# Searches for new physics with photons at CMS & ATLAS
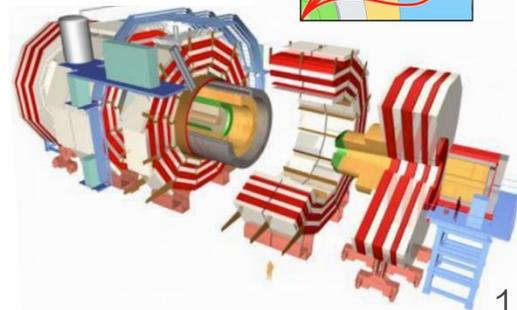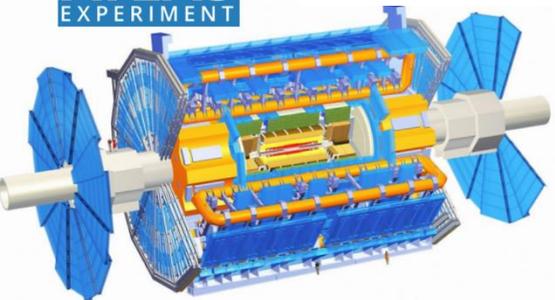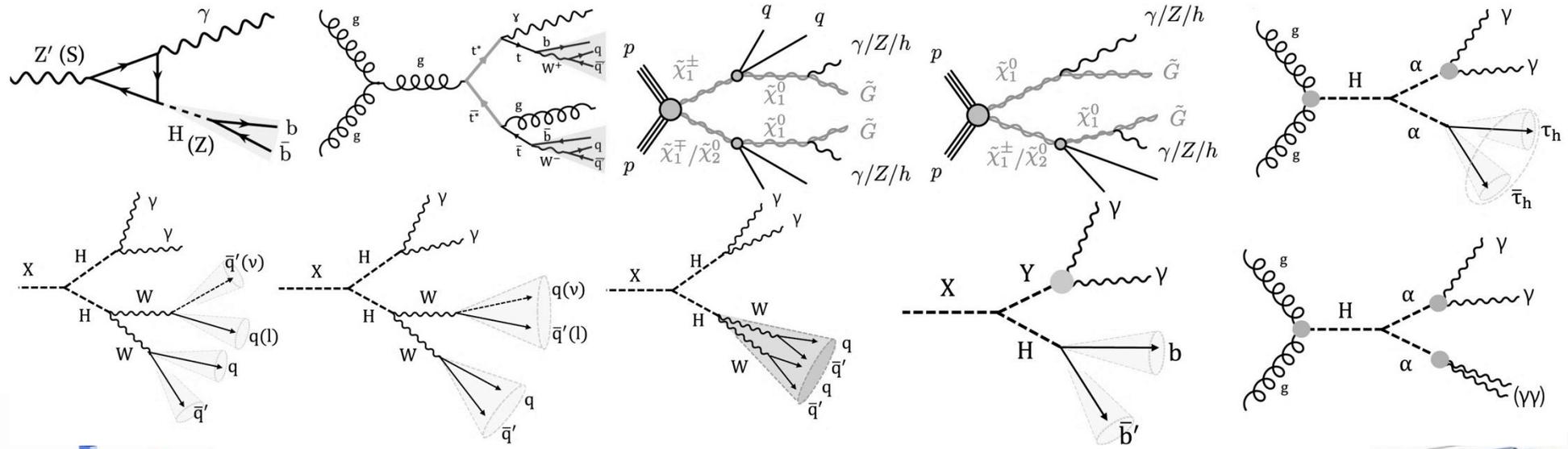
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PEKING UNIVERSITY

On behalf of ATLAS & CMS collaborations

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# Outline: results in this talk

Focusing on results releases over the past year:

| | Exp | ID & Links | Topology | Released |
|---|---|---|---|---|
| 1 | CMS | B2G-24-007 | X → Hγ or Zγ → 2b γ | May 25 |
| 2 | CMS | B2G-24-006 | t*t* → ttgγ → jets + γ | Apr 25 |
| 3 | ATLAS | SUSY-2021-07 | χχ → γ + jets + MET | Nov 25 * |
| 4 | CMS | B2G-24-010 | X → HH → WW γγ | Oct 25 * |
| 5 | CMS | B2G-24-001 | X → HY → bb γγ | Apr 25 |
| 6 | ATLAS | HMBS-2024-39 | H → AA → γγ $\tau_h \tau_h$ | Dec 24 |
| 7 | CMS | EXO-24-025 | H → AA → 4γ | Jul 25 |

\* very new results

The full list of results:
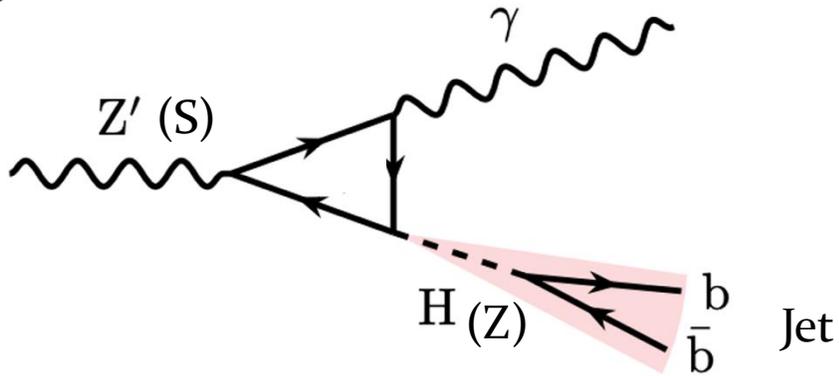
- Higgs and Diboson Searches
- Exotics Physics Searches

- B2G Preliminary  Publications
- Exotica results Preliminary  Publications
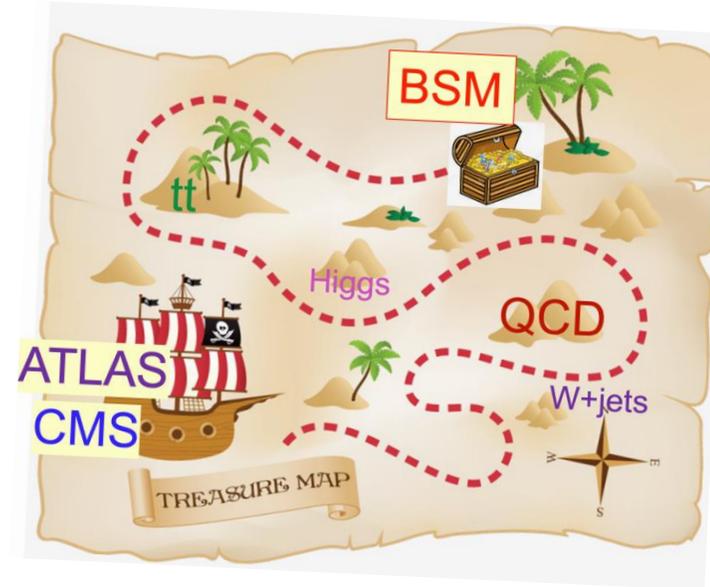
Full run 2 data:
140 fb$^{-1}$ ATLAS
138 fb$^{-1}$ CMS
@ 13 TeV

# Z' → Hγ → bbγ  &  S → Zγ → bbγ



γ

Z' (S)

H (Z)

b
b̄

Jet

Resonant signal search:
- [spin-1 Z]', couples to quarks & BSM.
- spin-0, S, a generic Higgs-sector extension.

Topology & Selection:
- H/Z→bb as a single, massive AK8 jets + γ.

- Global [Particle Transformer] (GloParT) algorithm, (314 classes) used to identify bb-jets: Xbb score.

- Use [ParticleNet]-regressed mass $m_j$ to select Z, H →
- 4 Signal Region (SR) on $X_{bb}$ & $m_j$.
- Searching for a peak over the $m_{j\gamma}$ spectrum →

# Z' → Hγ → bbγ  &  S → Zγ → bbγ
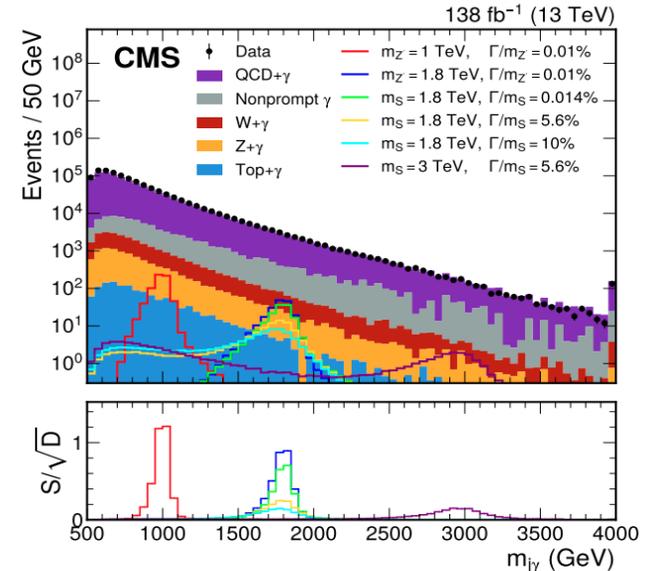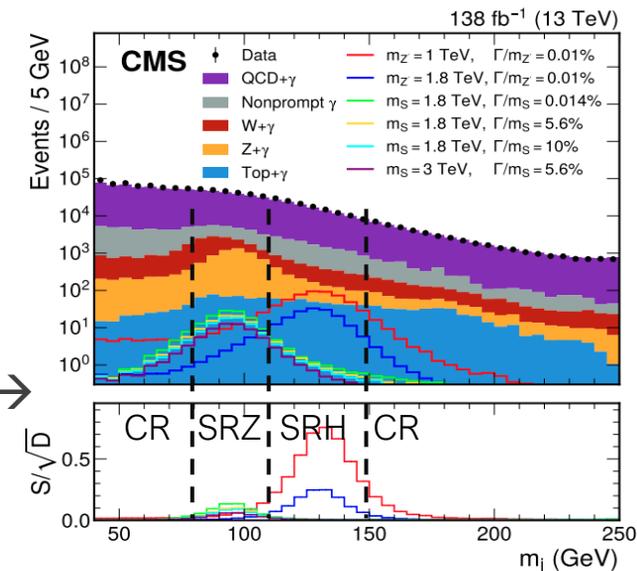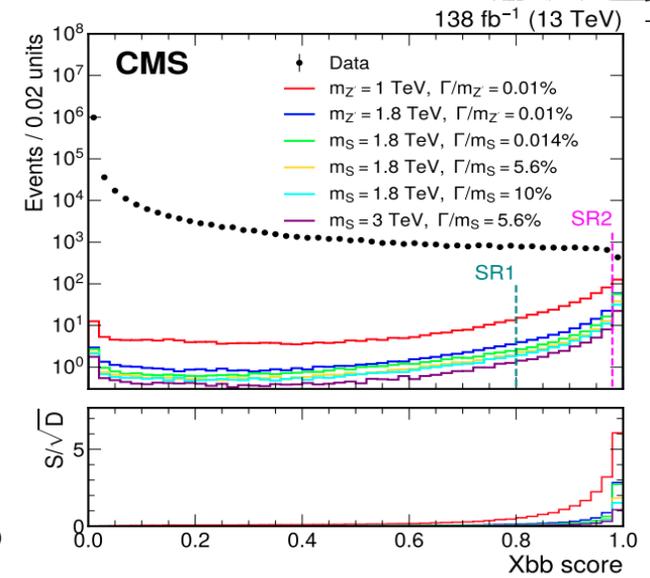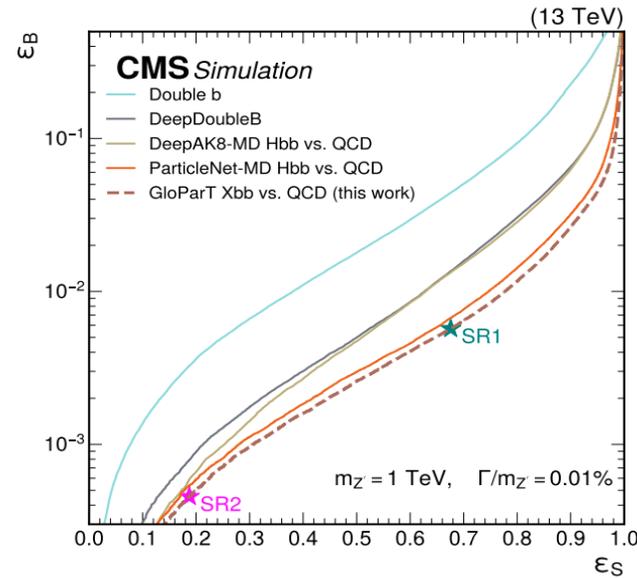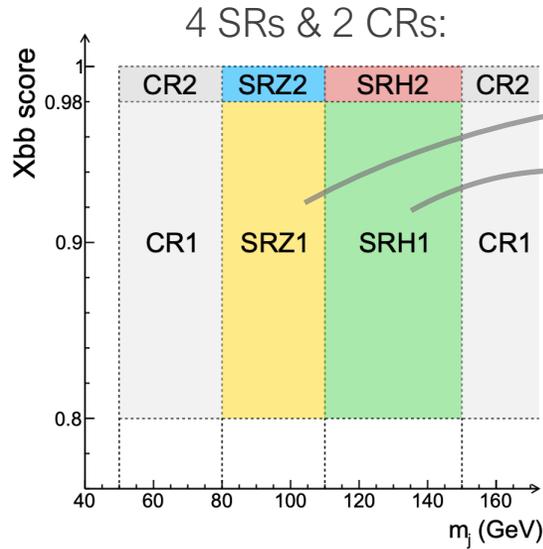
- BKG modeling with 6 parametric function in discrete proofing setup (envelope):

$$f_1(m) = p_0 m^{p_1 + p_2 \log(m)} \quad \text{(Dijet2)}$$

$$f_2(m) = p_0 m^{p_1 + p_2 \log(m) + p_3 \log^2(m)} \quad \text{(Dijet3)}$$

$$f_3(m) = p_0 m^{p_1} \quad \text{(ExPow1)}$$

$$f_4(m) = p_0 m^{p_1} e^{p_2 m} \quad \text{(ExPow2)}$$

$$f_5(m) = p_0 (1 + p_1 m)^{p_2} \quad \text{(InvPow2)}$$

$$f_6(m) = p_0 (1 + p_1 m)^{p_2 + p_3 m} \quad \text{(InvPow3)}$$

- Signal modeling with DSCB function.

