Introduction to particle physics: experimental part

- **RAW data to Physics**
  - **The road from collisions to physics publications**

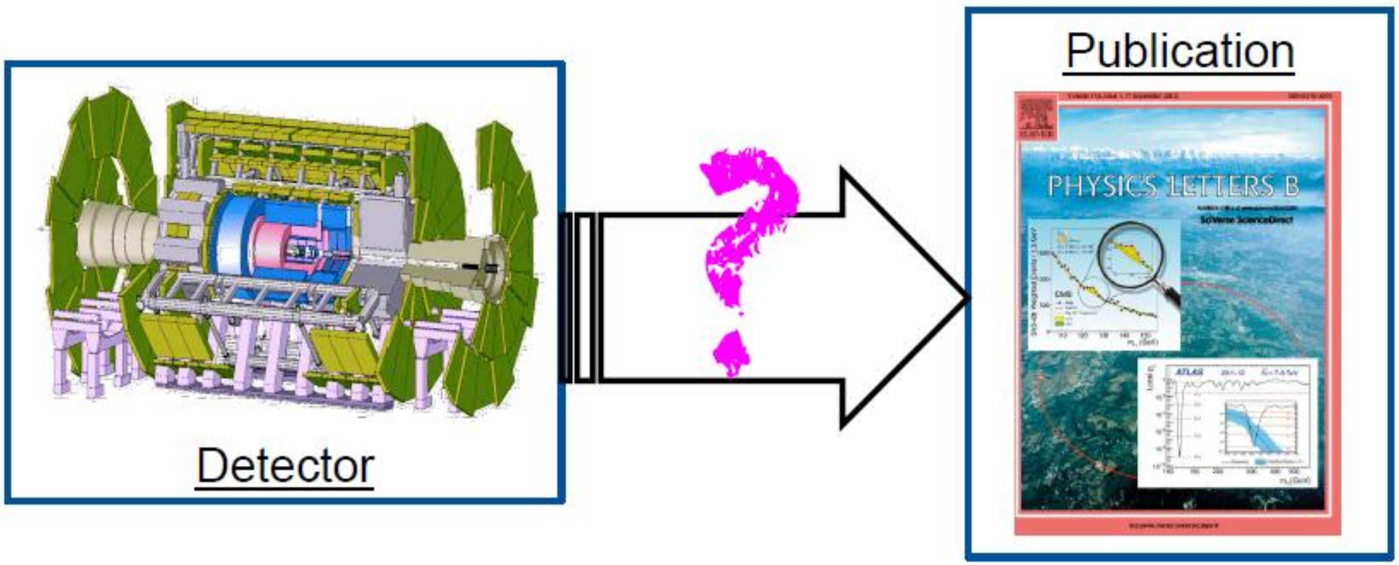
- **From RAW data to Standard Model particles**
  - **About measuring properties of the final particles created from proton-proton collisions**

- **From Standard Model particles to measurements and searches**
  - **About how we analys data using ingredients we have constructed**

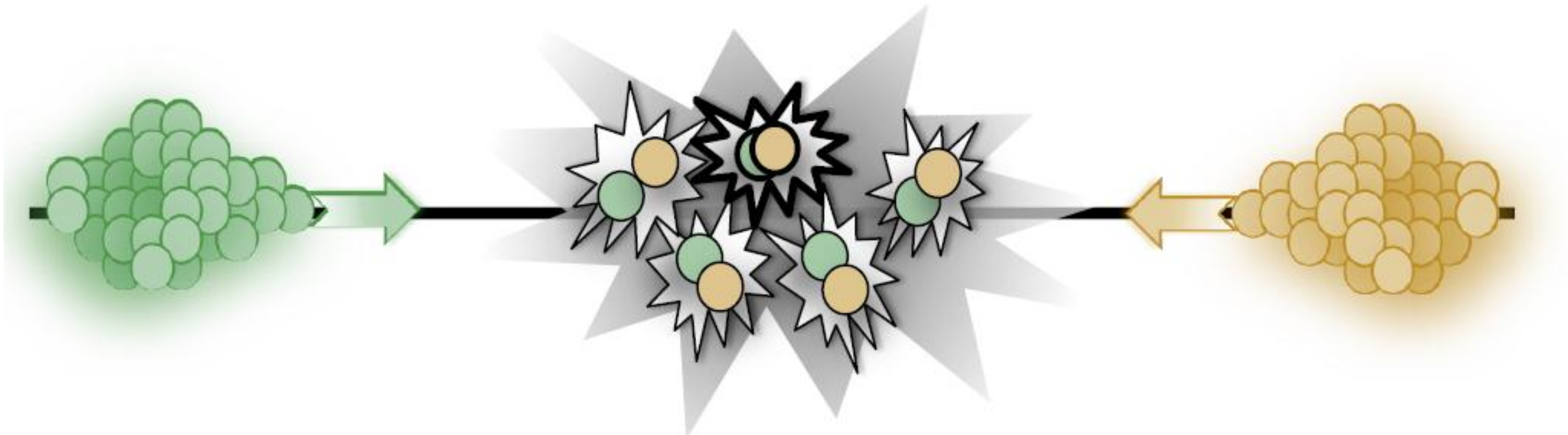
Large fraction of slides from A. Sfyrla lectures at CERN Summer School 2018

Prof. dr hab. Elżbieta Richter-Wąs

How do we deal with physics events
from when they leave the detector
till when they make it into our publications?



What is an event?



Proton bunches

>10^{11} protons/bunch

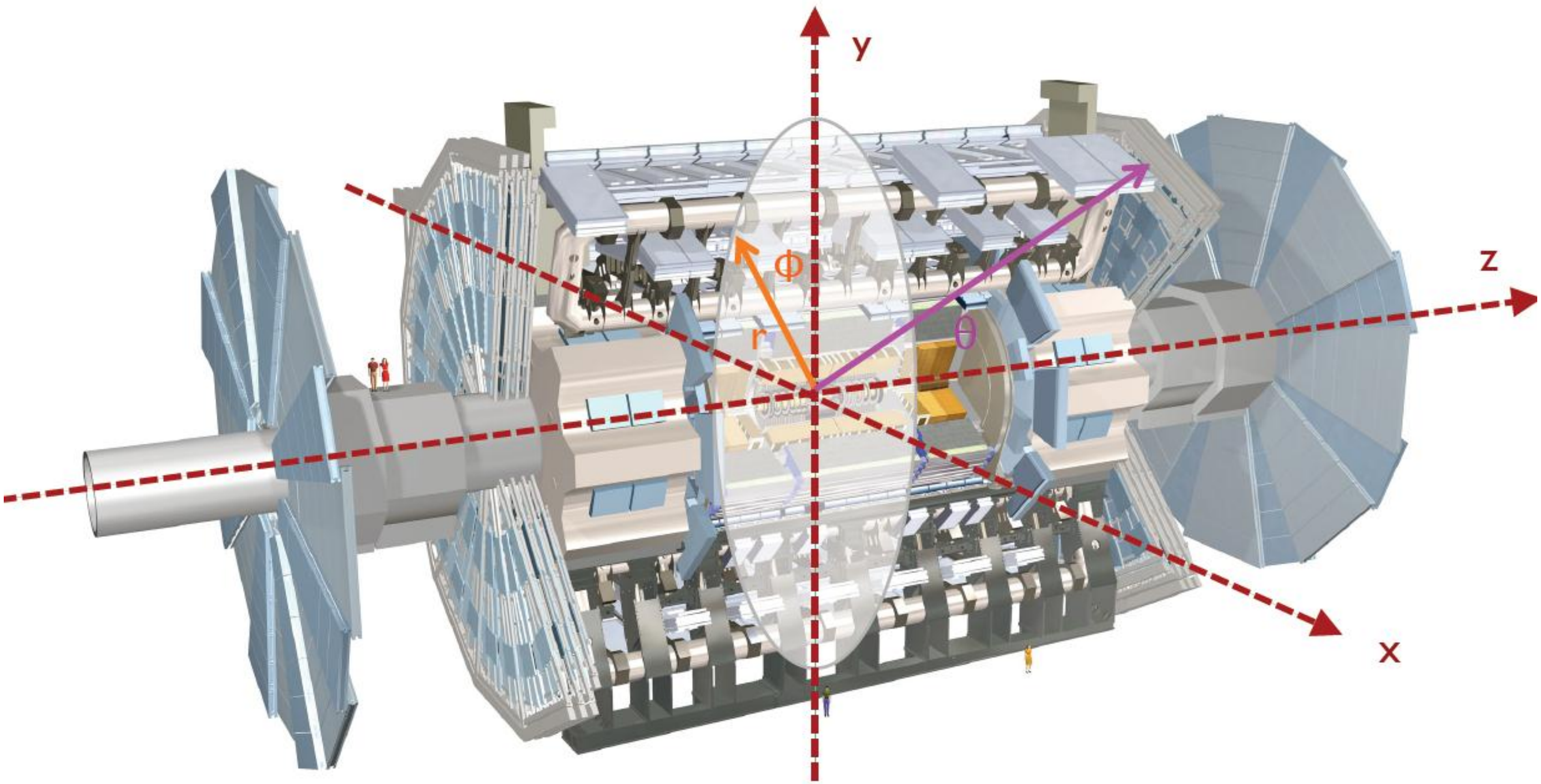
colliding at **13 TeV** and at ~**30 MHz in Run-2**

collided at **7/8TeV** and at ~**20 MHz in Run-1**

In 2018:

Up to 60 p-p collisions / bunch crossing

Collider experiment coordinates



Rapidity

Lorentz factor $\gamma = \frac{1}{\sqrt{1-\beta^2}} = \cosh\varphi$ Hyperbolic cosine of "rapidity"

$$E = m\cosh\varphi$$
$$|\vec{p}| = m\sinh\varphi$$

$$\varphi = \tanh^{-1}\frac{E}{|\vec{p}|} = \frac{1}{2}\ln\frac{E+|\vec{p}|}{E-|\vec{p}|}$$

- Particle physicists prefer to use modified rapidity along beam axis

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

Pseudorapidity

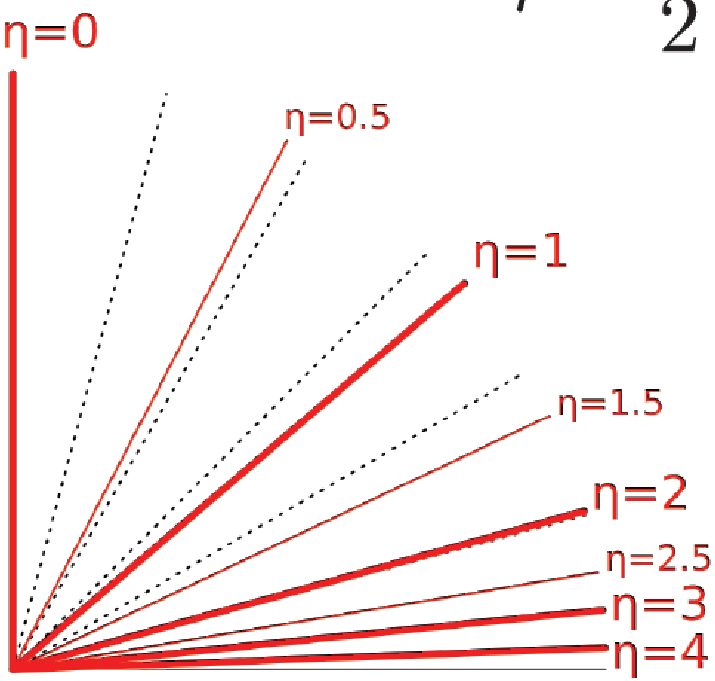
$$\eta = \frac{1}{2}\ln\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}$$

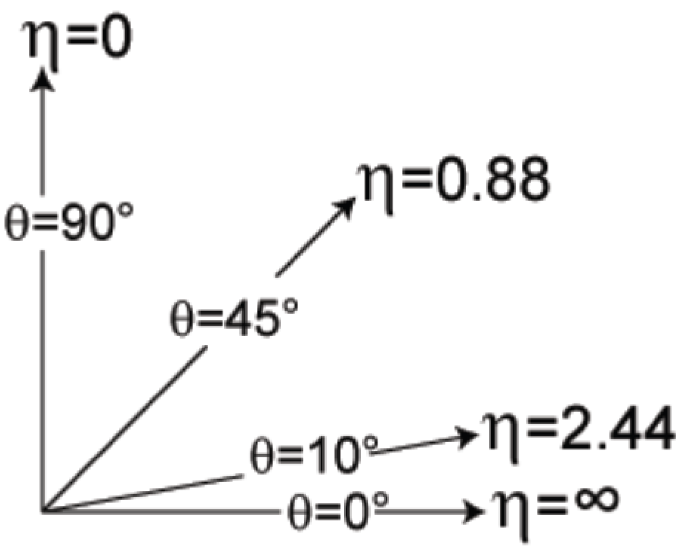
$$\eta = \frac{1}{2}\ln\left(\tan\frac{\theta}{2}\right)$$

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

$$\eta \simeq y$$

if E >> m





Transverse variables

- At hadron colliders, a significant and unknown fraction of the beam energy in each event escapes down the beam pipe.
- Net momentum can only be constrained in the plane transverse to the beam z-axis!

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$p_x = p_T \cos\phi$$
$$p_y = p_T \sin\phi$$
$$p_z = p_T \sinh\eta$$

$$|p| = p_T \cosh\eta$$

$$E_T = \frac{E}{\cosh\eta}$$

$$\sum p_X(i) = 0 \qquad \sum p_Y(i) = 0$$

Missing transverse energy and transverse mass

- If invisible particle are created, only their transverse momentum can be constrained: missing transverse energy

$$E_T^{\text{miss}} = \sum p_T(i)$$

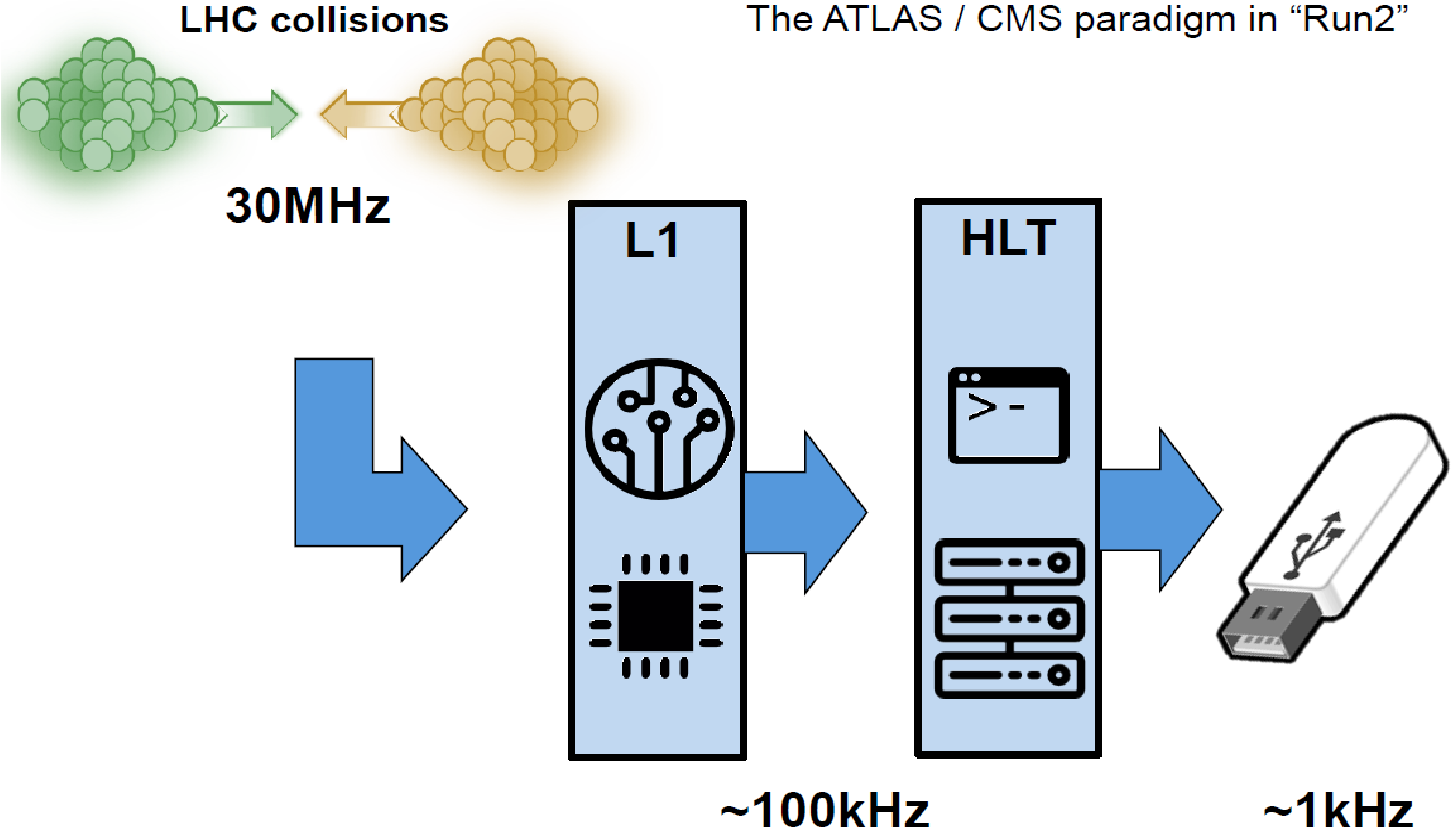
- If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can constrained with the transverse mass quantity

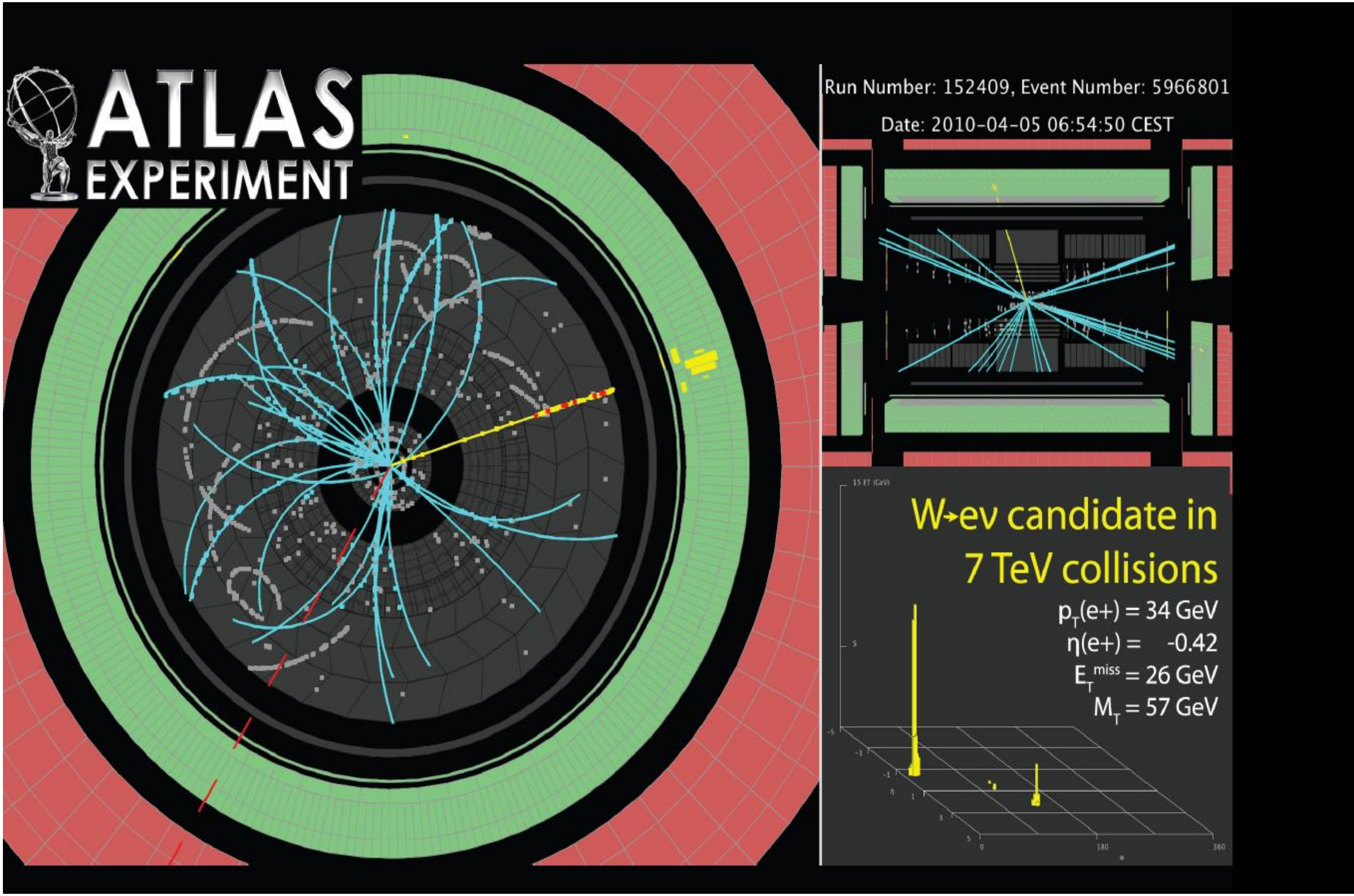
$$\begin{aligned} M_T^2 &\equiv [E_T(1) + E_T(2)]^2 - [\boldsymbol{p}_T(1) + \boldsymbol{p}_T(2)]^2 \\ &= m_1^2 + m_2^2 + 2[E_T(1)E_T(2) - \boldsymbol{p}_T(1) \cdot \boldsymbol{p}_T(2)] \end{aligned}$$

if $m_1 = m_2 = 0$ $\quad M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos\phi_{12})$

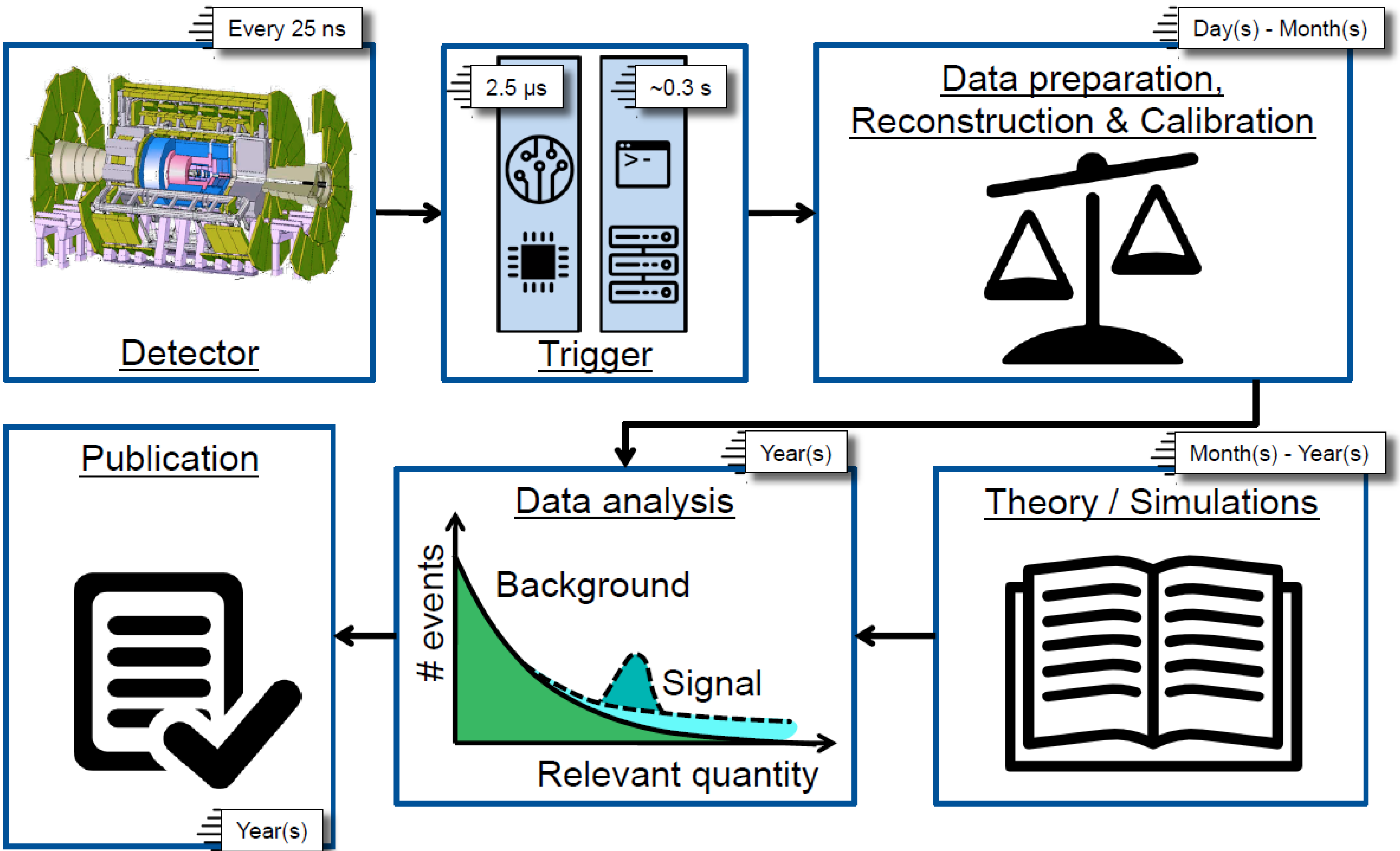
Triggering on physics

The ATLAS / CMS paradigm in “Run2”

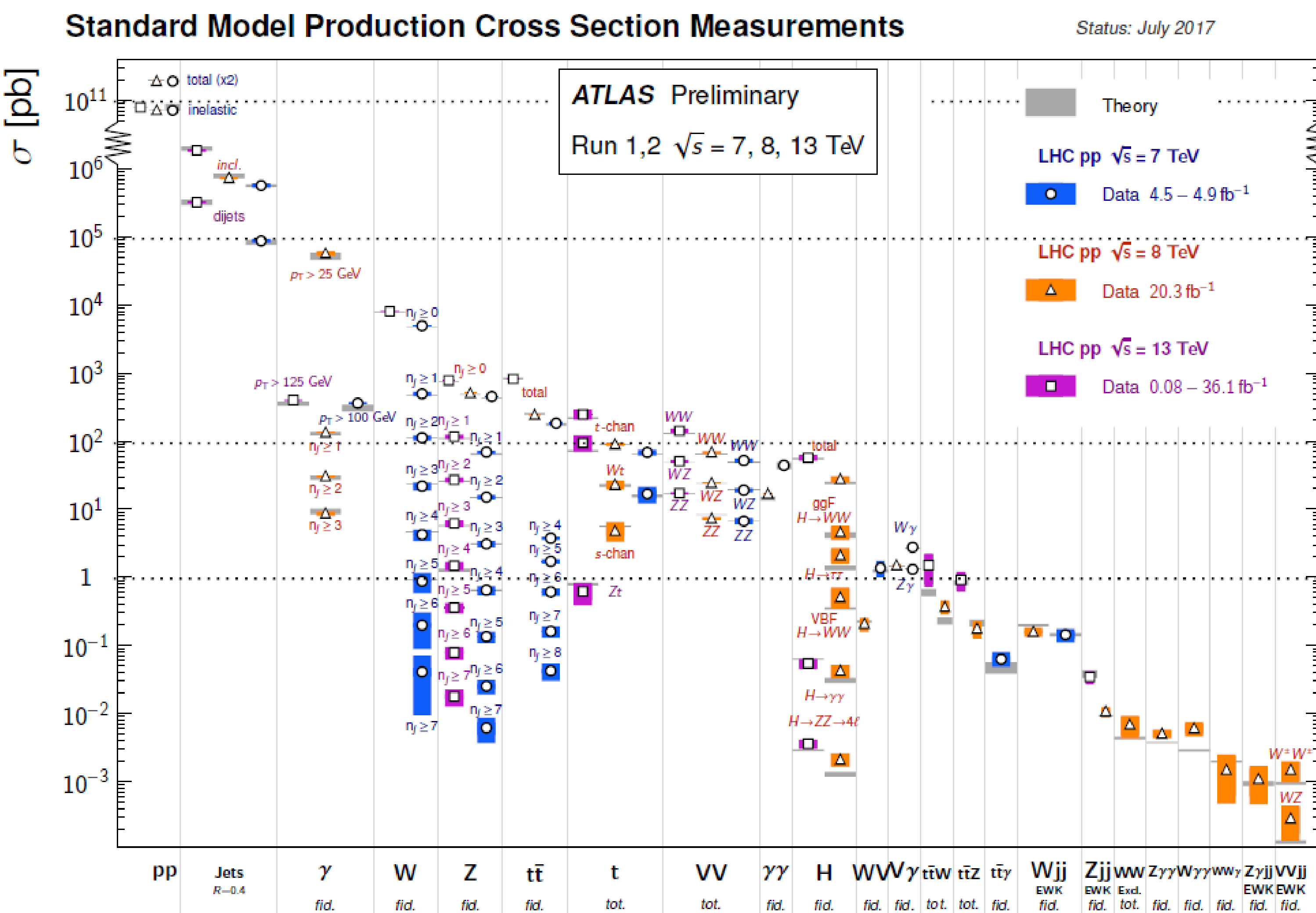



ATLAS
EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in
7 TeV collisions
$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

An event’s lifetime



Reminder: $\sigma = \frac{\#\ \text{events}}{L}$



Event Rate

$L_{inst} = 10^{34}\ cm^{-2}s^{-1}$

1 GHz

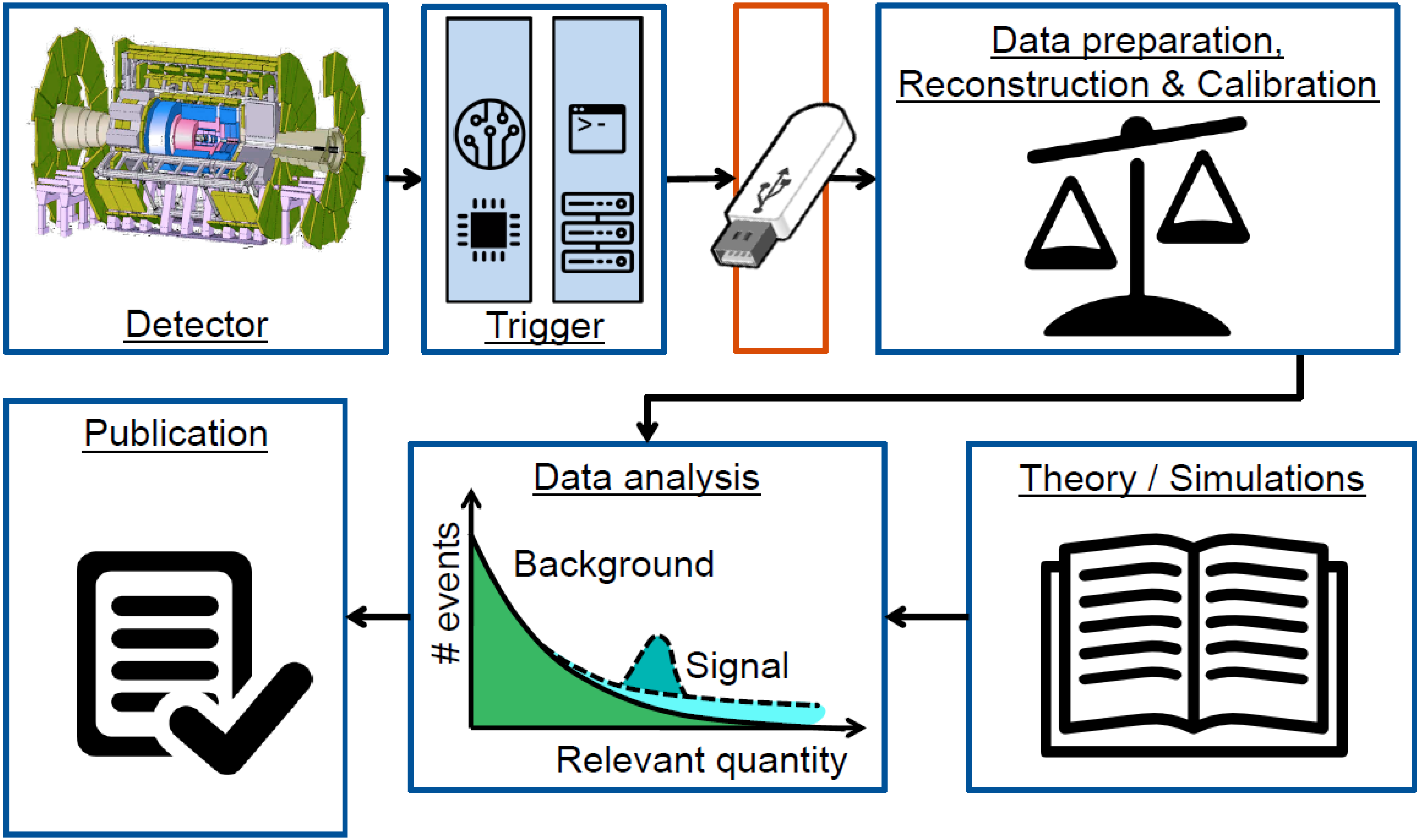
1 kHz

1 Hz

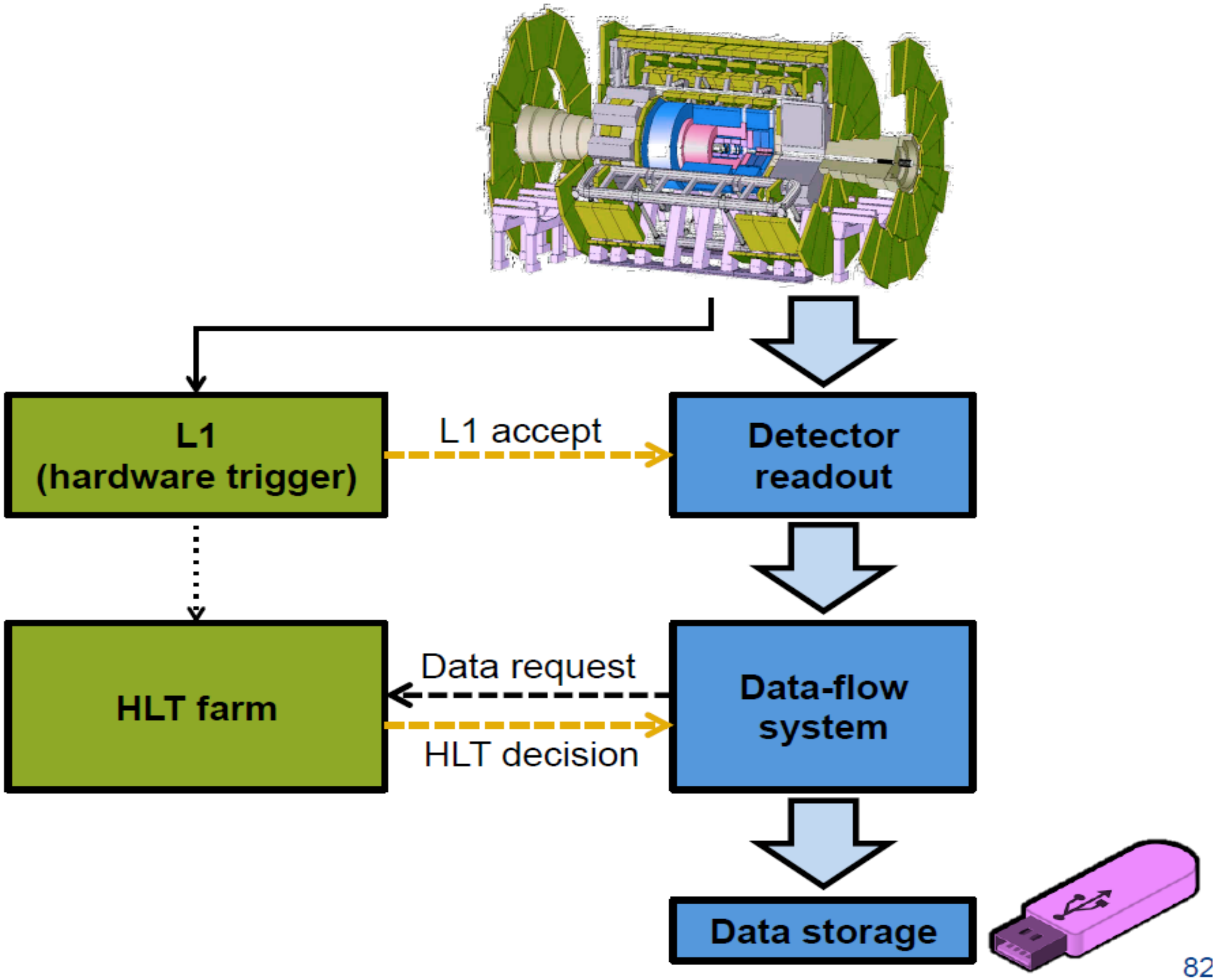
10^{-2} Hz

Viable SUSY & other exotics

An events's lifetime



The Data Acquisition (DAQ)



What does raw contain?

0x00000015	0x20000e3f	536874559	lvl1 trigger info[0]
0x00000016	0x100000c0	268435648	lvl1 trigger info[1]
0x00000017	0x8000043f	2147484735	lvl1 trigger info[2]
0x00000018	0x00021007	135175	lvl1 trigger info[3]
0x00000019	0x00000e10	3600	lvl1 trigger info[4]
0x0000001a	0x00080000	524288	lvl1 trigger info[5]
0x0000001b	0x02c00400	46138368	lvl1 trigger info[6]
0x0000001c	0x00020001	131073	lvl1 trigger info[7]
0x0000001d	0x00000816	2070	lvl1 trigger info[8]
0x0000001e	0x100000c0	268435648	lvl1 trigger info[9]
0x0000001f	0x80000018	2147483672	lvl1 trigger info[10]
0x00000020	0x00021001	135169	lvl1 trigger info[11]
0x00000021	0x00000e10	3600	lvl1 trigger info[12]
0x00000022	0x00000000	0	lvl1 trigger info[13]
0x00000023	0x02c00400	46138368	lvl1 trigger info[14]
0x00000024	0x00020000	131072	lvl1 trigger info[15]
0x00000025	0x00000010	16	lvl1 trigger info[16]
0x00000026	0x00000000	0	lvl1 trigger info[17]
0x00000027	0x00000008	8	lvl1 trigger info[18]
0x00000028	0x00000000	0	lvl1 trigger info[19]
0x00000029	0x00000810	2064	lvl1 trigger info[20]
0x0000002a	0x00000000	0	lvl1 trigger info[21]
0x0000002b	0x00000400	1024	lvl1 trigger info[22]
0x0000002c	0x00000000	0	lvl1 trigger info[23]

Enabled items, ID (info[0]–info[7]):
0, 1, 2, 3, 4, 5, 9, 10, 11, 29, 38, 39, 60, 64, 65, 66, 67, 68, 69, 74, 95, 96, 97, 98, 108, 113, 132, 137, 138, 139, 179, 202, 214, 215, 217, 224, 241

Enabled items, ID (info[8]–info[15]):
1, 2, 4, 11, 38, 39, 60, 67, 68, 95, 96, 108, 113, 132, 137, 138, 139, 202, 214, 215, 217, 241

Enabled items, name (info[16]–info[23]):
L1_EM18VH,
L1_2TAU11I_EM14VH,
L1_2TAU11_TAU20_EM14VH,
L1_2TAU11I_TAU15,
L1_2EM6_EM16VH

What does raw contain?

0x00000015	0x20000e3f	536874559	lvl1 trigger info[0]
0x00000016	0x100000c0	268435648	lvl1 trigger info[1]
0x00000017	0x8000043f	2147484735	lvl1 trigger info[2]
0x00000018	0x00021007	135175	lvl1 trigger info[3]
0x00000019	0x00000e10	3600	lvl1 trigger info[4]
0x0000001a	0x00080000	524288	lvl1 trigger info[5]
0x0000001b	0x02c00400	46138368	lvl1 trigger info[6]
0x0000001c	0x00020001	131073	lvl1 trigger info[7]
0x0000001d	0x00000816	2070	lvl1 trigger info[8]
0x0000001e	0x100000c0	268435648	lvl1 trigger info[9]
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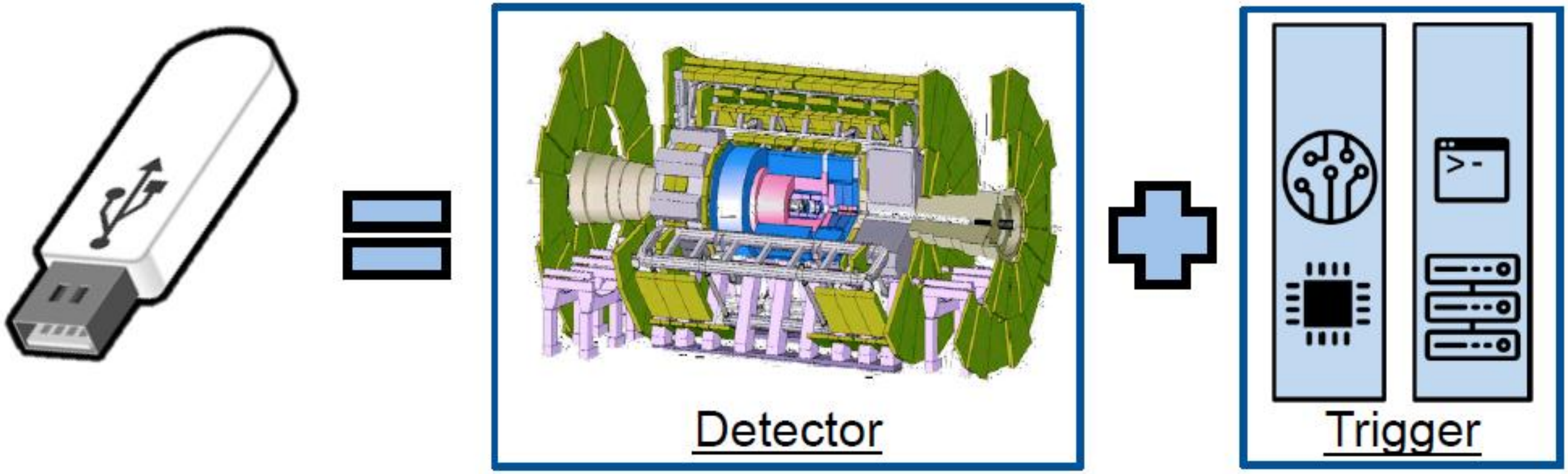
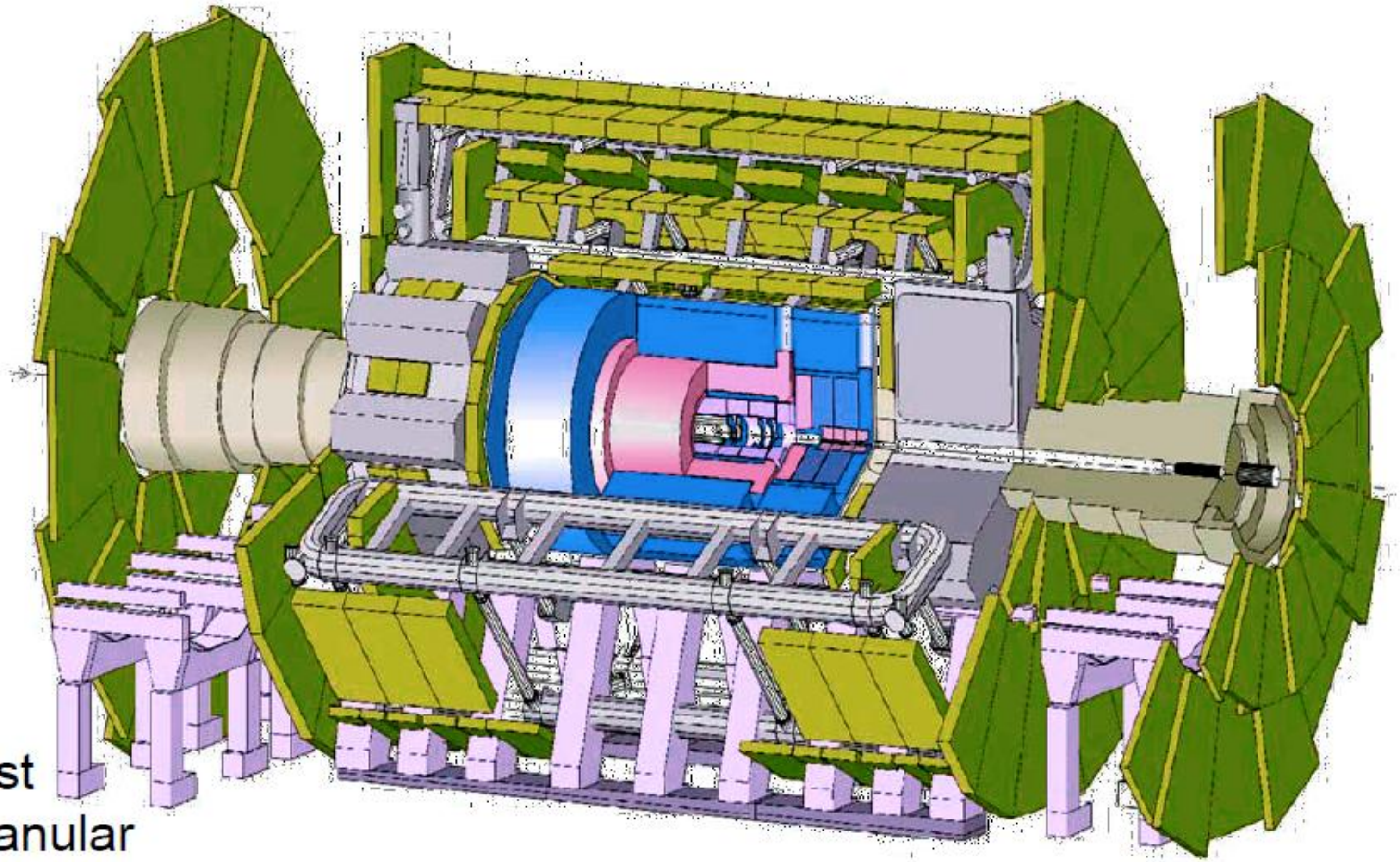
0x00000025	0x00000010	16	lvl1 trigger info[16]
0x00000026	0x00000000	0	lvl1 trigger info[17]
0x00000027	0x00000008	8	lvl1 trigger info[18]
0x00000028	0x00000000	0	lvl1 trigger info[19]
0x00000029	0x00000810	2064	lvl1 trigger info[20]
0x0000002a	0x00000000	0	lvl1 trigger info[21]
0x0000002b	0x00000400	1024	lvl1 trigger info[22]
0x0000002c	0x00000000	0	lvl1 trigger info[23]

- More than 300K such words in each event, corresponding to the full data from all the detector components.
- Data size: 1-1.5MB / event depending on the compression. Pretty consistent between ATLAS and CMS.
- **Challenge: make sense out of all these numbers!!**

What does raw contain?

