FROM RAW DATA TO PHYSICS

Slides inspired by previous summer student lectures on the same topic from Jamie Boyd. Many thanks to many for providing material.

ANNA SFYRLA (CERN)

SUMMER STUDENT LECTURES

JULY 2015

CONTENTS

Lecture 1

- **RAW data to Physics – step by step**
  - What does it take from getting the data out of the detector to producing a physics result.

Lecture 2

- **From RAW data to Standard Model Particles**
  - about measuring the properties of the ‘final’ particles created from a proton-proton interaction.

Lecture 3

- **From Standard Model Particles to measurements and searches**
  - about how…

ASSUMPTIONS

- You have never done a physics analysis.
- You know a bit about the LHC.
- You know a bit about a multi-purpose high-energy-physics detector.
- You know a bit about how we get to RAW data.

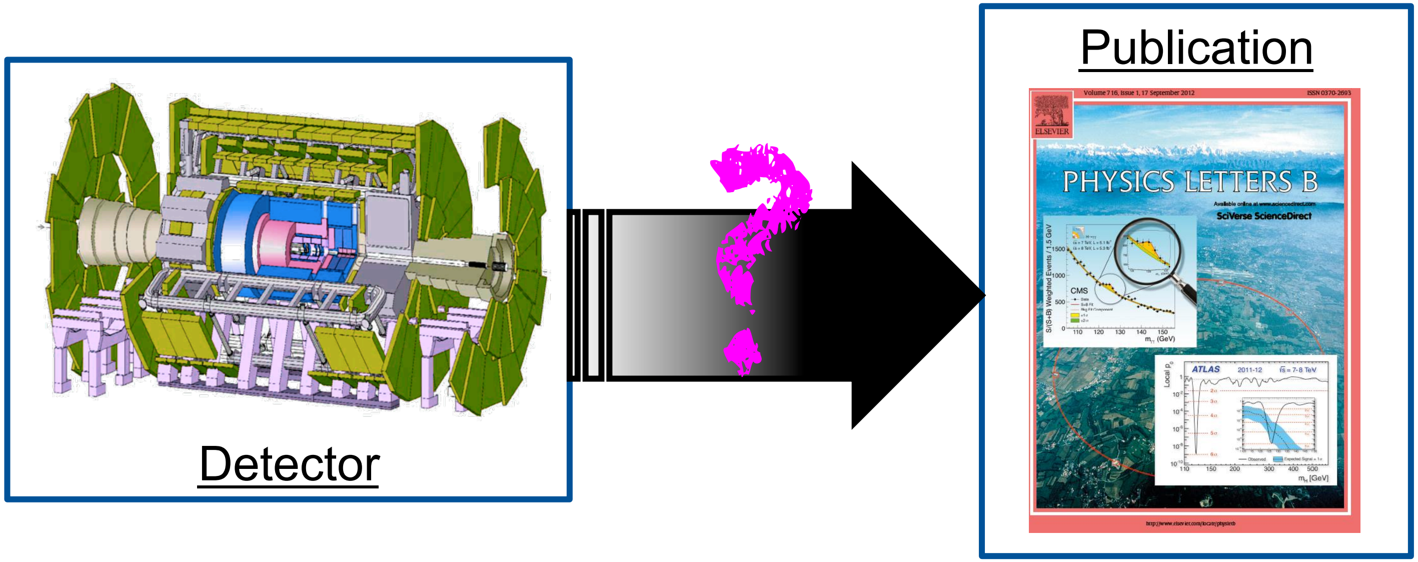
DISCLAIMER

- These lectures will have a “slight” bias towards ATLAS.

FROM RAW DATA TO PHYSICS

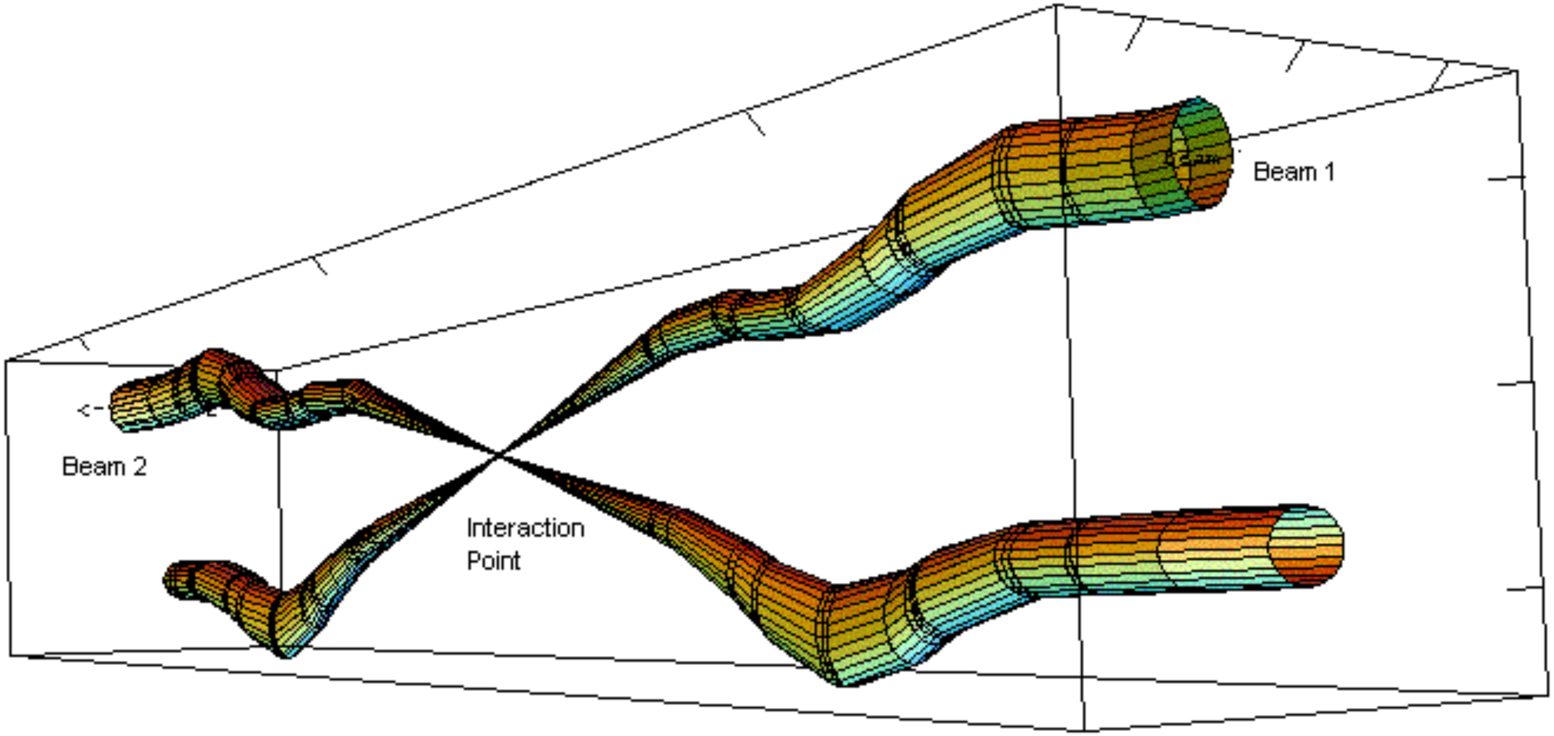
LECTURE 1

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



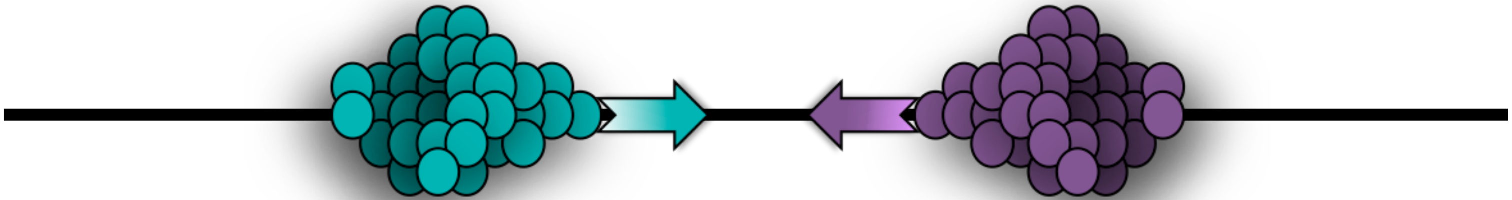
WHAT IS AN EVENT?

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



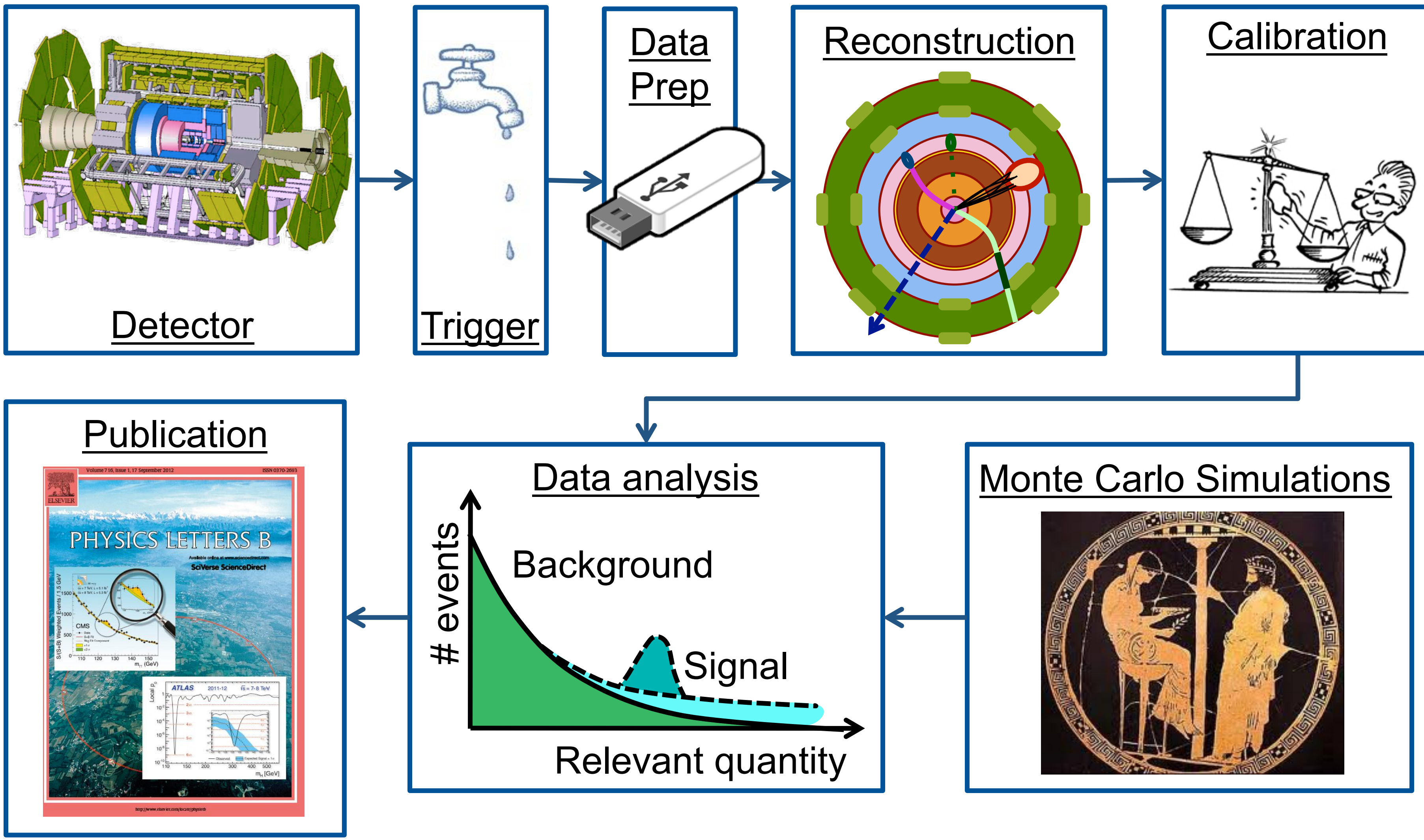
Relative beam sizes around IP1 (Atlas) in collision

WHAT IS AN EVENT?

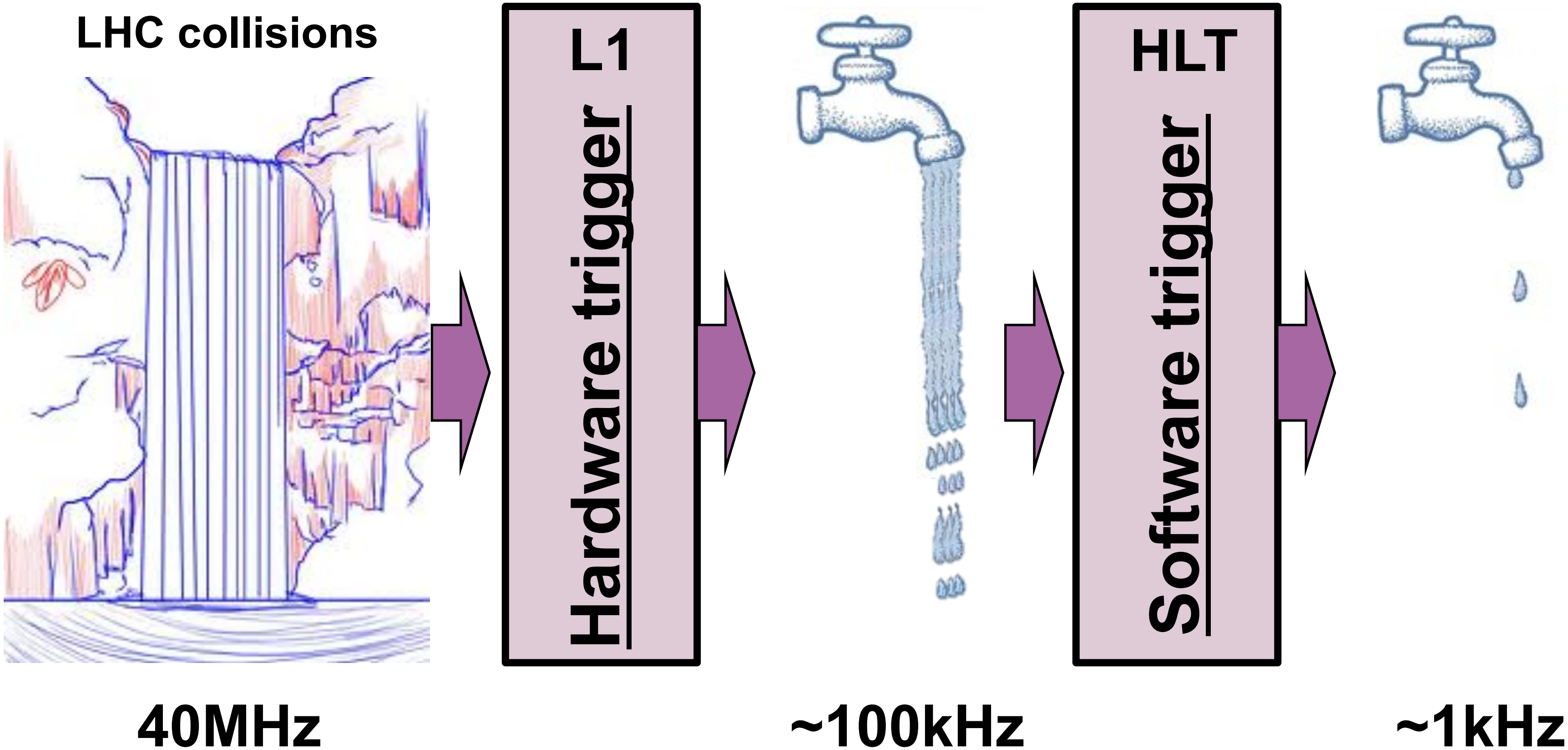


Proton bunches
>10^{11} protons/bunch
colliding at **13TeV** and at **40MHz in run2**
collided at **7/8TeV** and at **20MHz in run1**

AN EVENT'S LIFETIME

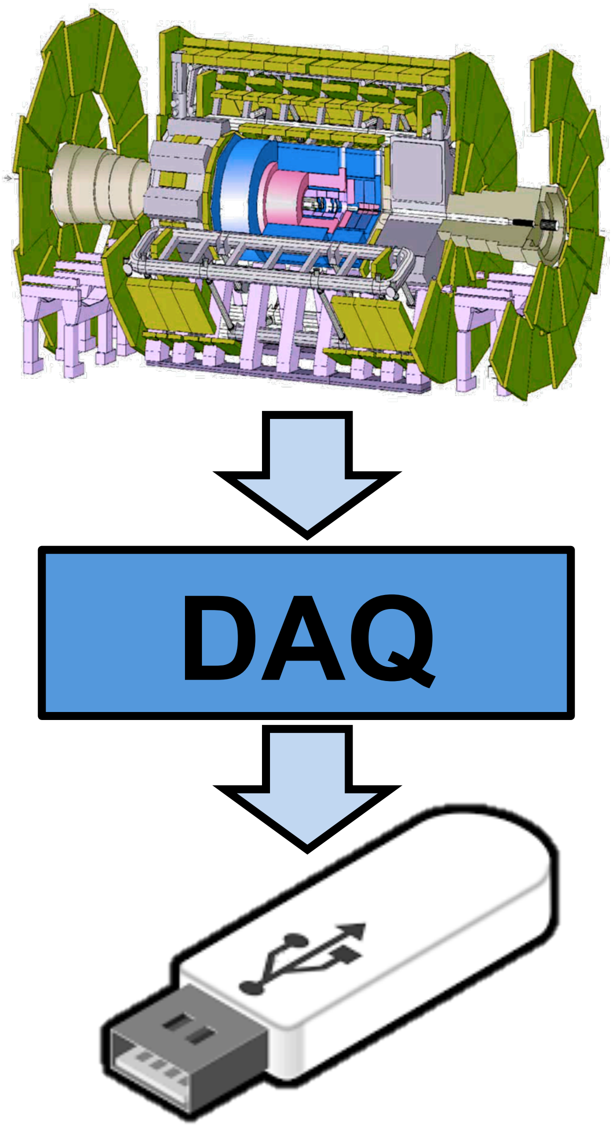


TRIGGERING ON PHYSICS



THE DATA ACQUISITION

At every trigger accept:



WHAT DOES RAW CONTAIN?

A simple example from the trigger on ATLAS (run1 data)

0x00000015	0x20000e3f	536874559	lvl1 trigger info[0]	L1 Trigger Bits Before Prescale
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]	L1 Trigger Bits After Prescale
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]	L1 Trigger Bits After Veto
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]	
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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

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1, 2, 4, 11, 38, 39, 60, 67, 68, 95, 96, 108, 113, 132, 137, 138, 139, 202, 214, 215, 217, 241

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Enabled items, name:
L1_EM18VH,
L1_2TAU11I_EM14VH,
L1_2TAU11_TAU20_EM14VH,
L1_2TAU11I_TAU15,
L1_2EM6_EM16VH

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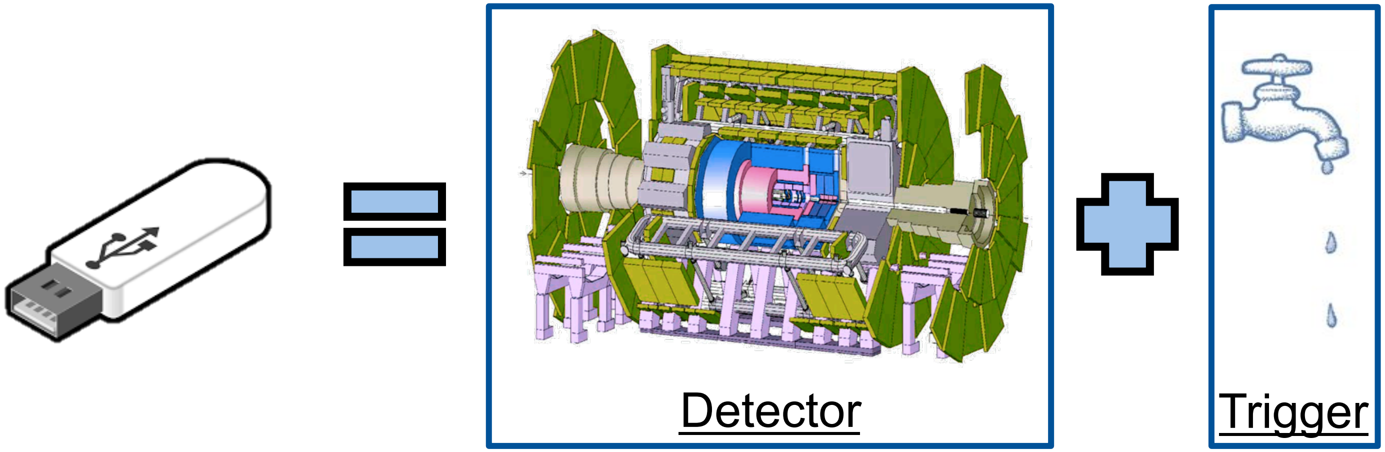
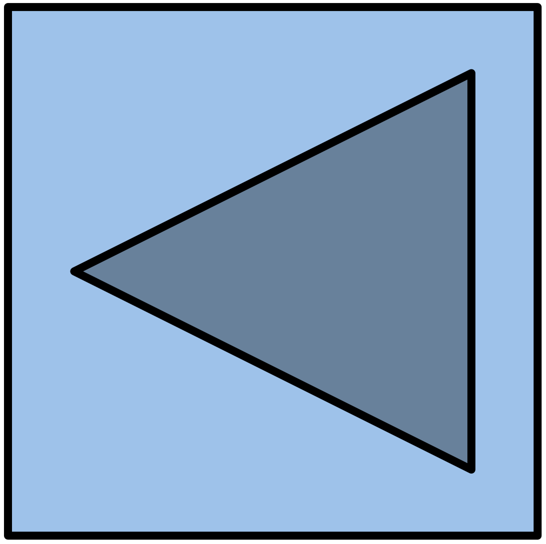
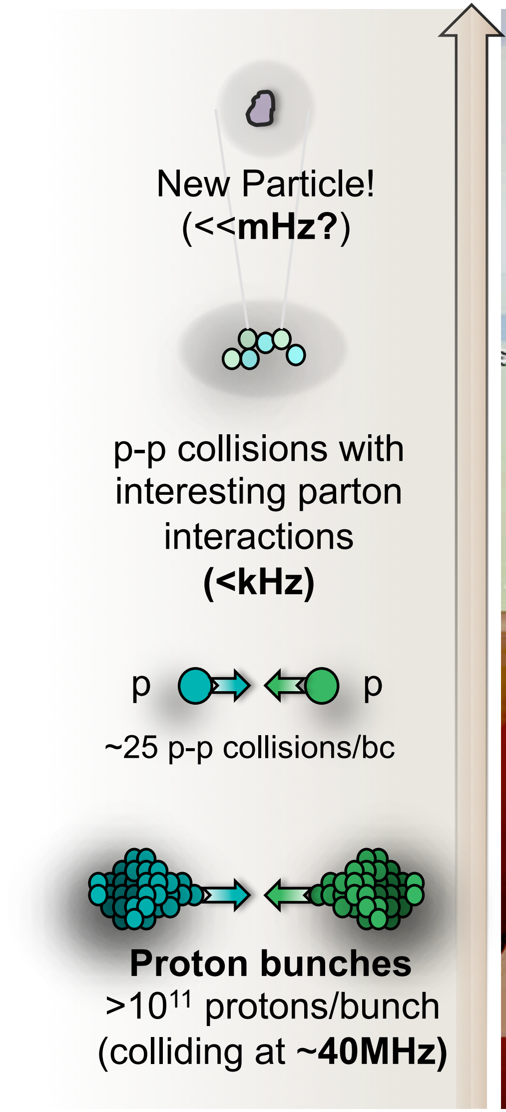
- More than 300K such words in each event, corresponding to the full data from all the detector components.
- Data size: 1-1.5MB / event depending on the compression. Pretty consistent between ATLAS and CMS.
- **Challenge: make sense out of all these numbers!!**

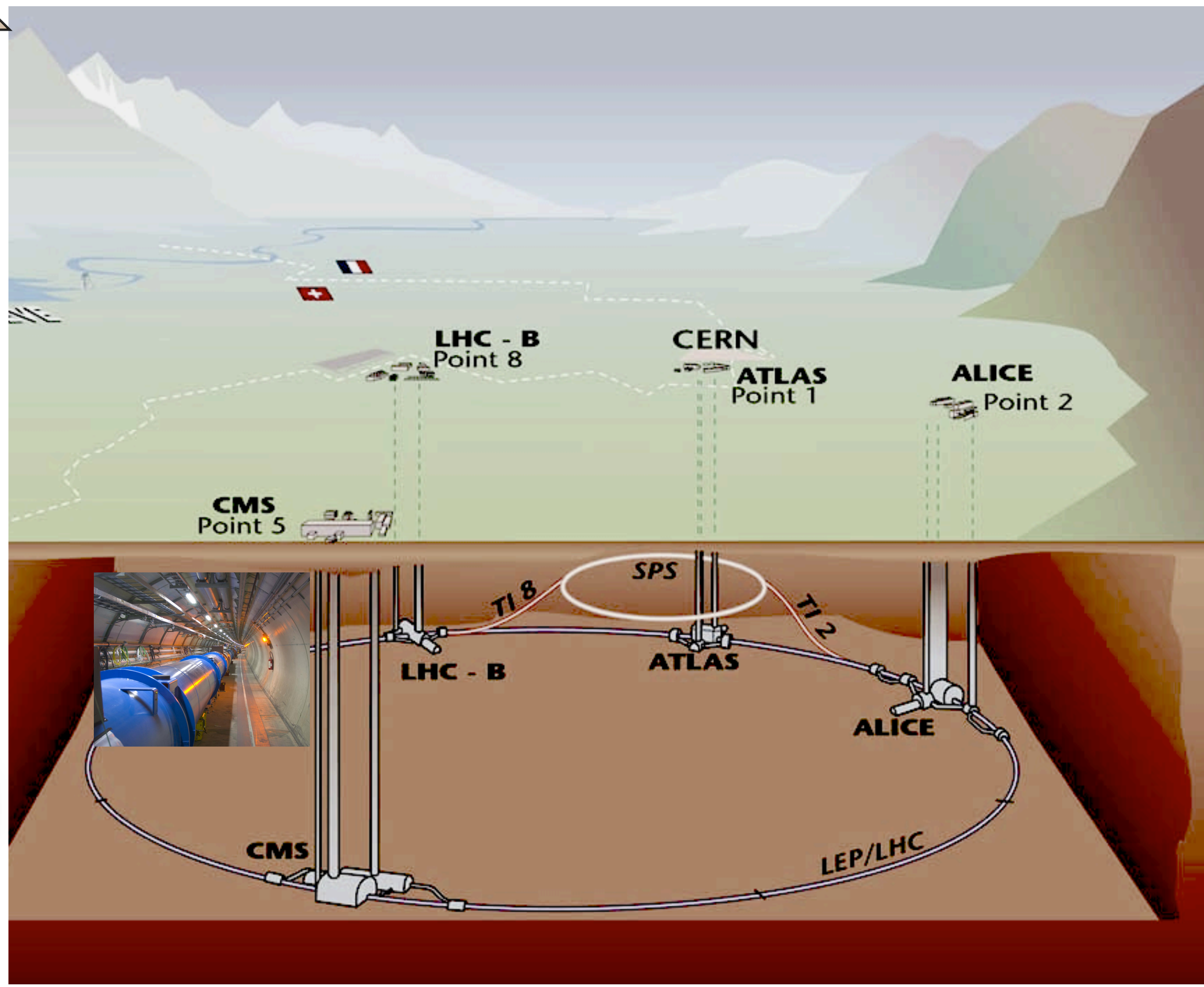
WHAT DOES RAW CONTAIN?