- Constrain signal over 2+2 SRs $m_{j\gamma}$ spectra.

- Cover also wide widths for S: $\Gamma_S/m_S$ = 5.6%, 10%.
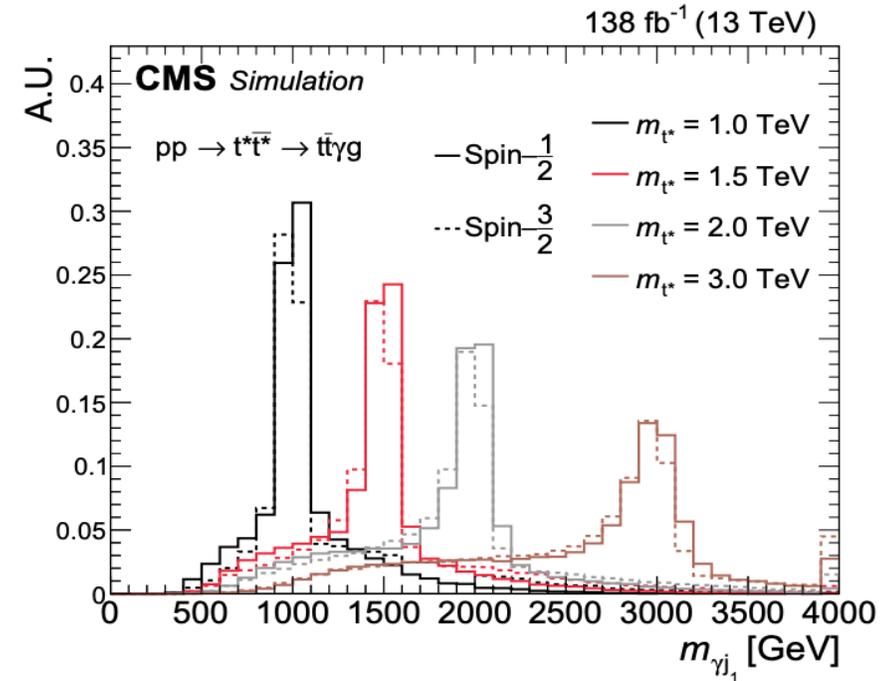
- Best-to-date model-independent limits on σB →



4 SRs & 2 CRs:

# t*t* → ttgγ → jets + γ



**3%**

AK8 jet
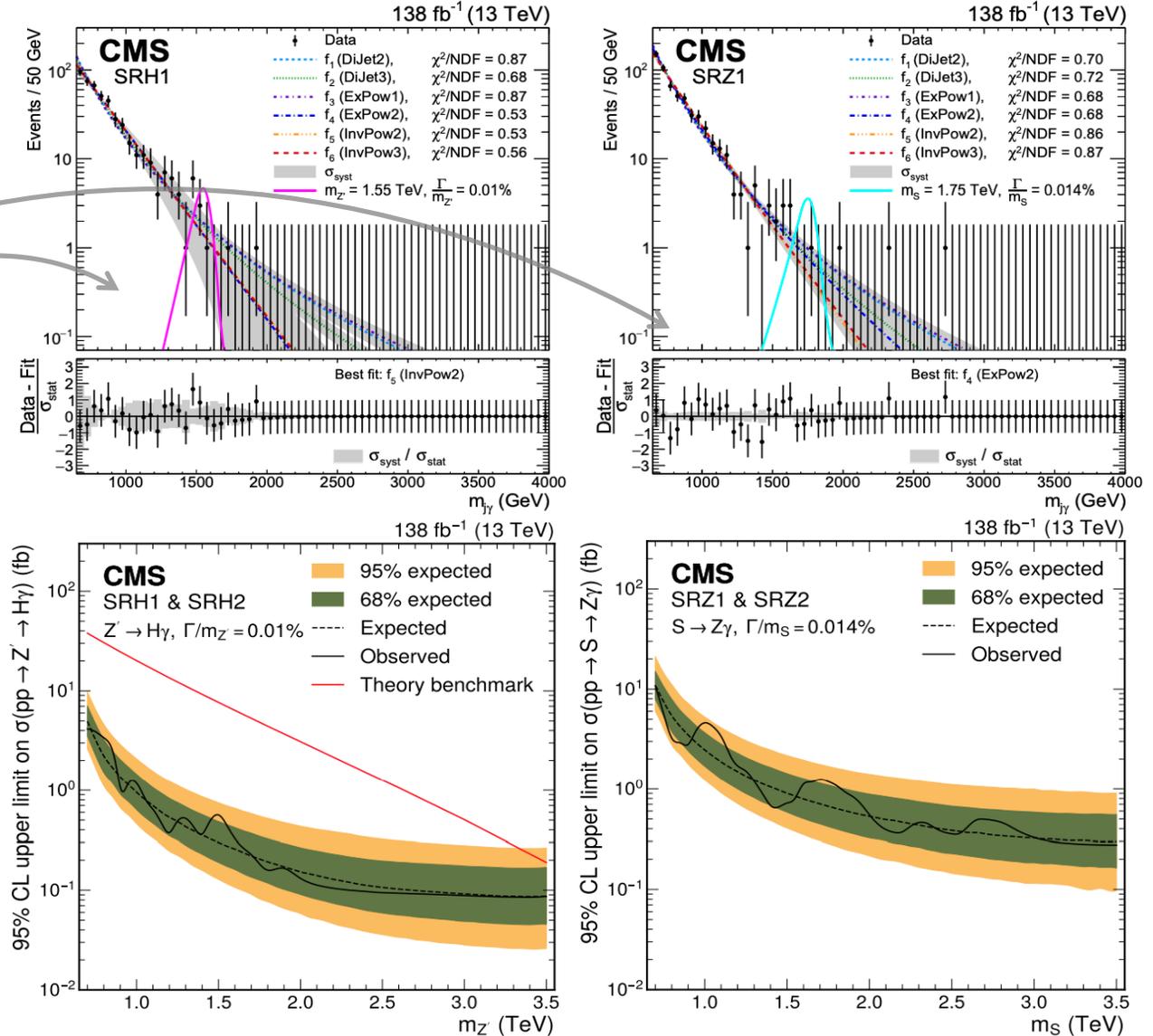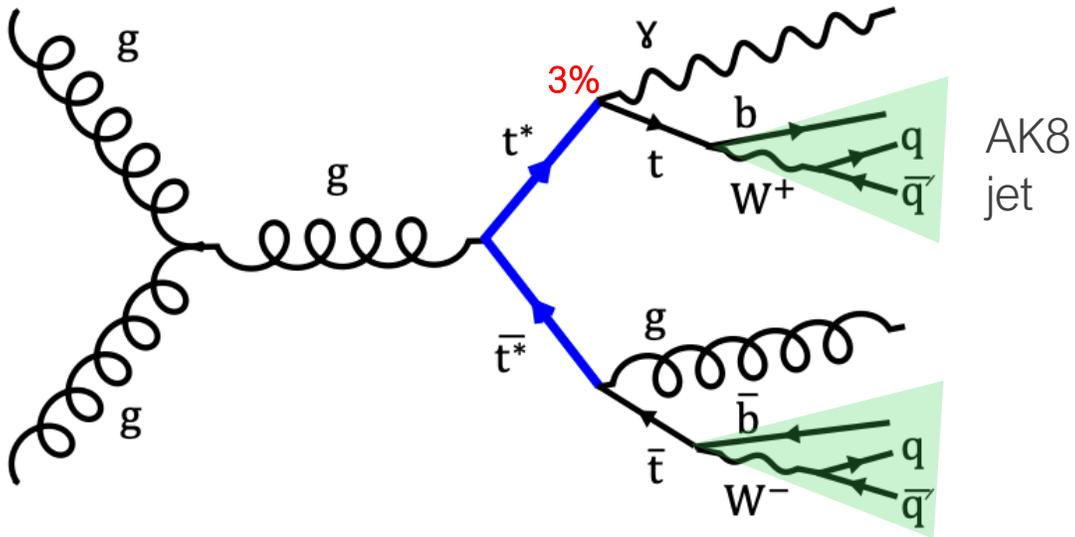
Topology & Selection:
- All hadronic final state: t→ bqq + γ.
- $m_{t*}$ > 0.7 TeV → boosted & merged t.

- At least 1 merged AK8 top-tagged jet: use Particle Net tagger & SD-mass: 125 < $m_j$ < 225 GeV.

- Search over the $m_{jγ}$ spectrum to extract signal.

- 1st search for resonances in this channel.

- Heavy, t*t*:  excited top states or TT, VLQ t-partners from ED & composite H models, with spin 1/2 or 3/2, T → tg, tγ can be dominant.

- B(t*→tg) = 0.97,  B(t*→tγ) = 0.03  following 1808.03649 model. Past searches assumed B(t*→tg)=100%.



138 fb⁻¹ (13 TeV)

CMS *Simulation*

pp → t*t̄* → tt̄γg

— Spin-1/2
--- Spin-3/2

— $m_{t*}$ = 1.0 TeV
— $m_{t*}$ = 1.5 TeV
— $m_{t*}$ = 2.0 TeV
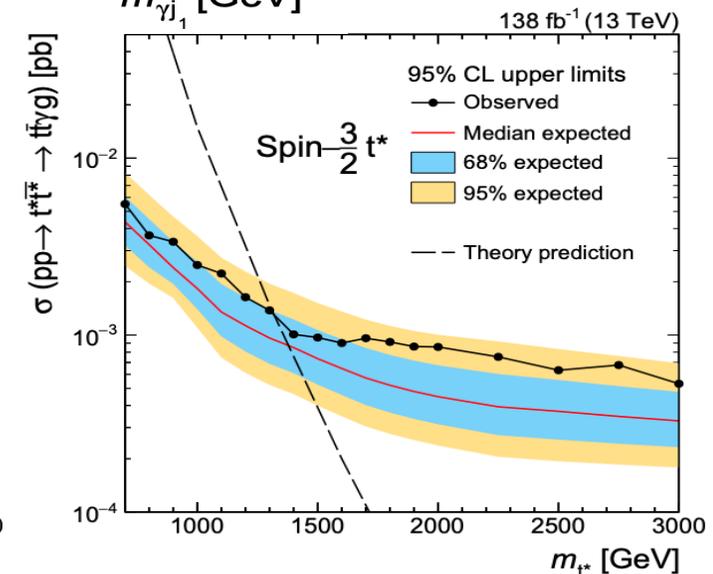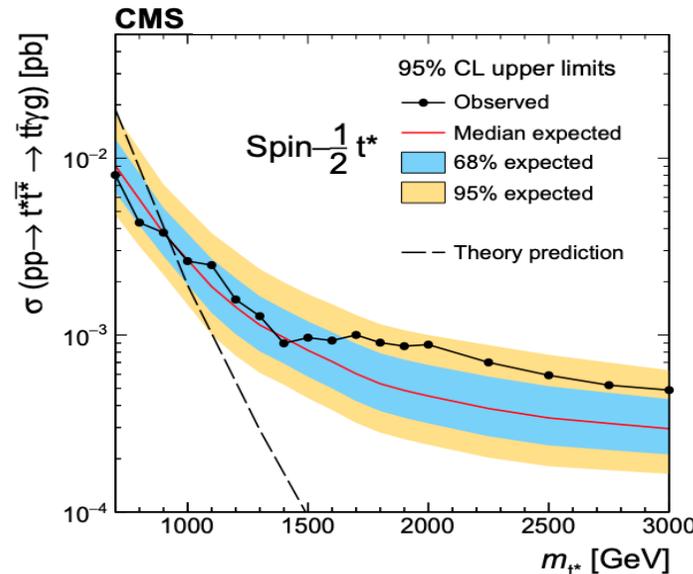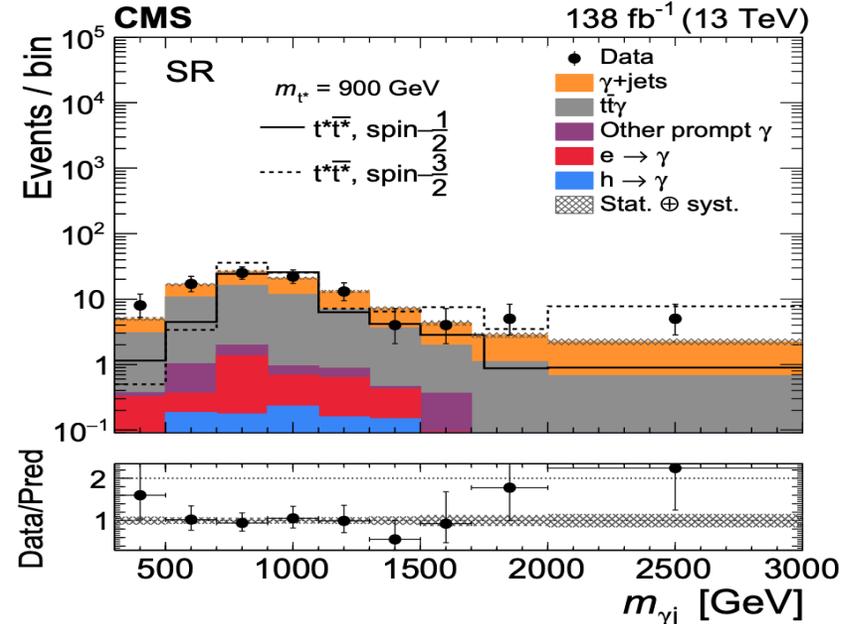— $m_{t*}$ = 3.0 TeV

$m_{γj_1}$ [GeV]

# t*t* → ttgγ → jets + γ

BKG Prediction:

**γ+jets** ~45%, data-driven:
- measure top mistag rate $r(p_T, m_{SD})$,
- build transfer factor TF = $(1-P)/P$,
- apply TF to predict yields in SR,
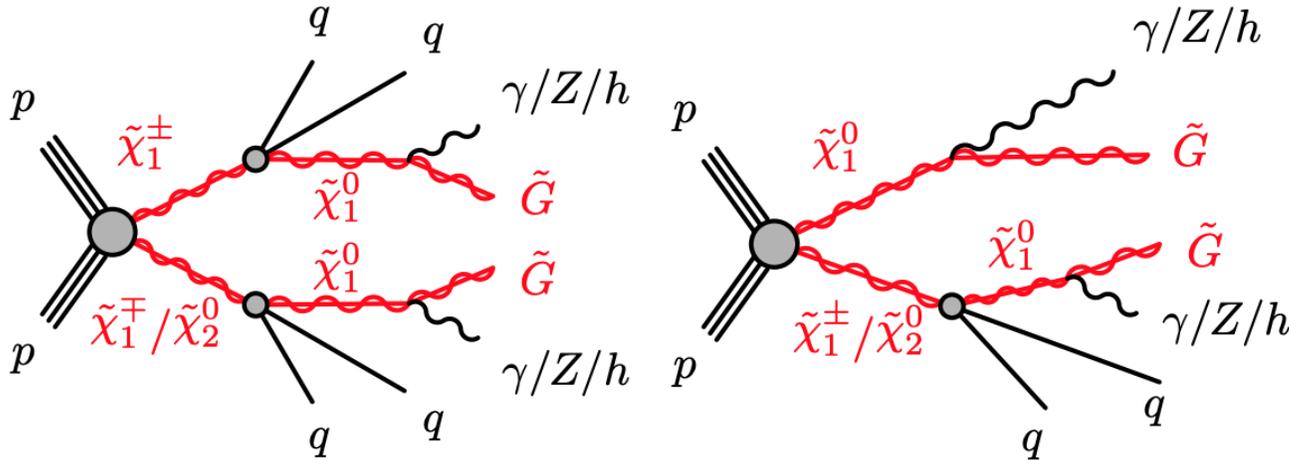
**$t\bar{t}\gamma$**: ~50%, use MC, validated in data.

- Fakes: ~5% estimated via ABCD fake-rate.

- Fit $m_{j\gamma}$ spectra in SR & VR1 to extract signal.

→ ~2.5σ local excess for $m_{t*} >$~2 TeV.

→ Competitive limits to ttgg:

| Channel | Observed [GeV] | | expected [GeV] | |
|---|---|---|---|---|
| | spin-1/2 | spin-3/2 | spin-1/2 | spin-3/2 |
| $pp \to t^*\bar{t}^* \to t\bar{t}\gamma g$ | 930 | 1330 | 930 | 1390 |
| $pp \to t^*\bar{t}^* \to t\bar{t}gg$ | 1050 | 1700 | 990 | 1690 |

# $\tilde{\chi}\,\tilde{\chi} \to \ldots \to \gamma + \widetilde{G}\,\widetilde{G} + \text{jets} + \ldots$



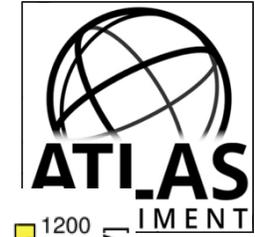- EWK-inos, with γ, jets & $E_T^{miss}$
- General Gauge Mediation (GGM) SUSY model used, an extension of the Gauge-mediated SUSY braking model. LSP: Gravitino $\widetilde{G}$ ~1 eV; wino decoupled at ~4.5 TeV.

- Phenomenology driven by NLSP ($\tilde{\chi}_1^0$) admixture:

$\tilde{\chi}_1^0$ bino-like : $\tilde{\chi}_1^0 \to \gamma + \widetilde{G}$
$\tilde{\chi}_1^0$ higgsino-like : $\tilde{\chi}_1^0 \to h/Z + \widetilde{G}$

- $B(\gamma\widetilde{G}) + B(Z\widetilde{G}) + B(h\widetilde{G}) = 1$ → Scan all BRs.

- Final states covered: γh, γZ, γγ + jets + $E_T^{miss}$

- Selection:
  ≥1γ, ≥1j, $E_T^{miss}$>200 GeV, $E_T^{miss}/m_{eff}$ >0.5, Δφ> ...

- 3 SRs formed over $E_T^{miss}$, $E_T^{miss}$-signif.= $\dfrac{p_T^{miss}}{\sqrt{\sigma_L^2\,(1-\rho_{LT}^2)}}$
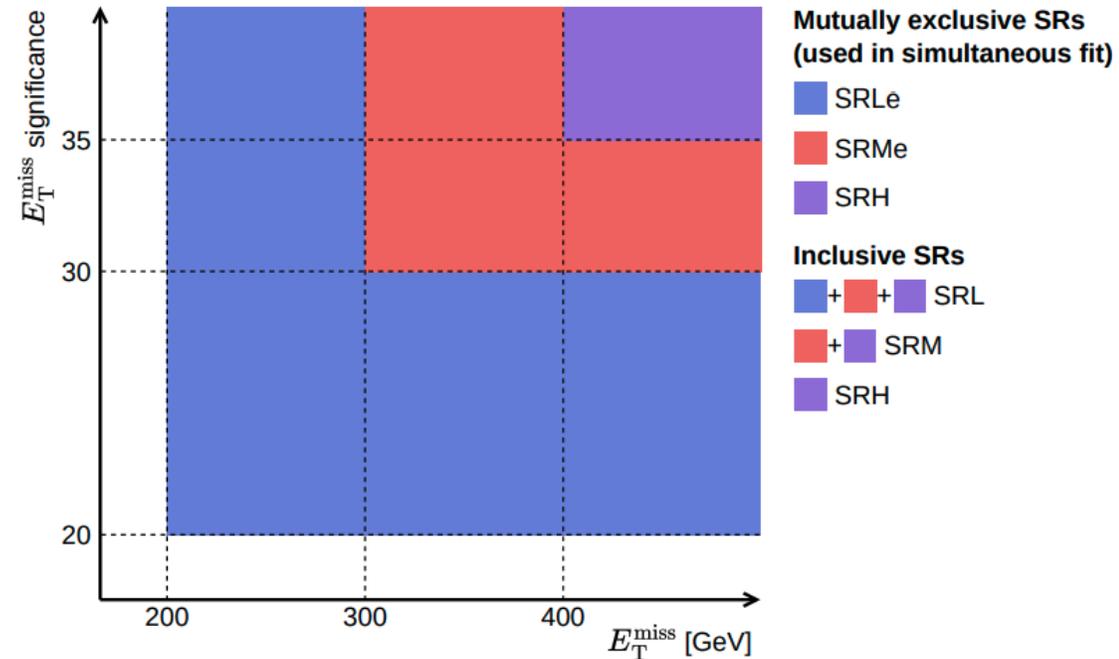
# $\tilde{\chi}\,\tilde{\chi} \rightarrow ... \rightarrow \gamma + \tilde{G}\,\tilde{G} + $ jets $+ ...$

- BKG processes:
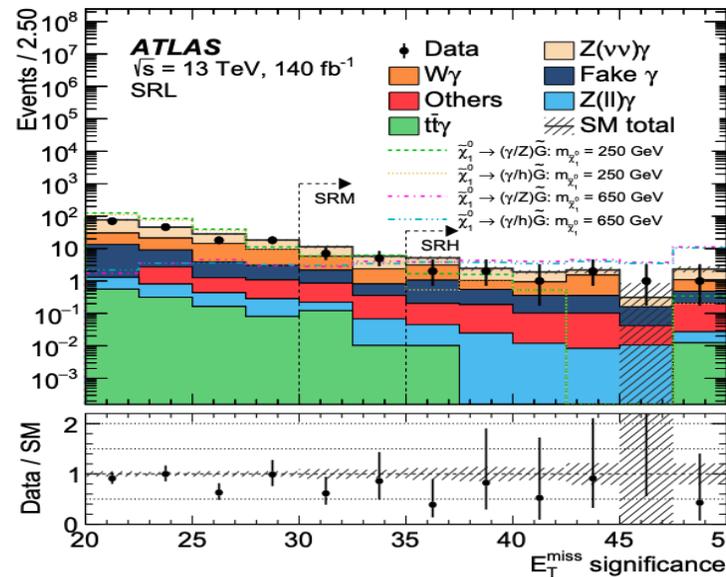
  ▫ $Z(\nu\nu)\gamma$ : 54%

  ▫ $W\gamma$ : 26%
    - shapes from MC,
    - rates from data in CRs with l.

  ▫ Fake $\gamma$: 13%, ABCD estimate.
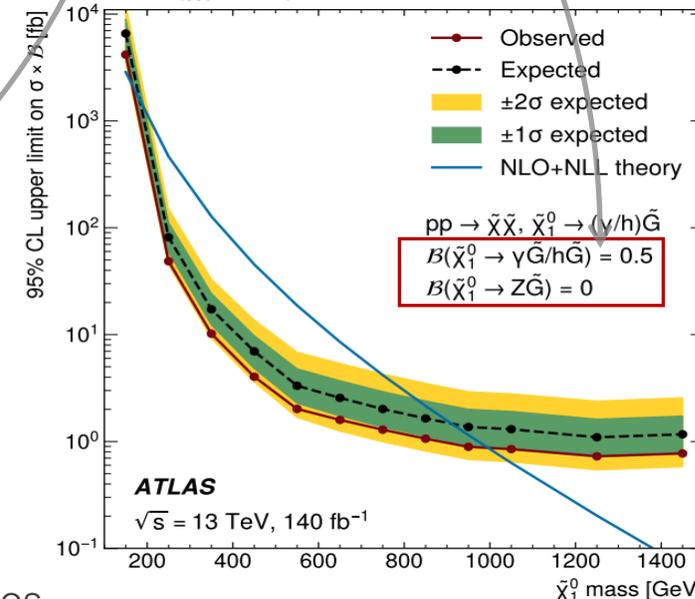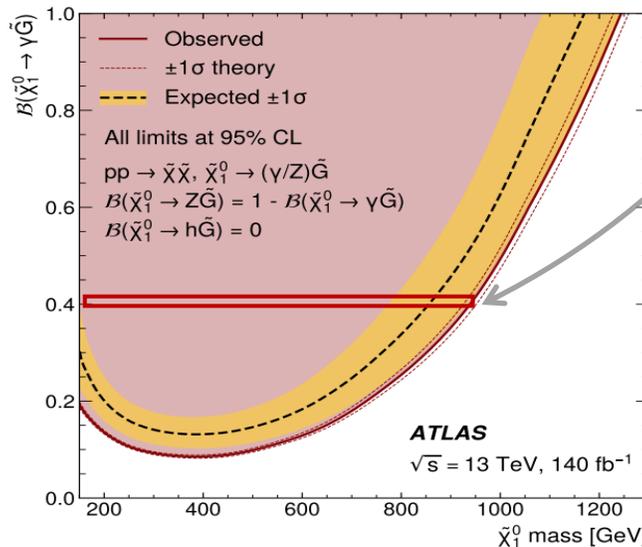
- 3 SRs combined in cut & count setup for the fit.
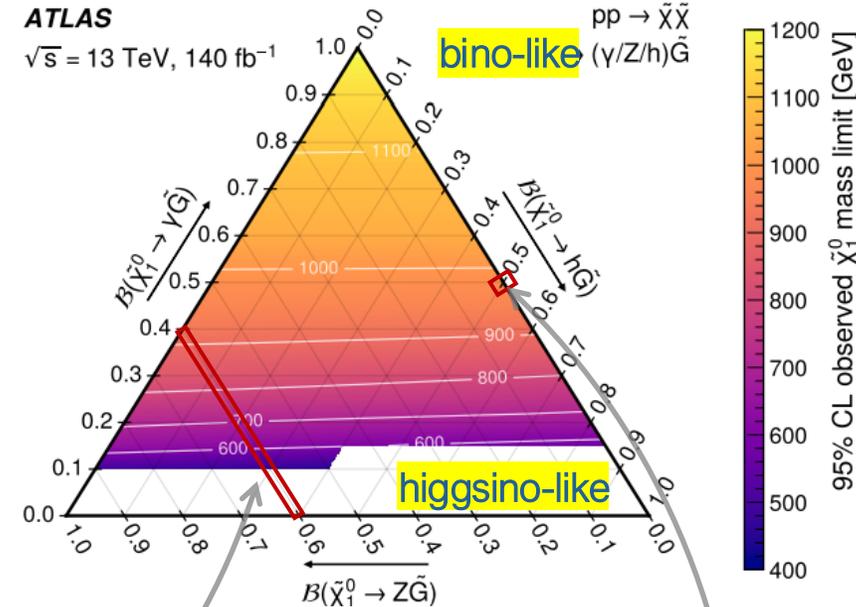
- Limits on: $B(\gamma\tilde{G})$ vs $f(\gamma\tilde{G},Z\tilde{G})$, observed stronger by ~1σ →