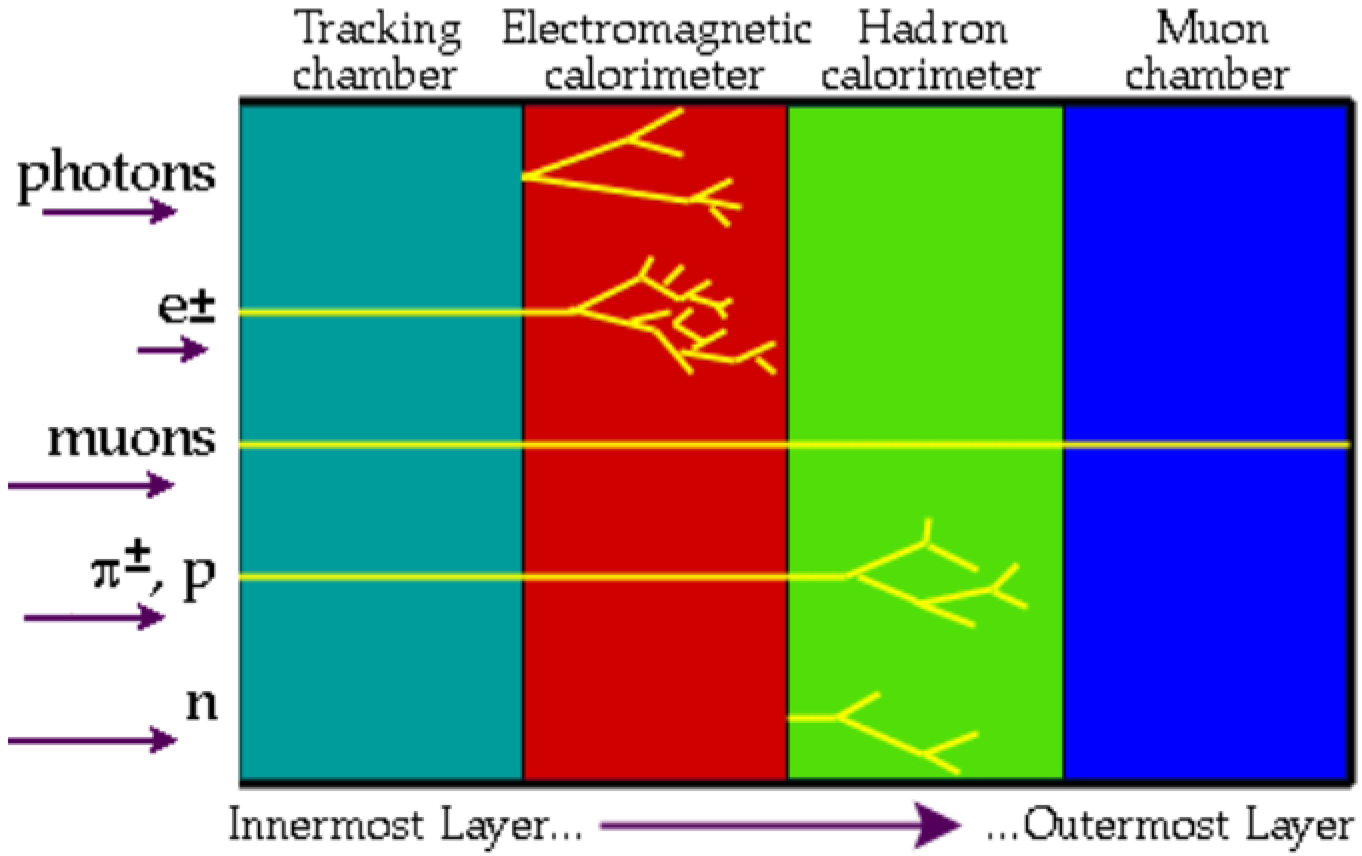


A detector (e.g. ATLAS)

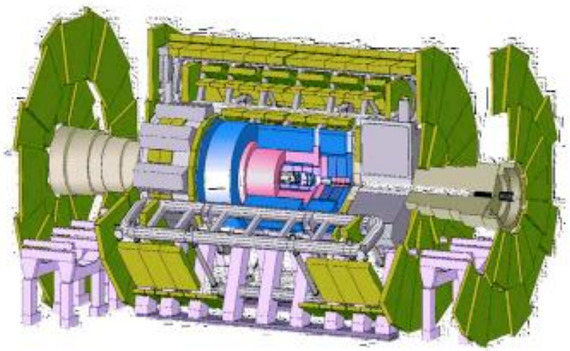


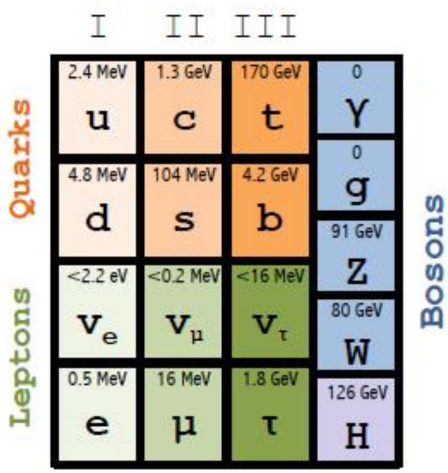
- ✓ Fast
- ✓ Granular
- ✓ Resistant to radiation

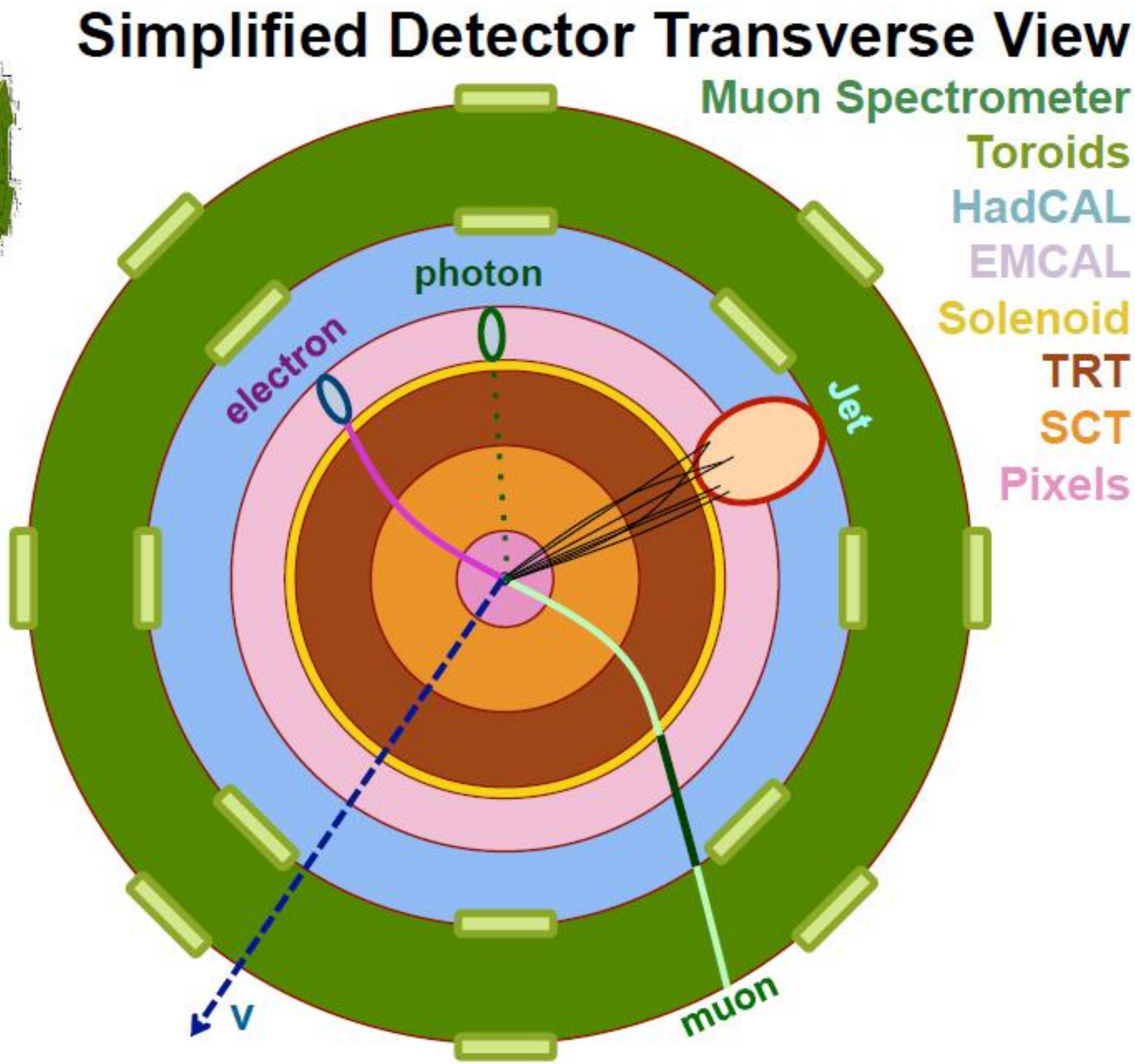
Particles through matter



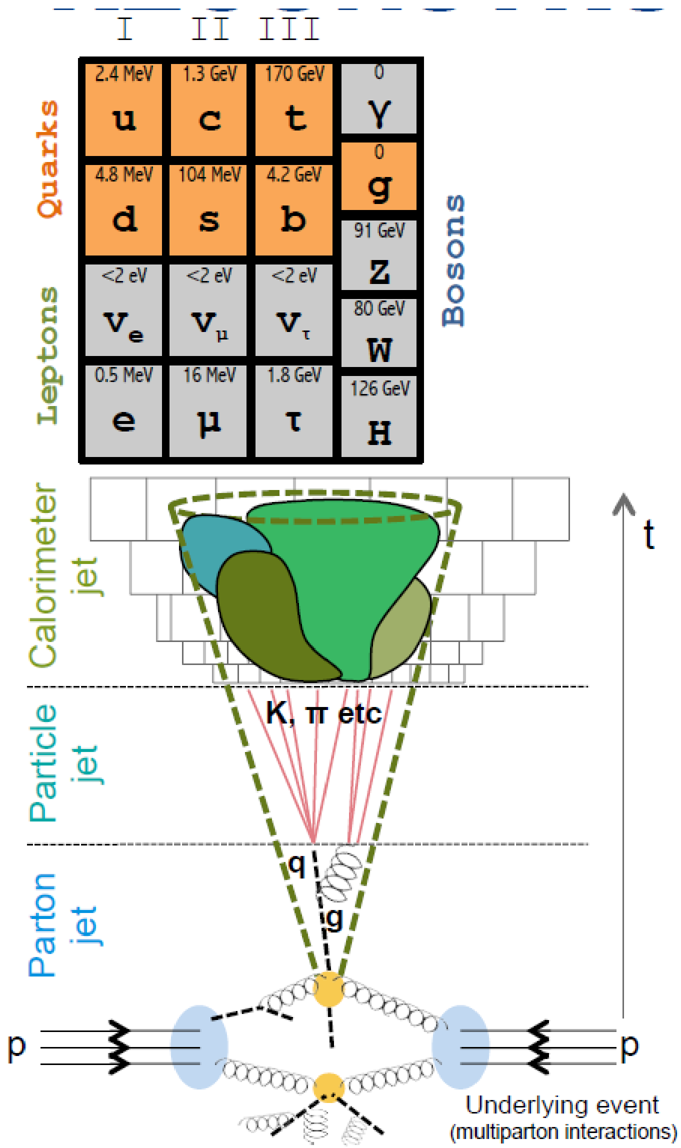
A detector (eg. ATLAS)

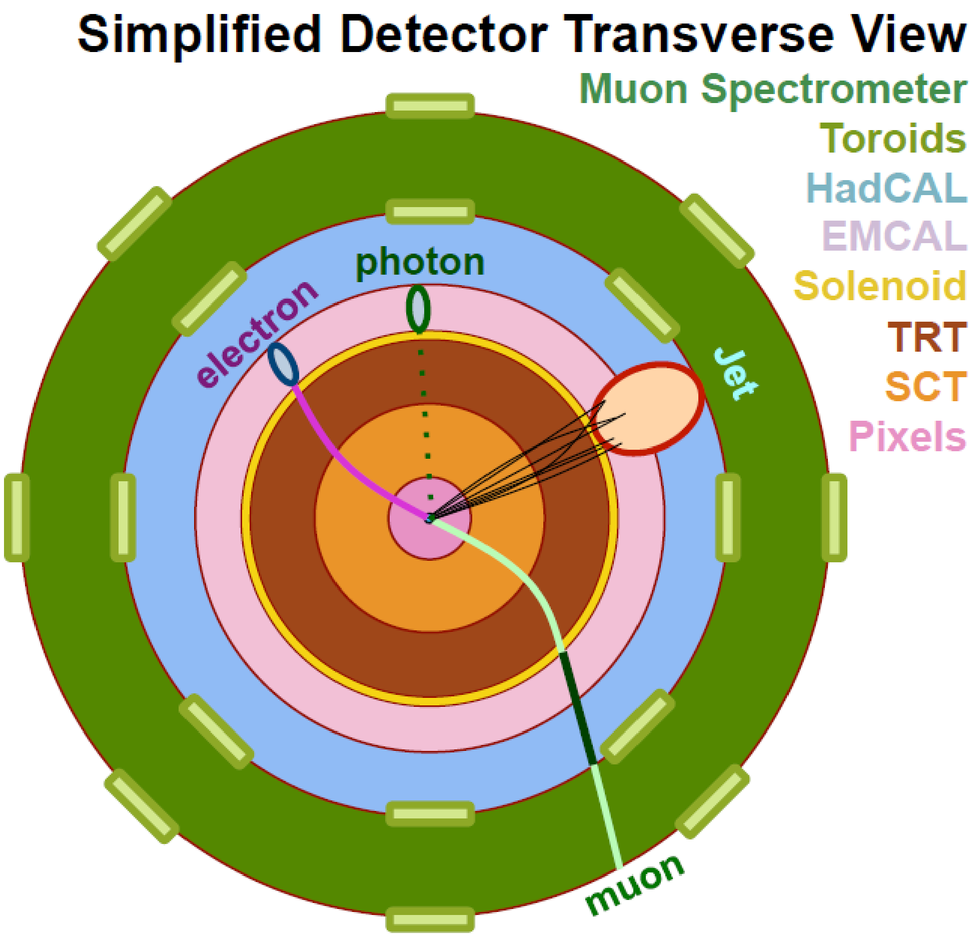




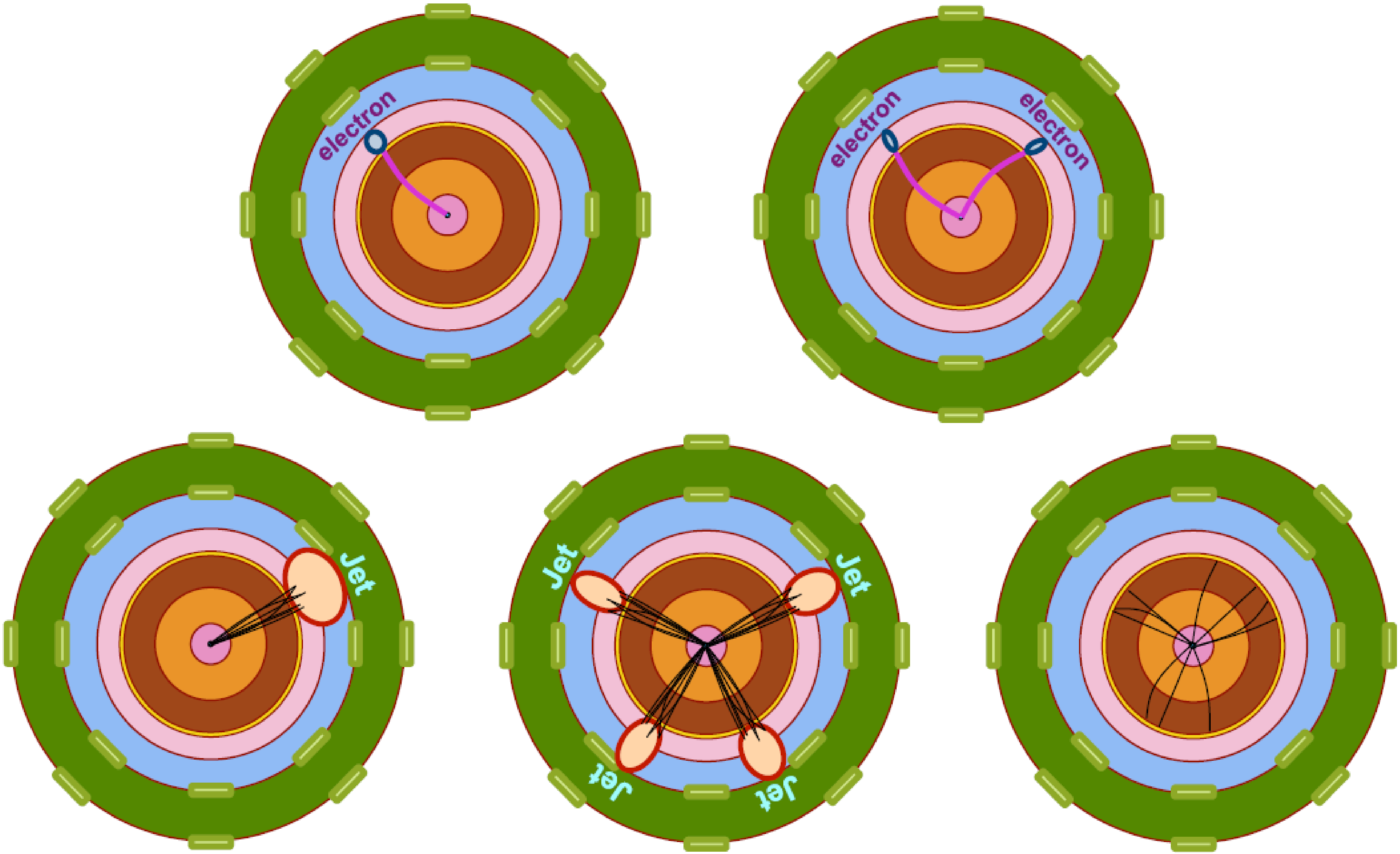


Reconstructing particles

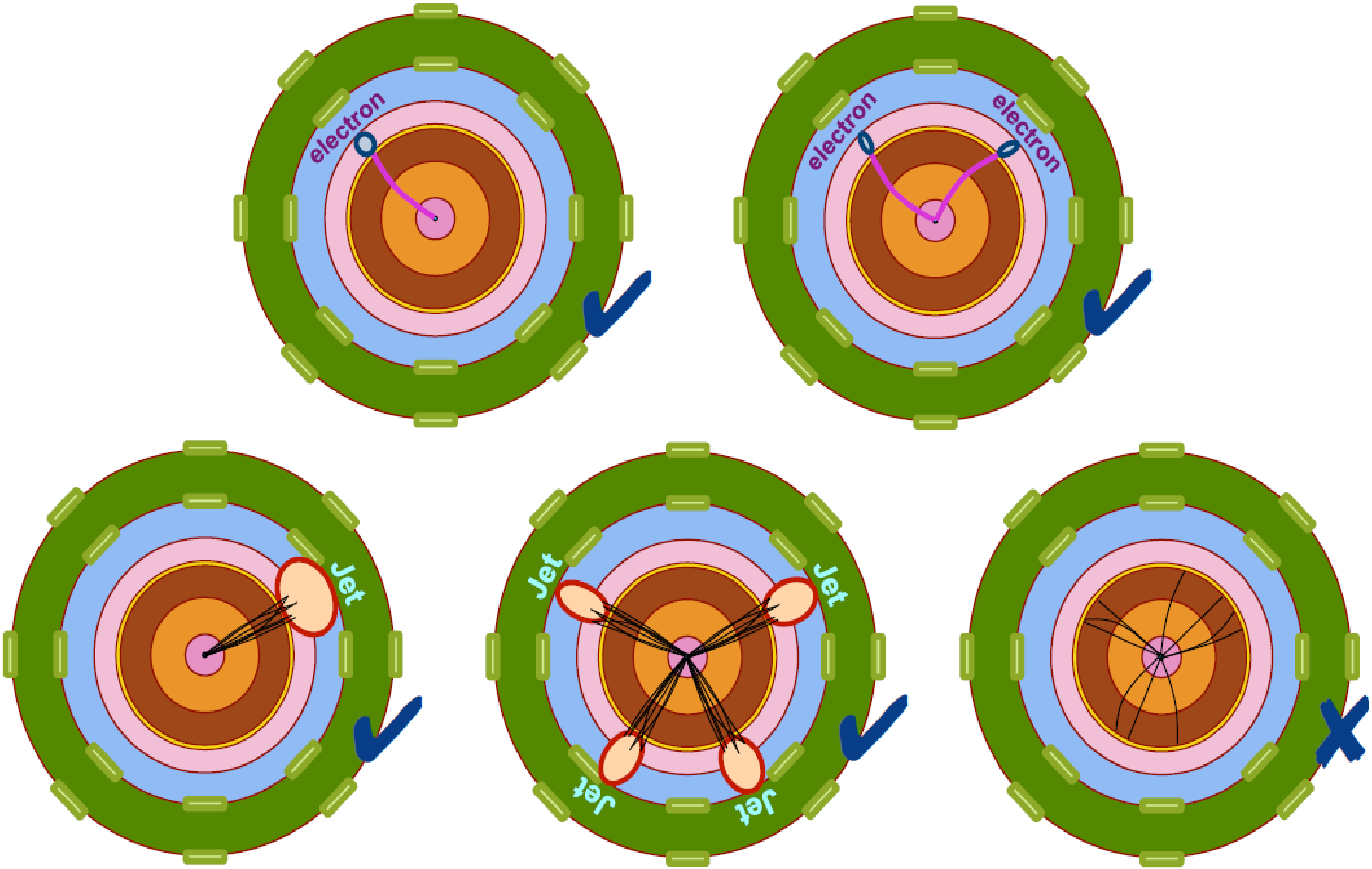




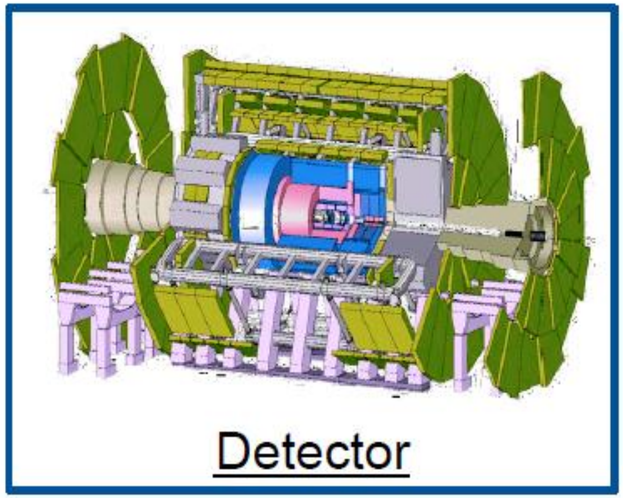
Online reconstruction



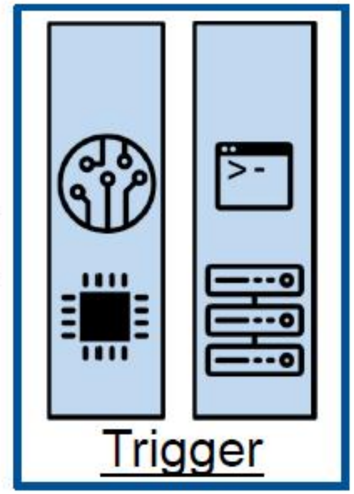
Triggering on physics



This is what raw data contain!



data to reconstruct offline!



decision plus online reconstructed objects

Streaming

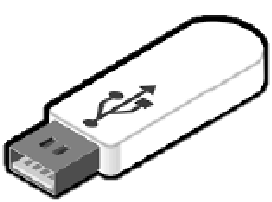
- Streaming is based on trigger decisions at all stages
- The Raw Data physics streams are generated at the HLT output level

Debug Streams
events for which a trigger decision has not been made, because of failures in parts of the online system

Physics Streams
data for physics analyses

Express Stream
full events for fast reconstruction

Calibration Streams
events delivering the minimum amount of information for detector calibrations at high rate

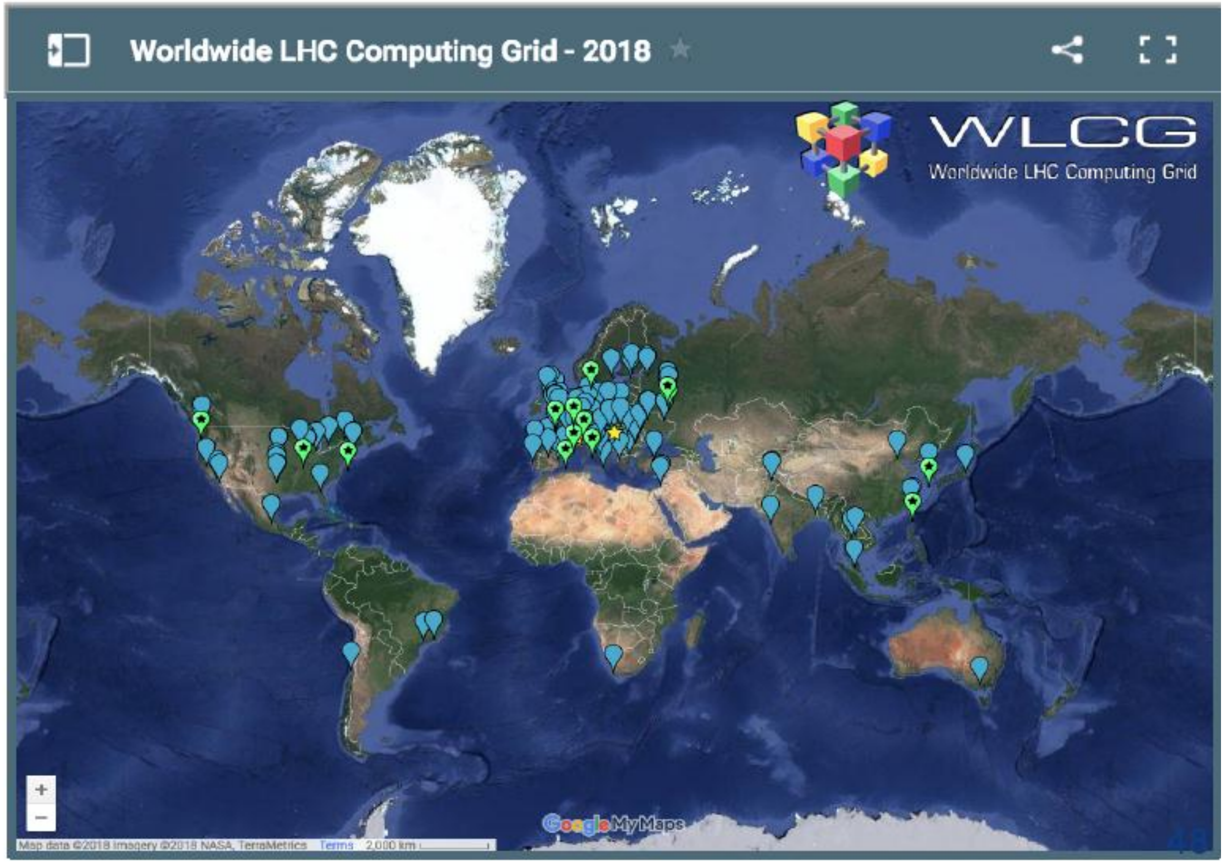


Huge amount of data …

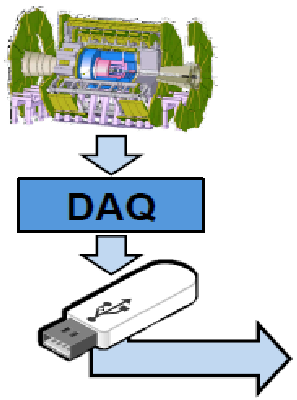
LHC delivered billions of recorded collision events to the LHC experiments from proton-proton and proton-lead collisions so far. This translates to many 100s PB of data recorded at CERN.

In 2018 alone,
50 PB of data

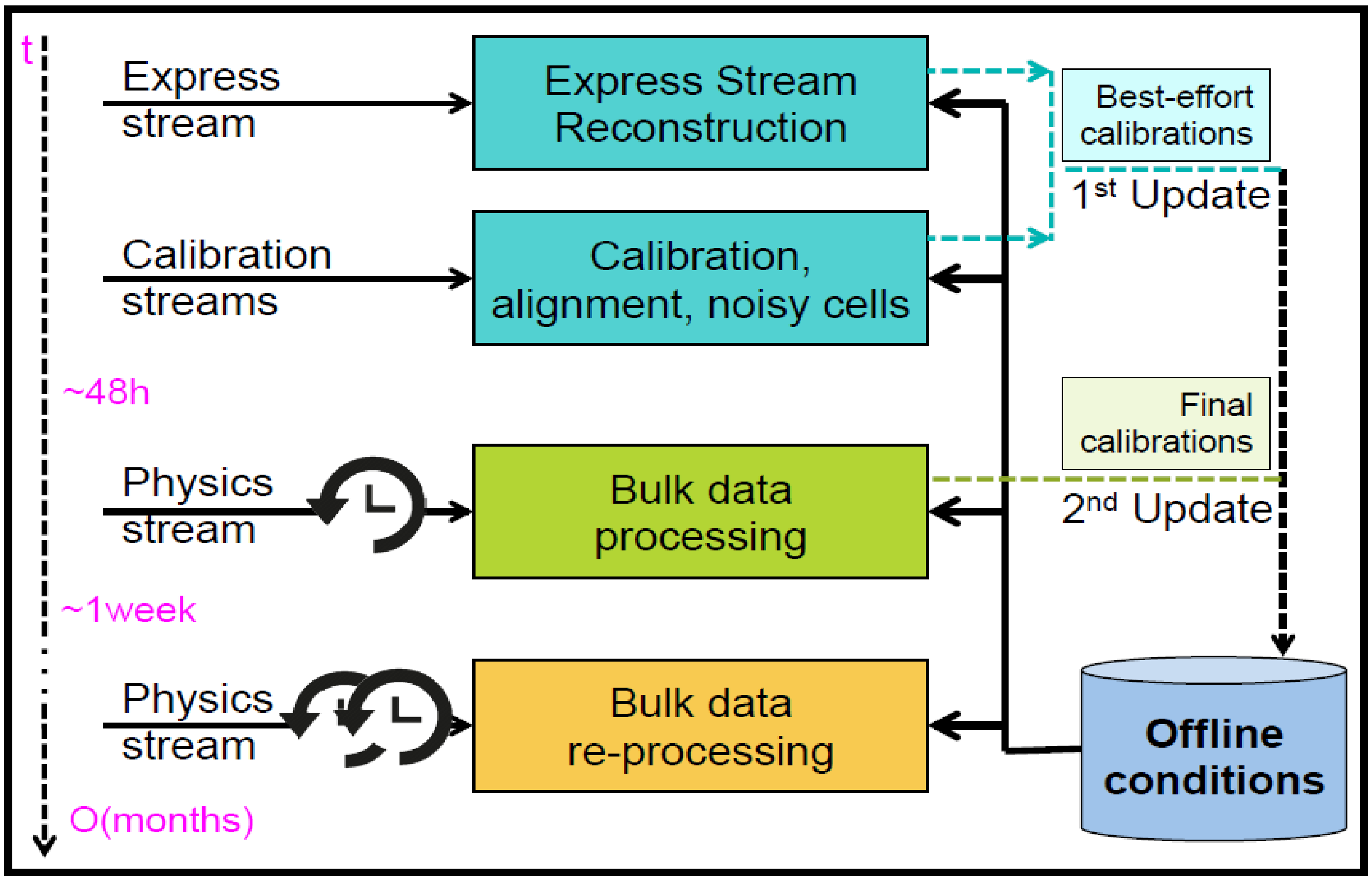
The challenge how to process and analyze the data and produce timely physics results was substantial but in the end resulted in a great success.



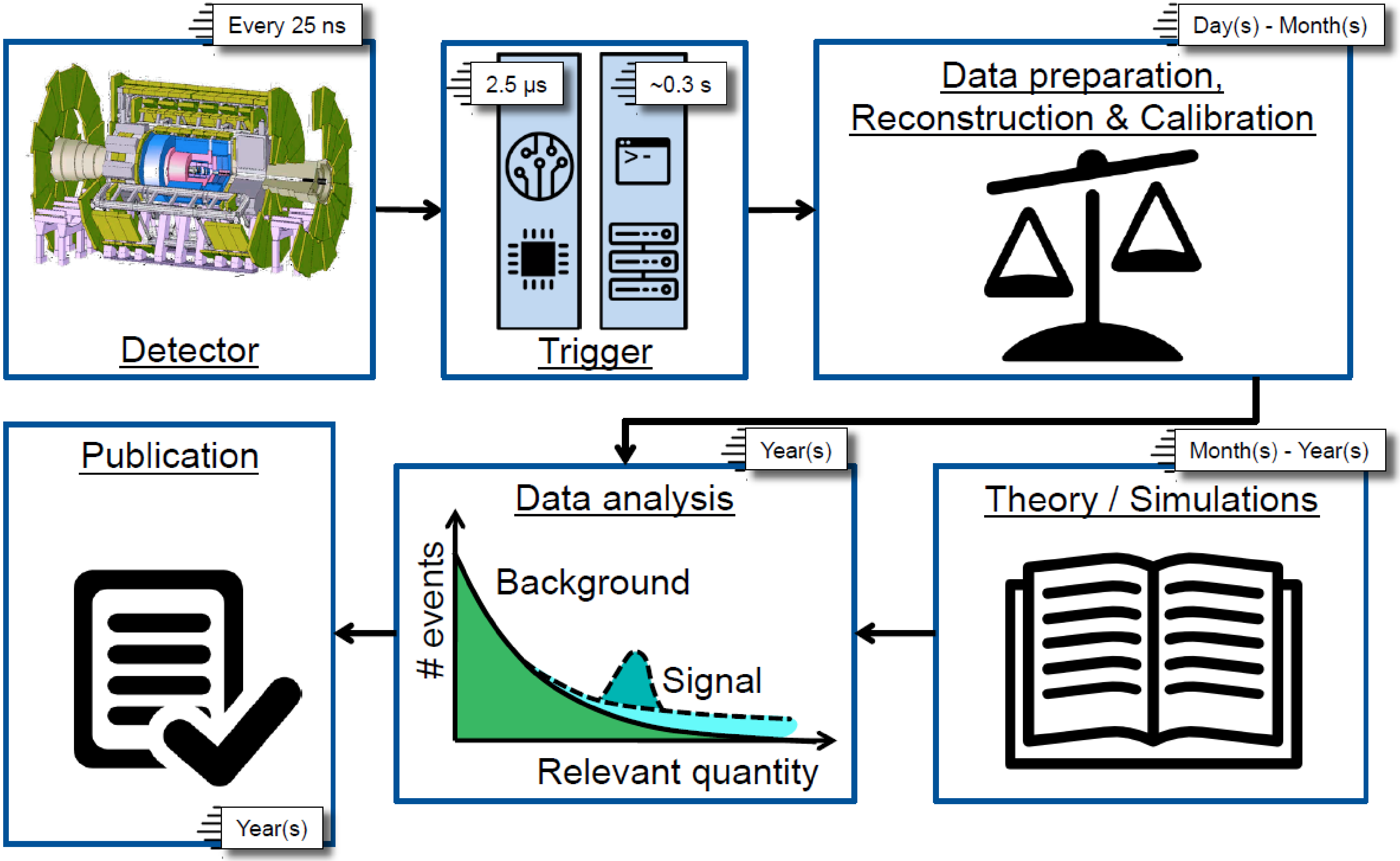
Huge amount of data …



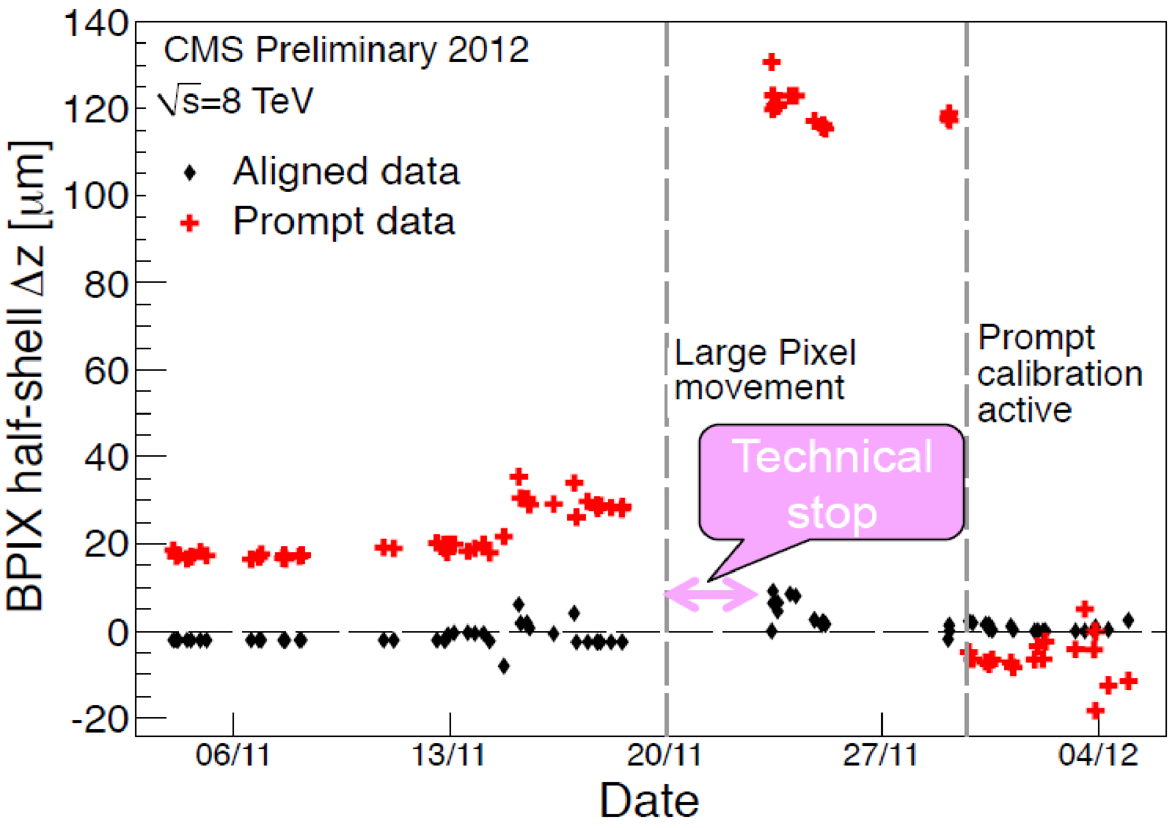
THE EVENT AT TIER0



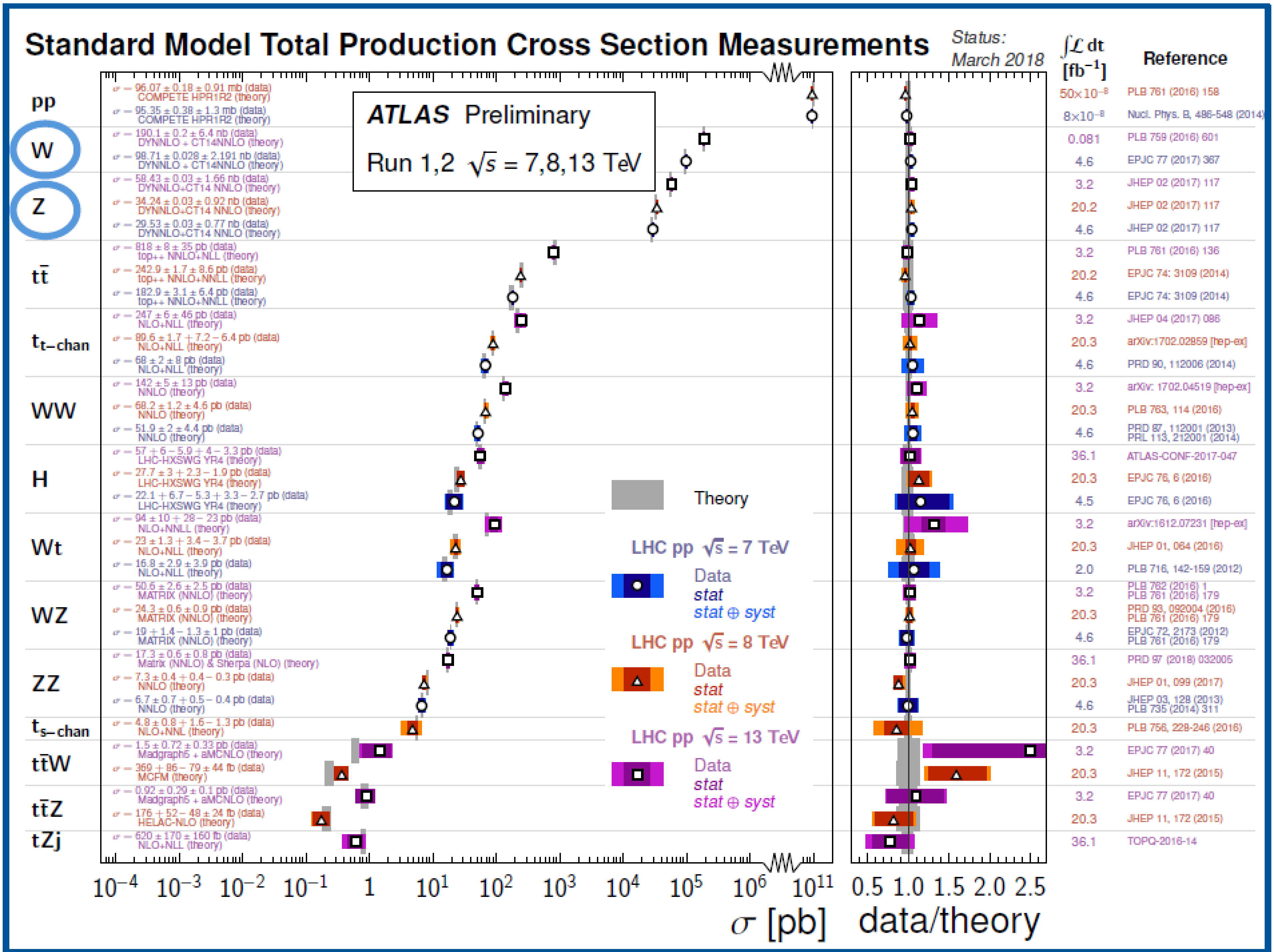
An event’s lifetime



EG. alignment



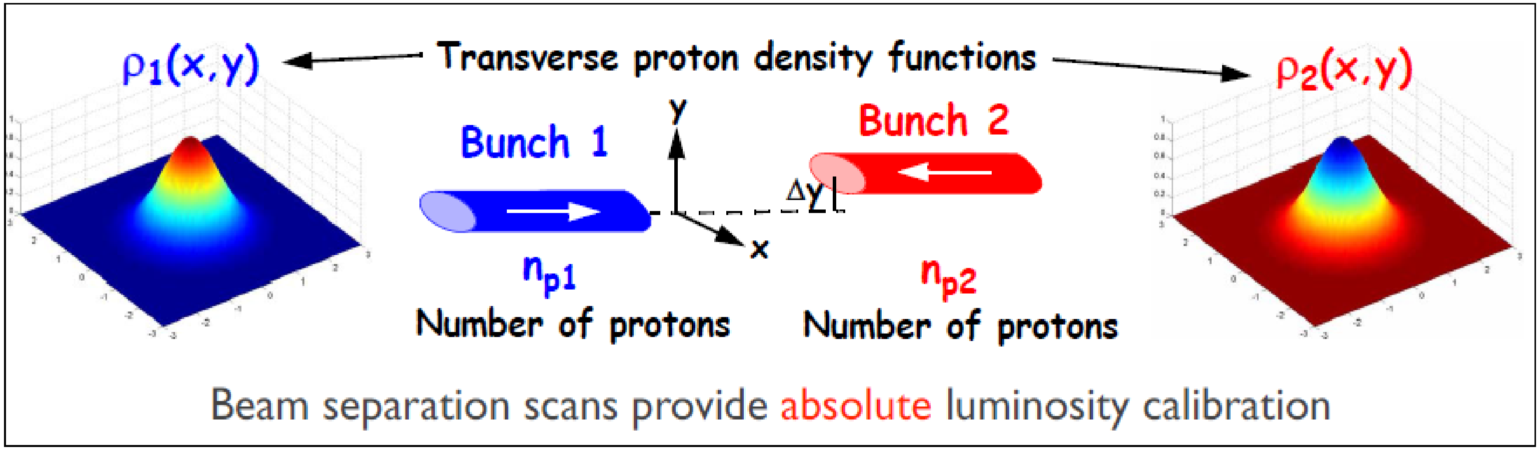
Day-by-day value of the relative longitudinal shift between the two half-shells of the BPIX as measured with the primary vertex residuals, for the last month of pp data taking in 2012.



Standard Model Total Production Cross Section Measurements
Status: March 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
pp
W
Z
tt̄
t t−chan
WW
H
Wt
WZ
ZZ
t s−chan
tt̄W
tt̄Z
tZj
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
σ [pb]
data/theory
∫ℒ dt [fb⁻¹]
Reference
50×10⁻⁸ PLB 761 (2016) 158
8×10⁻⁸ Nucl. Phys. B, 486-548 (2014)
0.081 PLB 759 (2016) 601
4.6 EPJC 77 (2017) 367
3.2 JHEP 02 (2017) 117
20.2 JHEP 02 (2017) 117
4.6 JHEP 02 (2017) 117
3.2 PLB 761 (2016) 136
20.2 EPJC 74: 3109 (2014)
4.6 EPJC 74: 3109 (2014)
3.2 JHEP 04 (2017) 086
20.3 arXiv:1702.02859 [hep-ex]
4.6 PRD 90, 112006 (2014)
3.2 arXiv: 1702.04519 [hep-ex]
20.3 PLB 763, 114 (2016)
4.6 PRD 87, 112001 (2013) PRL 113, 212001 (2014)
36.1 ATLAS-CONF-2017-047
20.3 EPJC 76, 6 (2016)
4.5 EPJC 76, 6 (2016)
3.2 arXiv:1612.07231 [hep-ex]
20.3 JHEP 01, 064 (2016)
2.0 PLB 716, 142-159 (2012)
3.2 PLB 762 (2016) 1 PLB 761 (2016) 179
20.3 PRD 93, 092004 (2016) PLB 761 (2016) 179
4.6 EPJC 72, 2173 (2012) PLB 761 (2016) 179
36.1 PRD 97 (2018) 032005
20.3 JHEP 01, 099 (2017)
4.6 JHEP 03, 128 (2013) PLB 735 (2014) 311
20.3 PLB 756, 228-246 (2016)
3.2 EPJC 77 (2017) 40
20.3 JHEP 11, 172 (2015)
3.2 EPJC 77 (2017) 40
20.3 JHEP 11, 172 (2015)
36.1 TOPQ-2016-14

Luminosity determination

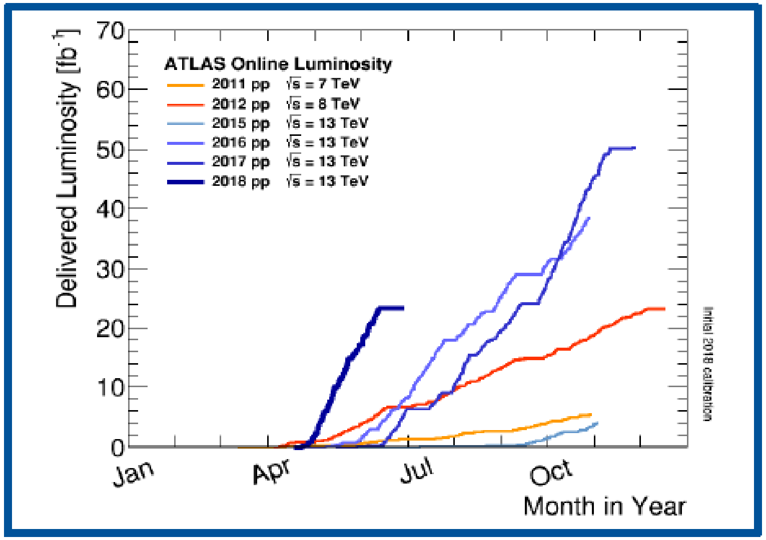
- A measurement of the number of collisions per cm^2 and second.
- Multiple methods used for determining luminosity: reducing uncertainties.
- Normalization is done with beam-separation scan (Van-der-Meer scan). Requires careful control of beam parameters.

