LHC Physics – Introduction

DESY Summer Student Lectures, 16.08-17.08.2022

Claudia Seitz

LHC Physics goals

Measure

Standard Model

parameters with high precision

Search for the

Higgs boson

and measure it's properties

Search for

New Physics

Beyond the Standard Model

Study

Quark-Gluon Plasma

Large Hadron Collider

Summer Student lecture goals

Standard Model

Higgs boson

New Physics

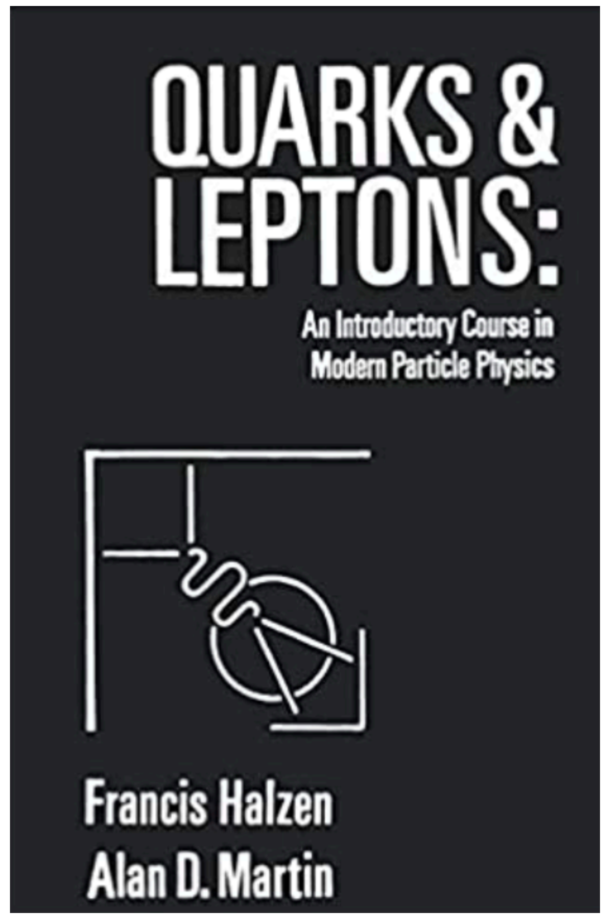
- What do we want to measure?
- How do we collect the data?
- How do we analyze the data?
- What are the main results so far?
- Where can we go next?

Large Hadron Collider

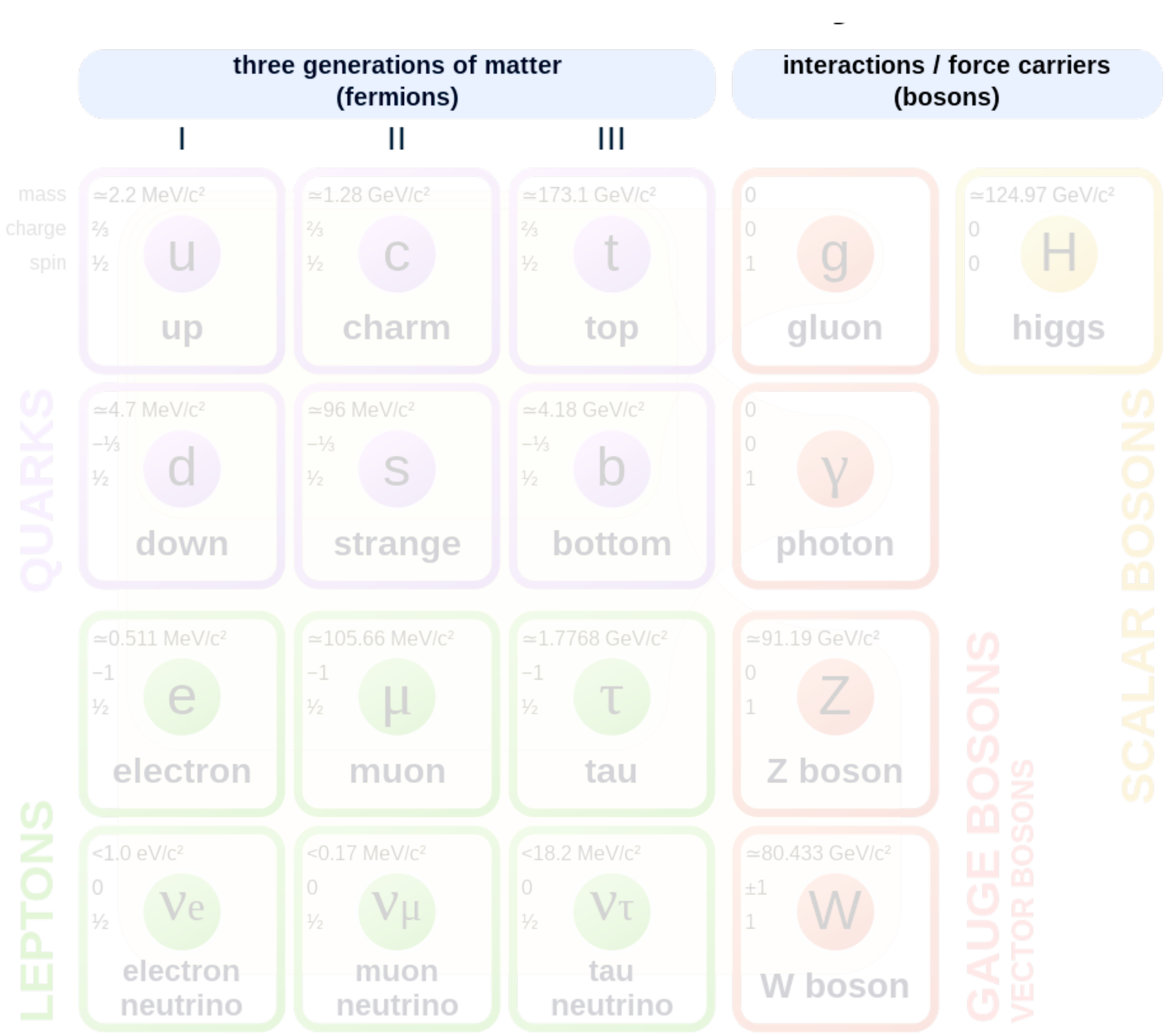
Material

- ATLAS publications and plots: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
- CMS publications and plots: http://cms-results.web.cern.ch/cms-results/public-results/publications/

- Educational:
  - Excellent sets of lectures:
    - Sarah Heim: https://indico.desy.de/event/23617/
    - Marumi Kado: https://indico.cern.ch/event/1132625/
    - Wikipedia is an excellent resource as well
    - Textbooks for mainly theoretical background



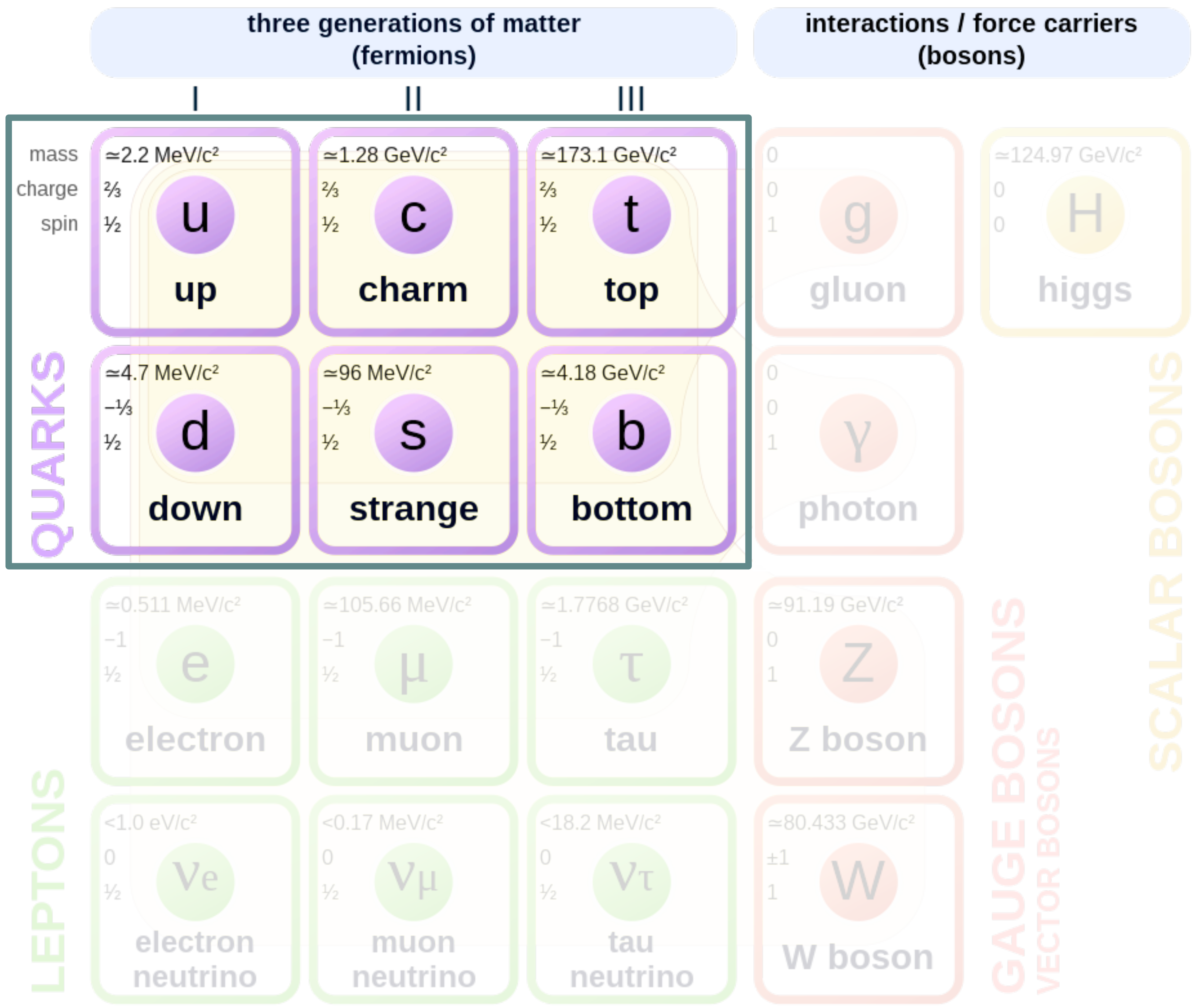
The Standard Model of Particle Physics



- Relativistic invariant quantum field theory
  - Described by the symmetry group
    - $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Contains:
    - Constituents of matter
    - Interactions
  - Extremely successful in predicting and explaining experimental measurements

https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

The Standard Model of Particle Physics



- Fermions: Spin 1/2
  - Quarks
    - 6 flavors: up, charm, top, down, strange, bottom
    - 3 color charges: r, g, b
    - Baryon number: 1/3

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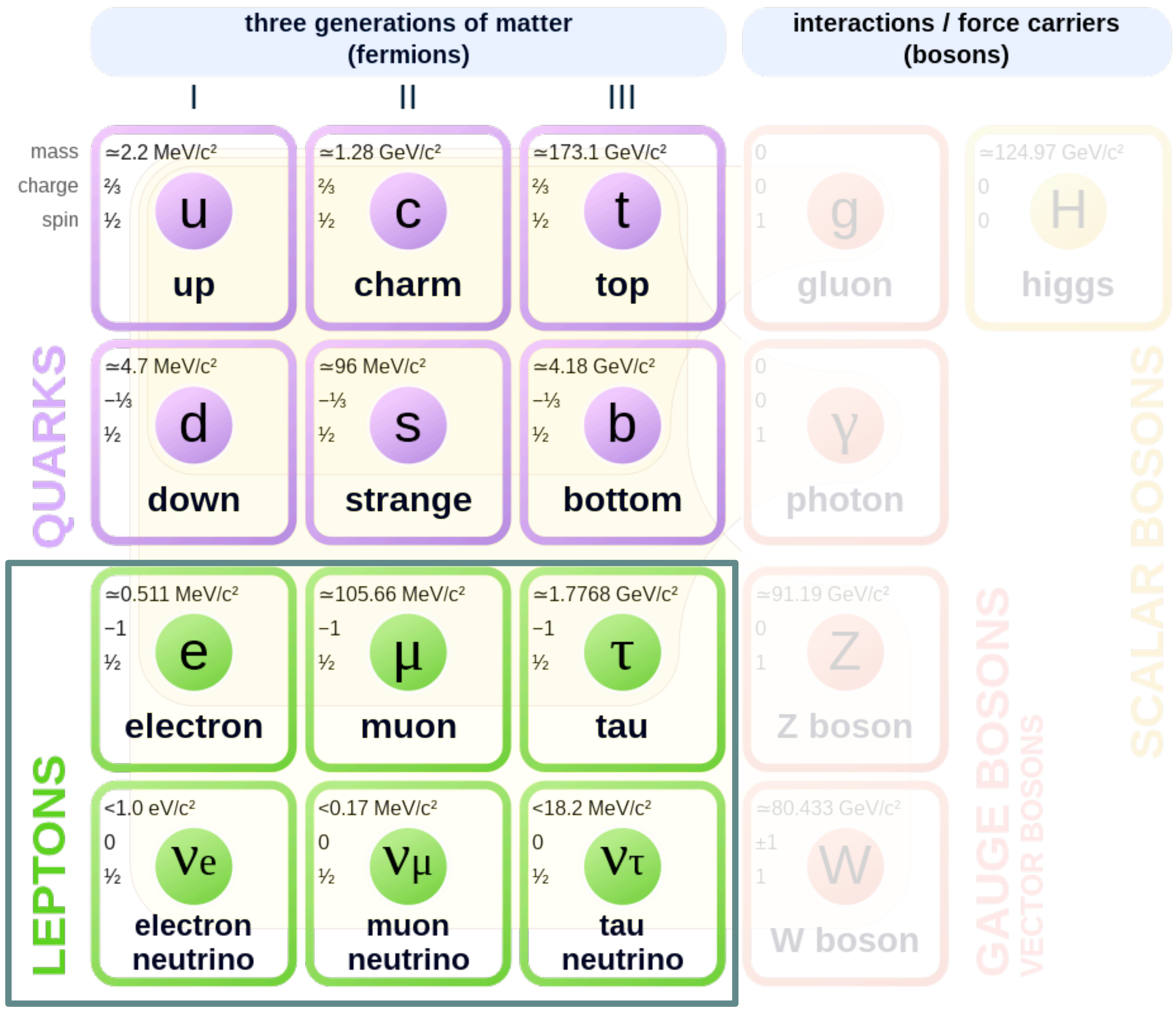
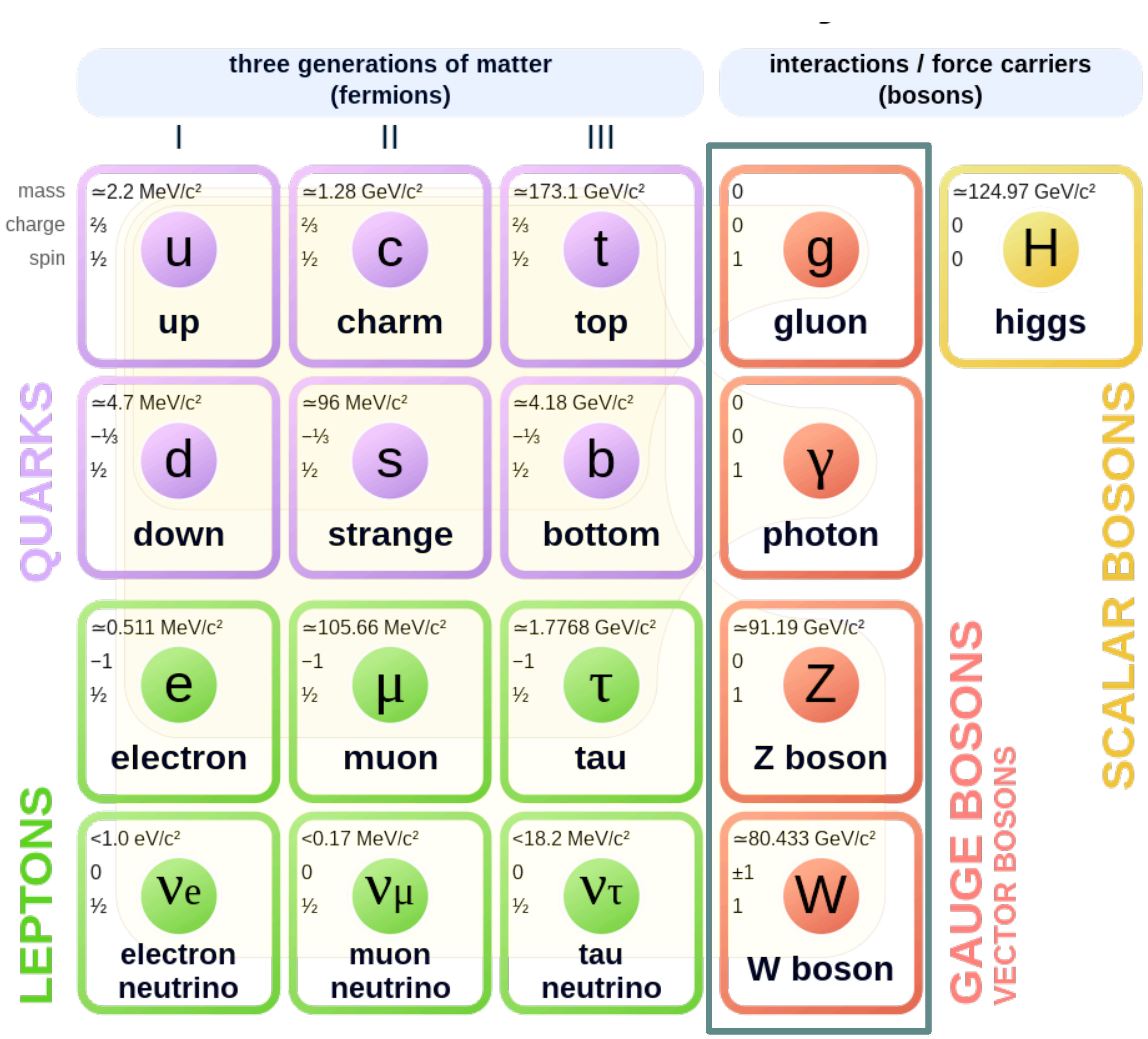
The Standard Model of Particle Physics



- Fermions: Spin 1/2
  - Quarks
    - 6 flavors: up, charm, top, down, strange, bottom
    - 3 color charges: r, g, b
    - Baryon number: 1/3
  - Leptons:
    - Electron, muon, tau
    - Neutrino for each lepton flavor
    - Lepton number: 1

https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

The Standard Model of Particle Physics



- Bosons: integer spin
  - Force carriers (Spin 1)
    - Gluon: strong force
    - Photon: electromagnetic
    - $W^{\pm}$, Z: weak force

