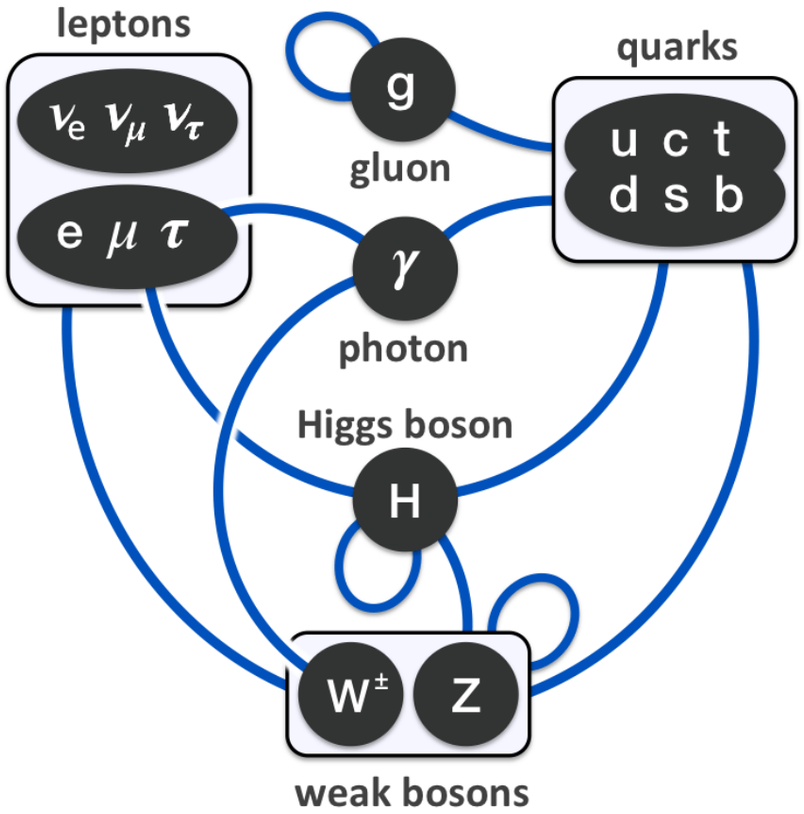
Search for new phenomena in the dilepton final state using proton-proton collisions

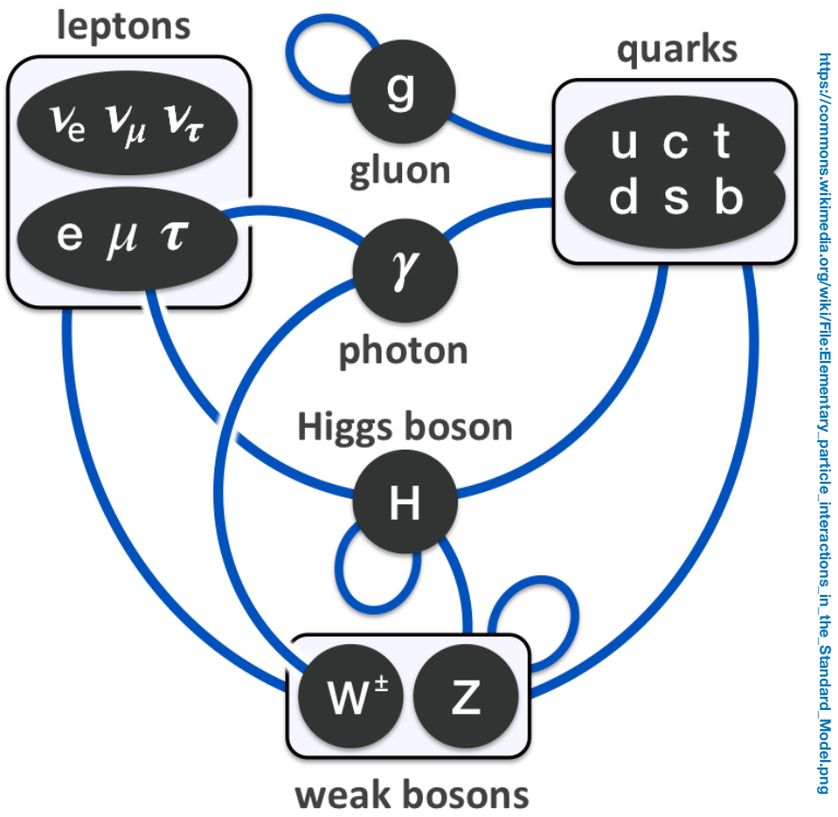
Simon Schmitz
DLR, HPC-SC

Standard Model of Particle Physics (SM)



https://commons.wikimedia.org/wiki/File:Elementary_particle_interactions_in_the_Standard_Model.png

Standard Model of Particle Physics (SM)

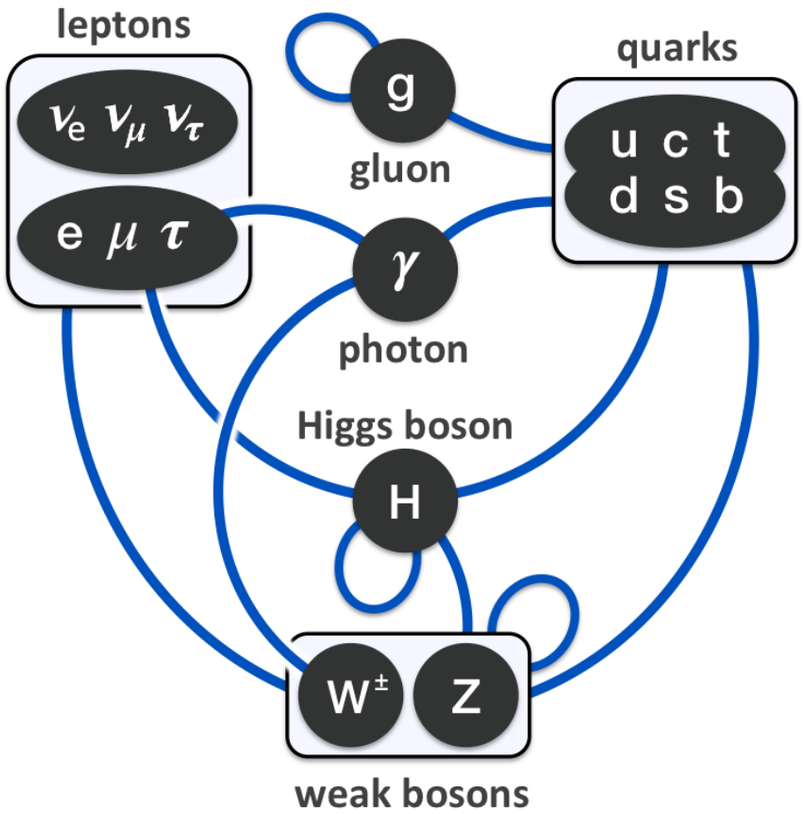


https://commons.wikimedia.org/wiki/File:Elementary_particle_interactions_in_the_Standard_Model.png

Mathematical formulation:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

Standard Model of Particle Physics (SM)



https://commons.wikimedia.org/wiki/File:Elementary_particle_interactions_in_the_Standard_Model.png

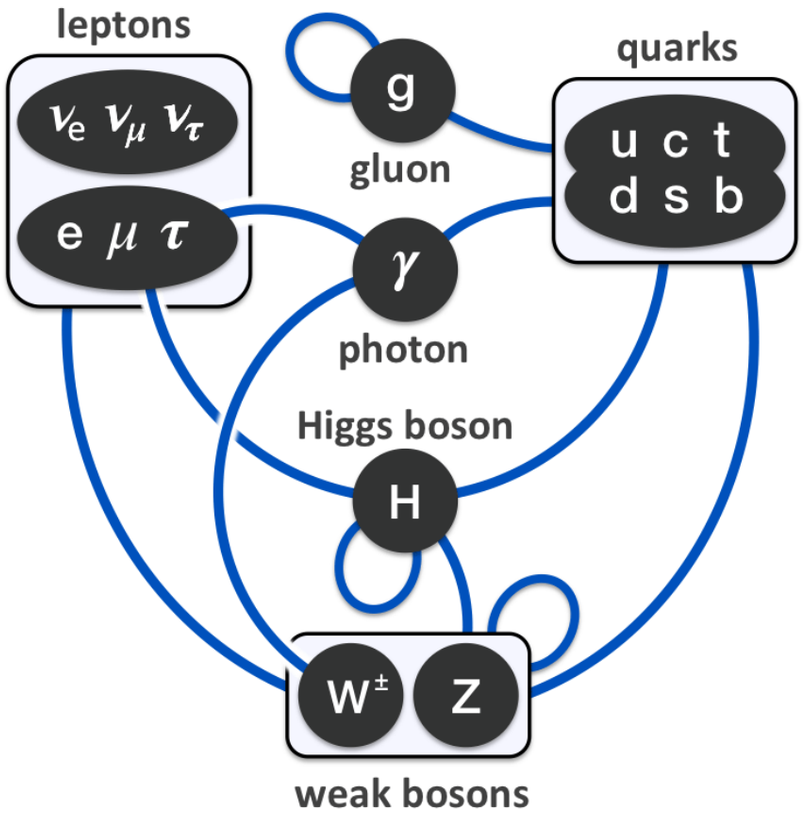
Mathematical formulation:

$$\begin{aligned}\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\psi \\ & + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\ & + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.\end{aligned}$$

What the SM not describes:

- Gravity
- Dark matter and dark energy
- Neutrino masses
- Matter-antimatter asymmetry
- …

Standard Model of Particle Physics (SM)



https://commons.wikimedia.org/wiki/File:Elementary_particle_interactions_in_the_Standard_Model.png

Mathematical formulation:

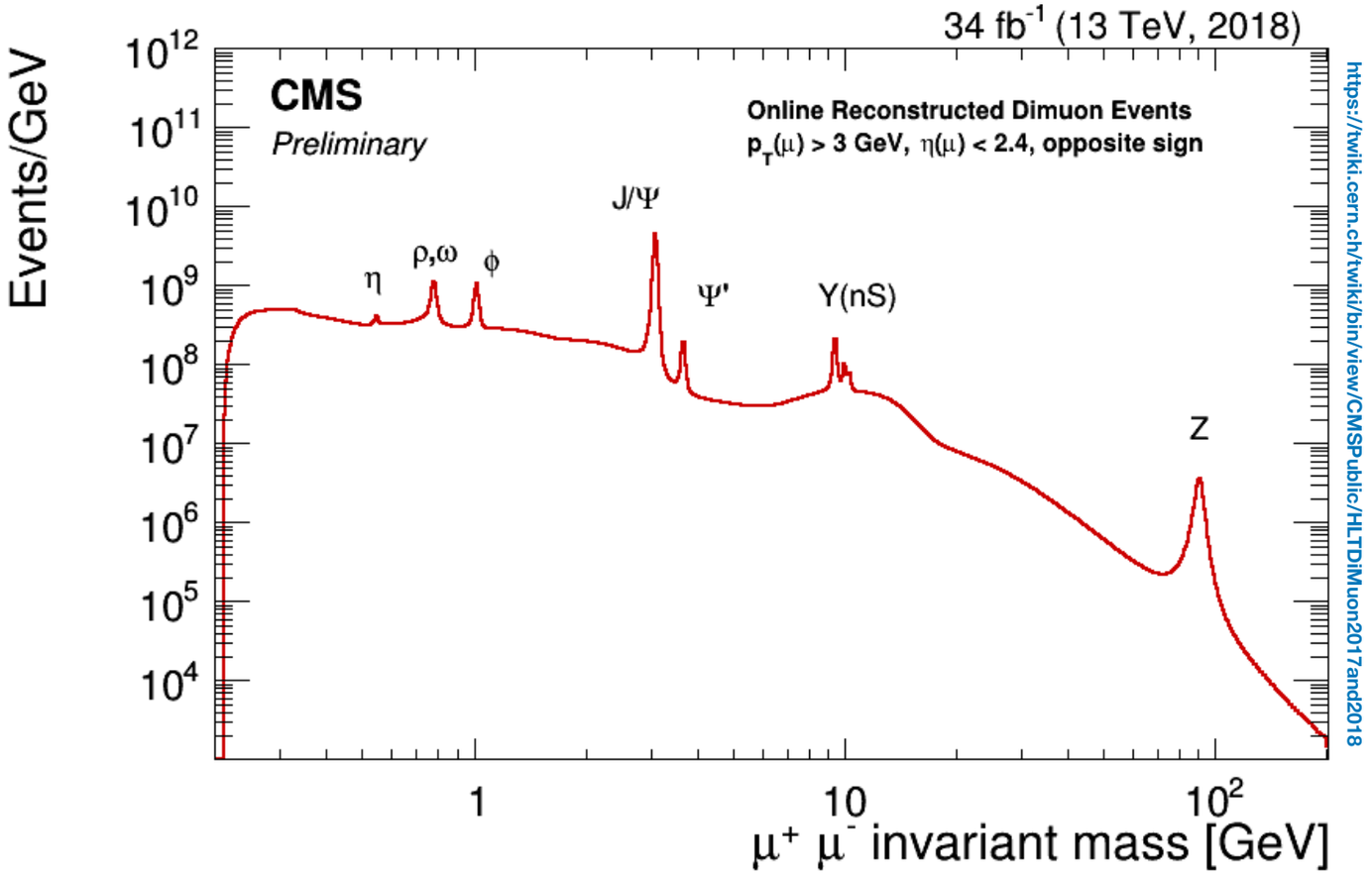
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