- Novelty: Scan of BRs triangle varying 2 of them.



bino-like

higgsino-like
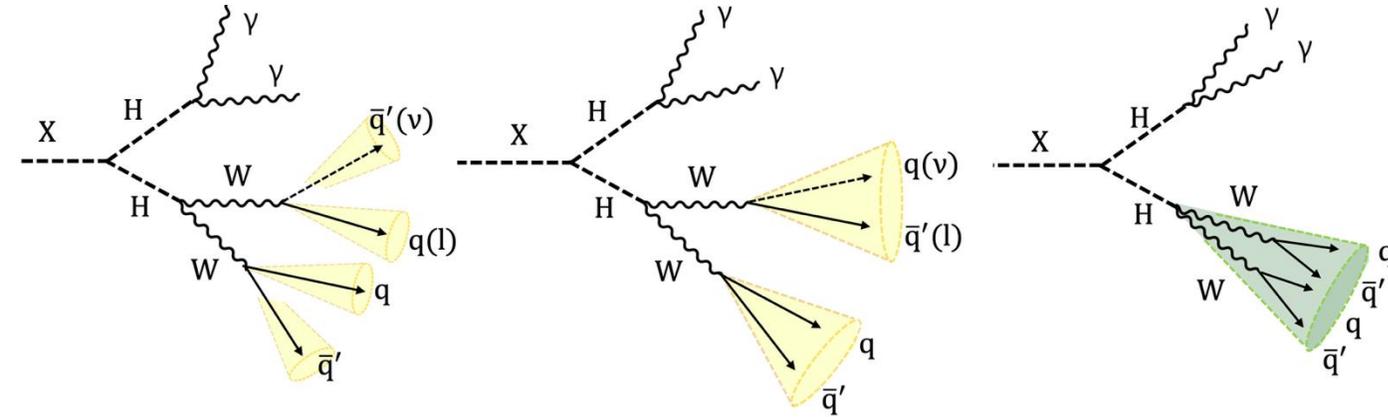
# X → HH → WW γγ → jets + γγ (+1l)
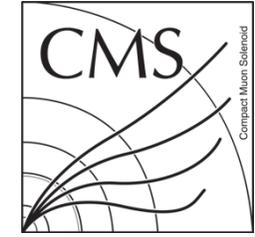


- Selection:
  ≥ 2γ, ≥ 1j, 100 < $m_{\gamma\gamma}$ < 180 GeV, 0l or 1l...

- Classify events into 5 topologies based on:
  AK8 jets, AK4 jets, 0l, 1l, WW-tagged, W-tagged

- Feed 2+3 classes in 2 Parameterized NN (PNNs) trained separately for resolved & boosted, with $m_X$ as the explicit parameter:

- Interpretation:
  X: spin-0 radion, or spin-2 graviton.
- Model independent probe covering $m_X$: 0.25—3 TeV.

- 2 channels: 0l & 1l,
- 2 topologies: boosted & resolved.

- BR(HH→WWγγ) ~ 0.1%

- 1st ever WWγγ full-hadronic search.
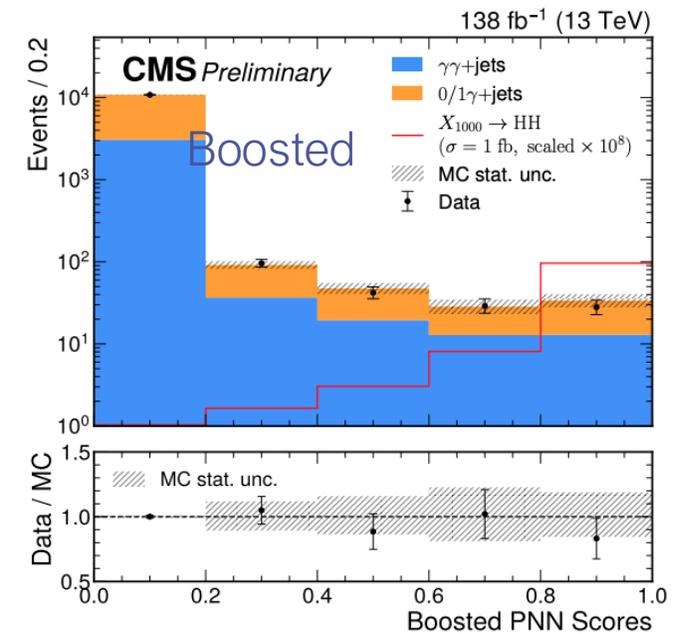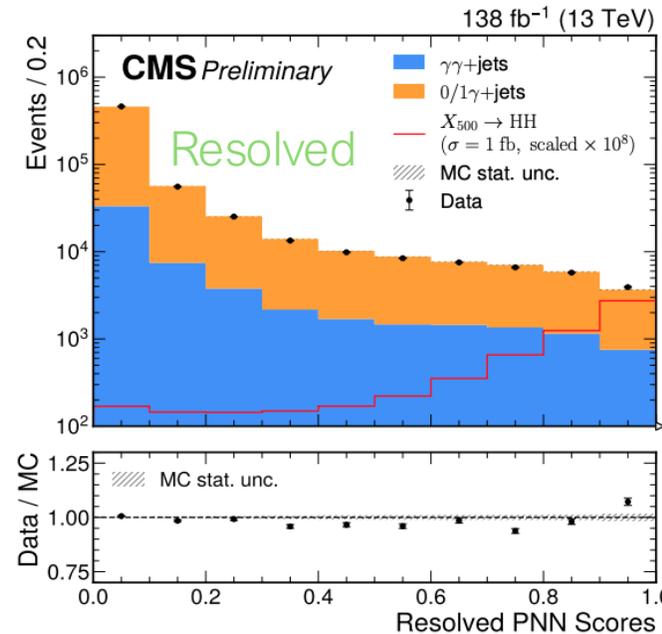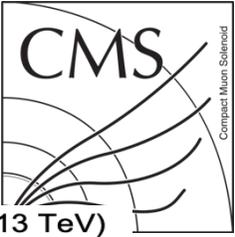
# X → HH → WW γγ → jets + γγ (+1l)
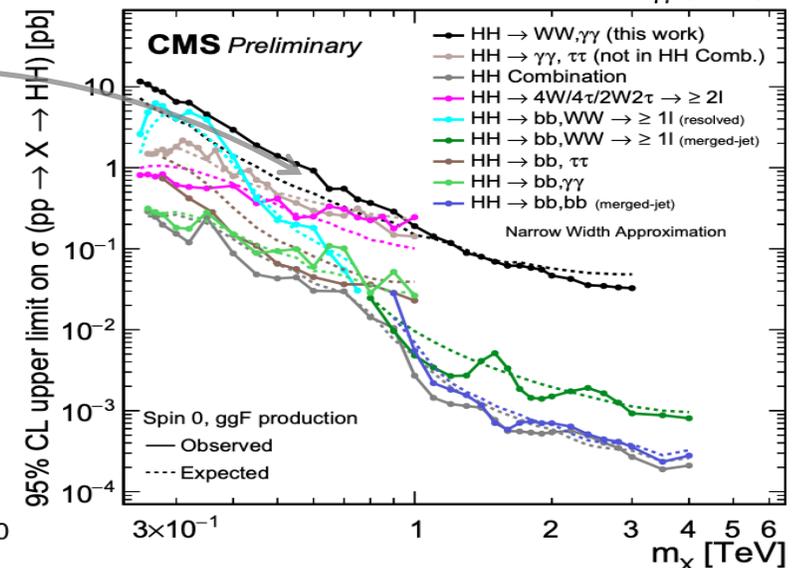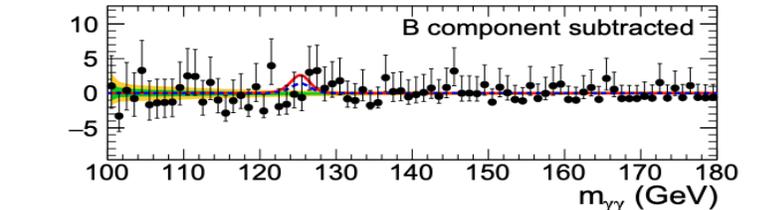
- For a given $m_X$, we select events based the PNN scores to form → 6 SRs: 4 boosted & 2 resolved.

- Tagging:
  H → 4q/3q with Particle Transformer;
  W → qq with ParticleNet.

- BKG modelled with parametric functions in discrete profiling setup, constrained in the sideband: 100—115 U 135—180 GeV.

- Signal modelled: with a sum of gaussians.

- Extract signal from $m_{\gamma\gamma}$ range: $115 < m_{\gamma\gamma} < 135$ GeV
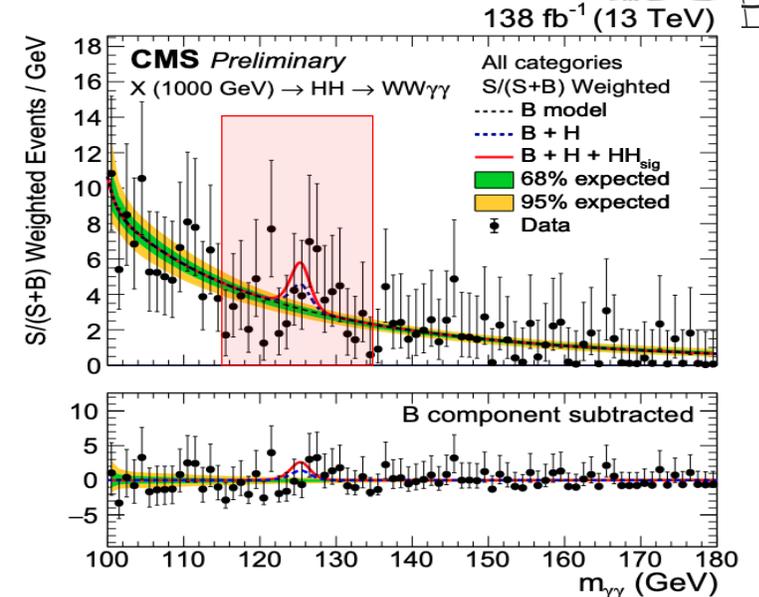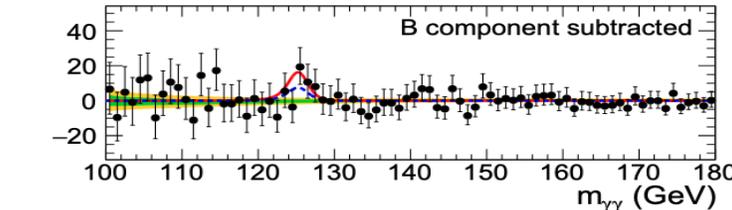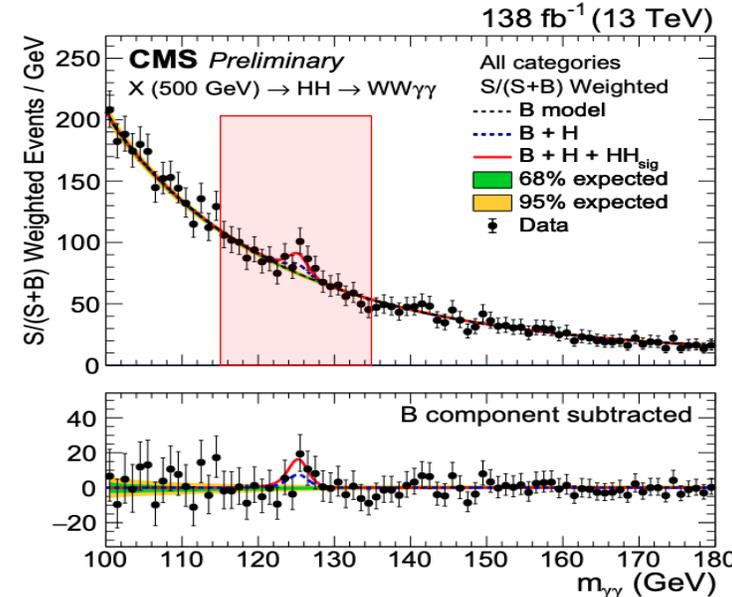
# X → YH → γγ bb
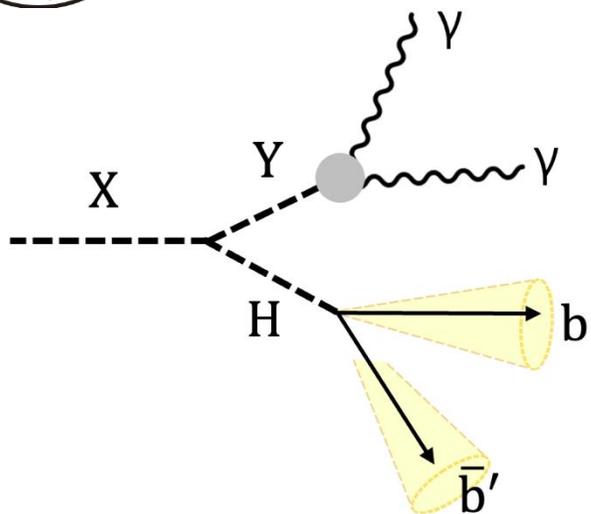
- Single PNN used to discriminate S vs B.

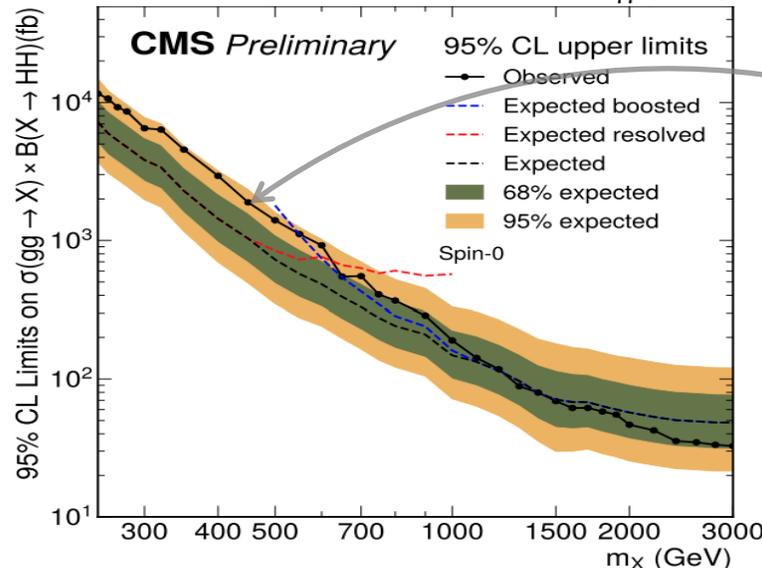- 31+2 param/s input; $m_X$, $m_Y$ as explicit parameters.
  (b-tag-scores, $\Delta R(\gamma,j)$, $\Delta R(\gamma,jj)$, $\Delta R(\gamma\gamma,j)$, $p_T$s....)

- The PNN output is transformed to flat BKG, and
  multiple SRs (8 here) are defined on this score:

Signal masses 2D grid:
- 224 points generated,
- 2000 with interpolations,
- modelled with DSCB function.

- X,Y generic scalars;
  model independent probe.
- Predicted by NMSSM, TRSM.
- Assuming $B_{Y\to\gamma\gamma} = B_{H\to\gamma\gamma} = 0.23\%$.

Selection:
- ≥ 2γ,  $p_T$>18 GeV,  $m_{\gamma\gamma}$ > 65 GeV,
- ≥ 2j AK4,  $p_T$ > 25 GeV,  $\Delta R(j,\gamma)$> 0.4.
- 2 highest DeepJet score as b$\bar{\text{b}}$.



CMS  132 fb$^{-1}$ (13 TeV)

Data
X → Y(γγ)H(bb)
QCD + γ+jets
γγ+jets
TT(+V/γ) + tZq
VV
V+γ
H+HH

$m_X$ = 280 GeV, $m_Y$ = 90 GeV

All masses (N=1699)
Nominal masses (N=224)

# X → YH → γγ bb
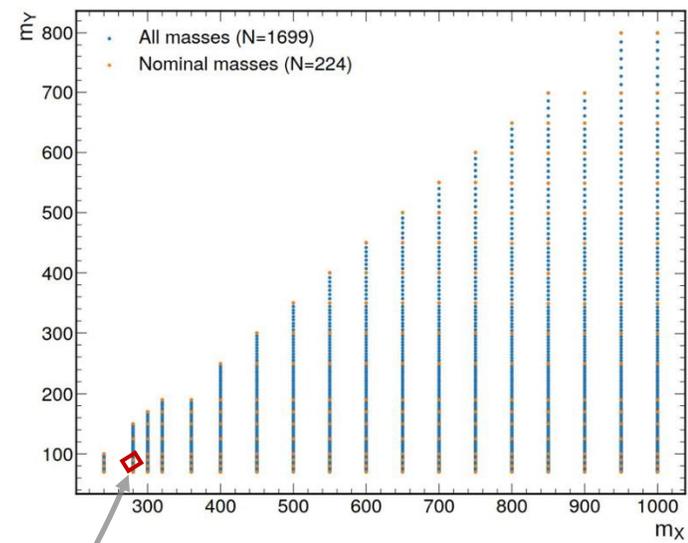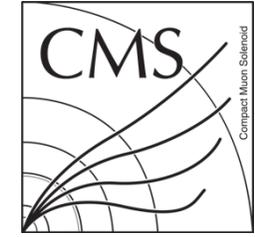
- BKG modeling:
1. Continuum: γγ+jets, fakes (γj, jj):
   analytic functions fit in $m_{\gamma\gamma}$ sidebands with discrete profiling.
2. Resonant:
   H→γγ: DSCB modelling, normalized by MC.
   Z→ee: ABCD method on: e-veto & PNN-score variables.
- Fit $m_{\gamma\gamma}$ range: $m_Y \pm 10$ GeV($m_Y/m_H$):
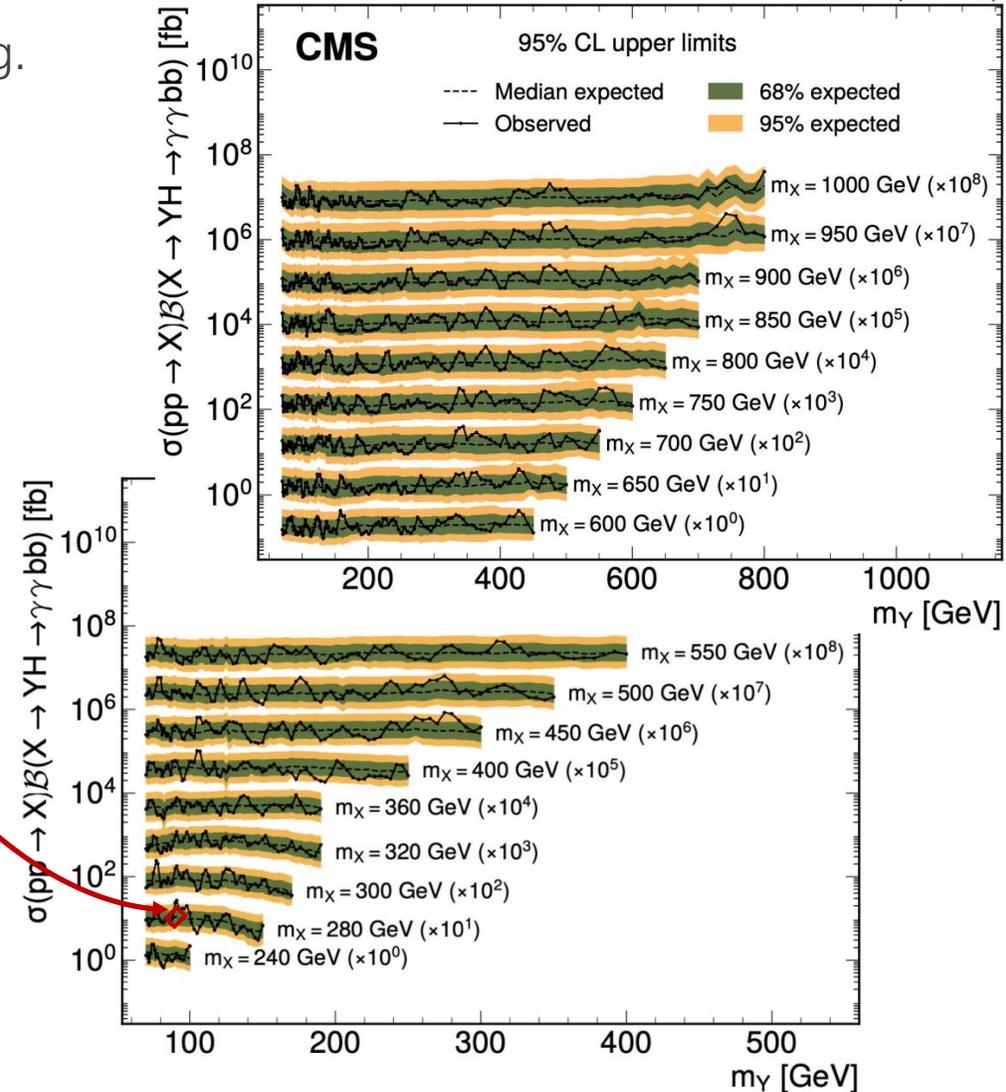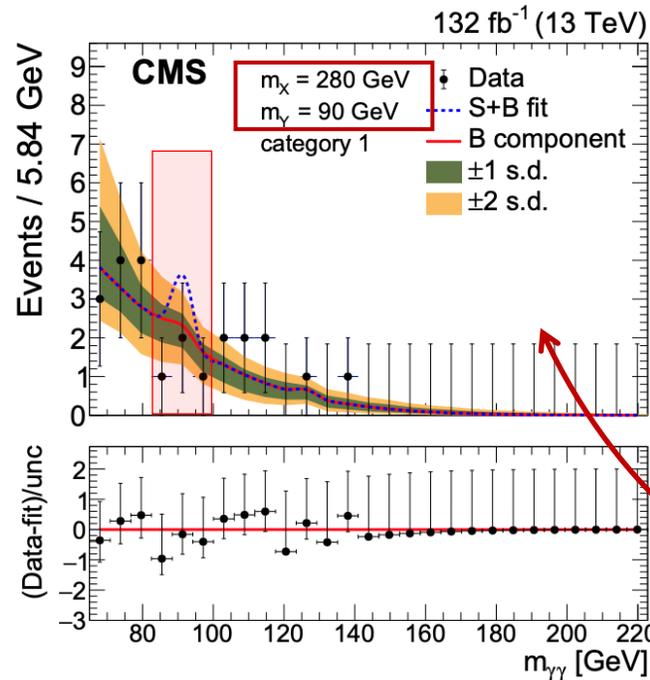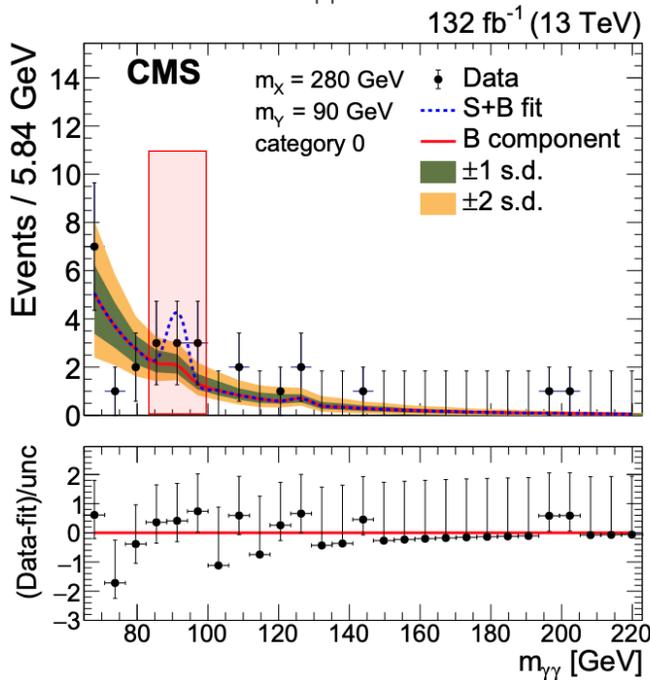


- Excess: $m_X$=300, $m_Y$=77 GeV: 3.33(0.65)σ local(global).

# H → αα → γγ τ$_h$τ$_h$
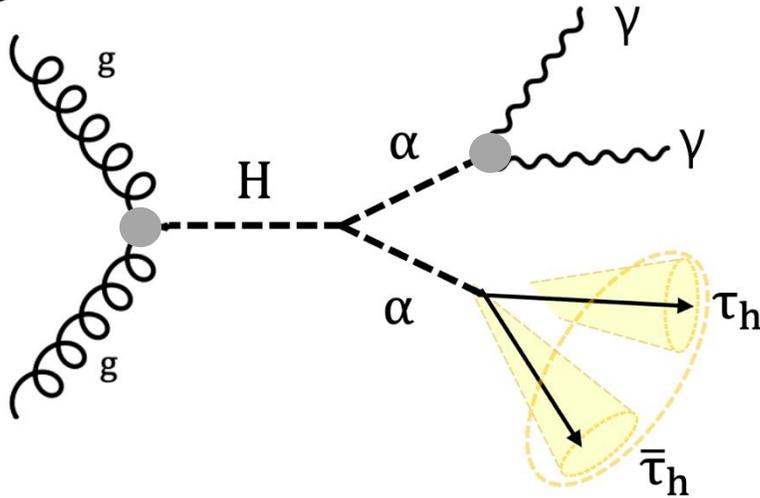
Strategy & Selection:
- γγ → clean trigger & narrow peak to fit.
- ττ → bkg suppression, $p_{T\tau h}$ > 20 GeV.
- 2γ tight-ID; e/μ veto. $p_T(\gamma\gamma)$ > 50 GeV.

2 topologies covered:
1. τ$_h$τ$_h$ resolved: 2 jets, R=0.4 → Recurrent-NN-based τ-ID.
2. τ$_h$τ$_h$ merged: 1 jet, R=1.0 → tagging with di-τ BDT for low-$m_a$.

- Motivated by: 2HDM+S, dark matter, 1$^{st}$-order EWPT, neutral naturalness.

- H: 125-GeV boson in ggF (~87%)

- α: spin-0, psedoscalar, photophilic: for $m_\alpha$: ~10-60 GeV:
  → B(α→ττ) dominant + large B(τ$_h$τ$_h$)~42%.
  → B(α→γγ) subdominant due to loop.

- 1$^{st}$ result in this γγ τ$_h$τ$_h$ final state.



ATLAS Simulation
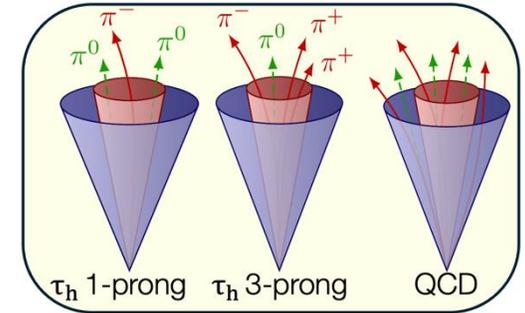$\sqrt{s}$ = 13 TeV
Di-τ tagging efficiency in signal

○ Boosted
□ Resolved
△ Boosted or resolved

Preselections:
Photon selections
Boosted: $p_{T,vis,truth}^{\tau\tau}$ > 50 GeV
Resolved: $p_{T,vis}^\tau$ > 20 GeV
Truth-matched

$m_a$ [GeV]

ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb$^{-1}$
Full selection, boosted di-τ only

Data
$m_a$ = 10 GeV
$m_a$ = 30 GeV
Stat. unc.

→ SR

Di-τ BDT score
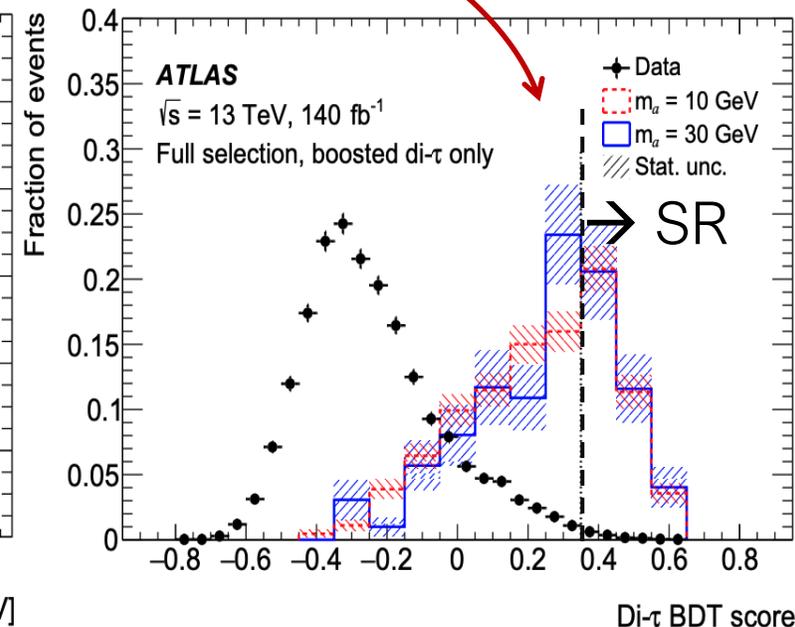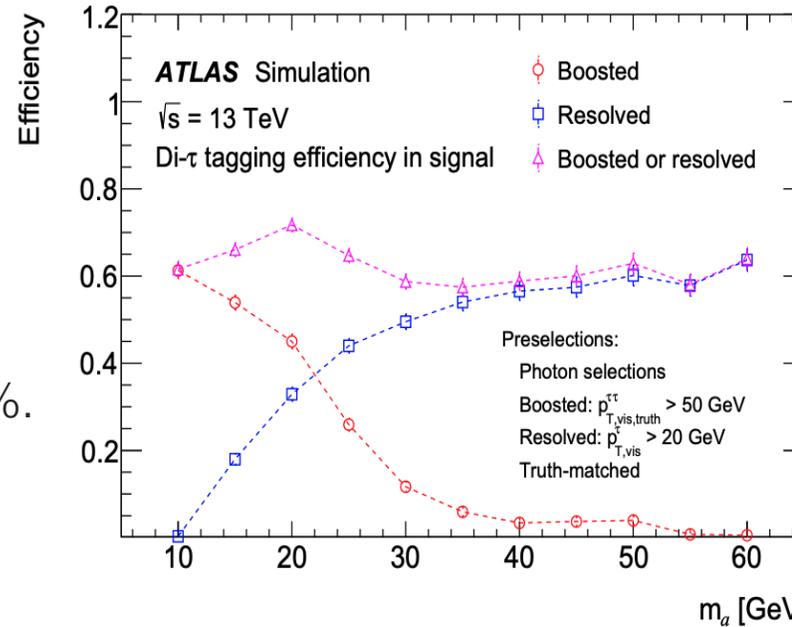
# H → αα → γγ τ_h τ_h

- Signal modeling → DSCB

- BKG components study vs $m_{\gamma\gamma}$
  → γγ (prompt) ~60%,
  → γj, jj (fakes), data-driven.

- Total BKG modeling combining γγ+γj+jj weighted by relative fractions.

- Parametrized by analytical function as:
  sigmoid + exponential tail.
- The plateau of the sigmoid dominates, i.e. flat BKG.

- Validated inverting di-τ selection.

- Fit the $m_{\gamma\gamma}$ in range 10--60 GeV.
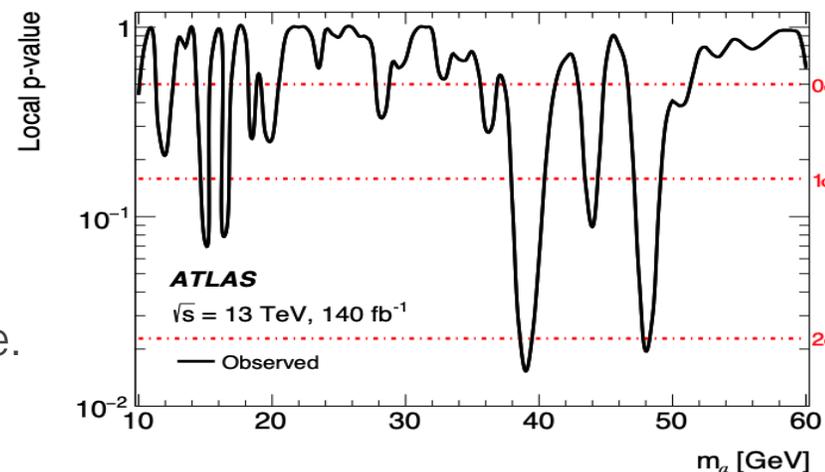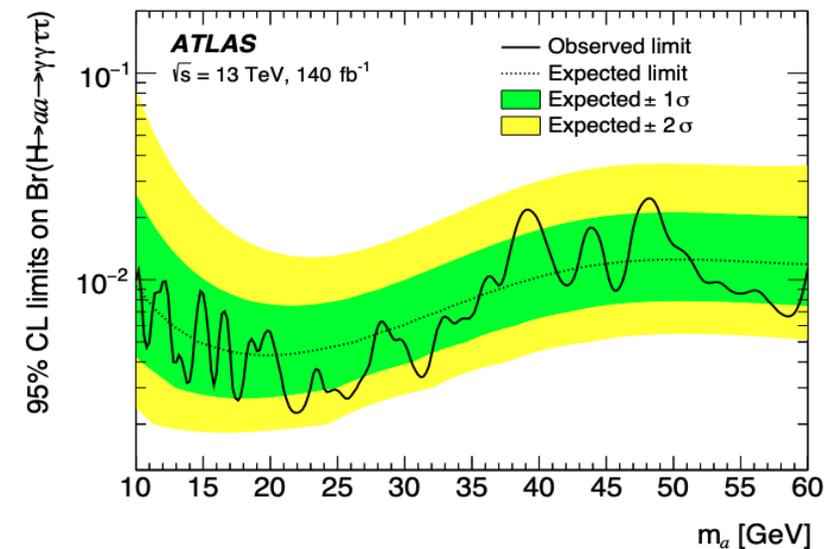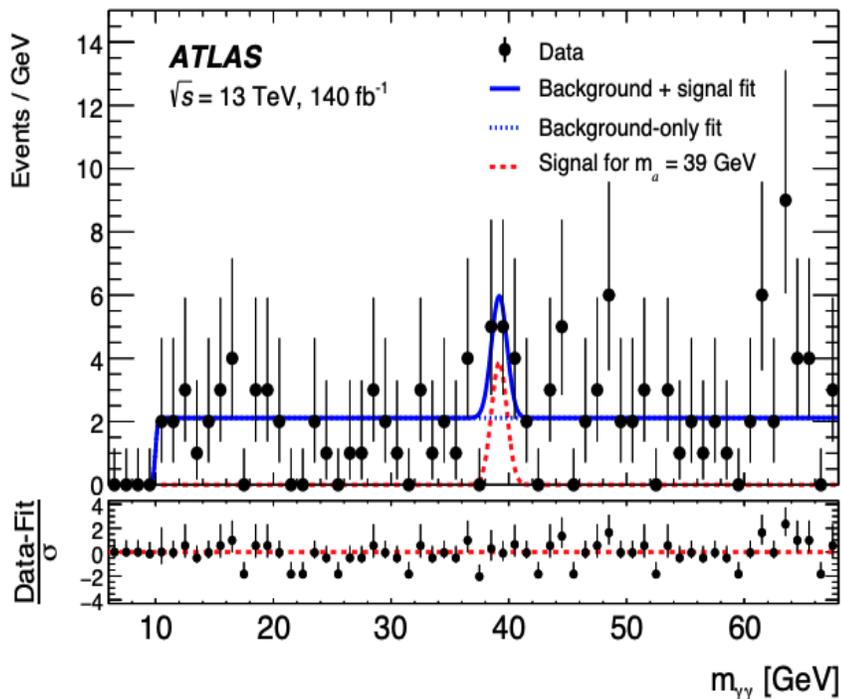
- Upper limits on B(H→αα→γγττ).

- 1st result in this γγ τ_h τ_h final state.

- ~2.2σ local excess at 39 GeV.

# H → αα → γγ (γγ)
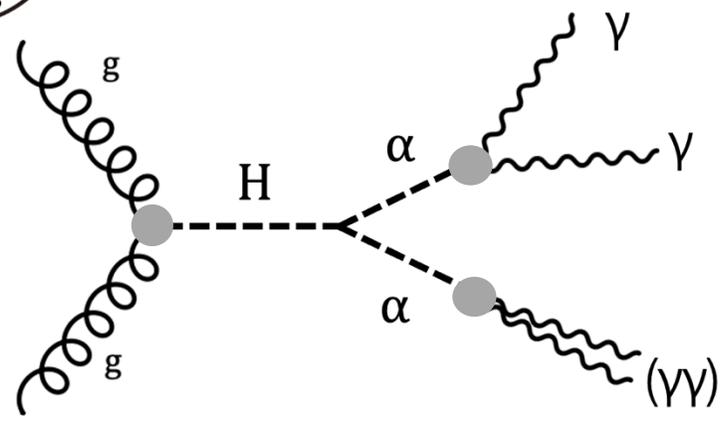
**Strategy & Selection:**

- 3γ,   $|\eta_\gamma| < 1.44$,   $p_{T\gamma} > 30, 18, 10$ GeV.
- Diphoton triggers,  $m_{\gamma\gamma} > 55$ GeV.

- Key innovation:
  GNN-based mass regression for merged γγ.
  NN trained directly on 128×128 ECAL
  crystal energy, calibration with Z→ee.

- Exotic decay of the 125 GeV H.
- Motivated by 2HDM+S & ALPs
  (α couples to BSM uncolored
  charged particles).

- $m_\alpha$: 1—15 GeV:
  one merged α→(γγ), 3γ final state

- Analysis (1st of its kind) designed
  to cover the gap between:
  fully resolved: 15–62 GeV &
  fully merged: 0.1–1.2 GeV.

# H → αα → γγ (γγ)
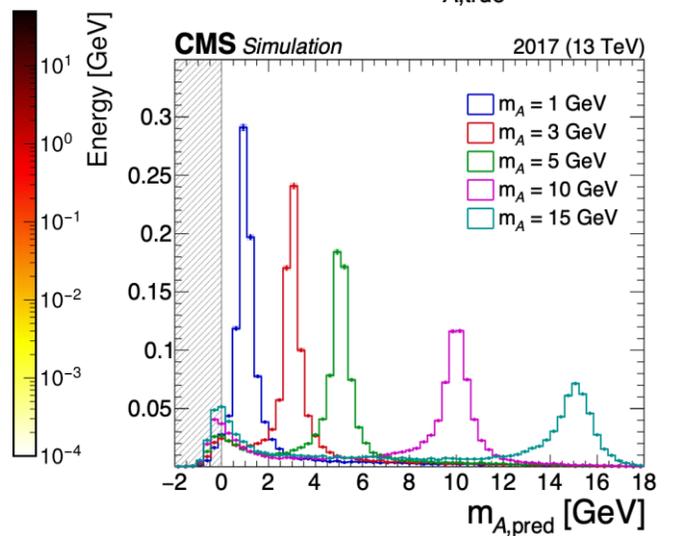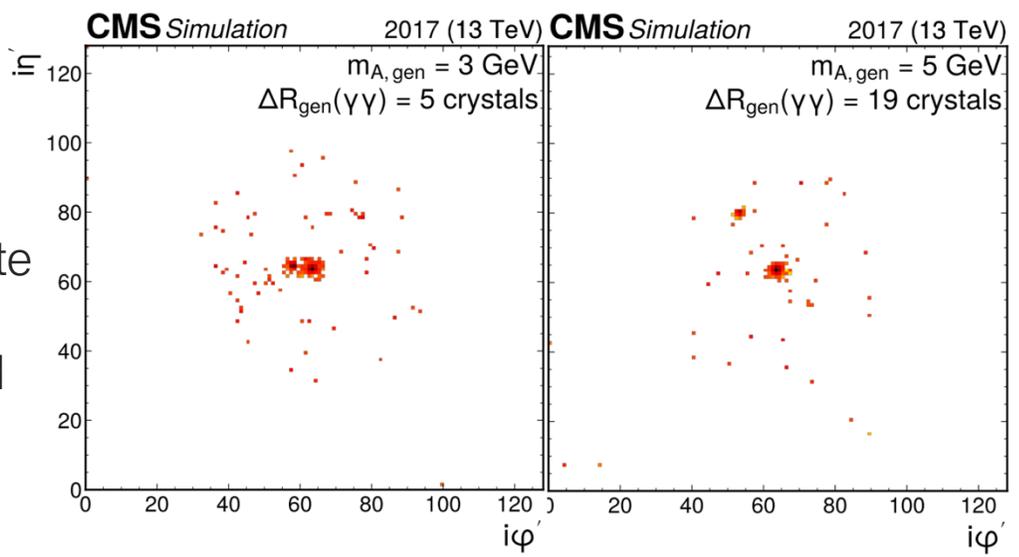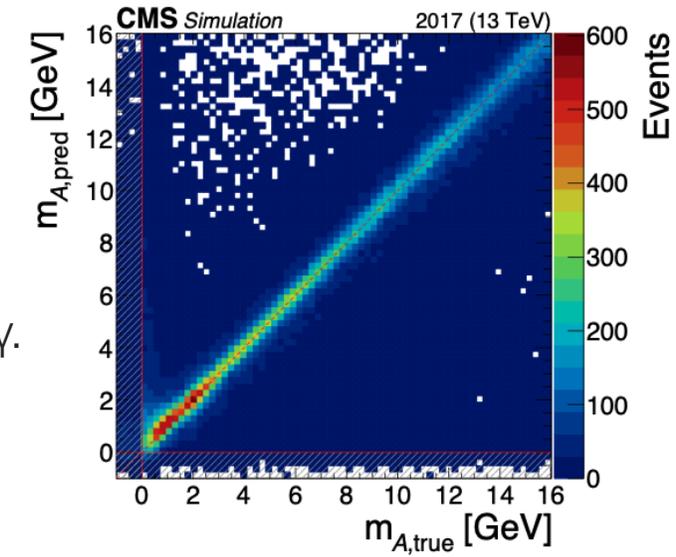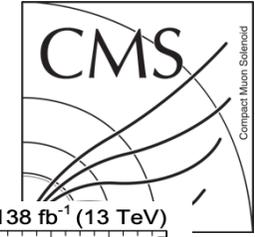
- SR: $|\Delta m_\alpha| < 2$ GeV & $m_{\gamma\gamma\gamma}$: 100—135 GeV

- 2D Fit to extract signal: $m_{\alpha 1}$, $m_{\alpha 2}$.

- Signal modeling with 2D templates:
- BKG estimate from data in sidebands:
  - → $m_{\gamma\gamma\gamma}$ : 90—100 U 135—180 GeV
  - → $|\Delta m_\alpha| > 2$ GeV

Merged (γγ)

Resolved γγ

Signal
SR
SB
Merged

BKG
SR
SB

→ Full 0.1–60 GeV coverage →

95% CL upper limits
— Observed
···· 95% expected

**CMS semi−merged** (this work)

**CMS fully−merged** Phys. Rev. Lett. 131 (2023) 101801

**CMS fully−resolved** JHEP 07 (2023) 148

**ATLAS** Eur. Phys. J. C 84 (2024) 742
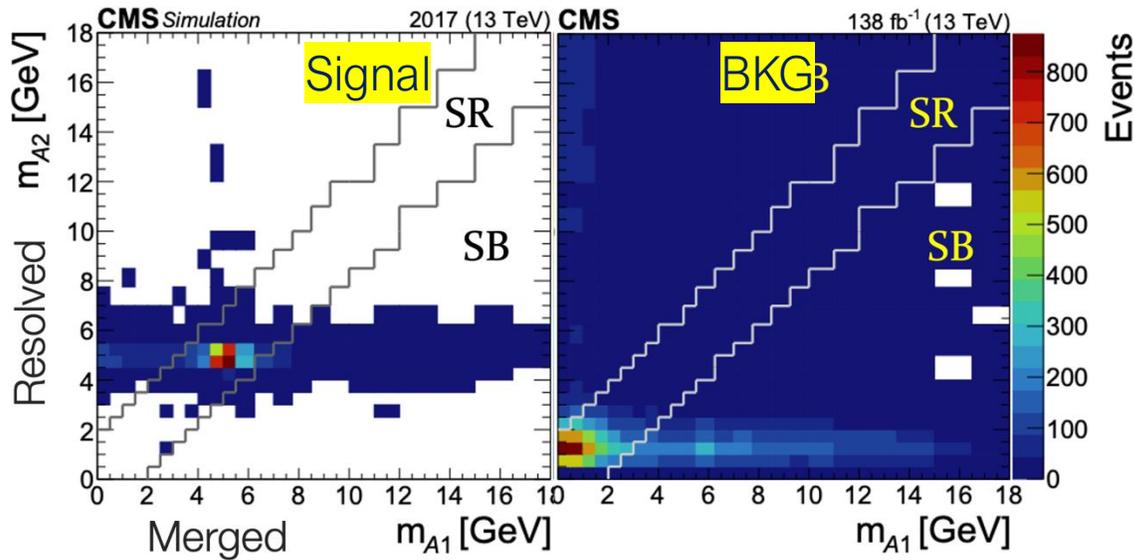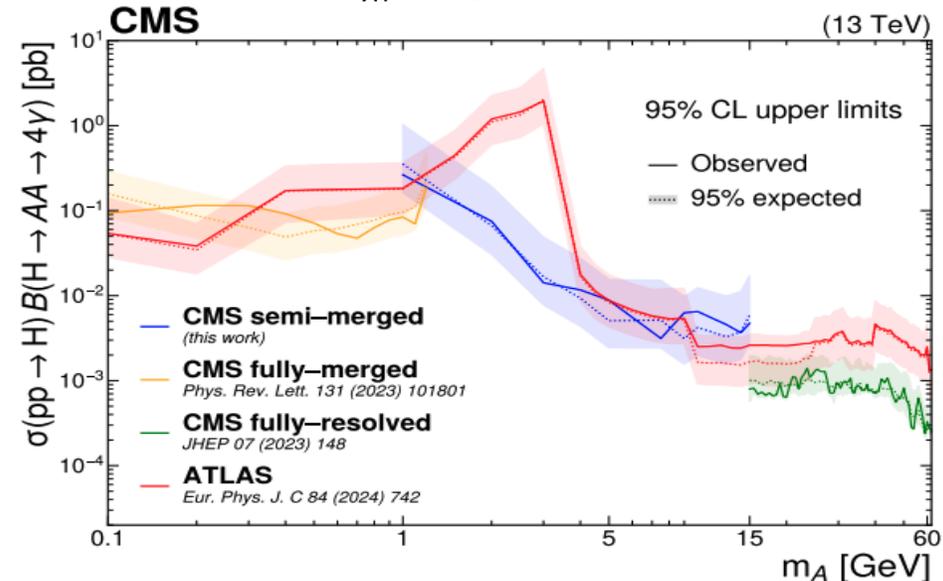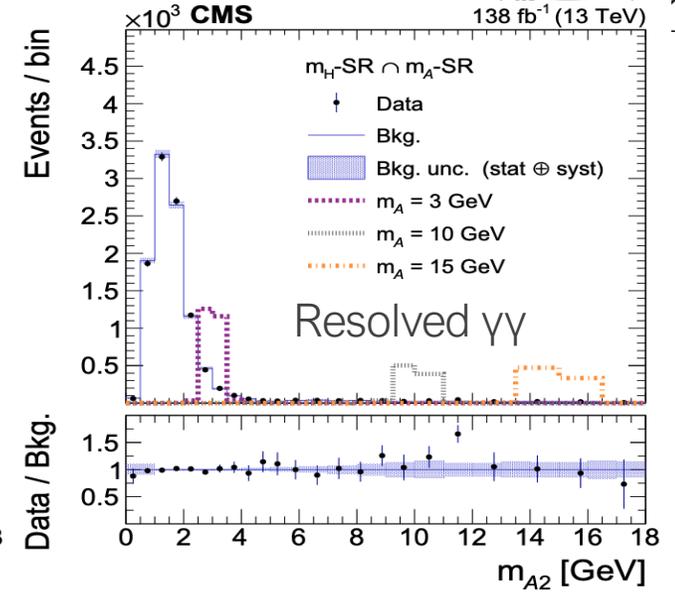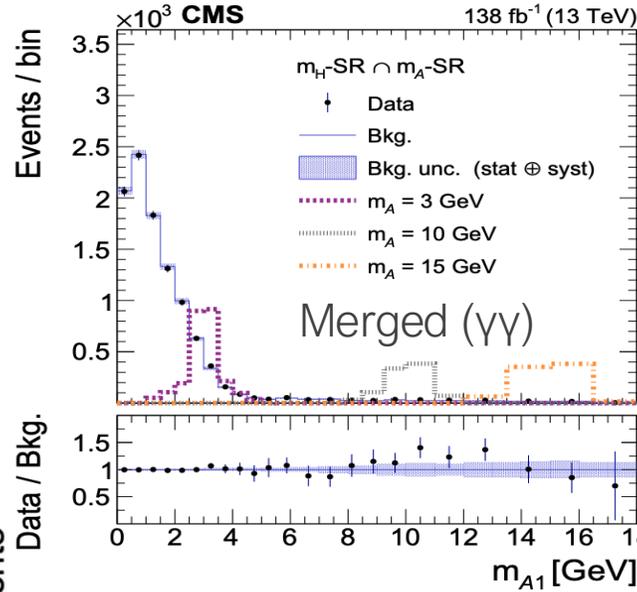
# Prospects & Summary

- Run-3 CMS single-γ trigger (2024–2025) CMS-DP-25-086.
- $E_T$ threshold: 110→40 GeV,
- barrel only: $|\eta_\gamma| < 1.48$, improved HLT γ-ID, better fake rejection → Rate ≤ 500 Hz.
- ~30% acceptance for gg→H→γX.
- Access to soft & central single γ final states. More here.



**CMS** *Preliminary*          13.6 TeV

$Z \rightarrow ee$ candidates

- 2024 part 1 (15 fb$^{-1}$)
- 2024 part 2 (94 fb$^{-1}$)
- 2025 (110 fb$^{-1}$)

Trigger efficiency (HLT+L1T) vs Offline $p_T$(e) [GeV]
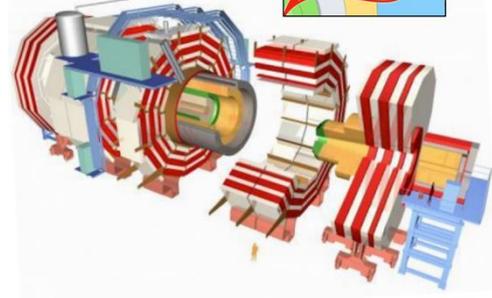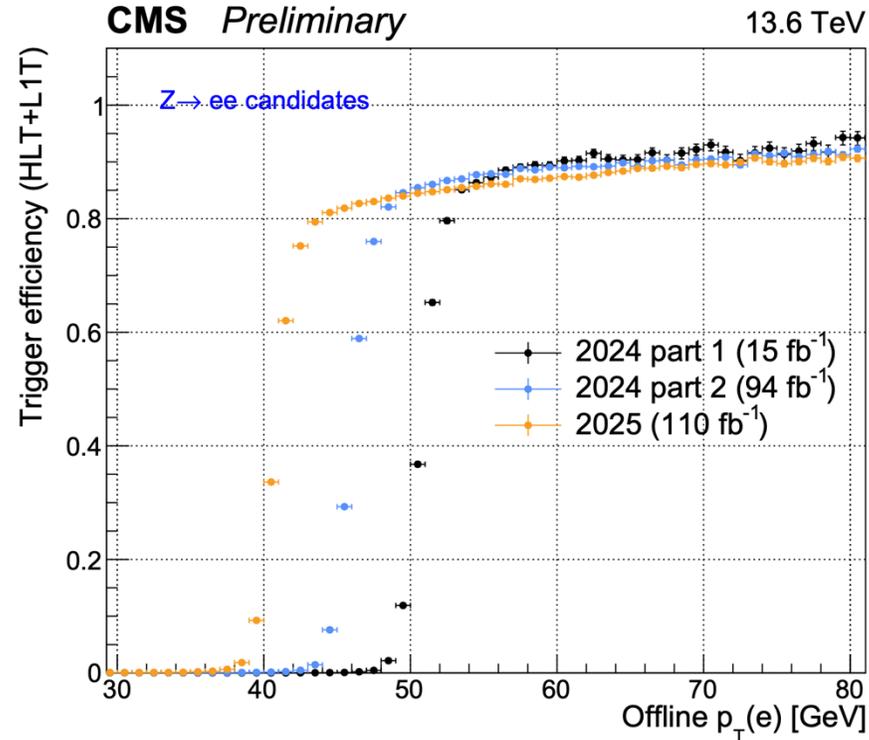
- 7 new Run-2 results presented.
- Comprehensive BSM models coverage (SUSY, ED, 2HDM, ..., ).
- Photons are powerful handles for probing BSM Physics at LHC.
- No significant deviation from SM expectations observed.
- Stay tunned for Run-3 processing and beyond!

- Higgs and Diboson Searches
- Exotics Physics Searches

- B2G Preliminary  Publications
- Exotica Preliminary  Publications
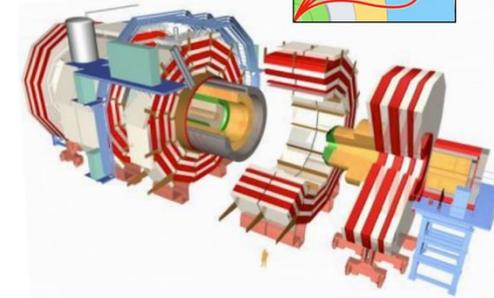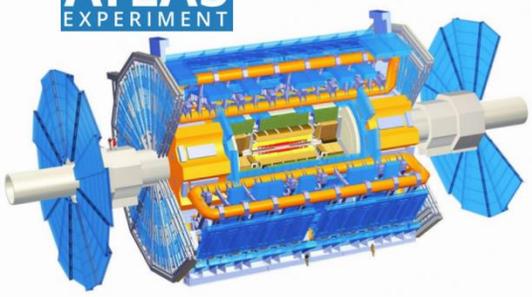
# Extra material

Moriond 26: Search for BSM with γ - Antonis Agapitos

# t*t* → ttgγ → jets + γ
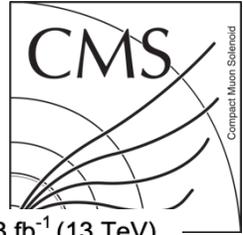
BKG Prediction:

**γ+jets** ~45%, data-driven:
- Measure top mistag rate $r(p_T, m_{SD})$
  (in a signal-free loose-γ sideband with γ failing medium ID).
- Build transfer factor: $(1-P)/P$ (per-event, where $P = \prod(1-r_i)$).
- Predict SR yield by applying TF to
  0-top-tagged data (AR) with medium-γ
- Validate in VRs with 1 AK8 jet.

**t$\bar{t}$γ**: ~50%, use MC, validated in data.

- Fakes: ~5% estimated via ABCD fake-rate.

- Fit $m_{jγ}$ spectra in SR & VR1 to extract signal.

→ ~2.5σ local excess for $m_{t^*} >~2$ TeV
→ Worse limits than ttgg but competitive:

| Channel | Observed [GeV] | | expected [GeV] | |
|---|---|---|---|---|
| | spin-1/2 | spin-3/2 | spin-1/2 | spin-3/2 |
| pp → t*t* → t$\bar{t}$γg | 930 | 1330 | 930 | 1390 |
| pp → t*$\bar{t}$* → t$\bar{t}$gg | 1050 | 1700 | 990 | 1690 |

# $\tilde{\chi}\,\tilde{\chi} \rightarrow ... \rightarrow \gamma + \tilde{G}\,\tilde{G} + \text{jets} + ...$



- EWK-inos, with γ, jets & $E_T^{miss}$
- General Gauge Mediation (GGM) model used, an extension of the Gauge-mediated SUSY braking model.
  - strongly & weakly interacting sparticles are decoupled,
  - binos & higgsinos mix to form neutralinos $\tilde{\chi}^0$ ,
  - wino decoupled with mass ~4.5 TeV along with q̃ & g̃.
- LSP: Gravitino $\tilde{G}$, ~1 eV
- Pheno is driven by NLSP ($\tilde{\chi}_1^0$) admixture:

$\tilde{\chi}_1^0$ bino-like       : $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$
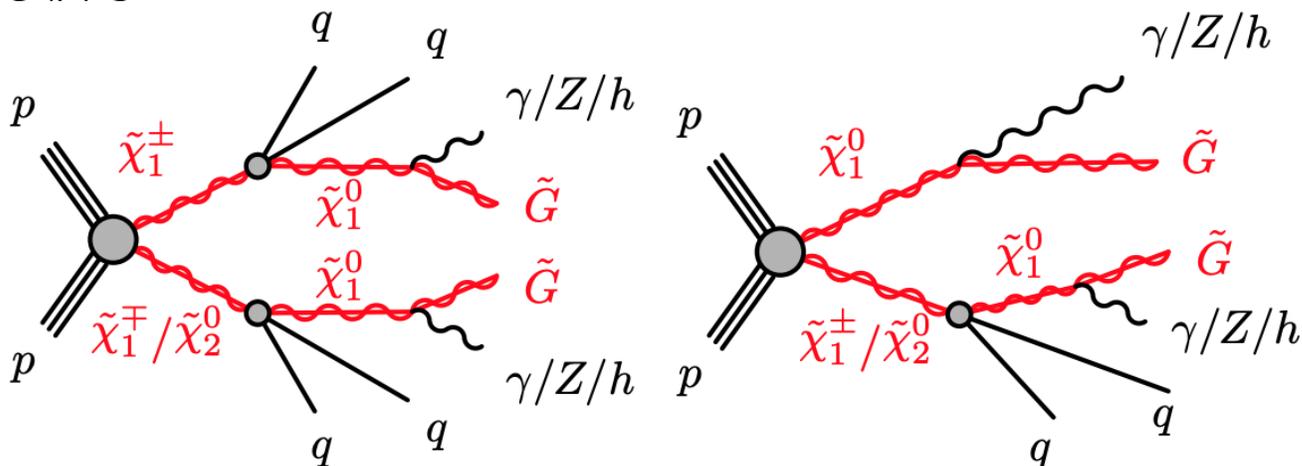$\tilde{\chi}_1^0$ higgsino-like : $\tilde{\chi}_1^0 \rightarrow h/Z + \tilde{G}$

- $B(\gamma\tilde{G}) + B(Z\tilde{G}) + B(h\tilde{G}) = 1$ → Scan all BRs
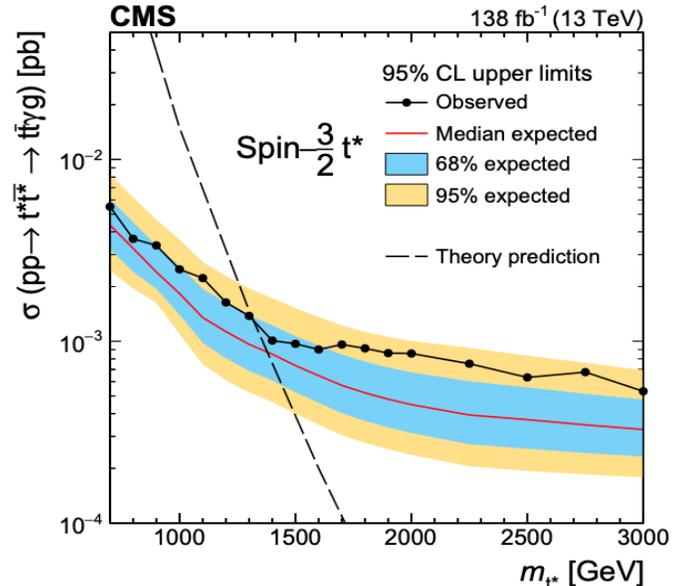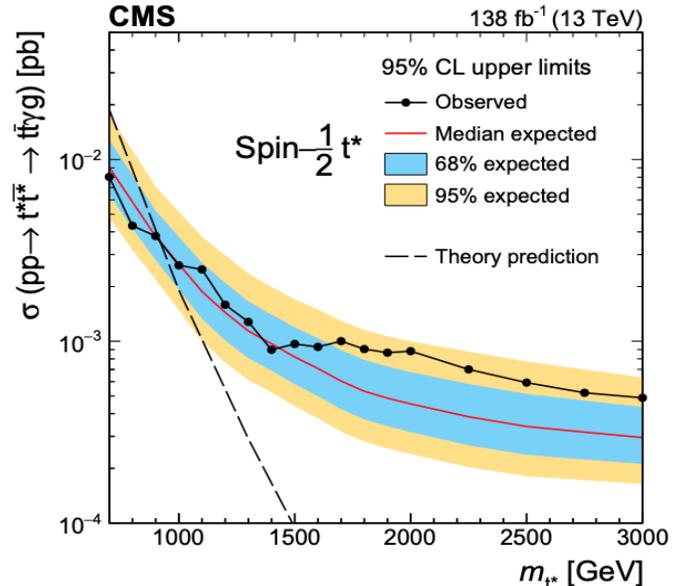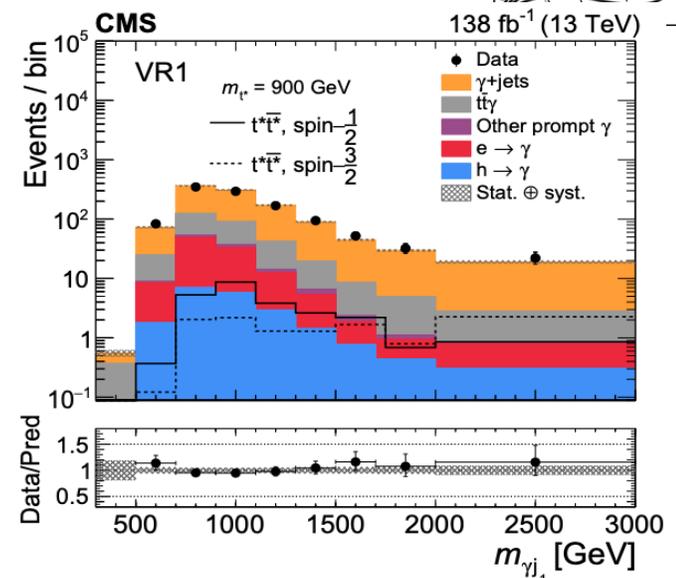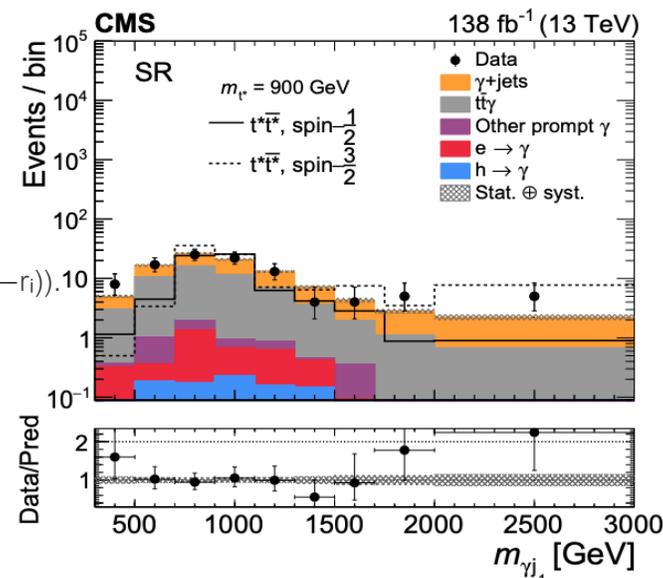
- Final states covered: hγ, Zγ, γγ + jets + MET

| Signal regions | SRL | SRM | SRH | SRLe | SRMe |
|---|---|---|---|---|---|
| $N_{photons}$ | | | | > 0 | |
| $p_T^{leading\,\gamma}$ [GeV ] | | | | > 145 | |
| $N_{jet}$ | | | | > 0 | |
| $\Delta\phi(jet, E_T^{miss})$ | | | | > 0.4 | |
| $\Delta\phi(\gamma, E_T^{miss})$ | | | | > 0.4 | |
| $E_T^{miss}/m_{eff}$ | | | | > 0.5 | |
| $m_{\gamma\gamma}$ [GeV ] | | | | $\notin$ [120, 130] | |
| $E_T^{miss}$ [GeV ] | > 200 | > 300 | > 400 | > 200 ($\notin$ SRM) | > 300 ($\notin$ SRH) |
| $E_T^{miss}$ significance | > 20 | > 30 | > 35 | > 20 ($\notin$ SRM) | > 30 ($\notin$ SRH) |

- 3 SRs formed over MET & MET-signif.: $\dfrac{p_T^{miss}}{\sqrt{\sigma_L^2\,(1-\rho_{LT}^2)}}$



Mutually exclusive SRs
(used in simultaneous fit)
- ■ SRLe
- ■ SRMe
- ■ SRH

Inclusive SRs
- ■ + ■ + ■ SRL
- ■ + ■ SRM
- ■ SRH

# X → HH → WW γγ → jets + γγ (+1l)

- Strategy: Classify events into 5 topologies based on: AK8 jets, AK4 jets, 0l, 1l, WW-tagged, W-tagged

| Class | Topology | Jets | Lepton | Tagger | PNN / Cat |
|-------|----------|------|--------|--------|-----------|
| FH H-like boosted | H→WW fully merged | ≥1 AK8 | 0 | ParT$_{HWW}$ (3q+4q) | Boosted / cat 4,5 |
| FH W-like boosted | Each W→qq merged | ≥1 AK8 | 0 | PNet WvsQCD | Boosted / cat 4,5 |
| SL W-like boosted | Had. W merged + lep. W | ≥1 AK8 | = 1 (iso/non-iso) | PNet WvsQCD | Boosted / cat 4,5 |
| FH resolved | 2 W→qq resolved | ≥4 AK4 | 0 | b-tag veto | Resolved / cat 0,1 |
| SL resolved | Had. W→qq + lep. W | ≥1 AK4 | = 1 iso | — | Resolved / cat 2,3 |

- Feed 2+3 classes in 2 Parameterized NN (PNNs) trained separately for resolved & boosted, with $m_X$ as the explicit param. validated in $m_{\gamma\gamma}$ sideband:

- Interpretation X: spin-0 radion or spin-2 graviton (Warped ED); also heavy Higgs (2HDM, NMSSM).
- Model independent probe of $m_X$ : 0.25—3 TeV.

- 2 channels x 2 topologies covered:
  → 0l & 1l, WW → 4q, lvqq, (FH, SL),
  → boosted & resolved.
- BR(HH→WWγγ)~0.1%

- 1st ever WWγγ full-hadronic search, and 1st time covering merged 4q/3q & 2 W→ qq jets in X → YH search.