The Comparison of Top-Antitop Monte Carlo Generators in Proton-Proton Collisions Data at Center-of-Mass Energy of 13TeV at the ATLAS Experiment

Afghan Physics Student Conference 2024

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10, September 2024

Top Quark

- The top quark was predicted by Kobayashi and Moskawa during the explanation of the observed CP violation in 1973

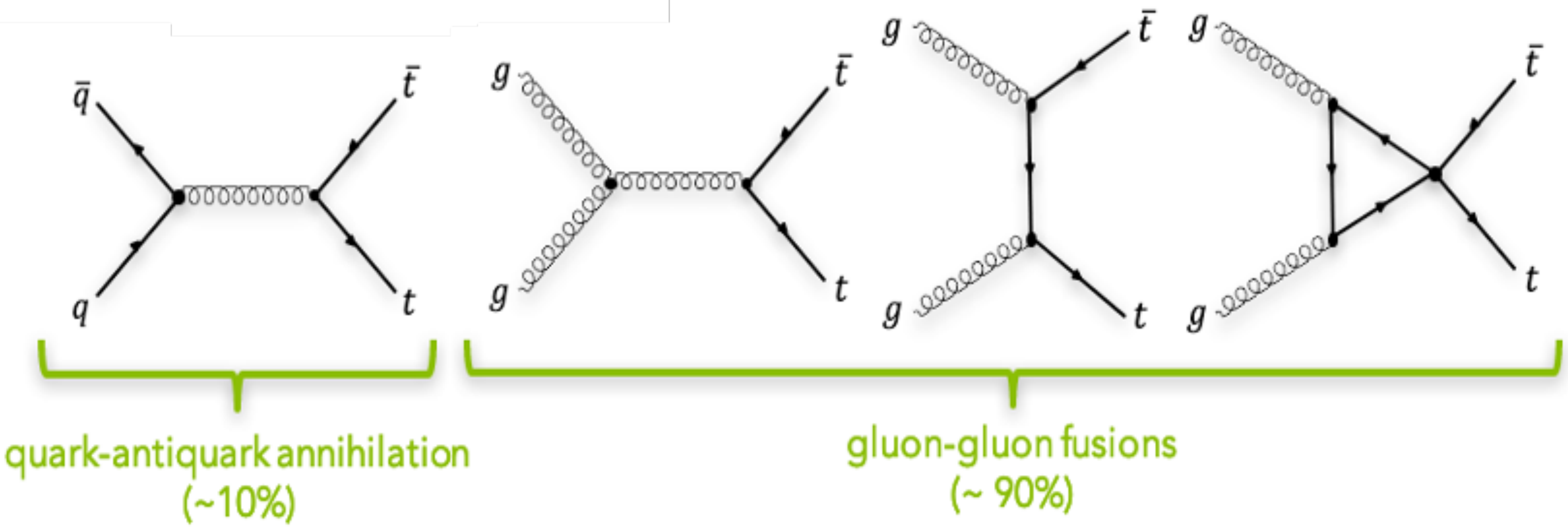
- Discovered in 1995 at Tevatron collider at Fermilab, by the CDF and D0 experiments

- The LHC using pp collisions is known as a top factory
  - ATLAS and CMS collected dataset counting $\sim$ 1 millions of top quark events

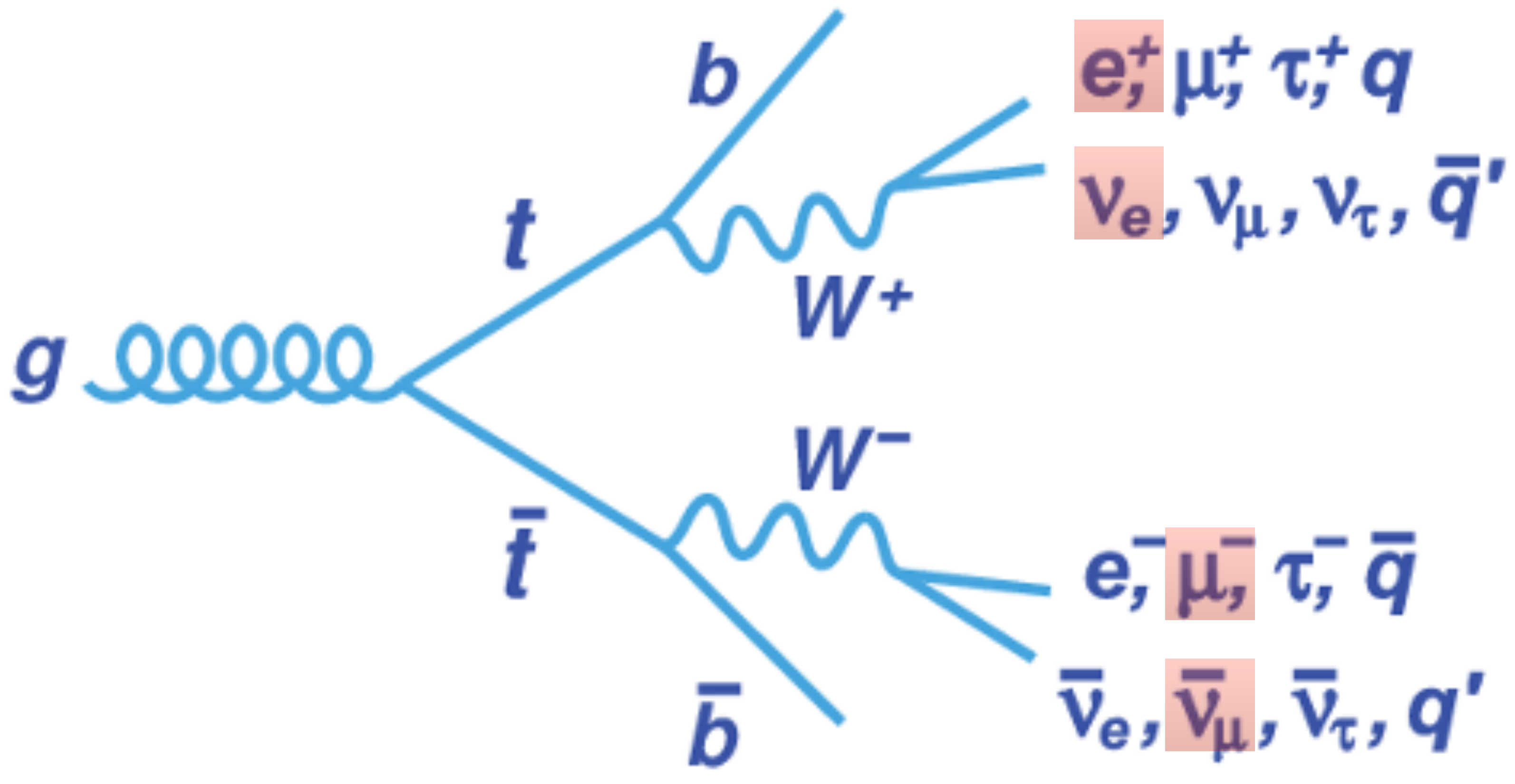
- Unique Properties
  - Most massive fundamental particle ($m_t = 174.3 \pm 5.1$ GeV)
  - Strong coupling with the Higgs boson and new predicted particles in the BSM
  - Short lifetime ($\sim 4 \times 10^{-25} s$)

