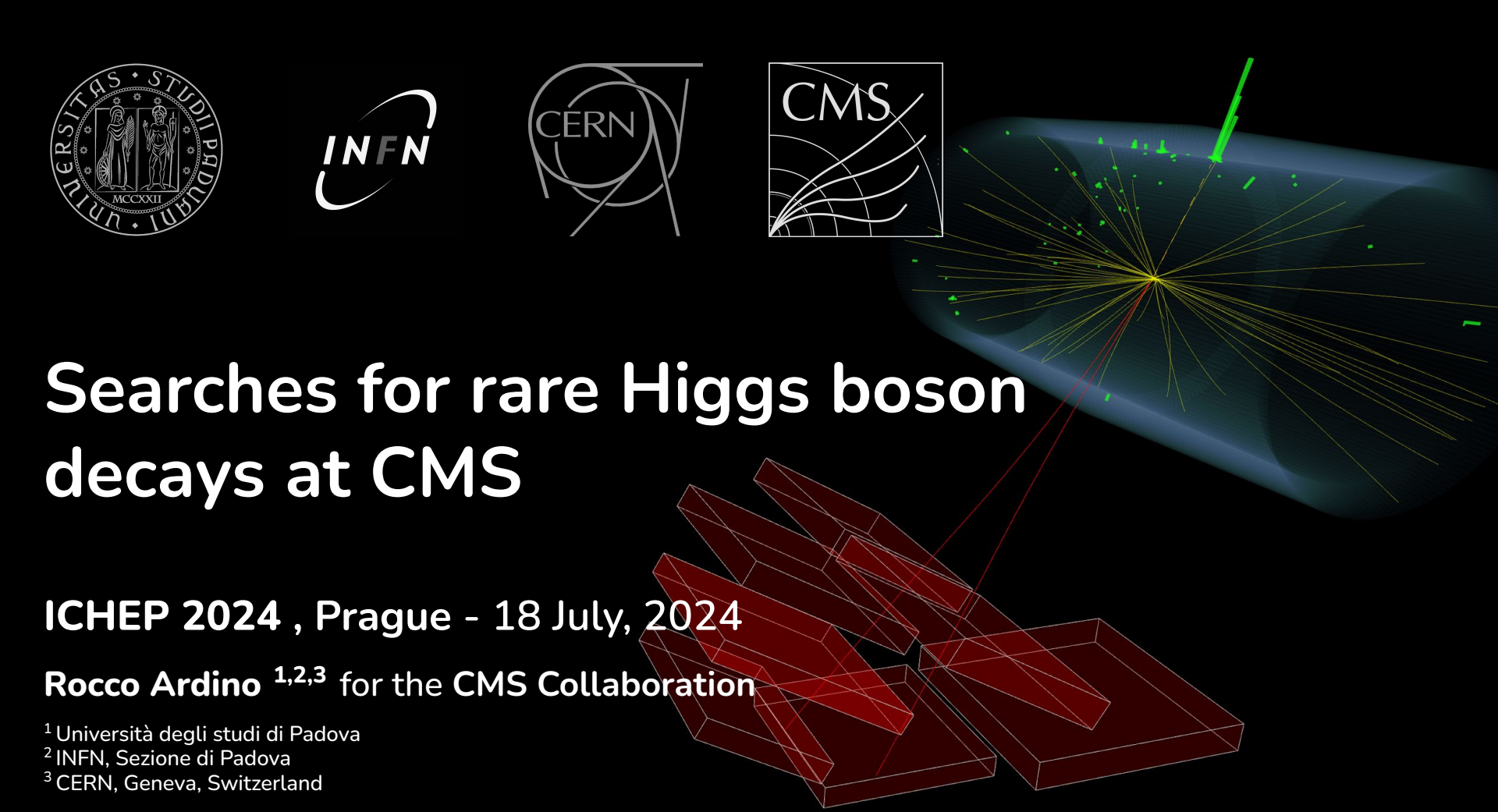


Searches for rare Higgs boson decays at CMS

ICHEP 2024 , Prague - 18 July, 2024

Rocco Ardino [1,2,3] for the **CMS Collaboration**

[1] Università degli studi di Padova
[2] INFN, Sezione di Padova
[3] CERN, Geneva, Switzerland

Background image: H→J/ψγ→μμγ candidate event display with CMS detector

Motivation and content of this talk

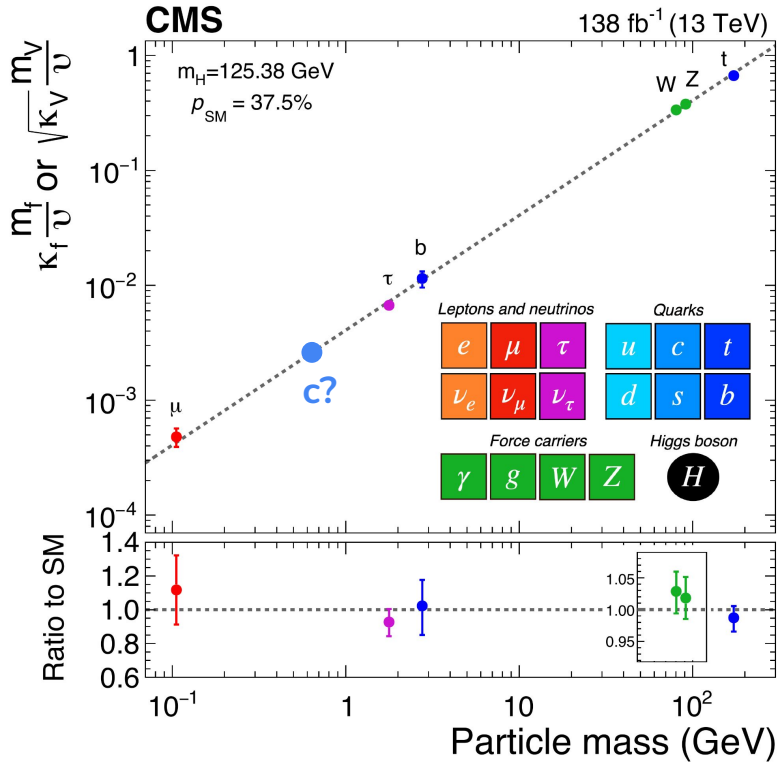


Figure: Higgs to fermions/gauge bosons coupling modifiers, as a function of the fermion/gauge boson mass [Nature 607 (2022) 60-68]