THE LARGE HADRON COLLIDER





THE LARGE HADRON COLLIDER

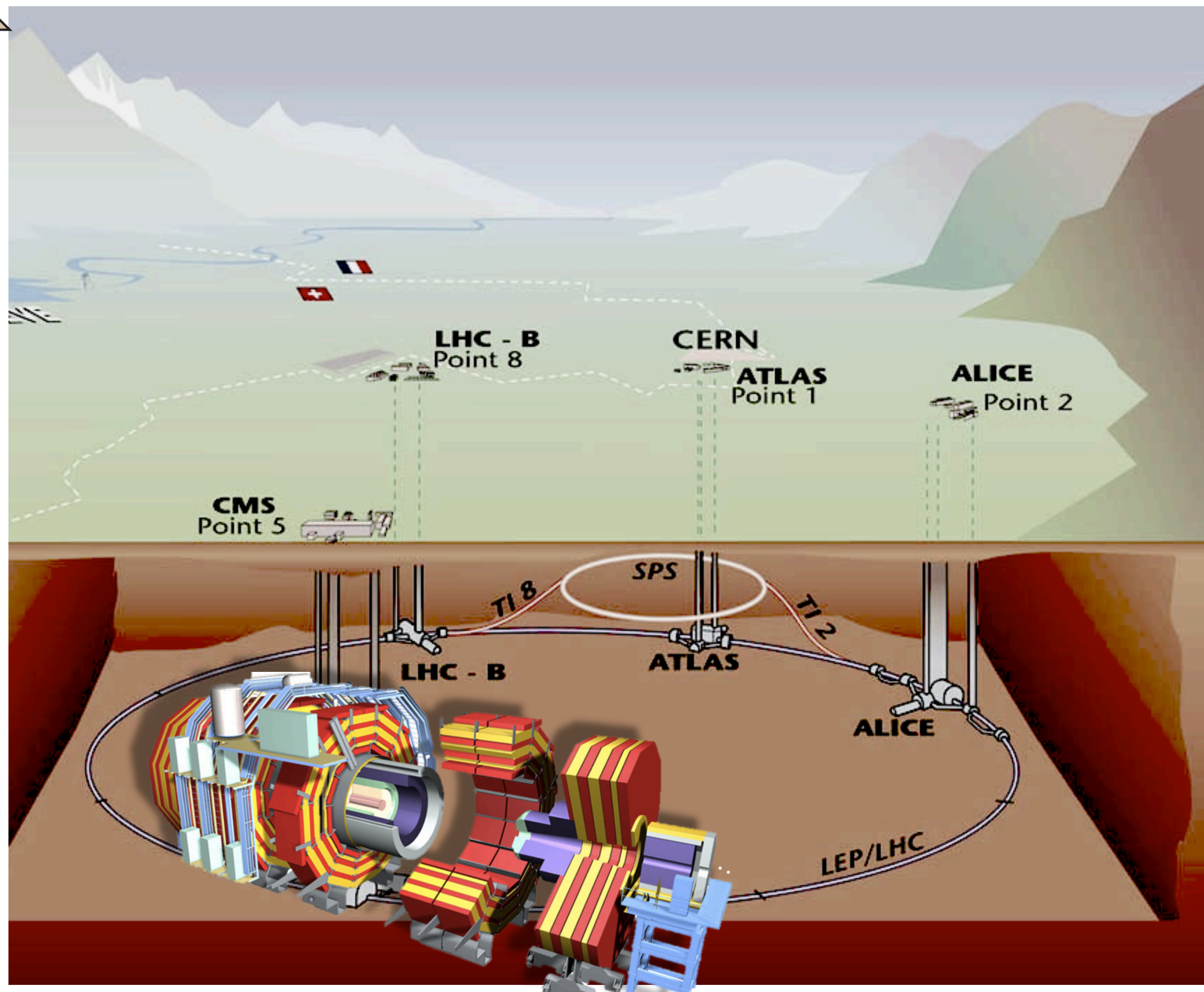
New Particle!
(<<**mHz?**)

p-p collisions with interesting parton interactions
(<kHz)

p p

~25 p-p collisions/bc

Proton bunches
$>10^{11}$ protons/bunch
(colliding at **~40MHz)**



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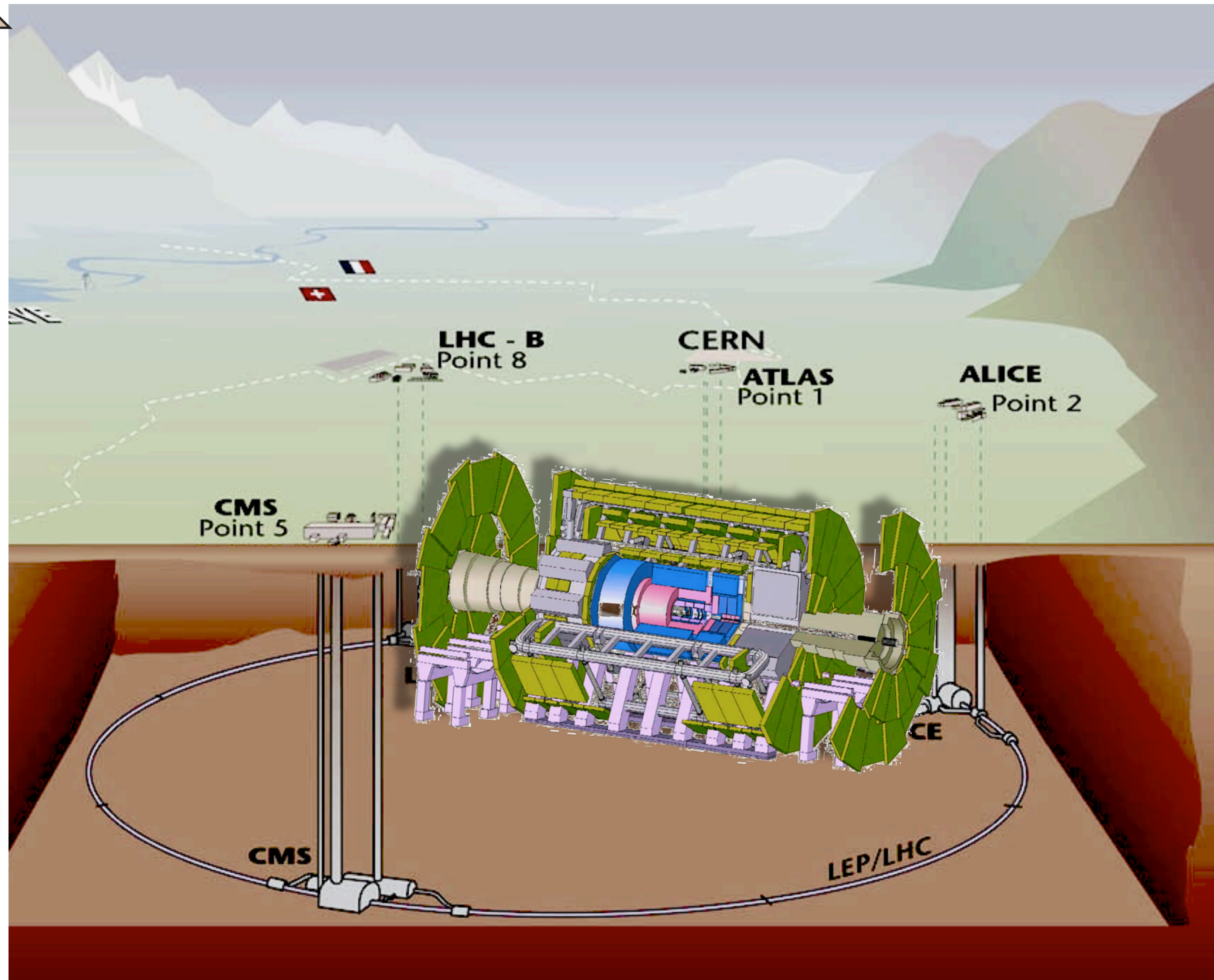

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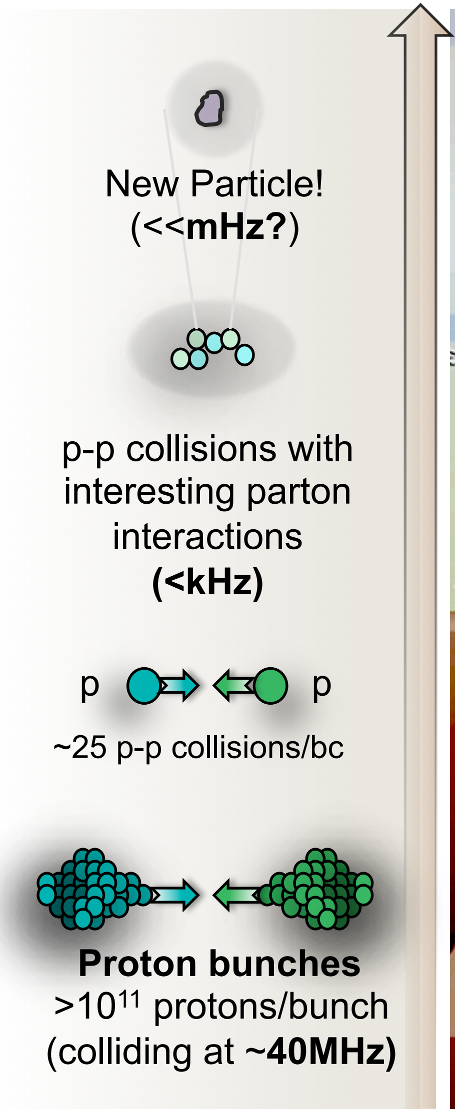

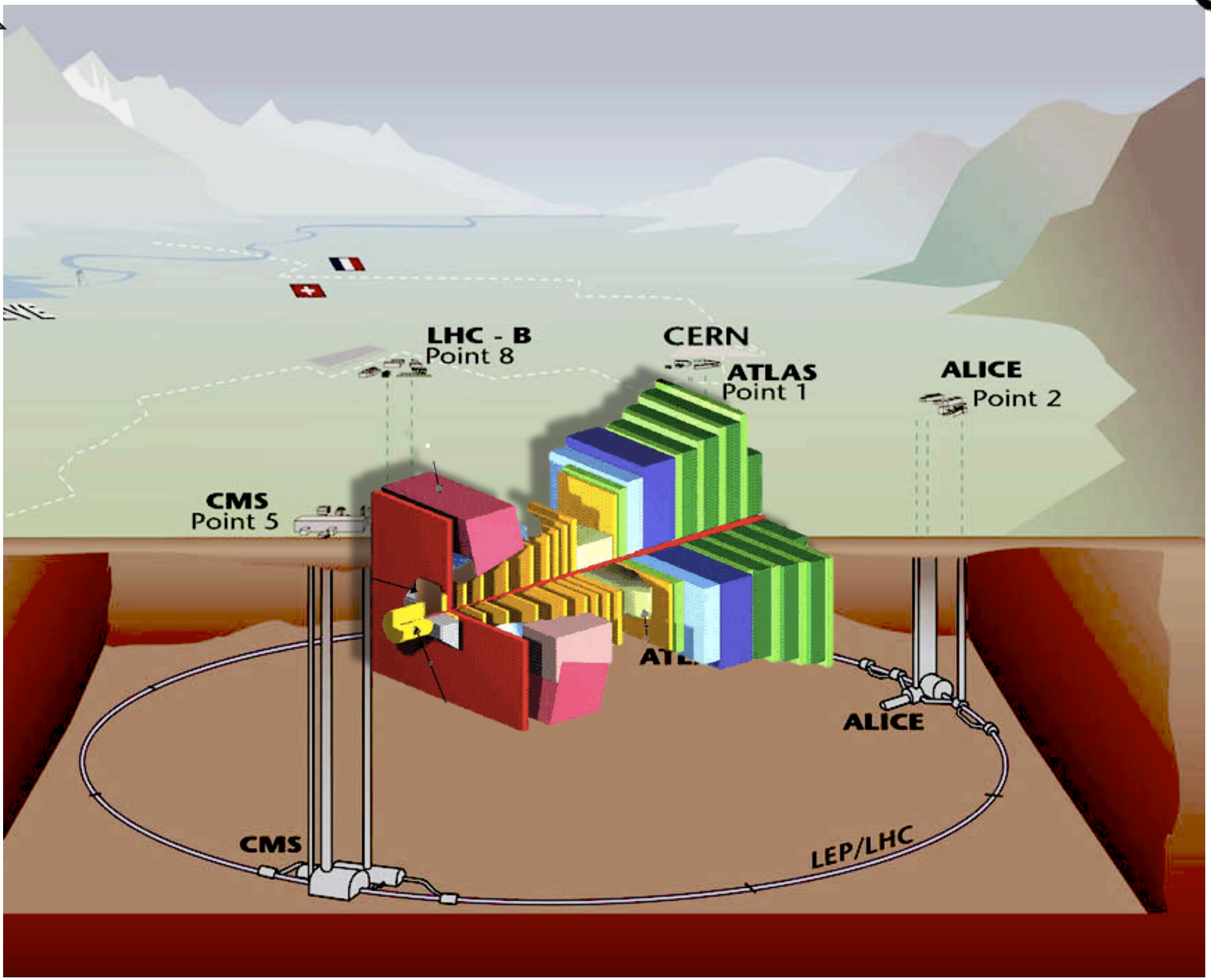

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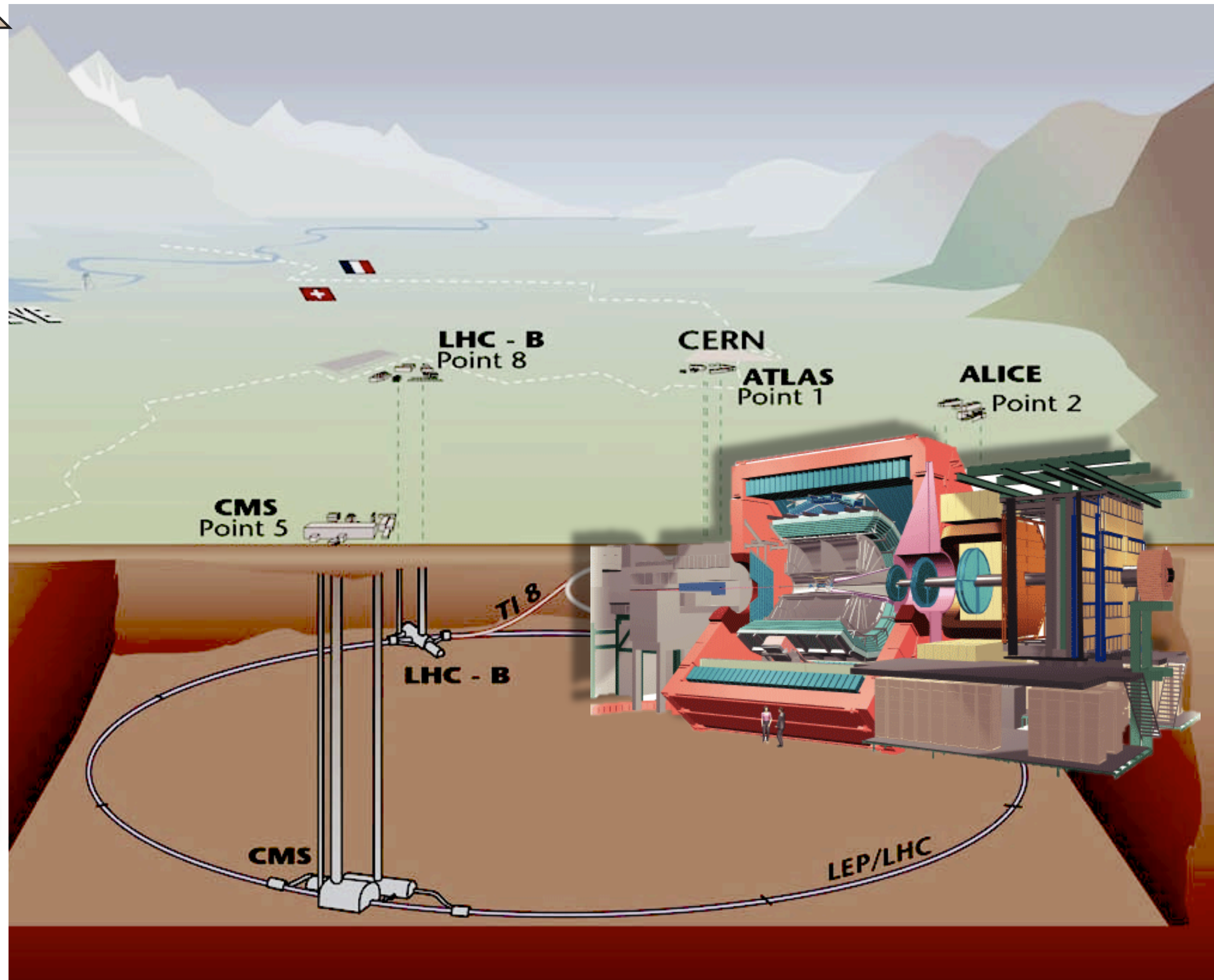
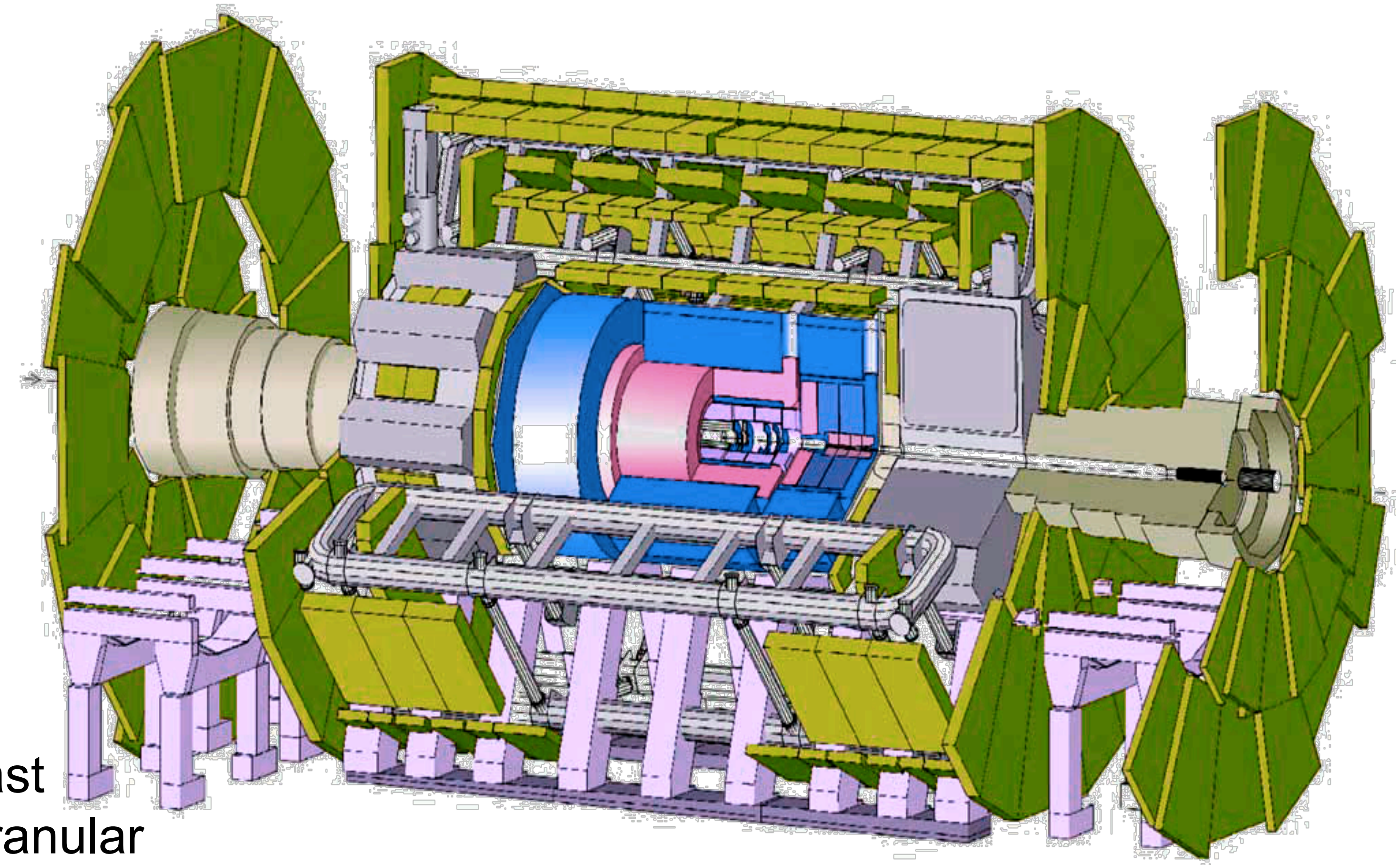
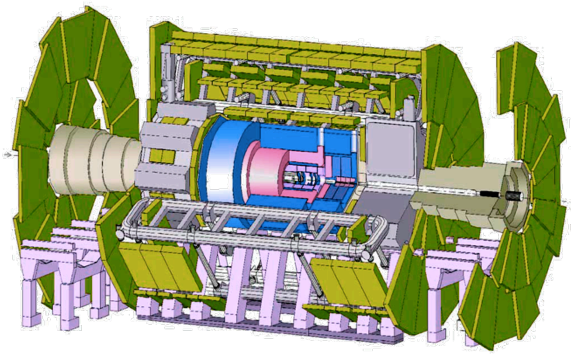


A DETECTOR (E.G. ATLAS)

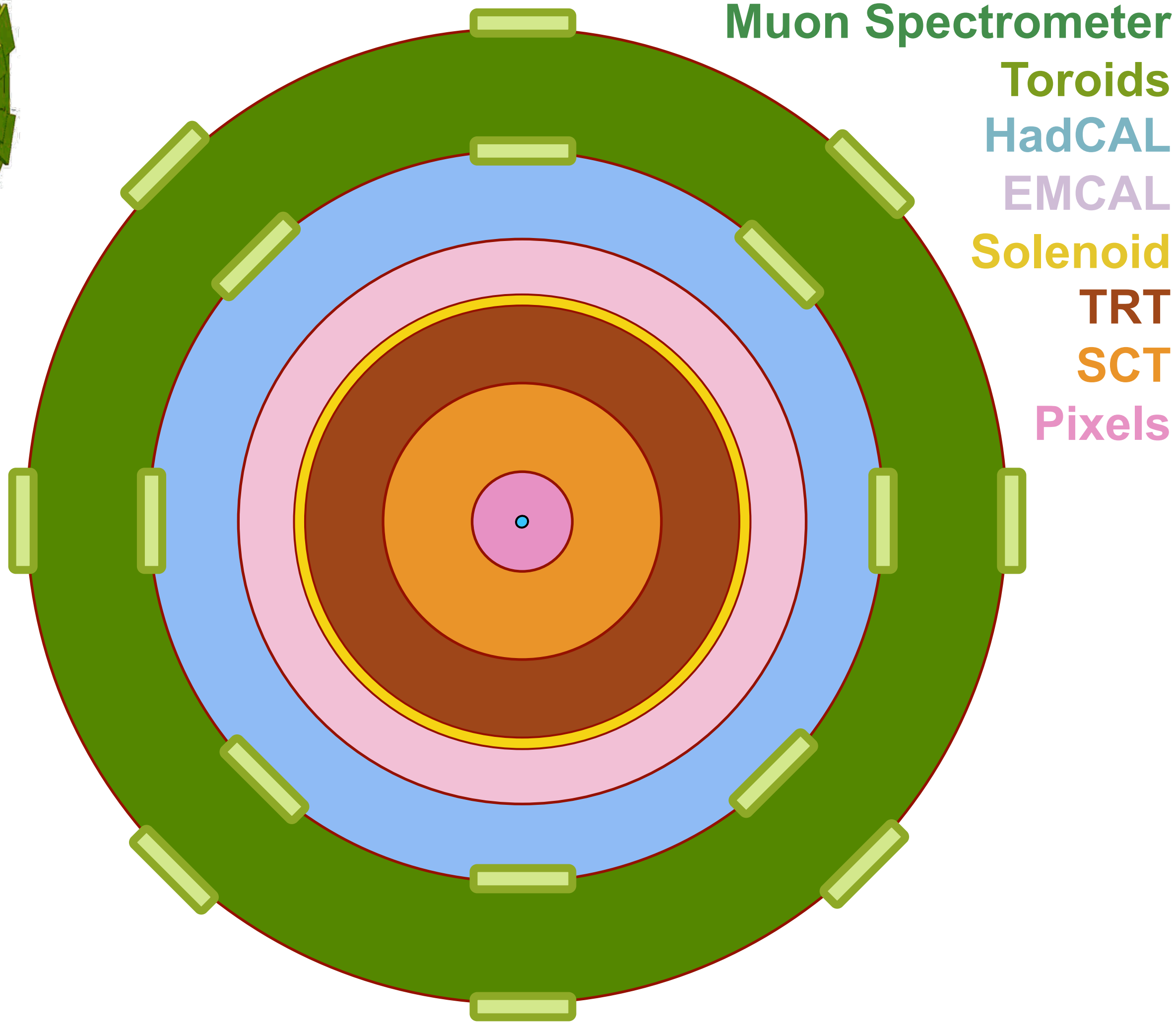


✓ Fast
✓ Granular
✓ Resistant to radiation

A DETECTOR (E.G. ATLAS)



