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**

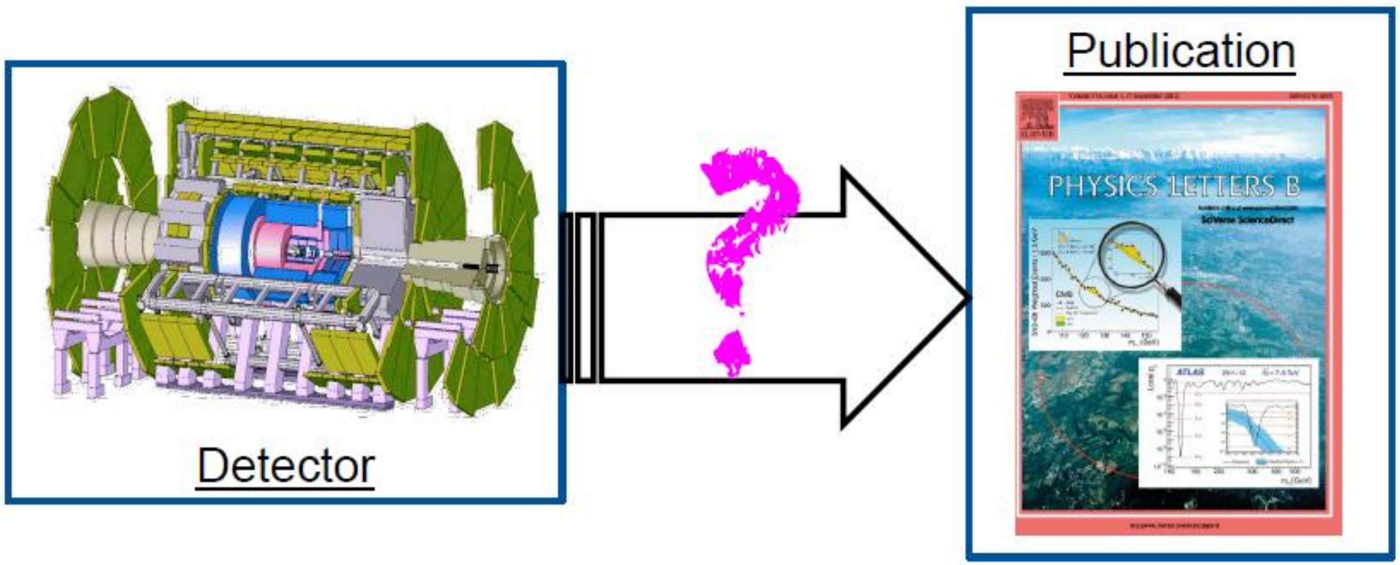
❖ **From Standard Model particles to measurements and searches**

- **About how we analys data using ingredients we have constructed**

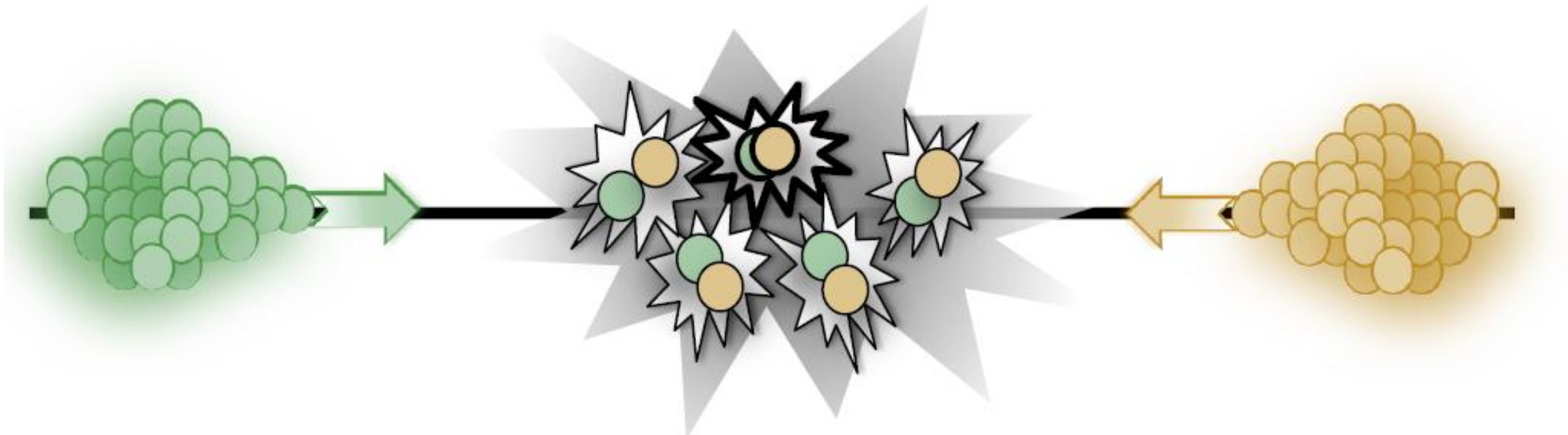
Large fraction of slides from A. Sfyrla lectures at CERN Summer School 2018

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**

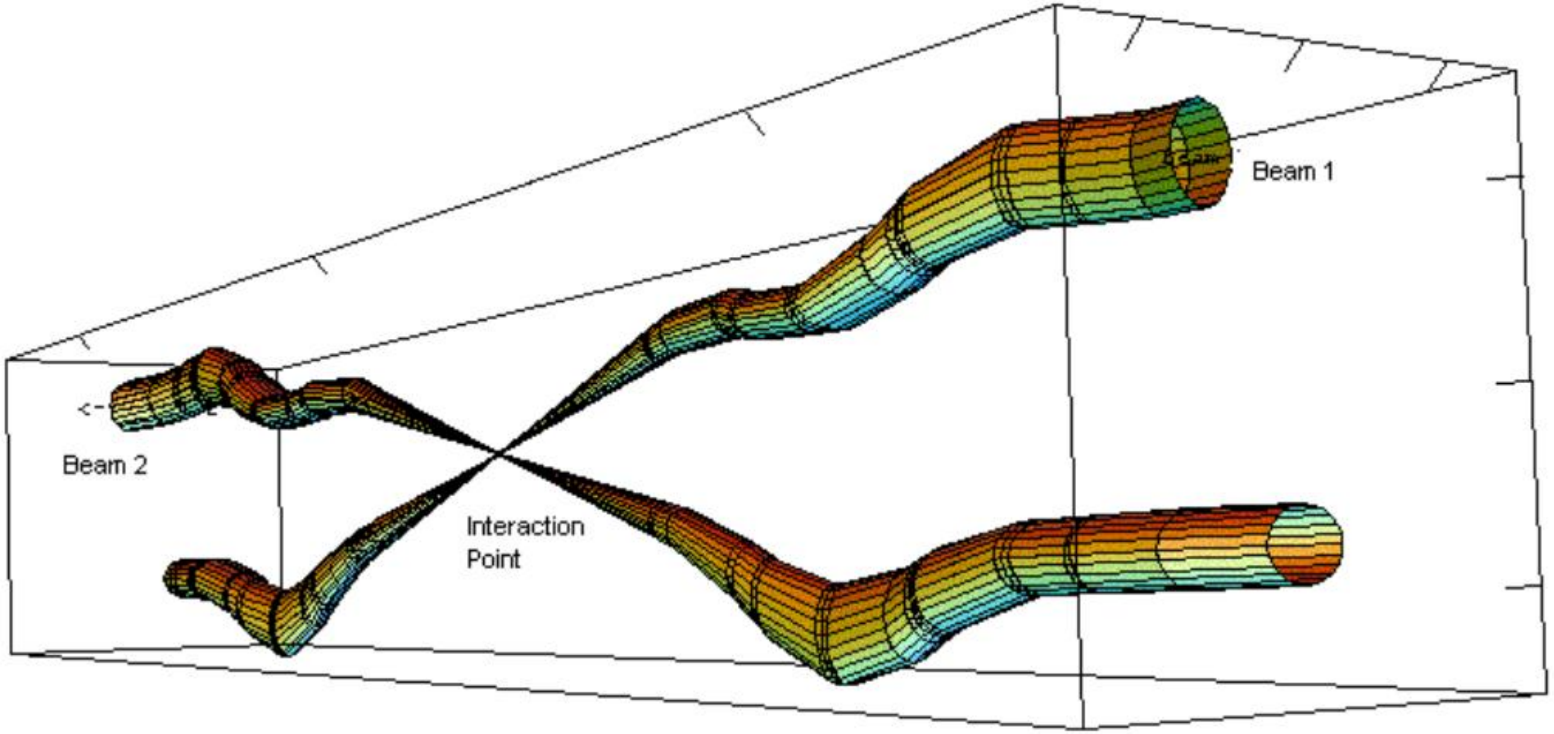
collided at **7/8TeV** and at ~**20 MHz in Run-1**

In 2018:

Up to 60 p-p collisions / bunch crossing

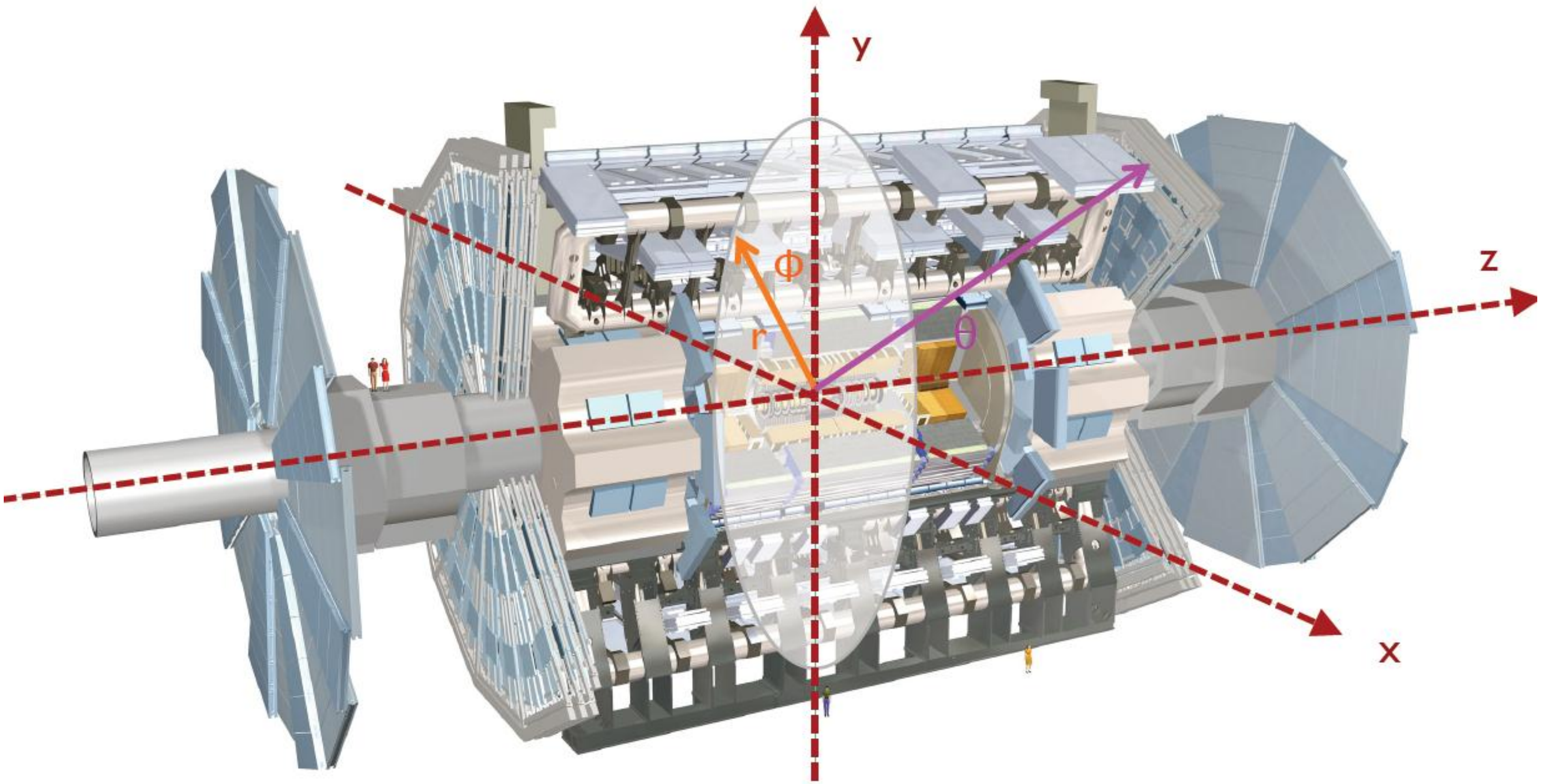
What is an event?

A crossing of the two LHC proton beams at an interaction point



Relative beam sizes around IP1 (Atlas) in collision

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

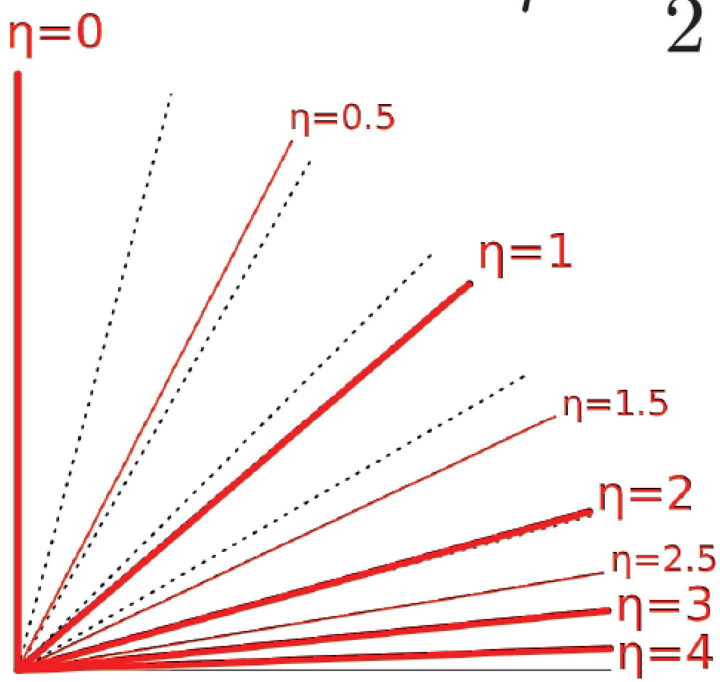
$$\eta = \frac{1}{2}\ln\frac{|\vec{p}|+p_z}{|\vec{p}|-p_z}$$

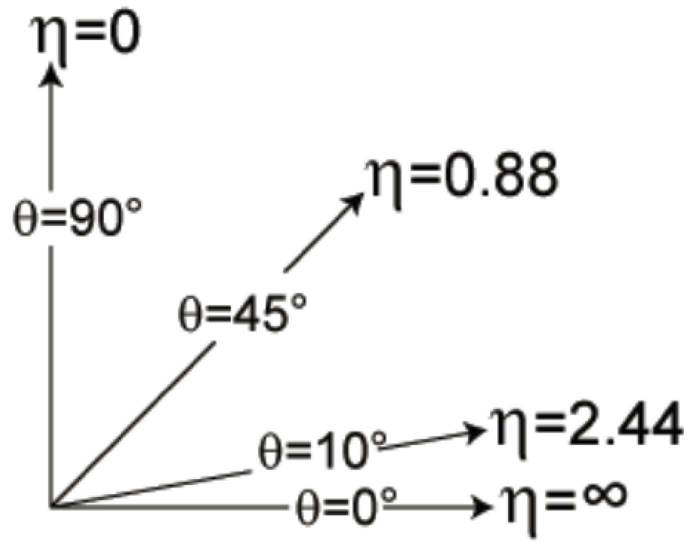
$$\eta = \frac{1}{2}\ln\left(\tan\frac{\theta}{2}\right)$$

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

$$\eta \simeq y$$

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

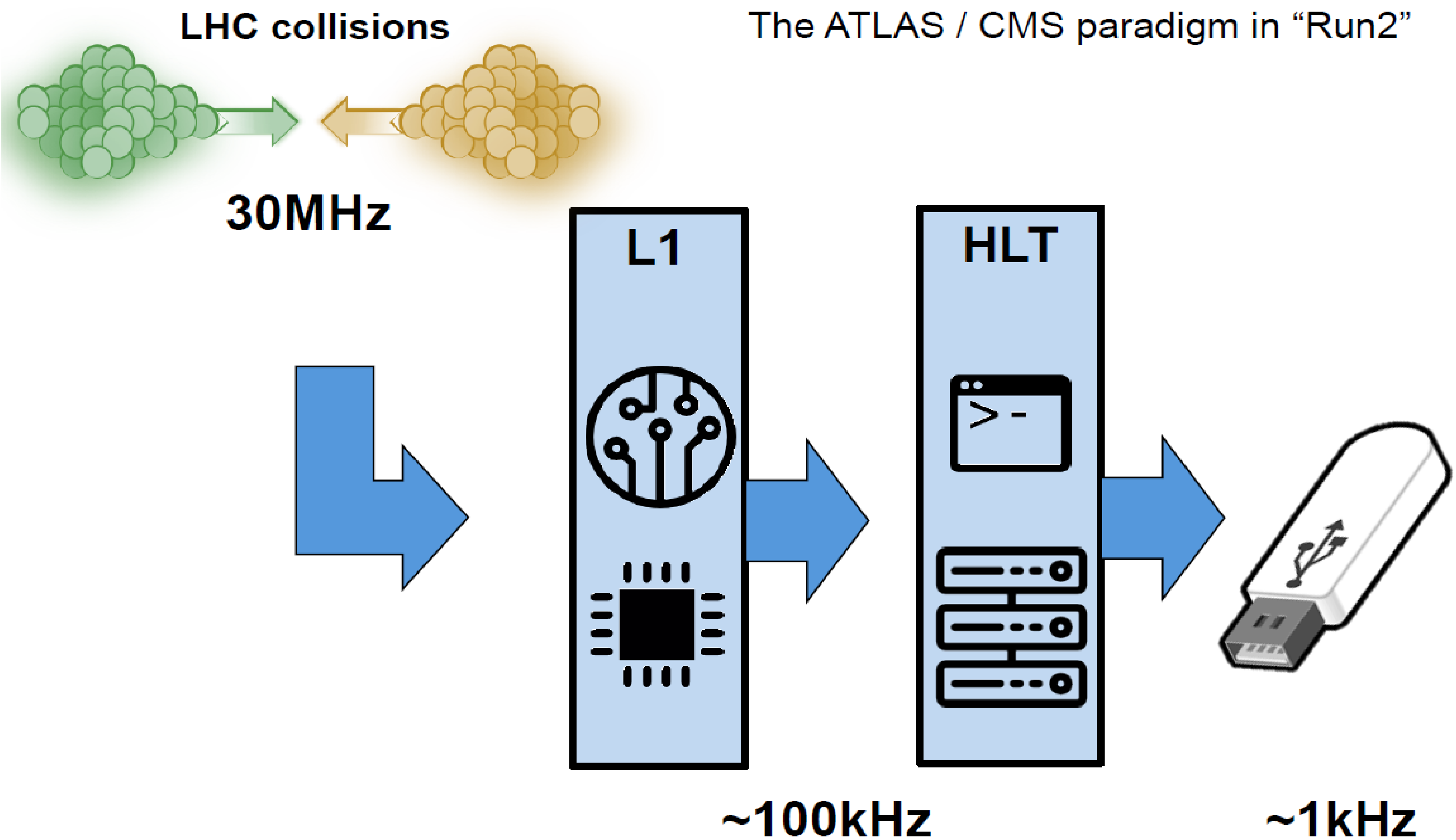
$$E_T^{\text{miss}} = \sum p_T(i)$$

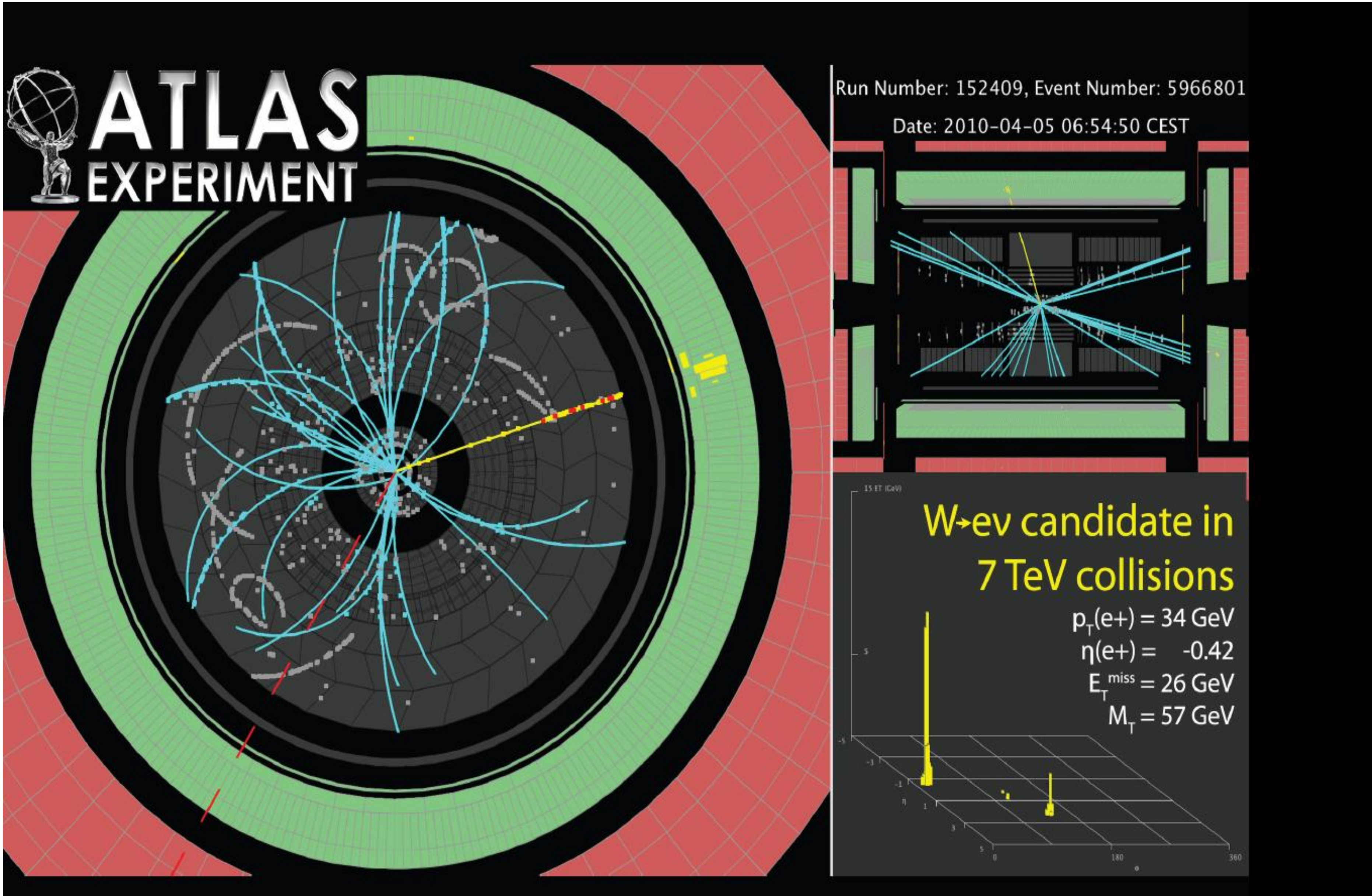
- If a heavy particle is produced and decays in two particles one of which is invisible, the mass of the parent particle can constrained with the transverse mass quantity

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

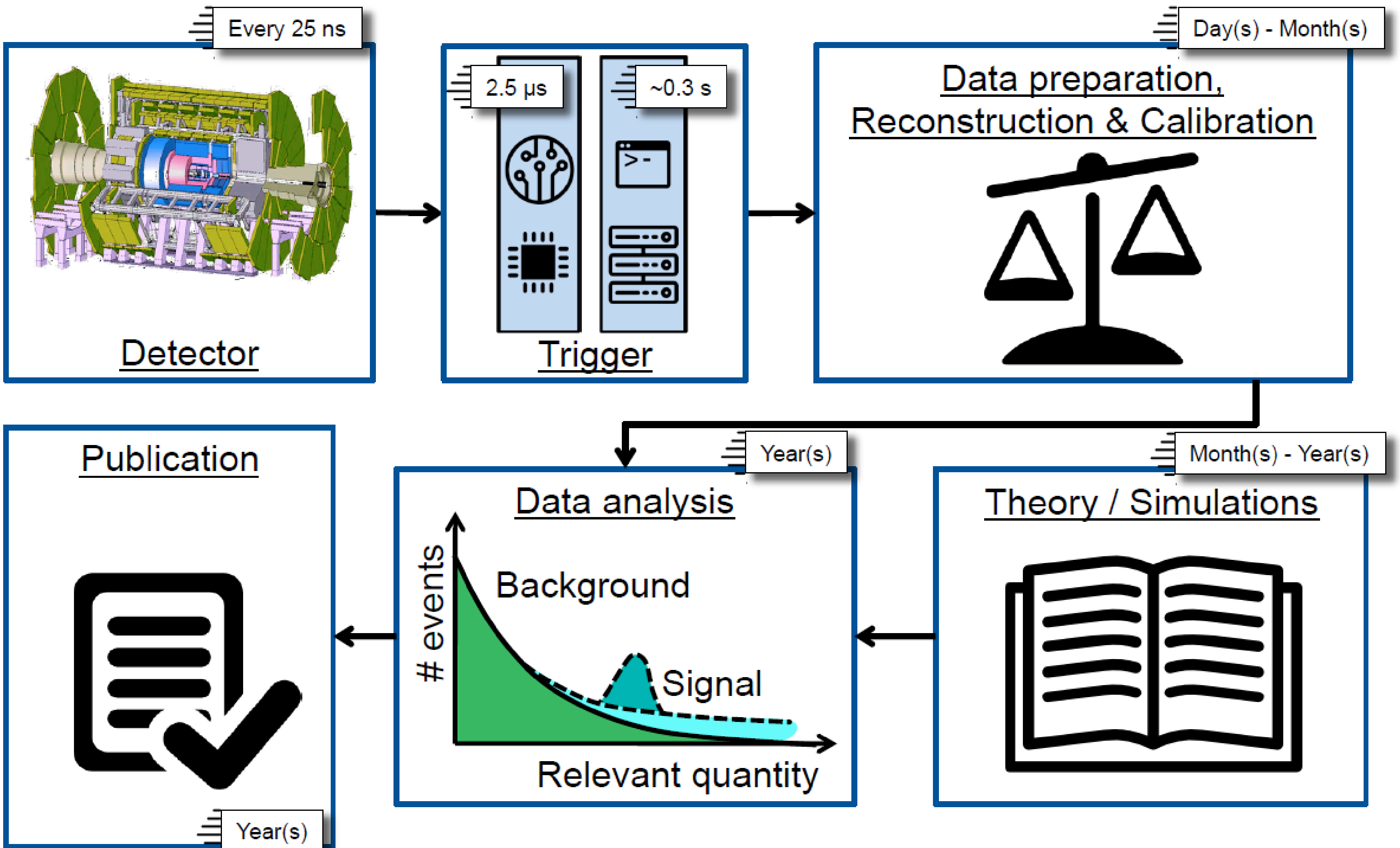
if $m_1 = m_2 = 0$ $\qquad M_T^2 = 2|\boldsymbol{p}_T(1)||\boldsymbol{p}_T(2)|(1 - \cos\phi_{12})$

Triggering on physics

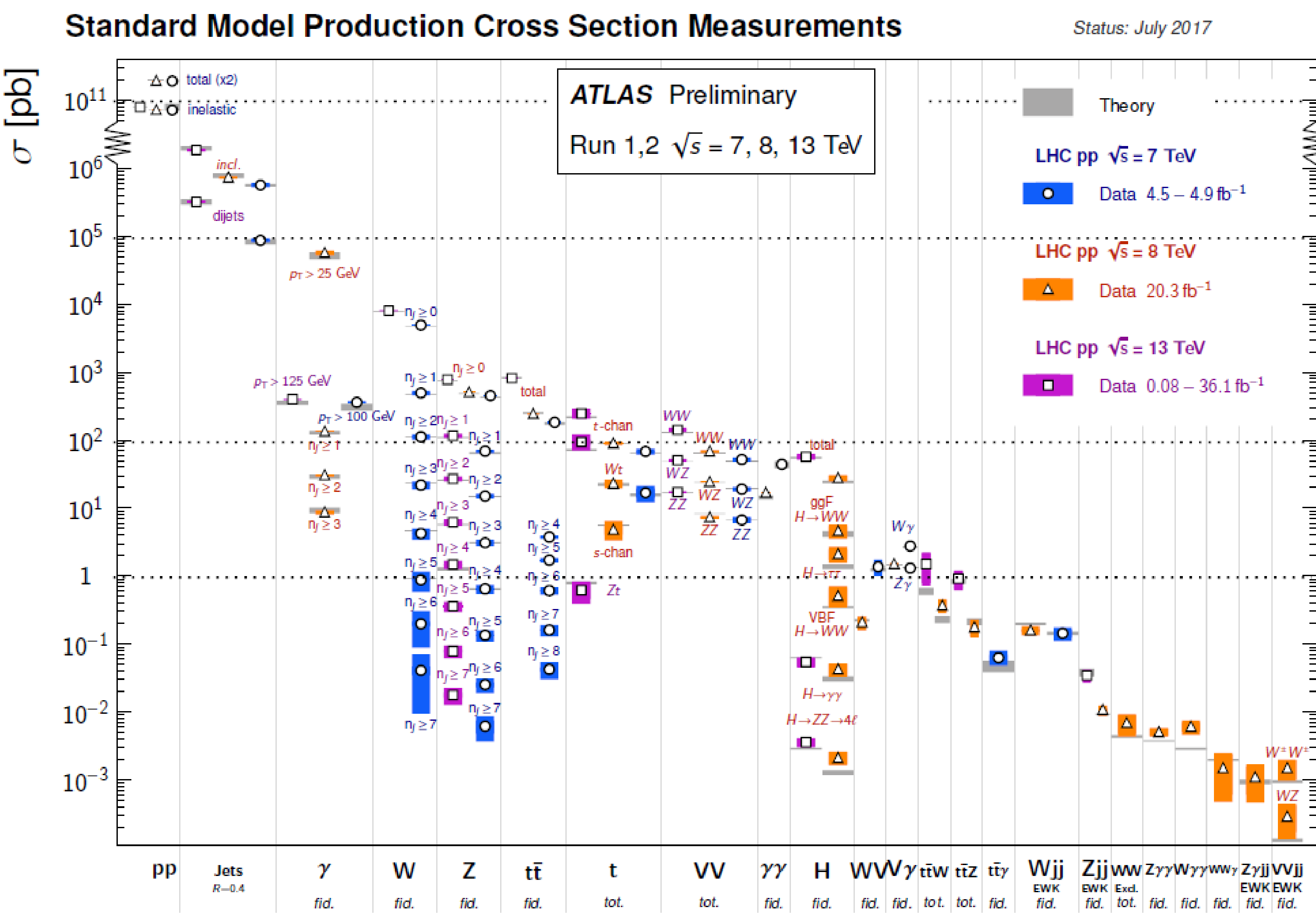



ATLAS
EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in
7 TeV collisions
$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