CMS and ATLAS measurements of couplings to Higgs

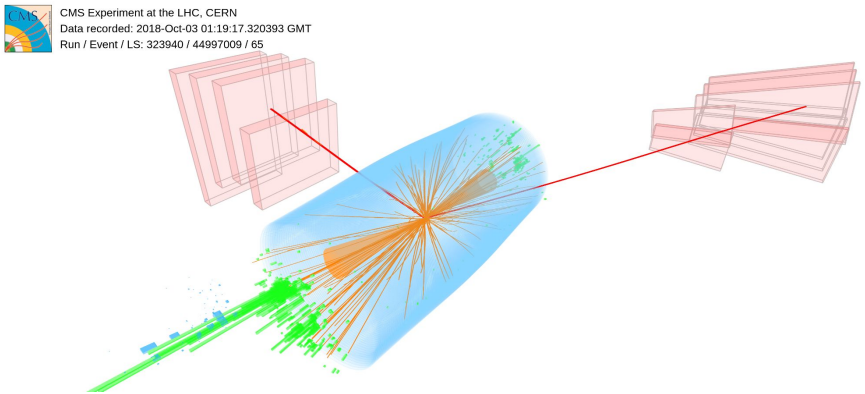
- Couplings to 3rd generation of fermions measured and consistent with SM
- **Focus on couplings to 2nd generation**
- Discrepancies? ⇒ Hint to Physics Beyond the SM and info on mechanism behind fermion masses hierarchy

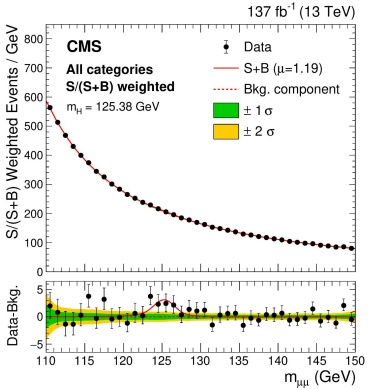
CMS experiment searches with Run-2 data set

- H→μμ [JHEP 01 (2021) 148]
- H→Zγ [JHEP 05 (2023) 233, PRL 132 021803]
- H→ργ, φγ, K^{*0}γ [PAS-HIG-23-005]
- H→J/ψγ, ψ(2S)γ [PAS-SMP-22-012]
- H→ZJ/ψ, J/ψJ/ψ, YY [PLB 842 (2023) 137534]
- H→Zρ, Zϕ [JHEP 11 (2020) 039]

Higgs boson decay to a pair of muons

H decay to μμ [JHEP 01 (2021) 148]





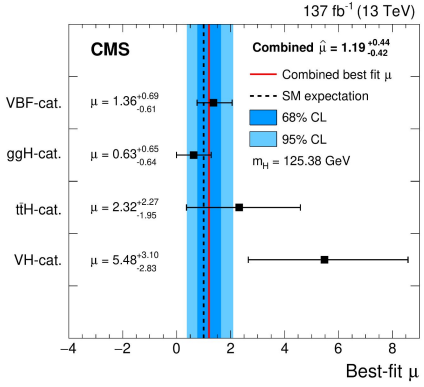


Figure: VBF candidate event display (top), $m_{\mu\mu}$ distribution for the weighted combination of all event categories (bottom-left) and 95% CL upper limits on μ (bottom-right)

CMS search for H→μμ using Run-2 data (137 fb^{-1})

- Sensitive to Yukawa coupling to muons
- Br(H→μμ) = 2.18 × 10^{-4} (± 1.7%)
- Trigger: single muon
- Categorization based on Higgs production mode
- Most sensitive channels: ggH, VBF

Measurement from combination of categories

- **First evidence (3.0σ)**
- **$\mu = 1.19^{+0.44}_{-0.42}$**
- **$0.85 < \kappa_\mu < 1.29$**

Higgs boson decay to a Z and a photon

H decay to Zγ [JHEP 05 (2023) 233, PRL 132 021803]

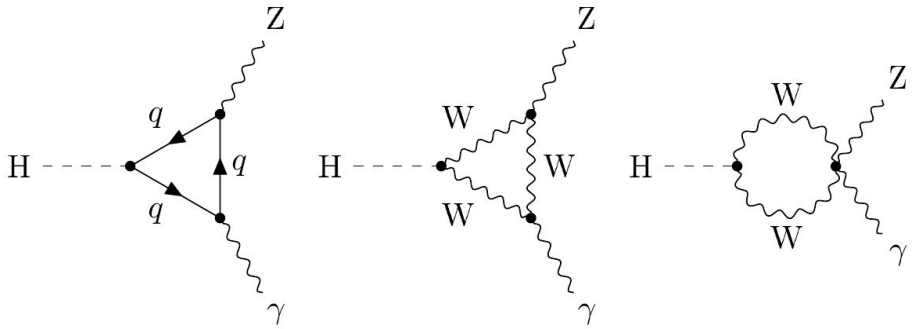


Figure: Feynman diagrams for H→Zγ decay

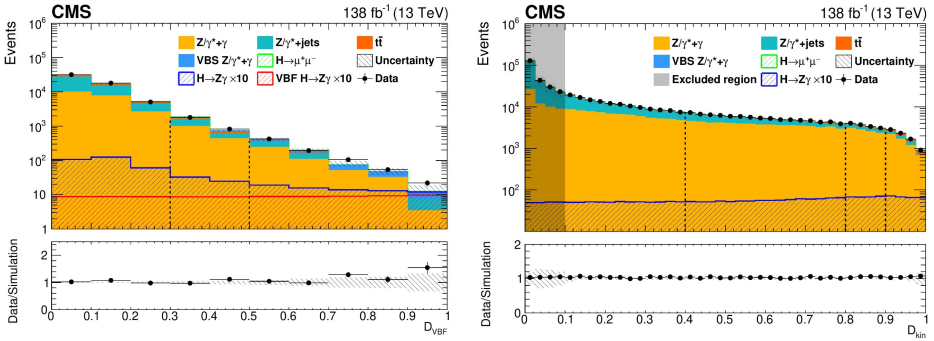


Figure: D_{VBF} (left) and D_{kin} (right) distributions for signal, simulated background, and data

Loop induced process ⇒ New physics in loops?

- Br(H→Zγ) = (1.57 ± 0.09) × 10^{-3}
- Br(Z→ee, μμ) ~ 6.8 × 10^{-2}
- **Final state: photon + pair of leptons (ee, μμ)**

CMS search performed with Run-2 data (138 fb^{-1})

- Trigger: dielectron / dimuon
- Backgrounds: Drell Yan with ISR γ or jets
- **Signal: narrow peak in $m_{\ell\ell\gamma}$ around H mass**
- 8 mutually exclusive categories
  - Lepton tag: presence of additional leptons
  - Dijet events (VBF): MVA discriminant D_{VBF}
  - Untagged (ggH): MVA discriminant D_{kin} for $m_{\ell\ell\gamma}$ system

H decay to Zγ [PRL 132 021803]

- **Evidence: significance of 3.4 std dev from combination with ATLAS!**
- **μ = 2.2 ± 0.7** (observed)
- Br(H→Zγ) = (3.4 ± 1.1) × 10^{-3} (1.9 std dev within SM prediction)
- **Dedicated poster by Yu-Hsuan Chou with more details here!**

