CONFERENCE ON HIGH ENERGY PHYSICS

11-14 SEPTEMBER 2023, YEREVAN, ARMENIA

Physics beyond the Standard Model with the CMS Experiment at the LHC

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on behalf of the CMS Collaboration

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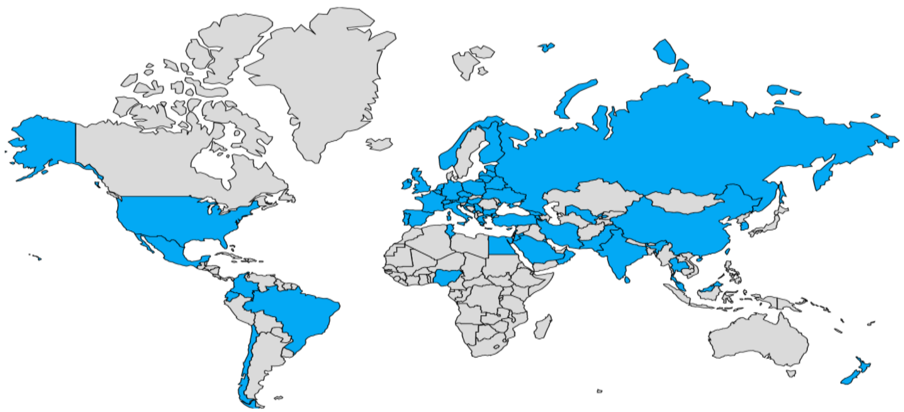
CMS Overview

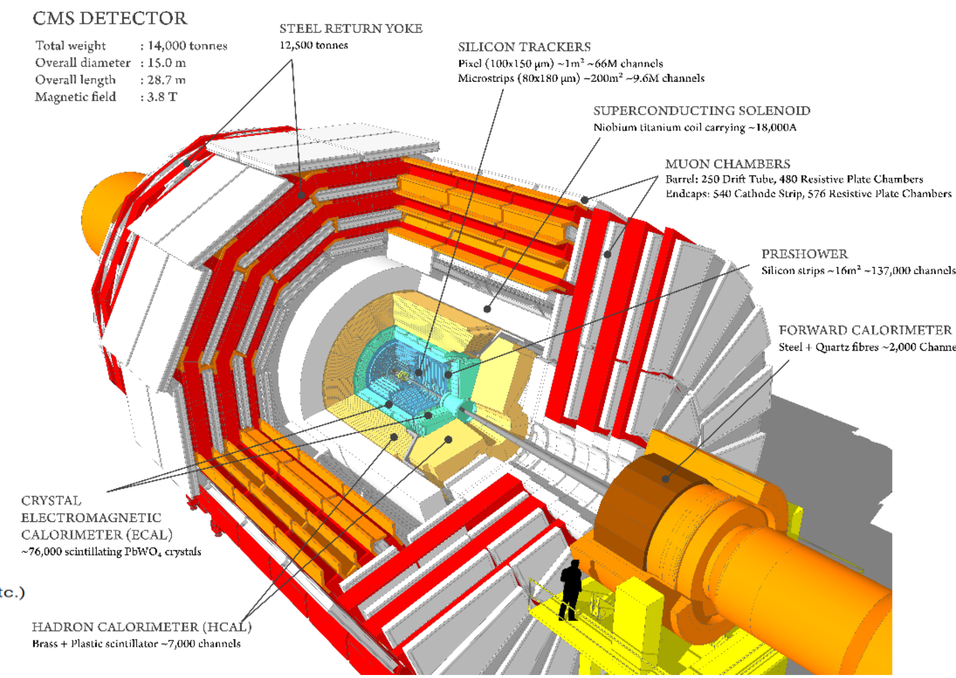
The CMS experiment has members from **255** institutes coming from **57** countries

3401 Physicists (1229 students) **1118** Engineers **283** Technicians



The CMS collaboration has around **6385** active people (physicists, engineers, technical, administrative, students, etc.)

2172	**1229**	**1118**	**1455**
Phd Physicists (405 women 1767 men)	Physics Doctoral Students (324 women 905 men)	Engineers (152 women 966 men)	Undergraduates (414 women 1041 men)

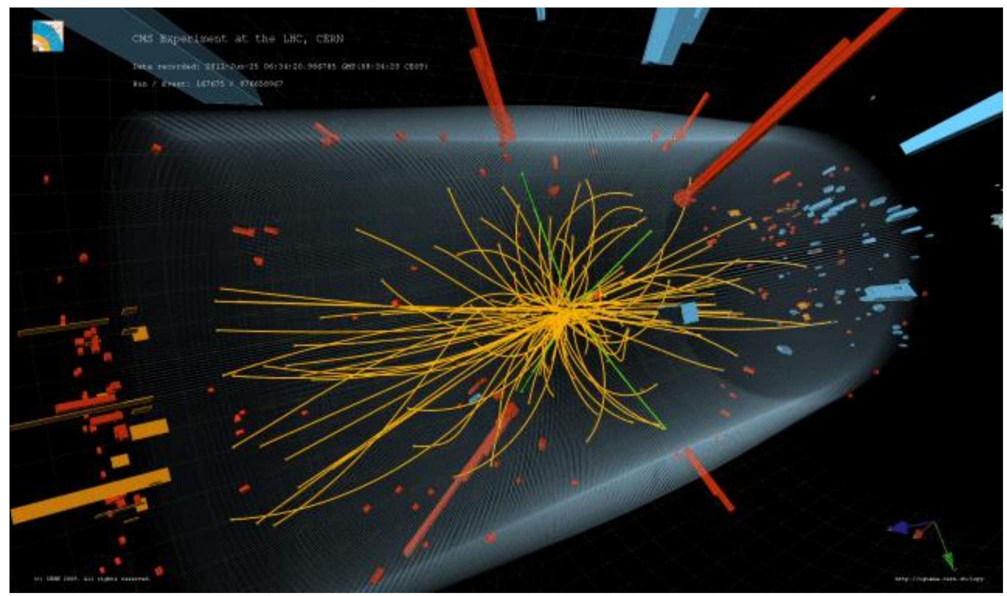


https://cms.cern/ https://cms-info.web.cern.ch/

AANL, Yerevan, Armenia, 12 September, 2023

Content

- Standard Model after over 10 Years of LHC Operations
- Why we are still expecting the New Physics?
- Conventional Signals (“standard candles”)
- Higgs Boson as a Tool to Search for the New Physics
- LLP Non-conventional Signals
- Summary



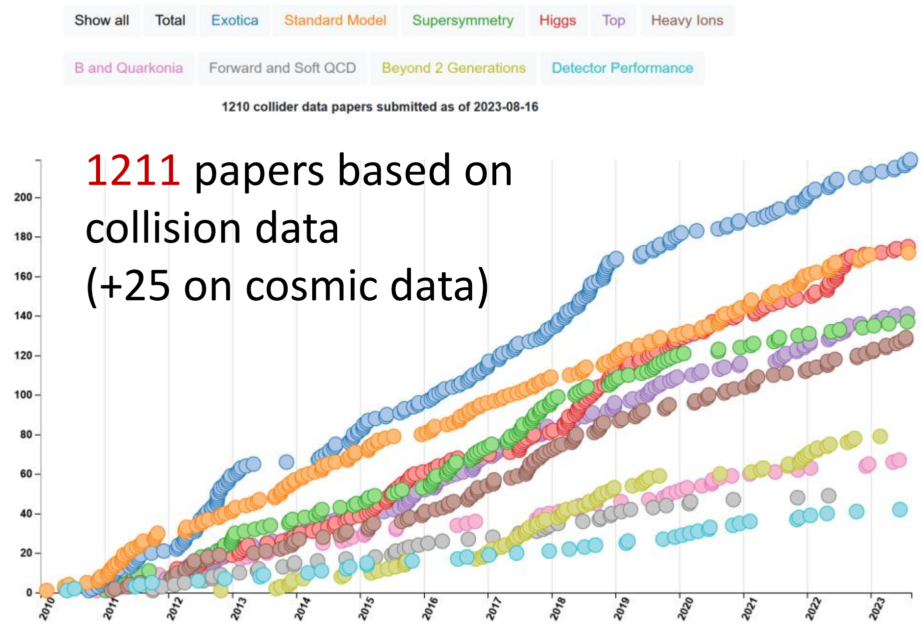
Some Statistics from CMS

This talk are summarized the selected (by me) the recent CMS results on Physics beyond the SM (Exotica/B2G/Higgs WG)

LHCP2023, 22-27 May, Belgrad,
EPS-HEP2023, 21-25 Aug 2023, Hamburg
Recent CMS Briefings

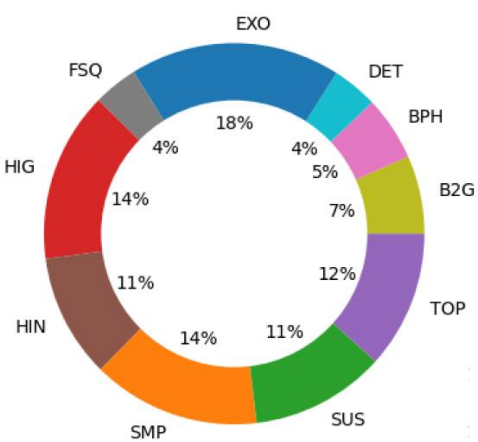
CMS Publications Page
https://cms-results.web.cern.ch/cms-results/public-results/publications/

CMS Public Results (newest)
https://cms-results-search.web.cern.ch/



1211 papers based on collision data
(+25 on cosmic data)

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



35% of Standard Model (SMP/FSQ/BPH/TOP)

14% of Higgs Physics

36% of BSM Physics (EXO/B2G/SUSY)

11% of Heavy Ion

- Exotica/SUSY/B2G – 435
- Higgs – 175
- Standard Model/Top/B and Quarkonia - 383
- Forward and Soft QCD – 49
- Heavy Ion – 129
- Detector Performance – 42

CHEP-Yerevan-2023 talks with the CMS Results

17 more talks with the CMS Results

Beyond the Standard Model

- Alexander Lanyov, Physics of Dimuons at the LHC
- Maria Savina, Dark Matter Search at the LHC
- Artur Apresyan, Searches for LLPs at CMS, and LLP-optimized detectors for future colliders

Precise Tests of the Standard Model

- Armen Tumasyan, Study of the Higgs boson decay to bottom quark pairs with CMS
- Aliaksei Raspiareza, Study of the CP structure of the Yukawa coupling between the Higgs boson and taus
- Seddigheh Tizchang, Rare Single Top-Quark production at CMS
- Vlad Shalaev, Polarization Effects in Processes of Dimuon Production
- Ilya Zhizhin, Photon induced background for DiMuon studies
- Vladimir Zykunov, Radiative corrections to dilepton production at LHC..
- Maxim Perfilov, Separation between top pair and single top contributions with tWb final state using NN
- Gholamhossein Haghighat, Latest FCNC results from the CMS experiment

QCD and Heavy Ions

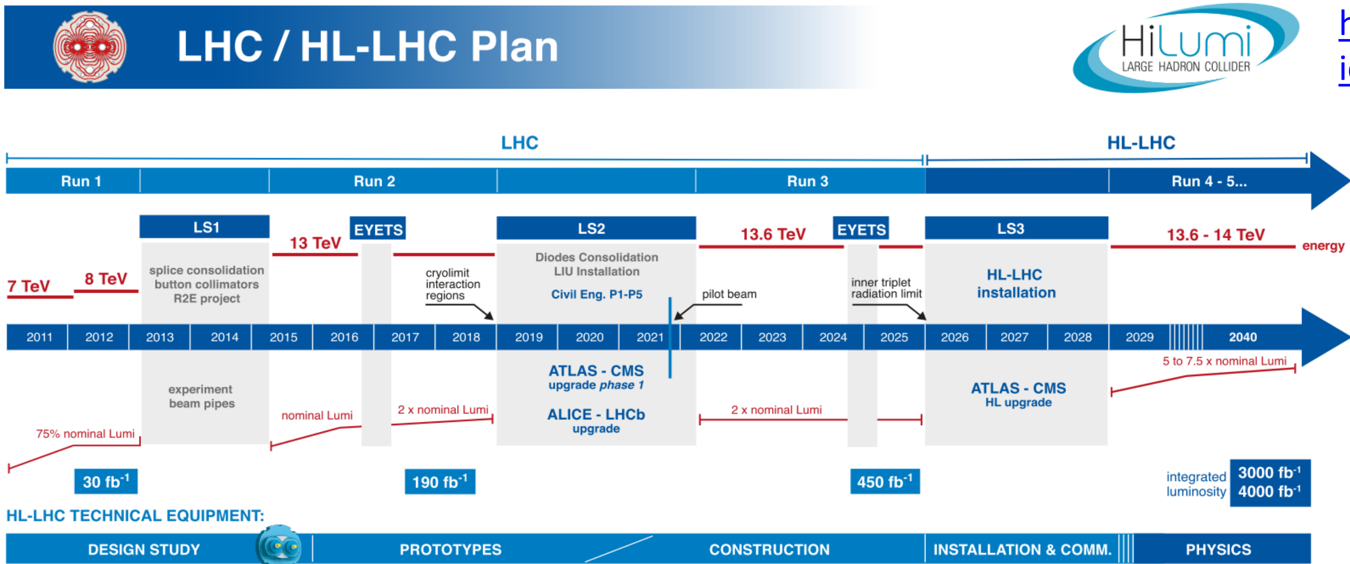
- Olga Kodolova, QCD Physics with CMS
- Sergei Shulha, Methodology of measurement of quark and gluon jet macro parameters at hadron collider
- Sergey Petrushanko, Recent heavy-ion results by CMS experiment

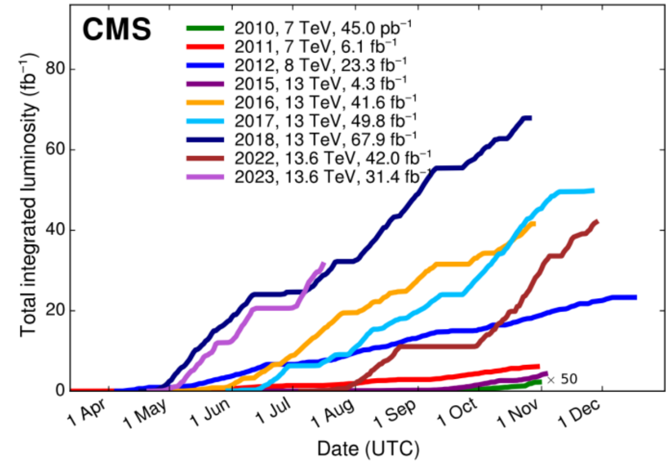
Detector Performance, Upgrade and Future Physics

- Vladimir Karjavine, JINR participation in the CMS upgrade for the High Luminosity LHC
- Vadim Alexakhin, CMS HGCAL cosmic test stand
- Milos Dordevic, Physics at HL-LHC and beyond

LHC Timeline and Data That We Have

CMS Luminosity Information
https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults



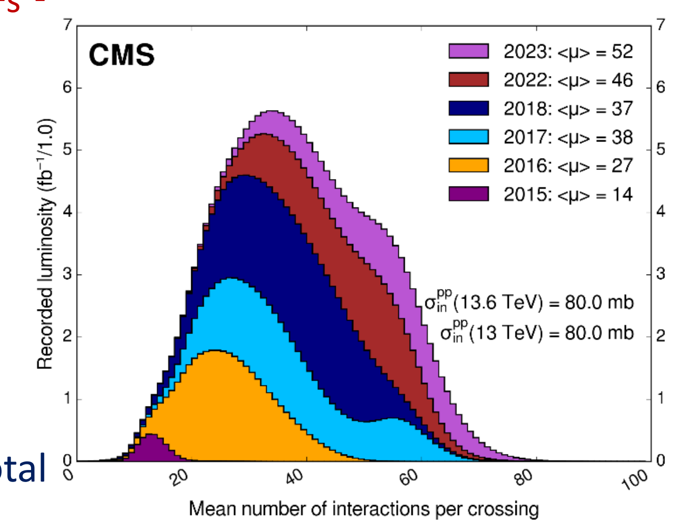


$L_{inst} = 2.1\times10^{34}\ cm^{-2}s^{-1}$

$L_{nisyt} = 7.5\times10^{34}\ cm^{-2}s^{-1}$

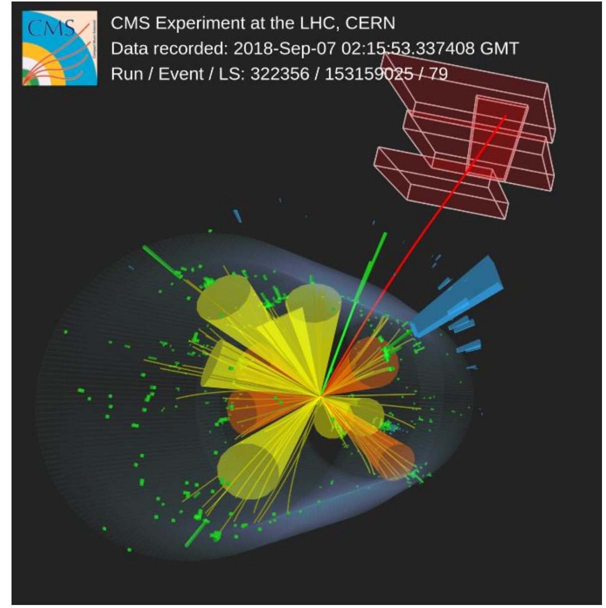
We are here

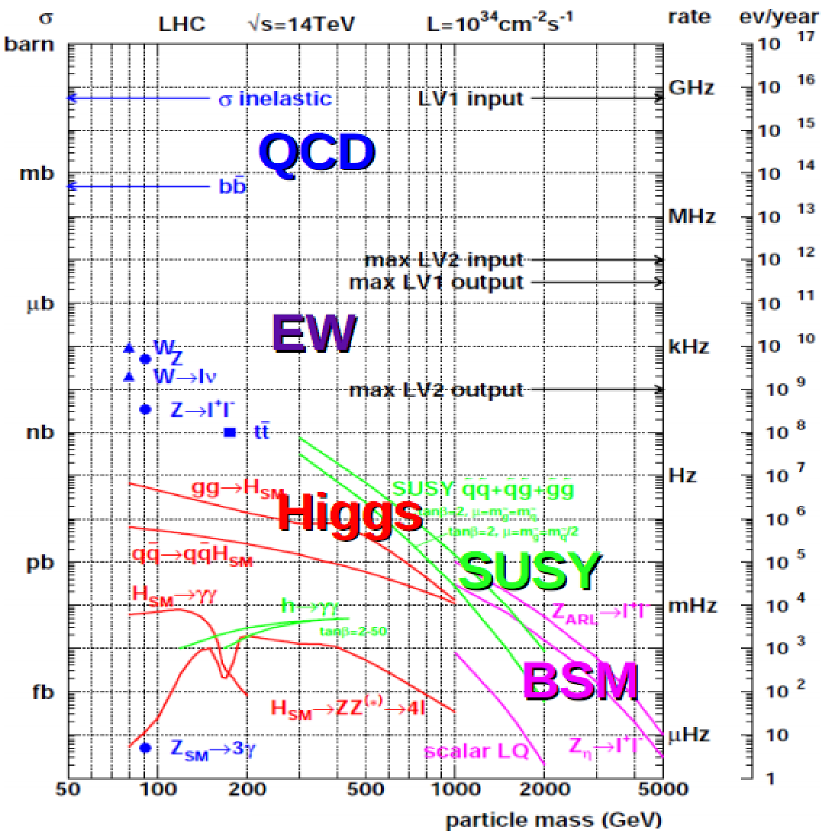
- CMS Dataset RUN2
  - ✓ ~163 fb^{-1} of proton-proton collisions @ 13 TeV is delivered
  - ✓ 151.78 fb^{-1} is recorded by CMS (data-taking efficiency ~93%)
- CMS Dataset RUN3
  - ✓ ~73.4 fb^{-1} is already delivered @ 13.6 TeV during the RUN3
  - ✓ 63.7 fb^{-1} is recorded by CMS (data-taking efficiency ~92%)
  - ✓ ~93% of collected data "good for physics" in 2023 (91% in 2022)
  - ✓ number of pp interactions per beam crossing (PU): $\langle\mu\rangle$ = 52 for 2023
- ~260 fb^{-1} it is expected @ 13.6 TeV for the end of the RUN3 (450 fb^{-1}, in total for RUN1/2/3)
- pPb and PbPb Runs (see talk by Serguei Petrushanko)



CMS Data Quality Information
https://twiki.cern.ch/twiki/bin/view/CMSPublic/DataQuality

What do we know today about the Standard Model from LHC?





- SM processes:

  $\sigma \sim 1/(100\ \mathrm{MeV})^2$

10^{-8} !

- New Physics:

  $\sigma \sim 1/(1\ \mathrm{TeV})^2$

During Run 2 the LHC produced 10^{16} collisions

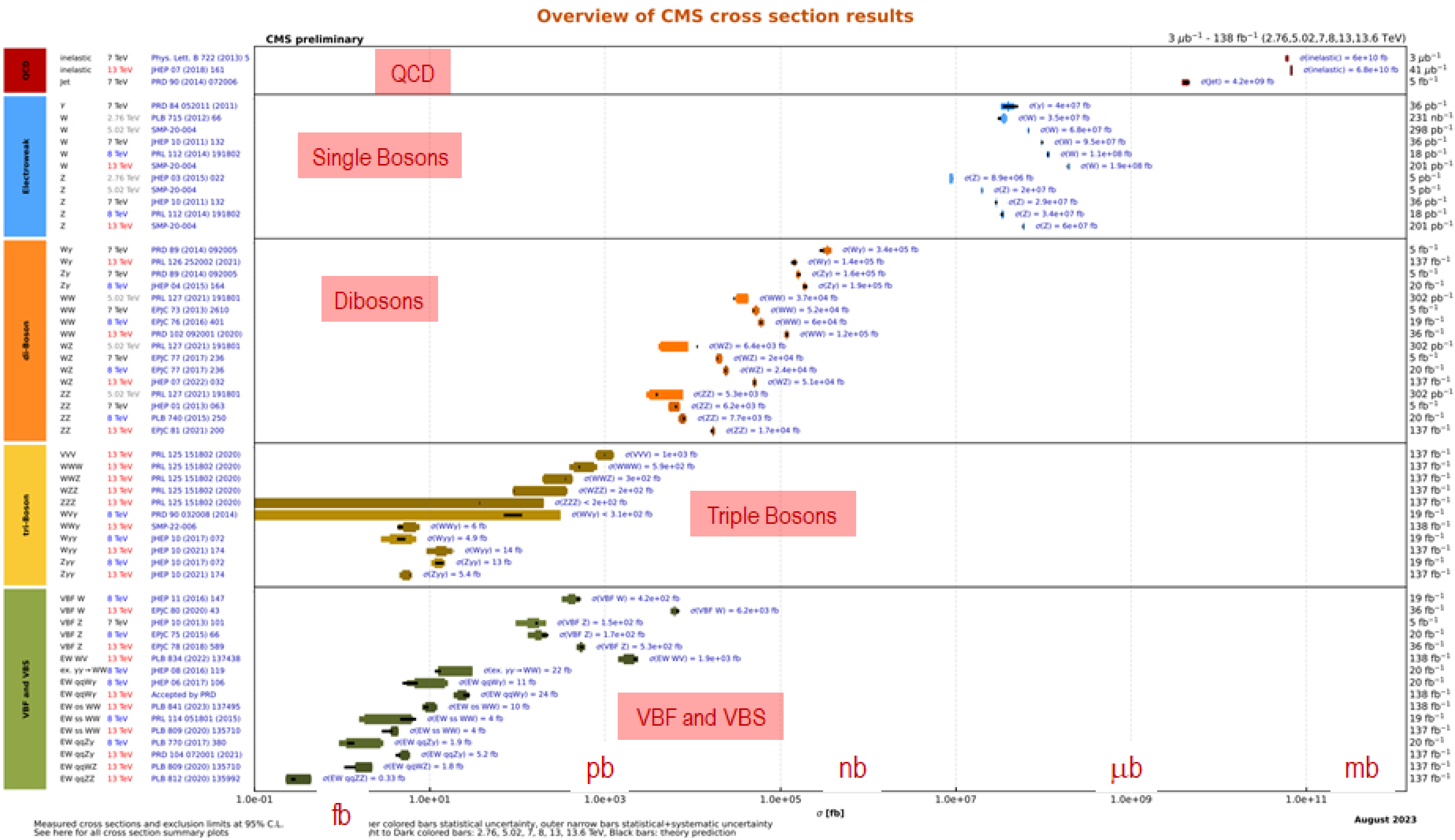
Large samples of various particles produced:

- W bosons: 12 billion
- Z bosons: 2.8 billion
- Top quarks: 300 million
- B quarks: 40 trillion
- Higgs bosons: 7.7 million

Summary of Standard Model Tests with EWK Bosons

Summaries of CMS cross section measurements
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

plots are updated for Summer 2023 Conferences



Summary of HLO Strinjent Tests

Summary of the cross sections standard model particles produced in association with jets

