LHC Physics - Introduction

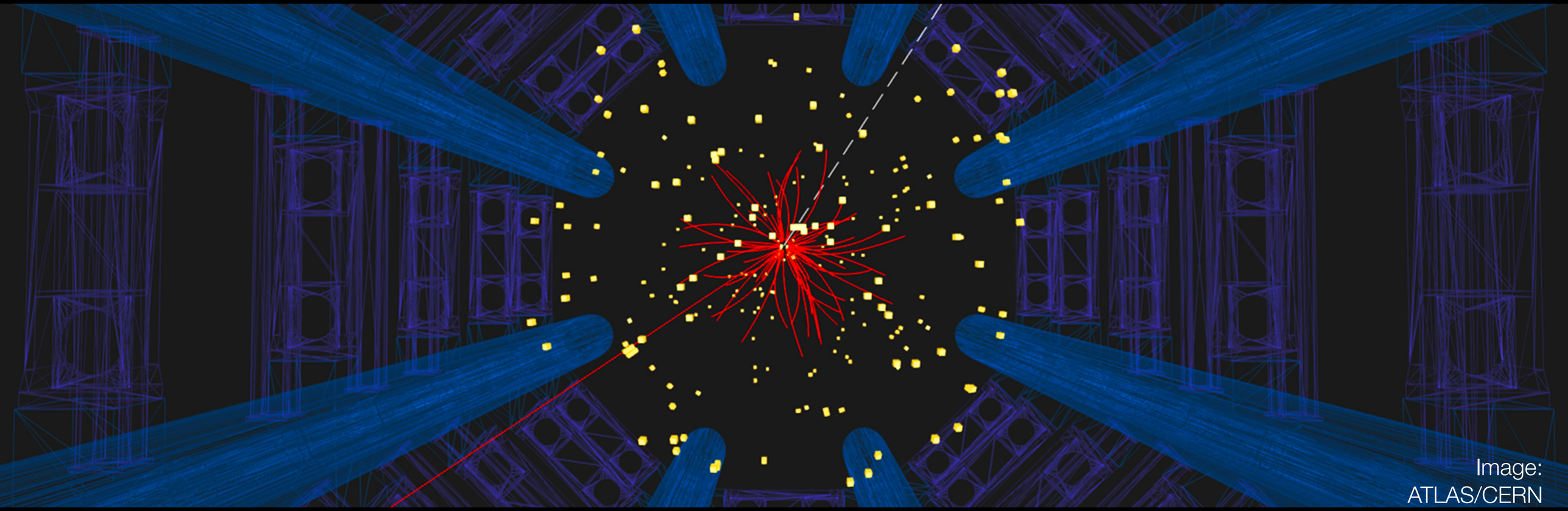


Image:
ATLAS/CERN

Lydia Beresford

DESY Summer Student Lectures

04.08.25

Goals

Goal of lectures: Give an introduction to LHC physics, techniques and plots

Illustrated using a selection of important ATLAS & CMS results

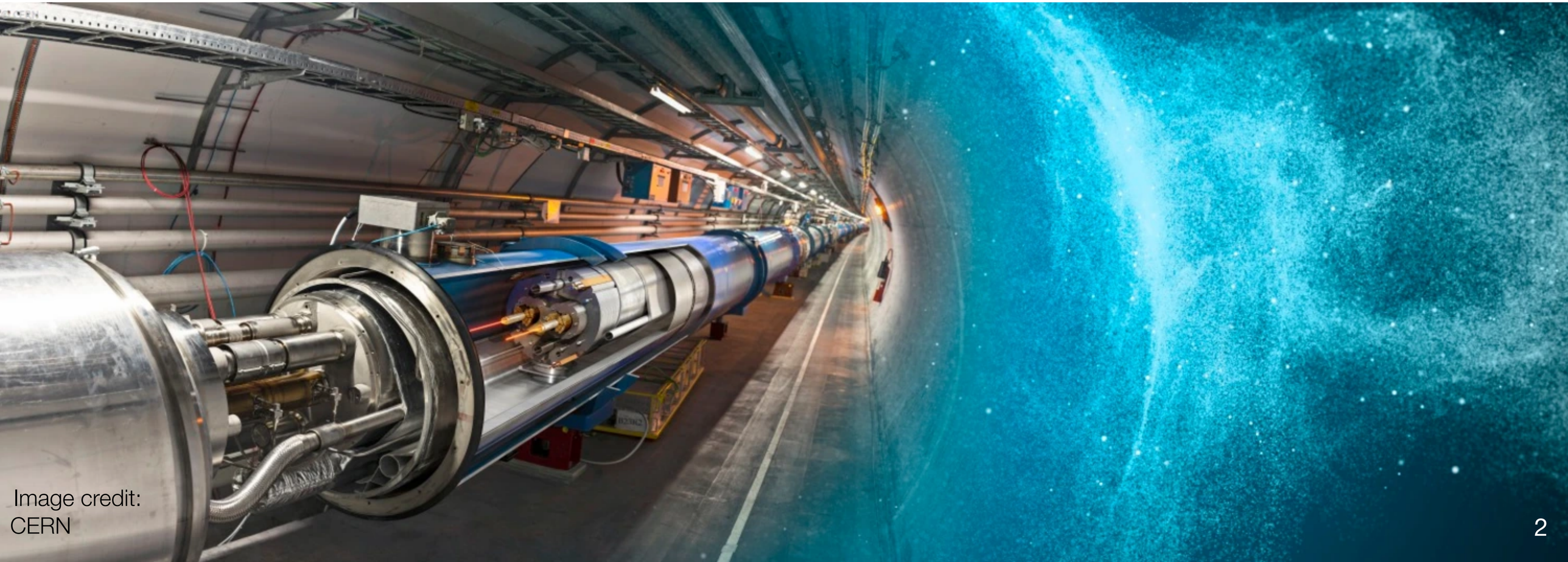


Image credit:
CERN

Acknowledgements

These lectures are based on the following excellent lecture series:

- DESY summer student LHC physics lectures by Claudia Seitz
- DESY summer student LHC physics lectures by Sarah Heim
- CERN summer student Experimental Physics at Hadron Colliders by Marumi Kado

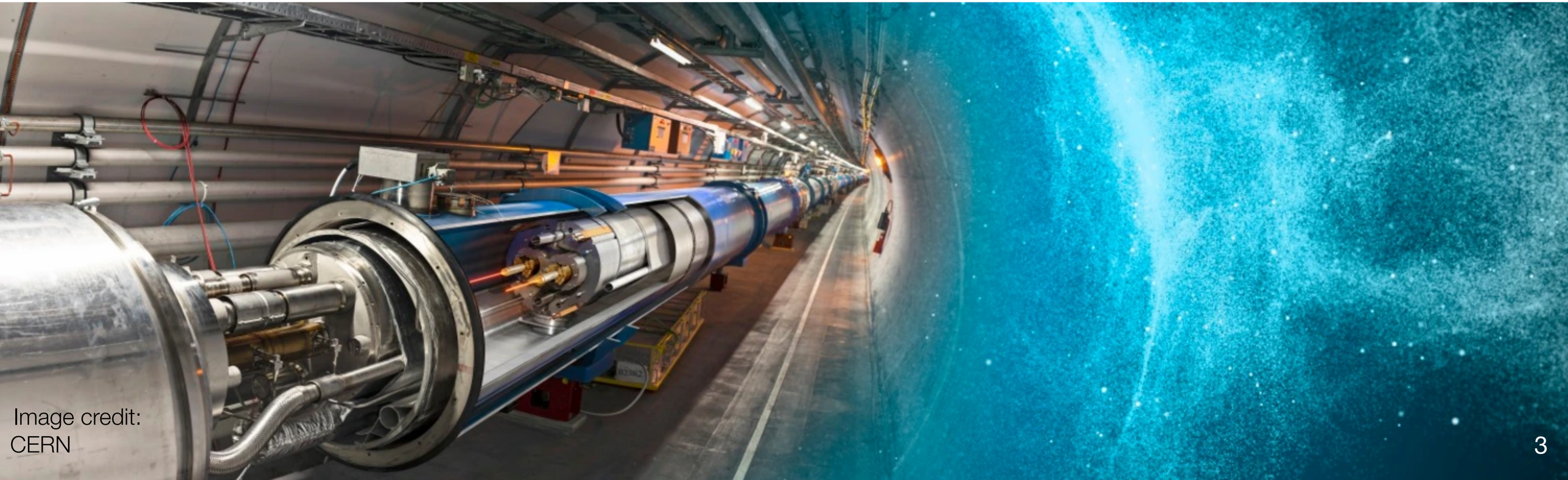


Image credit:
CERN

Physics Goals of the LHC

wikimedia

Measure the Standard Model

Search for the Higgs Boson

Search for New Physics

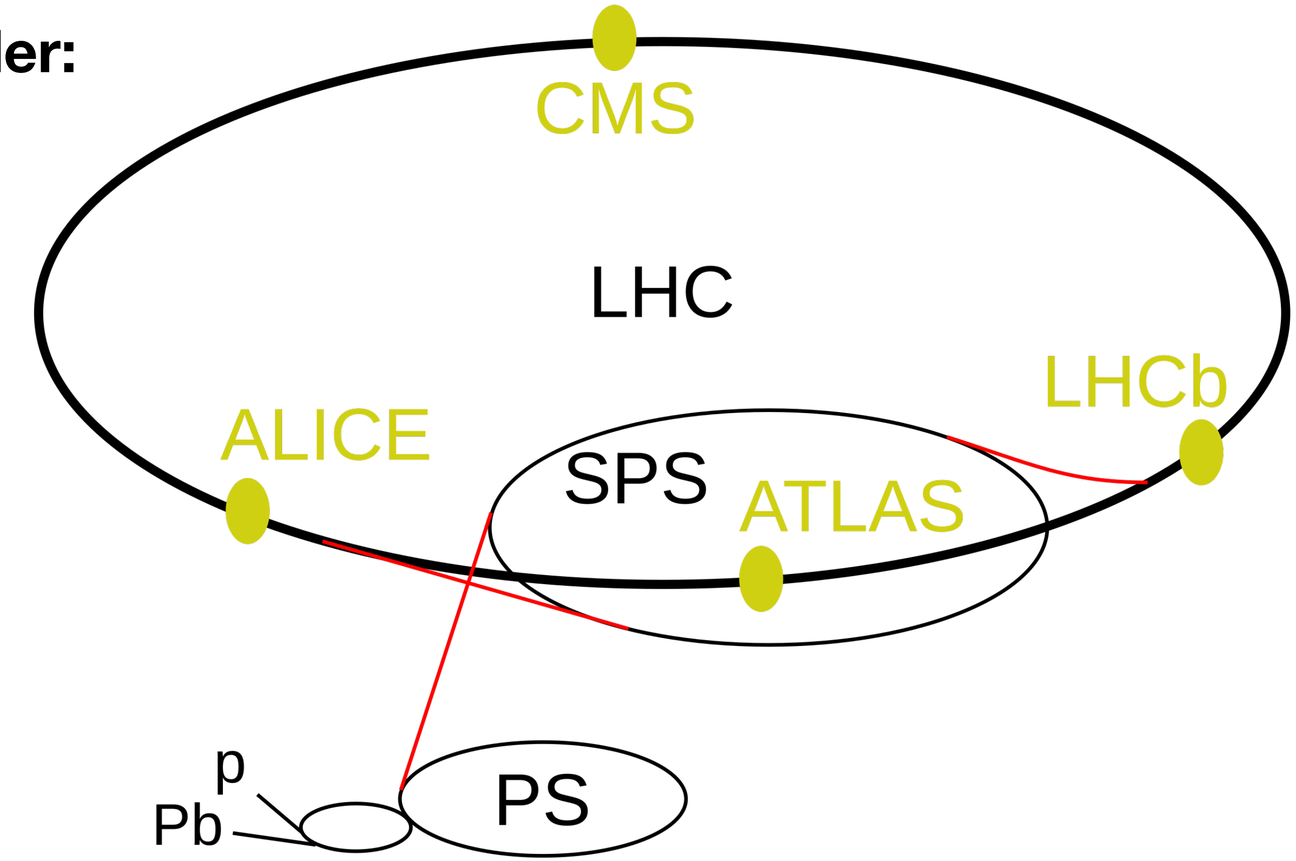
Study the Quark-Gluon Plasma

Large Hadron Collider

Highest energy particle collider in the world: pp, p+Pb, Pb+Pb, Xe+Xe, p+O, O+O, Ne+Ne

Center-of-mass energy: Achieved **13.6 TeV proton-proton collisions**

27 km circular collider:



See lectures by Michaela Schaumann & Gregor Loisch for more on accelerator physics

wikipedia

Instantaneous luminosity

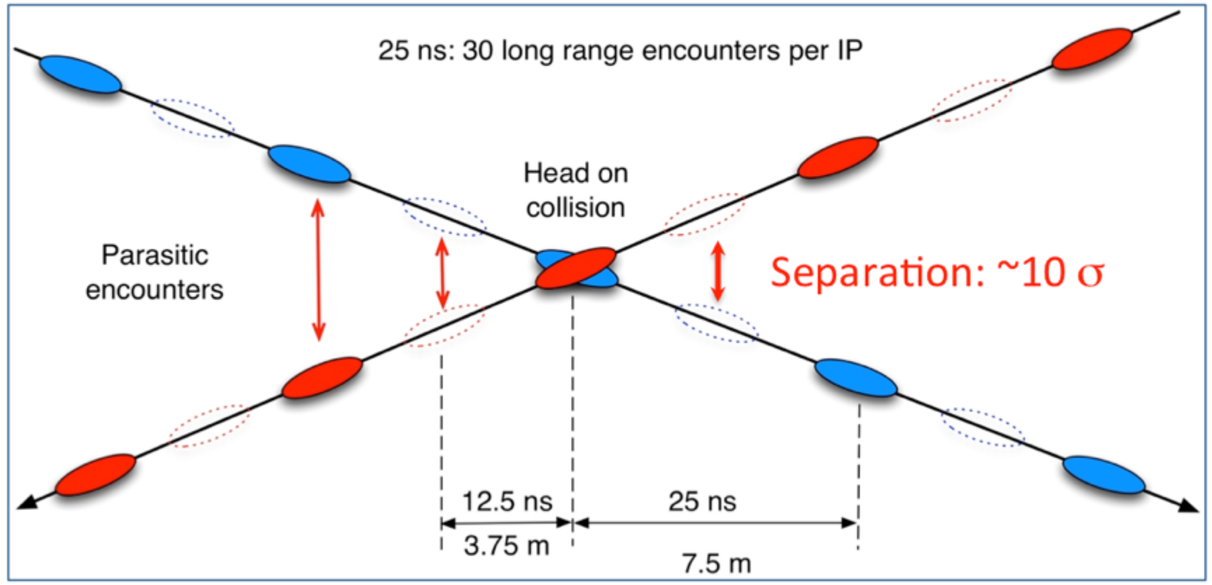
Two key collider quantities: centre-of-mass energy and luminosity

Precision measurement of luminosity is a key ingredient for most physics analyses

Related to:

- Rate of observed events: $R = \Delta N / \Delta t = \sigma \mathscr{L}$
- Machine parameters: $\mathscr{L} = \dfrac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$

2018 beam parameters (physics regime)
- revolution frequency: $\mathbf{f_r}$= 11246/s
- #bunches: $\mathbf{n_b}$ up to 2544
- #protons / bunch: $\mathbf{n_i}$= (1.1-0.9) × 10^{11}
- Width of beams overlap: $\boldsymbol{\Sigma y} > \boldsymbol{\Sigma x} \approx$ 10-20 μm



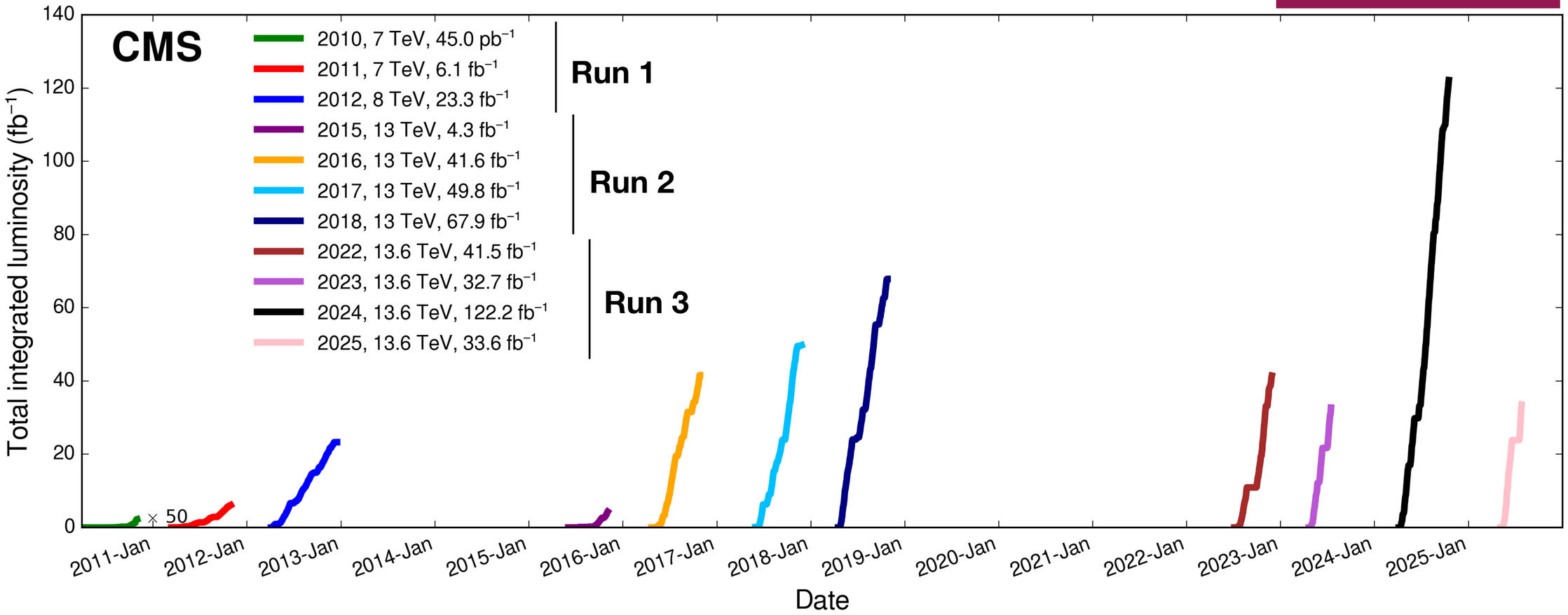
Peak luminosity reached in 2018: 2 x 10^{34} $cm^{-2}s^{-1}$