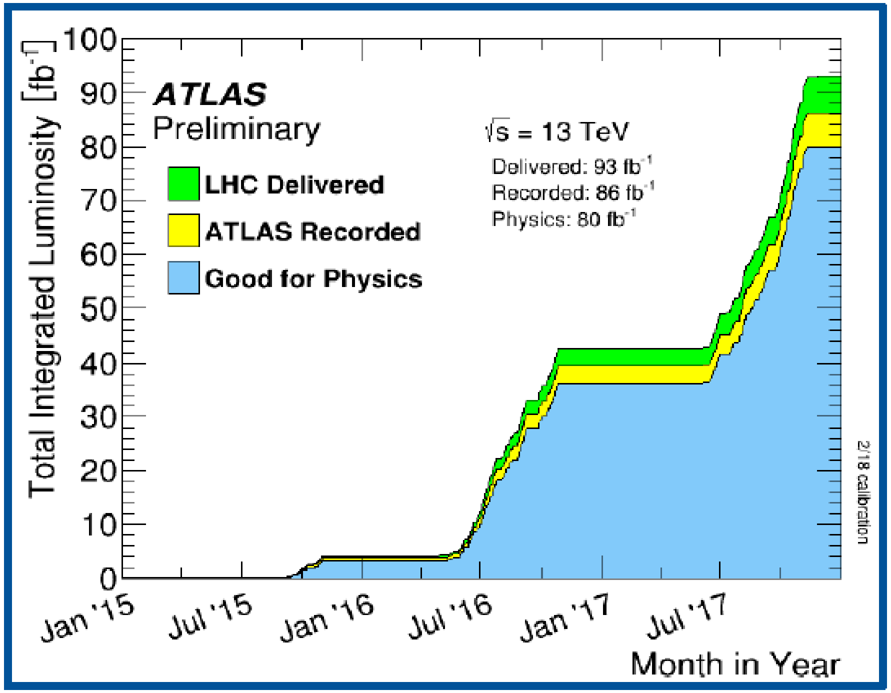


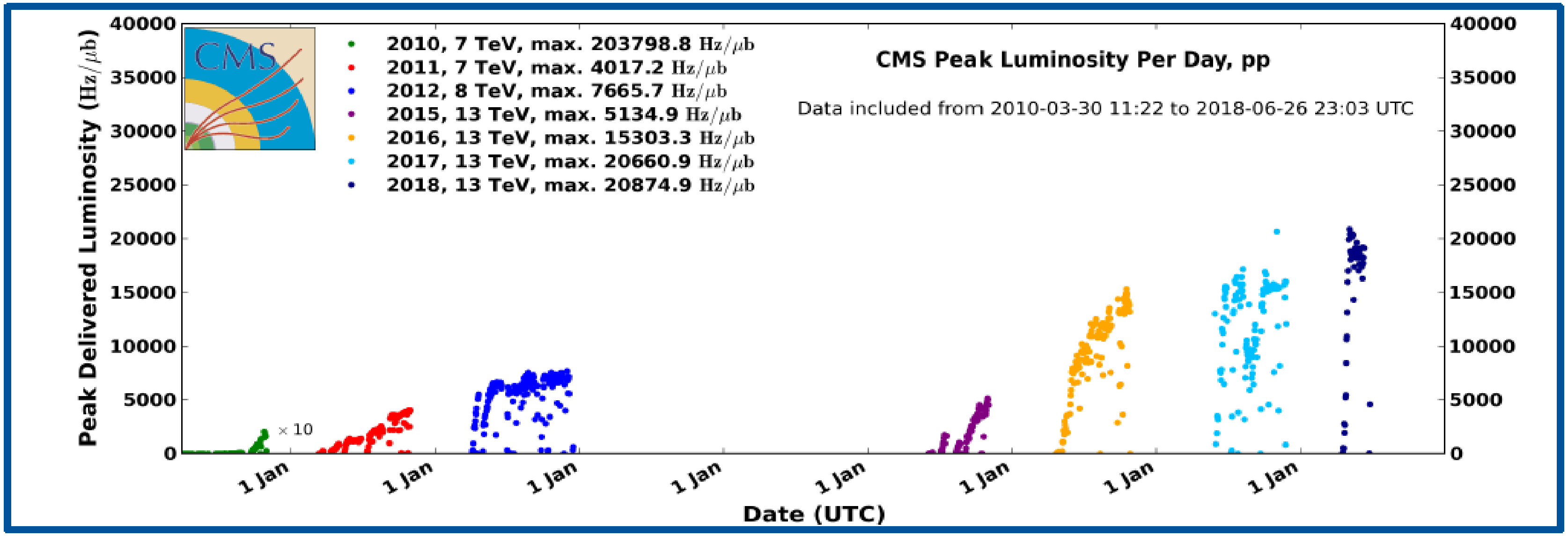
From http://cds.cern.ch/record/1490292/files/ATL-DAPR-SLIDE-2012-627.pdf

- Result: luminosity measurement with very small uncertainties (order of few %) with very fast turn-around time.

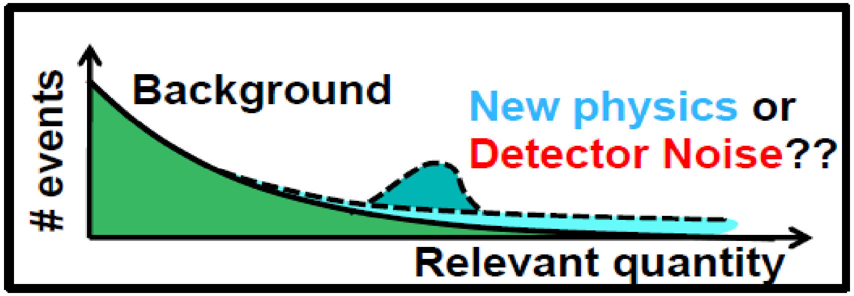
LUMINOSITY


ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
Delivered Luminosity [fb⁻¹]
Jan
Apr
Jul
Oct
Month in Year
Initial 2018 calibration


ATLAS
Preliminary
√s = 13 TeV
Delivered: 93 fb⁻¹
Recorded: 86 fb⁻¹
Physics: 80 fb⁻¹
LHC Delivered
ATLAS Recorded
Good for Physics
Total Integrated Luminosity [fb⁻¹]
Jan '15
Jul '15
Jan '16
Jul '16
Jan '17
Jul '17
Month in Year
2/18 calibration


CMS Peak Luminosity Per Day, pp
Data included from 2010-03-30 11:22 to 2018-06-26 23:03 UTC
2010, 7 TeV, max. 203798.8 Hz/μb
2011, 7 TeV, max. 4017.2 Hz/μb
2012, 8 TeV, max. 7665.7 Hz/μb
2015, 13 TeV, max. 5134.9 Hz/μb
2016, 13 TeV, max. 15303.3 Hz/μb
2017, 13 TeV, max. 20660.9 Hz/μb
2018, 13 TeV, max. 20874.9 Hz/μb
Peak Delivered Luminosity (Hz/μb)
× 10
1 Jan
Date (UTC)

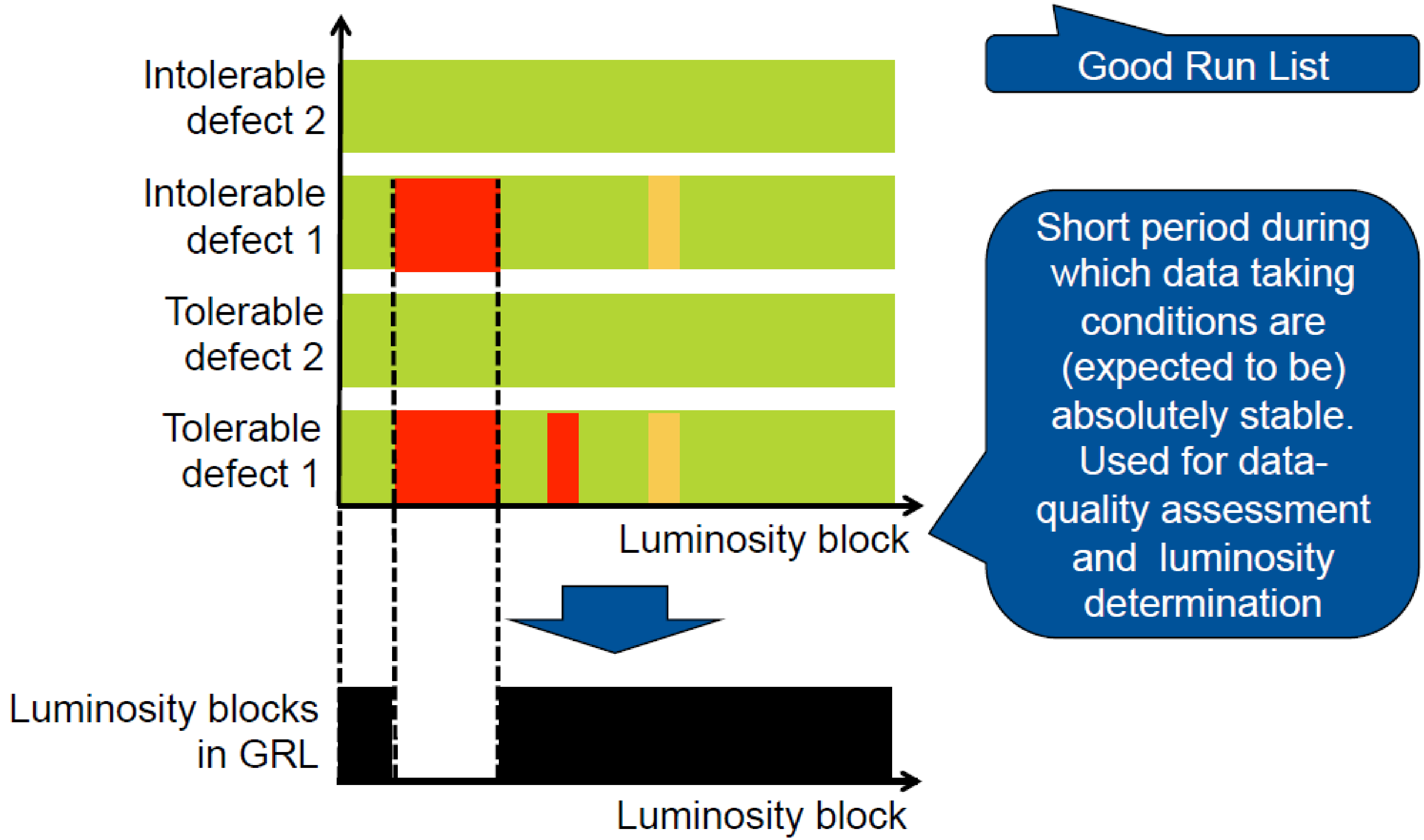
Data quality



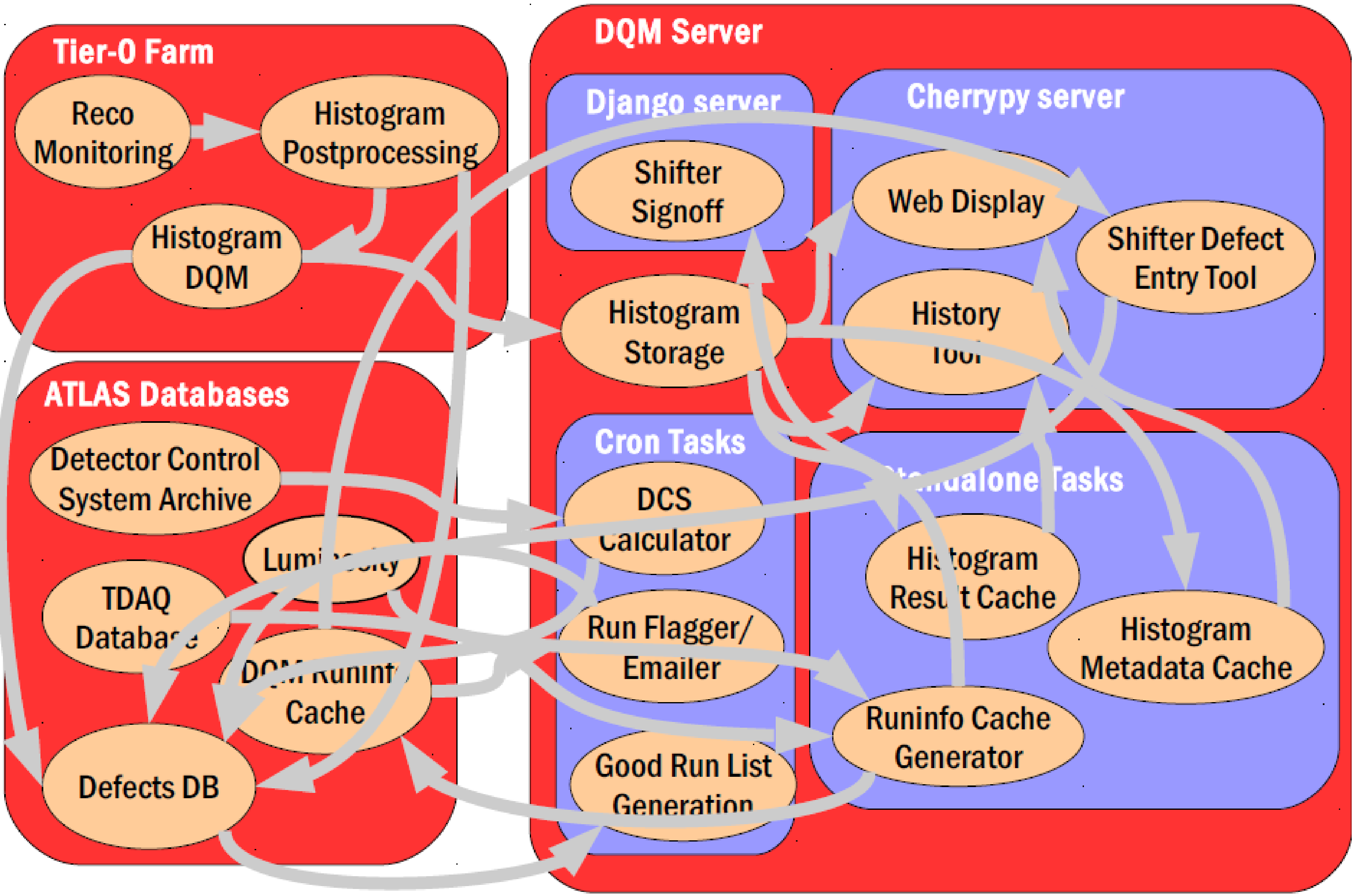
The data we analyze has to follow norms of quality such that our results are trustable.

- **Online: Fast monitoring of detector performance during data taking, using dedicated stream, "express stream".**
- **Offline: More thorough monitoring at two instances:**
  - Express reconstruction; fast turn-around.
  - Prompt reconstruction: larger statistics.
- **What is monitored?**
  - Noise in the detector.
  - Reconstruction (tracks, clusters, combined objects, resolution and efficiency).
  - Input rate of physics.
  - All compared to reference histograms of data that has been validated as "good".

Data quality and „GRL”

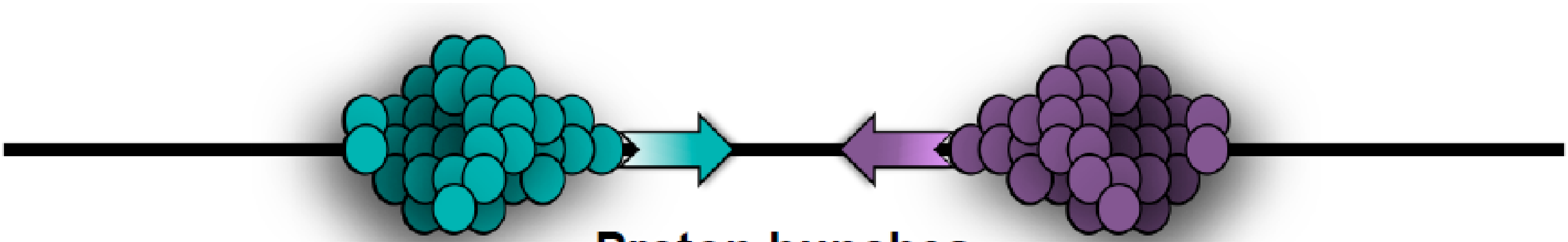


Data quality

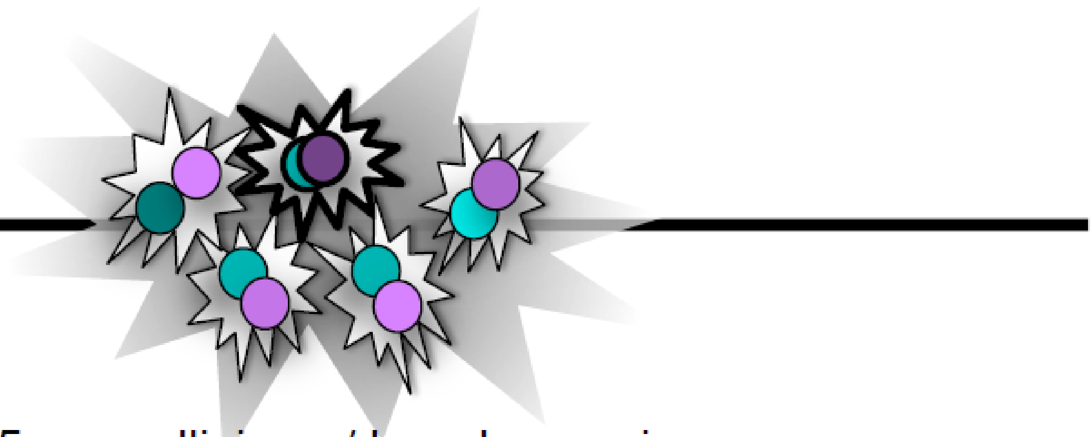


https://cds.cern.ch/record/2008725/files/ATL-SOFT-SLIDE-2015-179.pdf

Pile-up

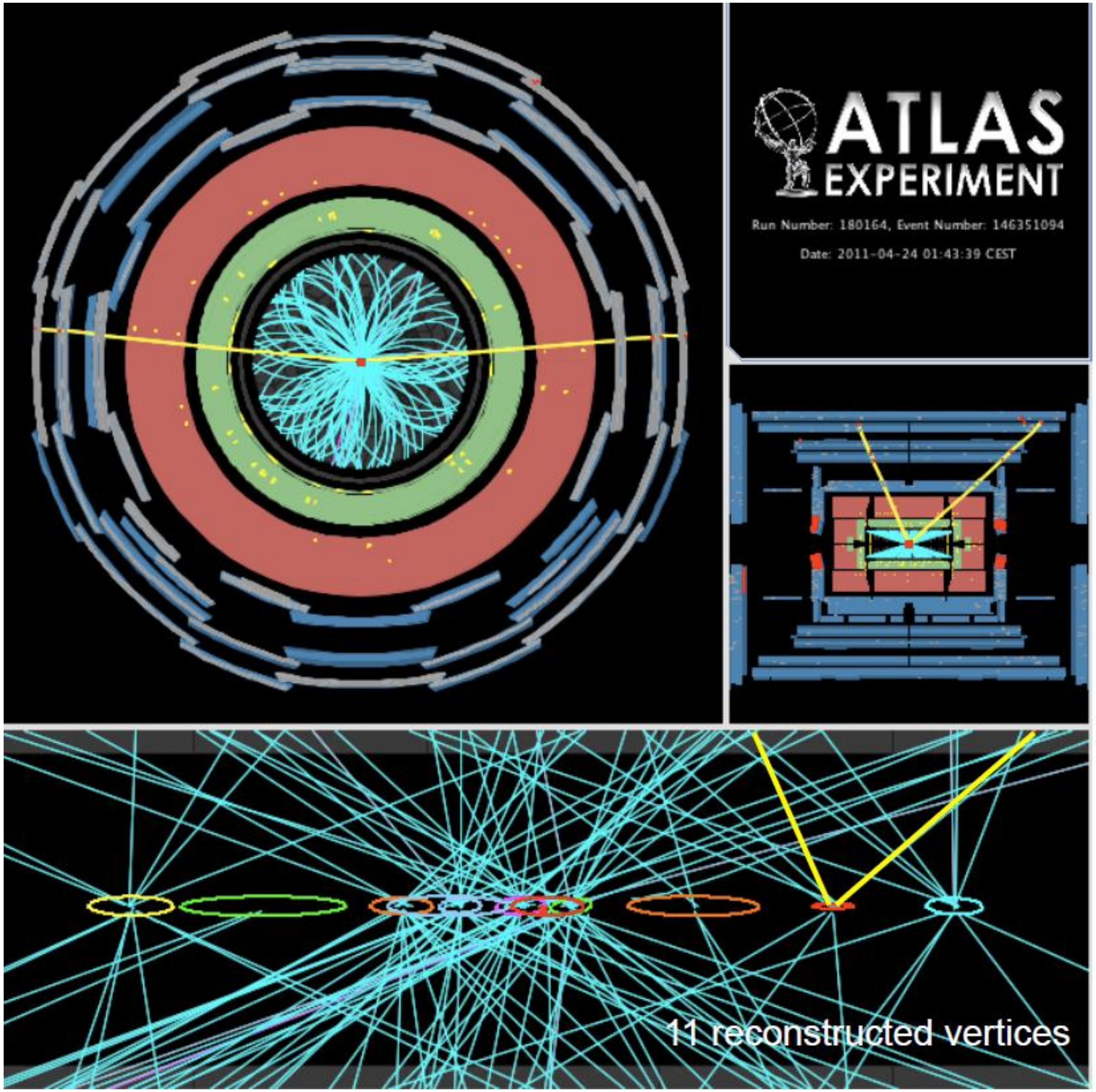


Proton bunches
>10^{11} protons/bunch
(colliding at ~**30MHz in run2)**



~25 p-p collisions / bunch crossing

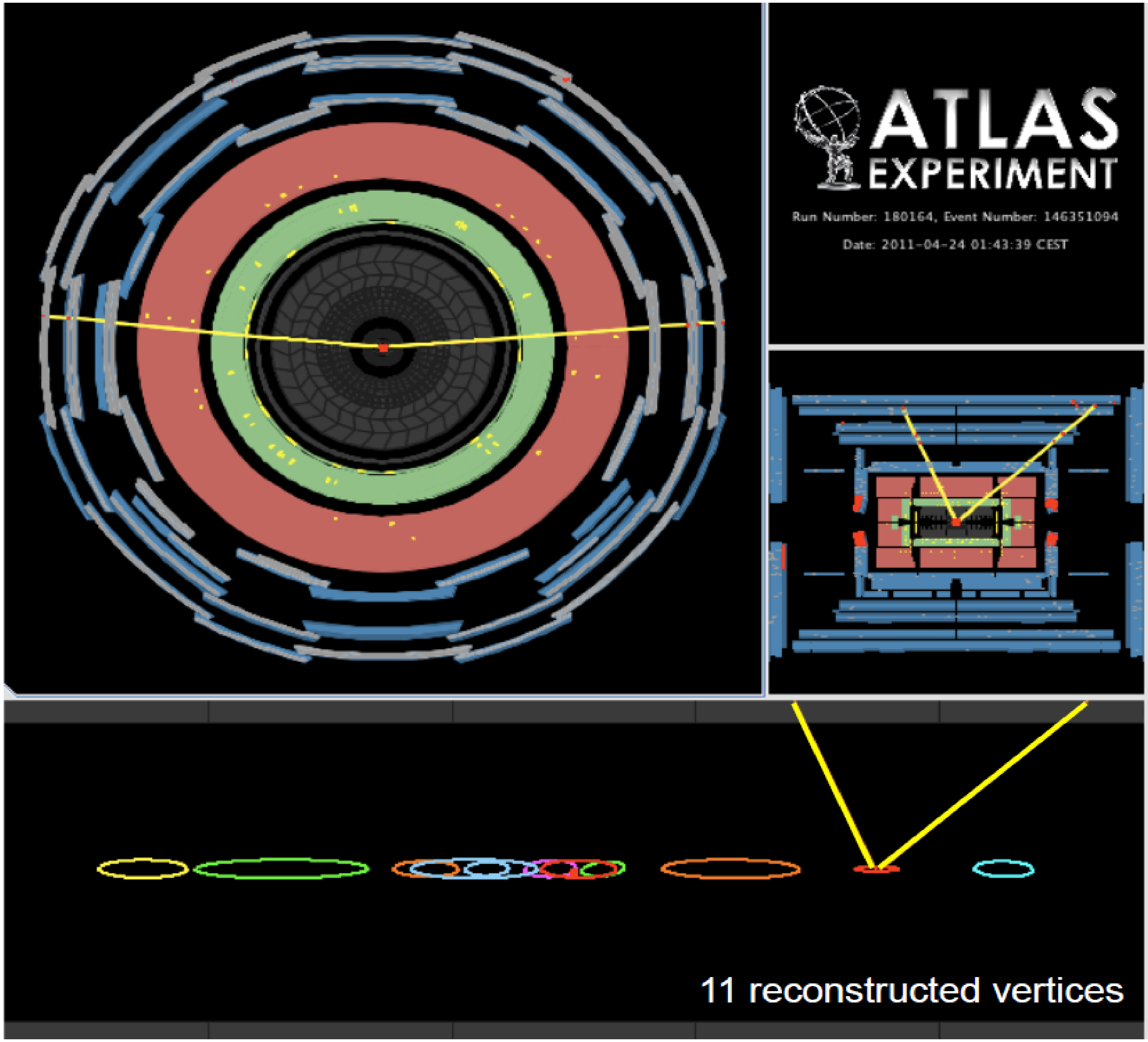
Pile-up



Z->μμ event;
2011 data.

Track pT > 0.5 GeV

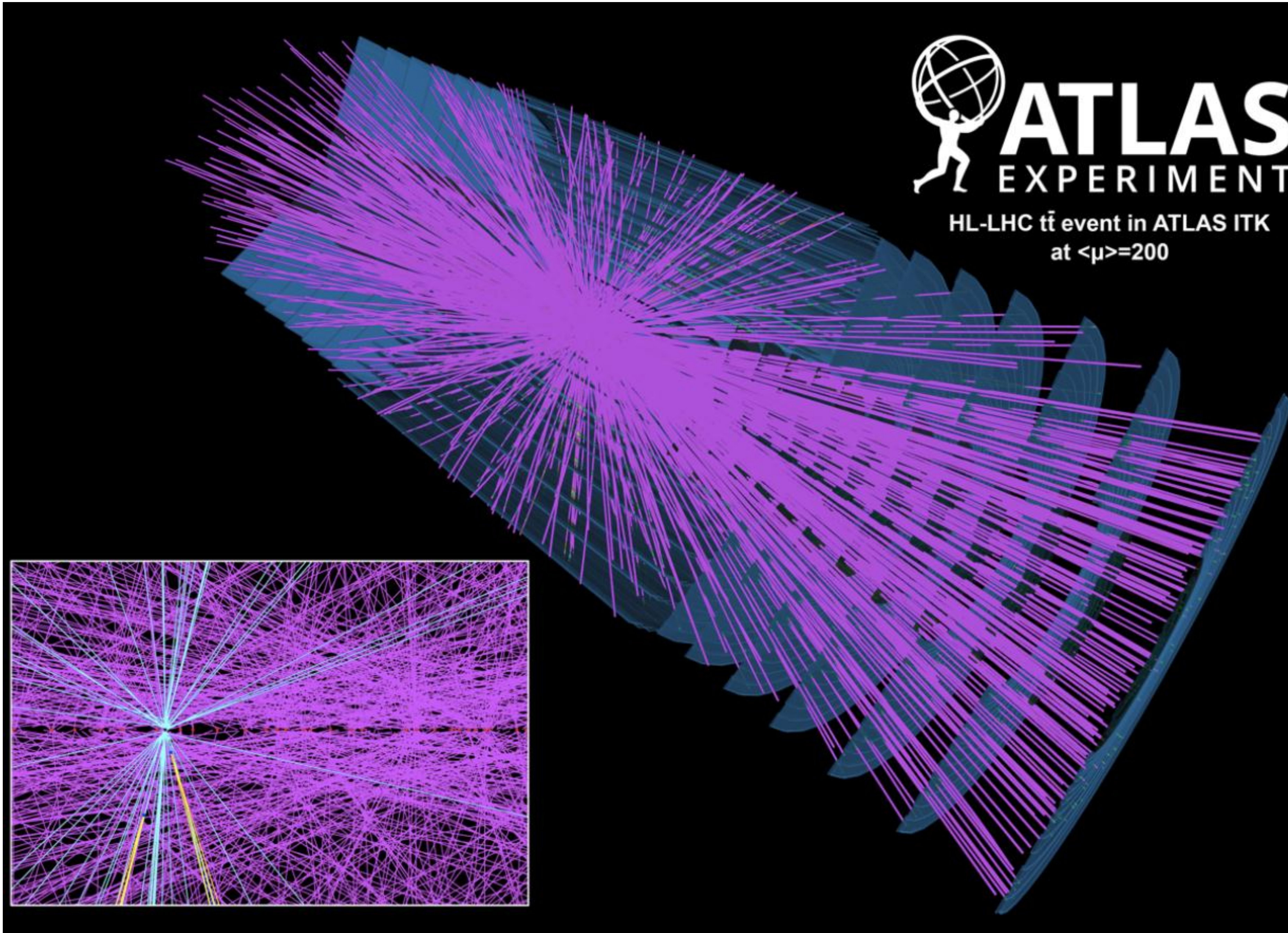
Pile-up



Z->μμ event;
2011 data.

Track pT > 10 GeV

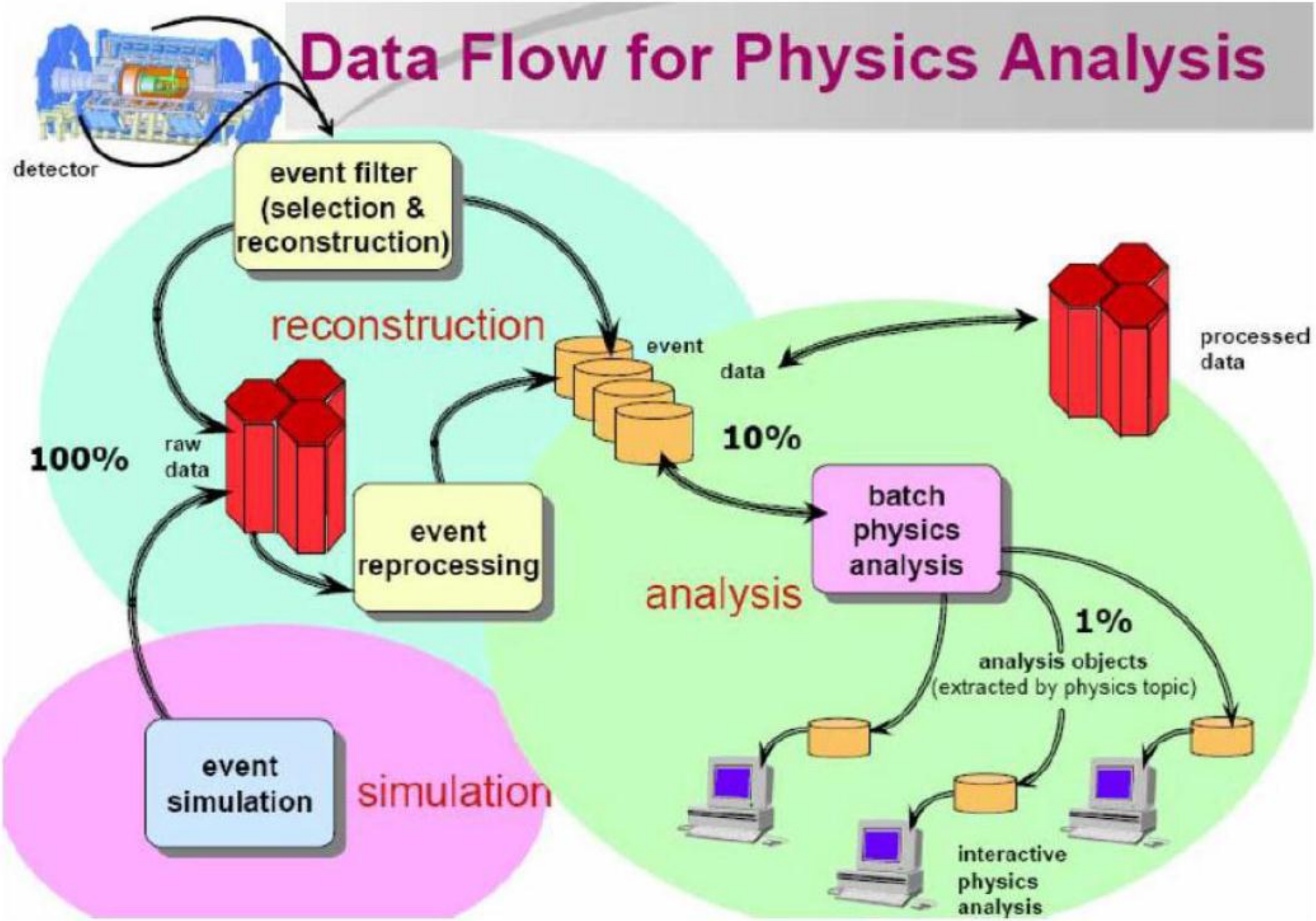
50


ATLAS
EXPERIMENT
HL-LHC tt̄ event in ATLAS ITK
at <μ>=200

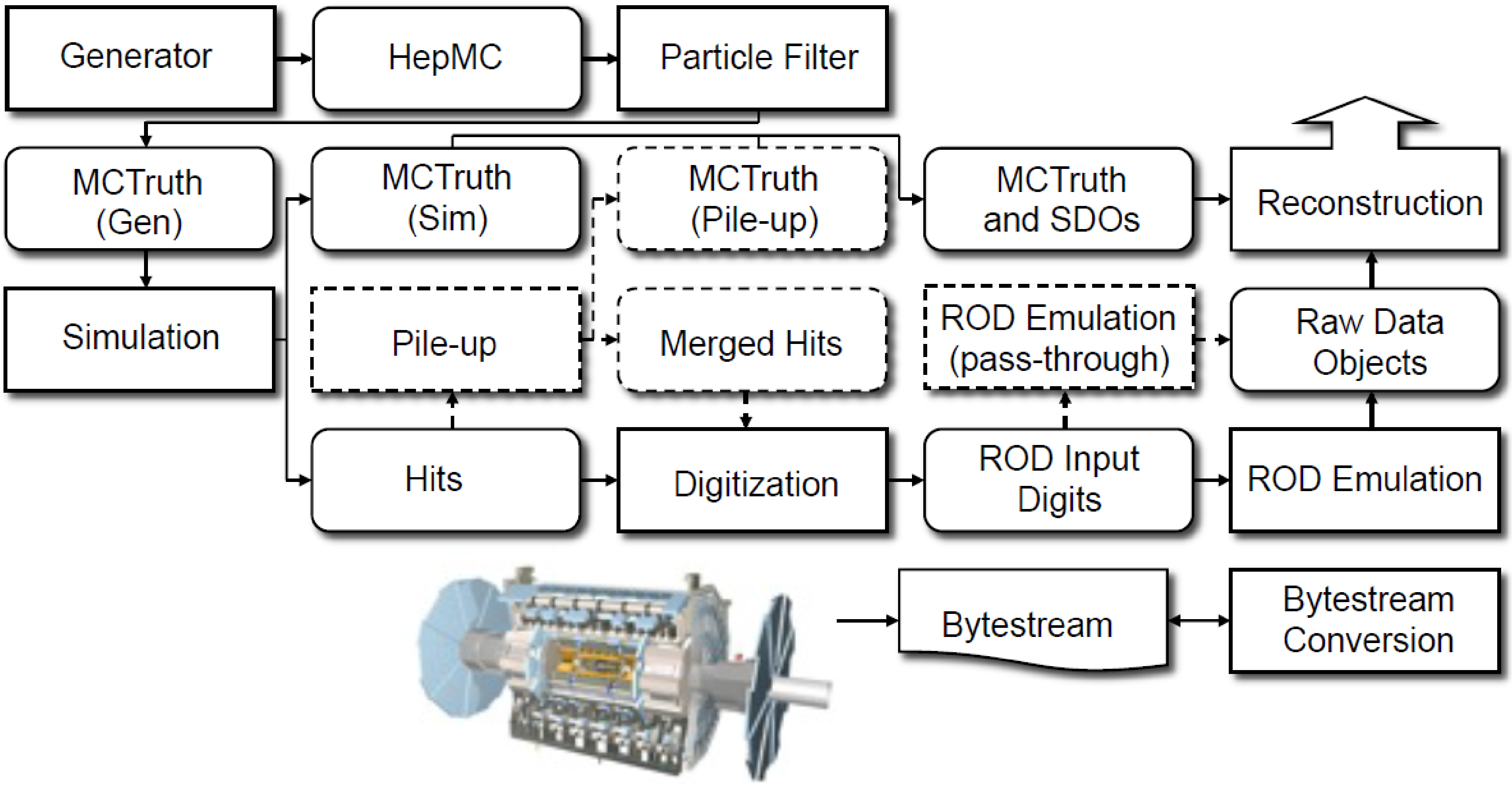
Monte Carlo simulation – why?

- **We only build one detector.**
  - How do we compromise physics due to detector design?
  - How would a different detector design affect measurements?
  - How does the detector behave to radiation?
- **In the detectors we only measure voltages, currents, times.**
  - It's an *interpretation* to say that such-and-such particle caused such-and-such signature in the detector.
  - Simulating the detector behavior we correct for inefficiencies, inaccuracies, unknowns.
- **We need a theory to tell us what we expect and to compare our data against.**
- **A good simulation is the way to demonstrate to the world that we understand the detectors and the physics we are studying.**

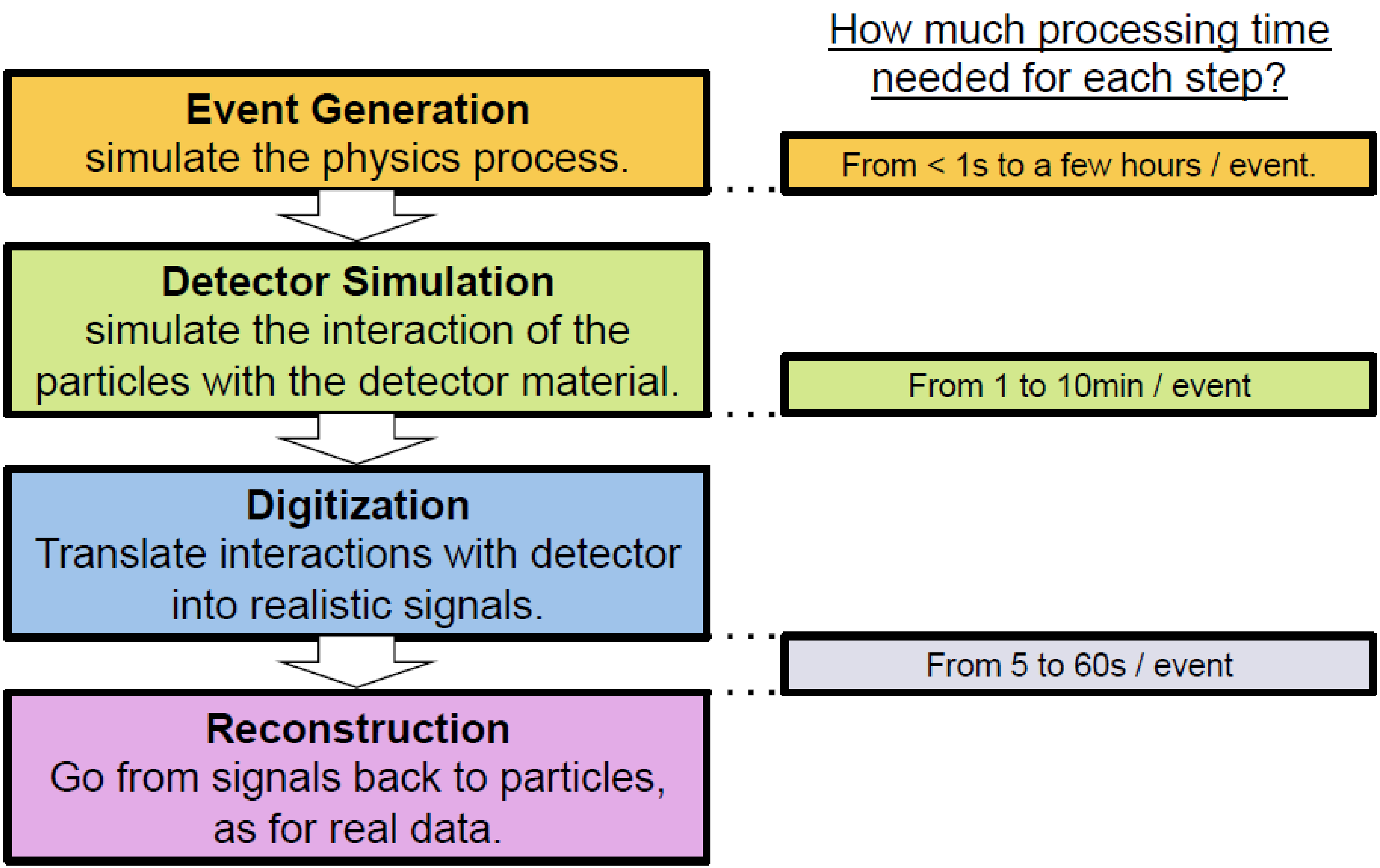
Data Flow for Physics Analysis



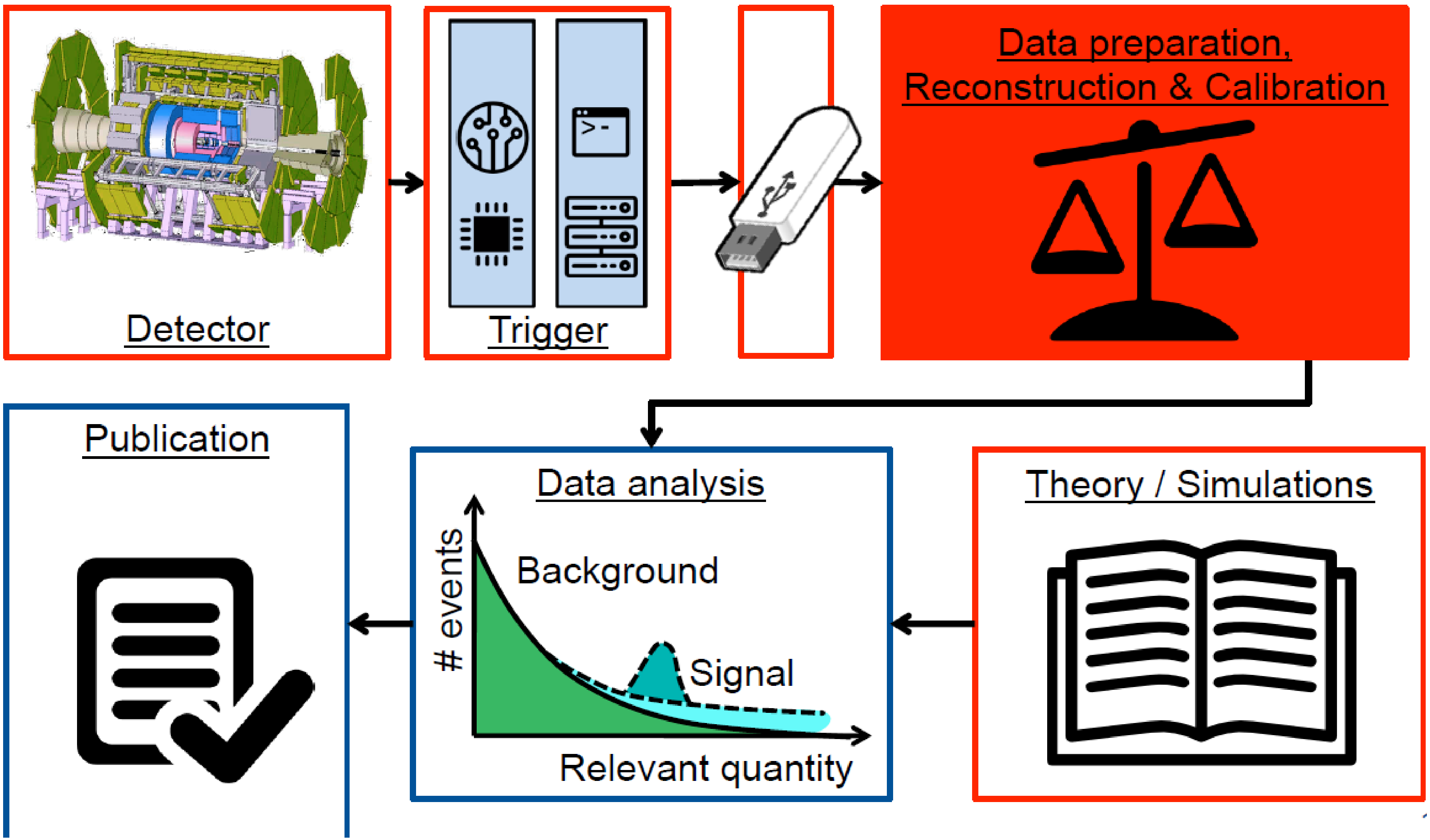
LHC simulation chain



Monte Carlo production chain



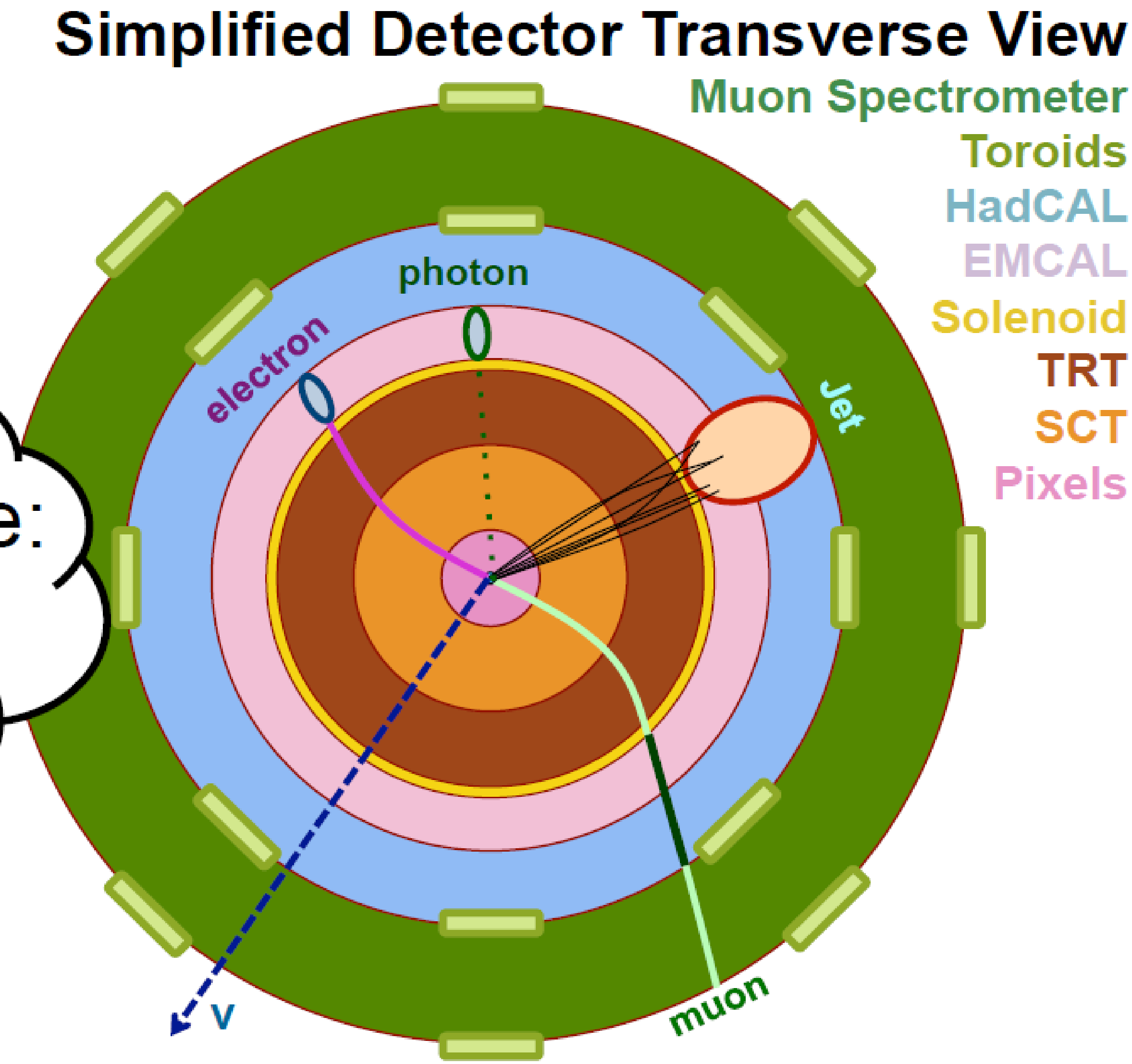
An event's lifetime



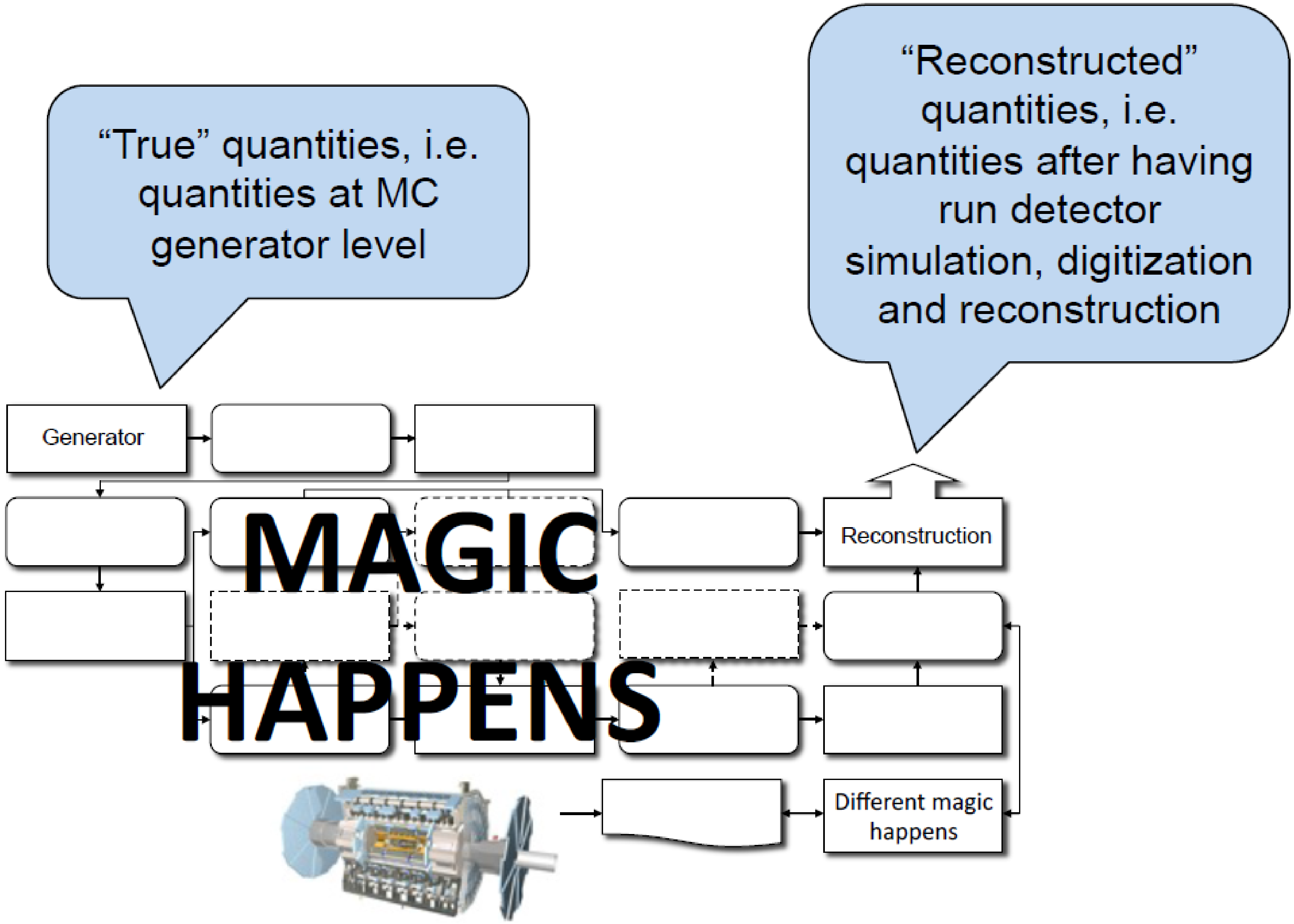
What do we reconstruct?

