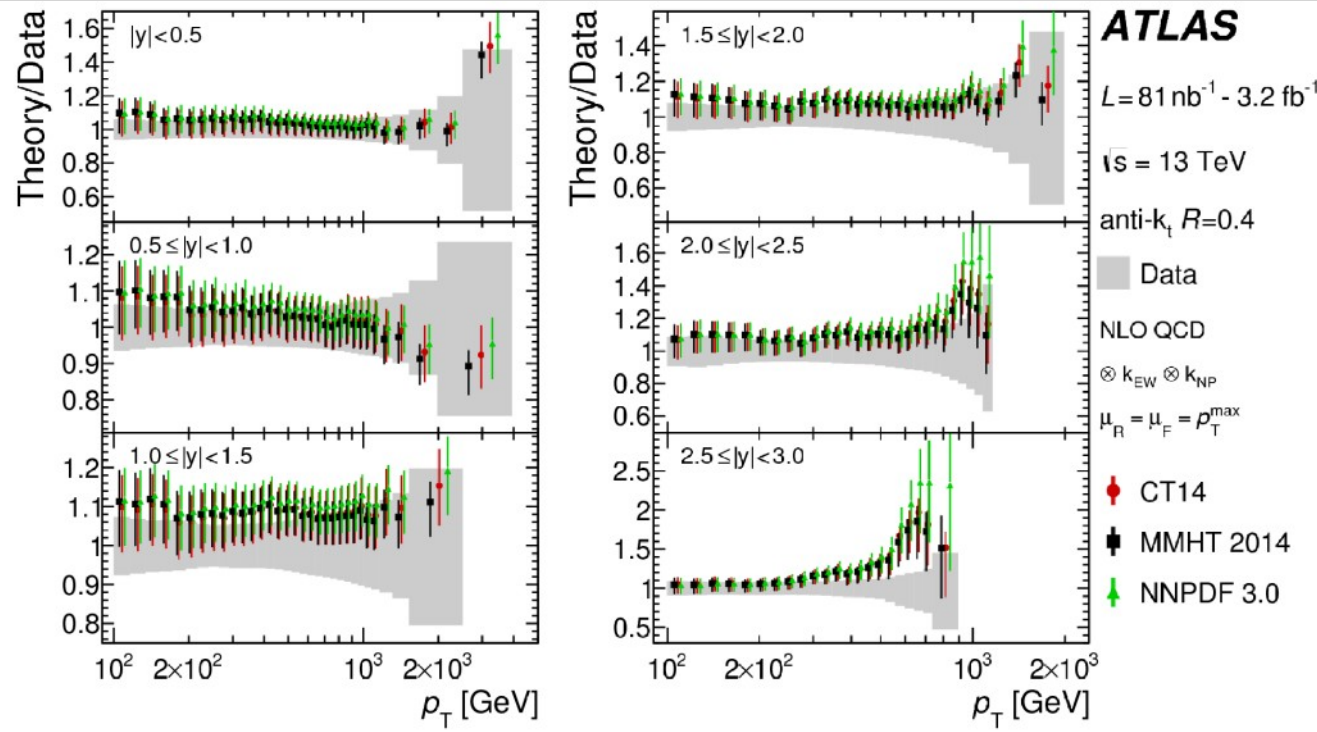


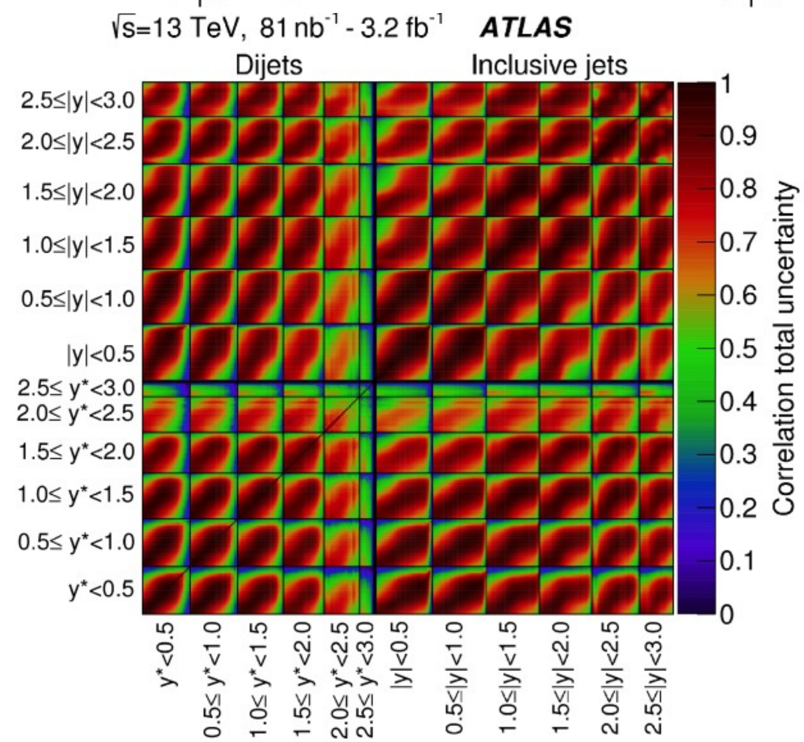




Comparison with PDFs

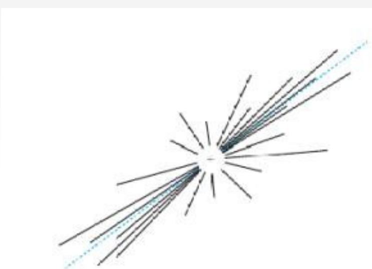
- Experimental results compared to Next-to Leading order QCD calculations, interfaced with several PDF sets
- Now also NNLO available
- To perform a meaningful comparison, it is not sufficient to observe data/MC difference by eye
- All experimental points are correlated by the JES, so a full correlation matrix has to be published to correctly assess agreement between data and MC