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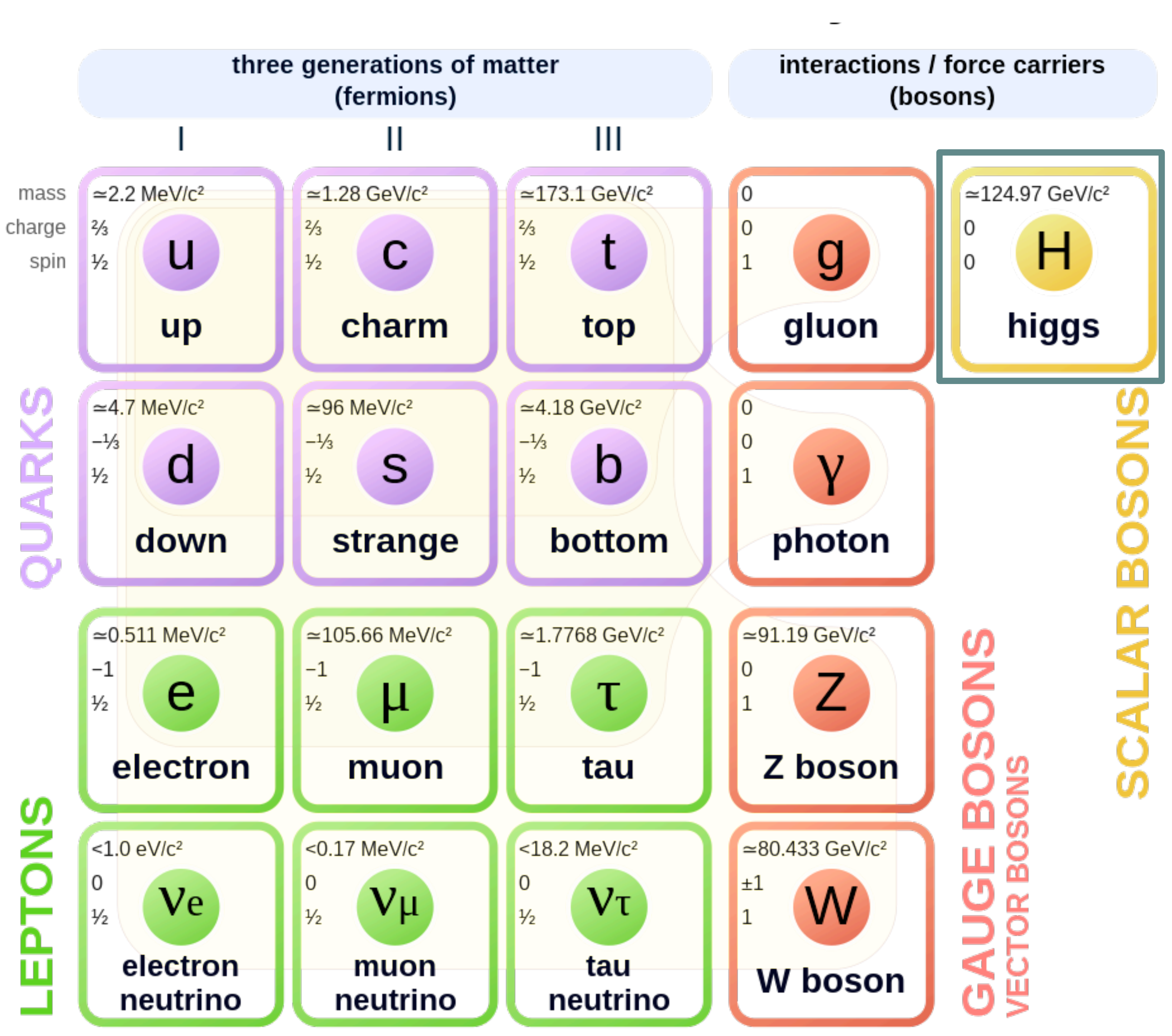
The Standard Model of Particle Physics

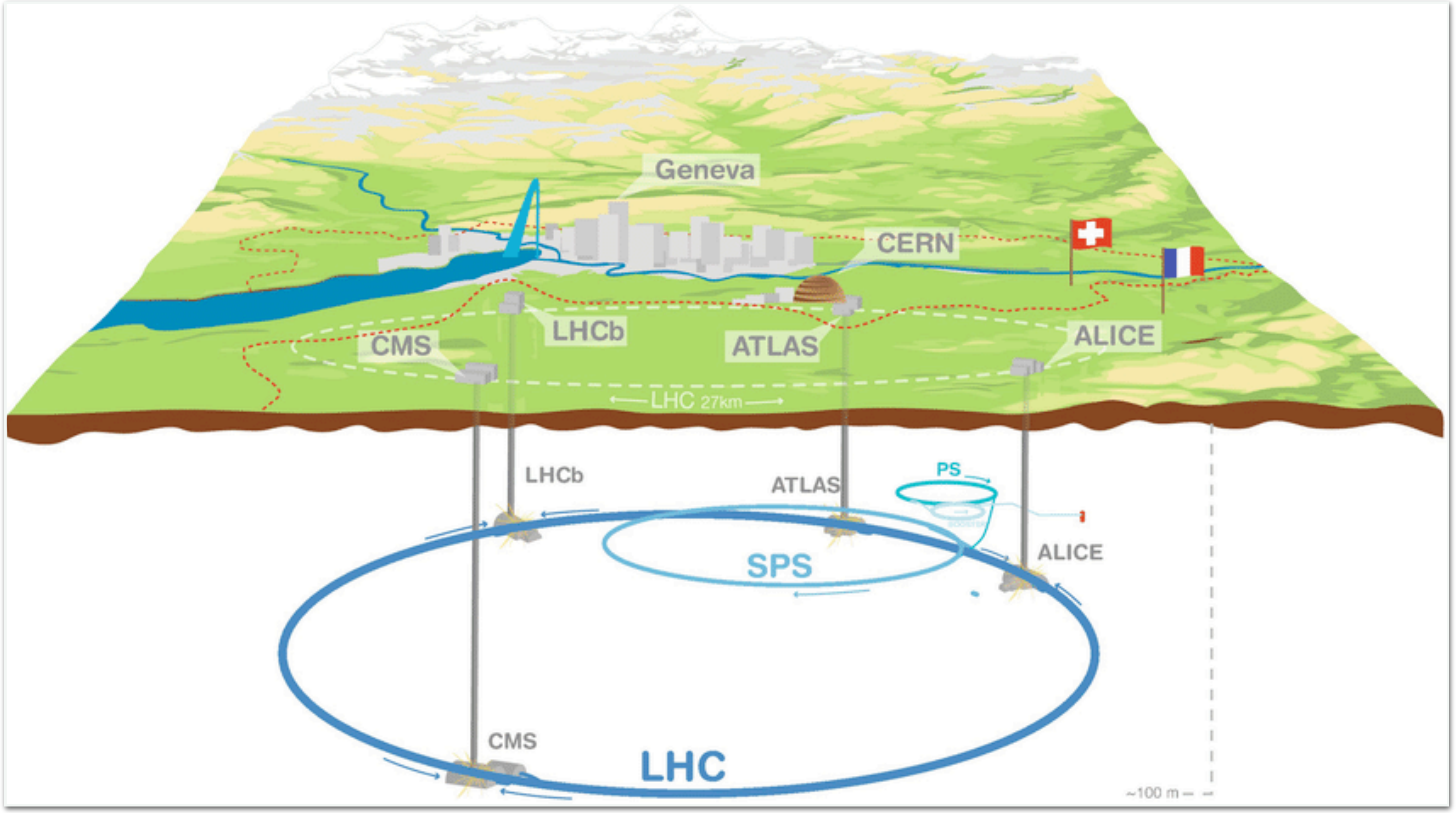


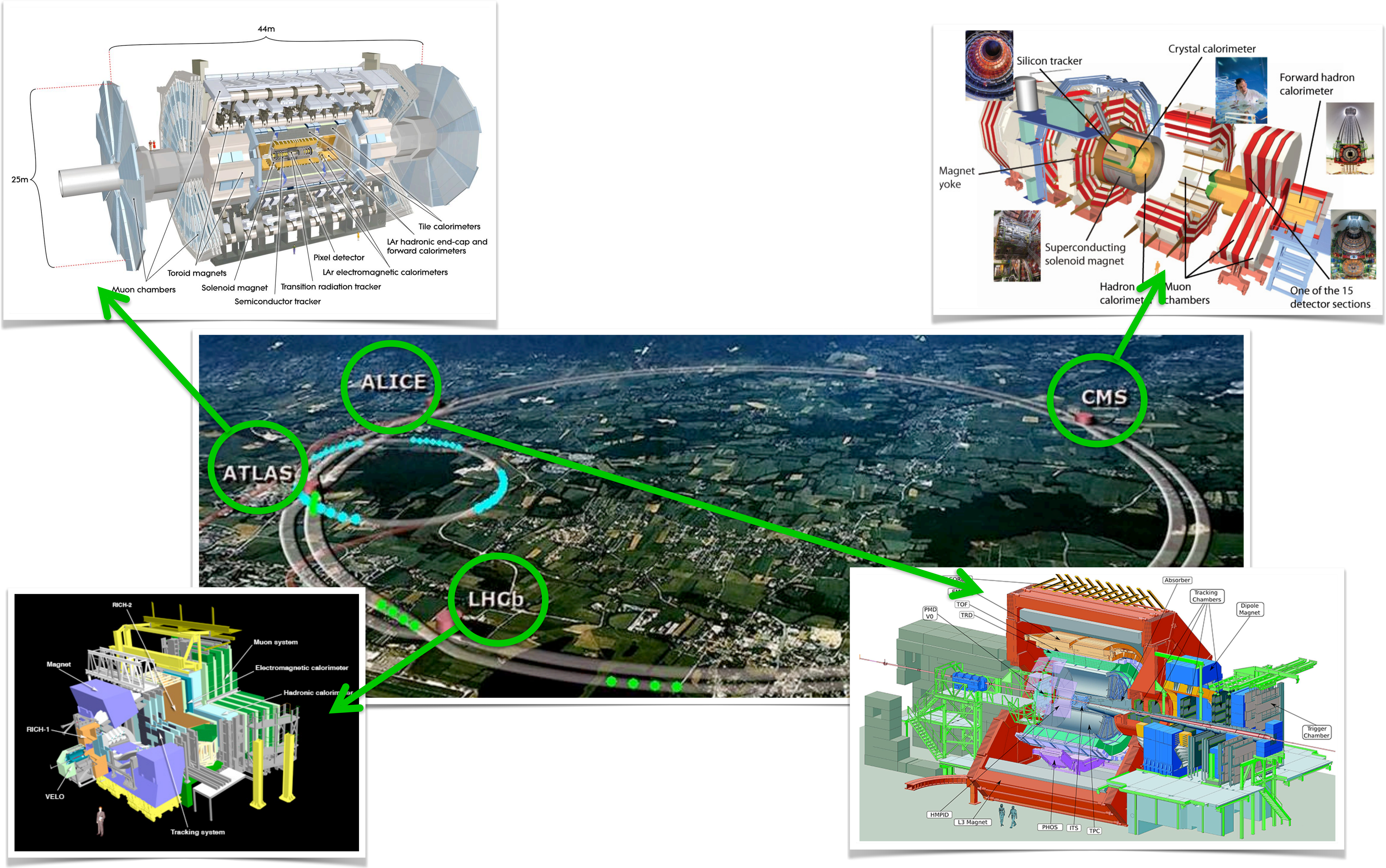
- Bosons: integer spin
  - Force carriers (Spin 1)
    - Gluon: strong force
    - Photon: electromagnetic
    - $W^{\pm}$, Z: weak force
  - Higgs boson (Spin 0)
    - Discovered by both LHC experiments in 2012 (recently had its 10th birthday)
    - Origin of electroweak symmetry breaking

https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg

Large Hadron Collider

- Proton-proton (proton-ion) collider with a circumference of 27 km located under the Swiss-French border near Geneva
- Center-of-mass energy 13 TeV (recently 13.6 TeV achieved)
- Over 1200 dipole magnets to keep proton beams on circular path

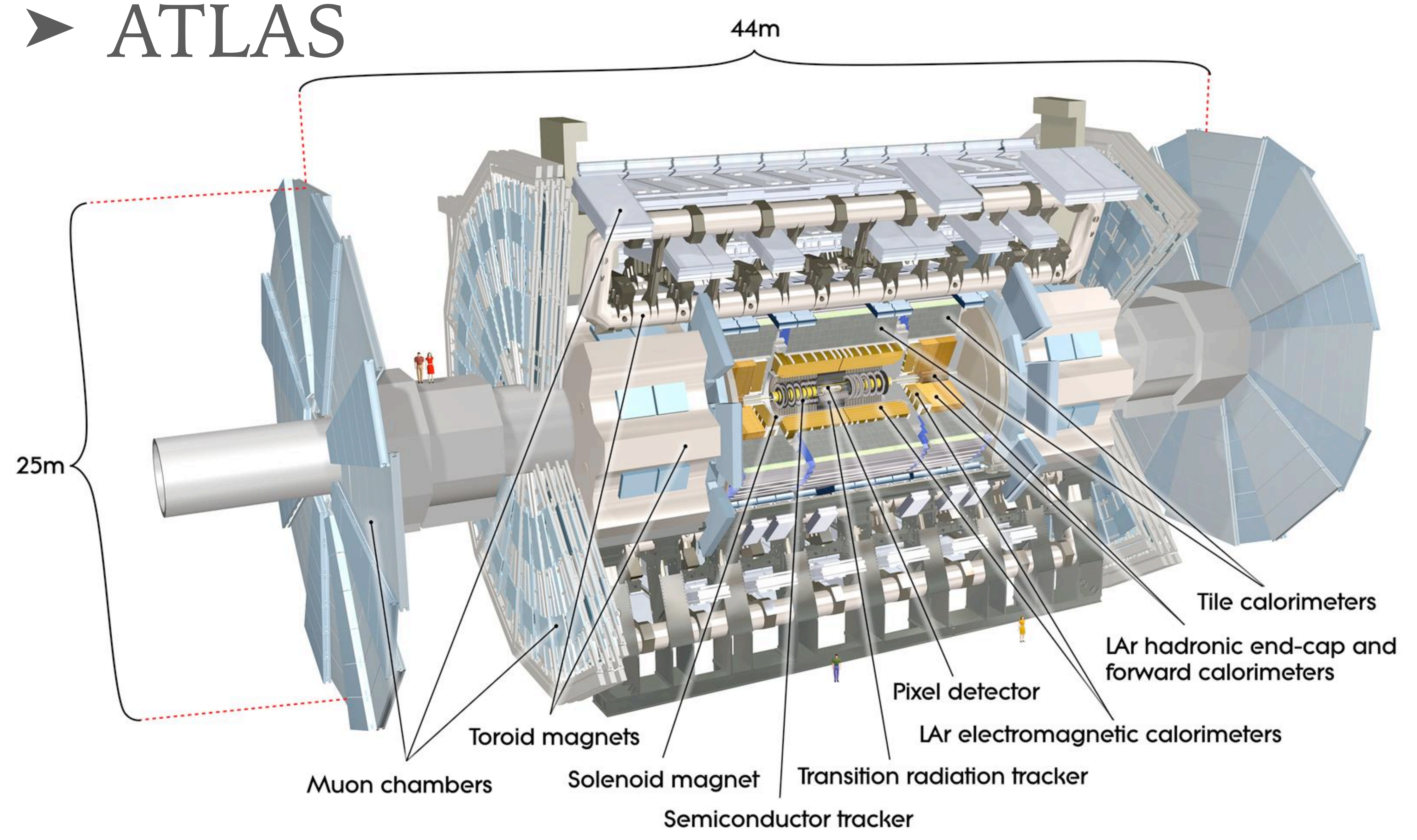




44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
Silicon tracker
Crystal calorimeter
Forward hadron calorimeter
Magnet yoke
Superconducting solenoid magnet
Hadron calorimeter
Muon chambers
One of the 15 detector sections
ALICE
ATLAS
CMS
LHCb
RICH-2
Muon system
Magnet
Electromagnetic calorimeter
Hadronic calorimeter
RICH-1
VELO
Tracking system
Absorber
Tracking Chambers
Dipole Magnet
PMD
V0
TOF
TRD
Trigger Chamber
HMPID
L3 Magnet
PHOS
ITS
TPC

The two main experiments for these lectures

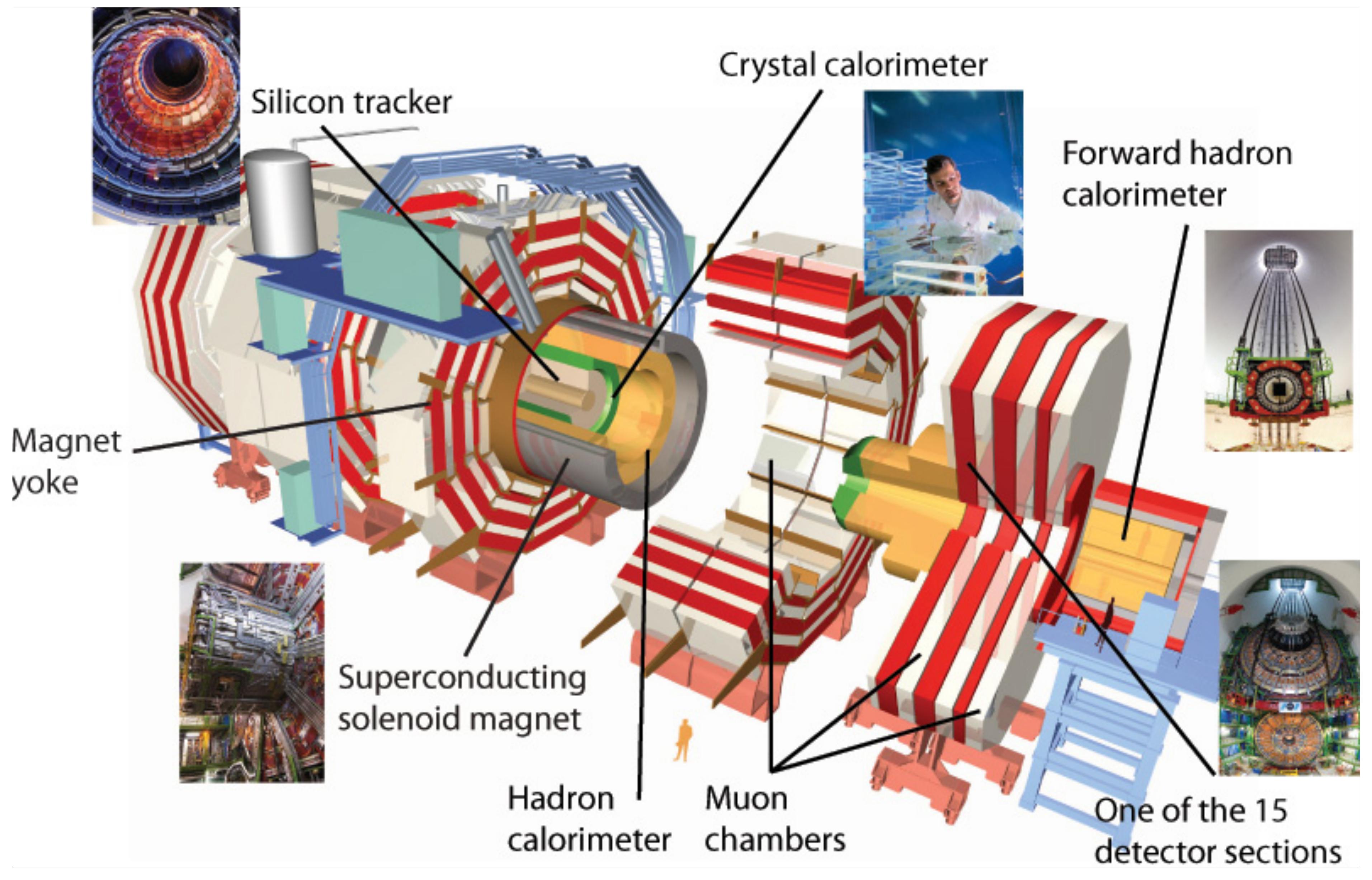
➤ ATLAS



➤ CMS Detector: 21 m long, 15 m diameter, about 14,000 tons, 4T solenoid

➤ CMS Collaboration: ~ 4000 people from over 40 countries

➤ CMS



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

➤ ATLAS Collaboration: ~ 6000 people from over 40 countries

Instantaneous Luminosity

- Most important quantity defining a collider at its center-of-mass energy
  - Precision measurement of the luminosity is a key ingredient for all physics analyses within ATLAS
    - Related to:
      - Rate of observed events
      - Machine parameters

$$R = \frac{\Delta N_{obs}}{\Delta t} = \sigma_{inel}\,\mathcal{L}$$

- Δt = luminosity block/lumi section
- $\mathcal{L}$ = instantaneous luminosity

- μ = mean number of inelastic pp collisions
- σ_{inel} = inelastic pp cross section