Simplified Detector Transverse View



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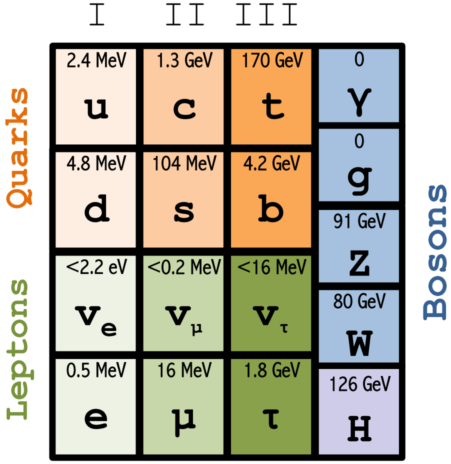
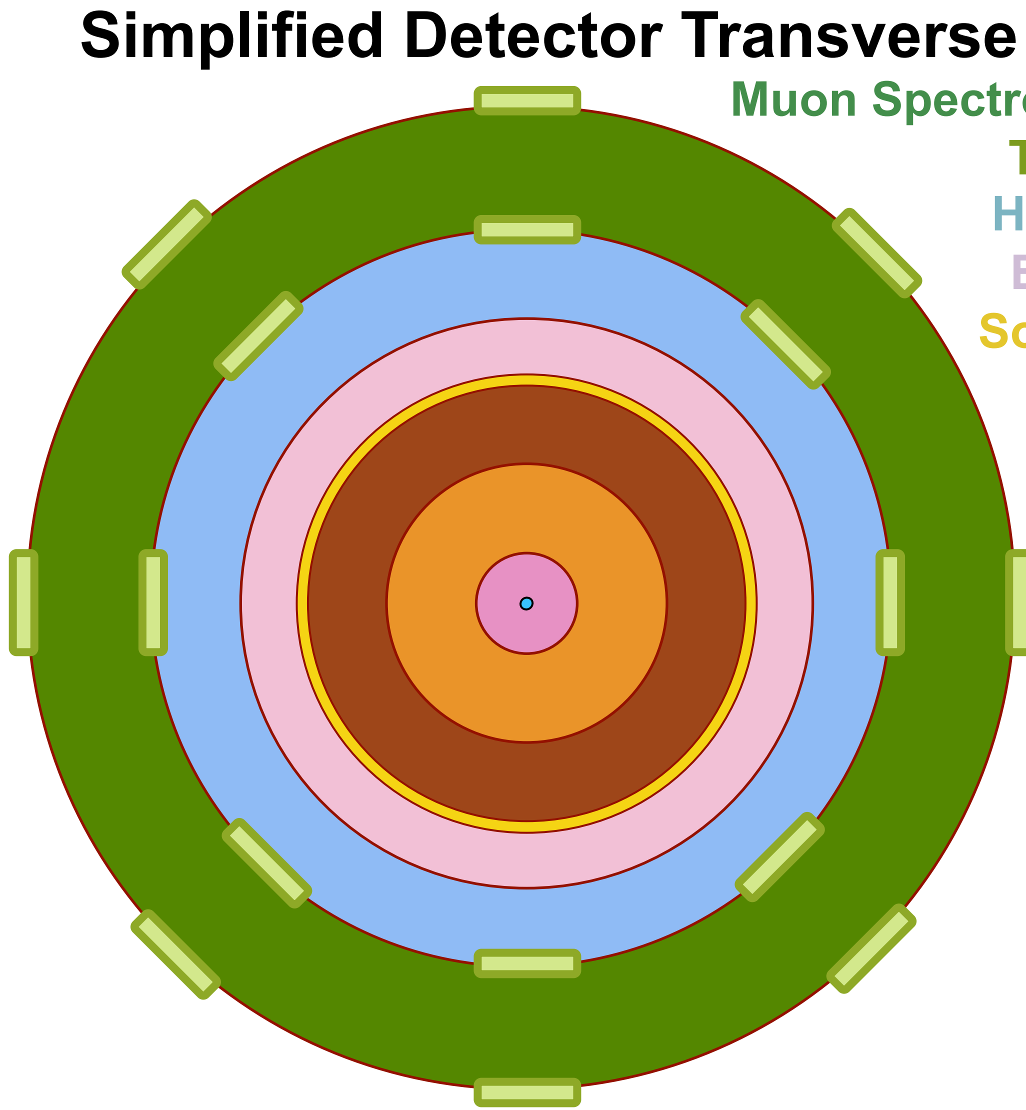
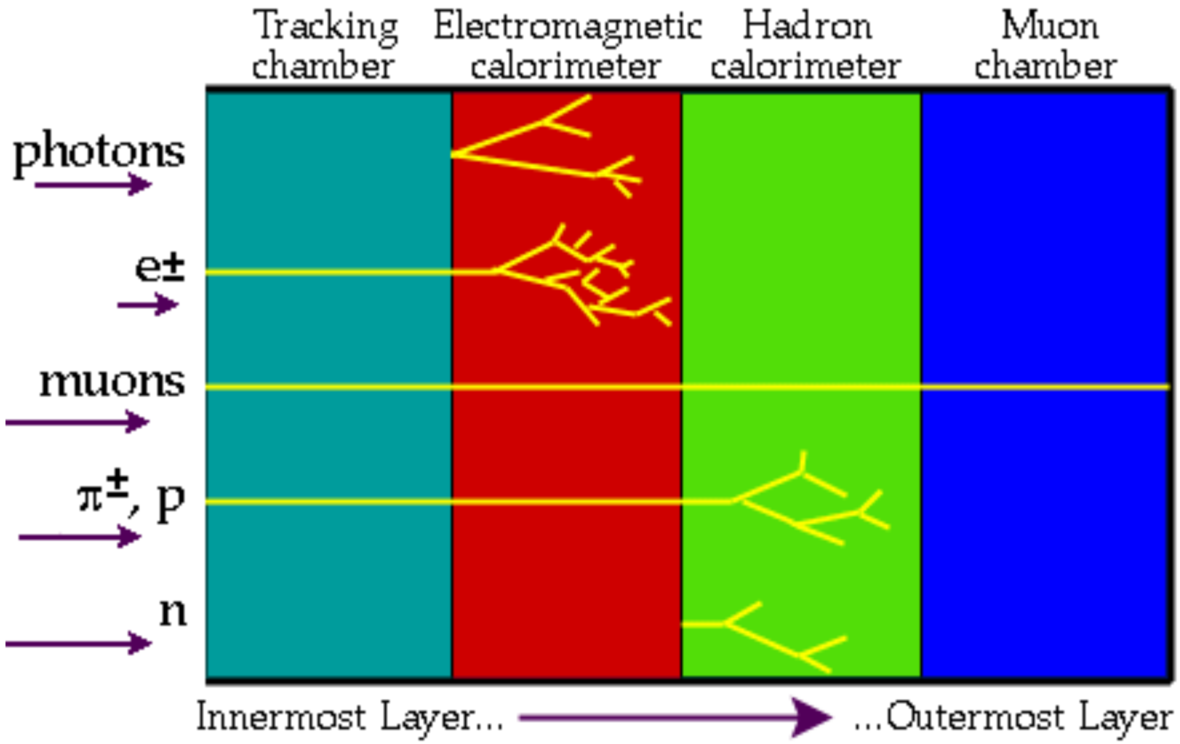




PARTICLES THROUGH MATTER



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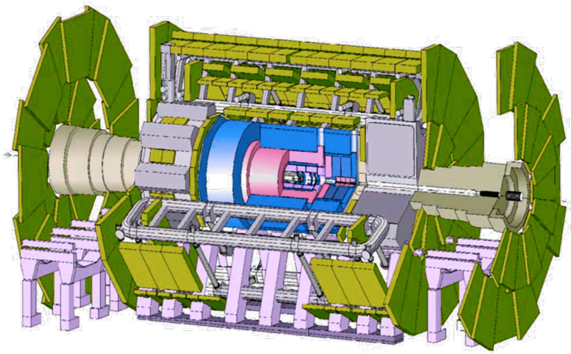

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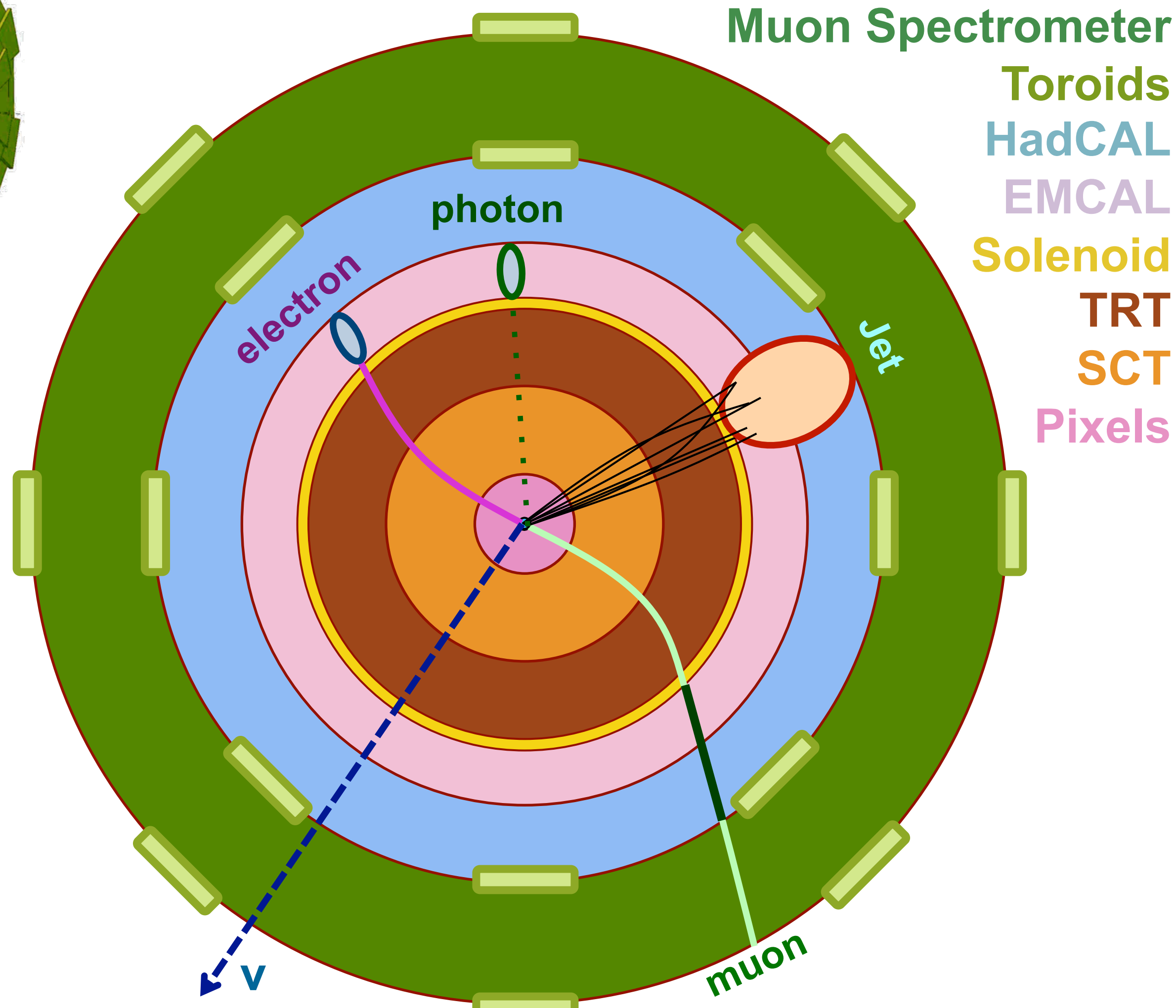
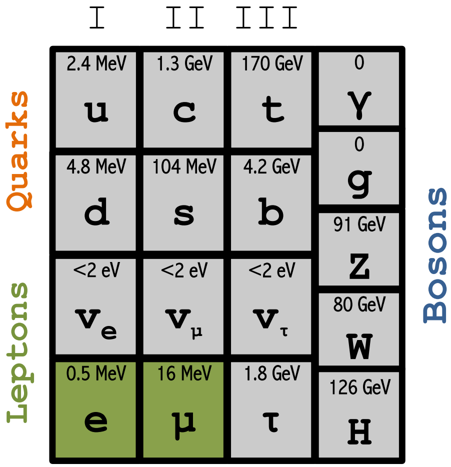
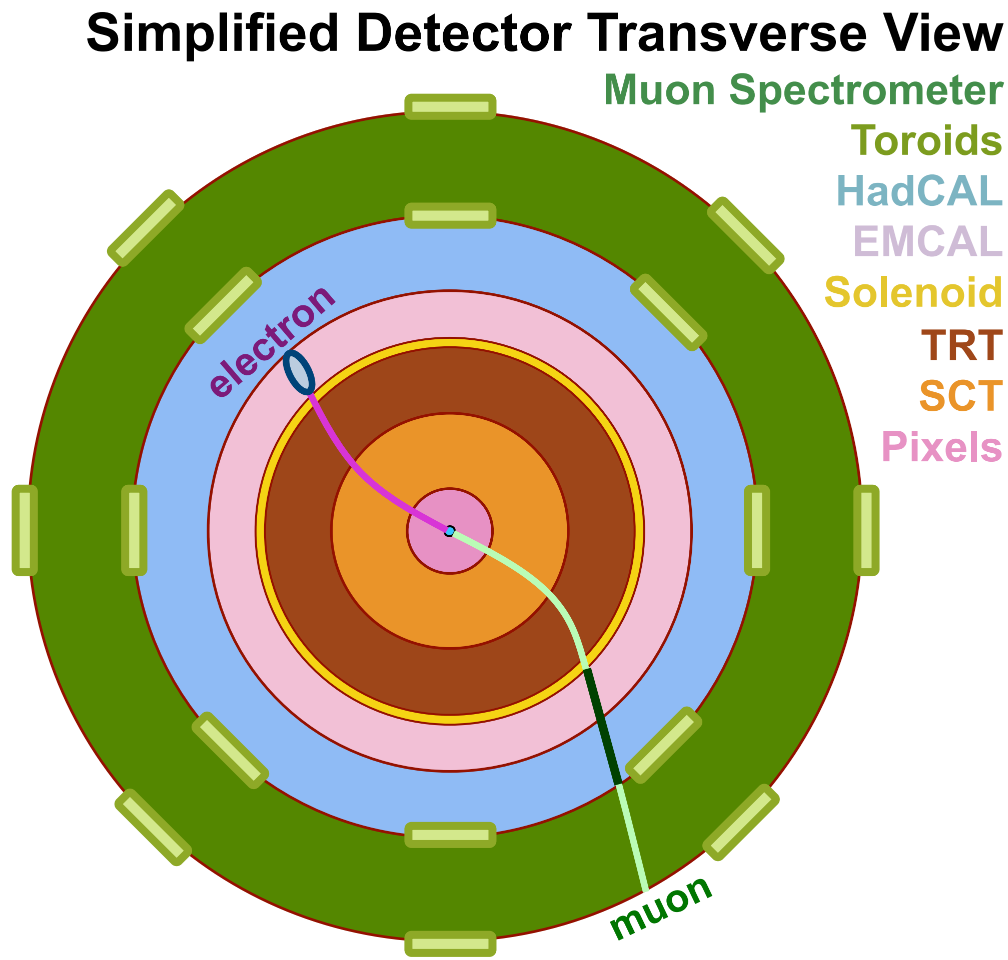


	I	II	III	Bosons
Quarks	2.4 MeV u	1.3 GeV c	170 GeV t	0 γ
Quarks	4.8 MeV d	104 MeV s	4.2 GeV b	0 g
Leptons	<2.2 eV ν_e	<0.2 MeV ν_μ	<16 MeV ν_τ	91 GeV Z
Leptons	0.5 MeV e	16 MeV μ	1.8 GeV τ	80 GeV W
				126 GeV H

RECONSTRUCTING PARTICLES





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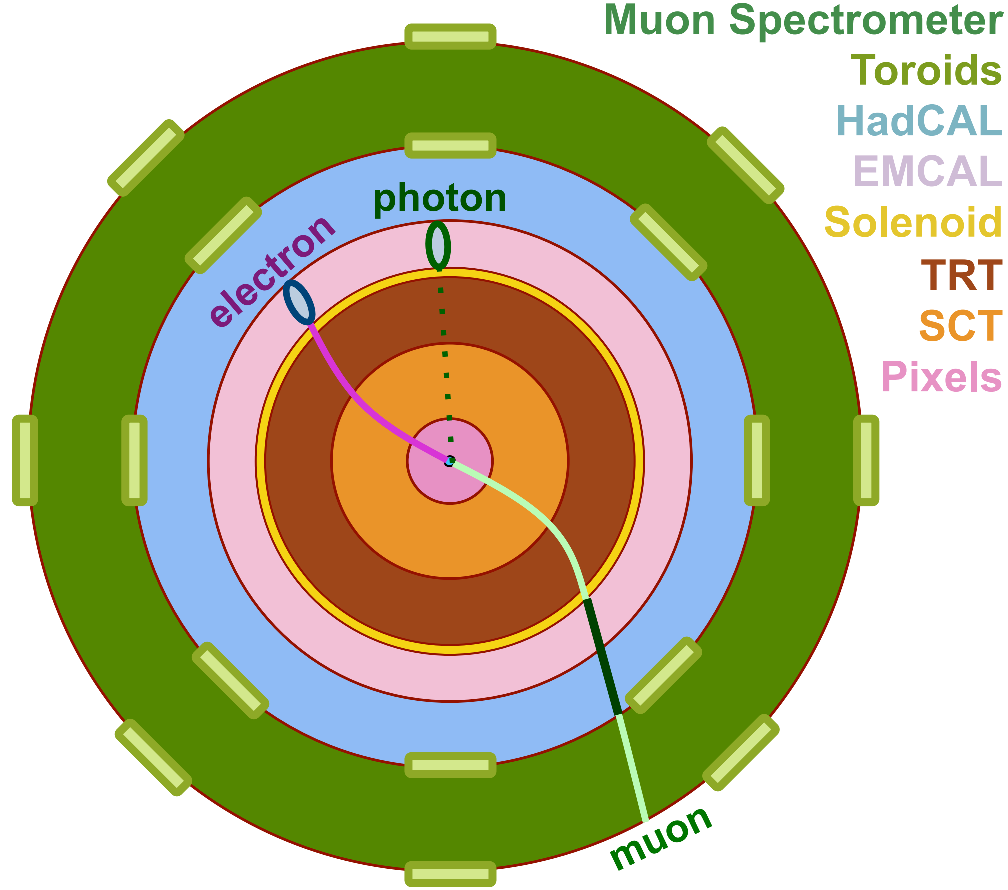

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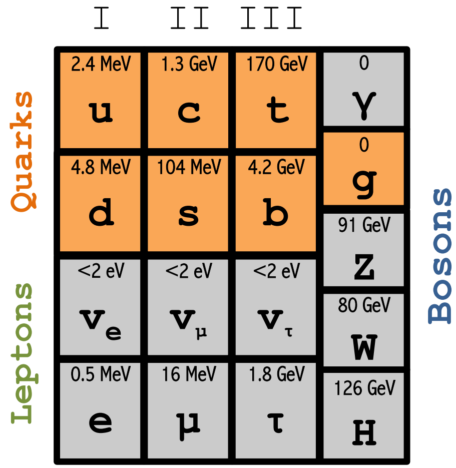

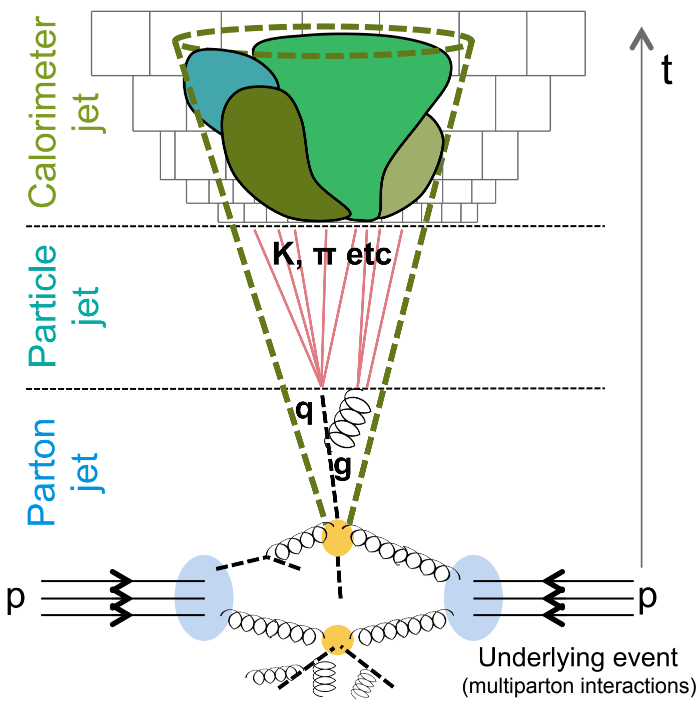

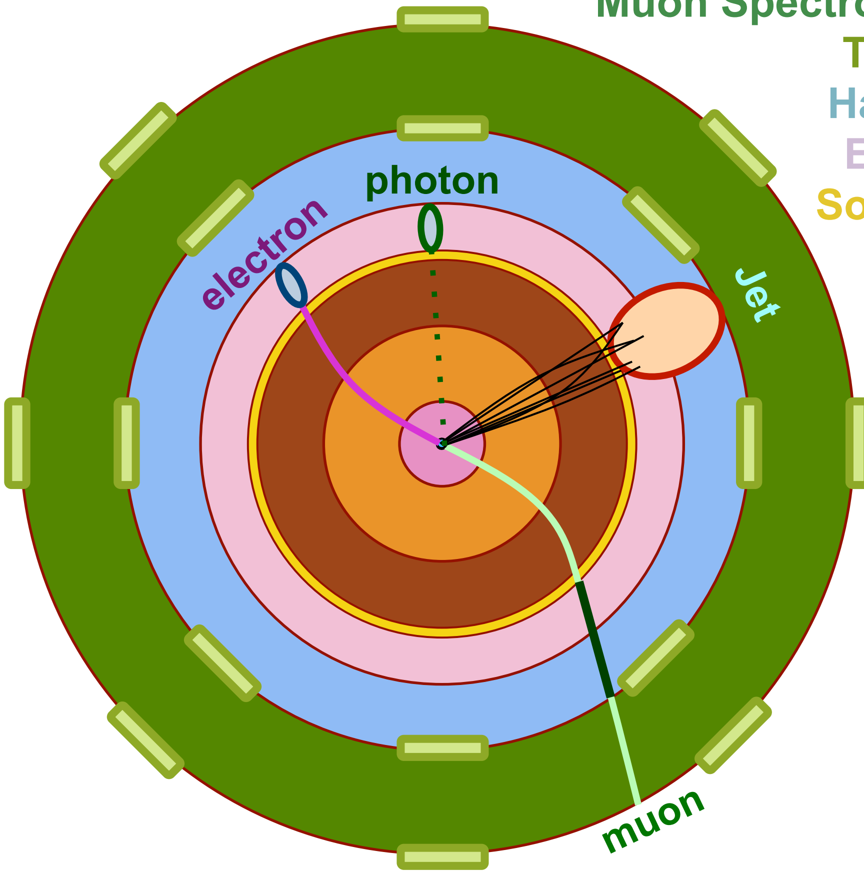

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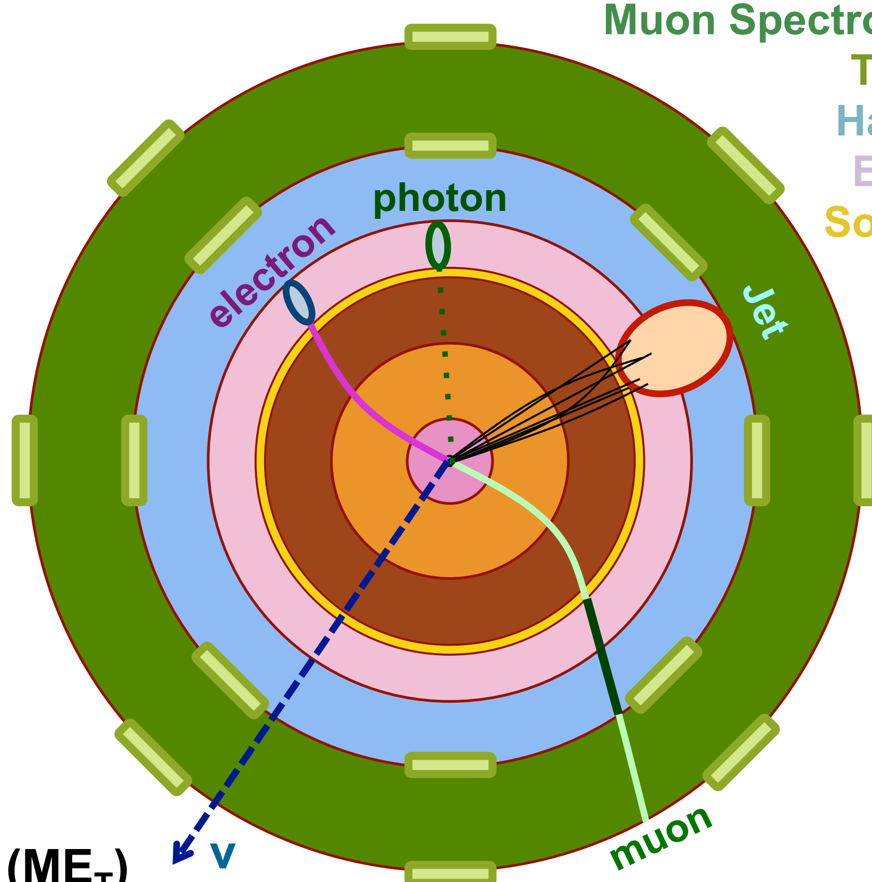


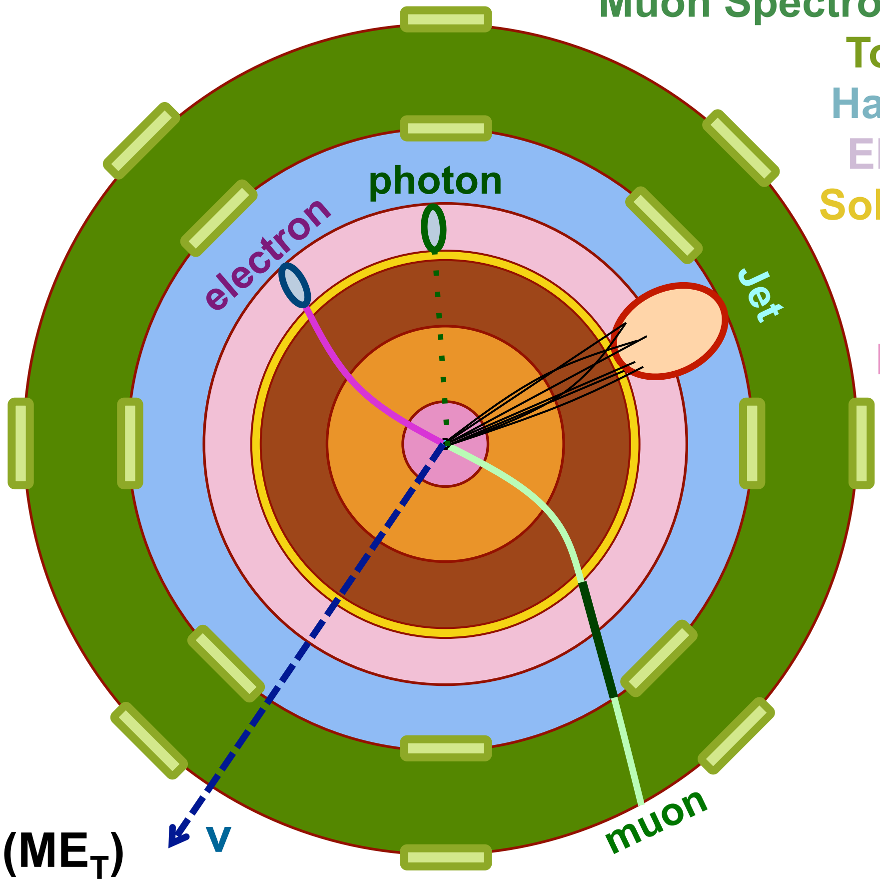
In the transverse plane:

$$\sum \vec{\mathrm{p}}_{\mathrm{T}} = 0$$

Missing Transverse Momentum (ME_T)

RECONSTRUCTING PARTICLES

Simplified Detector Transverse View



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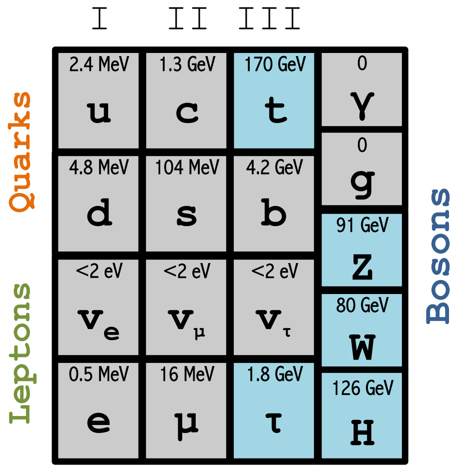

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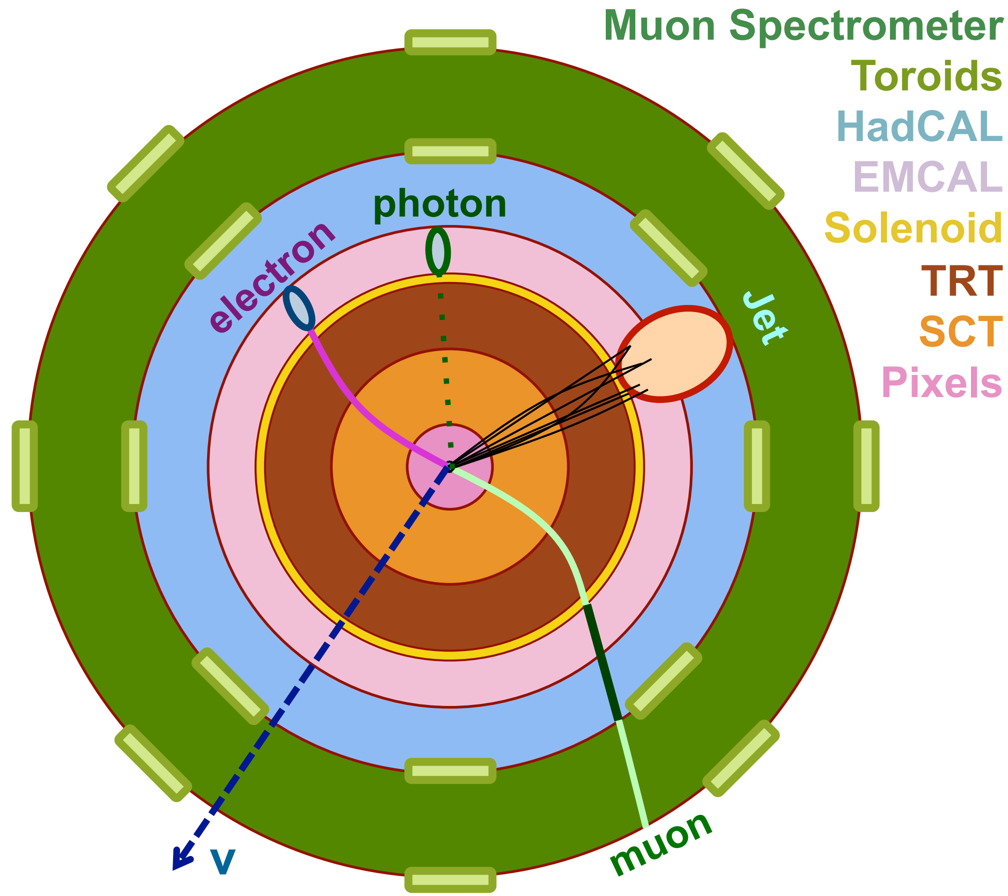
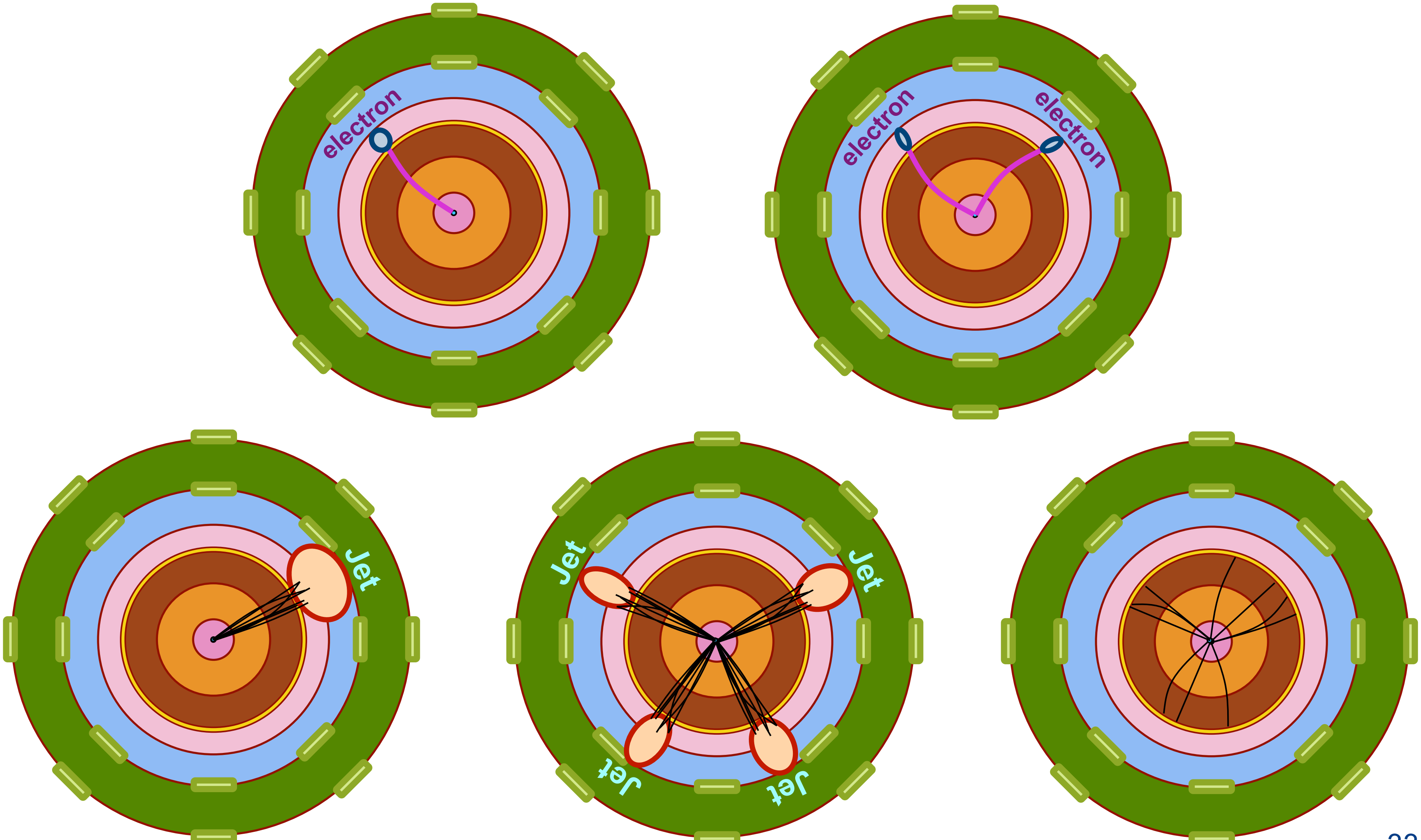
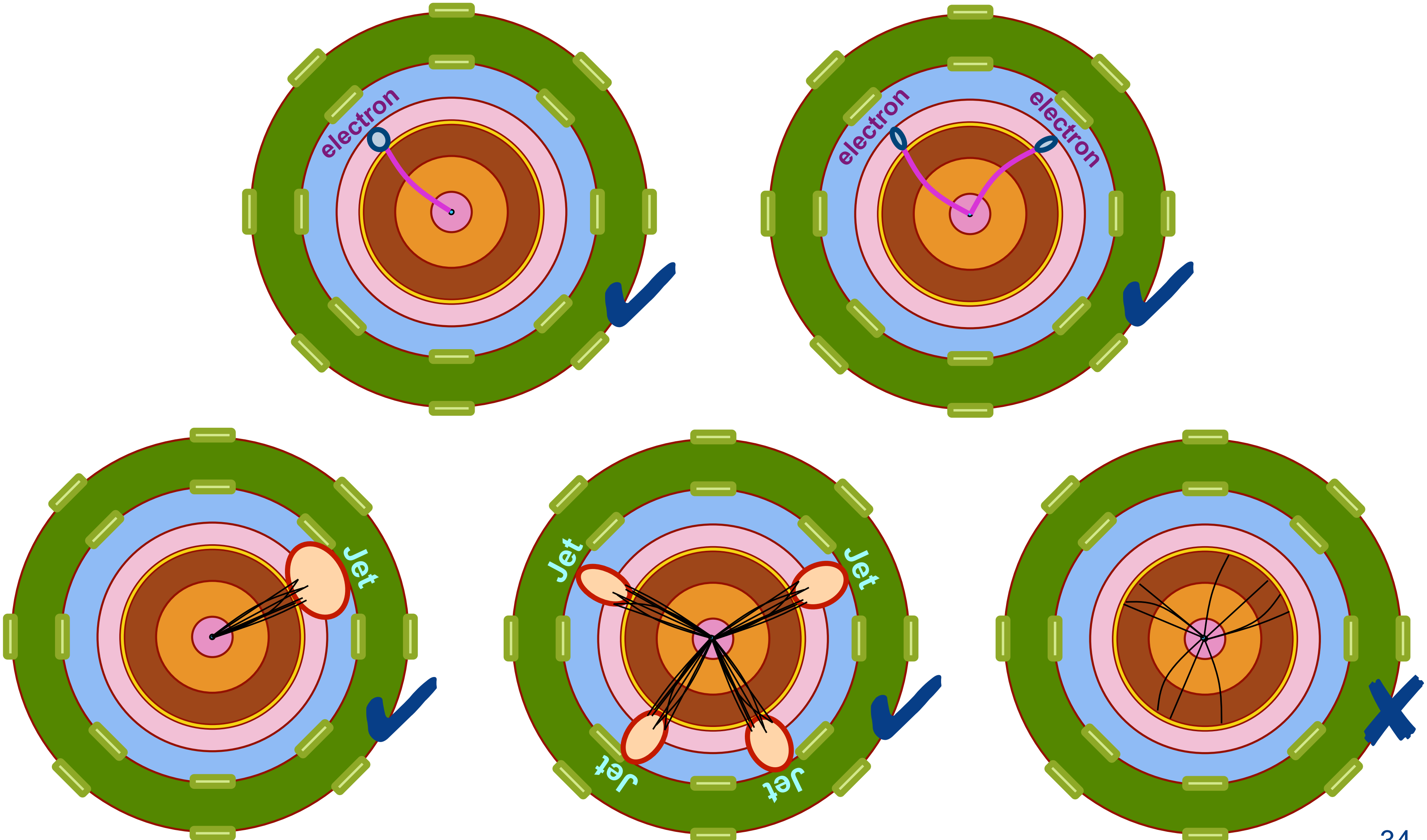


ONLINE RECONSTRUCTION



TRIGGERING ON PHYSICS



TRIGGER MENUS

Trigger	Typical offline selection	L1 Peak Rate (kHz) L_{peak}=7e33/cm^{2}s	EF Avg. Rate (Hz) $L_{\text{avg.}}$=5e33/cm^{2}s
Single leptons	Single iso μ, p_T >25 GeV	8	45
	Single iso e, p_T >25 GeV	17	70
Two leptons	Two μ's, each p_T >15 GeV	1	5
	Two μ's, p_T >20, 10 GeV	8	8
	Two e's, each p_T >15 GeV	6	8
	Two e's, p_T >25, 10 GeV	17	5
	Two τ's, p_T >45, 30 GeV	12	12
Two photons	Two γ's, each p_T >25 GeV	6	10
	Two γ's, p_T >40, 30 GeV	6	7
Single jet	Jet (R = 0.4), p_T >360 GeV	2	5
	Jet (R = 1.0), p_T >470 GeV		2
E_T^{miss}	E_T^{miss} >150 GeV	2	17
Multi-jets	4 jets, each p_T >85 GeV	1	8
	5 jets, each p_T >60 GeV		2
	6 jets, each p_T >50 GeV		4
b−jets	4 jets, each p_T >50 GeV out of which one is b−tagged	1	4
Total		< 75	400

STREAMING

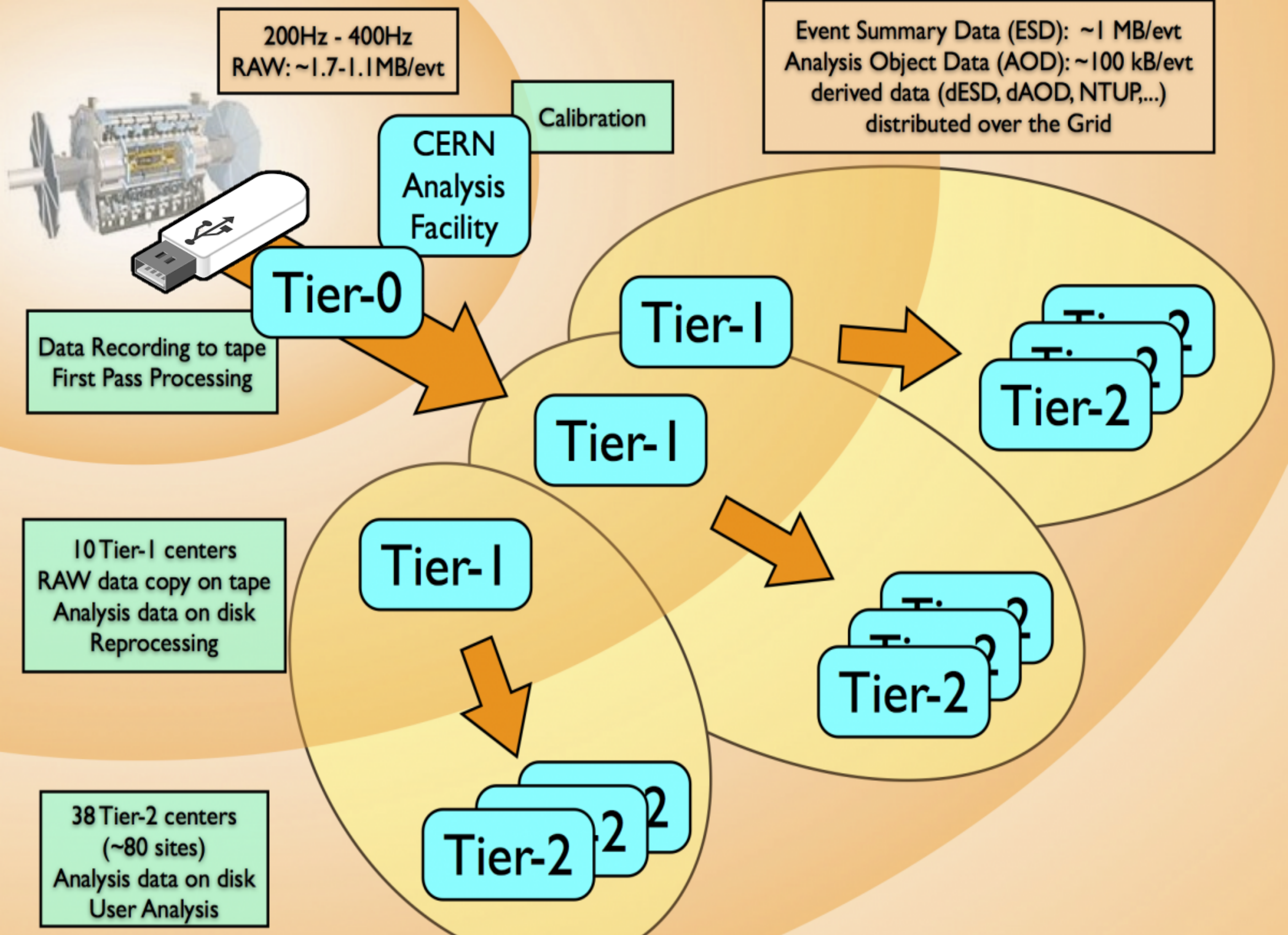
- Streaming is based on trigger decisions at all stages
- The Raw Data physics streams are generated at the HLT output level

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

<u>Physics Streams</u>
data for physics analyses

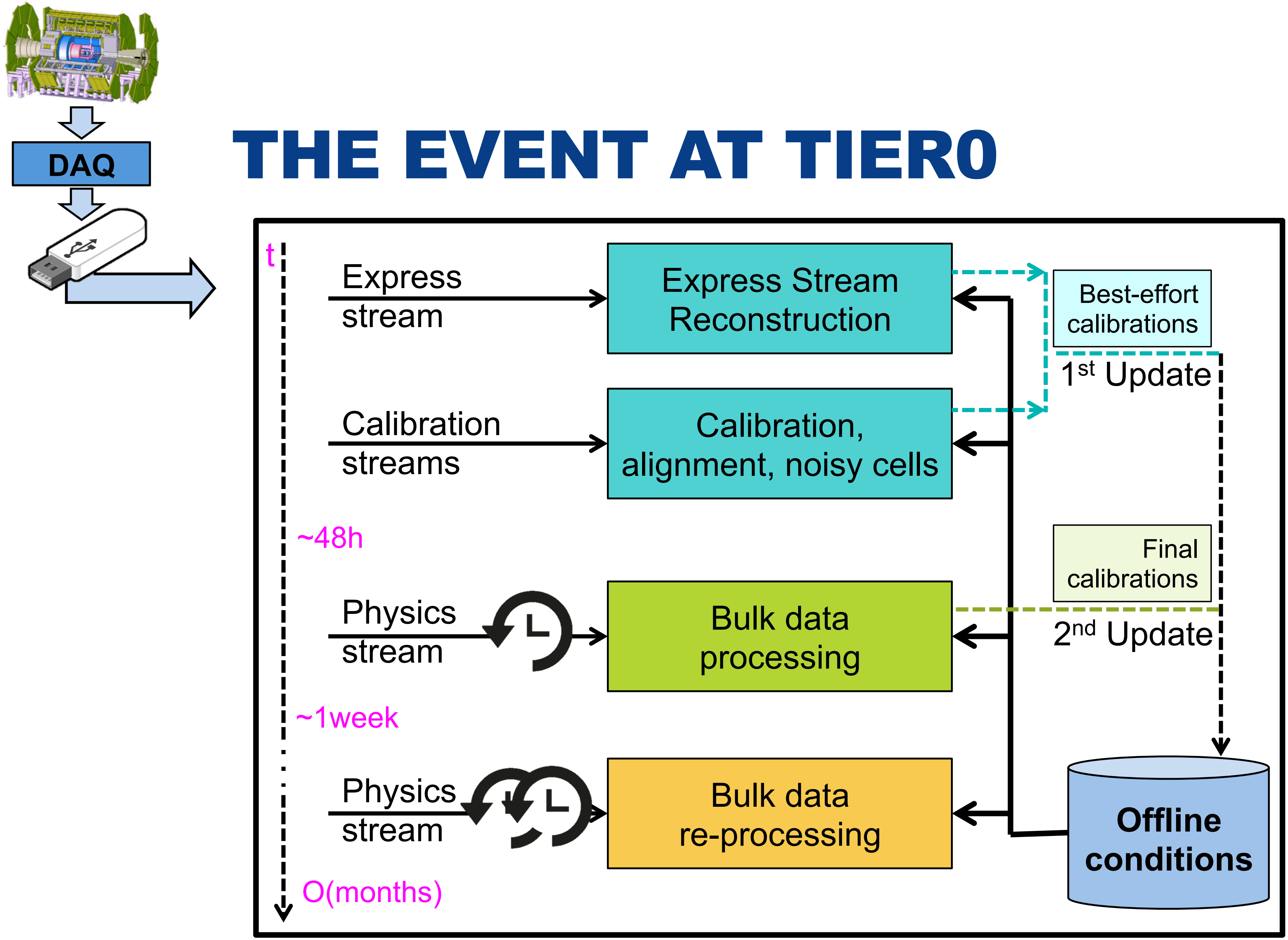
<u>Express Stream</u>
full events for fast reconstruction

<u>Calibration Streams</u>
events delivering the minimum amount of information for detector calibrations at high rate

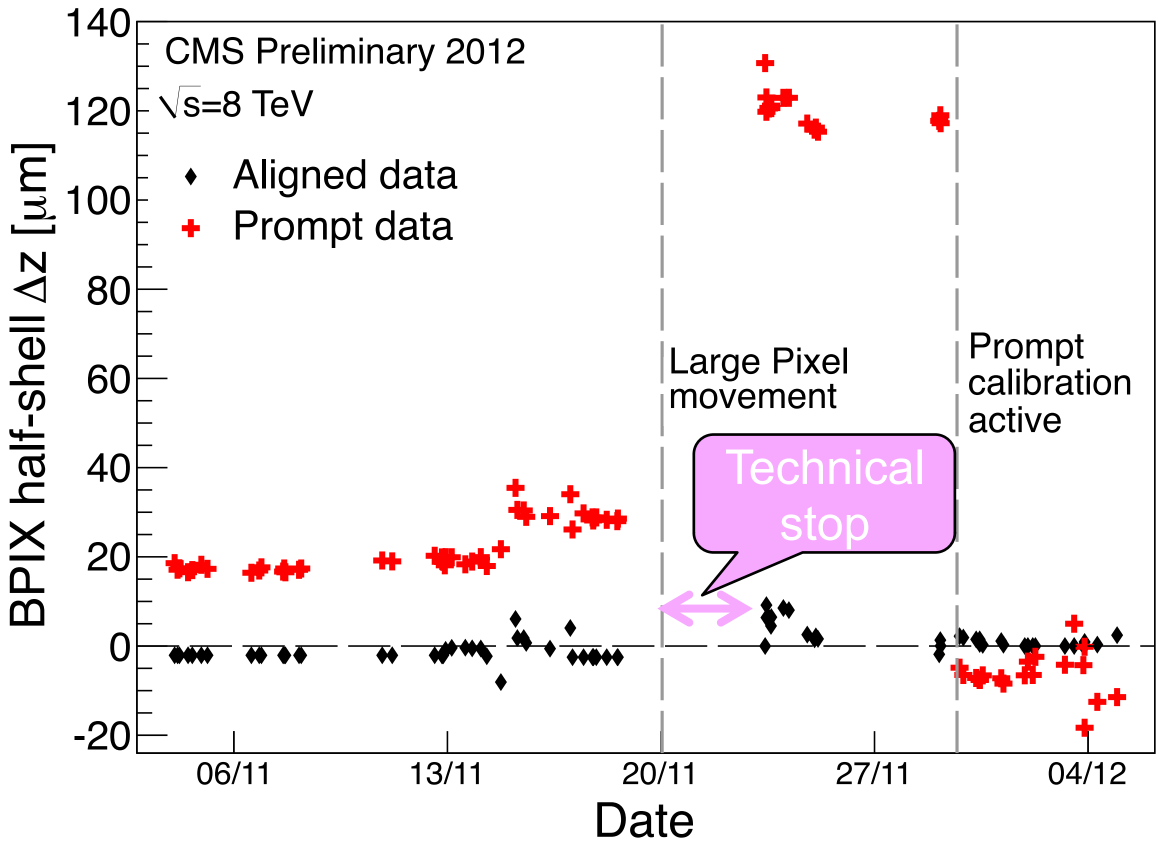


http://www.isgtw.org/feature/how-grid-computing-helped-cern-hunt-higgs

THE EVENT AT TIER0

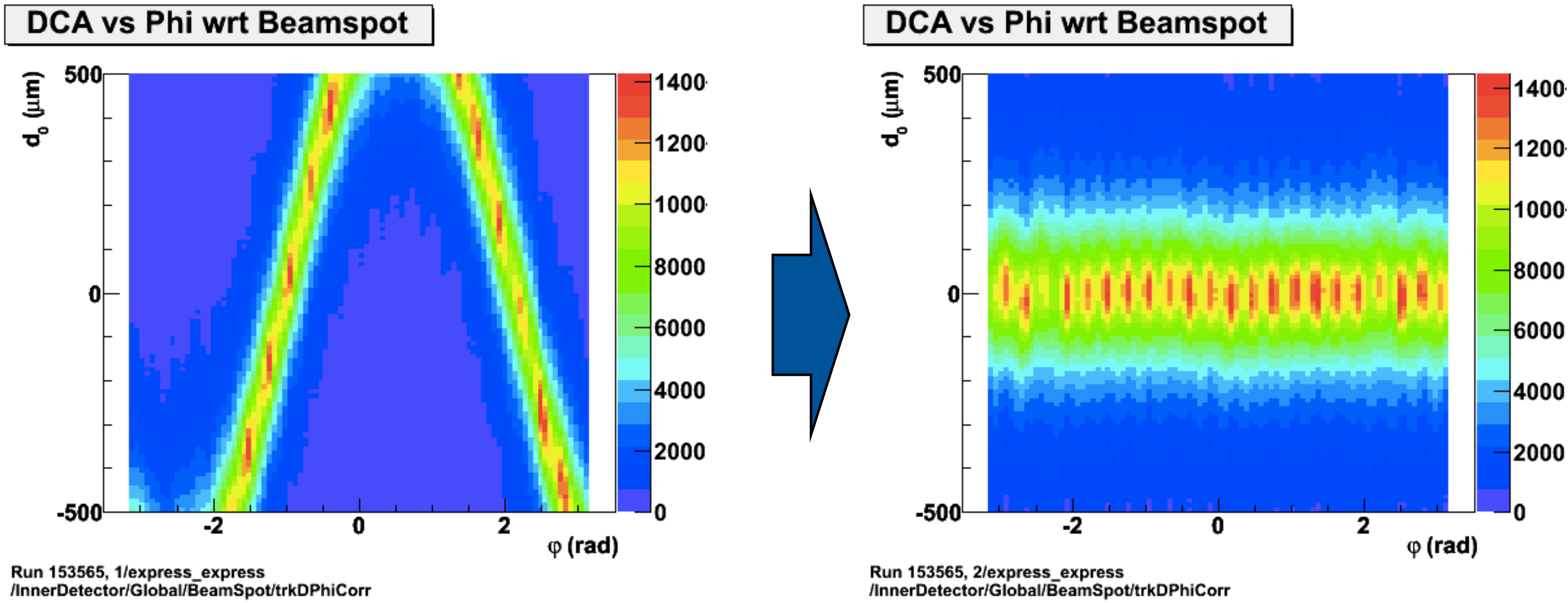


E.G. ALIGNMENT



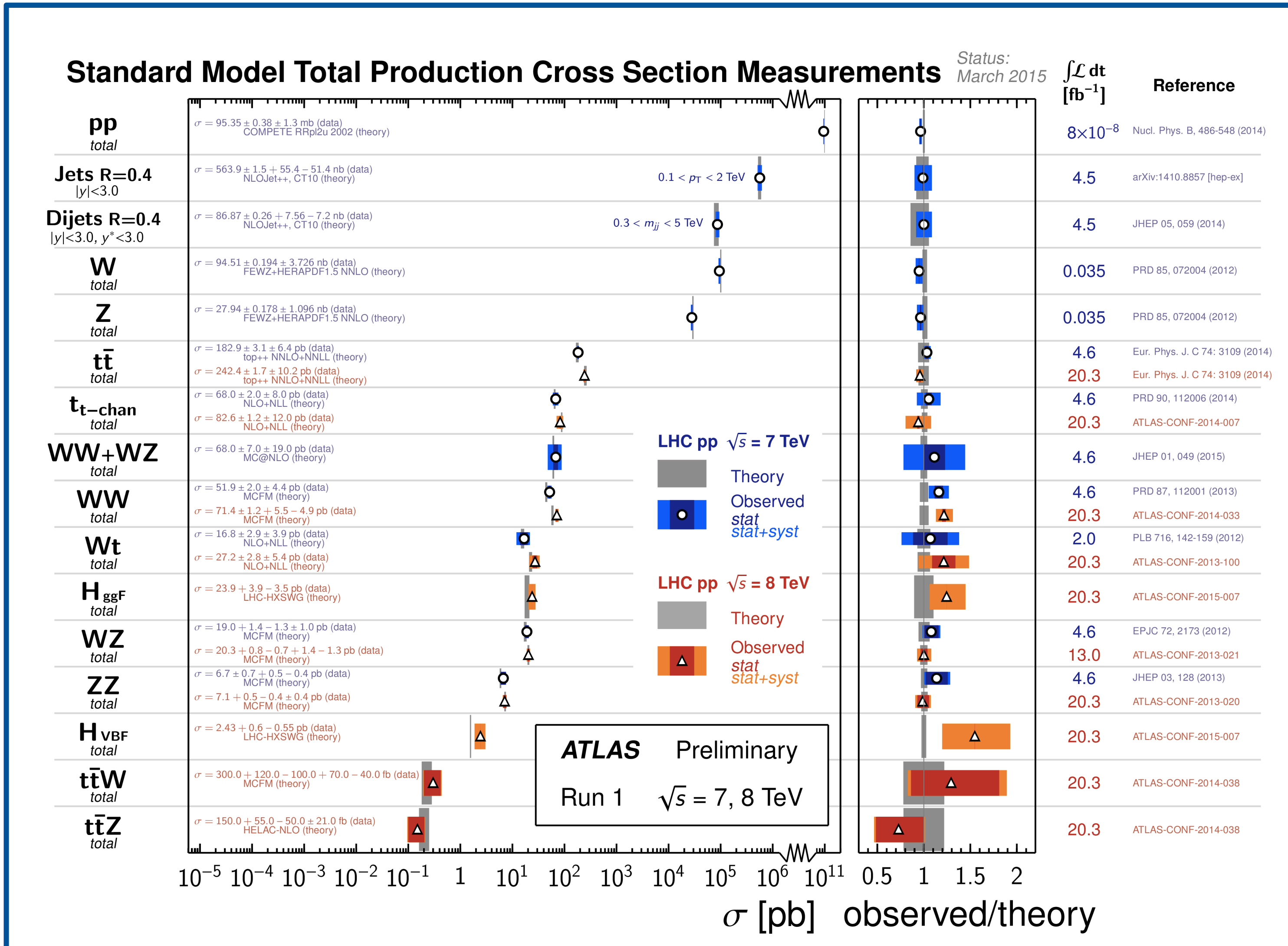
Day-by-day value of the relative longitudinal shift between the two half-shells of the BPIX as measured with the primary vertex residuals, for the last month of pp data taking in 2012.

