CMS Experiment at the LHC, CERN
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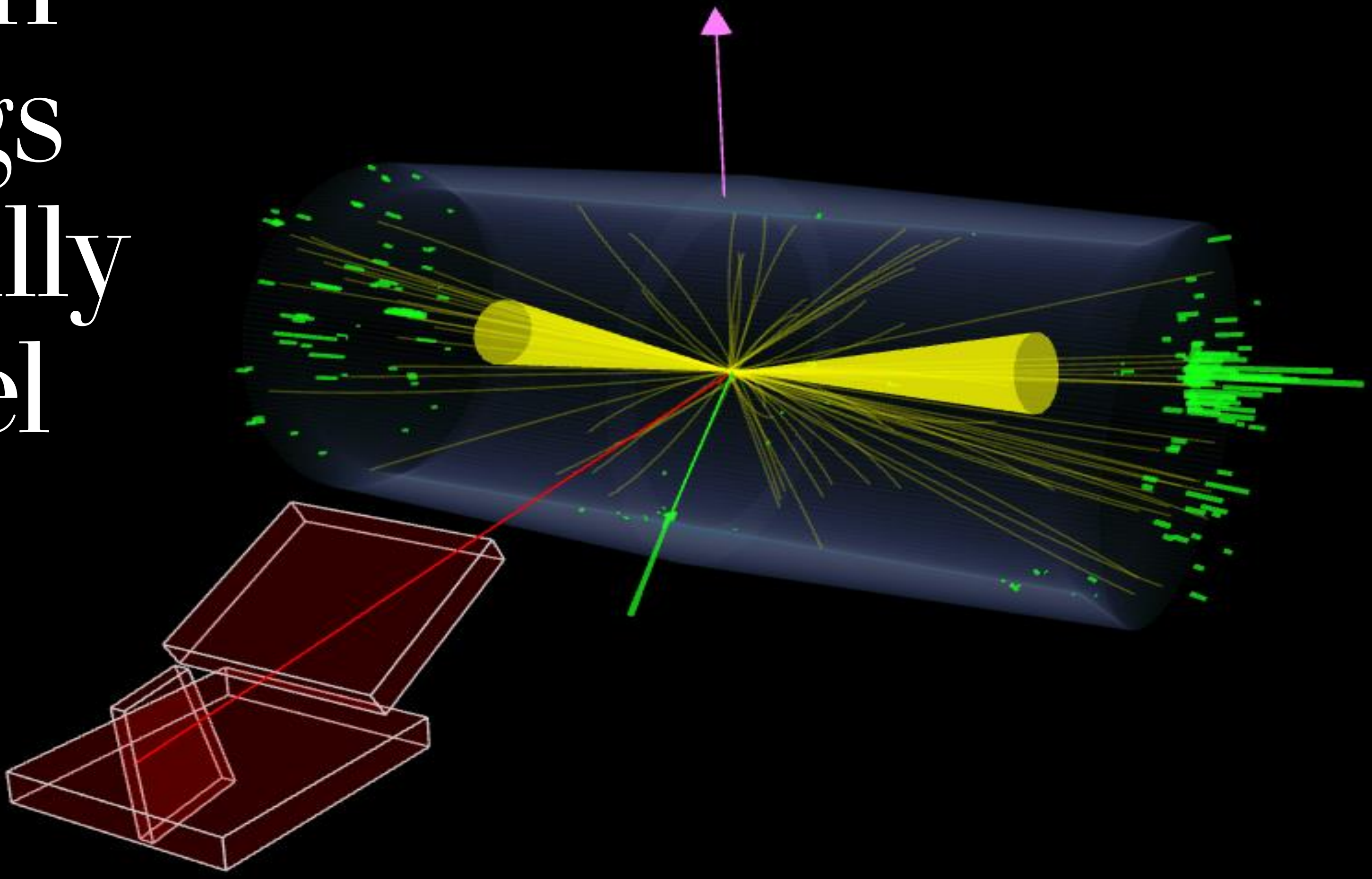
Optimal selection for charged Higgs analysis in the fully hadronic channel



Jere Mäki-Ikola

9.4.2024

Content

- Background
  - Standard Model (SM) and charged Higgs ($H^{\pm}$)
  - CERN and CMS
- $H^{\pm}$-analysis
  - The programs in use
  - The fully hadronic channel
- Thesis
  - The goal and how to get there
  - The problems
- Future work and summary

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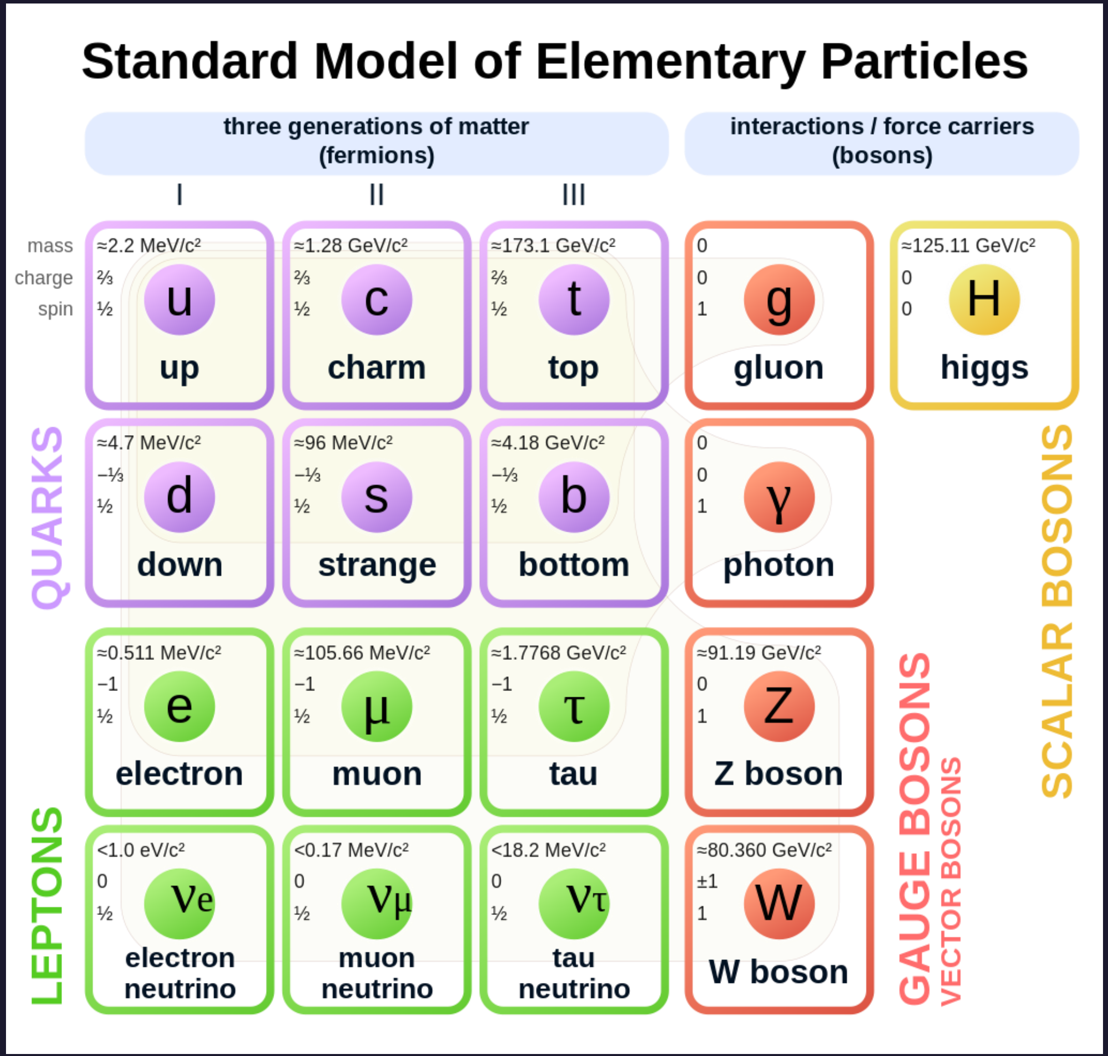
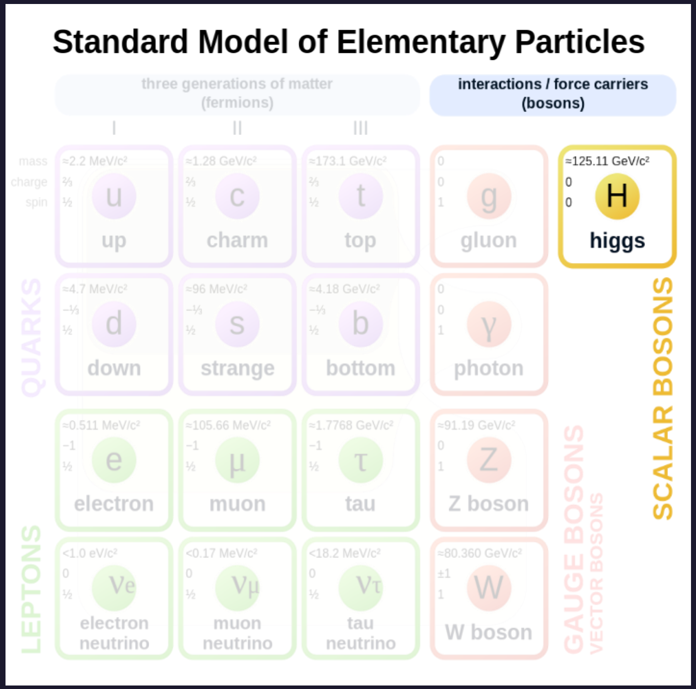
The Standard Model (SM)

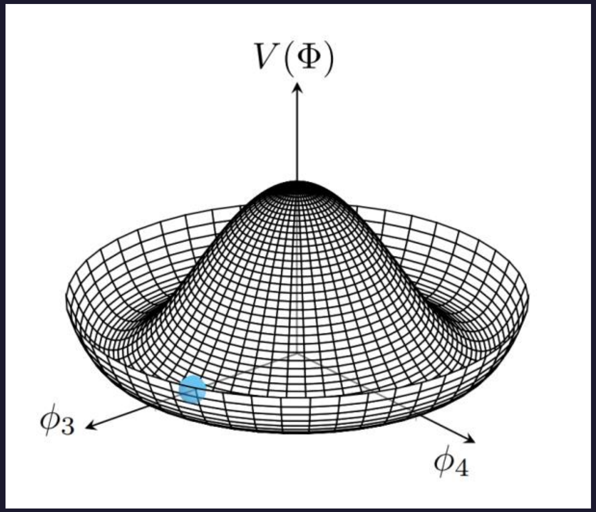
- SM is one of the most precise theories in particle physics
- Describes three out of four fundamental forces
- Divided into multiple subcategories
- Even though it is precise, it is incomplete
  - Gravity, dark matter, neutrino masses, etc.

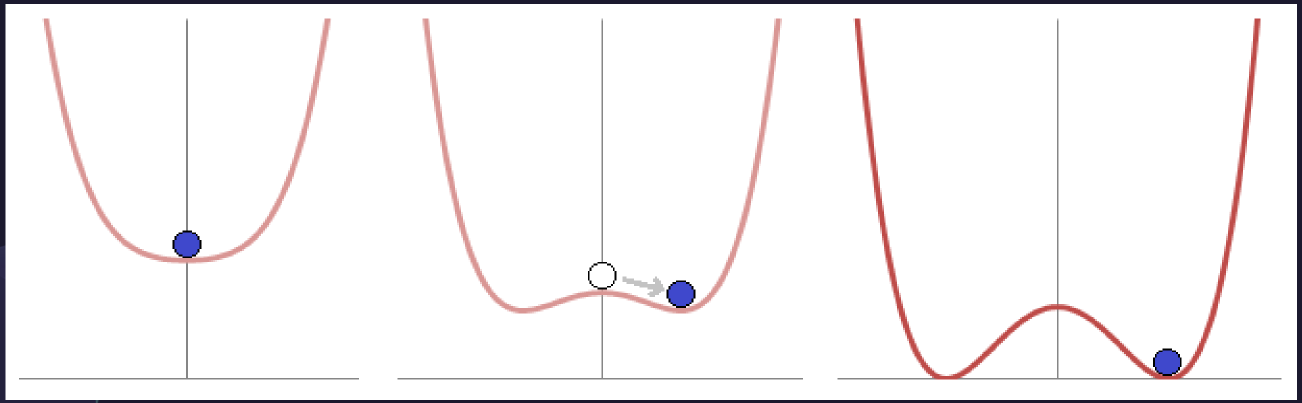


Higgs boson

- The only observed fundamental scalar boson (spin 0, no electric charge)
  - ➢ Mesons and alpha particle are composite, not fundamental
- Latest addition to the SM in 2012/2013
- Its field explains how particles (excluding neutrinos) obtain their rest masses
  - Spontaneous symmetry breaking (sombrero)
- Can be produced through different ways
  - Gluon fusion, vector boson fusion, etc.

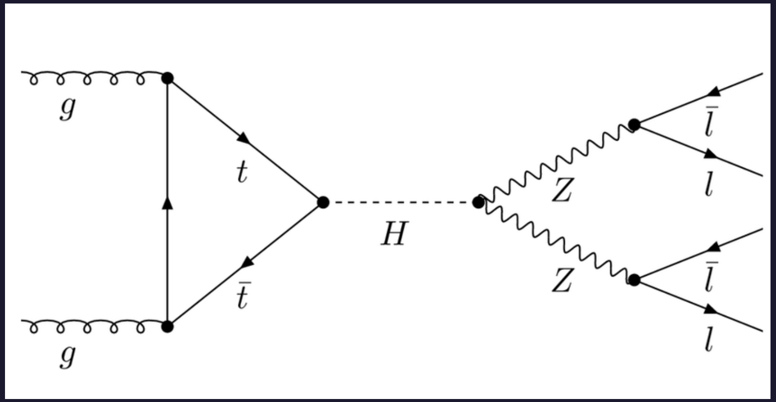




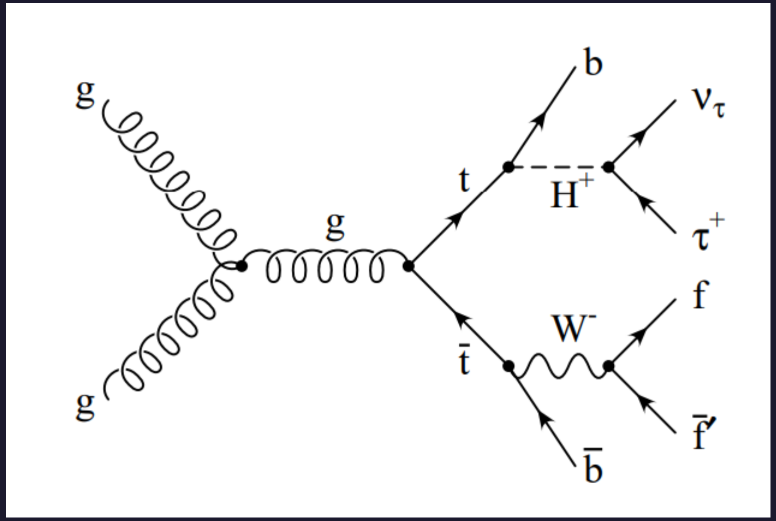


Charged Higgs boson aka $H^{\pm}$

- Predicted by multiple beyond the SM theories
  - If found, it would be direct evidence
- Could be produced the same way as SM Higgs
- Not been found yet
  - Not much data?



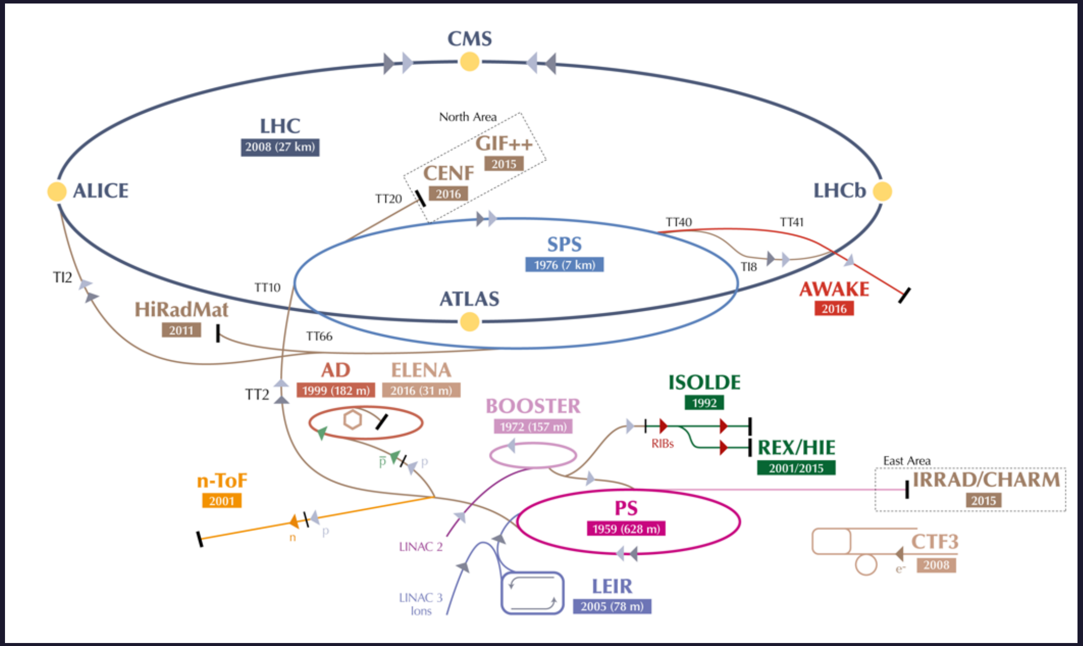
SM Higgs production

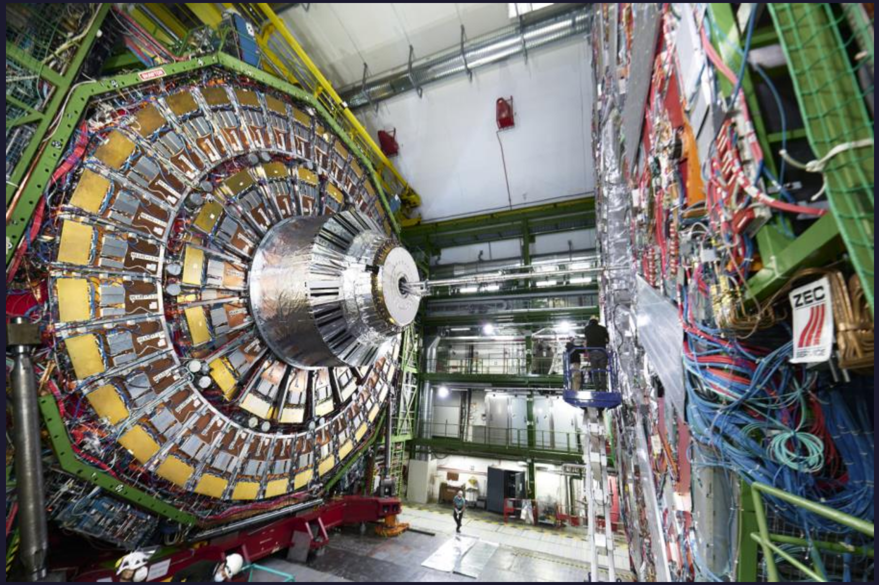


$H^{\pm}$ production

CERN, LHC and CMS

- CERN hosts the largest particle physics laboratory in the world
- LHC, aka Large Hadron Collider, is the world's largest and most powerful particle accelerator
- CMS, aka Compact Muon Solenoid, is one of the four largest experiments alongside ALICE, ATLAS, and LHCb
- Produces on average 15 PB/year of data from events





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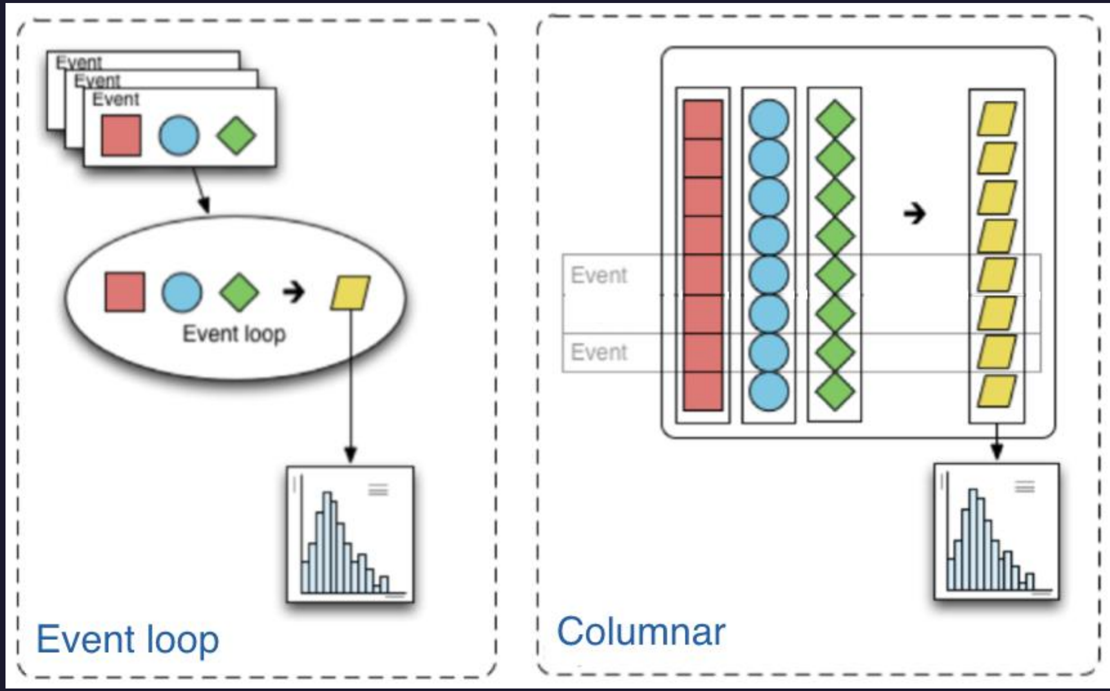
HPlus

- Two programs; HiggsAnalysis and NanoAnalysis
- HiggsAnalysis is "old" code meaning it is using Python 2, C++, and ROOT
- NanoAnalysis uses Python 3 and Coffea, and it is currently in development
- In my thesis, I will be using both because some parts have not yet been programmed into NanoAnalysis



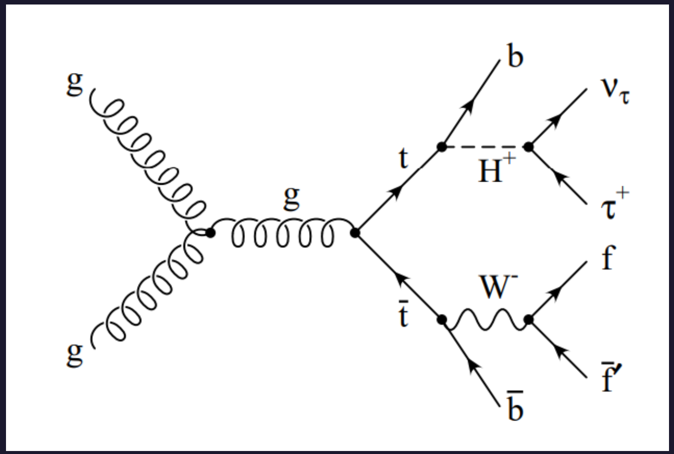
The fully hadronic channel (aka $H^{\pm} \to \tau^{\pm}\nu_{\tau}$)

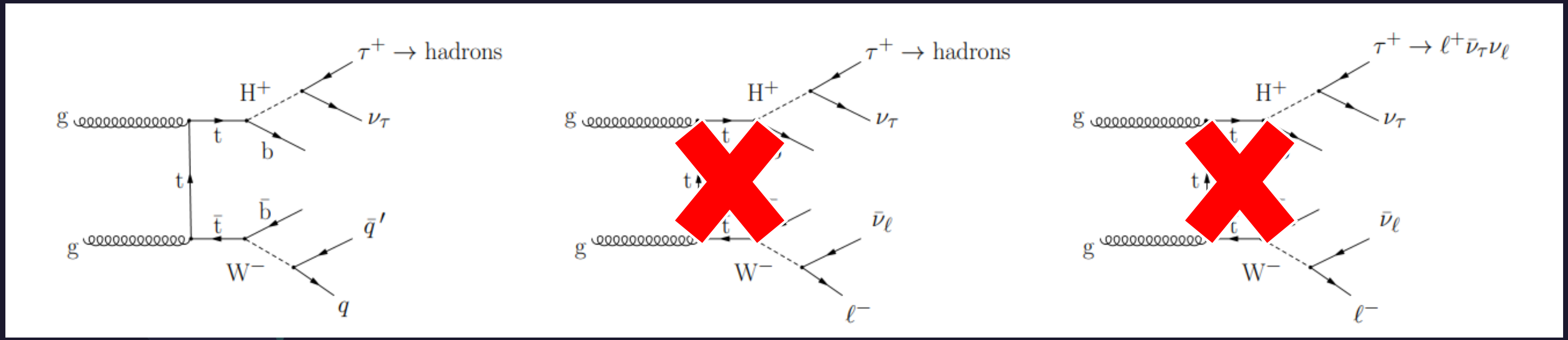
- There are multiple ways to produce/observe a charged Higgs if it exists

- This channel was chosen for thesis because of its high branching fraction (see next slide)

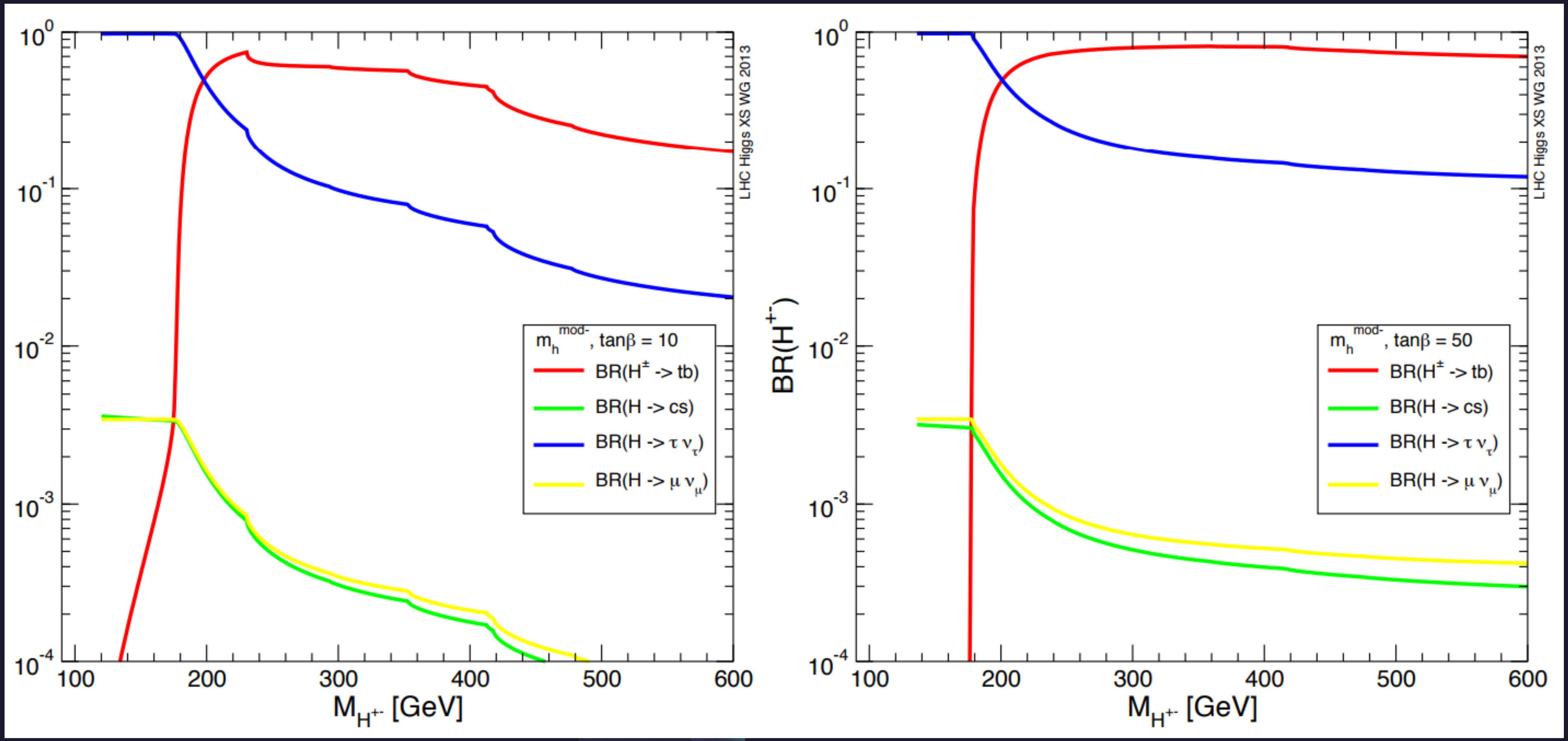
- Fully hadronic channel was chosen also because other research groups focus on different channels

Mode
$H^+ \to \tau^+\nu_\tau$
~~$H^+ \to \mu^+\nu_\mu$~~
~~$H^+ \to t\bar{b}$~~
~~$H^+ \to c\bar{b}$~~
~~$H^+ \to c\bar{s}$~~





The fully hadronic channel (aka $H^{\pm} \to \tau^{\pm} \nu_{\tau}$)



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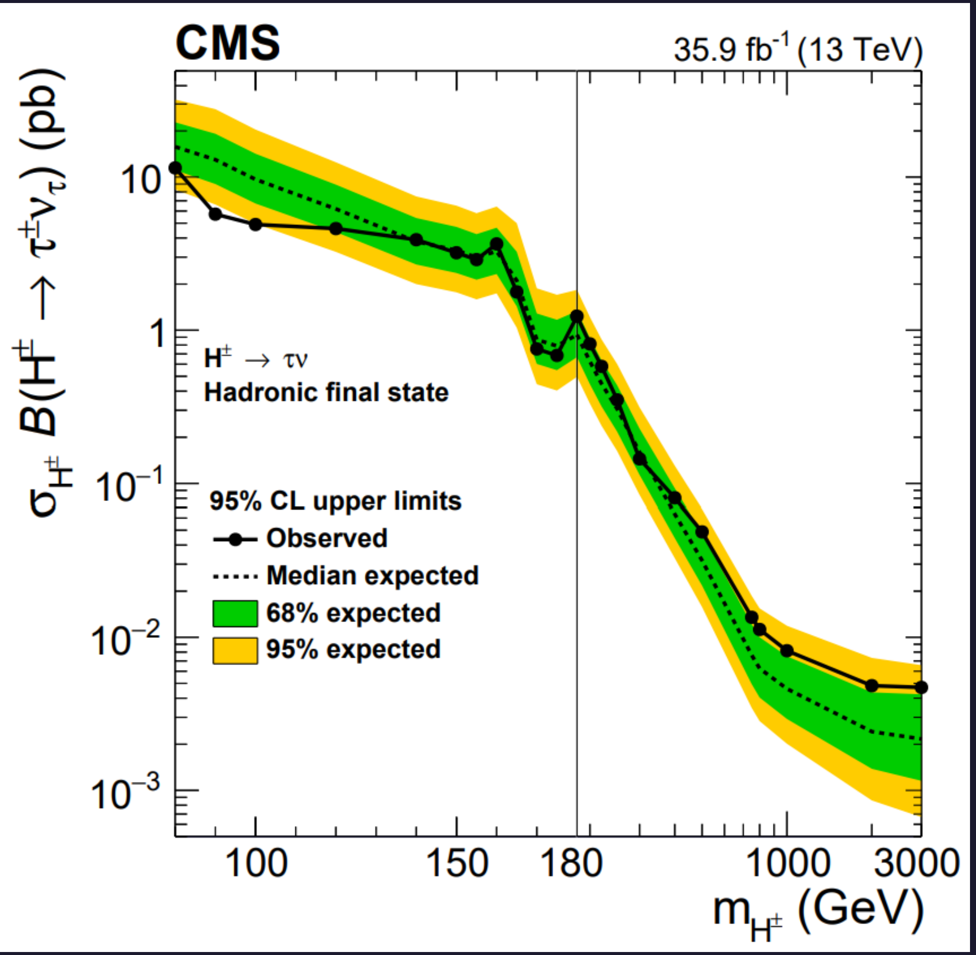
The goal of my thesis

- Short answer: To produce these kinds of plots
- Long answer: This section of the presentation
- The goal is to deduce the optimal selection for my (exclusion) limit plots
    - Selections change the output of the limit plots
    - For example, no isolated leptons (electrons/muons), neutrinos have at least >90 GeV transverse momentum and so on
    - I'm focusing on the number of jets and the number of bottom-tagged jets



How to produce the limit plots?

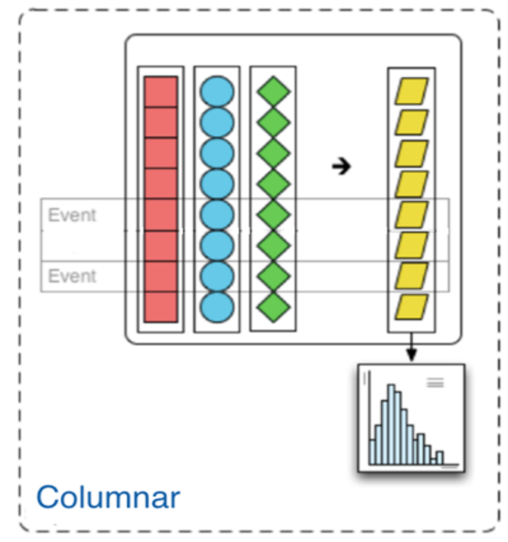
- The production can be divided into three subparts: data analysis, background measurement, and limit calculation

- In data analysis, events are analysed through to see if there is a wanted final state

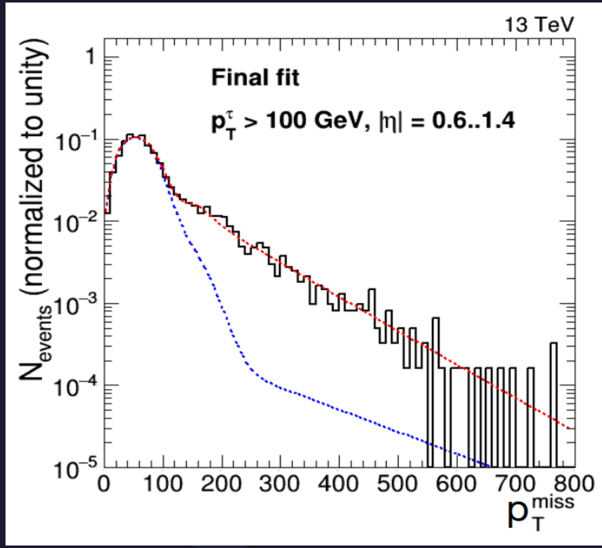
- Background measurement estimates the background events and “fake tau events”

- Limit calculation uses the results of previous two steps

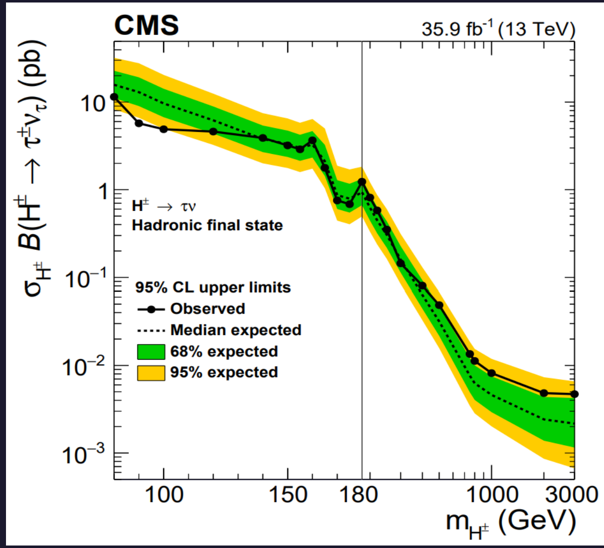
Data analysis



Background measurement



Limit calculation



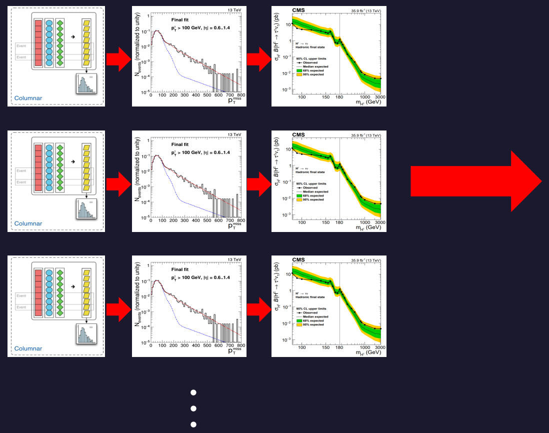
How to deduce the optimal selection

- Run the process for multiple selections for one year (for example year 2017) to find the best selection
- Then run the selection for Run 2
- Produce the combined limit plot

Selection 1

Selection 2

Selection 3



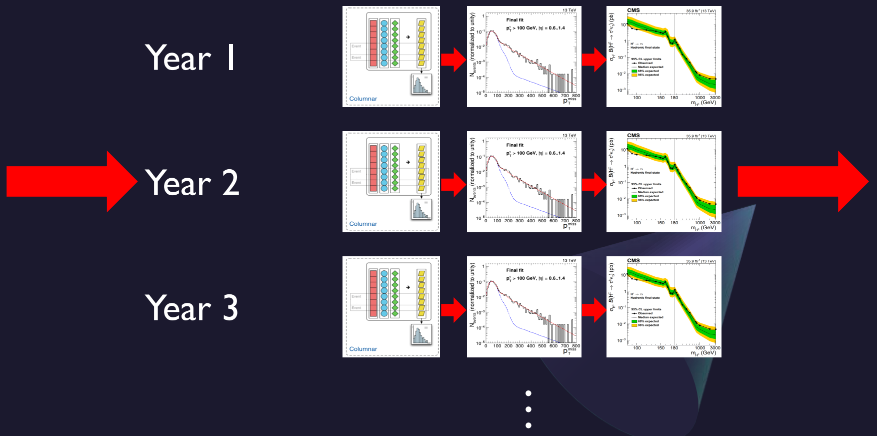
Best selection is x

Selection x

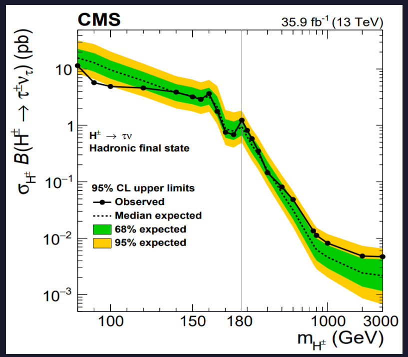
Year 1

Year 2

Year 3



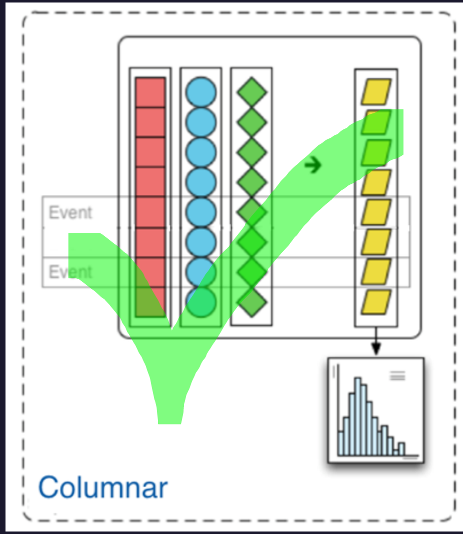
Combined limit plot



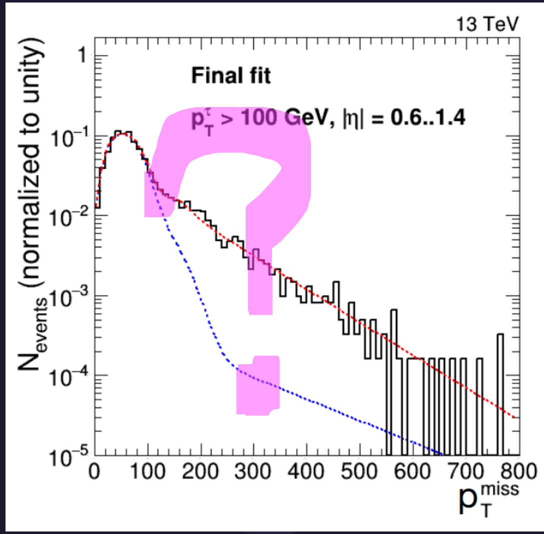
The problems in my work

- Data analysis runs smoothly and fine
- Background measurement had problems with ROOT versions and Python
- Background measurement is probably now working
- I can possibly move to limit calculation now
  - If background measurement produced results without any problems for later

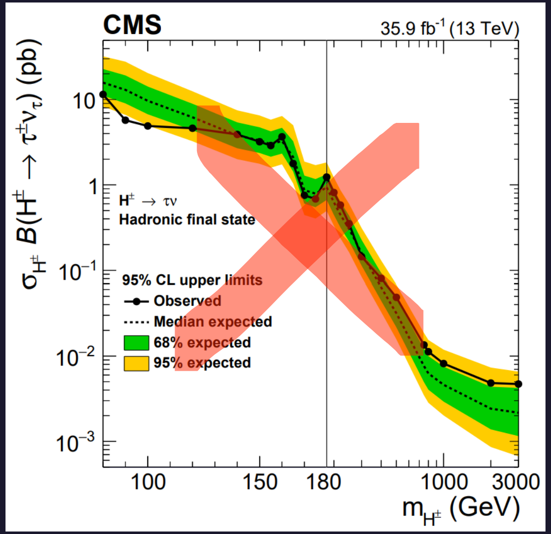
Data analysis



Background measurement



Limit calculation



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Future work

- Finish running the code and produce the limit plots for Run 2
- Deduce the optimal selection from running with different selections
- Produce the combined limit plot
- Producing these limit plots for full systematic errors (after thesis)
- Produce the results with machine learning methods (after thesis)?

Summary

- SM is a precise but incomplete theory
- Discovering $H^{\pm}$ would be direct evidence of beyond the SM theories
- Through varying different selections, one can produce limit plots to see what masses of $H^{\pm}$ are excluded
- Lot of work still left to produce the combined plot for Run 2

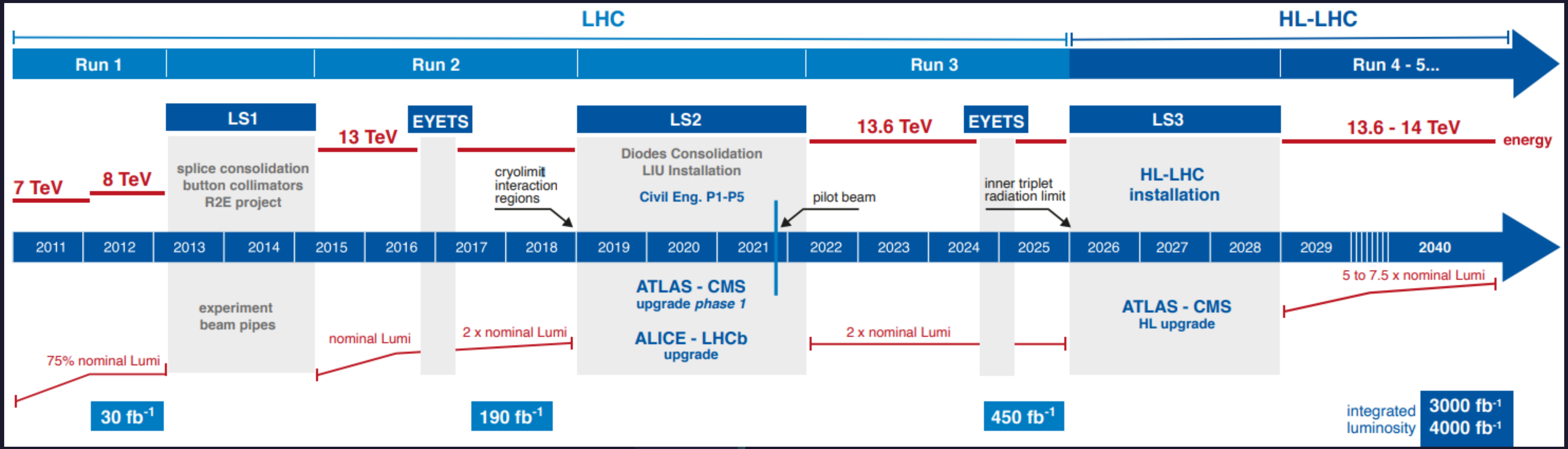
Thank you!

Questions or comments?

Backup slides

Run 2

- Run 2 means a time period when LHC was producing data between 2015 and 2018
- The schedule has changed because of COVID-19 and other things
- Integrated luminosity reflects the total number of data collected (not related to light)



Sources for pictures

- Slide 1
  - https://cms3d.web.cern.ch/HIG-20-013/
- Slide 4 and 5
  - https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg
  - https://commons.wikimedia.org/wiki/File:Spontaneous_symmetry_breaking_(explanatory_diagram).png
  - Laurila, S. (2019). Search for Charged Higgs Bosons Decaying to a Tau Lepton and a Neutrino with the CMS Experiment [Review of Search for Charged Higgs Bosons Decaying to a Tau Lepton and a Neutrino with the CMS Experiment]. https://helda.helsinki.fi/items/2c3bbc59-2740-4762-a92e-e79ce240d7c1
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  - Passon, O. (2019). On the interpretation of Feynman diagrams, or, did the LHC experiments observe H → γγ? European Journal for Philosophy of Science, 9(2). https://doi.org/10.1007/s13194-018-0245-1
  - G. Aad, Abbott, B., Abdallah, J., S. Abdel Khalek, Abdelalim, A. A., O. Abdinov, B. Abi, Abolins, M., AbouZeid, O. S., Abramowicz, H., Abreu, H., E. Acerbi, Acharya, B. S., Adamczyk, L., Adams, D. L., Addy, T. N., Adelman, J., S. Adomeit, Adragna, P., & T. Adye. (2012). Search for charged Higgs bosons decaying via H ± → τν in $ t\overline t $ events using pp collision data at $ \sqrt {s} = 7\;TeV $ with the ATLAS detector. Journal of High Energy Physics, 2012(6). https://doi.org/10.1007/jhep06(2012)039

Sources for pictures

- Slide 7
  - https://home.cern/
  - https://cds.cern.ch/record/2197559
  - https://home.cern/science/experiments/cms
- Slide 9
  - https://root.cern/
  - https://github.com/CoffeaTeam
  - https://commons.wikimedia.org/wiki/File:Python-logo-notext.svg
  - https://coffeateam.github.io/coffea/concepts.html

Sources for pictures

- Slide 10
  - https://indico.cern.ch/event/295196/contributions/1653065/attachments/553395/762440/OS_hplus_decays.pdf
  - G. Aad, Abbott, B., Abdallah, J., S. Abdel Khalek, Abdelalim, A. A., O. Abdinov, B. Abi, Abolins, M., AbouZeid, O. S., Abramowicz, H., Abreu, H., E. Acerbi, Acharya, B. S., Adamczyk, L., Adams, D. L., Addy, T. N., Adelman, J., S. Adomeit, Adragna, P., & T. Adye. (2012). Search for charged Higgs bosons decaying via $H^{\pm} \to \tau\nu$ in $ t\overline t $ events using pp collision data at $ \sqrt {s} = 7\;TeV $ with the ATLAS detector. Journal of High Energy Physics, 2012(6). https://doi.org/10.1007/jhep06(2012)039
  - Search for a light charged Higgs boson in top quark decays in pp collisions at √ s = 7 TeV. (2018). https://arxiv.org/pdf/1205.5736.pdf
- Slide 11
  - Heinemeyer, S., Mariotti, C., Passarino, G., & Tanaka, R. (2013). ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH Handbook of LHC Higgs cross sections: 3. Higgs Properties Report of the LHC Higgs Cross Section Working Group. https://doi.org/10.5170/CERN-2013-004
- Slide 13-16
  - Laurila, S. (2019). Search for Charged Higgs Bosons Decaying to a Tau Lepton and a Neutrino with the CMS Experiment [Review of Search for Charged Higgs Bosons Decaying to a Tau Lepton and a Neutrino with the CMS Experiment]. https://helda.helsinki.fi/items/2c3bbc59-2740-4762-a92e-e79ce240d7c1
  - https://coffeateam.github.io/coffea/concepts.html
- Slide 22
  - https://hilumilhc.web.cern.ch/sites/default/files/HL-LHC_Janvier2022.pdf