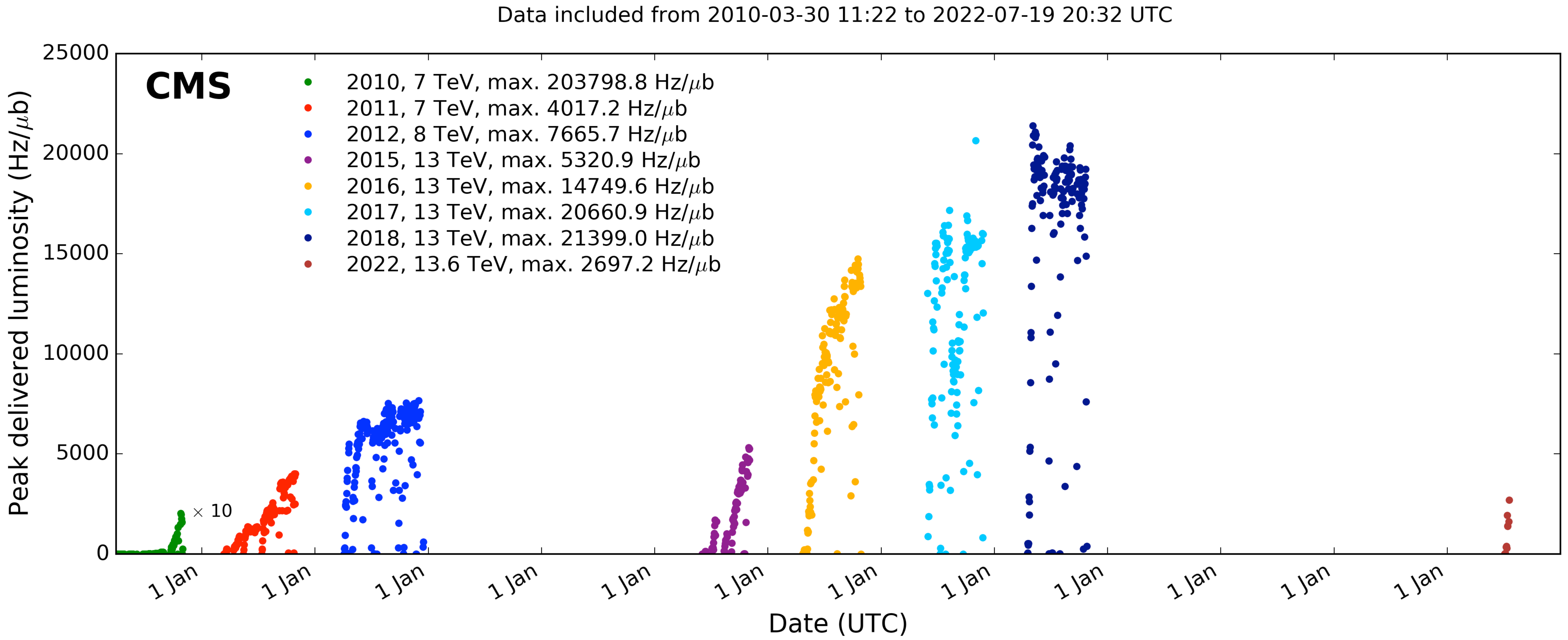
$$\mathcal{L} = \frac{n_b f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} = \frac{n_b f_r \mu_b}{\sigma_{\text{inel}}} = \frac{n_b f_r \mu_{\text{vis}}}{\sigma_{\text{vis}}}$$

LHC beam parameters

Can also be expressed by
- μ_{vis} = visible interaction rate
  σ_{vis} = visible pp cross section

Peak instantaneous Luminosity

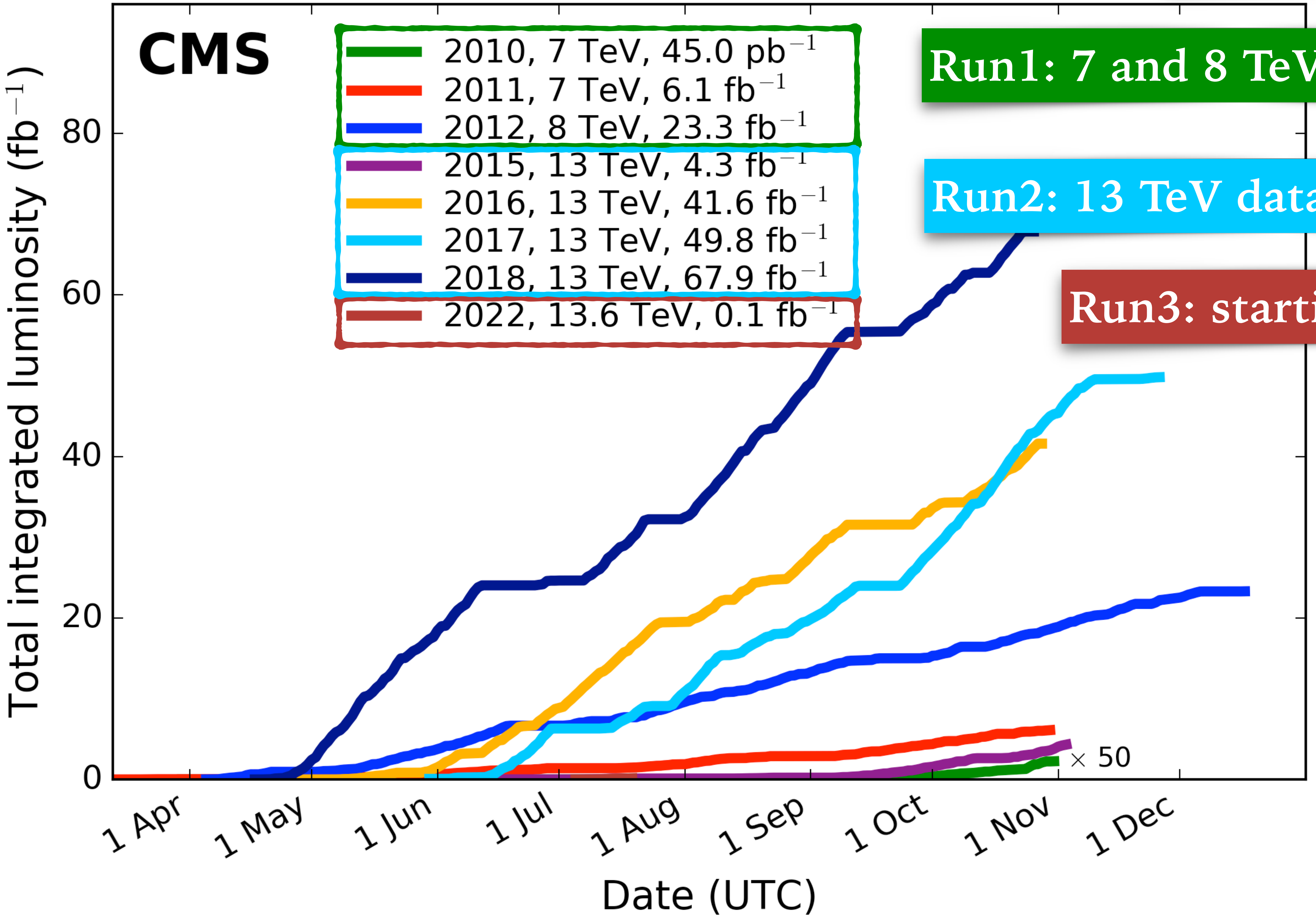
1 barn = 10^{-28} m^2



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

LHC proton-proton mode

Various running years with different energies

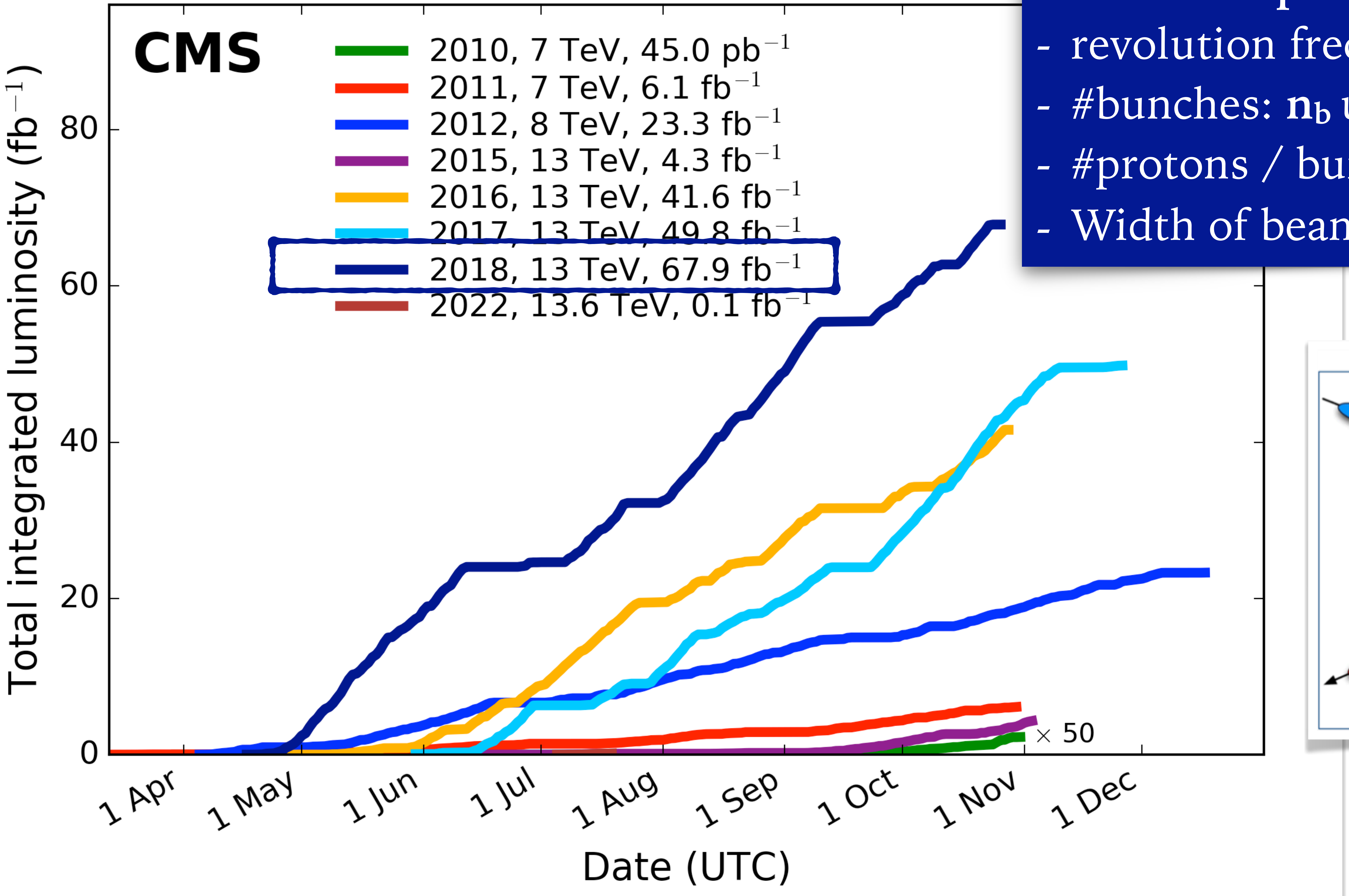


Run1: 7 and 8 TeV datasets

Run2: 13 TeV dataset ~ 150 fb^{-1}

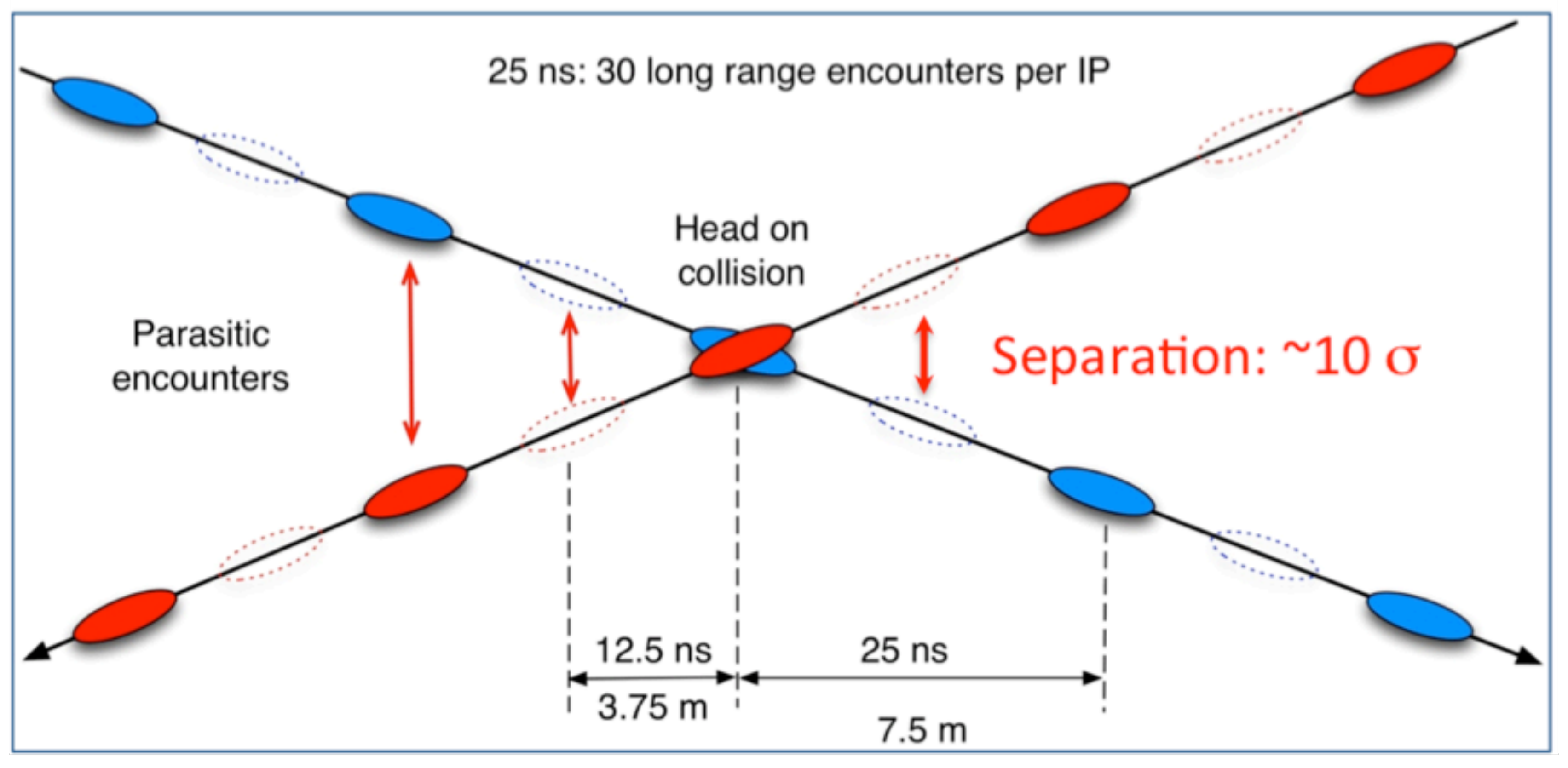
Run3: starting as we speak

LHC proton-proton mode

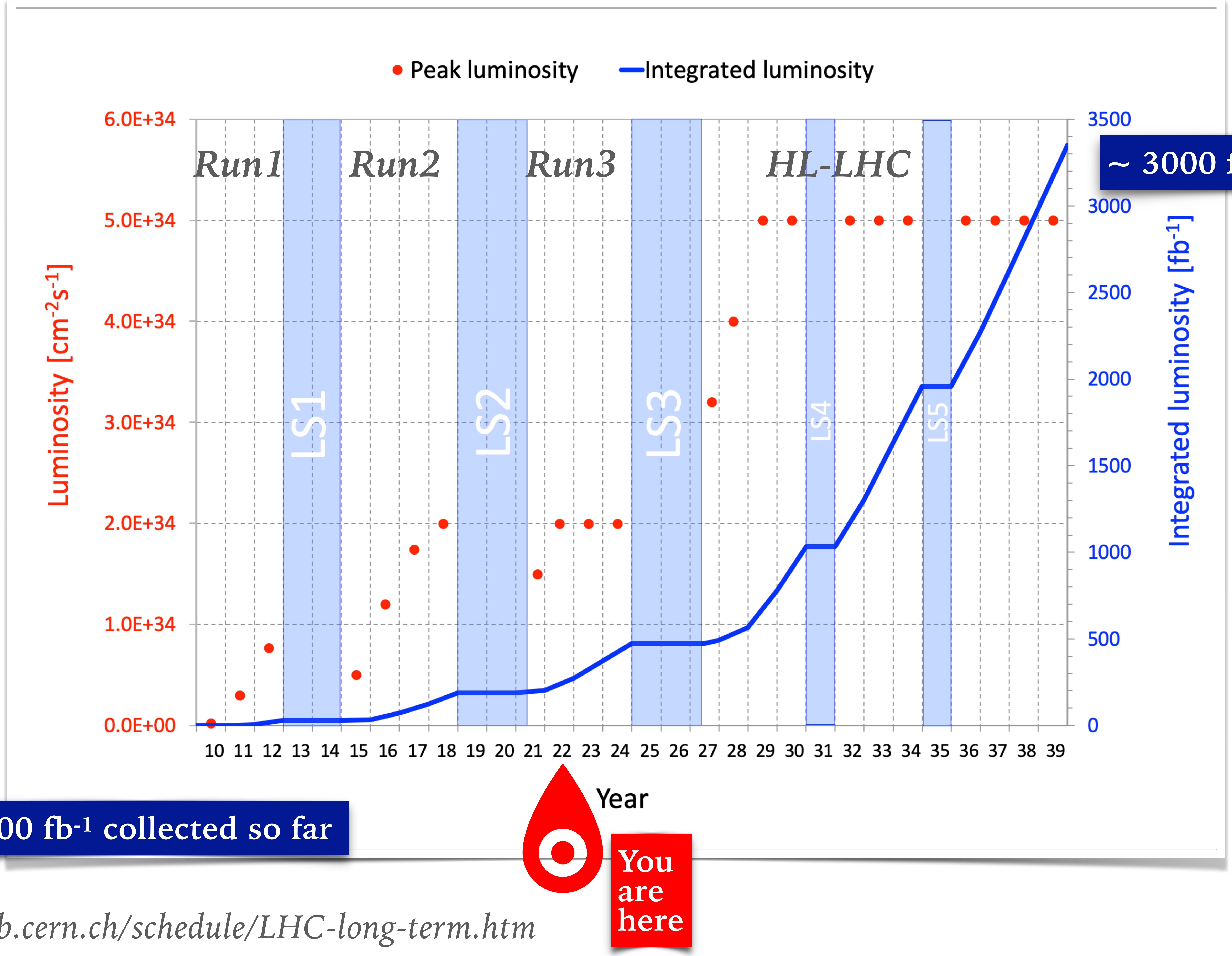


2018 beam parameters (physics regime)

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



Interlude: Run3 has started

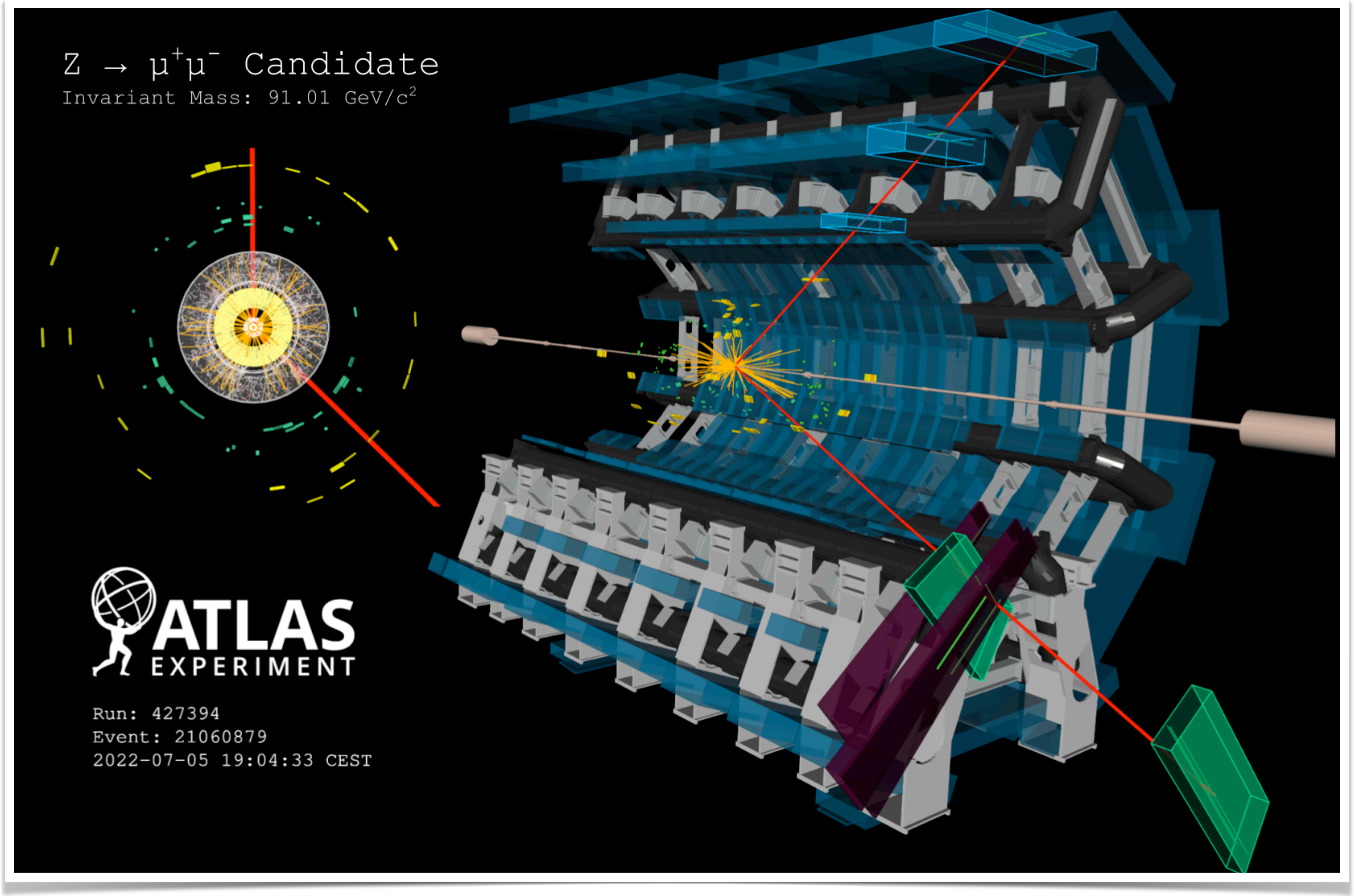


~ 3000 fb^{-1} expected by end of 2040

~ 200 fb^{-1} collected so far

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

Run3 has started



Event display 2022

Run3 has started

Andreas Hoecker, ATLAS spokesperson, beams as he connects to the live broadcast, while members of the ATLAS collaboration cheer in the background. (Image: A. Chrul/CERN)