An event’s lifetime



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



Event Rate

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

1 GHz

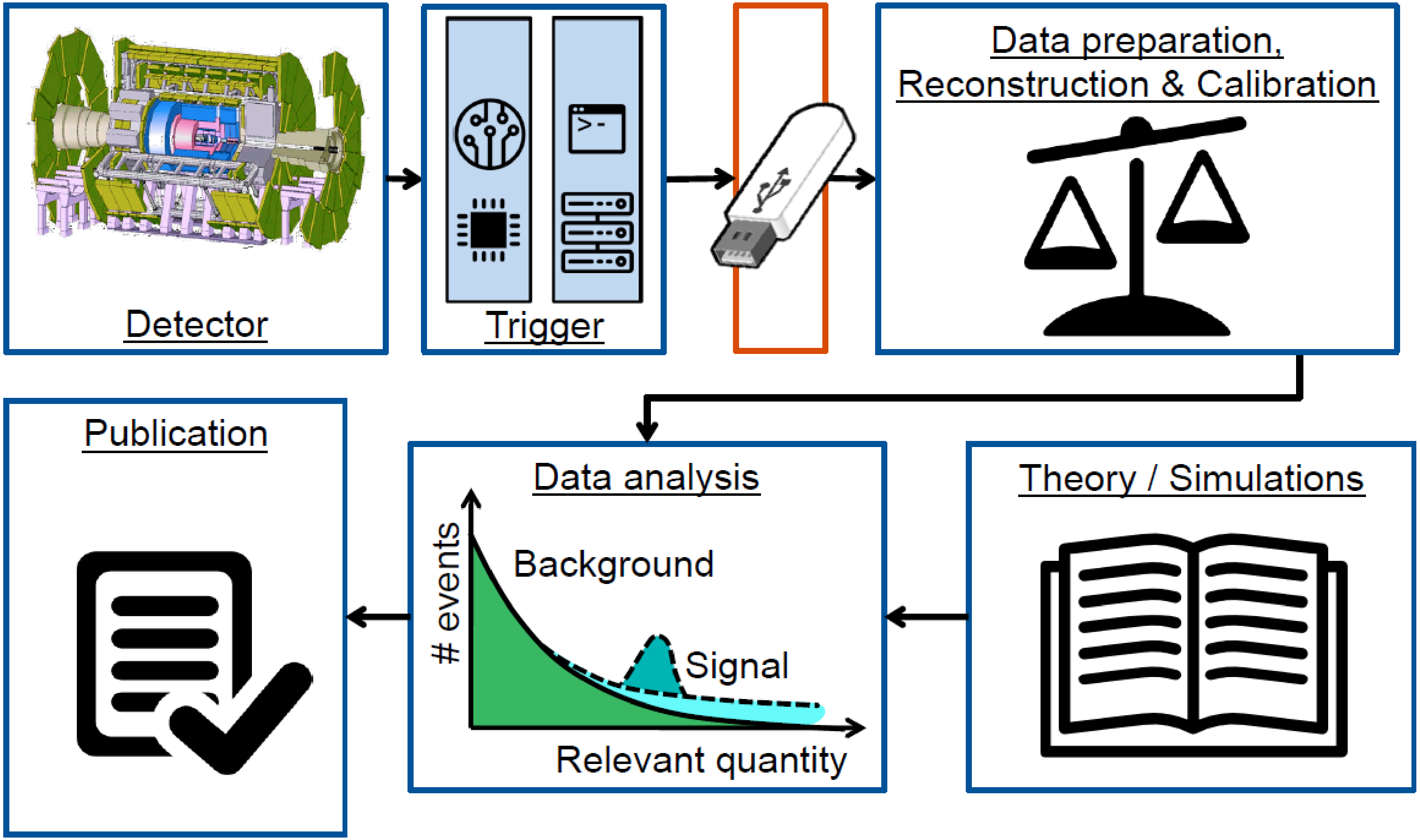
1 kHz

1 Hz

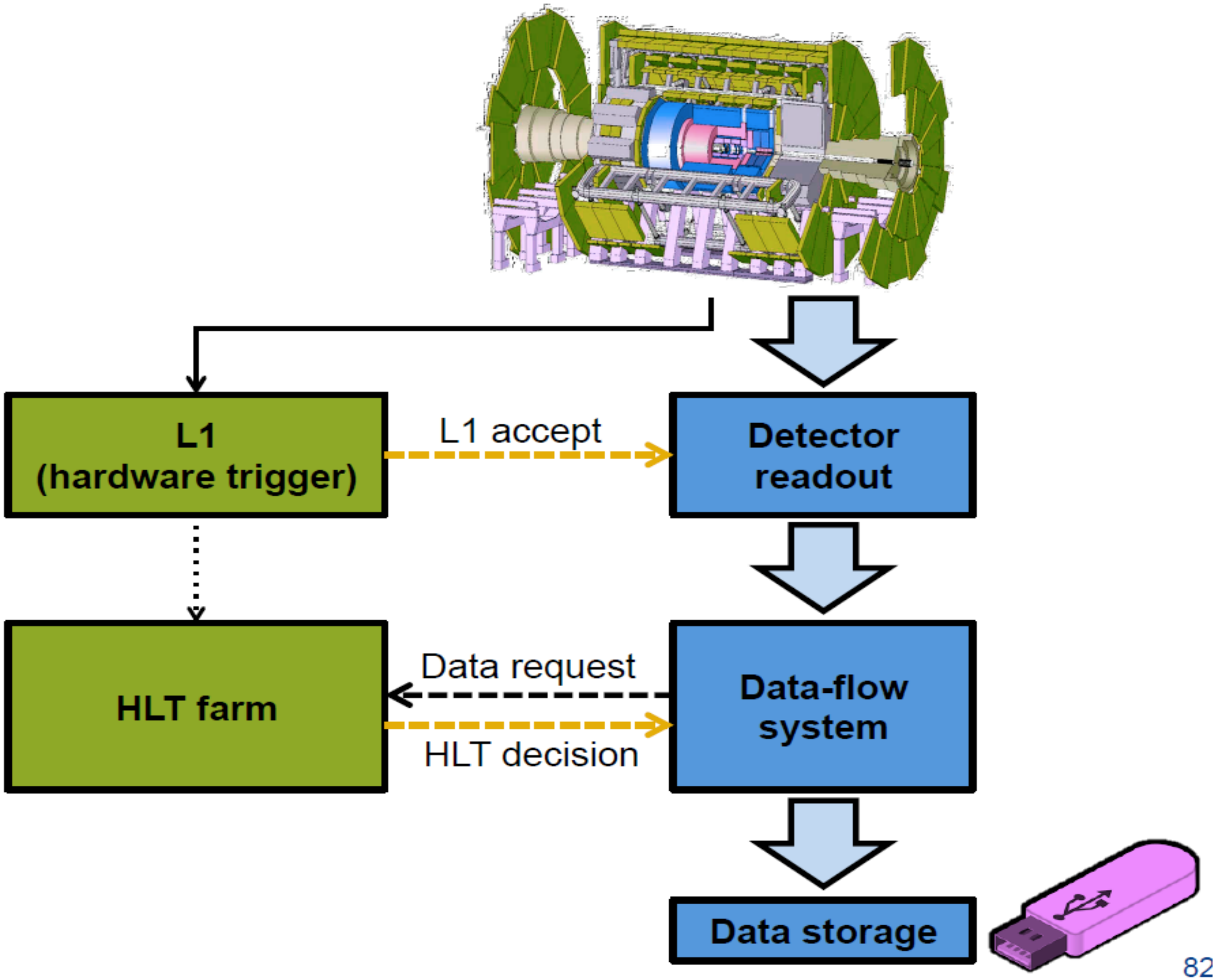
10^{-2} Hz

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:
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:
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:
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]
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0x0000001a	0x00080000	524288	lvl1 trigger info[5]
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0x0000001c	0x00020001	131073	lvl1 trigger info[7]
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0x00000029	0x00000810	2064	lvl1 trigger info[20]
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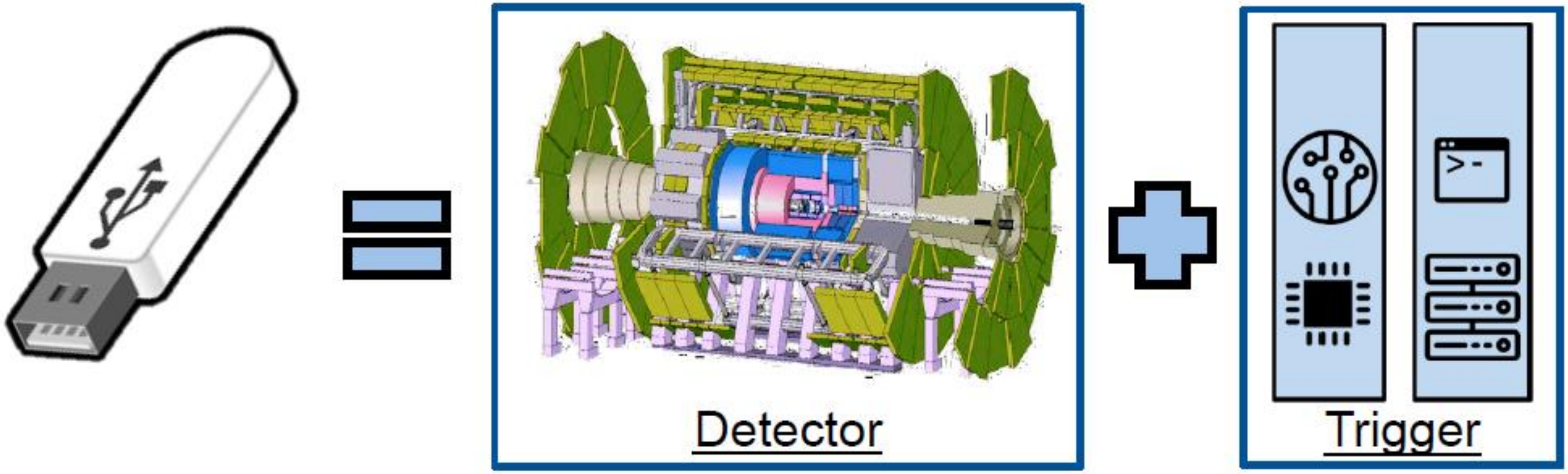
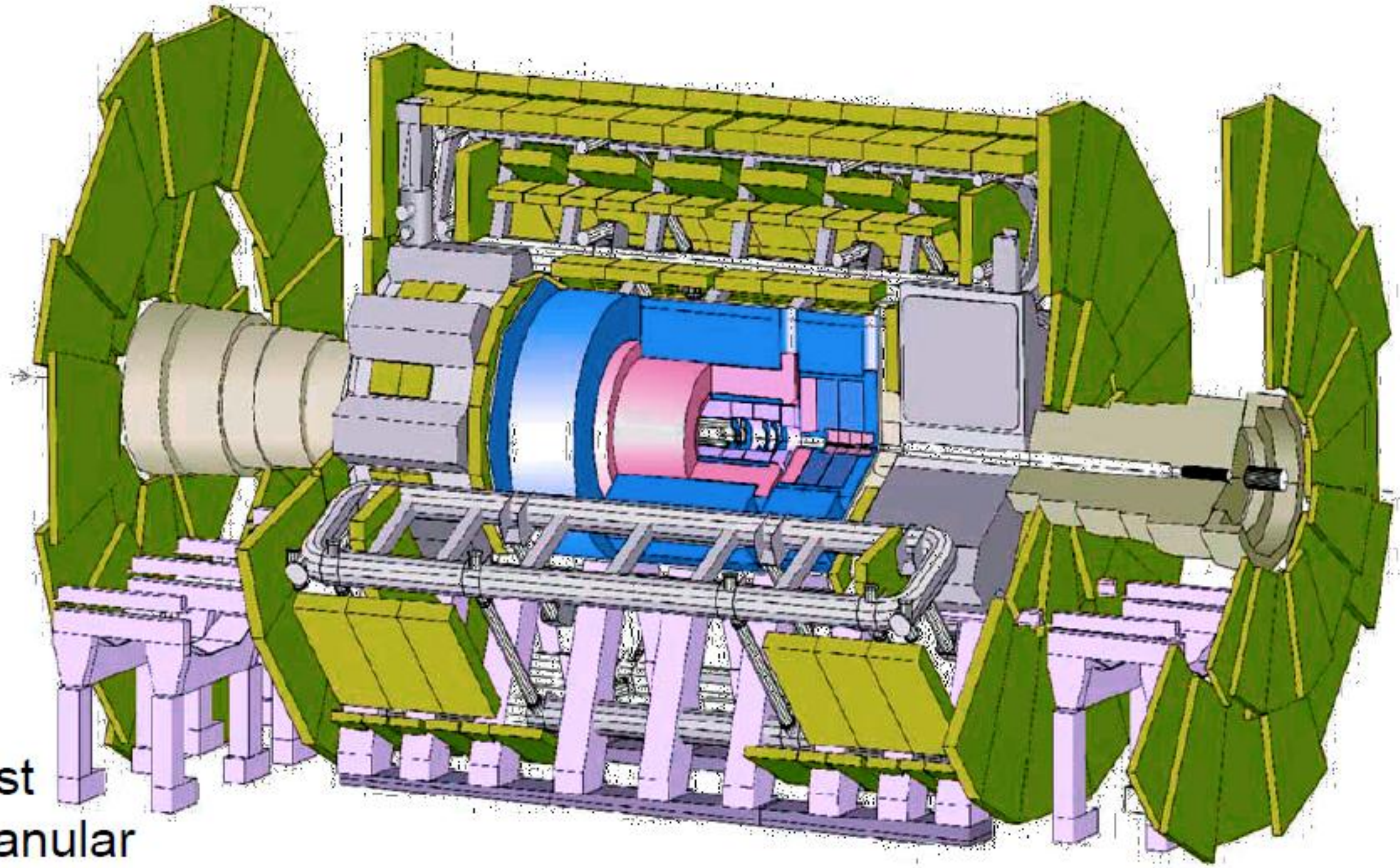
0x0000002b	0x00000400	1024	lvl1 trigger info[22]
0x0000002c	0x00000000	0	lvl1 trigger info[23]

- 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?

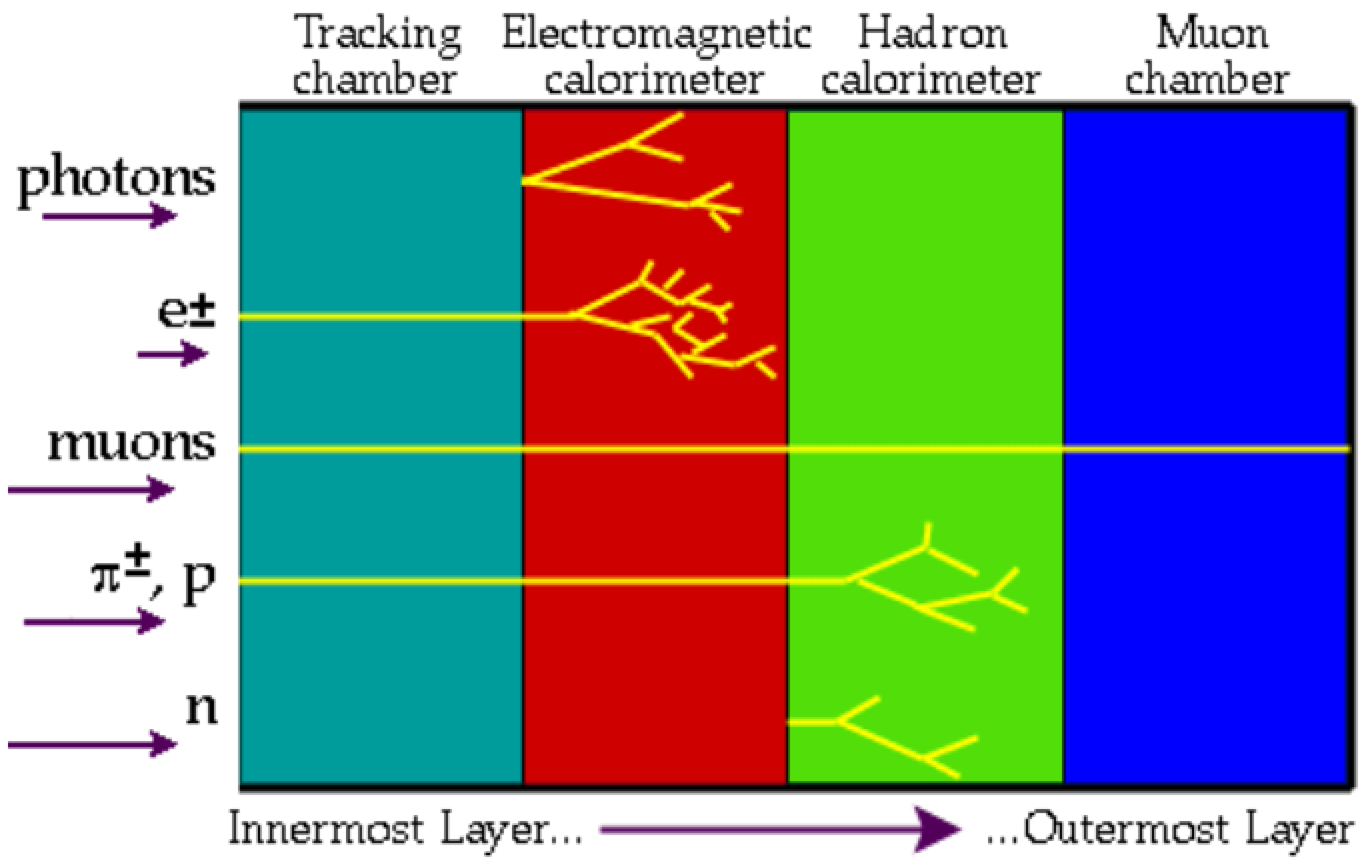


A detector (e.g. ATLAS)

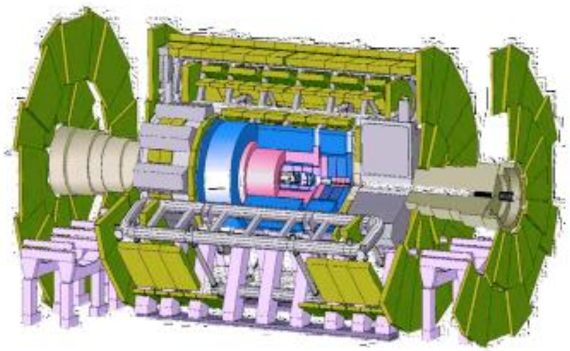


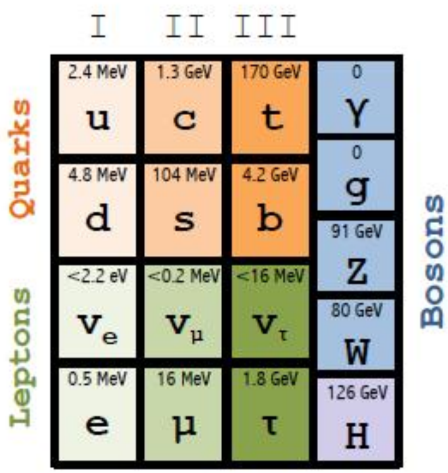
- ✓ Fast
- ✓ Granular
- ✓ Resistant to radiation

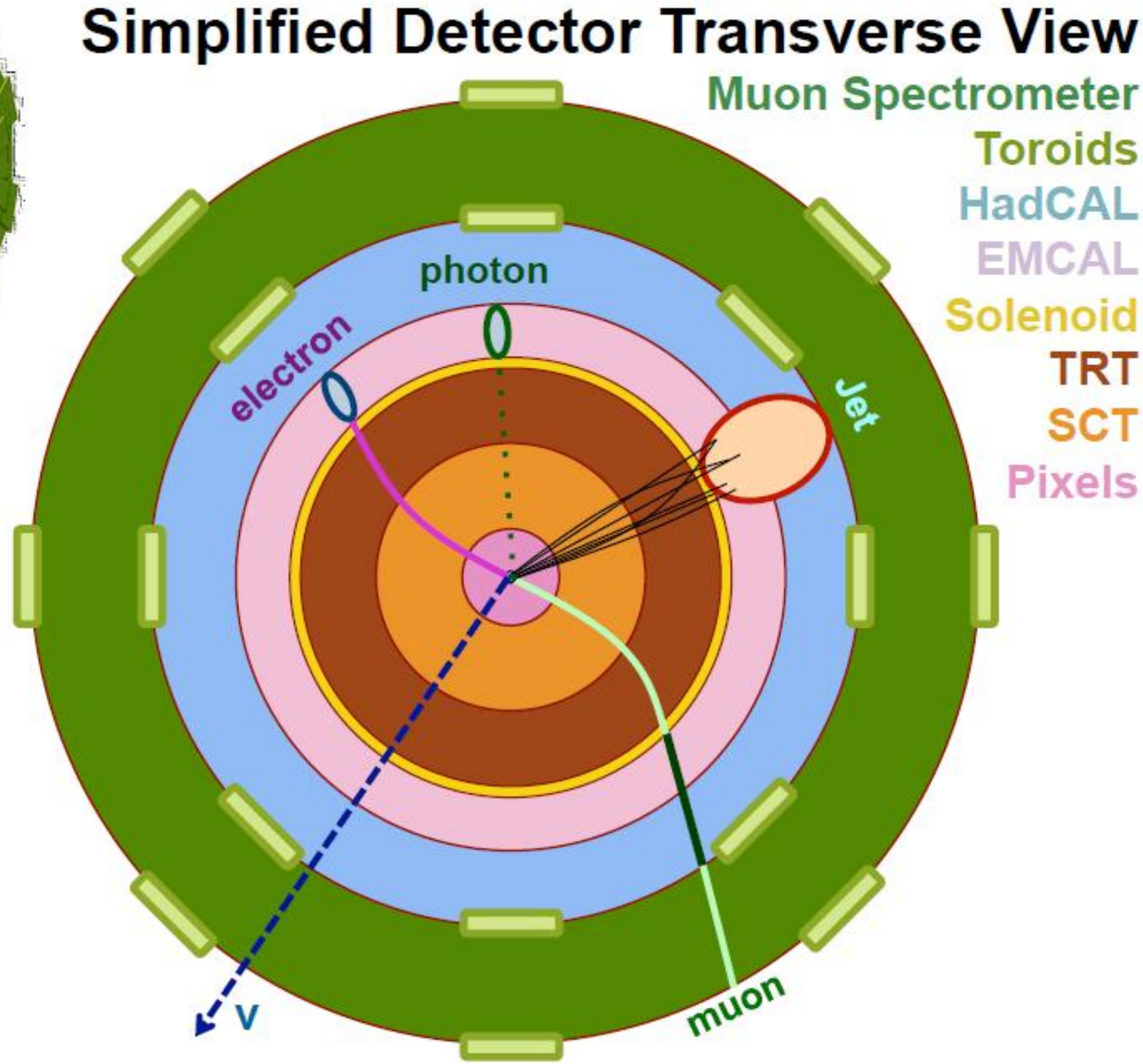
Particles through matter



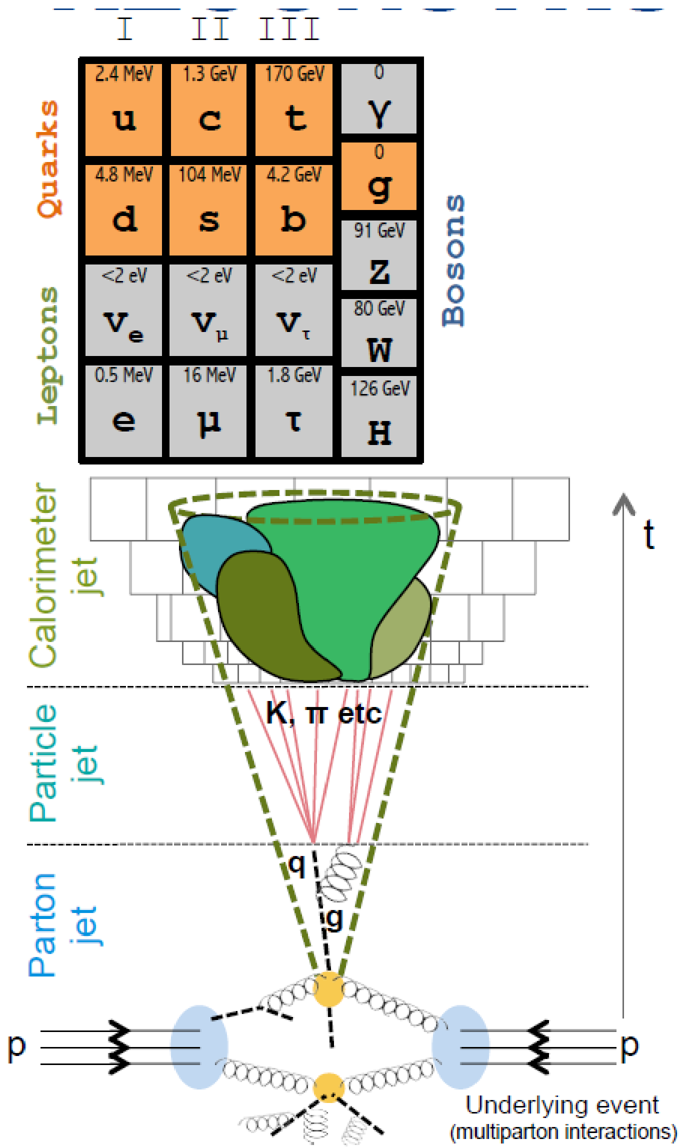
A detector (eg. ATLAS)

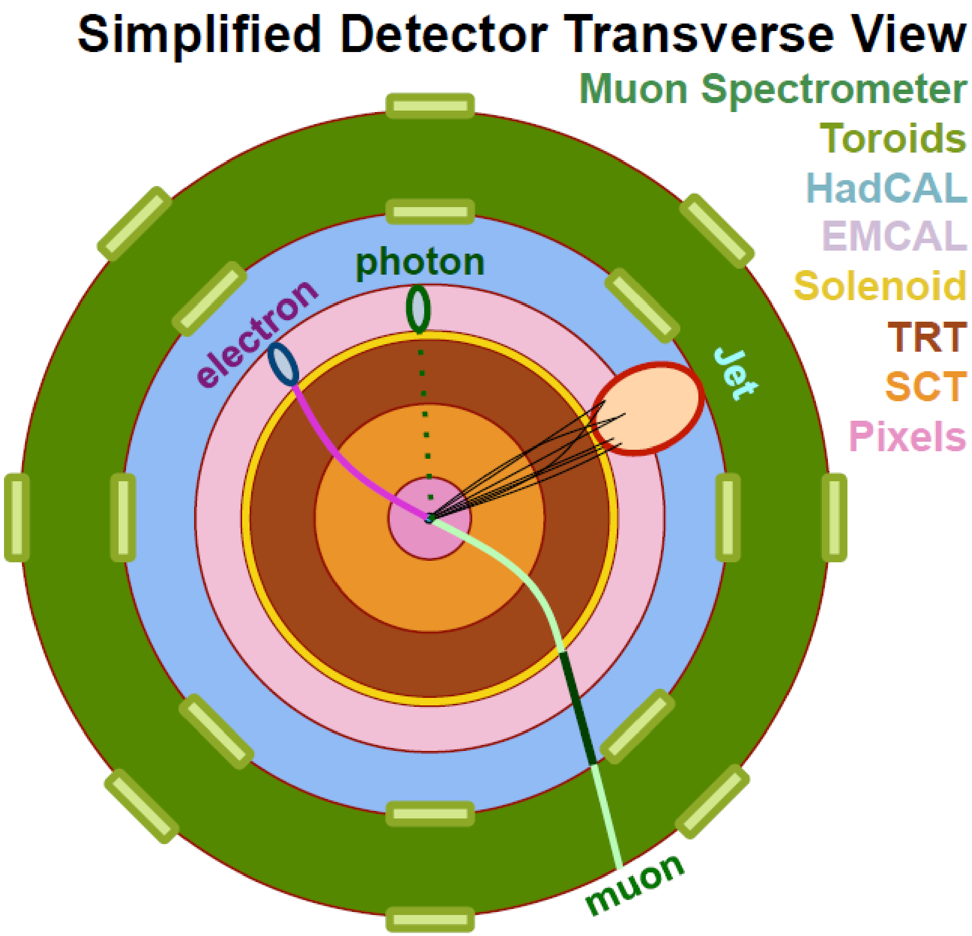




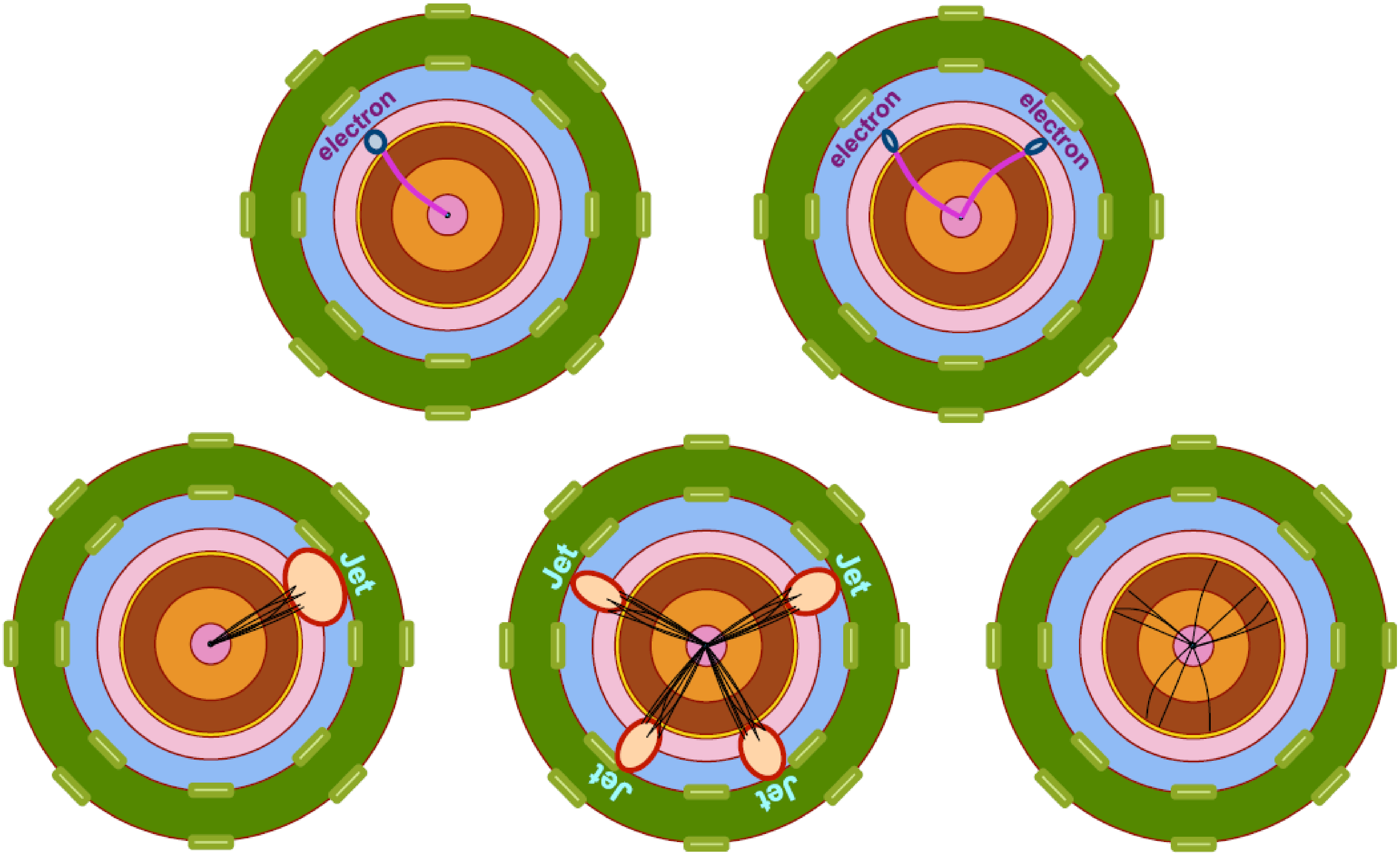


Reconstructing particles

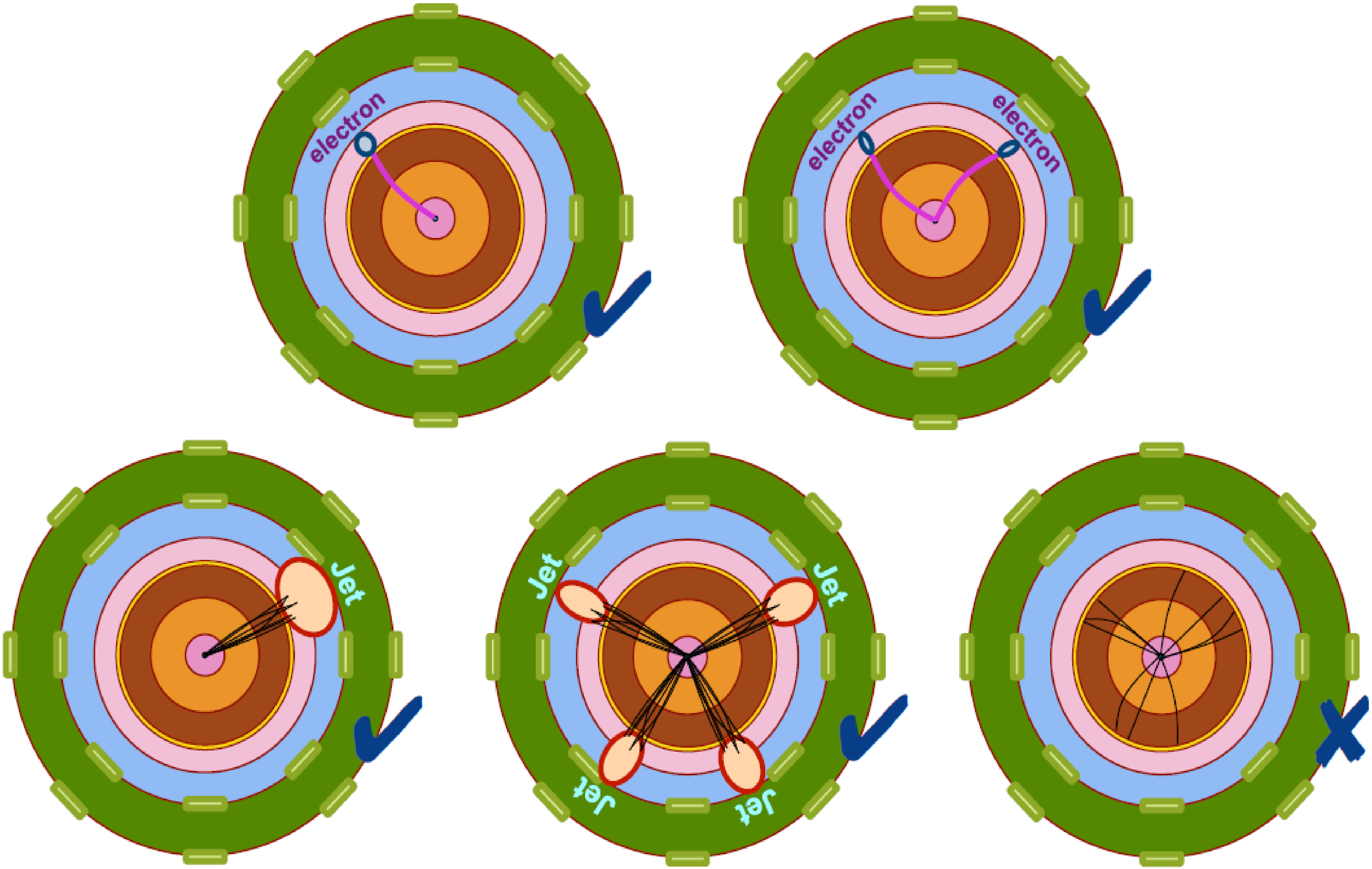




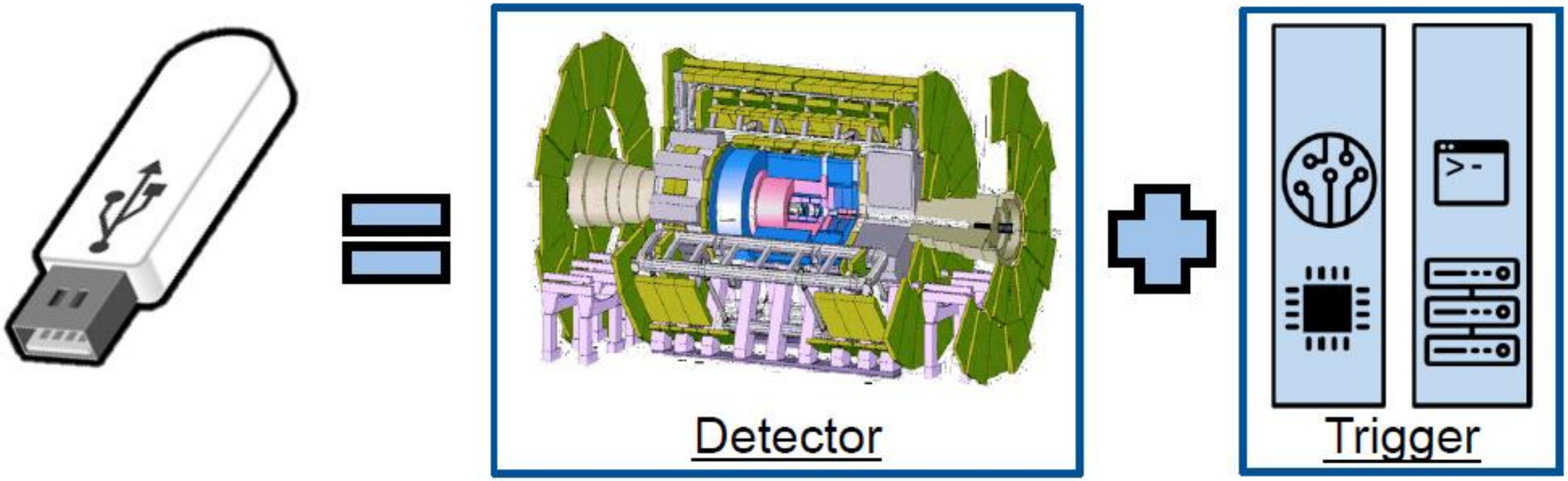
Online reconstruction



Triggering on physics



This is what raw data contain!