Tracks and Clusters

Combining those: "**objects**" ("particles")

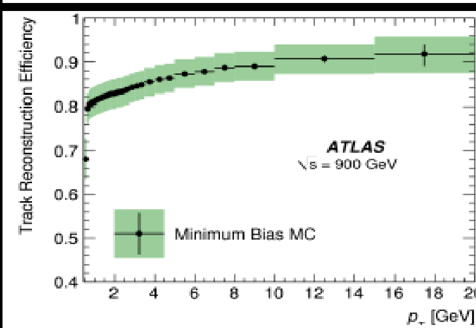
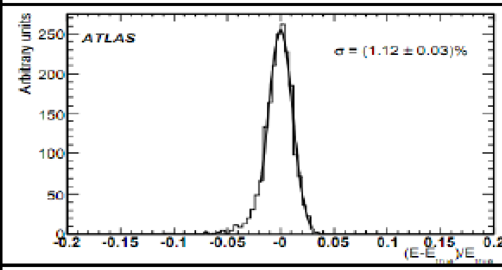
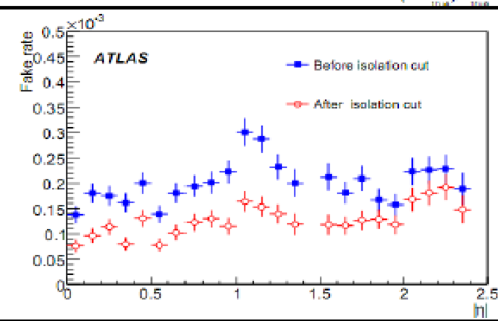


Reconstruction - figures of merit



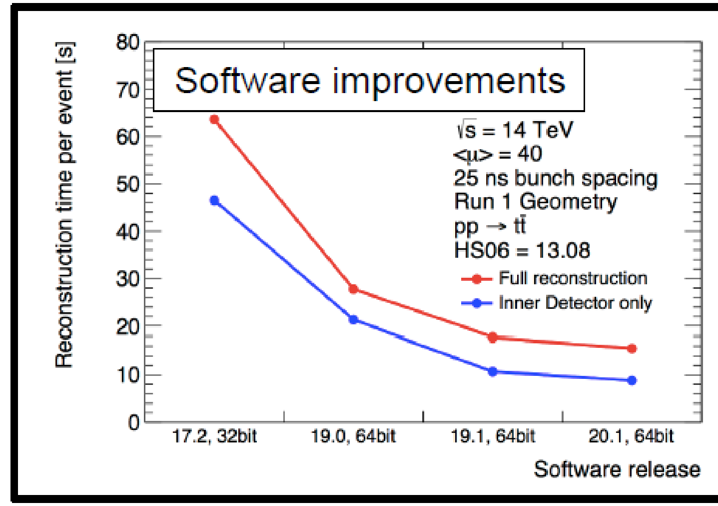
Reconstruction - figures of merit

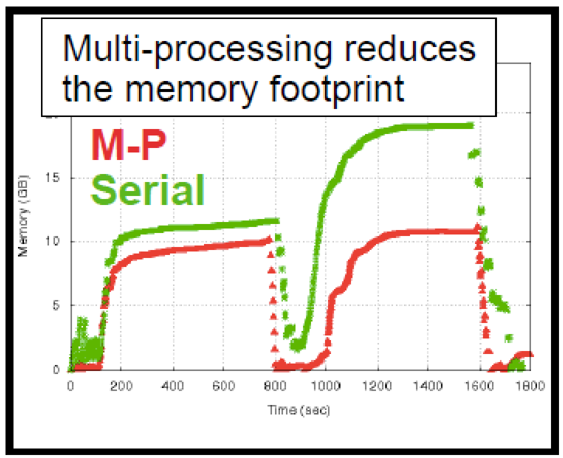
"**true**" quantity:
quantity at MC generator level.

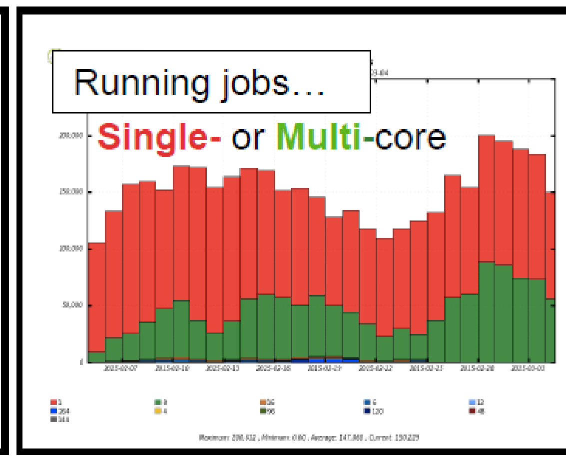
	Definition	Example		Needs be:
Efficiency	how often do we reconstruct the object	tracking efficiency = (number of reconstructed tracks) / (number of true tracks)		High
Resolution	how accurately do we reconstruct the quantity	energy resolution = (measured energy – true energy) / (true energy)		Good
Fake rate	how often we reconstruct a different object as the object we are interested in	a jet faking an electron, fake rate = (Number of jets reconstructed as an electron) / (Number of jets)		Low

Reconstruction - goals

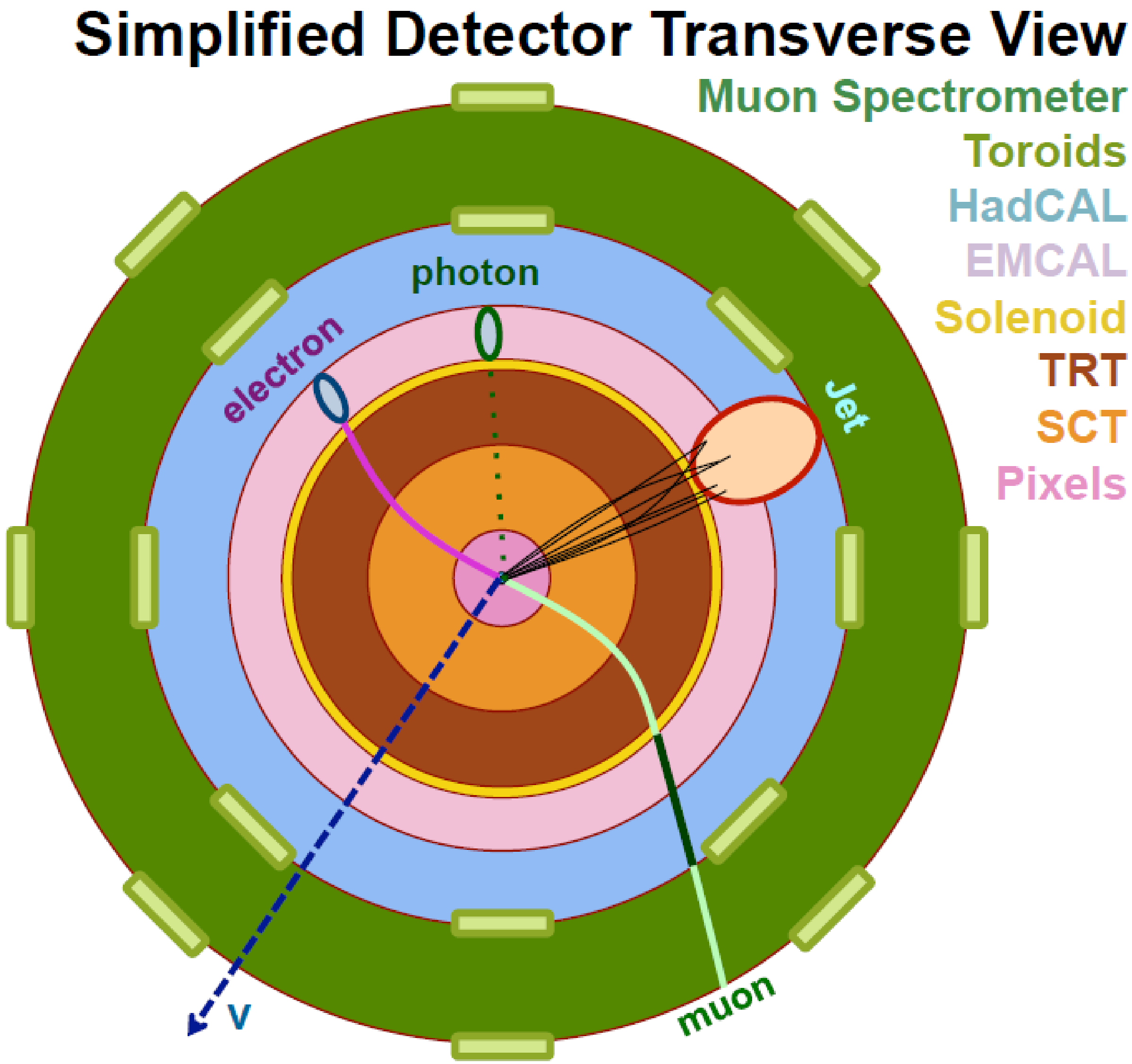
- High efficiency.
- Good resolution.
- Low fake rate.
- Robust against detector problems and data-taking conditions:
  - Noise.
  - Dead regions of the detector.
  - Increased pile-up.
- Computing-friendly. →
  - CPU time per event.
  - Memory use.







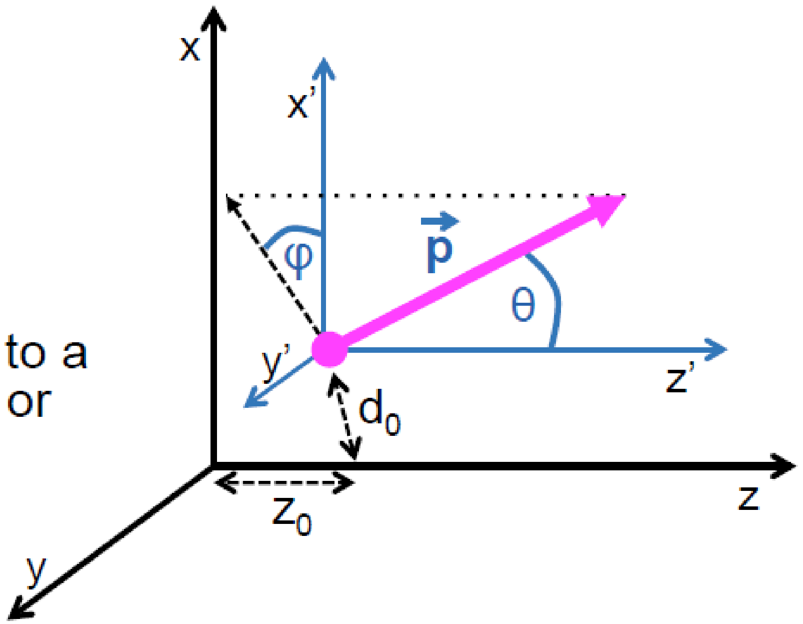
What do we reconstruct?



Tracking in a nutshell

- **A track represents a measurement of a charged particle that leaves a trajectory as it passes through the detector.**

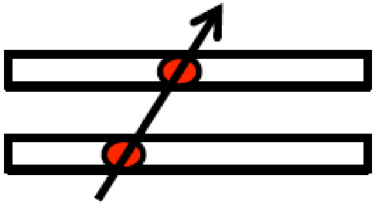
- **For a track we measure:**
  - Its momentum;
  - It's direction;
  - Its charge;
  - Its "perigee": the closest point to a reference line, transverse (d_0) or longitudinal (z_0).



- **Tracks are key ingredients of most of particle reconstruction.**

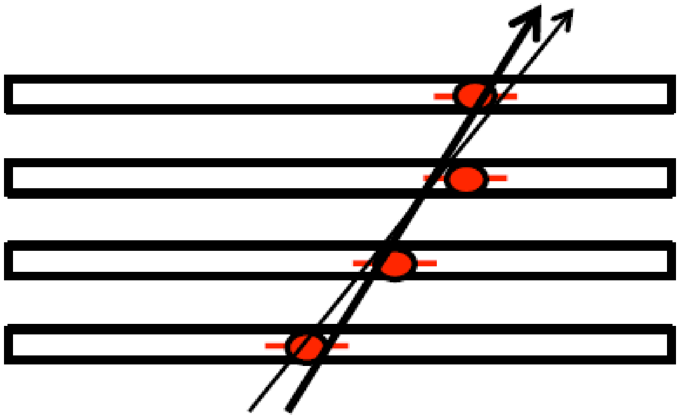
Tracking in a nutshell: track fitting

- **Perfect measurement – ideal**



- **Imperfect measurement – reality**

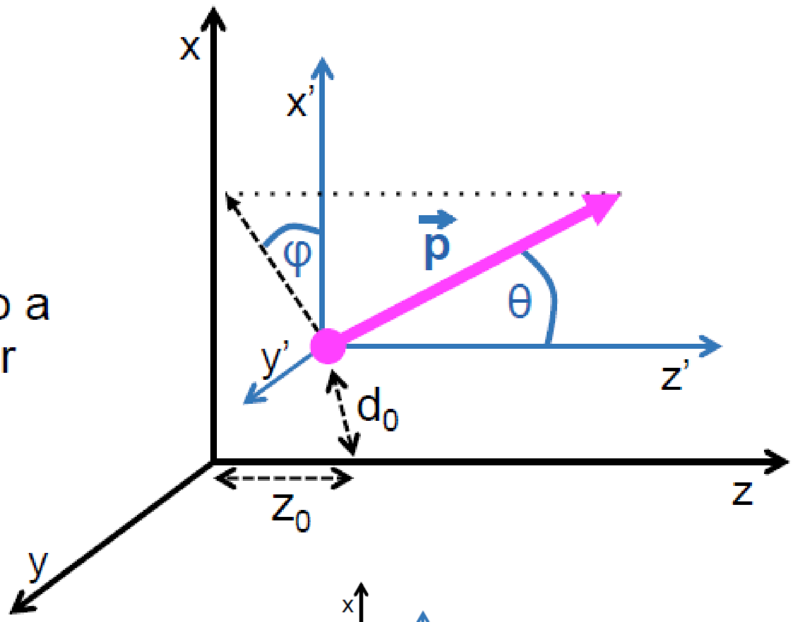
- **Small errors and more points help to constrain the possibilities**



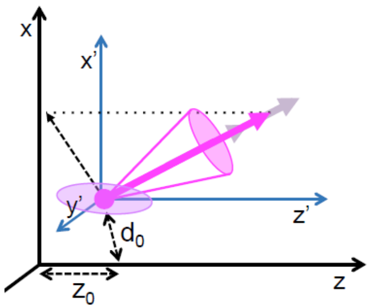
- **Quantitatively:**
  - Parameterize the track;
  - Find parameters by Least-Squares-Minimization;
  - Obtain also uncertainties on the track parameters.

Tracking in a nutshell: track fitting

- **For a track we measure:**
  - Its momentum;
  - It's direction;
  - Its charge;
  - Its "perigee": the closest point to a reference line, transverse (d_0) or longitudinal (z_0).



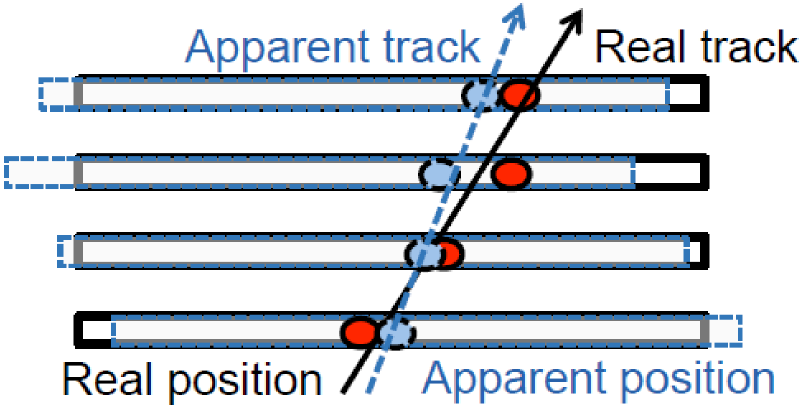
- **Small uncertainties are required.**
  - δd0 is O(10μm) and δθ O(0.1mrad).
  - Allows separation of tracks that come from different particle decays (which can be separated at the order of mm).



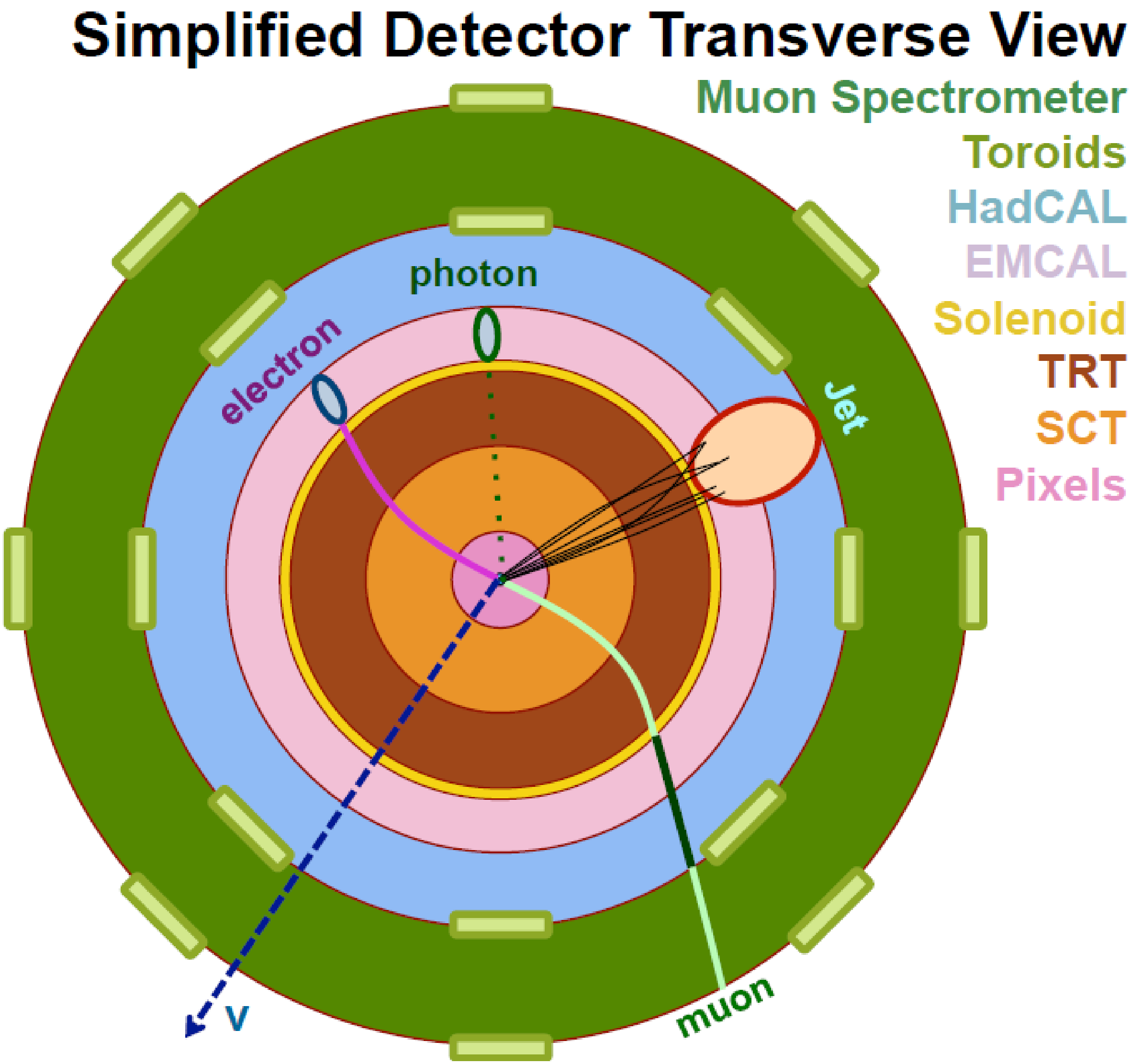
Tracking in a nutshell: the uncertainties

- **Presence of Material**
  - Coulomb scattering off the core of atoms
  - Energy loss due to ionization
  - Bremsstrahlung
  - Hadronic interaction

- **Misalignment**
  - Detector elements not positions in space with perfect accuracy.
  - Alignment corrections derived from data and applied in track reconstruction.

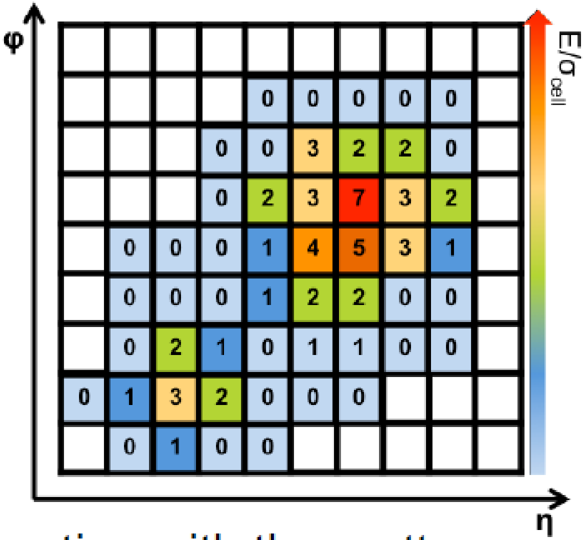


What do we reconstruct?



Clustering in a nutshell

- **Reconstruct energy deposited in the calorimeter by charged or neutral particles; electrons, photons and jets.**
- **For a cluster we measure:**
  - The energy;
  - The position of the deposit;
  - The direction of the incident particles;

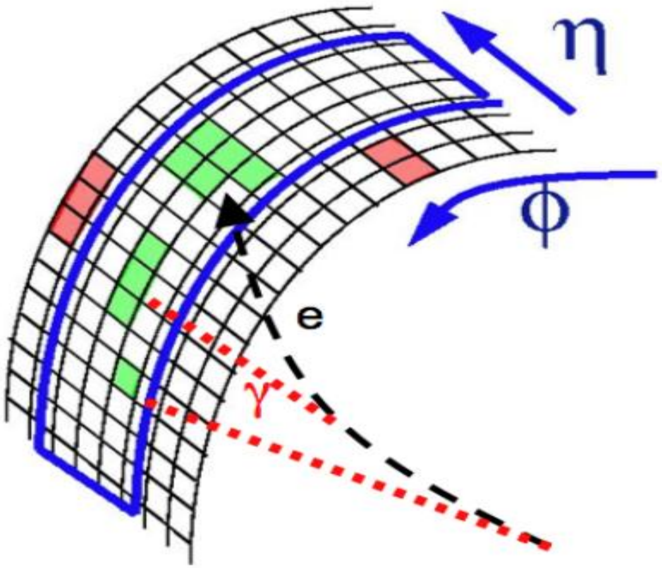


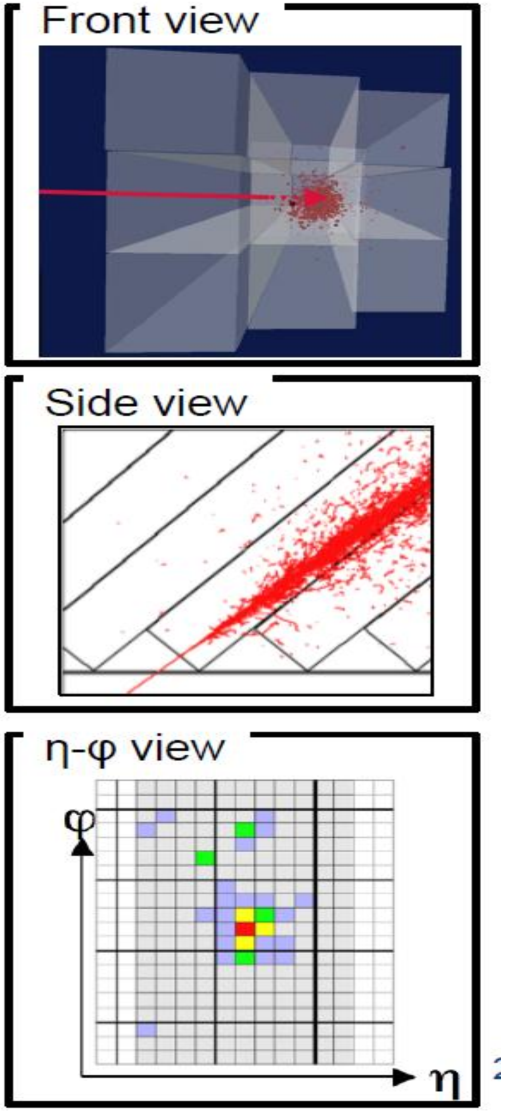
- **Calorimeters are segmented in cells.**
  - Typically a shower created by a particle interacting with the matter extends over several cells.
- **Various clustering algorithms, e.g.:**
  - **Sliding window**. Sum cells within a fixed-size rectangular window.
  - **Topo-clustering**. Start with a seed cell and iteratively add to the cluster the neighbor of a cell already in the cluster.

Cluster finding – an example

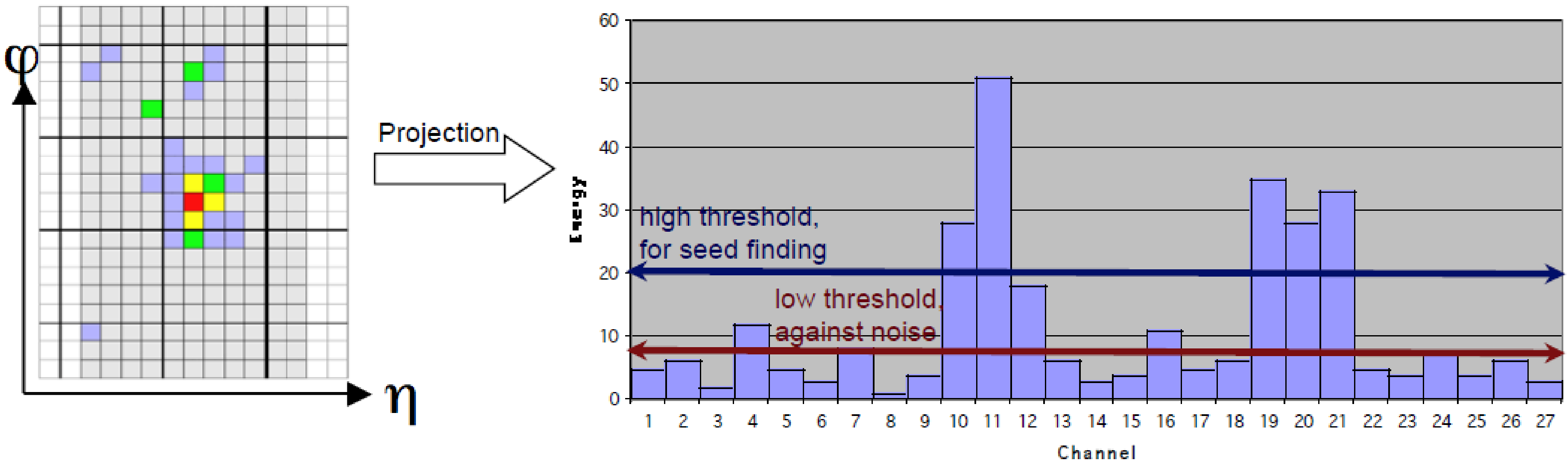
CMS crystal calorimeter – ECAL clusters

◎ electron energy in central crystal ~80%,
in 5x5 matrix around it ~96%.





Cluster finding – an example



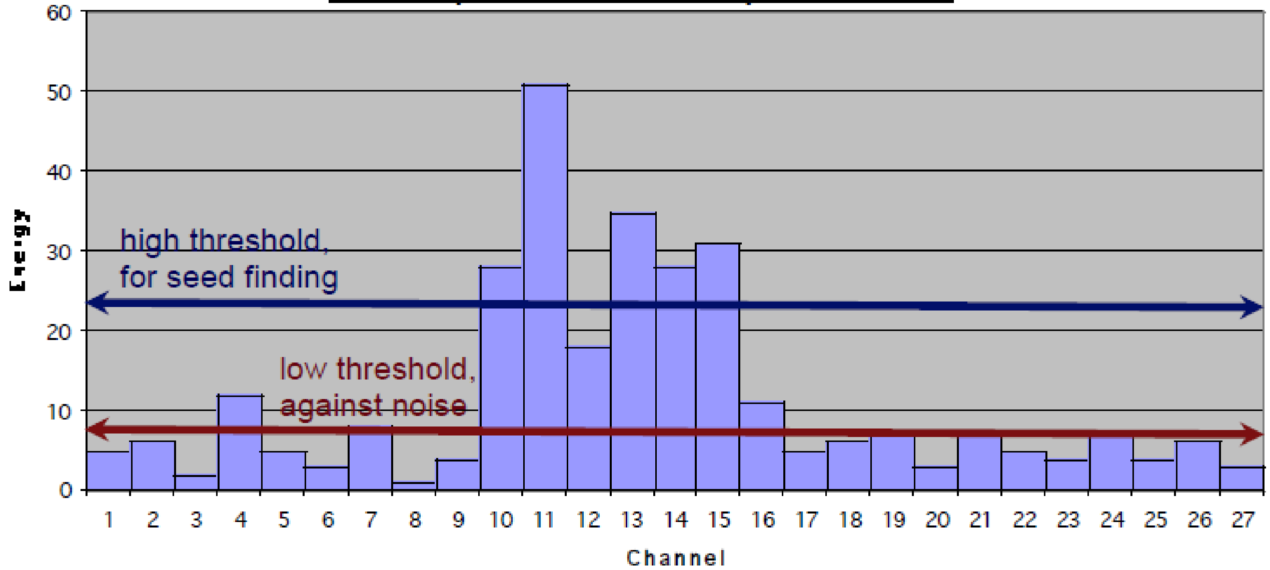
Simple example of an algorithm

- Scan for seed crystals = local energy maximum above a defined seed threshold
- Starting from the seed position, adjacent crystals are examined, scanning first in φ and then in η
- Along each scan line, crystals are added to the cluster if
    1. The crystal's energy is above the noise level (lower threshold)
    2. The crystal has not been assigned to another cluster already

Cluster finding – difficulties

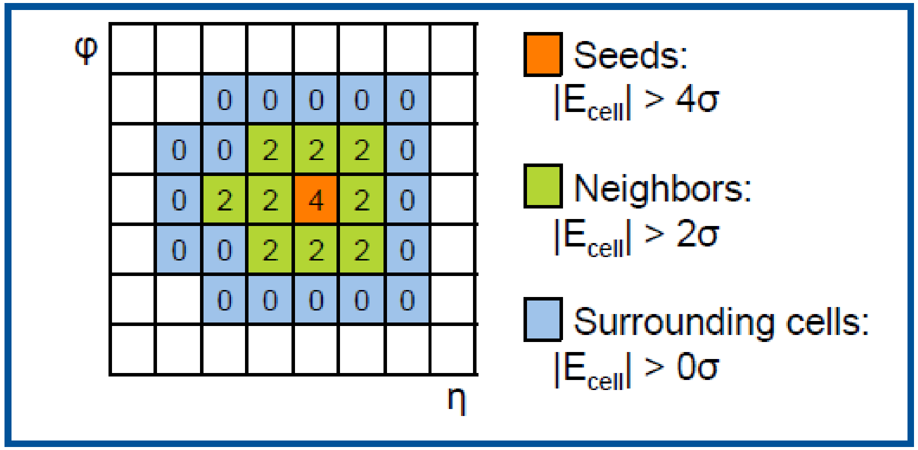
- **Careful tuning of thresholds needed.**
  - needs usually learning phase;
  - adapt to noise conditions;
  - too low : pick up too much unwanted energy;
  - too high : loose too much of "real" energy. Corrections/Calibrations will be larger.

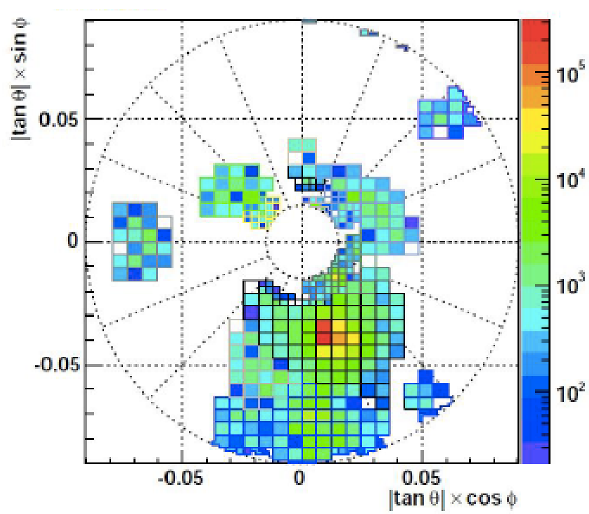
<u>example : one lump or two?</u>



Cluster finding – topological clustering

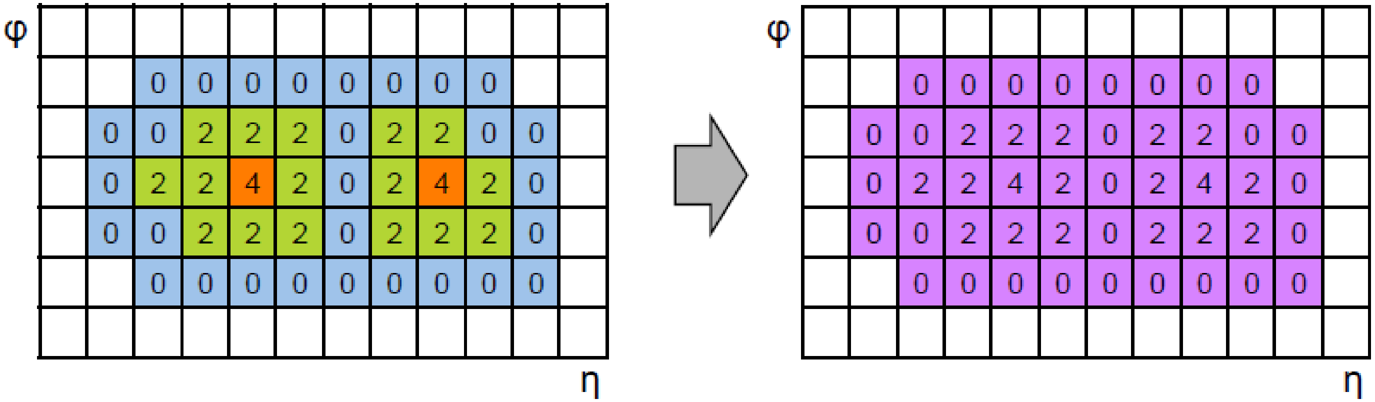
"Topological" clusters, i.e. "blobs" of energy inside the detector.



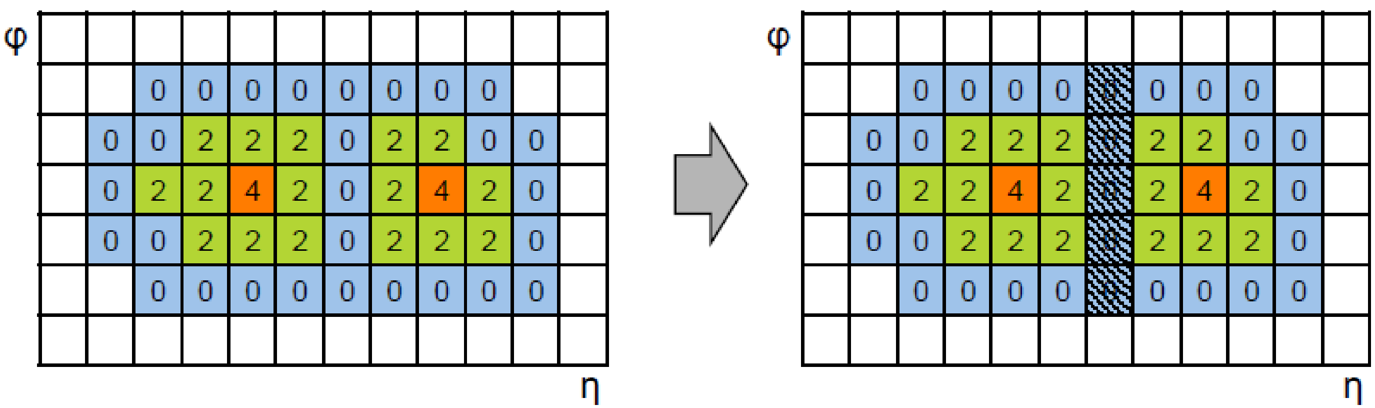


Cluster finding – merging and splitting

- If clusters have common neighboring cells, they are merged according to the basic algorithm.



- Clusters are split if more than one local maxima.

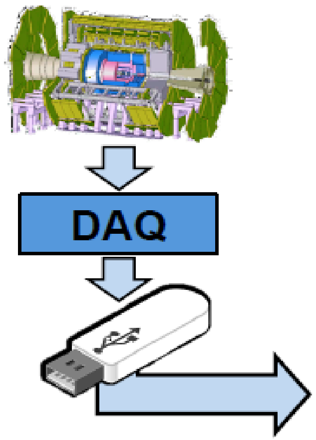


For common cells, a weight is applied to share them (shaded cells).

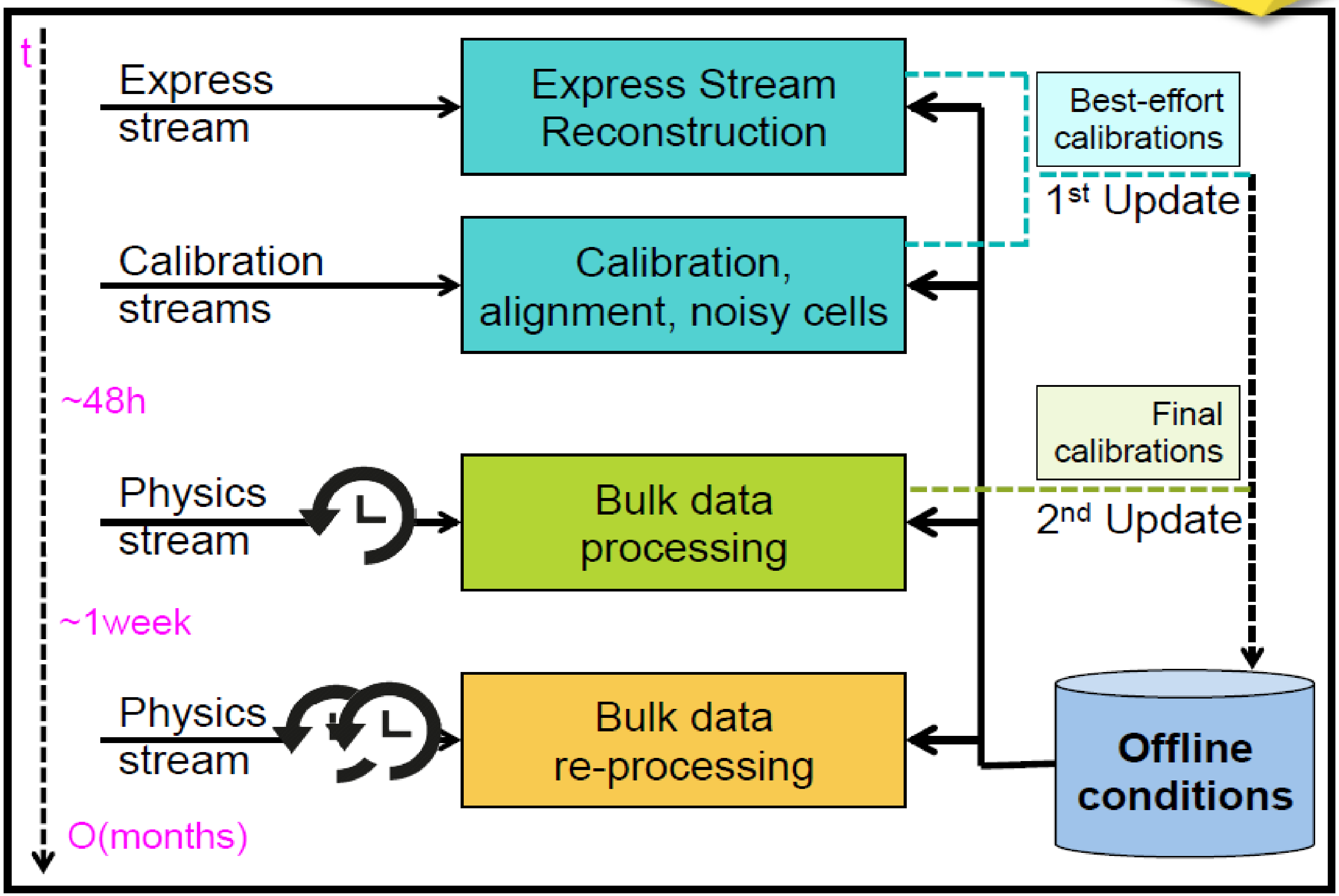
Cluster calibration

Possible energy measurements:

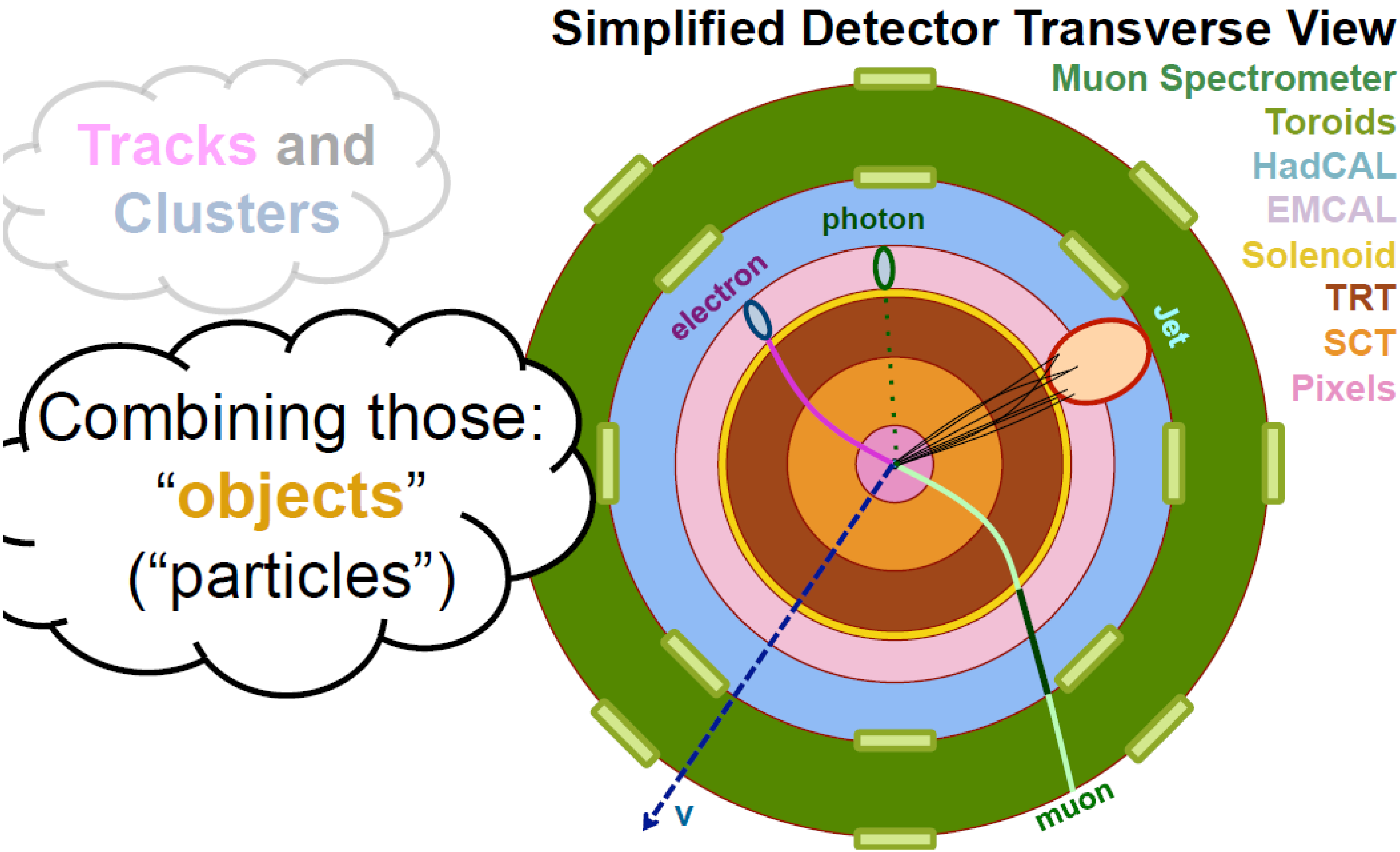
- **Non-calibrated clusters: sum energy using baseline cell-level detector calibration.**
  - That's NOT the true energy of the particle that originated the cluster.
- **Local calibration: apply weights to correct for:**
  - the different **calorimeter response** on an EM (e.g. π^0) or a hadronic (e.g. $\pi^\pm$) deposition.
  - the low energetic deposits, lost in the tails of the shower (**"out-of-cluster"** corrections, derived from simulation).
  - the presence of **dead material**, i.e. material without a read-out device, where energy is lost.
- **Corrections are complex functions of the energy and the position of the cluster and other parameters defining the cluster shapes.**



THE EVENT AT TIER0



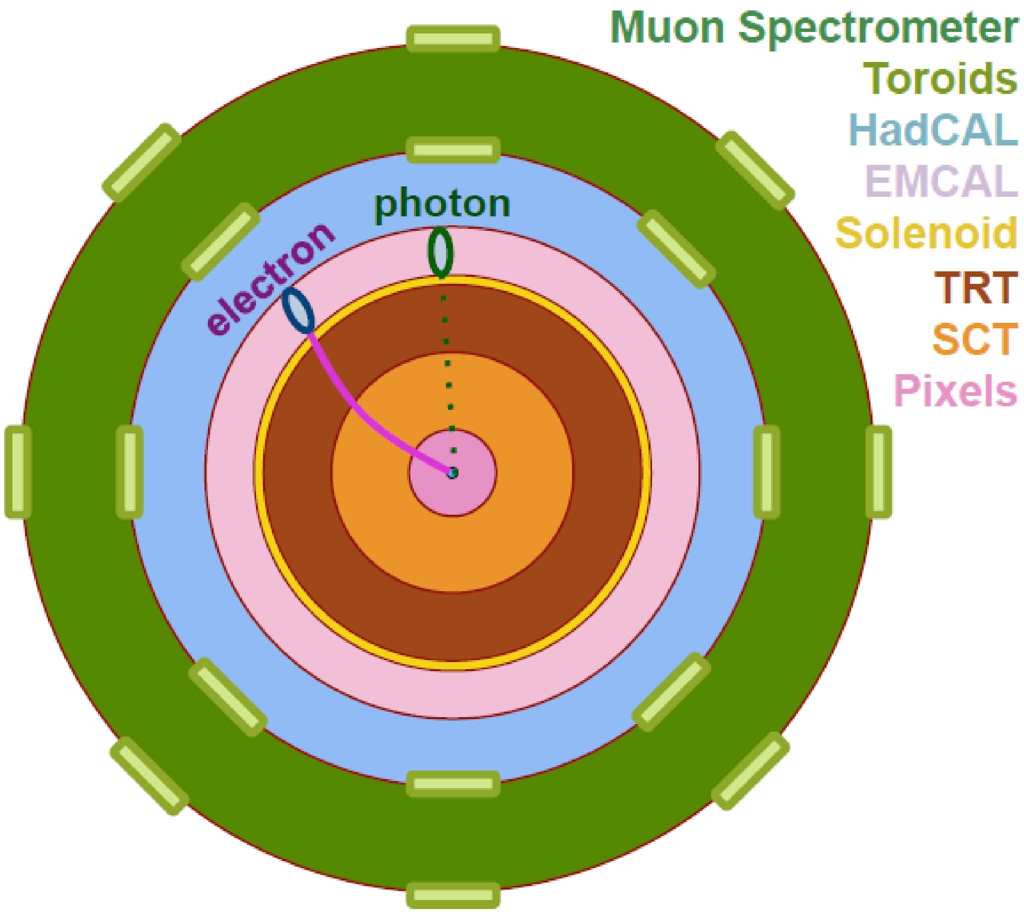
What do we reconstruct?