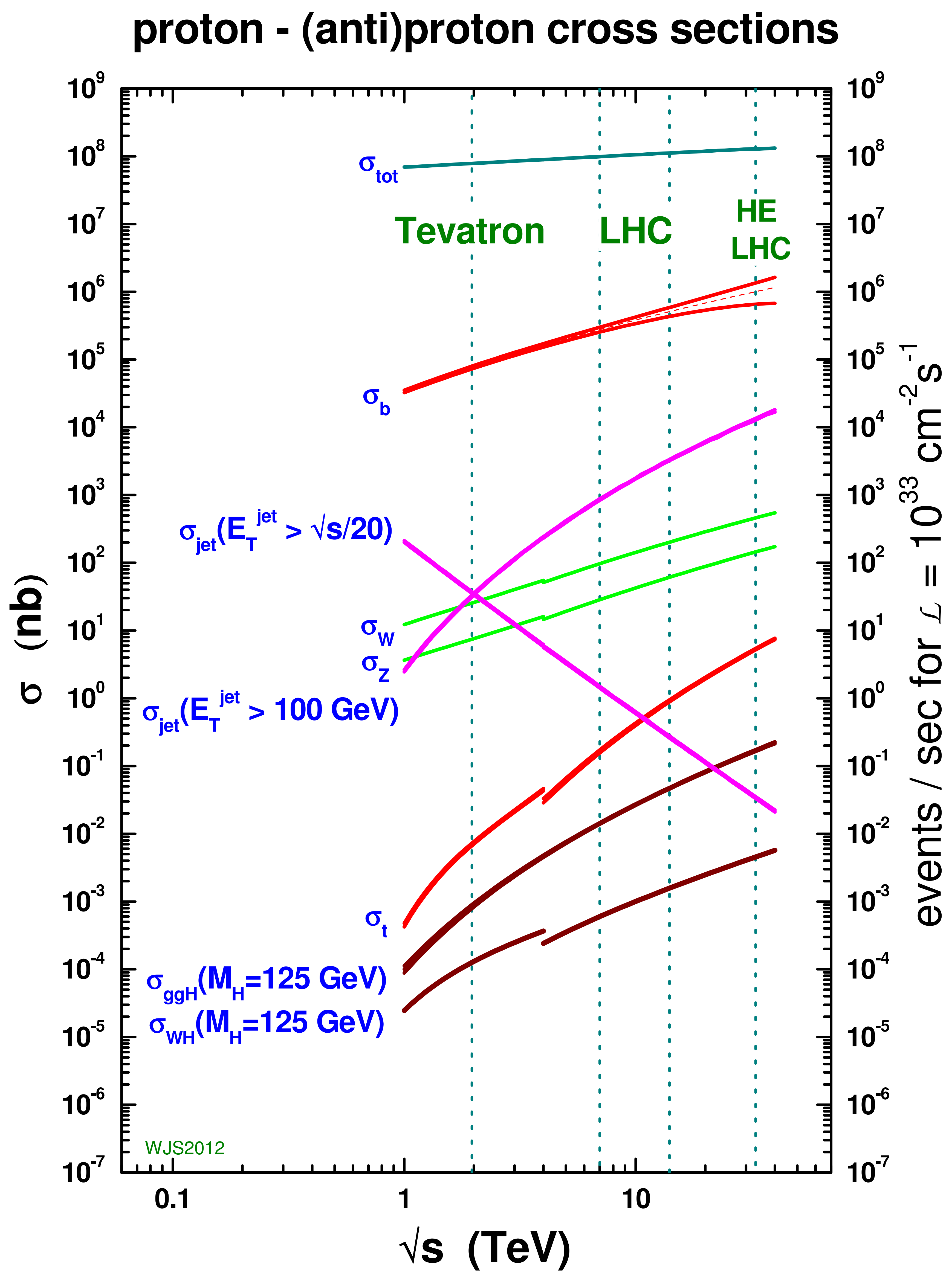
Applause in the ATLAS Control Room as first 13.6 TeV collisions are recorded. (Image: D. Price/ATLAS Collaboration)

The CMS control room full of joy

https://cms.cern/news/wait-overthe-lhc-run-3-has-started

https://atlas.cern/Updates/Press-Statement/Run3-first-collisions

Collisions at the LHC



- ~100 mb total proton-proton cross section

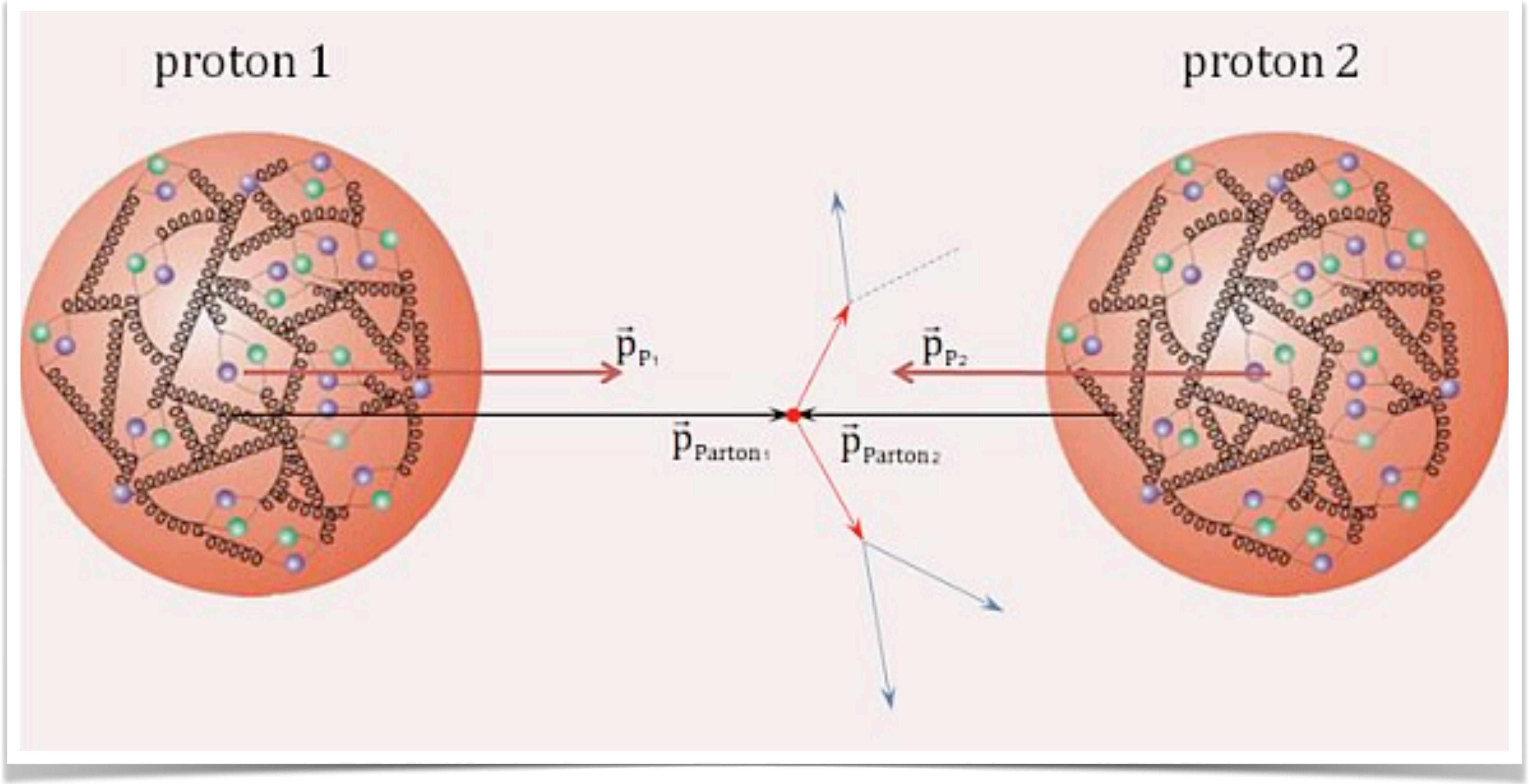
~ 60 mb in-elastic cross section
→ this is where will start seeing "interesting" physics the detector

$$R = \frac{\Delta N_{obs}}{\Delta t} = \sigma_{inel}\mathcal{L}$$

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

$= 1.2\ \text{x}\ 10^{9}$ collisions/second

Proton-Proton collision theory perspective

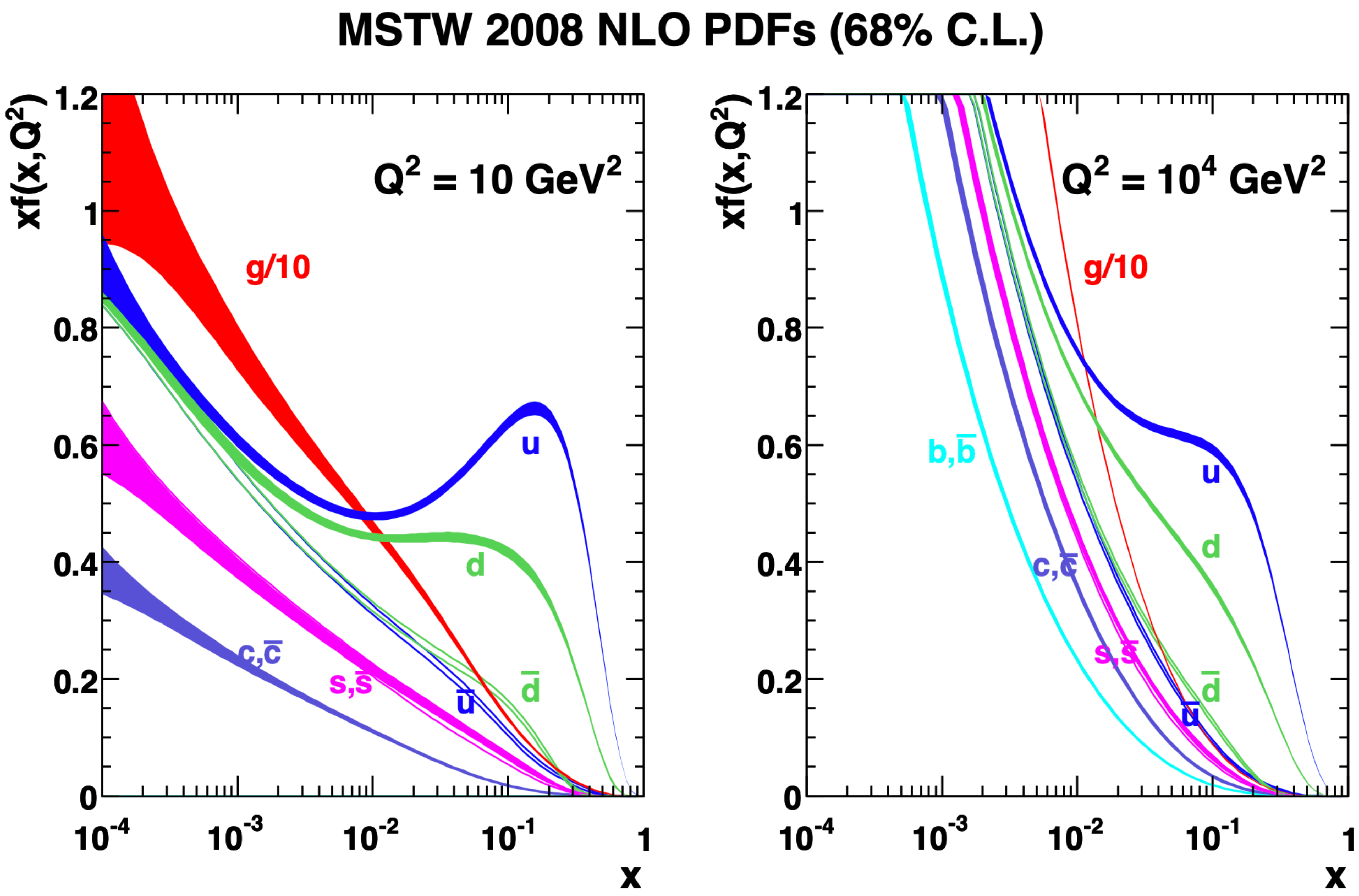


- Type of parton and momentum fraction (x) not known
- Exact center of mass energy of colliding quarks not known! (different at lepton colliders)
- => cross section are calculated by integrating over **Parton distribution functions**

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

[https://mstwpdf.hepforge.org/plots/plots.html]

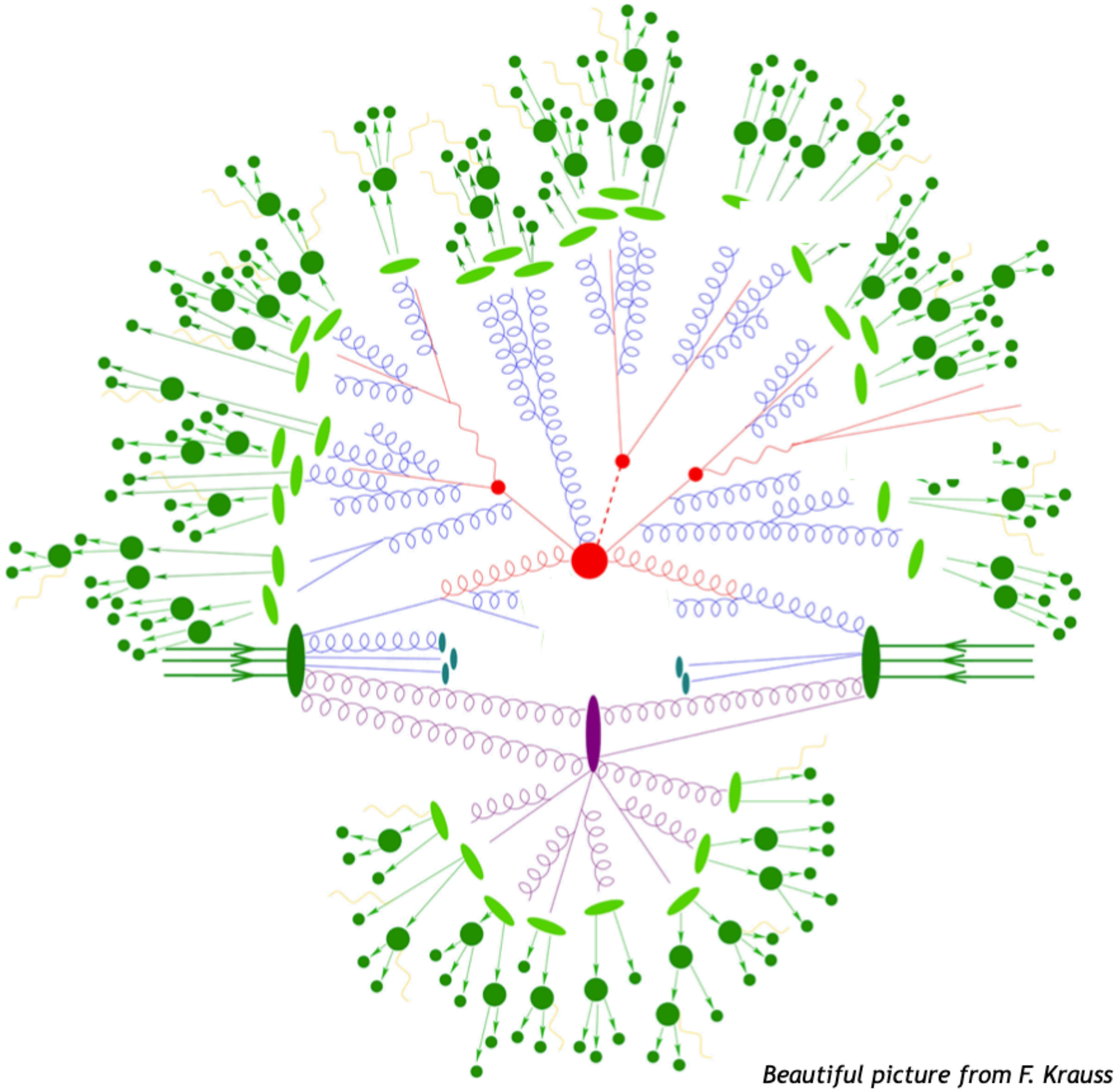
Parton distribution functions



- ➤ 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 DGLAP equations)
  - ➤ important uncertainty for measurements and searches!

Simulation in particle physics

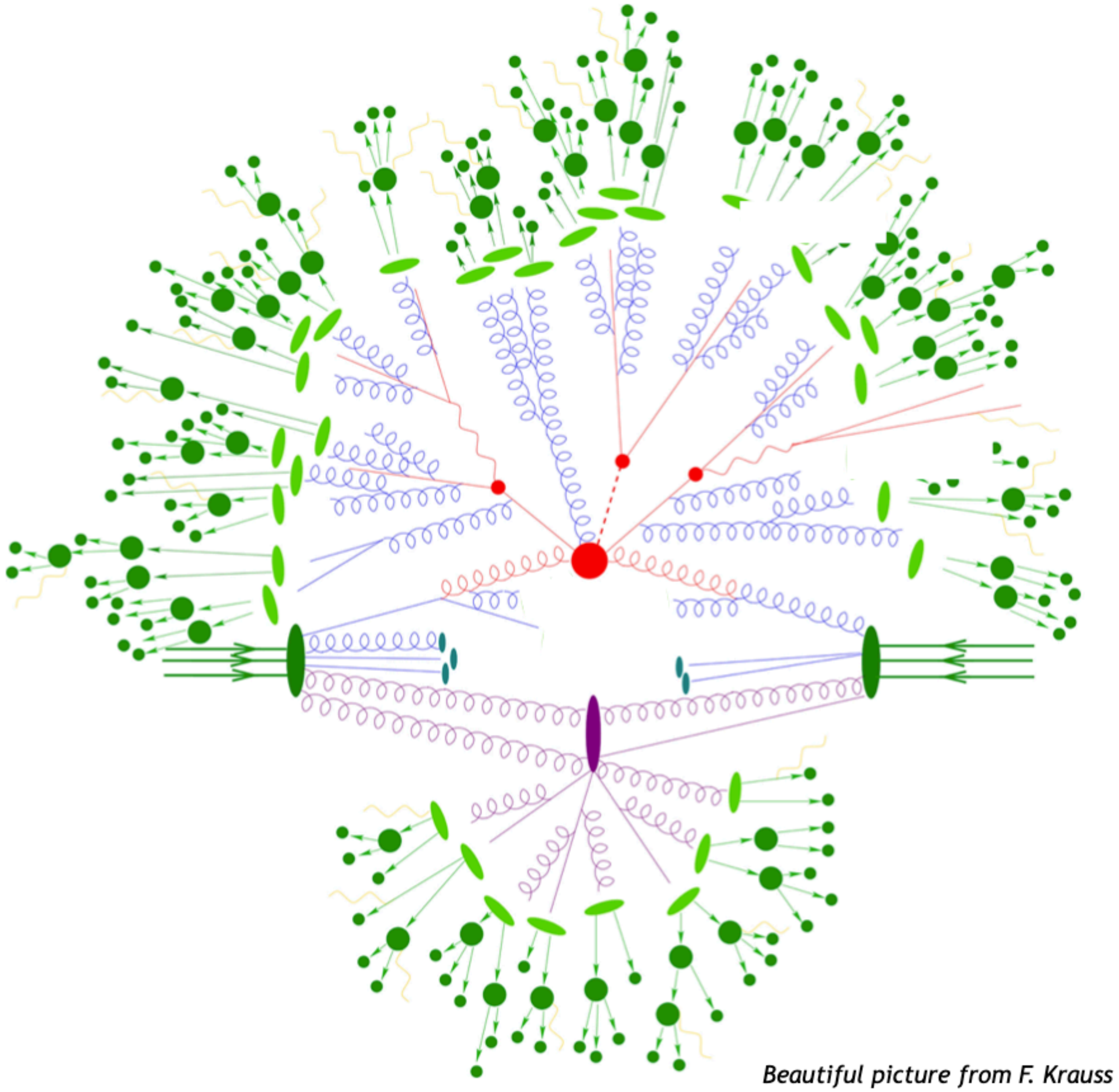
- Backbone for almost all LHC physics analyses
- Theory modeling of:
  - hard scatter, parton shower, hadronization, hadron decay



