Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

HEP experimental

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(FPAUO, HEP-EX)

Jornadas del ICTEA 2025 - ICTEA Days 2025
19–20 Jun 2025
Edificio Histórico de la Universidad de Oviedo

Grants PID2020-113341RB-I00 PID2023-147115NB-I00 funded by GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

The **Oviedo HEP-EX** group, with some former members, as of May 30th, **Alejandro Soto** PhD disertation

The CMS experiment

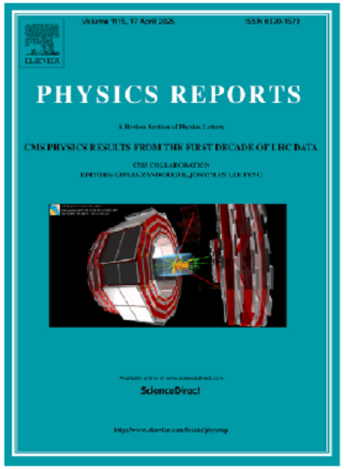
CMS has over 4000 particle physicists, engineers, computer scientists, technicians and students from around 240 institutes and universities from more than 50 countries.

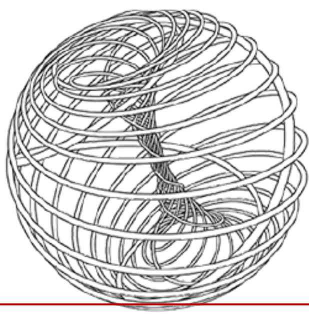
Two important things in 2025:

CMS Phys. Rep. [Link]

1. The Stairway to heaven
2. Stairway to discovery: cross section measurements
3. Review of top quark mass measurements
4. High density QCD
5. Searches for Higgs decays of heavy resonances
6. Dark sector searches
7. Vector like quarks, leptons and heavy neutral leptons
8. Searches through data scouting

Physics Reports, summary of Run 2





FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

CMS Collaboration

2025 Breakthrough Prize in Fundamental Physics:

For detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider.

The $1 million (of the $3 million prize) allocated to CMS was donated to the CERN & Society Foundation for grants to doctoral students from member institutes to spend research time at CERN.

CMS award for Carlos Vico (last week)

CMS Achievement Award for Carlos (for his work on MC in and beyond TOP)

+ Víctor Rodríguez
RSEF best hep-ex tesis 2023

The LHC mission

- <u>**Discovery of the Higgs boson**</u> or exclude the entire allowed mass range
- Find SUSY at the EW scale (or any other SUSY alternative, e.g., extra dimensions)
- Study the $W_L W_L$ scattering at TeV scale

LHC was built as the ultimate discovery machine, reflected by its initial mission:

- The strengths to reach the goals are unprecedented collision energy and luminosity which came with:
  - → **harsh environment characterized by high particle multiplicity and <u>pileup</u>**
  - → **computing and data handling challenges**

We are in an experimentally driven discovery era

Theories are needed, but we now take an approach that is "experimental" in essence.

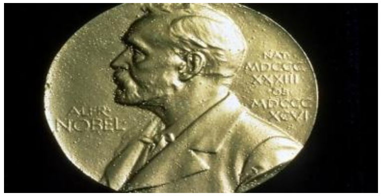
Higgs: Contribution to the observation in the WW channel

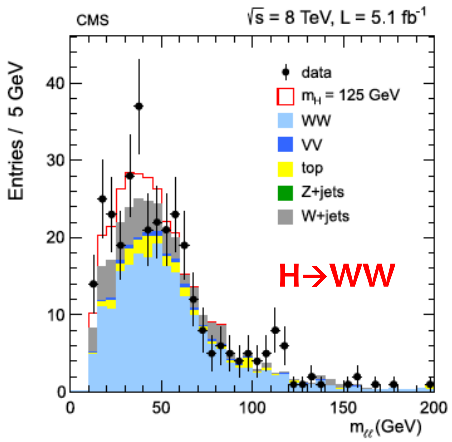
- Dileptonic channel:
  - 2011 analysis unchanged.
  - 2012 analysis with improvements in objects and methods to deal with the increase in pile-up. Cut-based analysis for ICHEP.
  - Shape analysis in eμ

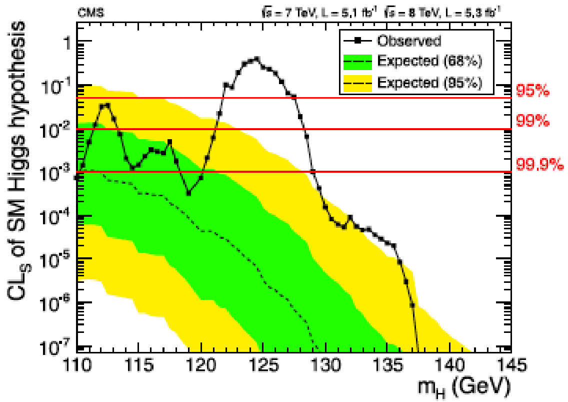
- **"This result constitutes evidence for the existence of a new massive state that decays into two photons."**

- **"Clear evidence for the production of a neutral boson … is presented."**

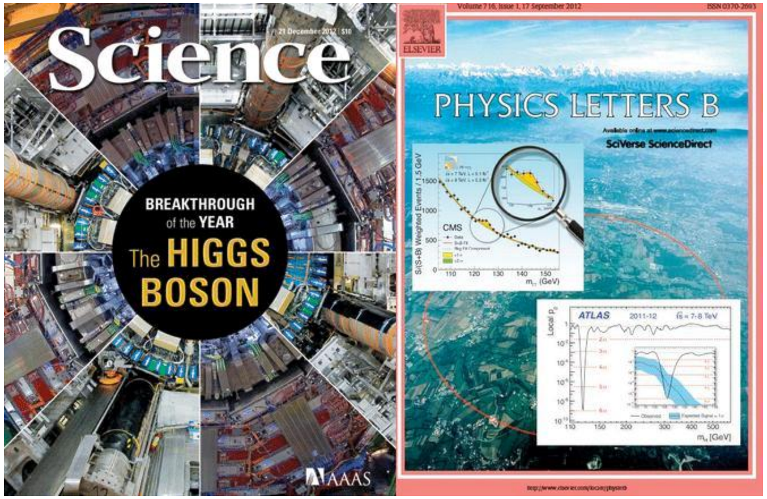
- **Goal for Runs 1-3 of the LHC and beyond:**
  - **Measure its mass and other properties including couplings**
    - **Is it alone?**







Exceso con una significancia estadística local observada de 5.0 σ (esperado de 5.8 σ)



Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC.
Physics Letters B. 716, pp. 30 - 61 (2012)

Immense and diverse physics program

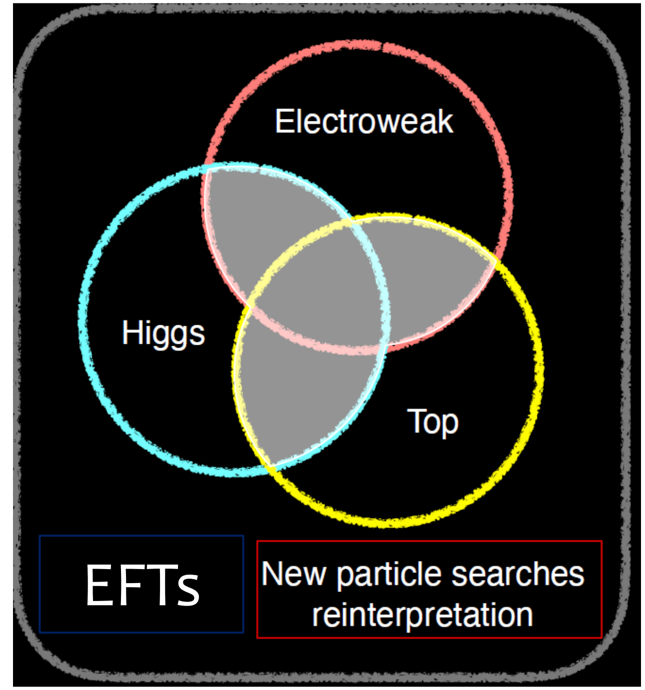
Experiments are pushing the boundaries of physics across multiple frontiers:

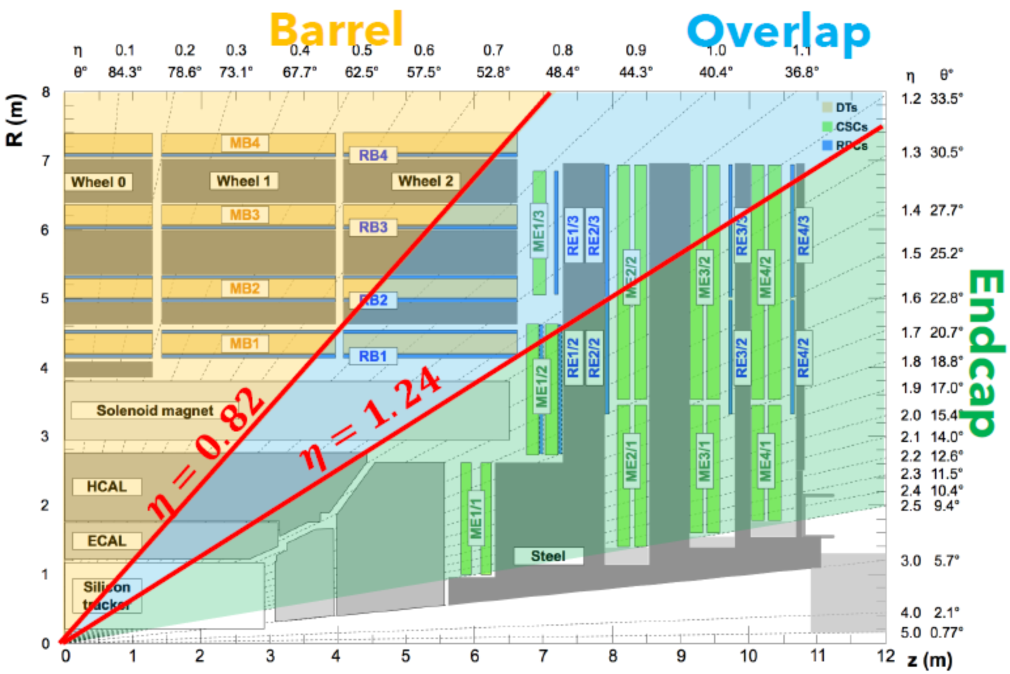
- **Energy Frontier**: searching for new physics up at the TeV scale.
- **Intensity Frontier**: investigating Higgs boson properties and EW phenomena.
  - Flavour Physics: ranging from testing CKM unitarity to hadron spectroscopy.
  - Heavy-Ion Physics: exploring high-density QCD and the Quark-Gluon Plasma.
  - Forward Physics: covering ultra-peripheral collisions, proton tagging, and more.

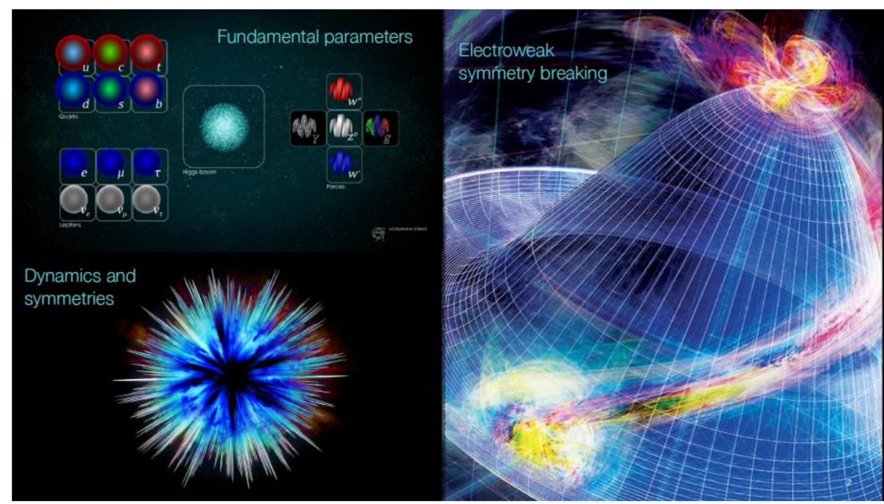
Driven by the outstanding performance and versatility of LHC experiments

An unexpected shift to precision physics has emerged. The experiments serve as key technology drivers, advancing areas like GPU reconstruction, real-time analysis, and AI.

- Oviedo main contributions:
  - Muon system, DT chambers, operation of the CMS detector.
  - L1 trigger.
  - Reconstruction, DQM, Machine learning, Monte Carlo, computing.
  - Physics:
    - Higgs, top quark, EWK, BSM searches.







Our contribution, as seen from the **CMS** collaboration: on average: **1/3 of the time of each researcher dedicated to the operation of the detector**

iCMS - EPR Institute Information for OVIEDO in 2024

iCMS DB search for OVIEDO --- iCMS DB members for OVIEDO

Hide details

Summary of the institute (ALL members, in EPR months (*))

Work Due :	**47.62**
Work done :	**72.00**
EPR (all) Shifts done :	**12.74**
Central Shifts done :	**4.49**
Work + EPR (all) Shifts done :	**84.74**
Ratio done/Expected :	**1.78** (EPR work plus Shifts done)/(AuthorDue)

# of Authors (not counting CMSEMERITUS)	11.90	**Work Due by Authors**	47.62	**Total CSP needed (nominal)**(Central Shift Credit points)	3.90
# of Applicants (new members)	2.00	**Work Due by Applicants**	0.00		
ShiftsPld:	12.74			**ShiftsDone:**	12.74
centralShiftsPld:	4.49			**centralShiftsDone:**	4.49
Author EPR **pledged** fraction pledged [%]	75.00 158	**Author** EPR **accepted** fraction accepted [%]	72.00 151	**Author** EPR **done** fraction done [%]	72.00 151
Applicant EPR **pledged** fraction pledged [%]		**Applicant** EPR **accepted** fraction accepted [%]		**Applicant** EPR **done** fraction done [%]	

(*) Central Shift Points (CSP) are converted to EPR months by: EPRmonths = CSP * 0.046. EPR done includes shifts.

green: more than 100% of expected work done
orange: 90%-100% of expected work done
red: < 90% of expected work done
Cooperating institute, no due, but can do EPR
Associated institute, no due, but can do EPR

The members of the group mainly develop their activities within the CMS experiment at the CERN LHC that by themselves constitutes an exceptional and unique scientific environment.

As a key performance indicator for the **last 5 years, 2020-2024**, the group has delivered:

- **31 published papers** in Q1 journals, mainly JHEP, EPJC, PRD and PRL: 4 Higgs physics (ttH, and one in Nature 607 (2022) 7917, 60-68,), 10 top quark physics (tt, tW, ttW, EFT), 2 of them on LHC Run 3 data, 5 BSM searches, 5 SM physics, 1 MC modeling, 2 CMS muon performance and trigger, 1 on CMS Muon DT system, 1 on Machine Learning.
- **4 close to completion analyses** (expected to be published in 2025): study of the ttH differential production (HIG-23-015), ttW differential (TOP-24-003) both based on LHC full Run 2 data, single top (TOP-24-011) on 5 TeV low PU data sample, and one on trigger EXO-23-016. **Three other early Run 3** measurements on single top t-channel, ttH and ttW, and **one on tt+tW (the "bb4l")** on Run 2 data.
- **65 presentations in international conferences** (01/01/2020 to 31/12/2024) (1 LeptonPhoton, 1 EPS, 6 LHCP, instrumentation, Moriond, TOP2022,23,24 SUSY2022,23,24 La Thuile, and others), 36 posters in international conferences (2 ICHEP, 3 EPS, 2 LP, 2 LHCP, and others), and **25 oral presentations in national workshops/conferences** (Winter meeting (IMFP), CPAN, LHC network, Bienal RSEF).
- **2 RyC positions** became **professors at UO** and an additional **one RyC** joined the group in 2023.
- **7 PhDs** and 6 ongoing.
- Several positions of responsibility (**L2 and L3 conveners of the LHC CMS collaboration**).
- Santi F. obtained an **ERC Starting Grant (INTREPID)** to explore innovative trigger technologies that may improve the discovery potential of BSM physics. The ERC is complementary with the goals of the group.