Electrons and photons

- **Final Electron momentum measurement can come from tracking or calorimeter information (or a combination of both).**
  - Often have a final calibration to give the best electron energy.
- **Often want "isolated electrons".**
  - Require little calorimeter energy or tracks in the region around the electron.

Simplified Detector Transverse View



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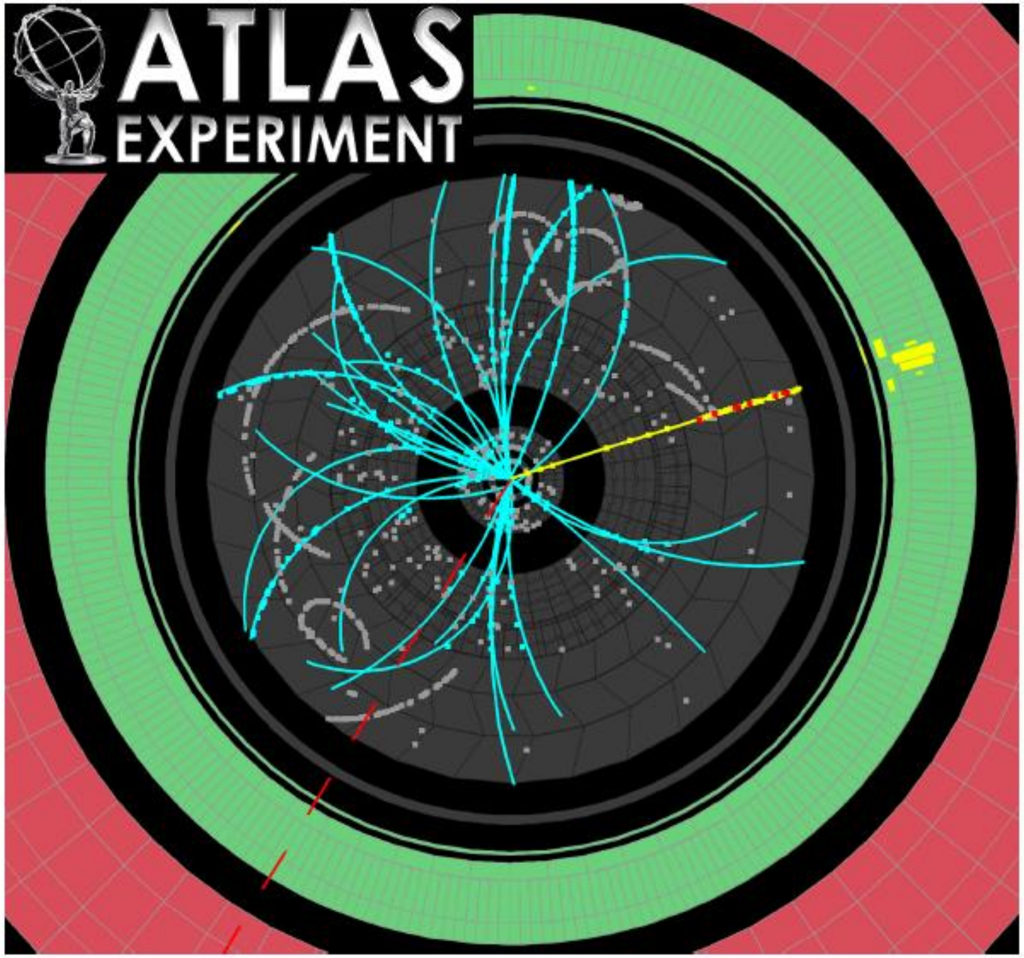
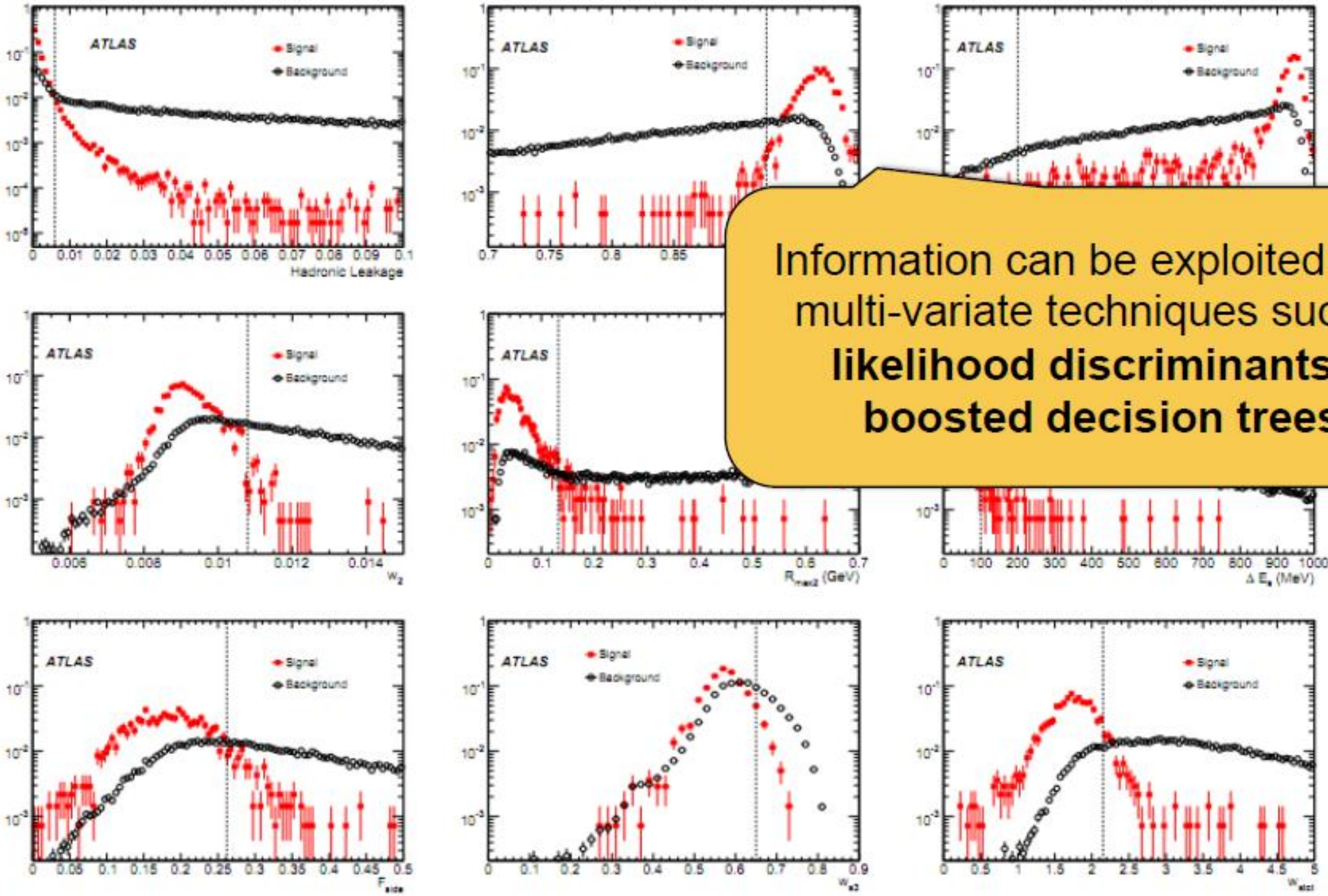


Electrons and photons (backgrounds)

- Hadronic jets leave energy in the calorimeter which can fake electrons or photons.
- Usually a Jet produces energy in the hadronic calorimeter as well as the electromagnetic calorimeter.
- Usually the calorimeter cluster is much wider for jets than for electrons/photons.
- So it should be "easy" to separate electrons from jets.
- However have many thousands more jets than electrons, so need the rate of jets faking an electron to be very small $\sim 10^{-4}$.
- Need complex identification algorithms to give the rejection whilst keeping a high efficiency.

Electrons and photons (backgrounds)

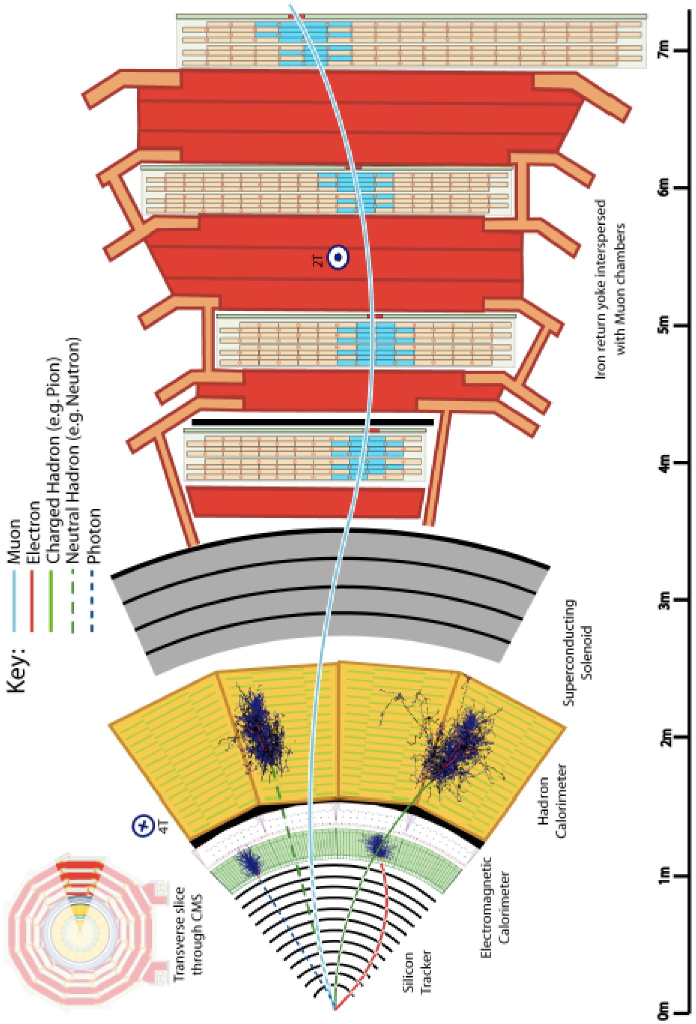


Information can be exploited using multi-variate techniques such as **likelihood discriminants** or **boosted decision trees**.

Example of different calorimeter shower shape variables used to distinguish electron showers from jets in ATLAS

Muons

- **Combine the muon segments found in the muon detector with tracks from the tracking detector**
- **Momentum of muon determined from bending due to magnetic field in tracker and in muon system**
  - Combine measurements to get best resolution
  - Need an accurate map of the magnetic field in the reconstruction software
  - Alignment of the muon detectors also very important to get best momentum resolution



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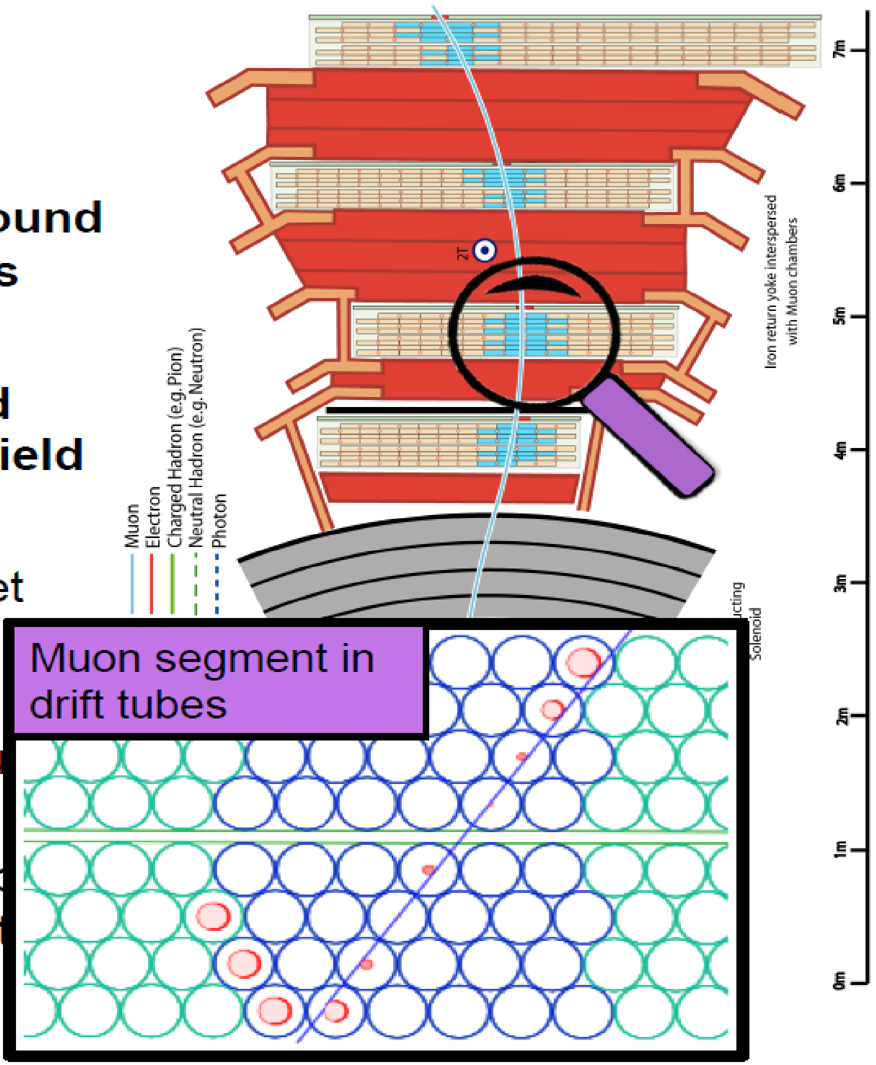

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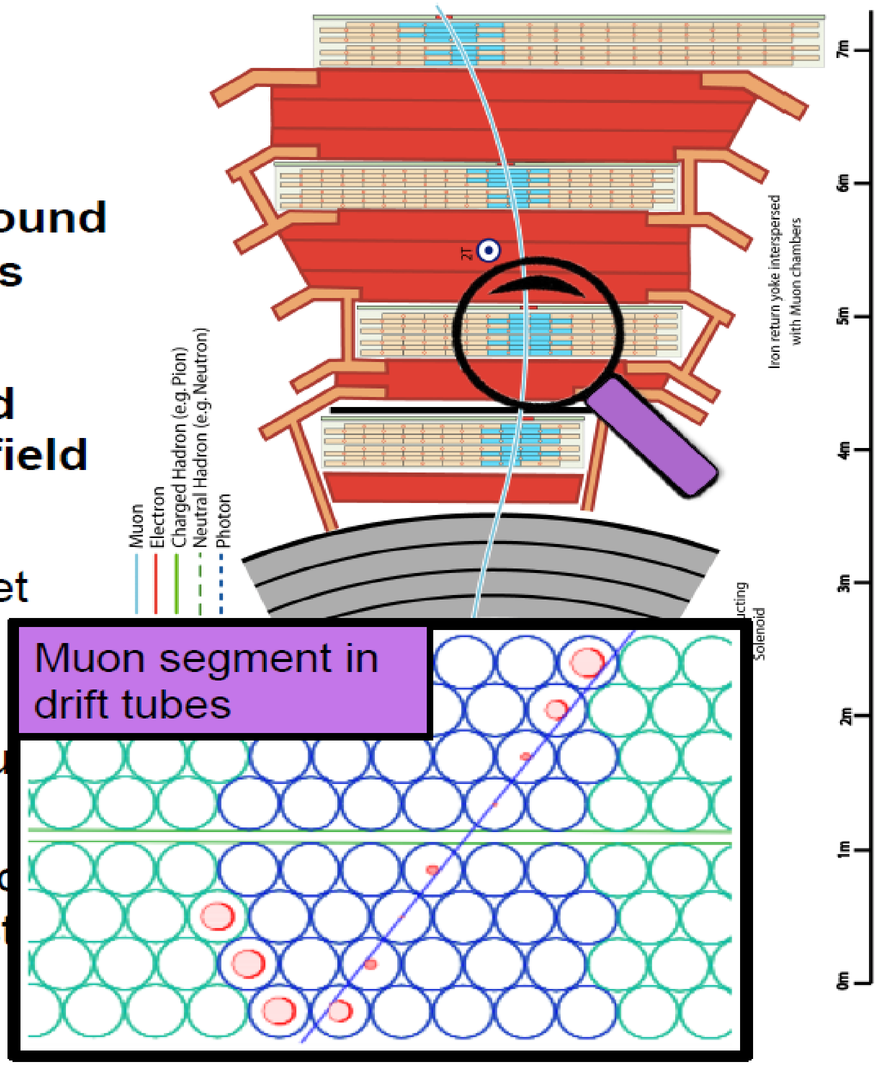
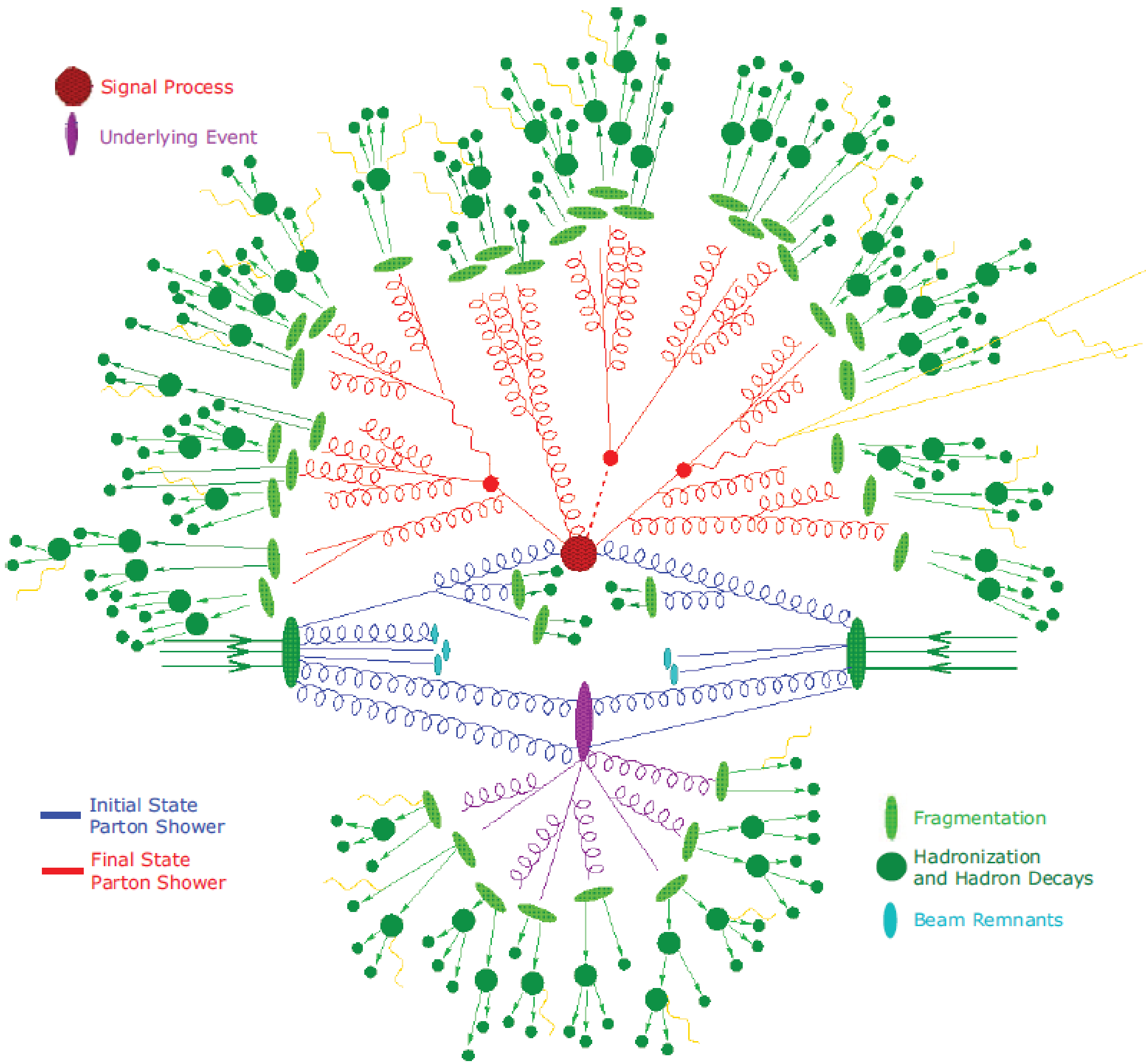
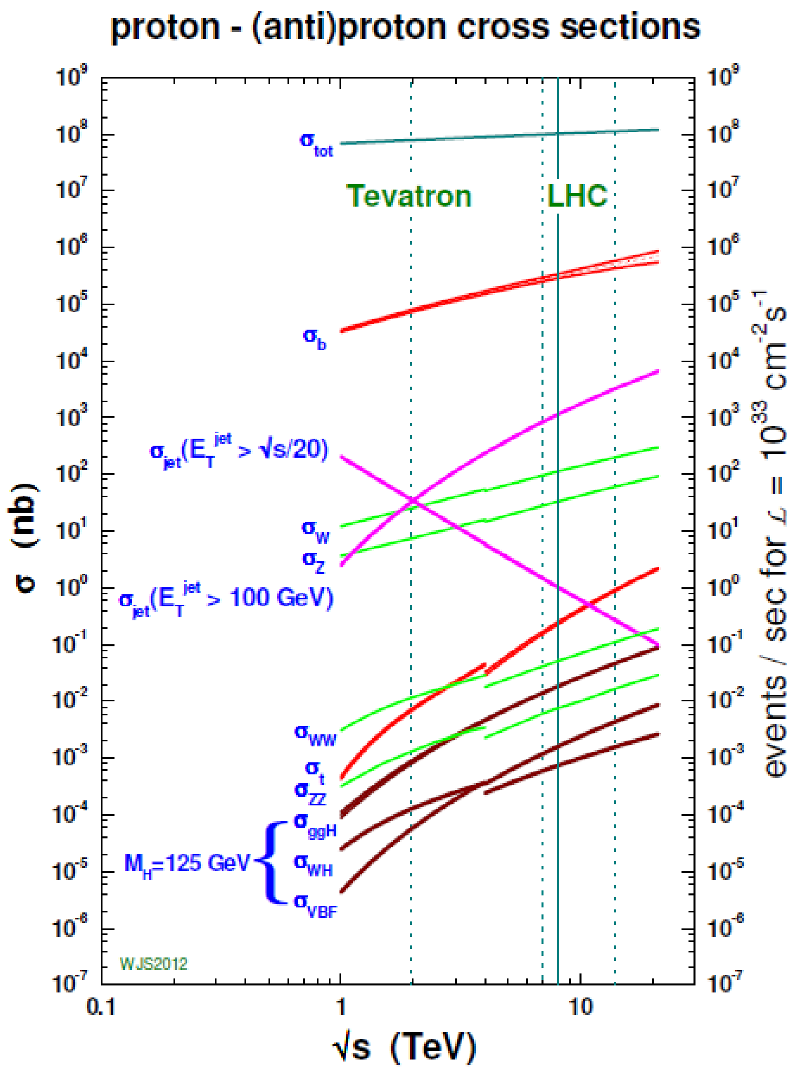


Jets


Signal Process
Underlying Event
Initial State
Parton Shower
Final State
Parton Shower
Fragmentation
Hadronization
and Hadron Decays
Beam Remnants

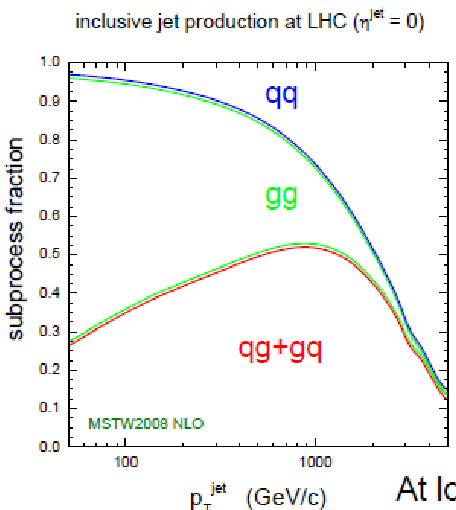
Standard Model processes



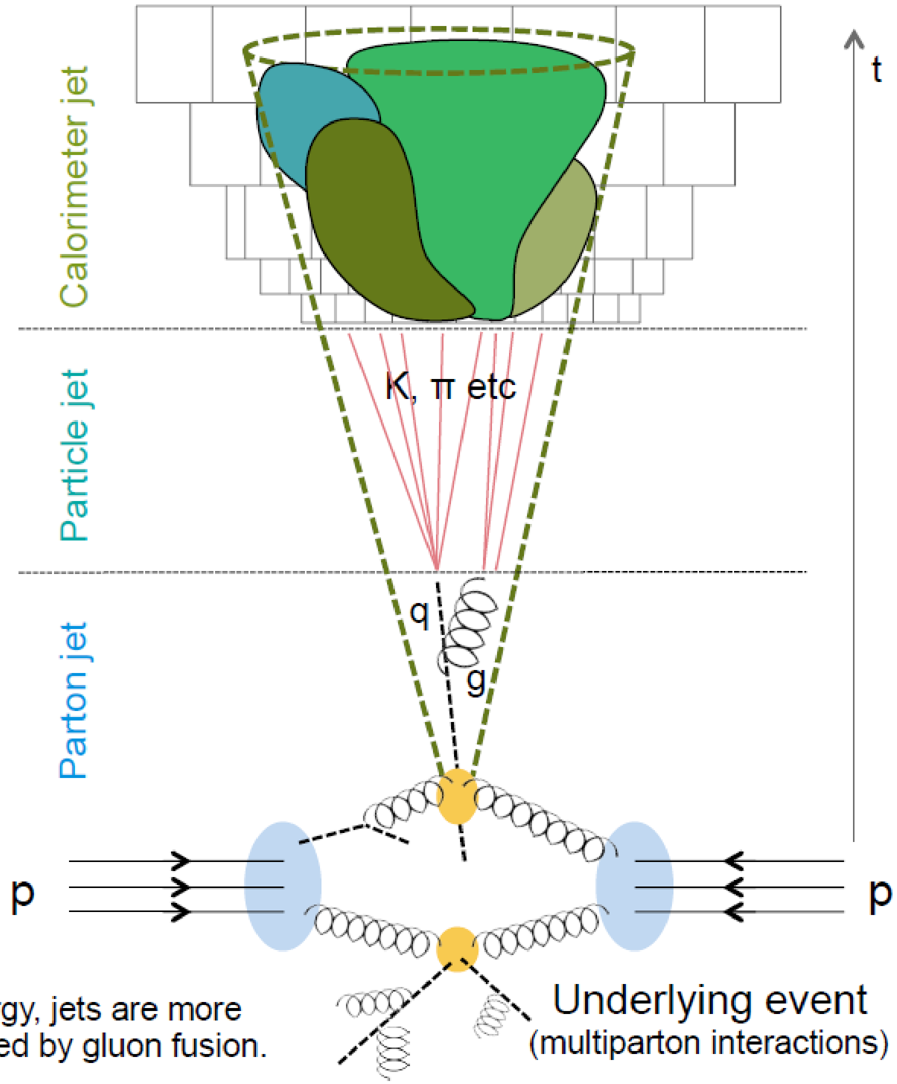
Jets are produced:

- by fragmentation of gluons and (light) quarks in QCD scattering.
- by decays of heavy Standard Model particles, e.g. W & Z.
- in association with particle production in Vector Boson Fusion, e.g. Higgs.
- in decays of beyond the Standard Model particles, e.g. in SUSY.

Jets

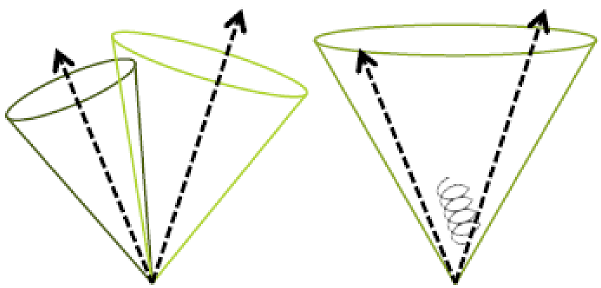


At low energy, jets are more likely produced by gluon fusion.

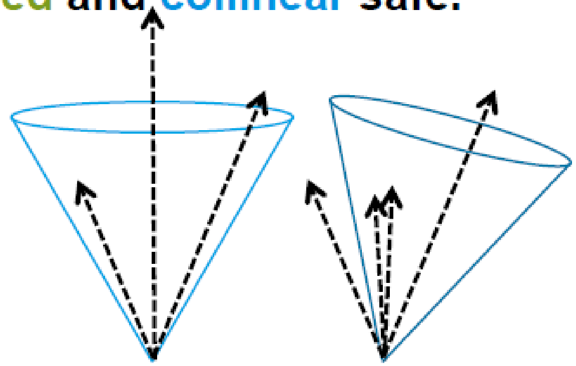


Jet algorithms

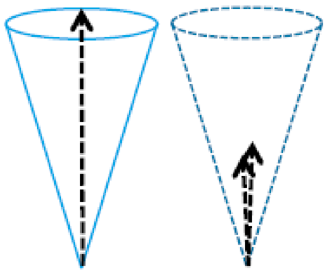
Theoretical requirements: **infrared** and **collinear** safe.



Soft gluon radiation
should not merge jets



Final jet should not depend on
the ordering of the seeds…



…and on signal split in two
possibly below threshold

Experimental requirements: **detector technology** & **environment** **independent**, **easily implementable**.

Insignificant effects of detector
- Noise
- Dead material
- Cracks

Stability with
- Luminosity
- Pile-up
- Physics process

Fully specified
Fast

Jet algorithm commonly used at the LHC: **'anti-k_t'**. A 'recursive recombination' algorithm. Starts from (topo-)clusters. Hard stuff clusters with nearest neighbor. Various cone sizes (standard R=0.4/0.5, "fat" R=1.0).

Jet calibration

Correct the energy and position measurement and the resolution.

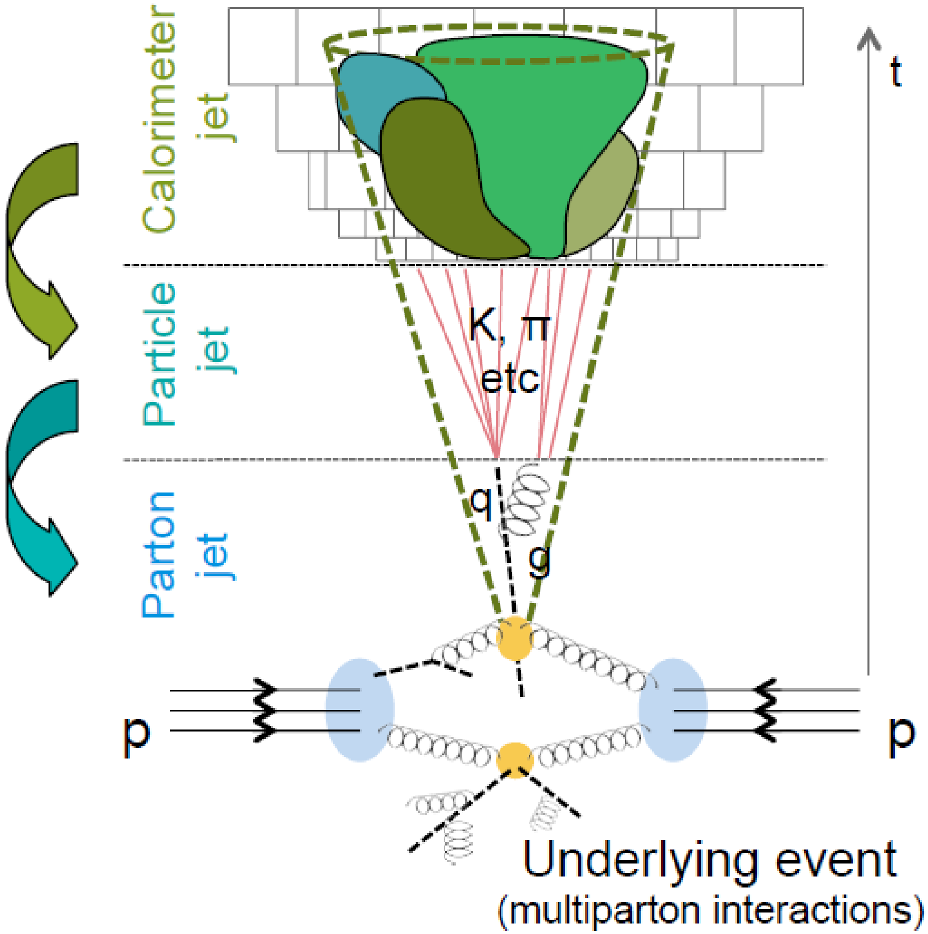
Account for:

Instrumental effects

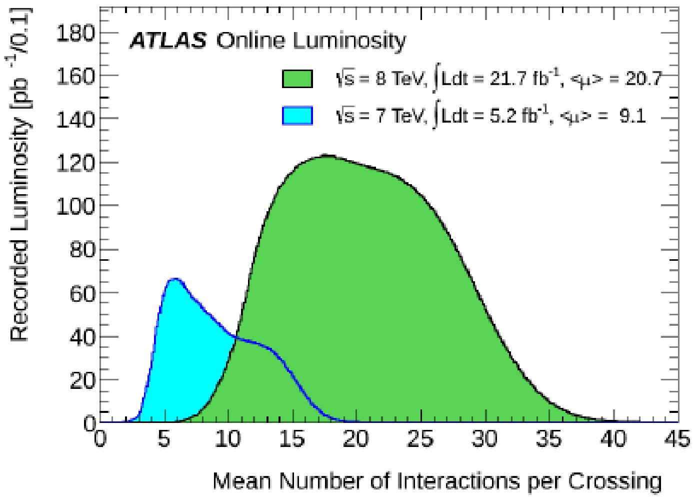
Detector inefficiencies
'Pile-up'
Electronic noise
Clustering, noise suppression
Dead material losses
Detector response
Algorithm efficiency

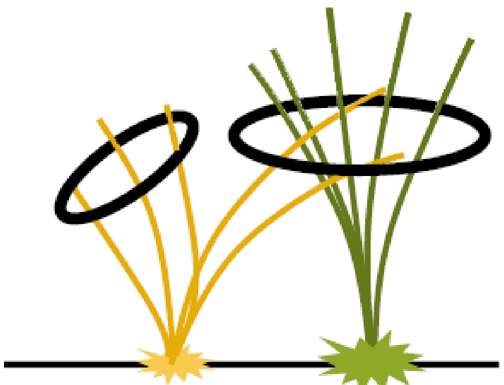
Physics effects

Algorithm efficiency
'Pile-up'
'Underlying event'



Jets & pile-up

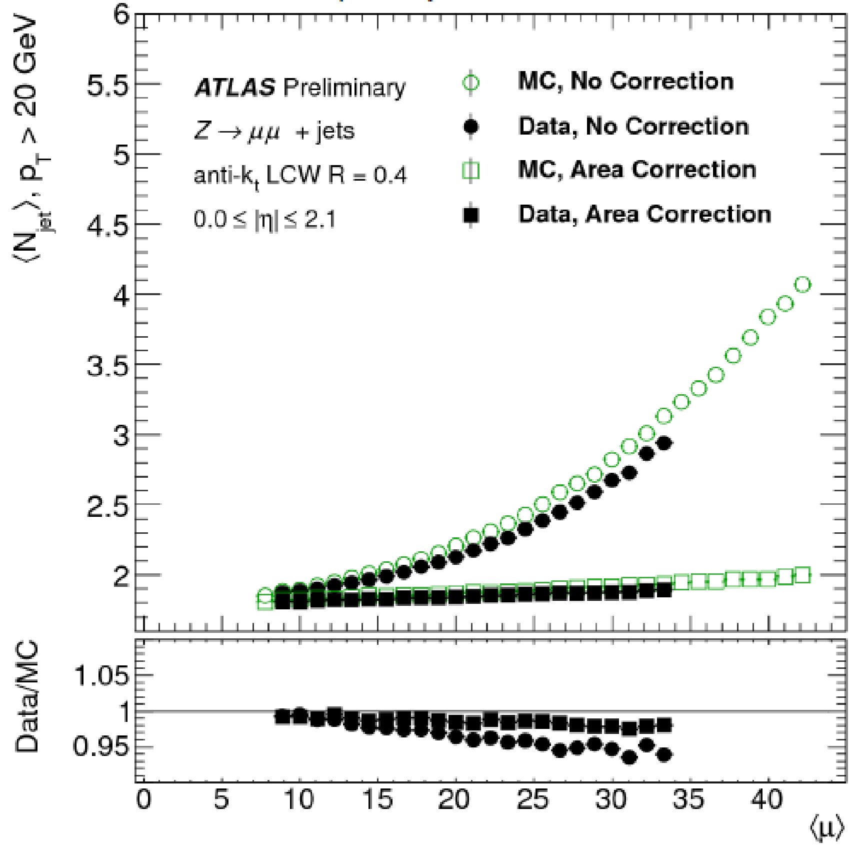




Multiple interactions from pile-up

‘Jet-areas’ corrections

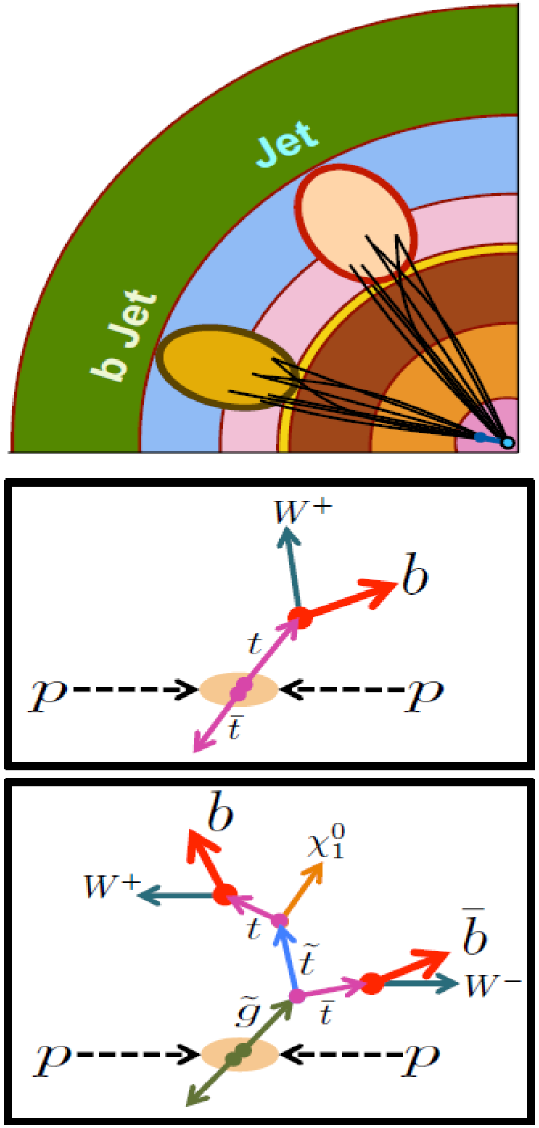
Inspired by arXiv:0707.1378



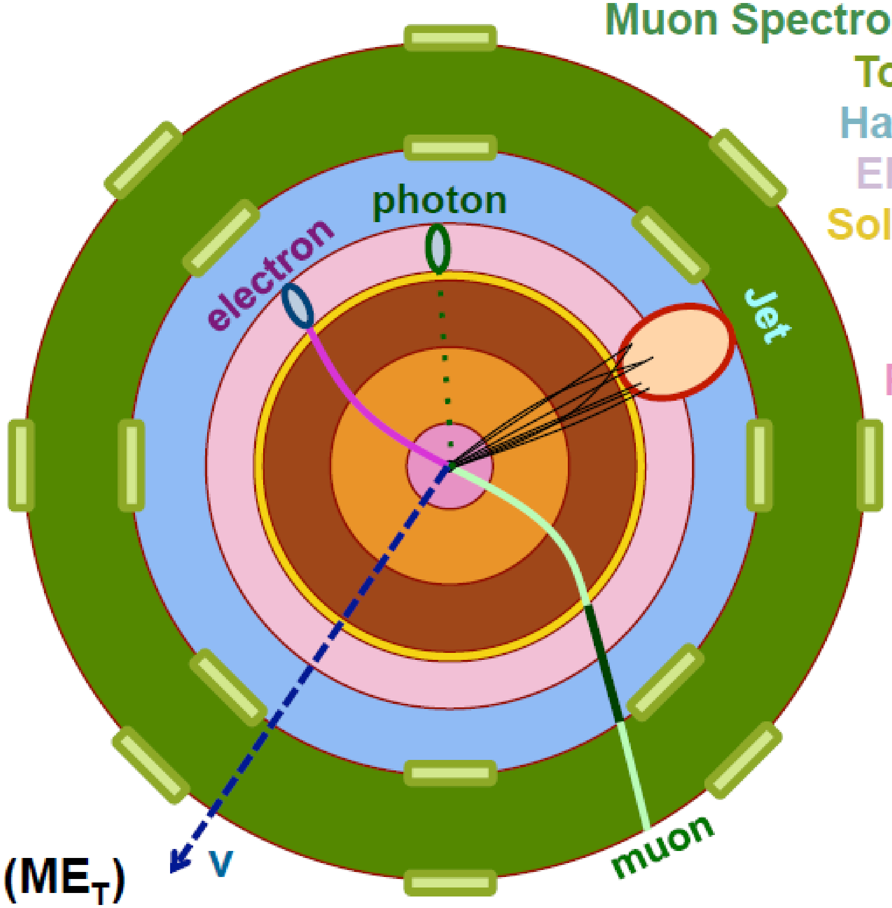
b-jets

- b-quarks have a lifetime of ~ 10^{-12} s.
- They travel a small distance (fraction of mm) before decaying.
- A "**displaced vertex**" creates a distinct jet, so b-jets can be tagged (**b-tagged**).
- b-tagging uses sophisticated algorithms, mostly **multi-variate**.

- b-jets create distinct final states, important for both **Standard Model measurements** and **searches for New Physics**.



Missing transverse momentum



In the transverse plane:

$$\sum \vec{p}_T = 0$$

Missing Transverse Momentum (ME_T)

Missing transverse momentum

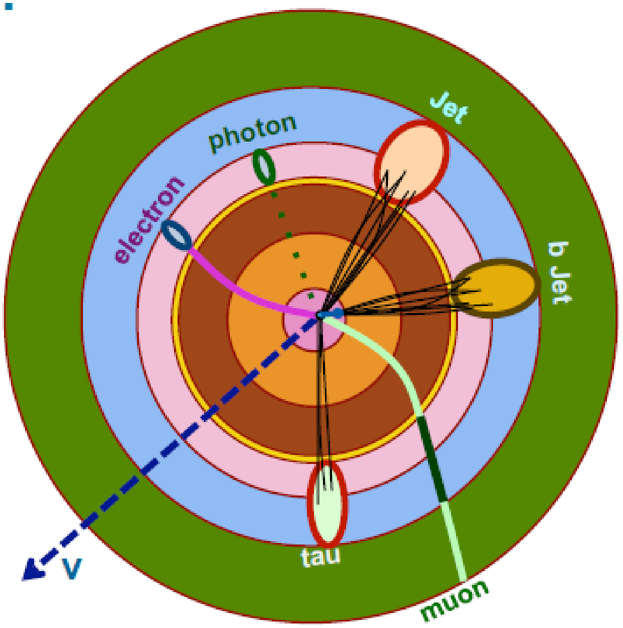
Impossible to measure particles that don't interact in the detector.