Beautiful picture from F. Krauss

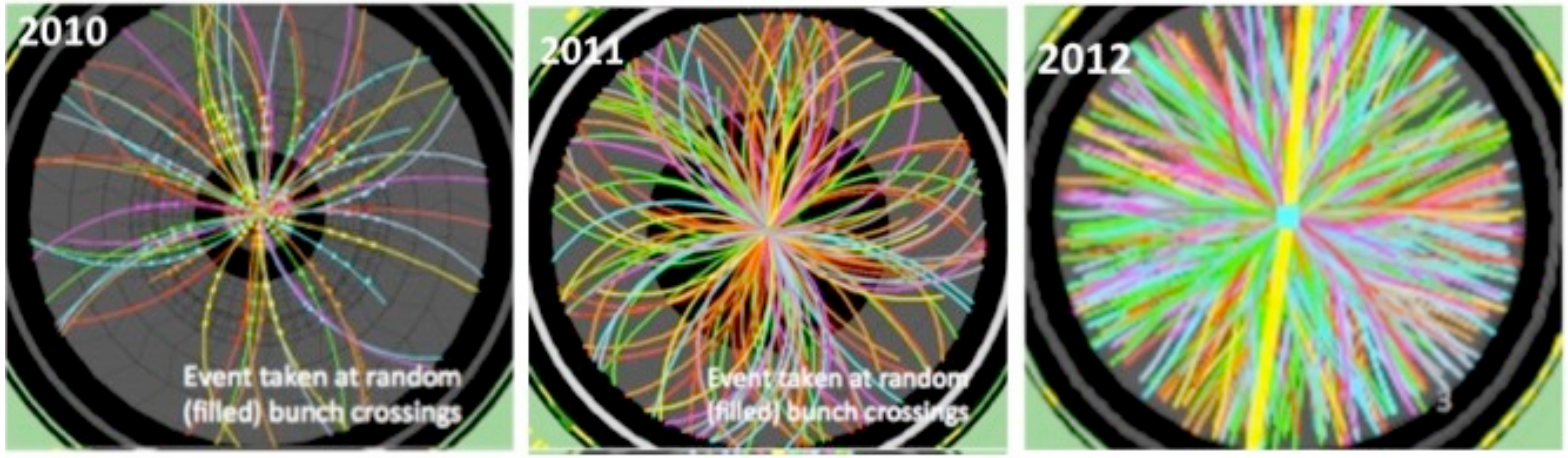
Simulation in particle physics

- Backbone for almost all LHC physics analyses
- Theory modeling of:
  - hard scatter, parton shower,
    hadronization, hadron decay
- Modeling of the detector:
  - particle interactions with the material (GEANT4)
  - Detector response
- Particle identification and event reconstruction
  - treat simulated data like real collision data
    ⇒ allows detailed comparison between experiment and simulation

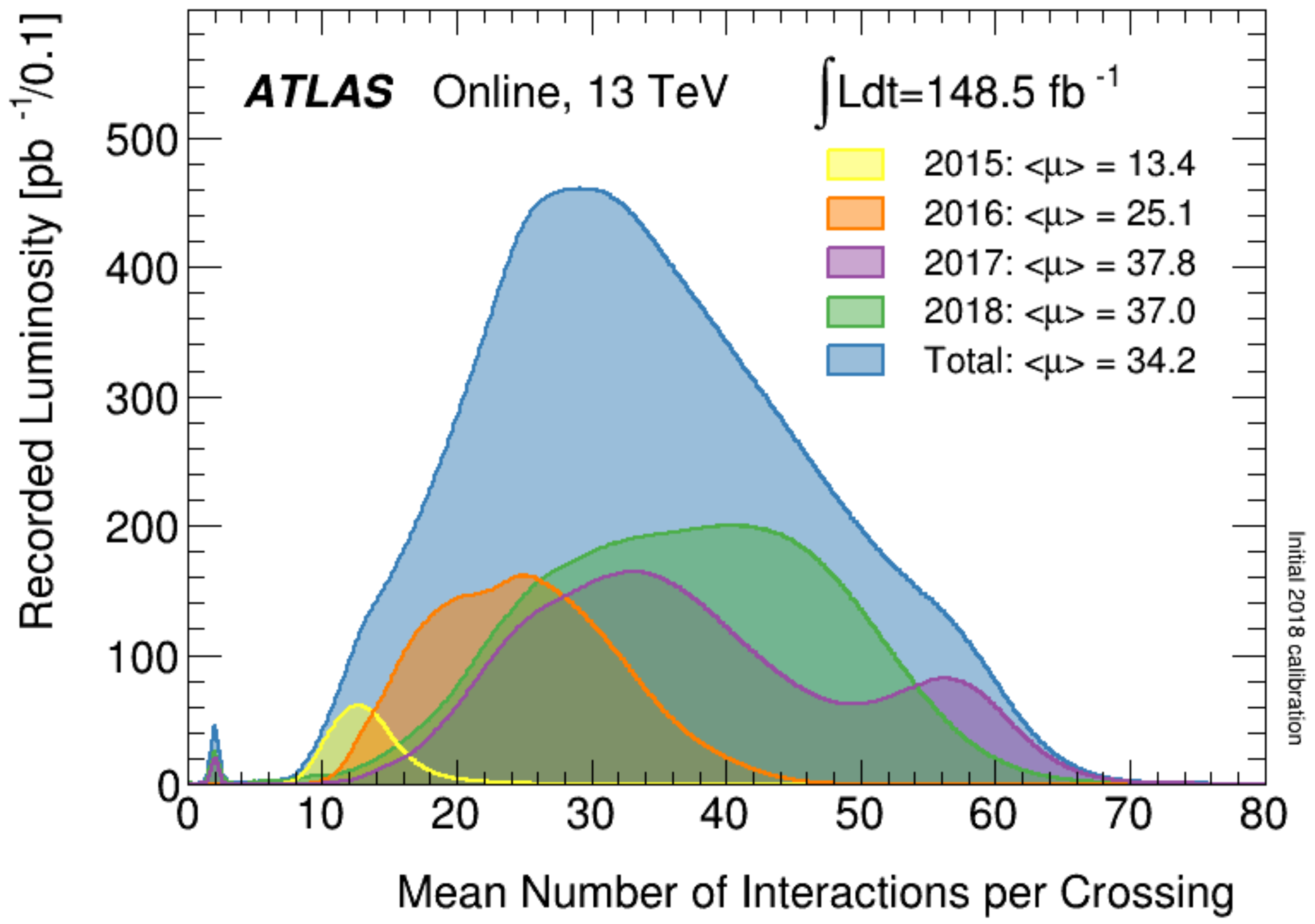


Beautiful picture from F. Krauss

Pileup



- **(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!

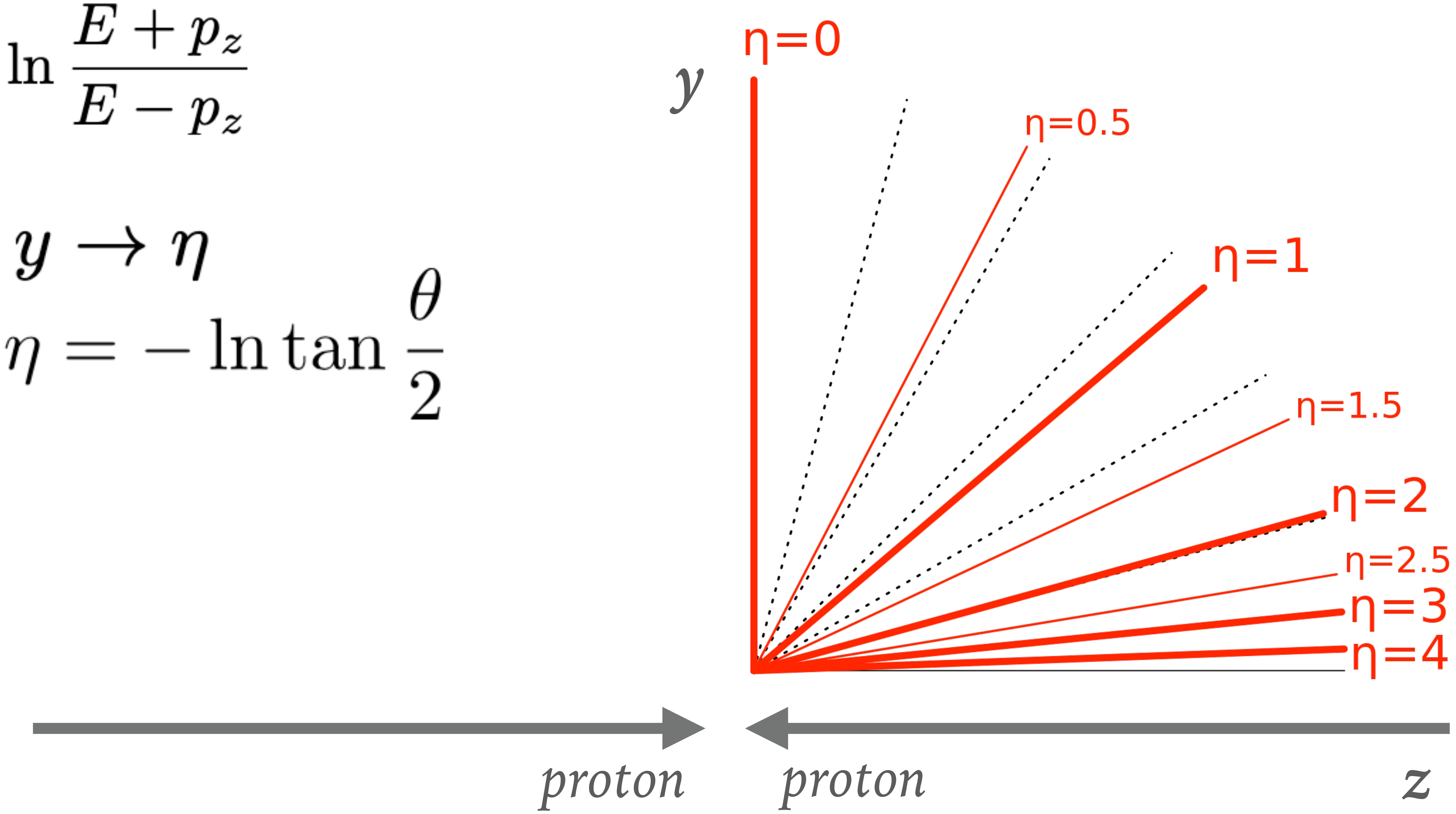


Interlude: Basic kinematic quantities

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

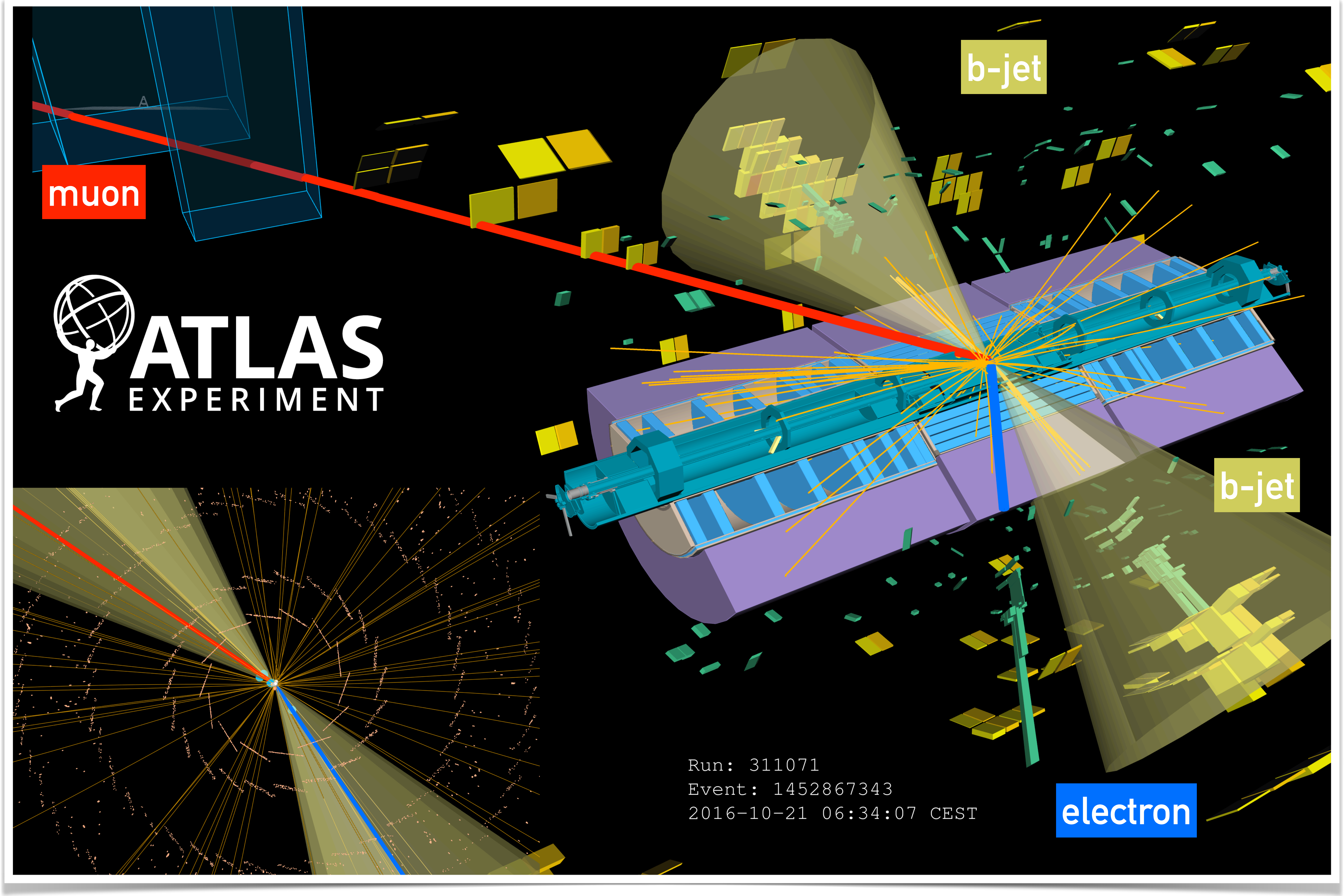
Pseudo-rapidity: $y \rightarrow \eta$

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



Transverse momentum: $p_T = p \cdot \sin\theta$

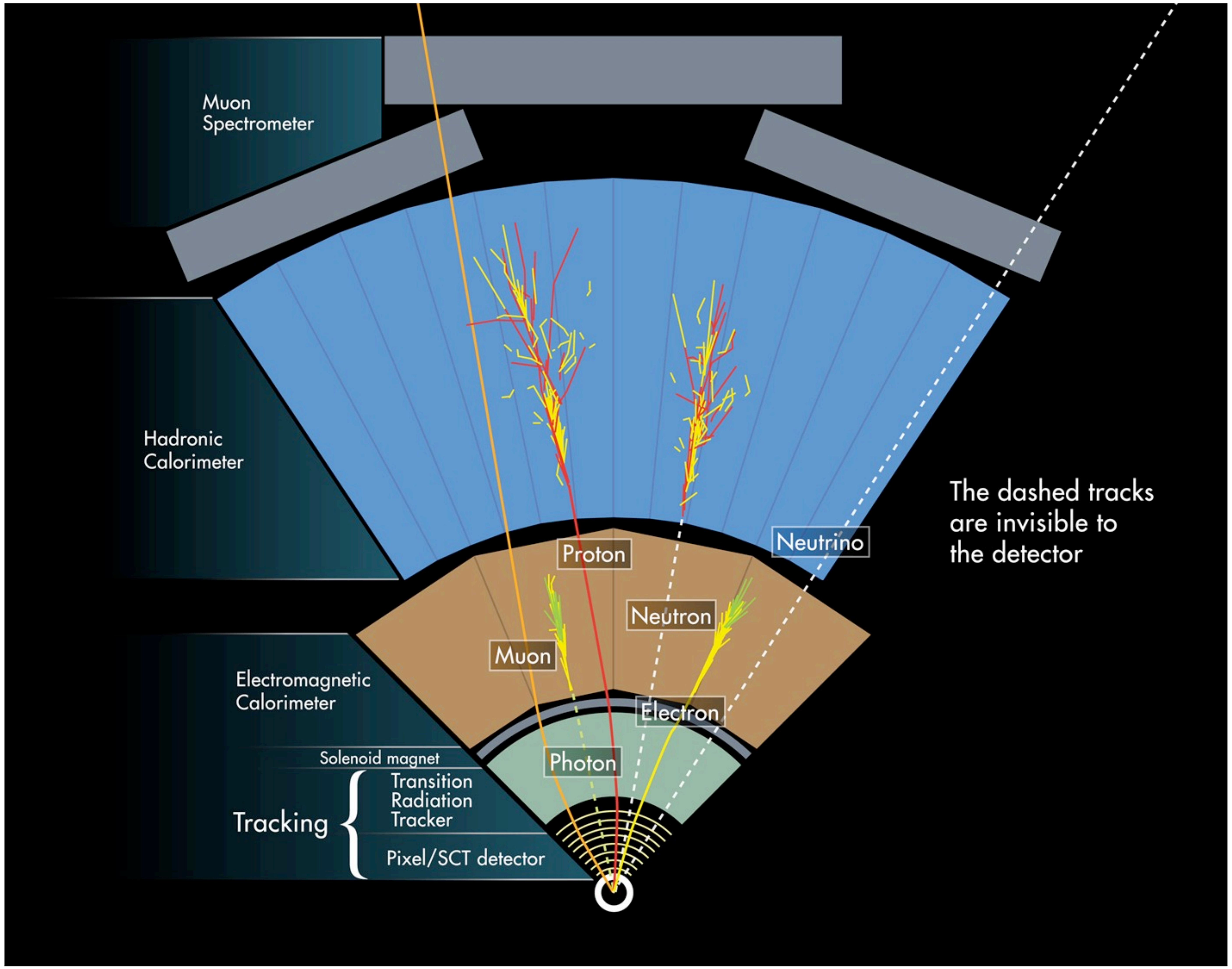
An “Event” in the detector



top quark pair candidate event

Particle identification in ATLAS

Onion-like structure



Explicit technology choices differ by experiment

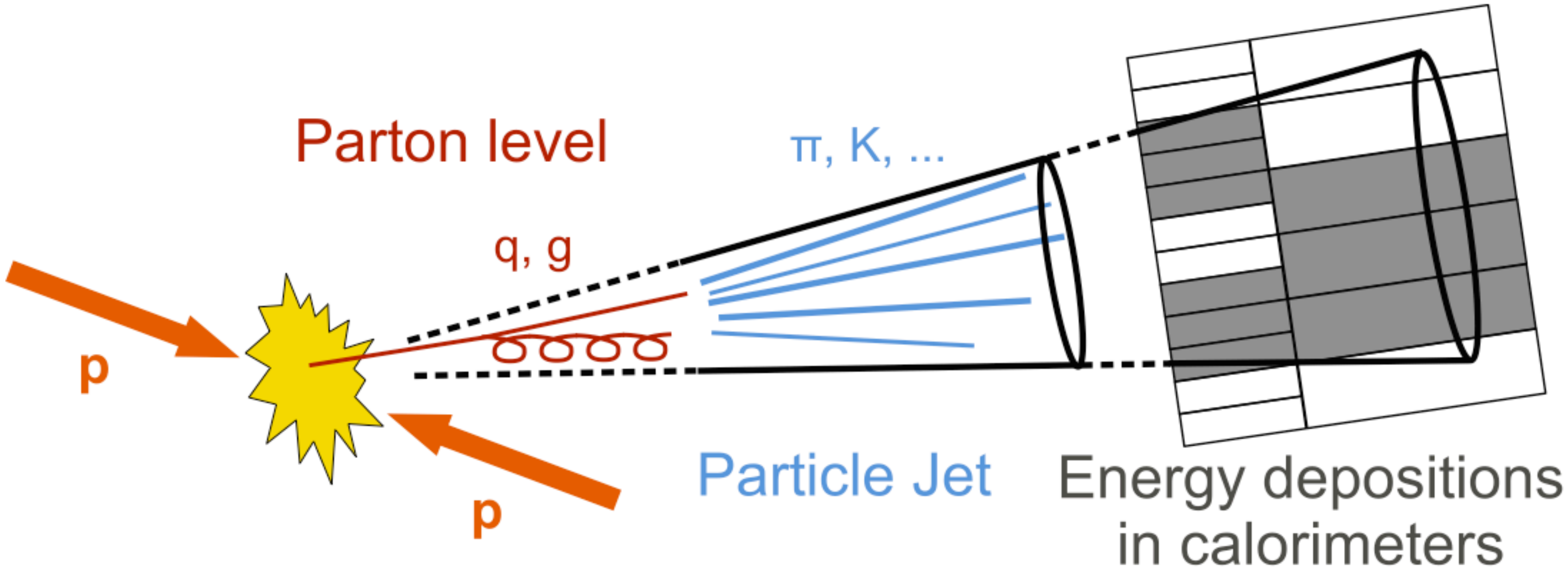
Particle identification

- Lot's of work goes into particle identification within the experiments
  - i.e. translate the 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 modeling
    - needs to be corrected, otherwise comparisons will be biased

