Intro to LHC physics

First Network School on

Collider Physics and Machine Learning

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January 2023

SMARTHEP

REAL-TIME ANALYSIS FOR
SCIENCE AND INDUSTRY

What will this lecture be about?

Introduction

- Definitions and basic concepts

Input to the physics

- The data: trigger, data preparation
- The theory: Monte carlo simulations
- Reconstruction, or how to translate detector signals to particles

Physics analyses

- Through example, step-by-step
- Discussion of analysis methods

SMARTHEP
REAL-TIME ANALYSIS FOR SCIENCE AND INDUSTRY

Is there a topic you would like to add to this material?
If so: please let me know at the end of this lecture and I will see if I can add it!

Important Disclaimers

A

- Strong bias to
  - LHC physics: the most challenging in terms of complexity!
  - ATLAS: personnal history
- Will give some examples from other experiments (and colliders)

B

- Diverse audience: the lecture might be too basic for some
- Let me know if you have specific topics you would like to see!

PART 1

What will this lecture be about?

Introduction

- **Definitions and basic concepts**

Input to the physics

- **The data: trigger**, data preparation
- The theory: Monte carlo simulations
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- Through example, step-by-step
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Introduction

$$
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)
$$

Gauge term

Interactions between fermions

Mass for fermions

Mass for bosons

Hermitian conjugate; Keeps the theory “sound”

Higgs potential

Also: https://iopscience.iop.org/article/10.1088/1361-6552/aa5b25/pdf

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

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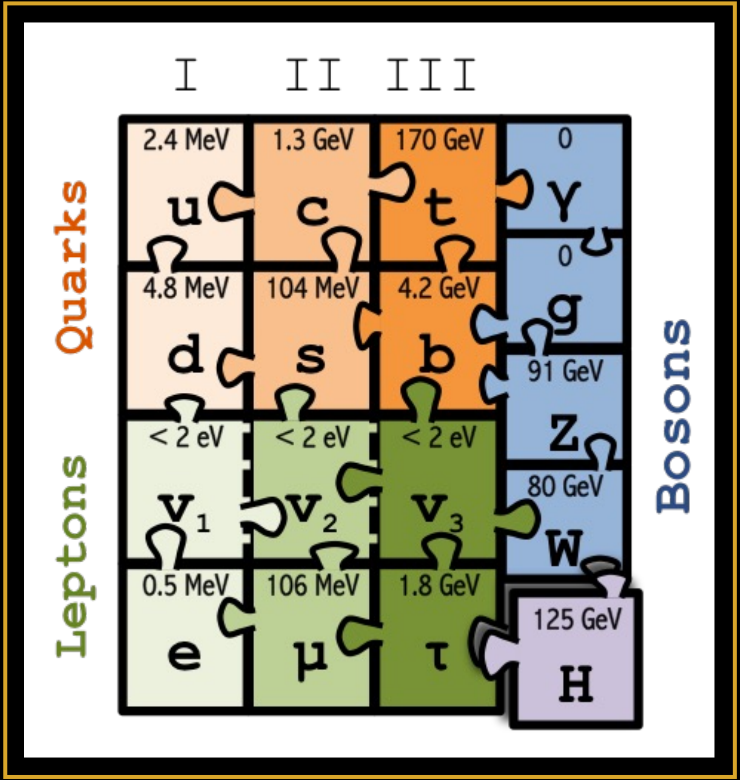


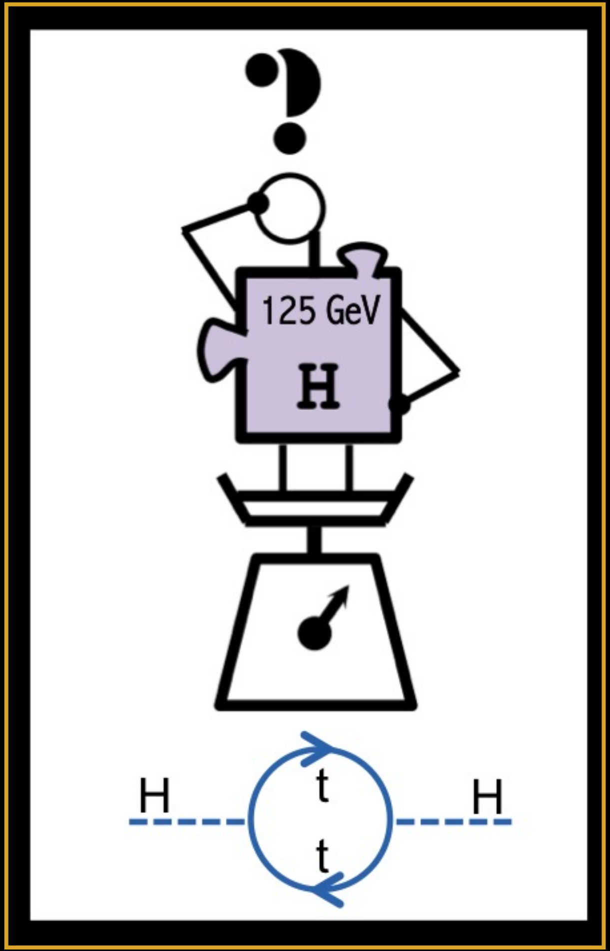
— Why are there three families of quarks and leptons?

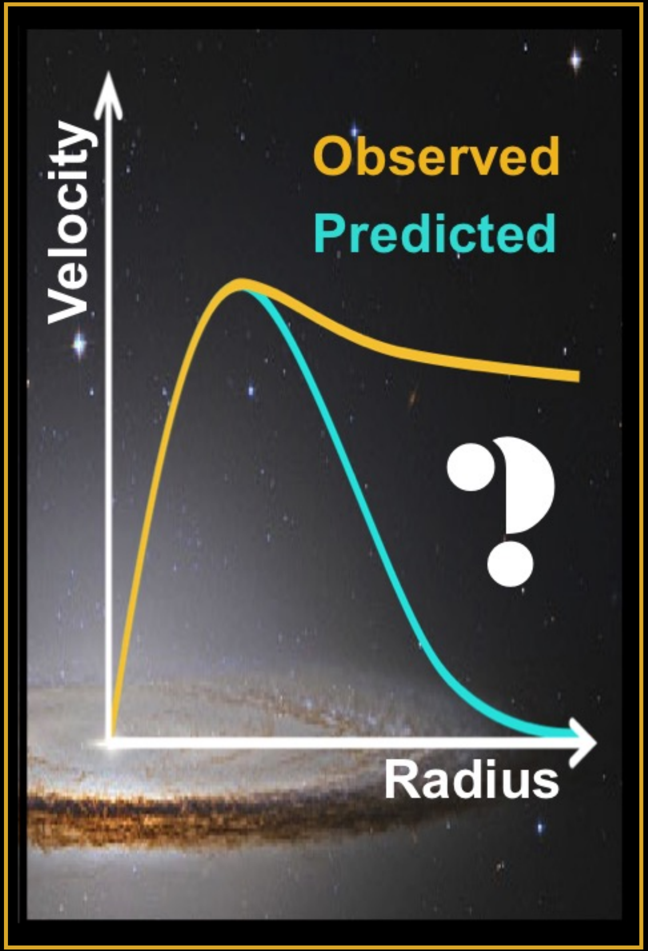
— What is the origin of the different quark and lepton masses?

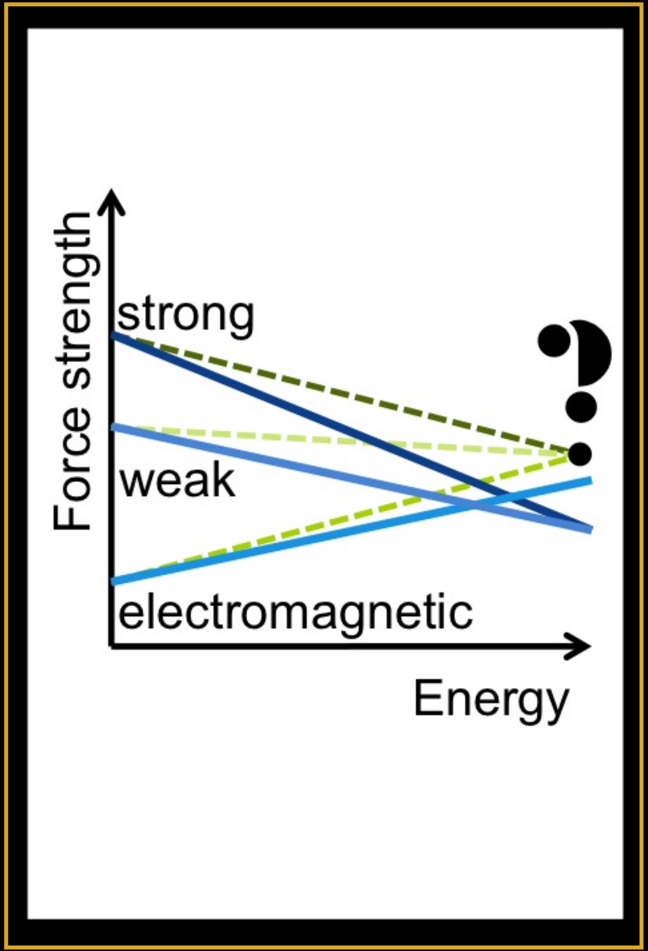
— Is there a further substructure of fundamental particles?

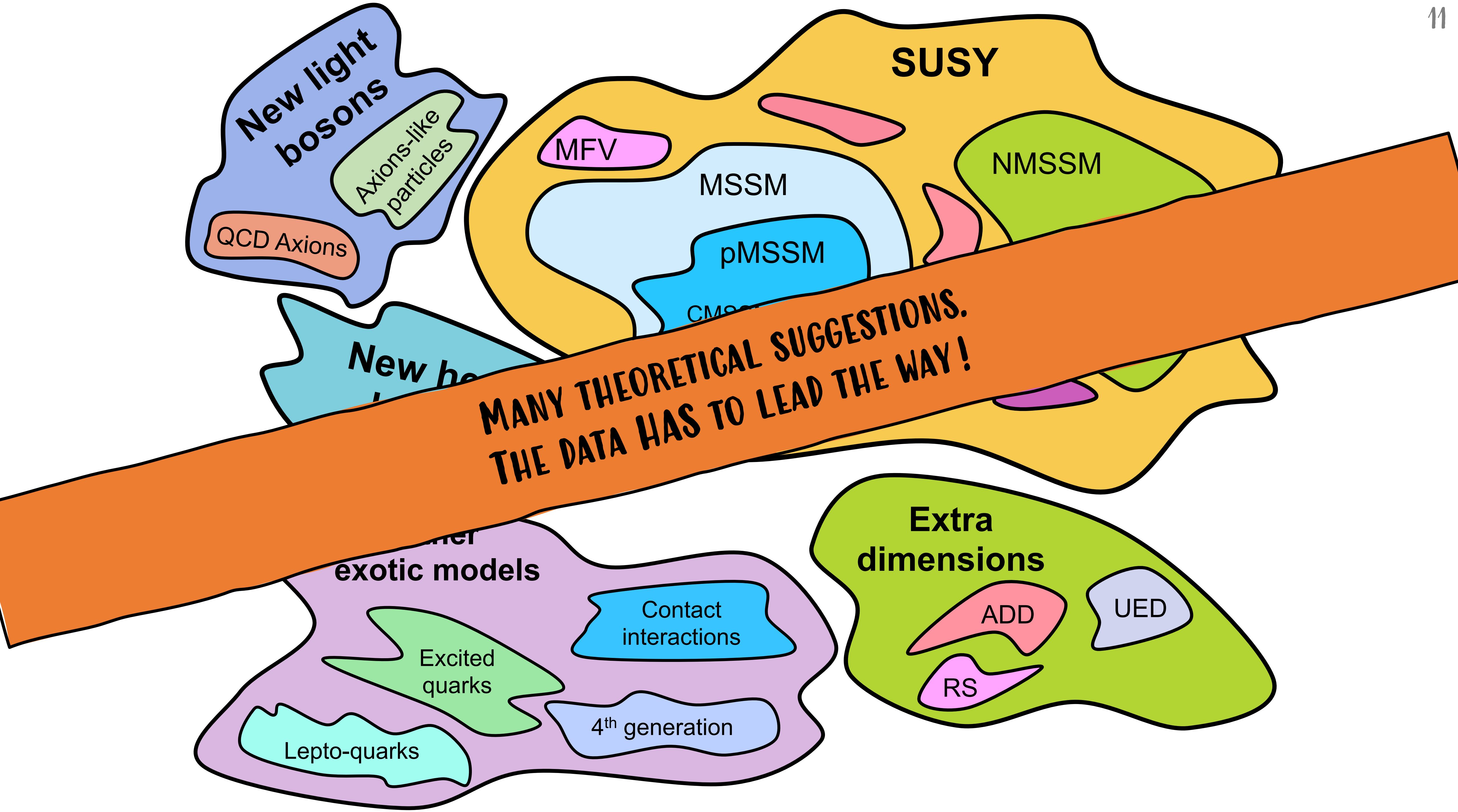
— Are there more fundamental forces at the microscopic level?

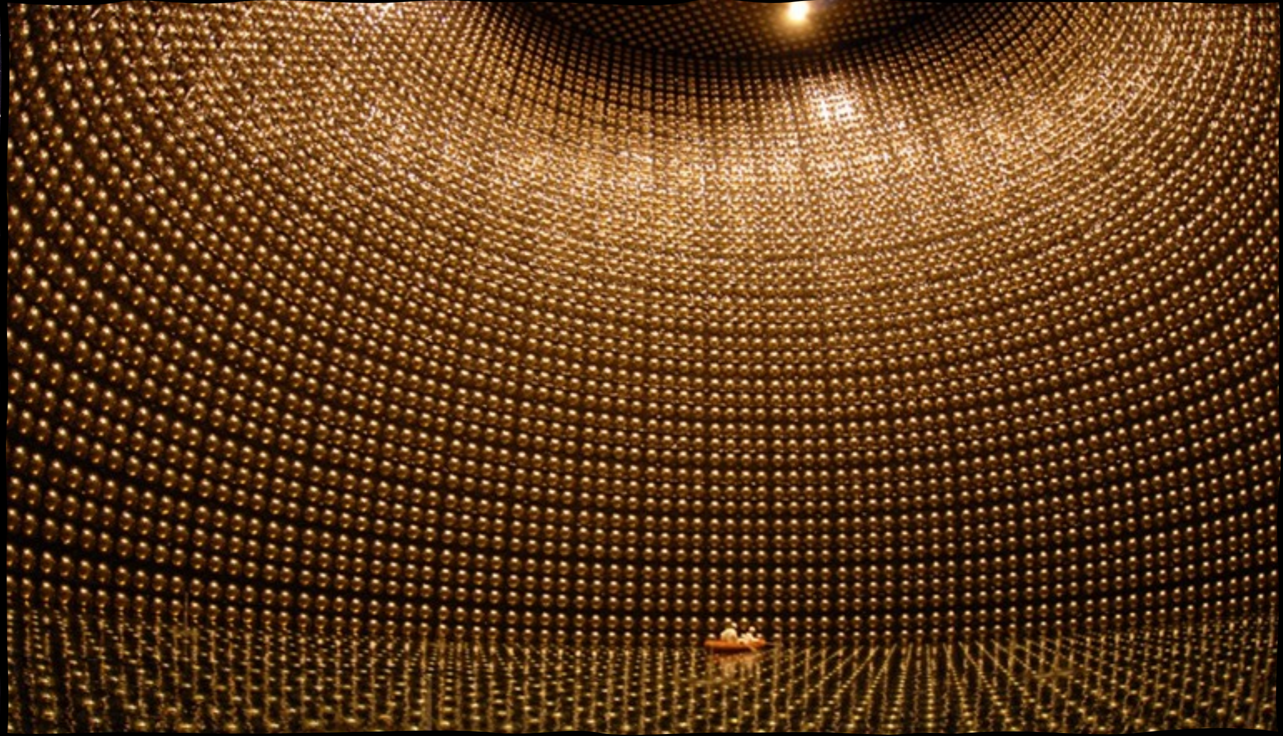
— What is the nature of the Higgs boson?

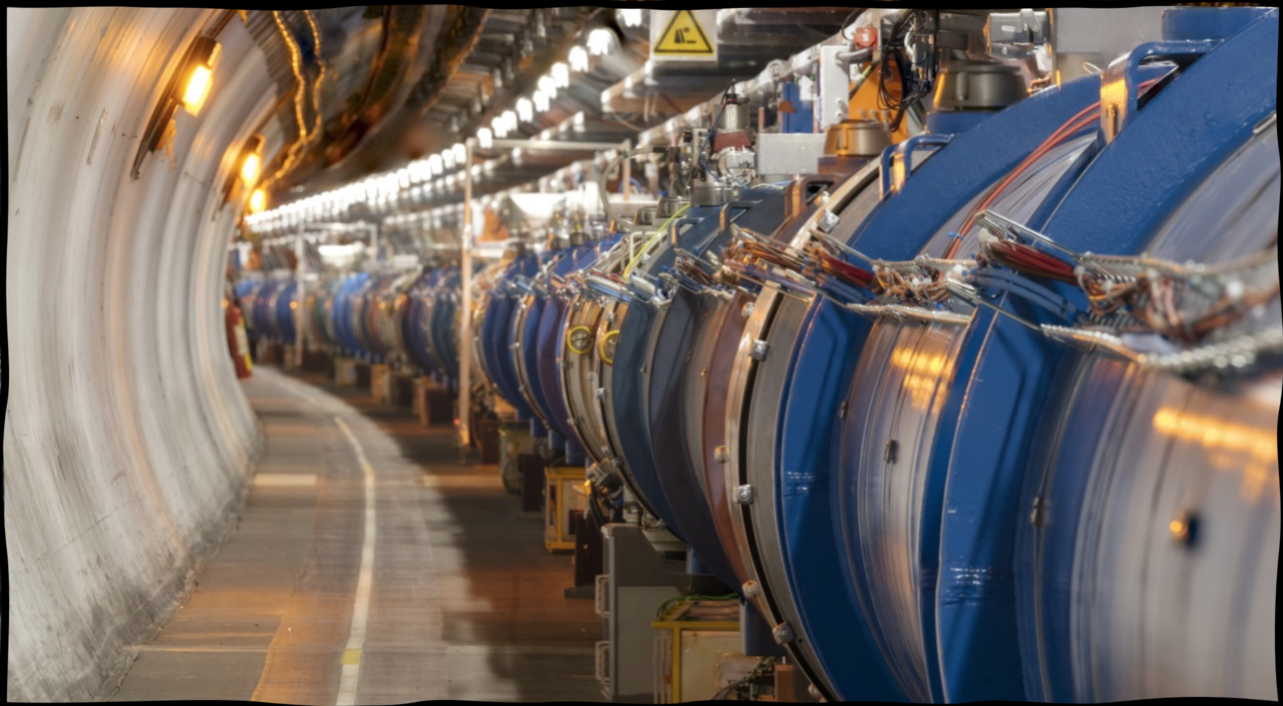

125 GeV
H
H
t
t
H


Velocity
Observed
Predicted
Radius


Force strength
strong
weak
electromagnetic
Energy


New light bosons
Axions-like particles
QCD Axions
SUSY
MFV
MSSM
pMSSM
NMSSM
New
Many theoretical suggestions.
The data has to lead the way!
exotic models
Contact interactions
Excited quarks
4th generation
Lepto-quarks
Extra dimensions
ADD
UED
RS



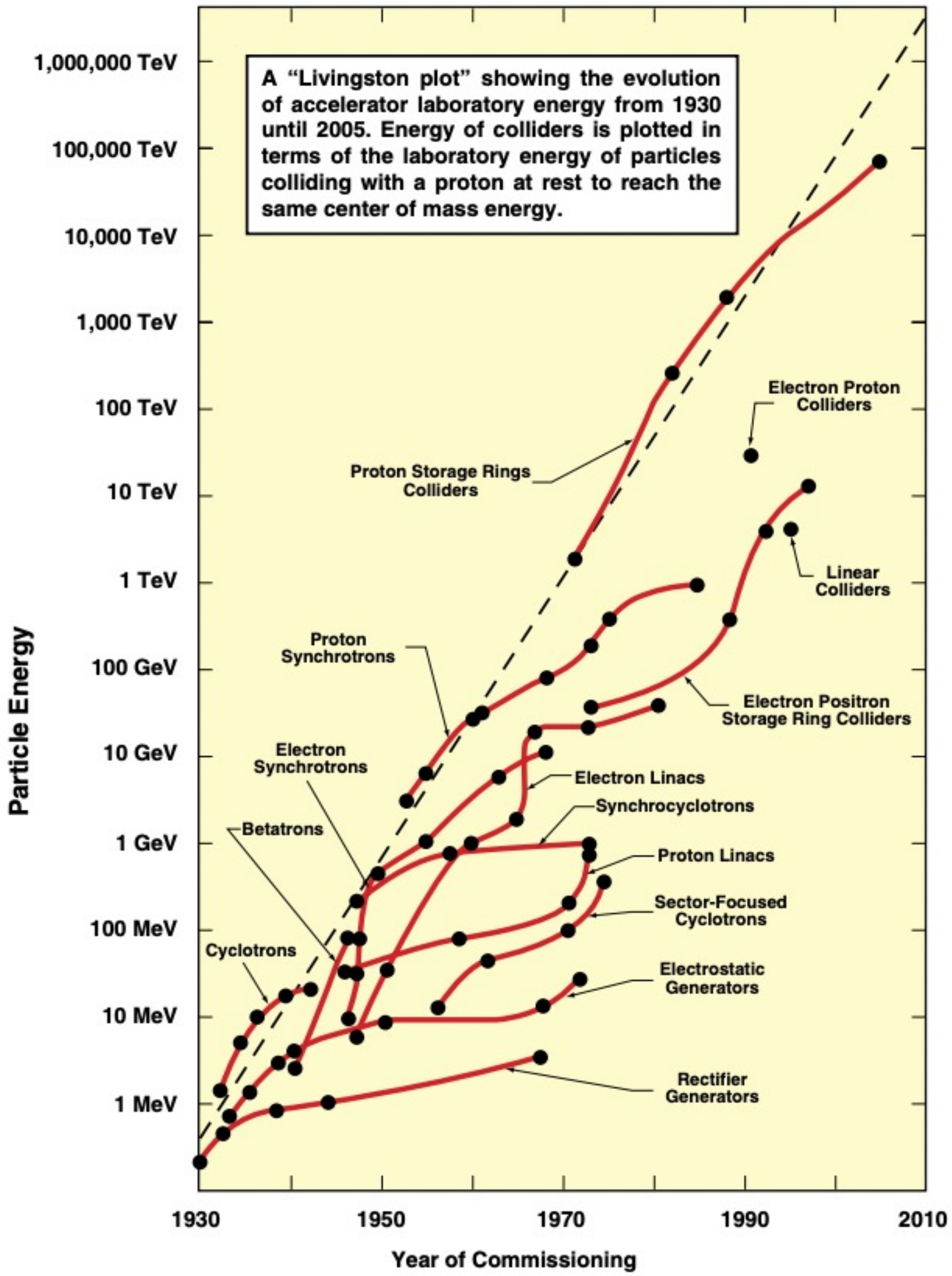
NEW DIRECTIONS IN SCIENCE ARE LAUNCHED BY NEW TOOLS MUCH MORE OFTEN THAN BY NEW CONCEPTS.

THE EFFECT OF A CONCEPT-DRIVEN REVOLUTION IS TO EXPLAIN OLD THINGS IN NEW WAYS.

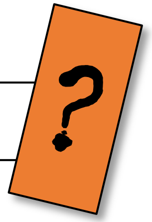
THE EFFECT OF A TOOL-DRIVEN REVOLUTION IS TO DISCOVER NEW THINGS THAT HAVE TO BE EXPLAINED.

Freeman Dyson

A “Livingston plot” showing accelerator energy versus time, updated to include machines that came on line after 1990s. The filled circles indicate new or upgraded accelerators of each type.



Why ~ 100 000 TeV for LHC?



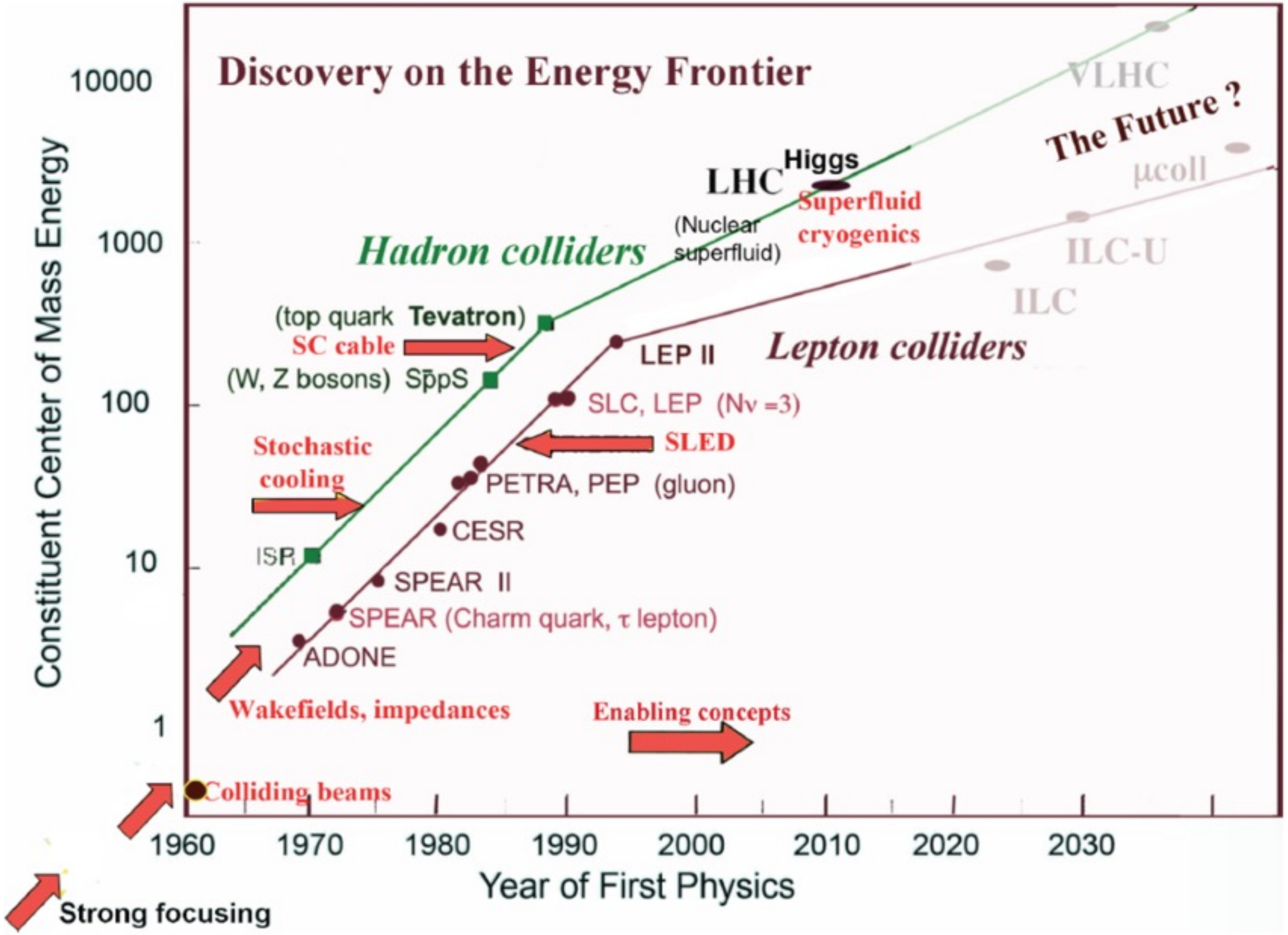
2001 snowmass accelerator RnD report
https://www.slac.stanford.edu/cgi-bin/getdoc/slac-pub-9483.pdf