➲ Instead, measure everything else & require momentum conservation in the transverse plane.

- Sensitive to pile-up and detector problems.

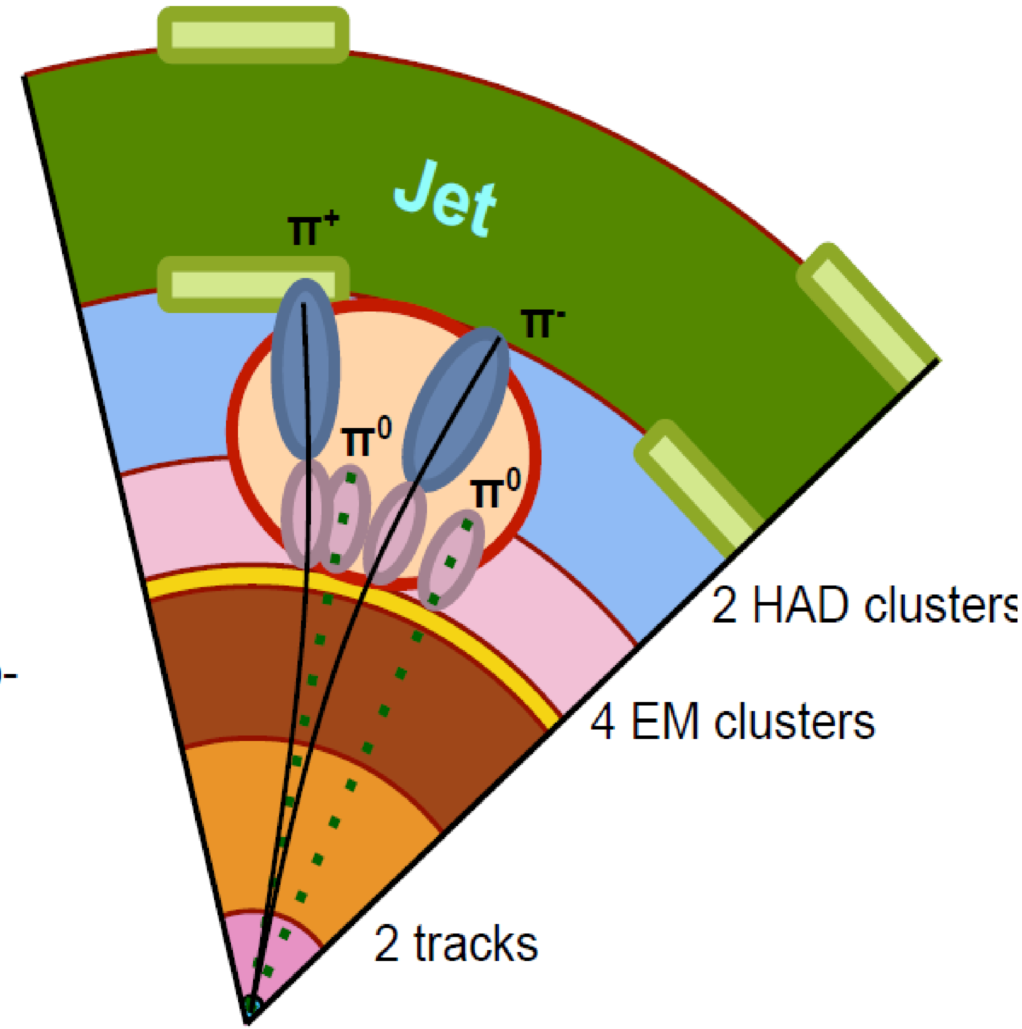
Only as good as its inputs.

- Use calibrated physics objects: electrons, photons, muons, taus, jets.
- Add remaining soft energy.



Particle flow

- "Flow of particles" through the detector.
- Reconstruct and identify all particles, photons, electrons, pions, …
- Use best combination of all sub-detectors for measuring the properties of the particles.
- First used at LEP (ALEPH) and then at the LHC (CMS).

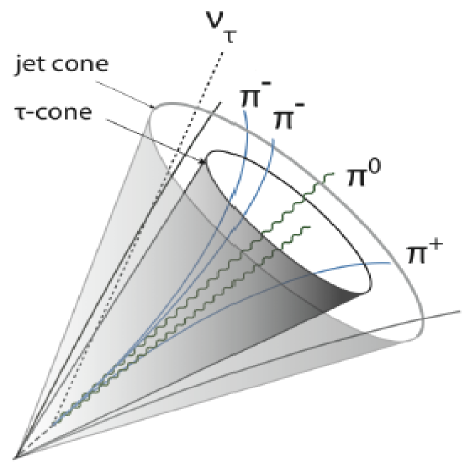


Reconstructing particles

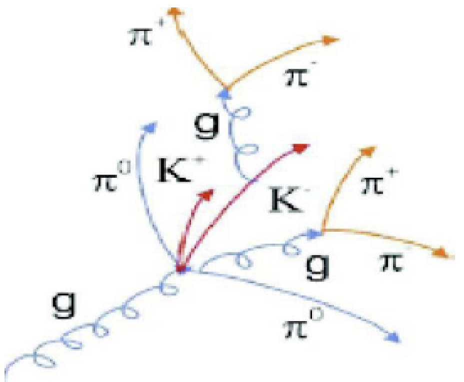
Tau Decay Mode			B.R.
Leptonic		$\tau^\pm \to e^\pm + \nu + \nu$	17.8%
		$\tau^\pm \to \mu^\pm + \nu + \nu$	17.4%
Hadronic	1-prong	$\tau^\pm \to \pi^\pm + \nu$	11%
		$\tau^\pm \to \pi^\pm + \nu + n\pi^0$	35%
	3-prong	$\tau^\pm \to 3\pi^\pm + \nu$	9%
		$\tau^\pm \to 3\pi^\pm + \nu + n\pi^0$	5%
Other			~5%

- Hadronic tau reconstruction extremely challenging.
- Using **multi-variate** techniques based on track multiplicity and shower shapes.

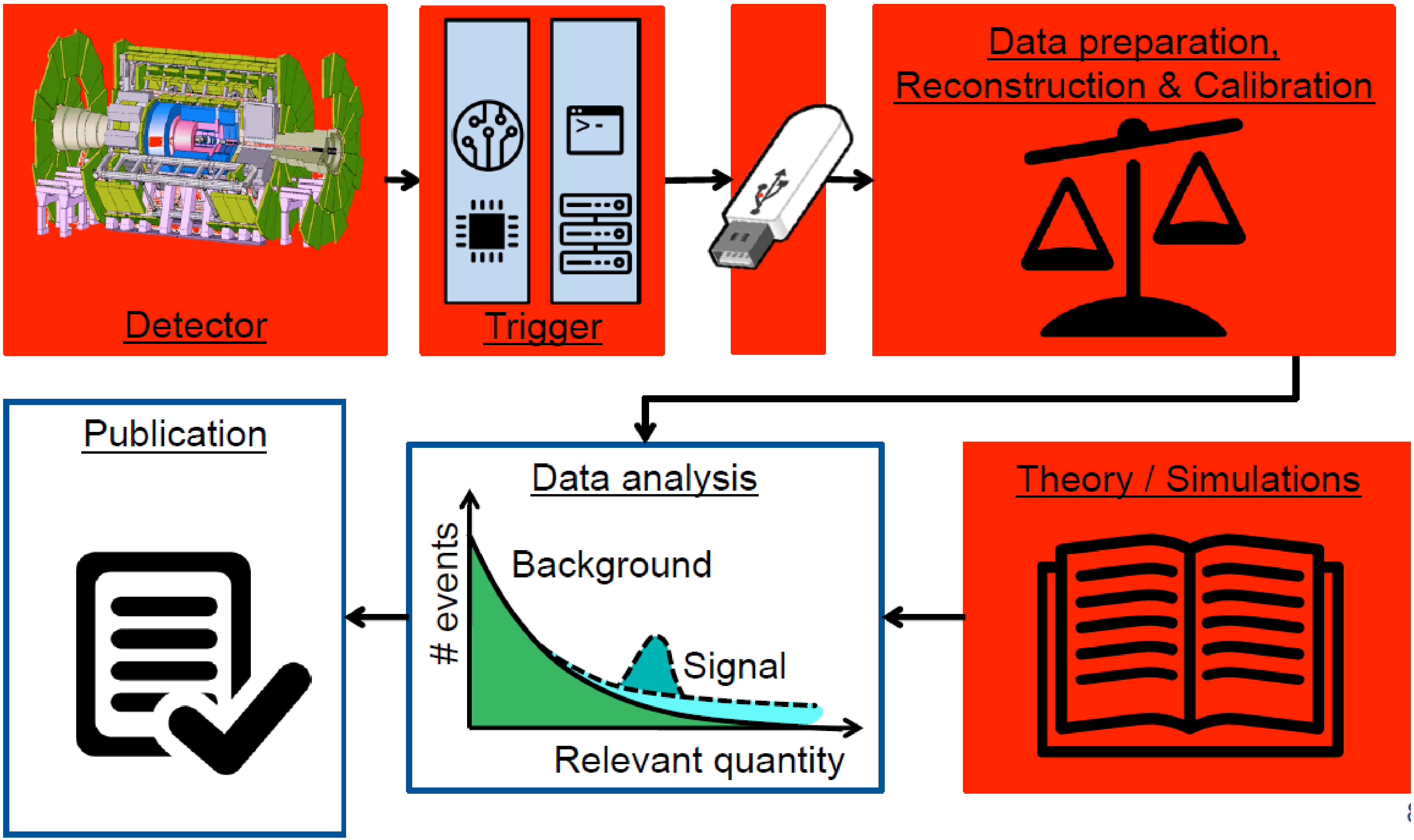
A tau jet (signal)...



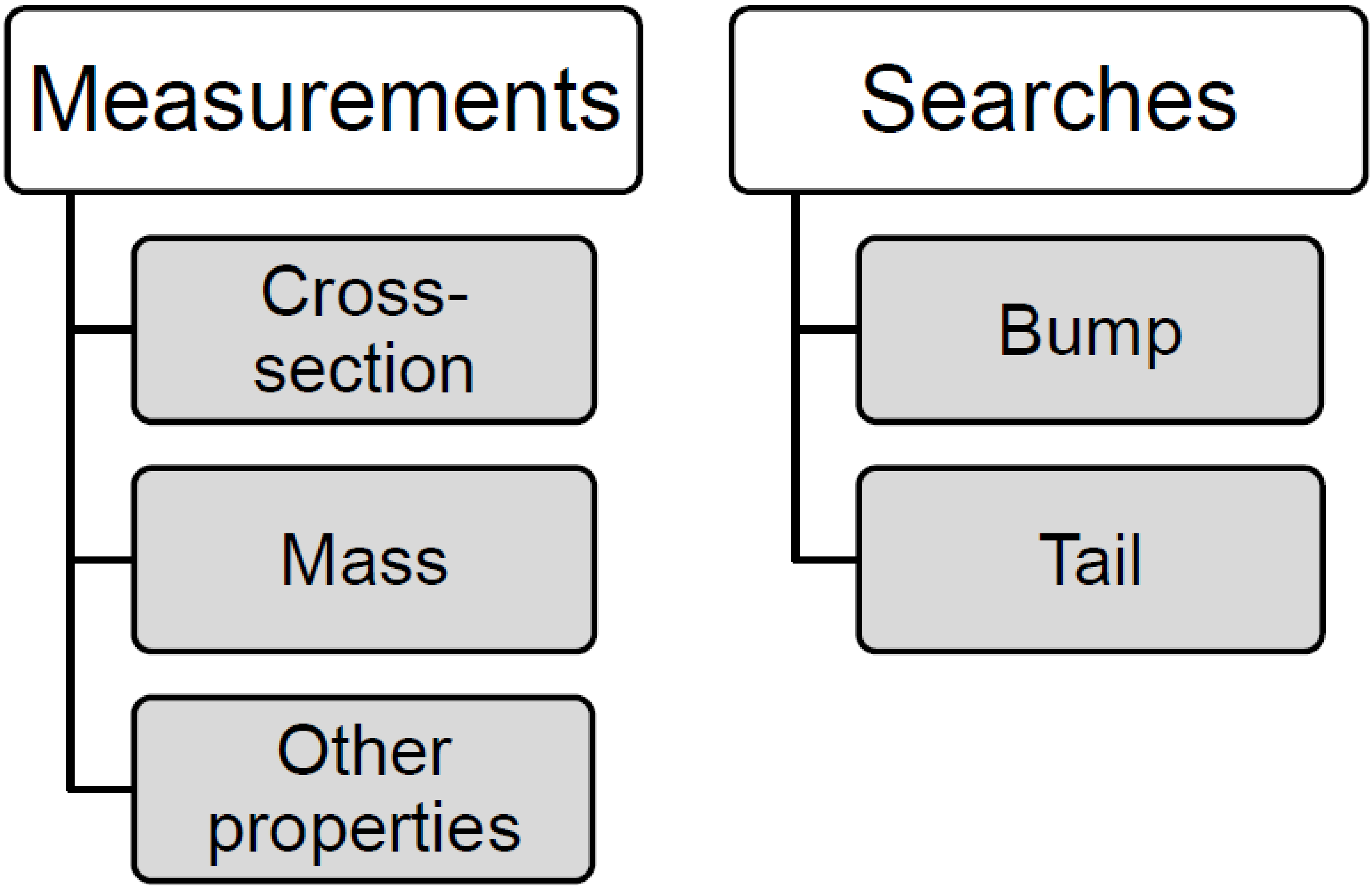
...vs. a QCD jet (background)



An event's lifetime



Physics analyses



Physcis analyses

Measurements

- Allow important tests of the consistency of the theory.
- Typically limited by systematic uncertainties.

Searches

- … For new particles.
- If no signal, set limits on some model.
- If signal, a potential discovery!
- More data typically improve a search.

Physics analyses

Measurements

- Allow important tests of the consistency of the theory.
- Typically limited by systematic uncertainties.

“Systematic” uncertainties are introduced by inaccuracies in the methods used to perform the measurement.

Searches

- ...al discovery!
- More data typically improve a search.

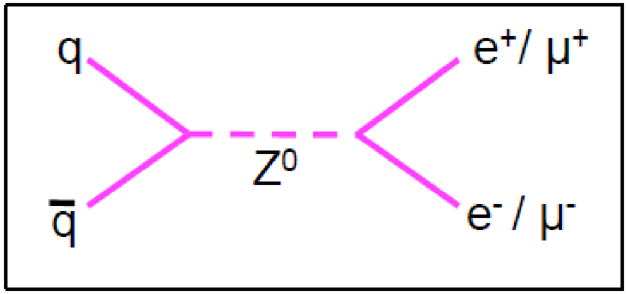
Physics analyses

SIMPLE EXAMPLE:

MEASURING Z^0 CROSS-SECTION AT LHC

Measuring Z^0 cross-section at LHC

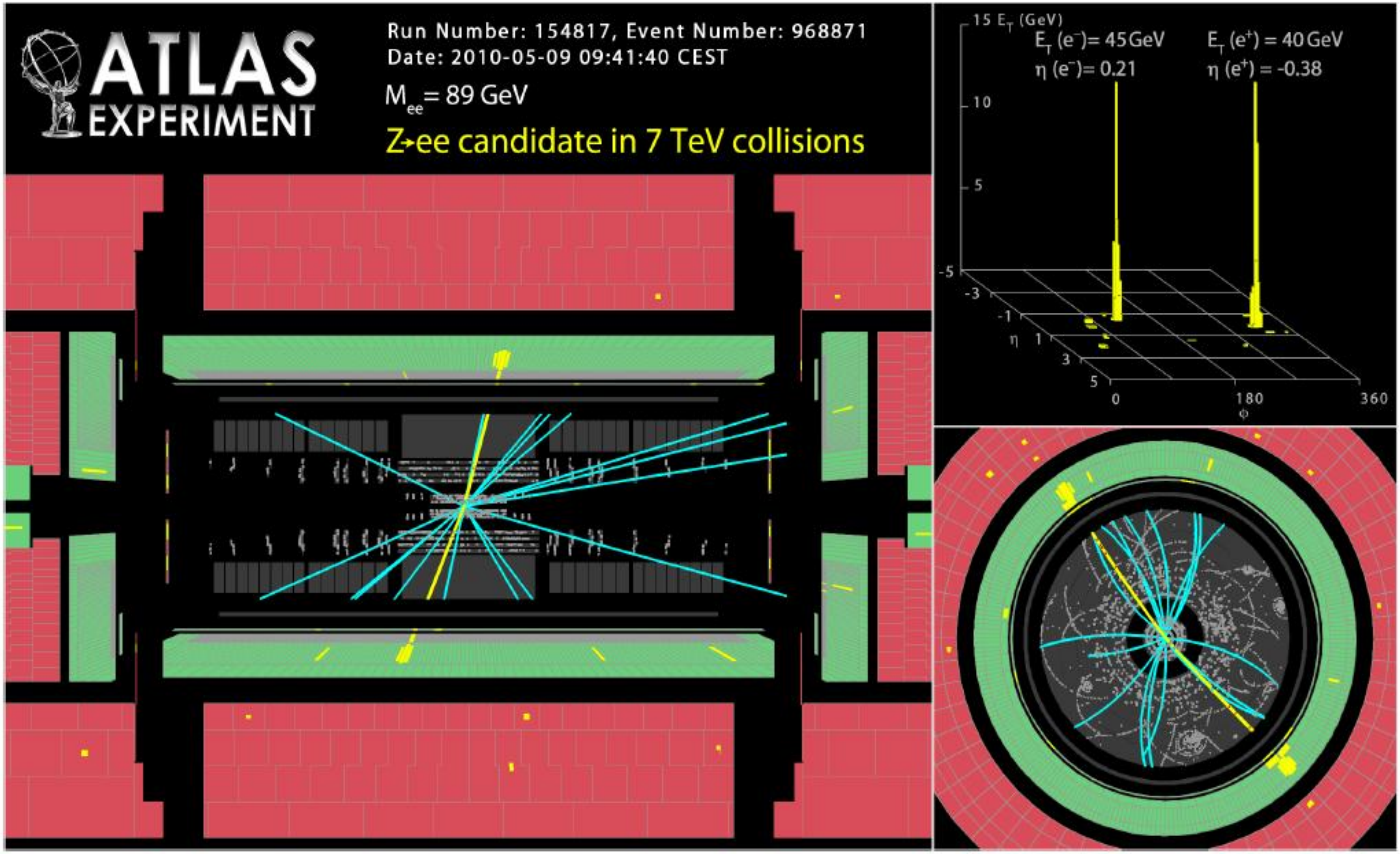
- **Z^0 boson decays to lepton or quark pairs**
  - We can reconstruct it in the e^+e^- or $\mu^+\mu^-$ decay modes



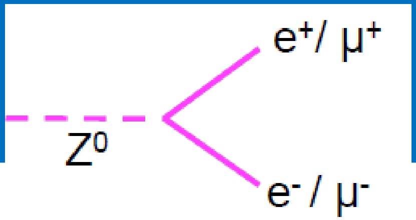
- Discovery and study of the Z^0 boson was a critical part understanding the electroweak force.

- And now, at the LHC?
  - **Important test of theory**: does the measurement agree with the theoretical prediction at LHC collision energy?
  - **A standard candle** for studying reconstruction and deriving calibrations.
  - Can be used for luminosity determination!

Physics analyses



Reconstructing Z^0's



How do we know it's a Z^0?

Identify Z decays using the invariant mass of the 2 leptons
$M^2 = (L_1+L_2)^2$ where $L_i = (E_i, \mathbf{p}_i)$ = 4-vector for lepton i

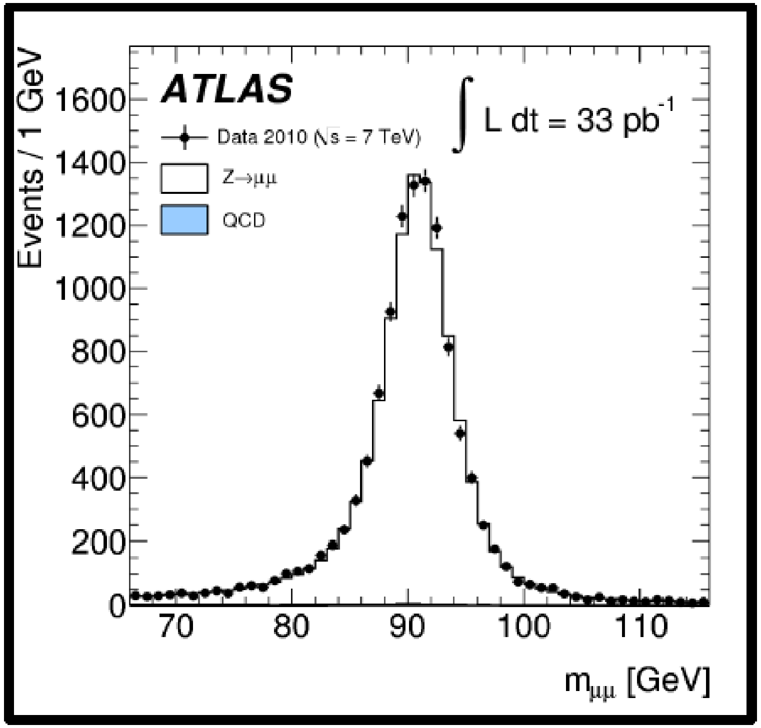
Under assumption that lepton is massless compared to mass of Z^0
=> $M^2 = 2 E_1 E_2 (1-\cos\vartheta_{12})$ where ϑ_{12}= angle between the leptons

- So need to reconstruct the electron and muon energy and direction. Then can calculate the mass.

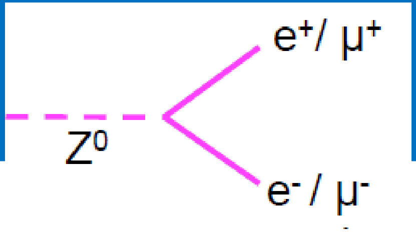
Select Z^0 events with 'analysis cuts':

- Events with 2 high momentum electrons or muons
- Require the electrons or muons are of opposite charge
- With di-lepton mass close to the Z^0 mass (e.g. $70<m_{l+l-}<110$ GeV)

Very little background in Z^0 mass region!



Reconstructing Z^0's



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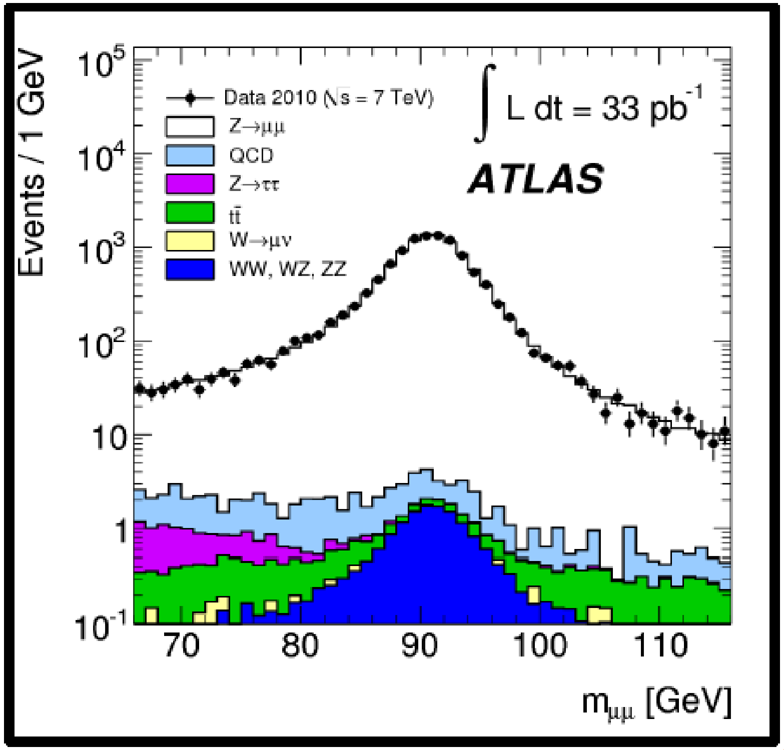
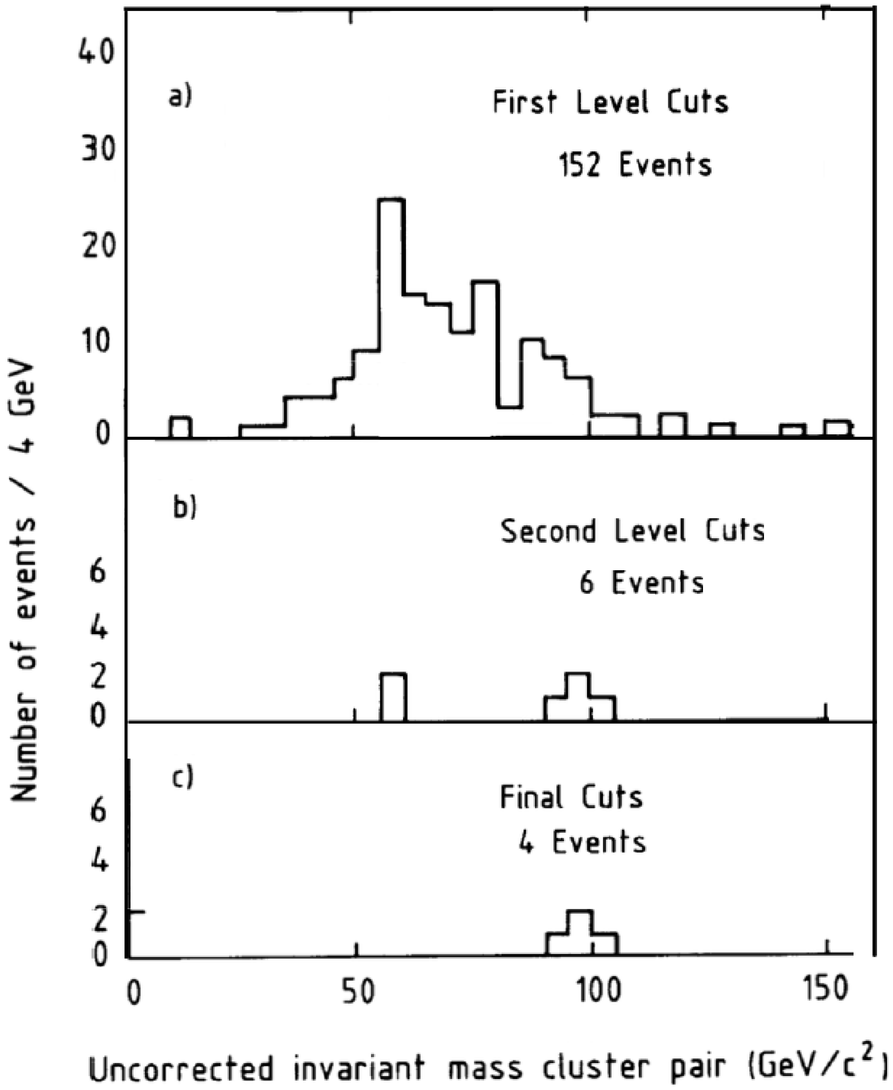


A step back in time …



Z->ee in UA1

Two EM clusters with E_T>25GeV.

As above plus a track with p_T>7GeV pointing to the cluster. Hadronic and track isolation requirements applied.

A second custer has also an isolated track.

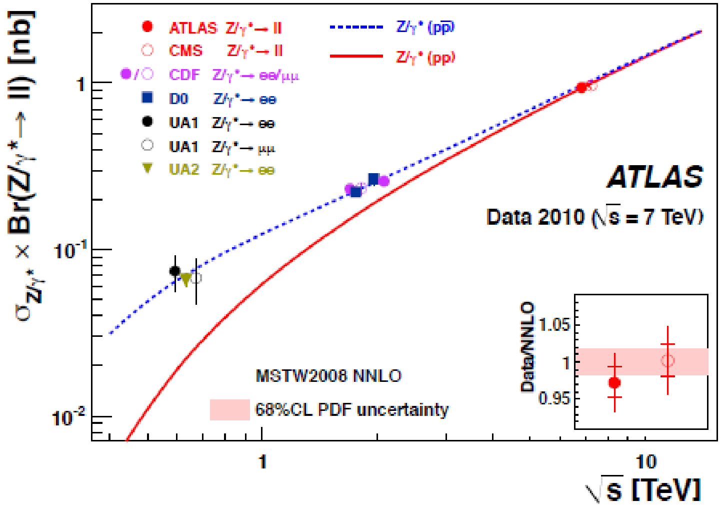
http://www.nobelprize.org/nobel_prizes/physics/laureates/1984/rubbia-lecture.pdf 20

Measuring the Z^0 cross-section

Theoretically

Cross-section calculated for:

- Specific production mechanism (pp, $p\bar{p}$, e^+e^-)
- Centre-of-Mass of the collisions (7, 8, 13 TeV at LHC)



Experimentally

$$\sigma \cdot \mathrm{BR} = \frac{\text{Number of events}}{\alpha \cdot \epsilon \cdot \mathrm{L}}$$

N of events:

N of events on data – N of expected background events

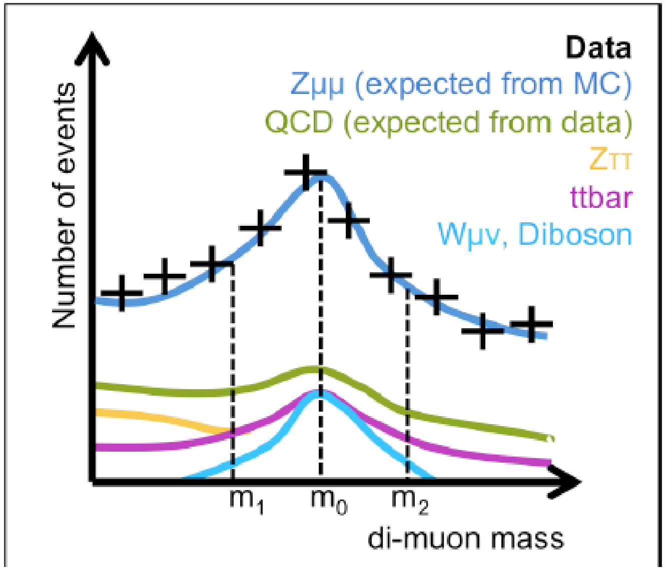
α – acceptance:

fraction of events passing selection requirements

ε – efficiency:

reconstruction efficiency of relevant objects

L – luminosity



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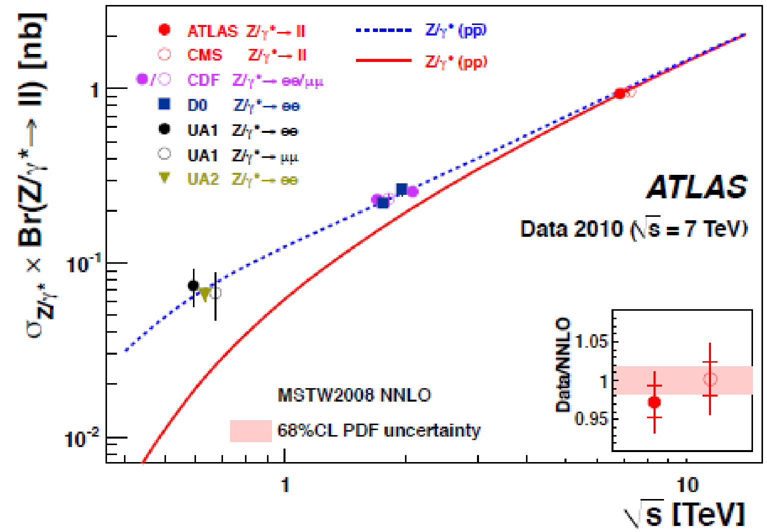

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N of events on data – N

α – acceptance:

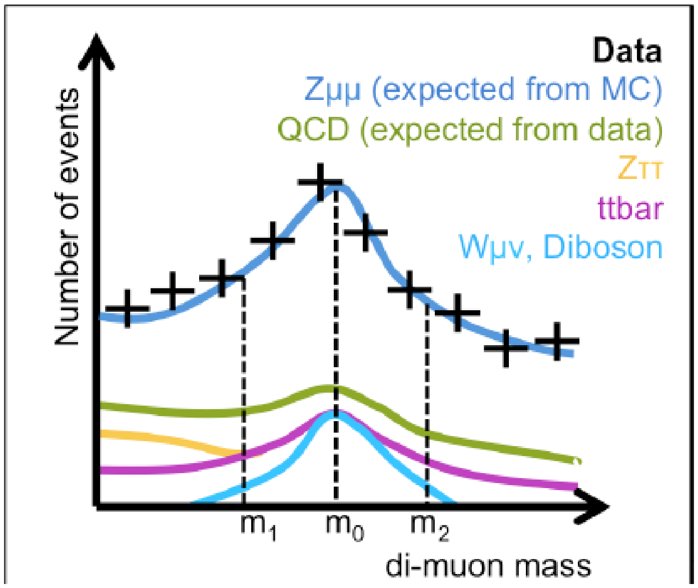
fraction of events passi

ε – efficiency:

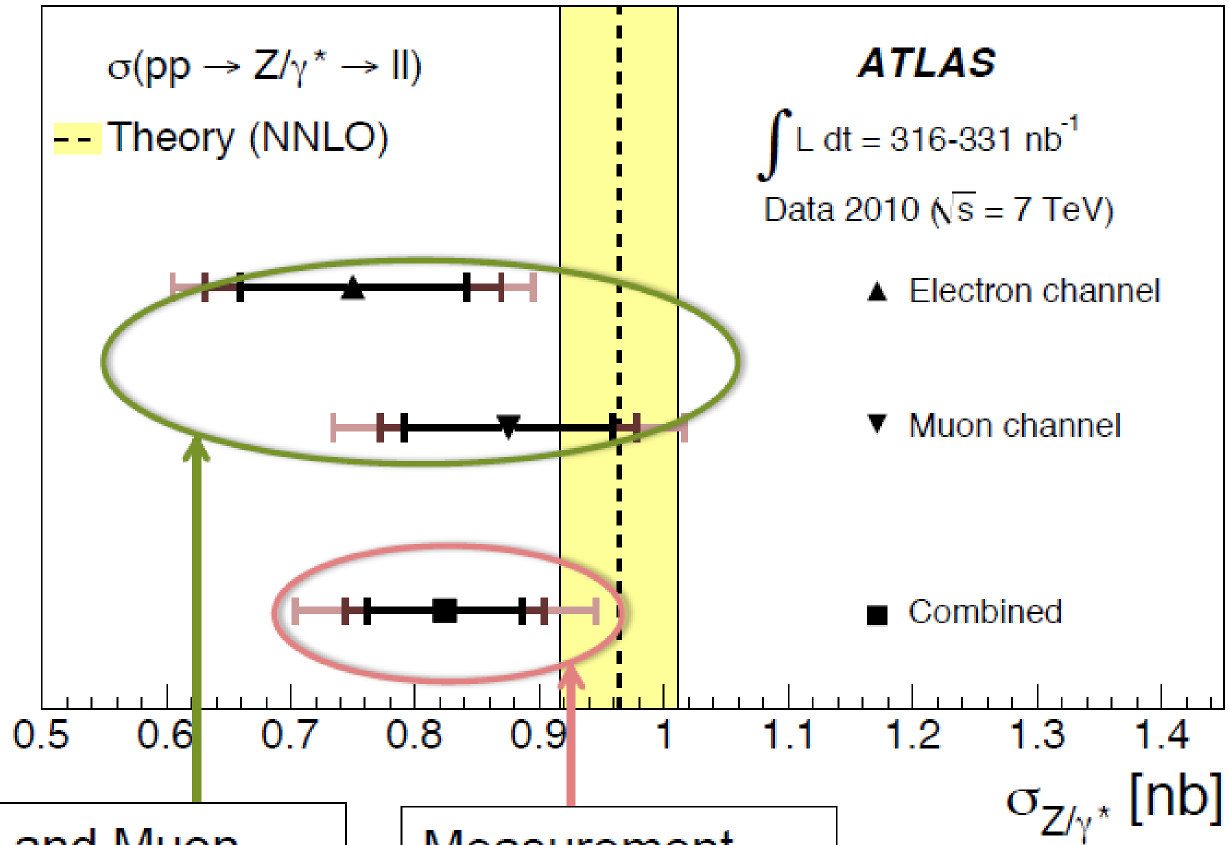
reconstruction efficienc

L – luminosity

All numbers carry uncertainties – both "statistical" and "systematic"!



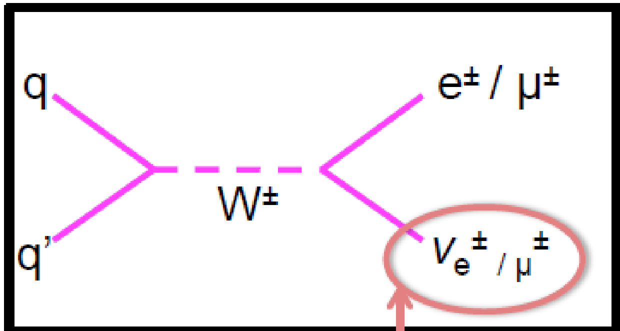
Measuring the Z^0 cross-section



Electron and Muon channel agree within uncertainties

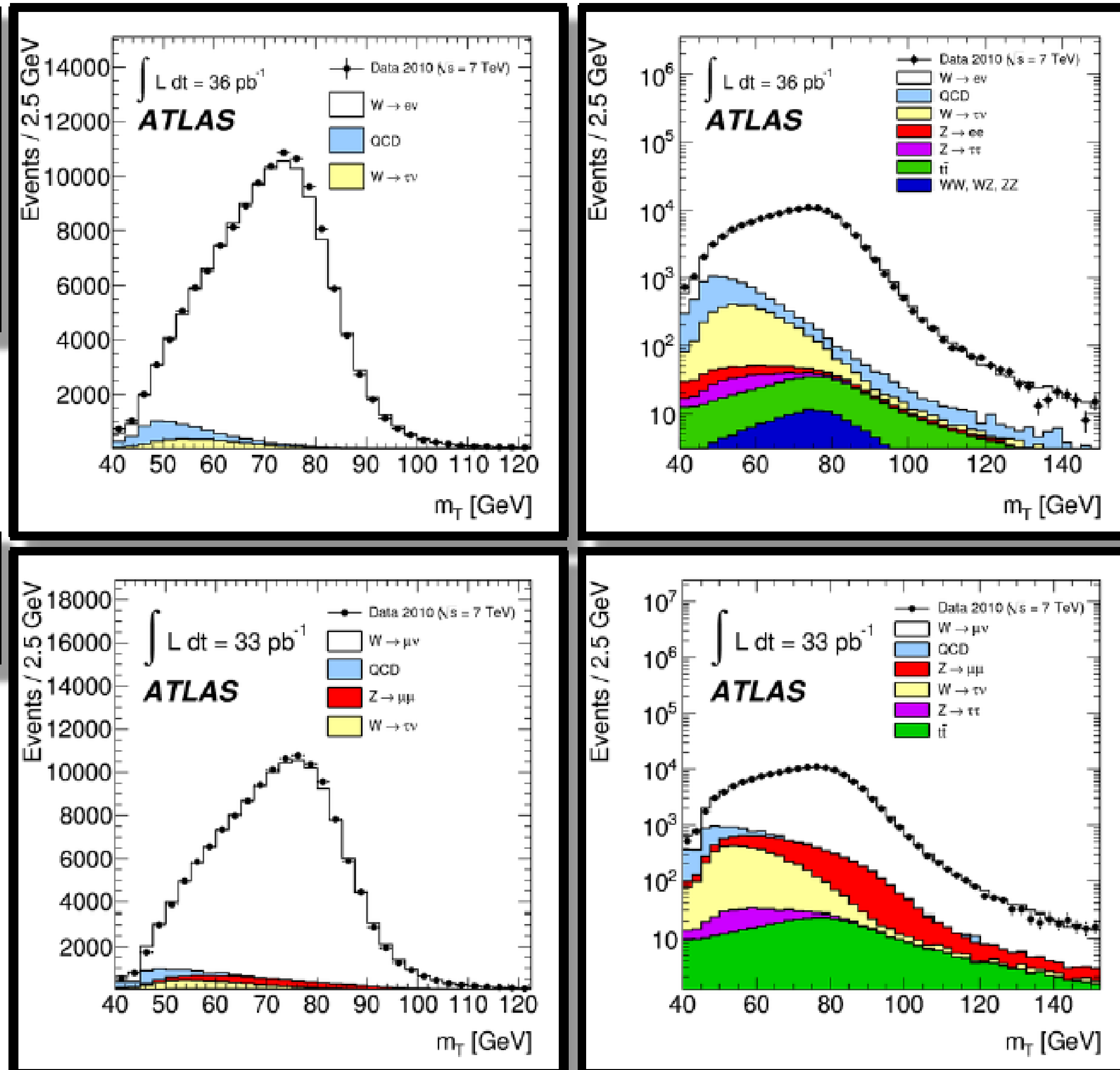
Measurement consistent with prediction within uncertainties

Measuring the W cross-section

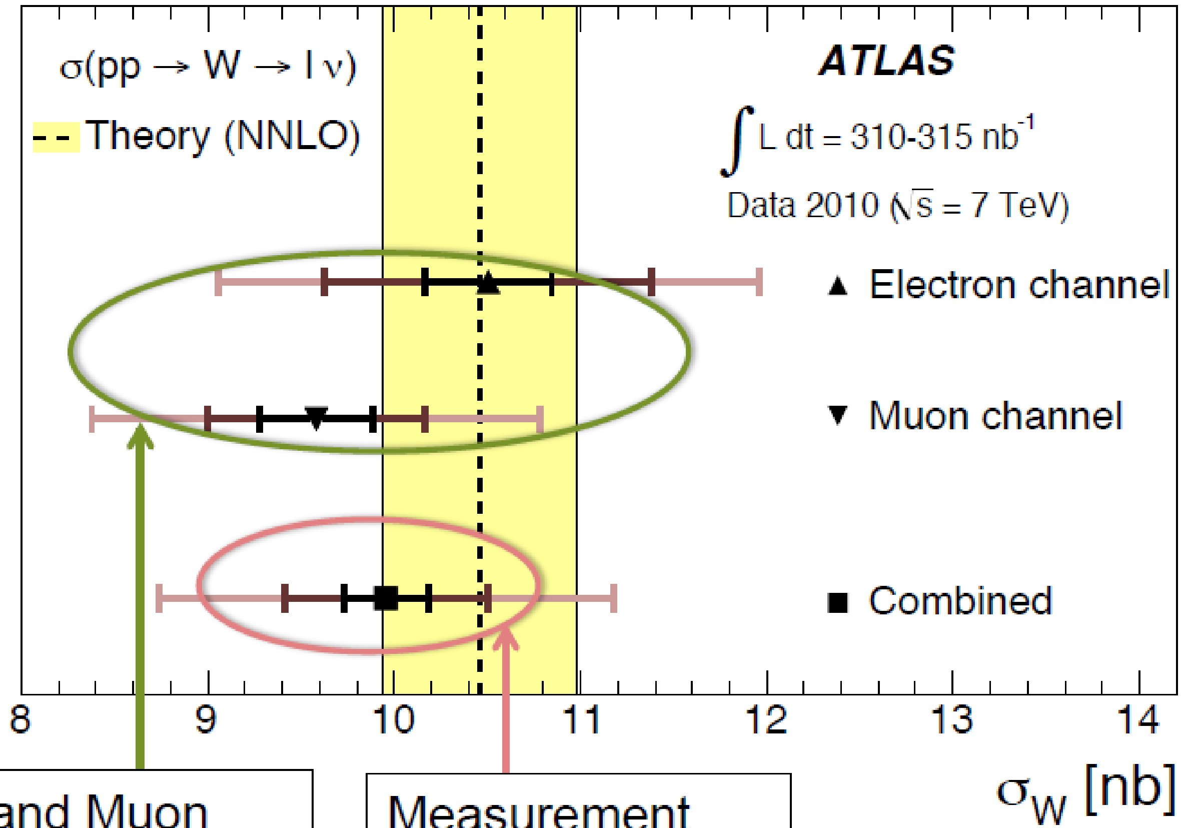


Available in the transverse plane only!

$$M_T^2 = 2\, E_{T1}\, E_{T2}\, (1-\cos\vartheta_{12})$$



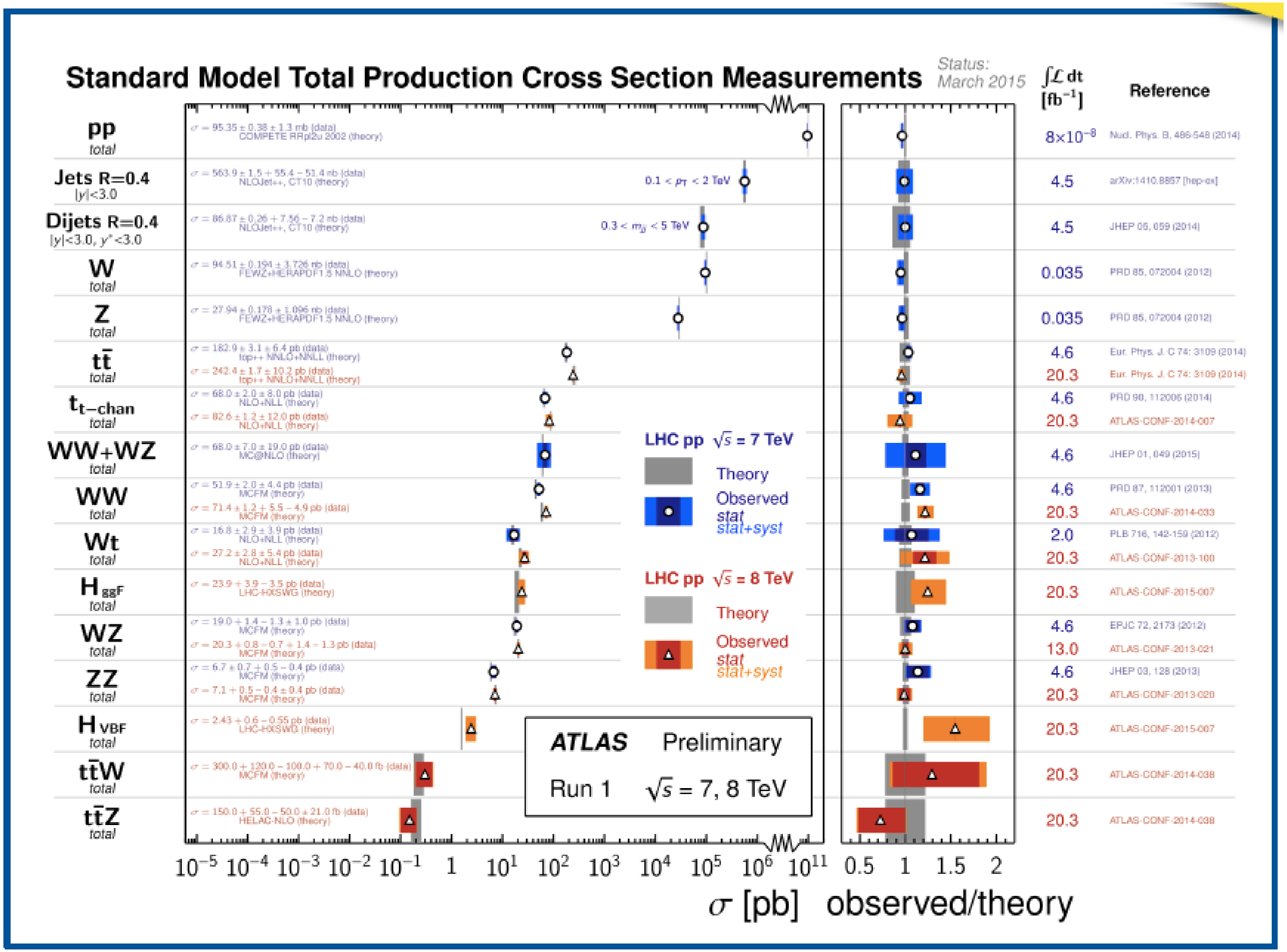
Measuring the W cross-section



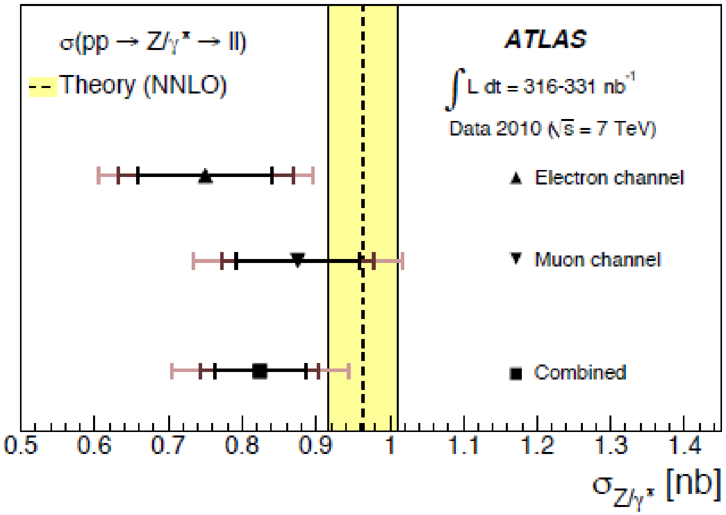
Electron and Muon channel agree within uncertainties