E.G. BEAMSPOT



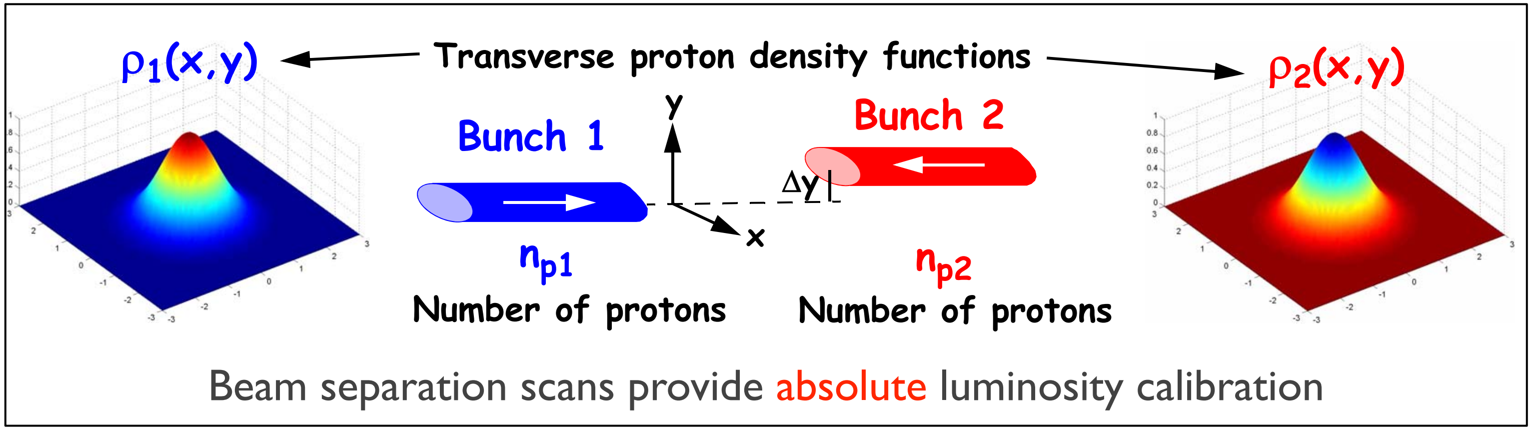
d0 vs phi with respect to the beam spot. For a correctly determined beam spot, this plot should be flat. For the first processing of the **express stream**, the beam spot is not yet known and therefore large variations as in this example are expected. In **bulk reconstruction** this effect is corrected.

“FINAL” CALIBRATION



LUMINOSITY DETERMINATION

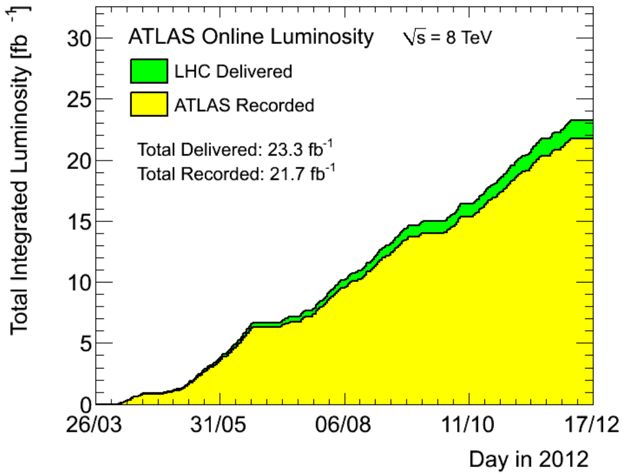
- A measurement of the number of collisions per cm^2 and second.
- Multiple methods used for determining luminosity: reducing uncertainties.
- Normalization is done with beam-separation scan (Van-der-Meer scan). Requires careful control of beam parameters.



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

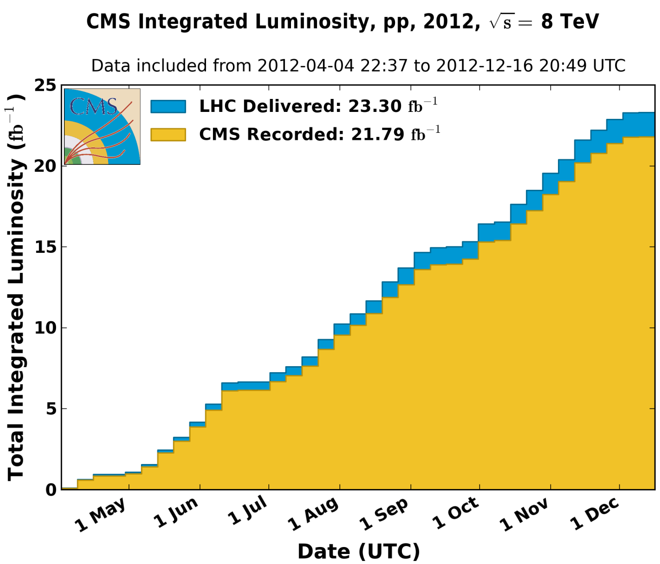
- Result: luminosity measurement with very small uncertainties (order of few %) with very fast turn-around time.

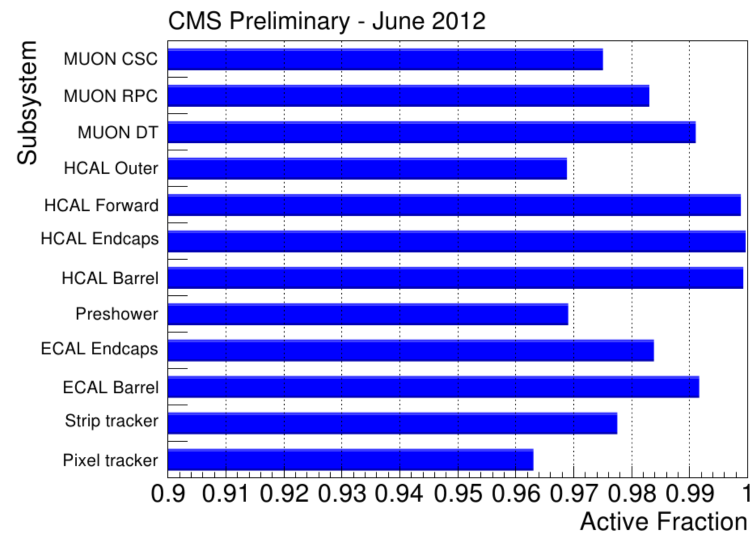
LUMINOSITY – RECORDED



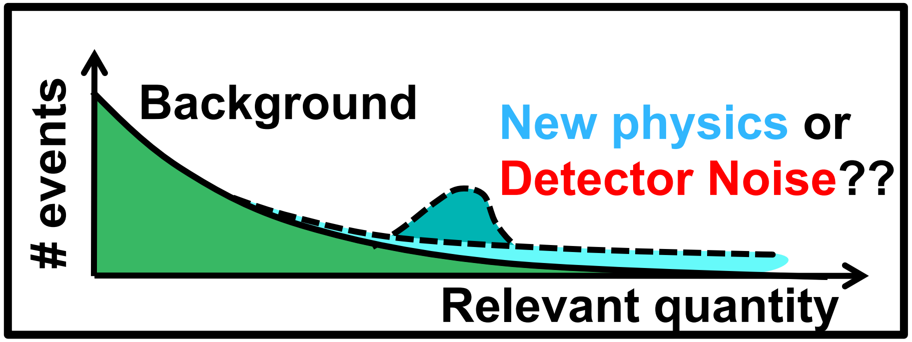
ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.5%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb^{-1} of recorded data.





DATA QUALITY

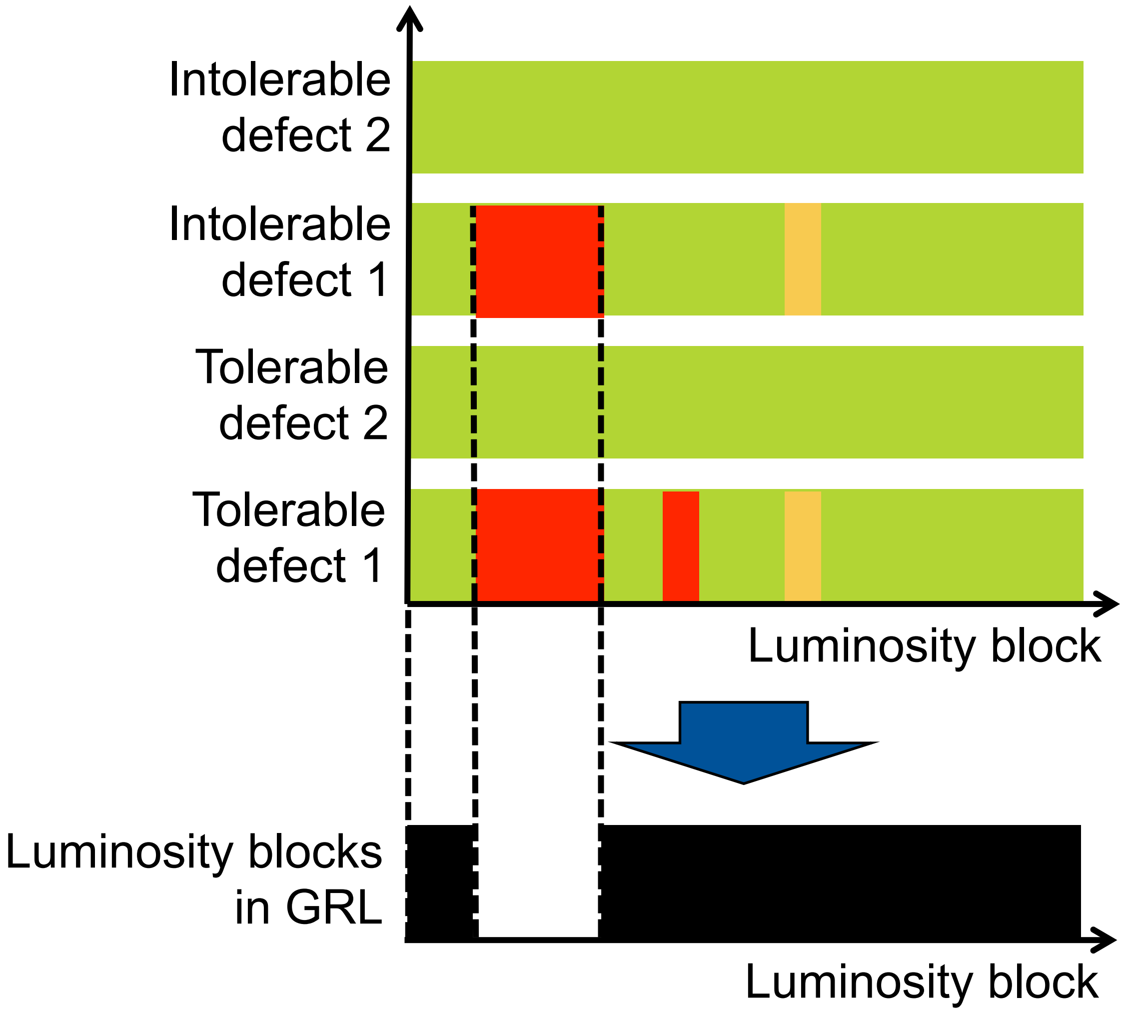


The data we analyze has to follow norms of quality such that our results are trustable.

- **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".

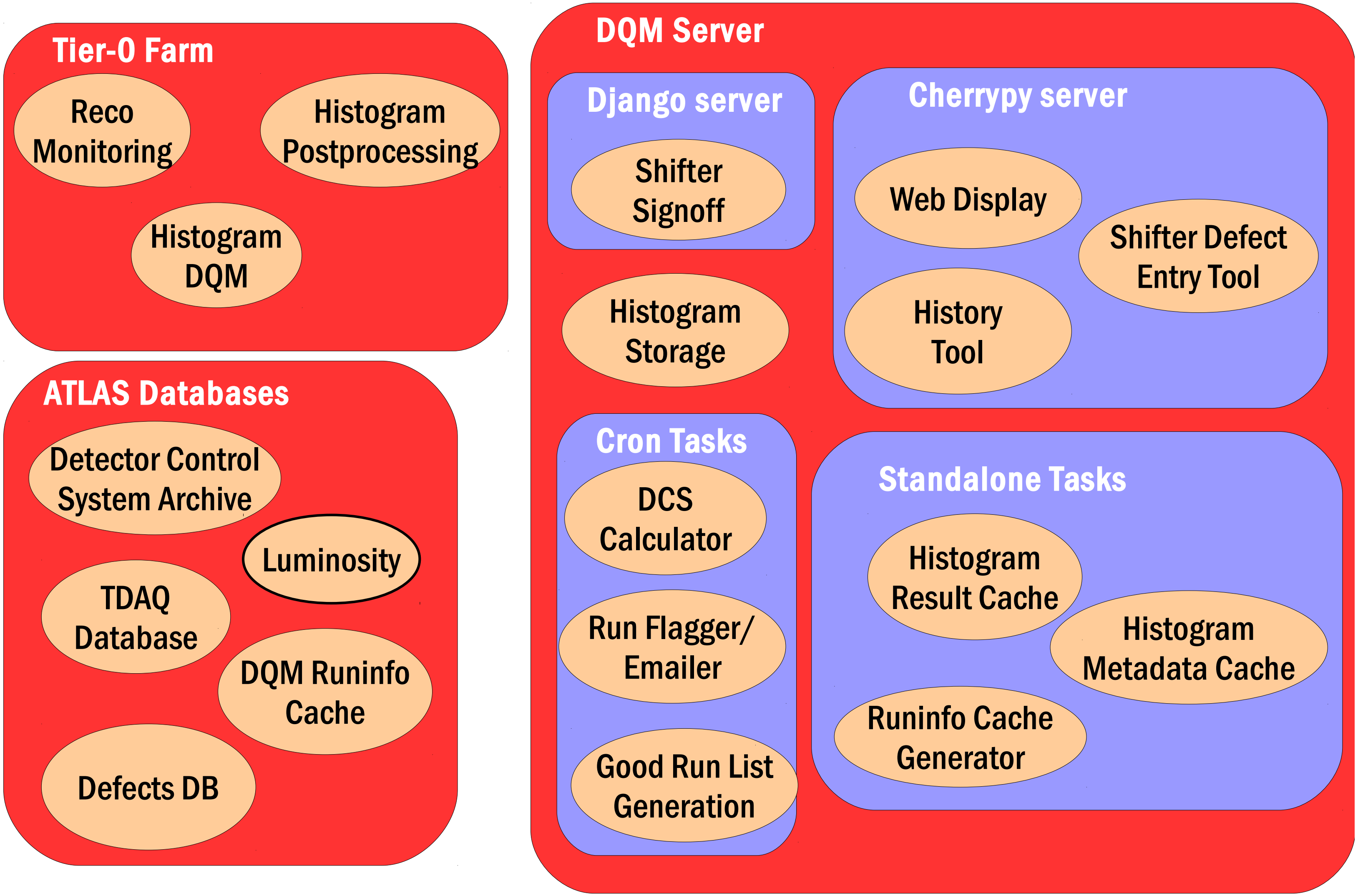
DATA QUALITY AND “GRL”

Good Run List



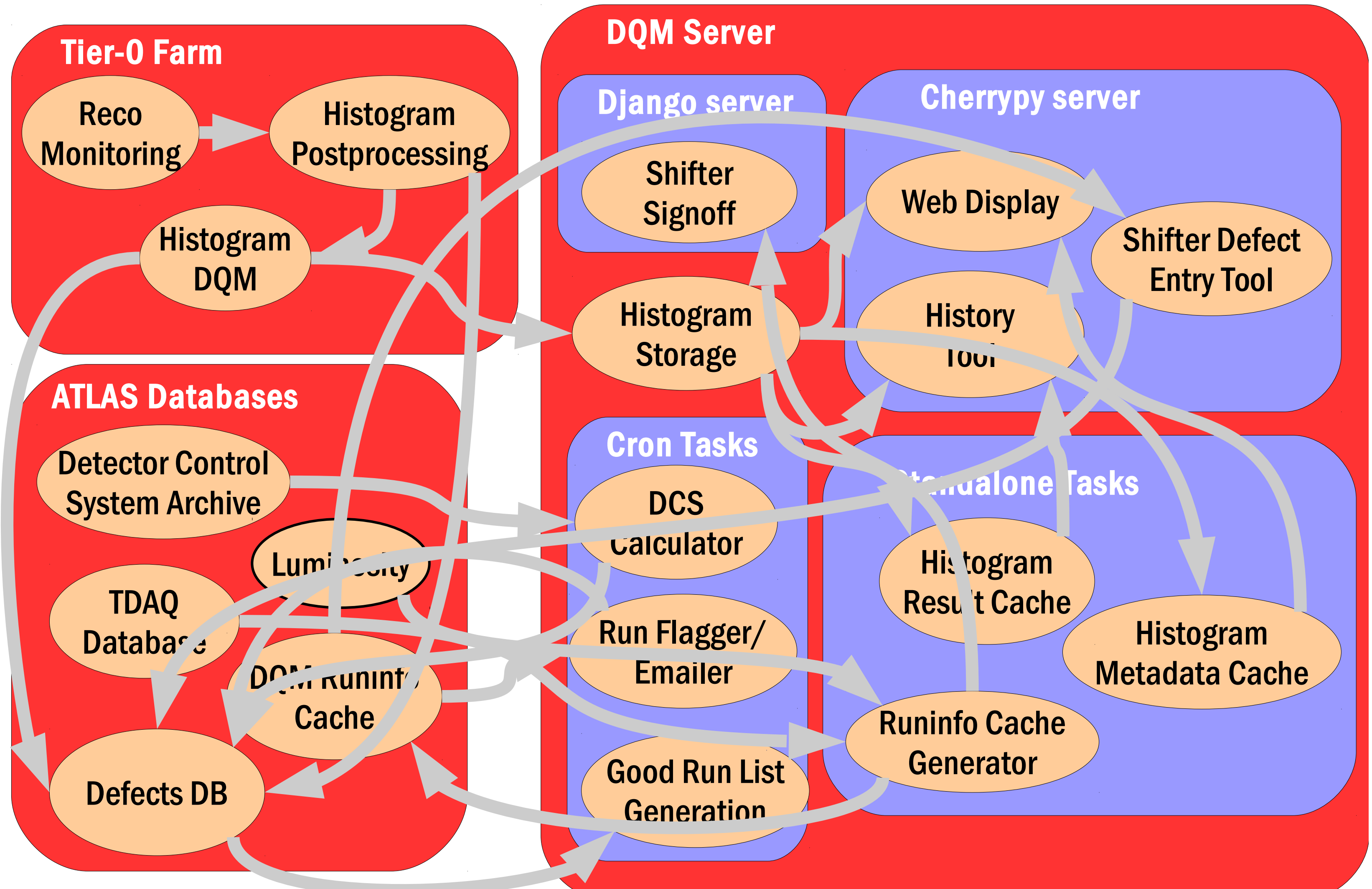
Short period during which data taking conditions are (expected to be) absolutely stable. Used for data-quality assessment and luminosity determination

DATA QUALITY

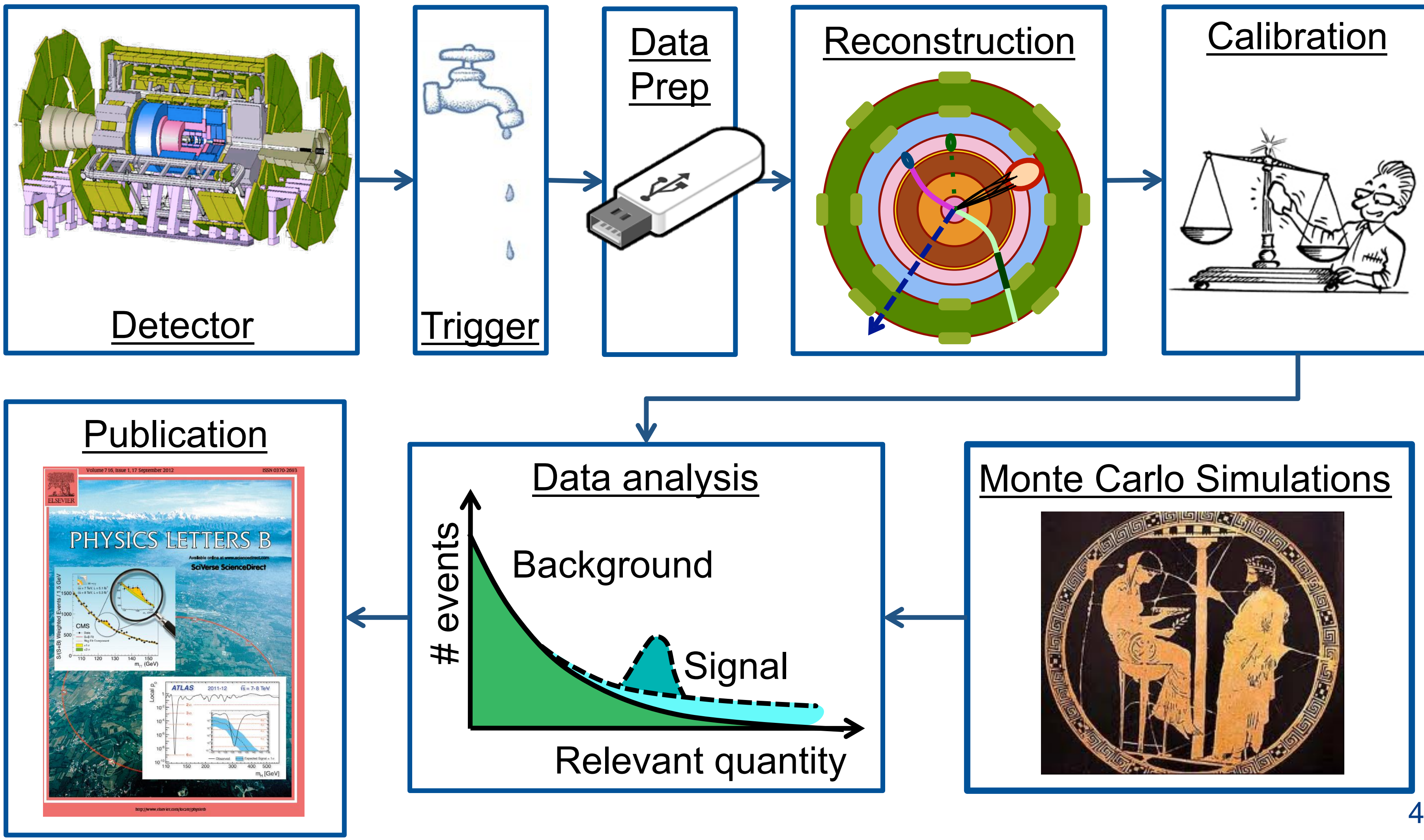


https://cds.cern.ch/record/2008725/files/ATL-SOFT-SLIDE-2015-179.pdf

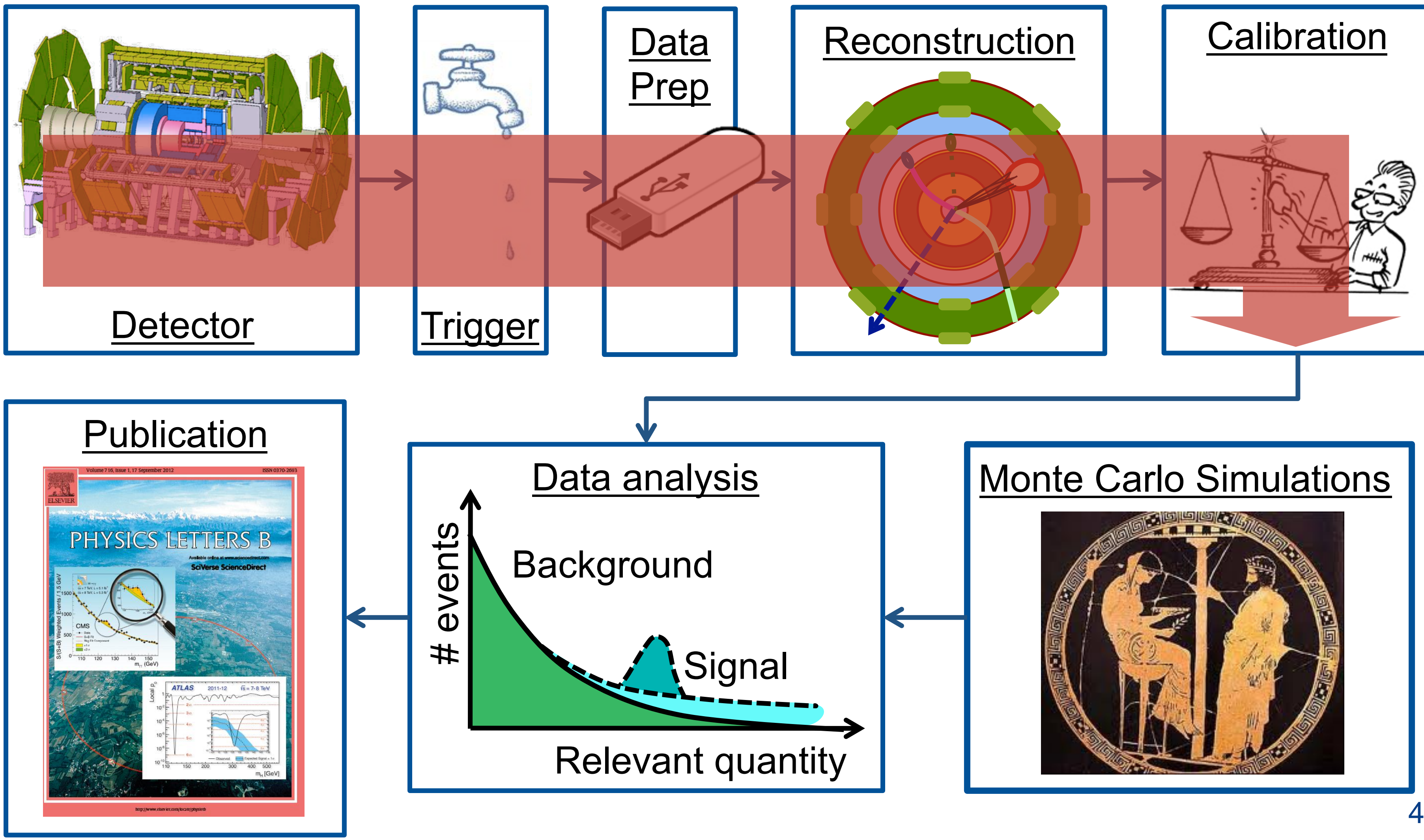
DATA QUALITY



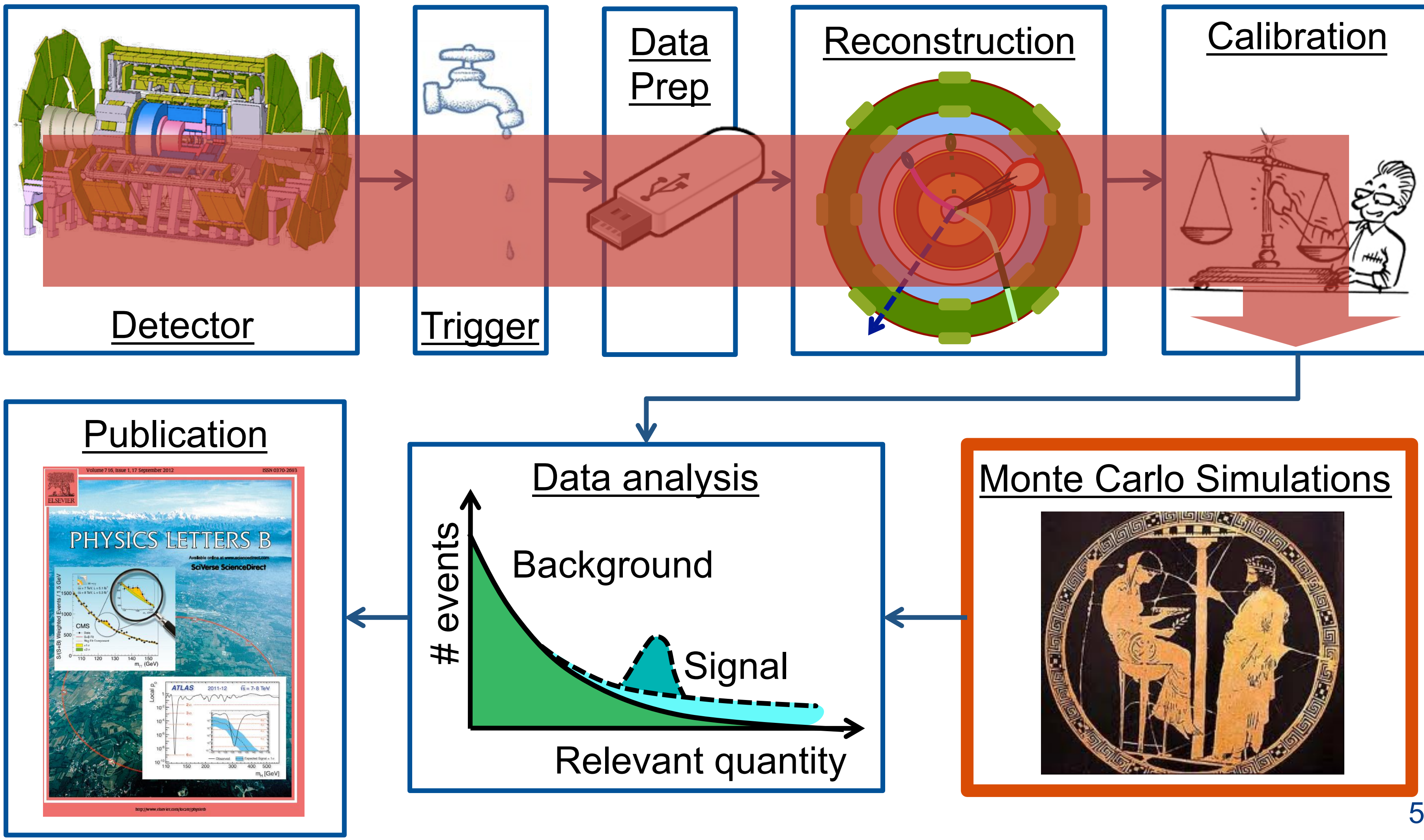
AN EVENT'S LIFETIME



AN EVENT'S LIFETIME



AN EVENT'S LIFETIME



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.**

(Simulation material by Z. Marshal)

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.

MONTE CARLO PRODUCTION CHAIN

How much processing time needed for each step?

Event Generation
simulate the physics process.

From < 1s to a few hours / event.

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

From 1 to 10min / event

Digitization
Translate interactions with detector into realistic signals.

From 5 to 60s / event

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

MONTE CARLO PRODUCTION CHAIN

How much processing time needed for each step?

Event Generation
simulate the physics process.

From < 1s to a few hours / event.

- ~ 50 MC generators on the market.
- >> 50 combinations of MC generators in a sample.
- ~ 35 K samples generated on ATLAS in the last "campaign" of 2012.
- ~ 7 B events!

MONTE CARLO PRODUCTION CHAIN

Event Generation
simulate the physics process.

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

From < 1s to a few hours / event.

- ~ 50 MC generators on the market. *How many can you name?*
- >> 50 combinations of MC generators in a sample.
- ~ 35 K samples generated on ATLAS in the last “campaign” of 2012.
- ~ 7 B events!

Courtesy: Z. Marshall

MONTE CARLO PRODUCTION CHAIN

How much processing time needed for each step?

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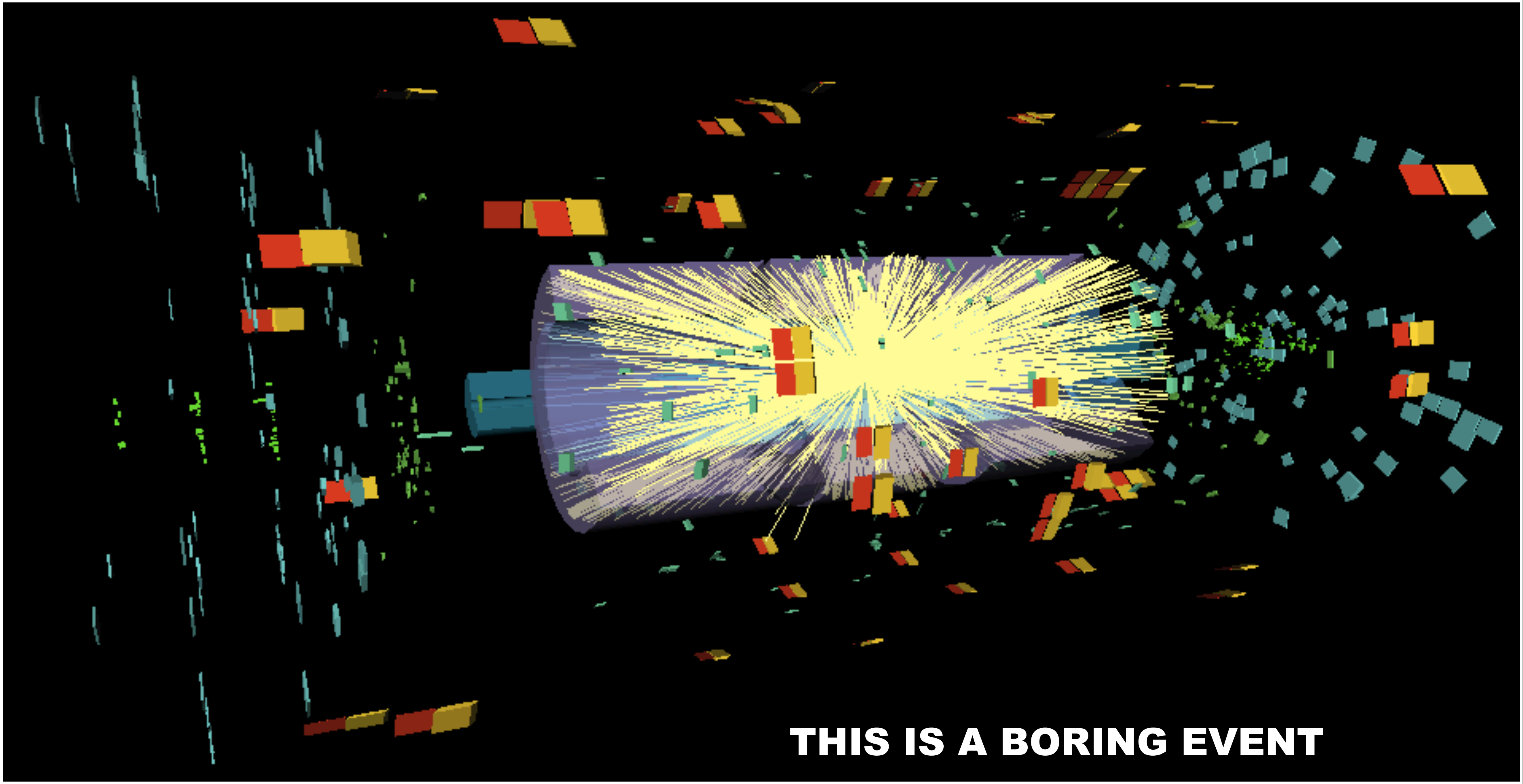
From 1 to 10min / event

Digitization
Translate interactions with detector into realistic signals.

From 5 to 60s / event

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

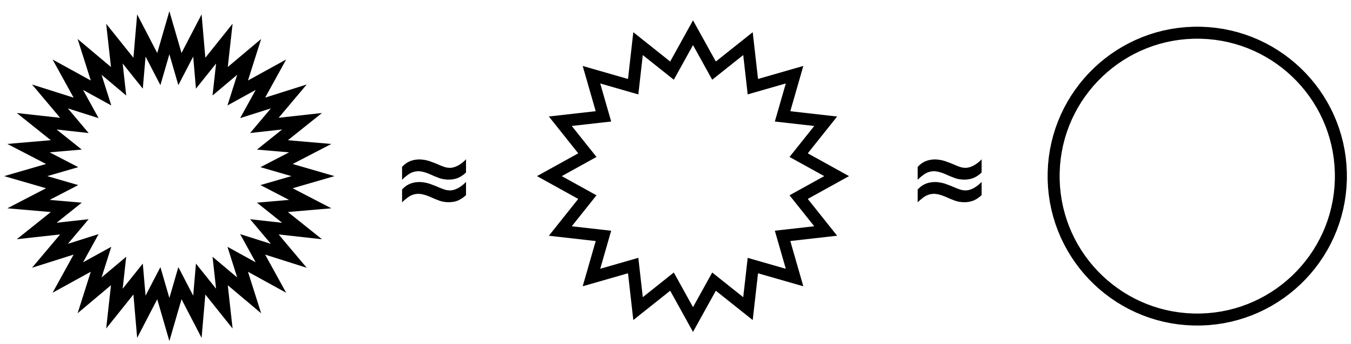
HOW TO SIMULATE THIS?



(Simulation material by Z. Marshal)

SIMULATION – HOW

1. **Break the problem up as much as possible.**
   - Do you understand all the steps of the system?
2. **For each piece of the problem, write some code**
   - Did you remember all the effect for each step?
3. **Figure out what accuracy is needed.**
   - And spend the appropriate time in working out the details.



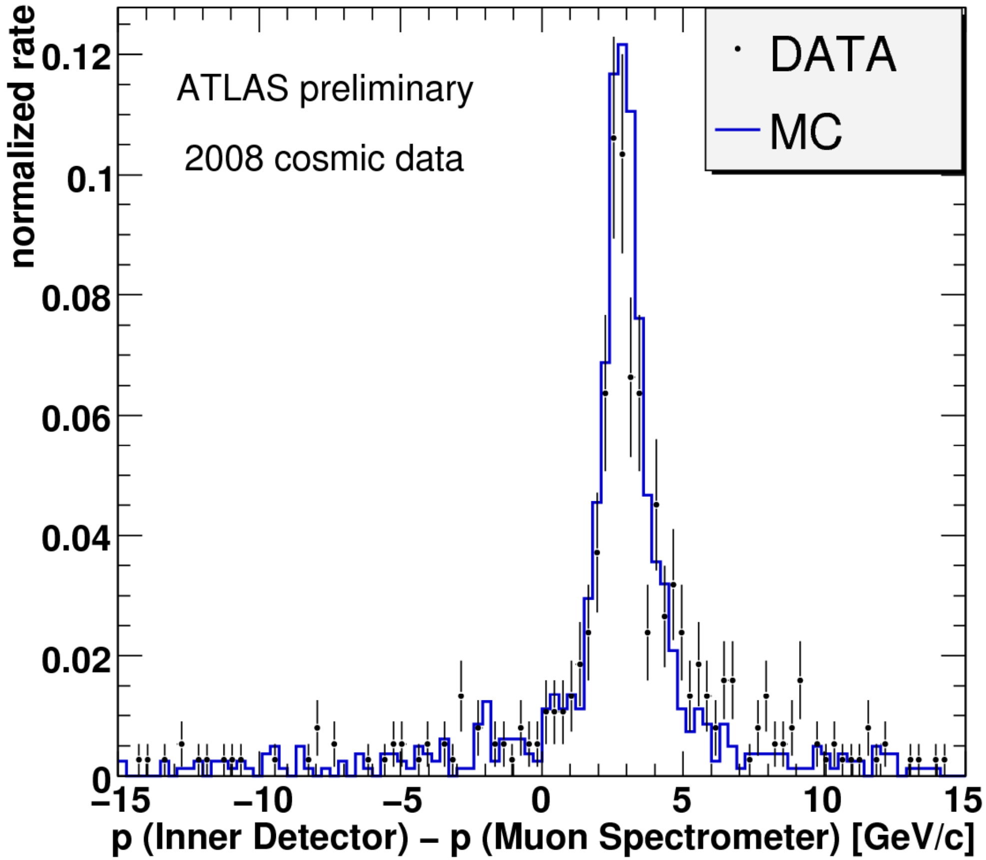
4. **Cross your fingers and press the button.**

HOW DO YOU KNOW IT WORKED?

- When the simulation can recreate something it *was not designed for*, you're doing well…

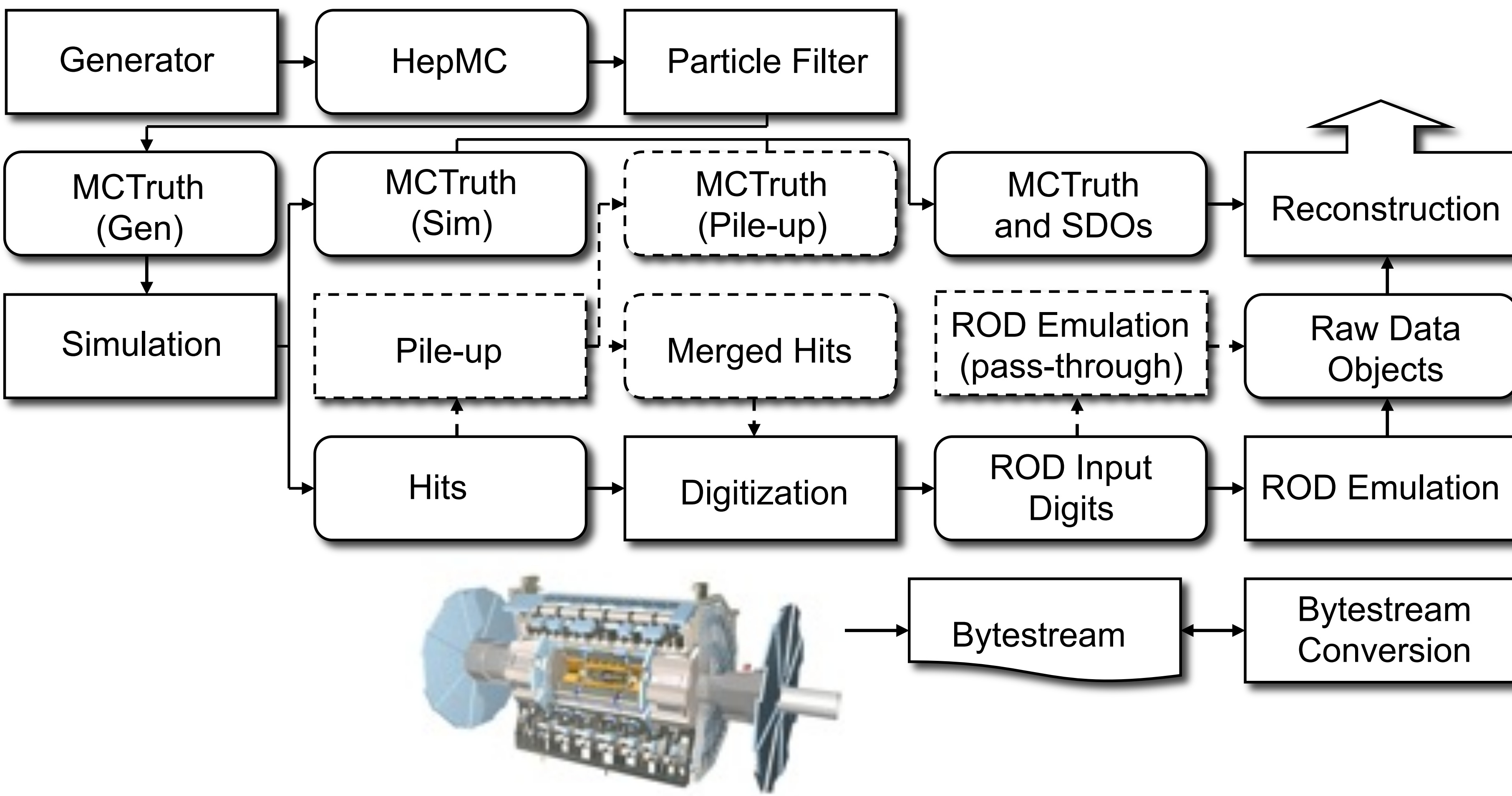
Cosmic rays are one interesting test. Use the simulation to propagate muons from the Earth's surface to the detector!

Here: energy loss in the calorimeter by a muon



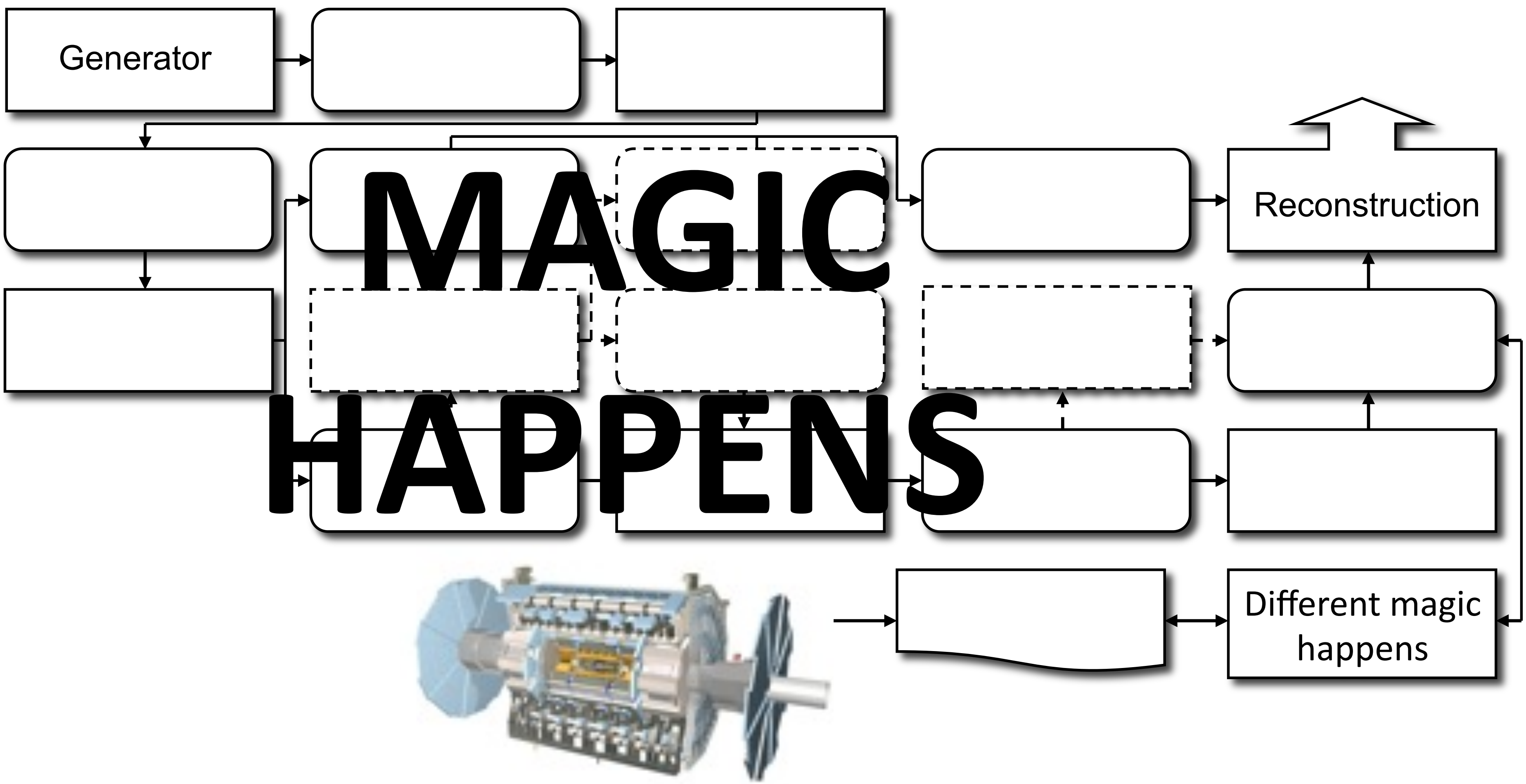
(Simulation material by Z. Marshal)

Our LHC Simulation: The Dream



Our LHC Simulation: The Reality?

This is most people's view of the chain



MONTE CARLO CHAIN

Event Generation
simulate the physics process.

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

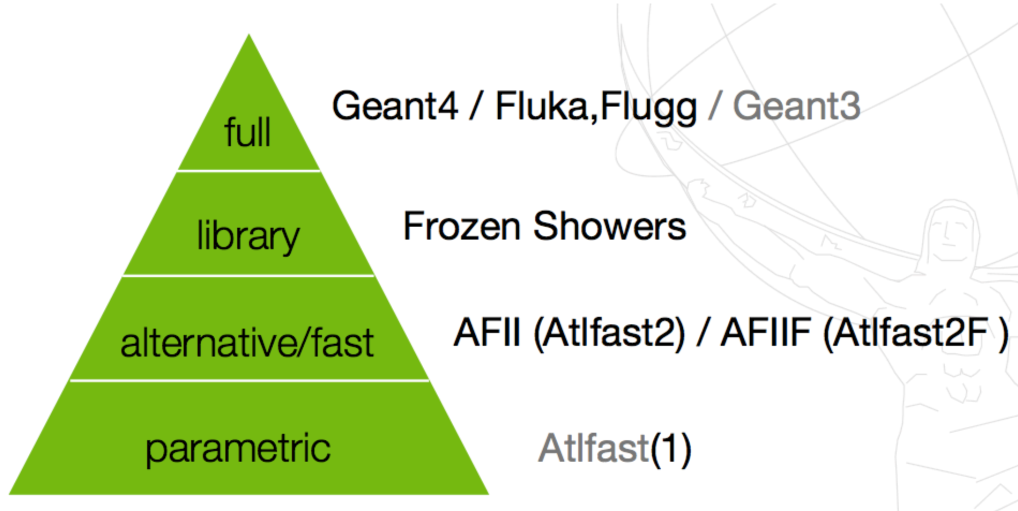
Digitization
Translate interactions with detector into realistic signals.

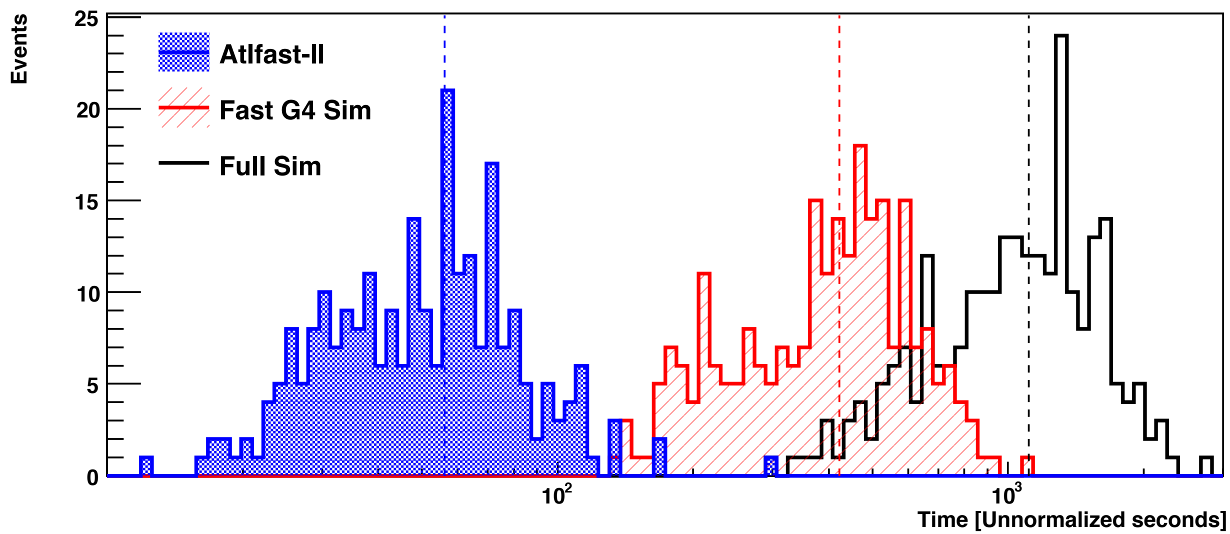
Reconstruction
Go from signals back to particles, as for real data.

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

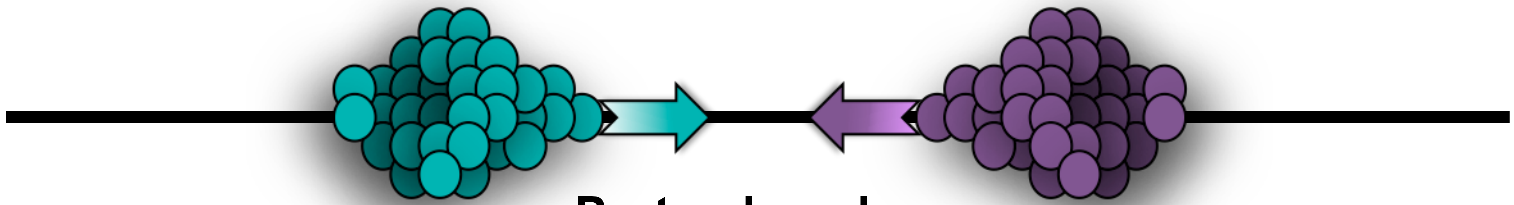
- Event Generation: From < 1s to a few hours / event.
- Detector Simulation: From 1 to 10min / event
- Digitization to Reconstruction: From 5 to 60s / event

SIMULATION – FULL AND FAST





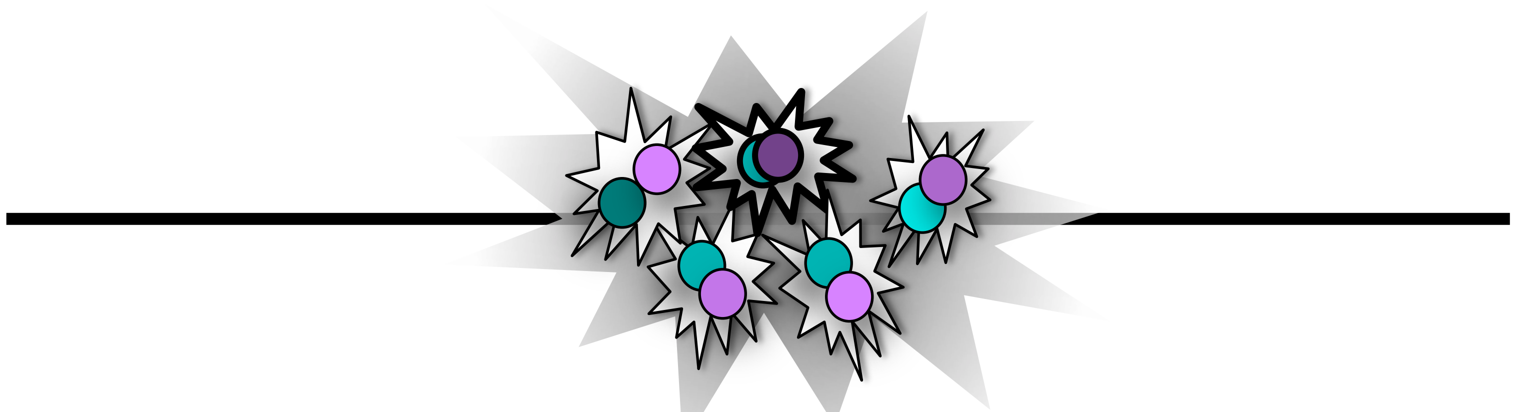
PILE-UP



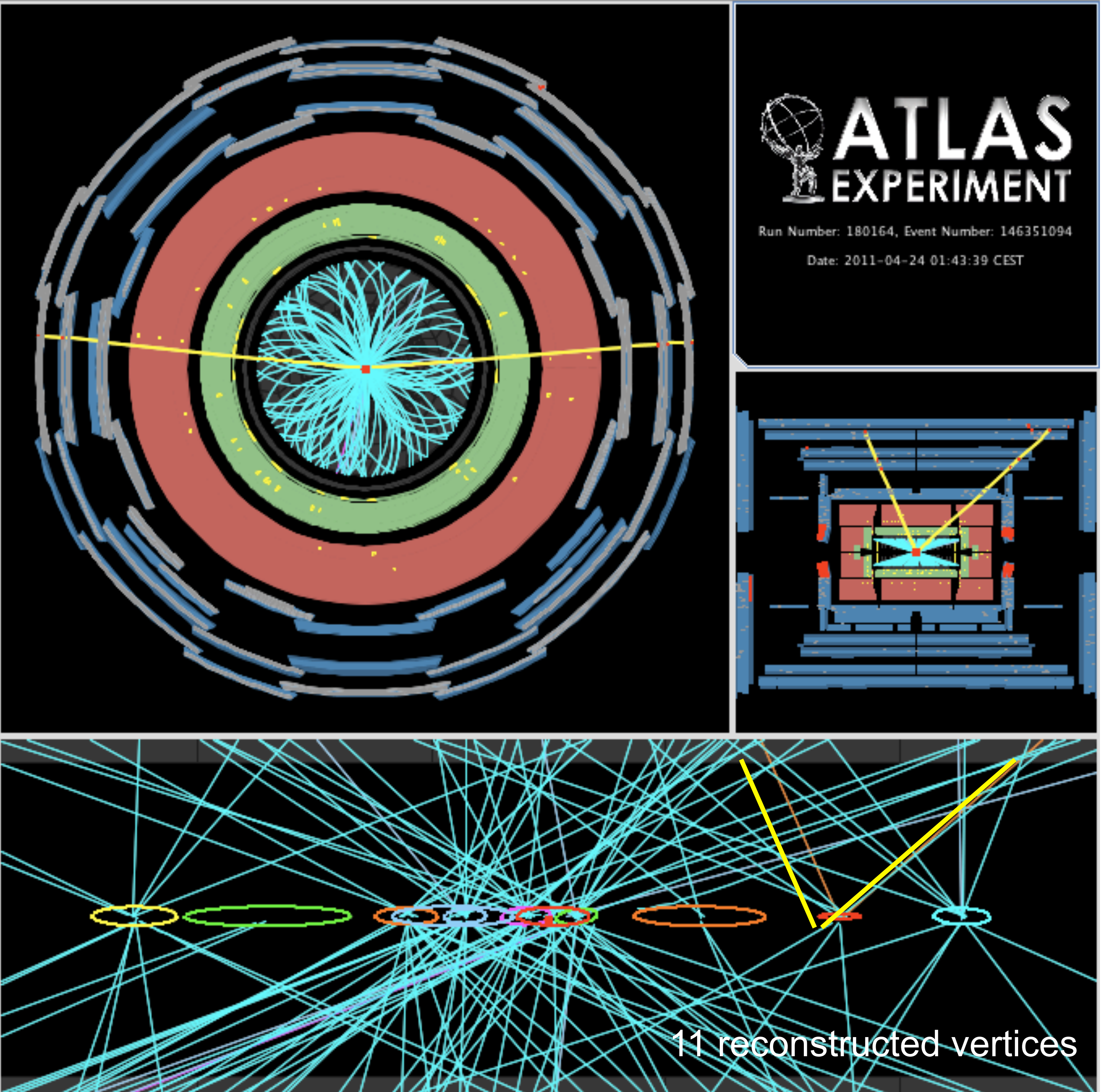
Proton bunches

>10^{11} protons/bunch

(colliding at ~**40MHz in run2)**

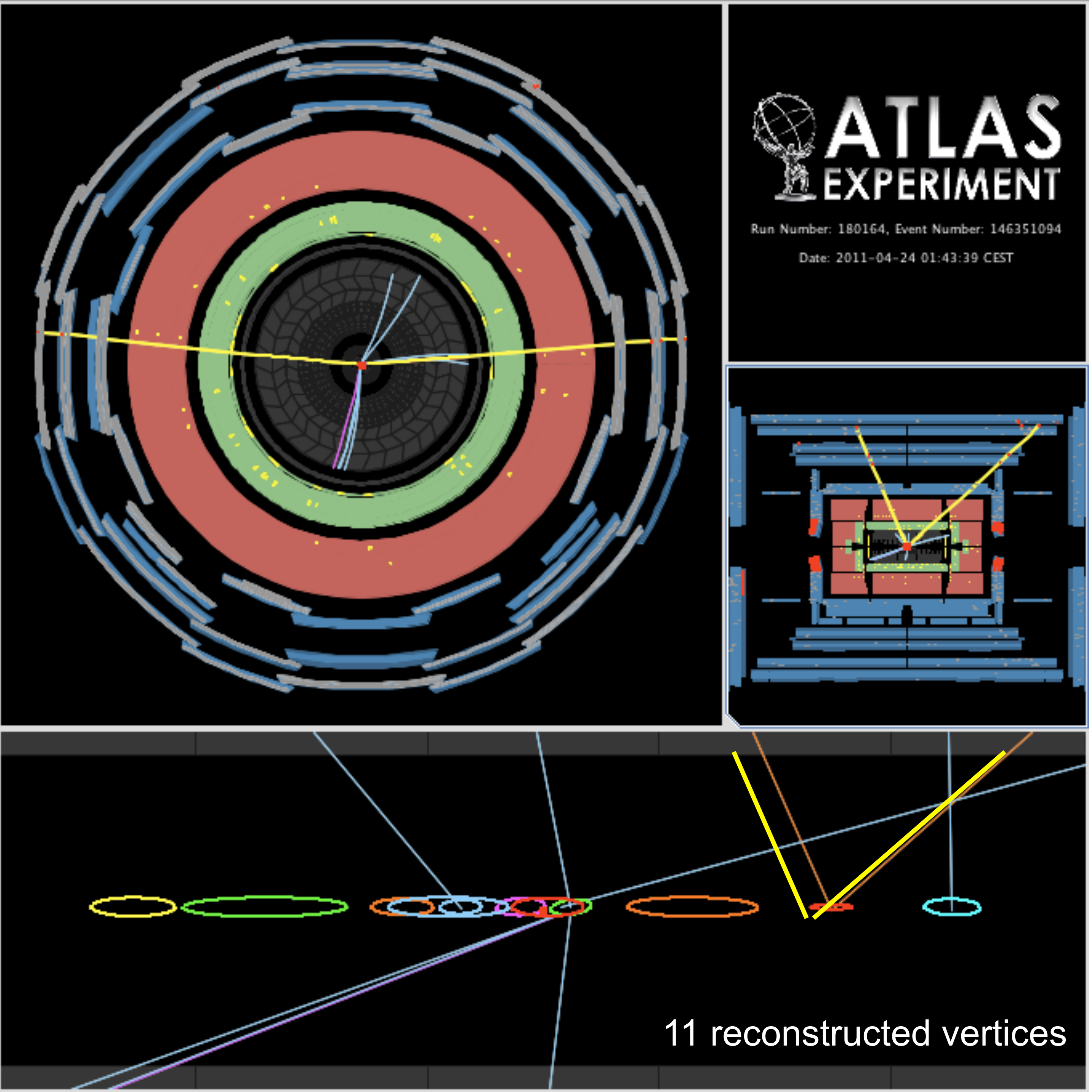


~25 p-p collisions / bunch crossing



Z->μμ event;
2011 data.

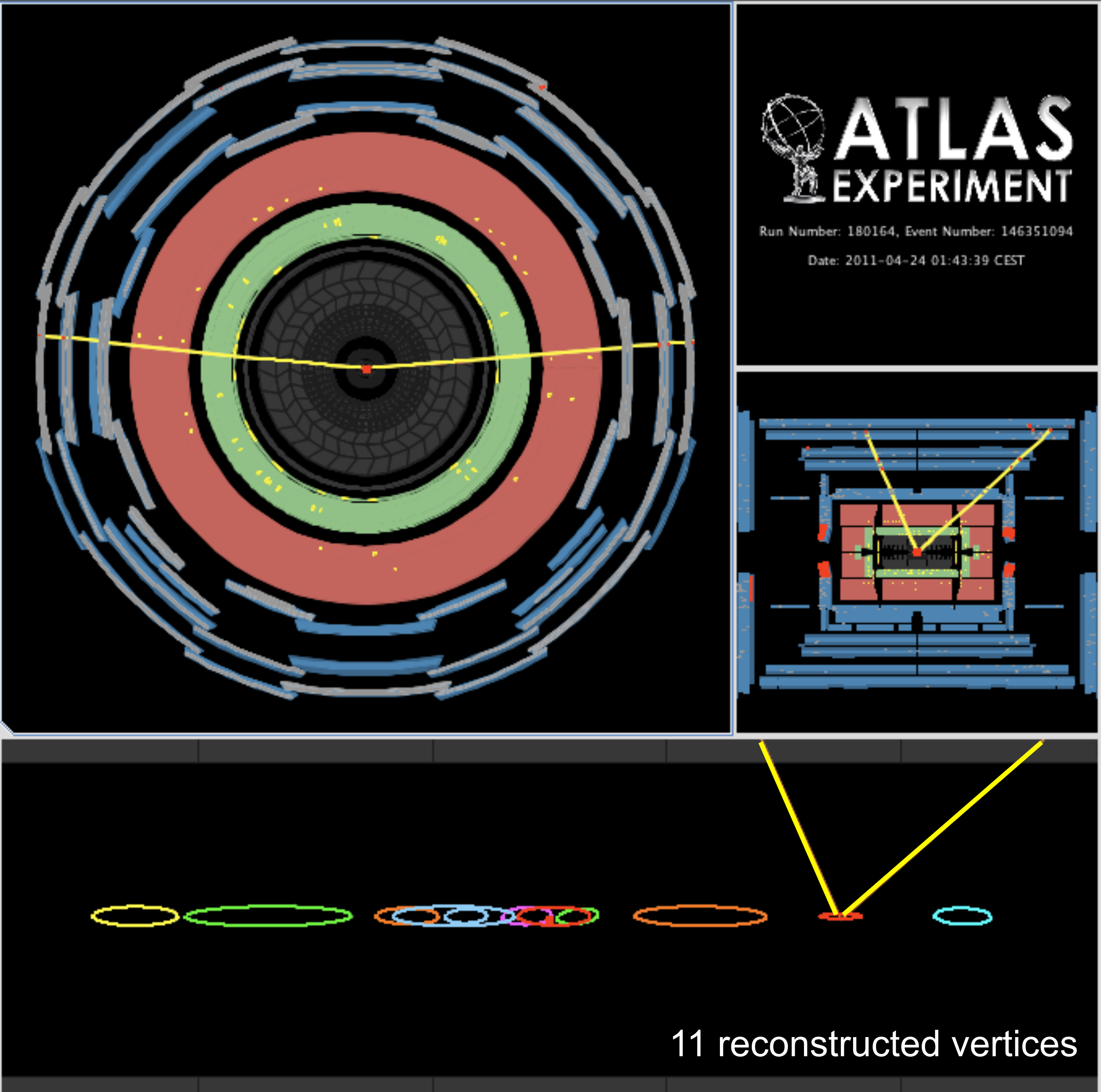
Track pT > 0.5 GeV



Z->μμ event;
2011 data.

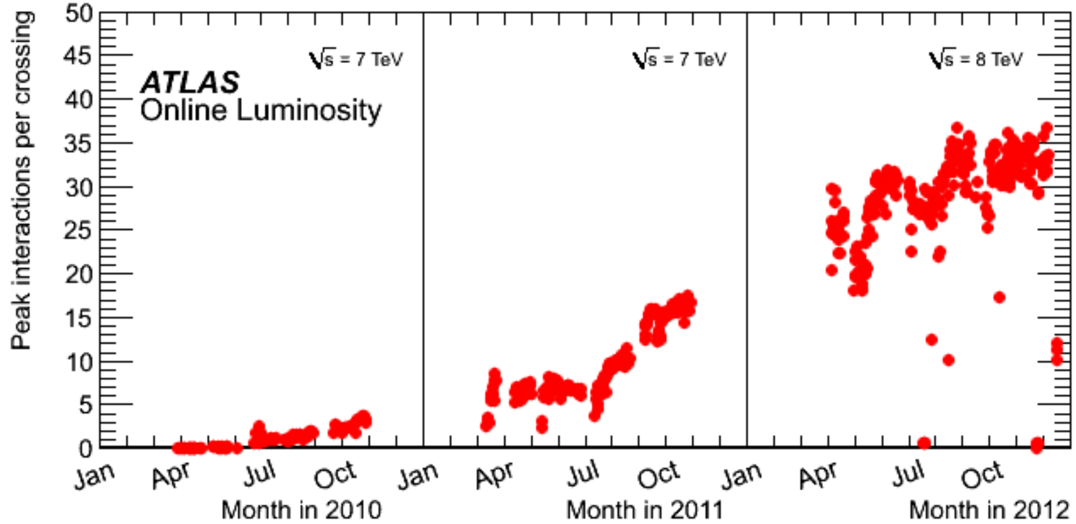
Track pT > 2 GeV

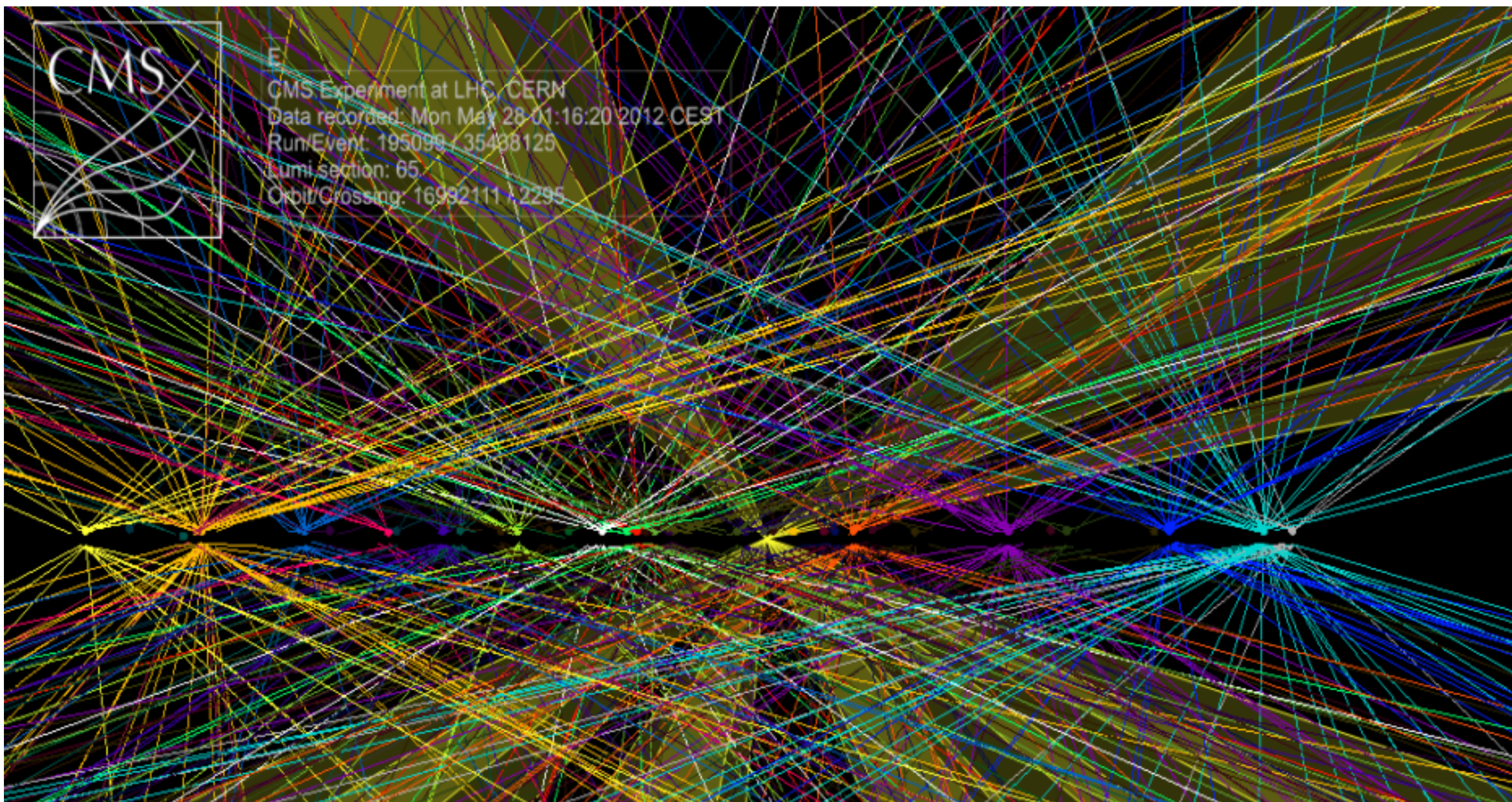
Z->μμ event;
2011 data.



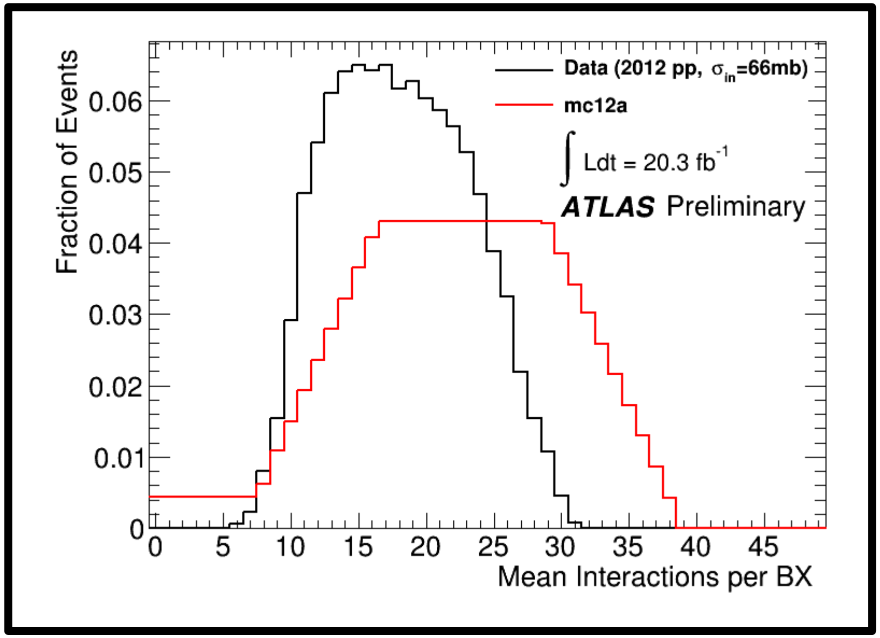
Track pT > 10 GeV

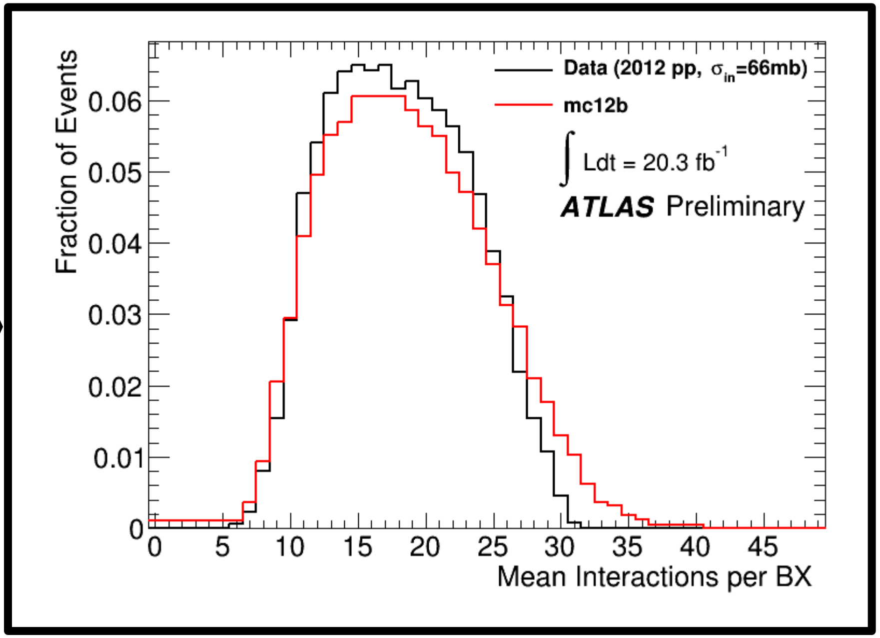
INT / XING


ATLAS
Online Luminosity
√s = 7 TeV
√s = 7 TeV
√s = 8 TeV
Peak interactions per crossing
0
5
10
15
20
25
30
35
40
45
50
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Month in 2010
Month in 2011
Month in 2012

