

# Tourniquet LLR 2024 - CMS physique pp

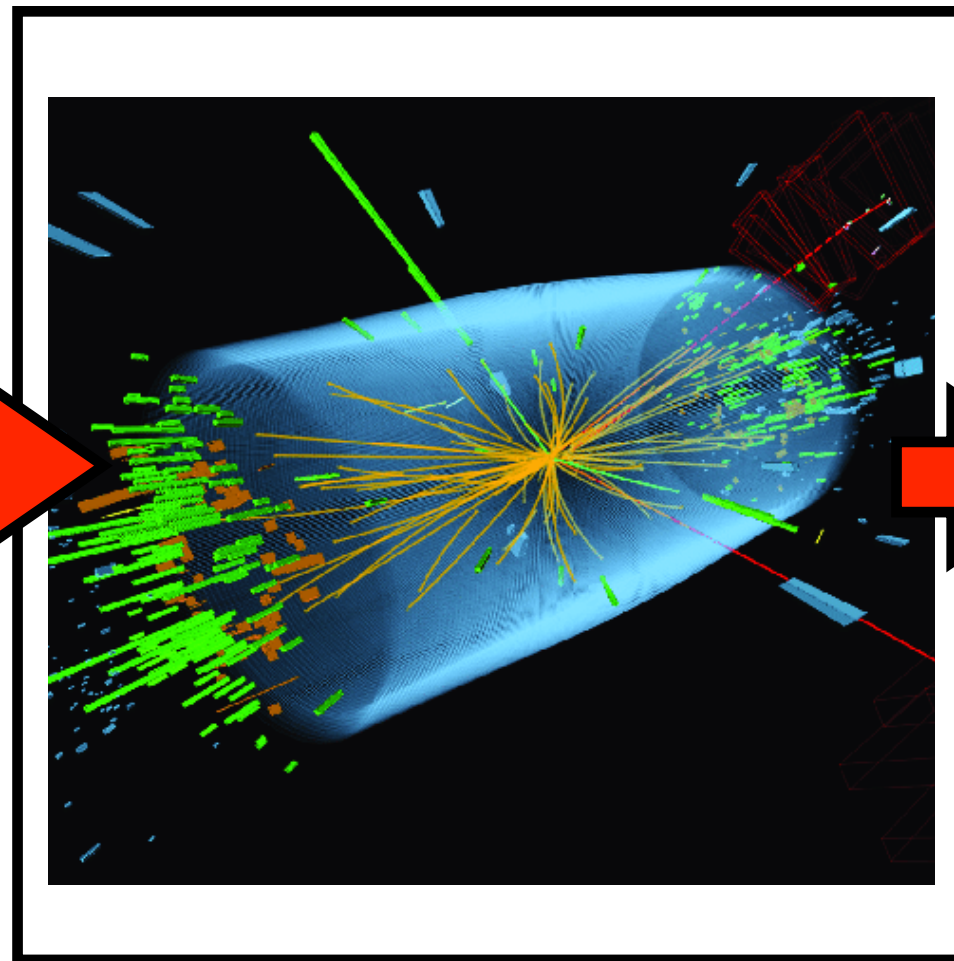
A. Gilbert | 18 Nov 2024

# Introduction

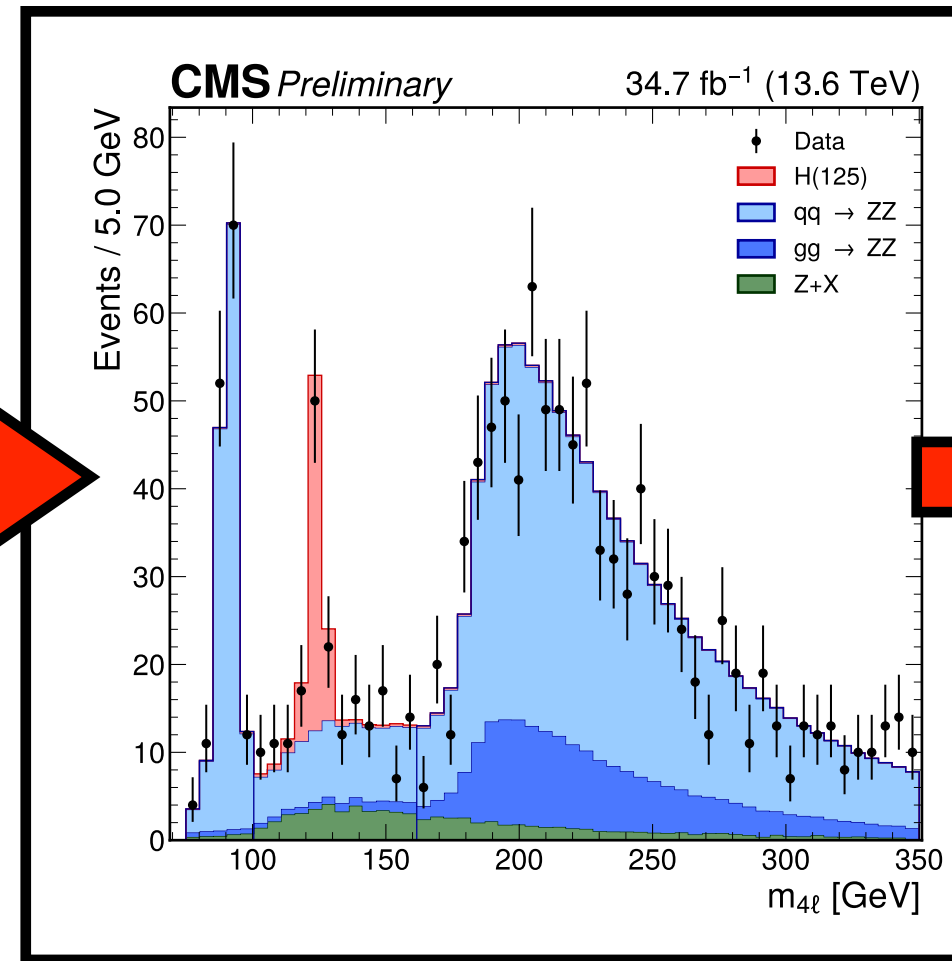
- **This talk:** activities related to LHC **proton-proton** data
  - **HL-LHC** upgrade in the next talk from Jean-Baptiste
  - **Heavy ion** physics in the next session from Matt
- Overview - strong group commitment through complete chain:



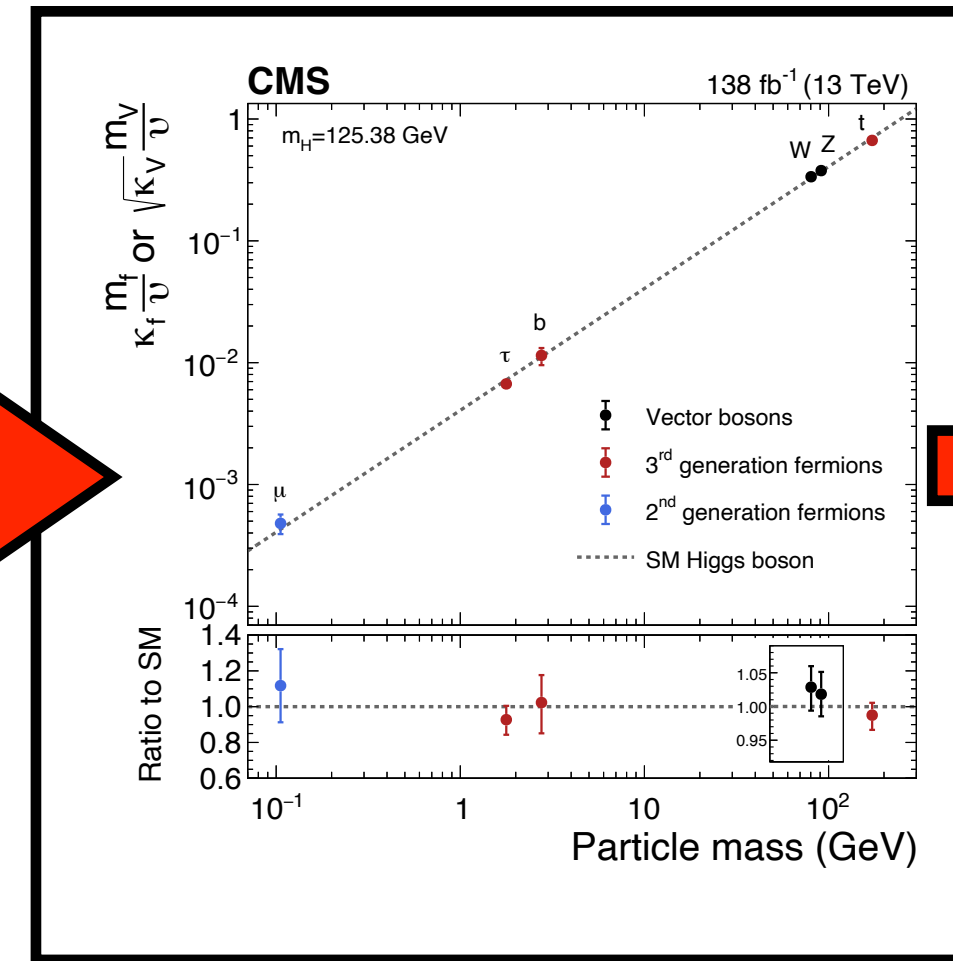
**Data-taking & operations**



**Reconstruction**  
and object performance



**Physics analysis:**  
Higgs & EW focus



**Interpretation:**  
Higgs properties  
Effective field theory



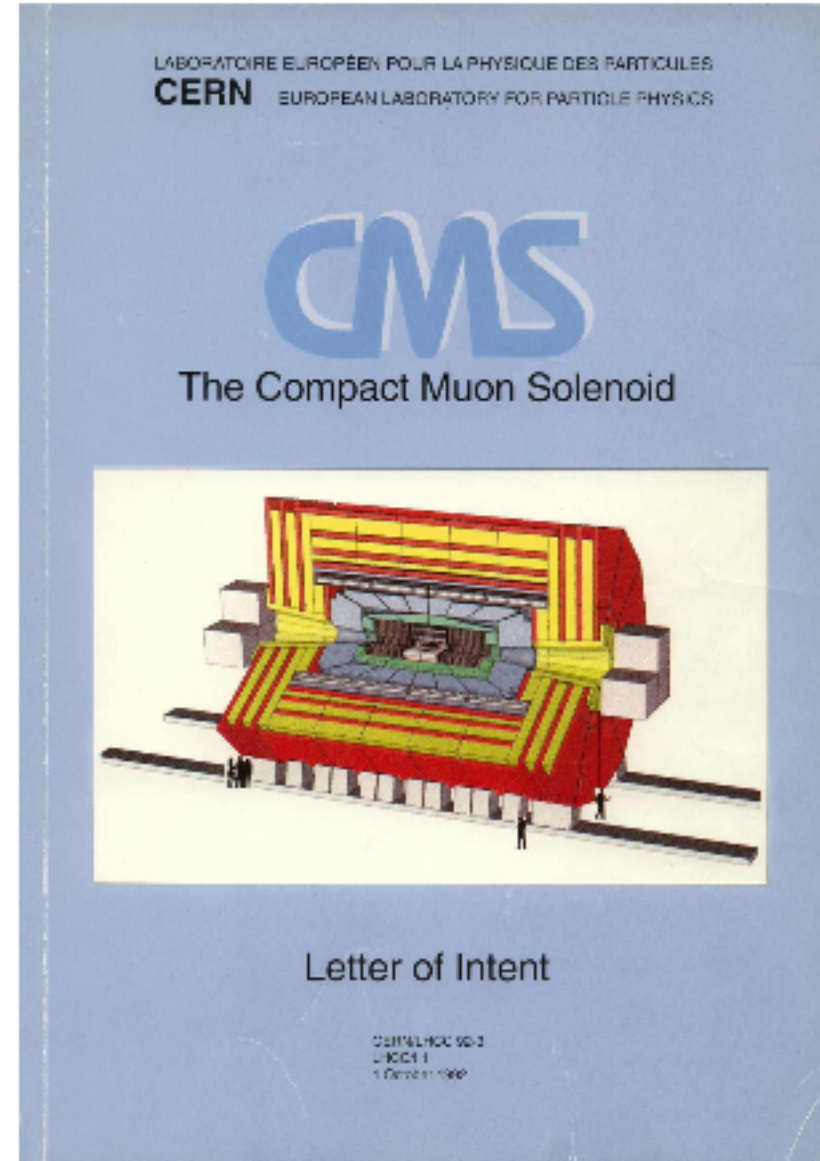
**Dissemination:**  
Conferences / outreach



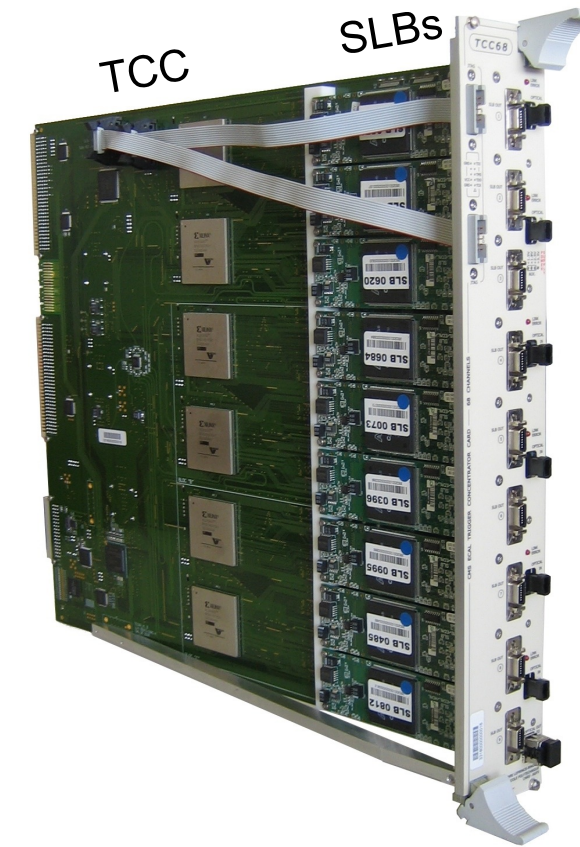
# Background

- Founding members of CMS

- LOI 1992
- Major contributions to CMS ECAL and e/γ projects
  - ▶ ECAL mechanics, tests of front-end cards, team beam campaigns, e/γ reconstruction & ID
  - ▶ ECAL trigger conception & construction
- Computing projects:
  - ▶ CMS software framework (CMSSW) & reconstruction
  - ▶ Development of major "GRID" facilities - LLR-GRIF

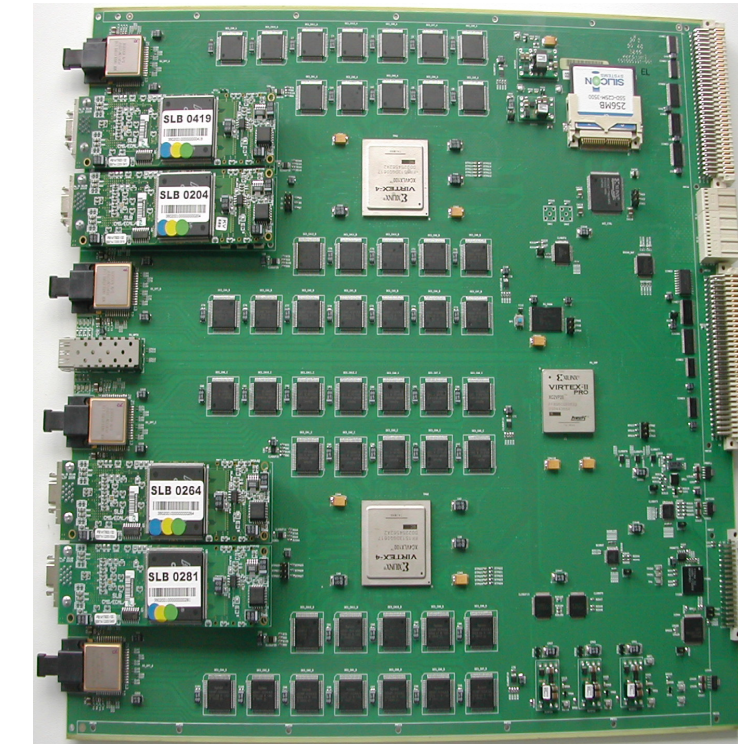


TCC-EB (« TCC68 »)  
36 boards, 68 trigger towers



Engineers: M. Bercher, D. Lecouturier,  
**Y. Geerebaert**  
Physicists: Ph. Busson, P. Paganini

EE Trigger Concentrator Card:  
72 boards, 48 « pseudo-strips »

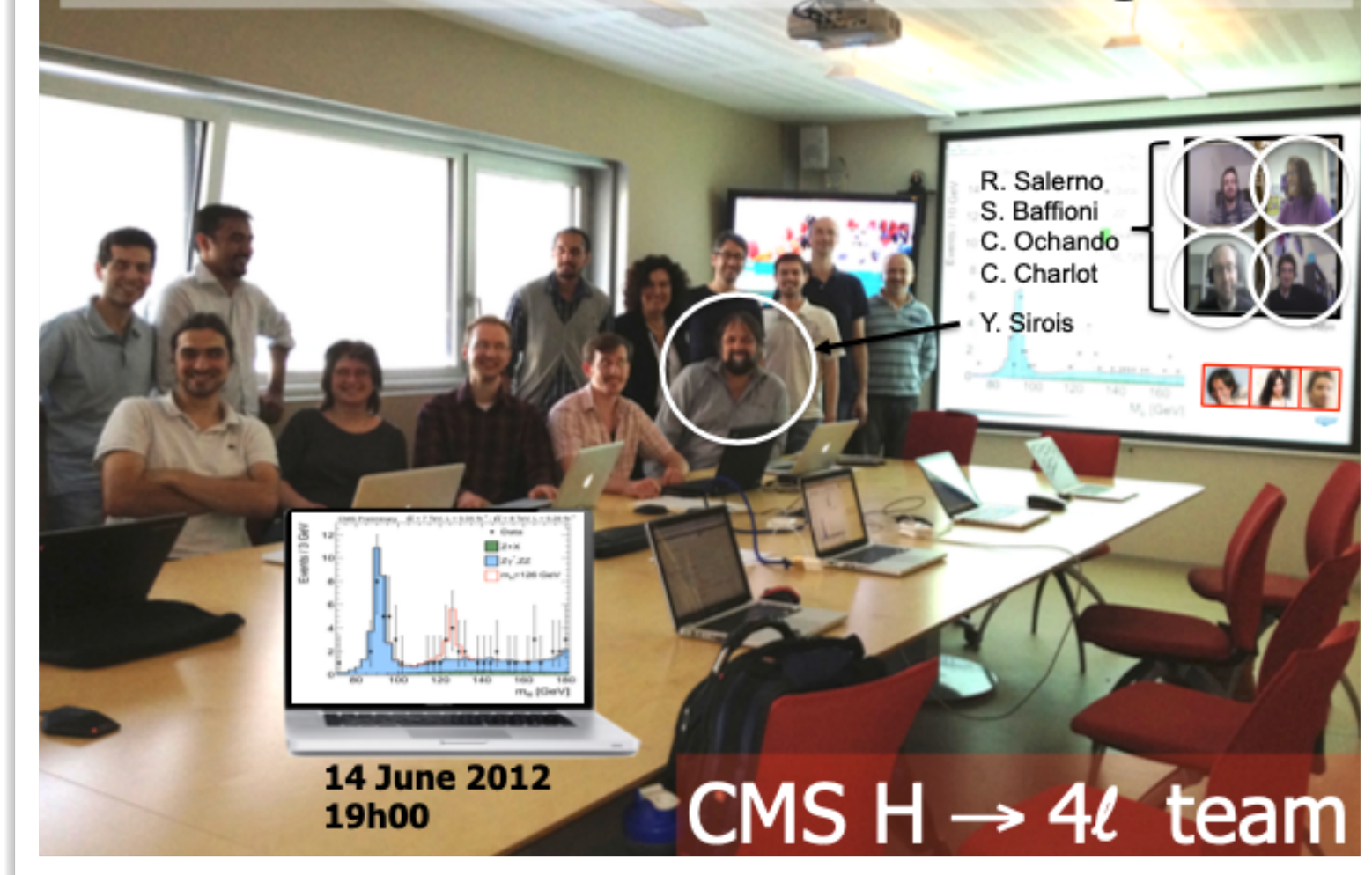


Engineer: **T. Romanteau**  
Physicist: Ph. Busson

- Significant contribution in search for the Higgs boson in the decay to four leptons
  - ▶ One of two "golden channels" leading to discovery in 2012 and Nobel Prizes for Higgs & Englert in 2013



Analysis groups meet separately around mid-June 2012  
CMS unblinds the critical masse range ...