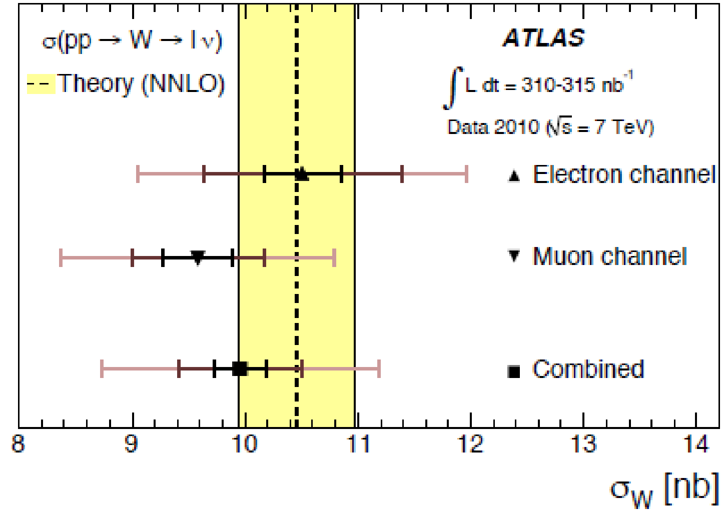
Measurement consistent with prediction within uncertainties

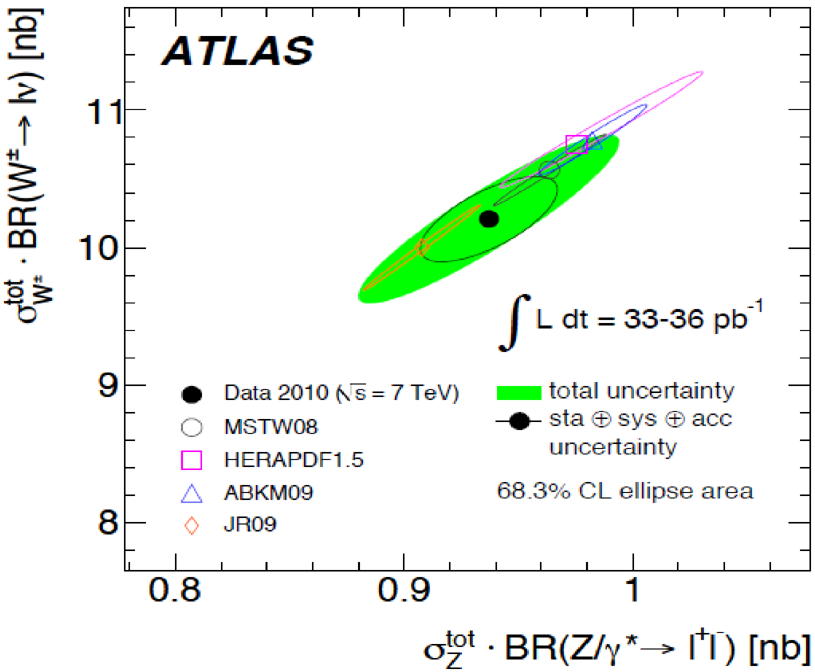
„Final” calibration

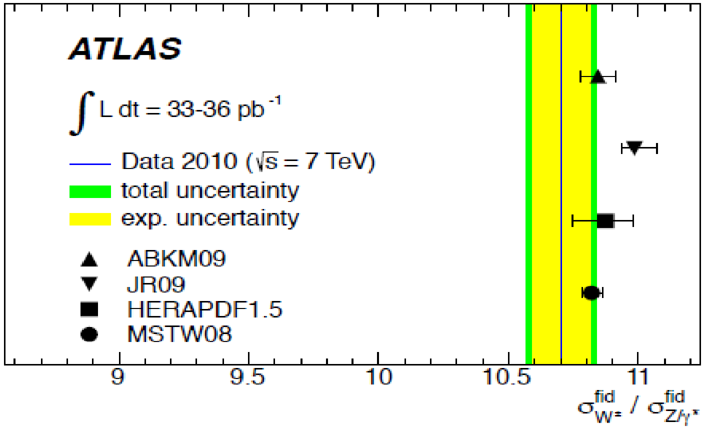


Measuring cross-sections ratio

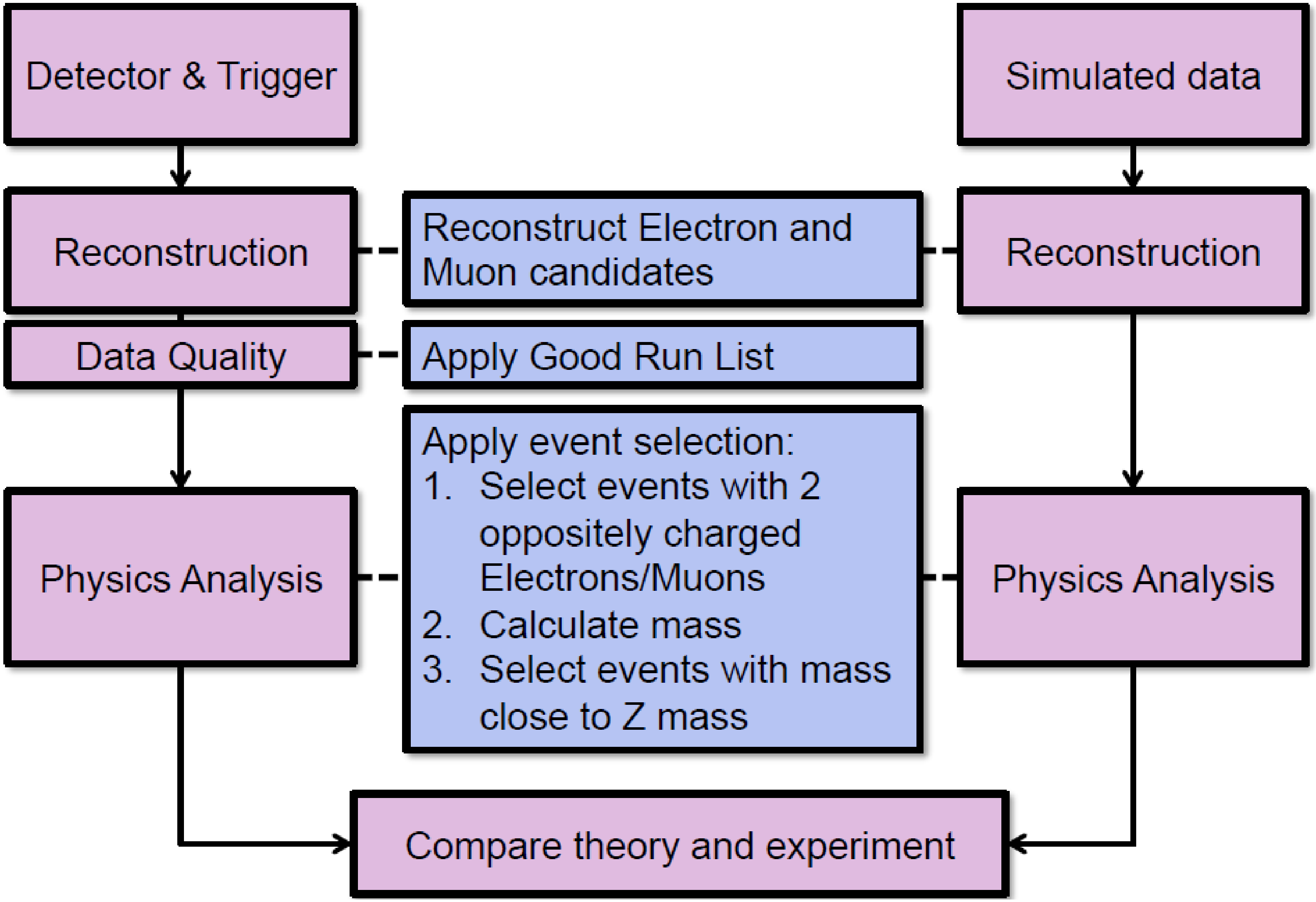








Analysis flow in Z^0 cross-section measurement



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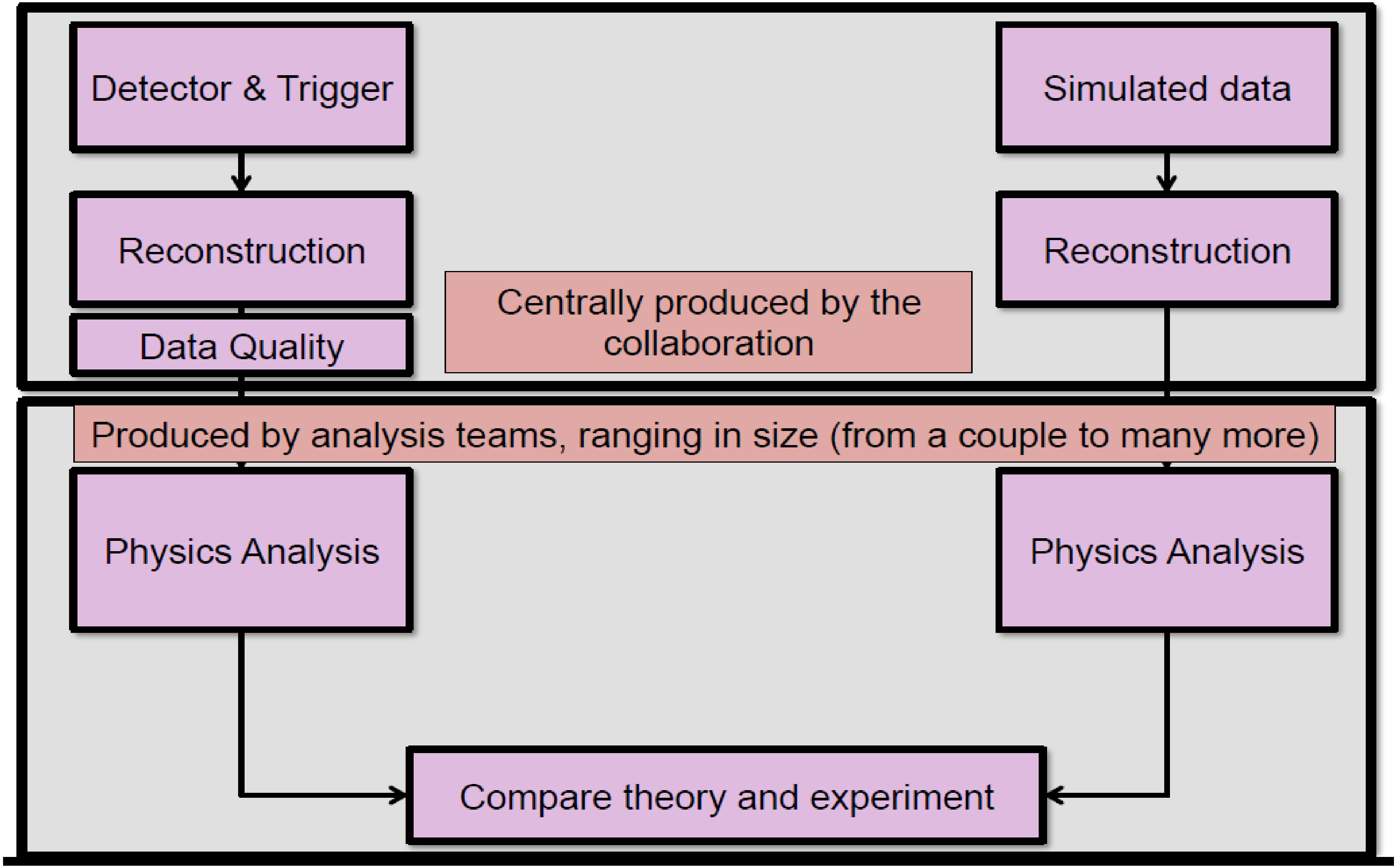
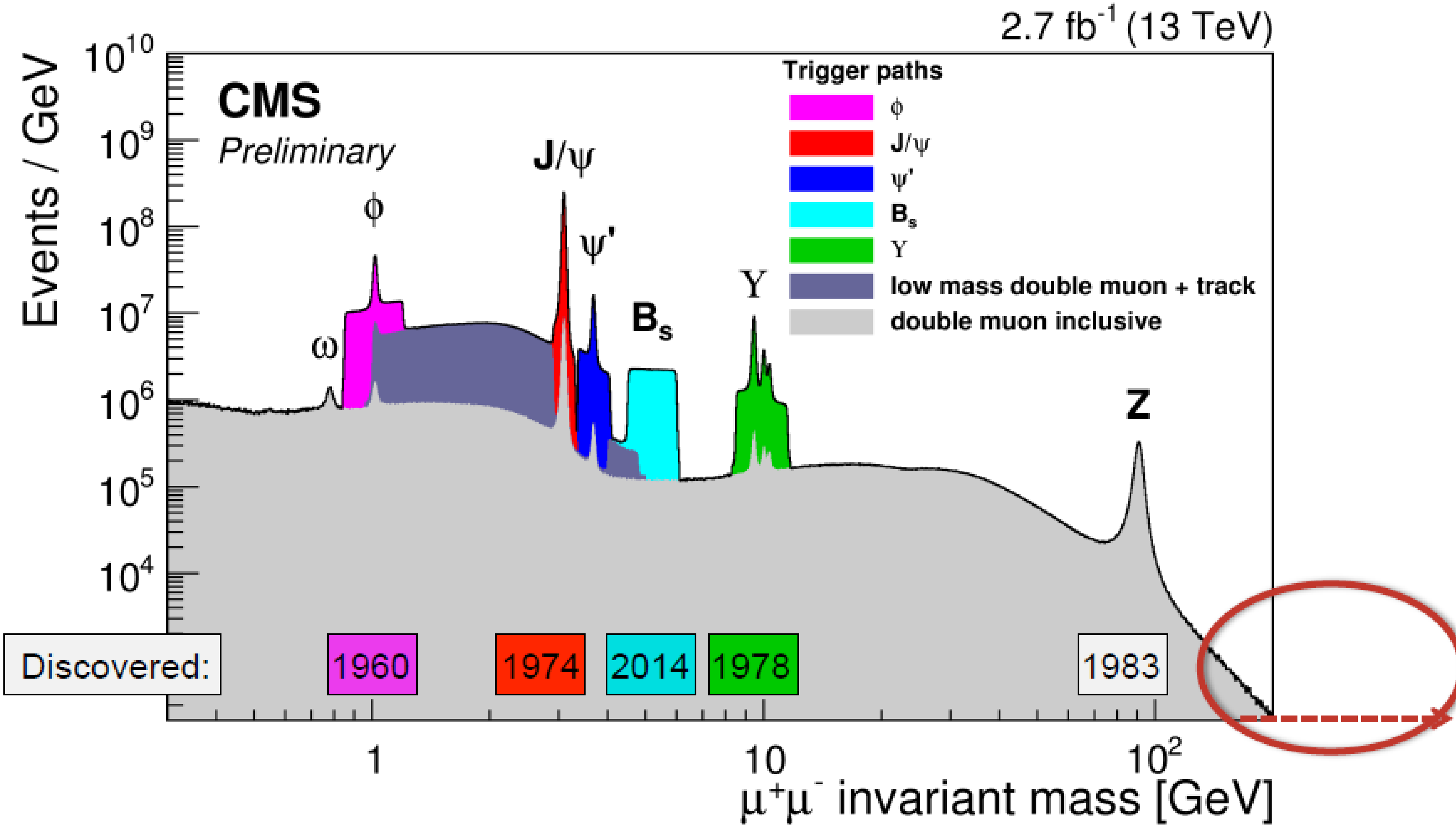




What's out there?

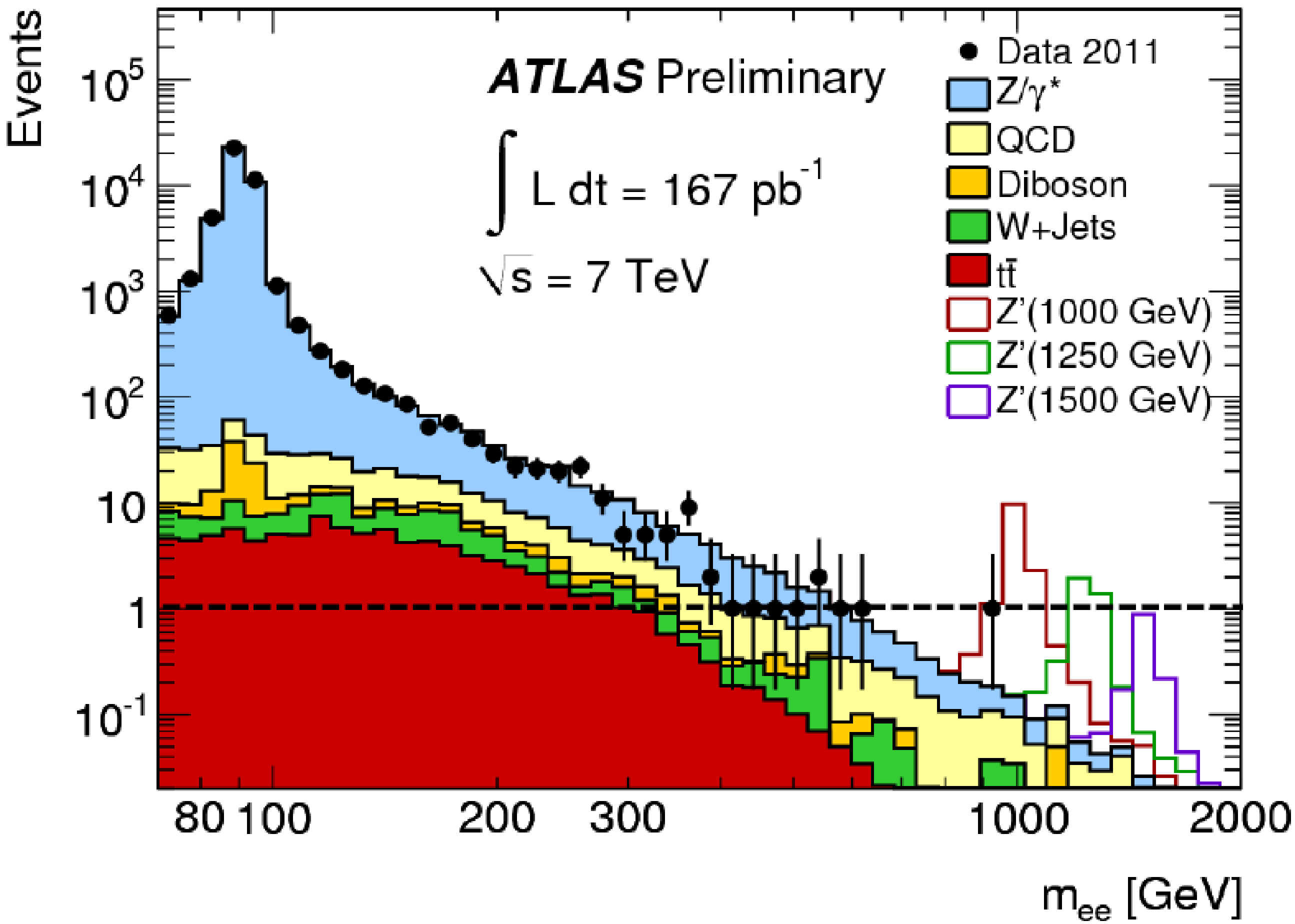
Simple search example

SIMPLE SEARCH EXAMPLE:

SEARCH FOR A HEAVY Z’

Search for a new heavy Z'

- Like Z->ee but at higher mass.



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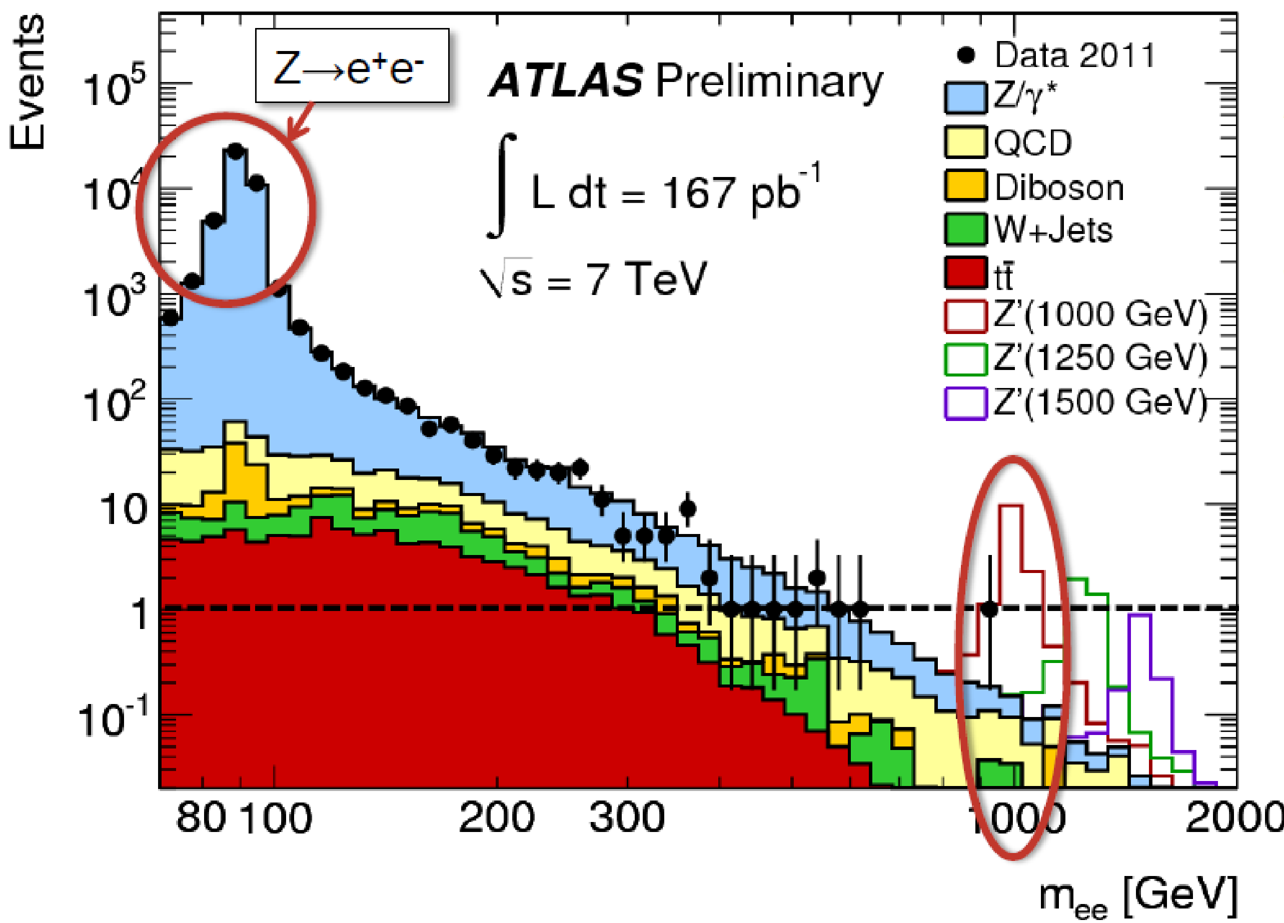


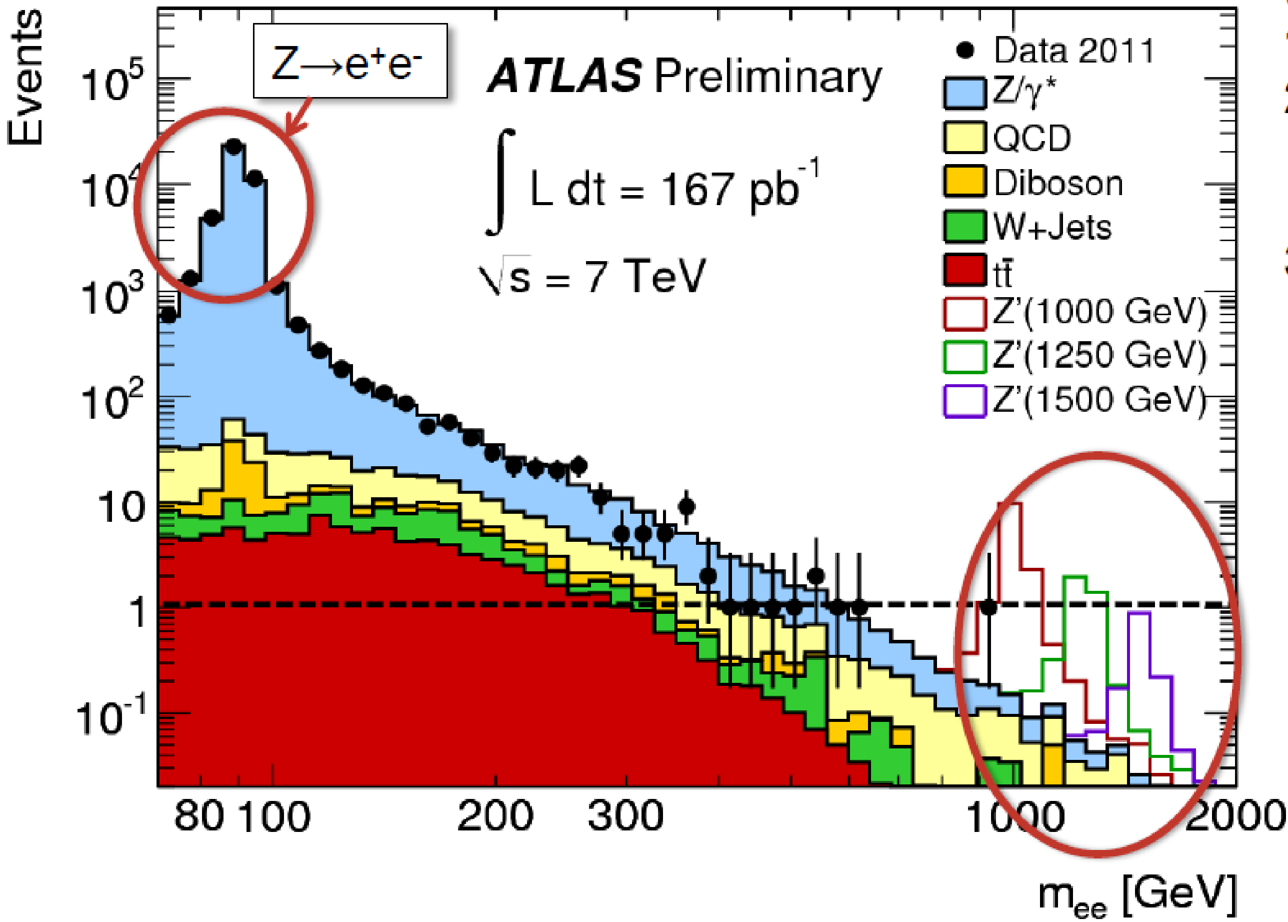
Select 2 electron candidates and plot their invariant mass for:

1. **Data**
2. **Simulated background events**
3. **Simulated signal with different masses**

Data inconsistent with a 1TeV Z'

Search for a new heavy Z’

◎ **Like Z->ee but at higher mass.**



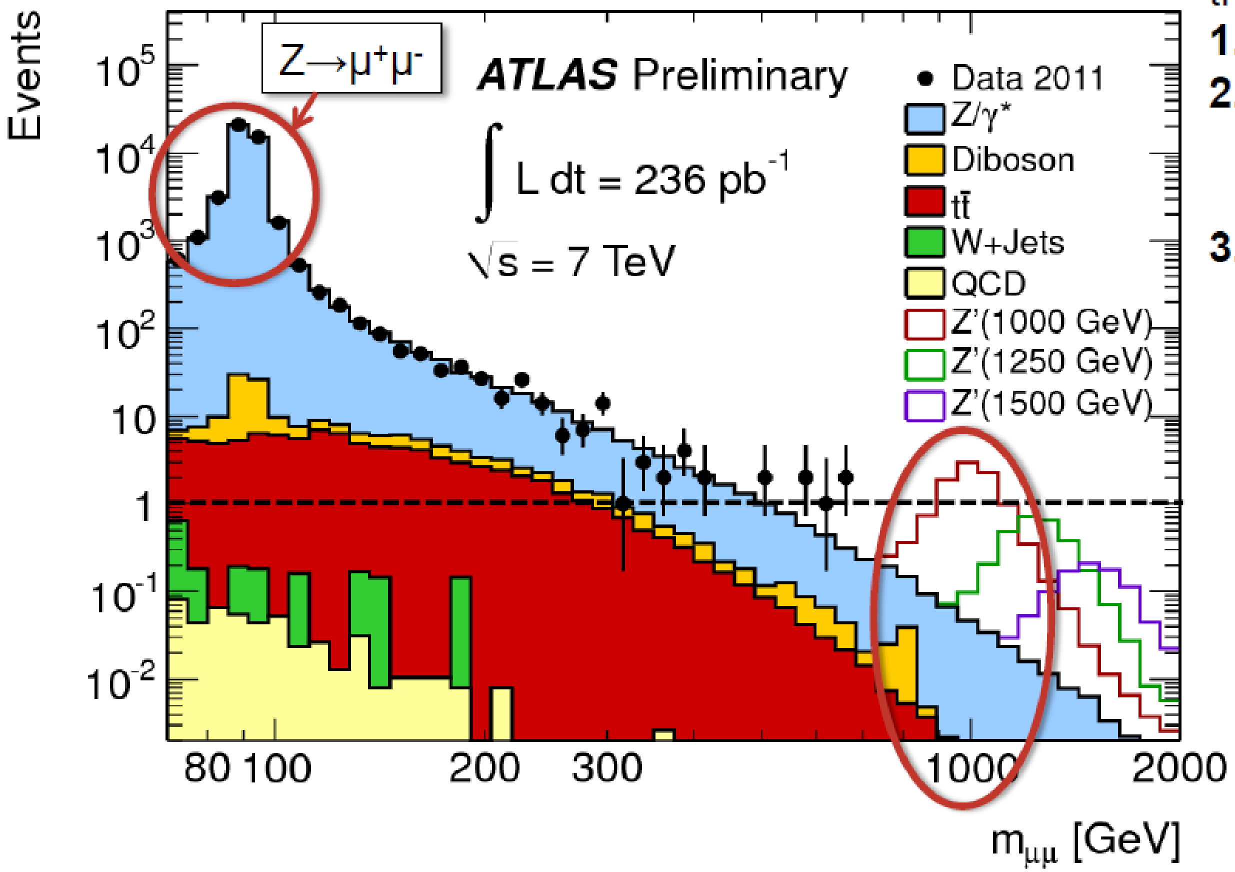
Select 2 electron candidates and plot their invariant mass for:

1. **Data**
2. **Simulated background events**
3. **Simulated signal with different masses**

Cross-section decreases with mass (higher the mass of the Z’, the more data needed to discover it)

Search for a new heavy Z'

And similar for muons



Select 2 muon candidates and plot their invariant mass for:

1. **Data**
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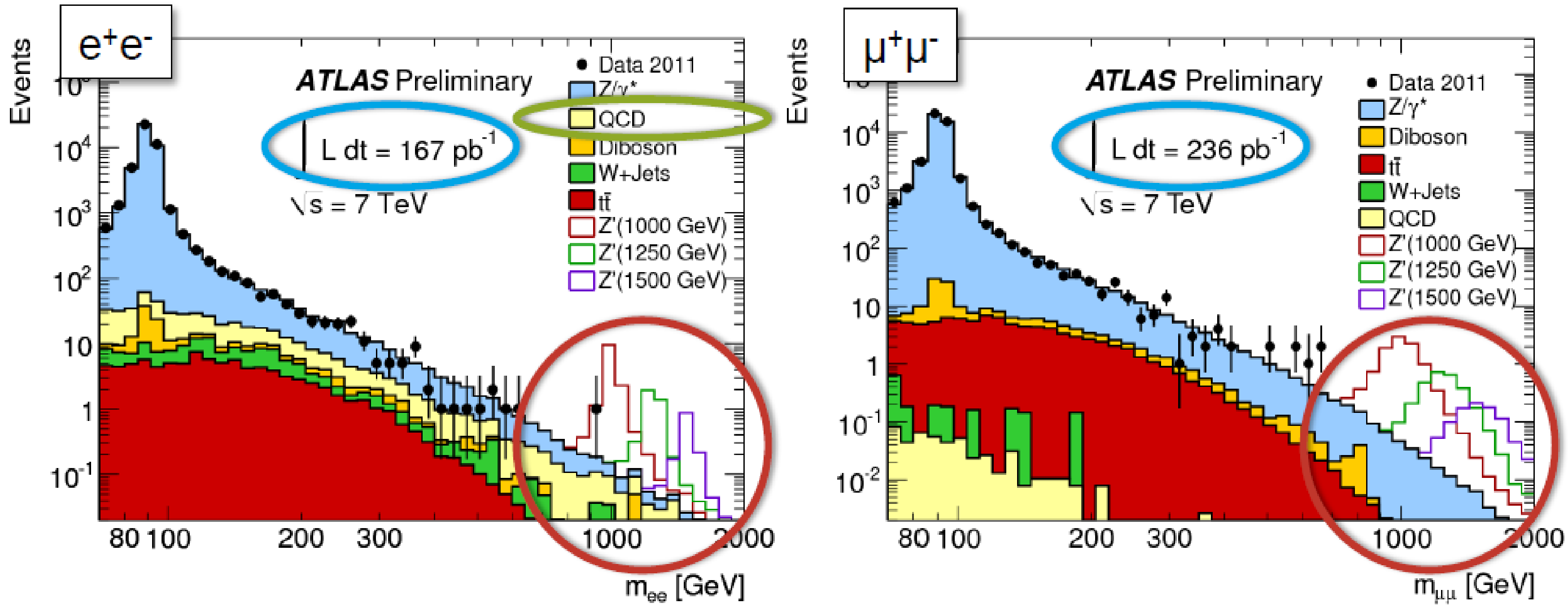
3. **Simulated signal with different masses**

Data inconsistent with a 1TeV Z'

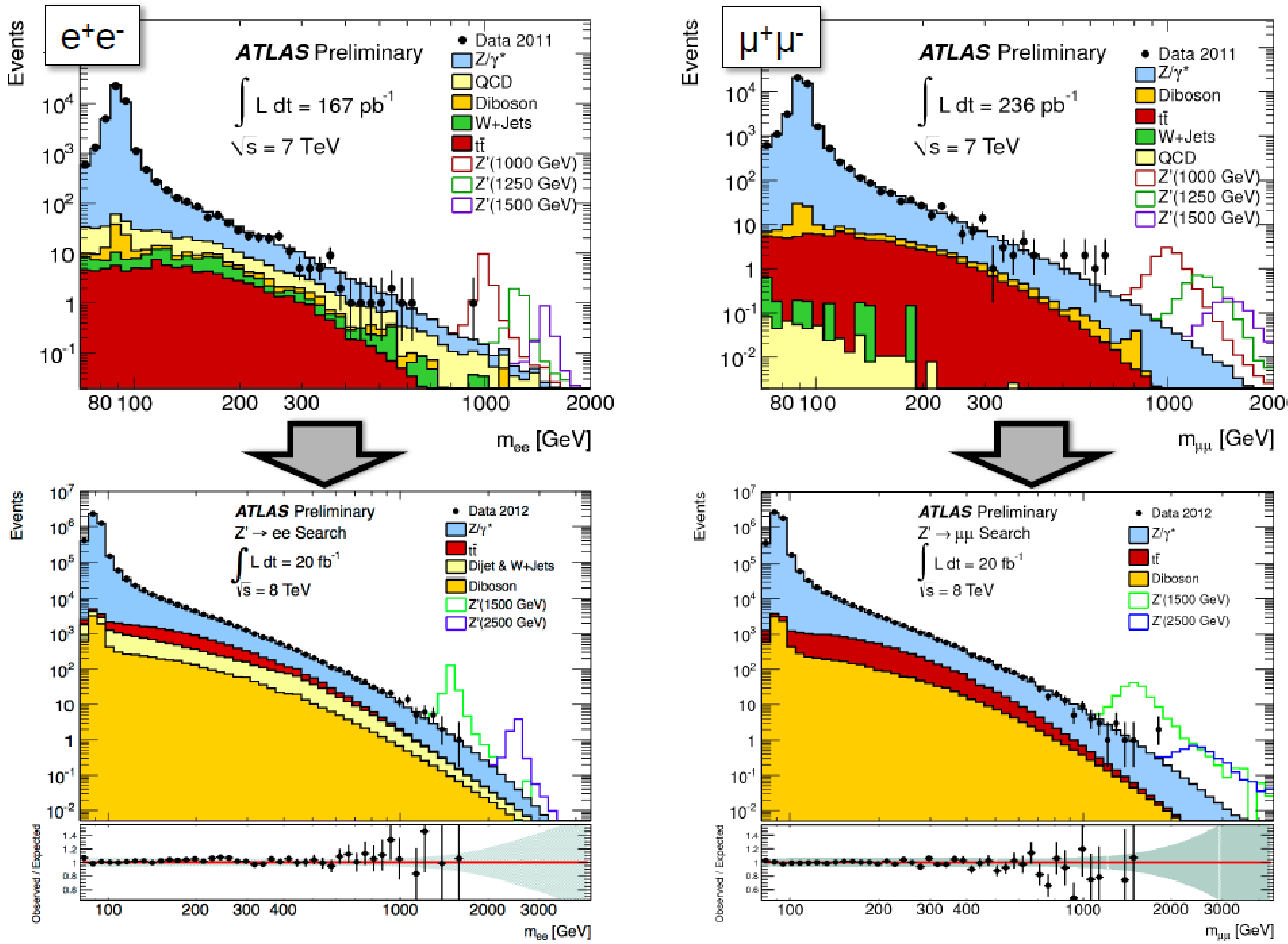
A small comparison



Differences in:

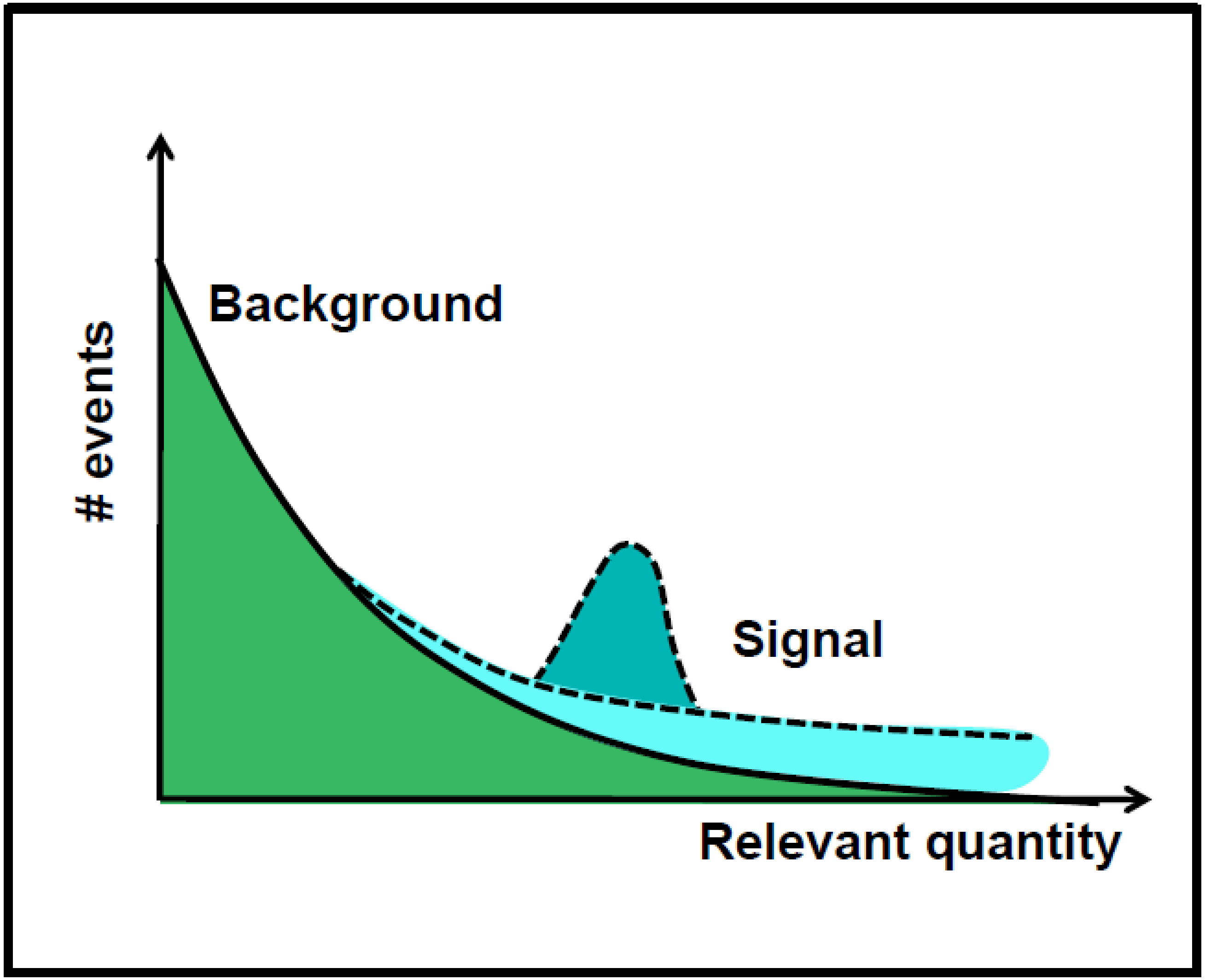
- **Resolution**
- **Background composition**
- **Dataset**

Evolution…

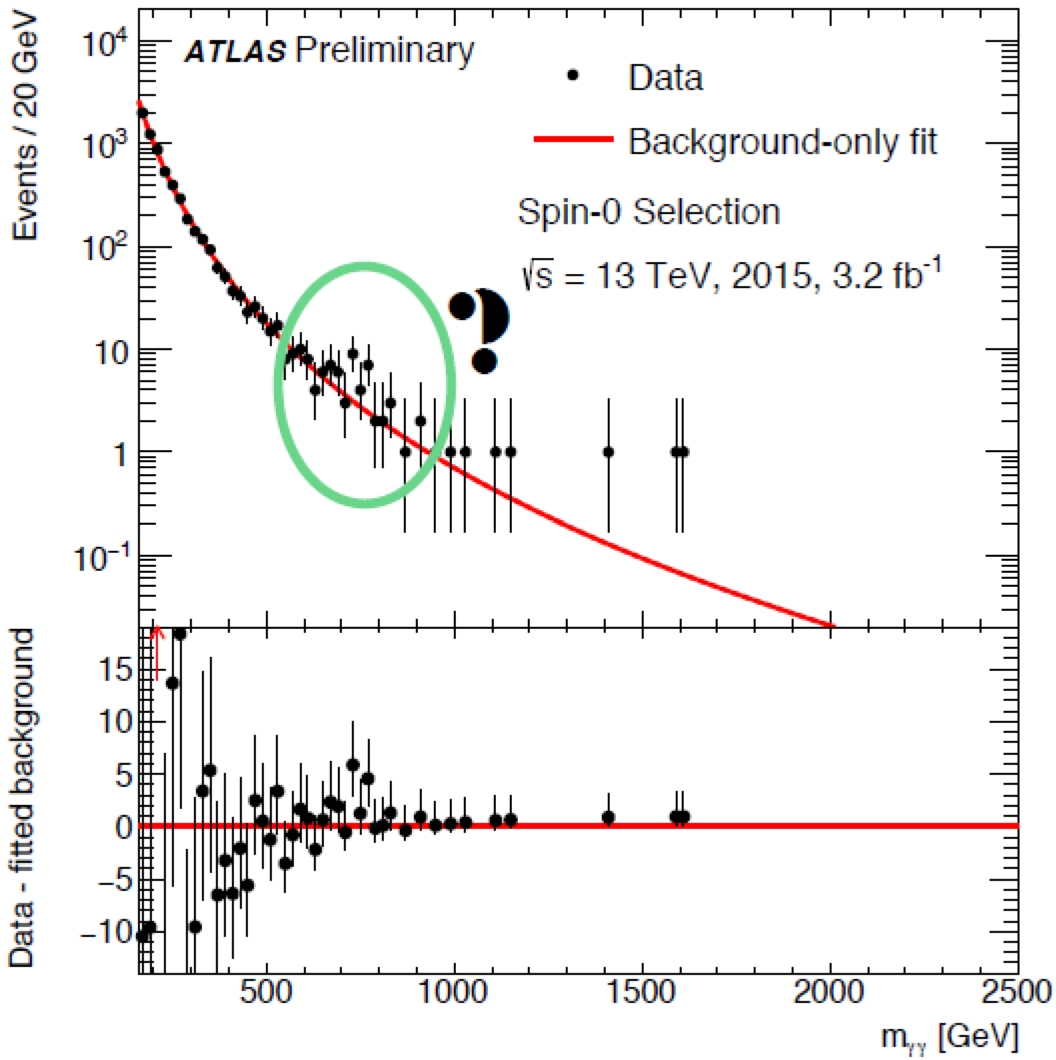


e+e-
ATLAS Preliminary
∫ L dt = 167 pb-1
√s = 7 TeV
Data 2011
Z/γ*
QCD
Diboson
W+Jets
tt̄
Z'(1000 GeV)
Z'(1250 GeV)
Z'(1500 GeV)
Events
mee [GeV]
μ+μ-
ATLAS Preliminary
∫ L dt = 236 pb-1
√s = 7 TeV
Data 2011
Z/γ*
Diboson
tt̄
W+Jets
QCD
Z'(1000 GeV)
Z'(1250 GeV)
Z'(1500 GeV)
Events
mμμ [GeV]
ATLAS Preliminary
Z' → ee Search
∫ L dt = 20 fb-1
√s = 8 TeV
Data 2012
Z/γ*
tt̄
Dijet & W+Jets
Diboson
Z'(1500 GeV)
Z'(2500 GeV)
Events
Observed / Expected
mee [GeV]
ATLAS Preliminary
Z' → μμ Search
∫ L dt = 20 fb-1
√s = 8 TeV
Data 2012
Z/γ*
tt̄
Diboson
Z'(1500 GeV)
Z'(2500 GeV)
Events
Observed / Expected
mμμ [GeV]

Searches



A well known bump search



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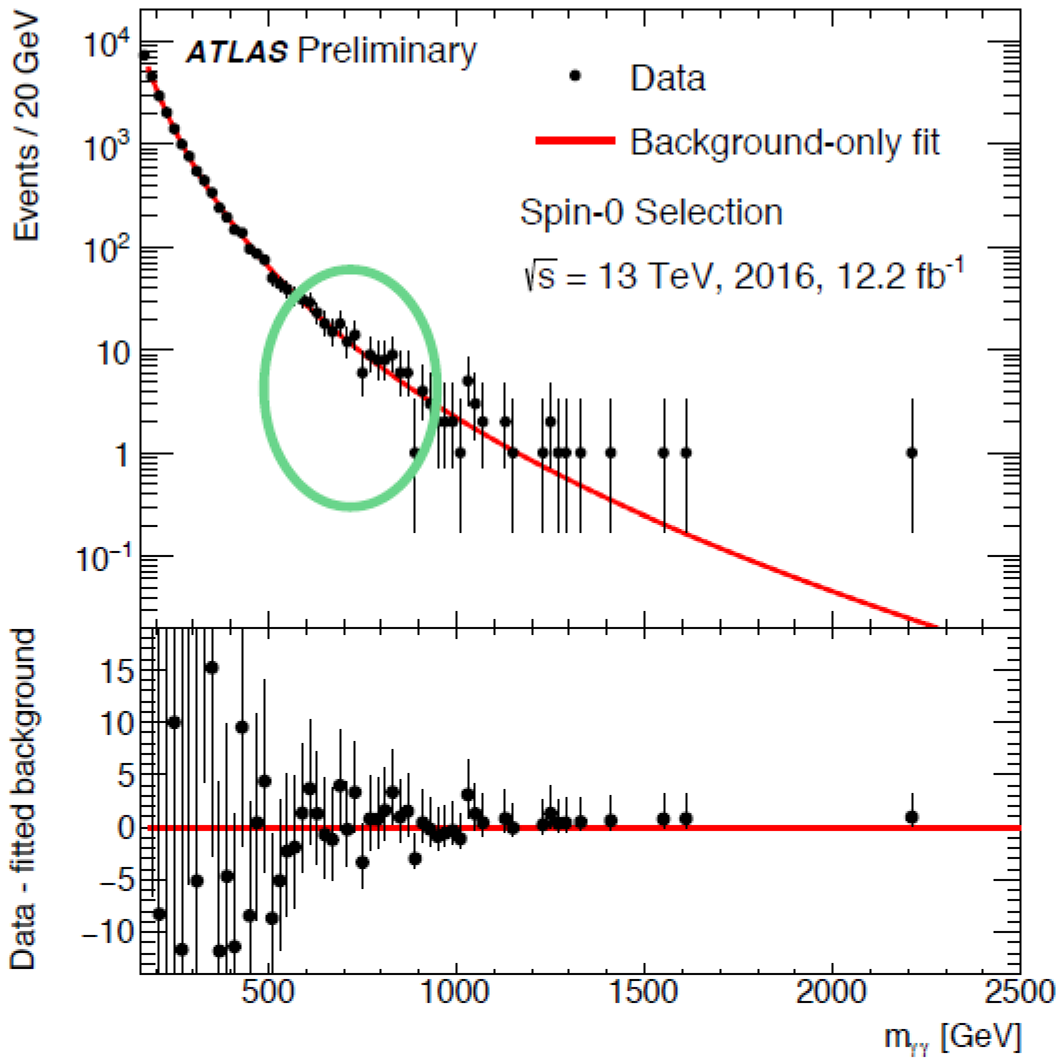
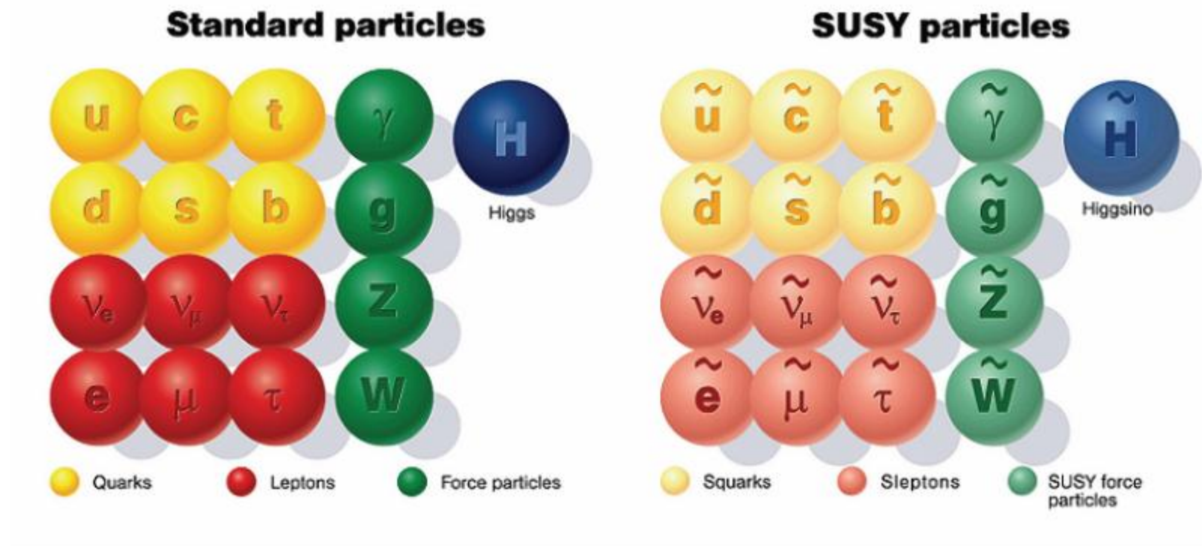


Typical SUSY searches

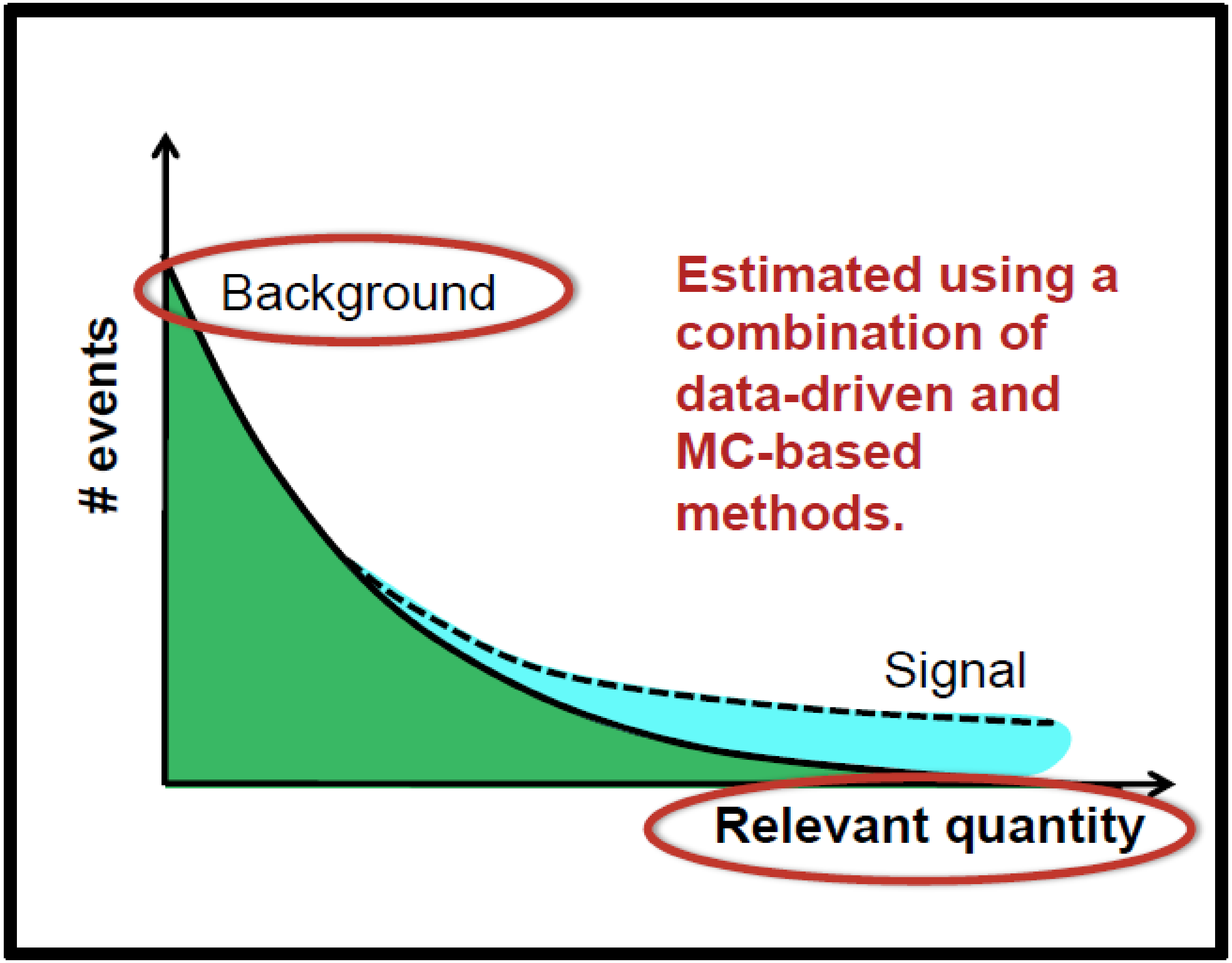
- Super-symmetry?



- Composite quark and/or leptons?
- New Heavy bosons?
- Gravitons?
- Dark Matter particles?
- ...

Any new theory need to agree with the SM!

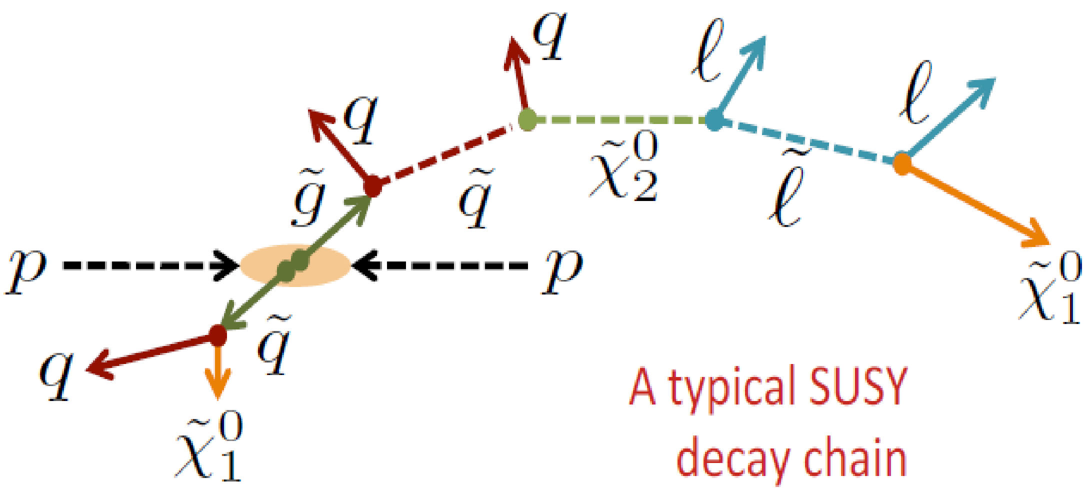
Typical SUSY searches



E.g. MET

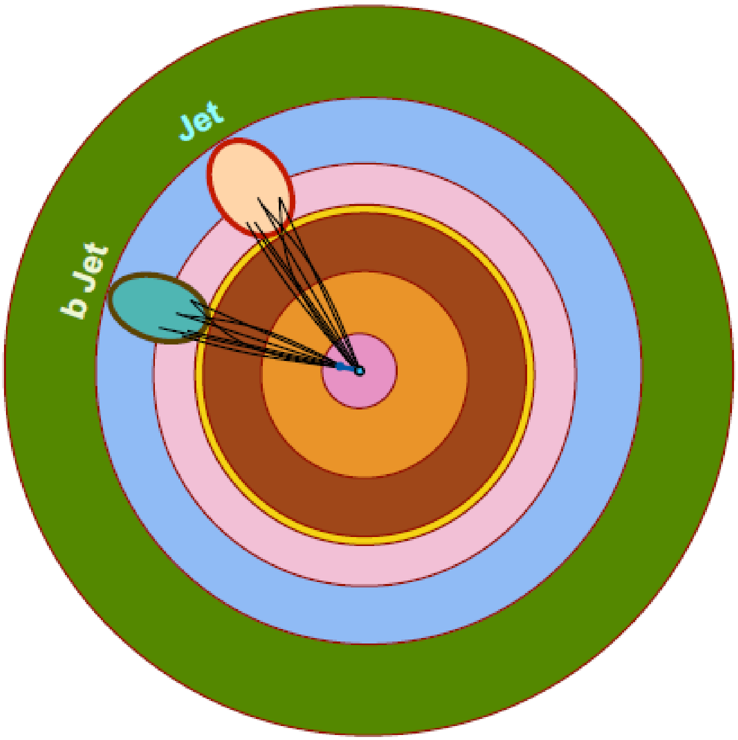
Another search example

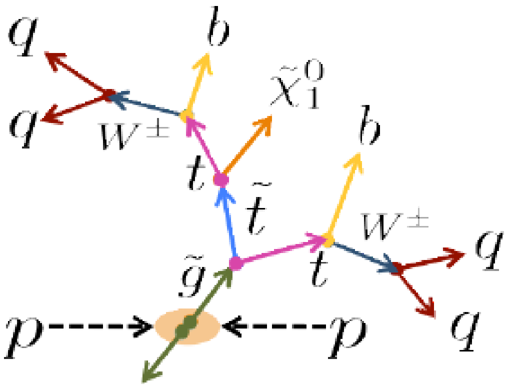
SEARCH FOR SUSY IN EVENTS WITH LARGE JET MULTIPLICITIES



Event selection

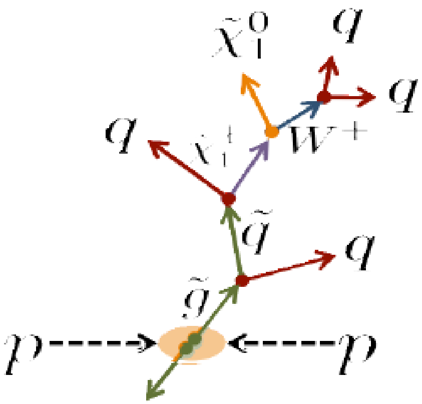
b-jets

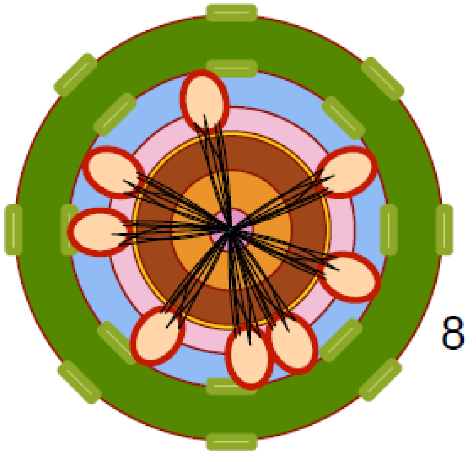




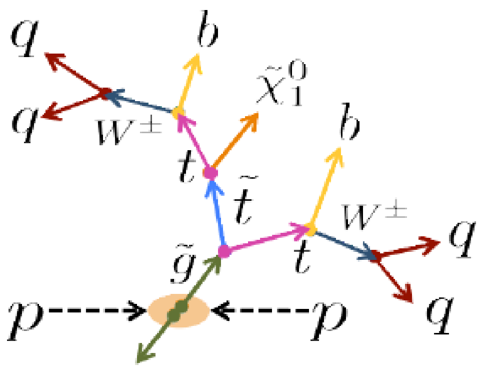
Event selection

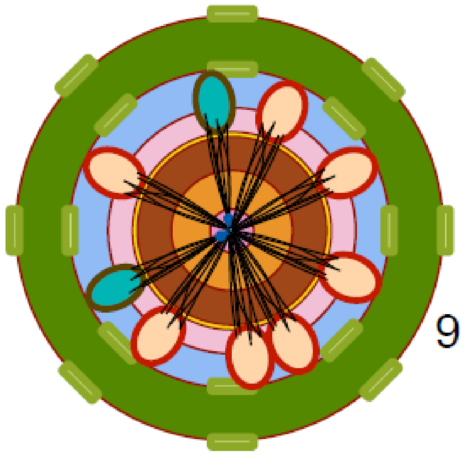
b-jets





8 jets, 0 b-jets



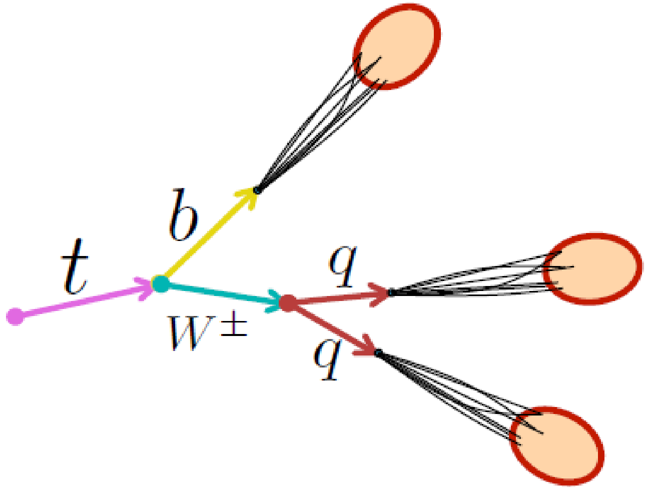


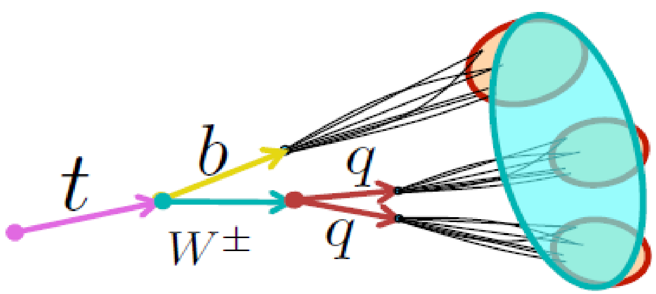
9 jets, ≥2 b-jets

Signal regions can range in jet p_T and jet & b-jet multiplicity.

Event selection

"fat-jets"

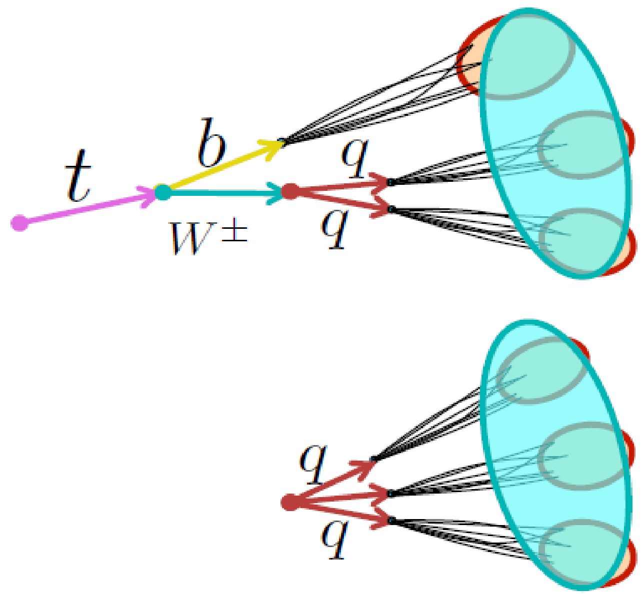


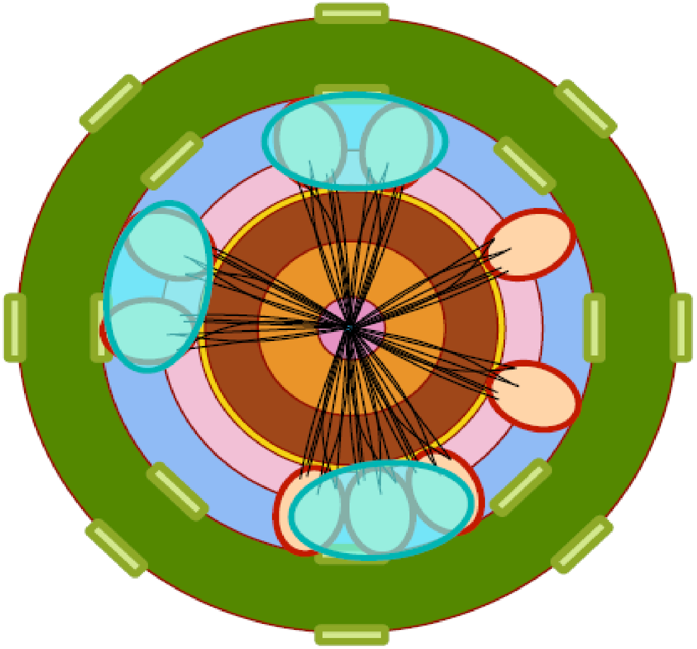


Fat-jets are a key signature in searches for boosted objects, e.g. boosted tops.

Event selection

"fat-jets"





m_j (QCD) $< m_j$ (SUSY)

Proposed in arXiv:1202.0558

$$M_J^{\Sigma} = \sum_{i=1}^{nJ} m_{j_i}$$

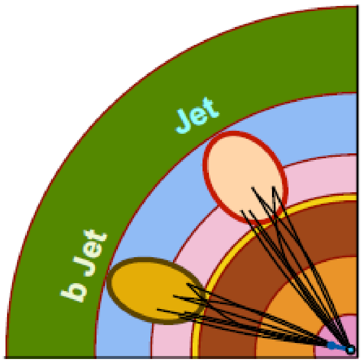
Signal regions can range in jet multiplicity and M_J^{Σ} cuts.

60

Example of search

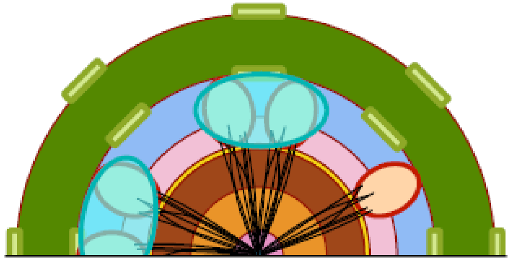
"b-jet stream"

ID	8j50			9j50			≥10j50	7j80			≥8j80		
Jet $\|\eta\|$	< 2.0												
Jet p_T	50 GeV							80 GeV					
Jet count	=8			=9			≥10	=7			≥8		
b-jets	0	1	≥2	0	1	≥2	-	0	1	≥2	0	1	≥2
$ME_T/\sqrt{H_T}$	> 4 GeV ½												



"fat-jet stream"

ID	≥8j50		≥9j50		≥10j50	
Jet $\|\eta\|$	< 2.8					
Jet p_T	50 GeV					
Jet count	≥8		≥9		≥10	
M_J^{Σ} (GeV)	>340	>420	>340	>420	>340	>420
$ME_T/\sqrt{H_T}$	> 4 GeV ½					



Proposed in arXiv:1202.0558

$$M_J^{\Sigma} = \sum_{i=1}^{nJ} m_{j_i}$$

Results

b-jet stream

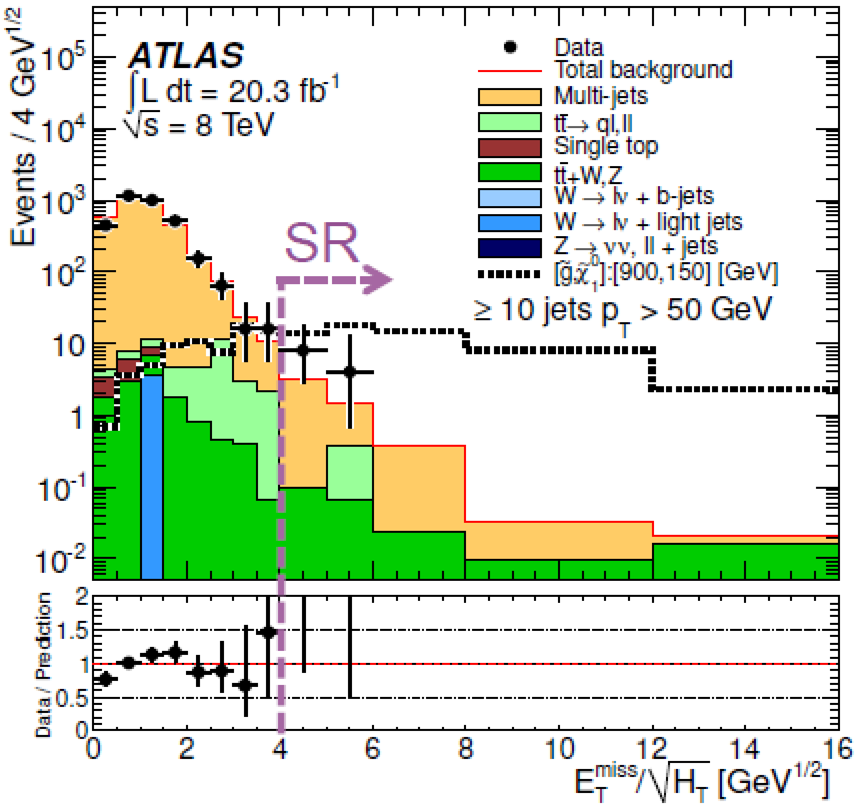
ID	8j50			9j50			≥10j50
b-jets	0	1	≥2	0	1	≥2	0
Expected evts	35±4	40±10	50±10	3.3±0.7	6.1±1.7	8.0±2.7	1.37±0.35
Observed evts	40	44	44	5	8	7	3
Significance (σ)	0.7	-0.02	-0.6	0.8	0.6	-0.28	1.11

ID	7j80			≥8j80		
b-jets	0	1	≥2	0	1	≥2
Expected evts	11.0±2.2	17±6	25±10	0.9±0.6	1.5±0.9	3.3±2.2
Observed evts	12	17	13	2	1	3
Significance (σ)	0.05	-0.14	-1.0	0.9	-0.28	-0.06

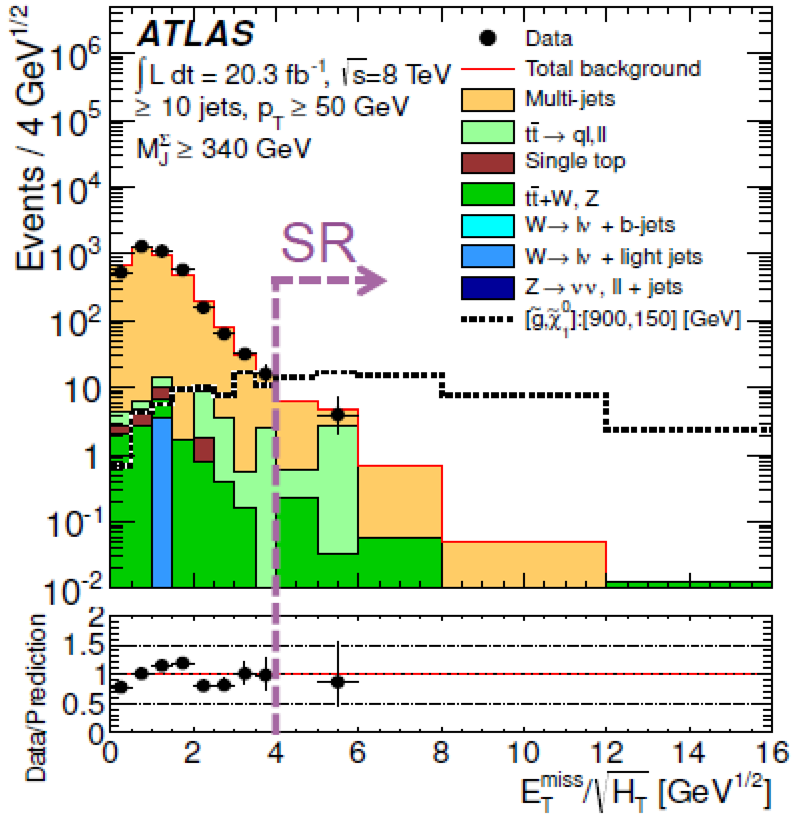
fat-jet stream

ID	≥8j50		≥9j50		≥10j50	
M_J^{Σ} (GeV)	340	420	340	420	340	420
Expected evts	75±19	45±14	17±7	11±5	3.2±3.7	2.2±2.0
Observed evts	69	37	13	9	1	1
Significance (σ)	-0.27	-0.6	-0.6	-0.34	-0.8	-0.6

Results



ATLAS
∫L dt = 20.3 fb⁻¹
√s = 8 TeV
Data
Total background
Multi-jets
tt̄→ ql,ll
Single top
tt̄+W,Z
W → lν + b-jets
W → lν + light jets
Z → νν, ll + jets
[g̃,χ̃⁰₁]:[900,150] [GeV]
SR
≥ 10 jets p_T > 50 GeV
Events / 4 GeV^1/2
Data / Prediction
E_T^miss/√H_T [GeV^1/2]

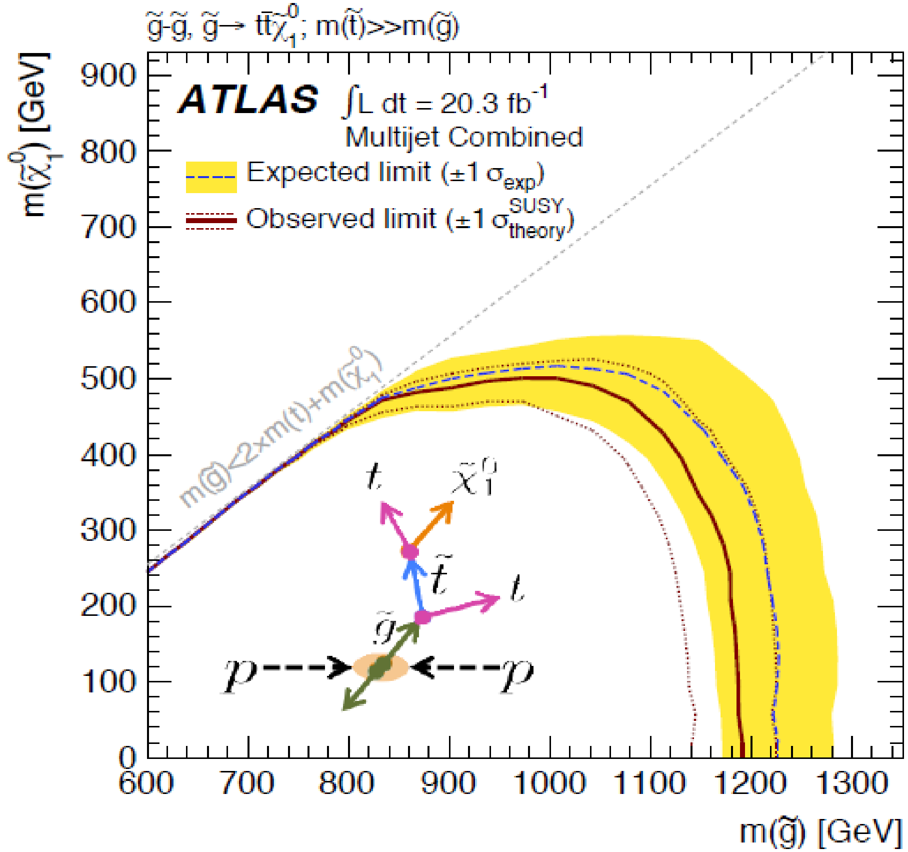


ATLAS
∫L dt = 20.3 fb⁻¹, √s=8 TeV
≥ 10 jets, p_T ≥ 50 GeV
M_J^Σ ≥ 340 GeV
Data
Total background
Multi-jets
tt̄→ ql,ll
Single top
tt̄+W, Z
W→ lν + b-jets
W→ lν + light jets
Z→ νν, ll + jets
[g̃,χ̃⁰₁]:[900,150] [GeV]
SR
Events / 4 GeV^1/2
Data/Prediction
E_T^miss/√H_T [GeV^1/2]

Interpretations

Real or Simplified models

- Simplified topologies include typically one production and one decay process. Provide useful information for theorists.



CONTENTS OF A RANDOM SEARCH INTERNAL DOCUMENTATION

Contents

Compotents of a physics analysis

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Background determination
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

Compotents of a physics analysis

- Data-set and Monte Carlo samples
- Trigger
- Object definitions
- Background dete
- Systematic unce
- Statistical metho
- Results
- [Interpretations]

The data and simulation samples used in the analysis. Data for the measurement / search, simulation to compare data to predictions.

Data-set specifics:

- Data quality ⇒ Good run list.
- Luminosity.

Monte carlo sample specifics:

- Generator, tunes.
- Statistics.

Compotents of a physics analysis

- Data-set and Monte Carlo samples
- Trigger
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- Background dete
- Systematic uncer
- Statistical metho
- Results
- [Interpretations]

The trigger used to collect the data with.

Trigger specifics:

- Prescales; typically unprescaled triggers are used, prescaled triggers for QCD / high stat measuments.
- Trigger (in)efficiencies.

Compotents of a physics analysis

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Backg
- Sy
- Stat
- Resu
- [Inter

The exact definition of objects (electrons, muon, jets, …) and how these are combined in selecting events to be analyzed.

Object definition specifics:

- "Flavor" of the identification (loose, medium, tight).
- Calibrations.

Event selection specifics:

- Event cleaning (e.g. from noise and cosmics).
- Momentum, geom. acceptance and multiplicity of objects.
- Higher level cuts, such as invariant mass.
- "**Signal regions**".

Compotents of a physics analysis

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event
- Background determination
- Systematic uncertainties
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- [Interpretations]

Events that are imitating the signal we are searching for or measuring.

Background determination specifics:

- Can/must be **data-driven** or **simulation-based**.
- "**Validation regions**" and "**control regions**" required. These can use different triggers wrt signal regions.

Compotents of a physics analysis

- Data-set and Monte Carlo
- Trigger
- Object definitions and eve
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- Systematic uncertainties
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- Any ‘intermediate’ measurement we have performed carries uncertainties (statistical and systematic).
- **“Systematic” uncertainties are introduced by inaccuracies in the methods used to perform the measurement.**
- Efficiencies, acceptance, number of events, luminosity, cross sections used in Monte Carlo scaling…
- Some of them are “centrally” assessed by the performance groups of an experiment. Some of them are analysis-specific.

Compotents of a physics analysis

- Data-set and Monte Carlo
- Trigger
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Dealing with large data-sets, we use statistical methods to make sense of the numbers we measure.

Typical method:

- Do a fit to extract signal from background.

Methodologies can vary a lot, but nowdays they are pretty unified within and across experiments.

Neural nets and other machine learning methods are broadly used, primarily to improve signal over background discrimination!

Compotents of a physics analysis

- Data-set and Monte Carlo samples
- Trigger
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- Statistical methods
- Results
- [Interpretations]

Produce the results in tables and plots. These include details of what is found in the signal region.

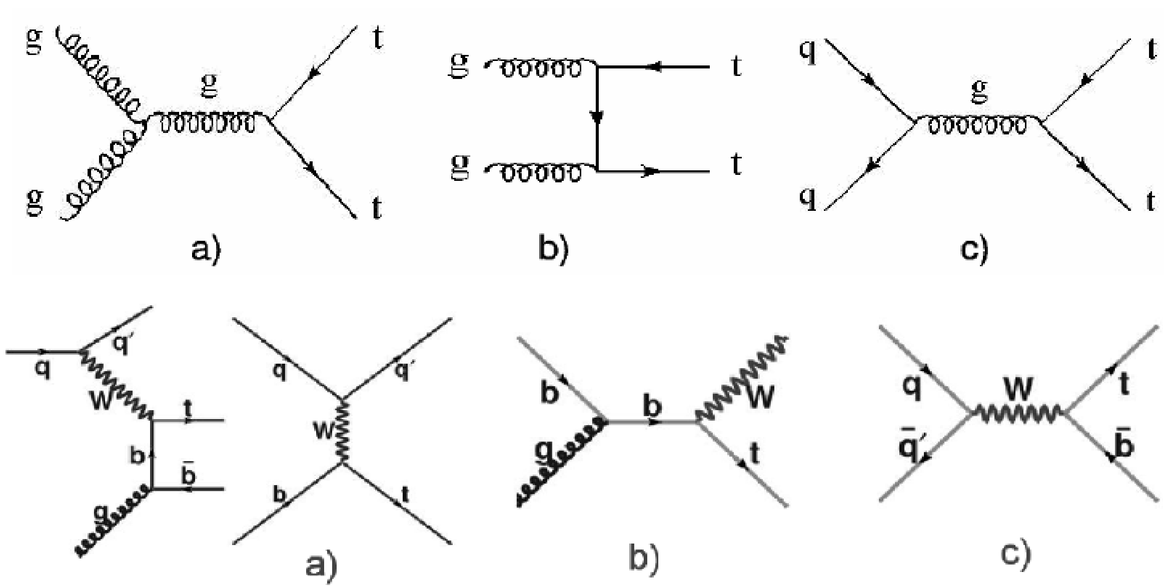
Compotents of a physics analysis

- Data-set and Monte Carlo samples
- Trigger
- Object definitions and event selections
- Background determination
- Systematic uncertainties
- Statistical methods
- Results
- [Interpretations]

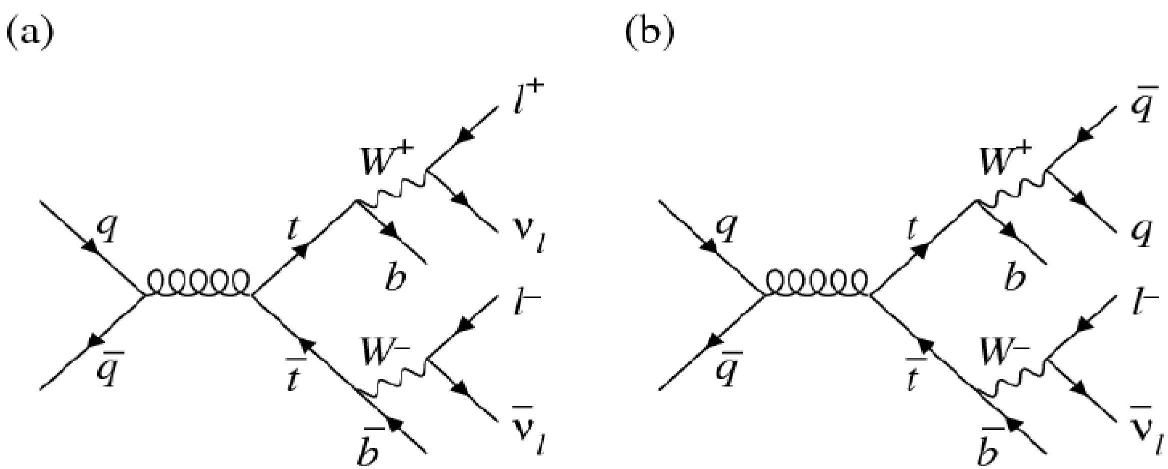
Put the results into context: interpret them in theoretical models.

SPARE SLIDES

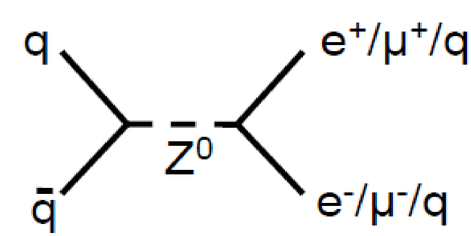
t,W,Z



Diagrams from http://arxiv.org/pdf/1201.5844.pdf



Diagrams from http://arxiv.org/pdf/1004.1181.pdf



Measuring particles

- Particles are characterized by
  - ✓ Mass [Unit: eV/c^2 or eV]
  - ✓ Charge [Unit: e]
  - ✓ Energy [Unit: eV]
  - ✓ Momentum [Unit: eV/c or eV]
  - ✓ (+ spin, lifetime, …)

Particle identification via measurement of:

e.g. (E, p, Q) or (p, β, Q)
(p, m, Q) ...

- … and move at relativistic speed

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\ell = \frac{\ell_0}{\gamma}$$ length contraption

$$t = t_0 \gamma$$ time dilatation

$$E^2 = \vec{p}^{\,2} c^2 + m^2 c^4$$

$$E = m\gamma c^2 = mc^2 + E_{\rm kin}$$

$$\vec{\beta} = \frac{\vec{p}c}{E} \qquad \vec{p} = m\gamma\vec{\beta}c$$

Relativistic kinematics in a nutschell

$$E^2 = \vec{p}^2 + m^2$$

$$\ell = \frac{\ell_0}{\gamma}$$

$$E = m\gamma$$

$$t = t_0\gamma$$

$$\vec{p} = m\gamma\vec{\beta}$$

$$\vec{\beta} = \frac{\vec{p}}{E}$$

Relativistic kinematics in a nutschell

Center of mass energy

- In the center of mass frame the total momentum is 0
- In laboratory frame center of mass energy can be computed as:

$$E_{\mathrm{cm}} = \sqrt{s} = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

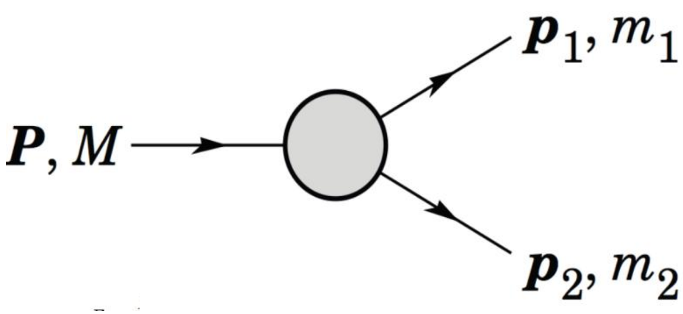
Hint: it can be computed as the "length" of the total four-momentum, that is invariant:

$$p = (E, \vec{p}) \qquad \sqrt{p \cdot p}$$

What is the "length" of a the four-momentum of a particle?

Kinematics

2-bodies decays



$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M}$$

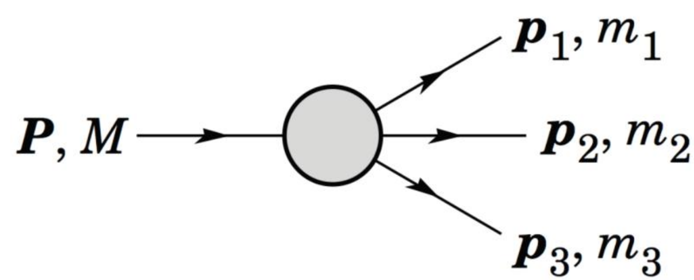
$$|\boldsymbol{p}_1| = |\boldsymbol{p}_2|$$

$$= \frac{\left[\left(M^2 - (m_1 + m_2)^2\right)\left(M^2 - (m_1 - m_2)^2\right)\right]^{1/2}}{2M}$$

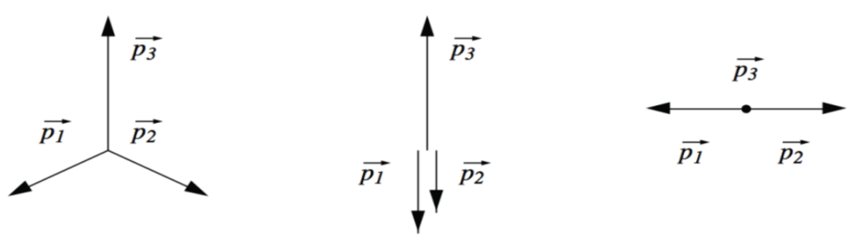
Invariant mass

$$M = \sqrt{\left(\sum E_i\right)^2 - \left(\sum \vec{p}_i\right)^2}$$

3-bodies decays



$$|\boldsymbol{p}_3| = \frac{\left[\left(M^2 - (m_{12} + m_3)^2\right)\left(M^2 - (m_{12} - m_3)^2\right)\right]^{1/2}}{2M}$$



(a) (b) (c)

$\max(|\vec{p}_3|)$ $(m_{12})_{min} = m_1 + m_2$

$\min(|\vec{p}_3|)$ $(m_{12})_{max} = M - m_3$

A real example: pion decays

pion decays at rest

$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}c \simeq 30\,\mathrm{MeV/c}$$

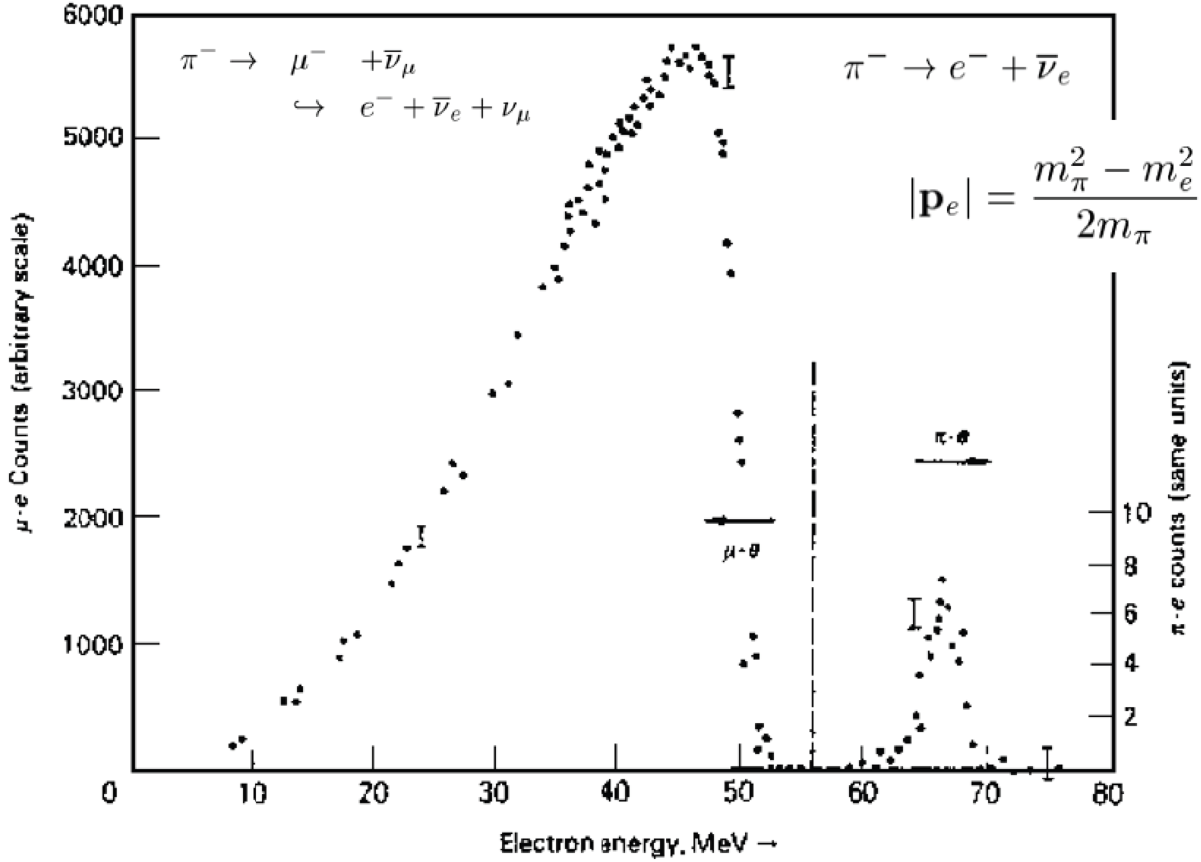
$$m_\nu = 0.$$

in most cases muon decays at rest

$$|\mathbf{p}_e|_{max} = \frac{m_\mu^2 - m_e^2}{2m_\mu}c \simeq 52\,\mathrm{MeV/c}$$

$$|\mathbf{p}_e|_{min} = 0$$

$$|\mathbf{p}_e| = \frac{m_\pi^2 - m_e^2}{2m_\pi}c \simeq 70\,\mathrm{MeV/c}$$



HEP, SI and „natural” units

Quantity	HEP units	SI units
length	1 fm	10^{-15} m
charge	e	$1.602 \cdot 10^{-19}$ C
energy	1 GeV	1.602×10^{-10} J
mass	1 GeV/c^2	1.78×10^{-27} kg
$\hbar = h/2$	6.588×10^{-25} GeV s	1.055×10^{-34} Js
c	2.988×10^{23} fm/s	2.988×10^{8} m/s
$\hbar c$	197 MeV fm	…

	“natural” units ($\hbar = c = 1$)
mass	1 GeV
length	1 GeV^{-1} = 0.1973 fm
time	1 GeV^{-1} = 6.59×10^{-25} s