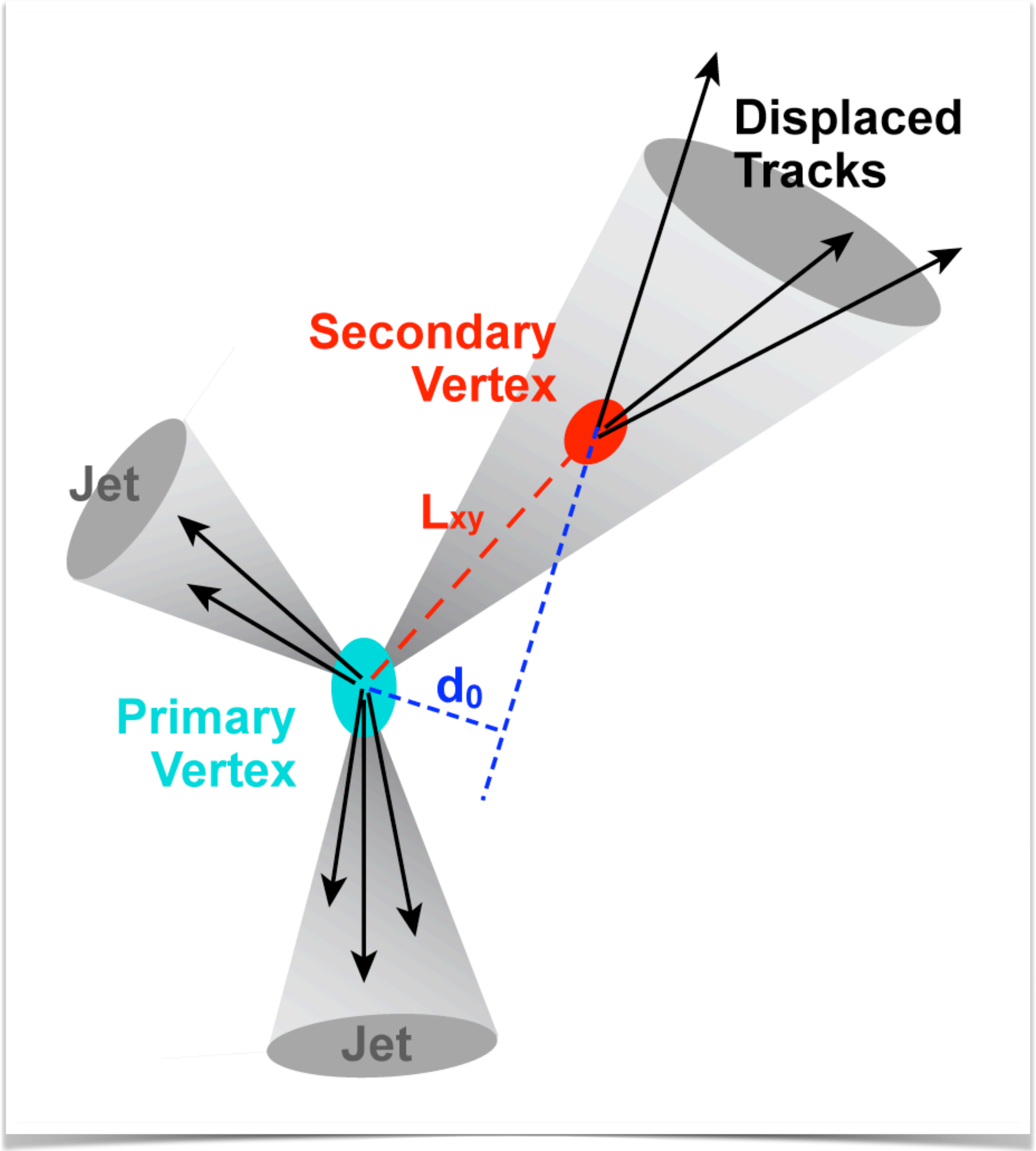
Jets: light flavor and gluons

- Quarks and gluons cannot be observed by themselves
  - They undergo the processes of parton shower and hadronization
- Experimental signature:
  - Spray of neutral and charged hadrons
    - Tracks in the inner silicon tracker (and TRT)
    - Energy deposits in the electromagnetic and hadronic calorimeters



Jets: heavy flavor

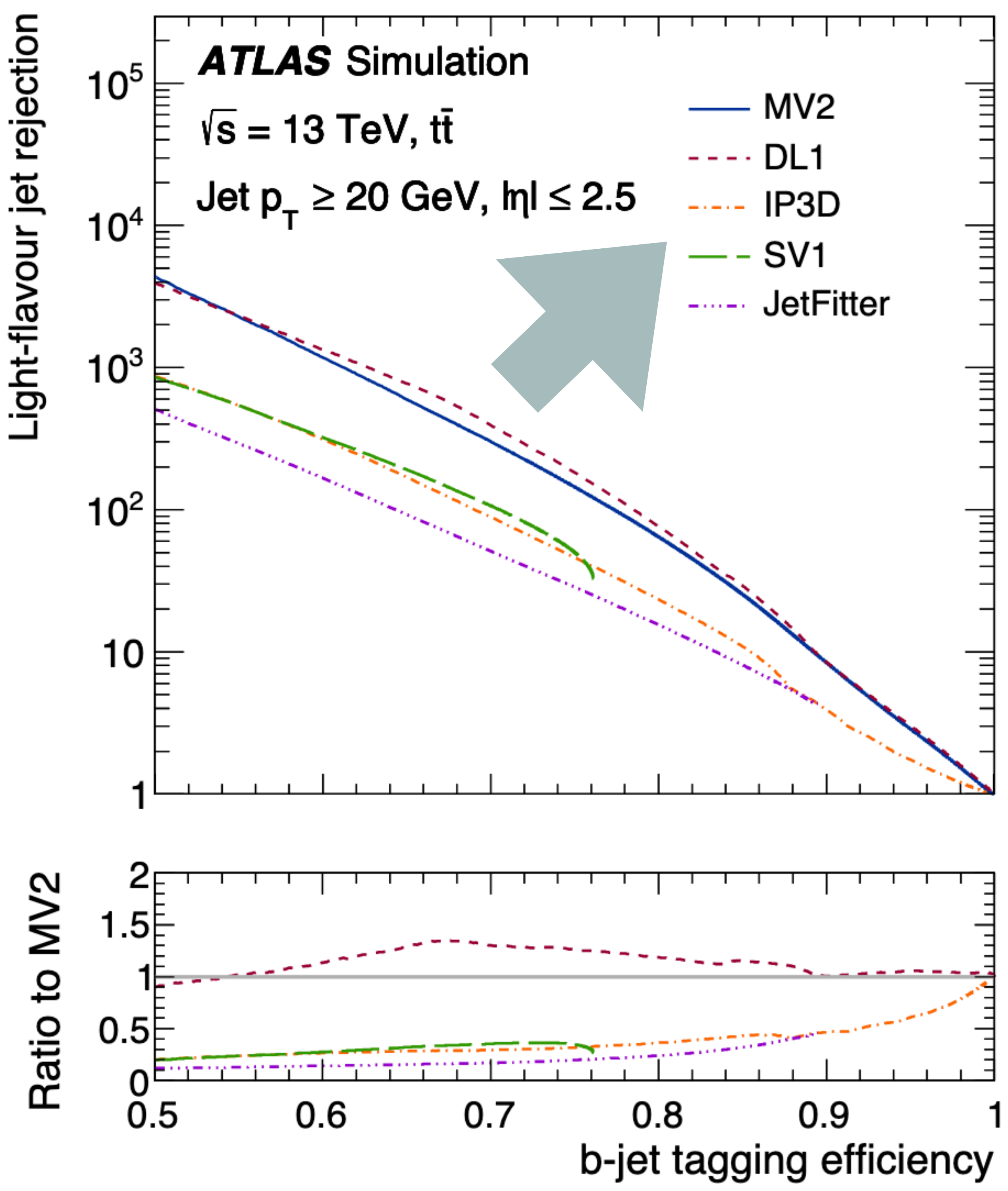
- b-quarks contain B-Hadrons in their parton shower evolution
- B-Hadrons have sufficient lifetime
  ⇒ travel away from the primary interaction point before decaying (~0.5mm)
  ⇒ Secondary vertex
- Often multivariate techniques are used to identify jets originating from b-quarks



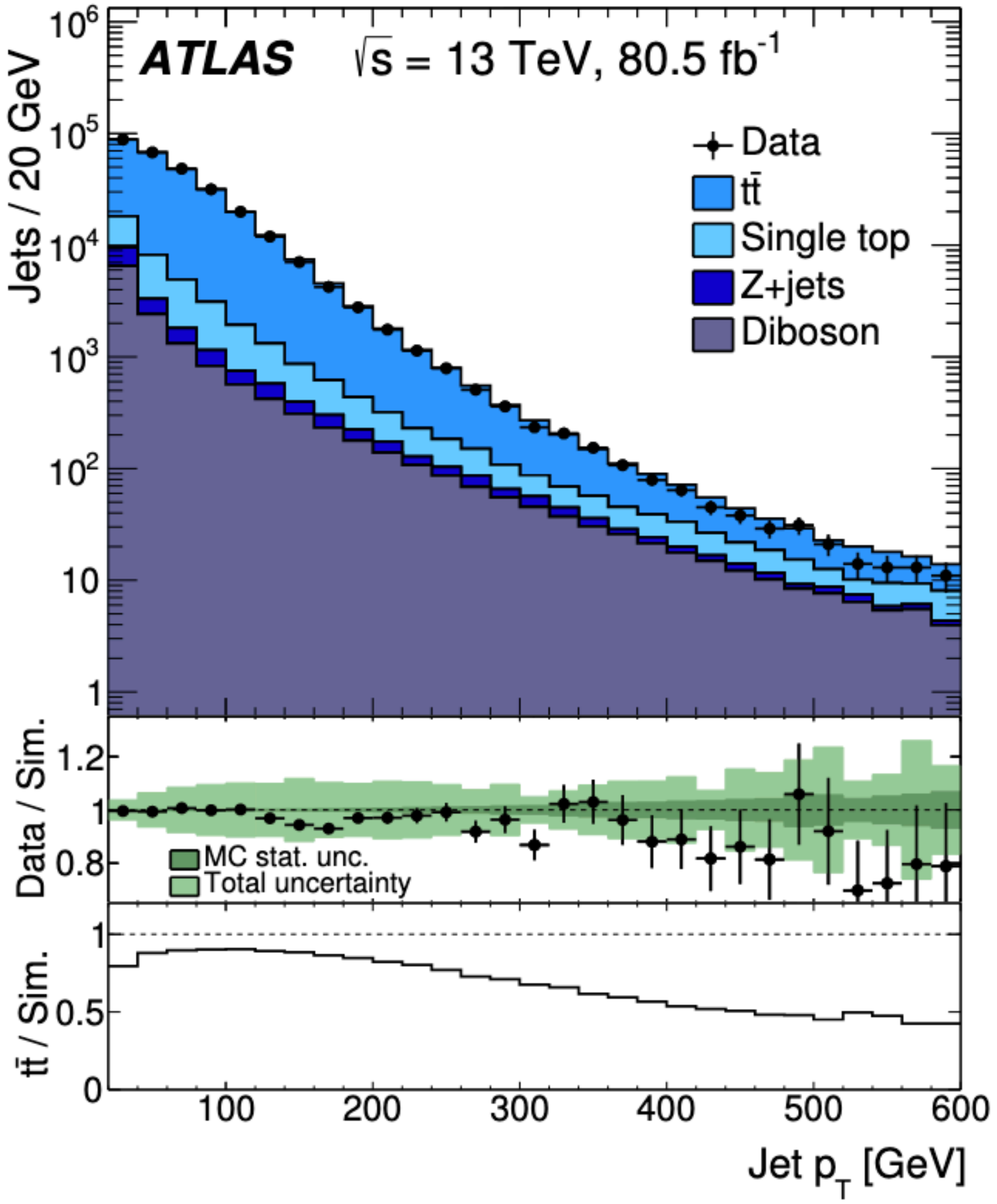
Jets: heavy flavor

- The goal is to identify and precisely measure particles that were produced in the collision
  - Develop algorithm based on simulation, pick most optimal one (i.e. high efficiency and low fake rate)
  - Measure efficiency in data and compare to simulation
  - Correct simulation (often called a **data-MC scale factor**)

ROC curves, to compare different algorithn



data-MC SF



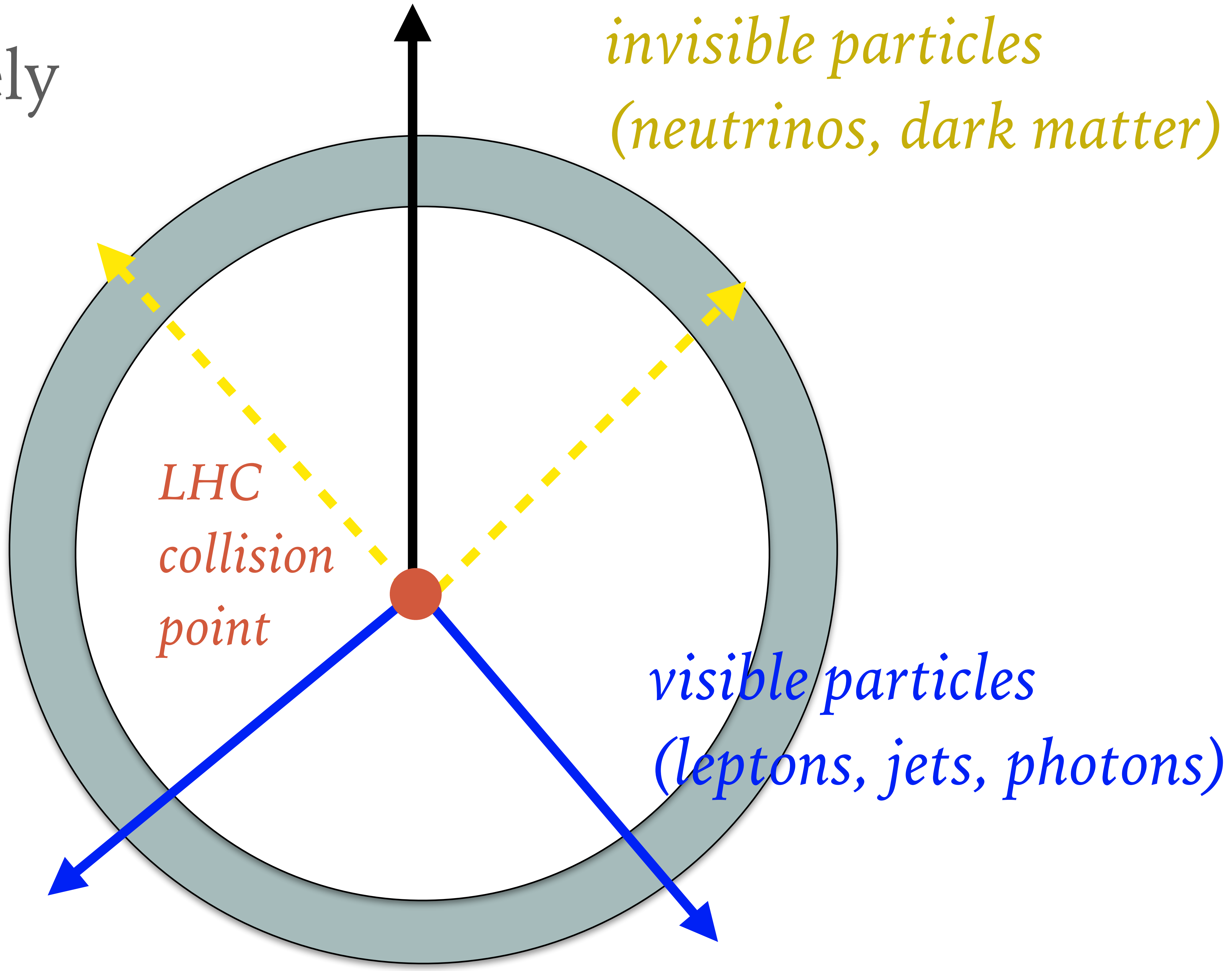
Example: b-jets in ttbar events

Missing transverse energy (MET)

- Important to infer the presence of non-interacting particles
  - Measure every interacting particle very precisely and take negative vector sum:

$$\mathbf{E}_T^{miss} = -\sum_{i}^{visible} \mathbf{E}_{T,i}$$

- Sounds trivial but can be very tricky:
  - not all particles might be reconstructed
  - pileup dependency can be an issue

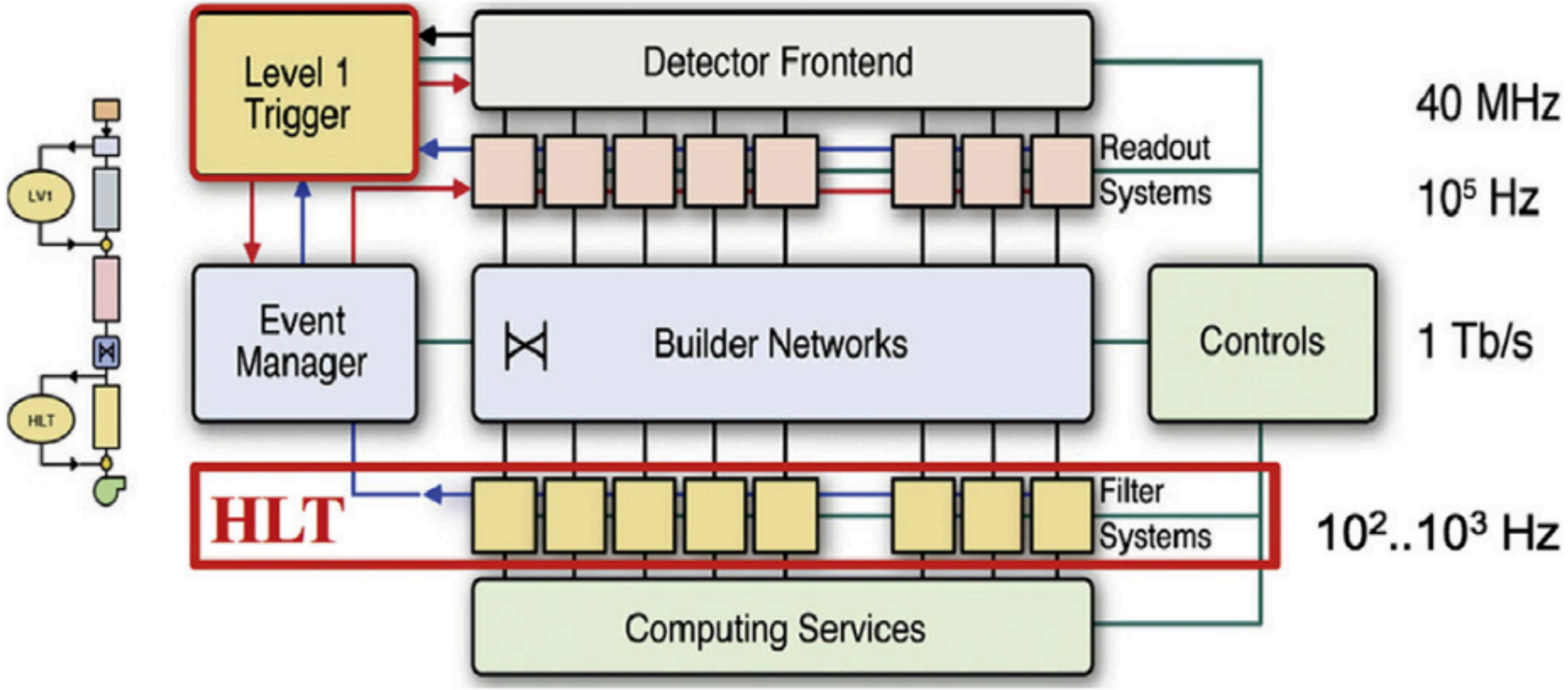


$$\mathbf{E}_T^{\text{miss}} = -\left(\mathbf{p}_T^{\text{hard}} + \mathbf{p}_T^{\text{soft}}\right) = \overbrace{-\sum_{\substack{\text{selected}\\\text{electrons}}} \mathbf{p}_T^{e} - \sum_{\substack{\text{accepted}\\\text{photons}}} \mathbf{p}_T^{\gamma} - \sum_{\substack{\text{accepted}\\\tau-\text{leptons}}} \mathbf{p}_T^{\tau} - \sum_{\substack{\text{selected}\\\text{muons}}} \mathbf{p}_T^{\mu} - \sum_{\substack{\text{accepted}\\\text{jet}}} \mathbf{p}_T^{\text{jet}}}^{\text{hard term}} \overbrace{- \sum_{\substack{\text{tracks or}\\\text{clusters}}} \mathbf{p}_T^{\text{soft terms}}}^{\text{soft term}}$$