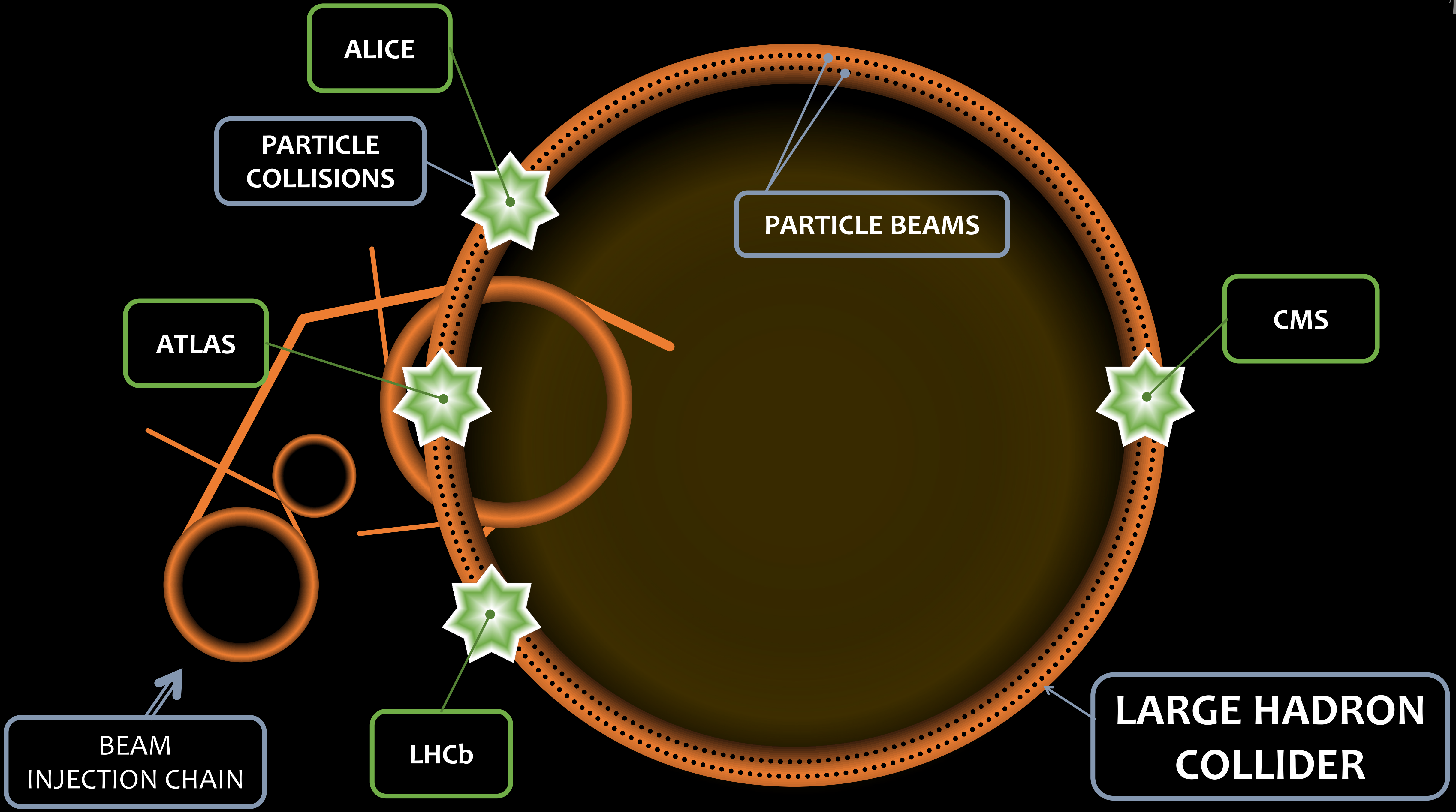
LHC

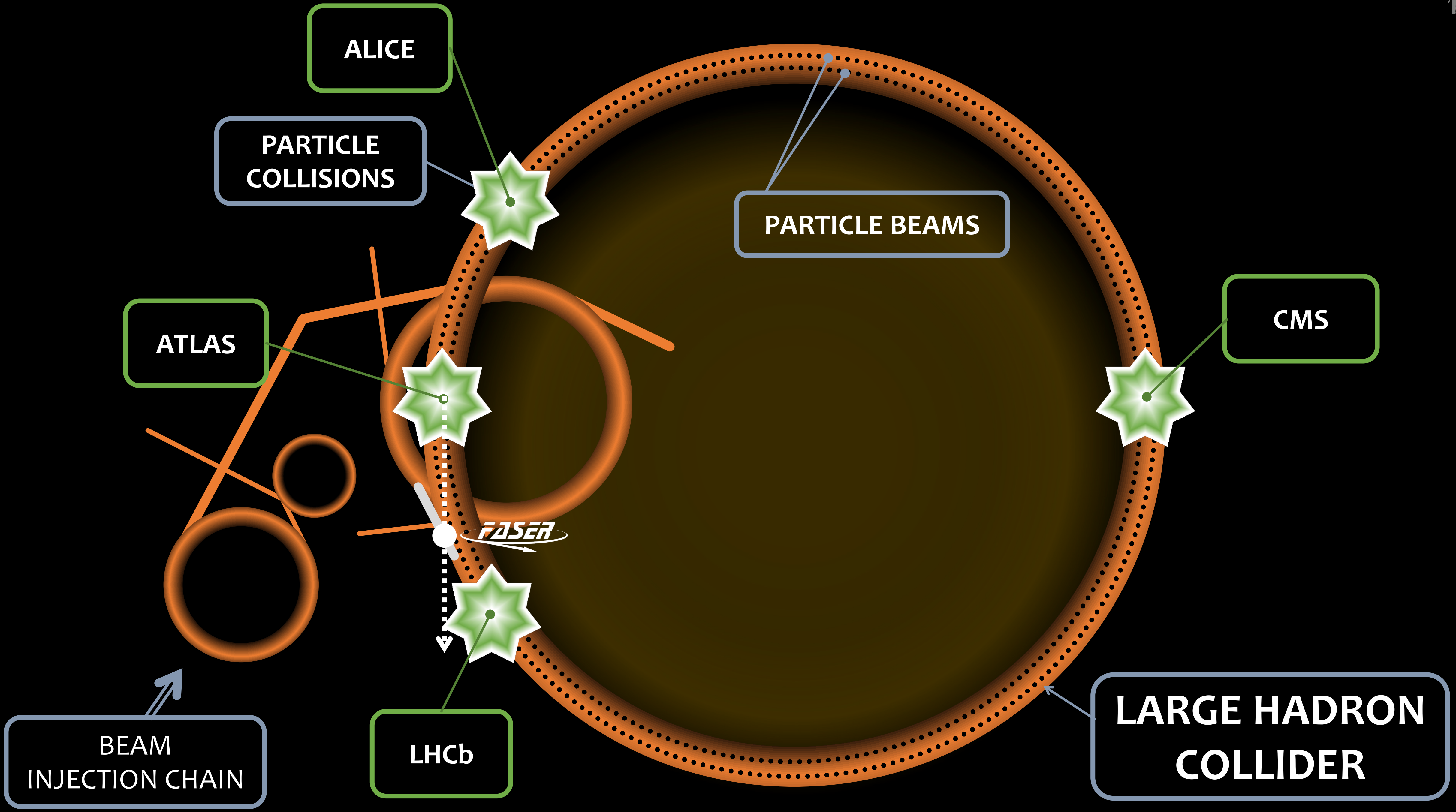
The Basics

The colliding particles

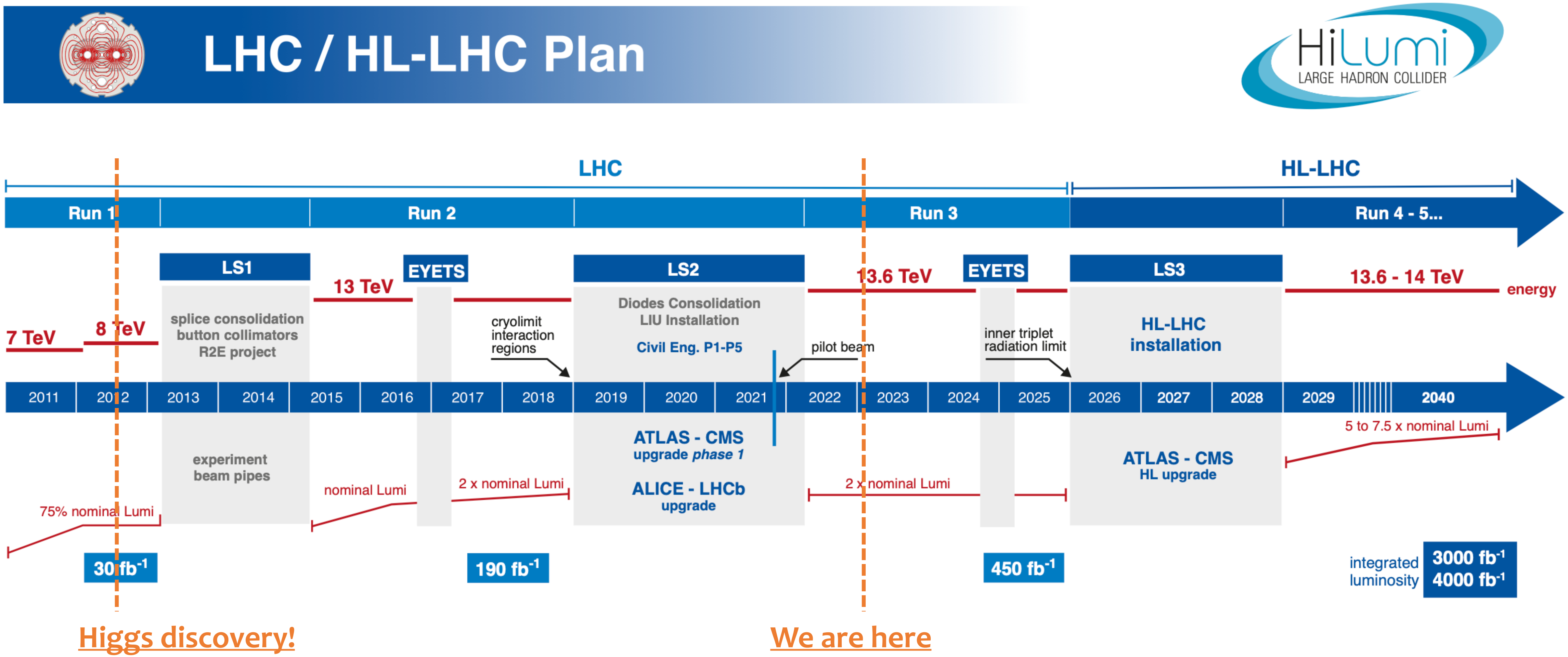
Why pp at the LHC ?
Why not e^+e^- or ppbar ?



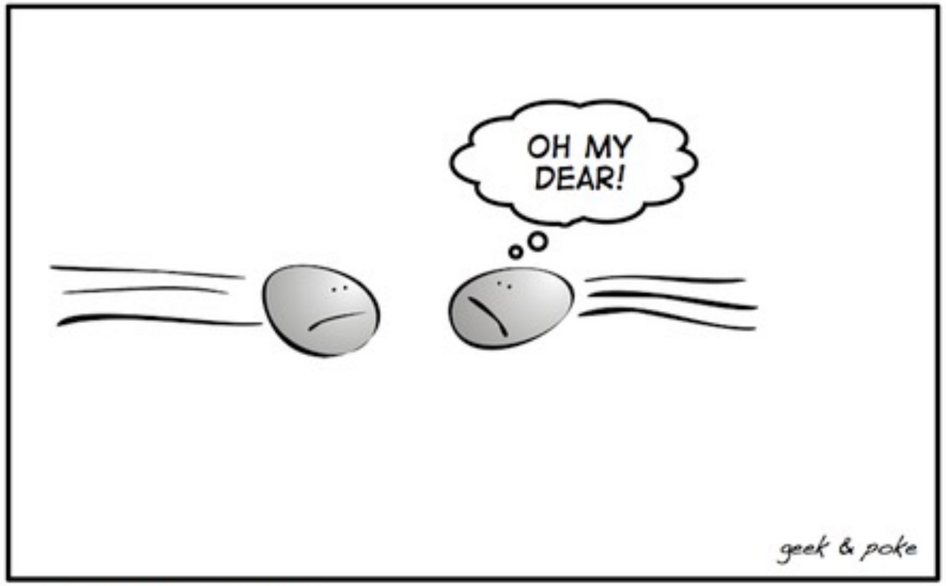

ALICE
PARTICLE COLLISIONS
PARTICLE BEAMS
ATLAS
CMS
BEAM INJECTION CHAIN
LHCb
LARGE HADRON COLLIDER


ALICE
PARTICLE COLLISIONS
PARTICLE BEAMS
CMS
ATLAS
FASER
BEAM INJECTION CHAIN
LHCb
LARGE HADRON COLLIDER

THE LHC SCHEDULE

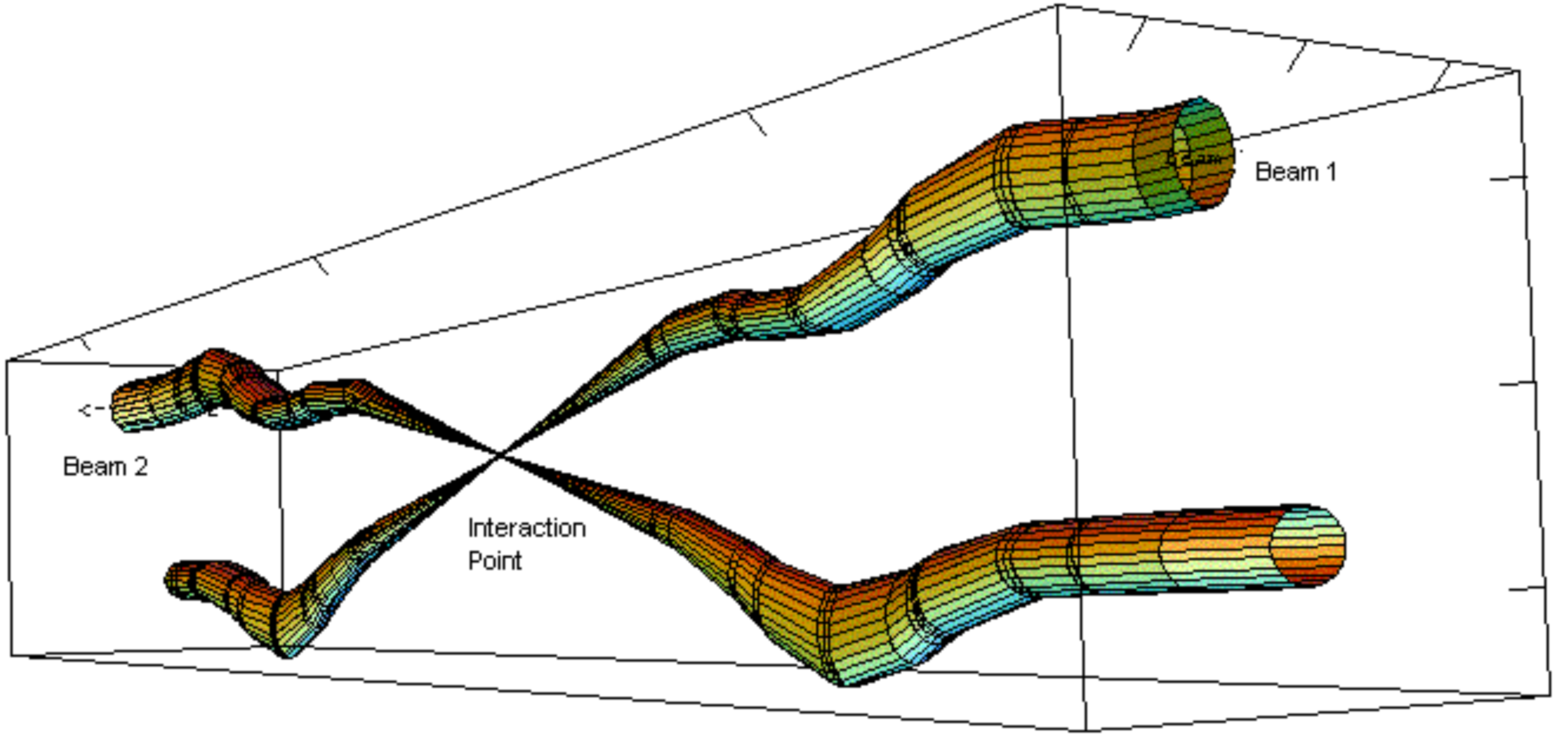


The proton-proton collision



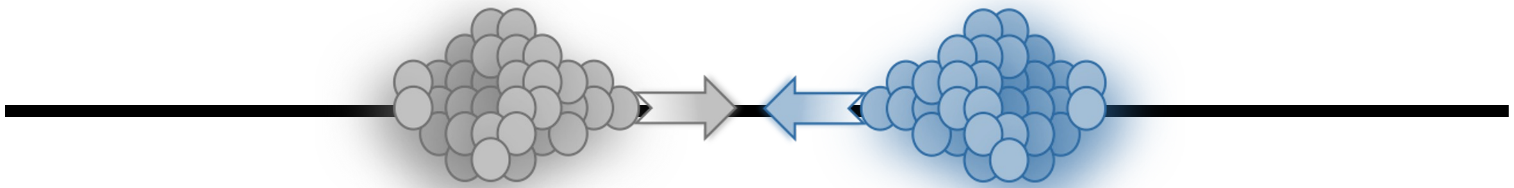
LATELY INSIDE THE LHC:
2 PROTONS 0.00000000000000000001 SEC BEFORE THE COLLISION

The proton-proton collision



Relative beam sizes around IP1 (Atlas) in collision

The proton-proton collision



Proton bunches
~ 1.5 x 10^{11} protons/bunch
Bunch spacing: 25 ns

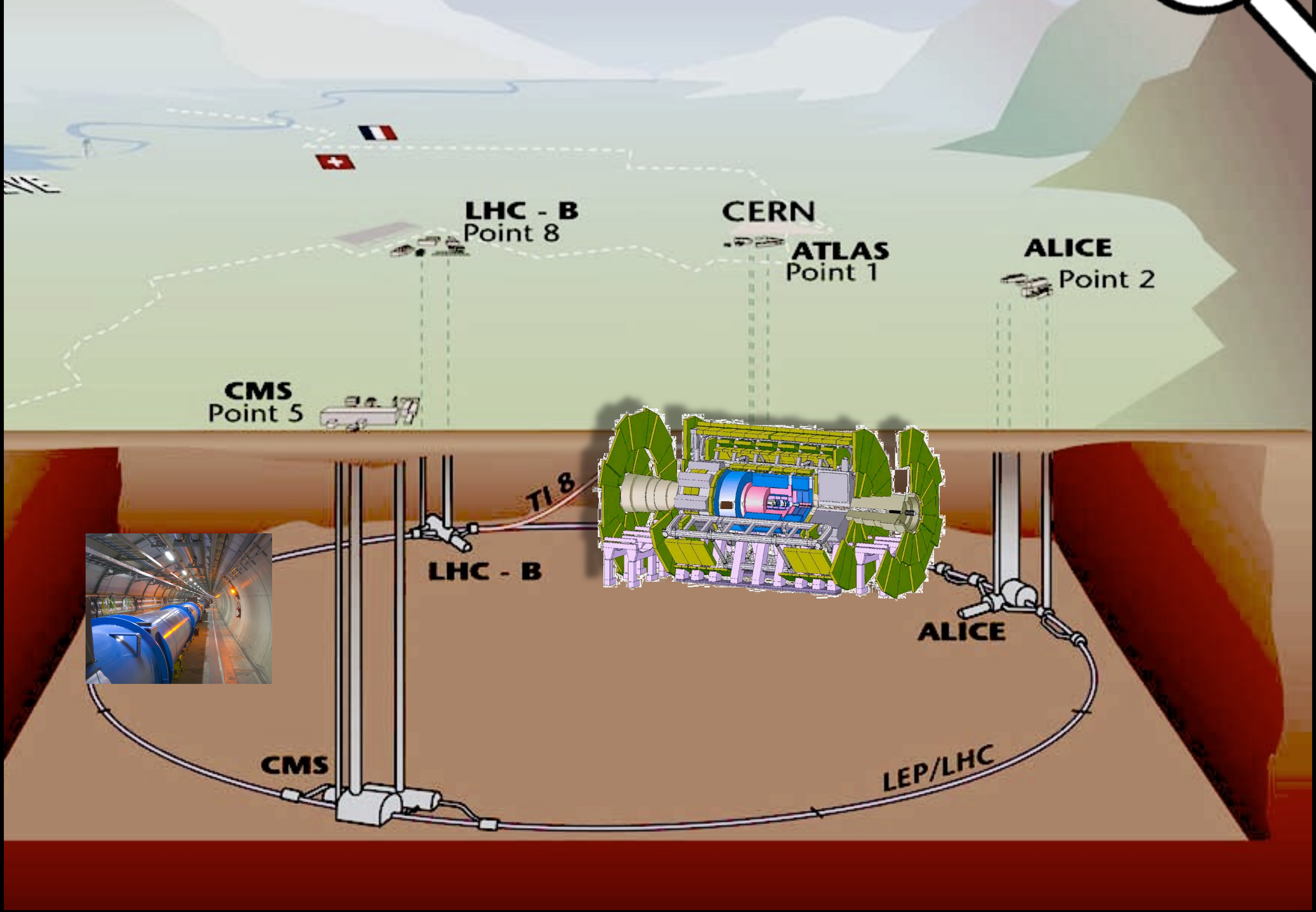
Knowing LHC circ 26.7 km – can you calculate yourselves:

- What is the revolution frequency?
- What is the maximum allowed number of bunches simultaneously circulating at the LHC?
- What is the maximum collision frequency?

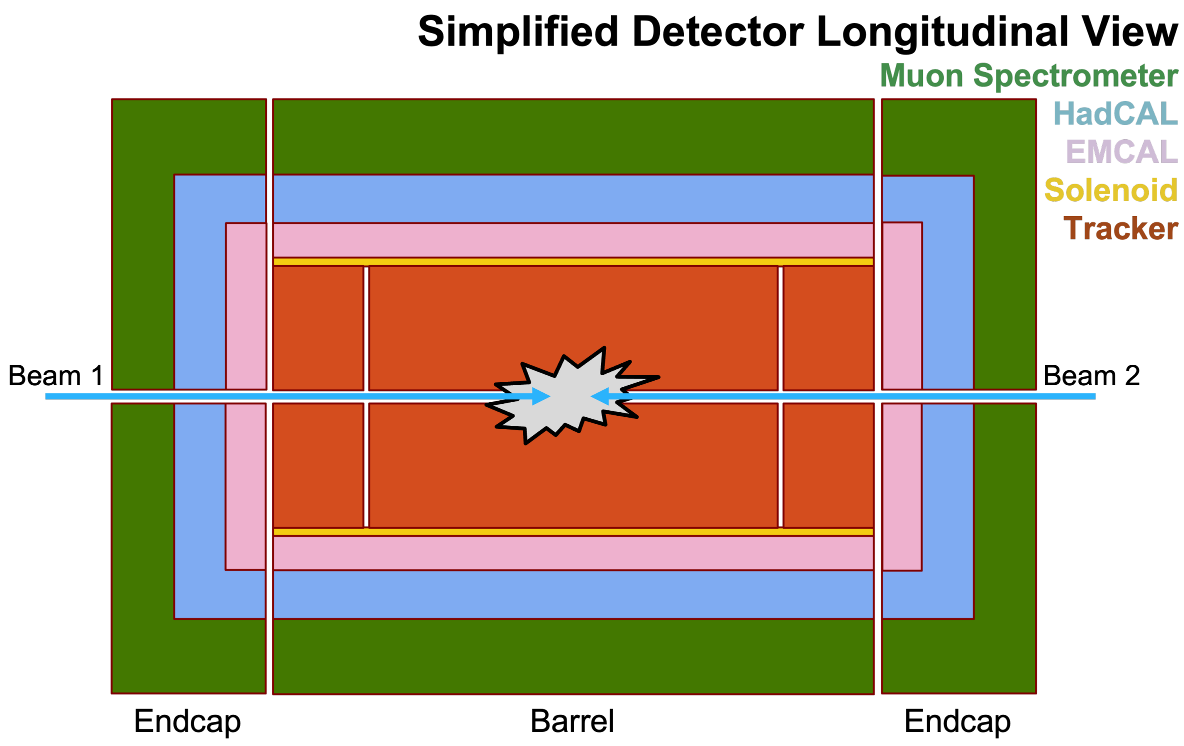
Detectors & Experiments

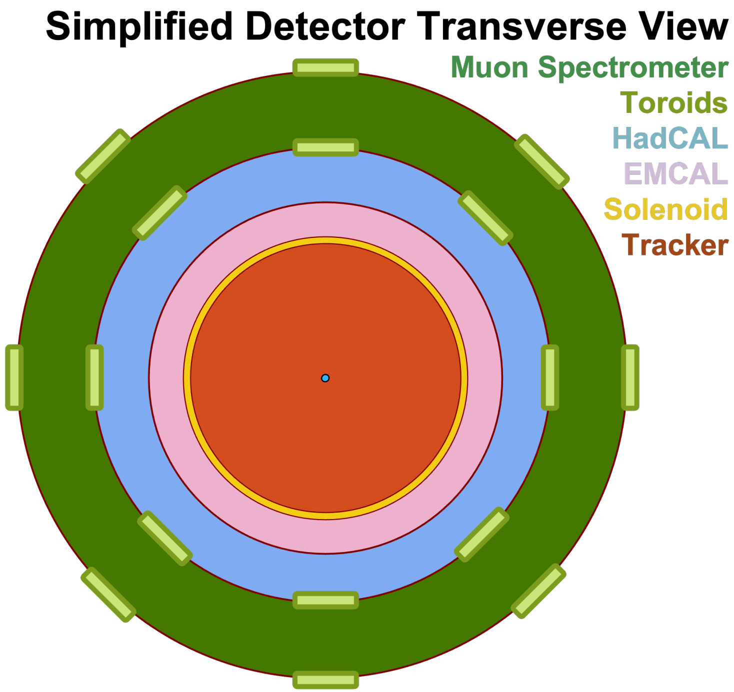
at the LHC

The LHC

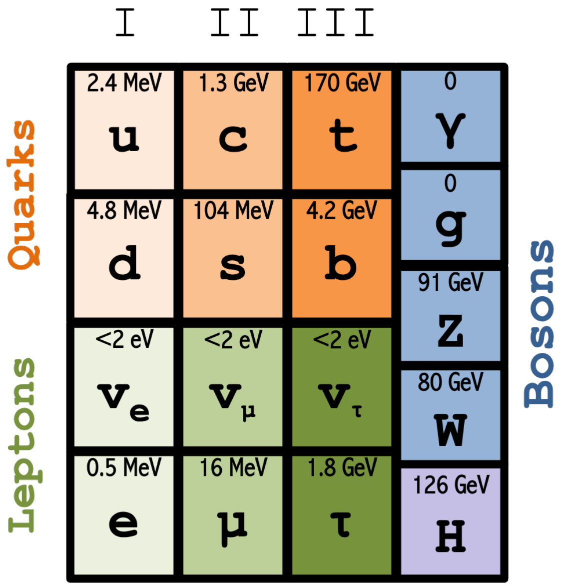

LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
TI 8
LHC - B
ALICE
CMS
LEP/LHC

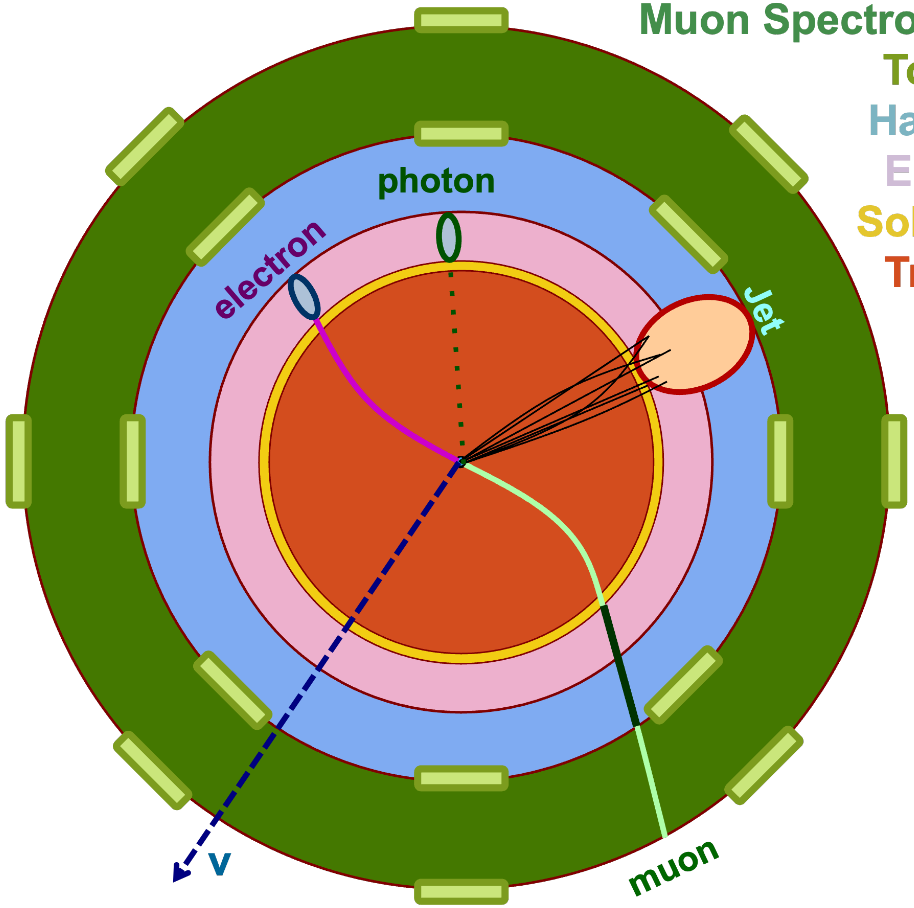
General purpose detectors at the LHC





Particles in the detector

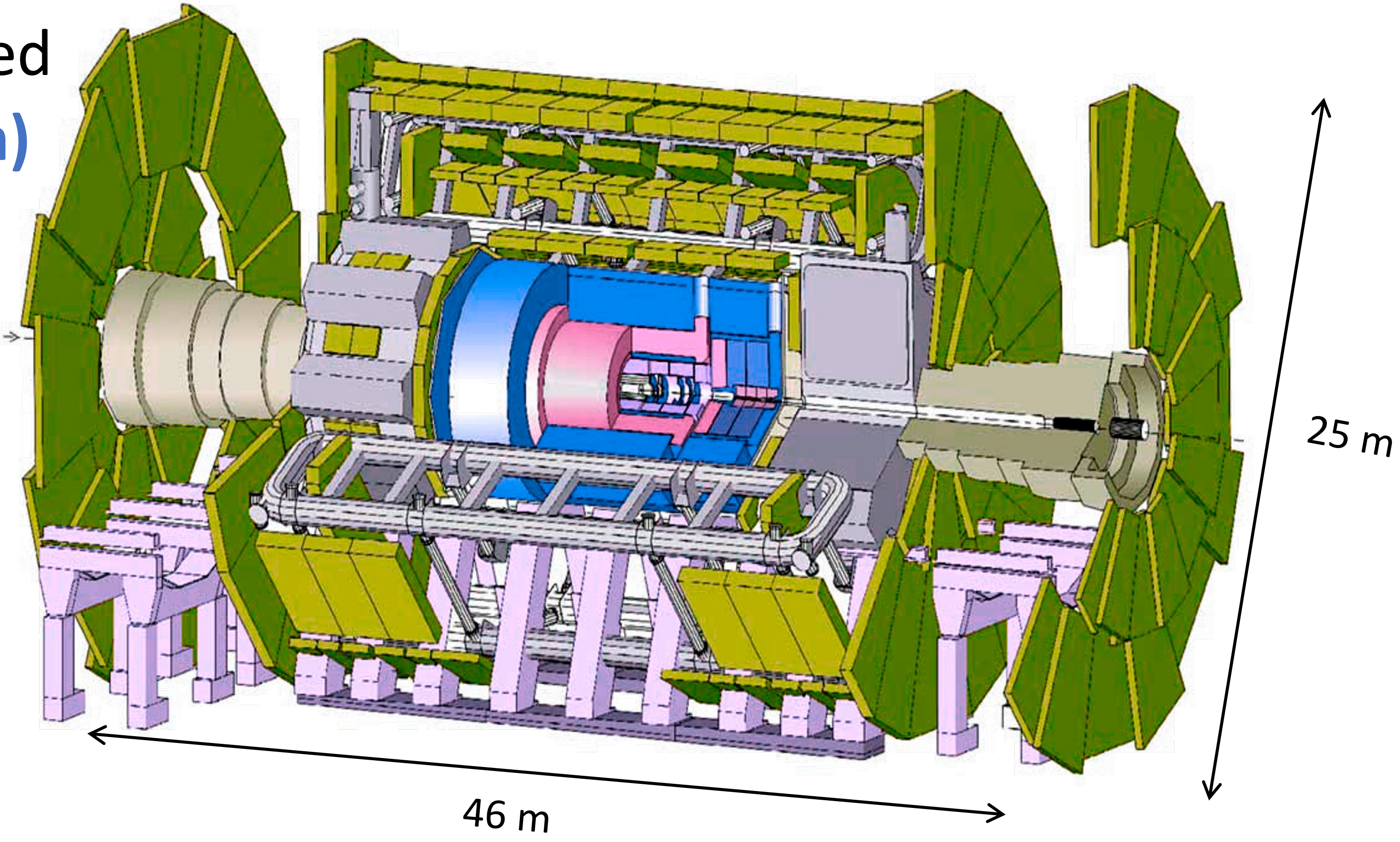




The ATLAS detector in numbers

- ✓ Weights **7 ktonnes**
- ✓ **2-4 T** superconducting magnets
- ✓ Position of particles recorded with an accuracy of **O(10µm)**
- ✓ **100 M** channels

- ✓ **1 Giga** collisions/second
- ✓ **1000** events/second stored
- ✓ **500 PB** data on disk & tape
- ✓ **0.5 M** CPU cores used 24/7



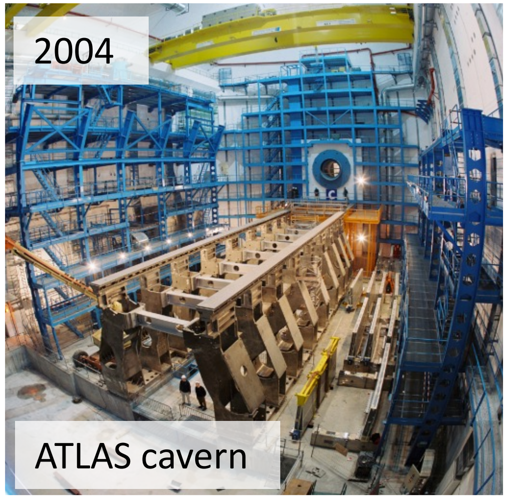
The ATLAS Collaboration

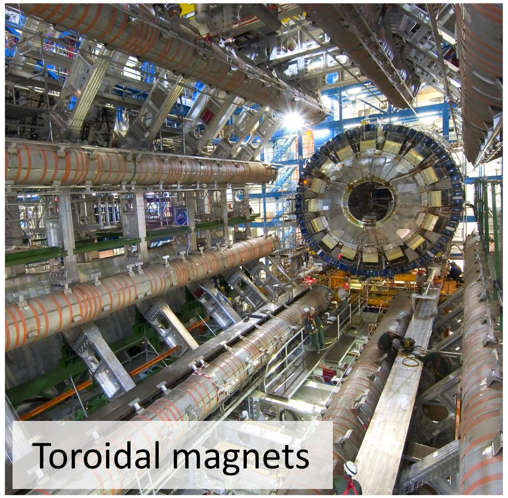
3000
Scientific authors

38
Countries

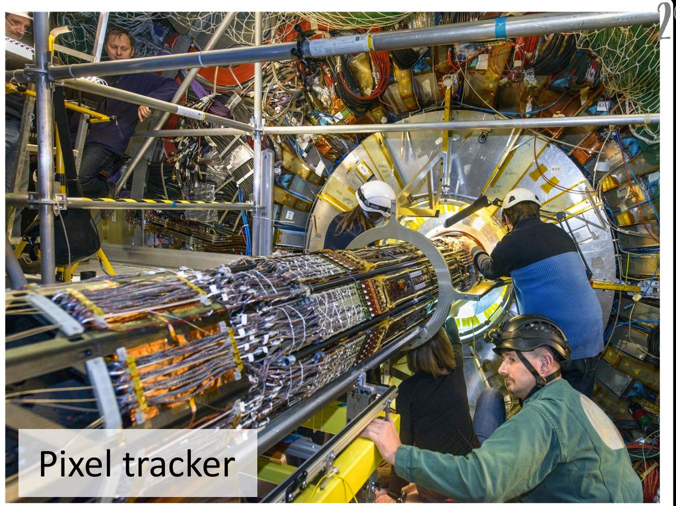
180
Institutions

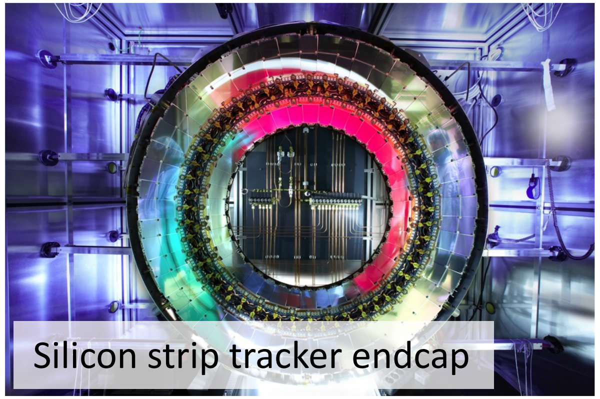
1200
Doctoral students

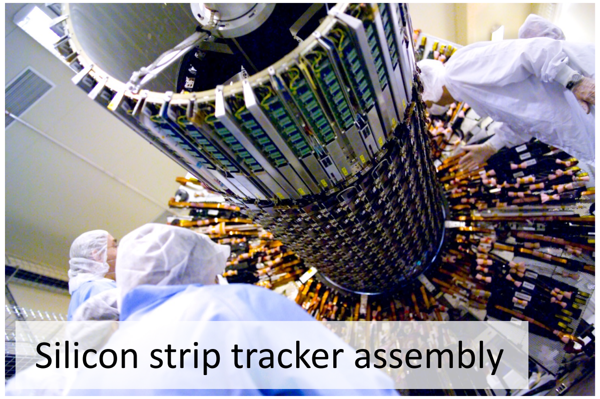

2004
ATLAS cavern

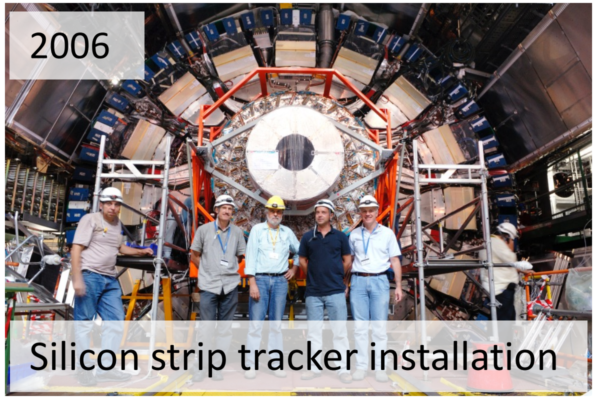

Toroidal magnets


Calorimeter


Pixel tracker

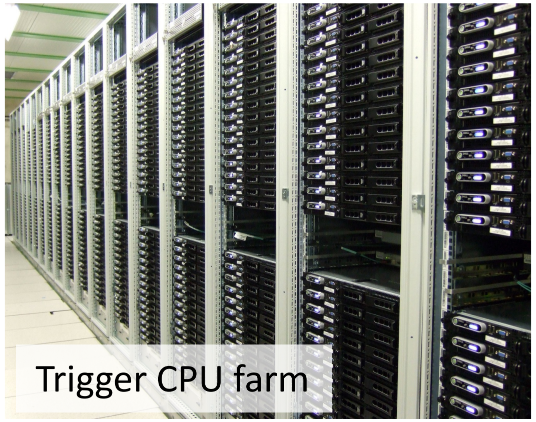

Silicon strip tracker endcap


Silicon strip tracker assembly


2006
Silicon strip tracker installation

ATLAS EXPERIMENT


2014
Innermost pixel tracker installation

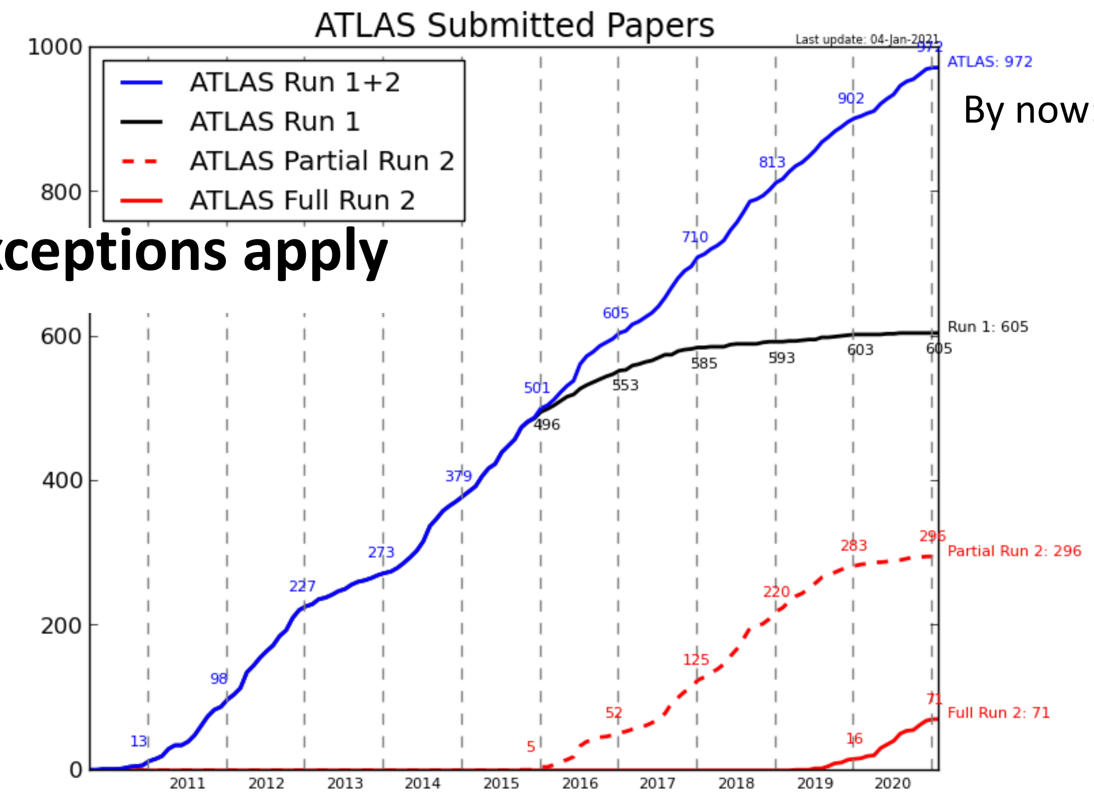

Trigger CPU farm

(Aspects relevant for all LHC detectors)

- Fast and radiation hard sensors
- Stability and accuracy of constructed structures
- Extremely fast readout systems for low latency processing
- Computing infrastructure to process enormous amounts of data

ATLAS AUTHOR-SHIP / LIST

- **Only ATLAS authors sign ATLAS papers; Exceptions apply**
- **All authors sign all papers**



By now: > 1000!

[Submitted on 13 Aug 2020 (v1), last revised 20 Nov 2020 (this version, v2)]

Search for new phenomena in final states with large jet multiplicities and missing transverse momentum using $\sqrt{(s)} = 13$ TeV proton−proton collisions recorded by ATLAS in Run 2 of the LHC

ATLAS Collaboration

Results of a search for new particles decaying into eight or more jets and moderate missing transverse momentum are presented. The analysis uses 139 fb^{-1} of proton−

The ATLAS Collaboration

G. Aad[102], B. Abbott[128], D.C. Abbott[103], A. Abed Abud[36], K. Abeling[53], D.K. Abhayasinghe[94], S.H. Abidi[166], O.S. AbouZeid[40], N.L. Abraham[155], H. Abramowicz[160], H. Abreu[159], Y. Abulaiti[6], B.S. Acharya[67a,67b,n], B. Achkar[53], L. Adam[100], C. Adam Bourdarios[5], L. Adamczyk[84a], L. Adamek[166], J. Adelman[121], M. Adersberger[114], A. Adiguzel[12c], S. Adorni[54], T. Adye[143], A.A. Affolder[145], Y. Afik[159], C. Agapopoulou[65], M.N. Agaras[38], A. Aggarwal[119], C. Agheorghiesei[27c], J.A. Aguilar-Saavedra[139f,139a,ad],

… 10 pages later …

C.G. Zhu[60b], C. Zhu[15a,15d], H.L. Zhu[60a], H. Zhu[15a], J. Zhu[106], Y. Zhu[60a], X. Zhuang[15a], K. Zhukov[111], V. Zhulanov[122b,122a], D. Zieminska[66], N.I. Zimine[80], S. Zimmermann[52], Z. Zinonos[115], M. Ziolkowski[150], L. Živković[16], G. Zobernig[180], A. Zoccoli[23b,23a], K. Zoch[53], T.G. Zorbas[148], R. Zou[37], L. Zwalinski[36].

A new collaborator becomes an author if:

- Have been a *qualifying ATLAS member* for *at least one year*.
- Not be an author of another major LHC collaboration at the time of application.
- Have spent *at least 80 working days* doing **pre-agreed** ATLAS technical work.

The CMS Collaboration

2100
Scientific authors

51
Countries

229
Institutions

1100
Doctoral students

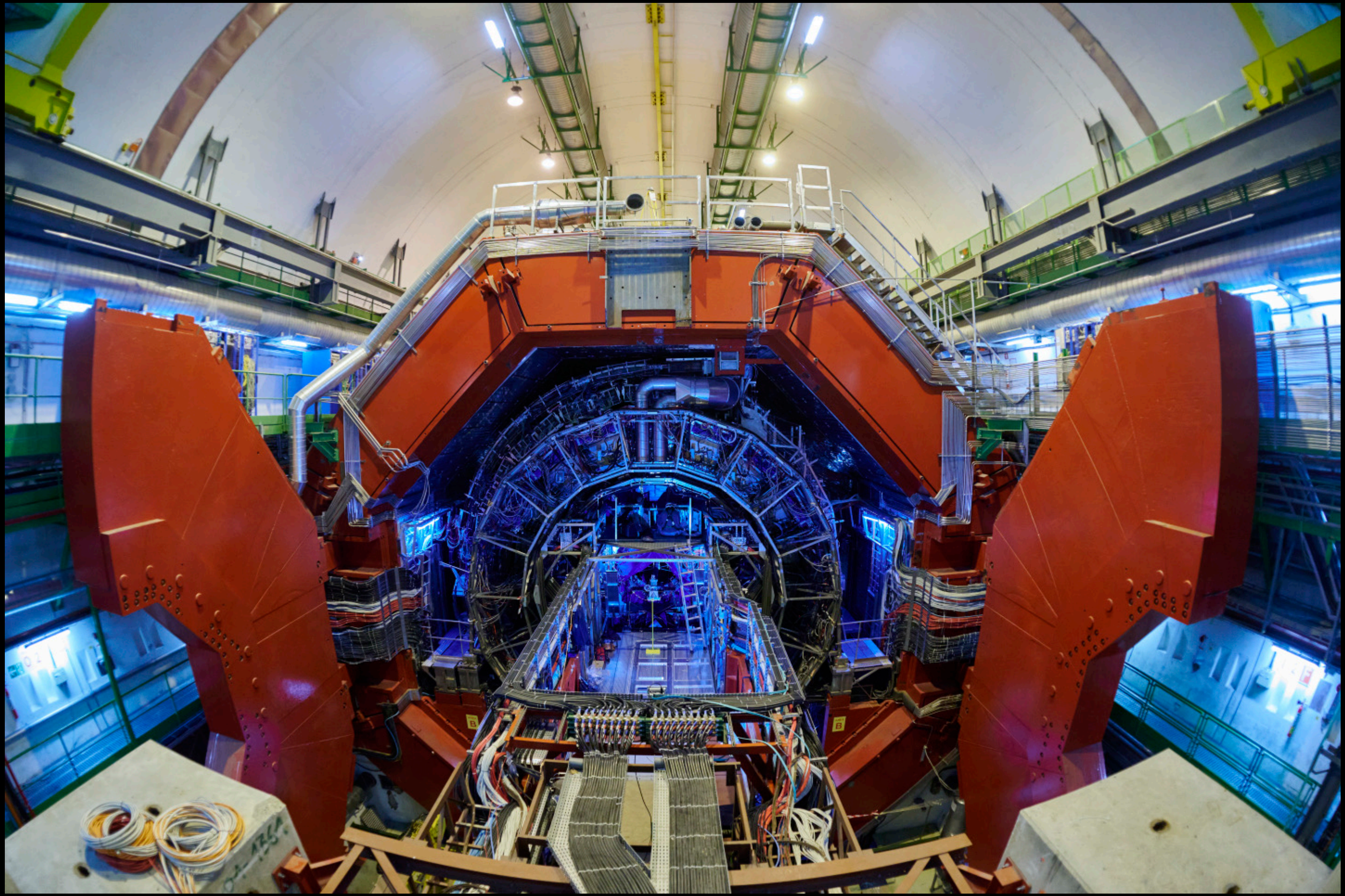
Outside ATLAS and CMS

The ALICE Collaboration

1990
Members

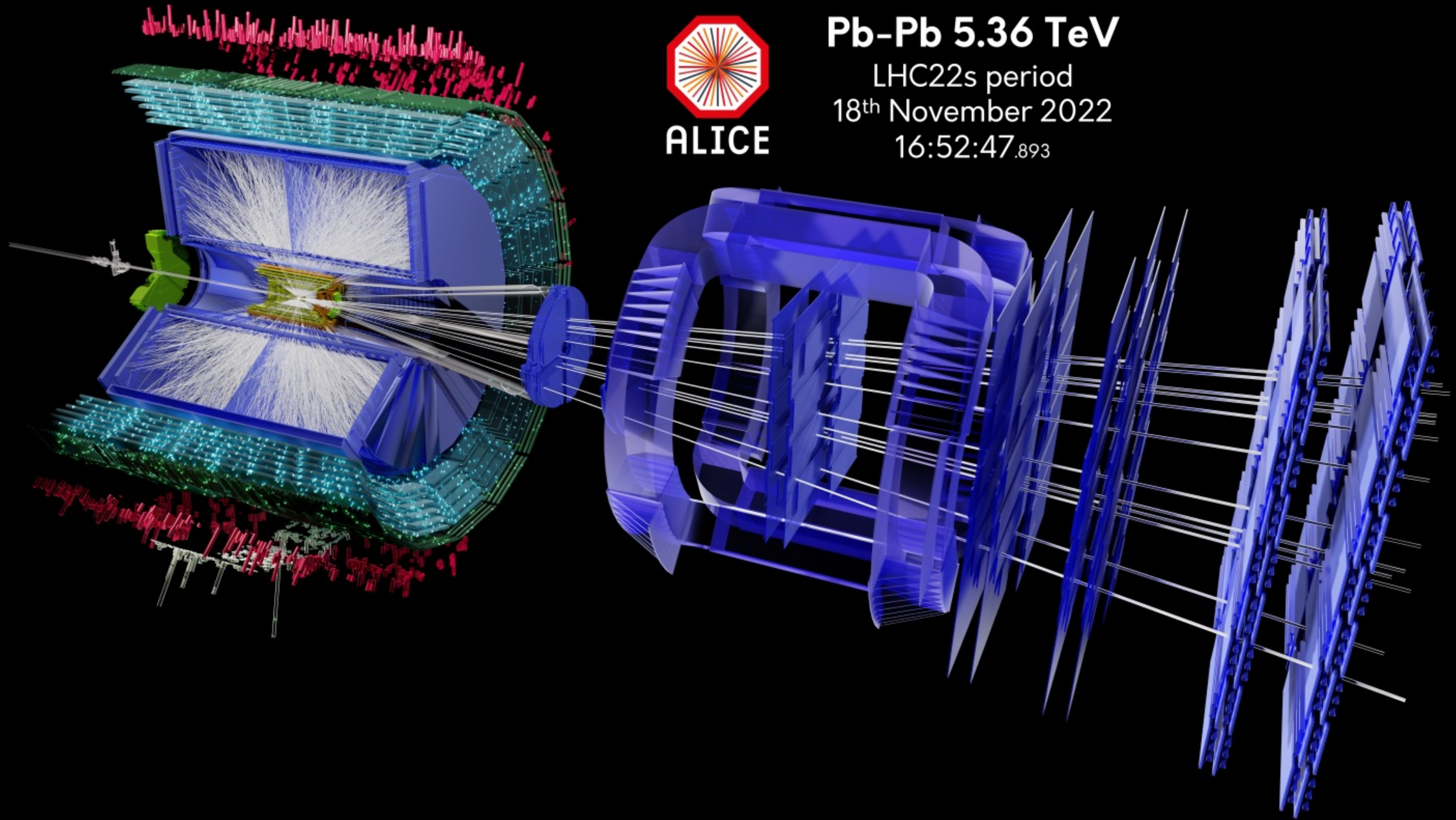
40
Countries

172
Institutions



Outside ATLAS and CMS

The ALICE Collaboration



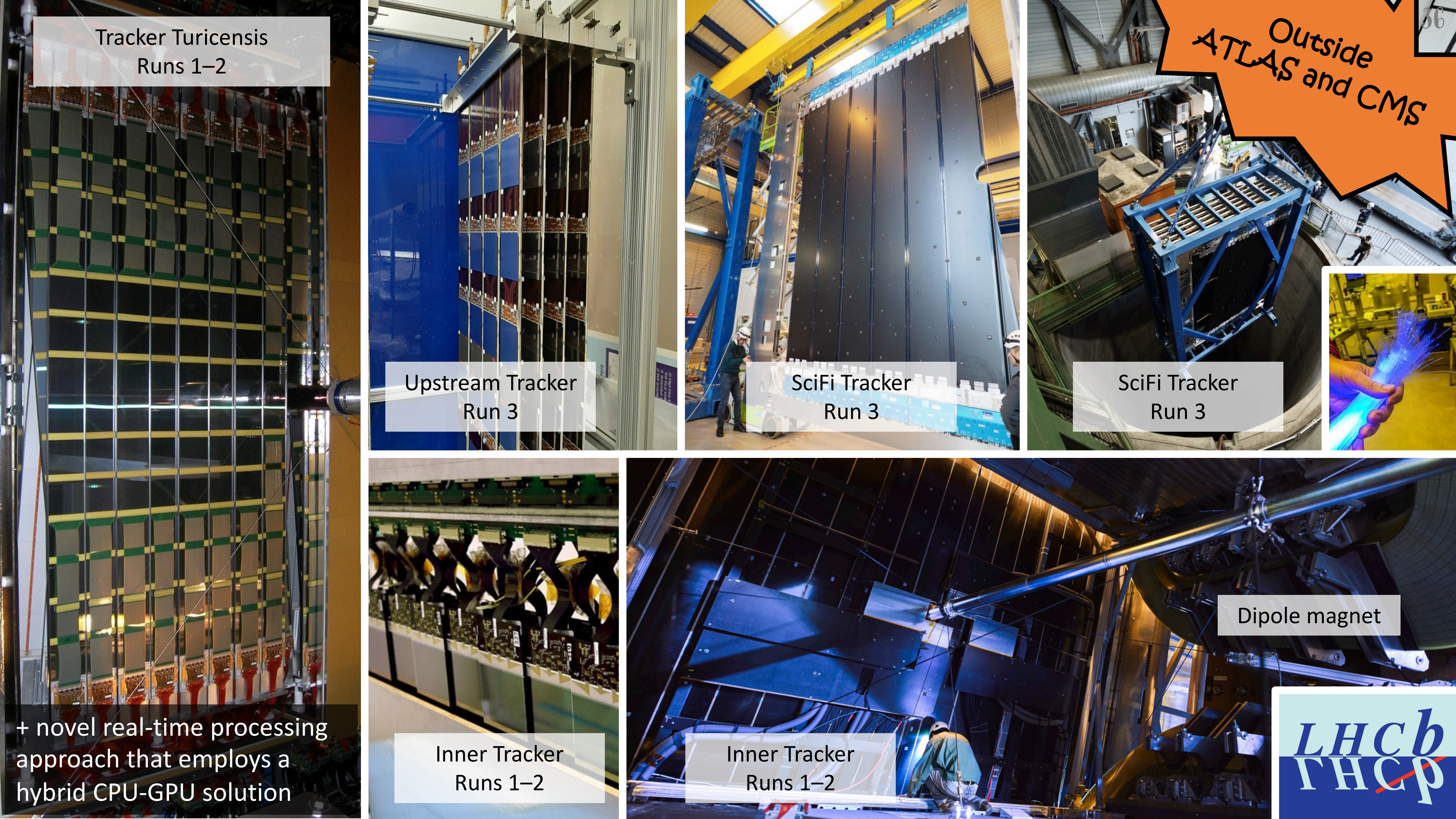
Outside ATLAS and CMS

The LHCb Collaboration

1500
Members

19
Countries

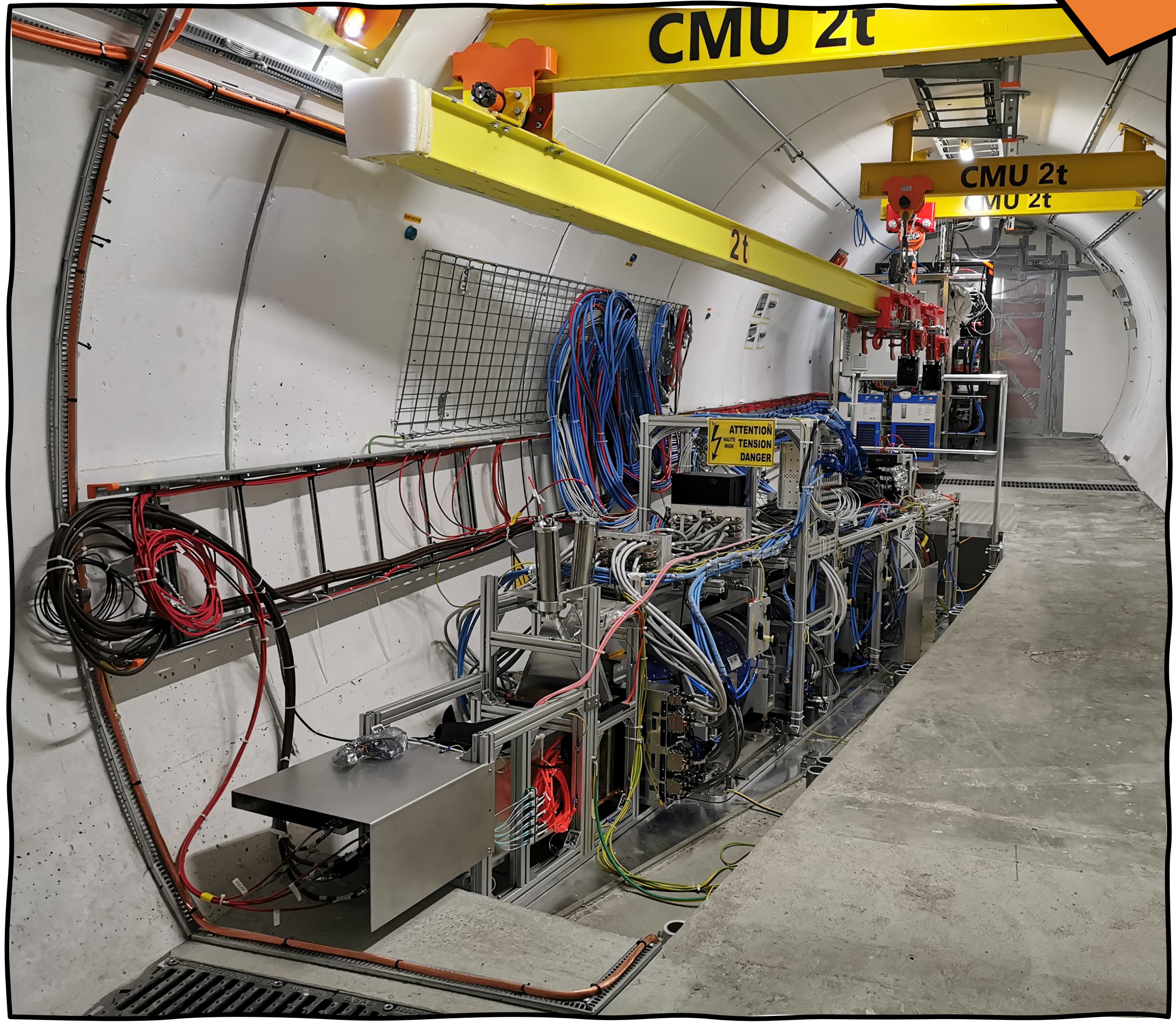
87
Institutions



Outside ATLAS and CMS
Tracker Turicensis
Runs 1–2
Upstream Tracker
Run 3
SciFi Tracker
Run 3
SciFi Tracker
Run 3
Inner Tracker
Runs 1–2
Inner Tracker
Runs 1–2
Dipole magnet
+ novel real-time processing approach that employs a hybrid CPU-GPU solution
LHCb

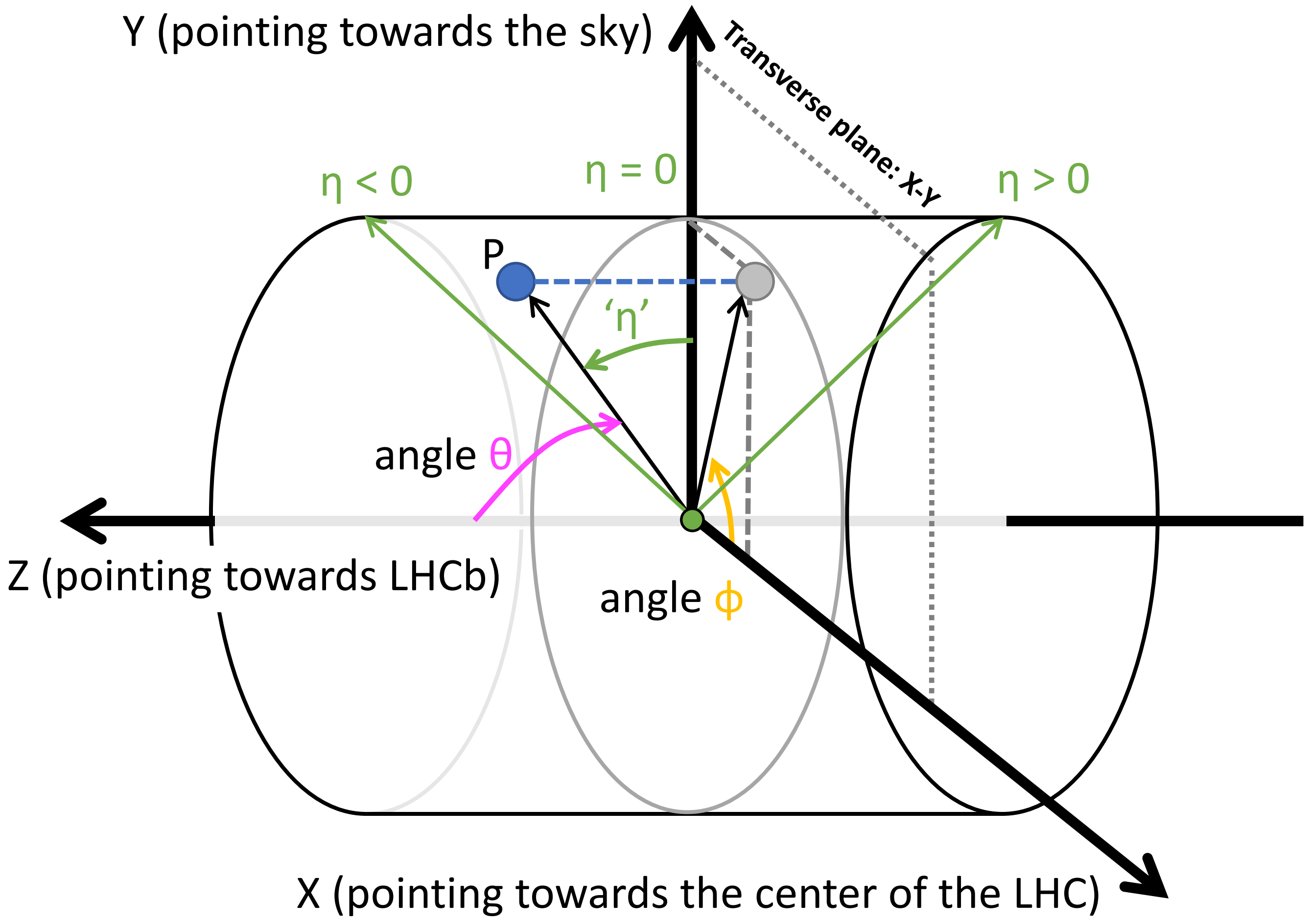
A DIFFERENT SCALE OF EXPERIMENT – FASER

Outside ATLAS and CMS



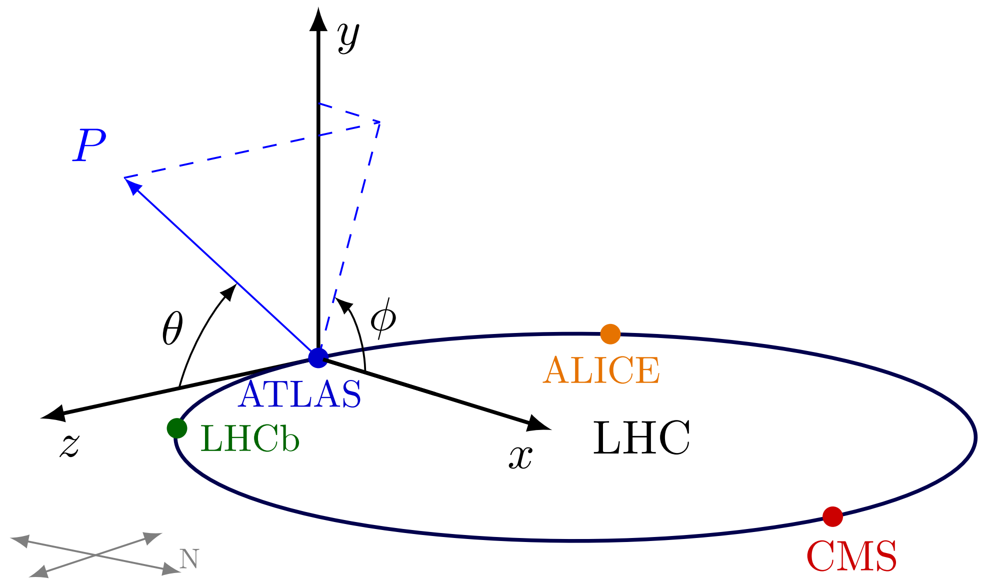
SOME BASIC CONCEPTS

(ATLAS) Coordinate system



$$\eta \equiv -\ln \tan \frac{\theta}{2}$$

Pseudorapidity ranges in ATLAS and CMS?
And how about LHCb (and FASER)?