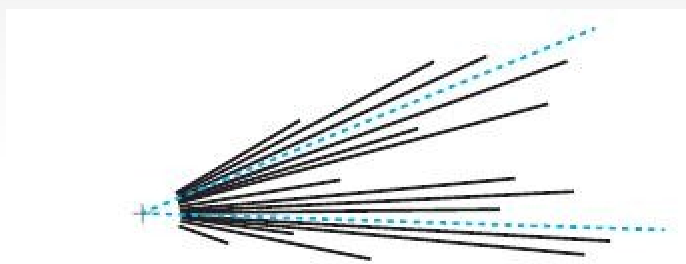


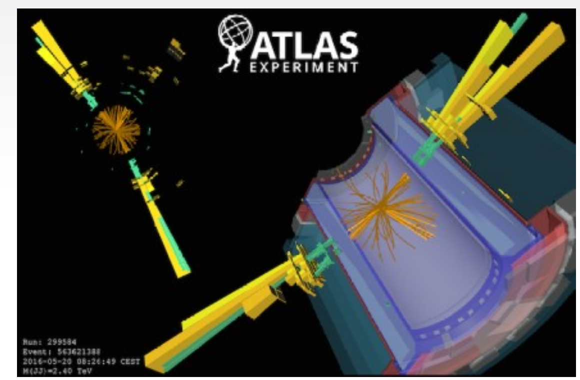


Jet substructure

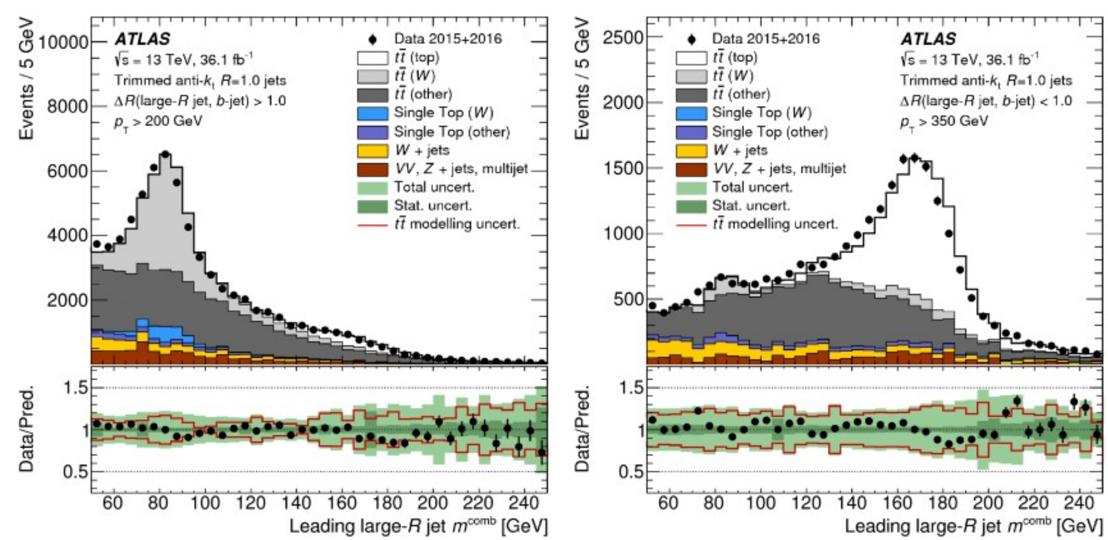
- Not all jets come from hadronisation of light quarks and gluons
- Hadronically-decaying W and Z bosons produce two jets; at high momentum they can be very collimated



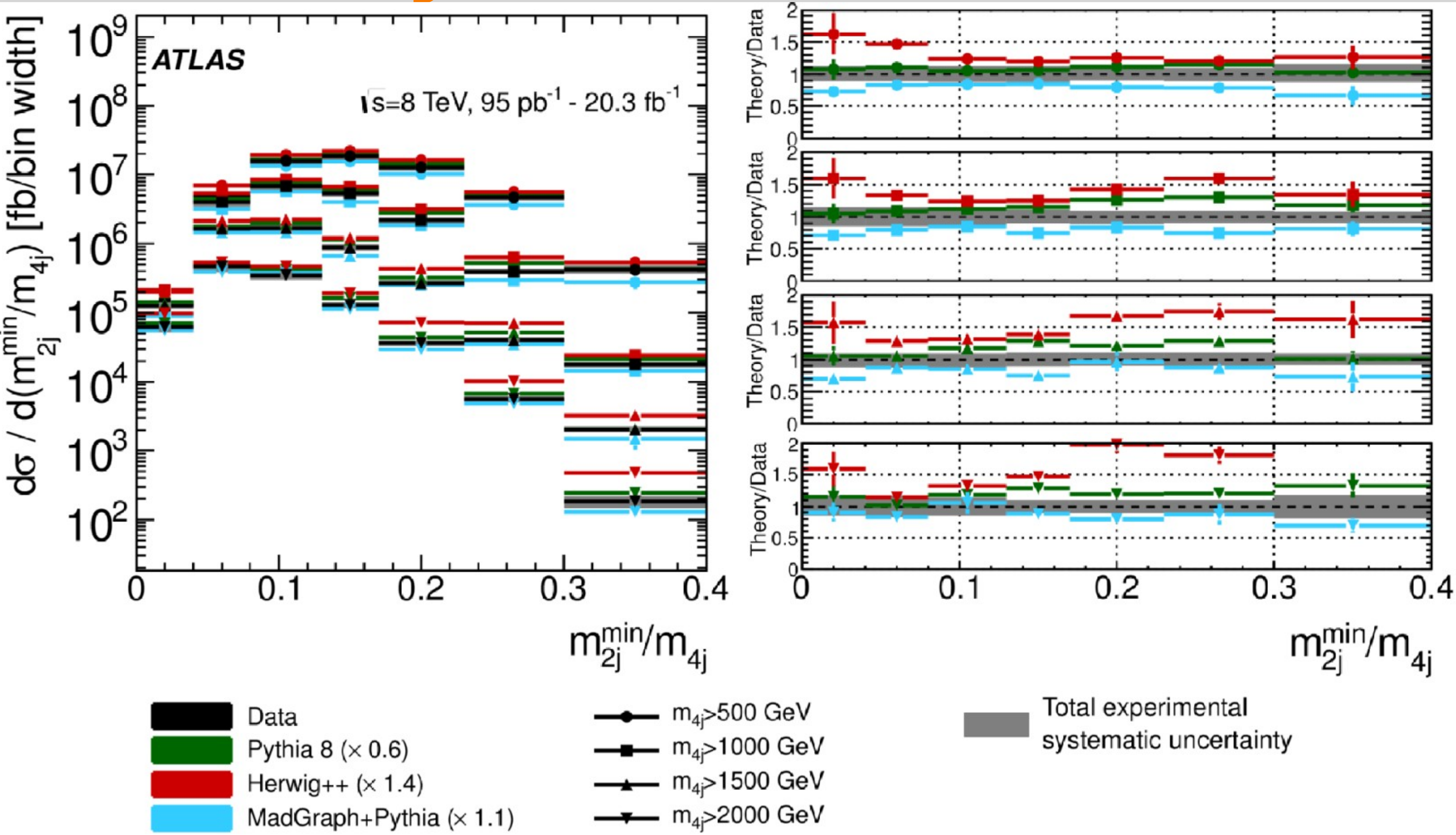




Selecting jets with 2-prong or 3-prong structure can strongly enhance fraction of jets coming from W(Z)-boson or top quark decays



