New Results from CMS

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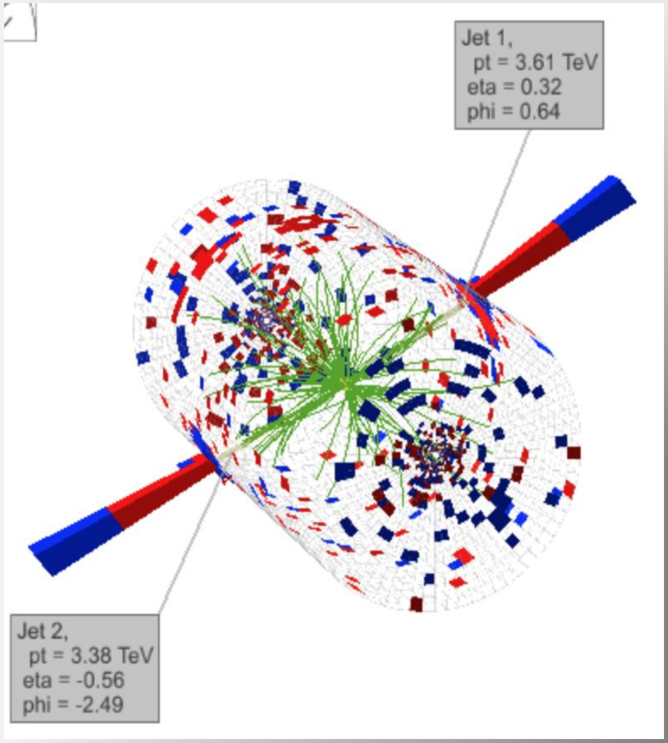
Corfu Summer Institute
21st Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece 2021

CERN



Outline

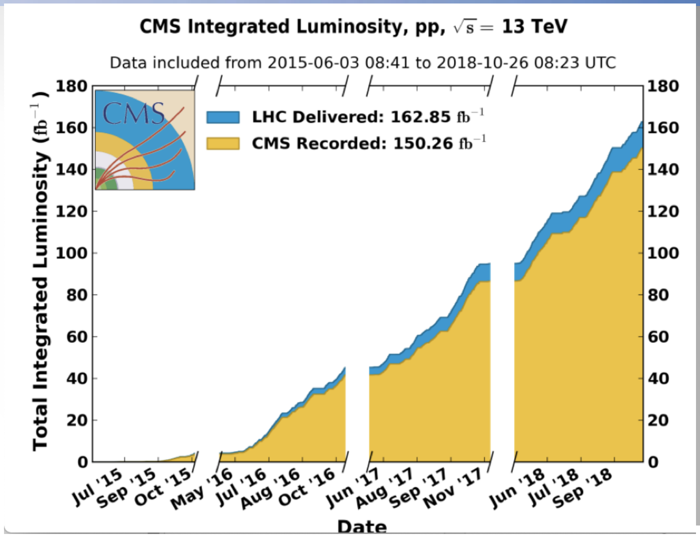
- Introduction
- Physics results
  - The Standard Model
  - The Higgs particle
  - Searches for New Physics
  - Searches for more Exotic particles in the Detector
- Summary/Outlook

Bird-eyes view on new results (personal selection)

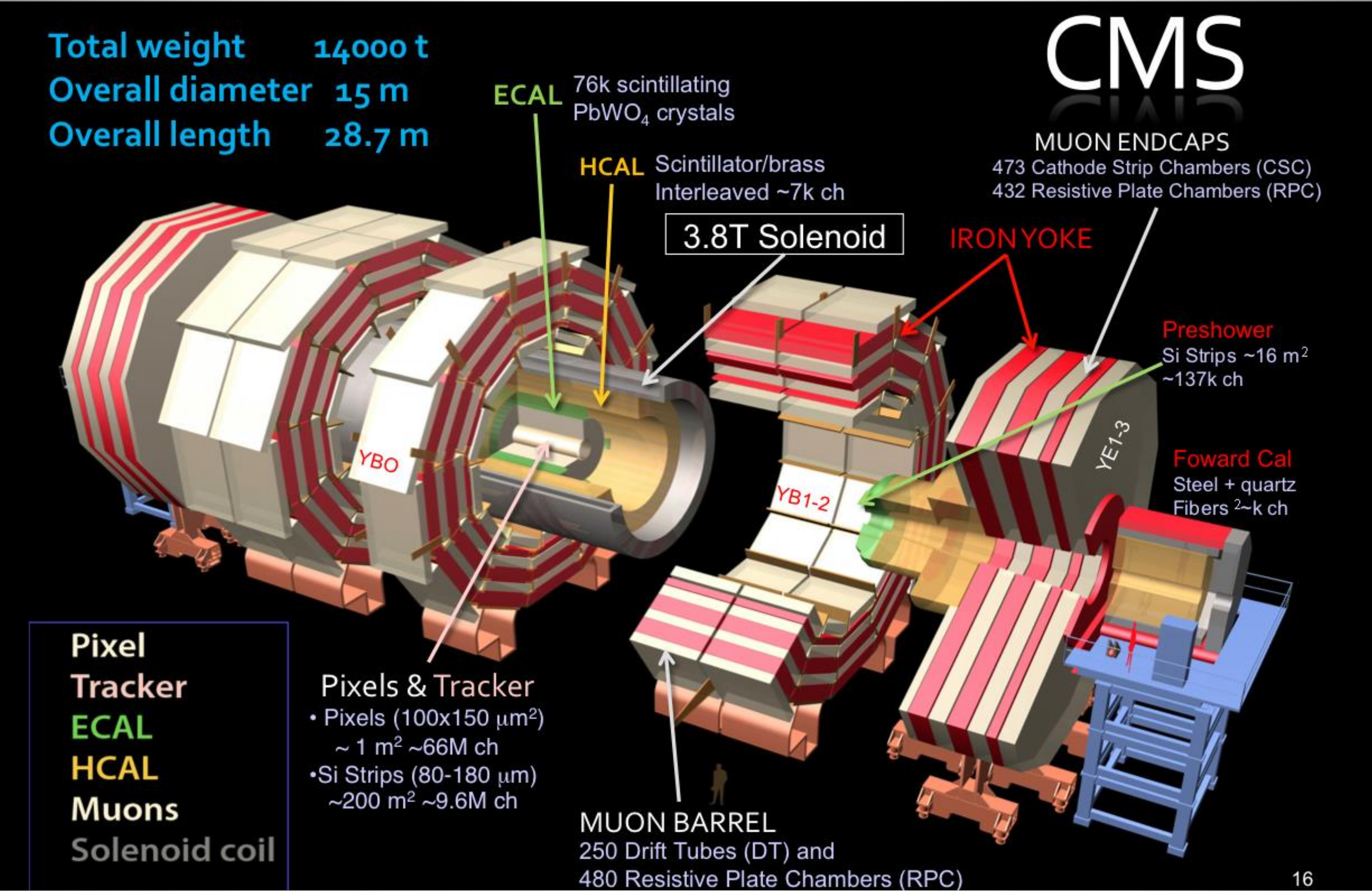
LHC Operations

pp Run-2 finished 24/10/18 6:00 am

- 2010-2012: Run-1 at 7/8 TeV CM energy
  - Collected ~ 27 fb^{-1}
- 2015-2018: Run-2 at 13 TeV CM Energy
  - Collected ~ 140 fb^{-1}



The CMS Detector



Last Year: 10 years of LHC Operation

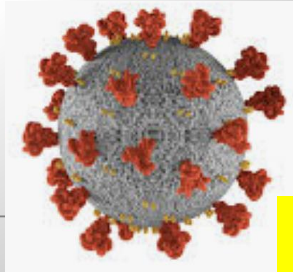
- LHC switched on at 7 TeV end of March 2010

  ->The highest energy in the lab!
- LHC @ 13 TeV from 2015 onwards
- Most important highlight so far:

  The discovery of a Higgs boson
- Many results on Standard Model process measurements, top-physics, b-physics, heavy ion physics, searches, Higgs physics
- Waiting for the next discovery…
  -> Searching beyond the Standard Model
- 10 years later: CERN in “safe mode” due to COVID19… ☹ ☹ ☹

March 30 2010 …waiting..
…since 4:00 am

12:58 7 TeV collisions!!!

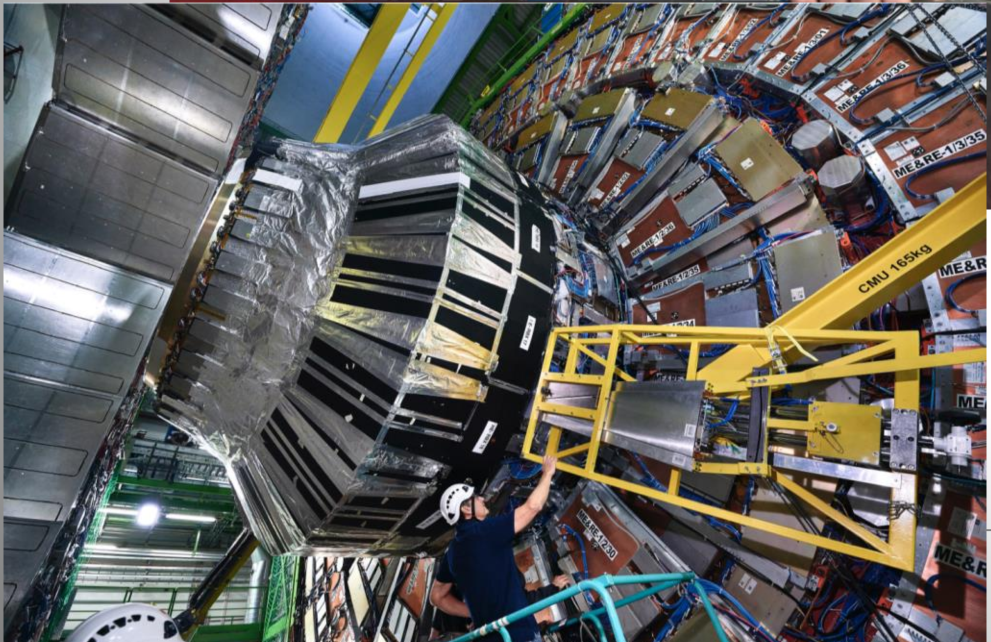


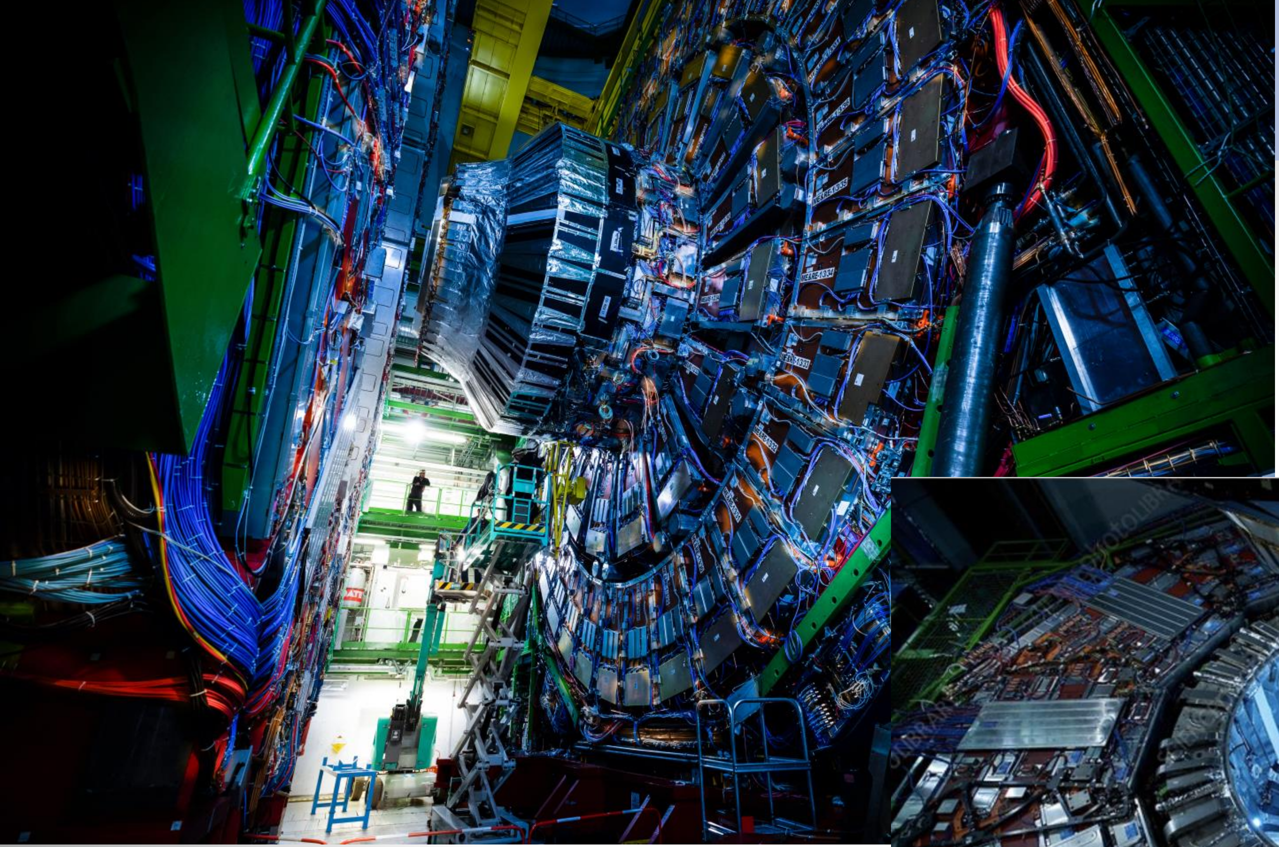
2020..2021

NOW:
Long Shutdown-2 till start of 2022

Pictures from the present shut-down and opening of the experiment

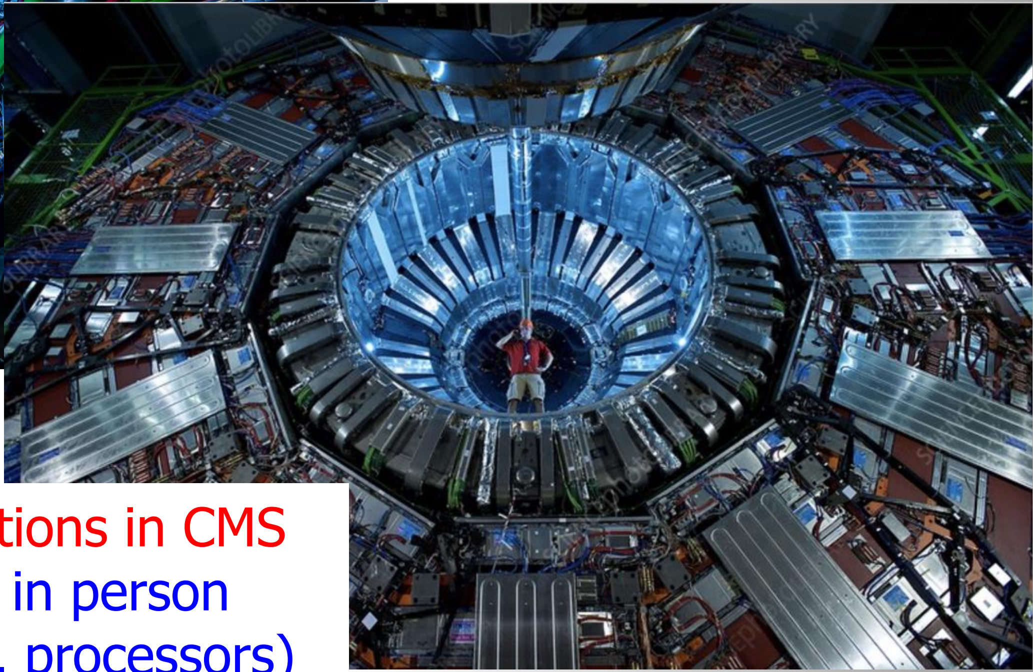
Many "virtual" visits to CMS in past months





NOW:
Long Shutdown-2 till start of 2022

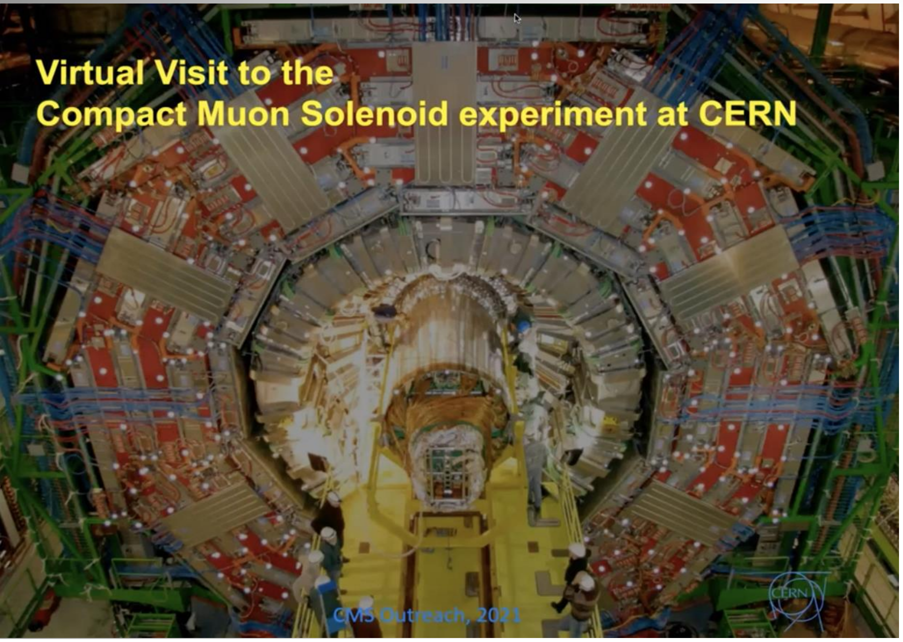
Scenic pictures…

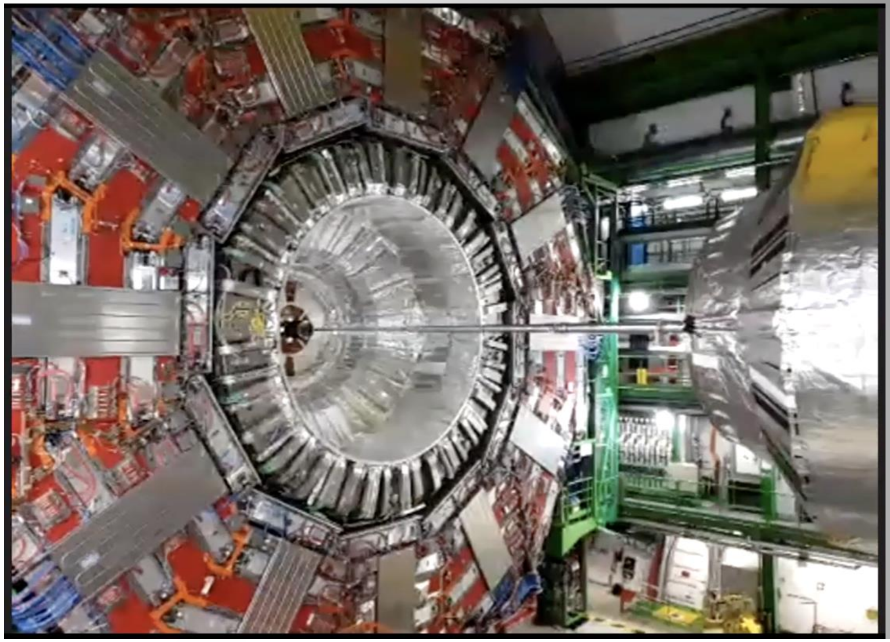


COVID has slowed down *some* operations in CMS
- Lockdown/travel restrictions/lack of in person
- Supplies from external sources (e.g. processors)
- All of these aspects impede progress indirectly

Nevertheless CMS continues progressing
- Preparation for Run-3
- Scientific output

Virtual Visits…

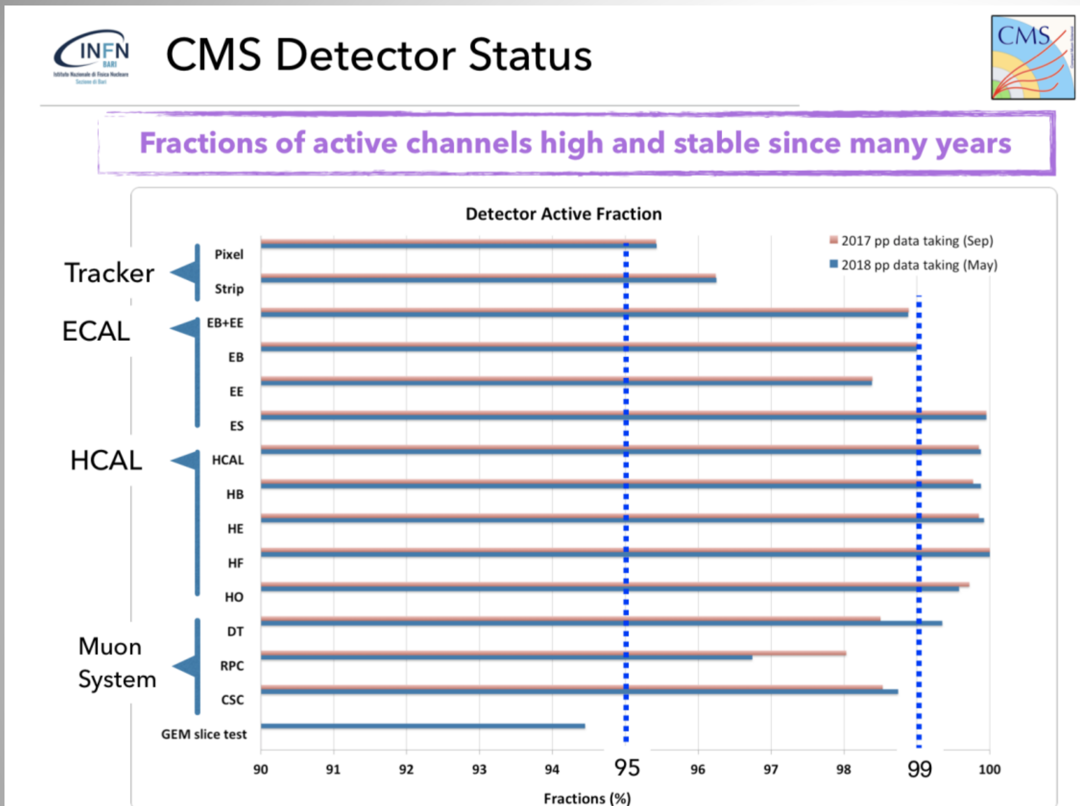




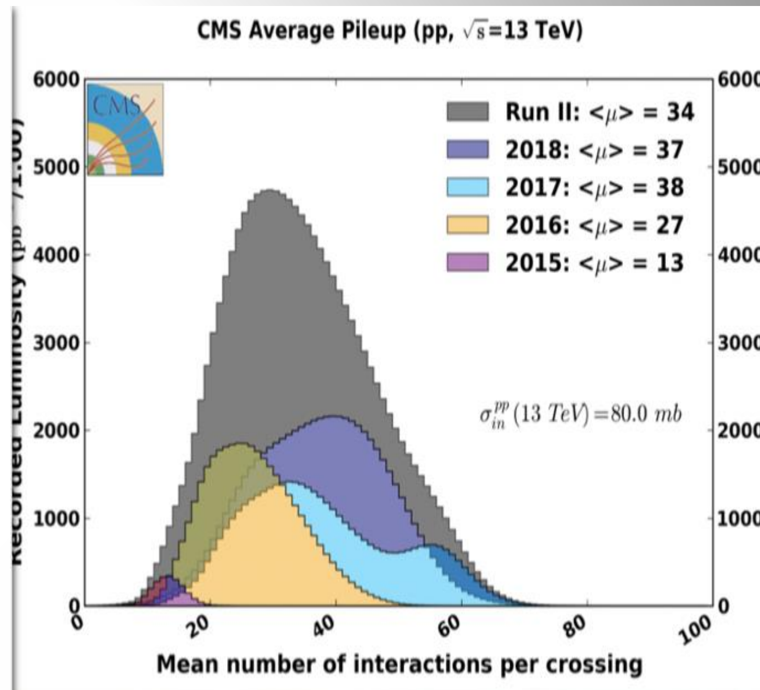
E.g. https://www.youtube.com/watch?v=tj3tE7e8KOU

Virtiual visit for the neutrino school early August 2021

CMS Detector Status for the last Run



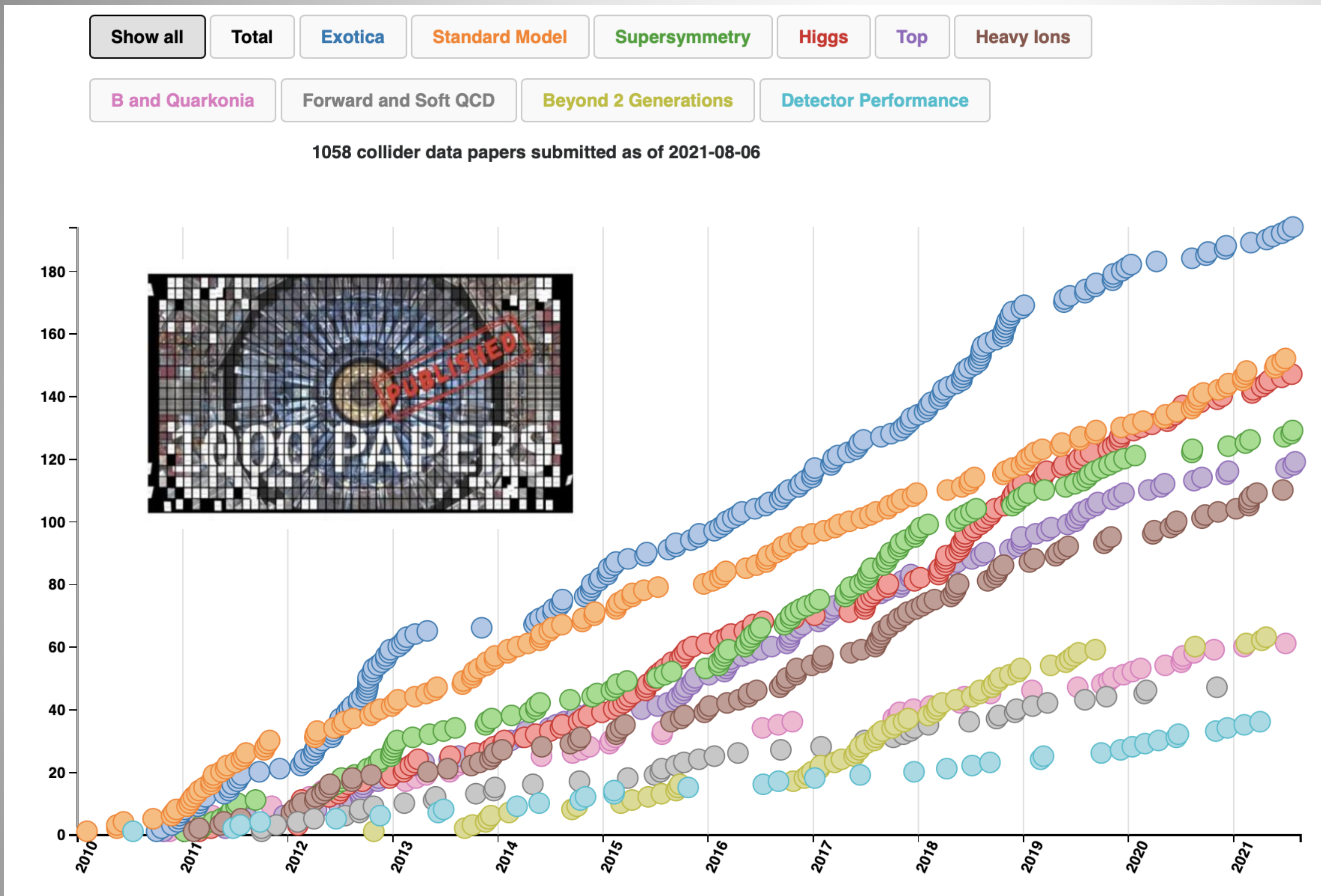
Pile-up during run-2



Run 2 pp data taking efficiency 92.3%
with 2018 data taking efficiency 94%

CMS experiment in a very good shape during run-2
We can successfully deal with pile-up ~ 40 events per bx

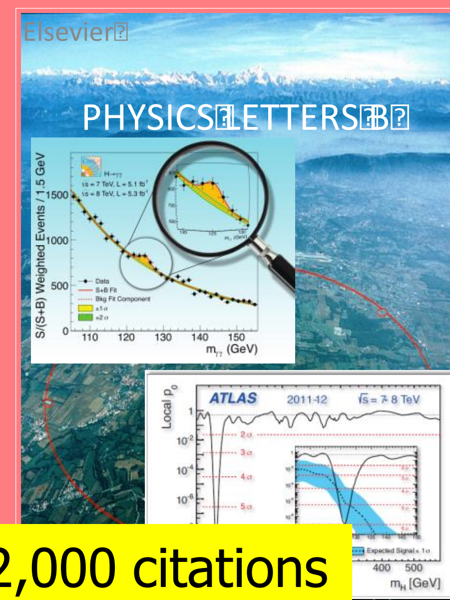
LHC Publications in CMS



~1060 publications on pp (and pPb/PbPb) physics since 1/2010

About 100 papers on Higgs studies!!