data to reconstruct offline!

decision plus online reconstructed objects

Streaming

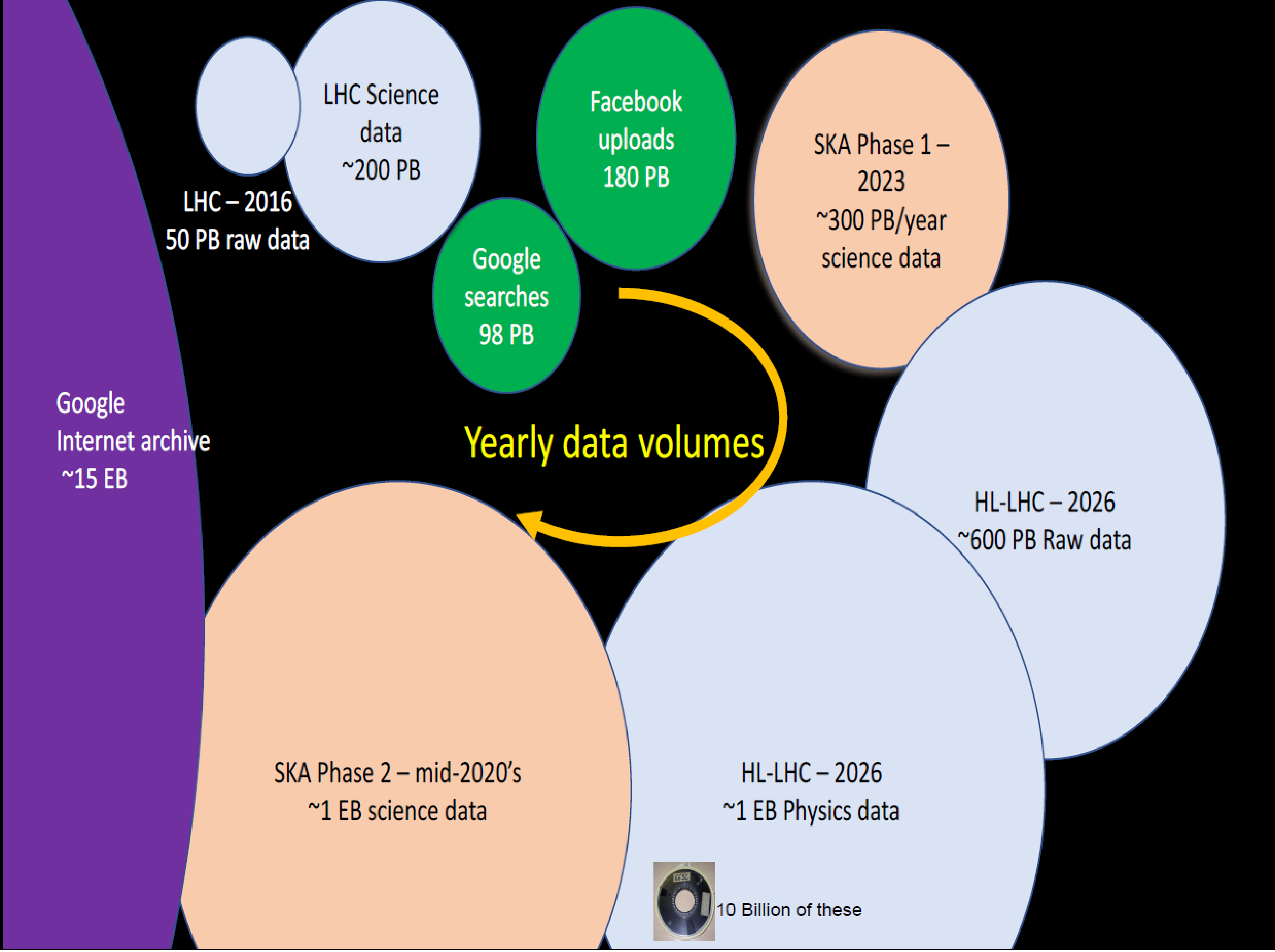
- Streaming is based on trigger decisions at all stages
- The Raw Data physics streams are generated at the HLT output level

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

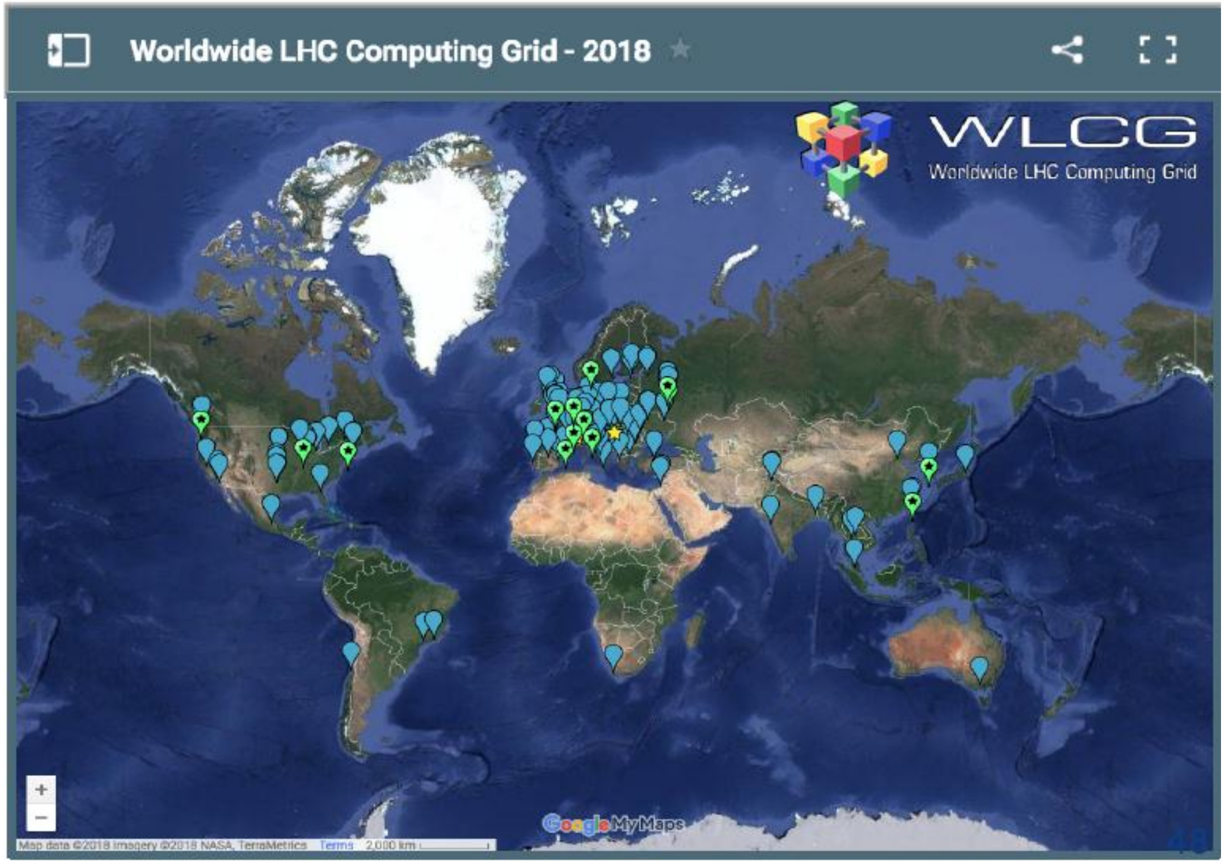

LHC Science data ~200 PB
LHC – 2016 50 PB raw data
Facebook uploads 180 PB
Google searches 98 PB
SKA Phase 1 – 2023 ~300 PB/year science data
Google Internet archive ~15 EB
Yearly data volumes
HL-LHC – 2026 ~600 PB Raw data
SKA Phase 2 – mid-2020's ~1 EB science data
HL-LHC – 2026 ~1 EB Physics data
10 Billion of these

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.

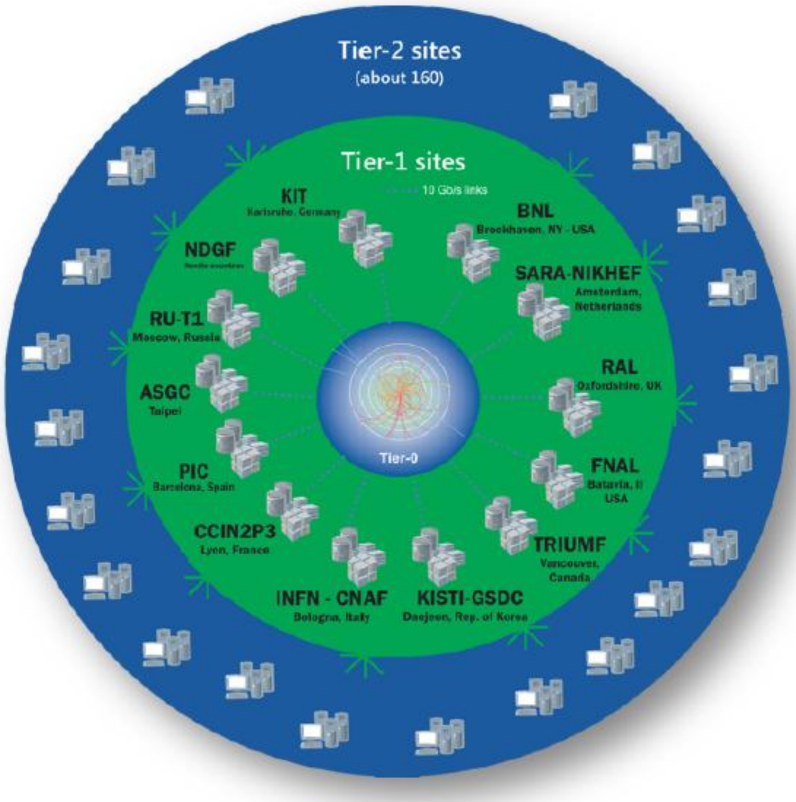


Worldwide LHC computing grid

Tier-0 (CERN and Hungary): data recording, reconstruction and distribution

Tier-1: permanent storage, re-processing, analysis

Tier-2: Simulation, end-user analysis



~170 sites, 42 countries

~750k CPU cores

~1 EB of storage

> 2 million jobs/day

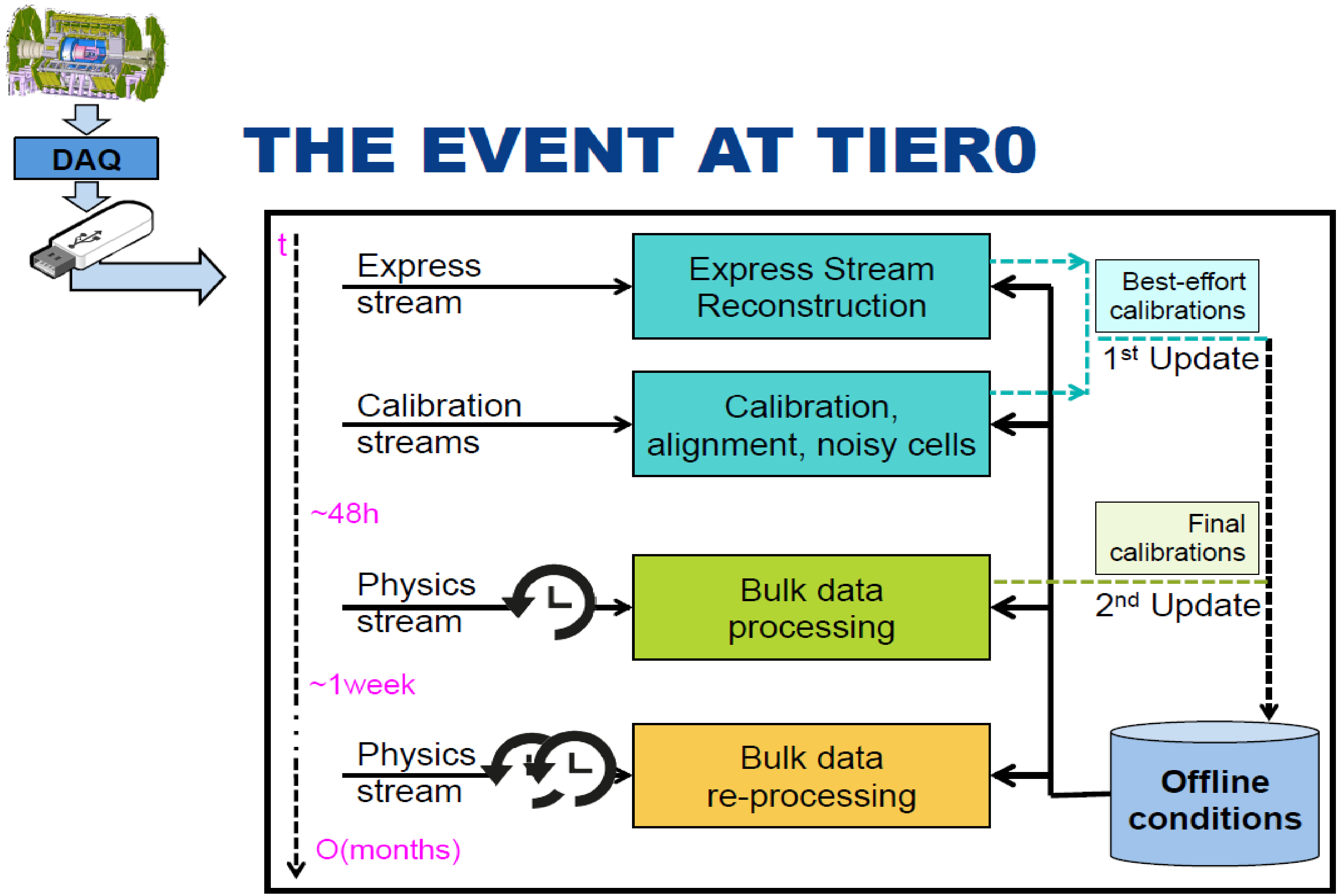
10-100 Gb links

WLCG:

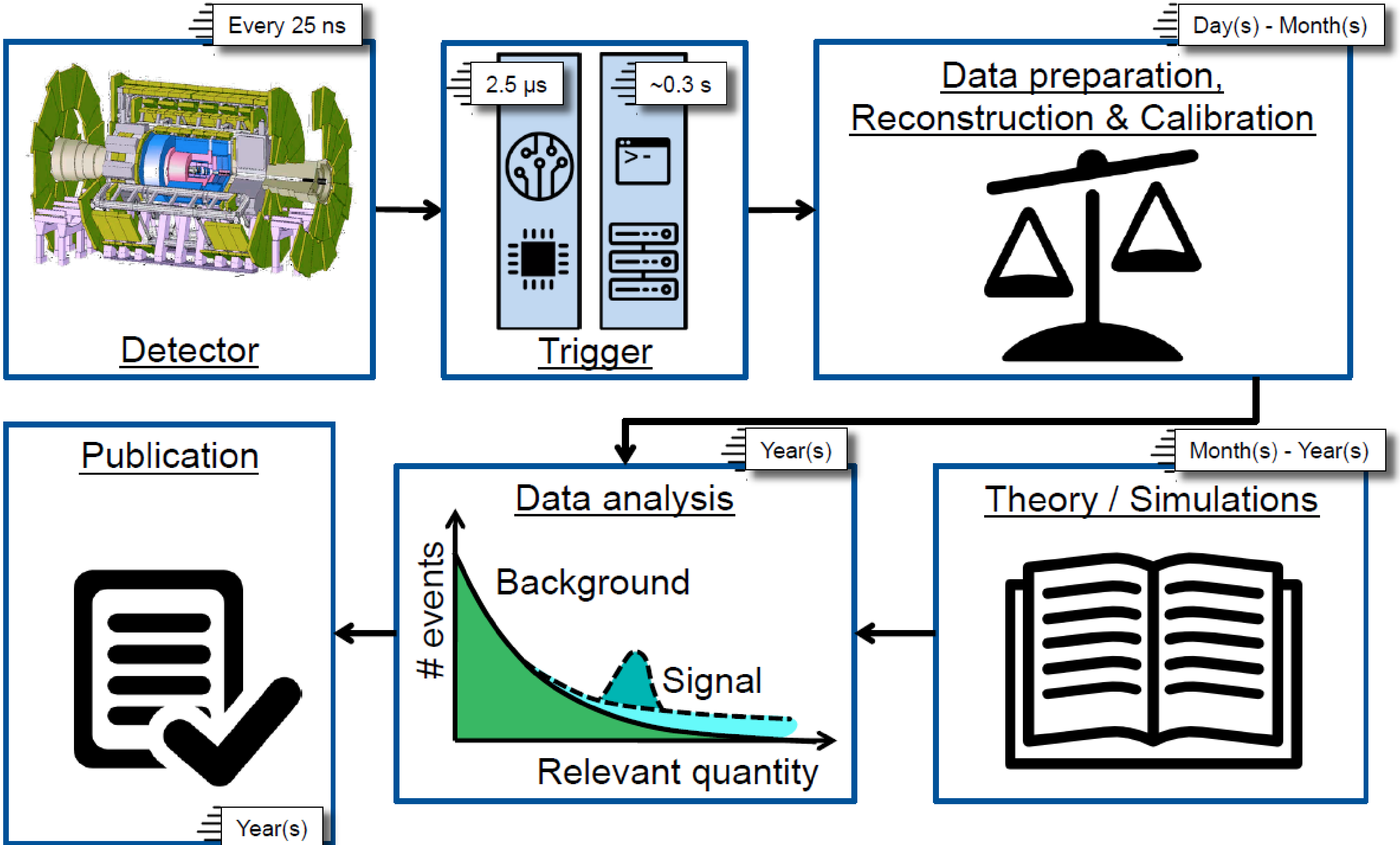
An International collaboration to distribute and analyse LHC data

Integrates computer centres worldwide that provide computing and storage resource into a single infrastructure accessible by all LHC physicists

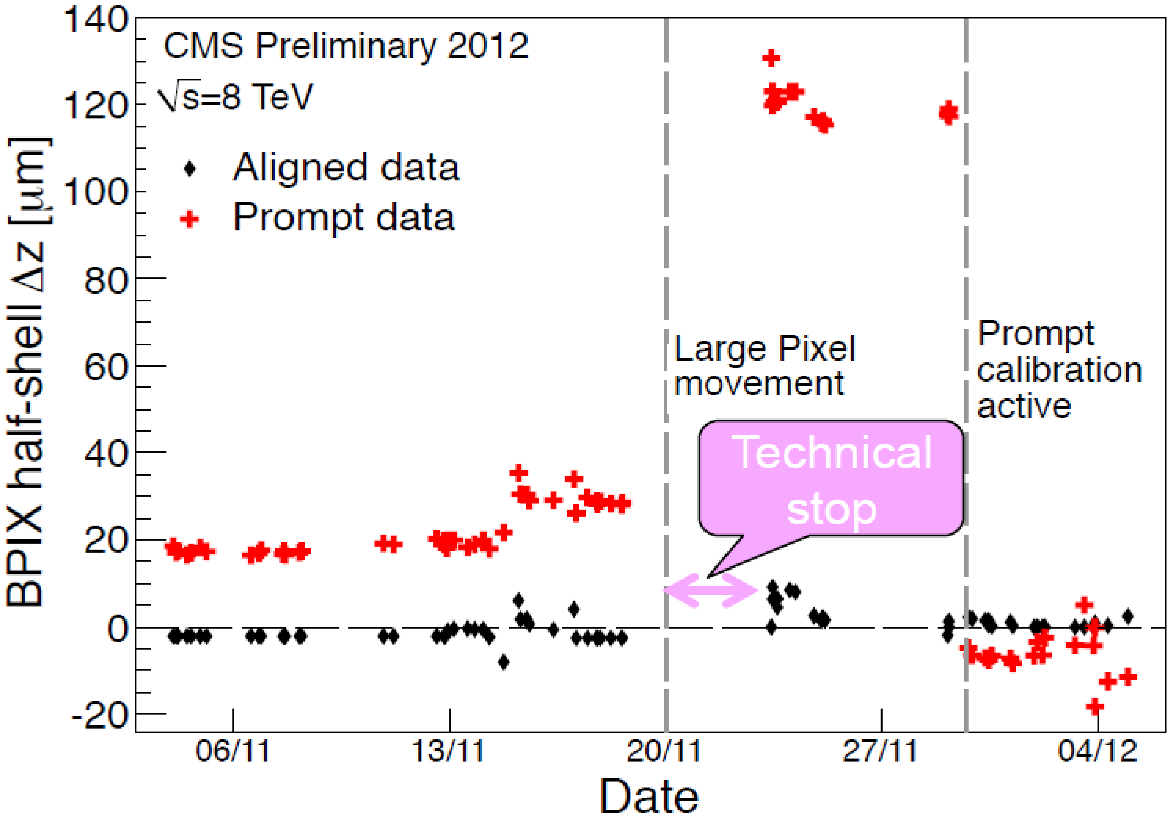
Huge amount of data …



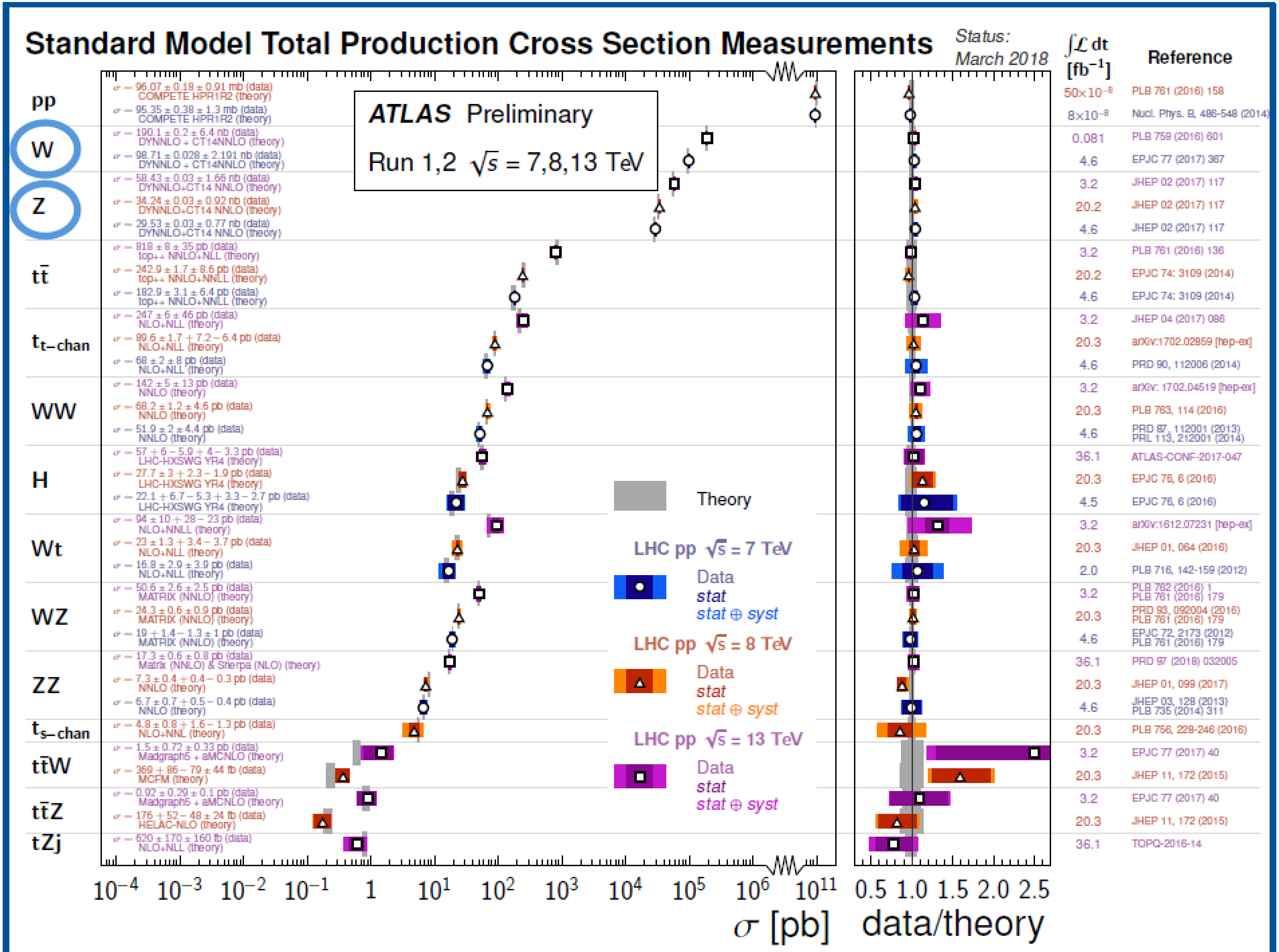
An event's lifetime



EG. alignment



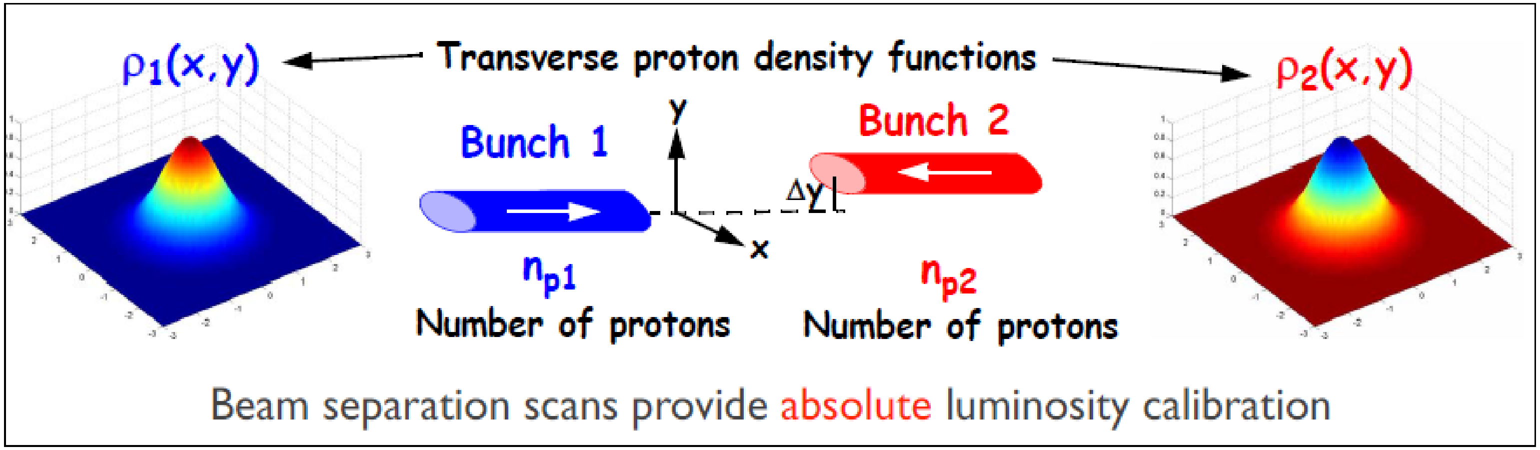
Day-by-day value of the relative longitudinal shift between the two half-shells of the BPIX as measured with the primary vertex residuals, for the last month of pp data taking in 2012.