[https://doi.org/10.1016/j.nima.2012.08.091]

A word on triggers

- Most collisions at the LHC are quite boring
  - Collisions occur every 25ns (40 Mhz) → impossible to record everything



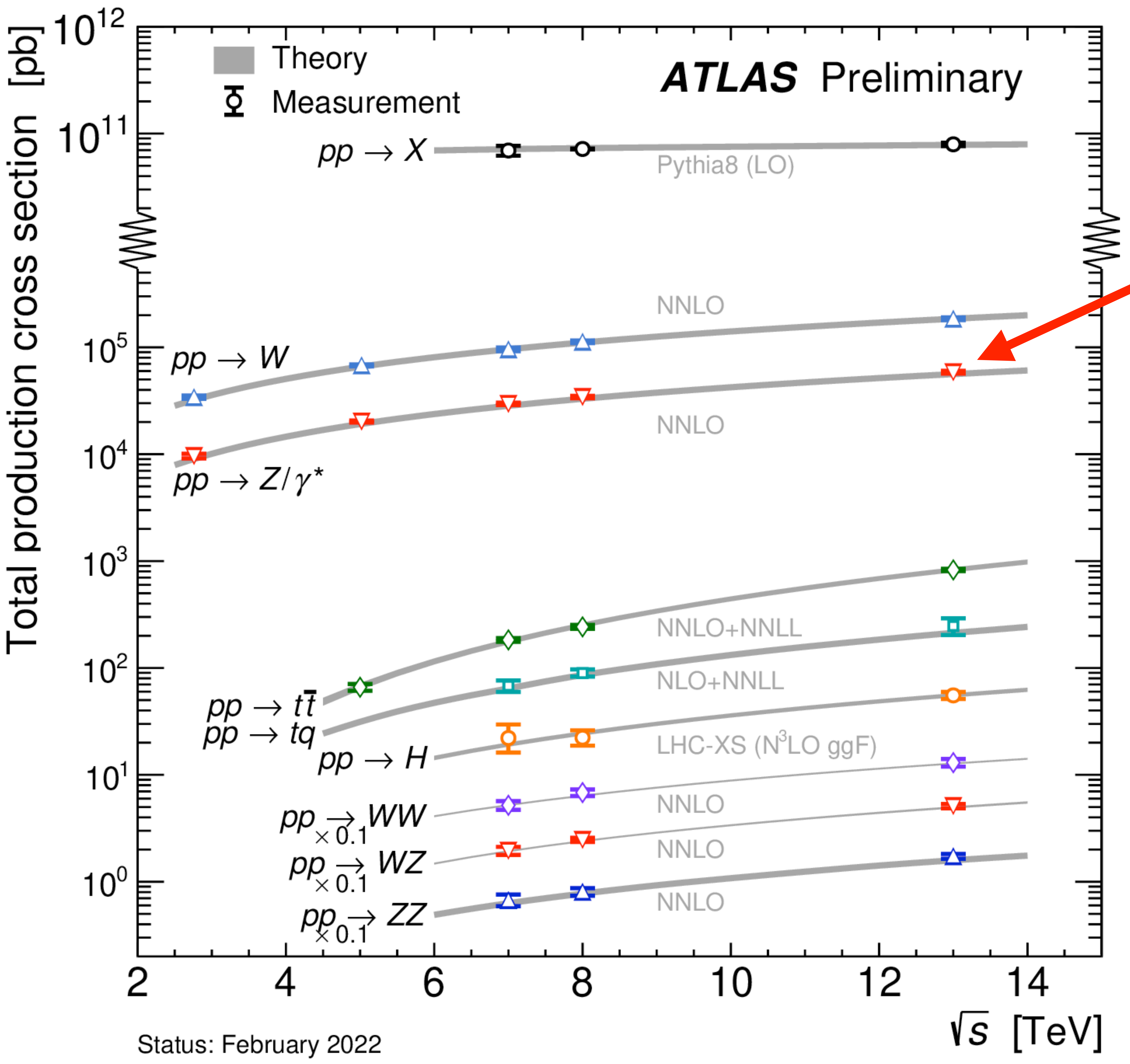
CMS trigger architecture

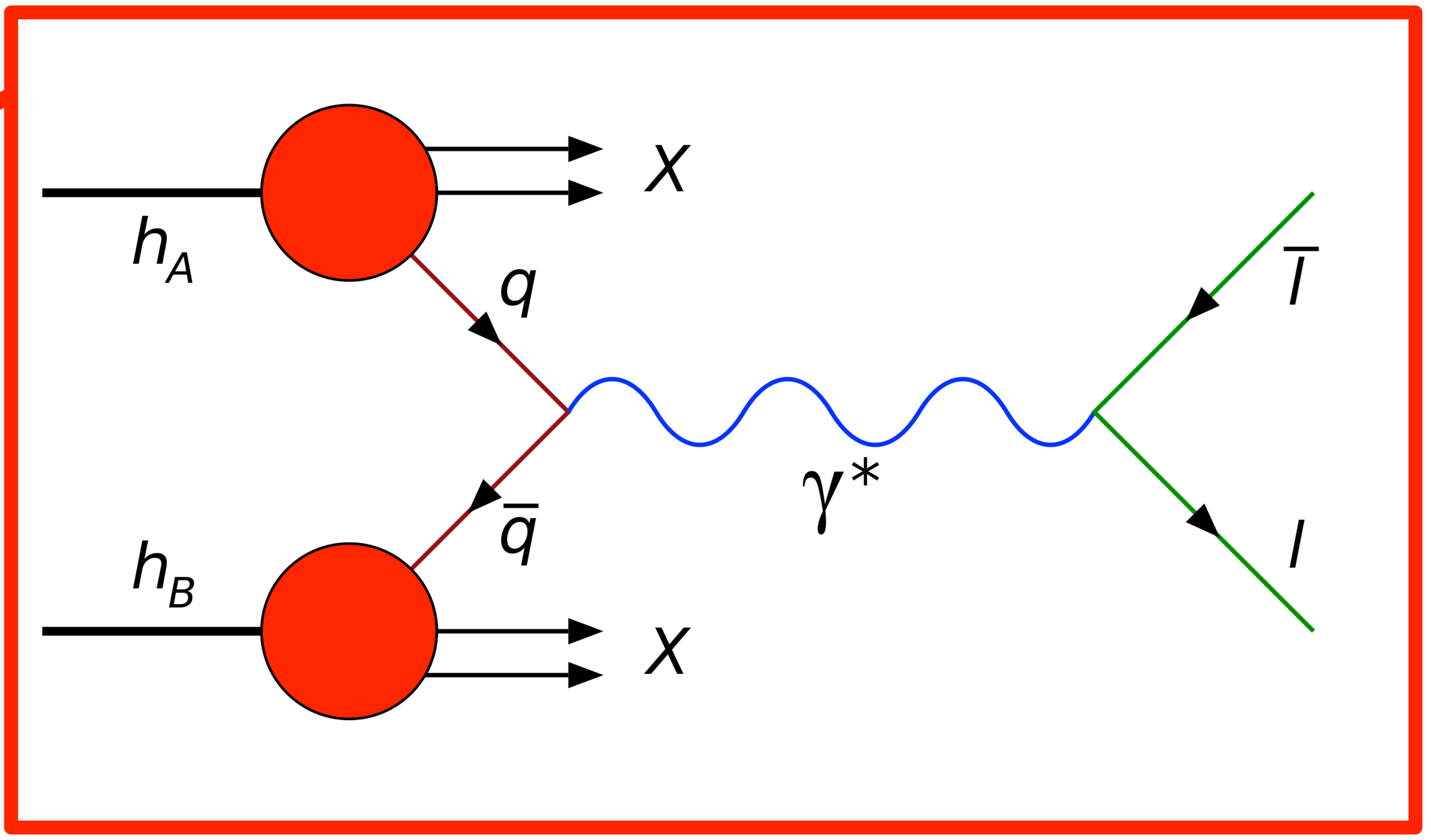
Measuring a cross section

$$\sigma_{tot} = \frac{N_{evts}}{\mathcal{A} \times \varepsilon \times \int \mathcal{L}dt}$$

- N_{evts}: Counting events with a specific selection
- A: Acceptance i.e. the ratio of selected simulated events over the number of all simulated events (estimated from theory/simulation)
- ε: experimental efficiency (i.e. event selection, object identification efficiency)
- $\int \mathcal{L}dt$: integrated luminosity of the dataset

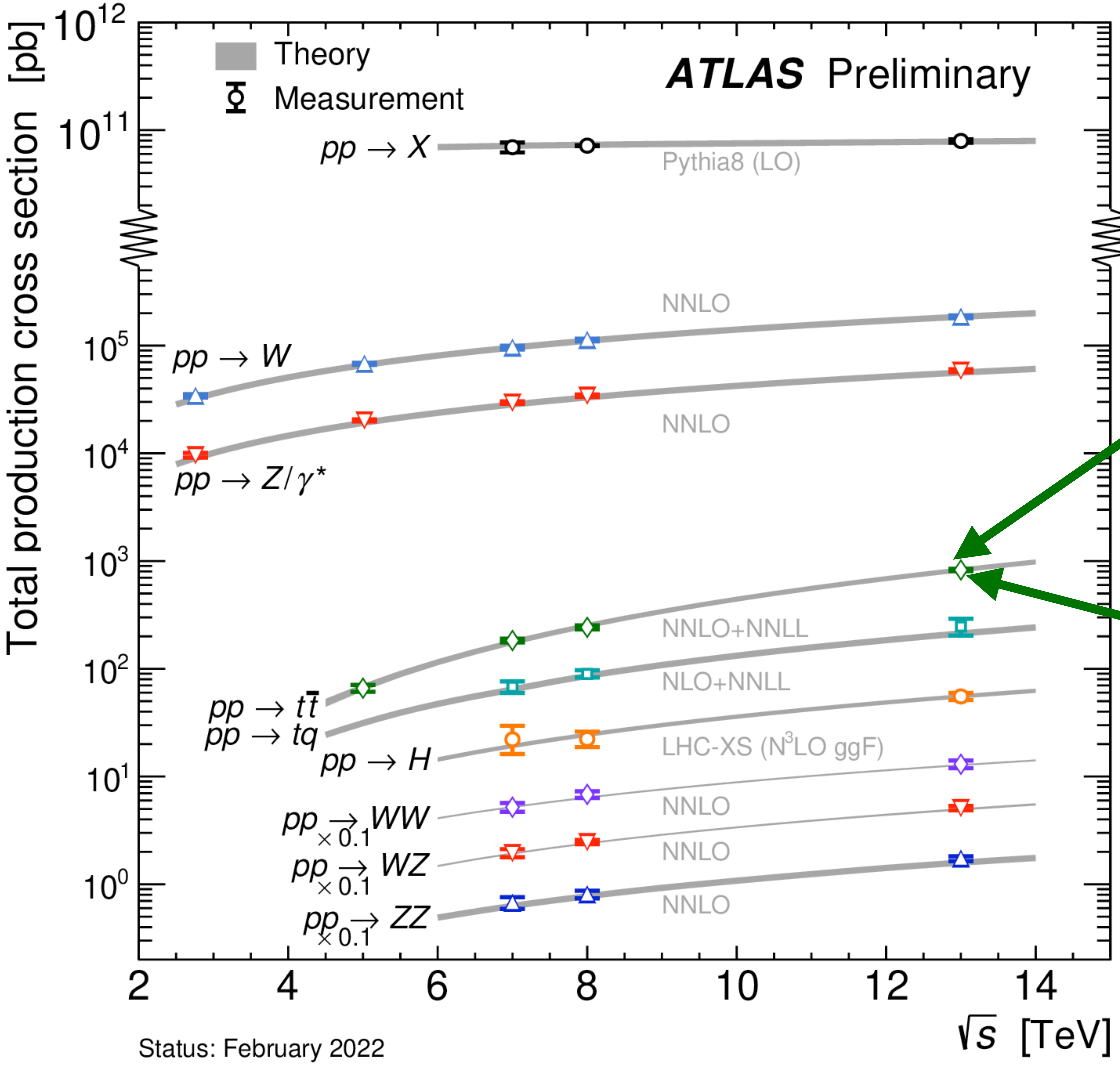
SM cross sections: LHC measurements

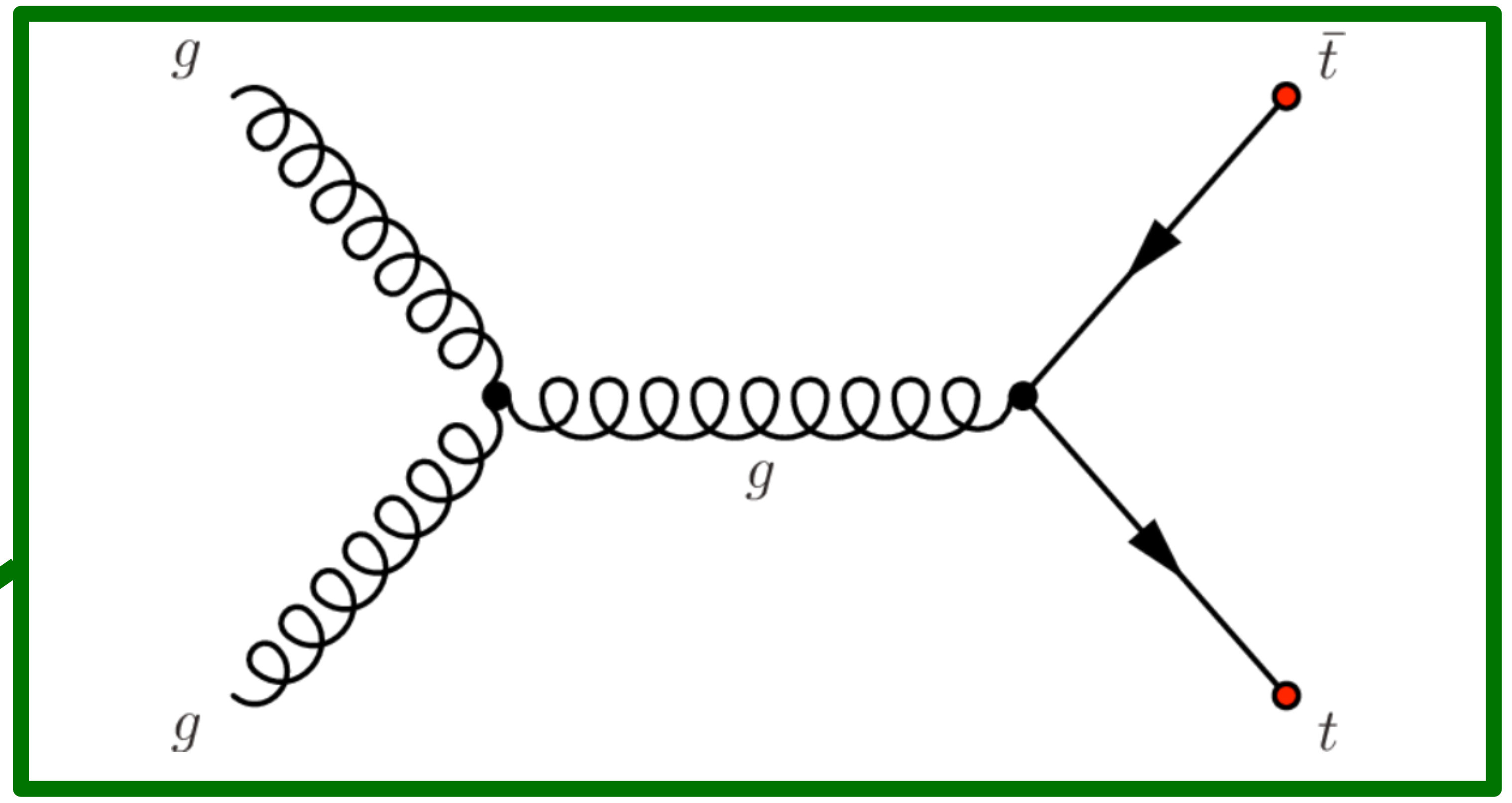




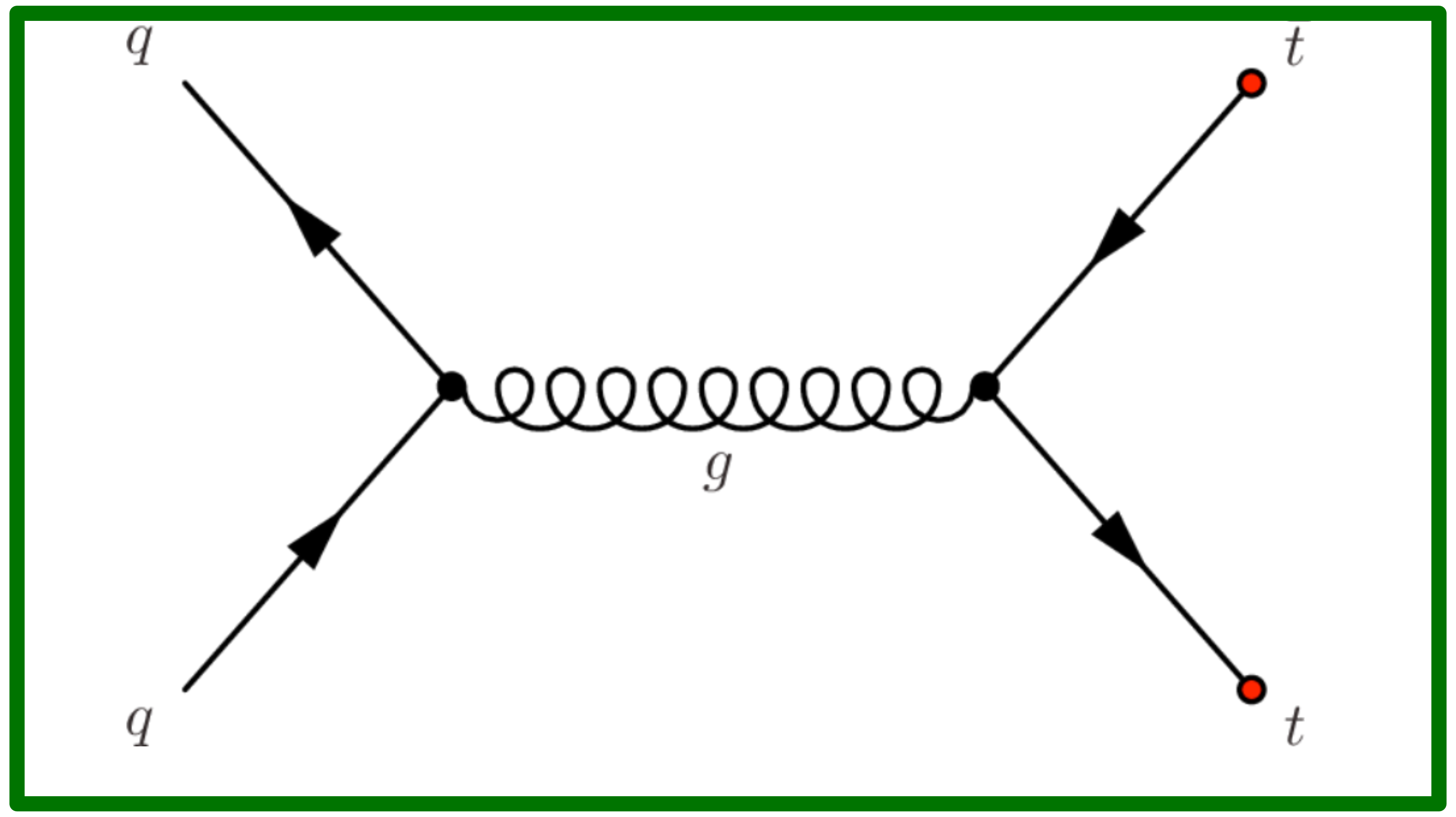
Z-boson/photon production
(Drell Yan)

