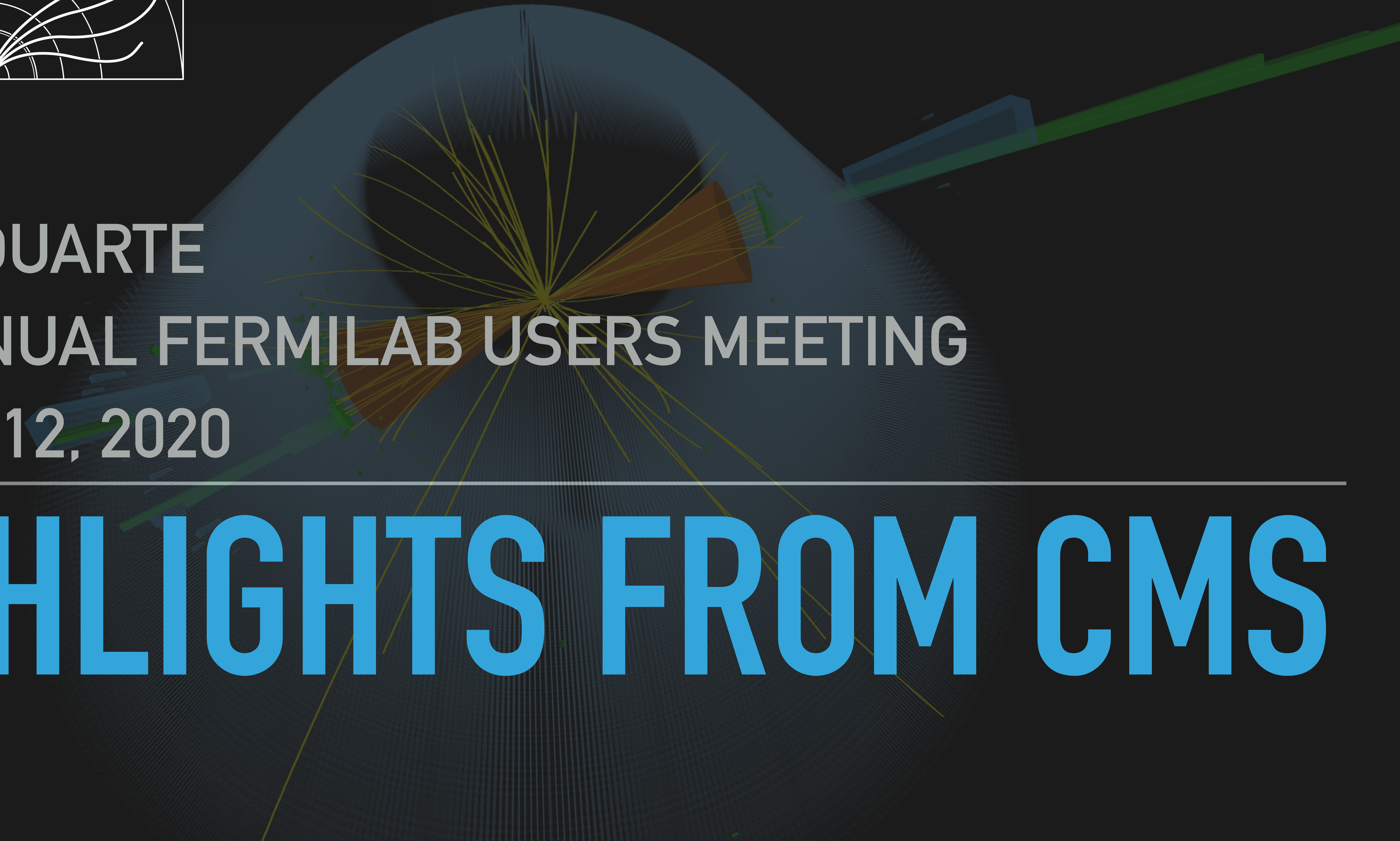


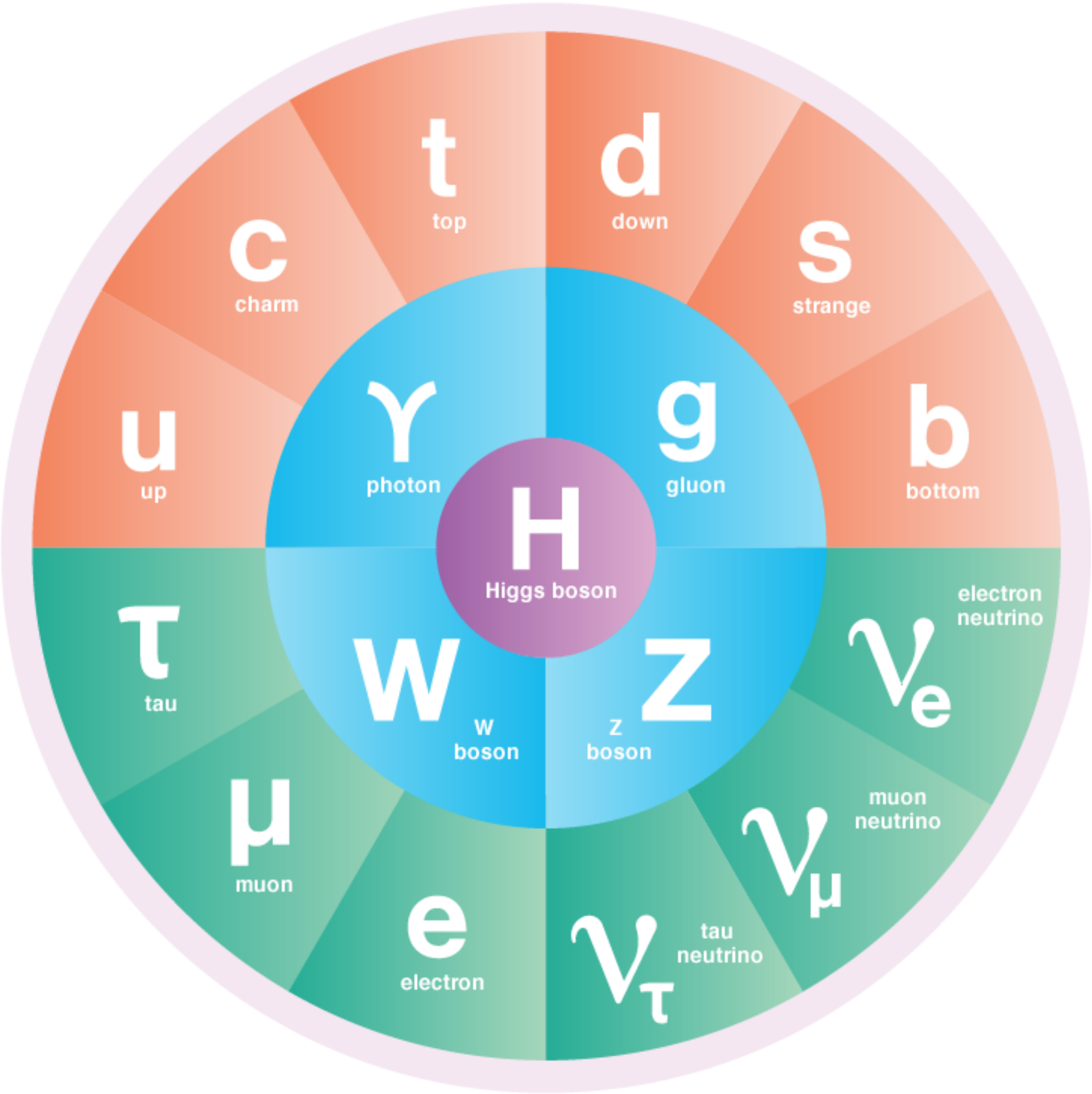
JAVIER DUARTE

53RD ANNUAL FERMILAB USERS MEETING

AUGUST 12, 2020

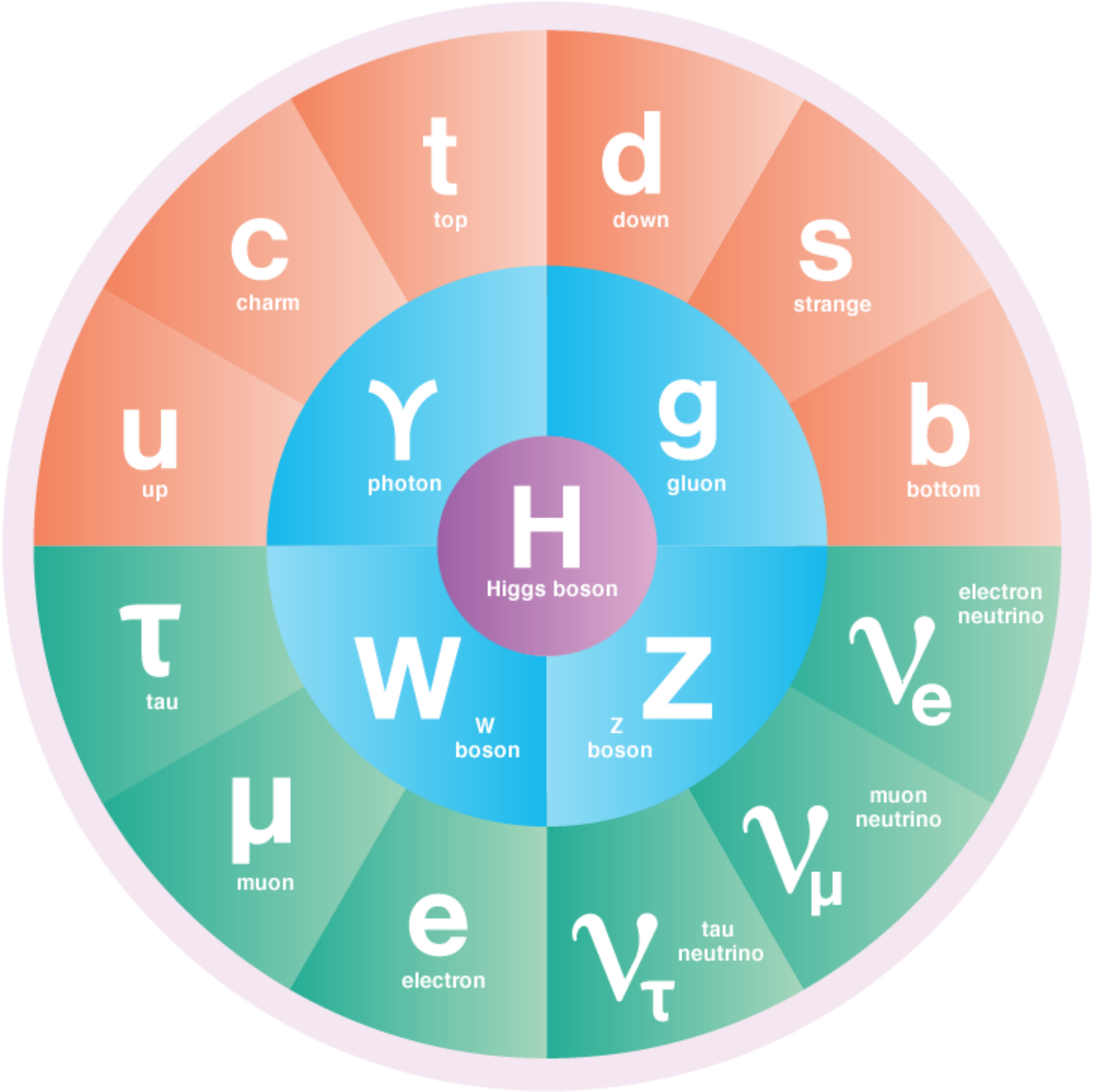
HIGHLIGHTS FROM CMS

THE STANDARD MODEL AND NEW PHYSICS



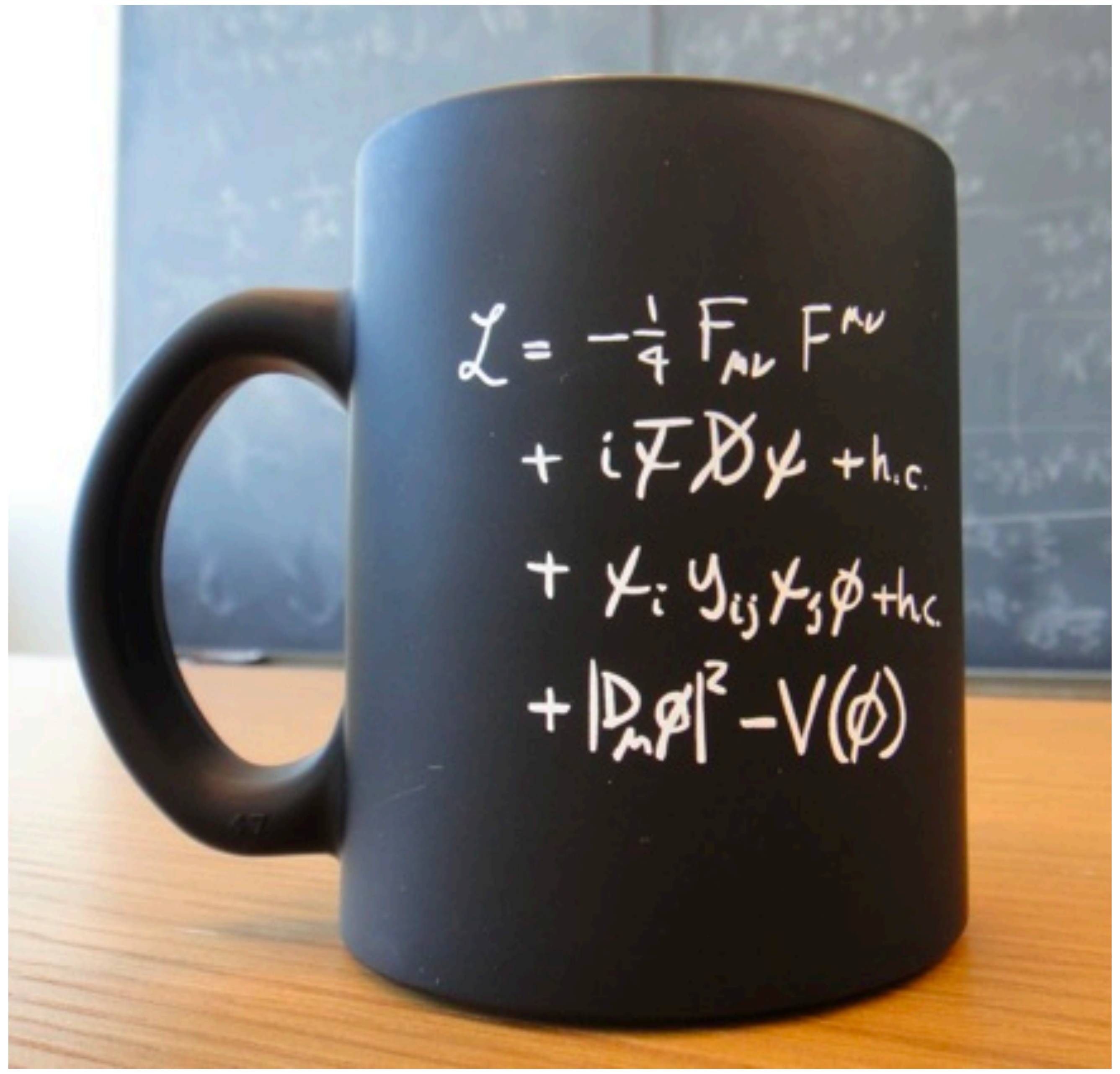
particles

THE STANDARD MODEL AND NEW PHYSICS



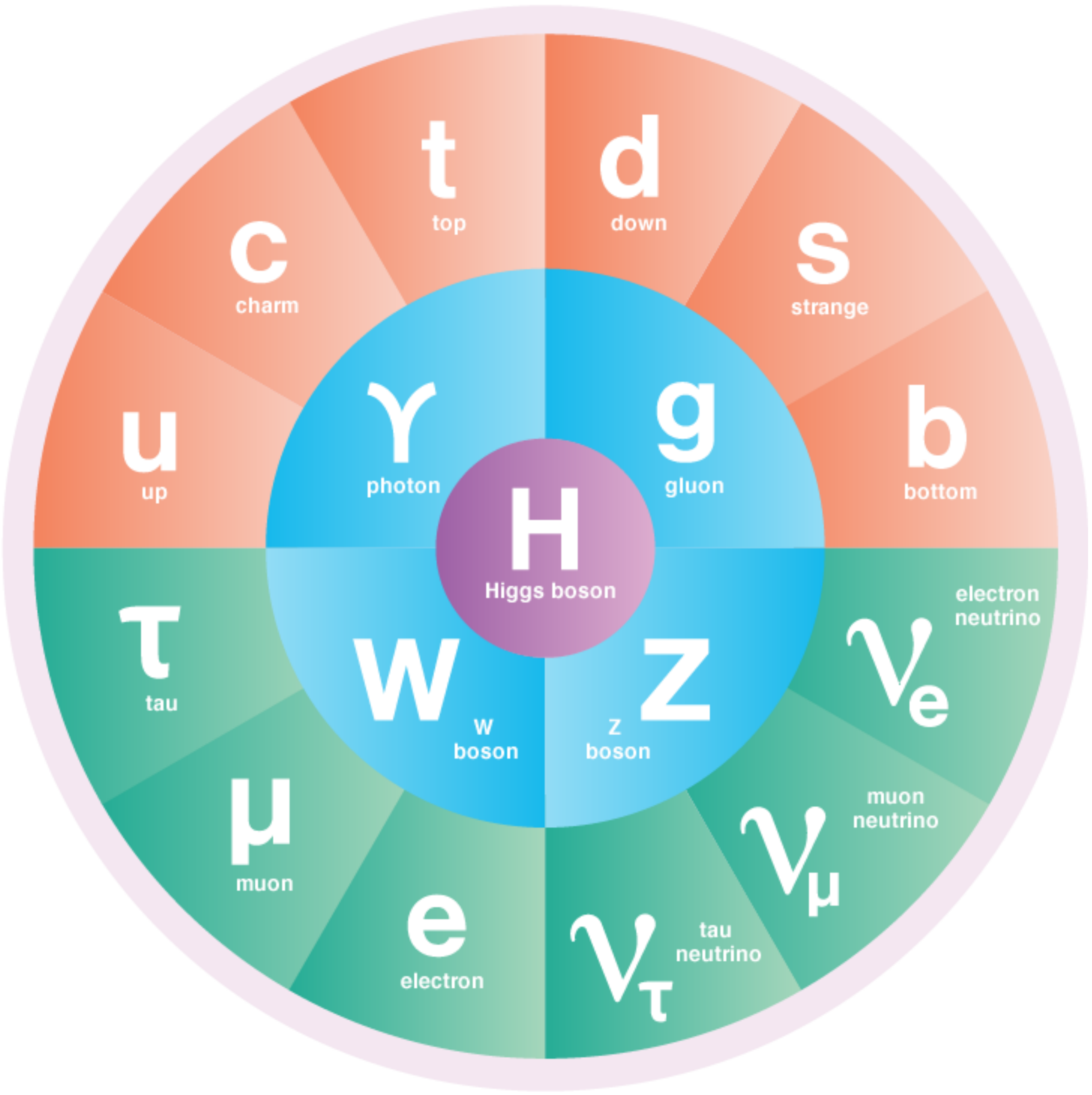
particles

+



interactions

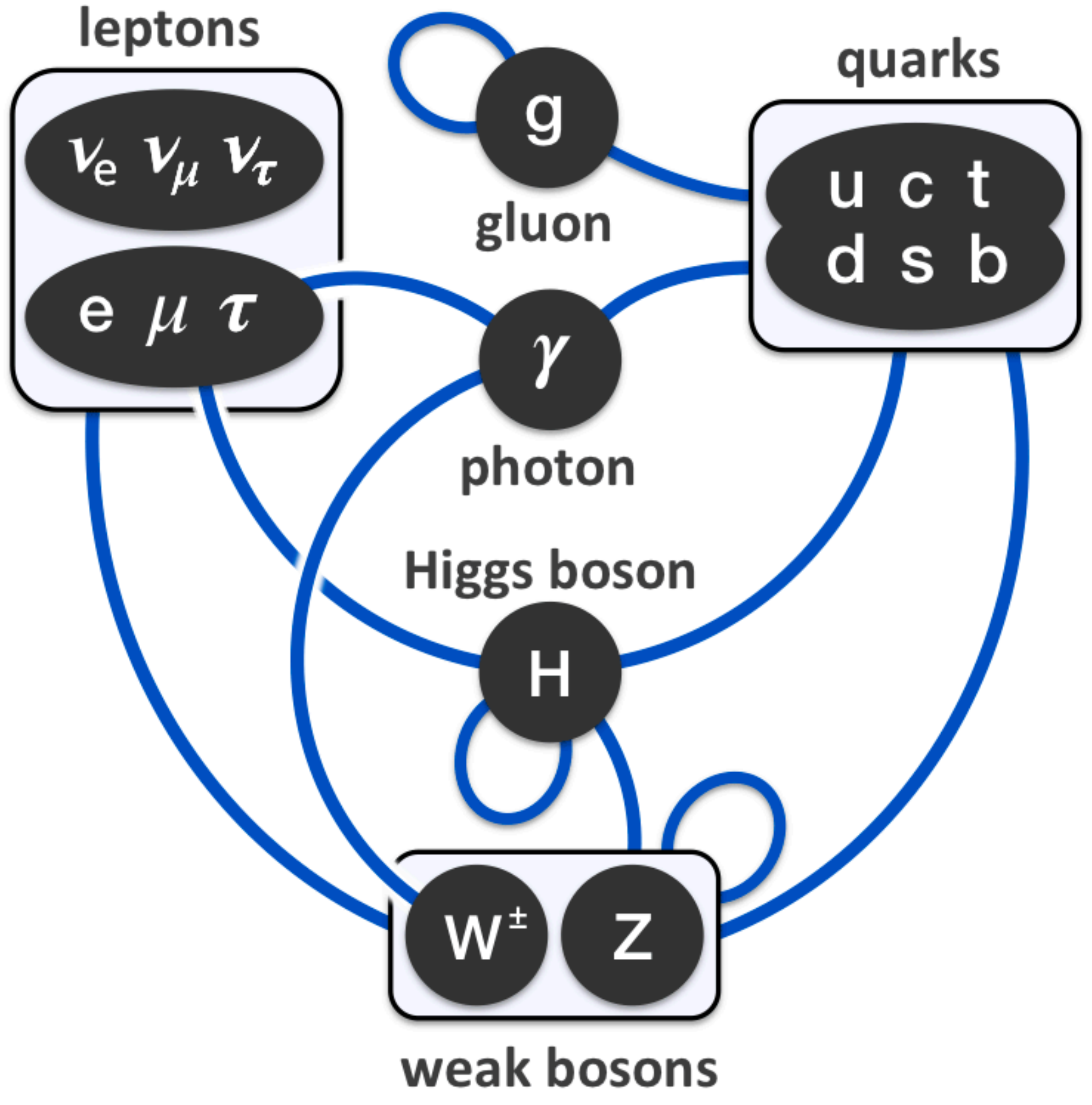
THE STANDARD MODEL AND NEW PHYSICS



particles

+

terms of L → links (*couplings*)
between particles



interactions

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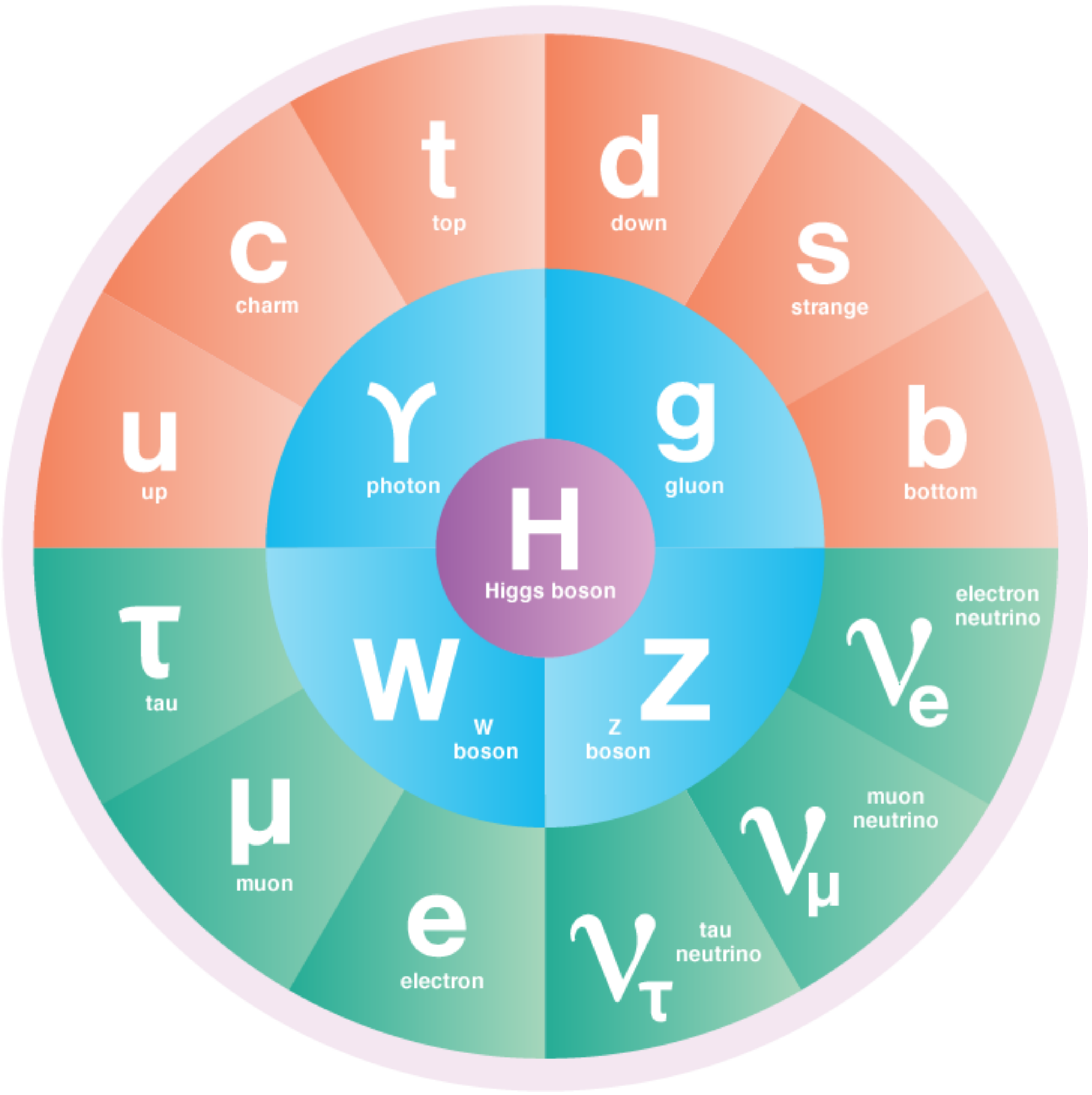

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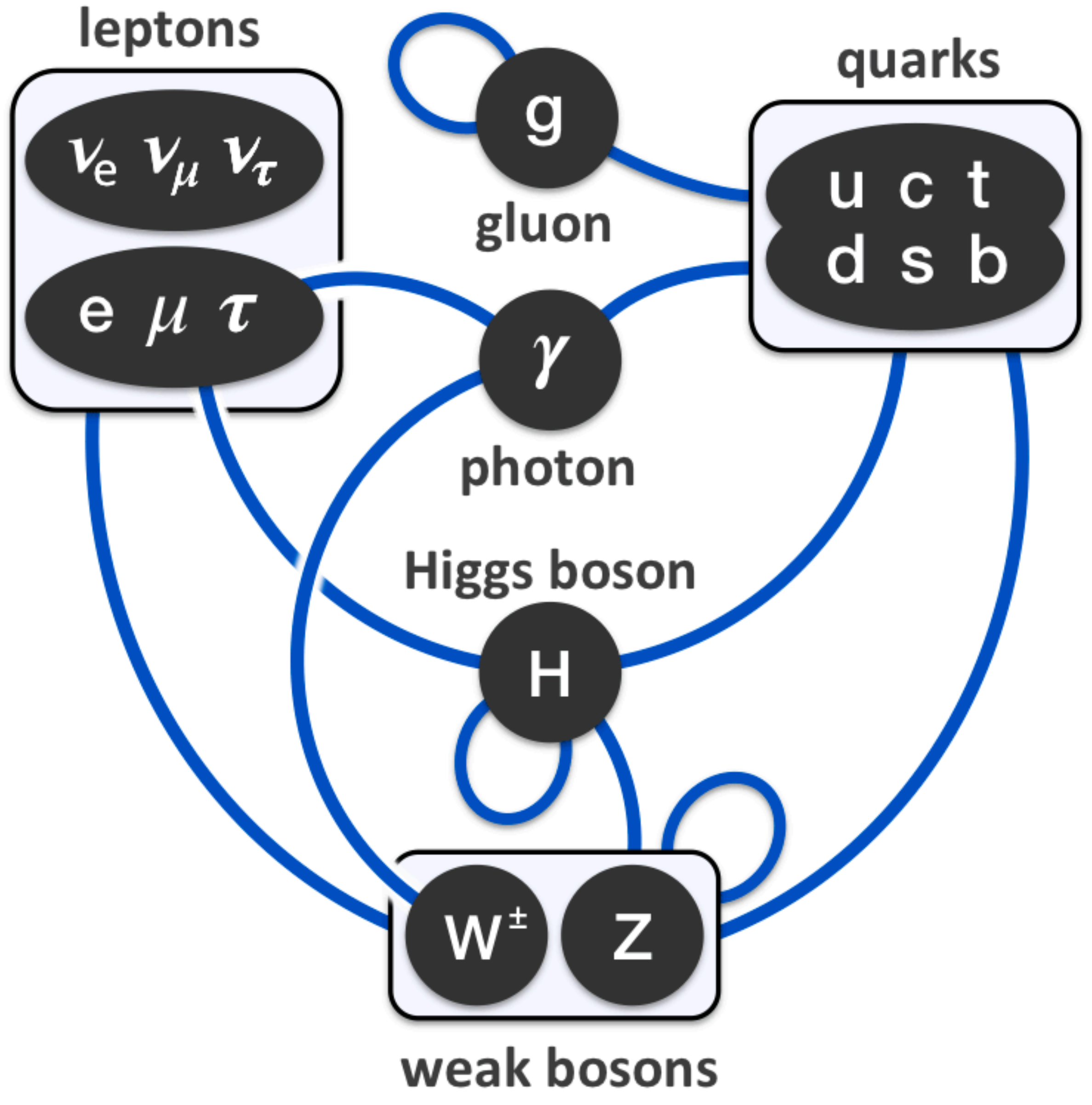
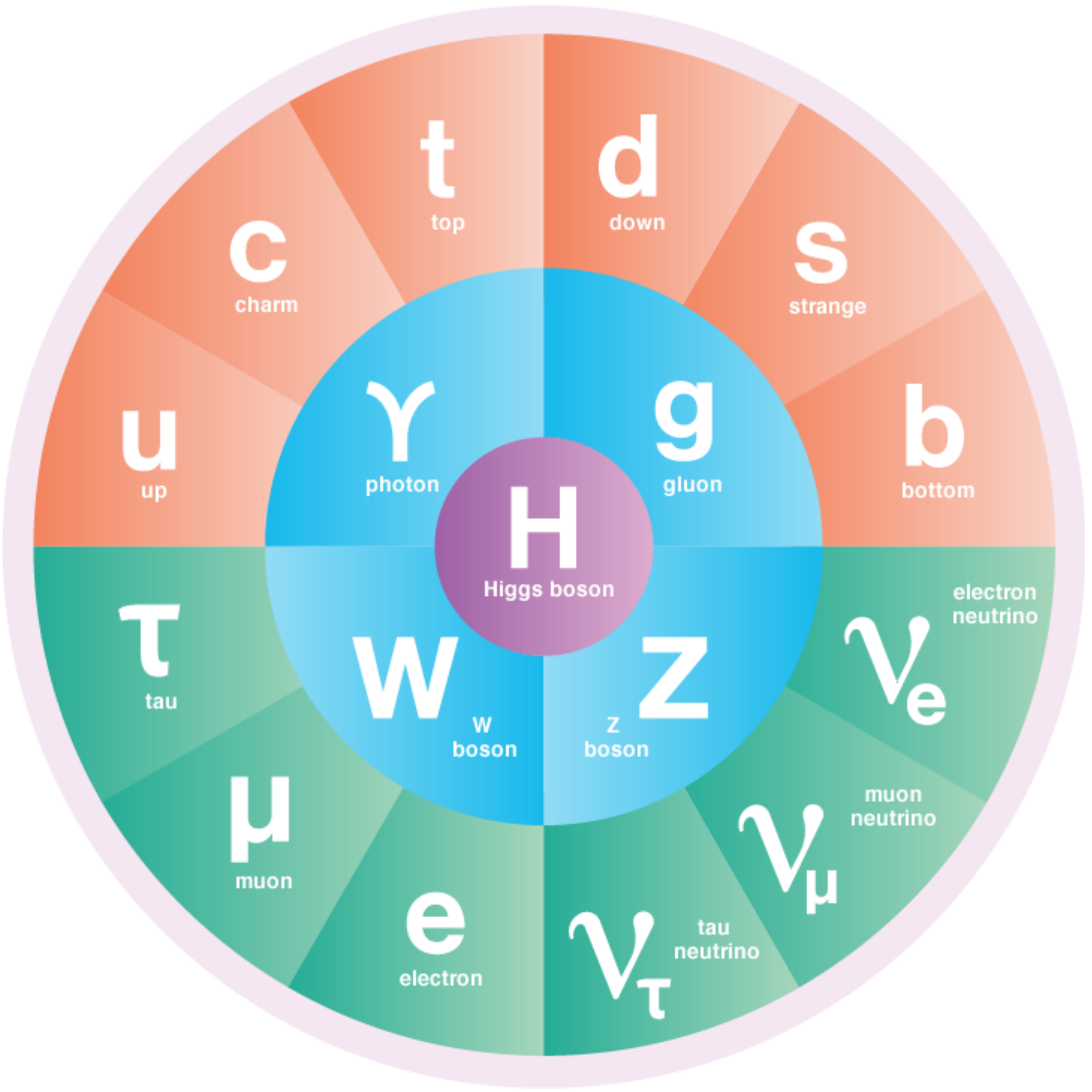


interactions

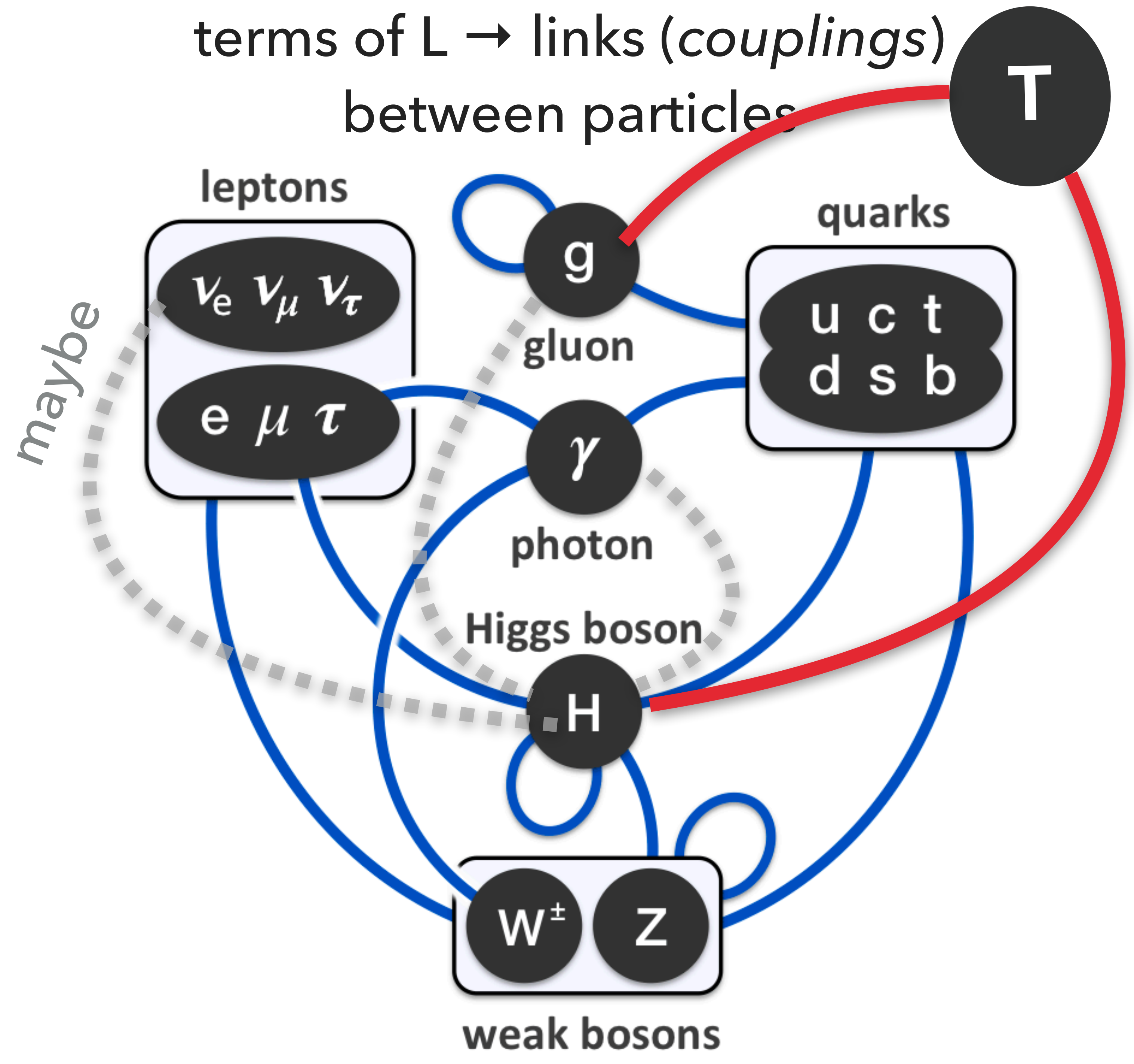
- But there has to be more to it! SM does not explain **dark matter**, **neutrino masses**, and the **matter-antimatter asymmetry**…

THE STANDARD MODEL AND NEW PHYSICS



particles

+



interactions

- But there has to be more to it! SM does not explain **dark matter**, **neutrino masses**, and the **matter-antimatter asymmetry**…
- Studying the SM precisely may give us clues to new particles or interactions

THE LARGE HADRON COLLIDER

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proton-proton collider @ 13 TeV center-of-mass energy

4 interaction points

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40 million collisions / second

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trigger selects ~1000 collisions / second

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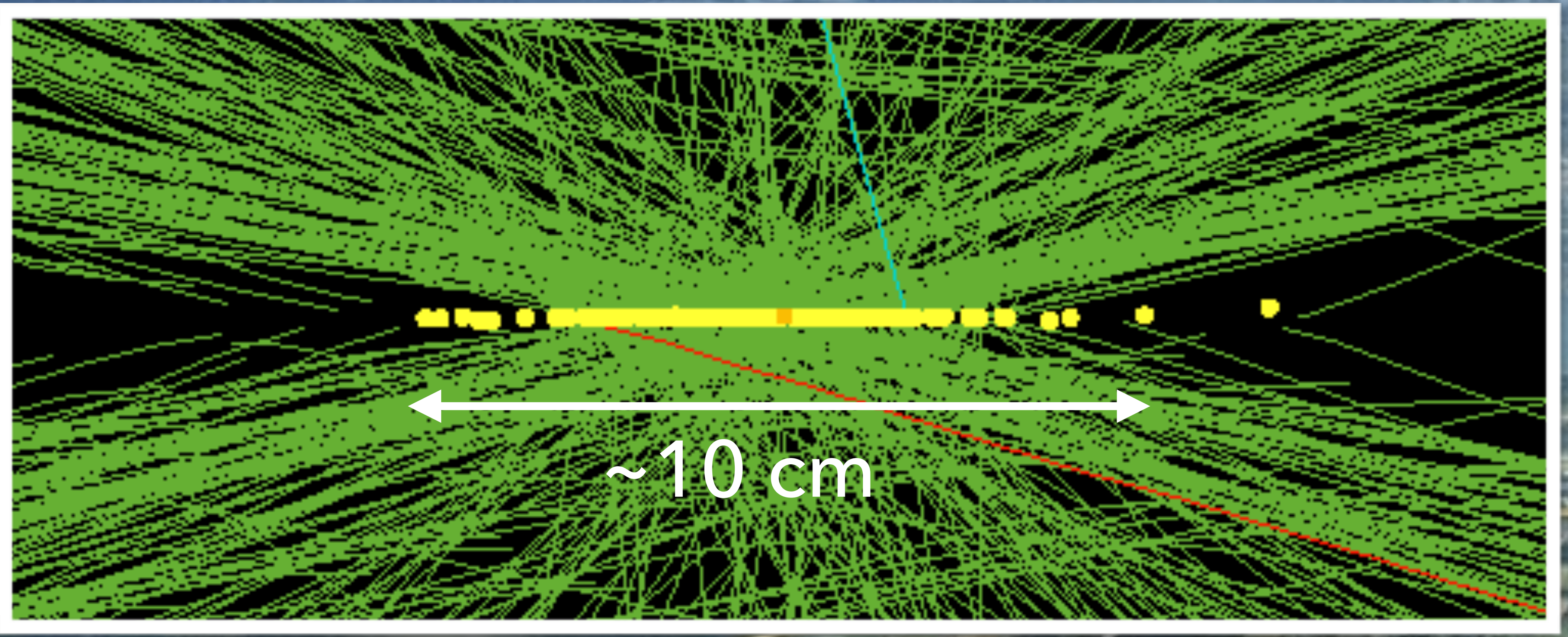

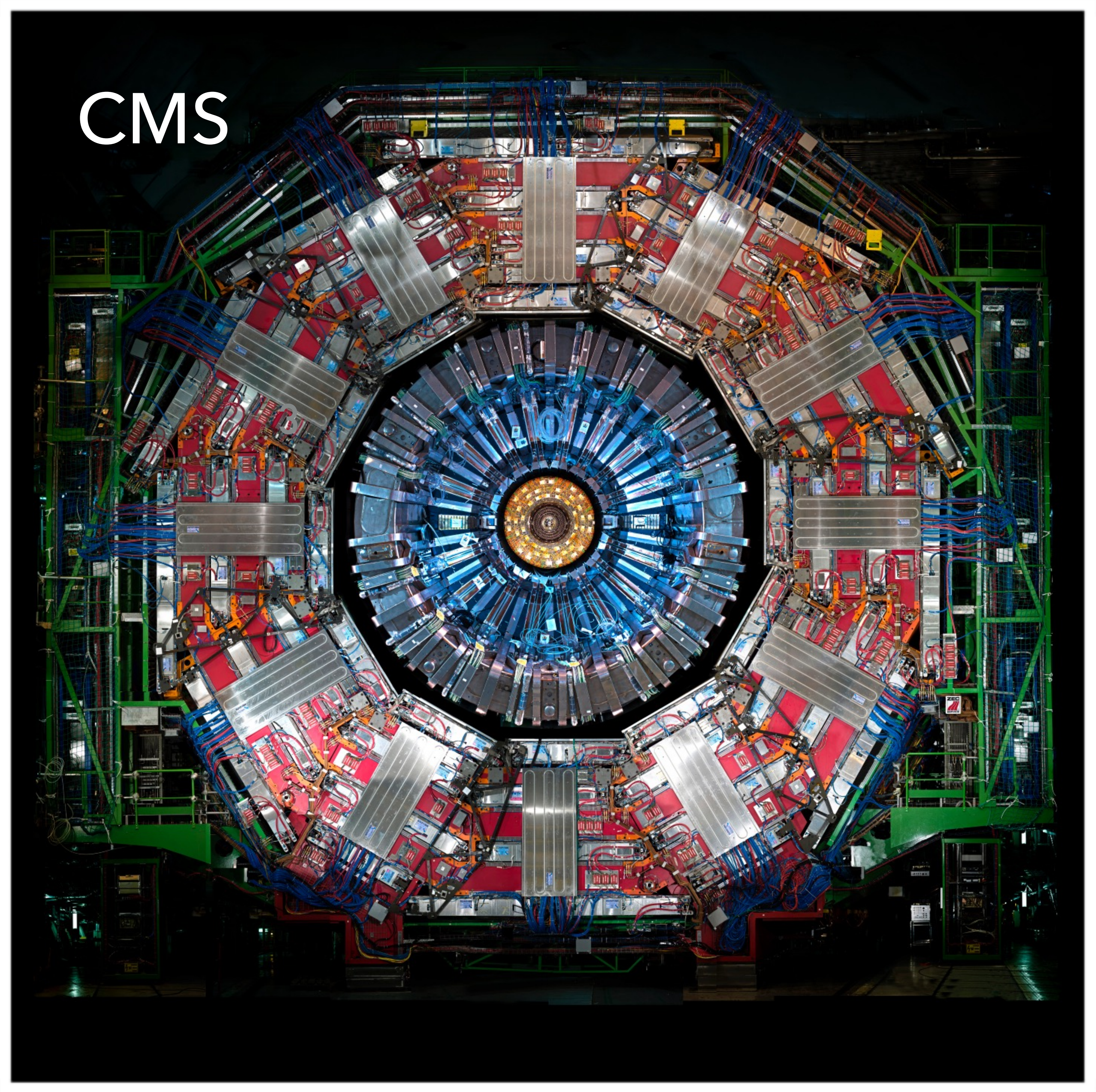

proton-proton collider @ 13 TeV center-of-mass energy

4 interaction points

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trigger selects ~1000 collisions / second

LHCb

CERN Prévessin

SUISSE

FRANCE

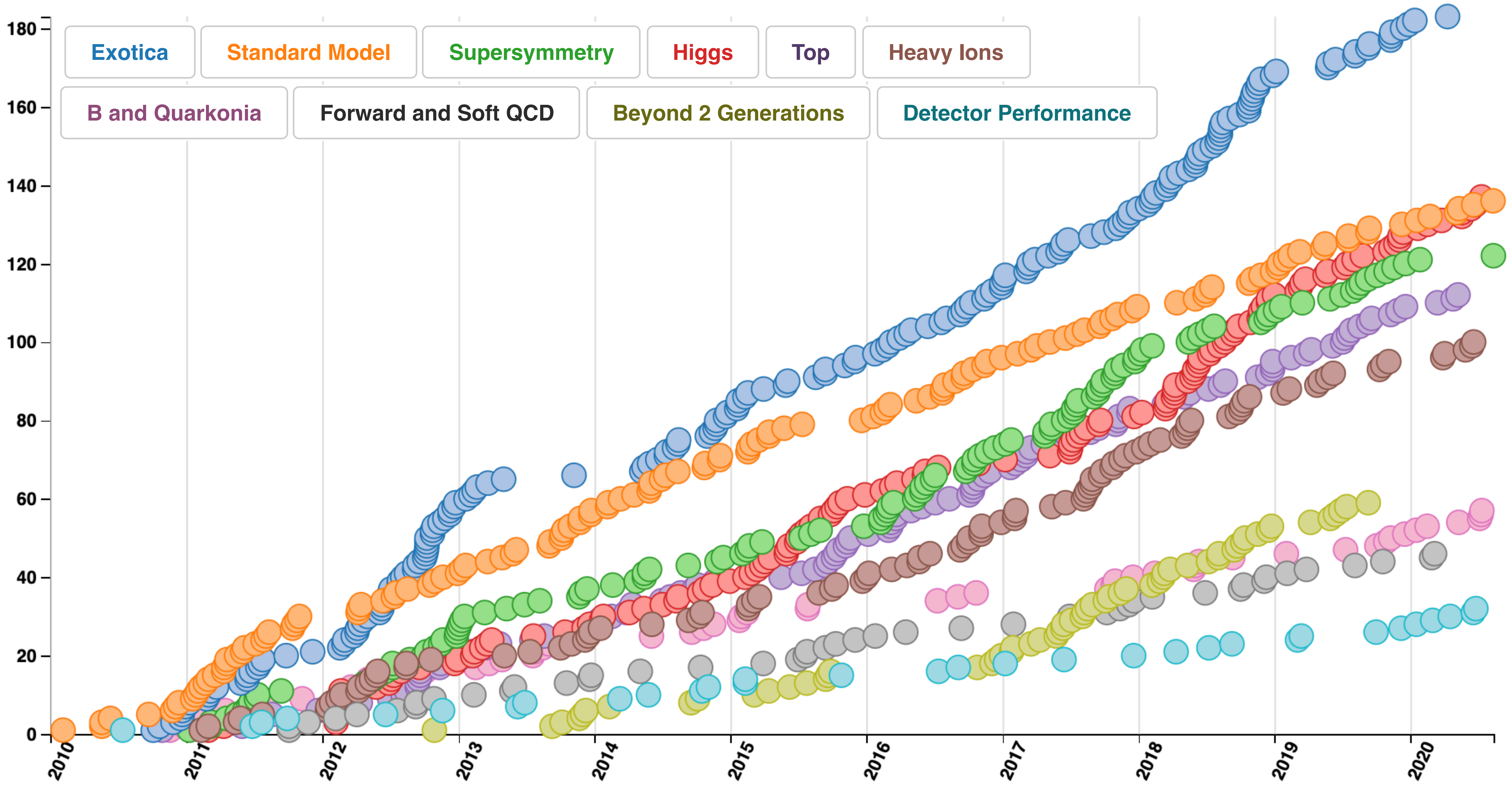
CMS

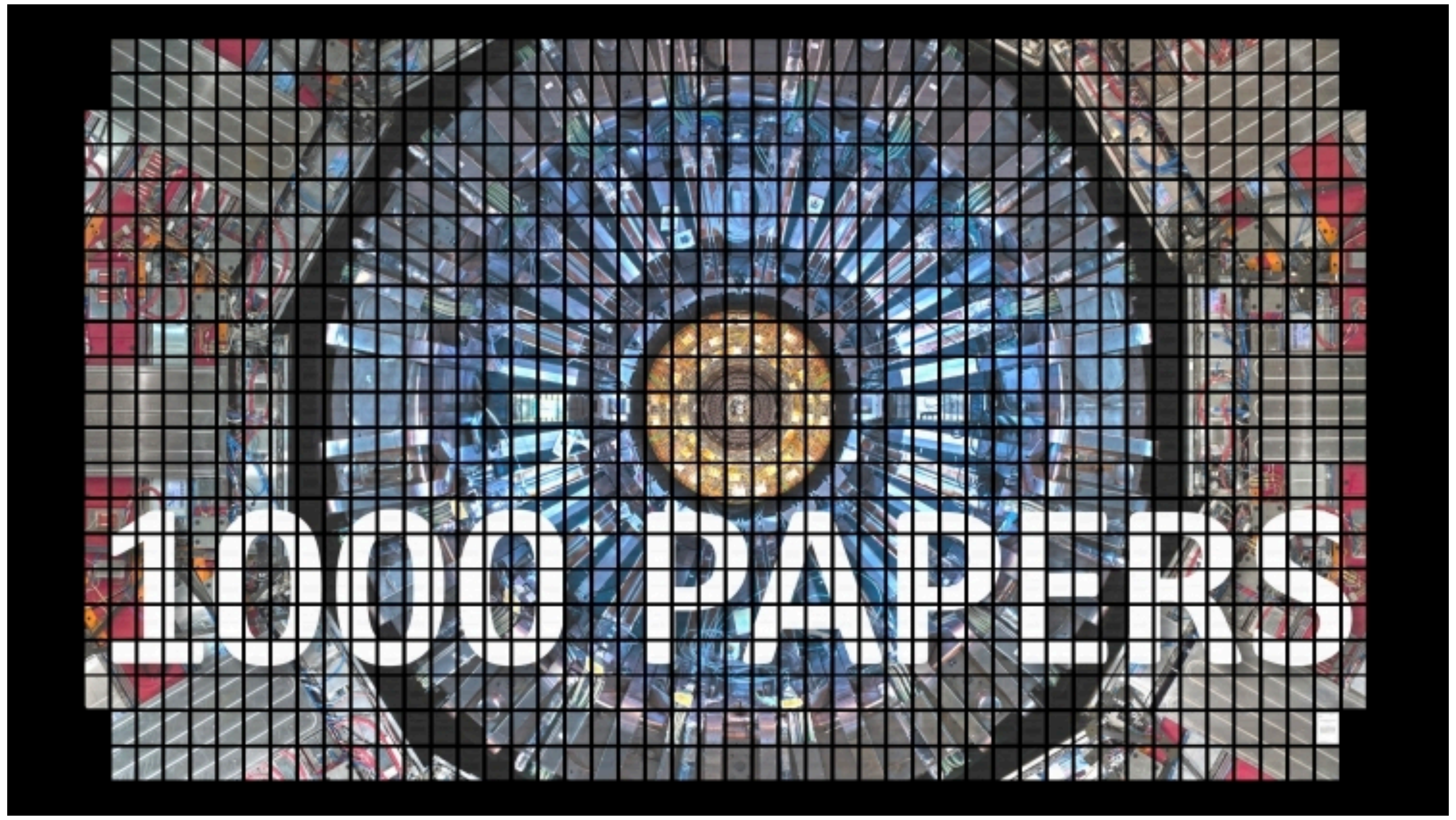
LHC 27 km

p p

CMS PUBLICATIONS

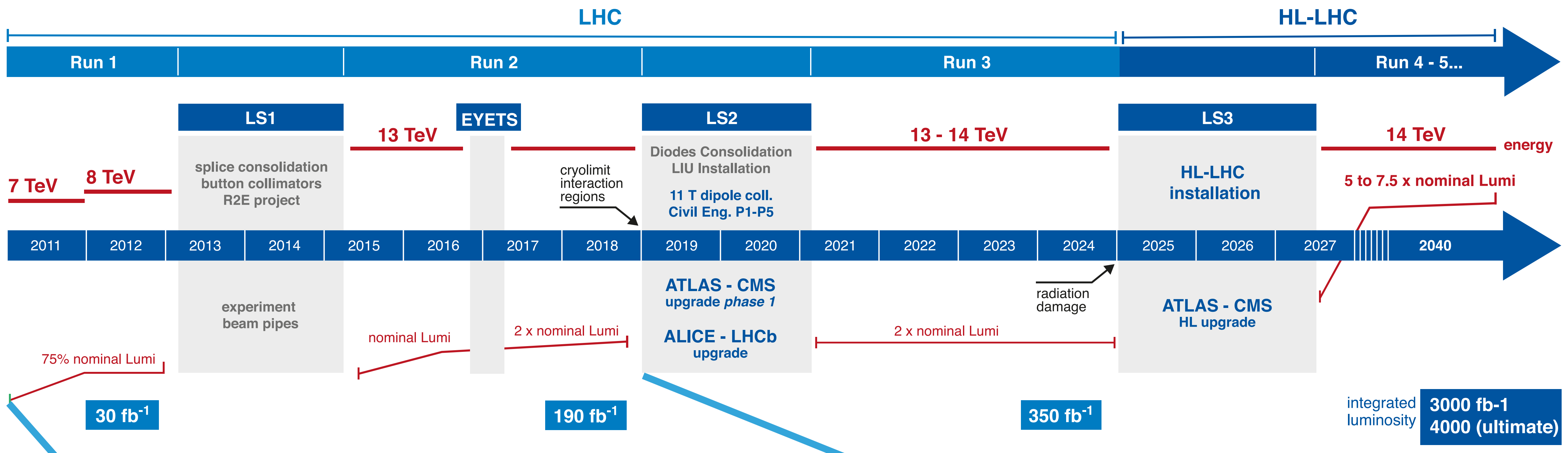
- 1009 publications submitted as of August 10, 2020
- Celebrated 1000th paper on June 19, 2020
- Many new papers are using the full Run 2 data set (137 fb^{-1})

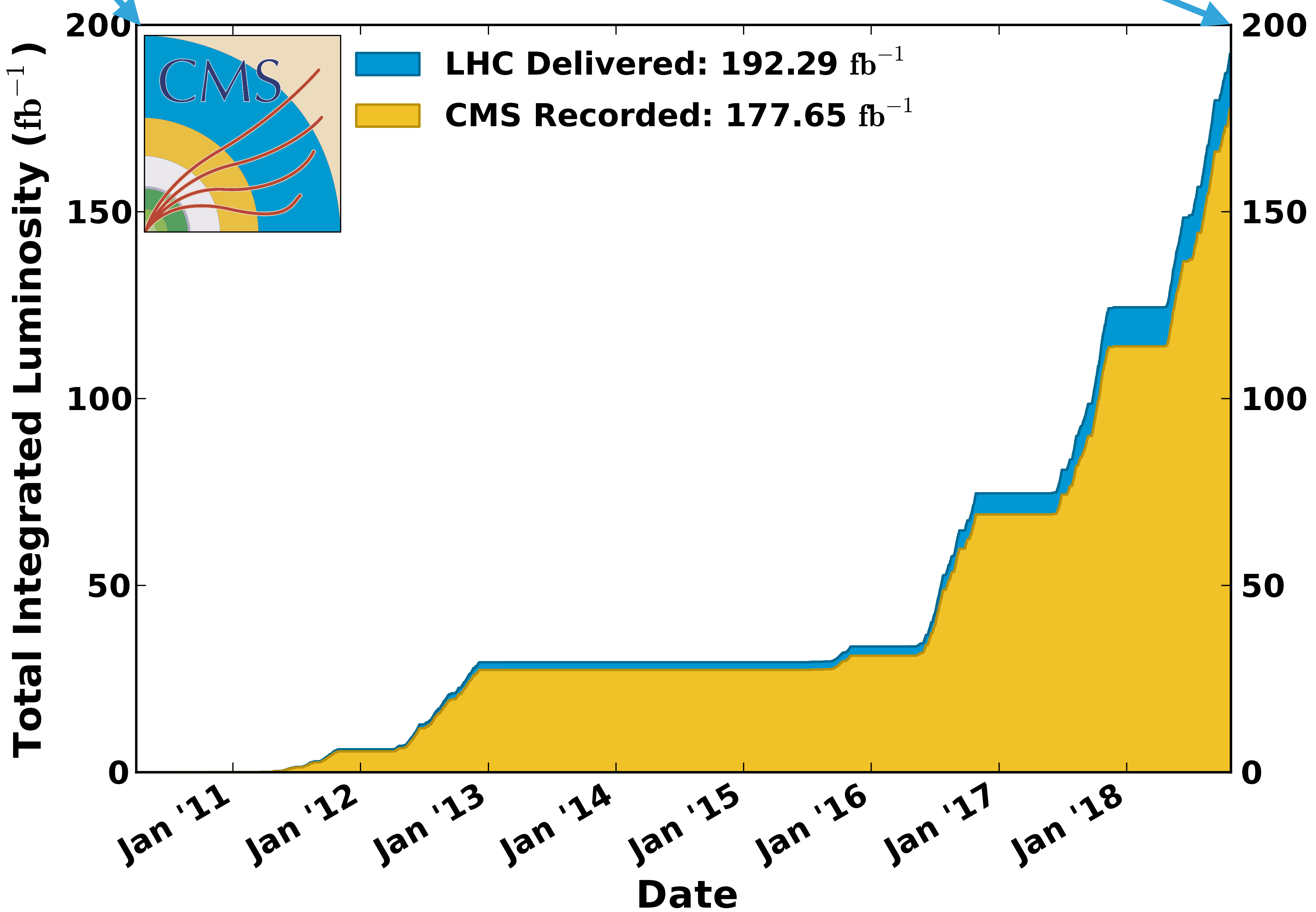




THE CURRENT PHASE OF CMS

- With Run 2 done, entering a new phase of the lifetime of the CMS experiment
    - Will take years (Run 3) to double current data set





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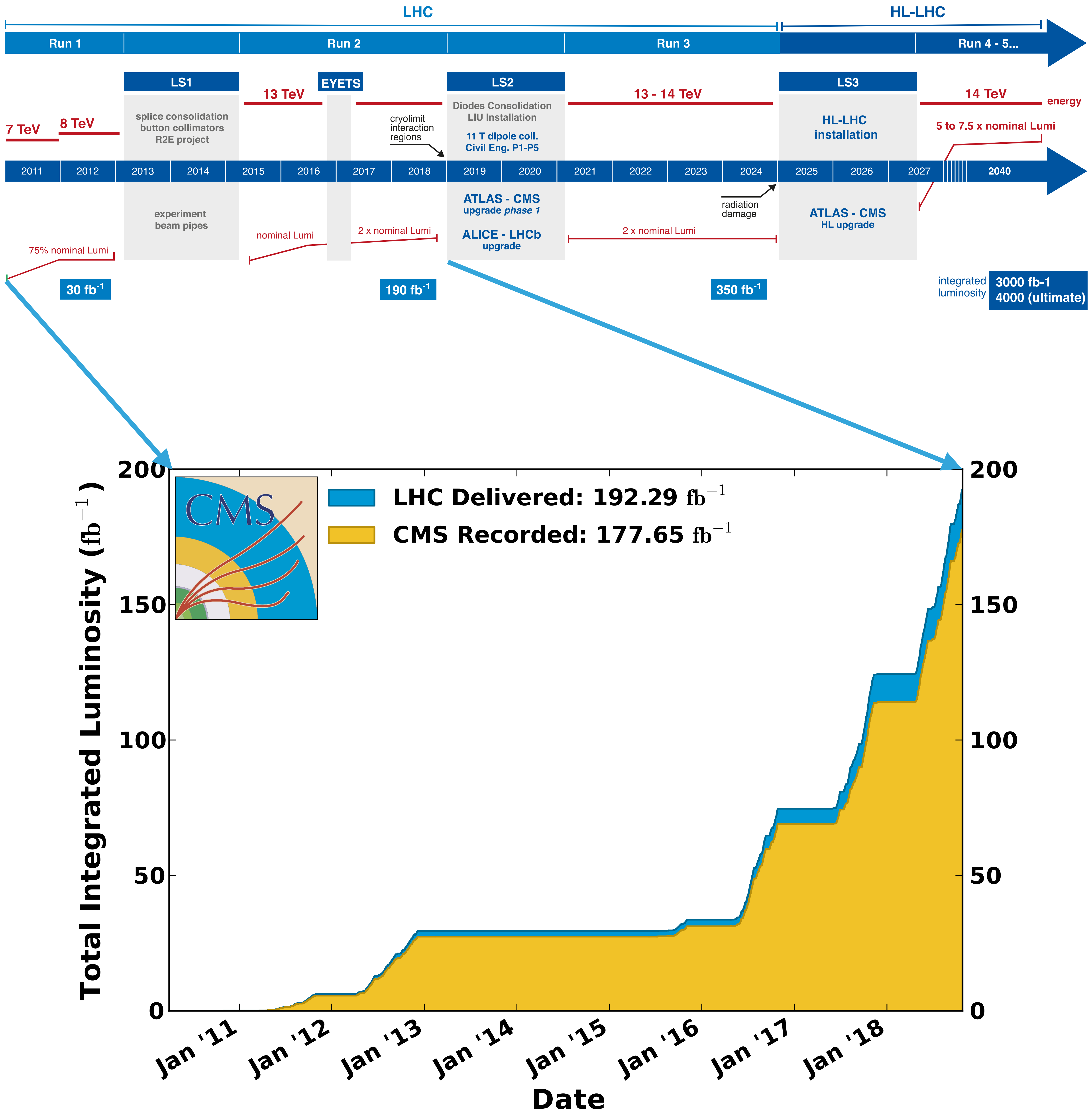
- Innovate to achieve more from this data:
  - Reduce systematic uncertainties to improve precision
  - Use machine learning (ML) to improve signal/background
  - Understand and target “gaps” in coverage, e.g. long-lived particles



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- Innovate to achieve more from this data:
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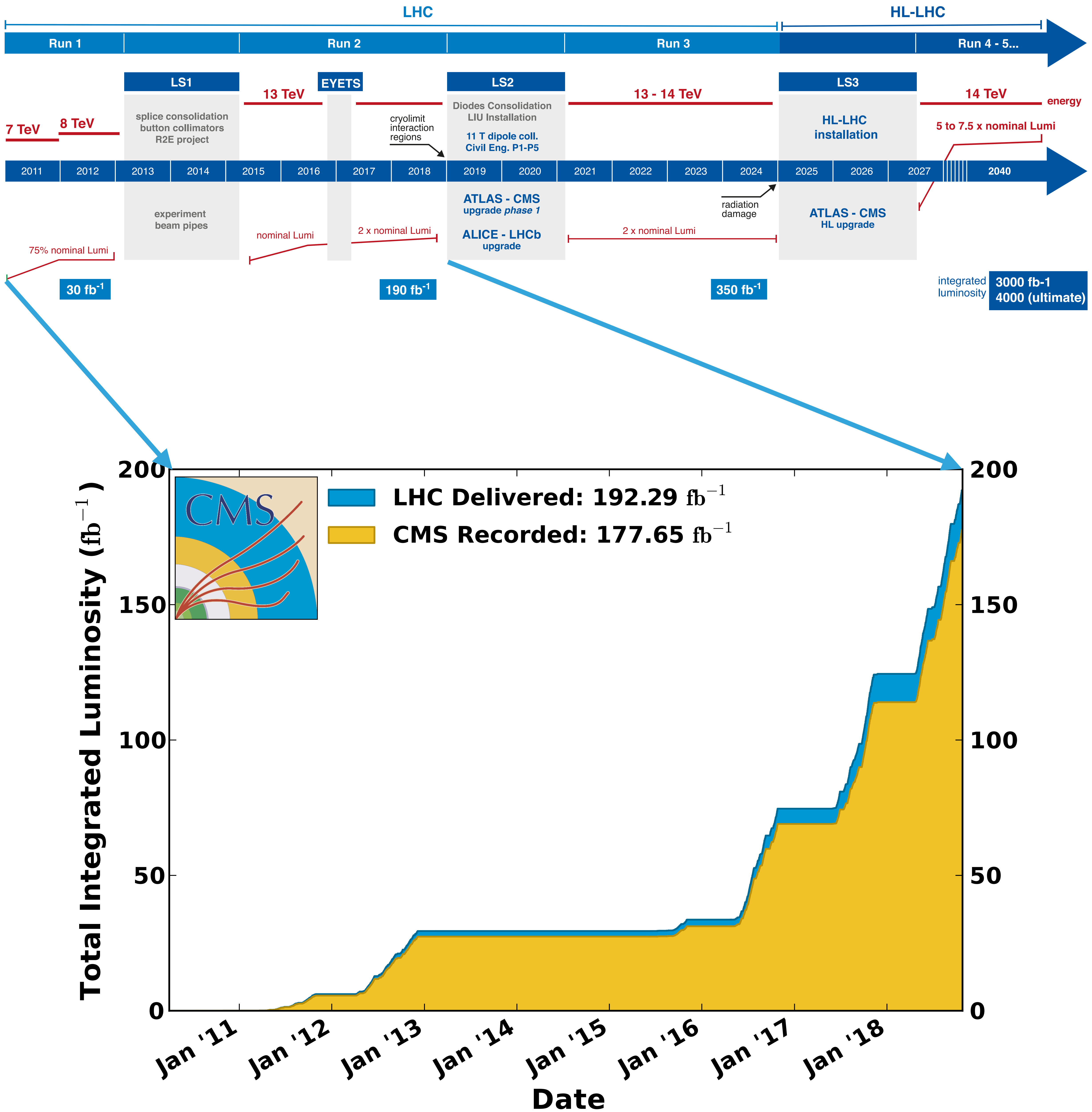
  - Use machine learning (ML) to improve signal/background
  - Understand and target “gaps” in coverage, e.g. long-lived particles
- Preparations (well) underway for Run 3 and HL-LHC



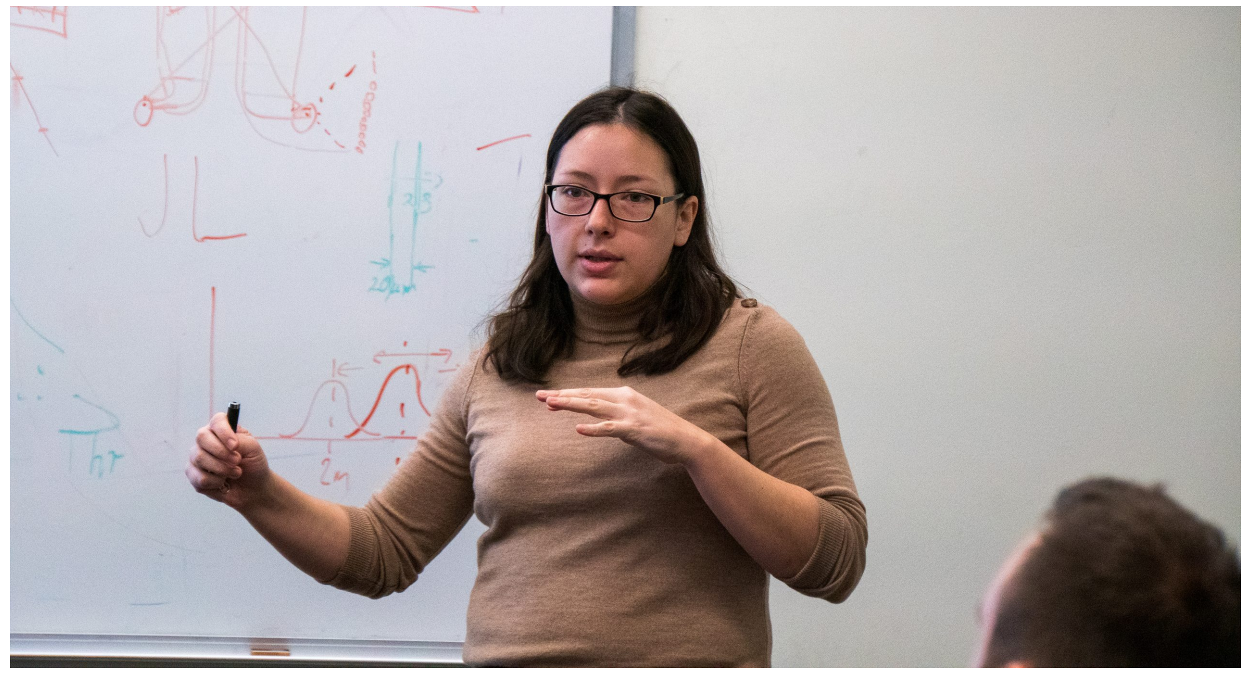
RECENT HIGHLIGHTS

- Many new results for LHCP and ICHEP 2020 covering: detector performance, SM measurements, direct searches, Higgs, B-physics, heavy ions
- SM/Higgs searches as probes for new physics
  - **Observation of VVV***
  - Search for longitudinally polarized same-sign WW*
  - **Search for Boosted H(bb)***
  - **Evidence for H(μμ)**
- Direct searches for new physics
  - Vector-like BB*
  - Long-lived particles to displaced jets

*Fermilab and LPC-led efforts

FERMILAB LHC PHYSICS CENTER

- Established CMS center of excellence
- More than 500 users and 150 residents
- 900 CMS collaborators use the LPC computing cluster for data processing and analysis
- ~800 participants in LPC-organized workshop and events, fostering interactions with theorists and non-CMS members

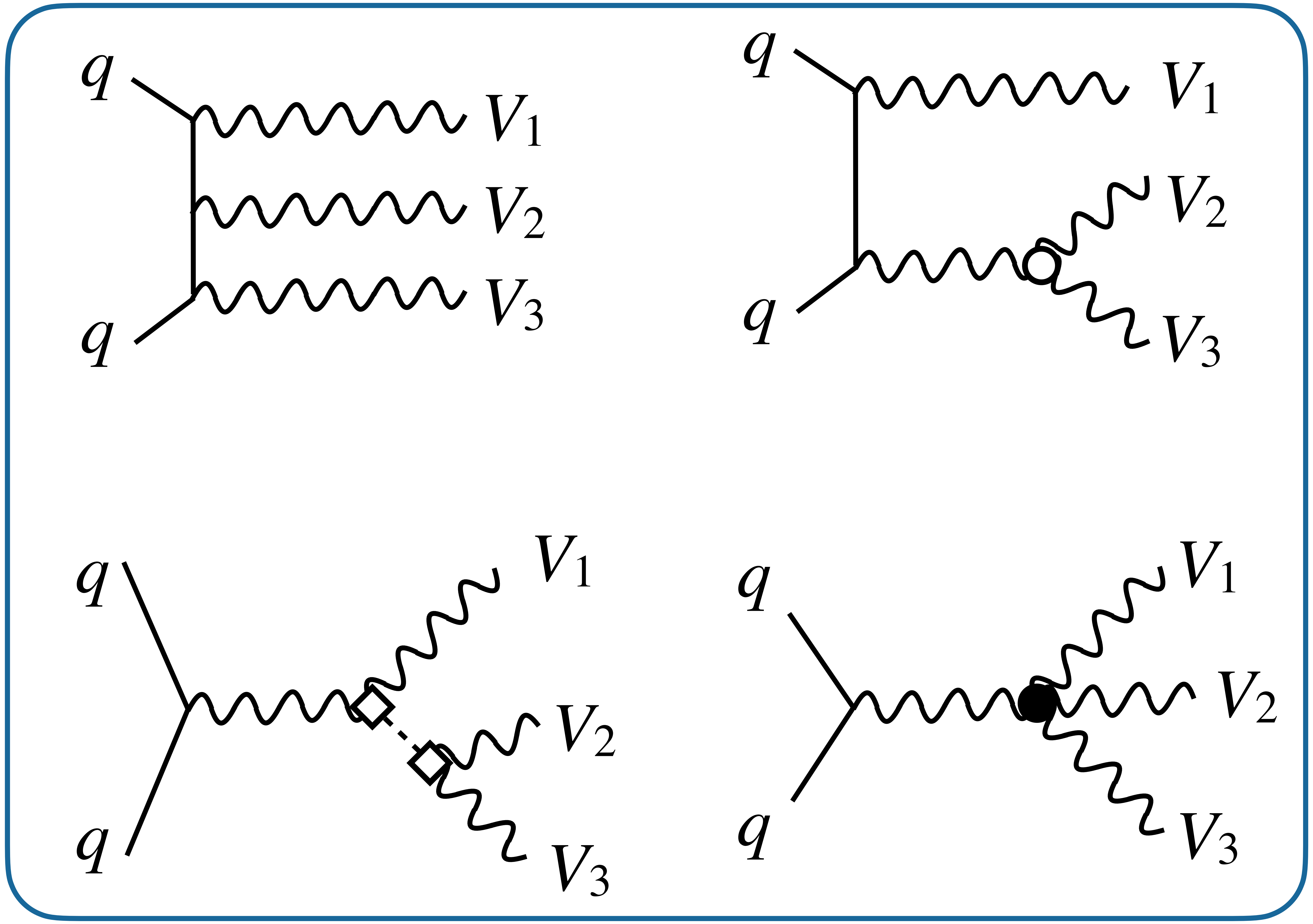


2020 Data Analysis School

Distinguished Researchers
Virtual Office Hours

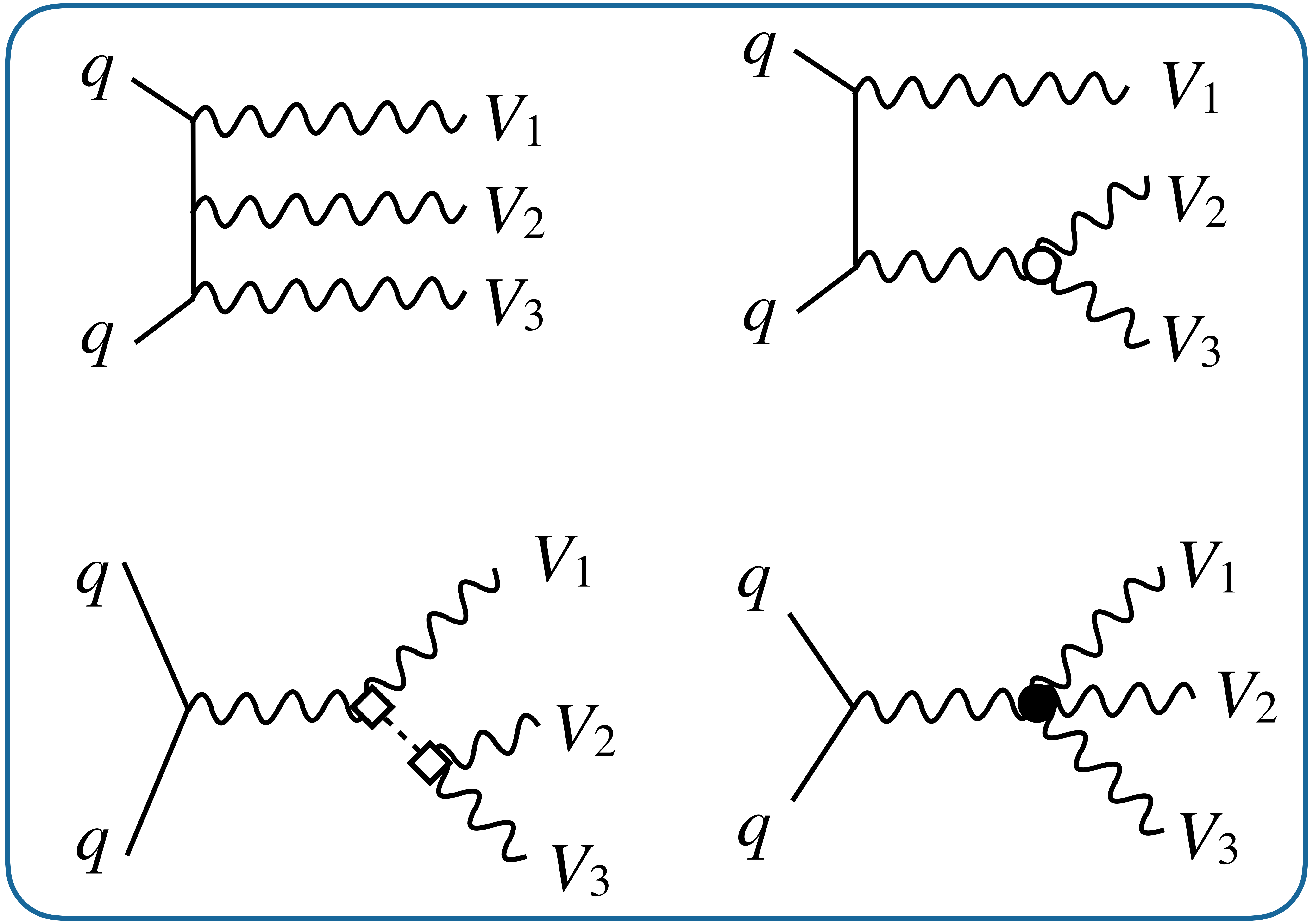
SM SEARCHES AS PROBES OF NEW PHYSICS

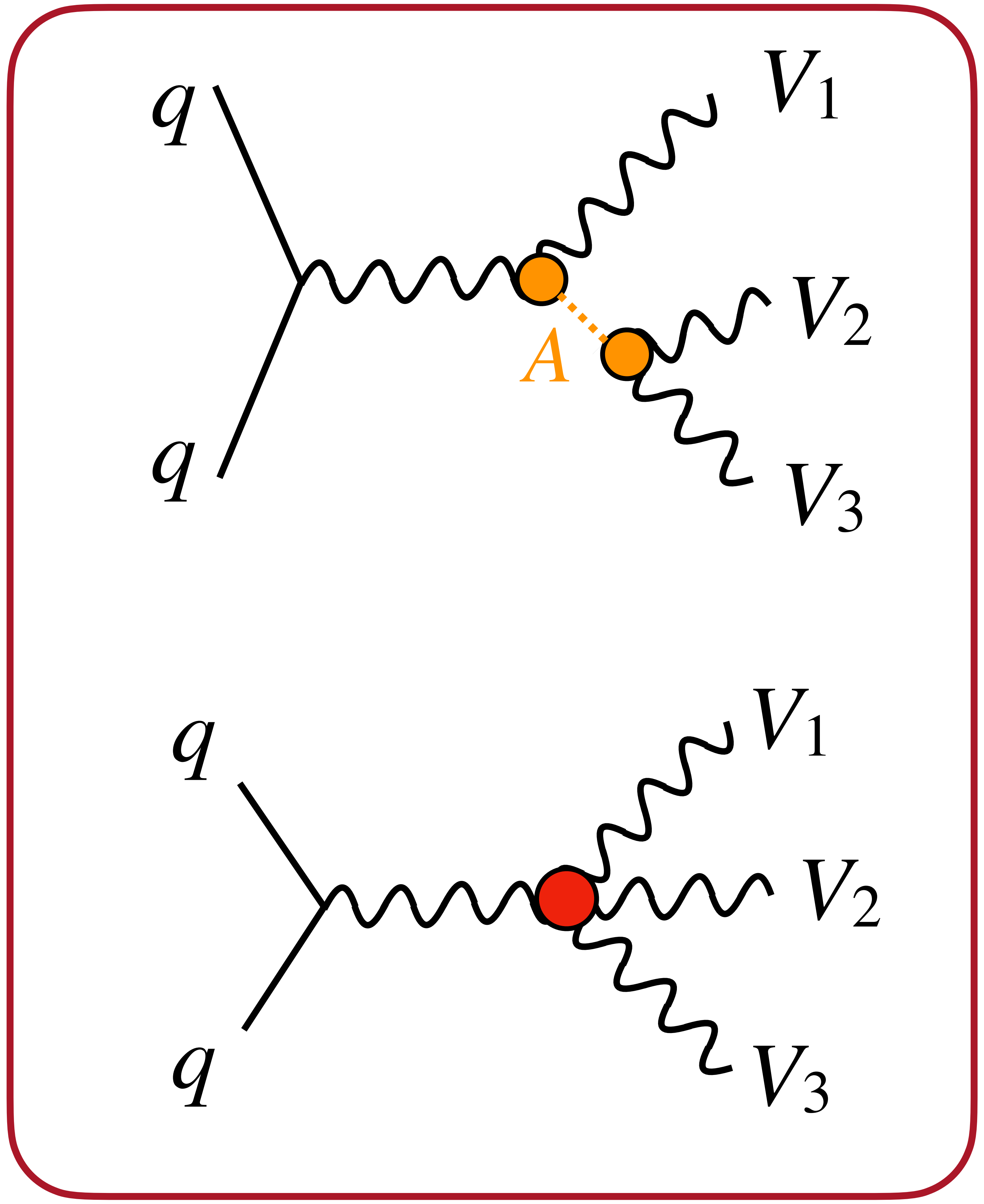
- VVV final state sensitive to many different EW interactions



SM SEARCHES AS PROBES OF NEW PHYSICS

- VVV final state sensitive to many different EW interactions
- May be sensitive to a new particle that couples to Vs or modified SM couplings





VVV PRODUCTION AND DECAY

- Focus on cleanest channels: fully leptonic (or same-sign) final states

VVV PRODUCTION AND DECAY

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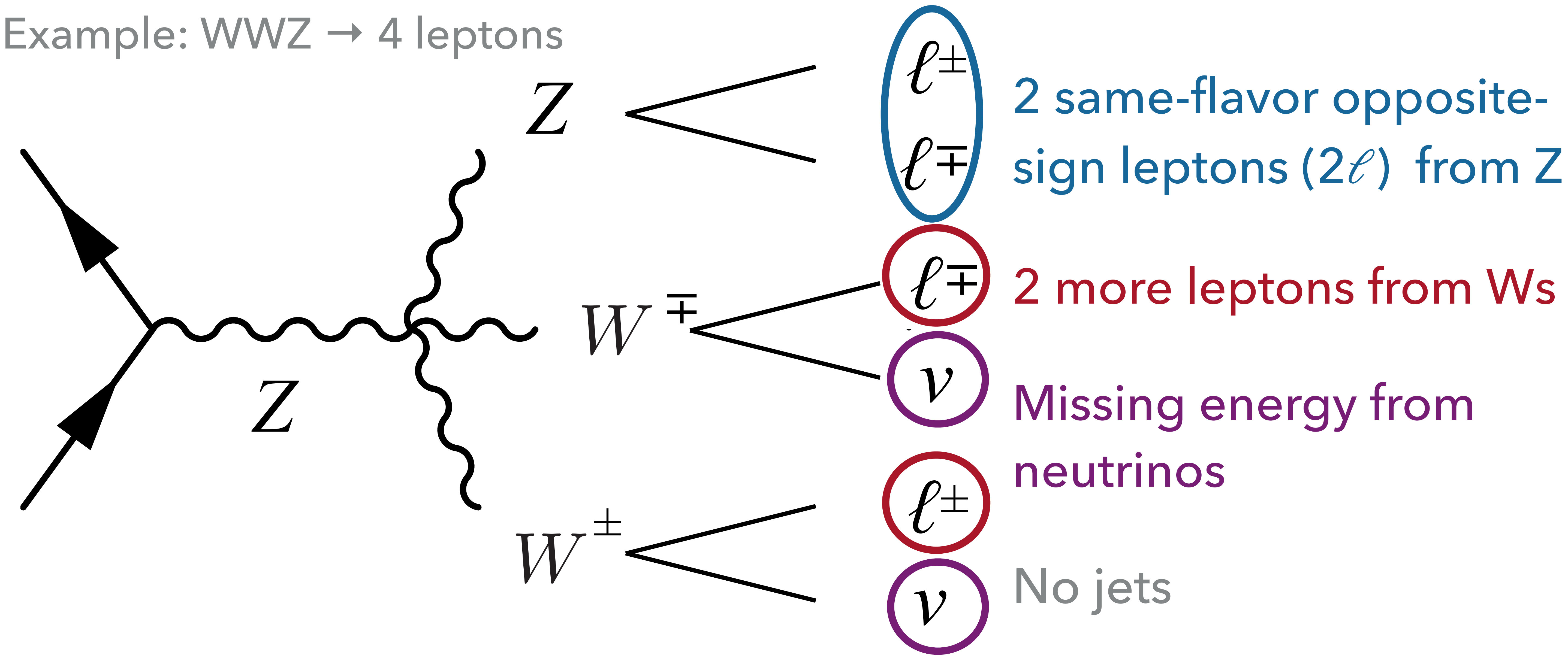
- Combination of 2–6 lepton channels
  - 4 lepton channel has best sensitivity
  - Optimize BDTs for event selection

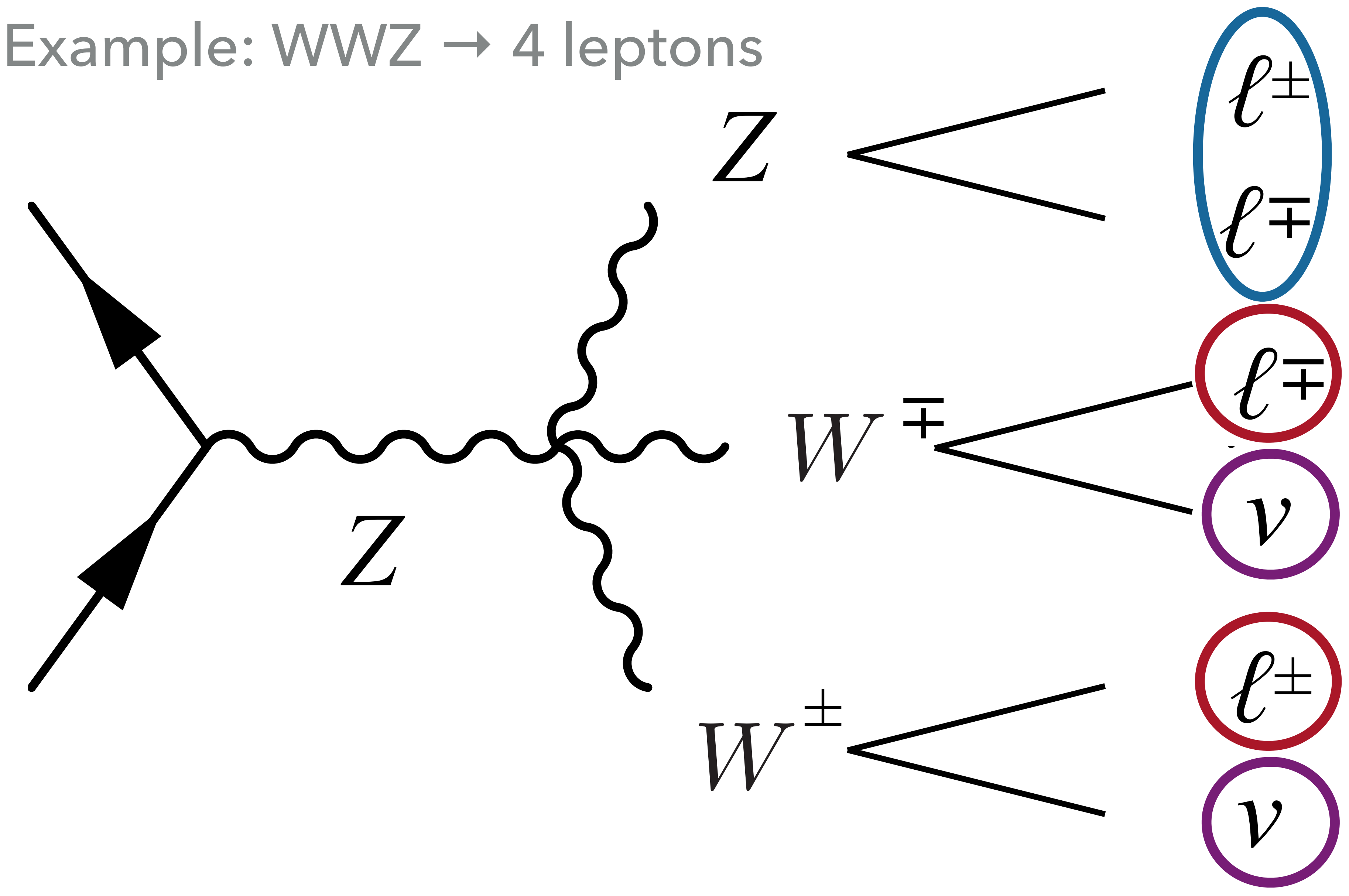
Example: WWZ → 4 leptons



VVV PRODUCTION AND DECAY

- Focus on cleanest channels: fully leptonic (or same-sign) final states
- Combination of 2–6 lepton channels
  - 4 lepton channel has best sensitivity
  - Optimize BDTs for event selection
- Data-driven background estimates from carefully chosen control regions

Example: WWZ → 4 leptons



2 same-flavor opposite-sign leptons (2ℓ) from Z

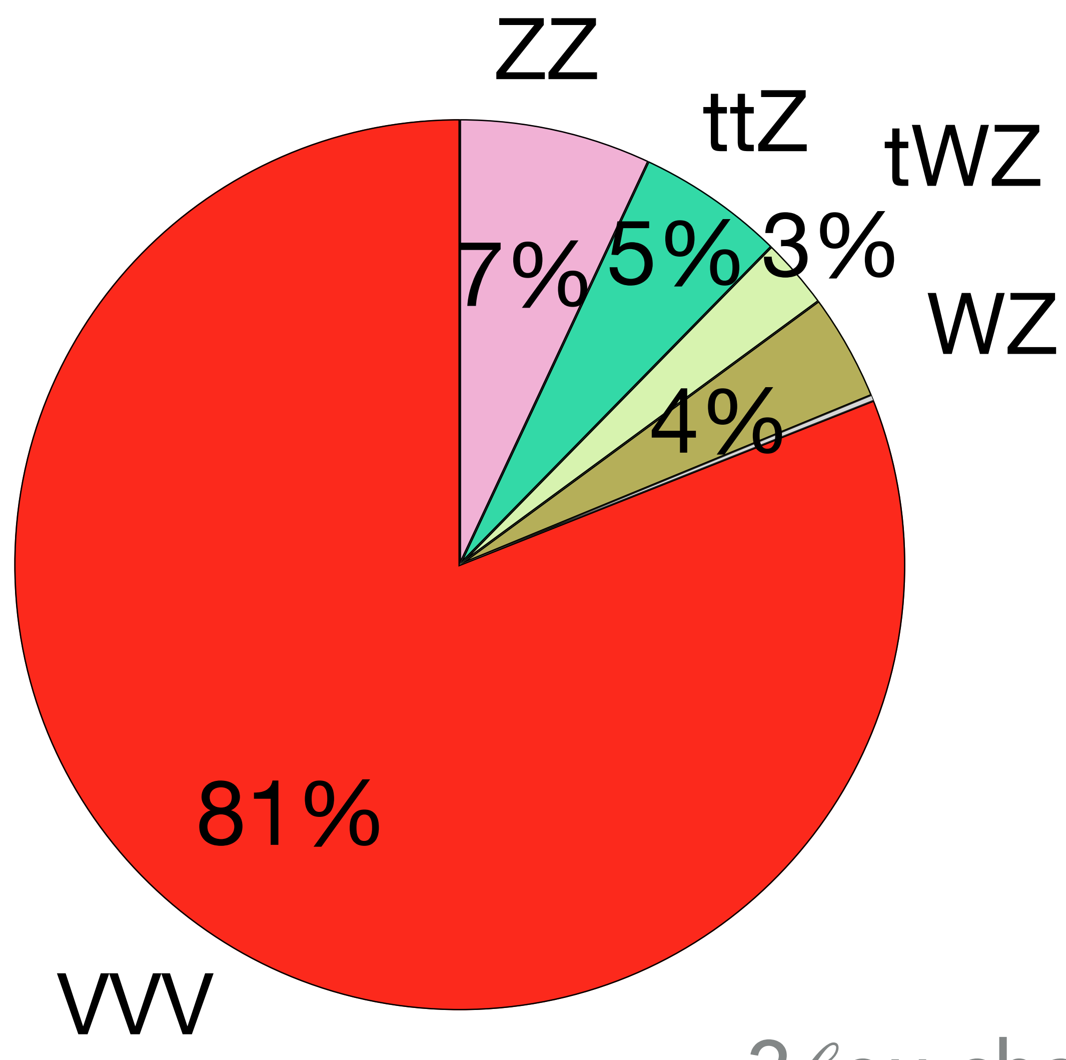
2 more leptons from Ws

Missing energy from neutrinos

No jets

Important background:
4 real leptons from ZZ

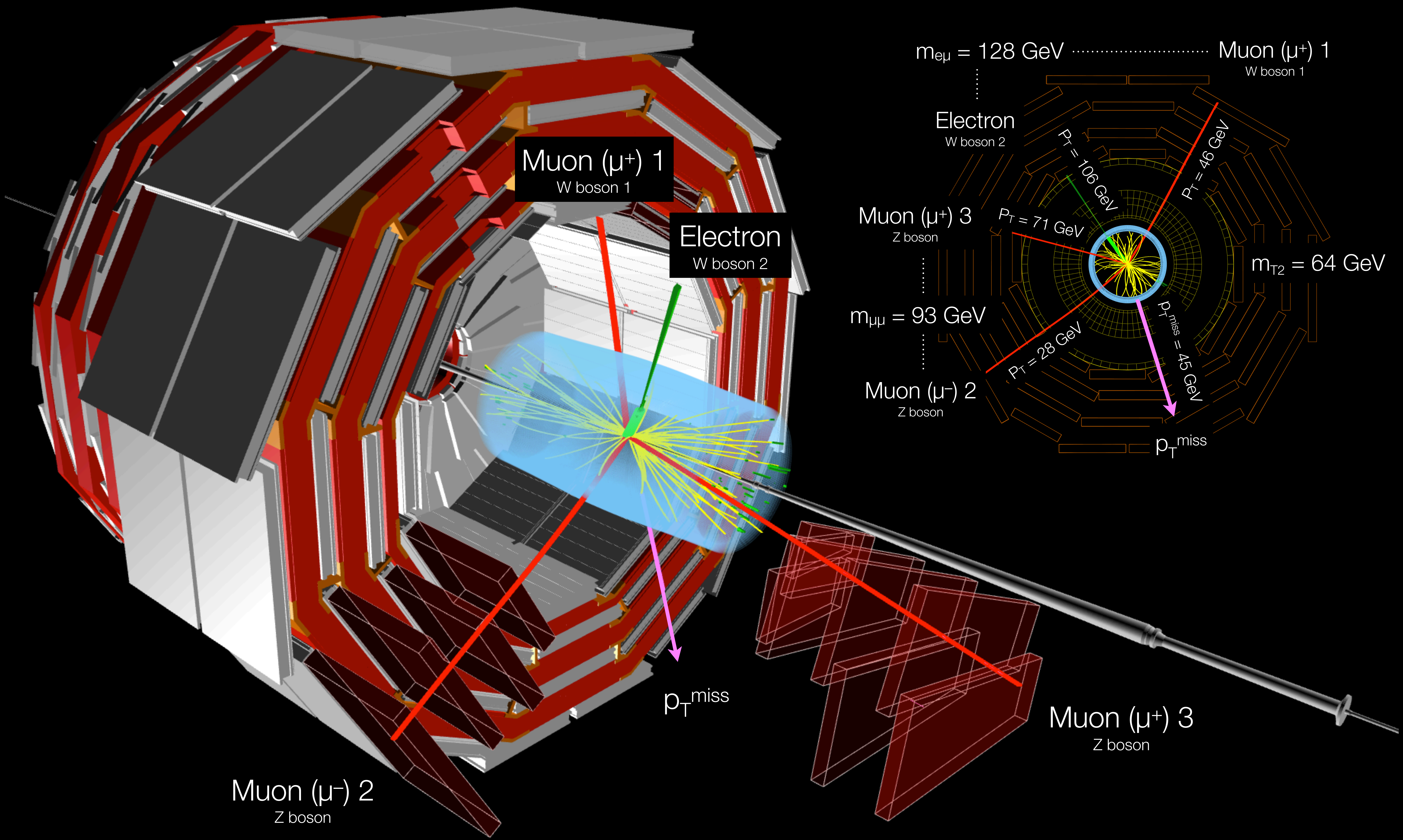
Reduce with 2ℓ off Z-peak and require 2ℓ+eμ



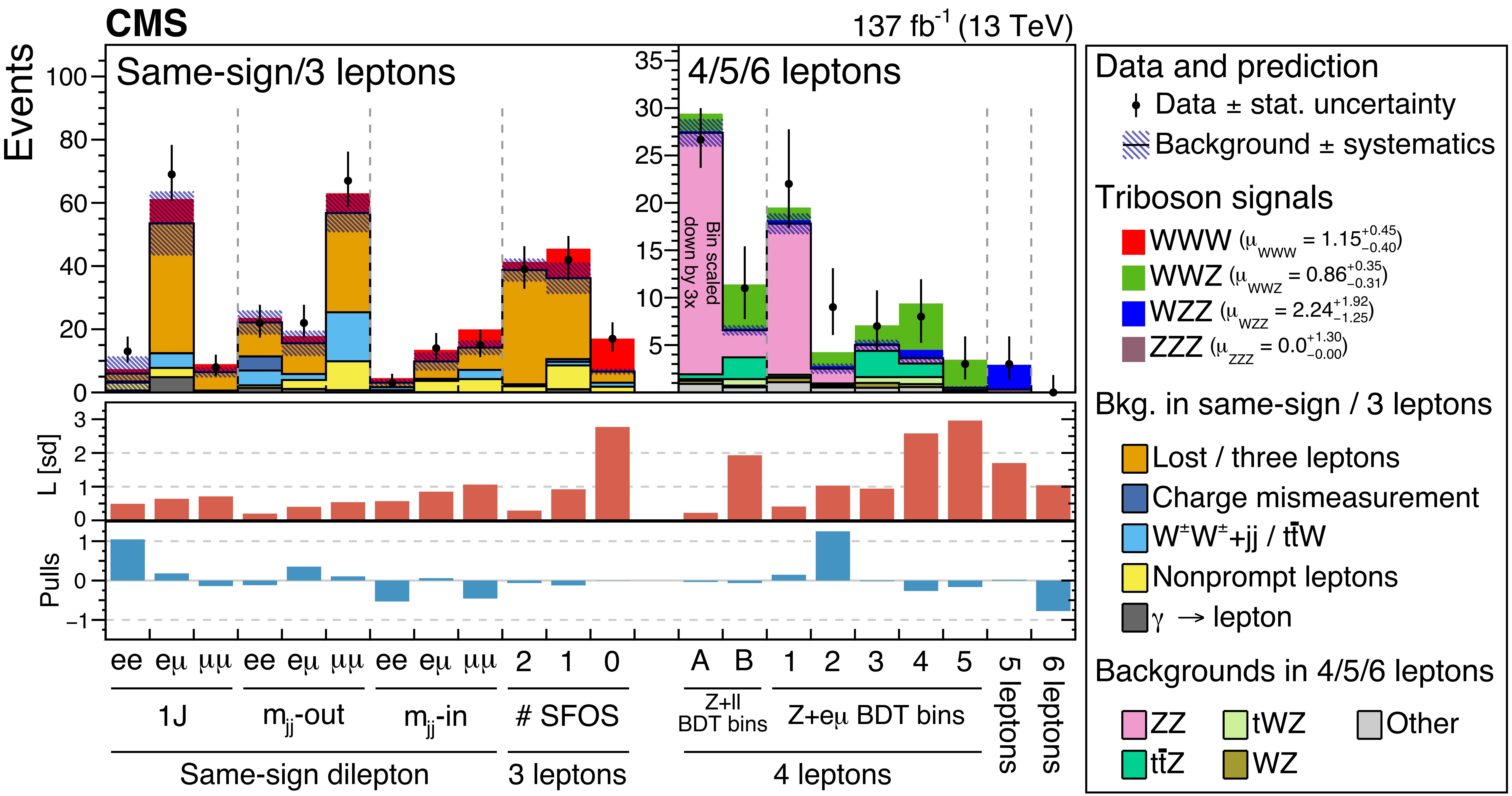
2ℓeμ channel

WWZ → 4 lepton event

CMS experiment at the LHC, CERN
Data recorded: 2016-Jul-23 08:13:27.898048 GMT
Run 277168, Event No. 3219714497 LS 1799



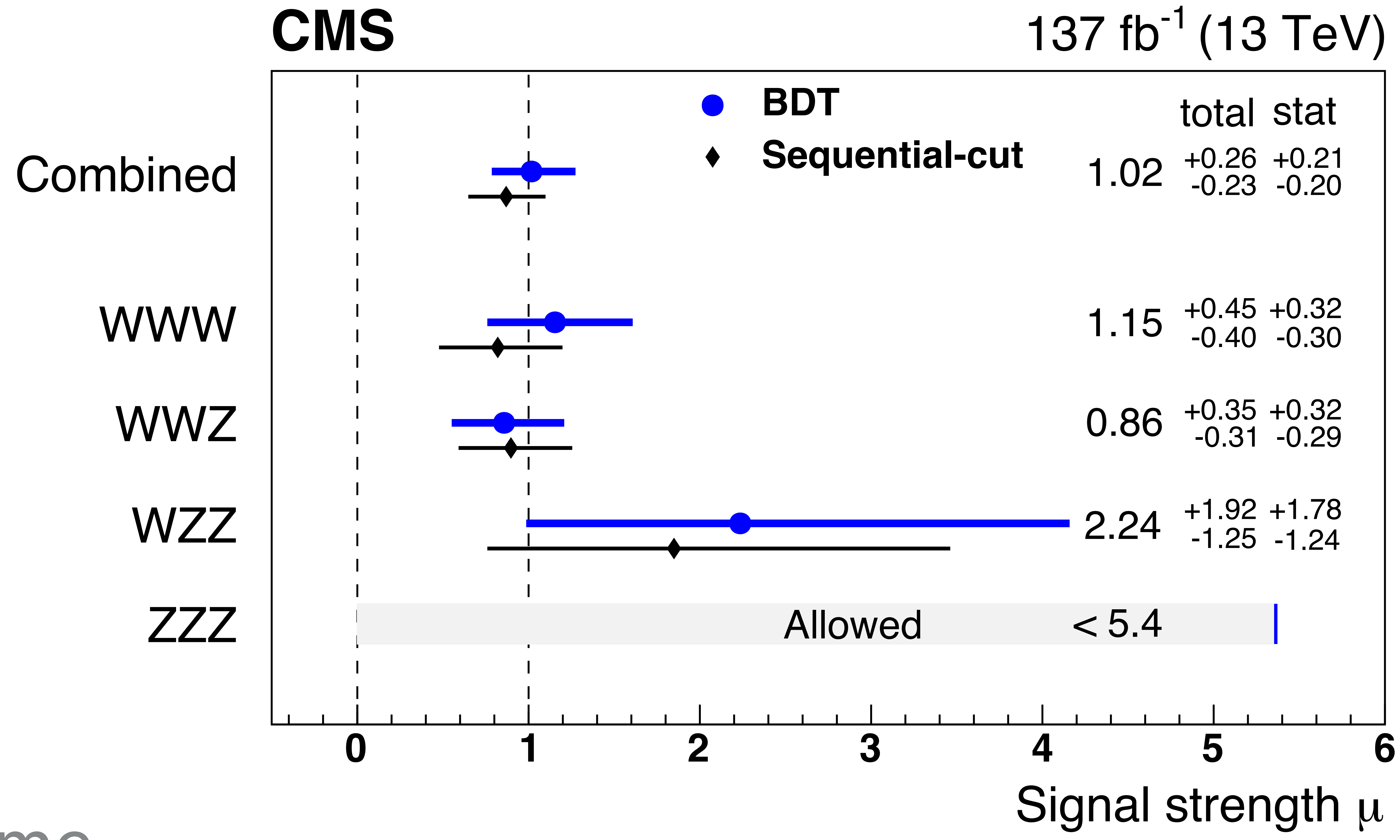
VVV RESULTS



- All channels together
- Best fit signal strengths for each process (WWW, WWZ, WZZ, ZZZ) shown

VVV OBSERVATION

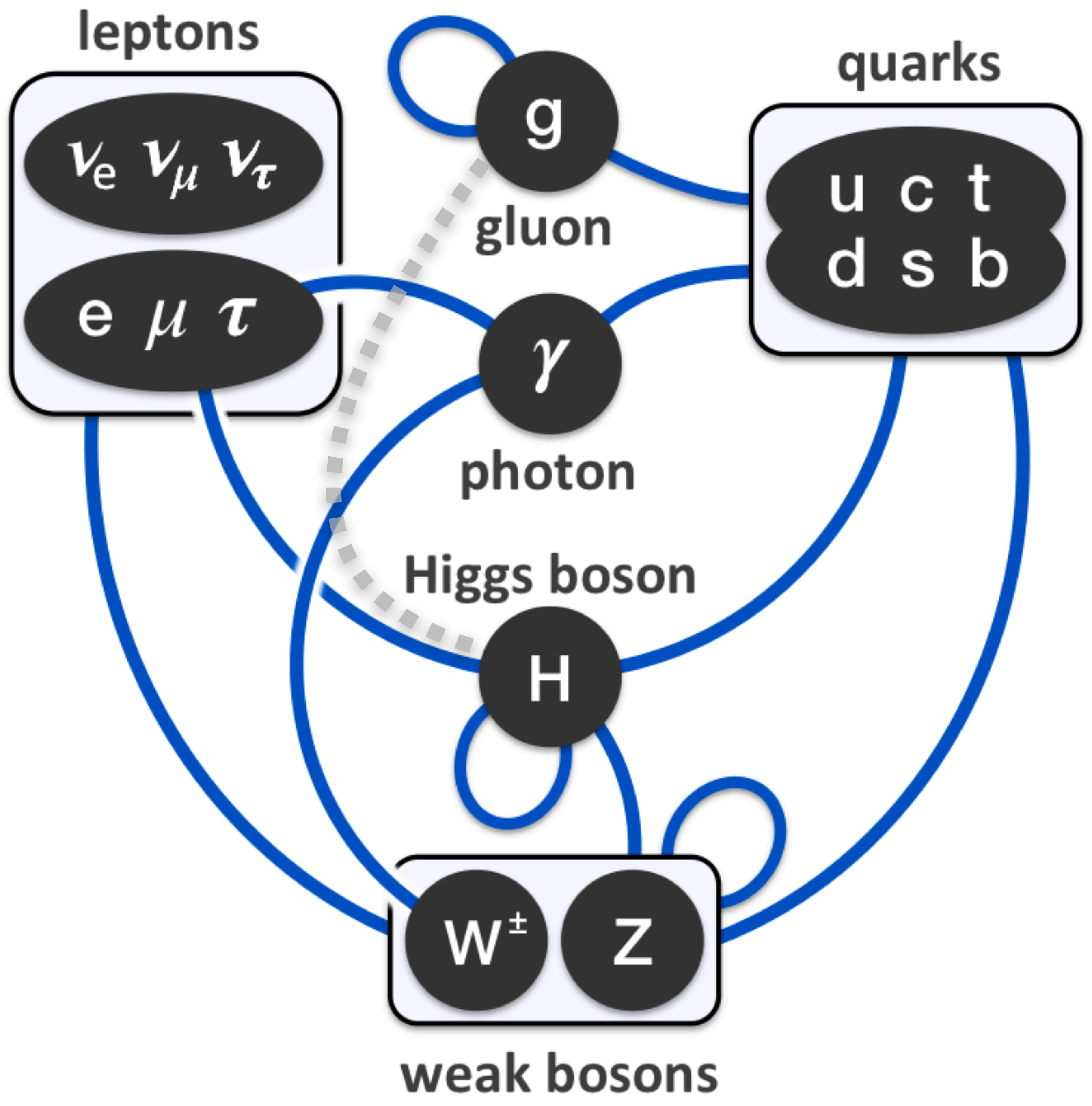
process	significance[σ] observed (expected)
WWW	3.3 (3.1)
WWZ	3.3 (4.1)
WZZ	1.7 (0.7)
ZZZ	0.0 (0.9)
combined	**5.7 (5.9)**

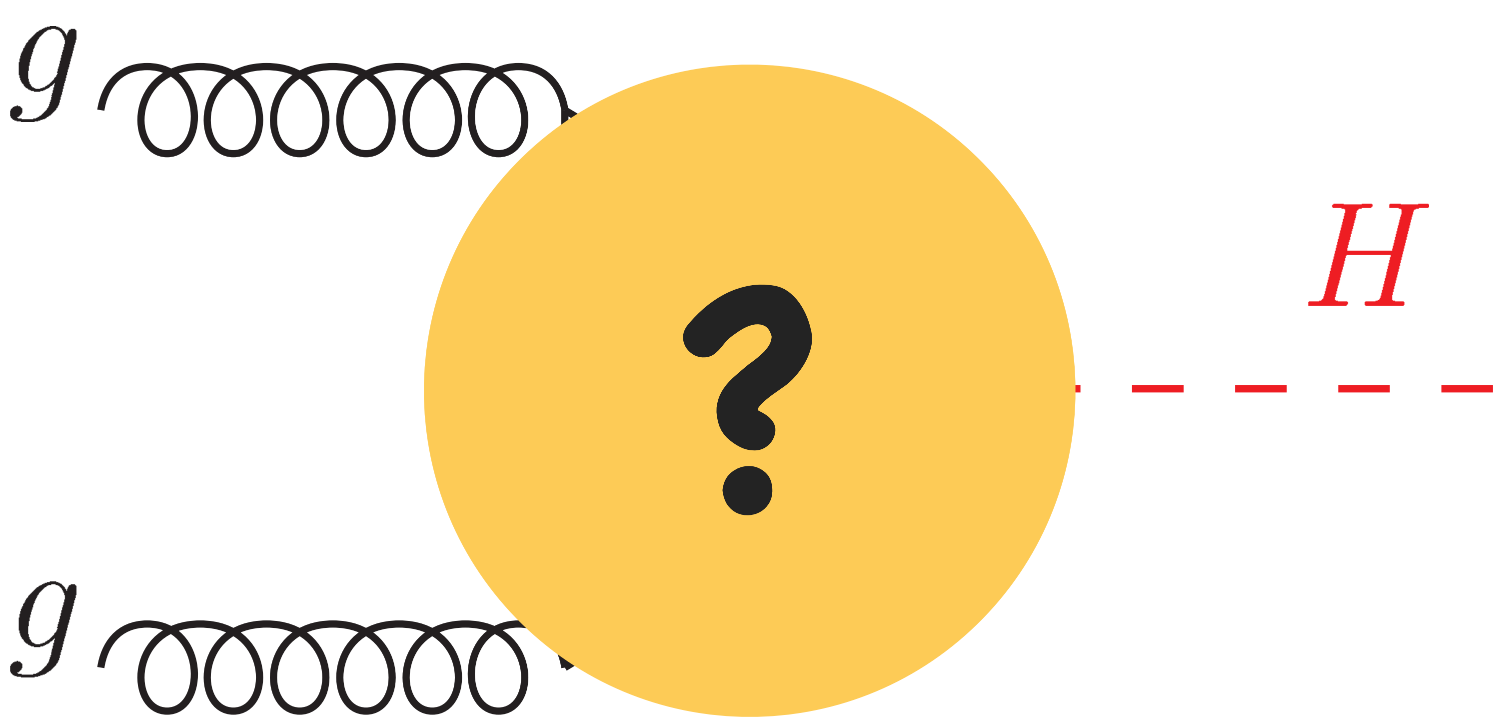


- Observed VVV for the first time
- Evidence for WWW and WWZ
- Measured VVV signal strength: $\mu = 1.01^{+0.21}_{-0.20}$(stat.)$^{+0.15}_{-0.12}$(syst.)
- Next step: add more final states and study high $\hat{s}$ regime for signs of new physics

GGH INTERACTIONS

- High-p_T Higgs processes are a probe of potential BSM particles in the loop
  - Appear as new ggH interactions





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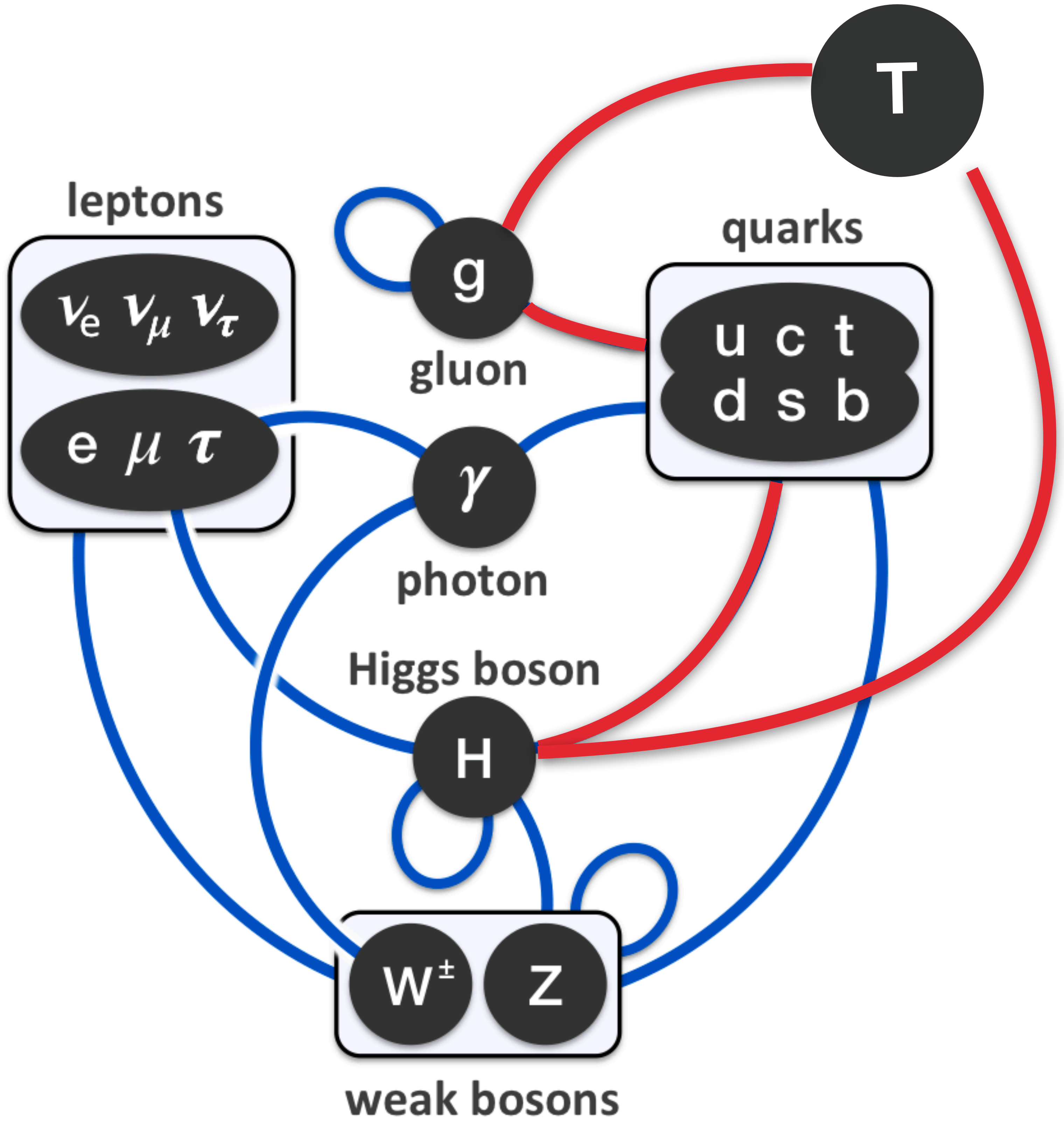

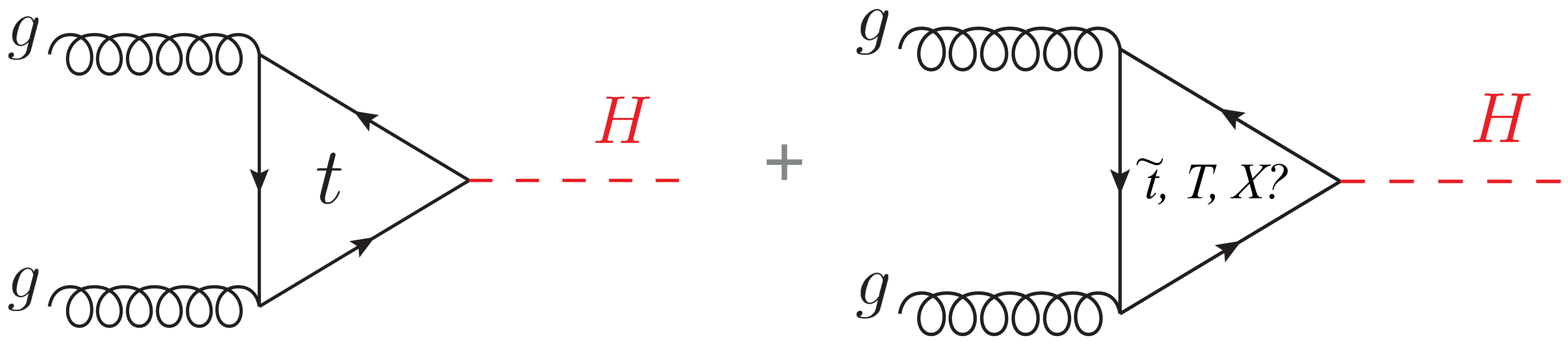

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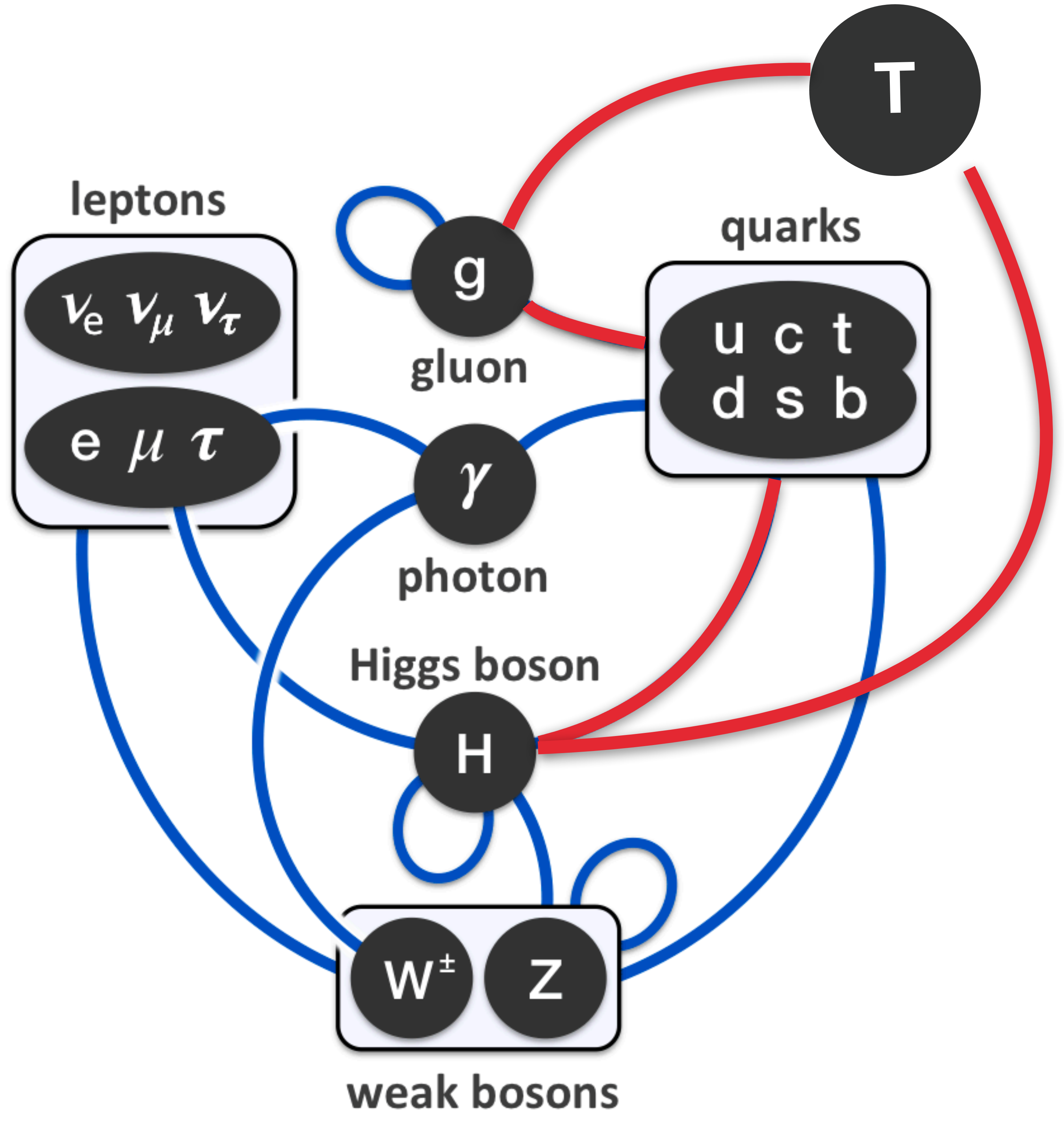
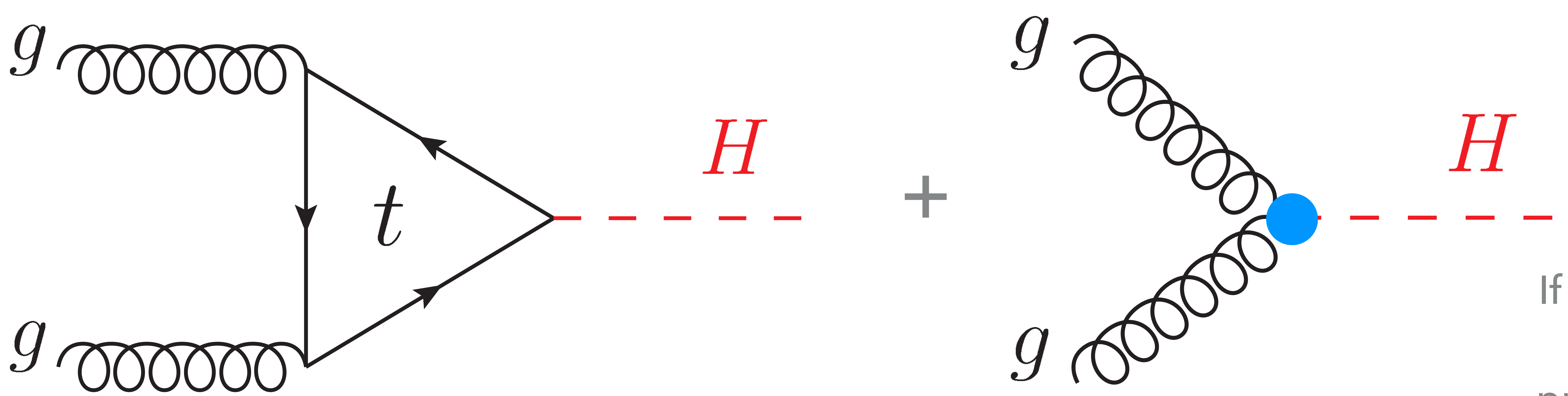
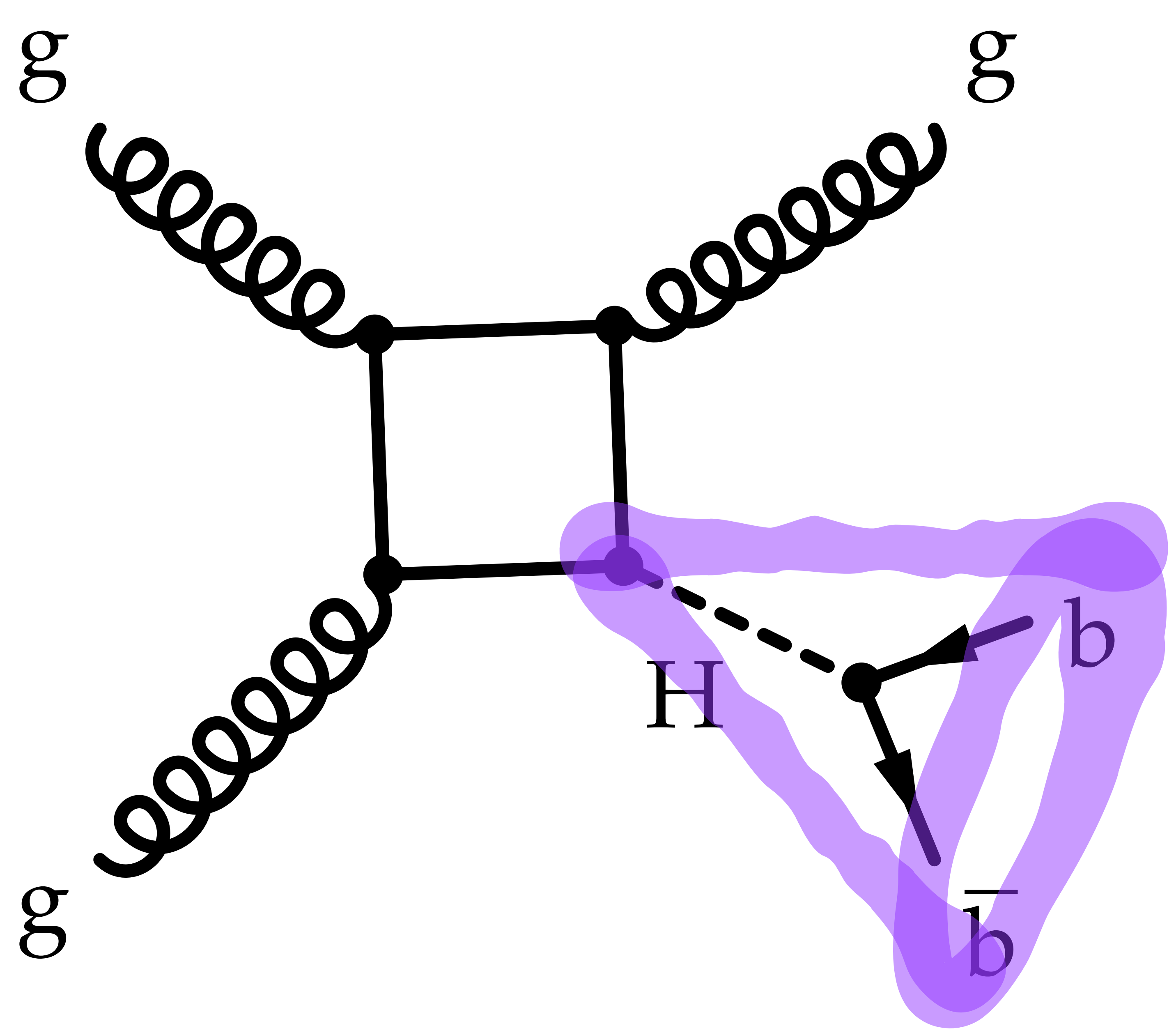


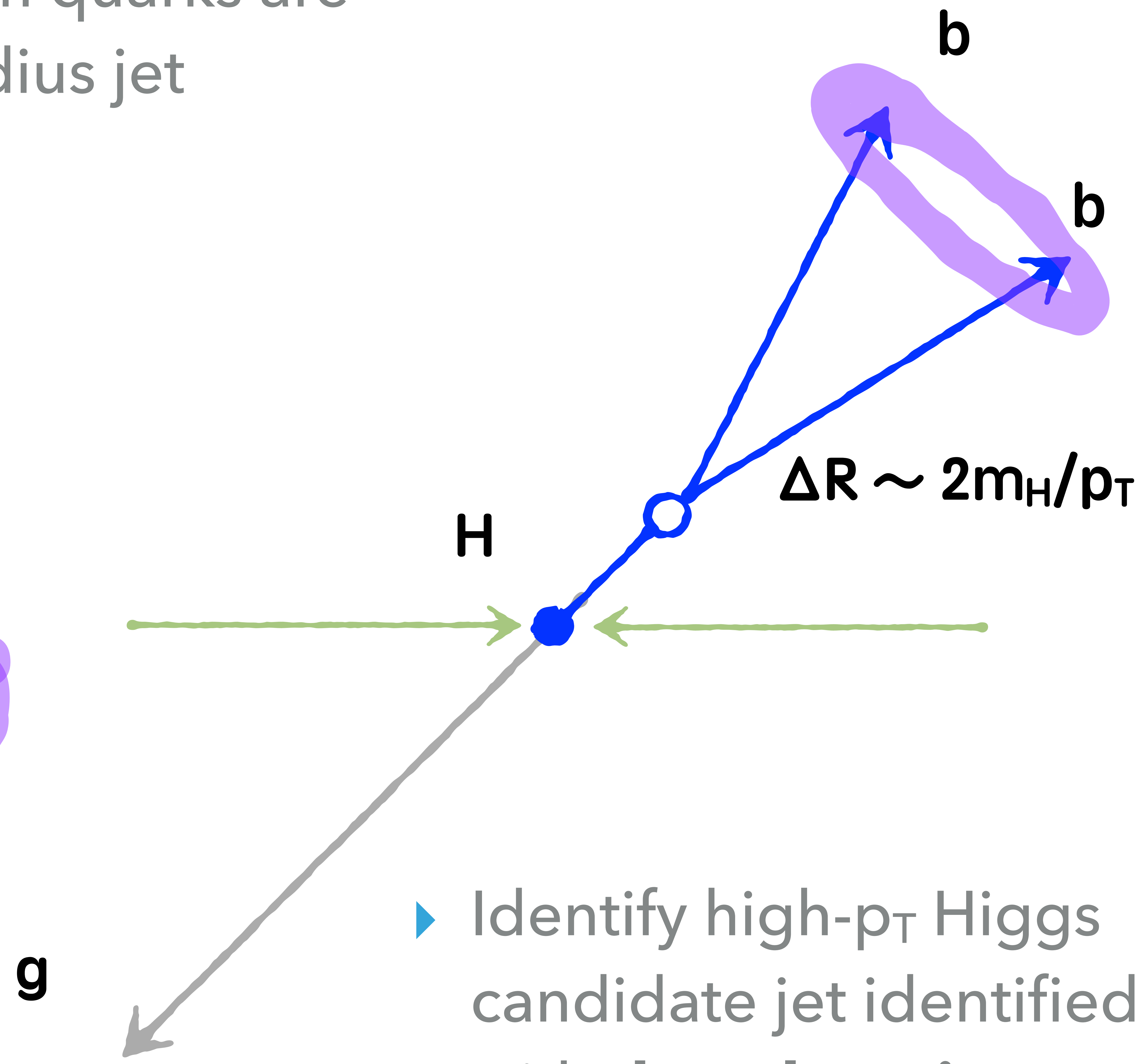


If the new particle is too heavy to be produced, this looks like a new interaction!

BOOSTING THE HIGGS

- At high momentum, the bottom quarks are ***boosted*** into a single large-radius jet

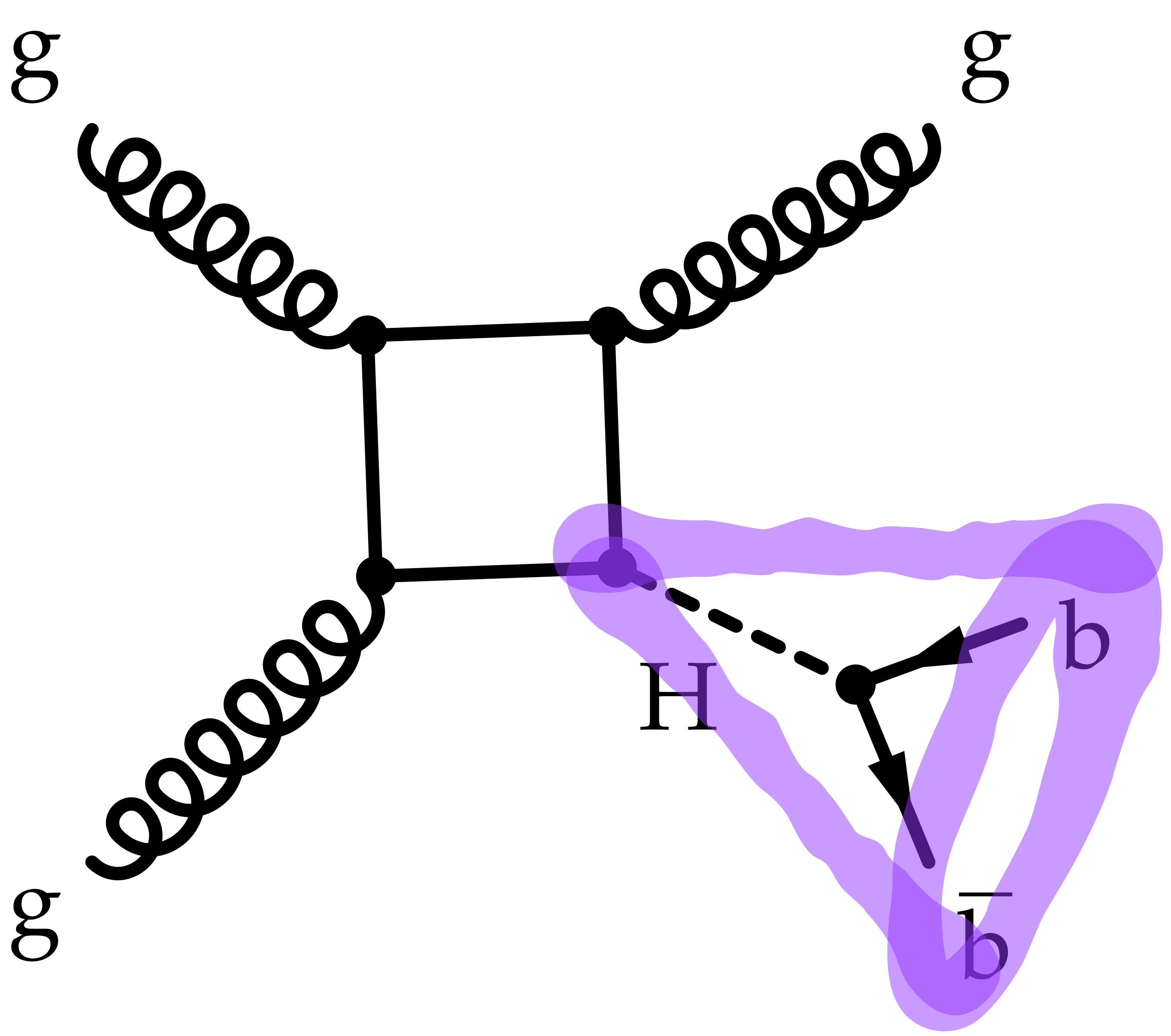


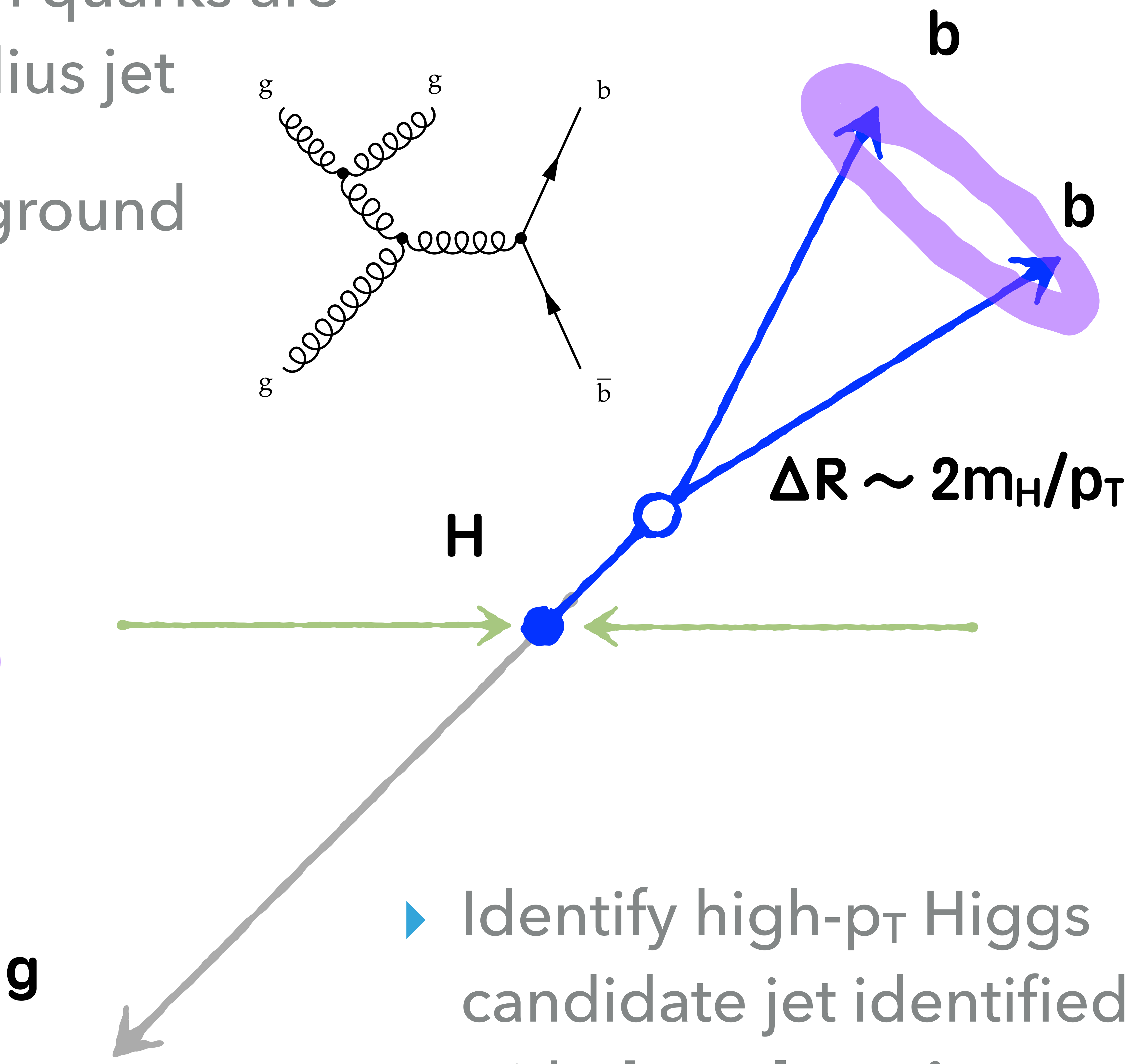


- Identify high-p_T Higgs candidate jet identified with **deep learning**

BOOSTING THE HIGGS

- At high momentum, the bottom quarks are ***boosted*** into a single large-radius jet
  - Smaller (relative) QCD background





- Identify high-p_T Higgs candidate jet identified with **deep learning**

DEEP DOUBLE-B TAGGER

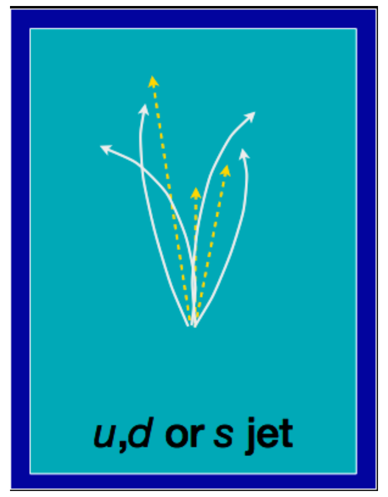
- Process track and SV inputs as ordered lists
  - Combine in final layer with expert inputs
- Performance gain over previous algorithm

track inputs

secondary vertex inputs

expert inputs

vs.



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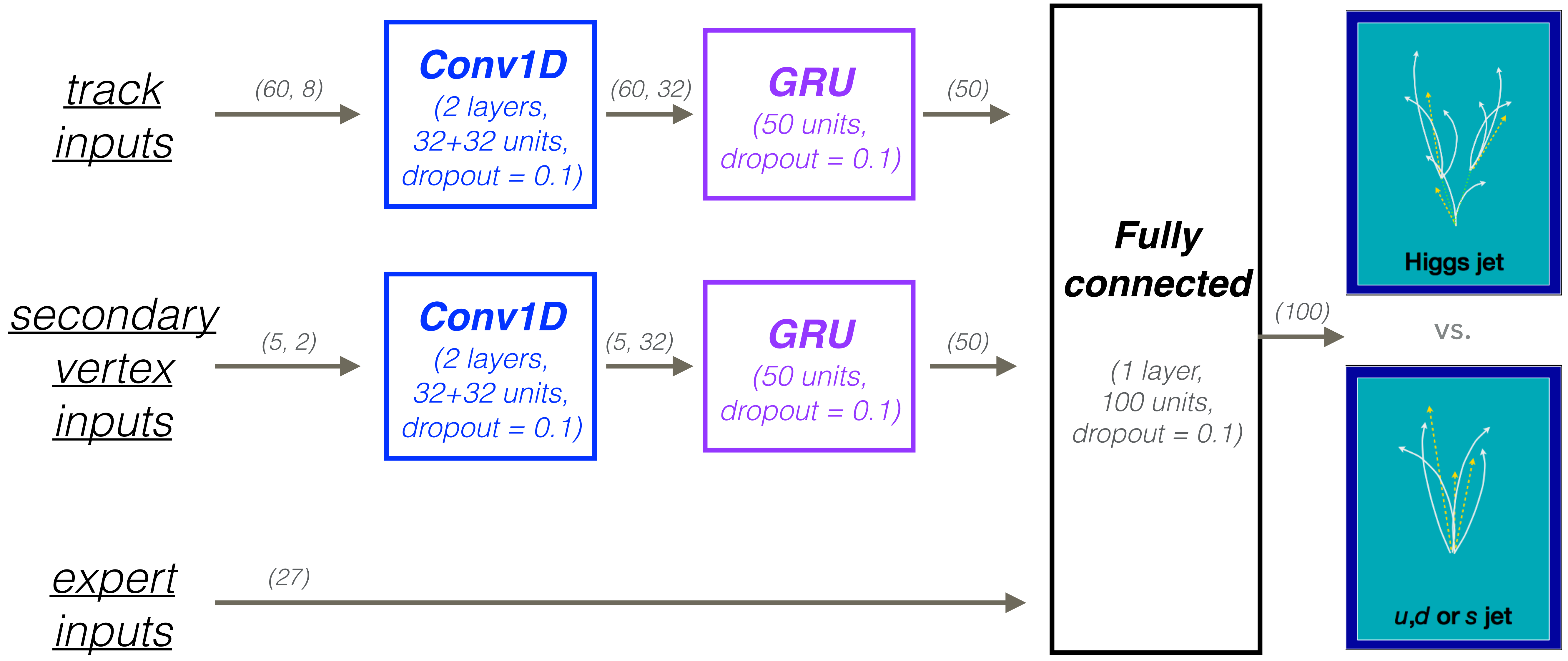

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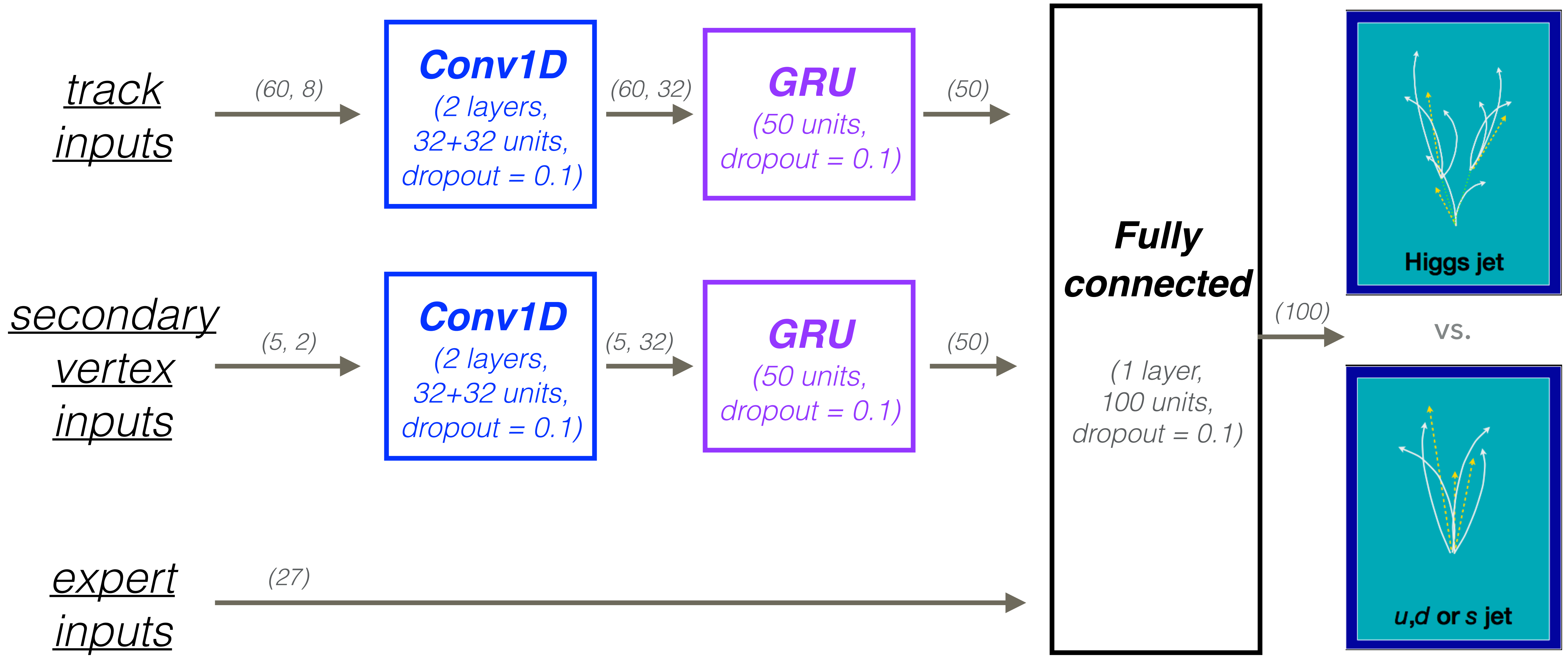
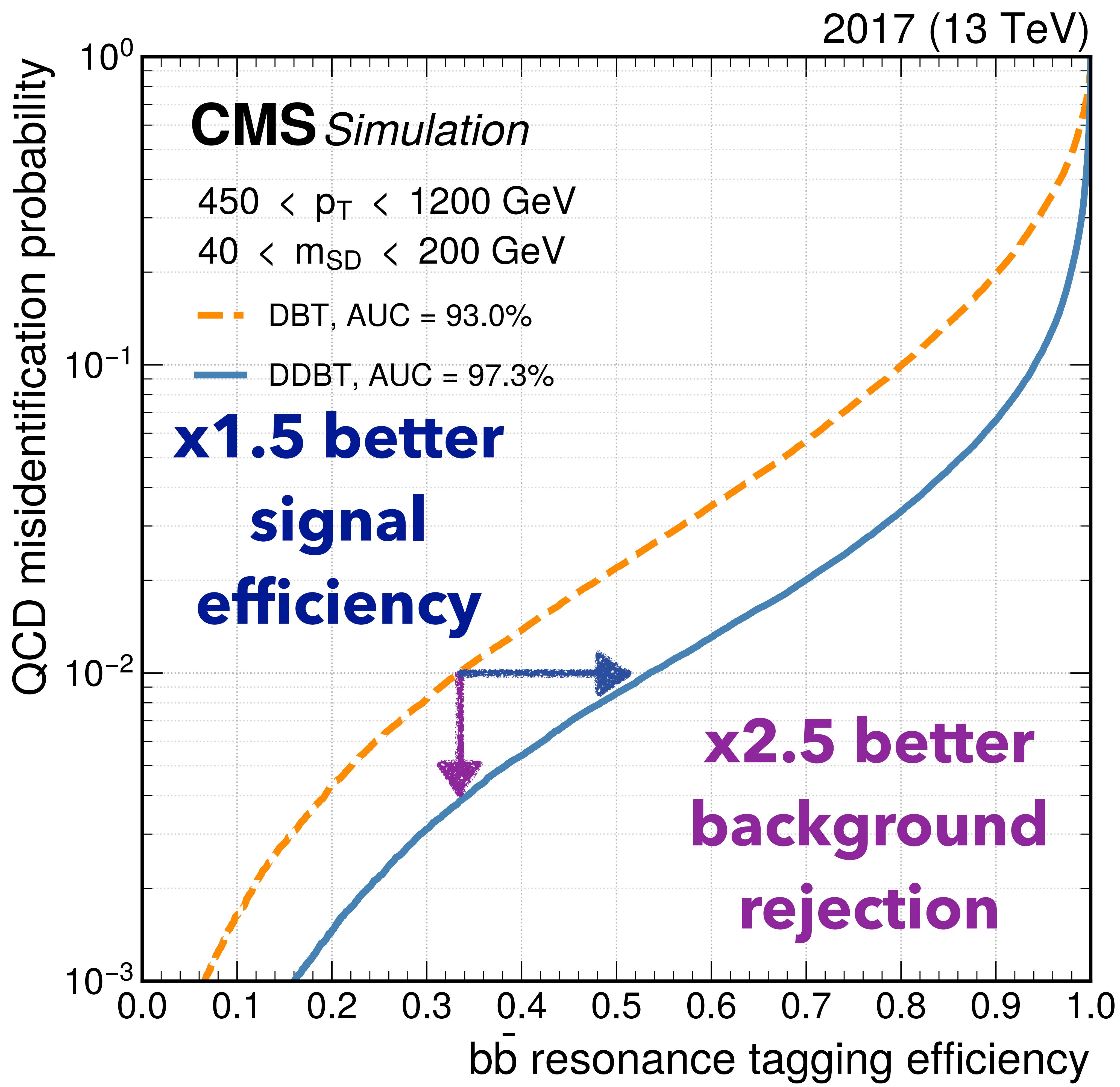
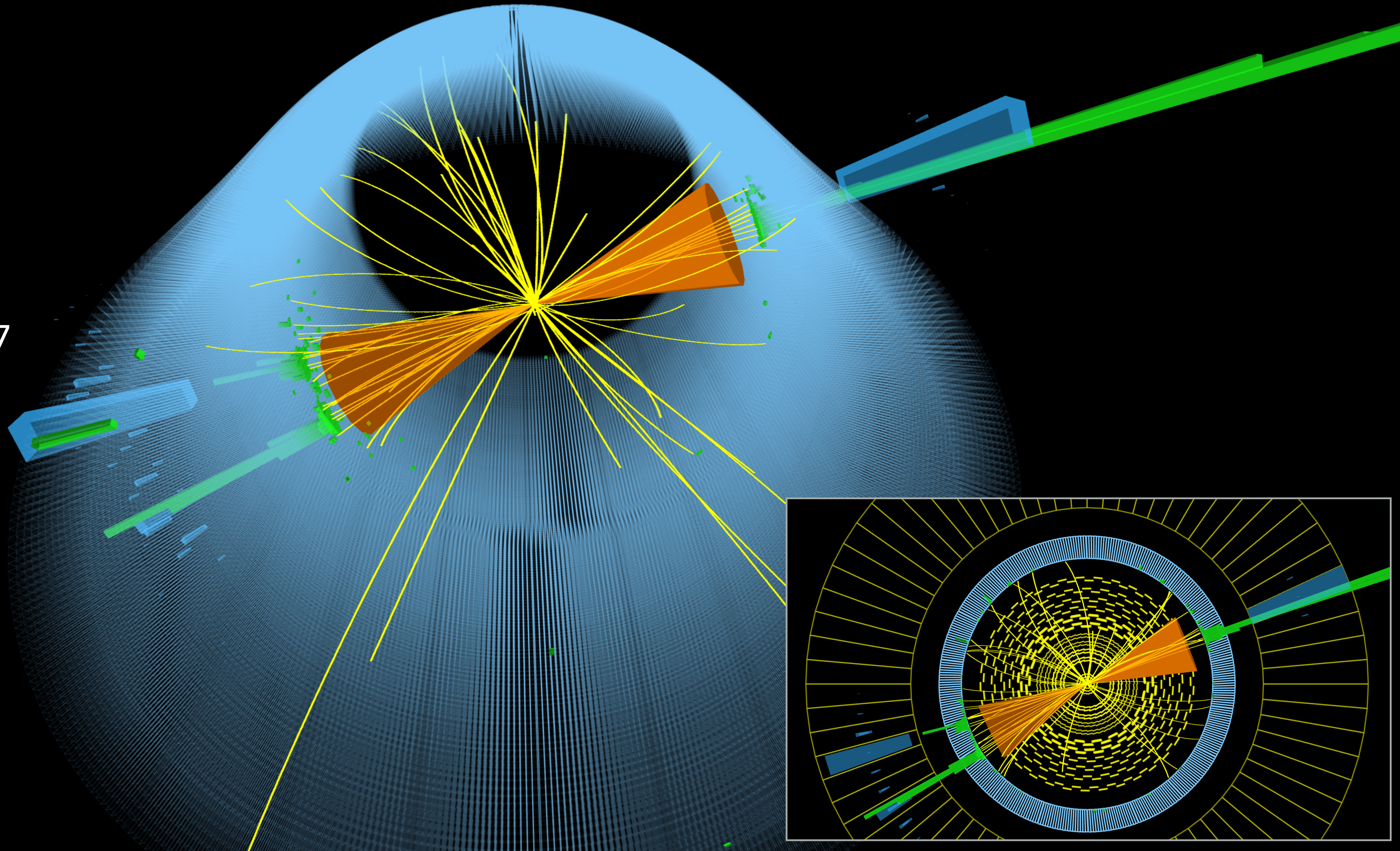




CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-20 03:55:39.135168 GMT
Run / Event / LS: 305313 / 624767783 / 361

CMS-PHO-EVENTS-2020-012

H(bb) cand. jet
p_T = 905 GeV
m_{SD} = 130 GeV
deep double-b = 0.97

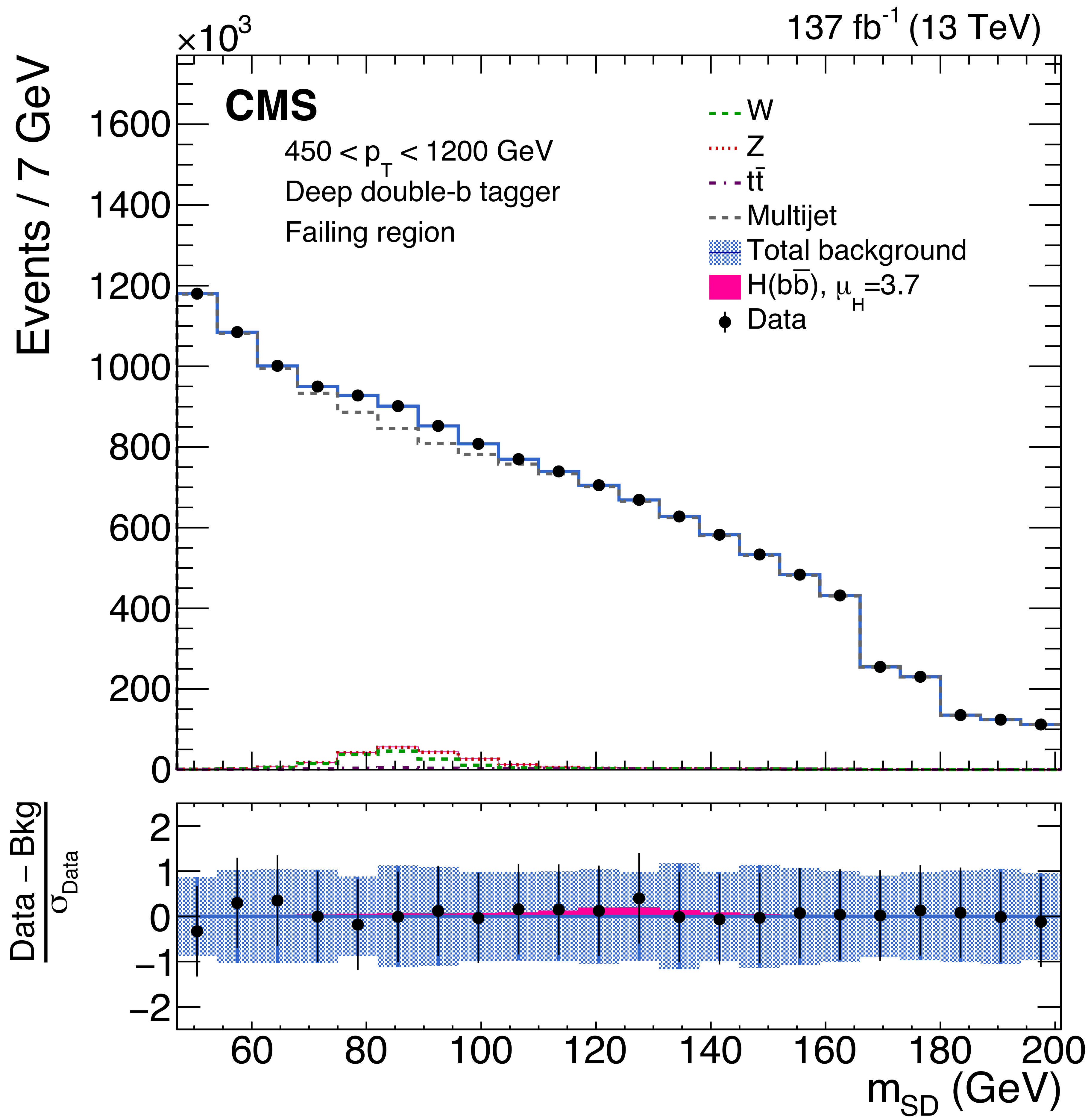


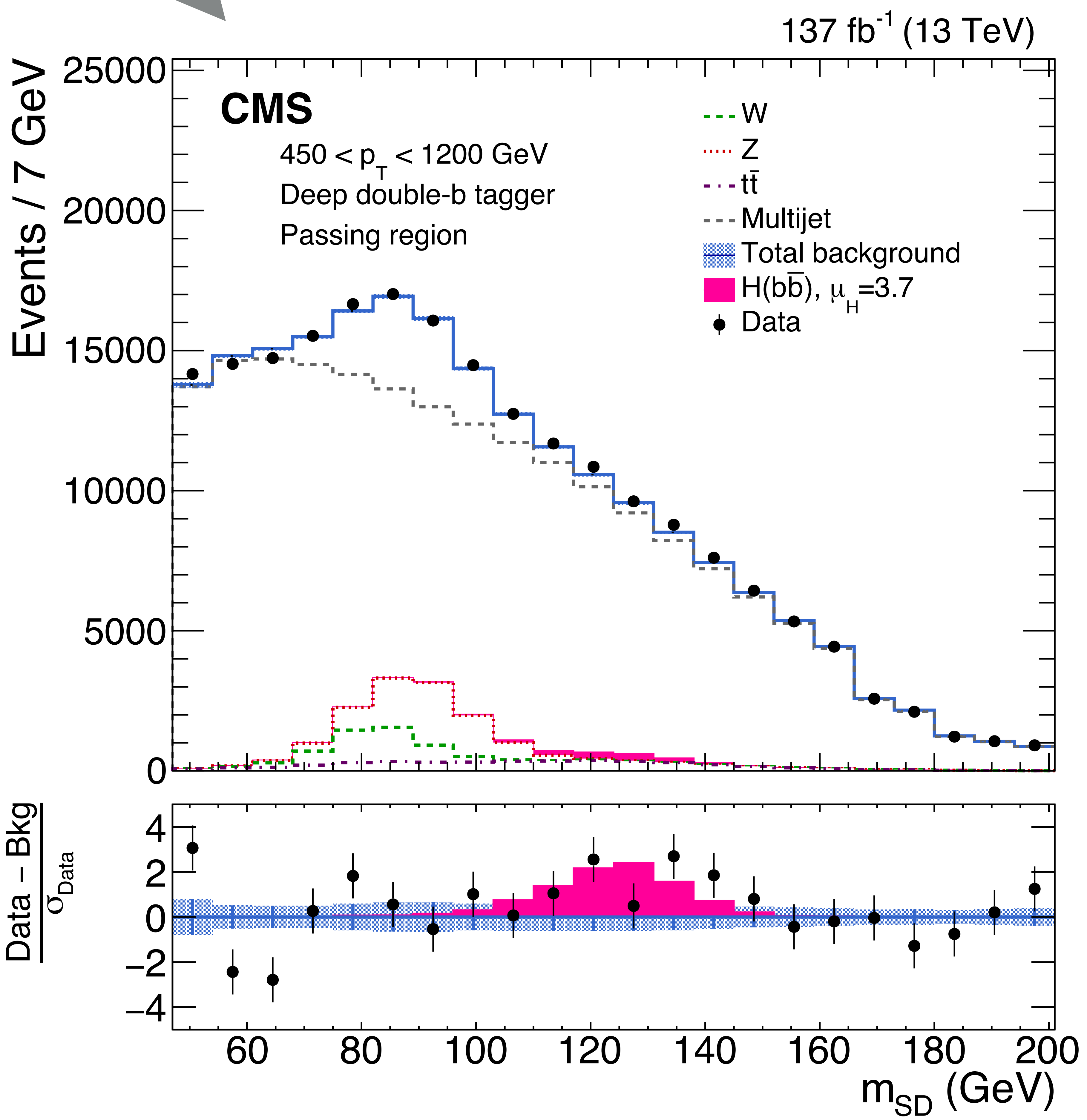
BOOSTED H(BB) RESULTS

CMS-HIG-19-003

FAILING

PASSING

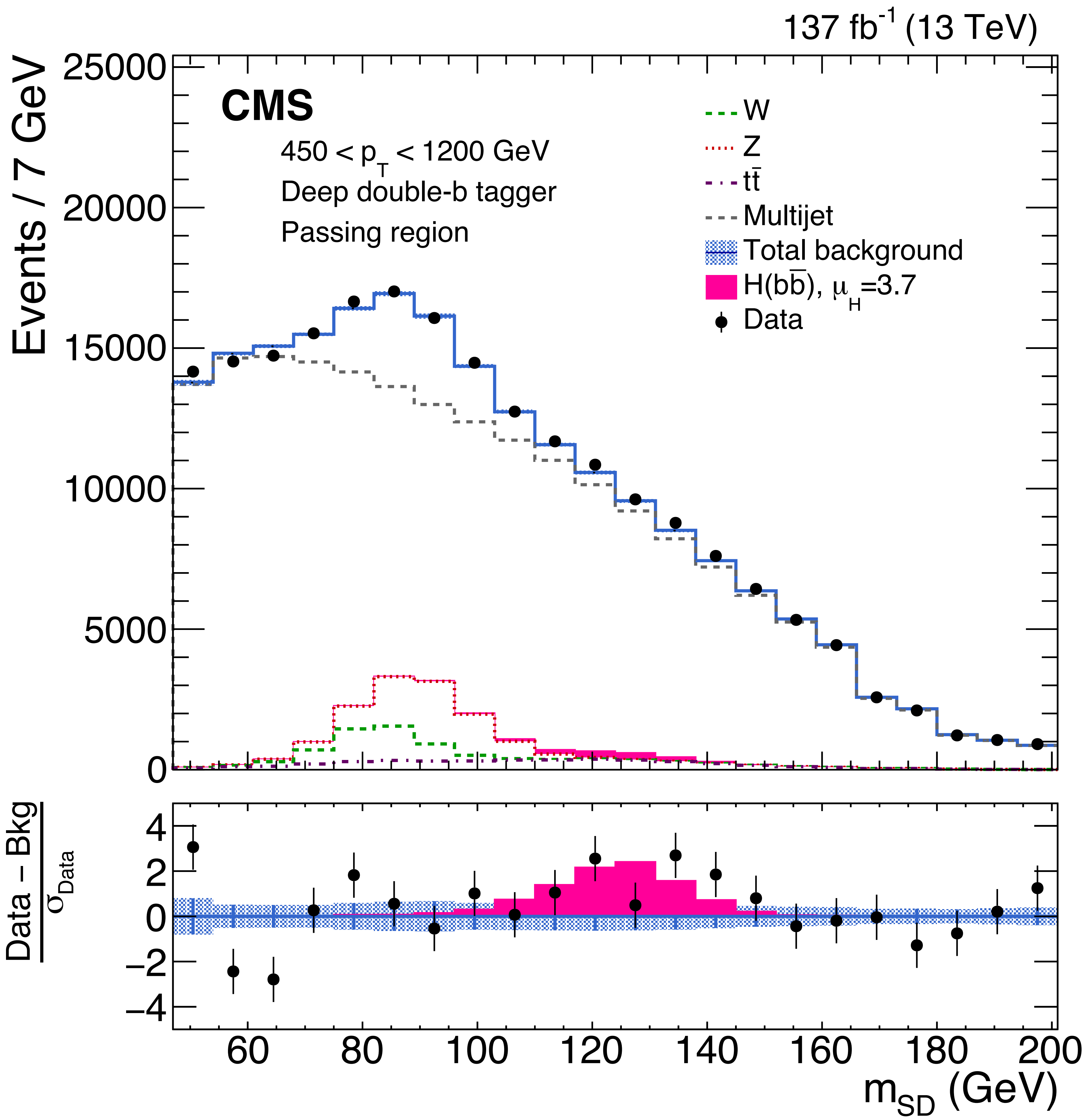




BOOSTED H(BB) RESULTS

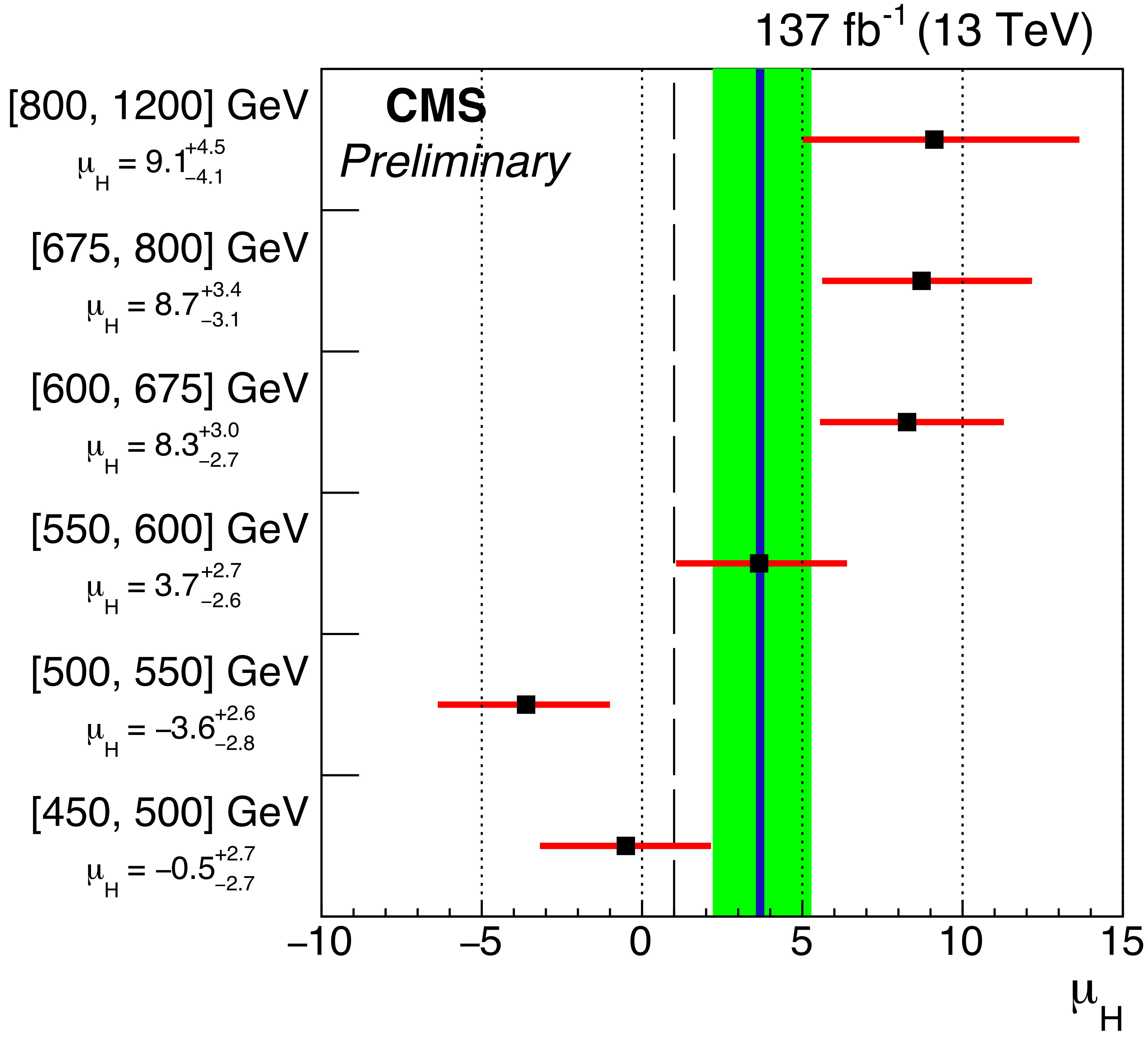
μ_Z	$1.01^{+0.24}_{-0.20}$
μ_H	$3.7^{+1.6}_{-1.5}$
Exp. H signif.	0.7σ
Obs. H signif.	2.5σ

PASSING



- Modest (1.8σ) excess over SM expectation

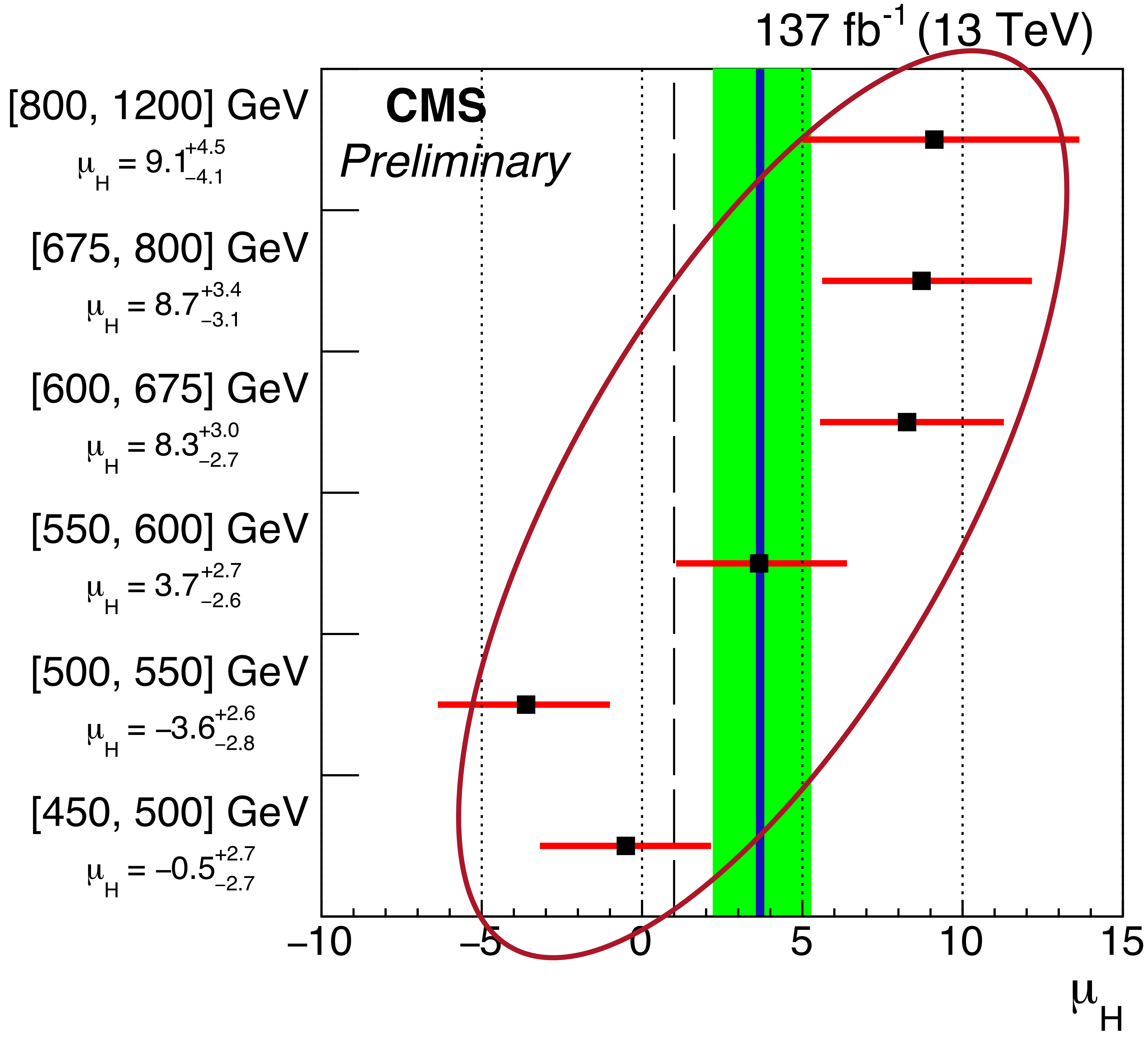
- Fits performed in categories of p_T



TRENDS IN HIGGS P_T

CMS-HIG-19-003

- Fits performed in categories of p_T
- Can look for trends as a function of Higgs p_T



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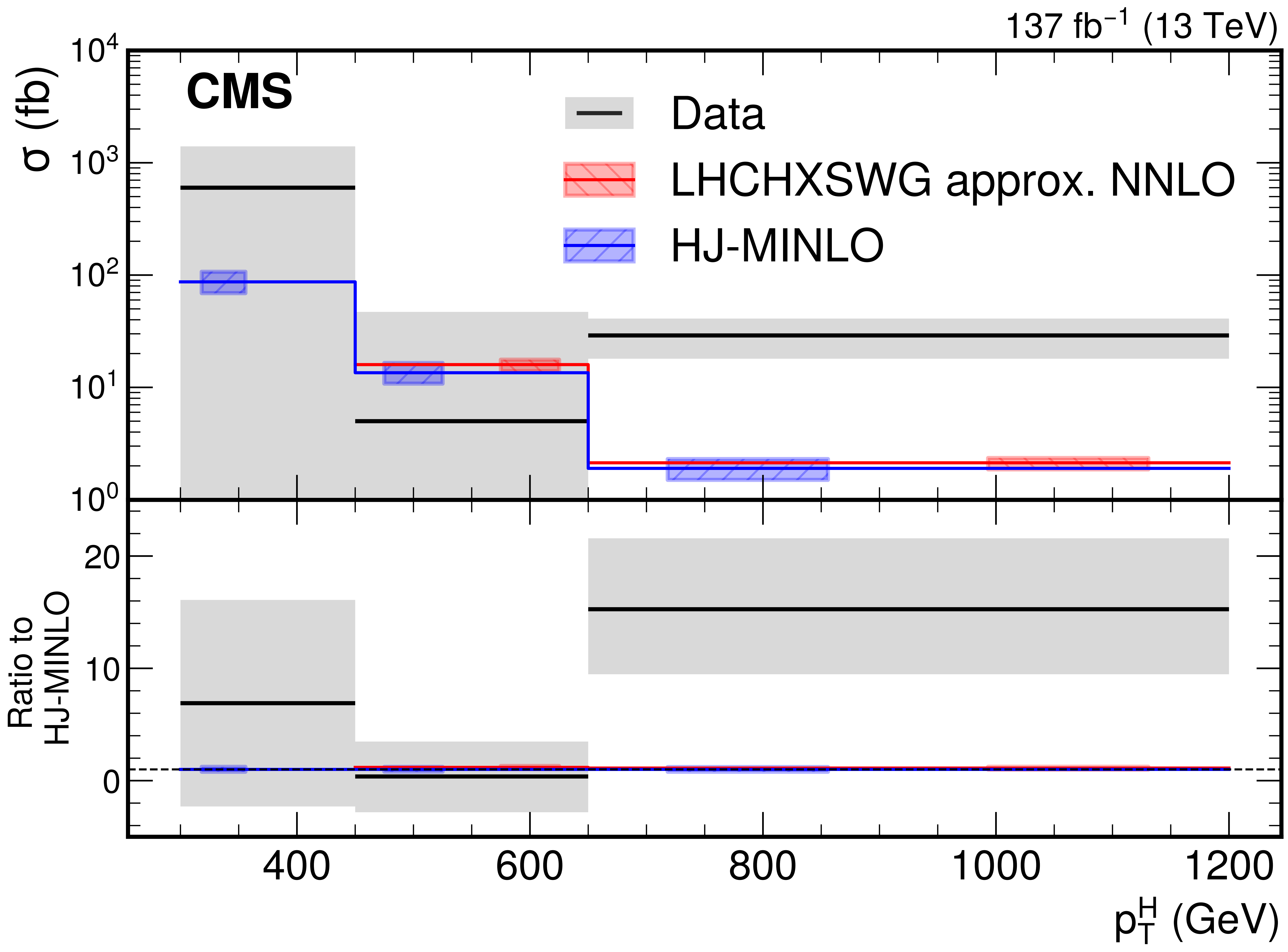
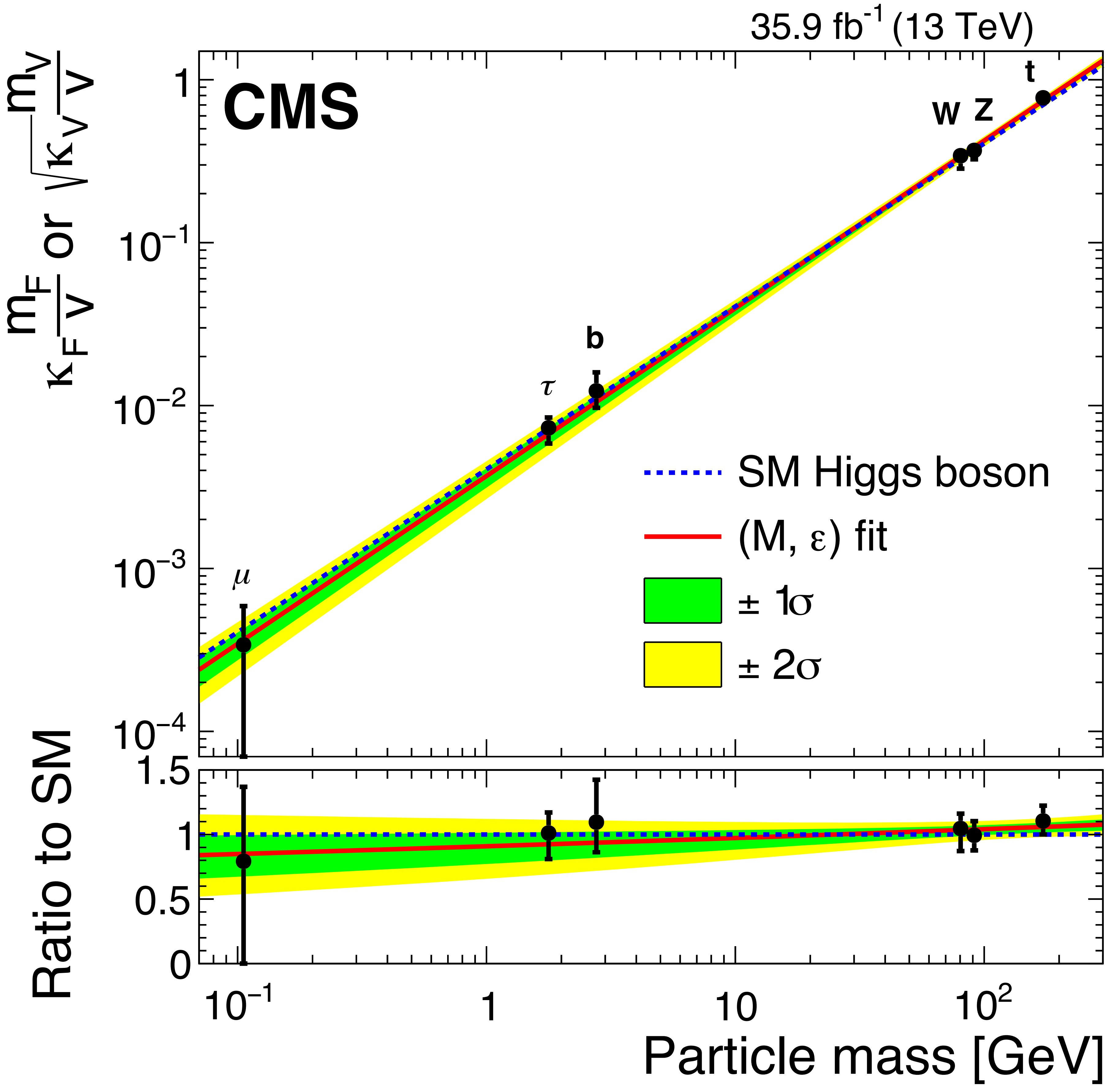


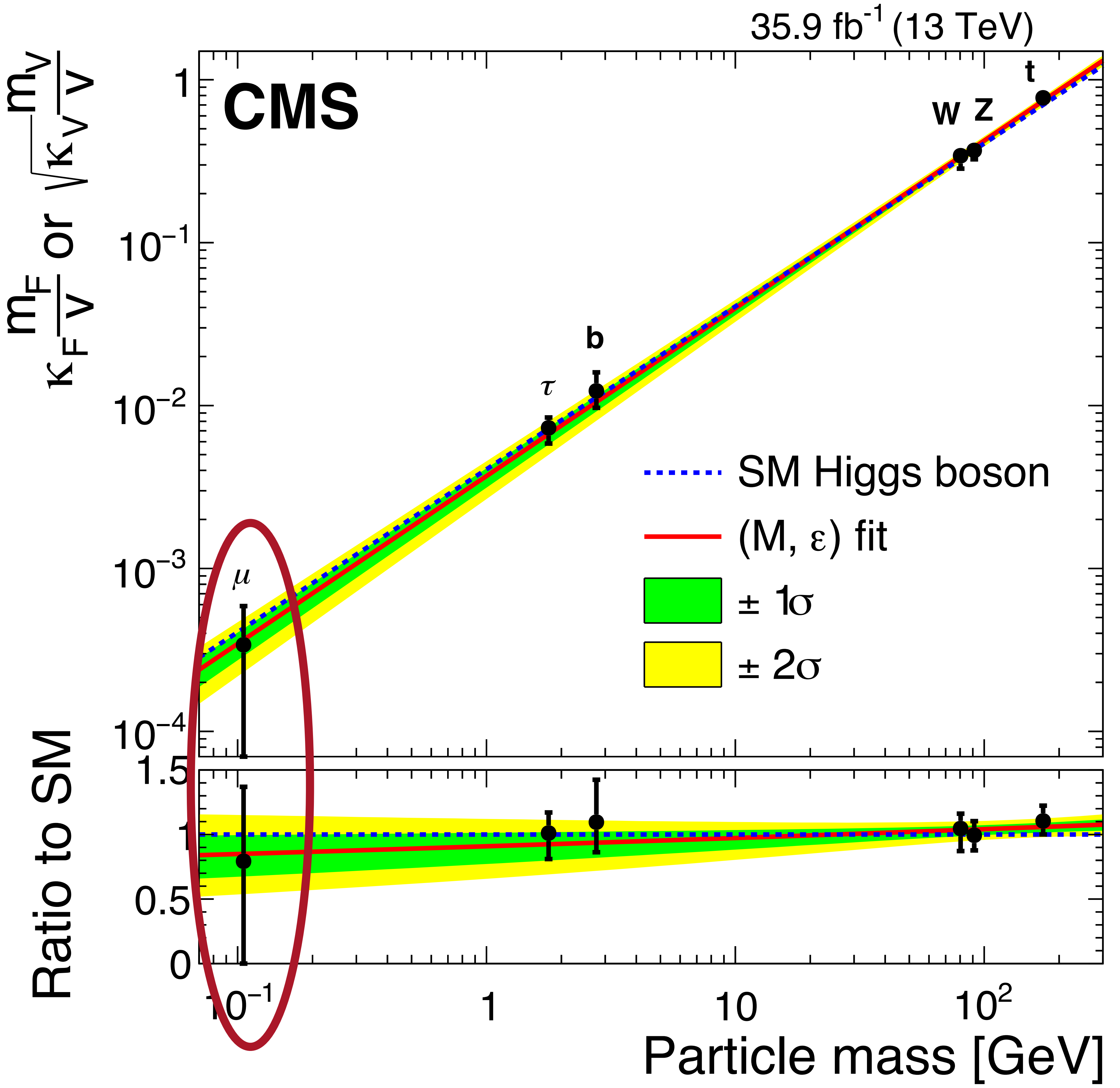
- Unfolded measurement in **Simplified Template XS** bins

- LHC Run 2 measured 3rd gen. Higgs couplings
  - tau lepton [PLB 779 (2018) 283]
  - top quark [PRL 120 (2018) 231801]
  - bottom quark [PRL 121 (2018) 121801]

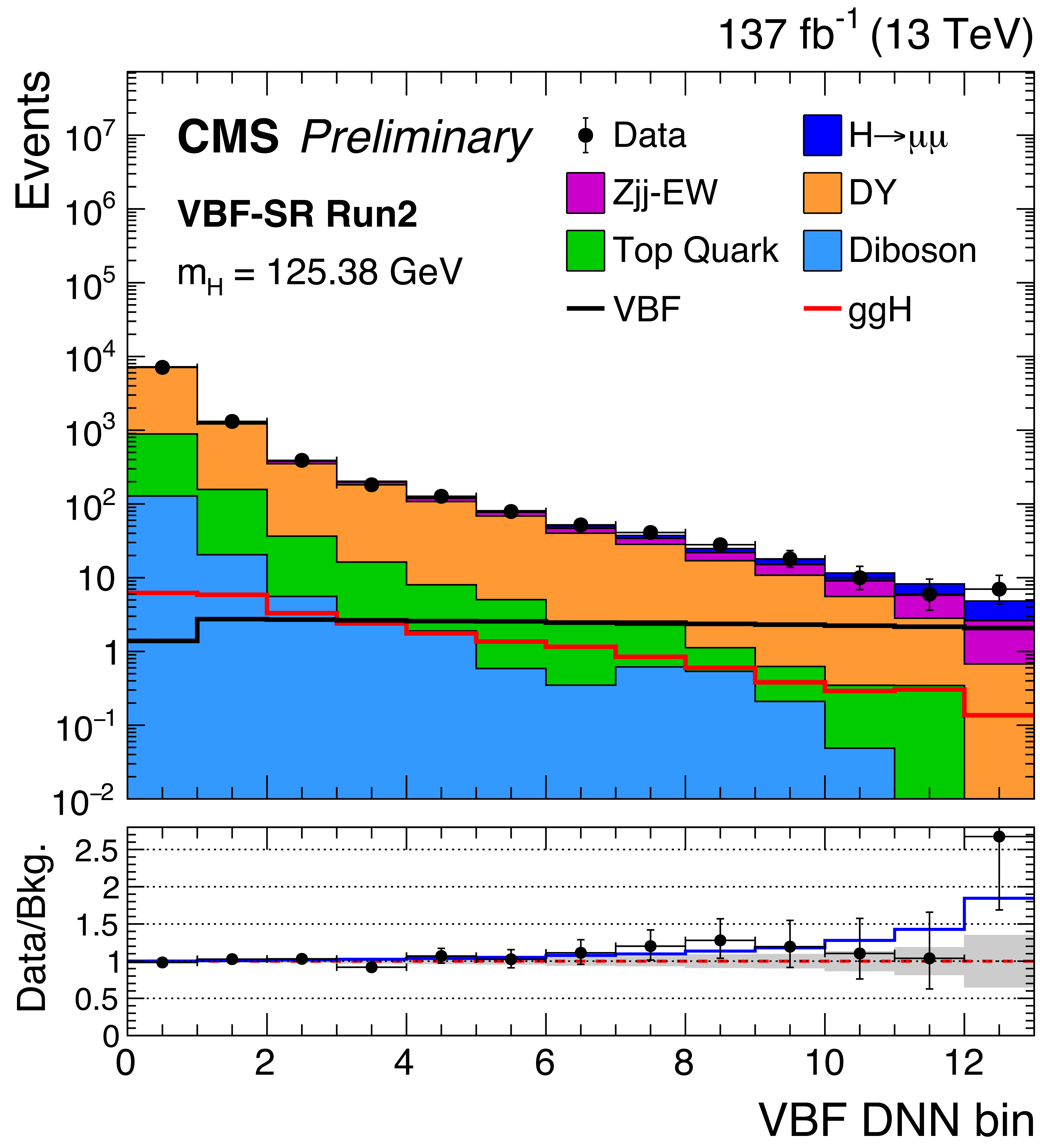


HIGGS 2ND GEN. COUPLINGS

- LHC Run 2 measured 3rd gen. Higgs couplings
  - tau lepton [PLB 779 (2018) 283]
  - top quark [PRL 120 (2018) 231801]
  - bottom quark [PRL 121 (2018) 121801]
- Next challenge: 2nd gen.
  - charm quark: μ < 70 (37 exp.) @ 95% CL [JHEP 03 (2020) 131]
  - muons (before ICHEP 2020)
    - CMS: μ < 2.9 @ 95% CL [PRL 122 (2019) 021801]
    - ATLAS: μ < 2.2 @ 95% CL [arXiv:2007.07830]

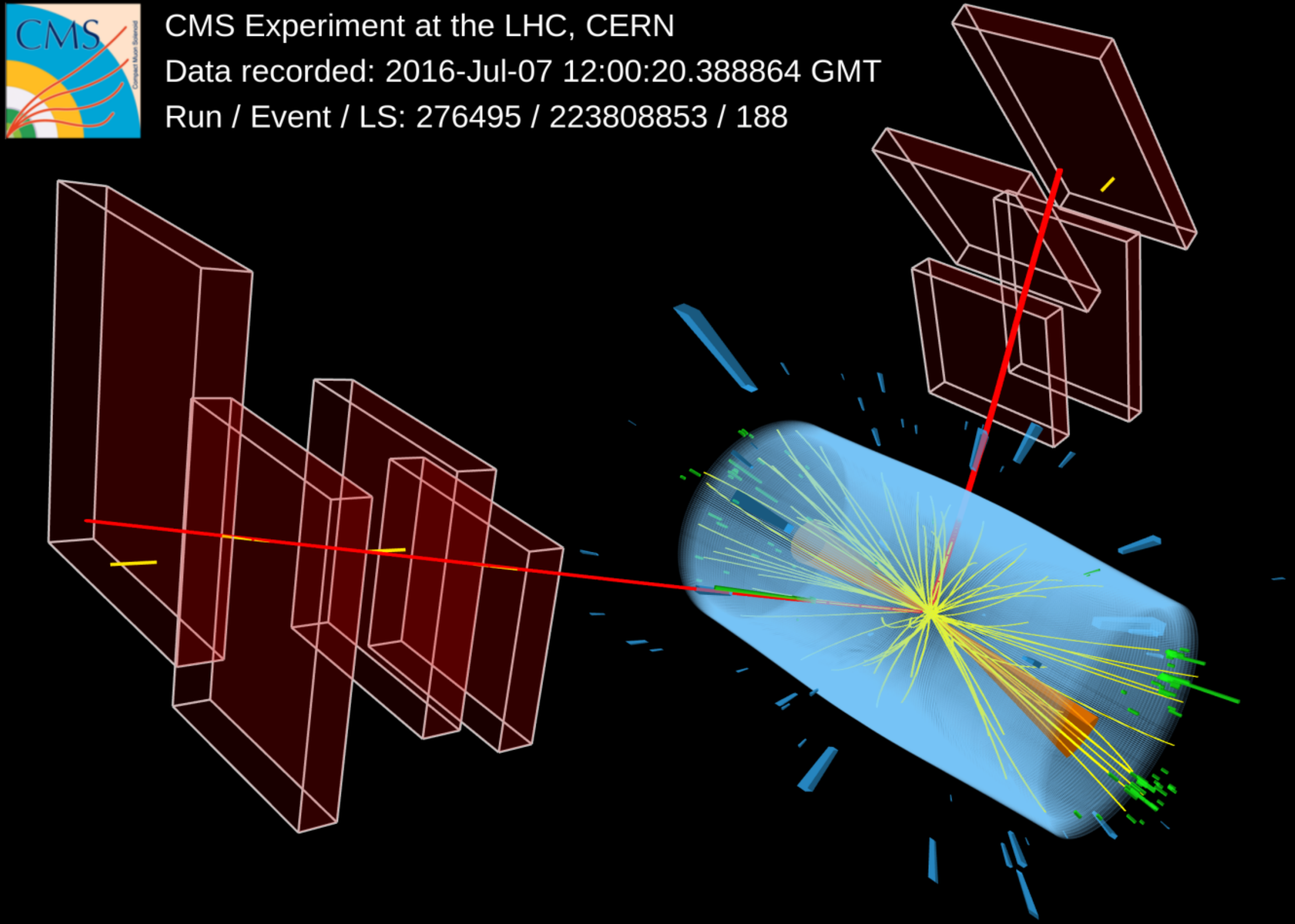


- Run 2 analysis (137 fb^{-1})
  - Targeting ggH, VBF, VH, and ttH prod.
  - VBF has best sensitivity due to background suppression from fwd. jets
- Combined with Run 1 data @ 7 and 8 TeV



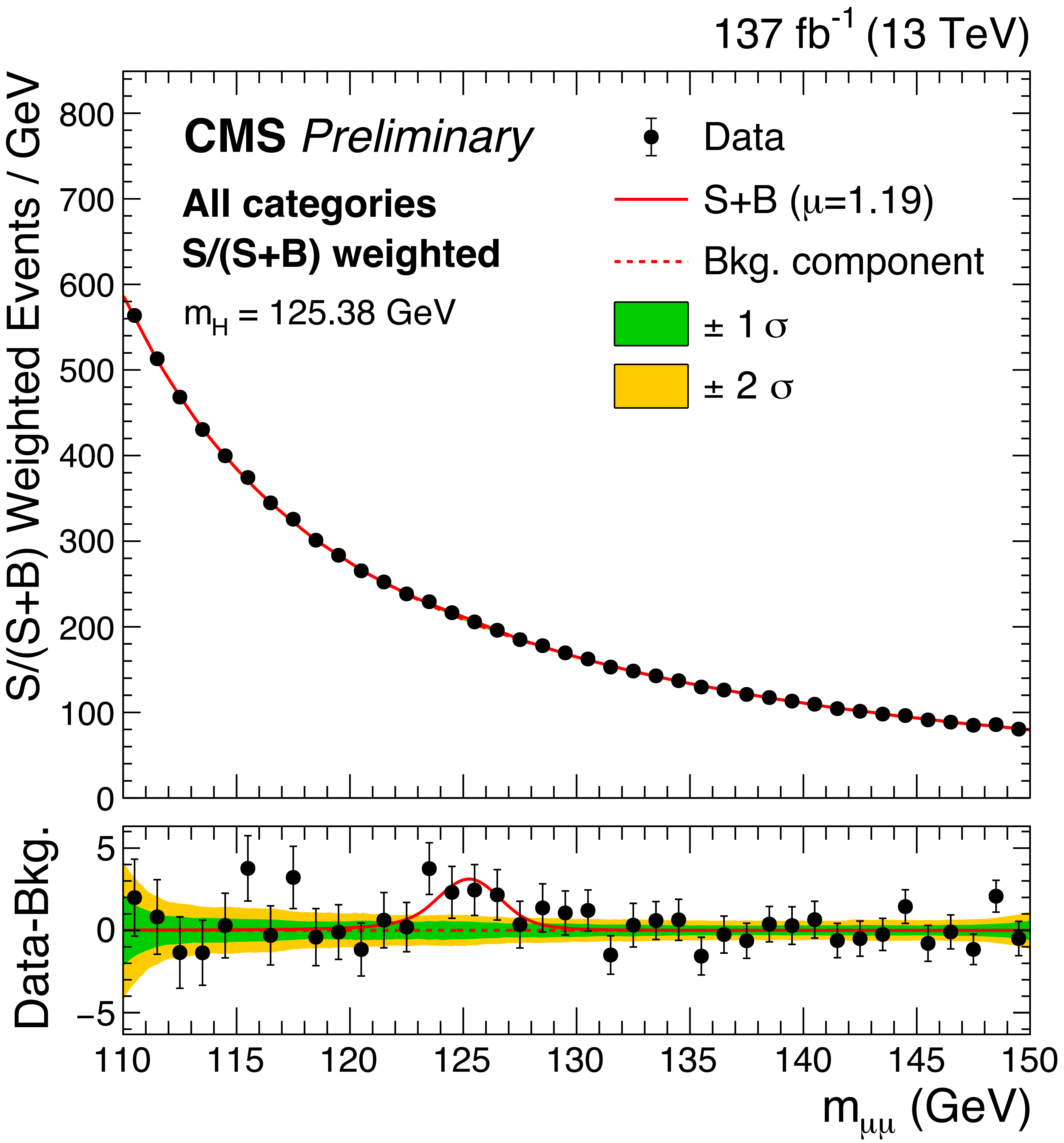
significance: 3.0σ (2.5σ exp.)

signal strength: $\mu = 1.19^{+0.41}_{-0.39}\text{(stat.)}^{+0.17}_{-0.15}\text{(syst.)}$

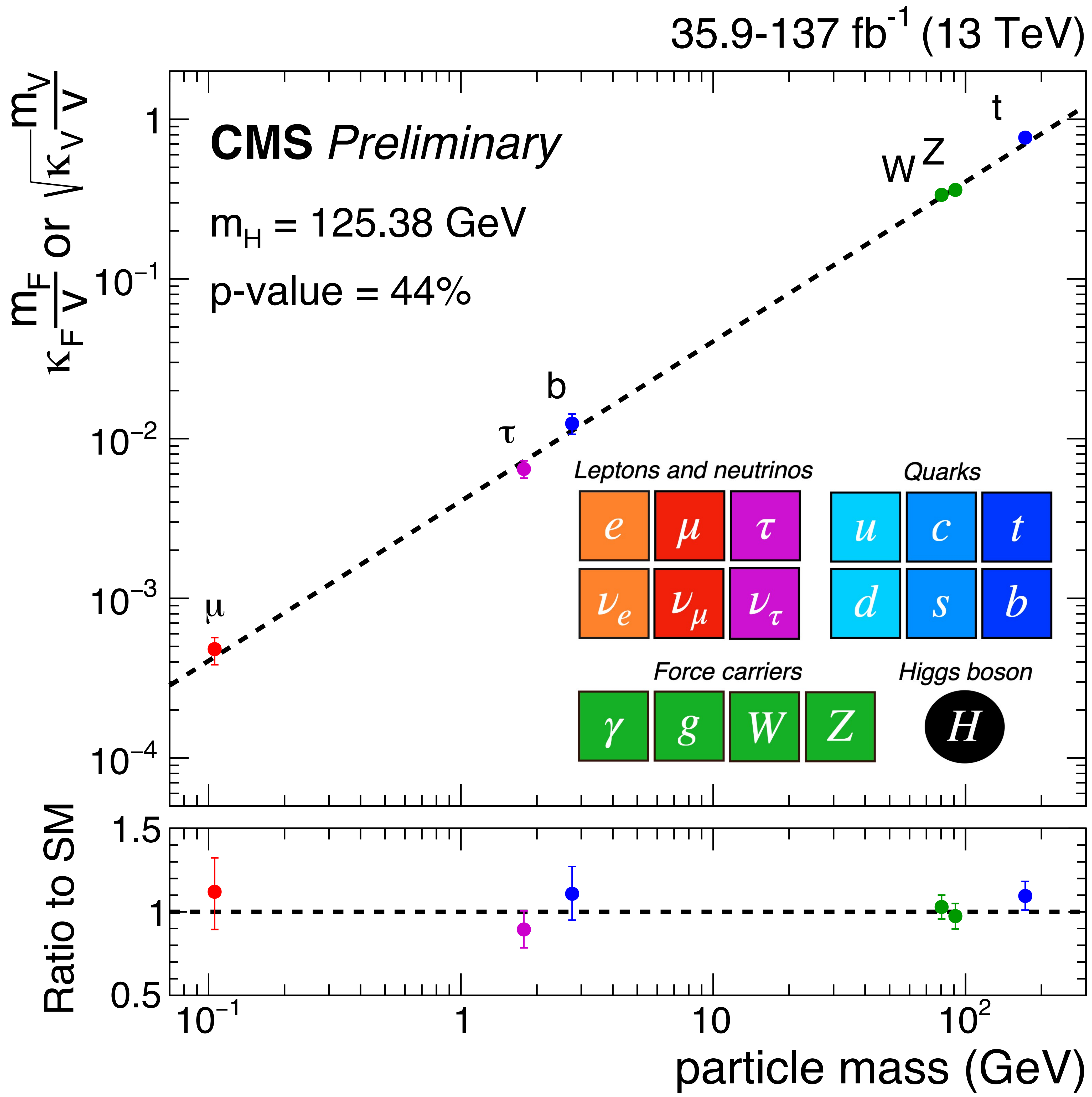

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2016-Jul-07 12:00:20.388864 GMT
Run / Event / LS: 276495 / 223808853 / 188

MEASUREMENT OF H $\rightarrow \mu\mu$

CMS-PAS-HIG-19-006



(weighted) $m_{\mu\mu}$ fit for all event categories

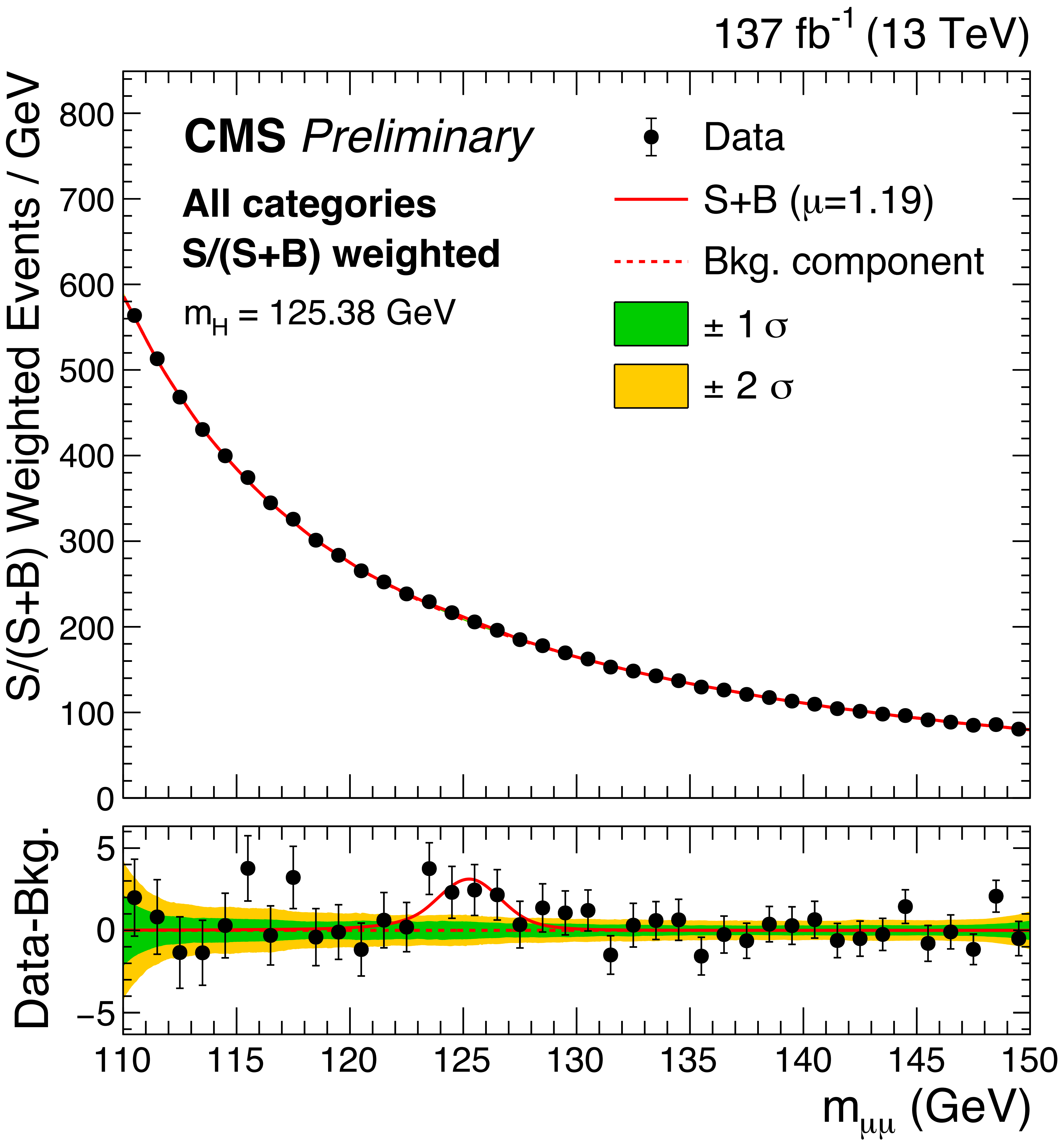


Best fit for 6 coupling strength modifiers as a function of particle mass,

$k_\mu = 1.13^{+0.21}_{-0.22}$

MEASUREMENT OF H $\rightarrow \mu\mu$

CMS-PAS-HIG-19-006



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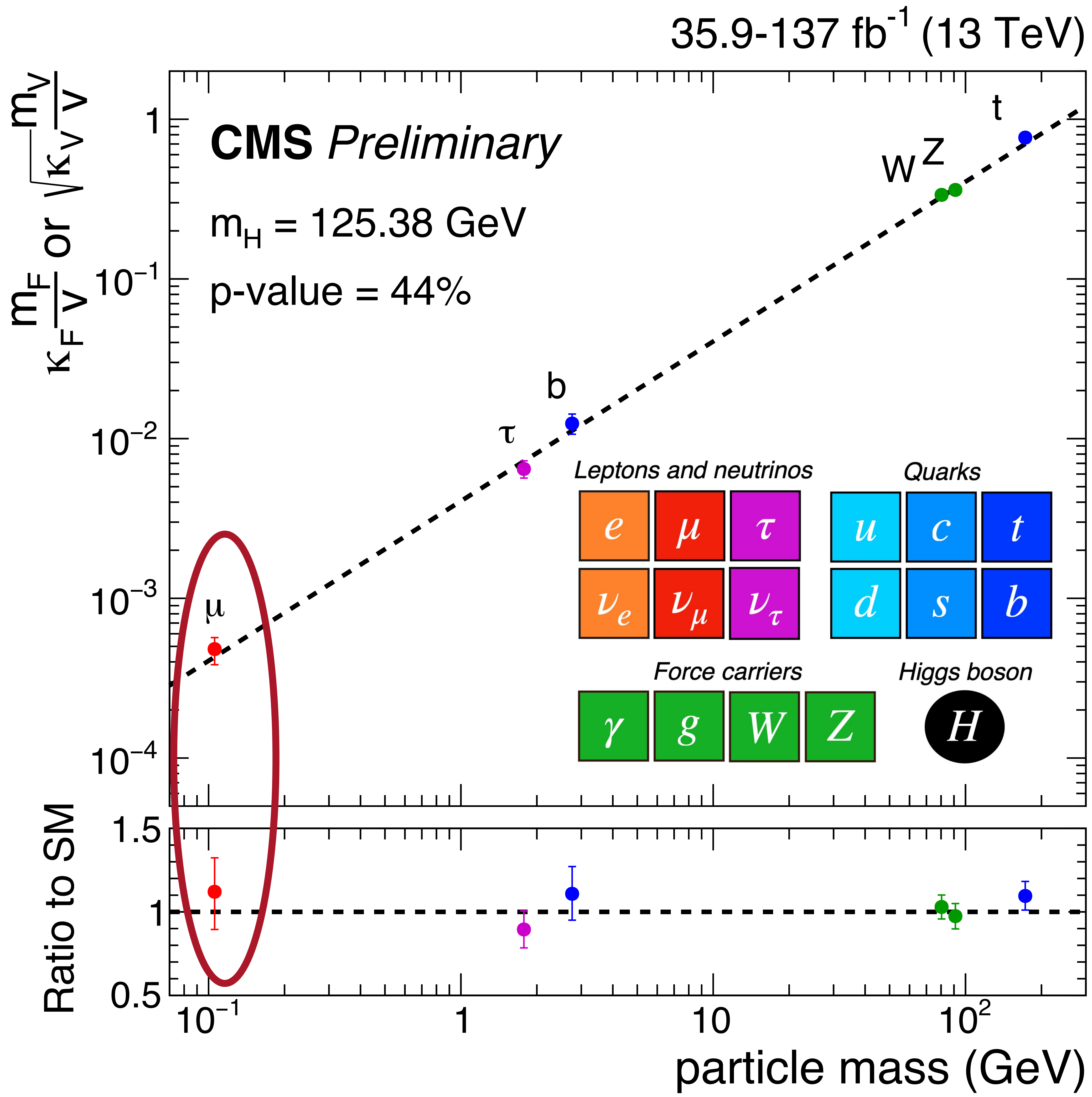


Best fit for 6 coupling strength modifiers as a function of particle mass, $k_\mu = 1.13^{+0.21}_{-0.22}$

CMS HL-LHC UPGRADE

- TDRs for the MIP timing detector and L1 trigger recently approved
- New phase of engineering, prototyping, and construction
  - COVID-19 has generated delays up to 3 months, still absorbable in the present contingencies

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

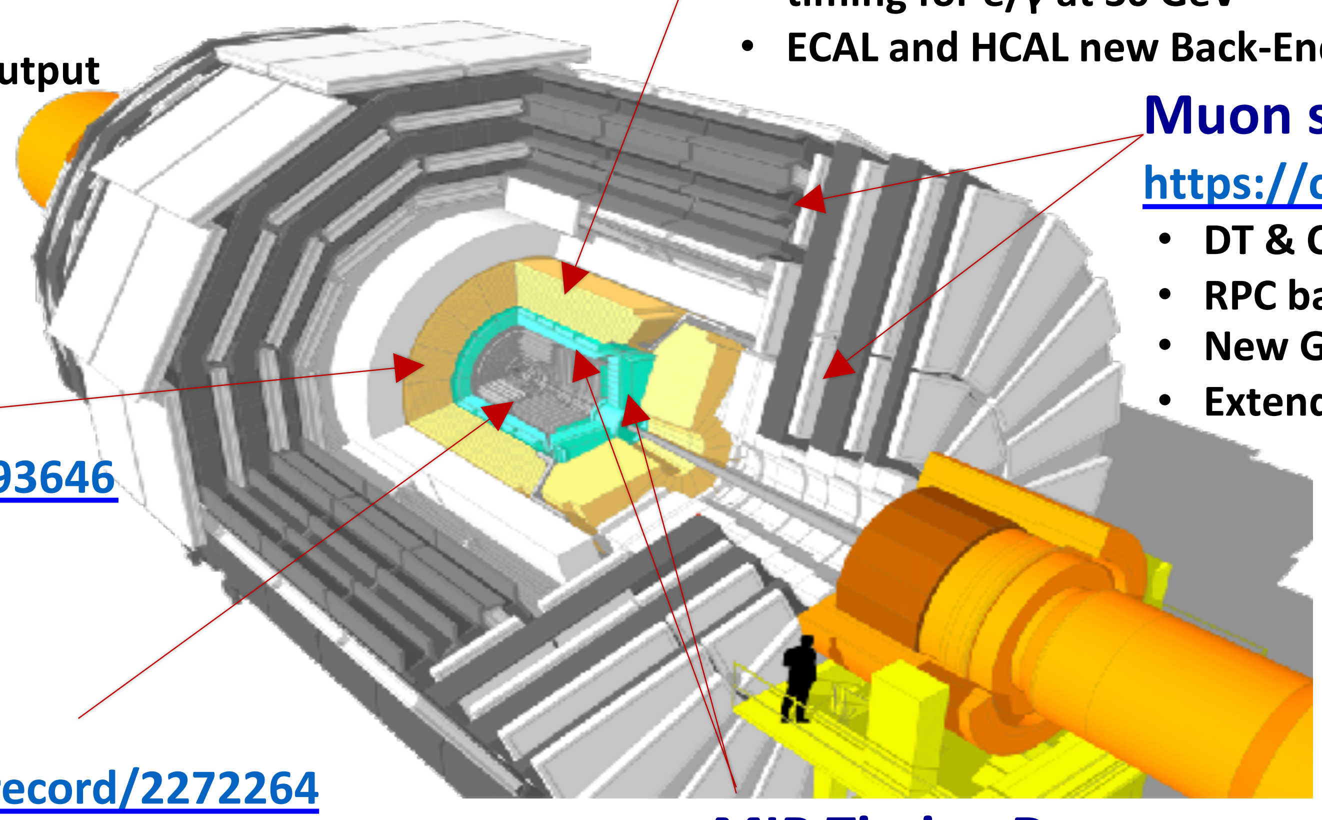
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

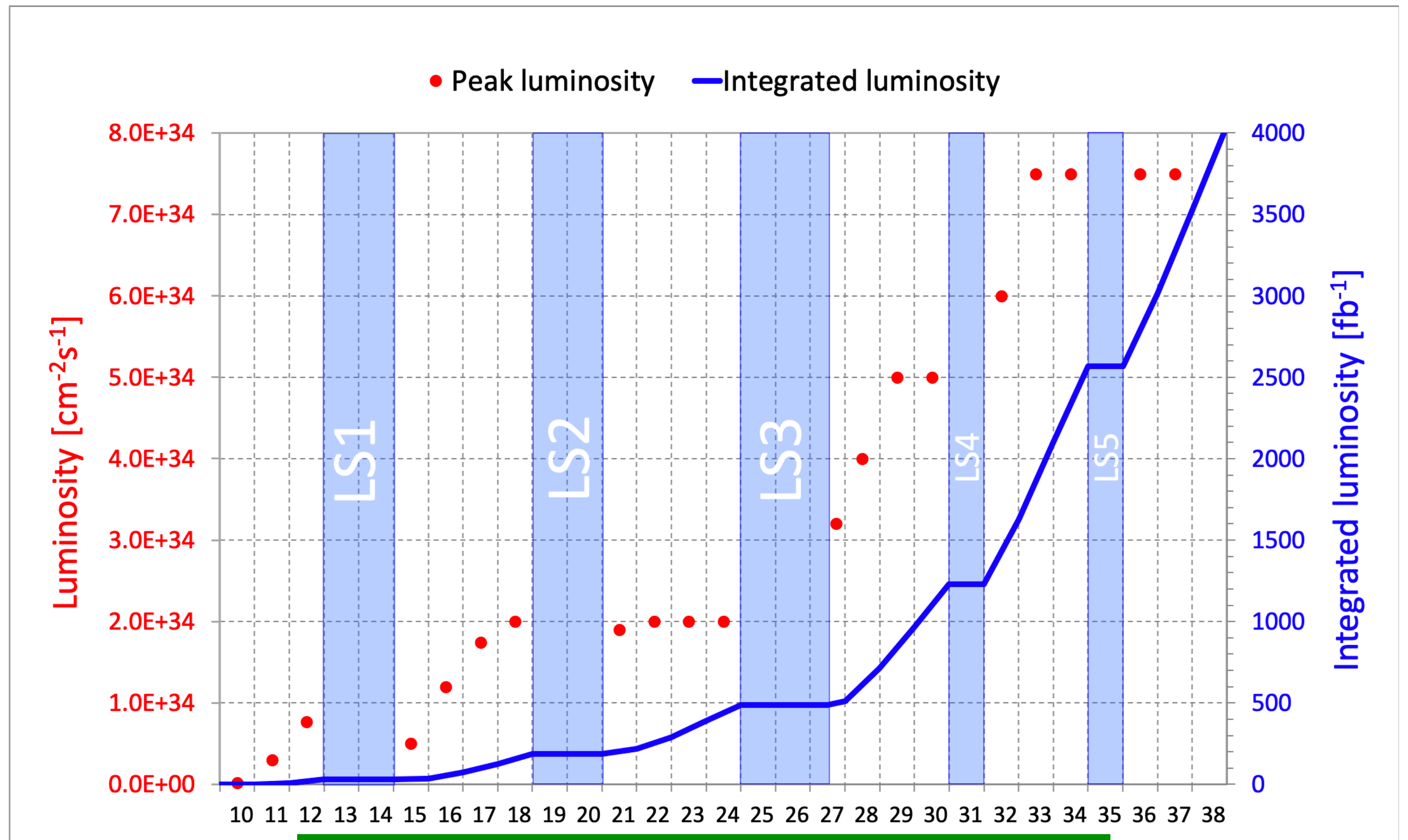
Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/002706512

Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes



a rewarding target

INNOVATIONS FROM CMS

- CMS has contributed many innovations to the field

INNOVATIONS FROM CMS

[arXiv:1804.06913](#)
[CMS-TDR-021](#)

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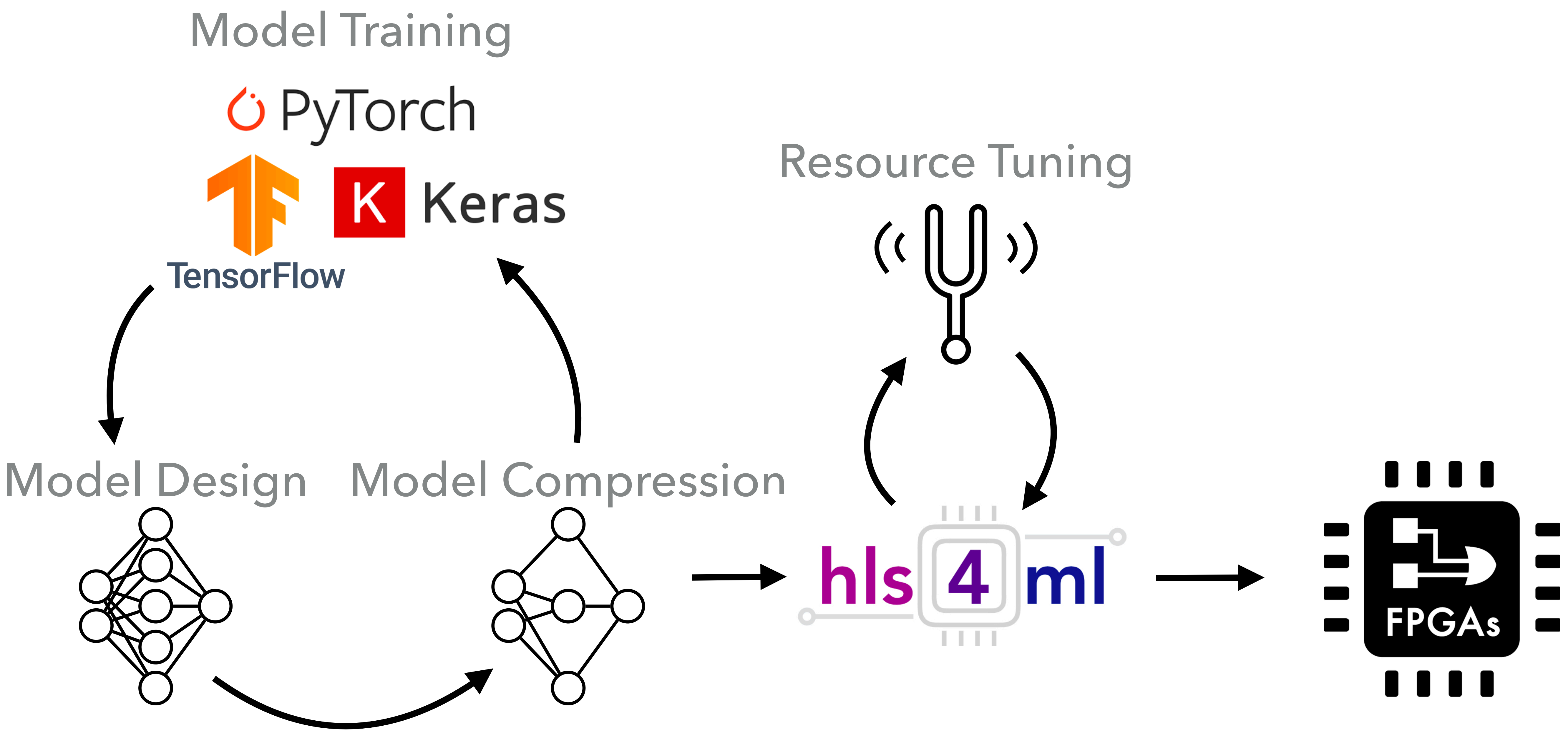
  - Fast ML project including **real-time, on-detector, and low-latency ML (hls4ml)** as well as high-throughput heterogeneous computing for big data



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arXiv:1804.06913
CMS-TDR-021

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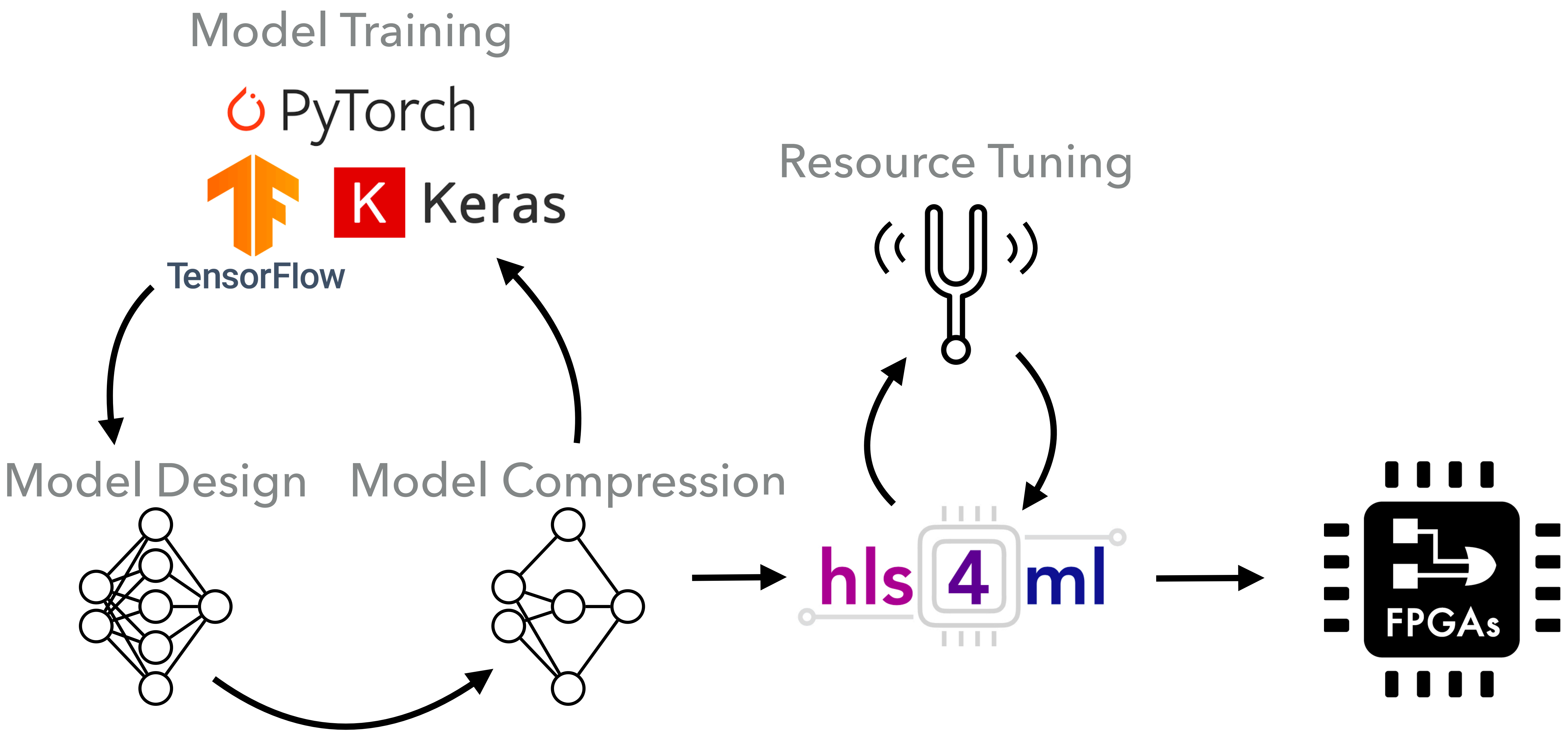
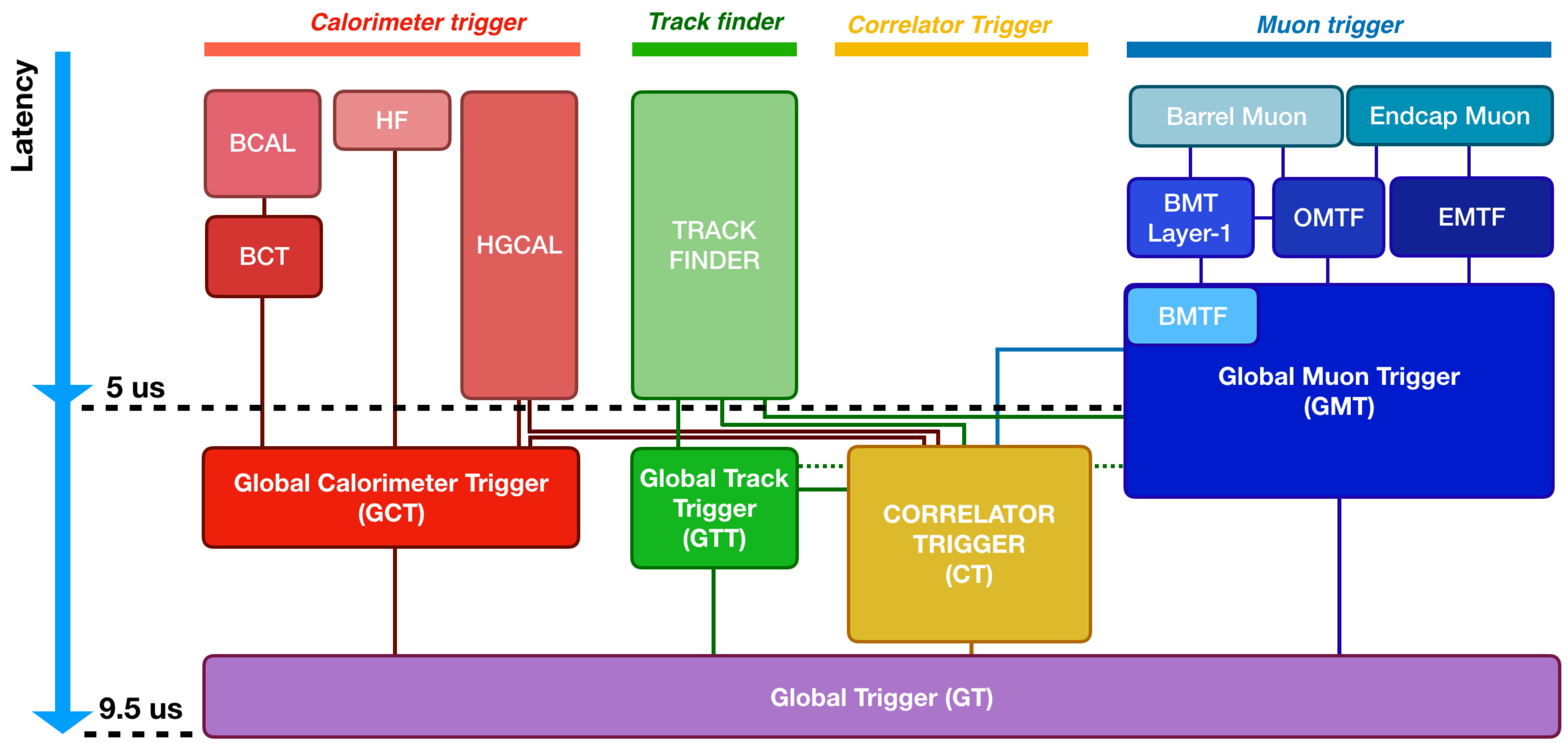
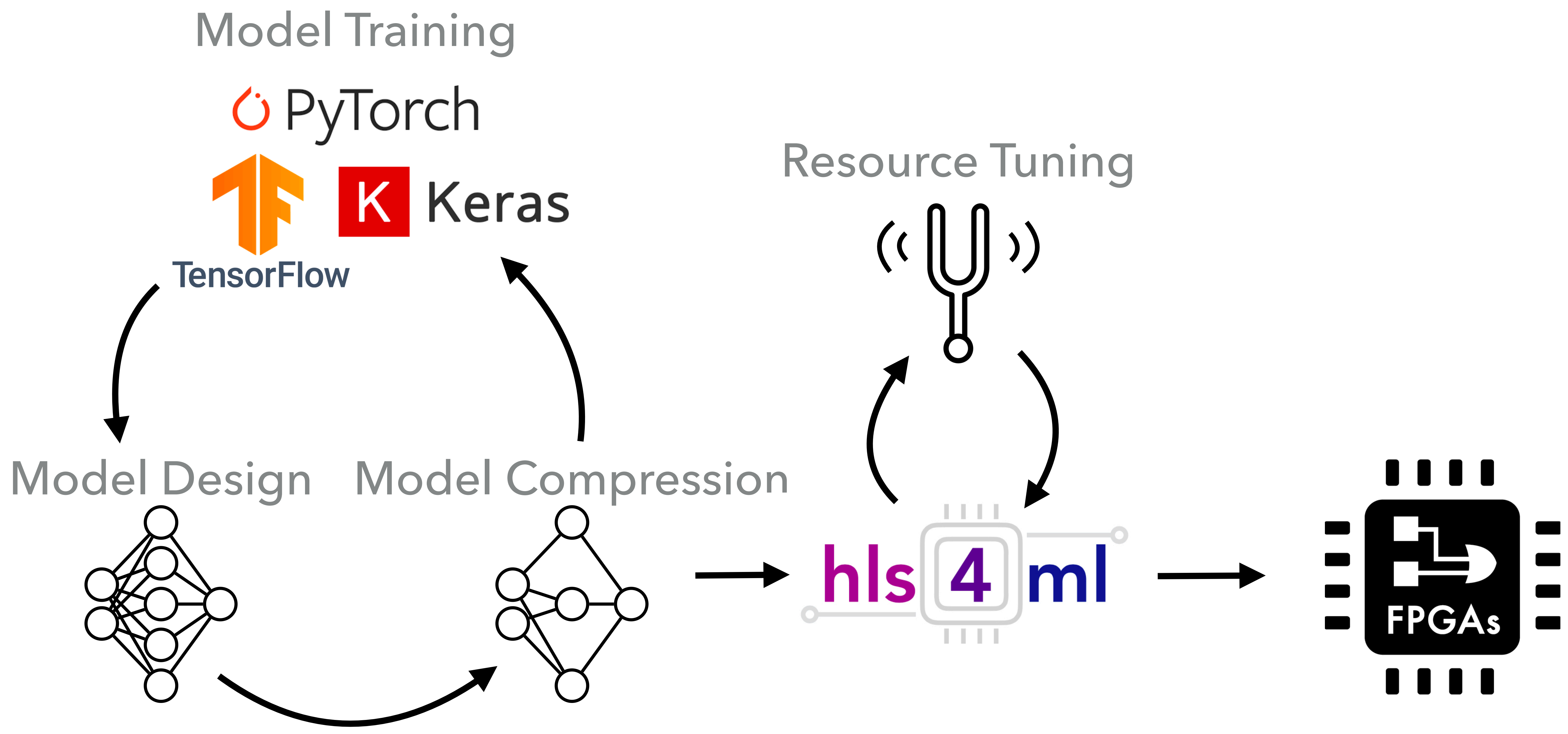
  - **Tracking and particle-flow reco. @ L1 Trigger**

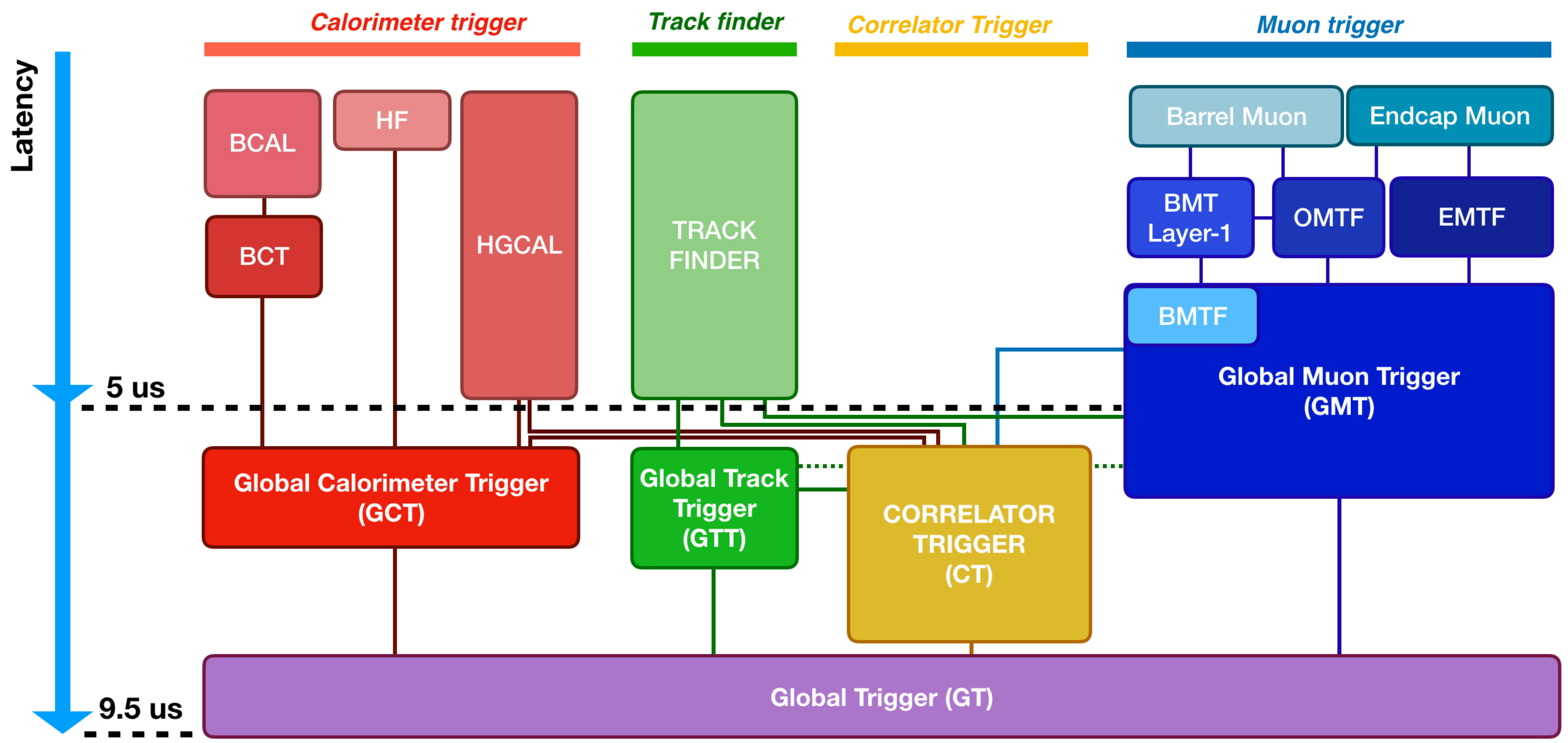




INNOVATIONS FROM CMS

- CMS has contributed many innovations to the field
  - Fast ML project including **real-time, on-detector, and low-latency ML (hls4ml)** as well as high-throughput heterogeneous computing for big data
  - **Tracking and particle-flow reco. @ L1 Trigger**
  - Precision timing detectors
  - Data scouting or "trigger-level analysis"





SUMMARY AND OUTLOOK

For more: http://cms-results.web.cern.ch/cms-results/public-results/publications/

- Excellent recent results with a very large scope
- Many years and luminosity in front of us (5% of the total delivered so far)
- Active in several different areas
  - Analysis, development of new reconstruction/computing/ML techniques, preparation for the upcoming Run 3, HL-LHC upgrade
- Great time to be part of an LHC collaboration, exposed to all of the different activities of an experimental physicist

JAVIER DUARTE

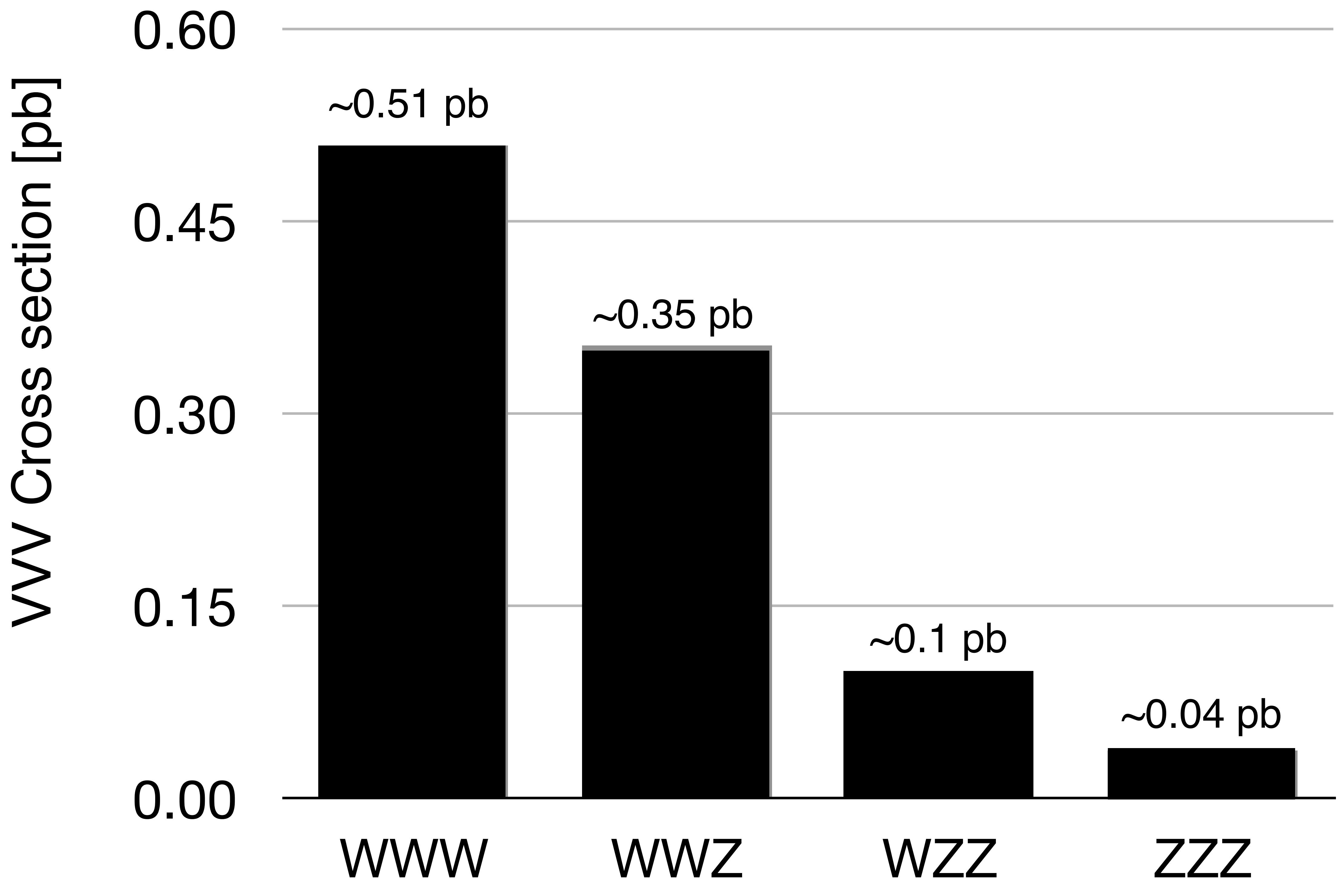
53RD ANNUAL FERMILAB USERS MEETING

AUGUST 12, 2020

BACKUP

VVV PRODUCTION AND DECAY

- Focus on cleanest channels: fully leptonic (or same-sign) final states
- Combination of 2–6 lepton channels
  - 4 lepton channel has best sensitivity
- Optimize BDTs for event selection
- Data-driven background estimates from carefully chosen control regions



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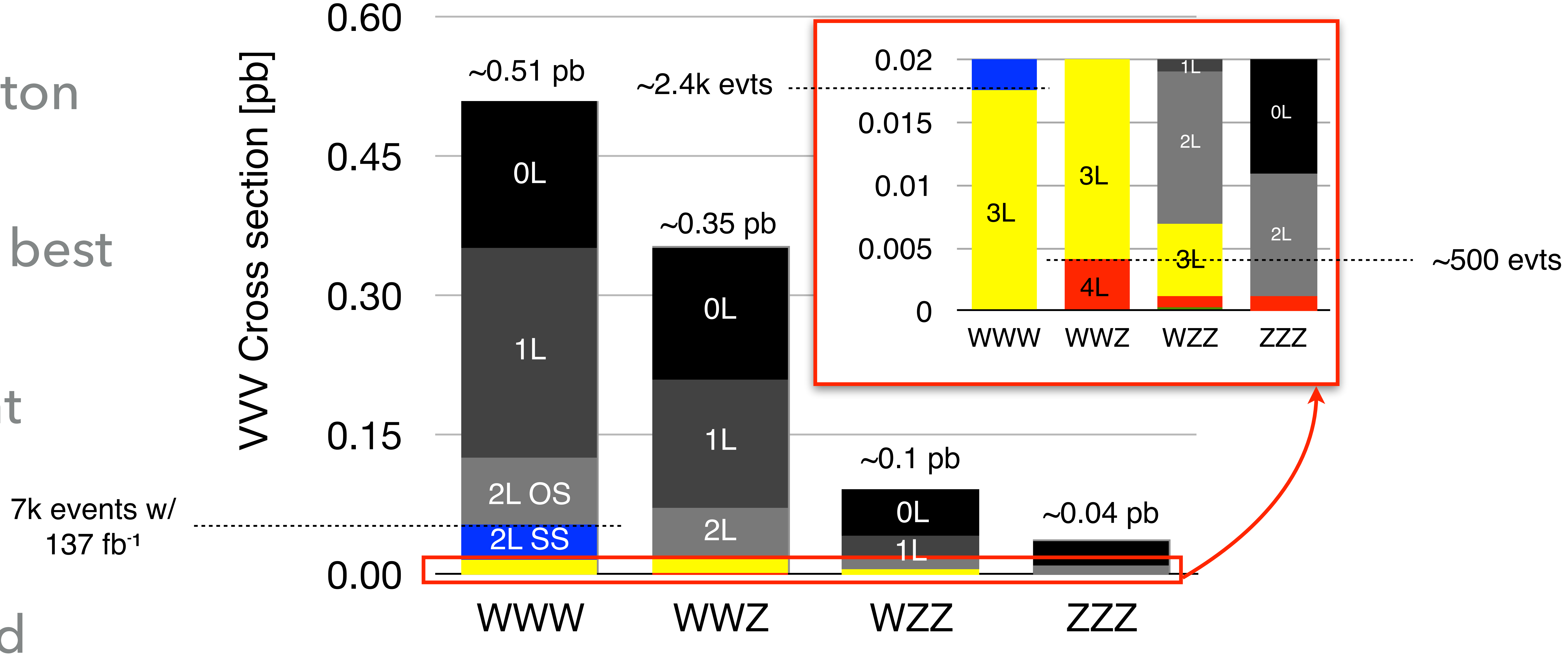
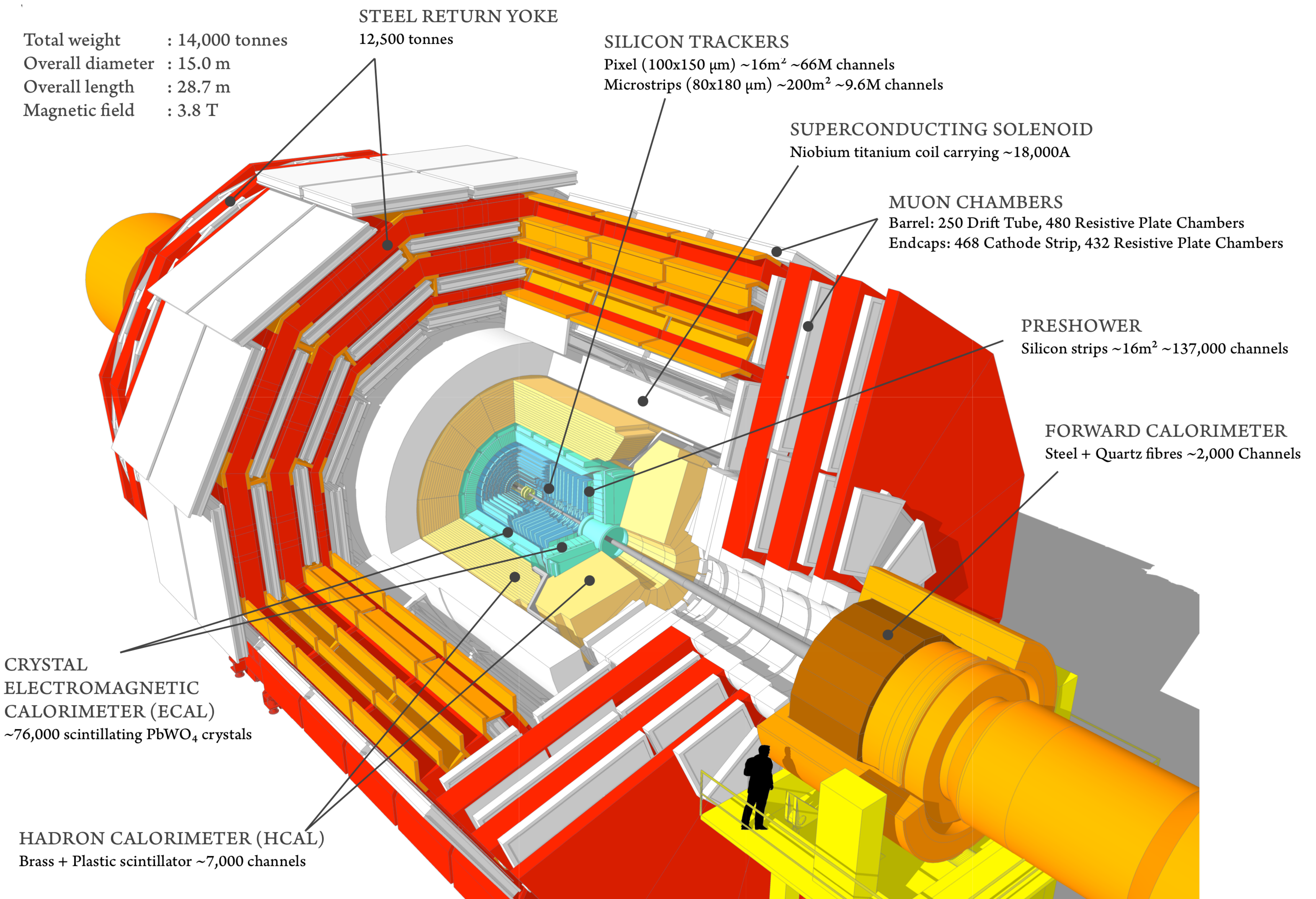
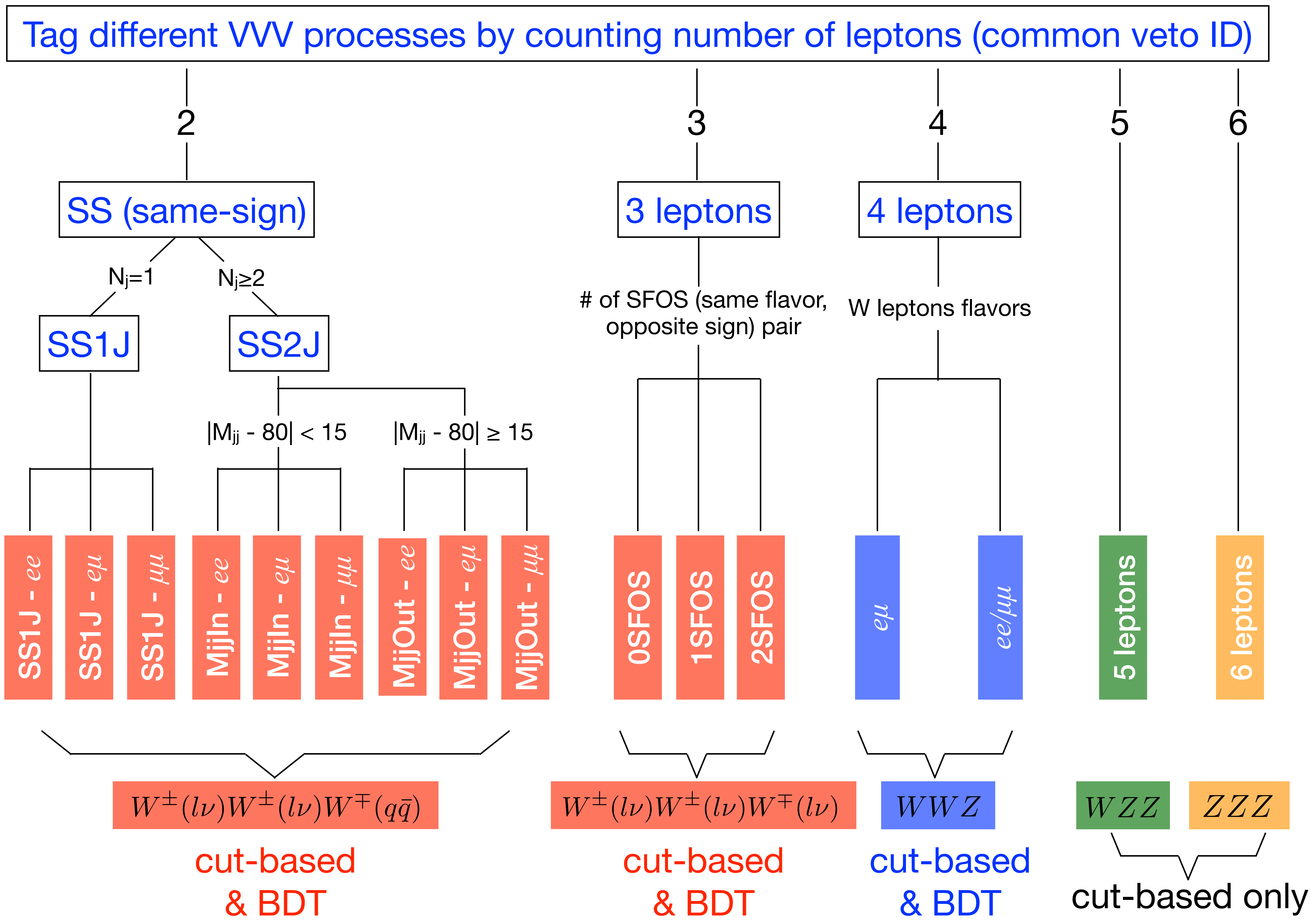


COMPACT MUON SOLENOID

- Specialized components to measure different particles
- 100 million channels



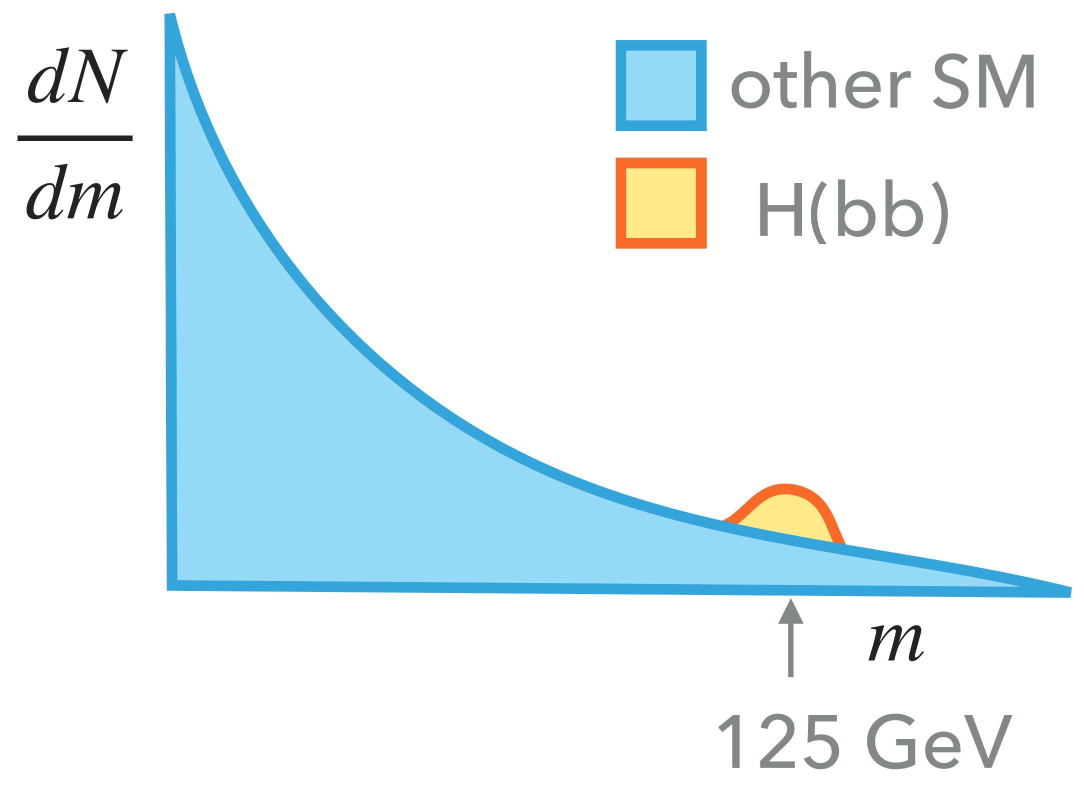
VVV: ANALYSIS STRATEGY



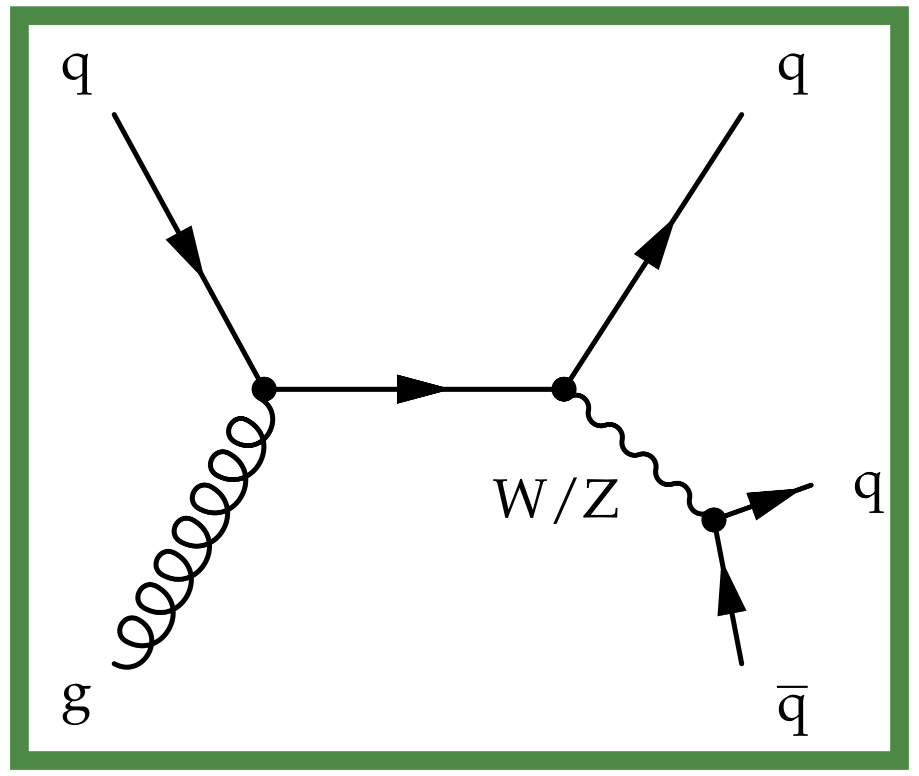
- Use BDTs for optimal sensitivity in event selection

EXECUTIVE SUMMARY

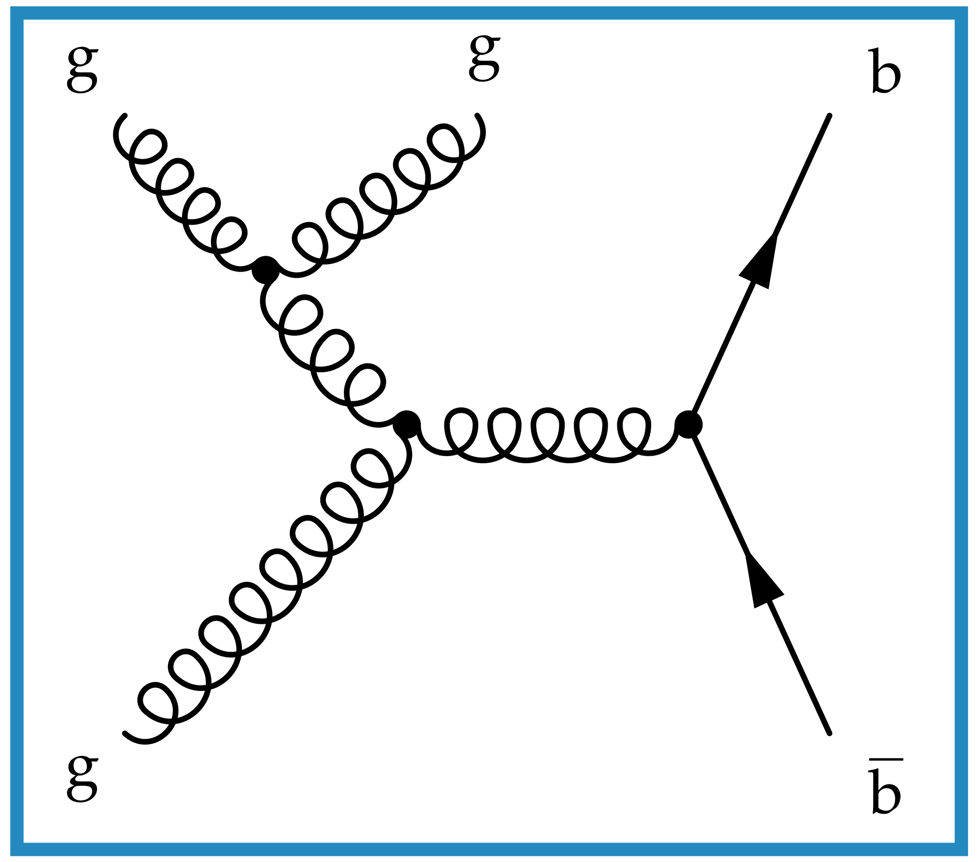
- High-p_T Higgs candidate jet identified with
  - jet substructure
  - **double-b tagging**
  - **jet mass**
- Backgrounds:



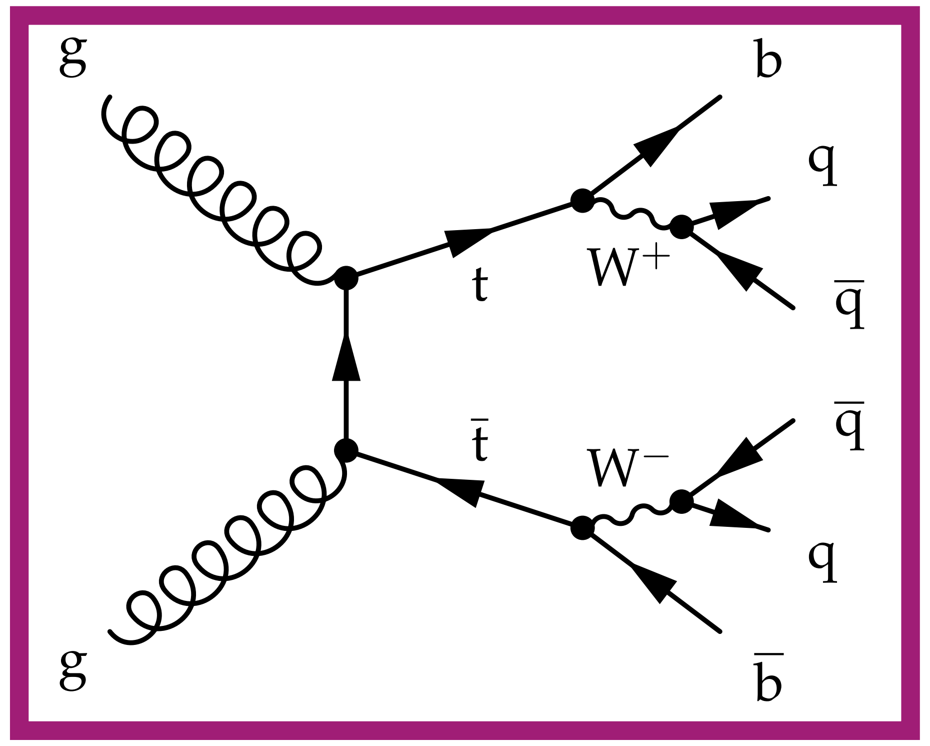
W/Z+jets (5%)



QCD (90%)

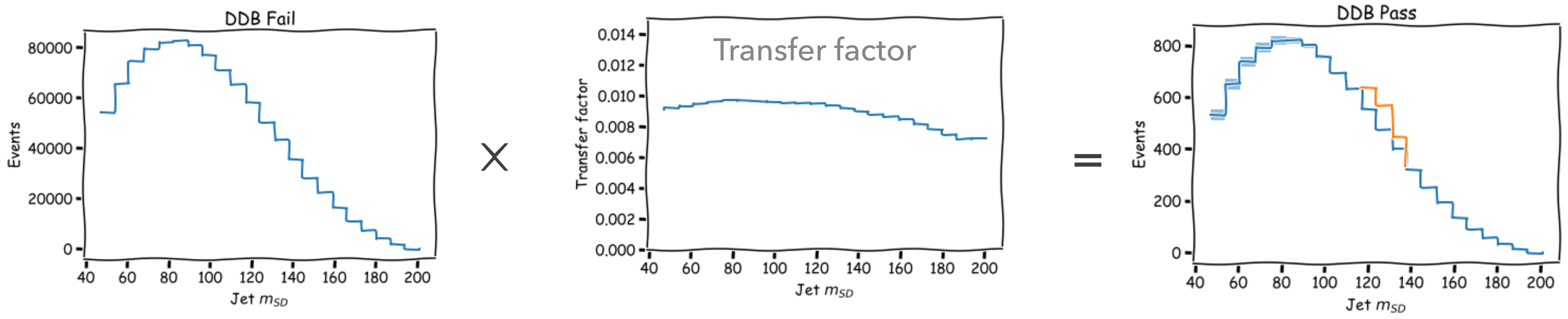


tt+jets (2%)



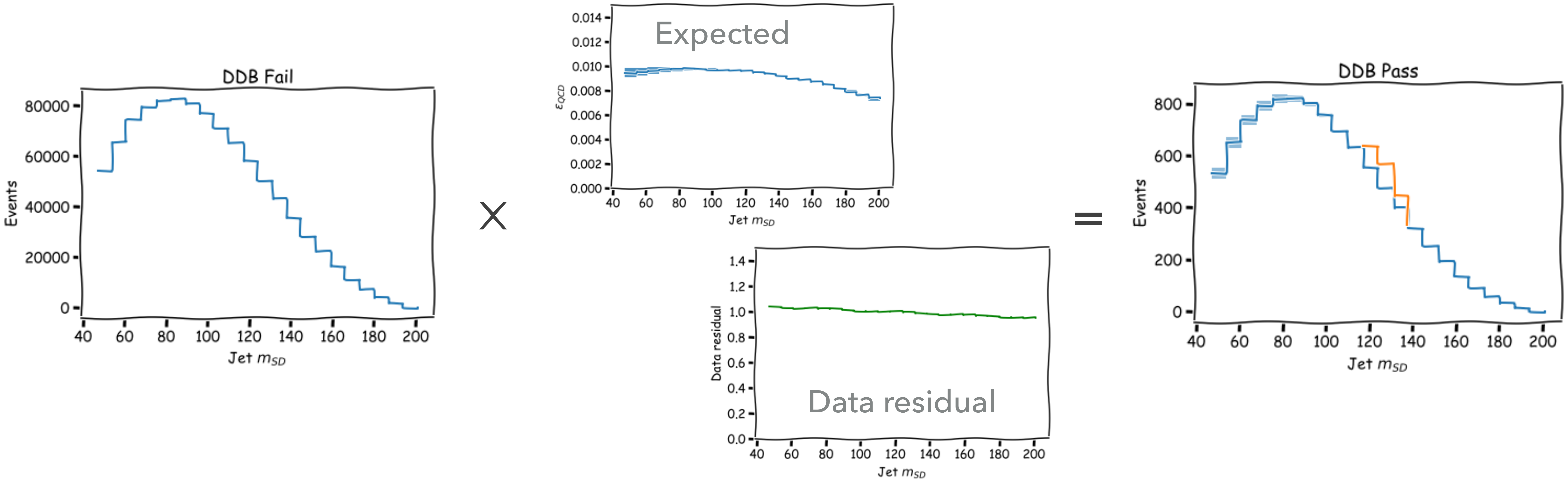
MAJOR IMPROVEMENTS IN FULL RUN 2 ANALYSIS

- Improved deep double-b tagger



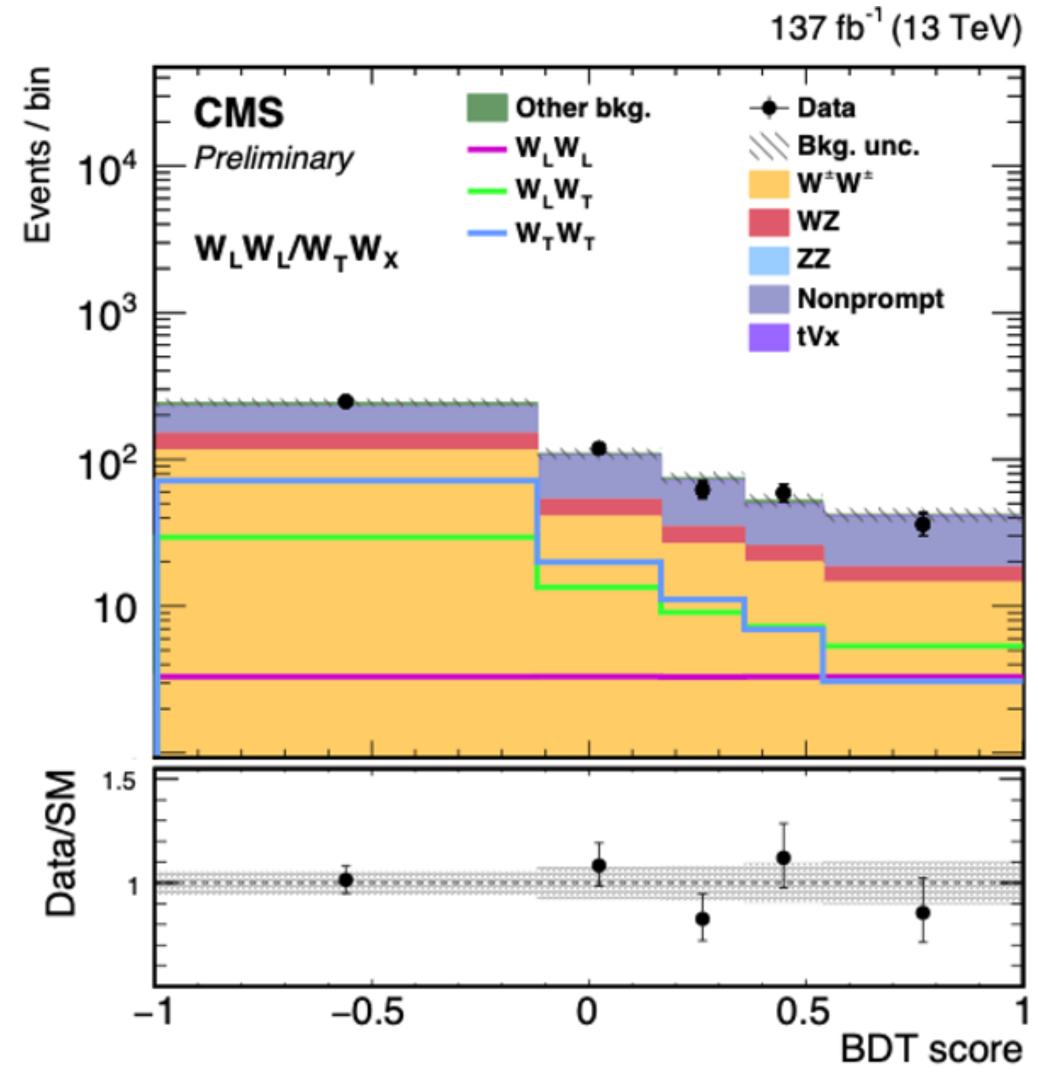
MAJOR IMPROVEMENTS IN FULL RUN 2 ANALYSIS

- Improved deep double-b tagger
- **Factorized background prediction**
- Updated Higgs p_T prediction
- Unfolded differential Higgs p_T measurement



Motivation

- production of longitudinally polarized gauge bosons via vector boson scattering is tightly linked to the mechanism of EW symmetry breaking
- modifications of the production cross sections are expected in BSM models, e.g., in scenarios involving additional Higgs bosons
- the precise measurement of the cross section is a long-term goal of the LHC program



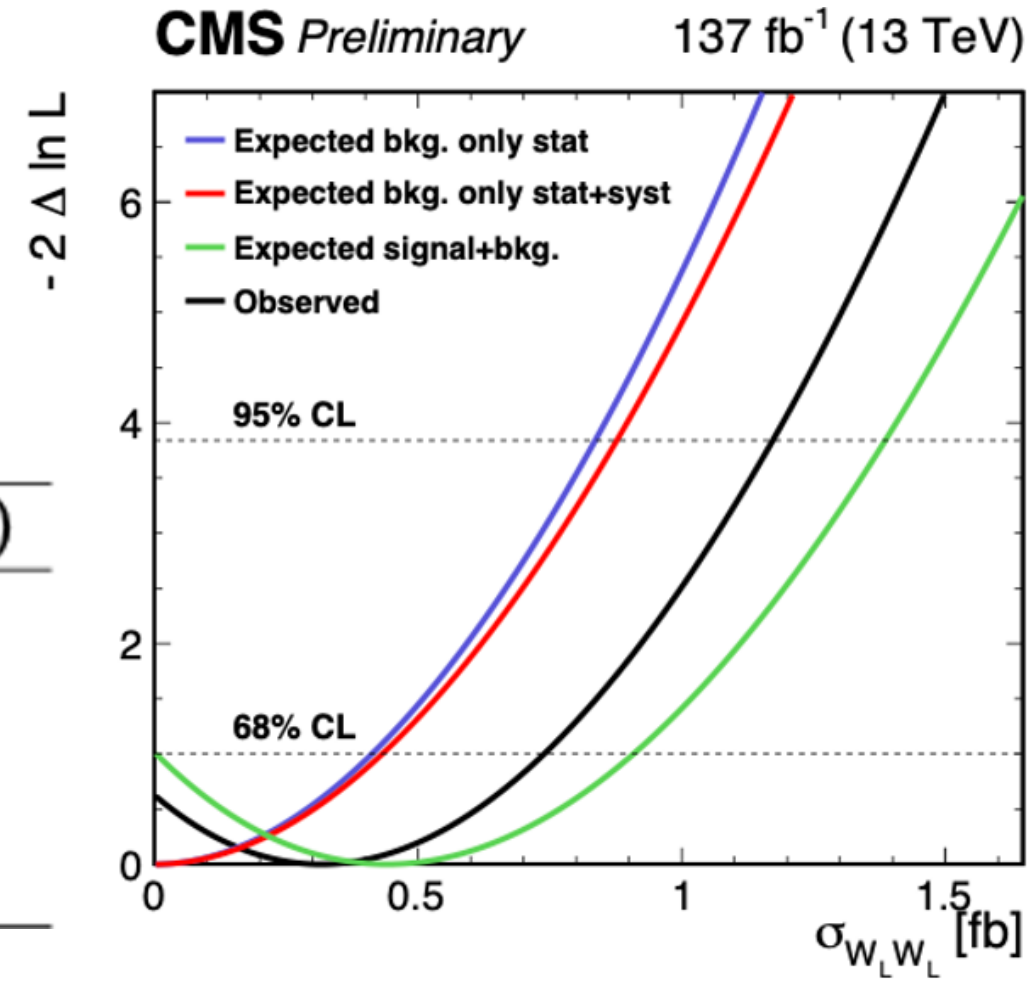
First measurement of production cross section of polarised $W^{\pm}W^{\pm}$ pairs in pp collisions

simultaneous measurement of W_LW_L&W_TW_X, or W_LW_X&W_TW_T production

- EW production with at least one W_L measured with 2.3σ (3.1σ) obs (exp)
- Upper limits (95% CL) for W_LW_L production at 1.17fb (0.88fb) obs (exp)

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

fiducial cross sections in the WW frame



LH scan of the W_LW_L cross section