technische universität dortmund

Department of Physics

Introduction to hadron collider physics

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BCD Summer School, Cargese, 30.03.2023

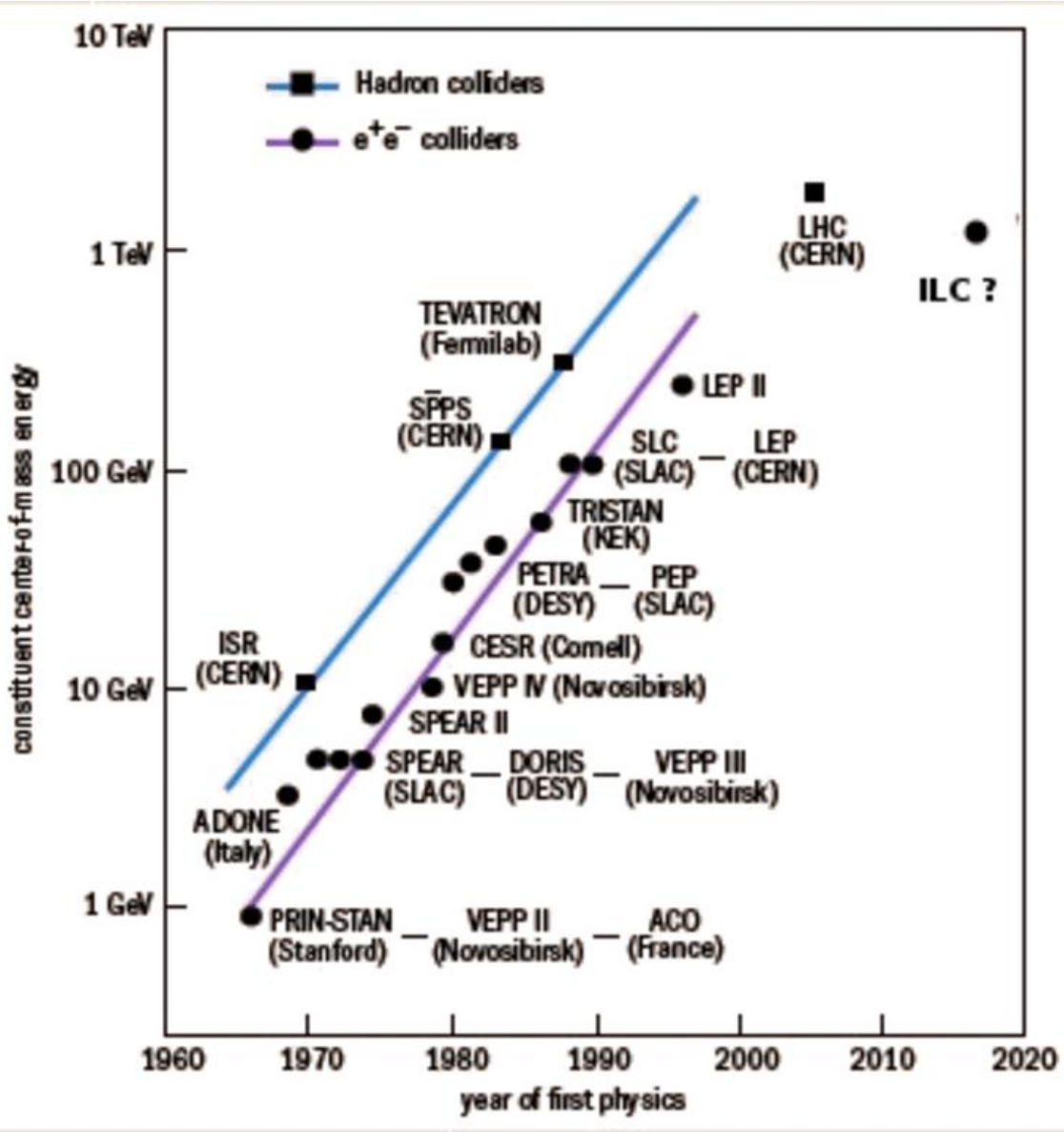
Motivation

Why hadron colliders?

- Large center-of-mass energy
- Discovery machines, in particular for heavy particles

Examples

- **SPPS** at 630 GeV: Discovery of the W- and Z-bosons
- **Tevatron** at 1 TeV and 1.96 TeV: Discovery of the top quark
- **LHC** at 7 TeV/8TeV/13 TeV/13.6 TeV: Discovery of the Higgs boson



Overview

Topics

- Proton-proton collisions
- The LHC in a nutshell
- Physics processes at hadron colliders
- Selected physics processes

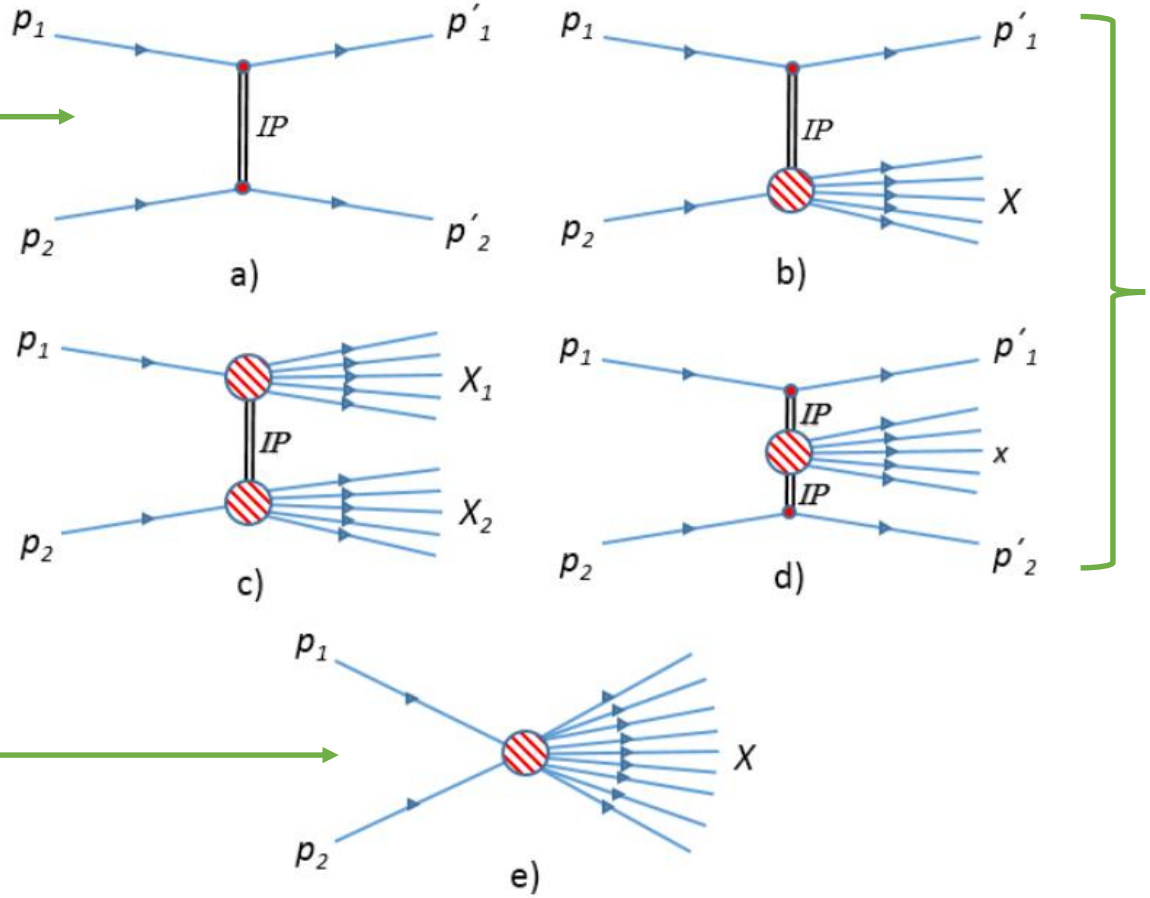
Skipping all the details: detectors, trigger, DAQ, physics objects, statistical methods, etc. → Lecture in Dortmund

Proton-proton collisions

What are we doing, actually?

Proton-proton collisions

elastic scattering



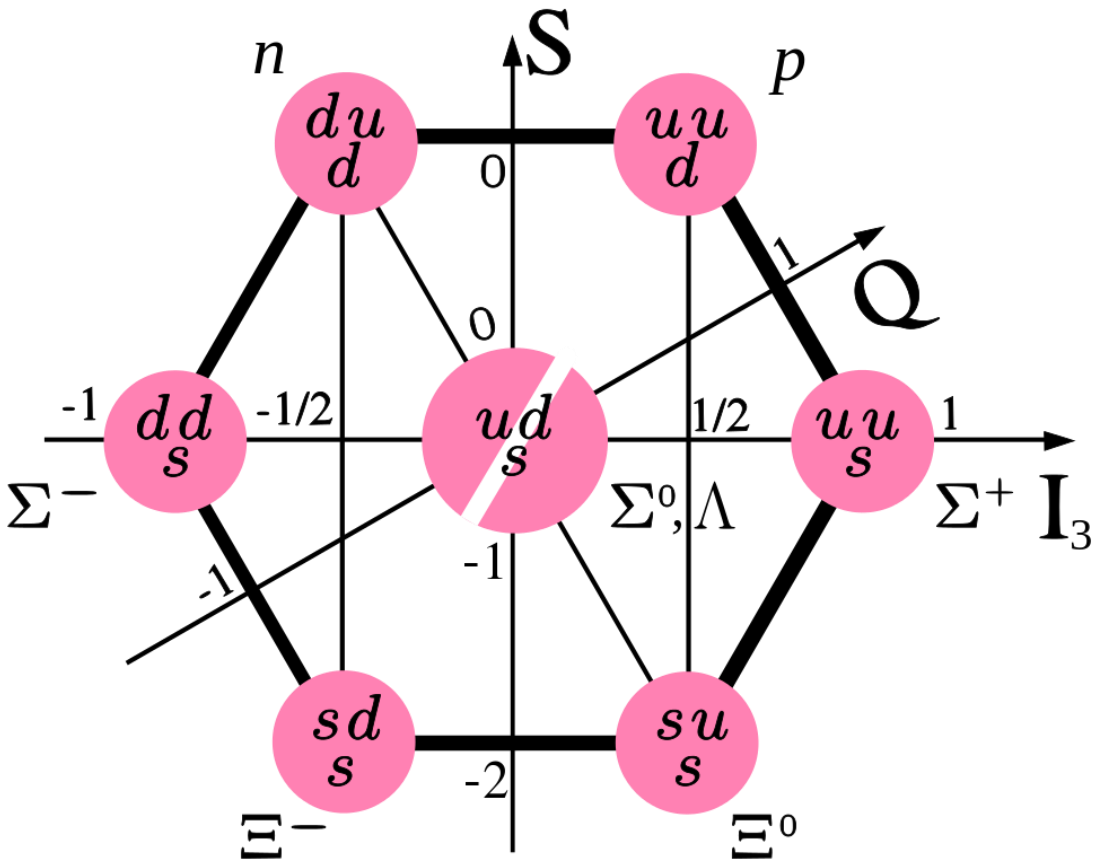
diffractive scattering

inelastic scattering

Proton-proton collisions

Proton structure

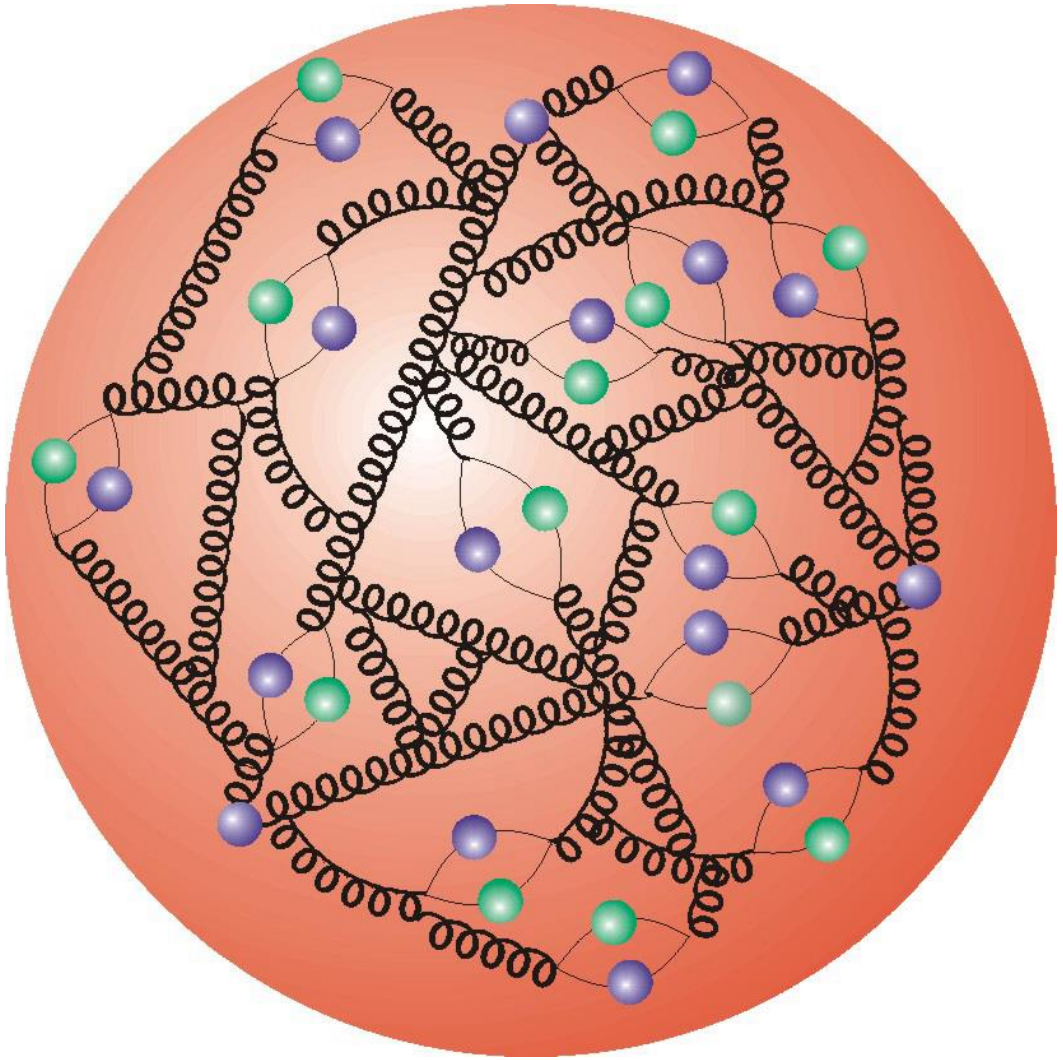
- Eightfold way (Gell-Mann et al., 1960er): all hadrons are made up of quarks
- Non-observation of free quarks did not help to make this theory popular
- Naïve parton model describes scattering, in particular deep inelastic scattering.



Proton-proton collisions

Proton structure

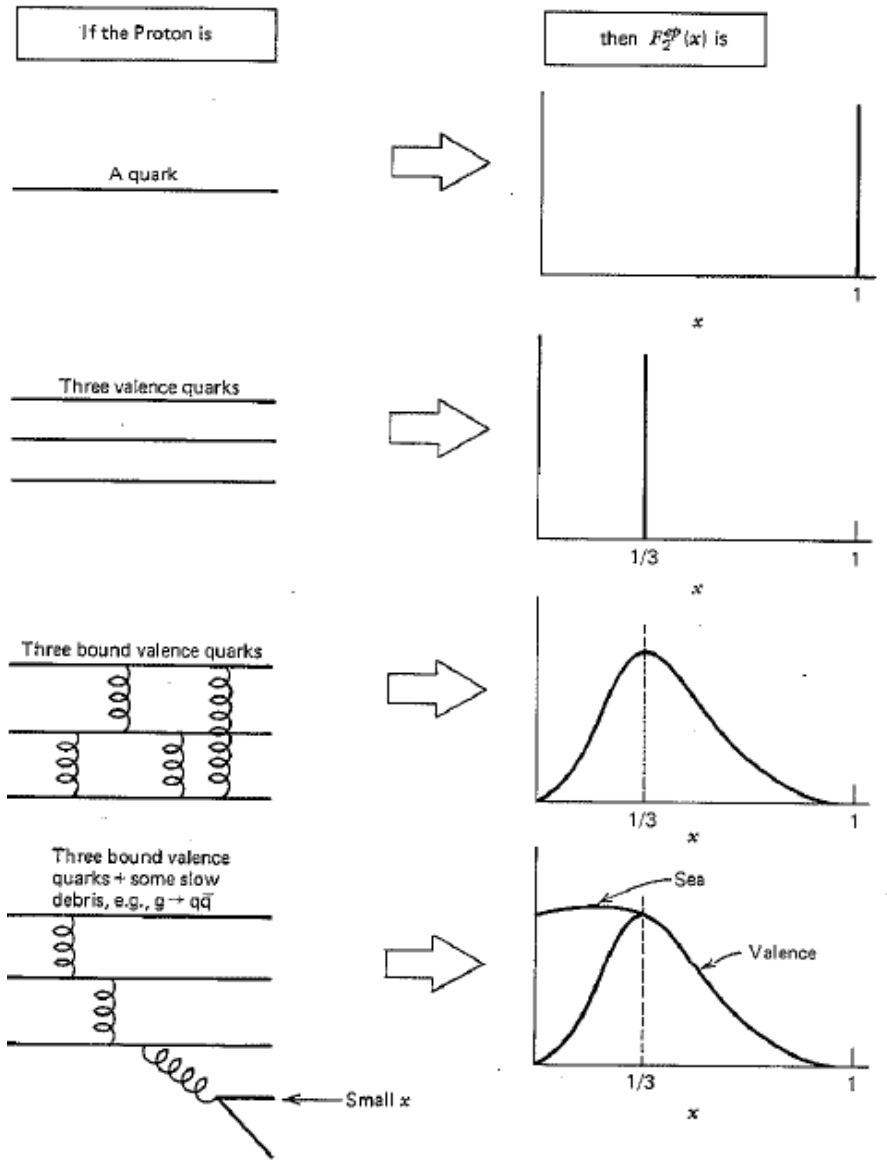
- QCD improved model
  - Quarks are not free because of confinement
  - Quarks interact via gluons
  - Probability to create quark-antiquark pairs within the proton
  - Proton consists of valence quarks, sea quarks and gluons



Proton-proton collisions

Parton distribution functions

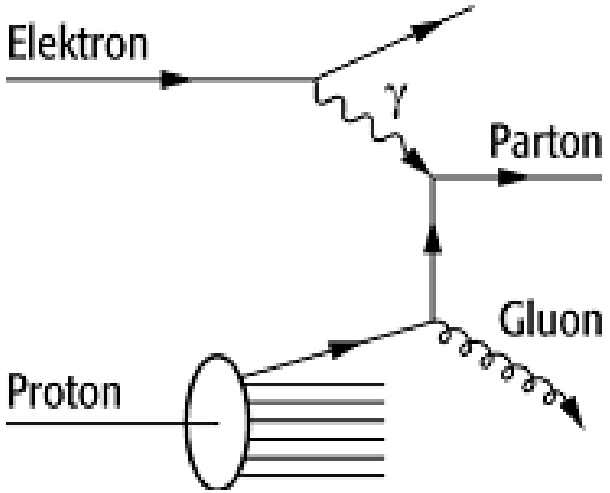
- Distribution of parton momenta inside the proton is universal
- Described by parton distribution functions
- Key variable x, i.e. fraction of proton's momentum carried by a single parton

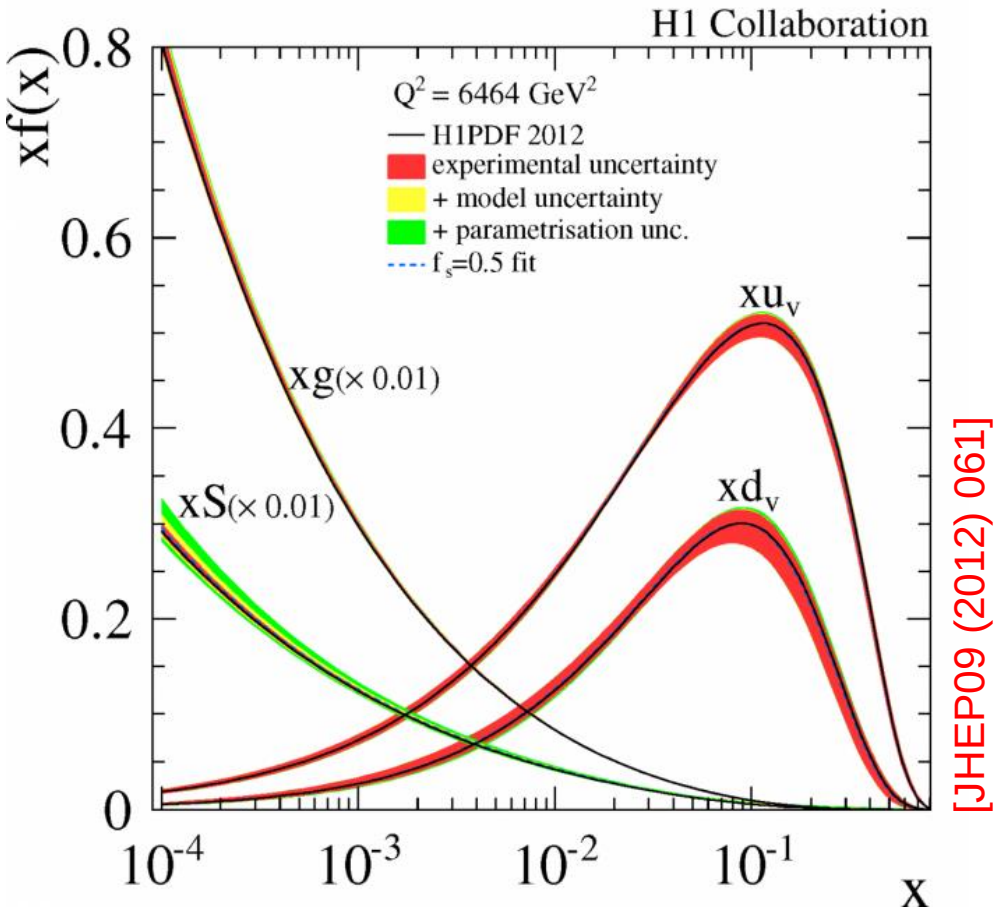


Proton-proton collisions

Parton distribution functions

- Measure e.g. by scattering electrons on protons
- Famous: HERA at DESY, Hamburg



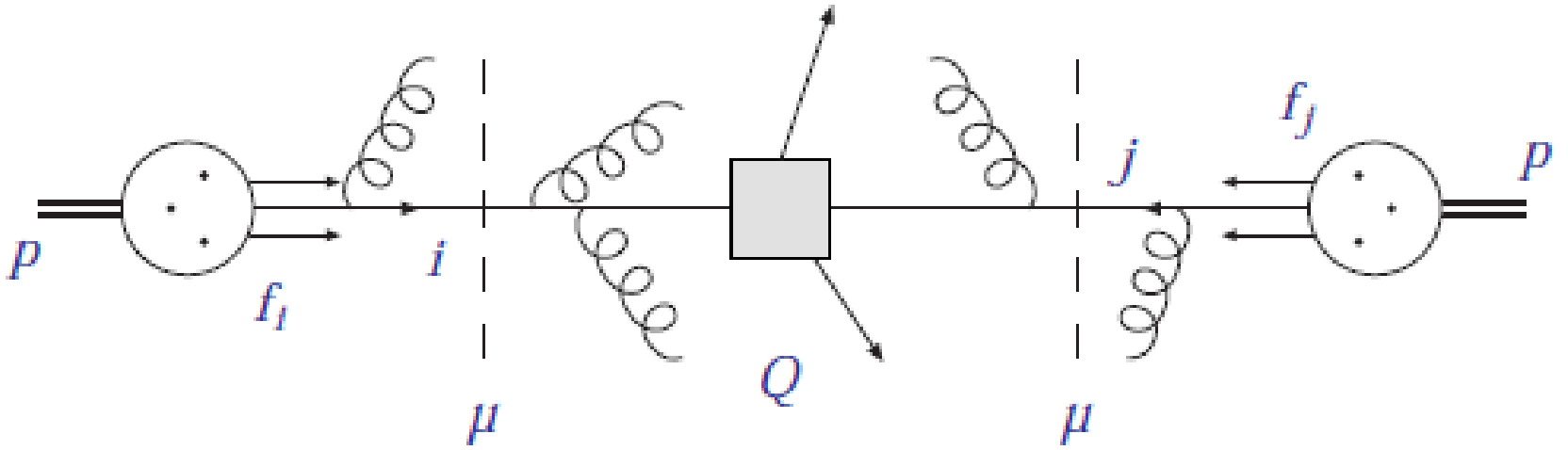


[JHEP09 (2012) 061]

Proton-proton scattering

Factorization theorem

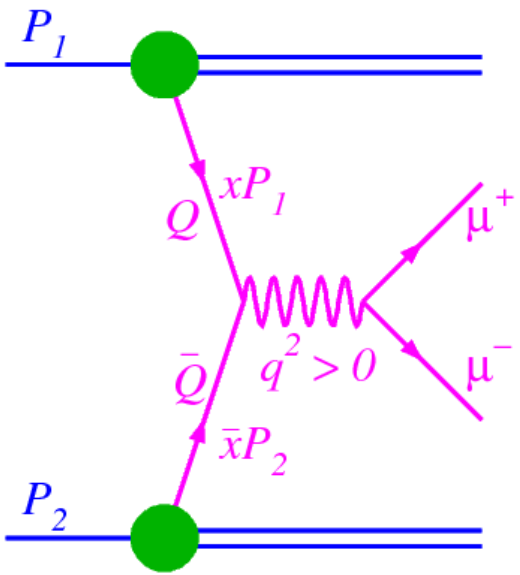
- Proton-proton cross section factorizes into two parts:
  - Extract partons from protons
  - Hard scattering process (of partons)

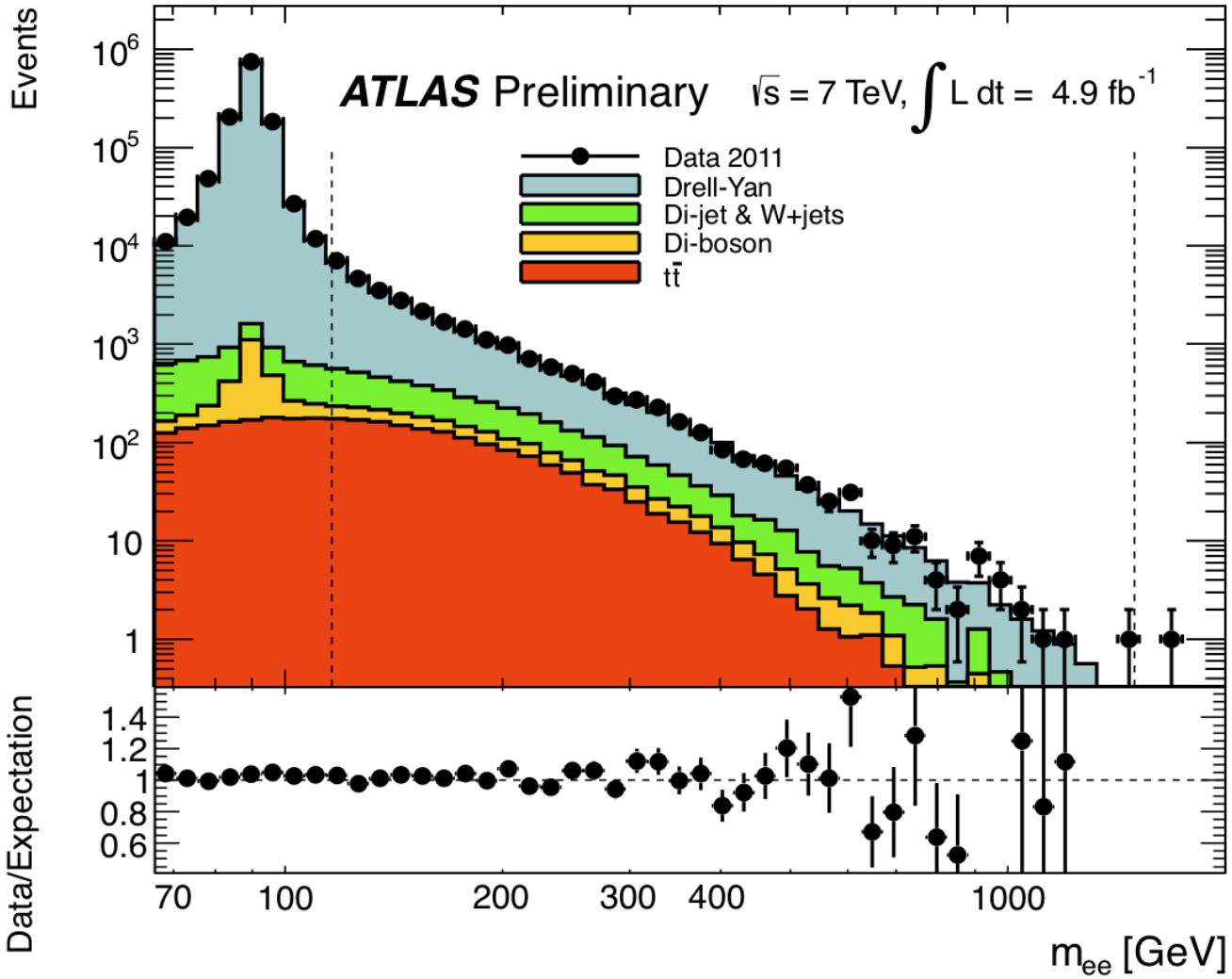


$$\sigma_{pp\to X} = \sum_{ij} \iint dx_i\, dx_j f_i(x_i, \mu_F) f_j(x_j, \mu_F) \cdot \hat{\sigma}_{ij\to X}(\alpha_S(\mu_R), Q^2, \mu_F, \mu_R)$$

Proton-proton collisions

- Examples for pp-collisions: Drell-Yan production (1970)

