LHC physics

DESY summer student lecture
August 2019

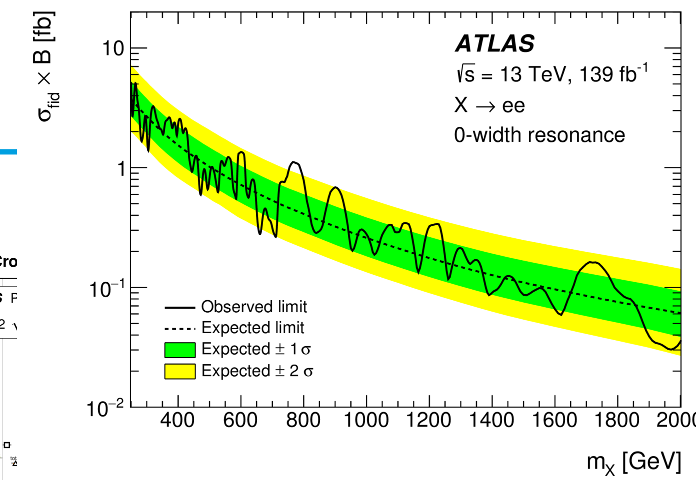
Sarah Heim, DESY

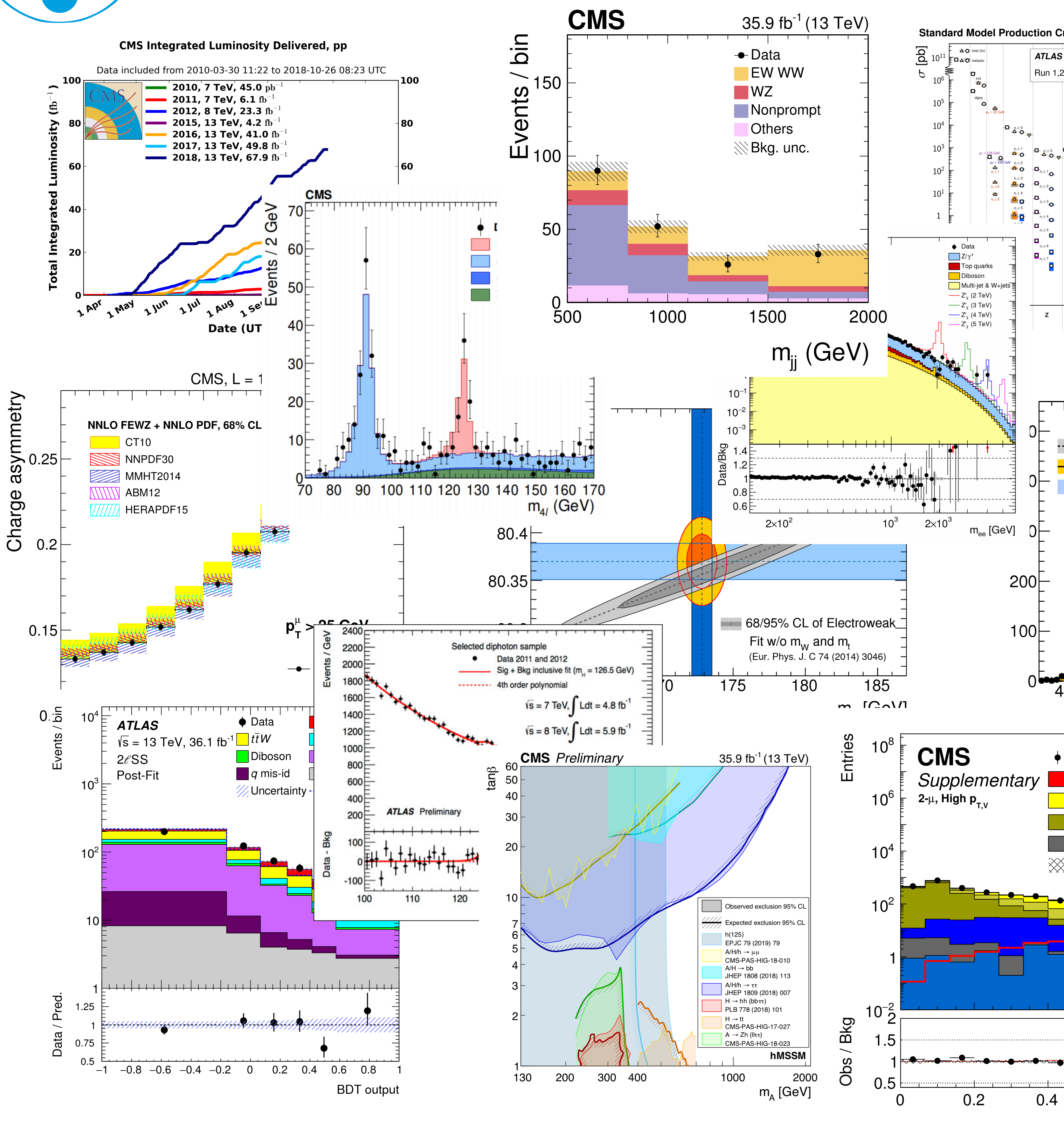
Overview of these lectures

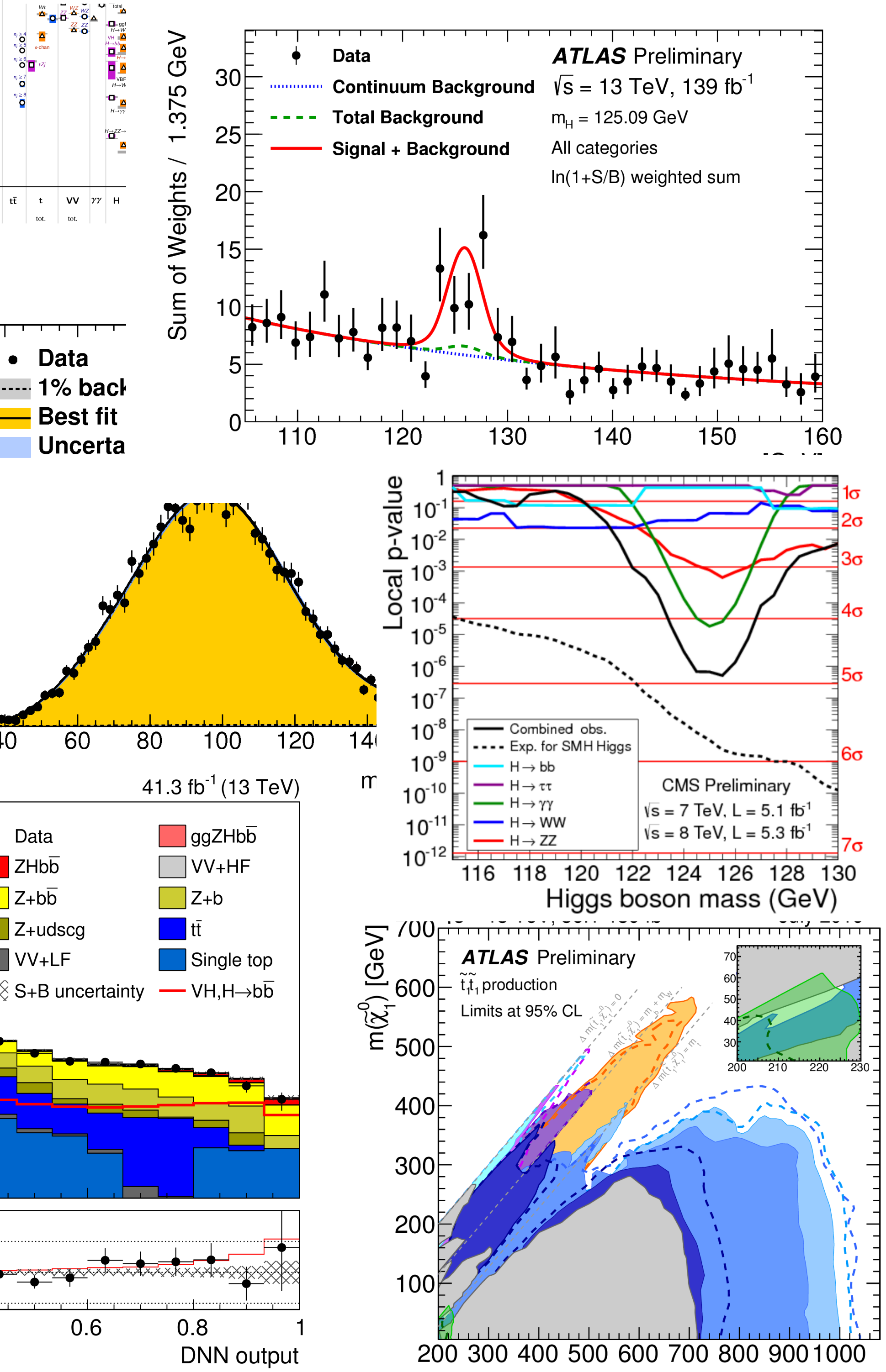
- Intro
- Electroweak physics, top quark
- Higgs boson
- Searches for physics beyond the Standard Model

Please ask questions! I will do so, too...

Plots, plots, plots







Goal for the lectures

What these lectures are

- I tried to select some exciting LHC results from the last years
- I will try to also show you some important measurement techniques/ statistical concepts
- goal: understanding LHC plots

What these lectures are not

- complete list of LHC results
- super balanced between all experiments
  >> will focus on ATLAS and CMS results
  >> There will be a heavy-flavor lecture later, which should cover LHCb results

How to find LHC papers

Experiments have webpages, sorted by physics topics

http://cms.web.cern.ch/news/cms-physics-results

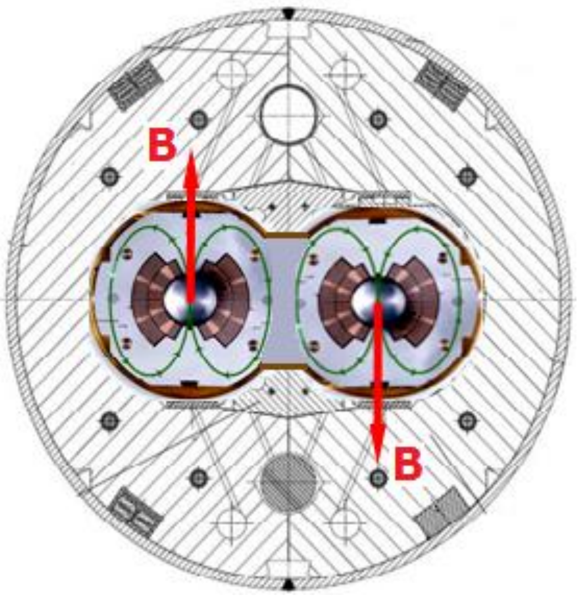
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

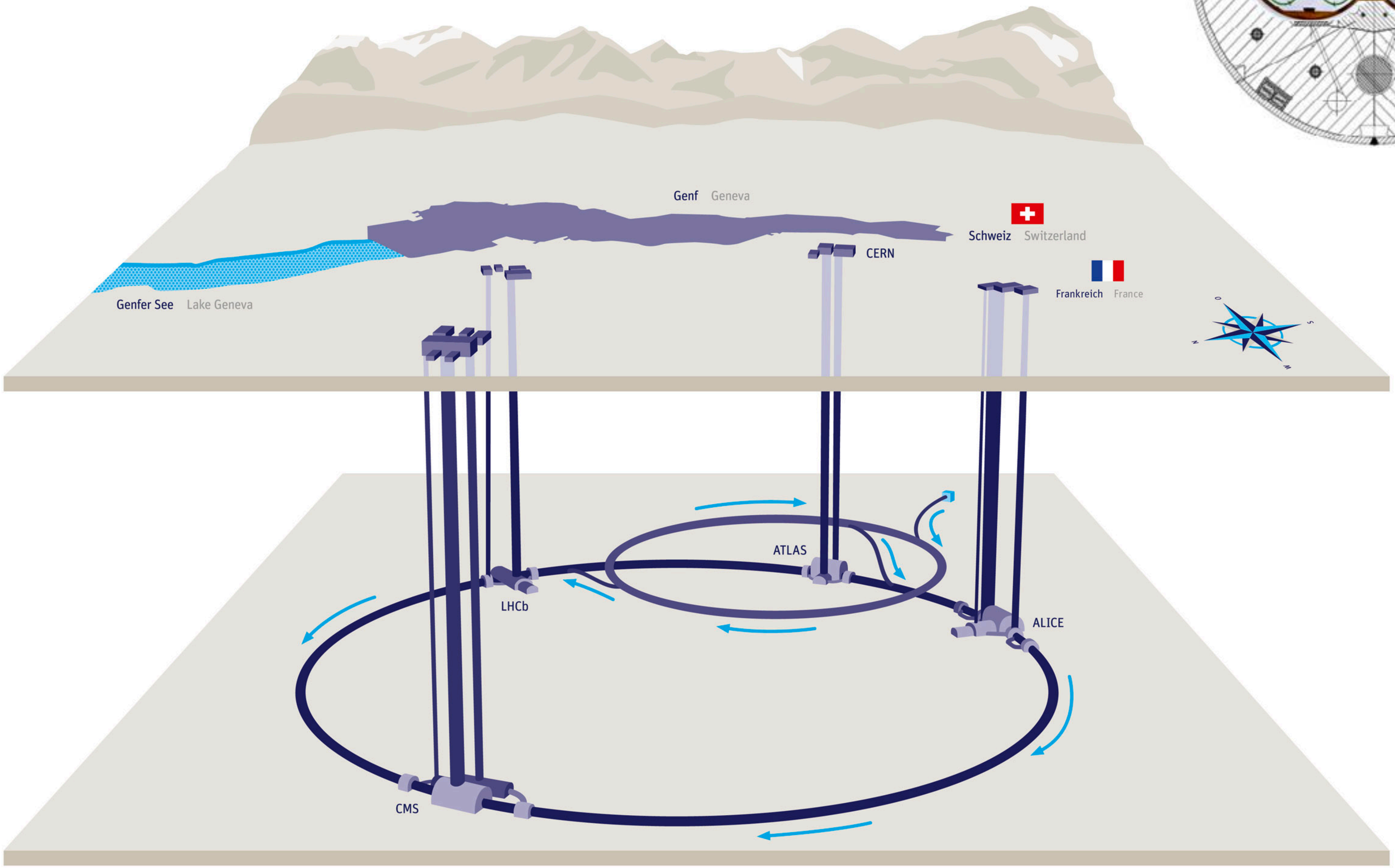
http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html