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

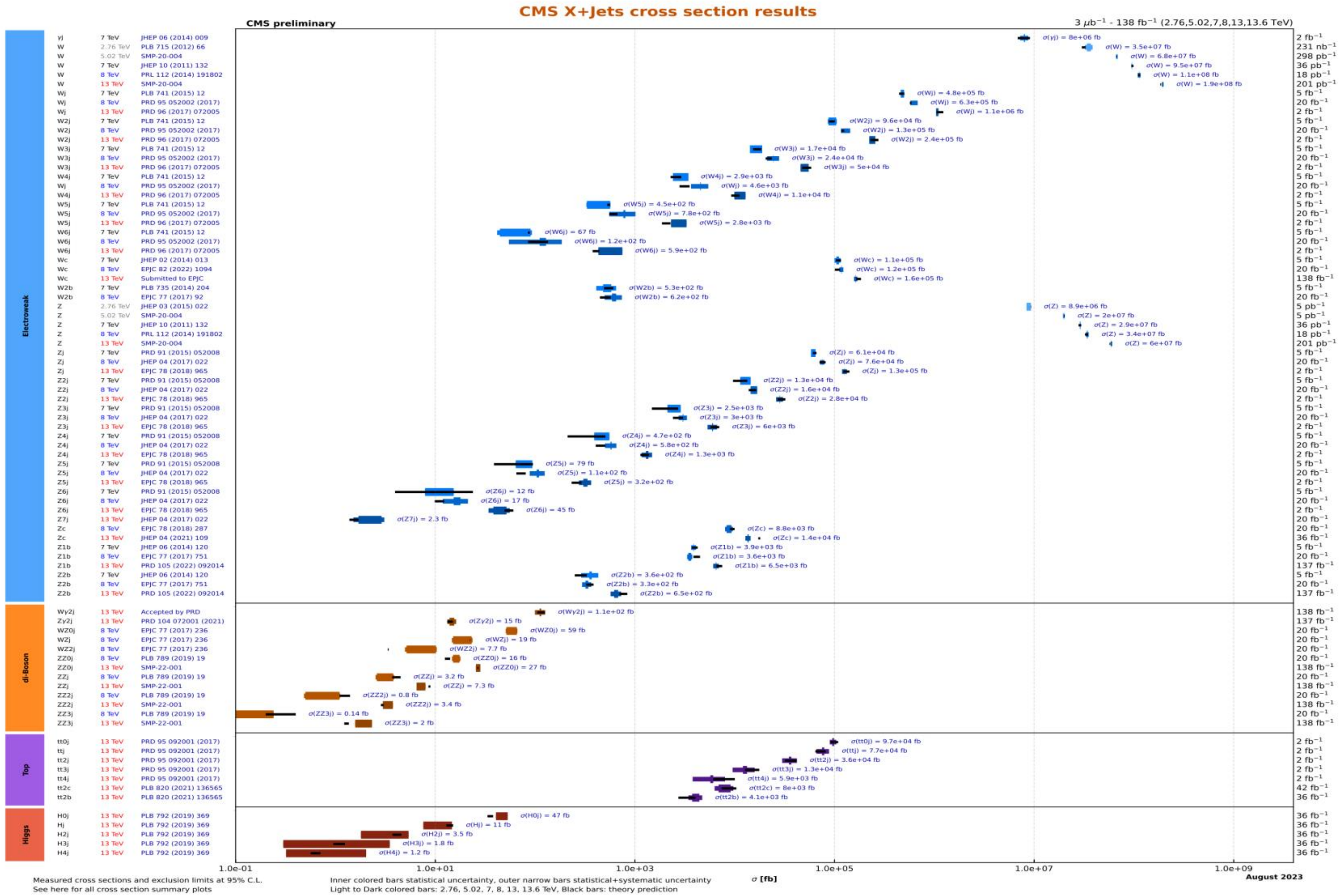
V+jets VV+jets

tt + jets

h + jets

up to 4 jets

plots are updated for Summer 2023 Conferences

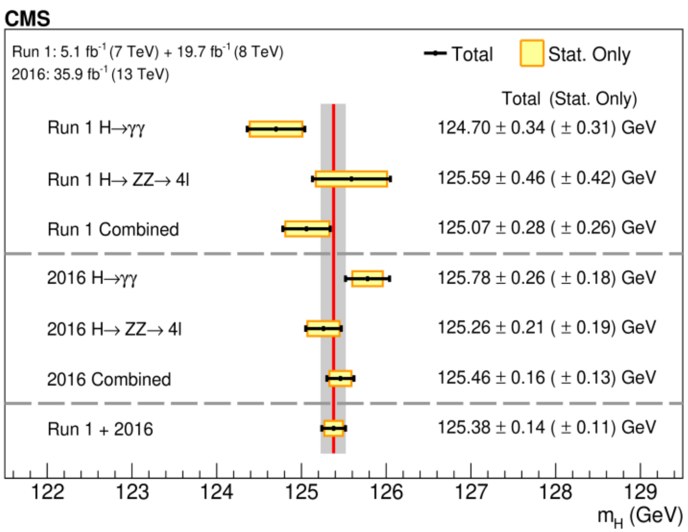


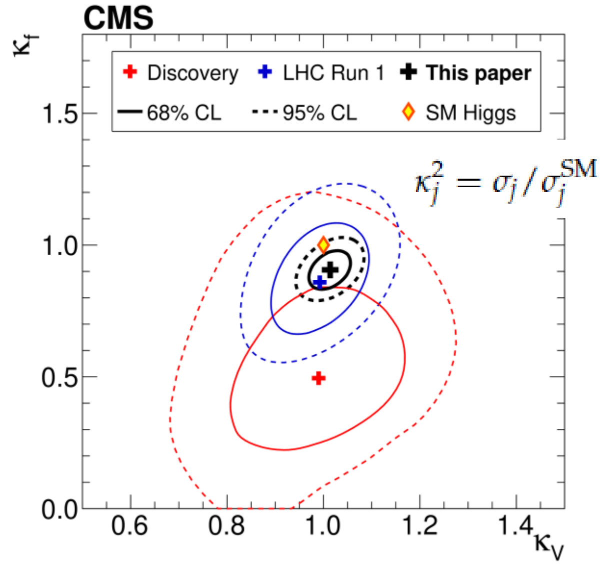
Agrees with the standard model prediction!

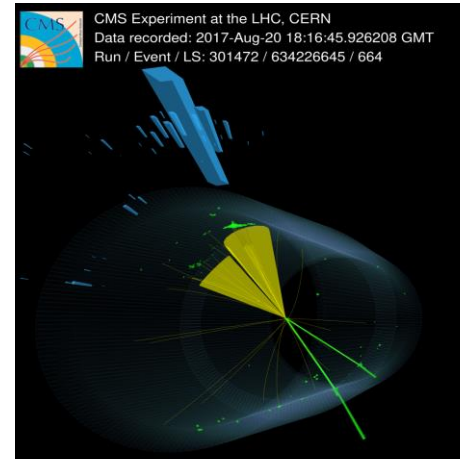
Higgs Portrait after 10 Years

During Run 2 of the LHC the experimental collaborations started to employ the combined data for precision measurements of Higgs properties (mass, width, couplings, CP, rare decays)

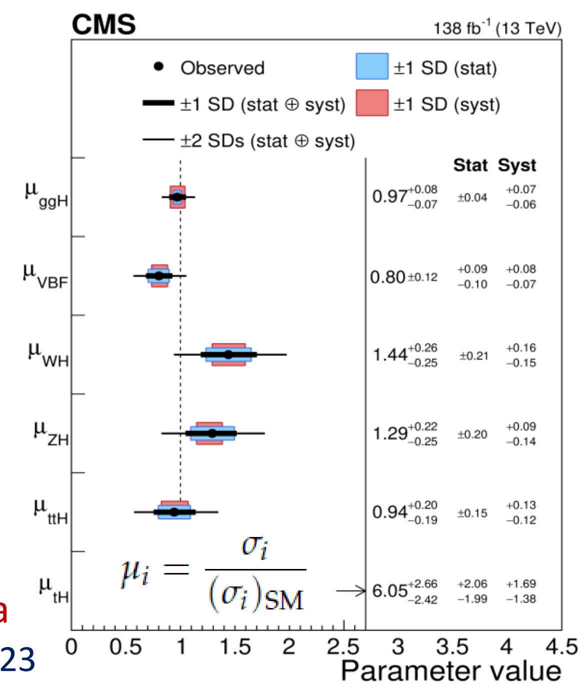
- All main production mechanisms are observed, including h → bbar, ttH, VH
- Mass of Higgs boson m_h is measured with an accuracy of 0.1% (!)







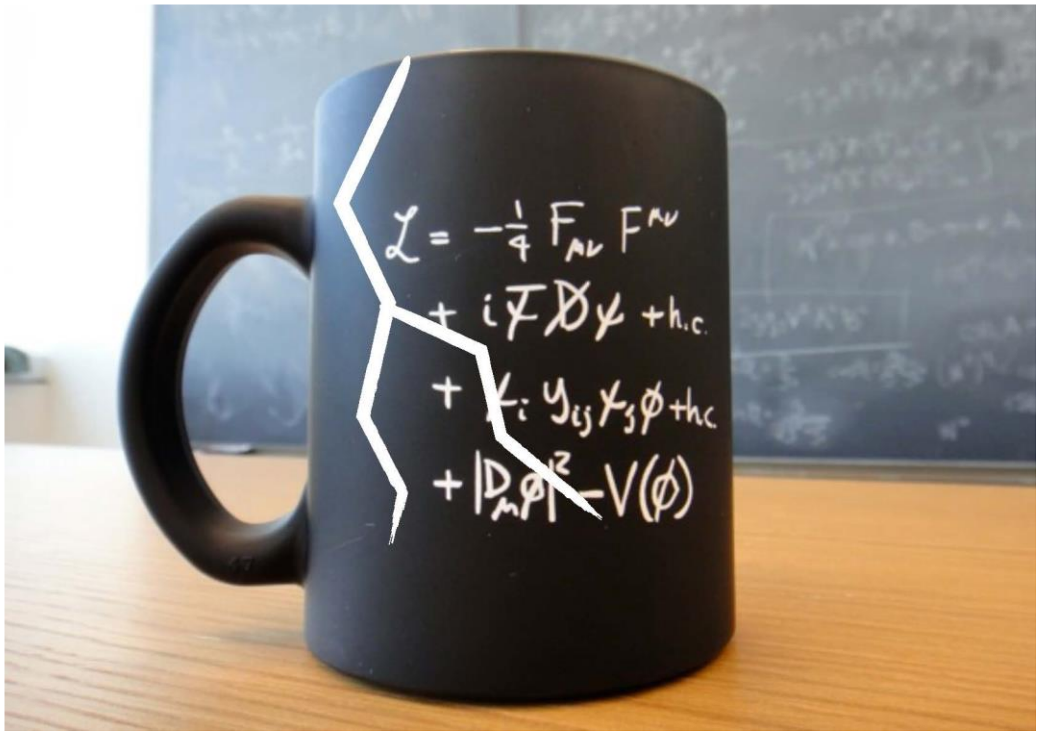
- Precisions of cross section and branching ratio measurements in combined channel are down to 8.5% level
- We have ~6-30% accuracy for measurements of couplings
- The absolute value of a width $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV is getting closer to the SM expectations (4.1 MeV). We still need to improve an accuracy.
- Spin, parity, differential distributions do not contradict the SM



see talks by A. Tumasyan and A. Raspiareza

What do we have as a result?

Why we are still expecting the New Physics?

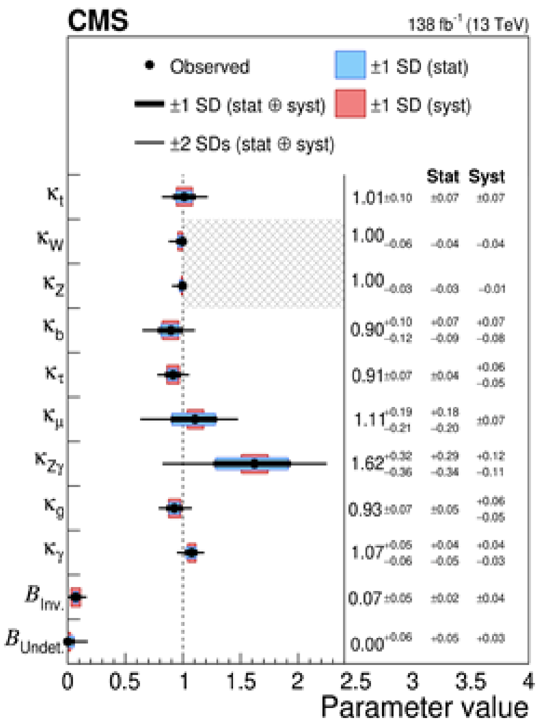


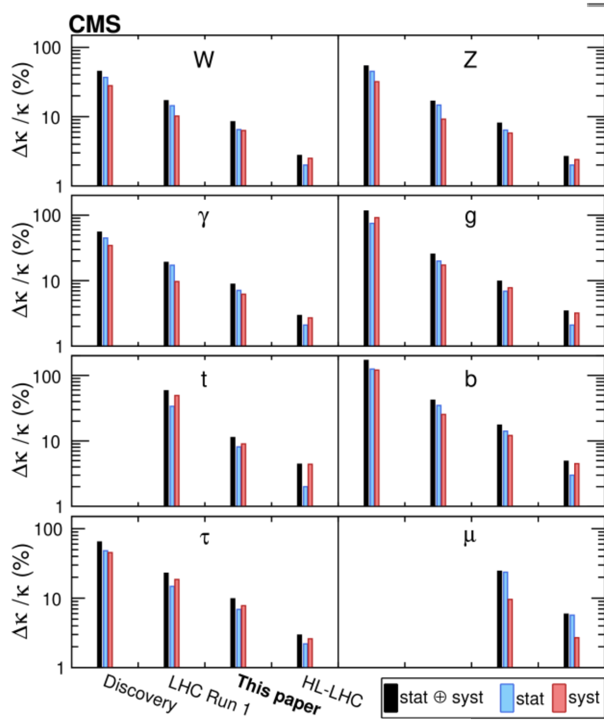
A room in Higgs Sector

… but the current accuracy of Higgs coupling measurements is still insufficient to reject BSM Higgs hypothesis

EPJC 79 (2019) 421

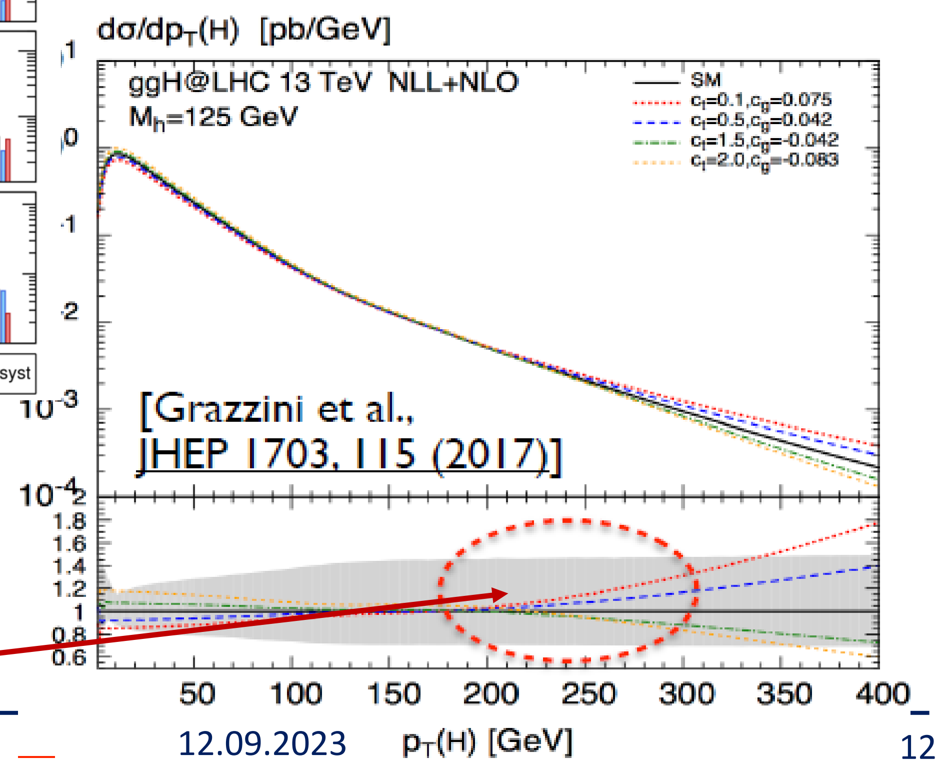
Summary of Higgs Couplings Measurements





The 95% CL upper limit on $\mathcal{B}_{\text{Undet.}}$ is found to be <0.16

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
ecoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

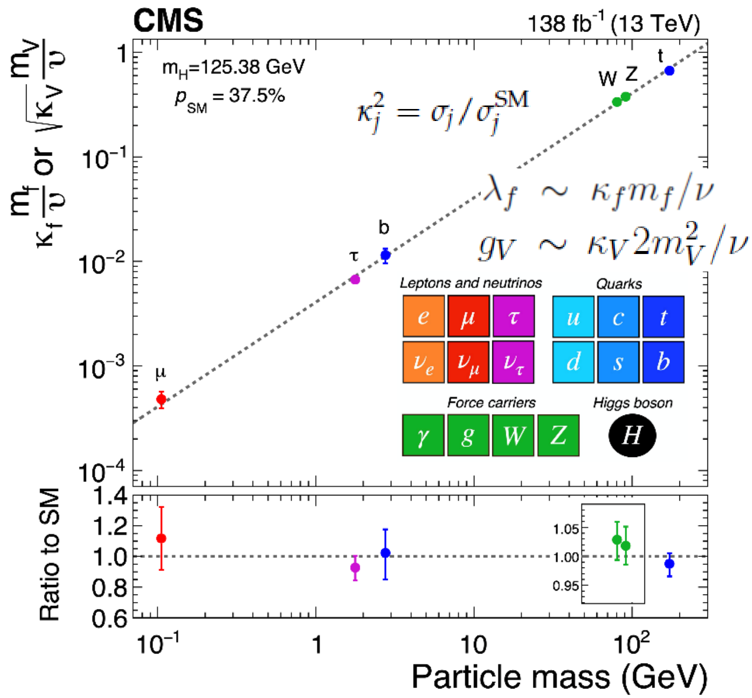


- Measurements precision continuous increasing
- Search for new higgs states and other BSM
  - ✓ BSM effects on in the differential distributions

Another Hint from the Higgs: Flavour Universality

The properties of the Higgs h_{125} agree fully with SM in decay into

- gauge bosons
- 3rd generation fermions (t/b/τ)
- and do not conflict with results for the 2nd generation (no deviations in cc/μμ decays after RUN2)



$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}}$$

$$\lambda_f \sim \kappa_f m_f / \nu$$

$$g_V \sim \kappa_V 2 m_V^2 / \nu$$

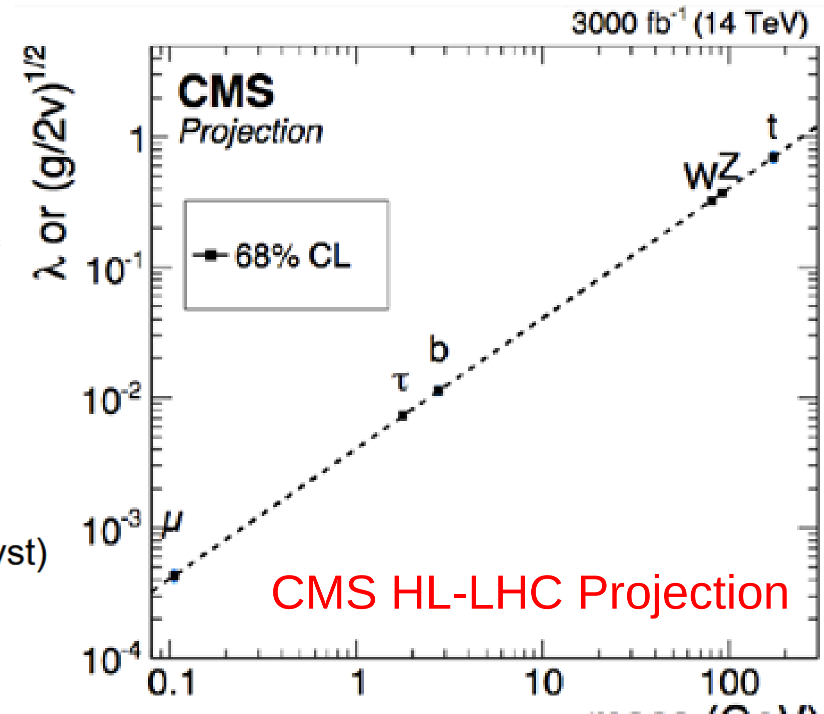
$$\mathcal{B}_{\mathrm{SM}}(H \to e^+e^-) \approx 9 \cdot 10^{-9}$$

$$\mathcal{B}_{\mathrm{SM}}(H \to \mu^+\mu^-) \approx 2{,}2 \cdot 10^{-4}$$

μμ: 3σ

$1.19^{+0.40}_{-0.39}$ (stat)$^{+0.15}_{-0.14}$ (syst)

JHEP 01 (2021) 148



CMS-TDR-15-02

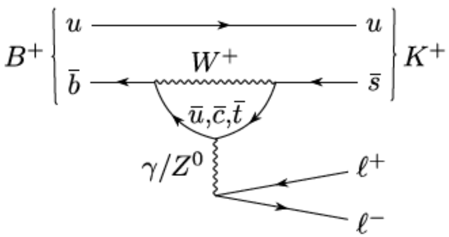
We do not know and will not know until the end of the LHC whether the coupling of the Higgs h_{125} to 1st generation fermions is in a “standard” way or not.

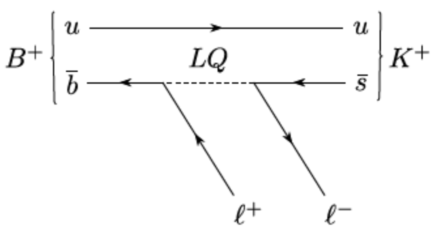
If we have no Extra Higgses! (rare decays are enhanced within Extended Higgs Sectors)

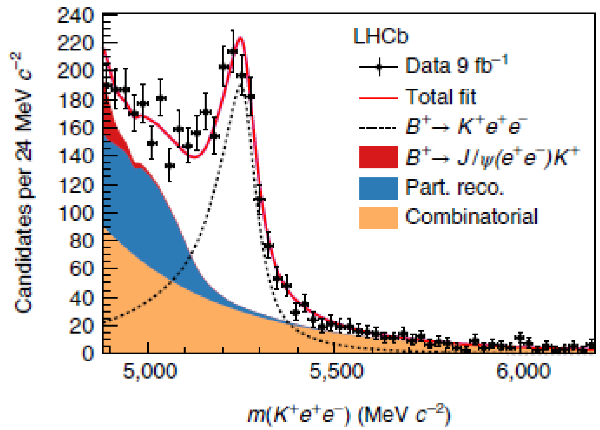
Lepton universality in beauty-quark decays

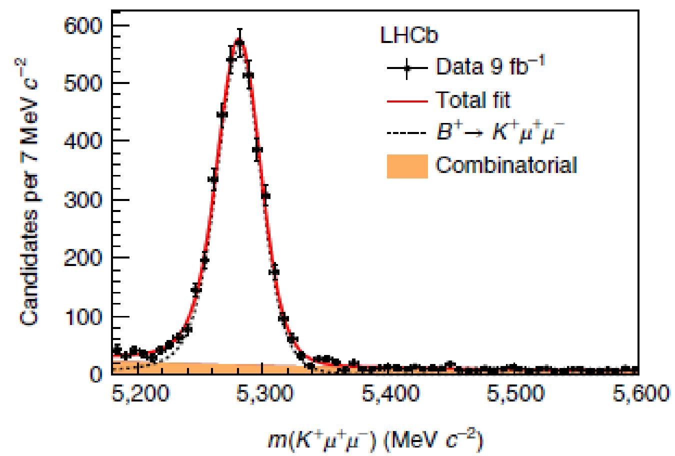
$$R_X \equiv \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to X e^+e^-)} = 1 \text{ in the SM}$$

All QCD effects cancel in ratios.
Small $\mathcal{O}(1\%)$ radiative corrections.