Top Quark

Production

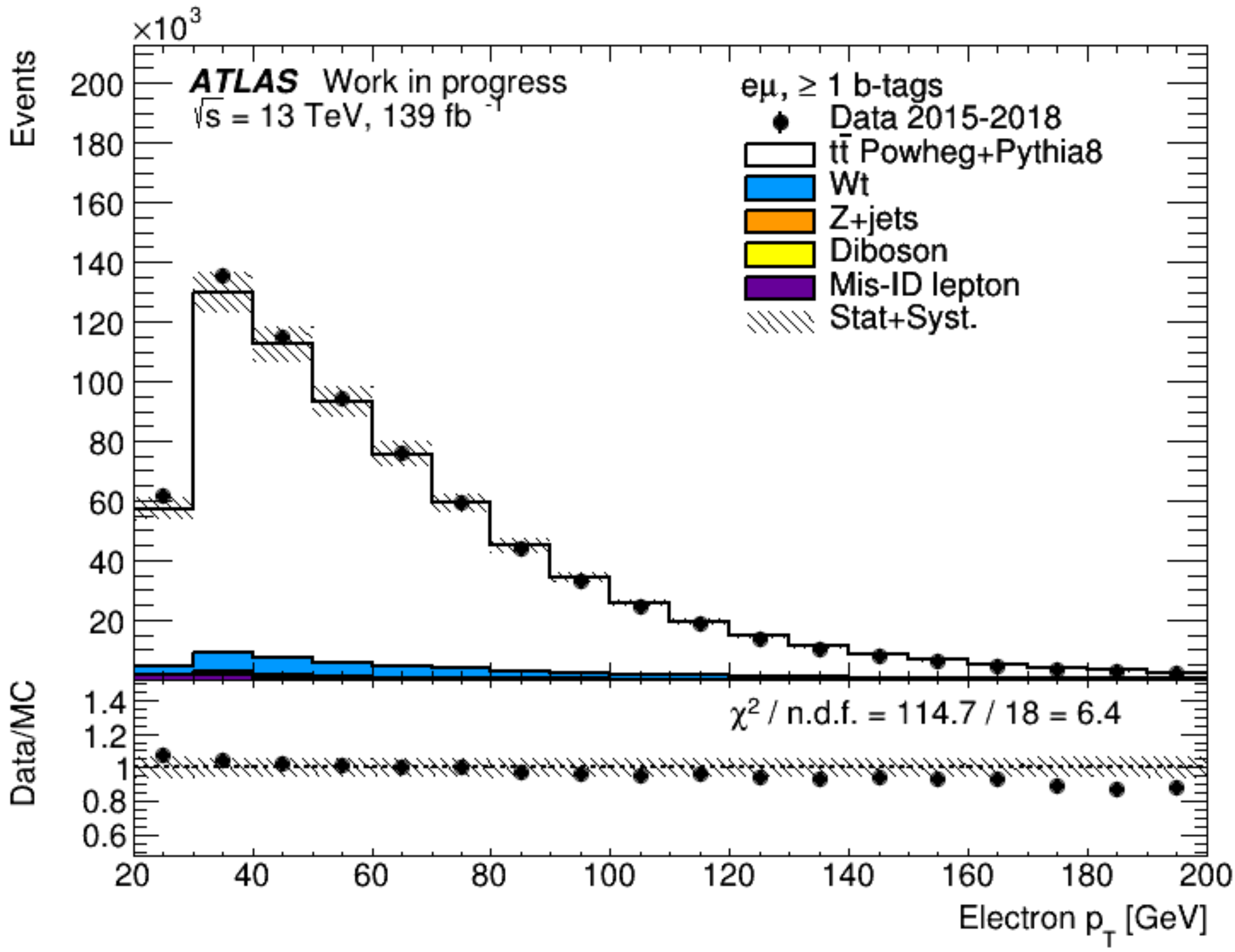


Decays



Introduction

- This research aims to compare real data with the estimations made by different Monte Carlo generators.
- Compared the modelling of some important observables (e.g. Electron transverse momentum (Electron p_{T})) with different Monte Carlo generators.
- An extended χ^2-test is performed to compare data and Monte Carlo predictions.
- The full dataset of the LHC Run 2 in proton-proton collisions at $\sqrt{s} = 13$ TeV collected by ATLAS detector

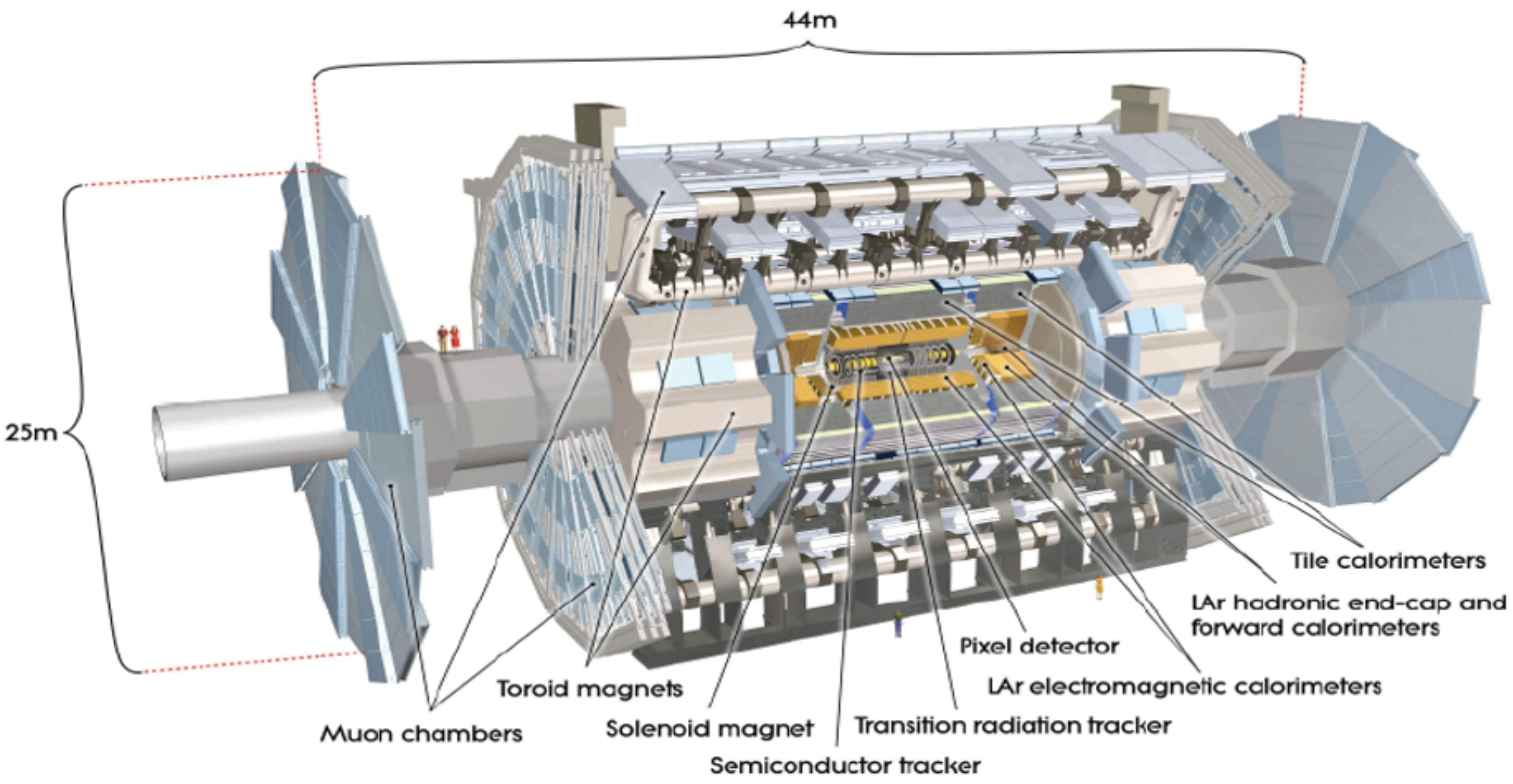


Motivation

- Top quark has an important role in the BSM, Higgs boson and exploiting bare quarks
- It is important to measure the top quark properties with high precisions
- Extraction of information from the experimental data requires to use theoretical predictions (MC generators)
- To produce digital twins of the real data the following MC generators are used:
  - POWHEG+PYTHIA 8
  - POWHEG+HERWIG7.0
  - POWHEG+HERWIG7.1
  - POWHEG+PYTHIA 8 $h_{damp}\chi^2$
  - aMC@NLO+PYTHIA 8
  - aMC@NLO+HERWIG7.1
- Thus it is crucial to identify the most precise generator for the production of $t\bar{t}$ events

ATLAS Detector

- **The ATLAS detector:** is one of the two giant multi-purpose detectors at CERN located at **Point 1**
  - Weight is almost **7000 tons**
  - The discovery **of Higgs boson** was the main goal of this experiment
- **The ATLAS detector comprises many different sub-detectors, each is used for various purposes**



Statistical Analysis

- A simple procedure that validates the consistency in an experiment between two distributions (e.g. data and prediction)

- χ^2**-test:** Used to compare data event counts with a sum of predictions

  - For the uncorrelated uncertainties in each bin of a histogram

$$\chi^2 = \sum_{i=1}^{m} \frac{(n_i - \mu_i)^2}{\mu_i + \sigma(\mu_i)^2}$$

  - For the correlated systematic uncertainties across all bins of a prediction

$$\chi^2 = \sum_{i} \sum_{j} (n_i - \mu_i) C_{ij}^{-1} (n_j - \mu_j)$$

For given a set of N systematic uncertainties impacting the prediction, representing by N alternative prediction histograms, $p^{'}_{k_k} = 1^N$

and $$C_{ij} = \sum_{k} (p^{'}_{ik} - p^{'}_{i})(p^{'}_{jk} - p^{'}_{j}) + \delta_{ij} p^{'}_{i}$$

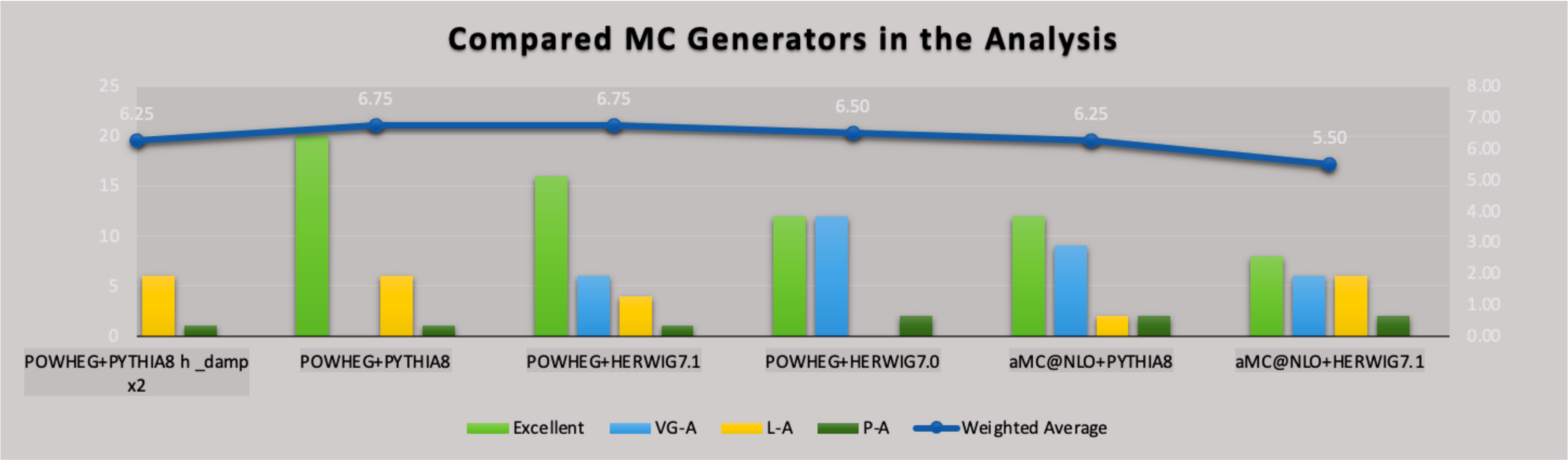
- i and j run on bins, k runs on independent sources of systematic uncertainty

Results

- Used abbreviations in the Table
  - *E − A*: Excellent agreement ($4 > \chi^2/_{NDF}$)
  - *VG-A*: Very good agreement ($6 > \chi^2/_{NDF} \geq 4$)
  - *L-A*: Less agreement ($9 > \chi^2/_{NDF} \geq 6$)
  - *P-A*: Poor agreement ($\chi^2/_{NDF} \geq 9$)

MC simulation generator	N_{jets}	N_{b-tags}	H_T	H_T^{all}	Electron p_T	Electron $\|\eta\|$	Muon p_T	Muon $\|\eta\|$	E_T^{miss}
POWHEG+PYTHIA8 $h_{damp}x2$	*E − A*	*E-A*	*V-A*	*VG-A*	*L-A*	*L-A*	*P-A*	*L-A*	*E-A*
POWHEG+PYTHIA8	*E-A*	*E-A*	*E-A*	*E-A*	*L-A*	*L-A*	*P-A*	*L-A*	*E-A*
POWHEG+HERWIG7.1	*VG-A*	*E-A*	*E-A*	*E-A*	*L-A*	*P-A*	*L-A*	*VG-A*	*E-A*
POWHEG+HERWIG7.0	*VG-A*	*VG-A*	*E-A*	*E-A*	*VG-A*	*P-A*	*P-A*	*VG-A*	*E-A*
aMC@NLO+PYTHIA8	*P-A*	*VG-A*	*L-A*	*E-A*	*E-A*	*P-A*	*VG-A*	*VG-A*	*E-A*
aMC@NLO+HERWIG7.1	*P-A*	*VG-A*	*VG-A*	*E-A*	*L-A*	*P-A*	*L-A*	*L-A*	*E-A*