Drawing: S. Franchellucci

Rapidity and Pseudo-rapidity

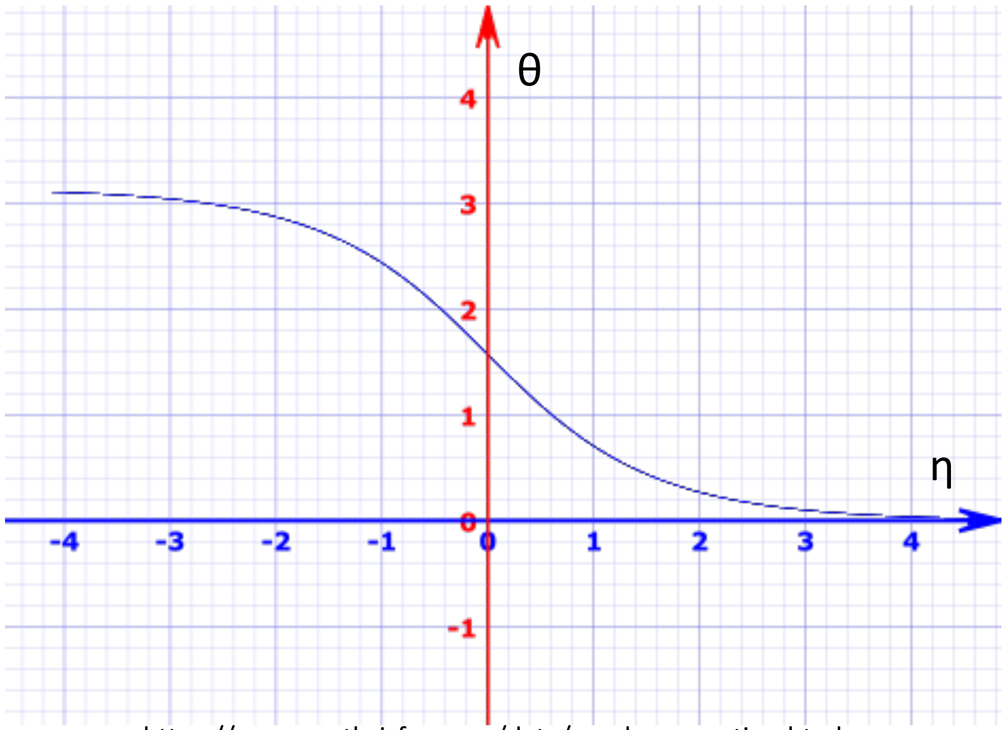
If we want to measure the angle between two particles, we should get the same answer in the lab frame and CM frame, and to connect the two we need a boost in z

Angle θ: not invariant in Lorenz boost in z-direction

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

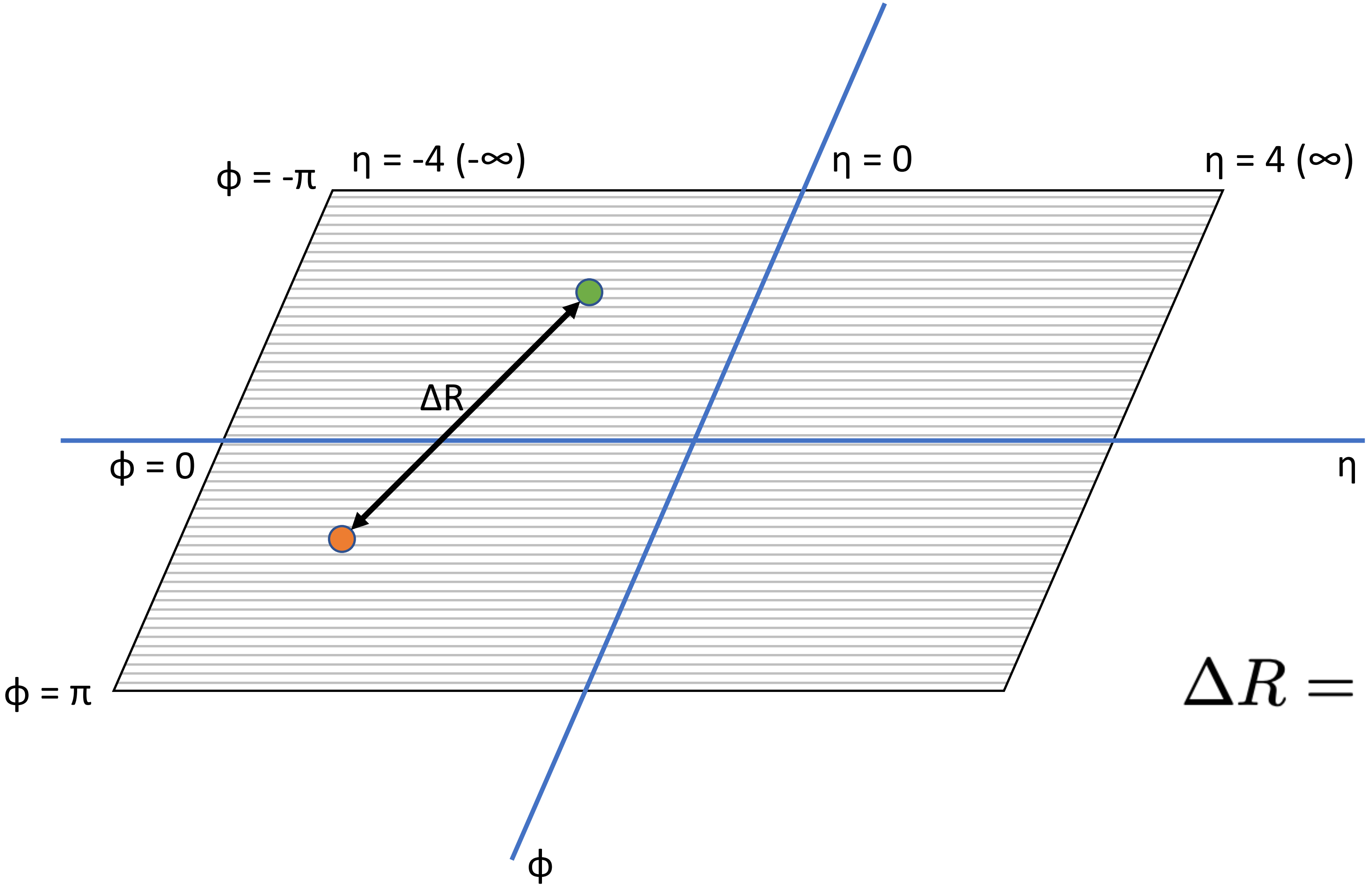
$$y \to y' = y + \ln\sqrt{\frac{1-\beta}{1+\beta}} \Rightarrow \Delta y' = \Delta y$$

Massless particle approximation: $\eta \equiv -\ln\tan\frac{\theta}{2}$



https://www.mathsisfun.com/data/grapher-equation.html

Distance Δ between two particles



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

Observables

Two key equations: $\Sigma_i p_{z,i} \neq 0$ $\Sigma_i p_{T,i} = 0$

Invariant mass: $m = \sqrt{E^2 - P^2} = \sqrt{(\Sigma_i E_i)^2 - (\Sigma_i \vec{p}_i)^2}$

Missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}} = -\Sigma_i \vec{p}_{T,i}$

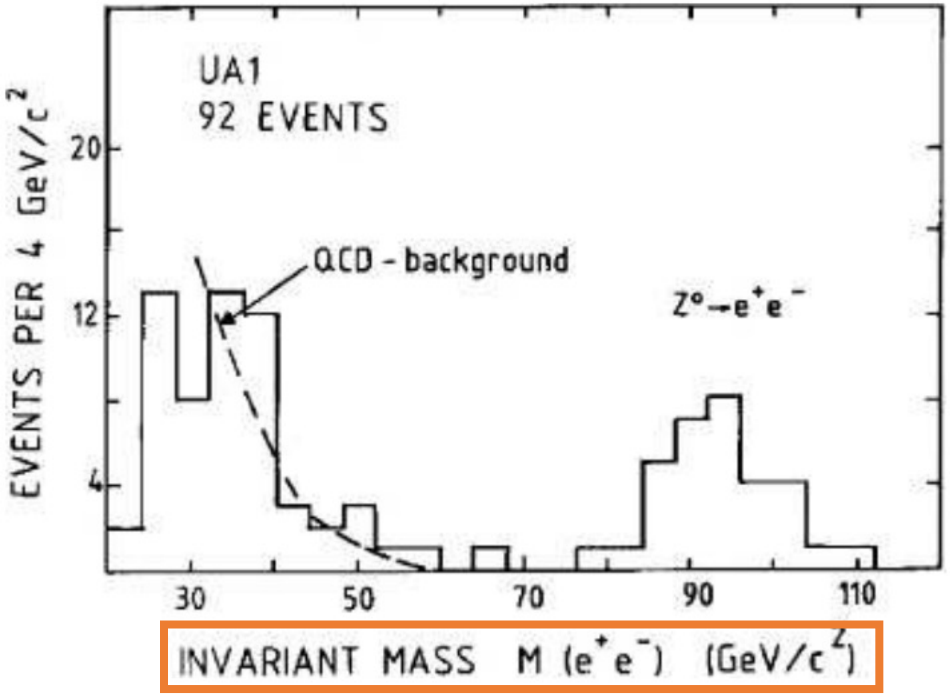
Transverse mass:

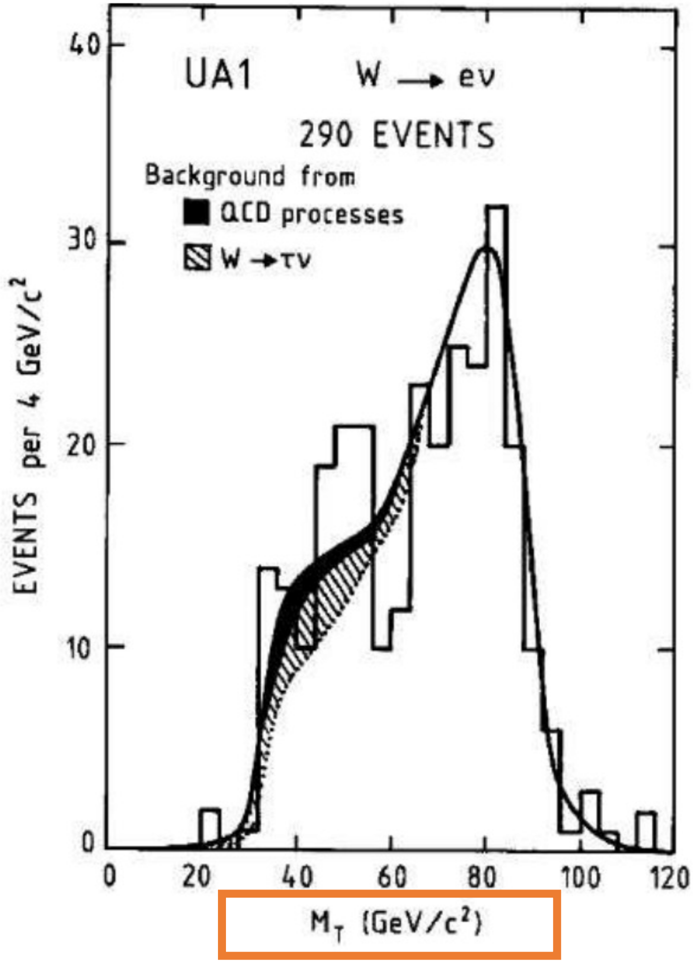
$$M_T^2 = (E_{T,a} + E_{T,b})^2 - (\vec{p}_{T,a} + \vec{p}_{T,b})^2 = 2|p_{T,a}||p_{T,b}|(1 - \cos\phi_{ab})$$

And many more, we will see some more as we go through the lecture…

A step back in time: Z and W discovery

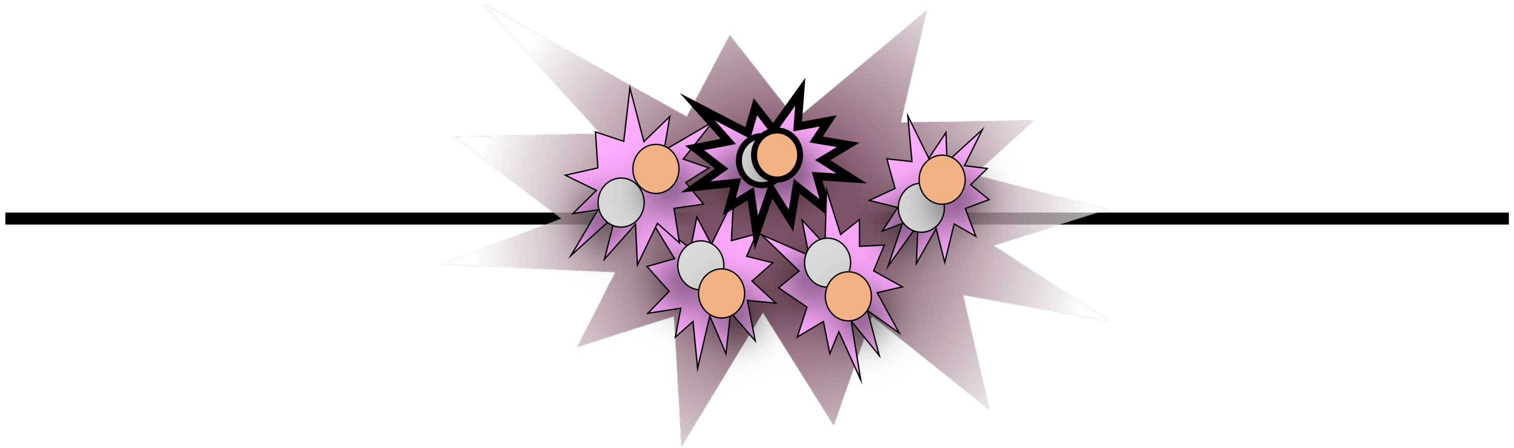
A step back in time





https://cds.cern.ch/record/2103277/files/9789814644150_0006.pdf?subformat=pdfa&version=1

Pile-up

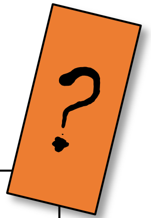


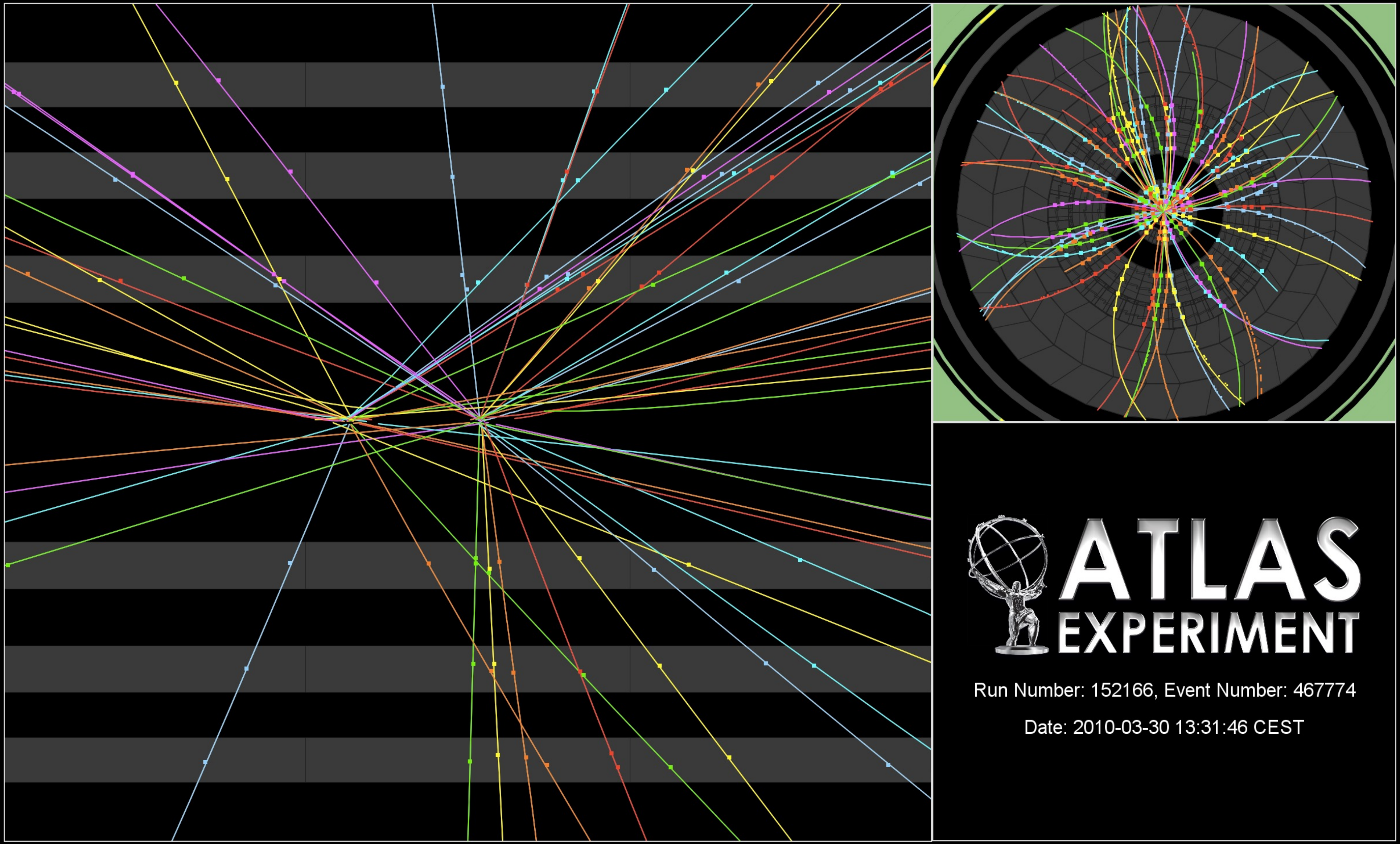
Up to 60-70 p-p collisions / bunch crossing

Two kinds: In-time and Out-of-time

Can you estimate yourselves (considering pp σ = 100 mb and 25 ns bunch xing):

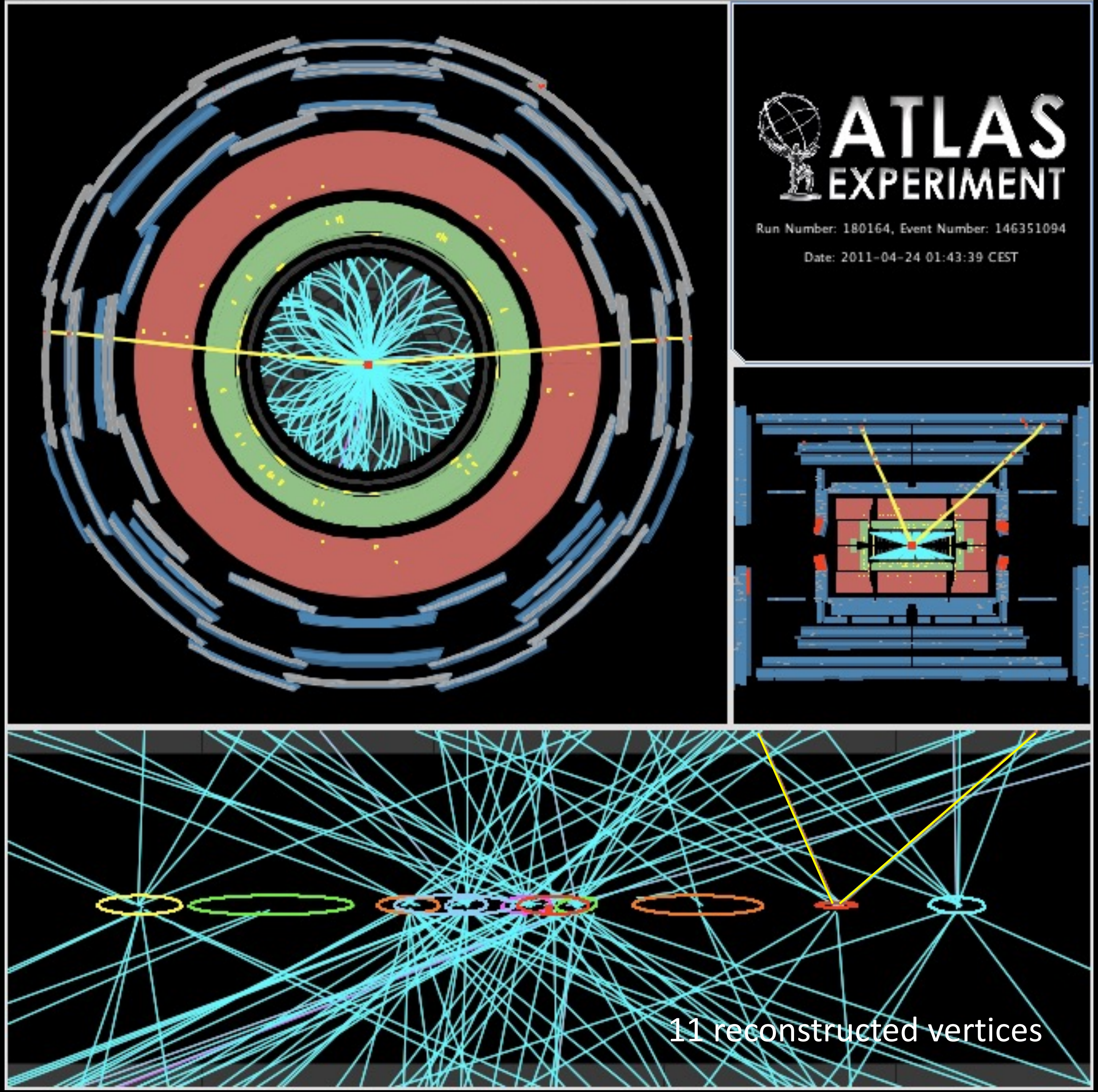
- What is the expected pile-up when the LHC runs at $1x10^{34}$ or $2x10^{34}$ / cm^2s?





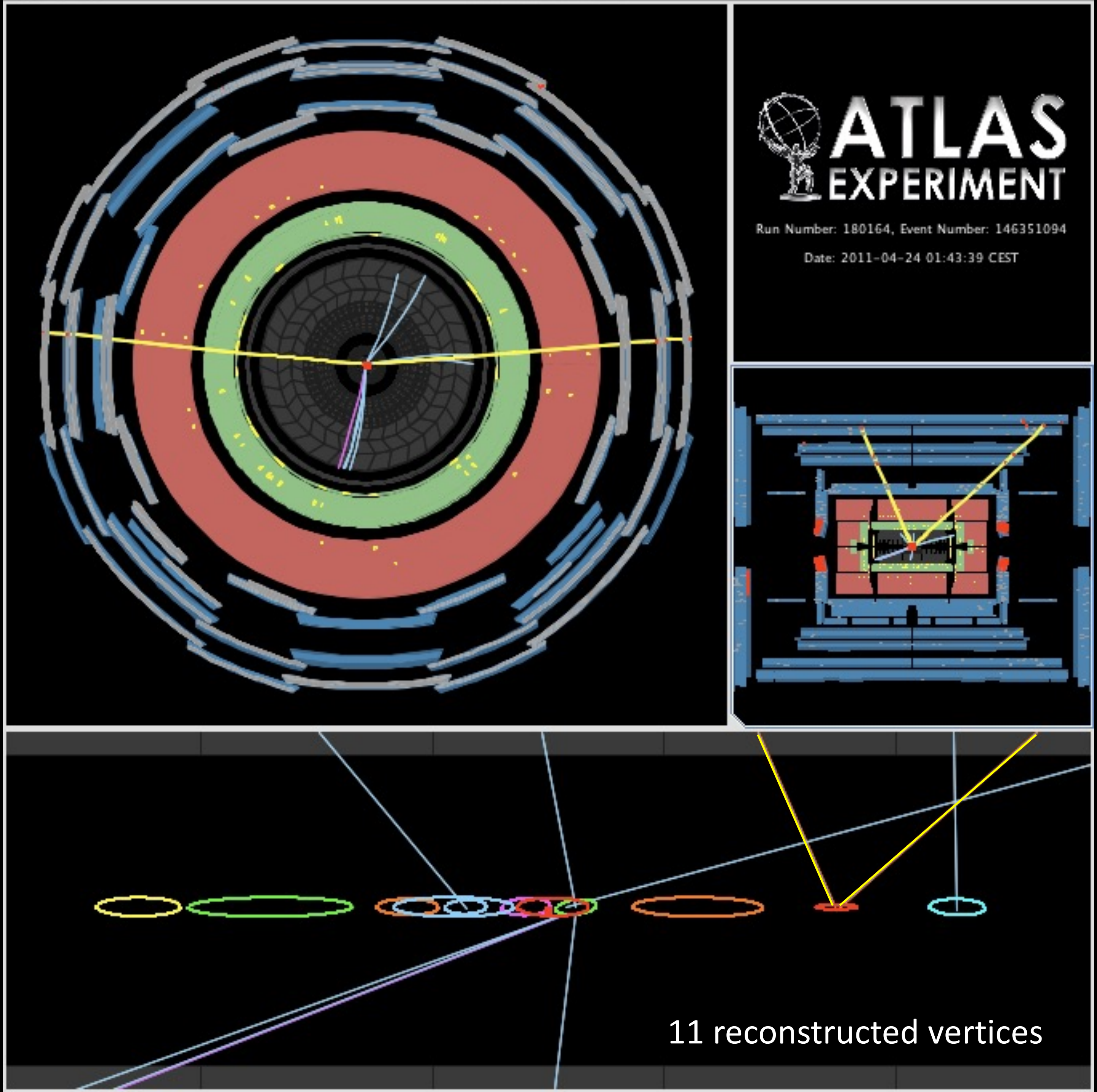
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Z->μμ event;
2011 data.

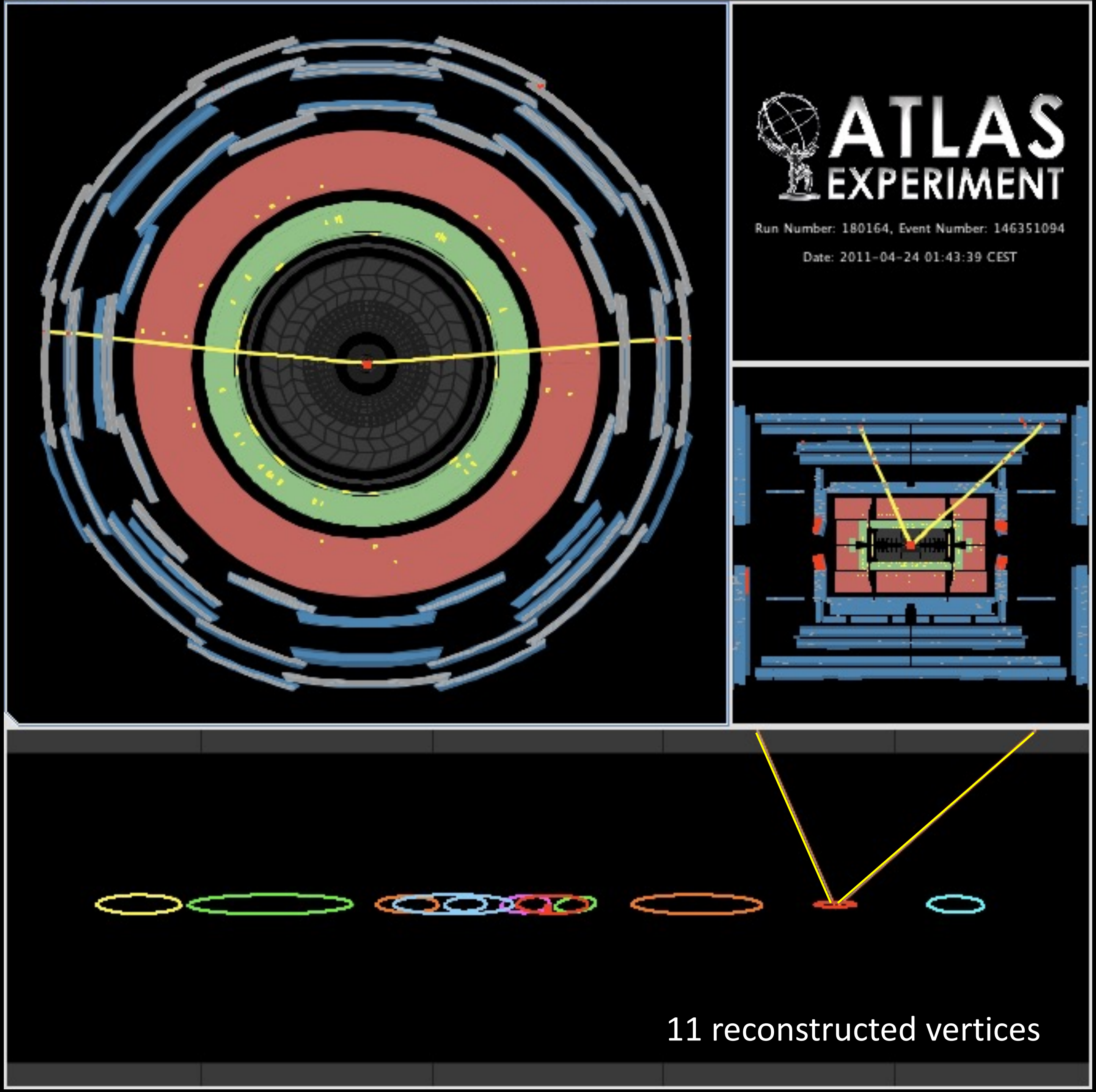


Track pT > 0.5 GeV

Z->μμ event;
2011 data.

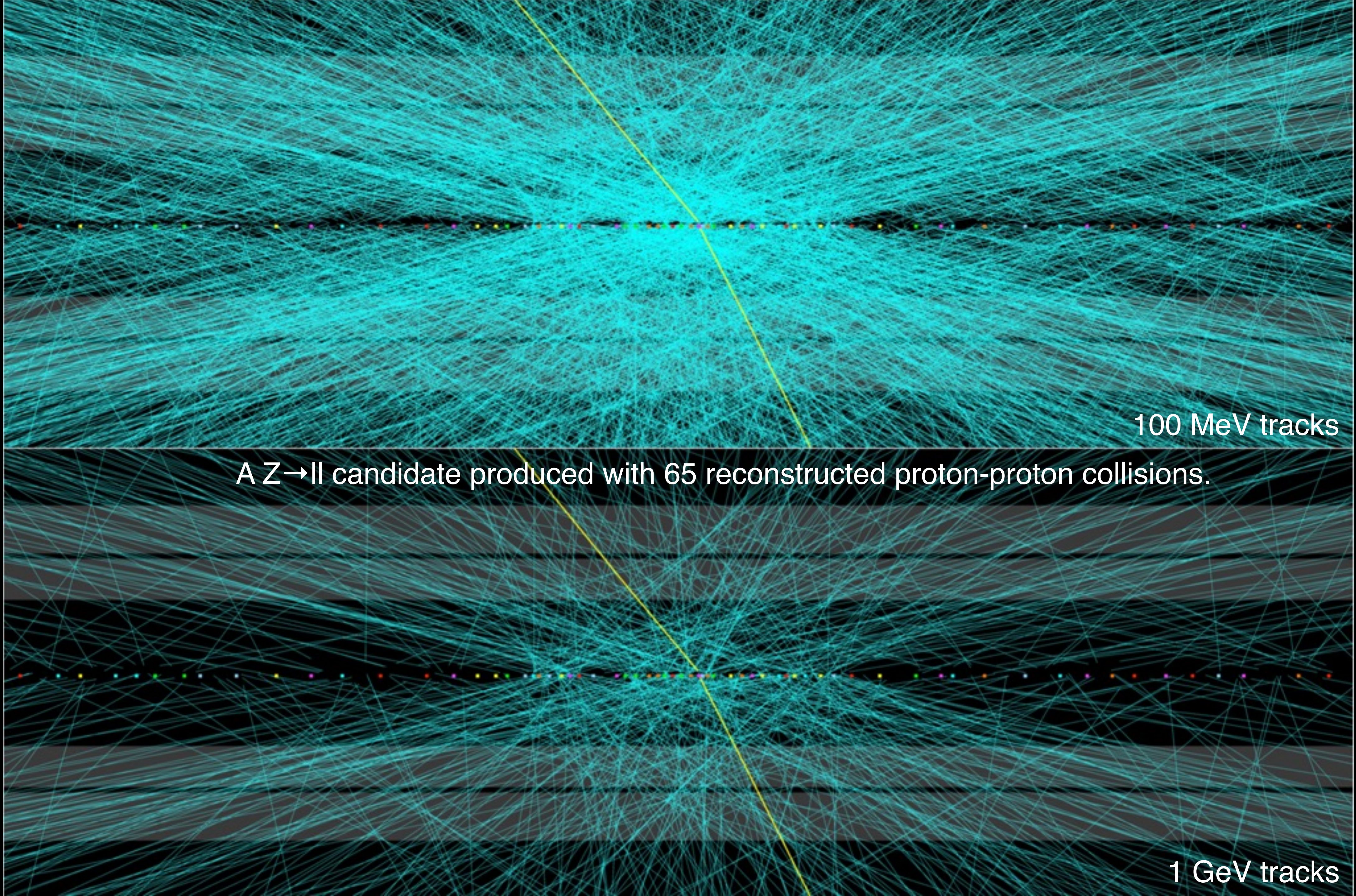


Track pT > 2 GeV

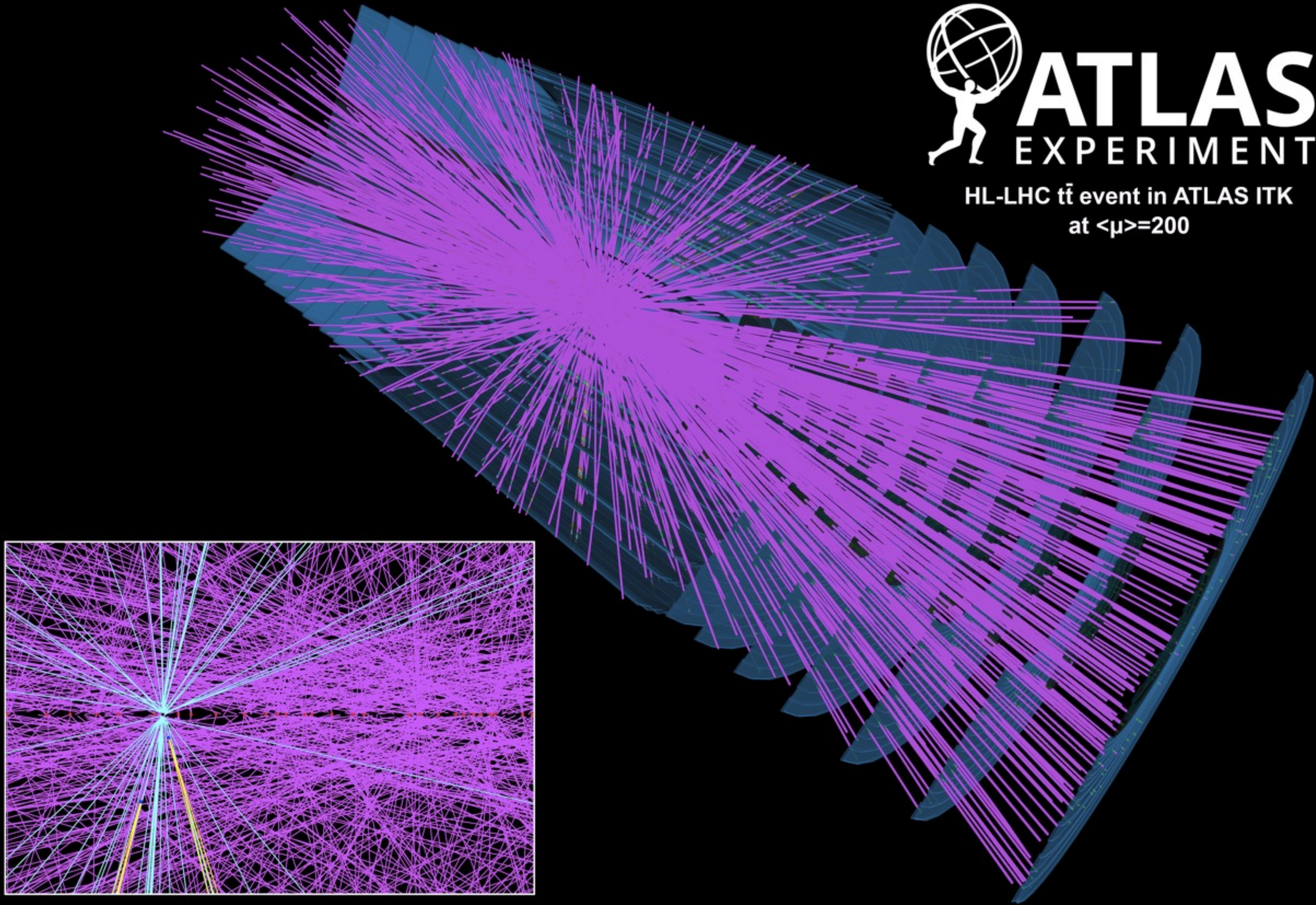


Z->μμ event;
2011 data.

