Exploring EFT with ML at the LHC

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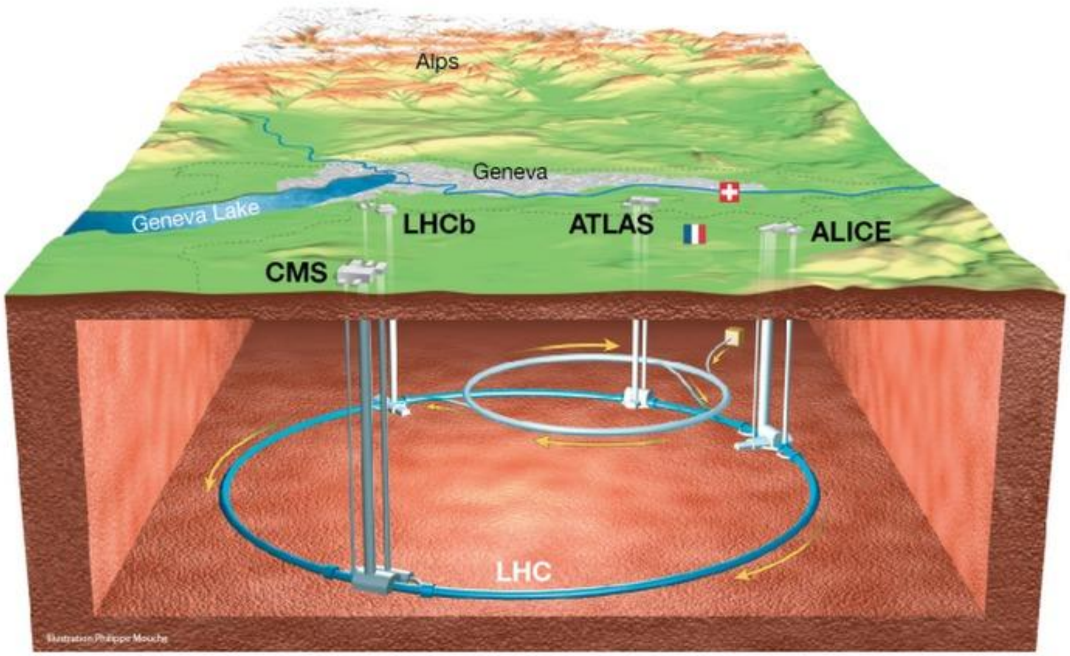
Machine Learning at GGI workshop

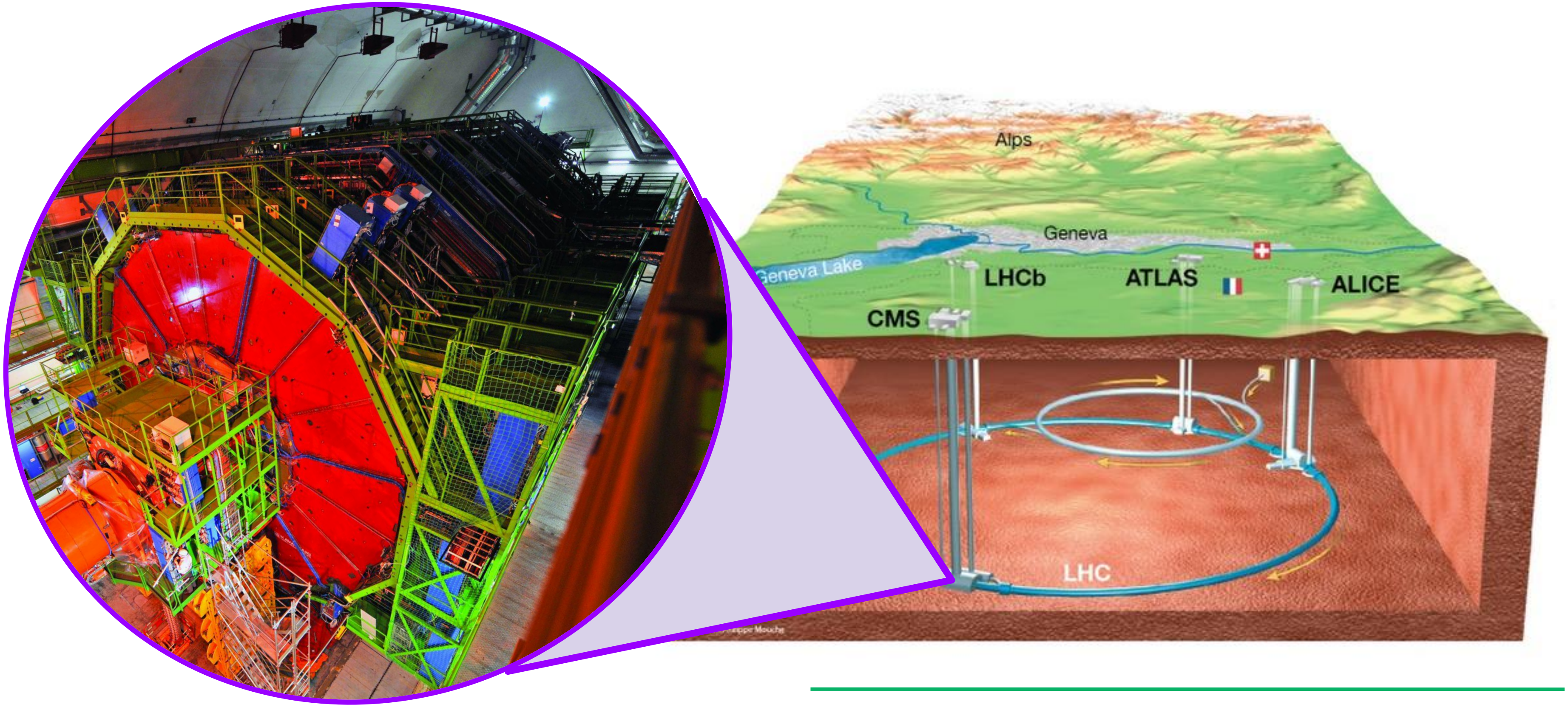
Florence, 31st August 2022

At the LHC

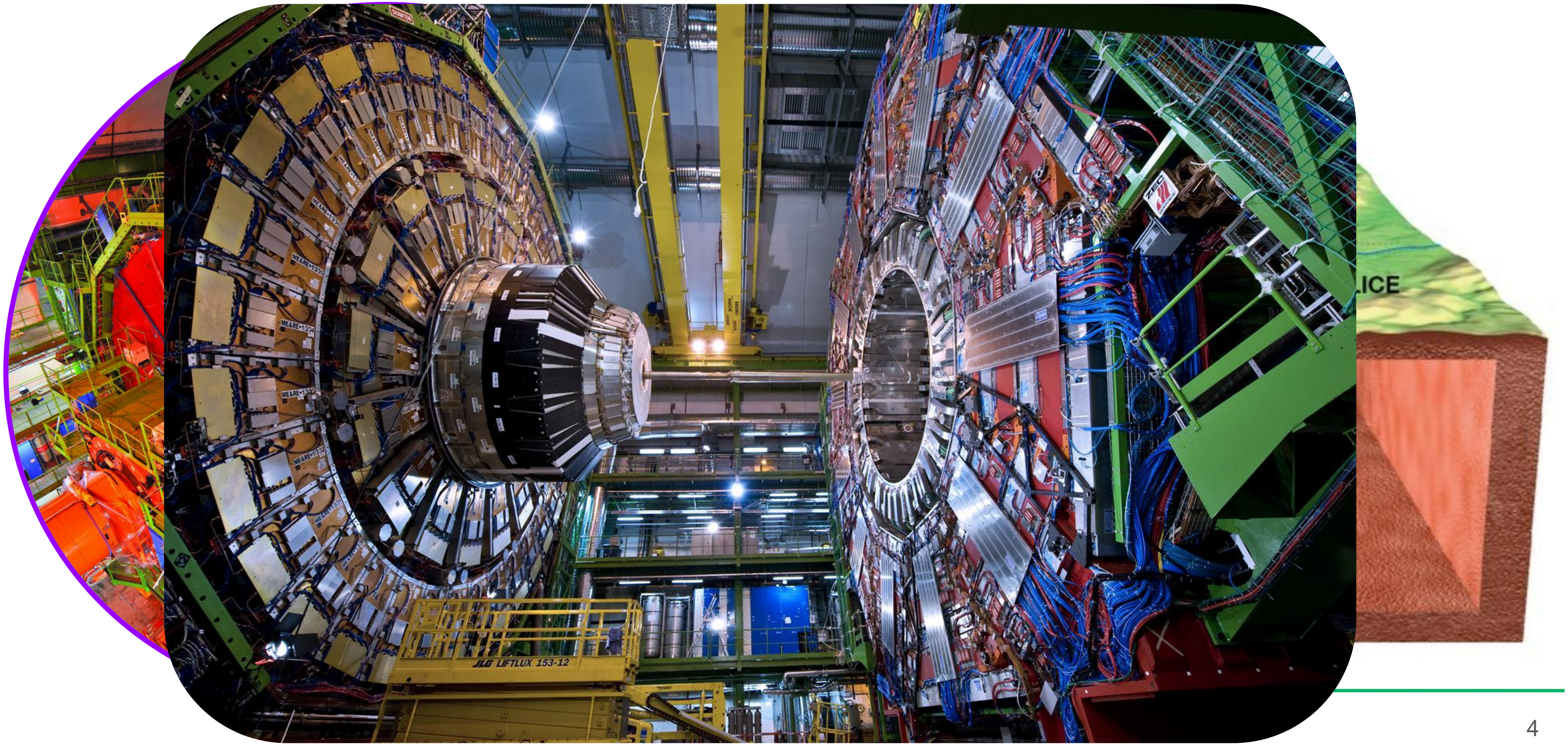
Goal: uncover what the universe is made of and how it works



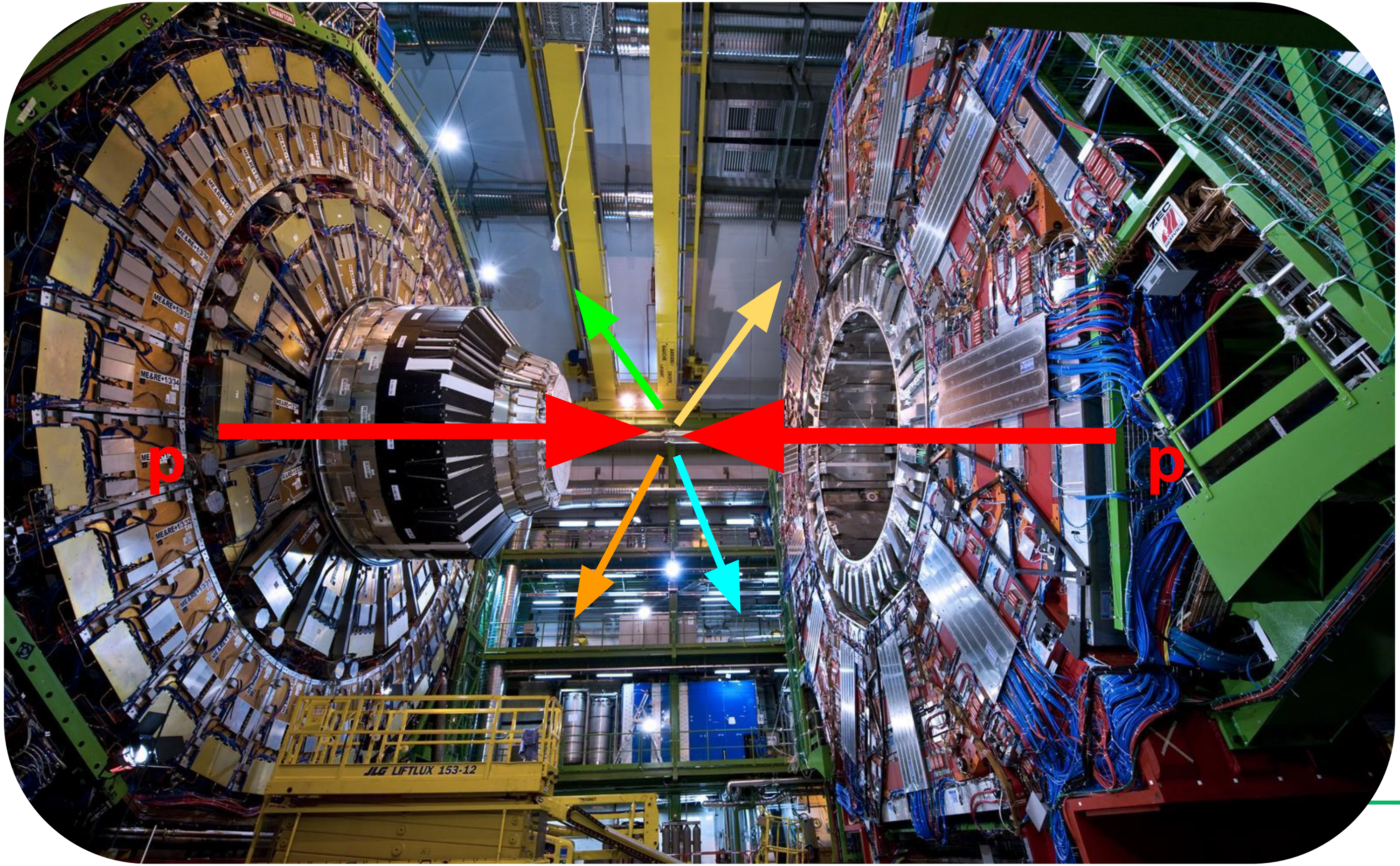
The CMS Experiment



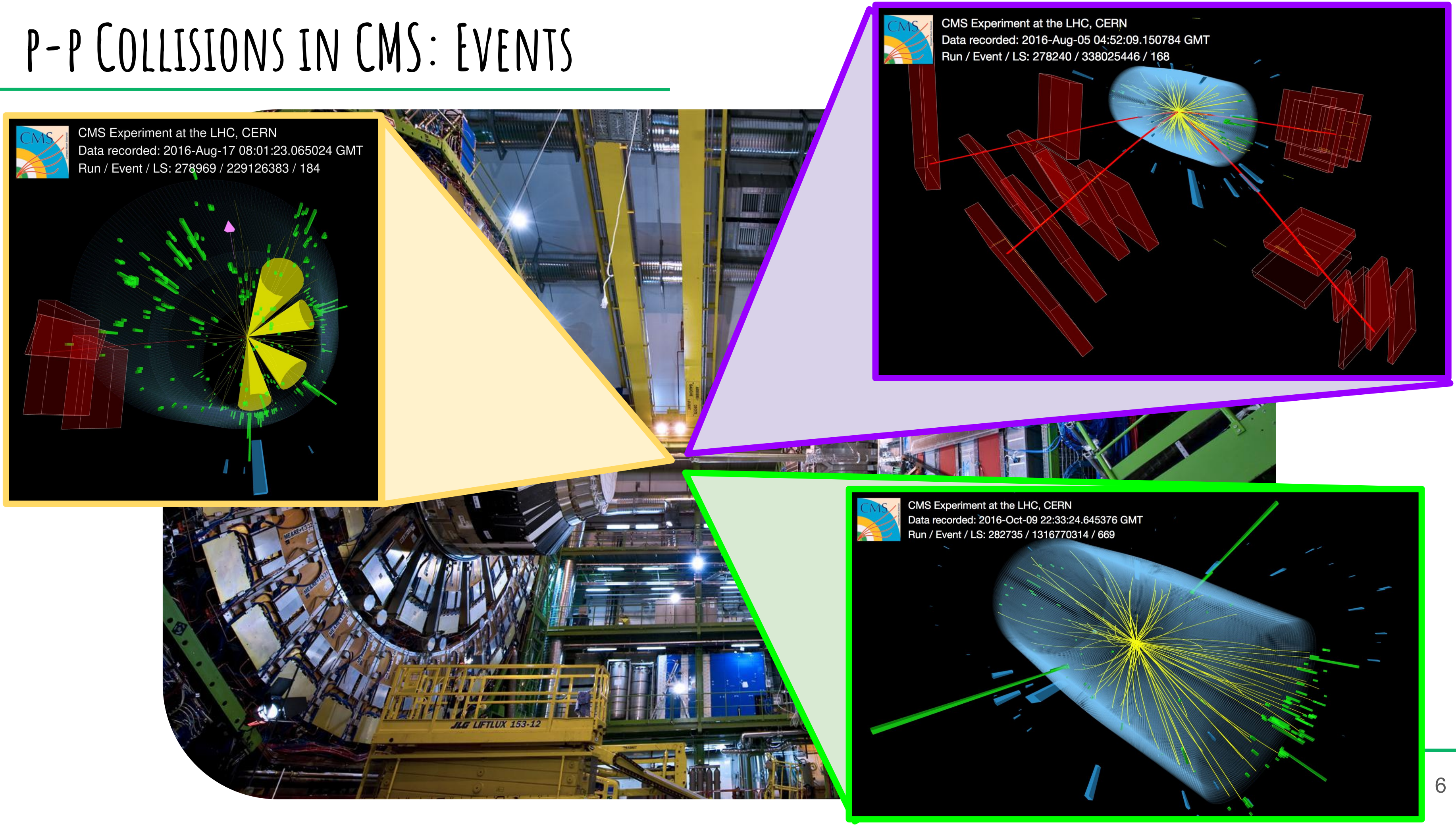
The CMS Experiment Detector



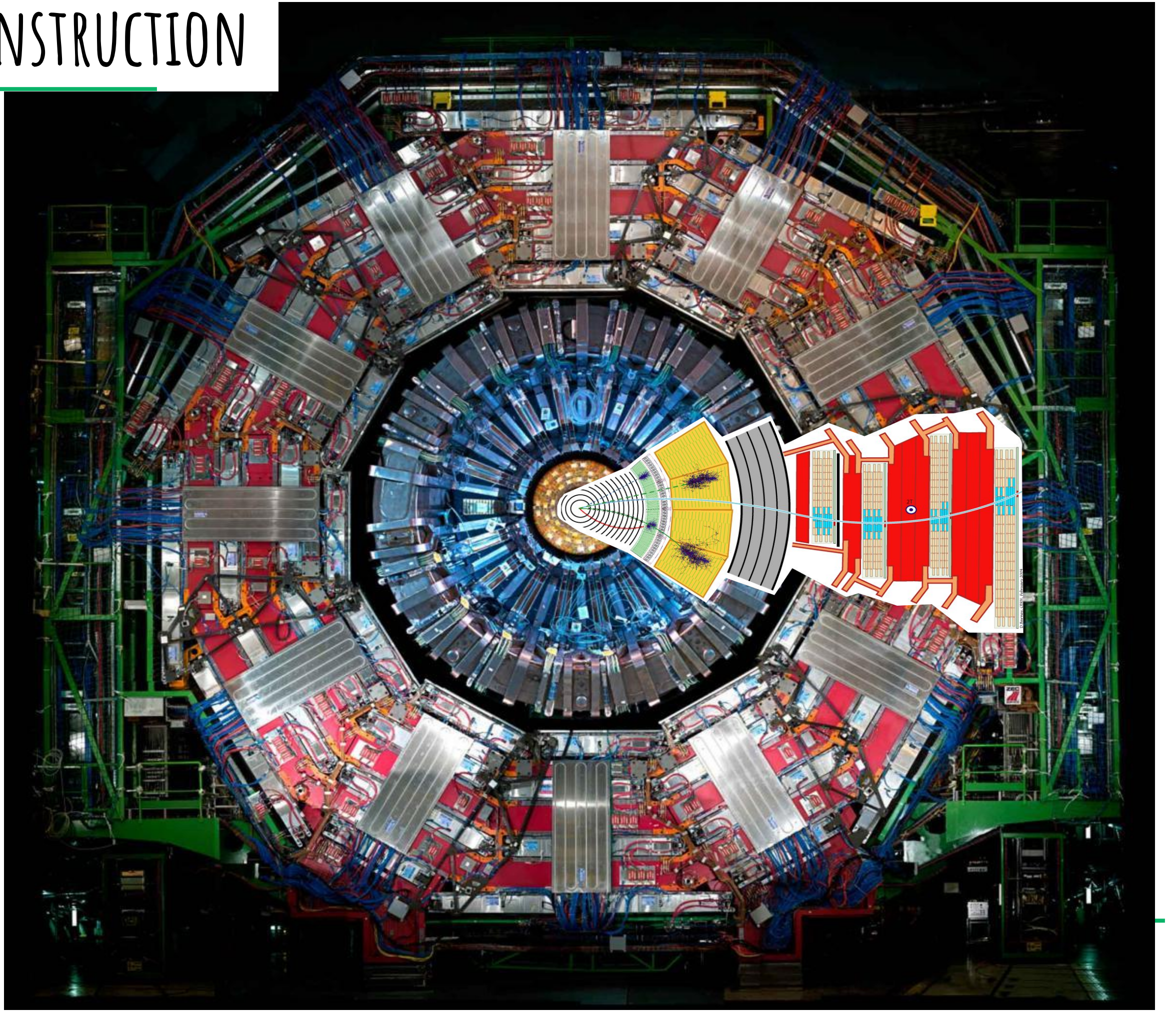
p-p Collisions in CMS



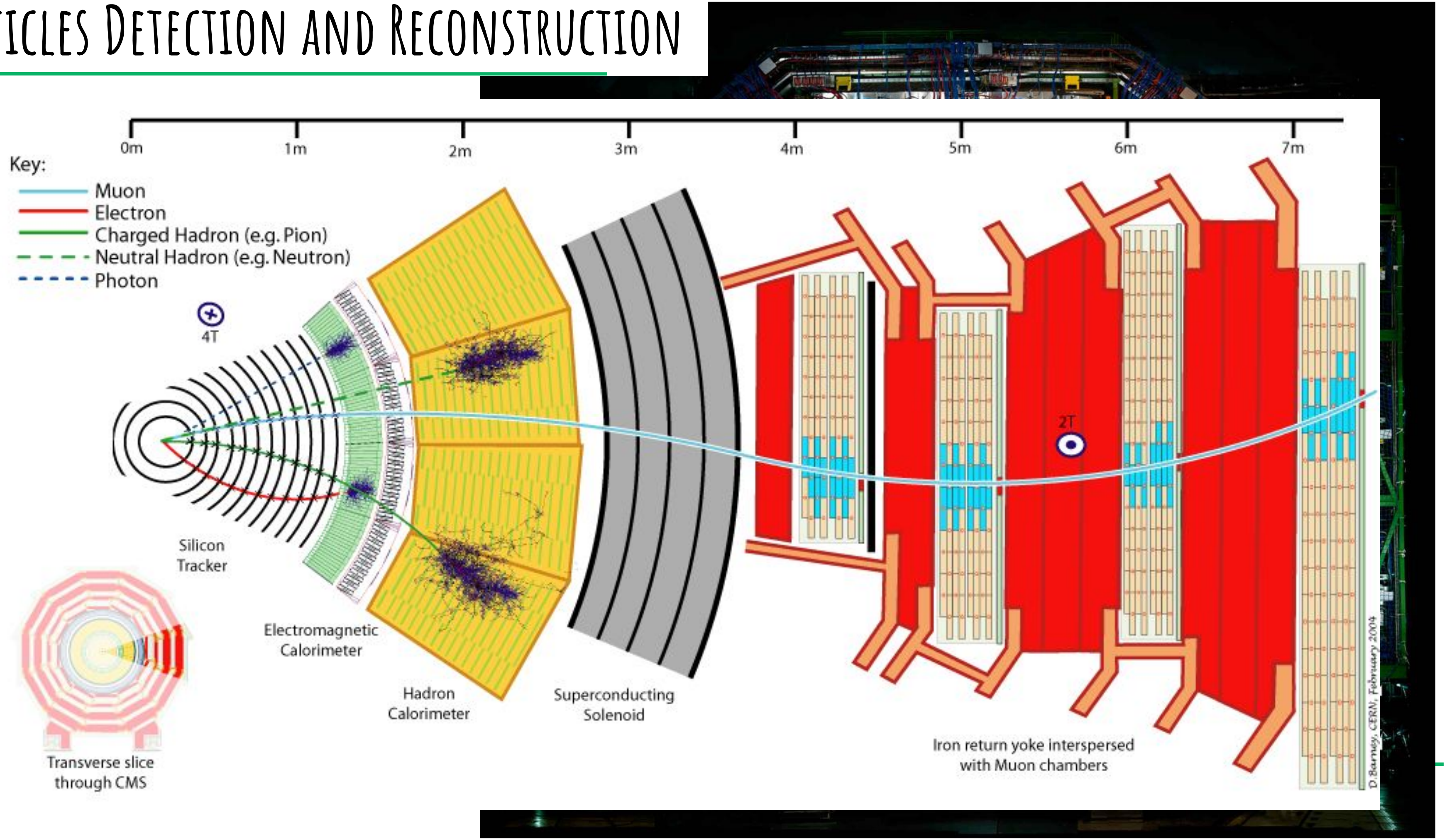
p-p Collisions in CMS: Events



Particles Detection and Reconstruction



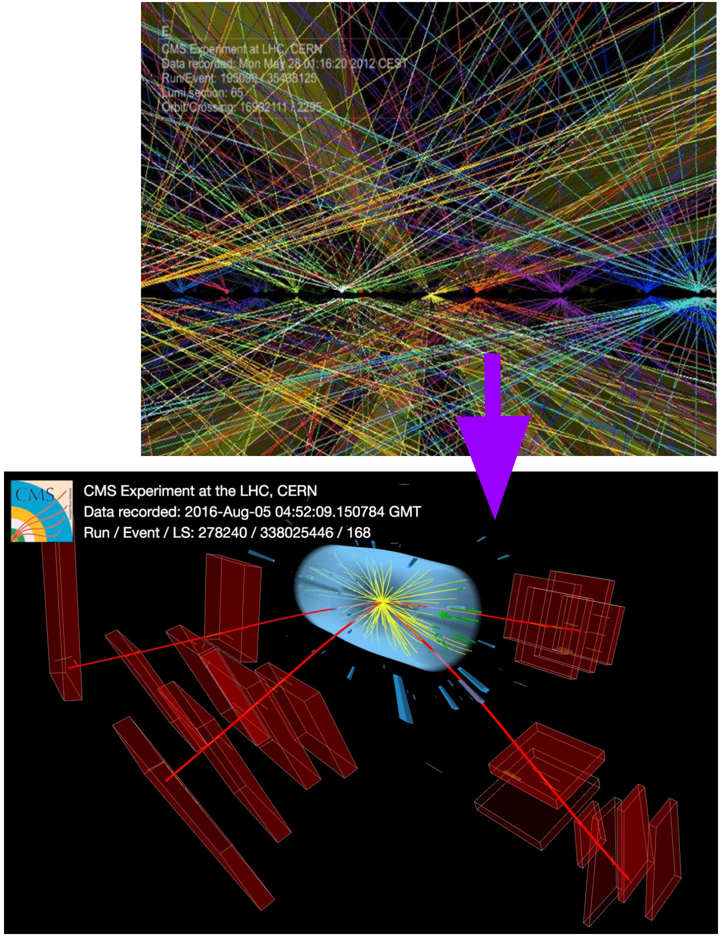
Particles Detection and Reconstruction



Events Selection

- **Trigger**:
  - collision rate at LHC 40 MHz
  - need to record only potentially interesting events

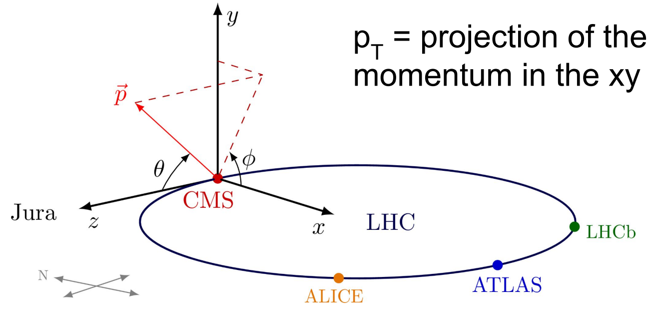
- **Offline selection**:
  - according to the **signature** of processes of interest, select events with certain characteristics (e.g. H→4l)
  - from particles reconstructed in detectors (final decay products), reconstruct **information** about **particles generated in the collisions** (e.g. Higgs or vector bosons)



Data Format

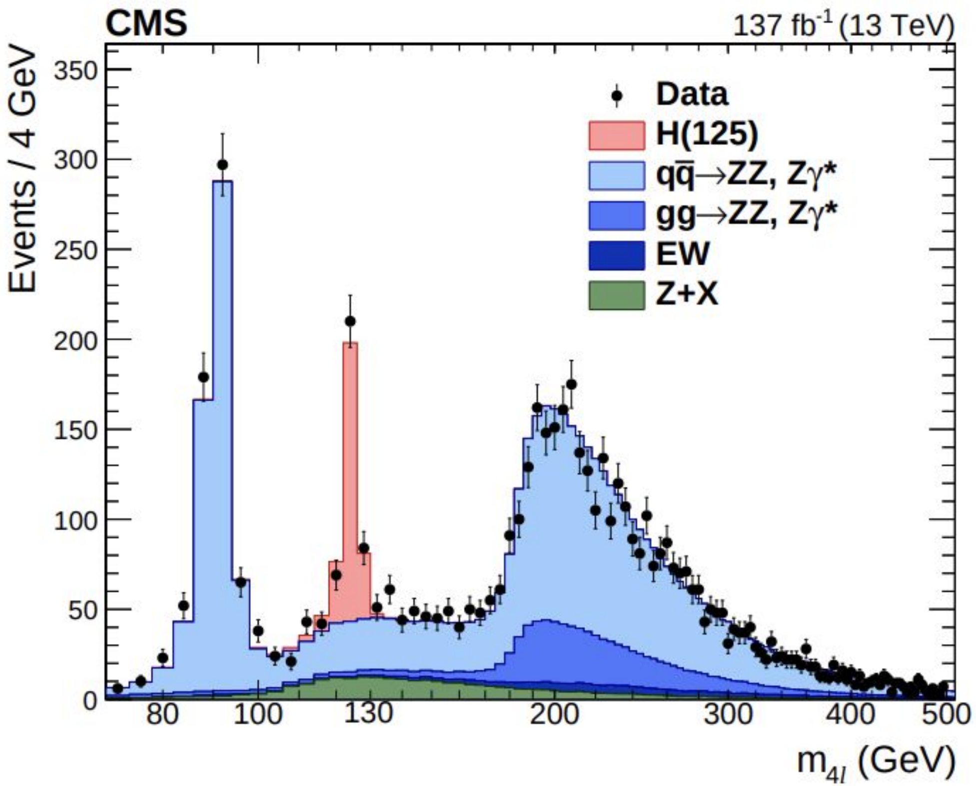
- Analysis is performed with **kinematic information** of selected particles
- Information in each event:
  - type of the particle
  - momenta
  - angles
  - invariant mass
  - …
- (MC only) per-event weights (normalization to process cross-section, corrections…)
- Format: usually .root files (tree structure), recently also pandas data frames
- Both **data** and Monte Carlo **simulation** (MC) have the same structure!

event #	lep_1 ID	lep_2 ID	lep_1 p_T [GeV]	lep_1 p_T [GeV]	m_{ZZ} [GeV]
108017	-11	11	22.42	69.22	122.48
108029	-11	11	54.52	38.88	123.64
108033	-13	13	35.66	41.013	108.98



p_T = projection of the momentum in the xy plane

Data-MC Plot



MC simulation obtained from the knowledge we have of the **Standard Model of Particle Physics**!

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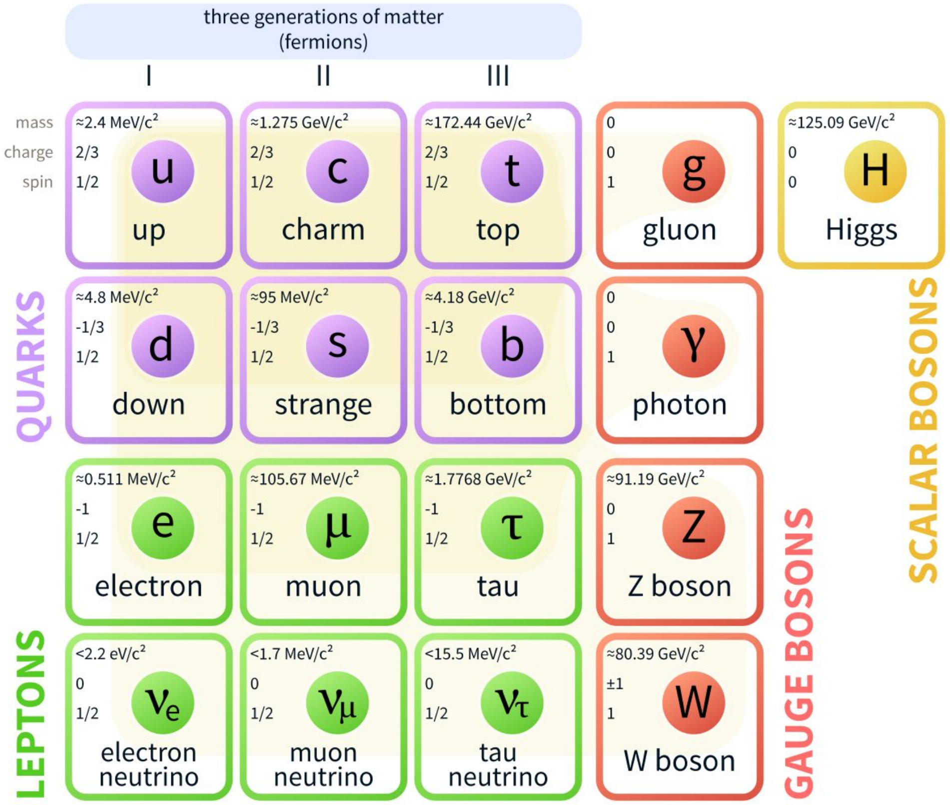
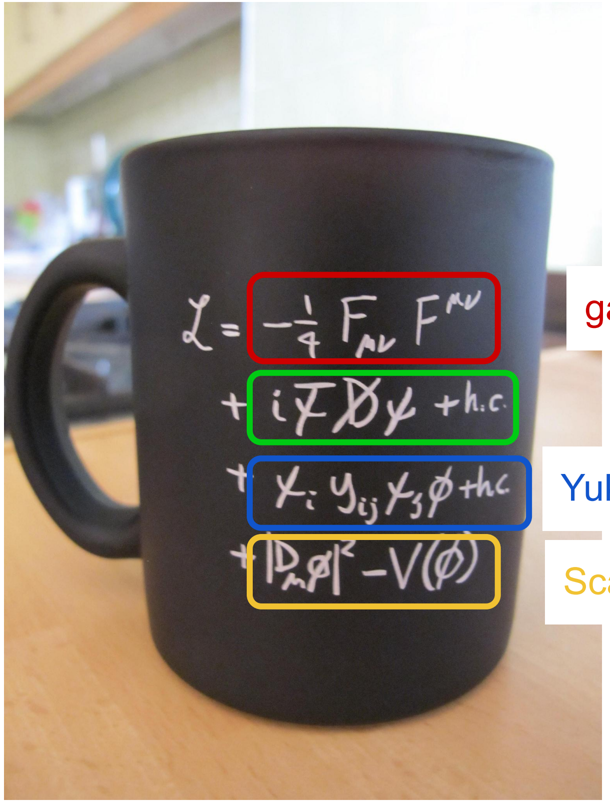
The Standard Model of Particle Physics

- Best understanding of how building blocks of the universe (fundamental particles and forces) are related to each others
- **Matter particles**:
  - 2 types: leptons and quarks organized in 3 generations
  - stable matter in the universe, made from 1st generation
- 3 of **fundamental forces**: electromagnetic, weak, strong. Result from the exchange of force-carrier particles
- The **Higgs boson**, responsible for the masses of elementary particles via the Brout-Englert-Higgs mechanism



The Standard Model of Particle Physics

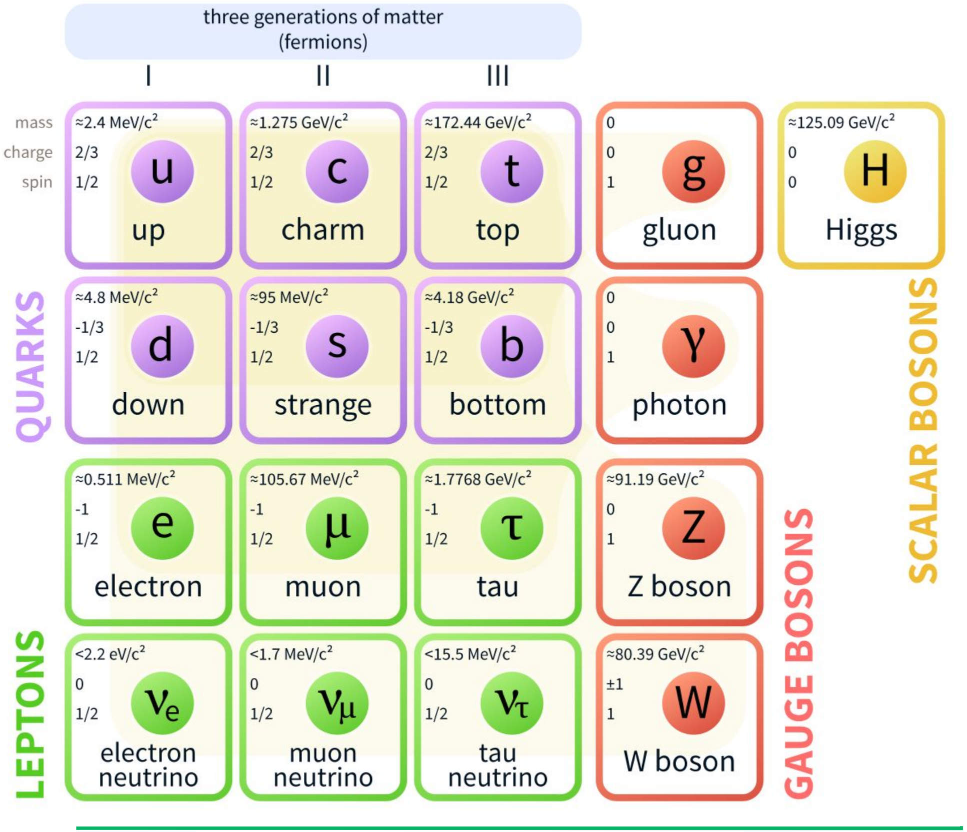


gauge bosons

fermions

Yukawa interactions

Scalar potential



Statistical Analysis

Likelihood function:

Probability Density Function characterizing the set of experimental observables considered in the analysis, given the parameters of the model

Signal strength modifier: $\sigma = \mu \cdot \sigma_{SM}$

Systematics uncertainties incorporated as nuisance parameters: $\theta = \{\theta_1, \ldots, \theta_n\} \rightarrow$ $p_i(\tilde{\theta}_i|\theta_i)$

$$\mathcal{L}(data|\mu, \theta) = \prod_c \mathcal{L}_c(data|\mu \cdot s(\theta) + b(\theta)) \cdot \prod_i p_i(\tilde{\theta}_i|\theta_i)$$

measured or pseudodatasets

c = channels (e.g. analysis categories)
s = signal
b = background

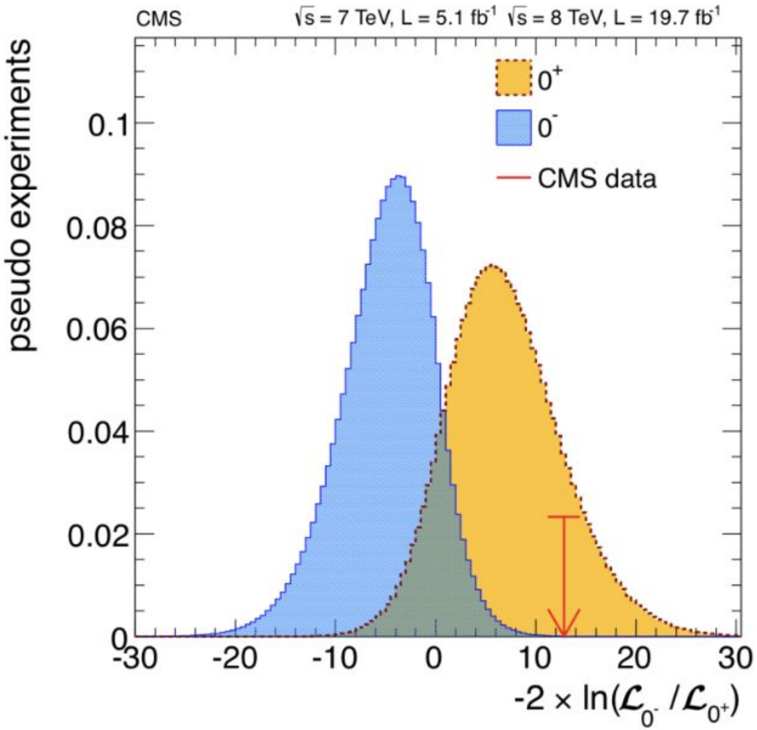
Hypothesis Testing

- test Hp on the basis of the observed data
- test statistics t: **likelihood ratio**
  - evaluate t according to the null (H_0) and alternative hypothesis (H_1)
  - **expected distributions of t** under the two Hp, generated as pseudodatasets from PDFs in the Likelihood

$$t = -2ln\frac{\mathcal{L}(data|\mu,\hat{\theta}_{\mu})}{\mathcal{L}(data|\hat{\mu},\hat{\theta})}$$

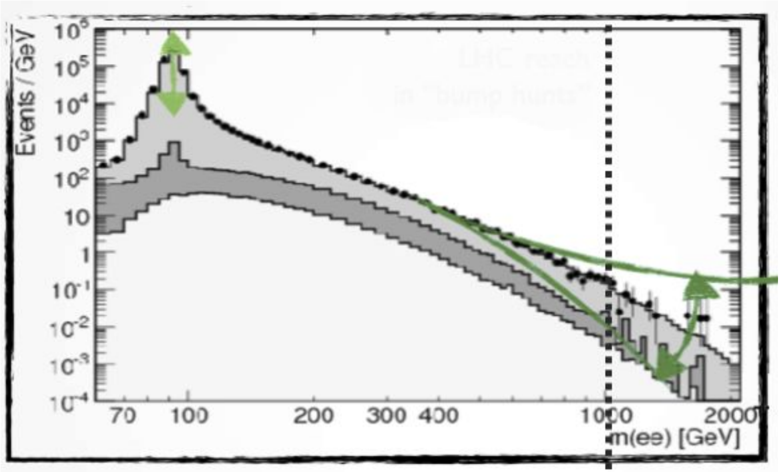
Used for:

- quantifying an excess
- setting upper limits
- parameters measurement



Standard Model, but not (yet) theory of everything

- SM leaves many **open questions**!
  - Gravity not included
  - dark matter
  - matter-antimatter asymmetry, …
- search for **new physics**:
  → can indicate the direction for a more complete theory
  - it can manifest as resonance (peak on the invariant mass distribution)
  - or **deviations** in kinematic distributions



Thanks Robert for this image

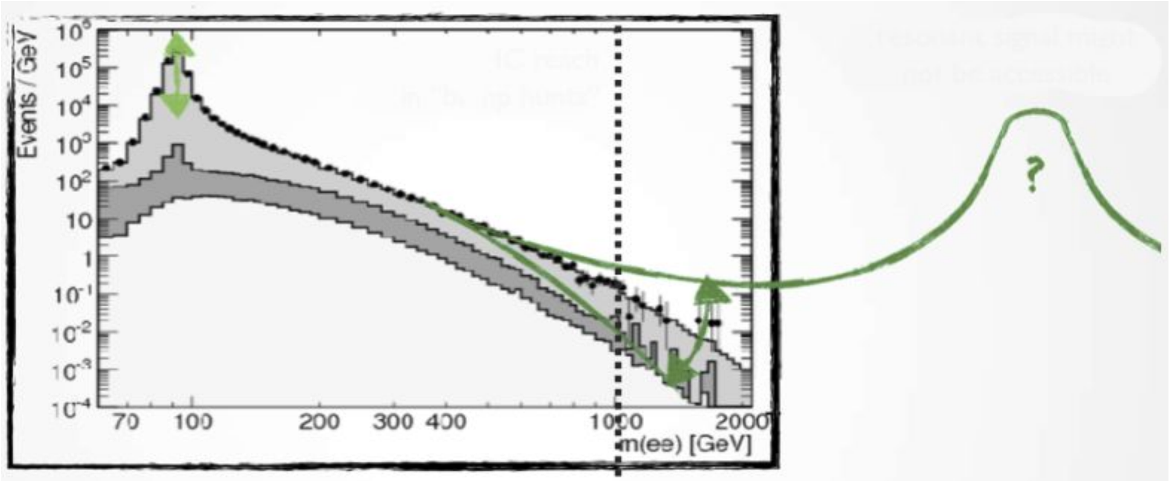
can be investigated with an Effective Field Theory approach

What is an Effective Field Theory ?

- an **approximation**
  - includes the appropriate degrees of freedom that describe the physical phenomena
  - ignores the substructures and the degrees of freedom of shorter distances (higher energies)

- only **valid** up to a certain regime

- useful to study **deviations** from the SM



How is EFT useful ?

- **Parametrizes** effect of physics at an energy scale Λ on observables at smaller energies **E<<Λ**, as a set of local **operators**

- Form of operators
  - fixed by light particles and symmetry structure of the theory
  - entirely independent of the high-energy model

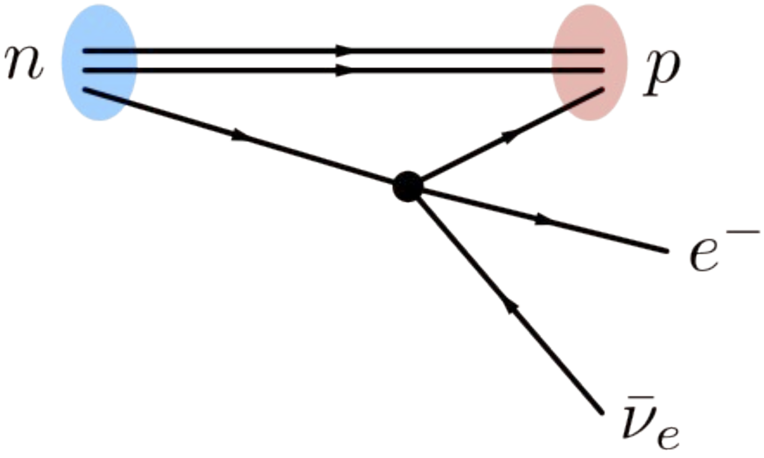
Λ — scale of the high energy theory

E<<Λ — regime of validity of the EFT

Taylor expansion of the Lagrangian in E/Λ

Operators enter the expansion weighted by **Wilson coefficients**, that describe new physics effects up to some order in E/Λ

An Example: Fermi's interaction



- Introduced to explain β decays
  - point-like interaction
  - describes weak interactions well!
- scale **$\Lambda = m_W \sim 80$ GeV**

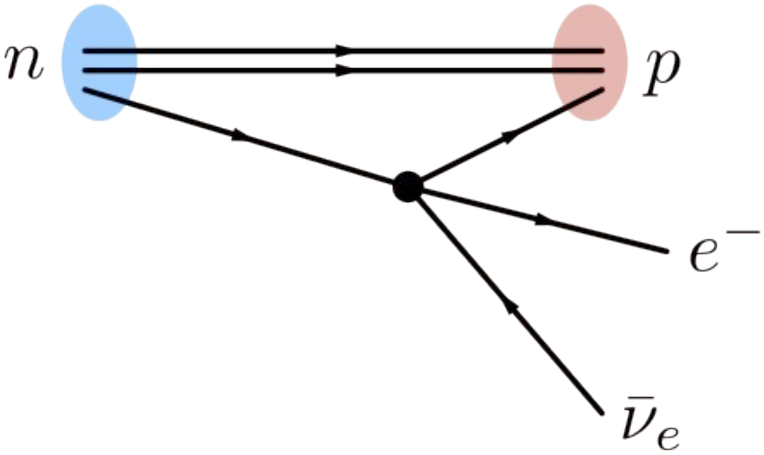
But:

- σ ~ E^2
  - cross section grows without bound!
  - → theory not valid at energies higher than Λ
- → effective explanation of higher energy theory

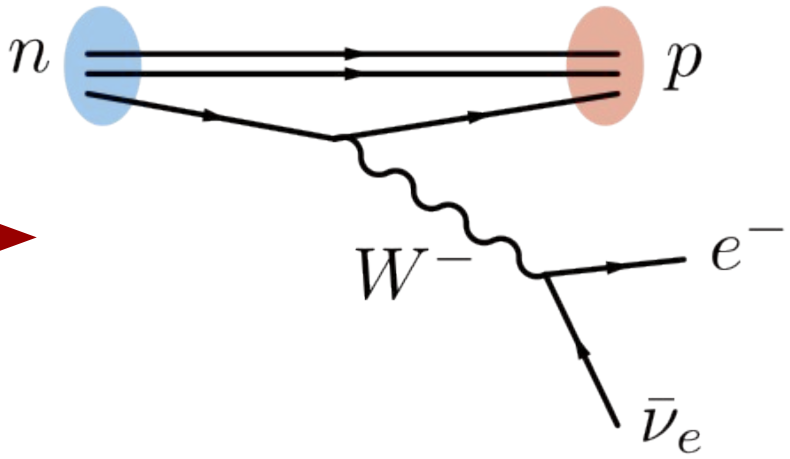
An Example: Fermi's interaction

Fermi's interaction: EFT

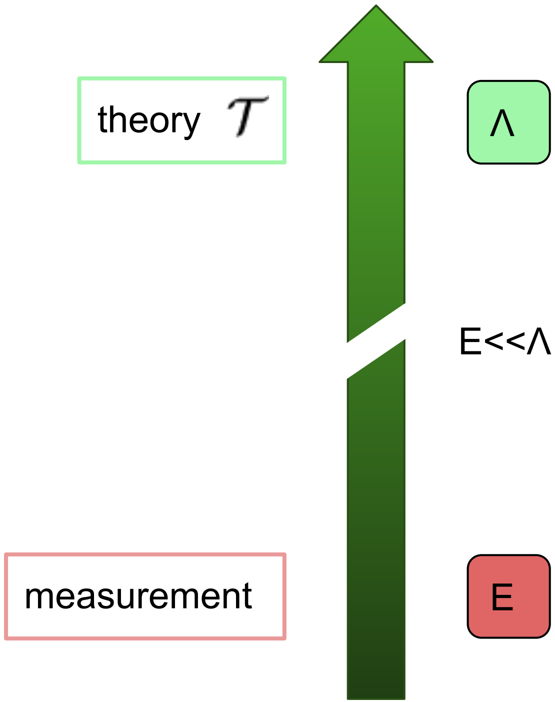
$\Lambda = m_W$



EW theory: higher energy theory



EFT bottom-up approach



knowledge of $\mathcal{T}$ not required

information on $\mathcal{T}$ can be inferred by measuring c_i

model with fields and symmetries $\xrightarrow{E/\Lambda}$ $\mathcal{L}_{EFT}^{(n)}$

- all allowed operators at $(E/\Lambda)^n$
- free parameters c_i

EFT to go Beyond the SM: SMEFT

Assumptions:

- new physics is nearly decoupled: **Λ >> E**
- at the accessible scale, **SM fields and symmetries** are respected

Taylor expansion in E/Λ :

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

$$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$$

Free parameters: **Wilson coefficients**

Gauge invariant **operators**, forming a complete, non-redundant basis

EFT to go Beyond the SM: SMEFT

neutrino mass

likely dominant new physics contribution

lepton number violating

interesting for specific LHC interactions (bosonic quartic couplings)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

$$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$$

Free parameters: **Wilson coefficients**

Gauge invariant **operators**, forming a complete, non-redundant basis

SMEFT OPERATORS

Warsaw basis: dim 6 operators

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

(SM)EFT to investigate new physics!

- **describes BSM effects** at the LHC in scenarios where BSM is out of colliders reach
- is a proper QFT, with regularization/normalization schemes
- minimal commitment to a specific BSM theory
- systematically **includes all BSM effects**
- **universal language** for data interpretation

  (can be used in different experimental setup)

Ultimate goal: **measure as many EFT parameters as possible** to infer higher energy theory information
→ important: **combination** of different processes