What the SM not describes:

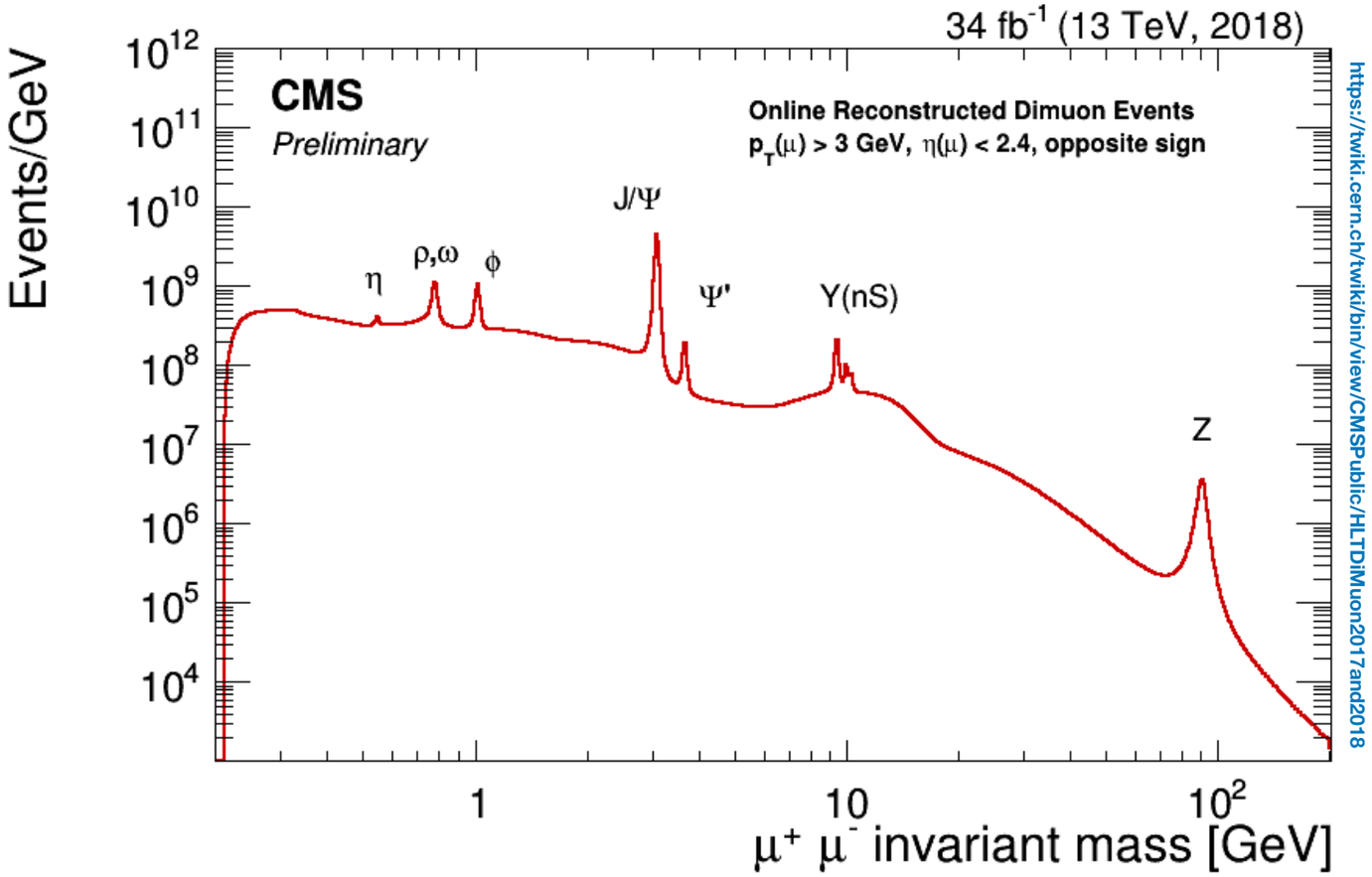
- Gravity
- Dark matter and dark energy
- Neutrino masses
- Matter-antimatter asymmetry
- …

→ **New Phenomena**

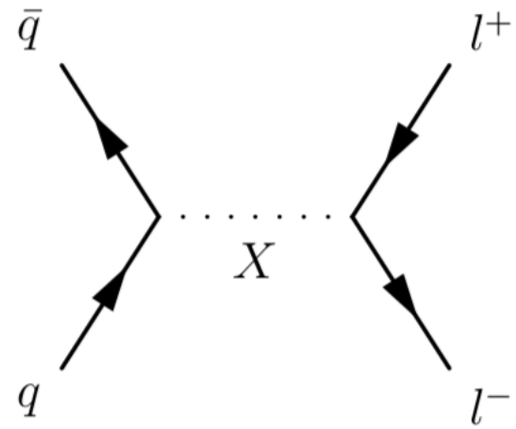
Physics Beyond the Standard Model



Physics Beyond the Standard Model

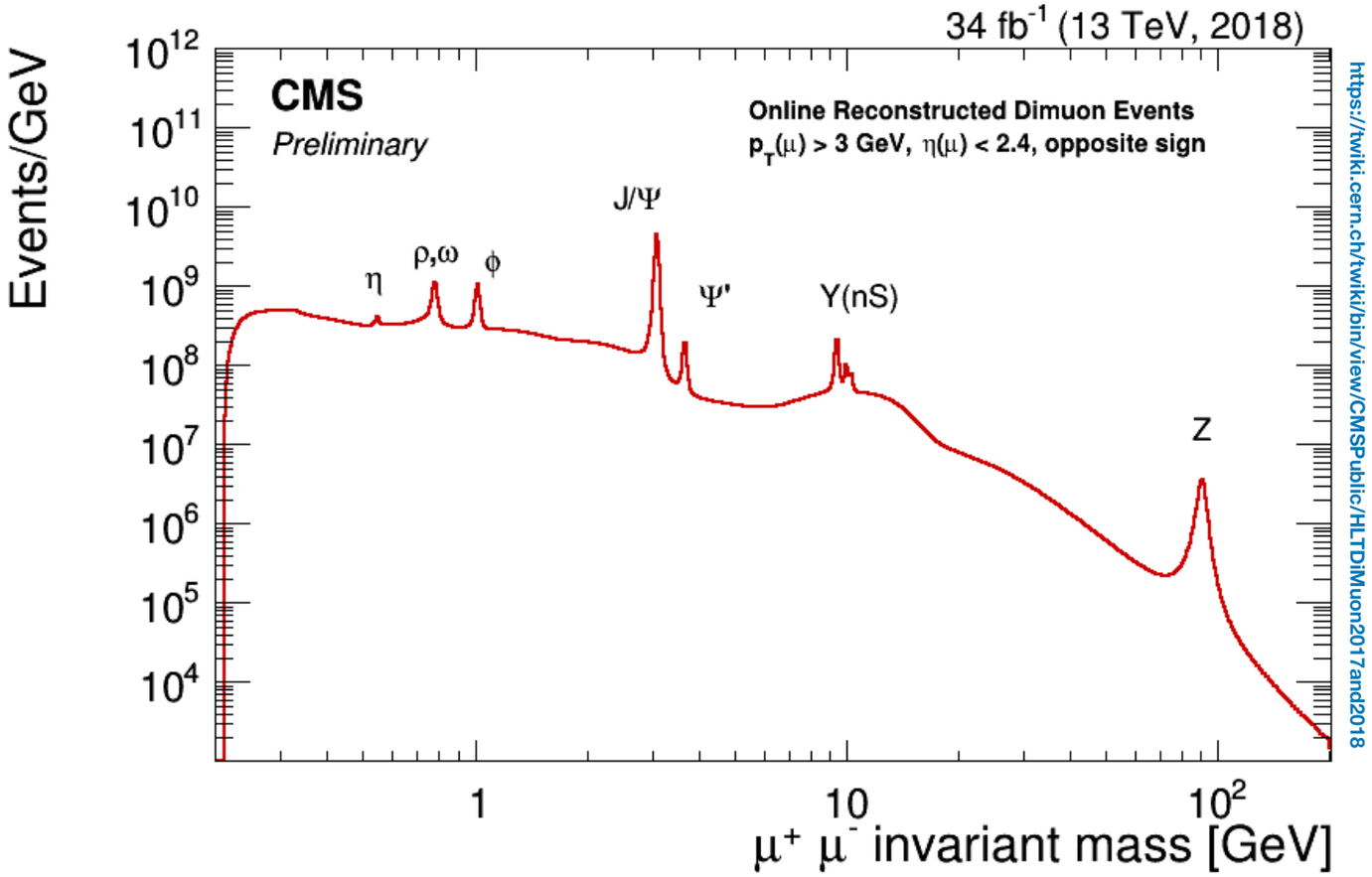


https://twiki.cern.ch/twiki/bin/view/CMSPublic/HLTDiMuon2017and2018

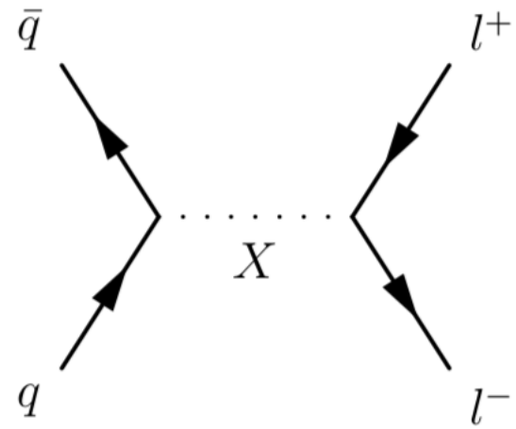


New Resonance?

Physics Beyond the Standard Model



https://twiki.cern.ch/twiki/bin/view/CMSPublic/HLTDiMuon2017and2018



New Resonance?

Theoretical motivation

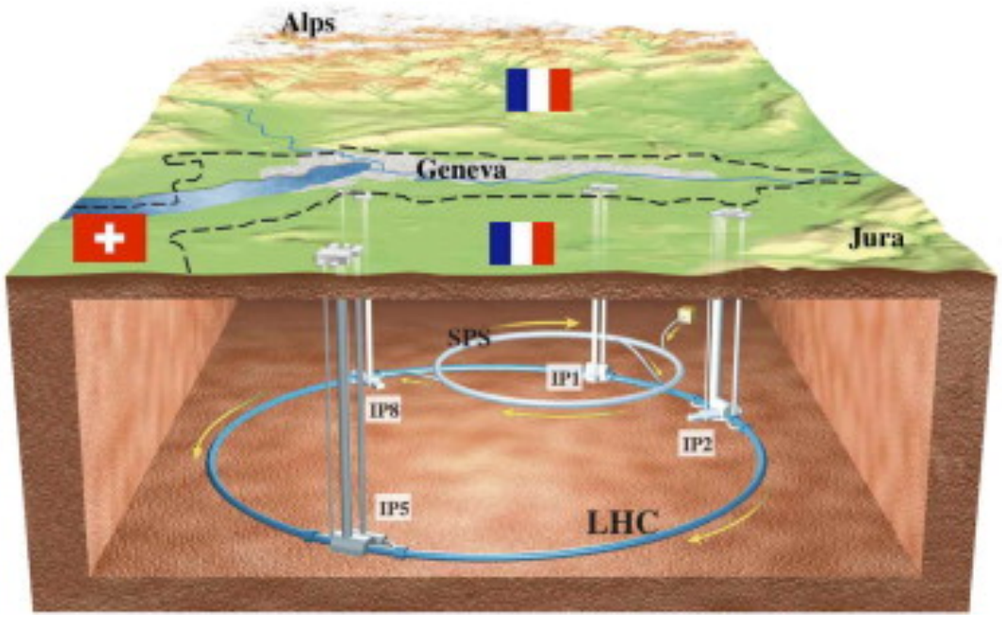
- Grand Unified Theories (GUTs)

  ➡ Many predict heavier versions of the Z boson

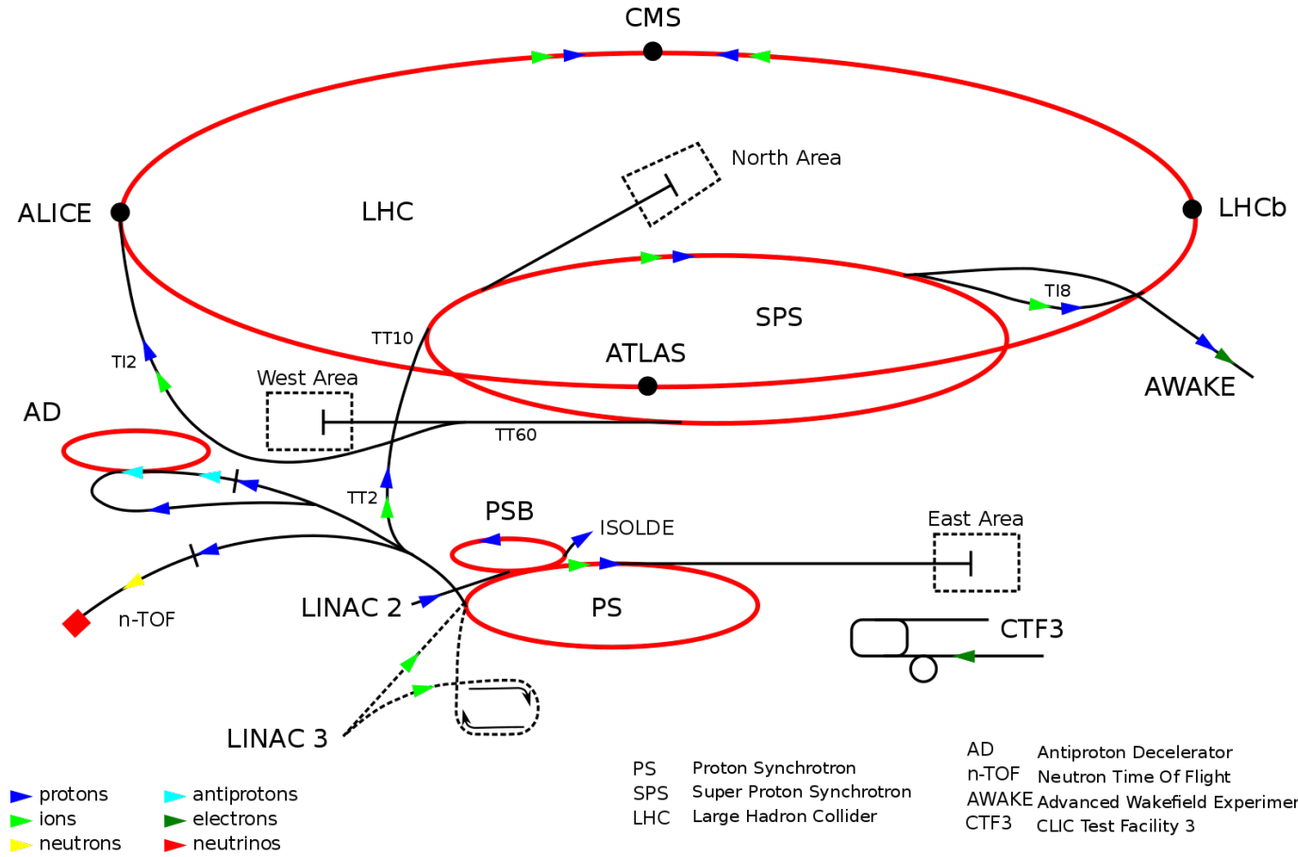
- Supersymmetry (SUSY)

  ➡ Extends SM by new symmetries (not relevant for this analysis)

Large Hadron Collider



https://cds.cern.ch/record/1443022/files/CERN-ATS-2012-064.pdf

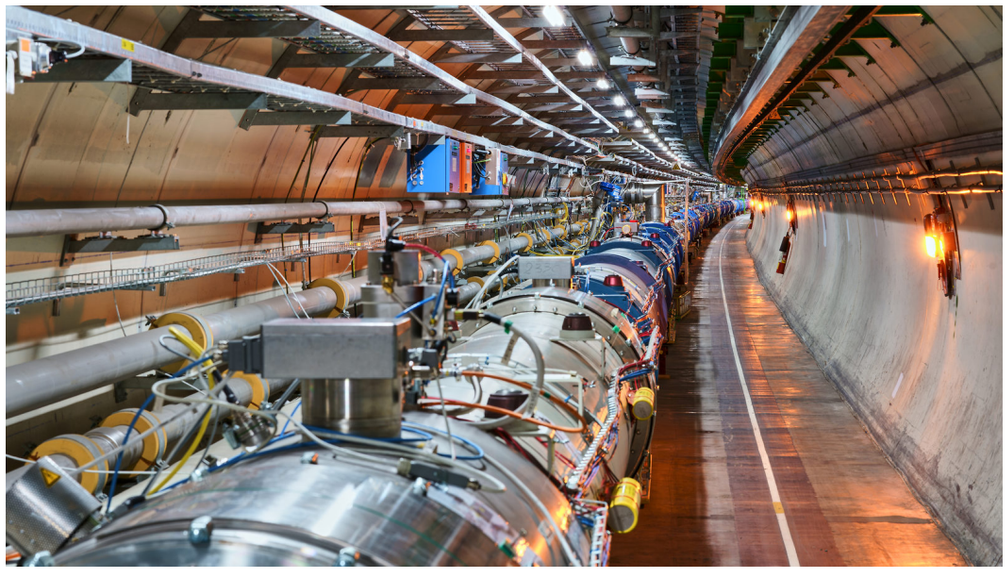


https://de.wikipedia.org/wiki/Datei:Cern-accelerator-complex.svg

- Beam divided in 2808 bunches containing around 1.2×10^{11} protons
- Produced proton-proton collisions at up to $\sqrt{s} = 14$ TeV and frequency of 40 MHz
- Currently in Long Shutdown 2 (preparing for Run 3 starting in 2021)

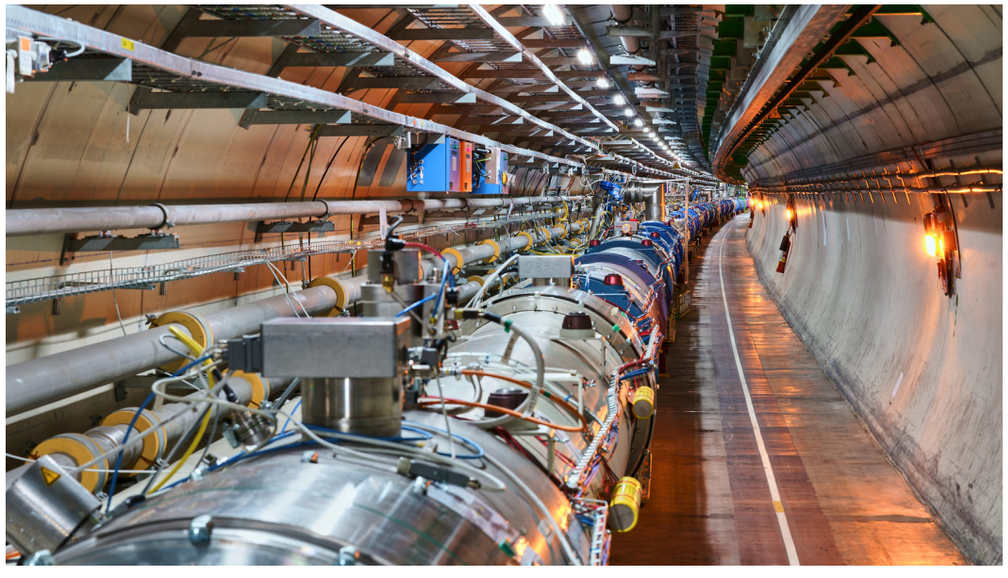

p
p

Large Hadron Collider (LHC)

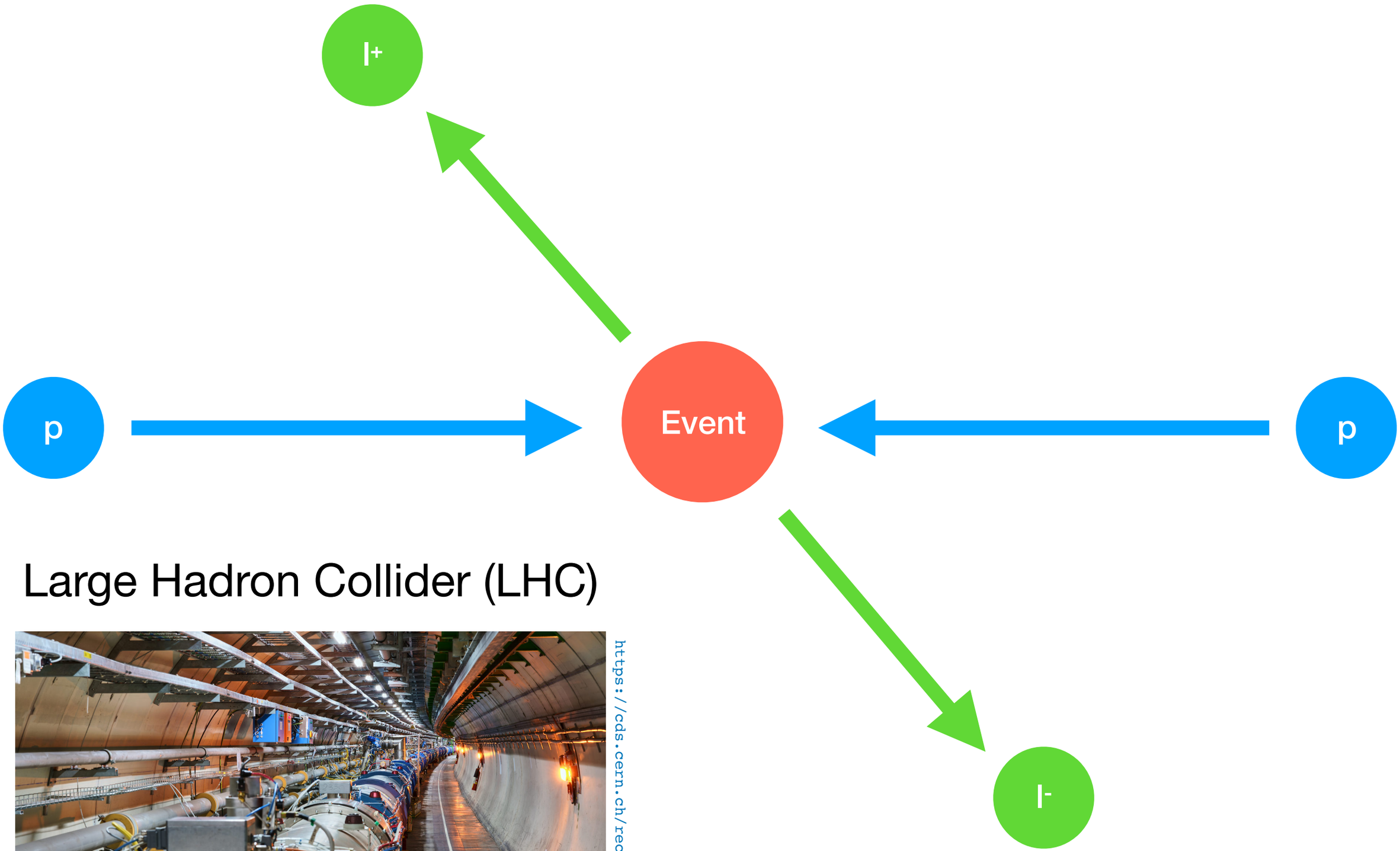


https://cds.cern.ch/record/2302977

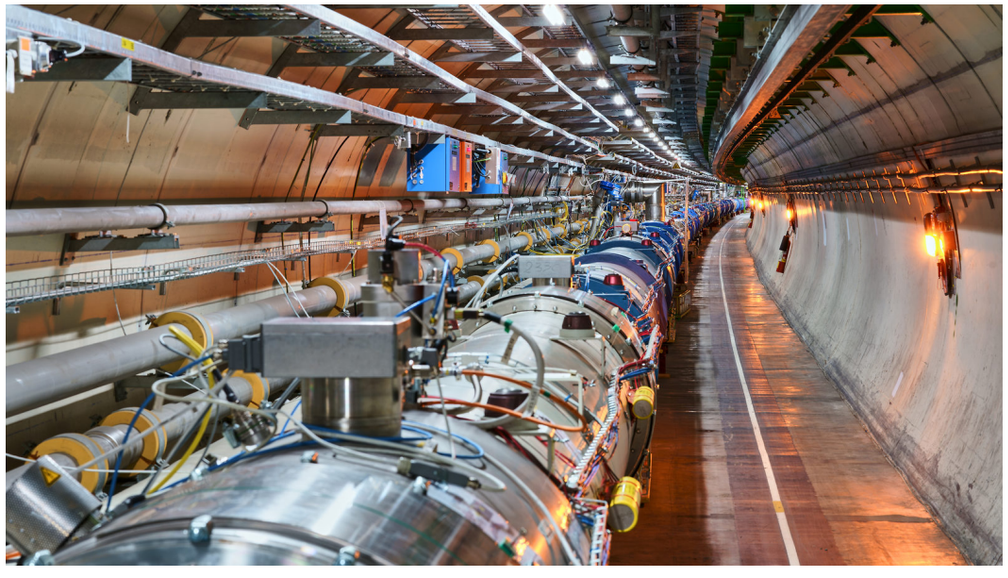
Large Hadron Collider (LHC)



https://cds.cern.ch/record/2302977



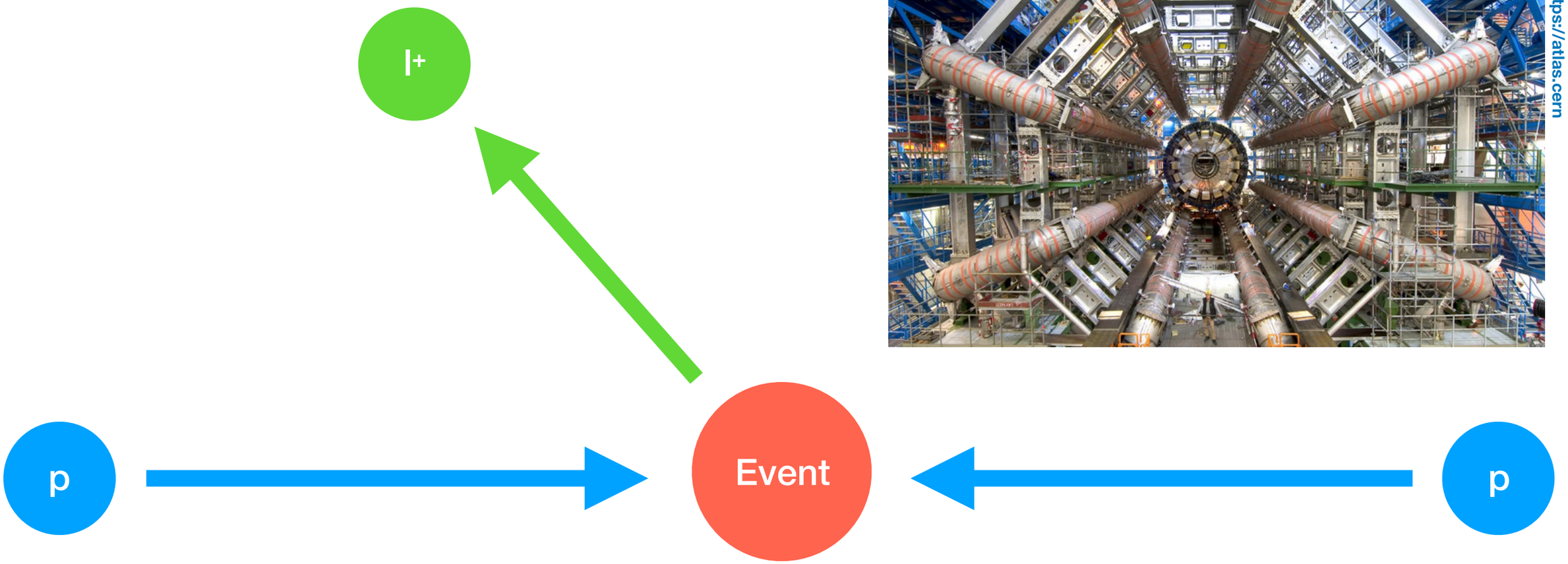
Large Hadron Collider (LHC)



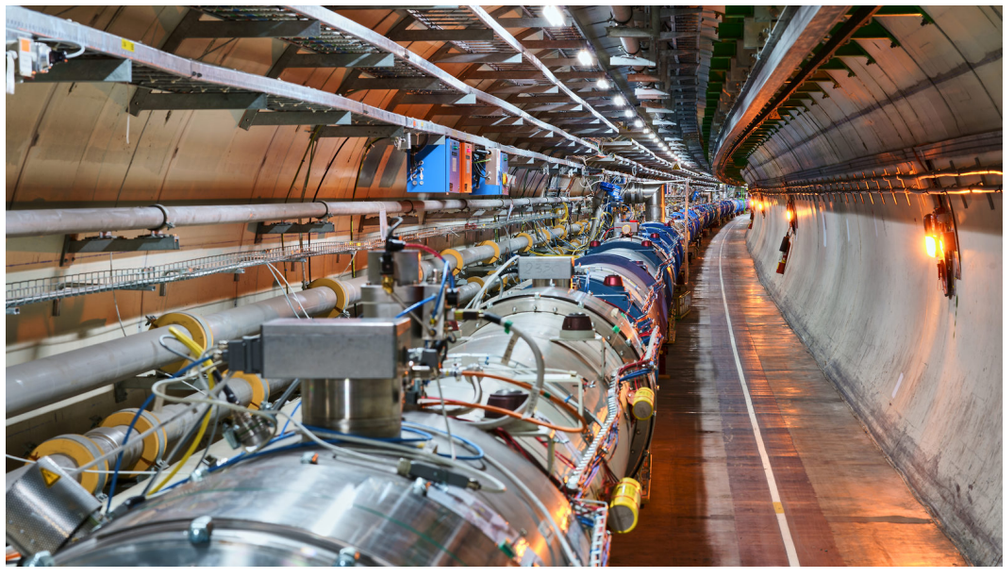
https://cds.cern.ch/record/2302977

ATLAS Detector

https://atlas.cern

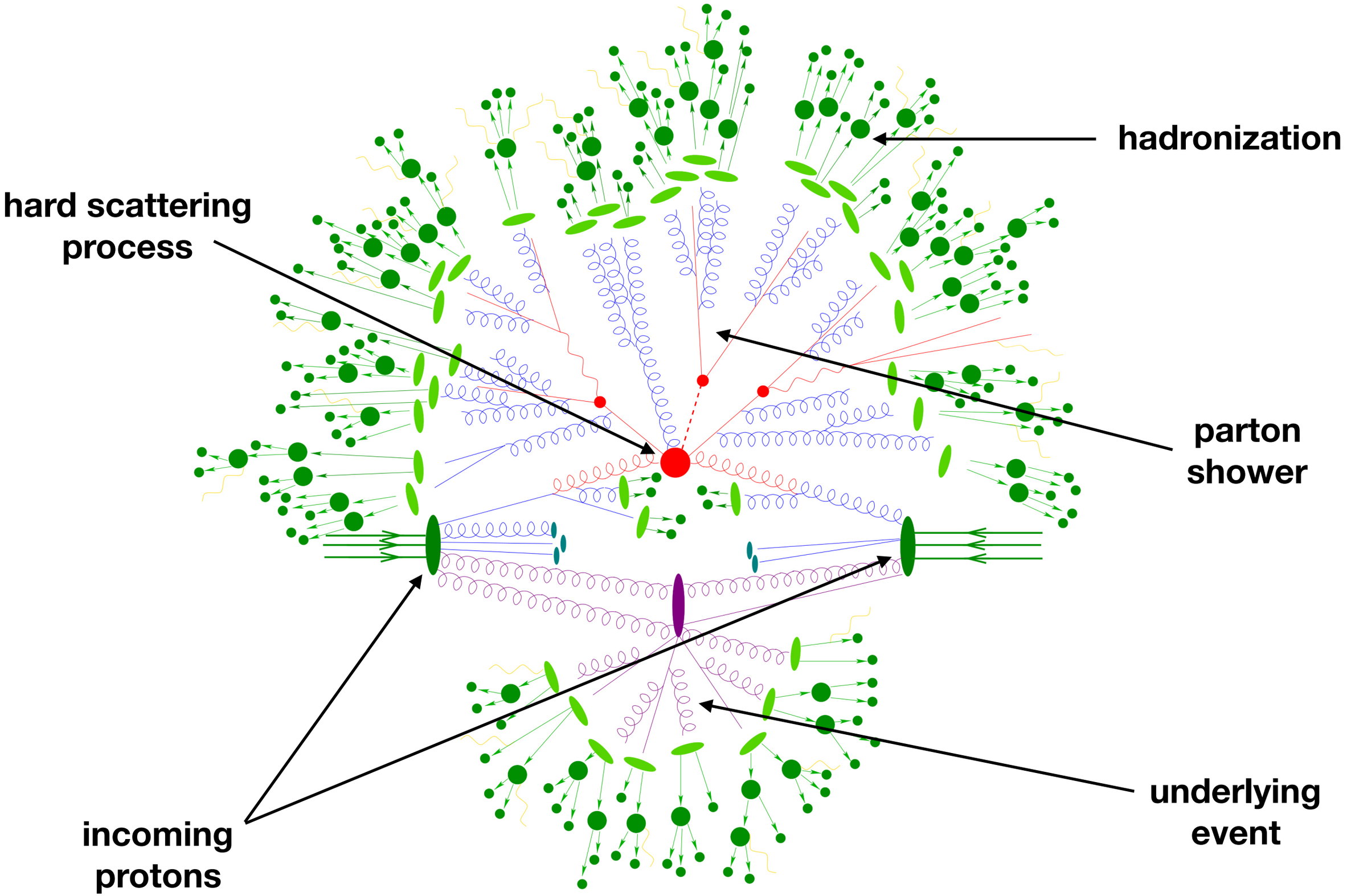


Large Hadron Collider (LHC)



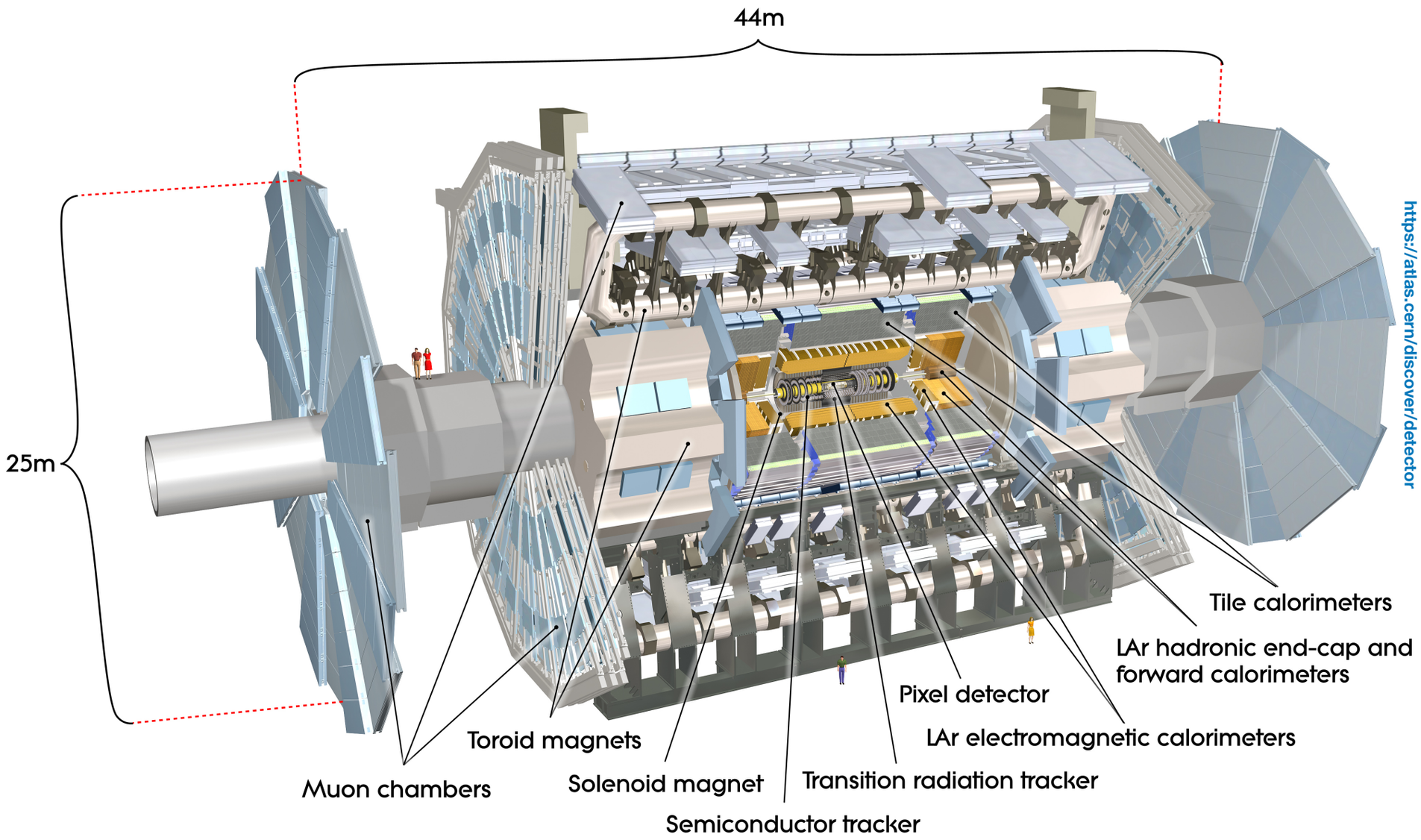
https://cds.cern.ch/record/2302977

Proton-Proton Collisions



https://doi.org/10.1007/978-3-319-41045-6_4

ATLAS Detector



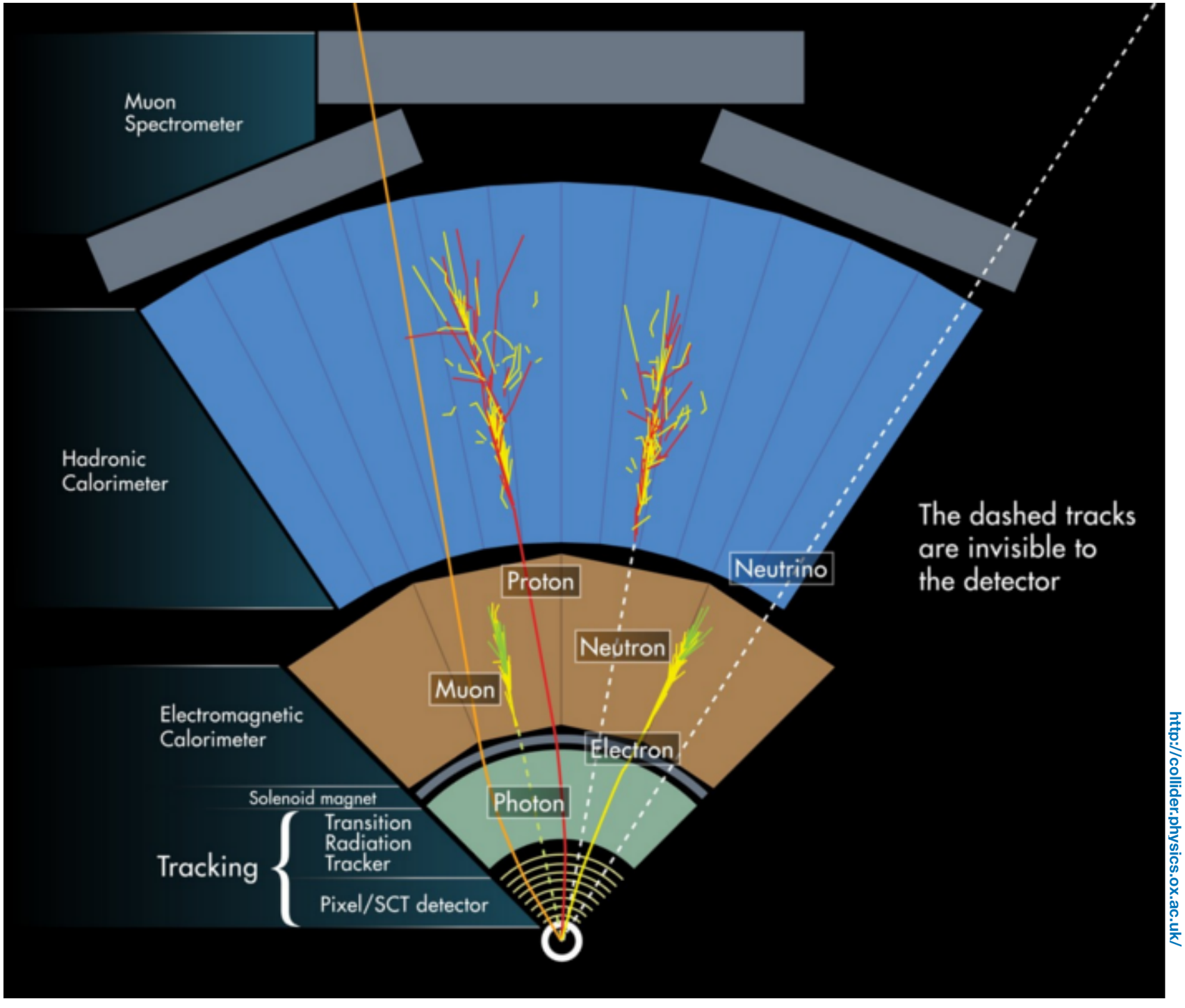
- Tracking system and muon spectrometer based on silicon and gaseous detectors

  ➡ Momentum measurement

- Electromagnetic and hadronic calorimeter system in sampling type

  ➡ Energy measurement

Particle Signatures

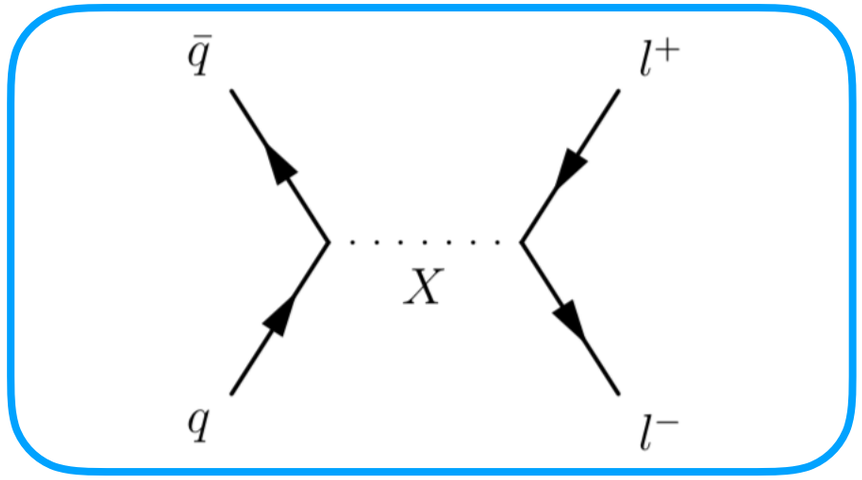


http://collider.physics.ox.ac.uk/

- Not shown: hadronization of quarks causes „jets“ which can fake particles

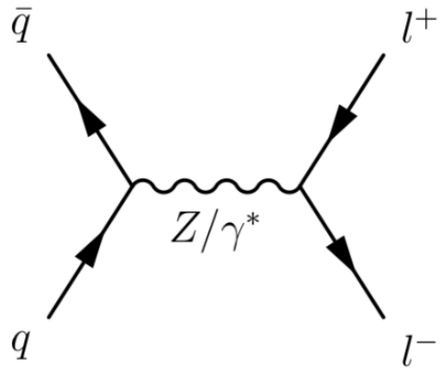
Analysis of Dilepton Final States

Signal Process

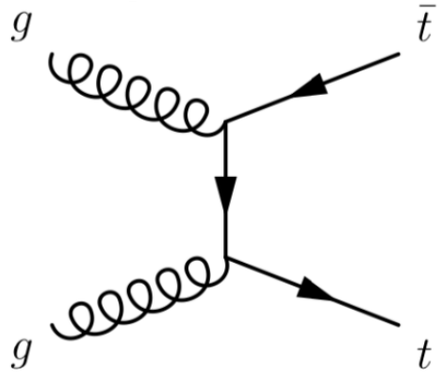


Background Processes

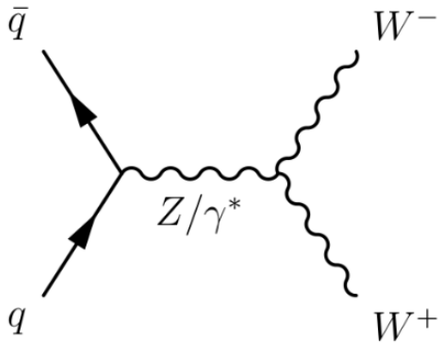
Drell-Yan



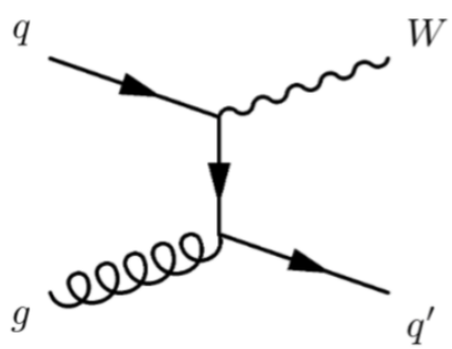
Top Quarks



Diboson



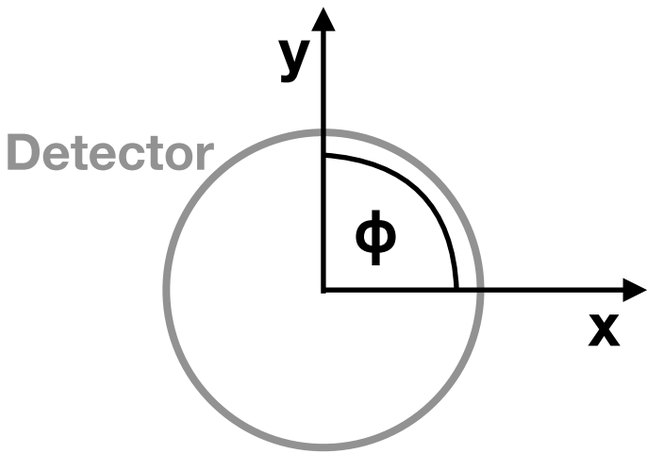
Fake Background



- All processes apart from fake background can be estimated with Monte-Carlo (MC) simulations
- Fake background is estimated with data-driven approach
- Invariant mass is used as discriminant variable ($m^2 = E^2 - \mathbf{p}^2$)
- Comparisons between data and MC simulations reveal new phenomena

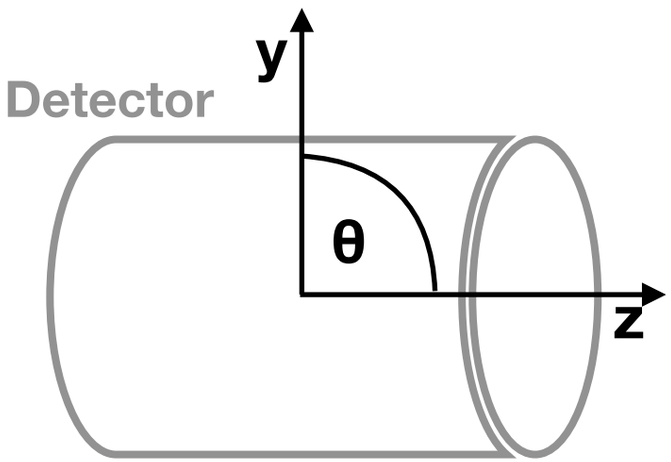
Kinematical Distributions

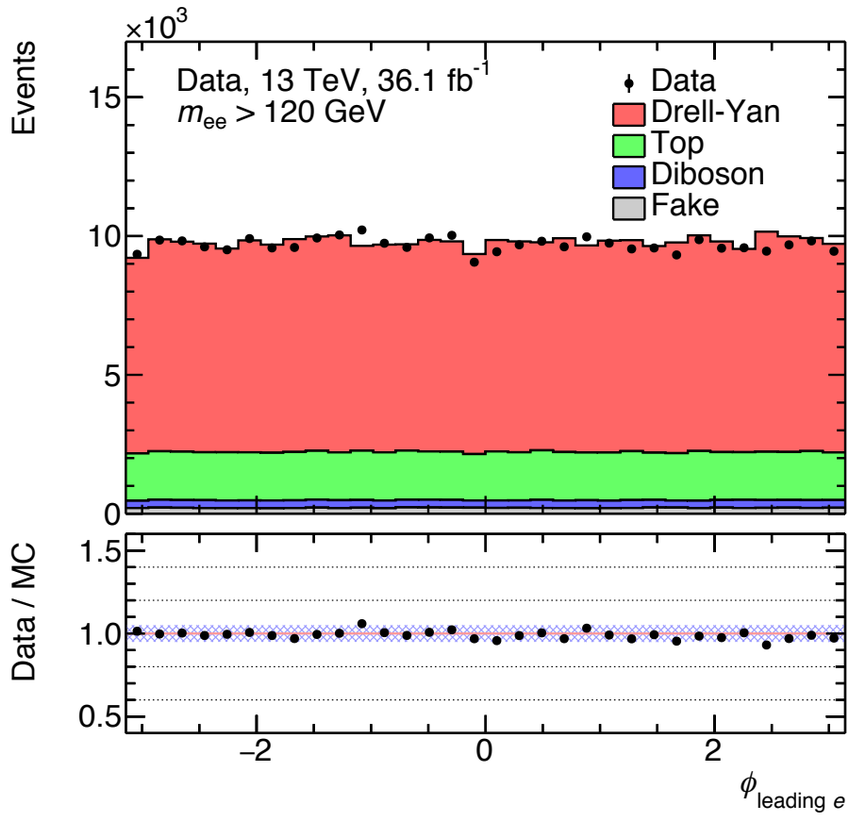
Azimuthal angle

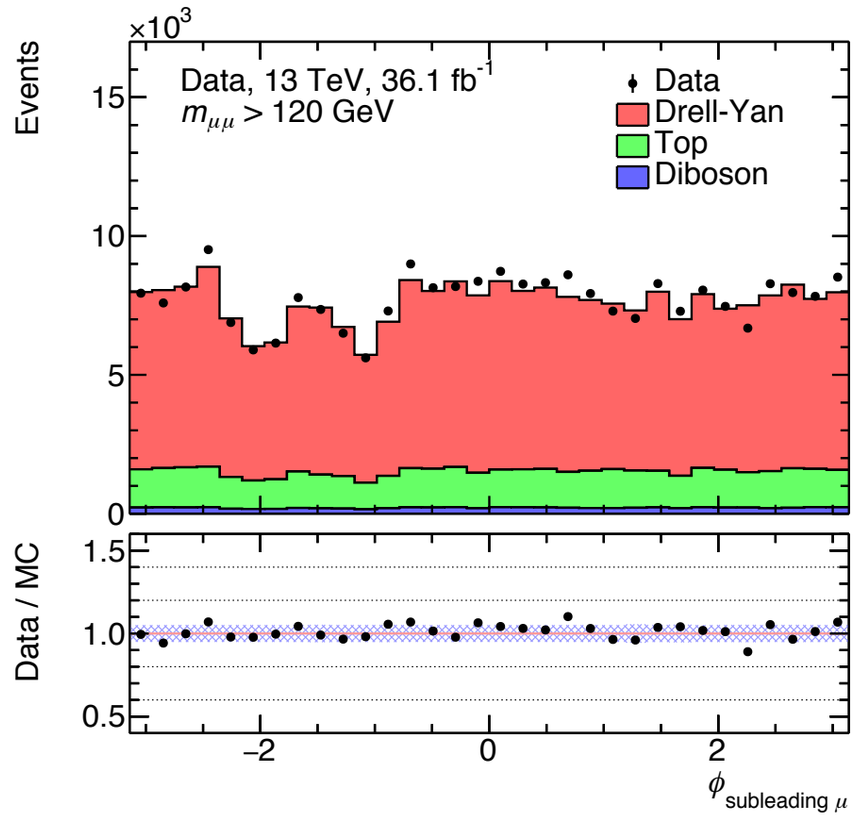


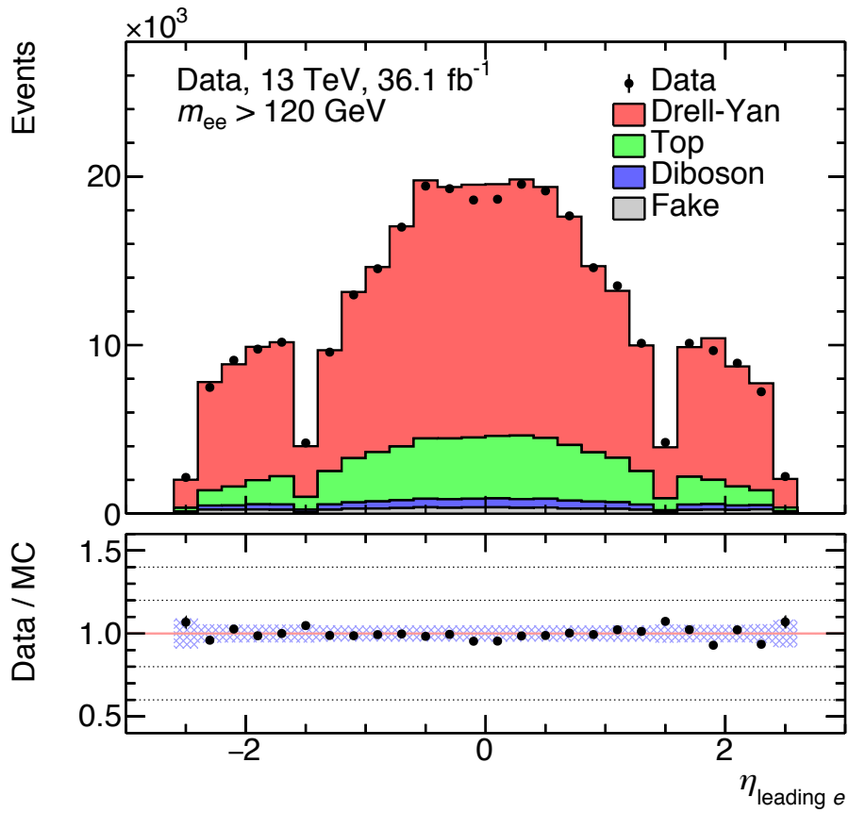
Pseudorapidity

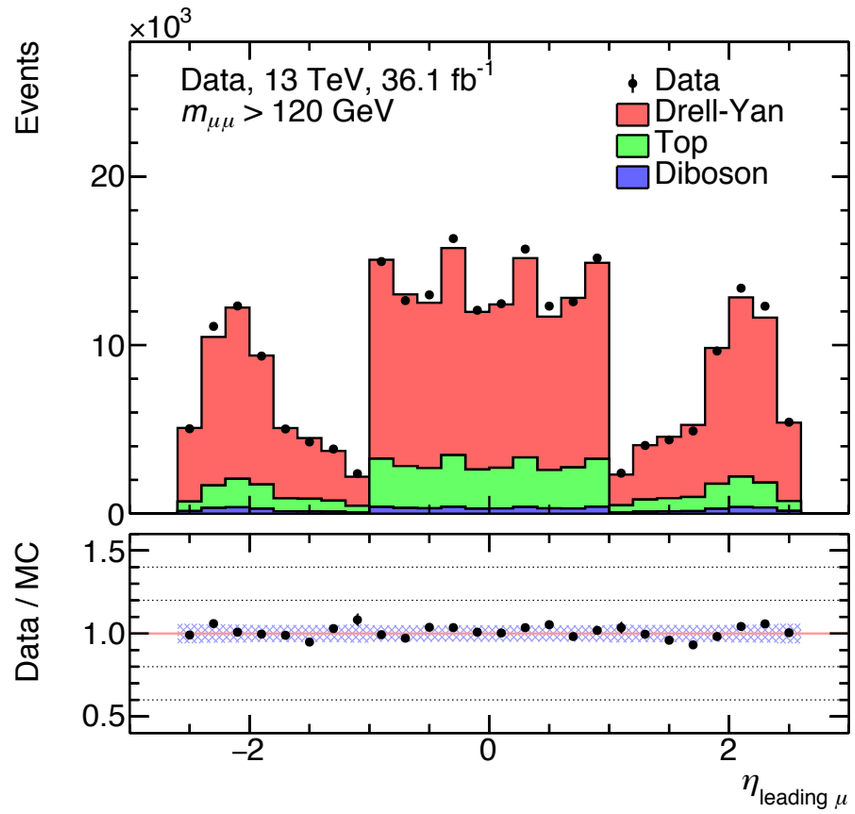
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



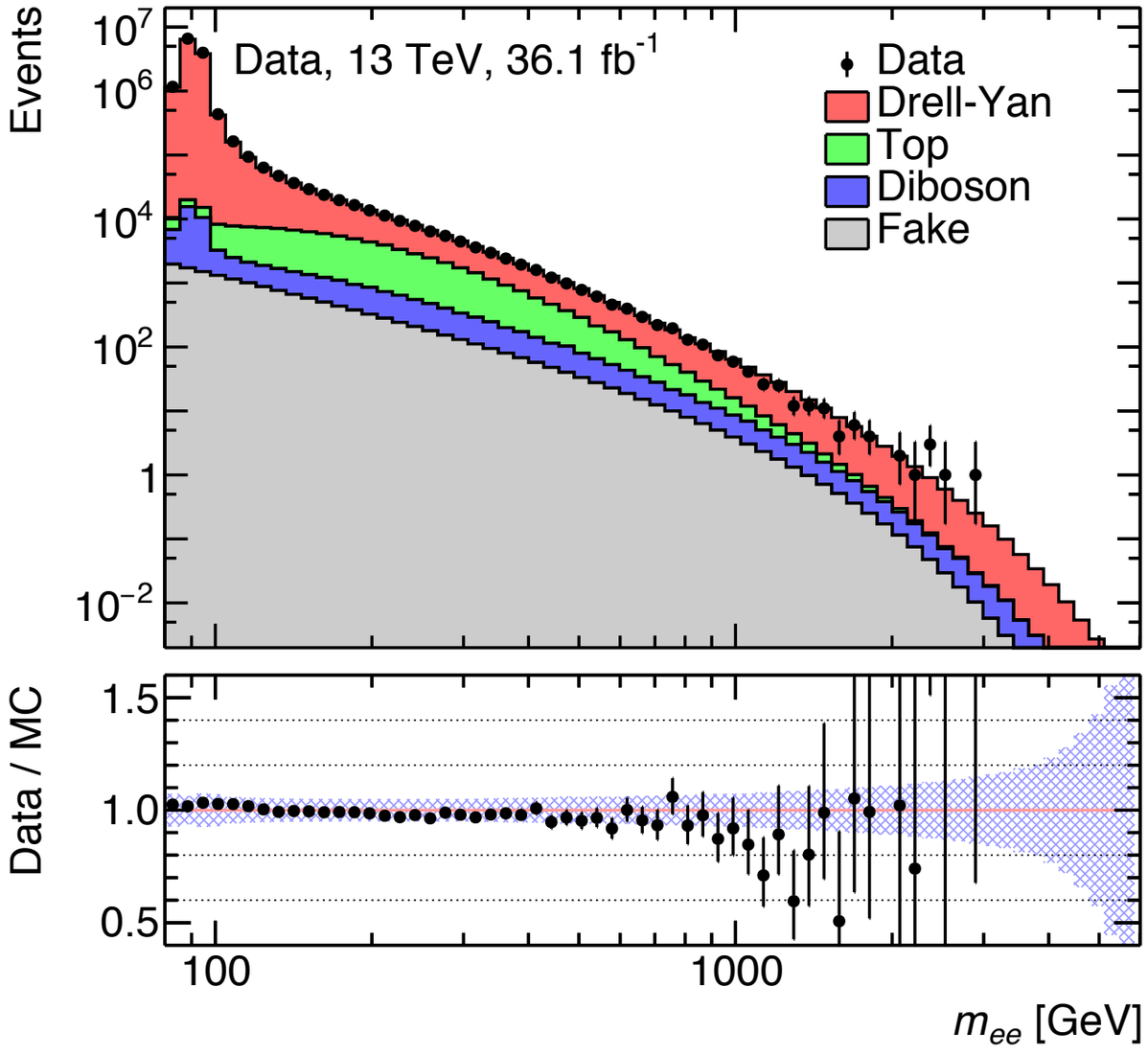


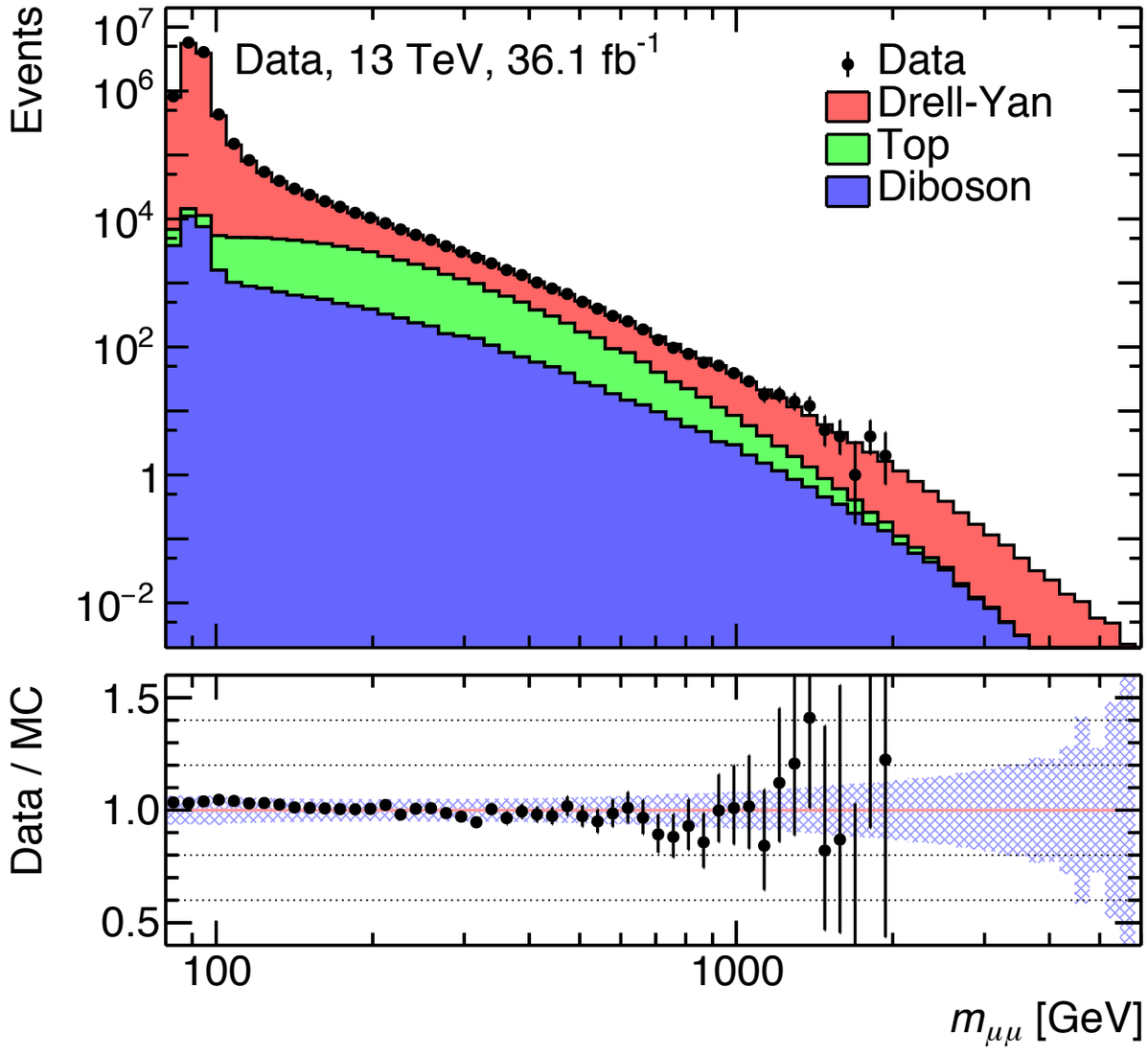






Invariant Mass Spectra





- No obvious resonance was observed

  ➡ Statistical interpretation

Statistical Interpretation

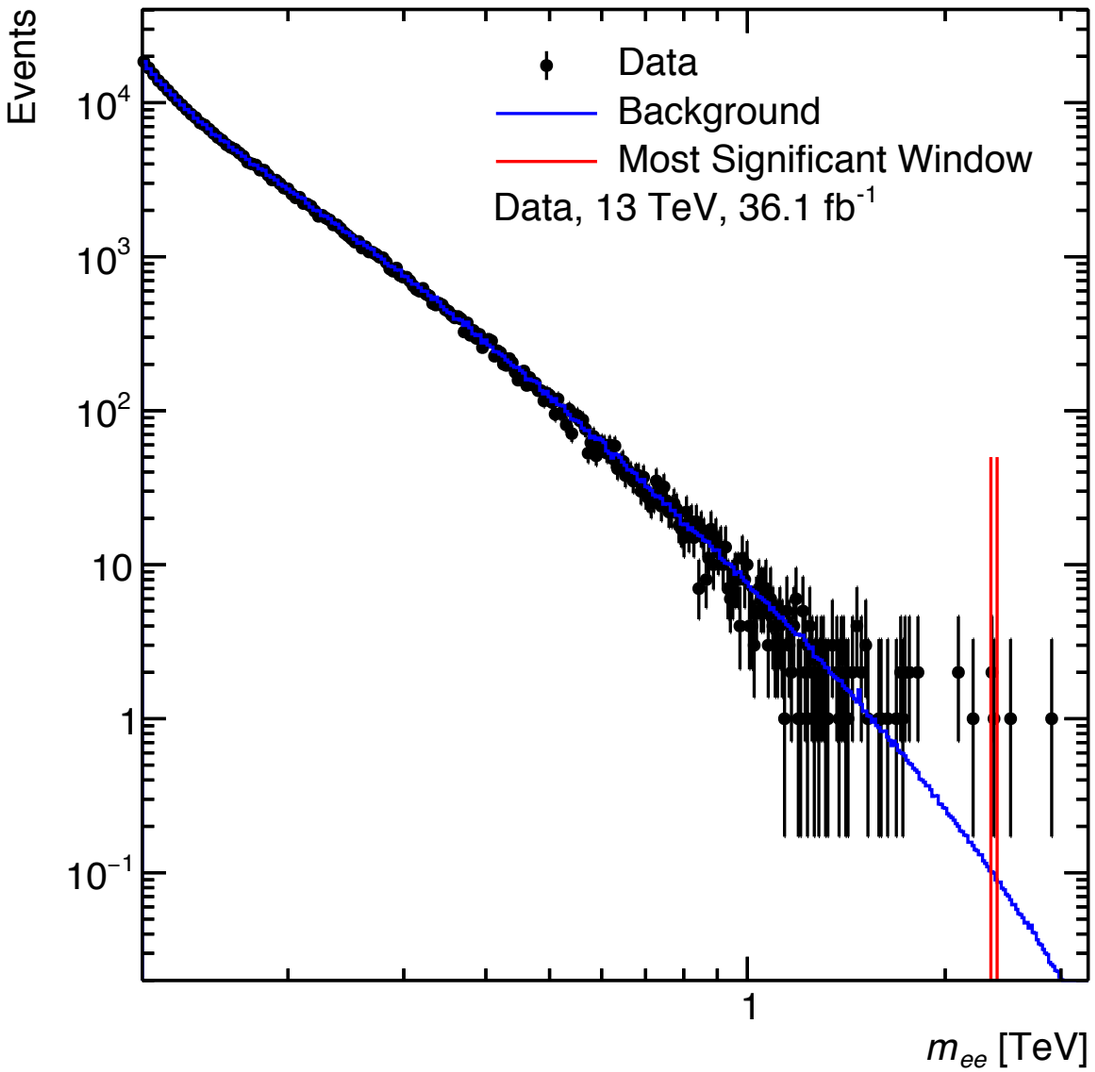
- In a counting experiment the observed data is distributed according to a Poisson distribution
- If d is the number of observed events in data and b the number of expected background events the probability describing the discrepancy between d and b can be expressed via

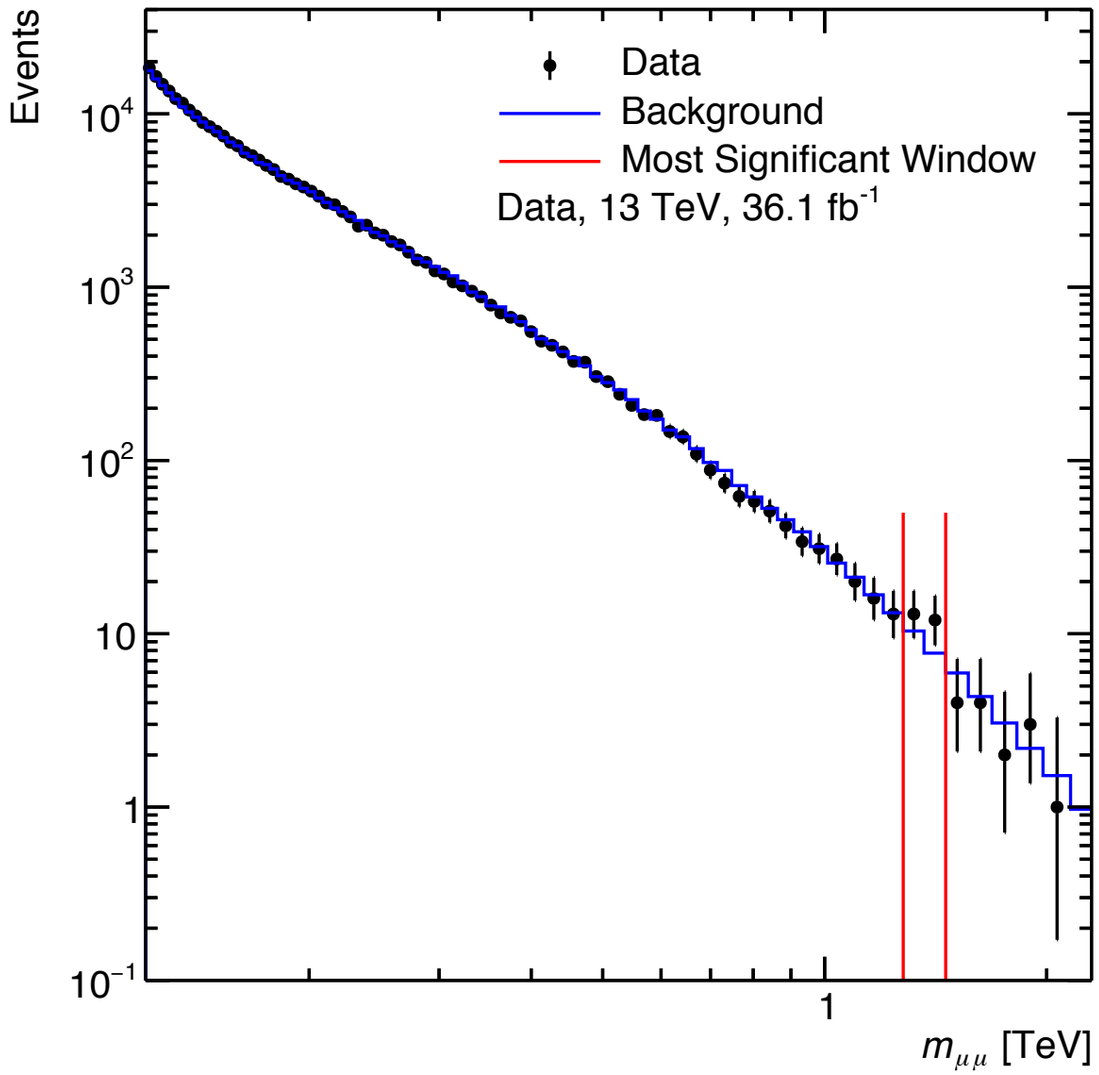
$$P(d \geq b) = 1 - P(d-1 \leq b) = 1 - \sum_{k=0}^{d-1} \mathrm{Poisson}(k; b)$$

- The bins in the invariant mass spectrum are scanned with windows of different widths
- A p-value is calculated for each of these windows

➡ BumpHunter method

BumpHunter Result





- Dielectron: largest discrepancy at around 2.4 TeV with local p-value of 2.7σ
- Dimuon: largest discrepancy at around 1.3 TeV with local p-value of 1.4σ

➡ Global p-values insignificant

Exclusion Limits

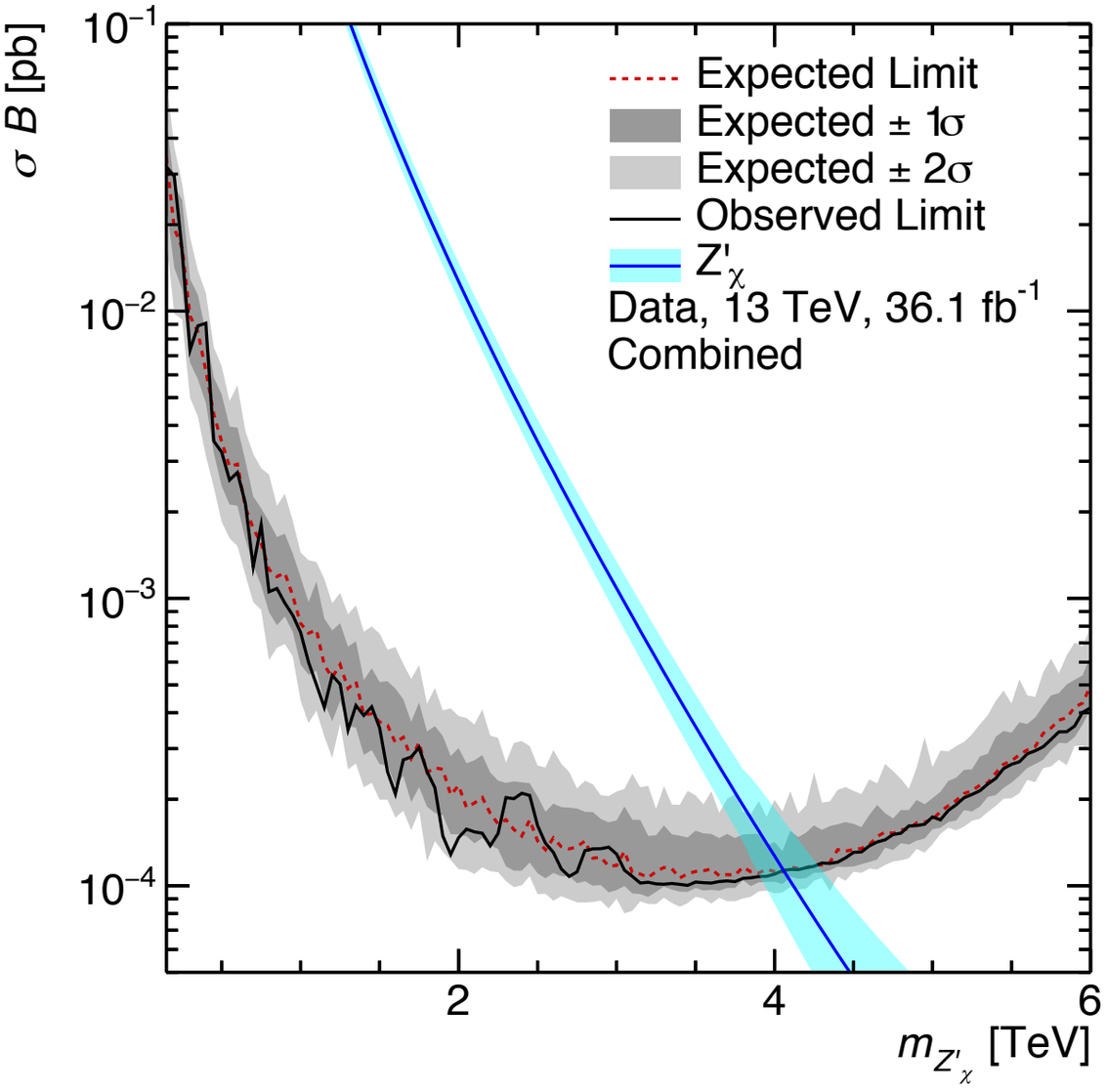
- Up to which mass can a resonance be exclude with a certain credibility?
- A MC simulation of signal process is used to estimate the expected number of background and signal events n
- The following likelihood can be constructed where Θ is the signal strength and **u** the uncertainties

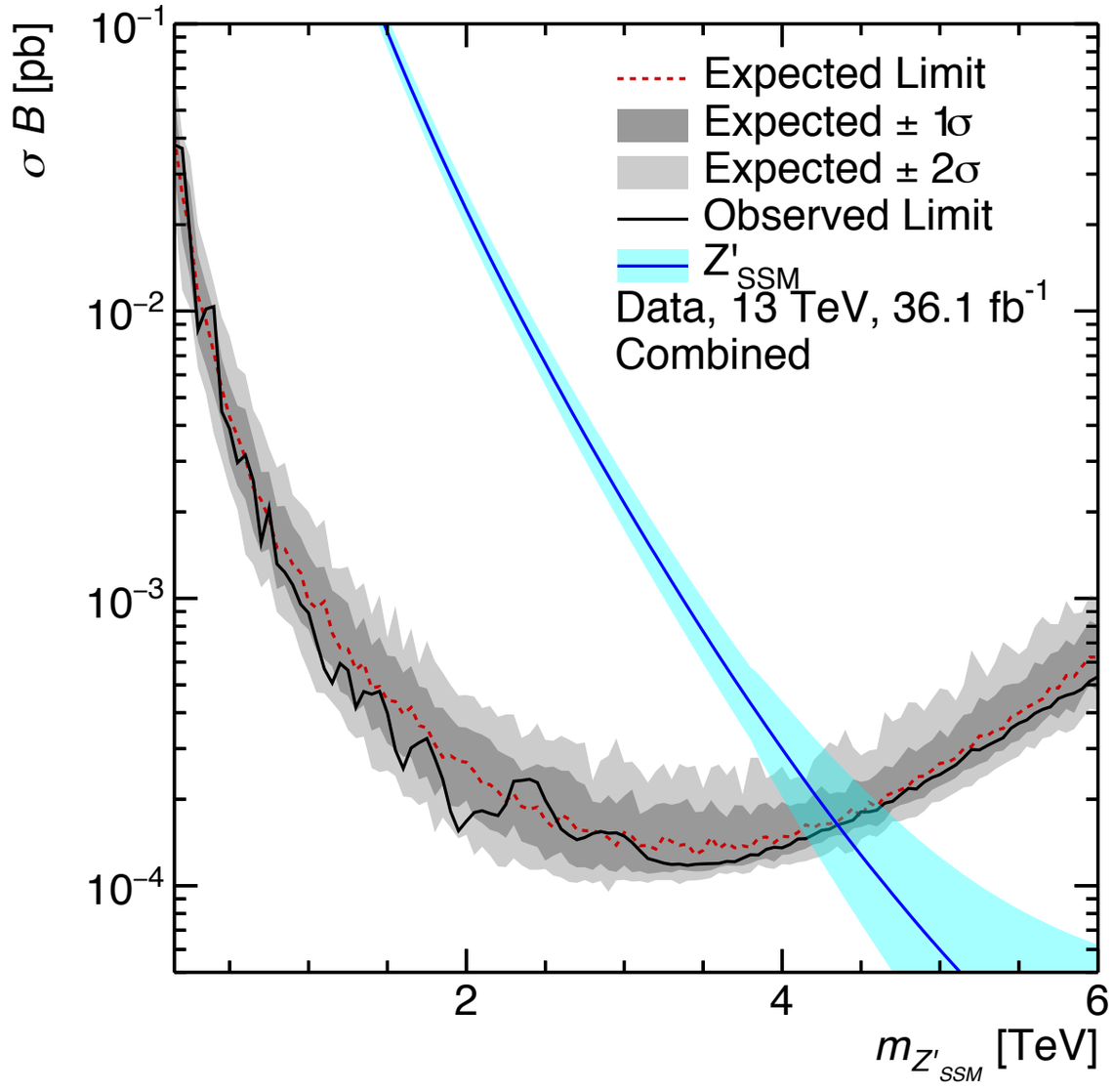
$$P(\vec{d}|\Theta,\vec{u}) = \prod_{i=1}^{N_{\mathrm{Bins}}} \frac{d_i^{n_i(\Theta,\vec{u})} e^{-n_i(\Theta,\vec{u})}}{d_i!}$$

- However, the interesting quantity is $P(\Theta,\vec{u}|\vec{d}) = \frac{P(\vec{d}|\Theta,\vec{u})P(\Theta,\vec{u})}{P(\vec{d})}$
- Integration over uncertainties

$$P(\Theta|\vec{d}) = \int P(\Theta,\vec{u}|\vec{d})d\vec{u} = N\int P_{ee/\mu\mu/\mathrm{Comb}}(\vec{d}|\Theta,\vec{u}) \prod_{i=1}^{N_{\mathrm{Sys}}} \frac{1}{\sqrt{2\pi}} e^{\frac{-u_i^2}{2}} d\vec{u}$$

Exclusion Limits





- Intersection of theoretical cross section and observed limit define lower limit on Z' mass (credibility interval of 95%)
- The E_6-motivated model yields a limit of 4.06 TeV
- The SSM yields a limit of 4.35 TeV

Conclusion

- The SM is not complete

  ➡ New physics has to be out there

- Presented the ATLAS experiment at the LHC

- Showed some details of the analysis of dilepton final states

- Statistical interpretation of the invariant mass spectrum has been presented

- Exclusion limits have been derived