

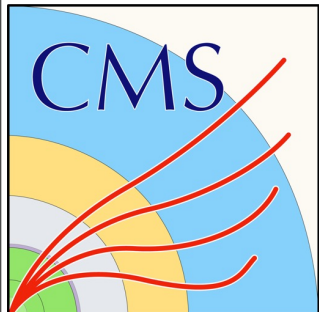
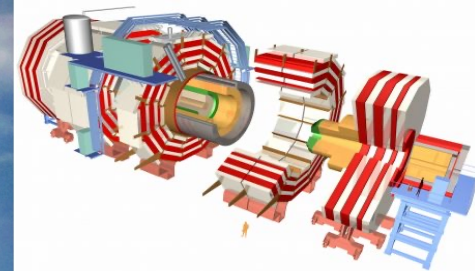
# *CMS Recent Results and Prospects*

*Sanjay K. Swain, NISER*

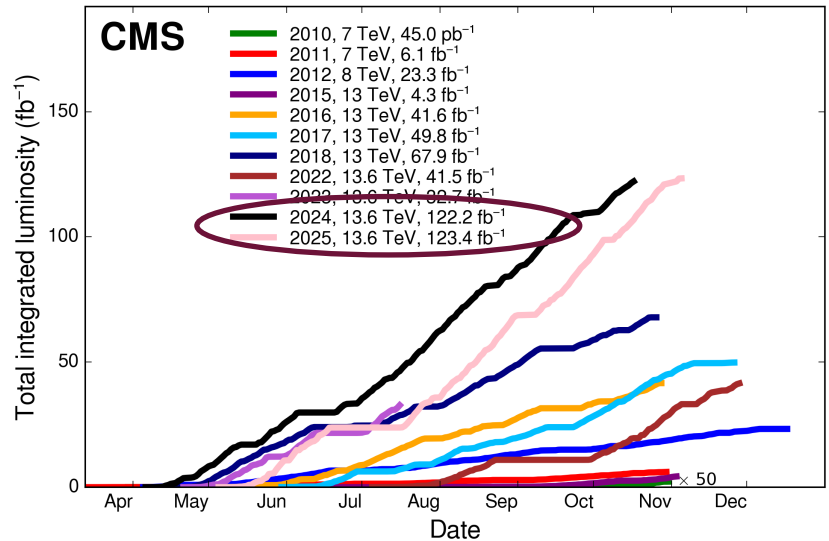
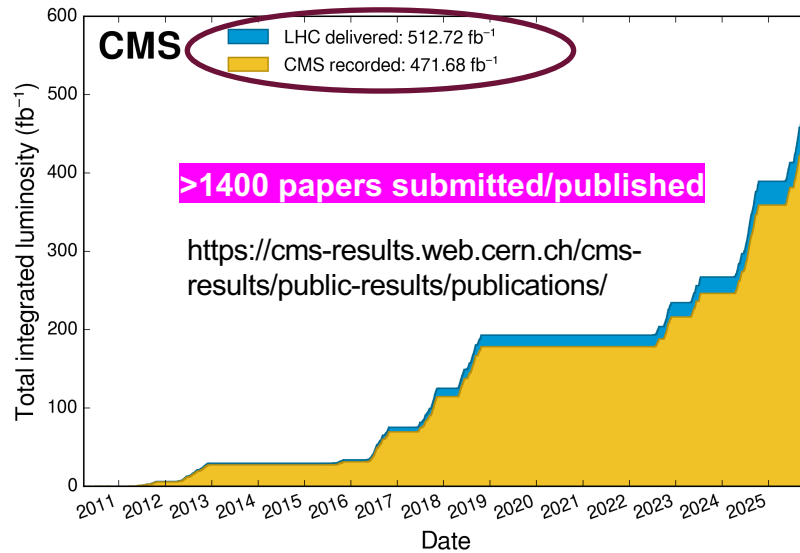
*12<sup>th</sup> Nov, 2025*

- ✓ Status of LHC
- ✓ Recent physics results (what we have learned so far)
  - SM results: Higgs, W/Z/QCD, top, B-mesons
  - BSM searches: SUSY, LLPs, BHs, Sphalerons
- ✓ Future prospects (3000fb<sup>-1</sup> data, HL-LHC scenario)
- ✓ Summary

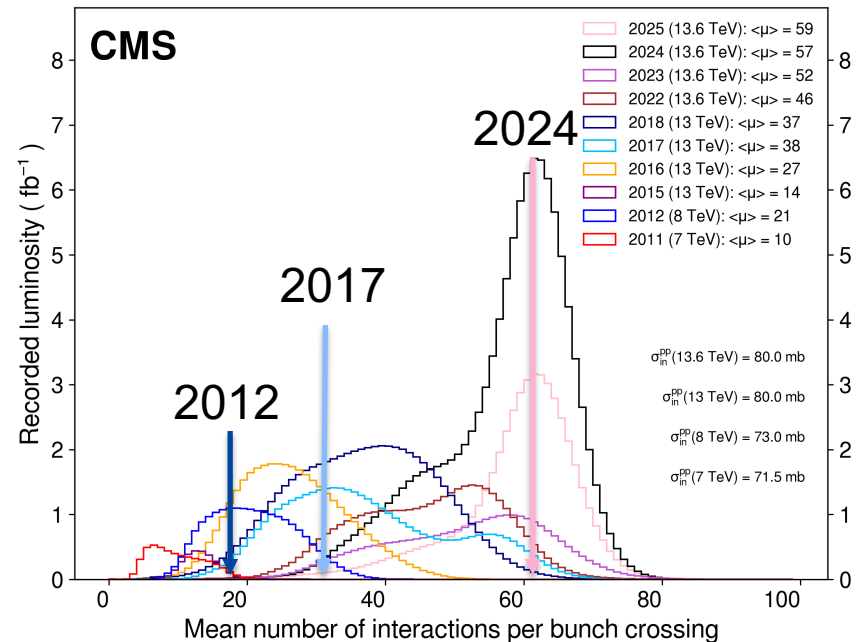
India-JINR Workshop on Particle, Nuclear, Neutrino Physics and Astrophysics



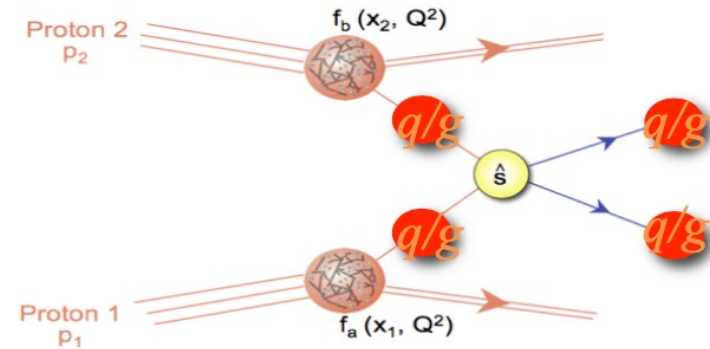
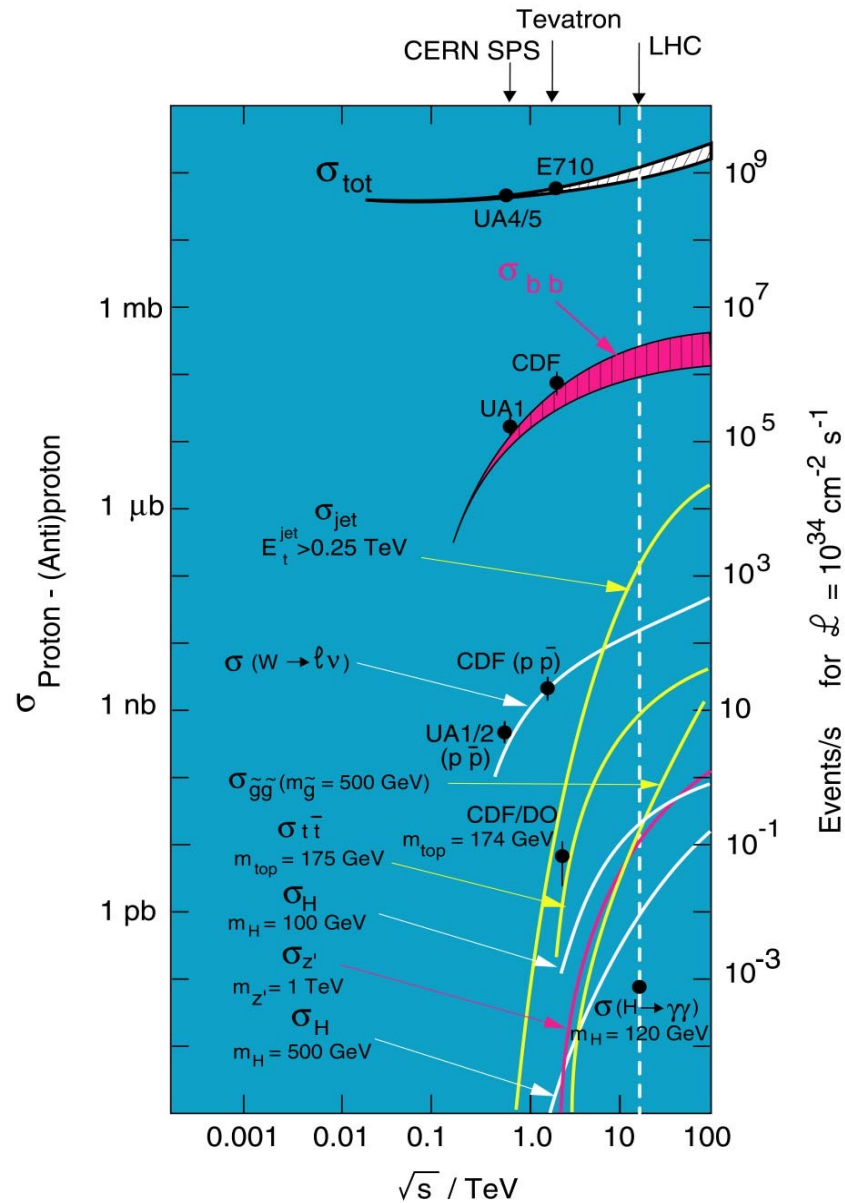
# LHC and CMS performance



- ✓ The LHC has provided > 500 fb<sup>-1</sup> data out of which CMS recorded ~92% of it.  
>50% of our total data collected in last 2-ys.
- ✓ The detectors have been performing very well.  
> 98 - 99% active channels during run
- ✓ Currently, LHC center of mass energy is 13.6 TeV. Allows us more interesting events (as no of events =  $\sigma \times \text{Luminosity}$ )
- ✓ Final goal is to get ~4000 fb<sup>-1</sup> data. Requires upgrade in accelerator (detectors need upgrade to survive high beam intensity)



# Physics production cross section with LHC



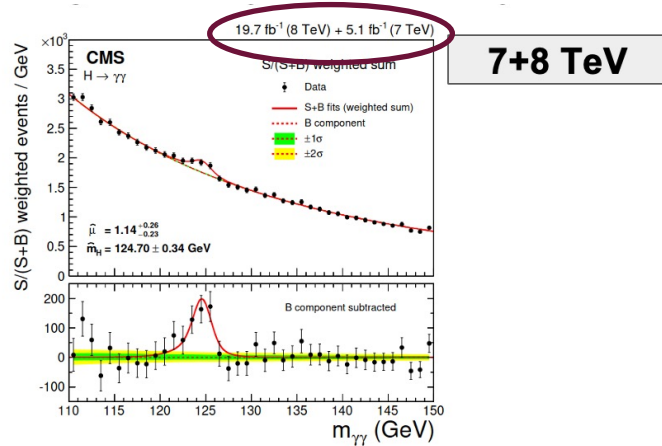
The current production cross-section for interesting physics events goes up significantly [some cases by several order of magnitude higher compared to Tevatron or even LHC@7 or 8 TeV]

Production cross-section is important, but the decay mode is equally crucial .

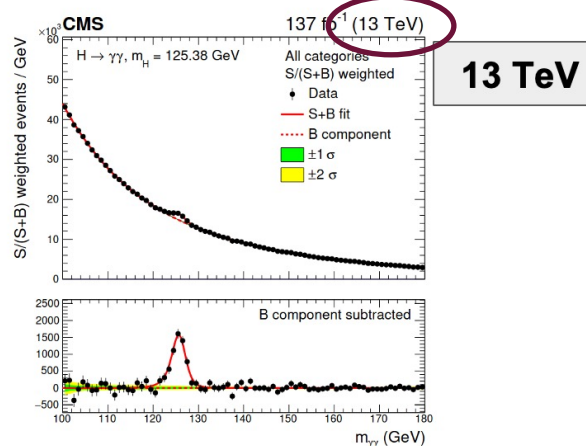
We carry out range of physics studies such as W/Z, Higgs, top-quark, flavor physics, QCD etc. (SM); SUSY, LLP, LQ, Dark Photons, T, W'/Z', BH etc(BSM).

***I will cover few selected results***

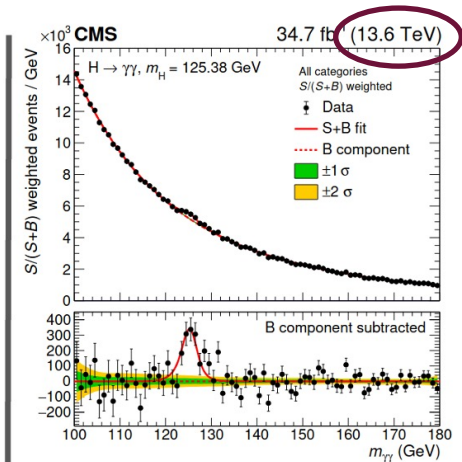
# Triumphs in Higgs sector



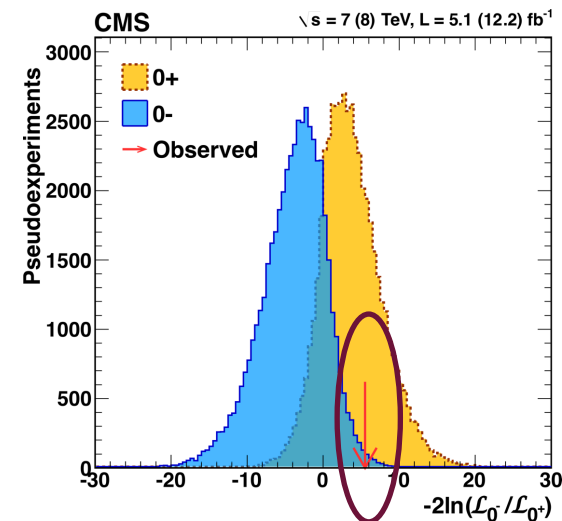
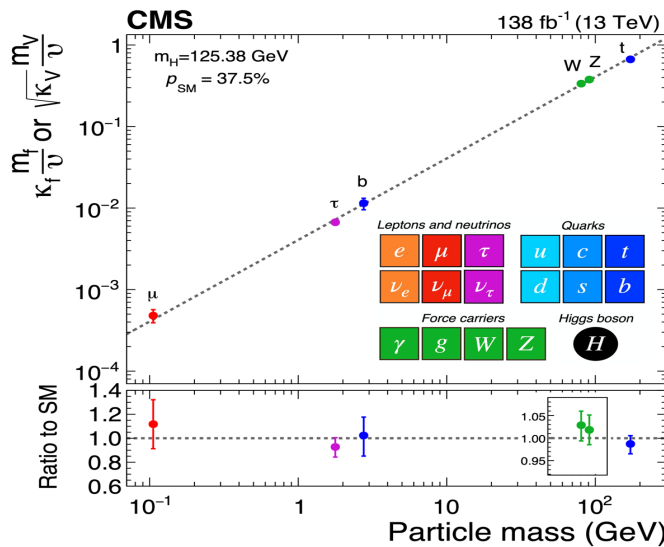
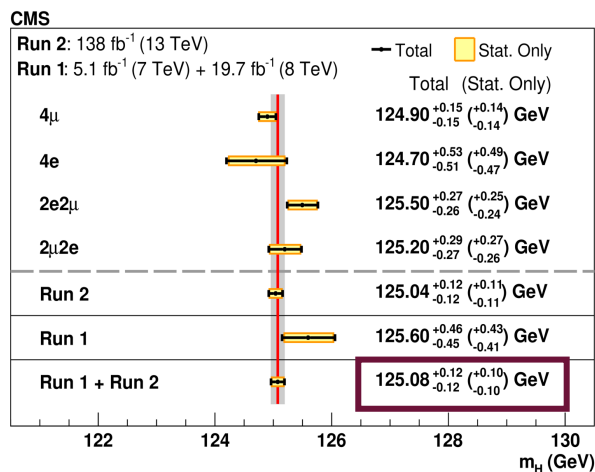
RUN 1 (2011-12)



RUN 2 (2016-18)



RUN 3 (2022-26)



- ✓ Higgs discovery has been one of the spectacular successes of SM
- ✓ CMS have been pursuing for the precision measurement of its properties such as mass, width, coupling to fermions, spin, parity, etc.



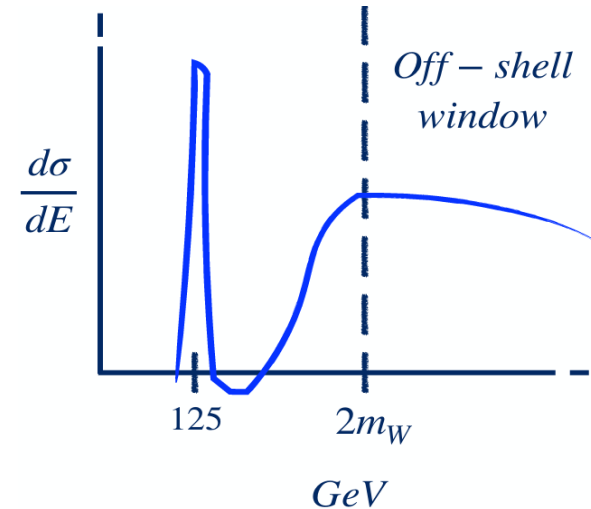
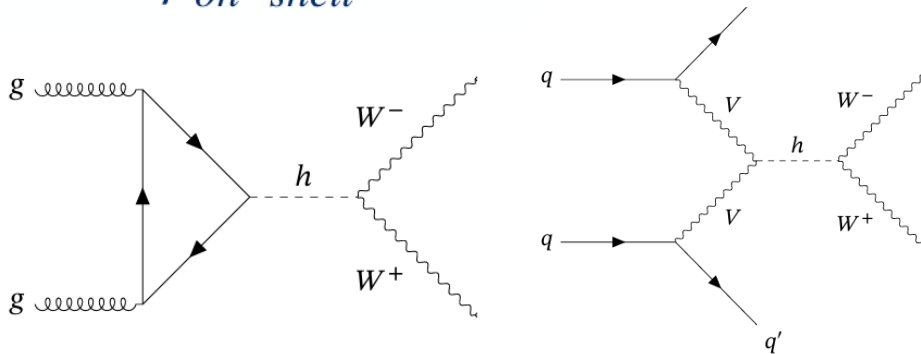
# $\Gamma_H$ using off-shell WW $\rightarrow 2\ell 2\nu$ mode

$$\sigma \propto \frac{g_p^2 g_d^2}{(p^2 - m^2) + m\Gamma_H} \sim \frac{g_p^2 g_d^2}{m\Gamma_H}$$

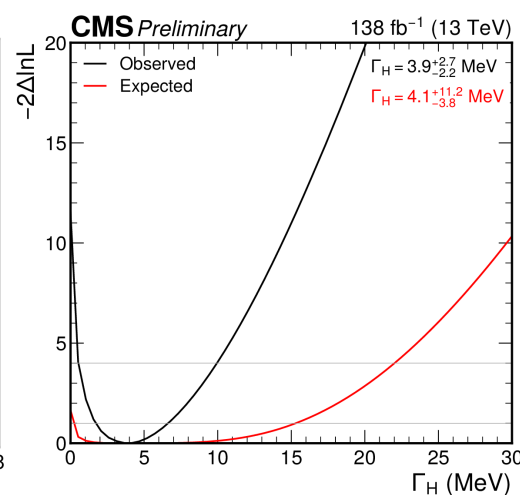
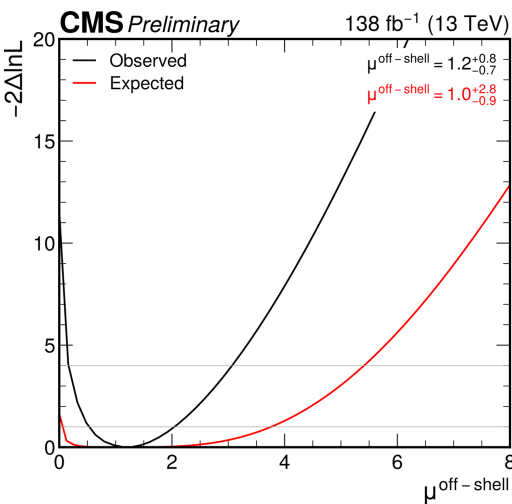
$$\mu_{on-shell} \propto \sigma_{on-shell} \propto \frac{g_p^2 g_d^2}{\Gamma_H}$$

$$\Gamma_H \propto \frac{\mu_{off-shell}}{\mu_{on-shell}} = r$$

$$\mu_{off-shell} \propto \sigma_{off-shell} = g_p^2 g_d^2$$



Parameter	c.v.	Observed		Expected	
		68% CL	95% CL	68% CL	95% CL
$\mu_{on-shell}$	1.25	1.09, 1.44	0.94, 1.65	0.85, 1.18	0.72, 1.38
$\mu_{ggF}^{off-shell}$	1.19	0.48, 2.15	< 3.40	< 4.31	< 6.21
$\mu_{VBF}^{off-shell}$	1.25	0.16, 3.09	< 5.59	< 6.41	< 11.2
$\mu_{off-shell}$	1.21	0.53, 2.05	0.17, 3.08	0.06, 3.75	< 5.4
$\Gamma_H$ (MeV)	3.91	1.72, 6.61	0.54, 9.94	0.25, 15.3	< 22.0



$$\Gamma_H = 3.9^{+2.7}_{-2.2} \text{ MeV @68% CL}$$

Improvement w.r.t Run-1 WW result  
Consistent with SM prediction: 4.1 MeV

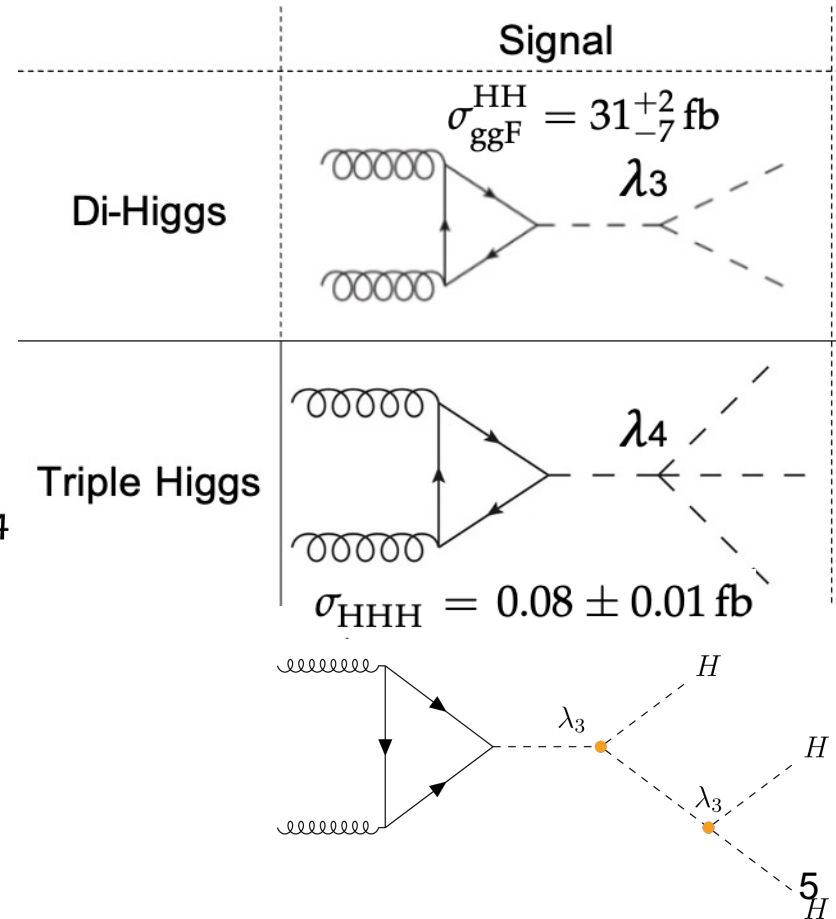
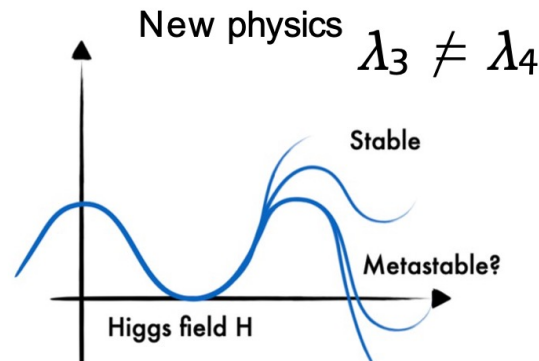
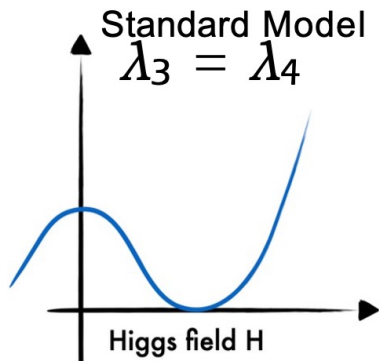
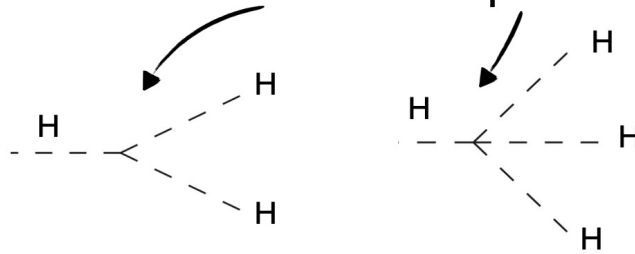
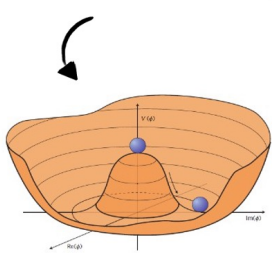
$$\mu_{off-shell} = 1.2^{+0.8}_{-0.7}$$