Standard Model Total Production Cross Section Measurements
Status: March 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
∫ℒ dt [fb⁻¹]
Reference
pp
W
Z
tt̄
t_{t−chan}
WW
H
Wt
WZ
ZZ
t_{s−chan}
tt̄W
tt̄Z
tZj
σ = 96.07 ± 0.18 ± 0.91 mb (data) COMPETE HPR1R2 (theory)
σ = 95.35 ± 0.38 ± 1.3 mb (data) COMPETE HPR1R2 (theory)
σ = 190.1 ± 0.2 ± 6.4 nb (data) DYNNLO + CT14NNLO (theory)
σ = 98.71 ± 0.028 ± 2.191 nb (data) DYNNLO + CT14NNLO (theory)
σ = 58.43 ± 0.03 ± 1.66 nb (data) DYNNLO+CT14 NNLO (theory)
σ = 34.24 ± 0.03 ± 0.92 nb (data) DYNNLO+CT14 NNLO (theory)
σ = 29.53 ± 0.03 ± 0.77 nb (data) DYNNLO+CT14 NNLO (theory)
σ = 818 ± 8 ± 35 pb (data) top++ NNLO+NLL (theory)
σ = 242.9 ± 1.7 ± 8.6 pb (data) top++ NNLO+NNLL (theory)
σ = 182.9 ± 3.1 ± 6.4 pb (data) top++ NNLO+NNLL (theory)
σ = 247 ± 6 ± 46 pb (data) NLO+NLL (theory)
σ = 89.6 ± 1.7 + 7.2 − 6.4 pb (data) NLO+NLL (theory)
σ = 68 ± 2 ± 8 pb (data) NLO+NLL (theory)
σ = 142 ± 5 ± 13 pb (data) NNLO (theory)
σ = 68.2 ± 1.2 ± 4.6 pb (data) NNLO (theory)
σ = 51.9 ± 2 ± 4.4 pb (data) NNLO (theory)
σ = 57 + 6 − 5.9 + 4 − 3.3 pb (data) LHC-HXSWG YR4 (theory)
σ = 27.7 ± 3 + 2.3 − 1.9 pb (data) LHC-HXSWG YR4 (theory)
σ = 22.1 + 6.7 − 5.3 + 3.3 − 2.7 pb (data) LHC-HXSWG YR4 (theory)
σ = 94 ± 10 + 28 − 23 pb (data) NLO+NNLL (theory)
σ = 23 ± 1.3 + 3.4 − 3.7 pb (data) NLO+NLL (theory)
σ = 16.8 ± 2.9 ± 3.9 pb (data) NLO+NLL (theory)
σ = 50.6 ± 2.6 ± 2.5 pb (data) MATRIX (NNLO) (theory)
σ = 24.3 ± 0.6 ± 0.9 pb (data) MATRIX (NNLO) (theory)
σ = 19 + 1.4 − 1.3 ± 1 pb (data) MATRIX (NNLO) (theory)
σ = 17.3 ± 0.6 ± 0.8 pb (data) Matrix (NNLO) & Sherpa (NLO) (theory)
σ = 7.3 ± 0.4 + 0.4 − 0.3 pb (data) NNLO (theory)
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data) NNLO (theory)
σ = 4.8 ± 0.8 + 1.6 − 1.3 pb (data) NLO+NNL (theory)
σ = 1.5 ± 0.72 ± 0.33 pb (data) Madgraph5 + aMCNLO (theory)
σ = 369 + 86 − 79 ± 44 fb (data) MCFM (theory)
σ = 0.92 ± 0.29 ± 0.1 pb (data) Madgraph5 + aMCNLO (theory)
σ = 176 + 52 − 48 ± 24 fb (data) HELAC-NLO (theory)
σ = 620 ± 170 ± 160 fb (data) NLO+NLL (theory)
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
10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1.0 1.5 2.0 2.5
data/theory
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

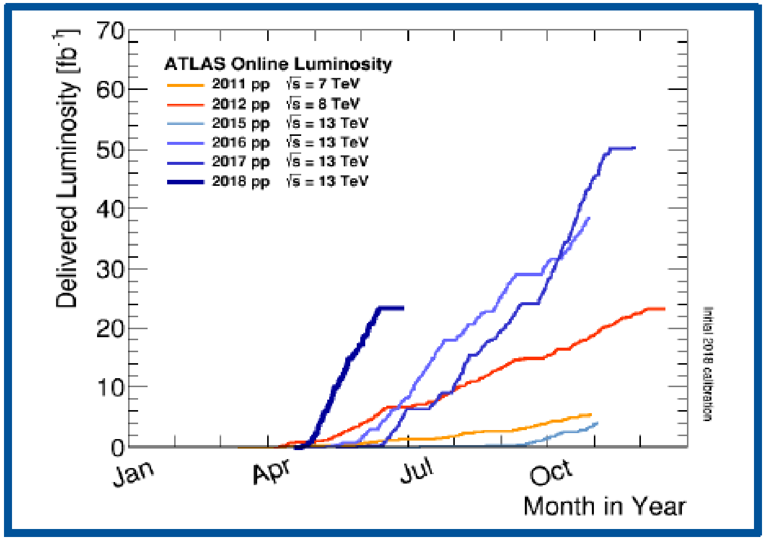
- A measurement of the number of collisions per cm^2 and second.
- Multiple methods used for determining luminosity: reducing uncertainties.
- Normalization is done with beam-separation scan (Van-der-Meer scan). Requires careful control of beam parameters.

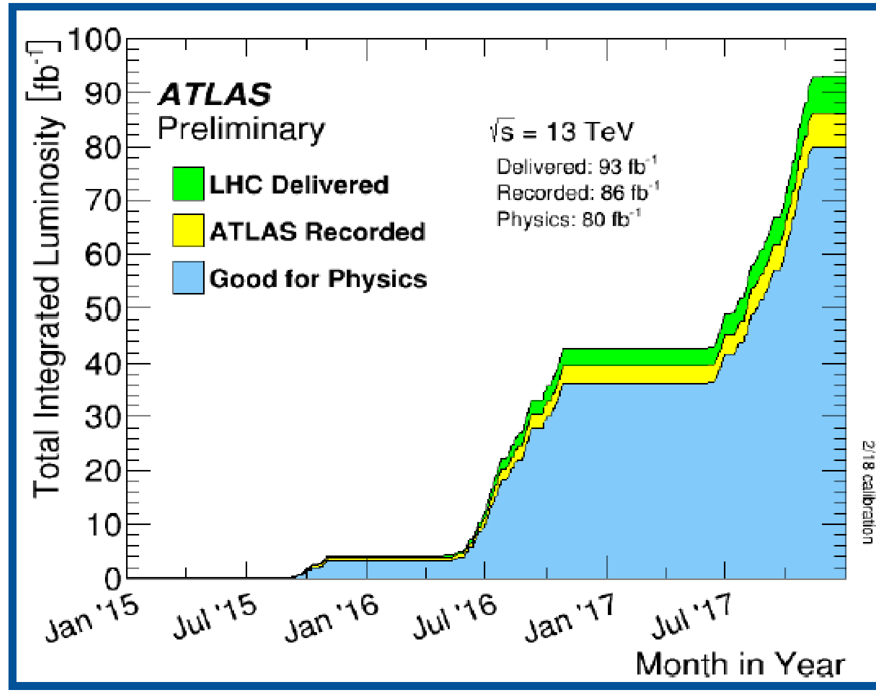


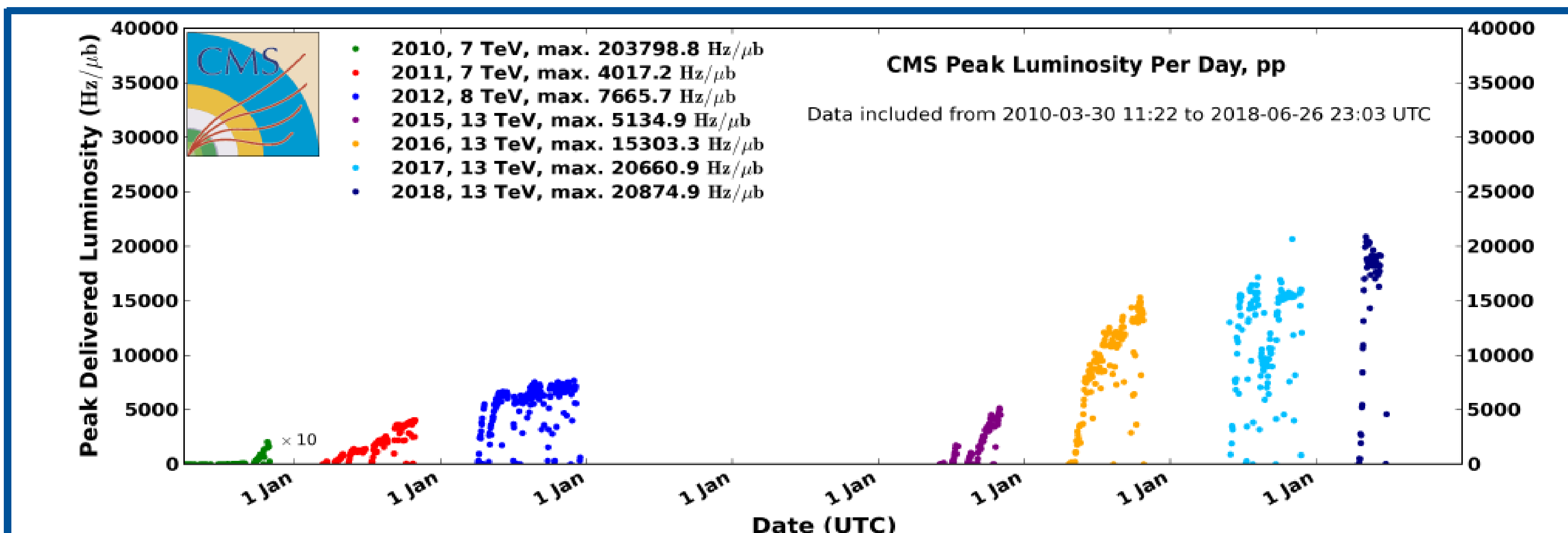
From http://cds.cern.ch/record/1490292/files/ATL-DAPR-SLIDE-2012-627.pdf

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

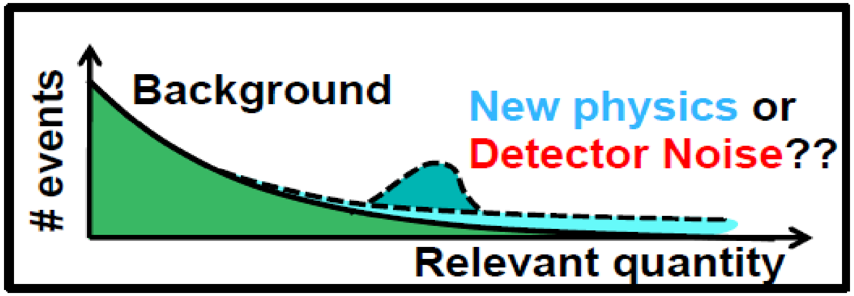
LUMINOSITY


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
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
CMS Peak Luminosity Per Day, pp
Data included from 2010-03-30 11:22 to 2018-06-26 23:03 UTC
Peak Delivered Luminosity (Hz/μb)
× 10
1 Jan
Date (UTC)

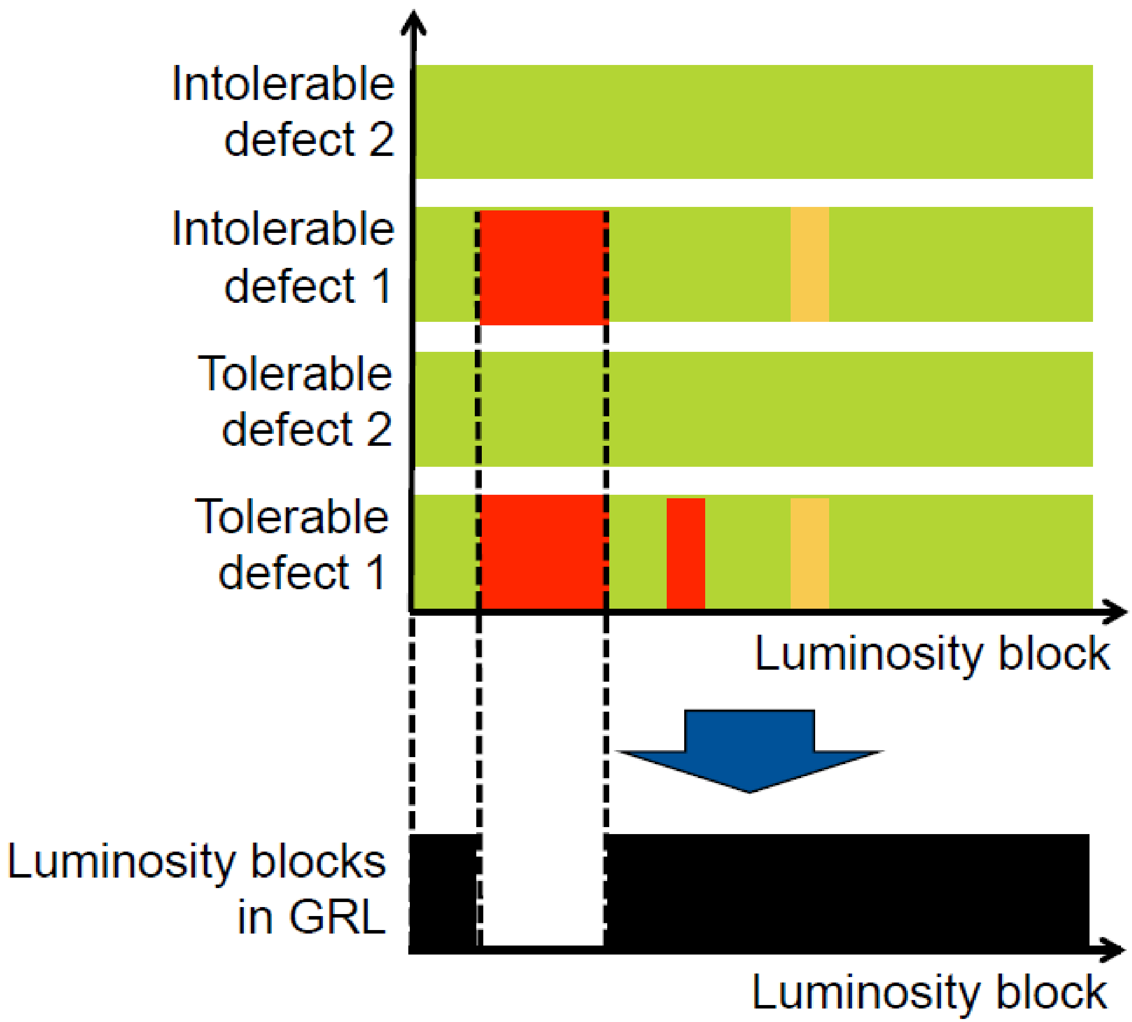
Data quality



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".

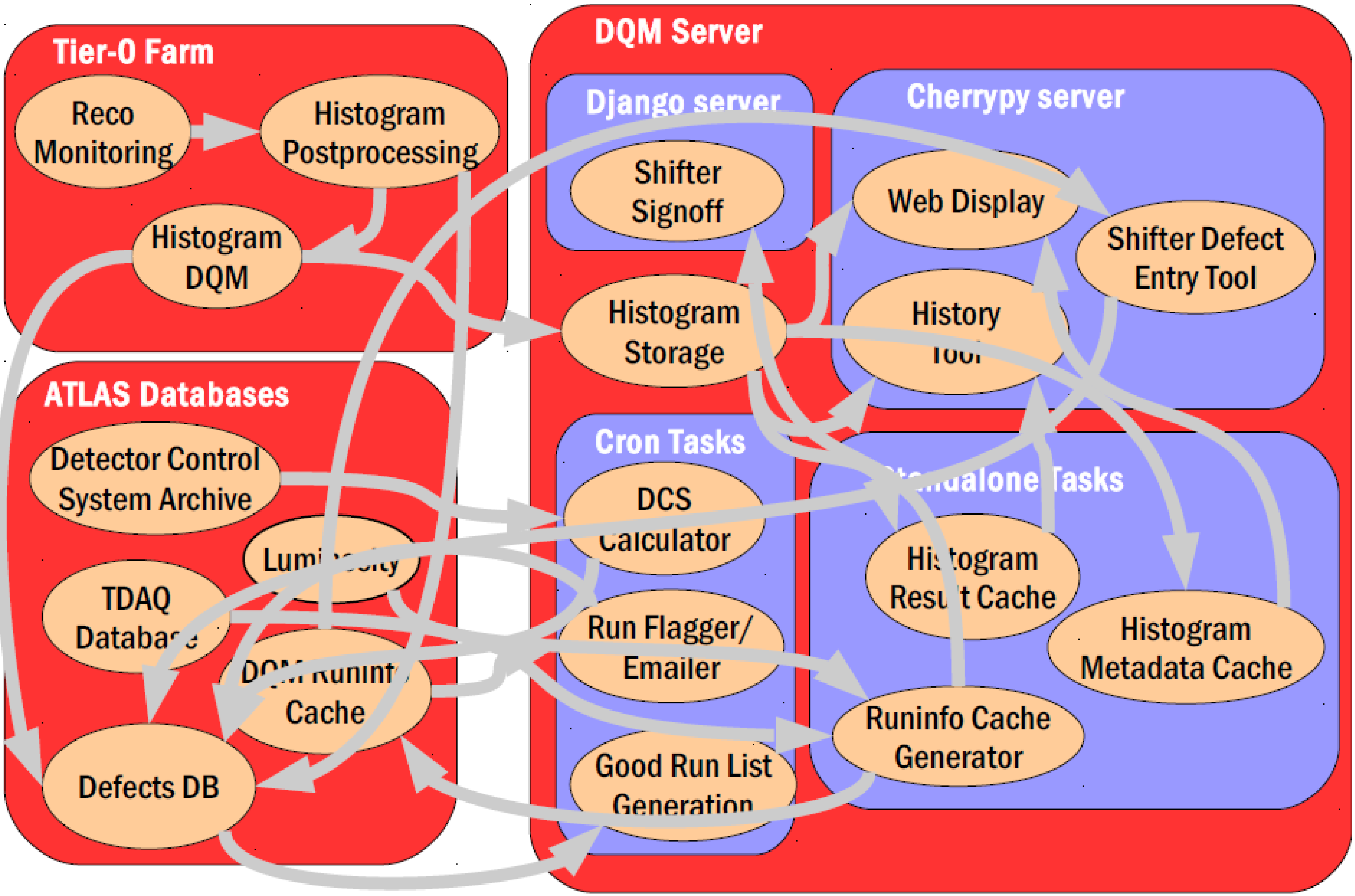
Data quality and „GRL”



Good Run List

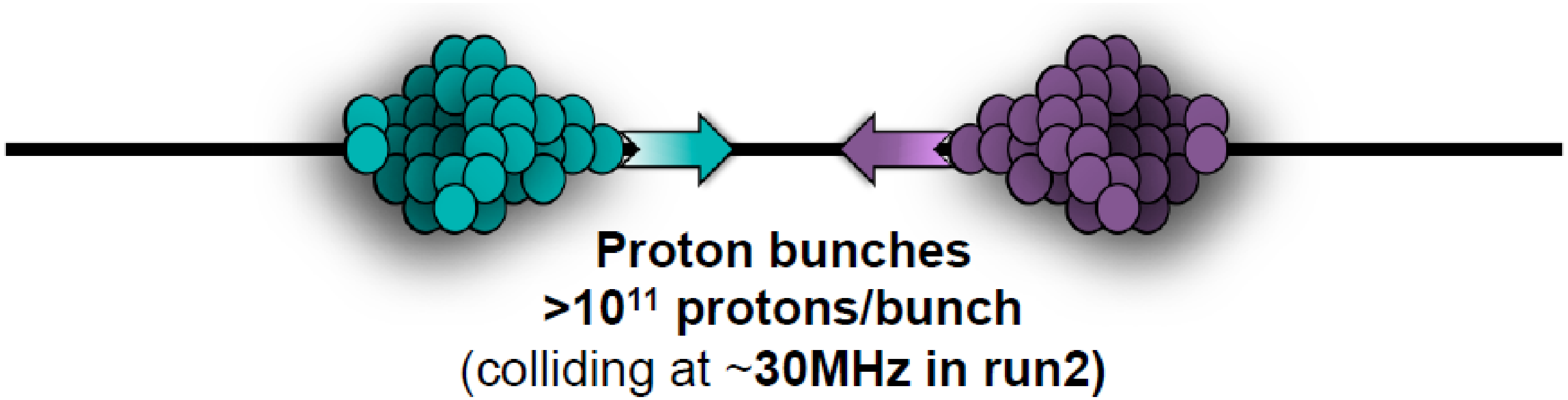
Short period during which data taking conditions are (expected to be) absolutely stable. Used for data-quality assessment and luminosity determination

Data quality

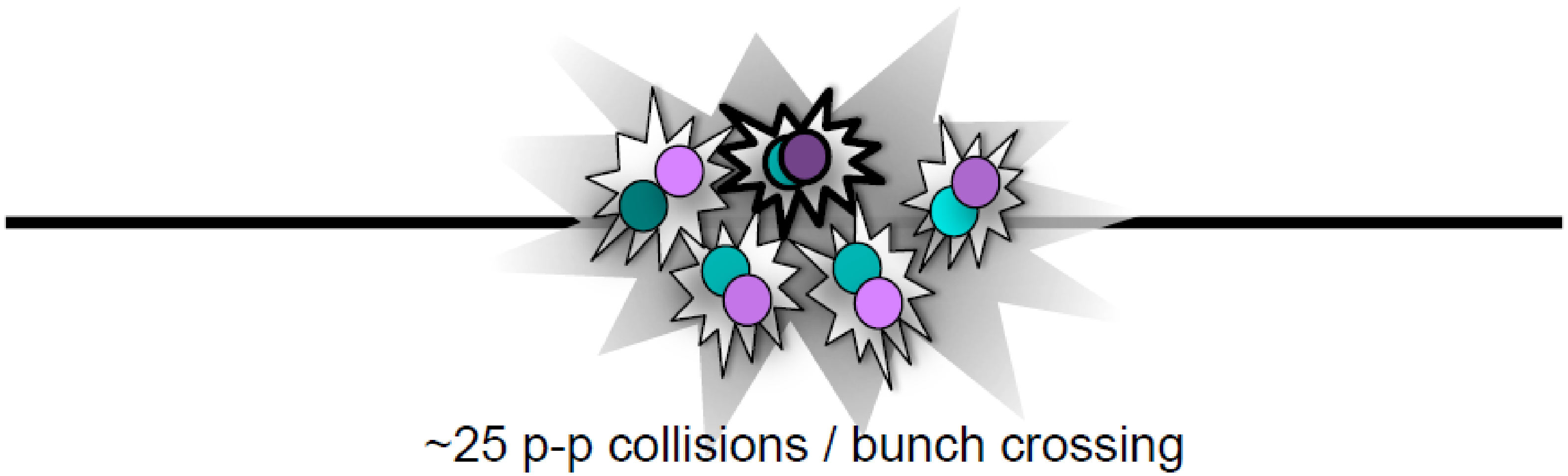


https://cds.cern.ch/record/2008725/files/ATL-SOFT-SLIDE-2015-179.pdf

Pile-up

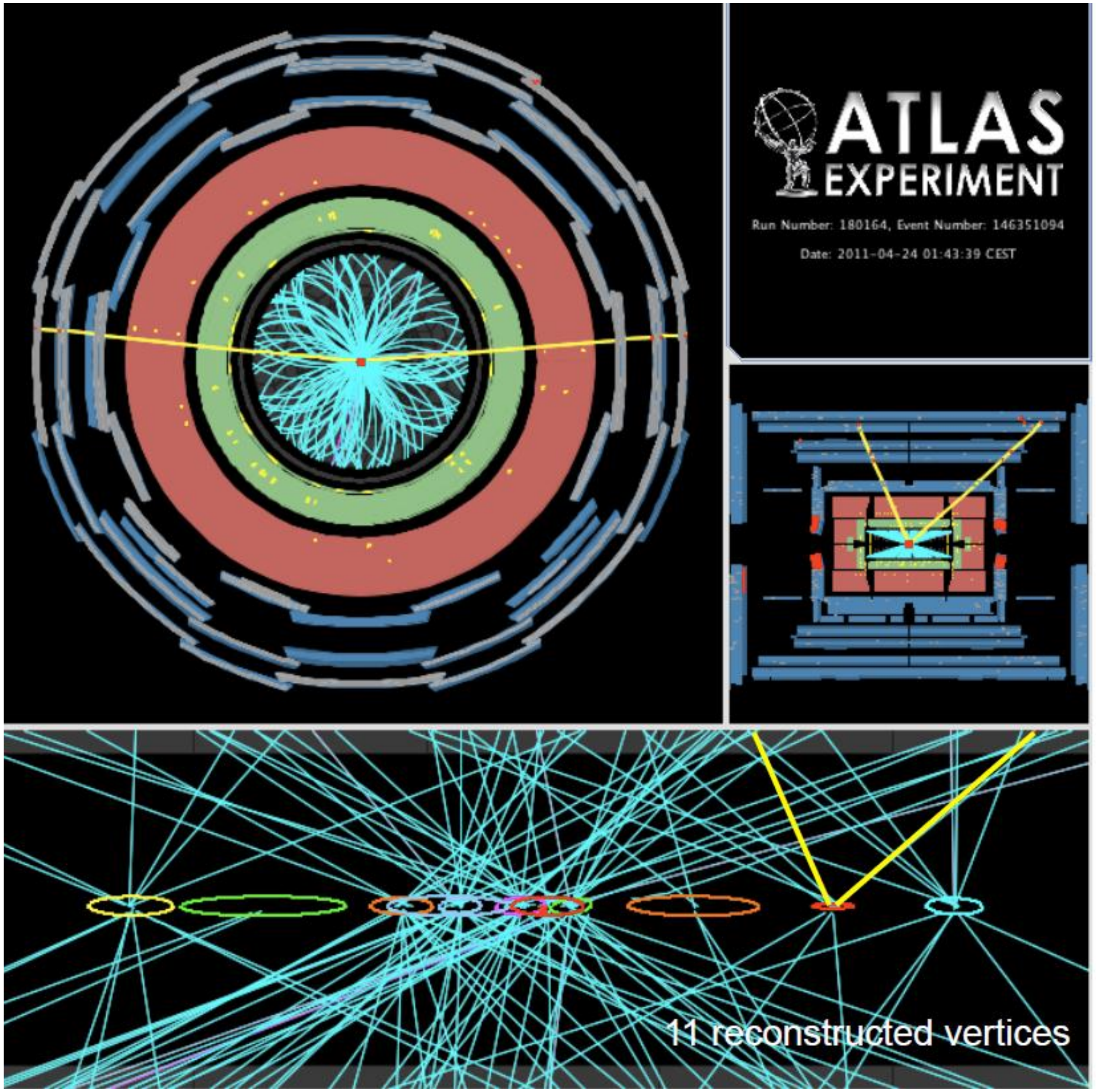


Proton bunches
>10^{11} protons/bunch
(colliding at ~30MHz in run2)



~25 p-p collisions / bunch crossing

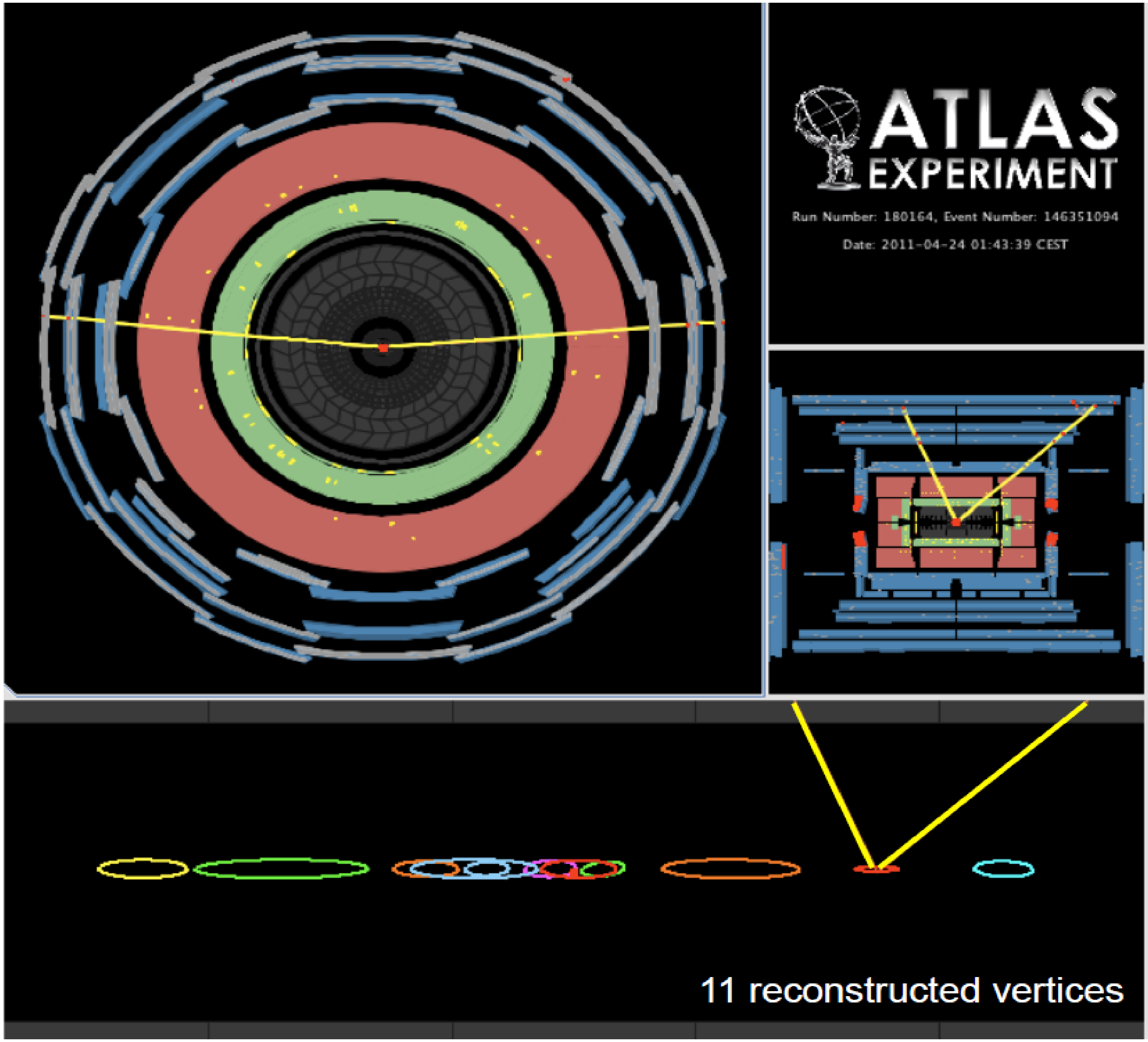
Pile-up



Z->μμ event;
2011 data.

Track pT > 0.5 GeV

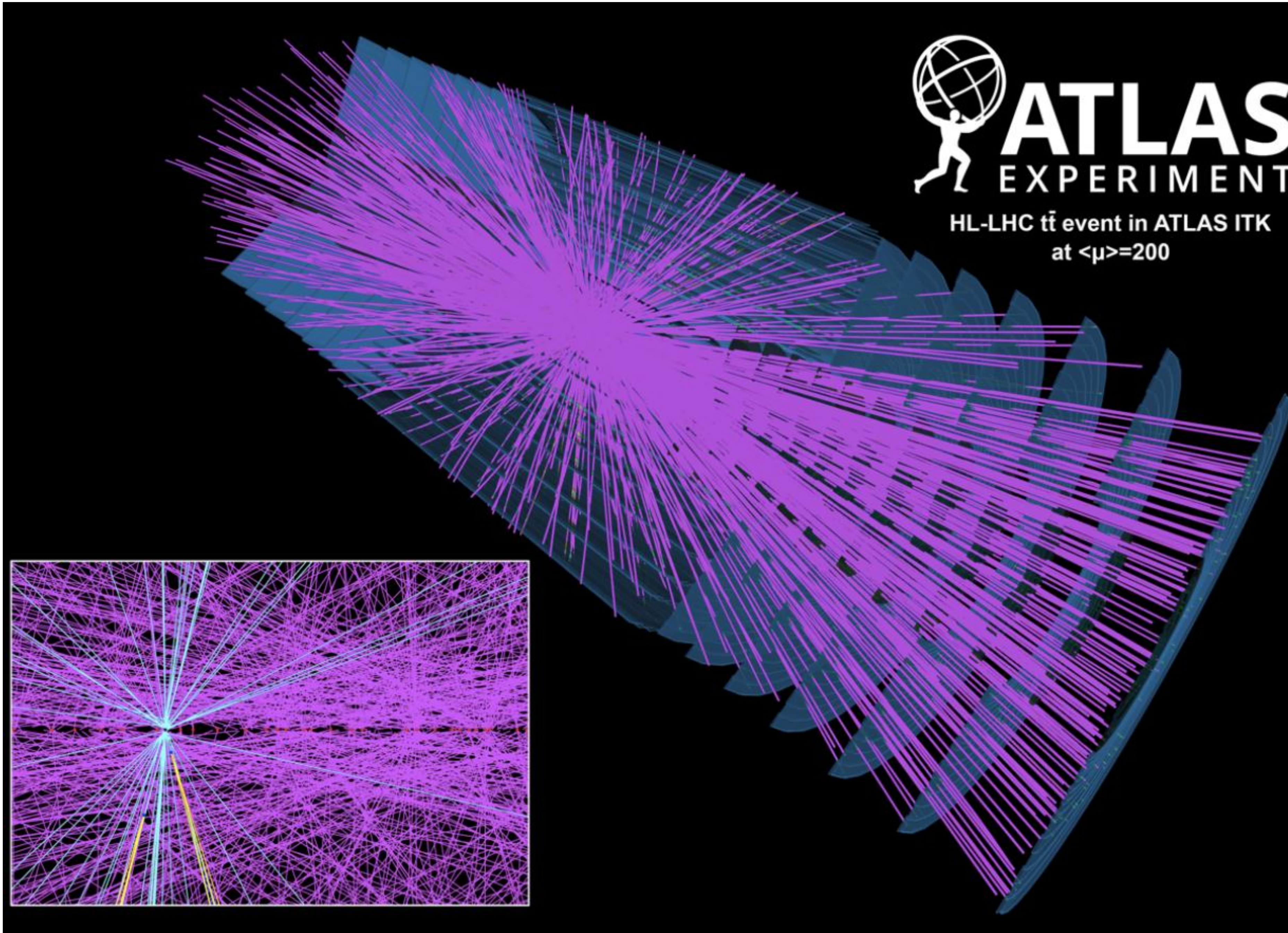
Pile-up



Z->μμ event;
2011 data.

Track pT > 10 GeV

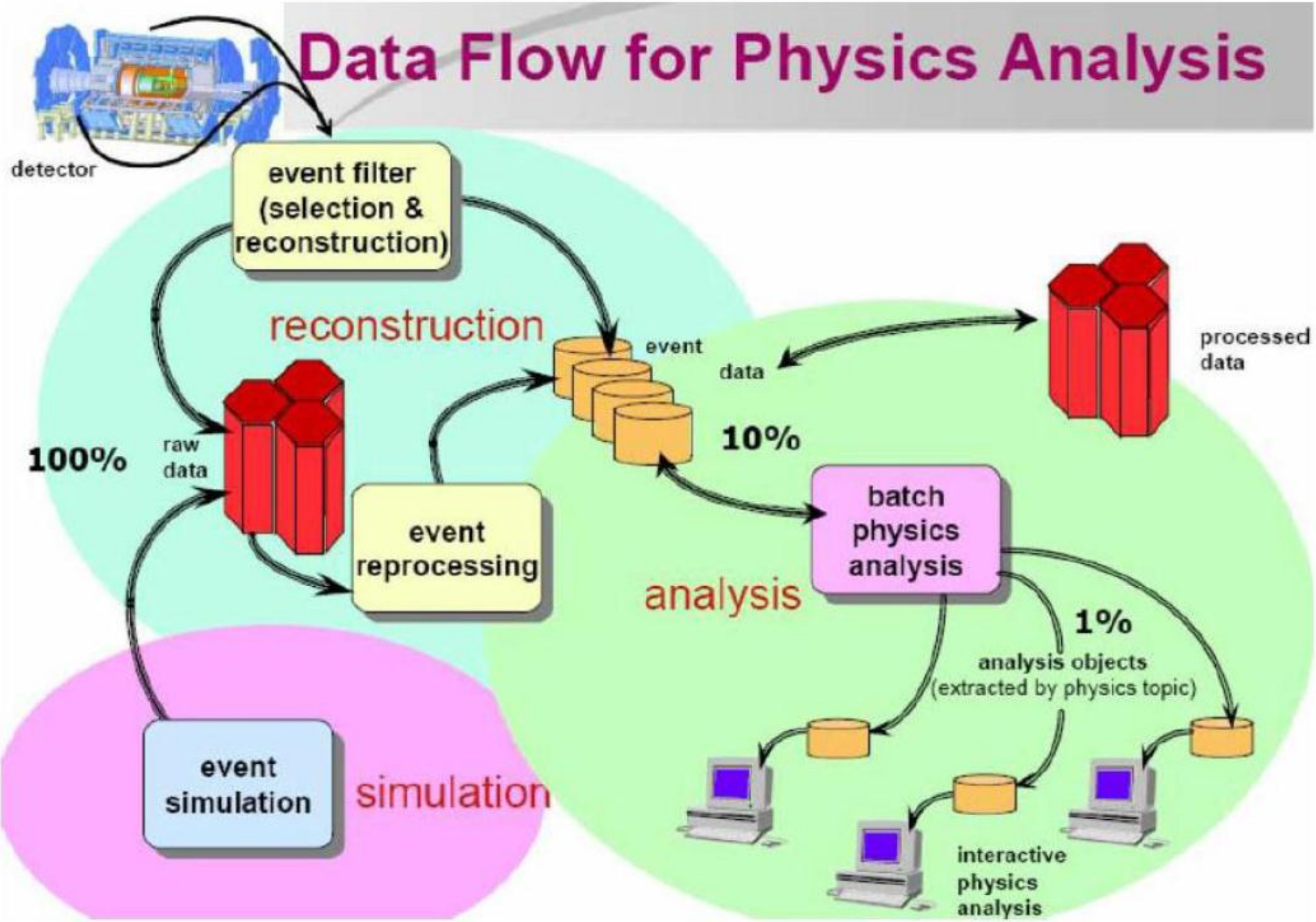
50


ATLAS
EXPERIMENT
HL-LHC $t\bar{t}$ event in ATLAS ITK
at <μ>=200

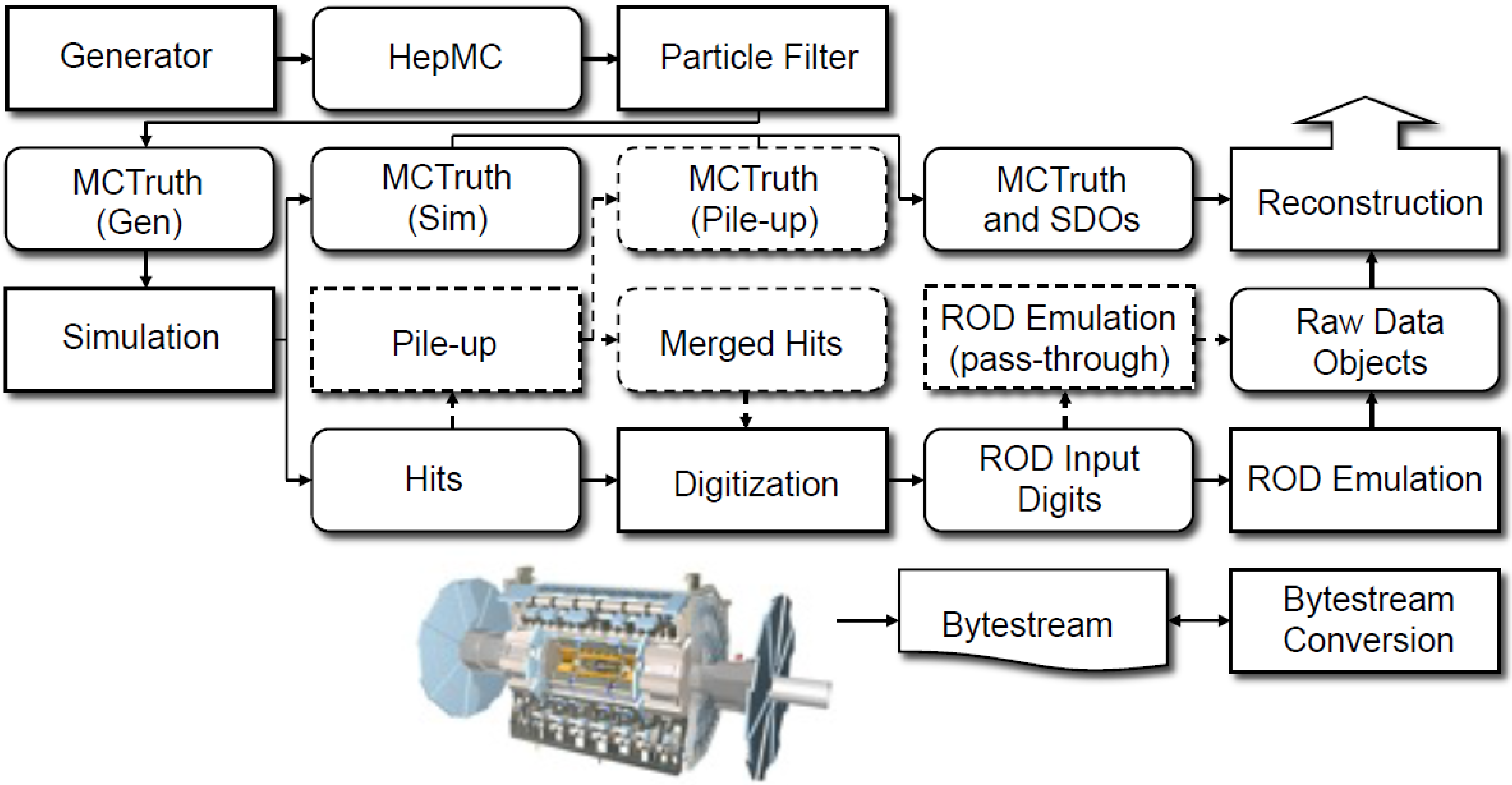
Monte Carlo simulation – why?

- **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

Event Generation
simulate the physics process.

Detector Simulation
simulate the interaction of the particles with the detector material.

Digitization
Translate interactions with detector into realistic signals.

Reconstruction
Go from signals back to particles, as for real data.

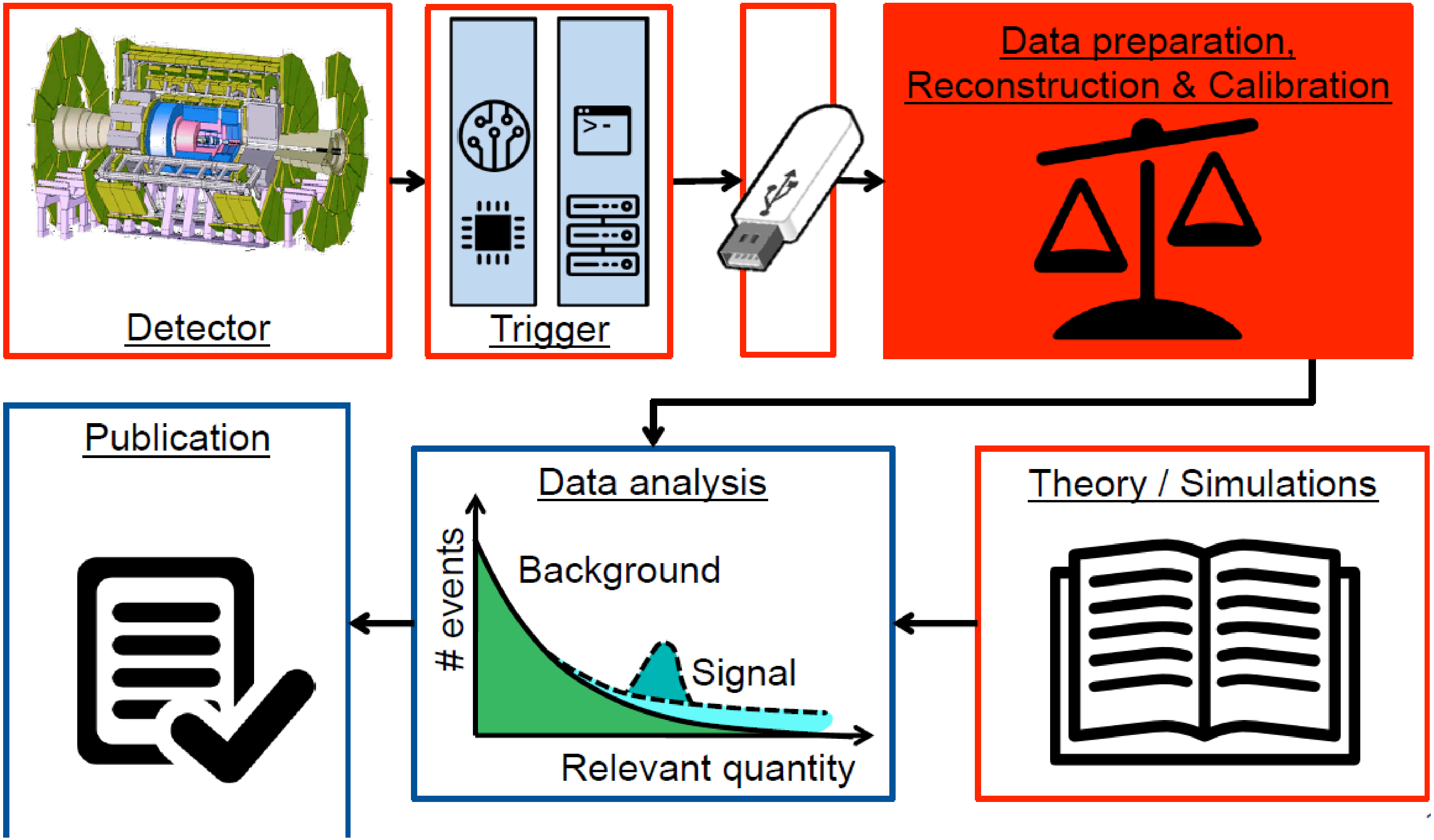
<u>How much processing time needed for each step?</u>

From < 1s to a few hours / event.

From 1 to 10min / event

From 5 to 60s / event

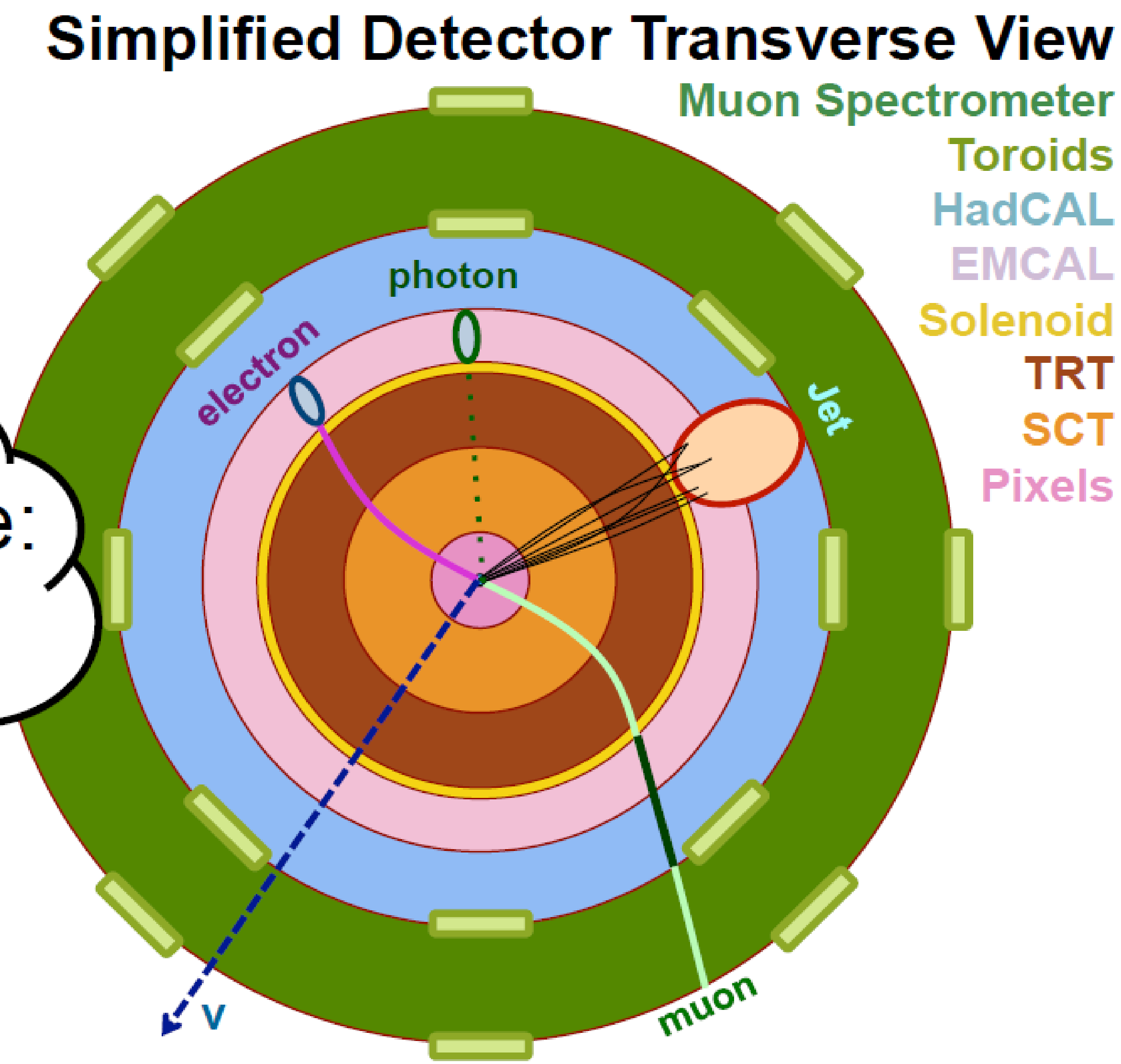
An event’s lifetime



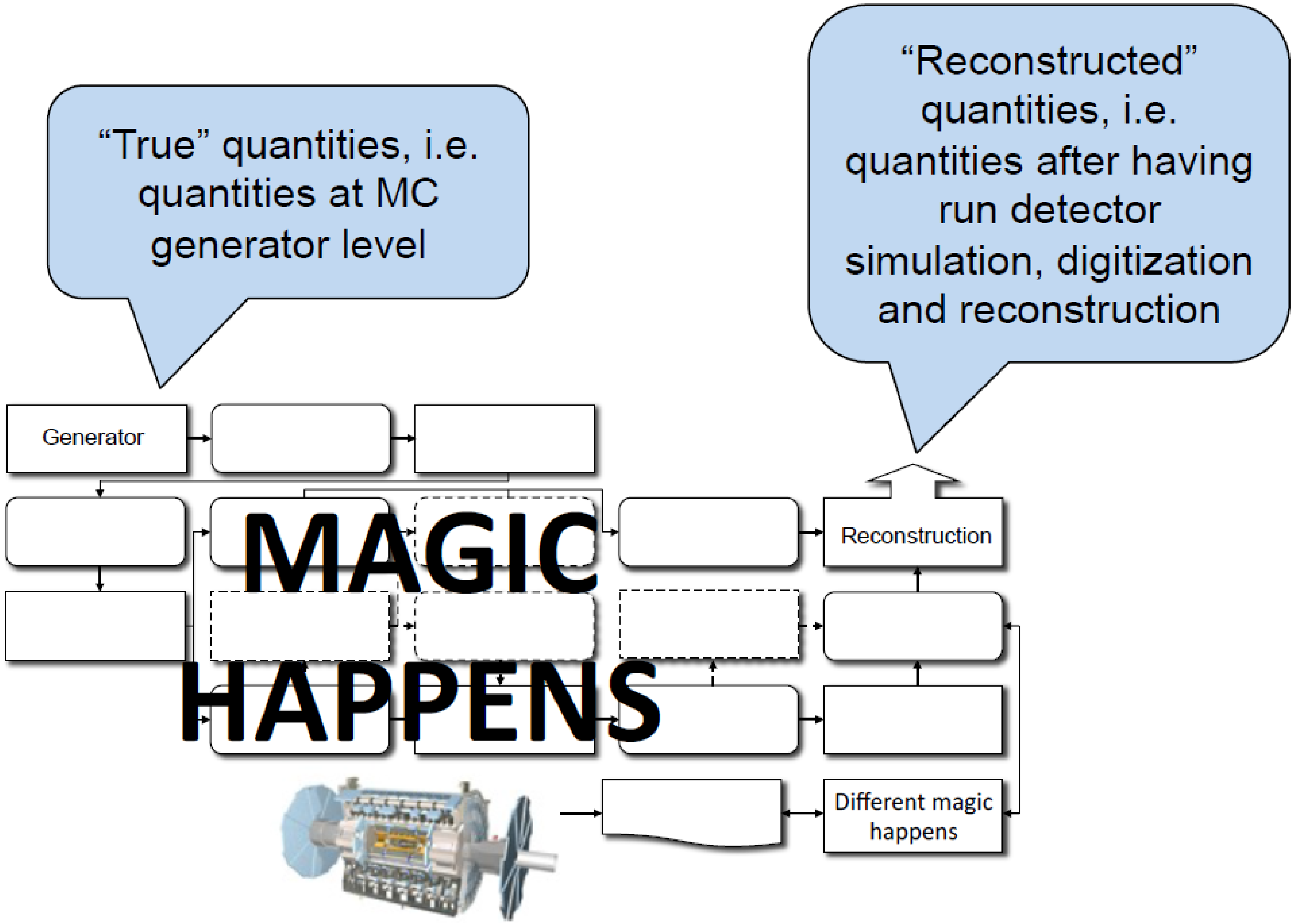
What do we reconstruct?

Tracks and **Clusters**

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

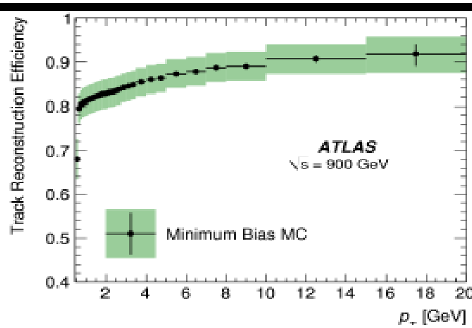
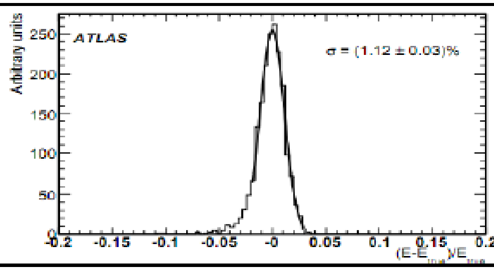
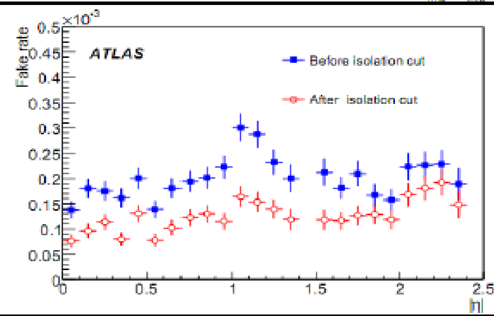


Reconstruction - figures of merit



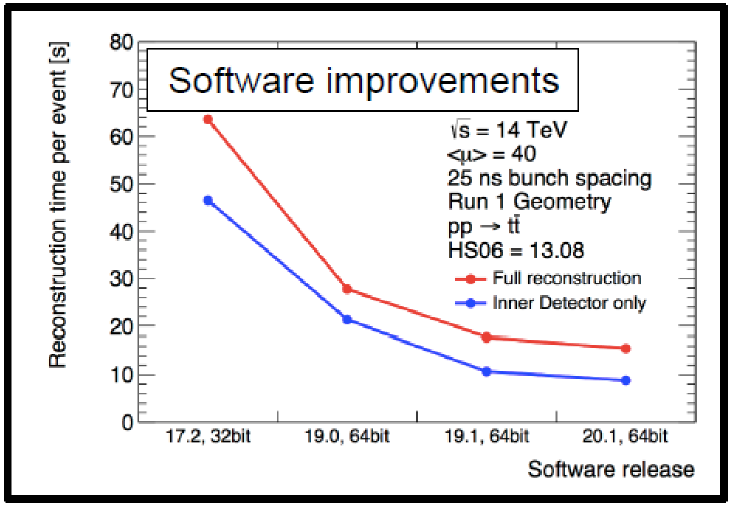
Reconstruction - figures of merit

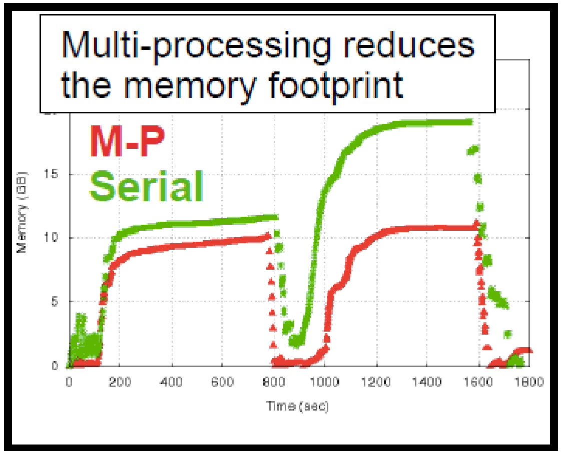
> "**true**" quantity:
> quantity at MC generator level.

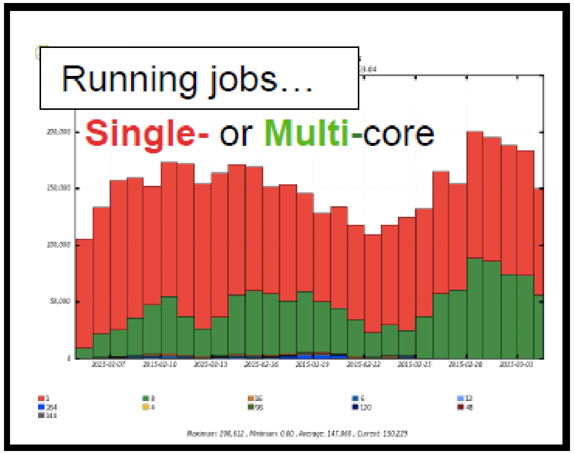
	Definition	Example		Needs be:
Efficiency	how often do we reconstruct the object	tracking efficiency = (number of reconstructed tracks) / (number of true tracks)		High
Resolution	how accurately do we reconstruct the quantity	energy resolution = (measured energy – true energy) / (true energy)		Good
Fake 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

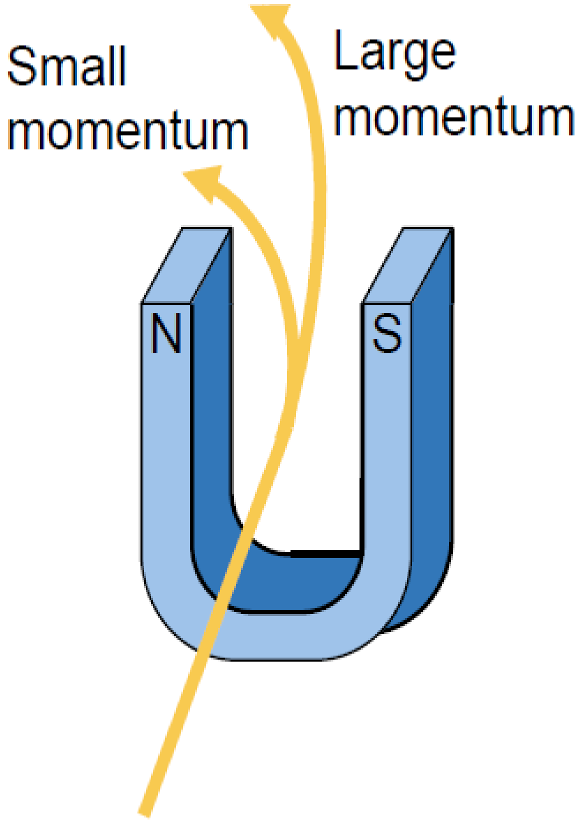
- High efficiency.
- Good resolution.
- Low fake rate.
- Robust against detector problems and data-taking conditions:
  - Noise.
  - Dead regions of the detector.
  - Increased pile-up.
- Computing-friendly. →
  - CPU time per event.
  - Memory use.

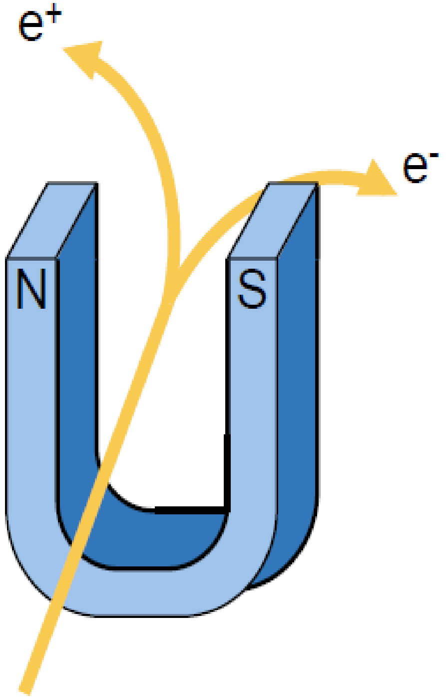




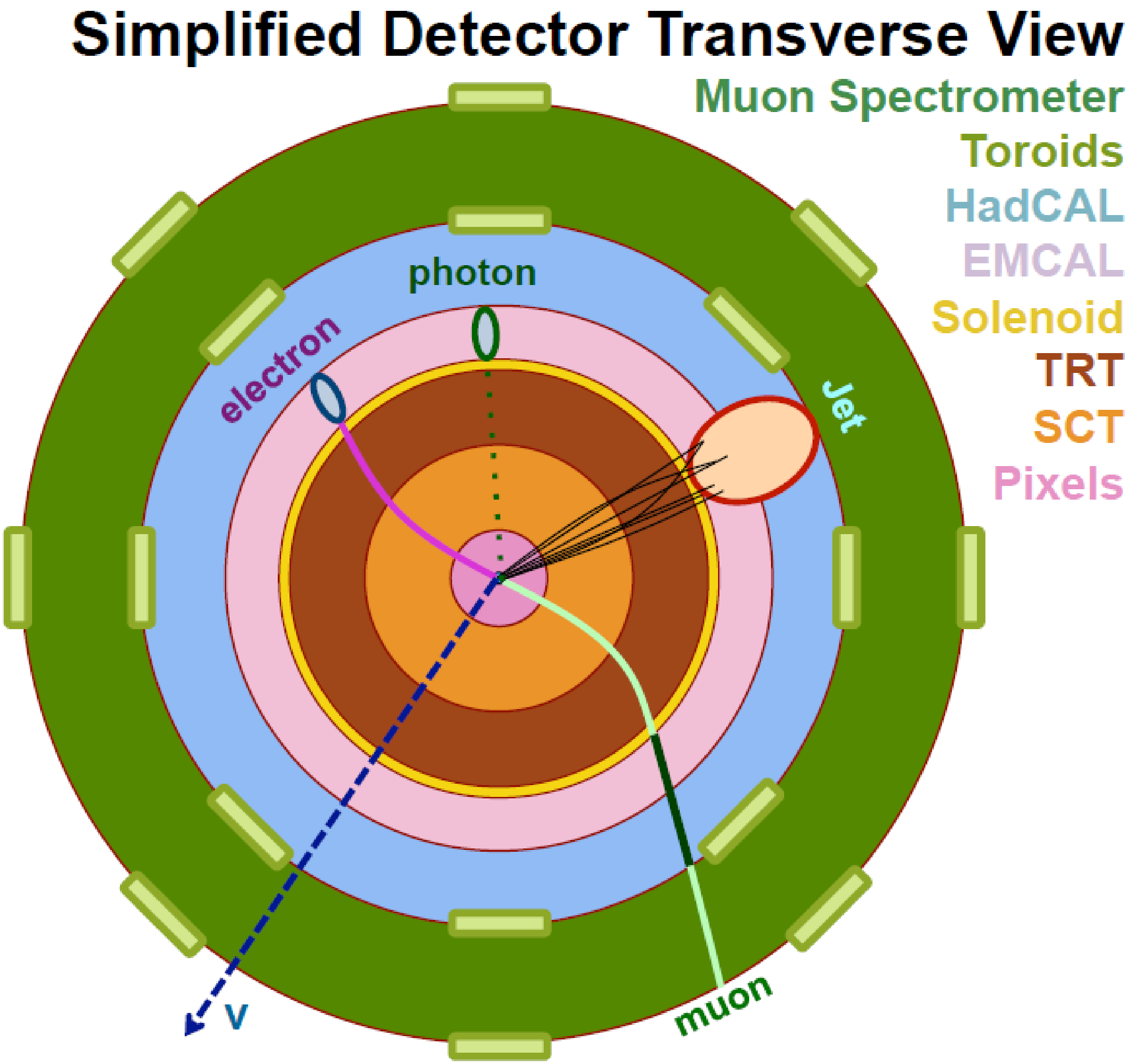


Why do we need magnetic field?