Other Jet measurements

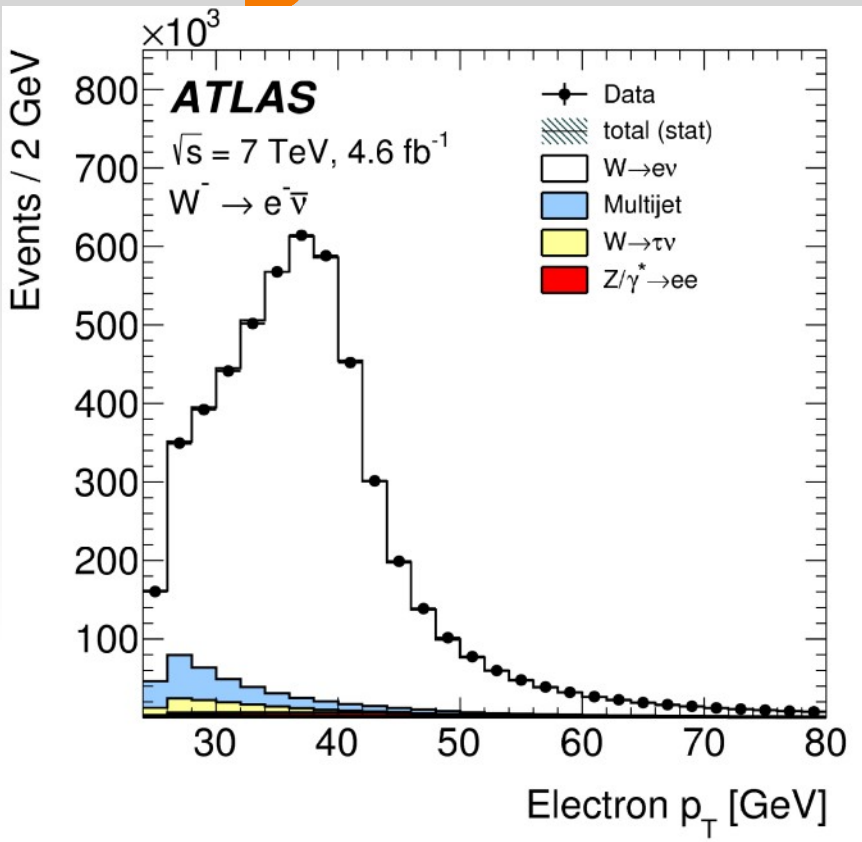


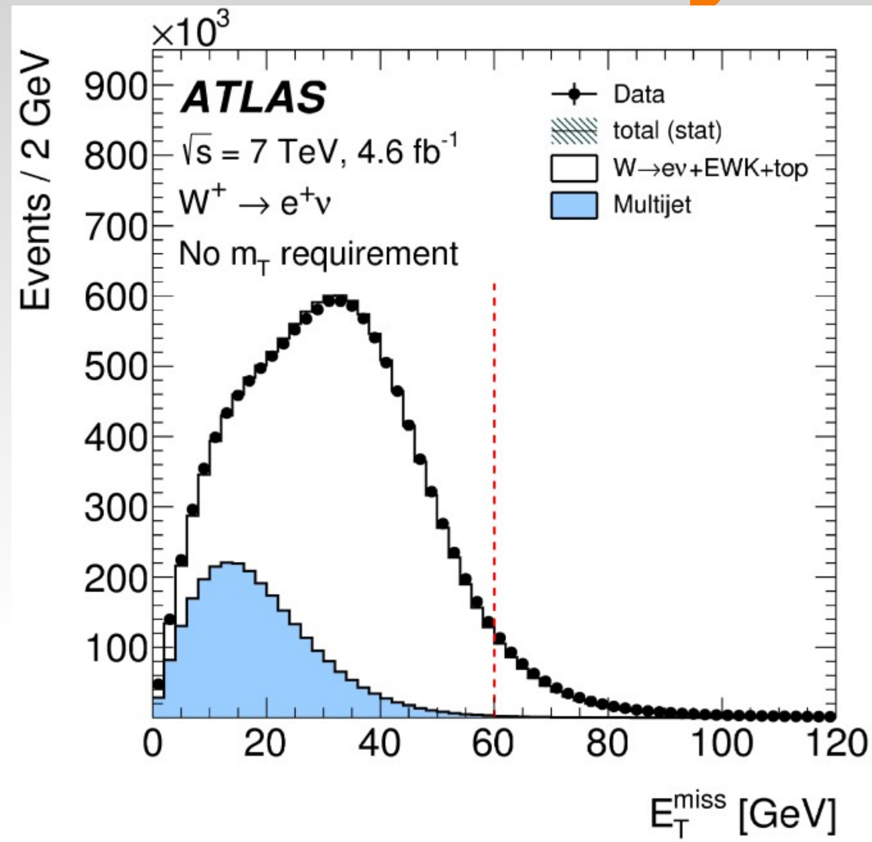
- Several QCD tests performed on jets, looking at multiplicity, angular distribution, radiation beteen dijets

Vector boson production

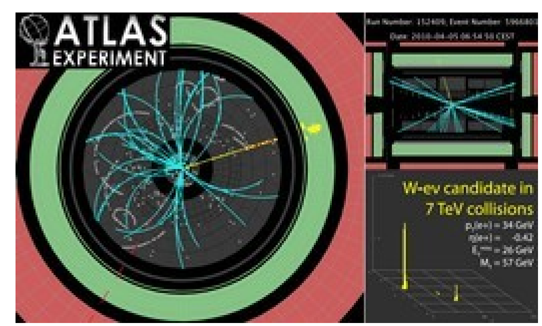
- Next important SM benchmark are W and Z productin, always accompanied by jets at the LHC.
- Relevant for Pdf determination, QCD studies
- W production about 10 times larger than Z, but analysis more difficult: no way to perform full reconstruction, so only transverse mass can be reconstructed
- Different BG from electron and muon channel:
- Neutral pions faking electrons
- Punch-through hadrons in muon chambers
- W forward-backward charge asymmetry very useful for Pdf's (how to define it in a pp machine??)