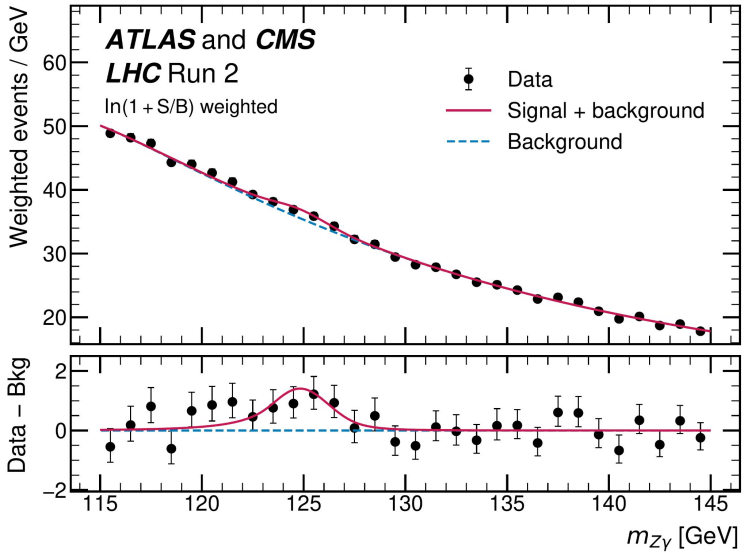


Figure: Zγ invariant mass distribution of from CMS+ATLAS data combination

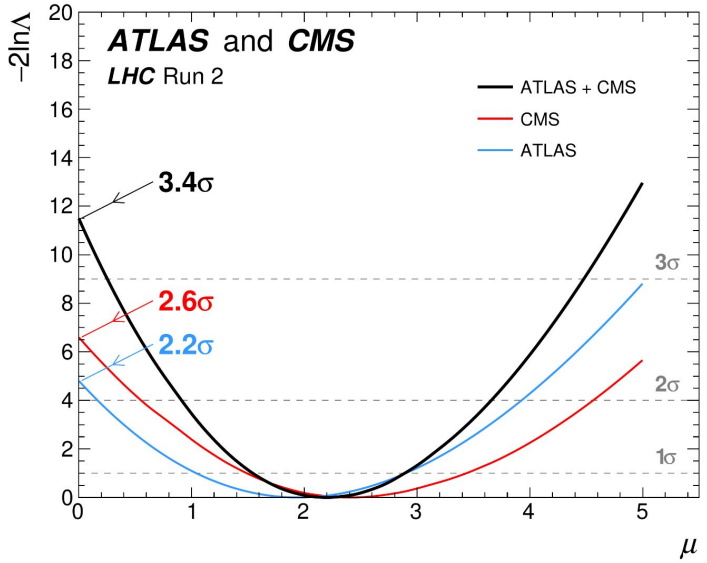


Figure: Negative profile log-likelihood scan of the signal strength modifier

Higgs boson decays to light mesons and a photon

H decay to ρ, ϕ or K^{*0} and a photon [PAS-HIG-23-005]

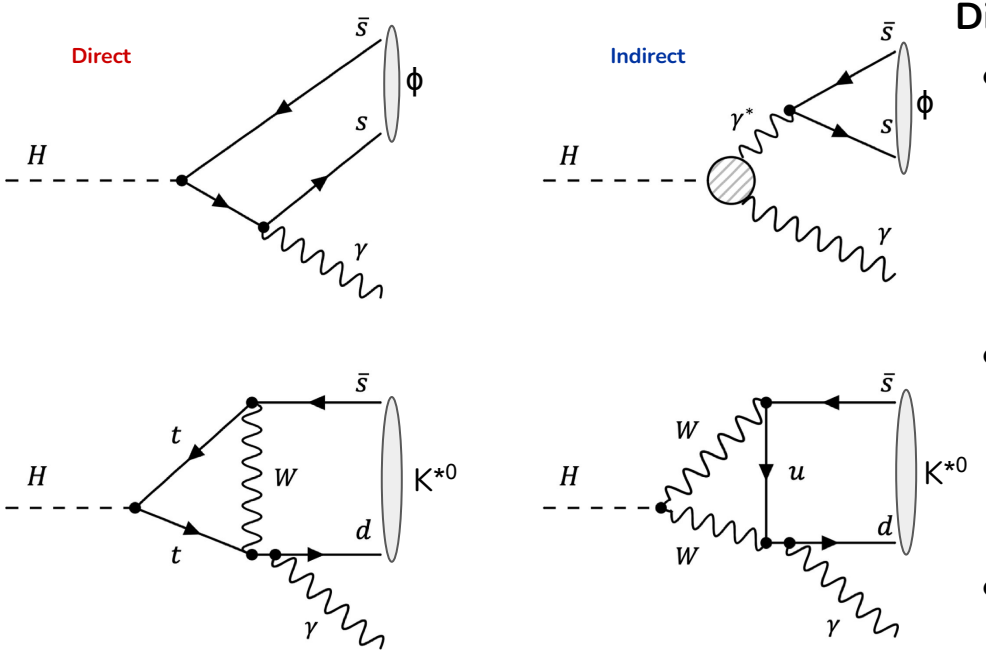


Figure: Leading-Order diagrams for $H \to \phi/K^{*}_{0} + \gamma$ processes, with direct and indirect contributions

Direct and indirect processes predicted by SM

- **Sensitive to Yukawa couplings of H to 1st/2nd generation quarks**
  - ργ: Info on coupling to u and d
  - ϕγ: Info on coupling to s
  - $K^{*0}\gamma$: flavour violating couplings of s and d
- SM predicted Br [JHEP 08 (2015) 012]
  - $Br(H \to \rho\gamma) = (1.68 \pm 0.08) \times \mathbf{10^{-5}}$
  - $Br(H \to \phi\gamma) = (2.31 \pm 0.11) \times \mathbf{10^{-6}}$
  - $Br(H \to K^{*0}\gamma) \sim 1.0 \times \mathbf{10^{-19}}$ (suppressed)
- Subsequent decays of the light meson
  - $\rho \to \pi^{+}\pi^{-}$ (Br ~ 100%)
  - $\phi \to K^{+}K^{-}$ (Br ~ 49%)
  - $K^{*0} \to K^{\pm}\pi^{\mp}$ (Br ~ 100%)

H→ρ/ϕ/K*^{0} + γ : overview

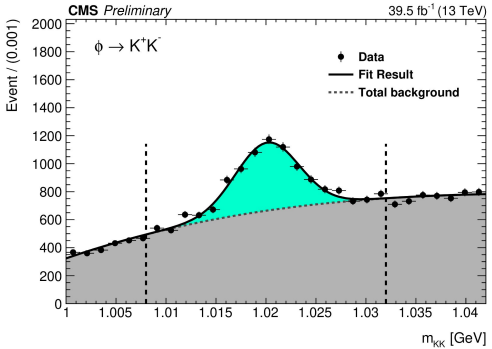


Figure: m_{KK} invariant mass distributions for H→ϕγ

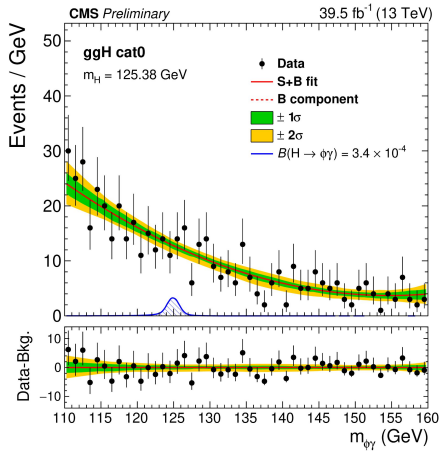


Figure: $m_{\phi\gamma}$ invariant mass distributions for H→ϕγ (cat0, ggH)