cern news

LHC proton-proton collisions

Various running years with different energies

1 barn = 10^{-24} cm^2



Run 1: 2010- 2012

7 and 8 TeV, ~30 fb^{-1}

Run 2: 2015 - 2018

13 TeV, ~150 fb^{-1}

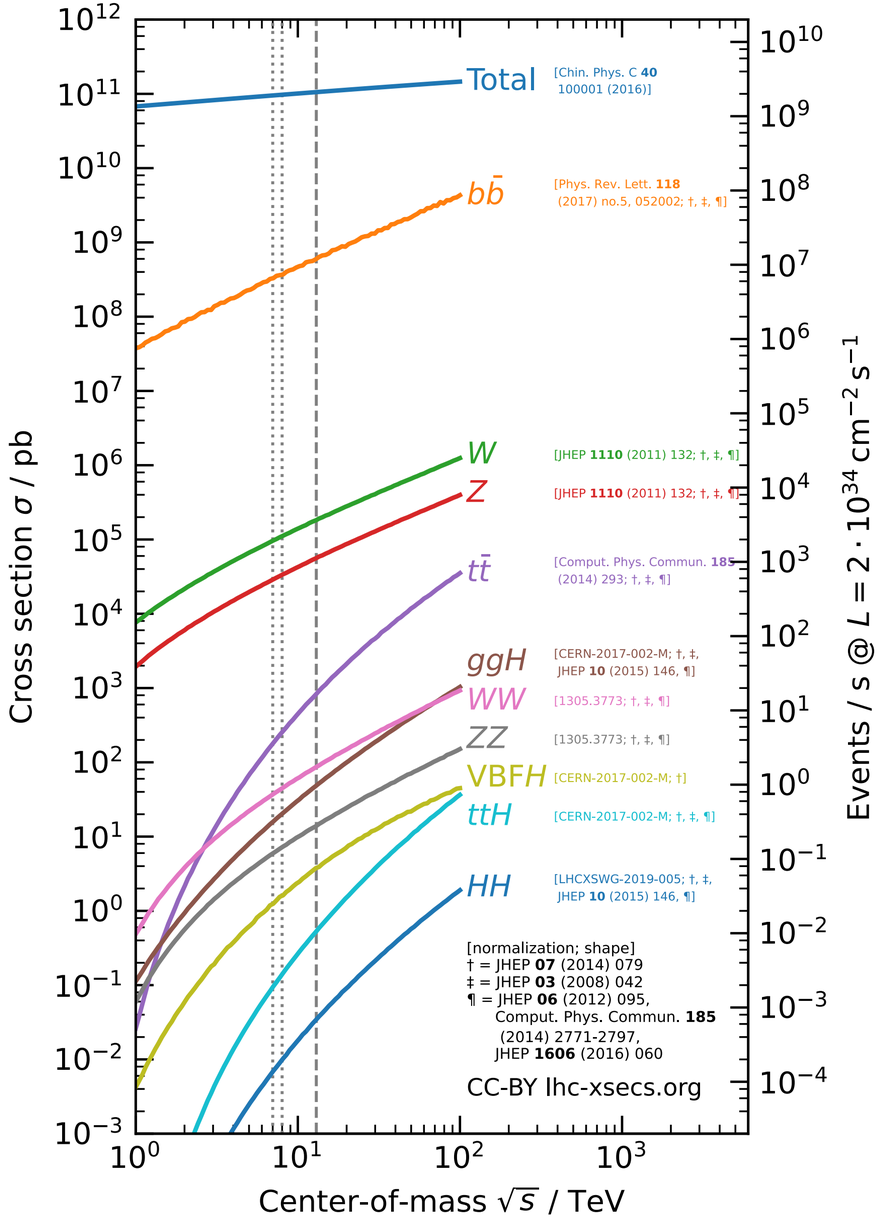
Run 3: 2022 - ongoing

13.6 TeV, already ~230 fb^{-1}

https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

LHC proton-proton collisions

F. Sauerburger,
LHC cross section plot,
https://lhc-xsecs.org



- **~100 mb total proton-proton cross section**
- **~ 60 mb in-elastic cross section**

$$R = \Delta N/\Delta t = \sigma_{\text{inel}}\mathscr{L}$$

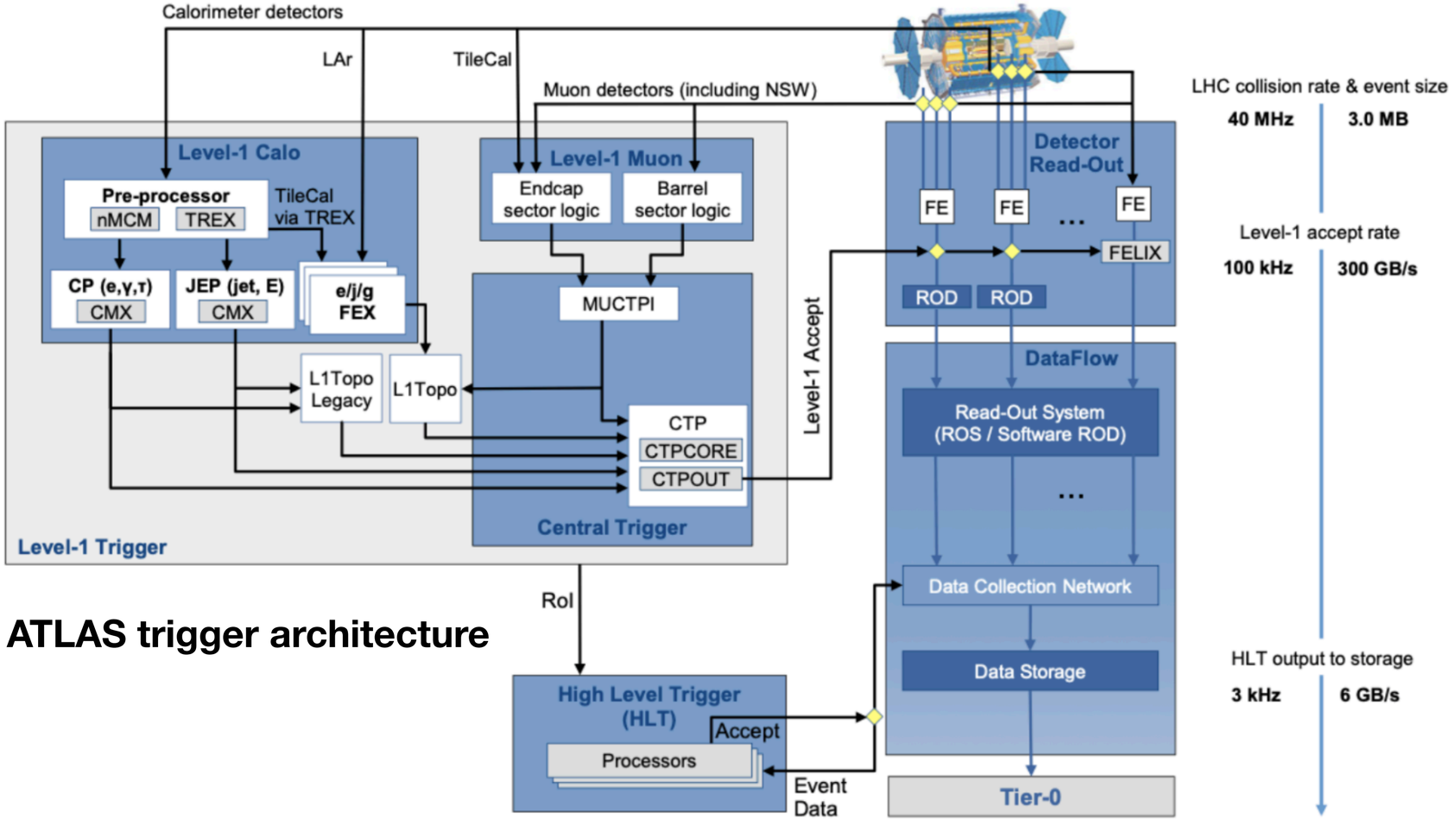
= (60 x 10^{-3} x 10^{-24} cm^2) x (2 x 10^{34} $cm^{-2}s^{-1}$)

= 1.2 x 10^9 in-elastic collisions/second

A word on triggers

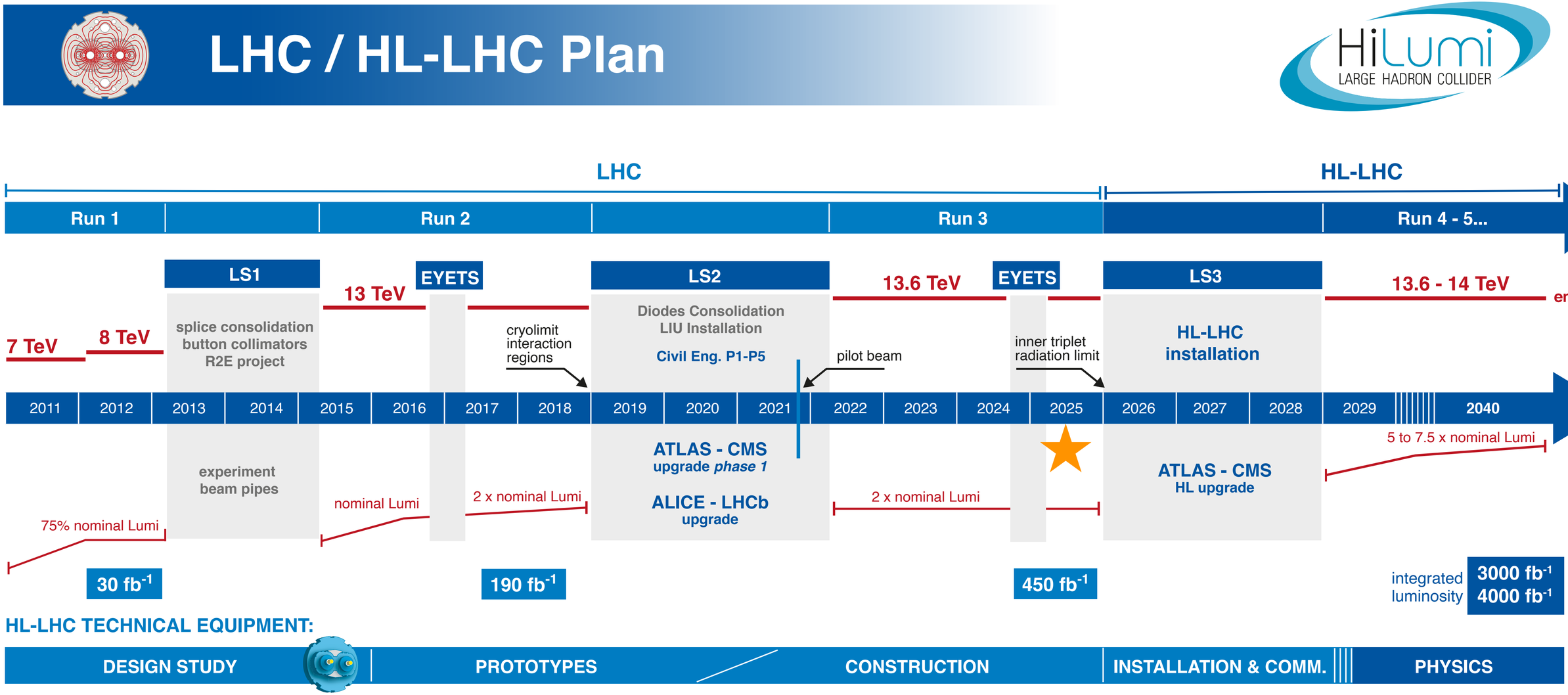
Collisions occur every 25 ns (40 MHz) → Impossible to record everything

Usually target higher transverse momentum particles and specific signatures



ATLAS trigger architecture

LHC schedule



https://hilumilhc.web.cern.ch

Interlude: Large Oxygen Collider?

See lectures by Andrew Taylor for more on astroparticle physics

In July 2025 LHC collided Oxygen (and Neon) for the first time

Measure fundamental processes in the lab → Improve air shower models

Astroparticle connections: Important milestone for cosmic ray physics!

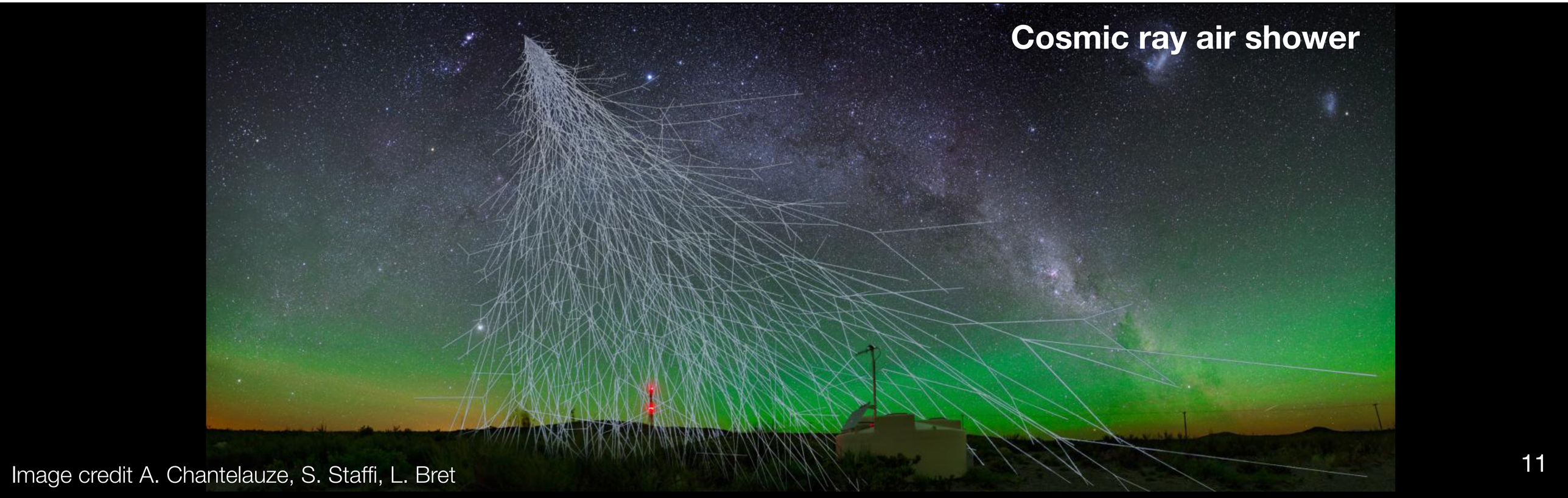
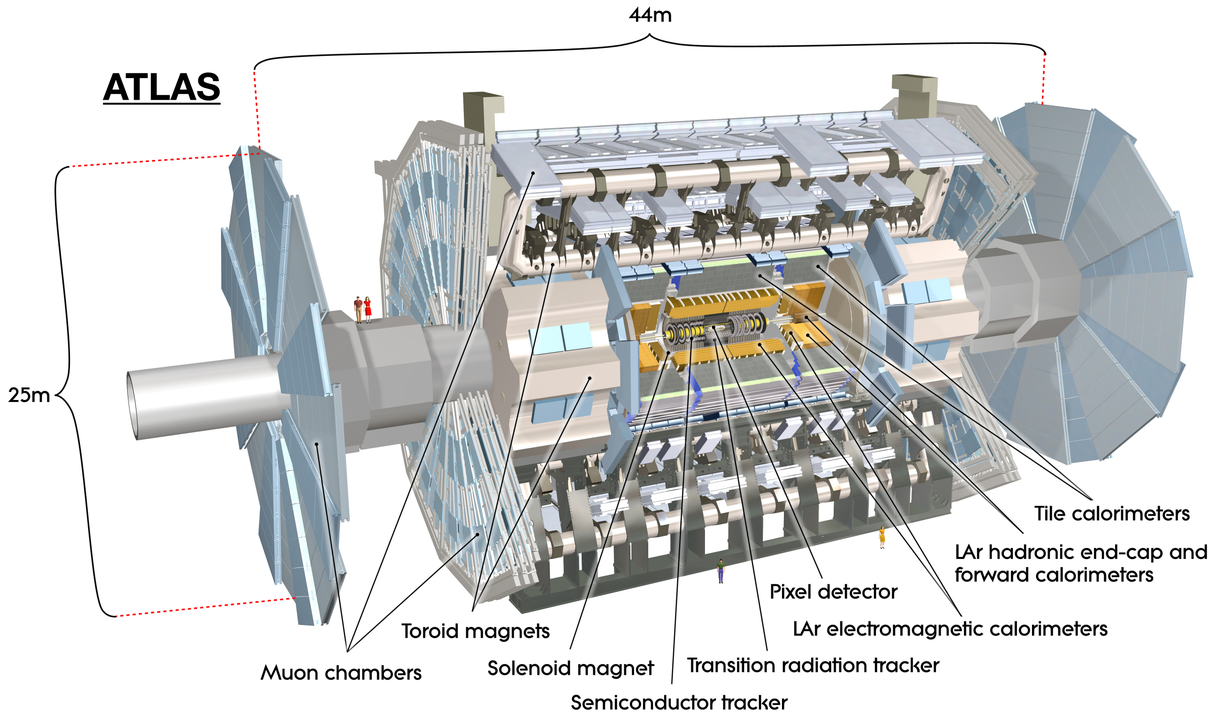


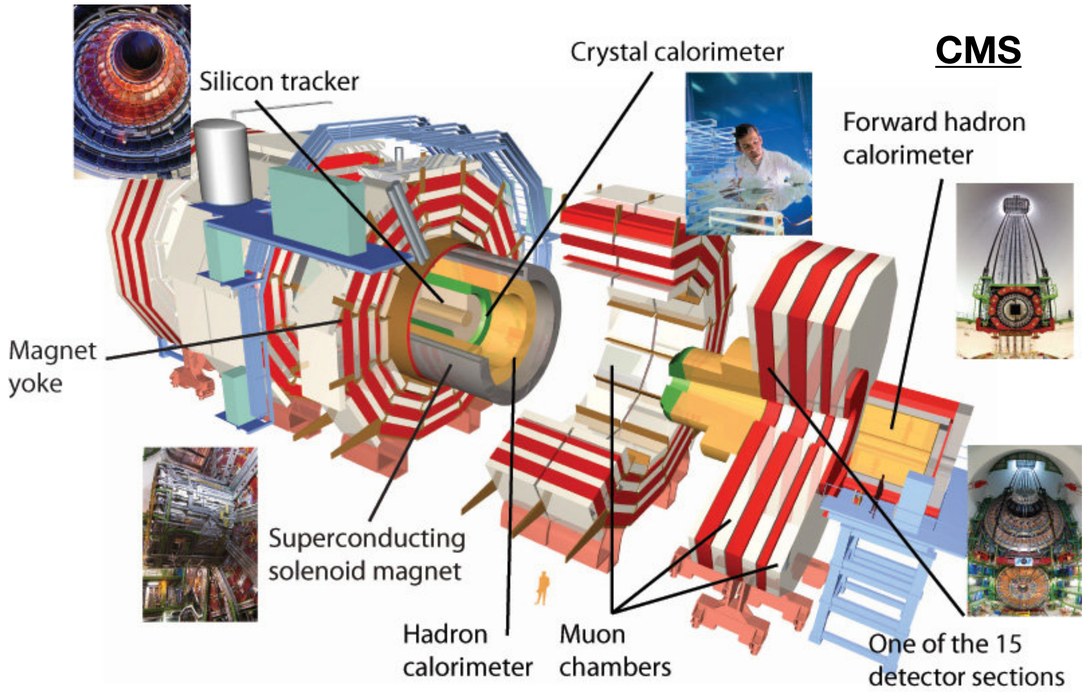
Image credit A. Chantelauze, S. Staffi, L. Bret