Ingradients of the analysis



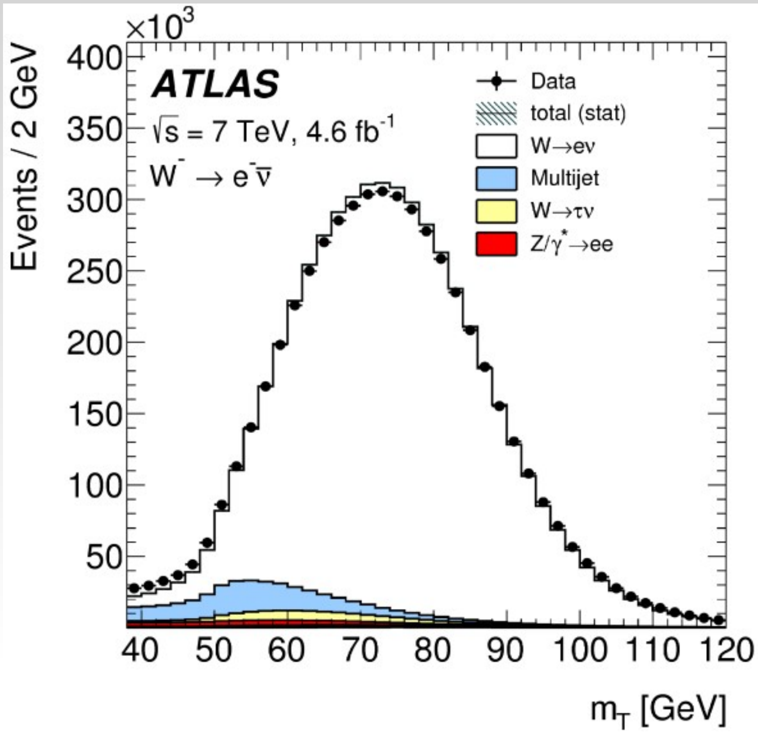


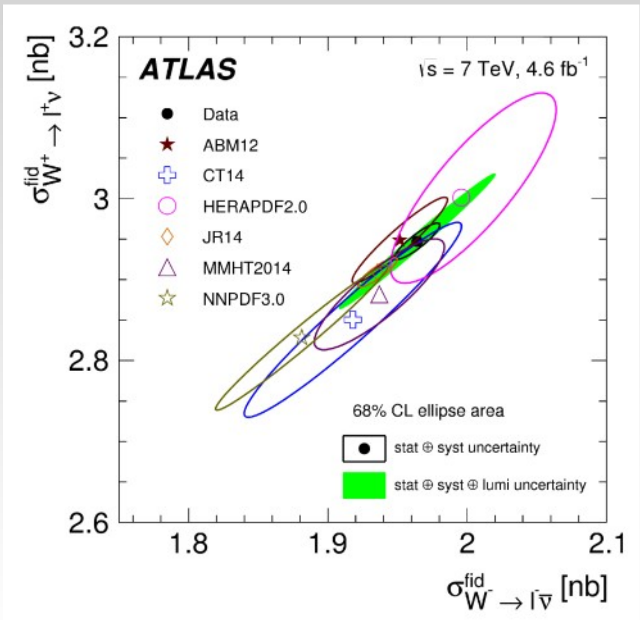
- Electron Pt MET



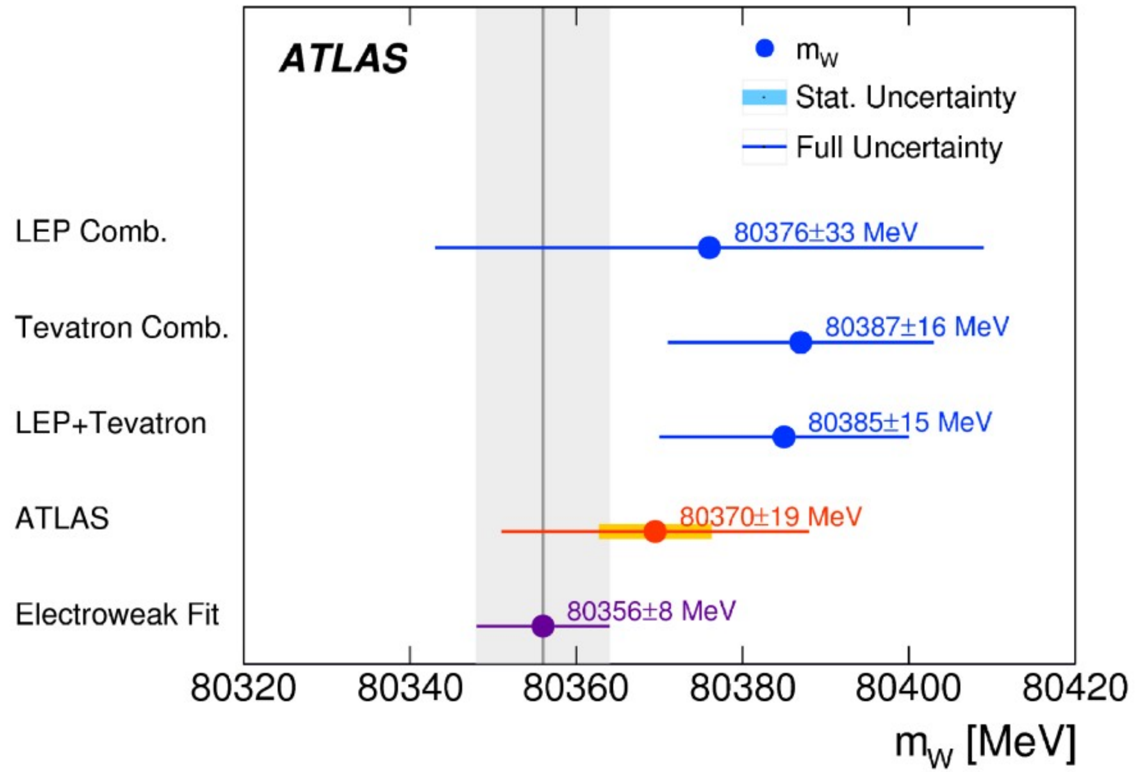
- for W-> enu events
- Signal purity quite high even for individual variables