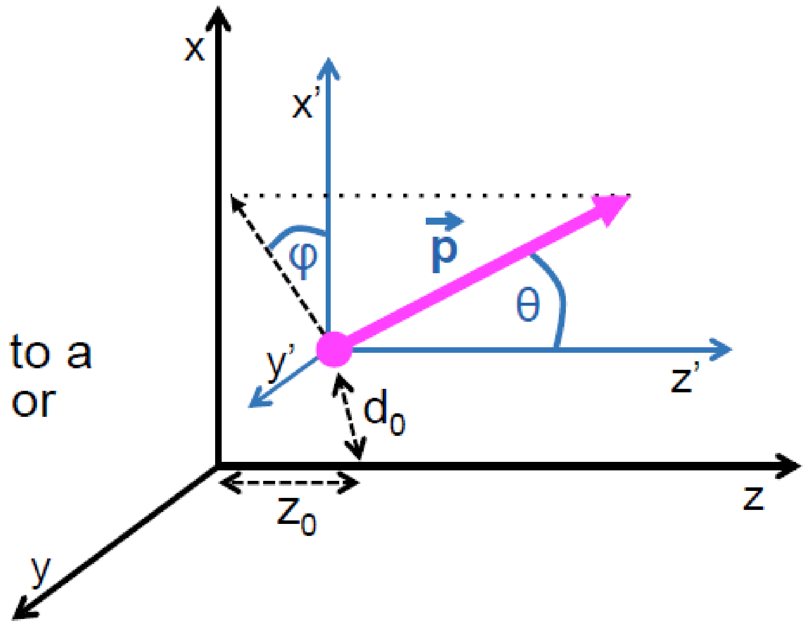
What do we reconstruct?



Tracking in a nutshell

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

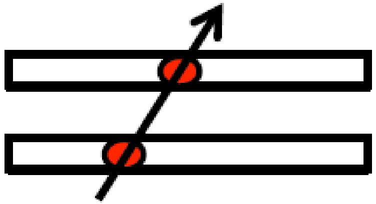
- **For a track we measure:**
  - Its momentum;
  - It's direction;
  - Its charge;
  - Its "perigee": the closest point to a reference line, transverse (d_0) or longitudinal (z_0).



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

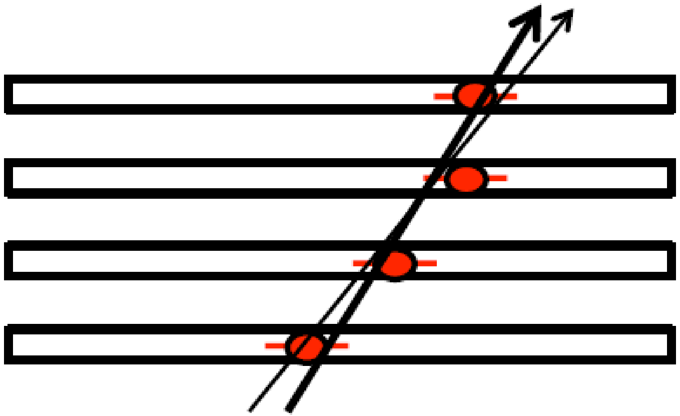
Tracking in a nutshell: track fitting

- **Perfect measurement – ideal**



- **Imperfect measurement – reality**

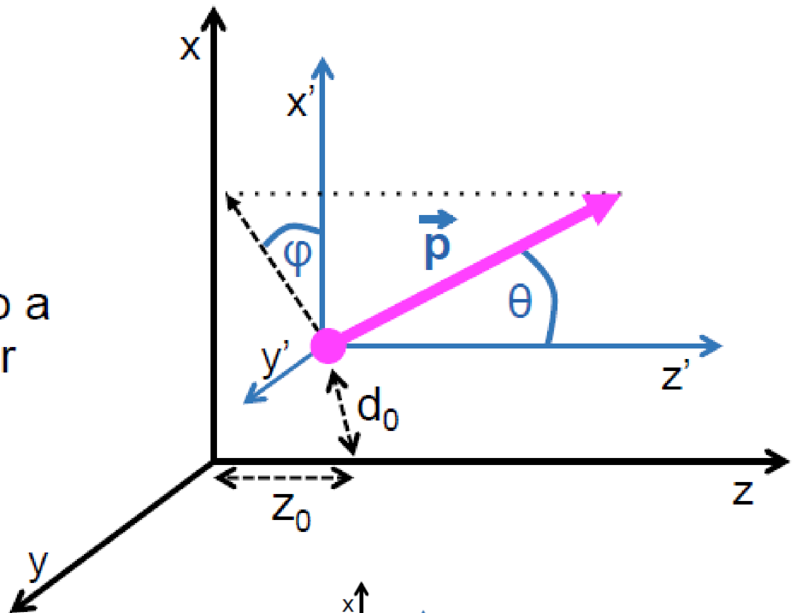
- **Small errors and more points help to constrain the possibilities**

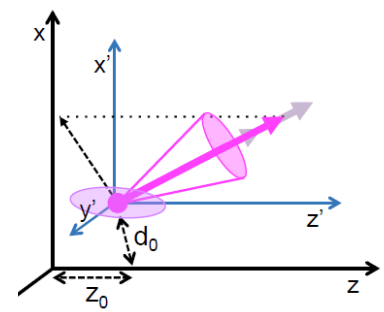


- **Quantitatively:**
  - Parameterize the track;
  - Find parameters by Least-Squares-Minimization;
  - Obtain also uncertainties on the track parameters.

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).



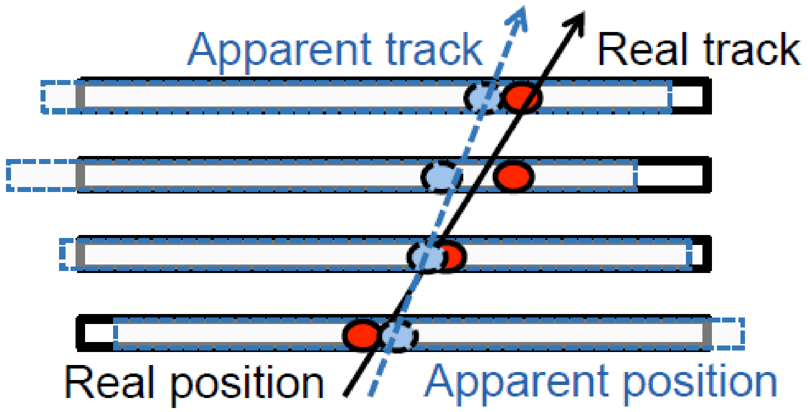


- **Small uncertainties are required.**
  - δd0 is O(10μm) and δθ O(0.1mrad).
  - Allows separation of tracks that come from different particle decays (which can be separated at the order of mm).

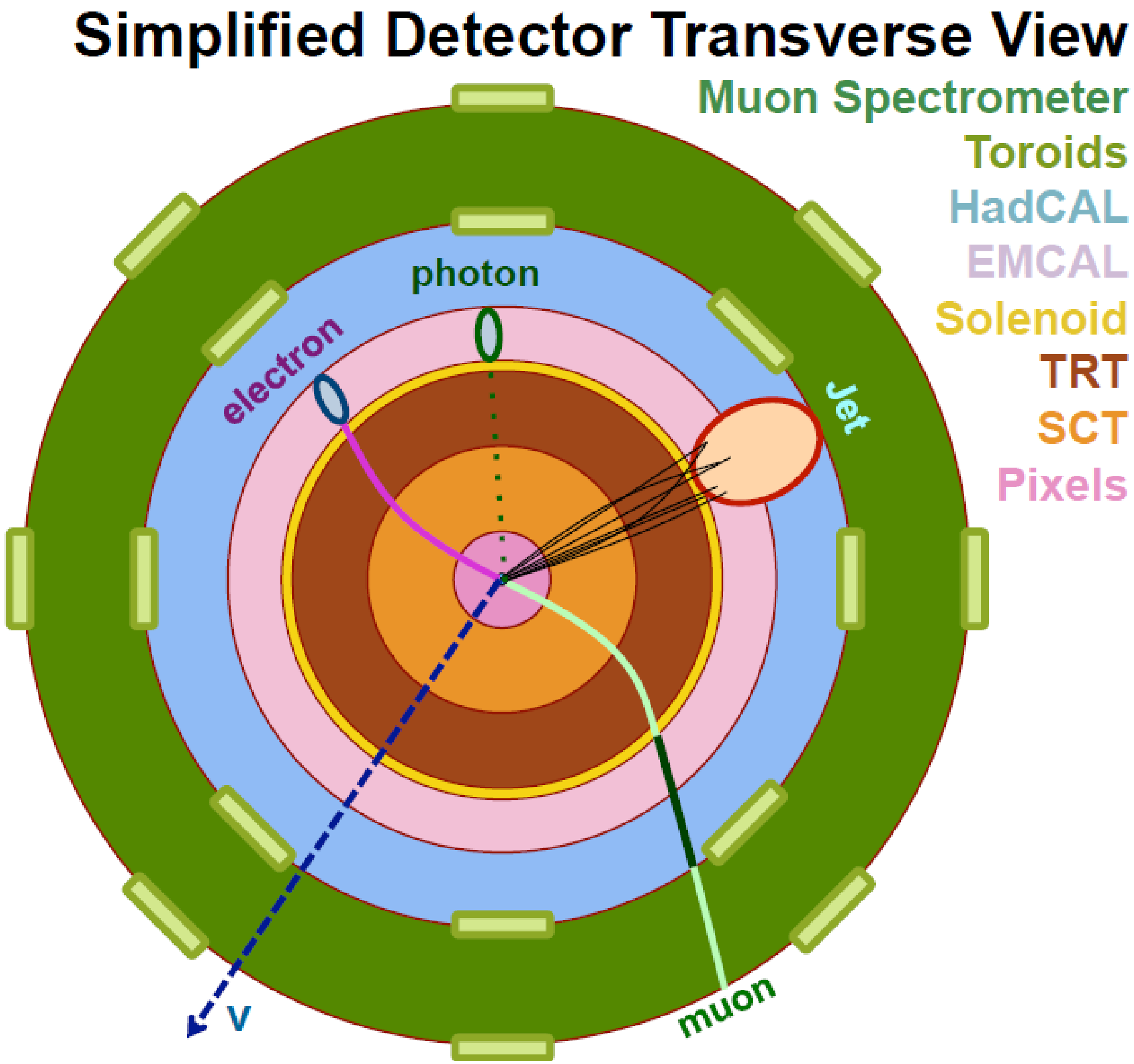
Tracking in a nutshell: the uncertainties

- **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.

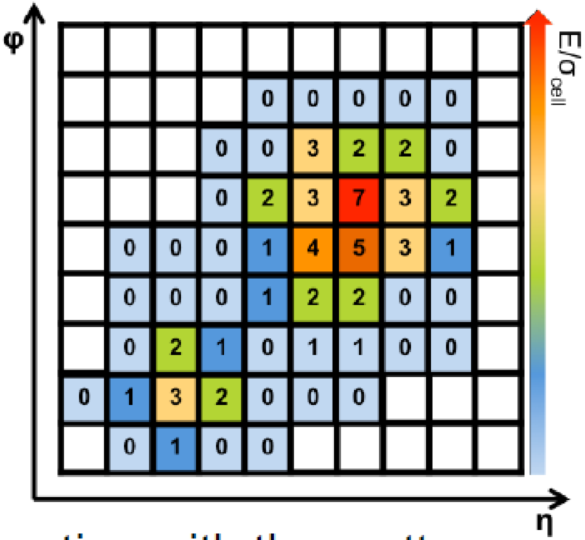


What do we reconstruct?



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;

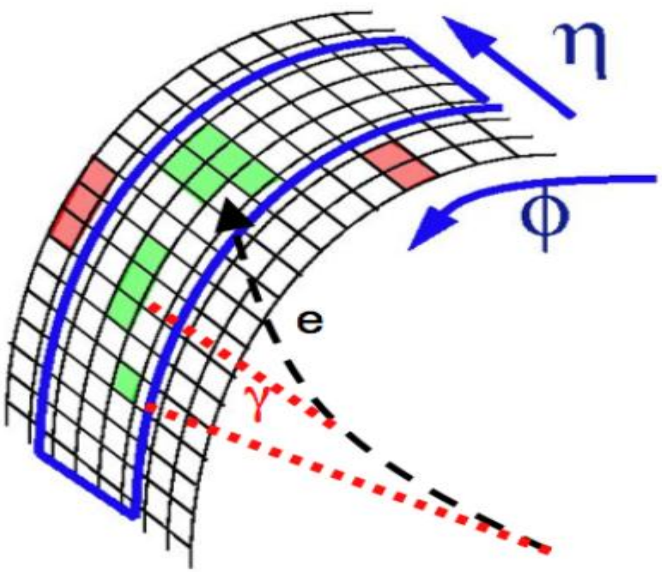


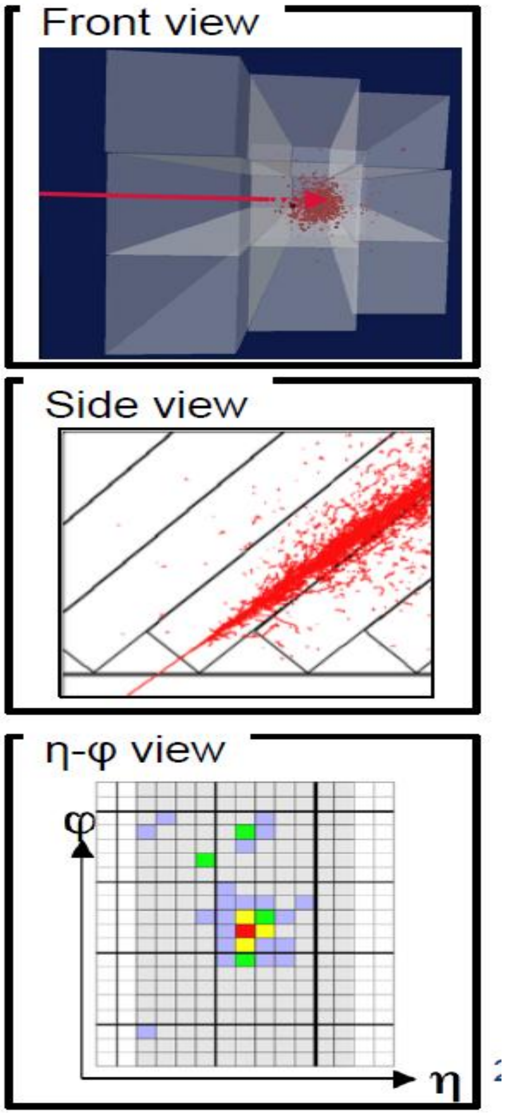
- **Calorimeters are segmented in cells.**
  - Typically a shower created by a particle interacting with the matter extends over several cells.
- **Various clustering algorithms, e.g.:**
  - **Sliding window**. Sum cells within a fixed-size rectangular window.
  - **Topo-clustering**. Start with a seed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

Cluster finding – an example

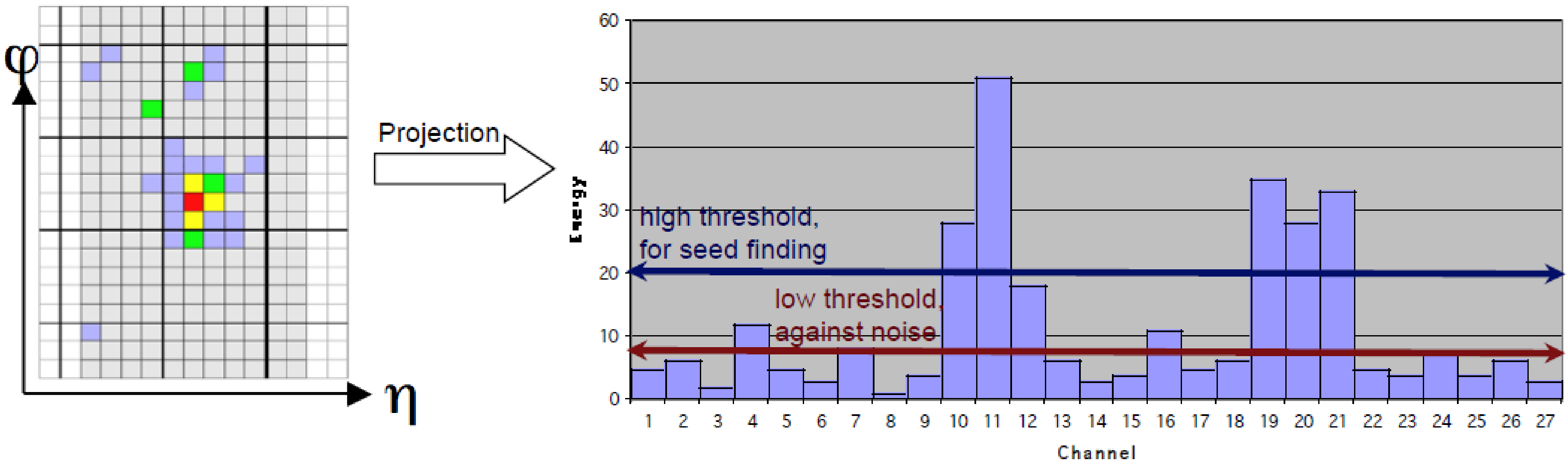
CMS crystal calorimeter – ECAL clusters

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





Cluster finding – an example



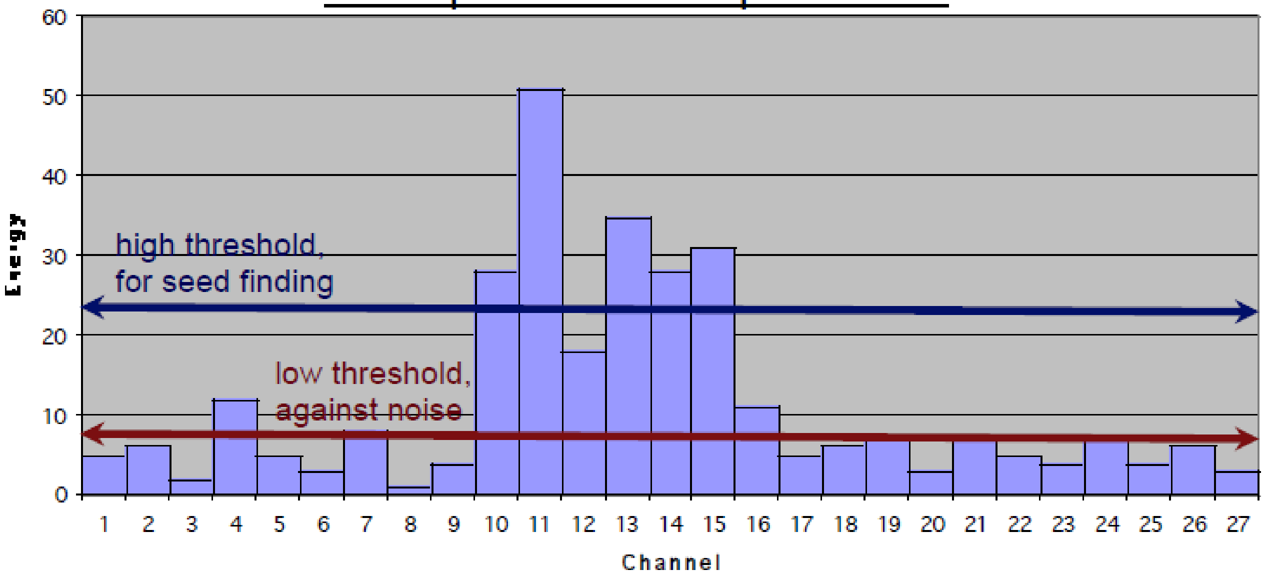
Simple example of an algorithm

- 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

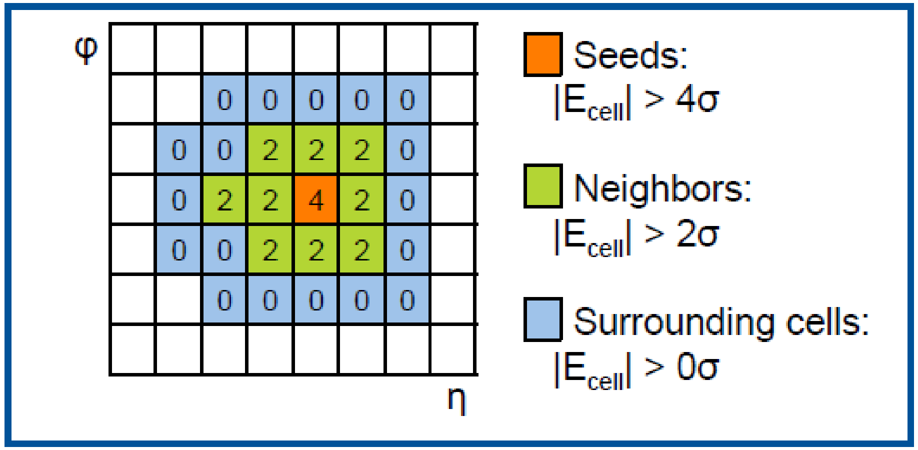
- **Careful tuning of thresholds needed.**
  - needs usually learning phase;
  - adapt to noise conditions;
  - too low : pick up too much unwanted energy;
  - too high : loose too much of "real" energy. Corrections/Calibrations will be larger.

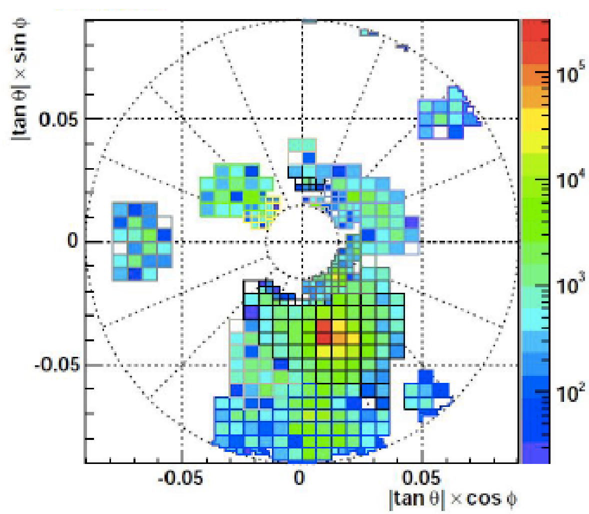
example : one lump or two?



Cluster finding – topological clustering

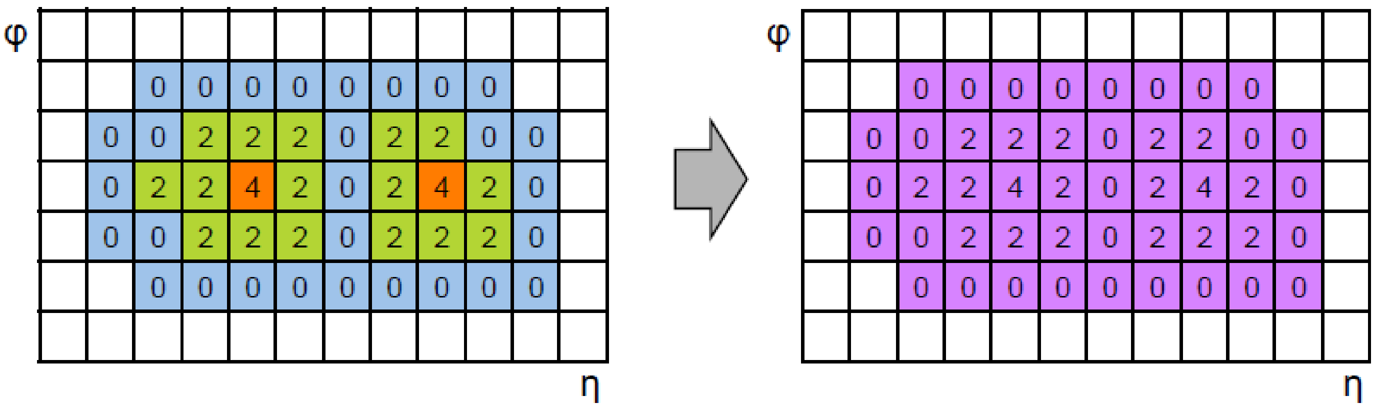
“Topological” clusters, i.e. “blobs” of energy inside the detector.



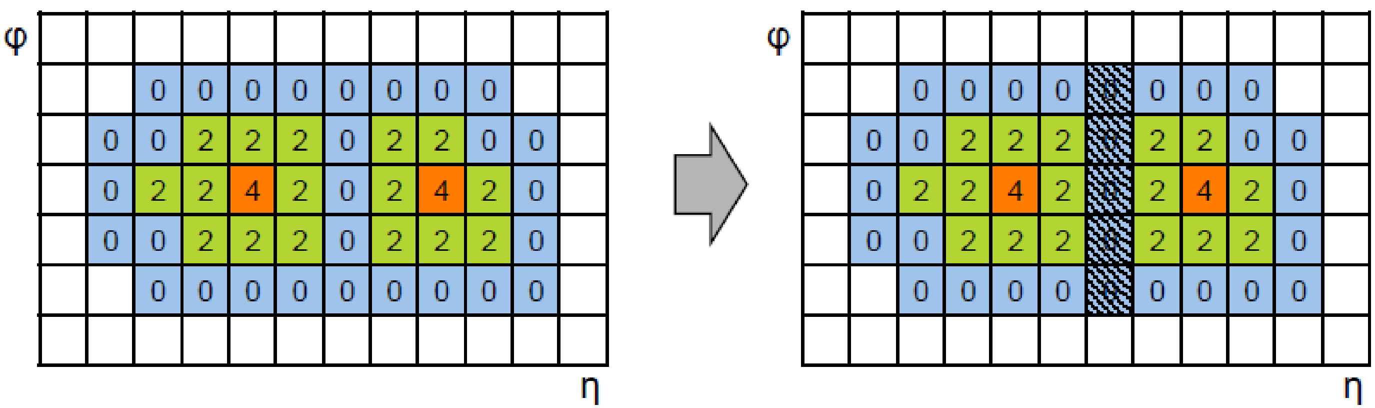


Cluster finding – merging and splitting

- 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).

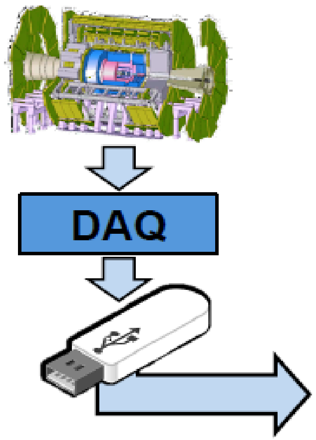
Cluster calibration

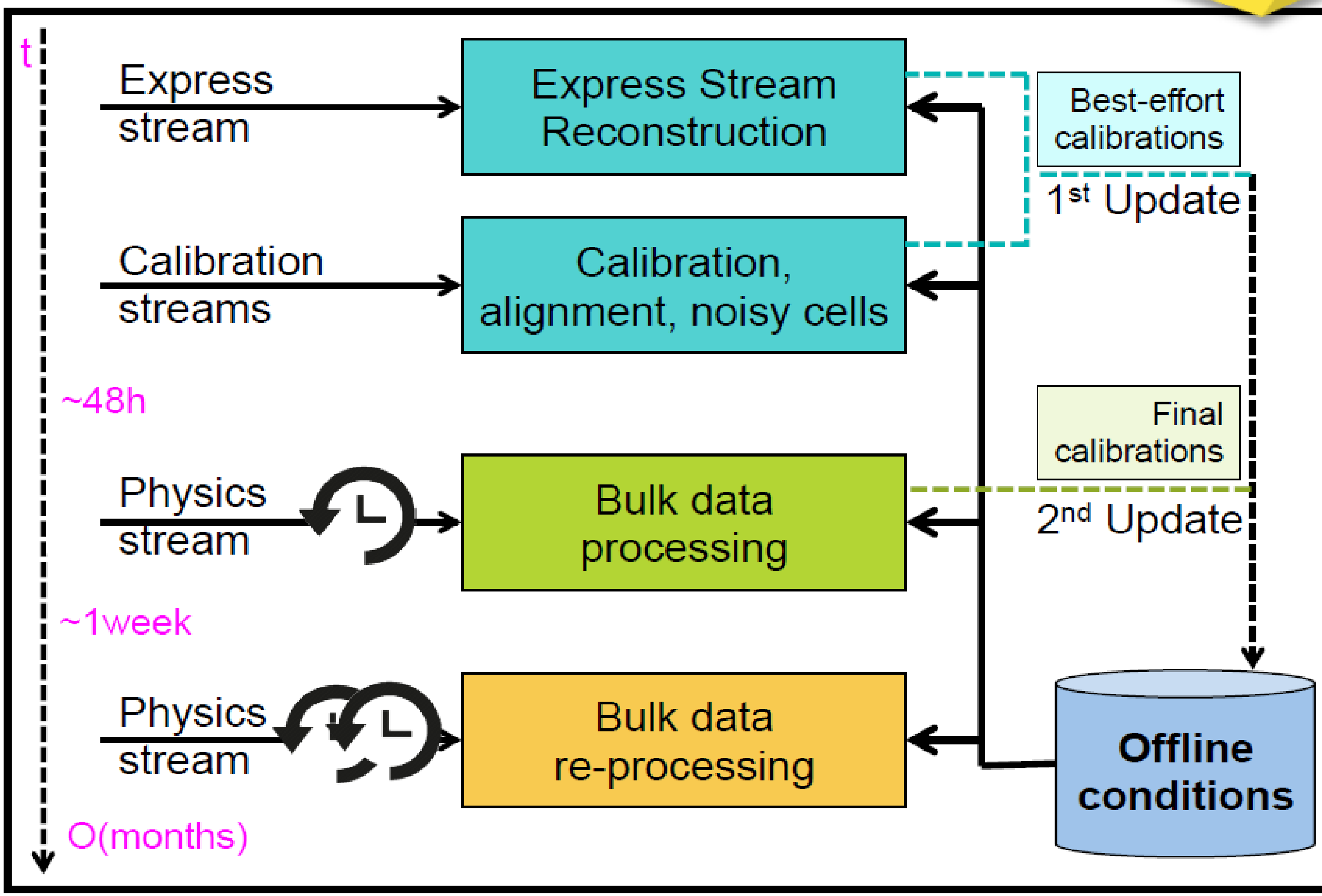
Possible energy measurements:

- **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.**

Reminder!

THE EVENT AT TIER0



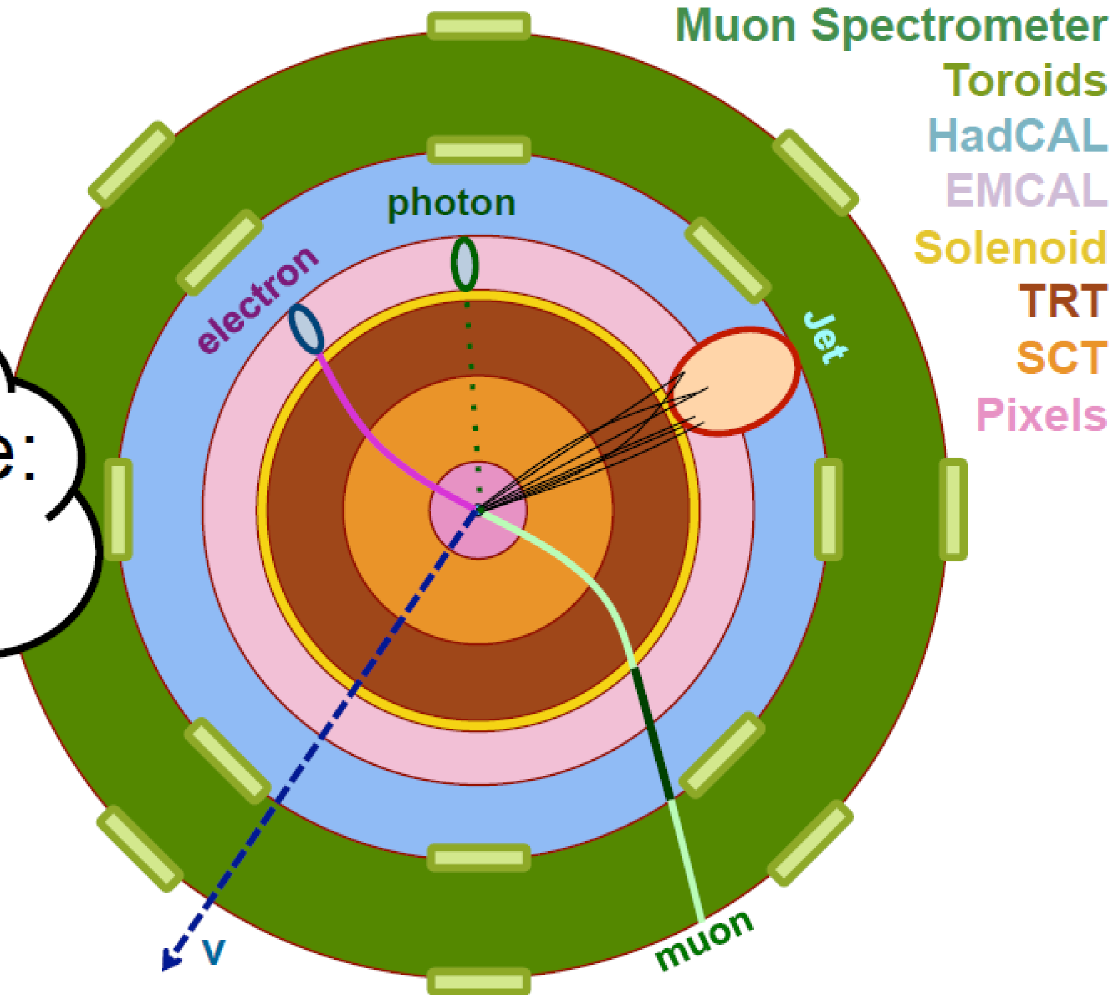


What do we reconstruct?

Tracks and Clusters

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

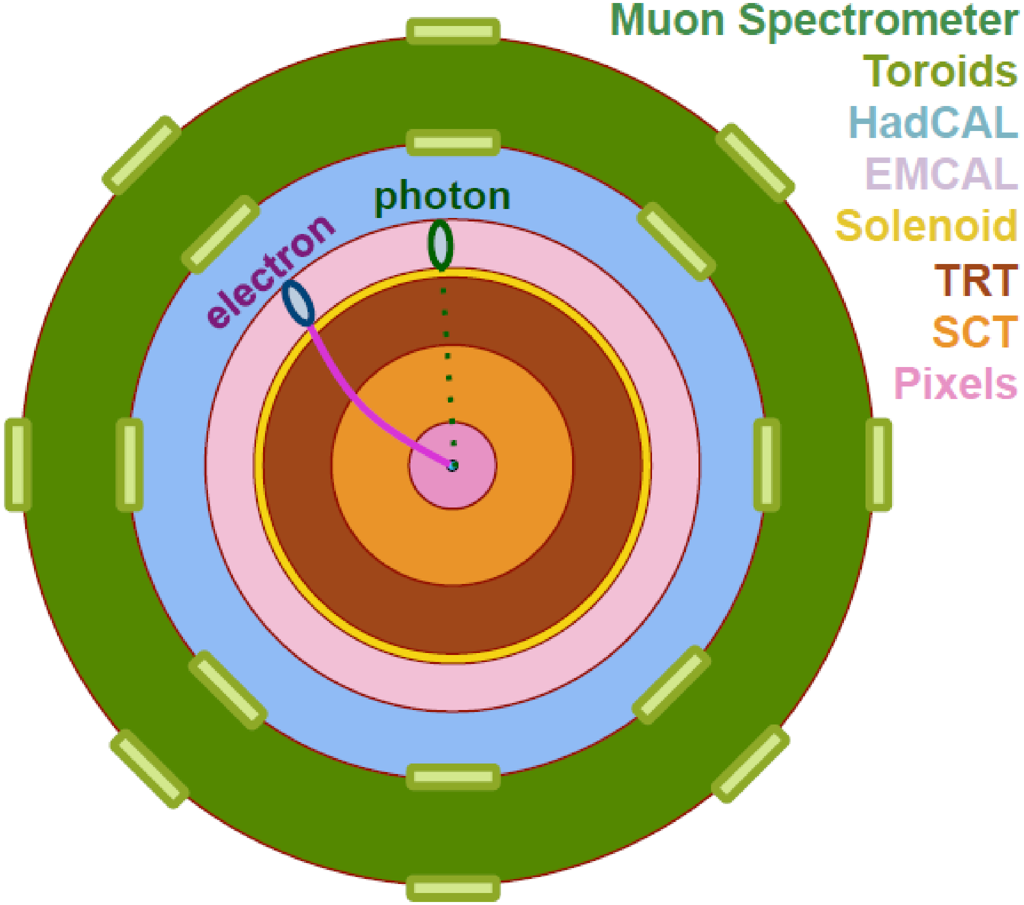
Simplified Detector Transverse View



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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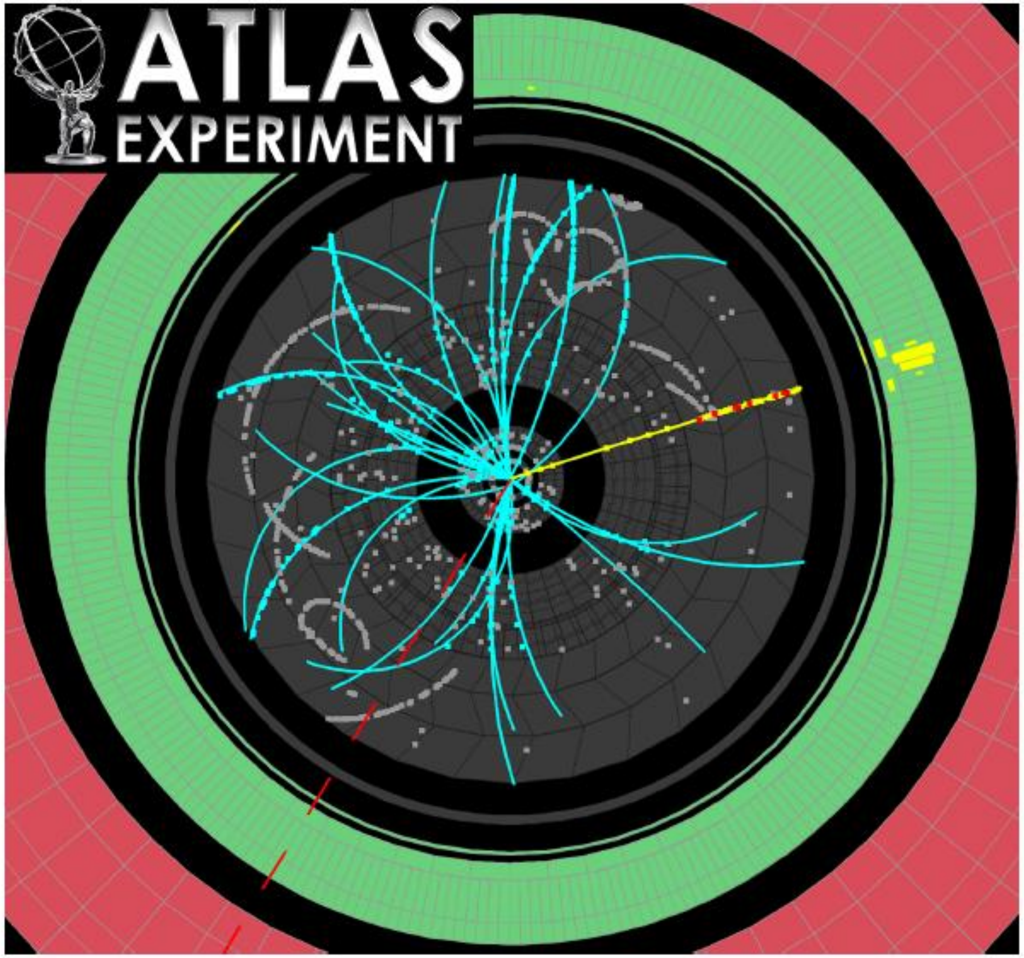
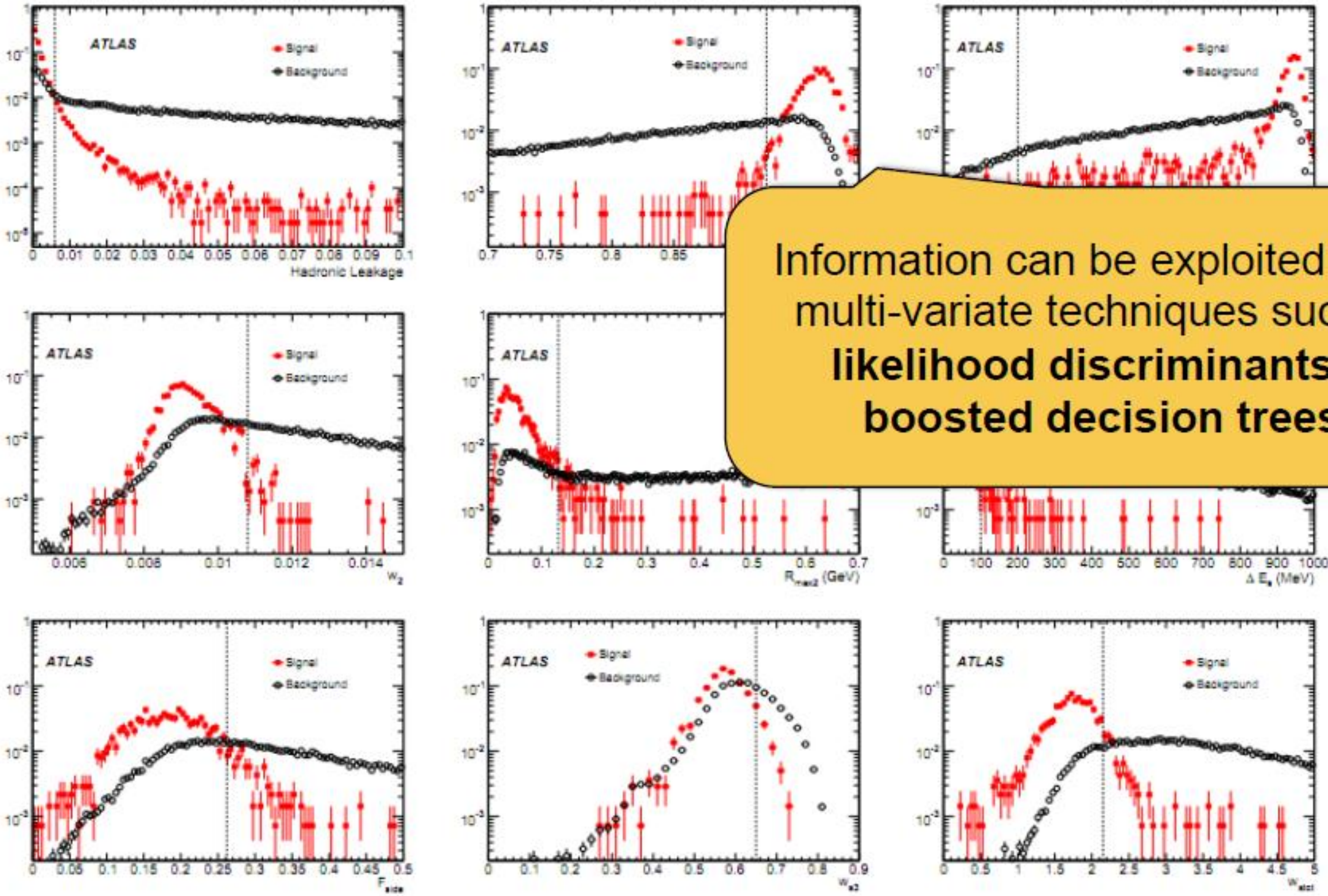


Electrons and photons (backgrounds)

- 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)

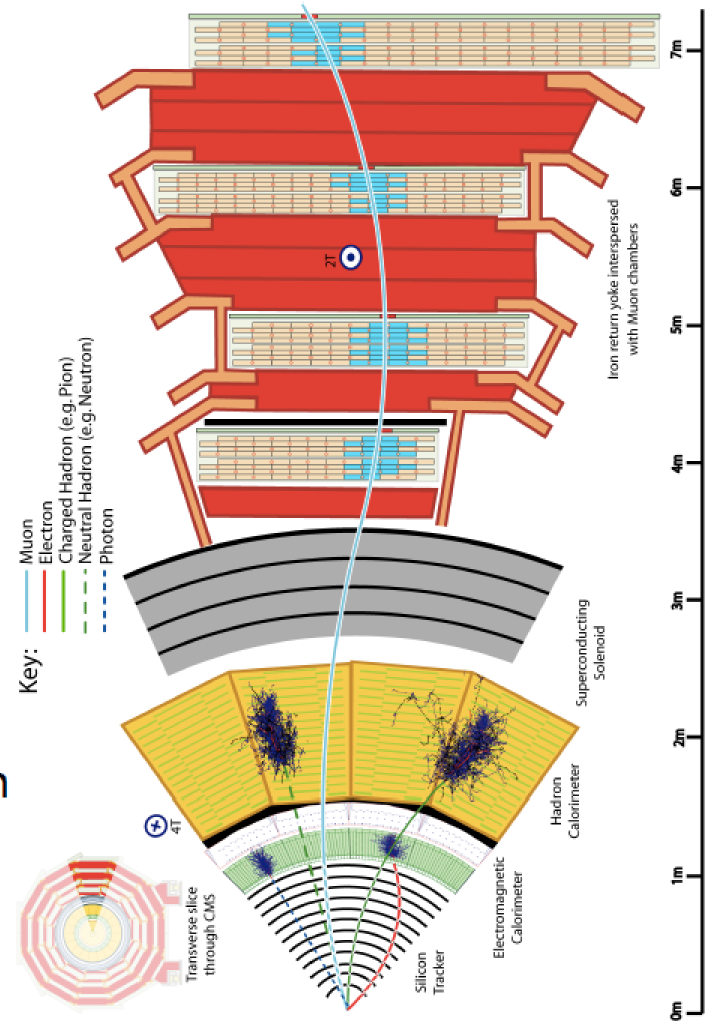


Information can be exploited using multi-variate techniques such as **likelihood discriminants** or **boosted decision trees**.

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

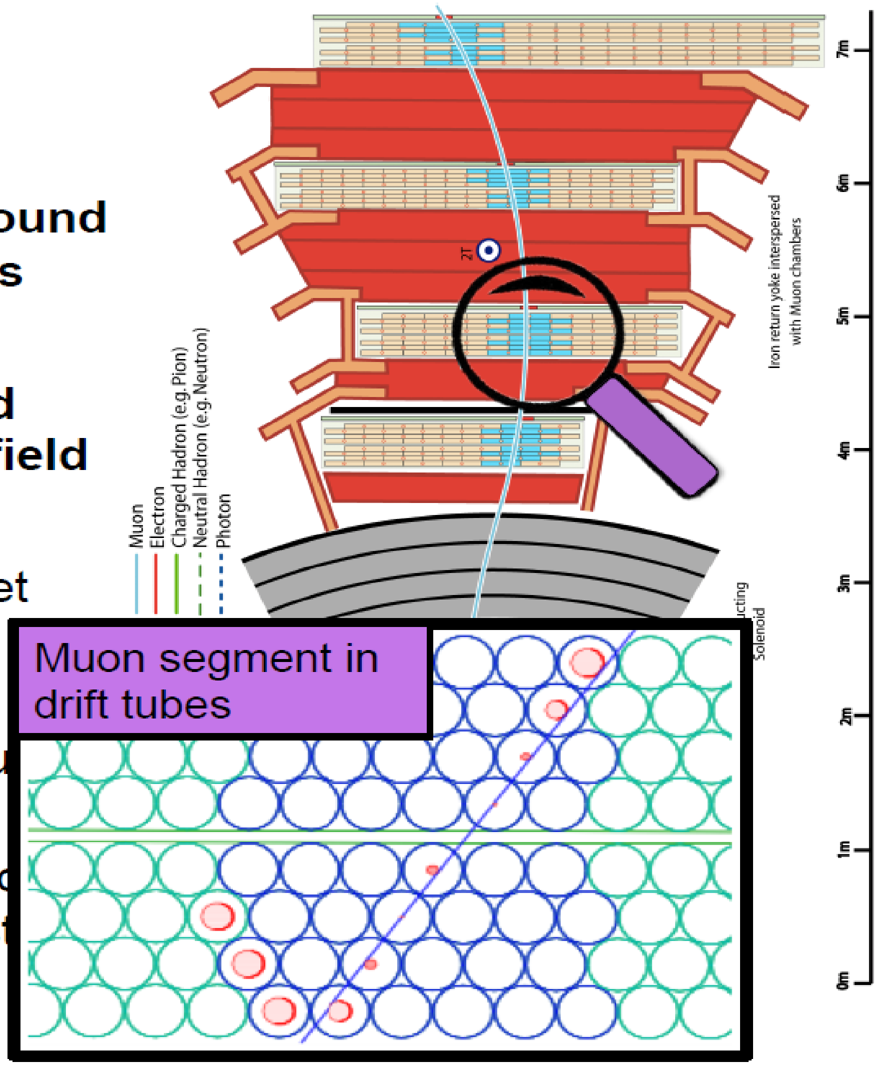
Muons

- **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



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 reconstru software
    - Alignment of the muon detecto also very important to get best momentum resolution



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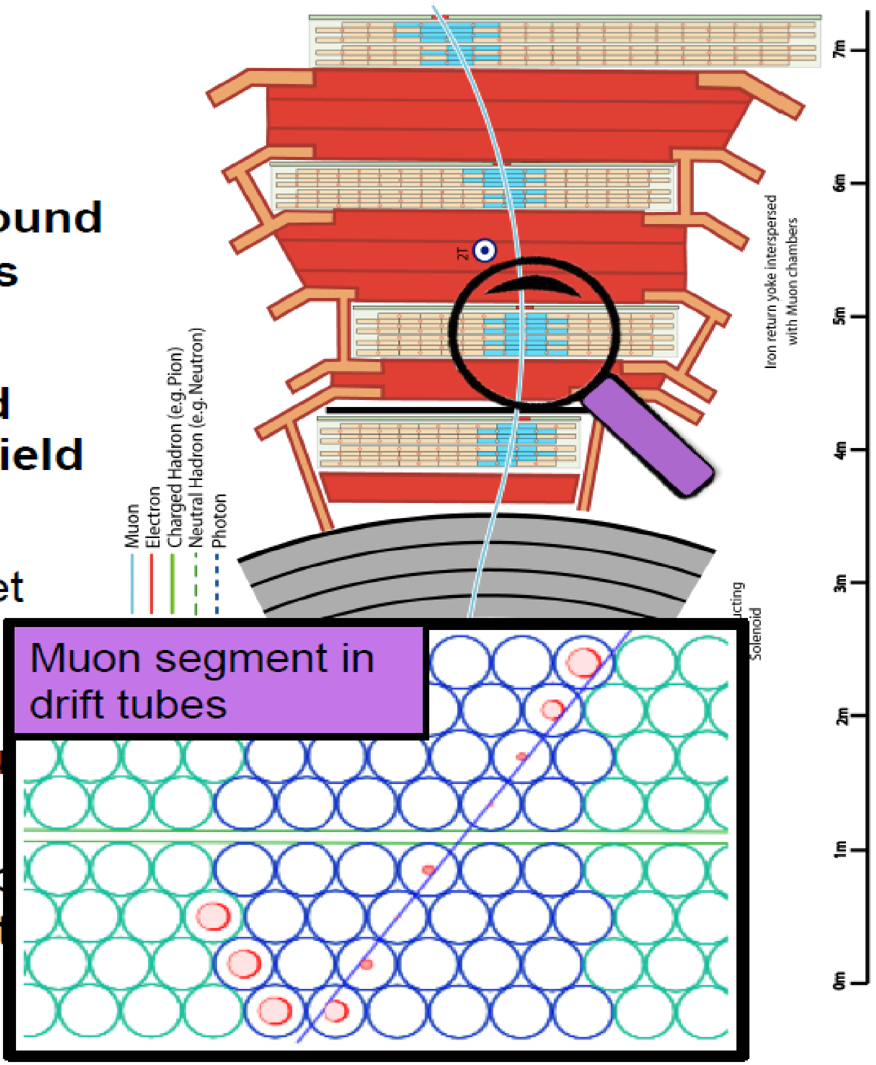
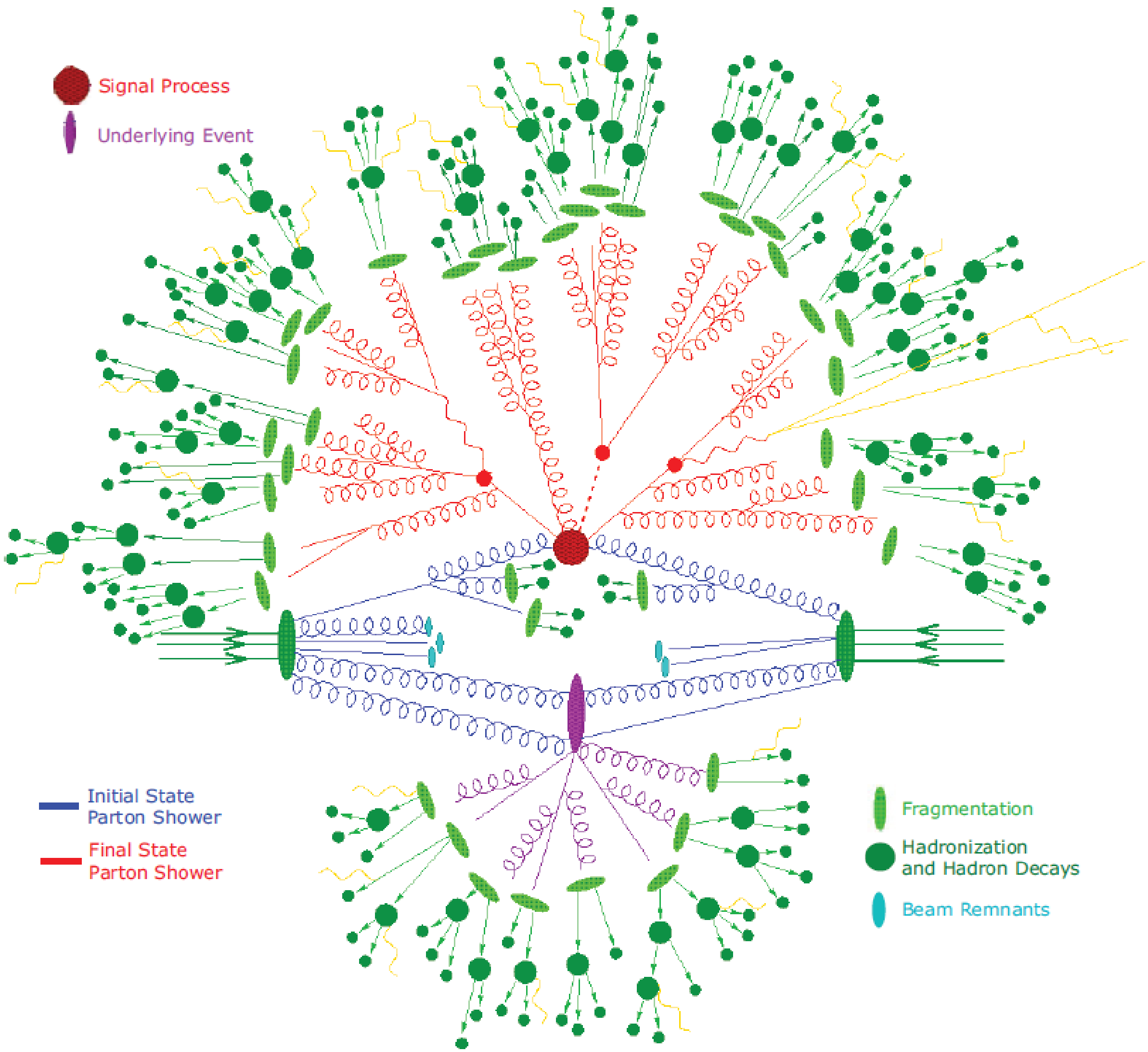
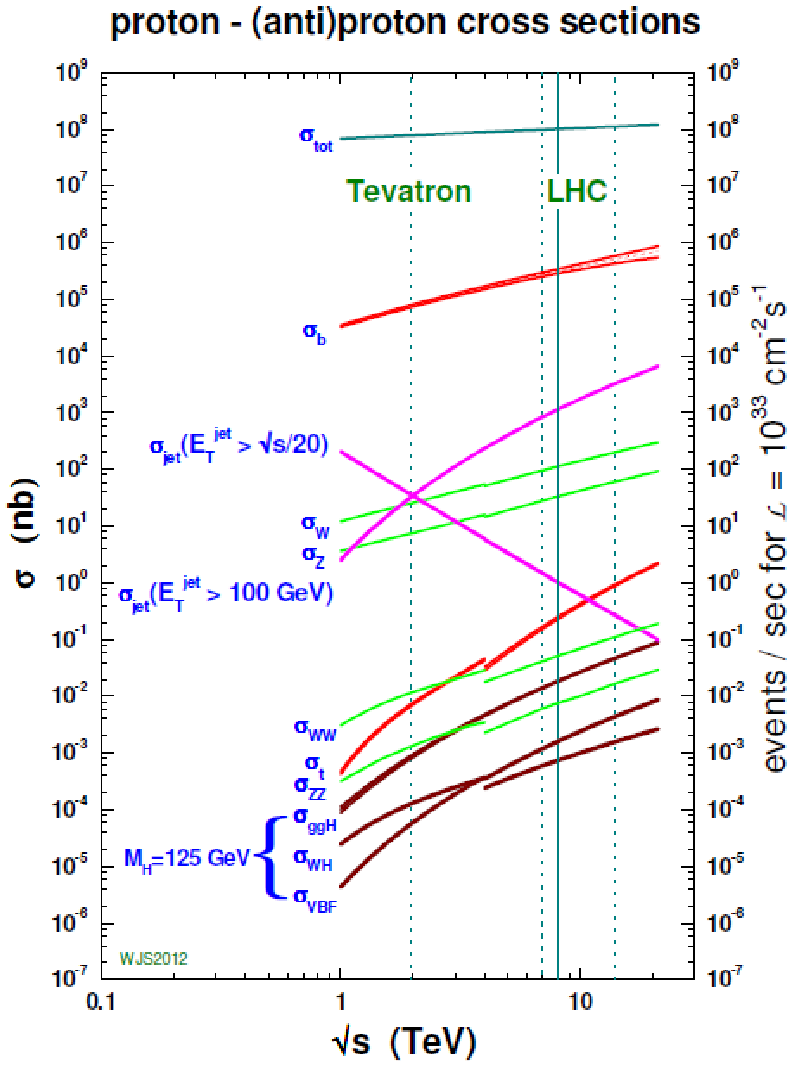


Jets



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

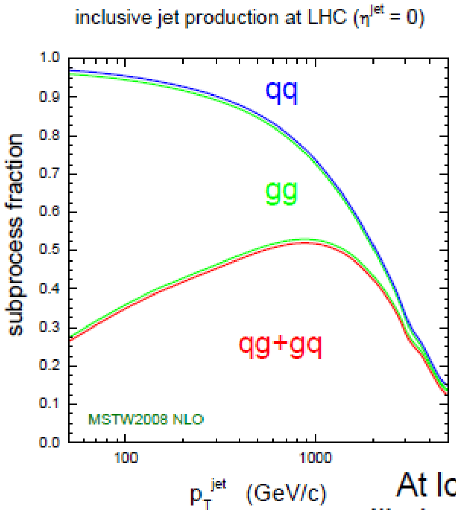
Standard Model processes



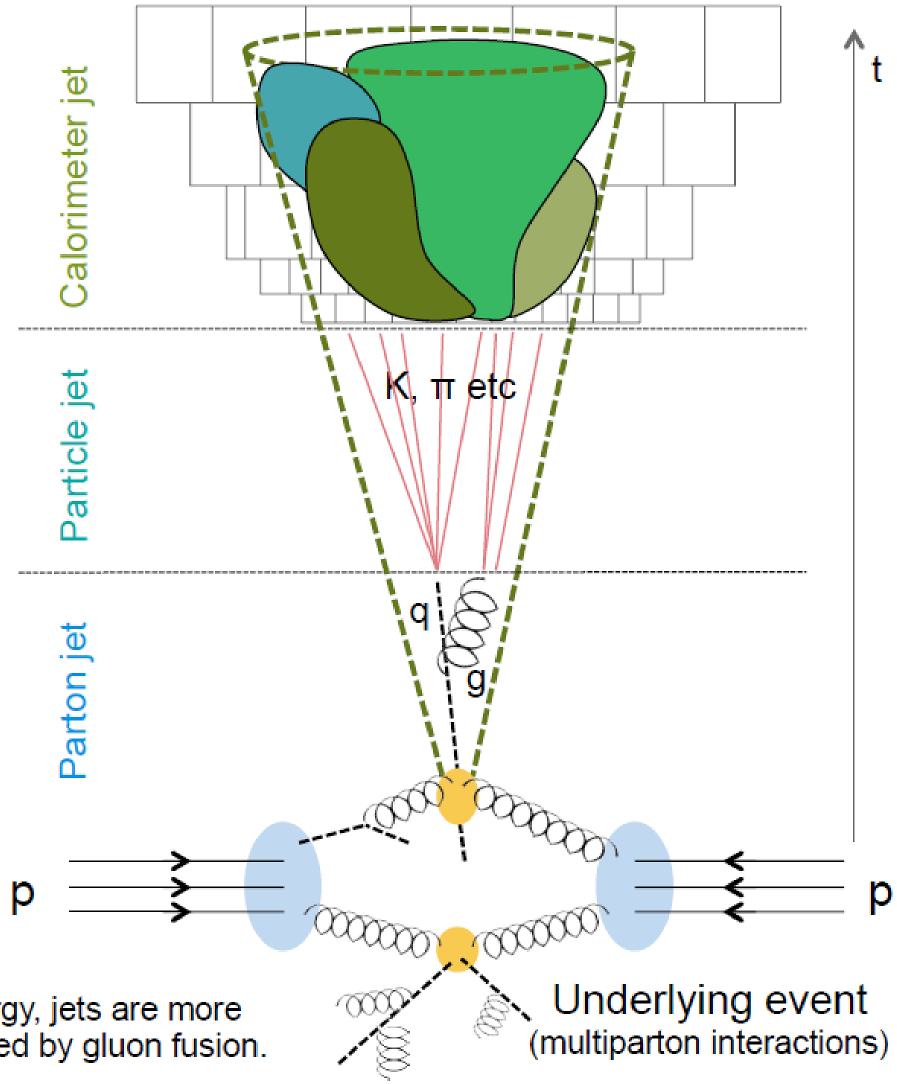
Jets are produced:

- 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

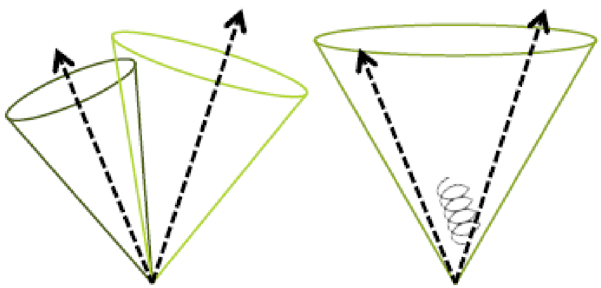


At low energy, jets are more likely produced by gluon fusion.

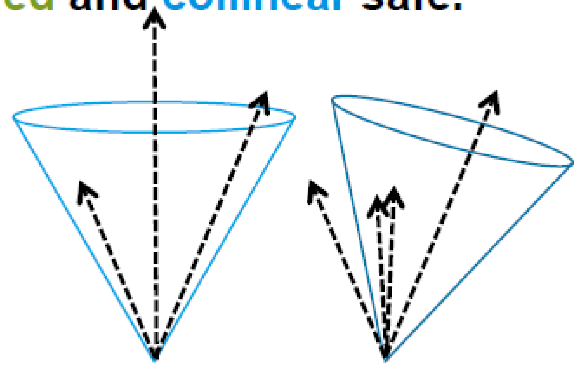


Jet algorithms

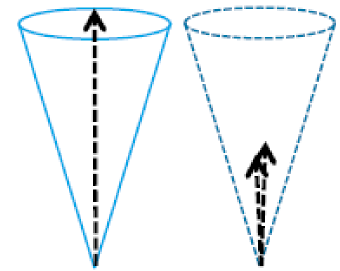
<u>Theoretical requirements</u>: infrared and collinear safe.



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

<u>Experimental requirements</u>: detector technology & environment independent, easily implementable.

Insignificant effects of detector
- Noise
- Dead material
- Cracks

Stability with
- Luminosity
- Pile-up
- Physics process

Fully specified
Fast

<u>Jet algorithm commonly used at the LHC</u>: '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).