Track pT > 10 GeV



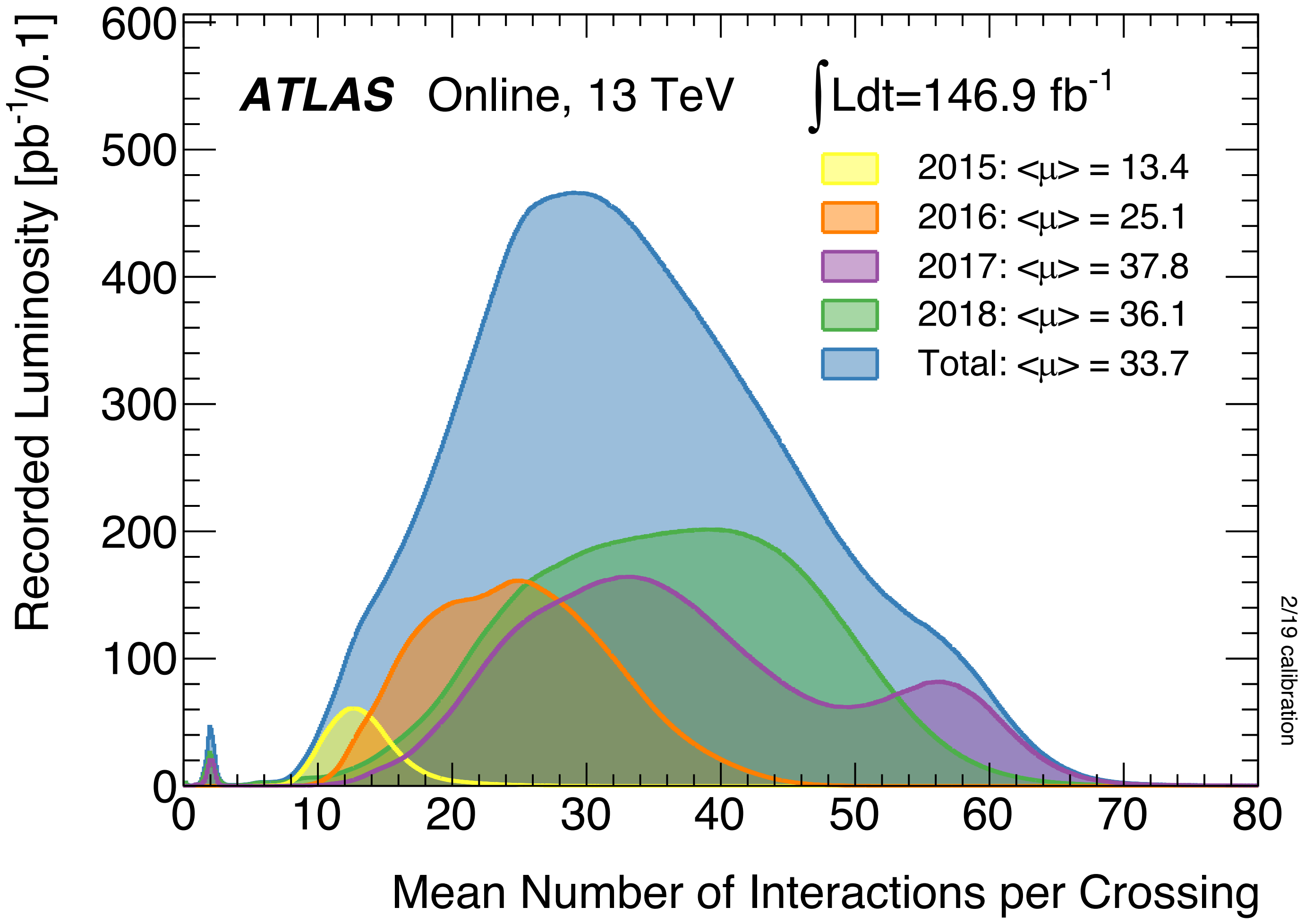
A Z→ll candidate produced with 65 reconstructed proton-proton collisions.



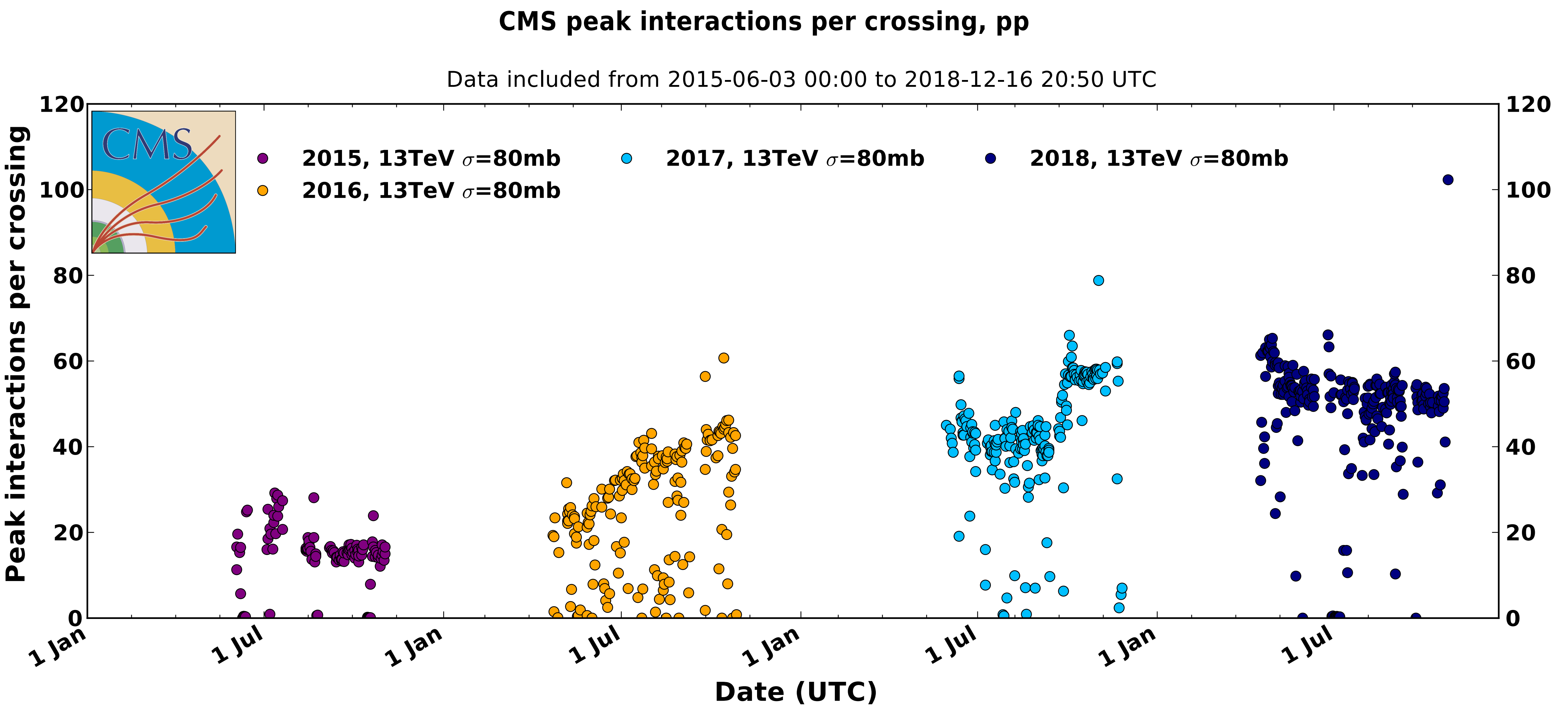
ATLAS EXPERIMENT

HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle\mu\rangle=200$

Pile-up on ATLAS in Run-2



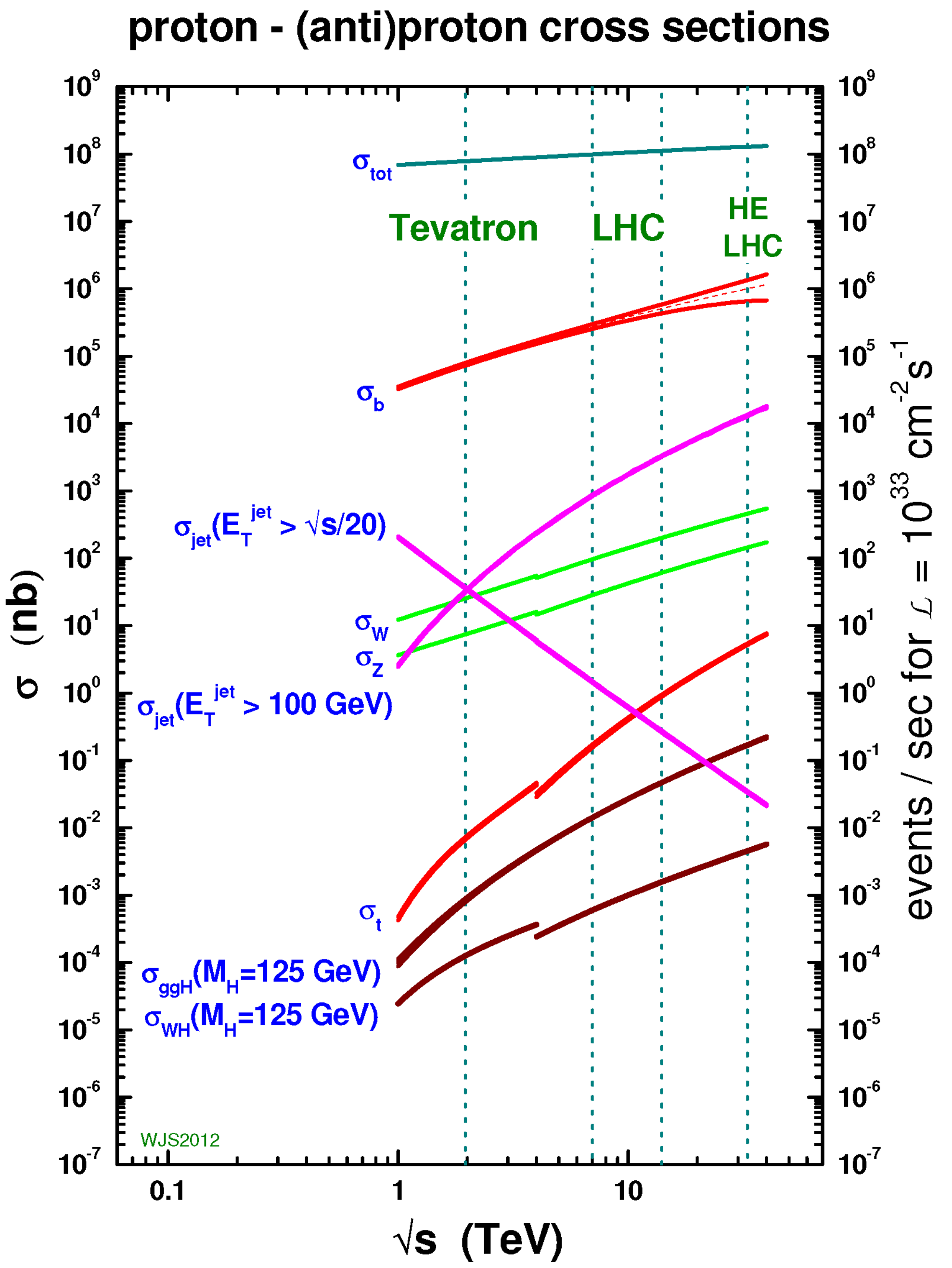
Pile-up on CMS in Run-2



The Proton-Proton Collision

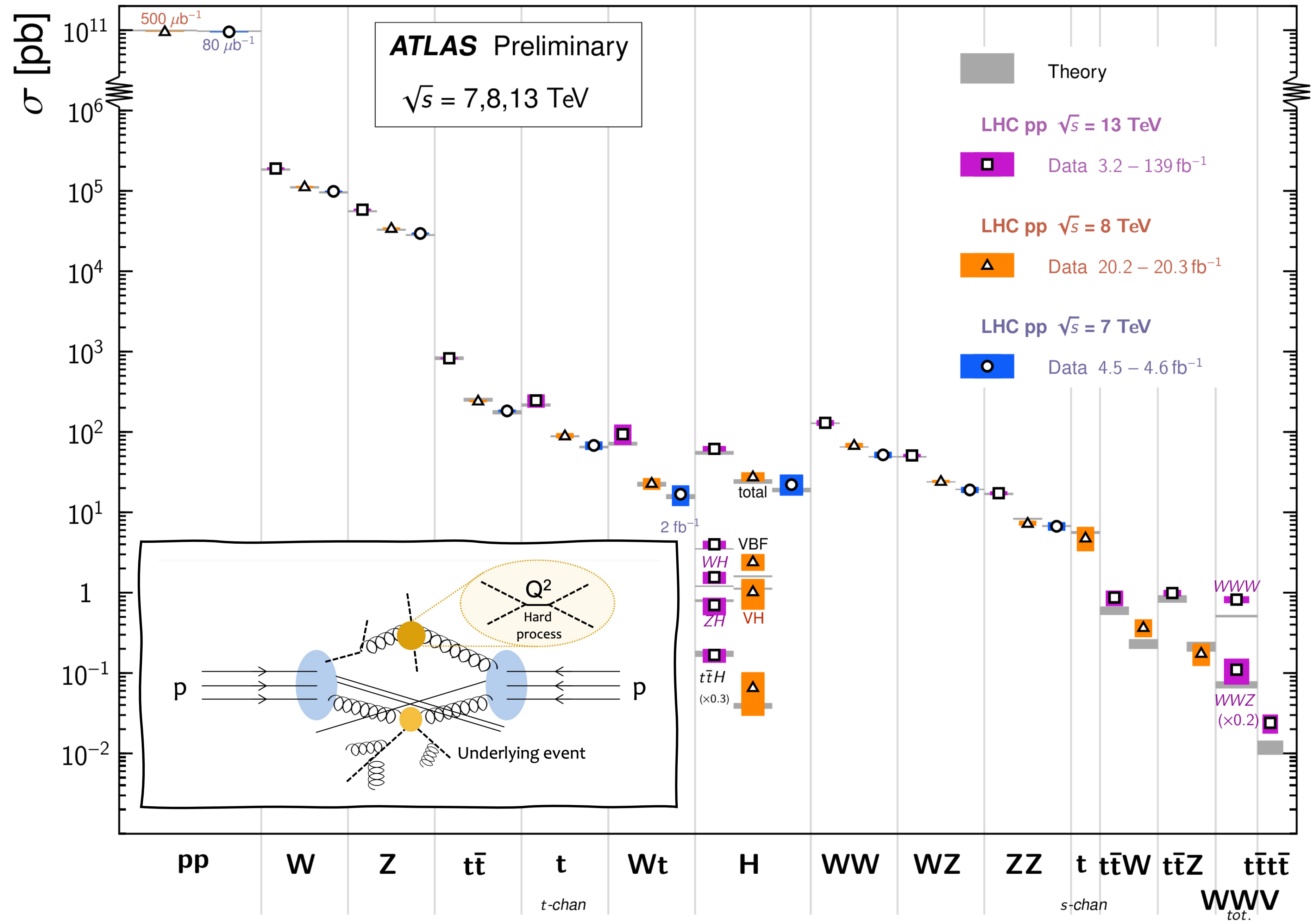
Stirling plot

More: https://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html



Standard Model Total Production Cross Section Measurements

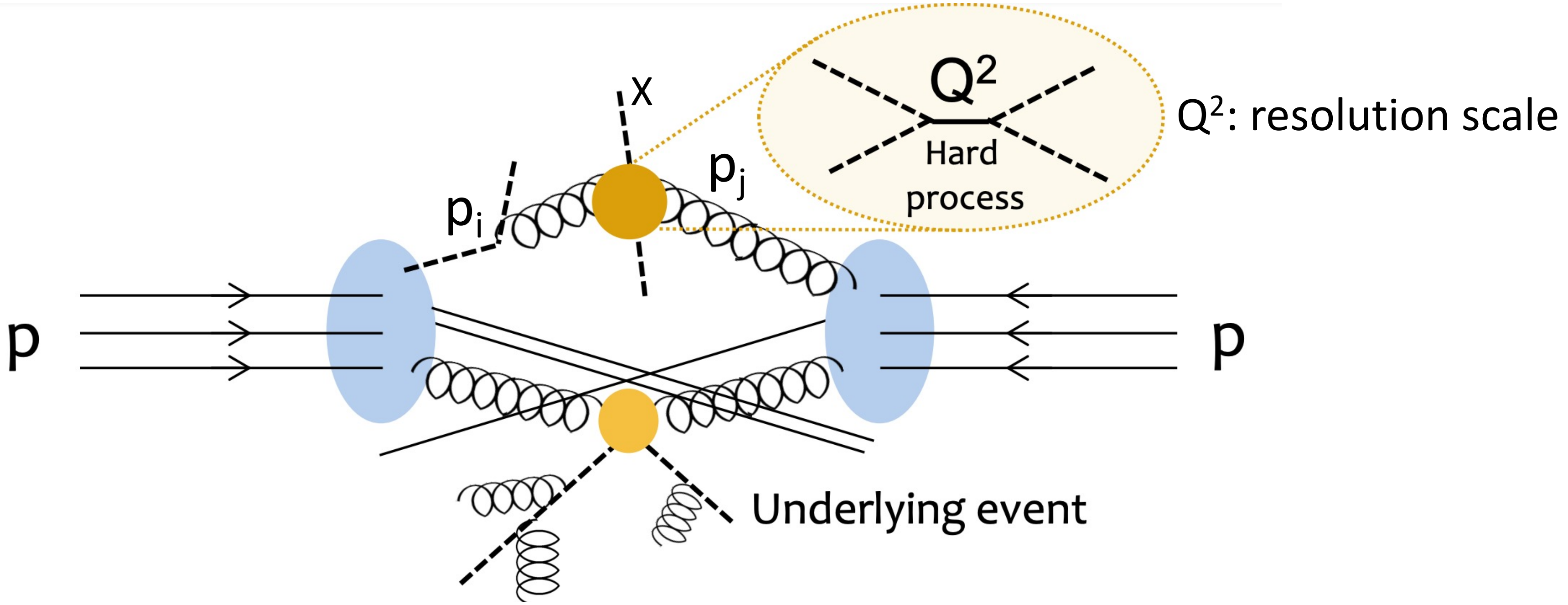
Status: February 2022



Hard process

The centre-of-mass energy of the interaction is not known a priori

$$\hat{s} = x_1 x_2 s$$

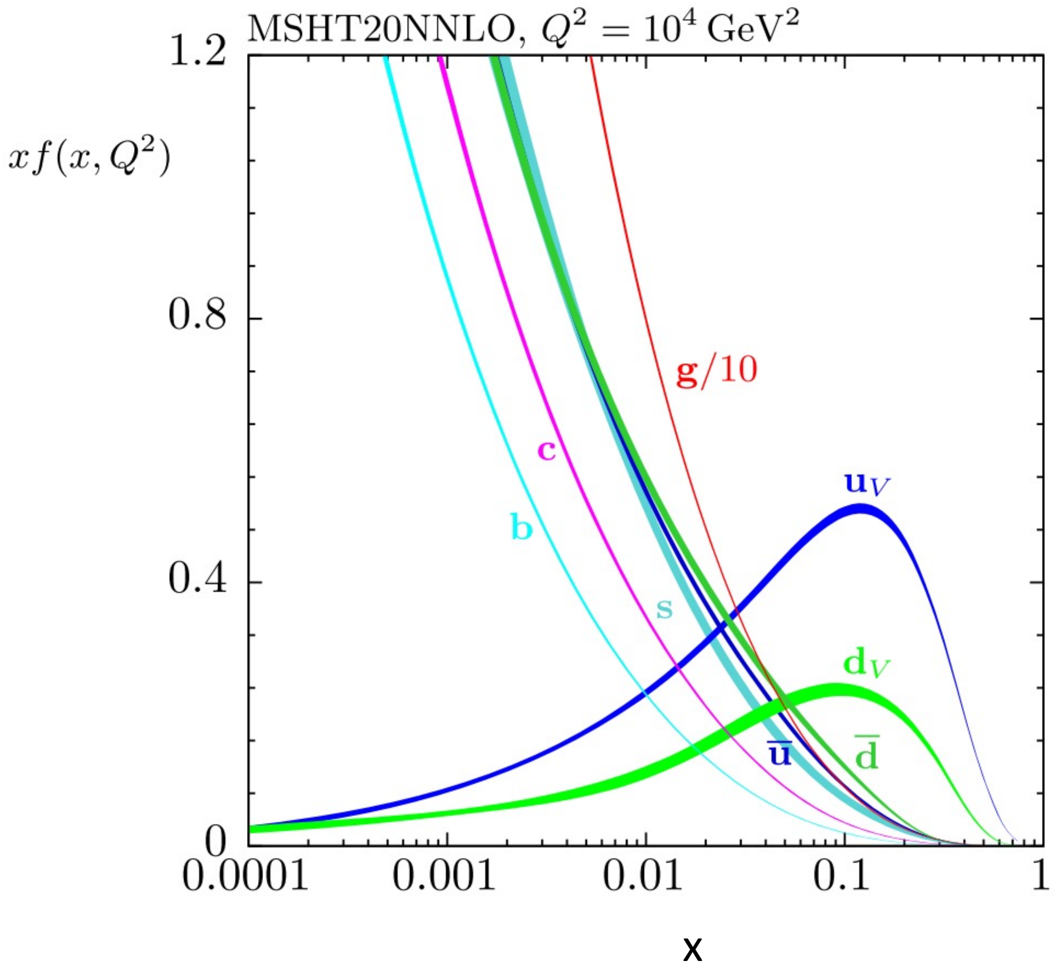


$$\sigma(pp \to X) = \Sigma_{i,j} \int dx_1 dx_2 f_{i,p}(x_1, Q^2) f_{j,p}(x_2, Q^2) \hat{\sigma}_{ij \to X}(x_1 x_2 s, Q^2)$$

sum runs over all possible initial-state partons, with longitudinal momentum fractions $x_{1,2}$, that can give rise to a final state X at a centre-of-mass energy of $\sqrt{x_1 x_2 s}$

Parton Distribution Functions

- probability to find a parton with a momentum fraction of x
- not calculable, but measured in DIS experiments

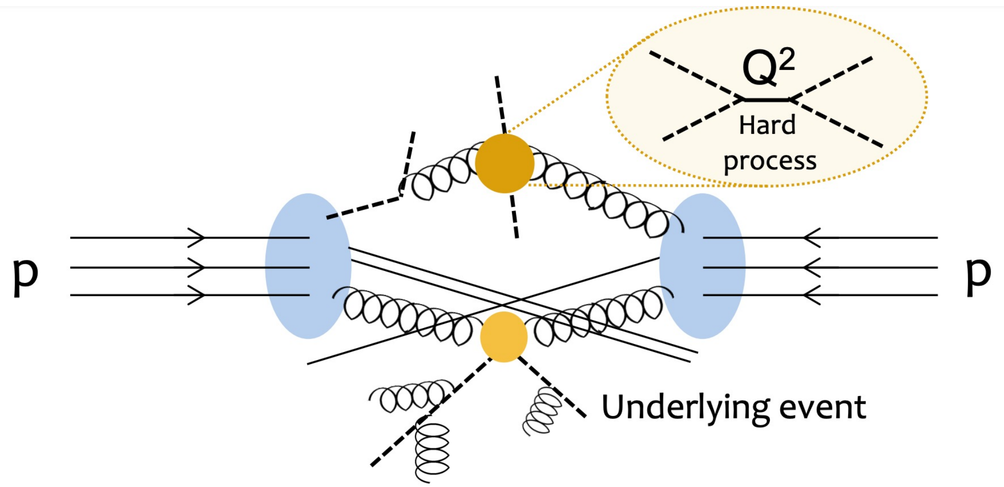


MinBias event

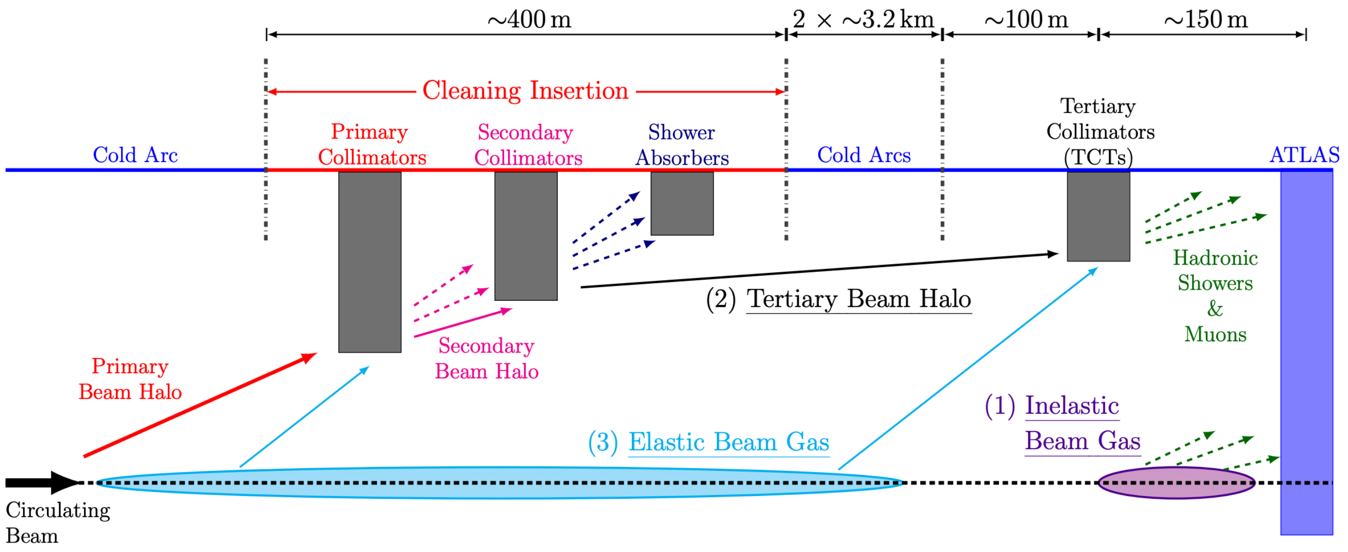
- Inelastic hadron-hadron events selected with an experiment's "minimum bias trigger"
- Usually associated with inelastic events
- Useful for studies of:
    - General characteristics of pp interactions
    - Multi-parton interactions, structure of protons, …
    - Understand the impact of the non-hard-scatter processes to the physics analyses

Underlying event

- The soft part associated with the hard-scattering process
    - beam-beam remnants
    - parton-parton interactions
    - Initial and final state radiation



Other background events: Beam induced



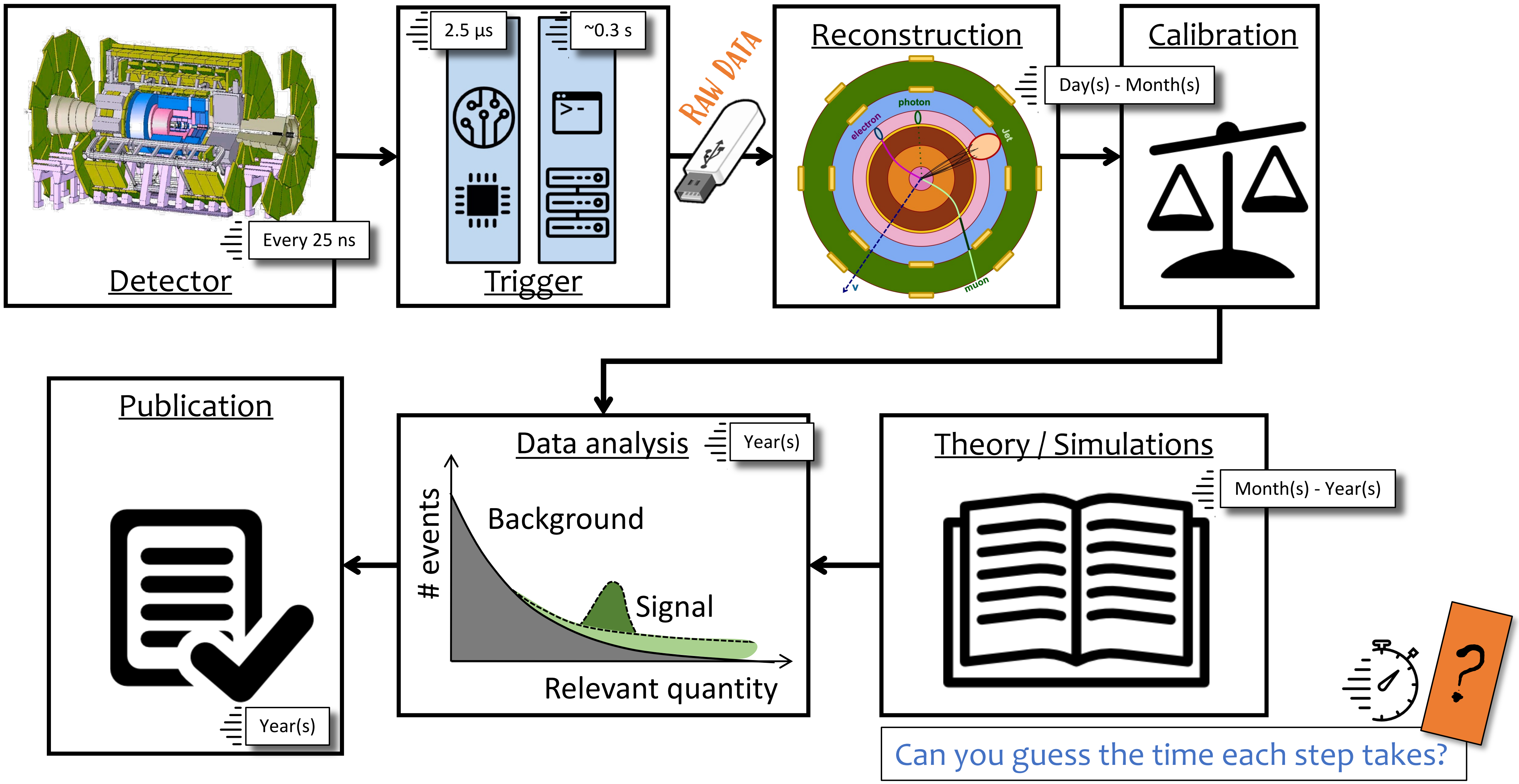
1. **Beam gas events:** collisions between the proton bunch and residual gas inside the beam-pipe. Can be inelastic (occuring off-center in the detector if nearby the detector) or elastic.

2. **Beam halo events:** the effect of protons from a bunch scraping against an up-stream collimator. The scraping results in sprays of muons running approximately parallel to the beam-line.

3. **Cavern background:** the gas of neutrons and photons inundating the cavern during a typical run of the LHC. These mostly contribute random hits in the muon system.

THE RAW DATA

The lifetime of a collision event



What does raw data contain?

