Oral Candidacy Exam Proposal:

Studying Associated Top Production with Effective Field Theory

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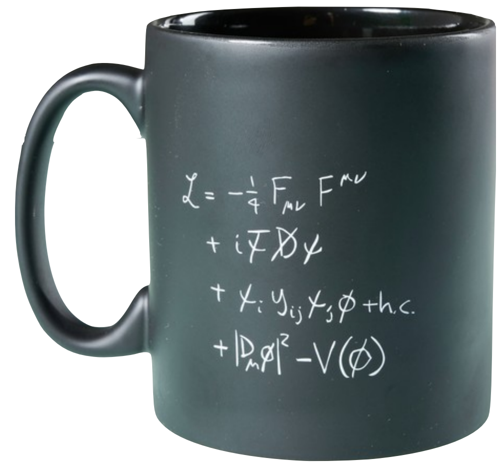
Standard model (SM) of particle physics

- The SM Lagrangian is the mathematical description of fundamental particles and forces and it fits on a mug



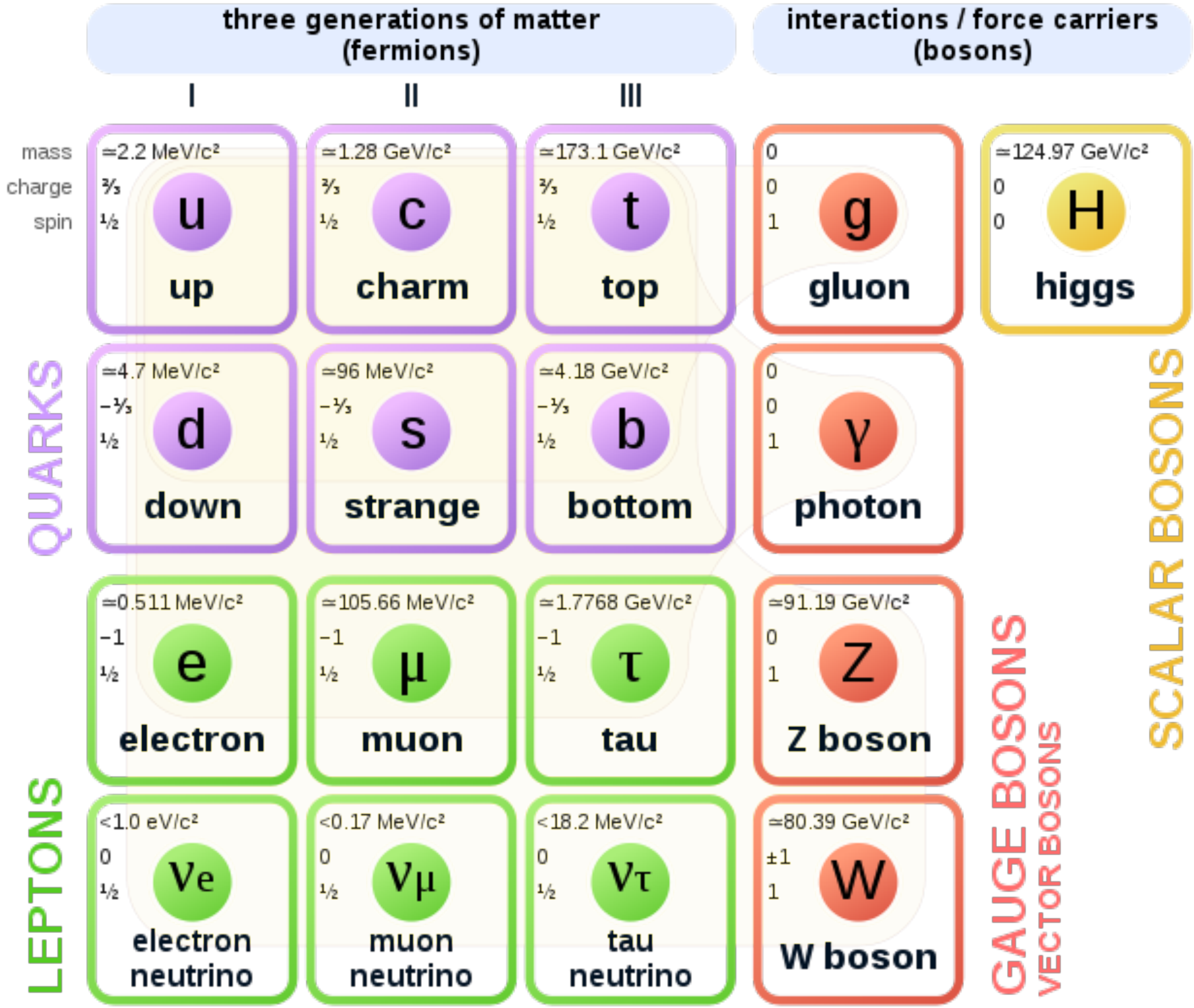
- Gauge symmetry SU(3)xSU(2)xU(1)

  - Not broken
  - Gauge boson associated with the symmetry: Gluon

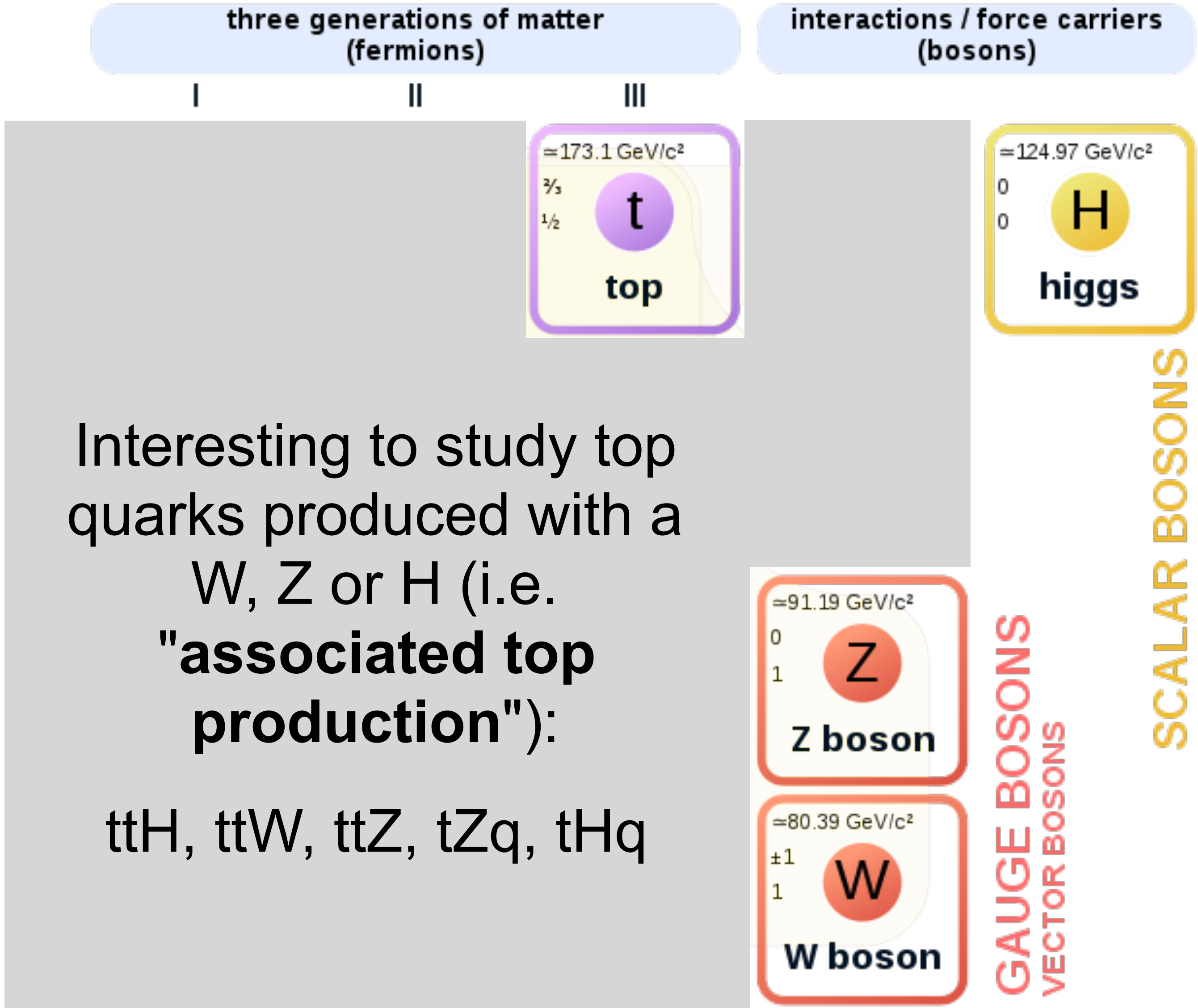
  - Spontaneously broken (Higgs mechanism)
  - Bosons: $W^{\pm}$, Z, and γ

- Fermions of the SM: Three generations of quarks (*u, d, c, s, t, b*) and leptons (e, ν_e, μ, ν_μ, τ, ν_τ)