Conclusions



- The best MC generator for describing each of the selected observables is POWHEG+PYTHIA8 followed by POWHEG+HERWIG7.1
- The poor level of agreement is provided by aMC@NLO+HERWIG7.1 and POWHEG+PYTHIA 8 $h_{damp} 2x$
- The main contribution to the total systematic uncertainty for all of the selected observables are from jet energy scale, jet energy resolution and electron identification uncertainties


THANK
YOU

Backup Slides

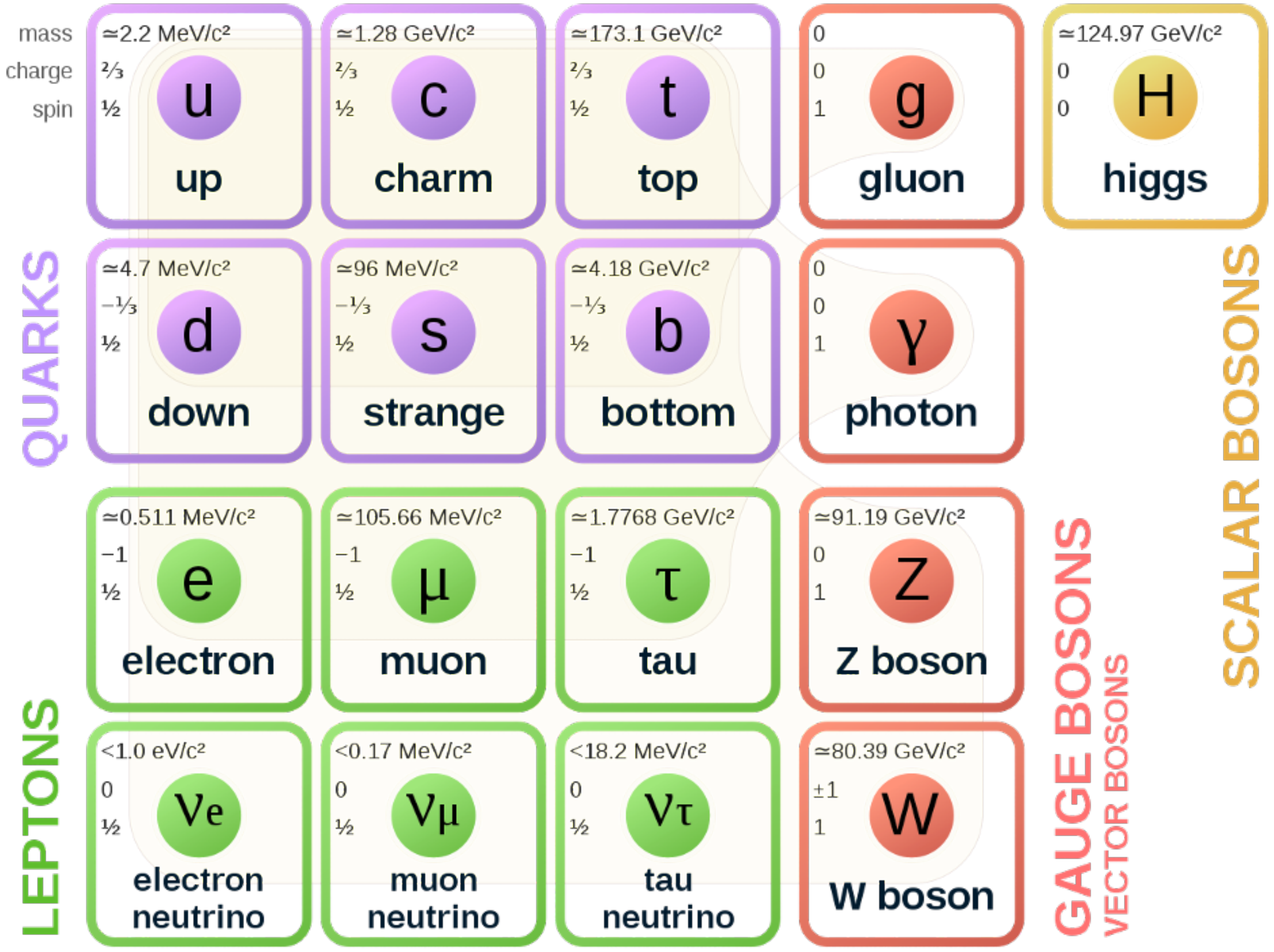
The Standard Model (SM) of Particle Physics

- ❑ The SM describes the fundamental particles and how they interact via three of the four fundamental forces of nature- strong interaction, weak interaction, electromagnetic interaction- gravity is not included

- ❑ Fundamental particles: Classified in two categories

  - The fermions: Have spin 1/2 and comprised of
    - ➢ The Quarks (up, down, charm, strange, top, bottom)
    - ➢ The leptons (electrons, muons, taus, and neutrinos)

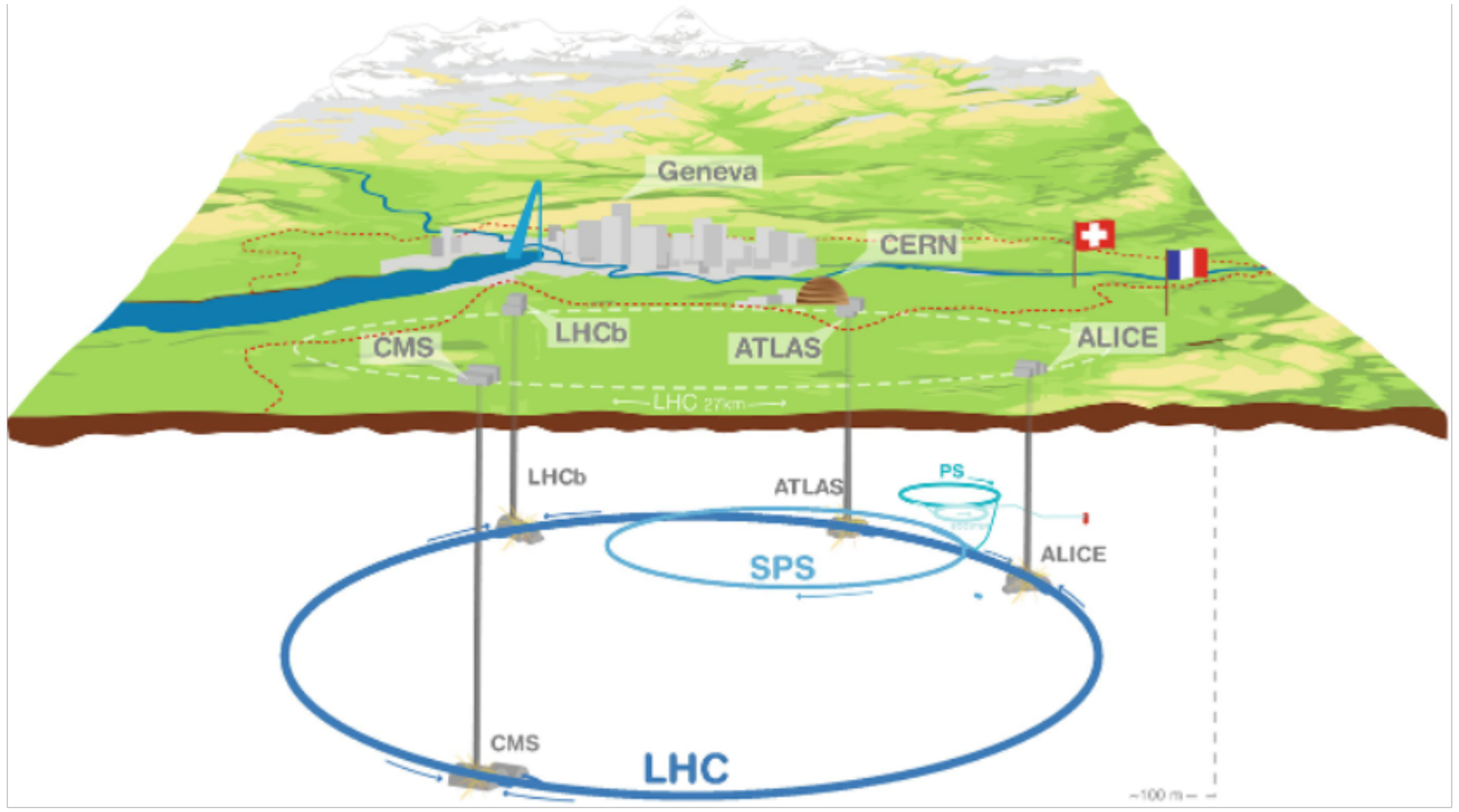
  - The bosons: Are the force mediators of the electromagnetic, strong and weak interactions
    - ➢ Photons (spin-1)
    - ➢ Gluons (spin-1)
    - ➢ Vector bosons (W and Z bosons, spin-1)
    - ➢ Higgs boson (spin-0)



Experimental Setup

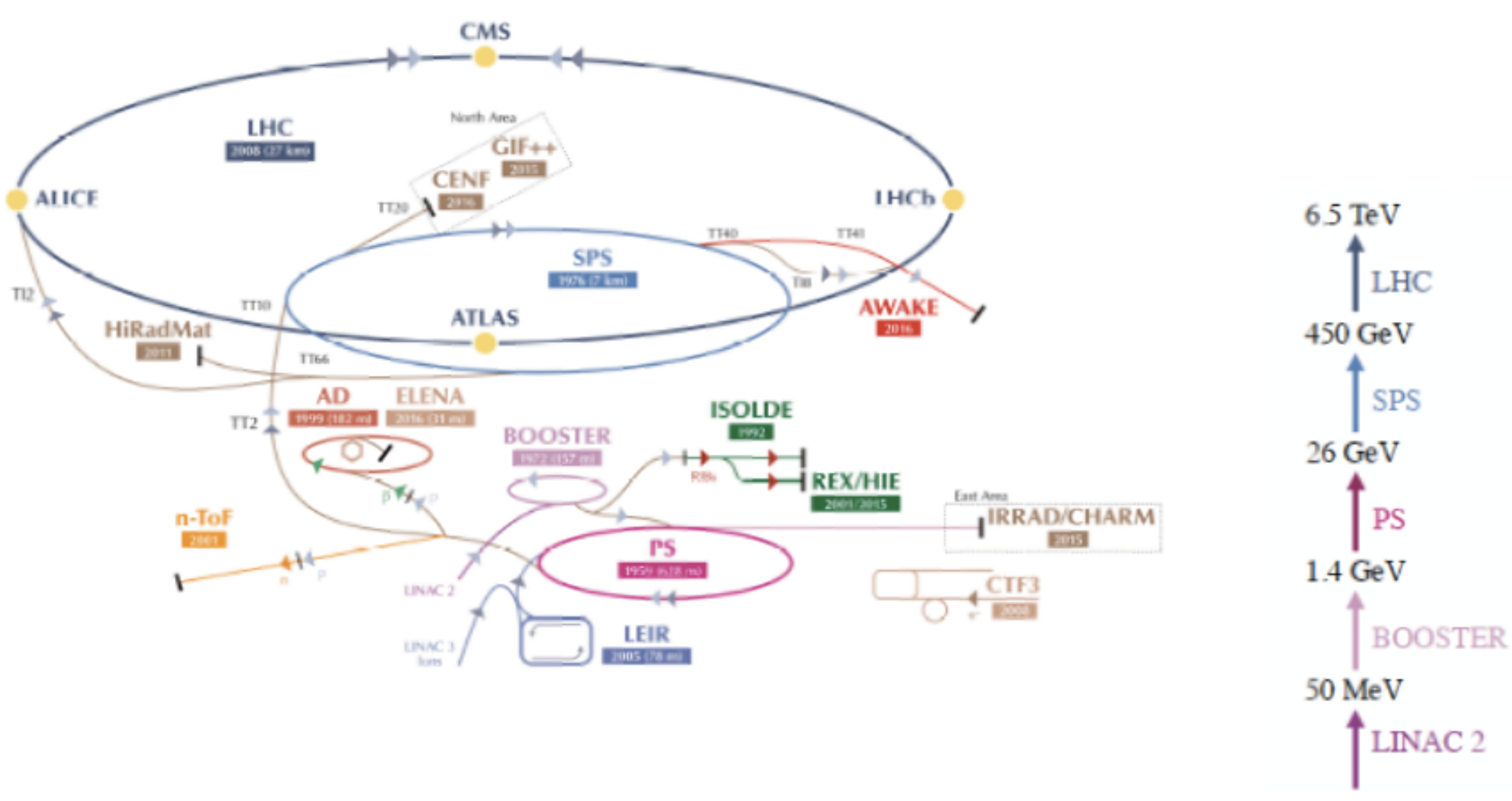
❑The Large Hadron Collider (LHC): **The world's powerful and highest energy particle accelerator**

- The Circumference of LHC ring is 27km installed roughly 100m underground at CERN, near Geneva, Switzerland.
- The four main experiments are ATLAS (multi purpose detector), CMS (multi purpose detector), ALICE (heavy-ion physics), and LHCb (bottom quark physics)
- The LHC provides collisions of both protons and heavy-ions



❑Centre-of-mass energies of proton-proton collisions at the LHC:

- √s = 7 TeV in Run 1 (2010-11)
- √s = 8 TeV in Run 1 (2012)
- √s = 13 TeV in Run 2 (2015-18)

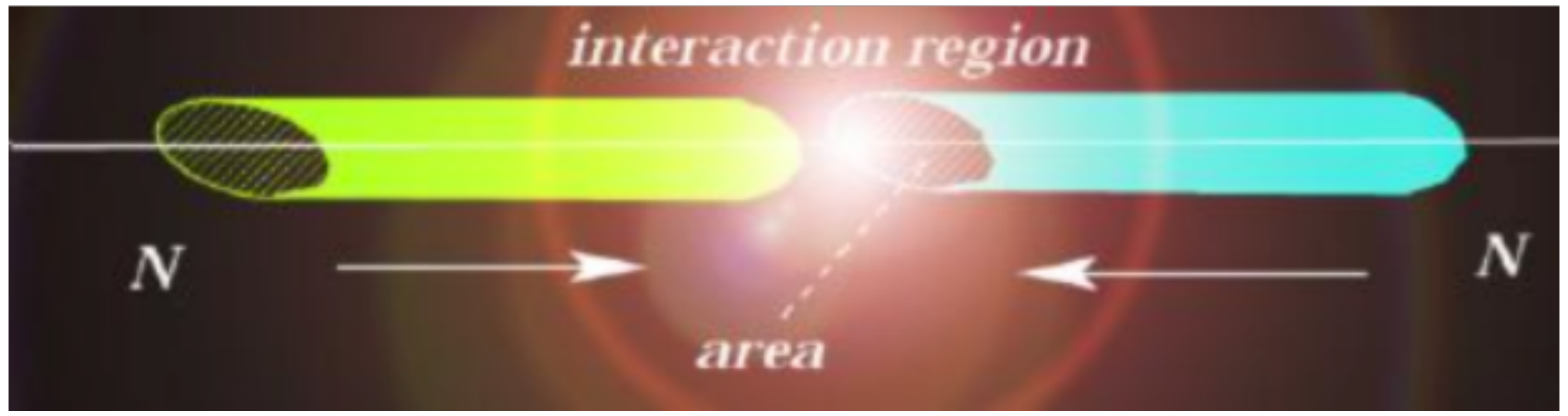


Basic Concepts

- **The centre-of-mass energy** or the total energy of the colliding system is $E_{cm} = 2E$
  - The centre-of-mass energy in a collision of two hadron pair is denoted by $\sqrt{s}$
- **Integrated luminosity ($\mathscr{L}_{int}$):** Describes the cumulative number of potential collisions over a given period

$$N = \int \mathscr{L} dt \cdot \sigma_{pp} = \mathscr{L}_{int} \cdot \sigma_{pp}$$

- **Cross-section (σ_{pp}):** Gives the probability that how often protons collide



- **Proton-proton collisions:** The proton is a composite particle, has three valence quarks uud and a virtual or sea of quark-antiquark and gluons
  - **When proton is at rest:**
    - Three valence quarks carry large amount of protons momentum
  - **When proton is accelerated:**
    - Gluons carry a large amount of momentum
- In the colliders, the collision of the protons is a hard interaction between one of the constituents of the first proton and one constituent of the second proton

Results

- The results are obtained through the evaluation of the χ^2-test

- NDF stands for the number of degrees of freedom (number of bins in the histogram)

- p-value shows the probability of consistency between the data and prediction and is calculated using covariance matrix.

- Results from the comparison of data with total predictions in each of the absolute detector-level observable distributions. The NDF is equal to the number of bins in the distribution.

Observable	PWG+PY8		PWG+PY8$h_{damp}x2$		PWG+H7.0		PWG+H7.1		aMC@NLO+PY8		aMC@NLO+H7.1	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Electron p_T	114.7/18	4.15 e-16	129.4/18	6.94 e-19	88.0/18	3.29 e-11	156.7/18	3.60 e-24	71.2/18	2.87 e-08	157.0/18	3.18 e-24
Muon p_T	170.7/18	6.67 e-27	175.7/18	6.67 e-28	170.9/18	5.94 e-27	153.4/18	1.61 e-23	99.6/18	2.68 e-13	139.0/18	9.69 e-21
Electron $\|\eta\|$	82.2/10	7.36 e-14	73.2/10	1.04 e-11	90.6/10	2.26 e-14	149.3/10	5.21 e-27	95.9/10	3.66 e-16	165.8/10	2.07 e-30
Muon $\|\eta\|$	62.0/10	1.50 e-09	74.9/10	5.02 e-12	52.6/10	8.98 e-08	45.3/10	1.93 e-06	58.3/10	7.71 e-09	62.5/10	1.20 e-09
N_{jets}	7.6/4	0.0614	2.7/4	0.6162	21.0/4	0.0003	23.3/4	0.0001	103.9/4	1.40 e-21	170.0/4	1.06 e-35
N_{b-tags}	9.5/3	0.0235	9.2/3	0.0269	18.9/3	8.64 e-05	7.1/3	0.0690	16.1/3	0.0010	15.2/3	0.0016
E_T^{miss}	32.3/20	0.0403	53.5/20	6.95 e-05	31.3/20	0.05181	28.0/20	0.10875	48.8/20	0.0003	21.6/20	0.3599
H_T	15.8/19	0.6718	91.8/19	1.58 e-11	13.6/19	0.8057	20.9/19	0.3384	145.2/19	1.82 e-21	96.9/19	1.92 e-12
H_T^{all}	30.6/18	0.0320	109.6/18	3.68 e-15	27.7/18	0.0667	20.9/18	0.2848	42.1/18	0.0010	53.7/18	2.04 e-05

- Results from the comparison of data with total predictions in each of the normalized detector-level observable distributions. The NDF is equal to the number of bins in the distribution minus one.

Observable	PWG+PY8		PWG+PY8 $h_{damp}x2$		PWG+H7.0		PWG+H7.1		aMC@NLO+PY8		aMC@NLO+H7.1	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Electron p_T	113.8/17	2.31 e-16	131.1/17	1.17 e-19	89.1/17	8.87 e-12	161.9/17	1.11 e-25	71.7/17	1.11 e-08	165.3/17	2.39 e-26
Muon p_T	169.8/17	3.06 e-27	177.3/17	9.82 e-29	172.4/17	9.32 e-28	157.2/17	9.56 e-25	100.0/17	8.63 e-14	144.1/17	3.44 e-22
Electron $\|\eta\|$	81.7/9	1.83 e-13	74.5/9	2.02 e-12	91.7/9	4.07 e-15	154.5/9	1.05 e-28	96.3/9	8.87 e-17	173.5/9	1.14 e-32
Muon $\|\eta\|$	61.7/9	6.33 e-10	76.0/9	9.88 e-13	53.3/9	2.52 e-08	46.8/9	4.33 e-07	58.7/9	2.41 e-09	65.1/9	1.37 e-10
N_{jets}	7.4/3	0.1088	2.6/3	0.4576	21.1/3	9.99 e-05	22.3/3	5.72 e-05	104.2/3	1.98 e-22	169.909/3	1.33 e-36
N_{b-tags}	9.1/2	0.0103	9.0/2	0.0113	33.2/2	8.98 e-08	6.3/2	0.0438742	16.0/2	0.0003	12.9/2	0.0015
E_T^{miss}	32.1/19	0.0306	53.8/19	3.58 e-05	31.6/19	0.0350	28.3/19	0.0772939	49.2/19	0.0001	20.7/19	0.3561
H_T	15.6/18	0.6181	92.2/18	5.78 e-12	13.6/18	0.7574	20.7 /18	0.2951	146.0/18	4.51 e-22	95.7/18	1.34 e-12
H_T^{all}	30.3/17	0.0243	110.4/17	1.01 e-15	27.9/17	0.0466	20.9/17	0.2321	42.3/17	0.0006	51.2/17	2.74 e-05