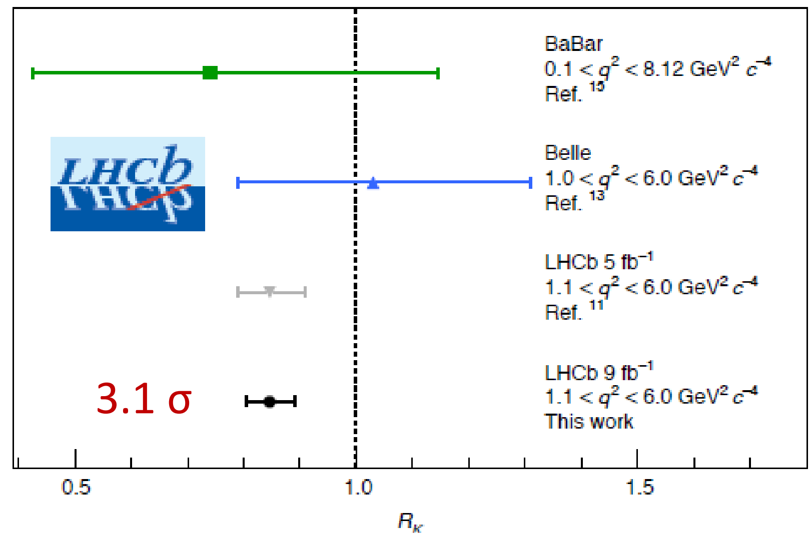








arXiv:2103.11769
Nature 18, 277 (2022)



- LHCb searches in B decays (90% CL limits):

$\mathcal{B}(B_s^0 \to e\mu) < 5.4 \times 10^{-9}$ [3 fb^{-1} JHEP03(2018)078]

$\mathcal{B}(B^+ \to Ke\mu^-) < 7 \times 10^{-9}$ [3 fb^{-1} hep-ex/1909.01010]

$\mathcal{B}(B_s^0 \to \tau\mu) < 3.4 \times 10^{-5}$ [3 fb^{-1} hep-ex/1905.06614]

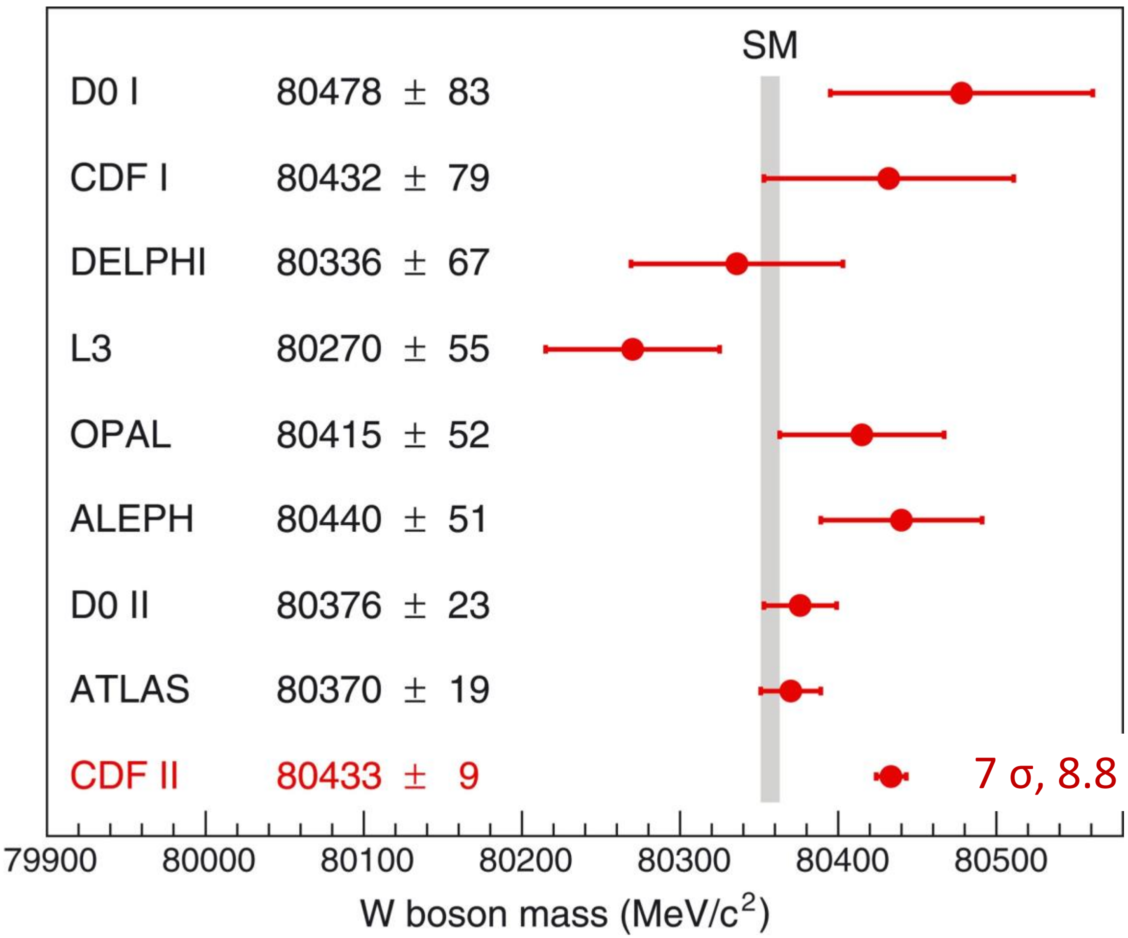
$$R_K(1.1 < q^2 < 6.0\,\text{GeV}^2 c^{-4}) = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

Control uncertainties by measuring double ratios:

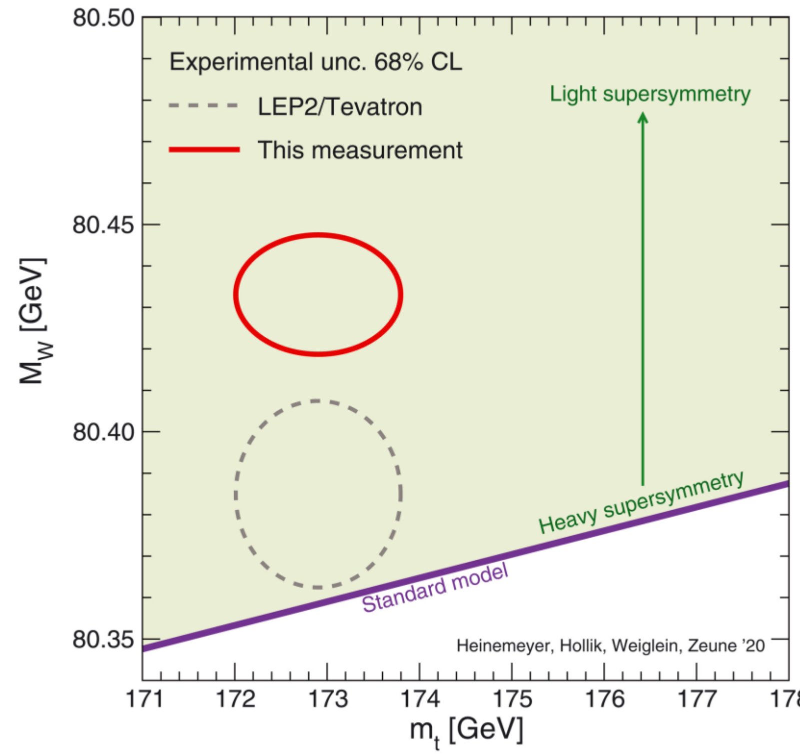
$$R_X \equiv \frac{\mathcal{B}(B \to X\mu\mu)}{\mathcal{B}(B \to X J/\psi(\to \mu\mu))} \frac{\mathcal{B}(B \to X J/\psi(\to ee))}{\mathcal{B}(B \to X ee)} = 1_{(SM)}$$

W boson mass with the CDF II detector

$W \to \mu\nu$ and $W \to e\nu$ decays.



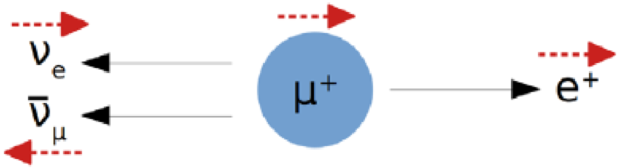
7 σ, 8.8 fb^{-1}

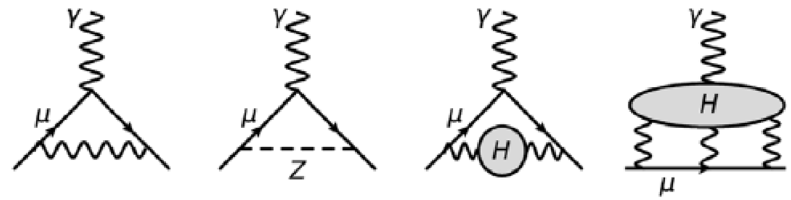


Science Vol 376, 170-176 (2022)

$$M_W = 80,433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80,433.5 \pm 9.4\ \text{MeV}/c^2$$

Fermilab Muon g – 2 Experiment





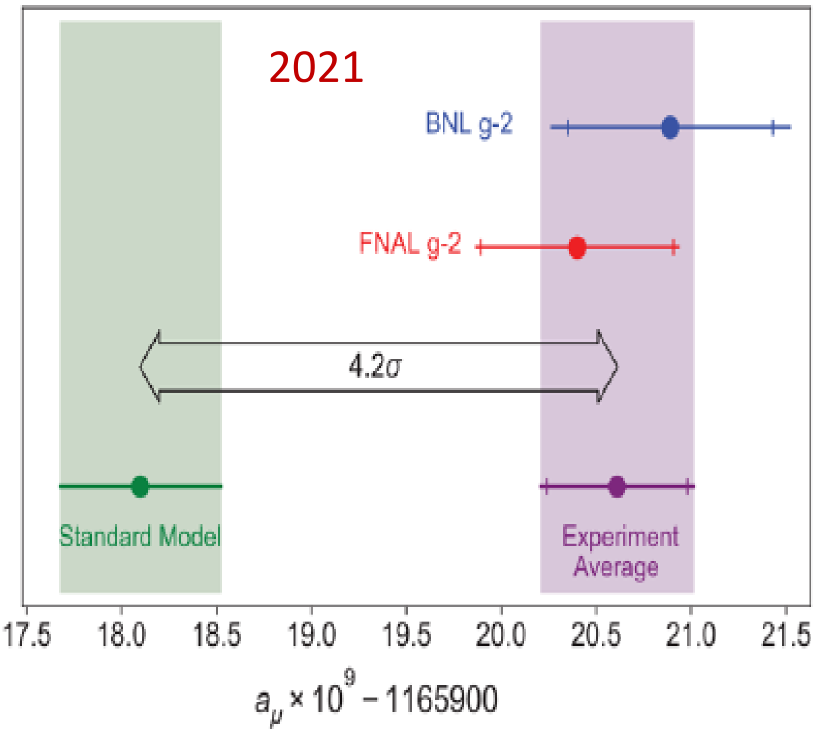
for J=1/2

$g = \mu/\mu_B J = 2$

$a_\mu = (g-2)/2$

$$a_\mu = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak} + a_\mu^{New Physics}$$

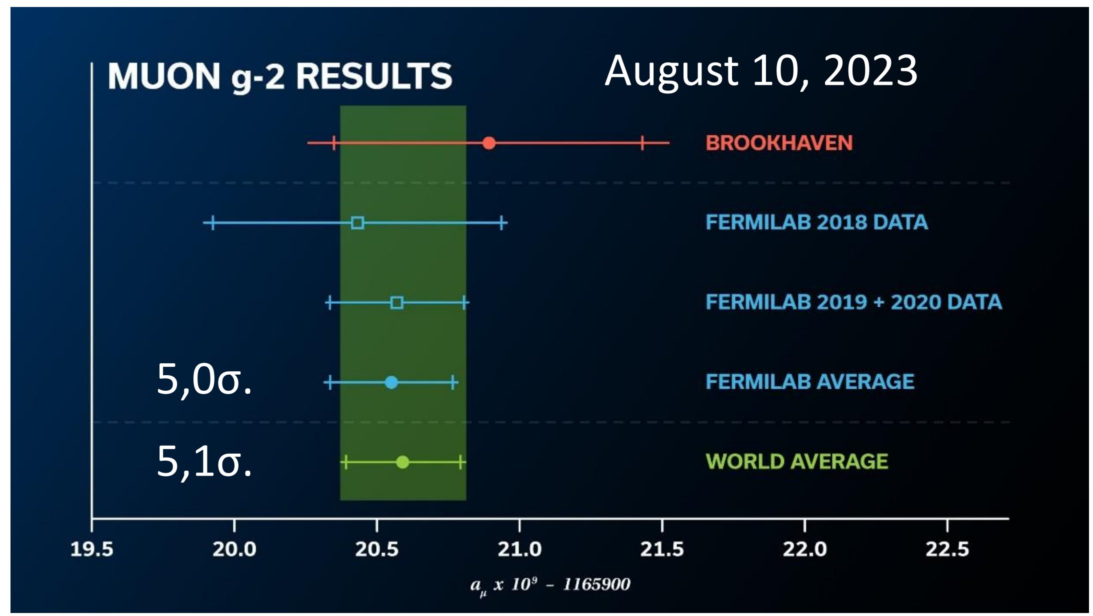
$$1{,}000{,}000 \quad : \quad 60 \quad : \quad 1.3 \quad : \quad \propto \left(m_\mu / m_X\right)^2$$



$$a_\mu^{Th} \ [2020] = 116\,591\,810(43) \times 10^{-11} \ (0.37 \text{ ppm})$$

$$a_\mu^{Exp} \ [2021] = 116\,592\,061(41) \times 10^{-11} \ (0.35 \text{ ppm})$$

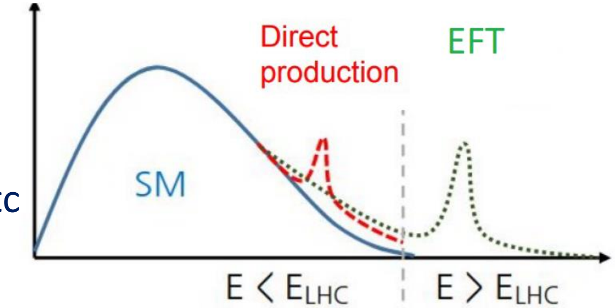
$$a_\mu^{Exp} - a_\mu^{Th} = (251 \pm 59) \times 10^{-11} \ (4.2\sigma)$$



The new experimental result is:
g-2 = 0.00233184110 +/- 0.00000000043 (stat.) +/- 0.00000000019 (syst.), 0.2 ppm

Analyses in the LHC Collaborations

- Direct Searches for the Physics Beyond the SM
  - ✓ Conventional Signals, such as new resonances in dileptons/diphotons/dijets spectra or non-resonant signals, combinations of physics objects (leptons/photons/jets) and MET/ b/t-jets tags, high-multiplicity events, etc



SUSY

Extra Dimensions

Extended Gauge Sector

LQ/CI/Excited Fermions/B3G

  - ✓ on-conventional Signals, for example displaced vertices/leptons/lepton-jets/dileptons from Long-Lived Particles or emerging jets/leptons from boosted heavy objects, $m \ll p_T$ (i.e. high-p_T Z/W/h_{125} bosons)

Long-Lived Particles (Dark Matter/Non-standard SUSY/Neutrino Masses/etc)

Extended Higgs and Dark Matter Sectors

- BSM-Higgs Physics
  - ✓ Searches for the new Higgs states (from extended Higgs sector including SUSY)
  - ✓ Probes for the New Physics with h_{125} (Higgs as a tool for new discovery)

Extra Higgses, Dark Matter, Flavour Universality Violation

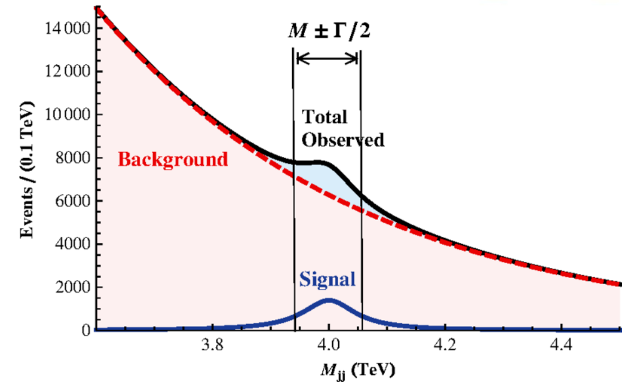
- Check for discrepancies with data and search for new physics via Effective Field Theory

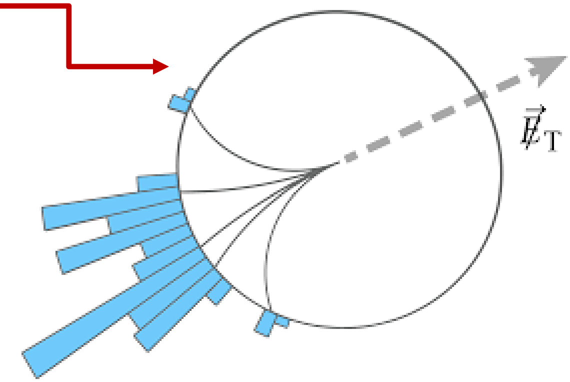
$$L = L_{SM}^{(4)} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \ldots$$

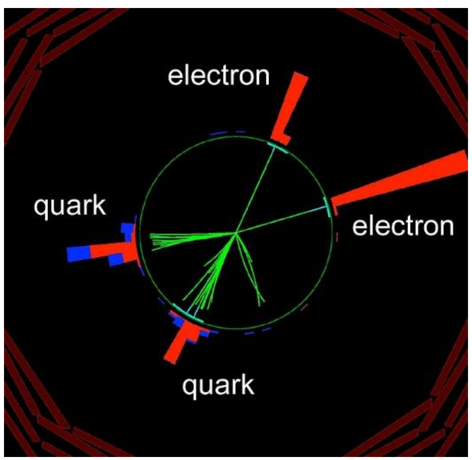
- Precision Tests of SM
  - ✓ Measurements of the W/Z, Drell-Yan (+ n jets) x-sections and angular characteristics
  - ✓ Search for rare decays of B-mesons
  - ✓ Observations of other rare process in top sector within SM (Wtb couplings, CP violating top quark couplings, flavor-changing neutral current interactions of the t-quark and h_{125})

Conventional Signals

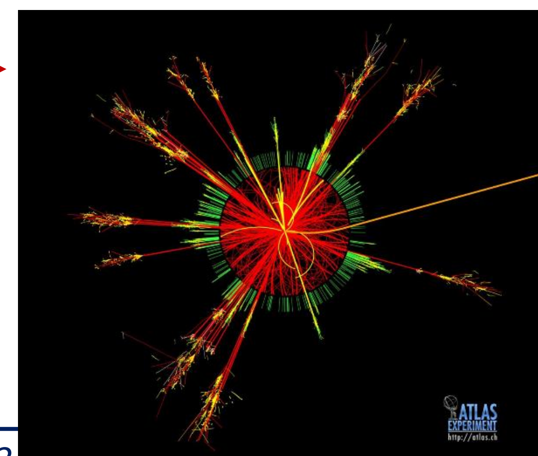
- Heavy Resonances (extended gauge models, extra dimensions, technicolor) ⇒ dileptons, dijets, diphotons, ttbar, WZ
- Non-Resonant Signals
- Mono-particle + Missing ET (extended gauge models, extra dimensions, technicolor, SUSY) ⇒ mono-jet + MET, mono-photon + MET, mono-lepton + MET
- Microscopic Black Holes (extra dimensions) ⇒ high-multiplicity events





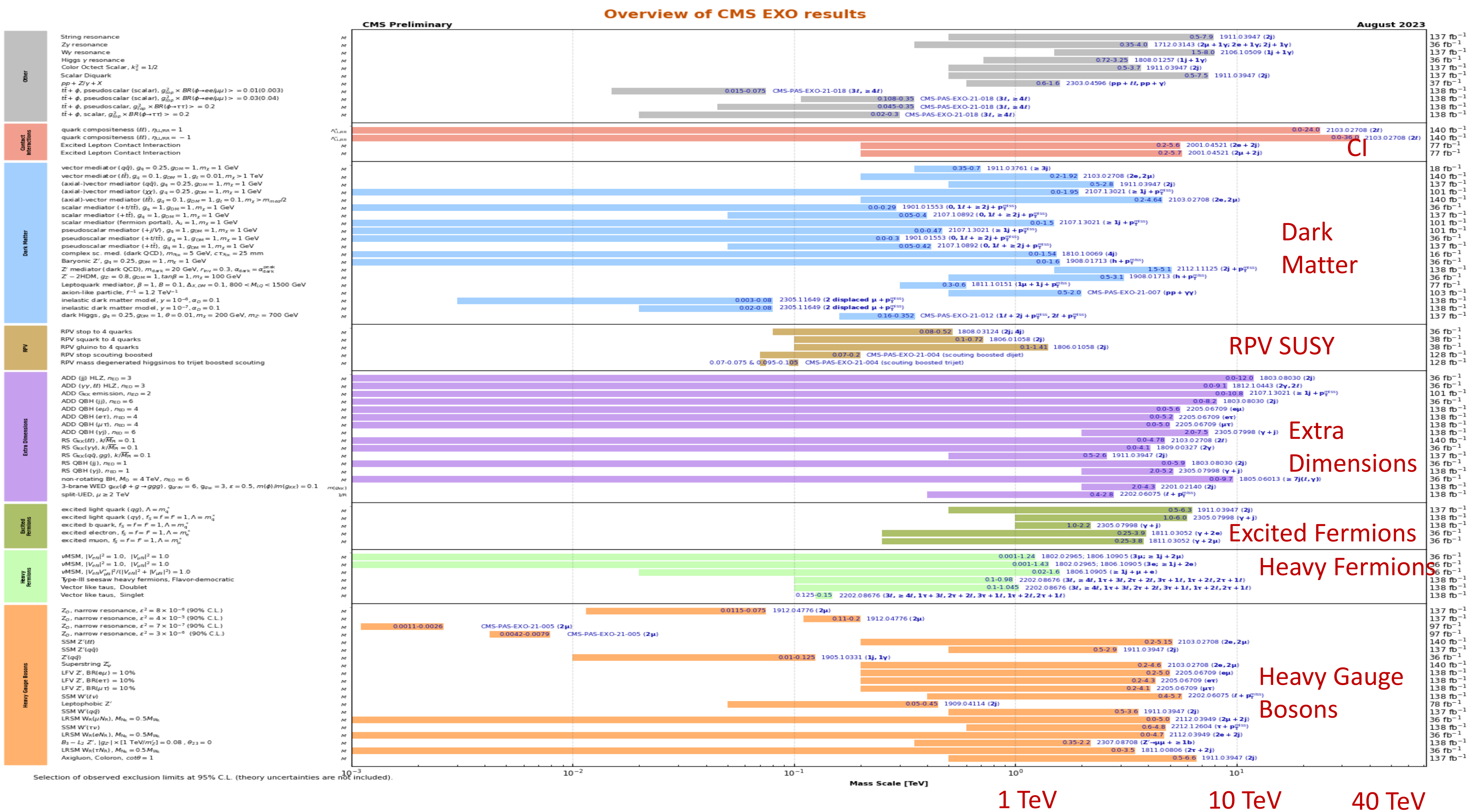


- Leptoquarks ⇒ lepton + jet
- 4^{th} Generation ⇒ leptons/jets, dilepton



Direct Search for BSM: Conventional Signals

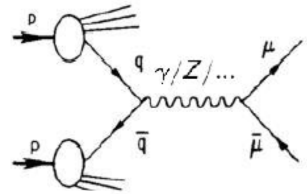
plots are updated for Summer 2023 Conferences



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

Searches for Heavy Resonances

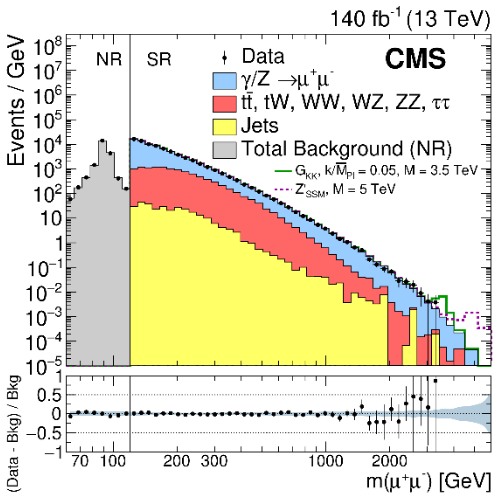
New Physics ($Z'/Z_{KK}/G_{KK}$) contributions to SM processes

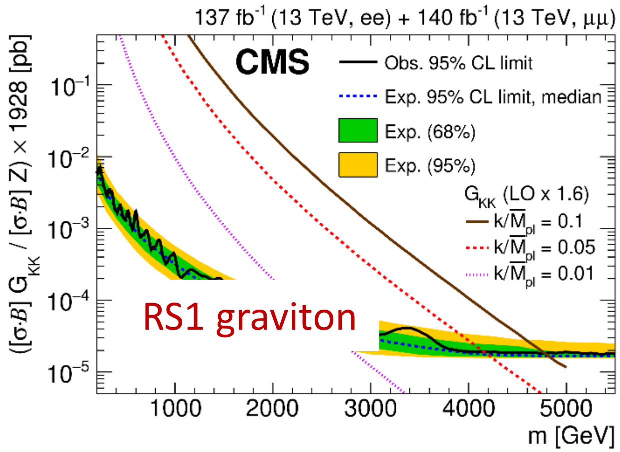


$$R_\sigma = \frac{\sigma(pp \to Z' + X \to l^+l^- + X)}{\sigma(pp \to Z^0 + X \to l^+l^- + X)}$$

Dileptons, full RUN2 data

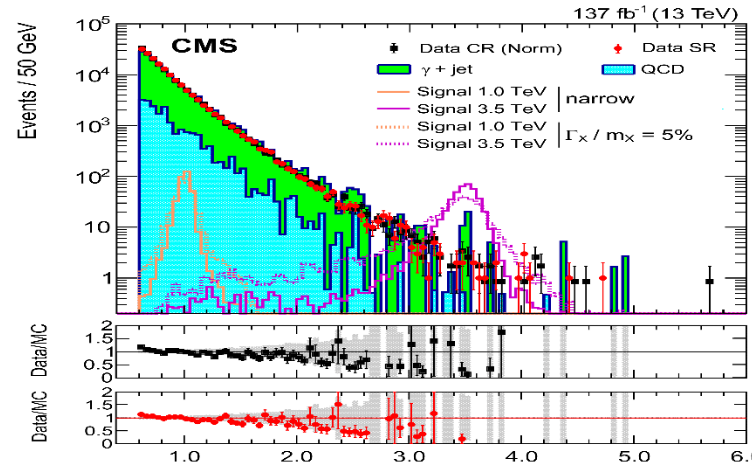
JHEP 07 (2021) 208

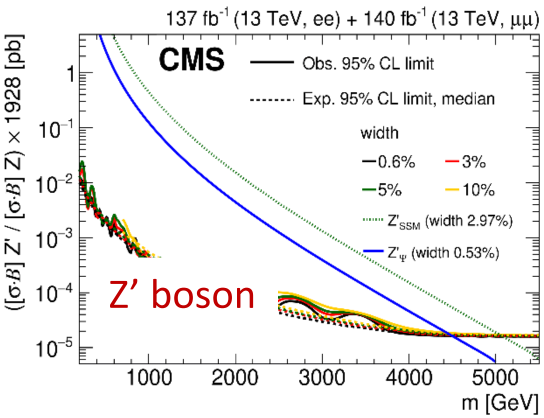


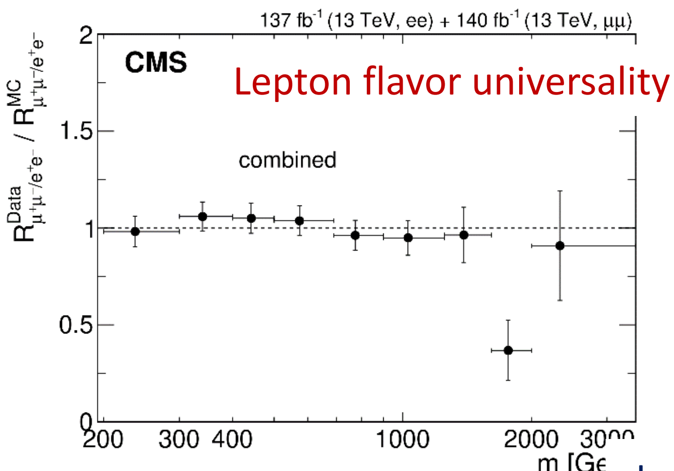


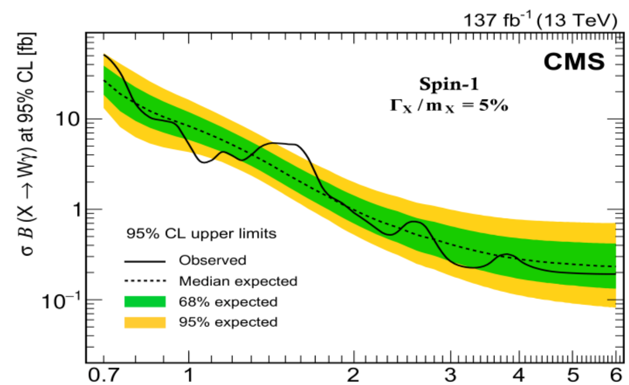
Wγ, full RUN2 data

PLB 826 (2022) 136888









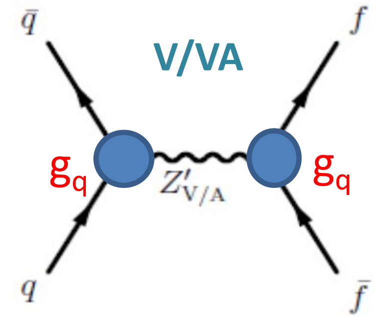
see talk by A. Lanyov

benchmark heavy scalar (vector) triplet bosons with masses between 0.75 (1.15) and 1.40 (1.36) TeV are excluded at 95% CL

Example of Dark Matter Searches in Dijets+Dileptons

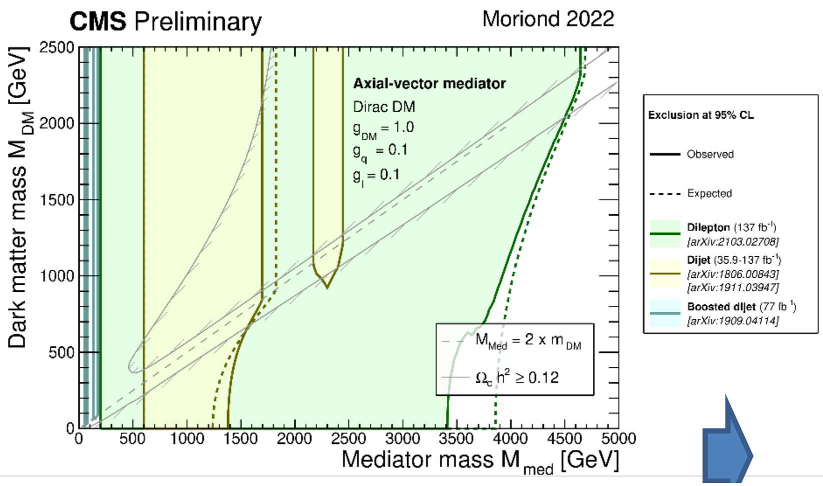
We consider a model that assumes the existence of a single DM particle that interacts with the SM particles through a spin-1 mediator, which can be either a vector or axial-vector boson.

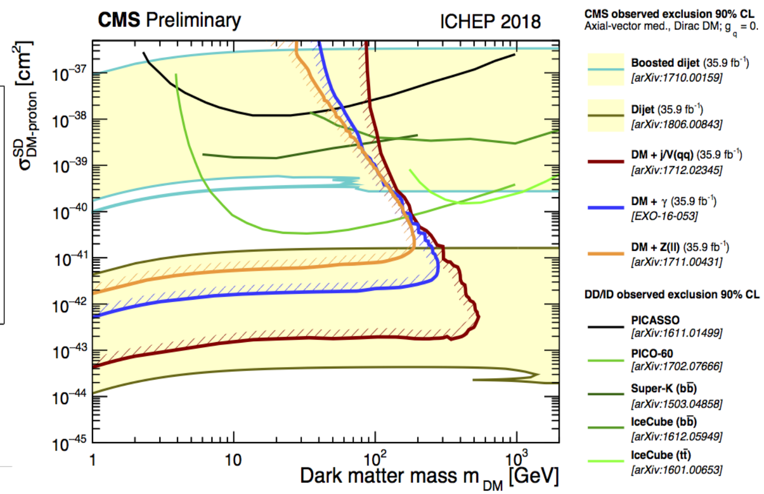
- vector mediator with small couplings to leptons, $g_{DM} = 1.0$, $g_q = 0.1$, $g_l = 0.01$
- axial-vector mediator with equal couplings to quark and leptons: $g_{DM} = 1.0$, $g_q = g_l = 0.1$



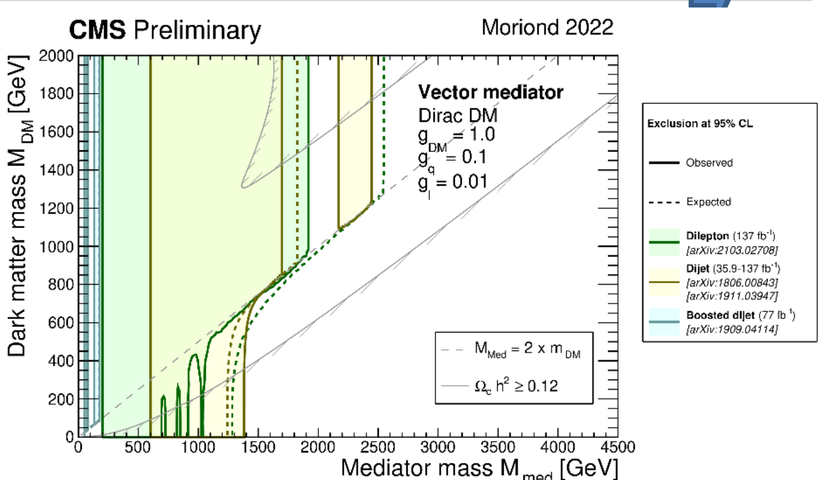
5 parameters:

m_{DM}, m_{Med}, g_{DM}, g_l, g_q

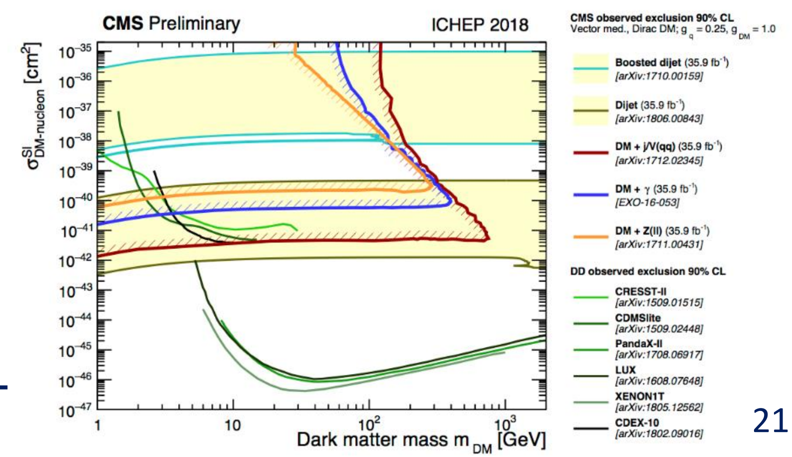




DM-nucleon upper limits on the cross section



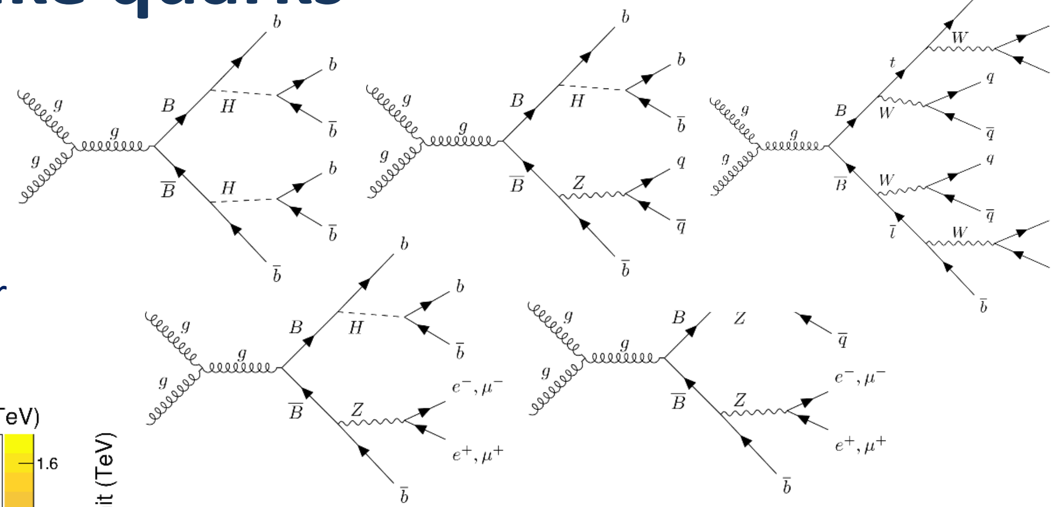
see talk by M. Savina for other scenarios

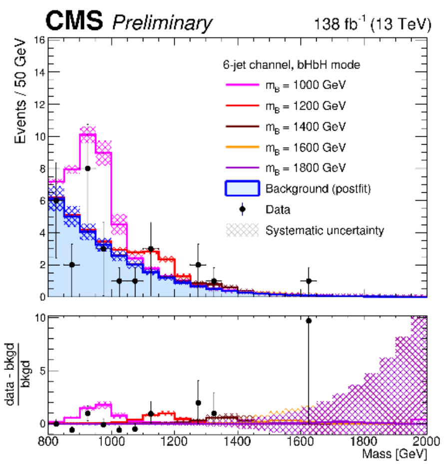


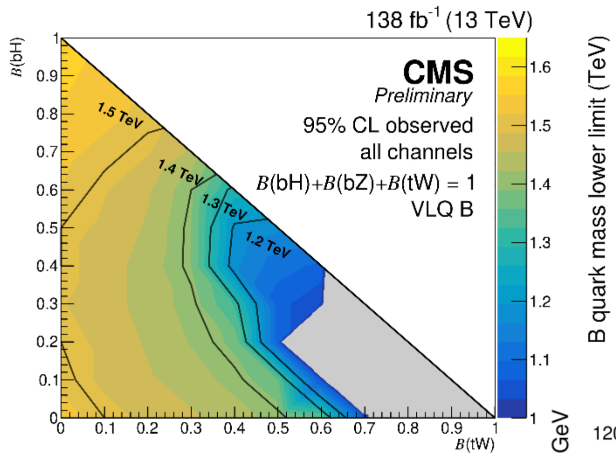
Vector-like quarks

Search for a pair of bottom-type vector-like quarks

- VLQ → b + H/Z, t + W
- both fully hadronic final states and those containing a lepton pair from a Z boson decay
- hadronic decays can be resolved as two distinct jets or merged into a single jet



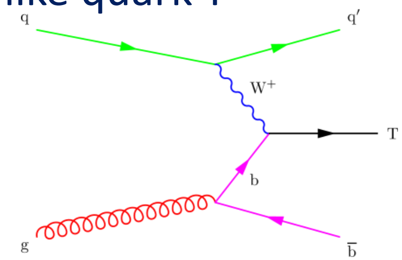




Search for a single vector-like quark T

- T VLQ → t + H/W
- all-hadronic final state

[CMS-PAS-B2G-19-001]

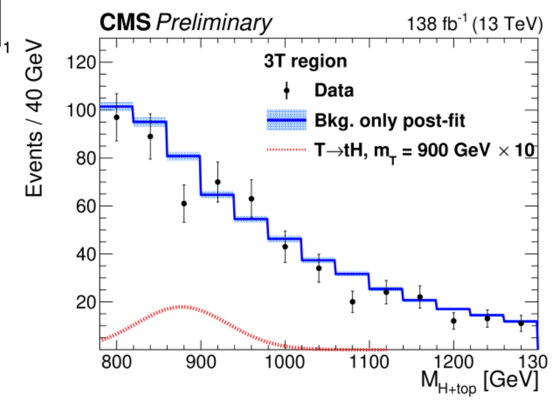


The limits on the B VLQ mass have been increased

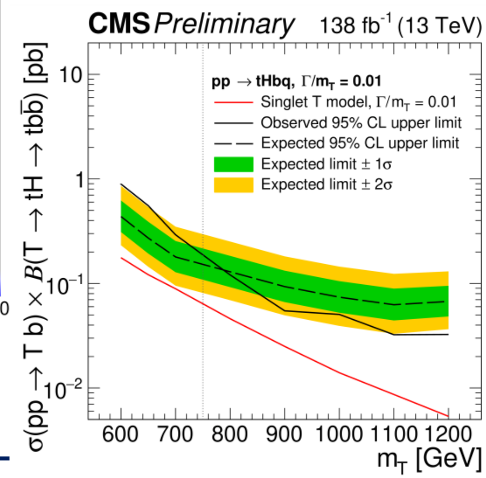
- 1570 GeV for 100% B → bH
- 1540 GeV for 100% B → bZ

For many cases, they exceed by 100 GeV or more those of previous results.

[CMS-PAS-B2G-20-014]

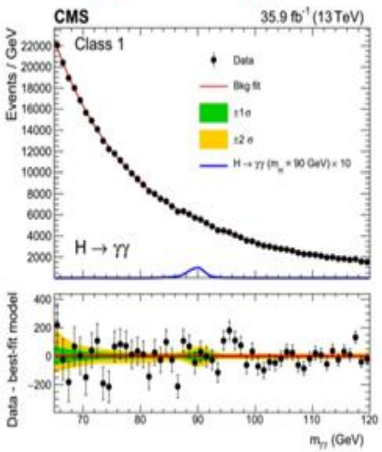


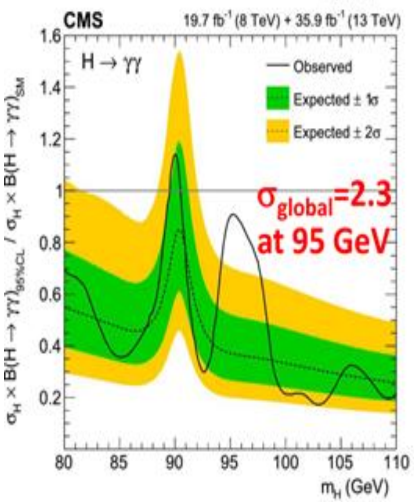
For m_T from 600 to 1200 GeV, the upper limits on the production cross section range from 1260 to 68 fb.



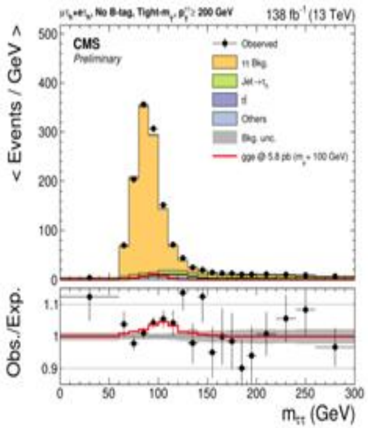
Some Selected Recent Excitements from LHC

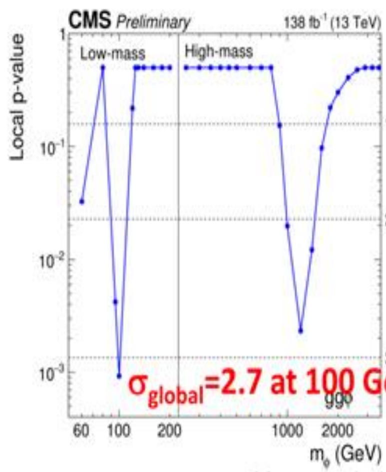
- Light X→γγ





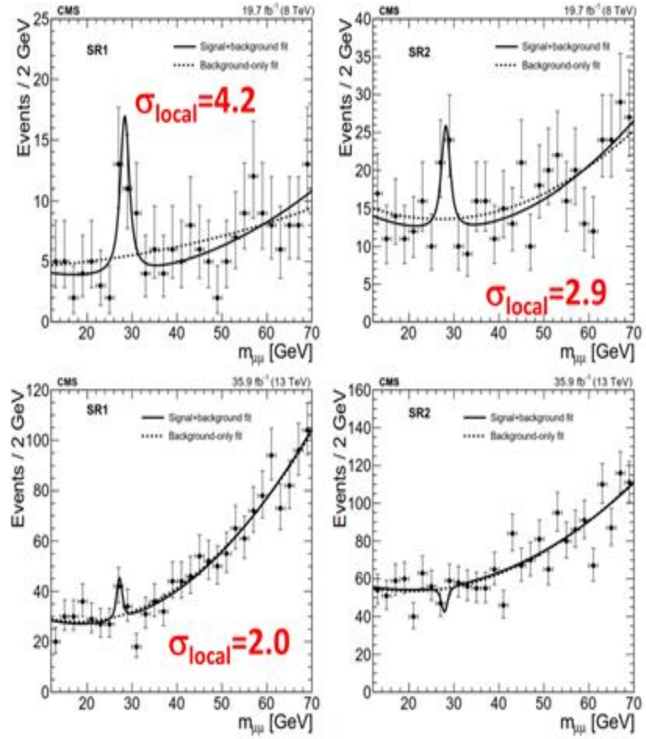
- Light X→ττ

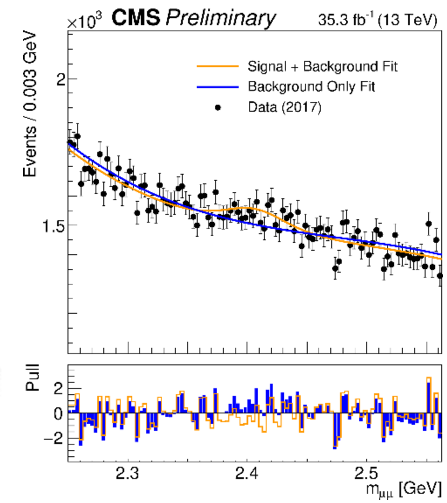


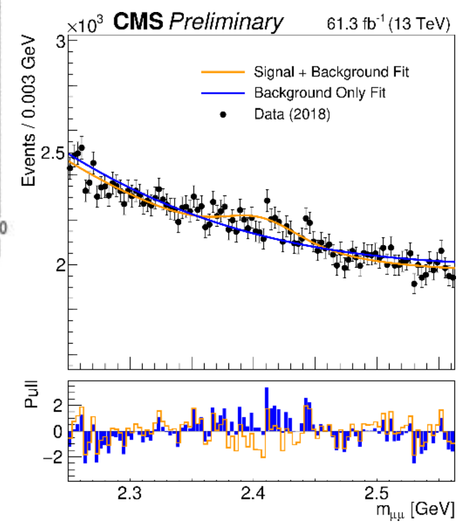


σ_{global}=2.7 at 100 GeV, 2.3 at 95 GeV

- Light X→μμ







A. Nikitenko

The Physics of the Dimuons at the LHC

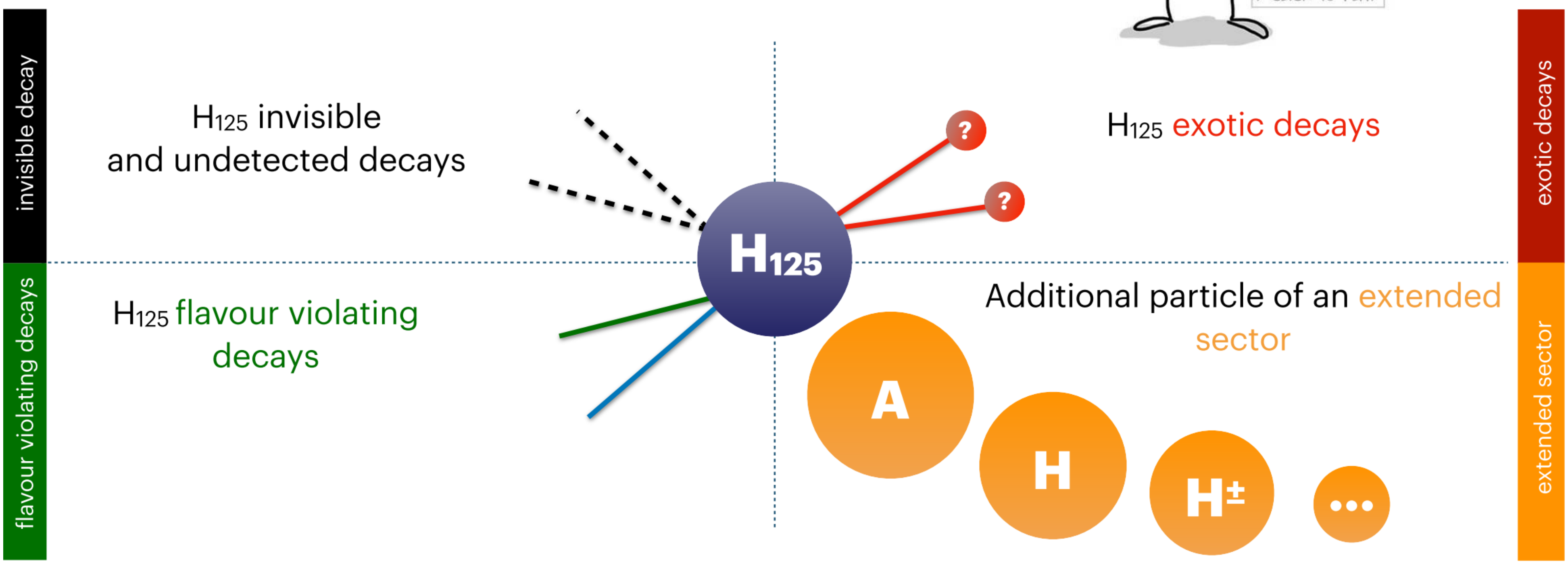
Dubna, Russia, 23-24 June, 2022

σ_{local}=3.2@2.41 GeV

CMS-PAS-EXO-21-005

RUN3 is a perfect judge for these challenges!

Higgs Boson as a Tool to Search for the New Physics

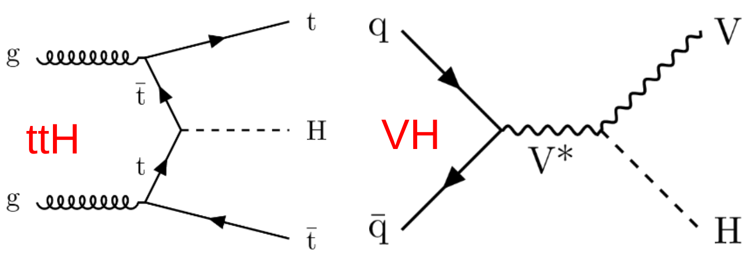


Higgs Invisible Decays

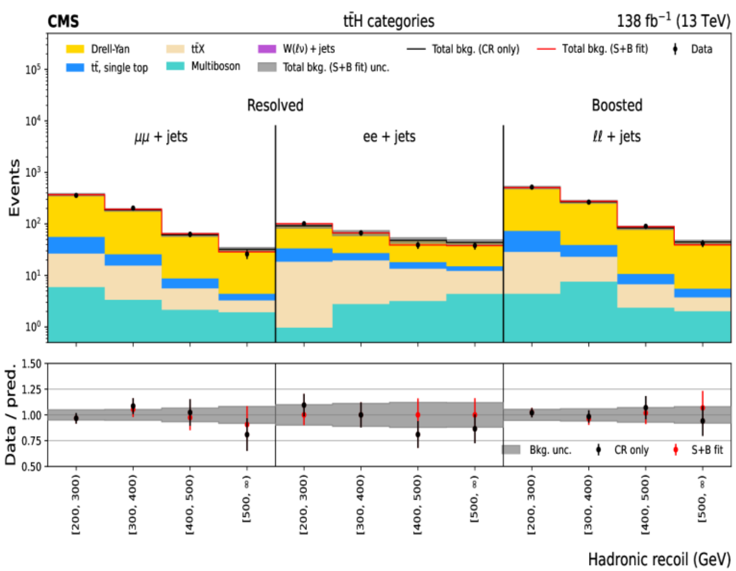
The expected in SM h_{125} the branching fraction $h_{125} \rightarrow$ inv $\mathcal{B}(h_{125} \rightarrow ZZ^* \rightarrow 4\nu) = 0.12\%$

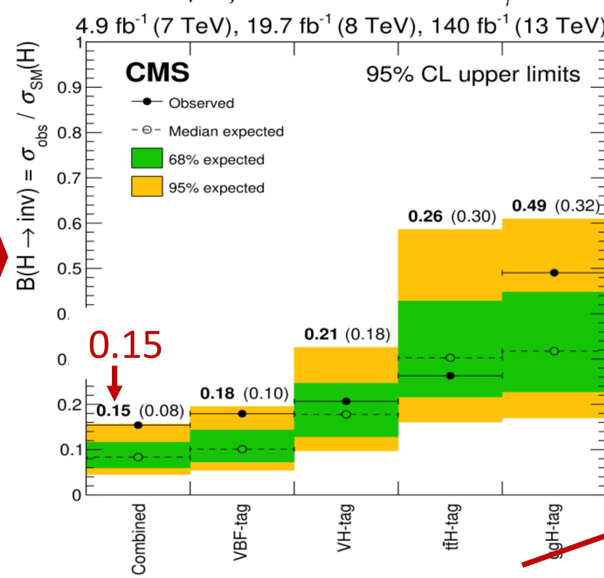
Several BSM scenario anomalous and sizeable values, $\mathcal{B}$ is significantly enhanced

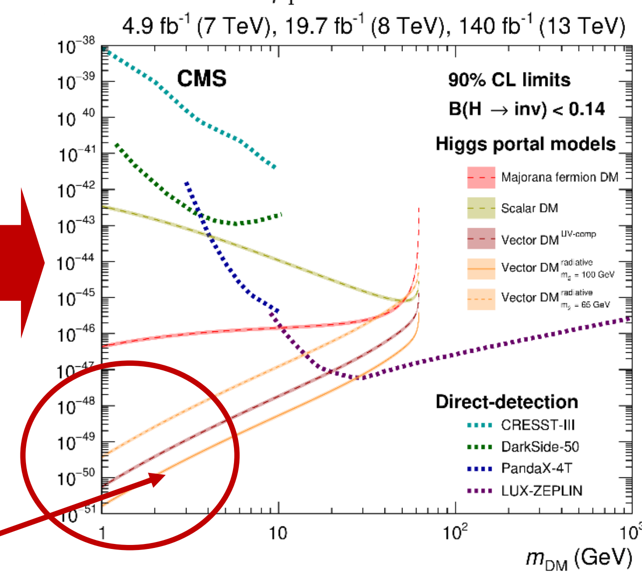
- a simple extension of the SM to provide a Dark Matter (DM) candidate and are able to predict the observed relic DM density vis s-channel $\chi\chi \rightarrow f\bar{f}$ CMS-HIG-21-007 arXiv:2303.01214



Control region	Category	n_{object} reqs.	Mass reqs. (GeV)	p_T reqs. (GeV)
μ + jets	$t\bar{t}H$ VH	$n_\mu = 1$	$50 < m_T^\mu < 110$	$p_{T,1}^\mu > 20$
e + jets	$t\bar{t}H$ VH	$n_e = 1$	$50 < m_T^e < 110$	$p_{T,1}^e > 40$
$\mu\mu$ + jets	$t\bar{t}H$ VH	$n_\mu = 2$	$75 < m_{\mu\mu} < 105$ $60 < m_{\mu\mu} < 120$	$p_{T,1}^\mu > 20$, $p_{T,2}^\mu > 10$
ee + jets	$t\bar{t}H$ VH	$n_e = 2$	$75 < m_{ee} < 105$ $60 < m_{ee} < 120$	$p_{T,1}^e > 40$, $p_{T,2}^e > 10$
γ + jets	VH	$n_\gamma = 1$	—	$p_T^\gamma > 230$







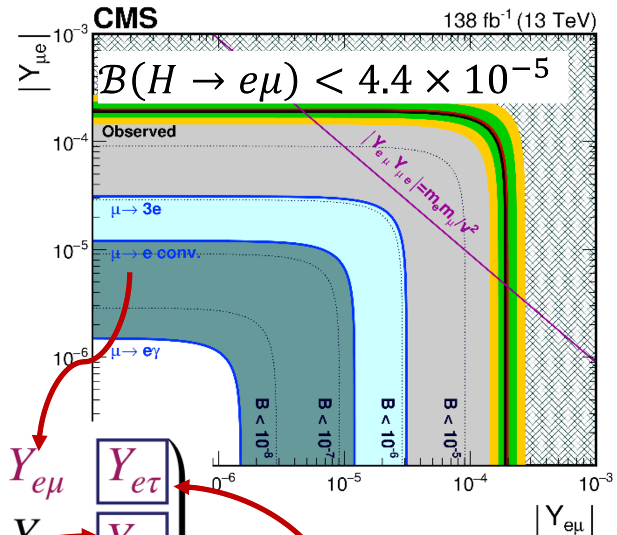
Low-mass region in the spin-independent dark-matter-nucleon scattering cross section

Lepton Flavour Violation Higgs Decays (1)

CMS-HIG-22-002

The decays $H \to e\mu/\mu\tau/e\tau$ trough the LFV Yukawa couplings arising in two Higgs doublet models, extra dimensions, models with flavor symmetries, models of compositeness, etc

- to verify h_{125} hypothesis, $m_{ll} = m_{h_{125}}$ (type 1)
- to search for new higgs states, $m_{ll} \neq m_{h_{125}} \Rightarrow$ broad invariant mass region (type 2)

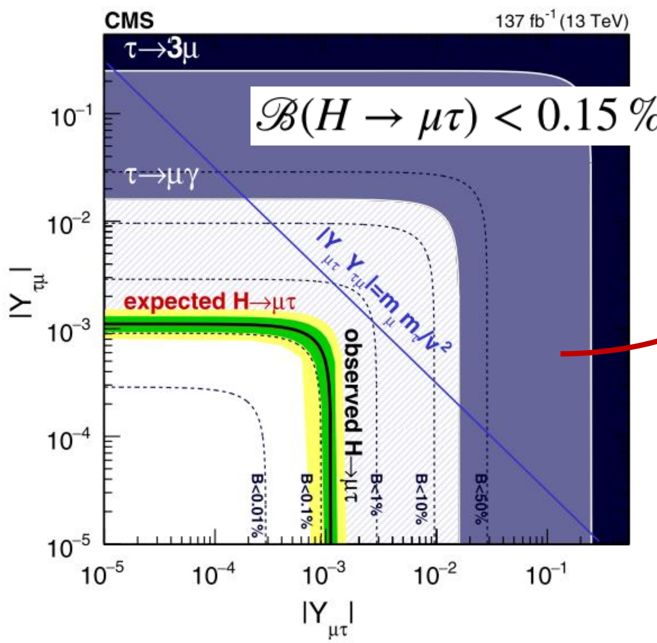


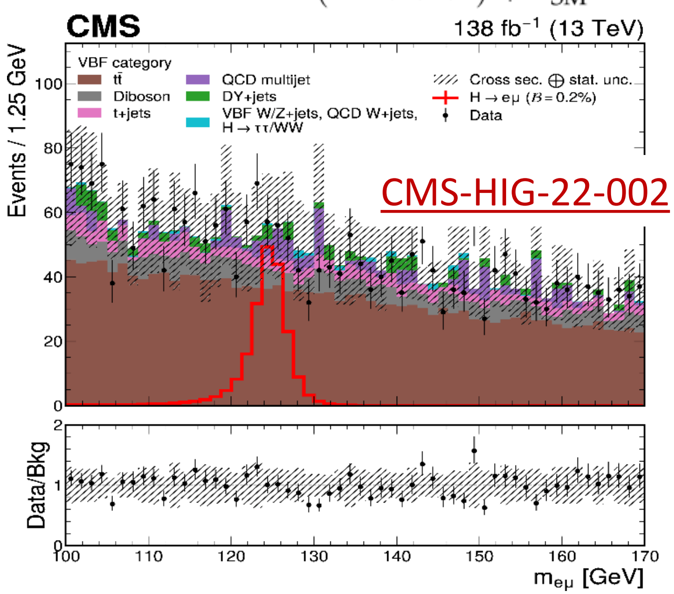
$$\begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ & Y_{\mu\mu} & Y_{\mu\tau} \\ & & Y_{\tau\tau} \end{pmatrix}$$

type 1, ggH, VBF

$$\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{m_\mathrm{H}}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right)$$

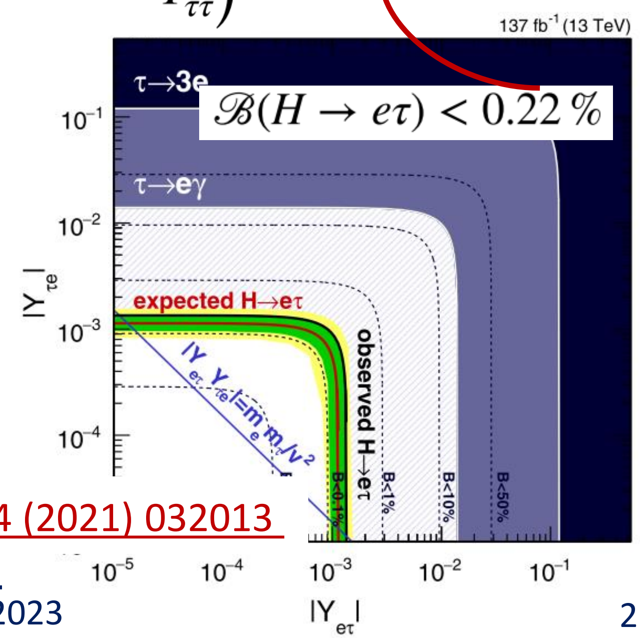
$$\mathcal{B}(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta)}{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) + \Gamma_\mathrm{SM}}$$





CMS-HIG-22-002

- $e\mu$, $e\tau_h$, $e\tau_\mu$, $\mu\tau_h$, $\mu\tau_e$
- jet categories: 0-3j (ggH), 0-2j (VBF),
- $m_{ll} \neq m_{h_{125}} \Rightarrow$ broad invariant mass region (type 2)
- BDT discriminant signal

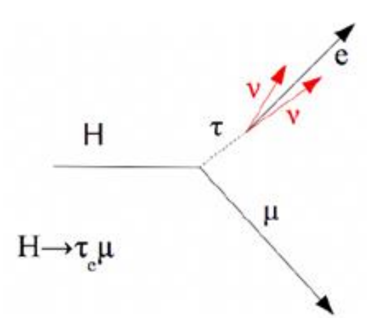


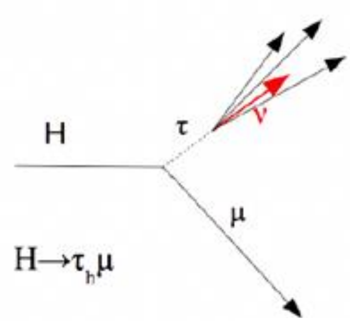
PRD 104 (2021) 032013

Lepton Flavour Violation Higgs Decays (2)

The first direct search for LFV $H \rightarrow \mu\tau/e\tau$ decays for an Extra Higgs mass in the range $200\ GeV < m_H <$ 900 GeV (neutral heavy Higgs boson)

type 2, ggH, τ lepton decay products are highly boosted

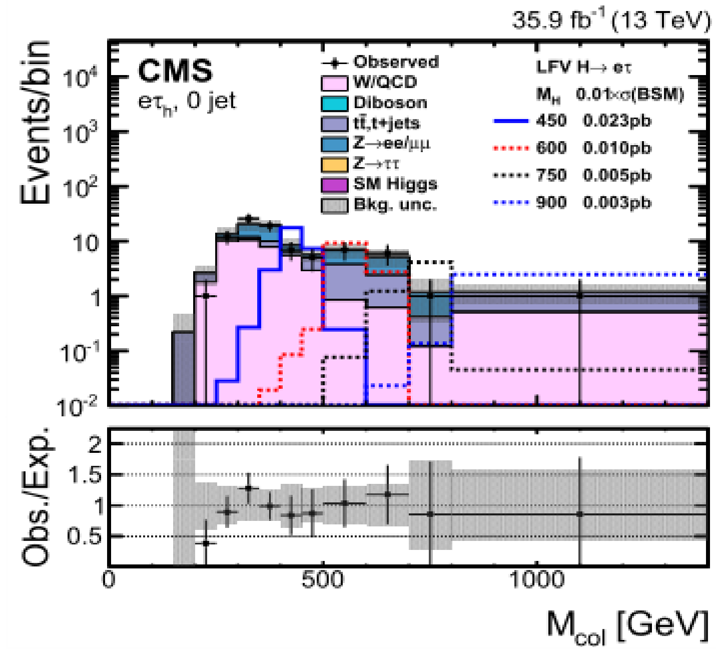


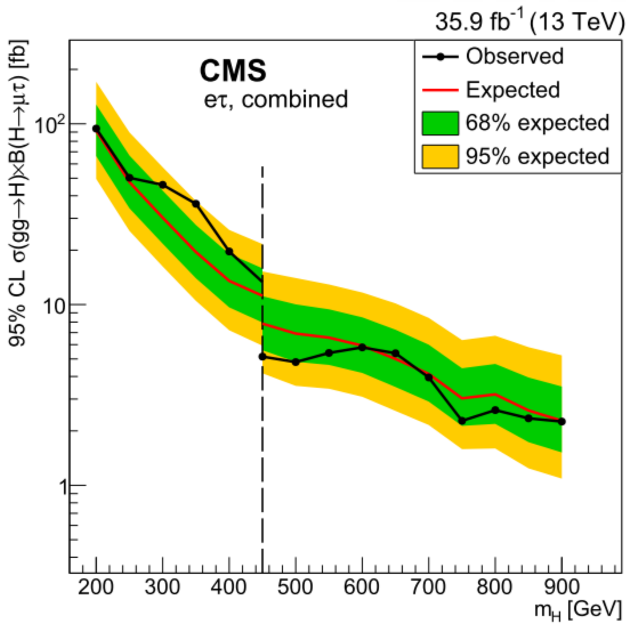


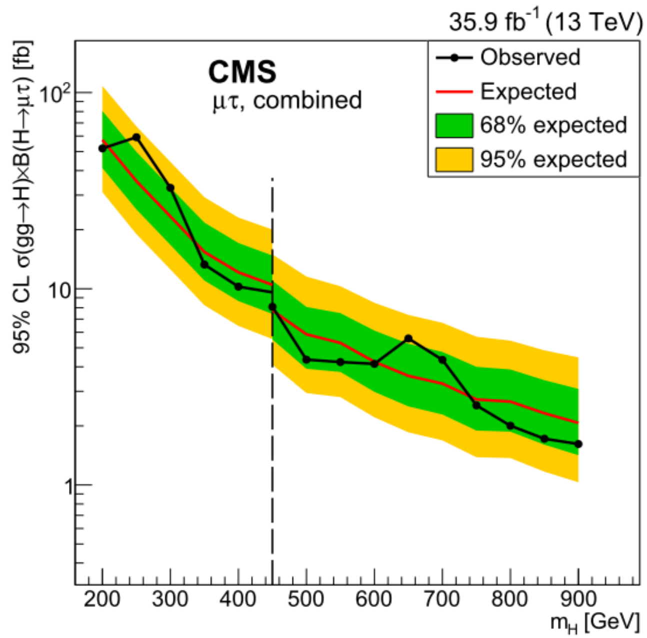
$$x_\tau^{\rm vis} = p_{\rm T}^{\vec{\tau}^{\rm vis}} / (p_{\rm T}^{\vec{\tau}^{\rm vis}} + p_{\rm T}^{\nu,\rm est})$$

$$M_{\rm col} = M_{\rm vis}/\sqrt{x_\tau^{\rm vis}}$$

$\varepsilon_\tau \approx 70\%$ (DNN)







The observed (expected) upper limits (95% CL) is

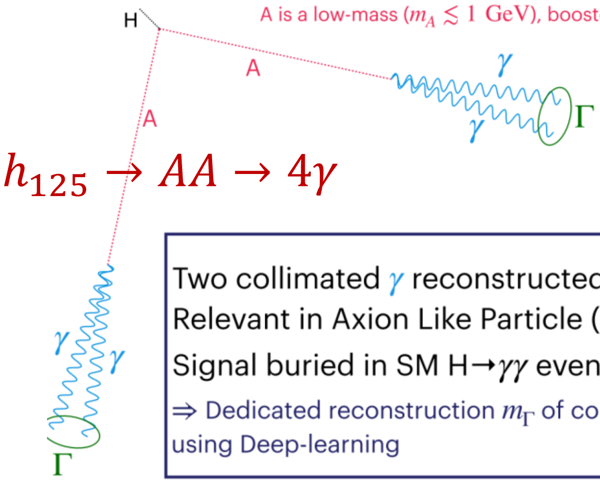
μτ: 51.9 (57.4) fb to 1.6 (2.1) fb

eτ: 94.1 (91.6) fb to 2.3 (2.3) fb

JHEP 03 (2020) 103

Searches for Low-Mass BSM Higgses/DM in h_{125} Decays

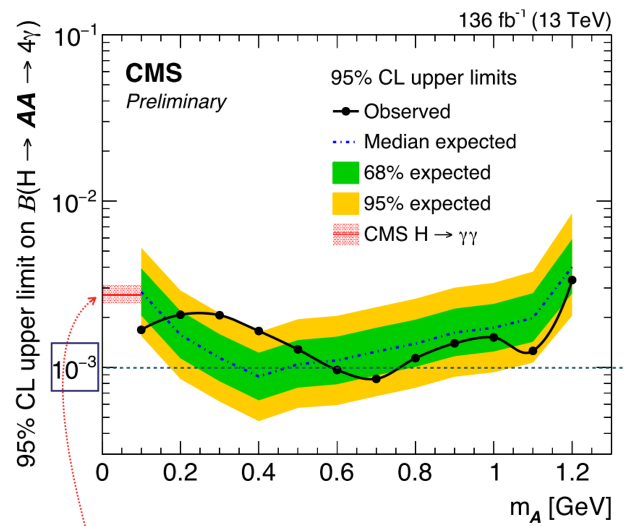
If $m_H > 2m_X$, some BSM scenarios allow Higgs bosons decays via one or two hypothetical on-shell new (pseudo)scalar(s) decaying to a pair of SM particles.



$h_{125} \to AA \to 4\gamma$

The topology

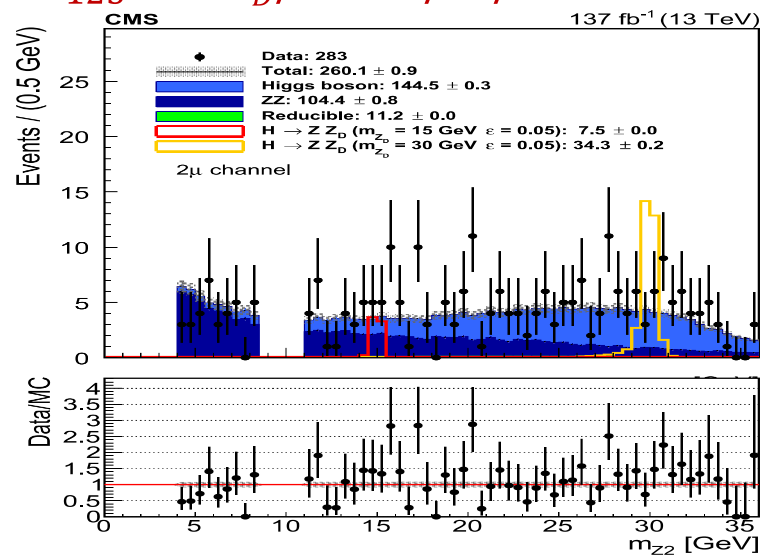
Two collimated γ reconstructed as single Γ
Relevant in Axion Like Particle (ALP) model
Signal buried in SM H→$\gamma\gamma$ events
⇒ Dedicated reconstruction m_Γ of collimated di-γ using Deep-learning

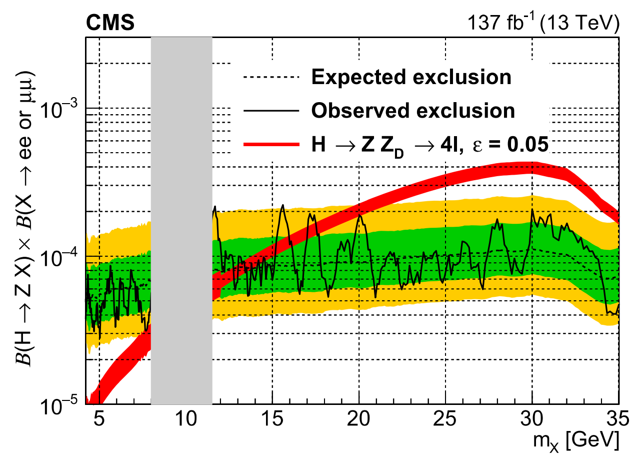


Upper bound provided by SM $H \to \gamma\gamma$

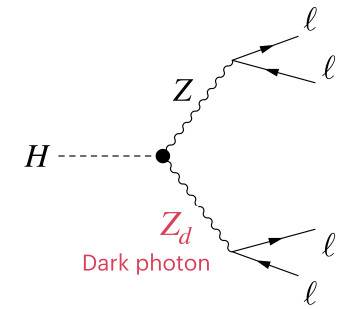
CMS PAS HIG-21-016

$h_{125} \to ZZ_D/ZDZD/ss/aa$

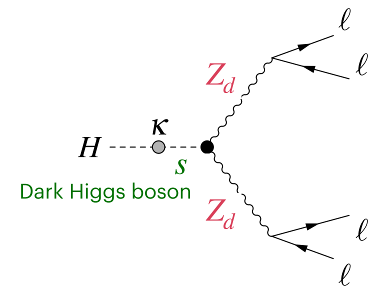




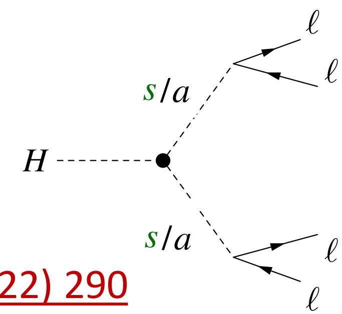
EPJ C 82 (2022) 290



U(1) gauge theory mixes with SM hypercharge



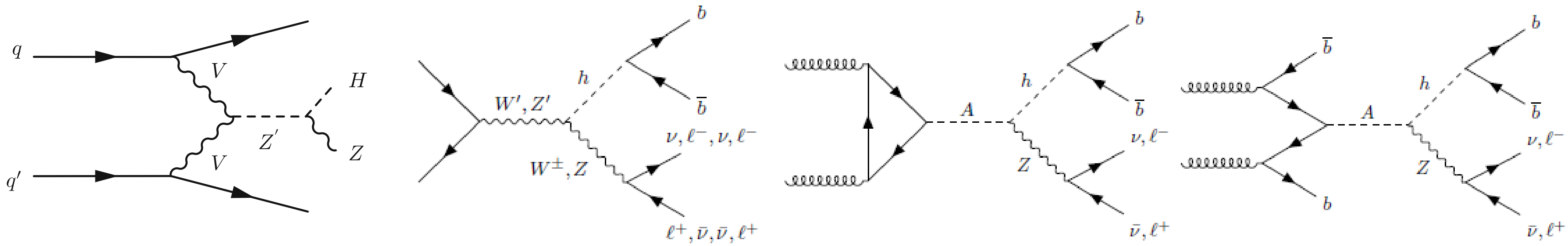
U (1) is broken by a hidden-sector Higgs mechanism



Extended Higgs sector ex. 2HDM, 2HDM+

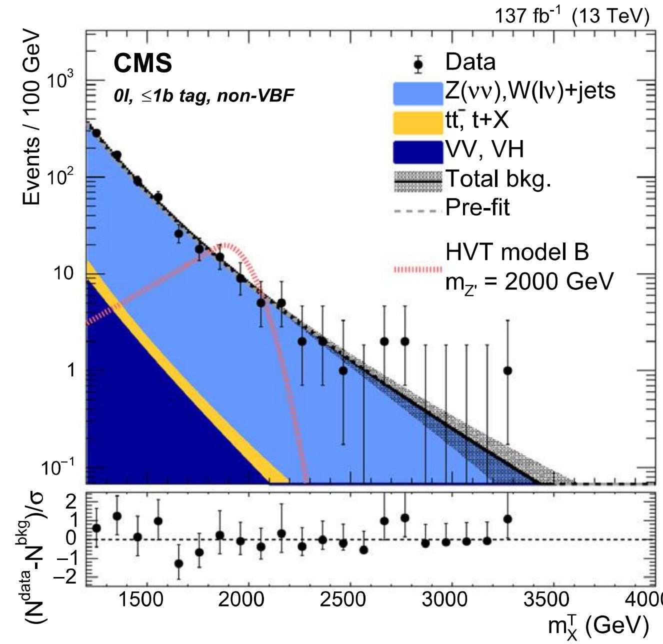
BSM Higgs/V' in Decays into h_{125}(+X)

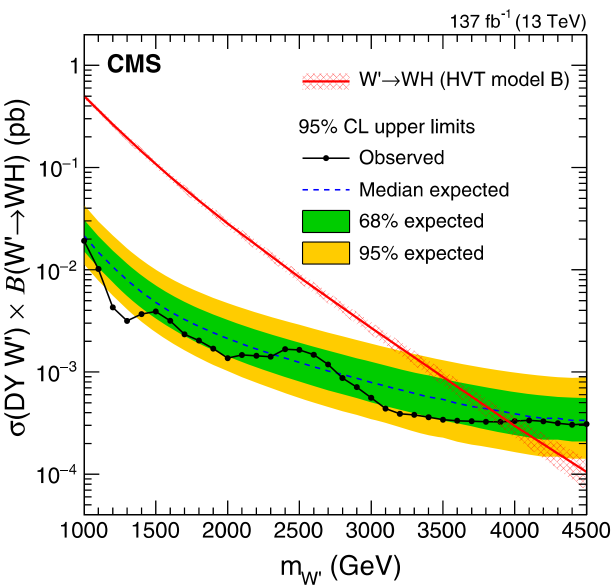
If $m_H < 2m_X$, the finals states are possible with h_{125} and SM gauge bosons

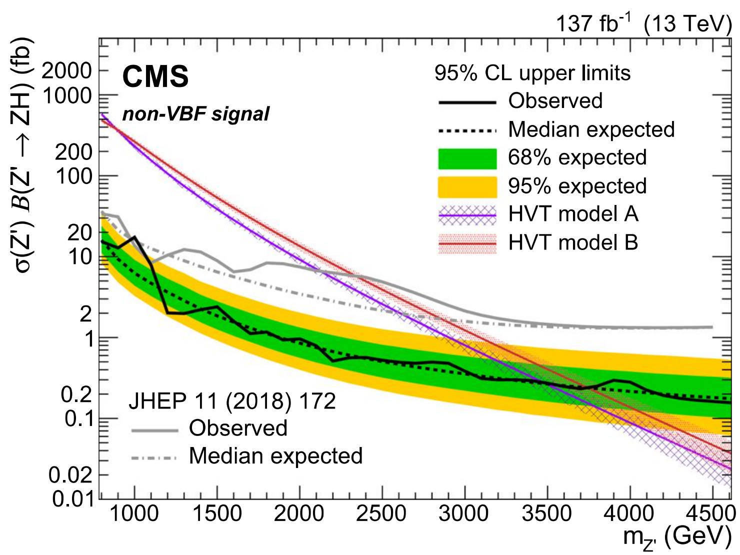


Strategy

- 0-, 1-, and 2-lepton channels
- b-tag jet categories (merged and resolved)
- Fit either $m_{T,VH}$ or m_{VH}







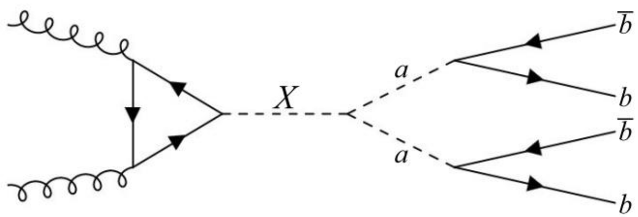
PRD 105 (2022) 032008

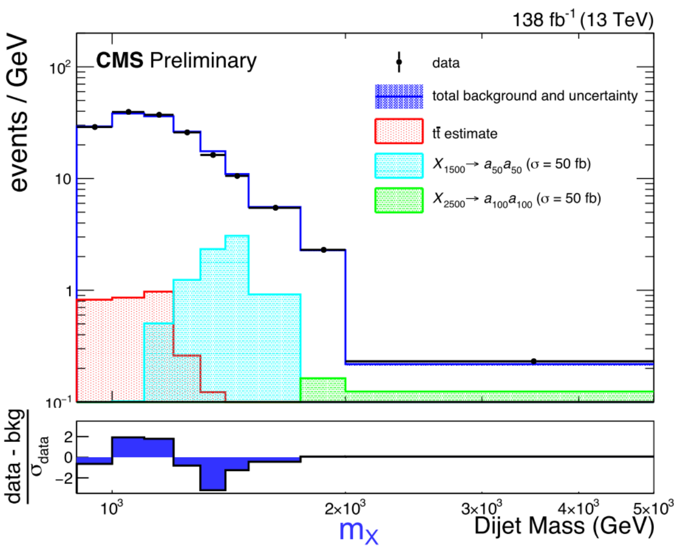
EPJ C 81 (2021) 688

BSM Higgs/X in Decays into BSM Particles

$X \rightarrow aa \rightarrow 4b$

CMS-PAS-B2G-20-003





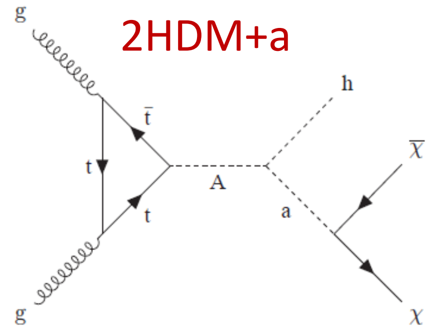
The analysis is restricted to the mass ranges m_a from 25 to 100 GeV and m_X from 1 to 3 TeV.

$A \rightarrow a(\rightarrow \chi\bar{\chi})h_{125} \rightarrow MET + h_{125}$

EPJC 79 (2019) 280

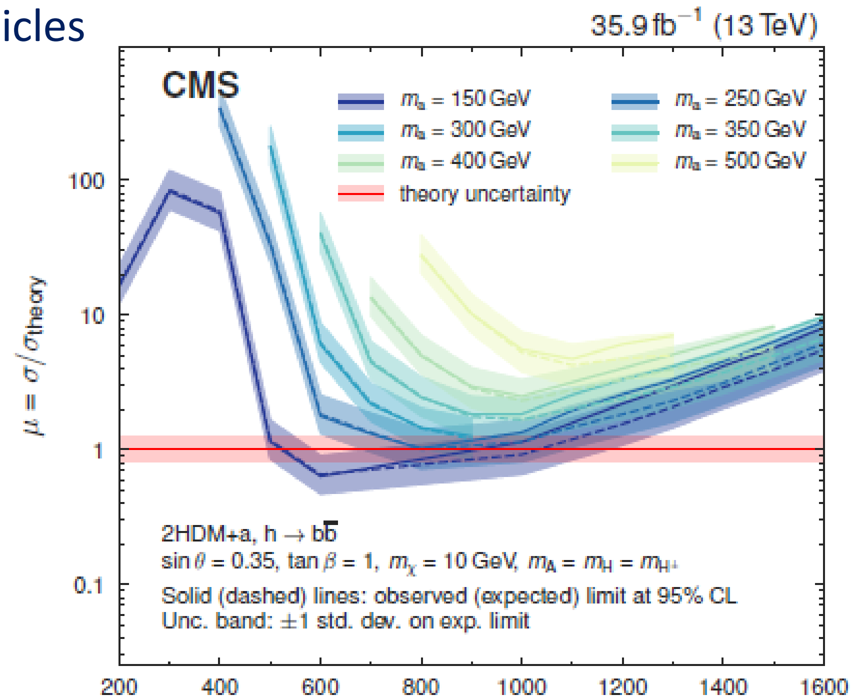
JHEP 03 (2020) 25

2HDM+a



h→ $b\bar{b}$, new pseudoscalar in invisible mode

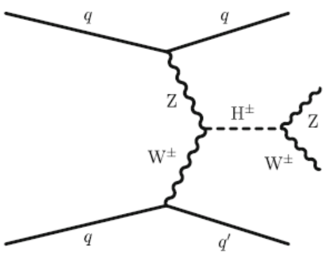
Free parameters: m_A, m_H, m_S, mixing angle between a and A $sin\theta$, VEV ratio for two higgs doublets $tan\beta$, couplings to SM and DM particles

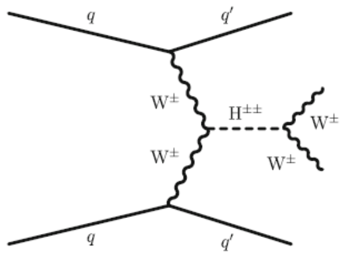


BSM Higgs/X in Decays into SM Particles

$H^{\pm} \rightarrow W^{\pm}Z$, $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$

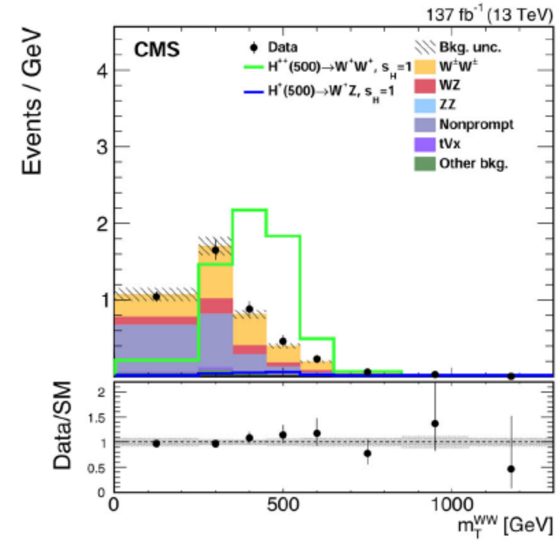
VBF tag, Charged Higgs boson mass explored: 200 – 3000 GeV

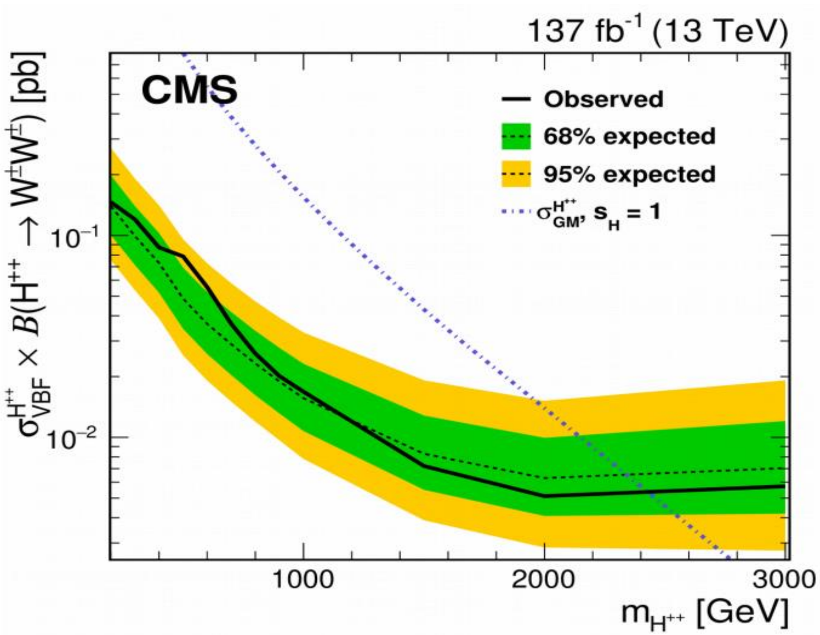


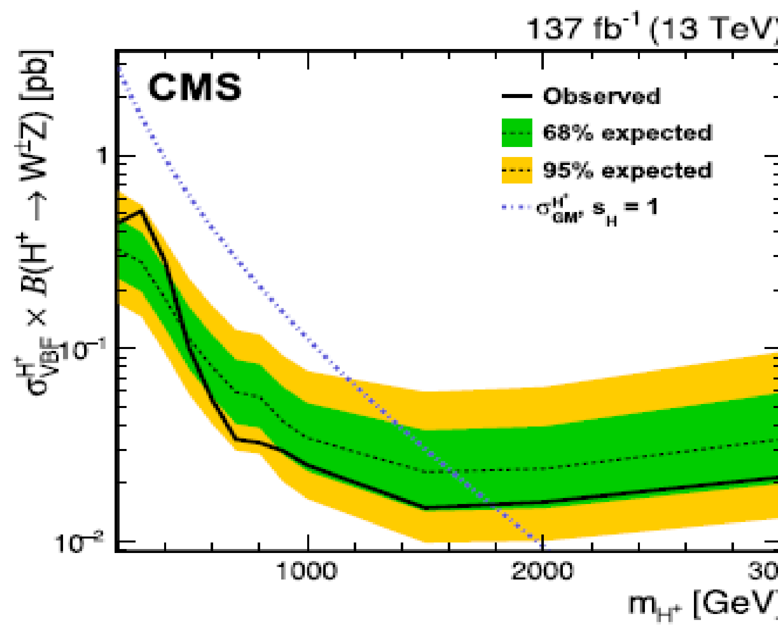


EPJC 81 (2021) 723

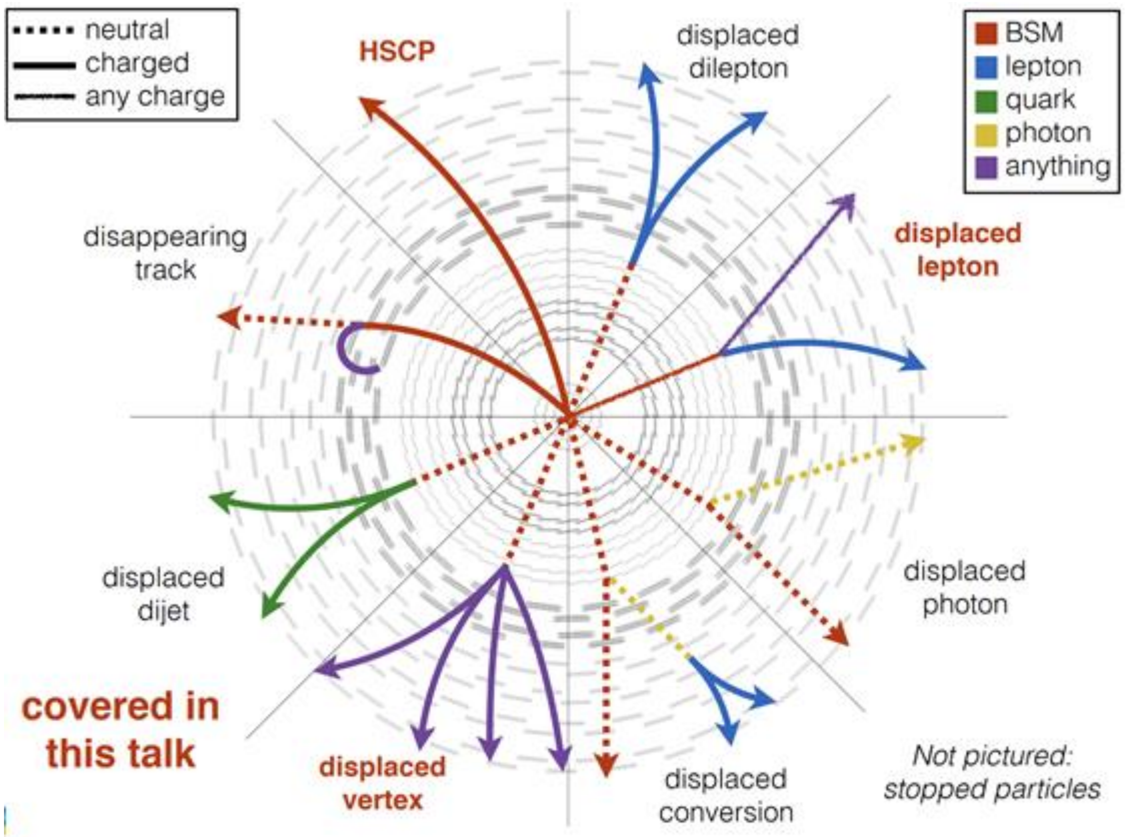
$$m_{\mathrm{T}}^{\mathrm{VV}} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$$

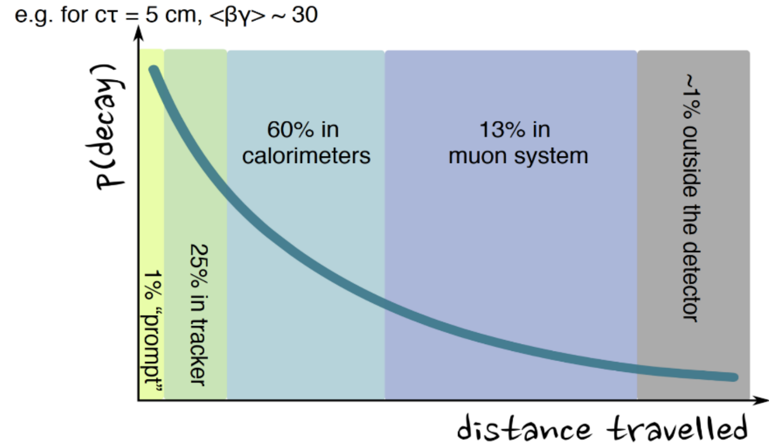






Direct Search for BSM: LLP Non-conventional Signals





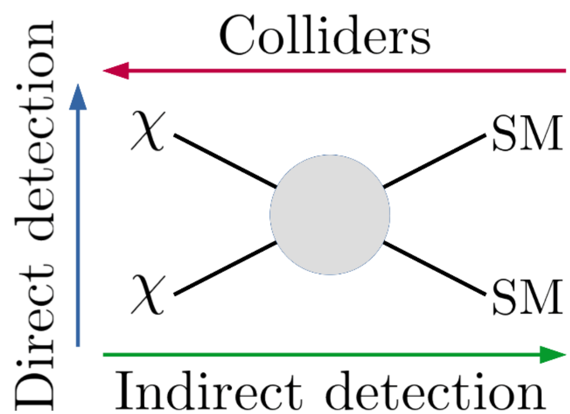
LLPs may have decay lengths up to several meters, hence traveling through the inner detector layers without leaving any trace

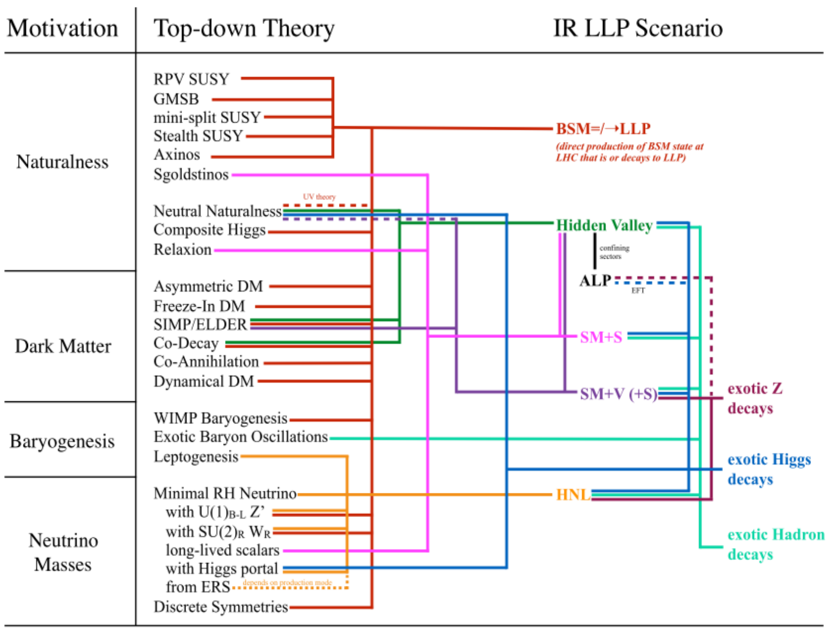
- a proper lifetime $c\tau_0$ is greater than or comparable to the characteristic size of the (sub)detectors
- small $c\tau_0$ that comparable to the inner tracker size, no displaced tracks → "standard" prompt decay
- intermediate $c\tau_0$ → LLP
- very large/infinite large $c\tau_0$ → stable particles, "standard" MET signatures

see talks by A. Apresyan

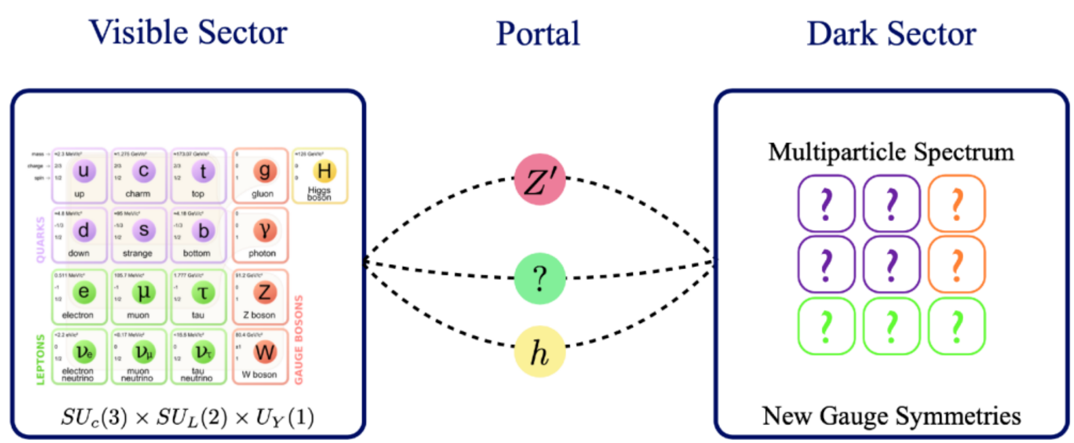
Inelastic Dark Matter at the LHC/LLP

- inelastic dark matter: relic particles that cannot scatter elastically off of nuclei the dark sector
- particles continue traveling for a long time and traverse several meters (Long-Lived Particles) before tunneling back into our visible universe (quarks or leptons)





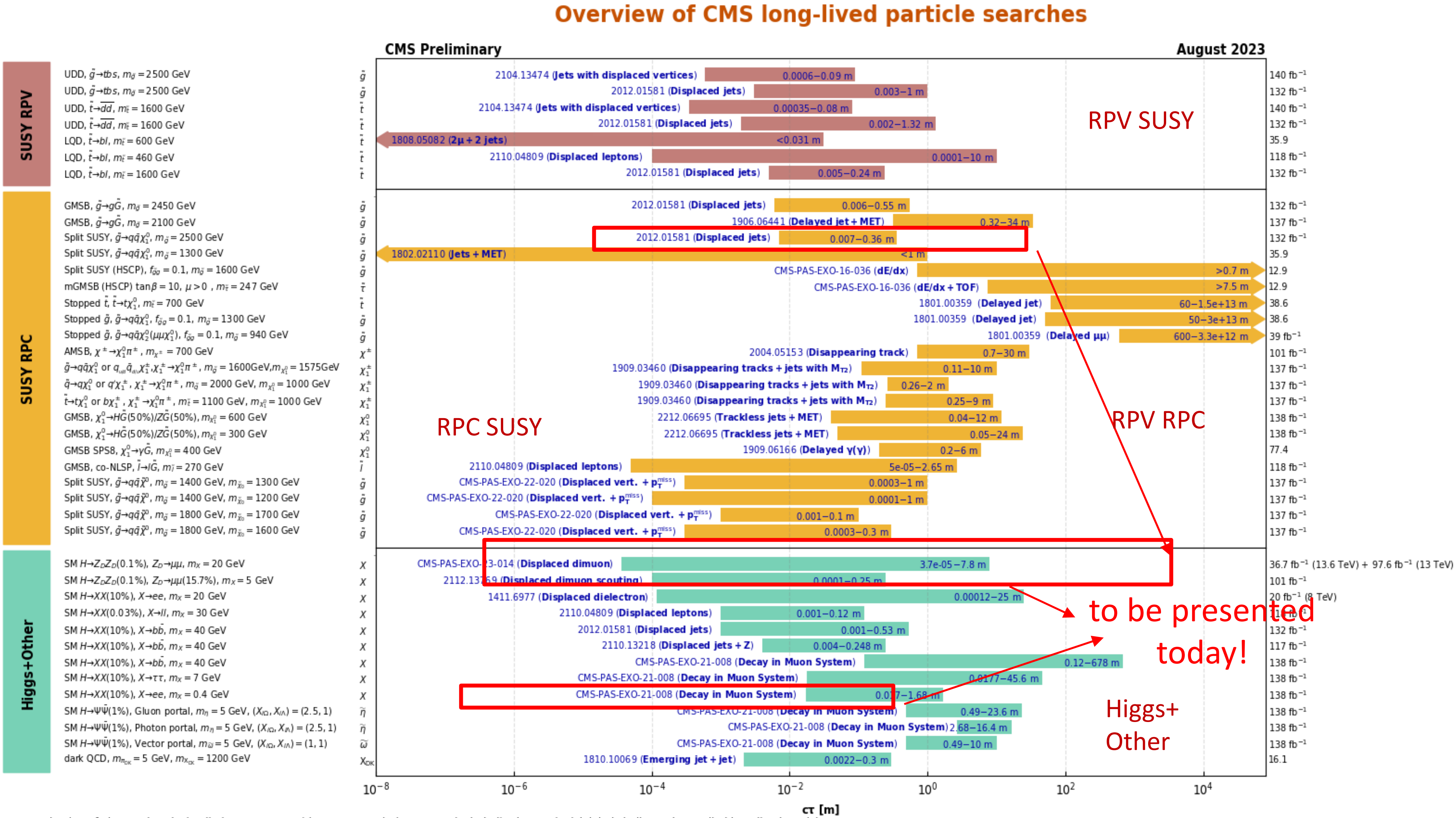
https://arxiv.org/abs/1901.04040



M. Lisanti

Overview of CMS Exotica LLP Searches

plots are updated for Summer 2023 Conferences



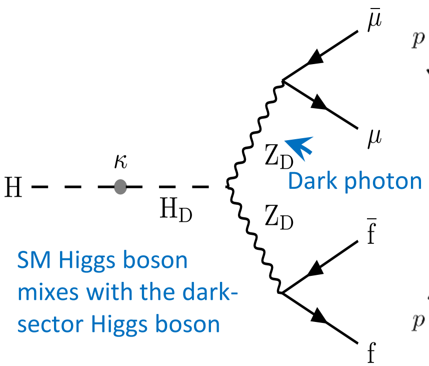
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

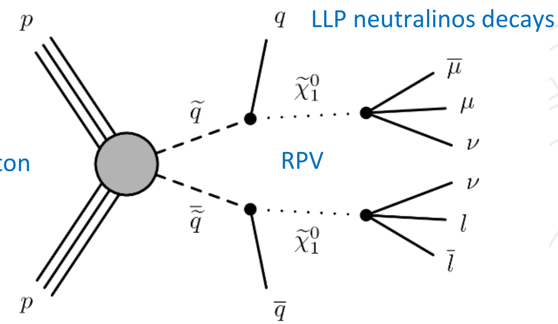
http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/LLP.html

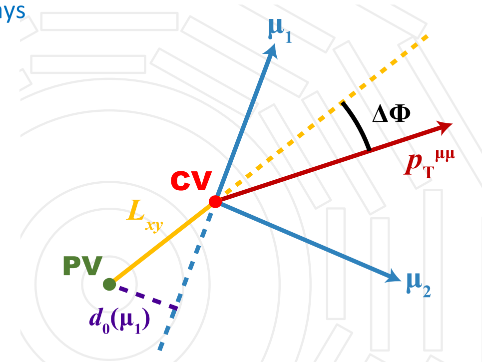
LLP with Displaced Dimuons

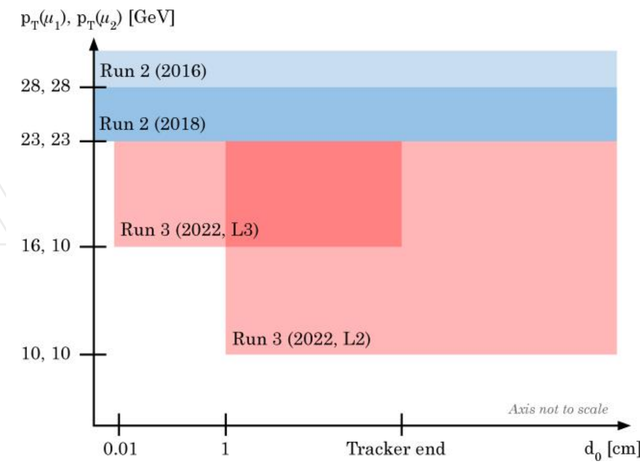
Dark photon and long-lived neutralinos decays

RUN3 data @ 13.6 TeV with 36.7 fb^{-1}





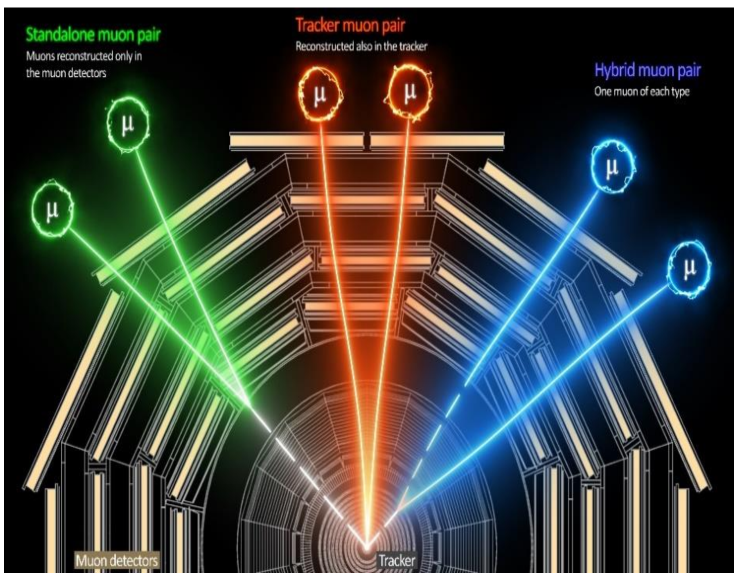


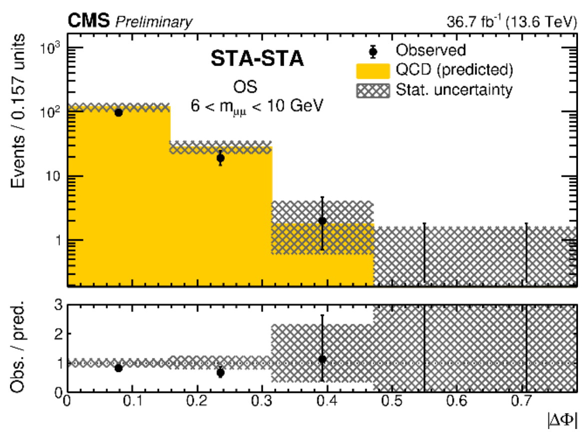


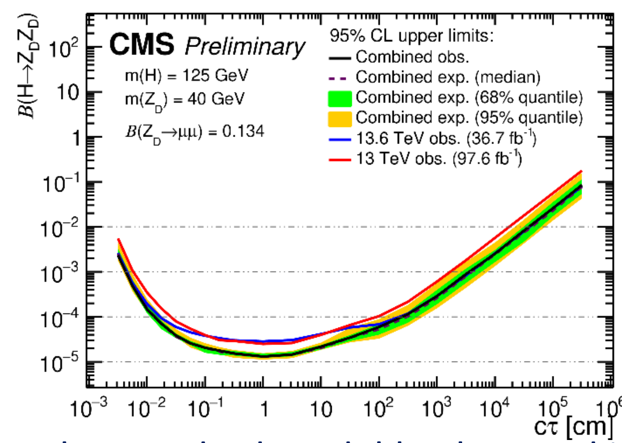
Three categories of events:

STA-STA, TMS-TMS, and STA-TMS

CMS-PAS-EXO-23-014



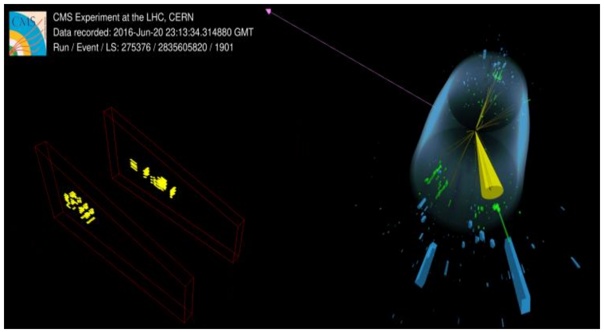




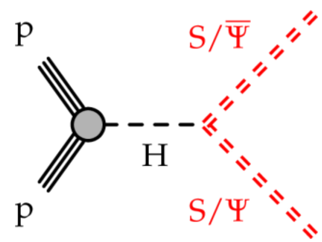
No significant excess of events above the standard model background is observed. The results are interpreted in the frameworks of the hidden Abelian Higgs model, in which the Higgs boson decays to a pair of long-lived dark photons; and of an R- parity violating supersymmetry model

LLP with Displaced Jets (Showers in Muon System)

- the scalar particle (a twin version of the Higgs boson) is likely to be one of the candidates for a messenger role between SM fields (“visible sector”) and DM sector (invisible “hidden sector”)
- they decay into SM particles only when they reach the outermost part of the CMS detector (the muon system)
- a signal is a shower of secondary particles that ionize the gas in the muon detectors (large multiplicity of hits that cluster together)

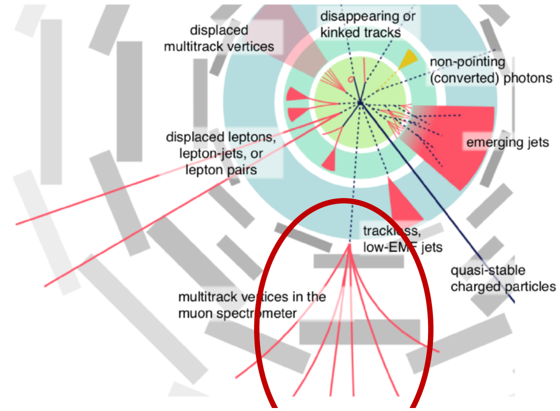


$h \rightarrow SS \rightarrow 4l \text{ or } 4q$

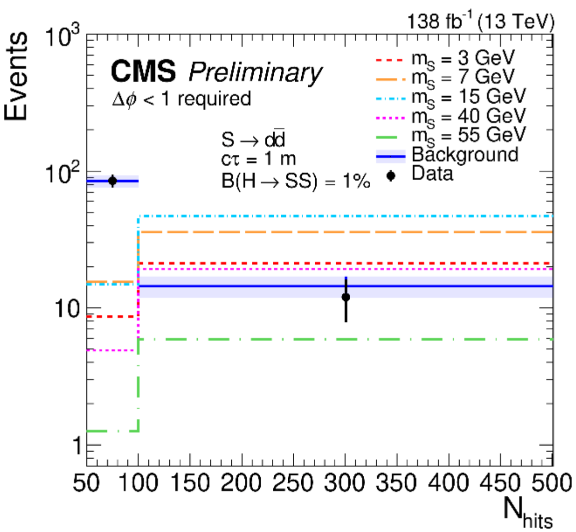


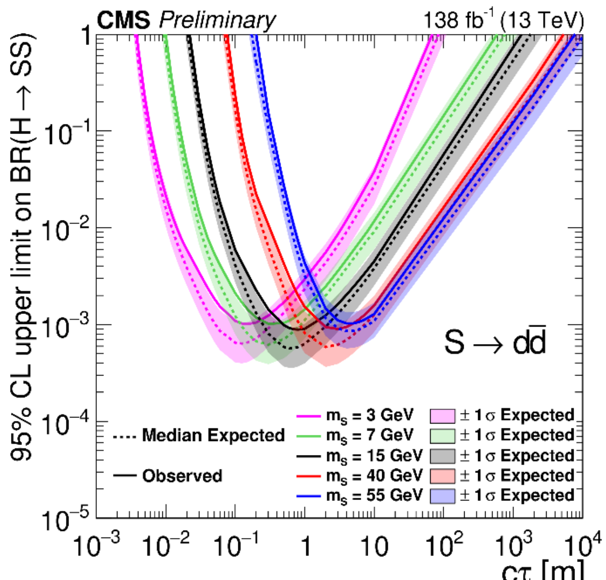
CMS-PAS-EXO-21-008
CMS Physics Briefings

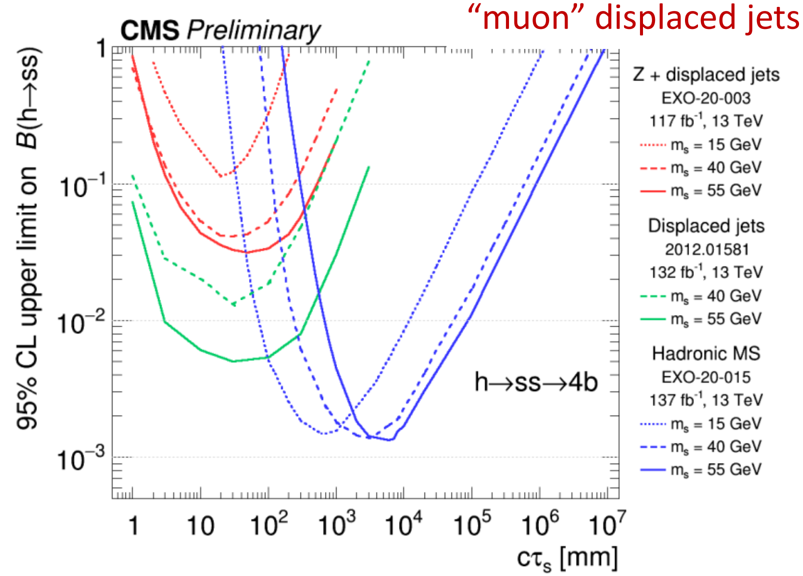
PRL 127 (2021) 261804
CMS Physics Briefings



“muon” displaced jets







the most stringent limit for proper decay lengths in the range 0.04-0.4 (0.3-0.9) m and above 4 (3) m for an LLP mass of 15 (40) GeV

Summary

Extensive searches for the New Physics are performed with CMS experiment on RUN1 and RUN2 data

- 219 of EXO analyses, 175 of Higgs analyses, 79 of B2G, 137 of SUSY

The tricks of the RUN2/3 are (procedure was updated during LS2 and will be improved further)

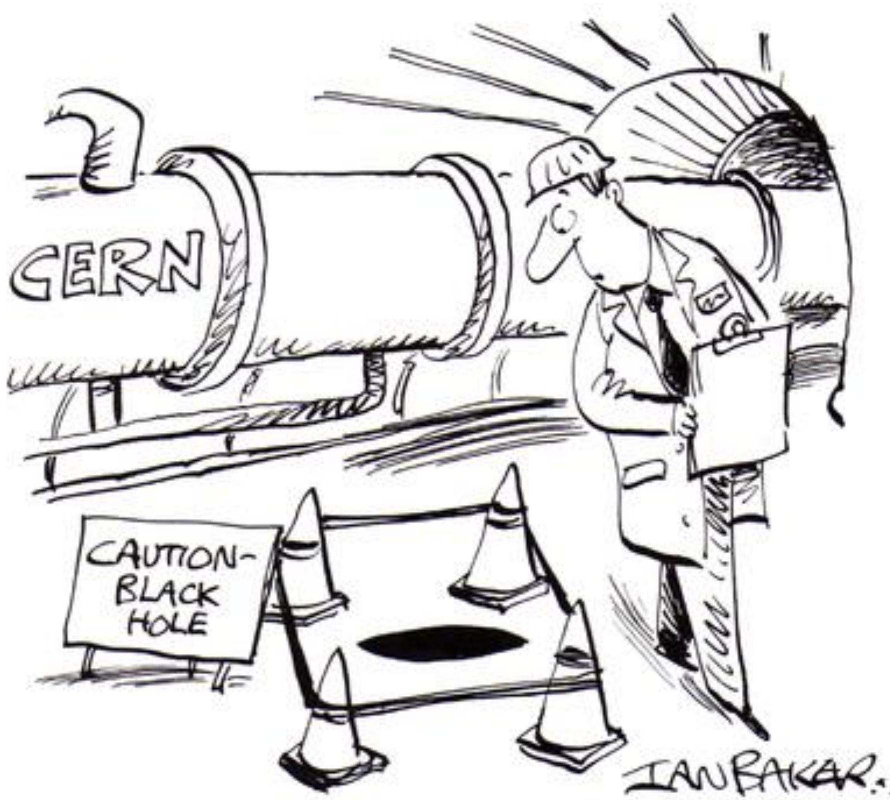
- higgs boson is intensively involved in searches
- non-conventional signals (displaced vertices, highly-boosted objects produced emerging jets/leptons)

Many new analyses made public

- for Summer Conferences, http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/CMS/index.html
- Physics Briefings at: https://cms.cern/tags/physics-briefing

The first RUN3 results are already available

THANK YOU FOR YOUR ATTENTION!



What does Brazilian Flag mean?

Dimuon example $R_\sigma = \dfrac{\sigma(pp \to Z' + X \to l^+l^- + X)}{\sigma(pp \to Z^0 + X \to l^+l^- + X)}$

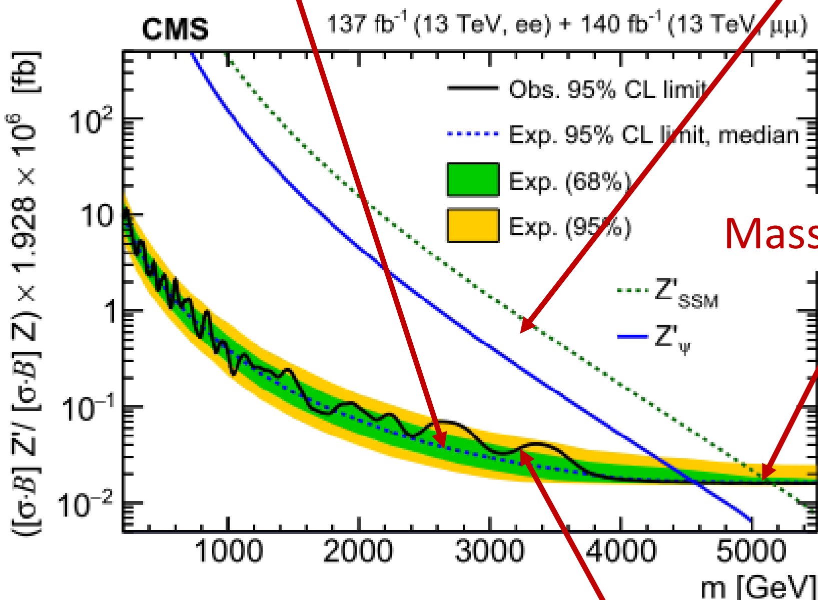
Extended gauge models

Models of low-energy gravity (RS1-type scenario of ED)

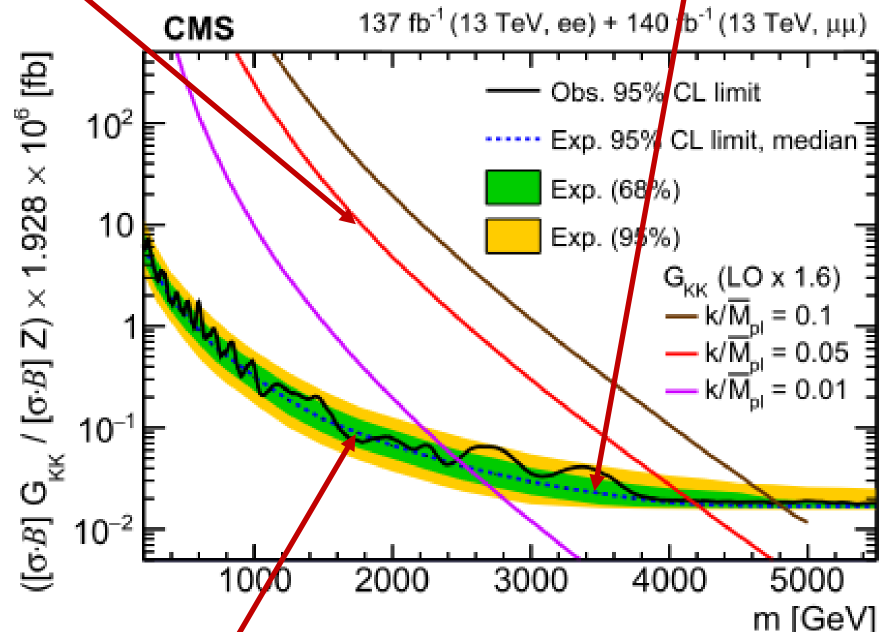
SM predictions

BSM predictions

SM predictions



Mass limit



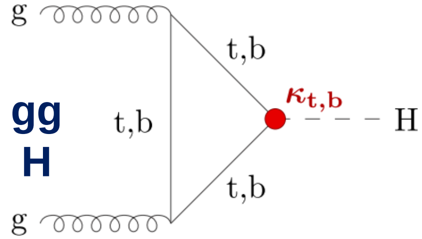
Model-independent limits on cross section (in narrow width approximation, NWA)

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

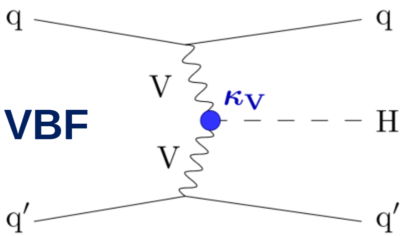
Channel	$k/\overline{M}_{Pl} = 0.01$ Obs. [TeV]	$k/\overline{M}_{Pl} = 0.01$ Exp. [TeV]	$k/\overline{M}_{Pl} = 0.05$ Obs. [TeV]	$k/\overline{M}_{Pl} = 0.05$ Exp. [TeV]	$k/\overline{M}_{Pl} = 0.1$ Obs. [TeV]	$k/\overline{M}_{Pl} = 0.1$ Exp. [TeV]
e e	2.16	2.29	3.70	3.83	4.42	4.43
$\mu^+\mu^-$	2.34	2.32	3.96	3.96	4.59	4.59
e e + $\mu^+\mu^-$	2.47	2.53	4.16	4.19	4.78	4.81

Production of SM Higgs boson

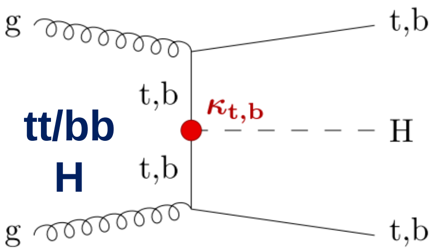
gg H



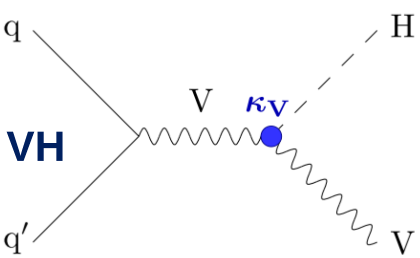
VBF

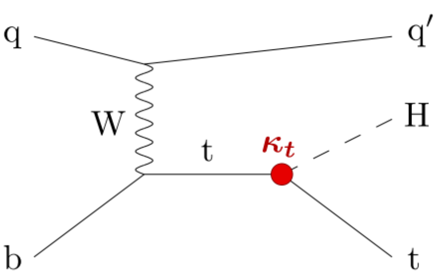


tt/bb H

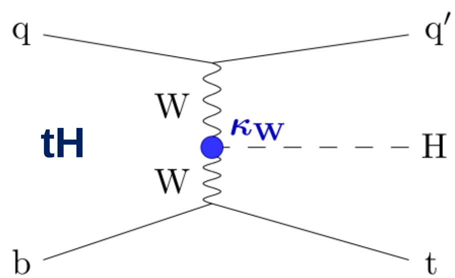


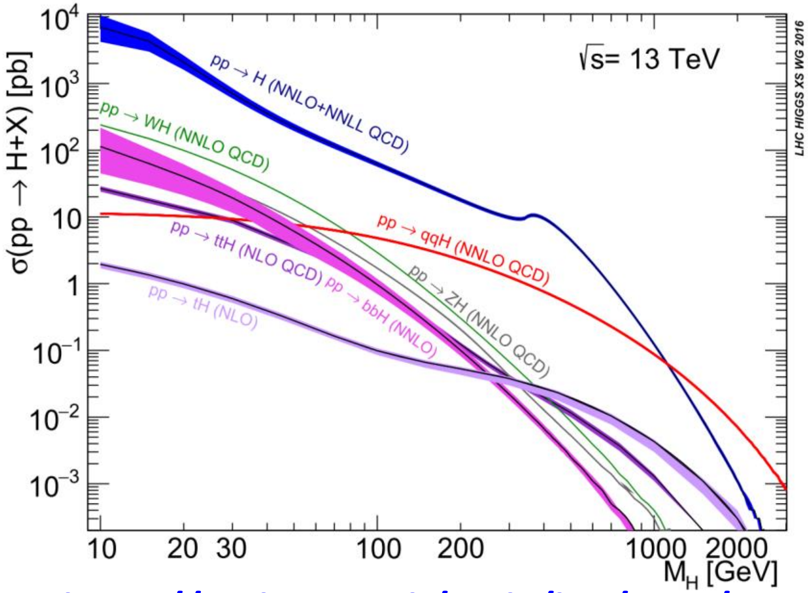
VH





tH





N(N)LO QCD + NLO EWK

$43.9\ pb^{-1}$, ggH, 7M
$3.77\ pb^{-1}$, VBF, 600K
$1.36\ pb^{-1}$, WH, 200K
$0.88\ pb^{-1}$, ZH, 140K
$0.5\ pb^{-1}$, ttH, 80K
$0.48\ pb^{-1}$, bbH, 77K
$0.08\ pb^{-1}$, tH, 13K
@ m_H =125.38 GeV

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR

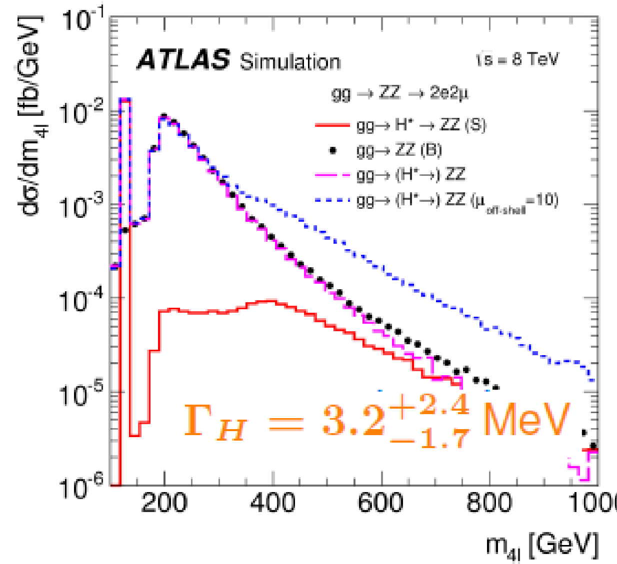
Higgs bosons per fb^{-1} (13 TeV)

	produced	selected
$H \to \gamma\gamma$	130	46
$H \to ZZ^*$	1400	1.5
$H \to WW^*$	12000	42
$H \to \tau\tau$	3500	17
$H \to b\bar{b}$	32000	66

Channel	Produced	Selected	Mass resolution
$H \to \gamma\gamma$	18,200	6,440	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$ 210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$ 5,880	20%
$H \to \tau\tau$	490,000	2,380	15%
$H \to bb$	4,480,000	9,240	10%

Higgs Width

- On-shell measurements in γγ and ZZ (4l)
  - total Higgs width of 4.1 MeV unmeasurably small, limited by detector resolution
  - in assumption the lack of signal-background interference
  - Γ_H < 1.1 GeV @ 95% CL in 4l

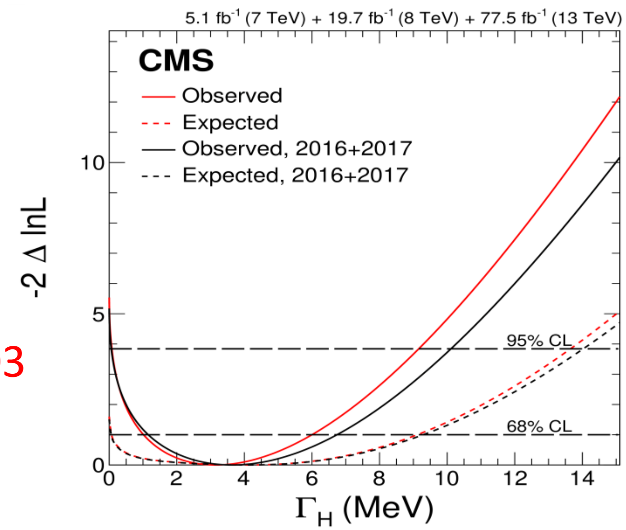


- Off-shell measurements in ZZ for gg-production

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2 + m^2_H \Gamma^2_H} \quad \Rightarrow \quad \sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

for $m_{ZZ} > 2m_Z \quad (m_{ZZ} - m_H) \gg \Gamma_H$

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



- on-shell (NWA) depends on Γ_H

$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma^{SM}_H}$$

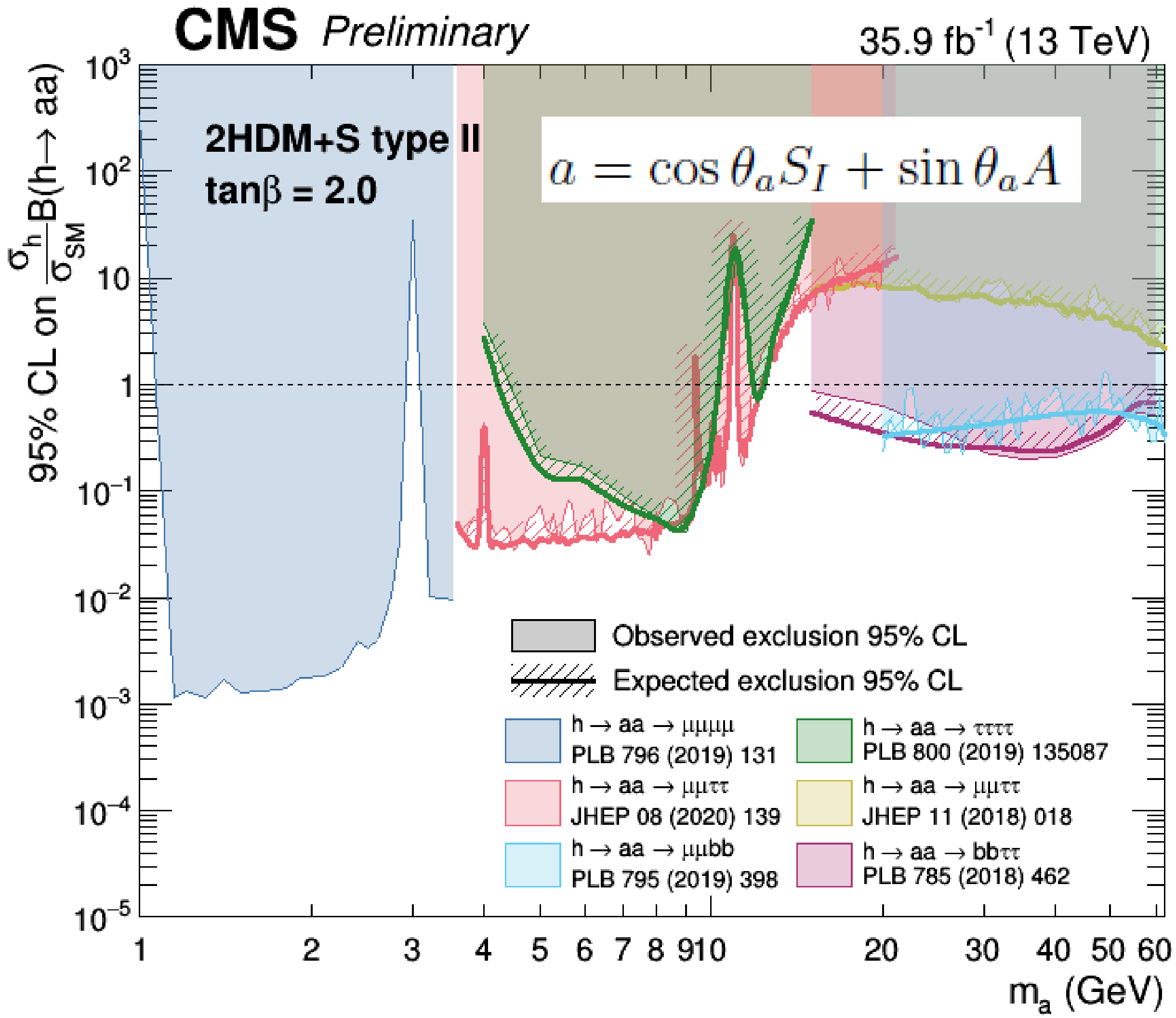
- off-shell does not depend

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

PRD 99 (2019) 112003

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]

Summary of 2HDM+S searches at 13 TeV

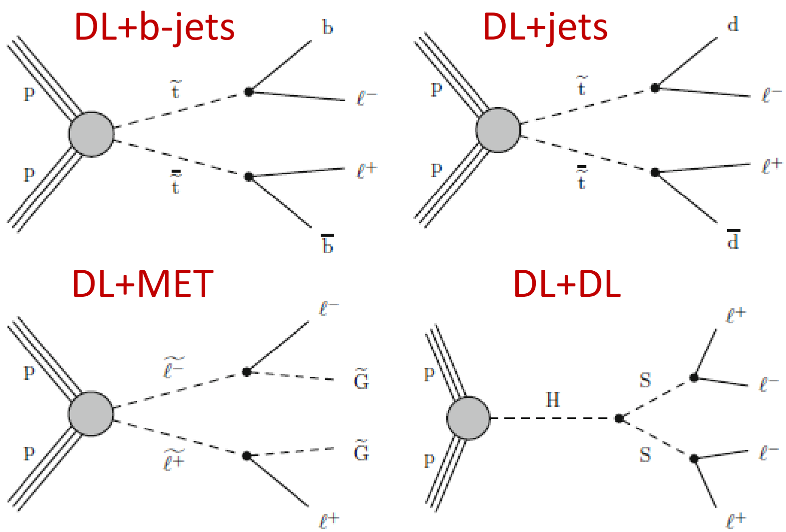


https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2

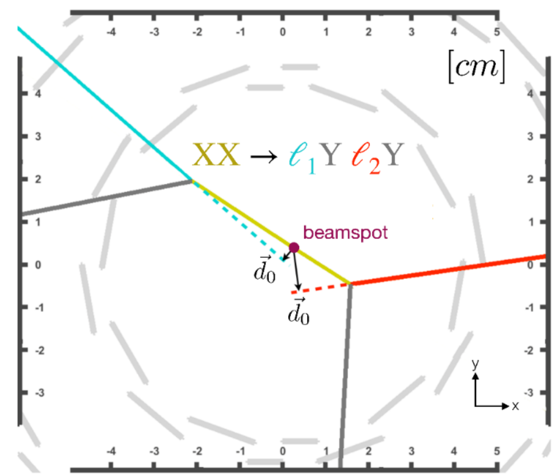
Displaced Leptons + Jets

EPJC 82 (2022) 153

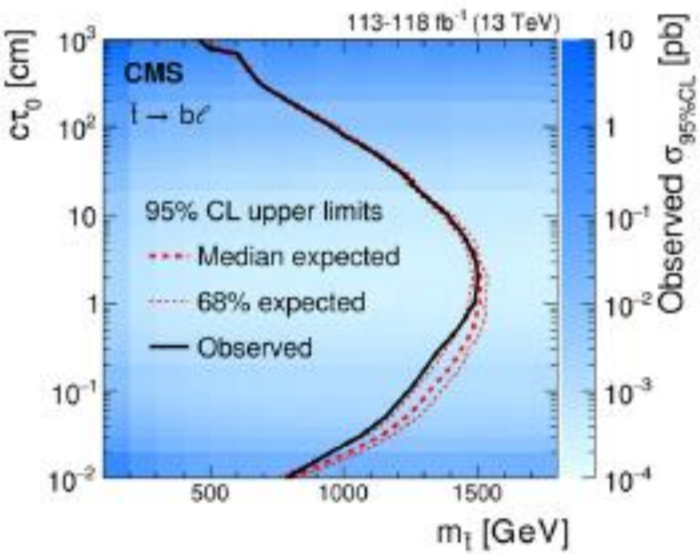
RPV SUSY, GMSB, and BSM Scalar Higgs



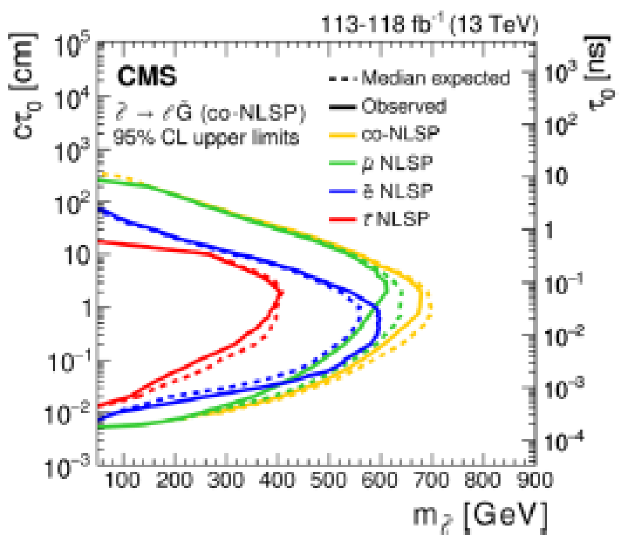
- Leptons could have common or different vertexes
- μμ, ee and eμ final states were used
- Trigger and event selection exclusively on displaced leptons
- leptons |d0| is the main discriminating variable (up to 10 cm)
- Data driven background estimation



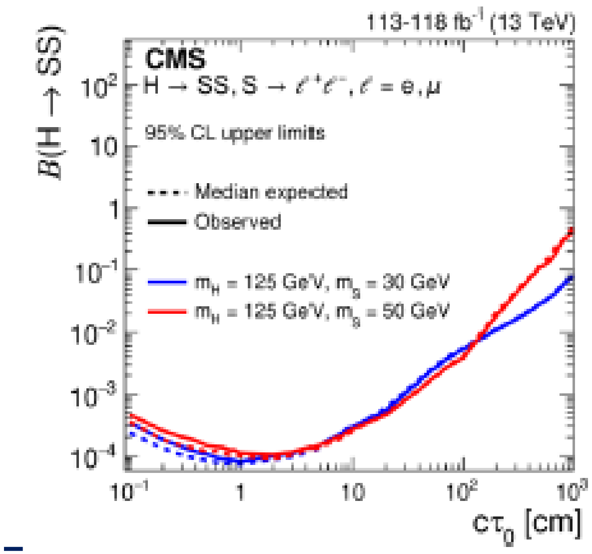
RPV SUSY



GMSB

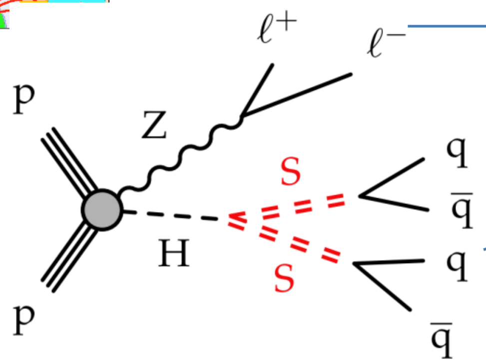


BSM Scalar Higgs



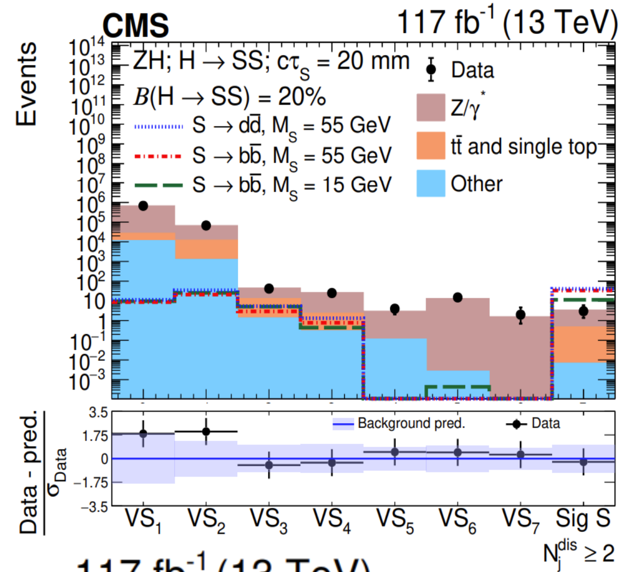
LPP + Z bosons

JHEP 03 (2022) 160

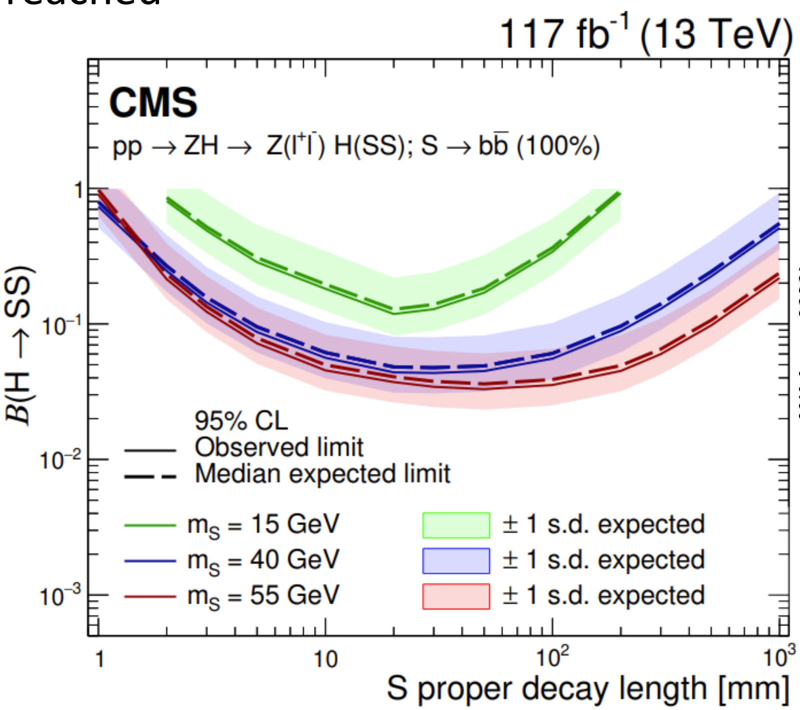


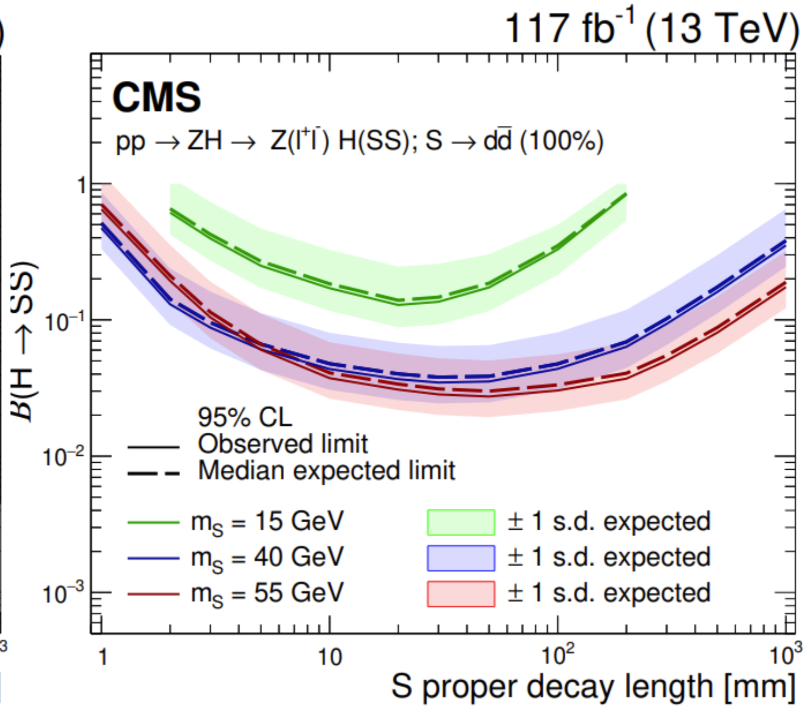
Used as a spectator in the event

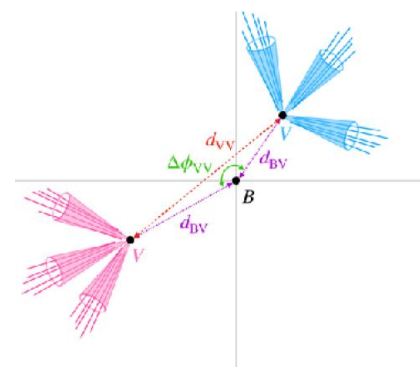
The multiplicity of displaced jets N_j^{dis} is the the main discriminator variable. Signal region is $N_j^{dis} \geq 2$



No excess over the expected SM event rate is observed.
New limits on branching Higgs to LLP scalar particles (S) are reached

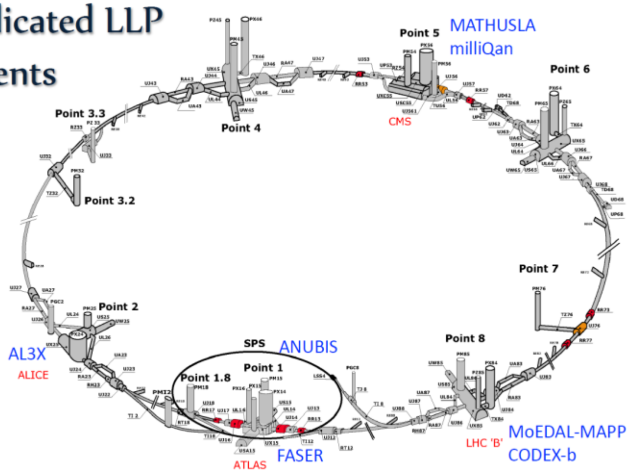






LHC Satellite Experiments

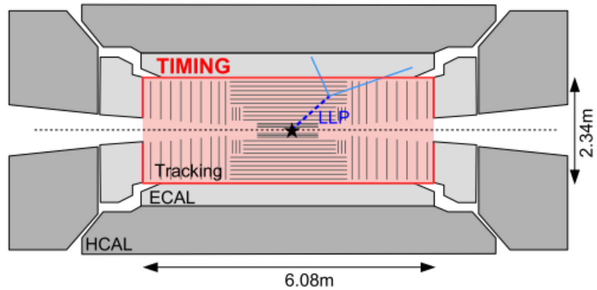
LHC dedicated LLP experiments



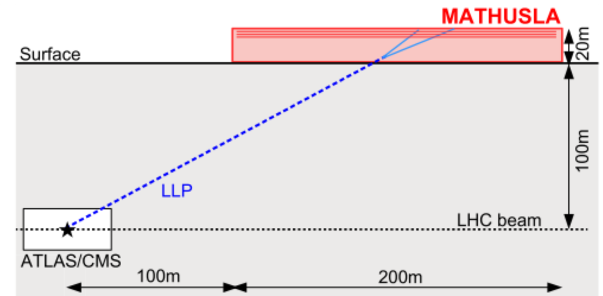
Phys. Rev. D 99 (2019) 015021

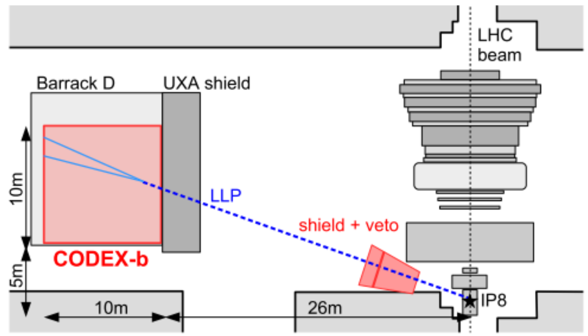
https://arxiv.org/abs/1901.04040

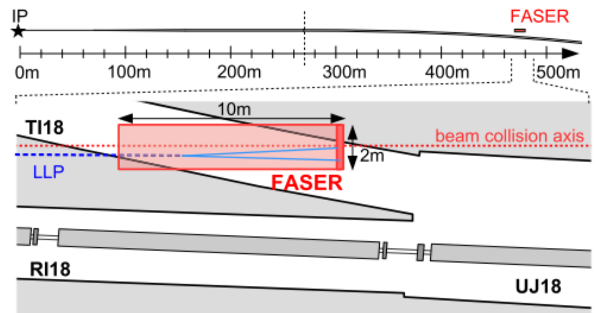
CMS/ATLAS



CMS

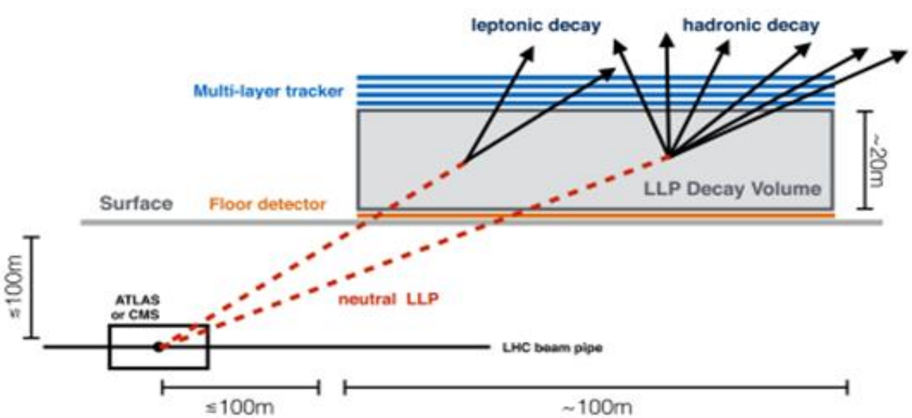


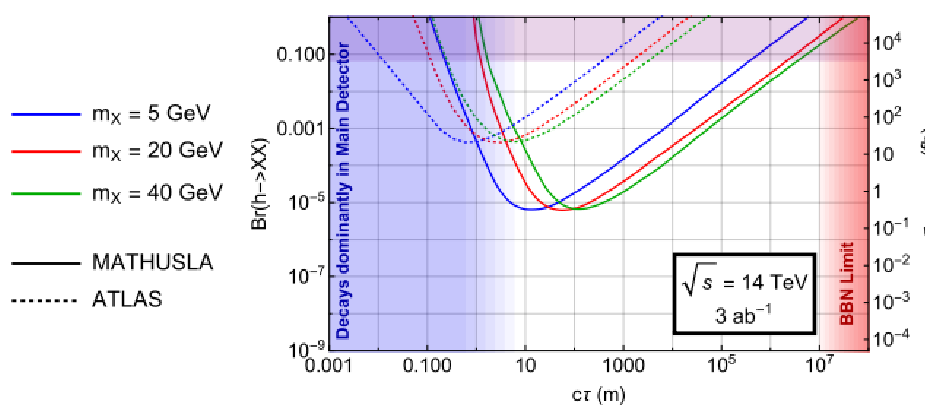




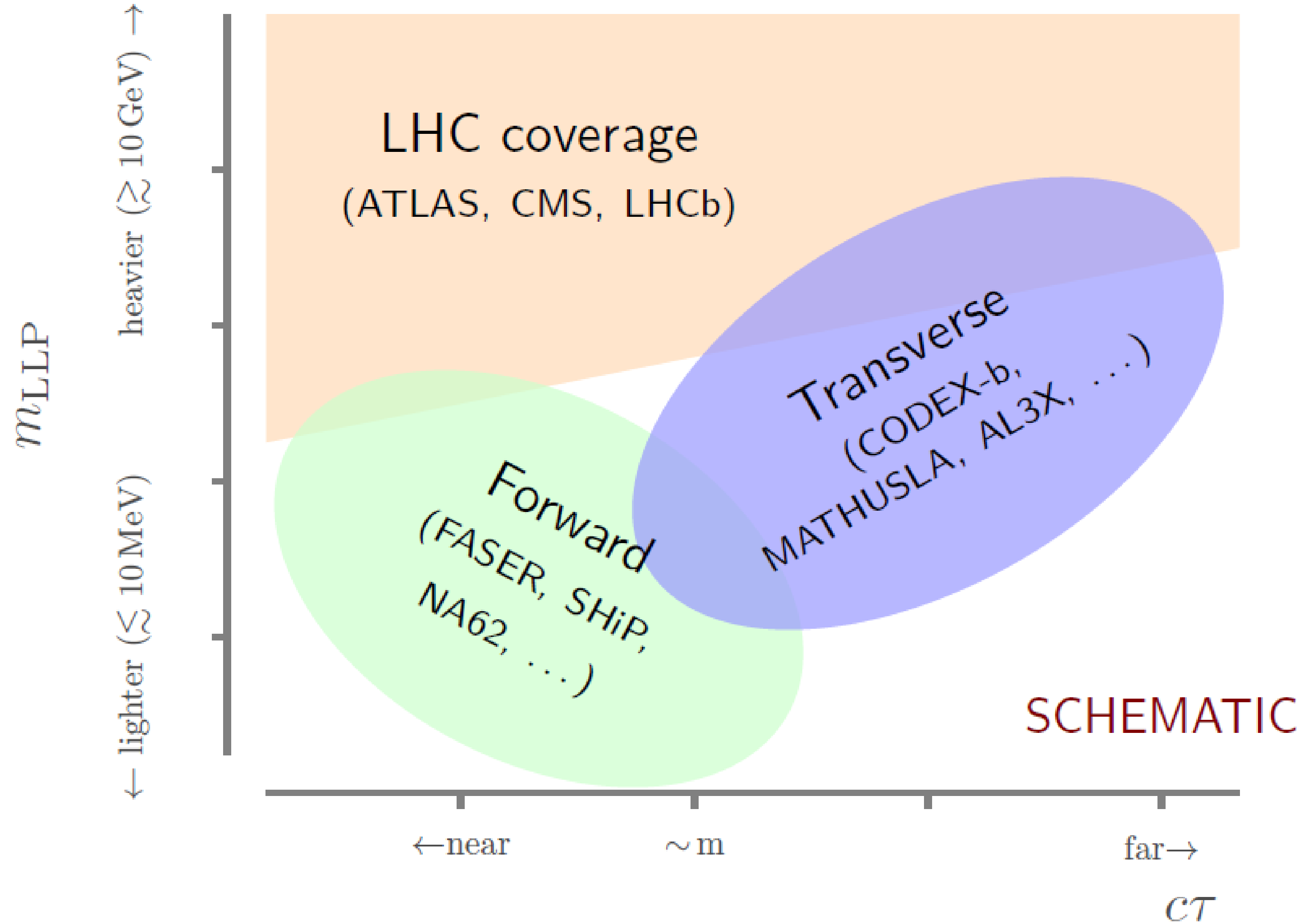
LHCb

ATLAS

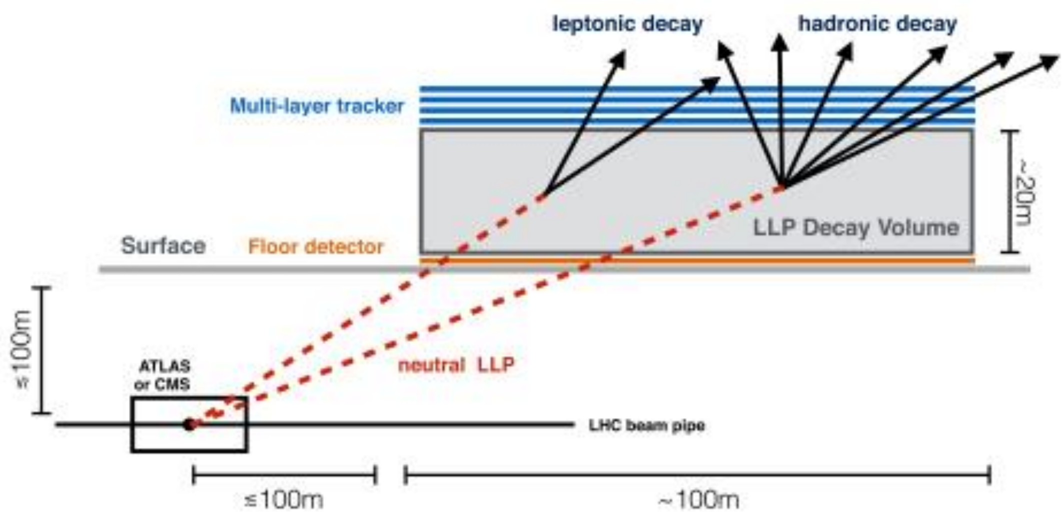


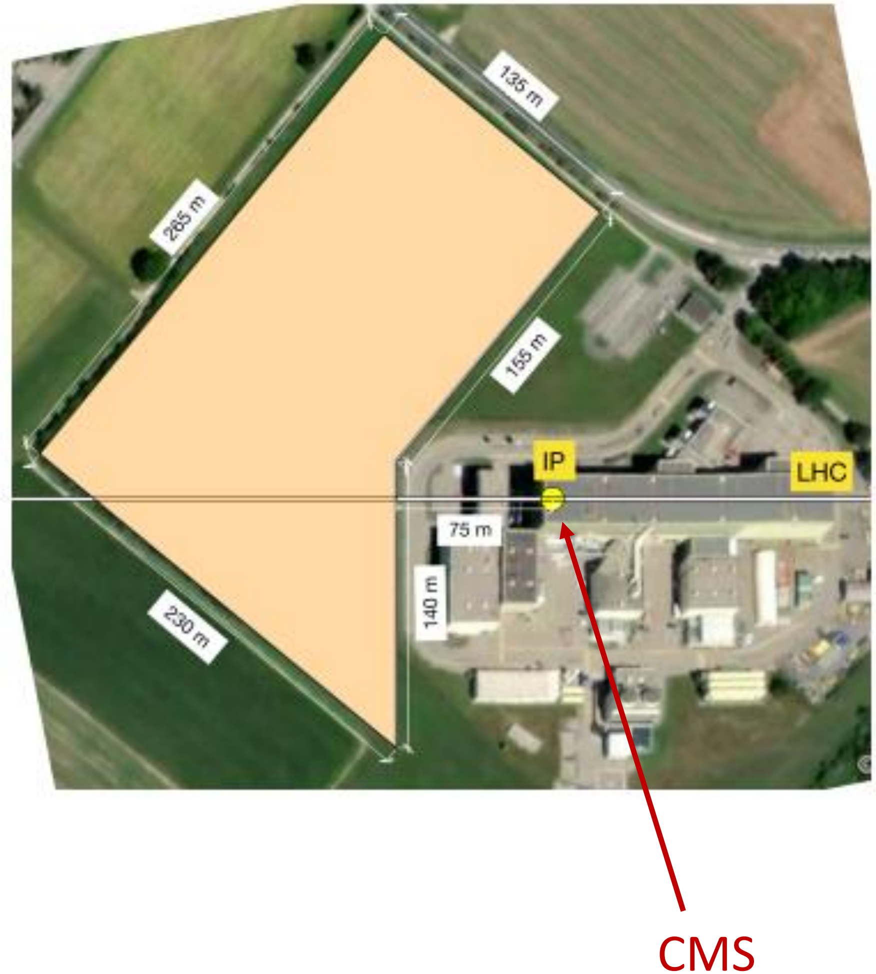


LLP Lifetime



MAssive Timing Hodoscope for Ultra-Stable neutraLpArticles





The full-scale detector could then become operational by 2025-26.

https://arxiv.org/abs/1901.04040