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

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]	L1 Trigger Bits Before Prescale
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]	L1 Trigger Bits After Prescale
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]	L1 Trigger Bits After Veto
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]	

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0x0000001a	0x00080000	524288	lvl1 trigger info[5]
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0x0000001c	0x00020001	131073	lvl1 trigger info[7]
0x0000001d	0x00000816	2070	lvl1 trigger info[8]
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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, ID (info[16]–info[23]):
4, 67, 132, 139, 202

What does RAW data contain?

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

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 data contain?

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

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]
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0x00000020	0x00021001	135169	lvl1 trigger info[11]
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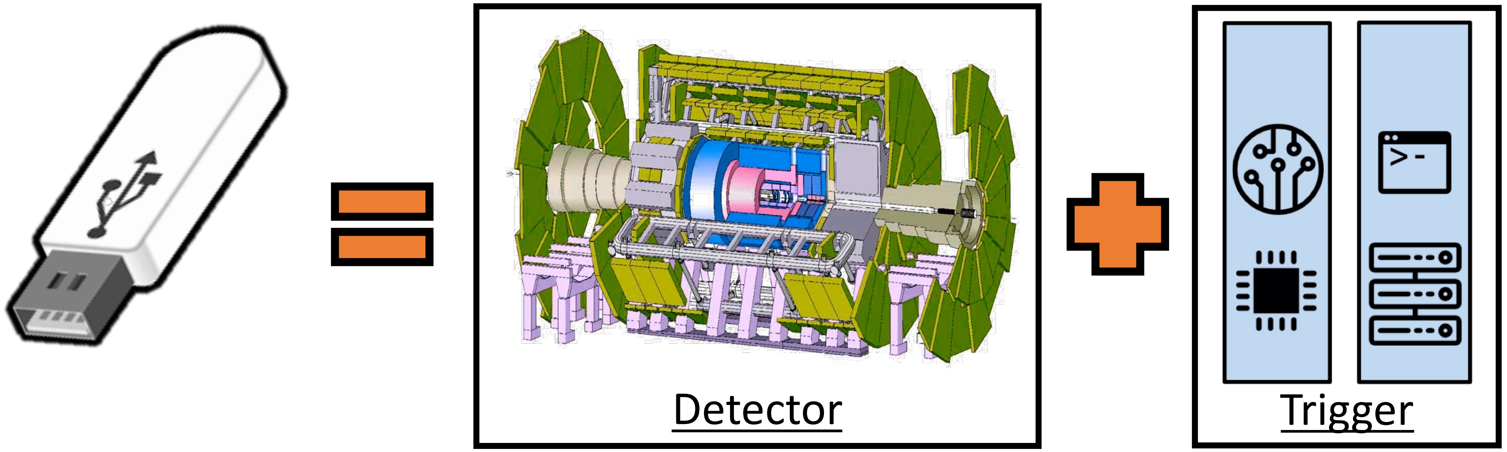
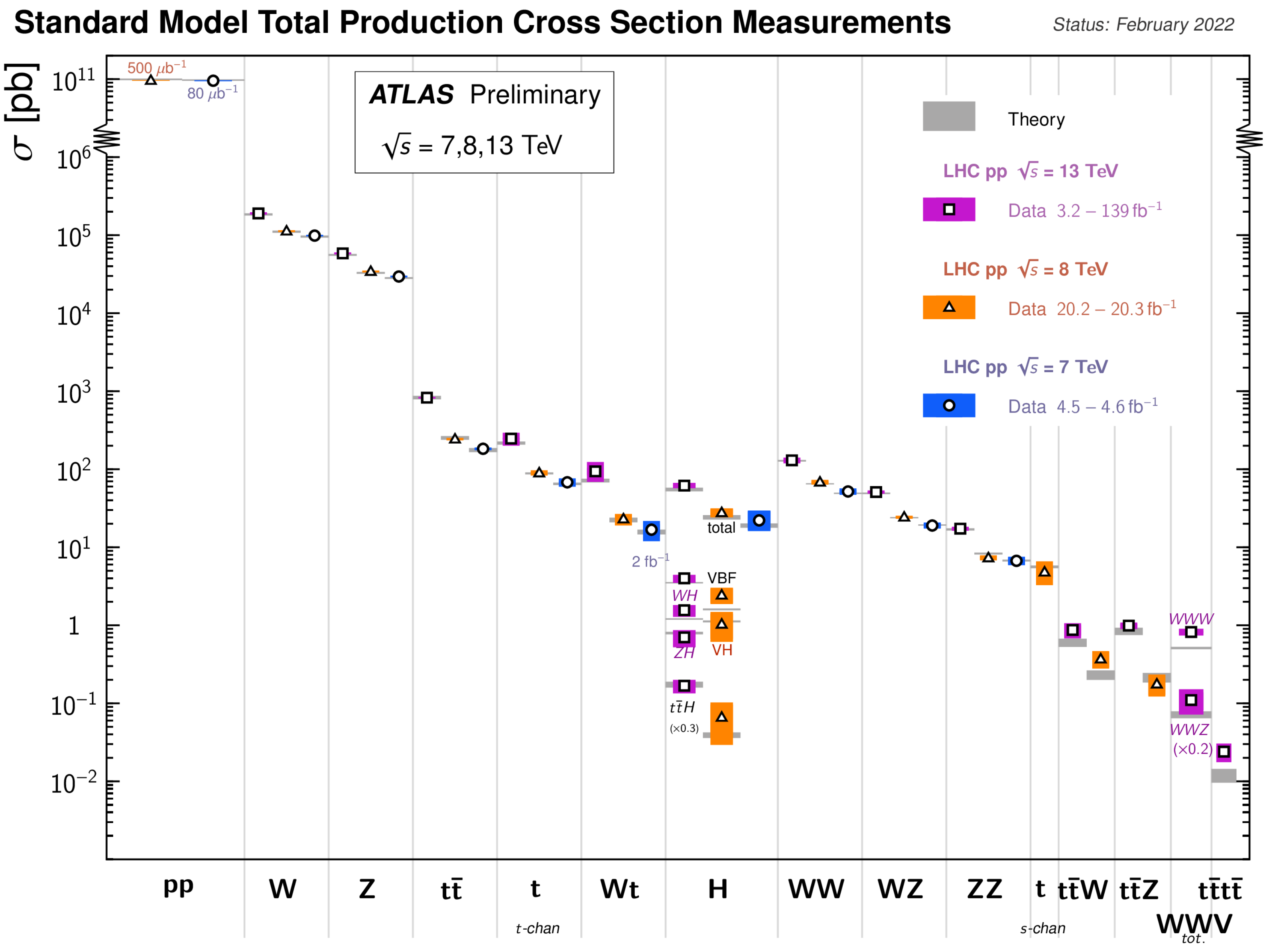
0x0000002a	0x00000000	0	lvl1 trigger info[21]
0x0000002b	0x00000400	1024	lvl1 trigger info[22]
0x0000002c	0x00000000	0	lvl1 trigger info[23]

- 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 data contain?



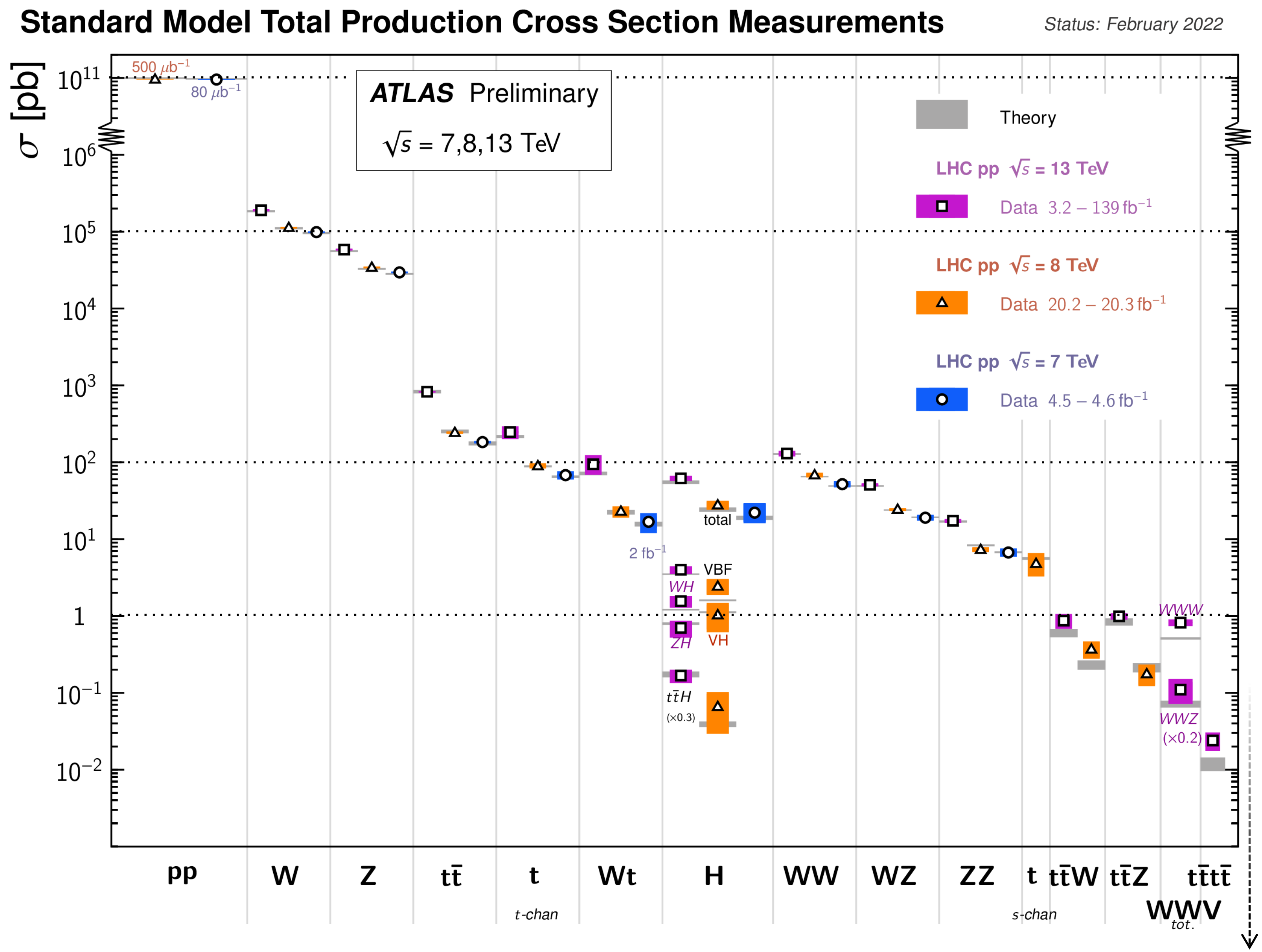
Trigger


Standard Model Total Production Cross Section Measurements
Status: February 2022
ATLAS Preliminary
√s = 7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 13 TeV
Data 3.2 – 139 fb−1
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb−1
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb−1
500 μb−1
80 μb−1
2 fb−1
total
VBF
WH
ZH
VH
tt̄H
(×0.3)
WWW
WWZ
(×0.2)
pp
W
Z
tt̄
t
t-chan
Wt
H
WW
WZ
ZZ
t
s-chan
tt̄W
tt̄Z
tt̄tt̄
WWV
tot.

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

Event Rate

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



What is the expected event rate?

Viable SUSY & other exotics

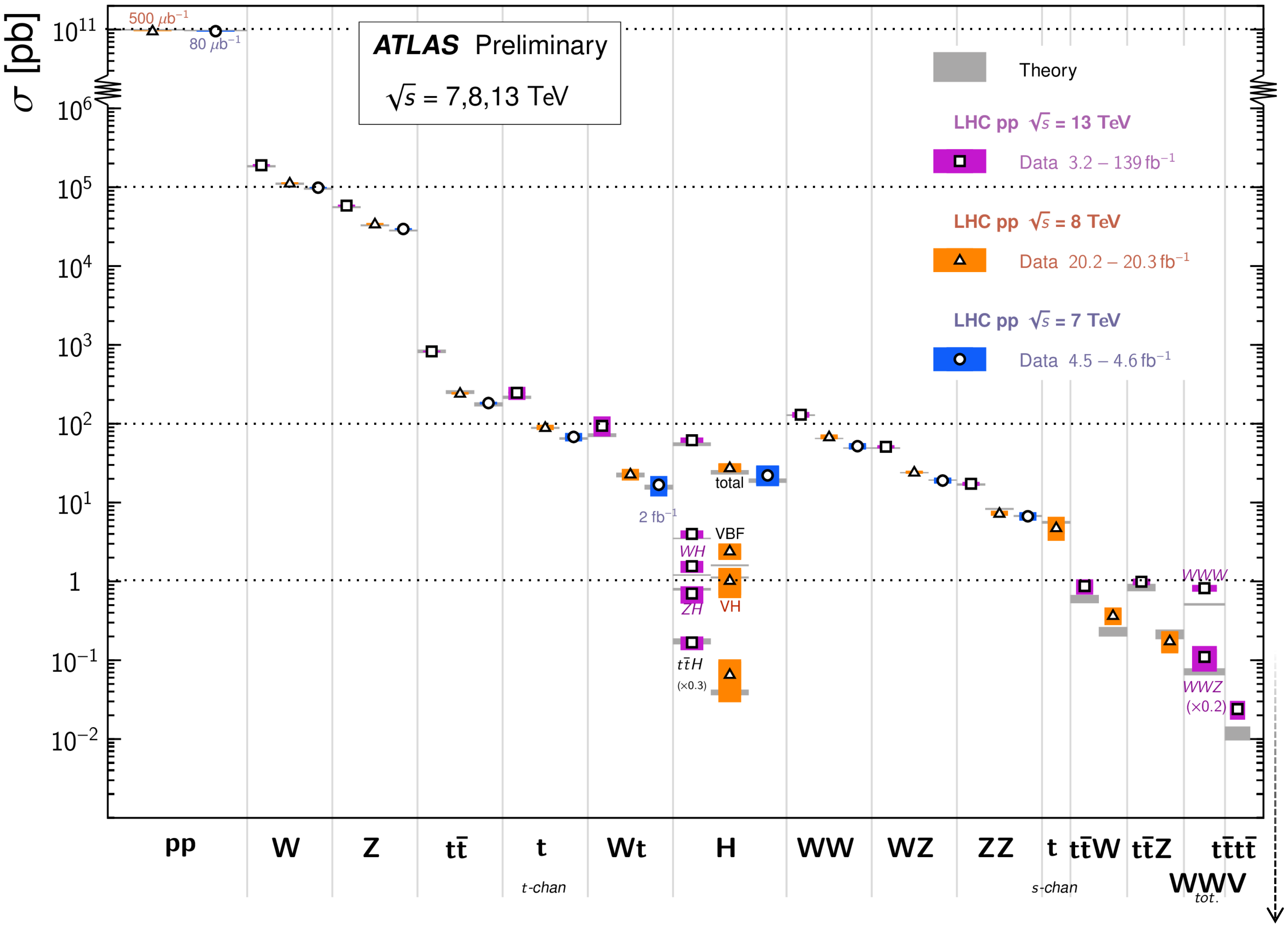
Reminder: $\sigma = \frac{\#\ \text{events}}{L}$

Event Rate

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

Standard Model Total Production Cross Section Measurements

Status: February 2022



1 GHz

1 kHz

1 Hz

10^{-2} Hz

Viable SUSY & other exotics

Triggering Challenge

Maintain a rich acceptance in physics (including unknown new phenomena!) while respecting the limitations of

- Detector readout
- DAQ system & HLT
- Computing system

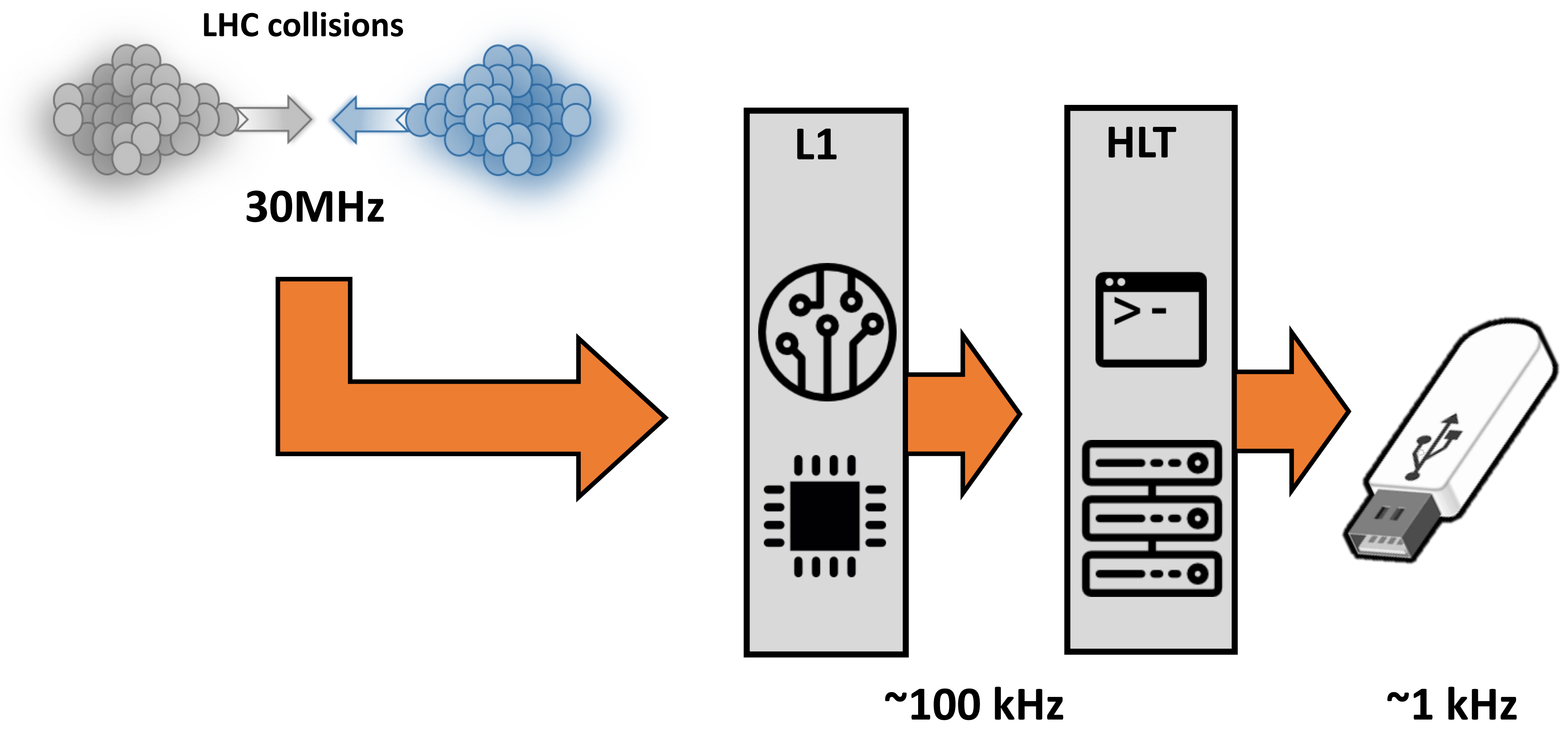
and knowing that the event rate is dominated by “backgrounds” and is significantly affected by pile-up.

➔ Find ways to reduce fakes and improve robustness to pile-up, respecting the limitations imposed by various systems.

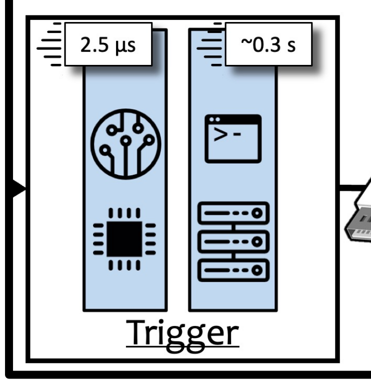
➔ Various upgrades and new features introduced in DAQ, L1 and HLT.

➔ Key feature: robustness; **events that are not triggered are lost forever.**

Triggering in Physics
The ATLAS / CMS paradigm

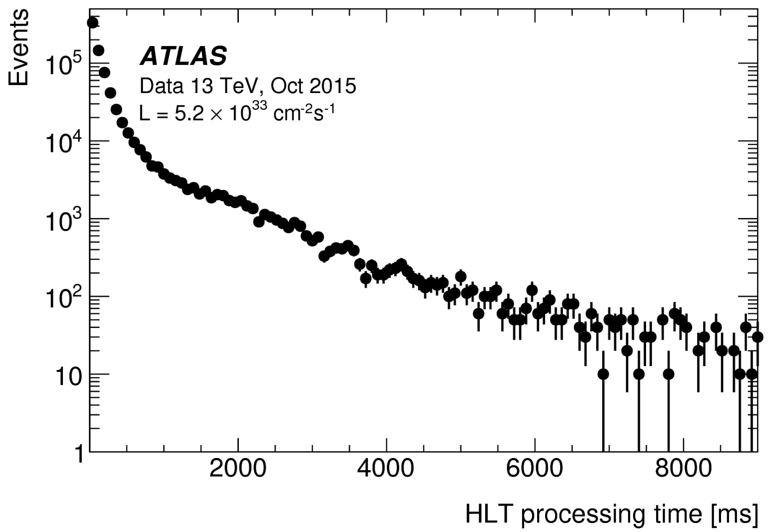


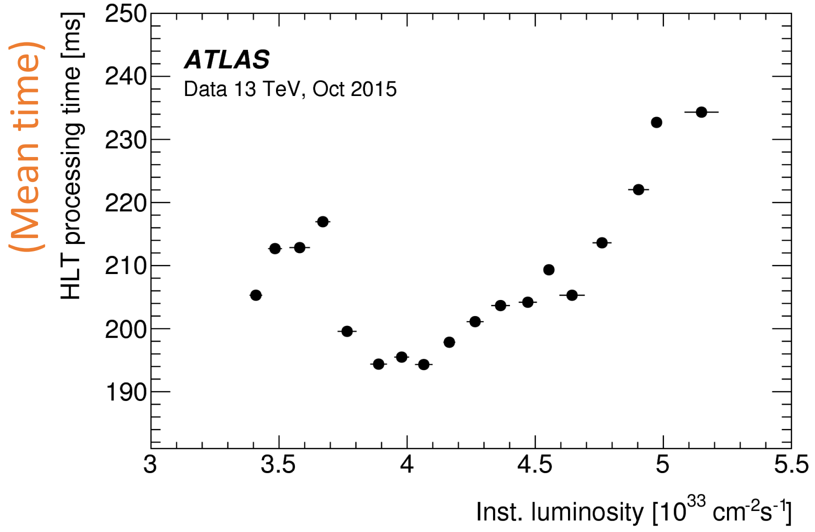
“Real-time” processing – how fast is it?



- The hardware level trigger system is a **‘fixed latency’ system**: every bunch crossing needs to be processed in the same amount of time for the system to remain in-sync.
- The high-level trigger system processes the event at a maximum allowed time, which is a lot higher than the **average processing time**

An example run in 2015:

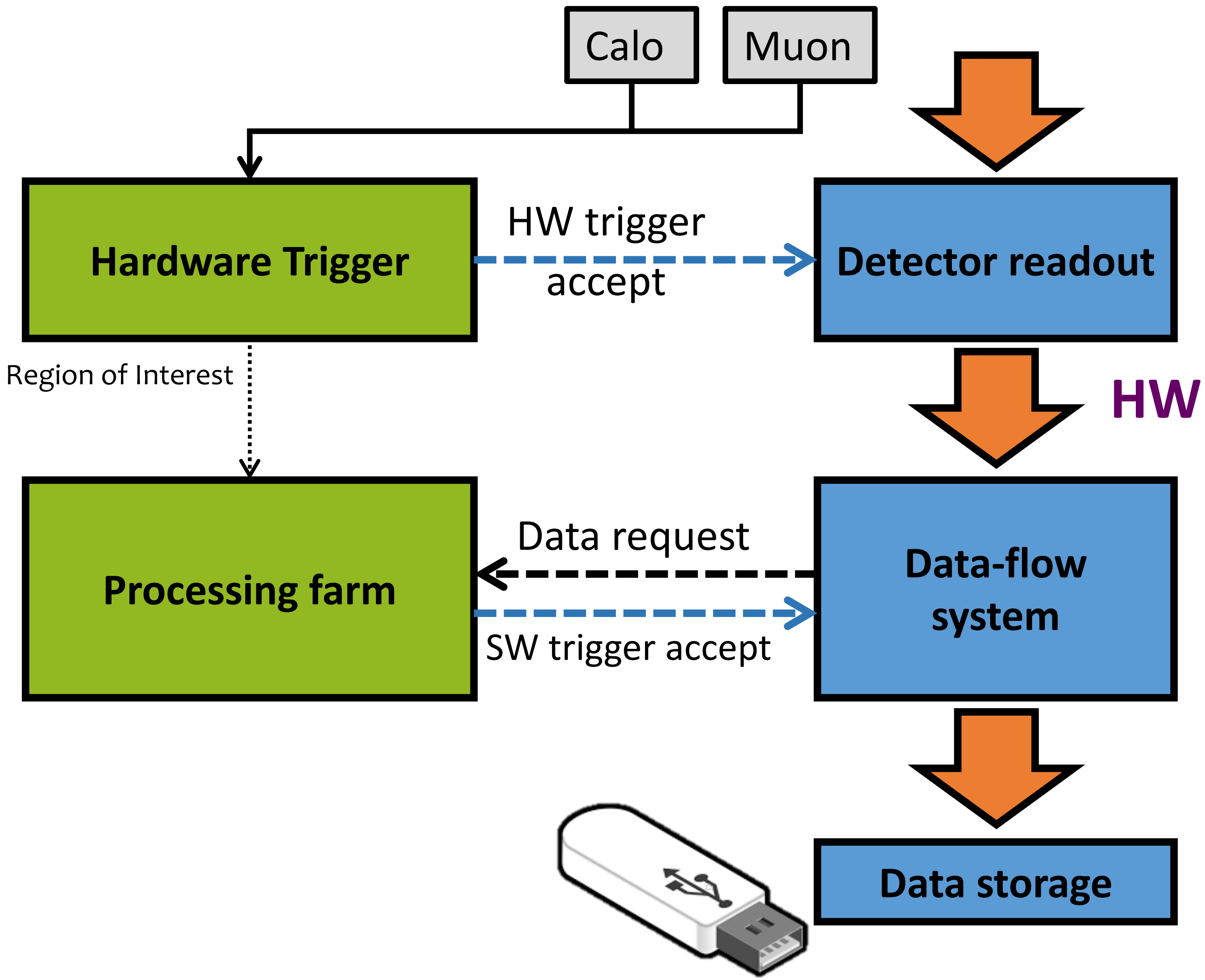




Triggering in Physics

Architecture: Very simplified view

In 2018



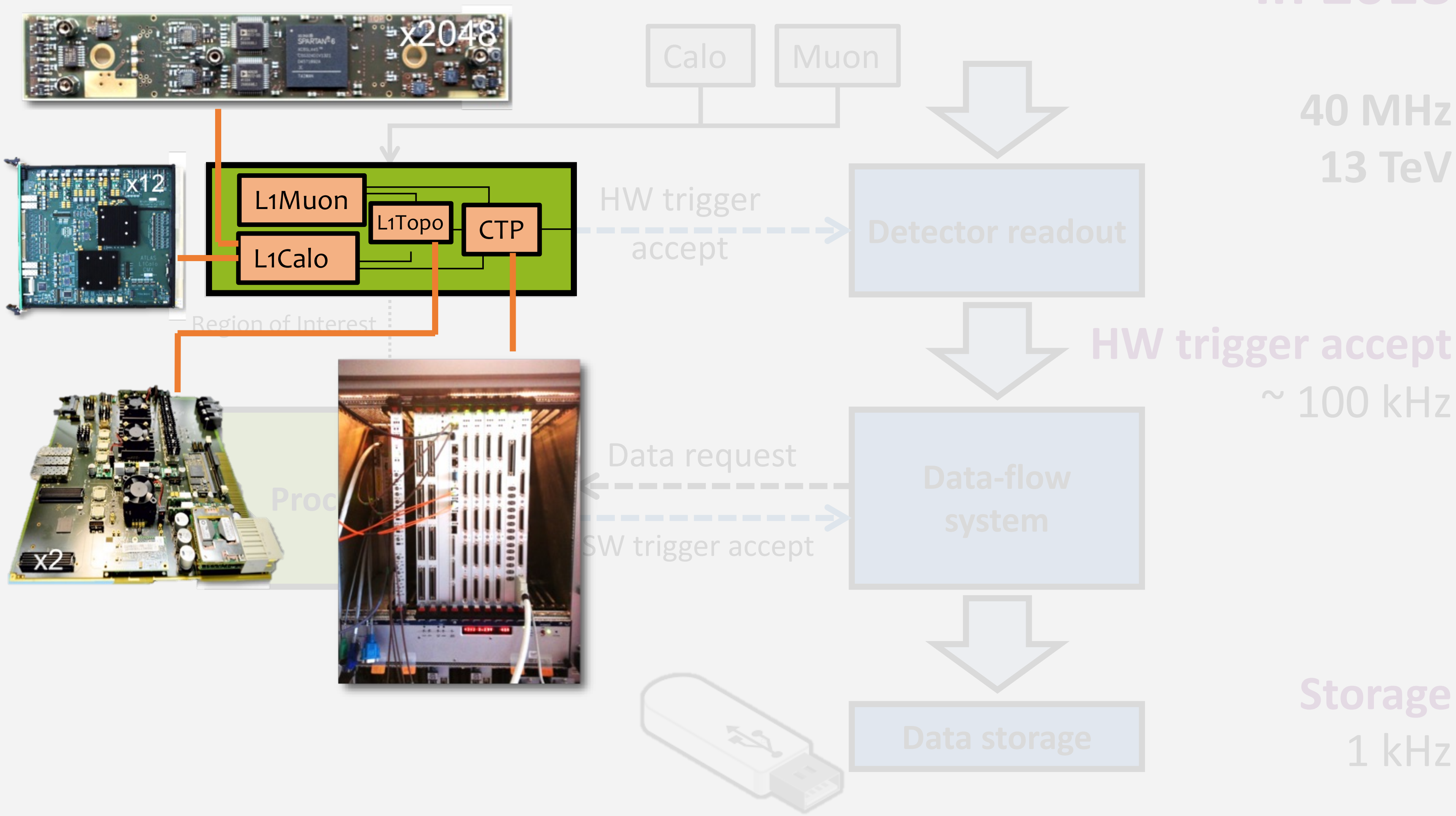
40 MHz
13 TeV

HW trigger accept
~ 100 kHz

Storage
1 kHz

Triggering in Physics

Architecture: Very simplified view



Triggering in Physics

Processing farm

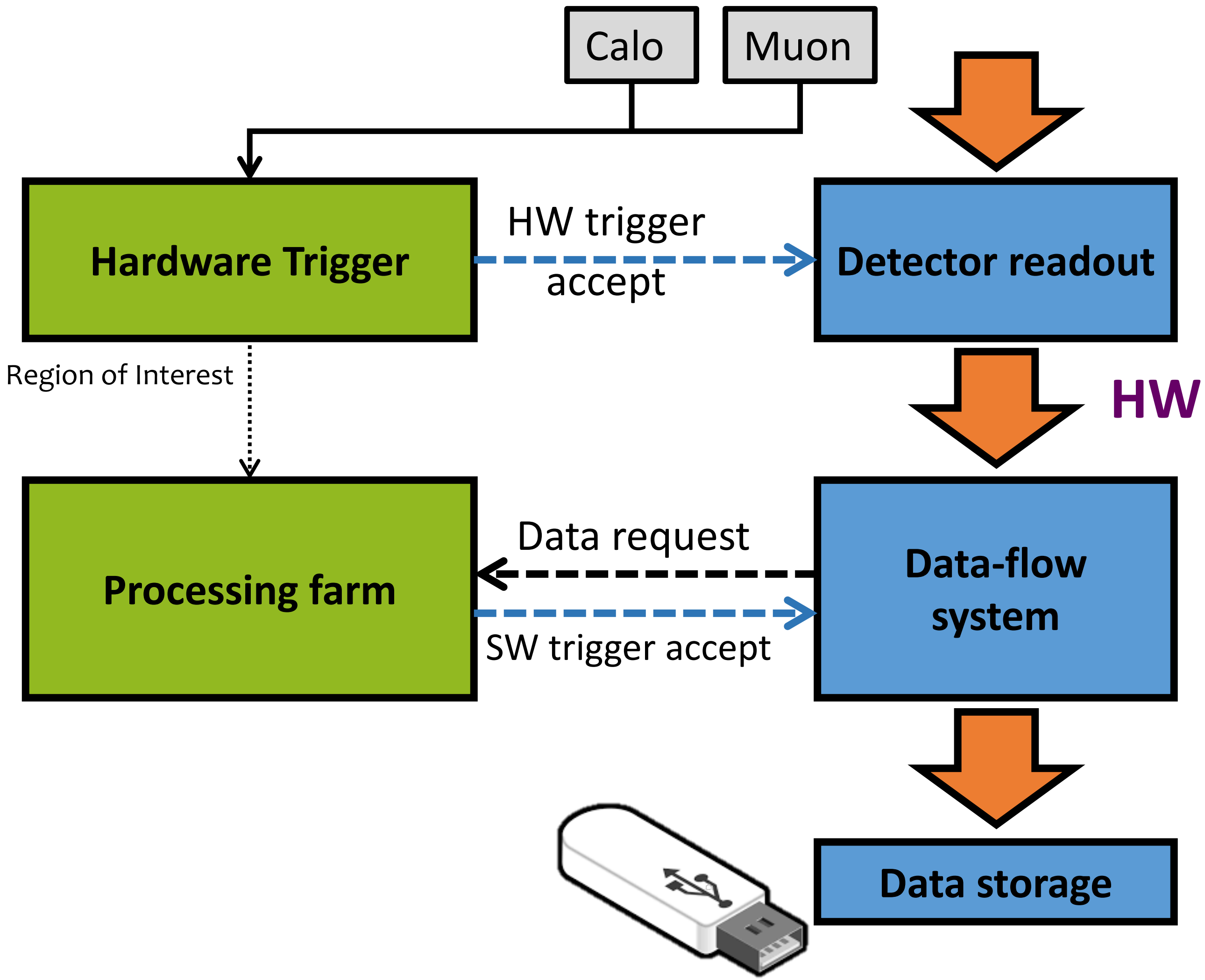
Either CPUs or CPUs + GPUs (LHCb, CMS) in Run3

Triggering in Physics

Architecture: Very simplified view

In 2018

40 MHz
13 TeV

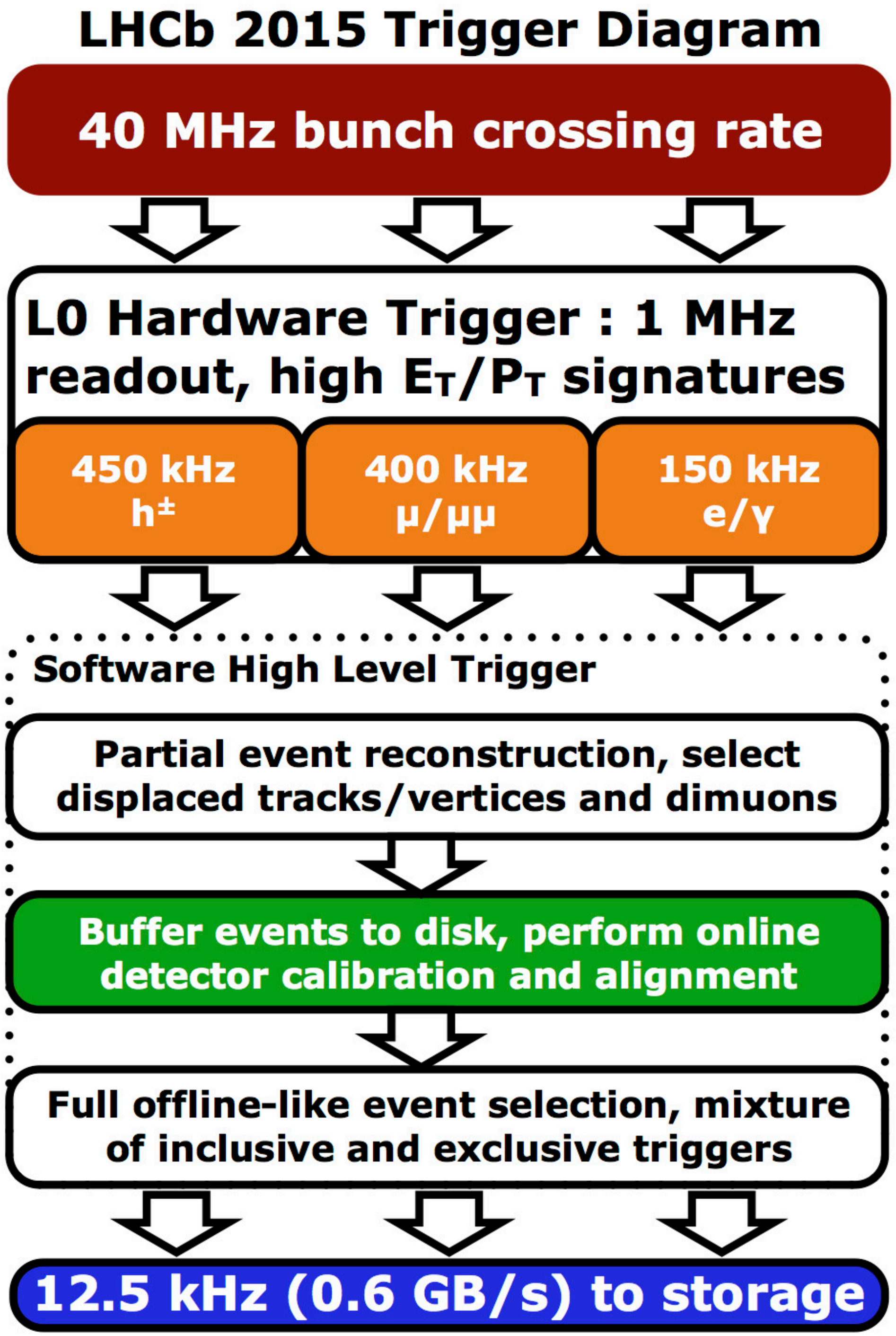


HW trigger accept
~ 100 kHz

Storage
1 kHz

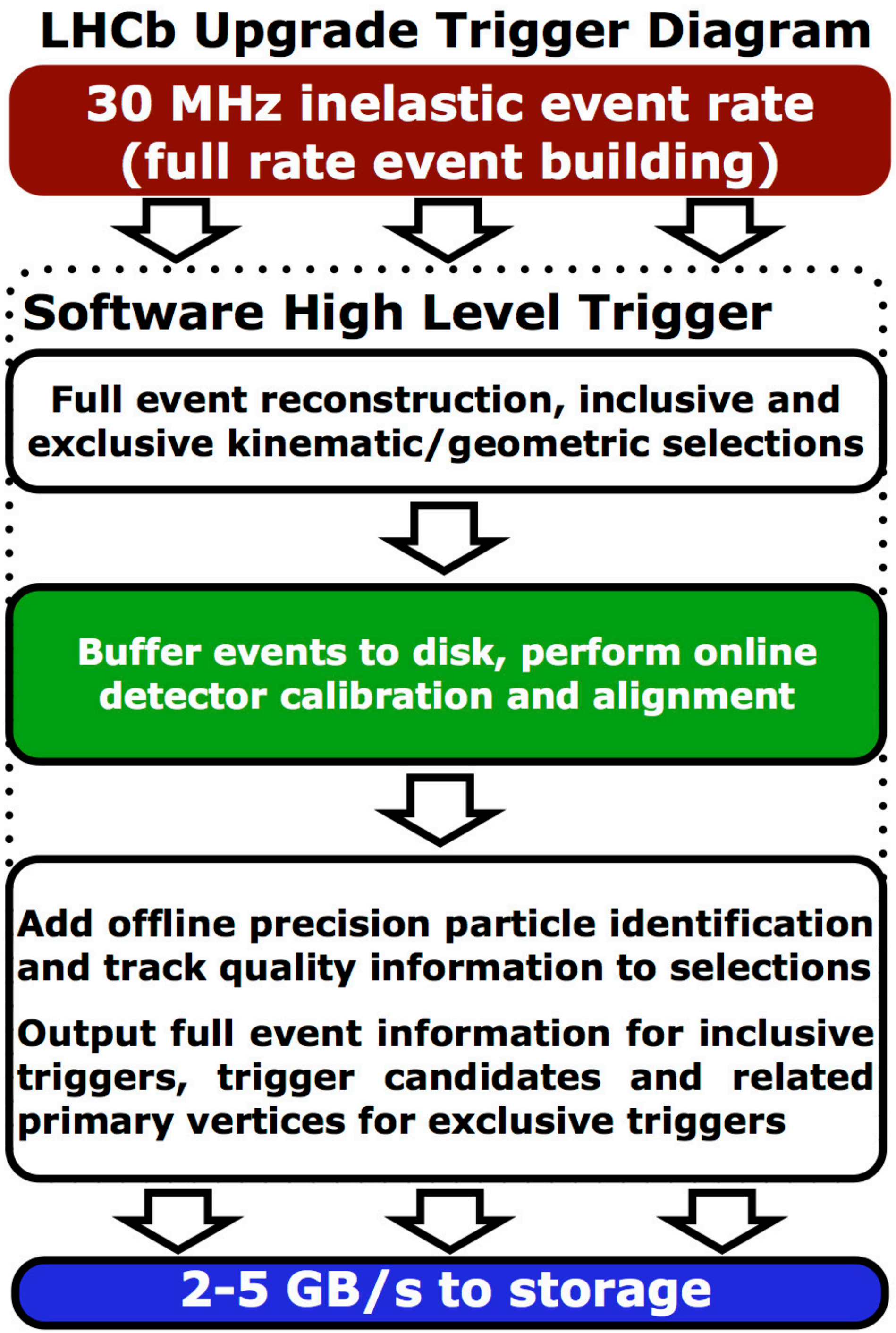
Limitations from:
- detector;
- data acquisition;
- computing

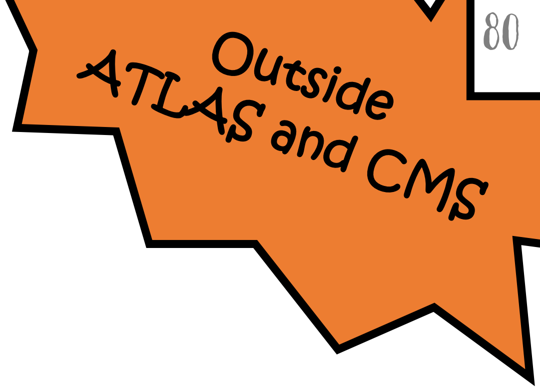
Triggering in physics in LHCb



Outside ATLAS and CMS

TRIGGERING IN PHYSICS IN LHCb

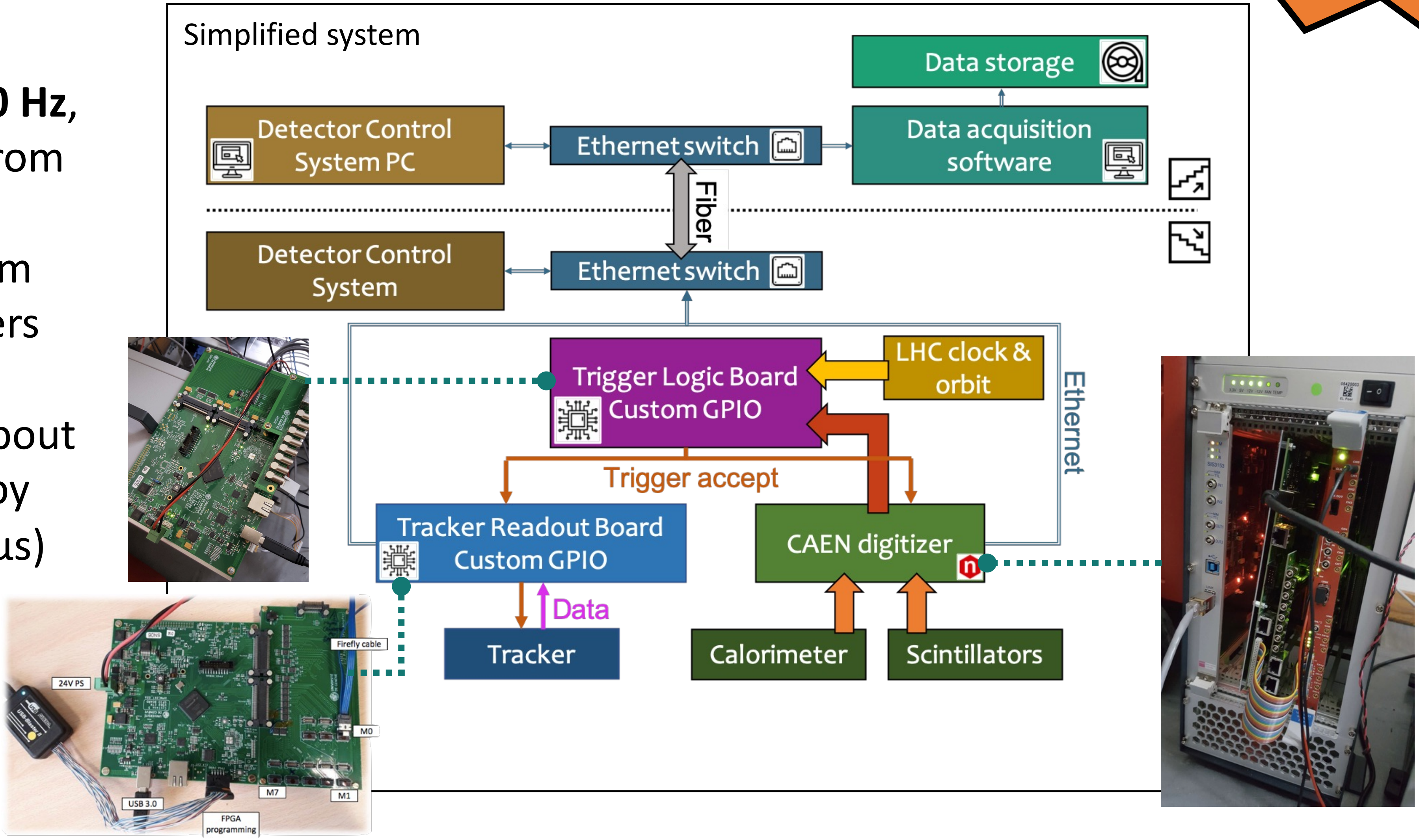




Triggering in physics in FASER

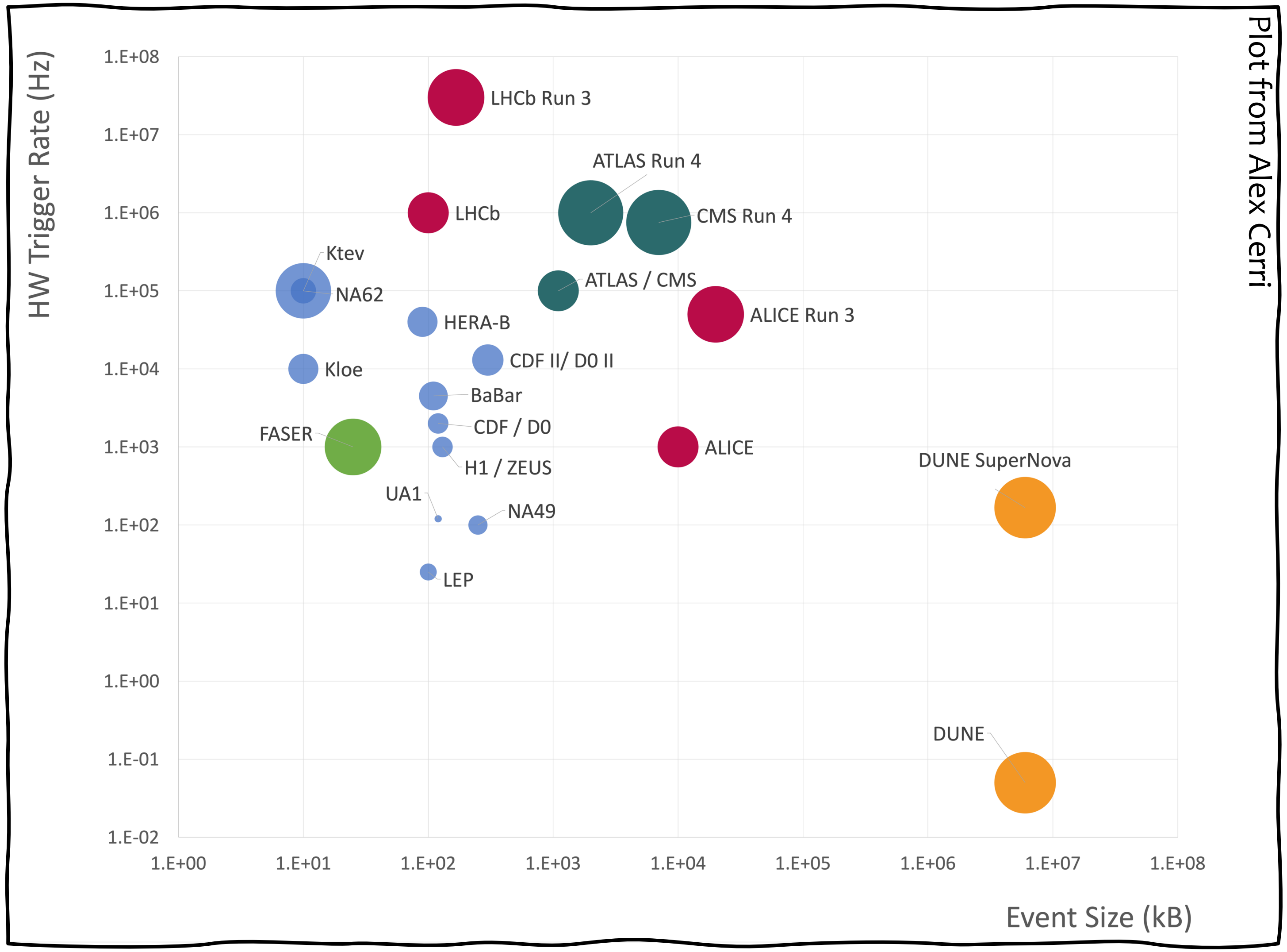
Outside ATLAS and CMS

- **Trigger rate** about **1000 Hz**, dominated by muons from the IP
  - L1A includes random and software triggers
- Expected **bandwidth** about **15 MB / s**, dominated by PMTs' wide signal (~ 1 µs)



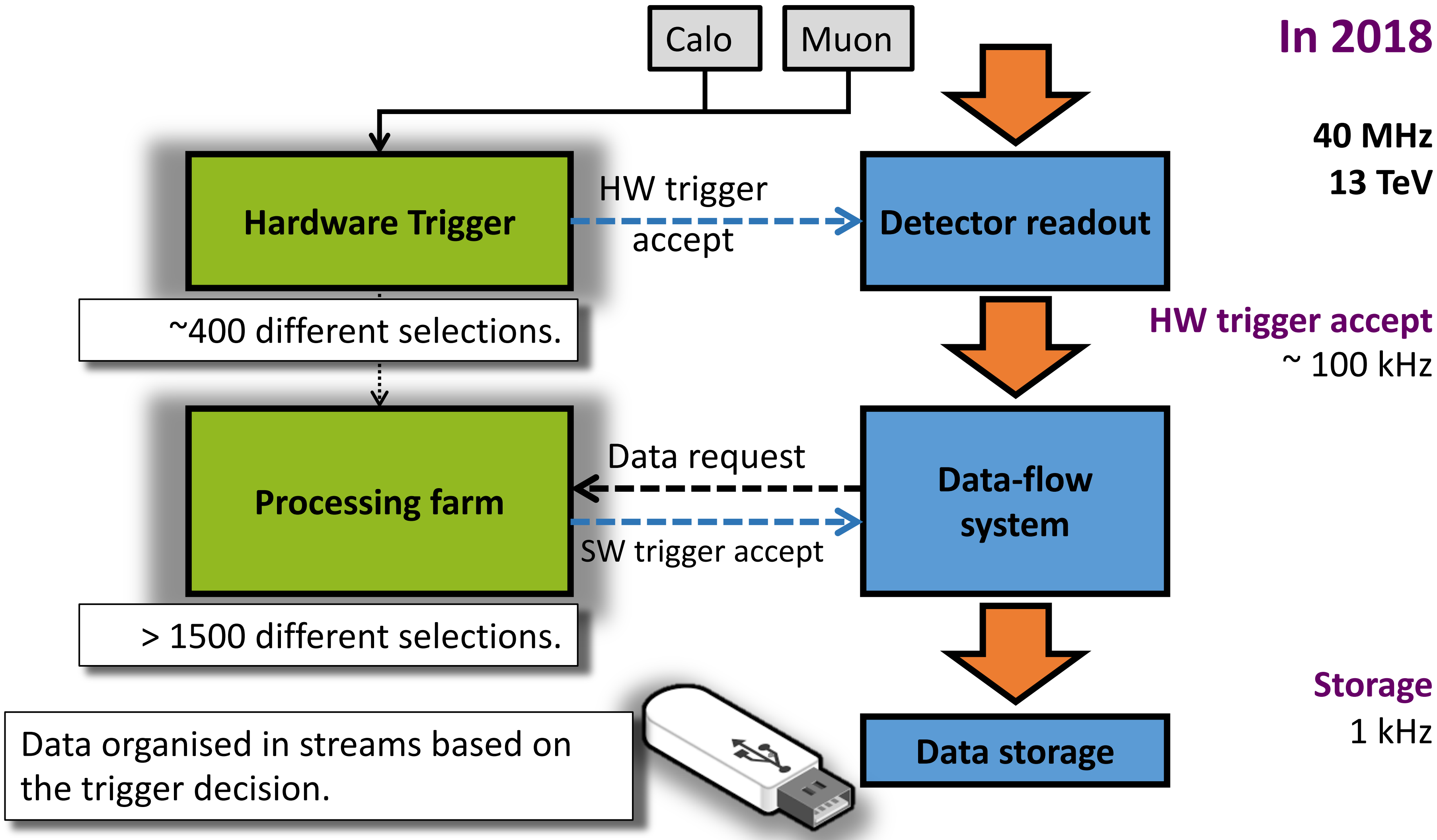
What TDAQ architecture to build?

- Depends on many parameters and numbers.
- For example: event size out of HW trigger level.



Triggering in Physics

Architecture: Very simplified view



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

Data scouting
Contains HLT objects; used for trigger-level analysis

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

Physics Menus

Menu constructed to respect limitations from:
- detector;
- data acquisition;
- computing

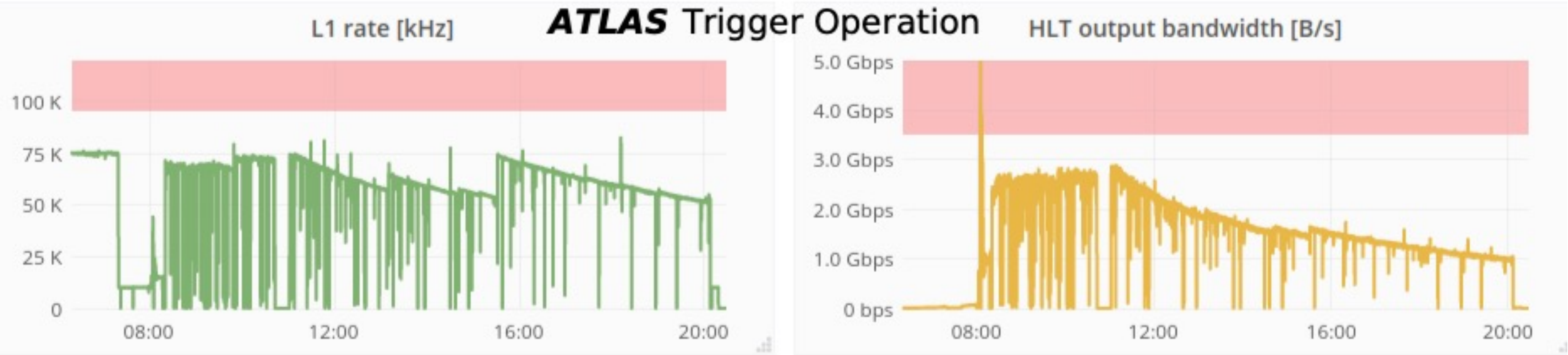
Trigger selection	**2015 offline threshold (GeV)**	**2016 offline threshold (GeV)**	**2017 offline threshold (GeV)**	**2022 offline threshold (GeV)**	**Representative physics case**
Peak Luminosity	5×10^{33} cm^{-2} s^{-1}	1.2×10^{34} cm^{-2} s^{-1}	1.7×10^{34} cm^{-2} s^{-1}	2.0×10^{34} cm^{-2} s^{-1}	
isolated single e	25	**27**	27	27	"Main" triggers. Thrs driven by Higgs (ZH, WH), Top, SUSY.
isolated single μ	21	**27**	27	25	
di-γ	40, 30	**40, 30**	40, 30	40, 30	Higgs (H→γγ, HH→bbγγ).
di-τ (+ jet)	40, 30	**40, 30**	40, 30	40, 30	Higgs (H→ττ, HH→bbττ), SUSY.
four-jet (incl. HF)	45	**45**	45	45	SUSY, Higgs, exotics
MET	180	**200**	200	200	

We will come back to trigger menus and performance when we will have talked about reconsturction!

Trigger operations

Limitations from:

- **detector:** e.g. L1 rate and processing latency
- **data acquisition:** e.g. HLT output bandwidth
- **computing:** e.g. HLT output bandwidth for prompt reconstruction

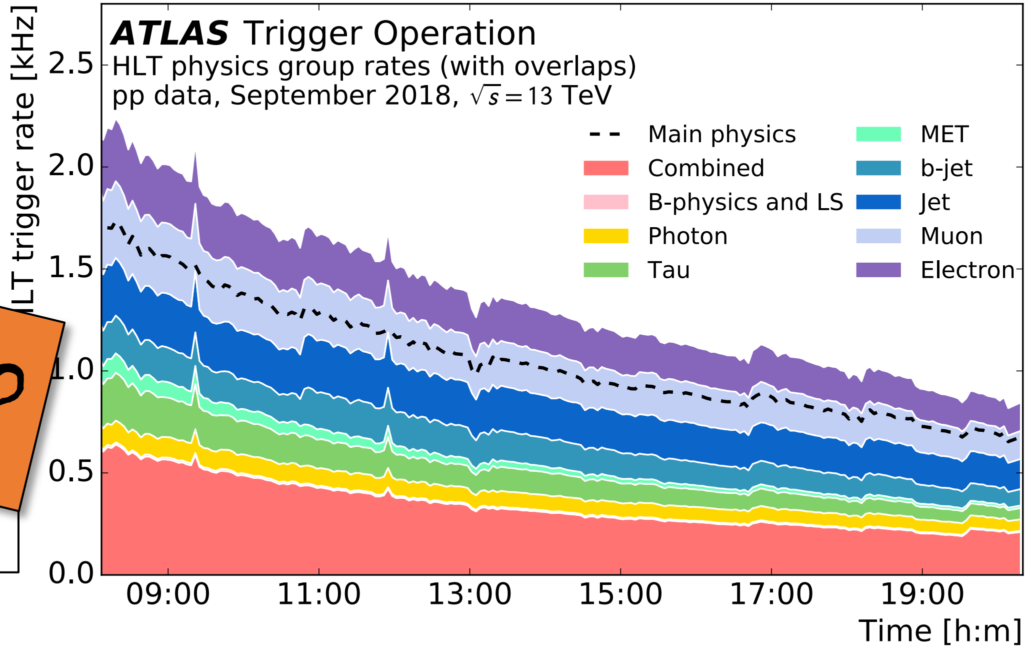


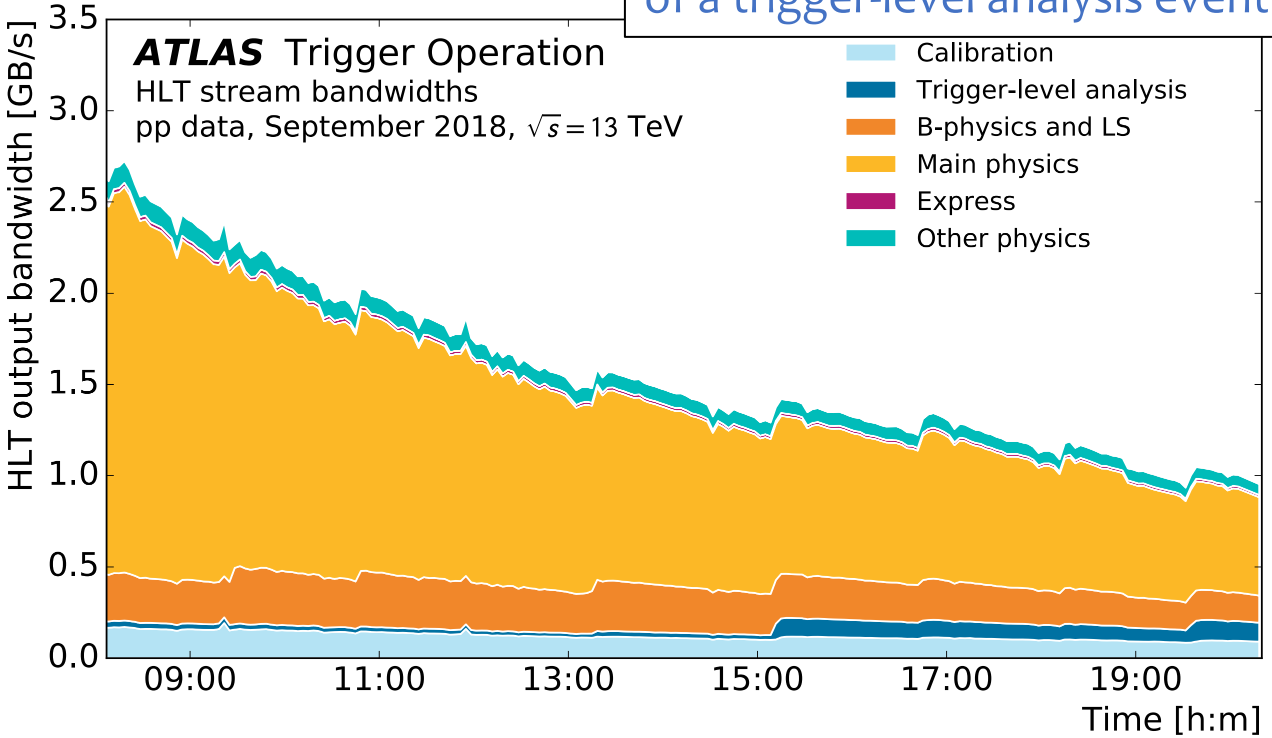
Trigger operations

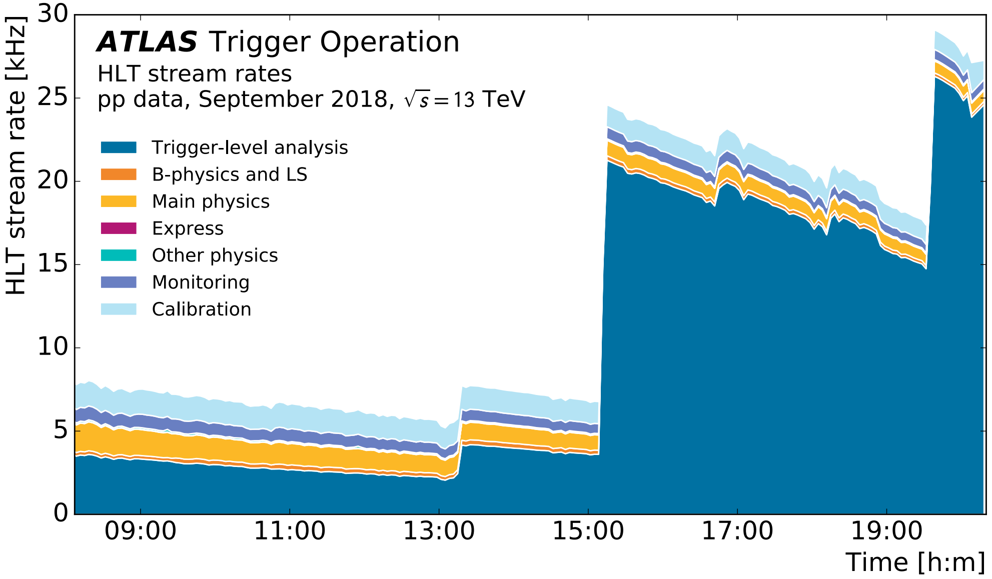
- **Bandwidth = Rate x Event size**
- Rate defines the number of events collected
- Can get higher rate if event size smaller…
  → Partial events for calibrations, but also physics!

Can you estimate the ~ size of a trigger-level analysis event?