SM particles



SM particles

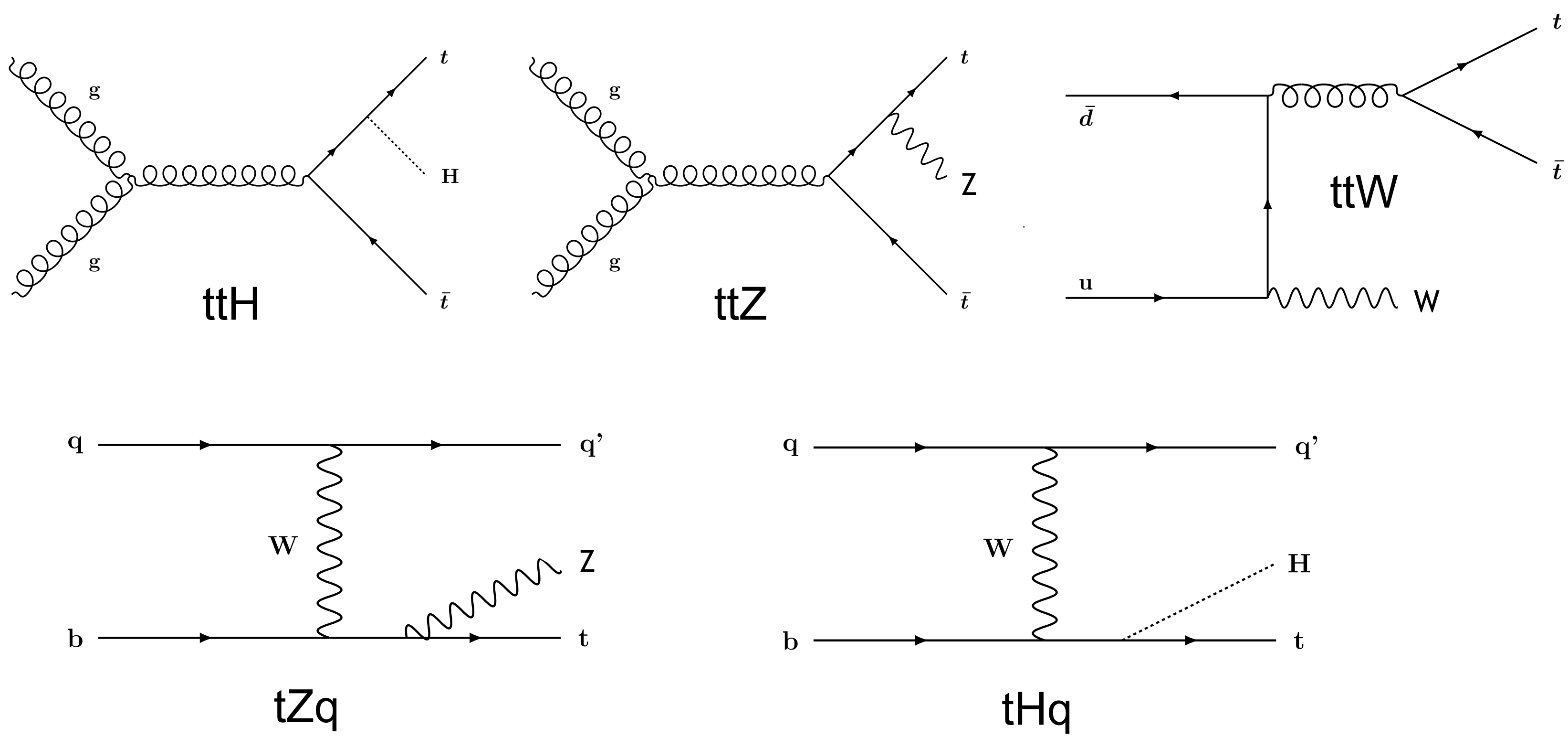


Interesting to study top quarks produced with a W, Z or H (i.e. "**associated top production**"):

ttH, ttW, ttZ, tZq, tHq

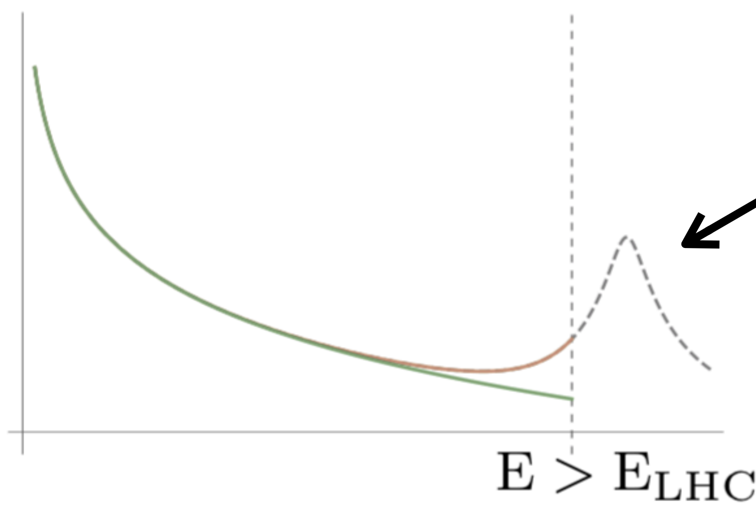
Why associated top production

- All of the particles involved are relatively heavy
- The interactions have not been studied as exhaustively as processes involving lighter particles



Beyond the SM

- The SM is not complete (does not describe dark mater, dark energy, gravity etc.) so we need to look for new physics
- The new physics may be too heavy to be produced directly at the LHC
- An effective field theory (EFT) framework allows us to indirectly probe higher energy scales, extending discovery reach of LHC



If new physics looks like this, EFT is a good way of modeling it

Modeling new physics with EFT

- EFT is a general method of parametrizing new physics
  - Treats SM Lagrangian as lowest order term
  - New physics appears as higher order terms
  - In natural units SM interactions are dimension 4 (i.e. units of E^4),
  - So "higher order" $\Rightarrow$ dimension 5 and up

- EFT Lagrangian is built out of three main pieces:
  1. Products of SM fields called operators ($\mathcal{O}$) that describe interactions
  2. Dimensionless numbers called Wilson coefficients (c) that describe strength of the interaction
  3. And an energy scale Λ

The EFT Lagrangian

Wilson Coefficient
(strength of interaction)

Energy scale of
the new physics

Operators are built of products of SM fields and their derivatives, correspond to vertices in feynman diagrams

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \underbrace{\sum_i \frac{c_i}{\Lambda}\mathcal{O}_i^{(5)}}_{} + \underbrace{\sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)}}_{} + \ldots$$

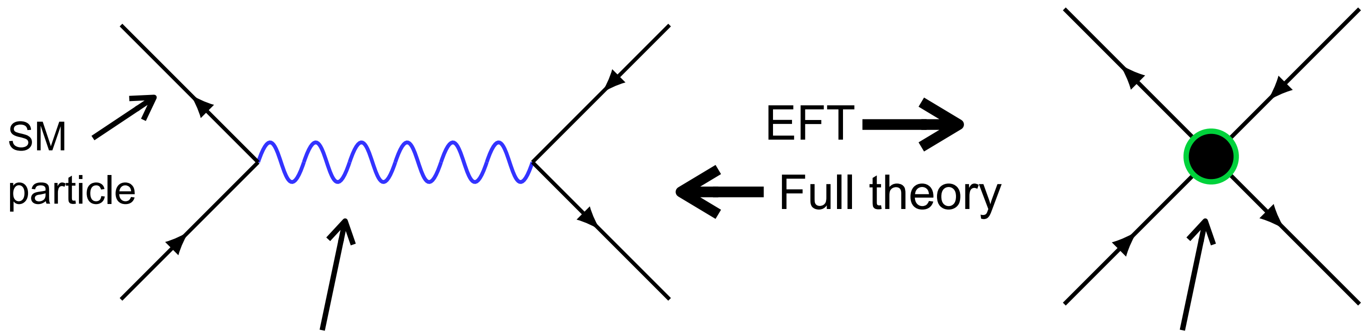
(i.e. interactions between particles)

Only one dim 5 term that preserves SM symmetries (majorana mass for neutrino)

We focus on dim 6 terms involving tops

- The sums over *i* are finite
- The sum over dimensions is infinite, but terms are suppressed by powers of Λ
- Note that if all $c_i = 0$, $\mathscr{L}_{eff} = \mathscr{L}_{SM}$ and SM is recovered

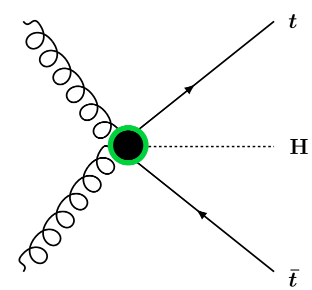
Using $\mathscr{L}_{EFT} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)}$ to describe interactions



Undiscovered particle that's too heavy to be produced on shell at the LHC

This effective operator combines four SM fields at a dimension 6 vertex, strength of interaction determined by value of the Wilson coefficient suppressed by mass scale squared

- Study 16 operators that have the ability to impact associated top production but do not have a large impact on background processes
- E.g. O_{ug} operator ($\frac{c_{tG}}{\Lambda^2}(\bar{Q}_3\sigma^{\mu\nu}T^A u_3)\epsilon H^* G^A_{\mu\nu}$) gives rise to t-t-g, t-t-g-h, t-t-g-g, t-t-g-g-h vertices, can affect ttH:



Our analysis strategy

- Parametrize predicted events in terms of Wilson coefficients
- Compare with observed number of signal events
- Use a likelihood fit to determine the values of the Wilson coefficients that maximize the probability of observing expected number of events
    - If a Wilson coefficient is significantly different from the SM (i.e. different from 0), new physics will have been identified
    - If all Wilson coefficients are consistent with the SM, then we can set limits on strength of new physics interactions

Parametrizing yields with Wilson coefficients: Writing the cross section

- To write predicted yields in terms of Wilson coefficients, first write the matrix element as the sum of SM and new physics components:

$$\mathscr{M} = \mathscr{M}_{SM} + \sum_i c_i \mathscr{M}_i$$

c_i are the Wilson coefficients

- Any cross section depends on the matrix element squared, so will depend quadratically on the c_i, e.g. for just one c_1:

$$d\sigma(c_1) \propto |\mathscr{M}_{SM} + c_1 \mathscr{M}_1|^2 \propto s_0 + s_1 c_1 + s_2 c_1^2$$

- The s_0, s_1, and s_2 correspond to the purely SM, interference, and purely EFT components, respectively, if we knew their values we would know the cross section for any value of c_1
- Could calculate cross section at 3 points and solve for s_0, s_1, and s_2

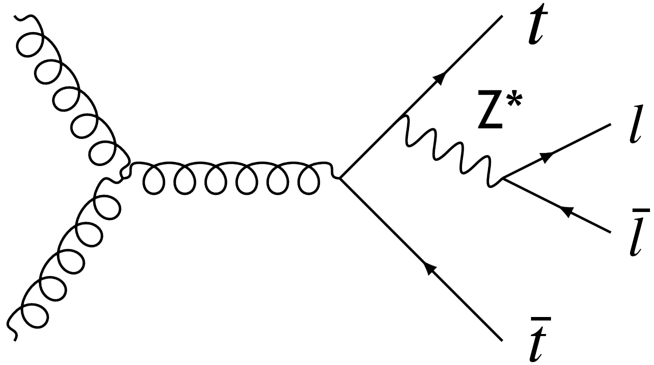
Parametrizing yields with Wilson coefficients: Using weighted events

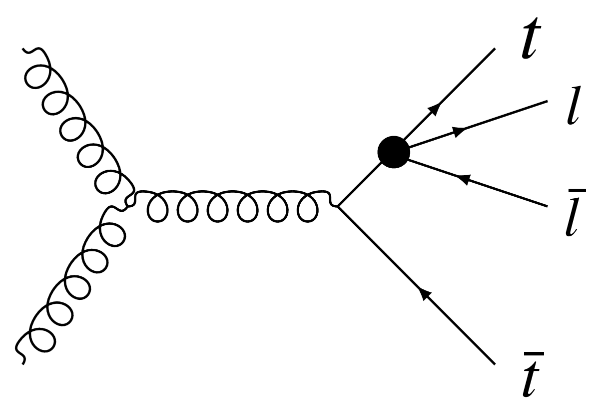
- However, we consider 16 Wilson coefficients (not just 1) so would need 153 samples (not just 3)
- Impracticable to produce that many Monte Carlo samples per process
- Instead, use the MadGraph event generator's ability to assign **weights** to each generated event
  - The weight accounts for the differential cross section's variation in an infinitesimal part of phase space around the event's kinematics
  - Weight depends quadratically on Wilson coefficients
  - Can calculate many weights (at least 153) then fit to a 16d quadratic $\Rightarrow$ only need one sample per process
- To find the predicted yield for a given category, sum the quadratic weight functions over all events passing selection requirements

Simulated samples

- Simulated samples produced with MadGraph event generator
- Associated top production includes **ttH**, **tHq**, ttW, ttZ, tZq, which can all produce multiple charged leptons in the final state
- We propose to focus on these <u>multilepton</u> final states
- Thus we will generate ttW, ttZ and tZq as **ttl$\boldsymbol{\nu}$**, **ttll**, **tllq**
  - Allow for on, off shell W and Z bosons
  - Incorporate the effects of 4-fermion operators

For example, the ttll we generate includes:





Backgrounds

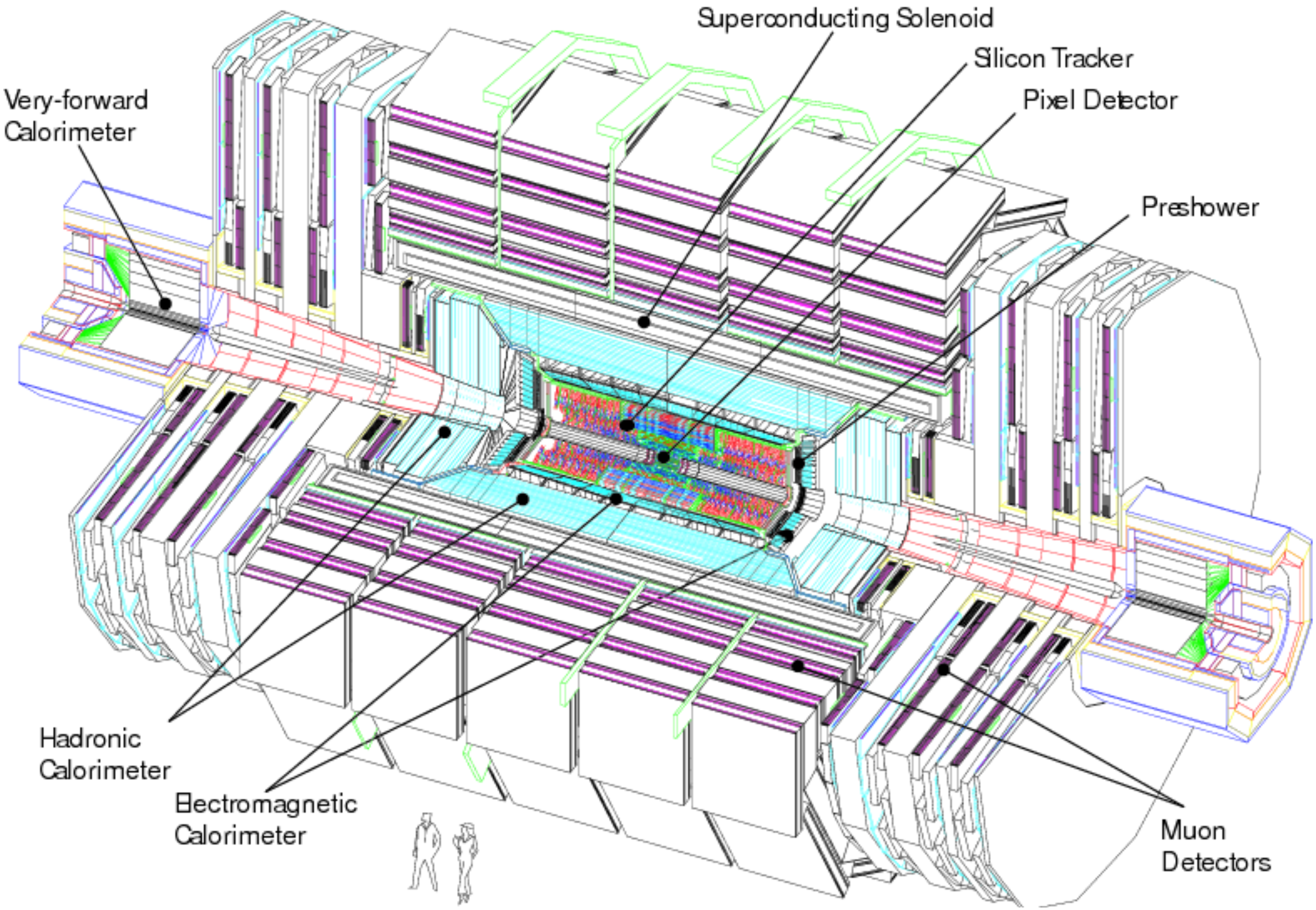
- Irreducible
  - Arise from processes that yield same final states as the signal but generated through a different physical mechanism
  - Modeled using **Monte Carlo simulation** (without any EFT effects)
  - Dominant contributions due to diboson, triboson production
- Reducible
  - Arise from imperfect object reconstruction
  - Estimated from **data**
  - Main categories:
    - Fakes: Caused by nonprompt (not directly produced by W/Z) or misidentified leptons that pass the object selection
    - Charge flips: Pertains to two-lepton-same-sign channel and caused by mis-measuring the charge of a lepton in an event containing a pair of oppositely charged leptons.

Data to be used for the analysis

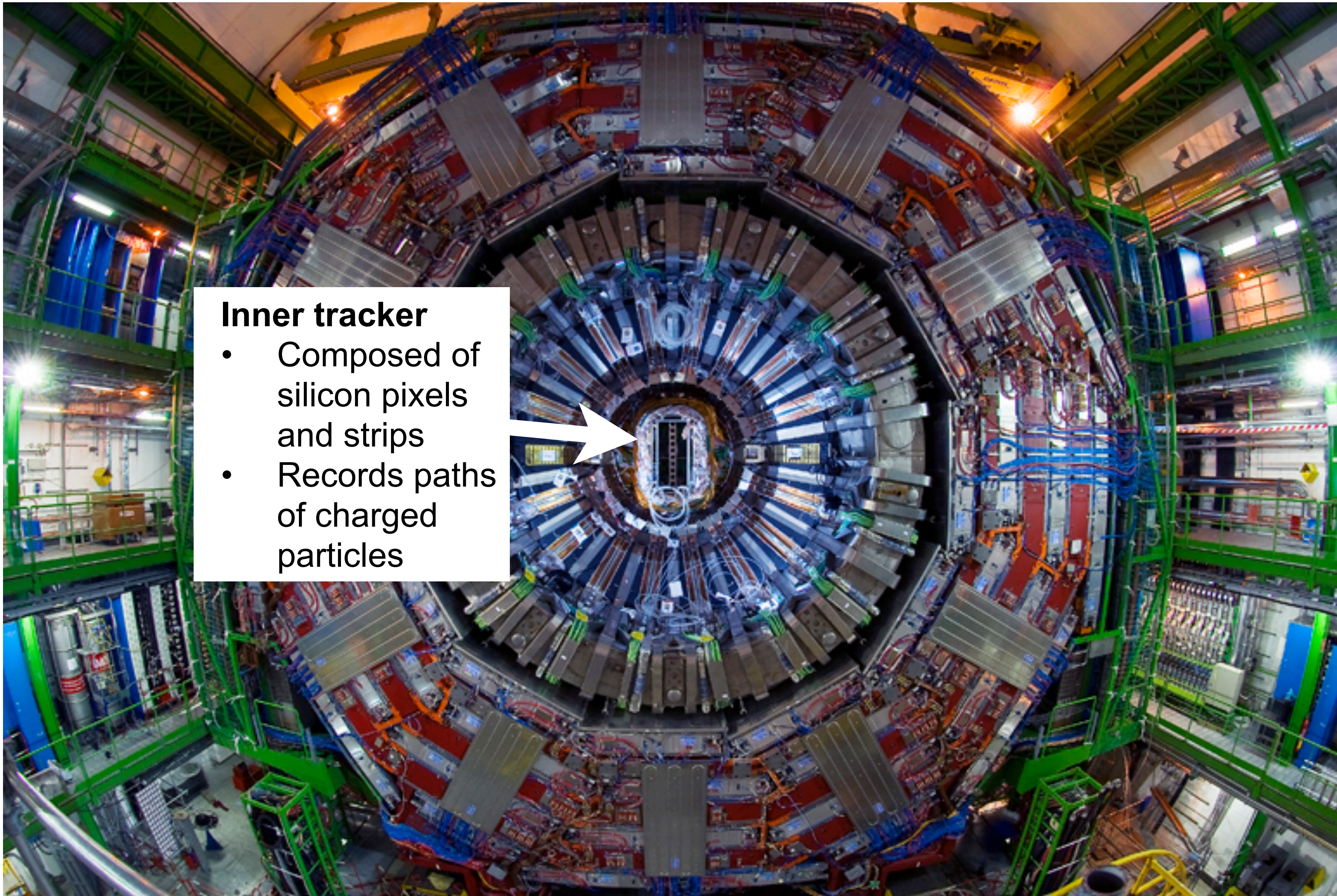
- The data that will be used for this analysis was collected by CMS detector during 2016, 2017, 2018 (the full Run 2 dataset)
- Proton-proton collisions at center of mass energy of 13 TeV
- Approximately 147 fb^{-1} of data
    - 2016: ~38 fb^{-1}
    - 2017: ~45 fb^{-1}
    - 2018: ~64 fb^{-1}

The Large Hadron Collider (LHC)

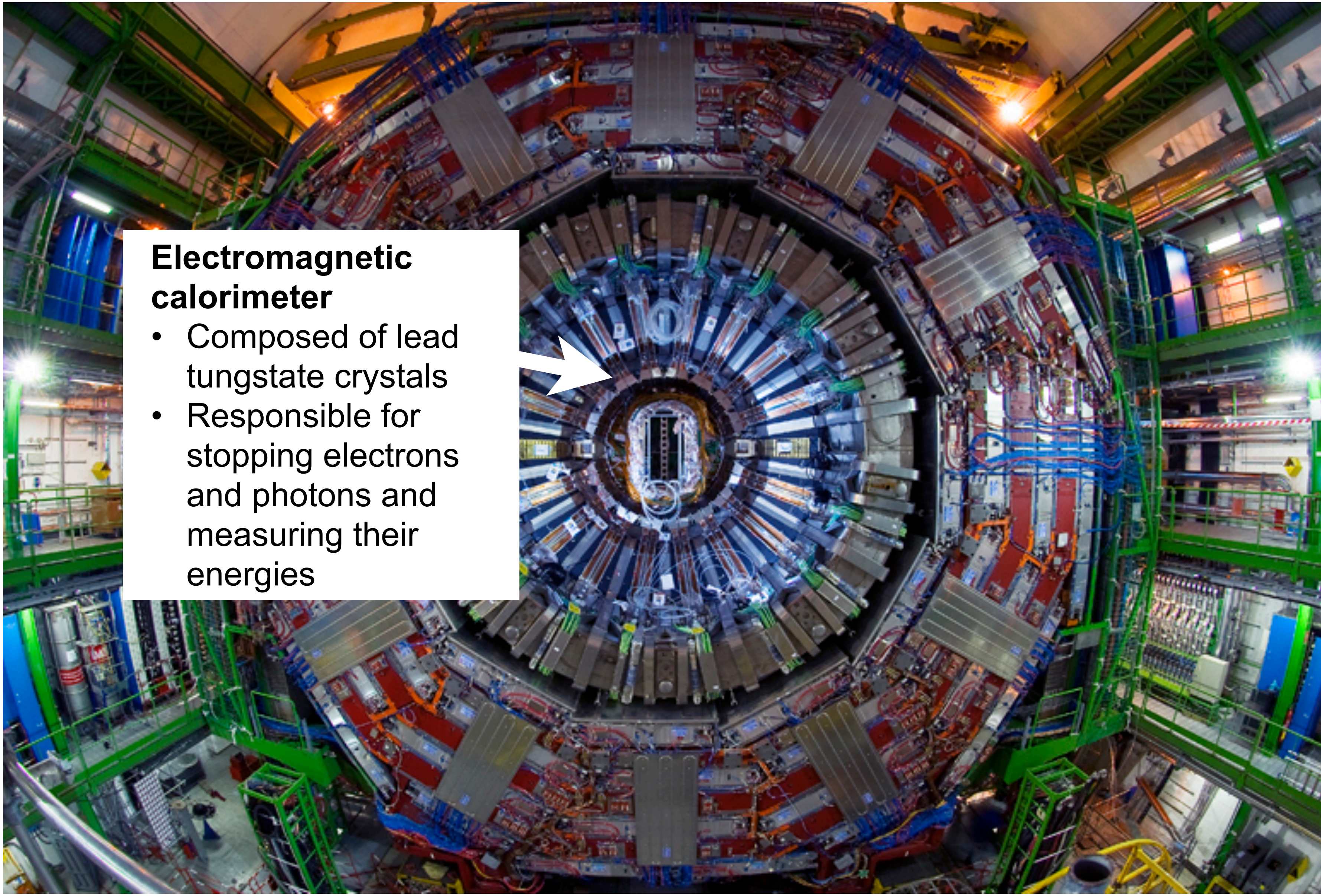
The CMS detector



The subdetectors of CMS



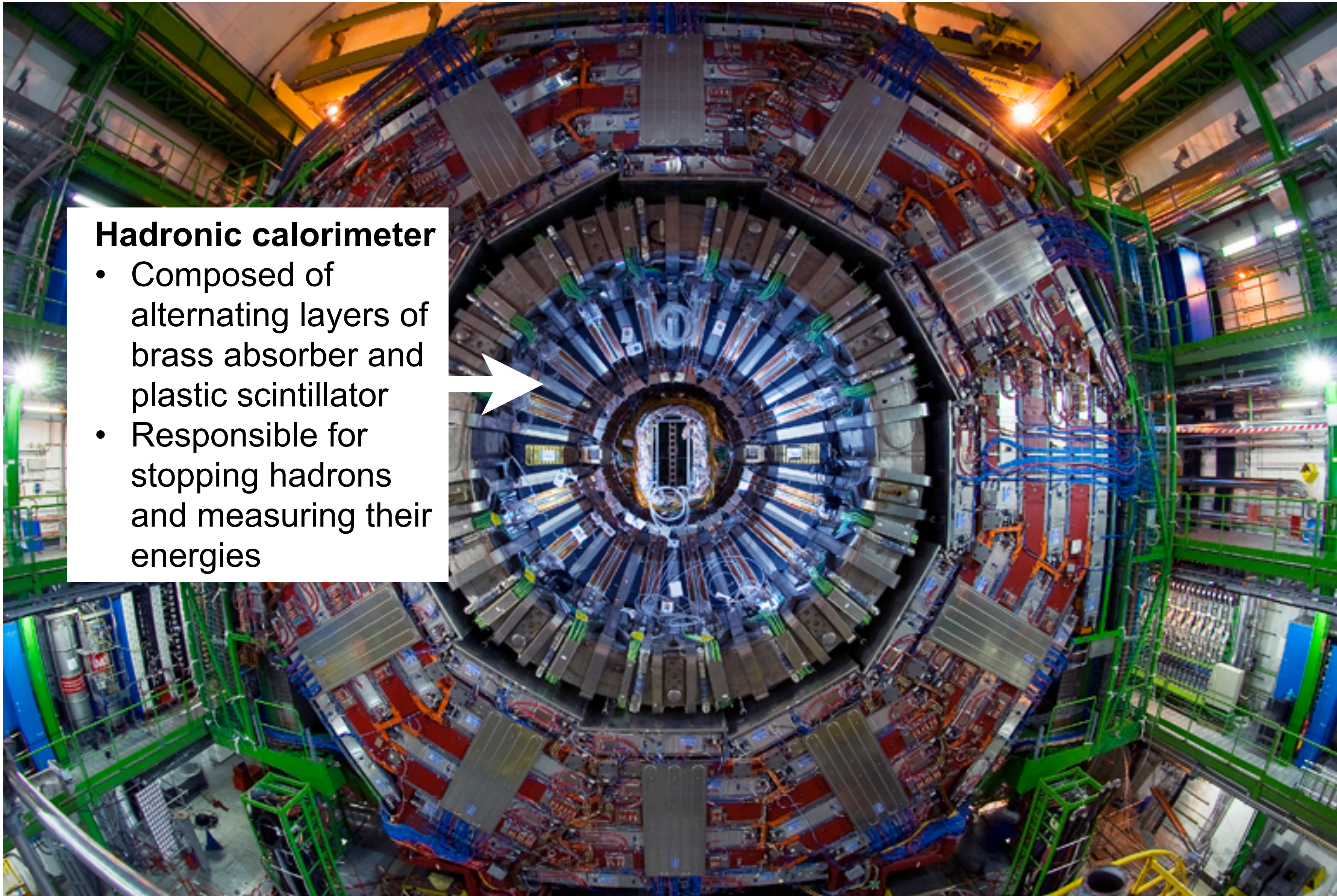
The subdetectors of CMS



Electromagnetic calorimeter

- Composed of lead tungstate crystals
- Responsible for stopping electrons and photons and measuring their energies

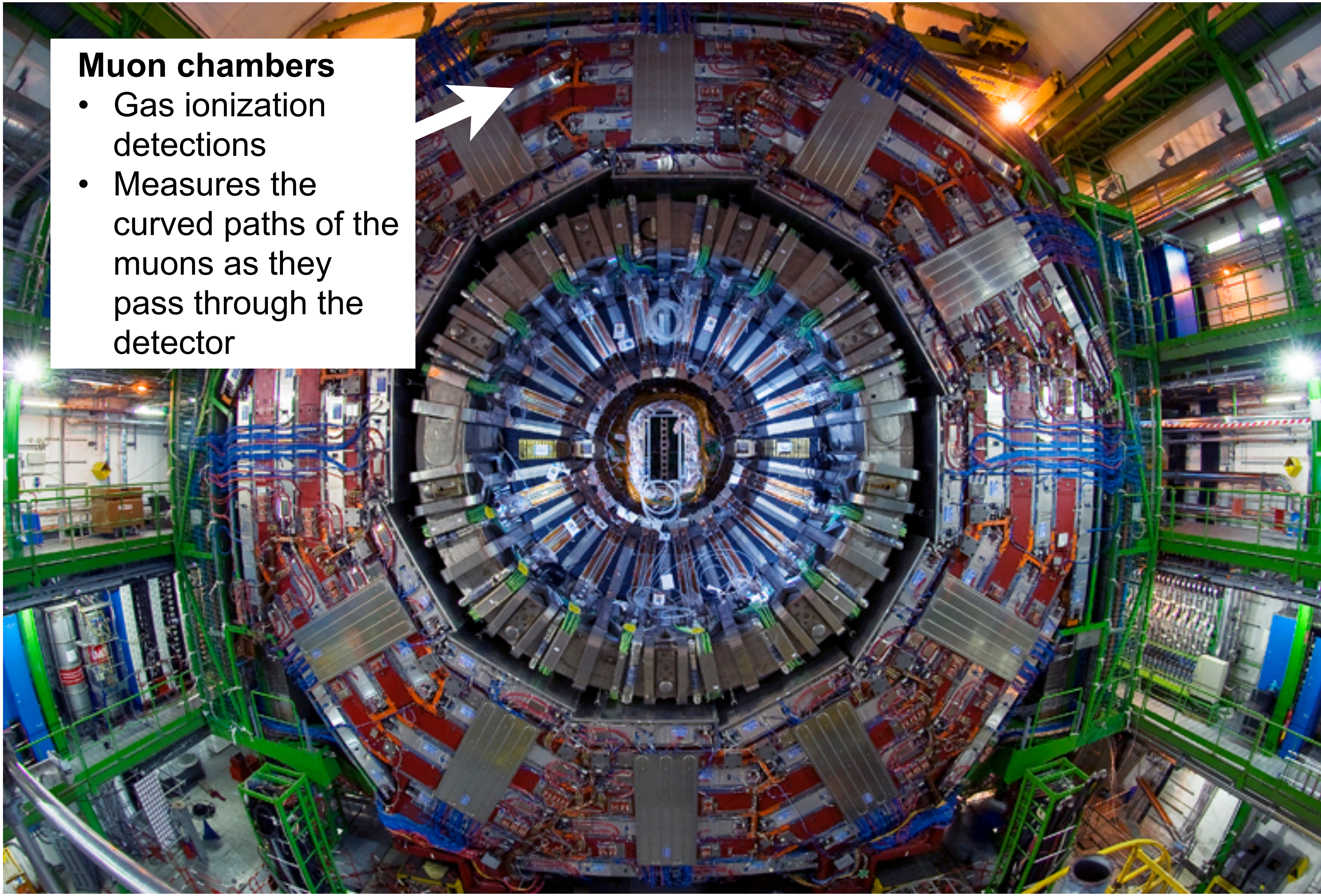
The subdetectors of CMS



Hadronic calorimeter

- Composed of alternating layers of brass absorber and plastic scintillator
- Responsible for stopping hadrons and measuring their energies

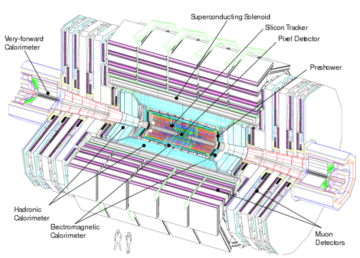
The subdetectors of CMS

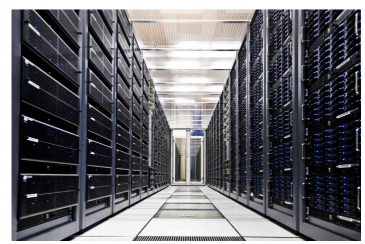


Muon chambers
- Gas ionization detections
- Measures the curved paths of the muons as they pass through the detector

The CMS trigger system

- Bunch crossings ~40MHz, ~1MB per event → too much data to record/store
- Only a small fraction of the events likely to contain new/interesting physics
- Purpose of trigger: Reduce event rate to manageable ~1kHz while keeping as many potentially interesting events as possible
- Trigger has a two-tiered structure:
    - Hardware based Level 1 (L1) trigger
    - Software based High Level Trigger (HLT)

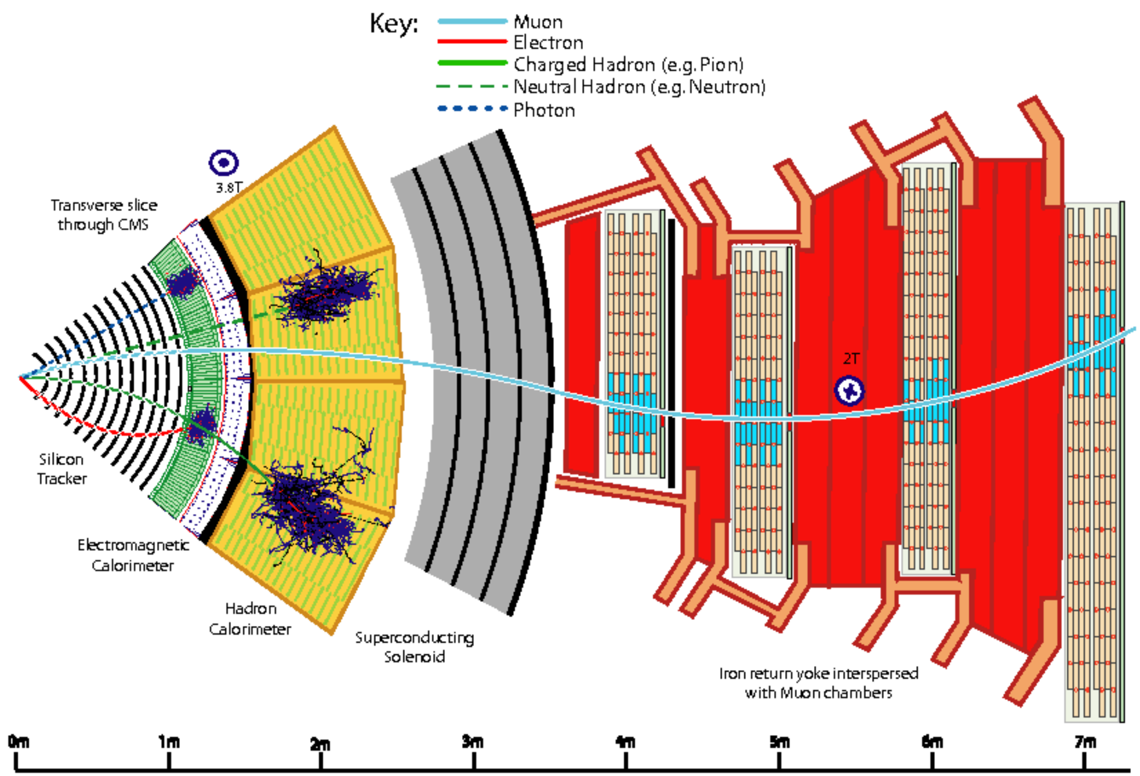




Bunch crossings in CMS → 40 MHz → L1 trigger → 100 kHz → High level trigger → 1 kHz → Offline reconstruction and analysis

Object reconstruction

- CMS uses a holistic reconstruction technique called **particle flow** to correlate the elements from each subdetector and construct a global picture of each event
- First identifies **muons**, then **electrons** and **isolated photons**, finally **charged hadrons**, **neutral hadrons**, **non-isolated photons**

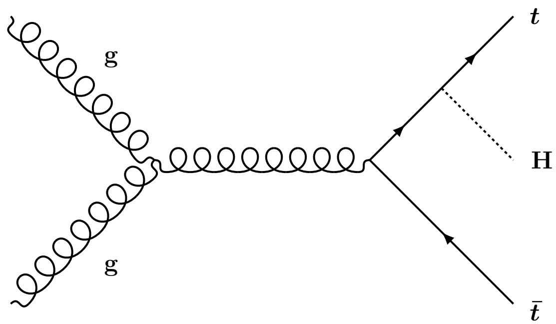


Event selection

- Final states containing a same-sign dilepton pair or three or more leptons → **multilepton** final states
  - Efficient triggering strategy
  - Relatively few backgrounds
- Categories:
  - 2 same-sign leptons (2ℓss)
  - 3 leptons (3ℓ)
  - 4 or more leptons (4ℓ)
- Do not consider 2 opposite-sign leptons since this category is dominated by top pair production
- Require jets and b tags to help distinguish from backgrounds

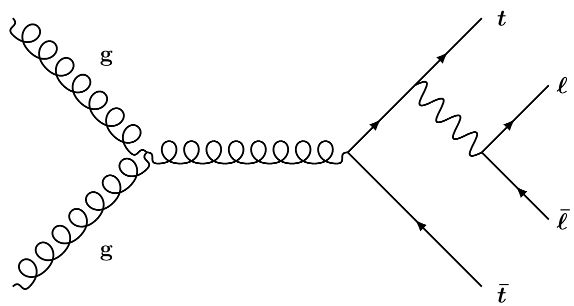
ttX final states

ttH



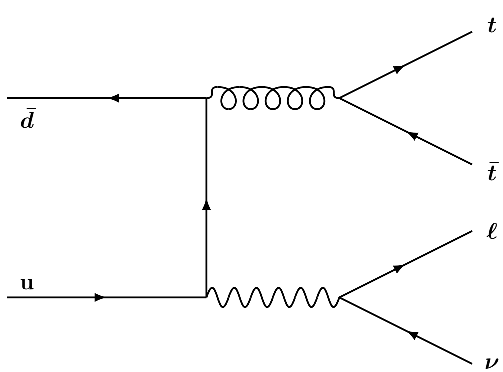
- Up to 6 leptons
- Can populate 2ℓss, 3ℓ, 4ℓ categories

ttll



- Up to 4 leptons
- Can populate, 3ℓ, 4ℓ categories

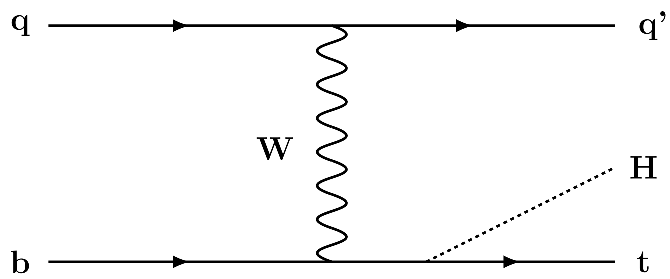
ttlν



- Up to 3 leptons
- Can populate 2ℓss, 3ℓ categories

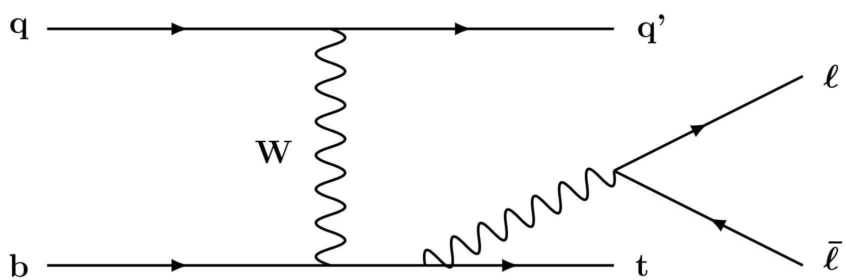
tXq final states

tHq



- Up to 5 leptons
- Can populate 2lss, 3l, 4l categories

tllq



- Up to 3 leptons
- Can populate 3l category

Some plans for improvement over first iteration of the analysis

- Full Run 2 dataset (over three times as much data as available for the first iteration of the analysis)
- Investigate effects of EFT operators on various kinematics quantities in order to take advantage of differences in kinematic variables (such as the transverse momentum of jets or the angular distributions of particles) to help improve the sensitivity of the analysis
- Potentially consider other signal processes (such as tttt, or ttXX where X is a Higgs, W, or Z)

Summary

- New physics beyond the SM must exist, but might not be light enough to be detected directly at the LHC
- EFT is an indirect probe of new physics that can extend the discovery reach of the LHC
- We propose to study associated top production in multilepton final states within the framework of EFT
    - Parametrize event yields in terms of Wilson coefficients
    - Compare with full Run 2 data
    - Find Wilson coefficient values that maximize probability of observing expected number of events
- We will build on techniques from the first iteration of this analysis, aim to improve sensitivity and set tighter constraints on Wilson coefficient values

Thanks for listening!

- And thank you to the collaborators who accomplished the first iteration of this analysis, many of whom will be continuing to work on the second iteration:
  - Reza Goldouzian[1], Mike Hildreth[1], Kevin Lannon[1], Tony Lefeld[2], Wuming Luo[2], Geoff Smith[1], Andrew Wightman[1], Brian Winer[2], Brent Yates[2]
- And thanks to our theory colleagues:
  - Han Kim[1], Adam Martin[1]

1: University of Notre Dame, 2: The Ohio State University

Backup

Luminosity, cross section, and event rate 1

- CMS uses the forward hadronic calorimeters to determine instantaneous luminosity in real time
- The instantaneous luminosity is the number of particles per unit area per second:

$$L_{inst} = f_{coll} \frac{n_1 n_2}{4\pi \sigma_x^* \sigma_y^*} F \leftarrow$$

n_1, n_2 are the numbers of particles in each bunch, f_{coll} is collision frequency (number of bunches per beam times revolution frequency), σ characterizes the rms transverse beam sizes in horizontal and vertical, F accounts for effects like crossing angle

(PDG "Accelerator Physics of Colliders" eqn. 30.2)

- Some numbers:
    - At the LHC, typical bunches per beam is ~2500
    - Instantaneous luminosity is about 2×10^{34} cm^{-2} s^{-1}
    - Average PU per bunch crossing is about 40

Luminosity, cross section, and event rate 2

- Integrate instantaneous luminosity over time to get integrated luminosity: $L_{integrated} = \int L_{inst} \mathrm{dt}$
- Event rate = (integrated luminosity)(cross section)

Units of 1/area   Units of area (E^{-2})

- Cross section: expresses the likelihood or expected frequency of occurrence of a particular final state
- Cross section is found from the matrix element:

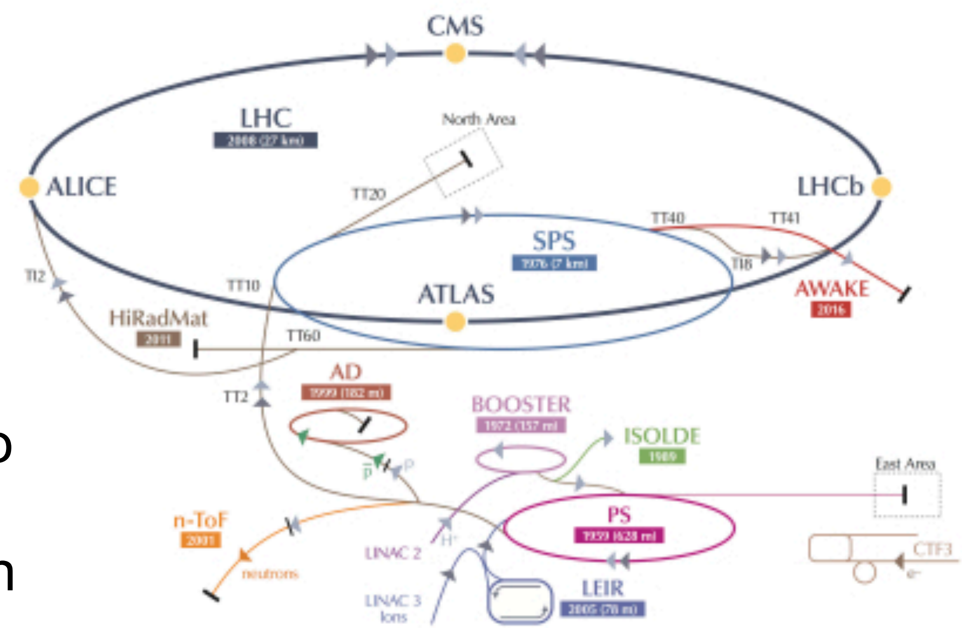
$$d\sigma(AB \to n) = \frac{1}{2E_A 2E_B |\vec{v}_A - \vec{v}_B|} |\mathscr{M}|^2 (d\Pi_{LIPS})_n \longleftarrow$$

lorentz invariant n-body phase space

spin averaged matrix element

LHC accelerator complex

- Proton source is a bottle of hydrogen gas
- Electrons are striped off with an electric field
- A series of accelerators boosts the energy before injecting into LHC
    - Linac2 accelerates the protons to 50 MeV
    - Proton Synchrotron Booster accelerates the protons to 1.4 GeV
    - Proton Synchrotron accelerates the protons to 25 GeV
    - Super Proton Synchrotron accelerates to 450 GeV



- Then the protons are injected into the LHC, where each beam is accelerated to 6.5 TeV

https://home.cern/science/accelerators/accelerator-complex

About the accelerators in the complex

- Linac2:
  - Uses radiofrequency cavities
  - Conductors are alternately charged positive and negative, protons pass through, pushed by the conductors behind them and pulled by the conductors ahead of them
  - Quadrupole magnets keep the protons in a beam
- PSB:
  - Composed of 4 synchrotron rings
- PS:
  - Circumference 628 meters
  - 277 electromagnets
- SPS:
  - Nobel-prize-winning discovery of W and Z bosons 1983 (as a proton-antiproton collider)
  - 1317 electromagnets

The LHC

- 27 km circumference (~17 mi)
- 16 radio frequency cavities accelerate the particles
  - Oscillate at 400MHz
  - Accelerate each beam to 6.5 TeV
  - Keep bunches separated
- Beams pipes are a vacuum (emptier than interstellar space)
- Particles steered around ring by superconducting electromagnets
  - Dipole: 1232 magnets, 15 m long, for bending the beams
  - Quadrupole: 392 magnets, 5–7 m long, for focusing the beams
- Cooled to −271.3°C, requires accelerator to be connected to a distribution system of liquid helium

https://home.cern/science/accelerators/large-hadron-collider

CMS solenoid magnet and solenoid magnetic field

- Superconducting solenoid, magnetic field of ~4T
- Requires about 18,000 A of current
- Steel return yoke to guide lines of magnetic field around outside of the solenoid back into other end (and becomes magnetized by the field and thus passively adds to field)
- How a solenoid works:
  - Use Ampere's law to find the magnetic field, depends on the current in the wire (I) and the number of turns per length in the wire (N/L):

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{inc}$$

$$BL = \mu_0 N I$$

$$B = \mu_0 \frac{N}{L} I$$

Assume top leg of loop
is far enough away
from the coil that the
field is negligible

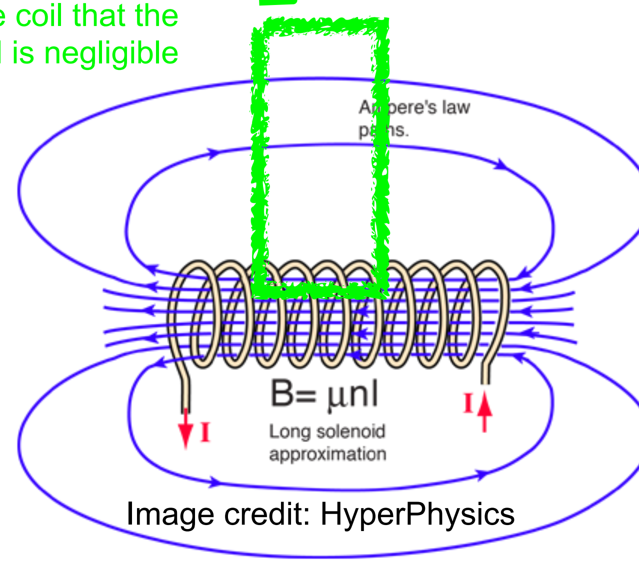


Image credit: HyperPhysics

Coordinates and conventions

- Origin centered at the nominal collision point
- Y-axis points vertically upward, x-axis points radially inward toward the center of the LHC, z-axis points along the beam direction
- Azimuthal angle ϕ measured from x axis in x-y plane, polar angle θ measured from z-axis
- Rapidity $y = \frac{1}{2} ln \frac{E + p_z}{E - p_z}$, pseudorapidity $\eta = \frac{1}{2} ln \frac{|\overrightarrow{p}| + p_z}{|\overrightarrow{p}| - p_z} = - \, ln \, tan \frac{\theta}{2}$
  - Note $y \to \eta$ when $|\overrightarrow{p}| \gg m$ since $E^2 = |\overrightarrow{p}|^2 + m^2 \Rightarrow E \approx |\overrightarrow{p}|$
  - Differences in rapidity preserved under boosts
- Momentum and energy transverse to beam direction (denoted p_T, E_T) computed from x, y components
- Angular separation in $\phi - \eta$ space is $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$

"The CMS experiment at the CERN LHC" The CMS Collaboration *et al* 2008 *JINST* **3** S08004

Hardware based L1 trigger: 40MHz → 100kHz

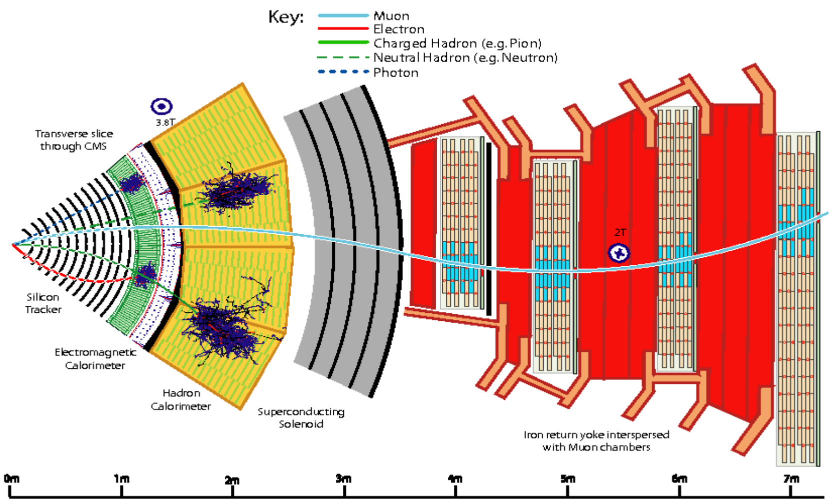
- Muon and calorimeter triggers identify particle candidates and calculate quantities such as MET, then pass this information to the global L1 trigger
  - The global L1T combines the candidates in up to 512 algorithms
- The final decision depends on a programable menu of the algorithms/paths:
  - If an event satisfies the criteria of any path in the menu (e.g. single muon, pT>22 GeV), the global trigger sends an accept signal to the detector electronics and the DAQ
  - The data is then merged and passed to the HLT

Software based HLT: 100kHz → 1kHz

- Physically comprised of a filter farm containing thousands of CPUs, the HLT allows a processing time of ~175ms per event
- HLT decisions are based on the HLT menu:
  - Each path in the menu is implemented as set of steps run in a predefined order that reconstructs physics objects and makes selections on these objects
  - The sequence is ordered by complexity so as to reject events as quickly as possible
- If an event is accepted, it is written to local storage and eventually transferred to the Tier-0 computing center for offline processing and permanent storage

Particle flow (PF) reconstruction 1

- PF is a reconstruction technique that correlates **elements** (tracks and clusters) from the sub detectors to identify final state particles and reconstruct particle properties based on the identification



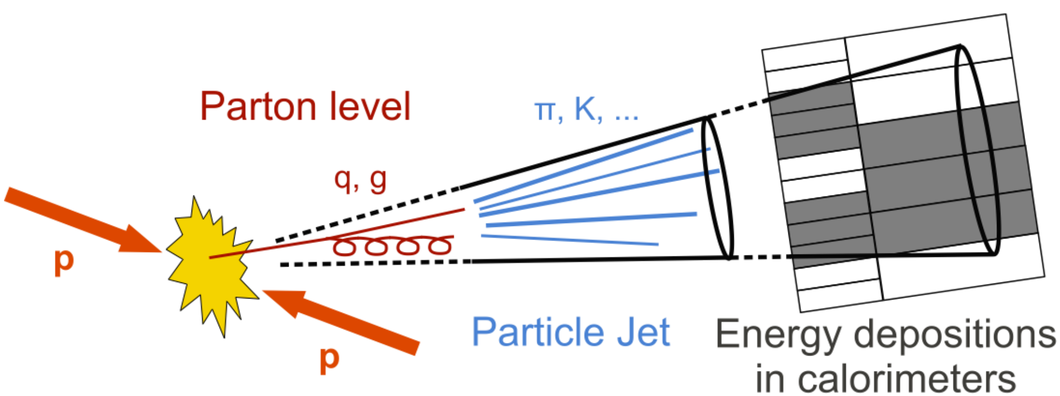
- A particle can give rise to multiple elements, so the reconstruction starts with a link algorithm to connect the elements into **PF blocks**
- In each block, the identification and reconstruction of the objects follows a set sequence.

Particle flow (PF) reconstruction 2

- **Muons**: Characterized by tracks in the muon chambers and inner tracker, lack of significant energy deposits in the calorimeters
- **Electrons and isolated photons**: Reconstructed together since electrons tend to emit bremsstrahlung radiation and photons tend to pair produce. Electron candidates seeded by track with corresponding energy deposits in ECAL, photons by ECAL cluster with no track. Both require lack of significant deposits in HCAL.
- **Hadrons and non-isolated photons**:
  - ECAL/HCAL clusters not linked to a track give rise to neutral hadrons and non-isolated photons
    - Inside tracker acceptance: ECAL clusters → photons, HCAL clusters → neutral hadrons
    - Outside tracker acceptance: Charged and neutral hadrons cannot be distinguish, so ECAL clusters linked to HCAL clusters → hadrons, ECAL clusters w/o link → photons
  - Each remaining HCAL cluster in PF block linked to tracks → charged hadrons, though a cross check for misidentified muons is also performed at this stage
- **Post processing** is performed to mitigate misidentification and misreconstruction

Jet clustering

- Quarks and gluons carry color charge, so cannot exist as isolated particles due to color confinement
- The hadronization of these particles results in a collimated spray of color-neutral particles called a **jet**
- CMS uses the anti-k_T algorithm to cluster objects into jets
- It is important to identify jets originating from b quarks since top quarks usually decay into a W and a b



The anti-k_T jet clustering algorithm

- The anti-k_T algorithm is a sequential recombination jet reconstruction algorithm
- Begins by defining a distance measure between objects (d_{ij}) and between objects and the beam (d_{iB}):

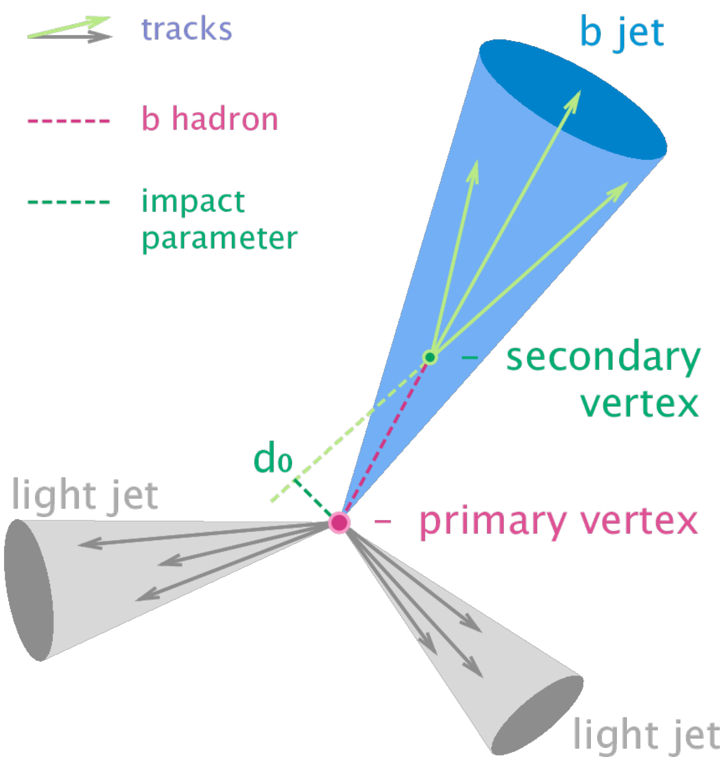
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \quad \longleftarrow \quad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = k_{ti}^{2p} \,,$$

  where k_{ti}, y_i, and ϕ_i are the transverse momentum, rapidity, and azimuth of particle *i*. For the anti-k_T, $p = -1$.
  - If the smallest distance is a d_{ij}, then combine the *i* and *j* objects
  - If the smallest distance is a d_{iB}, then call object *i* a jet and remove it from the list of objects
- Then recalculate the distances and repeats the procedure till all objects have been clustered into jets

b-tagging

- Top quarks almost always decay into a W and a b
- Identifying jets that arising from b quarks is called b-tagging
- To distinguish from jets arising from hadronization of lighter quarks or gluons: take advantage of b hadrons'
    - **large mass** (decay products with relatively large transverse momentum relative to jet axis)
    - **long lifetimes** (displaced tracks, secondary vertices)
    - Sizable **semileptonic branching ratio**



"b Tagging in ATLAS and CMS:" arxiv 1709.01290

Operators and Wilson coefficients: O_{ug} example

- We will consider Wilson coefficients that have a relatively large impact on signal processes without a large impact on background process, they fall into two categories:
    - Two quarks and two leptons
    - Two quarks plus bosons
- For example, consider the O_{ug} operator:

Gell-Mann matrices/2

Higgs doublet

Gluon field strength tensor

$$\frac{c_{tG}}{\Lambda^2}(\bar{Q}_3\sigma^{\mu\nu}T^A u_3)\epsilon H^* G^A_{\mu\nu} + \mathrm{h.c.}$$

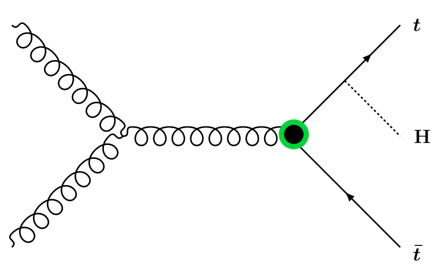
Left-handed third-generation quark doublet

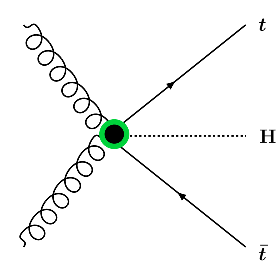
Right-handed third generation quark

Gives rise to vertices:

- t-t-g
- t-t-g-h
- t-t-g-g
- t-t-g-g-h

- Affects signal process ttH, so including it in the model will affect the predicted yields:





List of operators and Wilson coefficients

Notational conventions follow arxiv 1802.07237 (dim6TopEFT model paper), and further details on the operators and coefficients can be found there as well

Operators involving two quarks and one or more bosons		
Operator	Definition	Wilson coefficient
$\ddagger O_{u\varphi}^{(ij)}$	$\bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi)$	$c_{t\varphi} + i c_{t\varphi}^I$
$O_{\varphi q}^{1(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j)$	$c_{\varphi Q}^- + c_{\varphi Q}^3$
$O_{\varphi q}^{3(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j)$	$c_{\varphi Q}^3$
$O_{\varphi u}^{(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	$c_{\varphi t}$
$\ddagger O_{\varphi ud}^{(ij)}$	$(\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j)$	$c_{\varphi tb} + i c_{\varphi tb}^I$
$\ddagger O_{uW}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W_{\mu\nu}^I$	$c_{tW} + i c_{tW}^I$
$\ddagger O_{dW}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W_{\mu\nu}^I$	$c_{bW} + i c_{bW}^I$
$\ddagger O_{uB}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu} u_j)\quad \tilde{\varphi}B_{\mu\nu}$	$(c_W c_{tW} - c_{tZ})/s_W + i(c_W c_{tW}^I - c_{tZ}^I)/s_W$
$\ddagger O_{uG}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}G_{\mu\nu}^A$	$c_{tG} + i c_{tG}^I$

Operators involving two quarks and two leptons		
Operator	Definition	Wilson coefficient
$O_{\ell q}^{1(ijkl)}$	$(\bar{\ell}_i\gamma^\mu\ell_j)(\bar{q}_k\gamma^\mu q_\ell)$	$c_{Q\ell}^{-(\ell)} + c_{Q\ell}^{3(\ell)}$
$O_{\ell q}^{3(ijkl)}$	$(\bar{\ell}_i\gamma^\mu\tau^I\ell_j)(\bar{q}_k\gamma^\mu\tau^I q_\ell)$	$c_{Q\ell}^{3(\ell)}$
$O_{\ell u}^{(ijkl)}$	$(\bar{\ell}_i\gamma^\mu\ell_j)(\bar{u}_k\gamma^\mu u_\ell)$	$c_{t\ell}^{(\ell)}$
$O_{eq}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_\ell)$	$c_{Qe}^{(\ell)}$
$O_{eu}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_\ell)$	$c_{te}^{(\ell)}$
$\ddagger O_{\ell equ}^{1(ijkl)}$	$(\bar{\ell}_i e_j)\;\varepsilon\;(\bar{q}_k u_\ell)$	$c_t^{S(\ell)} + i c_t^{SI(\ell)}$
$\ddagger O_{\ell equ}^{3(ijkl)}$	$(\bar{\ell}_i\sigma^{\mu\nu} e_j)\;\varepsilon\;(\bar{q}_k\sigma_{\mu\nu} u_\ell)$	$c_t^{T(\ell)} + i c_t^{TI(\ell)}$

Weight function's dependence on WCs

- The weight function for event *i* can be written as:

$$w_i\left(\frac{\vec{c}}{\Lambda^2}\right) = s_{0i} + \sum_j s_{1ij}\frac{c_j}{\Lambda^2} + \sum_j s_{2ij}\frac{c_j^2}{\Lambda^4} + \sum_{j,k} s_{3ijk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

- The yield for an event selection category is estimated by summing the weight functions for events that meet the selection requirements of the given category

$$\begin{aligned}
N\left(\frac{\vec{c}}{\Lambda^2}\right) &= \sum_i w_i\left(\frac{\vec{c}}{\Lambda^2}\right) \\
&= \sum_i \left(s_{0i} + \sum_j s_{1ij}\frac{c_j}{\Lambda^2} + \sum_j s_{2ij}\frac{c_j^2}{\Lambda^4} + \sum_{j,k} s_{3ijk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}\right) \\
&= \left(\sum_i s_{0i}\right) + \sum_j\left(\sum_i s_{1ij}\right)\frac{c_j}{\Lambda^2} + \sum_j\left(\sum_i s_{2ij}\right)\frac{c_j^2}{\Lambda^4} + \sum_{j,k}\left(\sum_i s_{3ijk}\right)\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2} \\
&= S_0 + \sum_j S_{1j}\frac{c_j}{\Lambda^2} + \sum_j S_{2j}\frac{c_j^2}{\Lambda^4} + \sum_{j,k} S_{3jk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}
\end{aligned}$$

TOP-19-001 event selection

2ℓss category

- Exactly two same-sign tight leptons, $p_{\mathrm{T}} > 25/15\,$GeV, $|\eta| < 2.4$
- At least four jets, $p_{\mathrm{T}} > 30\,$GeV, $|\eta| < 2.4$
  - At least two b-jets, one of which must be a medium tag
- Split into sub-categories based on charge sum

3ℓ category

- Exactly three tight leptons, $p_{\mathrm{T}} > 25/15/10\,$GeV, $|\eta| < 2.4$
- At least two jets, $p_{\mathrm{T}} > 30\,$GeV, $|\eta| < 2.4$
- Split events with exactly one medium b-jet and events with two or more medium b-jets
- Further split into events with OSSF leptons inside the Z-peak ($10\,$GeV) and outside
- For sub-categories outside the Z-peak, split also based on charge sum

4ℓ category

- At least four tight leptons, $p_{\mathrm{T}} > 25/15/15/10\,$GeV, $|\eta| < 2.4$
- At least two jets, $p_{\mathrm{T}} > 30\,$GeV, $|\eta| < 2.4$
  - At least two b-jets, one of which must be a medium tag

TOP-19-001 systematics

$$N_{\text{exp}}(\vec{c}) = \sigma_{\text{th}}\mathcal{L}\,\frac{N_{\text{pass}}(\vec{c})}{N_{\text{gen}}(\text{SM})}$$

- Experimental
  - Lepton ID ($1-2\%$ per lepton), b-tag SFs ($1-7\%$), jet energy scale ($5-10\%$), trigger efficiency ($2-5\%$)
- Data-driven backgrounds
  - Fake rate ($25-30\%$) and charge flip (30%) estimates
- SM normalization
  - QCD scale ($1-13\%$), PDF theory ($2-5\%$)
- Acceptance and efficiency
  - PDF shape, Q^2 Scale, ISR/FSR, qCut matching

TOP-19-001 systematics

Source	Type	Notes
Luminosity	rate	Applied to signal and all MC backgrounds
Lepton ID/Iso	rate+shape	Applied to signal and all MC backgrounds
Trigger efficiency	rate+shape	Applied to signal and all MC backgrounds
Pileup	rate+shape	Applied to signal and all MC backgrounds
JES	rate+shape	Applied to signal and all MC backgrounds
b-Tag HF purity	rate+shape	Applied to signal and all MC backgrounds
b-Tag HF stats (linear)	rate+shape	Applied to signal and all MC backgrounds
b-Tag HF stats (quadratic)	rate+shape	Applied to signal and all MC backgrounds
b-Tag LF purity	rate+shape	Applied to signal and all MC backgrounds
b-Tag LF stats (linear)	rate+shape	Applied to signal and all MC backgrounds
b-Tag LF stats (quadratic)	rate+shape	Applied to signal and all MC backgrounds
b-Tag Charm (linear)	rate+shape	Applied to signal and all MC backgrounds
b-Tag Charm (quadratic)	rate+shape	Applied to signal and all MC backgrounds
Fakes FF measurement	rate+shape	Related to FF measurement for the fakes background.
Fakes AR stats	rate+shape	Due to statistics in the AR for the fakes background. Uncorrelated across categories.
Charge Flip	rate	Uncertainty on the charge flip background
QCD Scale ($\mathrm{t\bar{t}H}$)	rate	Scale uncertainty for NLO $\mathrm{t\bar{t}H}$ prediction
QCD Scale ($\mathrm{t\bar{t}\gamma}$)	rate	Scale uncertainty for NLO $\mathrm{t\bar{t}\gamma}$+jets prediction
QCD Scale ($\mathrm{t\bar{t}V}$)	rate	Scale uncertainty for NLO $\mathrm{t\bar{t}l\nu}$ and $\mathrm{t\bar{t}ll}$ prediction
QCD Scale (tHq)	rate	Scale uncertainty for NLO tHq prediction
QCD Scale (V)	rate	Scale uncertainty for NNLO W and Z prediction
QCD Scale (VV)	rate	Scale uncertainty for NLO diboson prediction
QCD Scale (VVV)	rate	Scale uncertainty for NLO triboson prediction
pdf (gg)	rate	Pdf uncertainty for gg-initiated processes except $\mathrm{t\bar{t}H}$ ($\mathrm{t\bar{t}ll}$, $\mathrm{t\bar{t}\gamma}$+jets)
pdf ($\mathrm{gg\_t\bar{t}H}$)	rate	Pdf uncertainty for $\mathrm{t\bar{t}H}$
pdf ($\mathrm{q\bar{q}}$)	rate	Pdf uncertainty for $\mathrm{q\bar{q}}$-initiated processes (tllq, $\mathrm{t\bar{t}l\nu}$, Diboson, Triboson)
pdf ($\mathrm{qg\_tHq}$)	rate	Pdf uncertainty for qg-initiated processes (tHq)
PDF	shape	Applied to signal and all MC backgrounds
Q^2 Scale Renorm. + Fact.	shape	Renormalization and factorization scale uncertainties: Applied to signal and all MC backgrounds
Parton Shower	shape	Parton-shower scale uncertainties: Applied to signal and all MC backgrounds
Matching Uncertainty	shape	Parton-shower matching uncertainty: Applied to signal samples produced with an extra parton ($\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}W}$, $\mathrm{t\bar{t}Z}$)
Missing parton uncertainty	shape	Introduced to account for the fact that an extra parton could not be included in the privately produced single top samples: Applied only to tllq and tHq.

Likelihood 1

- The total expected events is the sum of the signal and background: $s+b$
- Consider μ, where $\mu=1 \Rightarrow$ SM, ($\mu = \sigma/\sigma_{SM}$), so total events = $\mu s+b$
- The likelihood of seeing the observed number of events (n_{obs}) given that we expect $\mu s+b$ is given by a poisson distribution:

$$\mathscr{L}(\text{data}\,|\,\mu) = \text{Poisson}(n_{obs}\,|\,\mu s + b) = \frac{(\mu s + b)^{n_{obs}}}{n_{obs}!}e^{-(\mu s+b)}$$

- The μ that maximizes the the likelihood is the best fit μ

Likelihood 2

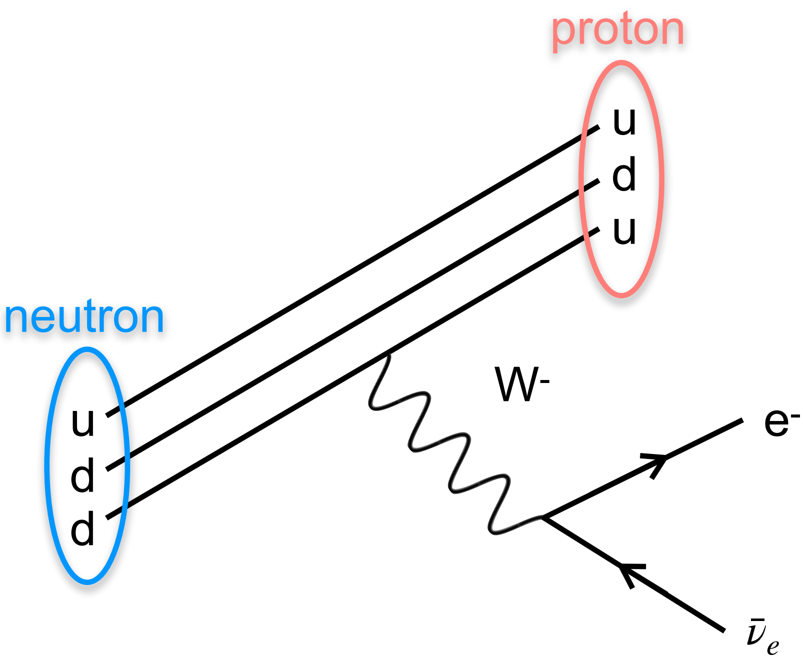
- The expected number of events varies for each bin, so we really have a product of poisson functions
- Account for systematic uncertainties with nuisance parameters θ, so s and b are functions of θ
- The expected value of θ is denoted by $\tilde{\theta}$, and $\rho(\tilde{\theta} | \theta)$ describes the likelihood that the nuisance parameters were measured to be $\tilde{\theta}$ when their actual values are θ
- So the likelihood is:

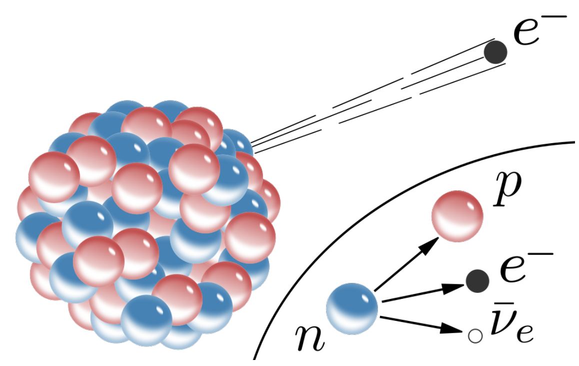
$$\mathscr{L}(\text{data} | \mu, \theta) = \prod_i \frac{(\mu s(\theta)_i + b(\theta)_i)^{n_i}}{n_i!} e^{-(\mu s(\theta)_i + b(\theta)_i)} \rho(\tilde{\theta} | \theta)$$

Signal extraction

- A likelihood fit will be used to determine the best fit value for the Wilson coefficients
- Expected yields will be calculated according to their quadratic dependence on Wilson coefficients
- Systematics will be accounted for via nuisance parameters (upon which the predicted yield also depends)
- The Wilson coefficient values will be varied until the negative of the log of the likelihood (NLL) has been minimized
- ΔNLL describes differences between NLL at a given point and the global minimum and will be used to establish confidence intervals.

Fermi theory for beta decay





When q/m_W is small, propagator can be expanded and so interaction becomes a dimension-6 four fermion interaction between d, u, e, and $\bar{\nu}_e$

$$i\mathcal{M} = (-i\frac{g}{\sqrt{2}})^2 \left[\bar{u}(\nu_u)\gamma^u \frac{1-\gamma^5}{2} u(\mu)\right] \frac{-i}{q^2-m_W^2+i\epsilon}\left(\eta_{\mu\nu}-\frac{q_\mu q_\nu}{m_W^2}\right)\left[\bar{u}(\nu_u)\gamma^u\frac{1-\gamma^5}{2}u(\mu)\right]$$

← Matrix element

propagator

($q \ll m_W$)

$$\frac{-i}{q^2-m_W^2+i\epsilon}\left(\eta_{\mu\nu}-\frac{q_\mu q_\nu}{m_W^2}\right) = i\frac{\eta_{\mu\nu}}{m_W^2} + \mathcal{O}\left(\frac{1}{m_W^4}\right)$$