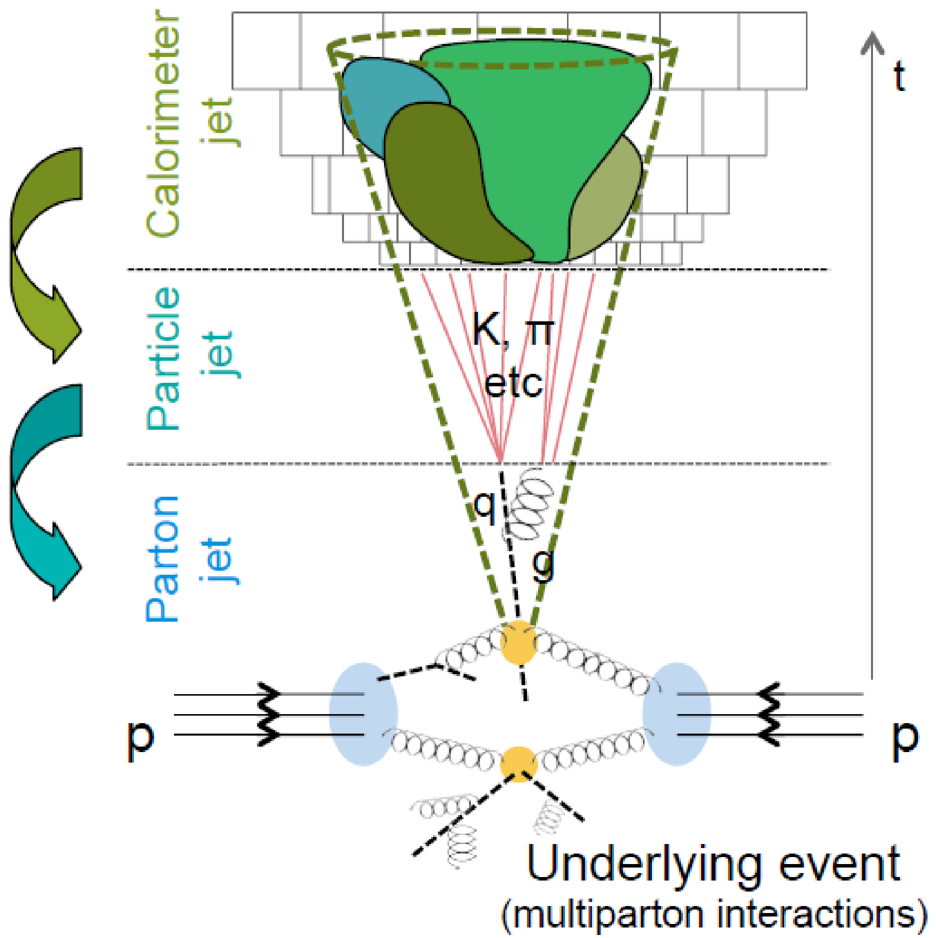
Jet calibration

Correct the energy and position measurement and the resolution.

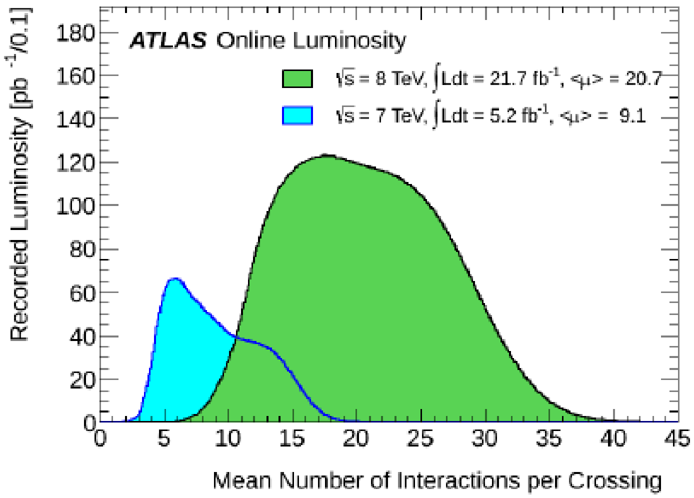
Account for:

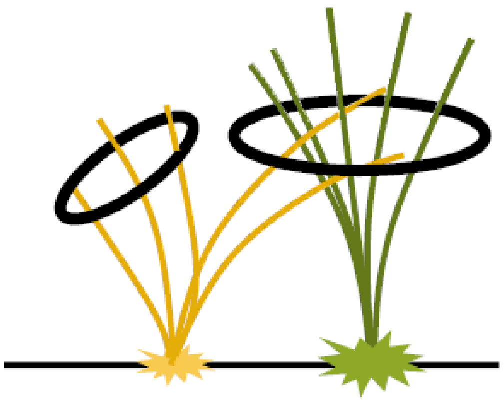
Instrumental effects
Detector inefficiencies
'Pile-up'
Electronic noise
Clustering, noise suppression
Dead material losses
Detector response
Algorithm efficiency

Physics effects
Algorithm efficiency
'Pile-up'
'Underlying event'



Jets & pile-up

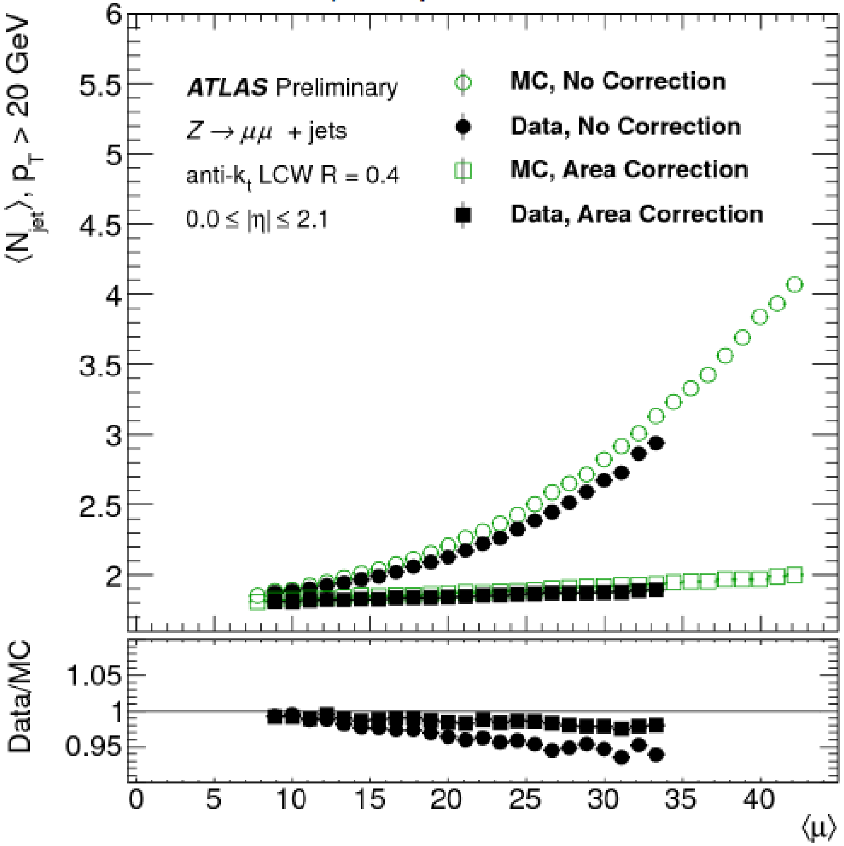




Multiple interactions from pile-up

'Jet-areas' corrections

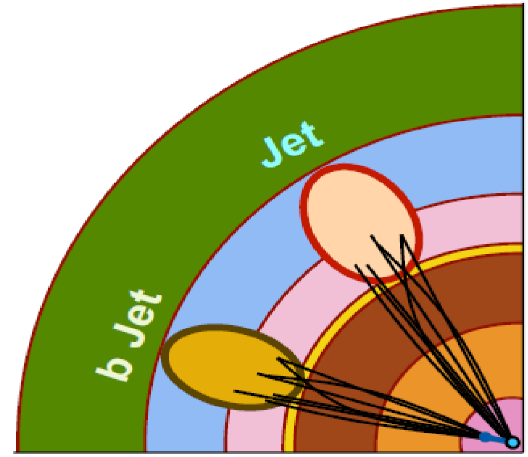
Inspired by arXiv:0707.1378

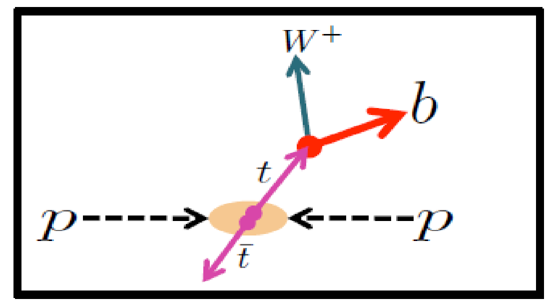


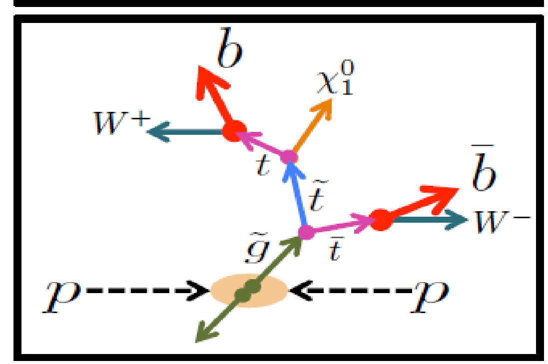
b-jets

- 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**.

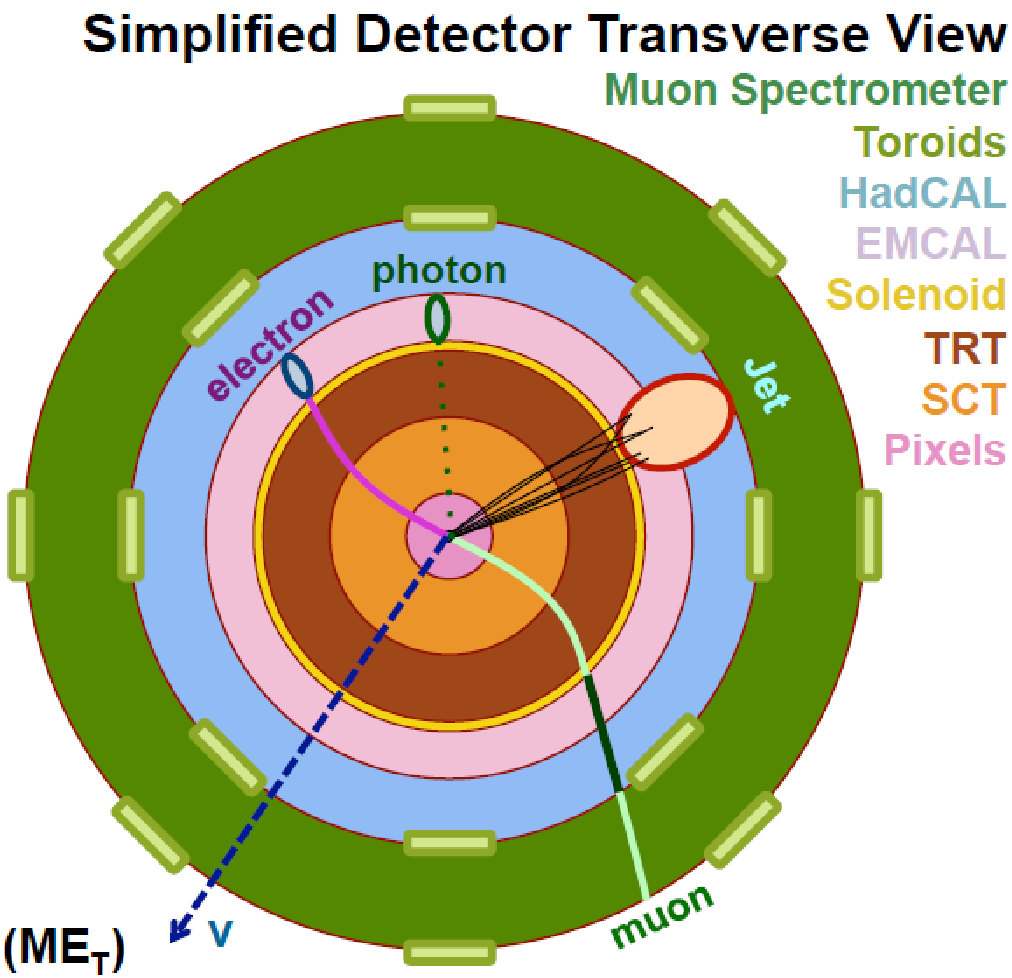
- b-jets create distinct final states, important for both **Standard Model measurements** and **searches for New Physics**.







Missing transverse momentum



In the transverse plane:

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

Missing Transverse Momentum (ME_T)

Missing transverse momentum

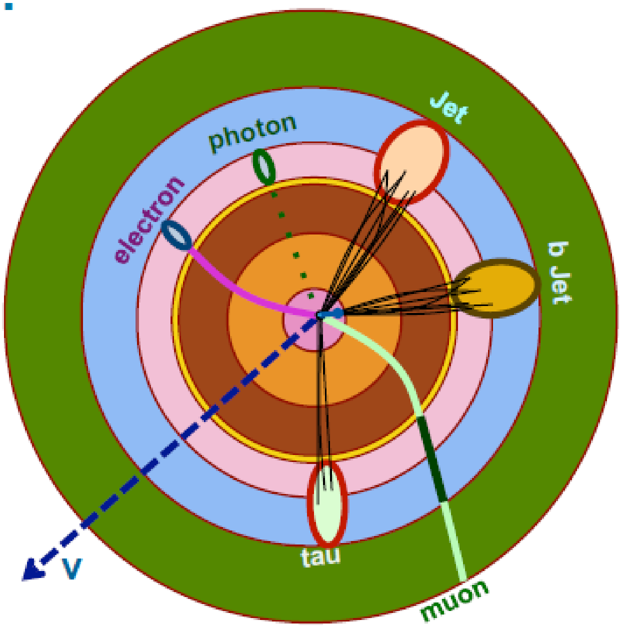
Impossible to measure particles that don't interact in the detector.

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

- ◎ Sensitive to pile-up and detector problems.

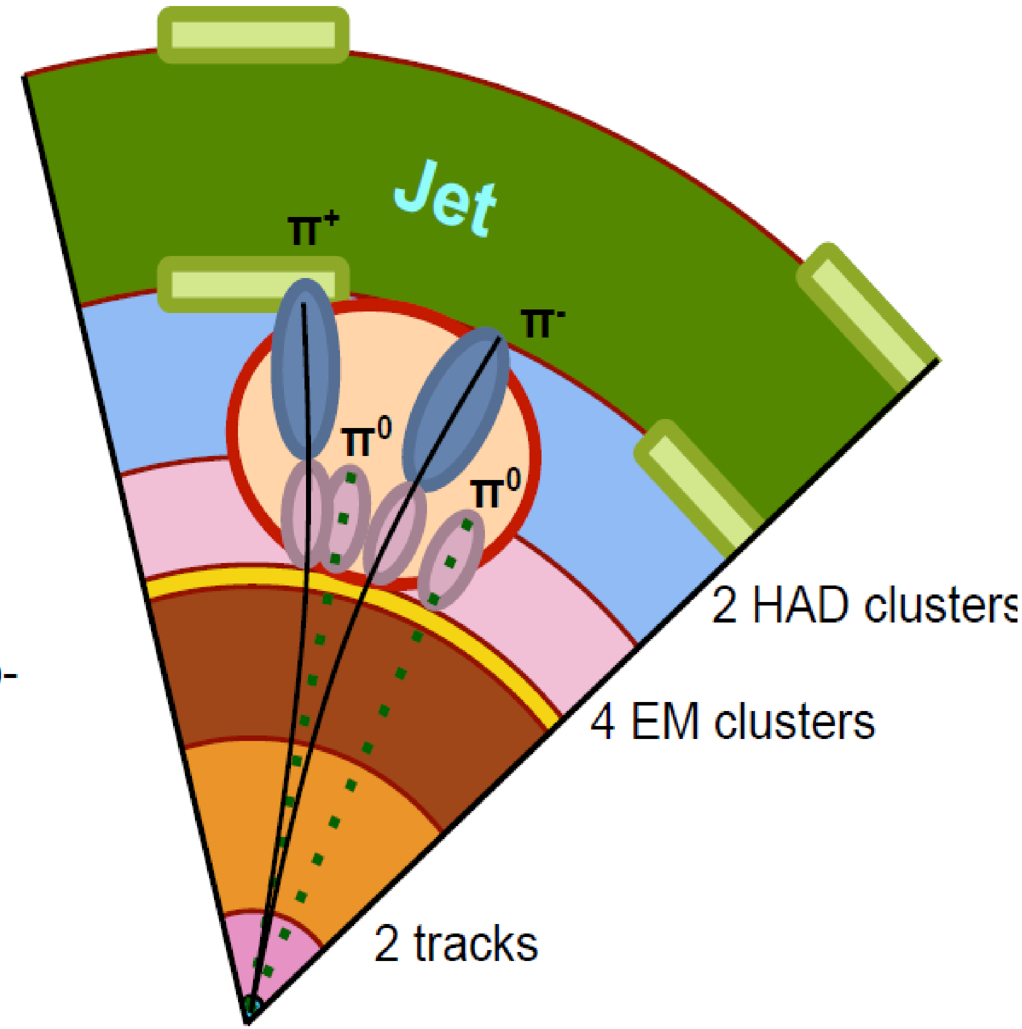
Only as good as its inputs.

- ◎ 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).

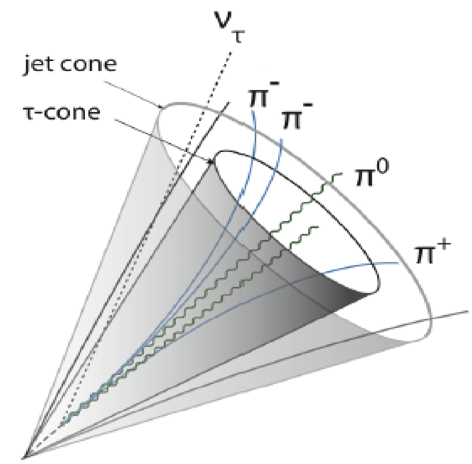


Reconstructing particles

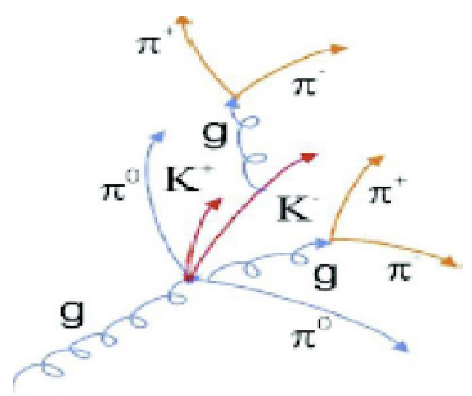
Tau Decay Mode			B.R.
Leptonic		$\tau^{\pm} \rightarrow e^{\pm} + \nu + \nu$	17.8%
		$\tau^{\pm} \rightarrow \mu^{\pm} + \nu + \nu$	17.4%
Hadronic	1-prong	$\tau^{\pm} \rightarrow \pi^{\pm} + \nu$	11%
		$\tau^{\pm} \rightarrow \pi^{\pm} + \nu + n\pi^{0}$	35%
	3-prong	$\tau^{\pm} \rightarrow 3\pi^{\pm}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

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

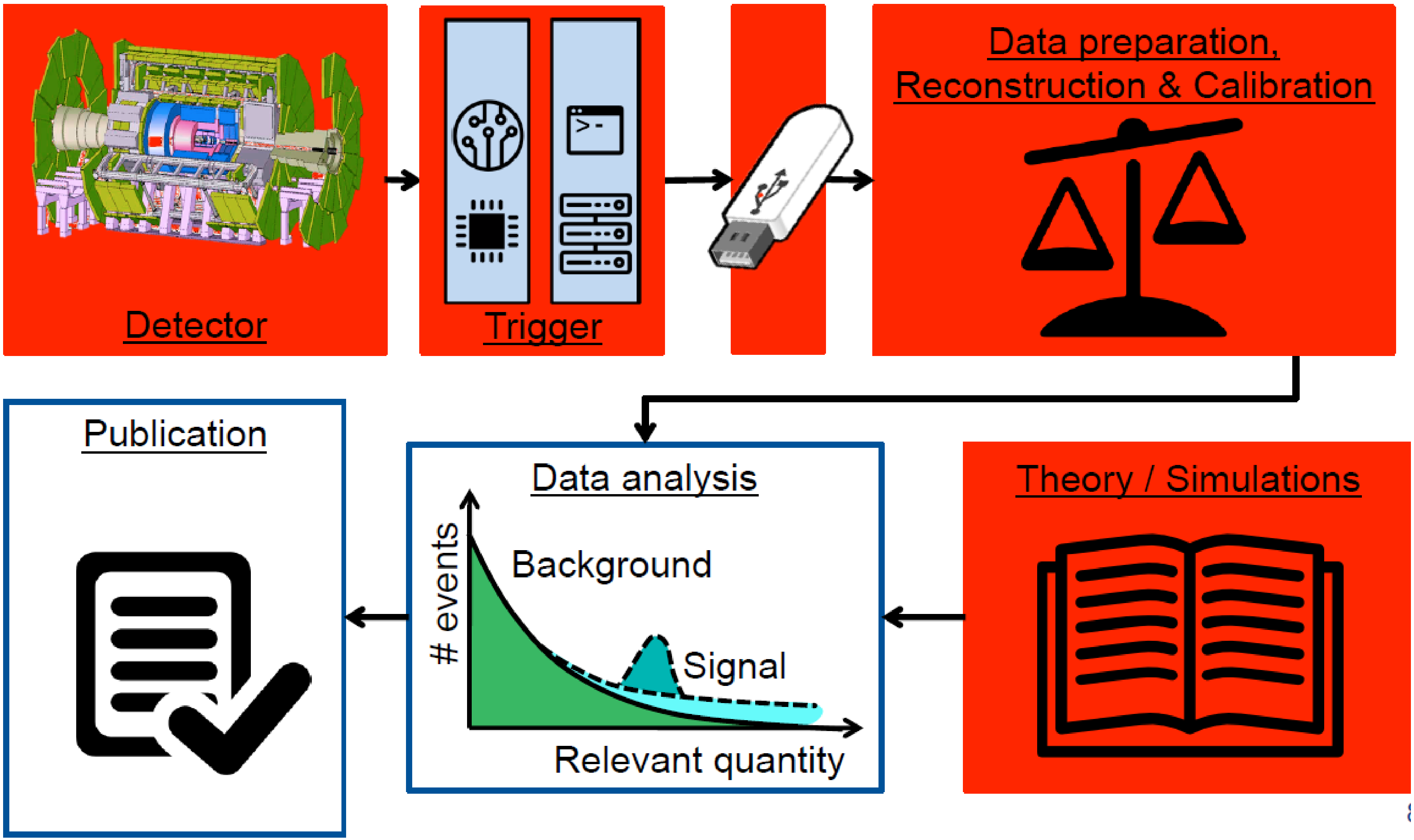
A tau jet (signal)…



…vs. a QCD jet (background)

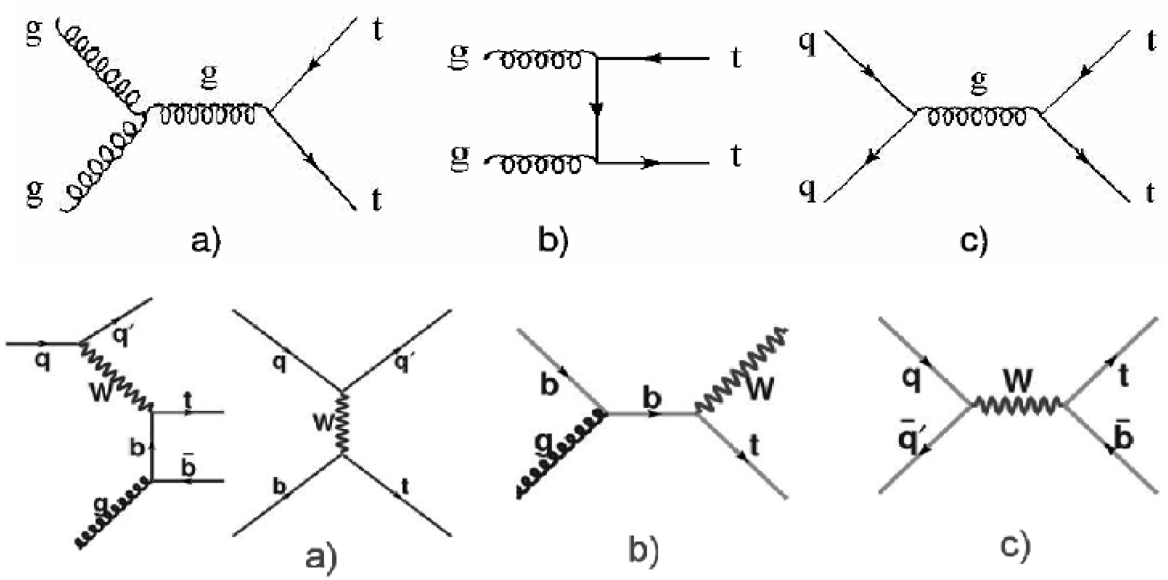


An event’s lifetime

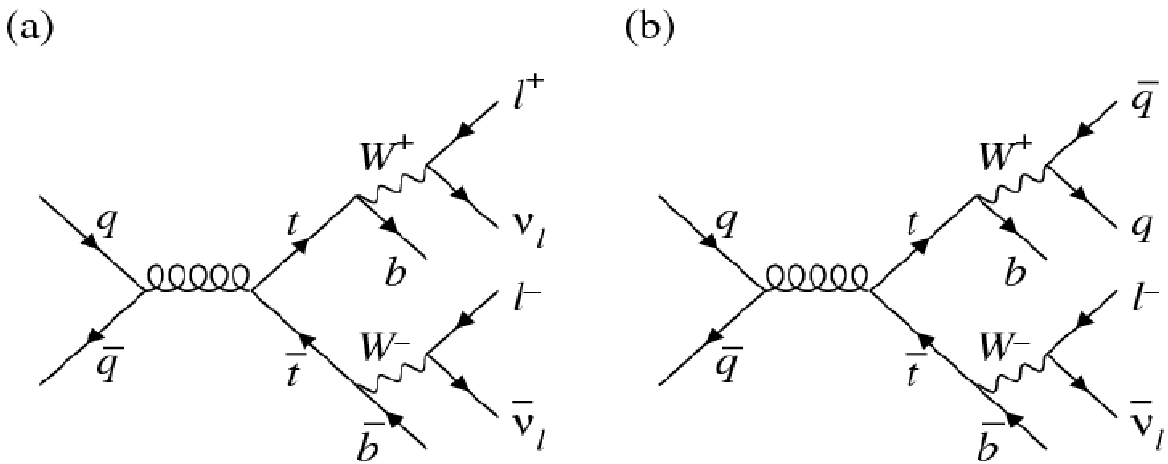


SPARE SLIDES

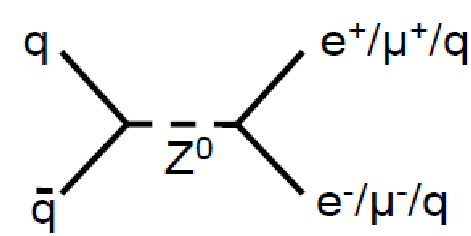
t,W,Z



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

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

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

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

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:

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

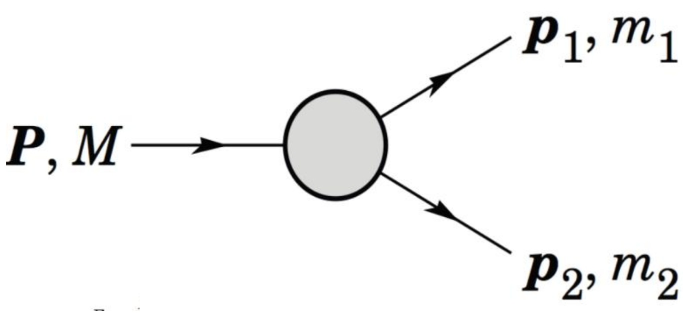
Hint: it can be computed as the "length" of the total four-momentum, that is invariant:

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

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

Kinematics

2-bodies decays



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

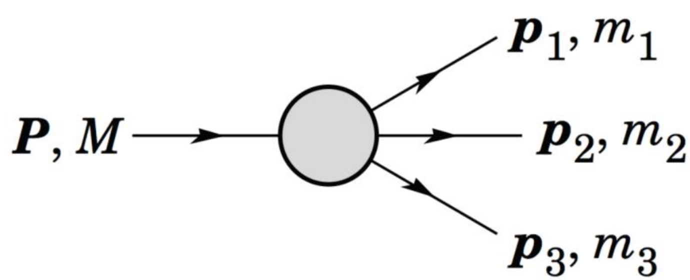
$$|\boldsymbol{p}_1| = |\boldsymbol{p}_2|$$

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

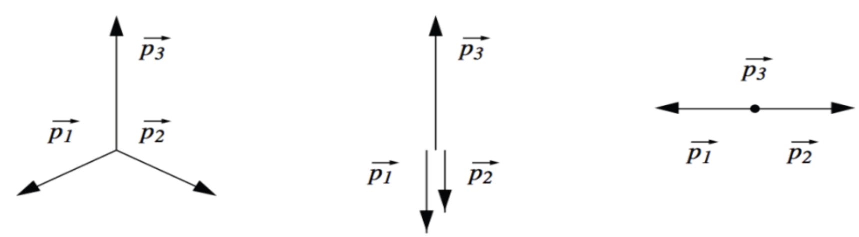
Invariant mass

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

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)

$\max(\lvert\vec{p}_3\rvert)$	$(m_{12})_{min} = m_1 + m_2$
$\min(\lvert\vec{p}_3\rvert)$	$(m_{12})_{max} = M - m_3$

A real example: pion decays

pion decays at rest

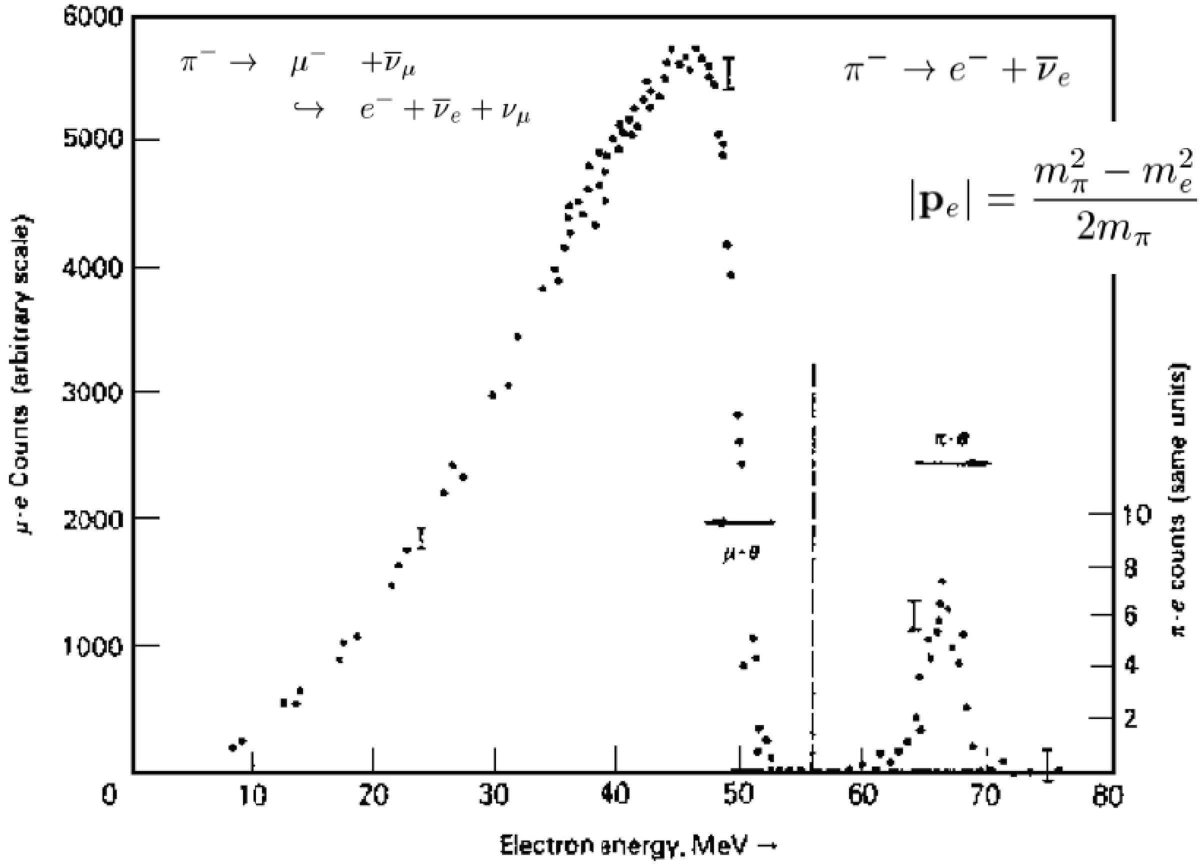
$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}c \simeq 30\,\mathrm{MeV/c}$$

$m_\nu = 0.$

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