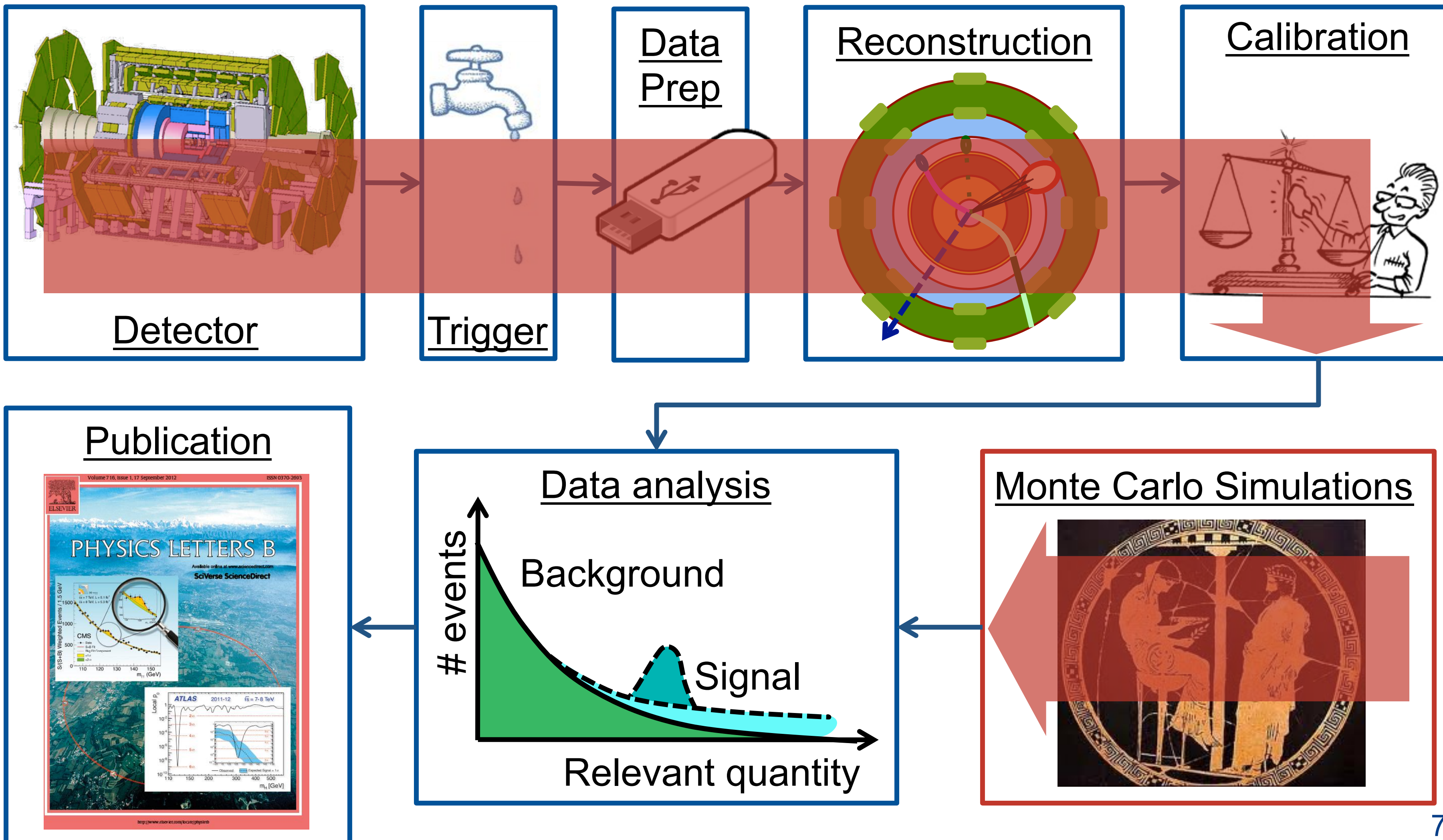

CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295

PILEUP IN SIMULATION



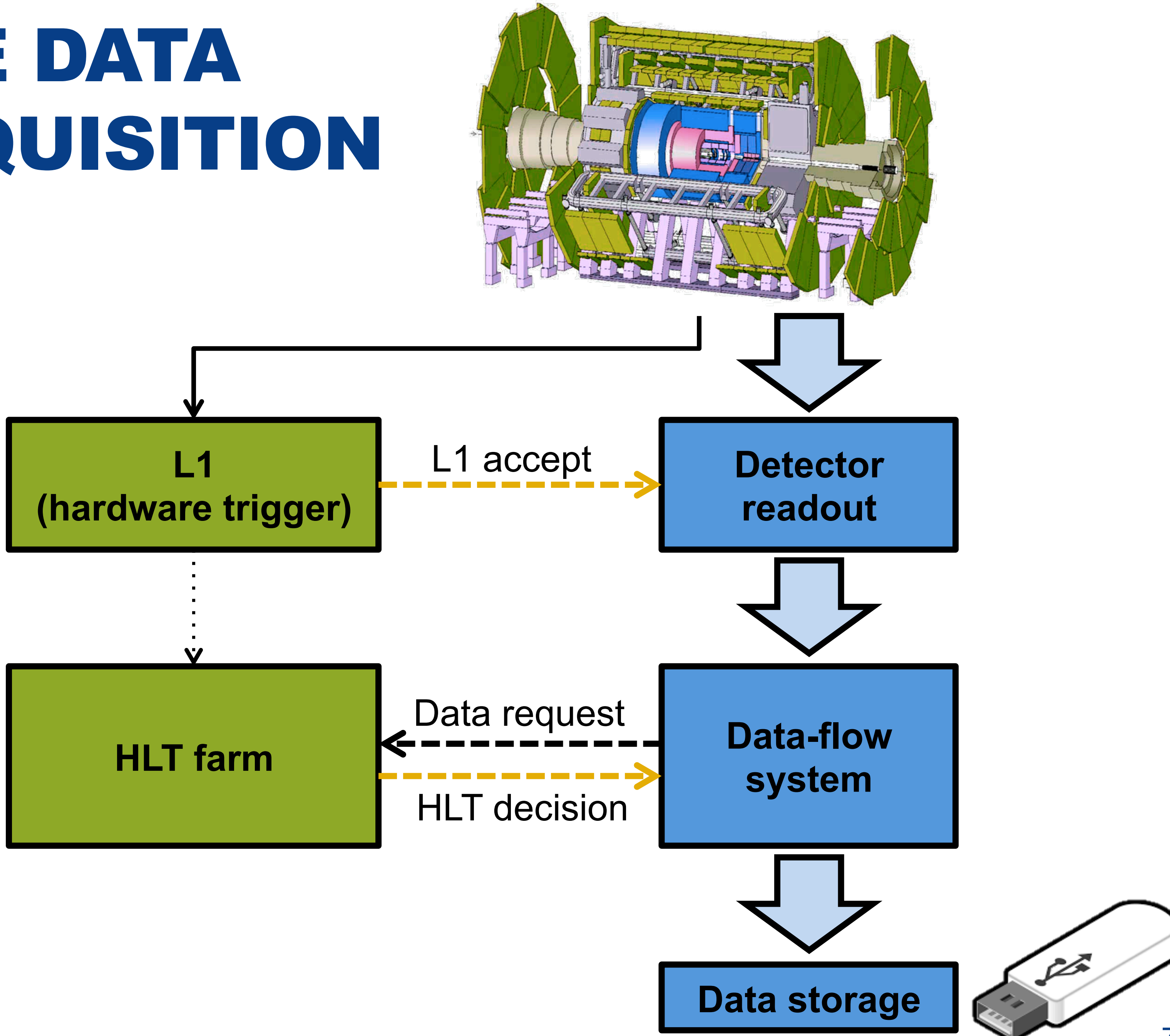


END OF LECTURE 1

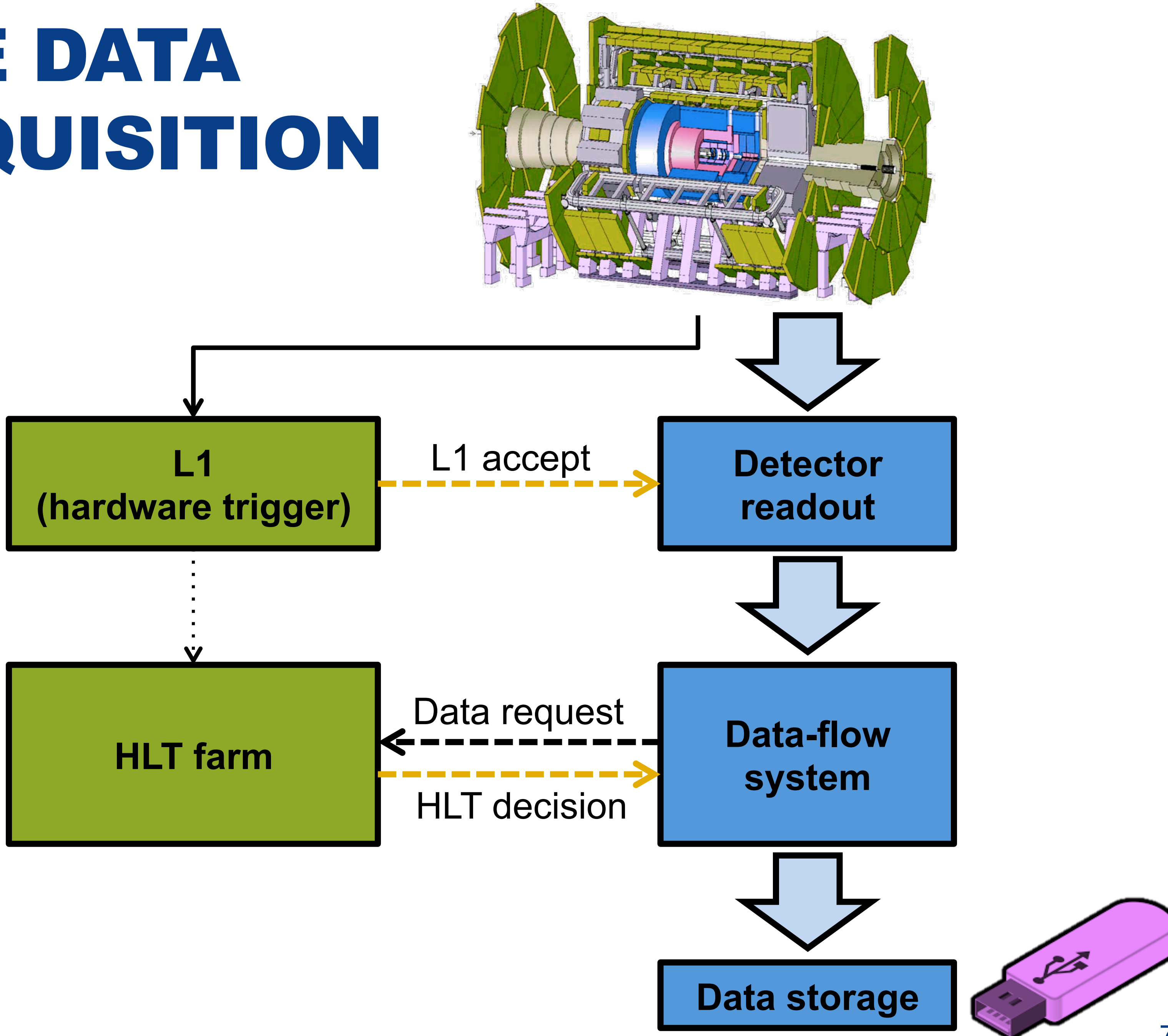


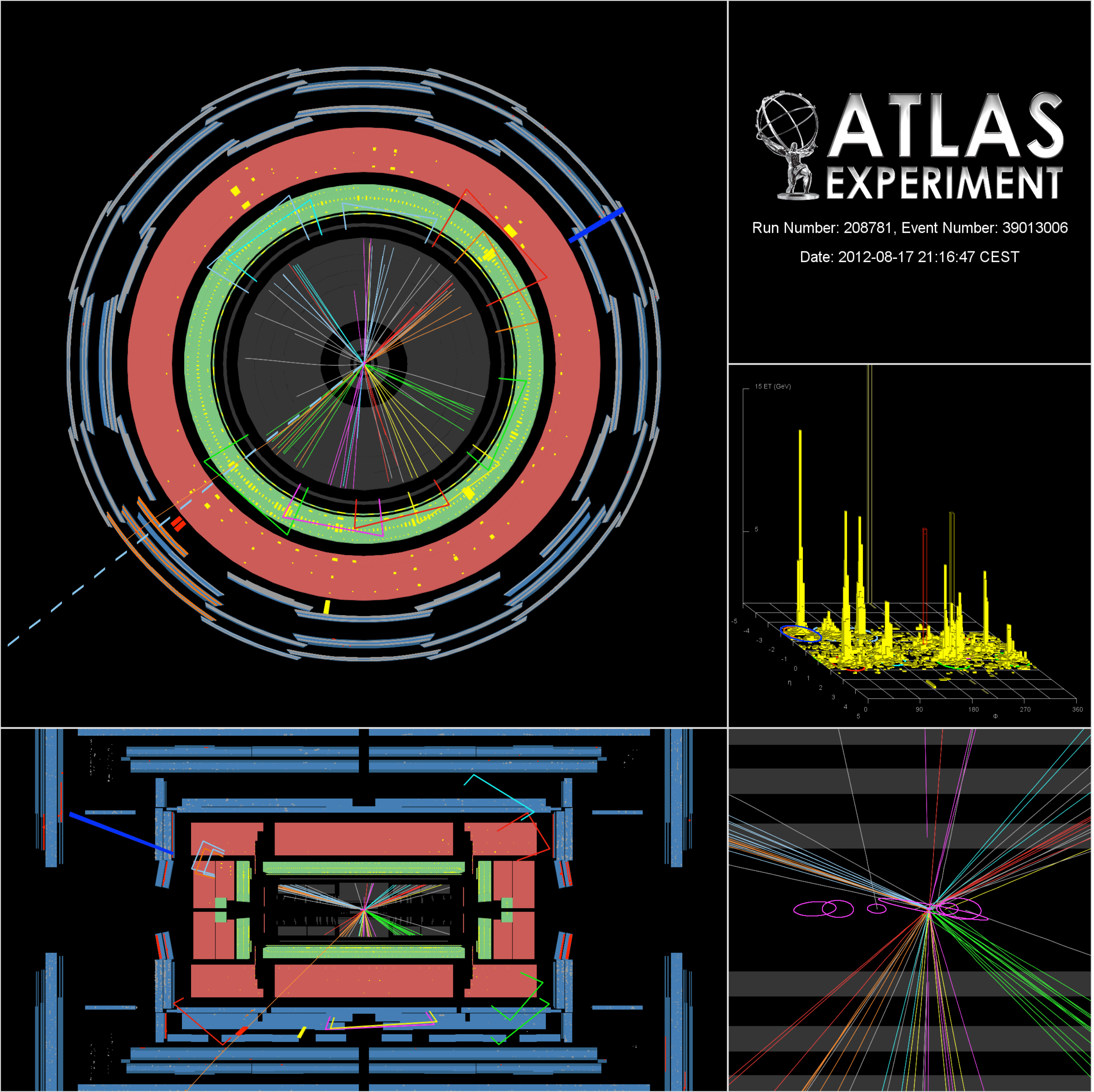
BACKUP

THE DATA ACQUISITION



THE DATA ACQUISITION



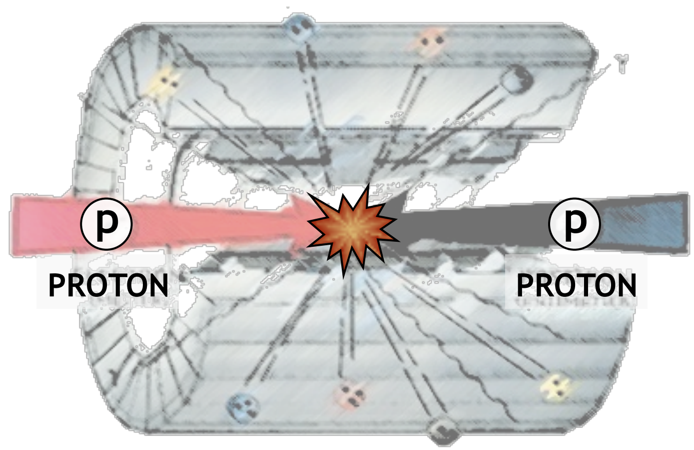


10 jets

with pT > 50GeV

ME_T = 120 GeV

IN A P-P COLLISION



TRIGGER MENUS FOR SUSY

Selection	EF trigger election	EF Avg. Rate (Hz) L_{avrg}=5e33/cm^{2}s
Single jet & E_T^{miss}	Jet E_T >145 GeV & EF-only E_T^{miss} >70 GeV	8
Single jet & E_T^{miss} & $\Delta\phi$(jet,E_T^{miss})	Jet E_T >80 GeV & E_T^{miss} >70 GeV & $\Delta\phi$ >1.0 rad	8
H_T	>700 GeV	8
Single electron & E_T^{miss}	Electron p_T >25 GeV & EF-only E_T^{miss} >35 GeV	26
Single muon & single jet & E_T^{miss}	Muon p_T >24 GeV & jet E_T >65 GeV & EF-only E_T^{miss} >40 GeV	15
Single photon & E_T^{miss}	Photon p_T >40 GeV & EF-only E_T^{miss} >60 GeV	5
3 electrons	p_T > 18, 2×7 GeV	<1
3 muons	p_T > 18, 2×4 GeV	<1
3 electrons & muons	p_T > 2×7 (e), 6 (μ) GeV	<1
	p_T > 7 (e), 2×6 (μ) GeV	<1

‘DELAYED’ TRIGGERS

Trigger	EF trigger Selection	
	Prompt Stream	**Delayed Stream**
Multi-jets	4×80 GeV	4×65 GeV
	5×55 GeV	5×45 GeV
	6×45 GeV	
H_T	700 GeV	500 GeV
Single jet (R = 1.0)	460 GeV	360 GeV
E_T^{miss}	80 GeV	60 GeV

THE ATLAS TRIGGER SYSTEM

Rate (2012 conditions)

Hardware

20 MHz
Bunch crossing rate

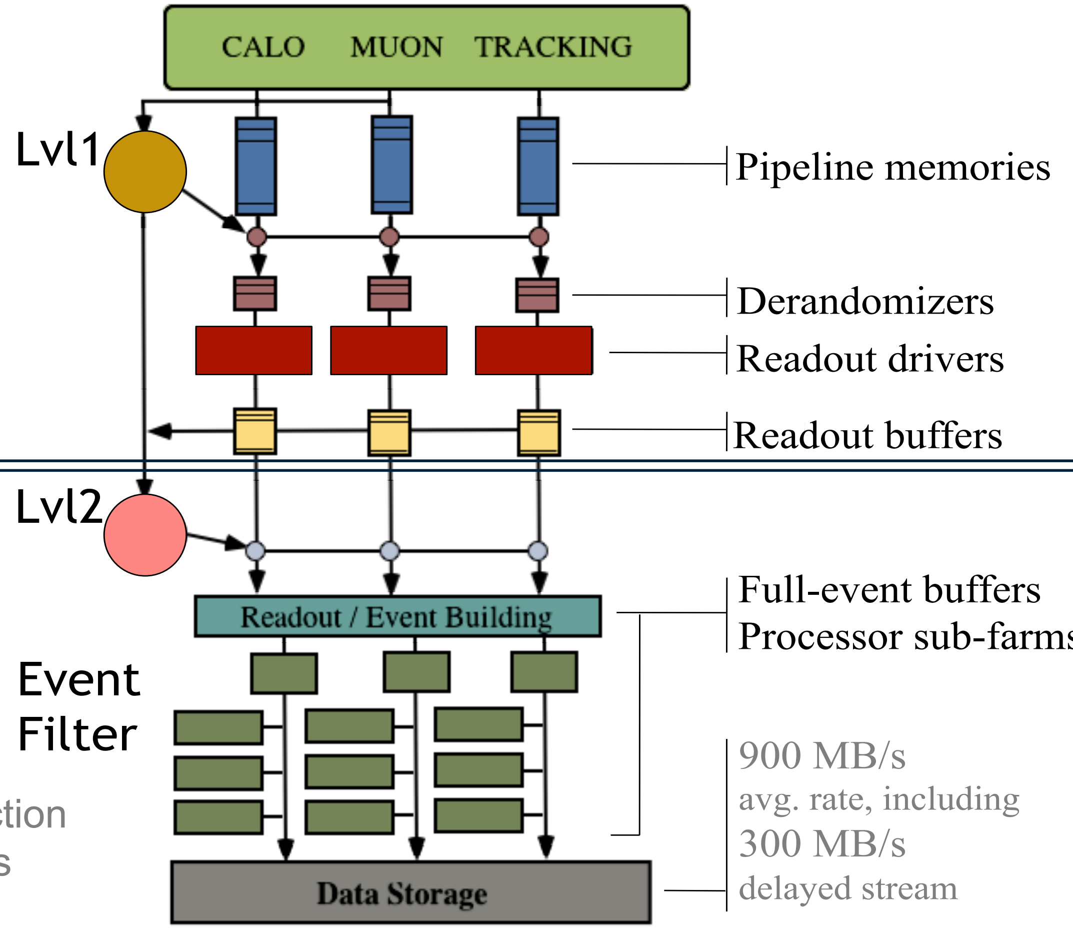
6.4×10^8
Interactions/s

75 kHz
Peak rate

Software

6 kHz
Peak rate

600 Hz
Avg. rate, including
200 Hz delayed stream
(stored for later reconstruction
when computing resources
available)

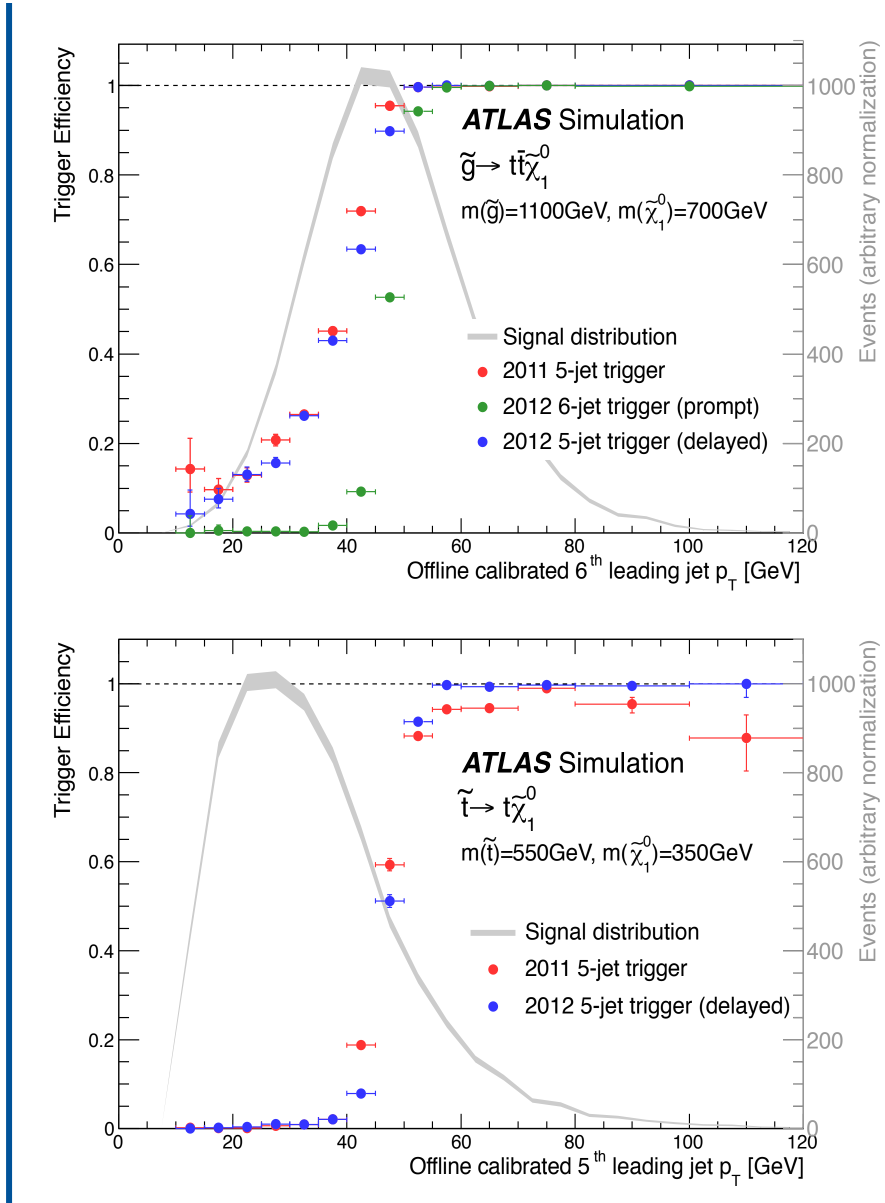


TRIGGER

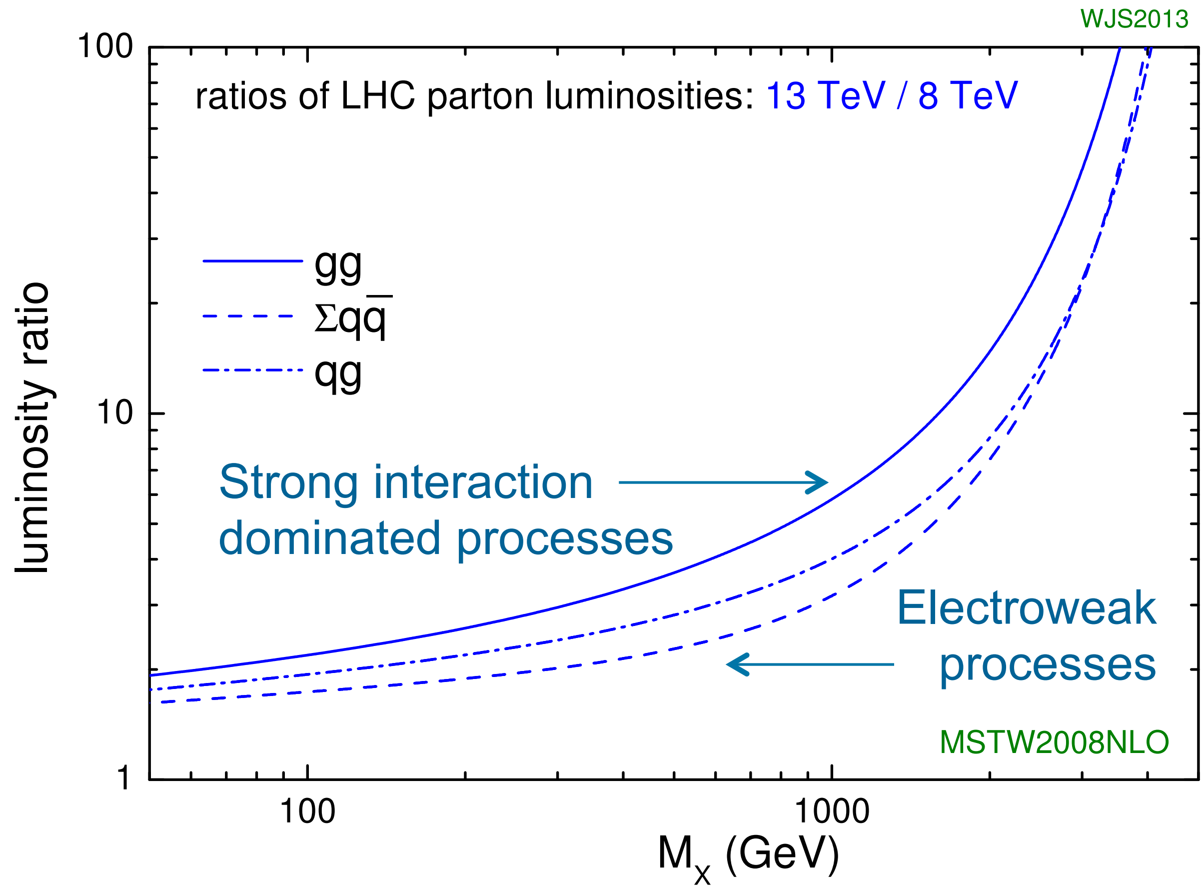
Signal triggers		
Jet Multiplicity	pT cut	|η|
6	45	3.2
5	55	

Background/support triggers	
Type	Purpose
Multijet (prescaled)	Efficiencies & Control regions
Single lepton	Control regions

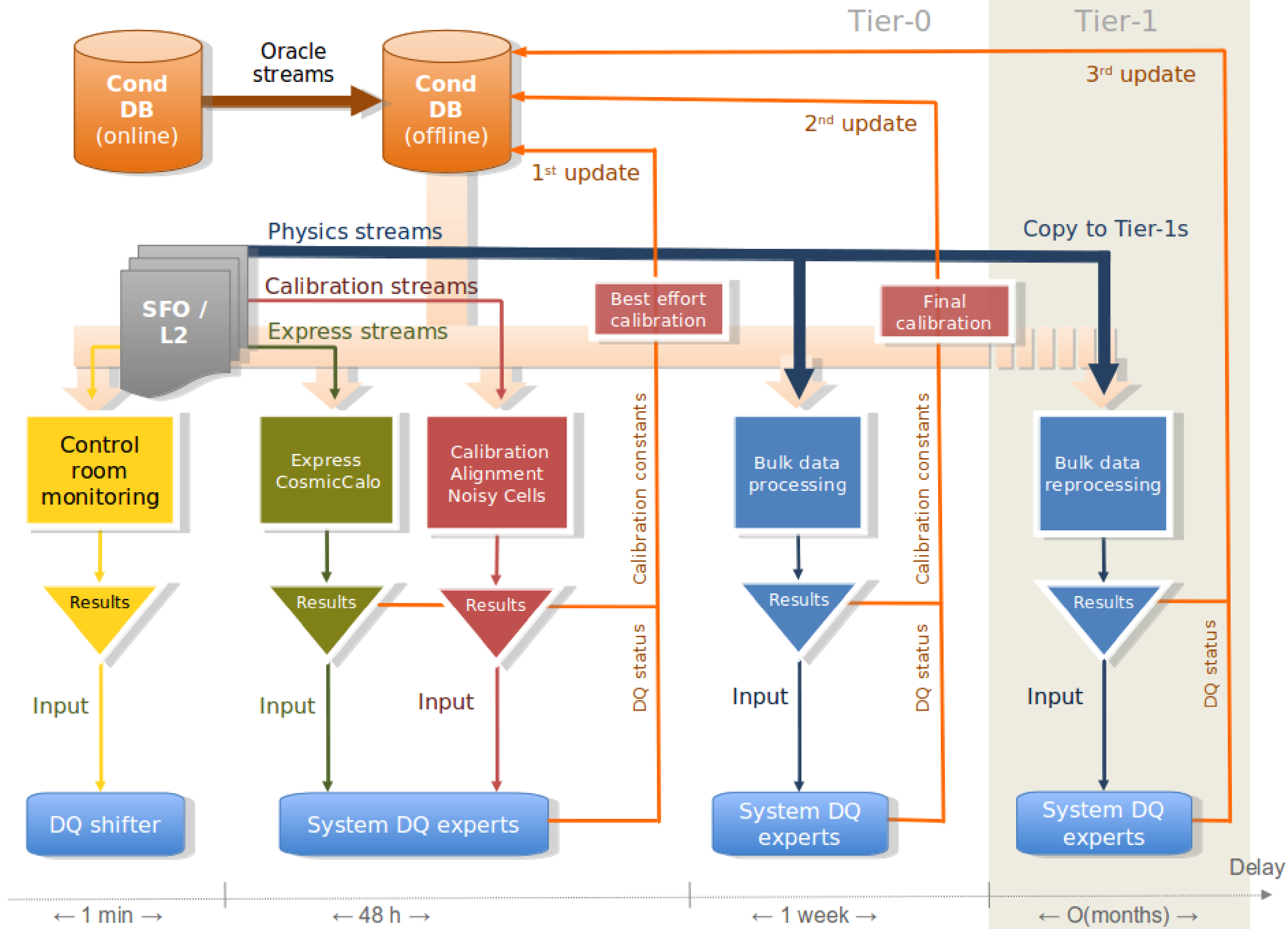
Multijet trigger improvements in 2012



THE BENEFITS



From Eric Torrence



DATA QUALITY – DEFECTS