Upgrade Muon Projects

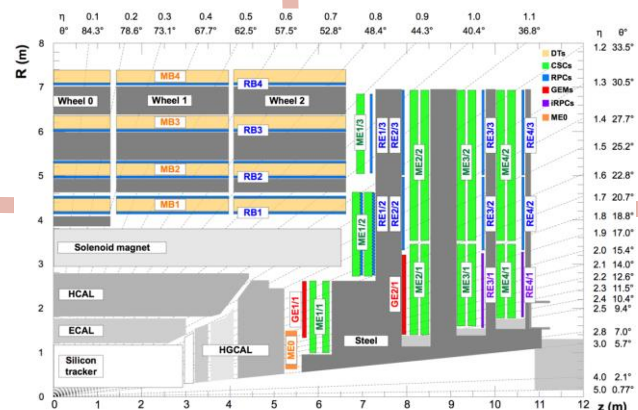
Drift Tubes (DTs)

- The front-end and readout electronics are **being replaced** with more modern, radiation-hard components
- The new electronics offer **improved time resolution**, lower noise, and **full digitization of signals**, enabling better offline analysis and triggering

New **O**n **B**oard electronics for **DT**s (**OBDT**):
- 650 (+250 spares) OBDT-phi boards
- 180 (+60 spares) OBDT-theta boards

Cathode Strip Chambers (CSCs)

- Upgrade of On-Chamber Electronics:
  - New front-end boards (CFEBs) with improved analog performance and digital readout
  - New Optical Data Motherboards (180 ODMBs) and Trigger Motherboards (TMBs)
- Data **bandwidth, timing resolution,** and **triggering precision** improvements



Resistive Plate Chambers (RPCs)

- **Extend coverage** into higher η regions
- New **I**mproved **RPCs** (**iRPCs**) are being installed in the endcap region: 72 chambers in total
- **iRPCs** are designed to work under higher particle fluxes and radiation doses expected at HL-LHC
- Use thinner gas gaps (1.4 mm) and operate at lower high voltage

Gas Electron Multipliers (GEMs)

- **Enhance muon detection** in the forward region and extend it to previously uncovered regions
- Improves the Level-1 trigger resolution and reduces fake rates
- The ME0 station will consist of **36 stacks** of triple-GEM detectors, with each stack comprising **six individual GEM detectors**

CMS Coordinator: **Bárbara Álvarez,**

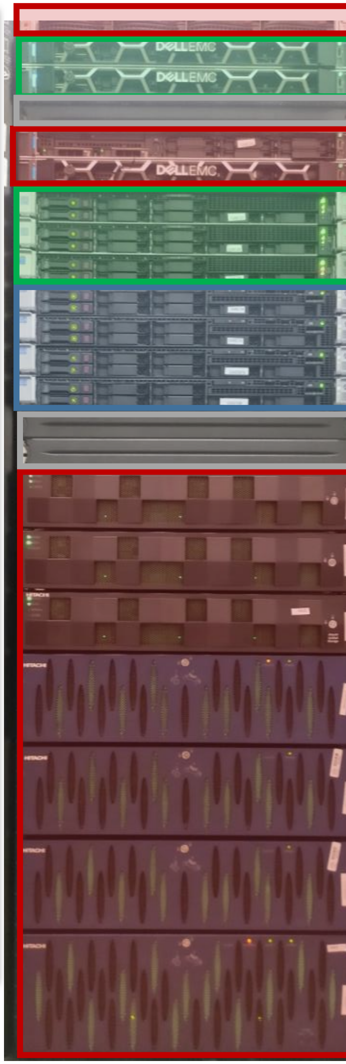
Isidro G., Santiago F., Javier F., with different responsibilities in the muon system

Computing

- **Key infrastructure** for our participation in the CMS experiment:
  - Tier-3 like (WLCG) infrastructure built over 15 years
  - Mainly at C^3 but also at F. Geology
- Mainly for **analysis**, but also **trigger** studies, **DQM**, **upgrade** (trigger and online SW),…
  - And, of course, academics: TFG, TFM,…
- **Computing**: ~600 slots in SLURM
  - And 250 threads in desktops, 200+ threads in services
  - **+250 slots** after summer
- **Mass Storage**: ~250 TB (real) in 3 storage systems
  - Connected at 10Gbps to computing nodes
  - File system accessible from "everywhere" (NFS + Lustre)
  - **+100 TB** after summer
- Switches, racks, PDUs, SAIs, …
  - And a Videoconference room
- Very close relation with Tier-2 @ IFCA & CIEMAT that provides extra computing and storage resources if needed

A plethora of services

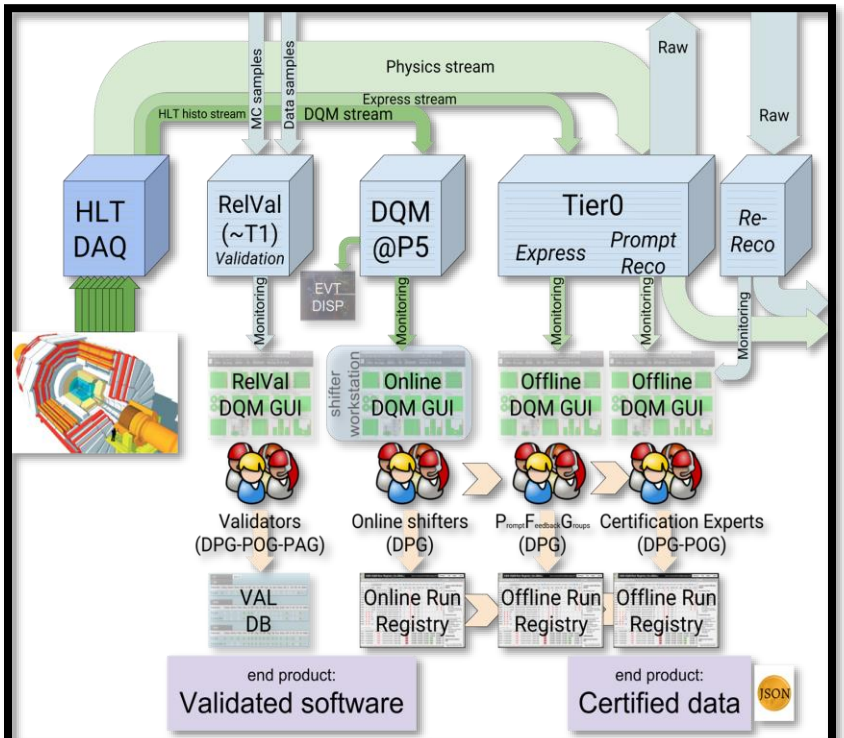
- **Storage**: NFS (disk sharing), Lustre (distributed file system)
- **Central access and authentication**: HAProxy and FreeIPA
- **CMS Specific**: FroNTieR (proxy) and CVMFS (experiment common software)
- **User services**: Apache web Server, Wiki, FlexLM (licenses)
- **Monitoring**: Ganglia and Grafana/Prometheus (developing)
- **Virtual Machines**: KVM (3 servers)
- **Backup**: Only user space

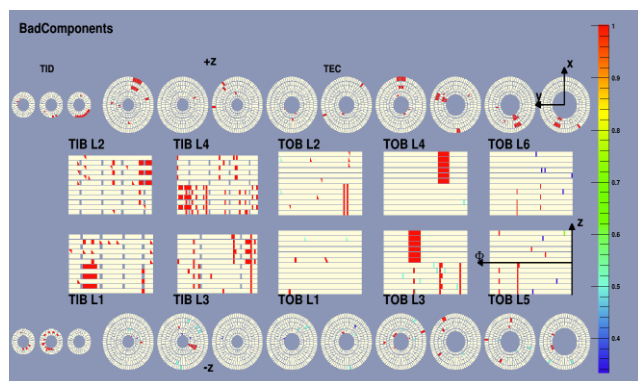


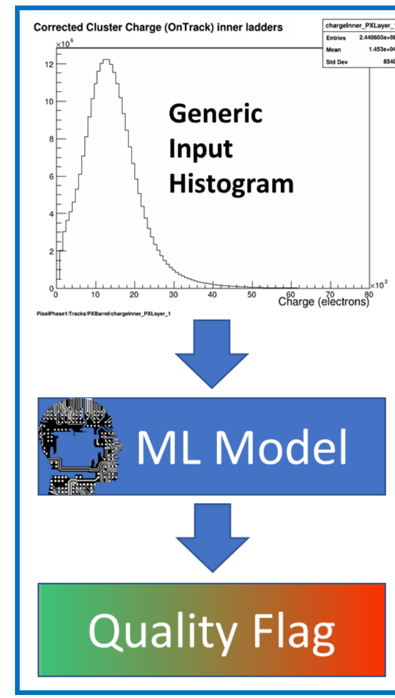
Long term responsible: **Isidro González**, with help from many

Data **Quality** Monitoring (DQM):
L2 position (Javier F.) **2017-2021** (coordinating ~200 people)

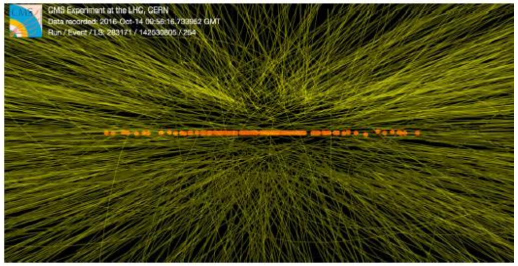
From DQM **Manual Certification** (humans) →→→
~**Automatic Certification** with ML (ML4DQM)



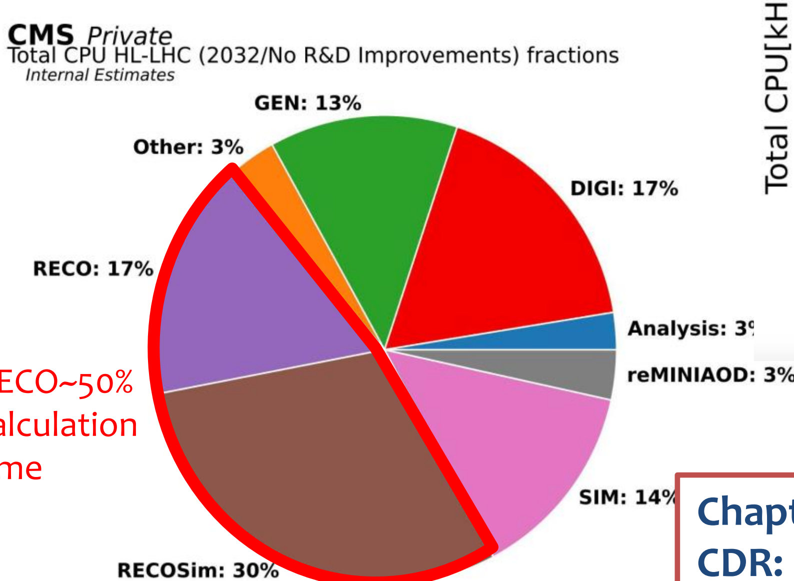




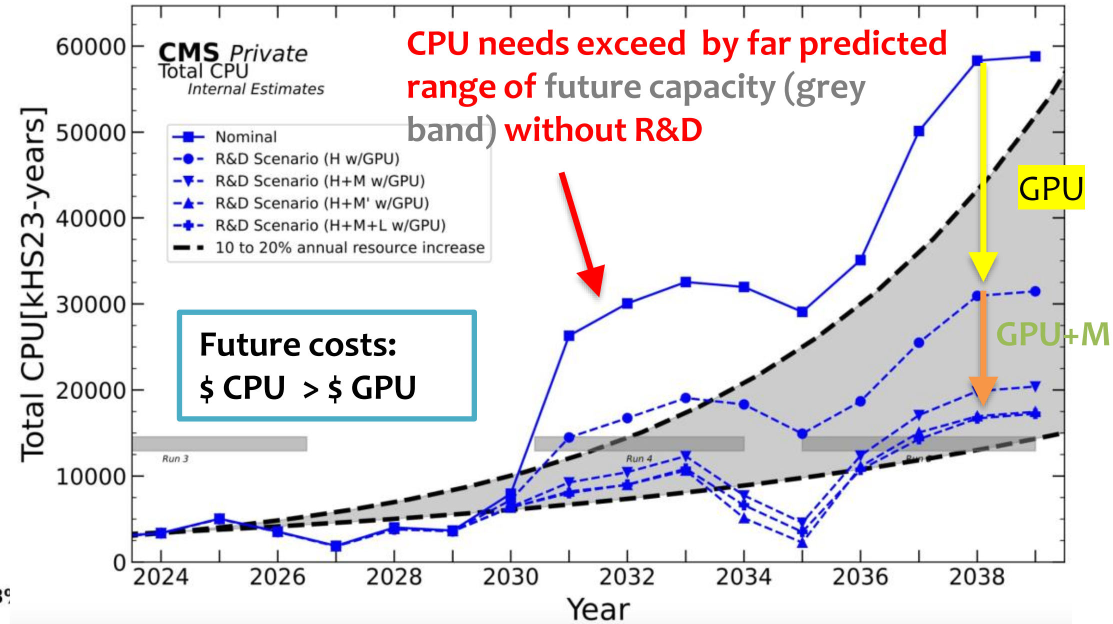
L2 (Javier F.) in Reconstruction (2023-…)



Need for heterogeneus computing (CPU+GPUs) and machine learning (ML)



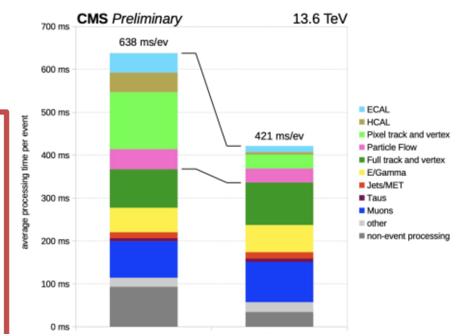
RECO~50% calculation time



CPU needs exceed by far predicted range of future capacity (grey band) without R&D

Future costs:
$ CPU > $ GPU

Chapter 8 of CDR:
- Key: SW using GPUs, R&D
- Speed gain x 2



Code optimization, vectorization, offload to GPUs 35% of computing

Offload to GPUs 65% of computing + ML inference

LHCtopWG

❖ Forum for discussions between the theory and exp. community at the LHC

➢ Open meetings twice a year and on-demand specific seminars

❖ Coordinators: F. Maltoni (Theory), **Enrique Palencia (CMS)**, K. Müller (LHCb), M. Vos (ATLAS)

❖ Public Twiki page at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG

❖ Povide **combinations** of LHC top-quark physics results (mainly by ATLAS and CMS)

➢ Reach highest precision and provide a unified experimental answer to the theory community

➢ Compare results in a coherent way and understand possible differences

→ Requires **detailed understanding** of analysis methodology, theoretical models used, categories of systematic uncertainties and correlations

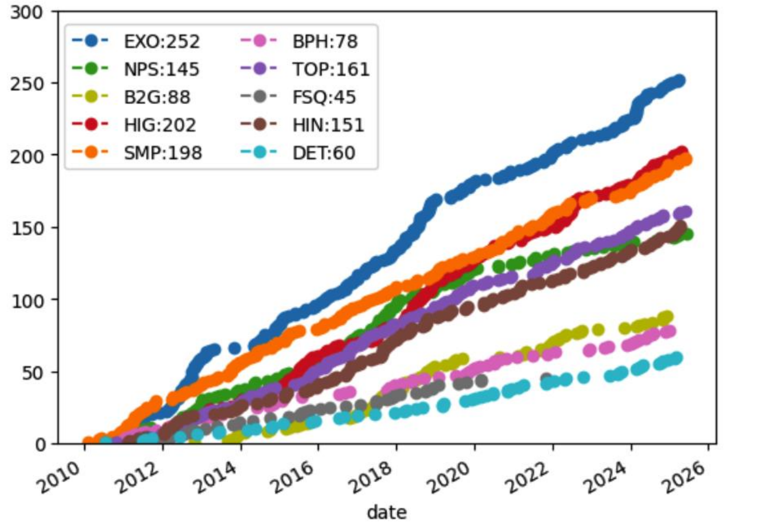
❖ Provide **summary plots** of experimental results in comparison to theory predictions)

➢ https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

❖ Provide recommendations and guidelines

➢ **Reference cross sections** as a common basis for measurements

➢ **Harmonize prescriptions** to facilitate comparisons and combinations



CMS publications

Run 3 data (2022-2026)

Run 3 Publications

15	TOP-24-012	Search for CP violation in events with top quarks and Z bosons at $\sqrt{s} = 13$ and 13.6 TeV	Submitted to PLB	27 May 2025
14	SMP-24-015	Measurement of WWZ and ZH production cross sections at $\sqrt{s} = 13$ and 13.6 TeV	Submitted to PRL	26 May 2025
13	HIG-23-014	Measurements of inclusive and differential Higgs boson production cross sections at $\sqrt{s} = 13.6$ TeV in the $\mathrm{H} \to \gamma\gamma$ decay channel	Submitted to JHEP	24 April 2025
12	HIN-24-009	Observation of coherent $\phi(1020)$ meson photoproduction in ultraperipheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV	Submitted to PRL	6 April 2025
11	SMP-22-017	Measurements of the inclusive W and Z boson production cross sections and their ratios in proton-proton collisions at $\sqrt{s} = 13.6$ TeV	Submitted to JHEP	12 March 2025
10	HIG-24-013	Measurements of Higgs boson production cross section in the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13.6$ TeV	Accepted by JHEP	24 January 2025
9	MUO-24-001	Identification of low-momentum muons in the CMS detector using multivariate techniques in proton-proton collisions at $\sqrt{s} = 13.6$ TeV	JINST 20 (2025) P04021	2025-04-17
8	SMP-24-005	Measurement of the inclusive WZ production cross section in pp collisions at $\sqrt{s} = 13.6$ TeV	JHEP 04 (2025) 115	2025-04-16
7	EXO-23-013	Search for light long-lived particles decaying to displaced jets in proton-proton collisions at $\sqrt{s} = 13.6$ TeV	ROPP 88 (2025) 037801	2025-02-03
6	TOP-23-008	Measurement of inclusive and differential cross sections of single top quark production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13.6$ TeV	JHEP 01 (2025) 107	2025-01-21
5	HIN-23-007	Pseudorapidity distributions of charged hadrons in lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV	PLB 861 (2025) 139279	2025-01-20
4	SMP-24-001	Measurement of inclusive and differential cross sections for W^+W^- production in proton-proton collisions at $\sqrt{s} = 13.6$ TeV	PLB 861 (2025) 139231	2024-12-31
3	EXO-23-014	Search for long-lived particles decaying to final states with a pair of muons in proton-proton collisions at $\sqrt{s} = 13.6$ TeV	JHEP 05 (2024) 047	2024-05-06
2	PRF-21-001	Development of the CMS detector for the CERN LHC Run 3	JINST 19 (2024) P05064	2024-05-23
1	TOP-22-012	First measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 13.6$ TeV	JHEP 08 (2023) 204	2023-08-30

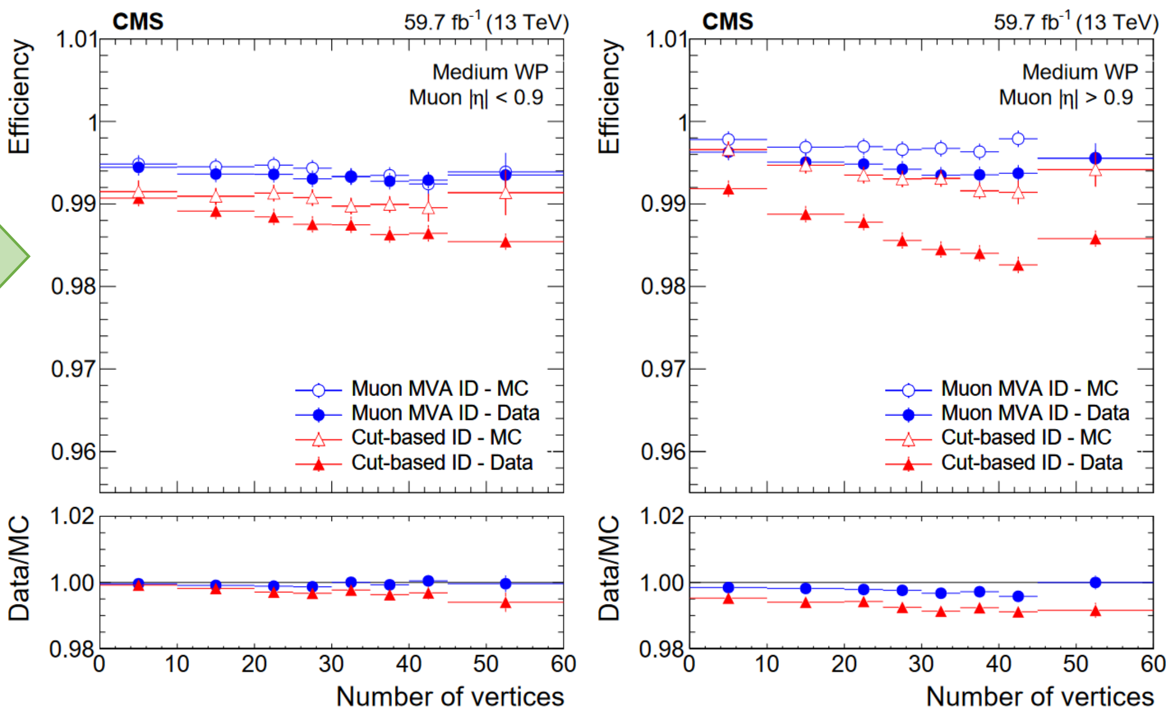
MUON MVA ID

2024 JINST 19 P02031

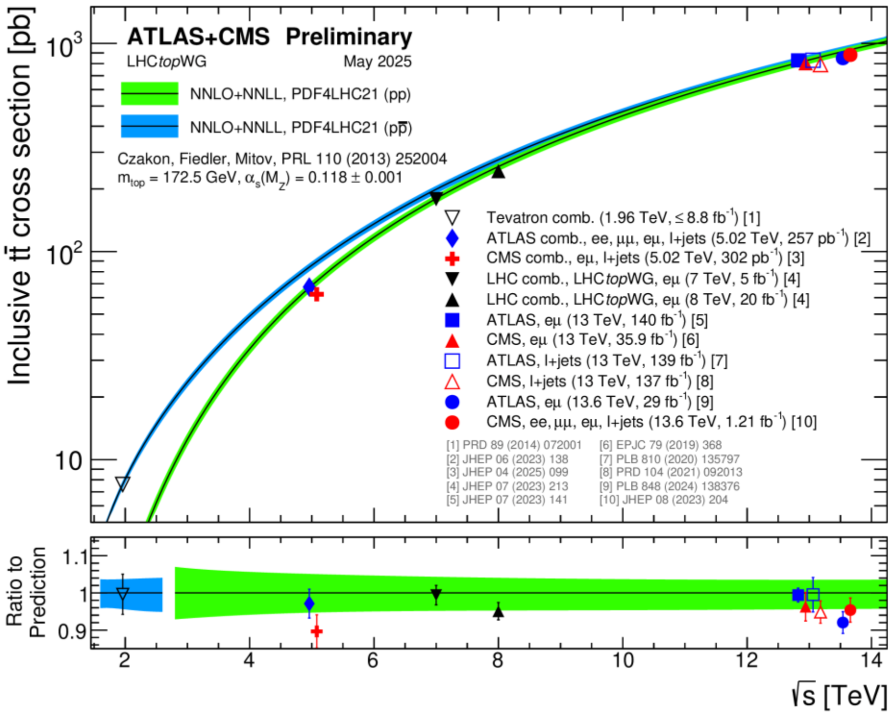
Efficiency as a function of number of PV

Medium MVA ID:

- Eff above 99% for all the PU range evaluated
- MVA is **more resilient to PU increase** than the cut-based ID → Crucial given the run 3 conditions

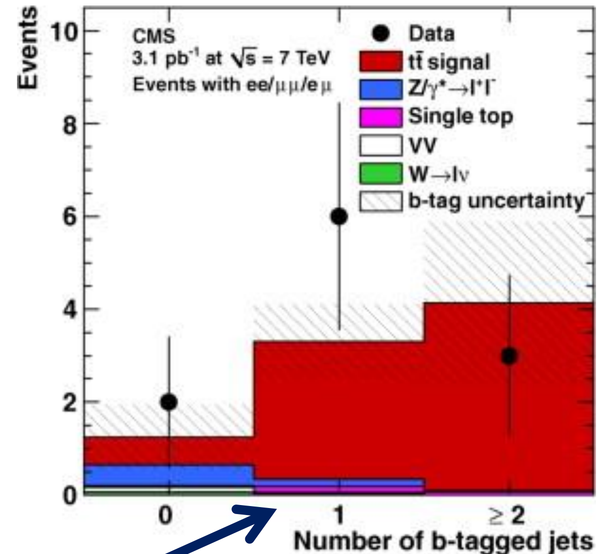


Top quark cross section measurements (2010-now)



LHCTopWG - LHC Top Physics Working Group

Contact person for CMS: Enrique Palencia



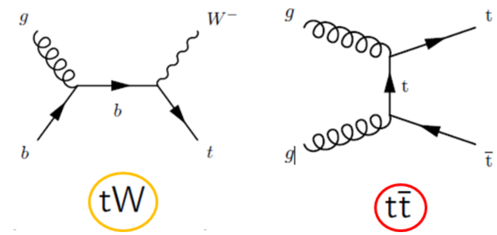
>20 papers on the subject at **all LHC CM energies** including LOW PU 5 TeV data

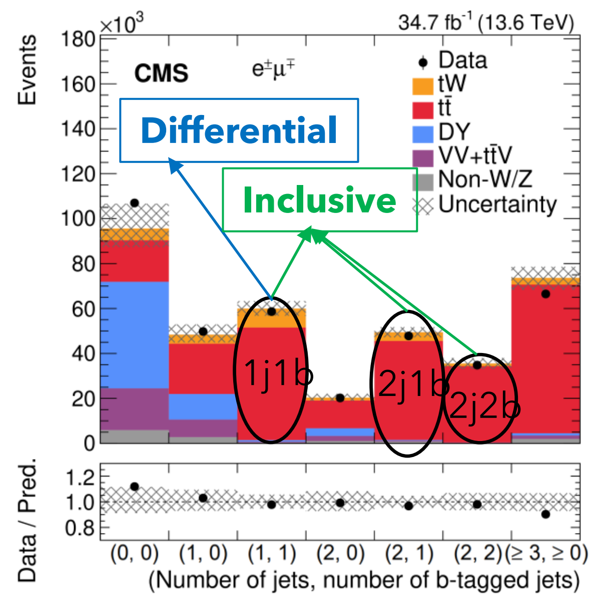
- http://dx.doi.org/10.1016/j.physletb.2010.11.058 **first at LHC**: (**using 0.0031 fb^{-1} of data at 7 TeV !!!**)
- http://dx.doi.org/10.1103/PhysRevLett.116.052002 **first at 13 TeV**:
  - Report of Referee A -- **The absence of new physics in top pairs at 13 TeV throws a significant bath of cold water on many models. This is a very significant result.** It is quite well written, even with all the necessary citations. Some speculations on impact would be ok, but then it is also ok to leave that to phenomonologists. Report of Referee B -- The measurement of the t t bar cross section provides an important test of the Standard Model since discrepancies may hint to new physics. The result reported in this letter is **the first measurement at 13 TeV, the highest energy ever produced in an accelerator and** thus deserves publication in PRL.

Contributions from all: Bárbara, Javier F., dR., C., Carlos, Alejandro, Jorge, Miguel, and in the past, Sergio (convenor of the CMS TOP group), Víctor, Xuan, Andrea, Clara, Santi, Rebeca, Patricia, Chus

tW inclusive and differential cross section measurements at 13.6 TeV

- **First** measurement of the **tW** process at $\mathbf{13.6\ TeV}$ and one of the first measurements done in Run 3 using the full 2022 dataset with $34.7\ \mathrm{fb}^{-1}$ of int. luminosity.
- **Main challenge**: irreducible $t\bar{t}$ background largely dominates signal contribution.
  - At NLO **tW** can contain an additional bottom quark and interfere with $t\bar{t}$ production.
- **Event selection:**
  - $e^{\pm}\mu^{\mp}$: the two leading leptons must be an electron and a muon of opposite charge.
  - Leading lepton $p_T > 25\ \mathrm{GeV}$ and subleading lepton $p_T > 20\ \mathrm{GeV}$.
  - All lepton pairs must satisfy $m(\ell_1, \ell_2) > 20\ \mathrm{GeV}$.
- We further classify our events based on the number of jets and b tagged jets.
  - The 1j1b, 2j1b and 2j2b regions are used for the inclusive measurement.
  - The 1j1b region is used for the differential measurement.





aN³LO

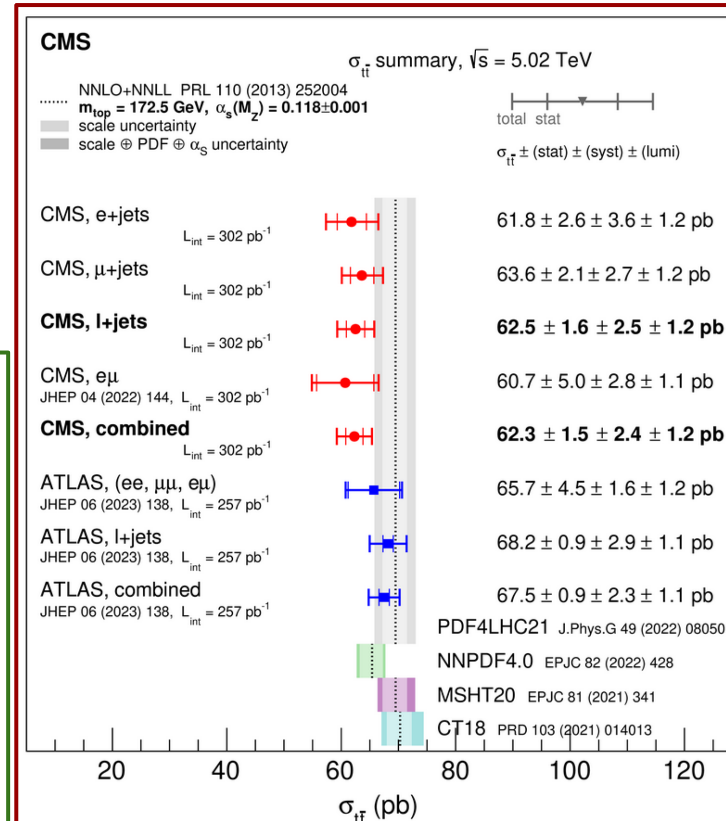
JHEP05 (2021) 278

$$\sigma_{tW}^{SM} = 87.9^{+2.0}_{-1.9}(\text{scale}) \pm 2.4(\text{PDF} + \alpha_S)\ \text{pb}$$

$$\sigma_{tW}^{obs} = 82.3 \pm 2.1(\text{stat})^{+9.9}_{-9.7}(\text{syst}) \pm 3.3(\text{lum})\ \text{pb}$$

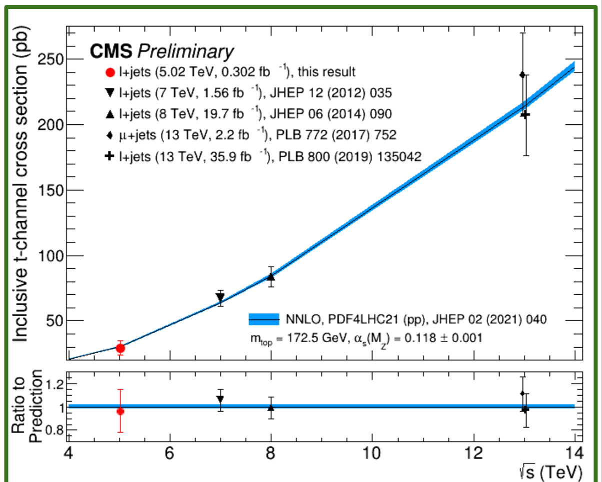
Measurements in the top sector at √s=5.02 TeV

- Study of the top sector with **0.302 fb^{-1}** of data (2017), at unusual centre-of-mass energy (√s=5.02 TeV).
  - Distinct feature: **low #interactions per bunch crossing (~2 vs Run 3-> 54) => clean environment.**
  - **tt measurement** -> most precise from CMS at that energy (JHEP 04 (2025) 099)



- **t-channel measurement**

⬇



- First from CMS at that energy
- Expected to be public in summer

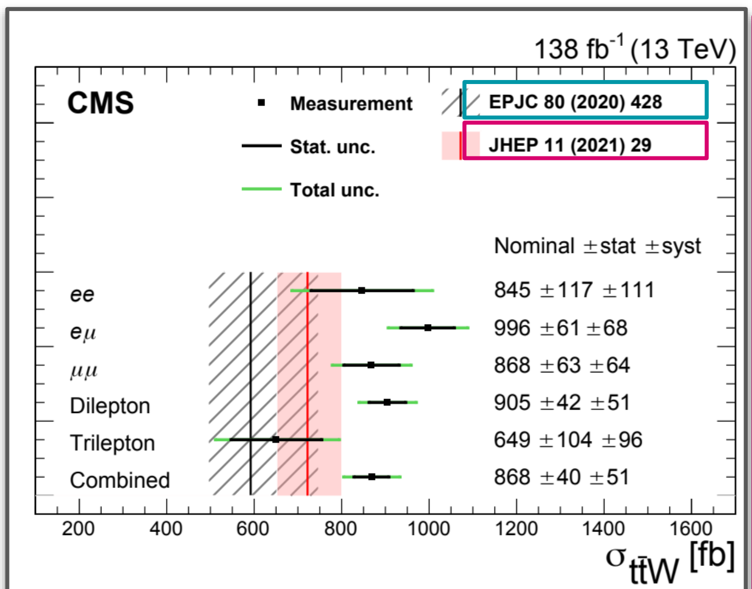
Study of t-channel production at 13.6 TeV ongoing, hopefully ready for Winter conferences

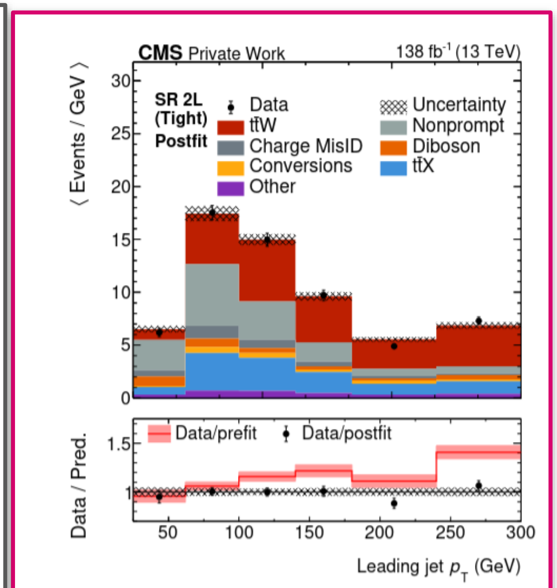
Measurements of ttW properties

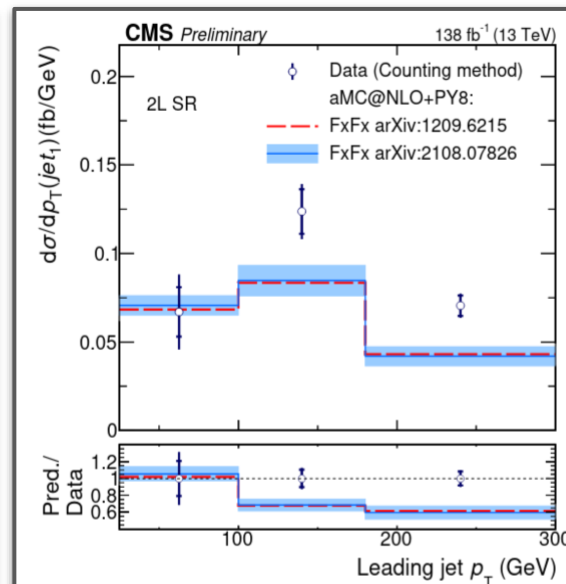
- The **measured $t\bar{t}W$ cross section** is in **slight tension** with the **latest** theoretical **predictions** at Next-to-Next-to Leading Order (~2 standard deviations).
- The disagreement remains unresolved → **differential cross section measurements might shed light.**
  - **Do we really have an excess on ttW? or do we have to improve our modelling of the process?**

JHEP07(2023)219

TOP-24-003

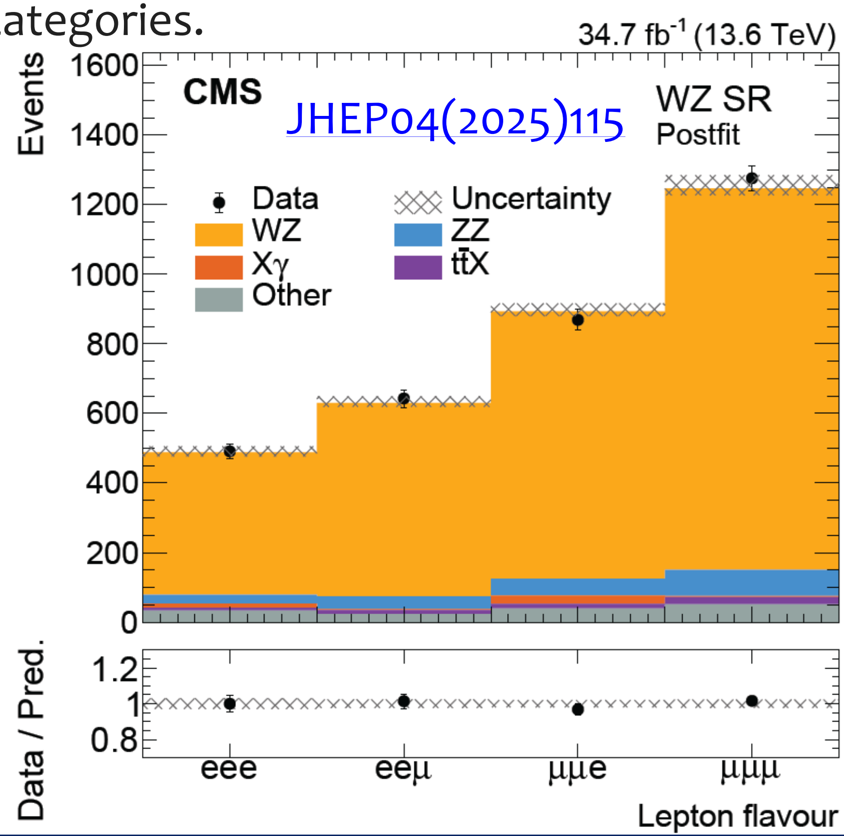




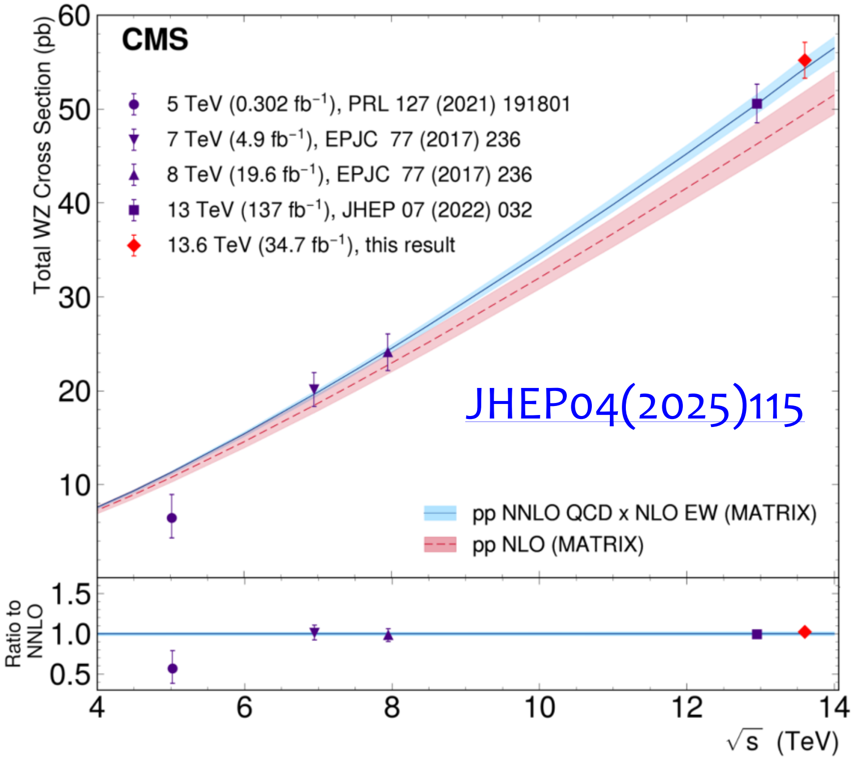


Measurements of WZ properties at 13.6 TeV

- The **WZ cross section** is **extracted** from a **maximum likelihood fit** to the **number of observed events** in **different light lepton** categories.



Evolution with center of mass energy

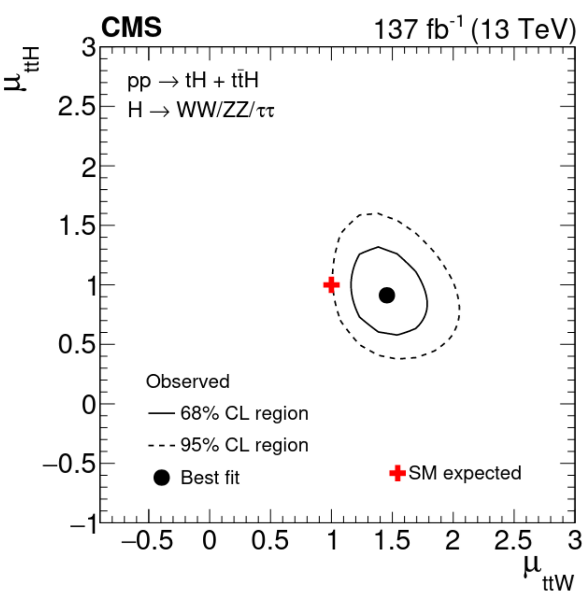


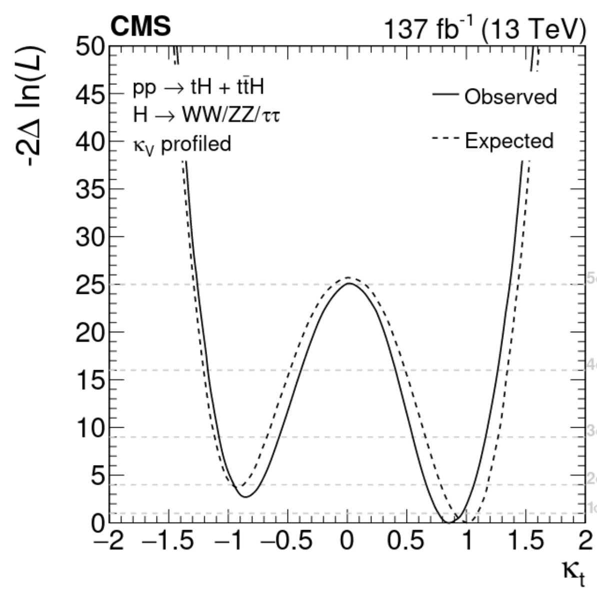
11 papers on diboson production at **all LHC CM energies** including LOW PU 5 TeV data

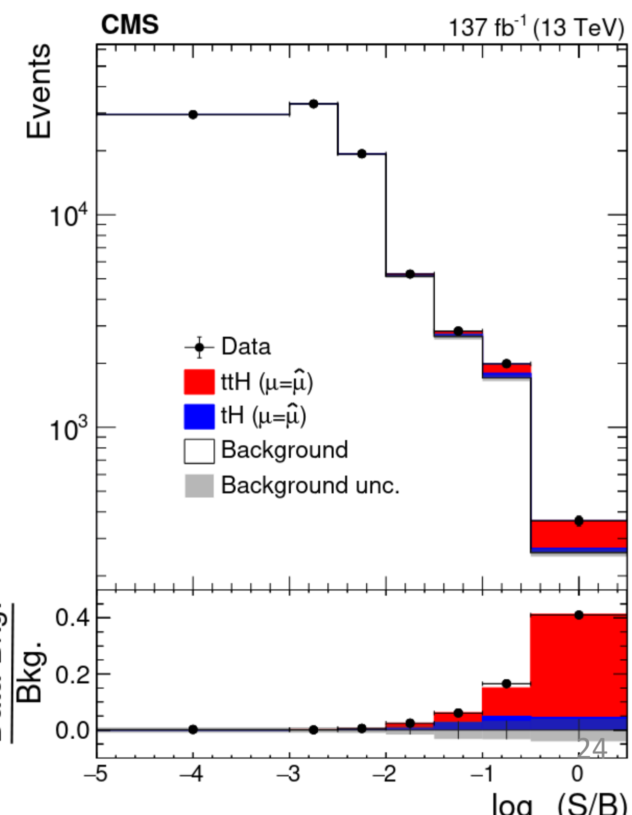
ttH production in multileptonic final states

- **>5 sigma sensitivity to ttH production**
- Result consistent with the SM: $\mu_{ttH}=0.92^{+0.26}_{-0.23}$
- ttH measured simultaneously with tH, ttW, ttZ
- Limits set on modifiers of the top Yukawa coupling

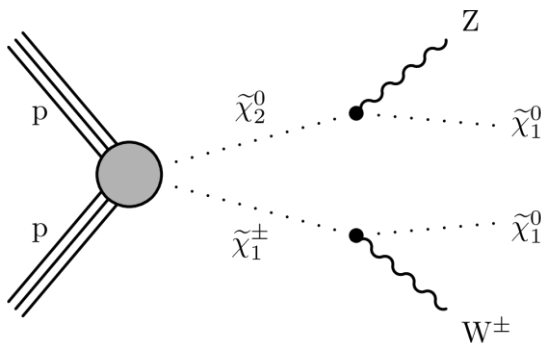
[Eur. Phys. J. C 81 (2021) 378]

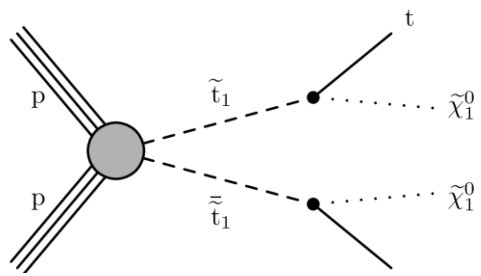




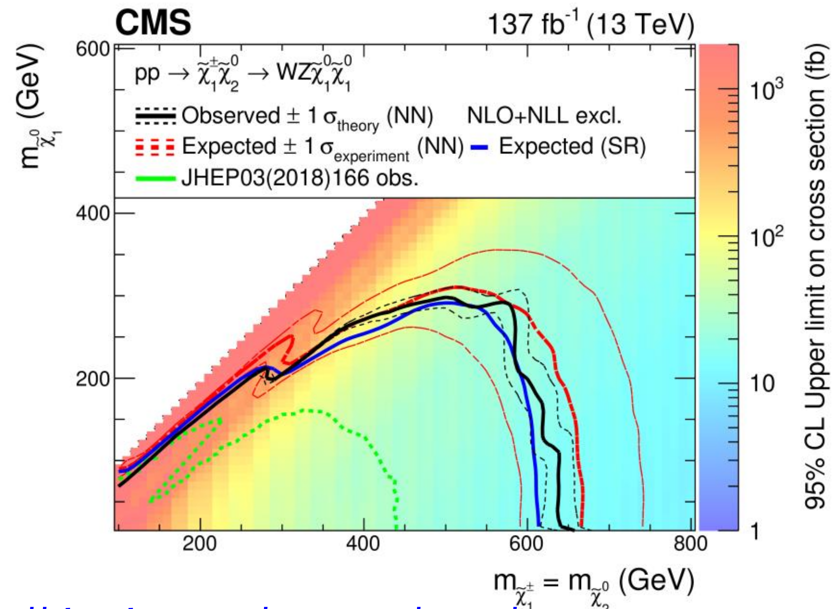


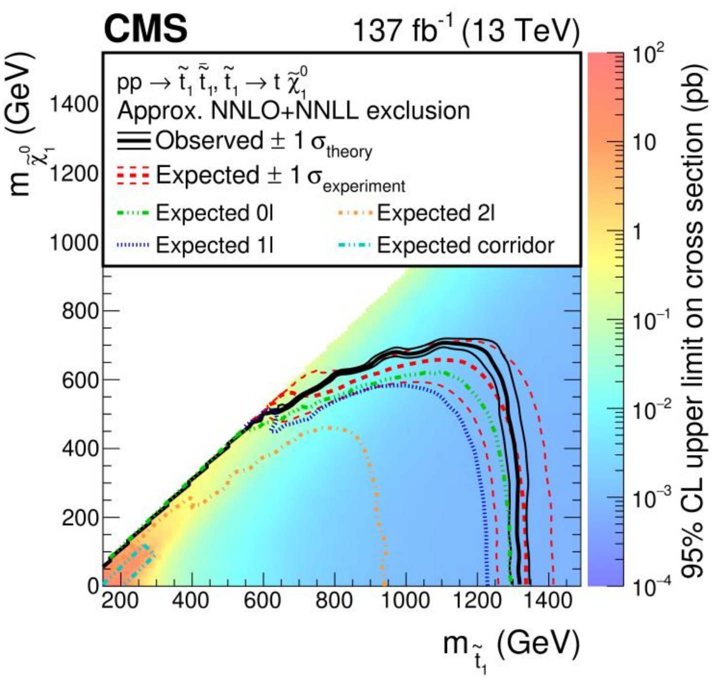
BSM, SUSY "Same sign", stop and EWK production



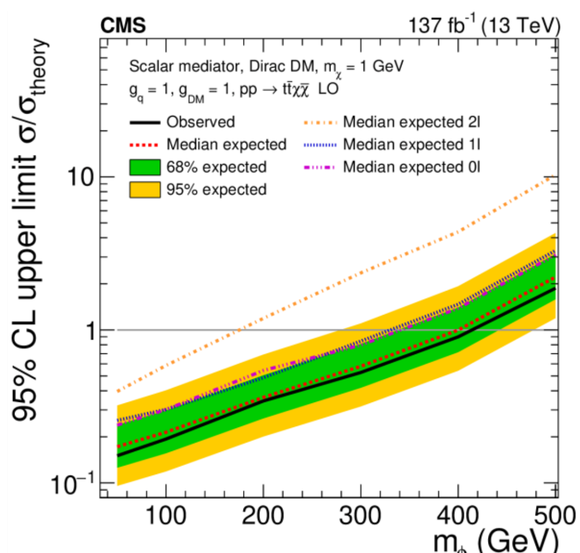


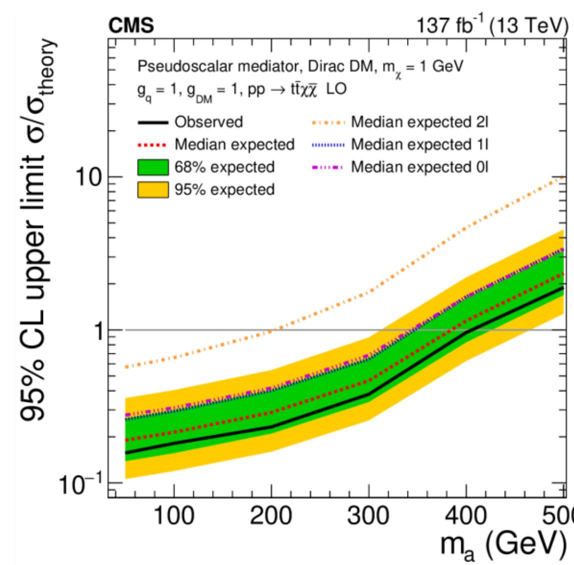
http://dx.doi.org/10.1007/JHEP04(2022)147





http://dx.doi.org/10.1140/epjc/s10052-021-09721-5



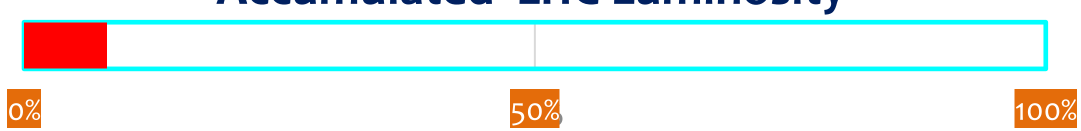


Dark matter interpretations

Excellent times at the LHC, and more to come

- **Last 13 years the LHC has been a prolific source of results on a broad spectrum of questions addressable at colliders**
  - Testing the Standard Model at higher and higher precision, including the resolution of a 50-year-old outstanding question
  - Constantly pushing the boundaries of where *Physics beyond the Standard Model* may hide
- **Success resulted from excellent accelerator and detector performance**
- **There is a lot more to do:**
  - (Very!) Challenging Upgrades employing cutting edge technologies
  - Analyzing the 95% of the data to come – **results for the next 20 years**!

Accumulated LHC Luminosity

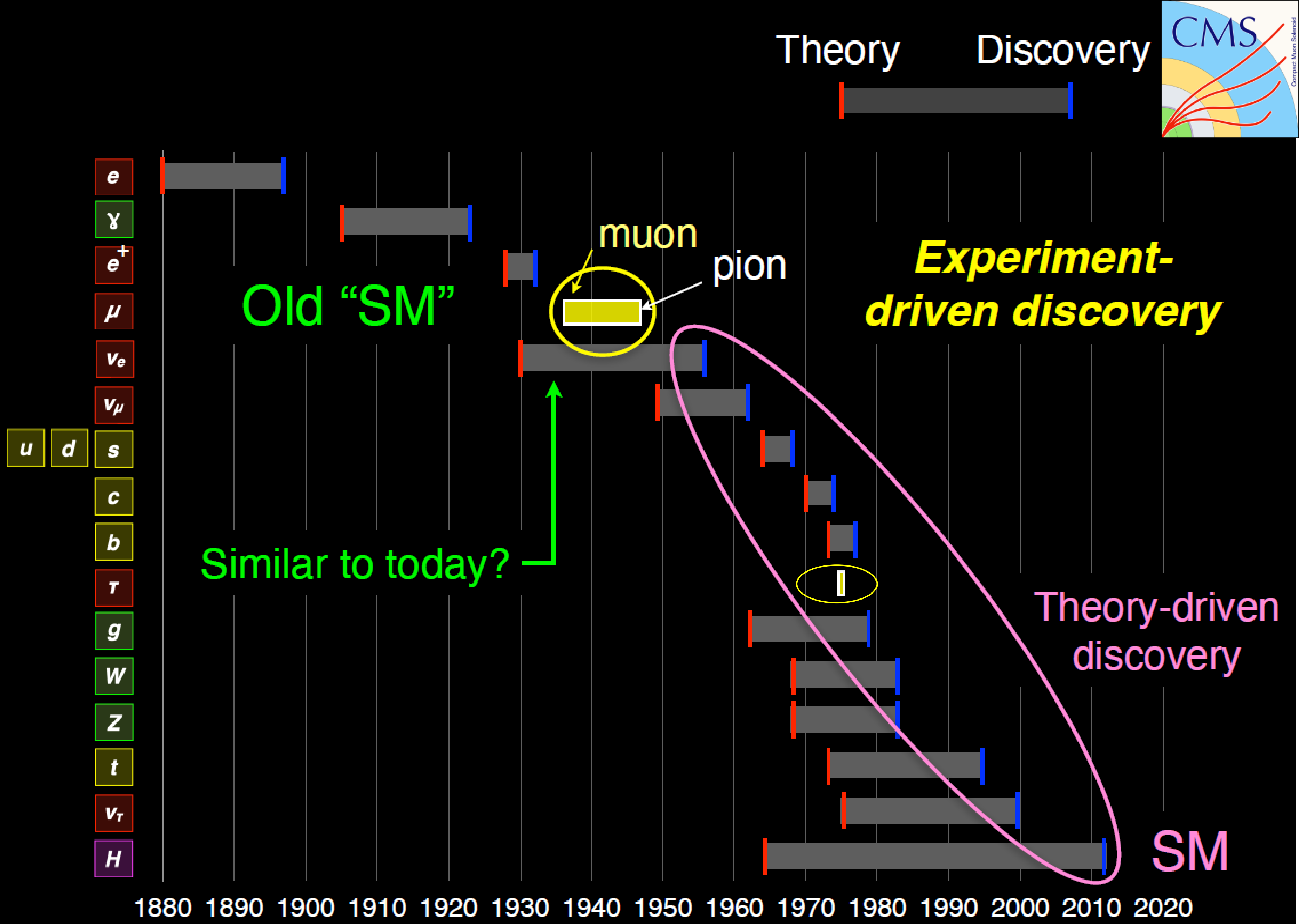


Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (
19 Members found (8 MO **2025** , 8 MO **2026** , **IMPORTANT: use this link to confirm**

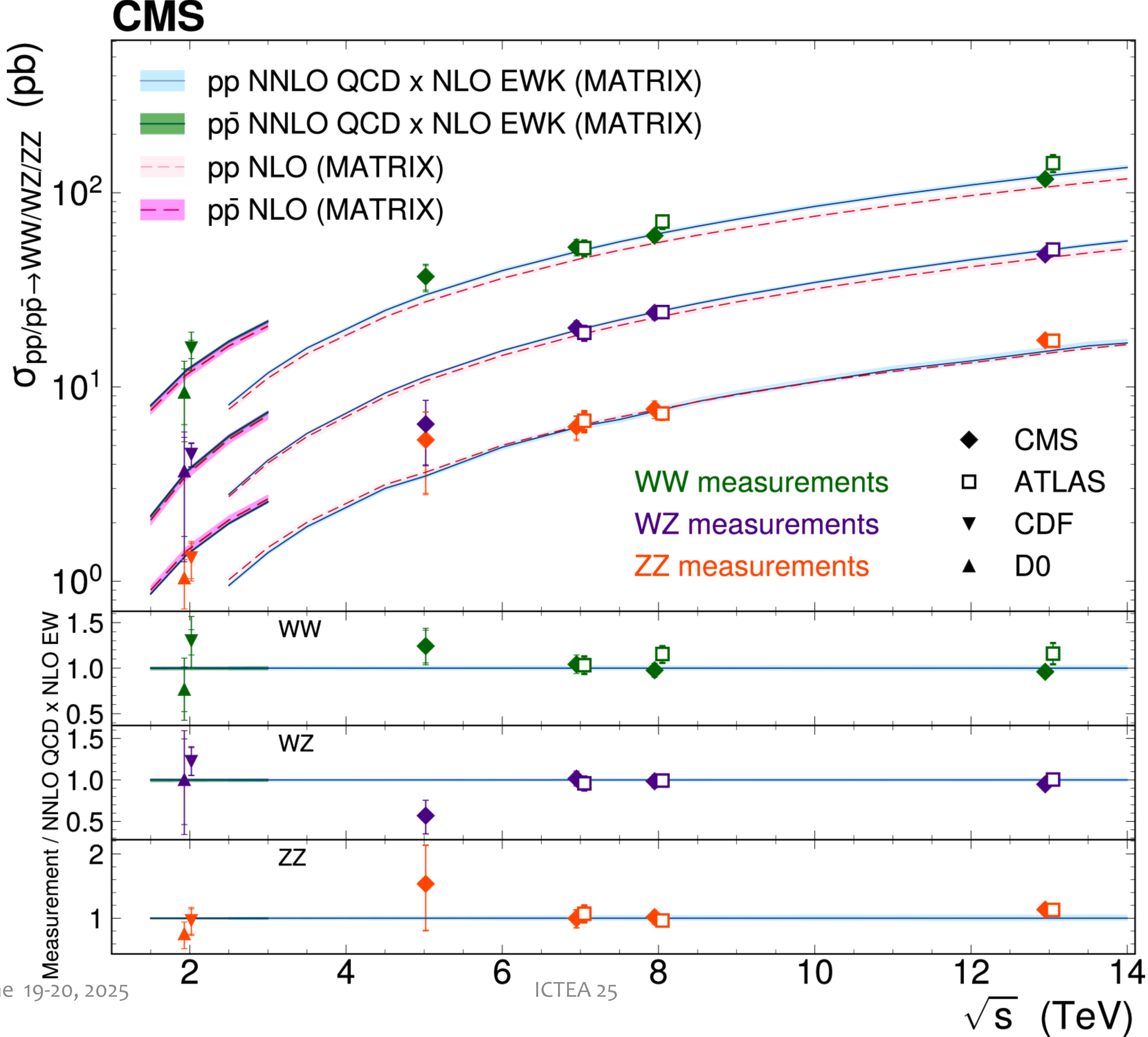
Show **Scientists** members of OVIEDO »

NameCMS	NamfCMS	Activity	Act Nyears	CMSstatus	CMS Nyears	InstCode	InstCode Other
Aller Gutierrez	Elena	Non-Doctoral Student | *change*	0.6	CMS | *set exmb*	0.6	OVIEDO | *move*	
Alvarez Gonzalez	Barbara	Physicist | *change*	7.4	CMS | *set exmb*	7.4	OVIEDO | *move*	
Ayllon Torresano	Jorge	Doctoral Student | *change*	1.3	CMS | *set exmb*	1.5	OVIEDO | *move*	
Cardini	Andrea	Physicist | *change*	3.8	CMS | *set exmb*	8.3	OVIEDO | *move*	
Cuevas	Javier	Physicist | *change*	28.4	CMS | *set exmb*	28.4	OVIEDO | *move*	
Del Riego Badas	Javier	Doctoral Student | *change*	1.9	CMS | *set exmb*	2.7	OVIEDO | *move*	
Estrada Acevedo	Daniel	Doctoral Student | *change*	0.9	CMS | *set exmb*	3.8	OVIEDO | *move*	
Fernandez Menendez	Javier	Physicist | *change*	22.0	CMS | *set exmb*	22.0	OVIEDO | *move*	
Folgueras	Santiago	Physicist | *change*	9.5	CMS | *set exmb*	16.2	OVIEDO | *move*	
Garcia Diaz	Laura	Non-Doctoral Student | *change*	0.2	CMS | *set exmb*	0.2	OVIEDO | *move*	
Gonzalez Caballero	Isidro	Physicist | *change*	29.3	CMS | *set exmb*	29.3	OVIEDO | *move*	
Leguina	Pelayo	Doctoral Student | *change*	2.5	CMS | *set exmb*	2.9	OVIEDO | *move*	
Obeso Menendez	Miguel	Doctoral Student | *change*	1.3	CMS | *set exmb*	1.5	OVIEDO | *move*	
Palencia Cortezon	Enrique	Physicist | *change*	15.3	CMS | *set exmb*	15.3	OVIEDO | *move*	
Prado Pico	Javier	Doctoral Student | *change*	2.4	CMS | *set exmb*	2.4	OVIEDO | *move*	
Soto Rodríguez	Alejandro	Doctoral Student | *change*	4.7	CMS | *set exmb*	5.2	OVIEDO | *move*	
Vico Villalba	Carlos	Doctoral Student | *change*	4.7	CMS | *set exmb*	5.2	OVIEDO | *move*	
Vischia	Pietro	Physicist | *change*	8.8	CMS | *set exmb*	16.2	OVIEDO | *move*	

Backup slides



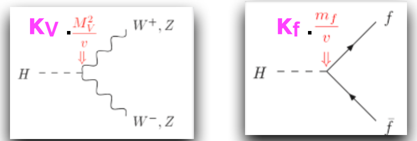
Theory
Discovery
CMS
Compact Muon Solenoid
e
γ
e+
μ
ν_e
ν_μ
u
d
s
c
b
τ
g
W
Z
t
ν_τ
H
muon
pion
Old "SM"
Experiment-driven discovery
Similar to today?
Theory-driven discovery
SM
1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020


CMS
pp NNLO QCD x NLO EWK (MATRIX)
pp̄ NNLO QCD x NLO EWK (MATRIX)
pp NLO (MATRIX)
pp̄ NLO (MATRIX)
$\sigma_{pp/p\bar{p}\to WW/WZ/ZZ}$ (pb)
10^2
10^1
10^0
WW measurements
WZ measurements
ZZ measurements
CMS
ATLAS
CDF
D0
WW
WZ
ZZ
Measurement / NNLO QCD x NLO EW
1.5
1.0
0.5
2
1
4
6
8
10
12
14
$\sqrt{s}$ (TeV)

The portrait of the Higgs boson

Nature 607 (2022) 60

Coupling modifier interpretation

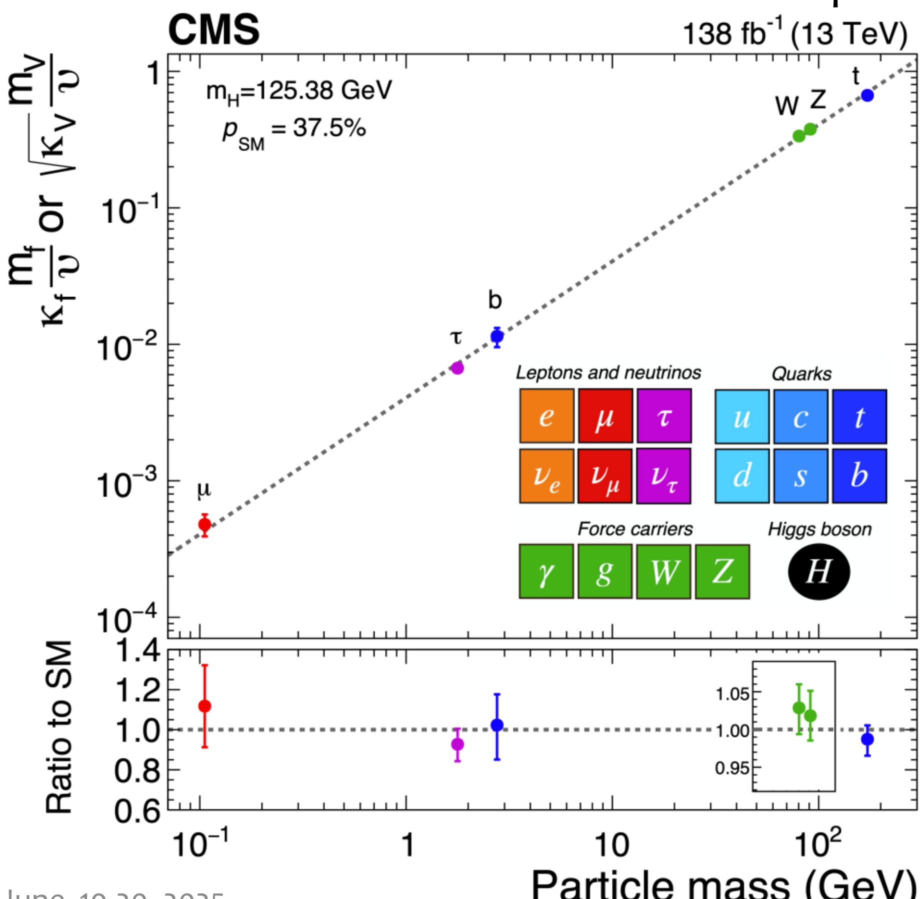


$$\sigma(i \rightarrow H \rightarrow f) = \sigma_i B_f = \frac{\sigma_i(\boldsymbol{\kappa})\Gamma_f(\boldsymbol{\kappa})}{\Gamma_H(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}})}$$

Total cross-section / Standard Model prediction

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$

Ratio of observed rate to predicted SM event rate for different combinations of Higgs boson production and decay processes.



The Higgs couples with the particle mass

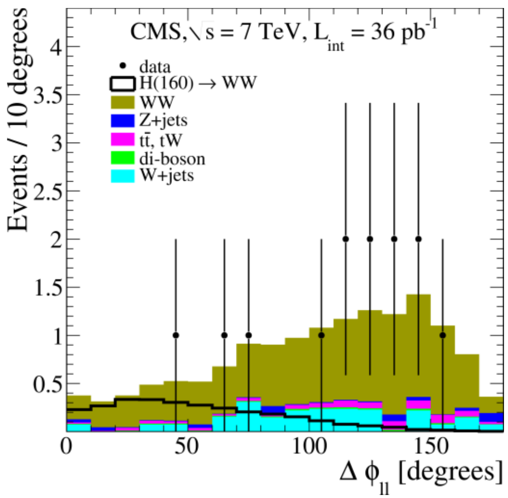
SM test over many orders of magnitude

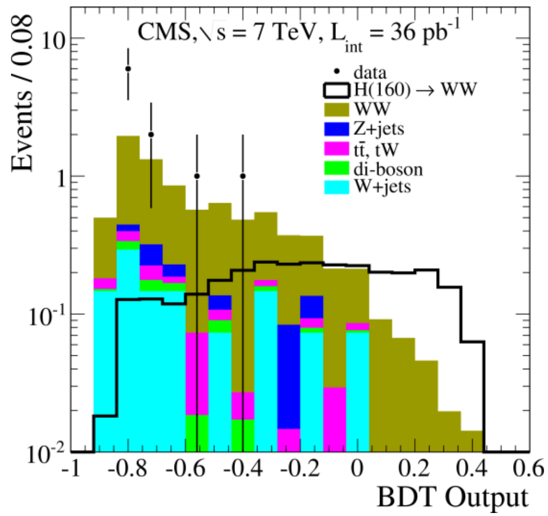
It couples to bosons, to leptons and to quarks of the 3rd generation. Just seen first evidence that it also couples to the 2nd generation.
So far it passes all tests, still a fundamental check: **HH**.

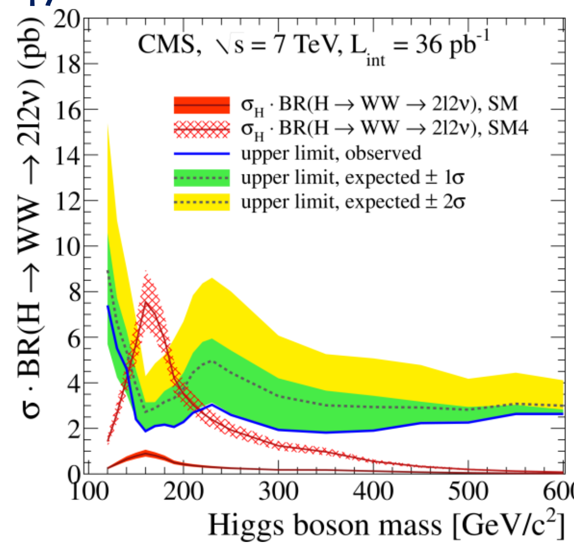
Precision measurements of the Higgs are increasingly important and, in many aspects, drive the future of HEP

Diboson measurements: W^+W^- production and search for the Higgs Boson in pp Collisions at √s = 7 TeV.

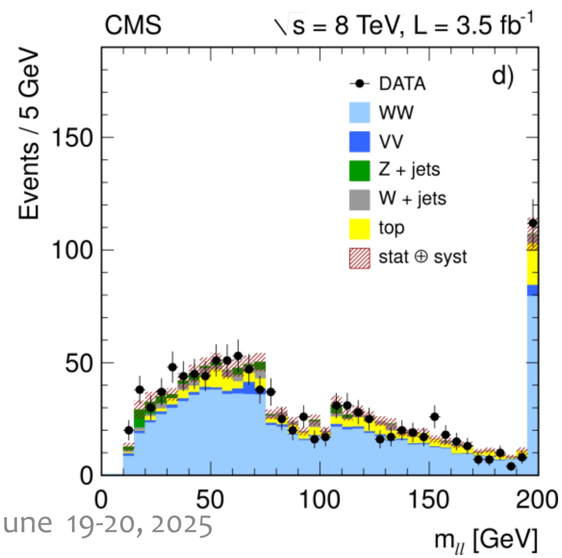
Phys. Lett. B699, **2 May 2011**, 25-47



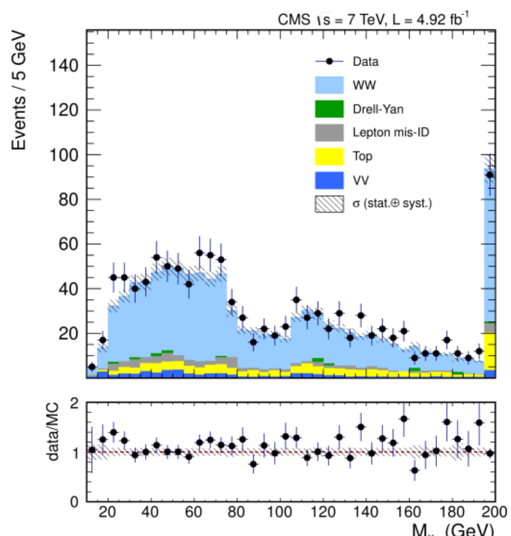




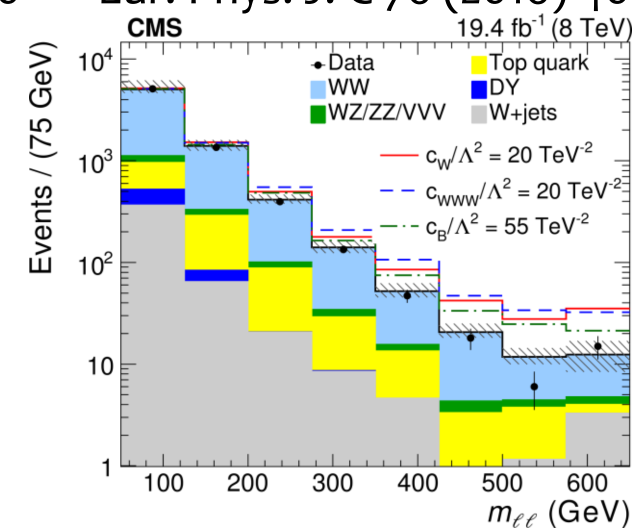
Phys. Lett. B 721 (2013) 190



Eur. Phys. J. C 73 (2013) 2610

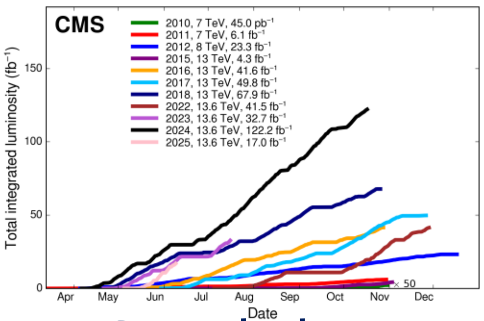


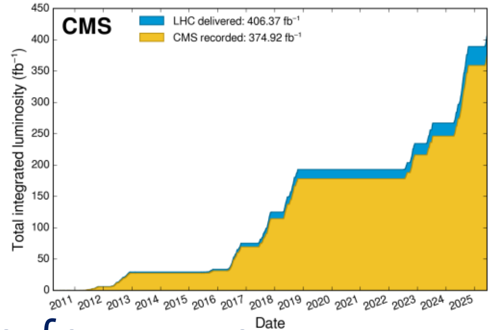
Eur. Phys. J. C 76 (2016) 401



The long road of the Higgs boson: a worldwide effort

LHC: from 7 to 13.6 TeV, L >370 fb^{-1}

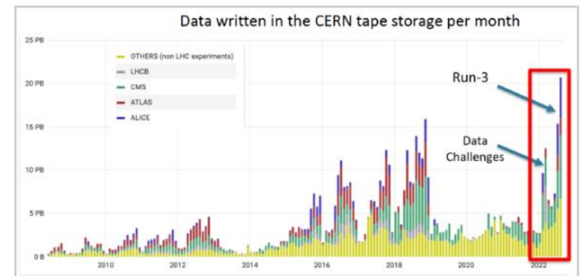


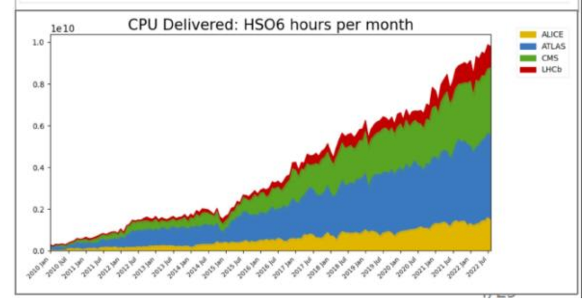


Run2 wrt Run1, Lumi ×10 more

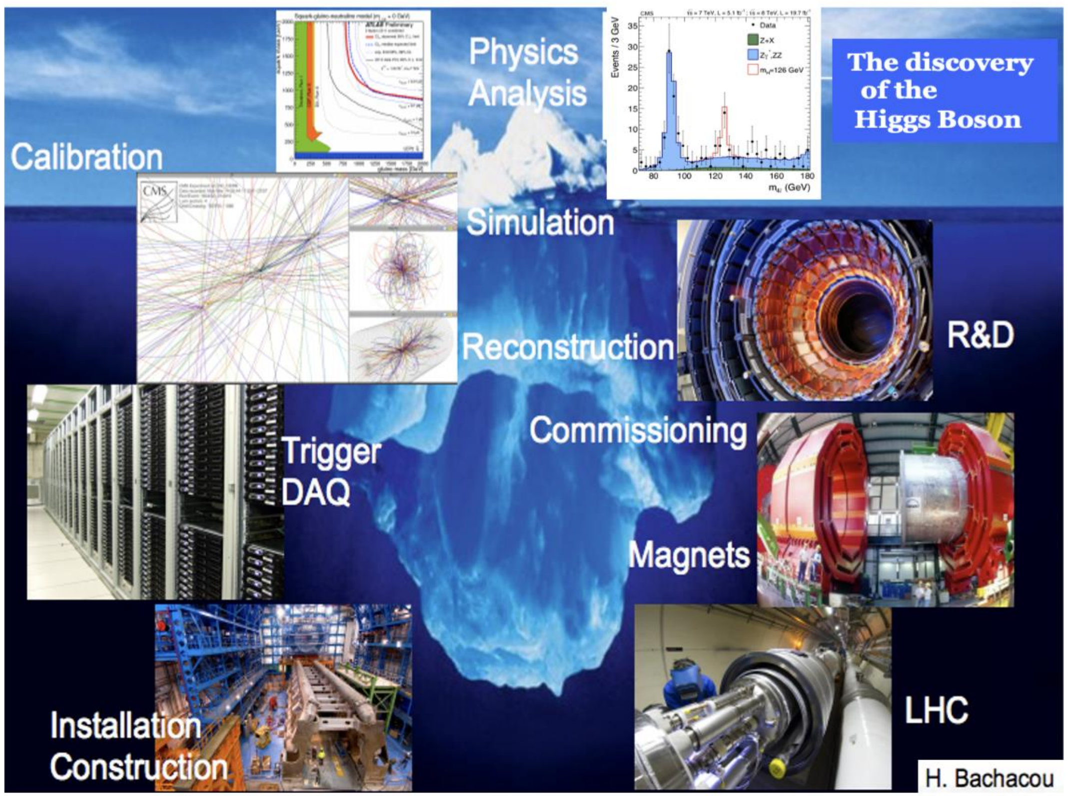
σ ×2–4 larger, **Higgs ×30 more**

The WLCG

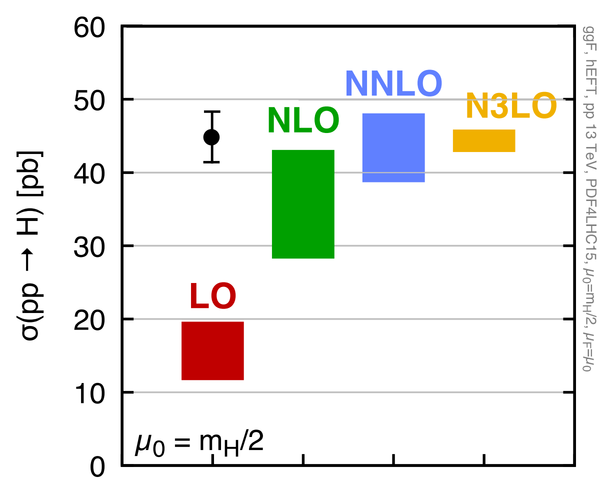




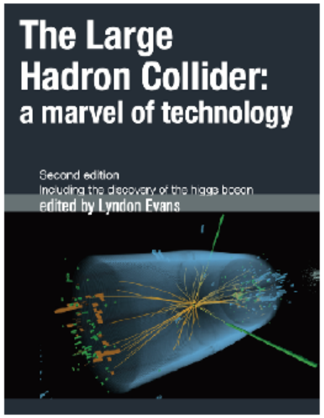
Superb detector performance



The LHCHXSWG



The LHC a Marvel of Technology



Link

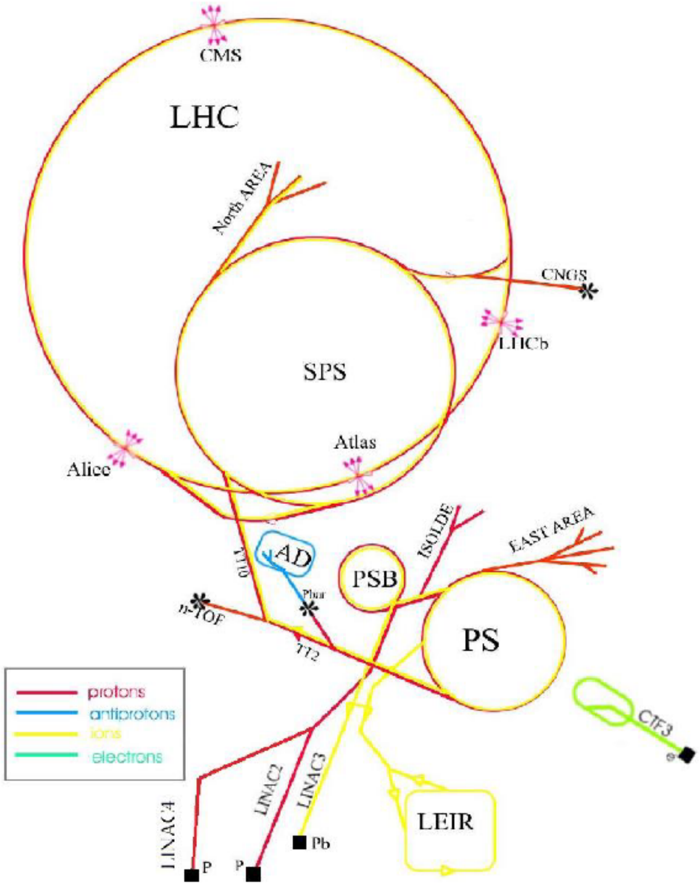
Unrivalled at Energy Frontier

13.6 TeV (COM energy)

Outstanding at Intensity Frontier

Record Luminosity* $2.26 \times 10^{34}\ cm^{-2}s^{-1}$

*Close to SuperKEKB at $5.1 \times 10^{34}\ cm^{-2}s^{-1}$



So far the LHC has delivered:

- 15 Million Higgs bosons produced
- 600 Million top quarks produced
- 15 Billion Z bosons with 300 Million per lepton flavour
- 60 Billion W bosons (3 billion per lepton flavour)
- 300 Trillion b quarks (approximately 2 Trillion for LHCb)

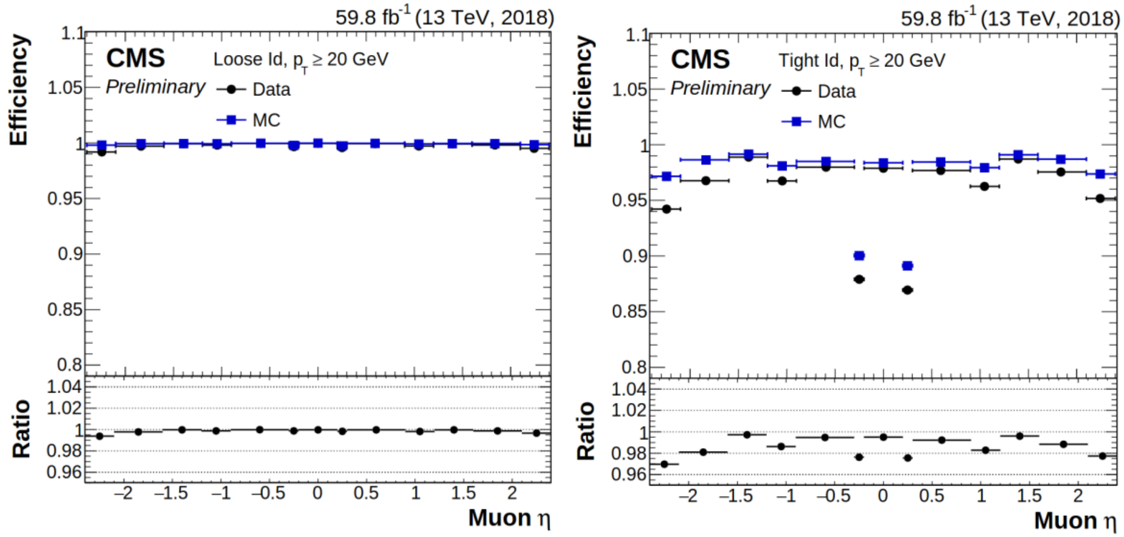
Still 10 times more statistics expected at HL-LHC!

More than 20 times more luminosity with the LHCb upgrade II

MUON SELECTION IN CMS

- Muon reconstruction uses information from the tracker and the muon system
- ~99% efficiency for global muons in the barrel

- Good performance of muon selectors during Run 2 [CMS-DP-2019-022]



- Revisited the Run 2 selectors and found there was room for improvement

- Developed a new MVA-based algorithm to be used during Run 3 [2024 JINST 19 P02031]

Muon MVA ID Selector

2024 JINST 19 P02031

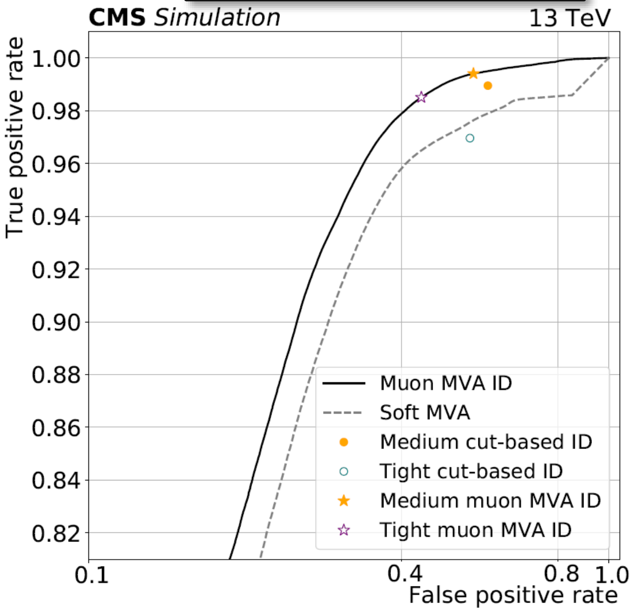
Signal and background definition

- Loosely identified muons with $p_T > 10$ GeV
- Signal: prompt muons (from bosons), muons from τ and heavy flavour decays
- Background: muons from pions and kaons (and other light) decays, spurious signatures in the muon system

Using geometrical matching with generation information

12 Input variables used to train a Random Forest

- Normalized χ^2 of the muon track fit
- Local χ^2 (inner-SA track)
- Segment compatibility
- χ^2 from the kink-finder algorithm on the inner track
- Number of matched stations with hits
- Fraction of valid tracker hits
- Number of valid pixel hits
- Number of tracker layers with hits
- Number of valid hits

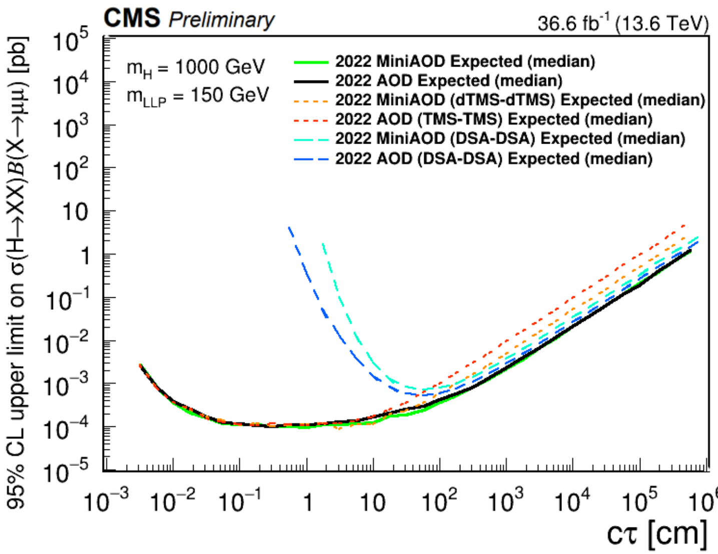


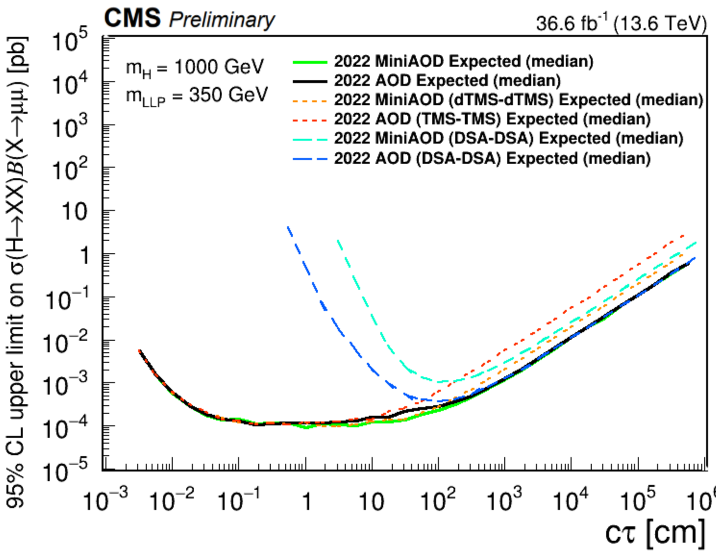
2 Working points defined

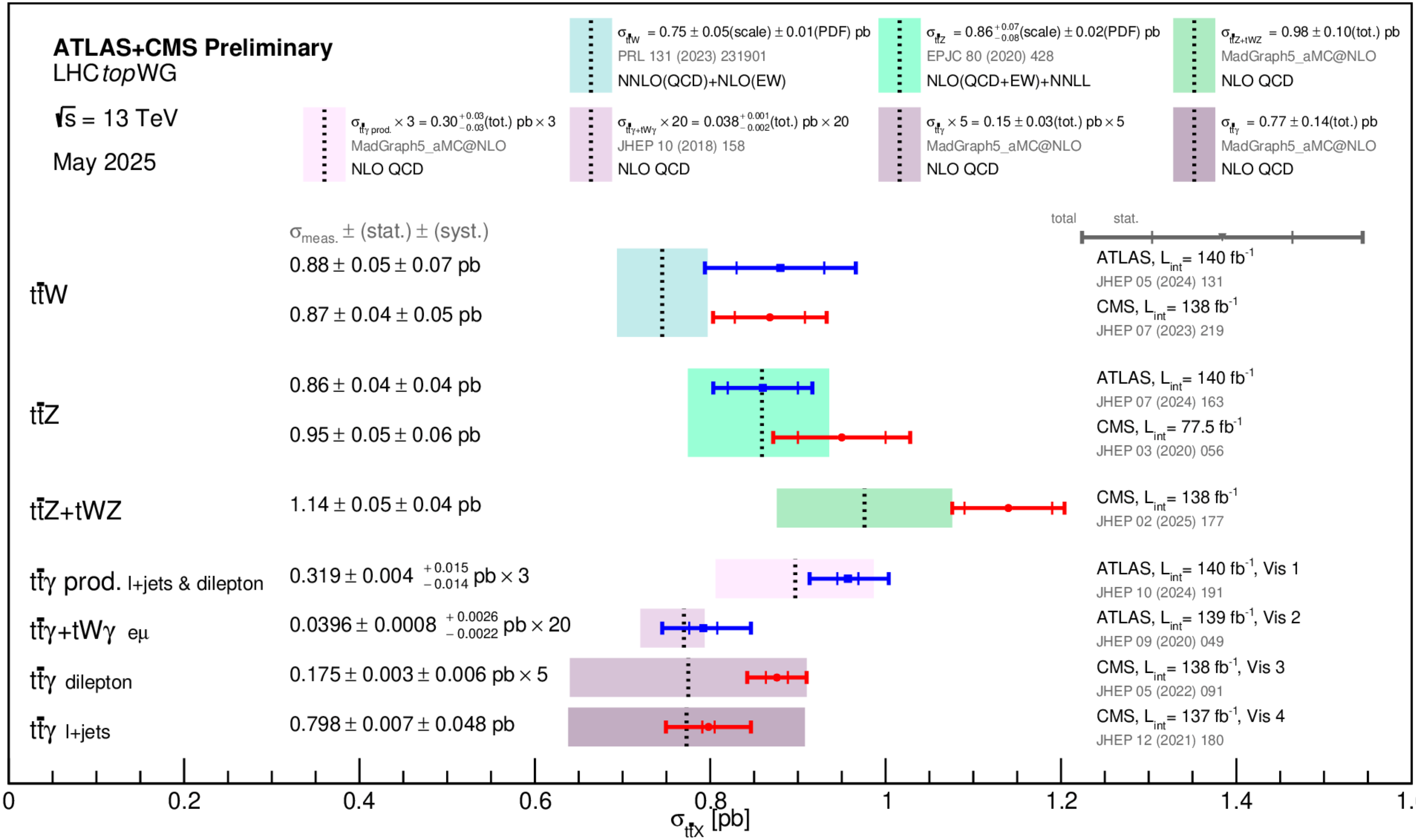
- medium (MVA > 0.08)
  - Same background rejection as Medium WP of Run 2 (cut-based) ID
- tight (MVA > 0.2)

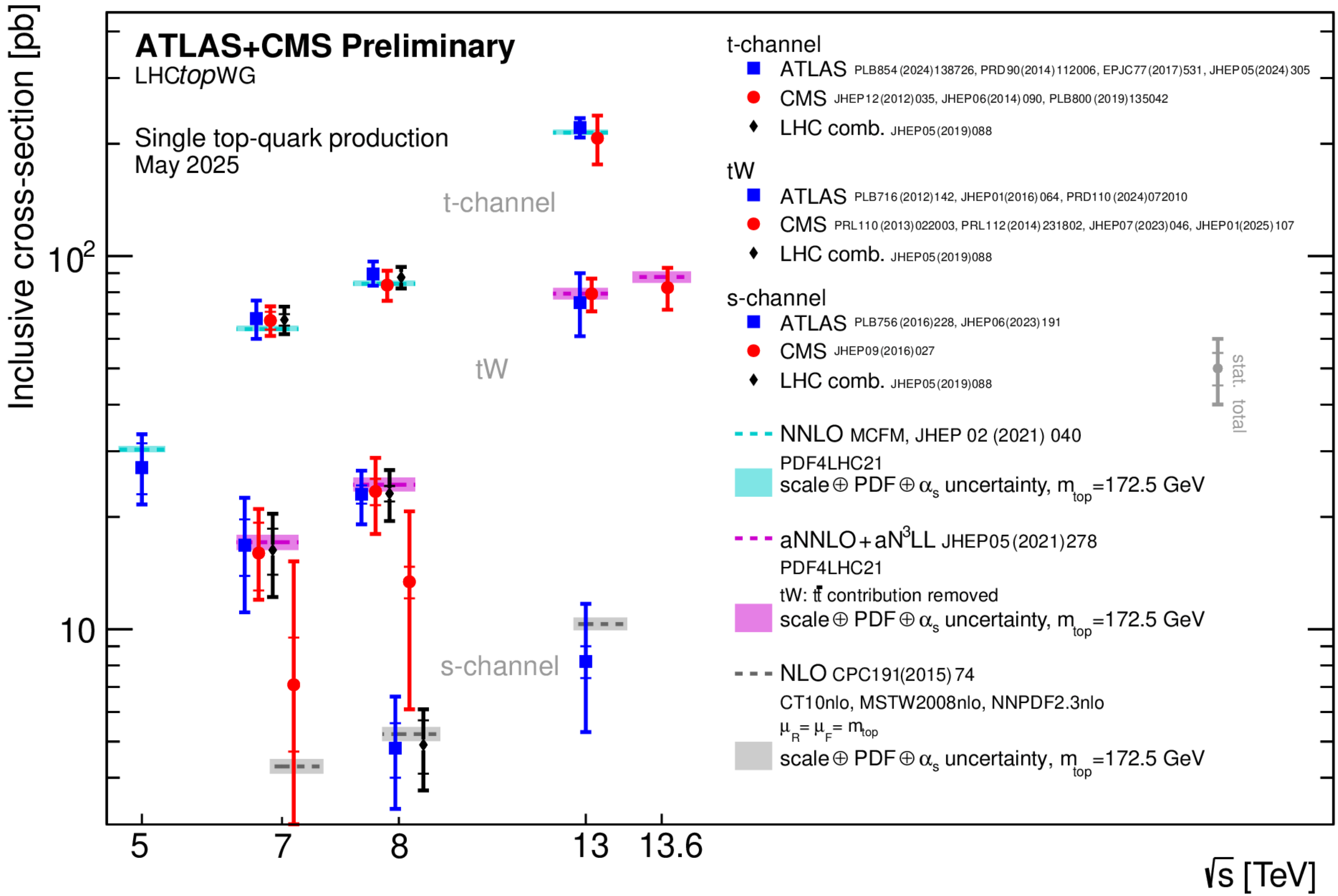
Future developments - MiniAOD

- Fully implemented the analysis starting from **MiniAOD**.
- Computed limits for MiniAOD and AOD workflows (per category and the combined result).
- Limits largely consistent.
- Visible improvement at $c\tau = 1 - 100$ cm.



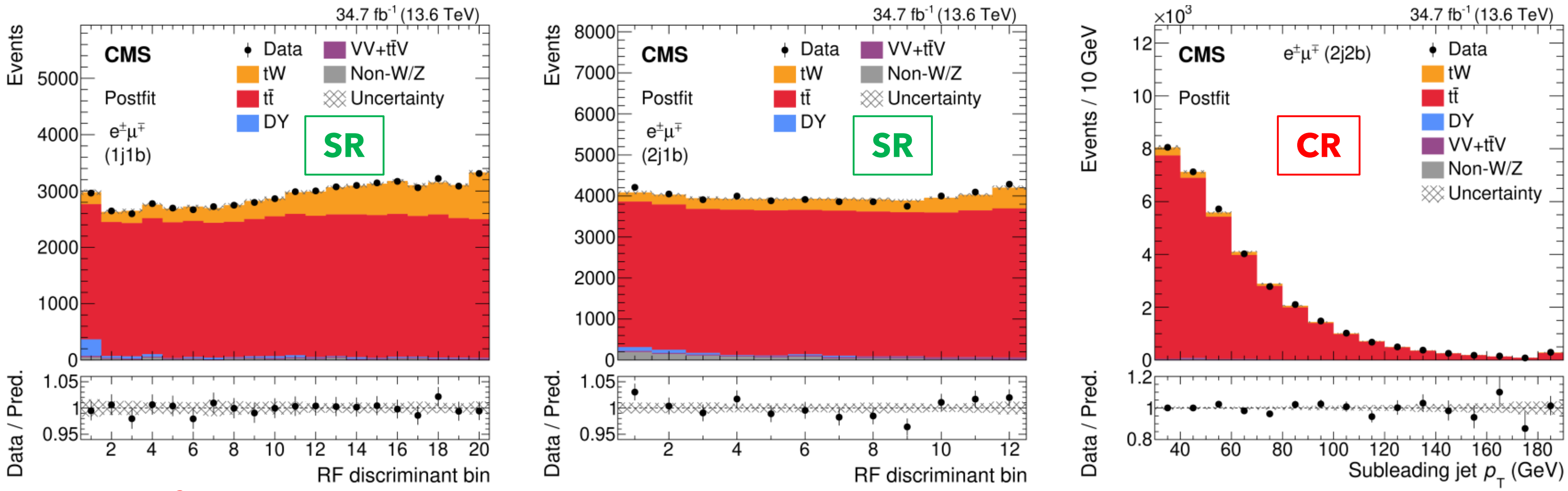



ATLAS+CMS Preliminary
LHC topWG
√s = 13 TeV
May 2025
σ_ttW = 0.75 ± 0.05(scale) ± 0.01(PDF) pb
PRL 131 (2023) 231901
NNLO(QCD)+NLO(EW)
σ_ttZ = 0.86 +0.07 −0.08 (scale) ± 0.02(PDF) pb
EPJC 80 (2020) 428
NLO(QCD+EW)+NNLL
σ_ttZ+tWZ = 0.98 ± 0.10(tot.) pb
MadGraph5_aMC@NLO
NLO QCD
σ_ttγ prod. × 3 = 0.30 +0.03 −0.03 (tot.) pb × 3
MadGraph5_aMC@NLO
NLO QCD
σ_ttγ+tWγ × 20 = 0.038 +0.001 −0.002 (tot.) pb × 20
JHEP 10 (2018) 158
NLO QCD
σ_ttγ × 5 = 0.15 ± 0.03(tot.) pb × 5
MadGraph5_aMC@NLO
NLO QCD
σ_ttγ = 0.77 ± 0.14(tot.) pb
MadGraph5_aMC@NLO
NLO QCD
σ_meas. ± (stat.) ± (syst.)
total
stat.
ttW
0.88 ± 0.05 ± 0.07 pb
ATLAS, L_int = 140 fb^-1
JHEP 05 (2024) 131
0.87 ± 0.04 ± 0.05 pb
CMS, L_int = 138 fb^-1
JHEP 07 (2023) 219
ttZ
0.86 ± 0.04 ± 0.04 pb
ATLAS, L_int = 140 fb^-1
JHEP 07 (2024) 163
0.95 ± 0.05 ± 0.06 pb
CMS, L_int = 77.5 fb^-1
JHEP 03 (2020) 056
ttZ+tWZ
1.14 ± 0.05 ± 0.04 pb
CMS, L_int = 138 fb^-1
JHEP 02 (2025) 177
ttγ prod. l+jets & dilepton
0.319 ± 0.004 +0.015 −0.014 pb × 3
ATLAS, L_int = 140 fb^-1, Vis 1
JHEP 10 (2024) 191
ttγ+tWγ eμ
0.0396 ± 0.0008 +0.0026 −0.0022 pb × 20
ATLAS, L_int = 139 fb^-1, Vis 2
JHEP 09 (2020) 049
ttγ dilepton
0.175 ± 0.003 ± 0.006 pb × 5
CMS, L_int = 138 fb^-1, Vis 3
JHEP 05 (2022) 091
ttγ l+jets
0.798 ± 0.007 ± 0.048 pb
CMS, L_int = 137 fb^-1, Vis 4
JHEP 12 (2021) 180
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
σ_ttX [pb]


ATLAS+CMS Preliminary
LHCtopWG
Single top-quark production
May 2025
t-channel
tW
s-channel
Inclusive cross-section [pb]
√s [TeV]
5
7
8
13
13.6
10
10^2
t-channel
ATLAS PLB854 (2024) 138726, PRD 90 (2014) 112006, EPJC77 (2017) 531, JHEP 05 (2024) 305
CMS JHEP12 (2012) 035, JHEP06 (2014) 090, PLB800 (2019) 135042
LHC comb. JHEP05 (2019) 088
tW
ATLAS PLB716 (2012) 142, JHEP01 (2016) 064, PRD110 (2024) 072010
CMS PRL110 (2013) 022003, PRL112 (2014) 231802, JHEP07 (2023) 046, JHEP01 (2025) 107
LHC comb. JHEP05 (2019) 088
s-channel
ATLAS PLB756 (2016) 228, JHEP06 (2023) 191
CMS JHEP09 (2016) 027
LHC comb. JHEP05 (2019) 088
stat. total
NNLO MCFM, JHEP 02 (2021) 040
PDF4LHC21
scale ⊕ PDF ⊕ αs uncertainty, mtop=172.5 GeV
aNNLO + aN3LL JHEP05 (2021) 278
PDF4LHC21
tW: tt̄ contribution removed
scale ⊕ PDF ⊕ αs uncertainty, mtop=172.5 GeV
NLO CPC191 (2015) 74
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
μR = μF = mtop
scale ⊕ PDF ⊕ αs uncertainty, mtop=172.5 GeV

Inclusive cross section measurement

- To discriminate between **tW** and **$t\bar{t}$** events, two Random Forest (RF), one in the **1j1b** region and the other in the **2j1b** region, are trained using the kinematic properties of the events.
- To extract the signal, a ML fit is performed using the two RF output and the subleading jet p_T in the **2j2b** region.



aN³LO

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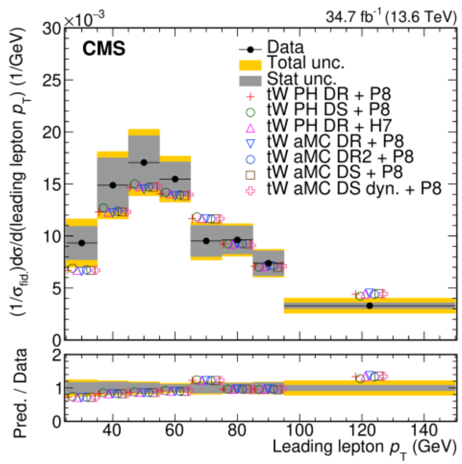
$$\sigma_{tW}^{SM} = 87.9^{+2.0}_{-1.9}(\text{scale}) \pm 2.4(\text{PDF} + \alpha_S)\ \text{pb}$$

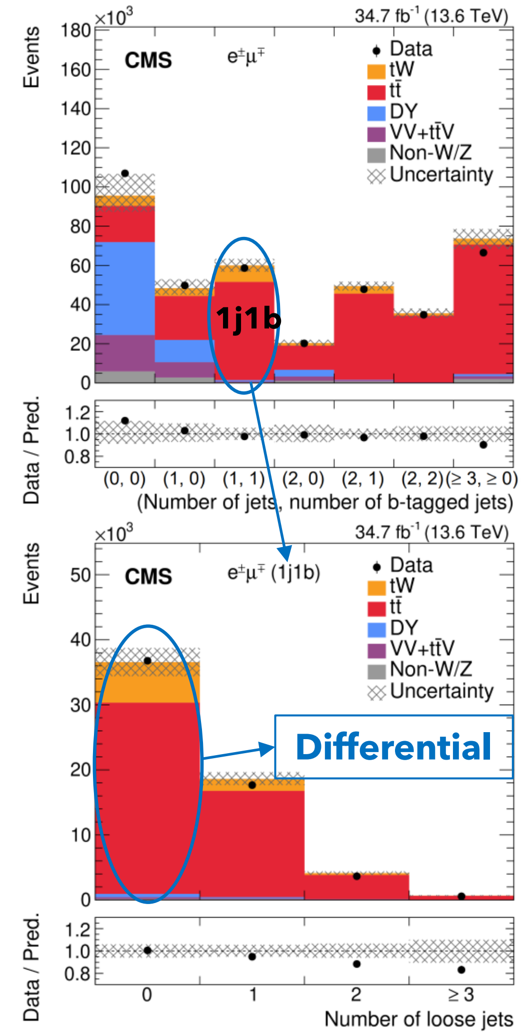
$$\sigma_{tW}^{obs} = 82.3 \pm 2.1(\text{stat})^{+9.9}_{-9.7}(\text{syst}) \pm 3.3(\text{lum})\ \text{pb}$$

Differential measurements

- Measurement performed in the **1j1b** region **vetoing events with low energy jets (loose jets)**.
- Signal extraction is performed by **background subtraction**.
- Unfolding from detector level to particle level is performed using **TUnfold** ([JINST 7 (2012) T10003]()).
- We measure the following observables:
  - p_T of the leading lepton.
  - p_T of the jet.
  - $\Delta\phi(e, \mu)$.
  - $p_z(e, \mu, \text{jet})$.
  - $m(e, \mu, \text{jet})$.
  - $m_T(e, \mu, \text{jet}, p_T^{\text{miss}})$.

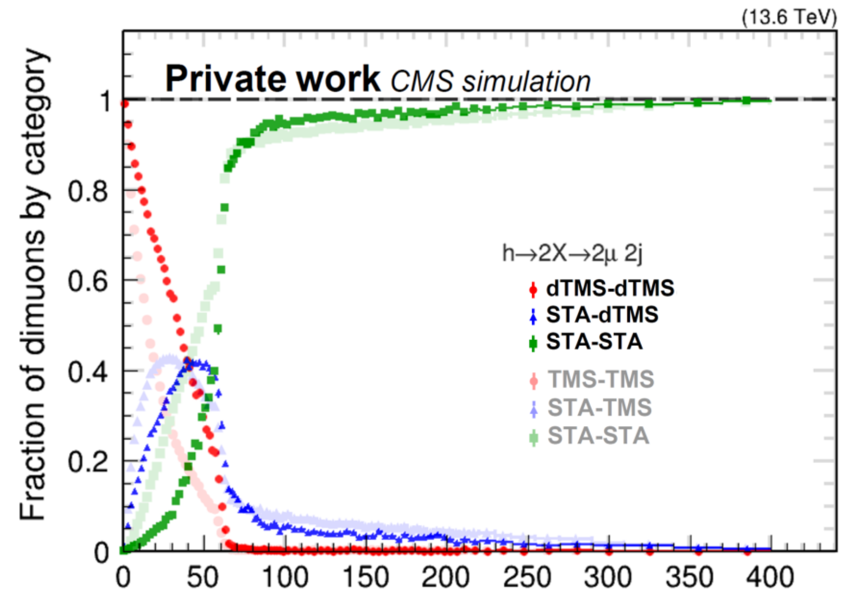
Results are normalised to the fiducial cross section and bin width.





Future developments - MiniAOD

- Worked on several **improvements** towards the **next result** with full Run 3 luminosity.
- The first focuses on migrating the analysis to a more compact data format: AOD to miniAOD.
  - Improved accessibility: AOD normally in tape.
  - Storage reduction: miniAOD weights 10 times less.
  - Expand the TMS category to include also displaced global muons.



Result with standard muons in shadow

AOD
- STA
- TMS

MiniAOD
- STA
- dTMS: TMS + displaced global muons

AOD: 480kB/ev
MiniAOD: 35-60kB/ev

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ttH observation CMS, Phys. Rev. Lett. 120, 231801 (2018)

- This observation allowed to establish directly the coupling of the Higgs boson to the heaviest quark and up-type fermion.
- Combination of Run 1 and 2 analyses
- Exploring bb, WW, ZZ, ττ and γγ decay modes of the Higgs boson
- All modes compatible with each other and with the SM
- **5.2 σ observation** of ttH production