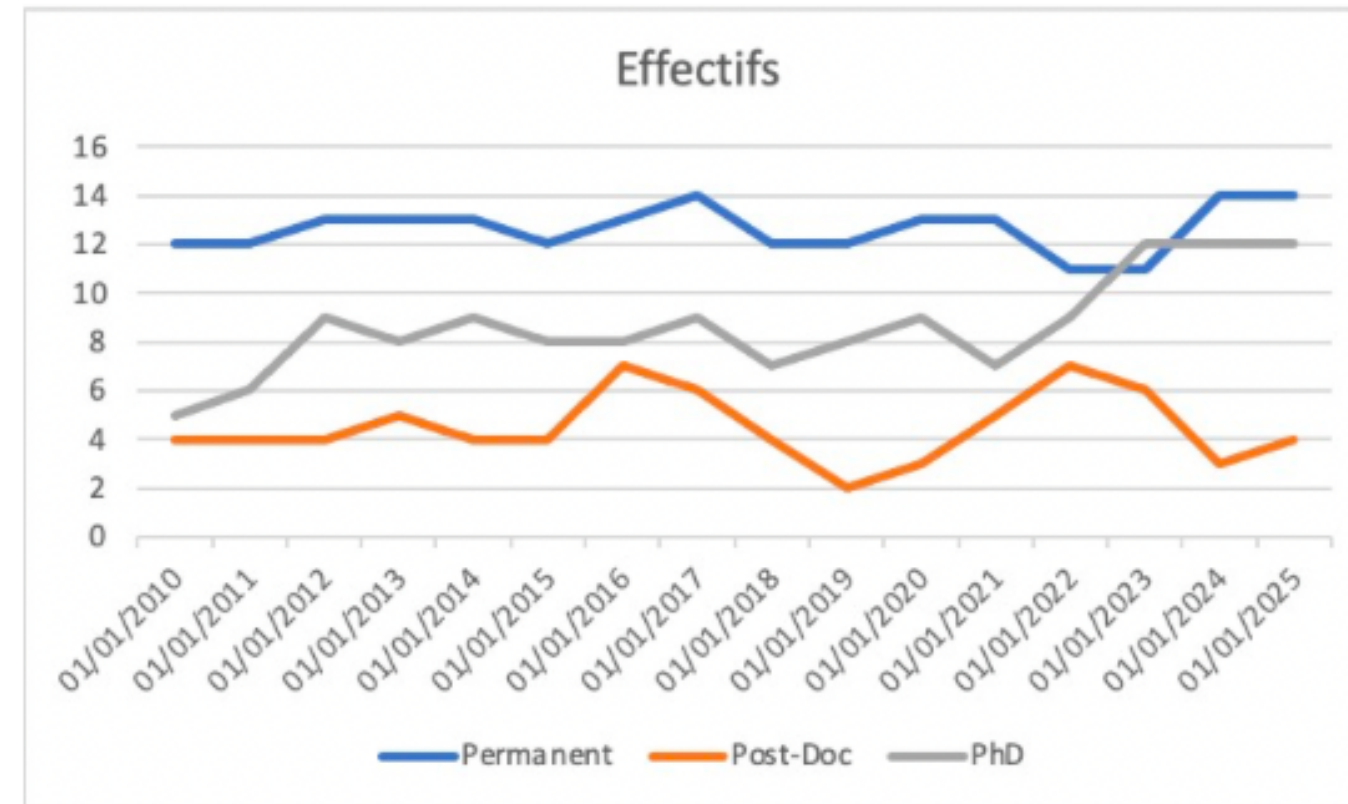


# Current composition of the team

- 14 permanents :

- Y. Sirois Directeur du laboratoire
- F. Beaudette Groupe resp.
- C. Ochando Groupe resp. adj.
- C. Charlot
- R. Granier de Cassagnac HI
- A. Zabi CERN users office dep.
- R. Salerno
- M. Nguyen HI
- A. Zghiche
- J.-B. Sauvan
- O. Davignon (arr 2020)
- A. Gilbert (arr 2023)
- A. de Wit (arr 2023)
- S. Ghosh (arr 2024) Ingénieur Physicien LLR

- Départ en retraite
  - P. Busson (2021)



- 4 postdocs :

- G. Boldrini
- L. Urda
- G. Sokmen Sahin
- S. Obraztsov

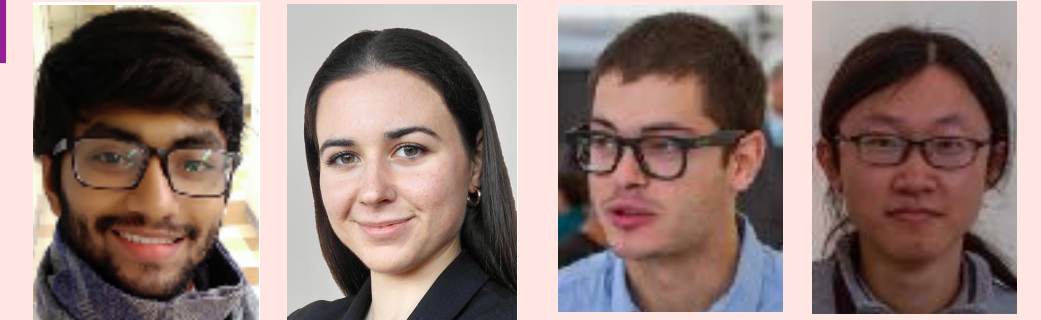


- Départs 2024
  - F. Damas
  - A. Cappati

- Doctorants :

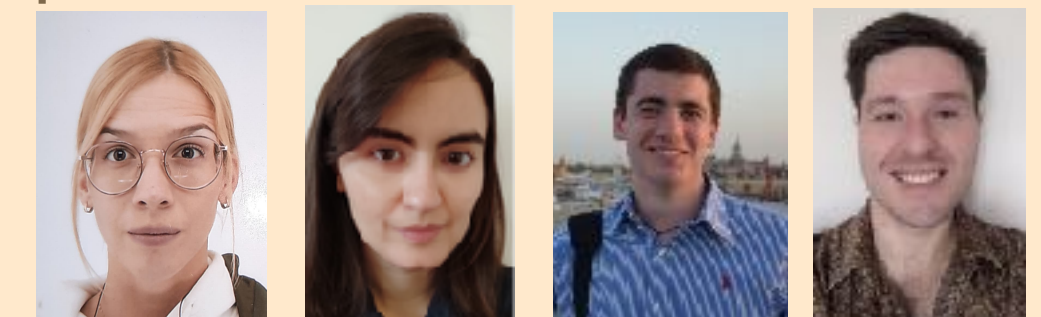
soutenance prévue

- Bharadwaj Harikrishnan HI
- Elena Vernazza
- Bruno Alves
- Geliang Liu



2024

- Ana Sculac (co-tutelle univ. Split)
- Lida Kalipoliti HI
- Marco Chiusi
- Isaac Ehle



2025

- Andro Petković (co-tutelle univ. Split)
- Théo Cuisset
- Martina Manoni
- Trisha Debnath



2026

- Léa-Maria Ravour
- Kirill Biriukov
- Ruth Amella Ranz
- Yuekai Song



2027



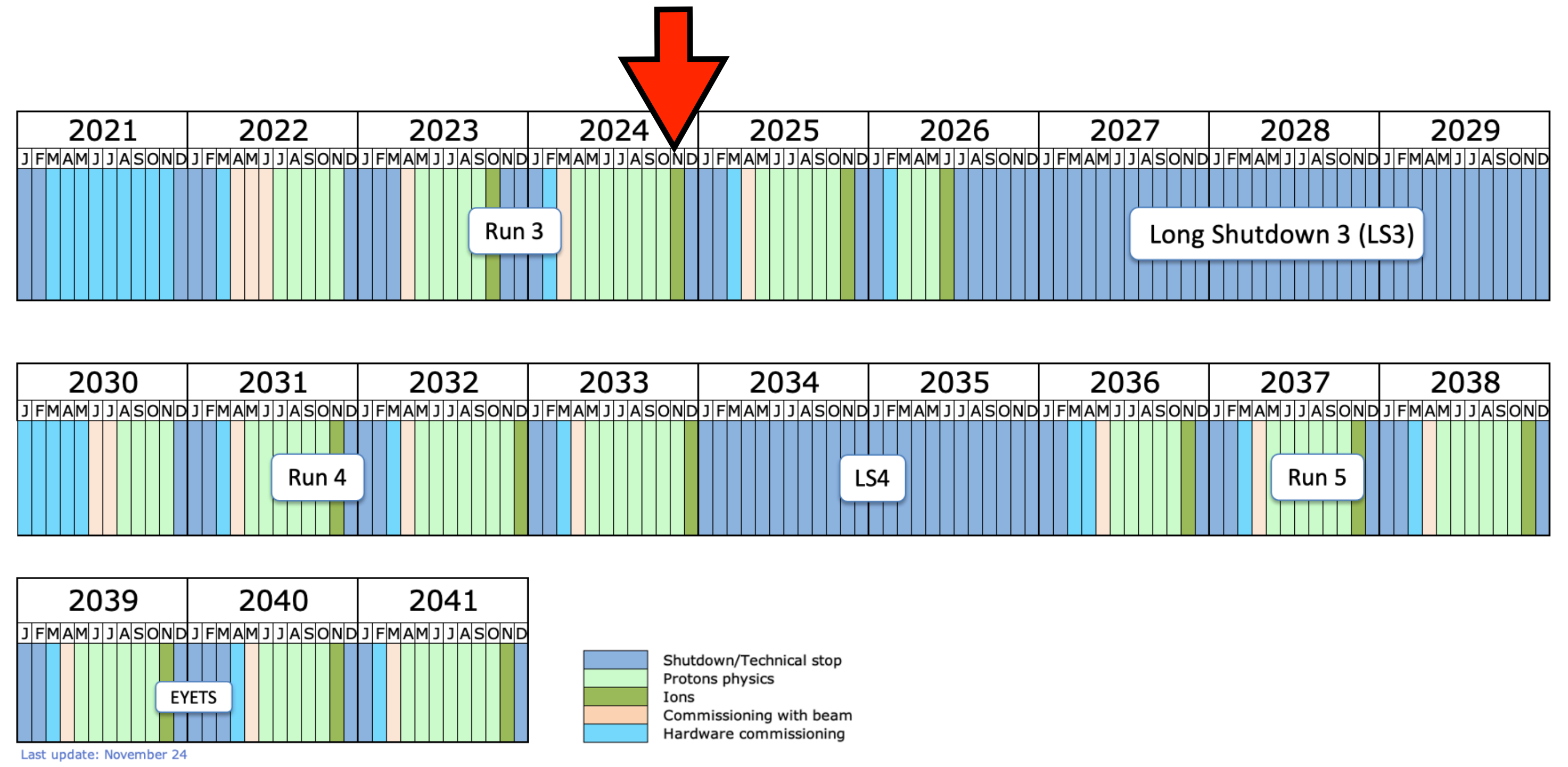
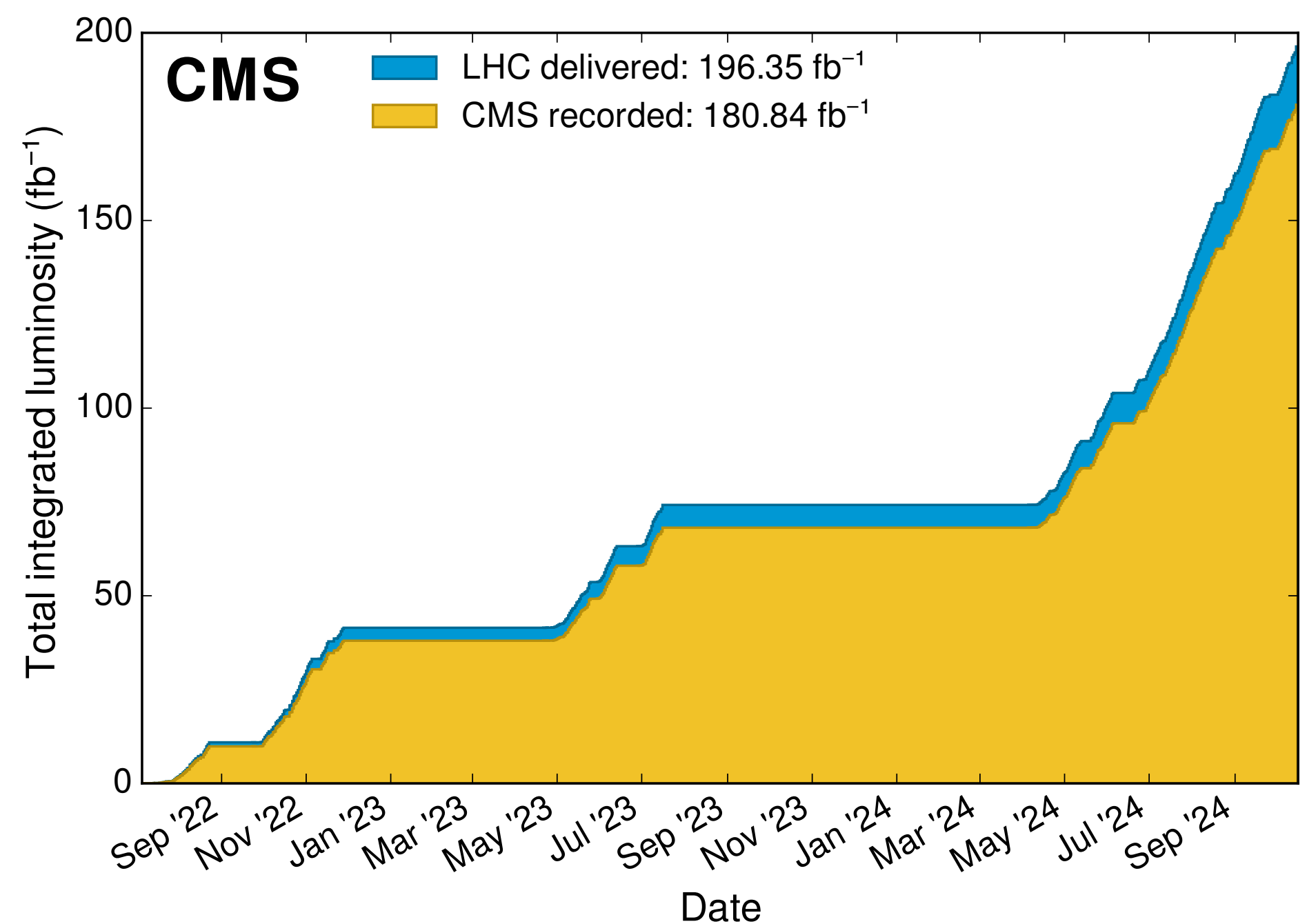
# LHC progress / data-taking

**Amina Zghiche**  
 ECAL DPG (L2)  
 2019-2020

**Amina Zghiche**  
 ECAL Run coordinator  
 2022-2023



- Excellent performance of the LHC & CMS in 2024
  - Run 3 (2022-24): **180 fb<sup>-1</sup>** recorded by CMS (> **139 fb<sup>-1</sup>** in Run 2)
  - Group fulfils its CMS "shift quota" (strong ECAL contribution) and service work commitments
- Full Run 3 will provide rich data set - will take several years to fully exploit for physics analysis
  - Recent update of LHC schedule: Run 3 extended to mid 2026, HL-LHC Run 4 to commence 2030
- Our strategy for analysis: significant effort on Run 3 + concluding on Run 2 analyses in ~ 1 year



# L1 trigger

**Alex Zabi**

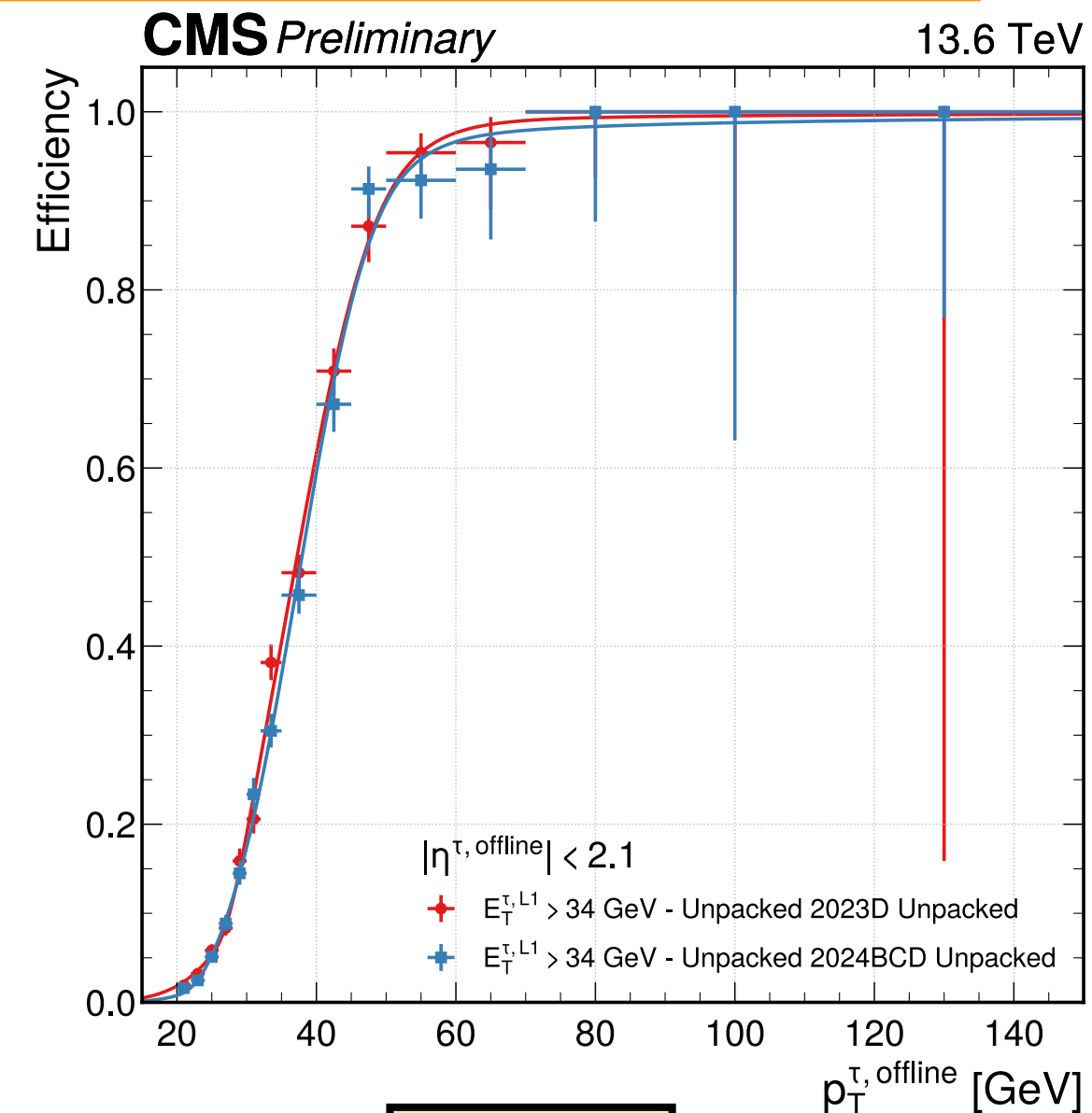
L1 Trg. project manager (L1) L1 Trg. Upgrade Coord (L2)  
2020-2024 2018-2020

**Olivier Davignon**

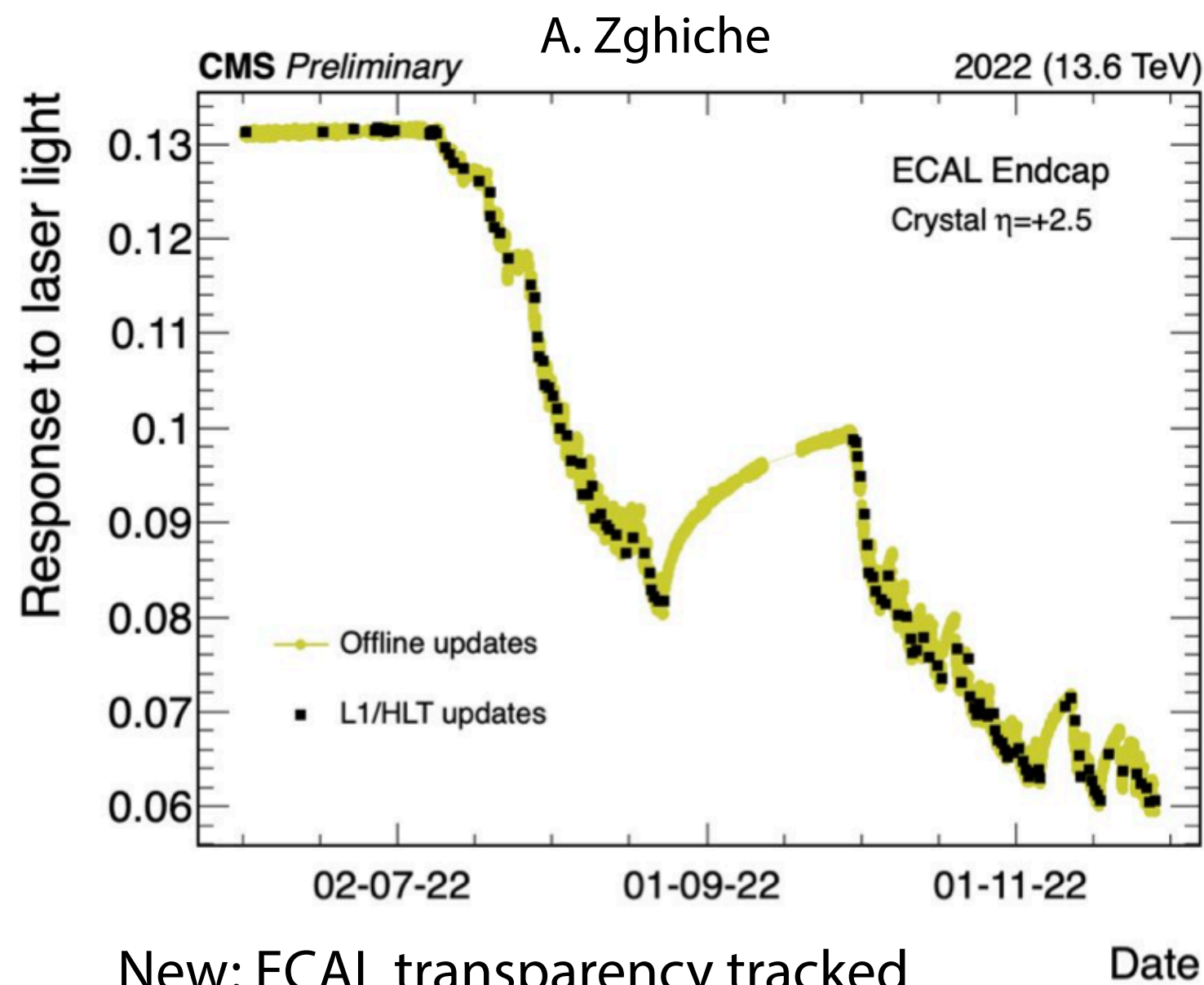
Trigger DPG (L2)  
2019-2020

- Sustained contribution to development and **calibration** of the level-1 trigger and the **algorithms** it relies on
  - Critical to maintain performance with ever-increasing pileup
  - Building advanced algorithms for HL-LHC
    - E.g. ML in FPGAs

Hadronic tau L1 trigger - crucial to performance in di-Higgs analysis



M. Chiusi

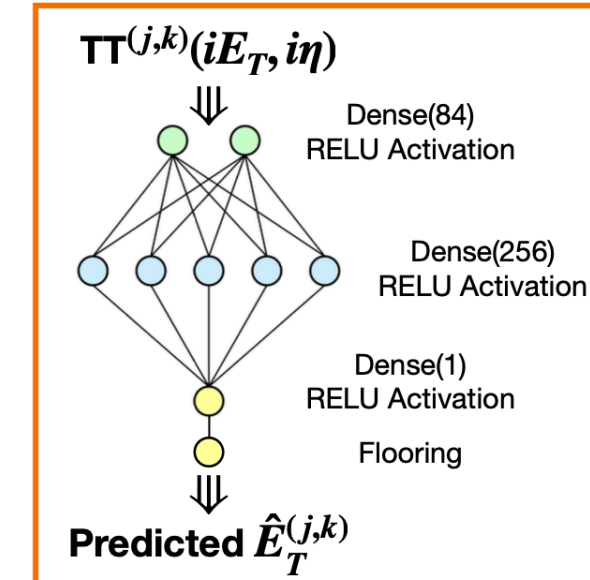


New: ECAL transparency tracked in real time @ L1 & HLT

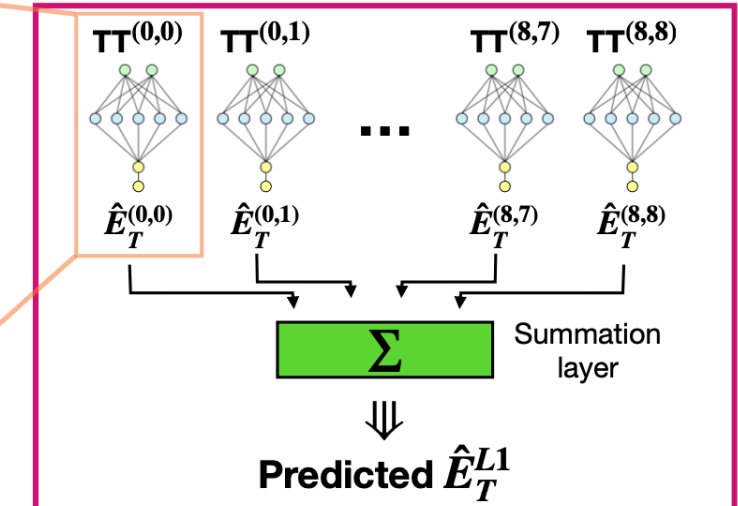
Careful ECAL performance monitoring in Run 3 data

A. Gilbert (LLR)

## TRIGGER TOWER PREDICTOR



## PREDICTIVE NETWORK MODEL

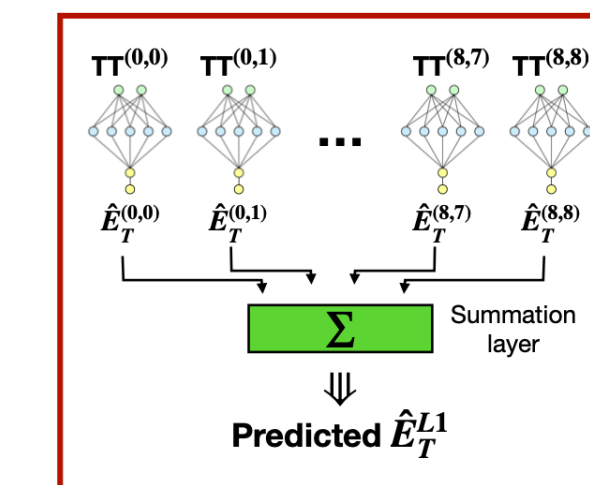


J. Motta

E. Vernazza

$e/\gamma$  - jet CL<sup>9x9</sup>

ZeroBias CL<sup>9x9</sup>/CL<sup>1x1</sup>



Energy regression

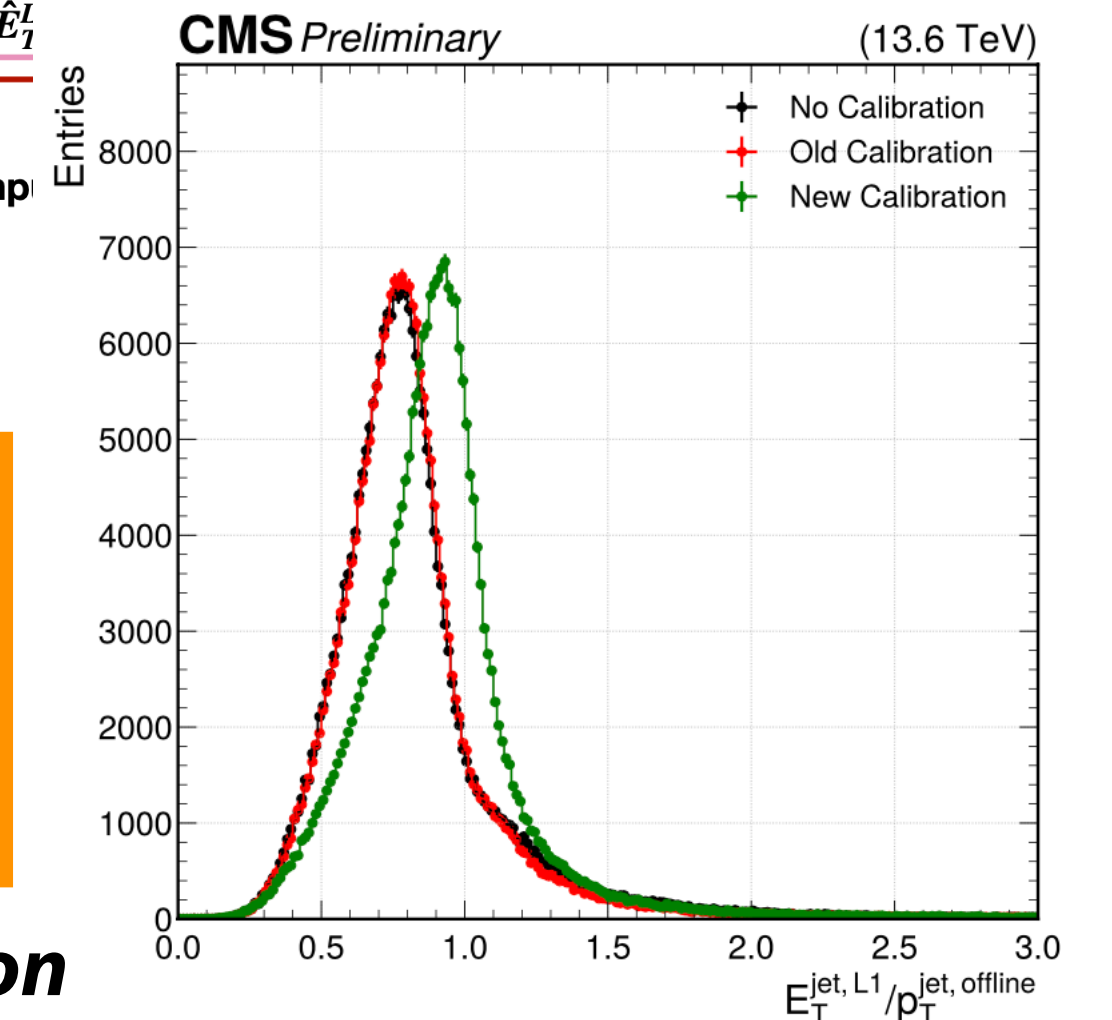
Proxy rate comp

$$E_T^{L1, jet} = \sum_{i\eta, i\phi} (\alpha(i\eta, E_T) \cdot E_T) \rightarrow E_T^{Reco, jet}$$

Improved calibration model using differentiable programming approach

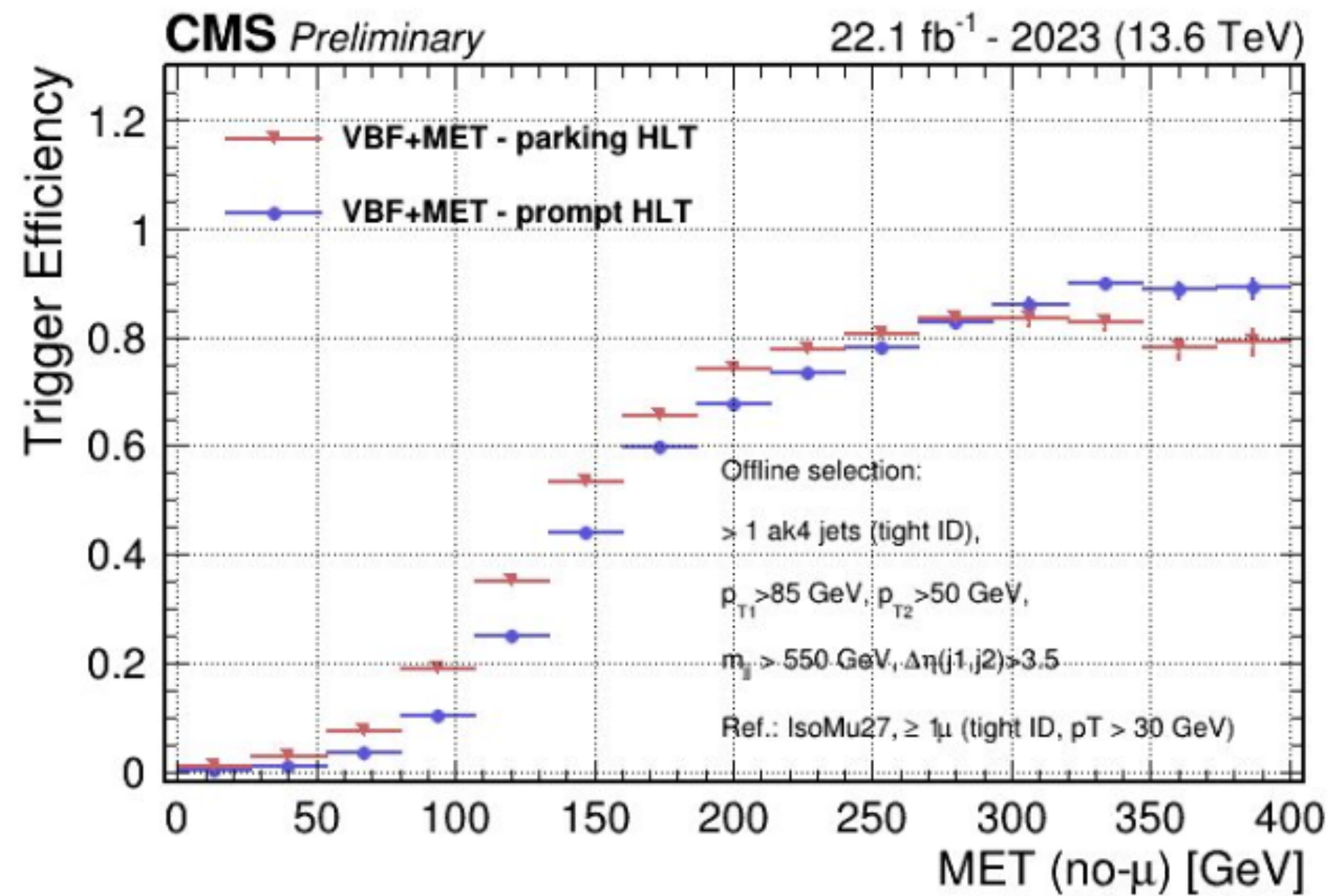
Publication in preparation

## CALIBRATOR MODEL



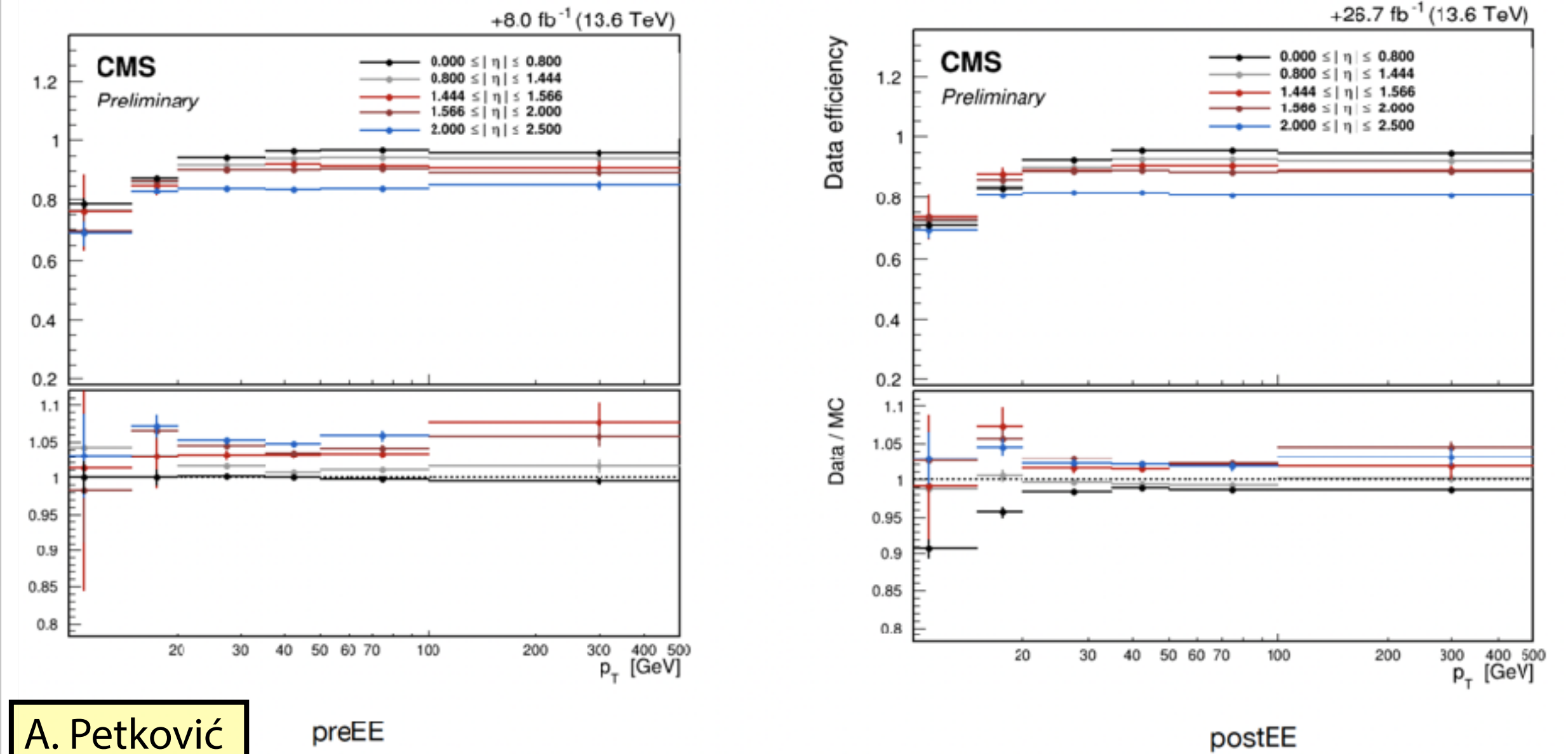


## Development and deployment of vector boson fusion "parking" triggers in Run 3



Significant increase of acceptance for Higgs, EW (VBS) and BSM searches

## Electron-ID Scale Factors pour le Run 3



A. Petković

+ Travail sur la définition des erreurs systématiques sur les SF appliqués aux électrons

⇒ input for Higgs → 4l analysis

# Physics analysis

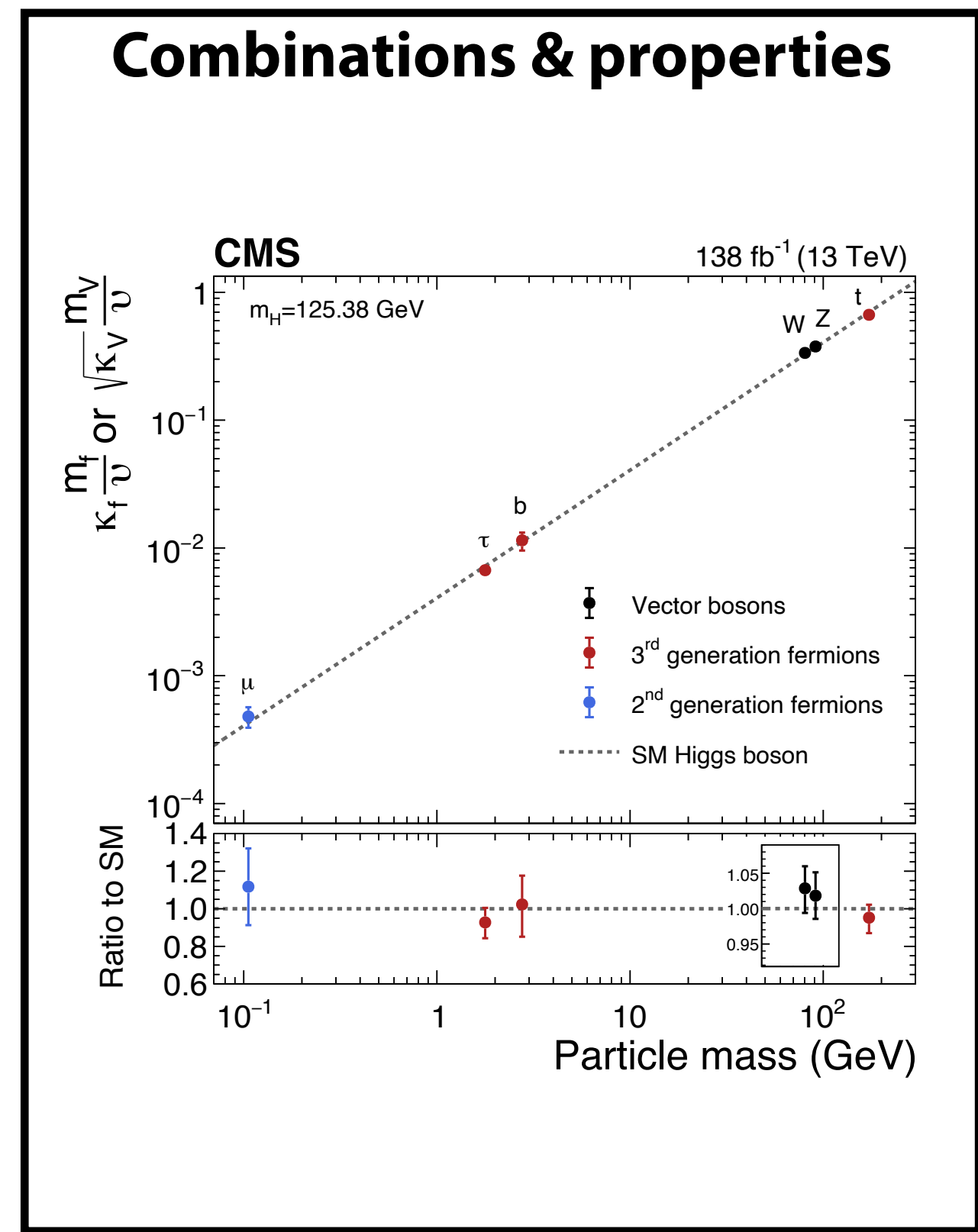
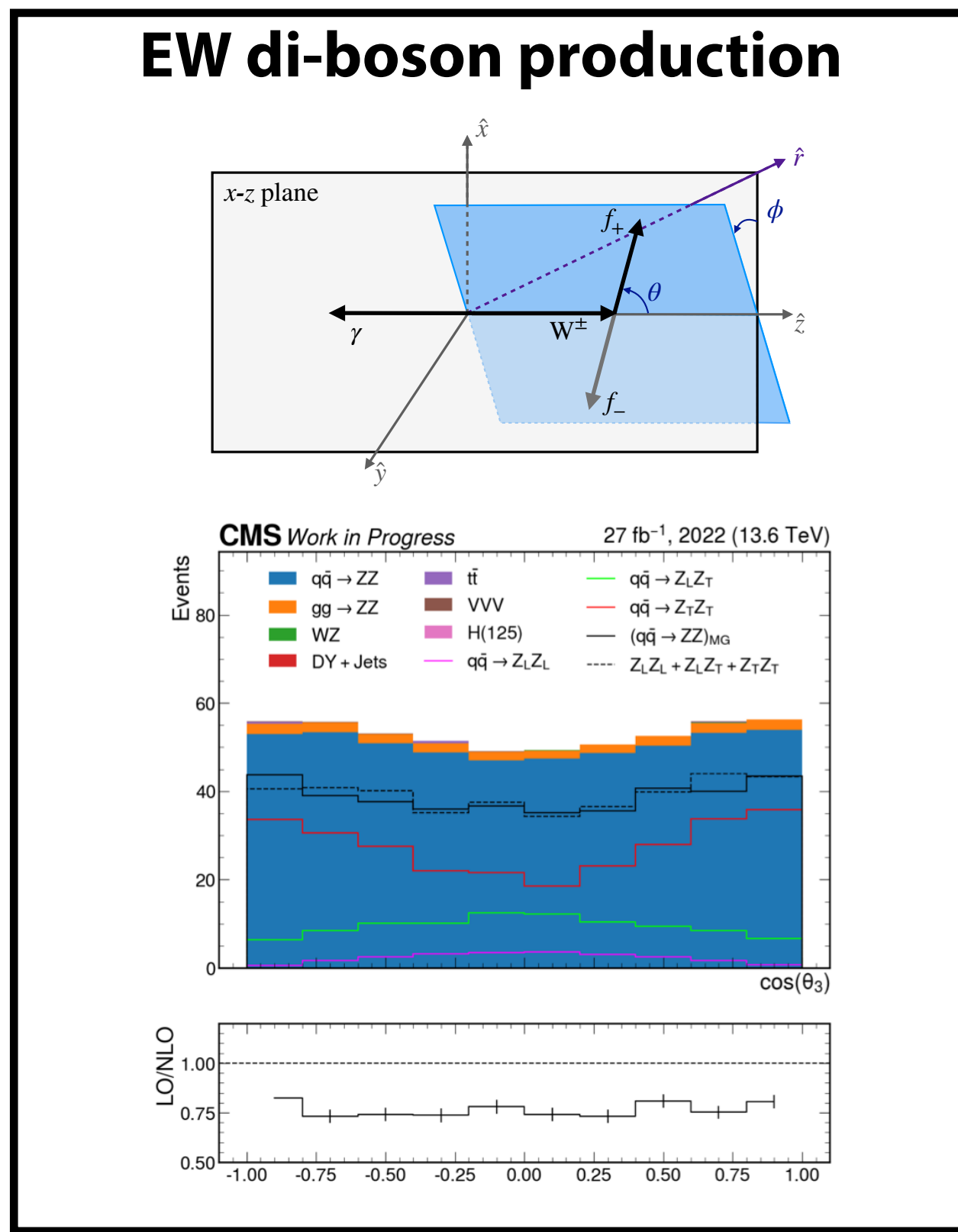
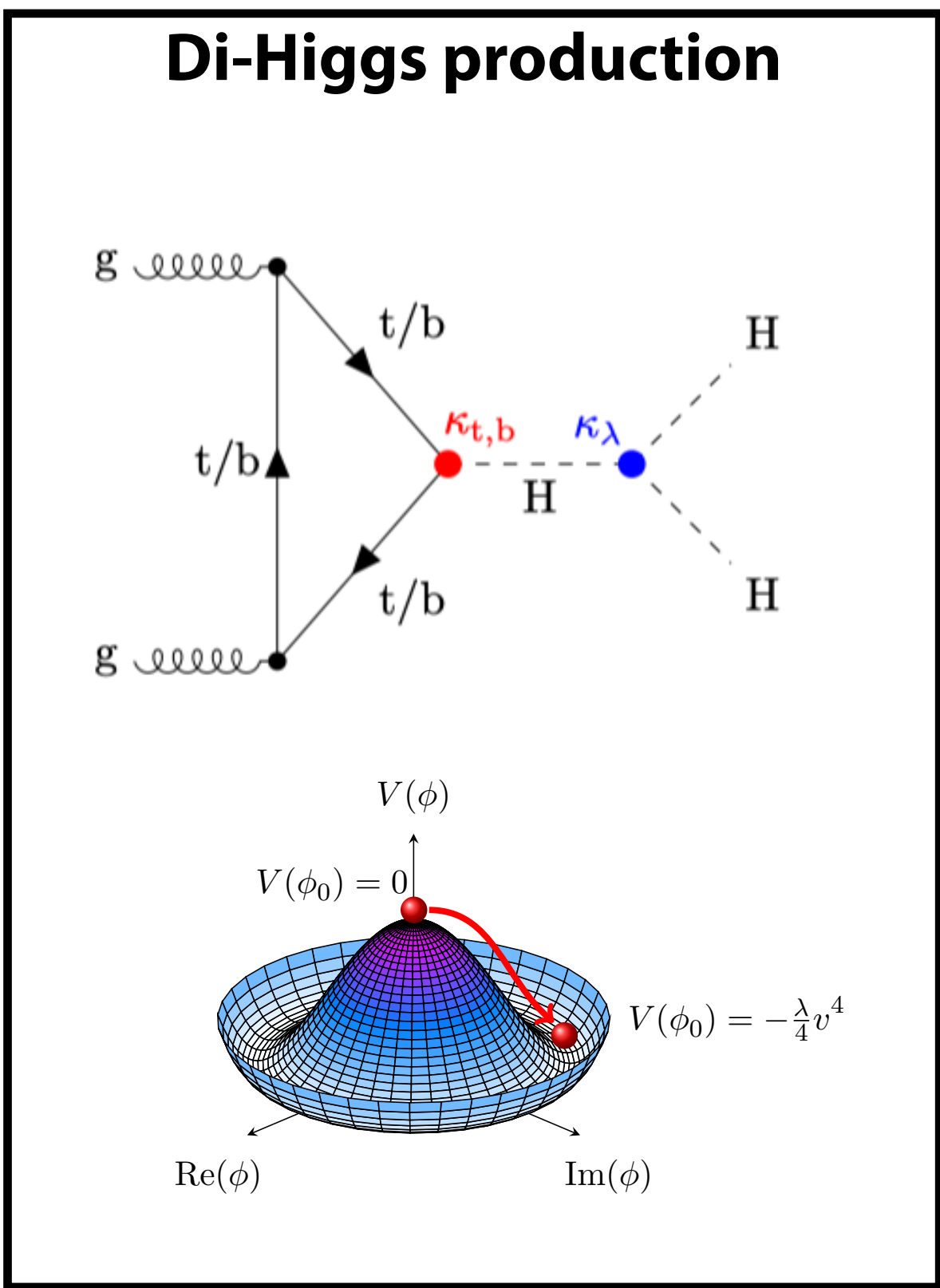
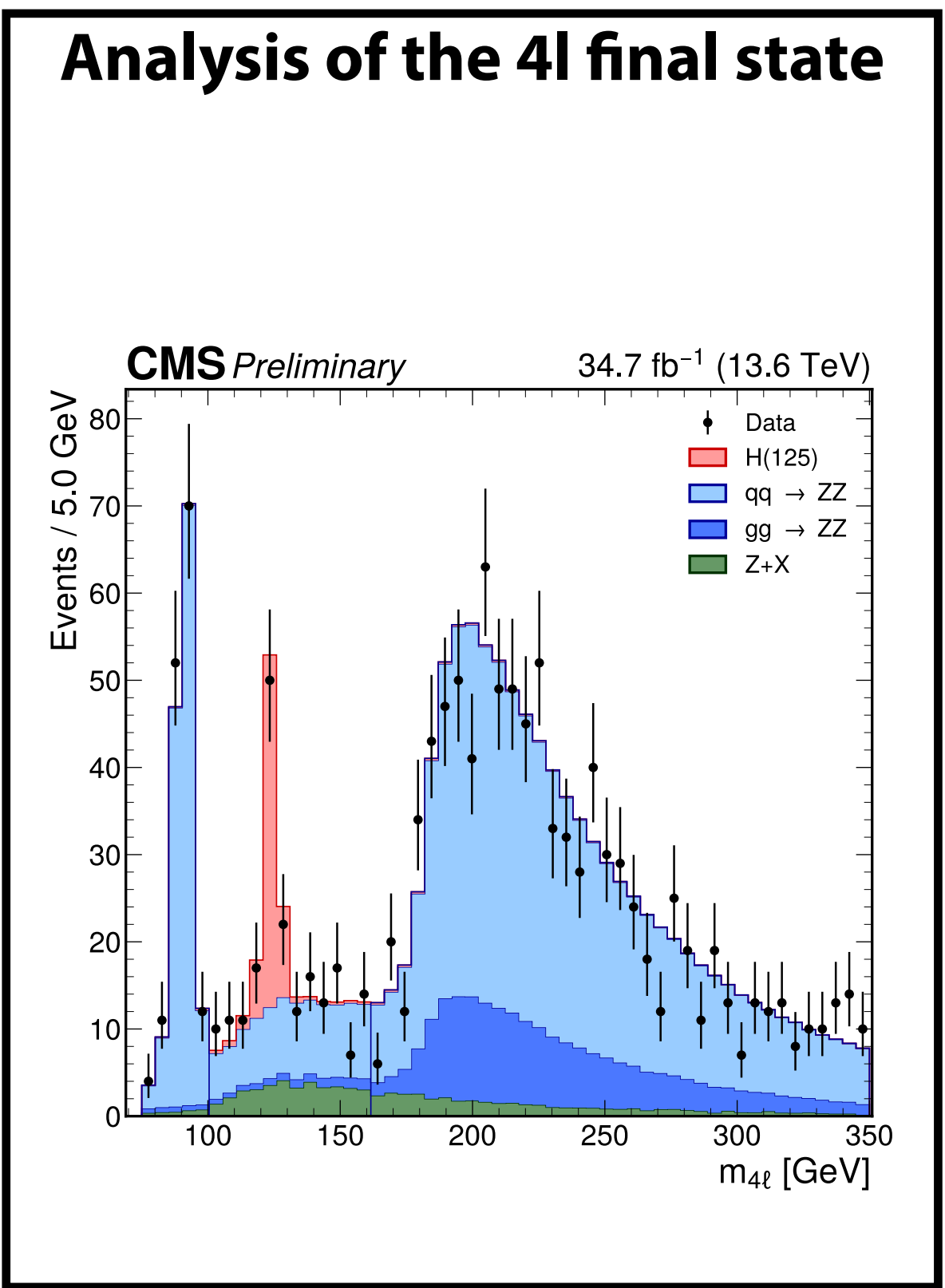
**Roberto Salerno**  
 CMS Physics coordinator  
 2023-2025  
 Higgs phys. convener  
 2018-2019

**Adinda de Wit**  
 Higgs phys. convener  
 2022-2024

**Andrew Gilbert**  
 SM phys. convener  
 2022-2024



- Long-term physics programme in Higgs boson & electroweak physics, and heavy ion physics



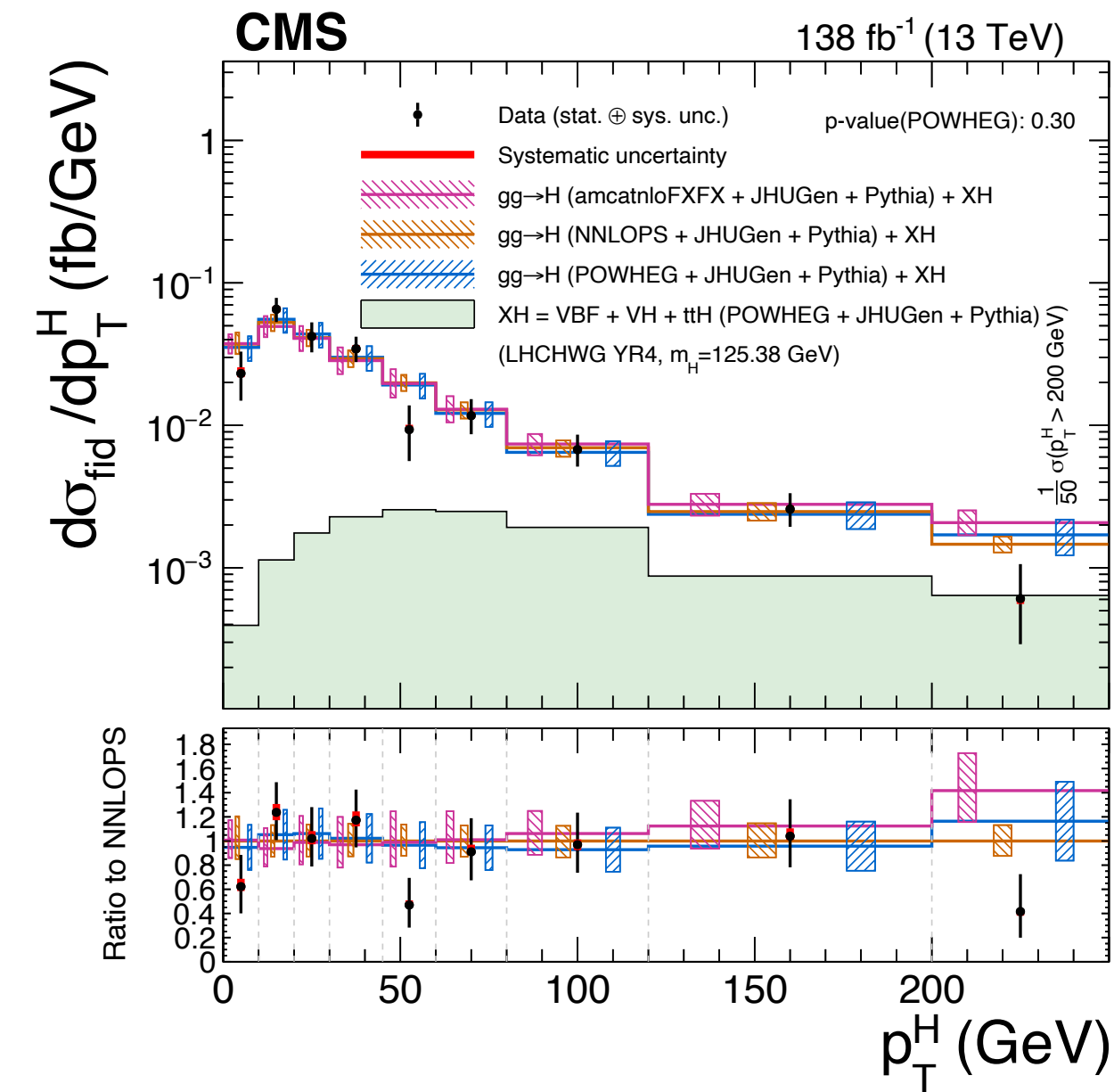


# SM $H \rightarrow ZZ \rightarrow 4\ell$

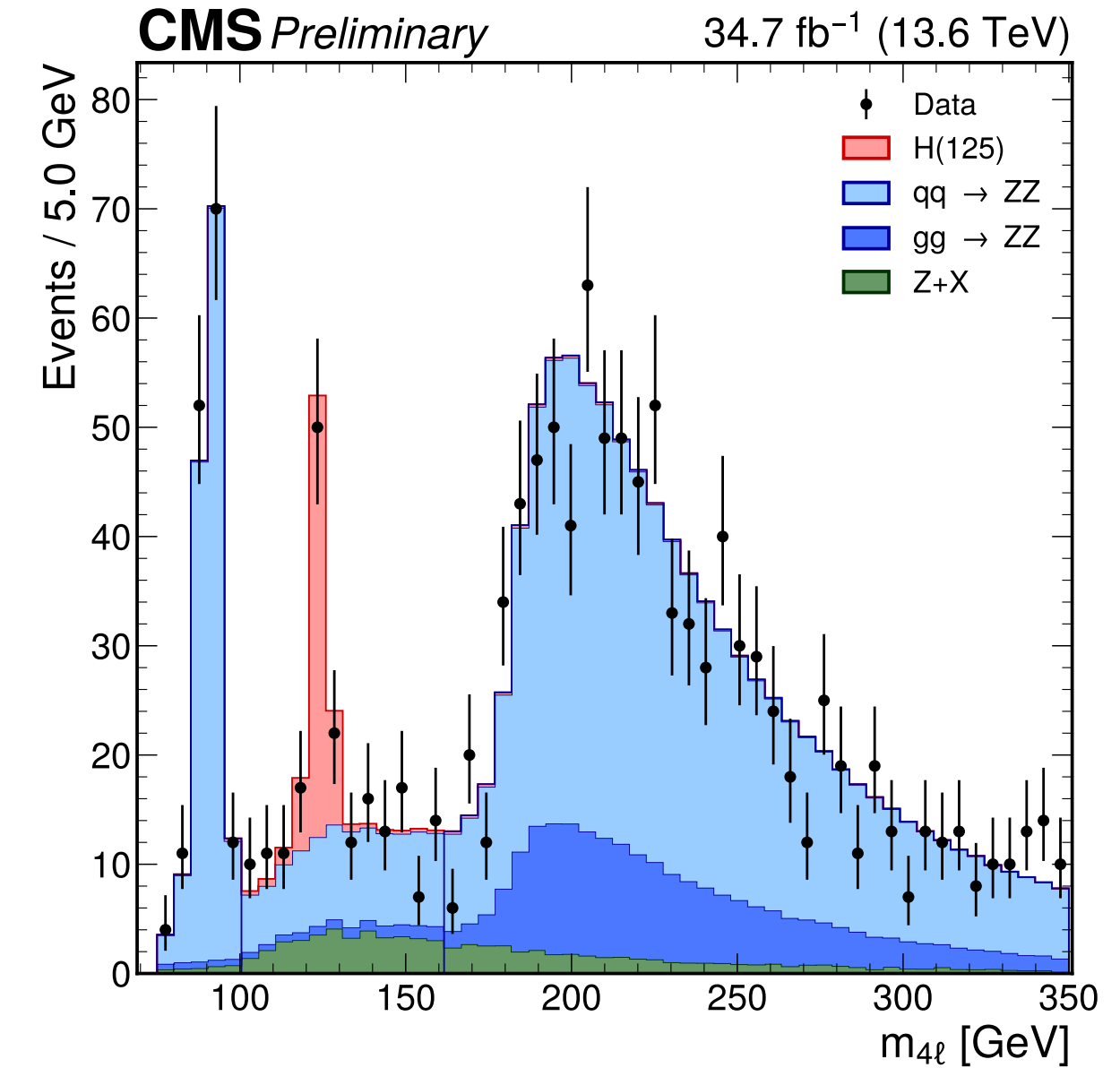
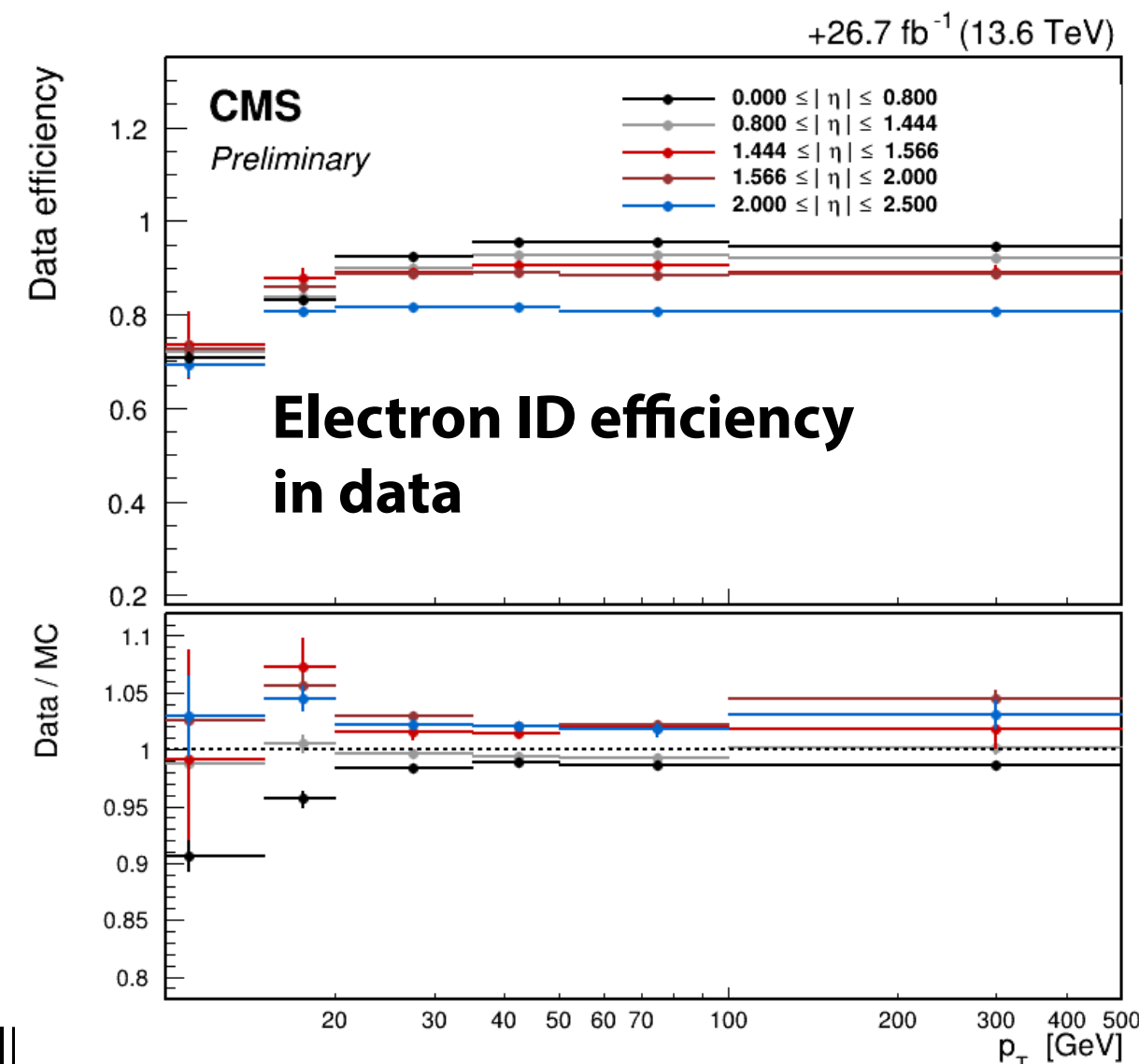
**Christophe Ochando**  
HZZ convener  
2018-2020

**Alessandra Cappati**  
HZZ convener  
2021-2023

- Precise Run 2 cross section & properties
  - Single & double-differential x-secs of wide set of observables
- First CMS  $H \rightarrow ZZ$  analysis of Run 3 data (13.6 TeV)
  - Demonstrates good quality of the data, excellent performance of electron and muon reconstruction
- Dedicated electron ID BDT, recalibrated for Run 3 with reduced uncertainty
  - $\epsilon_{\text{signal}} = 80\%$ ,  $\epsilon_{\text{bkg}} = 4\%$  (barrel)
- Next round of analysis underway M. Manoni
  - Focus on Higgs differential and off-shell analyses (constrain Higgs boson width)



*JHEP 08 (2023) 040*



CMS-PAS-HIG-24-013

**Presented ICHEP 2024**

*Analysis contact: A. Cappati*

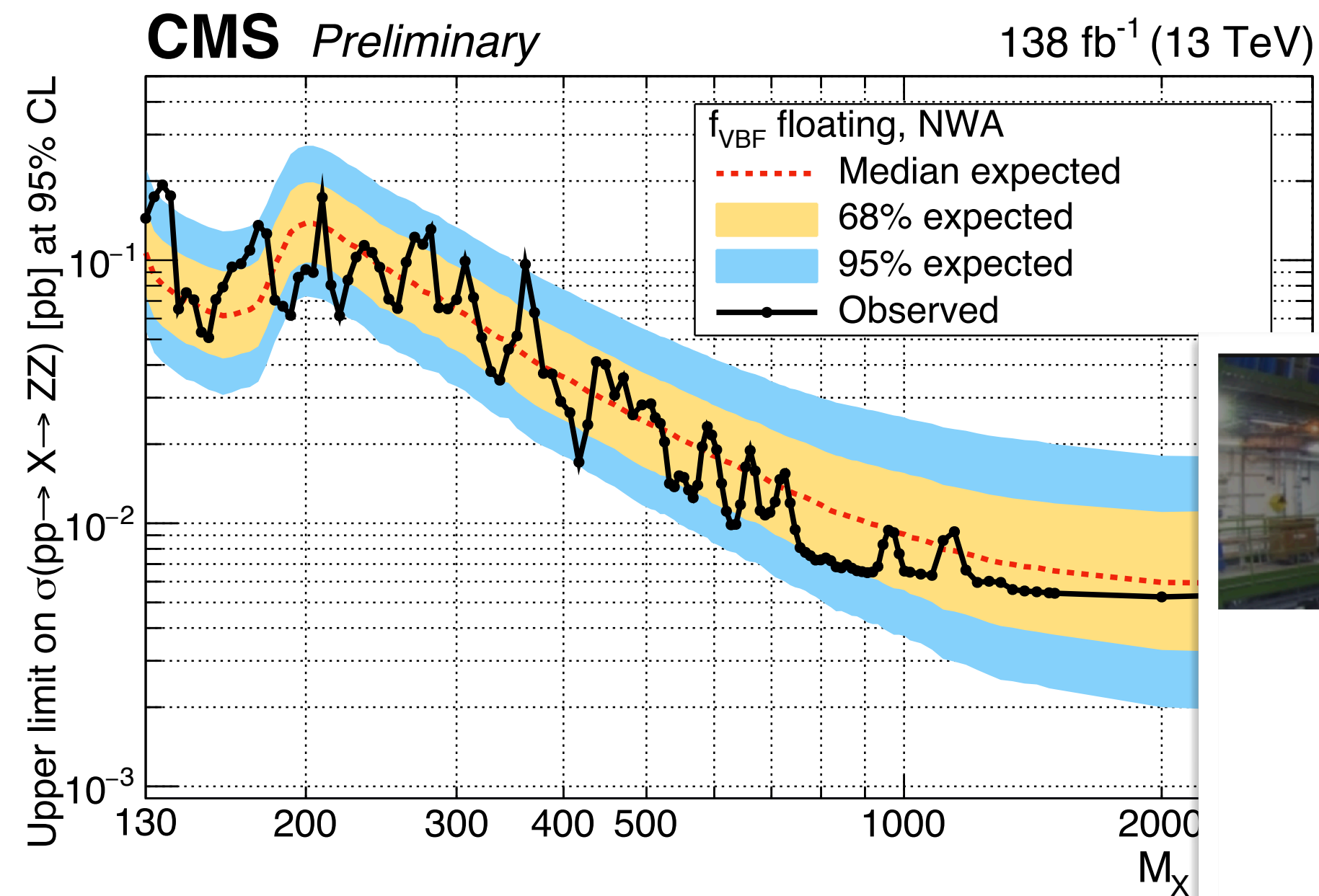
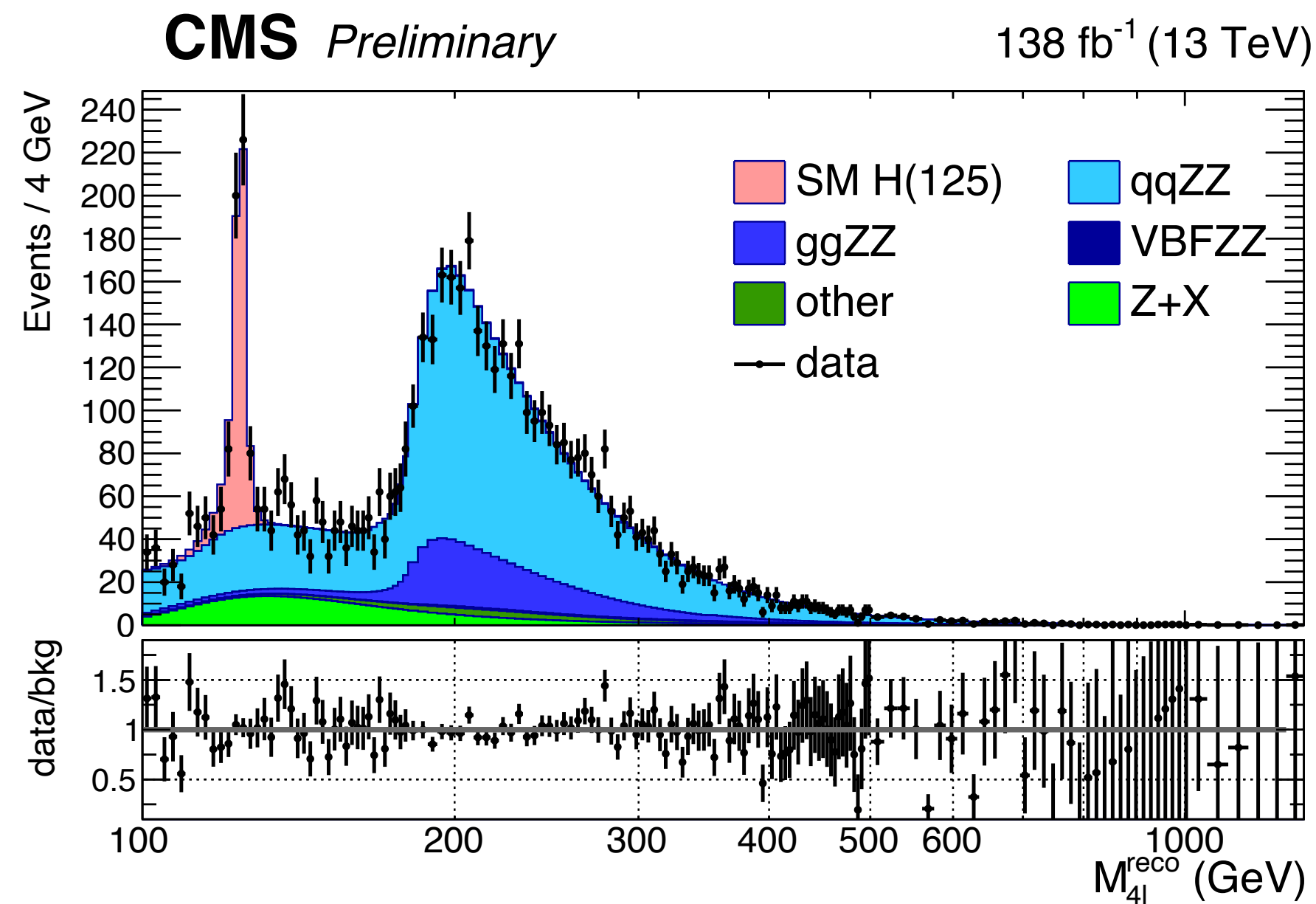
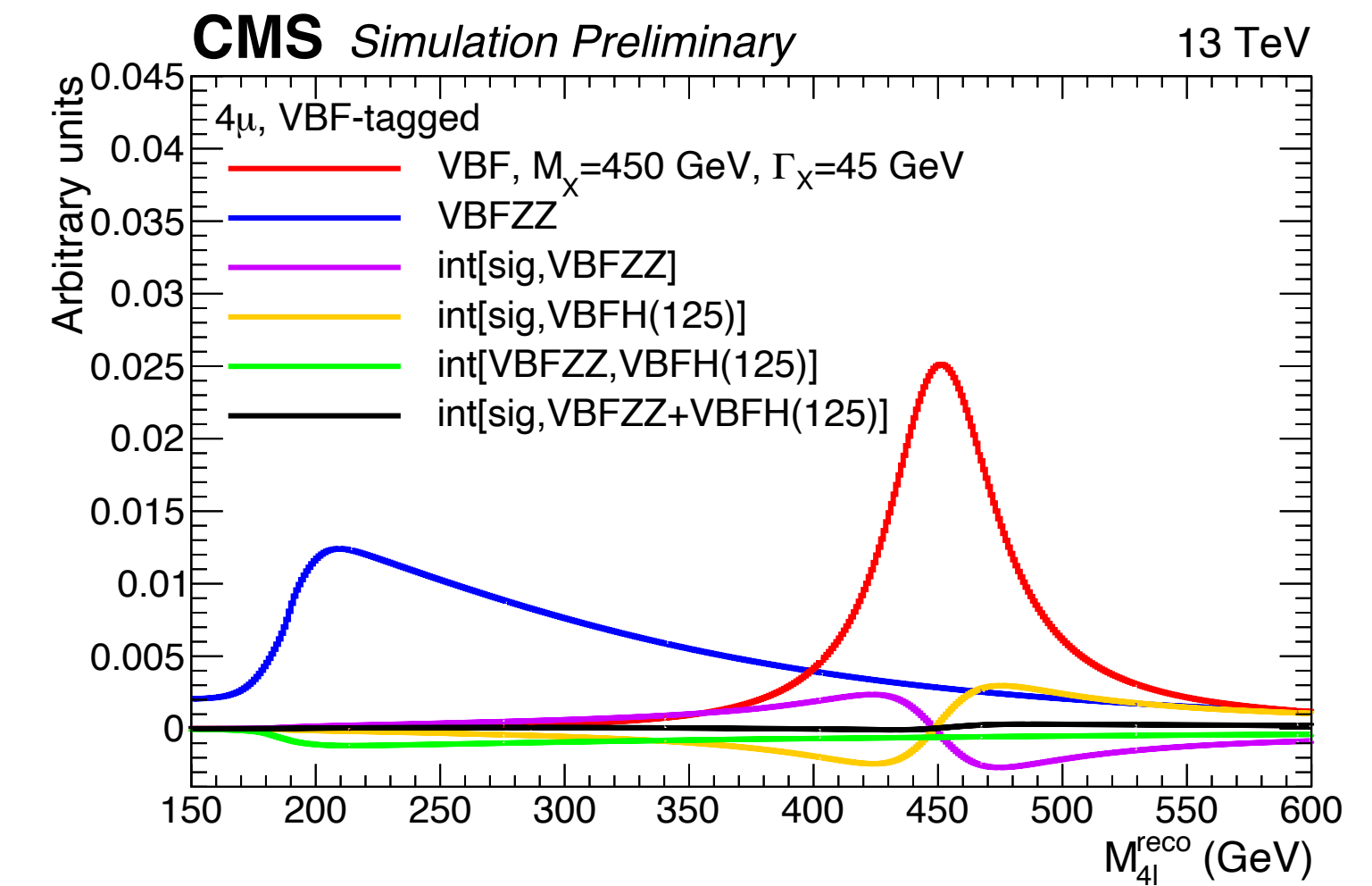
# Heavy scalar search $X \rightarrow ZZ \rightarrow 4l$

CMS-PAS-HIG-24-002

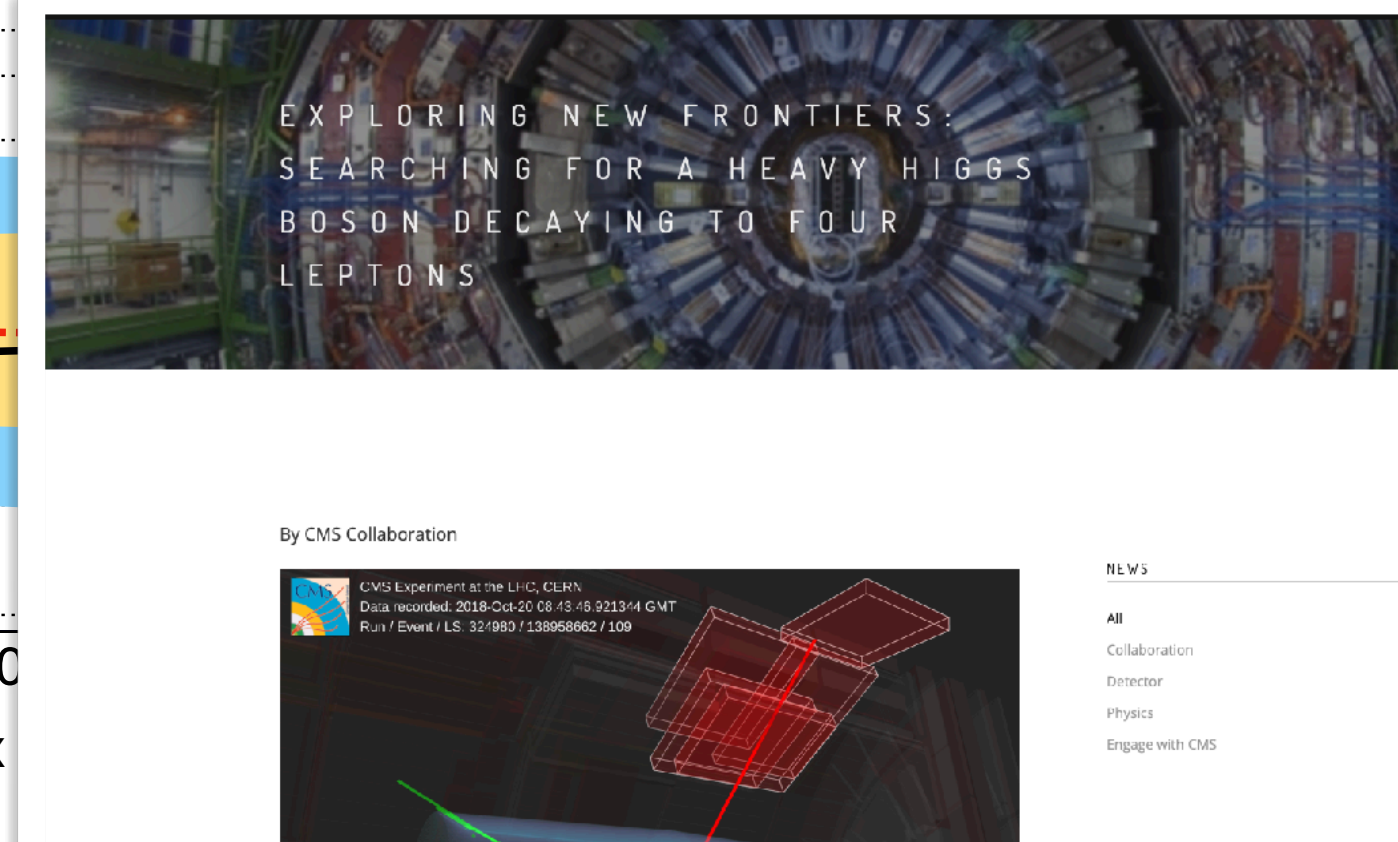
Analysis contact: G. Liu

Presented ICHEP 2024

- Many BSM models feature additional heavy resonances
- Build on extensive  $4l$  expertise in the group, search for  $m_X$  up to 3 TeV
- **New challenges:** consider resonances with non-negligible width, account for interference with backgrounds



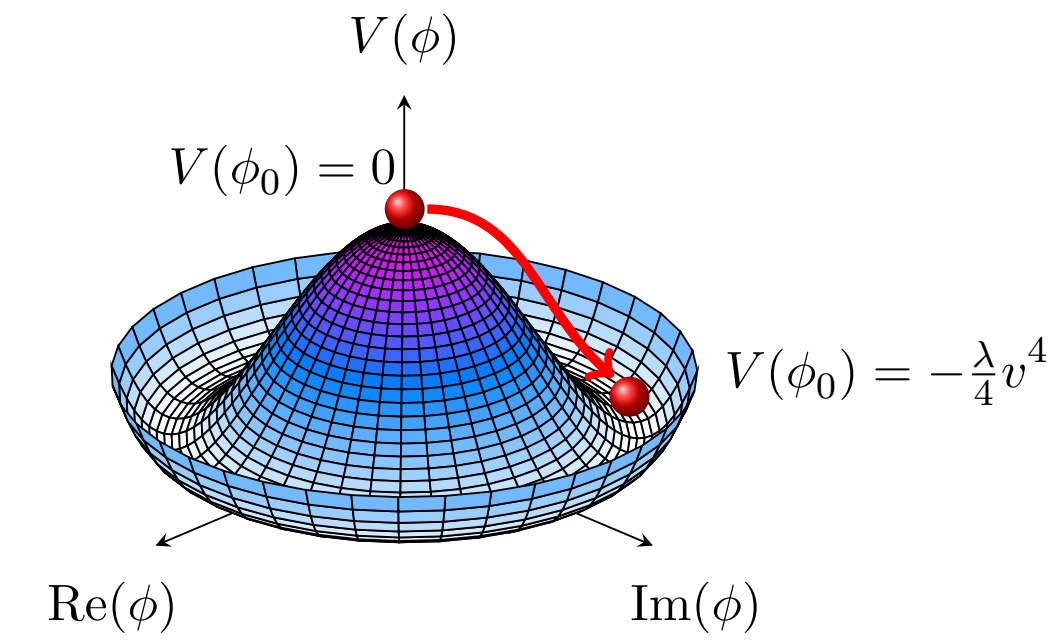
**CMS Physics briefing:**





# Di-Higgs production

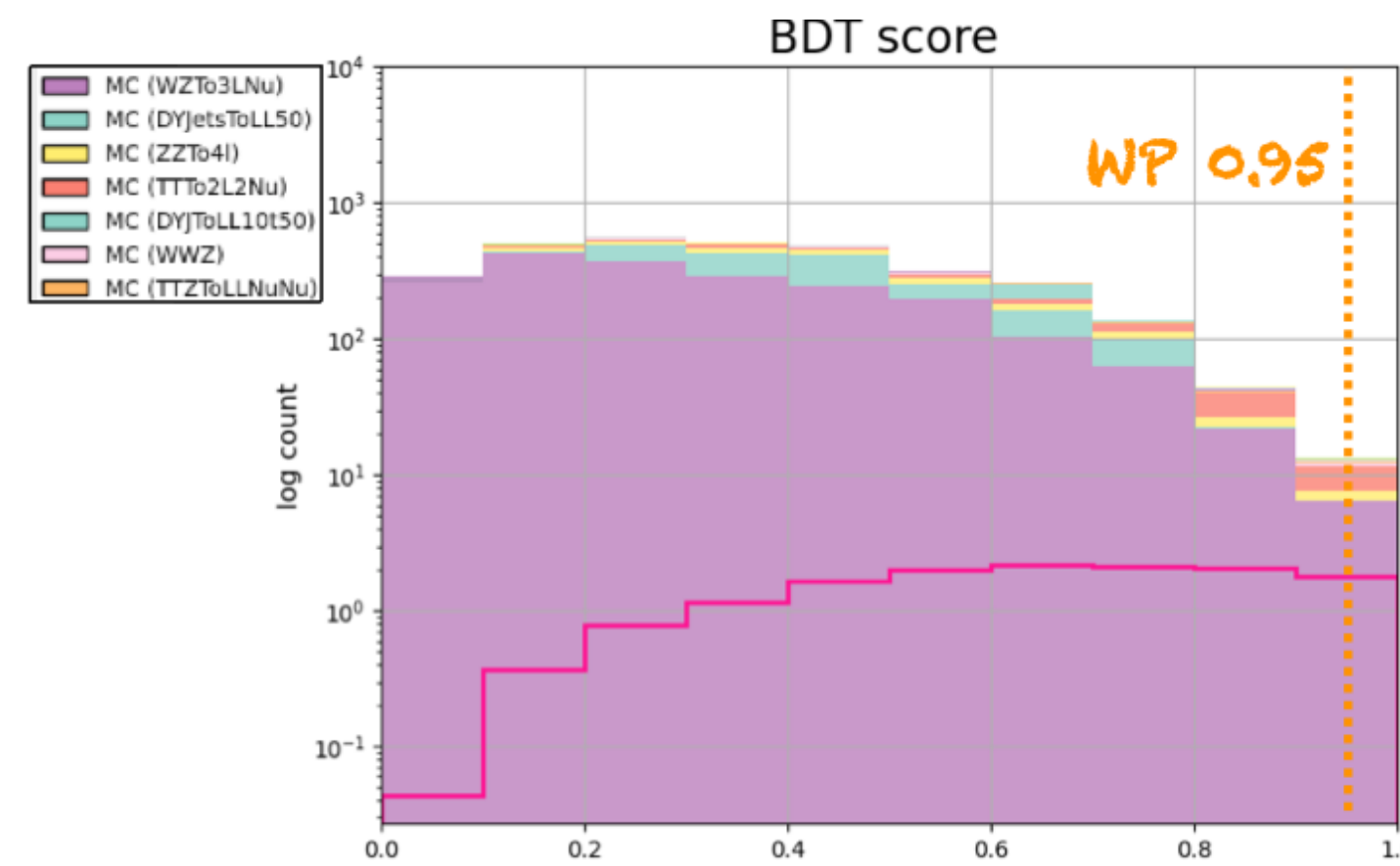
- In SM, Higgs boson mass defines all other properties, including shape of potential
  - Self-coupling,  $\lambda_{HHH}$  can be constrained directly in Di-Higgs production
  - Powerful test of SM  $\Rightarrow$  one of the primary physics goals of HL-LHC



$$V(H) = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v} H^4 - \frac{1}{4} \mu^2 v^2$$

$$= \frac{1}{2} m_H^2 H^2 + \lambda_{HHH} v H^3 + \lambda_{HHHH} H^4 - \frac{1}{8} m_H^2 v^2$$

$$\lambda_{HHH} = 4\lambda_{HHHH} = \frac{m_H^2}{v^2}$$



## Direct Di-Higgs searches

	bb	WW	gg	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34.1%					
WW	25.1%	4.63%				
gg	9.6%	3.52%	0.669%			
$\tau\tau$	7.3%	2.71%	1.03%	0.395%		
ZZ	3.08%	1.14%	0.432%	0.332%	0.070%	
$\gamma\gamma$	0.265%	0.098%	0.037%	0.029%	0.012%	0.001%

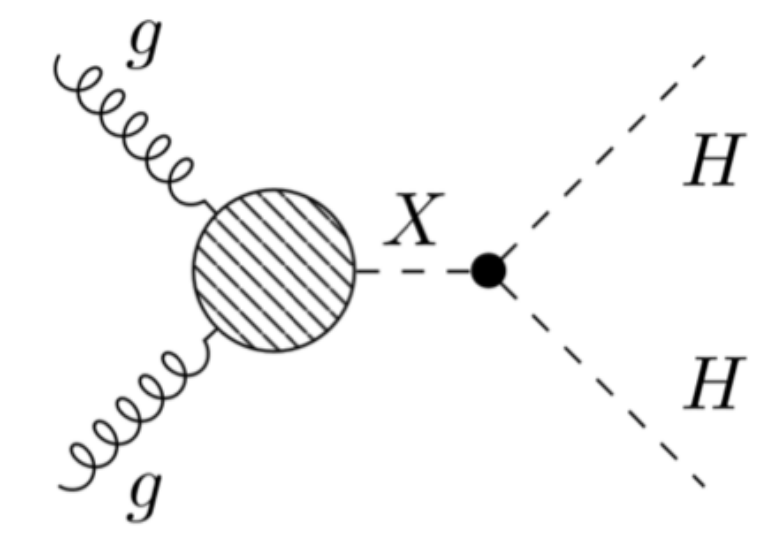
Branching ratio [%]

- Challenge: many possible final states!
  - Principle target of the group:  $bb\tau\tau$
  - Also opening new channels for the first time: **WWVV** A. Sculac
    - Where  $VV=WW/ZZ \rightarrow$  multi-lepton + multi-jet topology  $\rightarrow$  many combinations to consider

- Building a **long-term** di-Higgs programme: studies for FCC underway, part of ESPP - more in talk from Vincent

# bbττ

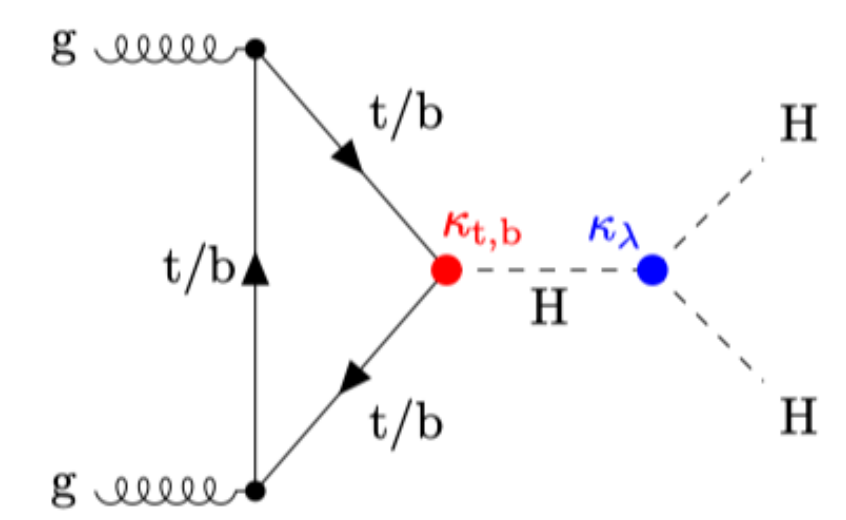
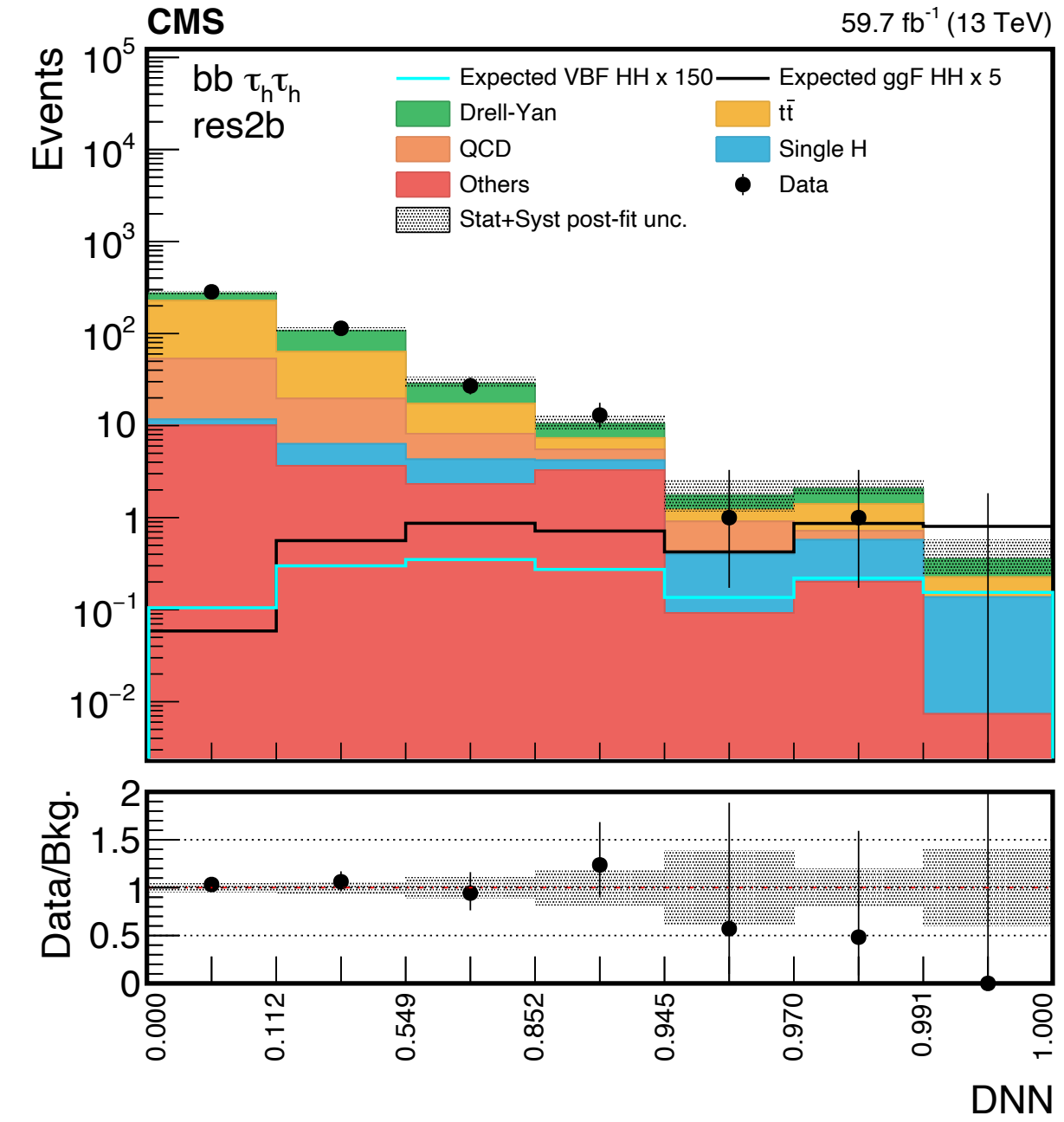
- Crucial channel for both **non-resonant** and **resonant** di-Higgs production
- Challenge: contend with large tt and DY backgrounds
  - Jet and tau ID using state-of-the-art deep neural networks
  - Signal extraction based on multivariate methods



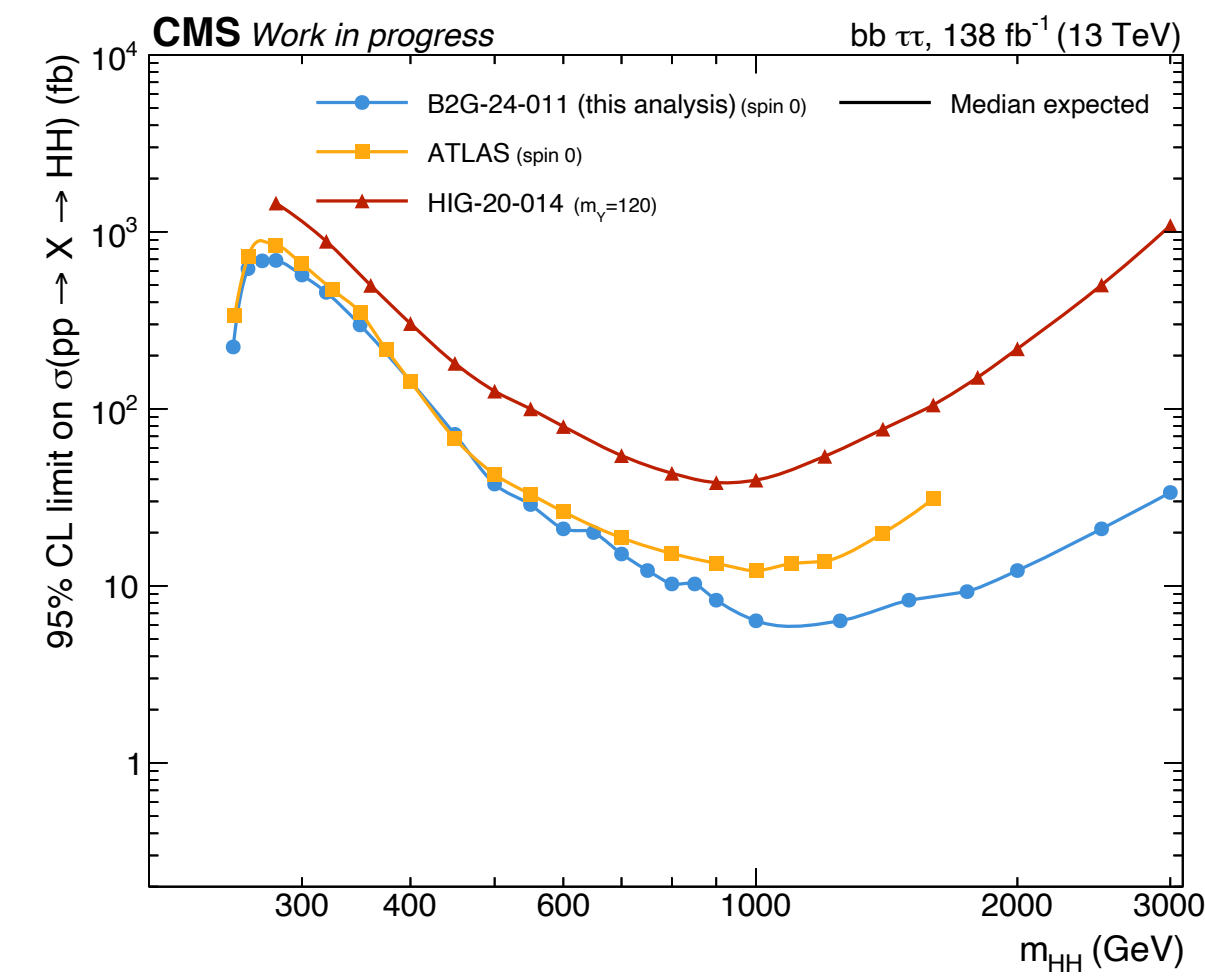
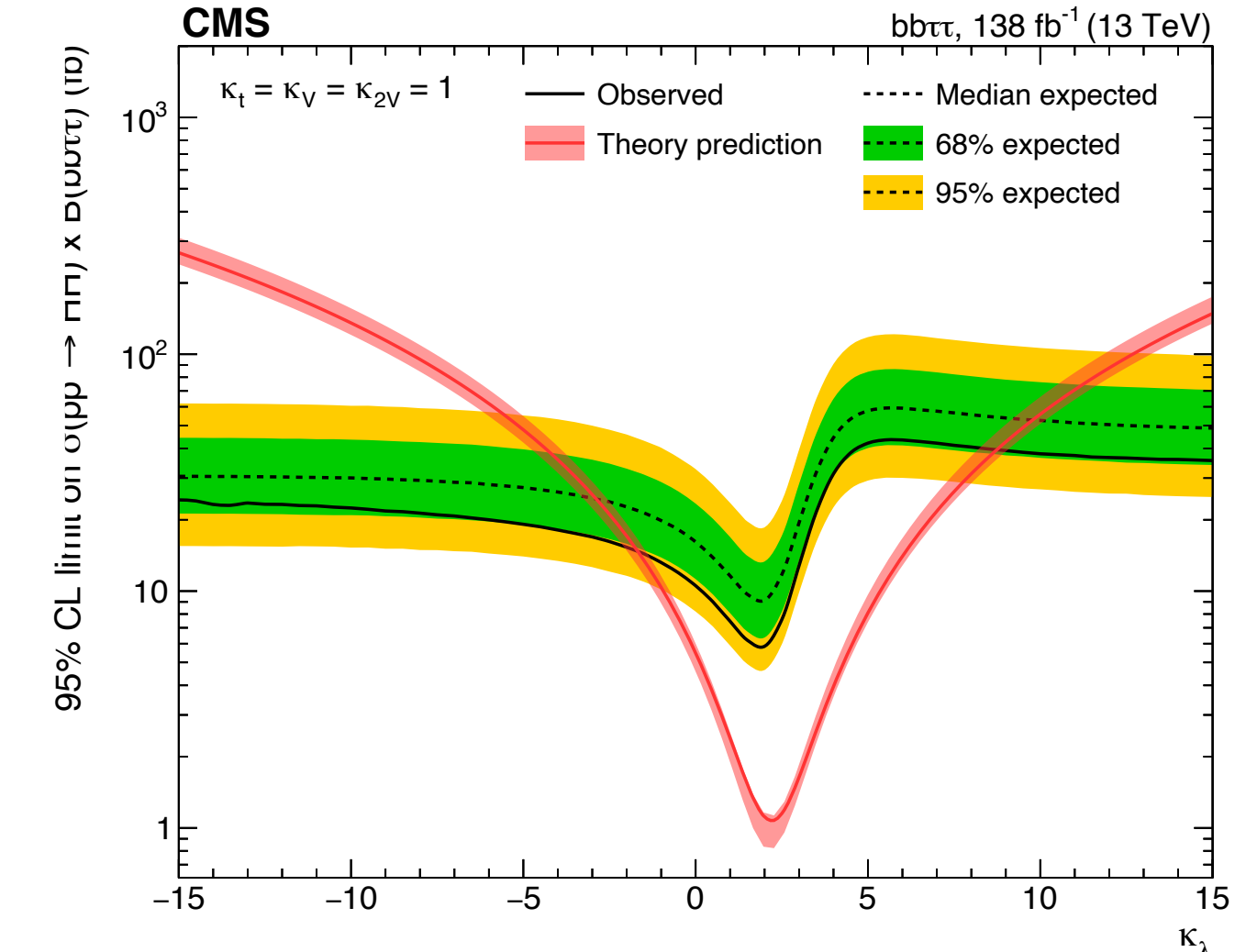
**Resonant X → HH**  
Full Run 2

B. Alves

- Improvement over existing CMS and ATLAS analyses
- Main overall driver of CMS sensitivity in intermediate mass range



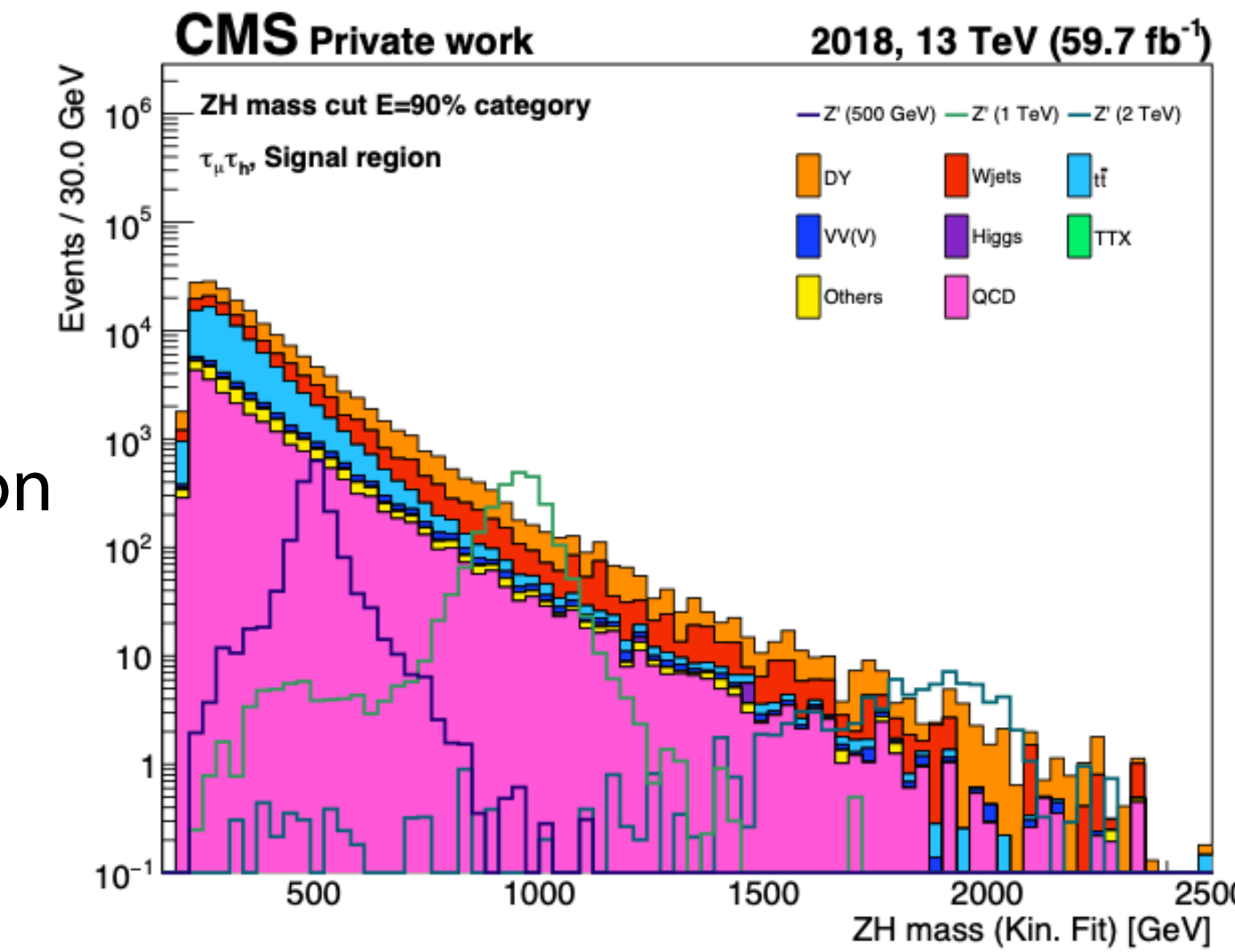
Constrain the Higgs self-coupling



**ZZ/ZH → bbττ**

- Full Run 2
- Measure SM production
- Search for high mass resonances

E. Vernazza



**Non-resonant HH(bbττ)**

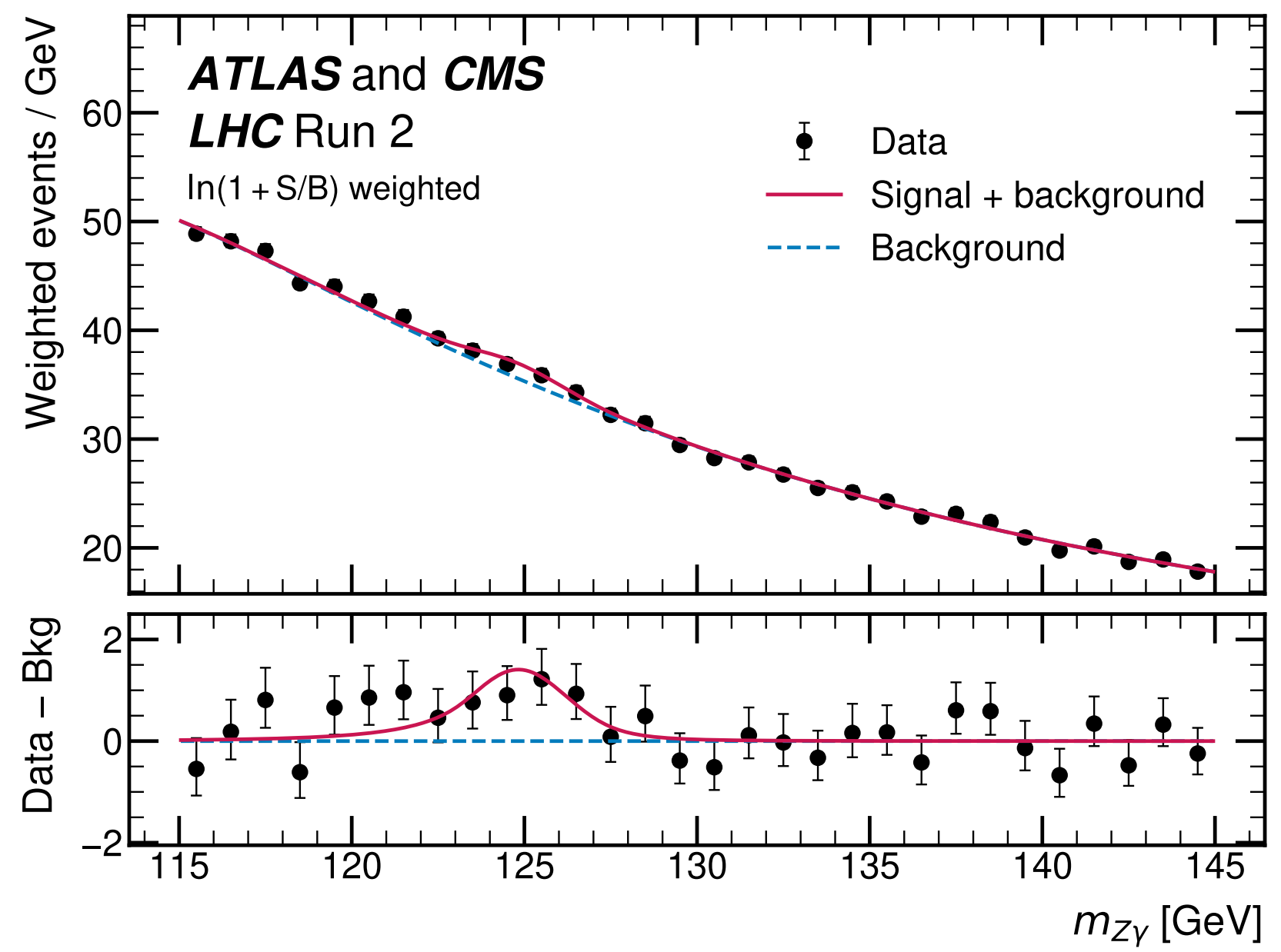
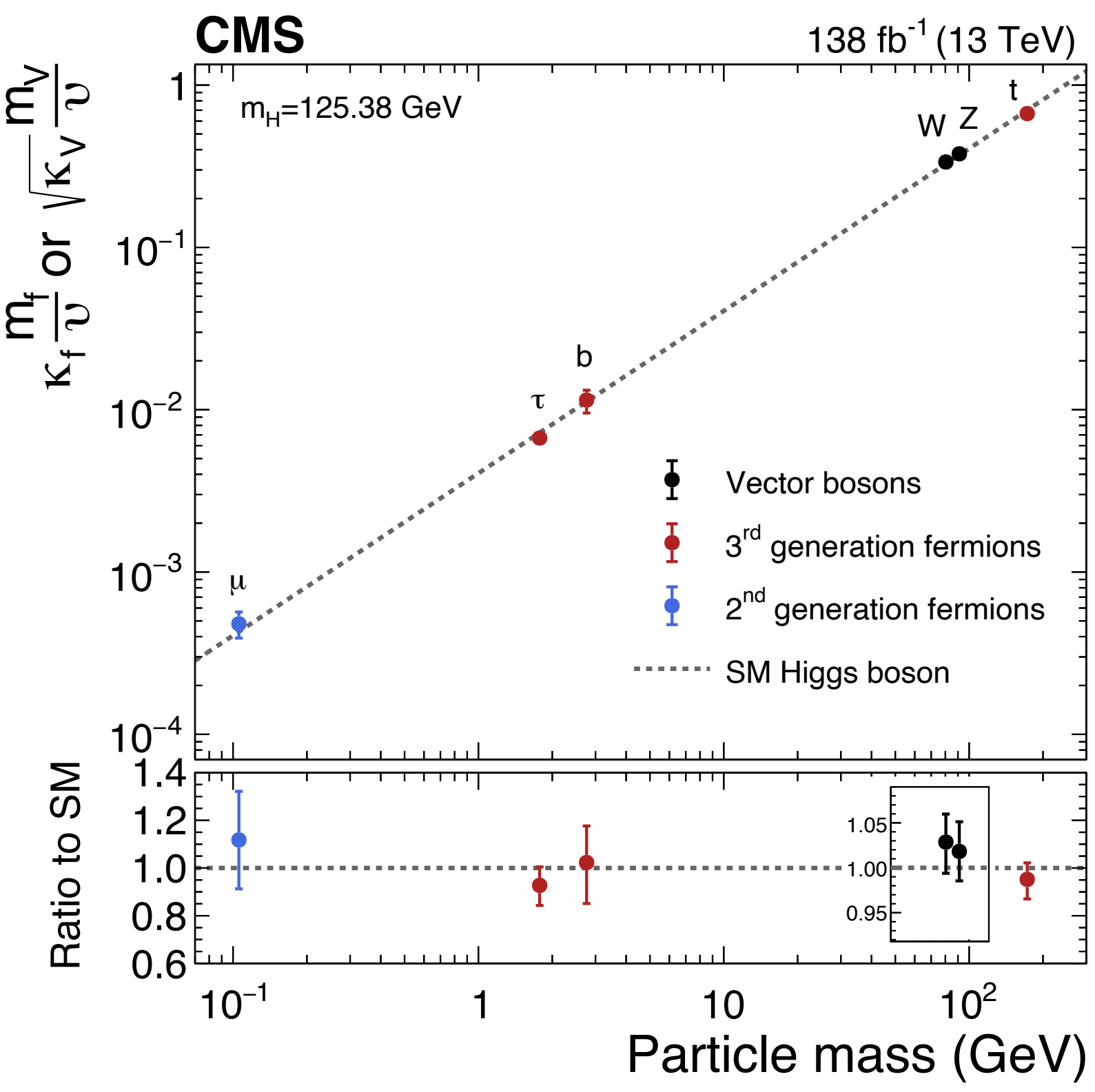
- Full Run 2
- Run 3 analysis underway

M. Chiusi T. Cuisset



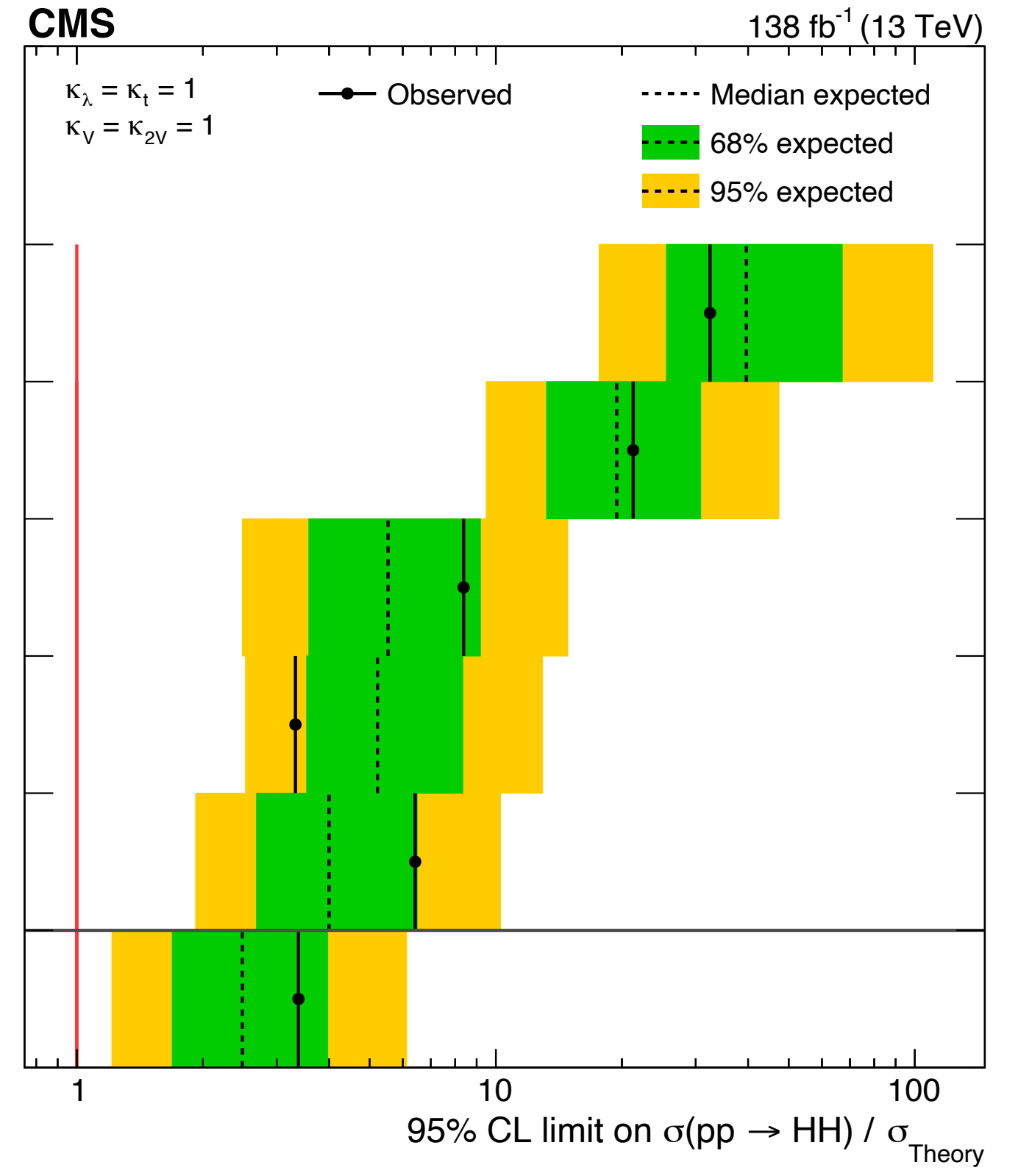
# Higgs properties & combinations

- Most precise measurements and limits come from combination of multiple channels
- Rare decay mode: main contribution in CMS+ATLAS  $H \rightarrow Z\gamma$  combination - first evidence!
- "Legacy" CMS combination of single Higgs production in Run 2 underway M. Manoni



Phys. Rev. Lett. 132 (2024) 021803

bb ZZ	Expected: 40	Observed: 32
Multilepton	Expected: 19	Observed: 21
bb $\gamma\gamma$	Expected: 5.5	Observed: 8.4
bb $\tau\tau$	Expected: 5.2	Observed: 3.3
bb bb	Expected: 4.0	Observed: 6.4
Combined	Expected: 2.5	Observed: 3.4



# Diboson & EFT

**Giacomo Boldrini**  
EFT forum convener  
2024-2026

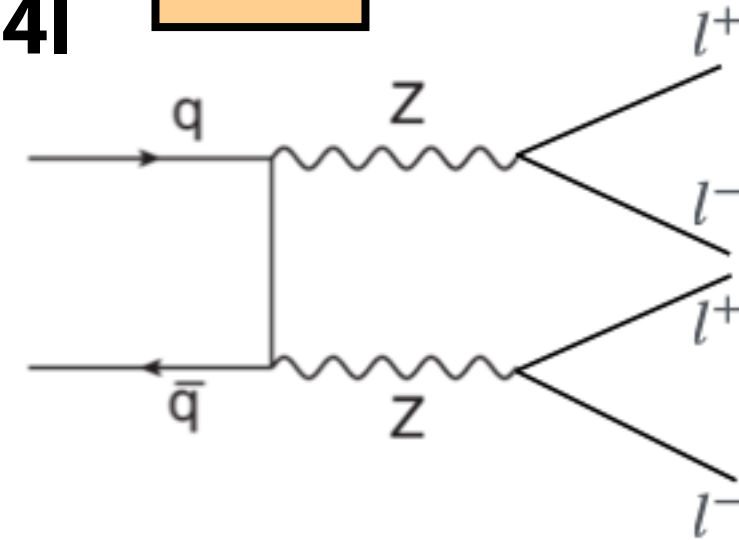
## EFT in $W\gamma$ diboson production

Run 3 analysis **T. Debnath**

⇒ Most sensitive to anomalous TGC

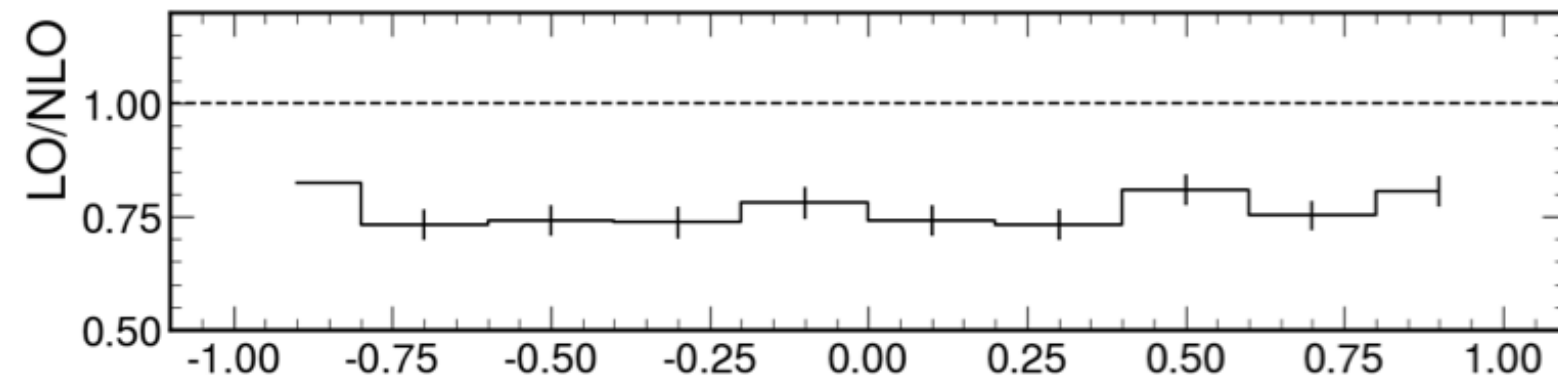
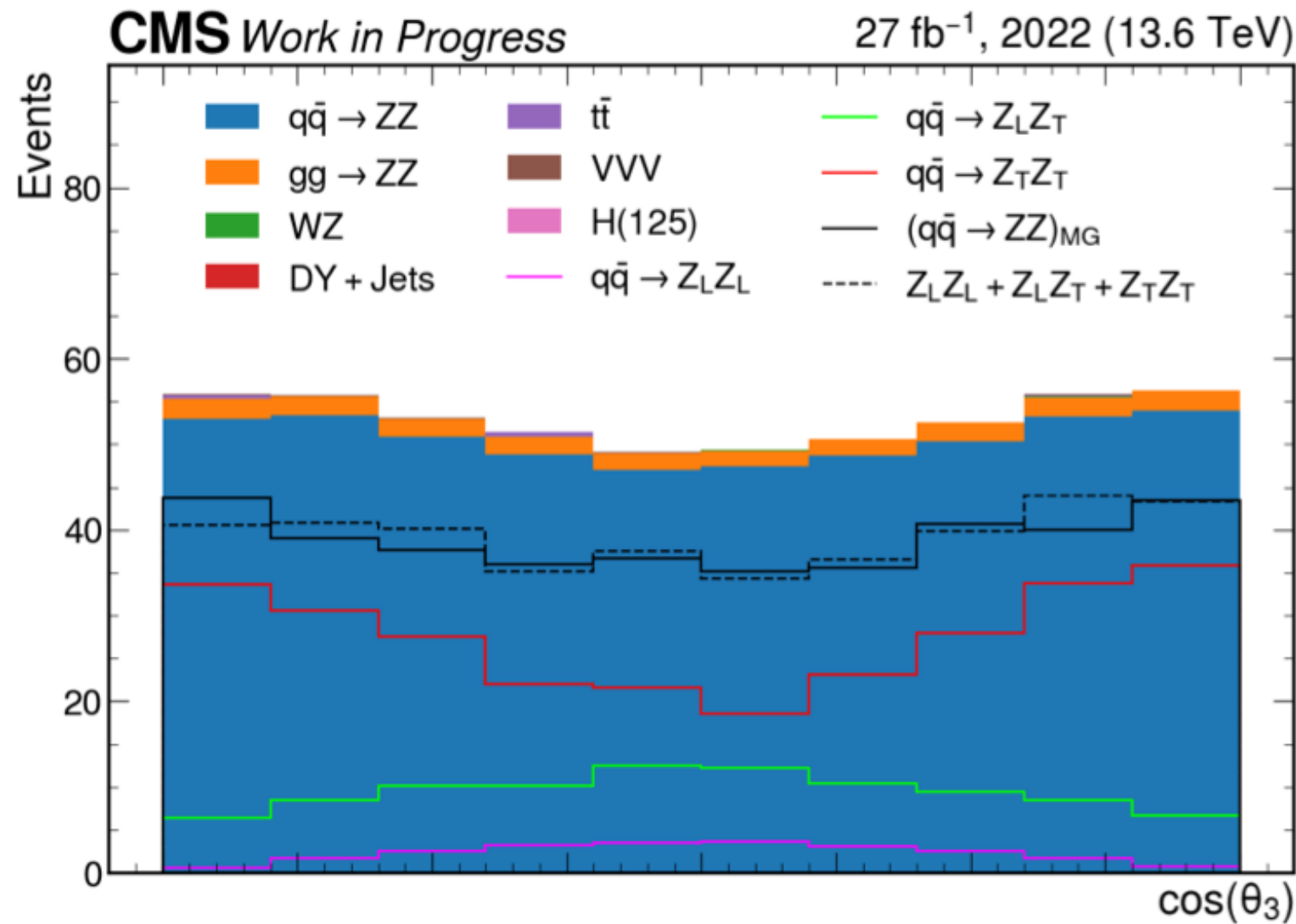
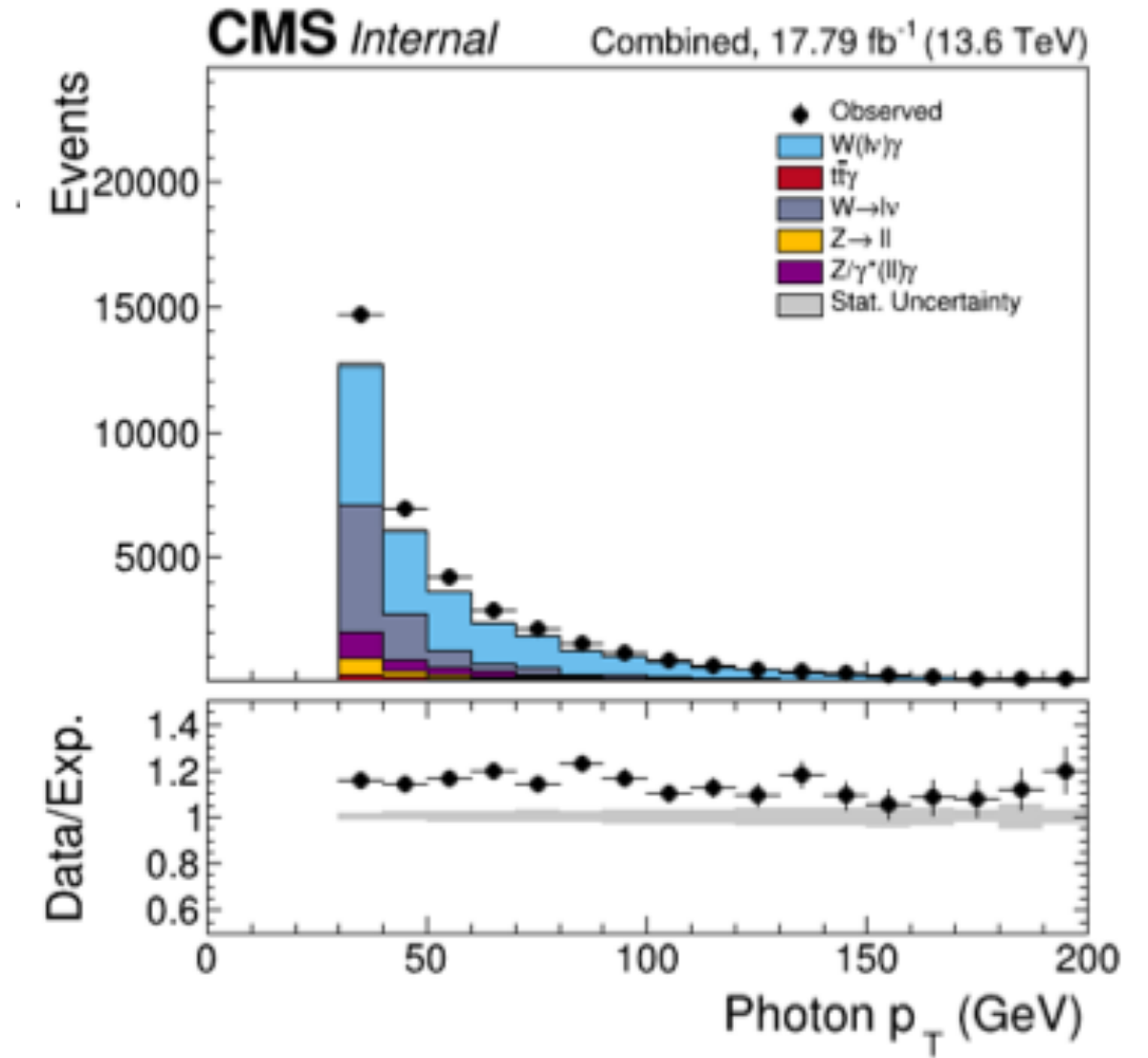
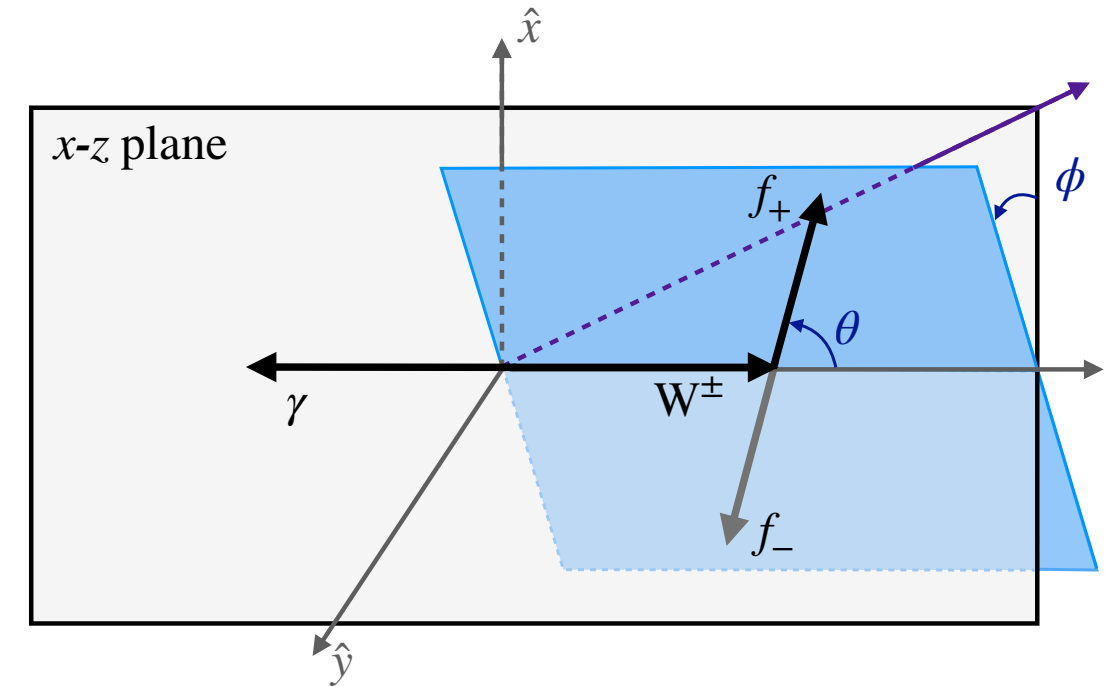
## Polarization fractions in $pp \rightarrow ZZ \rightarrow 4l$

I. Ehle



- Run 3 data
- Exploit angular information to extract longitudinal pol. fraction

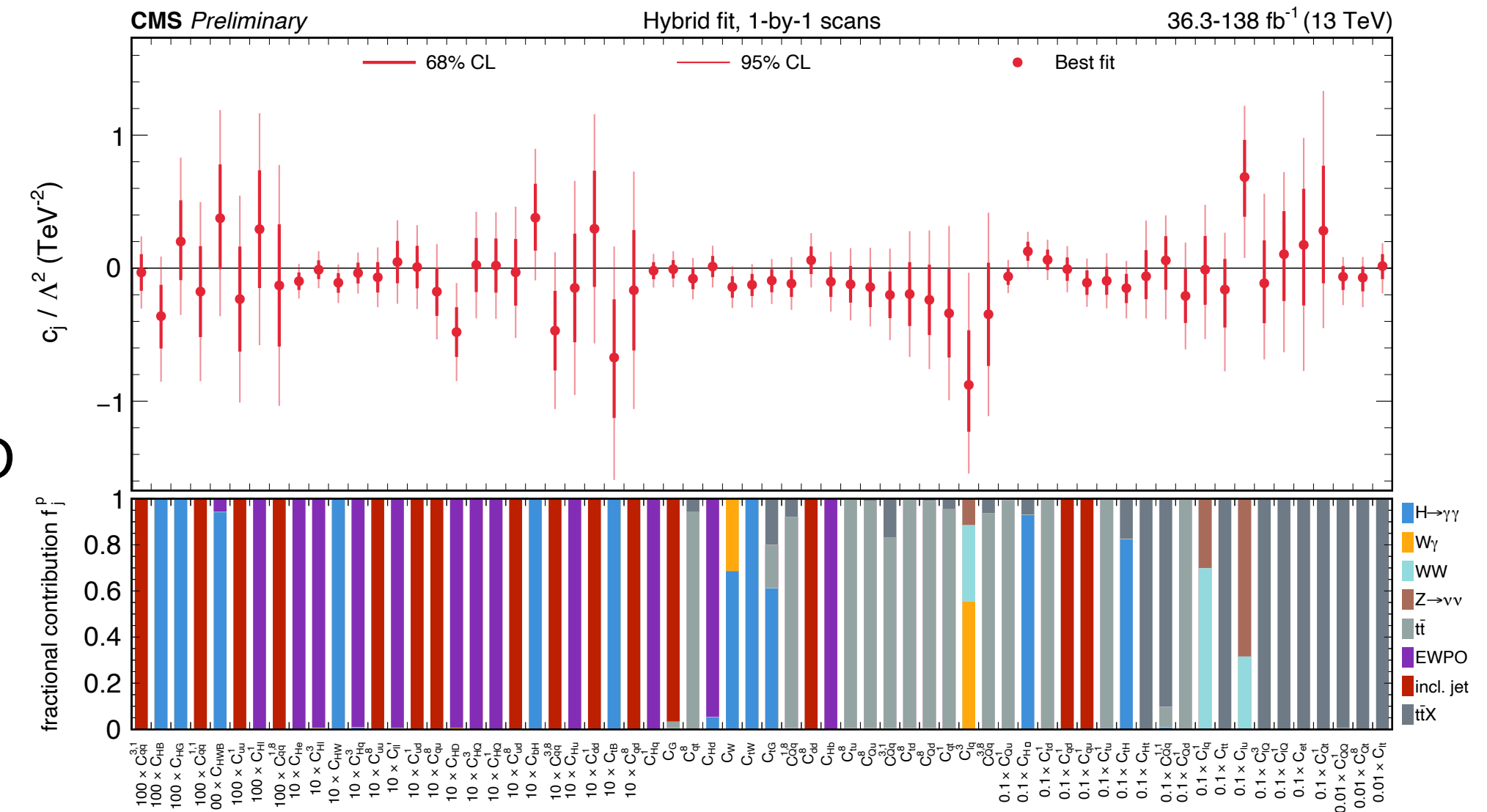
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \sum_i c_i^{(8)} \mathcal{O}_i^{(8)} + \dots$$



## Largest EFT combination to date

CMS-PAS-SMP-24-003

Combining measurements from Higgs + EW + top + QCD





# Group organisation & collaboration

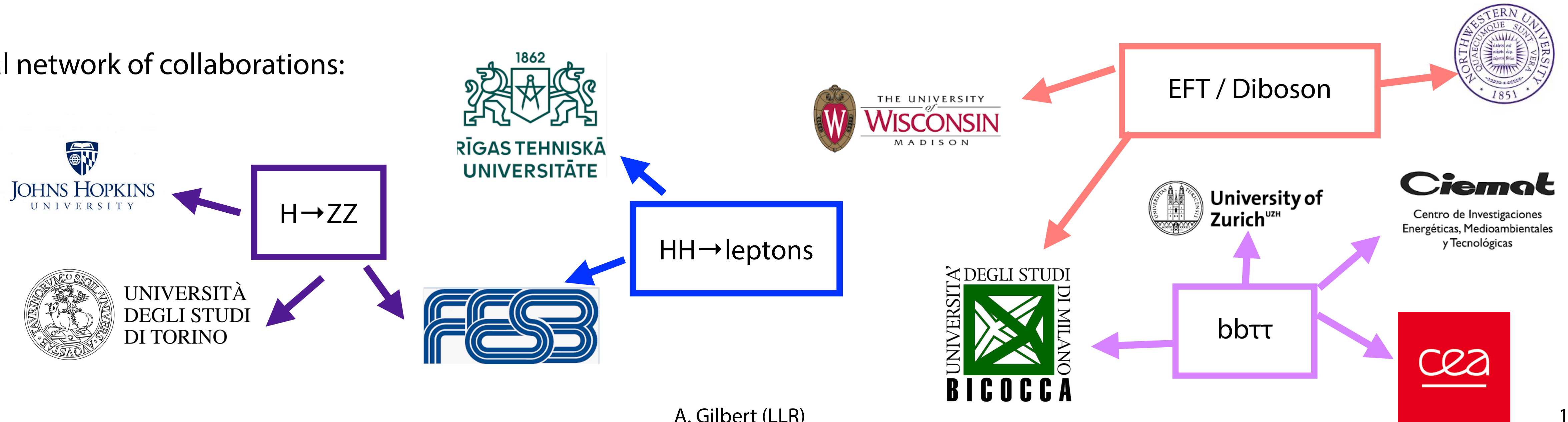
## November 2024

- Typical fortnight:

- Whole group every 4 weeks - review of data taking, roundtable of all activities & presentation highlight
- Regular working meetings (w/ collaborating institutes)
- + regular participation in official CMS meeting (status reports, pre-approval, approval etc)

	Mon	Tue	Wed	Thu	Fri
45	4	5	6	7	8
		CMS LLR group meeting HH multiboson meeting		4l (CJLST) meeting HH bbττ meeting	
46	11	12	13	14	15
				4l (CJLST) meeting EW bosons meeting	

- Global network of collaborations:



# Papers & Talks

- **Recent papers as main author(s) or with significant contributions**

Measurement of the Higgs boson mass and width using the four-lepton final state in proton-proton collisions at  $\sqrt{s} = 13$  TeV  
( Submitted to PRD )

Search for nonresonant Higgs boson pair production in final state with two bottom quarks and two tau leptons in proton-proton collisions at  $\sqrt{s} = 13$  TeV. Phys. Lett. B 842 (2023) 137531

A search for decays of the Higgs boson to invisible particles in events with a top-antitop quark pair or a vector boson in proton-proton collisions at  $\sqrt{s} = 13$  TeV. Eur. Phys. J. C 83 (2023) 933

Measurement of the W boson mass in proton-proton collisions at 13 TeV - CMS PAS SMP-23-002

Evidence for the Higgs boson decay to a Z boson and a photon at the LHC (Phys. Rev. Lett. 132 (2024) 021803)

Measurements of inclusive and differential cross sections for the Higgs boson production and decay to four-leptons in proton-proton collisions at  $\sqrt{s} = 13$  TeV. J. High Energ. Phys. 2023, 40 (2023)

A portrait of the Higgs boson by the CMS experiment ten years after the discovery. Nature volume 607, pages 60–68 (2022)

Performance of the CMS Level-1 trigger in proton-proton collisions at  $\sqrt{s} = 13$  TeV, CMS Collaboration, JINST 15 (2020) P10017

- ~ **20-30** talks per year at workshops and conferences on behalf of CMS



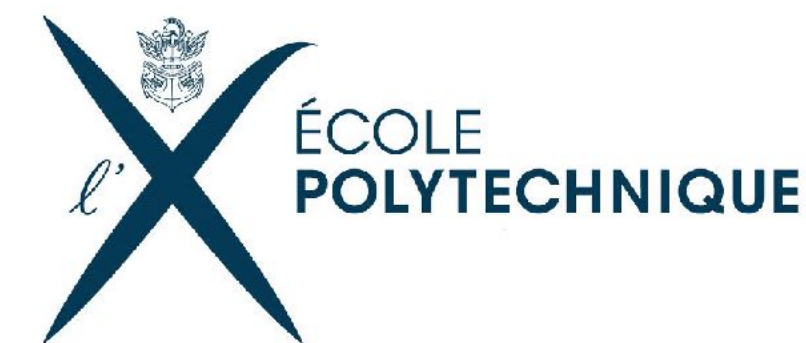
# Resources & funding

- **Computing:**

- All new arrivals provided with modern laptop (linux or mac)
- "Tier-3" farm with interactive nodes + **1600 batch cores**
- Access to **O(400) TB** storage
- + machines equipped with 4 **NVIDIA Tesla V100 GPUs** for machine learning applications

- **Funding:**

- **ANR** (2025-2029) - **COHERE** [Adinda de Wit]
- **CPJ** (2023-2026) - **STORM** [Andrew Gilbert, sub. Y. Sirois]
- **ANR** (2018-2023) - **HighGrants** [Jean-Baptiste Sauvan]
- **ANR** (2017-2020) - **HotShowers** [Matthew Nguyen]
- **ERC** - **QCDHighDensityCMS** [Matthew Nguyen & Leticia Cunqueiro]
- **Post-doc X** (1 year): [Shamik Ghosh, sub. F. Beaudette]
- **Eurotech cofund** (2022) - [Alessandra Cappati, sub. R. Salerno]
- **P2IO** 1/2 thesis (2022) - [Christophe Ochando]
- **CNRS-Imperial PhD Joint Programme** (2022-2025) [A. Zabi]



- Funding related to upgrades discussed in next talk





# Recognition

- **CMS Thesis prizes:**

- J. Motta (2023), M. Bonanomi (2021), C. Martin Perez (2020)

**CMS Awards 2023:**

- A. Zghiche (ECAL)
- E. Vernazza (HGCAL)
- J. Motta (L1Trig)

**CMS Awards 2019:**

- J. Rembser (O&C)
- L. Cadamuro (L1Trig)

**CMS Awards 2018:**

- A. Lobanov (HGCAL)



**Upgrade poster prize:** Théo Cuisset

**CMS Young Researcher Prize:** A. de Wit



**ICHEP poster prize 2024:** G. Liu



**CMS Young Researcher Prize:** M. Nguyen (2018)



# Other remarks

- **EPR & Shifts:**

- Group exceeds our quota of service pledges to the experiment
- Shift quota also fulfilled
- PhD students contribute from start of thesis and join author list within one year (6 months EPR)

- **Enseignements:**

- ~200h teaching at l'X/bachelor (Alexandre, Andrew, Roberto) + Adinda (from 2024)
- >24 h M2 courses (Christophe, Roberto)
- Projets de Recherche en Laboratoire at M1, bachelor (Adinda, Matthew)
- 6 students engaged in teaching: travaux de recherche en laboratoire, travaux pratiques (Bachelor), Ana & Andro teaching in Split

- **Students & postdocs regularly take advantage of 2-3 month ACV stays at CERN**

- **Very much appreciated ⇒ provides opportunity for sustained & direct collaboration**
- 2024: 13 months in total (5 persons)
- 2023: 10 months (4 persons)
- 2022: 6 months (3 persons)



# Outreach



**Masterclasses  
(2-3 sessions / an)**



**Fête de la Science**



PHOTOTHEQUE IN2P3 / CNRS



**+ 5 stages M1/M2 encadrés en 2024  
+ 3 stages Licence/Bachelor  
+ O(10) présentations aux élèves  
en stage de 3ème/2nde**