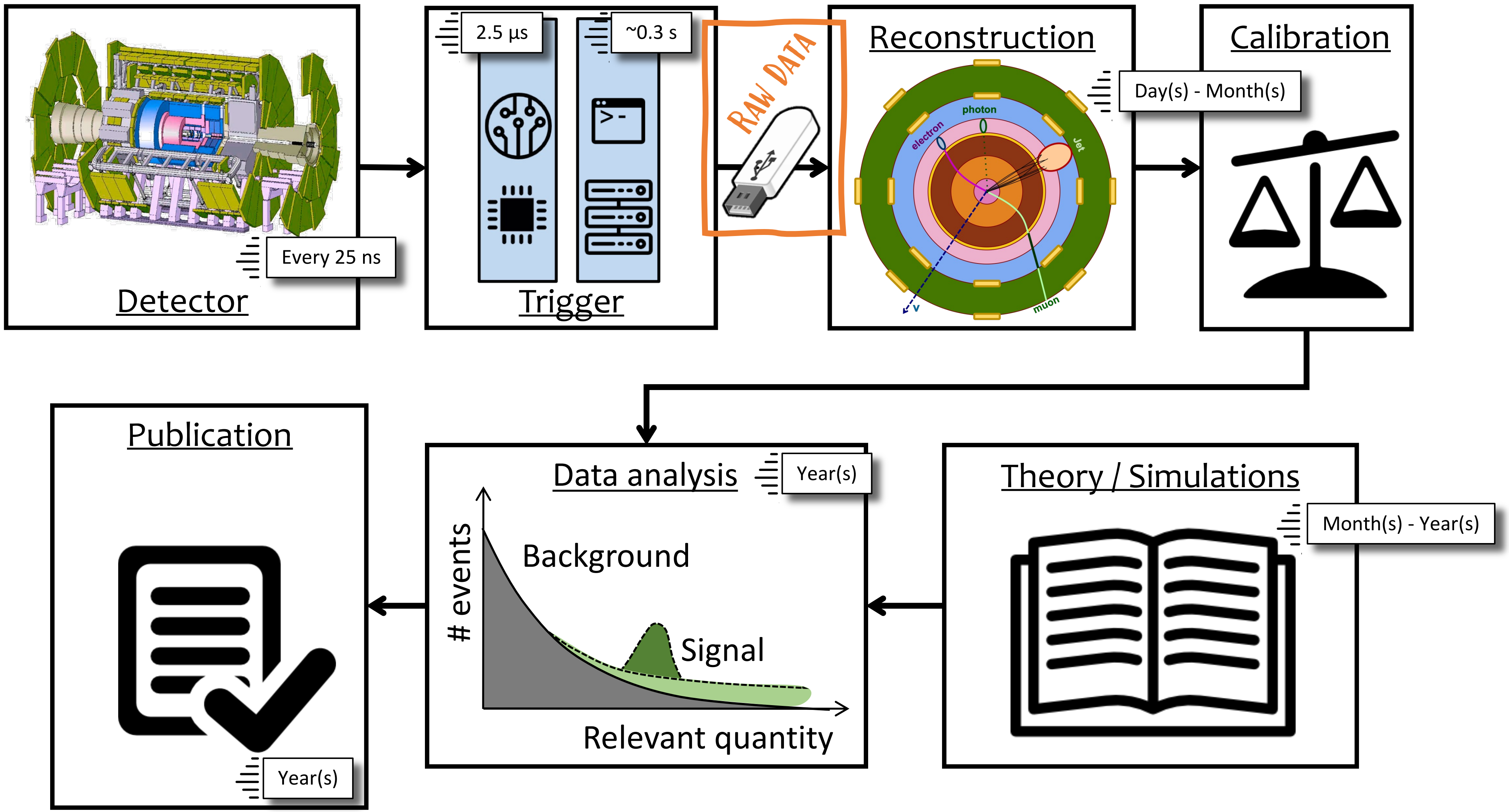
?







The lifetime of a collision event



Emulsion detectors

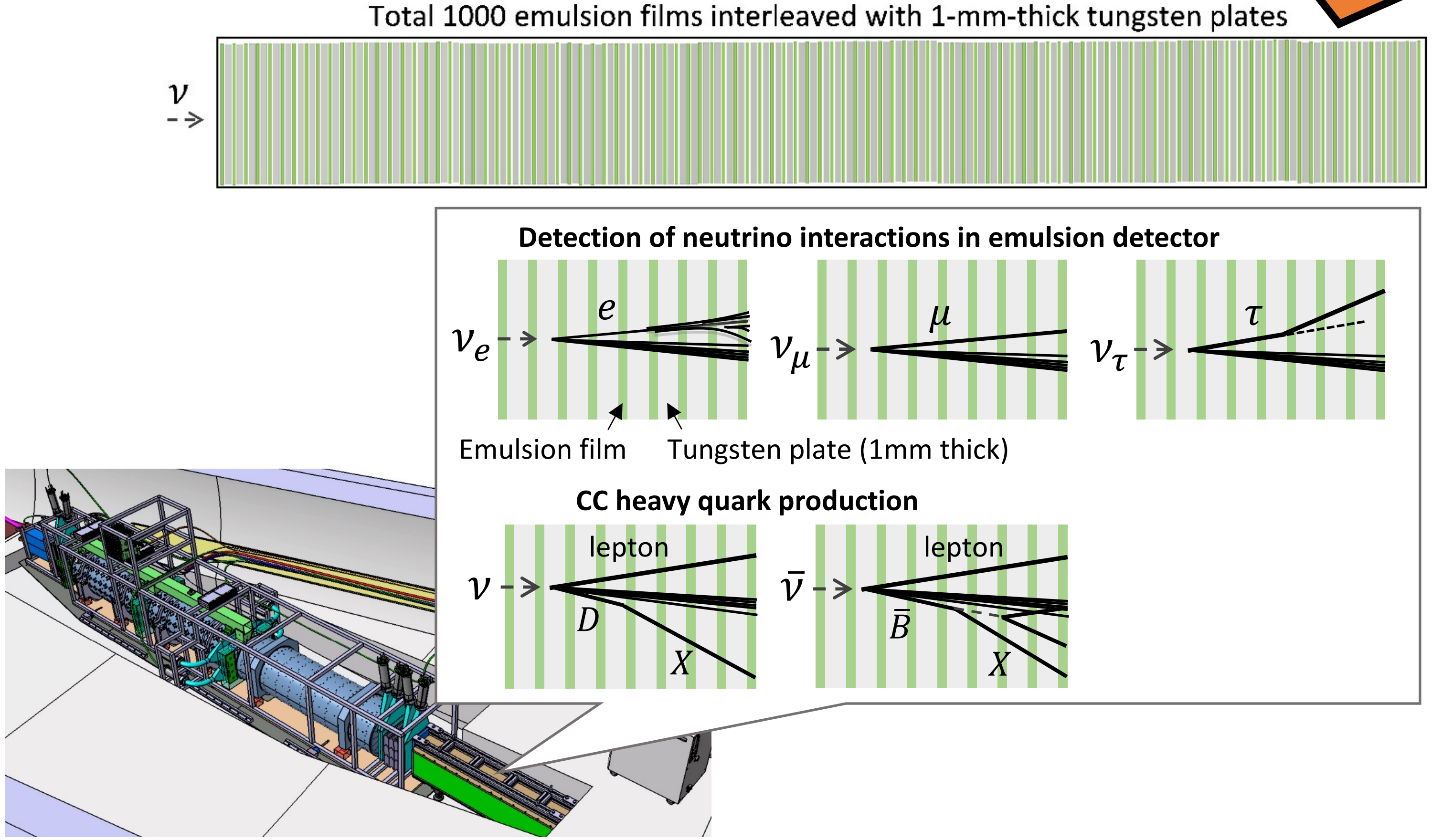
A totally different paradigm

Outside The LHC

Outside The LHC

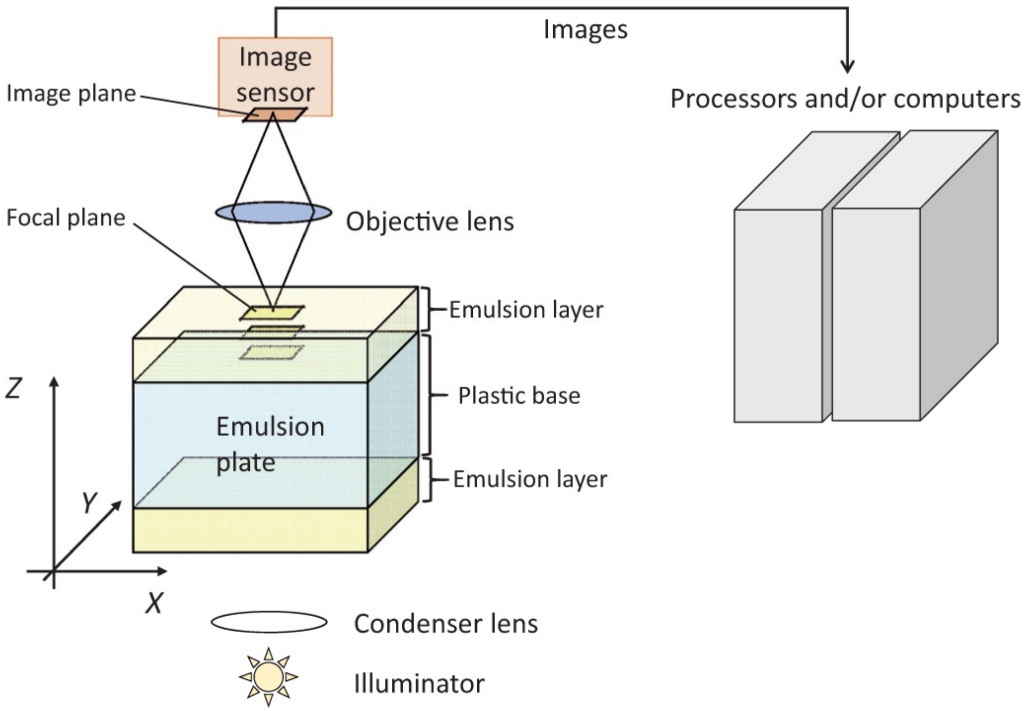
FASERν Detector – Emulsion

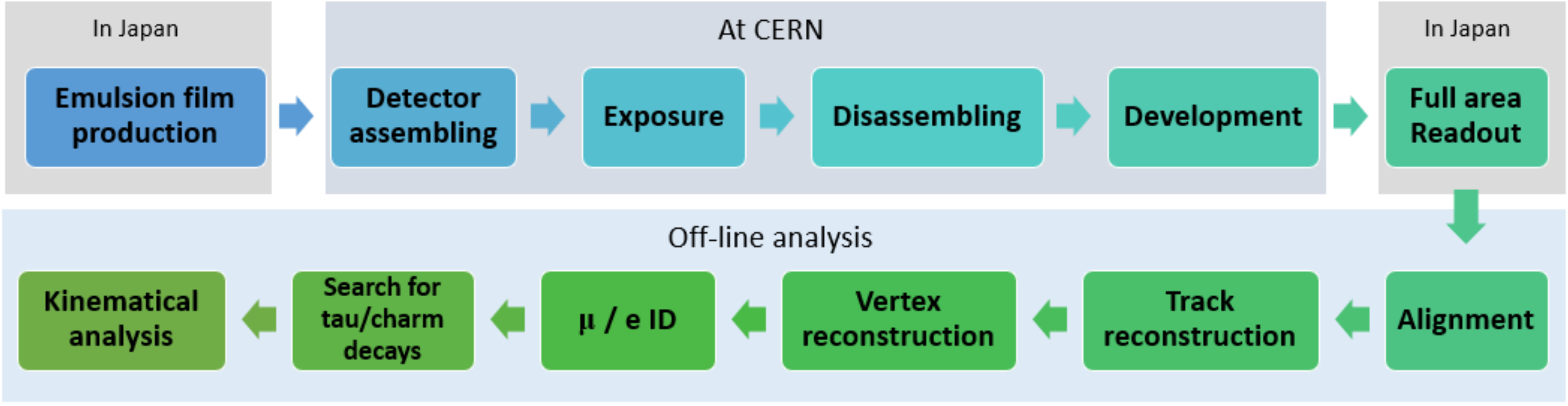
- Emulsion film detector with tungsten plates; well known neutrino detector technology
- Track position resolution O(50nm), and angular resolution O(0.35mrad). No timing resolution
- Replace every 20-50/fb to maintain manageable track density
- Challenge: replace the 1-ton-scale detector about 3 times/year



Outside The LHC

Read-out & Analysis





PART 2

SMARTHEP
REAL-TIME ANALYSIS FOR SCIENCE AND INDUSTRY

What will this lecture be about?

Introduction

- Definitions and basic concepts

Input to the physics

- **The data: trigger, data preparation**
- **The theory: Monte carlo simulations**
- Reconstruction, or how to translate detector signals to particles

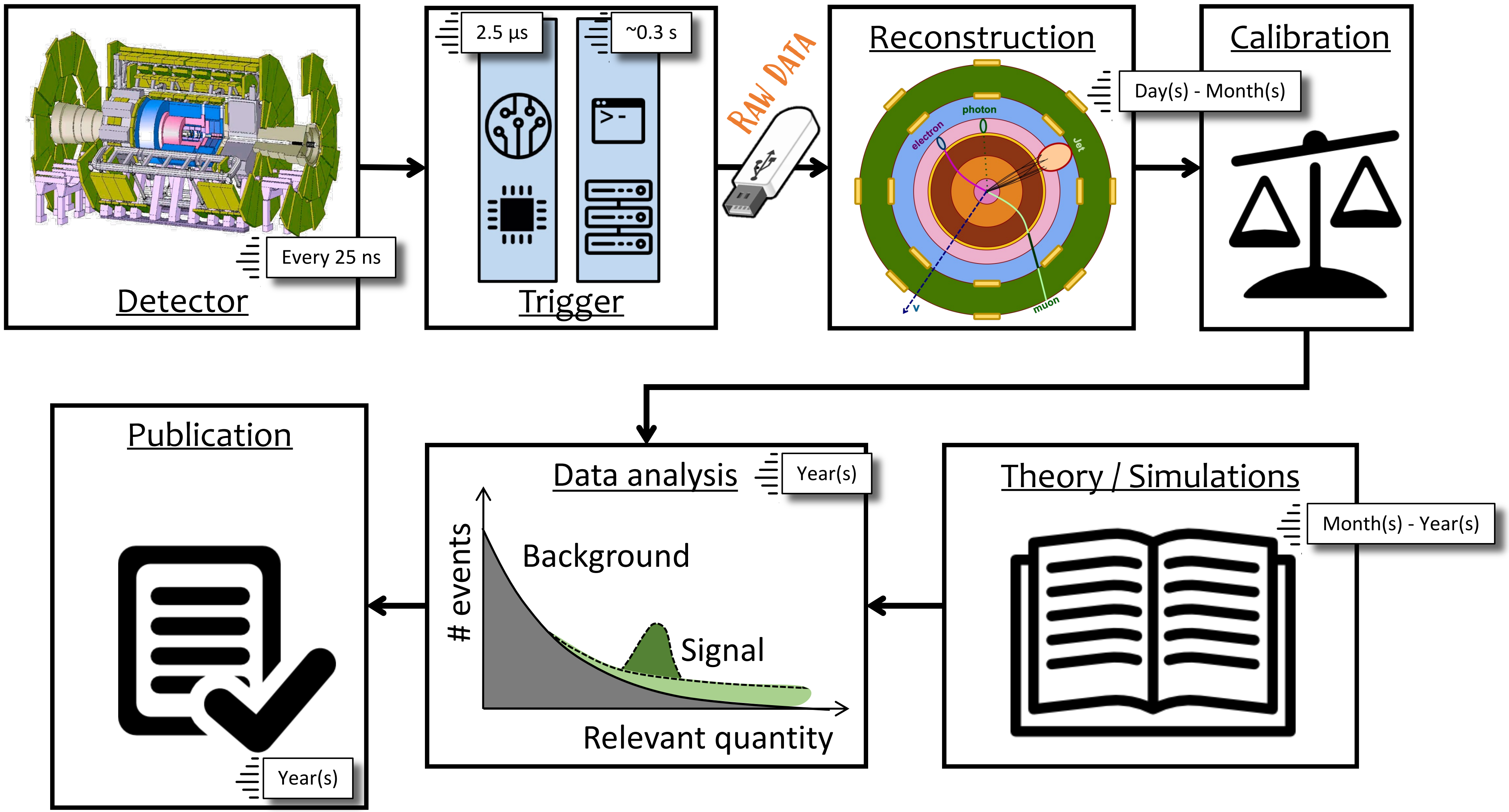
Physics analyses

- Through example, step-by-step
- Discussion of analysis methods

SMARTHEP
REAL-TIME ANALYSIS FOR SCIENCE AND INDUSTRY

Is there a topic you would like to add to this material?
If so: please let me know at the end of this lecture and I will see if I can add it!

The lifetime of a collision event

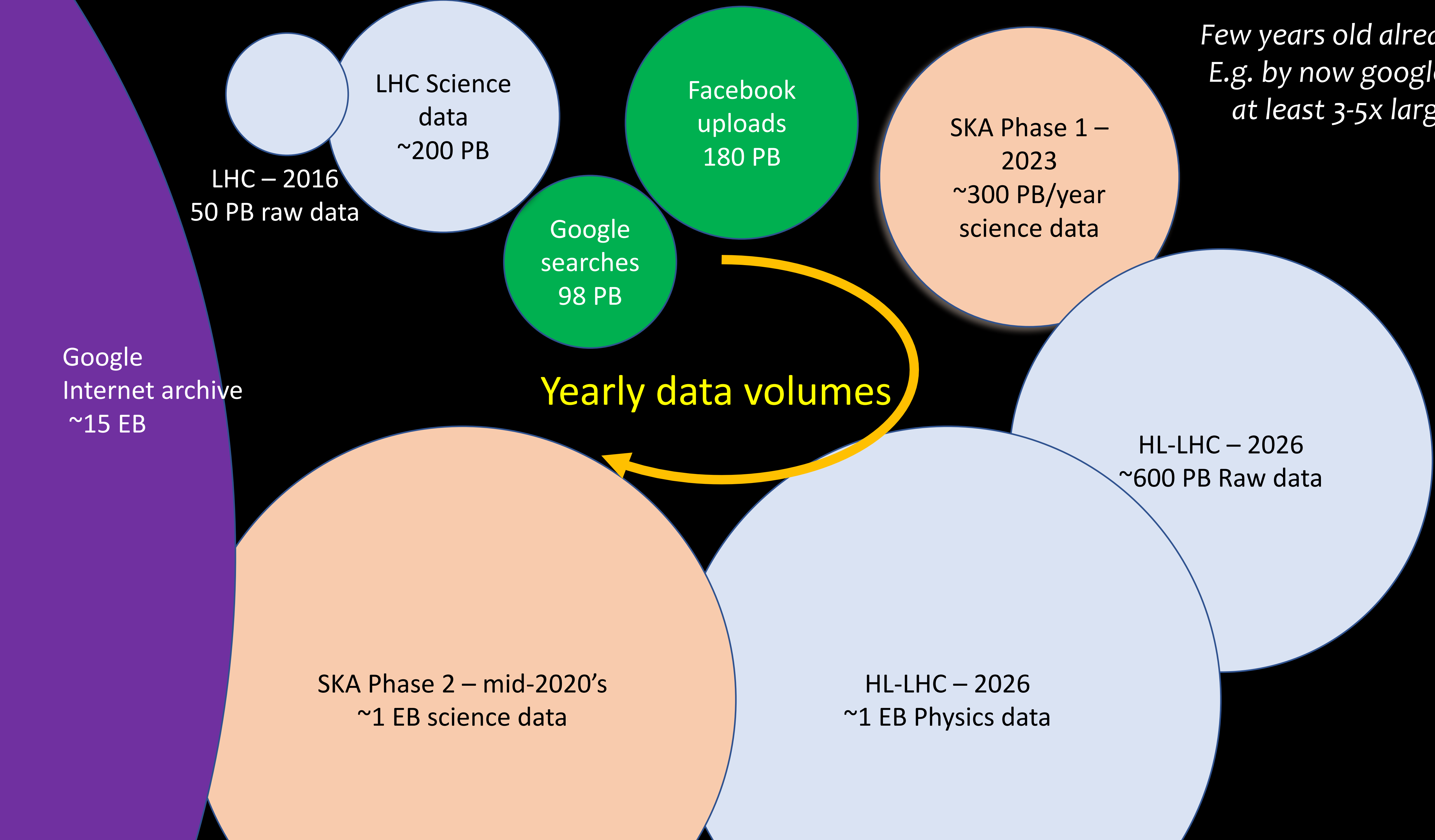


Data Preparation

Let's first talk about

COMPUTING!

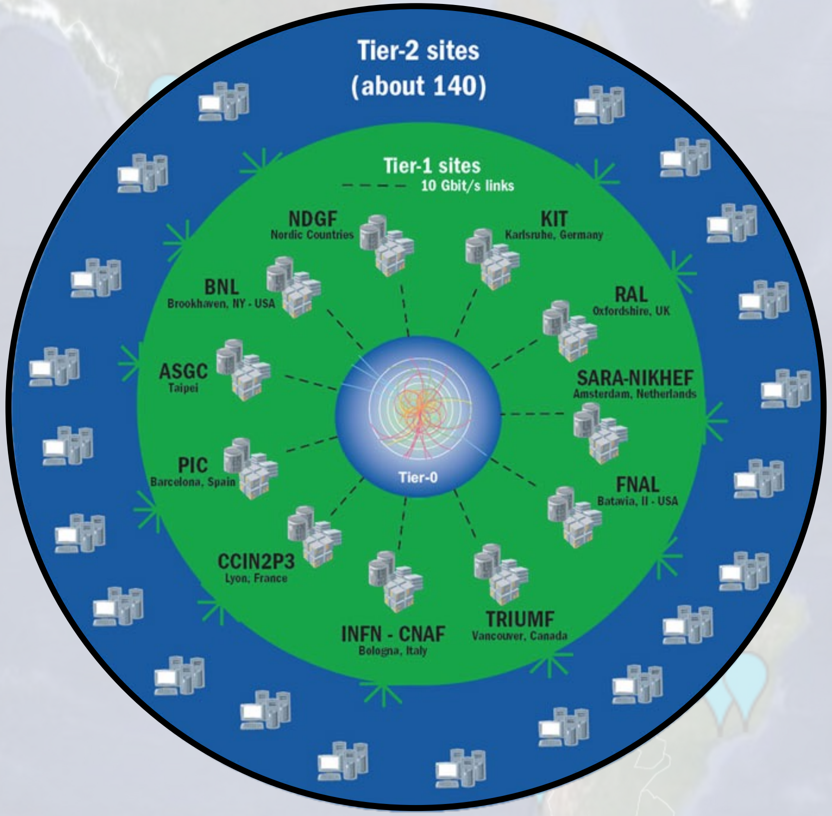
Few years old already
E.g. by now google is at least 3-5x larger!



Worldwide LHC Computing Grid

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.



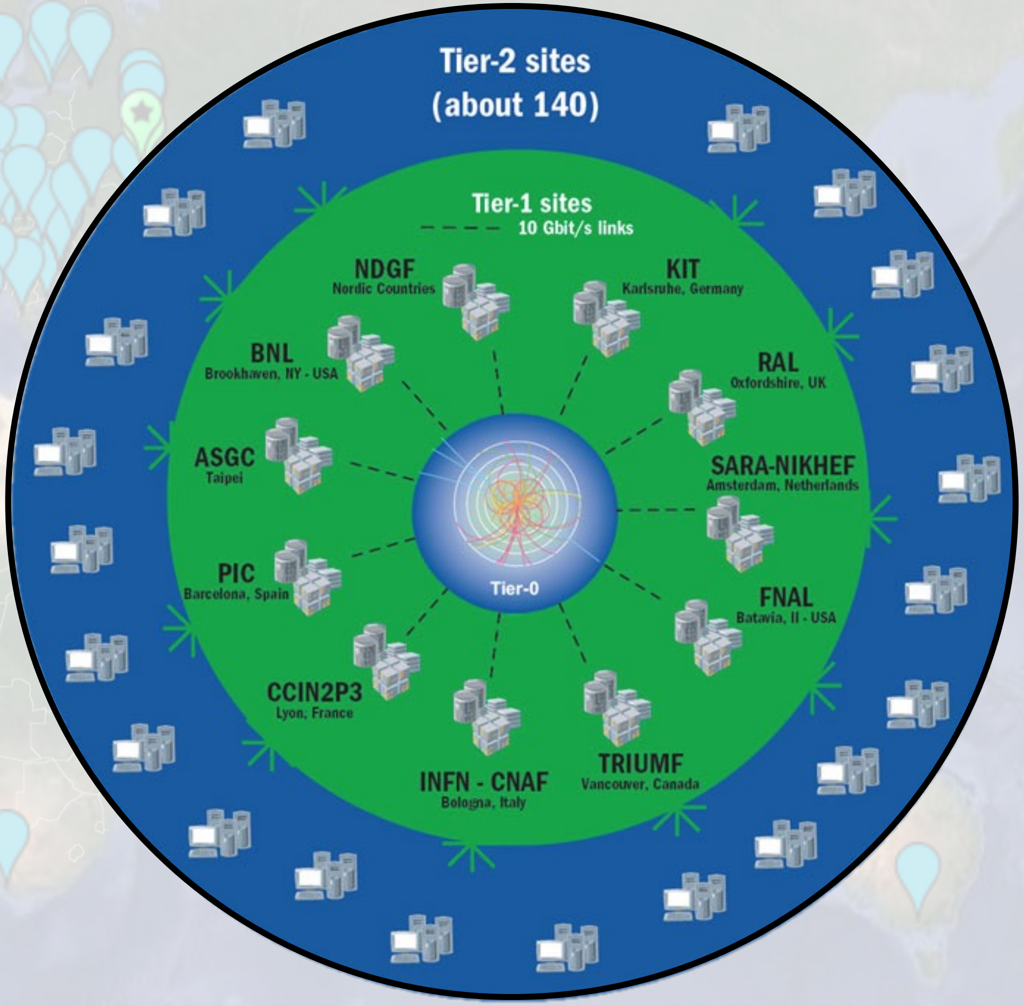
- **161 sites, 42 countries**
- **1 M CPU cores**
- **1 EB of storage**
- **> 2 M jobs/day**
- **> 100 PB moved/month**
- **accessed by 10k users**
- **10-100 Gb links**

Network proved better than anyone imagined: Any job can run anywhere

WLCG
Worldwide LHC Computing Grid

Worldwide LHC Computing Grid
The Tier System

- Tier-0 (CERN):
  - Data recording, reconstruction and distribution
- Tier-1:
  - Permanent storage, re-processing, analysis
- Tier-2:
  - Simulation, end-user analysis



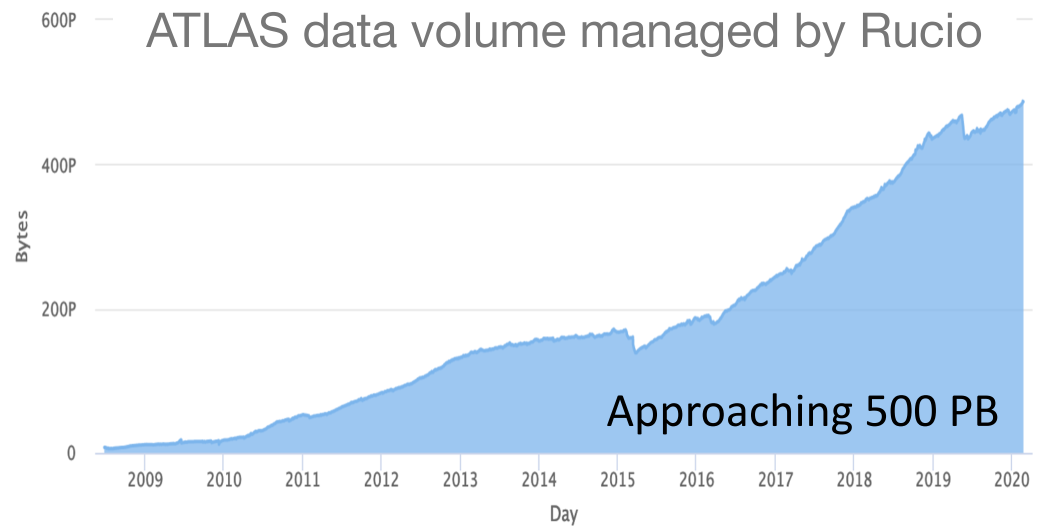
ATLAS DATA MANAGEMENT

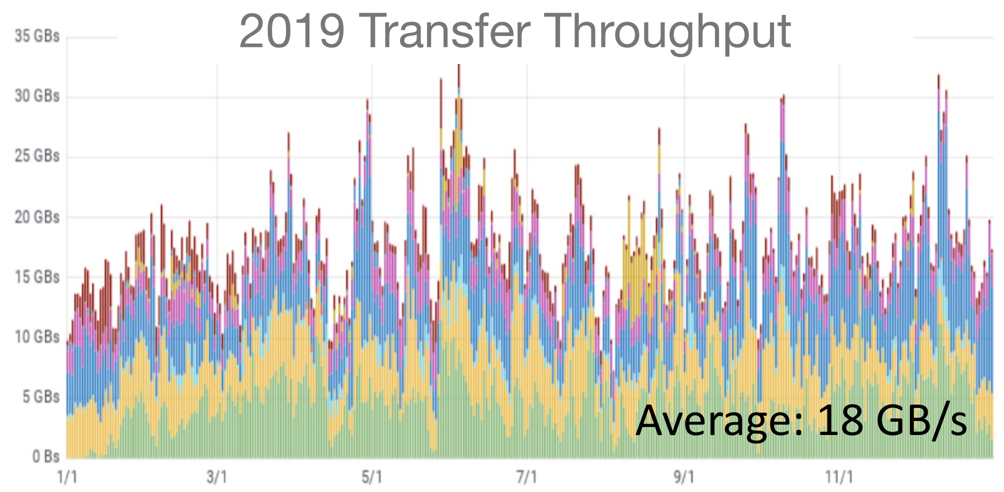
RUCIO

Data storage
Access
Replication
Deletion

Scalable
Policy-driven
Monitorable
Supporting "FAIR" data principles

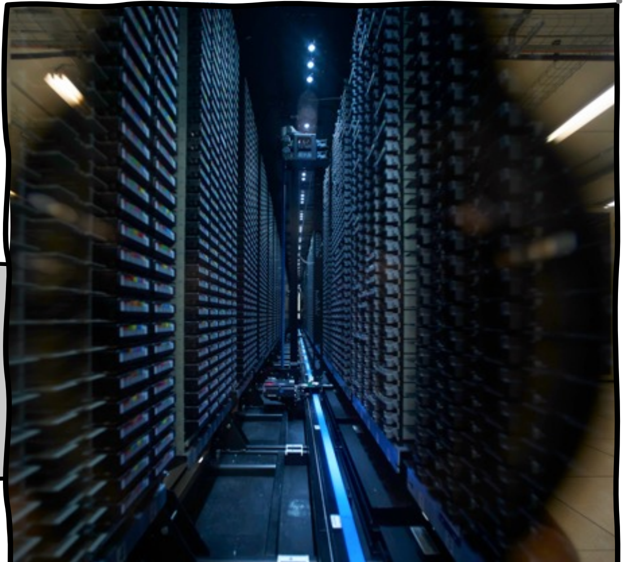
Findable
Accessible
Interoperable
Reusable





Now established in the HEP community and beyond

Hardware



Magnetic tapes, retrieved by robotic arms, are used for long-term storage

Storage	Tape (at CERN) about 270 PB	• Most reliable and cost-effective technology for large-scale archiving • Data stored there infinitely
	Disk about 200 PB	• Data for initial processing • Copies for further processing / user analysis • Data in disks gets staged from tape, on demand
Processing power	CPUs	• Mainly GRID • About 400k cores
	GPUs	• Mostly for RnD • Few 10s *Also considering for the future: FPGA accelerators*
	Opportunistic resources	• Online farm, 100k cores • High Performance Computers, primarily in the US • Volunteer computing

Nvidia GeForce

LHC@home Volunteer computing for the LHC

Software

athena
Project ID: 53790

70,356 Commits · 34 Branches · 1,374 Tags · 2.6 GB Files · 2.6 GB Storage · 124 Releases

The ATLAS Experiment's main offline software repository

- **All software organized in packages in Git.** For example:
  https://gitlab.cern.ch/atlas/athena
- **All software open source, copyrighted and licenced (Apache 2)**
  - "Copyright (C) 2002-2020 CERN for the benefit of the ATLAS collaboration"
  - For open use – but also for crediting developers who move out of academia
- **Thorough tracking of software developments a key of success**
  - Via the Jira software, supported by CERN IT Jira Software
  - Multiple releases exist for merging of new code with existing one
  - Automated tools run nightly to verify code sanity & performance
  - Globally the software projects are coordinated with careful planning
- **Software Tools**
  - Databases
  - Analysis tools: ROOT is the workhorse!

ROOT
Data Analysis Framework

- **Analysis-specific software developed by teams available to whole collaboration!**