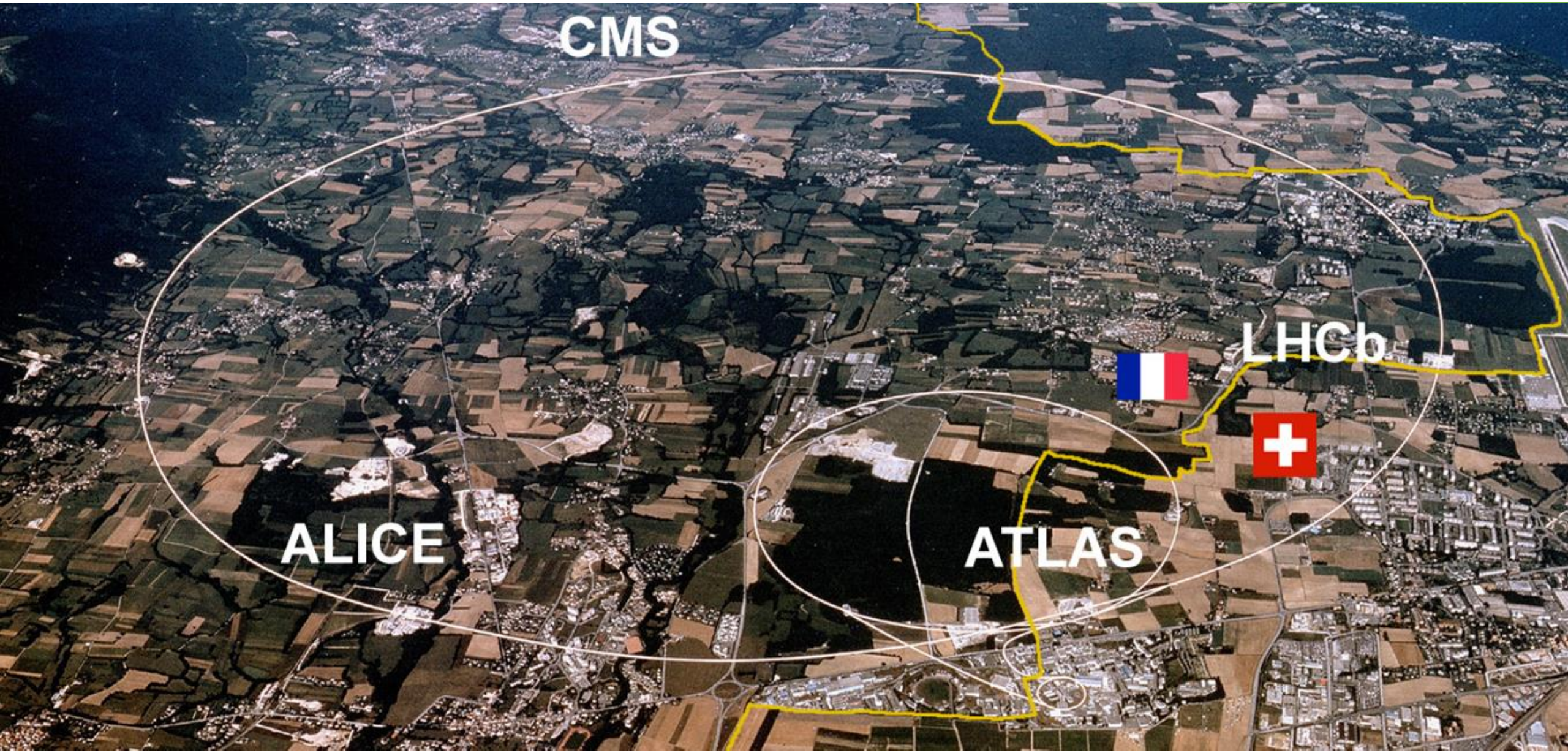




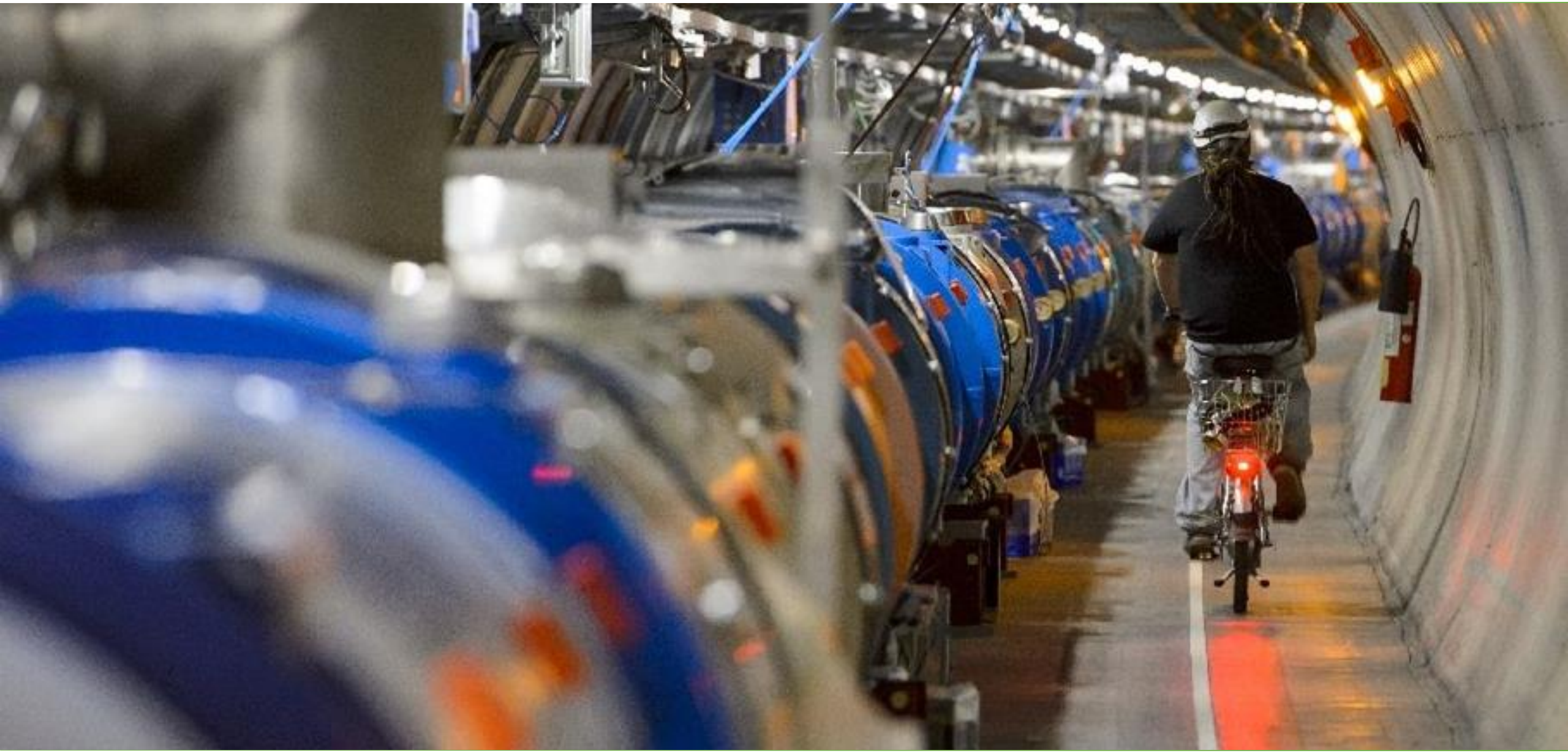
The LHC in a nutshell

Our flagship!

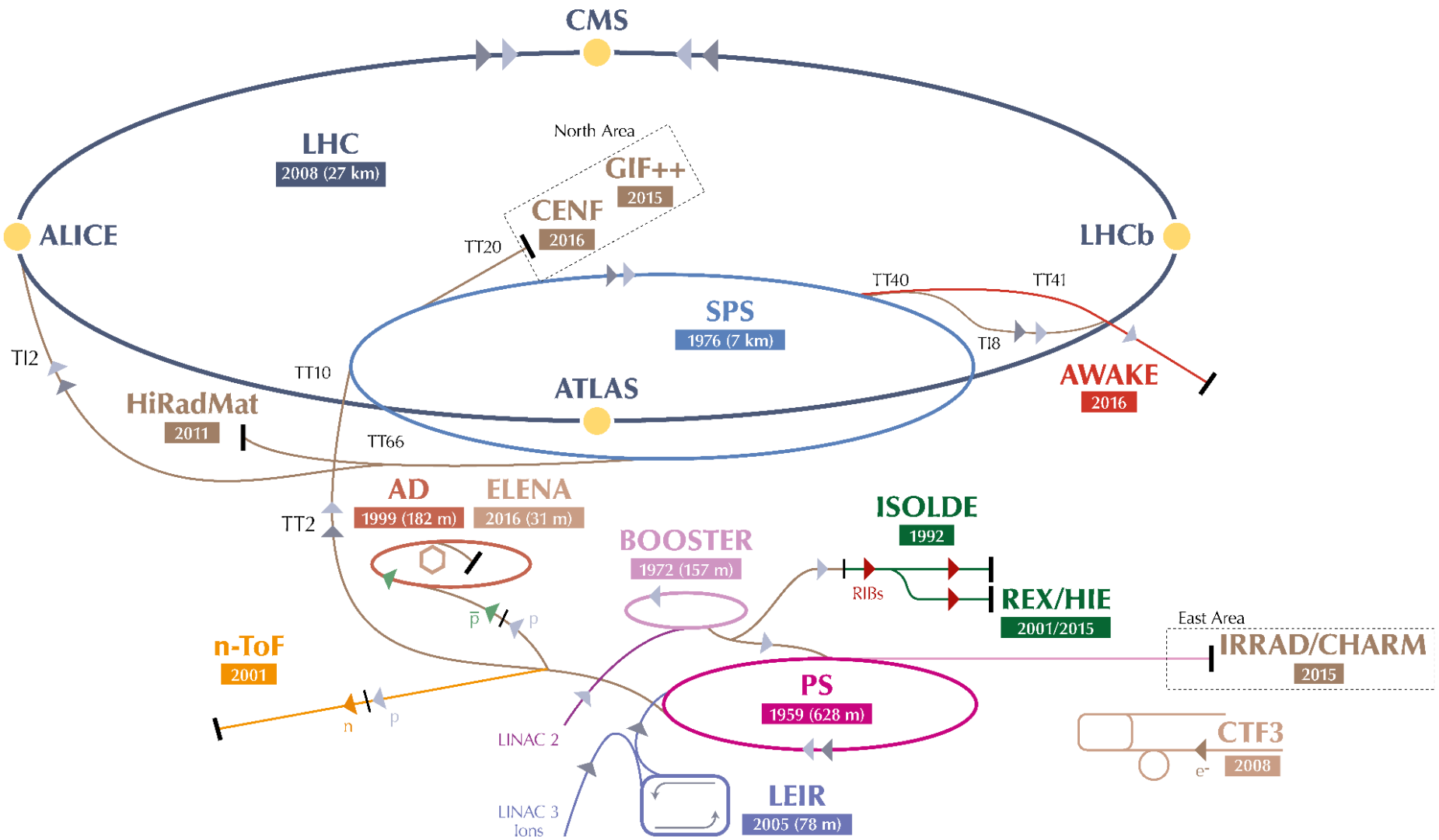
The LHC in a nutshell



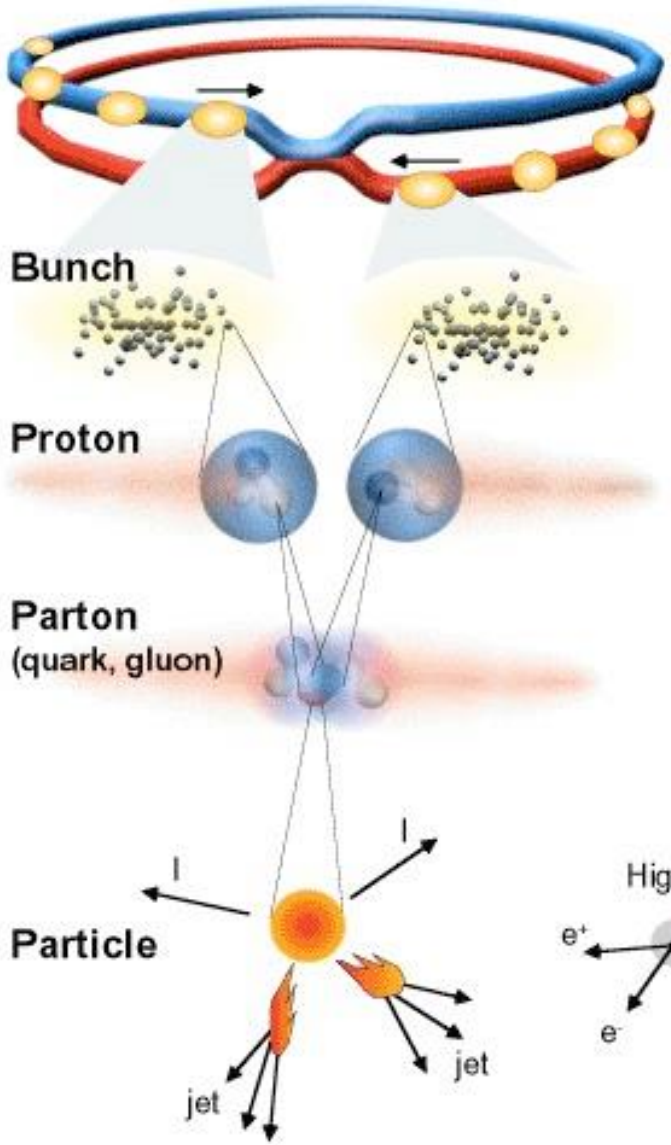
The LHC in a nutshell



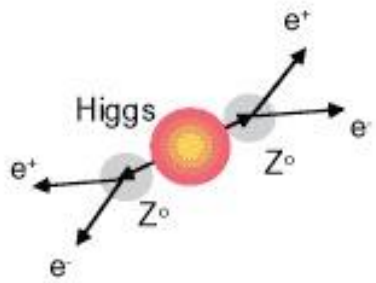
The LHC in a nutshell



The LHC in a nutshell



Proton-Proton	(2835 x 2835 bunches)
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz



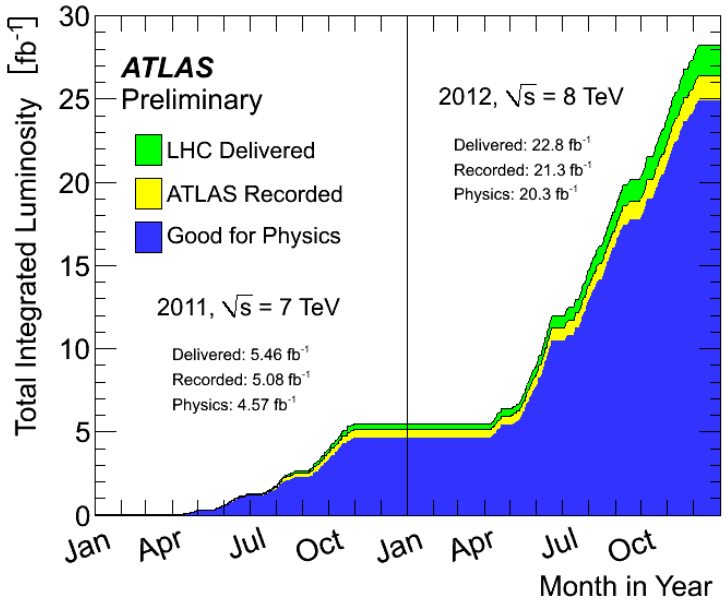
Higgs

SUSY.....

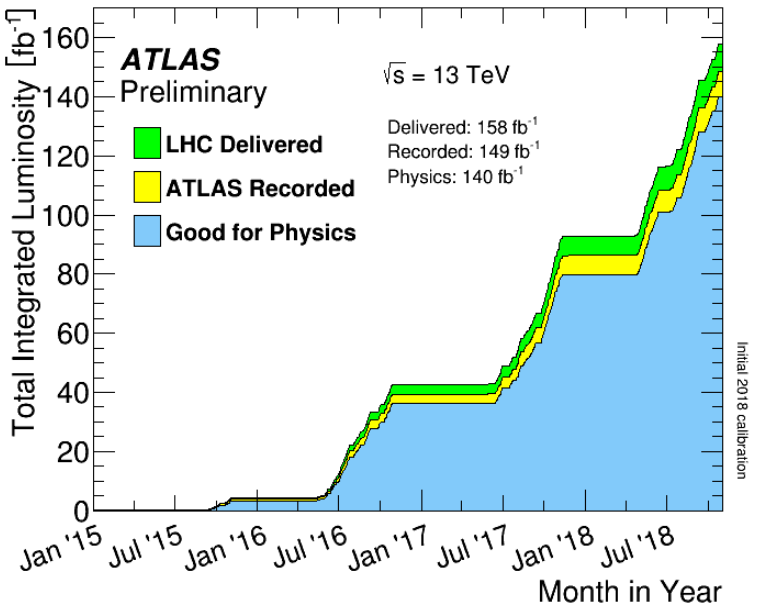
The LHC in a nutshell

Integrated luminosities

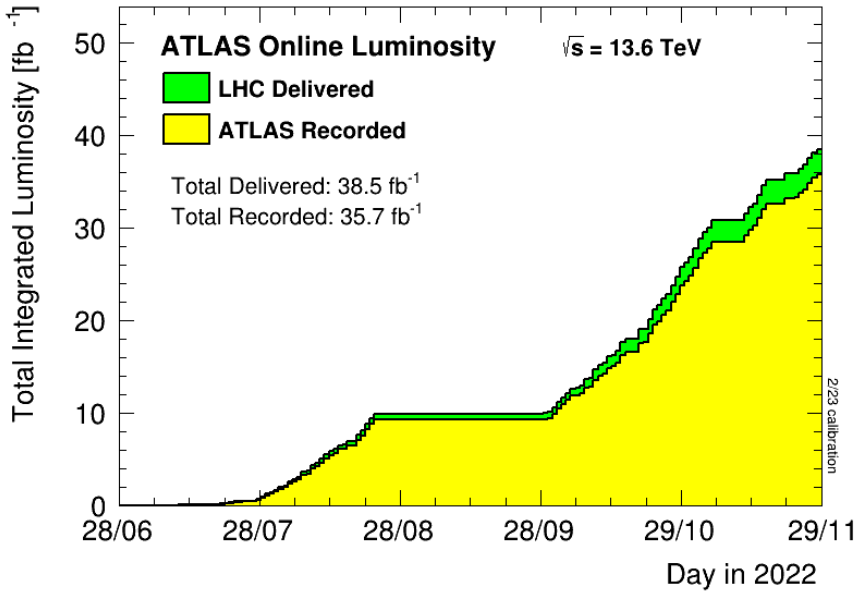
Run I (2011-12)



Run II (2015-18)



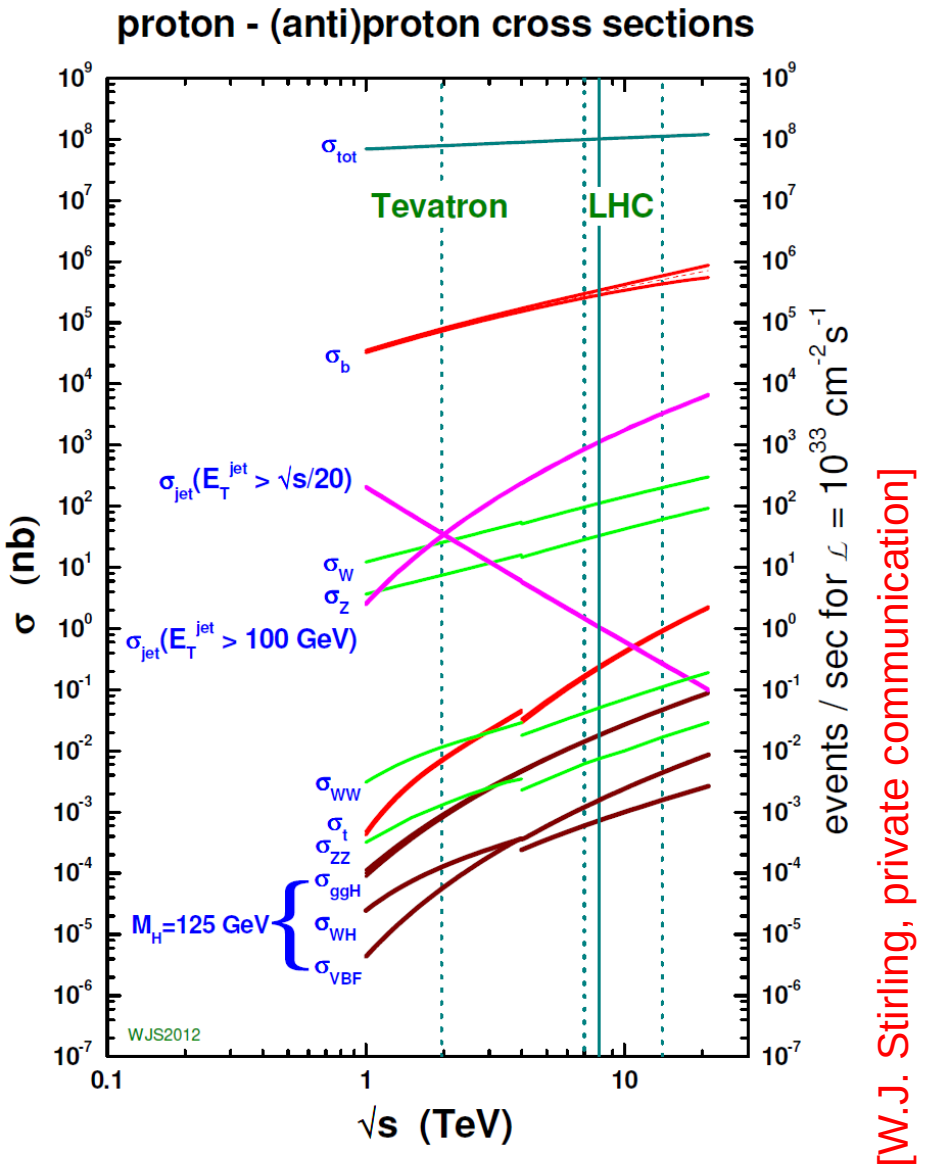
Run III (since 2022)



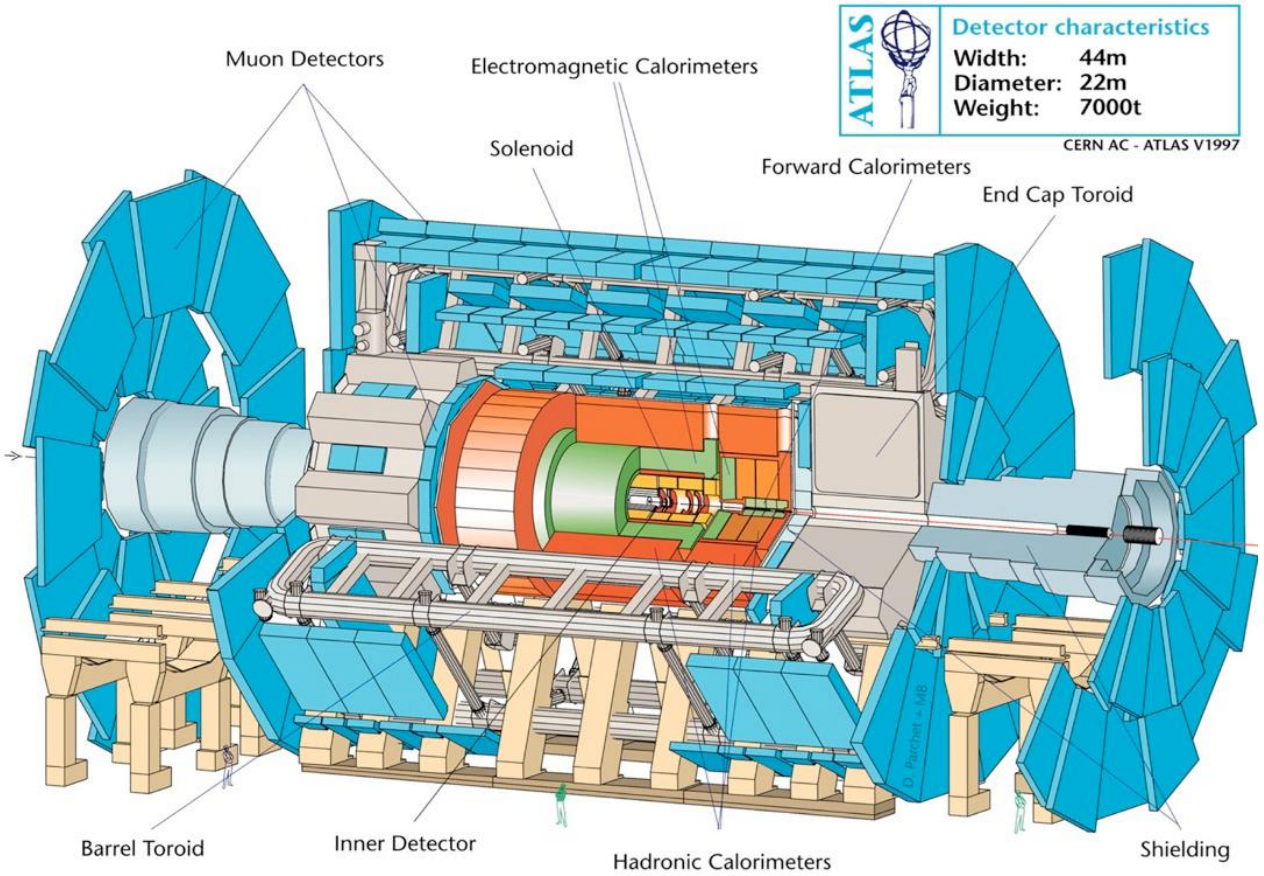
The LHC in a nutshell

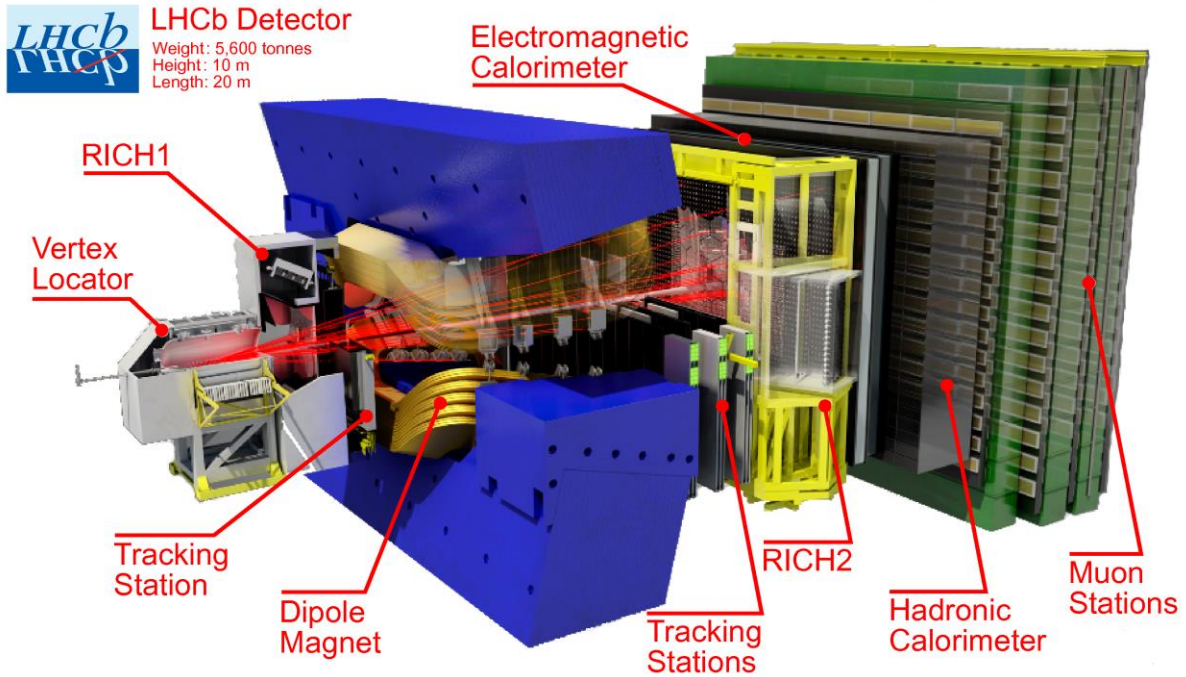
Physics processes at 7 TeV

- Processes at hadron colliders (at 7 TeV)
- Total cross section ~110 mb
  - Inelastic ~60 mb
  - Diffractive ~12 mb
  - Elastic ~40 mb
- Inclusive b production ~0,3 mb
- Jet production ~O(μb)
- Inclusive W production ~90 nb
- Top production ~165 pb
- Higgs production <10 pb
- New physics ???

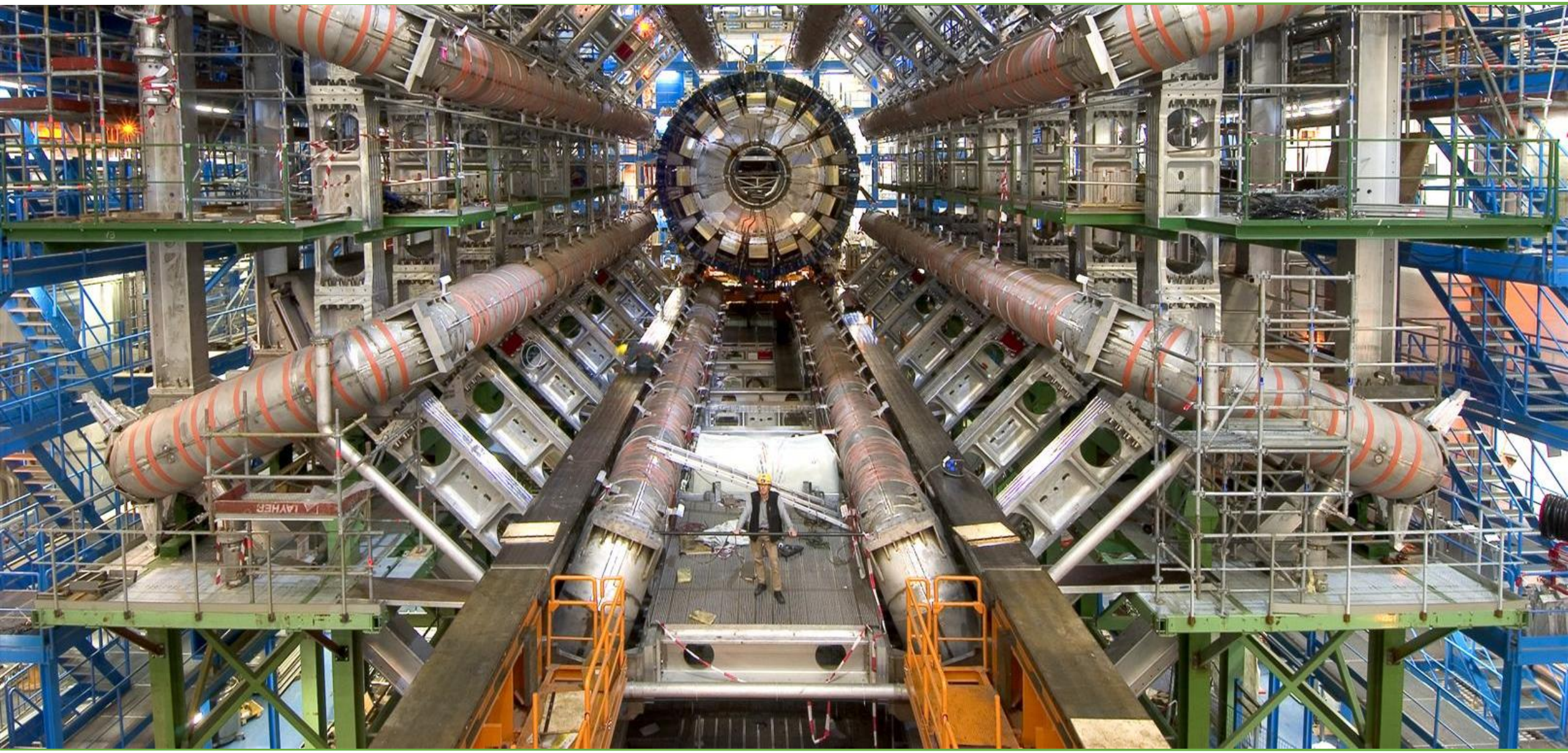


The LHC in a nutshell





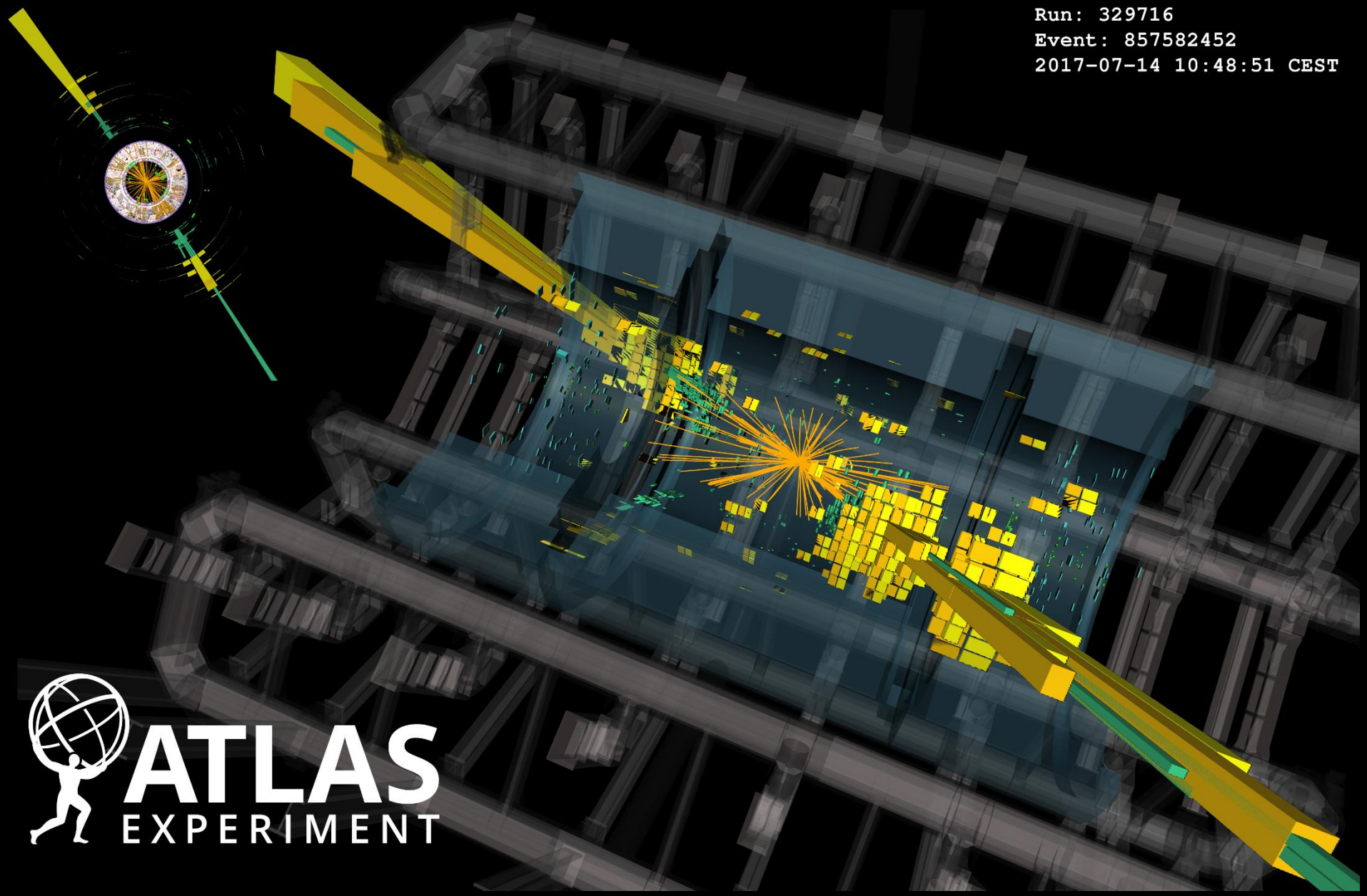
The LHC in a nutshell

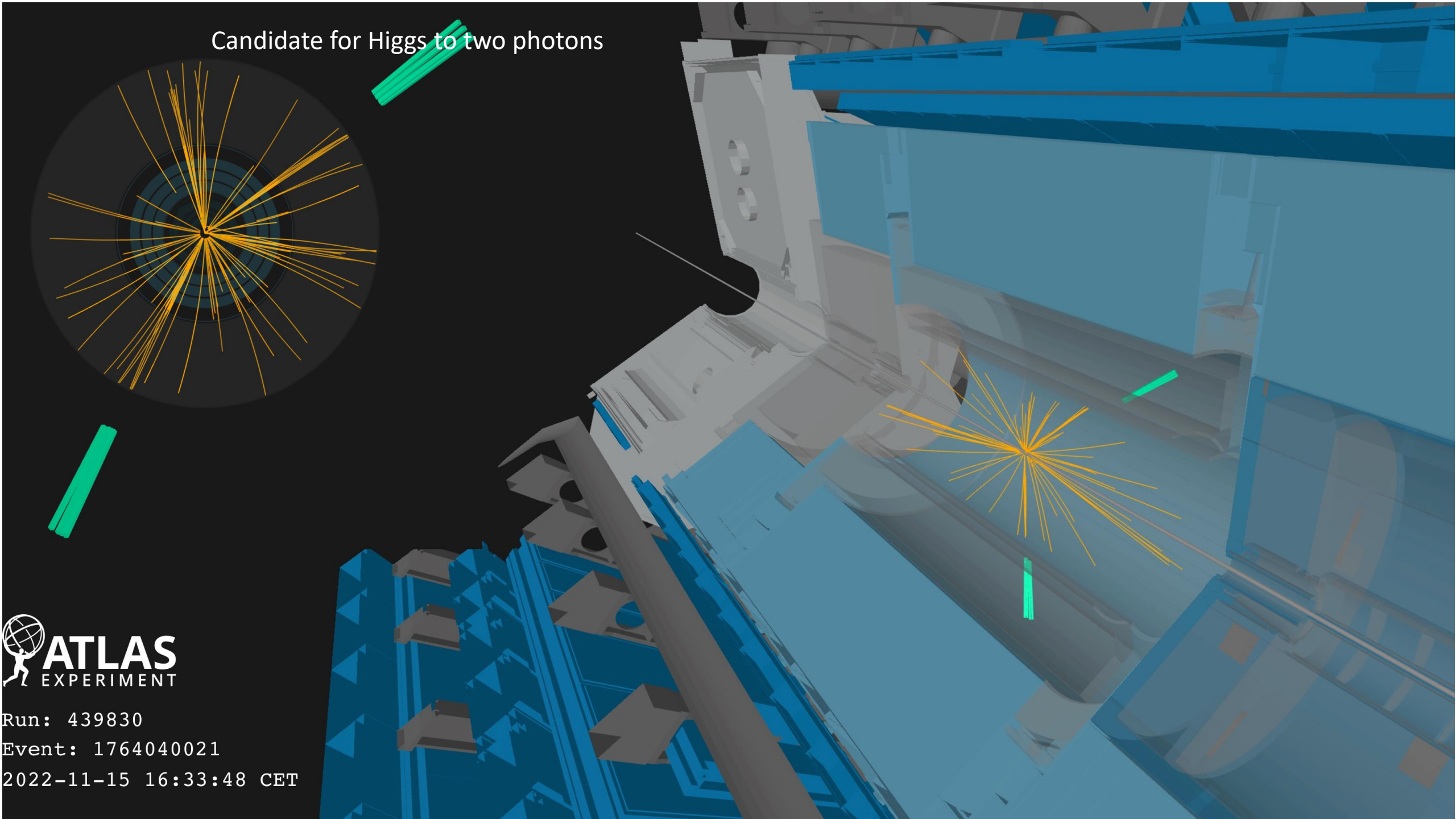


Physics processes at hadron colliders

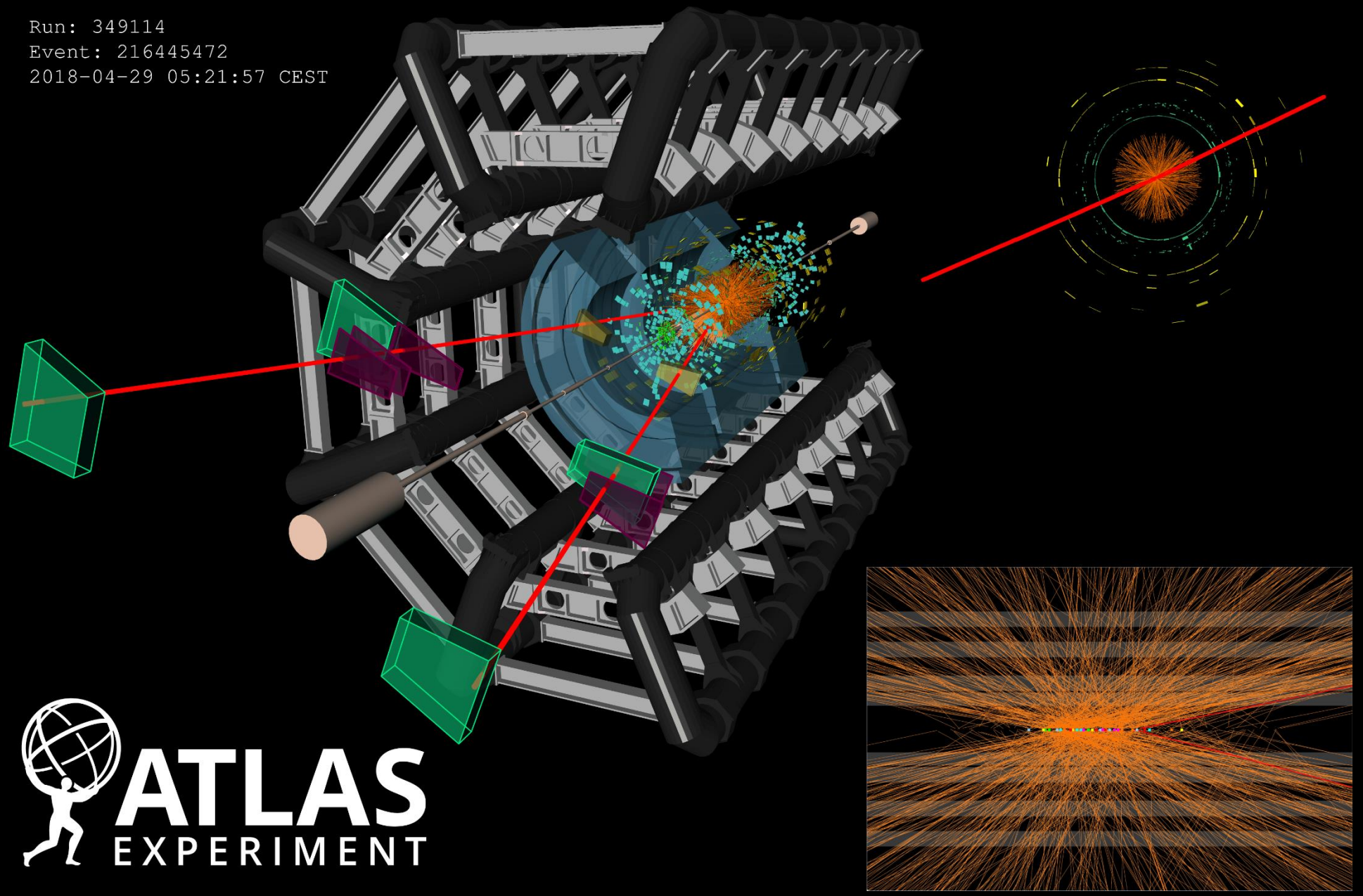
Finally!

Di-jet event with m_{jj}=9.3 TeV

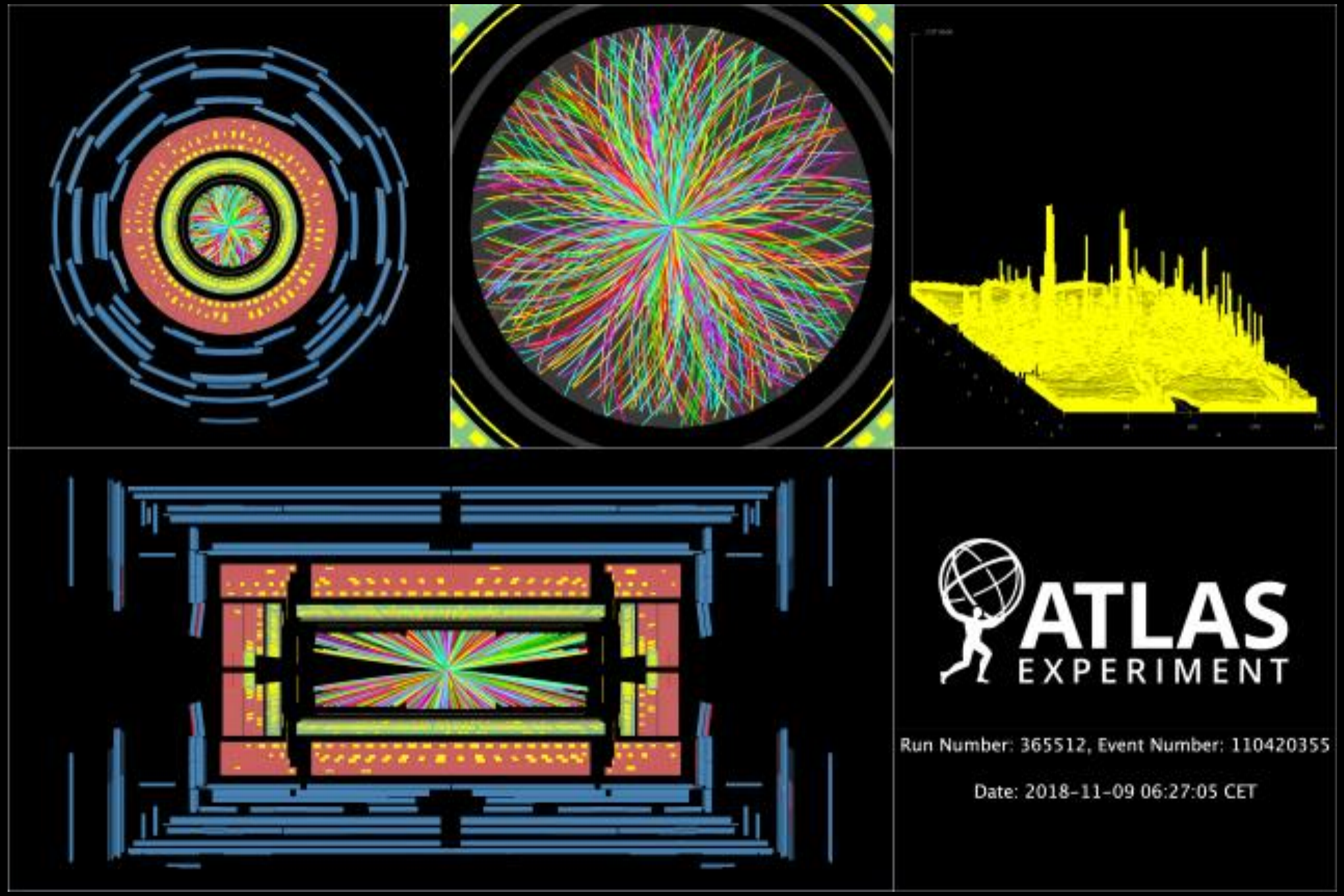


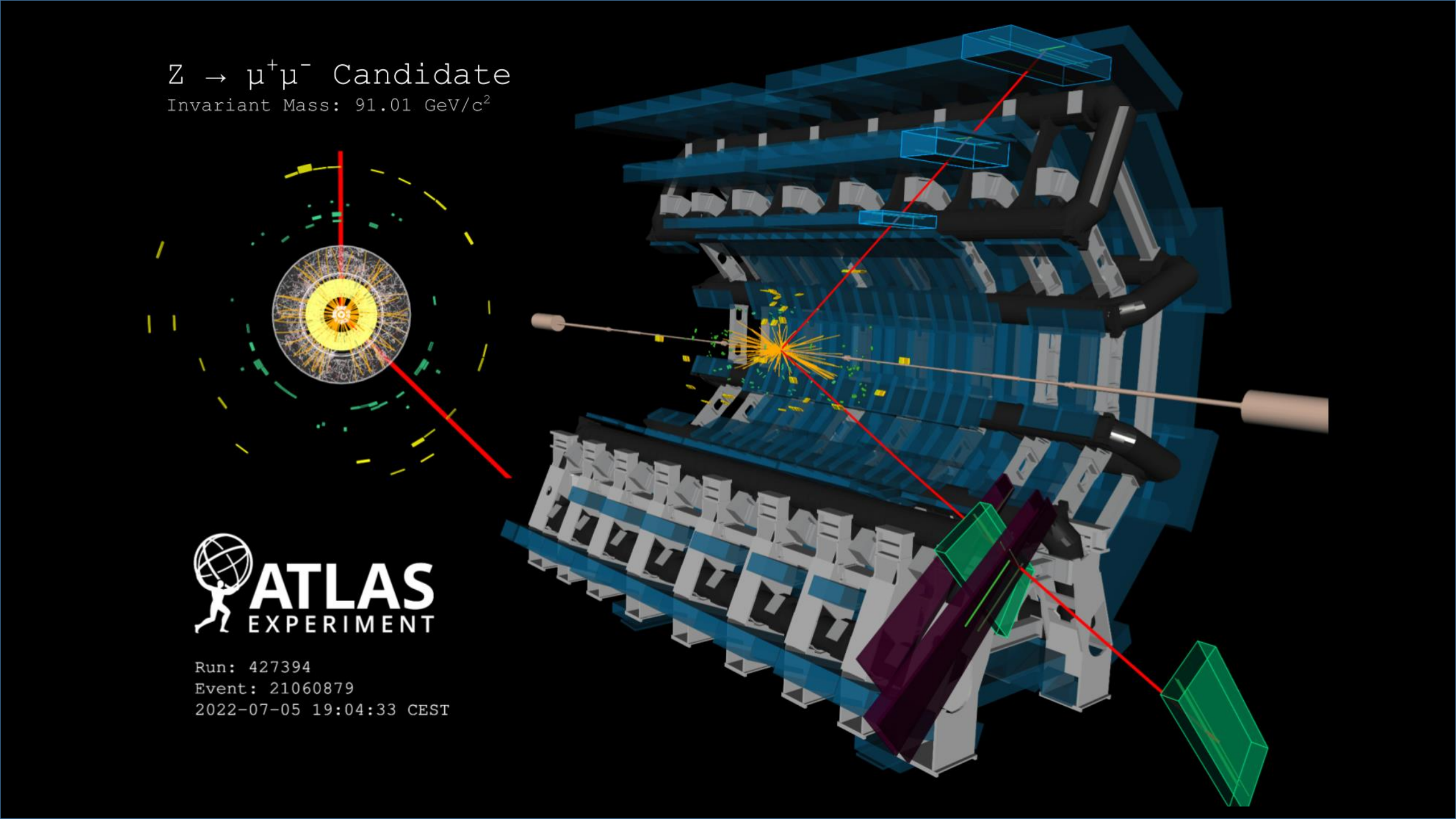

Candidate for Higgs to two photons
ATLAS
EXPERIMENT
Run: 439830
Event: 1764040021
2022-11-15 16:33:48 CET

Z → 2 muon event with additional vertices

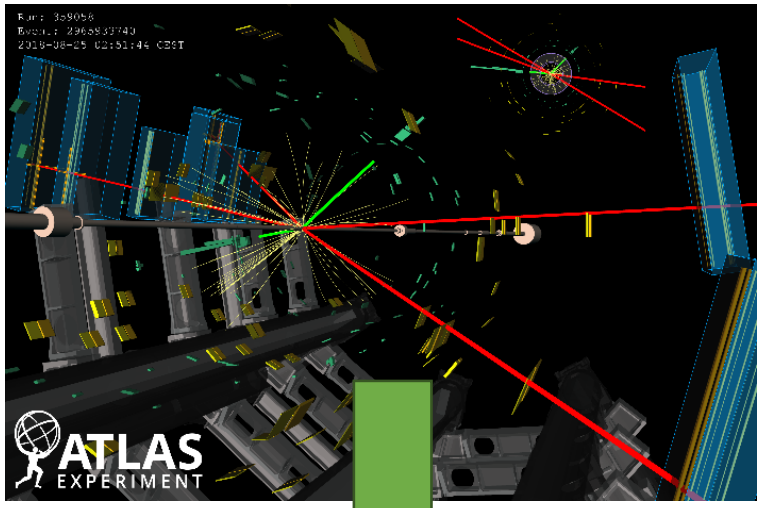


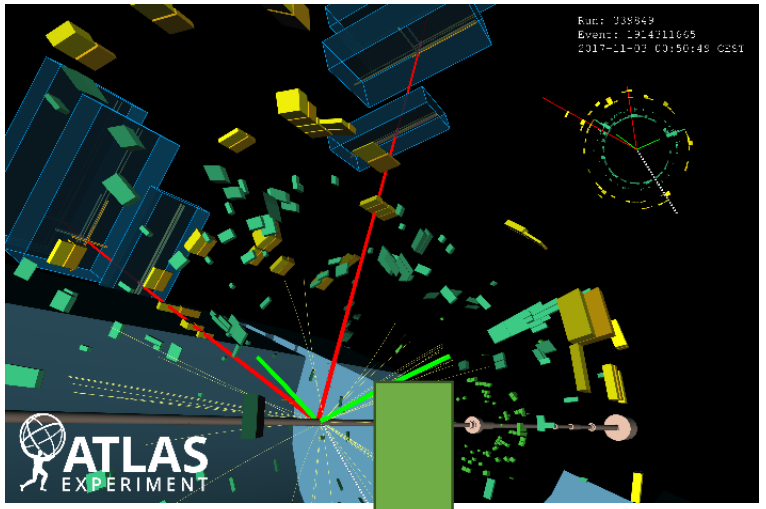
Lead-lead collisions

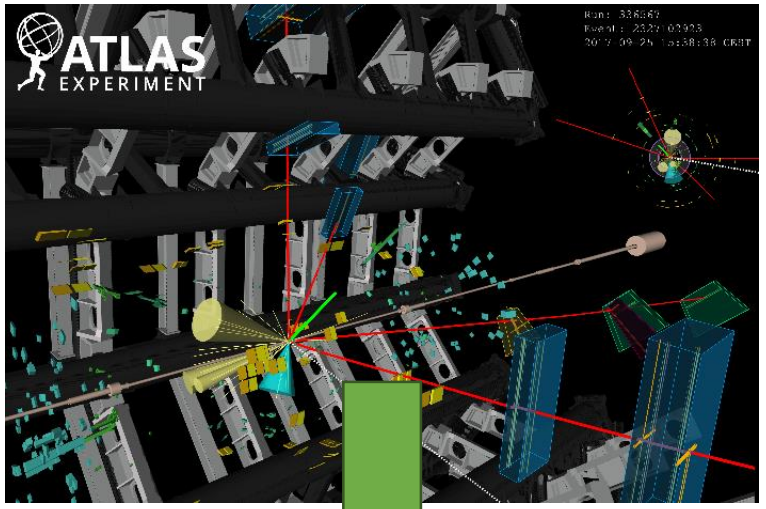


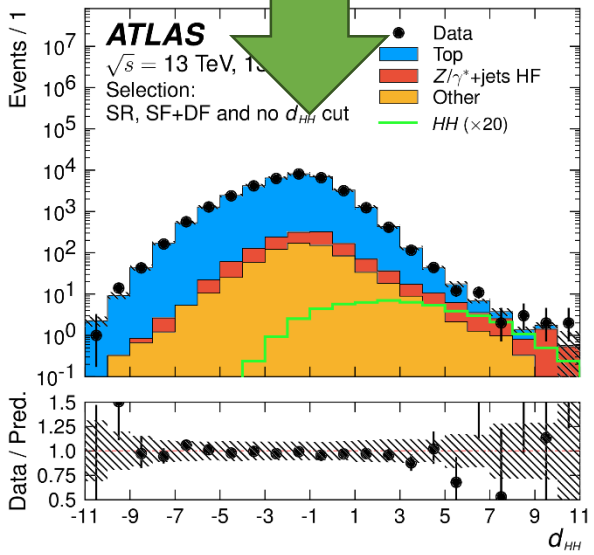

Z → μ⁺μ⁻ Candidate
Invariant Mass: 91.01 GeV/c²
ATLAS
EXPERIMENT
Run: 427394
Event: 21060879
2022-07-05 19:04:33 CEST

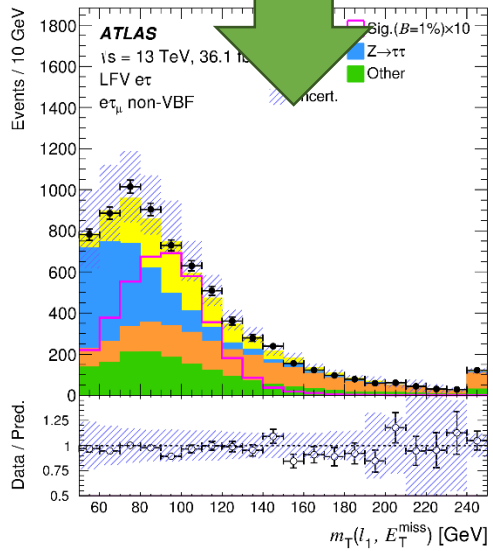
Physics processes at hadron colliders

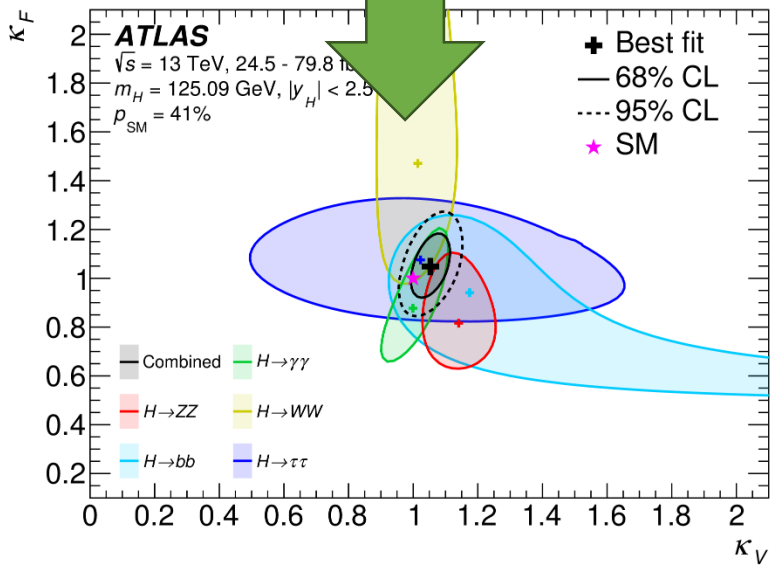










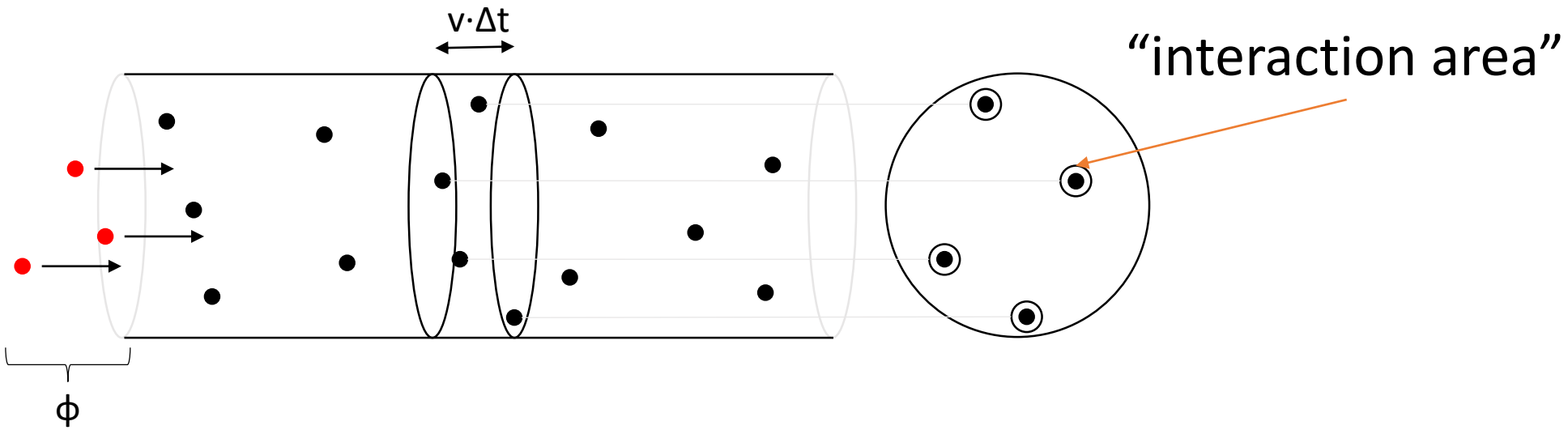


Physics processes at hadron colliders

Cross section

- Symbol: σ
- Unit: $[\sigma] = \text{barn} = 10^{-24}\,\text{cm}^2$

$$\sigma = \frac{\text{Number of interactions per particle and unit time}}{\text{Flux}}$$



Physics processes at hadron colliders

Fermi's golden rule of quantum mechanics

$$\Gamma_{fi} = 2\pi\,|T_{fi}|^2\,\rho(Ei)$$

Transition rate from initial state |i> to final state |j>

Transition matrix element determined by Hamiltonian

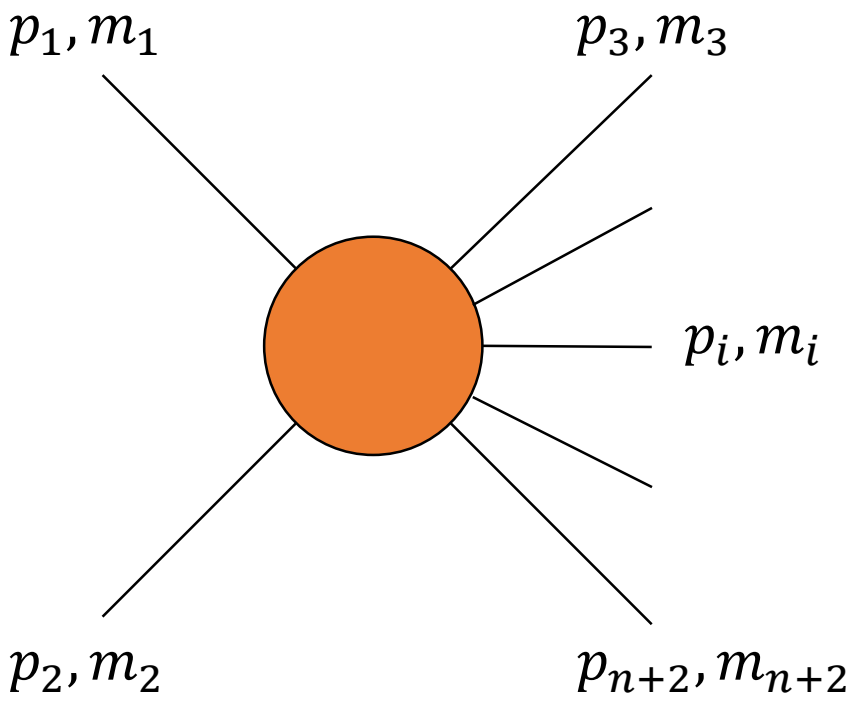
Density of states

- Important for the description of quantum processes e.g. in atomic physics

Physics processes at hadron colliders

Scattering of two particles

$$p_1 + p_2 \rightarrow p_3 + \cdots + p_{n+2}$$



Physics processes at hadron colliders

Relativistic form of Fermi's Golden Rule

$$\mathrm{d}\sigma = \frac{(2\pi)^4 |M|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1{}^2 m_2{}^2}} \mathrm{d}\Phi_n(p_1 + p_2; p_3 \dots; p_{n+2})$$

Flux factor (in center-of-mass frame):

$$\sqrt{(p_1 \cdot p_2)^2 - m_1{}^2 m_2{}^2} = p_{1,\mathrm{cm}} \cdot \sqrt{s}$$

Matrix element squared

Lorentz-invariant **phase space**

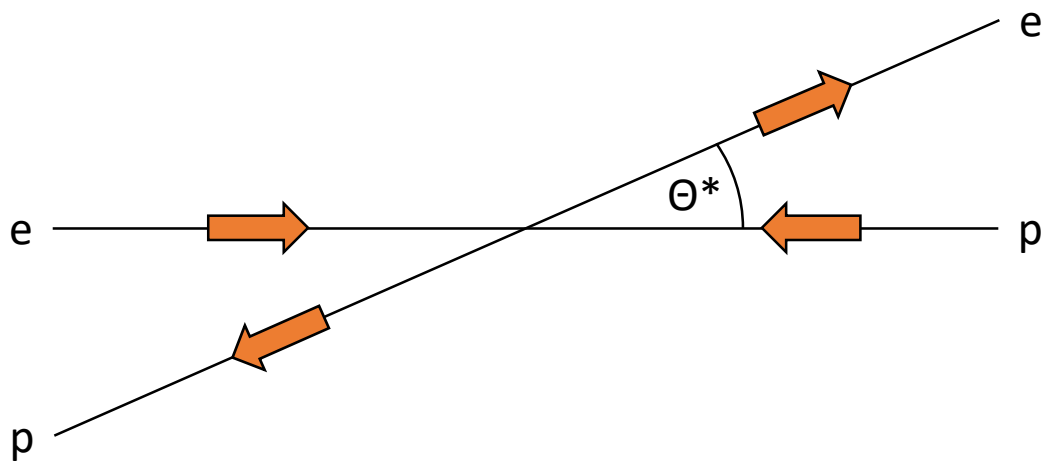
$$\mathrm{d}\Phi_n(p_1 + p_2; p_3 \dots; p_{n+2}) = \delta^4\left(p_1 + p_2 - \sum_{i=3}^{n+2} p_i\right) \prod_{i=3}^{n+2} \frac{\mathrm{d}^3 p_i}{(2\pi)^3 2E_i}$$

Physics processes at hadron colliders

Example: 2 → 2 scattering

- Cross section

$$\mathrm{d}\sigma = \frac{1}{64\pi^2 s}\frac{p_f^*}{p_i^*}\int |M|^2 \,\mathrm{d}\Omega^*$$



- Differential cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega^*} = \frac{1}{64\pi^2 s}\frac{p_f^*}{p_i^*}|M|^2$$

- Concrete examples: $e^+e^- \rightarrow \mu^+\mu^-$, $e^-p \rightarrow e^-p$, ...

Physics processes at hadron colliders

Measurement of a cross section

- The number of expected events ν is proportional to …
  … the cross section σ
  … the acceptance A
  … the efficiency ε (probability) to observe the event

$$\nu = L_{\text{int}} \cdot \sigma \cdot A \cdot \varepsilon$$

- The proportionality constant is the luminosity.
- The number of expected events can be estimated by the number of observed events N minus the background, N_{bkg}.
- This formula relates the theory (cross section σ) with the experiment (A, ε) and the analyst (N)

Physics processes at hadron colliders

Luminosity

- Measure for the number of collisions
- Property of the collider, i.e. the beam size ($\sigma_{x/y}$), the collision frequency f, number of colliding particles $n_{1/2}$
- Unit: inverse barn (inverse area) (per unit time)
- Instantaneous luminosity:

$$L = f \cdot \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

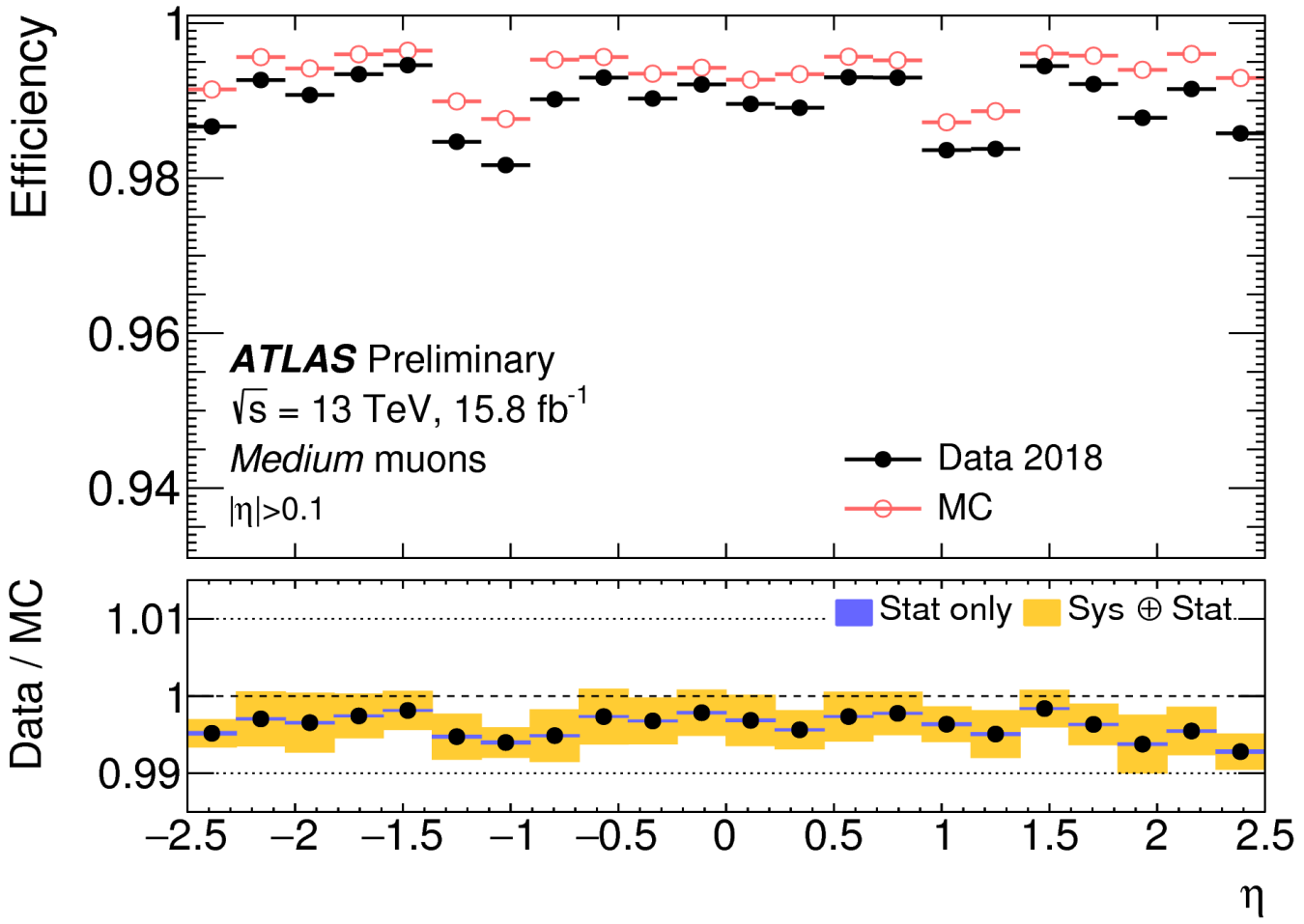
- Integrated luminosity:

$$L_{\text{int}} = \int L \, \mathrm{d}t$$

Physics processes at hadron colliders

Acceptance

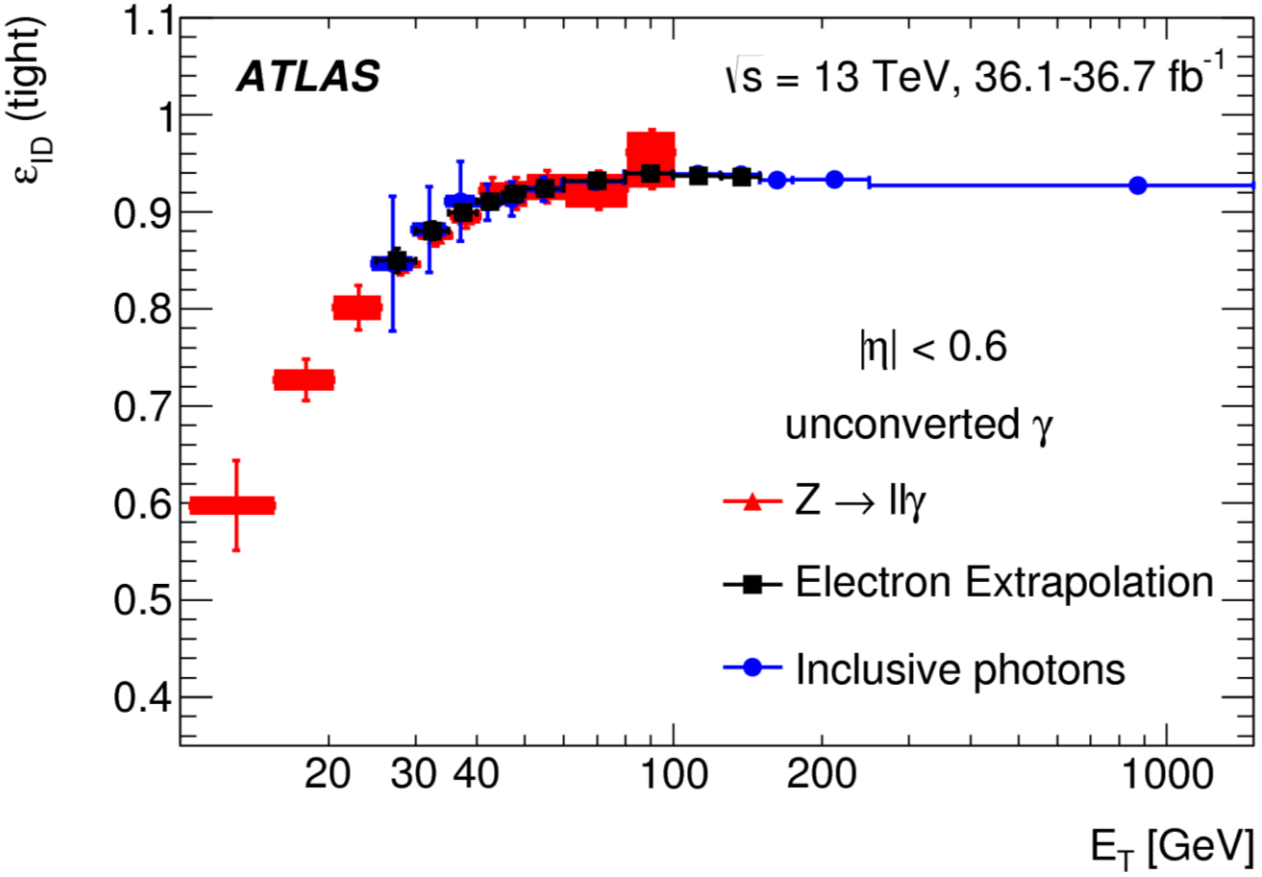
- Purely geometrical factor.
- Ideal world: 4π solid-angle coverage
- But:
  - Beam pipe
  - Detector feet
  - Cables, pipes, etc.
  - Read-out electronics
  - Iron yoke (magnet)
  - ...
- Example: muon reconstruction efficiency vs. angular variable



Physics processes at hadron colliders

Efficiency

- Probability to measure a certain particle if it is there
- Ideal world: measure all particles
- But:
  - Dead times
  - Extreme momenta
  - Losses
  - Electronic noise
  - Background
  - ...
- Example: photon reconstruction efficiency vs. energy variable

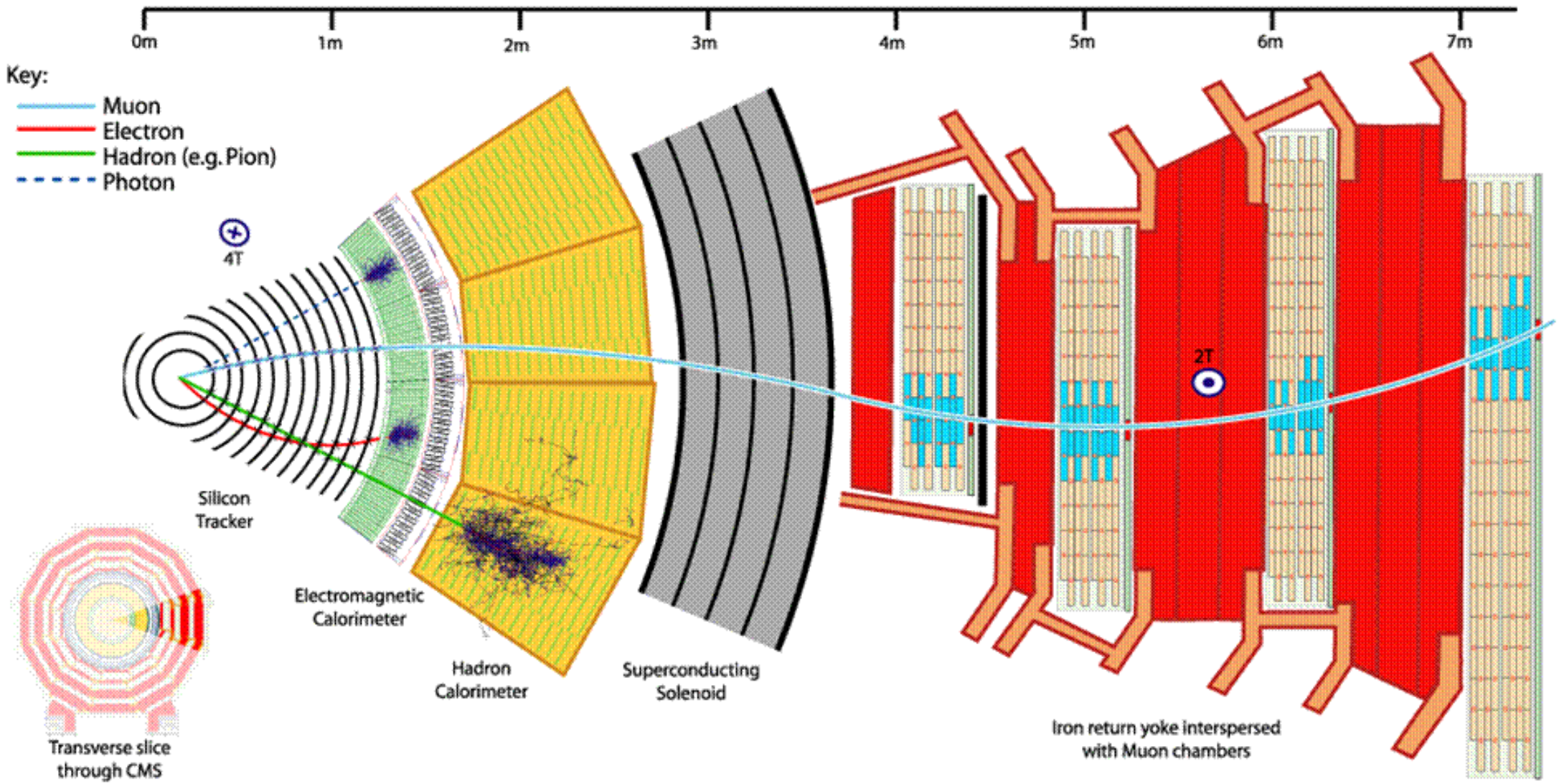


Physics processes at hadron colliders

N

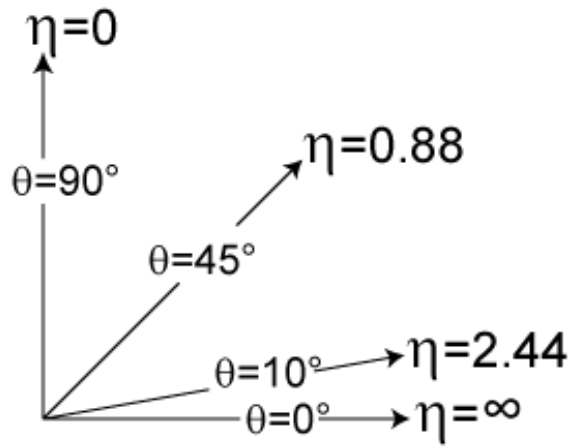
- One observes and counts “events”, think of them as a 3D photo of the collision
- The different detector components see different objects
- Objects:
  - Charged leptons, e.g. electrons, muons
  - Photons
  - Jets, i.e. hadronized quarks, e.g. pions, kaons, …, protons, …
  - missing transverse momentum, the signature of neutrinos
- But how are they reconstructed?
  - Hits and tracks
  - Vertices
  - Energy clusters

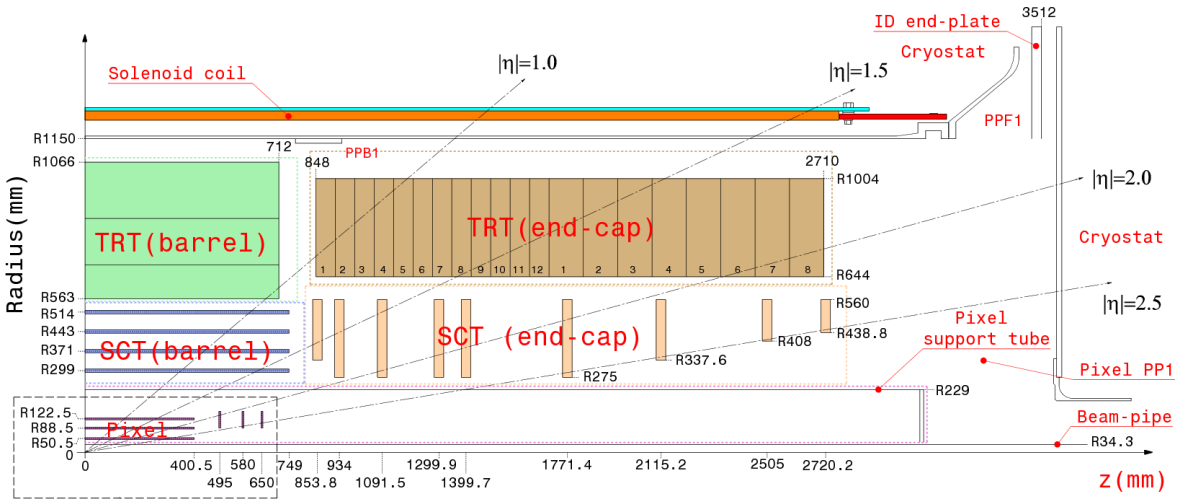
The LHC in a nutshell



Kinematic variables

- Particle are represented by 4-vectors
- Measureable quantities:
  - Energy E (calorimeters)
  - Transverse momentum p_T (tracking detectors plus magnetic field)
  - Azimuthal angle φ (tracking detectors, calorimeters)
  - (Pseudo-)rapidity η (tracking detectors, calorimeters)

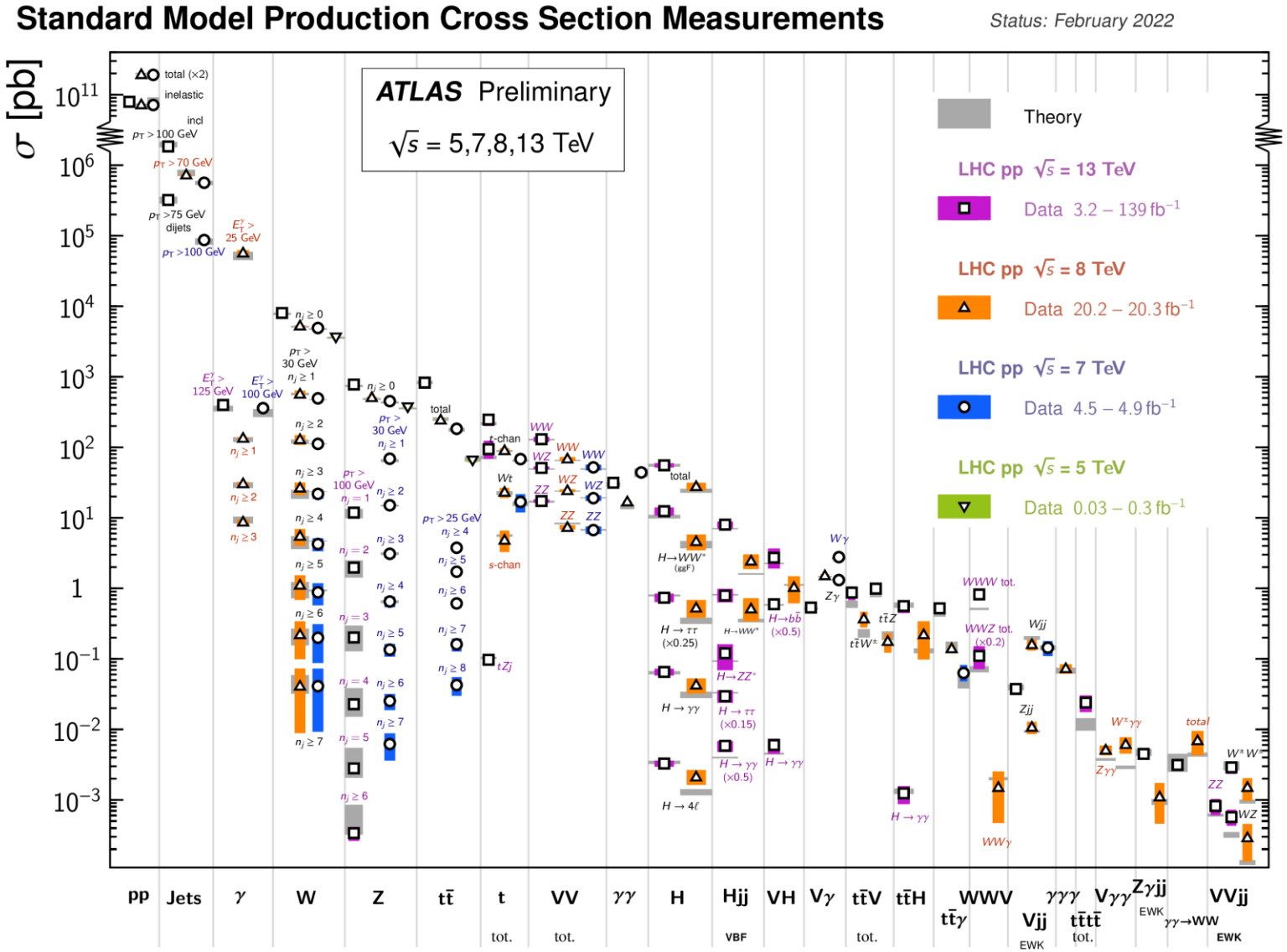




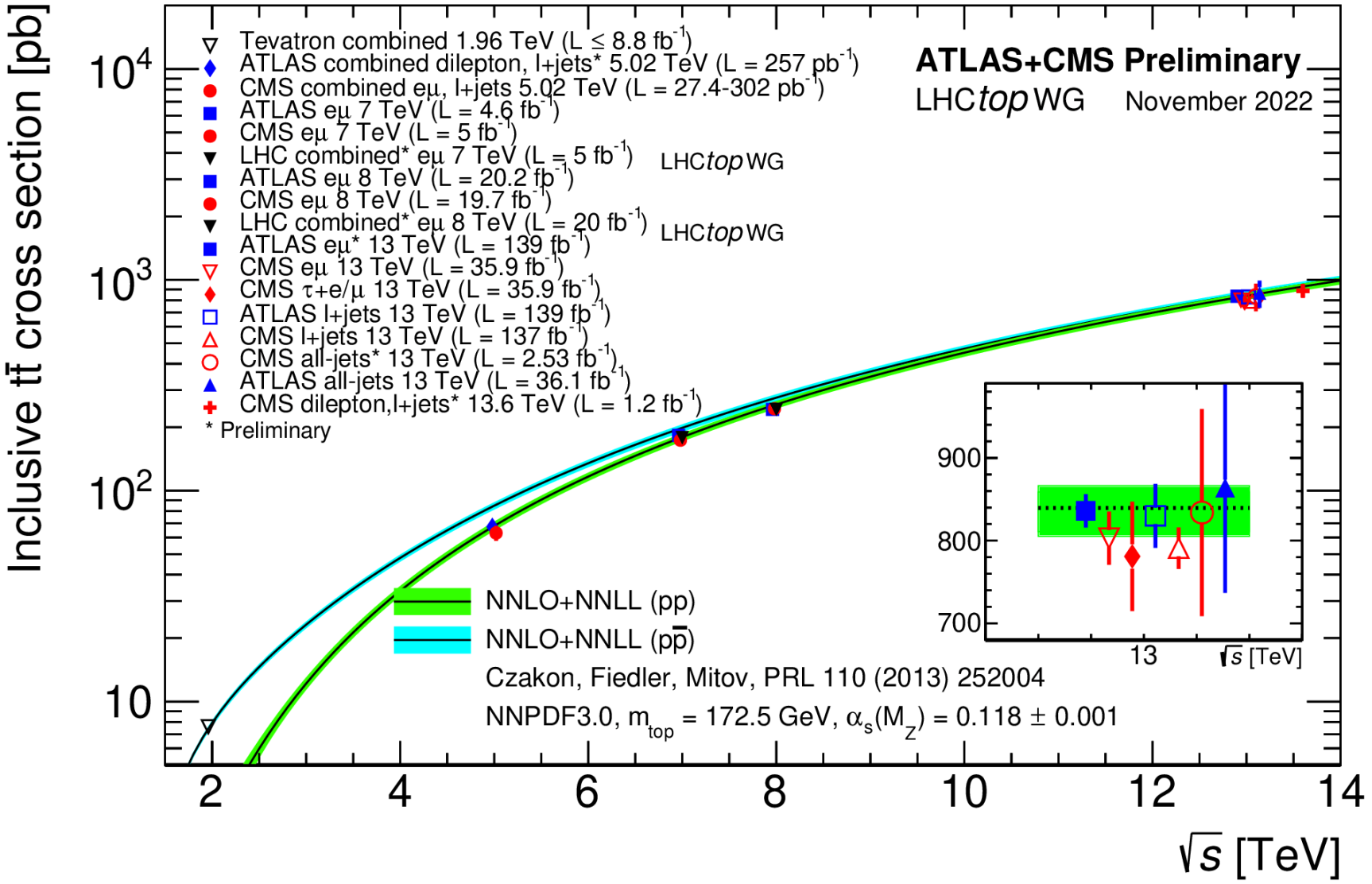
Selected physics processes

A biased selection to give you an idea

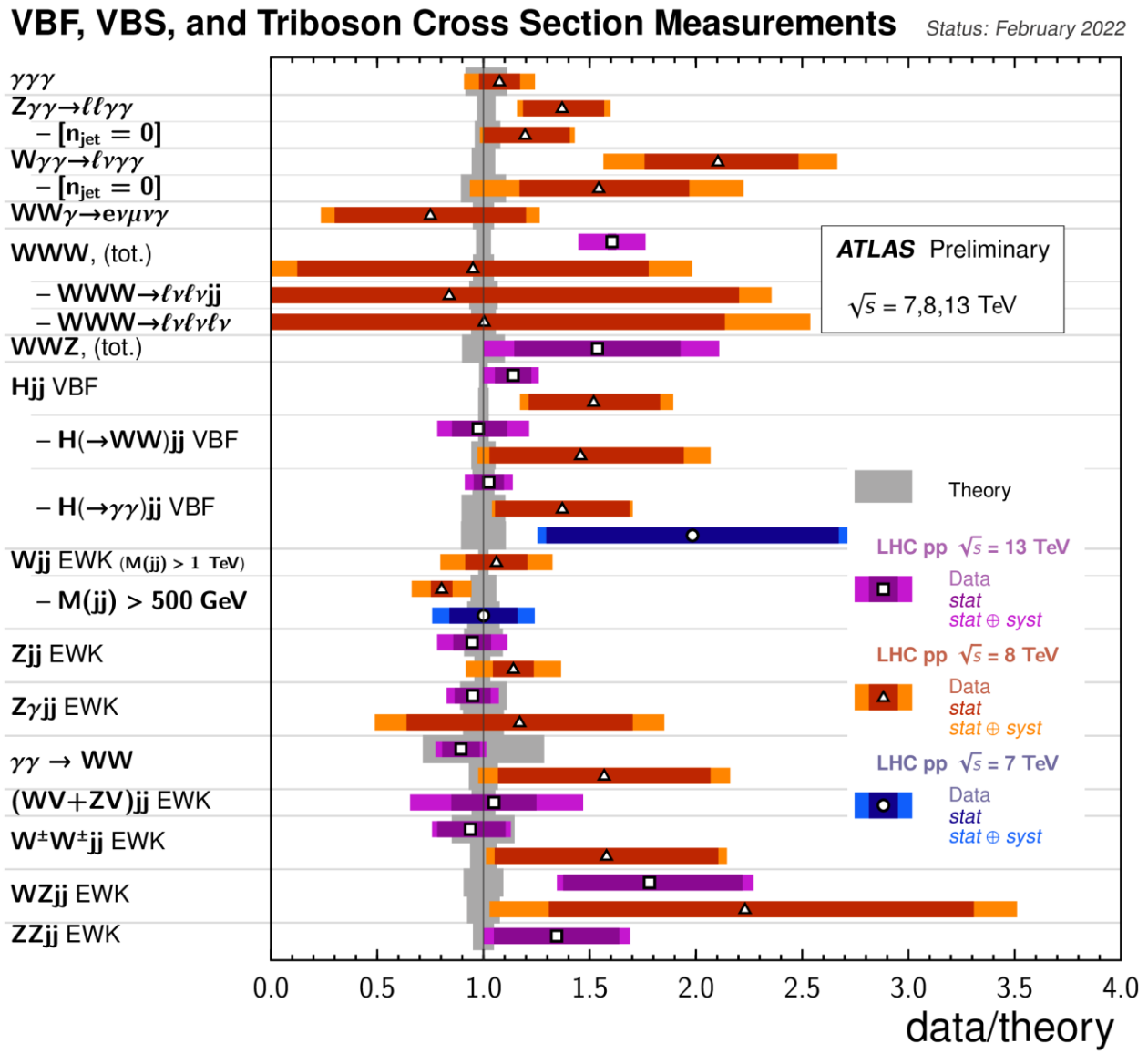
Physics processes at hadron colliders



Physics processes at hadron colliders



Physics processes at hadron colliders



→ Next: the top quark

Best quark in the world, but I can’t say that loud when flavor physicists are around