SM cross sections: LHC measurements





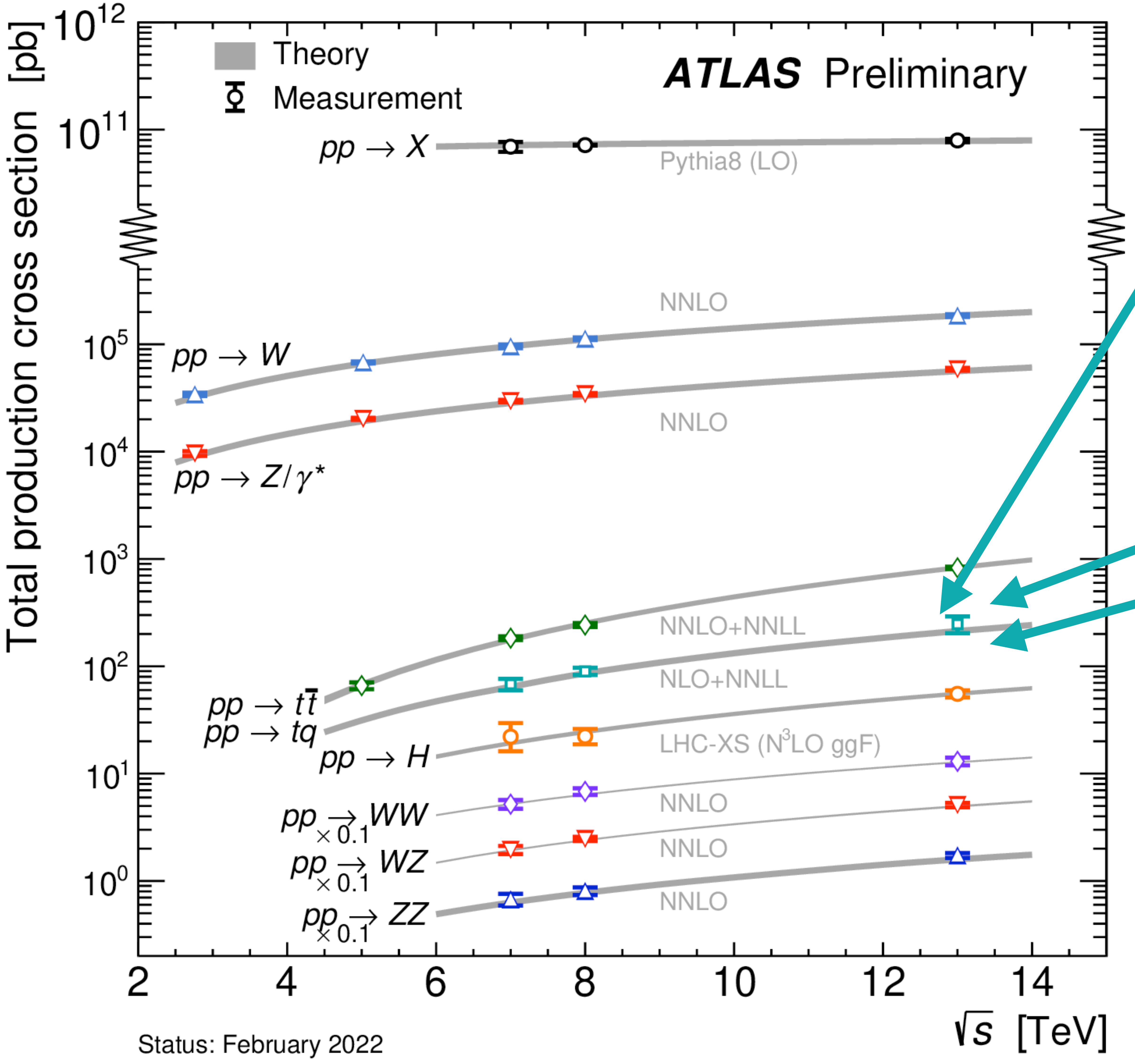
gluon fusion

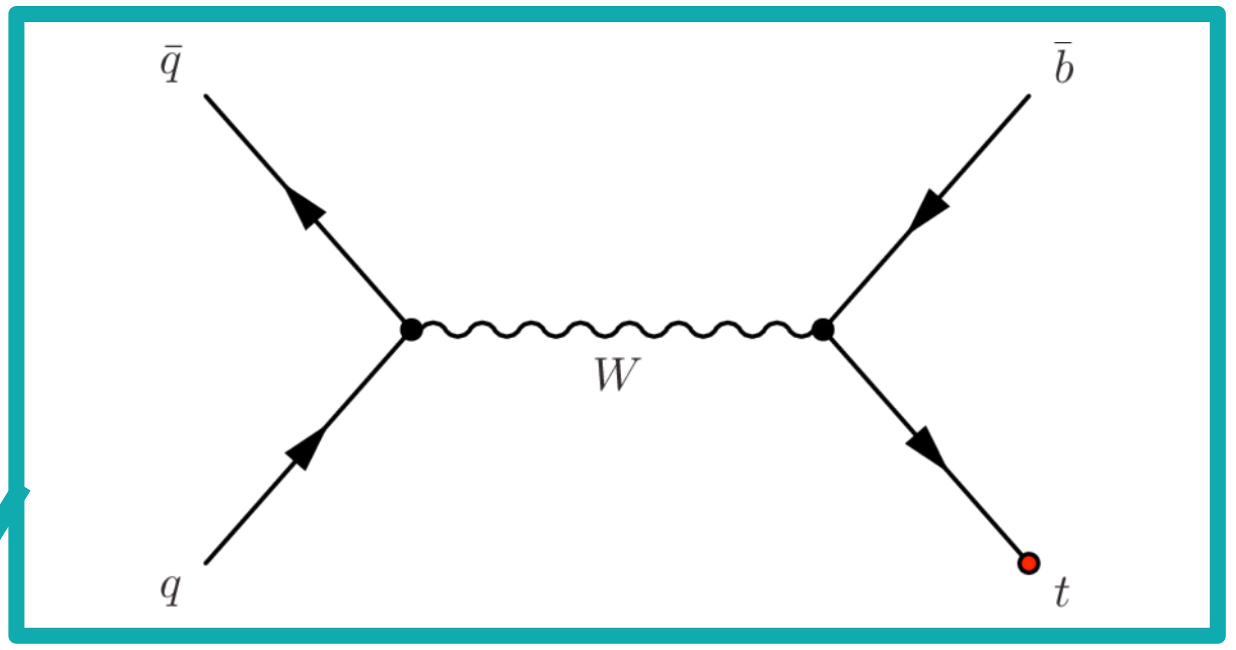


quark-antiquark annihilation

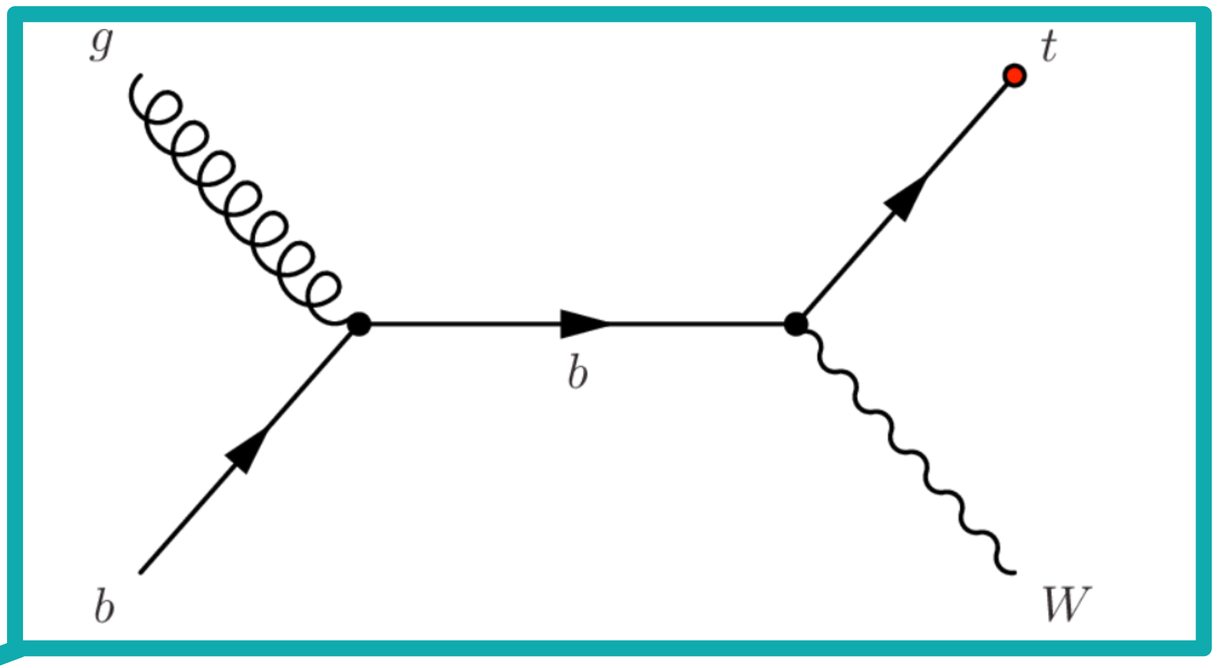
top quark pair production
~ 835 pb @ 13 TeV

SM cross sections: LHC measurements

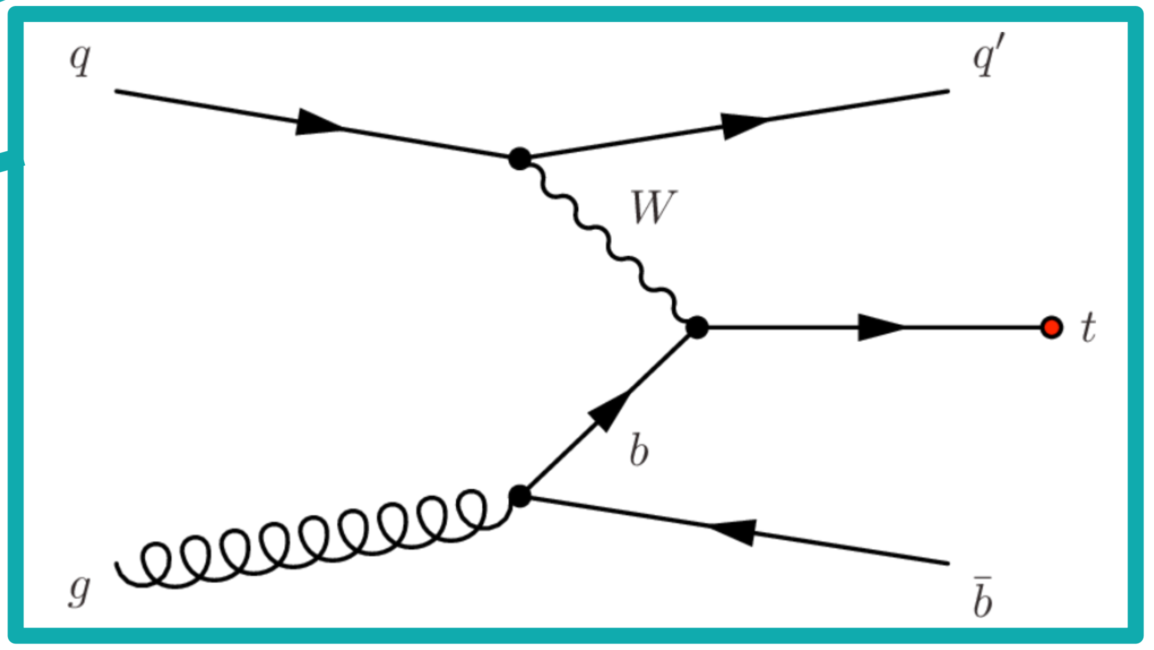




s-channel



t-channel



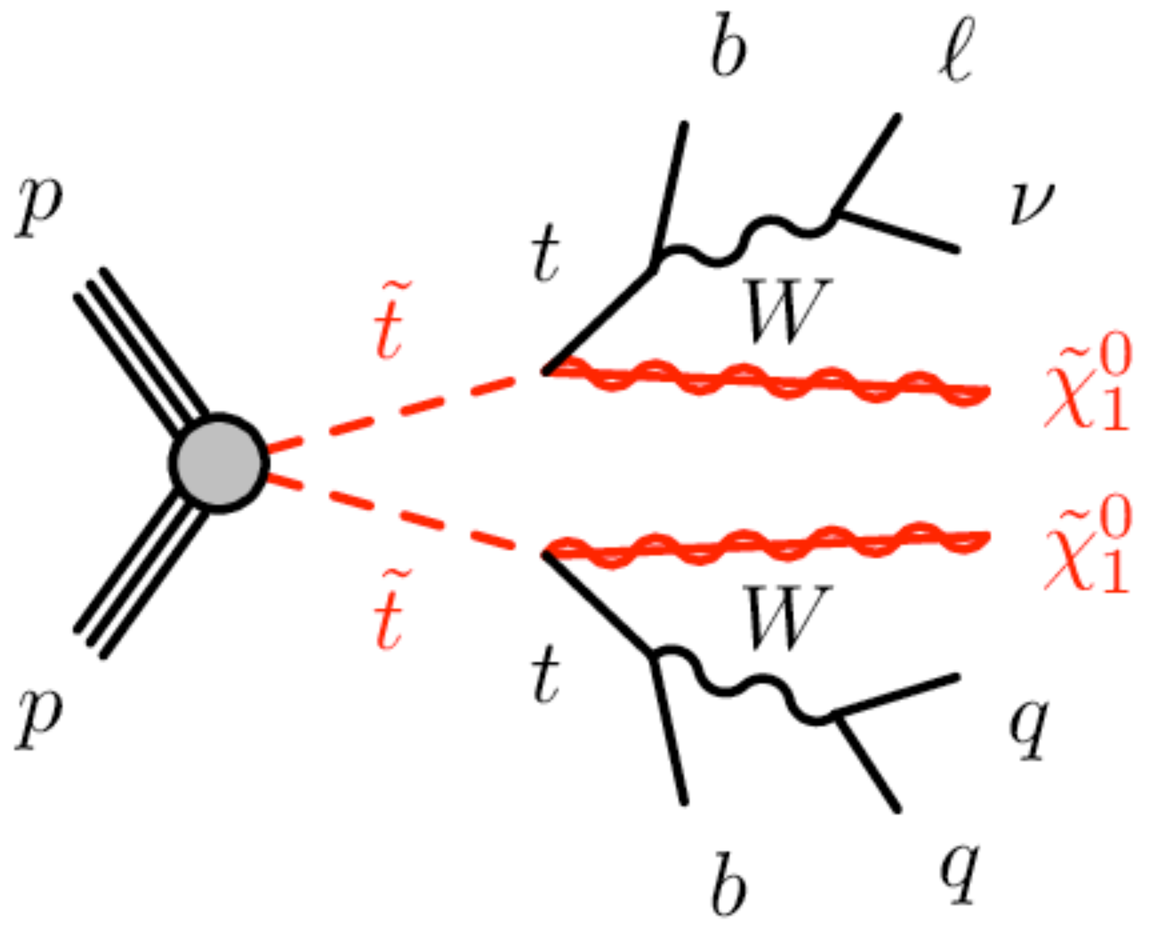
tW-channel

single top quark production
~ 200 pb @ 13 TeV

Signal and background

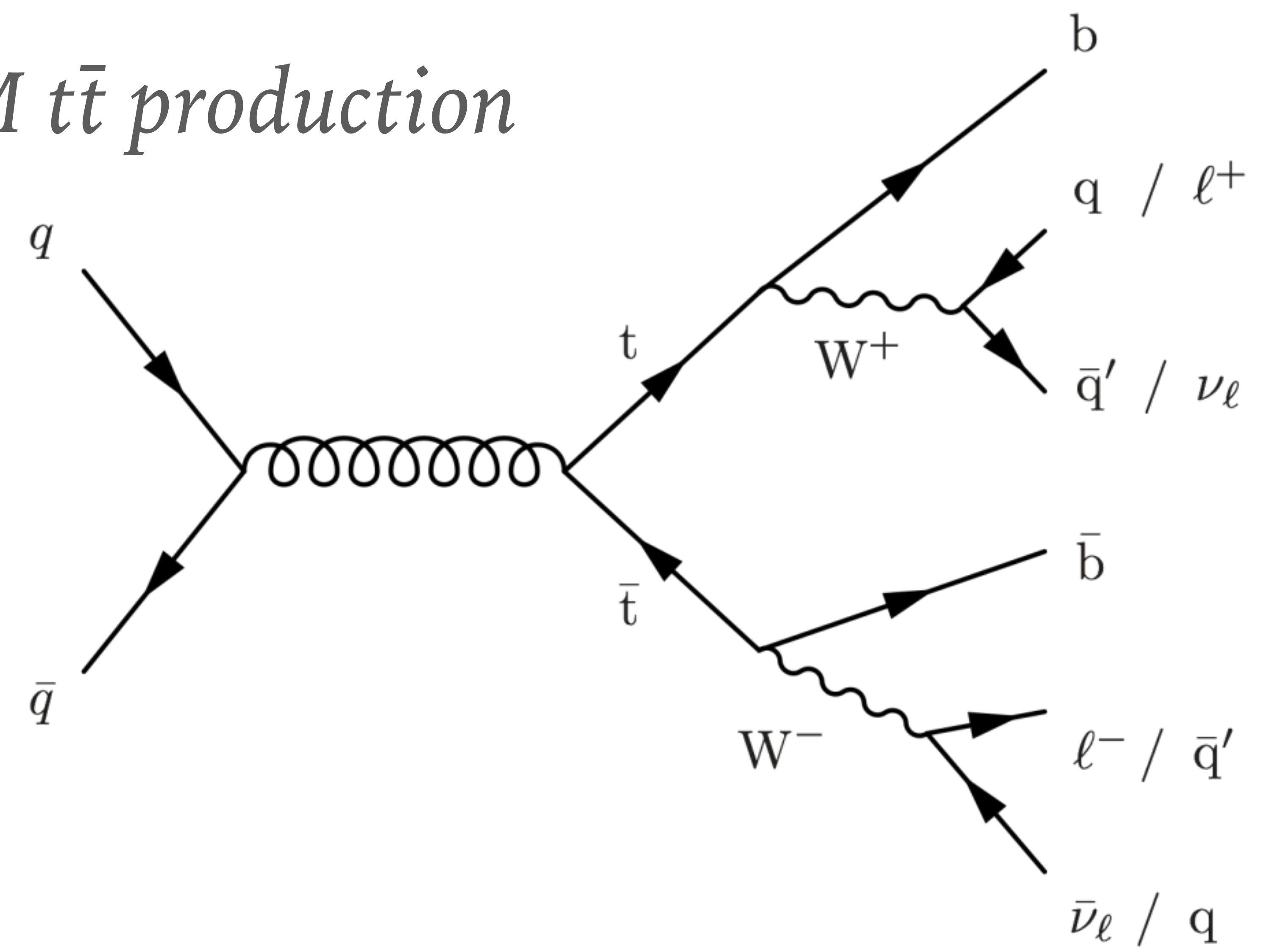
- In an ideal world we would just “count” the signal events and measure the cross section (or find a new process)
  ⇒ often other “SM” processes look very similar to the signal events

SUSY stop signal



- 1 lepton + 2 light jets + 2 b jets + MET

SM $t\bar{t}$ production



- 1 lepton + 2 light jets + 2 b jets + MET
- or 2 leptons + 2 b jets + MET
  - could “miss” the lepton: 1 leptons + 2b jets + MET
  - lepton could be a tau that is identified as a jet:
    1 leptons + 1 light jet + 2 jets + MET

Next Lecture

Measure **Standard Model** *parameters with high precision*	*Search for the* **Higgs boson** *and measure it's properties*	*Search for* **New Physics** *Beyond the Standard Model*	*Study* **Quark-Gluon Plasma**

Large Hadron Collider

- https://www.researchgate.net/figure/Overall-view-of-the-Large-Hadron-Collider-including-the-ATLAS-CMS-ALICE-and-LHCb_fig2_343206500
- https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg
- http://opendata.atlas.cern/release/2020/documentation/atlas/experiment.html
- https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.lhcb