W transverse mass

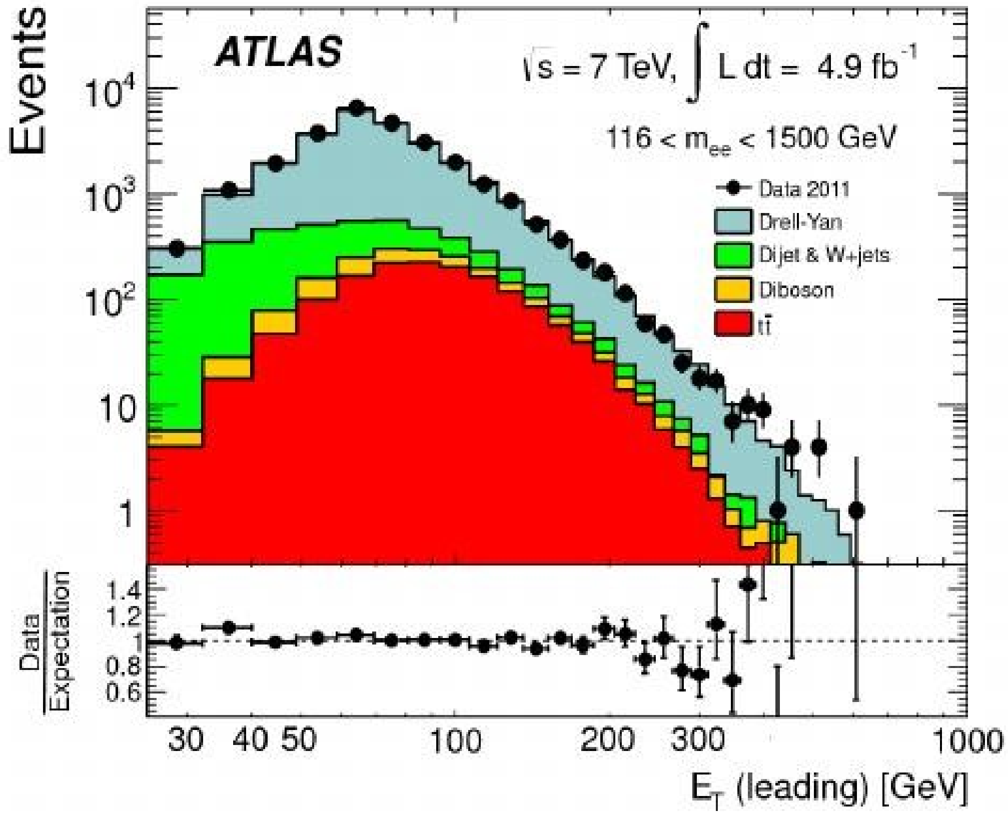


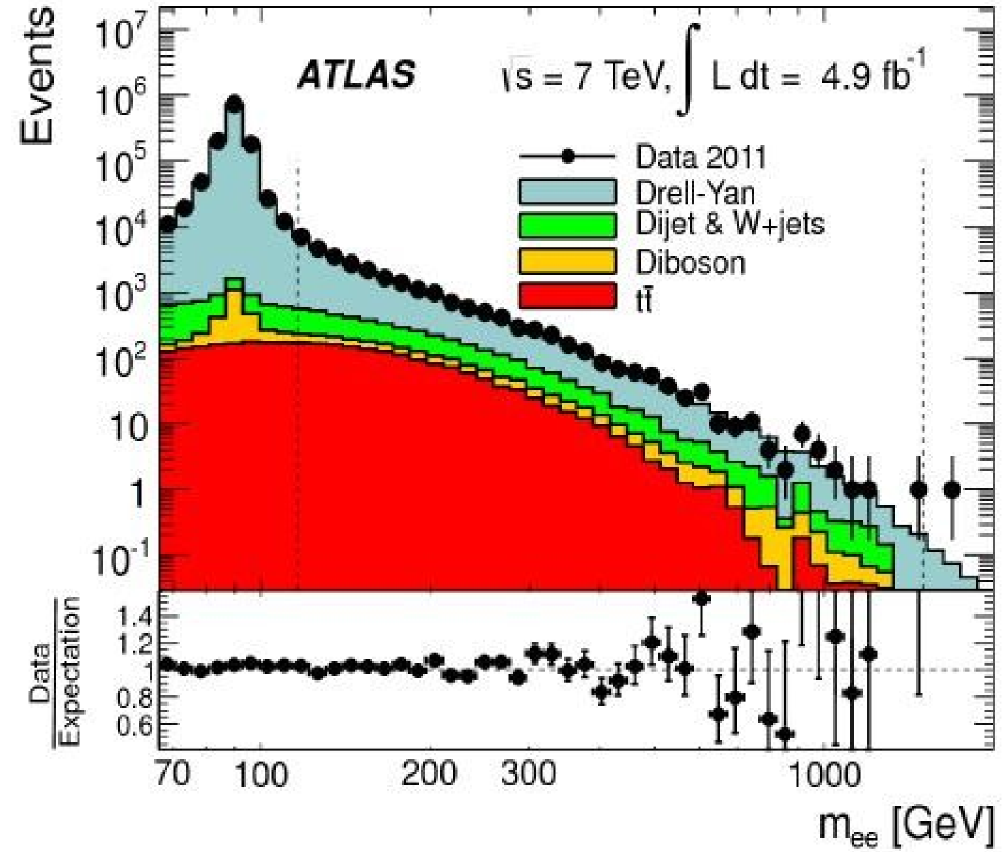


Even if only the transverse mass is measured, a very careful analysis and treatment of systematics allowed the measurement of the W mass with precision better than that of LEP and close to that of Tevatron



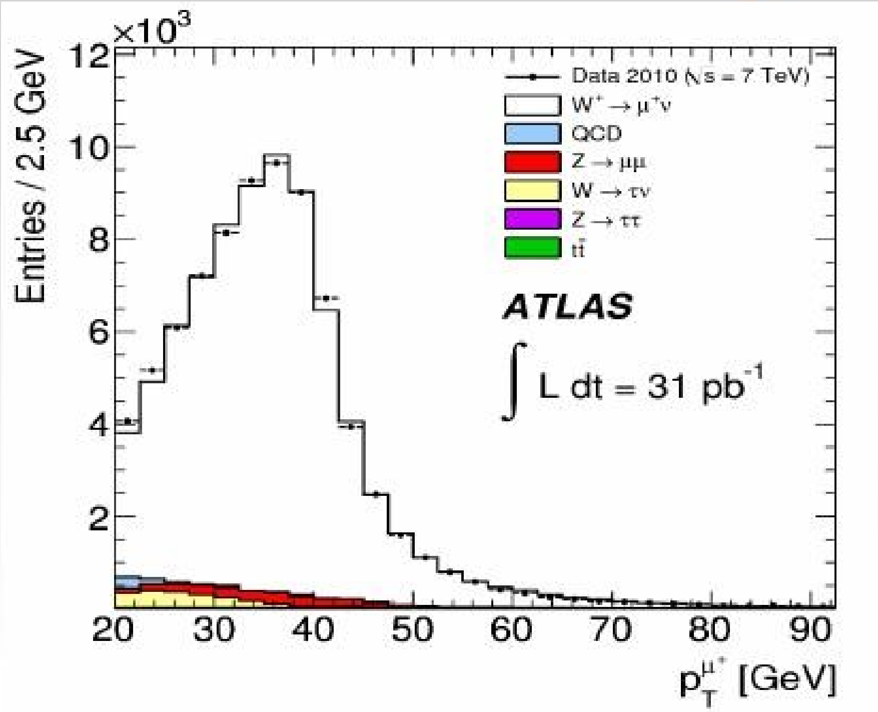
Z->ll analysis

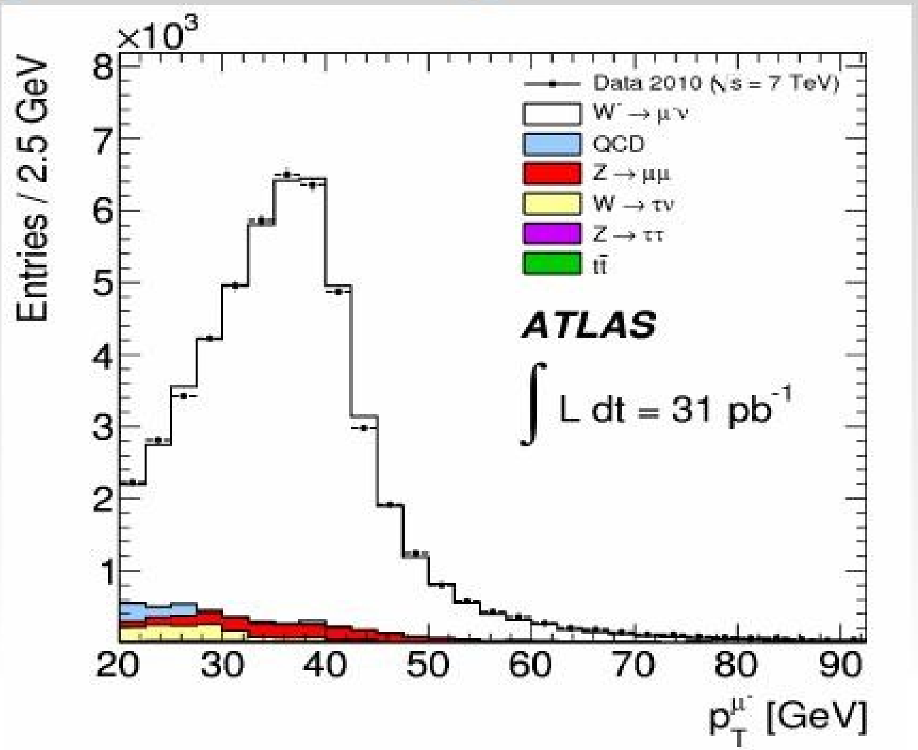


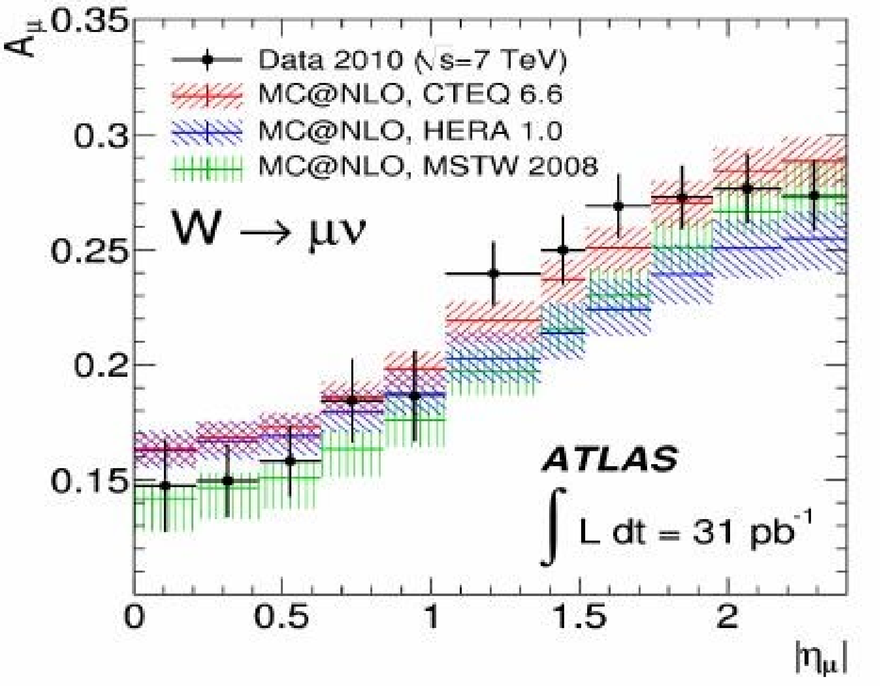


2-lepton requirement makes Z channel much cleaner, but statistics is poorer than W-hard to beat LEP's 4 million Z collected per experiment (and lineshape fit) in clean environment. Fundamental tool for calibration

W charge asymmetry



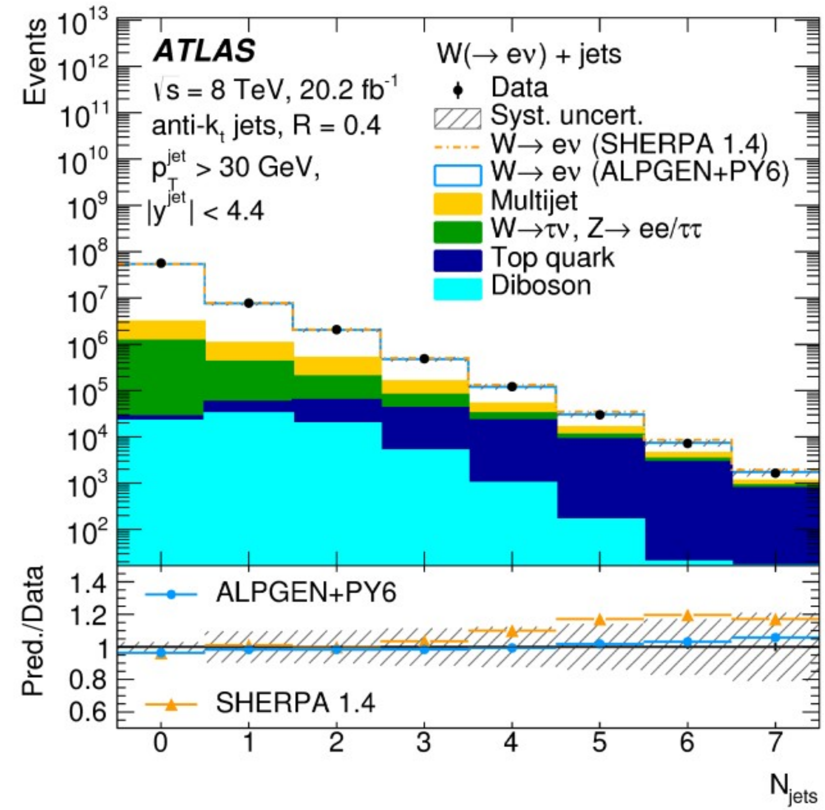


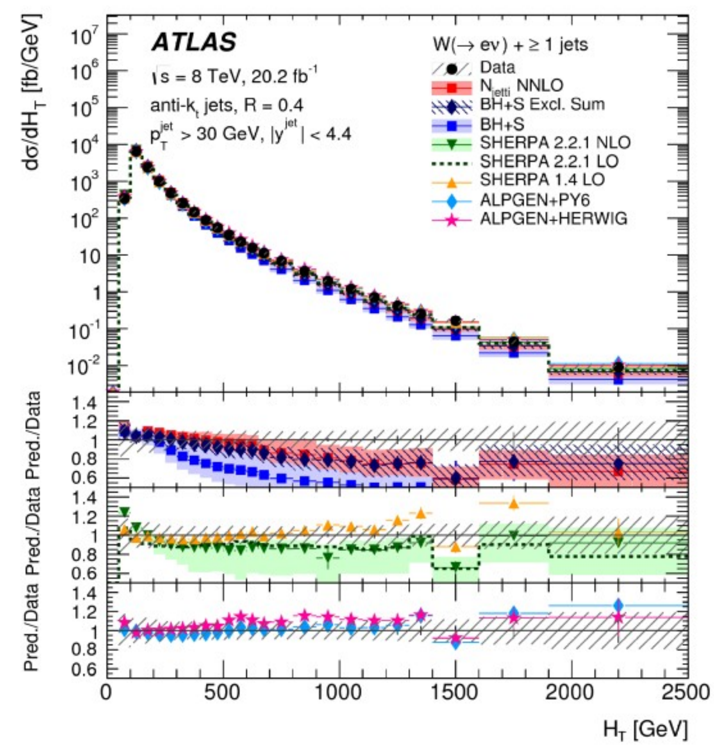


The idea: from Pdf's, u-quarks have higher average x, so W+ tend to be produced more forward. Even in pp, W asymmetry distribution can constraint Pdf's