https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults

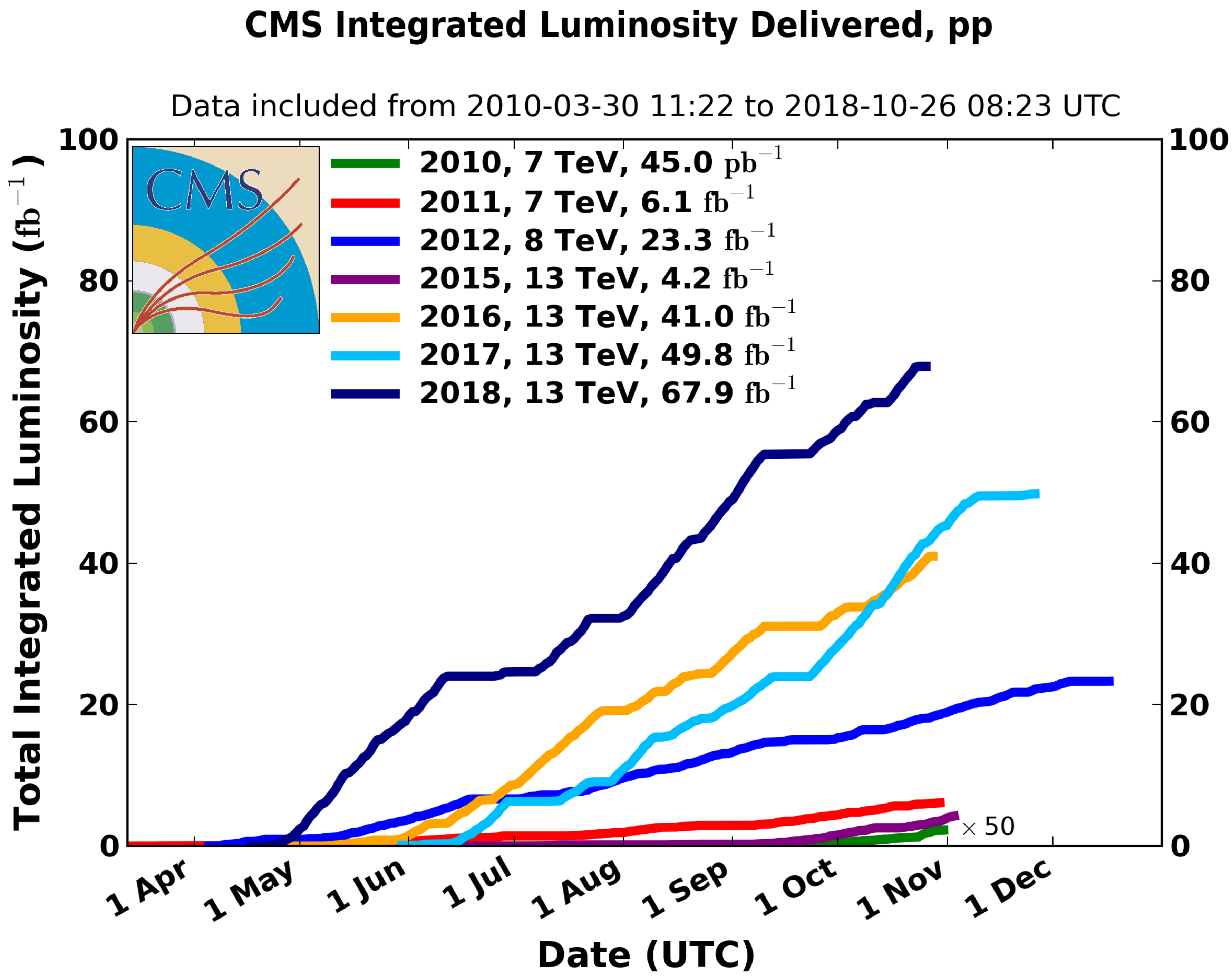
LHC

- 27 km circular collider
- collides protons with protons
- also collides heavy ions (lead)



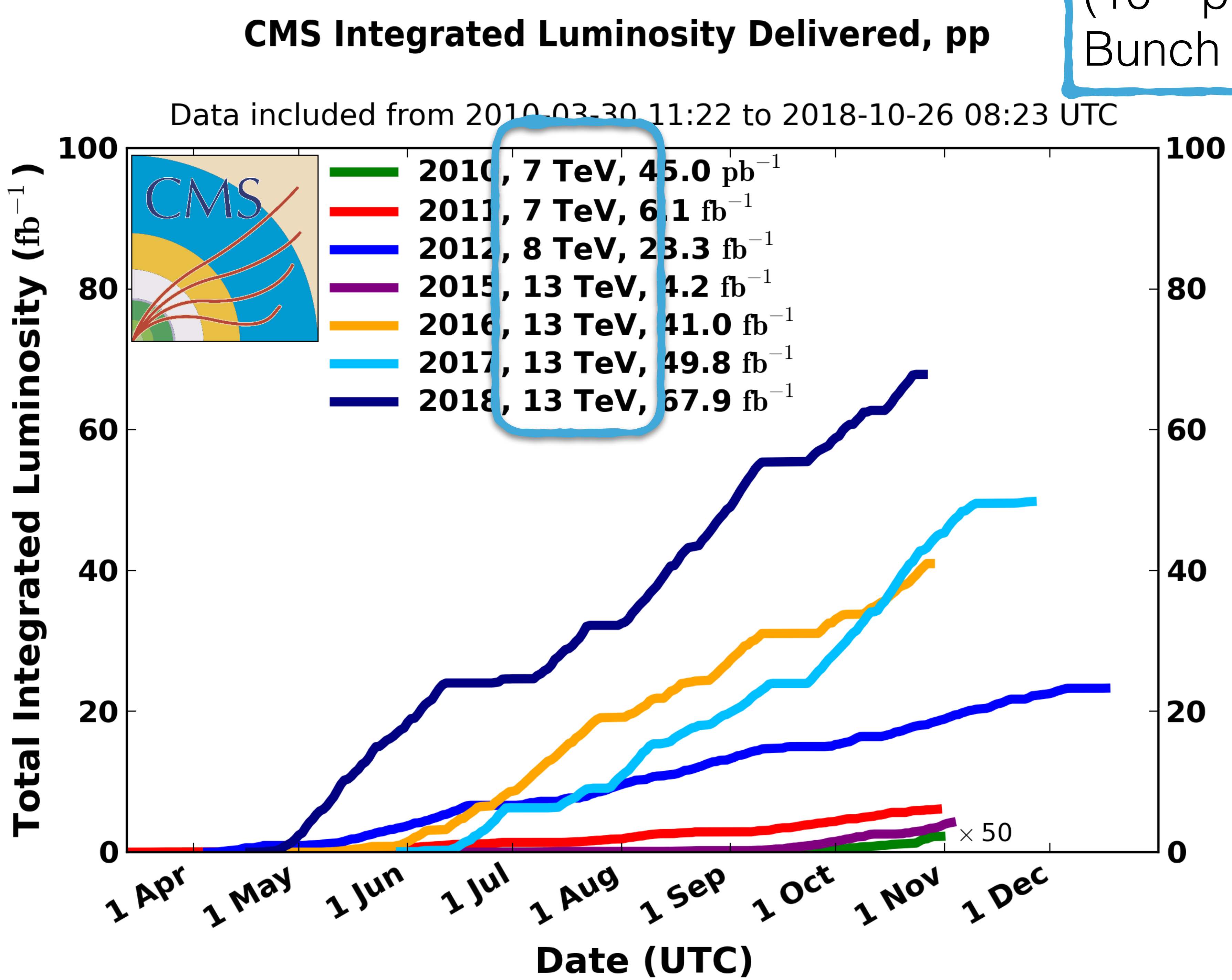


LHC - proton-proton mode

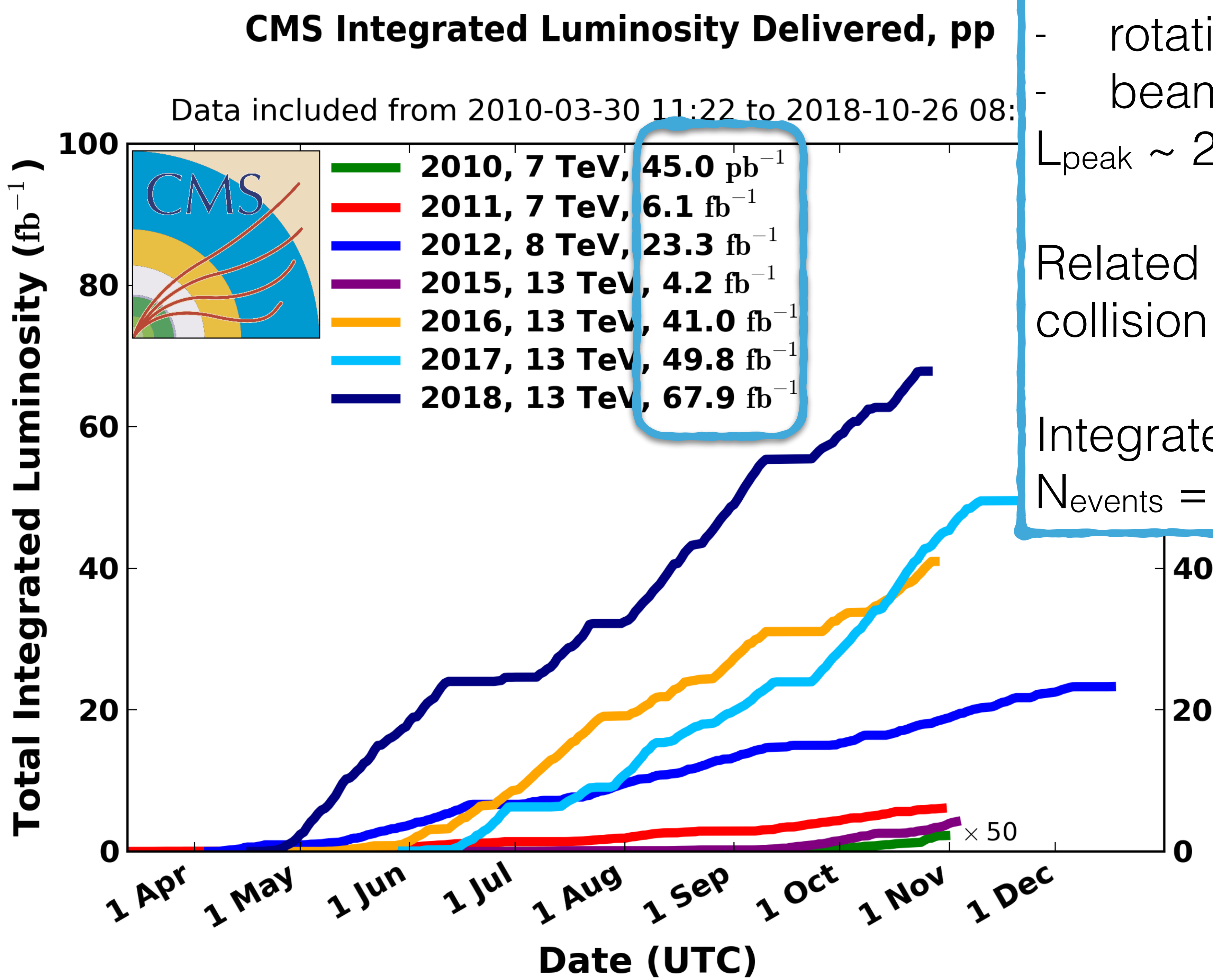


LHC - proton-proton mode

Design CM energy:
7 TeV per proton (14 CM)
Beam: Proton bunches
(10^{11} protons per bunch)
Bunch crossing rate: 40 MHz



LHC - proton-proton mode



Instantaneous luminosity depends on
- number of protons per bunch
- number of bunches in beam
- rotation frequency of beam
- beam overlap

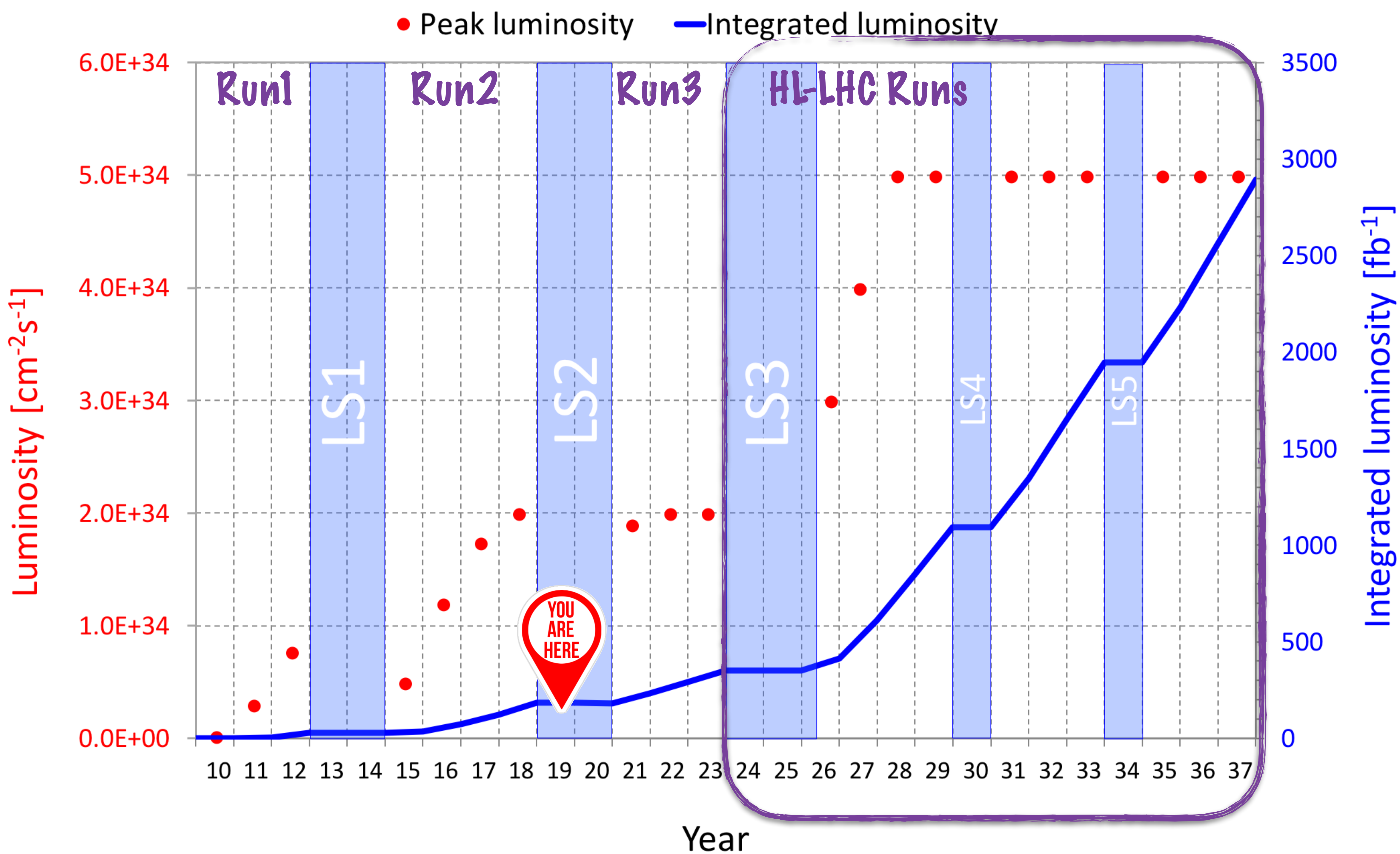
$L_{peak} \sim 2^{*}\, 10^{34}\ cm^{-2}s^{-1}$

Related to rate of produced collision events R = XS * L

Integrate luminosity over time
N_{events} = XS * L_{int}

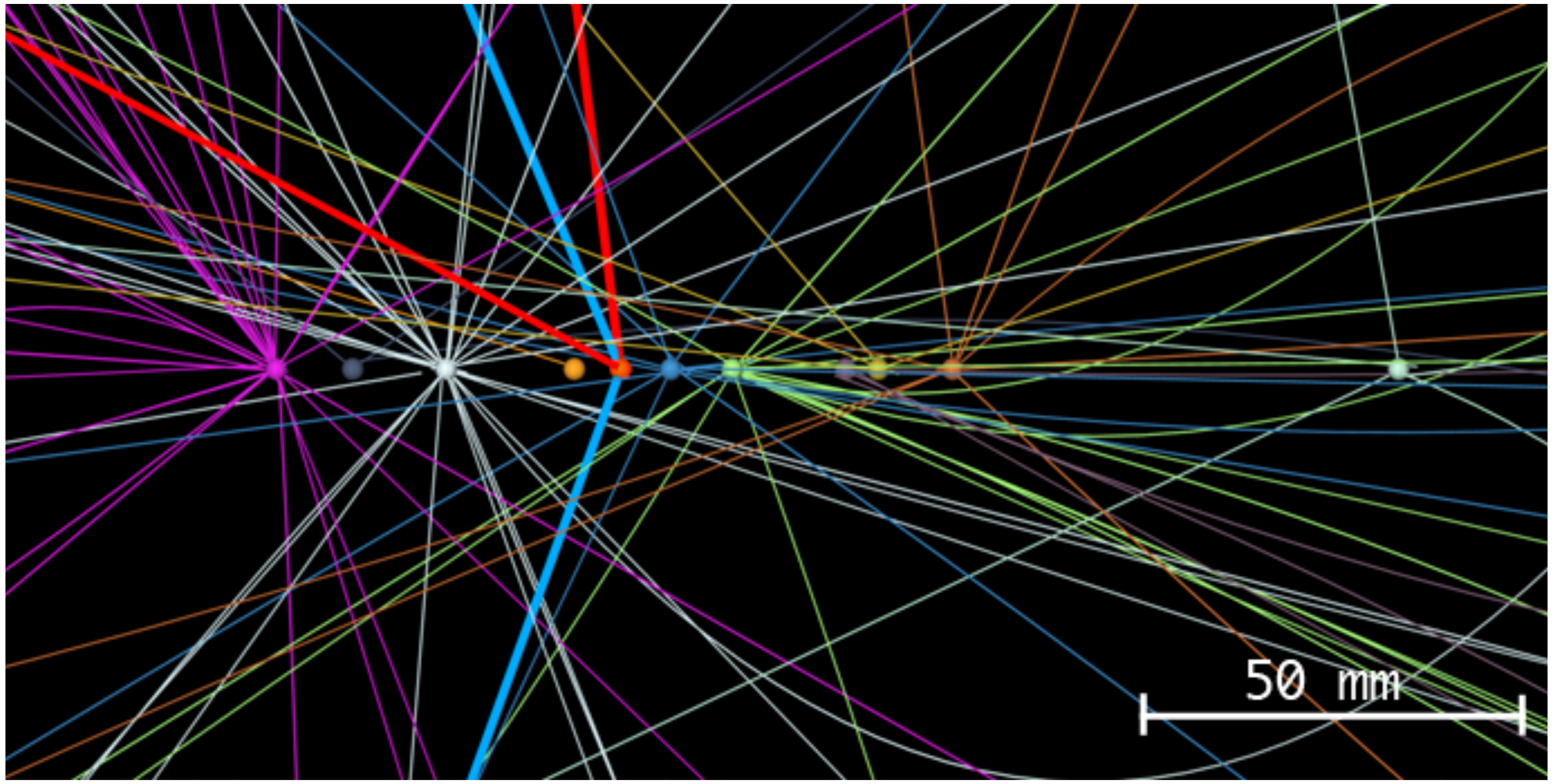
1 barn = $10^{-28}\ m^2$

LHC program



Peak luminosity
Integrated luminosity
Run1
Run2
Run3
HL-LHC Runs
LS1
LS2
LS3
LS4
LS5
YOU ARE HERE
Luminosity [cm^-2s^-1]
Integrated luminosity [fb^-1]
Year
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
3500
3000
2500
2000
1500
1000
500
0
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37

Price to pay for high instantaneous luminosity

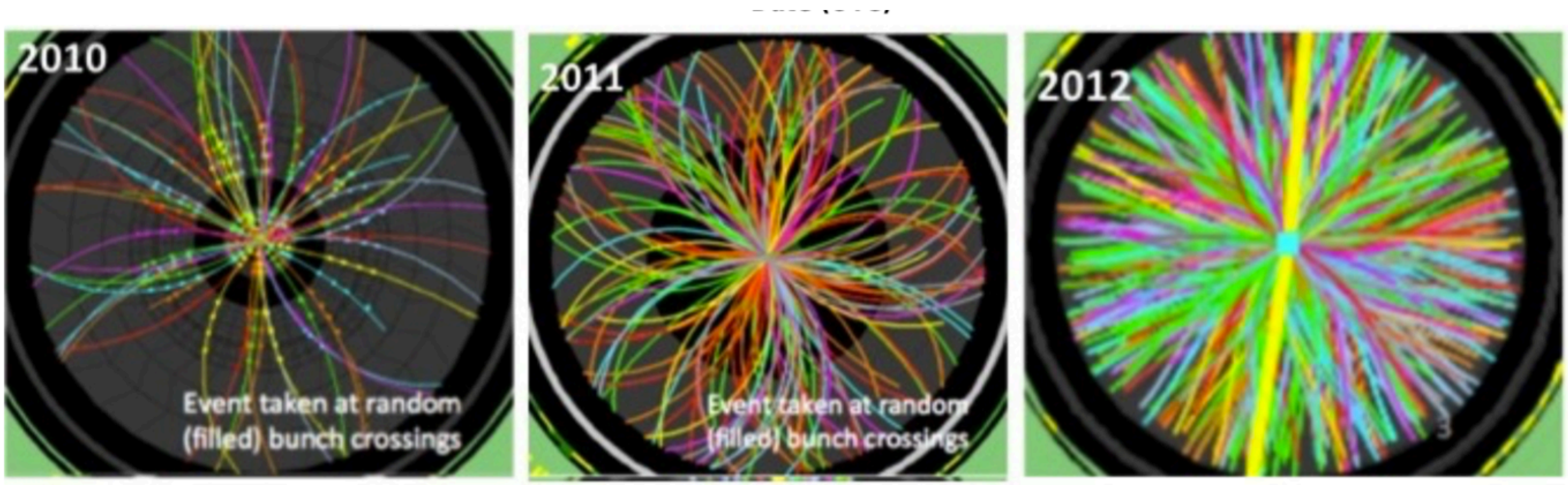


(In-time) pileup: Additional interactions per bunch crossing

Big challenge:
- not only collision of interest, but additional particles
- usually tracks and hadronic jets with fairly low transverse momentum

2018: on average ~38 interactions per bunch crossing!

Price to pay for high instantaneous luminosity



(In-time) pileup: Additional interactions per bunch crossing

Big challenge:
- not only collision of interest, but additional particles
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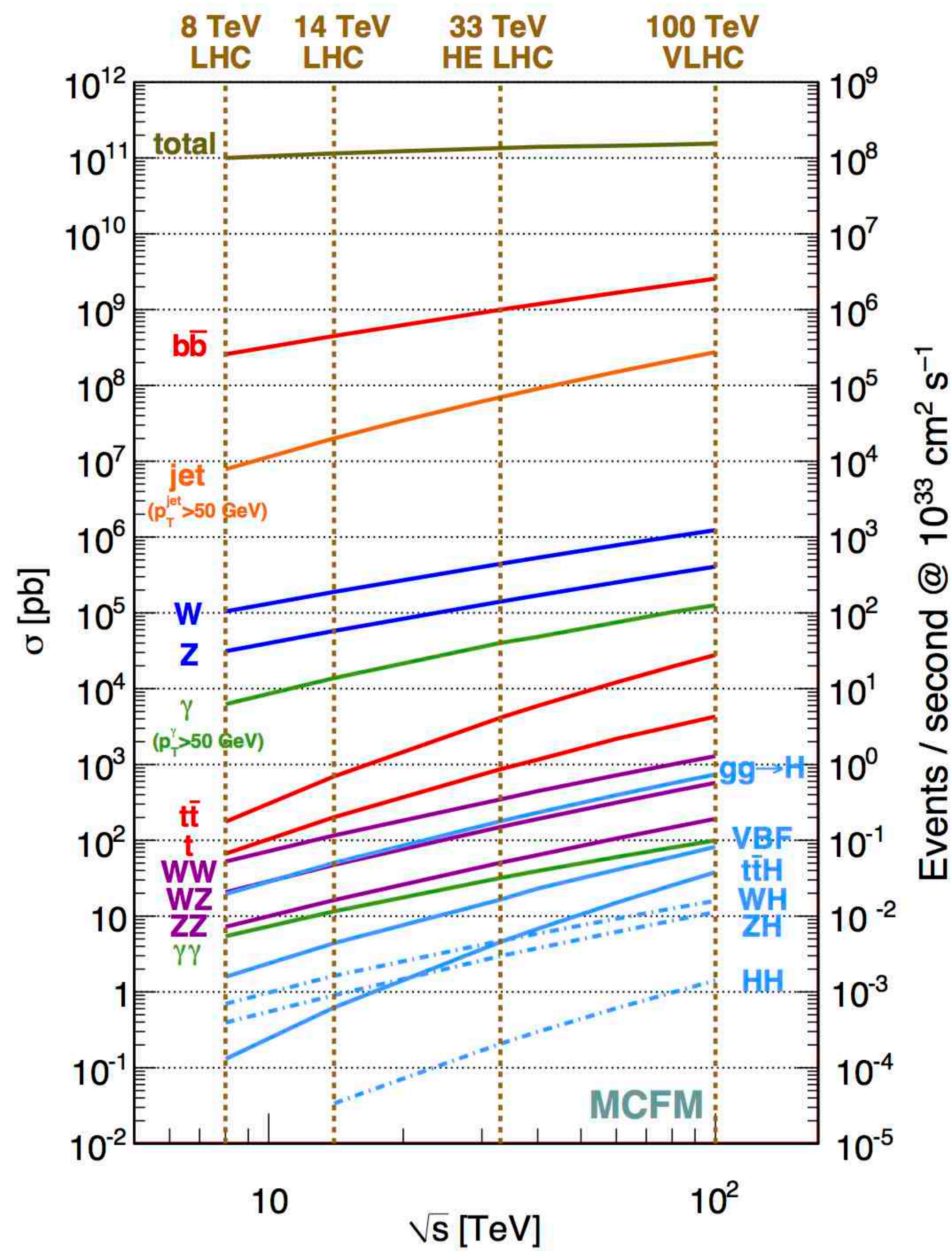
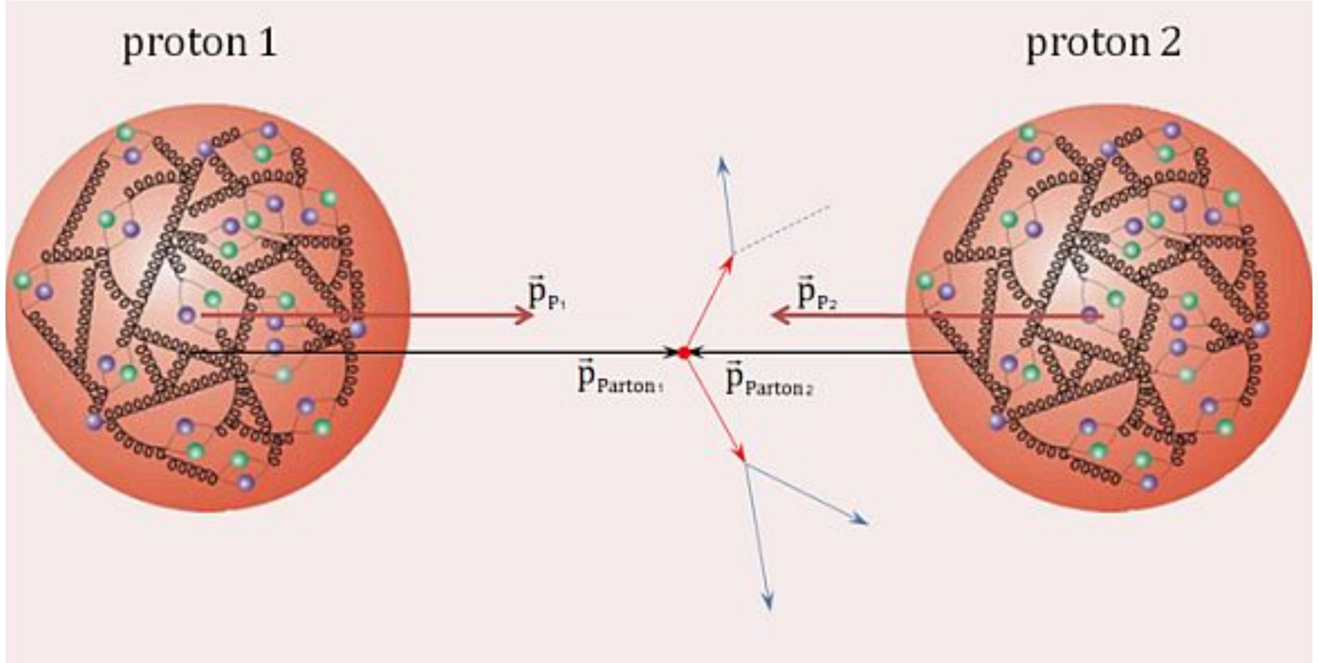
2018: on average ~38 interactions per bunch crossing!

Why do we care about energy and luminosity?



Peak lumi: $2*10^{34}$

A bit more about cross sections at pp colliders

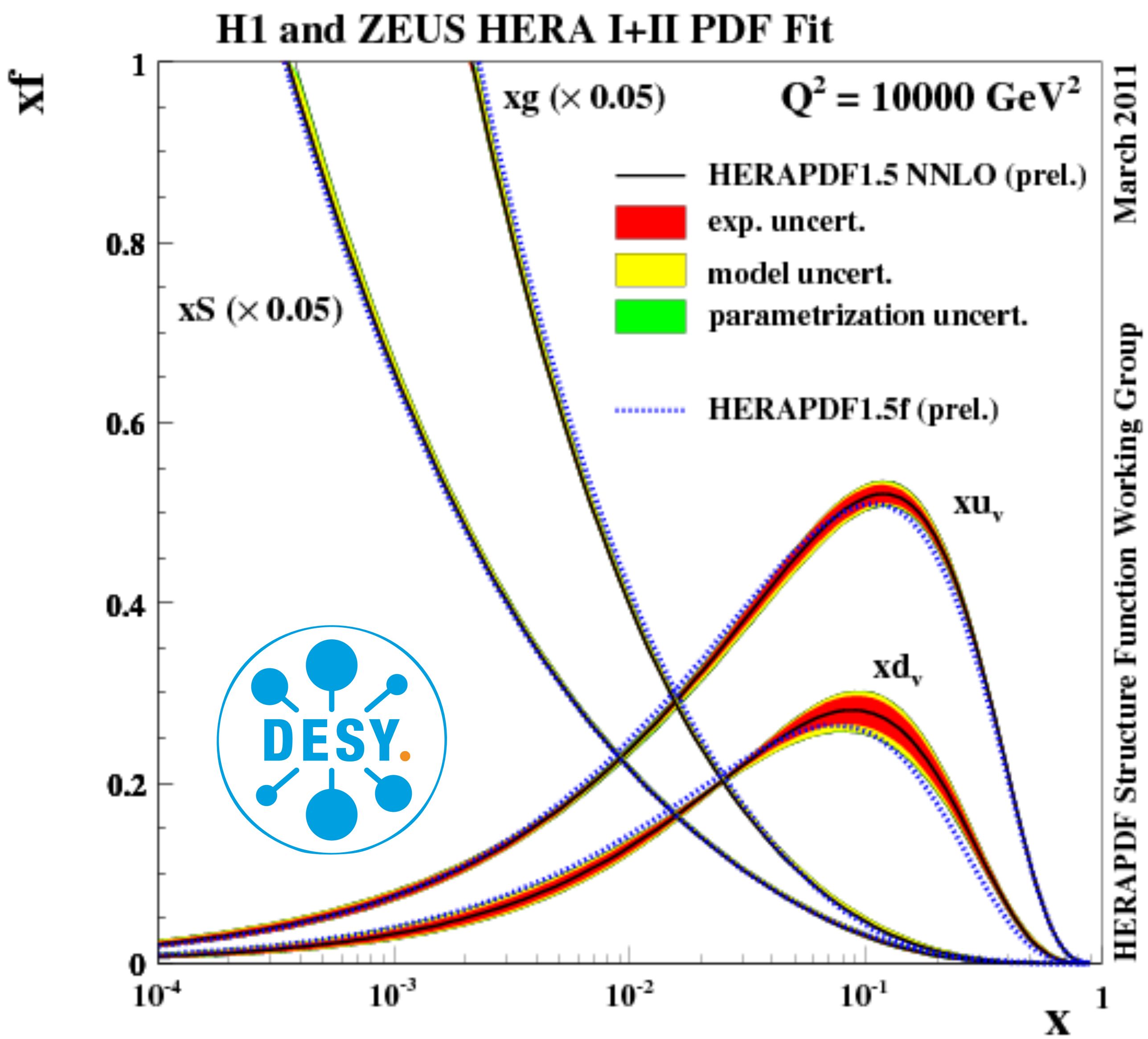


- Type of parton and momentum fraction (x) not known
- Exact center of mass energy of colliding quarks not known! (different at lepton colliders)

=> cross section are calculated by integrating over Parton distribution functions

$$\sigma(pp \to X) = \sum_{i,j} \int_0^1 dx_i dx_j f_i(x_i, Q^2) f_j(x_j, Q^2) d\hat{\sigma}(q_i q_j \to X, \hat{s}, Q^2)$$

Parton distribution functions



Q^2 = energy scale or momentum transfer

CM energy:
$x1*x2*s = mx^2$

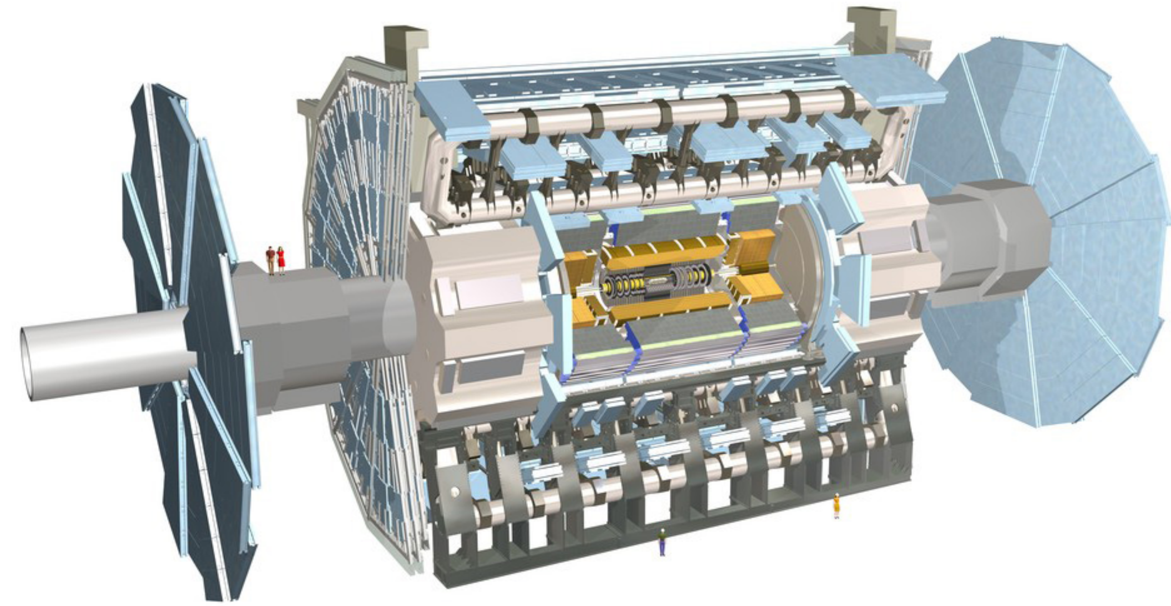
=> the higher s is, the smaller x can be
=> larger cross sections at higher CM energy

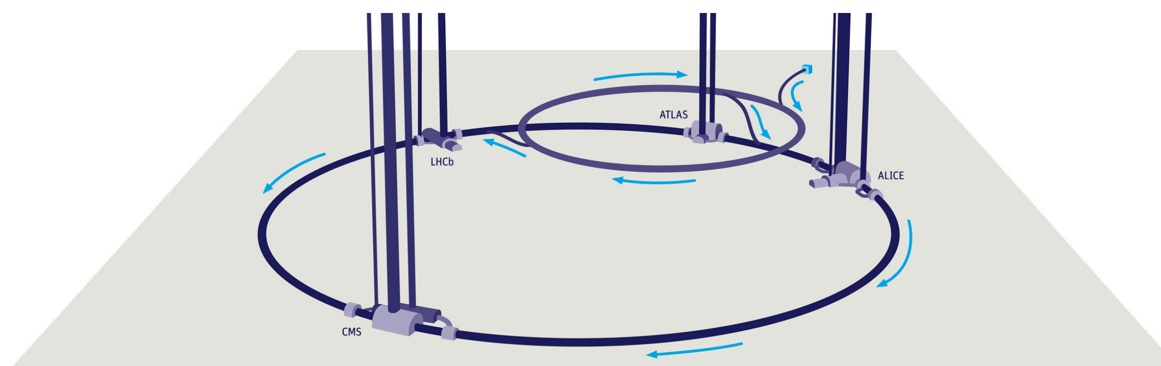
- PDFs are the probability to find a parton with a momentum fraction of x
- PDFs are not calculable, but measured in DIS experiments (with electron and neutrino scattering on nucleons)
- PDF evolution in Q^2 are calculable (with Altarelli-Parisi equations)

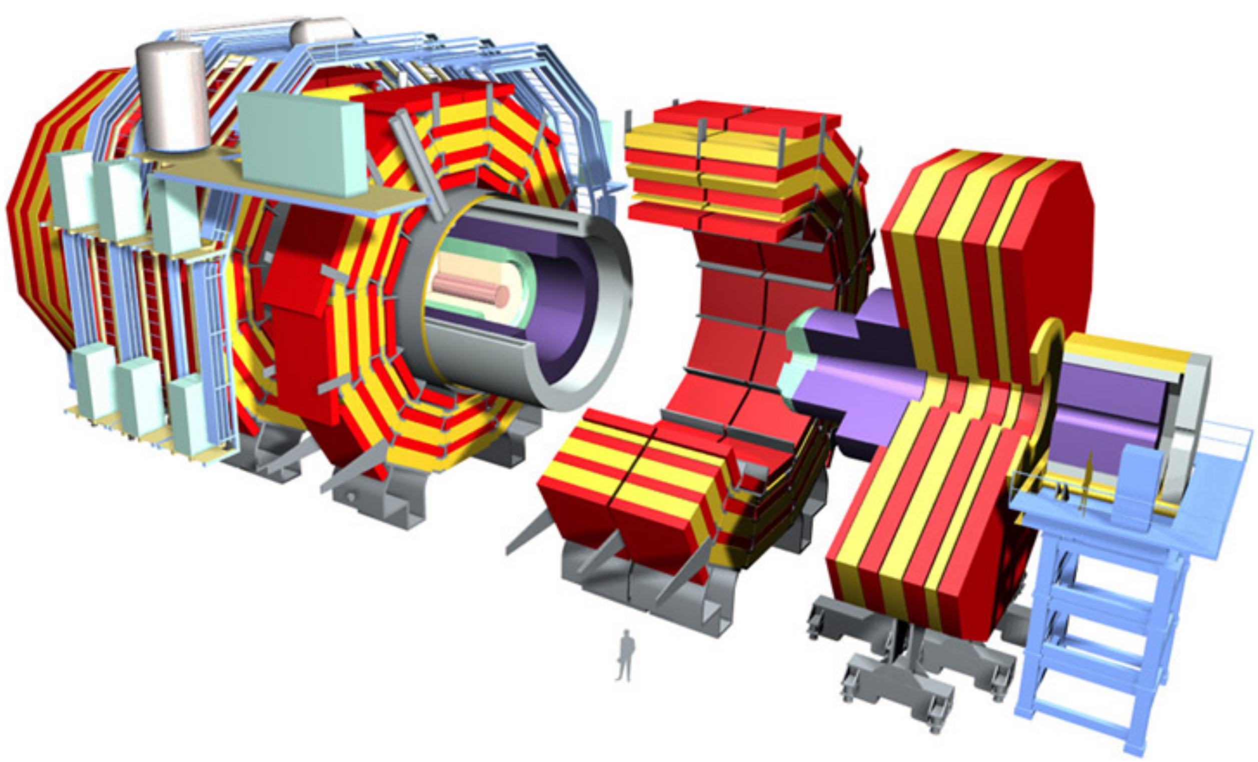
=> important uncertainty for measurements and searches!

LHC detectors - the generalists

ATLAS
- dimensions: 45*24*24 m
- magnet: 2T

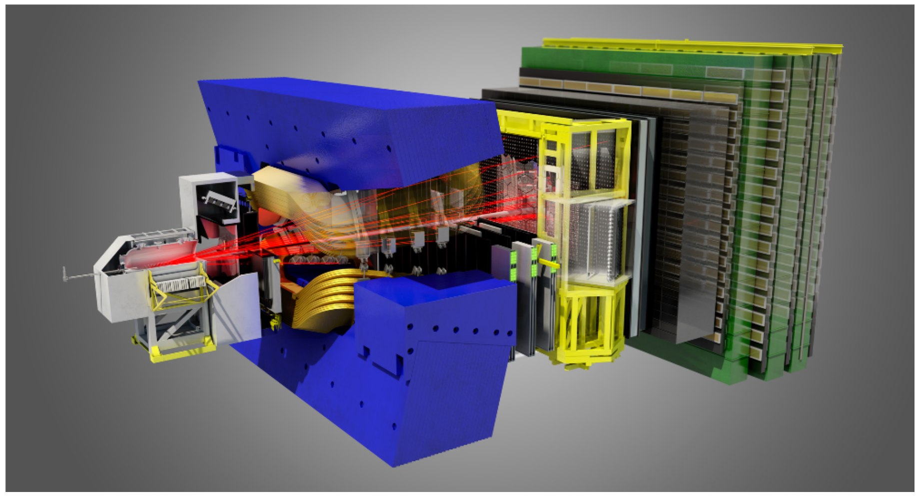




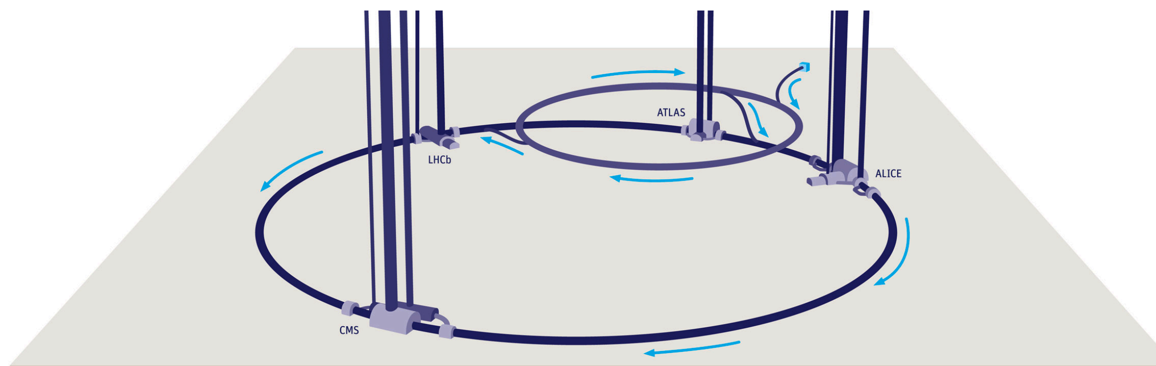


CMS
- dimensions: 22*15*15
- magnet: 4T

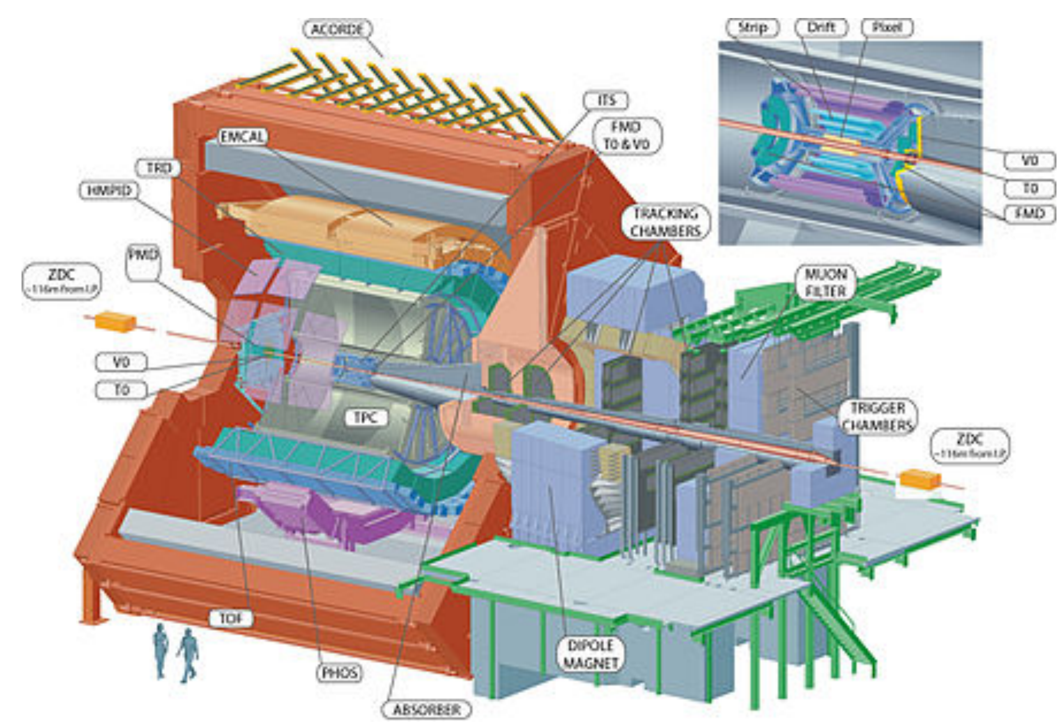
LHC detectors - the specialists



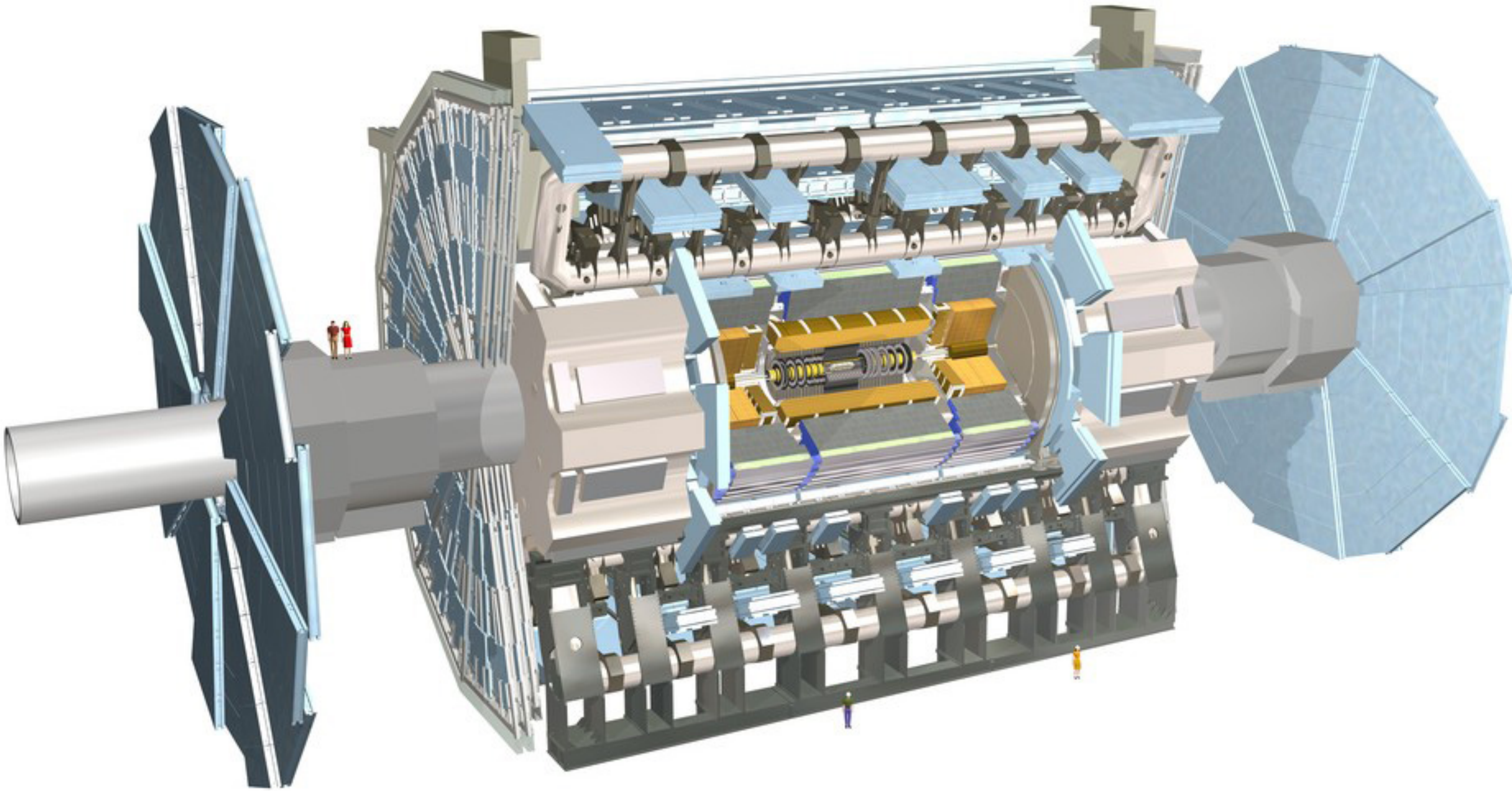
LHCb
- dimensions: 20*5*5 m
- Record decays of B mesons
- More forward than the other detectors



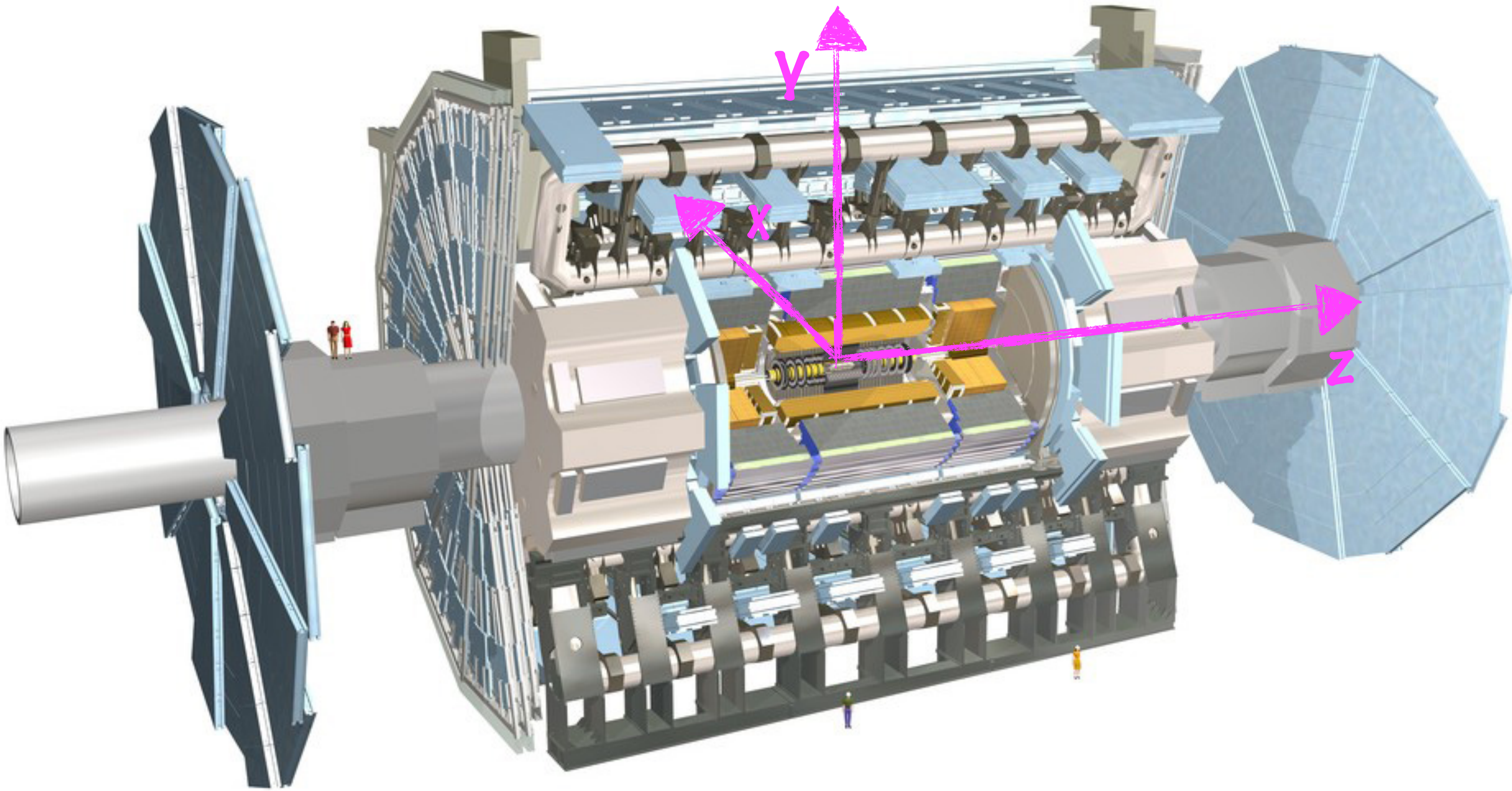
ALICE
- dimensions: 26*16*16 m
- Heavy ion collisions
- Quark gluon plasma



Closer look at the ATLAS detector

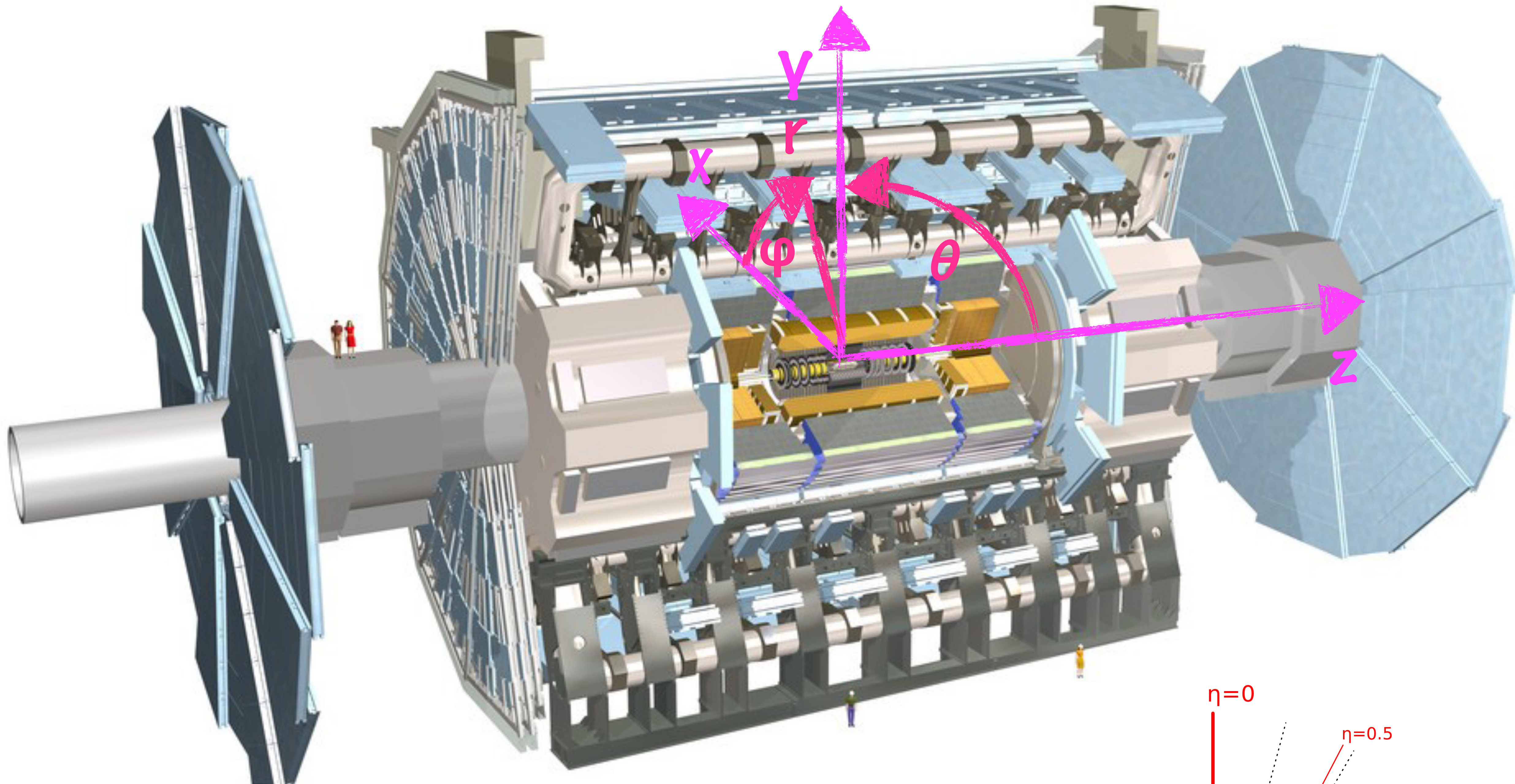


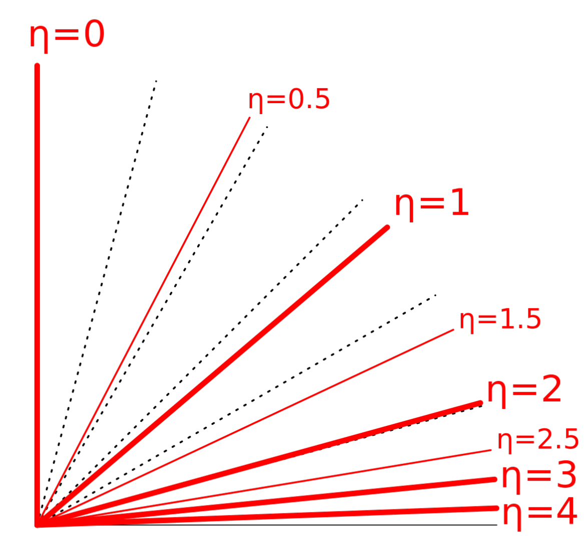
Coordinate system



x points towards the center of the ring

Coordinate system

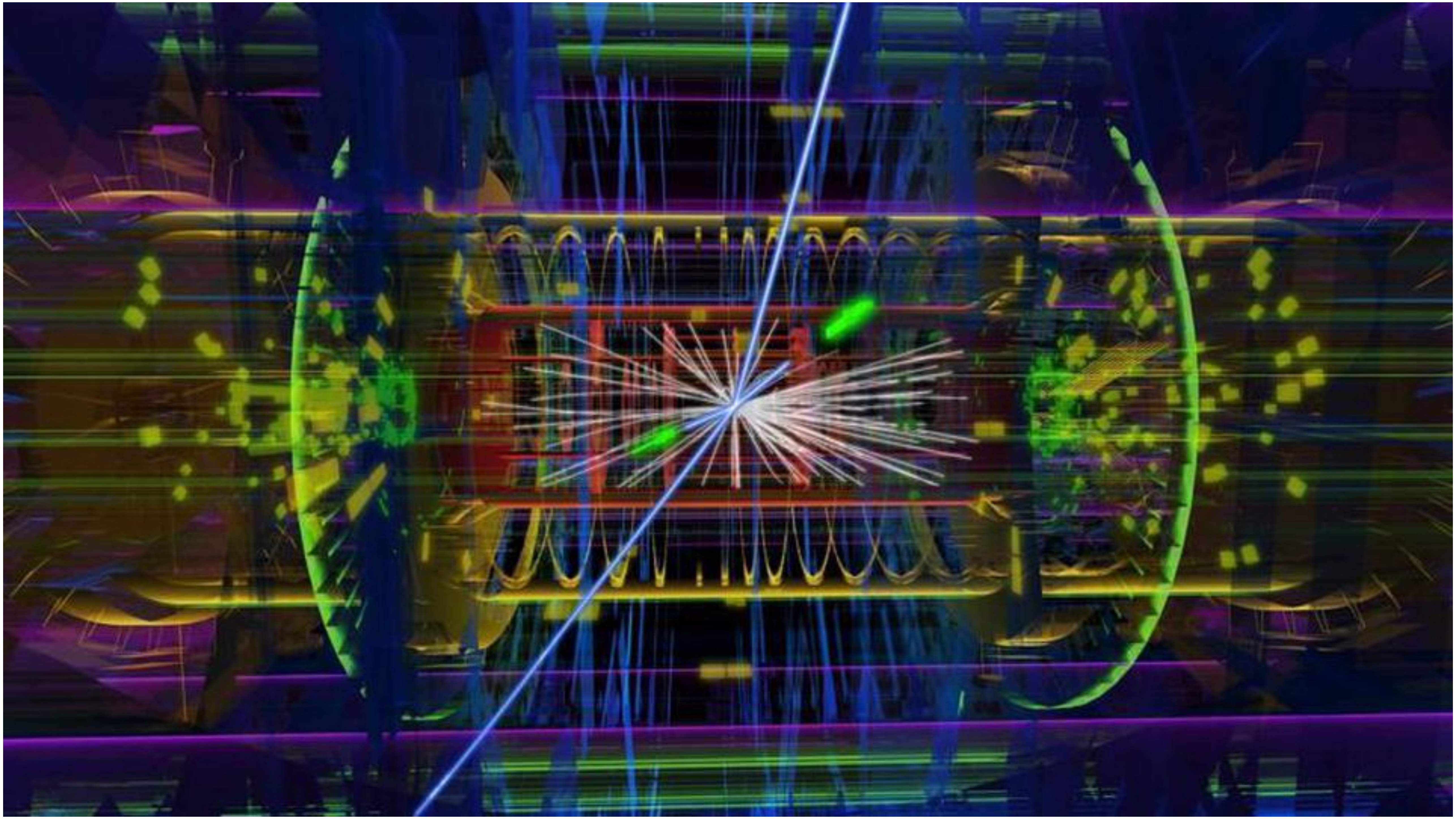




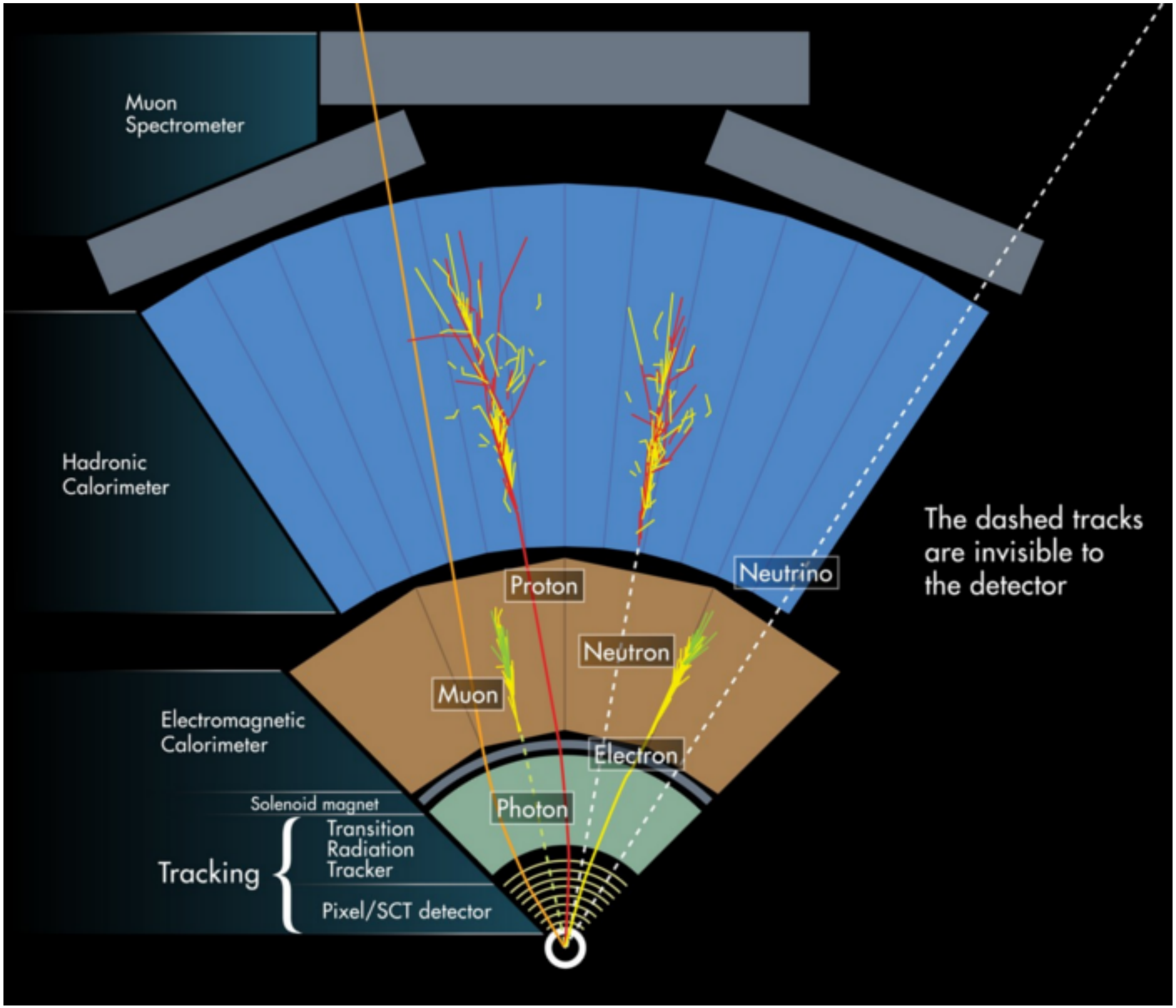
$\eta = -ln[tan(\theta/2)]$ (pseudo-rapidity)

$p_T = p \cdot \sin(\theta)$ (transverse momentum)

A collision "event"



Particle identification with the ATLAS detector



A lot of work goes into particle reconstruction

…our handle towards what's happening in the collision

Need efficient, fast reconstruction and identification

In addition

- Energy/momentum calibration
  - p.ex. cell energy in calorimeter => photon energy

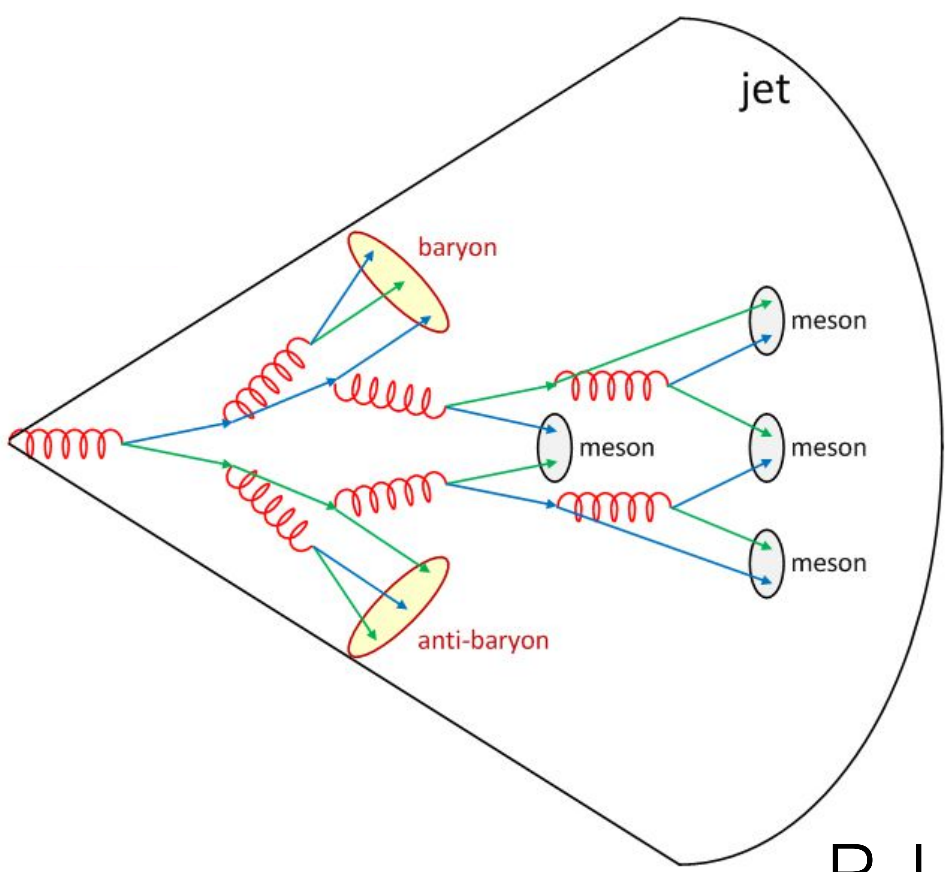
- Efficiency measurements
  - important to measure cross sections: $N_{events} = XS * L_{int} * A * eff$

- data - simulation
  - efficiencies are not the same due to imperfect detector modelling
  - needs to be corrected, otherwise comparisons will be biased

>> multivariate/machine learning techniques used where possible

Hadronic jets

- Lagrangians are written in terms of quarks and gluons
- Quark confinement: You cannot have a separate quark in the detector
- through hadronization, one quark will produce a bunch of hadrons, like pions, protons, kaons, etc



P. Loch

Hadronic jets

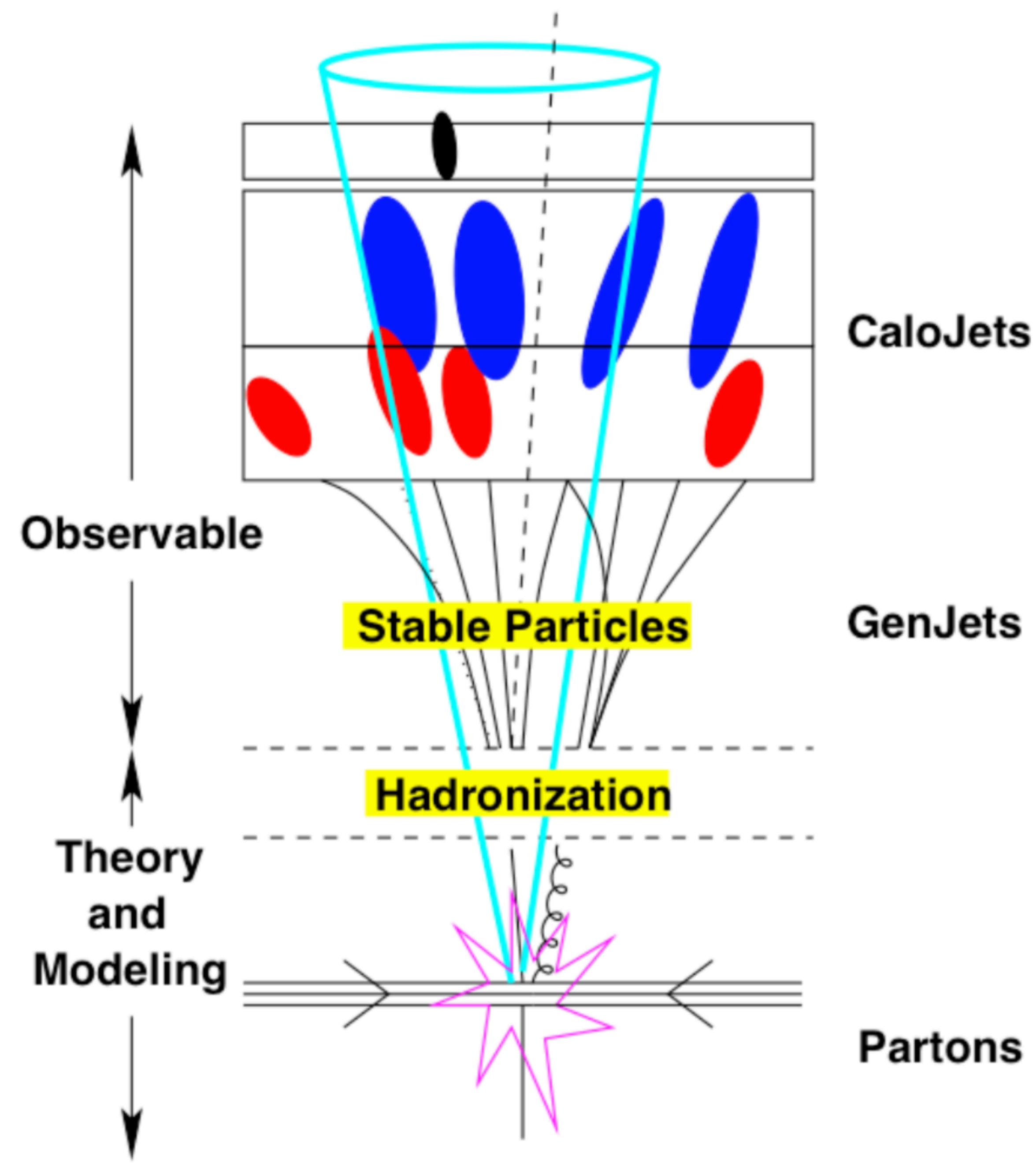
In the end, what we see in our detector is tracks and calorimeter deposits

>> need to reverse engineer the quarks/gluons

>> in a way that can be also done for theoretical predictions (p.ex. “infrared safe”)

>> different algorithms possible
- cone-based
- sequential clustering

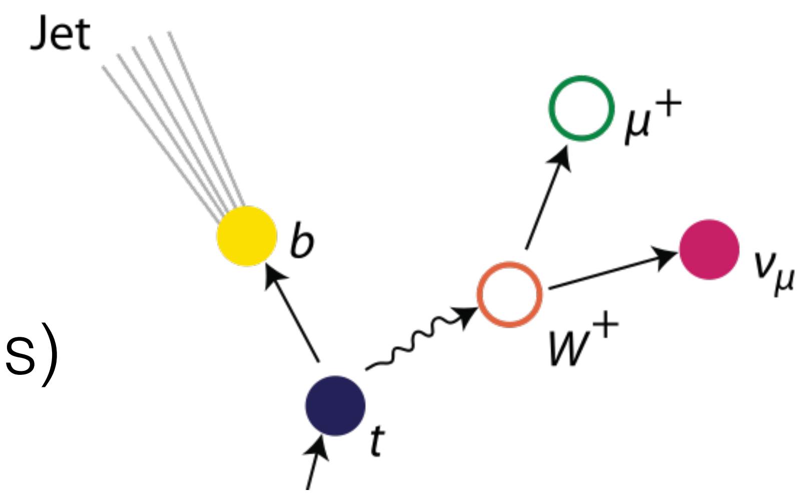
>> mostly used by ATLAS/CMS: sequential clustering (anti-kT)



P. Schifferdecker

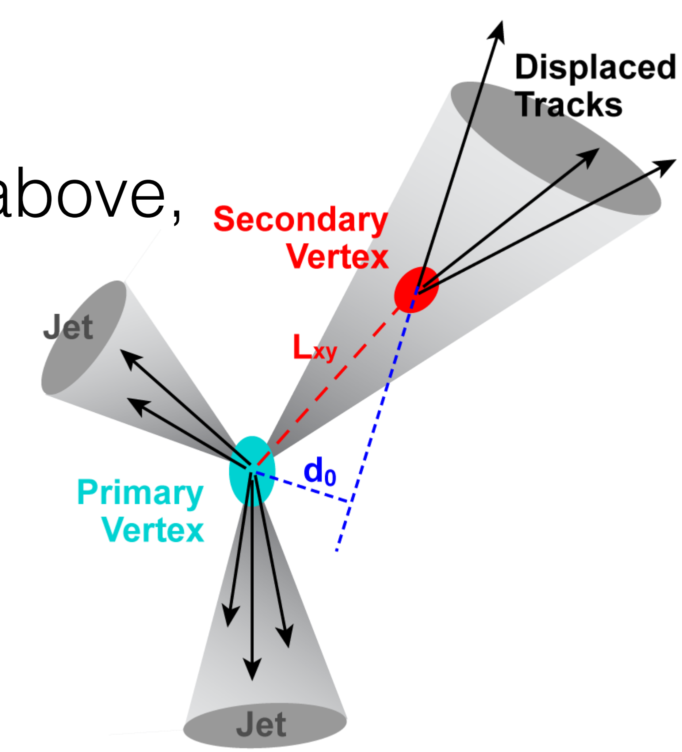
B-jets

b quarks (for example from top quark or Higgs decays) will form B-mesons
=> B-jets

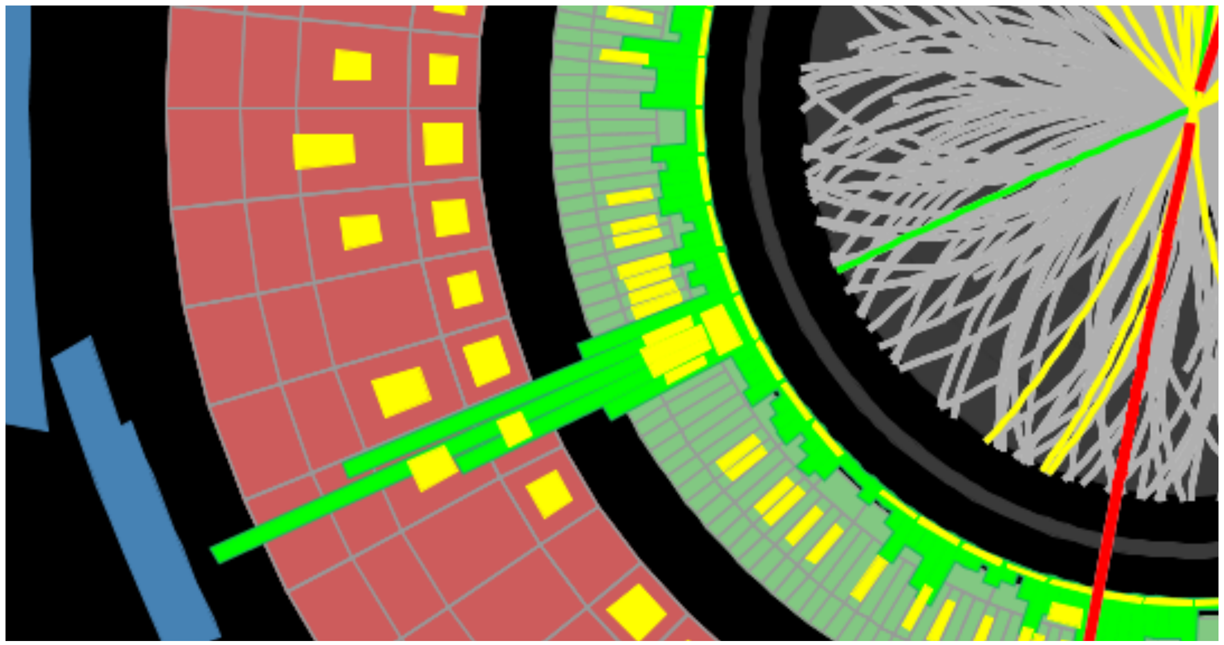


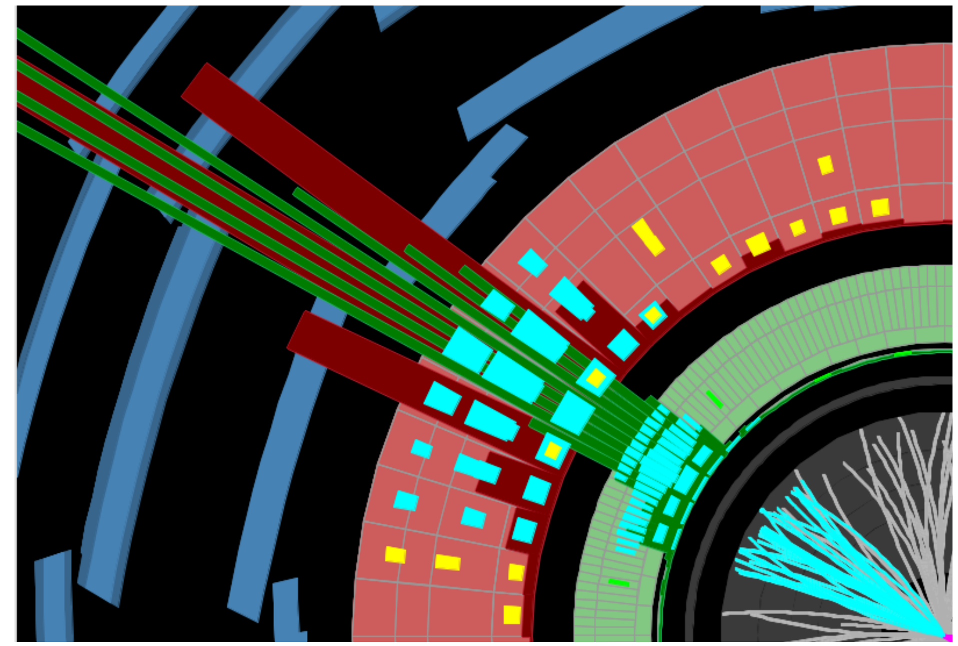
B-mesons
- large mass
- a long life-time: 1.6 * 10^{-12} s => long! (top quark: 10^{-24} s)
- large cτ: will travel ~0.5 mm before decay
- high number of charged particles per decay
- chance of leptonic decay

B-jets can be selected ("tagged") using some of the criteria above, especially the life-time (secondary vertex)
=> multivariate analysis



One word about fakes





- a particle is not always unambiguously identified
- example: electrons can be “faked” by jets

>> apply criteria to reject fakes
>> find ways to estimate this (usually in data)

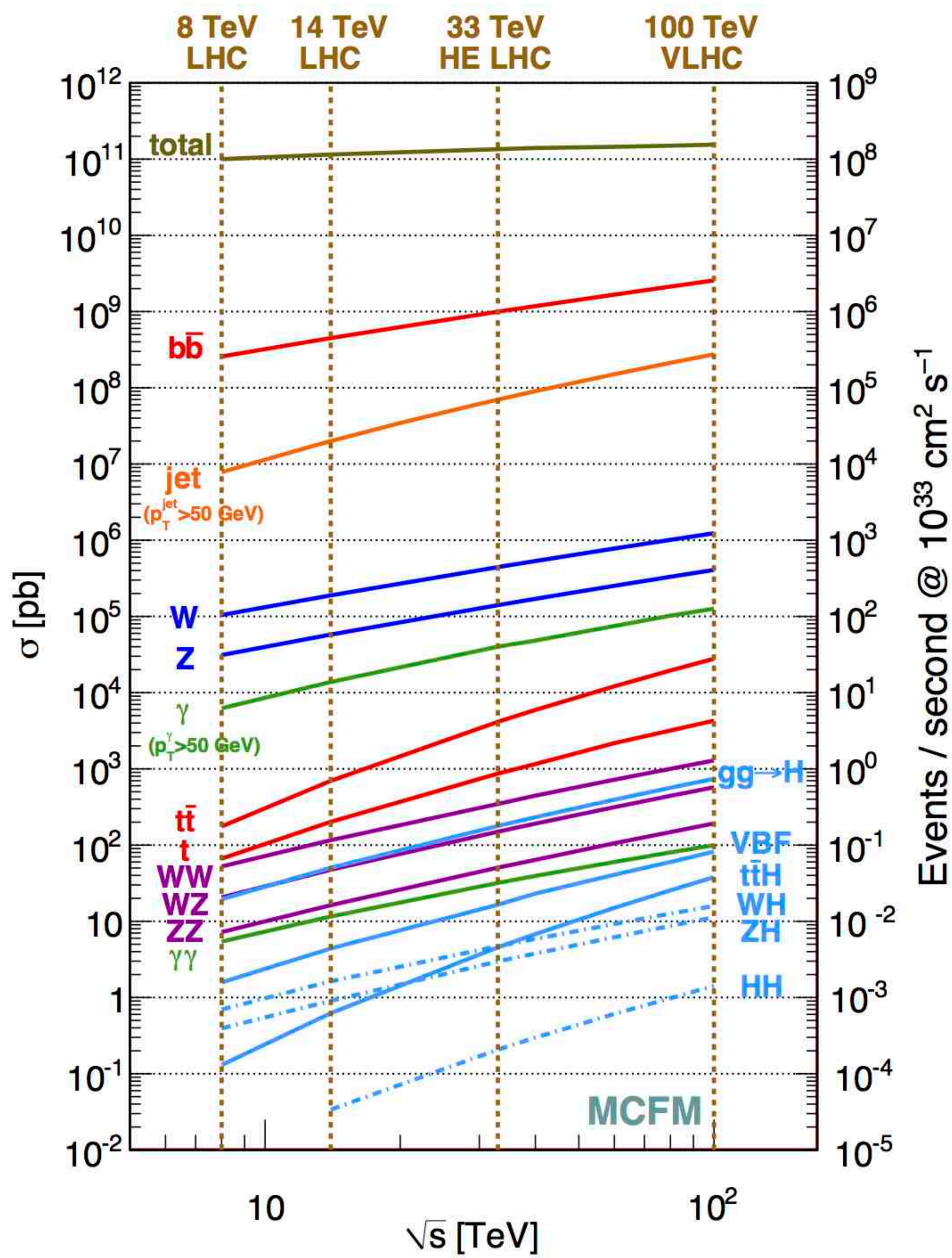
Most collisions are boring

- most pp collisions produce low energy quark/gluon jets

=> to find heavy particles, need to filter!

- Already during data-taking
  - We do not have enough space on disc to store all events
  - filter: “Trigger”
  - hardware and software component
  - 40 MHz => 1 kHz

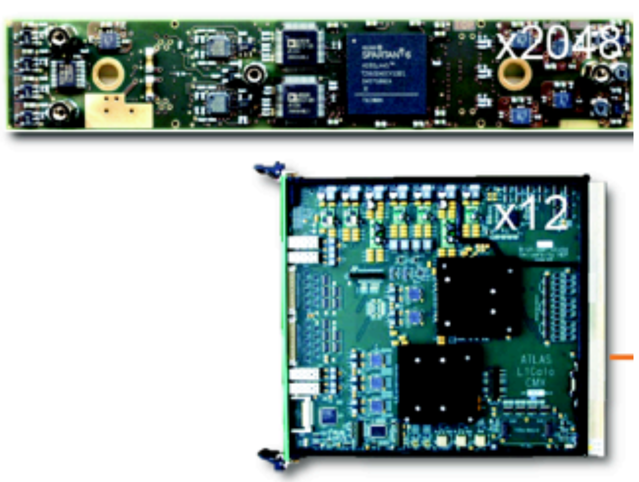
- More selection “offline” (next lecture)

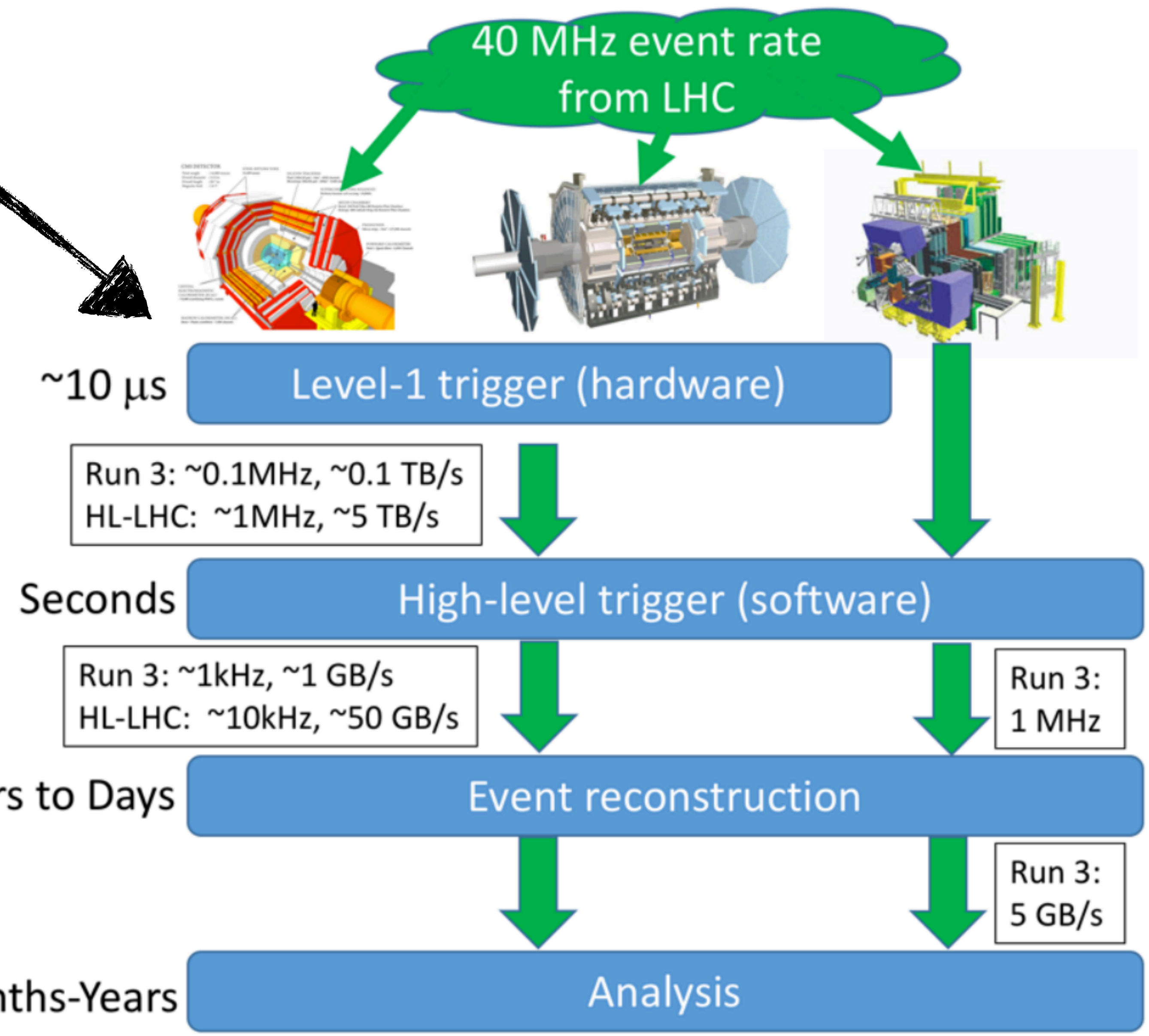


A bit more on the trigger

- super important! What is not triggered on is lost!

Calorimeter, fast muon detectors





Full detector readout
Close to offline reconstruction

A bit of collider history (not complete)

1978 – 1986

PETRA (DESY)

- e+e-, ~30 GeV

1981 – 1991

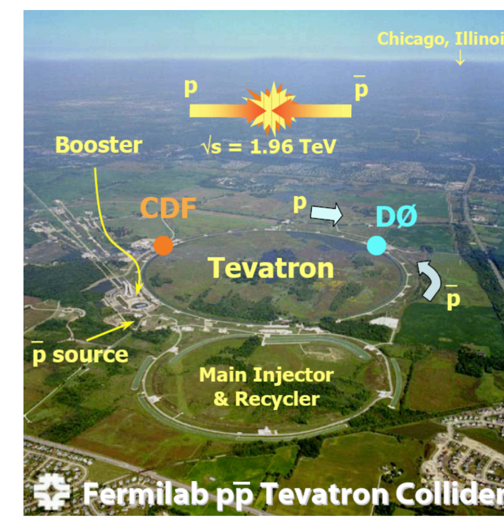
SPS (Cern)

- p anti-p collider, up to 450 GeV
- L_{int} ~ (10 pb^{-1}?)

1983 – 2011

Tevatron (Fermilab)

- p anti-p collider, 1.8-1.96 TeV
- L_{int} ~ 10 fb^{-1} (at 1.96 TeV)



1989 – 2001

LEP (Cern)

- e+ e- collider, up to 209 GeV
- L_{int} ~ 1 fb^{-1}

2009 – 2036

LHC (Cern)

- pp collider, 7-13 TeV
- L_{int} ~ 200 fb^{-1} and growing

Future

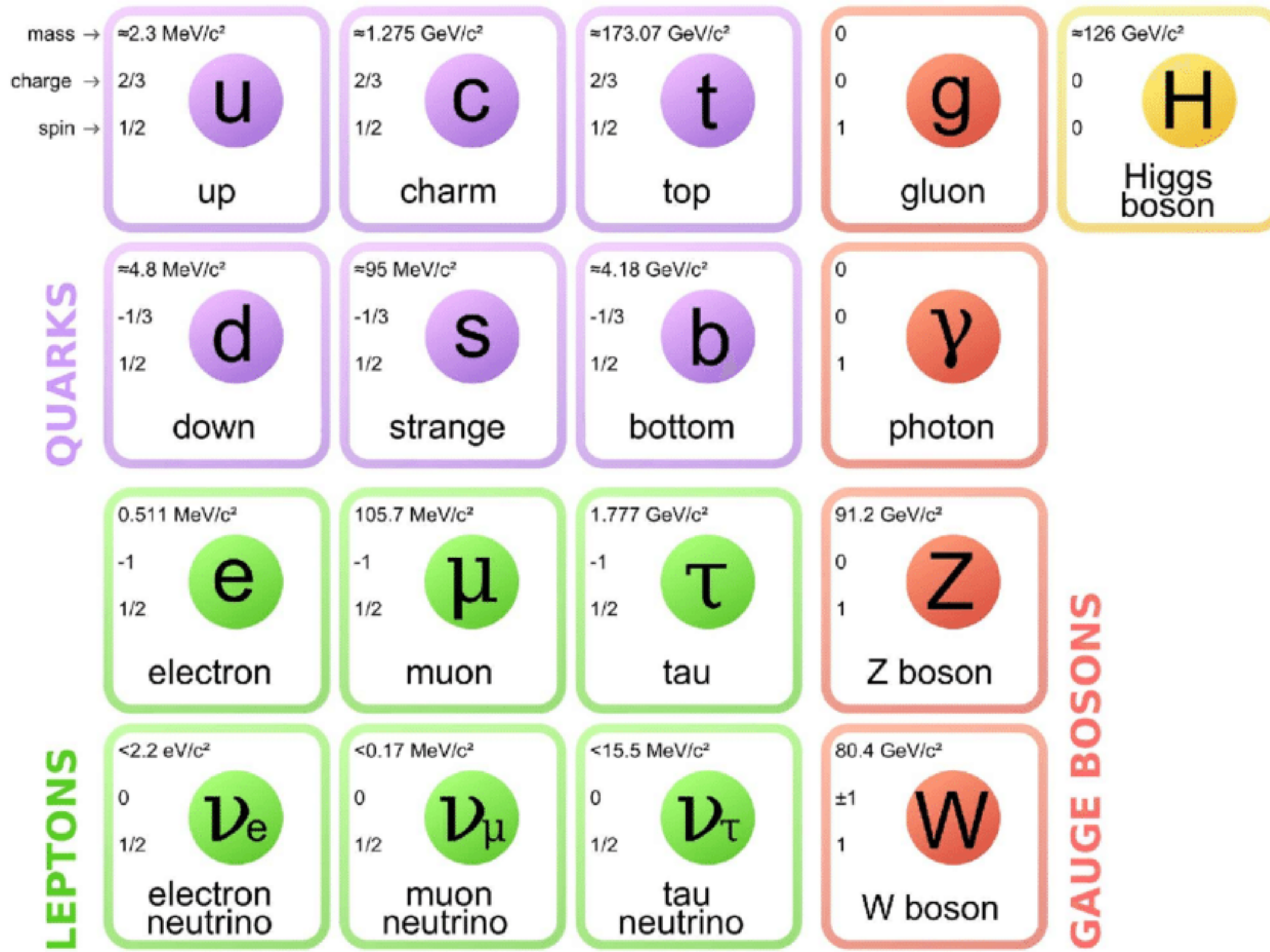
ILC/CLIC/FCC/CEPC?

The Standard Model of Particle physics

- Theory describing fundamental particles and their interactions through
  - Electromagnetic force
  - Weak force
  - Strong force

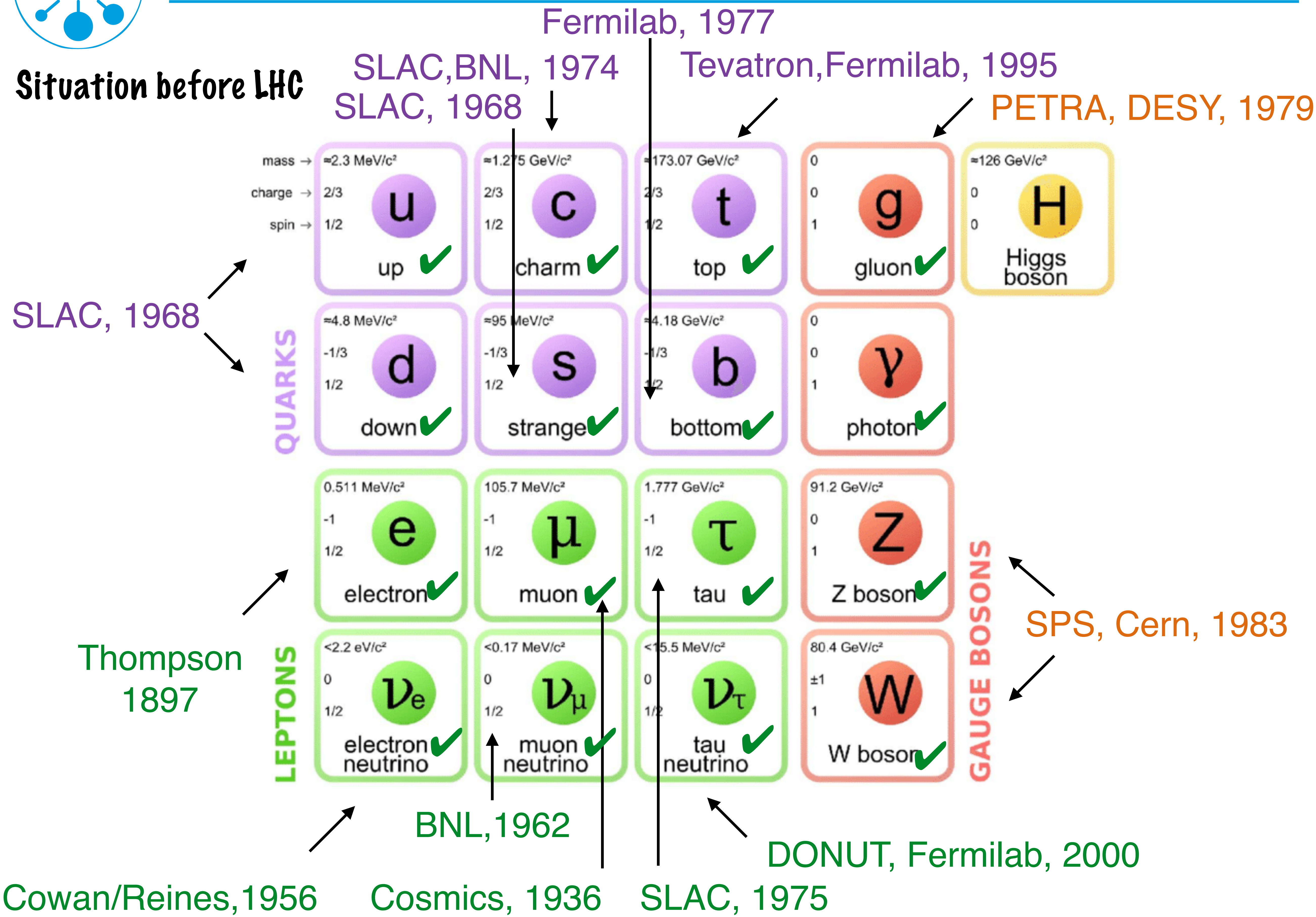
$$
\begin{aligned}
\mathcal{L} = & -{}^1/_4 F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\Psi} \not{D} \Psi + h.c. \\
& + \Psi_i y_{ij} \Psi_j \Phi + h.c. \\
& + |D_\mu \Phi|^2 - V(\Phi)
\end{aligned}
$$

The Standard Model - fundamental particles



The Standard Model - fundamental particles

Situation before LHC



Physics goals of the LHC

- Test the SM

- Find the Higgs boson

- Find physics beyond the Standard Model
  - as the Standard Model cannot explain dark matter, matter-anti-matter asymmetry etc.

Backup

Backup: ATLAS trigger system