Consistent with SM expectation to be 1

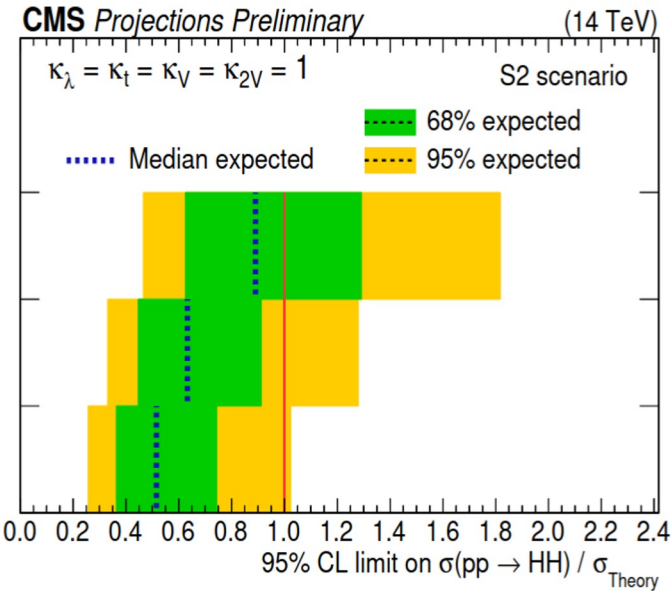
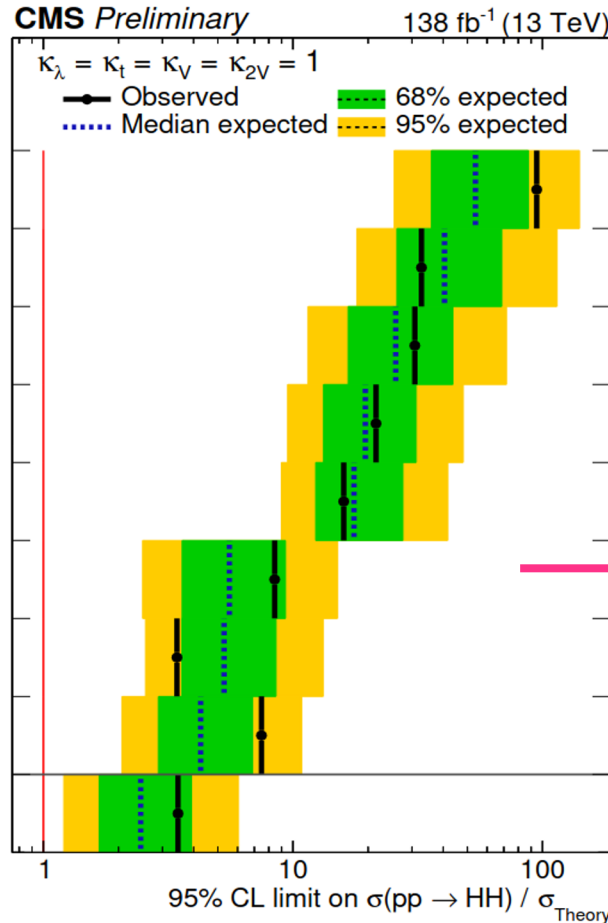
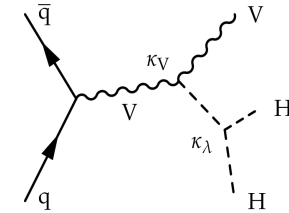
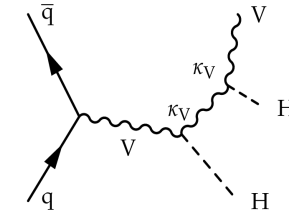
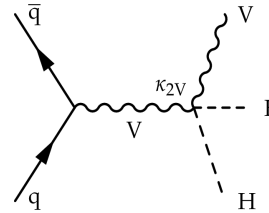
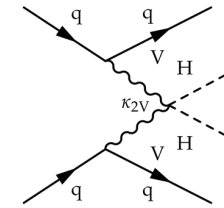
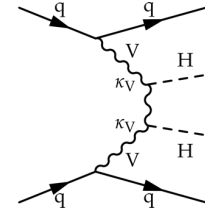
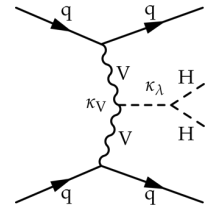
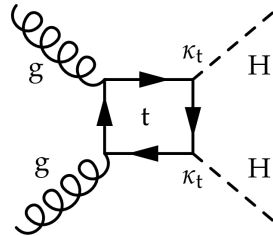
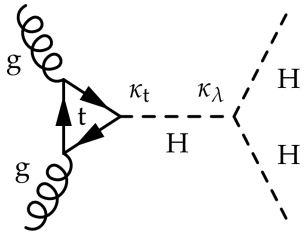
# HH and HHH production

- ✓ Higgs self coupling: One of the most important properties not measured yet
  - In SM: Higgs potential directly responsible for masses of particles
  - Trilinear coupling: responsible for HH production (sensitive to  $\lambda_3$ )
  - Quartic coupling: responsible for HHH production (sensitive to  $\lambda_3$  and  $\lambda_4$ )
- ✓ Full determination of Higgs potential only possible through combined measurements

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4$$



# Di-Higgs (HH) production

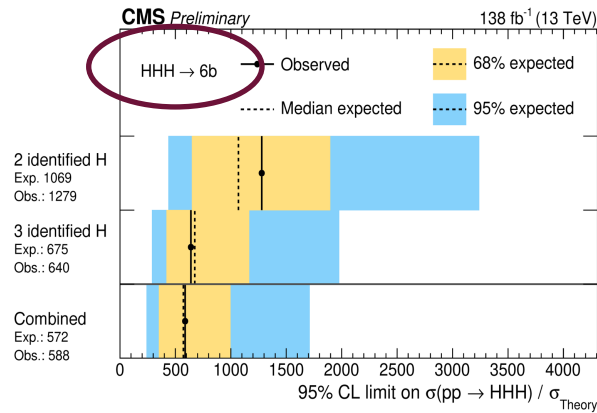
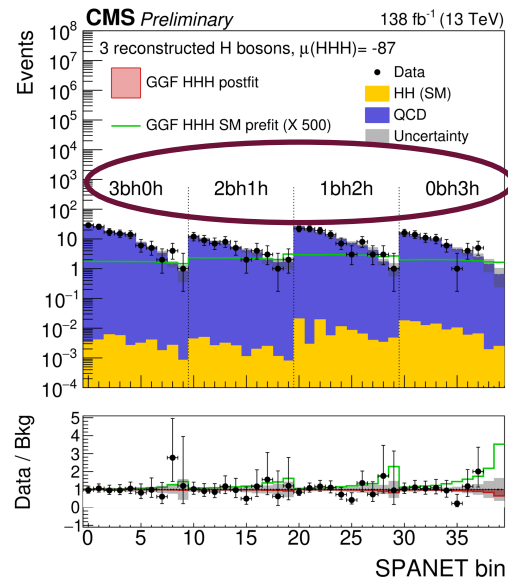


Current upper limit on HH production  $\sim 3 \times$  SM prediction

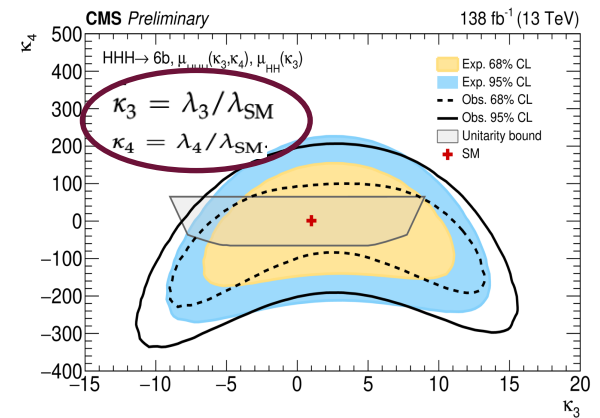
CMS-PAS-HIG-20-011

# Triple-Higgs (HHH) production

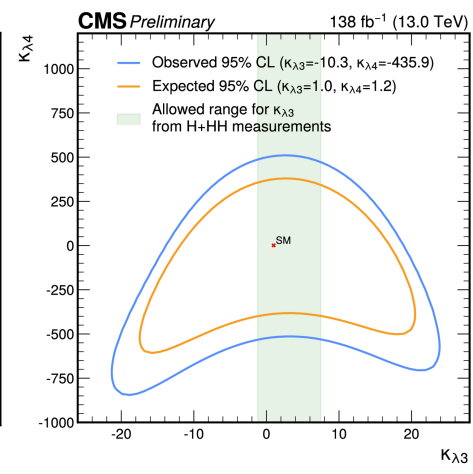
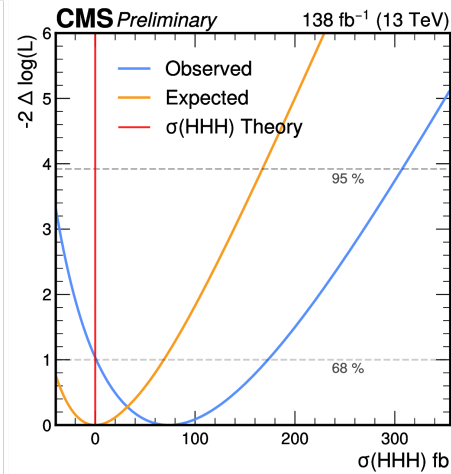
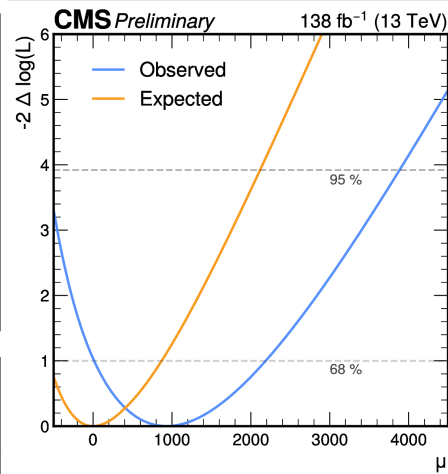
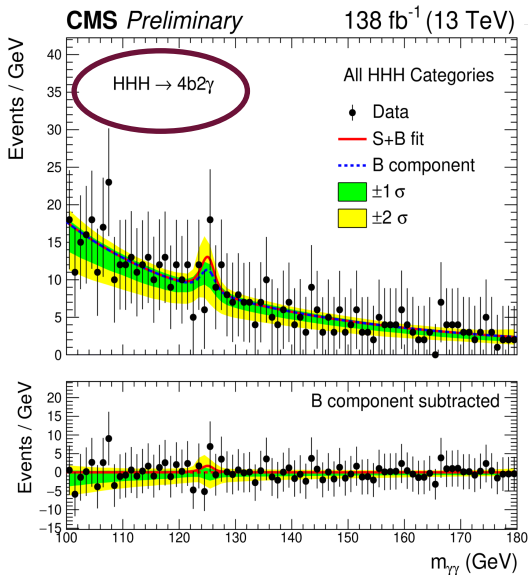
✓ H→bb has largest rate of ~60% (resolved or boosted jets)



**CMS-PAS-HIG-24-012**

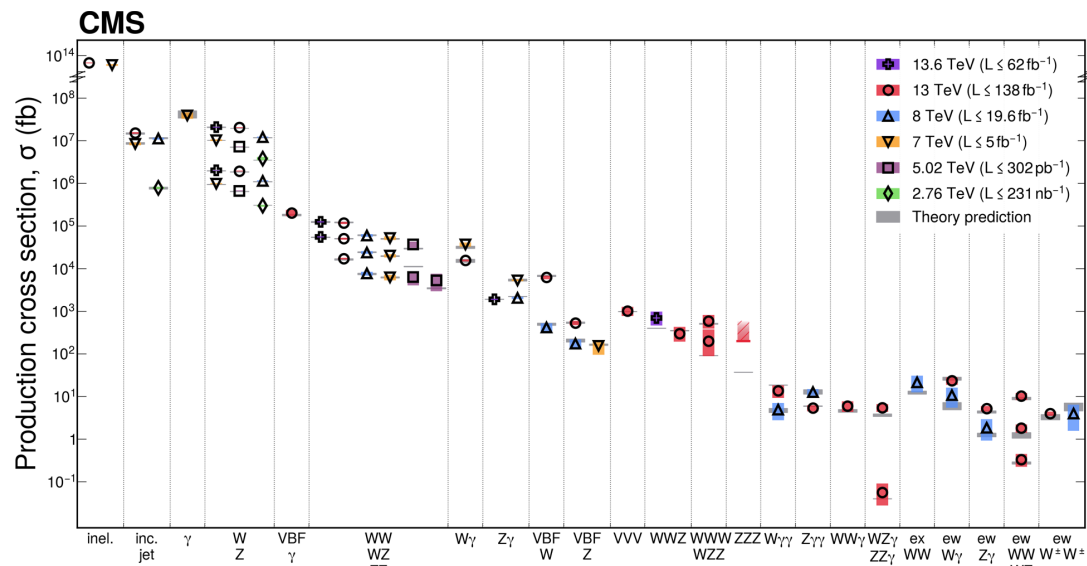
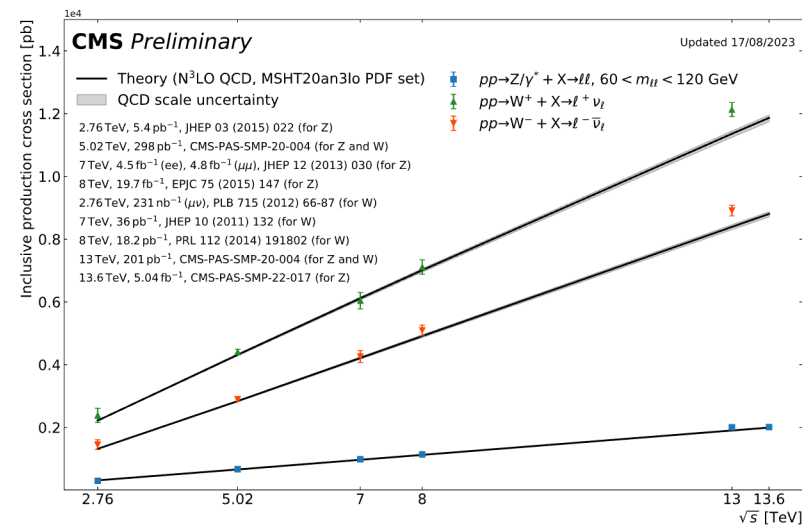


**CMS-PAS-HIG-24-015**



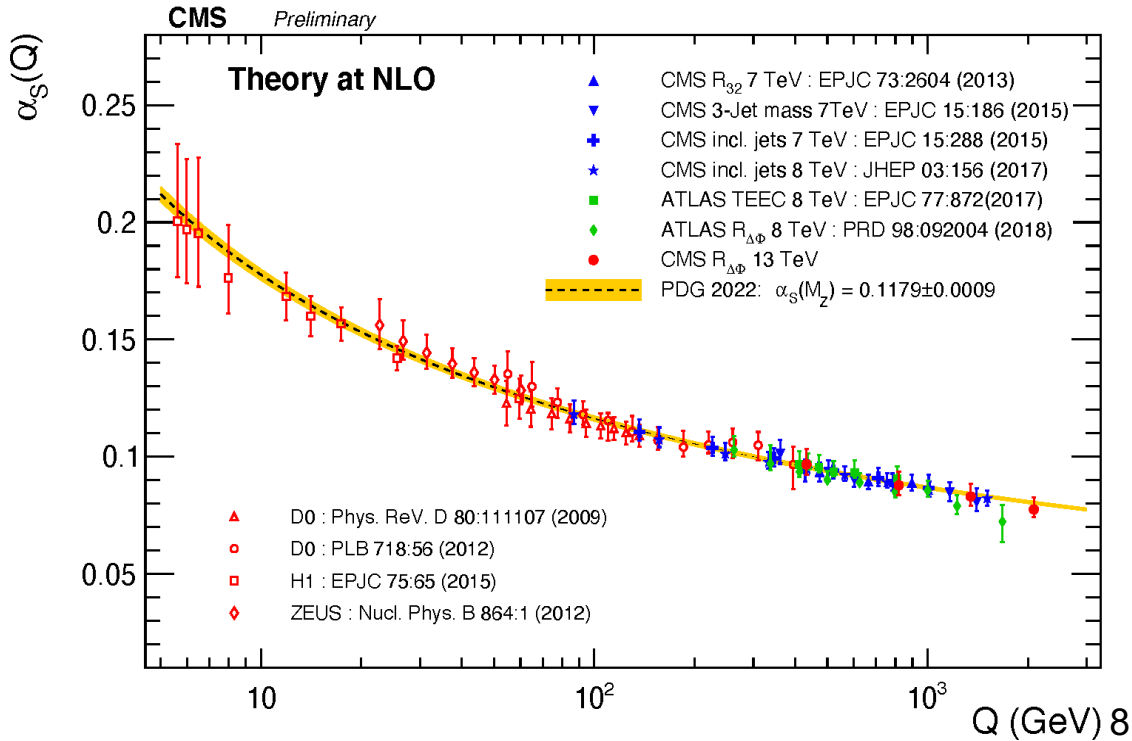
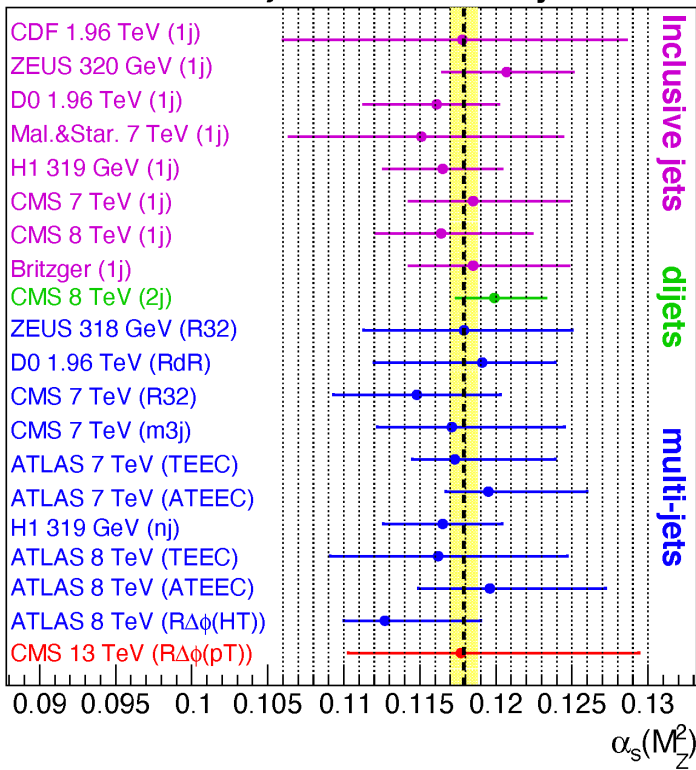
✓ Observation of HH, HHH will still be challenging with HL-LHC

# Triumph in SM W/Z/QCD sector



**CMS Preliminary**

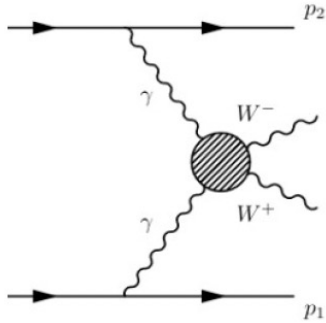
**Theory at NLO**





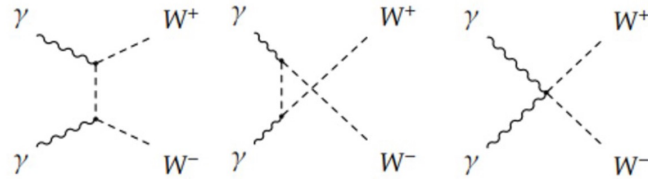
# $\gamma\gamma \rightarrow WW$ cross section

- Provides a pure electroweak environment  $\sigma(\gamma\gamma) \propto \log^3(\sqrt{s})$
- In SM the process proceeds via trilinear and quartic interaction
- Signal:  $WW \rightarrow e\nu_e \mu\nu_\mu$  (opposite sign leptons)
- Signal selection is based on detector activity around production vertex of W bosons (no other tracks attached to  $e\mu$  vertex)



$$\mathcal{L}_{WW\gamma} = -ie\{(\partial^\mu W^\nu - \partial^\nu W^\mu)W_\mu^+ A_\nu - (\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger})W_\mu^- A_\nu + W_\mu W_\nu^\dagger(\partial^\mu A^\nu - \partial^\nu A^\mu)\}$$

$$\mathcal{L}_{WW\gamma\gamma} = -e^2(W_\mu^+ W^\mu A_\nu A^\nu - W_\mu^+ A^\mu W_\nu^- A^\nu)$$

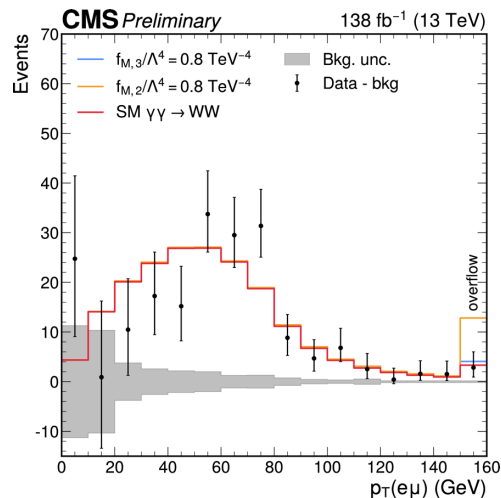
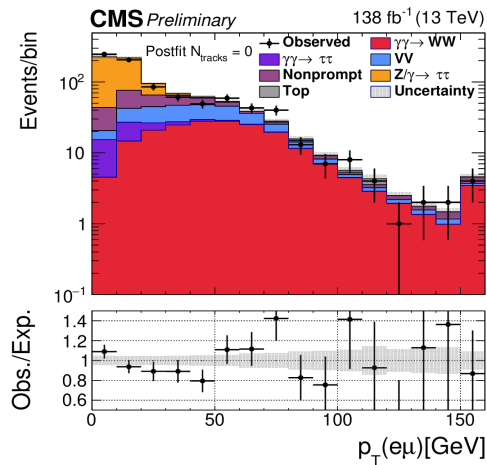


In signal region (no of track = 0)  
and control region ( $1 < n_{trk} < 5$ )  
excellent data-MC agreement

Measured inclusive cross-section:  
 $659 \pm 80 \text{ fb}$ , SM: 631 fb  
Fiducial cross-section:  $4.1 \pm 0.5 \text{ fb}$

Stringent constraints on dim-8  
operators in EFT approach

**CMS-PAS-SMP-24-019**

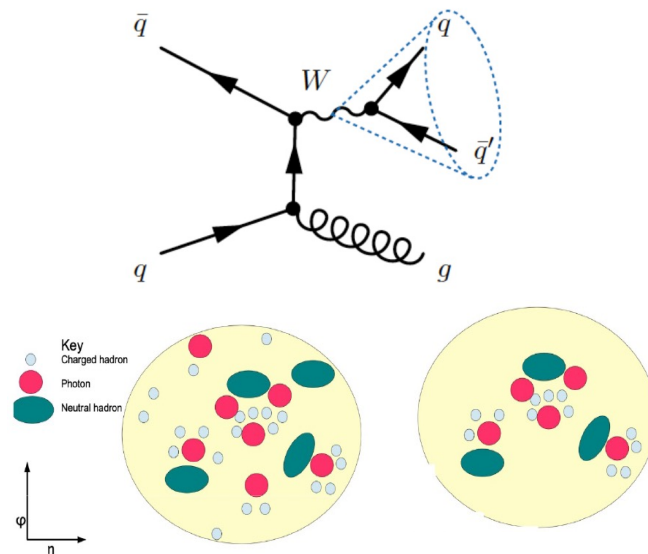


CMS Preliminary, July 2025		channel	limits	$\mathcal{U}^{\text{bound}}$ TeV
$f_{M,0} / \Lambda^4$	WW&ZV-ij (CMS-SMP-22-011)		[-0.539, 0.534]	=
	WW(ss)&WZ-ij (PLB 809 (2020) 135710)		[-2.700, 2.900]	=
	$\gamma\gamma \rightarrow WW(e\nu)$ (CMS-SMP-24-019)		[-3.470, 3.470]	=
	W $\gamma$ -ij (PRD 108 (2023) 032017)		[-5.600, 5.500]	1.7
	Z $\gamma$ -ij (PRD (2021) 072001)		[-15.80, 16.00]	1.3
$f_{M,1} / \Lambda^4$	$\gamma\gamma \rightarrow VV(\text{had})$ (JHEP 07 (2023) 229)		[-66.00, 66.00]	=
	WW&ZV-ij (CMS-SMP-22-011)		[-1.590, 1.620]	=
	WW(ss)&WZ-ij (PLB 809 (2020) 135710)		[-4.100, 4.200]	=
	W $\gamma$ -ij (PRD 108 (2023) 032017)		[-7.800, 8.100]	2.1
	$\gamma\gamma \rightarrow WW(e\nu)$ (CMS-SMP-24-019)		[-13.11, 12.85]	=
$f_{M,2} / \Lambda^4$	Z $\gamma$ -ij (PRD (2021) 072001)		[-35.00, 34.70]	1.5
	$\gamma\gamma \rightarrow VV(\text{had})$ (JHEP 07 (2023) 229)		[-245.5, 245.5]	=
	WW&ZV-ij (CMS-SMP-22-011)		[-0.530, 0.530]	=
	WW&ZV-ij (CMS-SMP-22-011)		[-0.703, 0.703]	=
	W $\gamma$ -ij (PRD 108 (2023) 032017)		[-1.900, 1.900]	2.0
$f_{M,3} / \Lambda^4$	Z $\gamma$ -ij (PRD (2021) 072001)		[-6.550, 6.490]	1.5
	$\gamma\gamma \rightarrow VV(\text{had})$ (JHEP 07 (2023) 229)		[-9.800, 9.800]	=
	$\gamma\gamma \rightarrow WW(e\nu)$ (CMS-SMP-24-019)		[-2.000, 1.960]	=
	WW&ZV-ij (CMS-SMP-22-011)		[-2.550, 2.550]	=
	W $\gamma$ -ij (PRD 108 (2023) 032017)		[-2.700, 2.700]	2.7
$f_{M,4} / \Lambda^4$	Z $\gamma$ -ij (PRD (2021) 072001)		[-13.00, 12.70]	1.7
	$\gamma\gamma \rightarrow VV(\text{had})$ (JHEP 07 (2023) 229)		[-36.00, 36.00]	=
	WW&ZV-ij (CMS-SMP-22-011)		[-1.480, 1.480]	=
	$\gamma\gamma \rightarrow WW(e\nu)$ (CMS-SMP-24-019)		[-1.910, 1.920]	=
	W $\gamma$ -ij (PRD 108 (2023) 032017)		[-3.700, 3.600]	2.3
$f_{M,5} / \Lambda^4$	Z $\gamma$ -ij (PRD (2021) 072001)		[-22.20, 21.30]	1.7
	$\gamma\gamma \rightarrow VV(\text{had})$ (JHEP 07 (2023) 229)		[-67.00, 67.00]	=
	WW&ZV-ij (CMS-SMP-22-011)		[-2.140, 2.130]	=
	$\gamma\gamma \rightarrow WW(e\nu)$ (CMS-SMP-24-019)		[-3.560, 3.620]	=
	W $\gamma$ -ij (PRD 108 (2023) 032017)		[-3.900, 3.800]	2.7
$f_{M,7} / \Lambda^4$	WW(ss)&WZ-ij (PLB 809 (2020) 135710)		[-5.400, 5.800]	=
	Z $\gamma$ -ij (PRD (2021) 072001)		[-22.20, 21.30]	1.7
	$\gamma\gamma \rightarrow VV(\text{had})$ (JHEP 07 (2023) 229)		[-67.00, 67.00]	=
	WW&ZV-ij (CMS-SMP-22-011)		[-2.630, 2.580]	=
	WW(ss)&WZ-ij (PLB 809 (2020) 135710)		[-5.700, 6.000]	=
$f_{M,8} / \Lambda^4$	W $\gamma$ -ij (PRD 108 (2023) 032017)		[-14.00, 14.00]	2.2
	$\gamma\gamma \rightarrow WW(e\nu)$ (CMS-SMP-24-019)		[-25.76, 26.22]	=
	Z $\gamma$ -ij (PRD (2021) 072001)		[-56.60, 55.90]	1.6
	$\gamma\gamma \rightarrow VV(\text{had})$ (JHEP 07 (2023) 229)		[-490.9, 490.9]	=

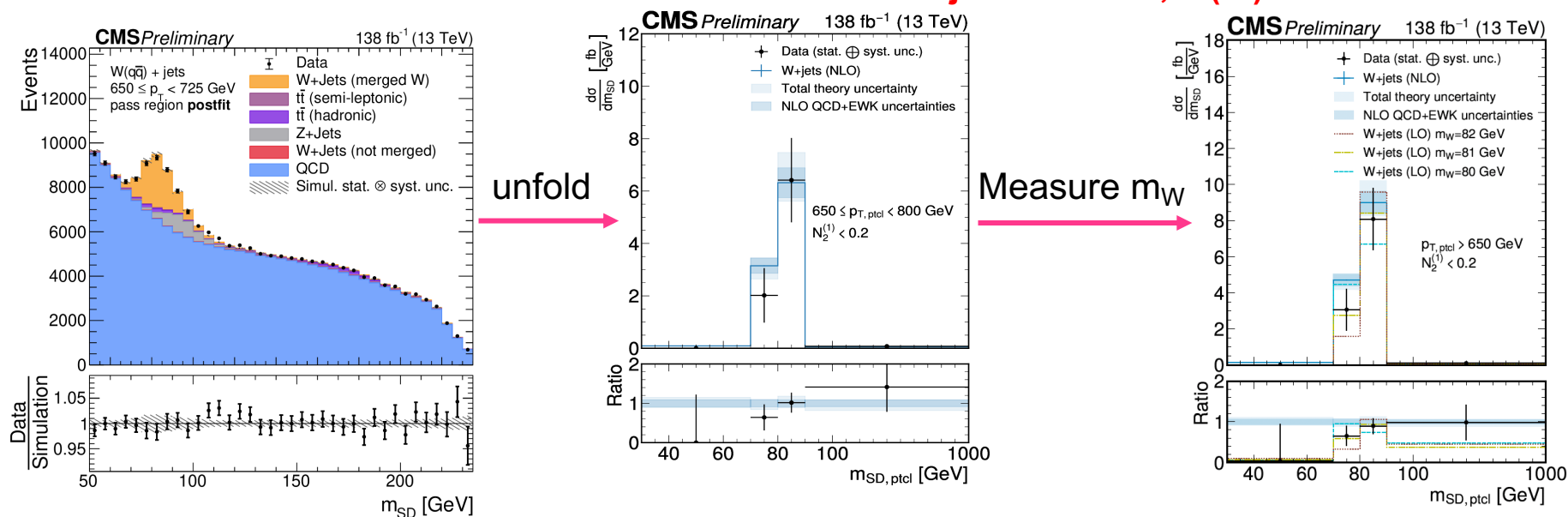
aQGC Limits @95% C.L. [TeV<sup>4</sup>]

# Jet mass distributions and W mass

- Cross section measurement of  $W(q\bar{q}) + \text{jets}$ 
  - At high momentum  $P_T > 650 \text{ GeV}$
  - Double-differential in jet  $P_T$  and jet mass
- $W(q\bar{q})$  object from wide  $\Delta R = 0.8$  jet
  - Substructure tagged for 2-prong with particleNeT algo
    - > to suppress QCD background
  - Mass from jet groomed with softdrop algorithm
    - > Suppresses soft and wide-angle emissions
- Unfolding to both particle level jet  $P_T$  and mass
- Sensitive to W mass -> turn into measurement
- **First measurement at a hadron collider of W-mass in all-jet final state,  $m(W) = 80.77 \pm 0.57 \text{ GeV}$**



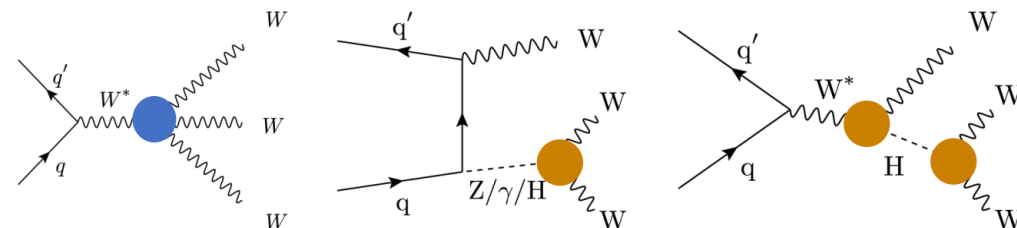
**CMS-PAS-SMP-24-012**



# New Physics in triple boson production

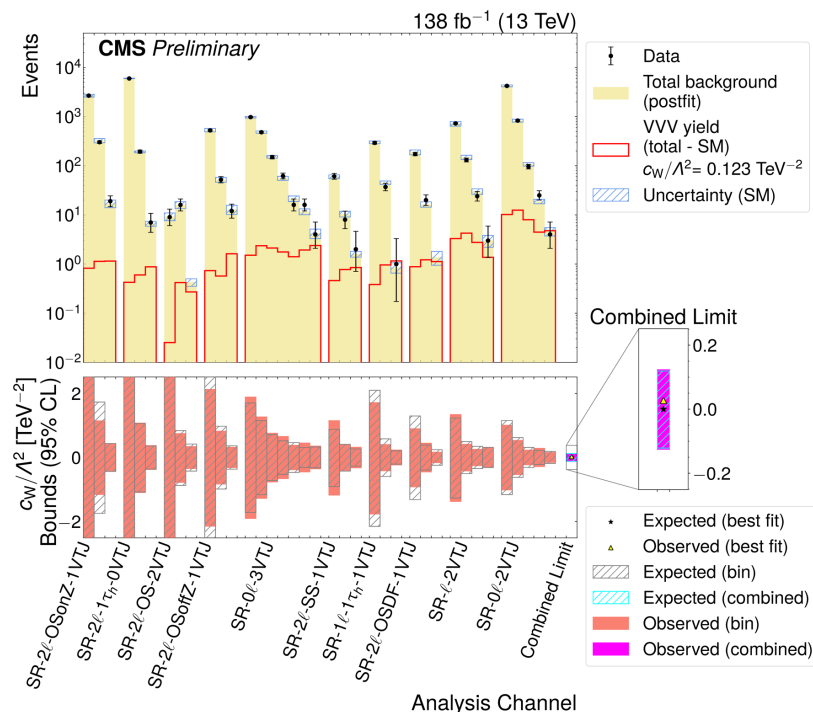
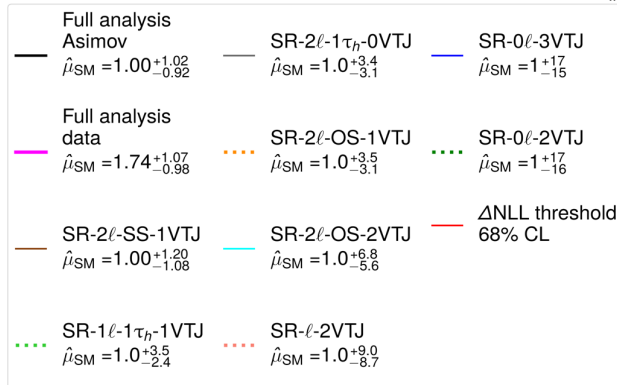
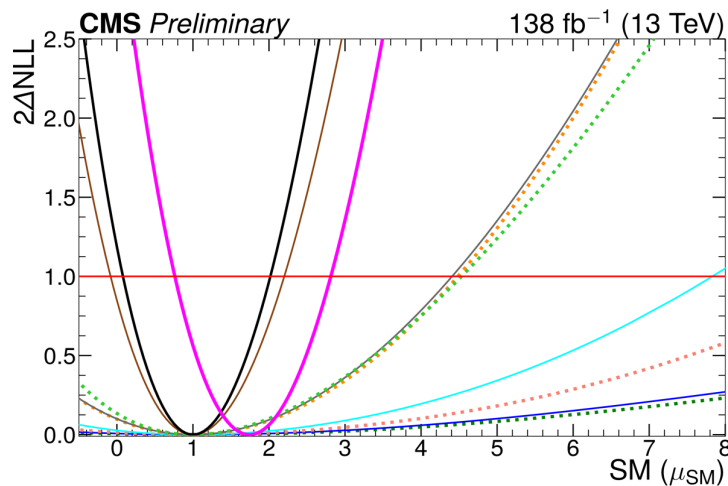
- ✓ Three massive VVV boson production is a rare process -> observed earlier by CMS & ATLAS
- ✓ Sensitive to TGC, QGC, Higgs gauge coupling -> focus on EFT interpretation of VVV
- ✓ The analysis is BSM search driven

This search includes:  
WWW, WWZ, WZZ, ZZZ  
(boosted region:  $P_T > 200$  GeV)



$$L = L_{\text{SM}} + \sum_{\text{dim}-6} \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_{\text{dim}-8} \frac{f_j}{\Lambda^4} \mathcal{O}_j.$$

zero in SM

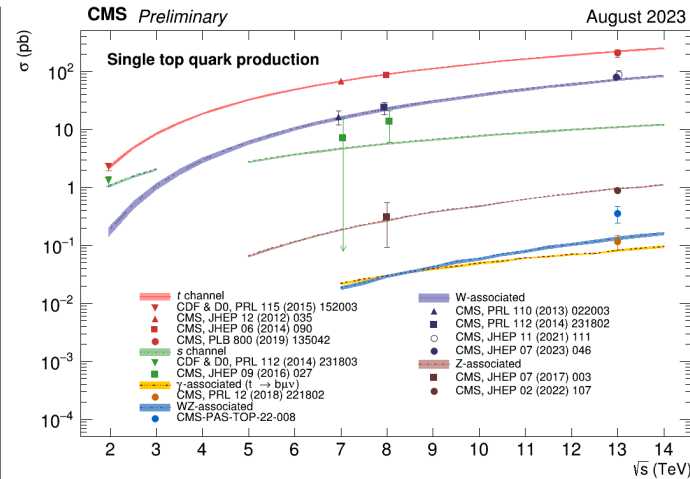
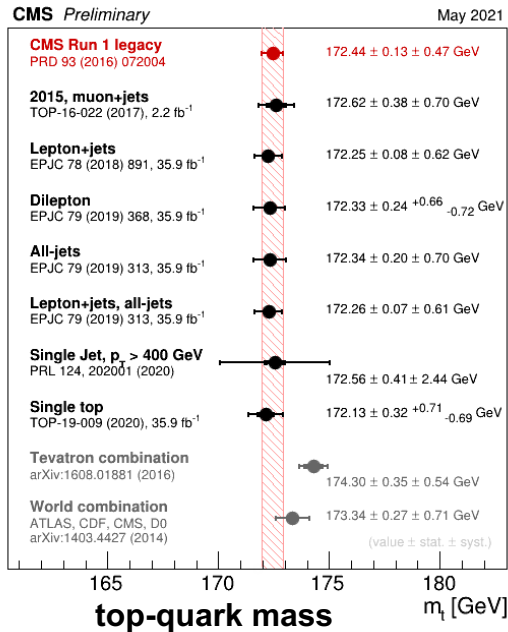


$$-0.13 < c_W / \Lambda^2 < 0.12 \text{ TeV}^{-2}$$

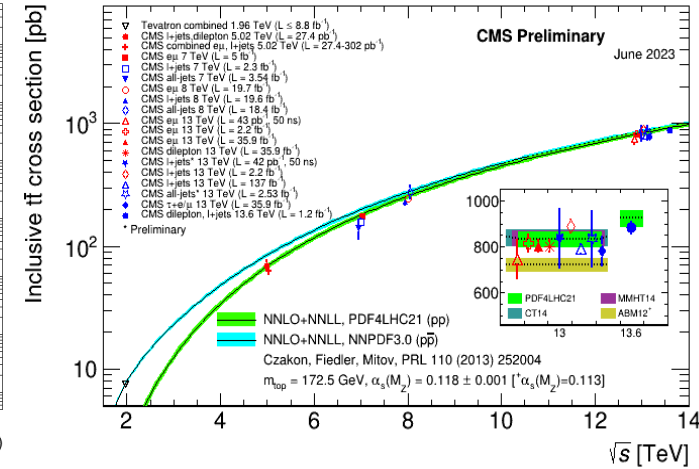
$$-0.24 < c_{Hq3} / \Lambda^2 < 0.21 \text{ TeV}^{-2}$$

CMS-PAS-SMP-24-017

# Triumphs in top-quark sector

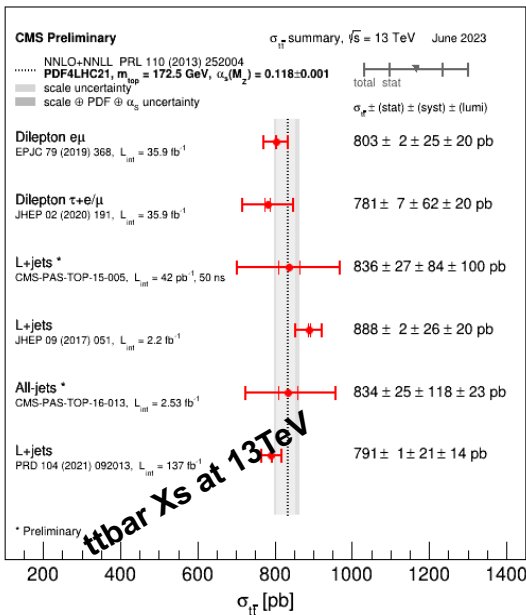
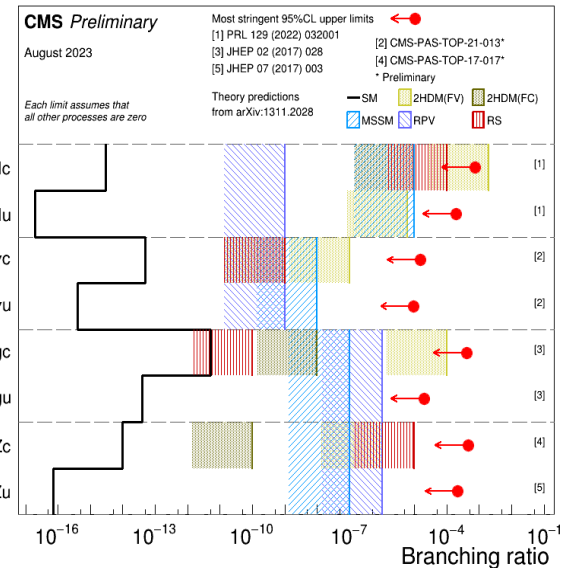
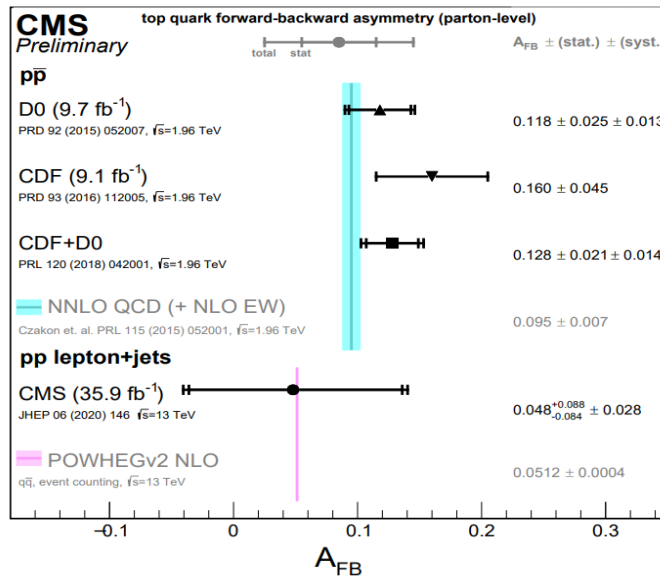


single top production cross section



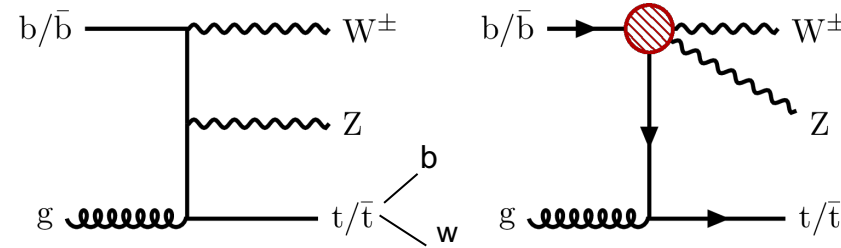
ttbar Xs as function of COM energy

top-antitop forward backward asymmetry



# Rare top production via tWZ process

- Provides access of EW coupling to top quark. Allows stringent test of gauge structure of SM.
- Events with 3 and 4 lepton final states with jets and missing  $P_T$  (final state: bWWZ, Z→opposite sign same flavor leptons, one of the W→ lepton/jets)
- Very small production cross section,  $136 \pm 10$  fb @13TeV and  $147.8 \pm 10$  fb @13.6TeV
- Challenging background ttZ and WZ+jets
- Simultaneous fit to multiple analysis regions
- $\sigma_{tWZ} = 248 \pm 52$  fb (13 TeV),  $244 \pm 74$  fb (13.6 TeV)
- $5.8\sigma$  observed significance ( $3.5\sigma$  expected)
- First observation of tWZ (Run2 and Run3 data)

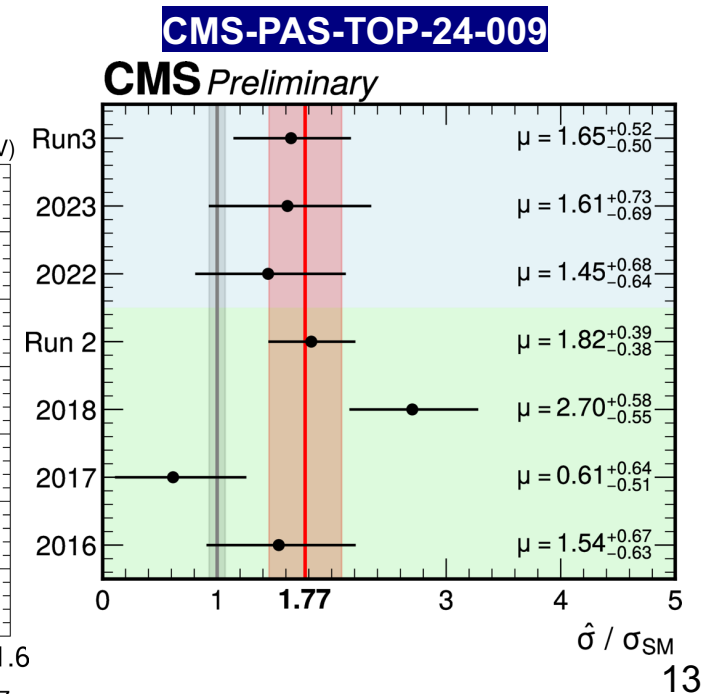
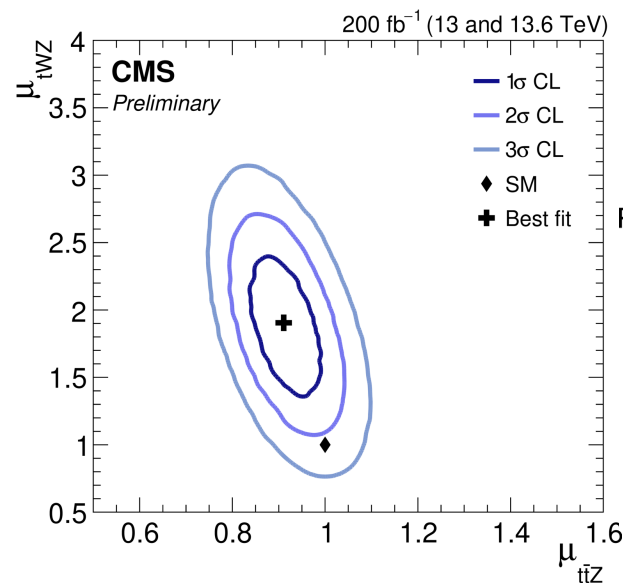
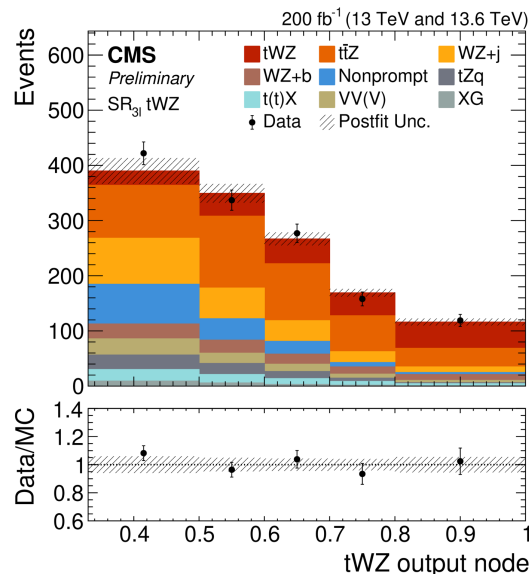


## Semi-leptonic tWZ

- At least 2 jets
- At least 1 b-jet
- Exactly 3 leptons
- $|m(\text{ll})-m(\text{Z})| < 15$  GeV

## Fully-leptonic tWZ

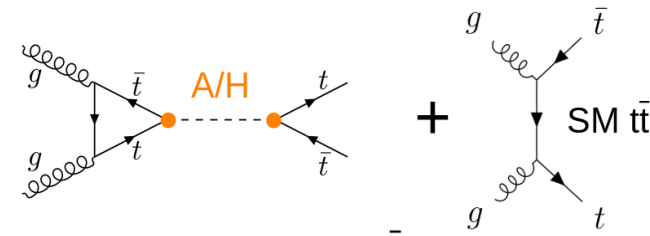
- At least 1 jet
- At least 1 b-jet
- Exactly 4 leptons
- $|m(\text{ll})-m(\text{Z})| < 15$  GeV



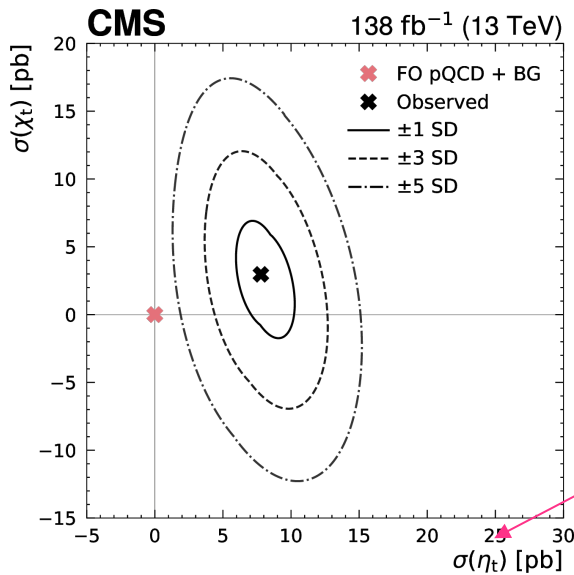


# Observation of pseudoscalar (toponium) to top pair

- $t\bar{t}$  pair don't form bound state due to short lifetime, but NRQCD predicts bound state enhancement at  $t\bar{t}$  threshold (toponium color singlet bound state)
- Final states: two leptons and at least two jets
- Signal extracted with 3D likelihood fit to  $m_{t\bar{t}}$ ,  $C_{\text{hel}}$ ,  $C_{\text{han}}$  ( $C_{\text{hel}}$ ,  $C_{\text{han}}$  are angular variables of leptons w.r.t parent  $t\bar{t}$ )



Rep. Prog. Phys 88 (2025) 087801

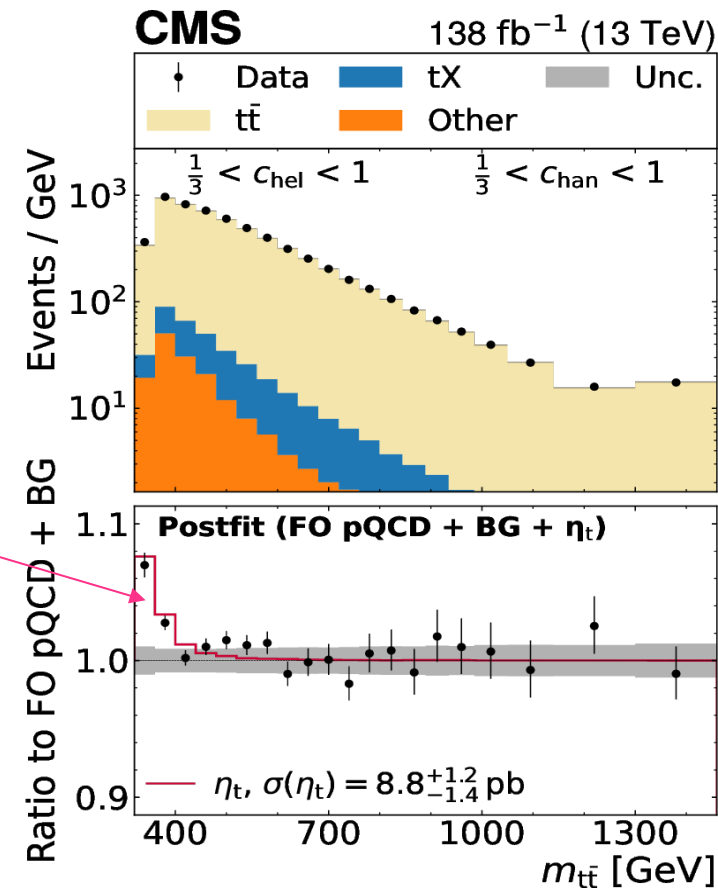


To determine the spin and CP structure, both pseudo-scalar ( $\eta_t$ ) and scalar ( $\chi_t$ ) components are included.

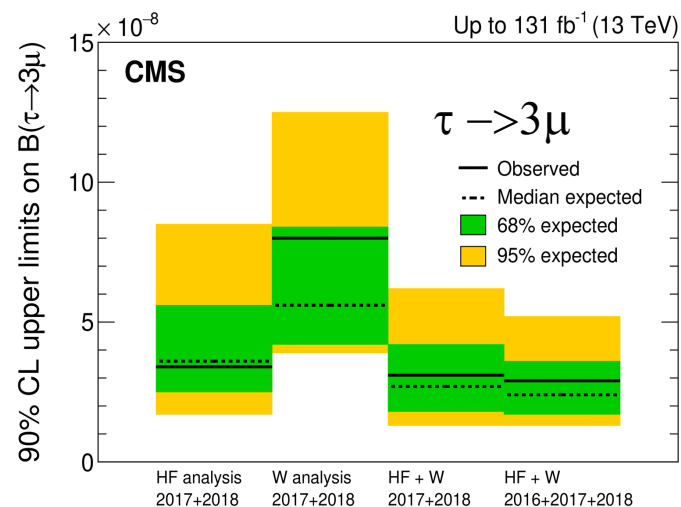
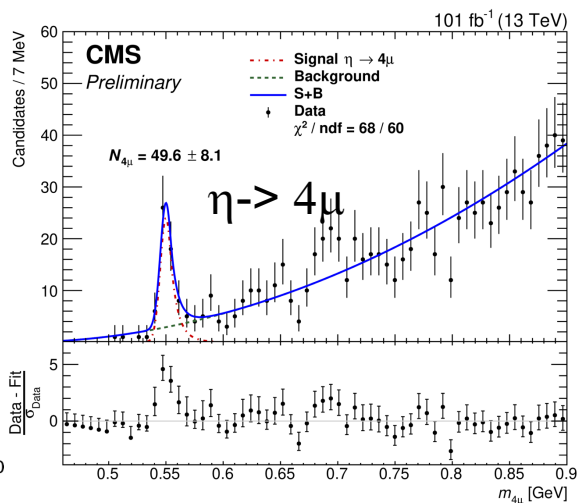
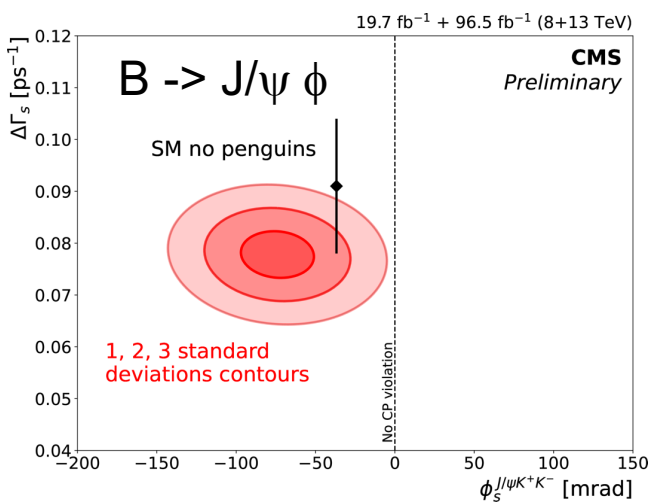
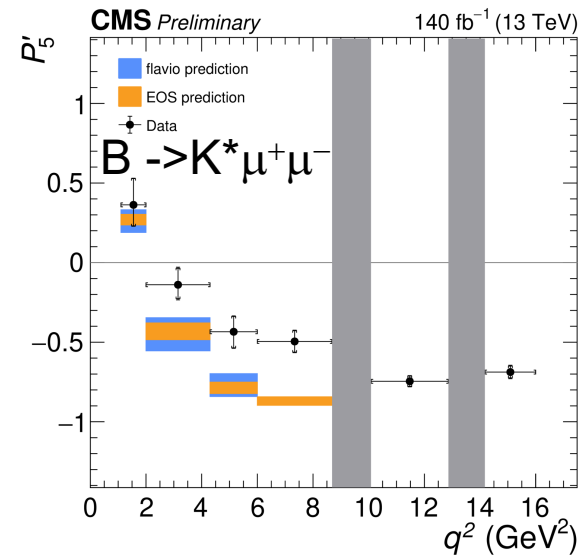
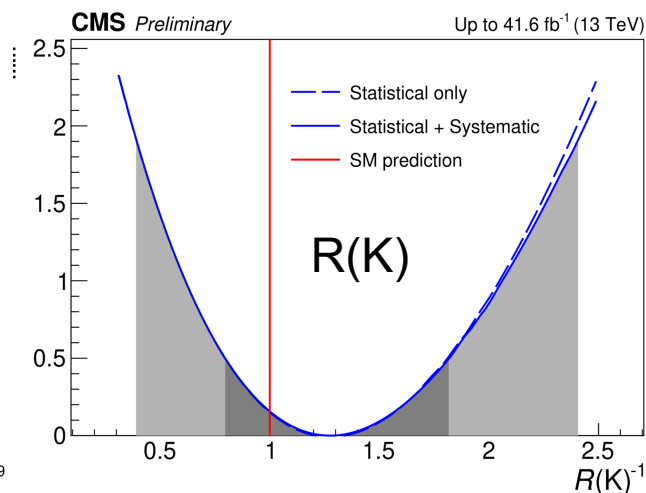
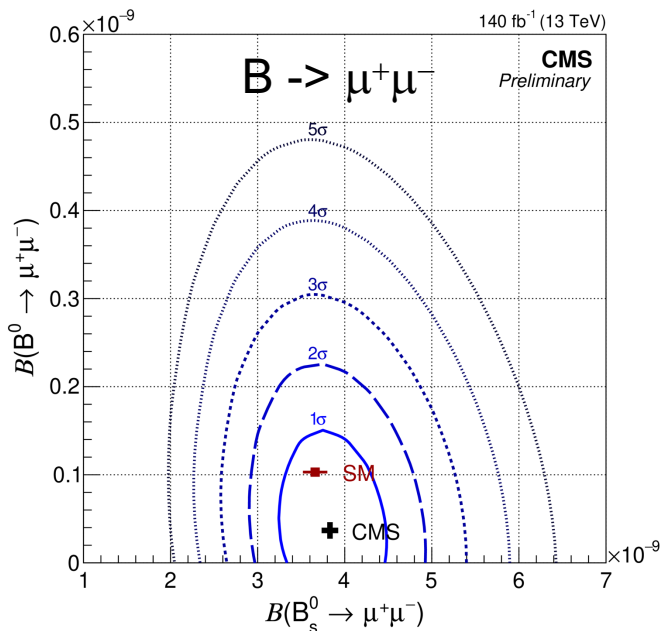
Excess compatible with pseudo-scalar hypothesis (more than  $5\sigma$  signal sig)

The result is compatible with formation of Pseudo-scalar state ( $\eta_t$ ) with cross section:

$$\sigma(\eta_t) = 8.8 \pm 0.5 (\text{stat})_{-1.3}^{+1.1} (\text{syst}) \text{ pb} = 8.8_{-1.4}^{+1.2} \text{ pb}$$



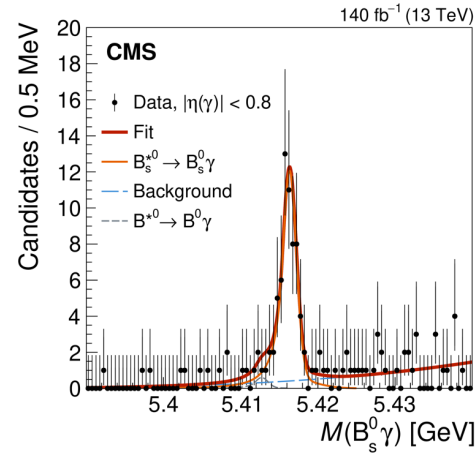
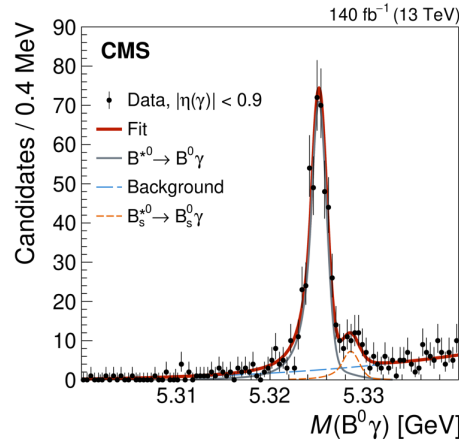
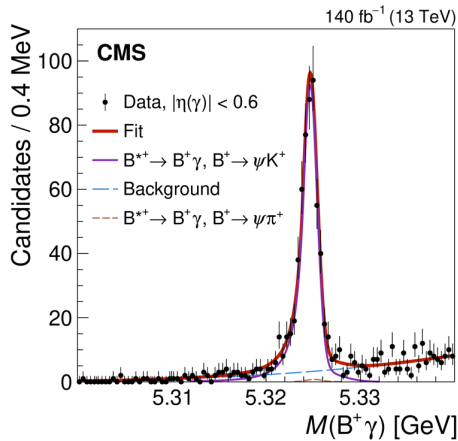
# Triumphs in B-meson-sector



# Exclusive B\* reconstruction

- First exclusive reconstruction of excited vector B meson states:  $B^{*+}$ ,  $B^{*0}$ ,  $B_s^{*0}$   
 -> Main challenge is low-energy photon (40-50 MeV) from  $B^* \rightarrow B\gamma$
- Low energy photons are reconstructed through conversions into  $e^+e^-$  pairs  
 -> Small angular separation  
 -> conversion vertex at least 1.5cm away from beam axis  
 -> Two tracks to originate from same vertex with zero invariant mass
- To improve resolution, the  $B\gamma$  invariant mass is evaluated using

$$M(B\gamma) = \dot{m}(B\gamma) - m(B) + M_B^{PDG}$$



$$\begin{aligned} \Delta m(B^{*+}) &\equiv m(B^{*+}) - m(B^+) & 45.277 \pm 0.039 \pm 0.027 \text{ MeV} \\ \Delta m(B^{*0}) &\equiv m(B^{*0}) - m(B^0) & 45.471 \pm 0.056 \pm 0.028 \text{ MeV} \\ \Delta m(B_s^{*0}) &\equiv m(B_s^{*0}) - m(B_s^0) & 49.407 \pm 0.132 \pm 0.041 \text{ MeV} \end{aligned}$$

**arXiv: 2508.05820**  
 (submitted to PRL)

~order of magnitude improvement in precision than the previous measurements

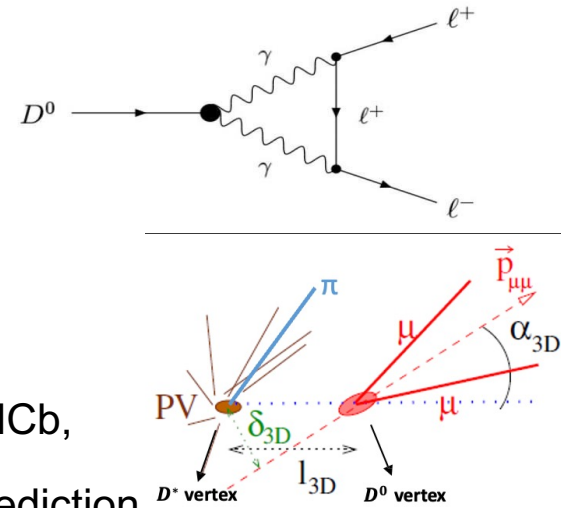
# Rare charm decay $D^0 \rightarrow \mu^+ \mu^-$

- ✓ Compared to "b  $\rightarrow$  s" ( $B_s$  meson decays,  $\sim 10^{-9}$ ), rare charm decays mediated by "c  $\rightarrow$  u" transition, are not explored much.