Vector bosons plus jets

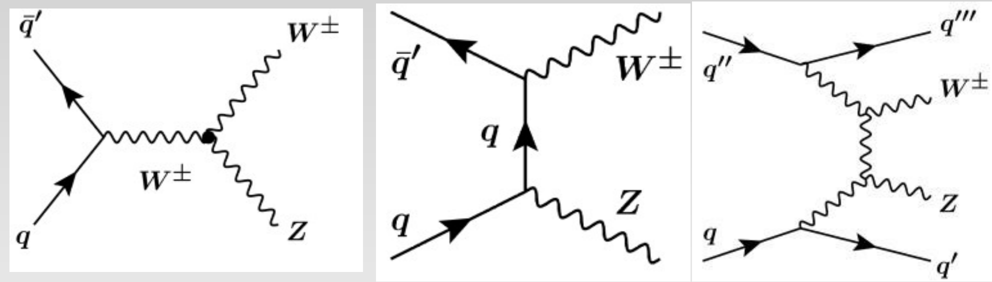
- Important test of perturbative calculations over many orders of magnitude is the measurement of production of vector bosons plus a large number of jets
-
- Tested against a large number of simulation codes



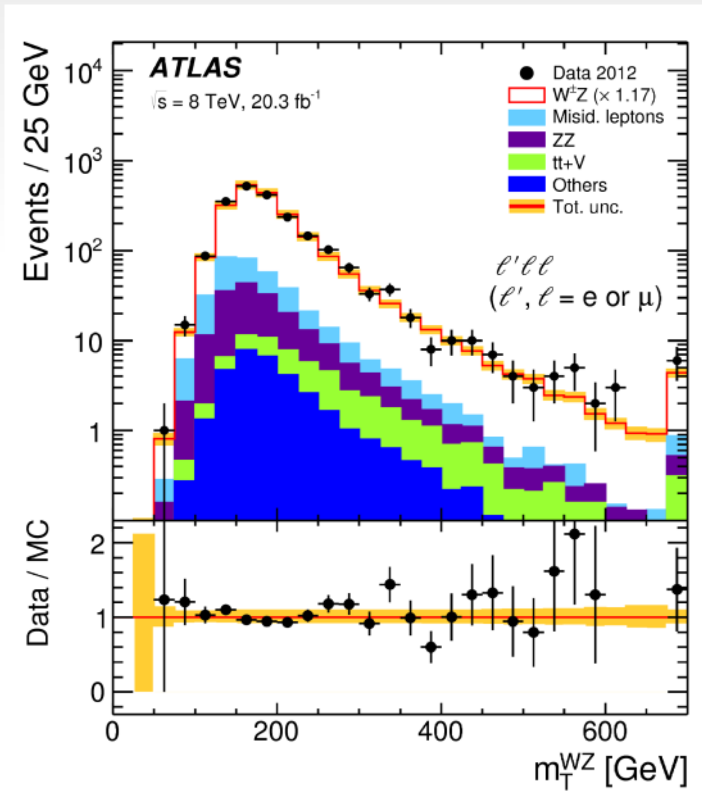


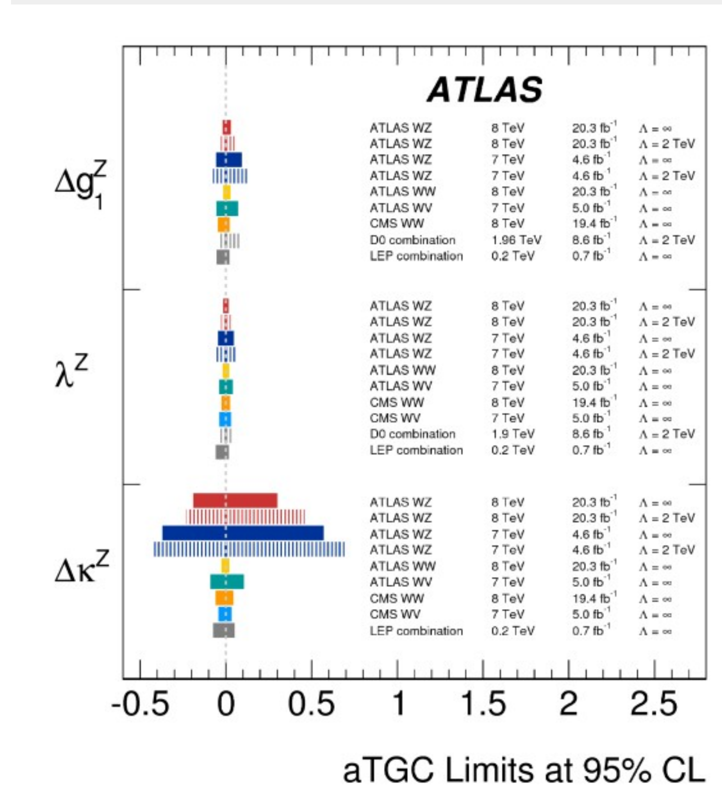
Multiple vector bosons and TGC

- Many processes can contribute to multiple vector boson production.



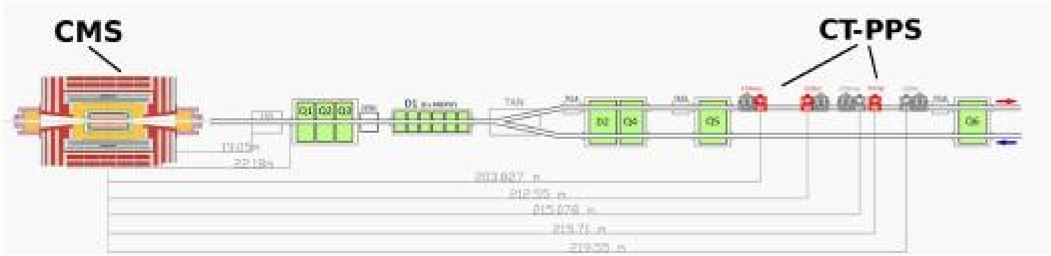
- Sensitive to new physics and anomalous Trilinear Gauge Couplings, used to test possible deviations from the SM

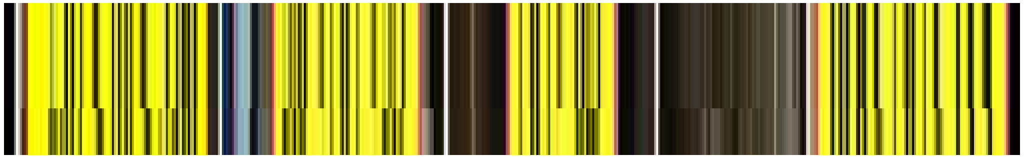


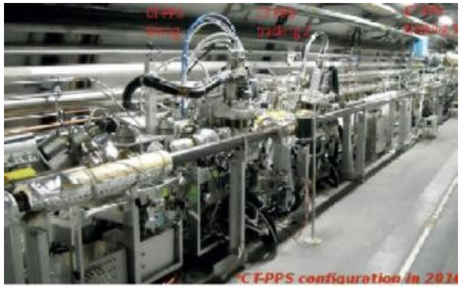


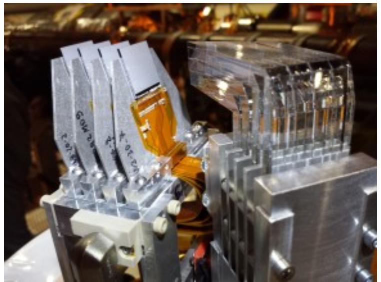
Full reconstruction of event kinematics

- In normal inelastic events, non-interacting quarks and gluons from the proton are lost in the beam pipe
- However we saw earlier that in diffractive collisions the protons can remain intact, albeit with reduced energy
- Special detectors are placed close to the beam line, to measure the protons using the LHC magnets as spectrometers



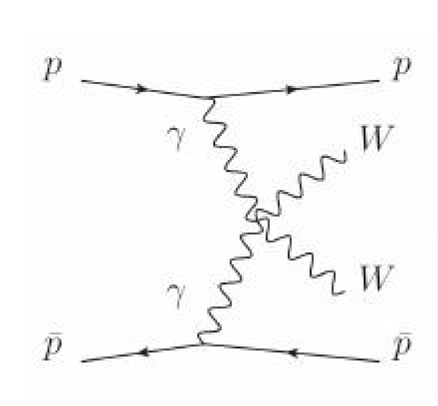


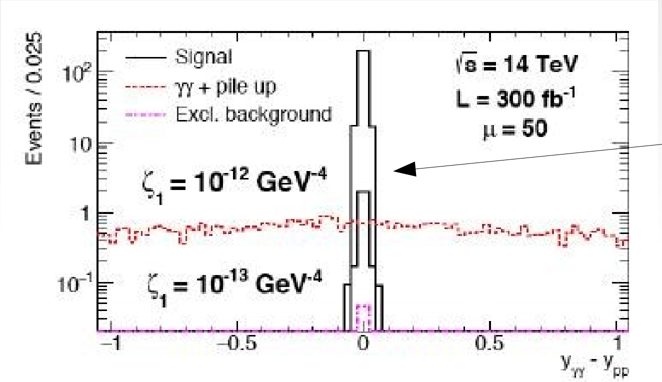




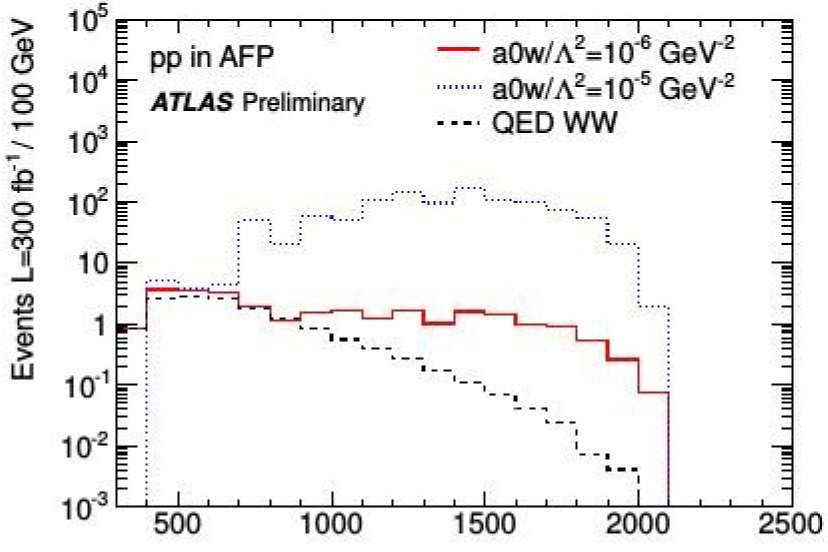
Vector bosons with intact protons

- If protons exchange singlets of strong interactions (photons, or ”gluon ladders”) they can be detected by the forward spectrometers, and their missing energy matched to the invariant mass of the central system.

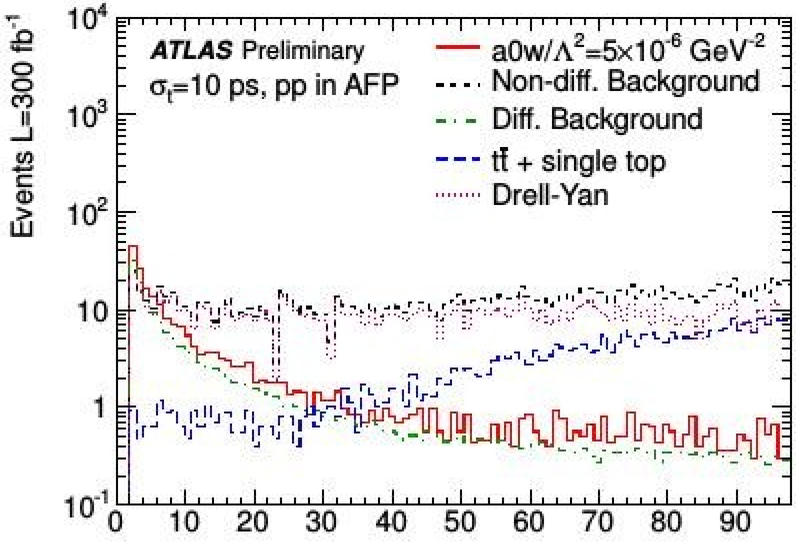




signal



Mpp



Conclusions

- As you saw, even just SM physics LHC is huge (only gave a few snapshots), and even if legions of physicists analyse the data, there is really a lot to be occupied over many years
- Taking the data is not trivial: a lot of work goes in the trigger and Data Acquisition system
- Detector calibration and monitoring very important (e.g. energy scale is the main systematics for jet measurements)
- Very high-precision measurements of jets, photons and vector bosons test the SM with incredible precision over many orders of magnitude
- Forward detctors allow full reconstruction of some events
- So far, no compelling deviations from the Standard Model observed