Paper 16 was the discovery paper!



http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

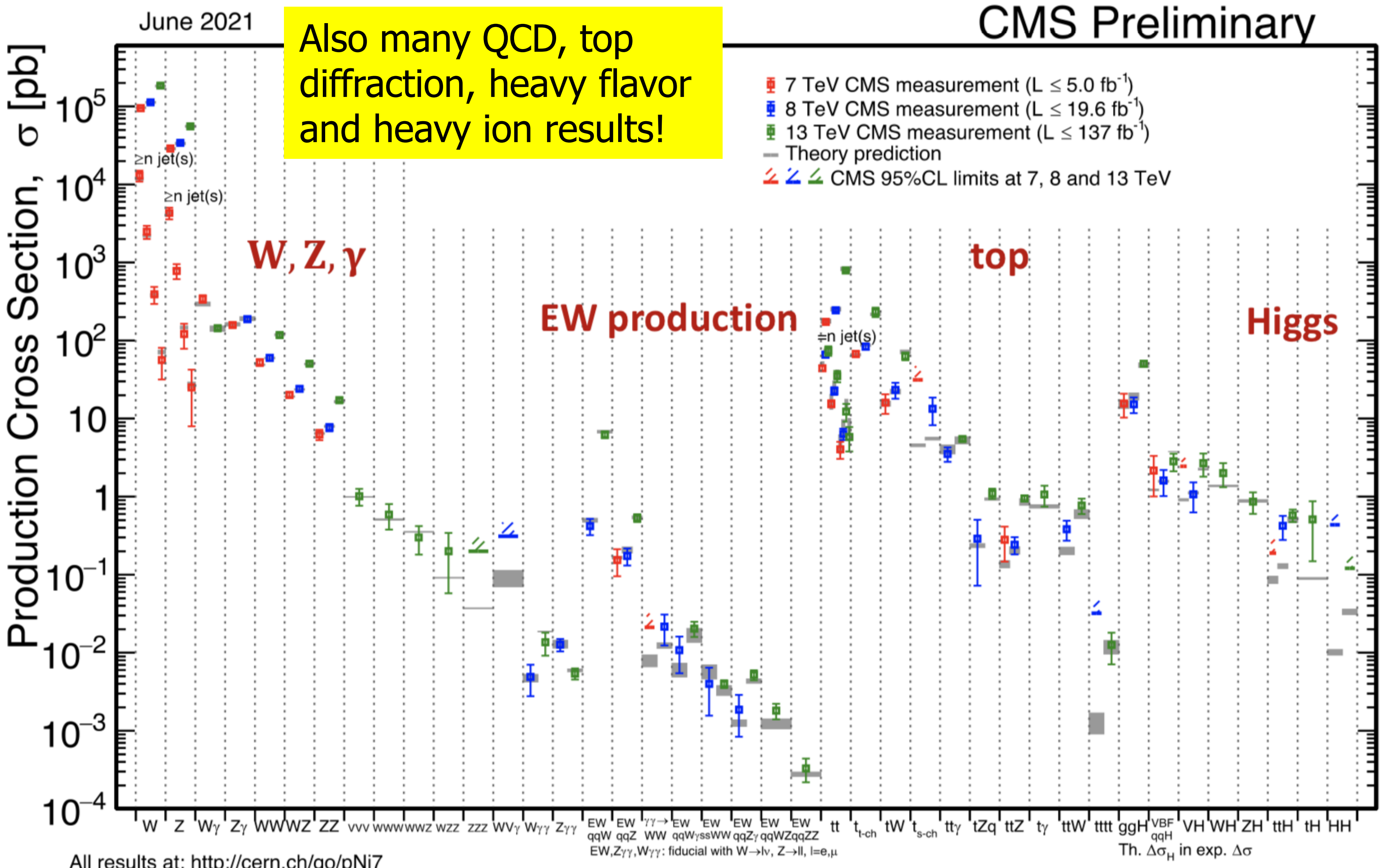
About 150 more since September two years ago…

>12,000 citations

Standard Model Measurement

Standard Model Measurements

Also many QCD, top diffraction, heavy flavor and heavy ion results!

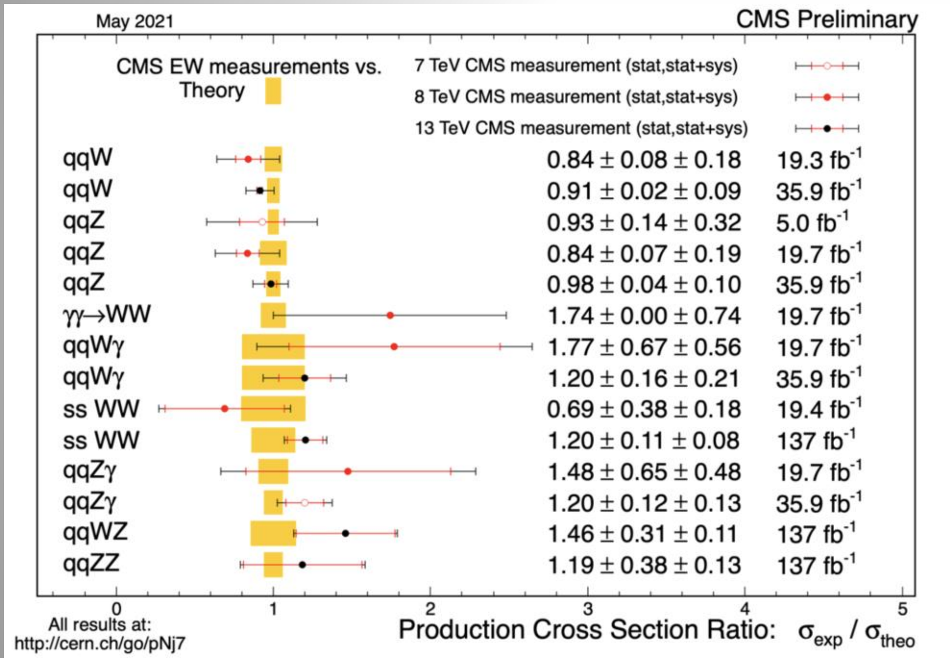


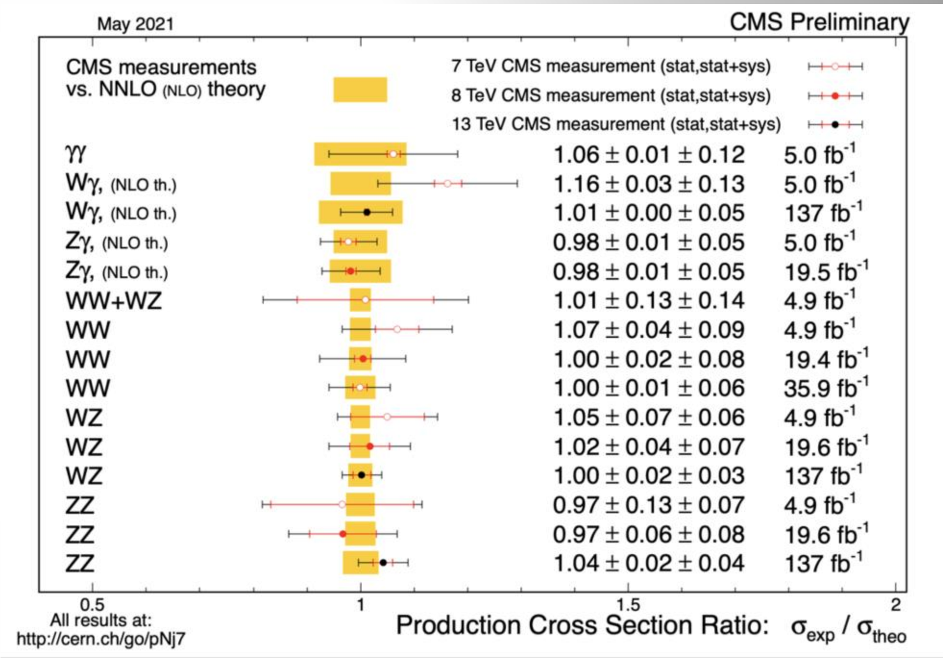
All measurements in good agreement with the Standard Model predictions!!

Standard Model Measurements

EWK Measurements

Measurements vs NNLO Theory

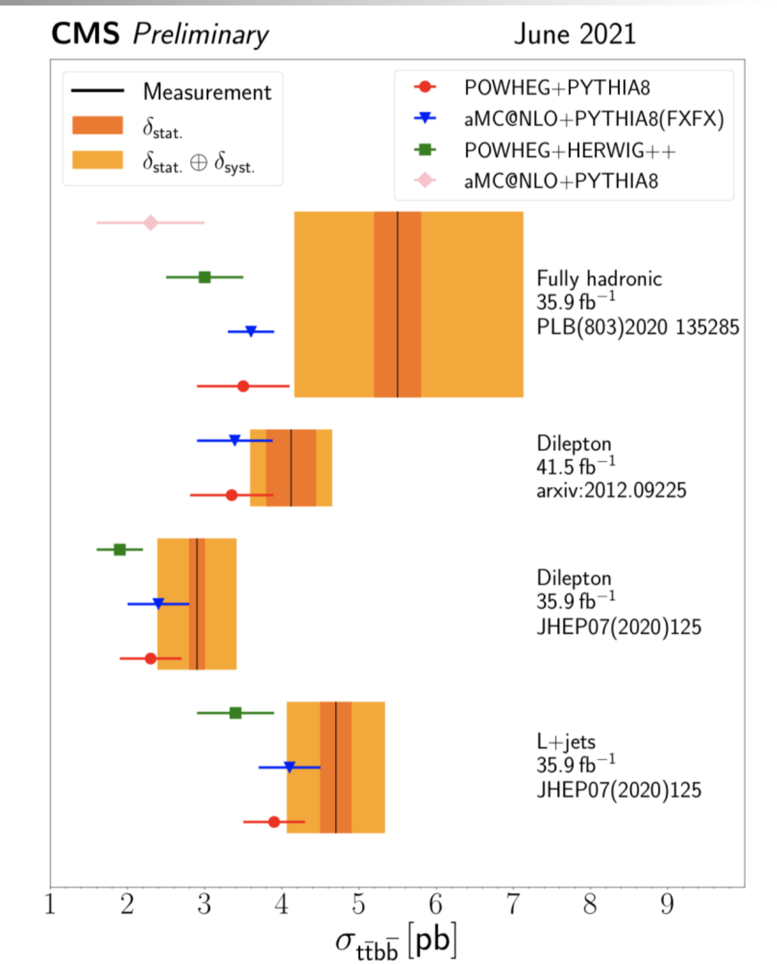


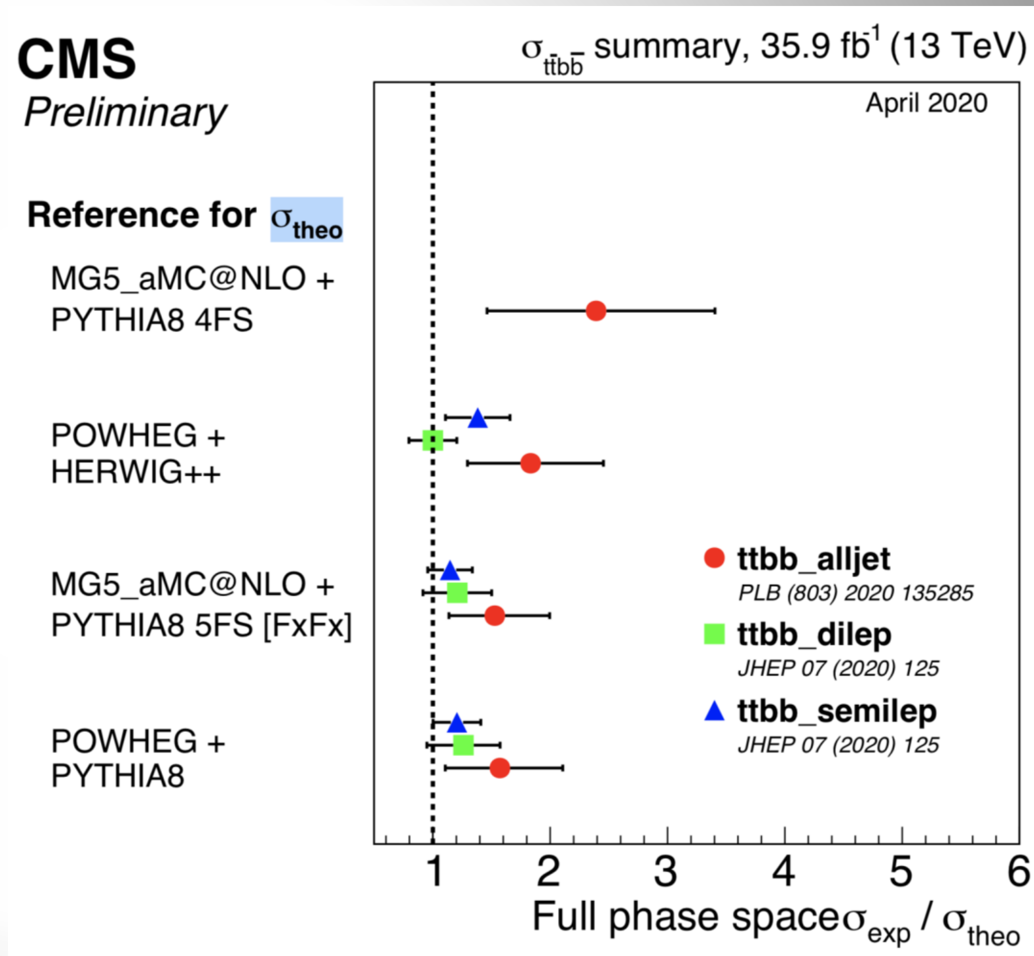


All measurements in good agreement with the Standard Model predictions!!

ttbb Cross Sections

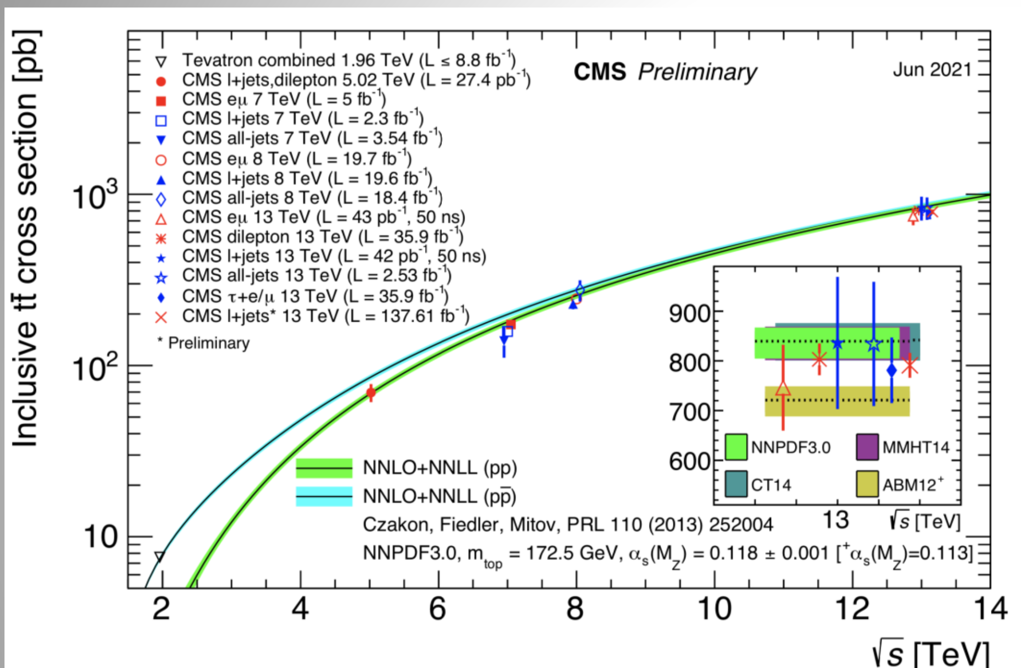
These processes are important backgrounds eg in Higgs (ttH) studies

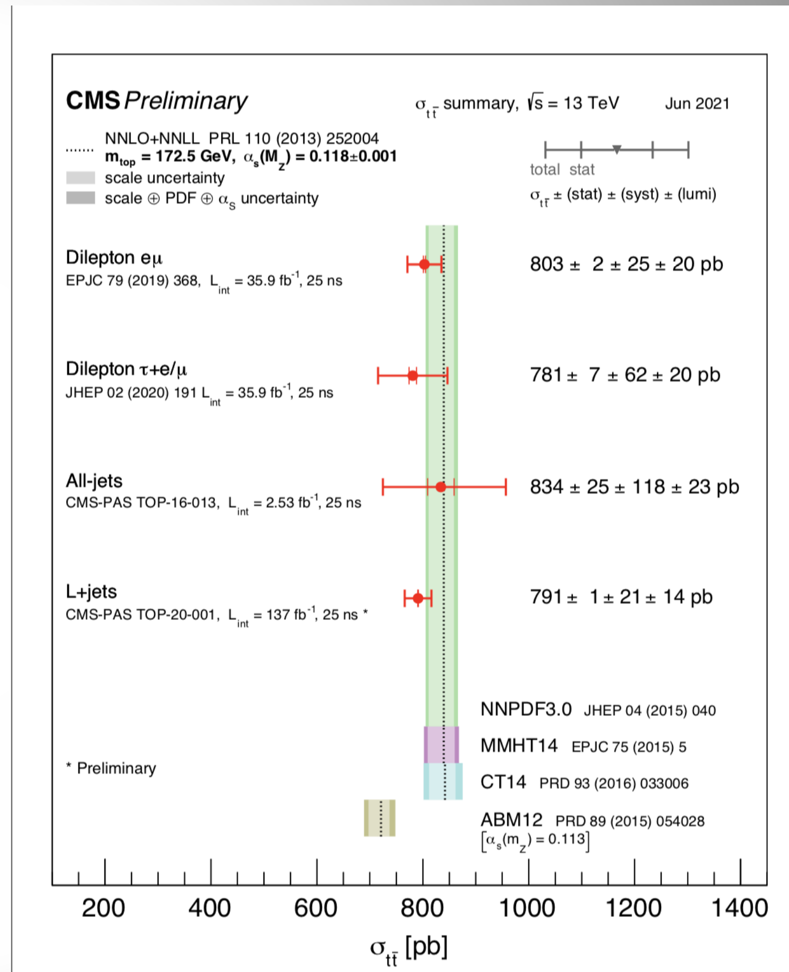




Measured cross sections systematically larger than predictions…

Top Cross Sections

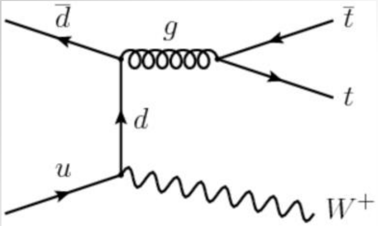


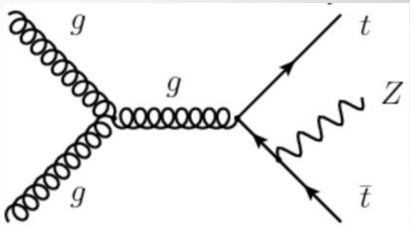


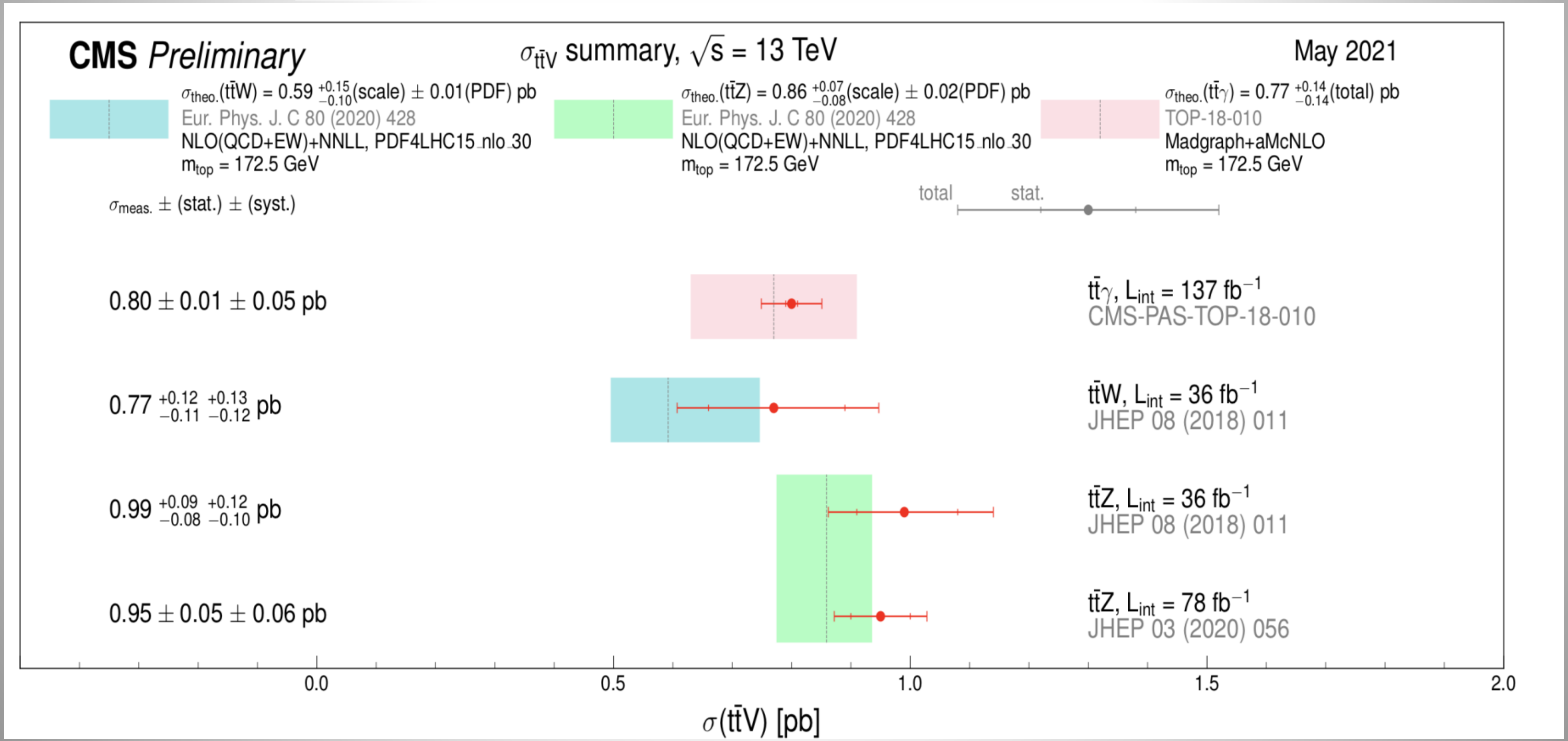
Many detailed top studies ongoing
Measurements get more precise…

Measurements in good agreement with the Standard Model predictions!!

tt plus Vector Boson Production

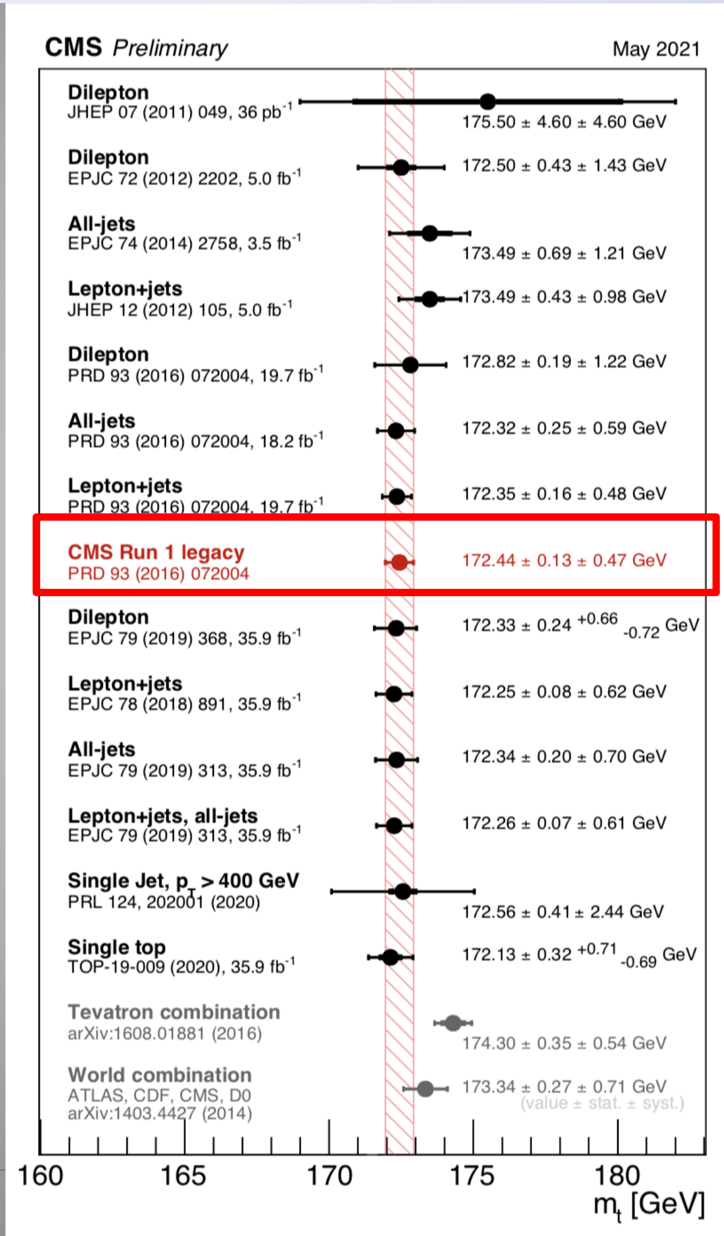






Measurements in good agreement with the Standard Model predictions!!

Top Mass Determination



Steady improvements over the last years in Run-1

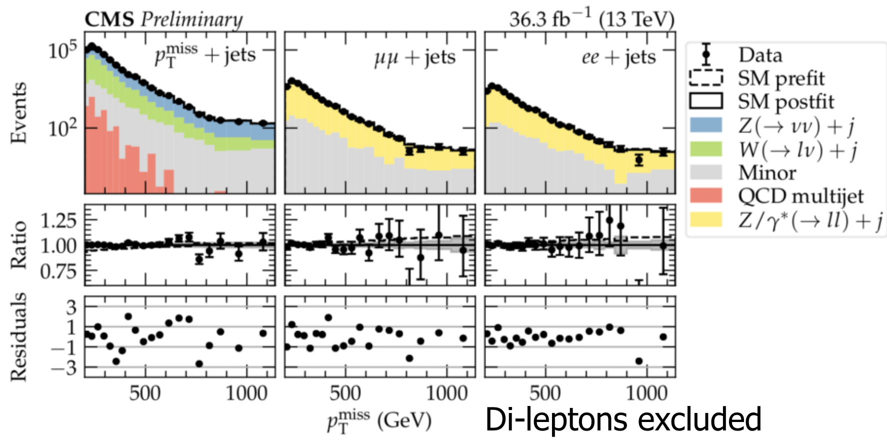
Precision better than 0.3%

Hadronization model uncertainties one of the main limitations

This is not the final word yet
-Run-2 combination under way
-Experiment combination next

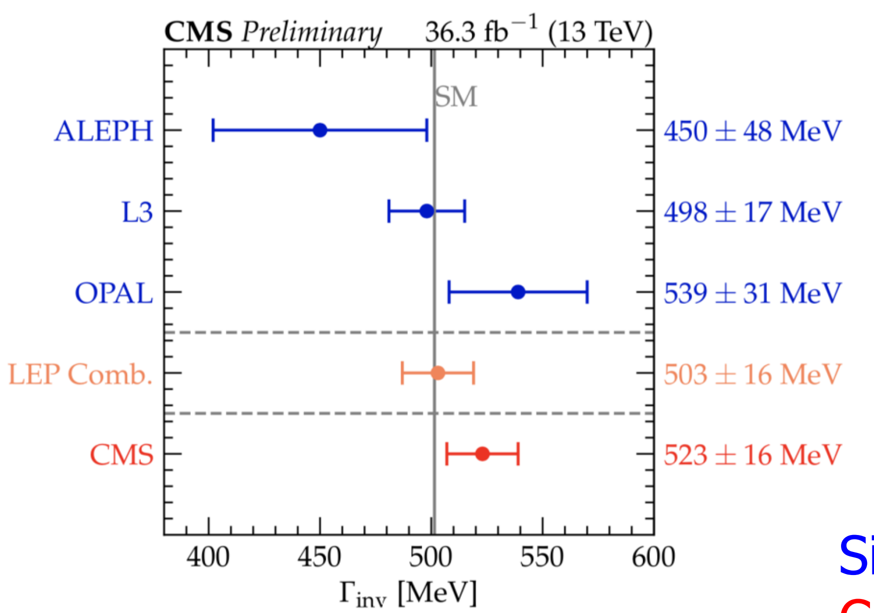
Note: the average value at LHC somewhat lower than Tevatron one: 174.30 ± 0.64 GeV
Driven by D0 result. Still not really Resolved yet…

Precision Measurement of the Z Invisible Width



Di-leptons excluded

SMP-18-014



- Utilizes the similarity in kinematic characteristics between the decay of the Z boson to neutrinos and to charged leptons (electrons/ muons)
- Select events with p_{Tmiss} and with dileptons & calculate the p_{Tmiss} excluding the dileptons from the event
- The invisible width, Γ_{inv} ,is then extracted from a simultaneous fit to data regions containing mostly Z boson decays to neutrinos and those dominated by Z boson decays to electron and muon pairs.

$$\Gamma_{inv} = 523 \pm 3\,(\text{stat}) \pm 16\,(\text{syst})\,\text{MeV}.$$

Single most precise direct measurement

Competitive with combined direct LEP result

W Decay Branching Fractions

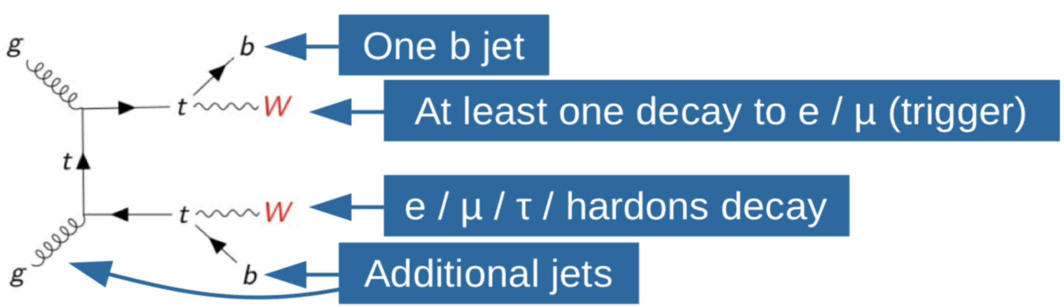
Precision measurement of the W boson decay branching fractions

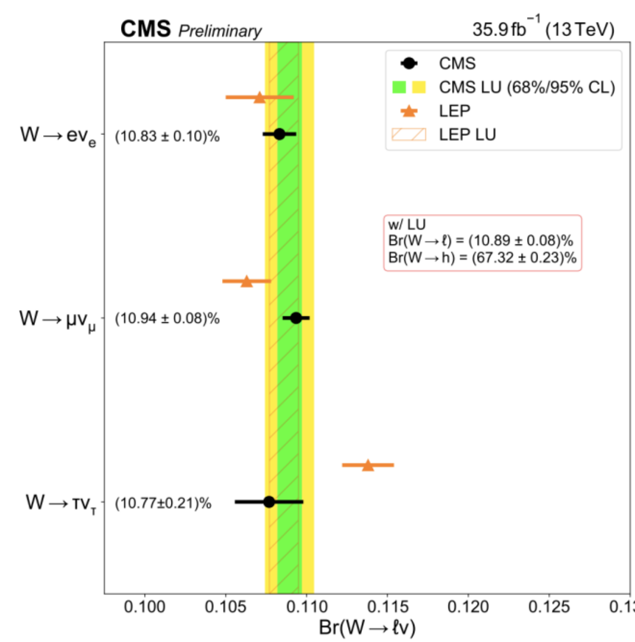
Combining all the measurements to get All BR

SMP-18-011

	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$10.71 \pm 0.14 \pm 0.07)$ %
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$10.63 \pm 0.13 \pm 0.07)$ %
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$11.38 \pm 0.17 \pm 0.11)$ %
$\mathcal{B}(W \to h)$	$(67.46 \pm 0.04 \pm 0.28)\%$	–
with LU		
$\mathcal{B}(W \to \ell\overline{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to h)$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

W bosons from top quark decays



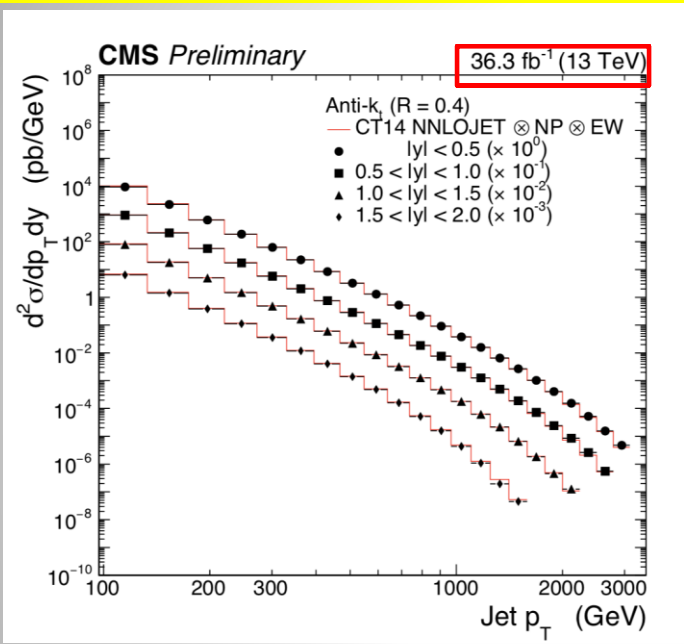


30 categories ->ML fit of the categories

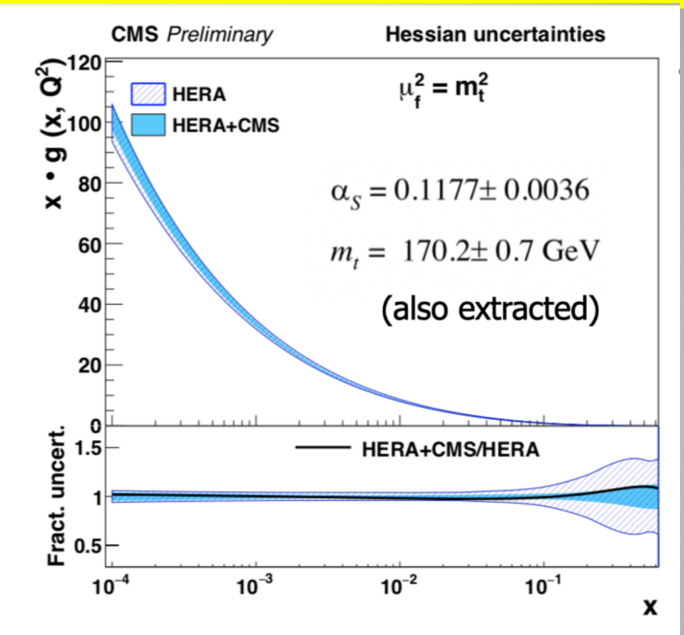
Jet Differential Distributions

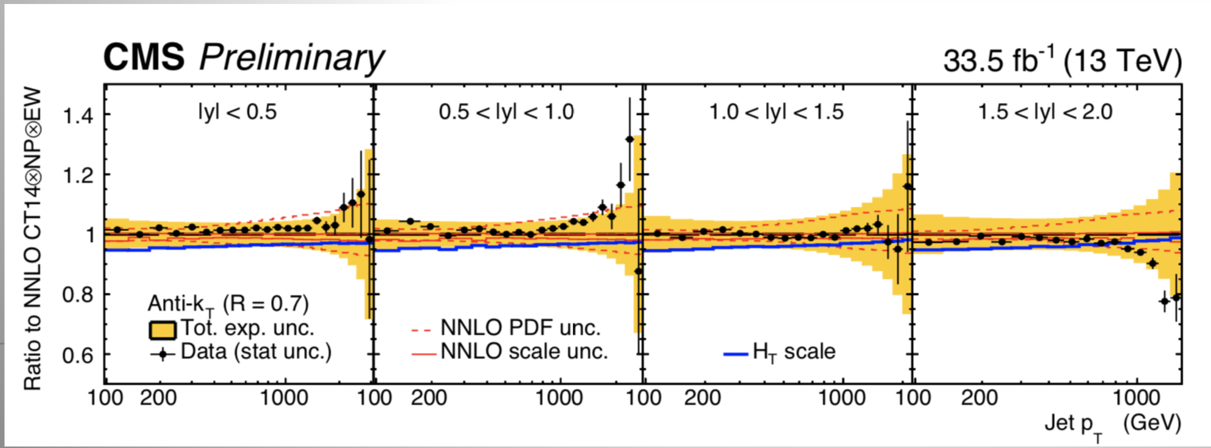
Inclusive jet cross sections in p_T and rapidity, with anti-k_T algorithm

HERA DIS + CMS (jet and top) measurements: effect on the gluon



SMP-20-011



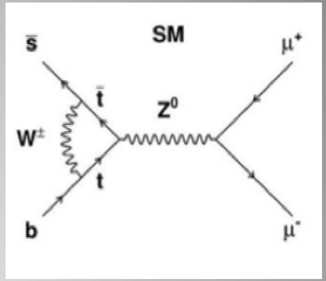


Comparison with NNLO calcvulations

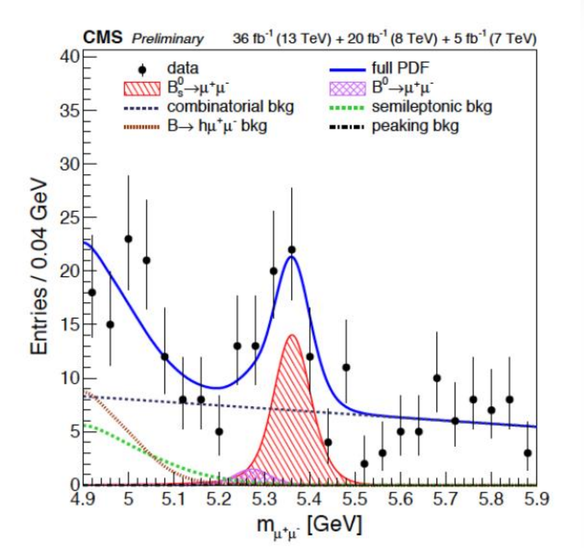
N. Glover et al.

Measurements of $B_{s(d)} \rightarrow \mu\mu$

Summer 2020 combination of $B_{s(d)} \rightarrow \mu\mu$ (ATLAS, CMS and LHCb)



Eg. BPH-20-003



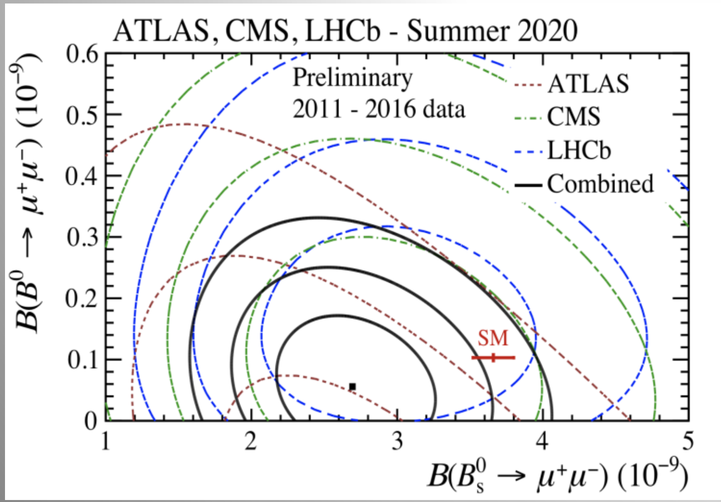
The results are compatible with the SM predictions within 2.1 standard deviations

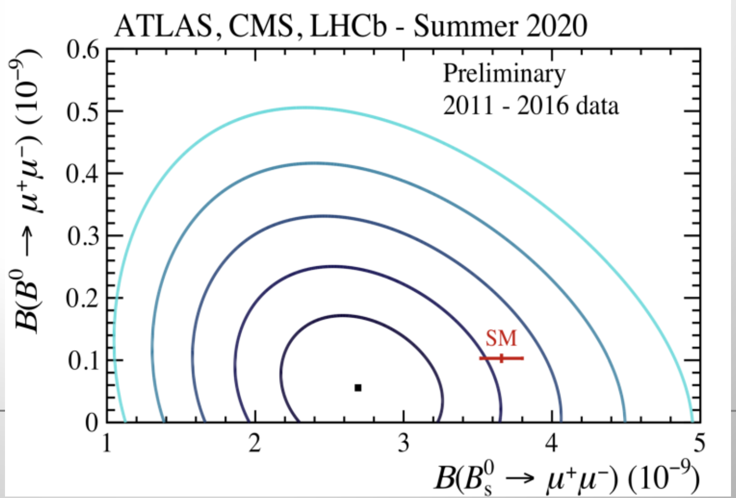
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.69\,^{+0.37}_{-0.35}) \times 10^{-9}$$

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 1.6\ (1.9) \times 10^{-10} \text{ at } 90\%\ (95\%)$$

$$\mathcal{R} < 0.052\ (0.060) \text{ at } 90\%\ (95\%)$$

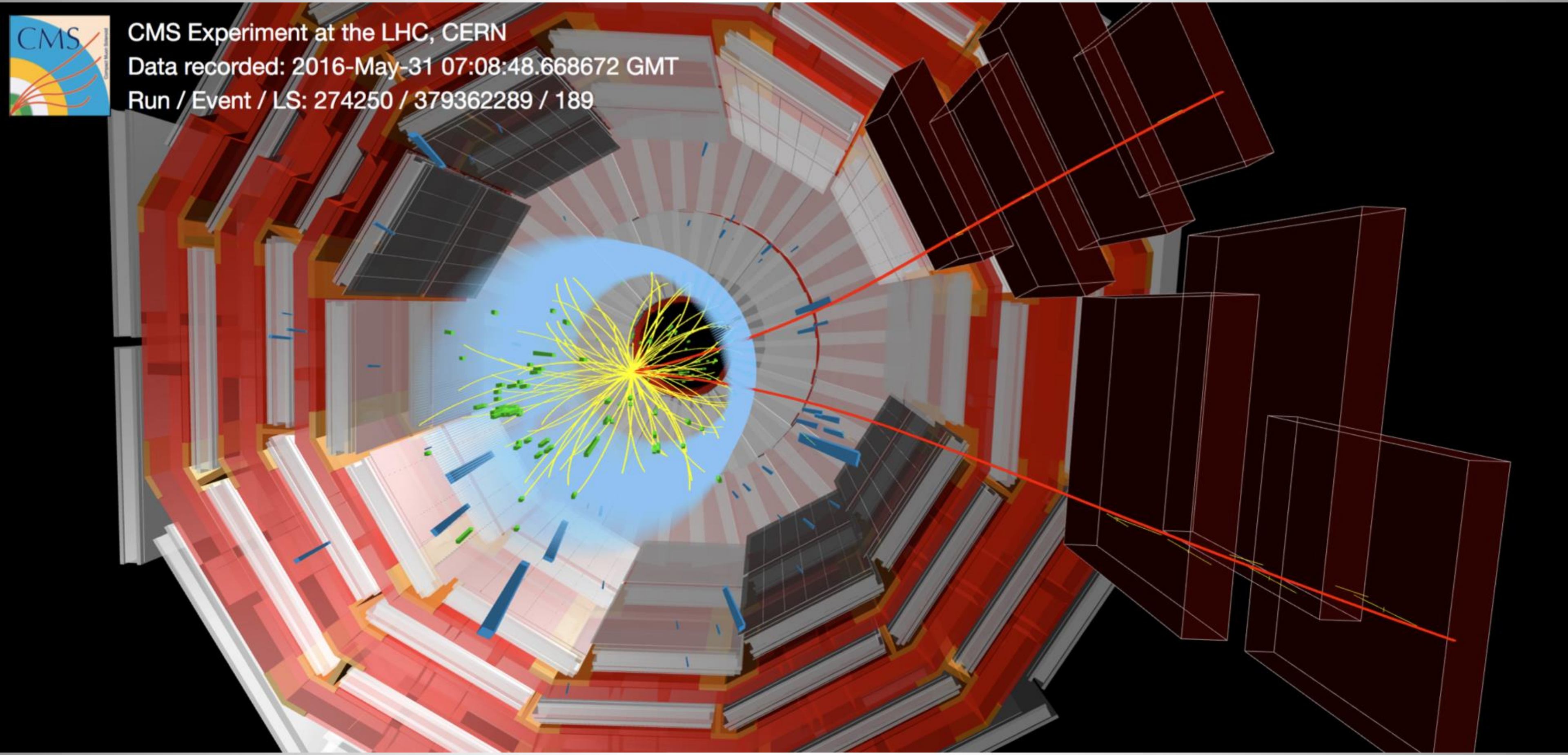




Includes data up to 2016

Next stop full Run-2 data incuded

Measurements of $B_{s(d)} \rightarrow \mu\mu$

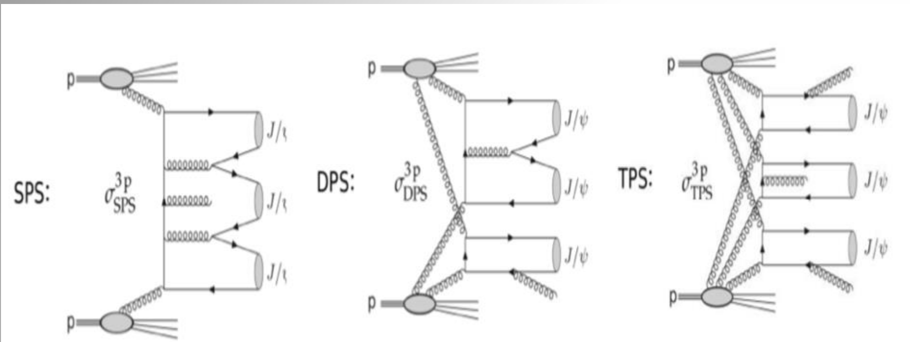


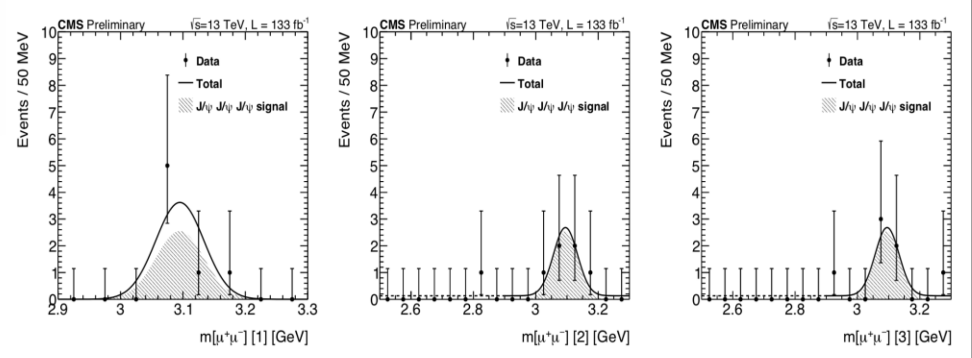
$B_s \rightarrow \mu\mu$ candidate

Observation of Triple J/Ψ production

Study of double and triple parton scattering in pp colisions
Five candidate events are observed in the full Run-2 data sample

BPH-21-004



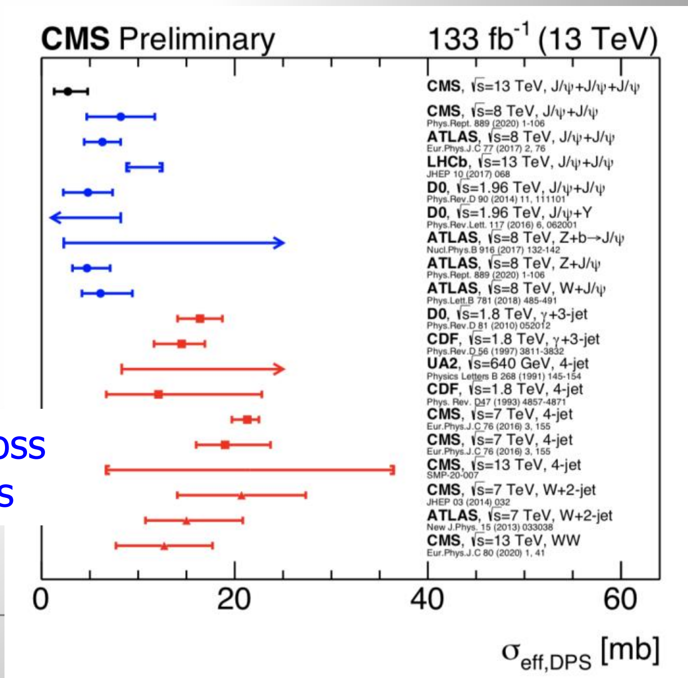


Production is expected to be dominated by DPS and TPS the DPS associated effective cross section parameter is:

$\sigma_{Eff,DPS} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo})\ \text{mb}$

where $\sigma_{\text{Eff.DPS}}$ is an effective interaction area:

$$\sigma^{pp\to\psi_1\,\psi_2+X}_{\text{DPS}} = \left(\frac{m}{2}\right)\frac{\sigma^{pp\to\psi_1+X}_{\text{SPS}}\ \sigma^{pp\to\psi_2+X}_{\text{SPS}}}{\sigma_{\text{eff,DPS}}}$$



DPS cross sections

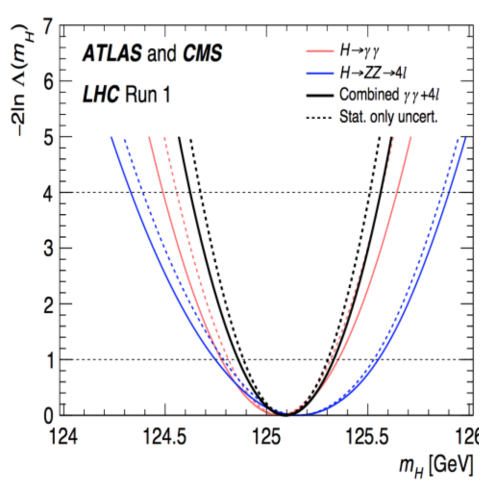
Fiducial cross section:

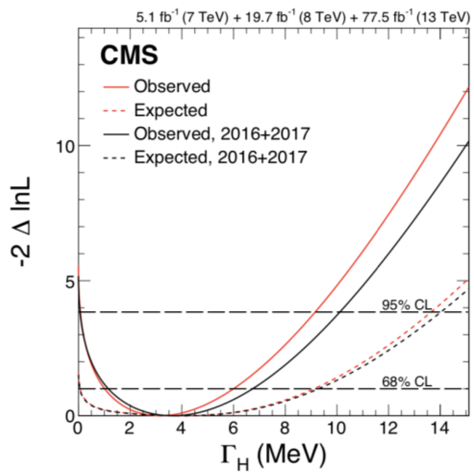
$\sigma(pp \to J/\psi\ J/\psi\ J/\psi\ X) = 272^{+141}_{-104}(\text{stat}) \pm 27\ (\text{syst})\ \text{fb}$

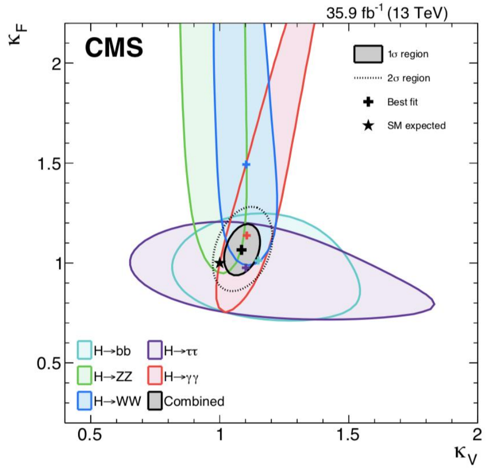
The Higgs

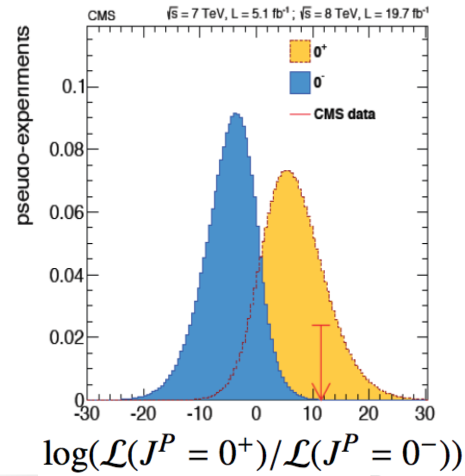
Brief Higgs Summary (2019)

We know already a lot on this brand New Higgs particle!!









Mass = CMS+ATLAS
125.09 ±0.21(stat) ±0.11(syst) GeV

Width < 9 MeV (95%CL)

Couplings are within ~15-20% of the SM values

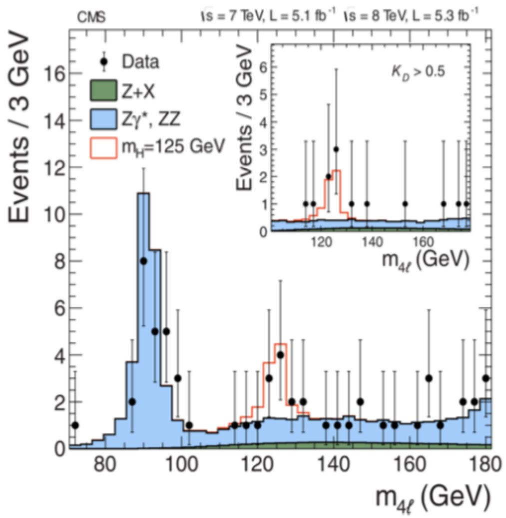
Spin = $0^{+(+)}$ preferred over 0^{-},1,2

We continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production, heavier Higgses, charged Higgses…

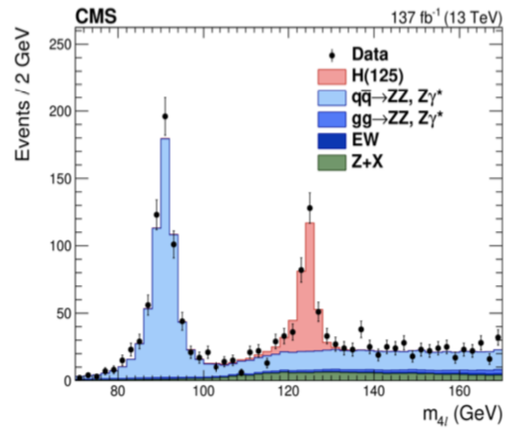
Higgs @ 13 TeV in Run-2

Higgs in 2021.

2012



2021



7.7 million Higgs produced in Run2 per experiment

- The mild deviations seen in Run-1 are gone ☹
- Observation of H→bb in the associated production channel
- Direct observation of ttH production
- No deviations from Standard Model Higgs expectations yet!!

The Higgs Boson is still very much Standard Model-like!

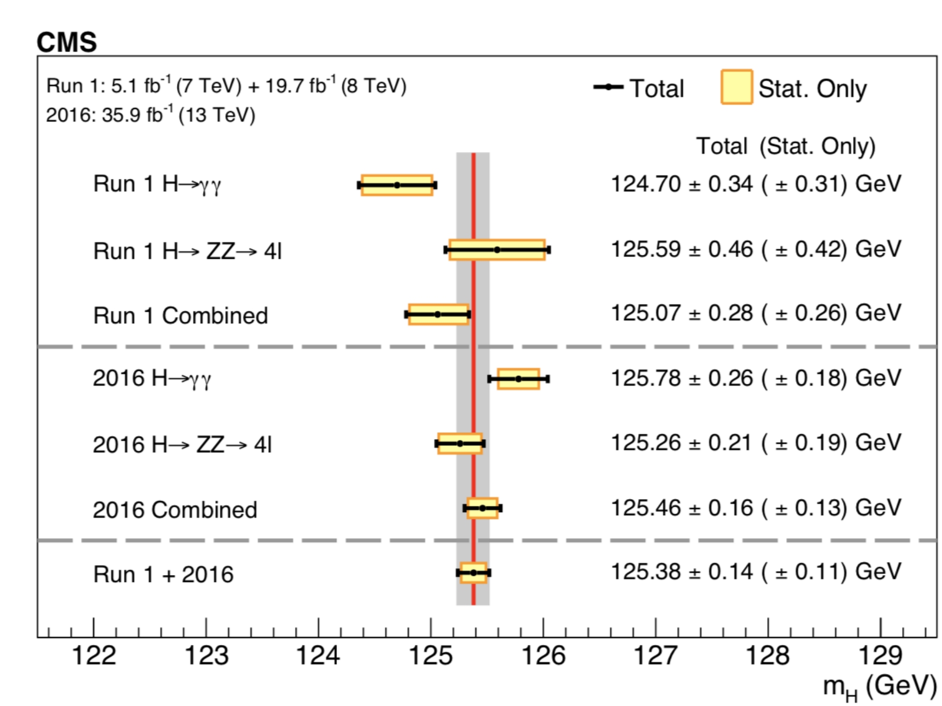
$$\mu = 1.17^{+0.10}_{-0.10}$$

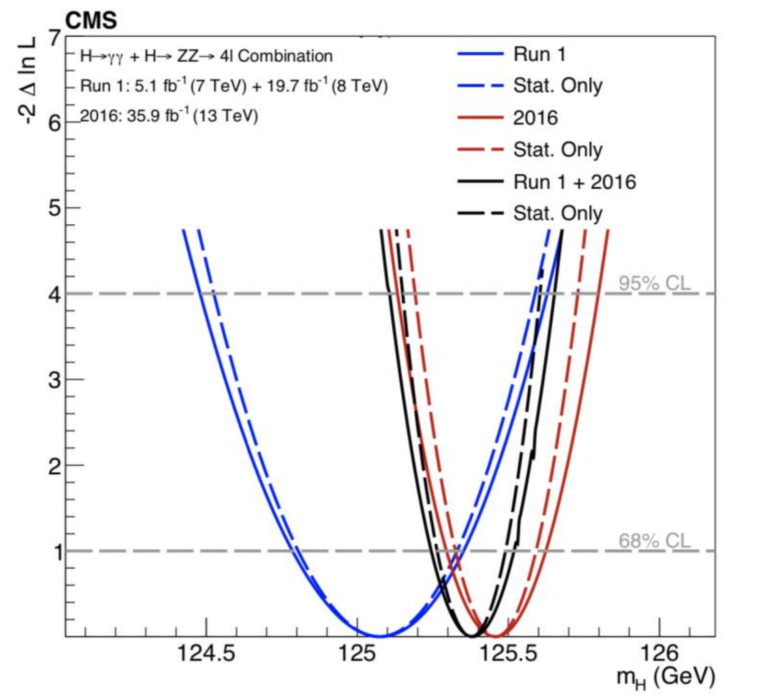
Higgs Mass

$H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ decay channels with the Run 1 and 2016 data

- excellent detector performance in lepton/photon energy scale determination
- single experiments are better than ATLAS + CMS Run I combination
- still dominated by statistical uncertainties

2002.06398





$$m_H = 125.38 \pm 0.14\,\mathrm{GeV}$$

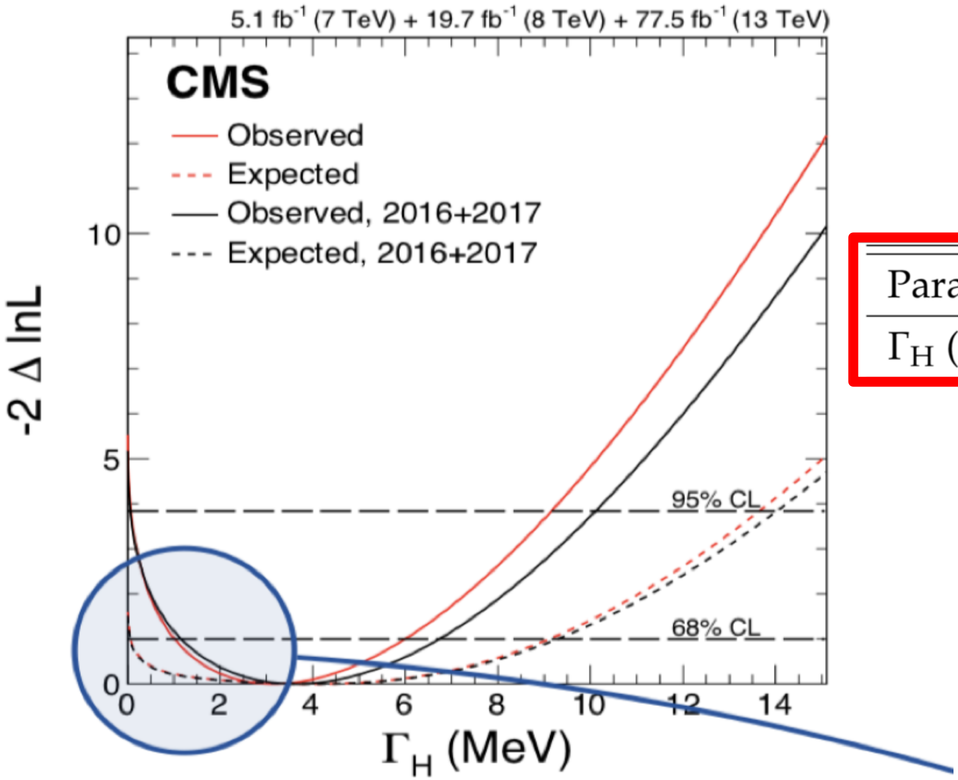
2019: $m_H = 125.26 \pm 0.21\,\mathrm{GeV}$

M_H is known to a precision of almost 1 per mille

Higgs Width

Technique: on-shell to off-shell cross section

arXiv:1901.00174



$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

SM Higgs width =4 MeV

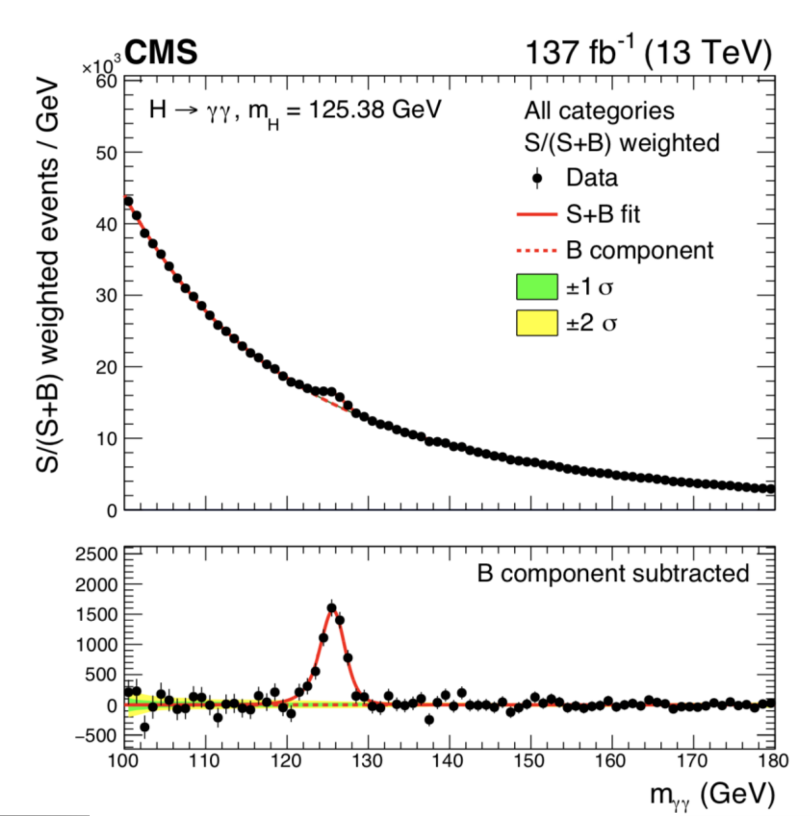
We start to get a lower bound on the Higgs width!

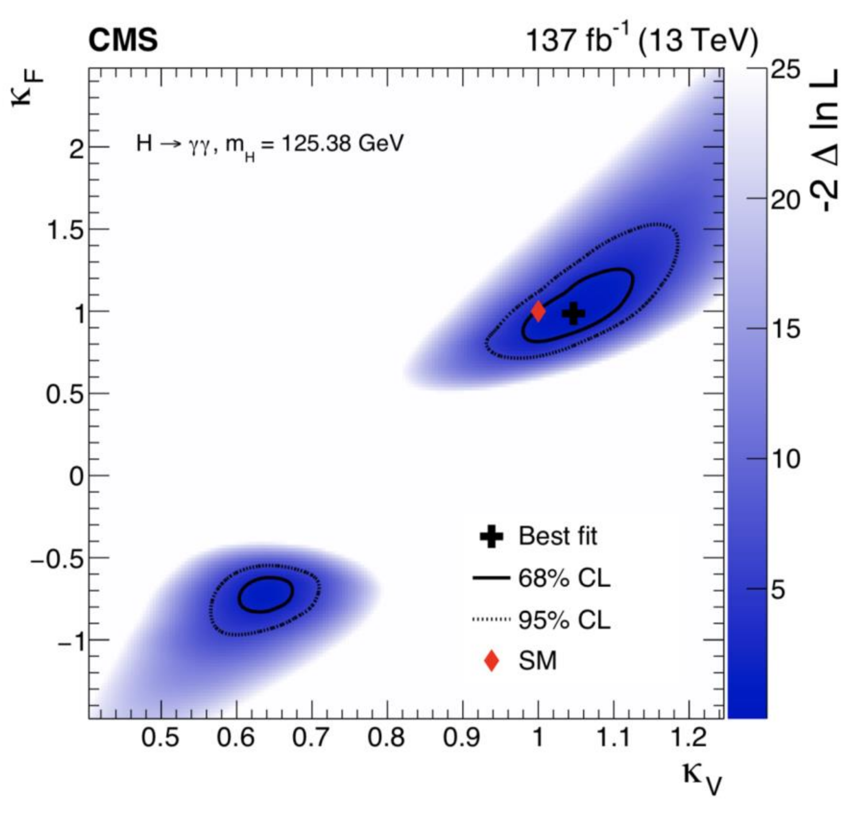
Γ < 9.16 MeV (13.7 exp.) @ 95% C.L.
Run1 + Run2, H → ZZ → 4ℓ*

Higgs to Diphoton Analysis

2103.06956

Full Run-2 results





All data: categories weighted
With S/(S+B)

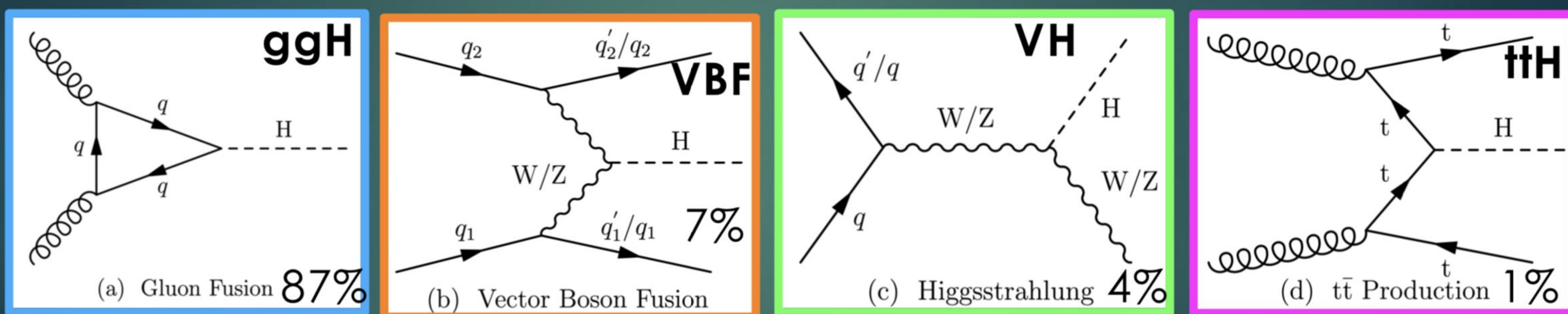
$$\mu = 1.12^{+0.09}_{-0.09} = 1.12^{+0.06}_{-0.06}\,(\text{theo})^{+0.03}_{-0.03}\,(\text{syst})^{+0.07}_{-0.06}\,(\text{stat})$$

Simplified Template Cross Sections

Simplied Template Cross Sections (STXS)

1610.07922

- ATLAS, CMS and the theory community have been working together in the LHC Higgs Working Group to setup a common framework for Higgs boson measurements in Run 2.
  - Reduce theory uncertainty and model dependence on measured bins
  - Each Higgs boson production mode is split into numerous templates by kinematic features that are highly correlated with reconstruction-level objects.



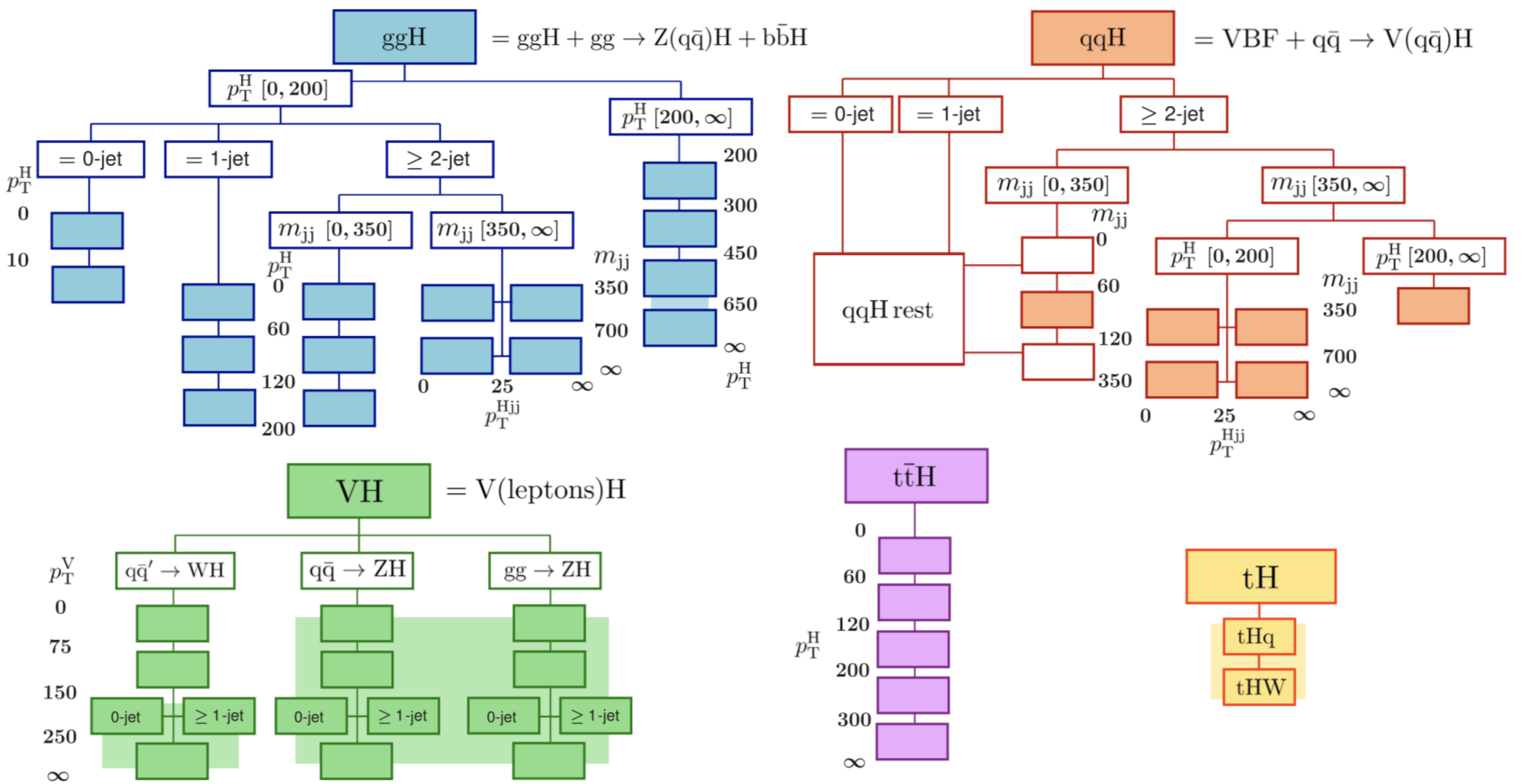
p_T (H)	Njets	p_T (V)	p_T (H)
Njets	Mjj, p_T(H+jj) (if Njets>1)	Njets	
Mjj, p_T(H+jj) (if Njets>1, VBF-like)	p_T (H)		

Adapted by the LHC experiments to maximally reduce impact of model dependence and theory assumptions

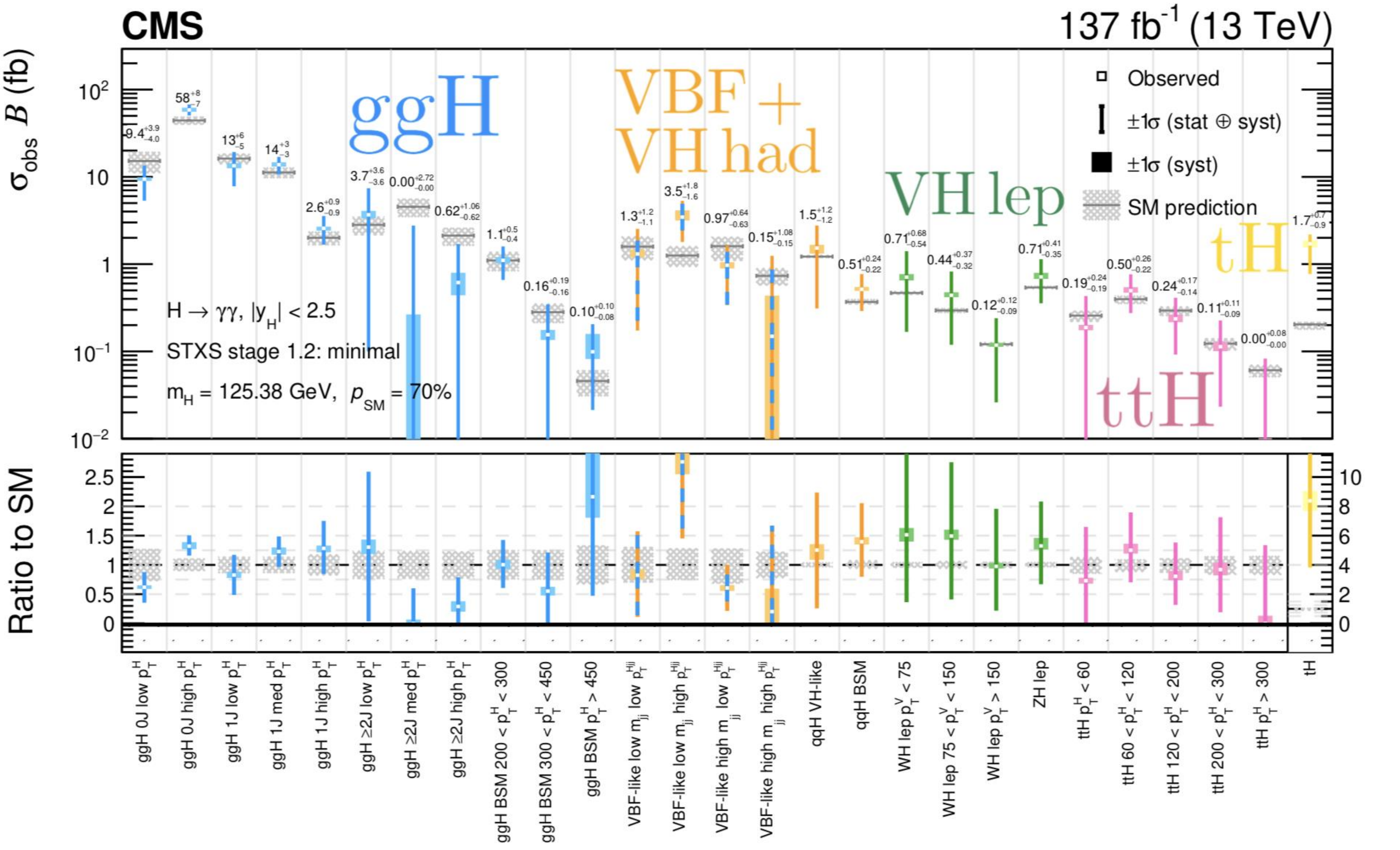
STXS: Higgs to Diphoton Analysis

2103.06956

"Event classification"



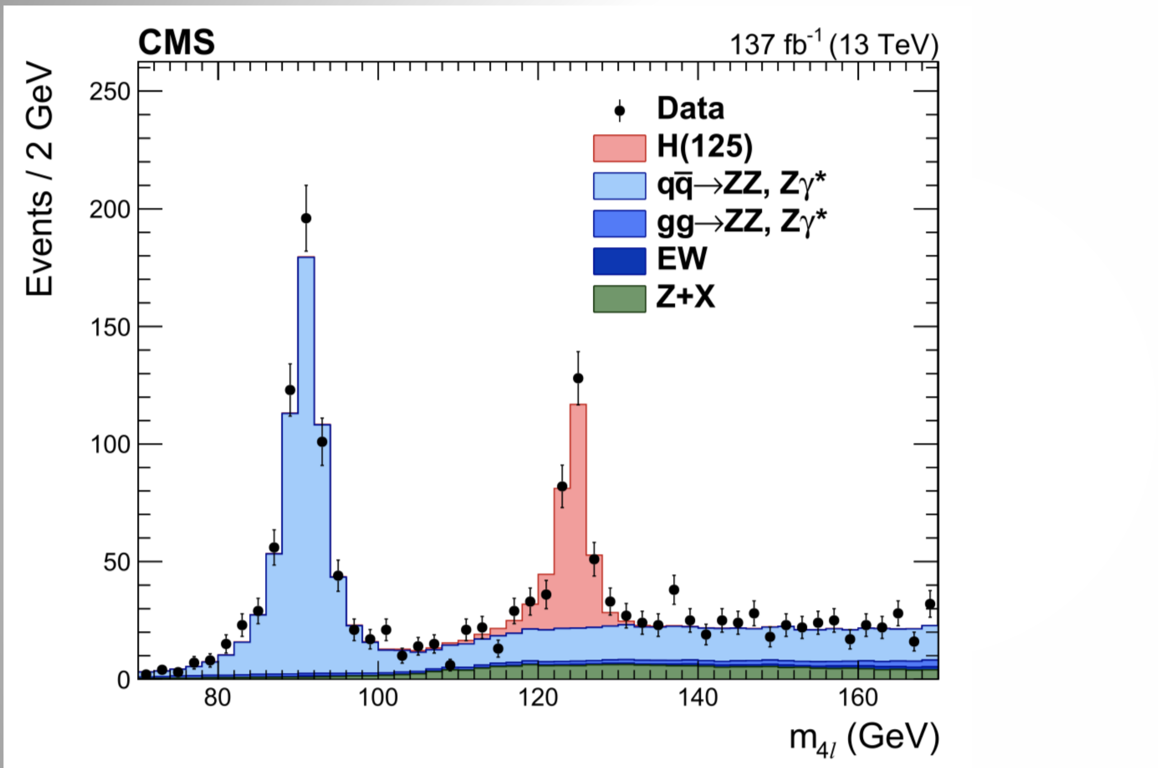
STXS: Higgs to Diphoton Analysis



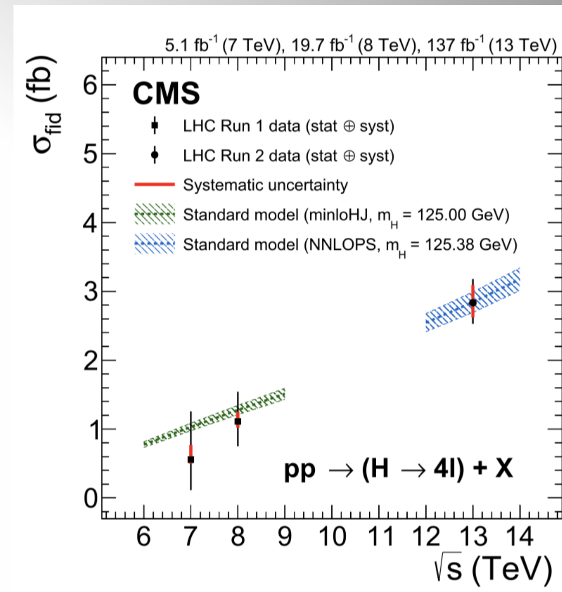
Higgs to ZZ -> 4 leptons

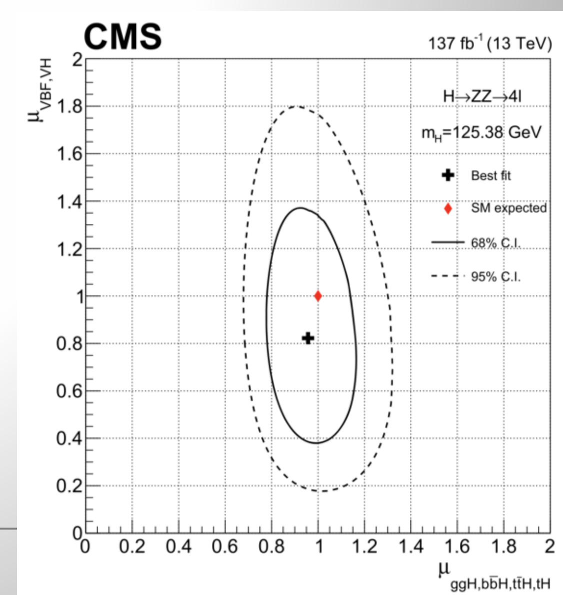
2103.04956

Full Run-2 results

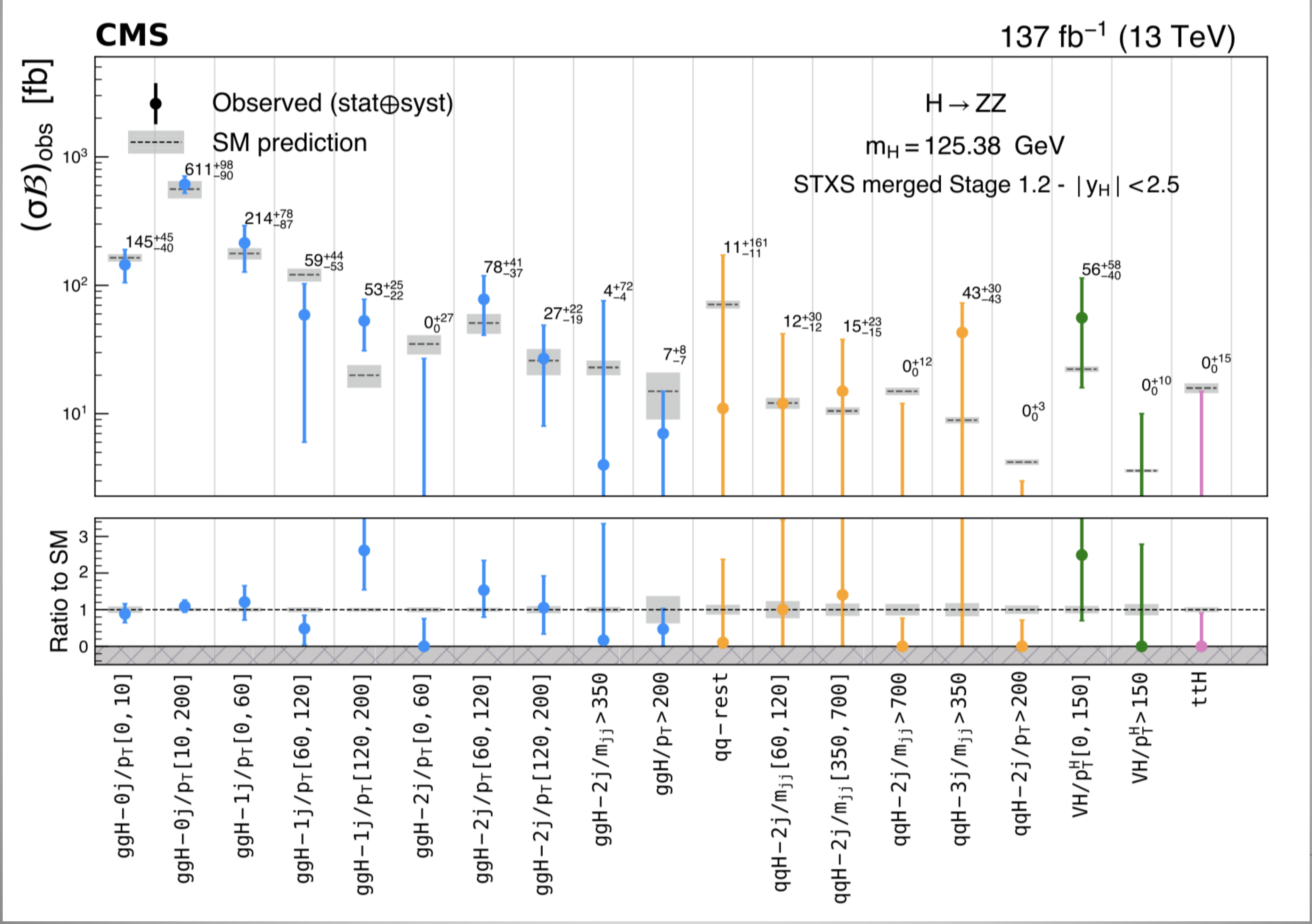


$$\mu = 0.94 \pm 0.07\,(\text{stat})^{+0.09}_{-0.08}\,(\text{syst})$$





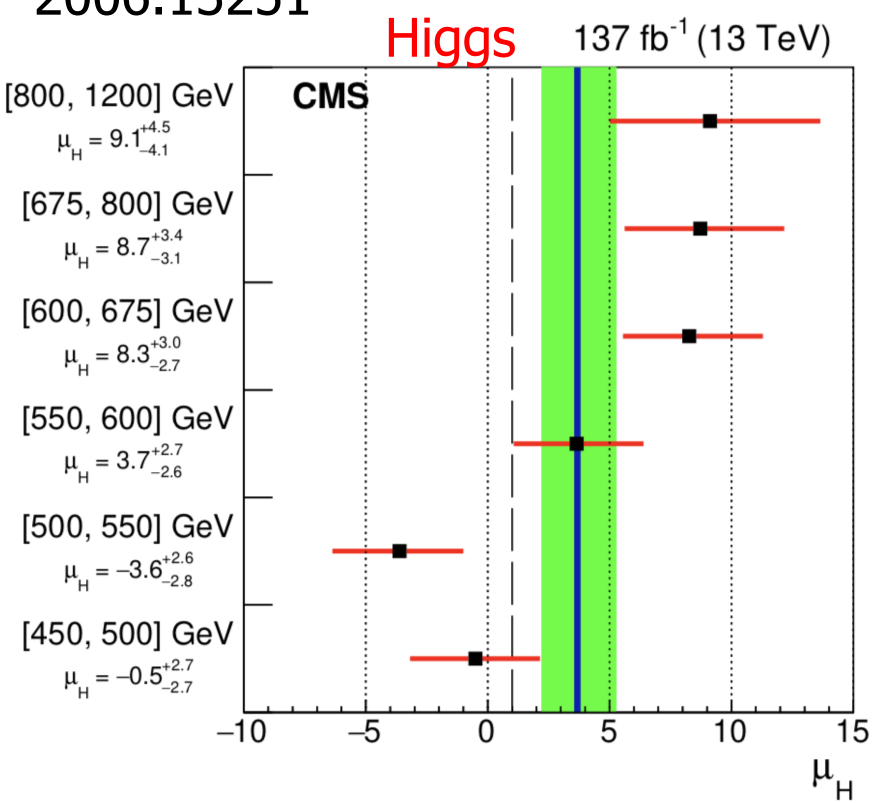
STXS: Higgs to Four Lepton Analysis

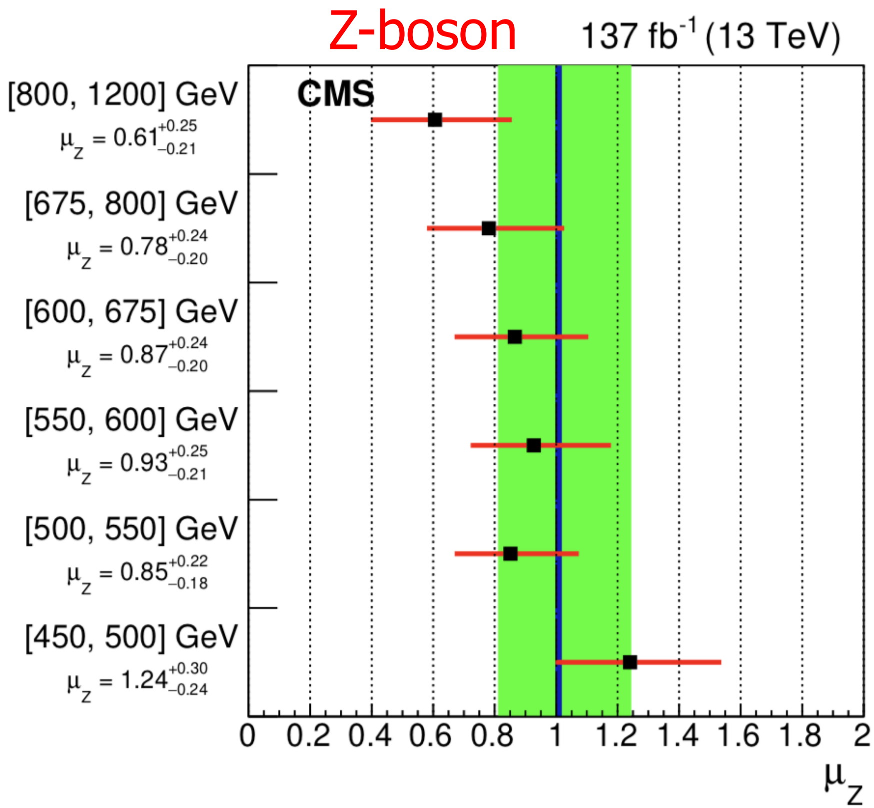


Boosted Higgs to bb pair

Higgs bosons (H) produced with transverse momentum (p_T) greater than 450GeV and decaying to bottom quark-antiquark pairs, and using Z->bb as monitor

2006.13251





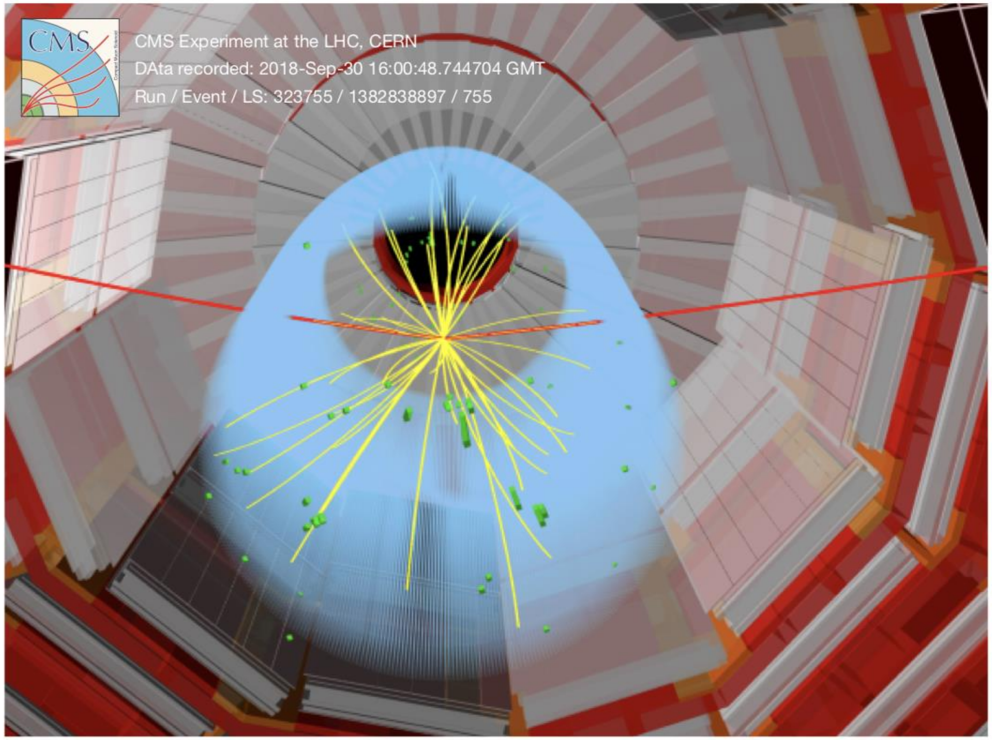
$$\mu_{\rm H} = 3.7 \pm 1.2\,({\rm stat})^{+0.8}_{-0.7}\,({\rm syst})^{+0.8}_{-0.5}\,({\rm theo})$$

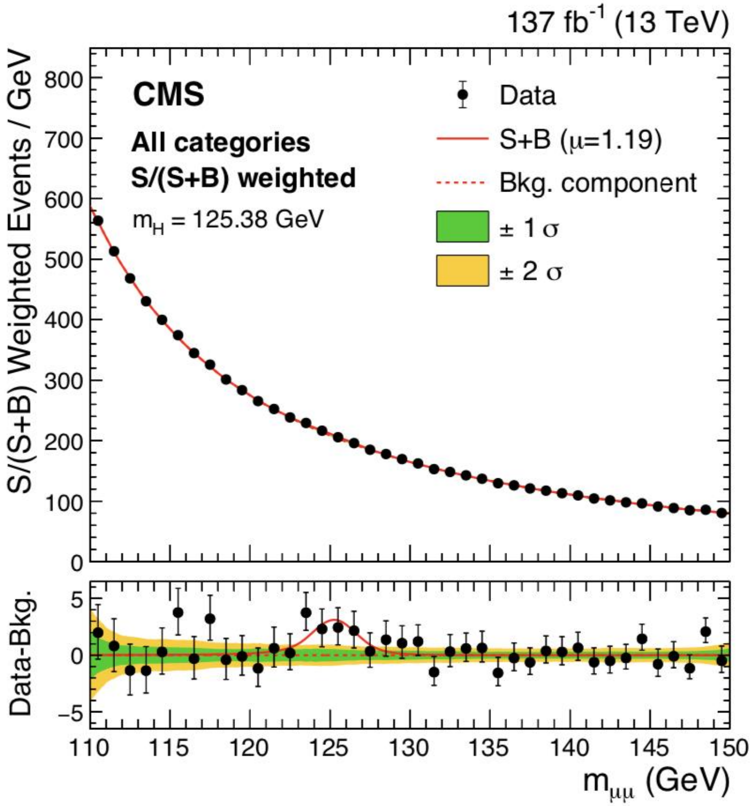
2.5$\boldsymbol{\sigma}$ effect

Higgs to Di-Muon Analysis

Evidence for H->$\mu\mu$ with full run-2 data sample (3 sigma)

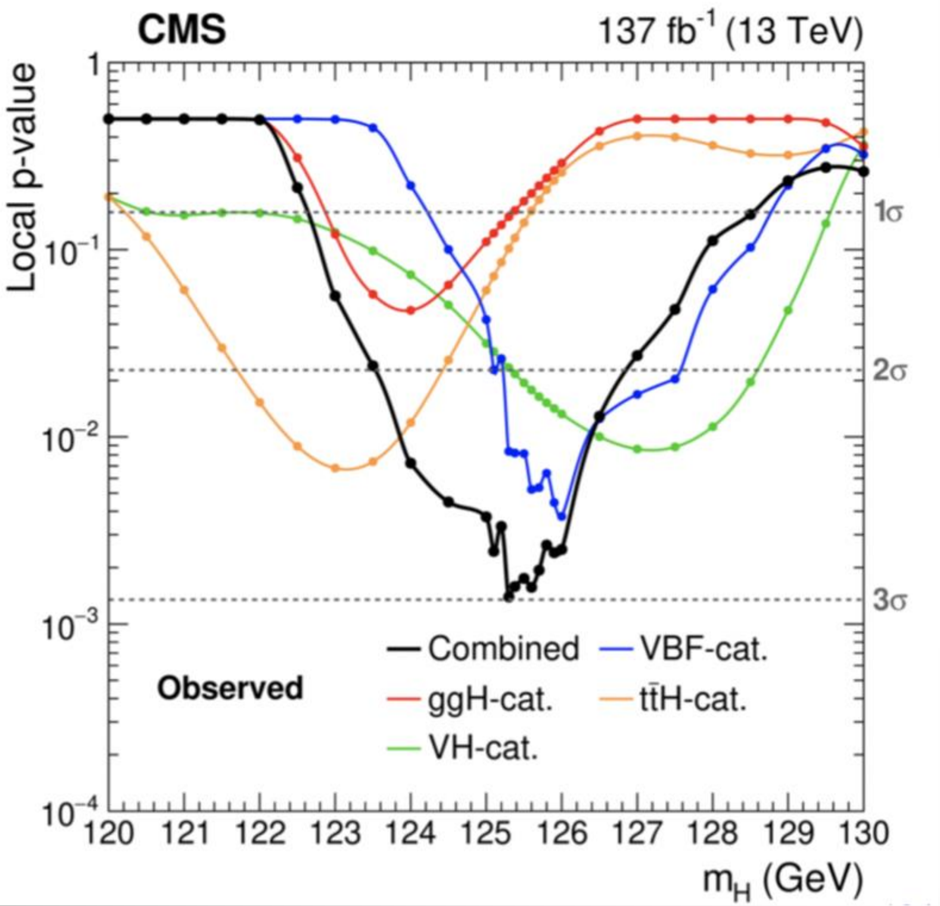
SM coupling strenght $1.19^{+0.40}_{-0.39}\,(\text{stat})^{+0.15}_{-0.14}\,(\text{syst})$ 2009.04363

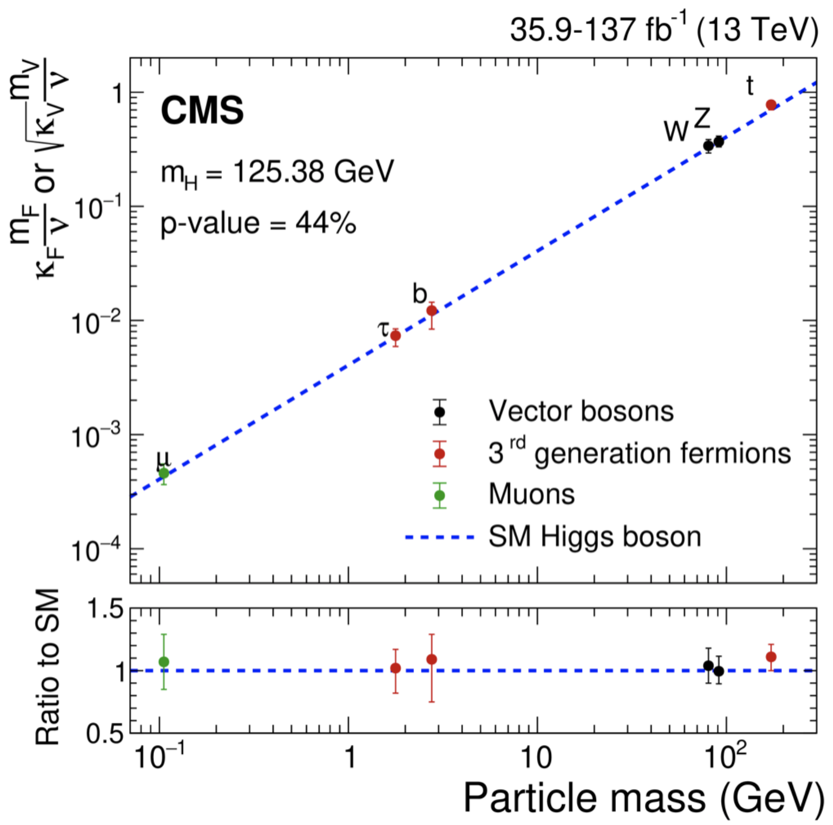




First evidence of Higgs coupling to second generation!

Higgs to Di-Muon Analysis

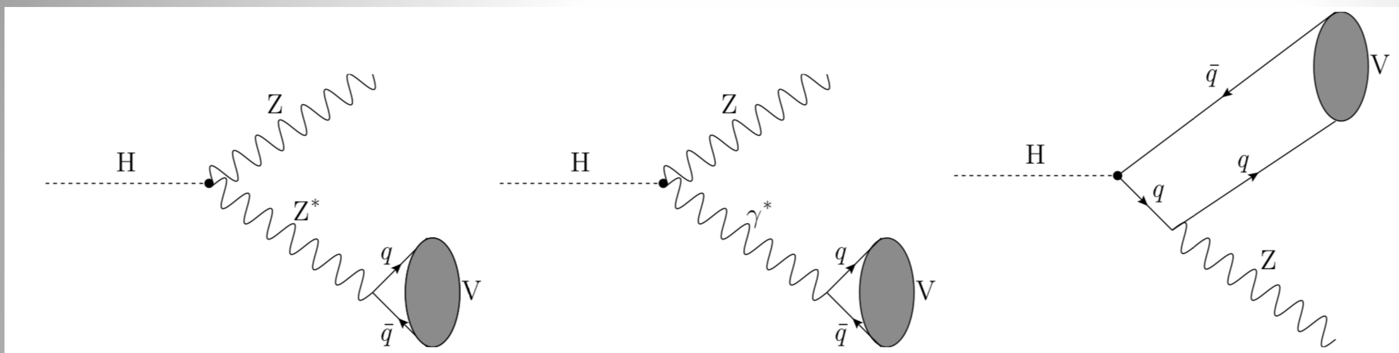




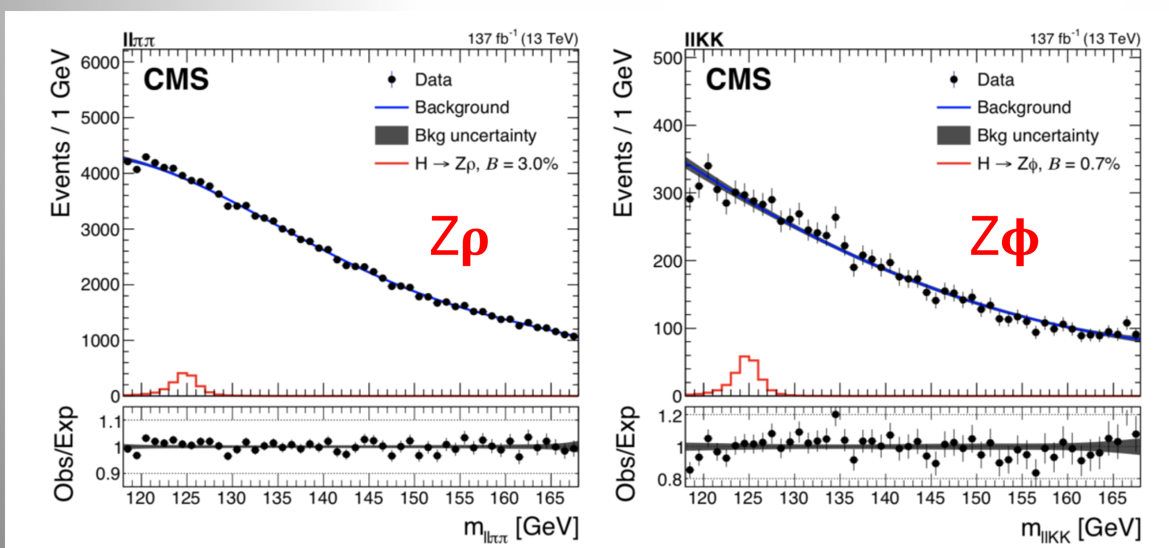
First evidence of Higgs coupling to second generation!

Searching for Decays to Z+meson

Decays can have information on couplings to first and second generation Fermions. Expected rates however very small (in SM)



arXiv:2007.05112

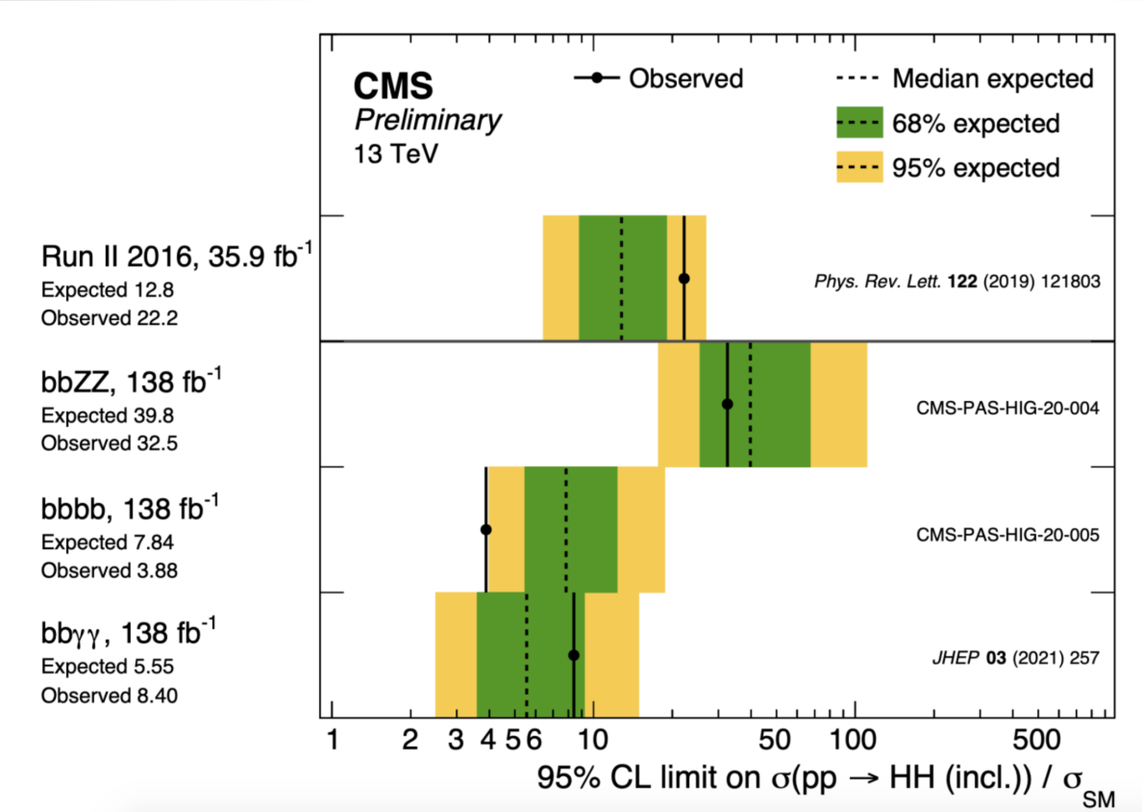


No signal observed

About factor 700 away to reach SM coupling sensitivity

Limits on HH Production

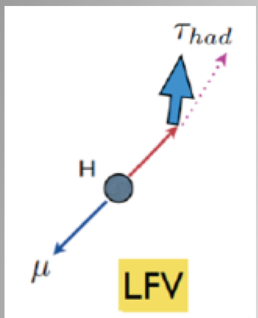
Expected and observed 95% CL upper limits on ratio of the cross section to the SM expectation for several channels B(HH→γγbb), B(HH→ZZbb) and B(HH→bbbb) with full Run-2 statistics

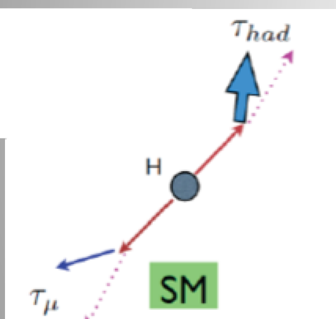


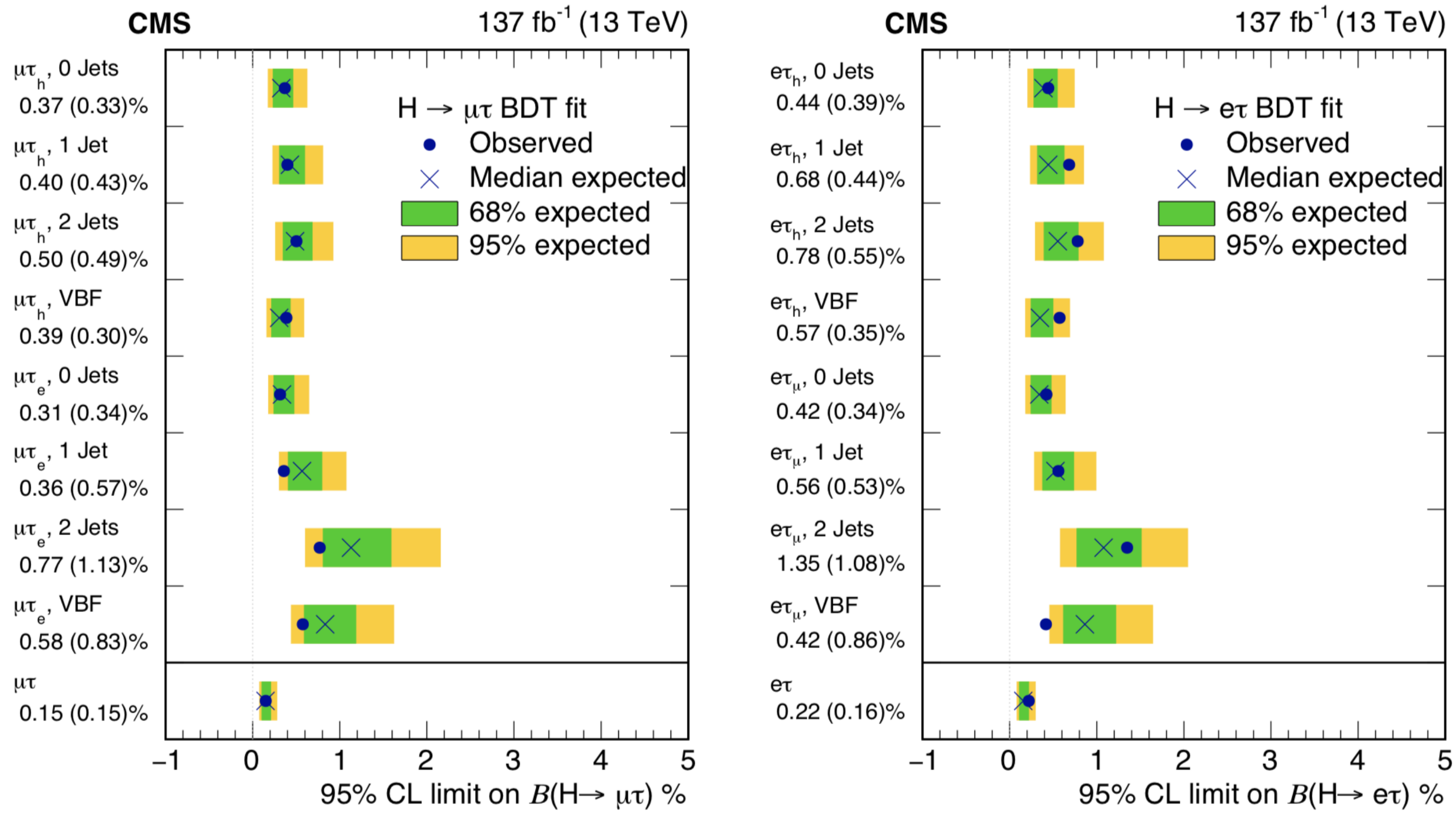
Getting closer !! … Will be a target for the HL-LHC

Search for LFV Decays: H →μτ, eτ

1912.01662





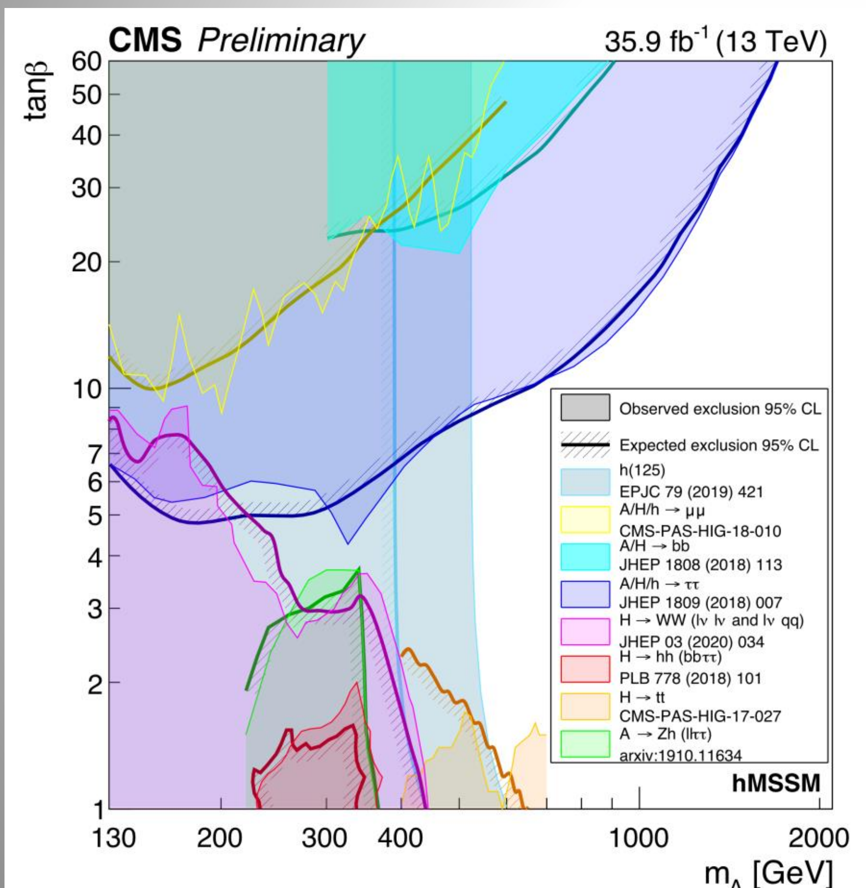


	Observed (expected) upper limits (%)	Best fit branching fractions (%)	Yukawa coupling constraints
$H \to \mu\tau$	<0.15 (0.15)	0.00 ± 0.07	$< 1.11\,(1.10) \times 10^{-3}$
$H \to e\tau$	<0.22 (0.16)	0.08 ± 0.08	$< 1.35\,(1.14) \times 10^{-3}$

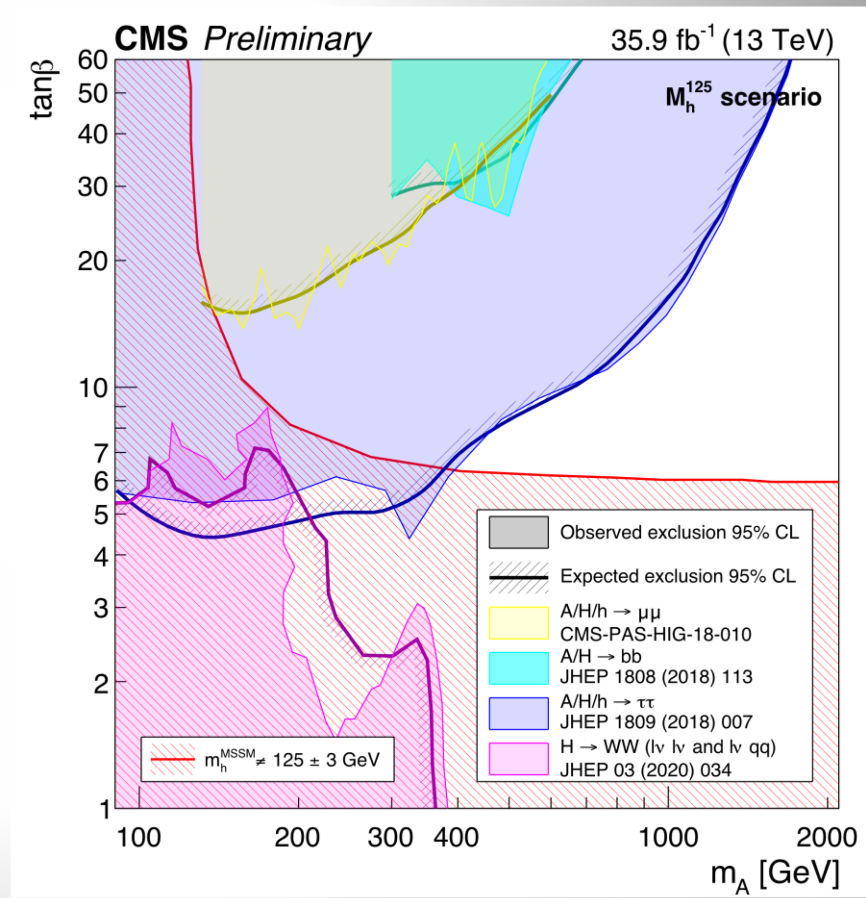
No sign of Lepton Flavour Violating Higgs decays in the data

MSSM Summary Results

Observed and expected 95% CL upper limits for m_A versus the MSSM parameter tanβ in the hMSSM benchmark scenario.



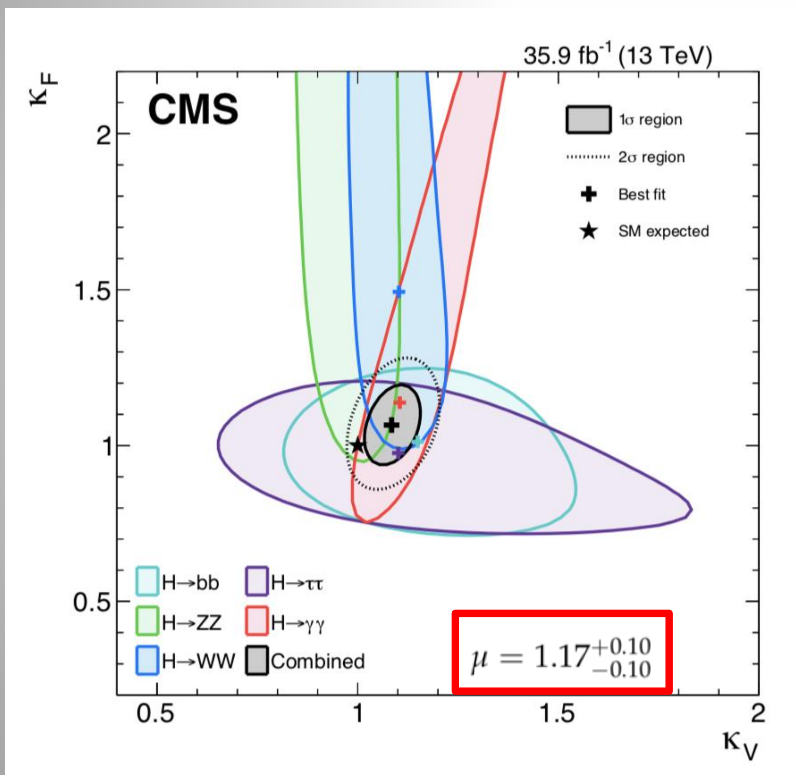
Observed and expected 95% CL upper limits for m_A versus the parameter tanβ in the M125h scenario; arxiv:1808.0754



No MSSM signal in the Higgs sector

Brief Higgs Summary: Run-2

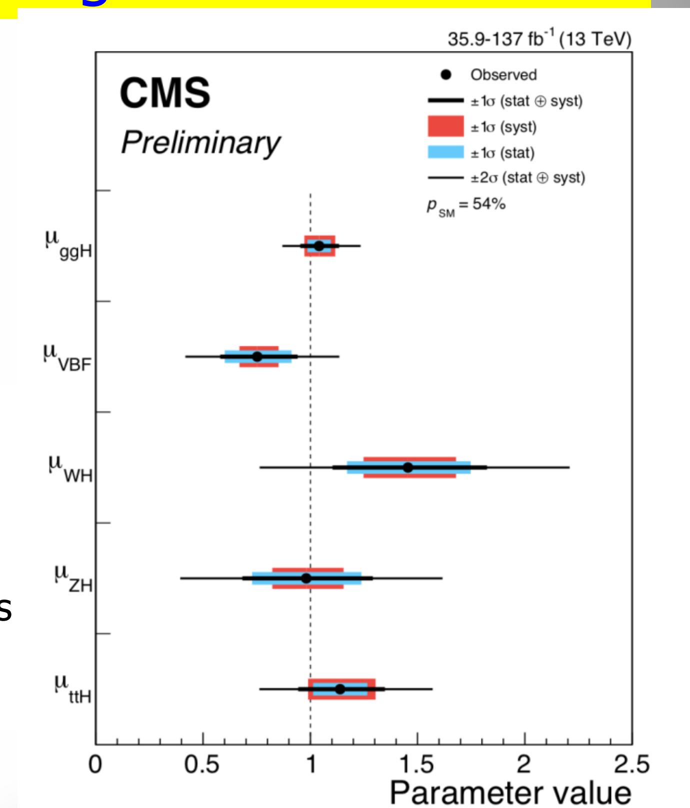
Combination of all Higgs production/decay channels at 13 TeV
Check of overall consistency of the couplings



arXiv:1809.10733

HIG-19-005
Update with 36-137 pb^{-1}

More channels being completed

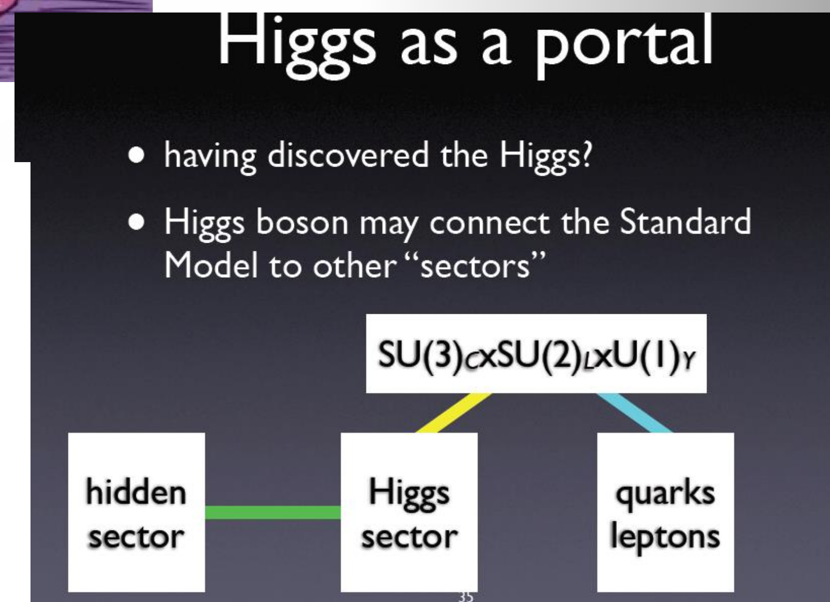


Results in agreement with the Standard Model

$$\mu = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\text{th}) \pm 0.04(\text{exp}) \pm 0.04(\text{stat}),$$

The Future: Studying the Higgs…

- More LHC Data 2022-2024
- LHC upgrade ! 2026-2036
- Experiment upgrades!!
- Other/new machines…



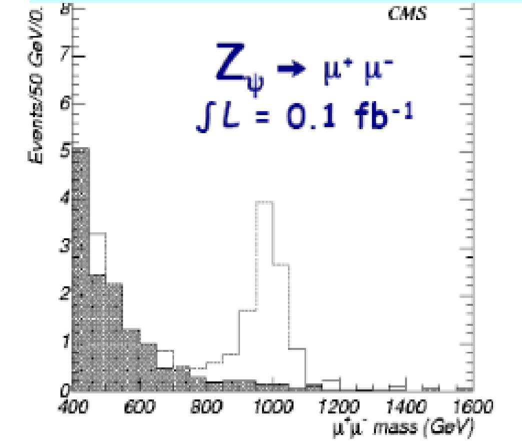
Many questions are still unanswered:

- What explain a Higgs mass ~ 125 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- What is the origin of neutrino masses?
- …

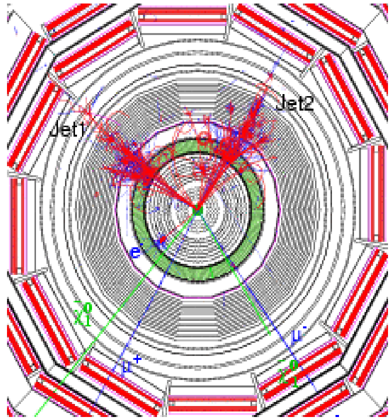
New Physics Searches

New Physics?

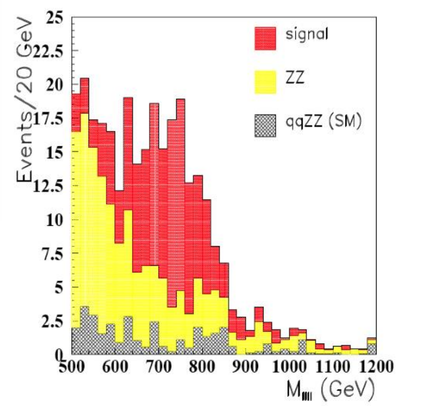
New Gauge Bosons?



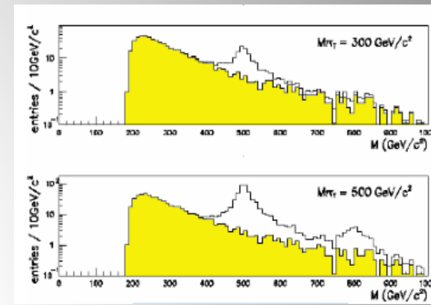
Supersymmetry



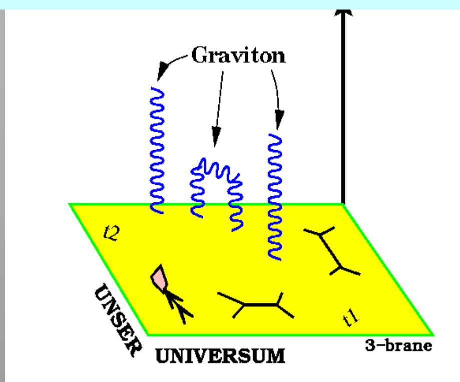
ZZ/WW resonances?



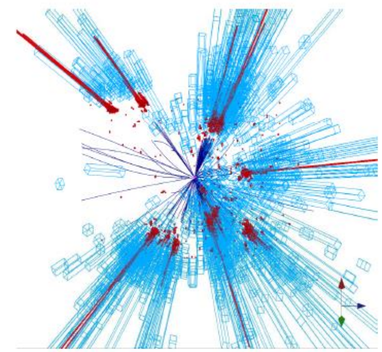
Technicolor?



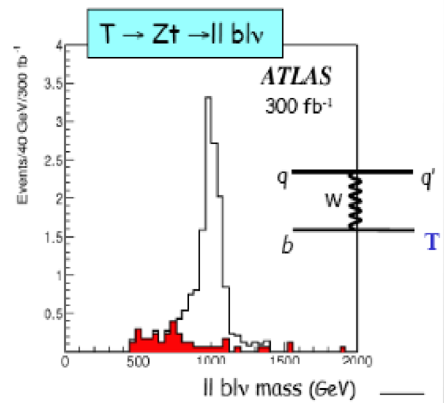
Extra Dimensions?



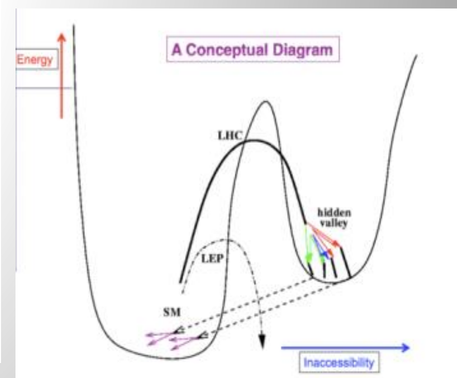
Black Holes???



Little Higgs?



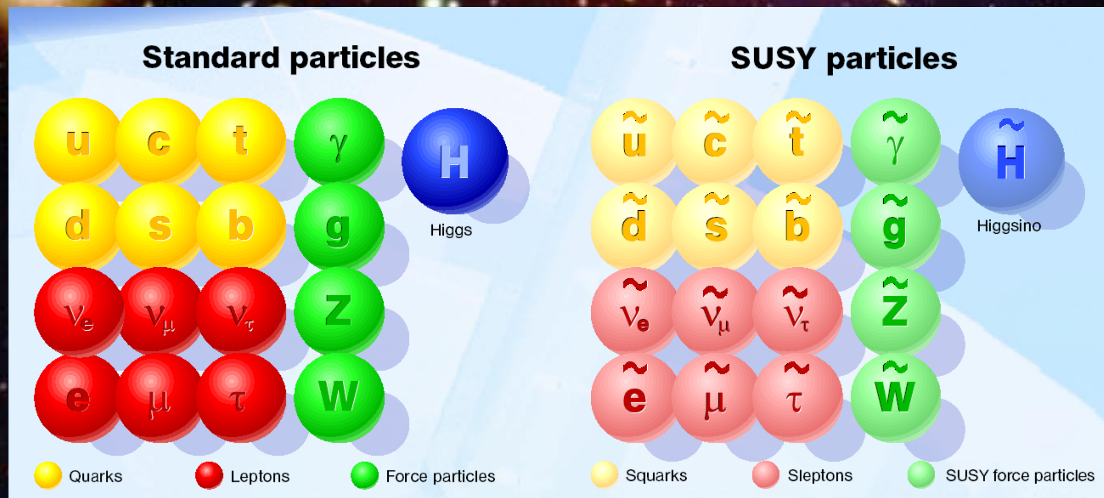
Hidden Valleys?



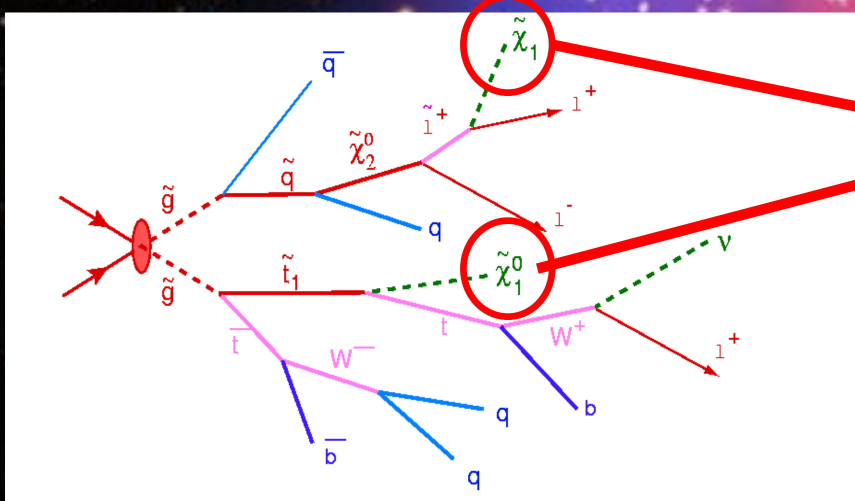
What stabelizes the Higgs Mass? Many ideas, not all viable any more

A large variety of possible signals. We have to be ready for that

Supersymmetry: a new symmetry in Nature?

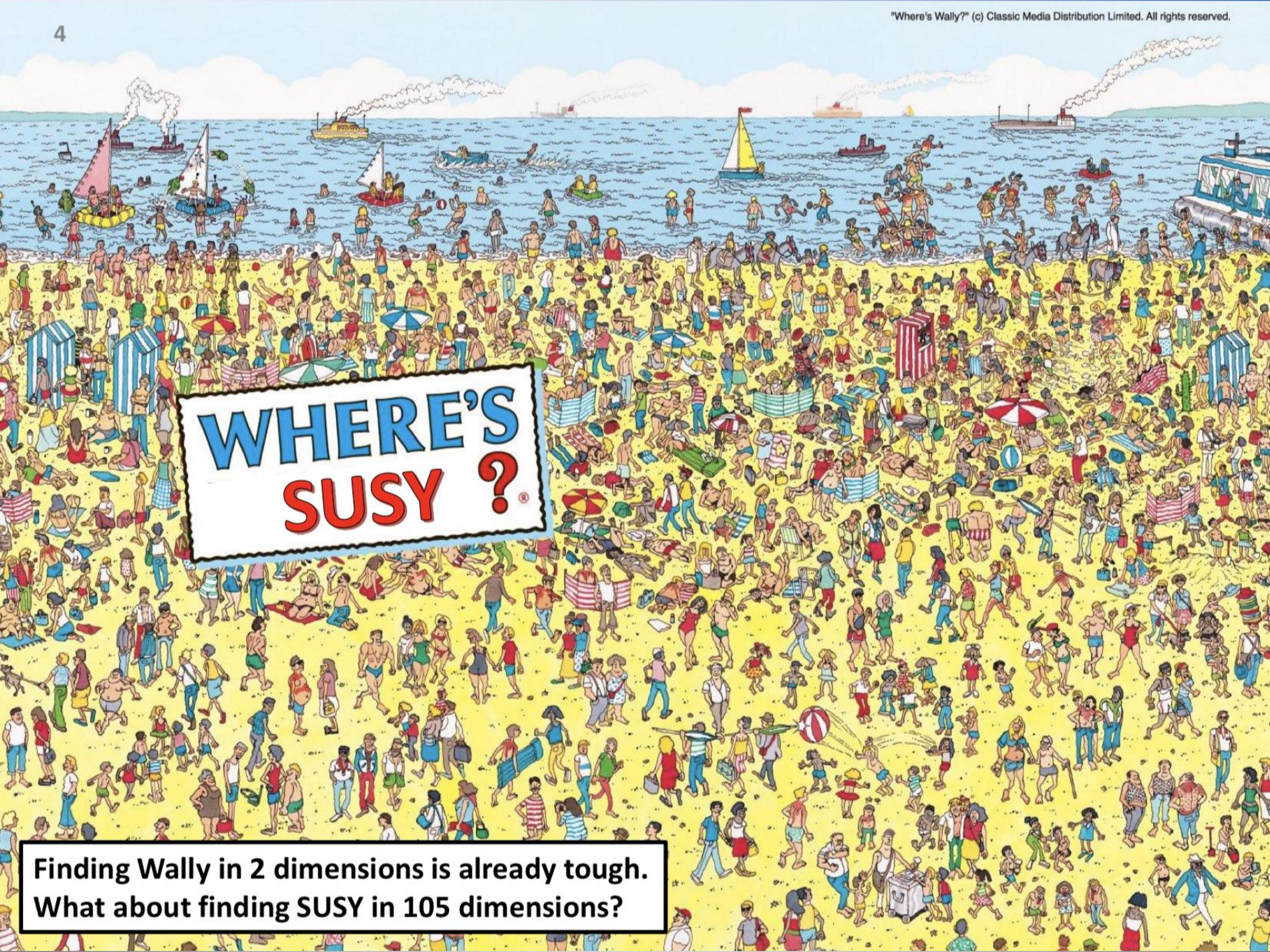


Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab



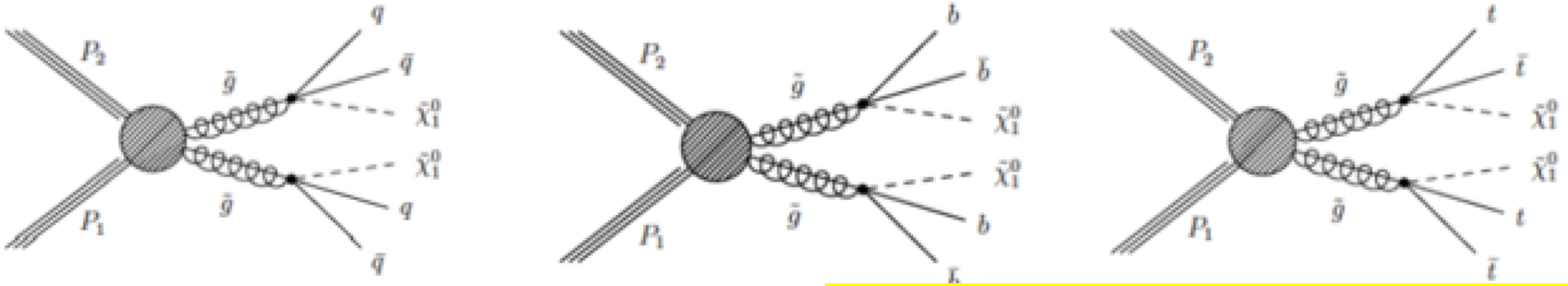
SUSY particle production at the LHC

Picture from Marusa Bradac

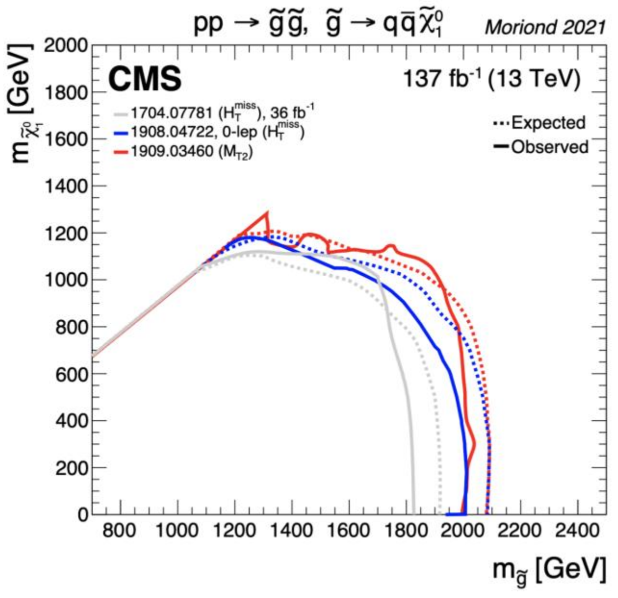


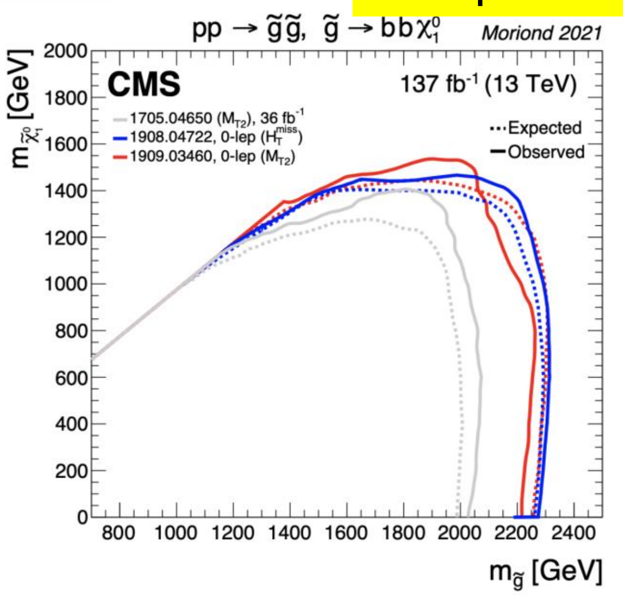
**Finding Wally in 2 dimensions is already tough.
What about finding SUSY in 105 dimensions?**

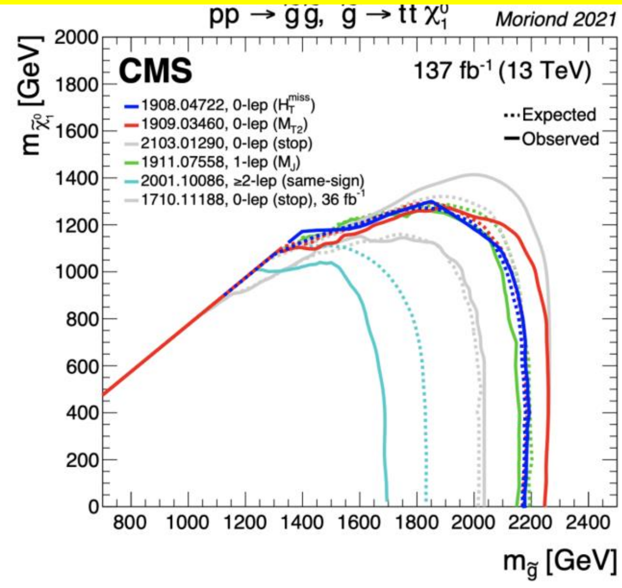
Supersymmetry: Gluinos



Interpretation in simplified models (SMS)







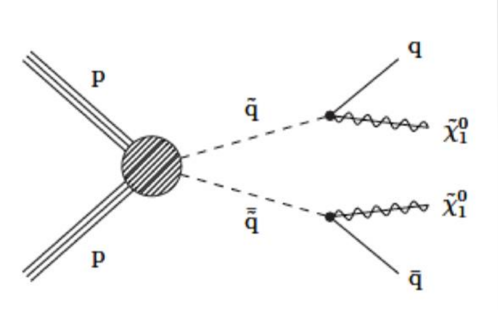
No significant signal to date

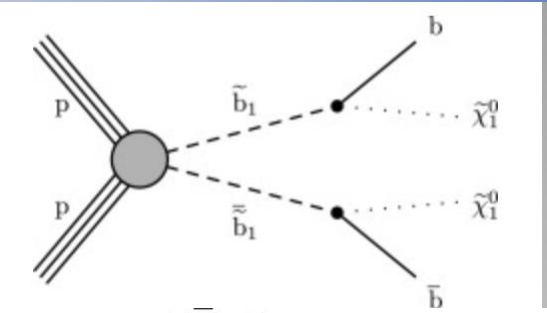
Within the context of the SMS:

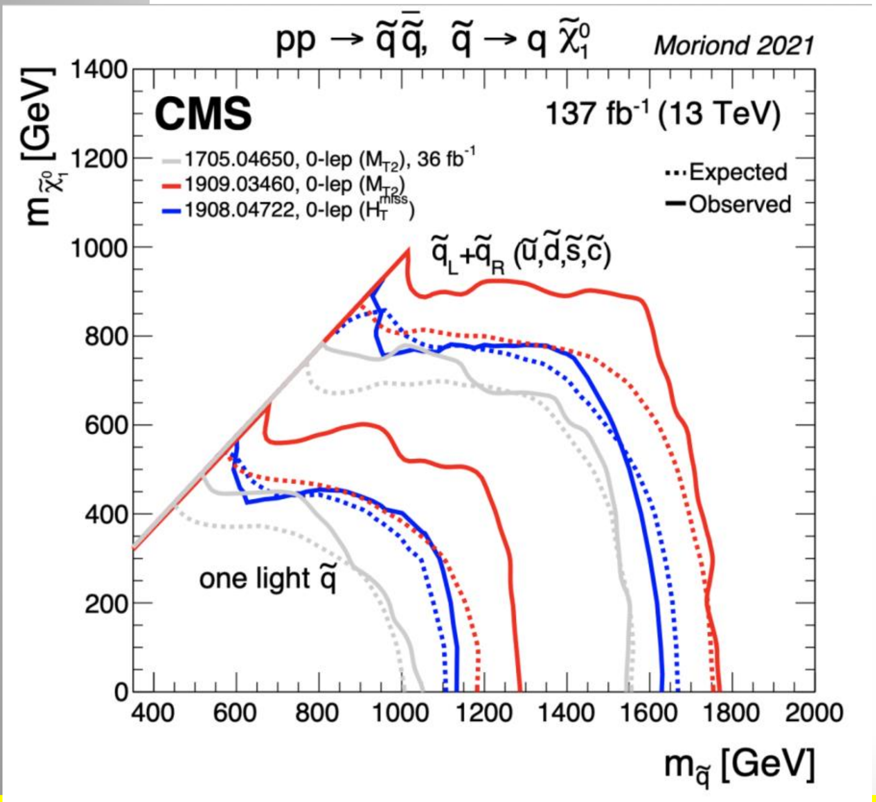
Exclude gluino masses ~ 2300 GeV for neutralino masses up to 1000 GeV

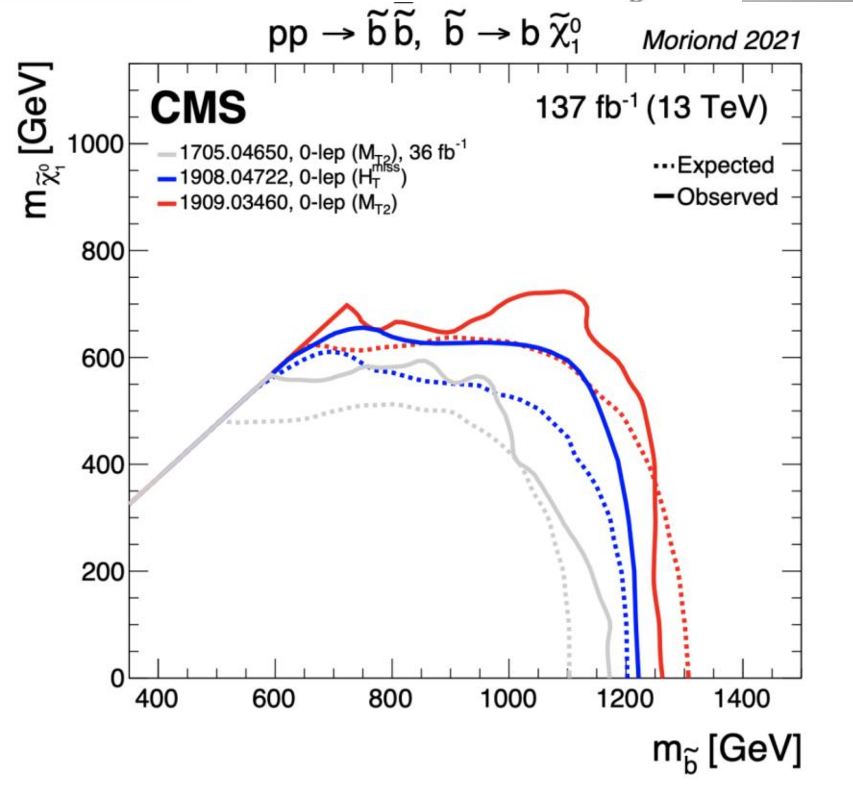
Supersymmetry: Quarks

b-squarks and light squarks







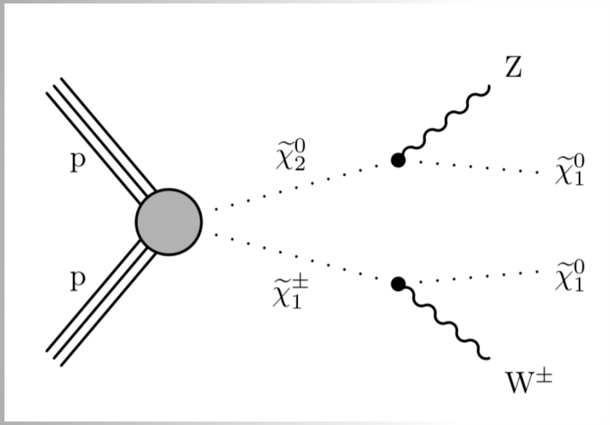


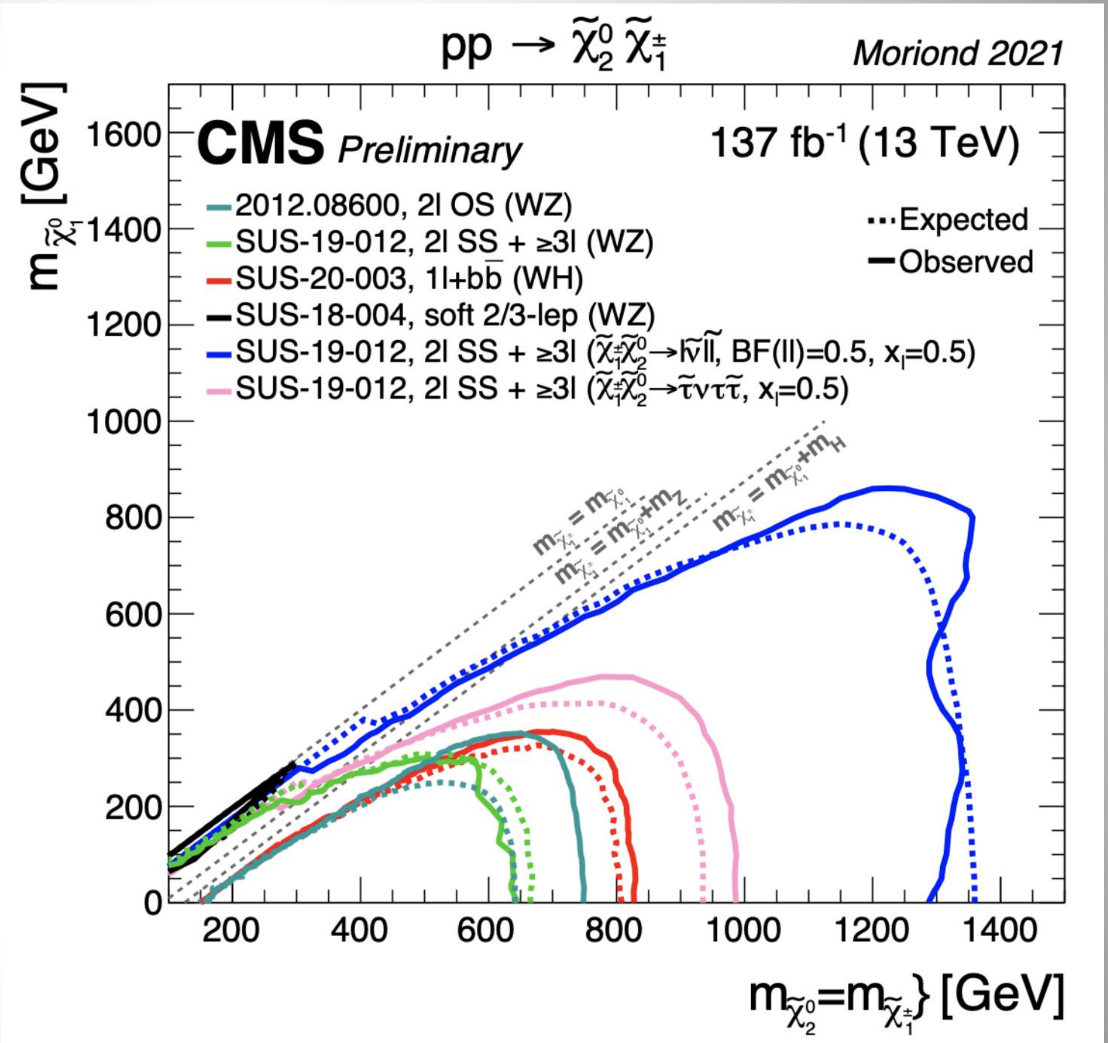
No significant signal to date

Within the context of the SMS: Exclude squark masses ~ 1700 GeV

Chargino and Neutralino Production

Direct production of "electroweakino" pairs

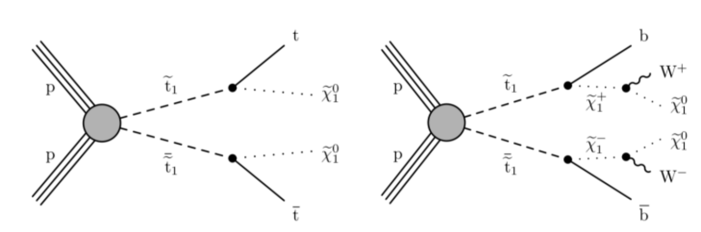




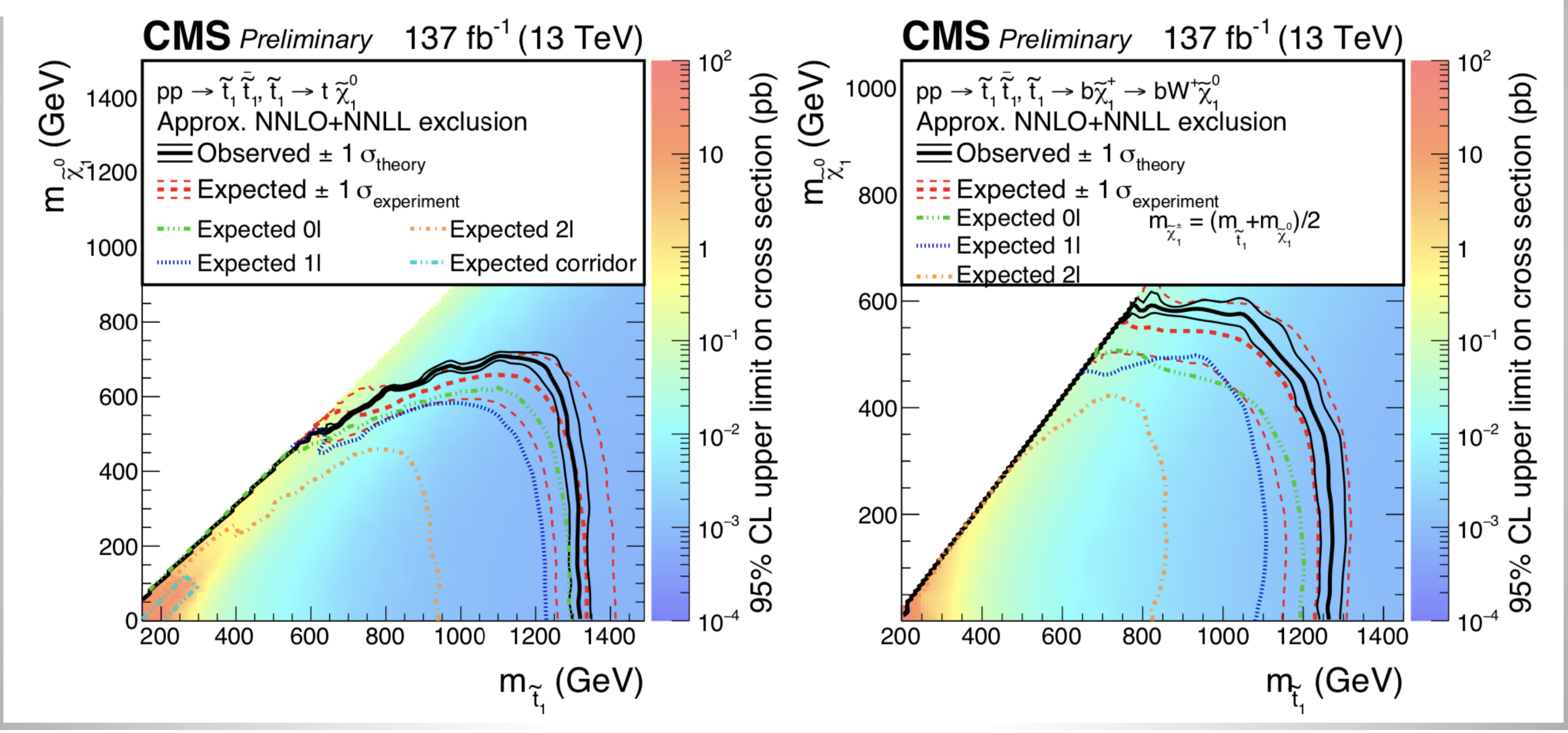
Exclude masses up to 1400 GeV for neutralino masses up to 800 GeV

Top Squark Search Summaries

Partner of the top quark – the stop– plays a prominent role in Natural Models



SUSY-20-002



Within the context of the SMS:
Exclude with masses up to 1300 GeV for neutralino masses up to 600 GeV

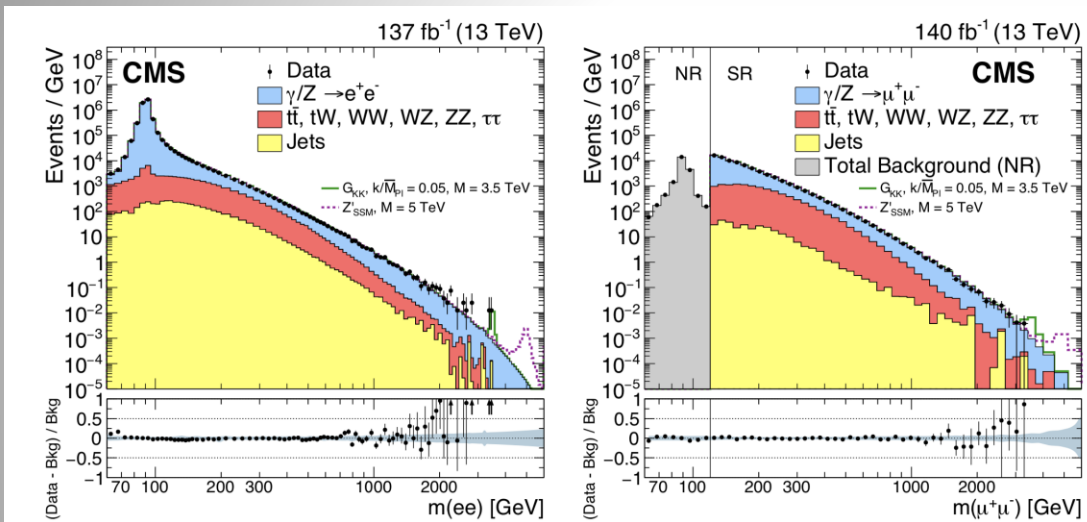
Is this getting critical for Natural Models??

Other Exotica (selection)

Search for Di-lepton Resonance

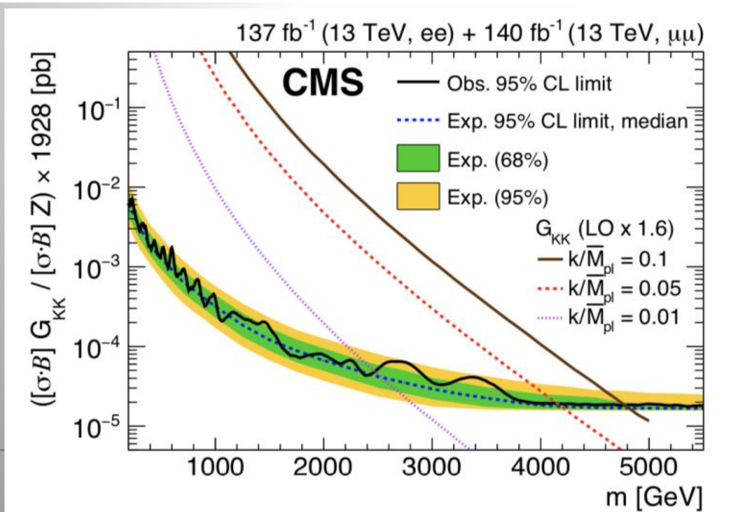
The "classical" search for high mass new neutral gauge bosons
Use opposite charge high p_T same flavor leptons

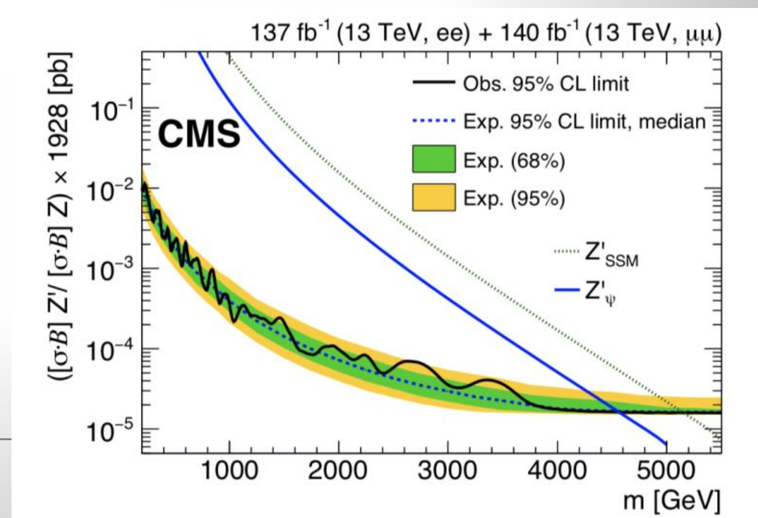
2103.02708



No signal -> New limits with the full Run-2 statistics

Channel	Z'_{SSM} Obs. [TeV]	Z'_{SSM} Exp. [TeV]	Z'_{ψ} Obs. [TeV]	Z'_{ψ} Exp. [TeV]
ee	4.72	4.72	4.11	4.13
$\mu\mu$	4.89	4.90	4.29	4.30
ee + $\mu\mu$	5.15	5.14	4.56	4.55

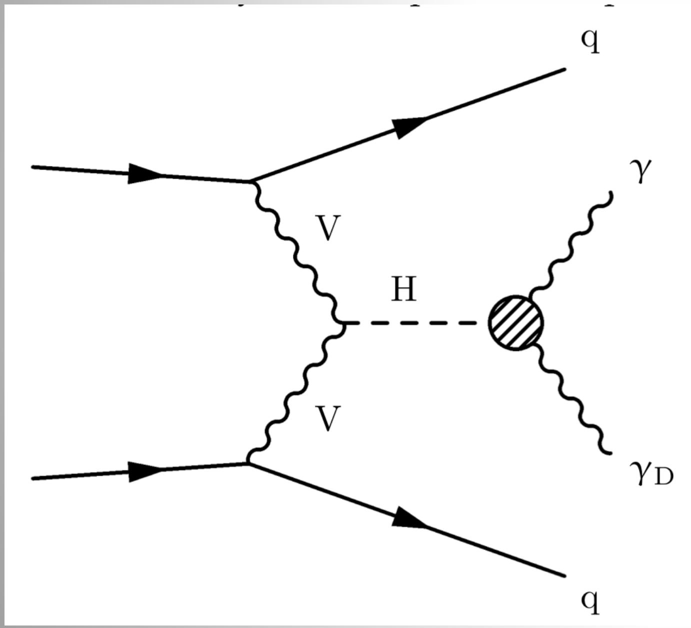


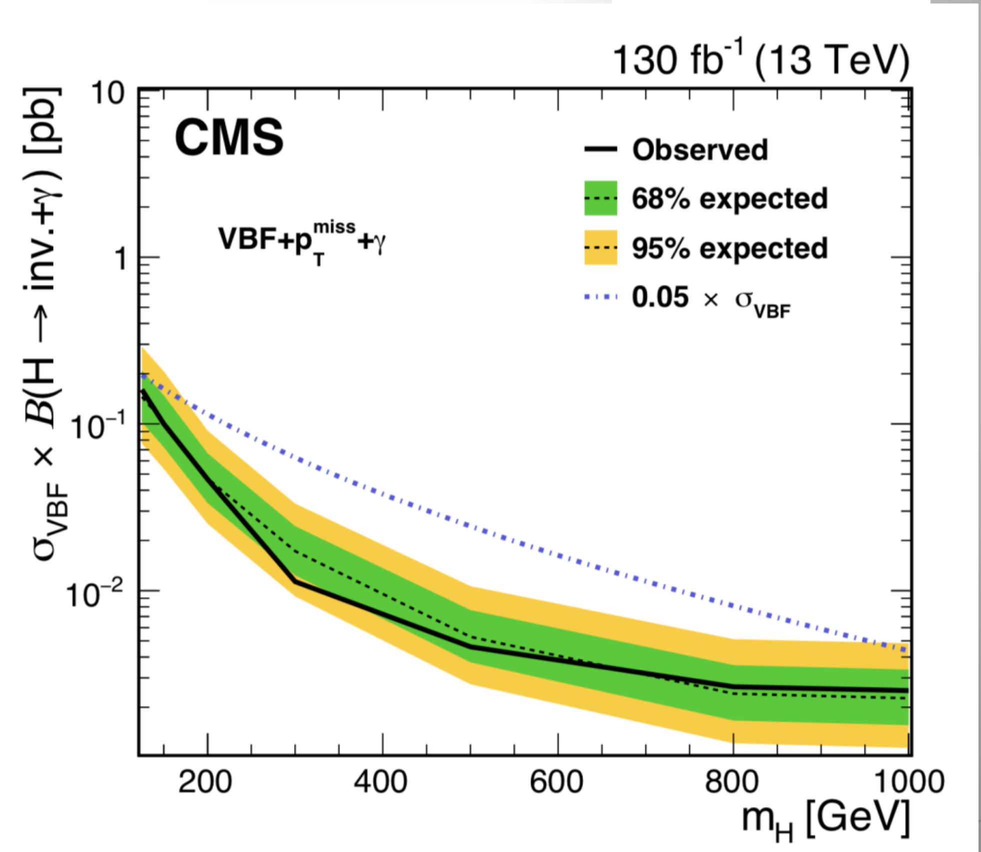


Search for Dark Photons in VBF Higgs

Search for a Higgs boson produced via vector boson fusion, decaying to an undetected particle and an isolated photon
Experimental search: 2 VBF-jets +photon+ Missing p_T

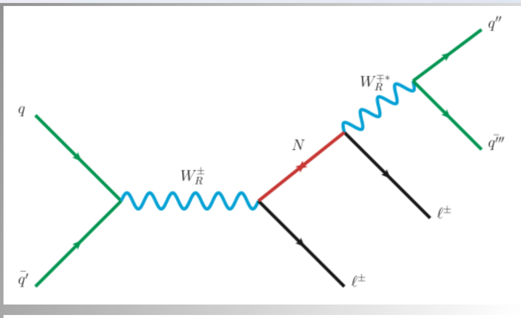
2009.14009





No excess observed

Search for Right-Handed W and Heavy Neutrino

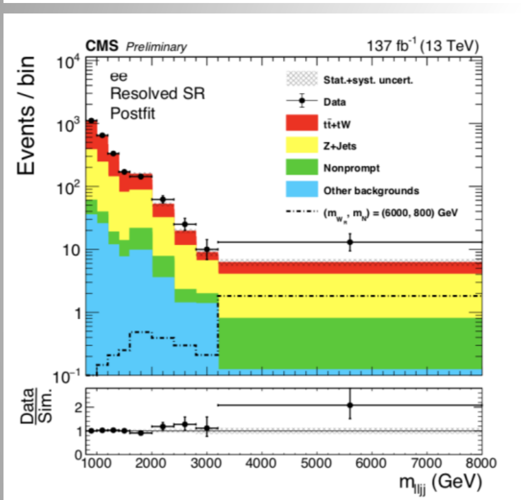


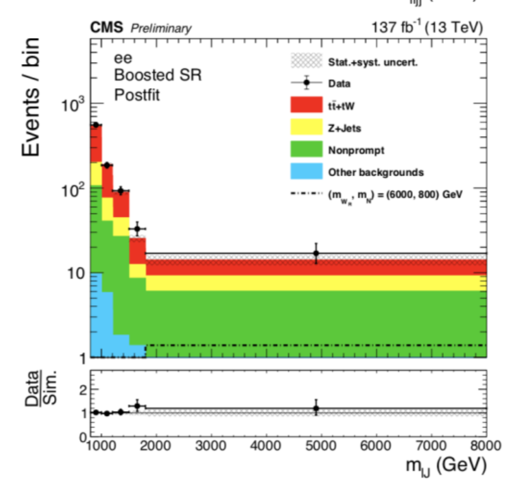
Events with two same-flavor leptons (e or μ) and two (boosted) quarks are selected.

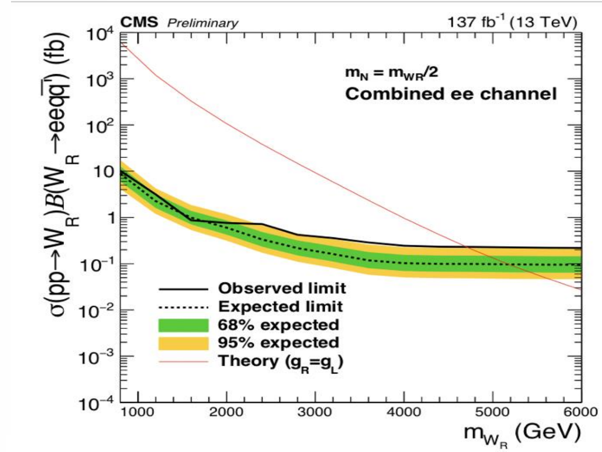
EXO-20-002

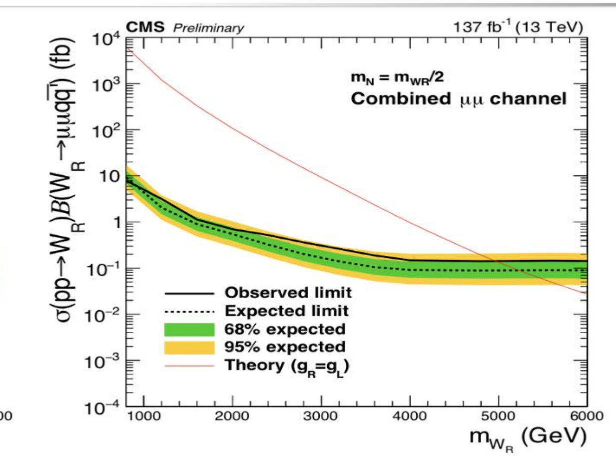
For $m_N = 1/2 m_{WR}$ W_R is excluded at 95% CL for 4.7 and 5.0 TeV for the e and the mu channel.

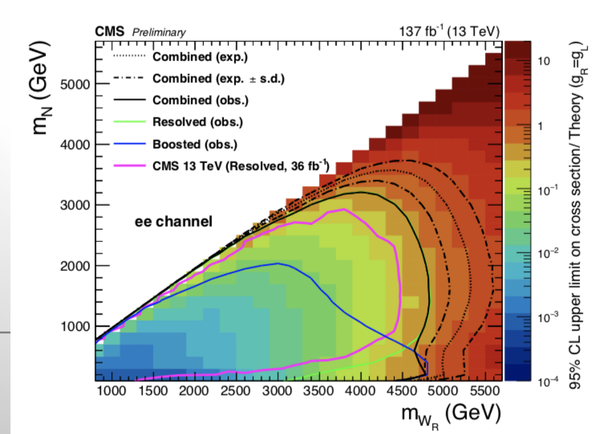
A 2.95σ deviation seen at (m_{WR}, m_N) = (6000, 800)GeV

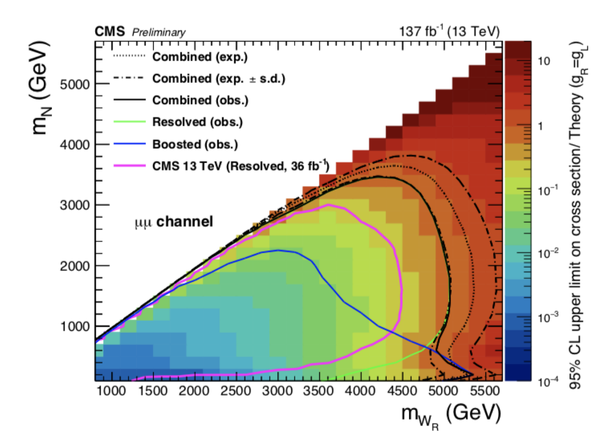






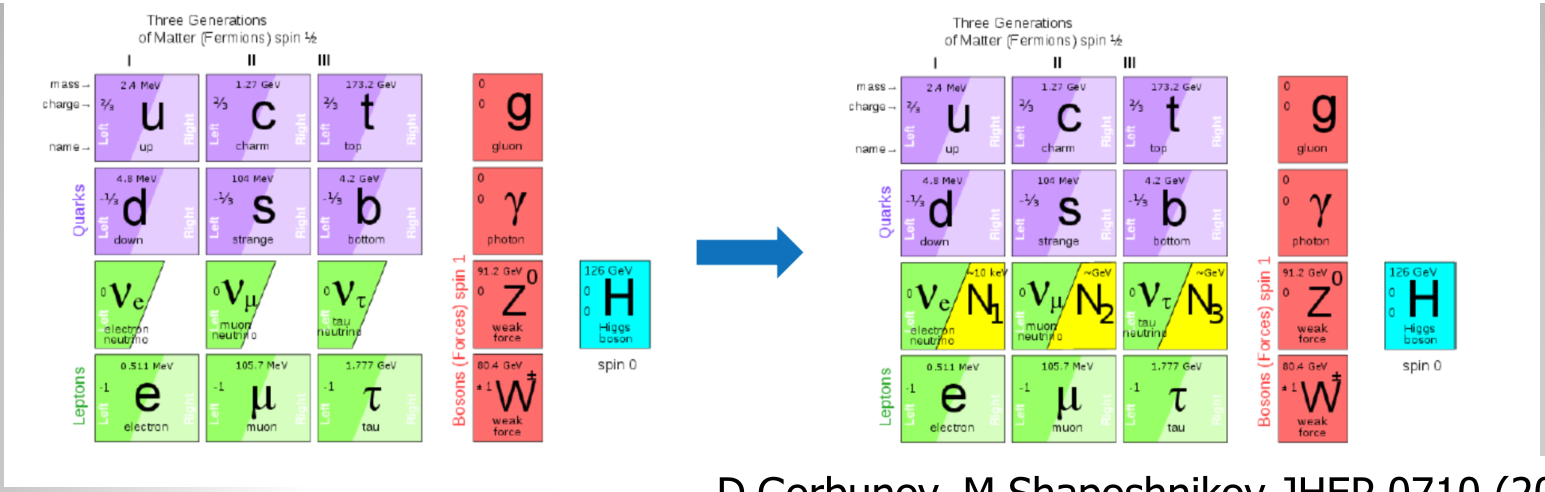






Heavy Neutral Leptons

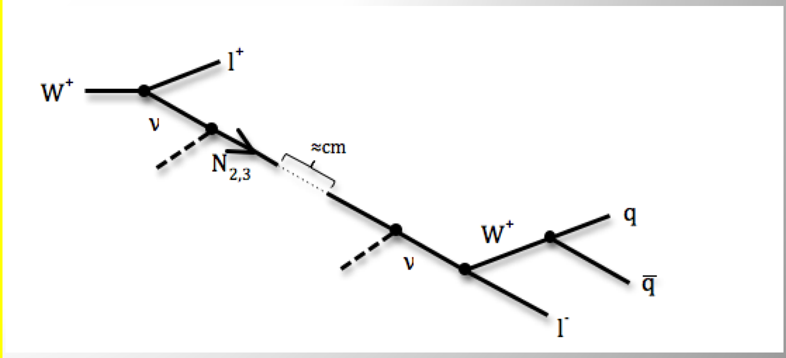
Neutrino portal: νMSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.



D.Gorbunov, M.Shaposhnikov JHEP 0710 (2007) 015

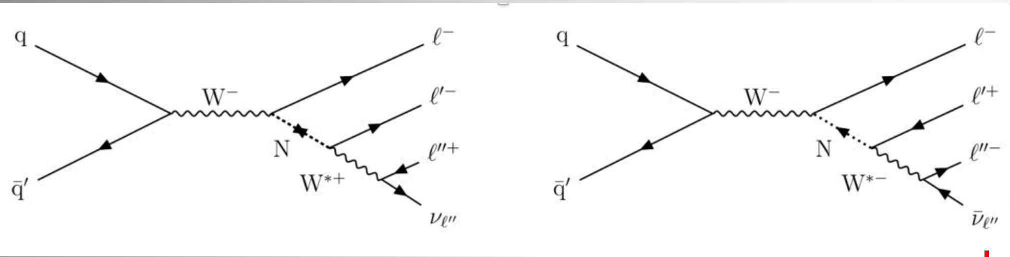
-The lightest singlet N_1 (mass ≈ KeV):
- Good dark matter candidate.

-N_2, N_3 (mass in 100 MeV - GeV region):
- Mechanism to give mass to neutrinos
- Explain baryon asymmetry



Displaced vertices

Search for Long Lived HNL



Search for long-lived heavy neutral leptons (HNLs)

EXO-20-009

HNLs produced through mixing with SM neutrinos in final state of 3 charged leptons + a neutrino

Low mass HNLs are long lived

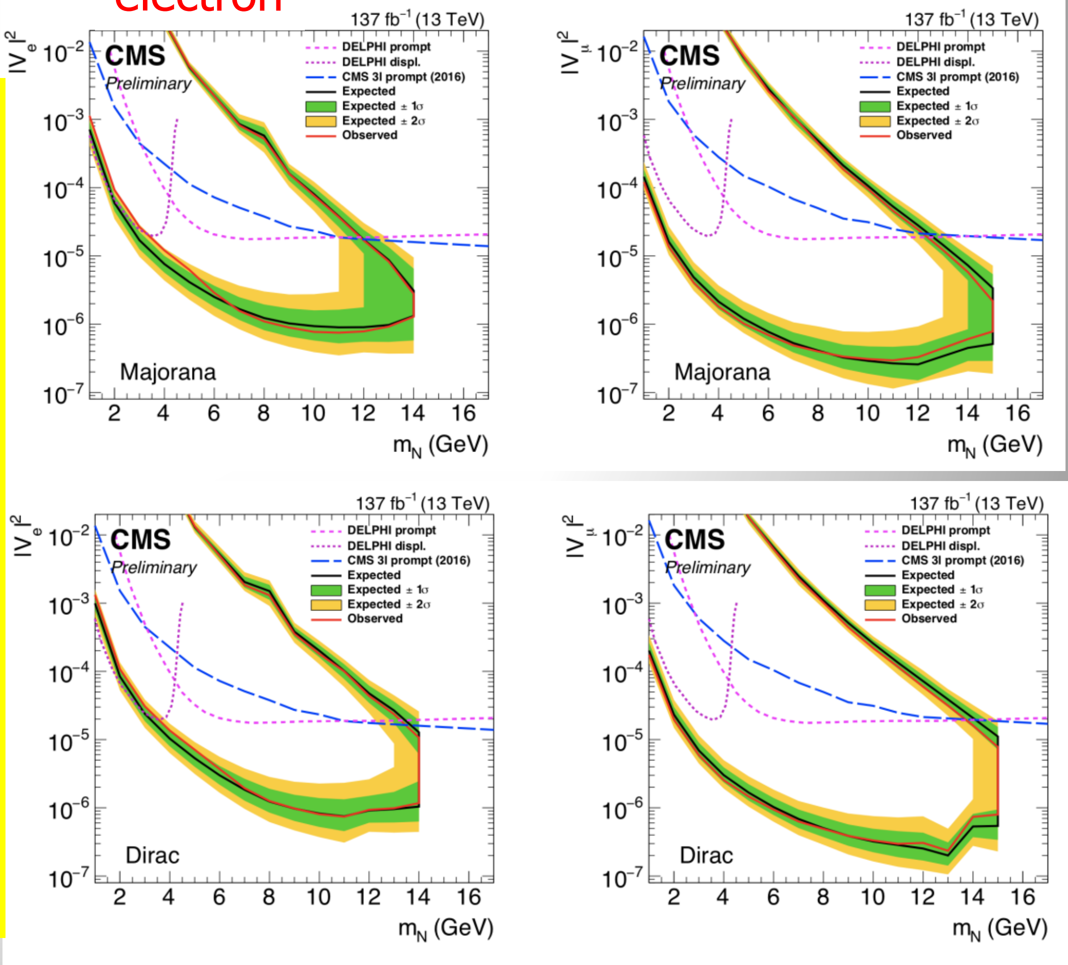
$$\tau_N \propto m_N^{-5} V_{Nl}^{-2}$$

Search for 3 leptons; two form a displaced vertex

Different sensitivities for Dirac and Majorano neutrinos

electron

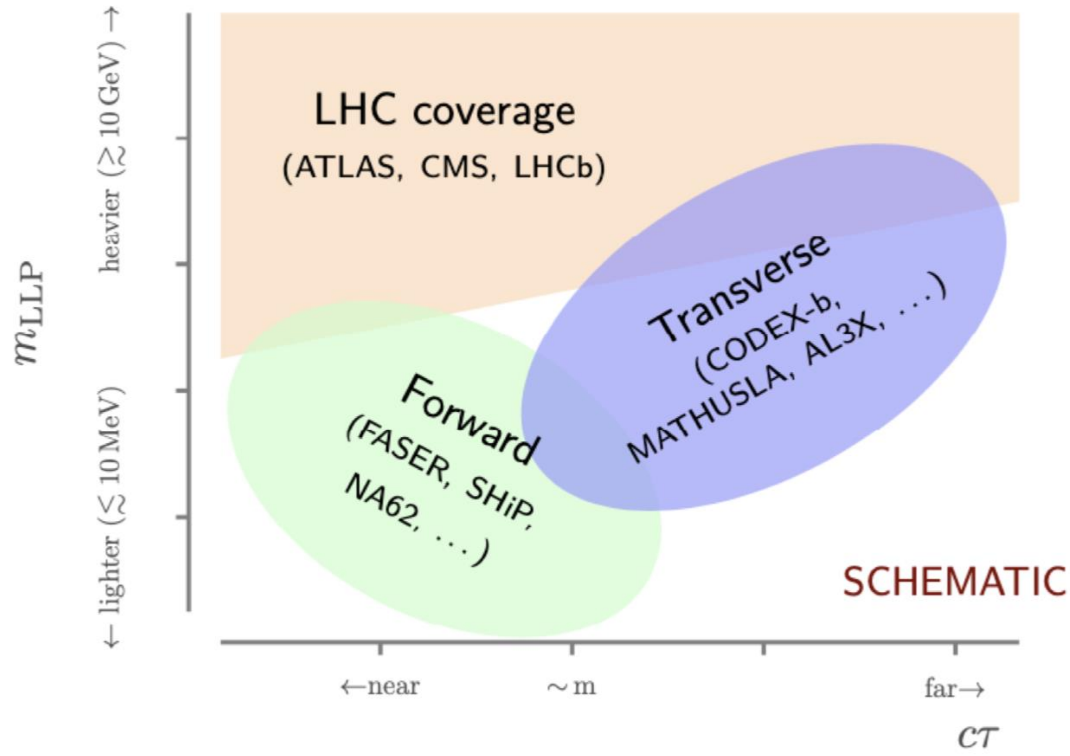
muon



Hunt for Long Lived Particles

CMS and LLPs

arxiv:1911.00481 — CODEX-b

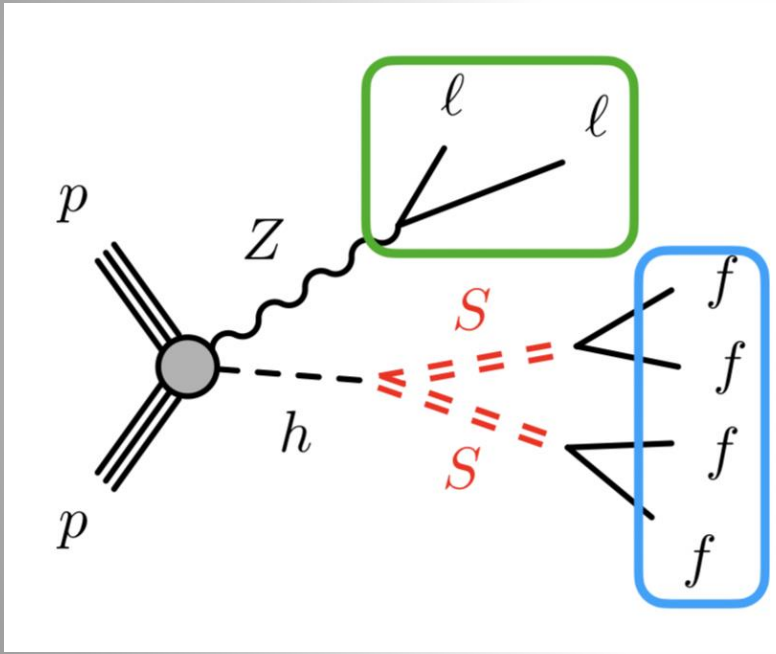


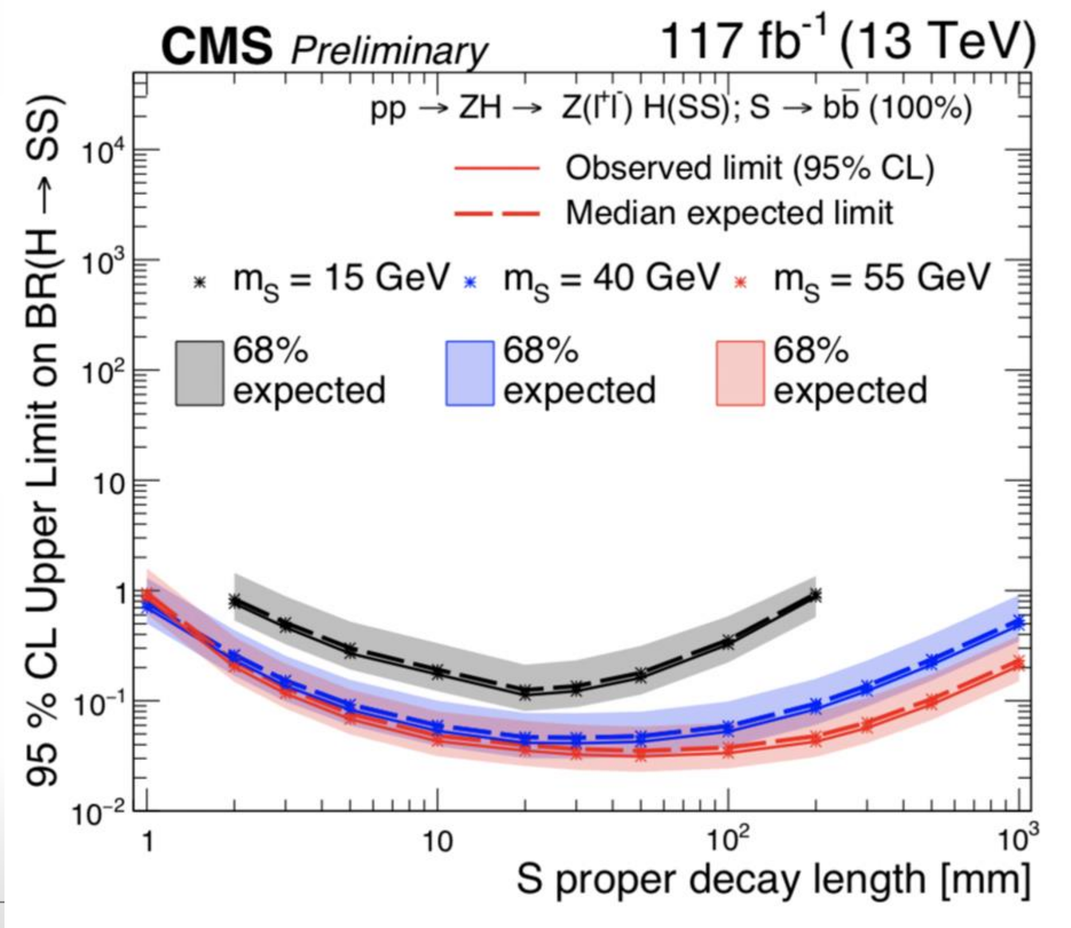
- How to unlock CMS' full LLP discovery reach?
- How far can we extend the mass and lifetime?

Search for LLPs associated with a Z

Higgs decay into long lived scalars
•Seach in central tracker for up to 4 displaced jets
•Trigger from Z leptons

EXO-2020-03





No excess observed

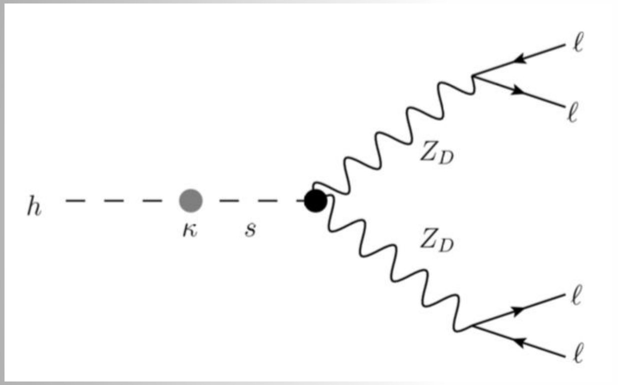
Search for Displaced Low Mass Dimuons

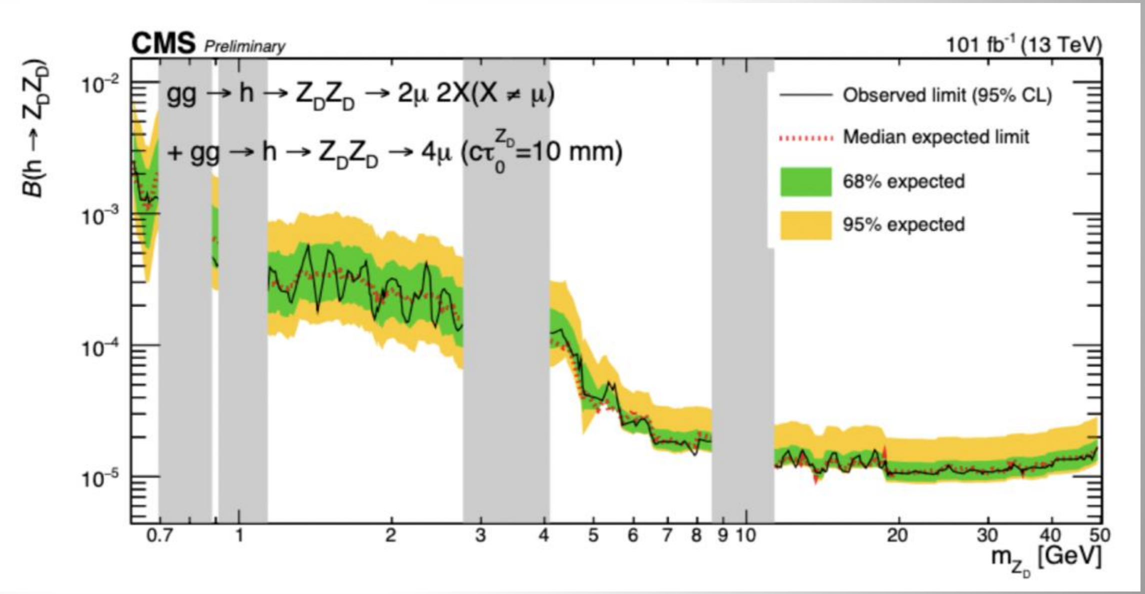
Use scouting data selected for multi-muon events

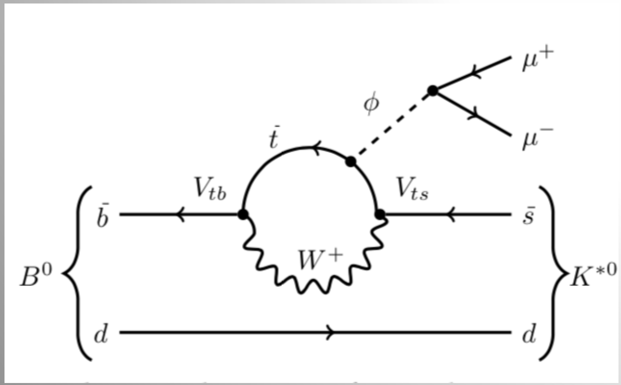
Example scenarios
- Dark photons
- Single scalar field resonances

EXO-20-14

Include 2 and 4 muon final states in the search



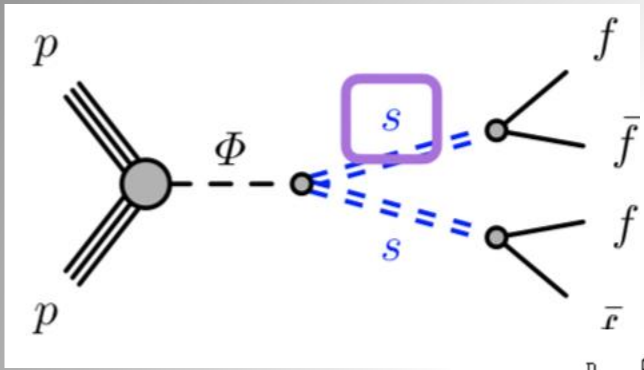




No excess observed
Limits on BR as low as to 10^{-5}

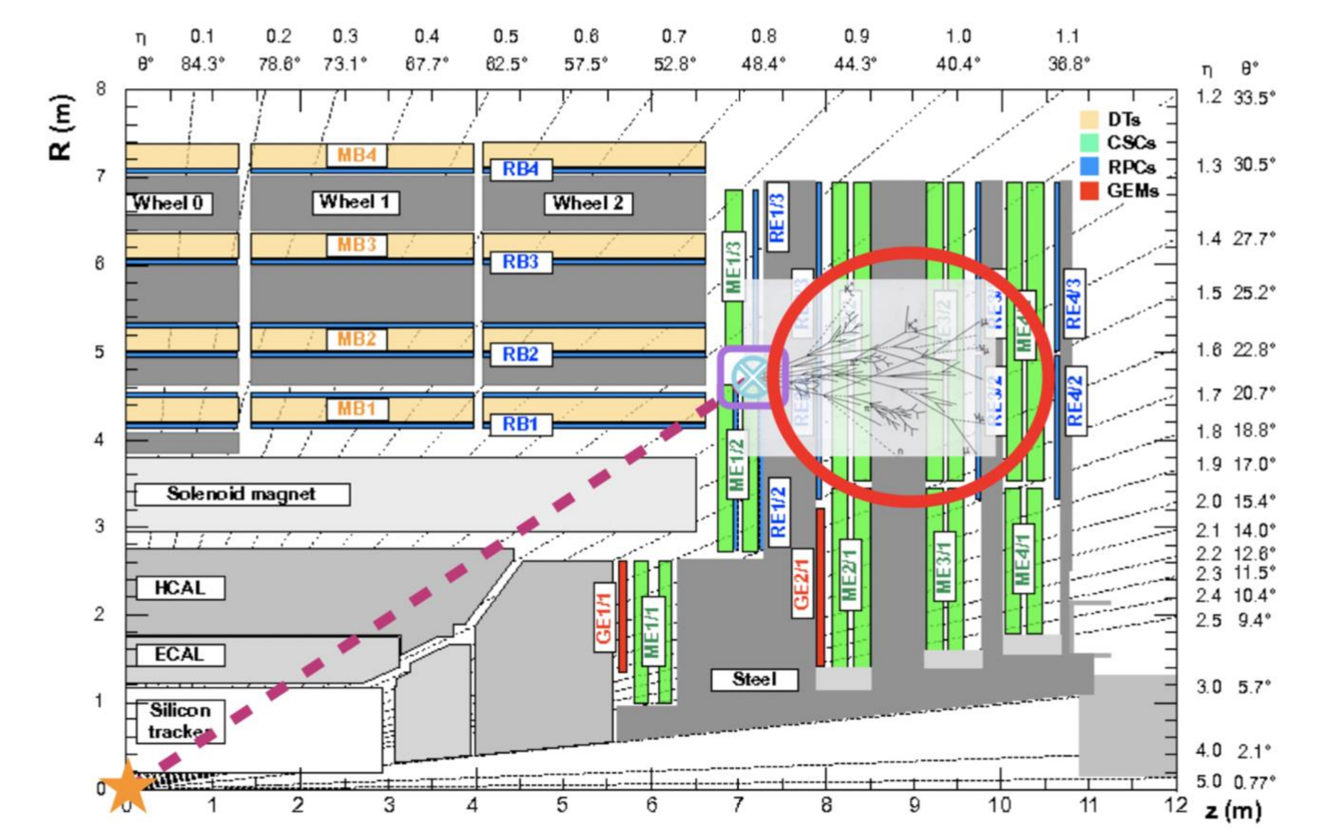
Search for LLPs in the muon system

EXO-20-015

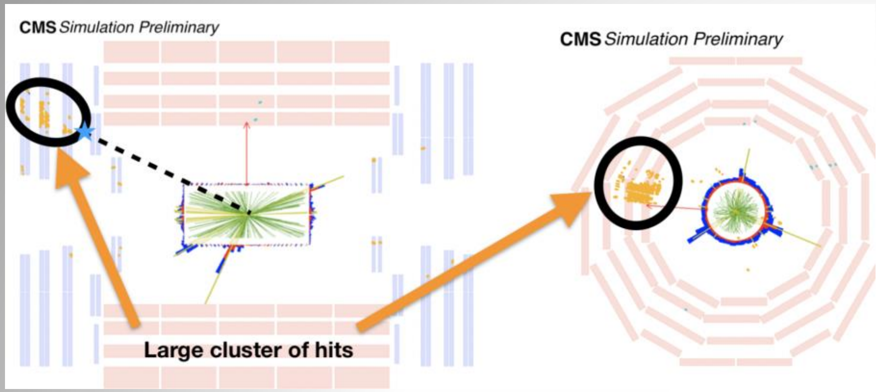


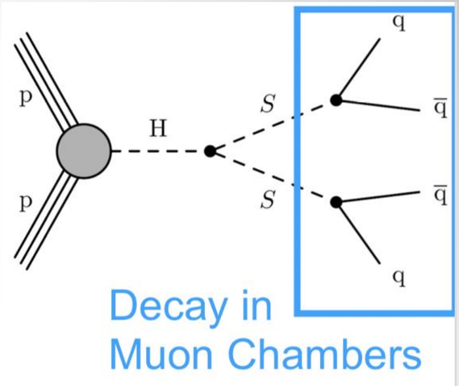
The muon system acts as a sampling calorimeter

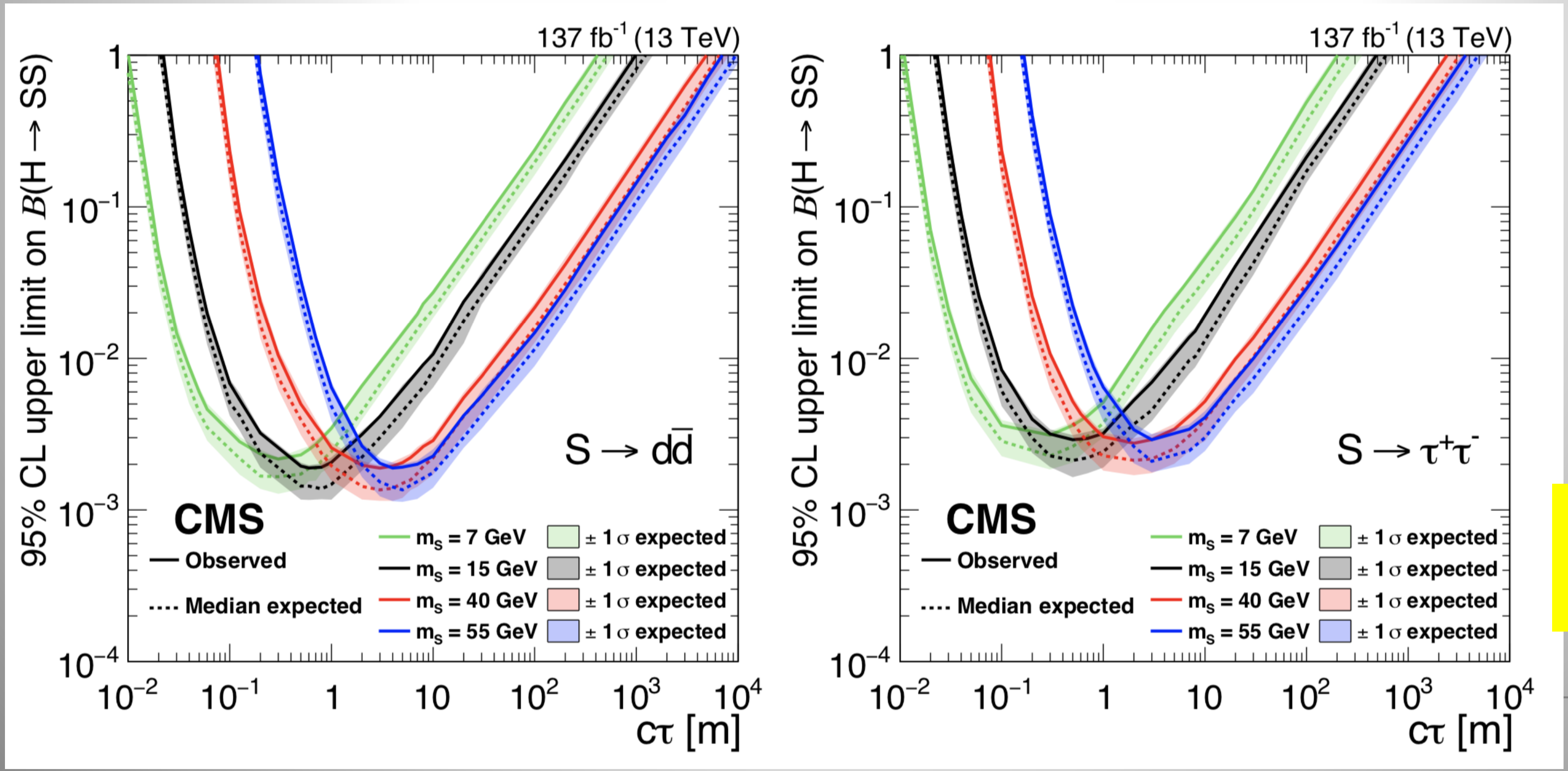
Sensitive to a broad range of LLP particles



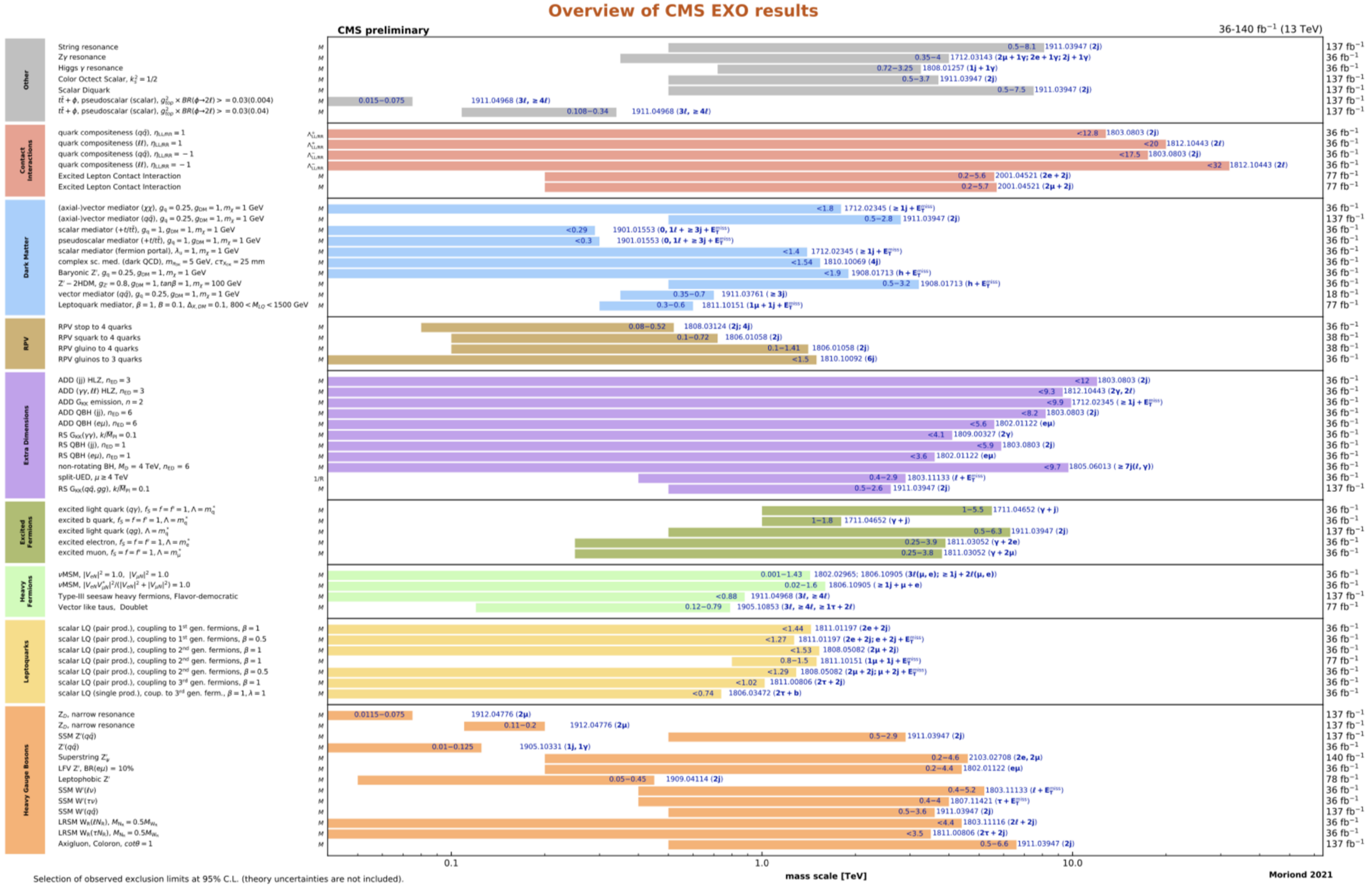
Search for LLPs in the muon system







No excess observed



Most standard searches have been carried out with full Run-2 data

Other exotic signals or new models been considered (eg bi-leptons, see later)

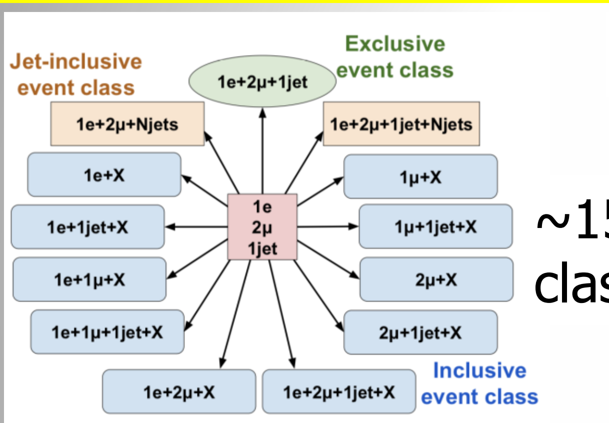
Increased interest in expanding towards long-lived particle searches

General Search for Excesses

- CMS: MUSIC tool to scan the data -> classifiy according to # of objects in event
- Use the invariant mass, S_T and p_{Tmiss}
- Automatic statistical analysis

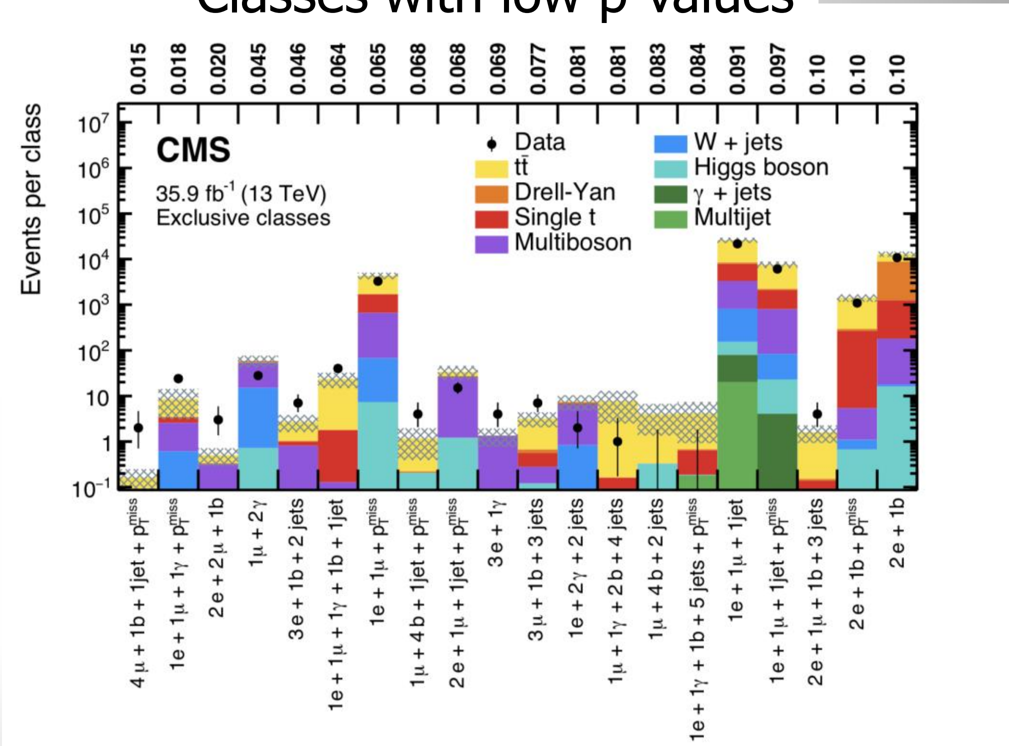
Object	p_T [GeV]	Pseudorapidity
Muon	>25	$\|\eta\| < 2.4$
Electron	>25	$0 < \|\eta\| < 1.44$ or $1.57 < \|\eta\| < 2.50$
Photon	>25	$\|\eta\| < 1.44$
Jet	>50	$\|\eta\| < 2.4$
b-tagged jet	>50	$\|\eta\| < 2.4$
Missing transverse momentum	>100	—

2010.02984

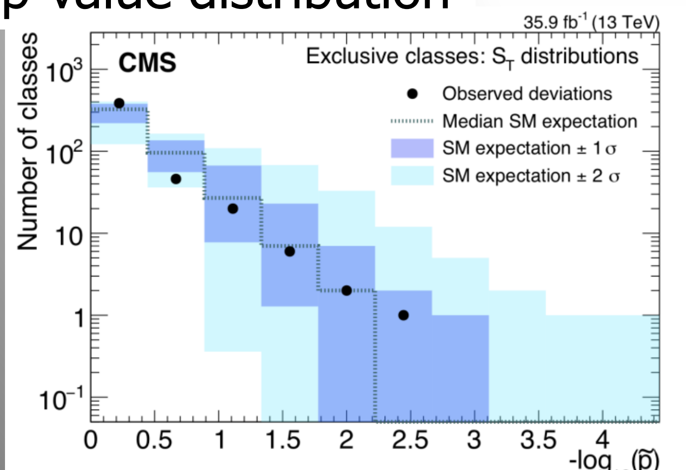


~1500 classes

Classes with low p-values



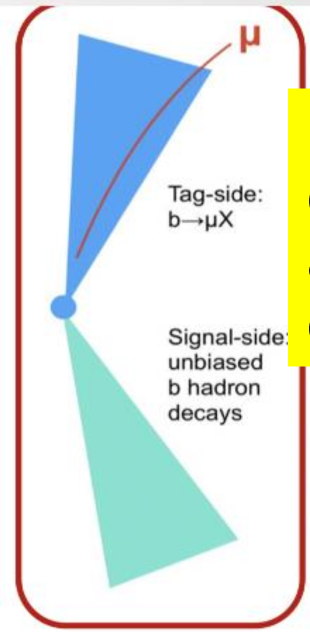
p-value distribution



->No new interesting signatures found ☹

Run-3 Opportunities

- B-parking
  - in 2018 we used low p_T displaced triggers to save a sample of unbiased B hadron decays recoiling wrt the triggered muon
    - Parked trigger rate ~2kHz was reconstructed after the end of the run
  - **Enables several analyses on LFU violation** currently in progress
    - Expect first approved results soon
  - **Studying how to further optimize the trigger in Run 3**
- Scouting
  - Analysis based on a reduced data format and on the online reconstruction in the HLT farm (do not save the full event data)
  - In Run 2 all analyses based about 5 kHz (~1 kHz of Particle Flow scouting)
  - **For Run 3 aim at running PF on higher rate, possible adding additional L1 triggers (use GPUs and pixel tracks)**
- LLP improvements
  - **Ongoing developments in the L1 trigger** area with the aim to increase efficiency for displaced signatures
    - Increase efficiency for displaced muons
    - Extend muon triggers to hadronic showers
    - Out of time ECAL and HCAL at L1
    - Using HCAL depth information
  - **HLT developments also ongoing**



Run-2 2018 data analysis on progress

Collected billions of unbiased B decays
12 billion events total

Mode	N_{2018}	f_B	$\mathcal{B}$
Generic b hadrons			
B_d^0	4.0×10^9	0.4	1.0
$B^\pm$	4.0×10^9	0.4	1.0
B_s	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
B_c	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0
Events for R_K and R_{K^*} analyses			
$B^0 \to K^*\ell^+\ell^-$	2600	0.4	6.6×10^{-7}
$B^\pm \to K^\pm\ell^+\ell^-$	1800	0.4	4.5×10^{-7}

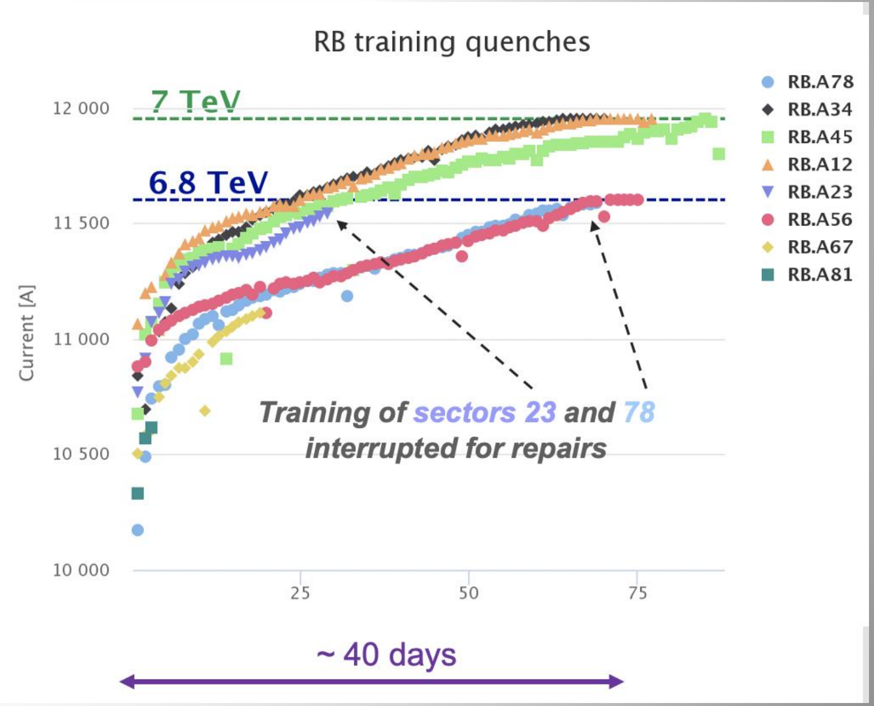
Run-3: What Energy?

The known hurdle: the dipole magnets need retraining..

Jörg Wenninger
EPS-HEP

Training to 7 TeV

- Training to 7 TeV was observed to require at least 70-80 quench cycles, in some sectors even more..
- Based on the current experience, **~ 700 quenches will be required for 7 TeV** – for a total of 1232 dipole magnets.
- Following the issues during training, the **target energy was lowered to 6.8 TeV** in June 2021.
  - Risk analysis of 6.8 TeV versus 7 TeV - due end of September.
- **Training status – 50% ready for 6.8 TeV**:
  - **Two sectors ready at 7 TeV** – 12 & 34.
  - **Two sectors ready at 6.8 TeV** – 45 & 56.



Run-3: Expected luminosity

Improvements at the LHC and in pre-accelerator complex (LINAC4, PS..)

Parameter`	Design	2018	Run 3
Bunch population N_b (10^{11} p)	1.15	~1.1	~1.8
No. bunches k	2780	2556	2748
Emittance ε (mm mrad)	3.5	~1.8	1.8-2.4
β^* (cm)	55	30 / 25	150 - 25
Full crossing angle (μrad)	285	320 - 260	320 - 260
Peak luminosity (10^{34} $cm^{-2}s^{-1}$)	1.0	~2.1	~4-5

The current estimate for the **integrated luminosity over Run3** (2022-2024) is

$\approx$ 160-200 fb^{-1}

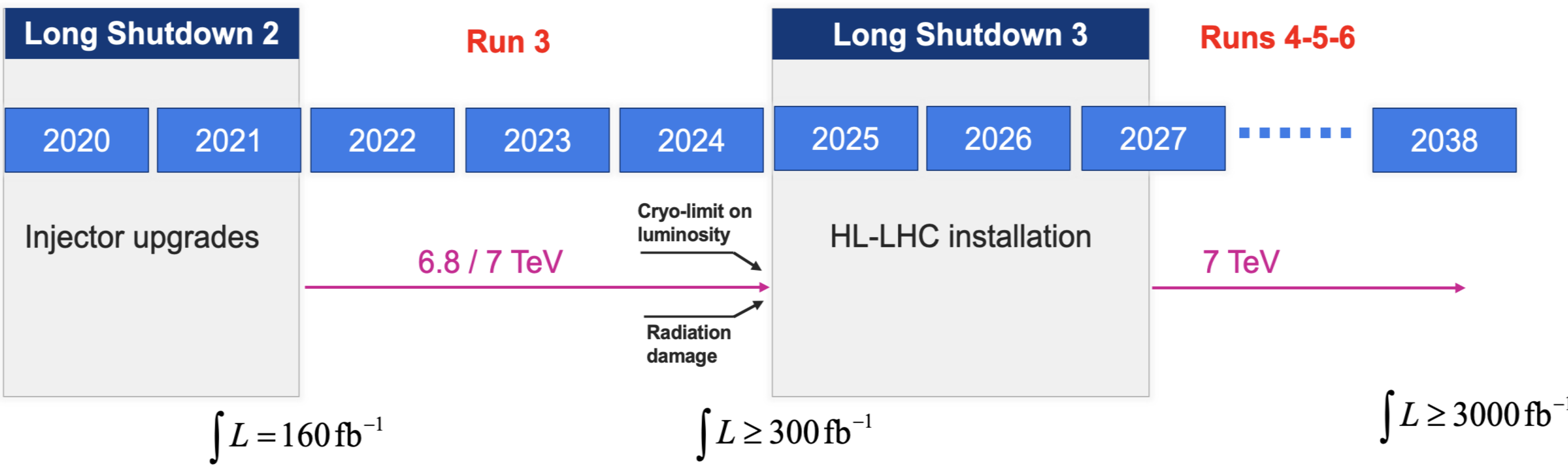
→ *doubling the Run 1 + Run 2 data set*

Luminosity leveling possible at start of the runs to reduce pile-up impact

- **The start of Run 3 beam commissioning** is scheduled for **March 7th 2022**.

LHC Beyond Run 3

Long term plan



Following the "loss" of 2021 to COVID, an extension of Run 3 into 2025 is under consideration, but possible radiation damage to some of the low-beta quadrupole assemblies is a worry.

Summary

- Measurements of Standard Model processes show good agreement with predictions. Precise measurements require precise calculations. New rare processes measured.
- Higgs measurements at 13 TeV. The Higgs remains very consistent with SM expectations. First access to the second generation fermion coupliungs. More precision with run-3.
- No sign of new physics in the 13 TeV data so far in run-2… Most analyses now with full run-2 statistics
- Long Lived Particle searches are being explored in a more systematic way. White paper arXiv:1903.04497
- New promising techniques for Run-3: B-parking
- The LHC is continuing to explore the Terascale. significant deviation to show the way!!

And hopefully one day soon: