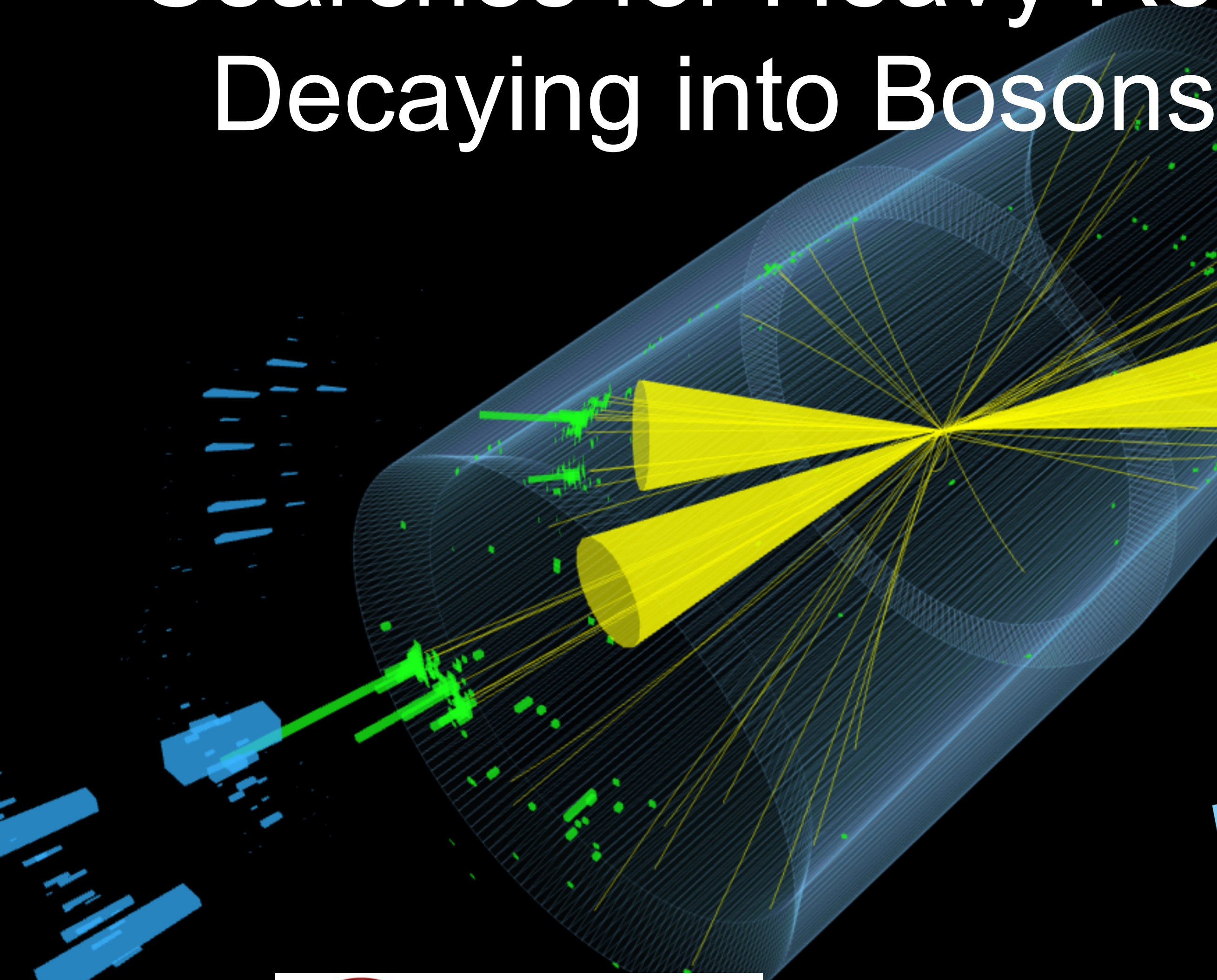
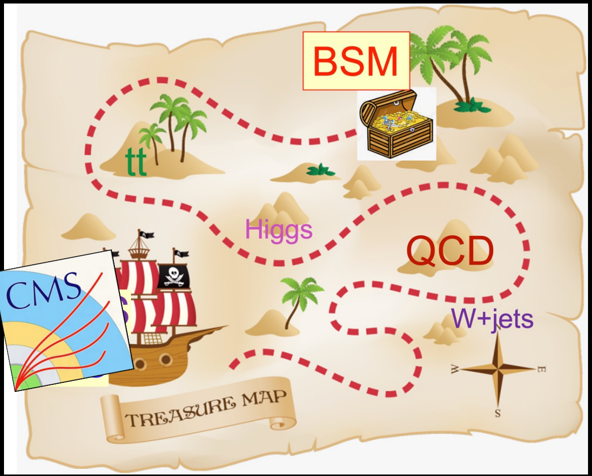
23/10/24 43rd International Symposium on Physics in Collision - PIC 2024

Searches for Heavy Resonances Decaying into Bosons at CMS





PEKING UNIVERSITY

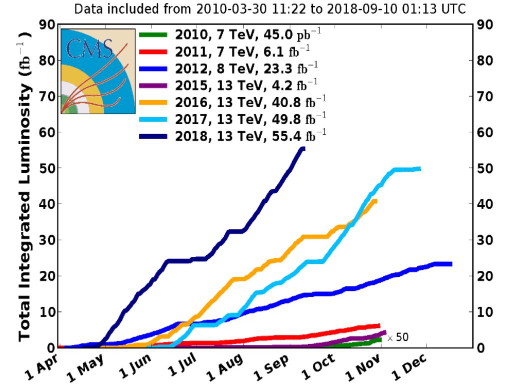
Antonis Agapitos
On behalf of the CMS collaborations

Outline: New results in this talk

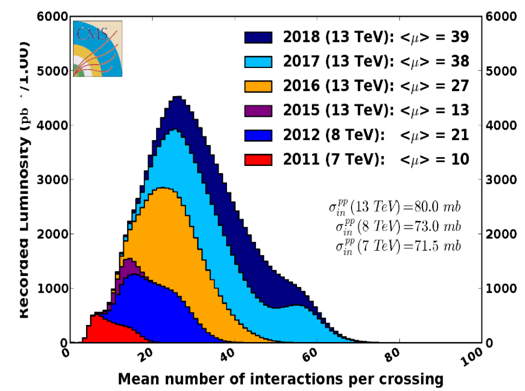
	ID & Links	Topology	Released	Model
1	B2G-23-004	$g_{KK} \to gR \to gWW$	June 24	EWED
2	B2G-23-006	$A \to ZH \to \ell\ell\, tt \to \ell\ell$+jets	March 24	2HDM
3	HIG-22-004	$A \to ZH \to \ell\ell\tau_h\tau_h$	July 24	2HDM
4	SUS-23-012	$A \to Ha \to \tau\tau\chi\chi$	July 24	2HDM+a
5	SUS-23-018	$(bb)H \to ZA \to \ell\ell\chi\chi$	July 24	2HDM+a
6	B2G-23-008	$Z' \to ZH \to \ell\ell/\nu\nu\ cc/4q$	March 24	HVT
7	B2G-23-002	$X \to YH$ / HH	March 24	many
8	EXO-22-024	$X \to \gamma\gamma$	March 24	WED,ADD
		Summary plots		
Relevant new results not covered; some in backups, others in Elisabetta's talk				
9	HIG-22-012	$X \to YH$ / $HH \to \tau\tau\gamma\gamma$	March 24	WED,ExtH
10	EXO-21-015	VBF $Z' \to WW \to \ell\nu\nu$	June 24	Z'
11	EXO-21-017	$X \to W\gamma \to \ell\nu\gamma$	March 24	W'
12	HIG-24-002	$X \to ZZ \to 4\ell$	July 24	2HDM,WED

New CMS results released last ~8 months

Full run 2 data: 138 fb^{-1}



CMS Average Pileup



Full list of CMS BSM physics results:

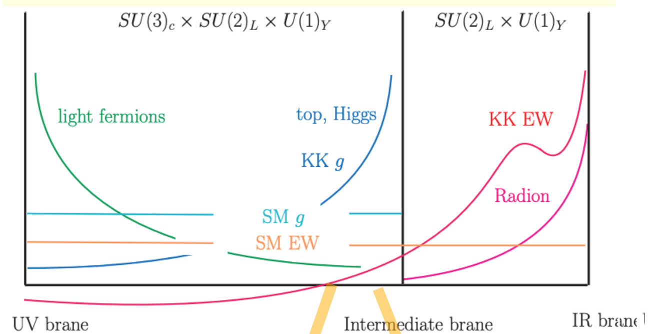
- Preliminary results: Here
- Publications: Here

EWED landscape & g_{KK}→gR→gWW

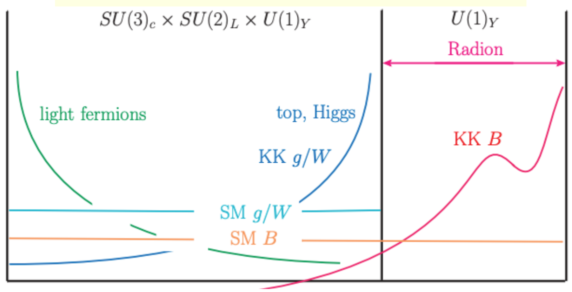
Extended Warped Extra Dimension (EWED) model (K.Agashe, et al, 1612.00047, 1711.09920, 1809.07334)

- Extra brane by splitting → extended bulk → 3 or more branes, 2 or more Radion
- "Di-SM-objects" suppressed, in favor of "tri-SM-objects" → A wealth of new signatures
- Various fields propagate in different sub-spaces, 3 main scenarios:

EW fields propagate at the bulk

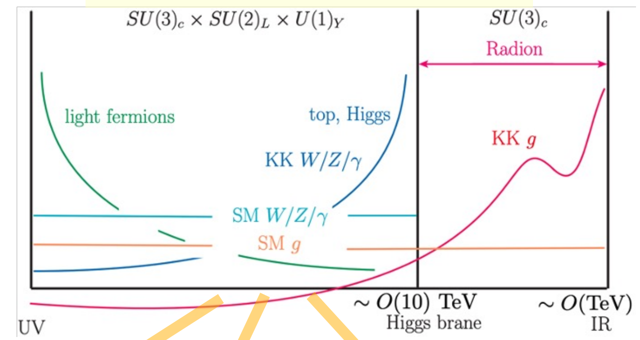


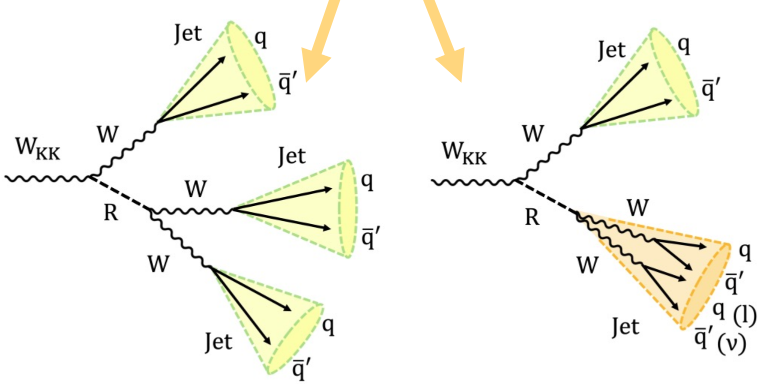
Hypercharge at the bulk



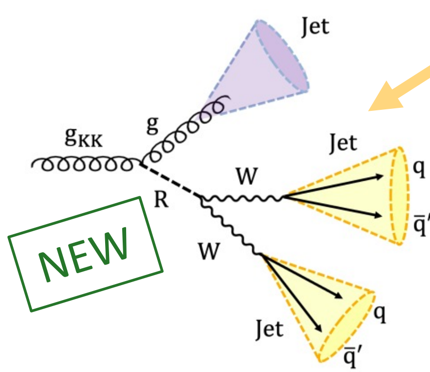
tri-γ signature - yet unexplored

QCD fields at the bulk

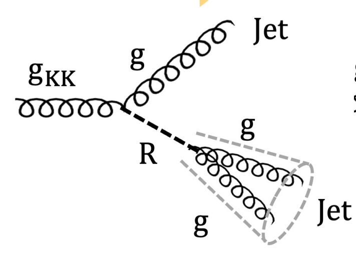




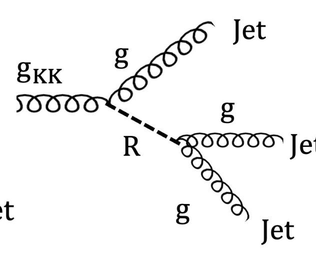
Tri-W; W_{KK} → WR → WWW
merged & resolved R; final states: 0l & 1l
2201.08476 , 2112.13090



This analysis
g_{KK} → gR → gWW
the following search



Di-jet (merged)
g_{KK} → gR → ggg
2201.02140

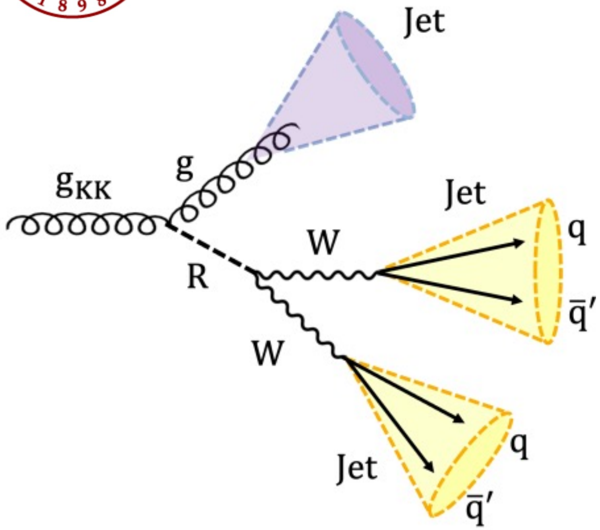


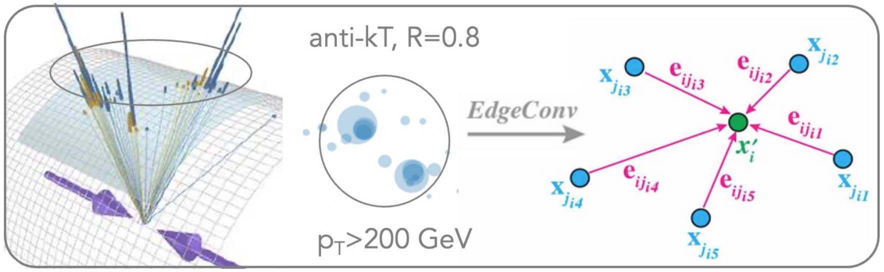
Tri-jet (resolved)
g_{KK} → gR → ggg
2310.14023

Search for $g_{KK} \to gR \to gWW$

B2G-23-004
CDS records

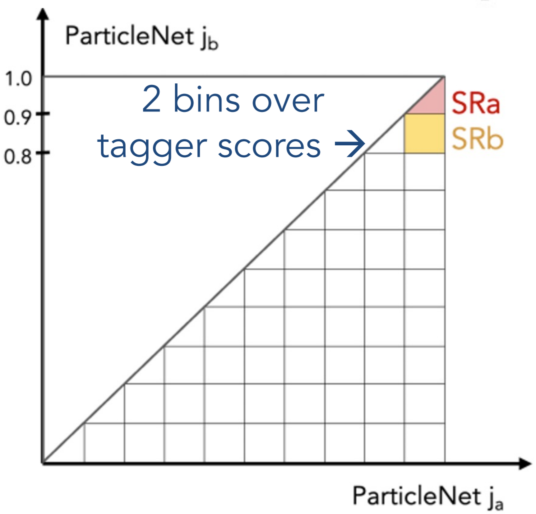
- 3 jets, AK8, PUPPI; 2 jets with SD-mass $m_{ja,jb}$>50 GeV
- W→qq identification with ParticleNet tagger 1902.08570



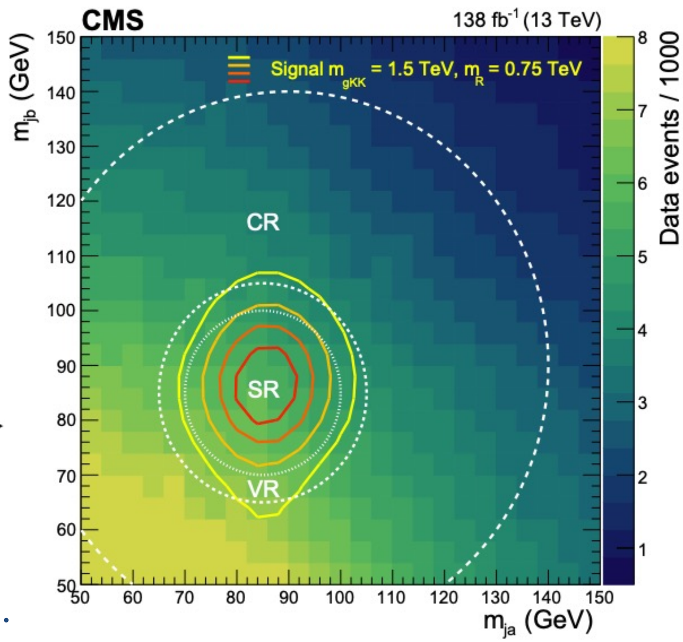


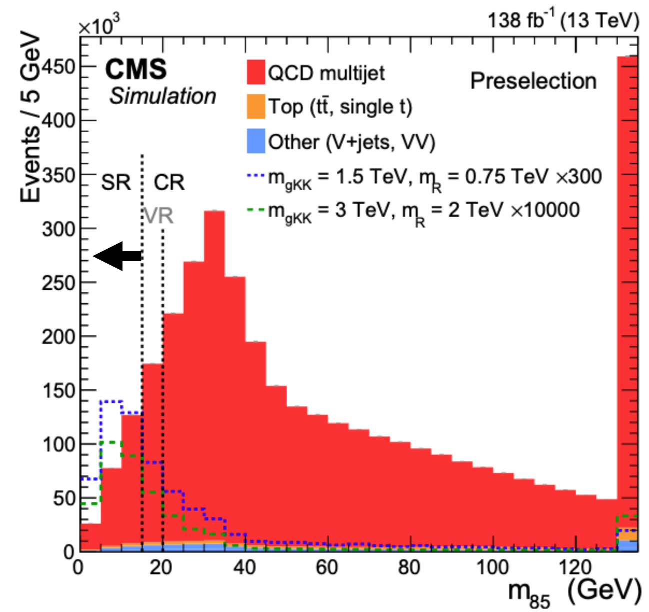
- Graph NN, treat jets as particle cloud
- Convolution on point clouds (EdgeConv 1801.07829)

- Tagger: p(W→qq) / [p(W→qq) + p(QCD)]



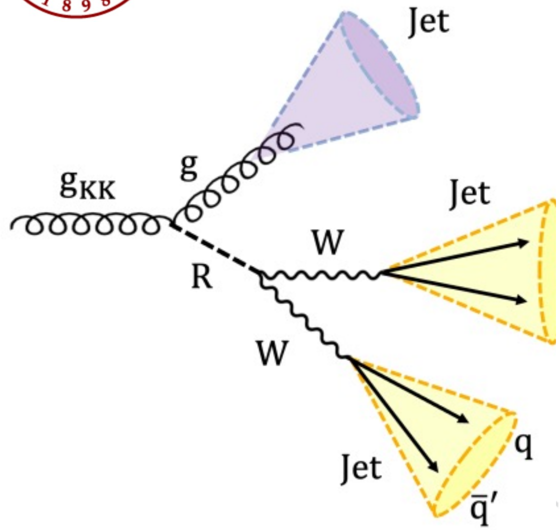
- SRs: m_{85}<15 GeV
- CRs: m_{85}>15 GeV used in QCD estimate.

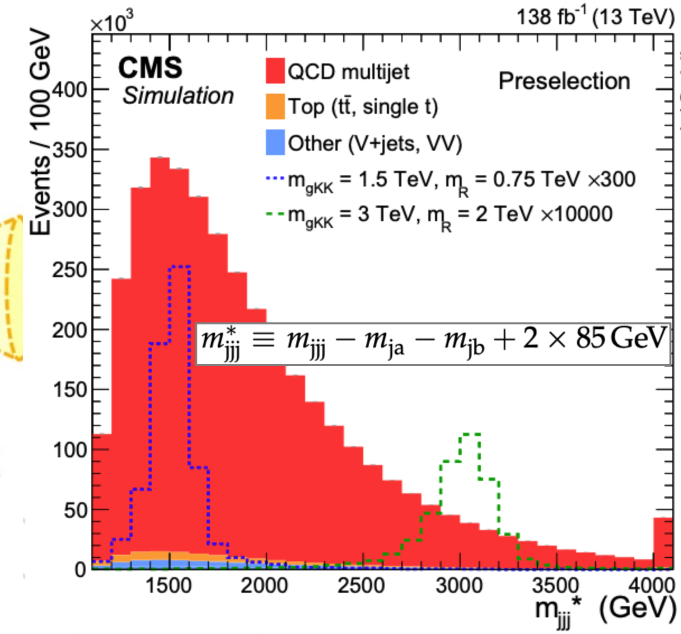


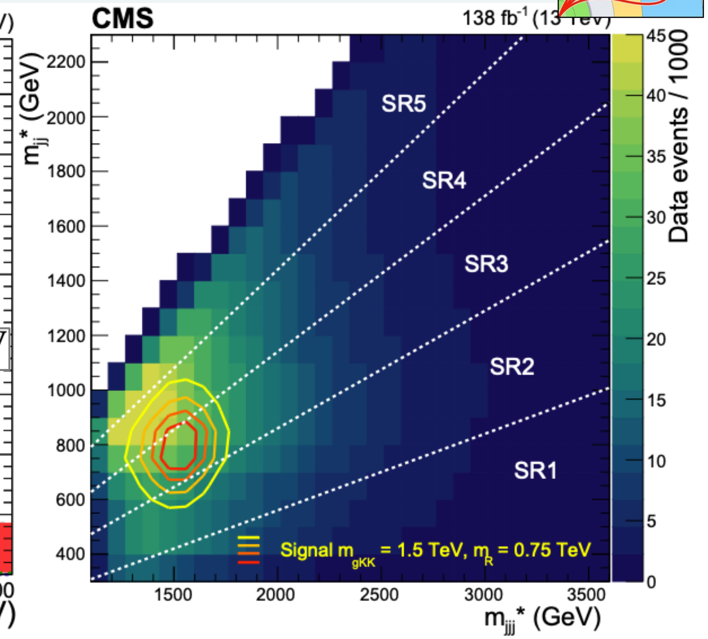


$$m_{85} \equiv \sqrt{(m_{ja} - 85\,\mathrm{GeV})^2 + (m_{jb} - 85\,\mathrm{GeV})^2}$$

$g_{KK} \to gR \to gWW$: binning, results, & limits







- Form $m_R = m_{jj}$, $m_{gKK} = m_{jjj}$
- Apply corrections to m_{jj}*, m_{jjj}* as:

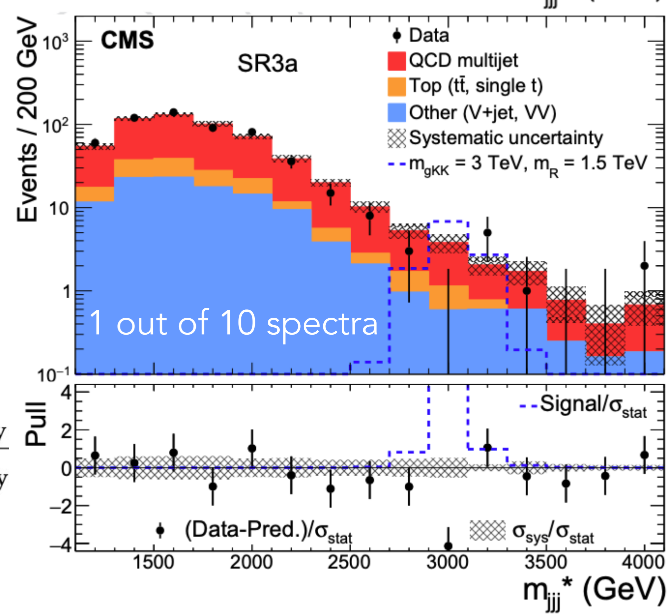
$$m^*_{jjj} \equiv m_{jjj} - m_{ja} - m_{jb} + 2 \times 85\,\text{GeV}$$

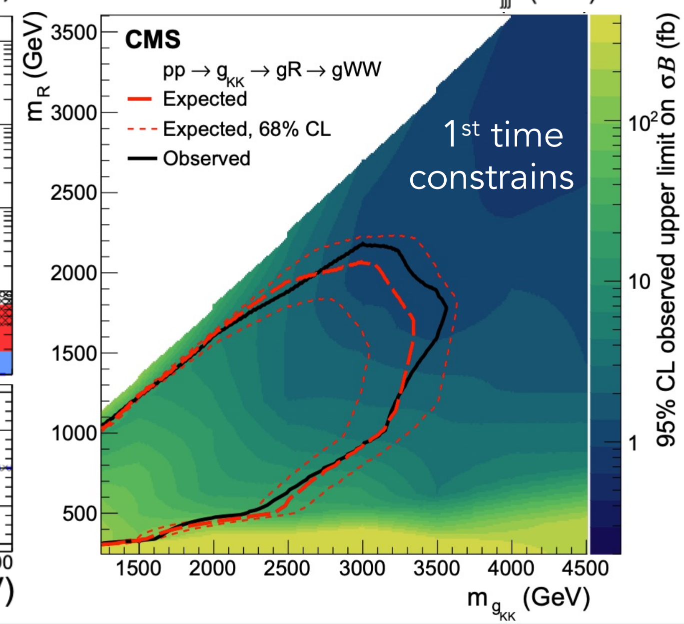
→ improved resolution

- Binning over m_{jj}*/m_{jjj}*
- 10 SRs are formed
- QCD estimate from CRs:

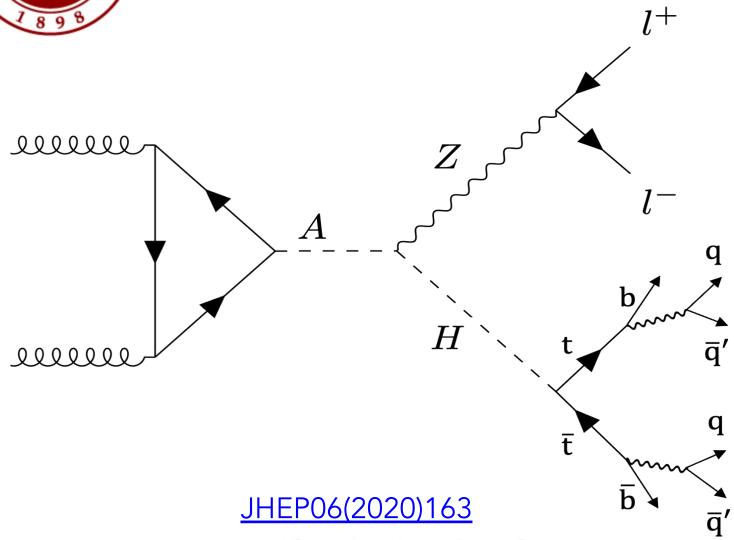
$$\text{Pred}^{\text{QCD}}_{\text{SRxy}} \equiv [\text{Data} - \text{Rest}]_{\text{CRxy}} \frac{\text{QCD}_{\text{SRxy}}}{\text{QCD}_{\text{CRxy}}}$$

- Fit the m_{jjj}* in 10 SRs →





Search for A→ZH→ ℓℓ tt_{had}



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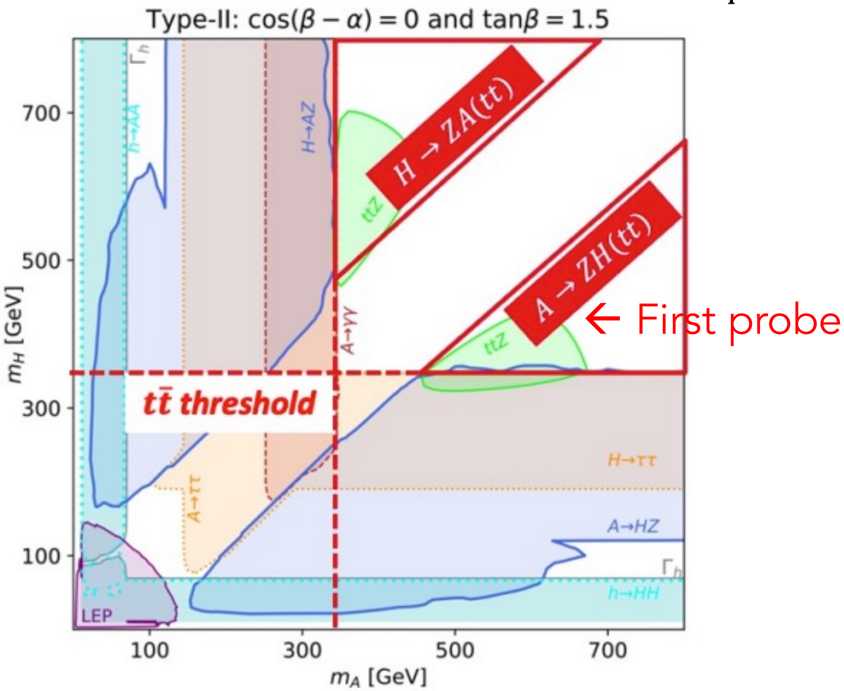
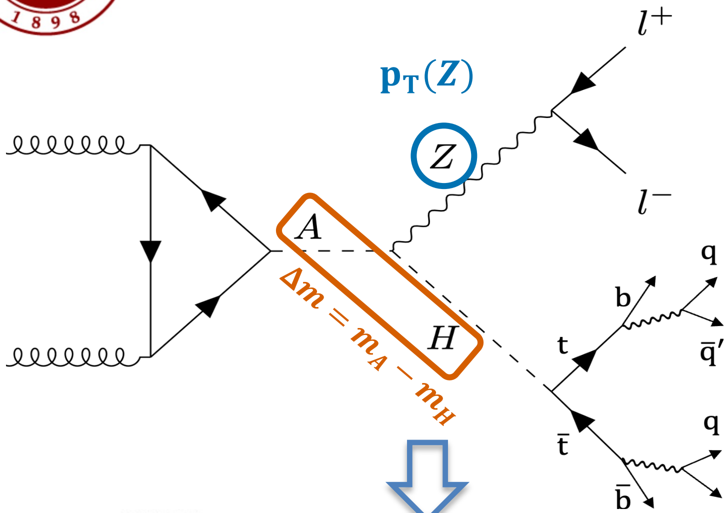
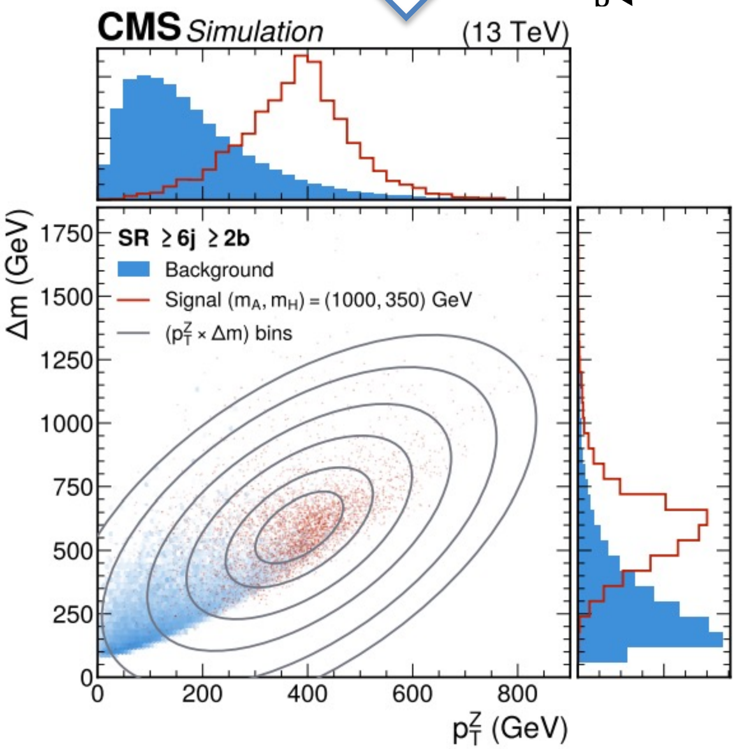


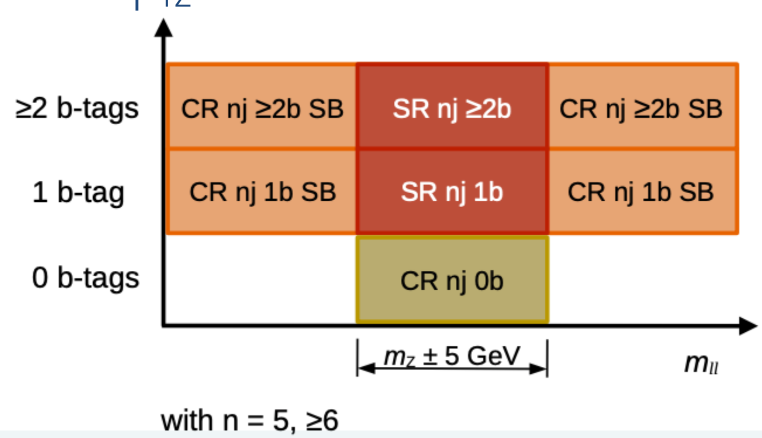
- Two Higgs Doublet Model (2HDM) introduces an additional Higgs doublet to the SM
  → 5 Higgs bosons: h, H, A, $H^{\pm}$
- Free params: m_A, m_H, $m_{H\pm}$, m_h, $\tan(\beta)=v_1/v_2$, α
- Alignment limit "$\cos(\beta-\alpha)=0$" → h is SM-like
- Low $m_{A/H}$, low tan(β) region explored in ℓℓ bb-channel JHEP(2020), H→bb dominant, sensitive for $m_H<m_{tt}$
- High $m_{A/H}$, unexplored at LHC so far: This AZH(ℓℓ tt) analysis focuses on $m_H>m_{tt}$ with H→tt dominant
- Further motivation: Baryon asymmetry can arise from EW baryogenesis facilitated by 2HDM configurations requiring a first-order electroweak phase transition (FOEWPT) 2208.14466 (fig.3, left).
  → This search targets this region.
- The tt→bqq bqq (resolved jets) & Z→ ℓℓ is considered [for 1st time]

A→ZH→ ℓℓ tt: selection & BKG estimate

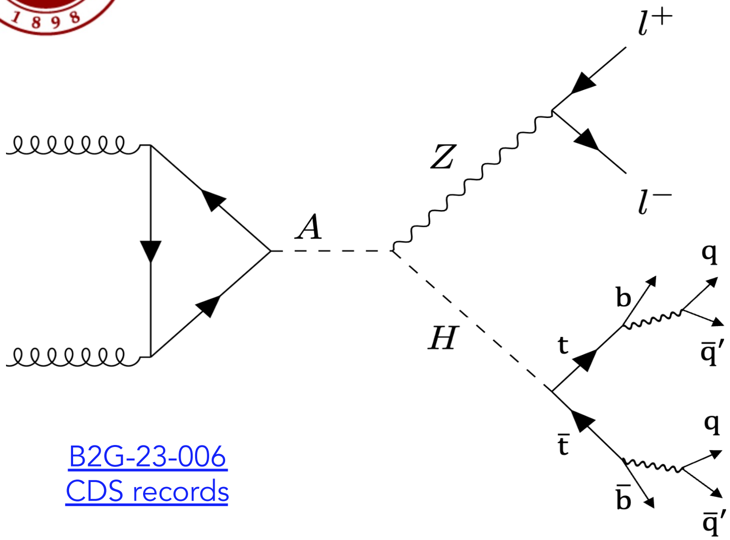




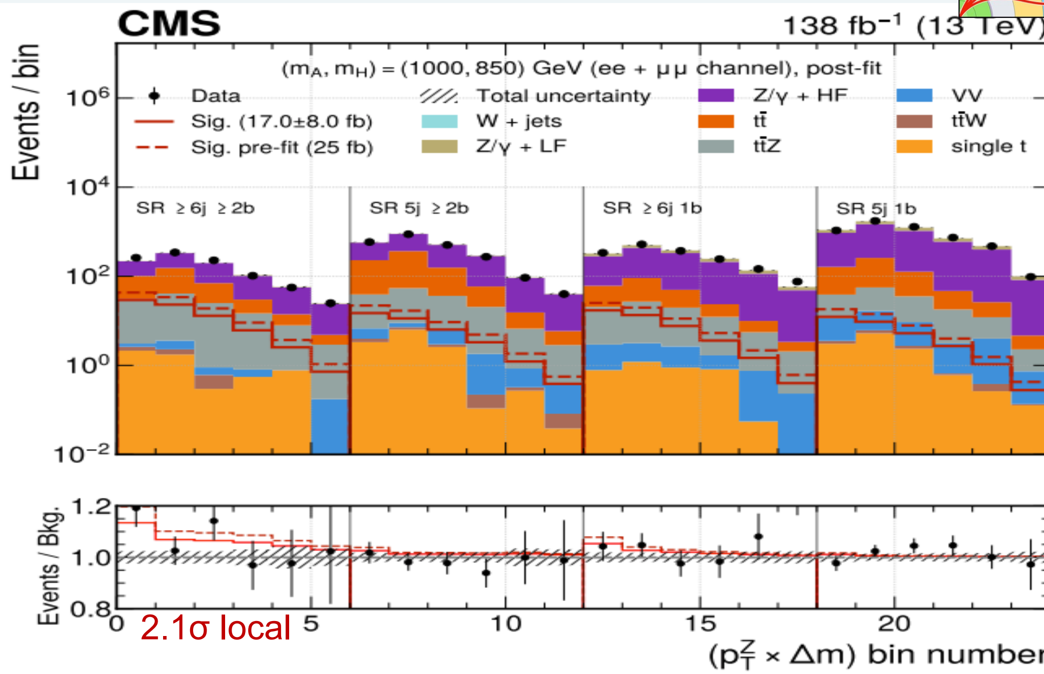
- Data: single/double-e/μ triggers (eff.>97%)
- Signal: LO (MG5), ggA production, $\Gamma/m_{A,H}$=3%.
- N_ℓ= 2, ee/μμ, OS, $|m_{\ell\ell} - m_Z|$< 5GeV
- tt → jets
  tt-system ($m_{tt}=m_H$) reconstructing minimizing a χ^2
- $N_j \geq 5$, AK4, CHS jets → binning
- N_b = 0,1,≥2 (DeepJet Mid-WP) → binning
- Use $\Delta m = m_A - m_H$, pT_Z variables[*] → form elliptical bins in $p_{TZ} \times \Delta m$ plain, centered at signal mean
- Dominant BKGs: tt, ttZ → from SB: $|m_{\ell\ell} - m_Z|$>5 GeV
  Z+jets → from N_b=0 CR
- 6 bins over N_b, N_j, (4 SRs, 2CRs),
  6 bins over $p_{TZ} \times \Delta m$ → 24 in total

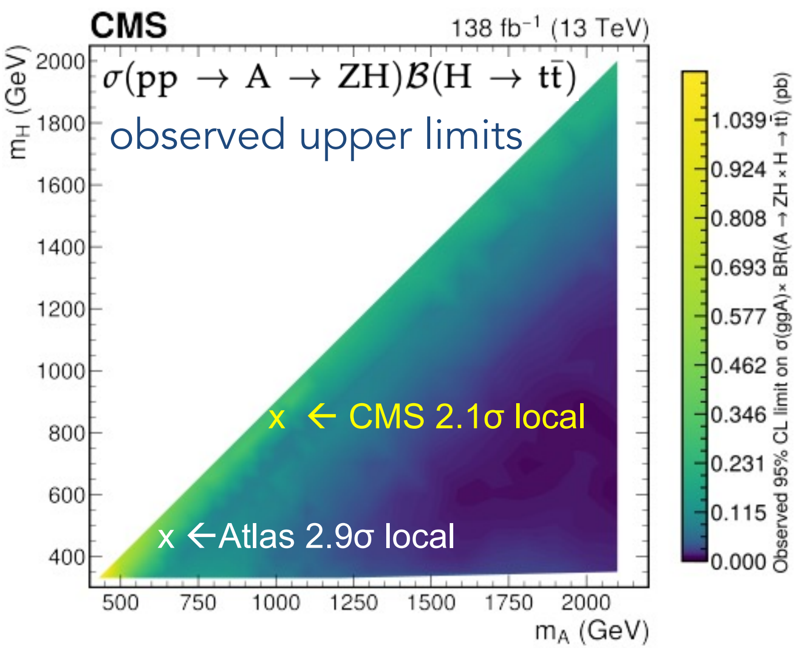


A→ZH→ ℓℓ tt: limits & 2HDM constrains

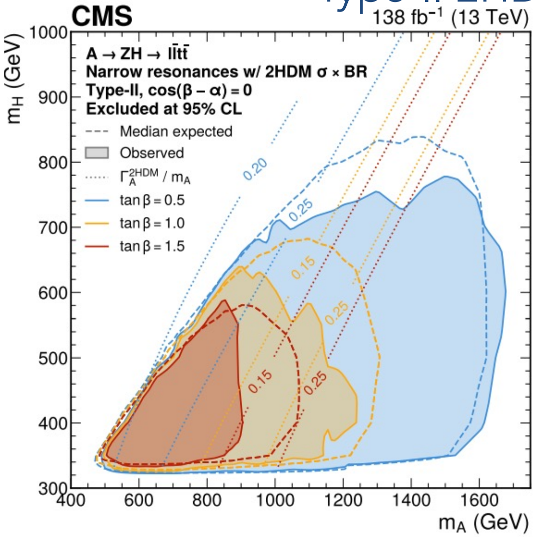


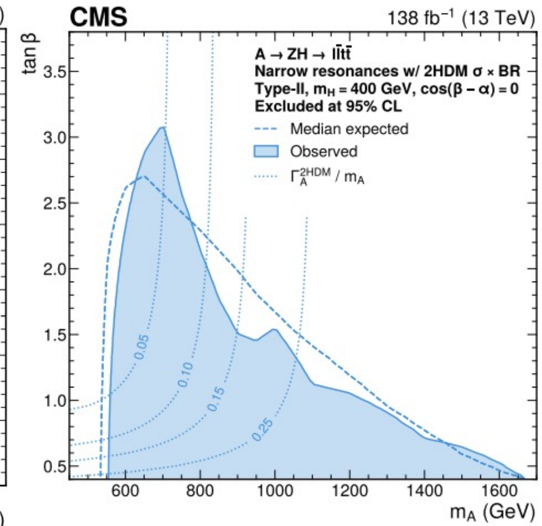
[B2G-23-006](#)
[CDS records](#)





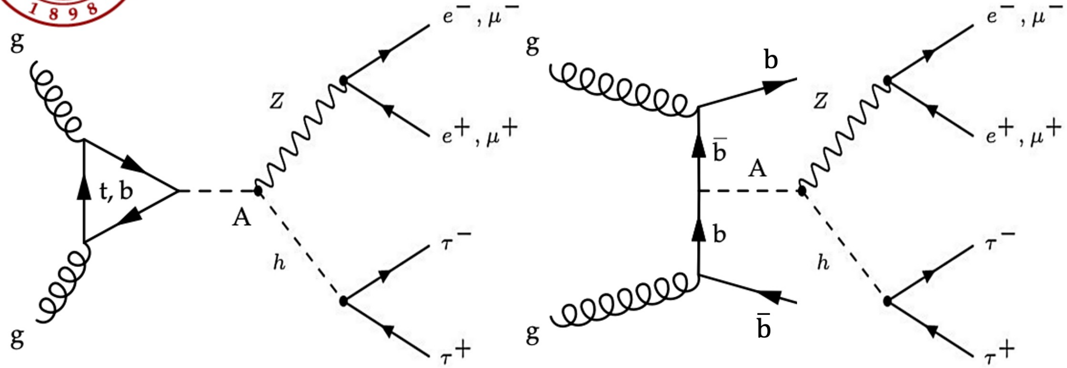
Type-II 2HDM constrains:





Search for A→Zh→ $\ell\ell\tau\tau$

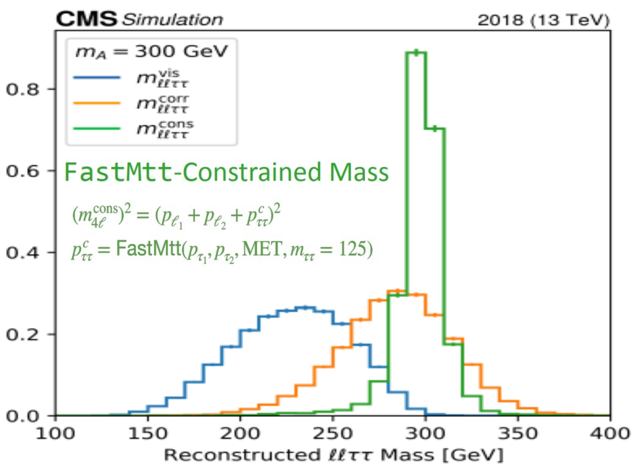
HIG-22-004
CDS records



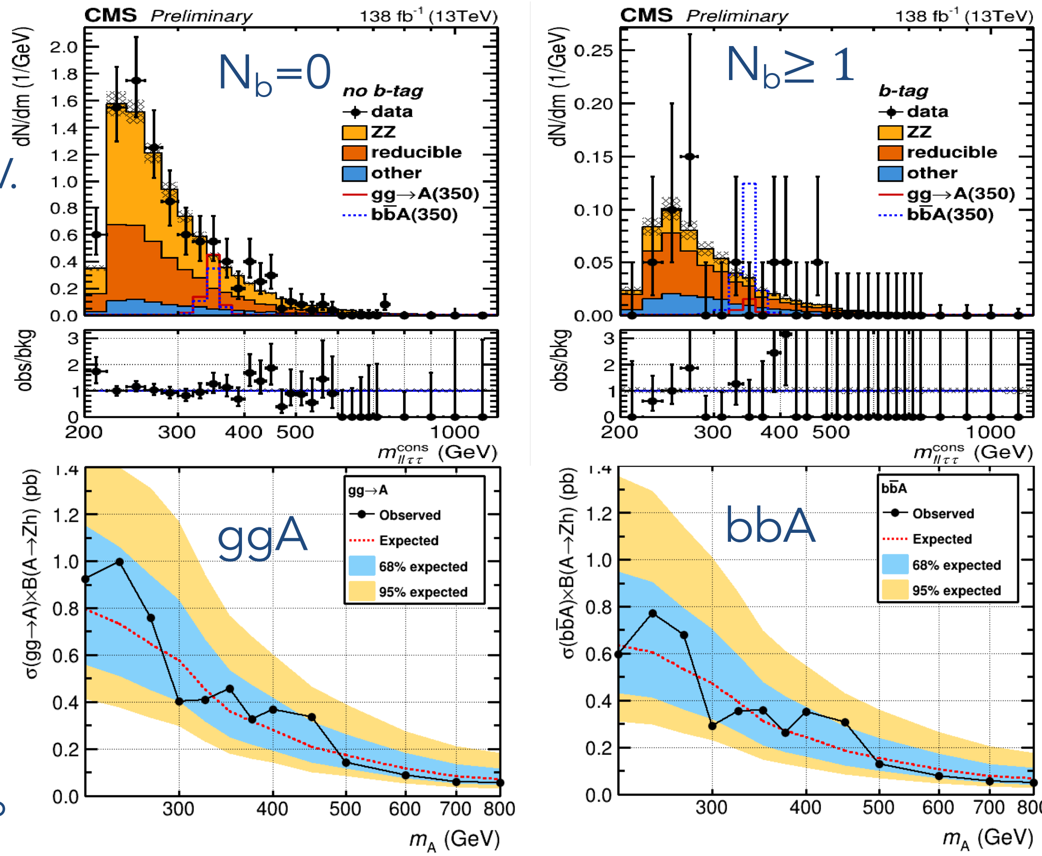
- 2HDM (CP-odd A, SM-like h):
- ggA productions → N_b=0
- bbA productions → $N_b \geq 1$
- 3 modes: $H \to \tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$ (DeepTau)
- 2 modes: Z →ee, μμ

e(μ)[b]: ID eff. 90(99)[80]%, misID eff. 1(0.2)[1]%

- Dedicated ττ-mass estimator used: FastMττ-algorithm, corrects for neutrinos using constrain: $m_{\tau\tau}$ =125 GeV.
- Fit the $m_{\ell\ell\tau\tau}^{cons.}$ variable in 6 channels.



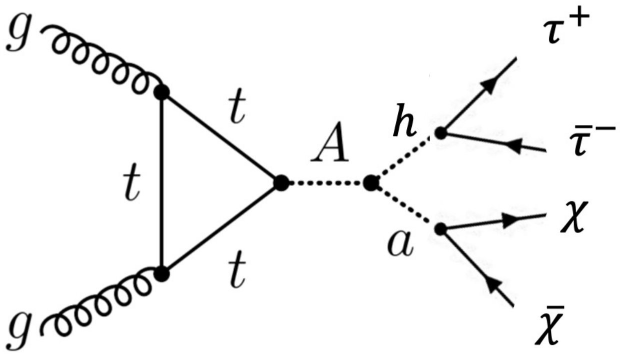
- Significant width improvement $\frac{\Gamma_A}{m_A}$: 5-7%



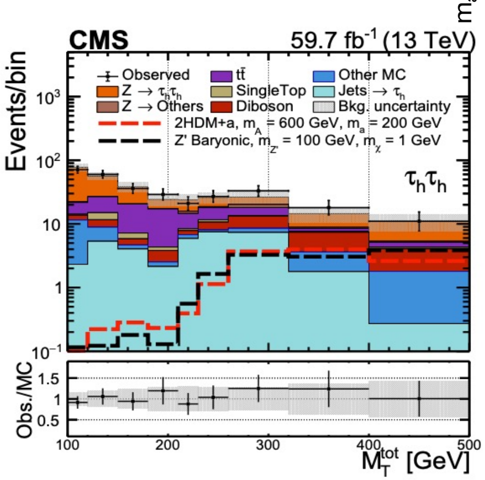
2HDM+α, A→ αh, bbH→ αZ

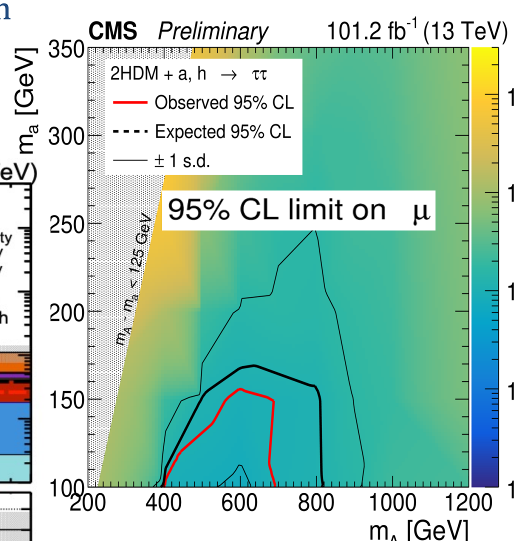
- 2HDM+α: α: additional pseudoscalar Dark Matter mediator, h: SM-higgs, H: BSM-higgs.
- Search for DM production in **"mono-h/Z" signatures**: h/Z boson recoiling high p_T^{miss}.

SUS-23-012
CDS records

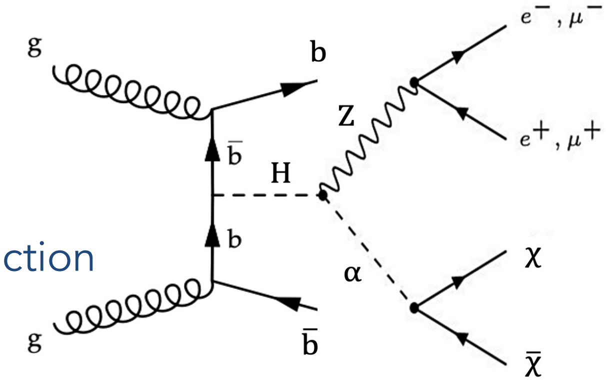


- ggA production
- $h \to \tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$ → 3 SRs.
- Fit the M_T^{total}.

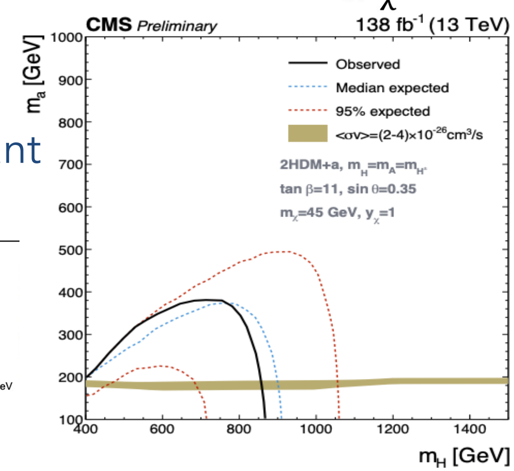


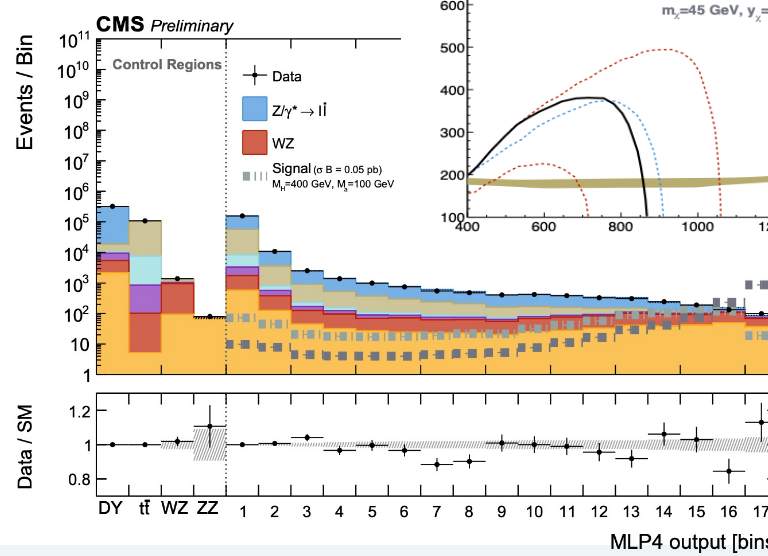


SUS-23-018
CDS records



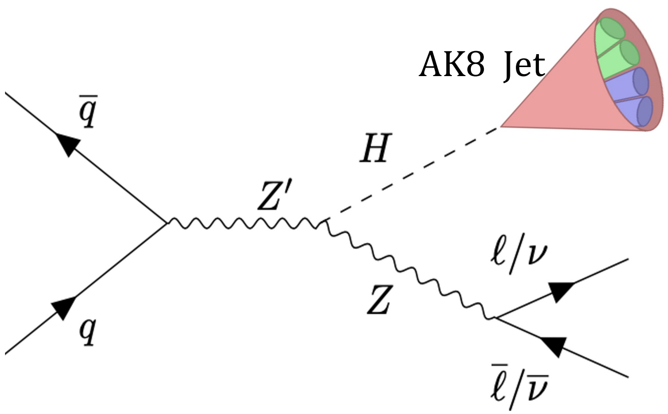
- bbH production
- $Z \to ee/\mu\mu$
- $N_b \geq 1$
- $M_T > 90$ GeV
- DY, ZV from CRs
- Fit MVA discriminant





Search for Z′→ZH→ ℓℓ/νν cc/4q

B2G-23-008
CDS records



- Z→ ee / μμ / νν
- H→cc (3%) / 4q (12%)
- Complementary to the H→ bb analysis 2102.08198

Selection:

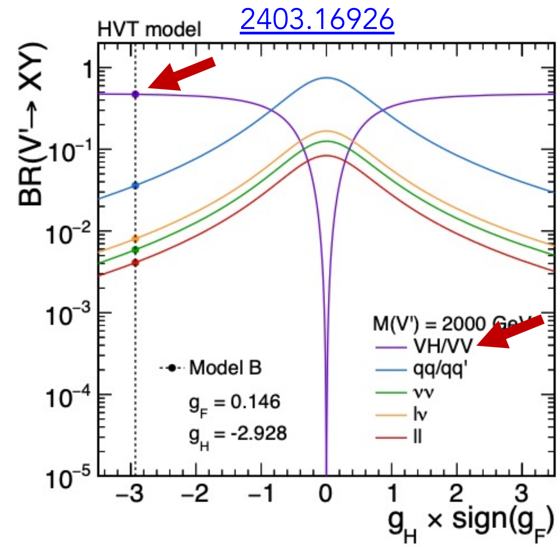
- 2 OS-SF ℓ , $p_T^{\ell\ell}$ > 200 GeV or
- p_T^{miss} > 250 GeV from Z→νν
- H-tagging: ParticleNet >0.95

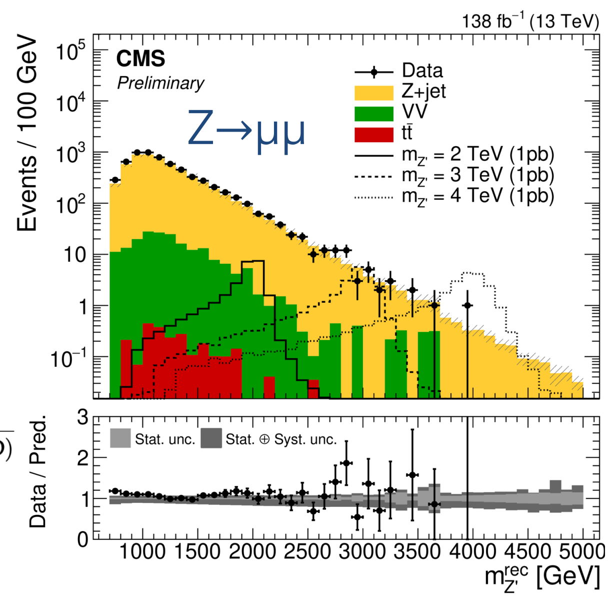
$$\mathrm{HvsQCD} = \frac{p(X \to b\bar{b}) + p(X \to c\bar{c}) + p(X \to q\bar{q})}{p(X \to b\bar{b}) + p(X \to c\bar{c}) + p(X \to q\bar{q}) + p(\mathrm{QCD})}$$

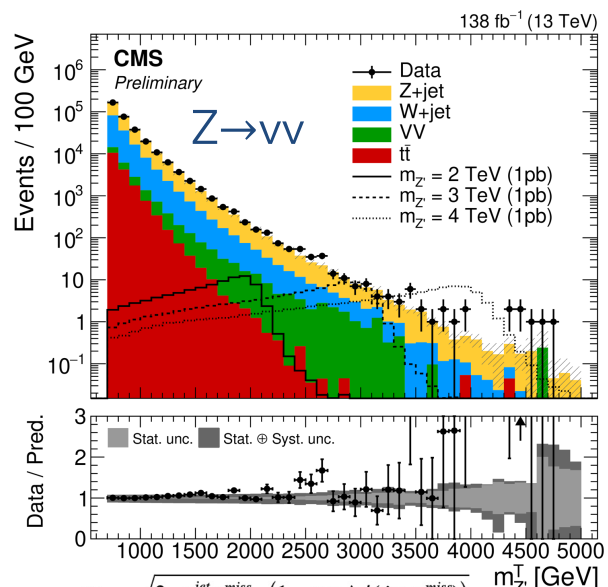
- Vetoing b-subjets.
- Signal eff.~50%, BKG-eff.~ 1%

- Heavy Vector Triplet (HVT) model → New spin1: Z′, W′
- Predicted by weakly coupled extended gauge sectors, little or composite Higgs models.
- Model B considered here
  $c_H = -0.976$, $c_F = 1.024$, and $g_V = 3$
  V′ →VV/VH is dominant →
- $m_{Z'}$>1.4 TeV → boosted jet

2403.16926

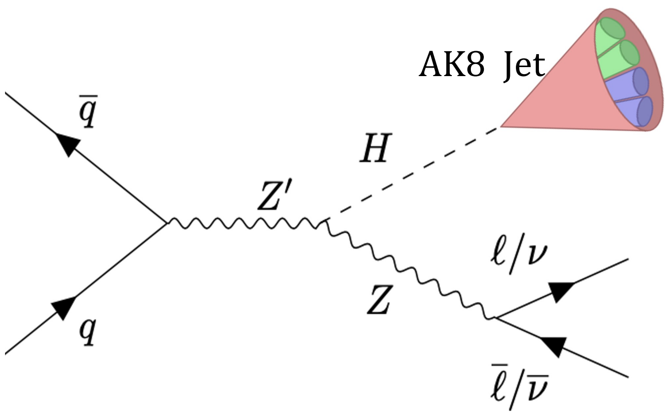






$$m_T = \sqrt{2 \cdot p_T^{jet} p_T^{miss} \cdot (1 - \cos\Delta\phi(jet, p_T^{miss}))}$$

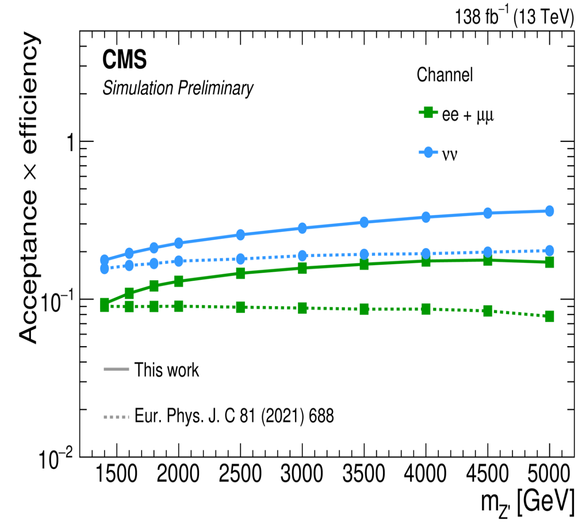
Z′→ZH→ ℓℓ/νν cc/4q, BKG modeling



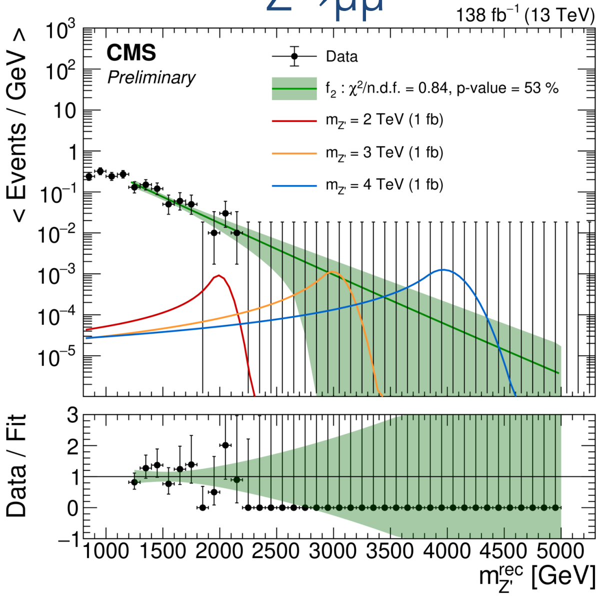
- Signal eff. better for the νν-channel →
- SM BKG prediction with parametric func.:

$$f(x) = \exp(p_0 + p_1 x + p_2 x^2)$$

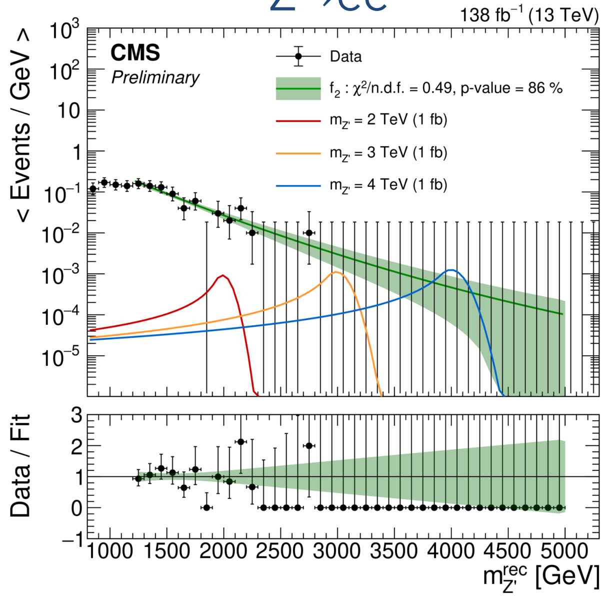
- Validation at low tagger scores VRs & simulation, & also F-tests applied.
- Signal: DS-Crystal-Ball.



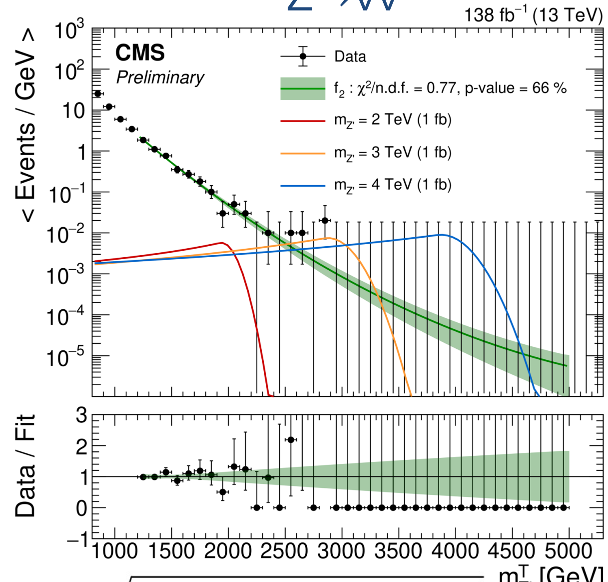
Z→μμ



Z→ee

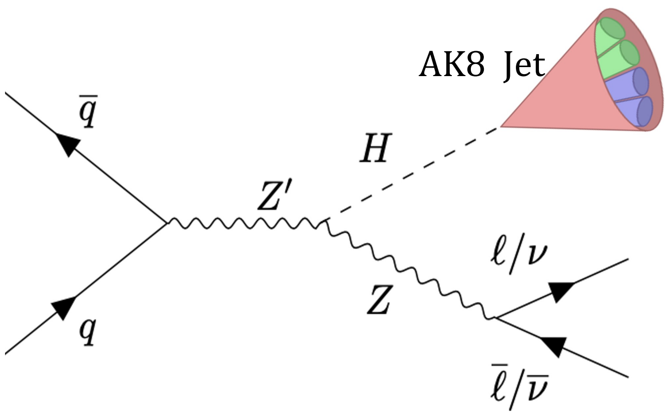


Z→νν

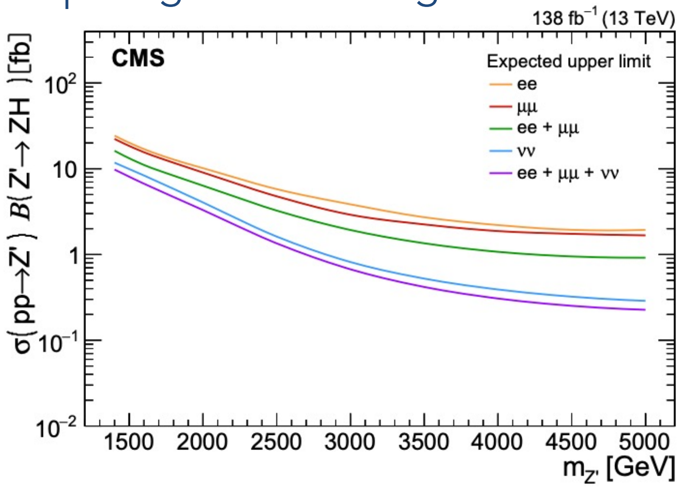


$$m_T = \sqrt{2 \cdot p_T^{jet} p_T^{miss} \cdot \left(1 - \cos\Delta\phi(jet, p_T^{miss})\right)}$$

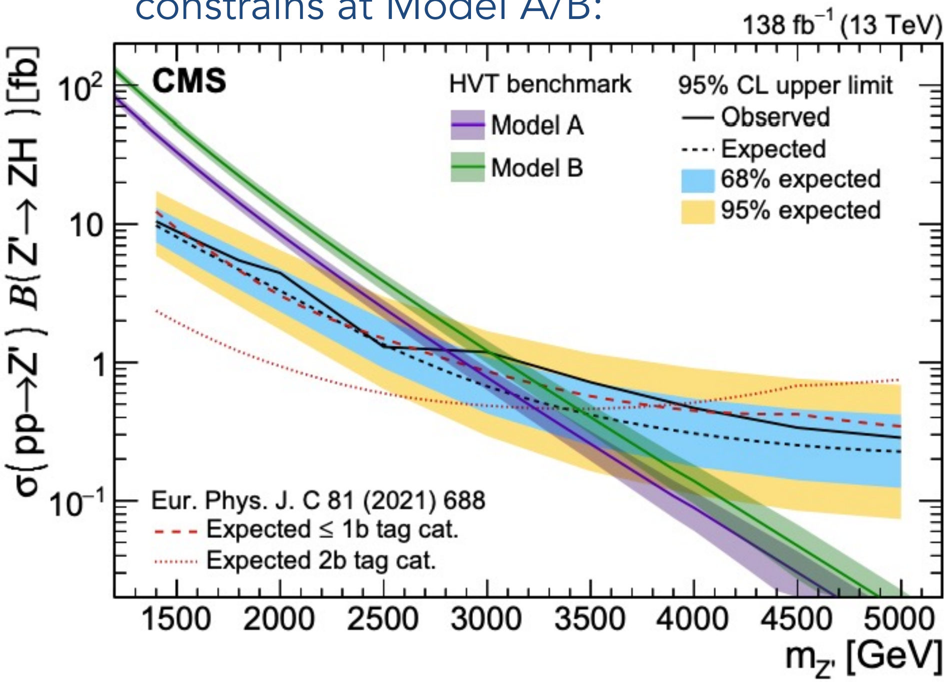
Z′→ZH→ ℓℓ/νν, cc/4q: Limits & Interpr.



- Comparing & combining the 3 channels:



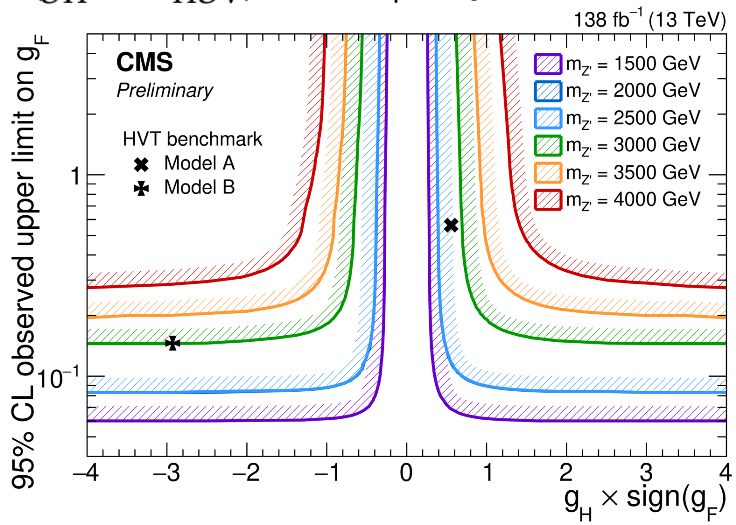
- Upper limits on σB(Z′→ZH) and constrains at Model A/B:



- Excluded g_F, g_H param. space for given $m_{Z'}$:

$(g_F = g^2 c_F / g_V)$ couplings of Z′ to H/V

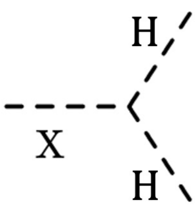
$(g_H = c_H g_V)$ couplings of Z′ to fermions

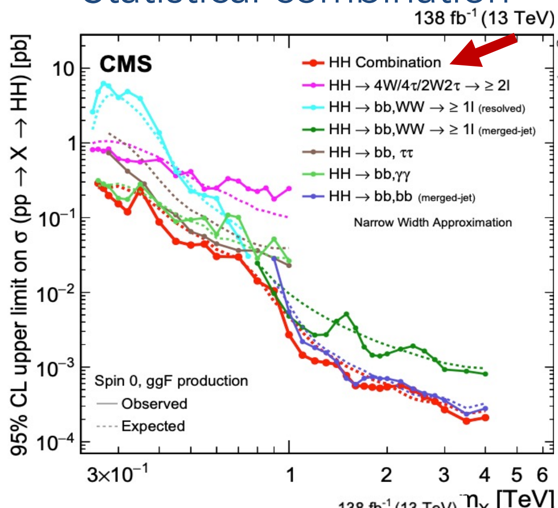


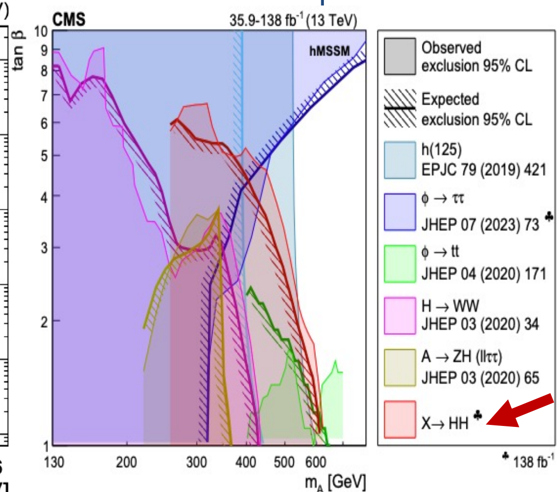
Review article: X → HH, HV, HY [2403.16926]

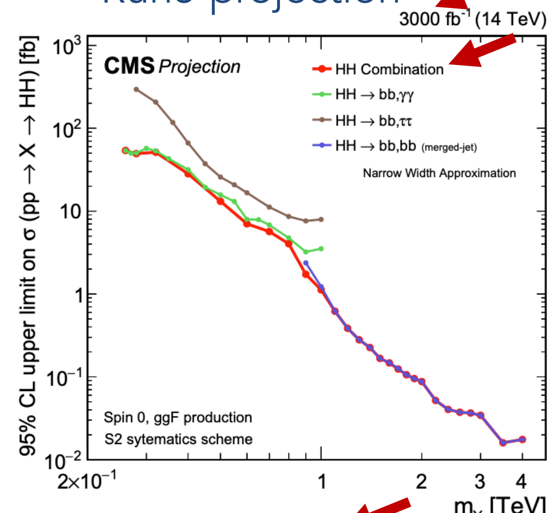
Searches for Higgs boson production through decays of heavy resonances

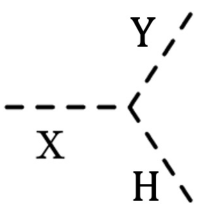
Statistical combination | hMSSM interpretation | Run5 projection

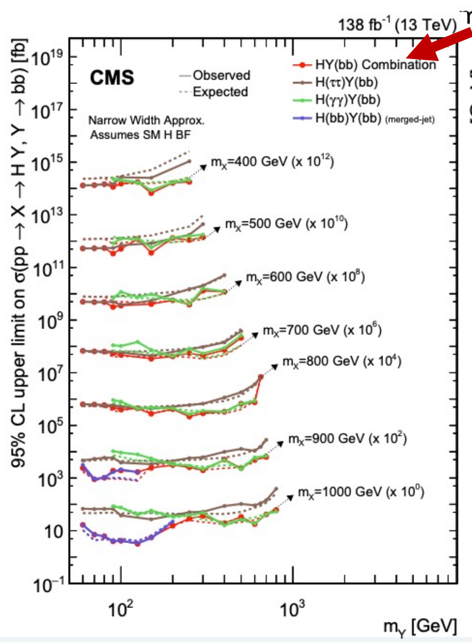


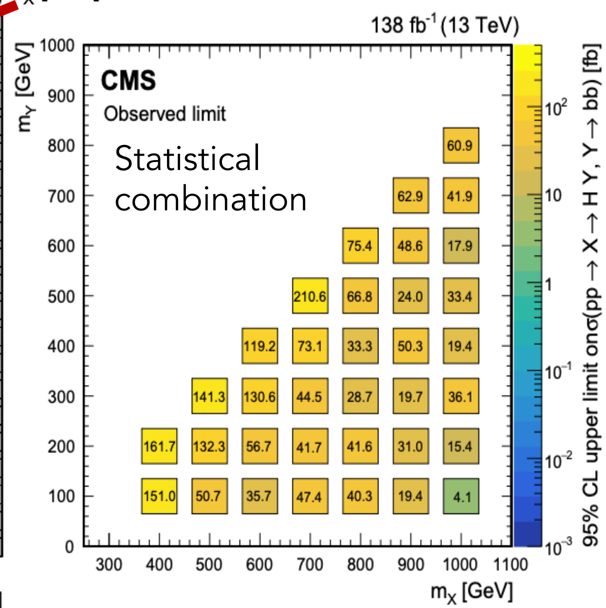


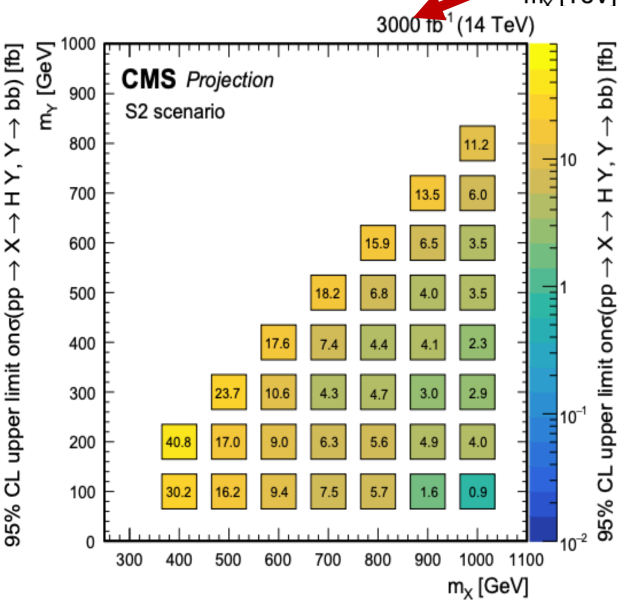




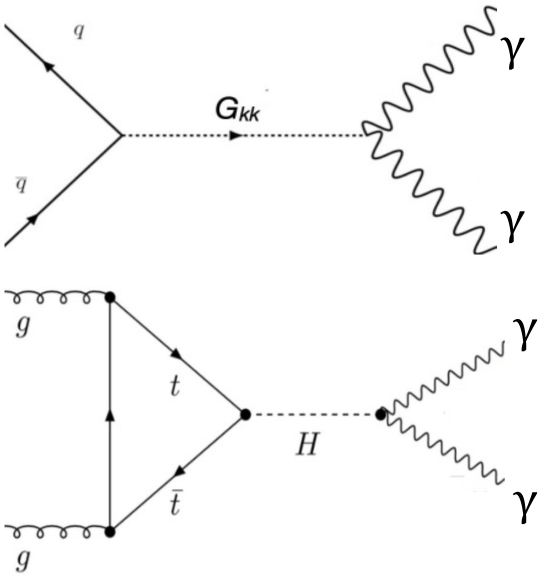


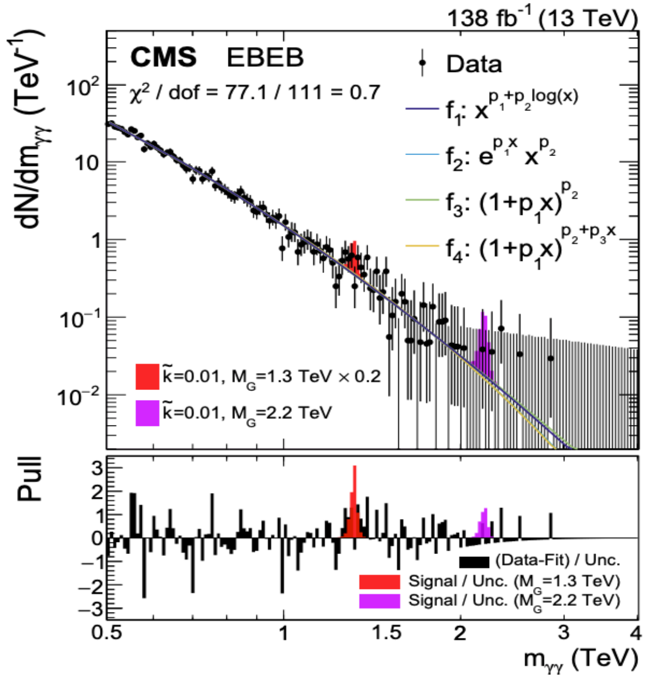


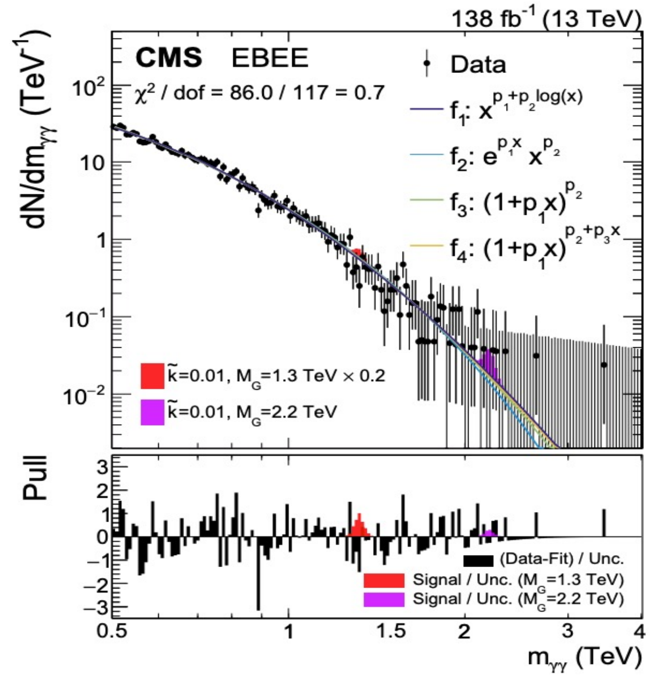




Search for resonant X→γγ 2405.09320





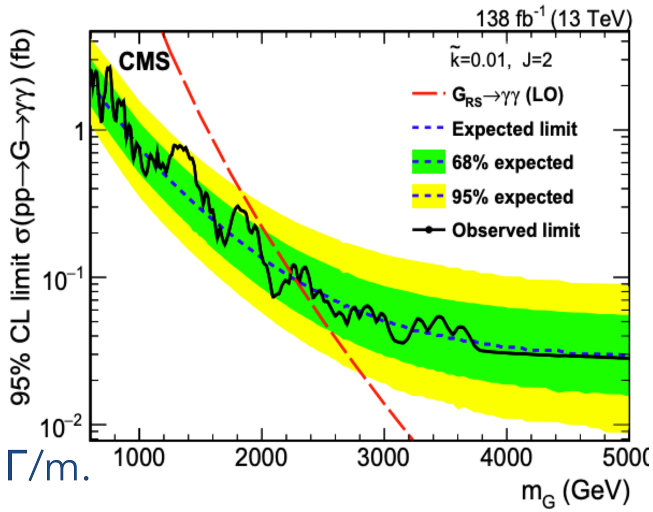


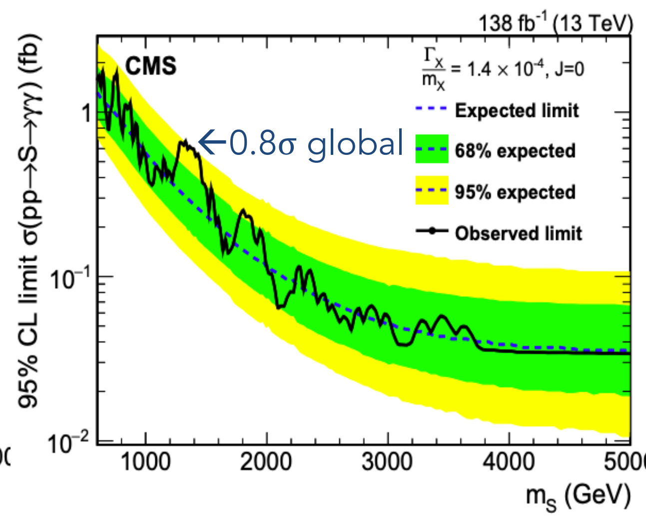
- RS spin-2 Graviton in WED
- Heavy H-like scalar (S)

- Select γγ events.
- Unbinned fit over the two EBEB, EBEE spectra $m_{\gamma\gamma}$.

- 4 parametric functions fit in data (discrete profiling scan)

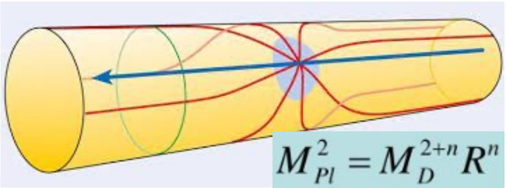
- Signal: pythia8 LO, multiple Γ/m.

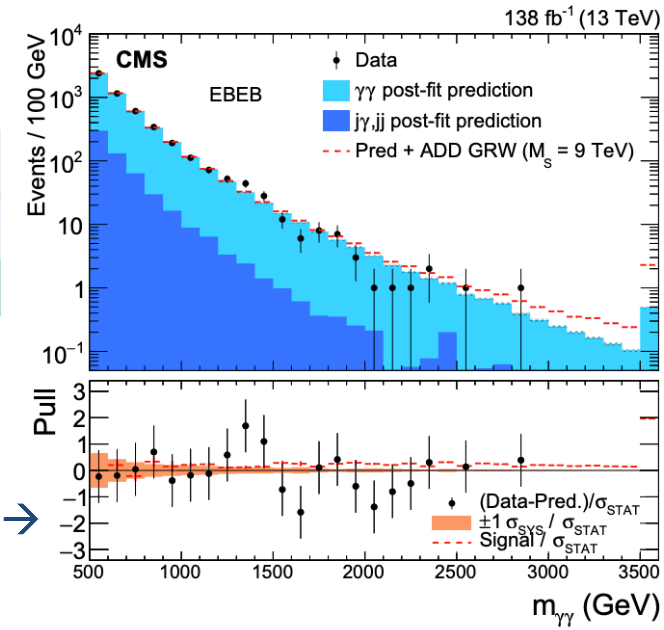


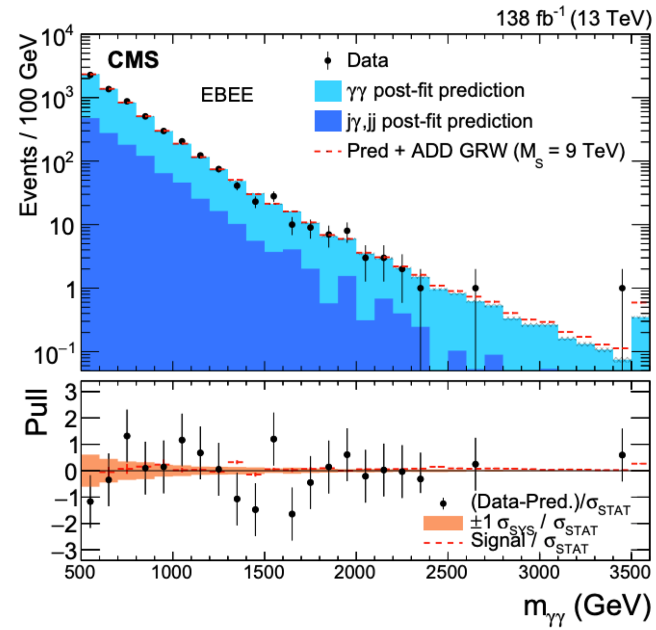


Search for non-resonant γγ signal [2405.09320]

- ADD large ED model



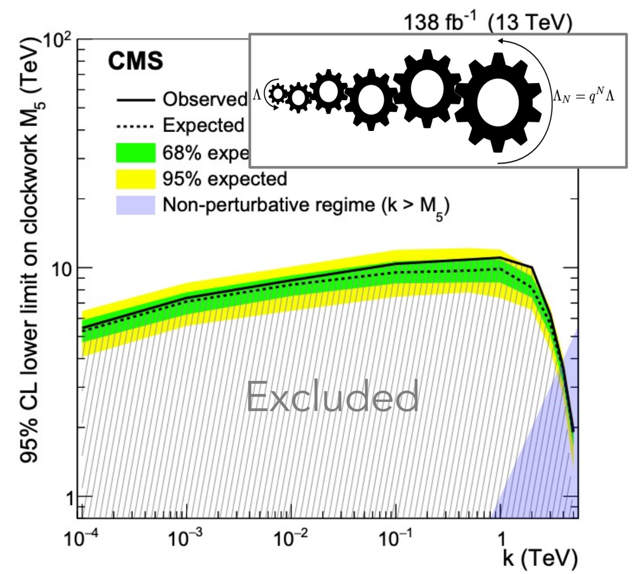




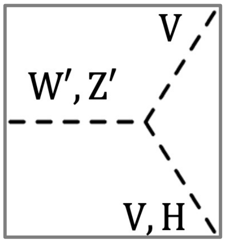
- Select γγ events.
- EBEB, EBEE categories→
- QCD BKG prediction:
  - γγ: Sherpa scaled at NNLO with MCFM.
  - jγ,jj = fakes: 10-30%, data0driven with fake rate.
- Fit the two binned $m_{\gamma\gamma}$ spectra in range 0.5-4 TeV.
- Lower limits on M_S (or Λ_T) scale vs number of ED: (~11 TeV)

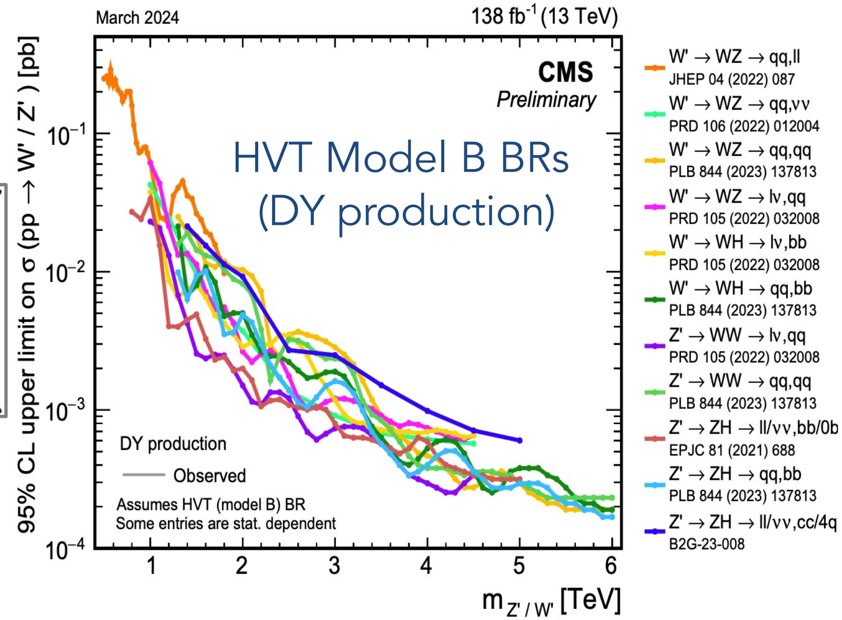
Signal:	GRW	Hewett		HLZ				
		negative	positive	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
Expected:	$8.7^{+0.7}_{-0.6}$	$7.3^{+0.3}_{-0.3}$	$7.8^{+0.6}_{-0.5}$	$10.3^{+0.8}_{-0.7}$	$8.7^{+0.7}_{-0.6}$	$7.9^{+0.6}_{-0.5}$	$7.3^{+0.6}_{-0.5}$	$6.9^{+0.6}_{-0.5}$
Observed:	9.3	7.1	8.3	11.1	9.3	8.4	7.8	7.4

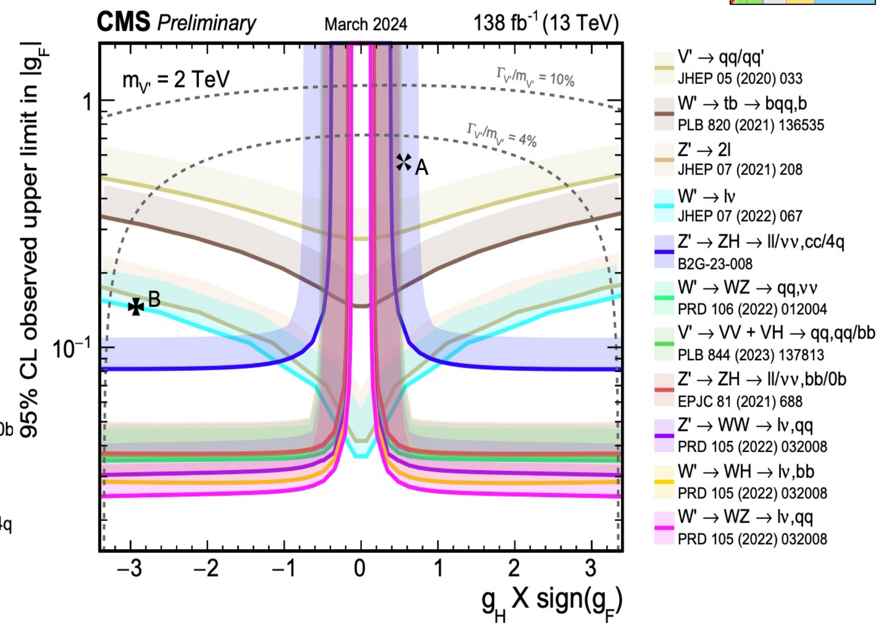
- Interpretation on Continuum Clockwork Mechanism →
  Constrains on M_5 mass vs clockwork spring "k".

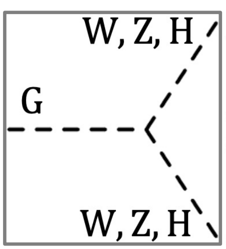


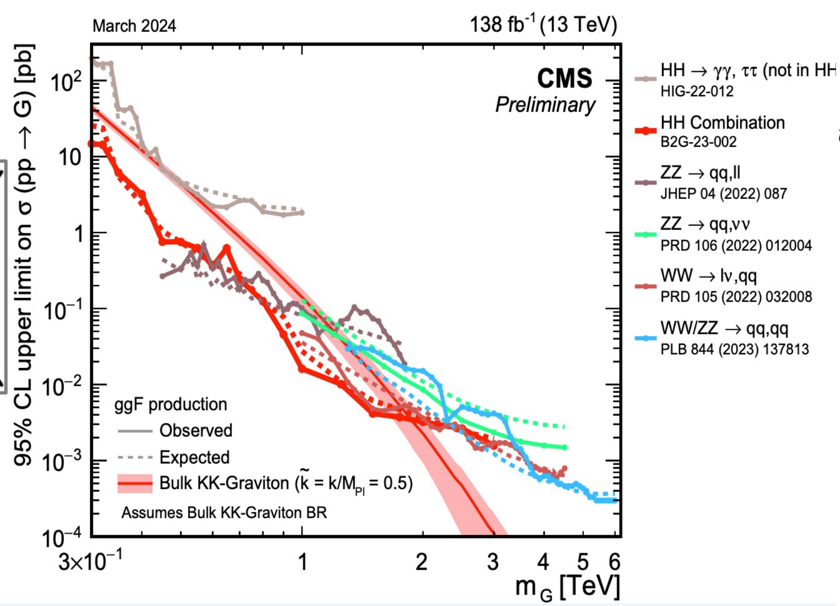
Summary plots & model constrains [Twiki]

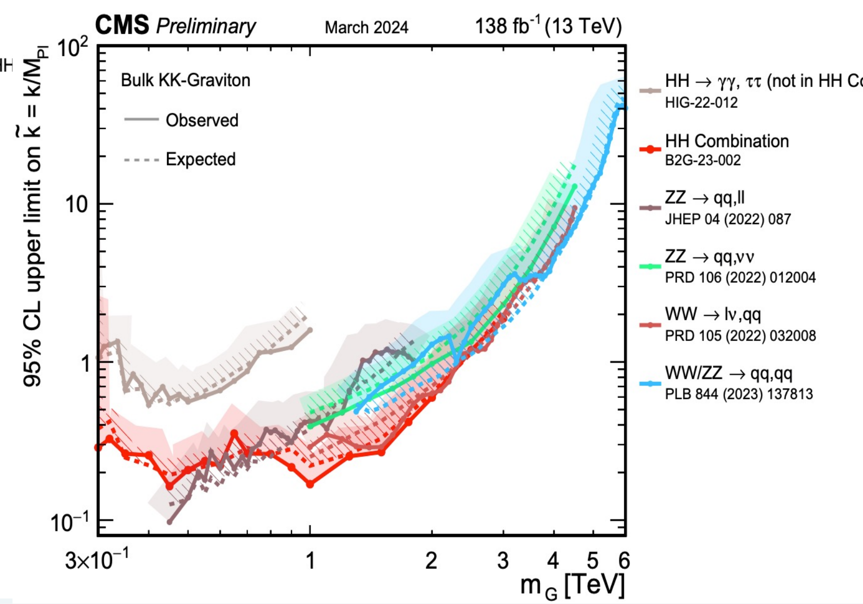




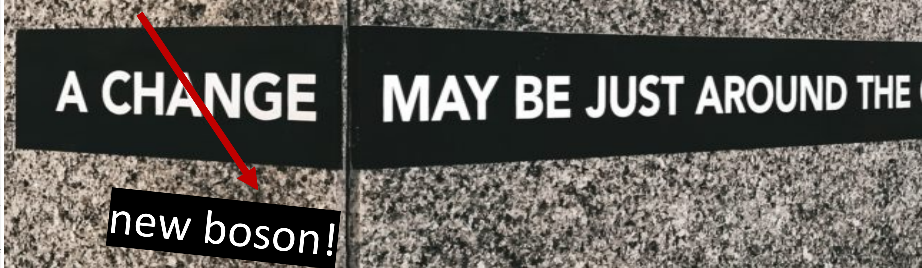


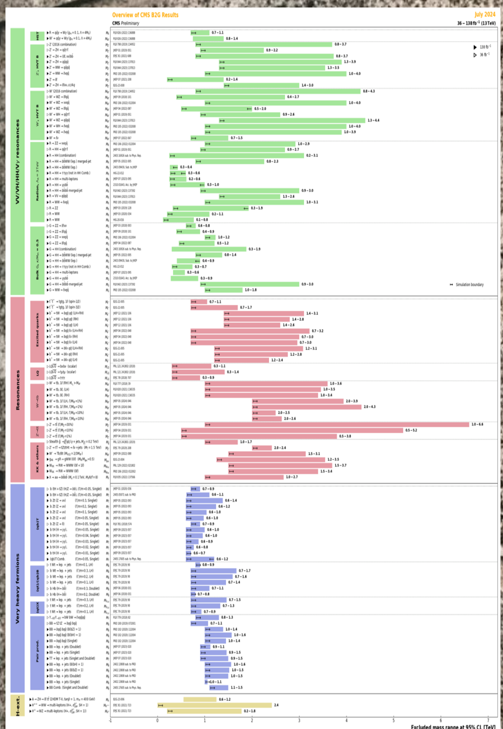


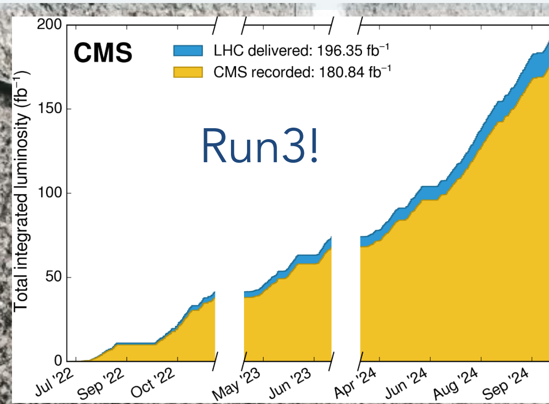




Run3 is ongoing, and BSM physics may be just around the corner - Stay tunned!



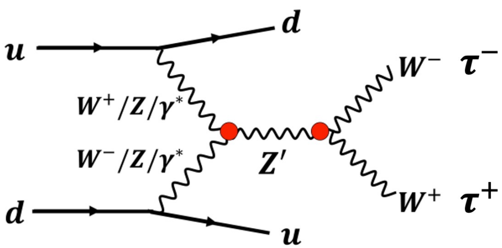




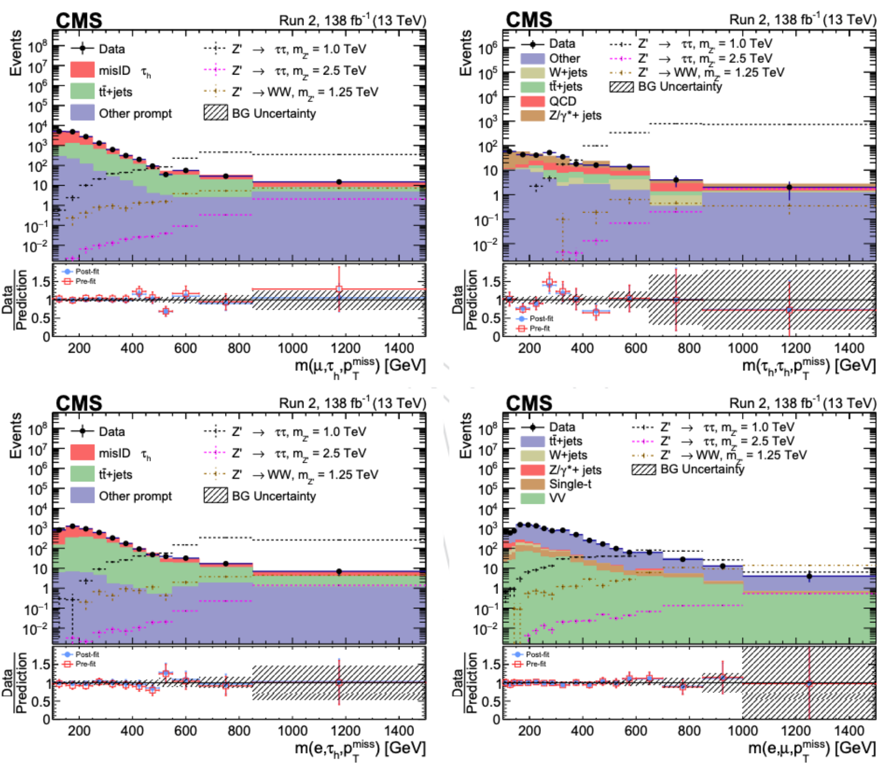
BSM hidden zoo

Backup slides

VBF Z'→WW→ ℓℓνν [EXO-21-015]



Four Z' decay channels are utilized: $e\mu$, $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$.



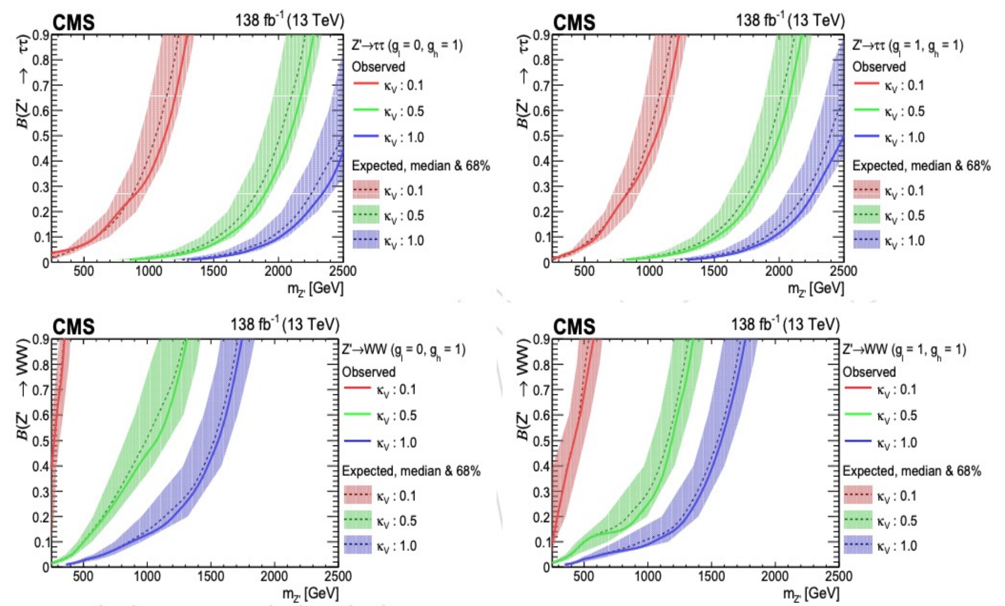
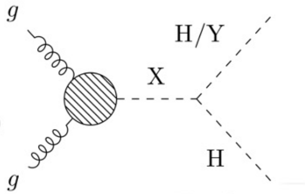


Figure 2: Combined 95% CL upper limits on $m_{Z'}$ as a function of the Z' branching fraction to (upper row) $\tau^+\tau^-$ and (lower row) W^+W^- for the (left column) $g_\ell = 0$ and (right column) $g_\ell = 1$ scenario. The red, green and blue curves show the observed limits corresponding to κ_V equal to 0.1, 0.5, and 1 respectively. The dashed curves and shaded bands show the expected limits with their 68% CL uncertainties.

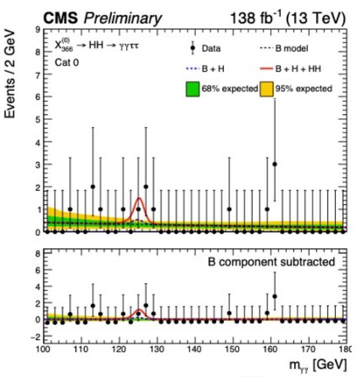
Reso & non-reso X→HH/HY→ττγγ [EXO-22-012]

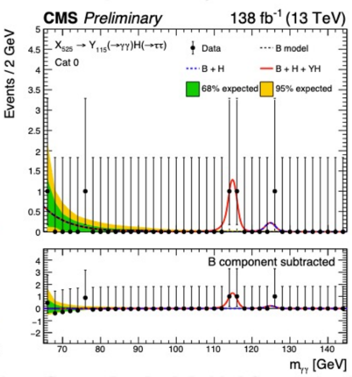
- Motivated by Warped Extra Dimensions and Extended Higgs sector models
  - heavy Higgs can decay to lighter Higgs



- HH → $\gamma\gamma\tau\tau$ has small branching fraction but clean signatures (*non-resonant not included here*)
  - four channels: $X^{(0)} \to HH$, $X^{(2)} \to HH$, $X \to Y(\tau\tau)H(\gamma\gamma)$, $X \to Y(\gamma\gamma)H(\tau\tau)$

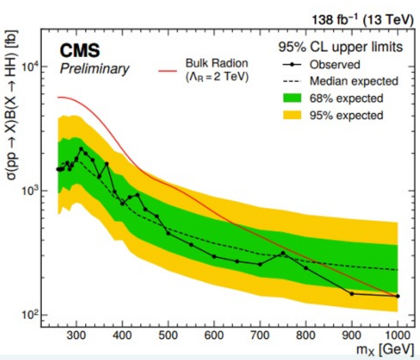
- Narrow width resonance searches
  - $X \to HH$ for 260 < m_X < 1000 GeV
  - $X \to Y(\tau\tau/\gamma\gamma)H(\gamma\gamma/\tau\tau)$ for 50/70 < m_Y < 800 GeV

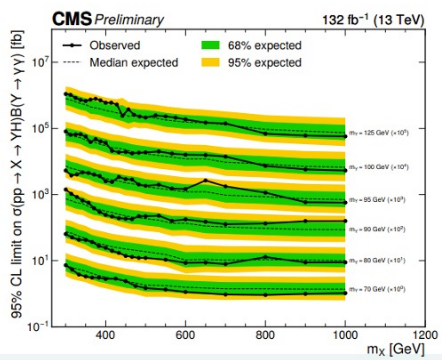


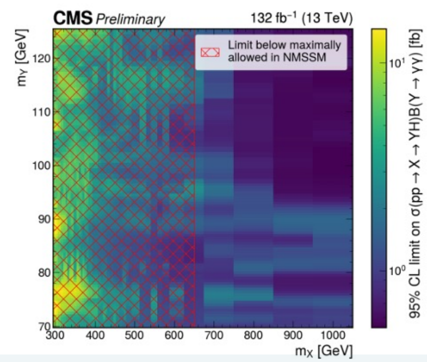


- Parametric NN is trained using multiple mass hypotheses vs backgrounds for each search channel
  - pNN output served for event categories

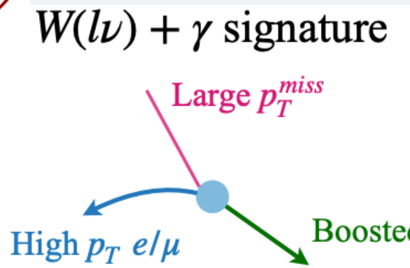
- Signal extraction is performed on $m_{\gamma\gamma}$ distribution
  - Main backgrounds from $\gamma\gamma$+jets (non-resonant) and single-H production (resonant)
  - A maximum likelihood fit on $m_{\gamma\gamma}$ distribution is done for each probed mass and event category
  - Some deviations from background-only hypothesis are observed in $X \to YH$ channels
    - $X \to Y(\tau\tau)H(\gamma\gamma)$: 2.6σ (2.2σ) local (global) significance at (m_X, m_Y) = (320, 60) GeV
    - $X \to Y(\gamma\gamma)H(\tau\tau)$: 3.4σ (0.1σ) logal (global) significance at (m_X, m_Y) = (525, 115) GeV

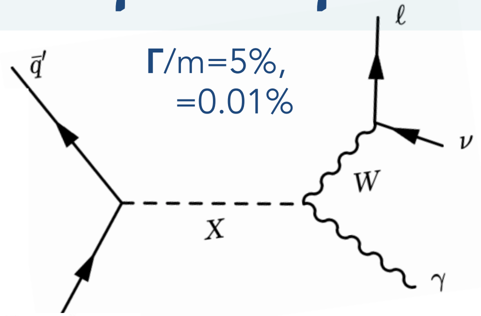






X→Wγ→lνγ [EXO-21-017]



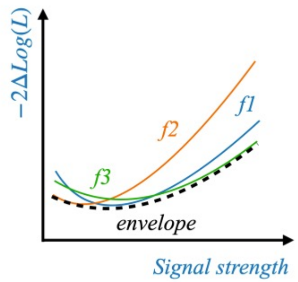


- Backgrounds are modeled with analytic functions
- Use envelope method to incorporate all 3 functions

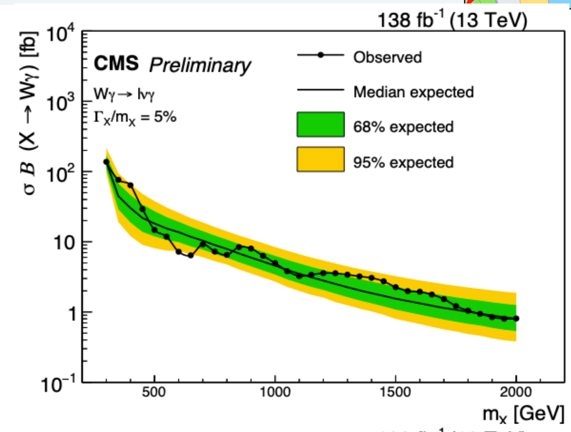
$$p_0 \times x^{\sum_{i=1}^{N} p_i \times \log^{i-1}(x)}$$

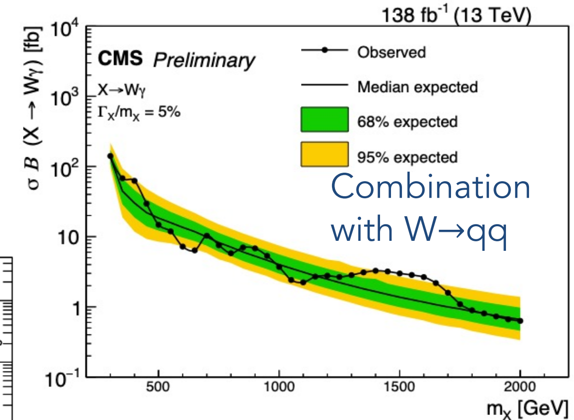
$$p_0 \times \frac{(1-x)^{p_1}}{x^{\sum_{i=2}^{N} p_i \times \log^{i-2}(x)}}$$

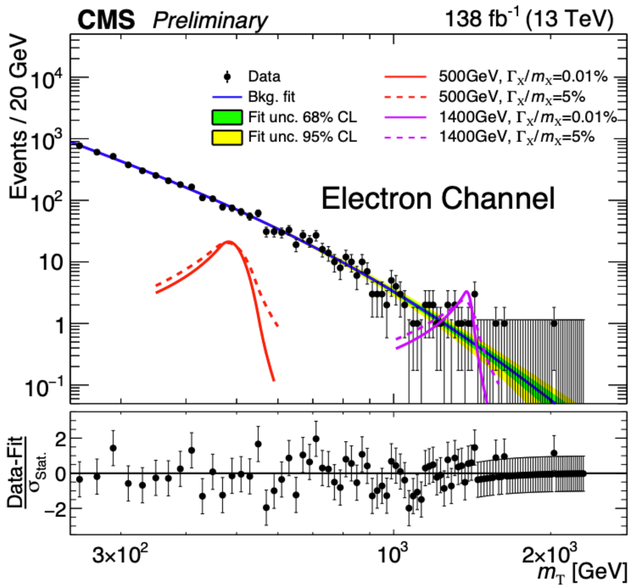
$$p_0 \times e^{p_1 x} x^{\sum_{i=2}^{N} p_i \times \log^{i-2}(x)}$$

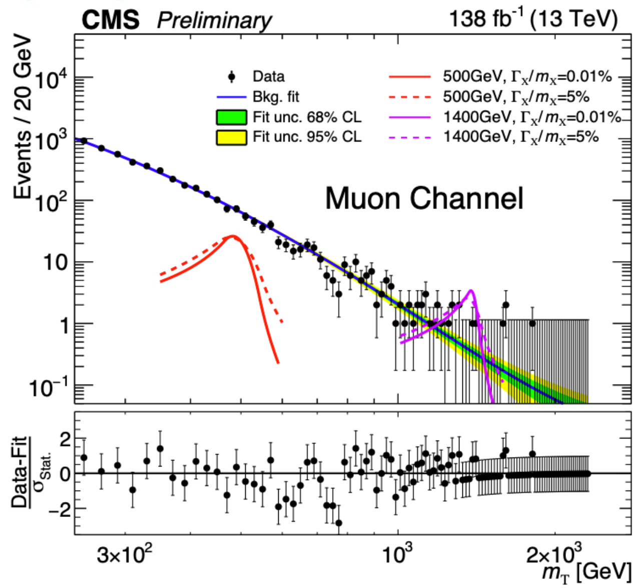


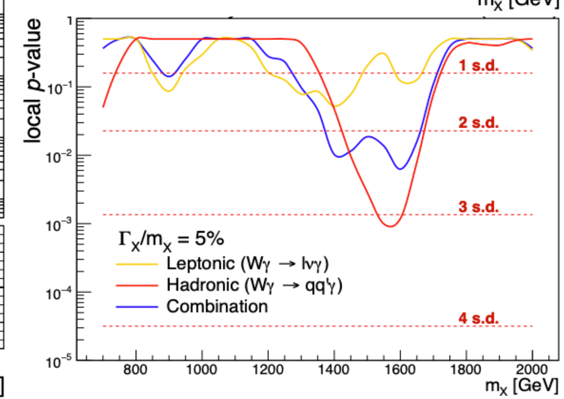
Lepton p_T	> 35 GeV	> 30
$m_{\ell\gamma}$ mass	$\lvert m_{e\gamma} - 91.0\rvert > 20$ GeV	–
Lepton ID	Tight	
Photon p_T	$0.4 m_T < p_T(\gamma) < 0.55 m_T$	
p_T^{miss}	$p_T^{miss} > 40$ GeV	
Photon η	$\lvert\eta\rvert < 1.44$	
Photon ID	Medium	
b jet veto	0 medium-tagged b jets	







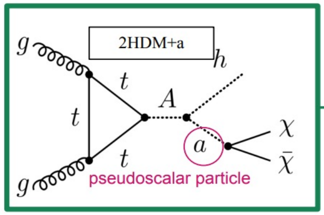




SUS-23-012

Introduction to Analysis:

- The fundamental nature of DM is not known. Weakly interacting massive particle (WIMP) may interact with SM through the Higgs sector, as in Higgs-portal models. WIMP DM is denoted χ
- Signature of mono-Higgs: Higgs + missing transverse momentum (p_T^{miss})
- Benchmark models:
  - 2HDM+a
  - Baryonic Z'



2HDM+a: Total 14 parameters

v, m_h, m_A, m_H, $m_{H\pm}$, m_a, m_χ, $\cos(\beta-\alpha)$, $\tan\beta$, $\sin\theta$, y_χ, λ_3, λ_{P1}, λ_{P2}

Fixed parameters: 7

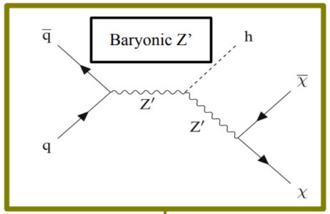
$v = 246$ GeV,
$m_h = 125$ GeV,
$\cos(\beta-\alpha) = 0$,
$\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$,
$y_\chi = 1$

mass parameter are set to be equal:

$m_A = m_H = m_{H\pm}$

Free parameters: 5

m_A, m_a, $\tan\beta$, $\sin\theta$, and m_χ



Baryonic Z': Total 2 parameters

Z' Mass: $m_{Z'}$

Dark matter mass: m_χ

Signal extraction strategy:

Analysis Selection:

- ❑ Select eτ, μτ, ττ pairs with opposite sign, third lepton-veto, bjet veto
- ❑ ΔR (lepton(e/μ), τ) > 0.5
- ❑ Higgs $p_T > 65$GeV
- ❑ Visible mass < 125 GeV
- ❑ MET > 105 GeV
- ❑ $M_T^{Tot} > 100$ GeV

Signal is extracted based on the likelihood fit on the total transverse mass variable in the signal region

$$M_T^{tot} = \sqrt{(E_T^{\tau_1} + E_T^{\tau_2} + p_T^{miss})^2 - (p_x^{\tau_1} + p_x^{\tau_2} + p_x^{miss})^2 - (p_y^{\tau_1} + p_y^{\tau_2} + p_y^{miss})^2}$$

SUS-23-018

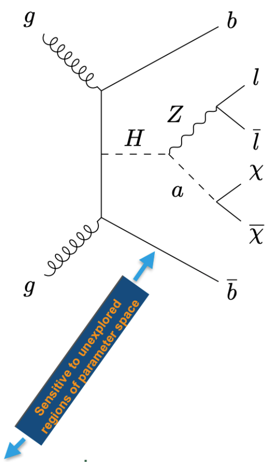
Introduction

Motivation

- **Fermi-LAT space telescope observes a gamma-ray excess in studies of the Milky Way Galactic Centre** arXiv:1511.02938
  - Might be interpreted as the existence of weak-scale DM annihilating into bb pairs
  - DM-nucleon interactions mediated by pseudoscalars are much below the reach of present DD experiments

Theoretical framework: 2HDM+a

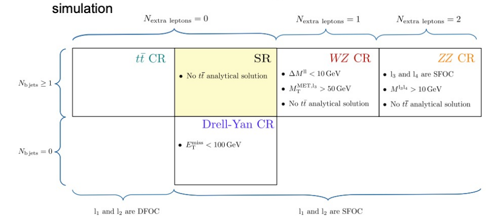
- **Two-Higgs Doublet Models extended with an additional pseudoscalar (DM mediator)** arXiv:1701.07427 arXiv:1705.09670
  - Can reproduce the observed DM relic density for relatively large $\tan\beta$
  - Would favor preferential coupling of DM mediator to down-type fermions
  - Associated production of Heavy scalar with b-quarks is enhanced

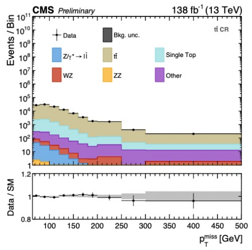


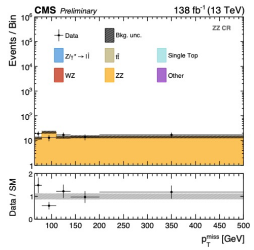
Presenting new search involving final state with two bottom quarks, a leptonically decaying Z boson, and p_T^{miss}

Event Selection and Background Modeling

- **Baseline Selection**
  - Two oppositely charged leptons (e^+e^- and $\mu^+\mu^-$) with invariant mass consistent with that of a Z boson
  - Requiring lepton pair to be moderately energetic and to have a large separation w.r.t. p_T^{miss}
  - p_T^{miss} > 65 GeV & $m_T^{p_T^{miss},ll} > 90GeV$
- **Signal region and background control regions**
  - Normalization of main four background controlled using subsidiary measurements in separate regions
  - Shape of DY modeling improved using data driven procedure, while the rest estimated mainly from simulation

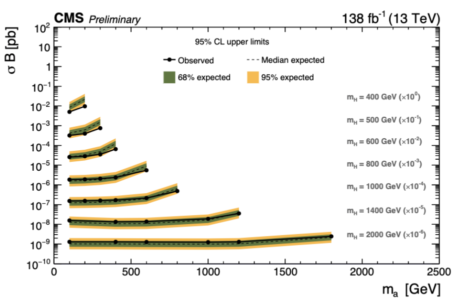


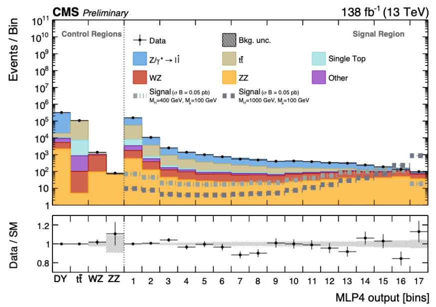




Signal Extraction

- **Multivariate discriminant (MLP) trained with leptonic and missing transfer momentum information**
  - Input: leading p_T^{l}, trailing p_T^{l}, p_T^{ll}, ΔR^{ll}, Δm^{ll}, p_T^{miss}, $m_T^{ll,p_T^{miss}}$, $\Delta\phi^{ll,p_T^{miss}}$, and m_{T2}^{ll},
  - Signal class: grouping of all simulated mass configurations for m_H and m_a
  - Background class: All process contributions normalized to their expected yields
- **MLP score is transformed and binned into 17 different subregions optimized of the different signal topologies studied**





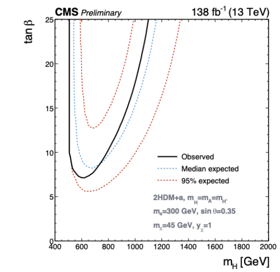
Control regions to extract normalization

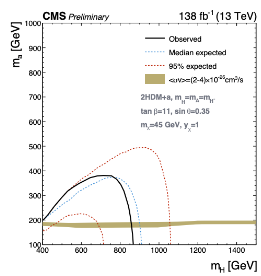
Signal region subdivided into 17 bins of the MLP4 discriminator

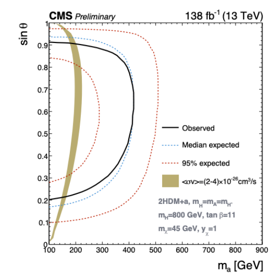
No significant deviation from SM expectation observed
Setting limits on product of the cross section and branching fraction

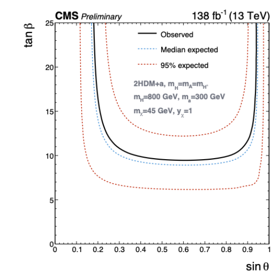
Interpretation in the 2HDM+a context

- **Excluded regions on the parameter phase space for the 2HDM+a model**
  - Four projections the various 2D planes are shown
  - Allowed phase-space values for each projection as estimated by assuming a range around the central value of $\langle\sigma v\rangle$ as resulting for assuming the observed DM relic density
- **Some preferred regions of the phase-space largely excluded by this analysis**









γγ Search Motivation

- SM shortcomings indicate some kind of BSM physics:

ADD large extra dimension
- n_{ED} extra dimension
- compactified with average radius R
- effective M_{Pl} ~TeV-scale

$$M_{\rm Pl}{}^2 \sim M_{\rm Pl(4+n)}^{2+n} R^n$$

- gravity has a strength comparable with the rest forces but dilutes in ED

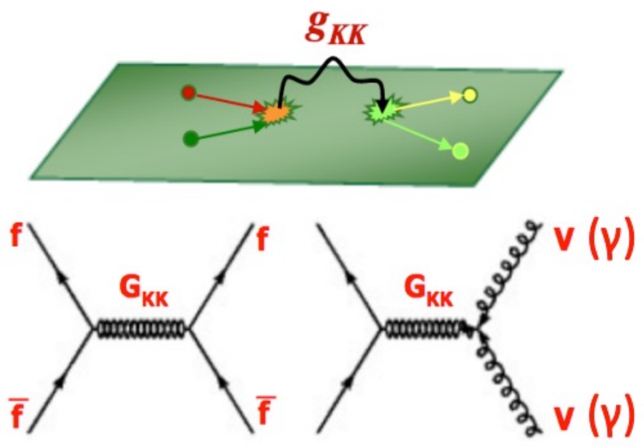
RS graviton (warped ED)
- one extra dimension
- compactified with r_c
- curvature k
- scales masses in 4D as:

$$m = e^{-kr_c\pi} m_0$$

- scaling M_{Pl} ~TeV-scale (kr_c ~ 11-12)

Continuum Clockwork
- coincides with a 5D gravitational theory
- mechanism that can take large effective interaction scales from dynamics occurring at much lower energies (arxiv:161007962).

- These three models are:
  → Solving hierarchy problem
  → Introducing ED and graviton
  → Can be visible in TeV-scale through KK graviton modes
  → Leads to visible SM discrepancies in γγ final state

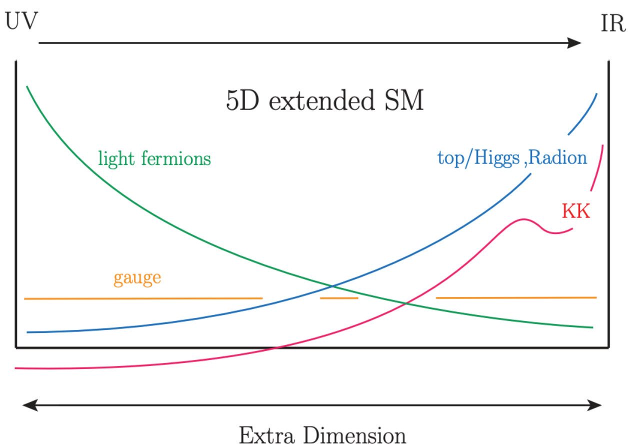


Motivation: BSM physics beyond minimal

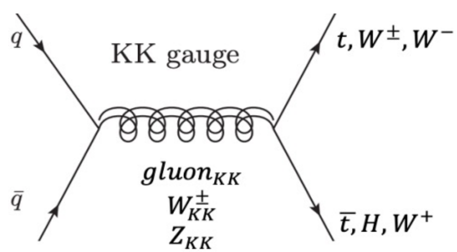
- Hierarchy: EW-M_{Pl} scale gap motivates BSM physics.
- No BSM physics yet → time to look in non-standard final states/scenarios.

Minimal Warped ED model:

- 2 Branes in bulk (in the RS framework). Everything propagates to the same bulk:

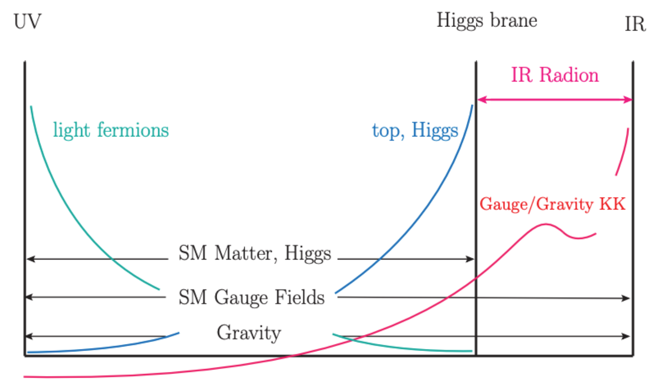


- Di-SM dominant phenomenology:
- Constrained by LHC searches.

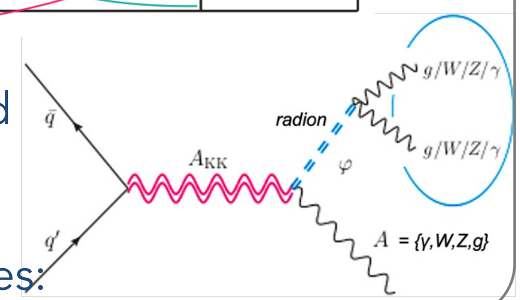


Extended Warped ED (EWED) model:

- Extra brane by splitting→ extended bulk.
- 3 or more branes, 2 or more Radions.
- Various fields propagate in diff. regions:



- Di-SM suppressed in favor of tri-SM:
- A wealth of new signatures emerges:

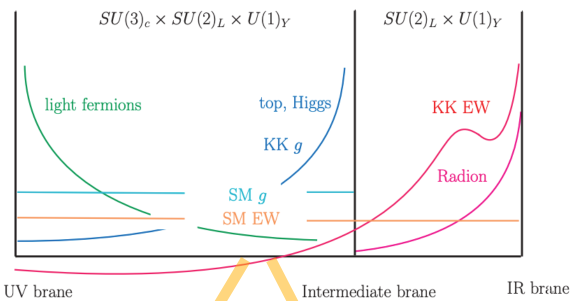


Theory sources:
Kaustubh Agashe, et al
his talk at CMS

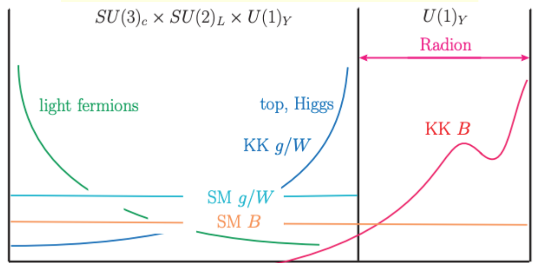
- LHC Signals from Cascade Decays of Warped Vector Resonances arXiv:1612.00047
- Dedicated Strategies for Triboson Signals from Cascade Decays of Vector Resonances arXiv:1711.09920
- Detecting a Boosted Diboson Resonance arXiv:1809.07334

EWED landscape & CMS searches

EW fields propagate at the bulk

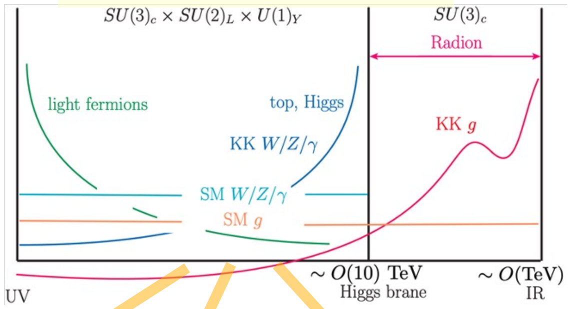


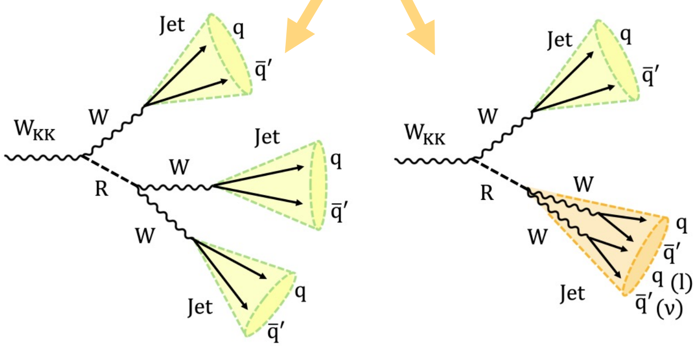
Hypercharge at the bulk



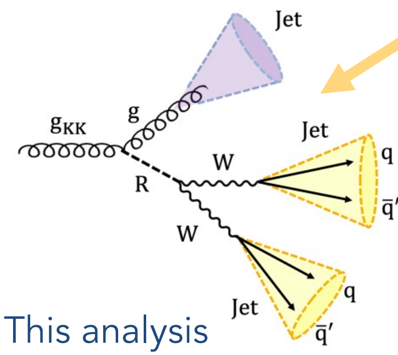
tri-γ signature - yet unexplored

QCD fields at the bulk

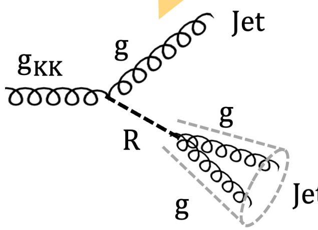




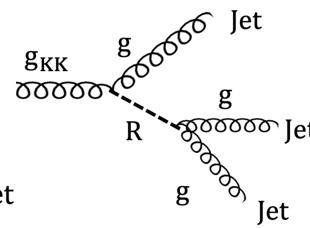
Tri-W; W_{KK}→WR→WWW
merged & resolved R; final states: 0l & 1l
2201.08476 , 2112.13090



This analysis
g_{KK}→gR→gWW
This search PAS



Di-jet (merged)
g_{KK}→gR→ggg
2201.02140



Tri-jet (resolved)
g_{KK}→gR→ggg
2310.14023

Benchmark points & associated dominant process →
(from 1612.00047)

	Process	Name	m_{KK}	m_φ	$g_{\gamma_{KK}}$	$g_{W_{KK}}$	$g_{g_{KK}}$	g_{grav}
γ_{KK}	$\gamma_{KK} \to \gamma\varphi \to \gamma gg$ (5.1)	γ-γgg-BP1	3	1	3	6	3	3
		γ-γgg-BP2	3	1.5	2.7	6	3	4.1
g_{KK}	$g_{KK} \to g\varphi \to g\gamma\gamma$ (5.2.2)	g-$g\gamma\gamma$-BP1	3	1	2.7	6	6	2.25
		g-$g\gamma\gamma$-BP2	3	1.5	2.7	6	6	3
	$g_{KK} \to g\varphi \to ggg$ (5.2.1)	g-ggg-BP1	3	1	2.7	6	3	2.45
		g-ggg-BP2	3	1.5	2.7	6	3	4
	$g_{KK} \to g\varphi \to gV_hV_h$ (5.2.3)	g-gVV-BP1	3	1	2.65	3	6	3
		g-gVV-BP2	3	1.5	2.65	3	6	5
W/Z_{KK}	$W_{KK} \to W_l\varphi \to W_lgg$ (5.3)	W-Wgg-BP1	2.5	1	3.5	4.4	3	3.5
		W-Wgg-BP2	3	1.5	3	3.5	3	5.1

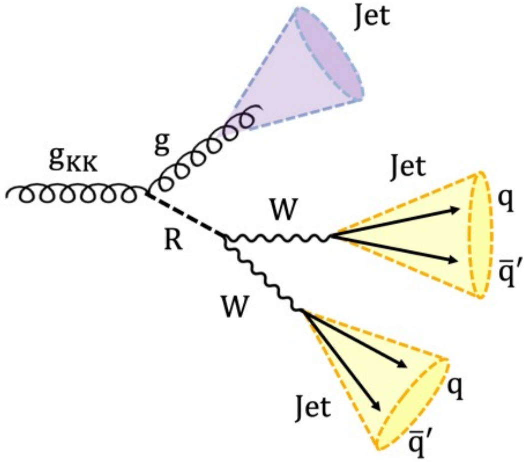
← 2201.02140 & 2310.14023 (g-ggg-BP2)

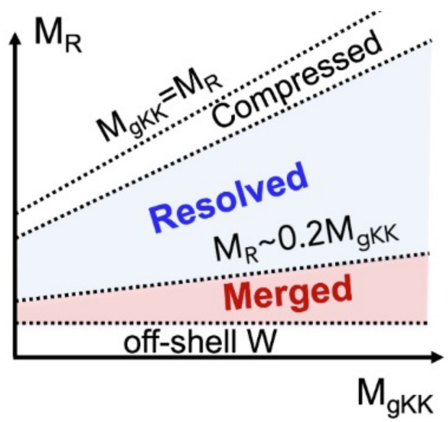
← This search PAS (g-gVV-BP2)

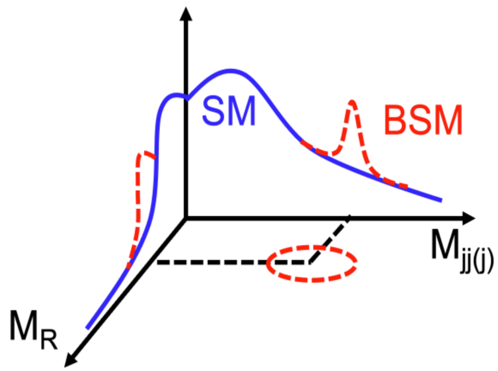
← 2201.08476 & 2112.13090 (W-Wgg-BP2)

Signal topology & Preselection

- We use benchmark point at which the dominant process is: $g_{KK} \rightarrow gR \rightarrow gWW$
- Big advantage of the W-tagging & narrow mass-window to suppress BKG.



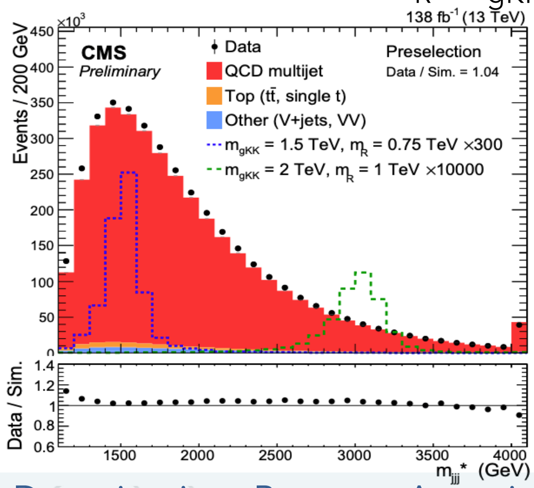




- g_{KK} is spin-1, R is spin-0
- We focus on the 0l channel: $g_{KK} \rightarrow gR \rightarrow gWW \rightarrow$ jets (BR~56%)
- We cover only the resolved R case: $0.2<m_R/m_{gKK}<0.9 \rightarrow$ 3 jets

Strategy:

1. Tri-jet selection,
2. identify (tag) 2 jets as W-candidates with PNet,
3. form m_{jj} (R) and m_{jjj}, (g_{KK}),
4. bin over m_{jj}, fit m_{jjj}. →



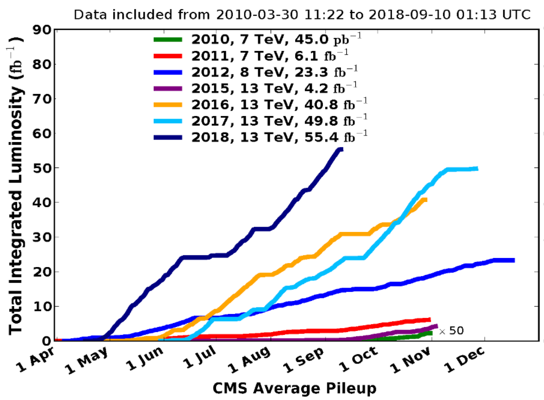
Preselection cuts:

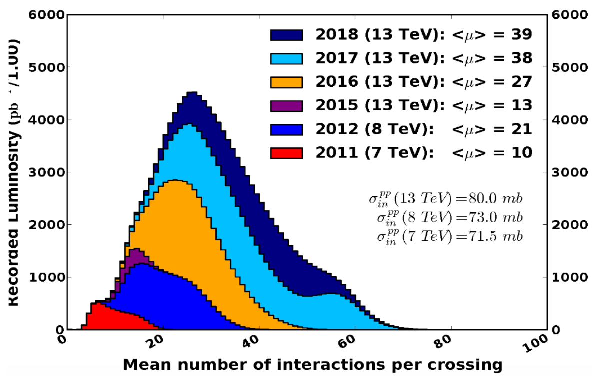
1. $N_{j\text{-}AK8}=3$, $N_{lep}=0$,
2. $p_{Tj1(j2,j3)}$ > 400 (200) GeV, $|\eta_j| < 2.4$, $\eta = -\ln[\tan(\theta/2)]$
3. $m_{ja,jb}$ > 50 GeV,
4. $H_T \equiv \sum_i p_T(jet[i])$>1.1 TeV

Datasets, Trigger, & MC samples

DATA: pp collision at 13 TeV

- Full Run 2 (JetHT) dataset used.
- Trigger paths:
  H_T ($H_T \equiv \sum_i p_T(jet[i])$) & m_{jAK8}–based
- L = 138 fb^{-1}
- Triggers OR combination found to be eff. >~99% for H_T>1.1 TeV.





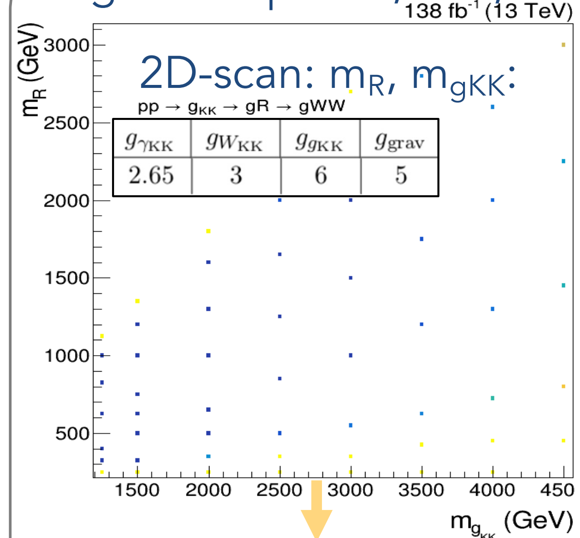
Simulation (MC) Madgraph, Pythia ...

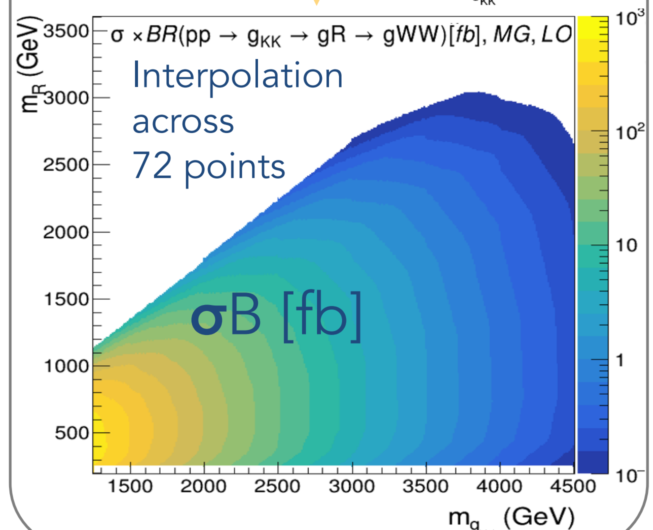
BKG samples

QCD_HT500to700_TuneCP5_I
QCD_HT700to1000_TuneCP5
QCD_HT1000to1500_TuneCP
QCD_HT1500to2000_TuneCP
QCD_HT2000toInf_TuneCP5_
TTToHadronic_TuneCP5_13T
TTToSemiLeptonic_TuneCP5
WJetsToQQ_HT-400to600_Tu
WJetsToQQ_HT-600to800_Tu
WJetsToQQ_HT-800toInf_Tun
ZJetsToQQ_HT-400to600_Tun
ZJetsToQQ_HT-800toInf_Tune
ZJetsToQQ_HT-600to800_Tun
ST_tW_antitop_5f_inclusiveD
ST_tW_top_5f_inclusiveDecay
ST_t-channel_antitop_4f_Inclu
ST_t-channel_top_4f_Inclusive
ST_s-channel_4f_hadronicDec
WW_TuneCP5_13TeV-pythia8
ZZ_TuneCP5_13TeV-pythia8
WZ_TuneCP5_13TeV-pythia8

- QCD multijet
- Top ($t\bar{t}$, single t)
- Other (V+jet, VV)

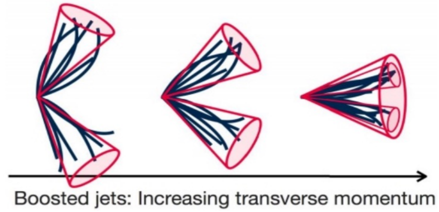
Signal: 72 points, MG, LO





W-candidate selection on m_{jet}

- W→qq are boosted: using the anti-KT algo form single AK8 jets

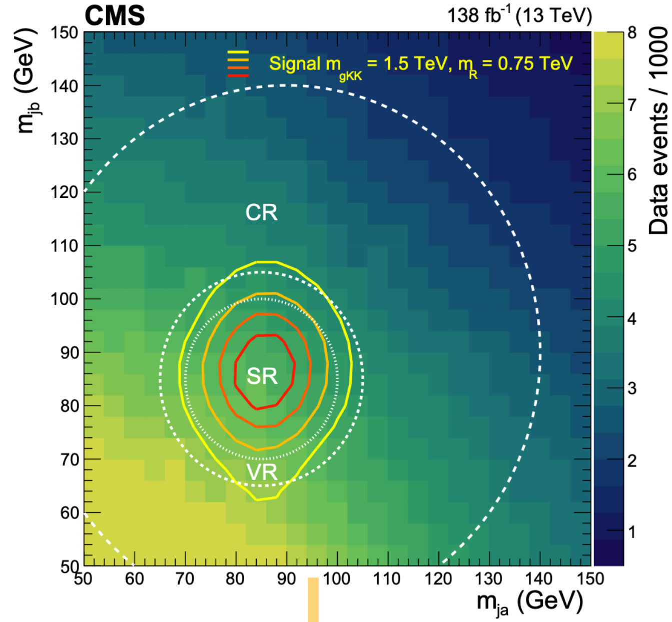


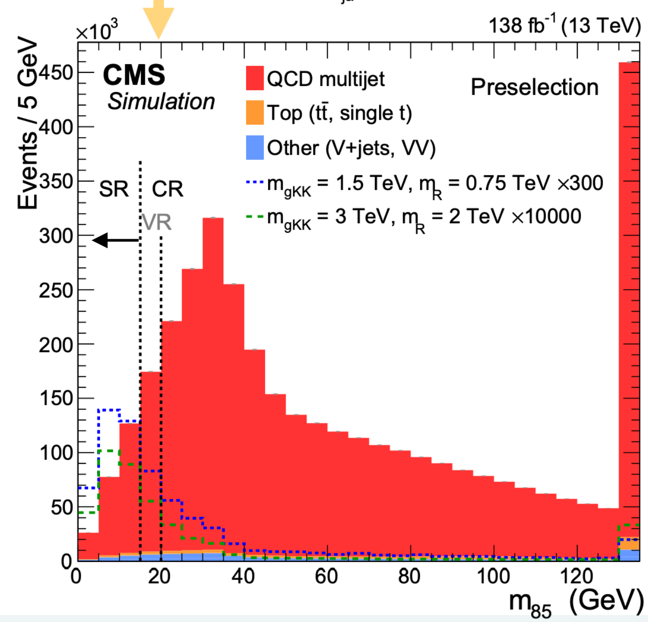
- The 2 highest ParticleNet score jets j_a, j_b are assigned to be the W-candid., gluon is j_c.

- We demand the jets Soft Drop masses $m_{ja,jb}$, to be on W-peak with the condition of m_{85} variable:

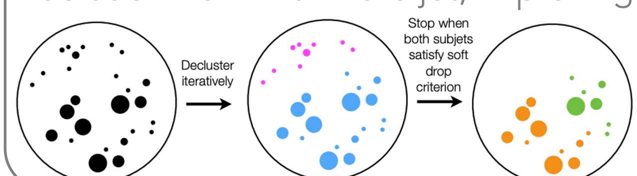
$$m_{85} \equiv \sqrt{(m_{ja}+85)^2 + (m_{jb}+85)^2} < 15\ \text{GeV}$$

- We define 3 regions based on m_{85}:
  - Signal Regions (SRs)have: $m_{85} < 15$ GeV.
  - Control Regions (CRs) are: $m_{85} > 15$ GeV & $m_{90} < 50$ GeV
  - Validation Regions (VRs): $15 < m_{85} < 20$ GeV.





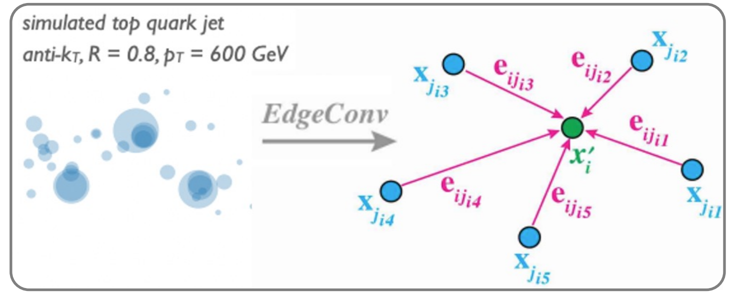
The Soft-Drop is an algorithm which remove soft & wide-angle radiation from within the jet, improving mass scale & resolution:



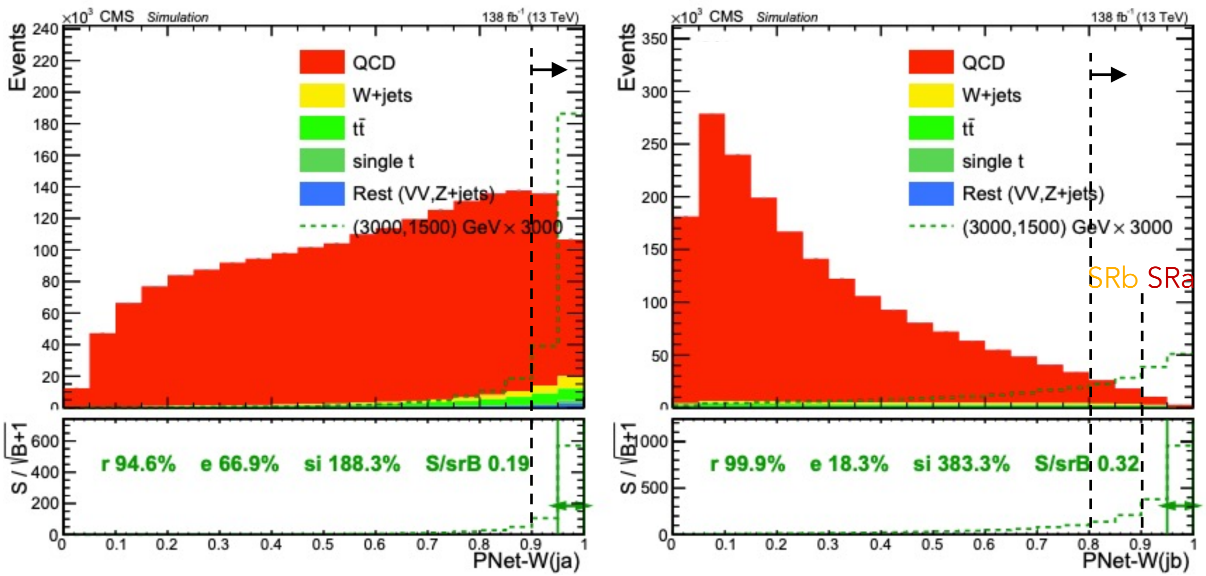
We use the anti-kT algo to cluster individual particles (PF candidates) into jets (using clustering param. R).

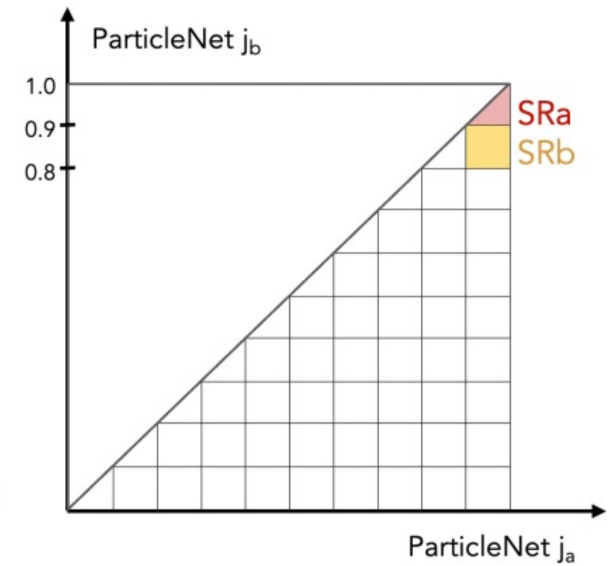
W-tagging with PNet & SR binning

- Use Particle Net (PNet) tagger (1902.08570) to identify W→qq merged jets.
  → Graph NN, treat jets as particle cloud →
  → Convolution on point clouds (EdgeConv 1801.07829)



- Use PNet (MD) scores of j_a & j_b to select as:





- SRa → both jets with $PNet_{ja,jb}$ >0.9
- SRb → $PNet_{ja}$>0.9 & 0.8<$PNet_{jb}$<0.9

- No demands for gluon candidate (m_{jc} or $PNet_{jc}$)
  → maintain generality and provide sensitive to signals like: X→AWW, or X→WW + $j^{ISR/FSR}$.

PNet Tagger is calibrated with SFs formed on tt data sample:

Jet p_T [GeV]	200–300	300–400	> 400
$s_{ja} > 0.9$	0.83 ±0.03	0.84 ±0.04	0.82 ±0.05
$0.8 < s_{jb} < 0.9$	1.08 ±0.03	1.01 ±0.04	1.02 ±0.05

R, gKK reconstruction & SR binning

- M_R reco. from j_a, j_b:

$$m_{jj}* \equiv m_{jj} - m_{ja} - m_{jb} + 2(85\ \mathrm{GeV})$$

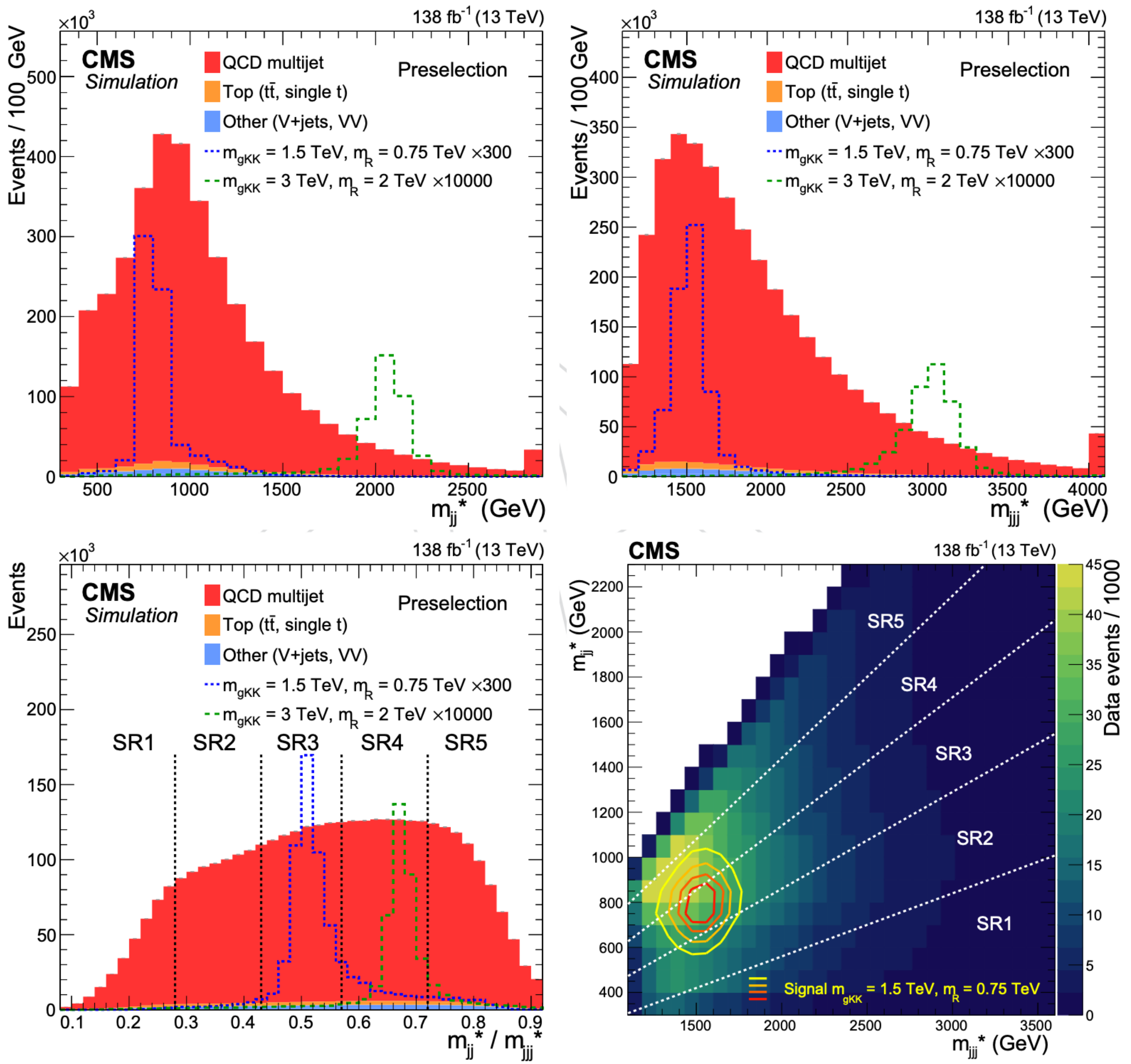
- M_{gKK} reco. from j_a, j_b, j_c:

$$m_{jjj}* \equiv m_{jjj} - m_{ja} - m_{jb} + 2(85\ \mathrm{GeV})$$

- → i.e. we correct invariant masses to mitigate reso. effect from jet SD masses.
  → sharper peaks (see Fig.4).
  → ~3% significance gain.

- From ratio $m_{jj}*/m_{jjj}*$ and define 5 bins SR1—5 →
- Effectively binning over m_R.
- In each of these 5 SR we have 2 SRs (SRa, SRb) based on PNet scores.

- Thus, we have 10 SRs.
- We fit the $m_{jjj}*$ spectra.



BKG prediction in 10 SRs

SR full selection summary

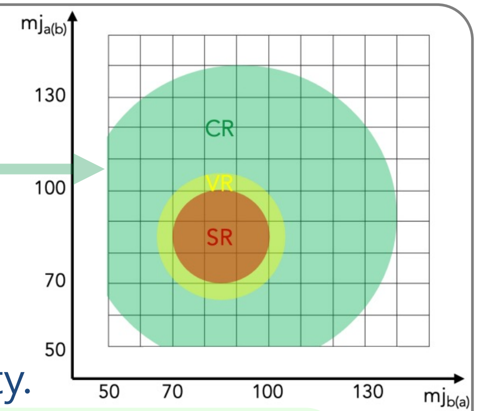
1. $N_{j\text{-}AK8}=3$, $N_{lep}=0$,
2. $p_{Tj1(j2,j3)}>400(200)$GeV $|\eta_j| < 2.4$,
3. $m_{ja,jb} > 50$ GeV,
4. $H_T > 1100$ GeV,
5. $m_{85} < 15$ GeV,
6. PNet > 0.8, & binning
7. $|\Delta\eta_{jj}|^{max} < 3$
8. $N_b=0$ (CHS, tight, deepflavor)

10 SRs categories:

Region	m^*_{jj}/m^*_{jjj}	s_{jb}
SR1a	< 0.28	> 0.9
SR1b		0.8–0.9
SR2a	0.28–0.43	> 0.9
SR2b		0.8–0.9
SR3a	0.43–0.57	> 0.9
SR3b		0.8–0.9
SR4a	0.57–0.72	> 0.9
SR4b		0.8–0.9
SR5a	> 0.72	> 0.9
SR5b		0.8–0.9

QCD multijet 80-90%

- Dominant → data-driven prediction
- Form Control Regions (CRs) defined in $m_{ja,jb}$ sideband as: $m_{85}>15$ & $m_{90}<50$ GeV keeping the rest conditions as in SRs.
- Form 10 CRs: CR1–5a & CR1–5b
- Similar kinem/cs to SRs; high QCD purity.
- Predict QCD with → $\mathrm{Pred}^{\mathrm{QCD}}_{\mathrm{SRxy}} \equiv [\mathrm{Data}-\mathrm{Rest}]_{\mathrm{CRxy}} \frac{\mathrm{QCD}_{\mathrm{SRxy}}}{\mathrm{QCD}_{\mathrm{CRxy}}}$
- We validate QCD pred. in 10 VRs (defined by $15<m_{85}<20$ GeV).



Top ($t\bar{t}$, single t) 3–8%
Other (V+jet, VV) 8–16%

- Subdominant BKGs → use MC for prediction
- We correct the MC applying SFs for PNet selection eff. per matched W→qq jets.
- We validate Top MC (shape & rate) in dedicated samples (bRs) like the SRs but with $N_b\geq1$.
- We assign conservative (large) rate unc. for these 3 BKGs.

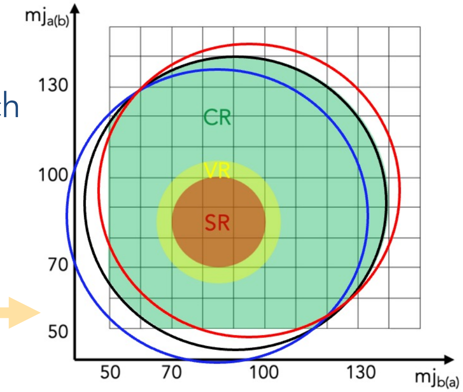
Systematic Uncertainties

BKG

Uncertainty source	Effect on	Magnitude	Number of NPs & correlations
Normalization QCD	Rate	20% ← Dominant	10, uncorr. across SRs
Normalization Top	Rate	50%	10, uncorr. across SRs
Normalization Other	Rate	30%	10, uncorr. across SRs
QCD bkg. shape due to m_{90} usage	Shape	$\pm 1\sigma$ templates	10, uncorr. across SRs
QCD bkg. shape due to other processes	Shape	$\pm 1\sigma$ templates	10, uncorr. across SRs

RATE
- QCD 20% based on validation prefit disclosure & MC low stat.
- Top 50% based on data in bRs, Other 30% based on similar search
  All uncorrelated across 10 SRs → 30 nuisances.

SHAPE
- Vary "rest" in QCD BKGs prediction by x2 down, x0 up.
- Shift CR circle center: m_{90}<50 (central) → m_{85}<50 (down), m_{95}<50 (up).



Signal

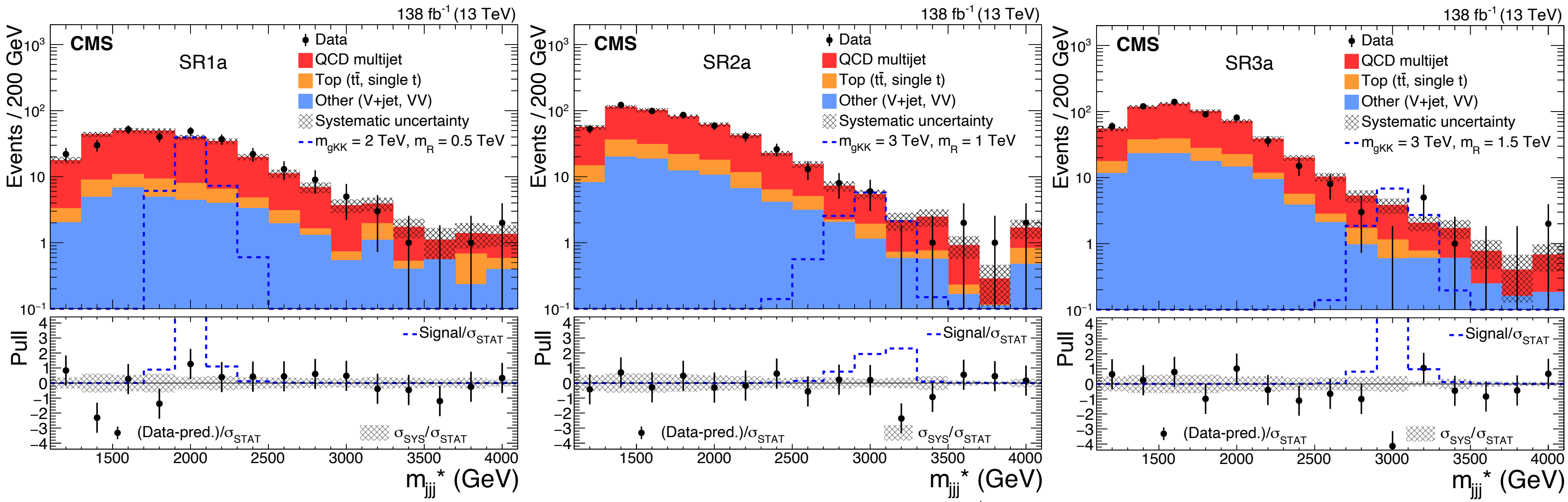
Uncertainty source	Effect on	Magnitude	Number of NPs & correlations
PU reweighting & int. luminosity	Rate	1.7%	1, correlated across all SRs
PDFs	Rate	$\leq 10\%$	1, correlated across all SRs *
μ_R / μ_F scales	Rate	$< 0.8\%$	1, correlated across all SRs *
PNet_W selection eff. per jet (event)	Rate	6% (12%) ← Dominant	1, correlated across all SRs
JEC	Shape	$\pm 1\sigma$ templates	1, correlated across all SRs *
JER	Shape	$\pm 1\sigma$ templates	1, correlated across all SRs *

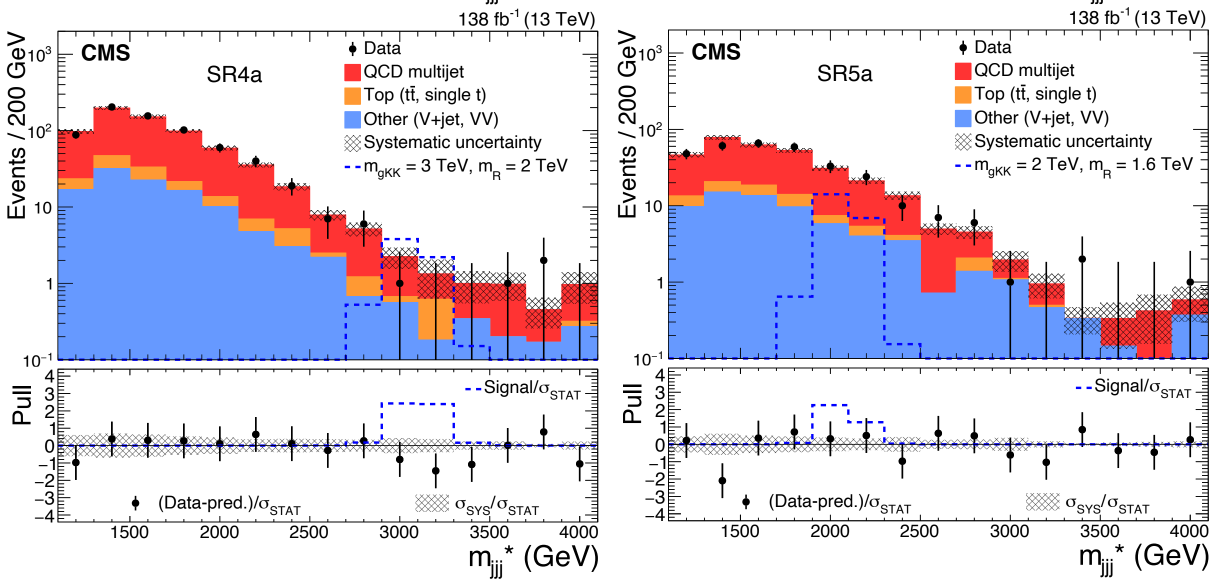
RATE
- Lumi, PU, PDFs, QCD scales μ_F, μ_R : 1—10%
- PNet SFs unc. → 6% [12%] per jet [event] (we have 2 W→qq jets/event)

SHAPE
- JEC & JER: +σ/-σ variations → forming templates per point, per SRs.

Results: SR1a—SR5a

- We fit simultaneously the m_{jjj}^* spectra in the 10 SRs, using Combine tool:

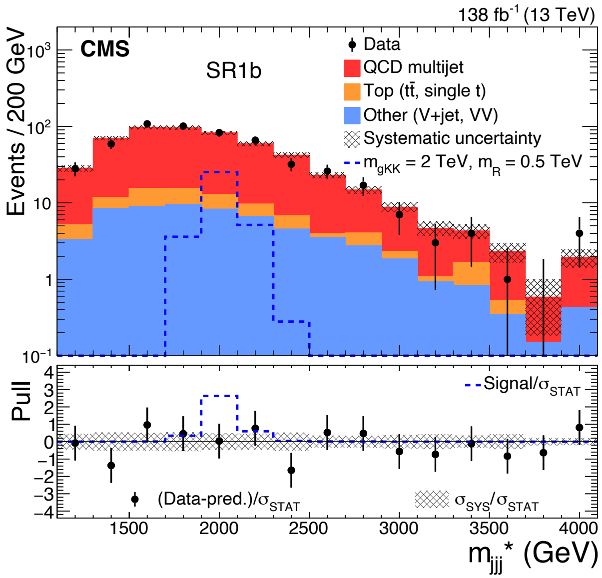


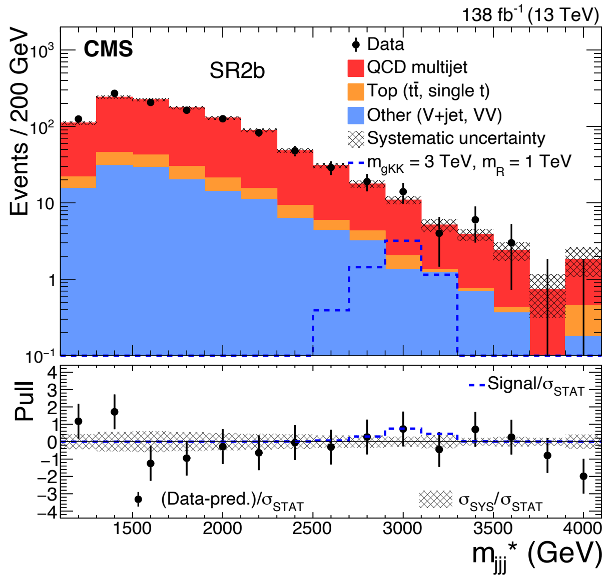


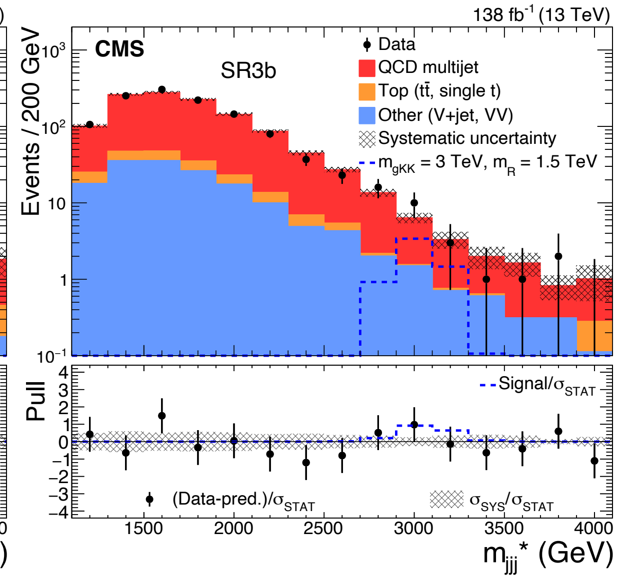
- No indication of signal.
- Excellent post-fit data/pred. agreement.

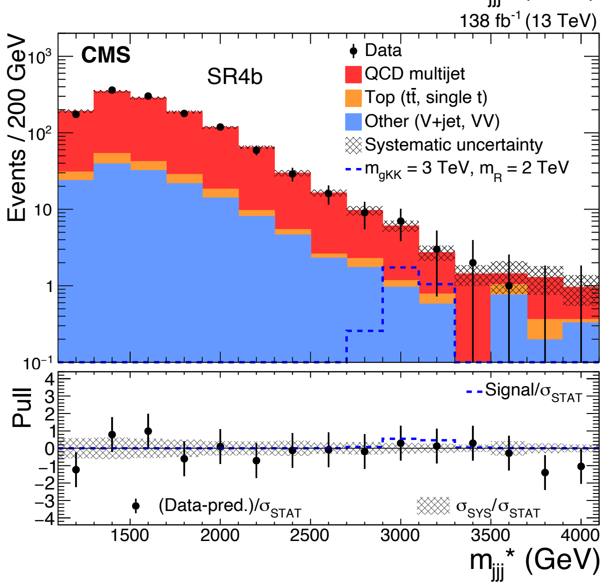
Results: SR1b—SR5b

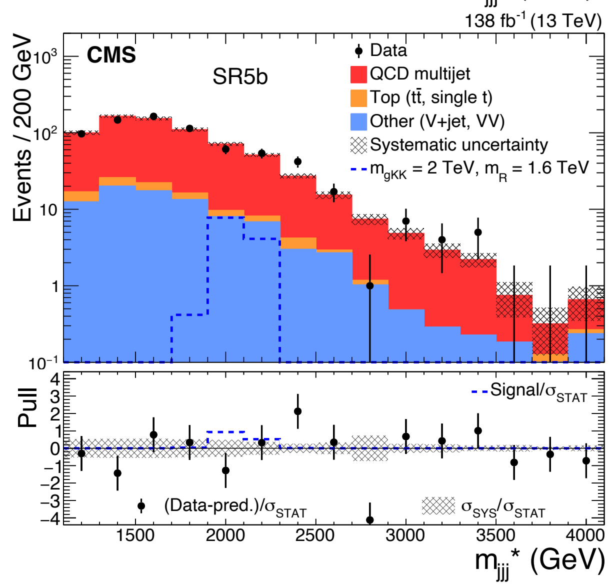
- We fit simultaneously the m_{jjj}^* spectra in the 10 SRs, using Combine tool:





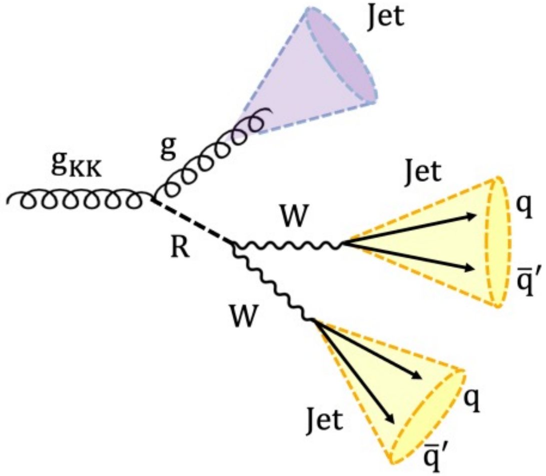


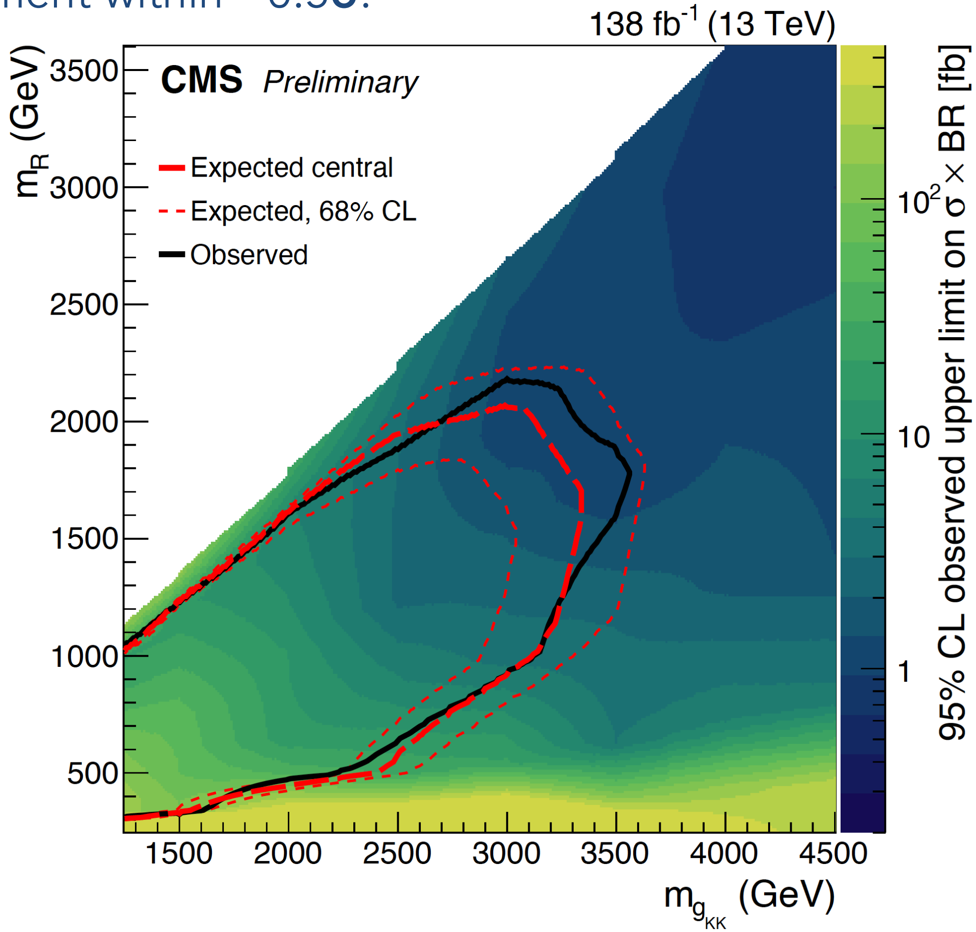




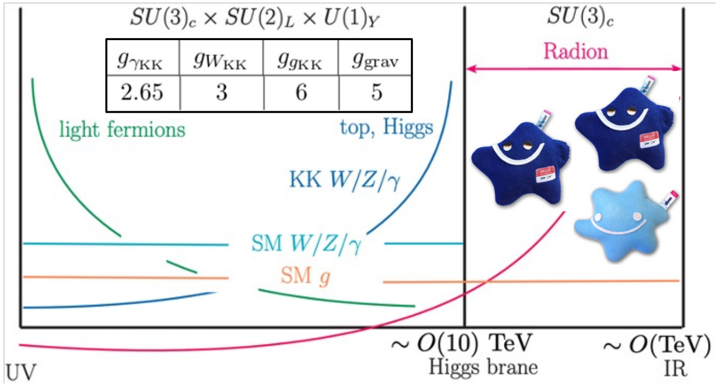
- No indication of signal.
- Excellent post-fit data/pred. agreement.

- We set upper limits, at 95% CL, on **σ**B, and lower limits on m_{gKK}-m_R masses plane:
- Expected and observed in agreement within ~0.5**σ**.





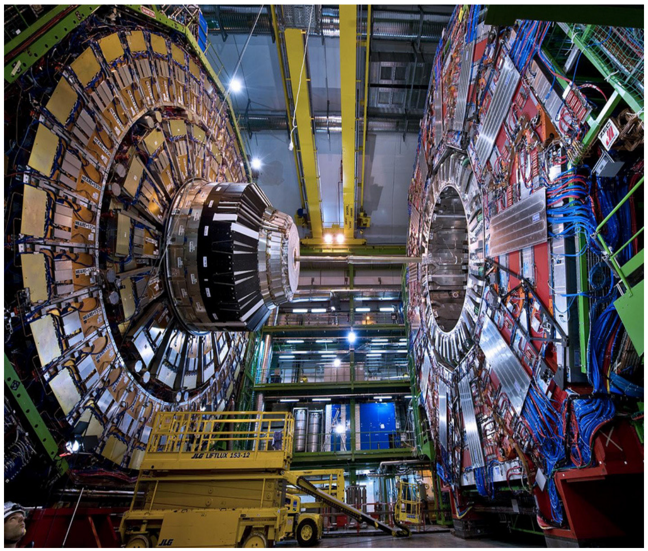
- First ever limits of this kind: EWED with QCD in bulk & gWW resonant…

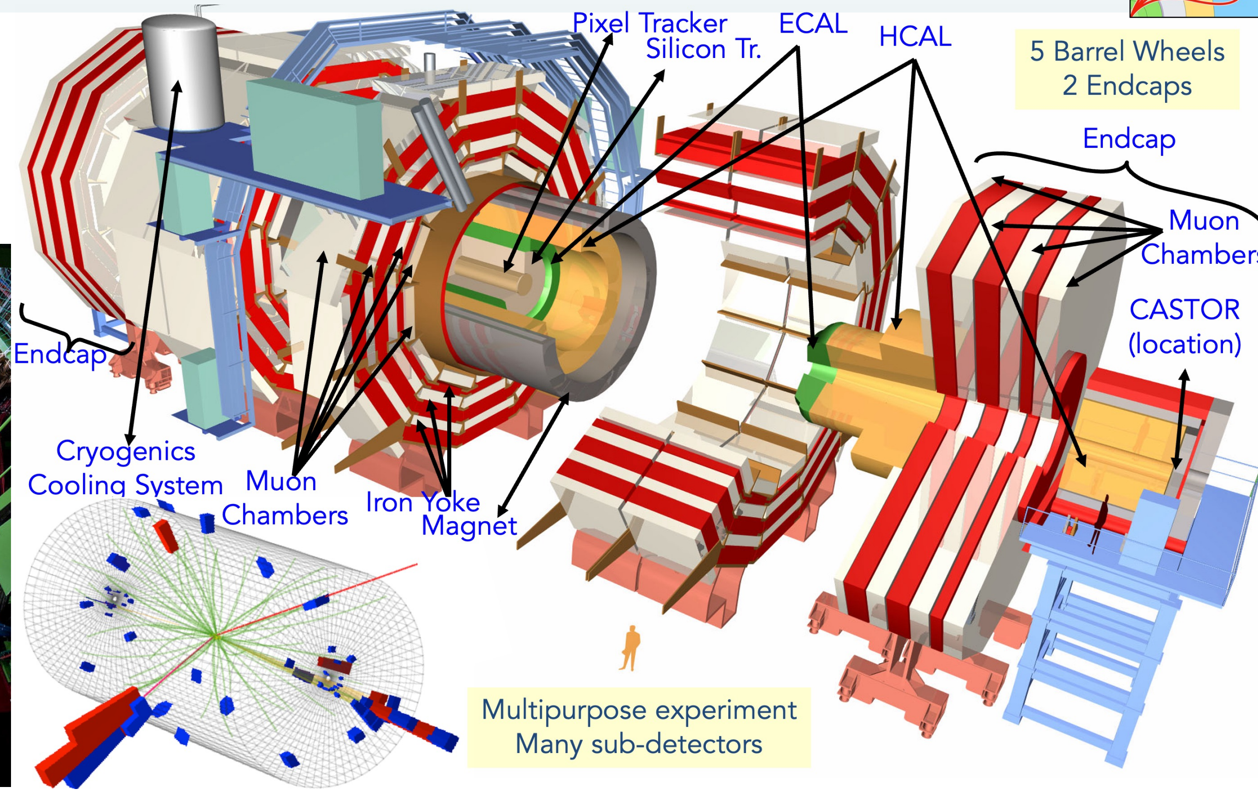


- Read our full paper (PAS) here for more.
- Visit the CMS B2G public results page and see our summary plots for more.

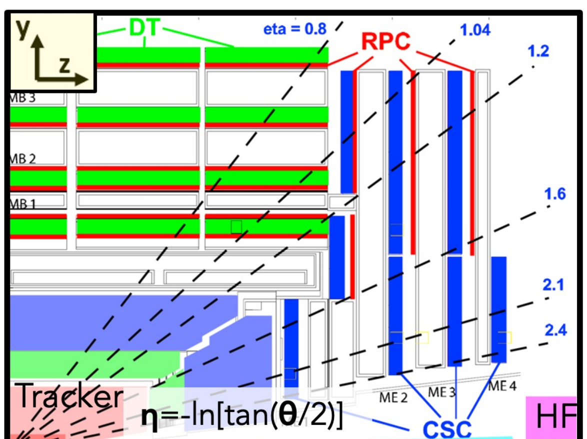
The CMS detect at the LHC

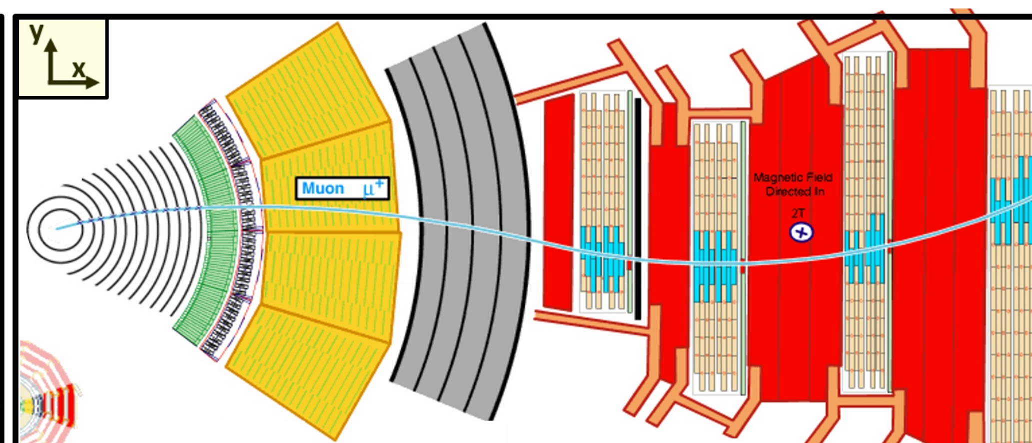
Compact Muon Solenoid
Mass: ~12500 Tones
Size: ~15m x 22m
Magnetic field: 4 T (3.8 T)
CMS collaboration is 30 y.o.
~6100 collaborators
~250 Institutes ~57 countries here for more





Multipurpose experiment
Many sub-detectors

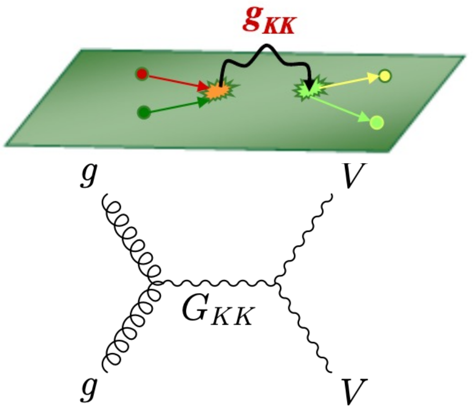




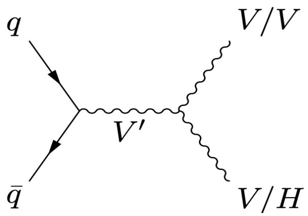
Motivation for a Diboson search

- SM shortcomings indicate some kind of New Physics (Hierarchy, Unific. DM, DE)

1. (Bulk RS) Warped ED,
   spin-0 Radion ($kr_c\pi = 35,\ \Lambda_R = 3\ \mathrm{TeV}$)
   spin-2 Bulk Graviton ($\sim k = 0.5, 1.0, \ldots$)

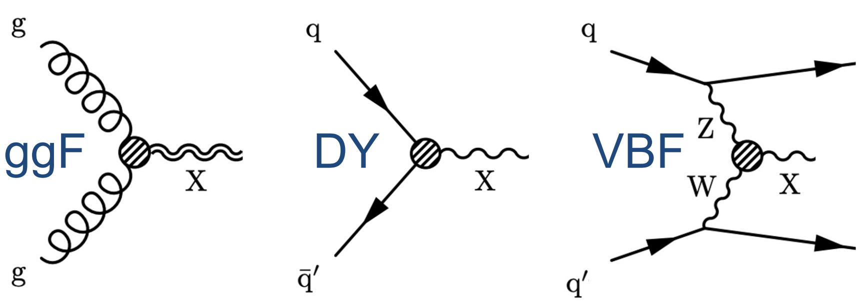


2. Heavy vector triplet (HVT)
spin-1 Z',W', coupling with SM
→ Models A, B, C



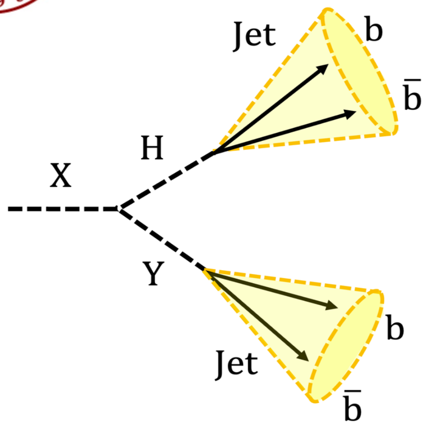
3. Little Higgs models
4. Two Higgs doublets models (MSSM)
5. Extended WED models (V_{KK}→RV)
6. Technicolor models

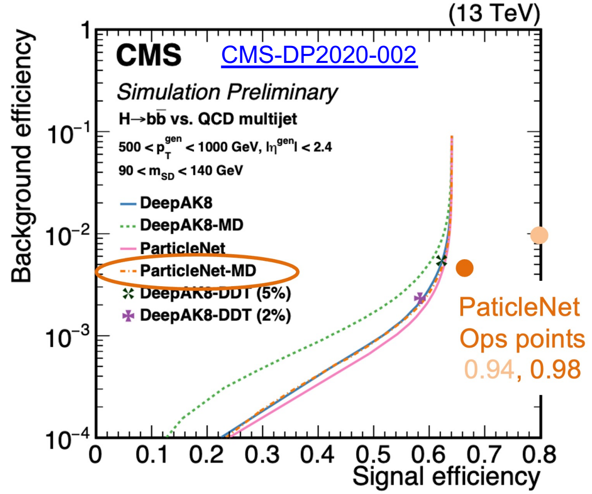
- Predict new heavy bosons at TeV
- 3 production modes:
- Decay modes include VV, VH

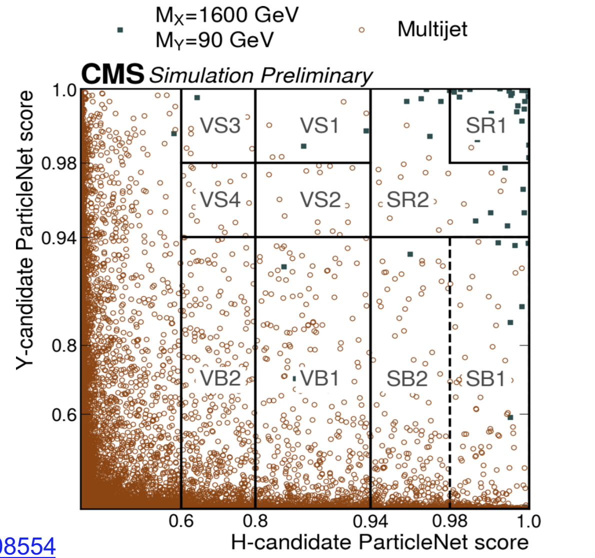


X → YH → 4b boosted

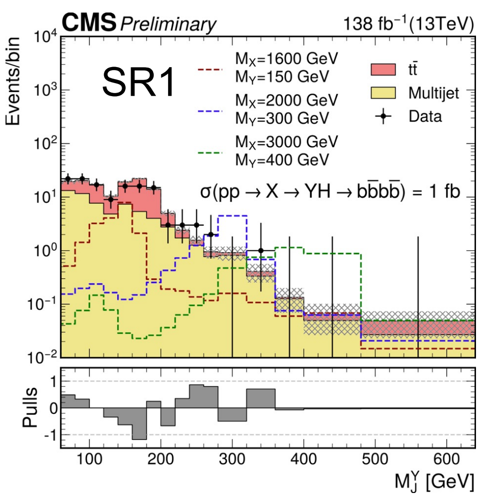
B2G-21-003

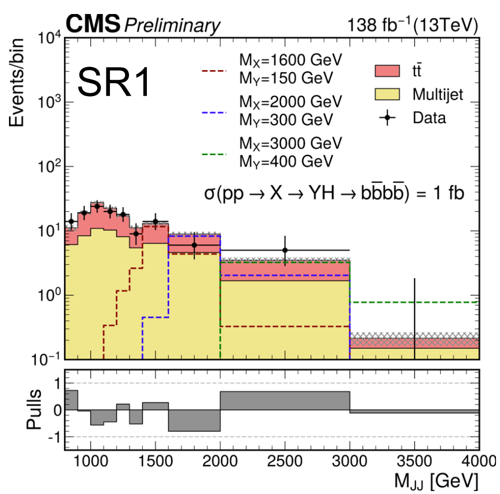


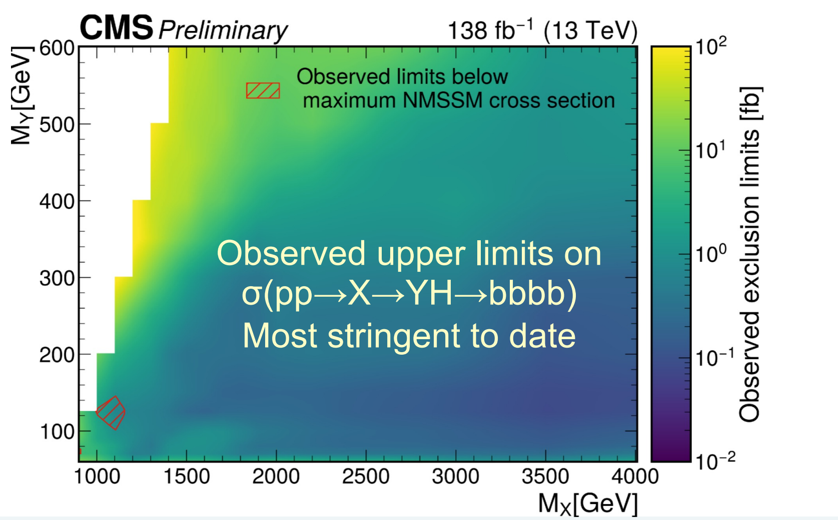




- X,Y: scalars, $M_X >> M_{Y(H)}$;
- Models: NMSSM 0910.1785, Two-real-scalar-singlet extension 1908.08554
- 2D search over M_{jj}, M_j^Y variables
- 2 (wide) jets, $m_{H(Y)}$: 110-140(>60) GeV, $|\Delta\eta_{jj}|$<1.3
- Tagging with Graph CNN (ParticleNet), mistag~0.5%, eff~70%, calibration with g→bb jets

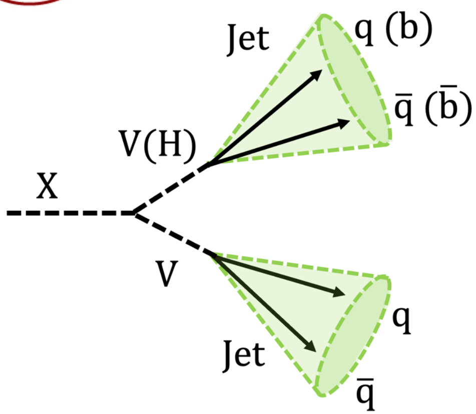






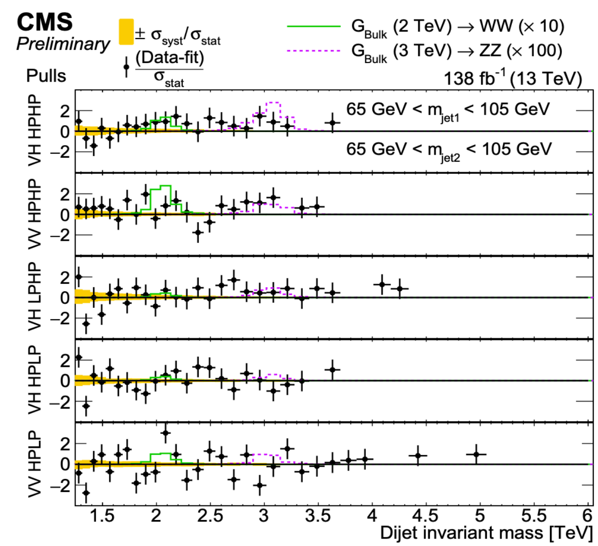
X → VV, VH in DY/gg & VBF

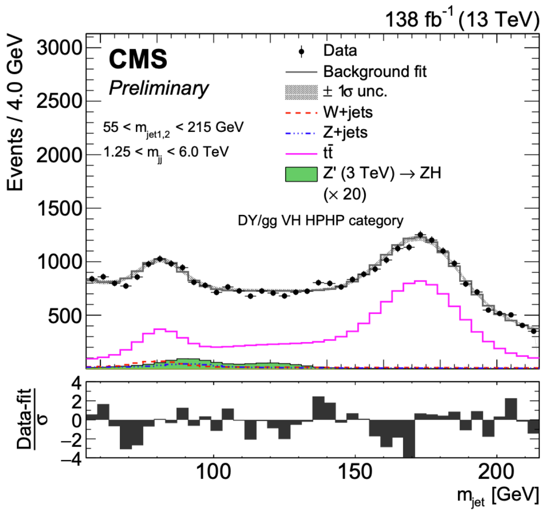
B2G-20-009

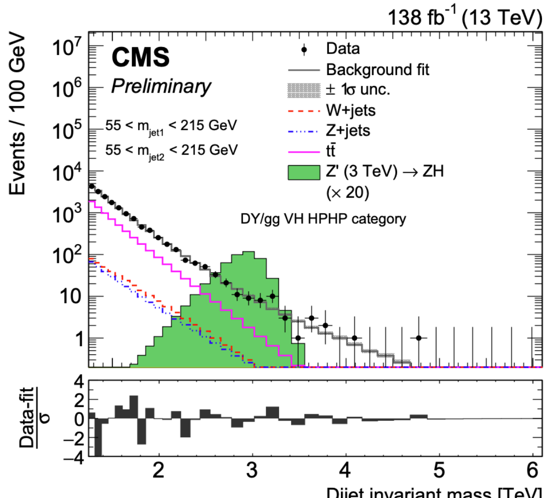


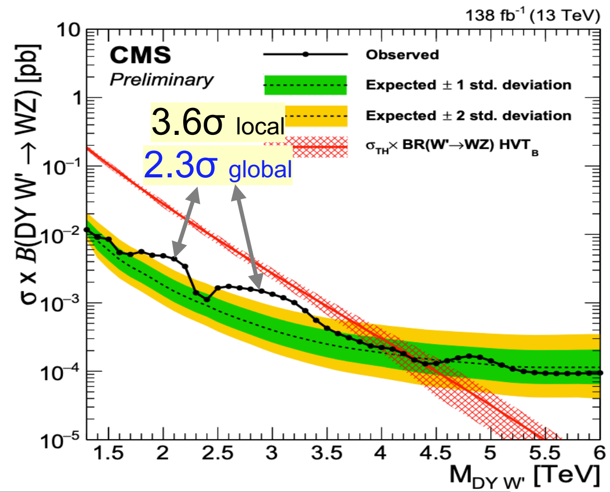
- HVT: W', Z'
- RS Warped ED: R, G_{bulk}

- X → WW, ZZ, WZ, WH, ZH
- Production: DY/ggF & VBF targeted
- 2 wide AK8 jets, $m_{j1,2}$: 55-215 GeV extra 2 narrow fwd jets for VBF
- Tagging with DeepAK8 classifier: W/Z/H → qq/bb, against q/g → 10 categories
- Method: 3D-fit of m_{j1}, m_{j2}, m_{jj}









Model		Observed limit (TeV)
Radion DY/gg	VV	2.7
HVT model B, W′	WZ / WH	4.4 / 4.0
HVT model B, Z′	WW / ZH	(1.3–3.1, 3.3–3.5) / 3.9
HVT model B, V′	VV+VH / VV / VH	4.8 / 4.5 / 4.2
G_{bulk} ($\tilde{\kappa} = 0.5$) DY/gg	VV	1.4

- Best limits to date →
- 2 modest excesses for W'→WZ at ~2.1, 2.9 TeV

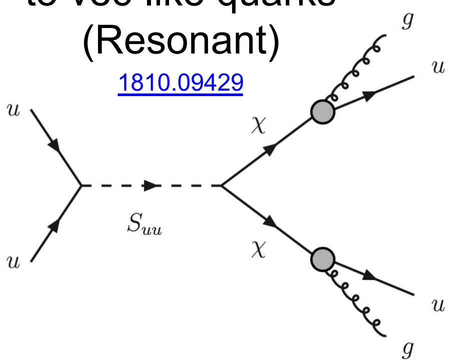
(Y) → XX → (jj)(jj) paired di-jets

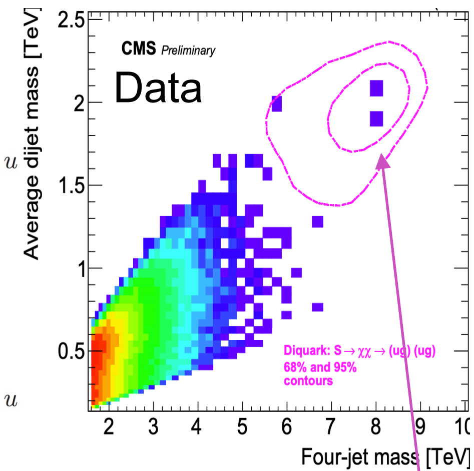
EXO-21-010

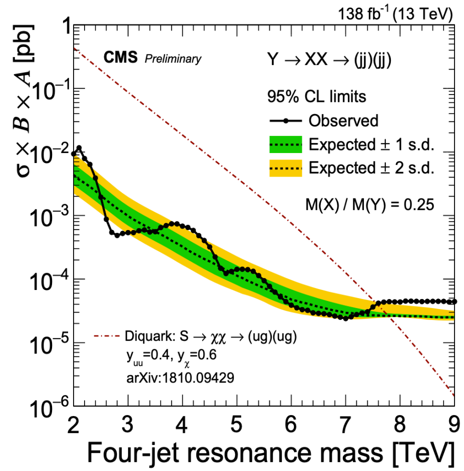
- 4 narrow jets → paired to 2 di-jets, symmetrized masses: $\frac{|m_1 - m_2|}{m_1 + m_2} < 0.1$
- Search over: m_{4j} and average di-jet mass $\bar{m}_{jj}$; fit 3p-function to the data in slices of $\frac{\bar{m}_{jj}}{m_{4j}}$

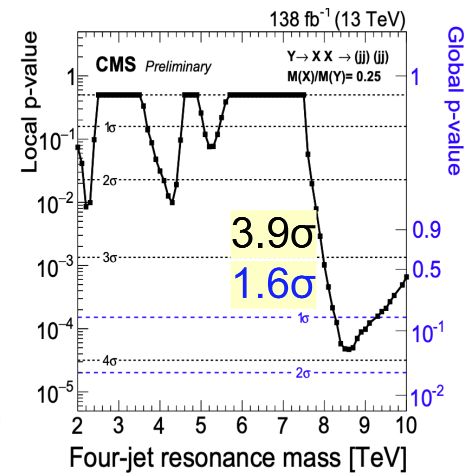
Ultraheavy di-quark to vec-like quarks (Resonant)

1810.09429



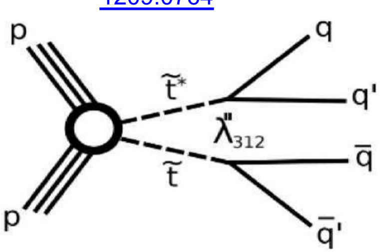


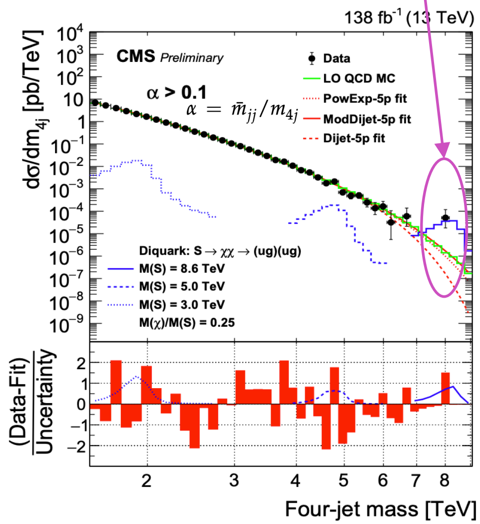


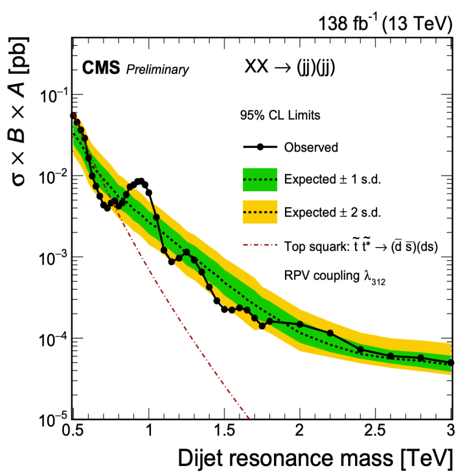


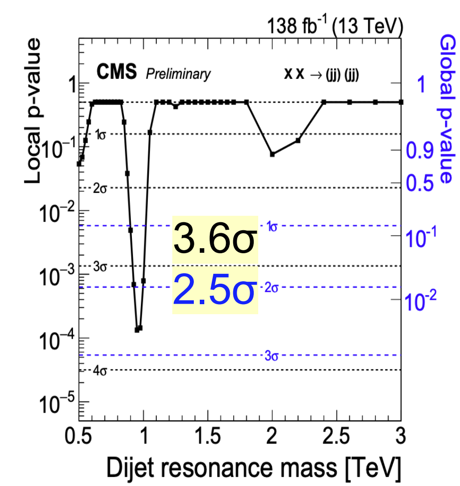
RPV SUSY (non-resonant)

1209.0764









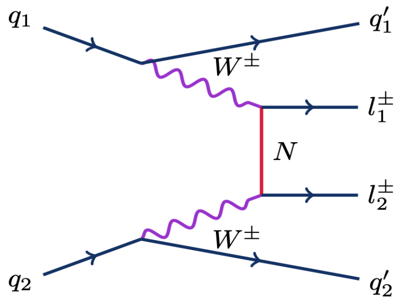
VBF → N → $\mu^\pm\mu^\pm$ Heavy Majorana N. & W.O. Probe

EXO-21-003

The “neutrinoless double-β decay” version of the LHC

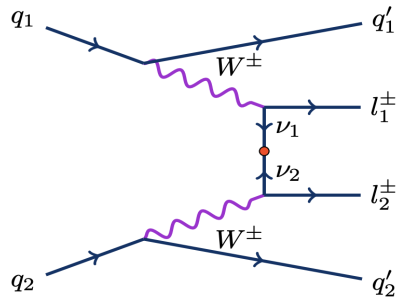
VBF HMN at Seesaw Type-I

mixing element $|V_{\mu N}|^2 = 1$

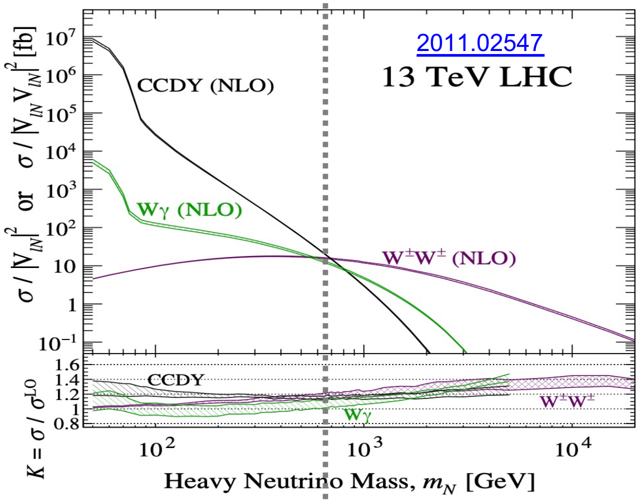


EFT Weinberg Oper. Dim. 5

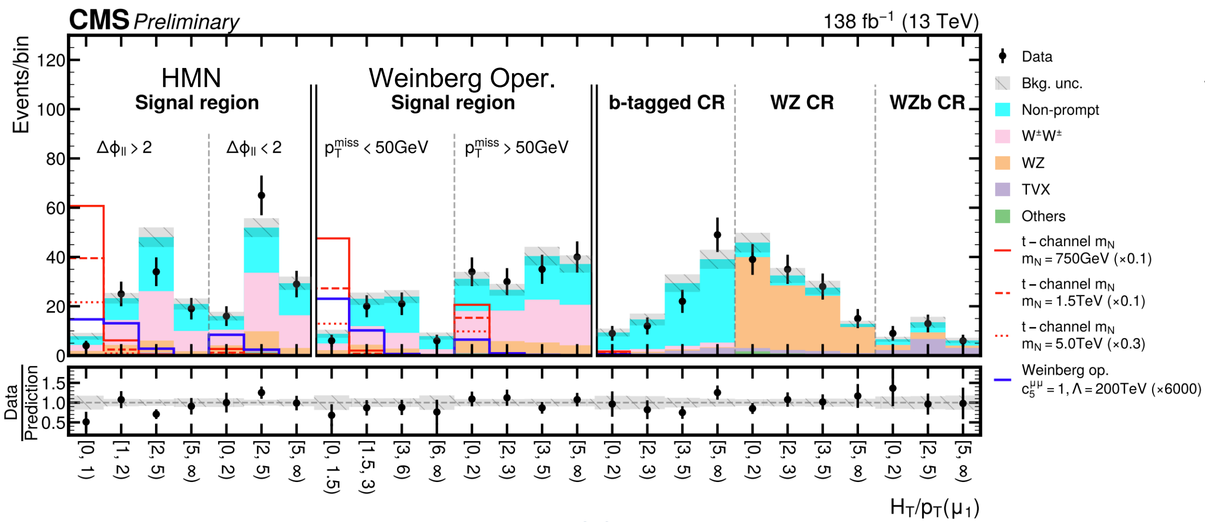
Wilson coef. $C_5^{ll'} = 1$

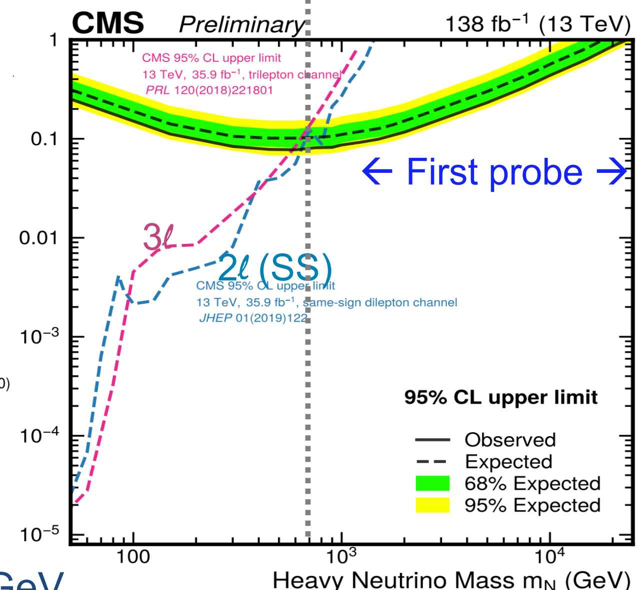


qq→W→ℓN direct ⟷ VBF t-channel



- Use VBF t-channel which dominates high m_N for first time
- 2μ SS + 2 fwd jets; cuts on $\Delta\eta_{jj}$, m_{jj}; fit on $H_T/p_{T\ell_1}$:

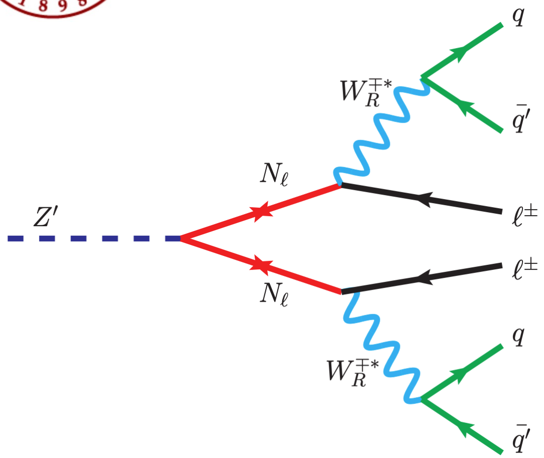




- HMN: excluded up to m_N~23 TeV
- WO: upper limit on eff. mass $|m_{\mu\mu}| \sim C_5^{ll'}$: obs(exp): 10.8(12.8) GeV

Z' → NN → ℓ jj ℓ jj Heavy Majorana Neutrino pair

EXO-20-006

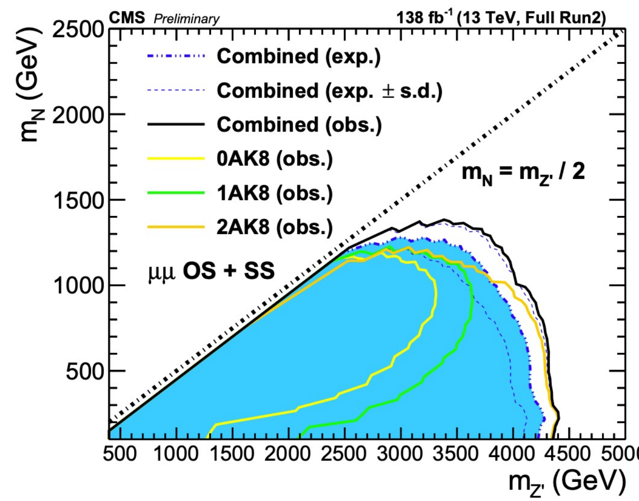


- LRSM: $\mathrm{Z}', \mathrm{W}_\mathrm{R}^\pm, \mathrm{N}_{e/\mu/\tau}$
- $\mathrm{m}_{\mathrm{N}_\ell} < m_{\mathrm{W}_\mathrm{R}^{\pm *}} = 5$ TeV
- Off-shell $\mathrm{W}_\mathrm{R}^{\pm *}$, no mixing

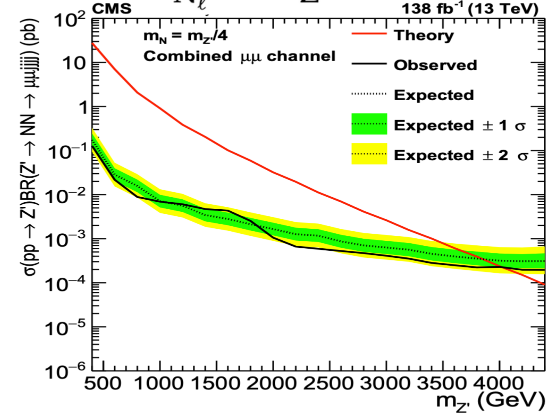
- ee, μμ (OS & SS), $\mathrm{m}_{\ell\ell} > 150$ GeV
- Resolved & Boosted probed
- Binning on # of wide AK8 jets:

SR	N(AK8 jet)	N(tight leptons)	N(AK4 jet)
SR1 (0AK8)	$= 0$	$= 2$	≥ 4
SR2 (1AK8)	$= 1$	≥ 1	≥ 2
SR3 (2AK8)	≥ 2	—	—

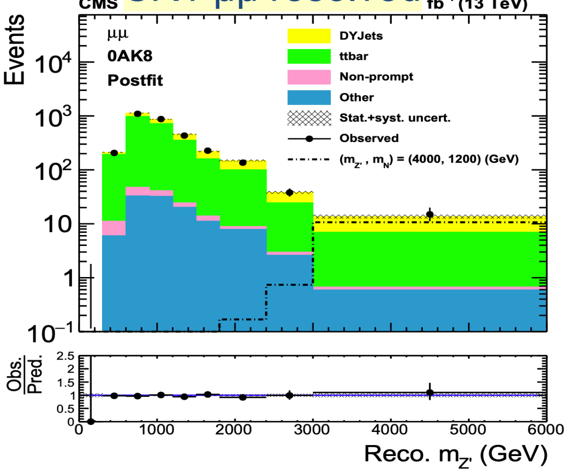
- Reconstruct N_ℓ as "jjℓ" and $\mathrm{m}_{\mathrm{Z}'}$ minimizing $\mathrm{m}(\mathrm{jj}\ell)$-asymmetry
- Prediction from eμ, $\mathrm{m}_{\ell\ell}$ SBs



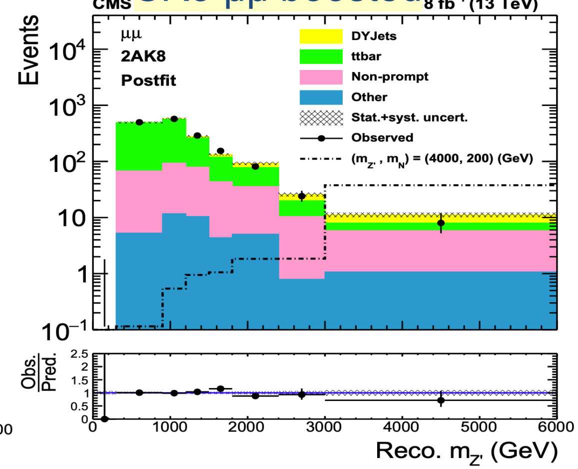
$m_{\mathrm{N}_\ell} = m_{Z'}/4$



SR1 μμ resolved

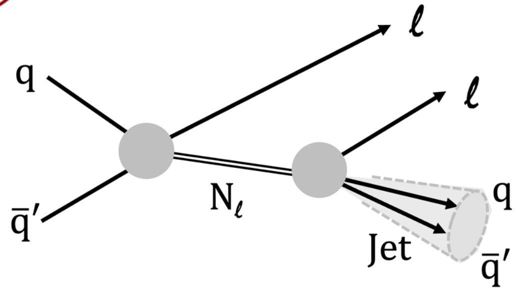


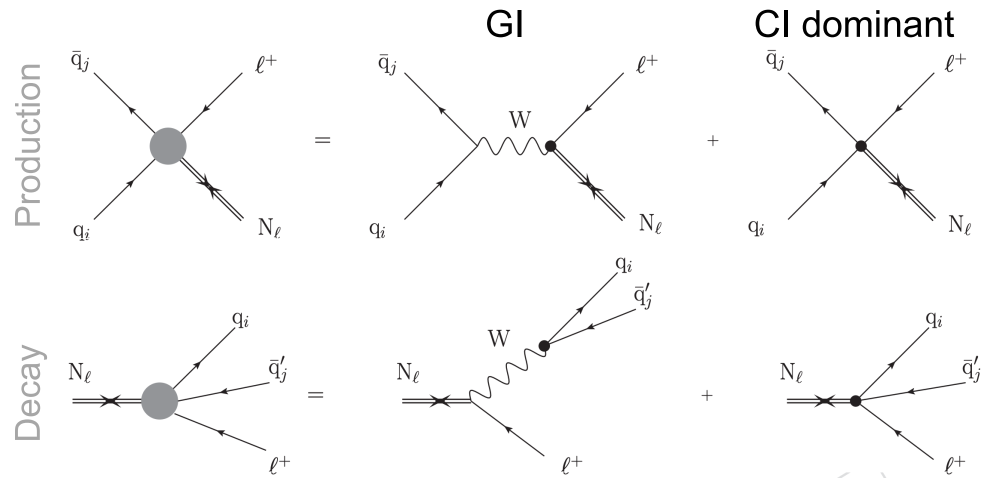
SR3 μμ boosted



- First search of this type for Run2
- Best direct limits on $\mathrm{m}_{\mathrm{Z}'}, \mathrm{m}_\mathrm{N}$ plane

Heavy Composite Majorana Neutrino $N\ell \to \ell\ell(qq)$



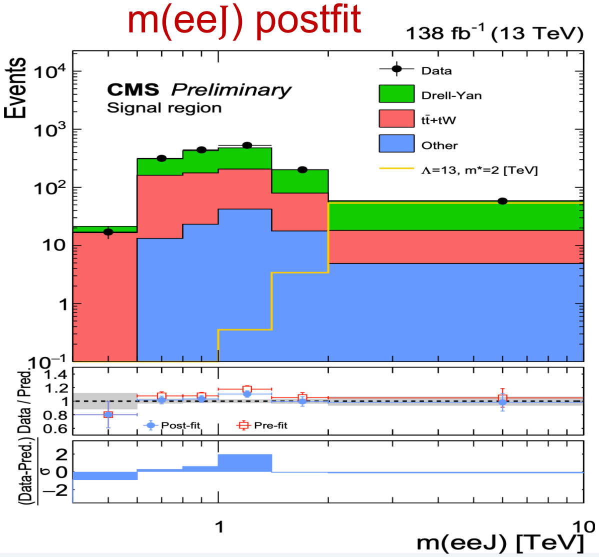


- Composite-fermion models
  1510.07988, 1707.00844, 1810.00374, 1903.12285

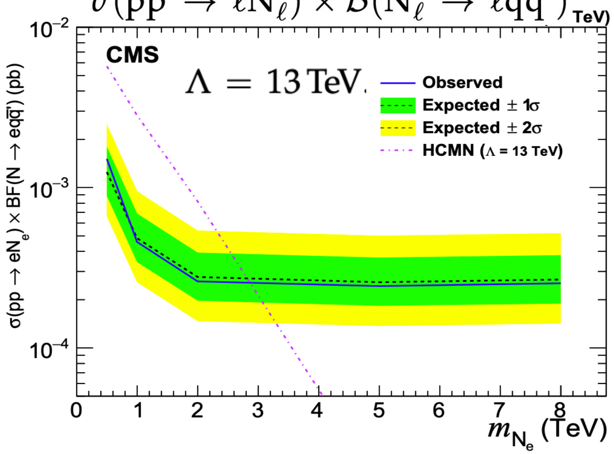
  → Excited states of SM fermions
  → Effective interactions: gauge (GI) & contact (CI) between ordinary and excited fermions
  → $m(N_\ell)$: [500 GeV, Λ]

- ee, μμ (SS&OS), $m(\ell\ell)$>300 GeV, ≥1 wide AK8 jet
- Use eμ, $m_{\ell\ell}$: 150-300 GeV as CRs
- Fit: $m(\ell\ell J)$ constrain separately N_μ, N_e masses

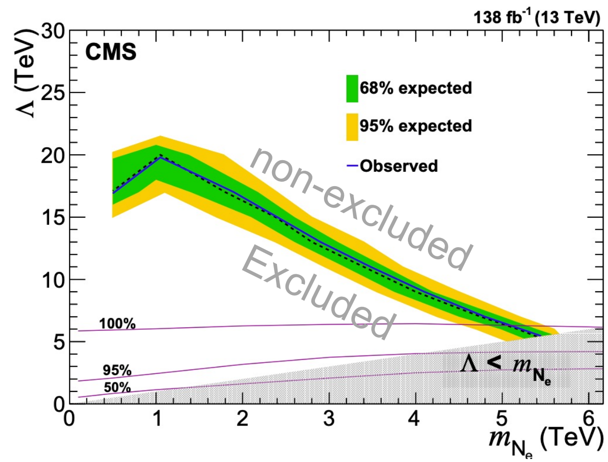
m(eeJ) postfit



Upper x-sec. limits on:
$\sigma(pp \to \ell N_\ell) \times \mathcal{B}(N_\ell \to \ell q\bar{q}')$

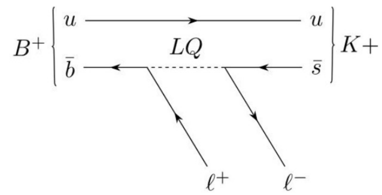


Limits on $m(N_\ell)$, Λ plane

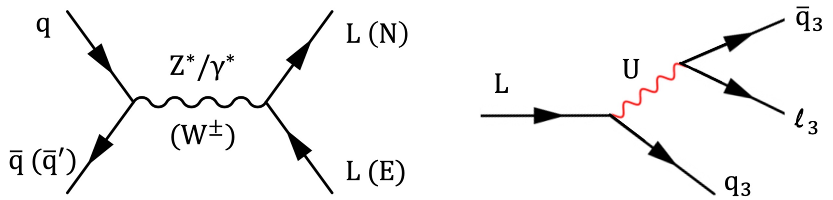


Vector-like lep. pair LL → … → 4b, ττ/τν/νν

- Model 4321 1808.00942, 1708.08450
  Potential to explain B-physics anomalies: R(D*), R(K), evidence for LFV



- EW production of VLL-pair, decay via off-shell vLQ: U



- VLL → 3rd gen fermions: b/t, τ/ν_τ (3-body decay) due to flavor non-universal coupling of vLQ: U

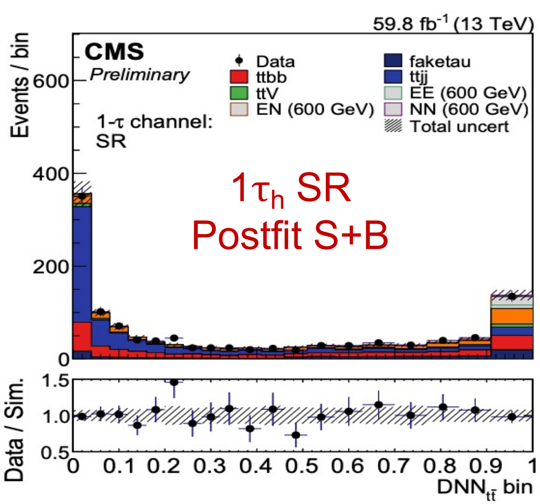
- Wealth of signatures:
- Focus on events with:
  ≥3 b-jets
  0,1,2 τ_h
  0,1,2 ν_τ (MET)

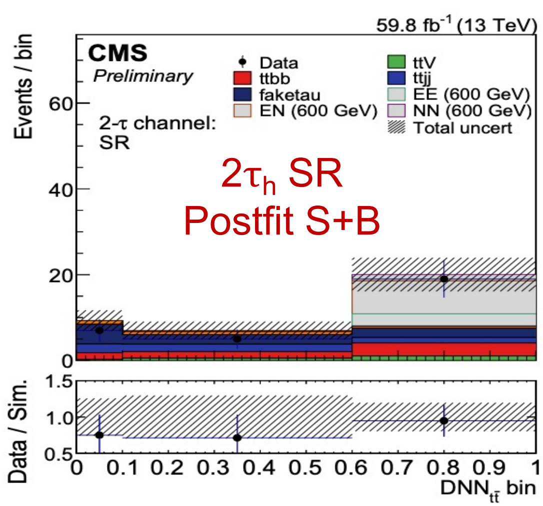
	final state
$0\,\tau$	$4b+4j+2\nu_\tau$
	$4b+6j+2\nu_\tau$
	$4b+8j+2\nu_\tau$
$1\,\tau$	$4b+2j+\tau+\nu_\tau$
	$4b+4j+\tau+\nu_\tau$
	$4b+4j+\tau+\not\nu_\tau$
	$4b+6j+\tau+\nu_\tau$
$2\,\tau$	$4b+2\tau$
	$4b+2j+2\tau$
	$4b+4j+2\tau$

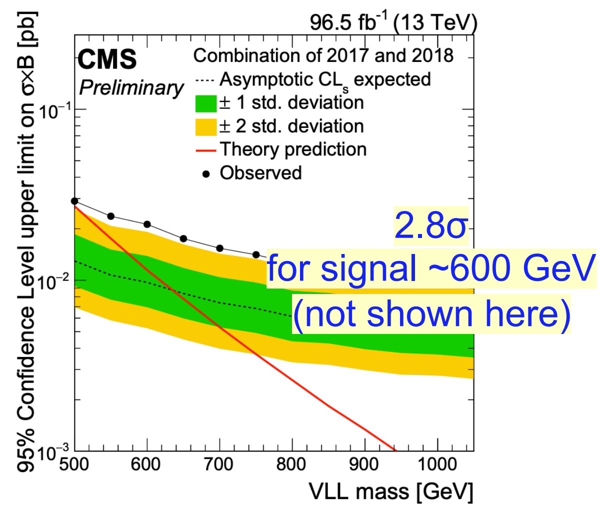
- Tagging:
  - DeepTau
  - DeepJet(b)

- DNN (ABCNet) to reject QCD and tt

- Binning and fitting over: #j, #τ_h, DNN_{tt}







Resonant Triboson: X → WR→ WWW

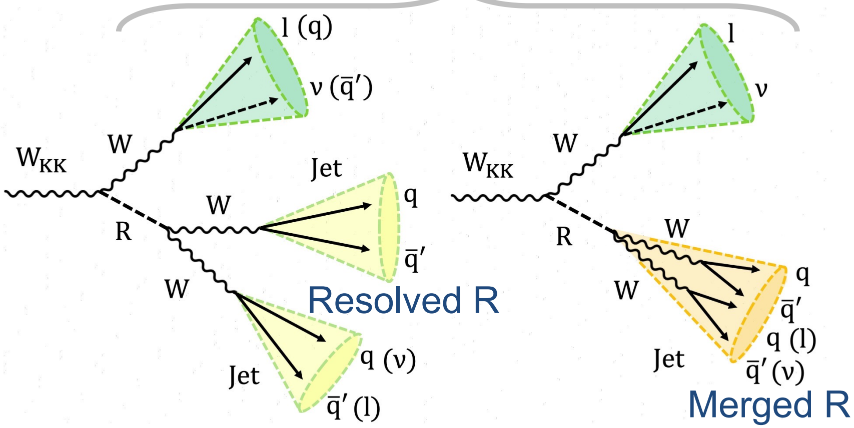
Extended (3 branes) Warped ED model

1711.09920, 1612.00047, 1809.07334

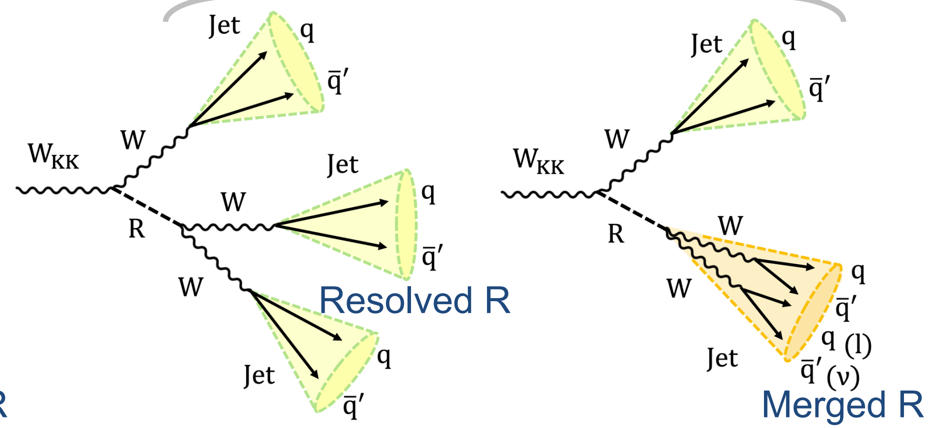
B2G-20-001

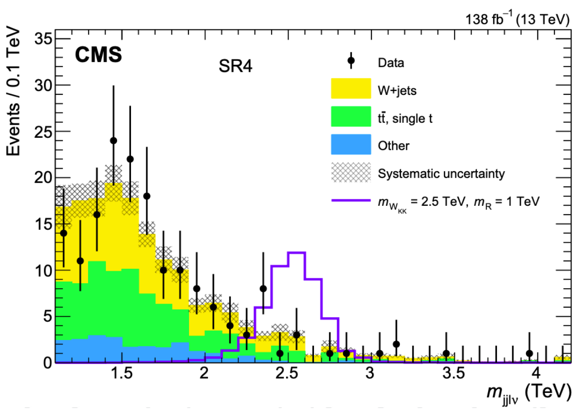
B2G-21-002

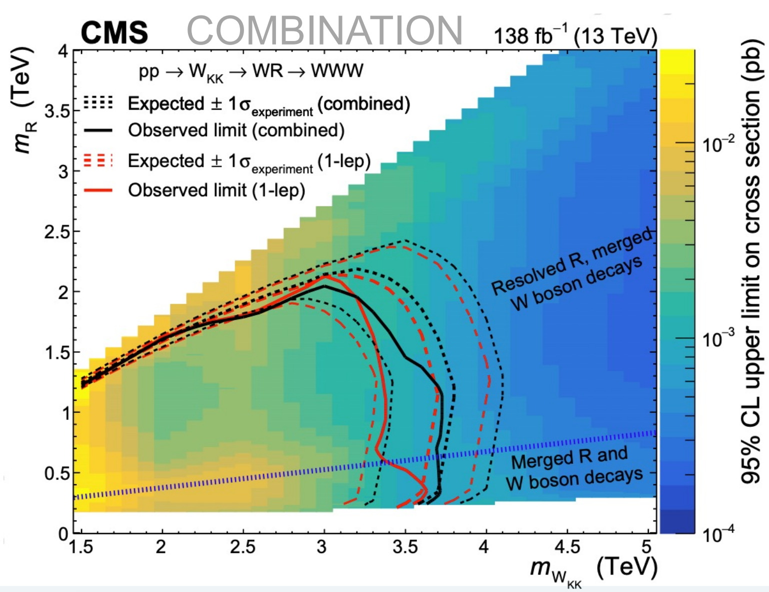
1-lep + jets

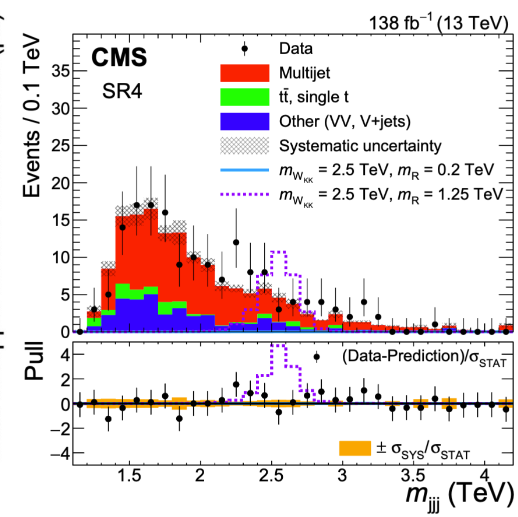


Full-hadronic





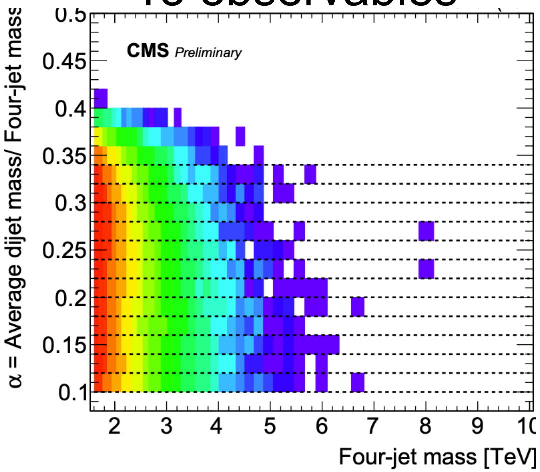




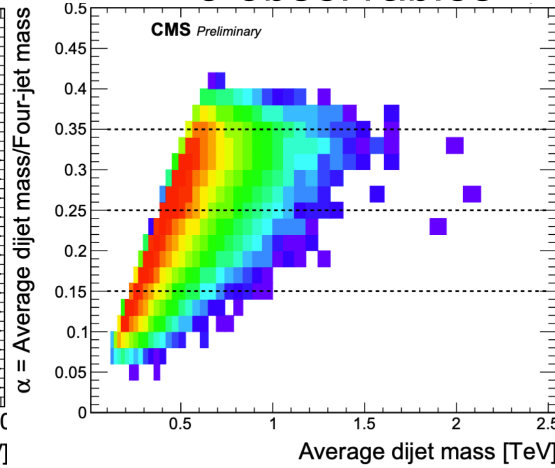
(Y) → XX → (jj)(jj) paired di-jets

B2G-21-010

13 observables



3 observables



$$\Delta R = |(\Delta R_1 - 0.8)| + |(\Delta R_2 - 0.8)|$$

$$\Delta R_1 = \sqrt{(\eta_{j_a} - \eta_{j_b})^2 + (\phi_{j_a} - \phi_{j_b})^2} < 2.0$$

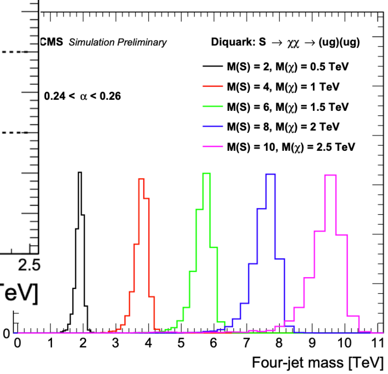
$$\Delta R_2 = \sqrt{(\eta_{j_c} - \eta_{j_d})^2 + (\phi_{j_c} - \phi_{j_d})^2} < 2.0$$

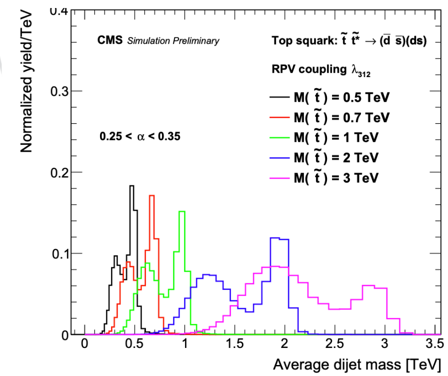
$$\Delta\eta = |\eta_1 - \eta_2| < 1.1$$

$$\text{asymmetry} = \frac{|m_1 - m_2|}{m_1 + m_2} < 0.1$$

$$\bar{m}_{jj} = (m_1 + m_2)/2$$

$$\alpha = \bar{m}_{jj}/m_{4j}$$





Dijet-3p:

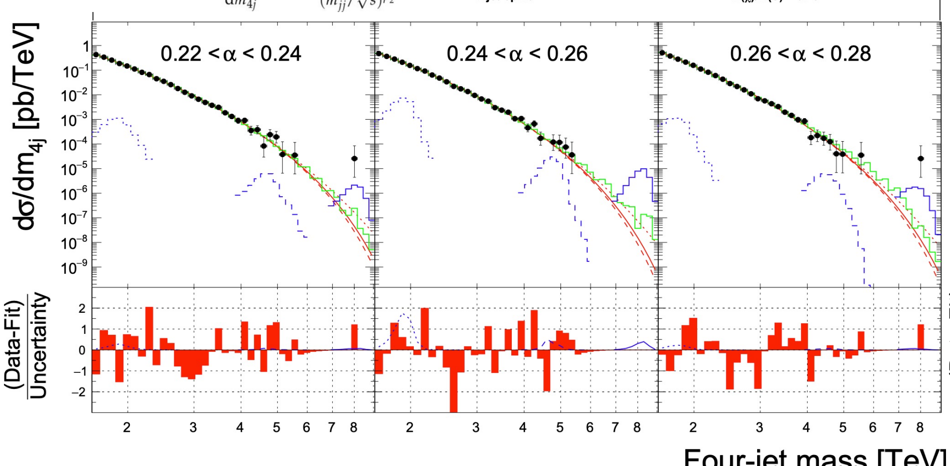
$$\frac{d\sigma}{dm_{4j}} = \frac{p_0(1 - m_{jj}/\sqrt{s})^{p_1}}{(m_{jj}/\sqrt{s})^{p_2}}$$

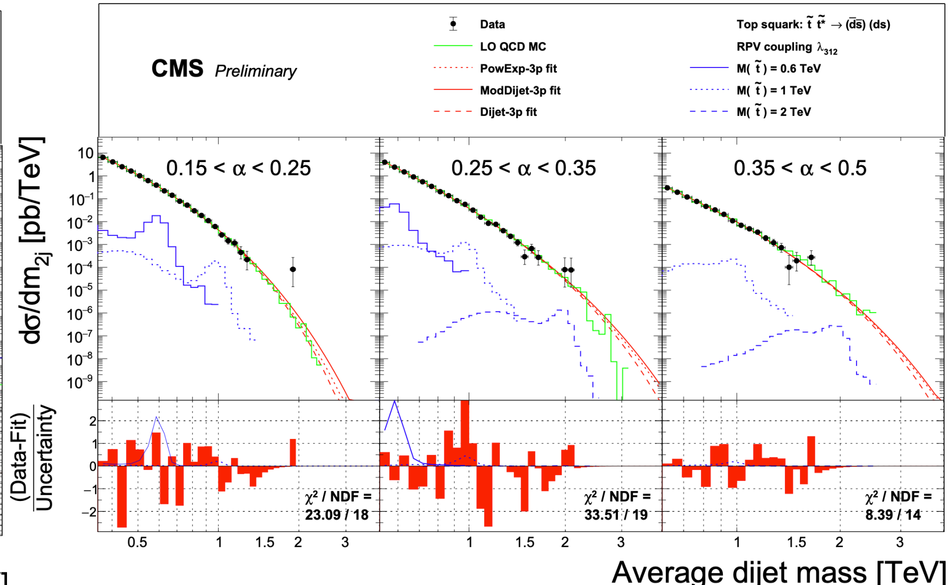
PowExp-3p:

$$\frac{d\sigma}{dm_{4j}} = \frac{p_0}{(m_{jj}/\sqrt{s})^{p_1}} e^{-p_2(m_{jj}/\sqrt{s})}$$

ModDijet-3p:

$$\frac{d\sigma}{dm_{4j}} = \frac{p_0(1 - (m_{jj}/\sqrt{s})^{1/3})^{p_1}}{(m_{jj}/\sqrt{s})^{p_2}}$$

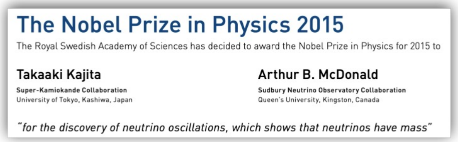




Majorana Neutrinos & Weinberg Op. Probe

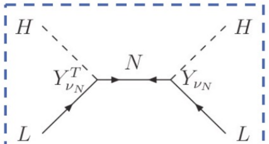
Introduction: Physics Background

➔ Neutrino masses:
- ❖ Confirmed by neutrino oscillation experiments
- ❖ Not included in the SM


The Nobel Prize in Physics 2015
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to
Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan
Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

➔ Why no neutrino mass mechanism in the SM?
- ❖ $SU(2)_L \times U(1)_Y$ EW symmetry & only Dimension-4 operators in Lagrangian
- ❖ Economical particle content:
  - Only left-hand neutrinos, Dirac mass is thus forbidden.

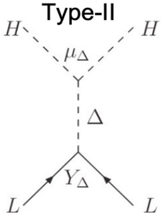
➔ To generate neutrino masses, one must go beyond the SM:
- ❖ Potential BSM particle solution: Seesaw models

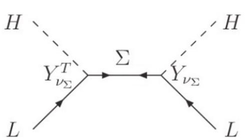


SM + fermion singlet
"Heavy Neutrino"
Type-I

BSM Model for This analysis

SM + scalar triplet
"Secondary Higgs"
Type-II



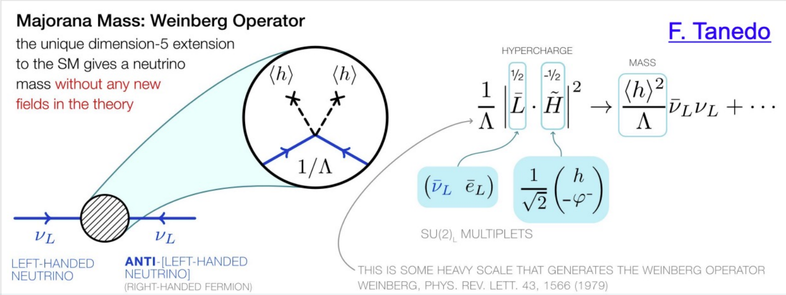


SM + fermion triplet
Type-III

Why named as Seesaw?
The heavier BSM particle is,
The lighter SM neutrino will be!

- ❖ EFT solution: Weinberg Operator

Phys.Rev.Lett. 43 (1979) 1566-1570



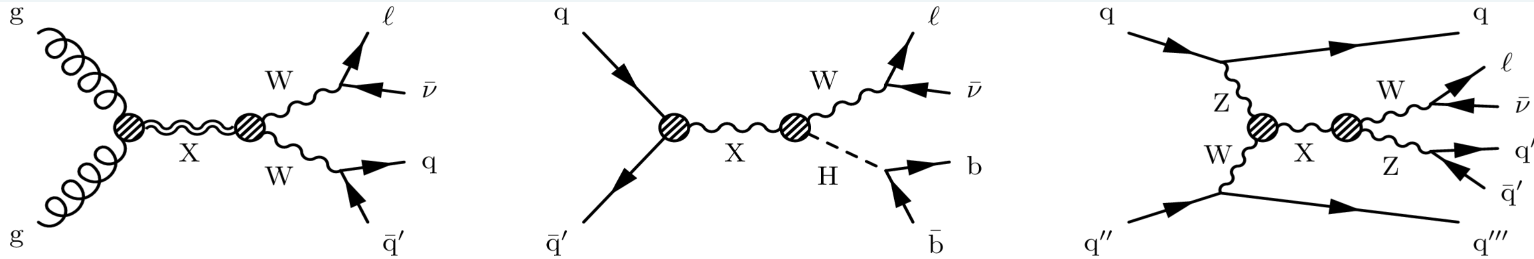
$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}\left[\Phi\cdot\overline{L_\ell^c}\right]\left[L_{\ell'}\cdot\Phi\right]$$

$\sqrt{2}\Phi \approx v + h$

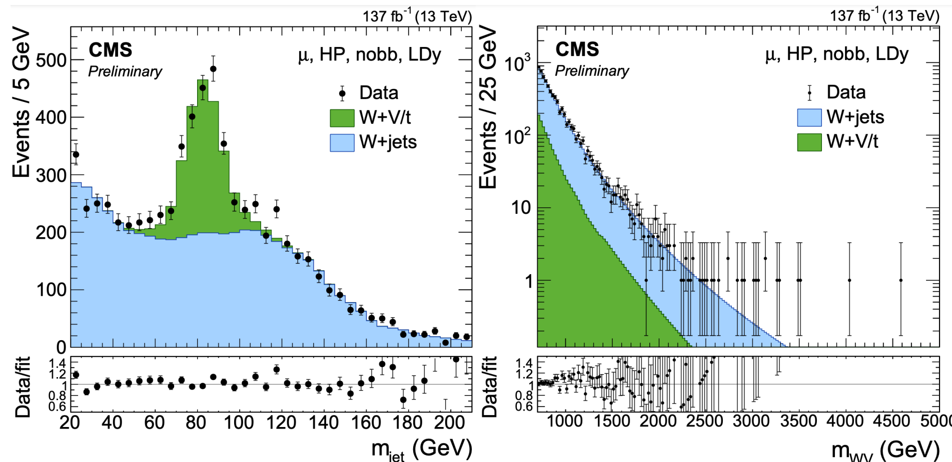
$$\mathcal{L}_5 = -\frac{C_5^{\ell\ell'}}{2\Lambda}hh\overline{\nu_\ell^c}\nu_{\ell'} - \frac{C_5^{\ell\ell'}v}{\Lambda}h\overline{\nu_\ell^c}\nu_{\ell'} - \frac{C_5^{\ell\ell'}v^2}{2\Lambda}\overline{\nu_\ell^c}\nu_{\ell'} + \text{H.c.}$$

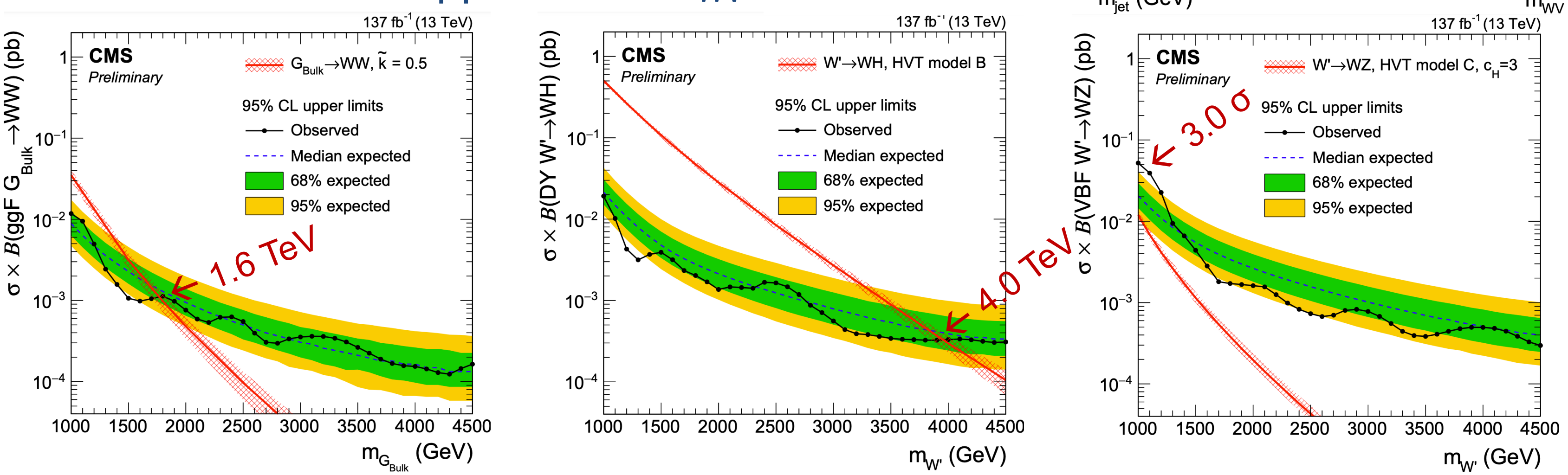
X → WV, WH → lν qq/bb

B2G-19-002



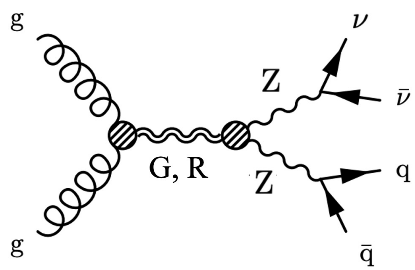
- 2D fit to the m_{Jet}, M_{WV} masses
- V/H-tagging: τ_{21}^{DDT}, double-b tagger
- $W_{l\nu}$, J, back-to-back
- 2 forward jets for VBF, 0 b-jets
- 24 categories based on 4 criteria: e/μ, L/H purity, VBF/bb/nobb, L/H $\Delta y_{J,l\nu}$
- BKGs: non-reso (W+jets), reso (tt) Prediction with kernel-approach at M_{WV}

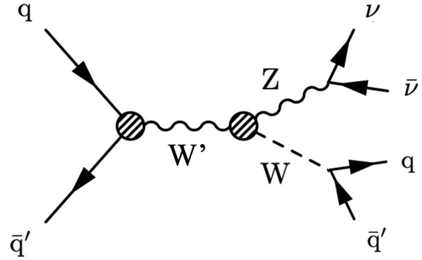


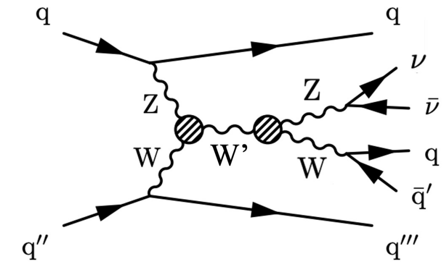


X → ZV → νν qq

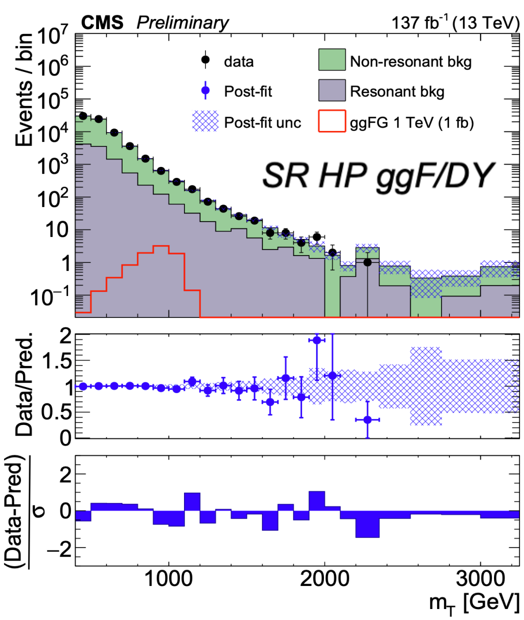
B2G-20-008

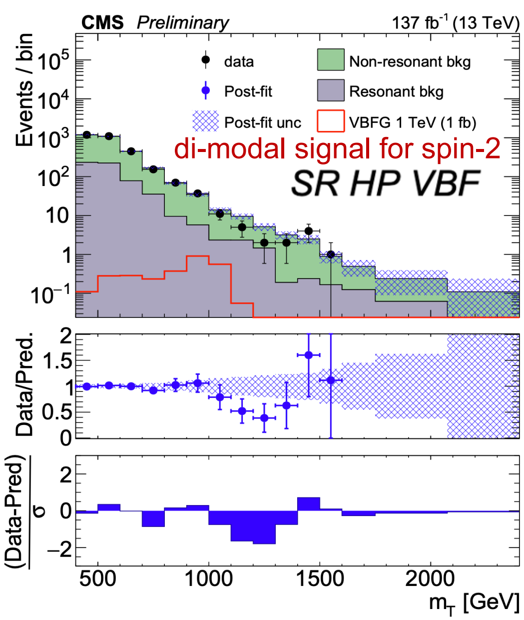


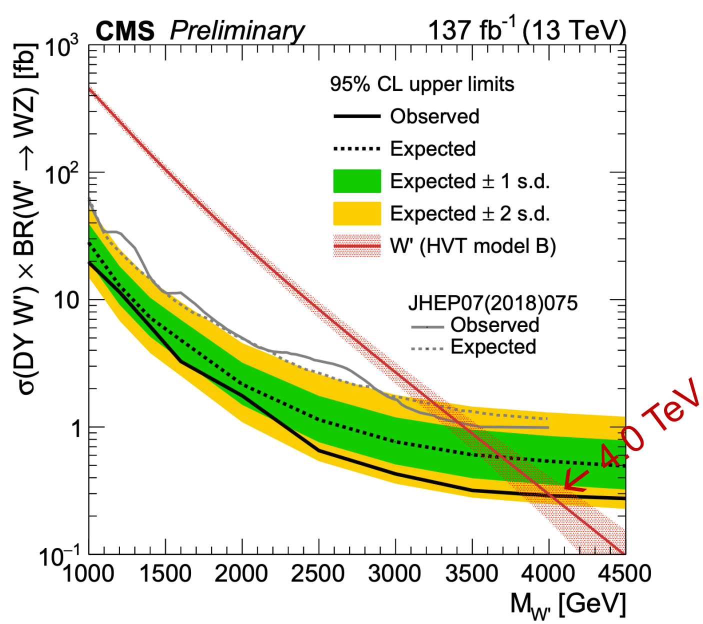




- Use $M_T(J,p_T^{miss})$ as observable; τ_{21} for V-tagging; veto b, l, τ_h, γ, p_T^{miss} ∥ j events
- Categorization to 4 sample: VBF, ggF/DY topology $|\Delta\eta_{jj}|<4$, $\eta_1\eta_2<0$, $m_{jj}>500$ GeV
  τ_{21} High/Low purity $\tau_{21}<0.35$, $0.35<\tau_{21}<0.75$
- SR: $65<m_J<105$ GeV; CR: m_J sideband (m_J : 30-65, 135-300 GeV)
- Dominant BKG: W/Z+jets, estimated from the data in CR per M_T bin



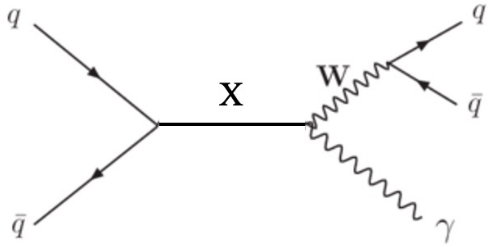




X → Wγ → qq γ

EXO-20-001

Generic V_{qq}+γ search



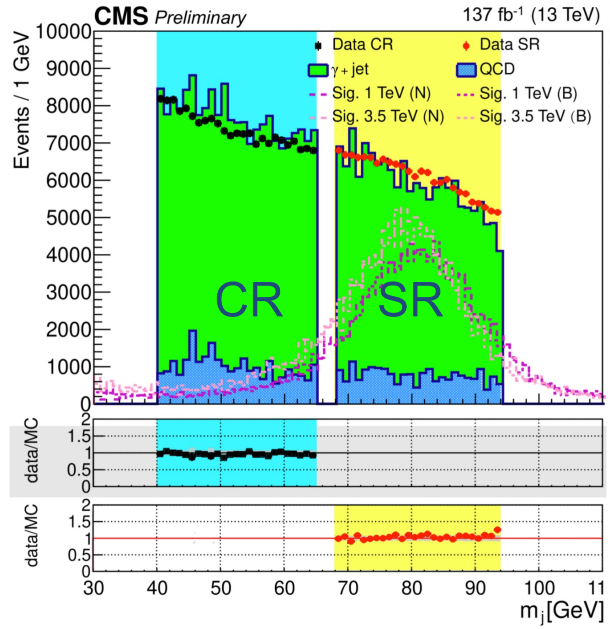
- W→qq merged (R=0.8) jet
- W-tagging with τ_{21}, m_J^{SD}
- Central γ

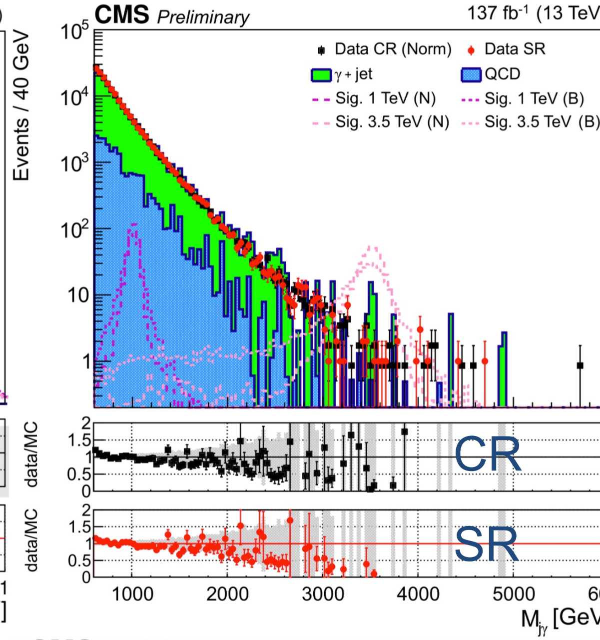
- Main BKG: γ+jets
- Low m_J^{SD} as CR

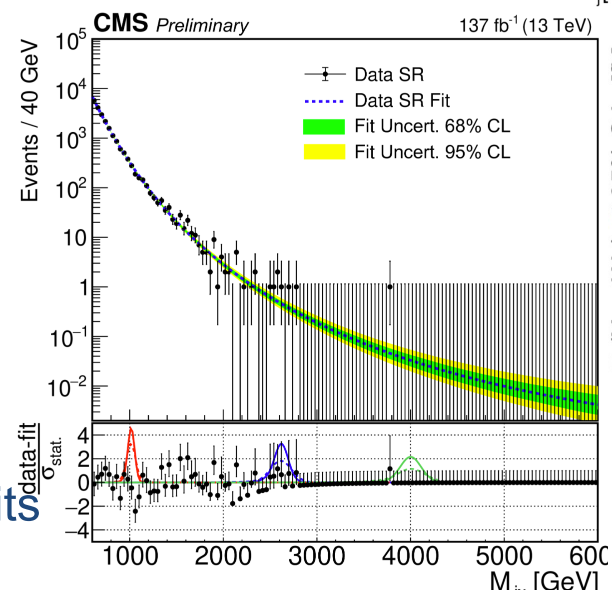
- BKG estimate: fitting analytic function to $M_{J\gamma}$

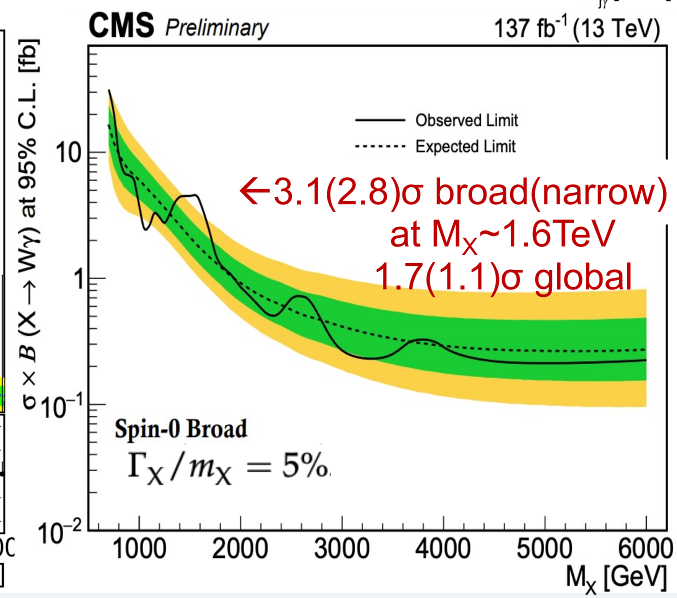
- Best limits to date on: $\sigma_{pp\to X} \times Br(X \to Wq q\gamma)$

- Model (in)dependent limits spin 0&1, narrow/broad





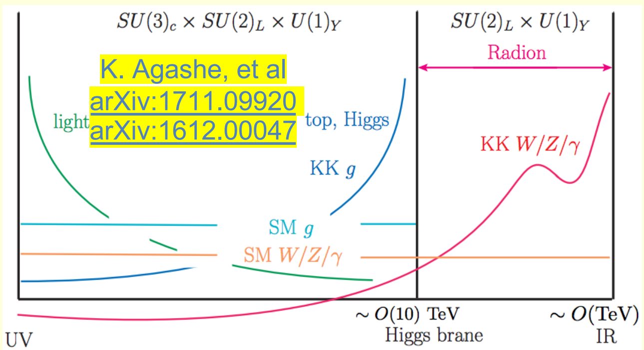




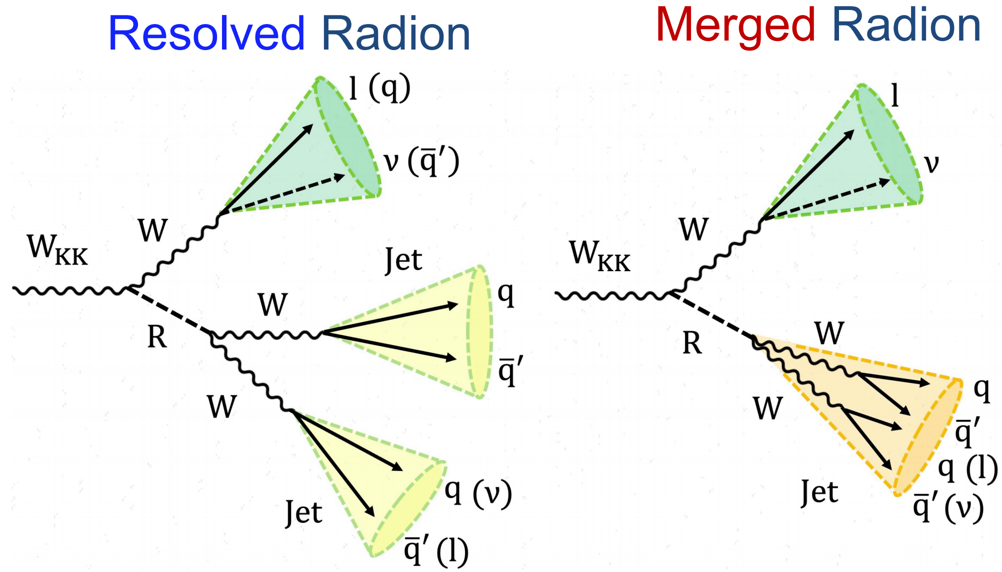
X → RW → WWW → lν jets

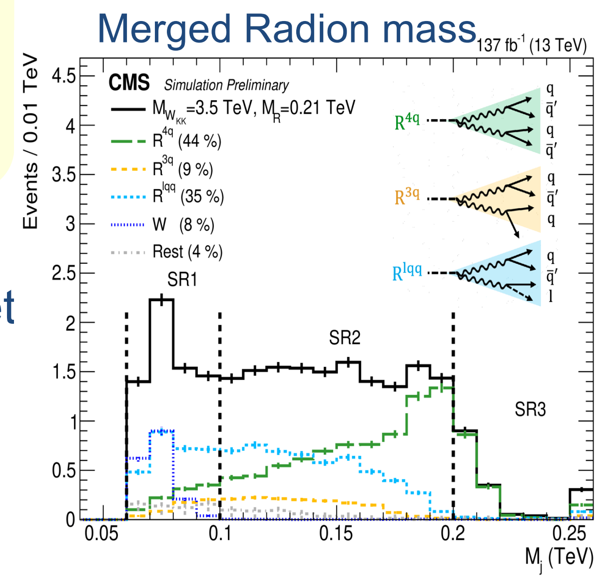
B2G-20-001

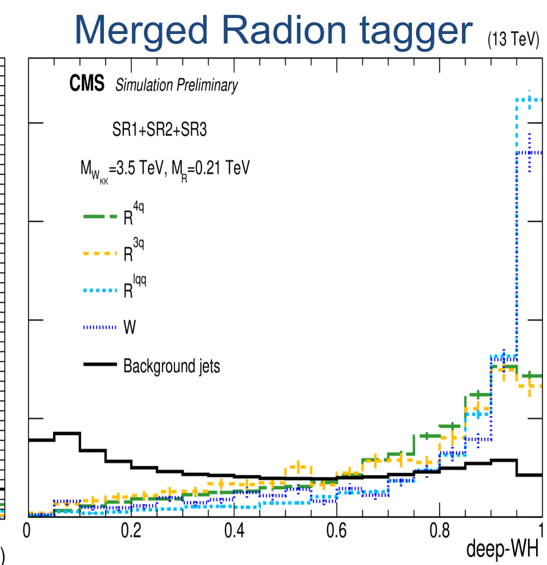
- First tri-boson search
- New model: Extended Warped ED
  → suppressed di-SM processes
  → enhanced tri-SM processes



- Only EW in extended bulk dominant: $V_{KK} \rightarrow R\,V \rightarrow VVV$
  Di-resonant
- W→lν: reconstruction
- 1 or 2 AK8 massive jets, 0 b-jet
- deep-AK8 taggers for W & R
- Radion tagging with H_{4q} & W_{qq}
- Calibration with SM-proxy jets: top for $R^{3q,4q}$, W for R^{lqq}



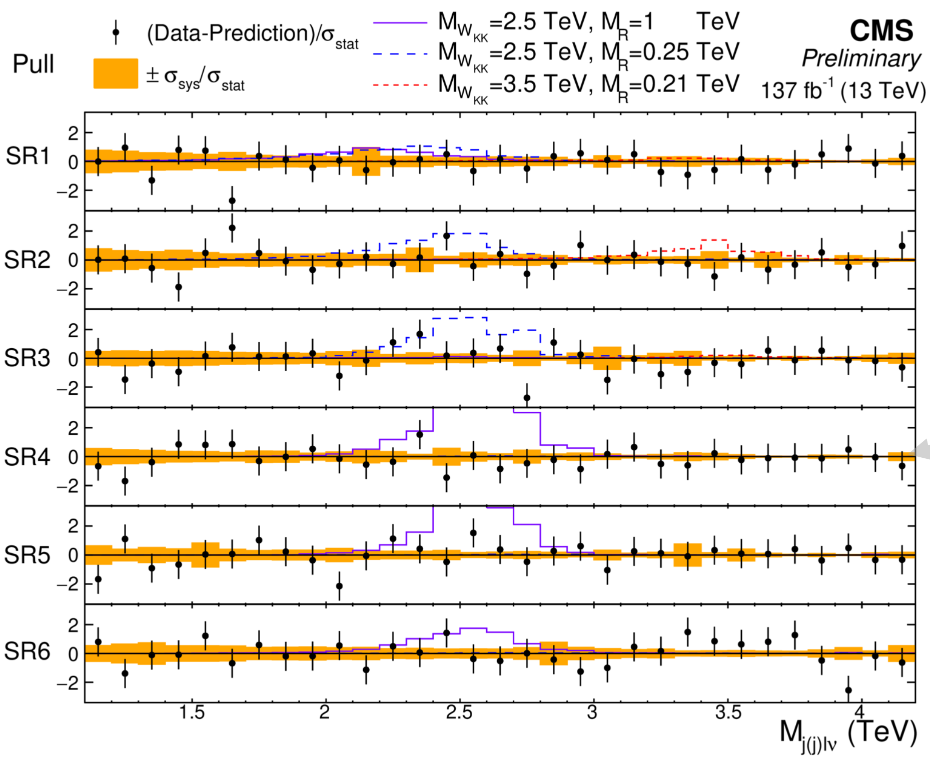




Triboson results

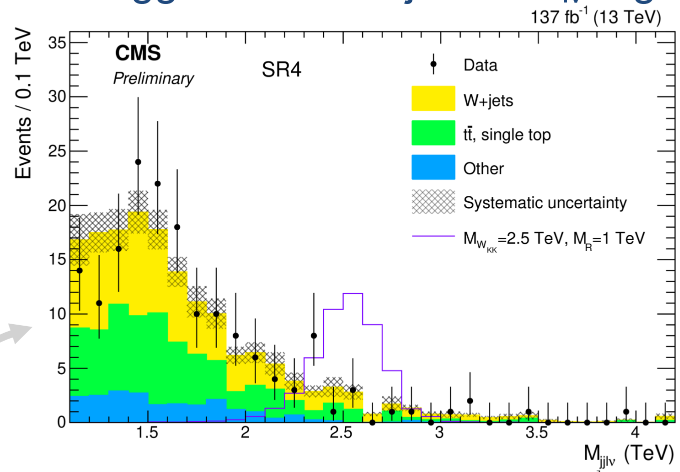
B2G-20-001

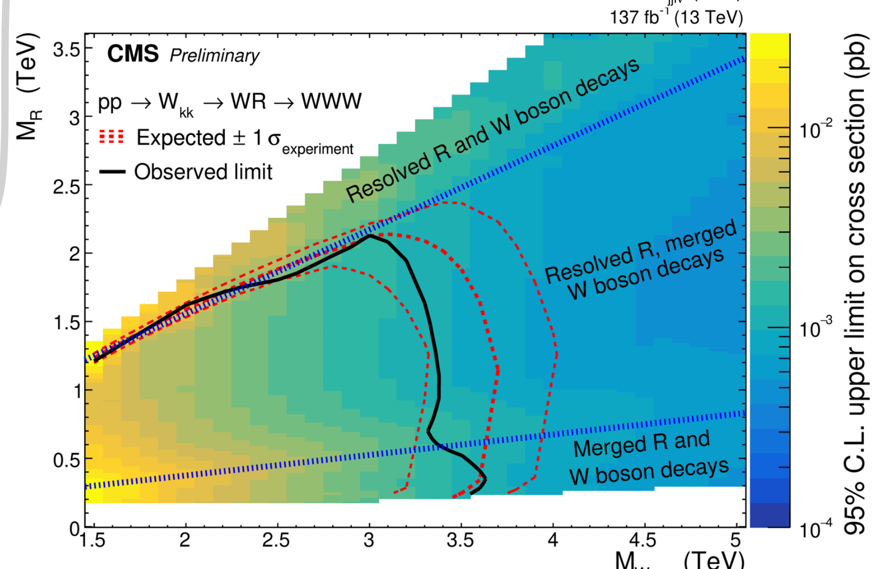
- Probe simultaneously merged & resolved
- Categorize to 6 SRs:
  SR1-3 → 1 jets (merged) → M_{lvj}
  SR4-6 → 2 jets (resolved)→ M_{lvjj}



- First limits on $\sigma(W_{KK} \to RW \to WWW)$ and on $[M_{WKK}, M_R]$ space

2 W-tagged massive jets + W_{lv} region:



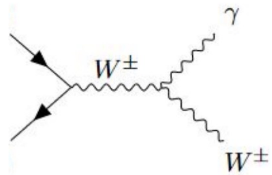


Results interpretation in $Z_{KK} \to ZWW$
Relevant search $g_{KK} \to Rg \to ggg$ at talk

$X \rightarrow W\gamma \rightarrow qq\ \gamma$

EXO-20-001

- Generic search for V_{qq}+γ



- W→qq AK8 jet
- tagging with $\tau_{21}<0.35$
- $p_{Tj(\gamma)}>225$ GeV, $|\eta_{j(\gamma)}|<2(1.44)$

  $\Delta R_{J\gamma}>1.1$, $p_{T\gamma}/m_{J\gamma}>0.37$, $\cos\theta^*<0.6$

- Main BKG: γ+jets
- Calibration from low m_j CR

- BKG estimate: fitting analytic function to $M_{J\gamma}$

- Best limits to date on:
  $\sigma_{pp\rightarrow X}\times Br(X\rightarrow Wqq\gamma)$

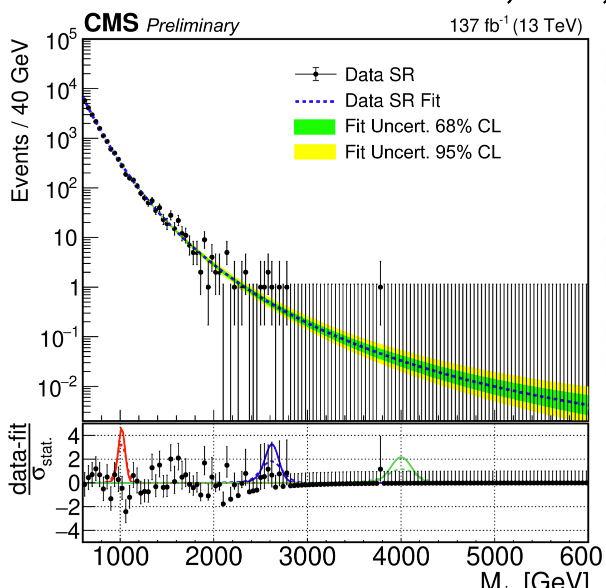
- Model independent limits for spin 0,1, narrow 0.01%, broad 5%

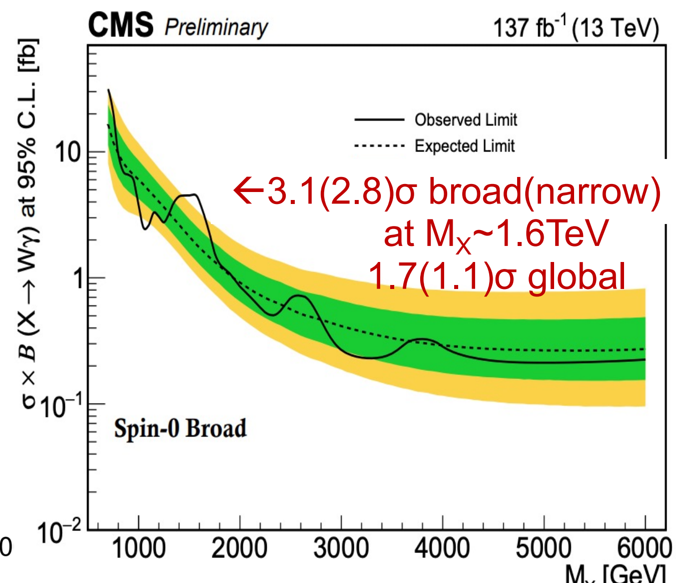
Theory motivation:

- Triplet pseudo-Goldstone bosons π_3
  (https://arxiv.org/pdf/1608.01675.pdf)
- Scalar or pseudoscalar $SU(2)_L$ Φ^α
  coupling via anomaly-induced interaction

- Two Higgs doublet (H+) MSSM
- Technicolor
- HVT

JER: 15%, 8%, 4% for 10, 100, 1000 GeV

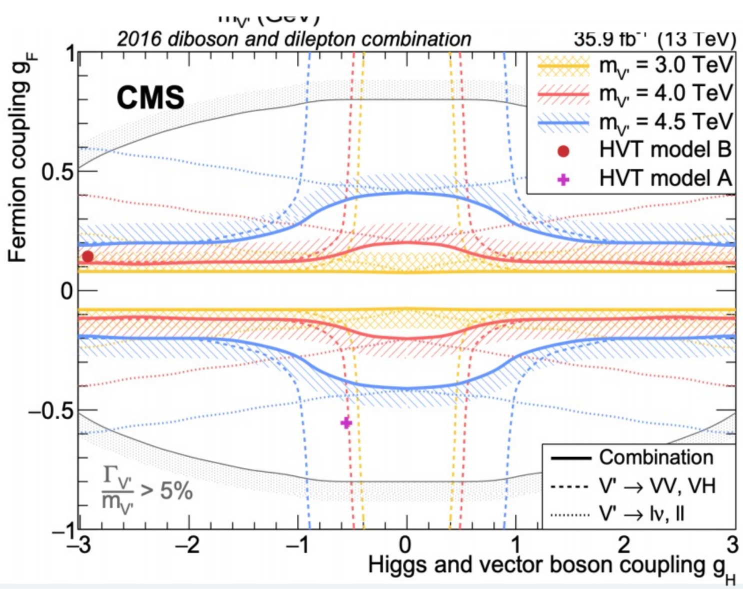




HVT couplings

Coupling strengths scale factors

HVT	$g_F = g^2 c_F / g_V$	$g_H = g_V c_H$	g_V	c_H, c_F	Pheno
Model A	-0.55	-0.56	1		BF(f,f)~BF(V,V)
Model B	0.14	-2.9	3	-0.98, 1.02	DY (min. composite H)
Model C	0	-0.56	1	1, 0	VBF (Fermiophobic)



Limits interpreted over g_H-g_f plane

$$g_H = g_V c_H$$

$$g_f = g^2 c_F / g_V$$

Heavy vector triplet (HVT) coupling with SM: c_H, gV, cF

spin-1 Z',W'

model A (comparable BF to f, V, $g_V = 1$)

model B ($c_H = -0.98, gV = 3, cF = 1.02$), DY

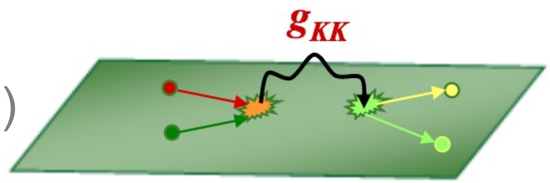
model C ($c_H = gV = 1, cF = 0$), VBF only

Parameter	Model A	Model B	Model C
c_H	-0.556	-0.976	1
c_F	-1.316	1.024	0
g_V	1	3	1

More at : https://arxiv.org/pdf/1906.00057.pdf

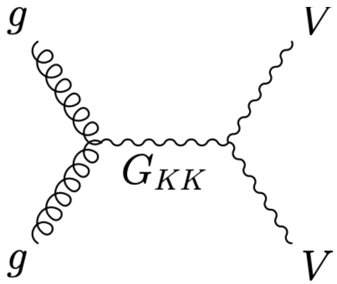
Motivation for a Diboson search

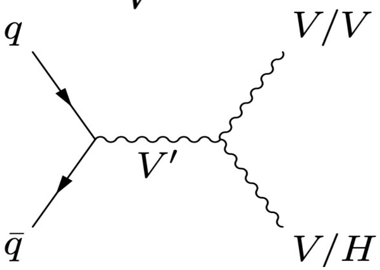
- SM shortcomings indicate some kind of New Physics
  (Hierarchy problem, Unific.of Gravity, Dark Matter/Energy)



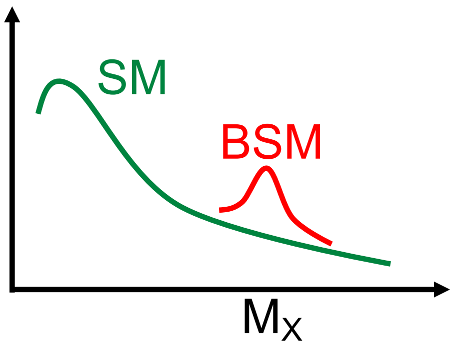
- Many BSM theories have been proposed:
  (Extended Gauge-Symmetry models; RS Warped ED;
  Two Higgs doublet models; Little/Composite Higgs)
  → Predicting new heavy boson(s) X with
    - spin 0: Radion/Higgs
    - spin 1: W'/Z' (HVT)
    - spin 2: Graviton

  at the TeV scale decaying to a pair of SM bosons→ W, Z, H, γ





- Therefore we can search for BSM Physics in Dibosons FSs



→ HOW TO... search?
Probing Diboson FS at TeV-scale is a challenge to reconstruct boosted & merged V/H reveling substructure

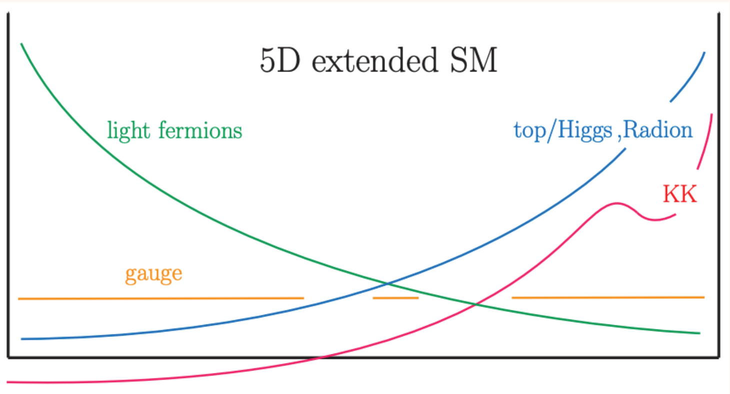
- Selection based on V-like objects suppressing BKG
- Predict in a Data-Driven way the SM BKG
- Look for a peak-structure at M_{VV} tails

Motivation for “tri-object” search

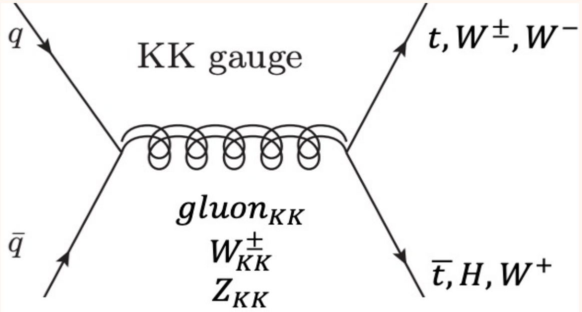
- M_{Pl}-EW scale gap motivates BSM physics (hierarchy problem)
- No BSM physics yet → time to look at non-standard final states/scenarios

Standard (Minimal) Warped ED model

- 2 Branes in Bulk (in the RS framework)
- Everything propagates to the same bulk
- Constrained by LHC searches

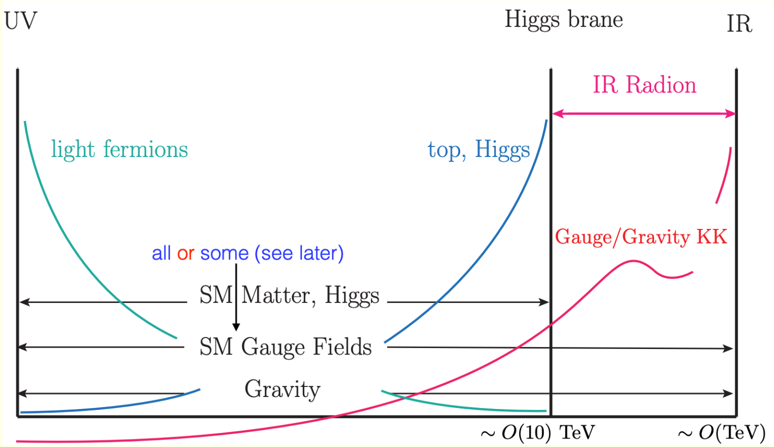


- “di-SM” dominant phenomenology

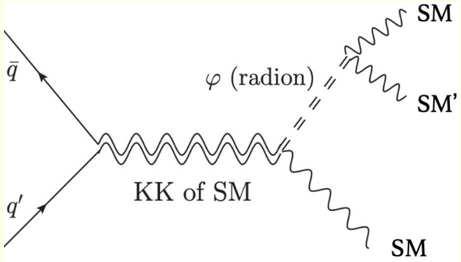


Extended Warped ED model:

- Extra brane by splitting → Extended Bulk
  3 (or more) branes, 2 (or more) Radions
- Various fields propagate in diff. regions



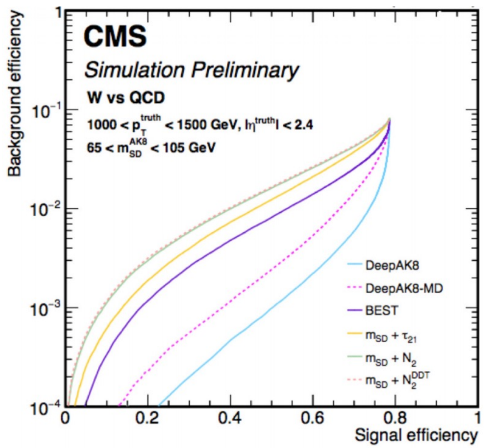
- A wealth of new signatures emerges
- “di-SM” suppressed in favor of “tri-SM”



K. Agashe’s talk
arXiv:1711.09920
arXiv:1612.00047

Jet tagging with deepAK8 framework

- 17 jets categories/scores
- Mass-decorrelated versions
- Powerful BKG rejection (binarized)



- Extra power from modularity: non-binarized, customized taggers
- Modularity reveals the actual power of deep-AK8, but comes with the price of N/A SFs

JME-18-002

Output

Category	Label
Higgs	H (bb)
	H (cc)
	H (VV*→qqqq)
Top	top (bcq)
	top (bqq)
	top (bc)
	top (bq)
W	W (cq)
	W (qq)
Z	Z (bb)
	Z (cc)
	Z (qq)
QCD	QCD (bb)
	QCD (cc)
	QCD (b)
	QCD (c)
	QCD (others)

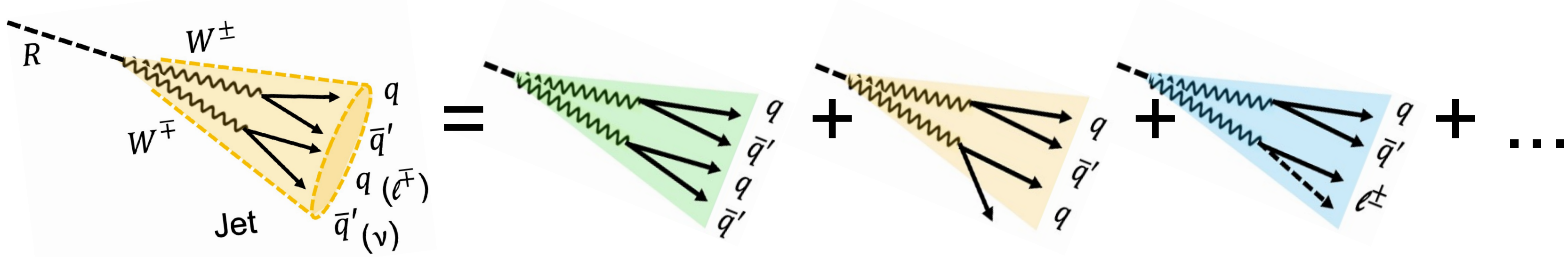
We use two taggers:

W tagging with "binary" scores

$$\text{deep-W} = \frac{W_{qq,qc}}{QCD_{g,q,b,..} + W_{qq,qc}}$$

Radion tagging with hybrid:

$$\text{deep-WH} = \frac{W_{qq,qc} + H_{4q}}{QCD_{g,q,b,..} + W_{qq,qc} + H_{4q}}$$



Parameters & conventions in Diboson searches

Several signal benchmark scenarios are used to interpret the results of the search. Spin-0 radions [38–40] and spin-2 gravitons [41–43] decaying to WW are generated for the bulk scenario of the RS model of warped extra dimensions [7, 8]. For bulk gravitons, denoted as G_{bulk}, the ratio $\tilde{k}$ of the unknown curvature scale of the extra dimension k and the reduced Planck mass $\overline{M}_{Pl}$ is set to $\tilde{k} = 0.5$, which ensures that the natural width of the graviton is negligible with respect to the experimental resolution [44]. For bulk radions, we consider a scenario with $\Lambda_R = 3\,\text{TeV}$ and $kl = 35$ [44]. Spin-1 resonances decaying to WW, WZ, or WH are studied within the HVT framework [9] in the benchmark model B (Drell–Yan production) and model C (vector boson fusion). The HVT framework introduces a triplet of heavy vector bosons with similar mass, of which one is neutral (Z′) and two are electrically charged ($W'^{\pm}$). Its benchmark models are expressed in terms of a few parameters: the strength c_F of the couplings to fermions, the strength c_H of the couplings to the Higgs boson and longitudinally polarized SM vector bosons, and the interaction strength g_V of the new vector boson. In HVT model B ($g_V = 3$, $c_H = -0.98$, $c_F = 1.02$ [9]), the new resonances are narrow and have large branching fractions to vector boson pairs, while the fermionic couplings are suppressed. In model C ($g_V \approx 1$, $c_H \approx 1$, $c_F = 0$), the fermionic couplings are zero, and the resonances are produced only through vector boson fusion and decay exclusively to pairs of SM bosons. Monte Carlo (MC) simulated samples for bulk radions, bulk gravitons, and resonances of the HVT models are generated at leading order (LO) in quantum chromodynamics (QCD) with MadGraph5_aMC@NLO versions 2.2.2 and 2.4.2 [45]. For each model, resonance masses in the range 1.0–4.5 TeV are considered, and the resonance width is set to 0.1% of the resonance mass, which ensures that the narrow-width approximation is fulfilled, thereby making our modelling of the detector effects on the signal shapes independent of the actual benchmark scenario used to generate the events.

Tools for BSM multiboson searches

Boosted objects → small angular separation → merged jets

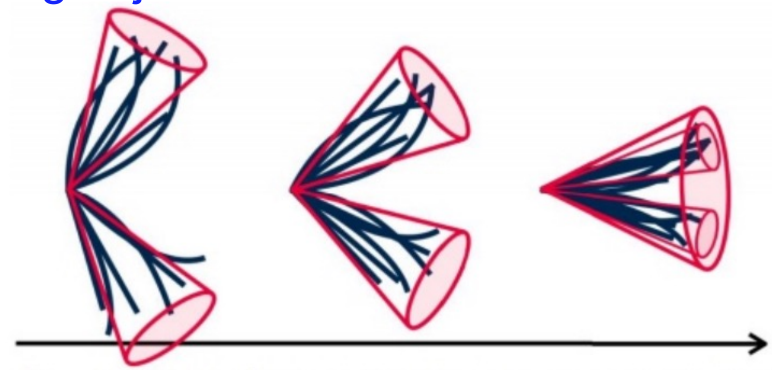
W/Z→qq;

H→bb/qqqq/qqlv

→ anti-kt clustering

→ Large-R jets: $\Delta R = \sqrt{(\Delta\varphi^2 + \Delta\eta^2)} \approx 2m/p_T$

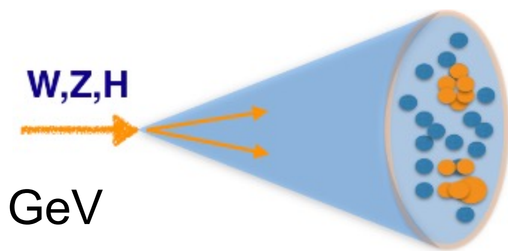
→ "Groomed" Soft-Drop Masses: $M_J \sim M_V \pm 0.2\, M_V$

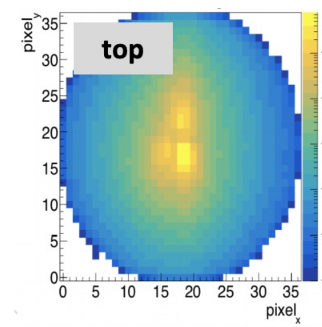


Taggers based on (2-prong) substructure

- τ_N = N-subjettiness → ratios: $\tau_2/\tau_1 = \tau_{21}$ → $\tau_N = \frac{1}{d_0}\sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$
- Decorrelated taggers τ_{21}^{DDT}

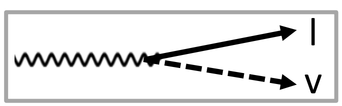
Deep-NN taggers & Image taggers (soon)

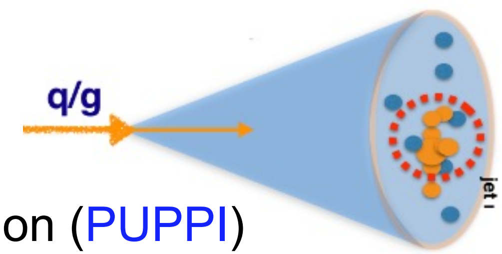


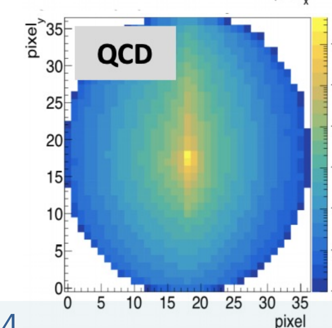


MET + lep from Boson:

→ Reco the W(H) assuming $M_{W(H)}$=80(125) GeV







b-jet tagging based on MVA, DNN

PU effect → Pile Up Per Particle Identification (PUPPI)