The two main experiments for these lectures



ATLAS Detector: 46 m long, 25 m diameter, about 7000 tons, 2T solenoid

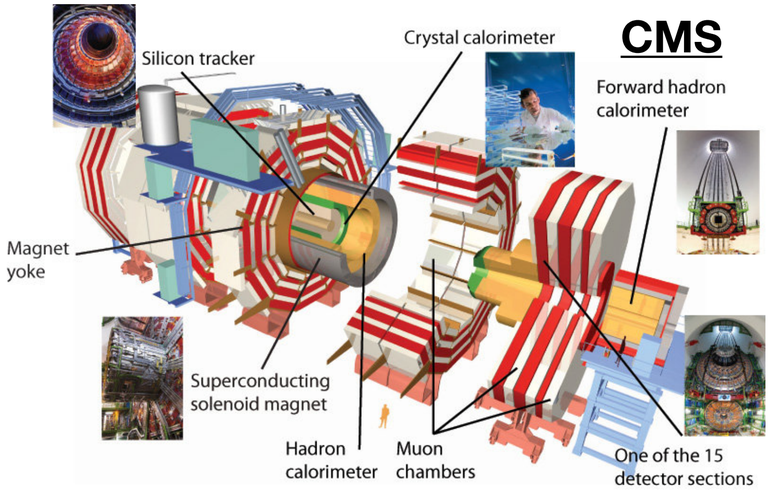
CMS Detector: 21 m long, 15 m diameter, about 14000 tons, 4T solenoid



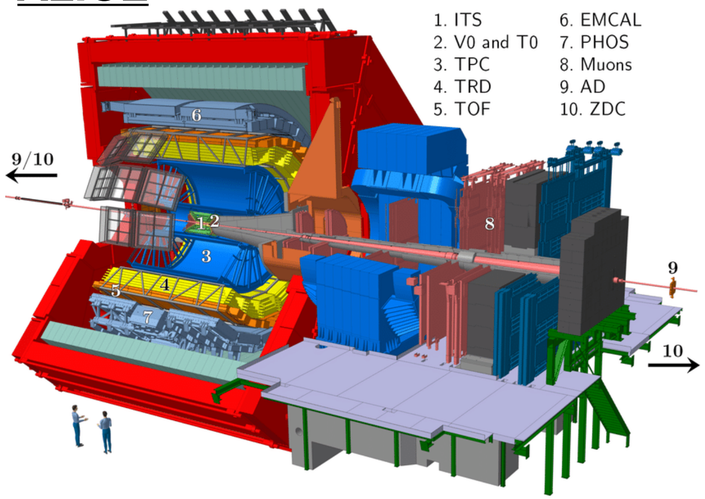
See lectures by Ingrid-Maria Gregor & Simon Spannagel for more on detectors for HEP

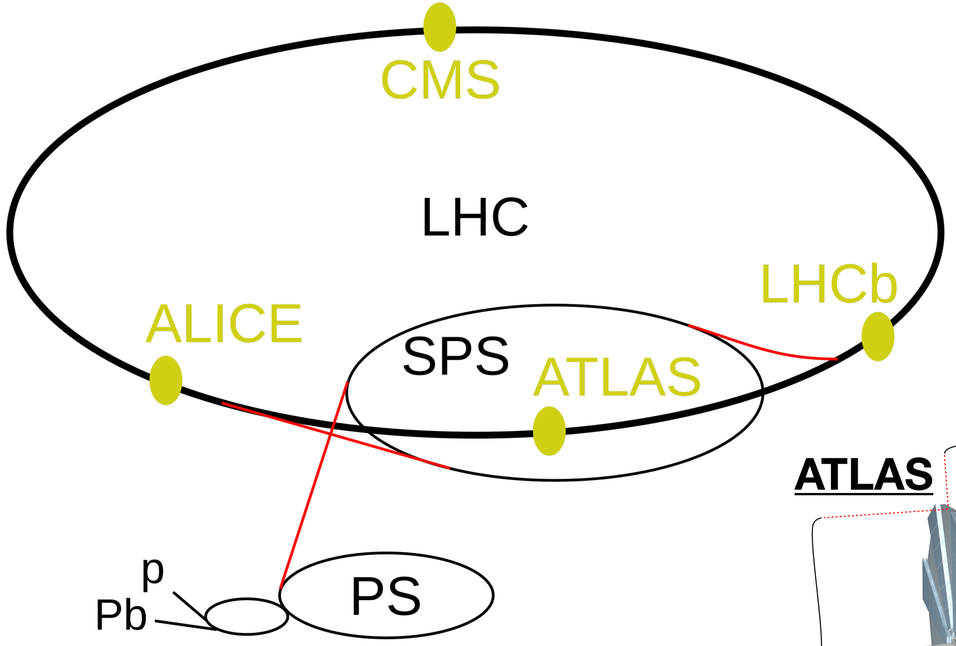
The big four

CMS

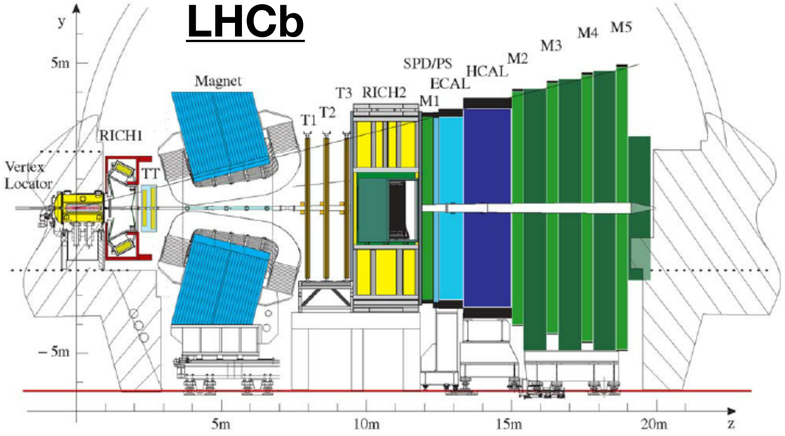


ALICE

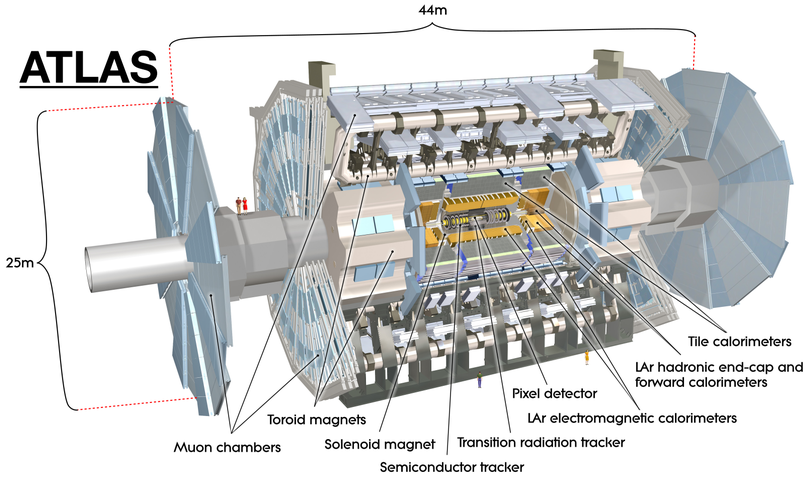




LHCb



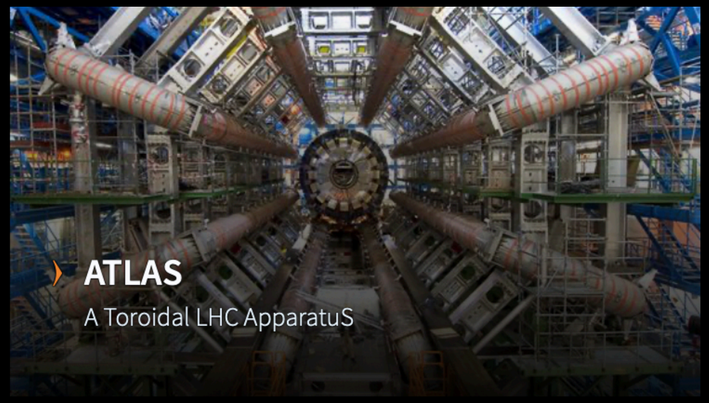
ATLAS

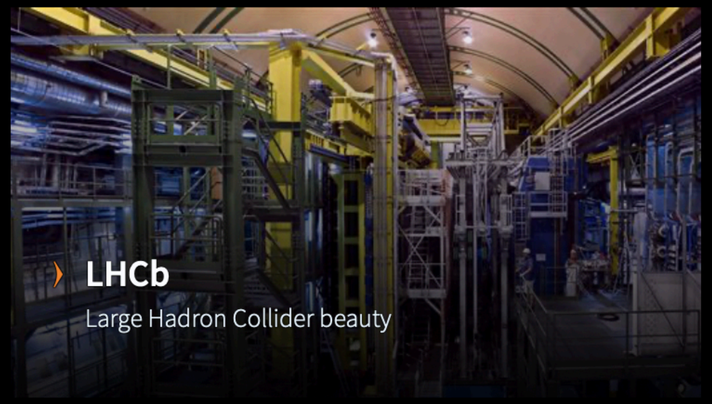


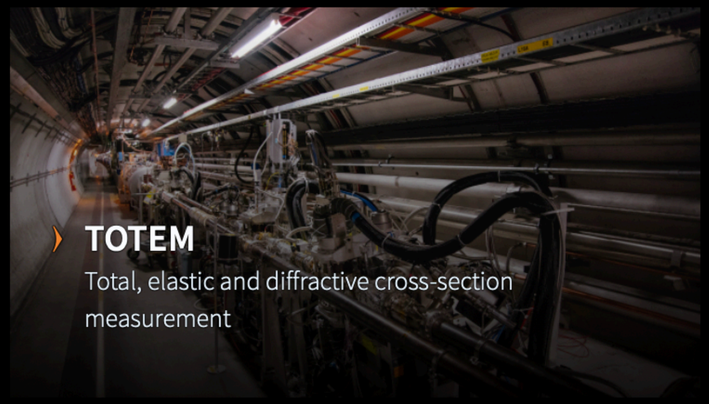
Quiz: Can you name any other LHC experiments?

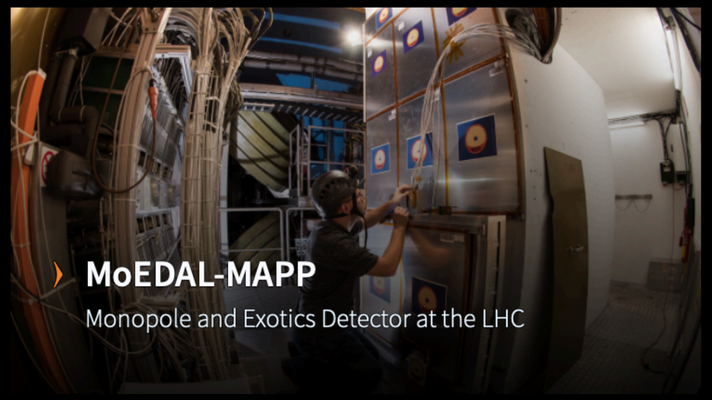
wikipedia

LHC experiments









The Standard Model of Particle Physics

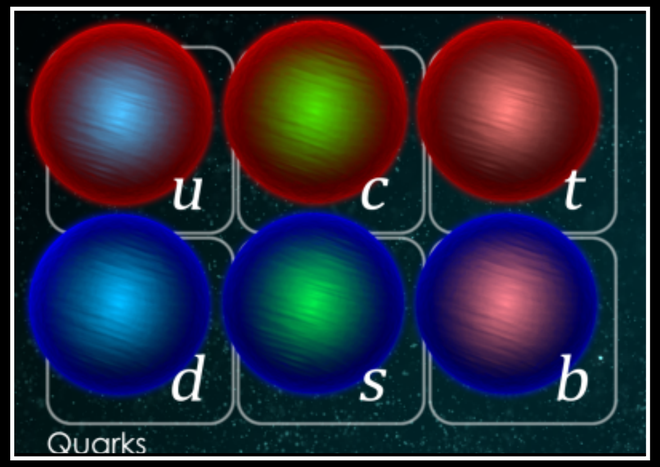
Theory describing fundamental particles and interactions

Extremely successful in predicting and explaining experimental measurements

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

See lectures by Hyungjin Kim for more on HEP Theory

Standard Model particles

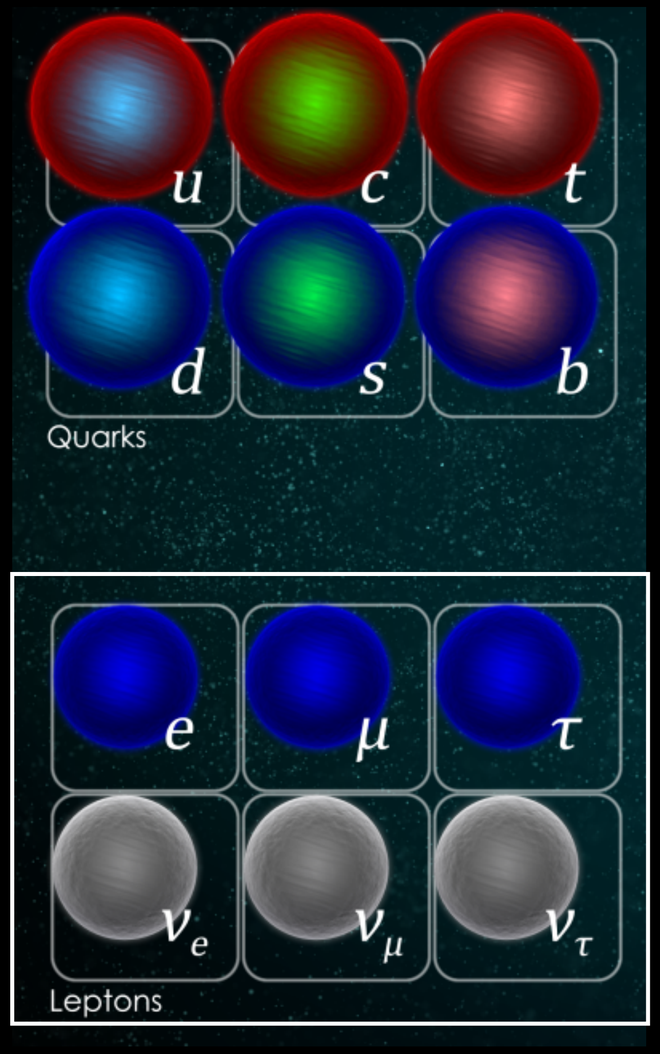


Fermions: spin 1/2

- **Quarks**
  - 6 flavours: up, down, charm, strange, top, bottom
  - 3 colour charges: r, g, b
  - Baryon number: 1/3

Image: Daniel Dominguez/CERN

Standard Model particles



Fermions: spin 1/2

- **Quarks**
  - 6 flavours: up, down, charm, strange, top, bottom
  - 3 colour charges: r, g, b
  - Baryon number: 1/3
- **Leptons**
  - Electron, muon, tau
  - Neutrino for each lepton flavour
  - Lepton number: 1

Image: Daniel Dominguez/CERN

Standard Model particles

Bosons: integer spin

- **Force carriers (Spin 1)**
  - Gluon: strong force
  - Photon: electromagnetic
  - W±, Z: weak force

Image: Daniel Dominguez/CERN

Standard Model particles

Bosons: integer spin

- **Force carriers (Spin 1)**
  - Gluon: strong force
  - Photon: electromagnetic
  - W±, Z: weak force
- **Higgs boson (Spin 0)**
  - Disovered 2012 by ATLAS & CMS
  - Higgs field gives rise to particle masses