Triggering on these processes is fundamental and challenging

- **CMS Run-2 analysis targeting different Higgs production**
  - VH: lepton triggers **(138 fb^{-1})**
  - VBF: single photon (E_T > 75 GeV) + a VBF jet pair **(86.9 fb^{-1})**
  - ggF: single photon (E_T > 35 GeV) + τ-like jet (p_T > 35 GeV) with two tracks **(39.5 fb^{-1})**
- Meson candidate reconstruction from tracks with kinematic vertex-constrained fit
- **MVA classifier to improve signal selection**
  - Discriminate from γ+jet and multijet backgrounds for ggF and VBF
  - Split in two sub-categories of different purity (cat0/1) depending on MVA score threshold
- **Combine photon to meson candidate and perform fit on final state invariant mass distribution**

H→ρ/ϕ/K*⁰ + γ : upper limit results

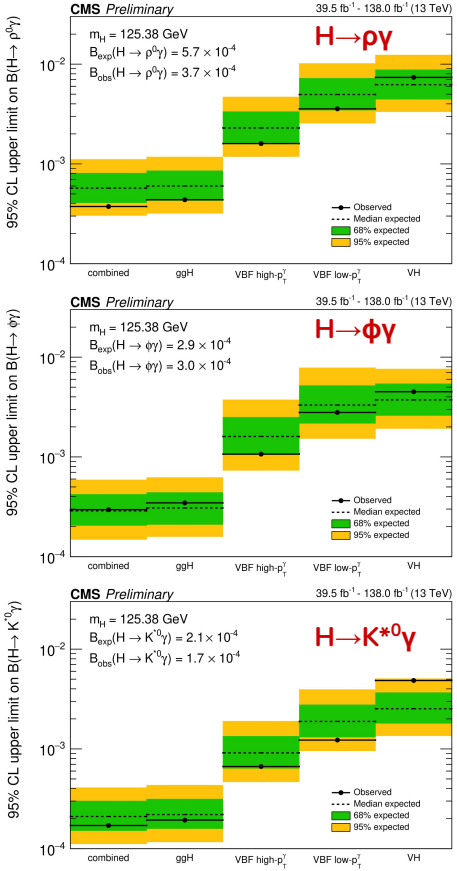


Figure: Upper limits summary plots

Upper limits on branching fraction set at 95% CL

- **No significant excess/discrepancy found w.r.t. SM prediction**
- **Most stringent experimental limits to date on the ργ and ϕγ decay channels**
- Dedicated trigger for ggF category deployed in 2018, thus expected significant improvement from Run-3 data set

	U.L. $\mathcal{B}(\mathrm{H} \to \rho^0\gamma)$		U.L. $\mathcal{B}(\mathrm{H} \to \phi\gamma)$		U.L. $\mathcal{B}(\mathrm{H} \to \mathrm{K}^{*0}\gamma)$	
category	Exp.(10^{-4})	Obs.(10^{-4})	Exp.(10^{-4})	Obs.(10^{-4})	Exp.(10^{-4})	Obs.(10^{-4})
VH	$62.3^{+25.6}_{-17.9}$	73.7	$37.3^{+16.9}_{-11.3}$	45.0	$25.3^{+11.4}_{-7.3}$	48.5
low-p_T^γ VBF	$49.6^{+22.5}_{-15.0}$	35.6	$33.1^{+18.7}_{-11.5}$	27.9	$18.8^{+8.90}_{-5.7}$	12.3
high-p_T^γ VBF	$22.9^{+10.5}_{-6.9}$	16.0	$16.0^{+9.0}_{-5.5}$	10.7	$9.13^{+4.25}_{-2.75}$	6.66
ggH	$6.01^{+2.53}_{-1.72}$	4.37	$3.08^{+1.33}_{-0.98}$	3.46	$2.20^{+0.94}_{-0.62}$	1.93
combined	$5.71^{+2.37}_{-1.63}$	3.74	$2.88^{+1.33}_{-0.83}$	2.97	$2.10^{+0.90}_{-0.58}$	1.71

Higgs boson decays to heavy mesons and a photon

H decay to J/ψ or ψ' and a photon [PAS-SMP-22-012]

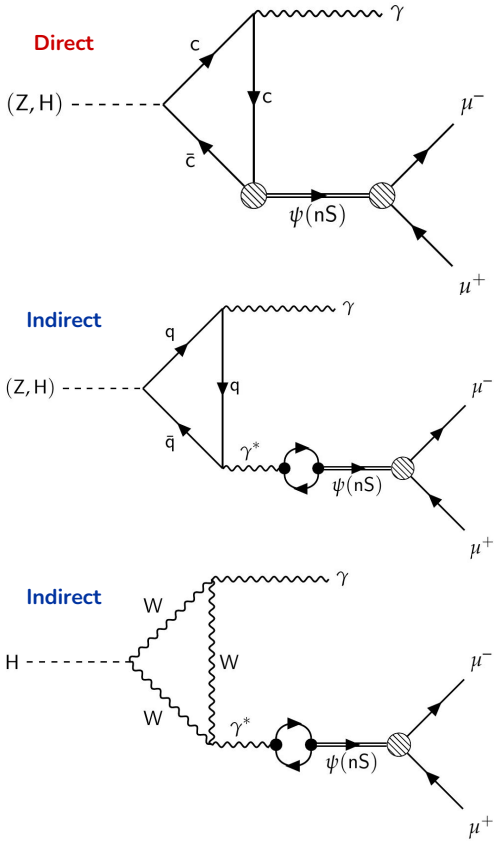


Figure: Leading-Order diagrams for Z,H→ψ(nS)γ processes, with direct and indirect contributions

Direct and indirect processes predicted by SM

- **Sensitive to Yukawa coupling of H to charm**
- Departures from SM ⇒ Anomalous coupling, BSM physics
- Similar Z decay likely to be observed before H decay ⇒ benchmark for theoretical prediction method
- SM branching fractions (J/ψ≡ψ(1S), ψ'≡ψ(2S)) [PRD 100 054038]
  - $Br(H\to\psi(1S)\gamma) = (2.99 \pm 0.15) \times \mathbf{10^{-6}}$
  - $Br(H\to\psi(2S)\gamma) = (1.03 \pm 0.06) \times \mathbf{10^{-6}}$
  - $Br(Z\to\psi(1S)\gamma) = (8.96 \pm 1.51) \times \mathbf{10^{-8}}$
  - $Br(Z\to\psi(2S)\gamma) = (4.83 \pm 1.02) \times \mathbf{10^{-8}}$
- Consider subsequent meson decays
  - $\psi(1S)\to\mu^+\mu^-$ (Br ~ 5.9%)
  - $\psi(2S)\to\mu^+\mu^-$ (Br ~ 0.8%)
- **μμγ final state ⇒ Very clean, low/reducible SM backgrounds**

Z,H→ψ(nS)γ : overview

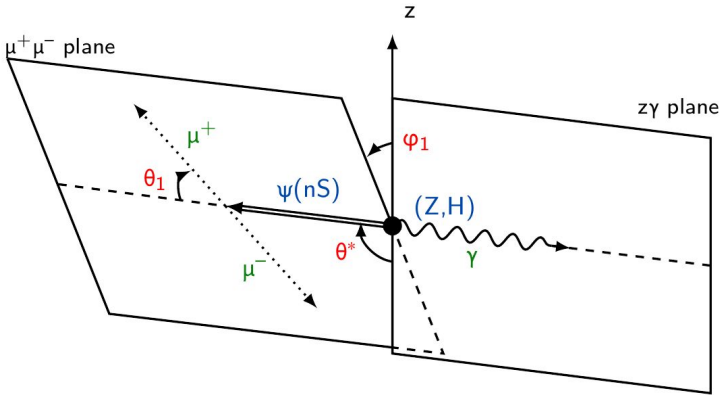


Figure: Process topology and main angular variables θ^*, θ_1, φ_1

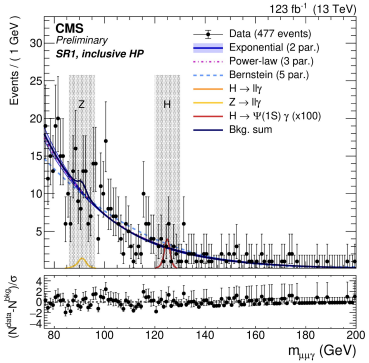


Figure: H→ψ(1S)γ, ggF HP category

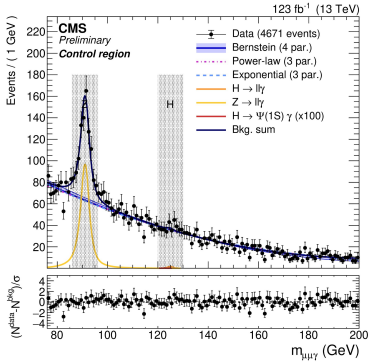


Figure: Control Region and Z FSR peak

Analysis performed using CMS Run-2 data set (123 fb^{-1})

- Signal: two resonances (Z/H and ψ(nS) meson)
- Backgrounds: QCD multijet, H/Z→μμγ
- Trigger: single muon + photon
- Meson candidate: μ pair closest in ΔR, compatible $m_{\mu\mu}$
- **Control Region (CR): inversion of $m_{\mu\mu}$ window cut**

Categorization

- **Z→ψ(1S)γ ⇒ Angular Likelihood Discriminator**
  - Based on main angular variables ⇒ Low/High Purity
- **H→ψ(1S)γ ⇒ H production mode**
  - VBF (2 forward jet), Heavy Flavour (b-tag jet, ttH+bbH)
  - Inclusive (ggH), High/Low Purity based on angular vars

Combine photon to meson candidate and perform fit on final state invariant mass distribution

Z,H→ψ(nS)γ : upper limit results

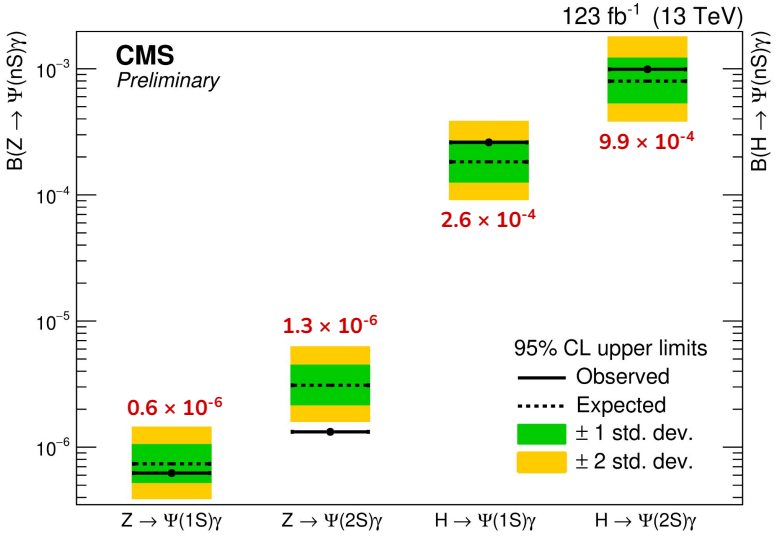


Figure: Upper limits summary plot

Process	This analysis (123 fb^{-1})		
	$\mu_{obs}(\mu_{exp})$	$\sigma_{obs}(\sigma_{exp})$ [pb]	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$
$Z \to \Psi(1S)\gamma$	$7.2\ \left(8.6^{+4.1}_{-2.7}\right)$	$3.8\ \left(4.4^{+1.9}_{-1.3}\right) \times 10^{-2}$	$0.6\ \left(0.7^{+0.3}_{-0.2}\right) \times 10^{-6}$
$Z \to \Psi(2S)\gamma$	$29\ \left(68^{+36}_{-22}\right)$	$8\ \left(19^{+8}_{-6}\right) \times 10^{-2}$	$1.3\ \left(3.1^{+1.4}_{-0.9}\right) \times 10^{-6}$
$H \to \Psi(1S)\gamma$	$88\ \left(62^{+30}_{-19}\right)$	$1.4\ \left(1.0^{+0.5}_{-0.3}\right) \times 10^{-2}$	$2.6\ \left(1.8^{+0.9}_{-0.6}\right) \times 10^{-4}$
$H \to \Psi(2S)\gamma$	$970\ \left(781^{+417}_{-259}\right)$	$5.5\ \left(4.4^{+2.3}_{-1.5}\right) \times 10^{-2}$	$9.9\ \left(8.0^{+4.2}_{-2.6}\right) \times 10^{-4}$

Upper limits on branching fraction set at 95% CL

- **No significant excess/discrepancy found with respect to SM prediction**
- 2.2σ downward fluctuation for Z→ψ(2S)γ
- Most stringent experimental limits to date on Z→ψ(nS)γ and H→ψ(2S)γ
- Constraints on Z→μμγ from Control Region

  $\mu(Z\to\mu\mu\gamma) = \sigma / \sigma^{SM} = 1.18 \pm 0.12$
- **Interpretation of results in κ-framework provides constraints on κ_c / κ_γ at 95% CL**

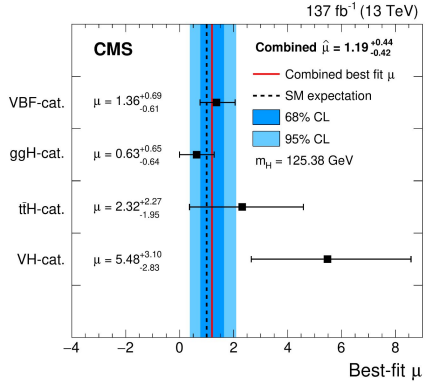
  $\kappa_c / \kappa_\gamma \in$ (-157, +199) (observed)

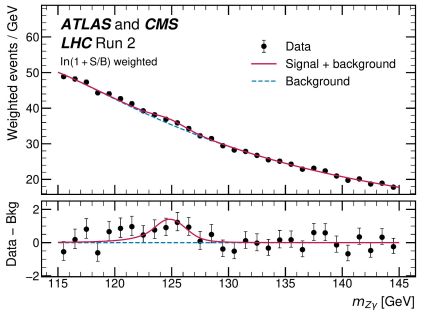
  $\kappa_c / \kappa_\gamma \in$ (-121, +161) (expected)

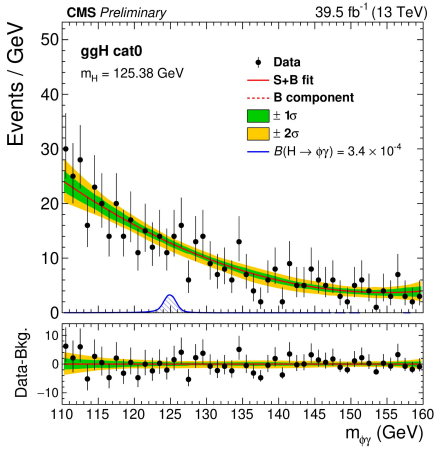
Dedicated poster with more details here!

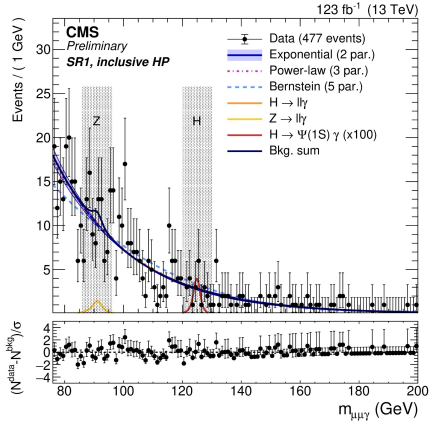
Conclusions

Conclusions









Higgs rare decays searches at CMS

- **Probe unobserved H couplings and search for discrepancies with SM (e.g. loop contributions)**
- Upper limits on branching fraction at 95% CL
- **No significant excess/discrepancy (for now!)**

Probes presented today, searched by CMS with Run-2 data set

- **H→μμ** [JHEP 01 (2021) 148]
  - Evidence of 3.0 std dev, compatible with SM
- **H→Zγ** [JHEP 05 (2023) 233, PRL 132 021803]
  - Evidence of 3.4 std dev, compatible with SM
- **H→ρ/ϕ/K*0 + γ** [PAS-HIG-23-005]
  - probe coupling to u,d,s quarks
- **H (and Z)→ψ(nS)γ** [PAS-SMP-22-012]
  - Probing coupling to c quark
  - Significantly improved previous CMS analysis

Summary of most recent results

Search	Code and reference	Results	Comments
$H \to \mu\mu$	JHEP 01 (2021) 148	$\mu = 1.19^{+0.44}_{-0.42}$ $0.85 < \kappa_\mu < 1.29$	Evidence of 3.0 std dev significance
$H \to Z\gamma$	Phys. Rev. Lett. 132 (2024) 021803	$\mathcal{B} = (3.4 \pm 1.1) \cdot 10^{-3}$ $\mu = 2.2 \pm 0.7$	1.9 std dev within SM prediction Evidence of 3.4 std dev significance
$H \to \rho^0\gamma$	CMS-PAS-HIG-23-005	$\mathcal{B} = 3.74\ (5.71^{+2.37}_{-1.63}) \times 10^{-4}$	
$H \to \phi\gamma$		$\mathcal{B} = 2.97\ (2.88^{+1.33}_{-0.83}) \times 10^{-4}$	
$H \to K^{*0}\gamma$		$\mathcal{B} = 1.71\ (2.10^{+0.90}_{-0.58}) \times 10^{-4}$	
$H \to Z\rho$	JHEP 11 (2020) 039	$\mathcal{B} = 1.04$–1.31% $(0.63$–$0.80\%)$	740–940 times the SM expectation
$H \to Z\phi$		$\mathcal{B} = 0.31$–0.40% $(0.27$–$0.36\%)$	730–950 times the SM expectation
$H \to \psi(1S)\gamma$	CMS-PAS-SMP-22-012	$\mathcal{B} = 2.6\ (1.8^{+0.9}_{-0.6}) \times 10^{-4}$	88 (62) times the SM prediction
$H \to \psi(2S)\gamma$		$\mathcal{B} = 9.9\ (8.0^{+4.2}_{-2.6}) \times 10^{-4}$	970 (781) times the SM prediction
$H \to ZJ/\psi$	Phys. Lett. B 842 (2023) 137534	$\mathcal{B} = 1.9\ (2.6^{+1.1}_{-0.7}) \times 10^{-3}$	826 times the SM prediction
$H \to Z\psi(2S)$		$\mathcal{B} = 6.6\ (7.1^{+2.8}_{-2.0}) \times 10^{-3}$	
$H \to J/\psi J/\psi$		$\mathcal{B} = 3.8\ (4.6^{+2.0}_{-0.6}) \times 10^{-4}$	
$H \to \psi(2S)J/\psi$		$\mathcal{B} = 2.1\ (1.4^{+0.6}_{-0.4}) \times 10^{-3}$	
$H \to \psi(2S)\psi(2S)$		$\mathcal{B} = 3.0\ (3.3^{+1.5}_{-0.9}) \times 10^{-3}$	
$H \to \Upsilon(nS)\Upsilon(mS)$		$\mathcal{B} = 3.5\ (3.6^{+0.2}_{-0.3}) \times 10^{-4}$	5.8 times earlier SM predictions
$H \to \Upsilon(1S)\Upsilon(1S)$		$\mathcal{B} = 1.7\ (1.7^{+0.1}_{-0.1}) \times 10^{-3}$	

Backup slides

H→ρ/ϕ/K*^{0} + γ : overview

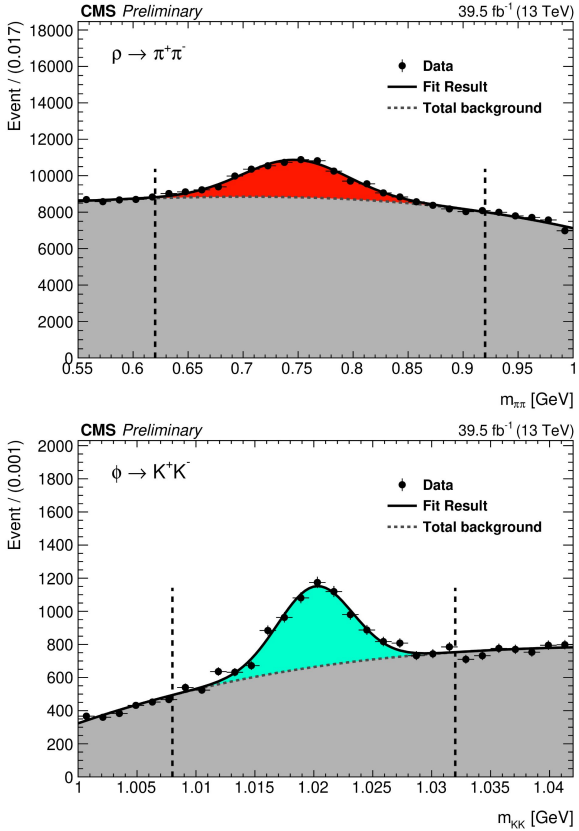


Figure: $m_{\pi\pi}$ (top) and m_{KK} (bottom) invariant mass distributions for H→ρ/ϕ + γ searches by CMS experiment

Triggering on these processes is fundamental and challenging

- **CMS Run-2 analysis targeting different Higgs production**
  - VH: lepton triggers **(138 fb^{-1})**
  - VBF: single photon (E_T > 75 GeV) + a VBF jet pair **(86.9 fb^{-1})**
  - ggF: single photon (E_T > 35 GeV) + τ-like jet (p_T > 35 GeV) with two tracks **(39.5 fb^{-1})**
- Meson candidate reconstruction
  - Tracks from PV and satisfying “high-purity” reco requirements
  - Meson decay vertex determined with a kinematic vertex-constrained fit and track momenta recalculated accordingly
  - Assume K/π mass in m_{2trk} invariant mass calculation
  - Dedicated isolation of the candidate from particle-flow momenta
- **MVA classifier to improve signal selection**
  - Discriminate from γ+jet and multijet backgrounds for ggF and VBF categories
  - m_{2trk} sideband region for MVA training (ggF) or validation (VBF)
  - Split in two sub-categories of different purity (cat0/1) depending on MVA score threshold

H→ρ/ϕ/K*^{0} + γ : event modelling

Combine photon to meson candidate and perform fit on final state invariant mass distribution

- Background parameterization using Chebyshev/Bernstein polynomials and Exponentials
- Use discrete profiling method to handle systematic uncertainty from the choice of the bkg model
- Signals modelled using Double-Sided Crystal Ball

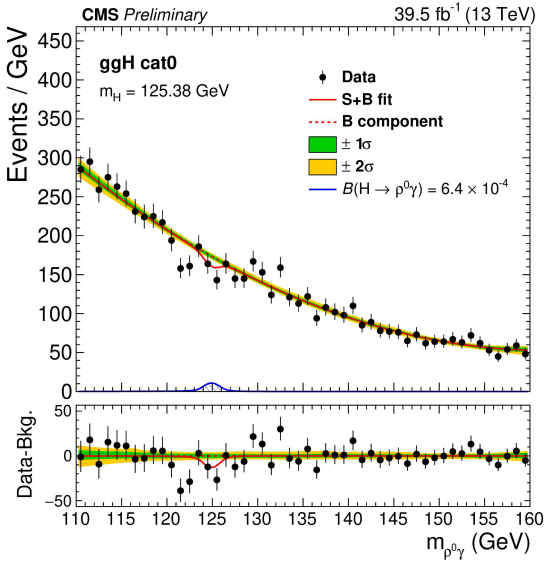


Figure: H→ργ search (cat0, ggH)

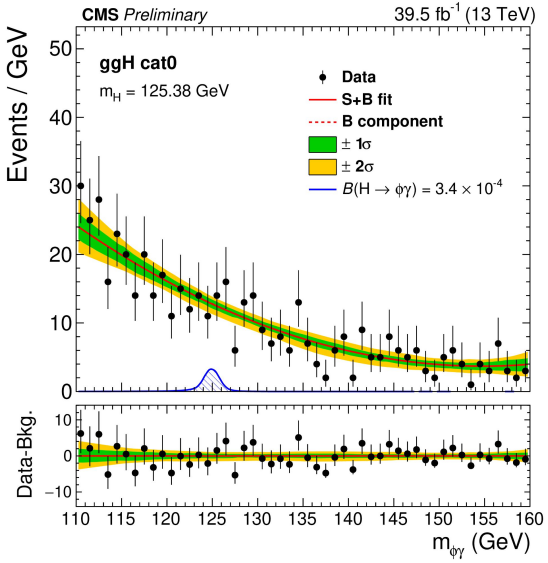


Figure: H→ϕγ search (cat0, ggH)

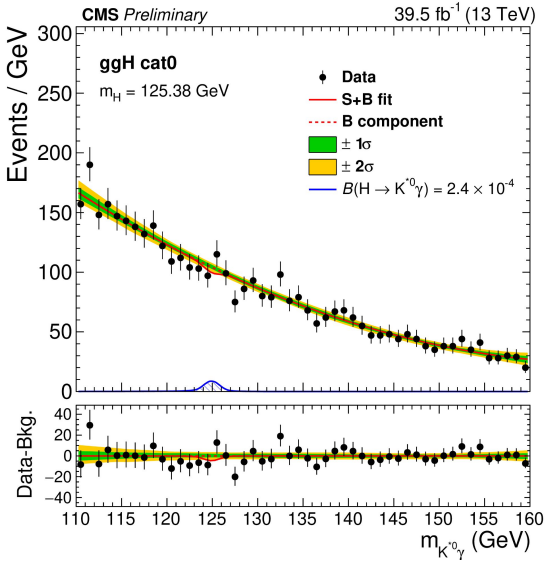


Figure: H→K*^{0}γ search (cat0, ggH)

Z,H→ψ(nS)γ : overview

Analysis performed using CMS Run-2 data set (123 fb^{-1}) and looking for μμγ final state

- **Excellent reconstruction performance of the final state particles**
- Signal expected to appear with two resonances (Z/H and ψ(nS) meson)
- Main background: QCD multijet with and without a ψ(nS) meson
- Resonant backgrounds: Z→μμγ Final State Radiation (FSR) and H→μμγ "Dalitz" decays
- **Strategy:** reconstruct the invariant mass distributions $m_{\mu\mu}$ and $m_{\mu\mu\gamma}$, where the signal is expected to peak unlike the SM backgrounds

Event selection

- "Single muon + photon" trigger with p_T threshold of 17 (30) GeV on the muon (photon)
- Muons: $p_T(\mu_1) > 18$ GeV, $p_T(\mu_2) > 18$ GeV, "medium prompt" identification and tight isolation from hadronic activity
- Photon: $p_T(\gamma) > 32$ GeV, multivariate identification at 80% efficiency + pixel seed veto
- ψ(nS) candidate as the one with pair of OS muons with closest angular distance ΔR
- **Signal regions: $m_{\mu\mu} \in [3.0, 3.2]$ GeV (SR1), $m_{\mu\mu} \in [3.6, 3.75]$ GeV (SR2)**
- **Control Region (CR): inversion of $m_{\mu\mu}$ window cut**

Z,H→ψ(1S)γ : categorization

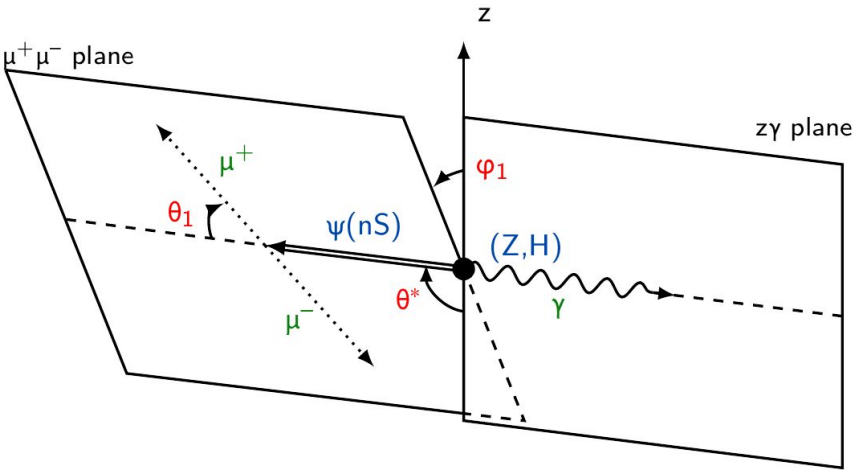


Figure: Process topology and main angular variables θ^*, θ_1, φ_1

Likelihood Discriminator (LD) for Z→ψ(1S)+γ search

- **Built using main angular variables of process**
  - cos θ*: cos of angle ψ(nS)-z in H/Z rest frame
  - cos θ_1: cos of angle μ^+-ψ(nS) in ψ(nS) rest frame
  - φ_1: angle between the normals of $\mu^+\mu^-$ and γz planes
- Train LD on Control Region data to discriminate main QCD background from signal
- **"Low Purity" (LP)** category: LD < 0.5
- **"High Purity" (HP)** category: LD > 0.5

Categorization for H→ψ(1S)+γ search based on H production mode

- **VBF**: require at least two jets in the forward region with m_{jj} > 350 GeV
- **Heavy Flavour (HF)**: targeting ttH and bbH, requiring at least 1 b-tag jet
- ggF: inclusive category including events to entering in the previous regions. Splitted based on |cos θ*|
  - **ggF "High Purity"**: |cos θ*| > 0.5
  - **ggF "Low Purity"**: |cos θ*| < 0.5

Z,H→ψ(nS)γ : event modelling

Combine photon to meson candidate and perform fit on final state invariant mass distribution

- Parametrize QCD background with Power-laws, Exponentials, Bernstein functions: **discrete profiling!**
- Signal parametrized using Gaussian + Double-Sided Crystal Ball
- **Constrain Z→μμγ background from control region** (and measure Z→μμγ signal strength)

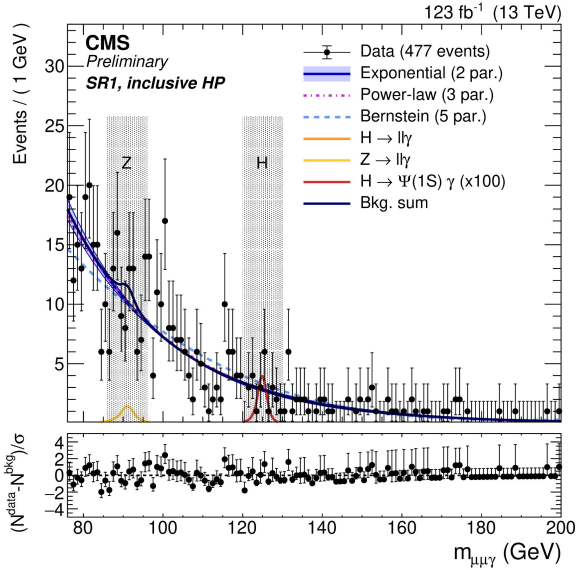


Figure: H→ψ(1S)γ search, ggF HP category

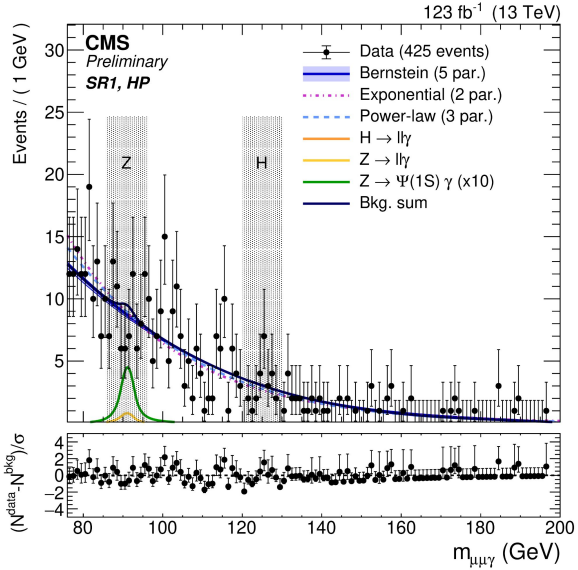


Figure: Z→ψ(1S)γ search, HP category

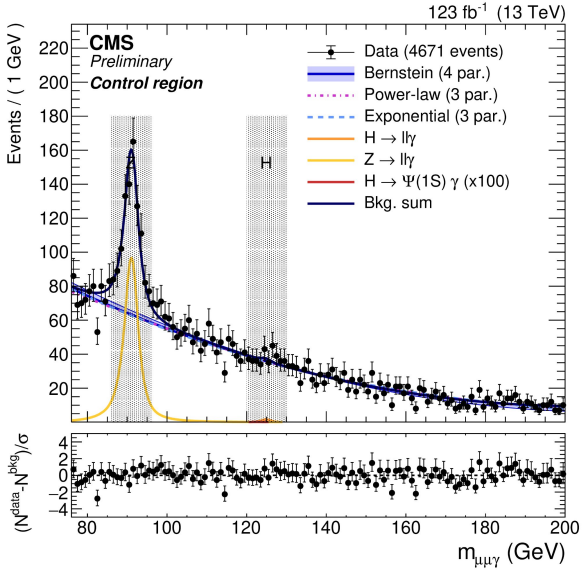


Figure: Control Region and Z FSR peak