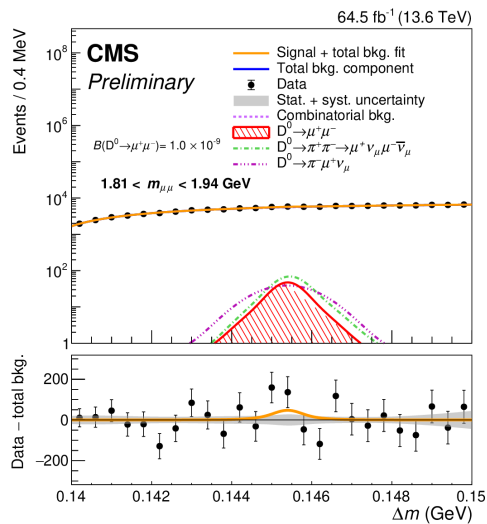
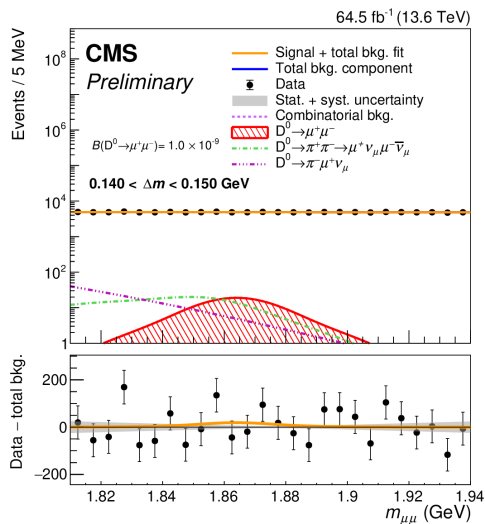
- SM Prediction:  $\text{BF}(D^0 \rightarrow \mu\mu) > \sim 3 \times 10^{-13}$  (Long distance)

PRD 66 (2002) 014009

- Most stringent experimental  $\text{BF} < 3.5 \times 10^{-9}$  at 95% CL from LHCb, PRL 131, 041804, which is 4 orders of magnitude larger than SM prediction



- ✓ Look for  $D^0 \rightarrow \mu^+ \mu^-$  through cascade decay of  $D^{*+} \rightarrow D^0 \pi^+$
- ✓ The extra soft pion reduces the background by orders of magnitude
- ✓ Signal yield extracted with 2D fit to:  $D^0(\mu^+ \mu^-)$  mass and  $\Delta m$  ( $m_{D^{*+}} - m_{D^0}$ )



$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) = \mathcal{B}(D^0 \rightarrow \pi^+ \pi^-) \frac{N_{D^0 \rightarrow \mu^+ \mu^-}}{N_{D^0 \rightarrow \pi^+ \pi^-}} \frac{\epsilon_{D^0 \rightarrow \pi^+ \pi^-}}{\epsilon_{D^0 \rightarrow \mu^+ \mu^-}}$$

No significant excess over background expectation is found

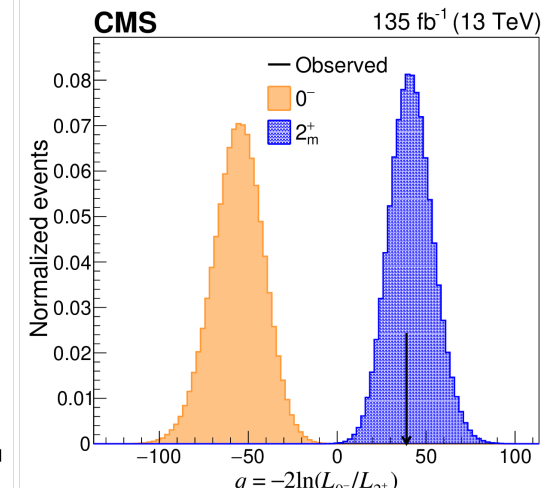
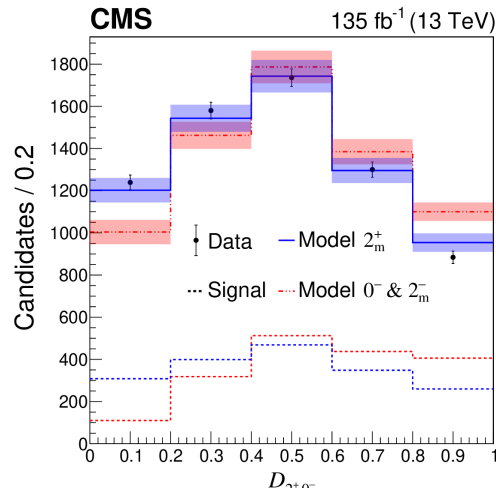
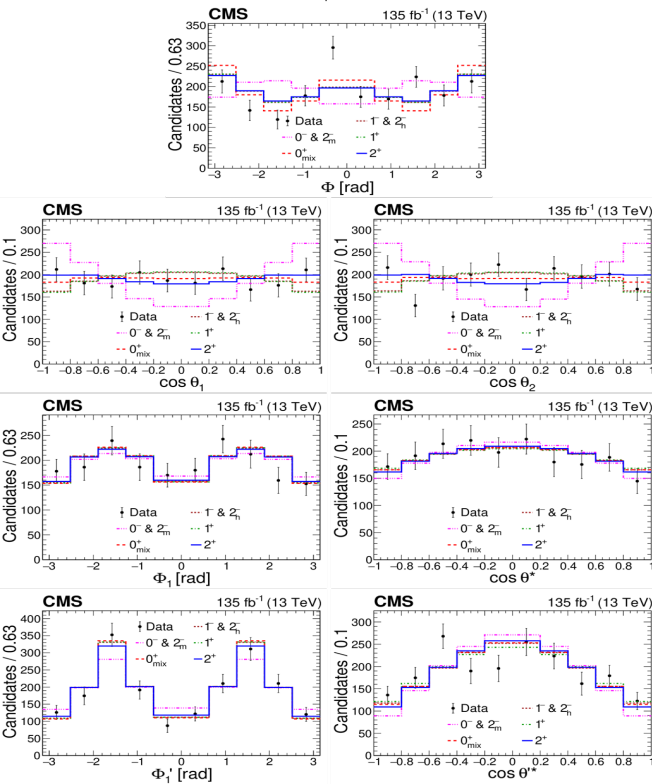
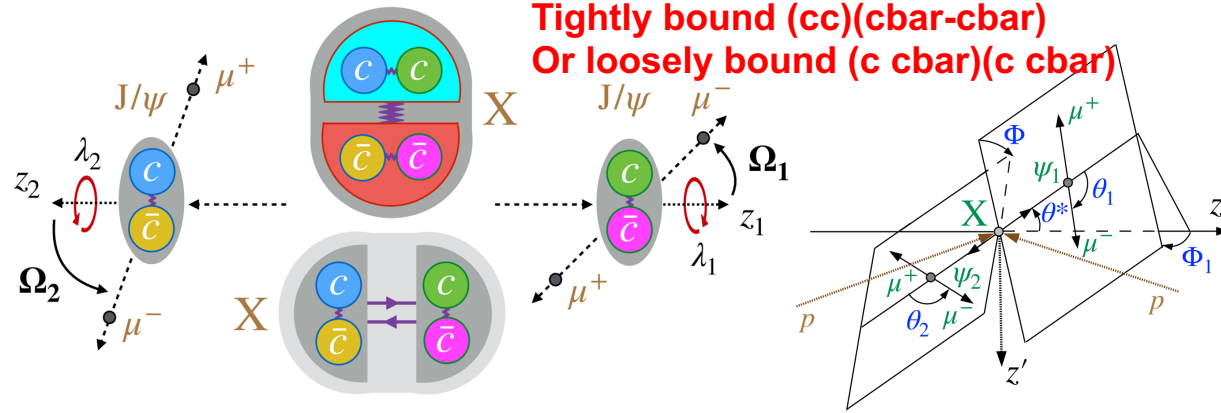
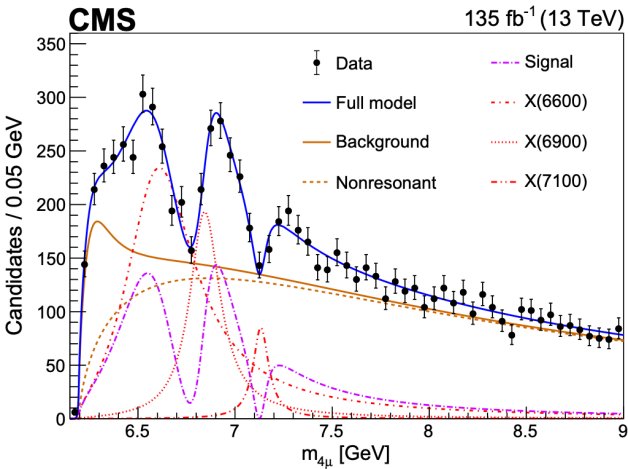
$$\mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 2.6 \times 10^{-9} \text{ at 95\% CL}$$

30% improvement over the previous limit

**PRL 135 (2025) 151803**

# Spin and Parity of all-charm tetrquark

- ✓ Although several Baryons and Mesons are seen, the observation of tetra-quark and penta-quark are recent development (starting 2003). Needs detail study of their internal structure.



$J^{PC}$	Models $J_i^P$	Contributing amplitudes	<b><math>J^{PC} = 2^{++}</math> favored</b>
$0^{-+}$	$0^-$	$A_{++} = -A_{--}$	
$0^{++}$	$0_m^+$ and $0_h^+$	$A_{++} = A_{--}$ and $A_{00}$	
$1^{-+}$	$1^-$	$A_{+0} = -A_{0+} = A_{-0} = -A_{0-}$	
$1^{++}$	$1^+$	$A_{+0} = -A_{0+} = -A_{-0} = A_{0-}$	
$2^{-+}$	$2_m^-$ and $2_h^-$	$A_{++} = -A_{--}$ and $A_{+0} = A_{0+} = -A_{-0} = -A_{0-}$	
$2^{++}$	$2_m^+$	$A_{++} = A_{--}, A_{00}, A_{+0} = A_{0+} = A_{-0} = A_{0-},$ and $A_{+-} = A_{-+}$	

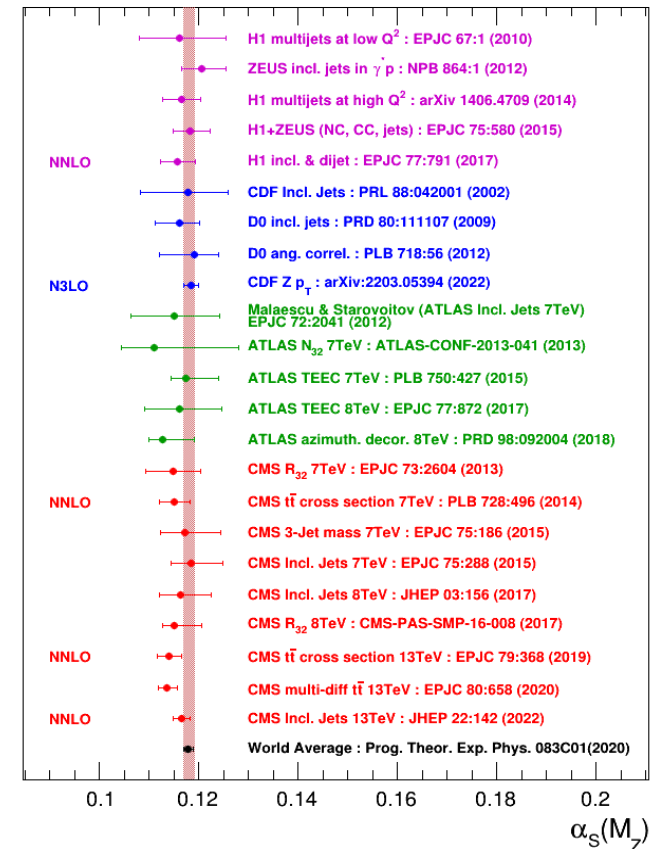
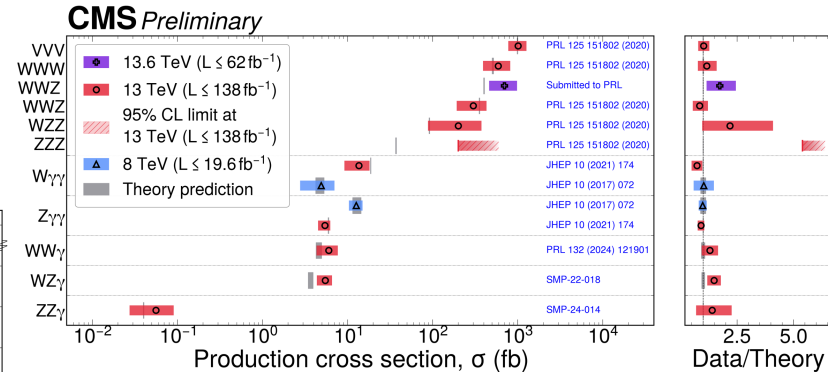
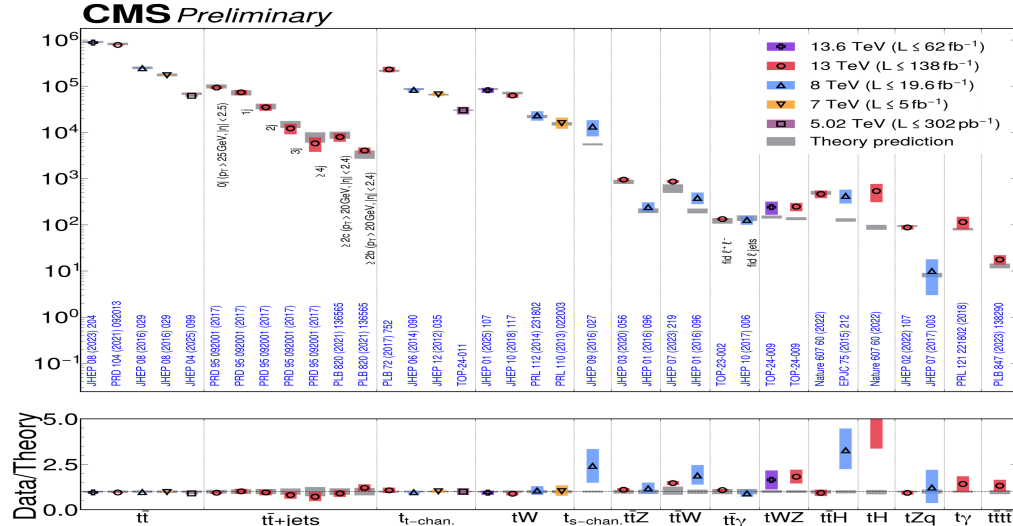
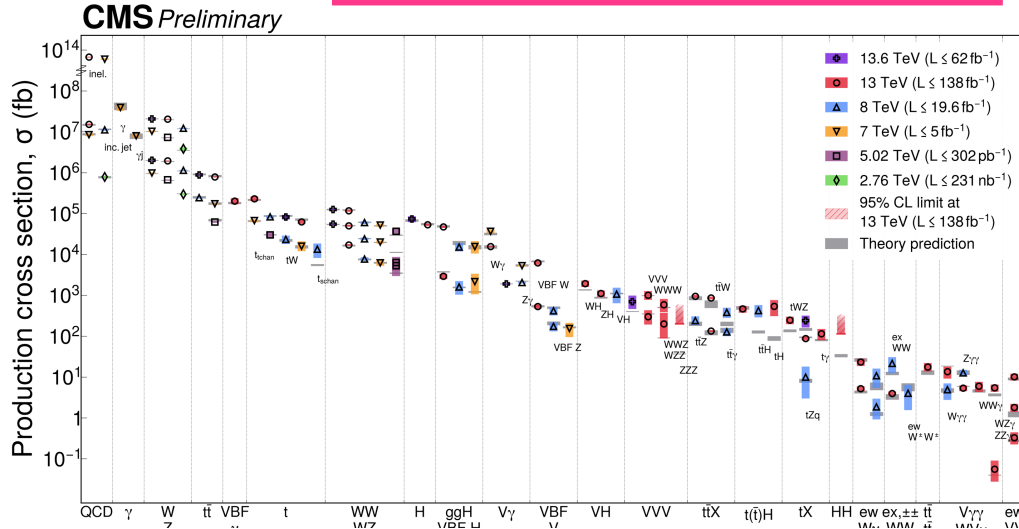
**CMS-PAS-SMP-24-017**  
**Accepted by Nature**



# SM as a successful model

SM Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + \frac{1}{2} \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$



# Going beyond SM (SUSY searches)

CMS Preliminary

July 2023

## Overview of SUSY results: GMSB / GGM

137 fb<sup>-1</sup> (13 TeV)

### pp → $\tilde{g}\tilde{g}$

$\gamma + \text{MET}$ : arXiv:1711.08008 (max. exclusion) [36 fb<sup>-1</sup>]

$\gamma + \text{HT}$ : arXiv:1707.06193 (max. exclusion) [36 fb<sup>-1</sup>]

$\gamma\gamma$ : arXiv:1903.07070 (max. exclusion) [36 fb<sup>-1</sup>]

$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 \rightarrow q\bar{q}\gamma\tilde{G}/q\bar{q}'\tilde{\chi}_1^\pm \rightarrow q\bar{q}'W\tilde{G}$ :  $\gamma + \text{MET}$ : arXiv:1711.08008 (max. exclusion) [36 fb<sup>-1</sup>]

$\gamma + \text{HT}$ : arXiv:1707.06193 (max. exclusion) [36 fb<sup>-1</sup>]

$\gamma + \ell + \text{MET}$ : arXiv:1812.04066 (max. exclusion) [36 fb<sup>-1</sup>]

combined: arXiv:1907.00857 (max. exclusion) [36 fb<sup>-1</sup>]

$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow (\gamma/H)\tilde{G}$ :  $\gamma + b + \text{MET}$ : SUS-21-009 (max. exclusion)

$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow (\gamma/Z)\tilde{G}$ :  $\gamma + b + \text{MET}$ : SUS-21-009 (max. exclusion)

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow (\gamma/Z)\tilde{G}$ :  $\gamma + b + \text{MET}$ : SUS-21-009 (max. exclusion)

$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$ : 2 $\ell$  opposite-sign: arXiv:2012.08600 (max. exclusion)

### pp → $\tilde{q}\tilde{q}$

$\gamma + \text{MET}$ : arXiv:1711.08008 (max. exclusion) [36 fb<sup>-1</sup>]

$\gamma + \text{HT}$ : arXiv:1707.06193 (max. exclusion) [36 fb<sup>-1</sup>]

$\gamma\gamma$ : arXiv:1903.07070 (max. exclusion) [36 fb<sup>-1</sup>]

$\tilde{q} \rightarrow (q\tilde{\chi}_1^0 \rightarrow q\gamma\tilde{G}/q\tilde{\chi}_1^\pm \rightarrow qW\tilde{G})$ :  $\gamma + \text{MET}$ : arXiv:1711.08008 (max. exclusion) [36 fb<sup>-1</sup>]

$\gamma + \text{HT}$ : arXiv:1707.06193 (max. exclusion) [36 fb<sup>-1</sup>]

$\gamma + \ell + \text{MET}$ : arXiv:1812.04066 (max. exclusion) [36 fb<sup>-1</sup>]

### pp → $\tilde{t}\tilde{t}$

$\gamma + b + \text{MET}$ : SUS-21-009 (max. exclusion)

### pp → $\tilde{\chi}_1^0\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$

$\gamma + \ell + \text{MET}$ : arXiv:1812.04066 [36 fb<sup>-1</sup>]

$\gamma + b + \text{MET}$ : SUS-21-009

$\gamma + \text{MET}$ : arXiv:1711.08008 BF(Z:H; $\gamma$ ) = 1:1:2 [36 fb<sup>-1</sup>]

$\gamma + b + \text{MET}$ : SUS-21-009 BF(Z:H; $\gamma$ ) = 1:1:2, Higgsino-like NLSPs

## Higgsino – like NLSPs

### pp → $(\tilde{\chi}_1^\pm, \tilde{\chi}_2^0, \tilde{\chi}_1^0)(\tilde{\chi}_1^\pm, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$

$\geq 3\ell/\tau_h$ : arXiv:2106.14246

$h \rightarrow b\bar{b}$ : arXiv:2201.04206

$h \rightarrow \gamma\gamma$ : arXiv:1908.08500 [78 fb<sup>-1</sup>]

combined: SUS-21-008

2 $\ell$  opposite-sign: arXiv:2012.08600 BF = 50%

$\geq 3\ell/\tau_h$ : arXiv:2106.14246 BF = 50%

$h \rightarrow \gamma\gamma$ : arXiv:1908.08500 BF = 50% [78 fb<sup>-1</sup>]

combined: SUS-21-008 BF = 50%

2 $\ell$  opposite-sign: arXiv:2012.08600

$\geq 3\ell/\tau_h$ : arXiv:2106.14246

combined: SUS-21-008

### pp → $(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

$\gamma + b + \text{MET}$ : SUS-21-009 BF = 50%

$h \rightarrow b\bar{b}$ : arXiv:2201.04206

mass scale [GeV]

CMS Preliminary

June 2023

## Overview of SUSY results: electroweak production

137 fb<sup>-1</sup> (13 TeV)

### pp → $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$

2 $\ell$  same-sign and 3 $\ell$ : arXiv:2106.14246 flavour democratic,  $x = 0.5$

2 $\ell$  same-sign and  $\geq 3\ell$ : arXiv:2106.14246 flavour democratic,  $x = 0.05$

2 $\ell$  same-sign and  $\geq 3\ell$ : arXiv:2106.14246 flavour democratic,  $x = 0.95$

2 $\ell$  same-sign and 3 $\ell/\tau_h$ : arXiv:2106.14246  $\tau$  enriched,  $x = 0.5$

3 $\ell/\tau_h$ : arXiv:2106.14246  $\tau$  enriched,  $x = 0.05$

3 $\ell/\tau_h$ : arXiv:2106.14246  $\tau$  enriched,  $x = 0.95$

pp →  $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu\tau\tilde{\tau} \rightarrow \tau\nu\tau\tau\tilde{\chi}_1^0\tilde{\chi}_1^0$ :  $\tau$  dominated,  $x = 0.5$

pp →  $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow W\tilde{H}\tilde{\chi}_1^0\tilde{\chi}_1^0$ : 2 $\ell$  same-sign and  $\geq 3\ell/\tau_h$ : arXiv:2106.14246

1 $\ell$ +jets: arXiv:2107.12553

0 $\ell$  W+X: arXiv:2205.09597

Combination: SUS-21-008

2 $\ell$  opposite-sign: arXiv:2012.08600

2 $\ell$  same-sign and 3 $\ell$ : arXiv:2106.14246

2 $\ell$  and 3 $\ell$  soft: arXiv:2111.06296  $\Delta M = 5-10$  GeV

0 $\ell$  W+X: arXiv:2205.09597

Combination: SUS-21-008

2 $\ell$  and 3 $\ell$  soft: arXiv:2111.06296 higgsino simplified model,  $\Delta M = 5-10$  GeV

### pp → $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$

2 $\ell$  opposite-sign: arXiv:1807.07799  $M_{\tilde{\chi}_1^\pm} = 1$  GeV ( $\mathcal{L} = 35.9$  fb<sup>-1</sup>)

0 $\ell$  W+X: arXiv:2205.09597

2 $\ell$  opposite-sign: arXiv:1807.07799 BF( $\tilde{\nu}\nu$ ) = 50%,  $x = 0.5$  ( $\mathcal{L} = 35.9$  fb<sup>-1</sup>)

### pp → $\tilde{\ell}\tilde{\ell}$

$\tilde{\nu}\nu, \mu\mu, \tau\tau$ : arXiv:2012.08600

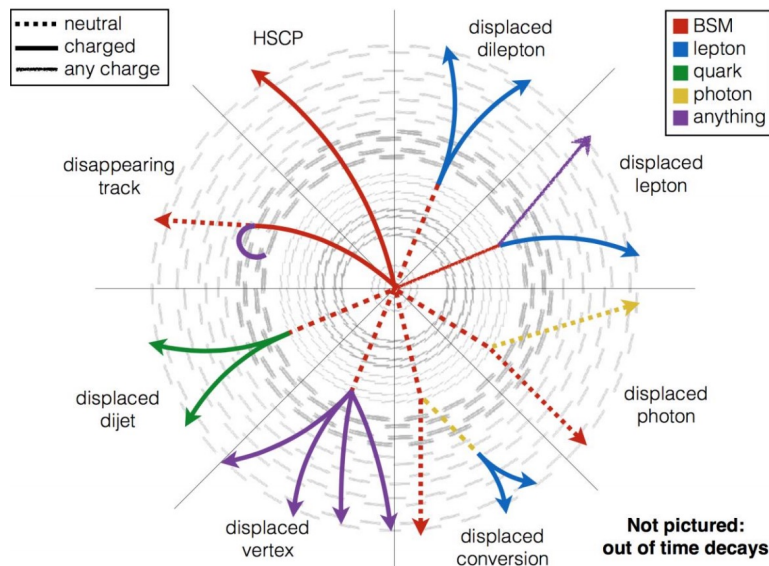
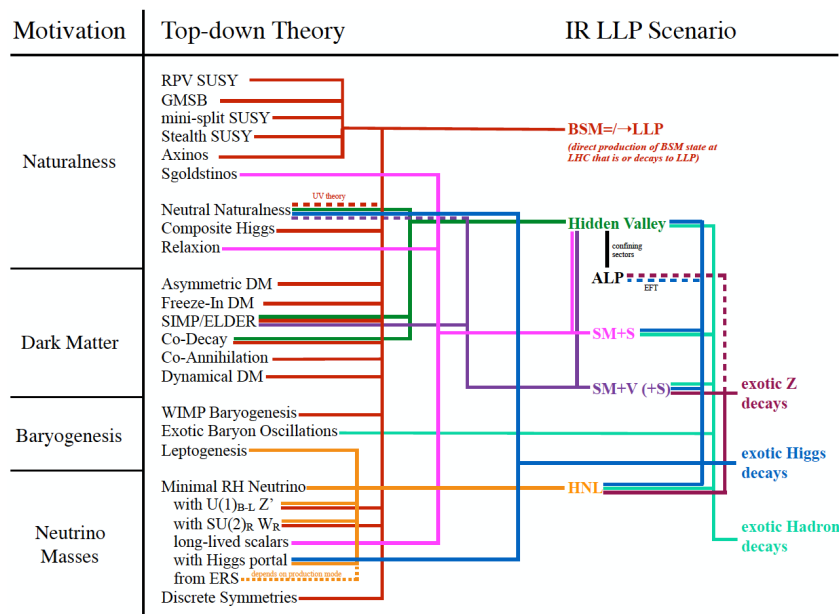
mass scale [GeV]

✓ Several search modes (involving gluinos, squarks, stop, chargino, neutralino, sleptons) have been explored using LHC data over last decade.

✓ No hints for SUSY

✓ The exclusion limit, for some cases, is as big as 2TeV or even more

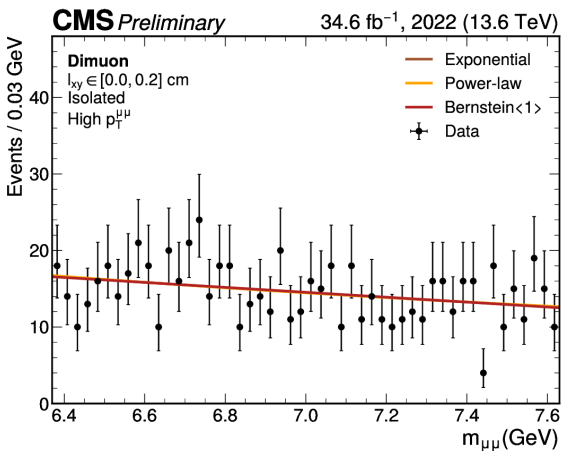
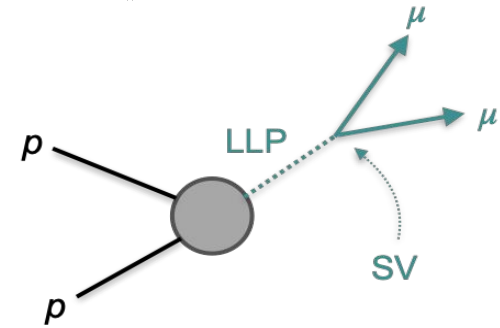
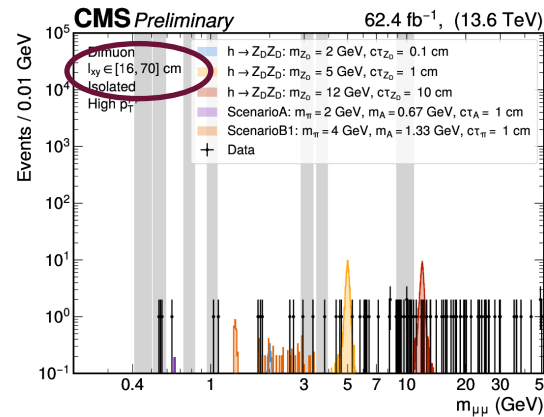
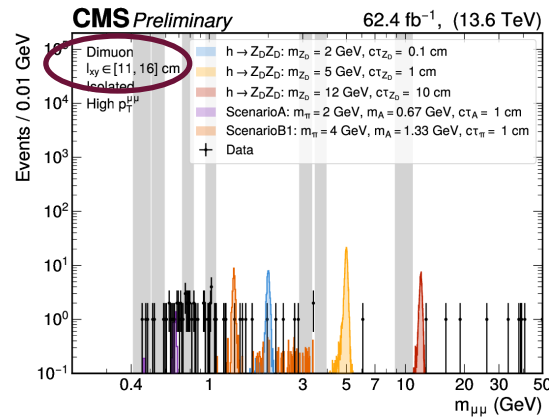
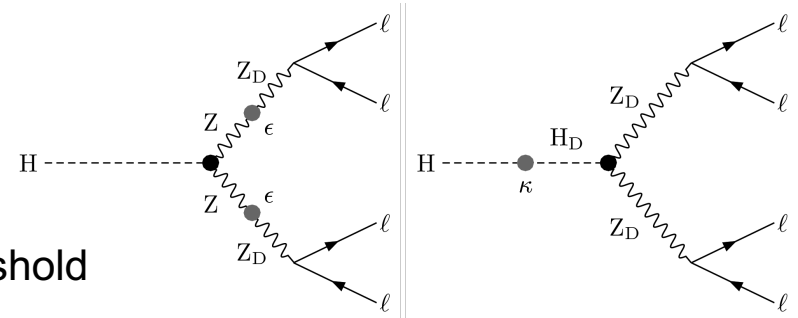
# BSM search through LLPs



- ✓ Several BSM theories try to explain hierarchy problem, dark matter, baryogenesis, non-zero neutrino masses, etc.  
=> No BSM found till date
- ✓ Most BSM searches focus on heavy states that promptly decay to high energy visible particles such as jets, leptons, photons etc.
- ✓ A generic and much less explored alternative is that BSM shows up as new Long Lived Particles (LLPs) decaying to SM particle at some macroscopic distance away from production points.
- ✓ Several such displaced signatures (shown on the left figure) are being searched at LHC
- ✓ The lifetime of the LLPs are in general free parameters of the model (can live up to  $10^7 m$ ).

# LLPs decaying to two muons

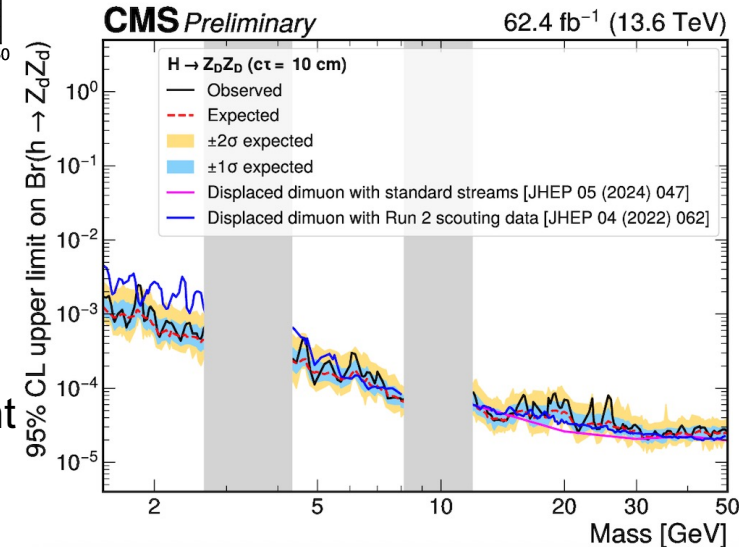
- Dark photons  $Z_D$  decaying to pairs of muons
- Assume  $Z_D$  is long lived  $\rightarrow$  Displaced vertex  
Either produced via kinetic  $Z$ - $Z_D$  mixing  
or via decays of a mixed dark Higgs boson
- Dedicated dimuon trigger with low momentum threshold
- Fit around each signal hypothesis to test for signal



No significant excess in the dimuon invariant mass.

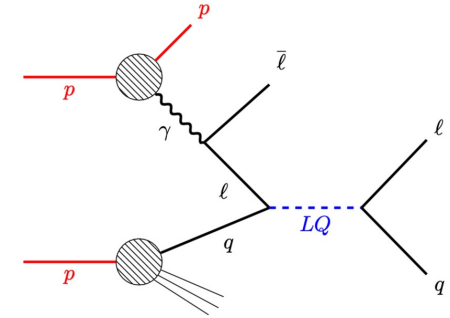
Most stringent limits at low masses and large displacement

**CMS-PAS-EXO-24-016**

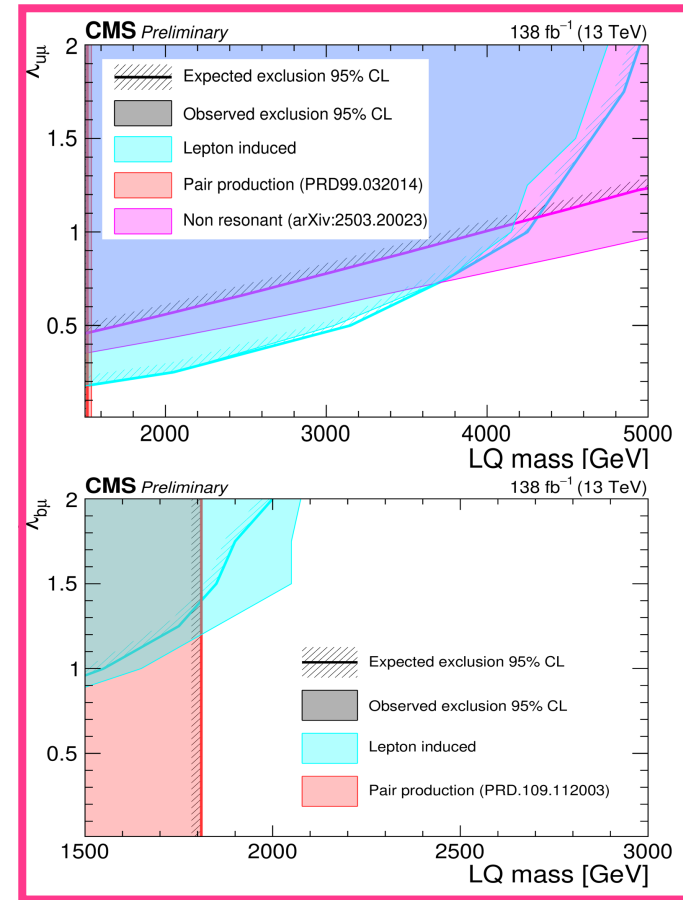
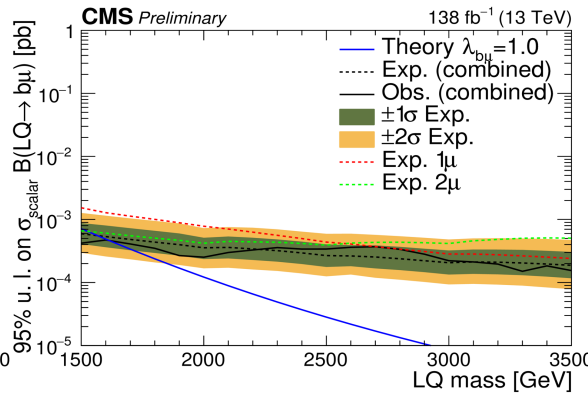
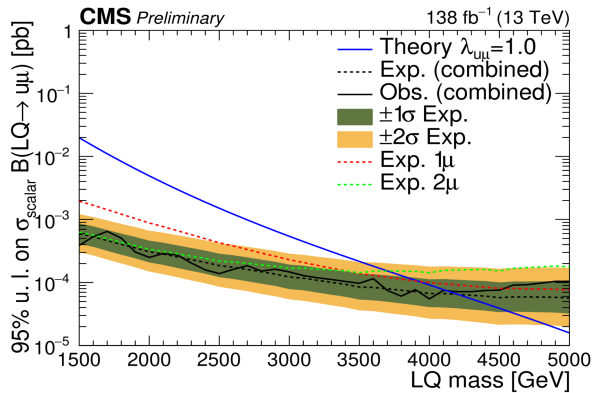
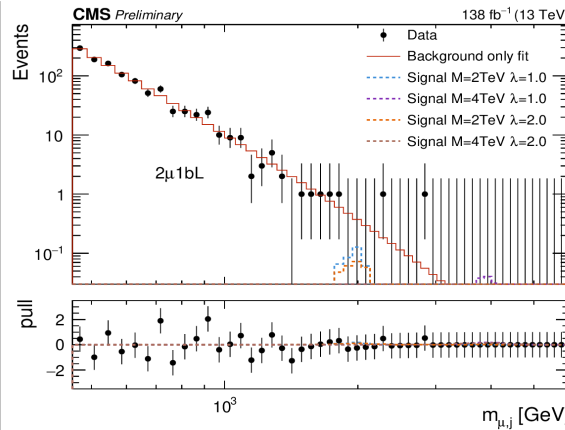
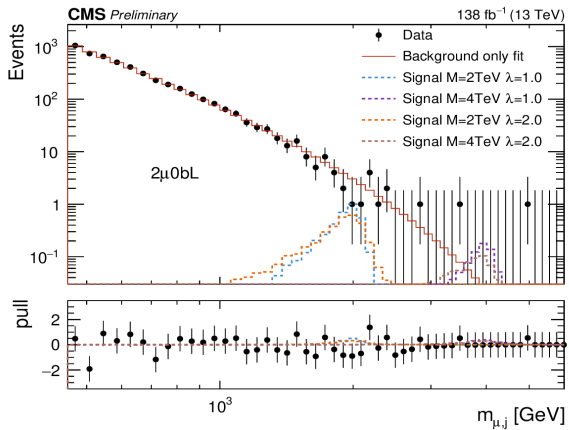


# Scalar for lepto-quark (LQ) via muon-quark scattering

- LQs are foreseen in many BSM models: GUT, SUSY, RPV, etc
- 1<sup>st</sup> (eq), 2<sup>nd</sup> ( $\mu q$ ), 3<sup>rd</sup> ( $\tau q$ ) generation of LQs
- In LHC LQs can be produced in different modes, however, here we considered lepton induced production
- Final state: High  $P_T$  lepton and a jet from LQ, with a second same flavor lepton from photon
- light-quark mass: 1.5-3.6 TeV,  $\lambda$ : 0.2-0.6 excluded
- b-quark mass: >1.8 TeV,  $\lambda$ : >1 excluded



**CMS-PAS-EXO-24-005**





# Search for Microscopic BH and Sphalerons

✓ Extra dimensions theory provides solutions to Hierarchy problems

-> Predicts microscopic Blackholes  $M_{pl}^2 \sim M_D^{n+2} R^n$   $R$  is size of each extra dimensions

When  $n$  is large  $M_D \sim \text{TeV}$  (within reach of LHC) -> decay to high multiplicity jets and leptons

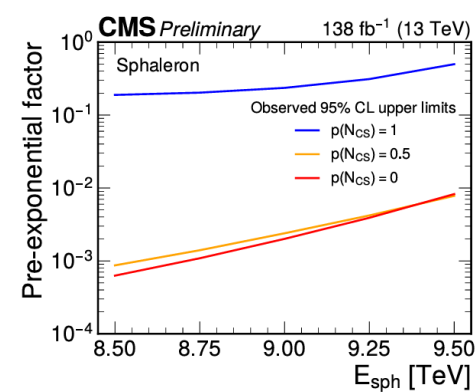
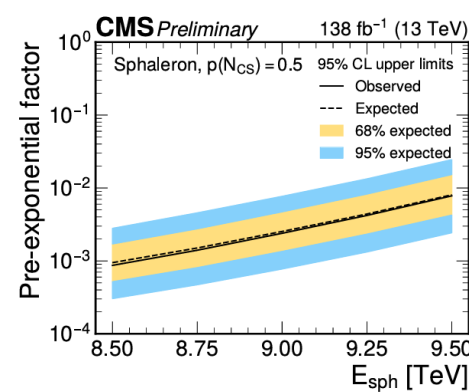
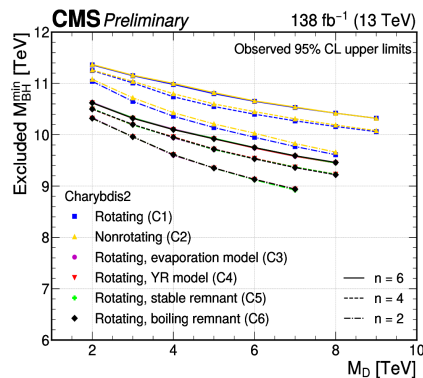
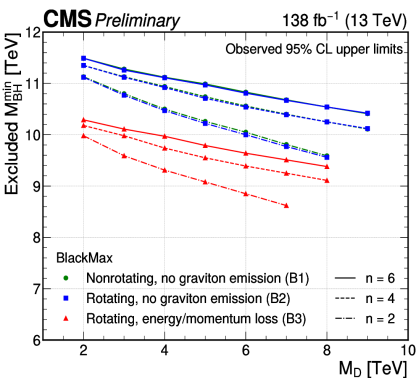
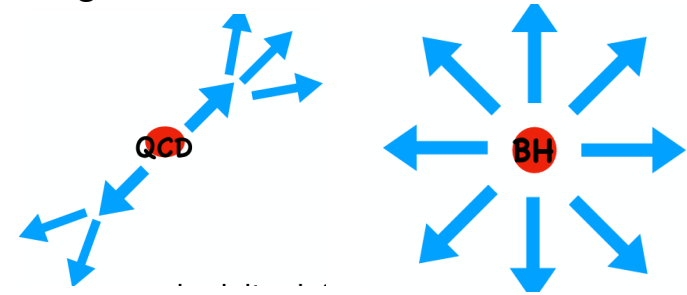
✓ Sphaleron gives solutions to baryon asymmetry by B and L violation

- Decay to 12 fermions, either all matter or all anti-matter
- One lepton from each generation, three quarks from each generation

$l1q1q1q1\ l2q2q2q2\ l3q3q3q3$ , e.g.  $e\ u u d\ \mu\ c c s\ \tau\ t t b$

✓ The most important variable to look  $s_T = \left( \sum_{i=1}^N p_{T,i} \right) + p_T^{\text{miss}}$

✓ Also look for sphericity of the event:



- ✓ No excess seen over the background expectation
- ✓ Excludes blackholes with masses below 9-11.4 TeV

**CMS-PAS-EXO-24-028**

# LLP search summary from CMS

SUSY RPV

UDD,  $\tilde{g} \rightarrow t\bar{b}s$ ,  $m_{\tilde{g}} = 2500$  GeV  
 UDD,  $\tilde{g} \rightarrow t\bar{b}s$ ,  $m_{\tilde{g}} = 2500$  GeV  
 UDD,  $\tilde{t} \rightarrow \bar{d}d$ ,  $m_{\tilde{t}} = 1600$  GeV  
 UDD,  $\tilde{t} \rightarrow \bar{d}d$ ,  $m_{\tilde{t}} = 1600$  GeV  
 LQD,  $\tilde{t} \rightarrow b\bar{l}$ ,  $m_{\tilde{t}} = 600$  GeV  
 LQD,  $\tilde{t} \rightarrow b\bar{l}$ ,  $m_{\tilde{t}} = 460$  GeV  
 LQD,  $\tilde{t} \rightarrow b\bar{l}$ ,  $m_{\tilde{t}} = 1600$  GeV

SUSY RPC

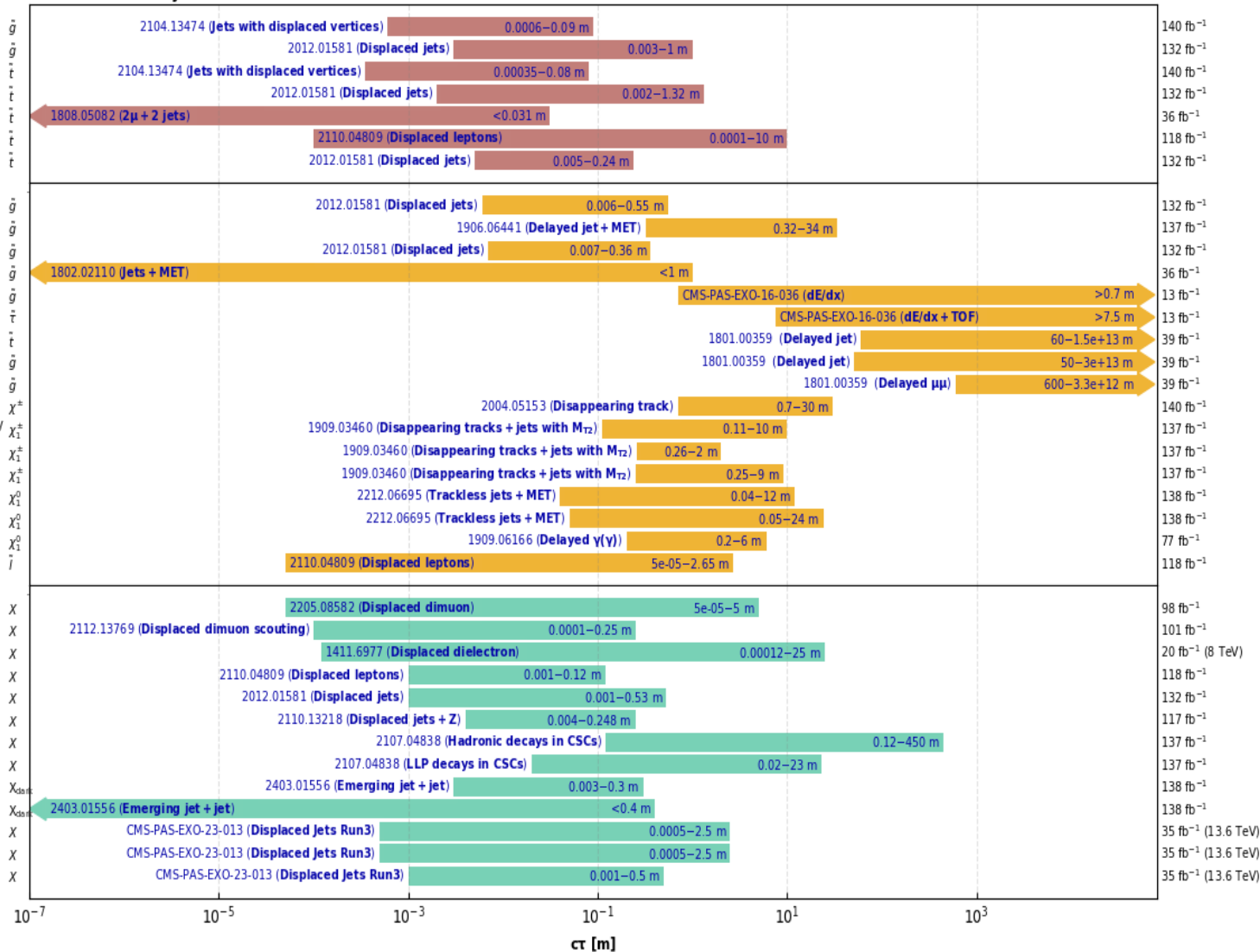
GMSB,  $\tilde{g} \rightarrow g\tilde{G}$ ,  $m_{\tilde{g}} = 2450$  GeV  
 GMSB,  $\tilde{g} \rightarrow g\tilde{G}$ ,  $m_{\tilde{g}} = 2100$  GeV  
 Split SUSY,  $\tilde{g} \rightarrow q\bar{q}\chi_1^0$ ,  $m_{\tilde{g}} = 2500$  GeV  
 Split SUSY,  $\tilde{g} \rightarrow q\bar{q}\chi_1^0$ ,  $m_{\tilde{g}} = 1300$  GeV  
 Split SUSY (HSCP),  $\tilde{f}_{50} = 0.1$ ,  $m_{\tilde{g}} = 1600$  GeV  
 mGMSB (HSCP)  $\tan\beta = 10$ ,  $\mu > 0$ ,  $m_{\tilde{t}} = 247$  GeV  
 Stopped  $\tilde{t}$ ,  $\tilde{t} \rightarrow t\chi_1^0$ ,  $m_{\tilde{t}} = 700$  GeV  
 Stopped  $\tilde{g}$ ,  $\tilde{g} \rightarrow q\bar{q}\chi_1^0$ ,  $\tilde{f}_{50} = 0.1$ ,  $m_{\tilde{g}} = 1300$  GeV  
 Stopped  $\tilde{g}$ ,  $\tilde{g} \rightarrow q\bar{q}\chi_1^0 (\mu\mu\chi_1^0)$ ,  $\tilde{f}_{50} = 0.1$ ,  $m_{\tilde{g}} = 940$  GeV  
 AMSB,  $\chi^{\pm} \rightarrow \chi_1^0 \pi^{\pm}$ ,  $m_{\chi^{\pm}} = 700$  GeV  
 $\tilde{g} \rightarrow q\bar{q}\chi_1^0$  or  $q_{\text{iso}}\tilde{q}_{\text{iso}}\chi_1^0$ ,  $\chi_1^{\pm} \rightarrow \chi_1^0 \pi^{\pm}$ ,  $m_{\tilde{g}} = 1600$  GeV,  $m_{\chi_1^{\pm}} = 1575$  GeV  
 $\tilde{q} \rightarrow q\chi_1^0$  or  $q'\chi_1^{\pm}$ ,  $\chi_1^{\pm} \rightarrow \chi_1^0 \pi^{\pm}$ ,  $m_{\tilde{q}} = 2000$  GeV,  $m_{\chi_1^{\pm}} = 1000$  GeV  
 $\tilde{t} \rightarrow t\chi_1^0$  or  $b\chi_1^{\pm}$ ,  $\chi_1^{\pm} \rightarrow \chi_1^0 \pi^{\pm}$ ,  $m_{\tilde{t}} = 1100$  GeV,  $m_{\chi_1^{\pm}} = 1000$  GeV  
 GMSB,  $\chi_1^0 \rightarrow H\tilde{G}$  (50%)/ $Z\tilde{G}$  (50%),  $m_{\chi_1^0} = 600$  GeV  
 GMSB,  $\chi_1^0 \rightarrow H\tilde{G}$  (50%)/ $Z\tilde{G}$  (50%),  $m_{\chi_1^0} = 300$  GeV  
 GMSB SPSB,  $\chi_1^0 \rightarrow \gamma\tilde{G}$ ,  $m_{\chi_1^0} = 400$  GeV  
 GMSB, co-NLSP,  $\tilde{l} \rightarrow l\tilde{G}$ ,  $m_{\tilde{l}} = 270$  GeV

Higgs+Other

$H \rightarrow Z_0 Z_0$  (0.1%),  $Z_0 \rightarrow \mu\mu$ ,  $m_H = 125$  GeV,  $m_X = 20$  GeV  
 $H \rightarrow Z_0 Z_0$  (0.1%),  $Z_0 \rightarrow \mu\mu$  (15.7%),  $m_H = 125$  GeV,  $m_X = 5$  GeV  
 $H \rightarrow XX$  (10%),  $X \rightarrow ee$ ,  $m_H = 125$  GeV,  $m_X = 20$  GeV  
 $H \rightarrow XX$  (0.03%),  $X \rightarrow ll$ ,  $m_H = 125$  GeV,  $m_X = 30$  GeV  
 $H \rightarrow XX$  (10%),  $X \rightarrow b\bar{b}$ ,  $m_H = 125$  GeV,  $m_X = 40$  GeV  
 $H \rightarrow XX$  (10%),  $X \rightarrow b\bar{b}$ ,  $m_H = 125$  GeV,  $m_X = 40$  GeV  
 $H \rightarrow XX$  (10%),  $X \rightarrow b\bar{b}$ ,  $m_H = 125$  GeV,  $m_X = 40$  GeV  
 $H \rightarrow XX$  (10%),  $X \rightarrow \tau\tau$ ,  $m_H = 125$  GeV,  $m_X = 7$  GeV  
 dark QCD,  $m_{X_{\text{dark}}} = 1500$  GeV,  $m_{\pi_{\text{dark}}} = 10$  GeV, agonistic  
 dark QCD,  $m_{X_{\text{dark}}} = 1500$  GeV,  $m_{\pi_{\text{dark}}} = 10$  GeV, GNN  
 $H \rightarrow XX$  (10%),  $X \rightarrow b\bar{b}$ ,  $m_H = 125$  GeV,  $m_X = 40$  GeV  
 $H \rightarrow XX$  (10%),  $X \rightarrow d\bar{d}$ ,  $m_H = 125$  GeV,  $m_X = 40$  GeV  
 $H \rightarrow XX$  (10%),  $X \rightarrow \tau\tau$ ,  $m_H = 125$  GeV,  $m_X = 40$  GeV

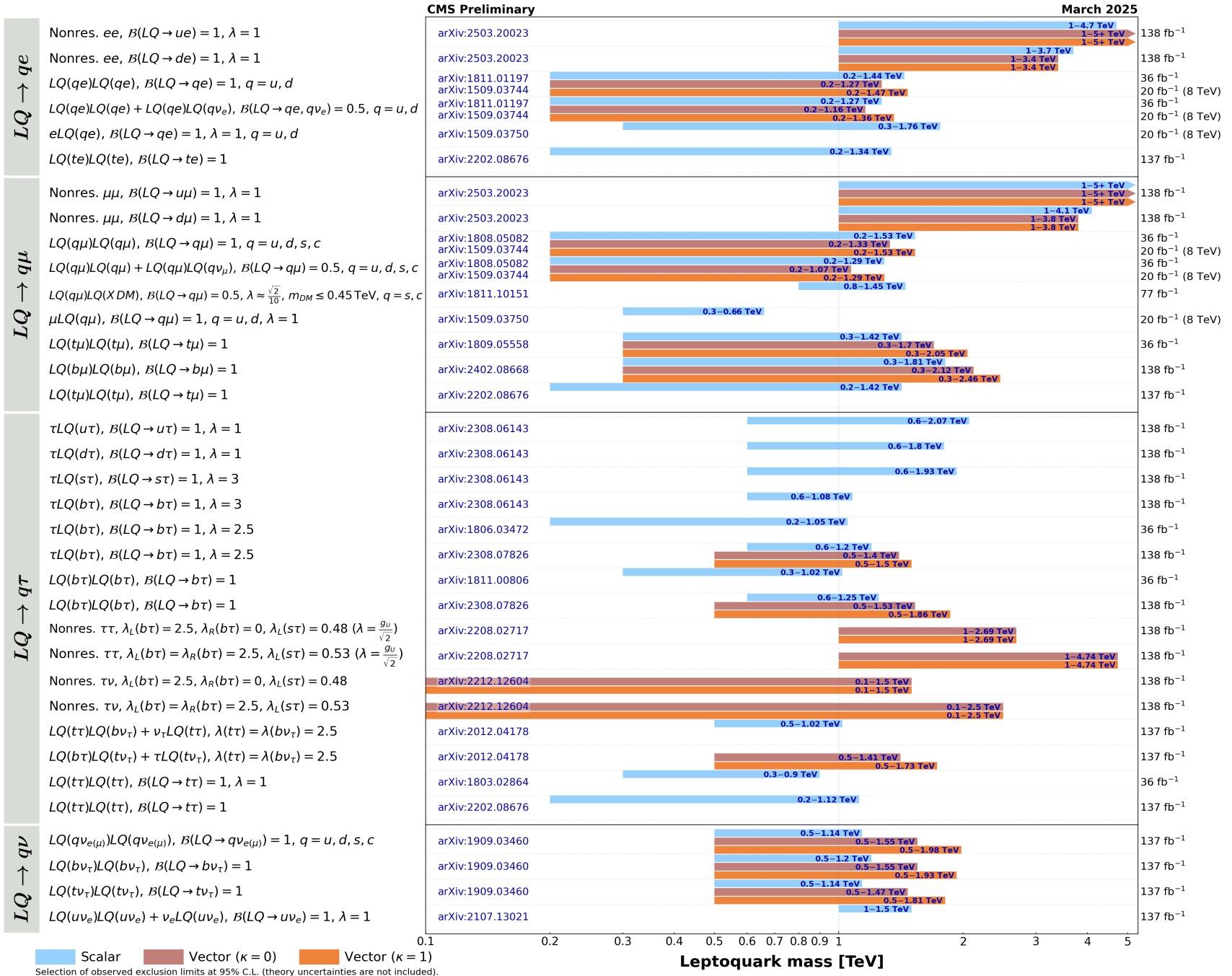
CMS Preliminary

March 2024

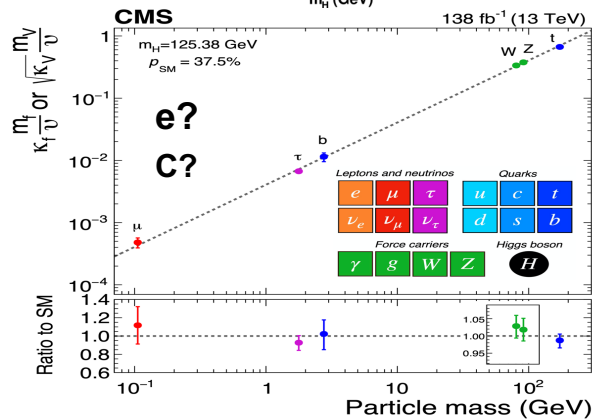
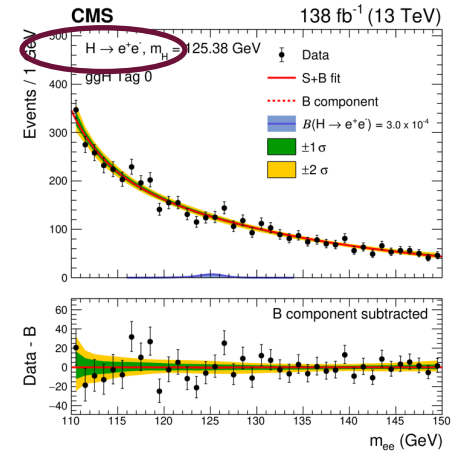
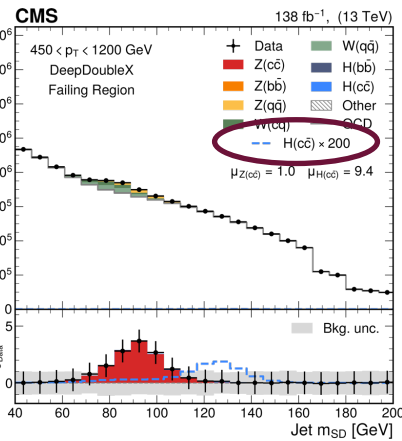
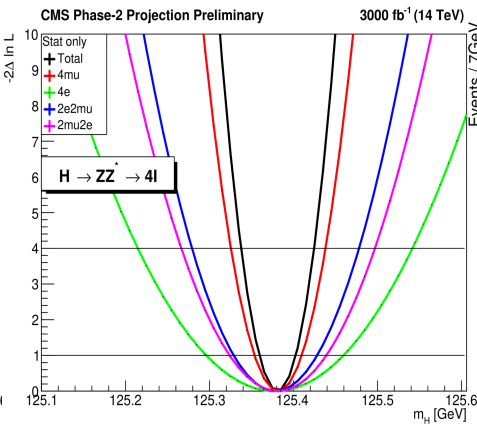
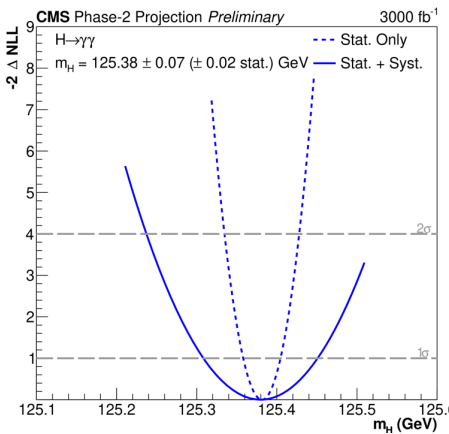


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

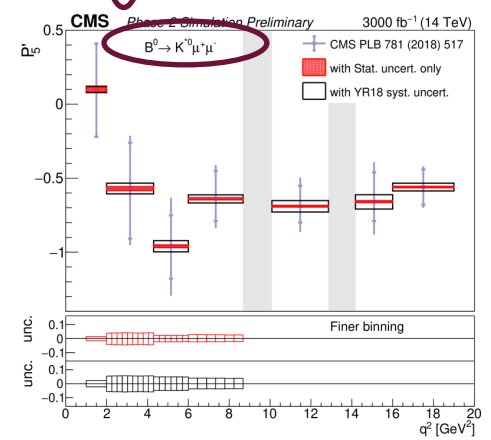
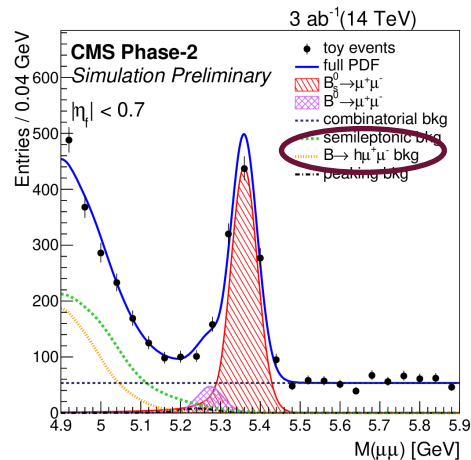
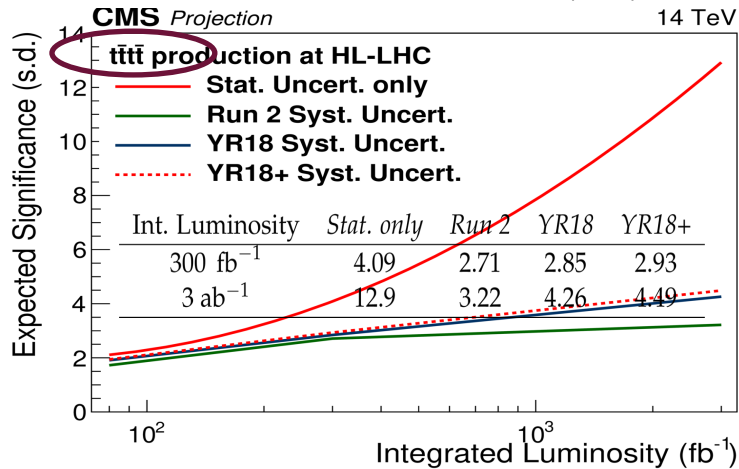
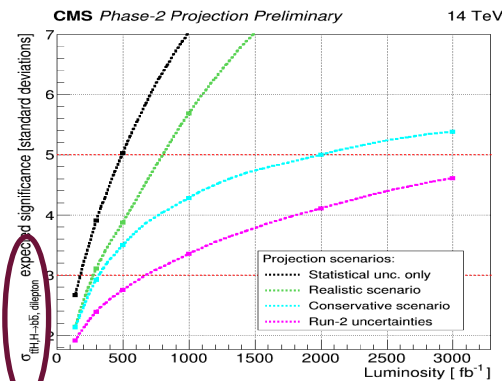
# LQ search summary from CMS



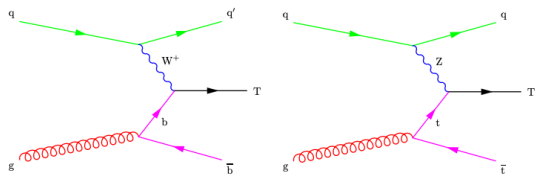
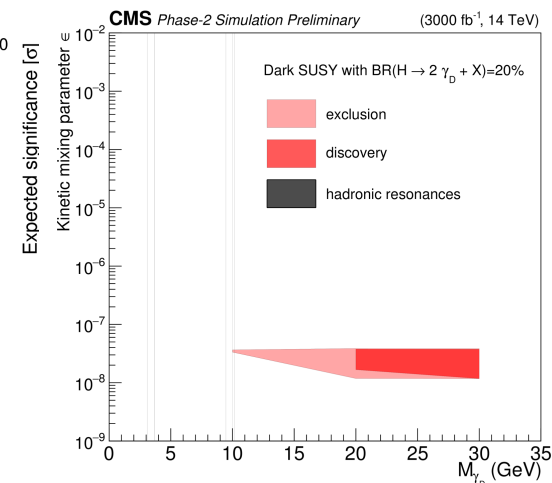
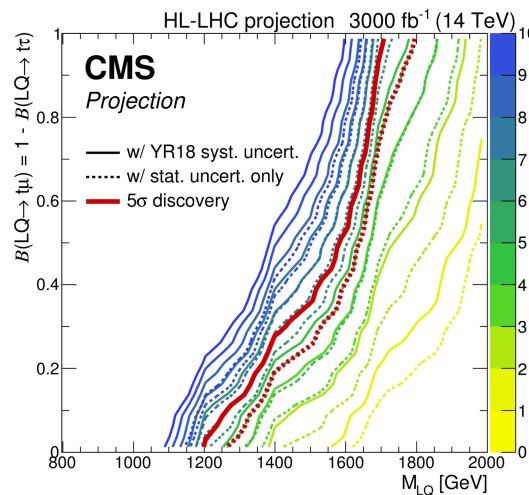
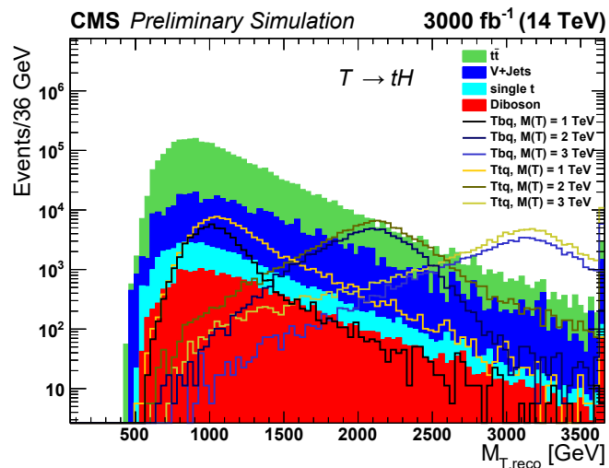
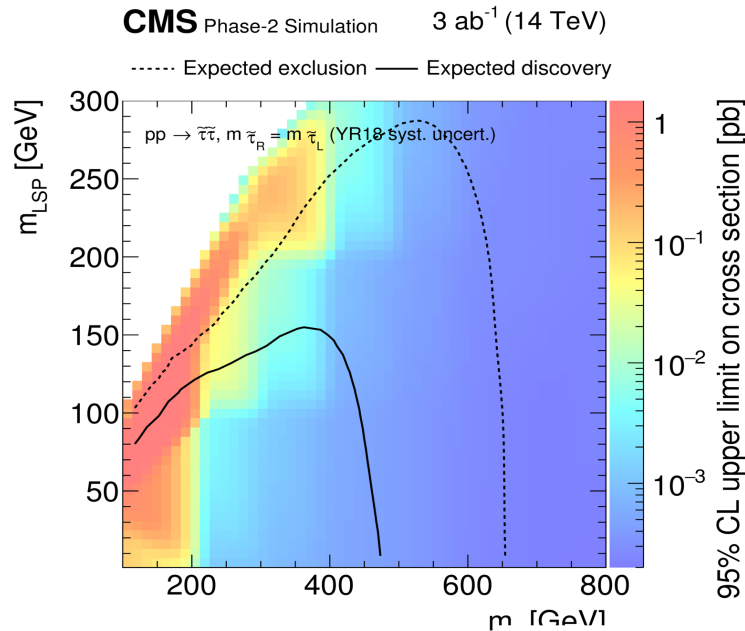
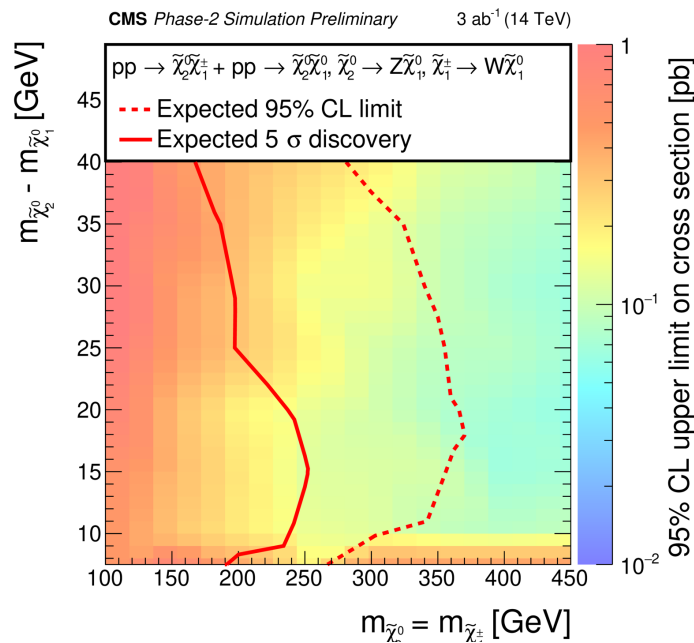
# SM measurements with HL-LHC (3 ab<sup>-1</sup>)



Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bbττ	1.4	1.6	1.4	1.3
bbWW(lνlν)	0.56	0.59	3.5	3.3
bbγγ	1.8	1.8	1.1	1.1
bbZZ(llll)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71



# BSM measurements with HL-LHC (3 ab<sup>-1</sup>)



Mass (GeV)	Expected cross section upper limit (fb)	
	Tbq (LH)	Ttq (RH)
1000	85.9	54.7
1500	28.4	20.3
2000	12.8	9.06
2500	7.20	4.64
3000	4.69	4.69

## Summary

- LHC has provided greater insight and understanding of Standard Model of Particle Physics.
- We re-established several SM predictions in top, b-flavor W/Z, flavor sector, etc, with greater precision.
- Higgs discovery (and measurement of its properties) is a tremendous success of LHC.
- No BSM found till date.
- The future plan for LHC is to run with more intense beam ( $\sim 5$  x instantaneous luminosity)
- This HL-LHC condition (with higher beam intensity and center-of-mass energy) will provides us with better physics potential for further precision tests in all SM sector and BSM searches.
- However, the HL-LHC beam intensity will create harsher environment for our detectors.
- Major upgrades for CMS featuring finer granularity, new technologies and new capabilities, is planned during 2026-2030.
- Eventually, we will have  $\sim 3000 \text{ fb}^{-1}$  data (x 6-7 what we have now) to be collected by 2040.
- Look forward to wonderful years ahead with HL-LHC.

***Thank you for listening !***



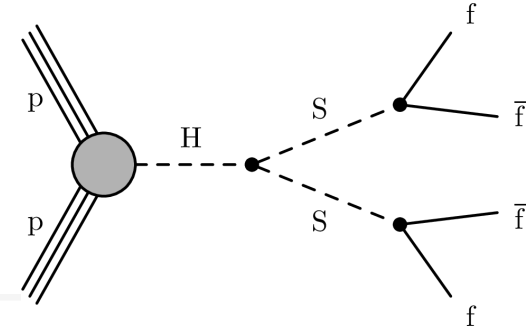
## Standard model lagrangian

$$\begin{aligned}
 \mathcal{L} = & \left( \begin{array}{c} \text{Kinetic terms of} \\ \text{gauge bosons} \end{array} \right) + \left( \begin{array}{c} \text{Kinetic term} \\ \text{of Higgs} \end{array} \right) + \left( \begin{array}{c} \text{Kinetic terms} \\ \text{of fermions} \end{array} \right) + \left( \begin{array}{c} \text{Yukawa} \\ \text{terms} \end{array} \right) - \left( \begin{array}{c} \text{Higgs} \\ \text{potential} \end{array} \right) \\
 = & \underbrace{\frac{1}{2} (\text{Tr}(G_{\mu\nu}G^{\mu\nu}) + \text{Tr}(W_{\mu\nu}W^{\mu\nu}) + B_{\mu\nu}B^{\mu\nu})}_{\text{Kinetic terms of gauge bosons}} + \underbrace{\frac{1}{2}|D_\mu\phi|^2}_{\text{Kinetic term of Higgs}} \\
 & + \underbrace{i\bar{l}_L \not{D} l_L + i\bar{l}_R \not{D} l_R + i\bar{q}_L^a \not{D} q_{La} + i\bar{u}_R^a \not{D} u_{Ra} + i\bar{d}_R^a \not{D} d_{Ra}}_{\text{Kinetic terms of fermions}} \\
 & + \underbrace{(y_d \bar{q}_L^a \phi d_{Ra} + y_u \bar{q}_L^a \tilde{\phi} u_{Ra} + y_l \bar{l}_L^a \phi l_{Ra} + \text{conjugate})}_{\text{Yukawa terms}} - \underbrace{V(\phi)}_{\text{Higgs potential}}
 \end{aligned}$$

$y_d$ ,  $y_u$ , and  $y_l$  are coupling constants

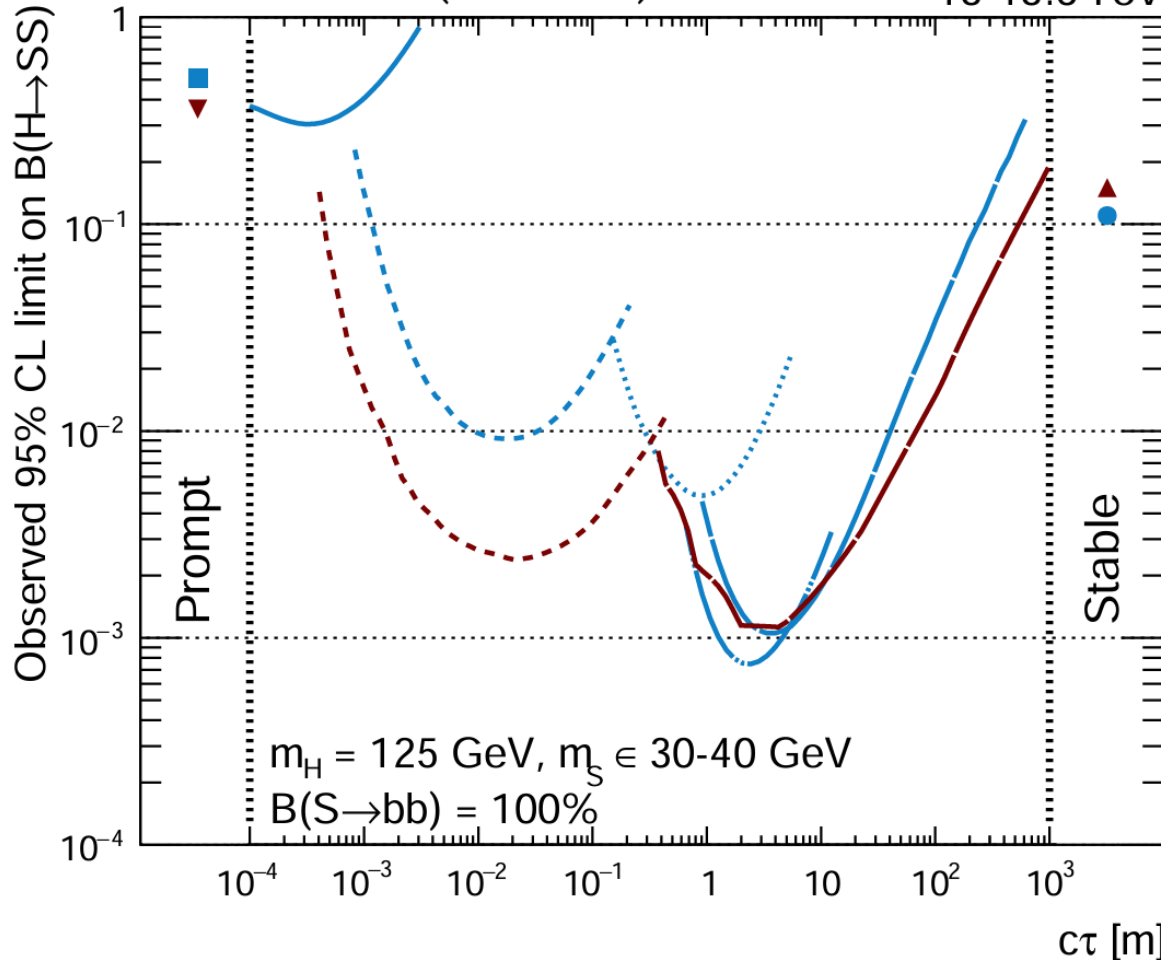
# Low mass LLP via di-jet final state

- Decay of 125 GeV Higgs (H) to two long lived neutral scalars(S)  
-> pair of SM fermions (quark pairs or tau lepton pairs)
- Look for di-jets with displaced vertex, reconstructed using the displaced trackers associated with jets



**ATLAS+CMS Preliminary**  
Hidden Sector (Feb 2025)

13-13.6 TeV



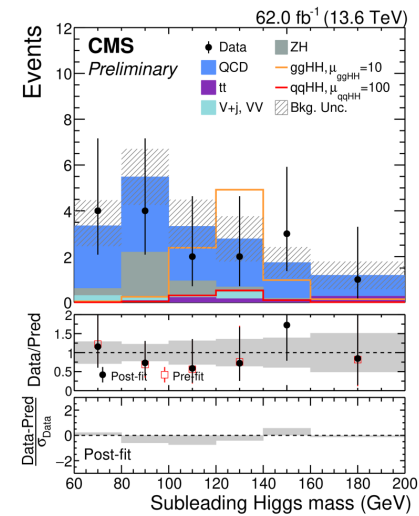
## CMS

- Prompt (with b-tag)**, 138 fb<sup>-1</sup> (13 TeV)  
JHEP 06 (2024) 097
- Displaced jets**, 34.7 fb<sup>-1</sup> (13.6 TeV)  
Rept. Prog. Phys. 88 (2025) 037801
- Muon System**, 138 fb<sup>-1</sup> (13 TeV)  
Phys. Rev. D 110 (2024) 3 032007
- H → invisible**, 4.9-140 fb<sup>-1</sup> (7-8-13 TeV)  
Eur.Phys.J.C 83 (2023) 933

## ATLAS

- Prompt (with b-tag)**, 36 fb<sup>-1</sup> (13 TeV)  
JHEP 10 (2018) 031
- Displaced vertices**, 140 fb<sup>-1</sup> (13 TeV)  
Phys. Rev. Lett. 133 (2024) 161803
- Calorimeter**, 140 fb<sup>-1</sup> (13 TeV)  
JHEP 11 (2024) 036
- Muon System (2 vtx)**, 139 fb<sup>-1</sup> (13 TeV)  
Phys. Rev. D 106 (2022) 3 032005
- Muon System**, 36 fb<sup>-1</sup> (13 TeV)  
Phys. Rev. D 99 (2019) 052005
- H → invisible**, 4.7-139 fb<sup>-1</sup> (7-8-13 TeV)  
Phys.Lett.B 842 (2023) 137963

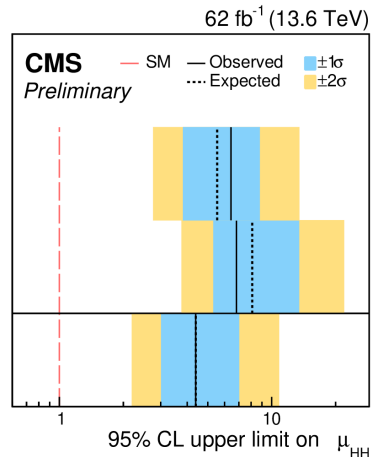
# Di-Higgs (HH) to 4b/bbyy



**Resolved**  
Obs. 6.4  
Exp. 5.5

**Merged**  
Obs. 6.8  
Exp. 8.1

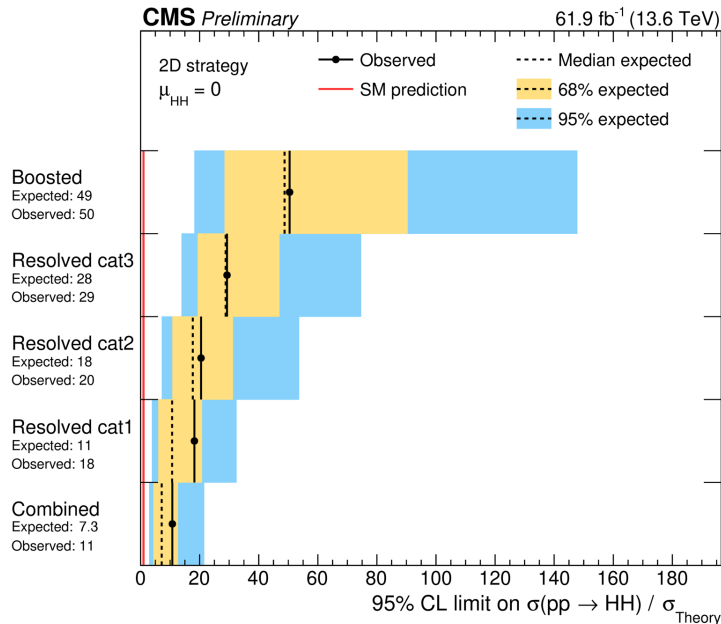
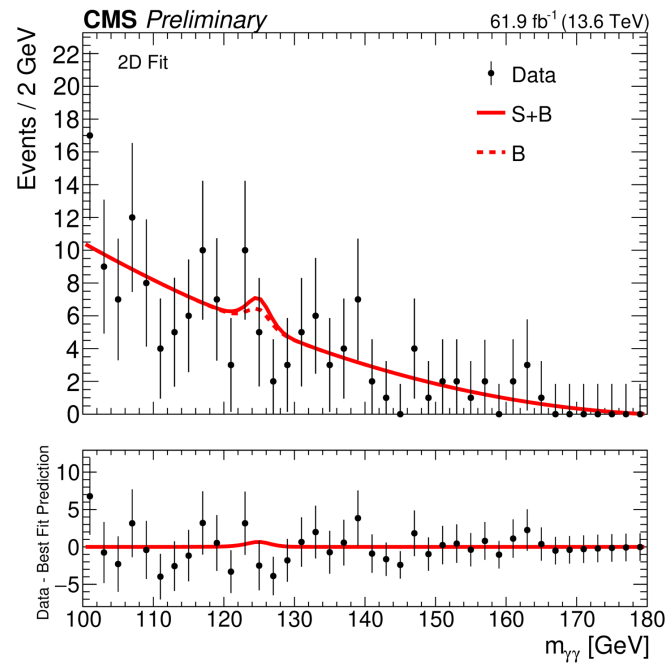
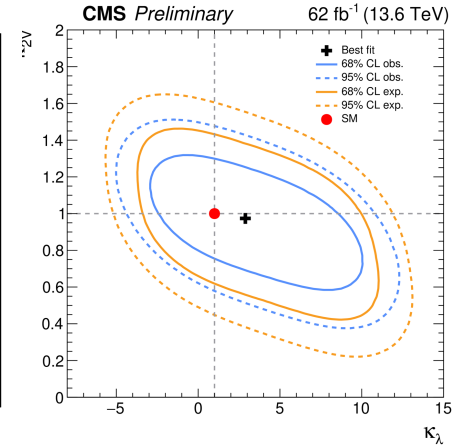
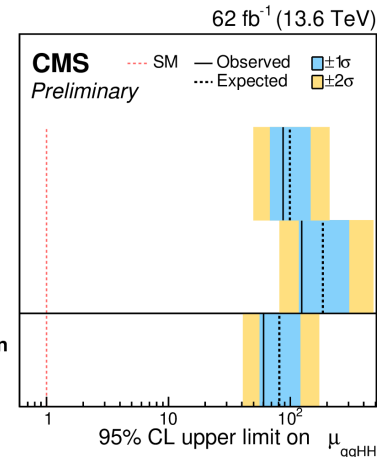
**Combination**  
Obs. 4.4  
Exp. 4.4

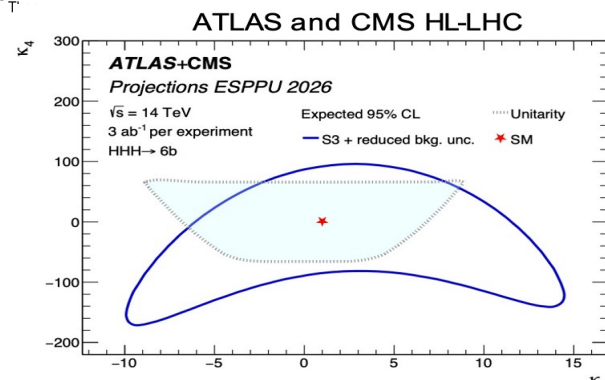
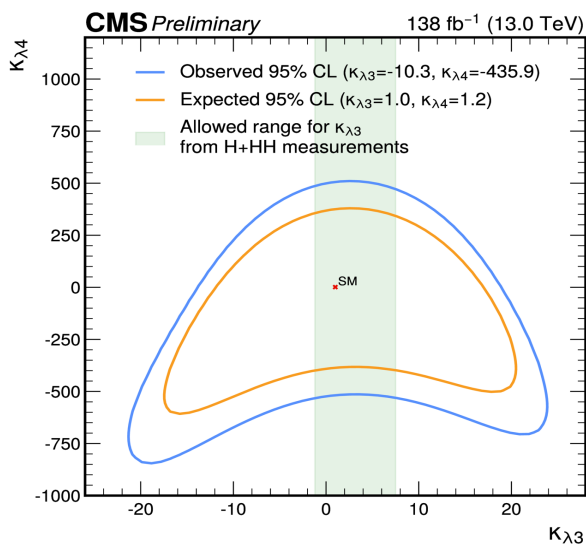
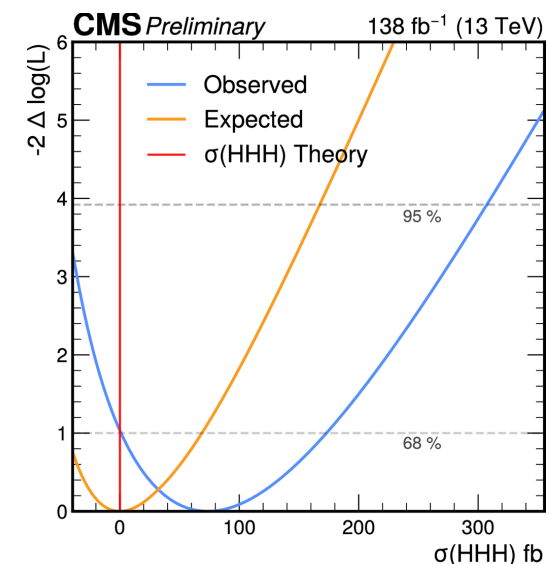
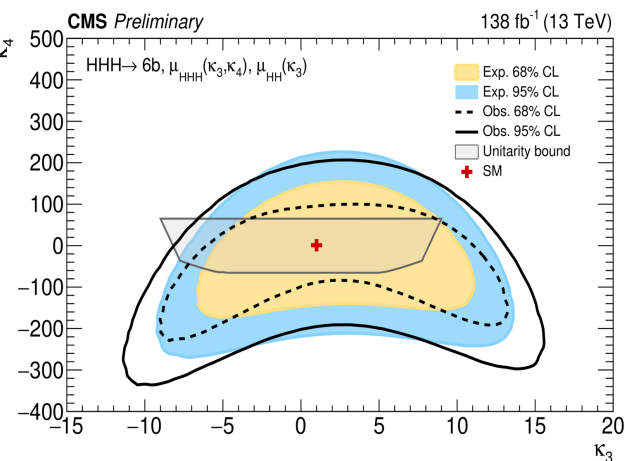
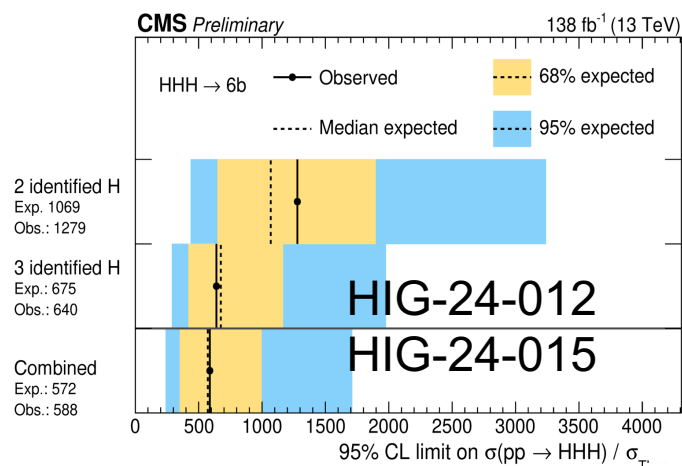
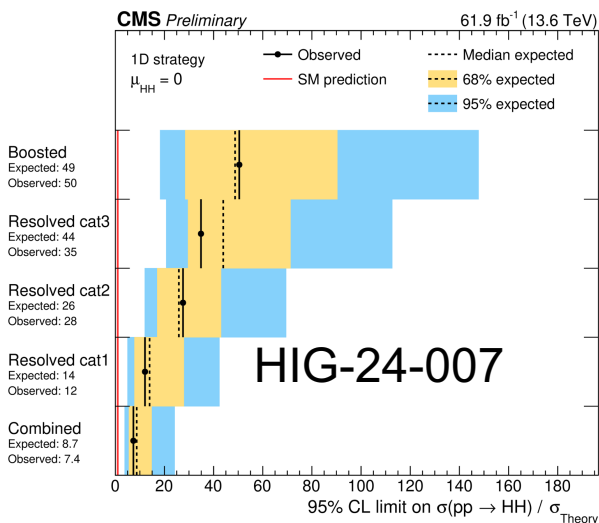


**Resolved**  
Obs. 87  
Exp. 99

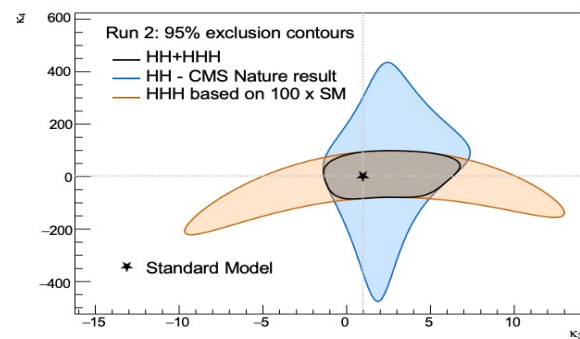
**Merged**  
Obs. 124  
Exp. 185

**Combination**  
Obs. 60  
Exp. 81





**Run 3 goals:**  
**Combined HH and HHH measurement**



# B-physics expectations with HL-LHC

Experiment Assumed data sample	ATLAS 20.3-99.7 fb <sup>-1</sup>	CMS 116-140 fb <sup>-1</sup>	LHCb 2-9 fb <sup>-1</sup>	Belle II 364-1075 fb <sup>-1</sup>
<b>Leptonic <math>\bar{B}</math> decays</b>				
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) [10^{-9}]$	$^{+0.8}_{-0.7}$ [none-none-none]	0.45 [none-none-none]	0.48 [none-none-none-none]	—
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) [10^{-10}]$	$< 2.1^*$ [none-none-none]	$< 1.5$ [none-none-none]	0.79 [none-none-none-none]	—
$\tau_{\text{eff}}(B_s^0 \rightarrow \mu^+ \mu^-) [\text{ps}]$	$^{+0.45}_{-0.18}$ [none-none-none]	0.23 [none-none-none]	0.29 [none-none-none-none]	—
<b>Flavour-changing neutral current <math>b \rightarrow s\ell\ell</math> decays</b>				
$P'_5(B^0 \rightarrow K^{*0} \mu^+ \mu^-) [10^{-3}]^{\dagger}$	390 [none-none-none]	100 [none-none-none]	111 [none-none-none-none]	—
<b>Lepton flavour violation in <math>\tau</math> decays</b>				
$\mathcal{B}(\tau^+ \rightarrow \mu^+ \gamma) [10^{-8}]$	—	—	—	$< 7.5$ [none-none]
$\mathcal{B}(\tau^+ \rightarrow \mu^+ \mu^+ \mu^-) [10^{-8}]$	$< 37.6$ [none-none-none]	$< 2.9$ [none-none-none]	$< 4.6$ [none-none-none-none]	$< 1.8$ [none-none]

<sup>†</sup> The sensitivity for the  $P'_5$  variable is quoted for the range  $q^2 \in [4.0, 6.0]$  GeV<sup>2</sup> for ATLAS and LHCb and  $q^2 \in [4.3, 6.0]$  GeV<sup>2</sup> for CMS.

Experiment Assumed data sample	ATLAS 3000 fb <sup>-1</sup>	CMS 3000 fb <sup>-1</sup>	LHCb 300 fb <sup>-1</sup>	Belle II 50 ab <sup>-1</sup>
<b>Leptonic <math>B</math> decays</b>				
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) [10^{-9}]$	(0.33 – 0.40)	0.22	0.16	—
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) [10^{-10}]$	(0.32 – 0.48)	0.12	0.12	—
$\tau_{\text{eff}}(B_s^0 \rightarrow \mu^+ \mu^-) [\text{ps}]$	$^{+(0.07-0.11)}_{-(0.05-0.08)}$	0.05	0.05	—
<b>Flavour-changing neutral current <math>b \rightarrow s\ell\ell</math> decays</b>				
$P'_5(B^0 \rightarrow K^{*0} \mu^+ \mu^-) [10^{-3}]^{\dagger}$	(47 – 82)	23	12	—
<b>Lepton flavour violation in <math>\tau</math> decays</b>				
$\mathcal{B}(\tau^+ \rightarrow \mu^+ \gamma) [10^{-8}]$	—	—	—	$< 0.7$
$\mathcal{B}(\tau^+ \rightarrow \mu^+ \mu^+ \mu^-) [10^{-8}]$	$< (0.13 - 0.64)$	$< 0.39$	$< 0.26$	$< (0.02 - 0.17)$

<sup>†</sup> The sensitivity for the  $P'_5$  variable is quoted for the range  $q^2 \in [4.0, 6.0]$  GeV<sup>2</sup> for ATLAS and LHCb and  $q^2 \in [4.3, 6.0]$  GeV<sup>2</sup> for CMS.