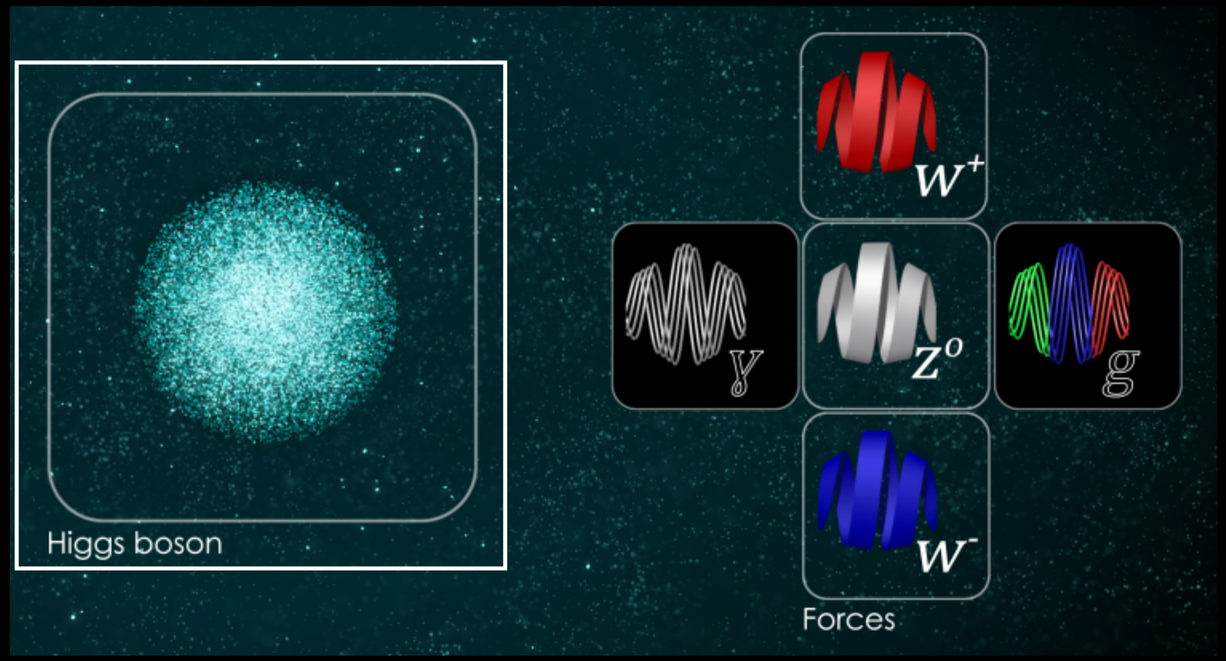


Image: Daniel Dominguez/CERN

Standard Model particles

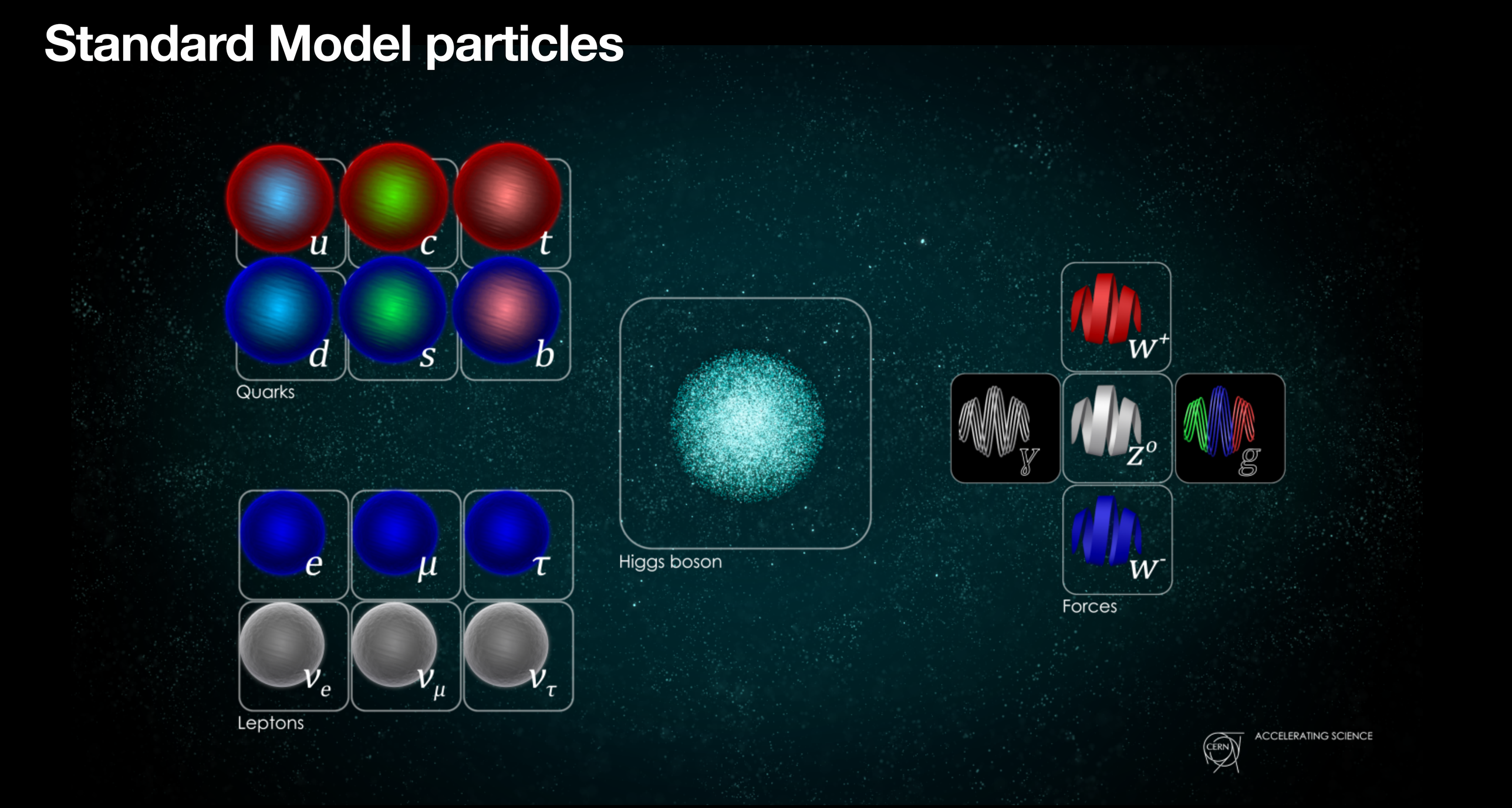
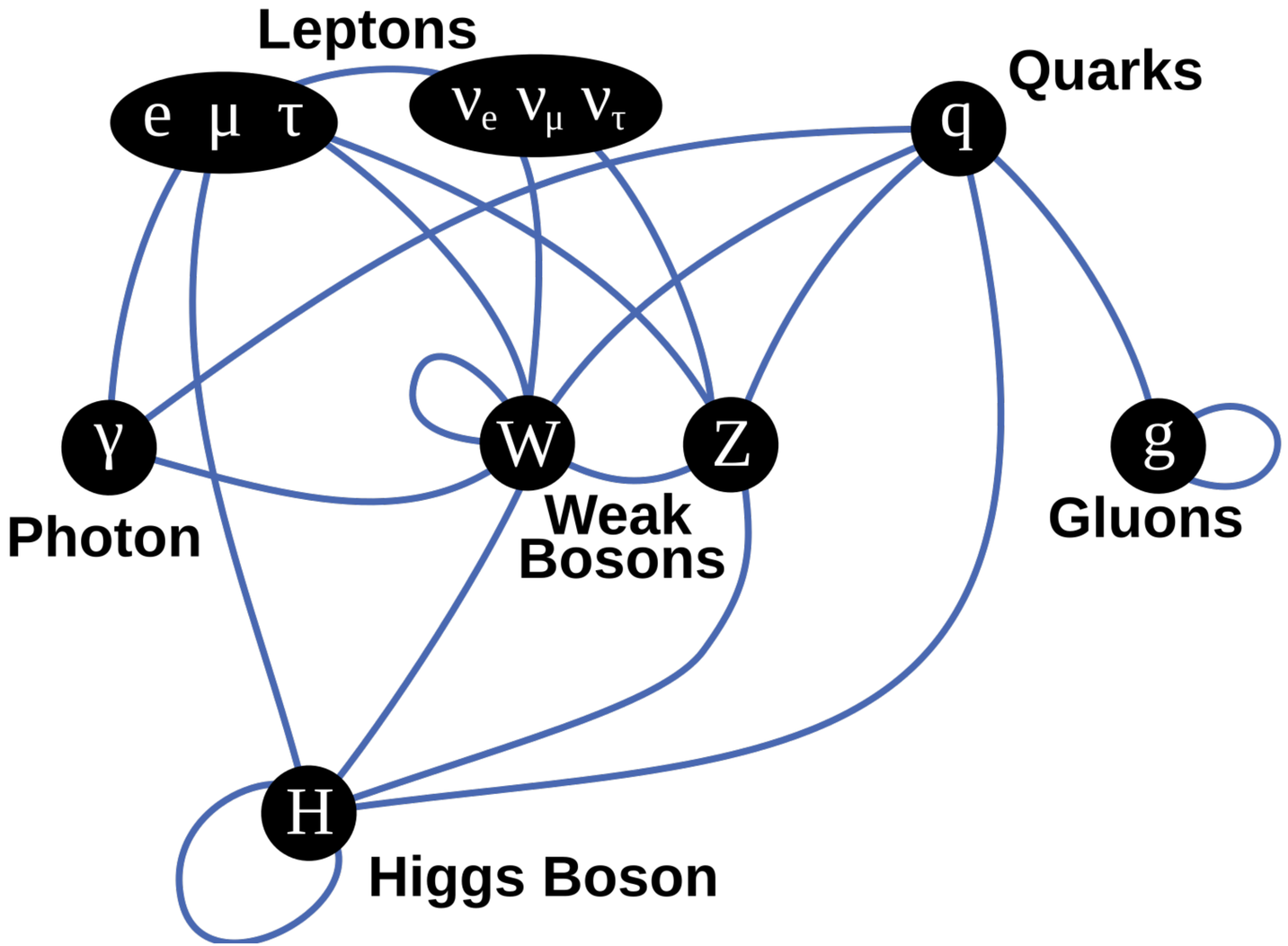


Image: Daniel Dominguez/CERN

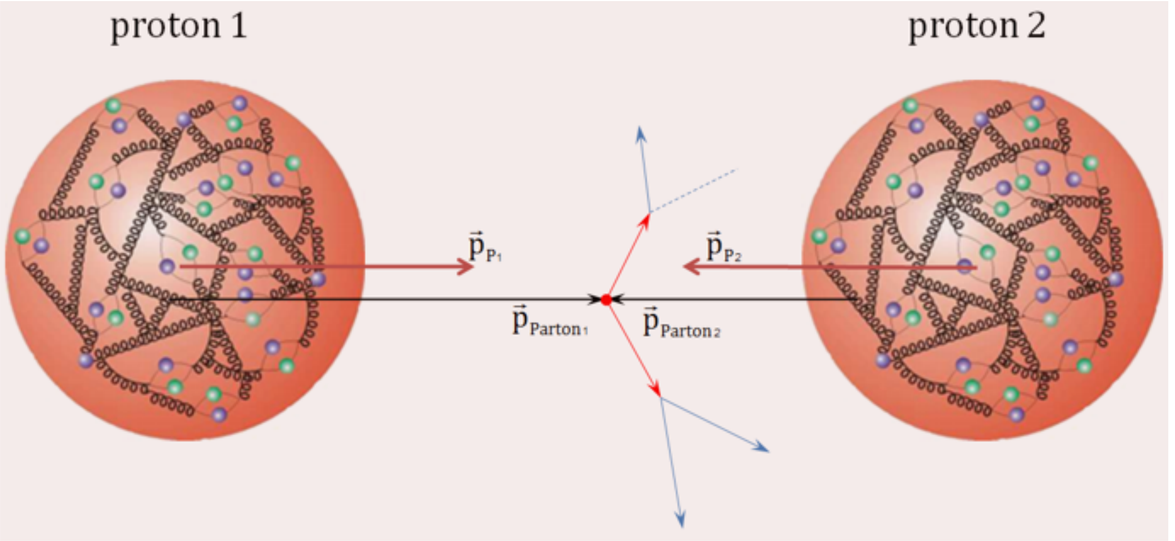
Standard Model interactions



wikipedia

Proton-proton collision theory

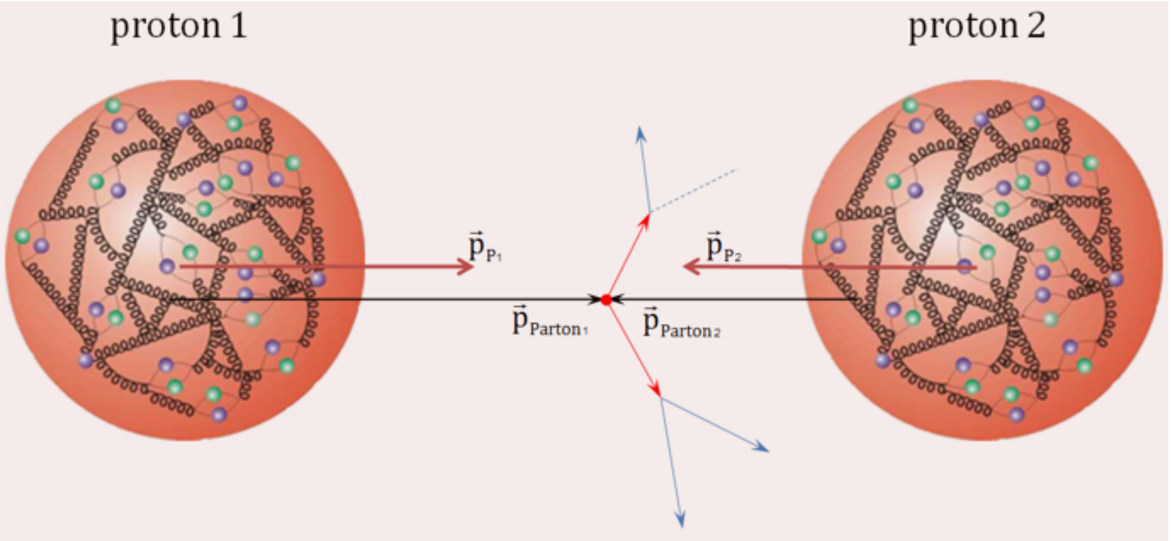
Proton:
uud (valence quarks)
& a sea of interacting quarks, anti-quarks and gluons



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

.

Proton-proton collision theory

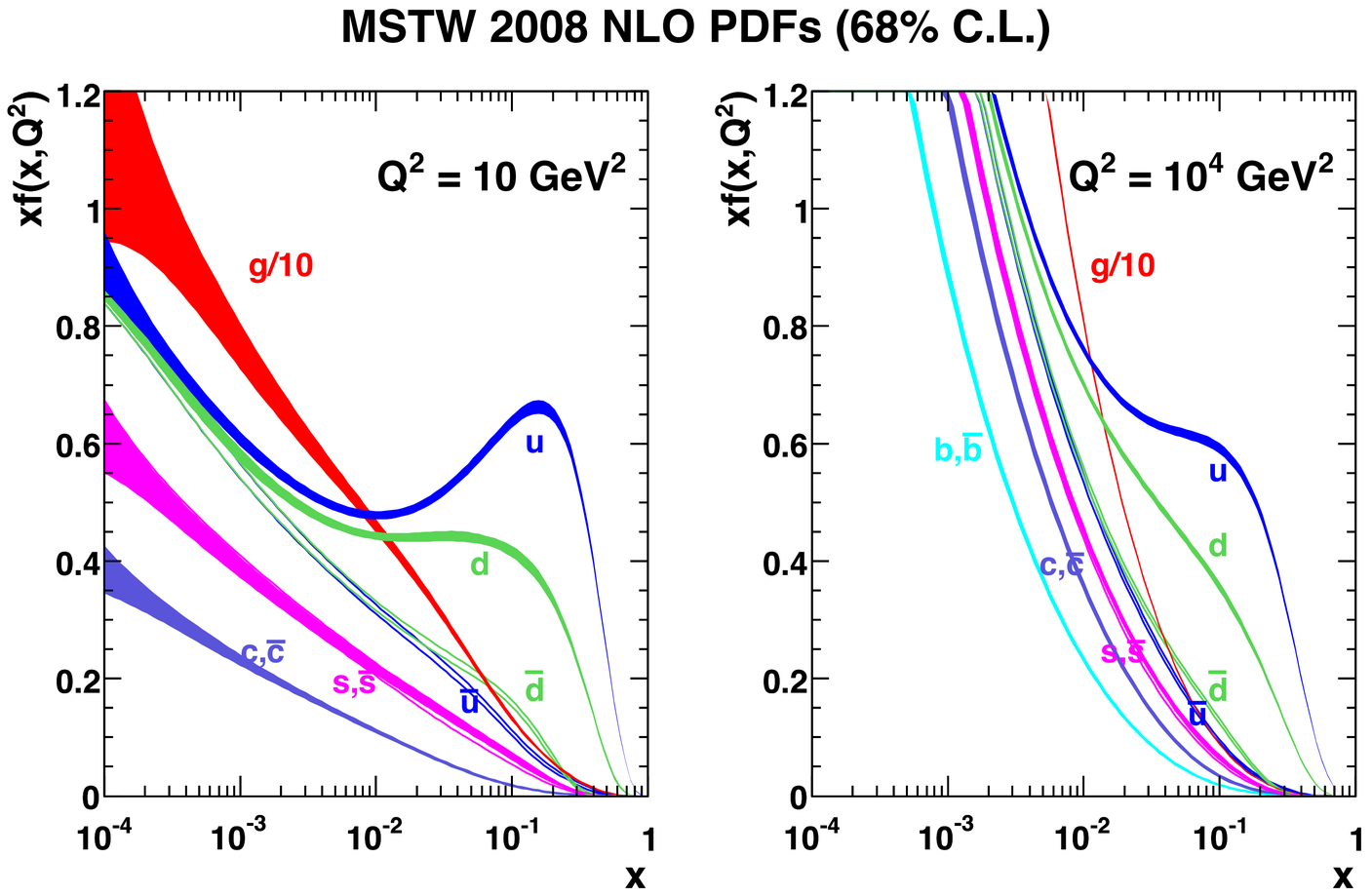


→ **Cross section calculated by integrating over Parton Distribution Functions (PDFs)**

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

Marumi Kado lectures

Parton distribution functions (PDFs)



Q^2 = energy scale or momentum transfer

- **PDFs are the probability to find a parton with momentum fraction x**
- **Not calculable but measured in Deep Inelastic Scattering (DIS) experiments** (with electron & neutrino scattering on nucleons)
- **PDF evolution in Q^2 are calculable** (with DGLAP equations)
- **Important uncertainty for measurements and searches**

mstw

Simulation in particle physics

- **Backbone for almost all LHC physics analyses**
- **Theory modelling of:**

  Hard scatter, parton shower,
  hadronisation, hadron decay,
  multiple parton interaction

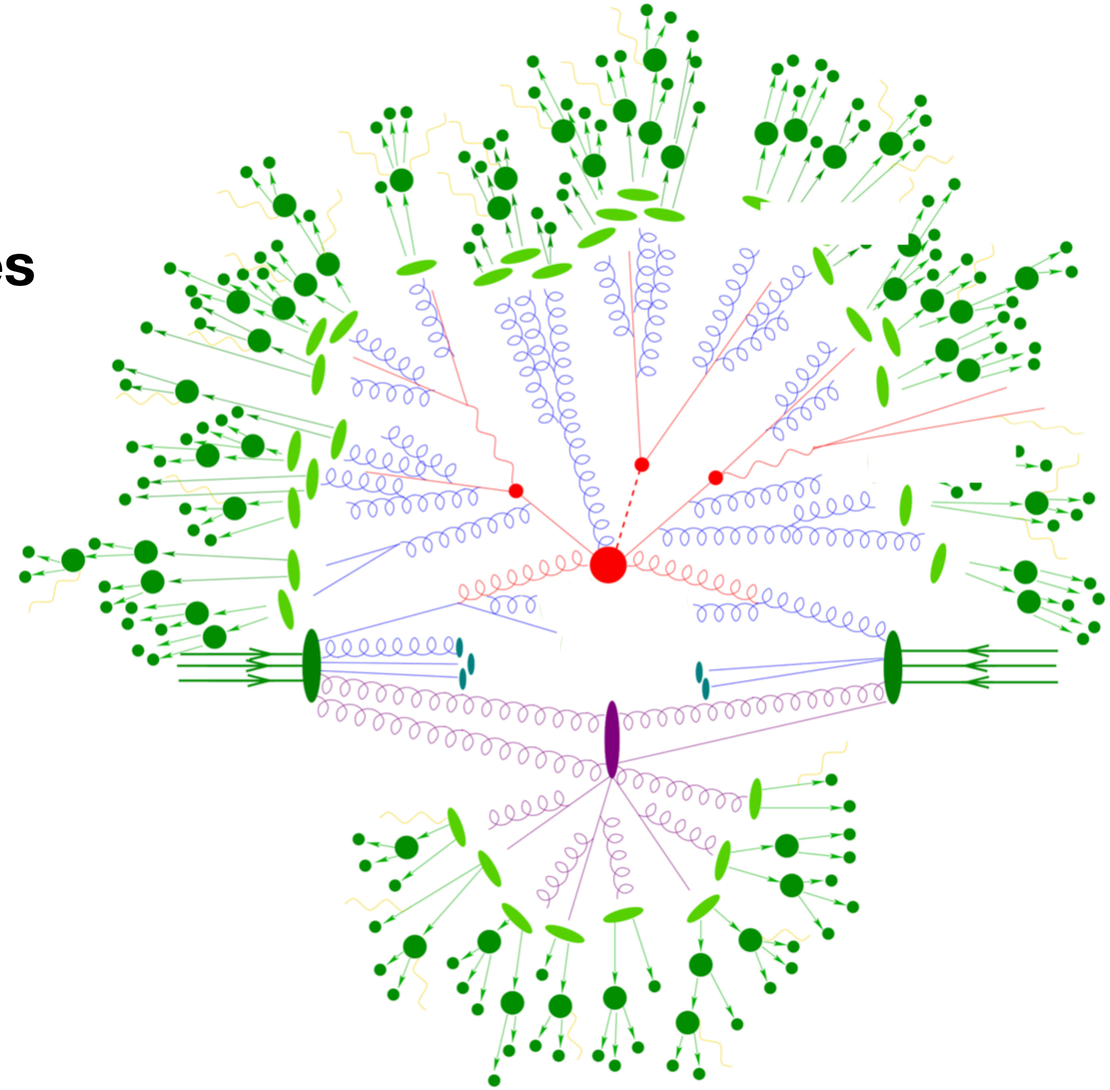


Image credit: Frank Krauss

Simulation in particle physics

- **Backbone for almost all LHC physics analyses**
- **Theory modelling of:**

  Hard scatter, parton shower,
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  multiple parton interaction

- **Modelling of the detector**

  Particle interactions with the material (GEANT4)

  Detector response

- **Particle identification and event reconstruction**

  Treat simulated data like real collision data

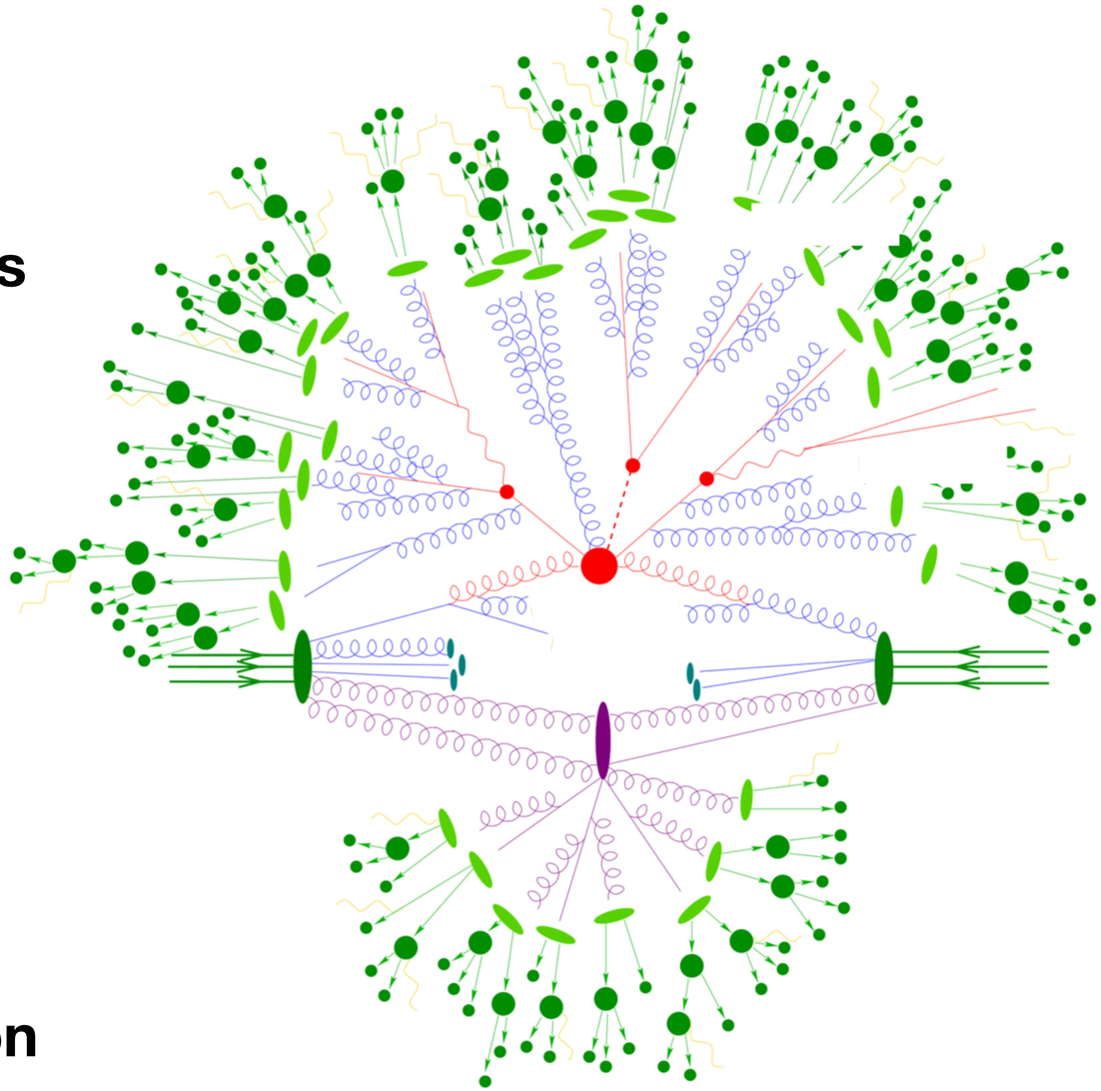
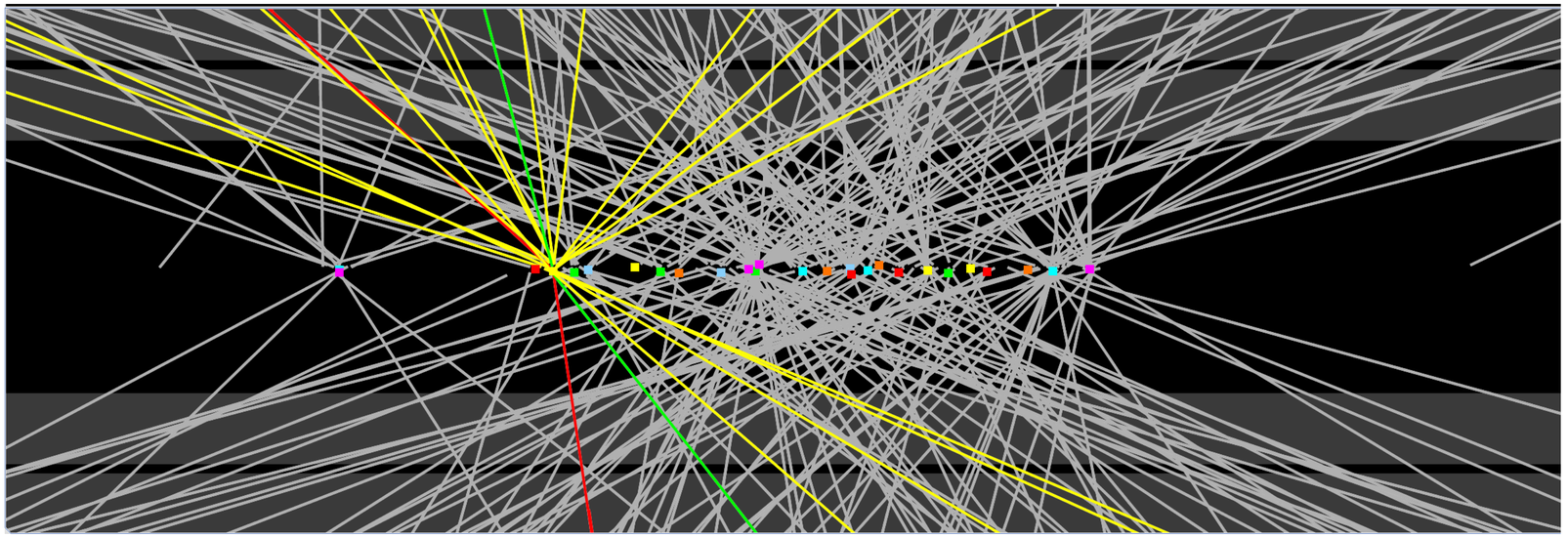


Image credit: Frank Krauss

Pileup

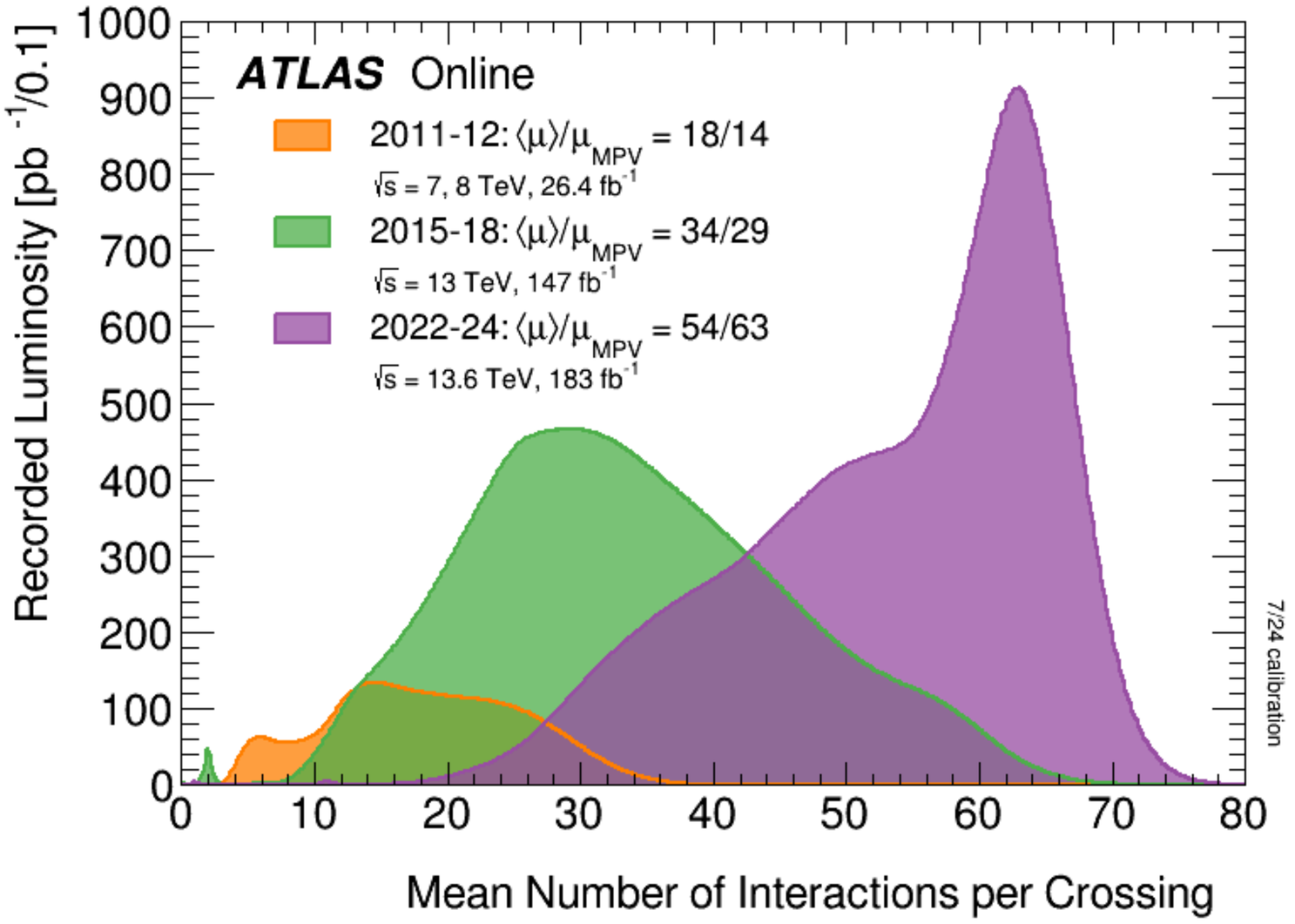
Price to pay for high instantaneous luminosity



- **In-time pileup:** additional interactions in the same bunch crossing
- **Out-of-time pileup:** additional interactions in a different bunch crossing
- **Big challenge:** Collision of interest + additional particles usually tracks & hadronic jets with low transverse momentum

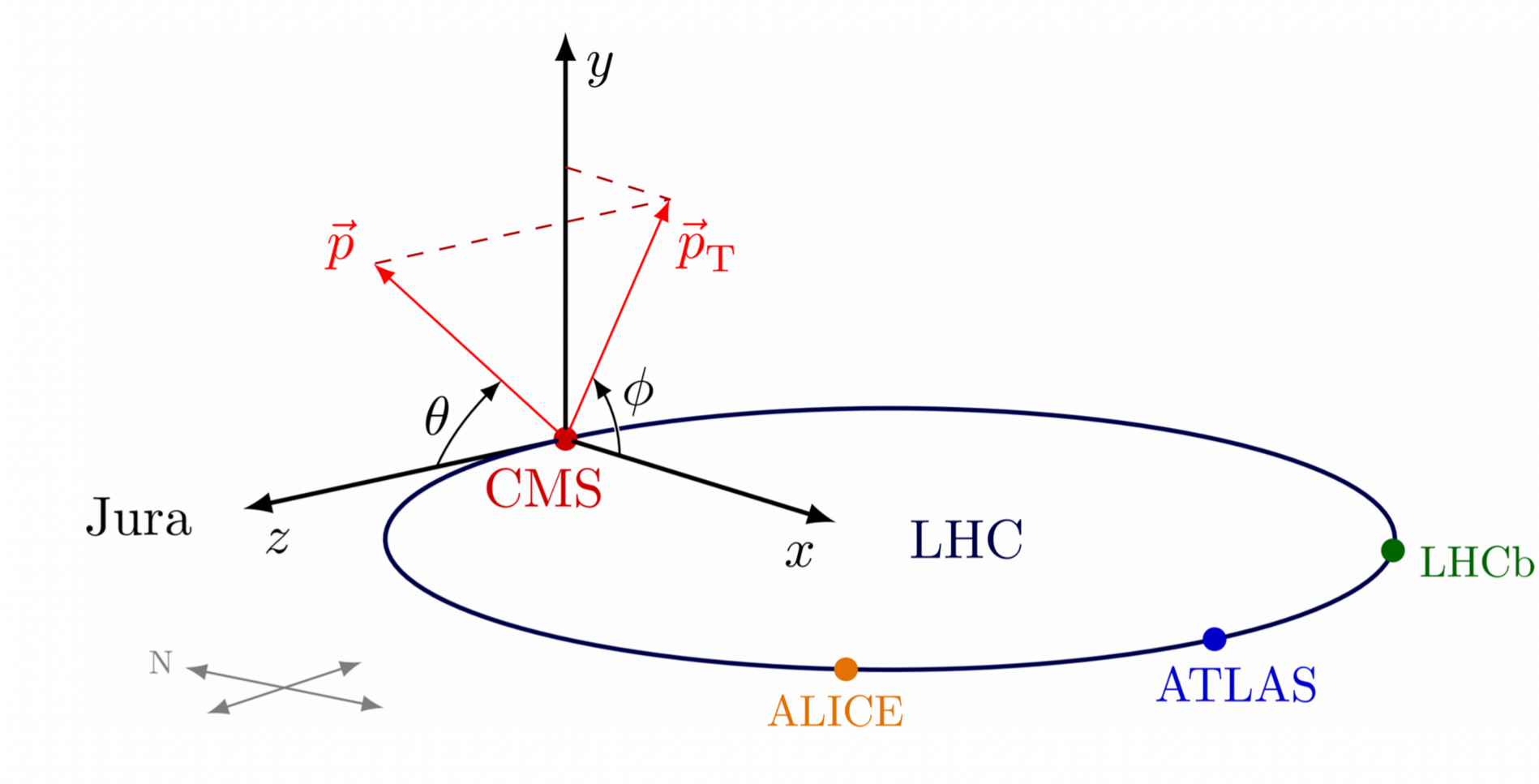
Pileup

Price to pay for high instantaneous luminosity



ATLAS public results

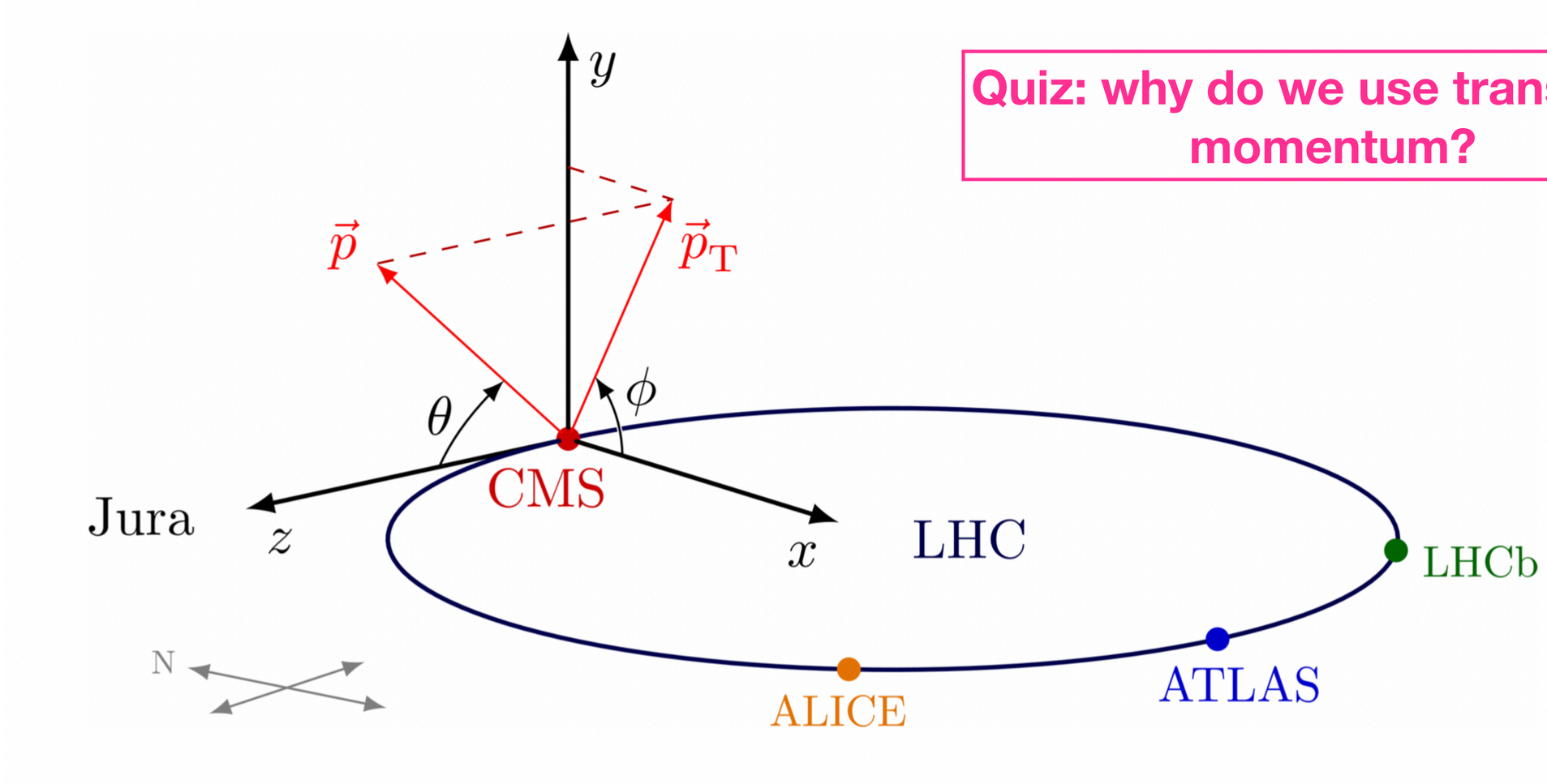
Interlude: coordinates & basic kinematic quantities



Transverse momentum: $p_T = p \,.\, \sin\theta$

Image credit Izaak Neutelings

Interlude: coordinates & basic kinematic quantities



Quiz: why do we use transverse momentum?

Transverse momentum: $p_T = p \,.\, \sin\theta$

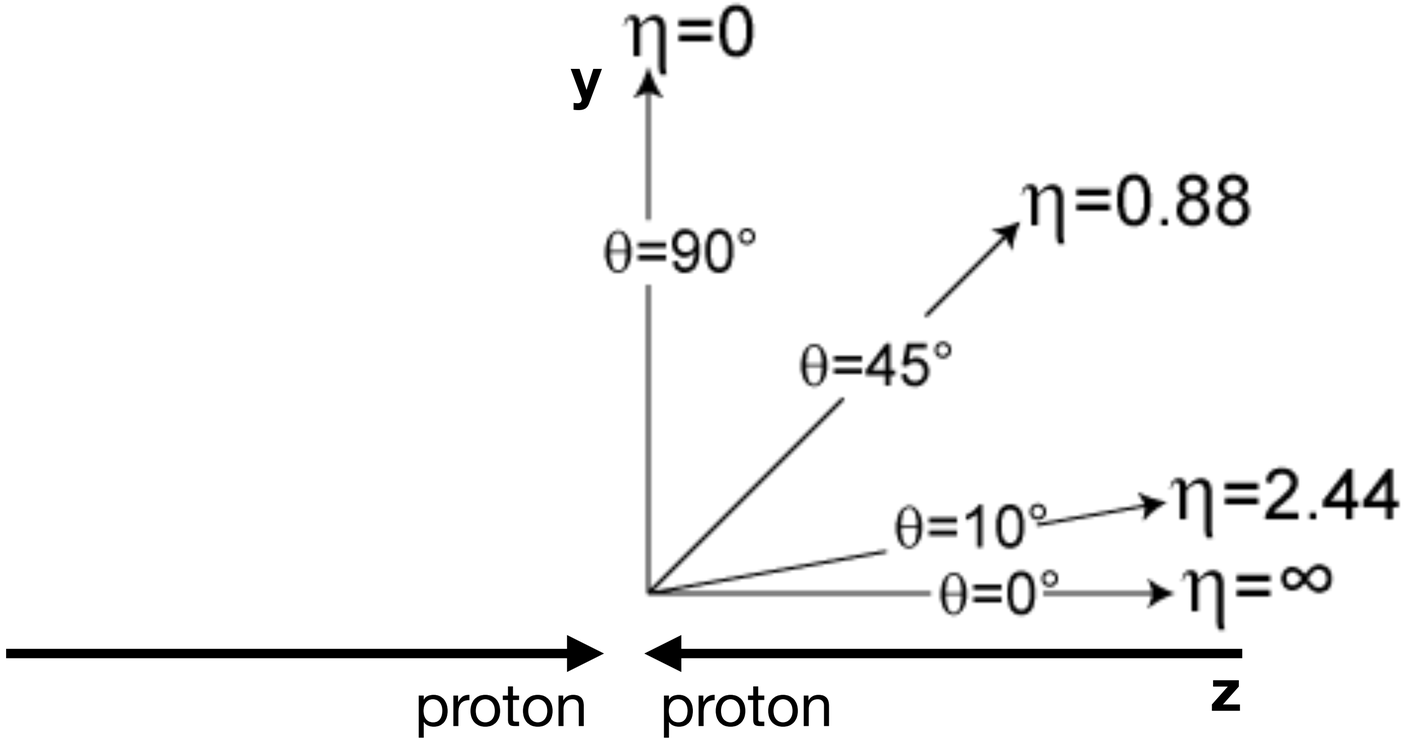
Image credit Izaak Neutelings

Interlude: coordinates & basic kinematic quantities

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

Pseudo-rapidity: $y \to \eta$ (relativistic/massless limit)

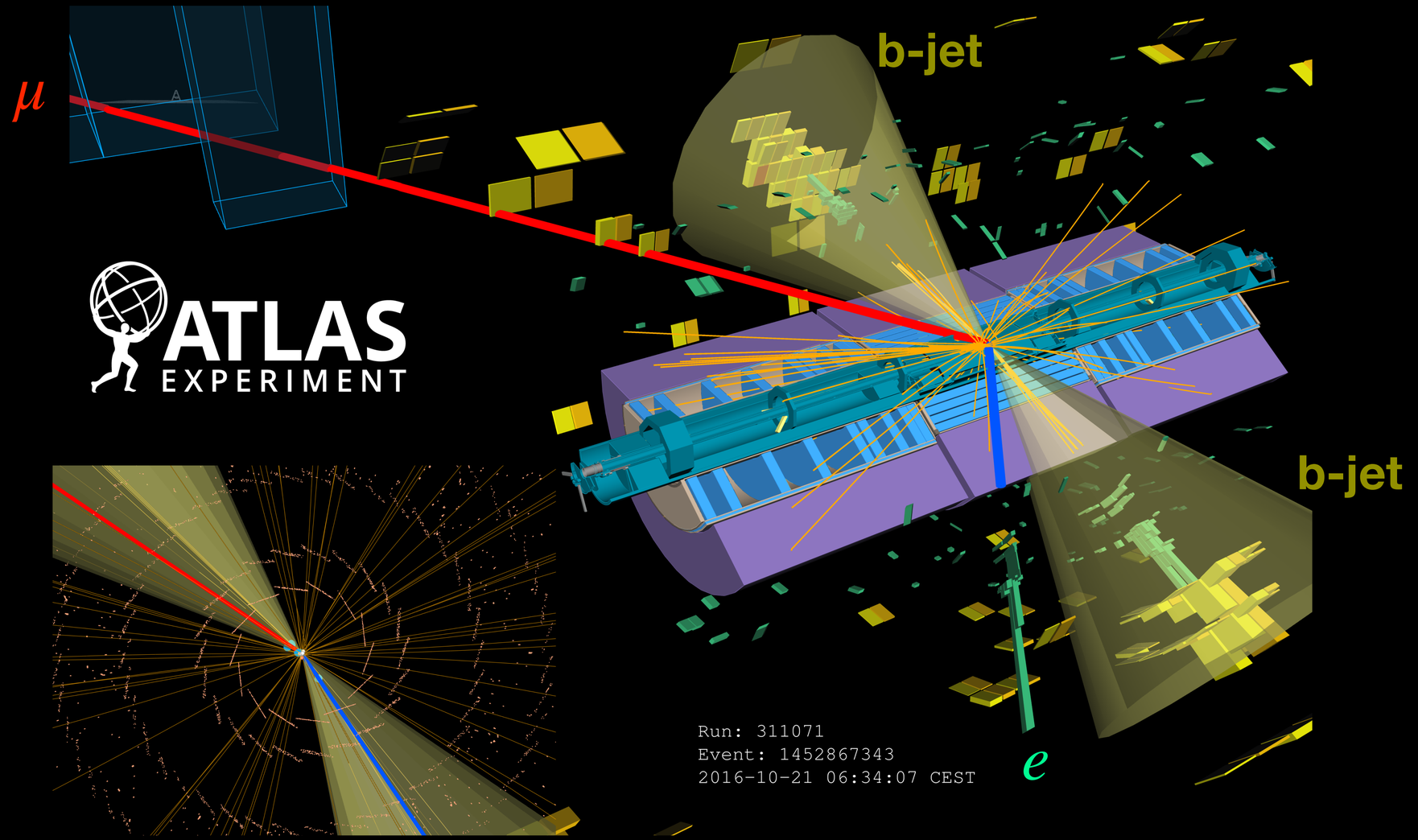
$$\eta = -\ln \tan\frac{\theta}{2}$$



wikipedia

A collision “event”

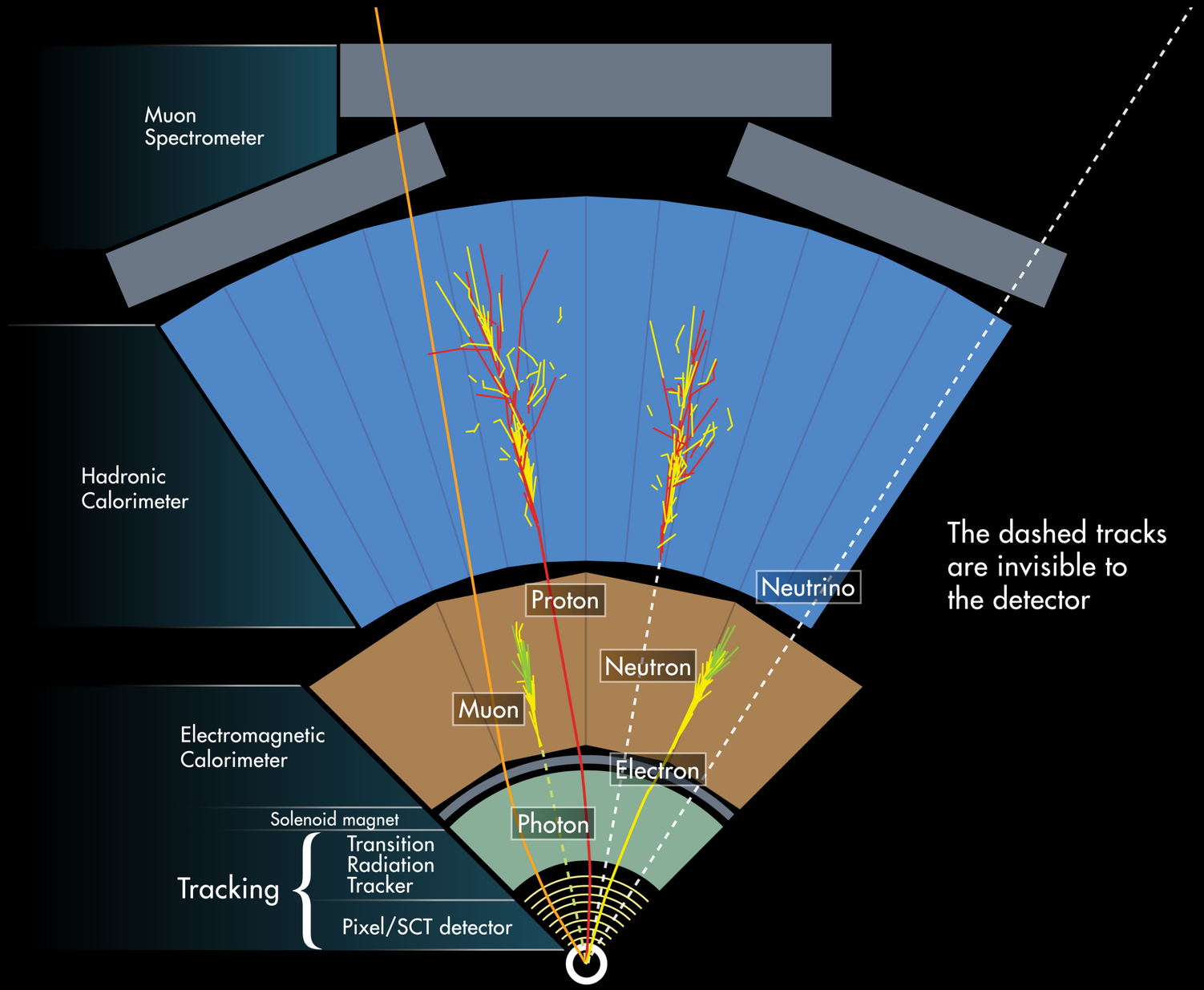
Top quark pair candidate event



ATLAS Event Display

Particle identification with ATLAS

Onion-like structure



The dashed tracks are invisible to the detector

1505342

Particle identification

- **Lots of work goes into particle identification within the experiments**

  i.e. translate various detector measurements into “particles”

  Examples:

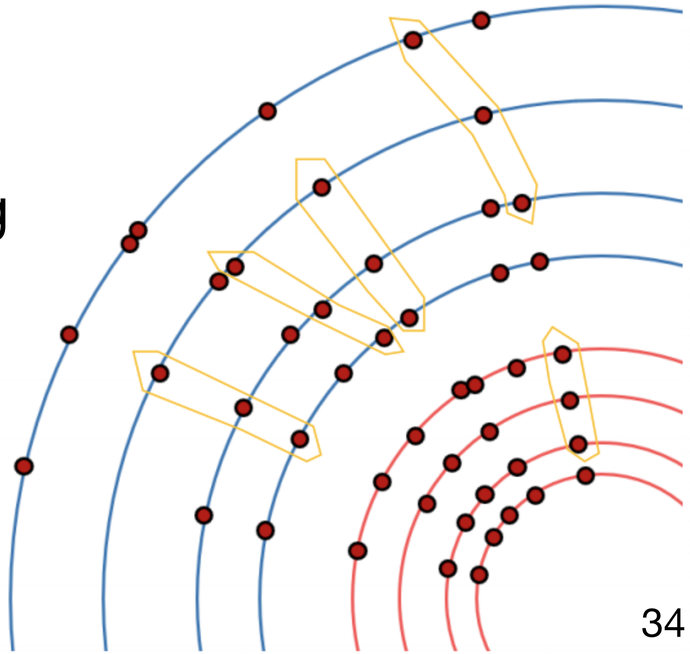
  Cell energy in calorimeter → photon energy

  Tracking → reconstruct “correct” particle trajectory from signals in various layers

- **Compare real data to simulation**

  Efficiencies are not the same due to imperfect detector modelling

  Correct to avoid biased comparisons

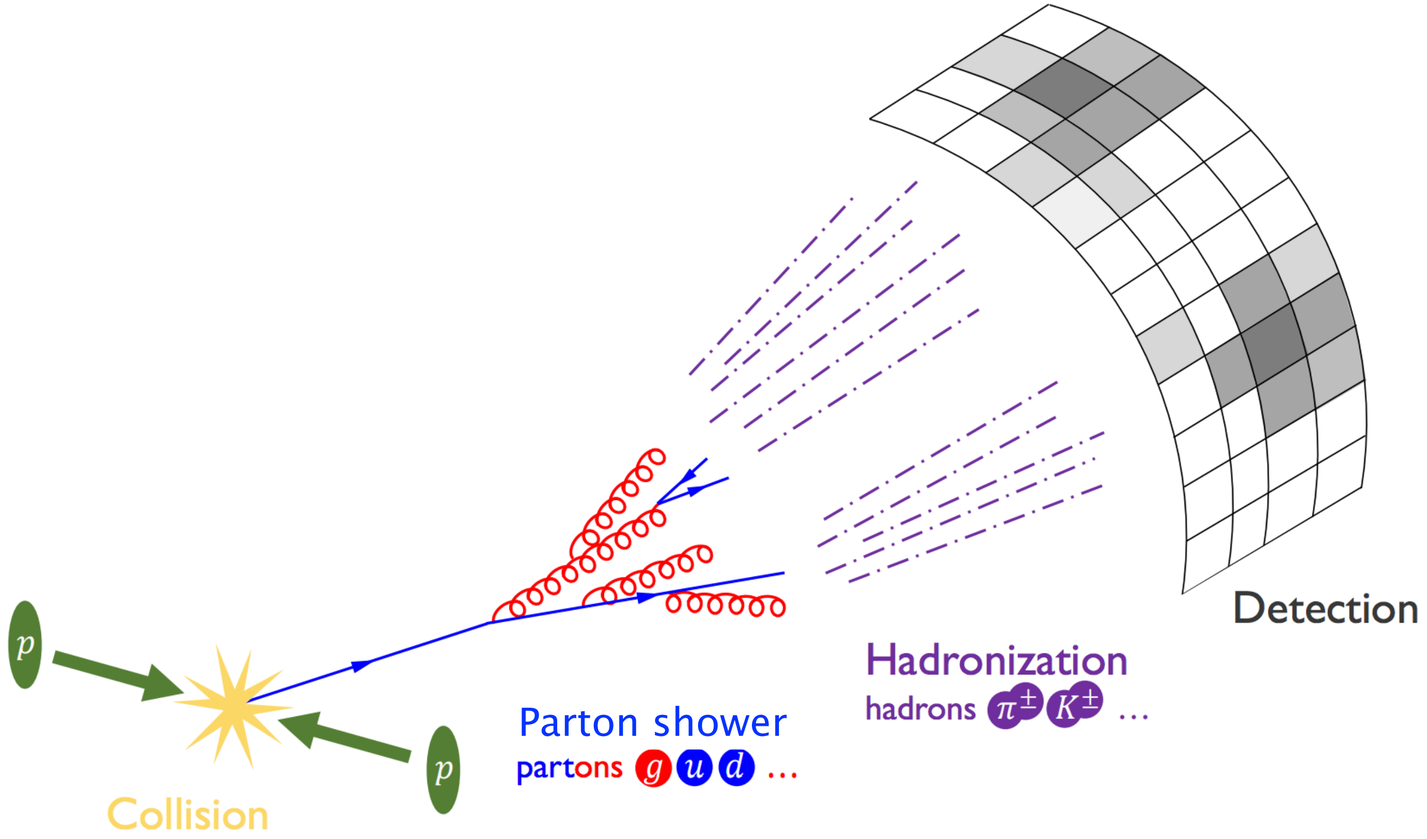


atlas software docs

Hadronic jets: light flavour and gluons

- **Quarks and gluons cannot be observed by themselves**
  → Undergo processes of parton shower and hadronisation

- **Experimental signature: Spray of neutral and charged hadrons**



Adapted from Eric M. Metodiev

Hadronic jets: light flavour and gluons

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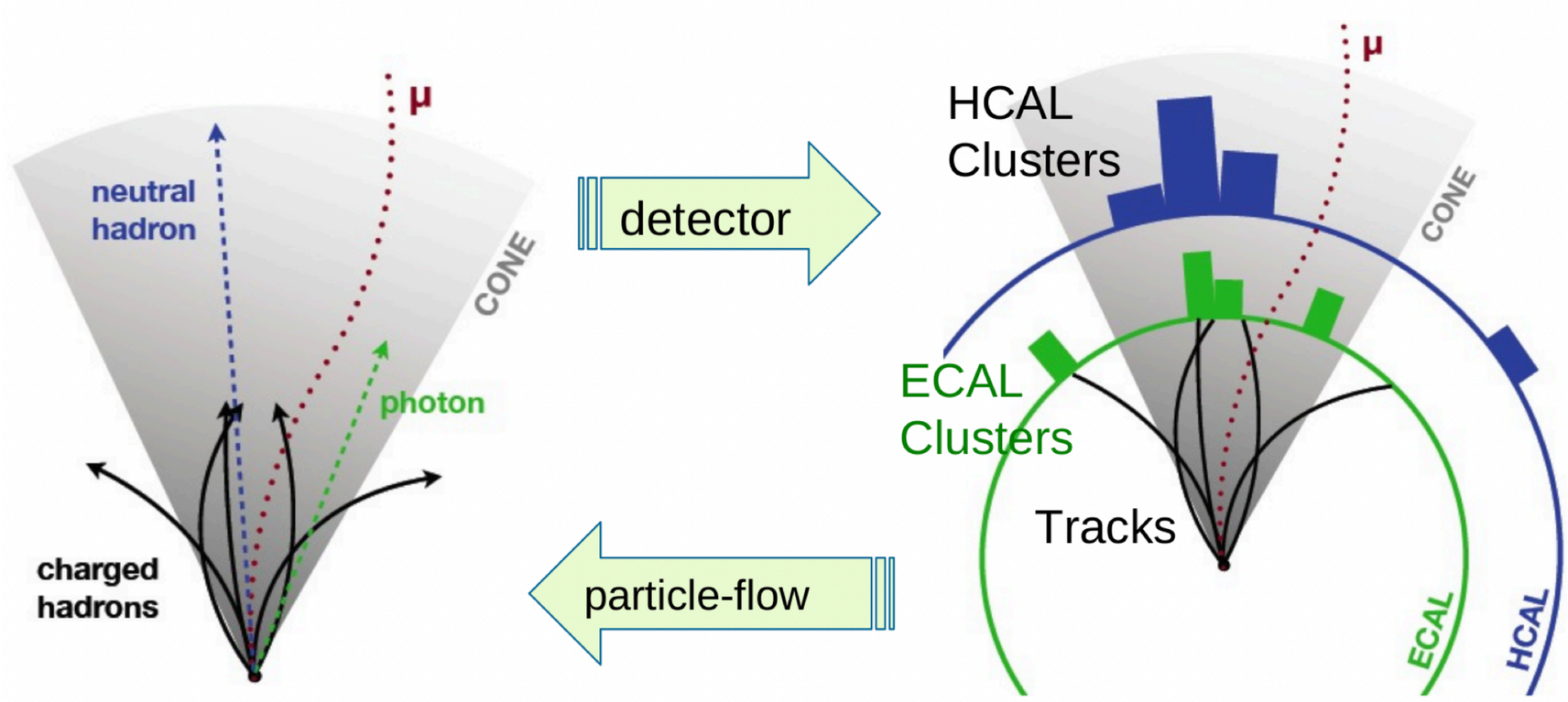


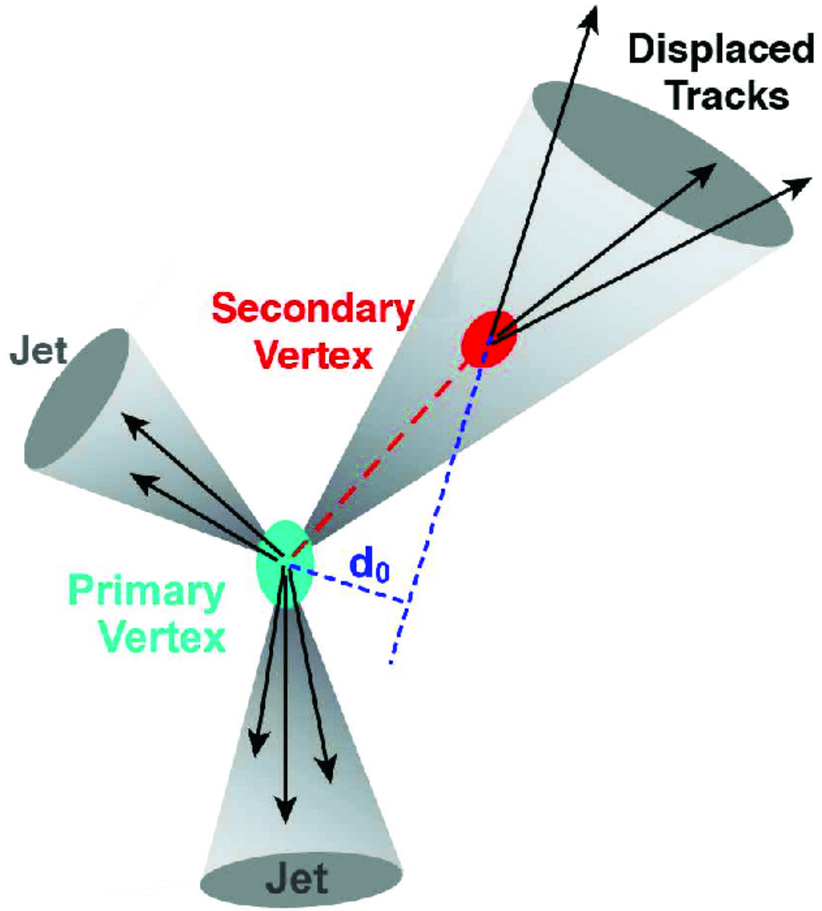
Hadronic jets: heavy flavour

- **b-quarks contain B-Hadrons in their parton shower**
- **B-Hadrons have sufficient lifetime**

  → Travel away from primary interaction point before decaying (~0.5 mm)

  → Secondary vertex

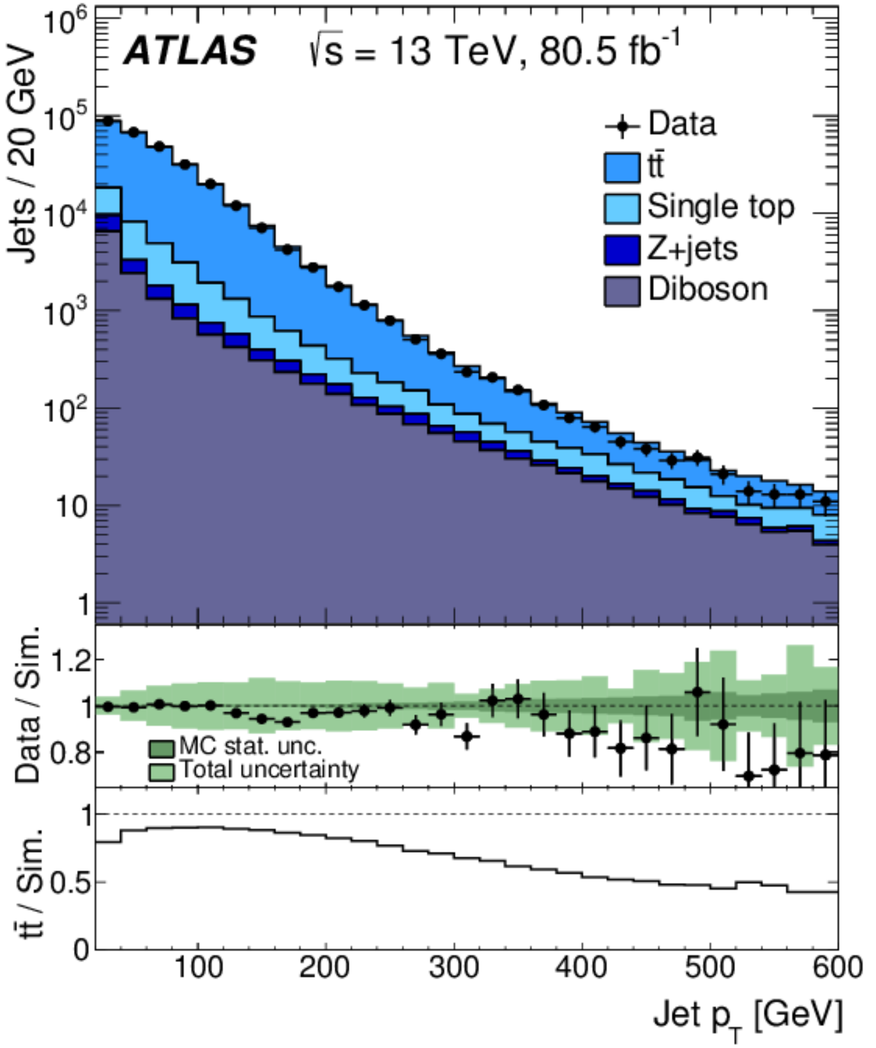
- **Often multivariate techniques used to identify jets originating from b-quarks**



Hadronic jets: heavy flavour

- **Often multivariate techniques used to identify jets originating from b-quarks**
  - Develop algorithm based on simulation
  - Pick most optimal one (high efficiency, low fake rate)
- **Measure efficiency in data & compare to simulation**
- **Correct simulation (often called data-MC scale factor)**

data-MC SF

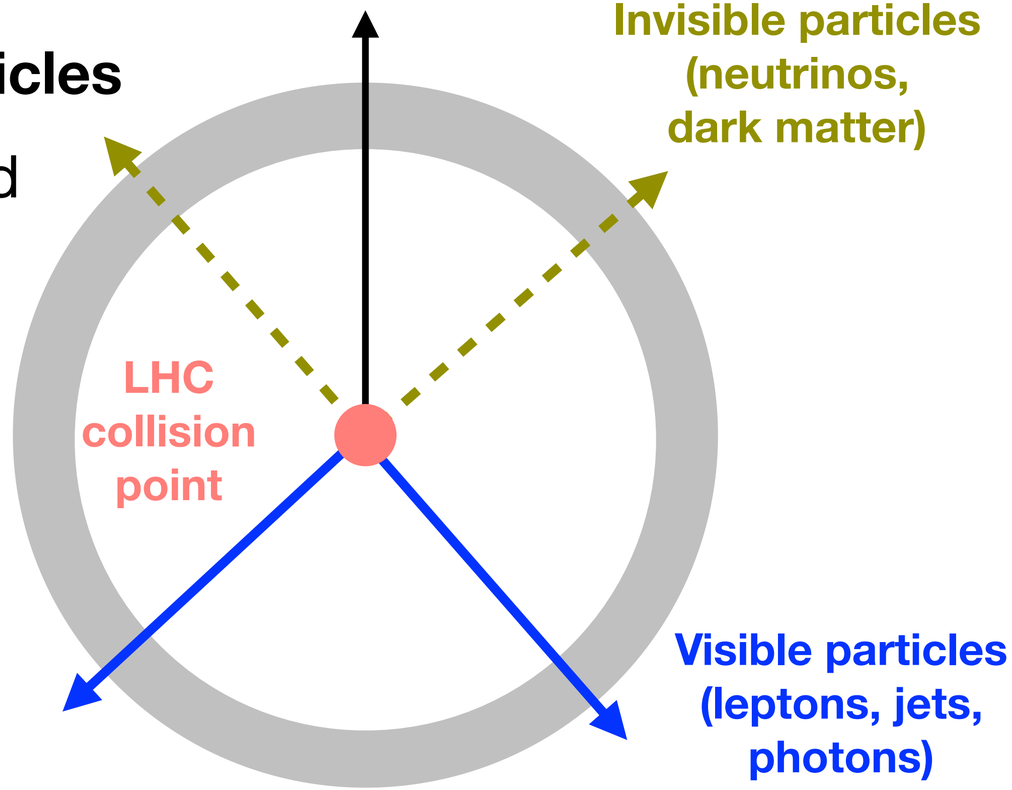


Example: b-jets in $t\bar{t}$ events

1907.05120

Missing transverse energy (MET)

- **Important to infer presence of non-interacting particles**
  - Measure every interacting particle very precisely and take negative vector sum
- **Can be very tricky**
  - Not all particles might be reconstructed
  - Pileup dependency can be an issue



$$\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}} = -\Bigg(\underbrace{\sum_{\substack{\text{selected}\\ \text{electrons}}} \boldsymbol{p}_{\mathrm{T}}^{e} + \sum_{\substack{\text{accepted}\\ \text{photons}}} \boldsymbol{p}_{\mathrm{T}}^{\gamma} + \sum_{\substack{\text{accepted}\\ \tau\text{-leptons}}} \boldsymbol{p}_{\mathrm{T}}^{\tau} + \sum_{\substack{\text{selected}\\ \mu}} \boldsymbol{p}_{\mathrm{T}}^{\mu} + \sum_{\substack{\text{accepted}\\ \text{jets}}} \boldsymbol{p}_{\mathrm{T}}^{\mathrm{jet}}}_{\text{hard term}} + \underbrace{\sum_{\substack{\text{unused}\\ \text{tracks}}} \boldsymbol{p}_{\mathrm{T}}^{\mathrm{track}}}_{\text{soft term}} \Bigg)$$

Also known as $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$ or MET

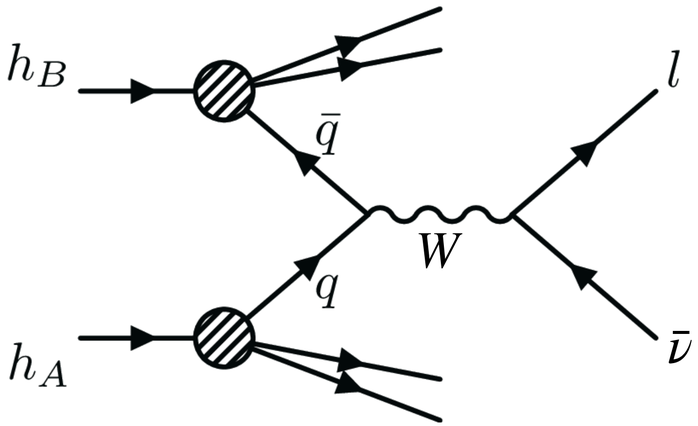
2402.05858

Signal and background

Ideally just “count” signal events & measure cross-section (or discovery new process)

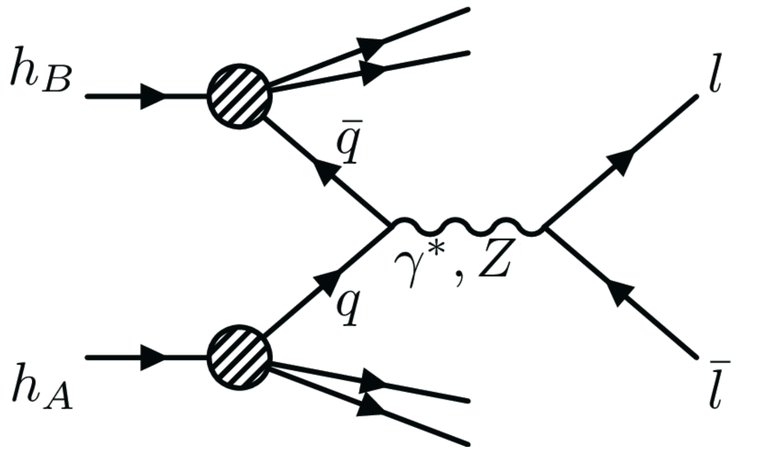
→ Often other “SM” processes look similar to our signal

W boson signal



1 lepton + MET

Z boson background



2 leptons: Could “miss” one lepton

Fakes: Note also particles are not always unambiguously defined e.g. jet could fake an electron

Images adapted from 254469235

Measuring a cross section

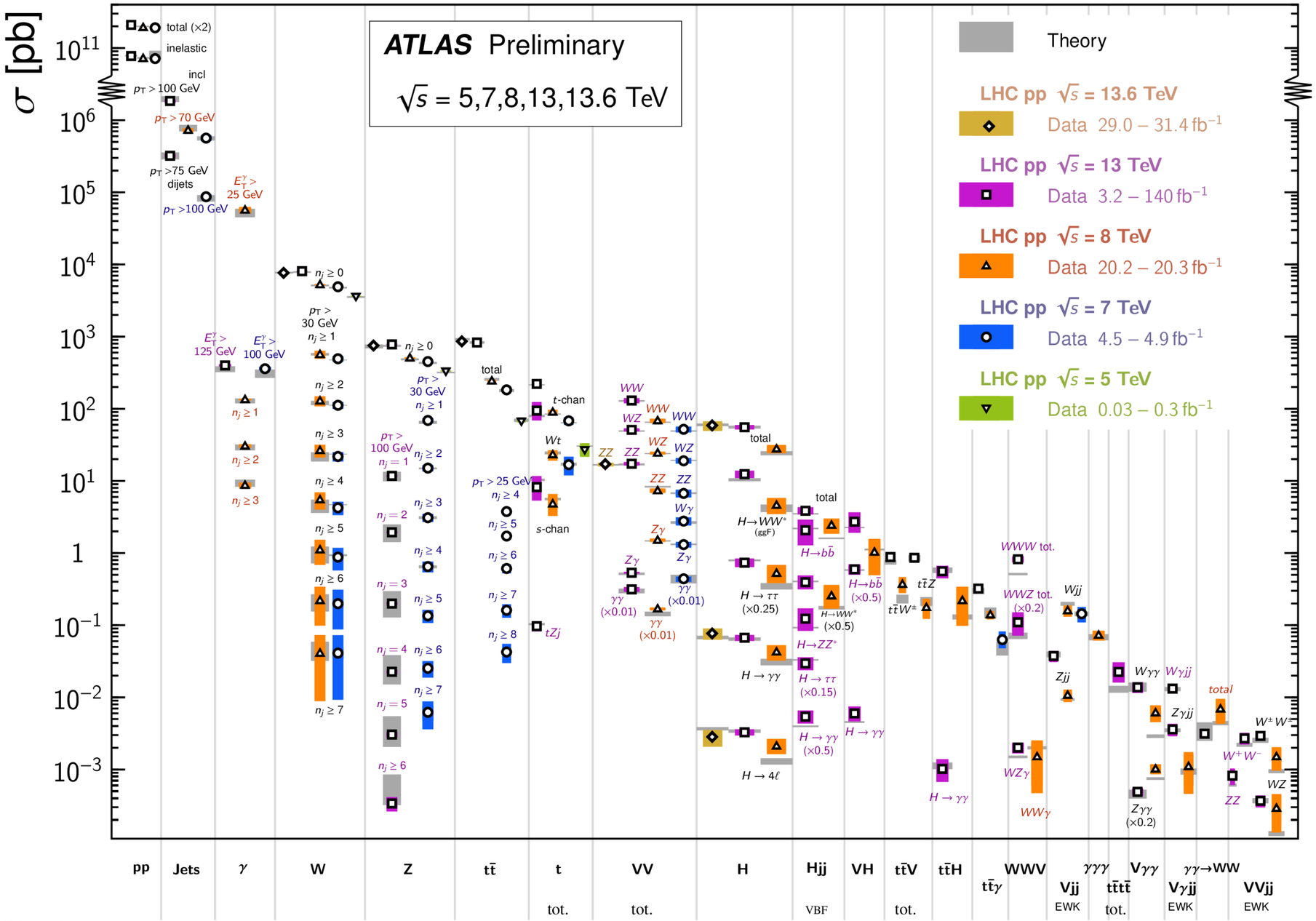
$$\sigma = \frac{N_{\text{occured}}}{\mathscr{L}_{\text{int}}} = \frac{N_{\text{observed}}}{A \times \epsilon \times \mathscr{L}_{\text{int}}}$$

- N_{observed}: Counting events with a specific selection
- A: Acceptance i.e. ratio of selected simulated events over all simulated events (estimated from theory/simulation)
- ϵ: Experimental efficiency (i.e. event selection, object identification efficiency)
- $\mathscr{L}_{\text{int}}$: Integrated luminosity of the dataset

Note: we can also measure ‘fiducial’ cross-sections without correcting for A

Standard Model Production Cross Section Measurements

Status: June 2024



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Next lecture

wikimedia

Measure the Standard Model

Interlude: coordinates & basic kinematic quantities

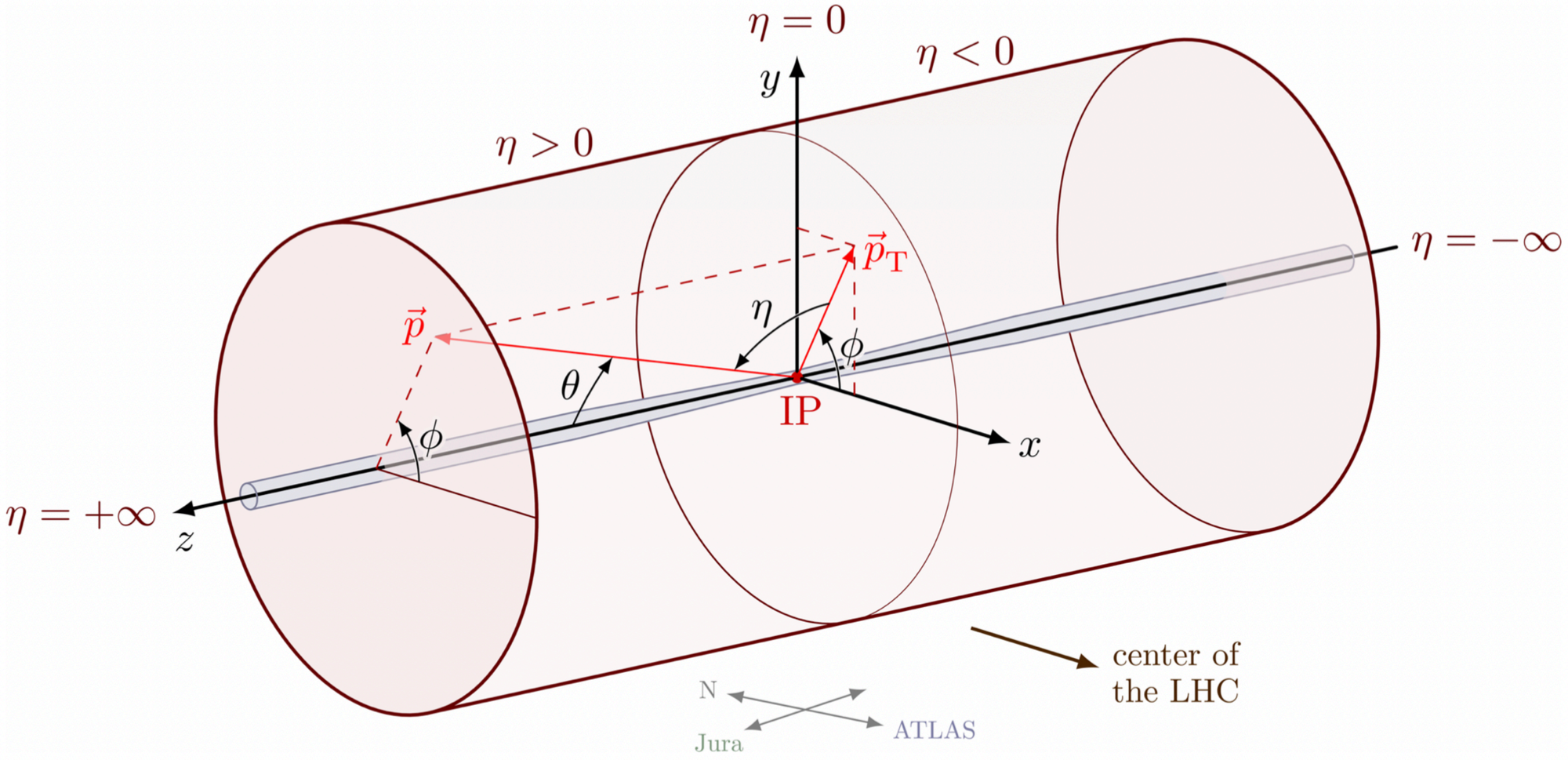
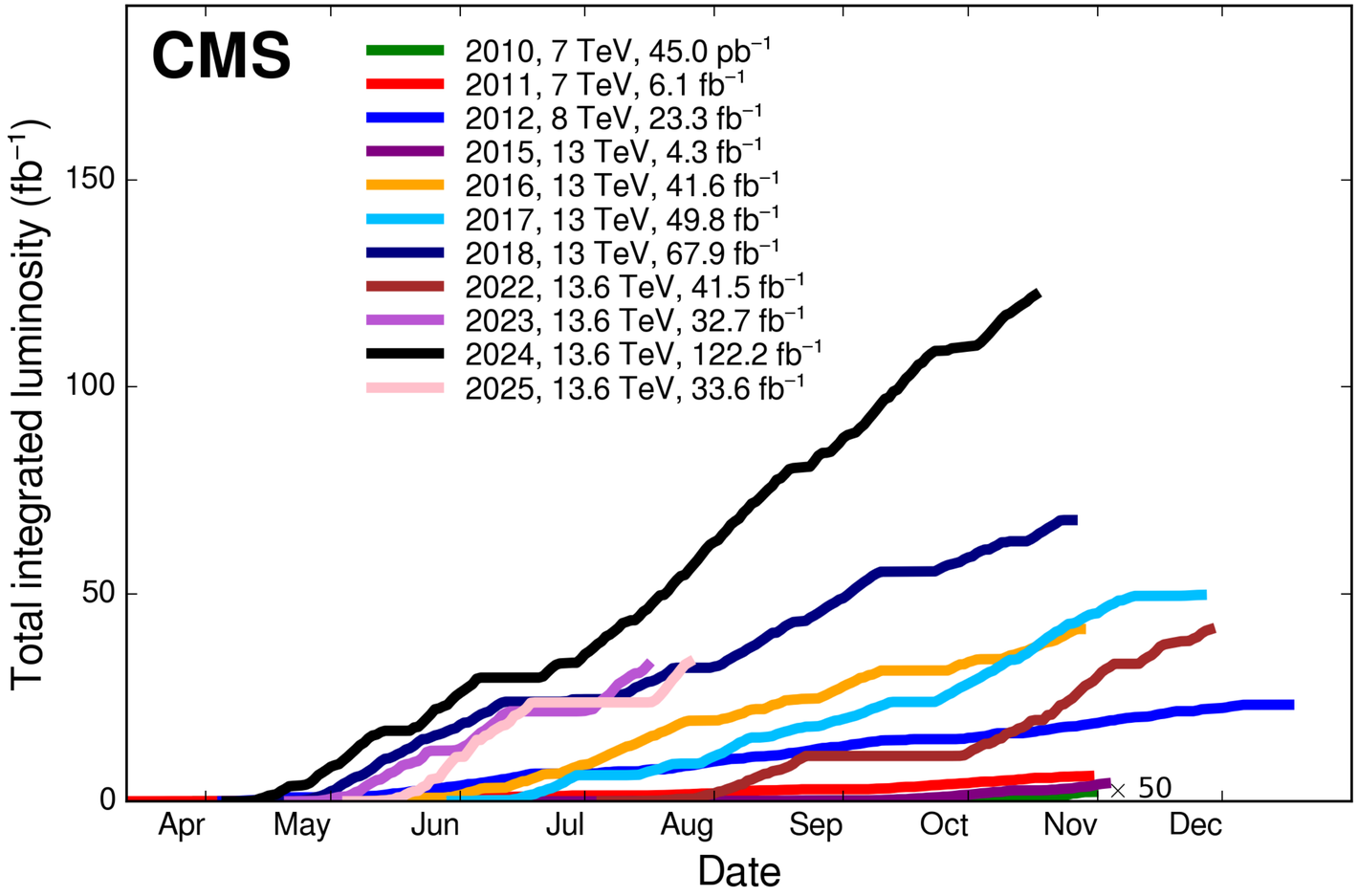


Image credit Izaak Neutelings

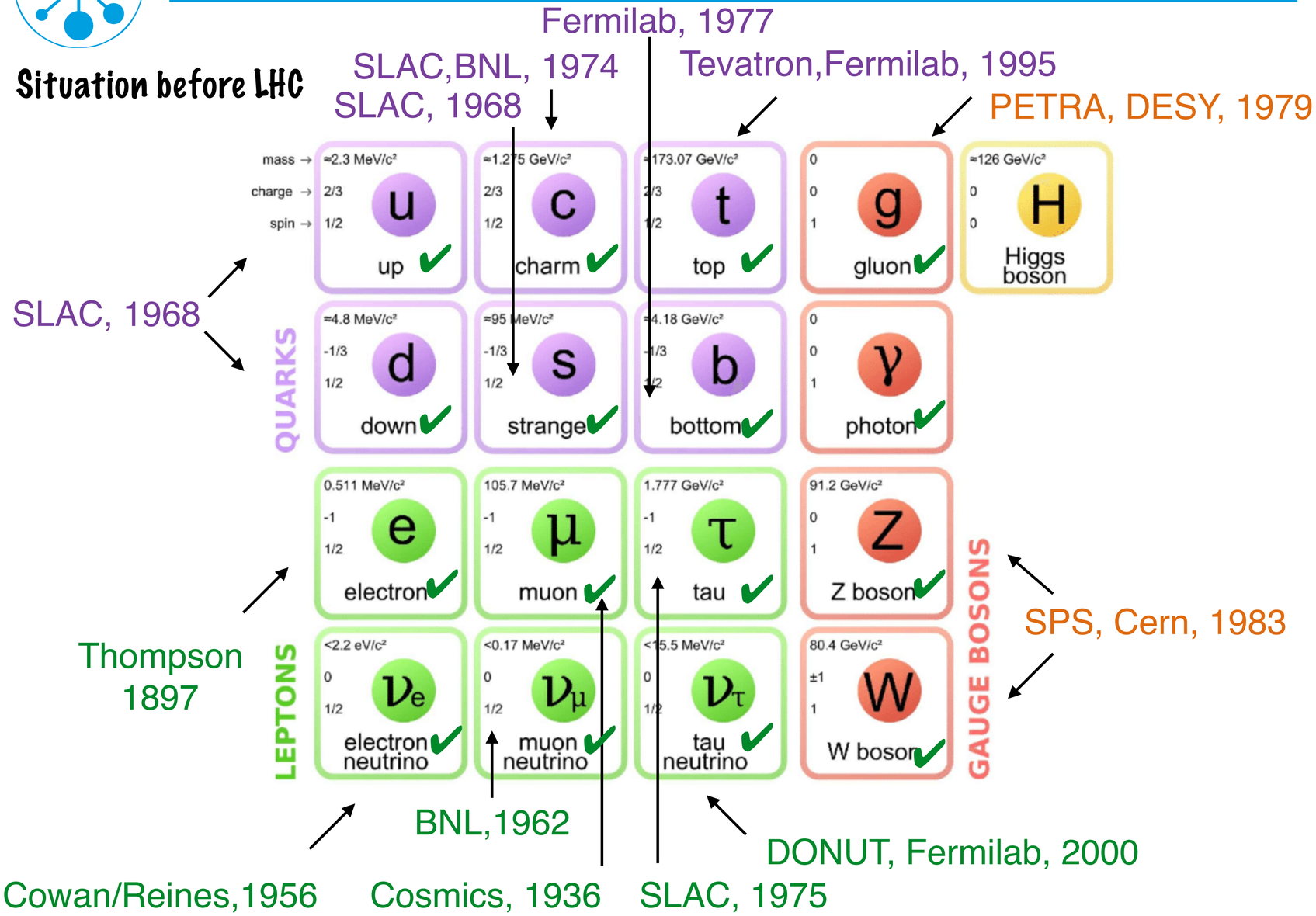
LHC proton-proton collisions



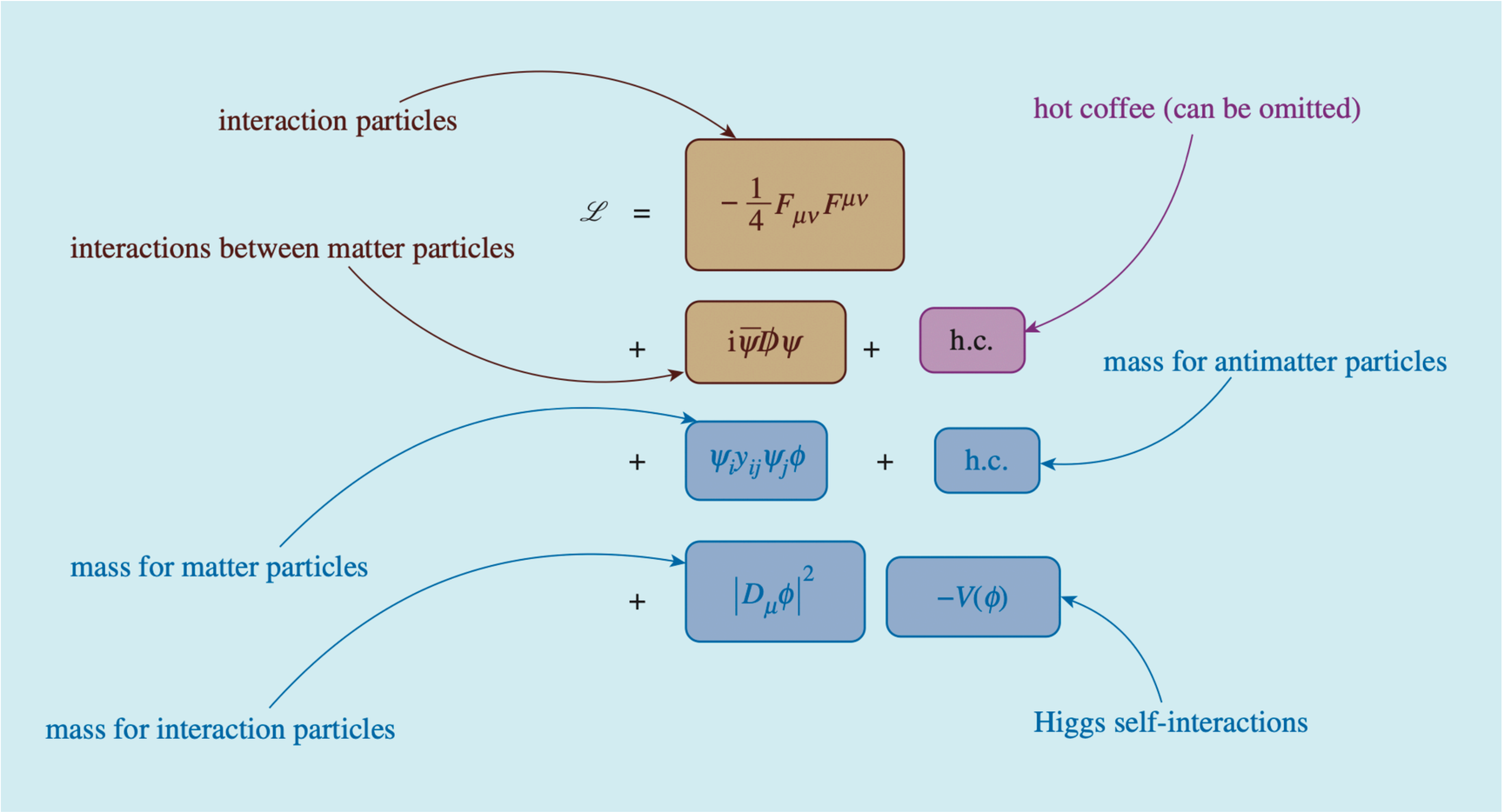
https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

The Standard Model - fundamental particles

Situation before LHC

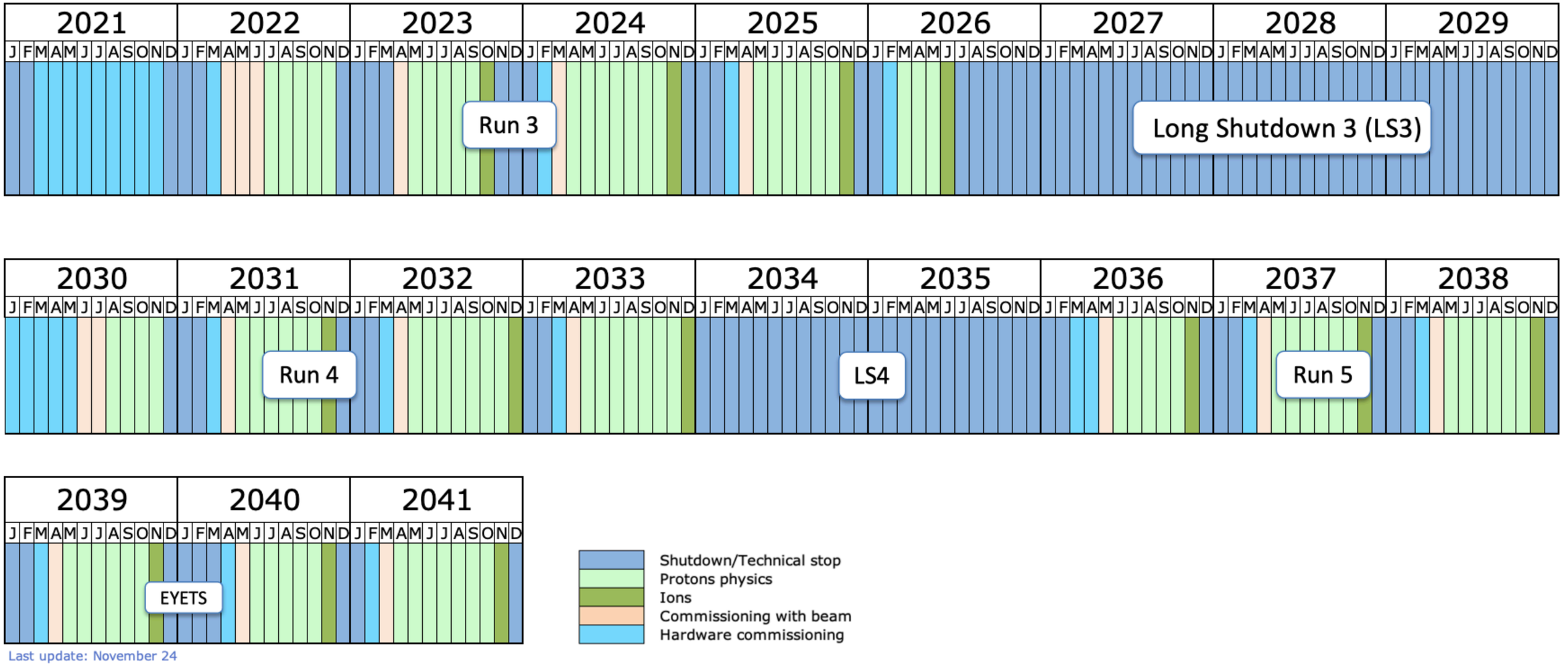


The Standard Model



Julia Woithe et al 2017 Phys. Educ. 52 034001

The LHC schedule



http://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm