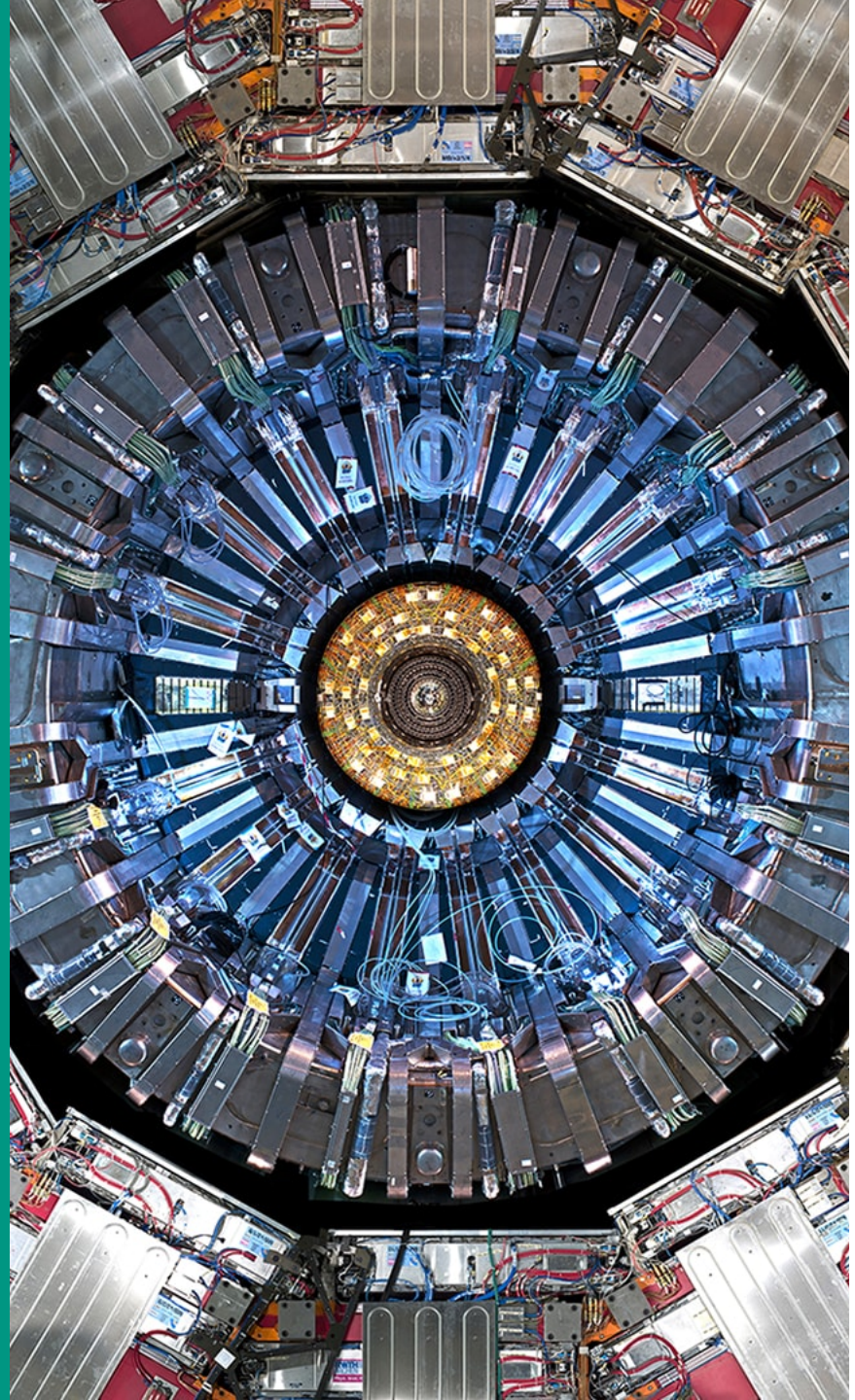
Search for Light Pseudoscalar Bosons from Higgs Boson Decays in the Four-Kaon Final State



56th Herbstschule HEP

Johannes Hornung

September 8, 2025

KIT

ETP Institute of Experimental Particle Physics

CMS Germany

BMBF FSP-CMS

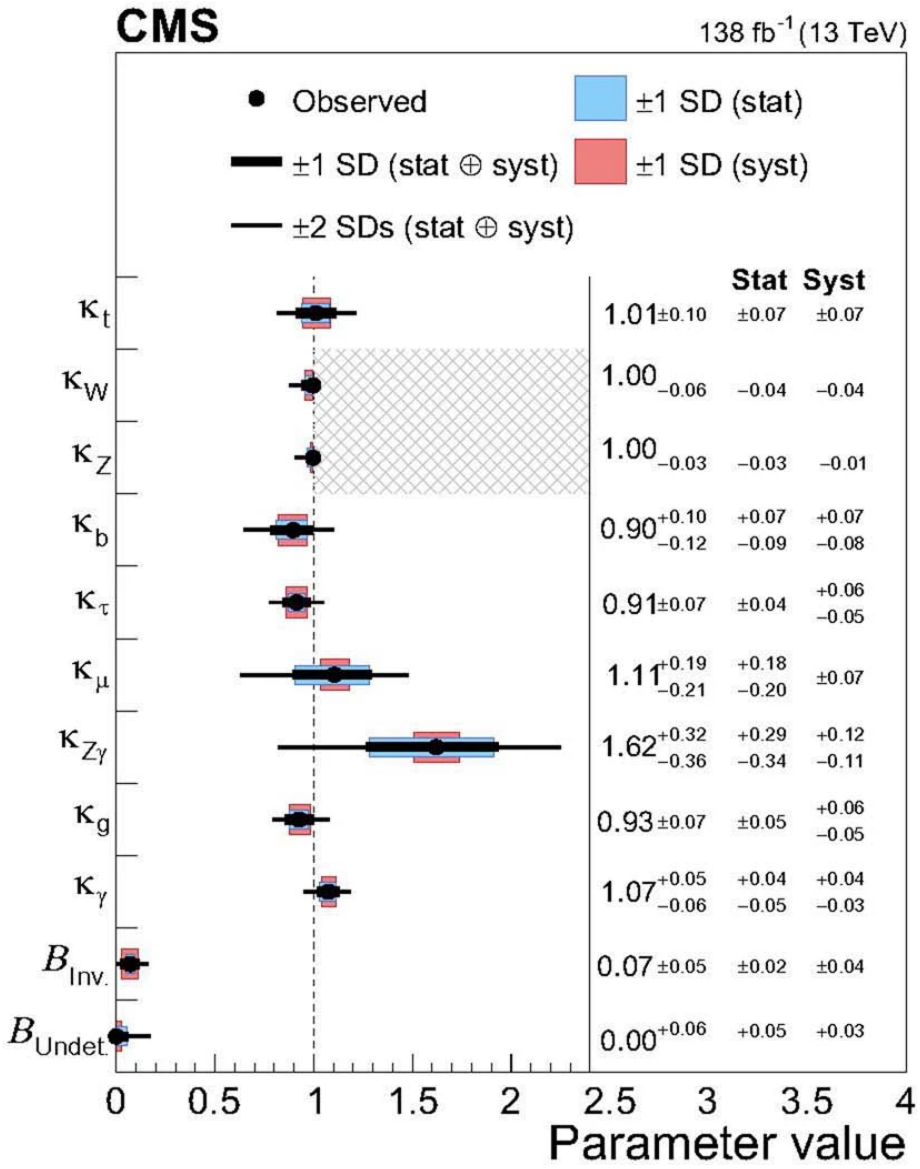
Q & A Session

Please scan this QR code, it'll bring you to a Google Doc, where I'll answer questions after the talk.

Motivation

- h_{125} decay width $\Gamma_{\text{theo}} = 4.1\,\text{MeV}$
  - Indirect off-shell measurements exist assuming no BSM contribution
  - No direct measurements possible at the LHC
- Branching ratios still measured via signal strengths with the κ-framework
- Branching ratios of individual Higgs decay channels measurable
- Branching ratio of h_{125} into undetected decay modes BR_{undet}
  - non-detectable decays into SM particles
  - decays into BSM particles
- Current upper limit on BR_{undet}: 0.16 at 95 % CL

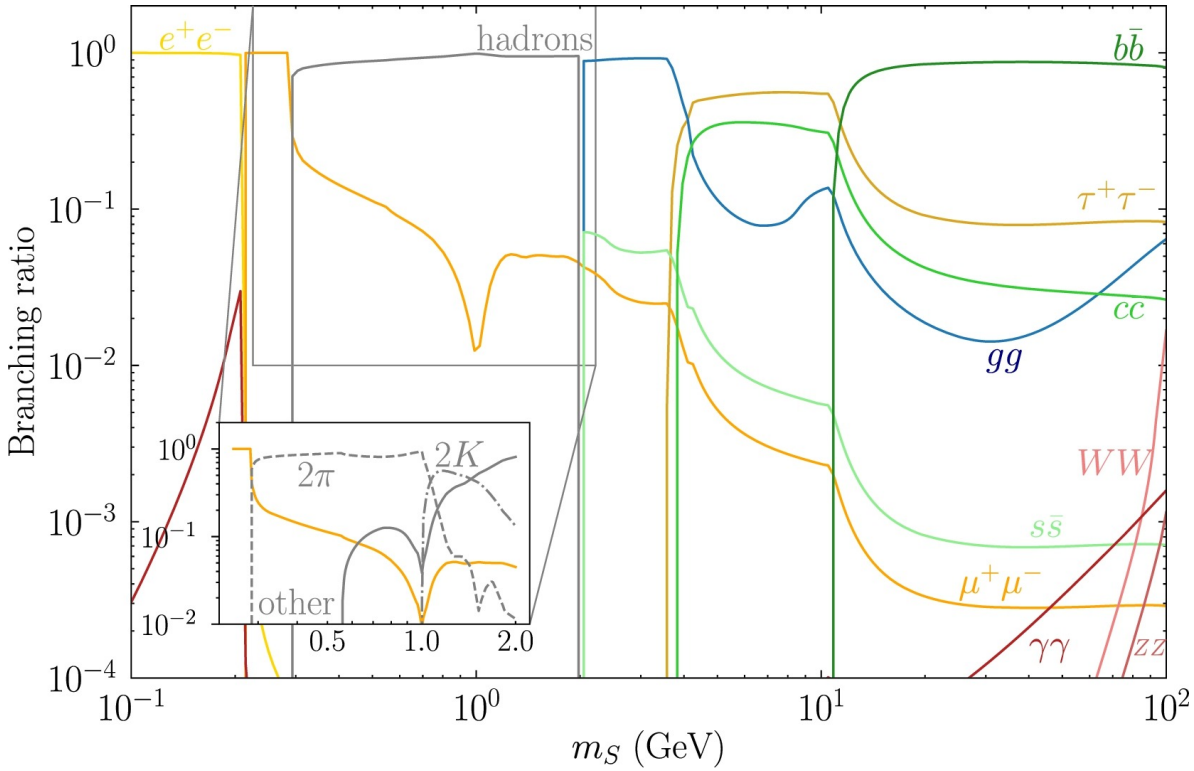
→ Searches for exotic h_{125} decays



(The CMS Collaboration, A portrait of the Higgs boson by the CMS experiment ten years after the discovery, Nature 607, 60-68 (2022))

Signal Model

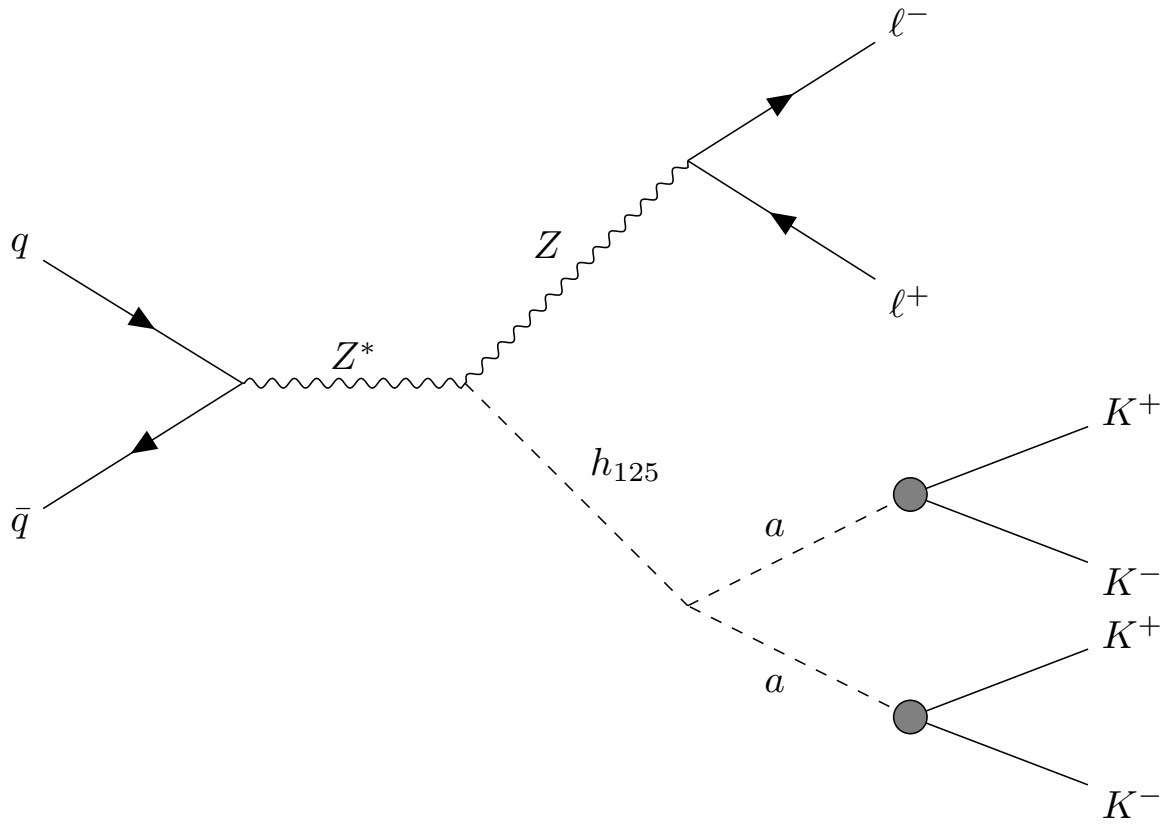
- $h_{125} \to aa \to K^+K^-K^+K^-$
  - Decay chain possible if $2 \cdot m_{K^\pm} \leq m_a \leq m_{h_{125}}/2$
  - $a \to K^+K^-$ dominant for $1\,\mathrm{GeV} \leq m_a \leq 2\,\mathrm{GeV}$
  - Pseudoscalar ALPs, additional Higgs bosons, ...
- Properties of pseudoscalar bosons a
  - Mass $m_a = 1.5\,\mathrm{GeV}$
  - Decay promptly
  - No electric charge, color charge or spin



(Y. Gershtein et al., Probing naturally light singlets with a displaced vertex trigger, Physics Letters B, Vol. 823 (2021), 136758)

Signal Topology

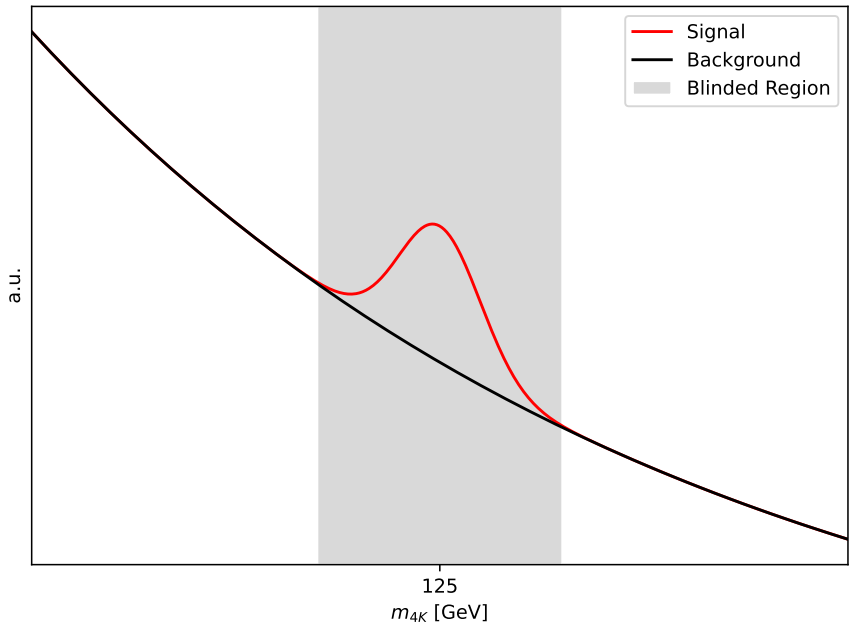
- Zh_{125} production
  - $Z \to \ell\ell$ decay provides clean signature
  - $\to$ Suppress QCD multijet background
- $K^{\pm}$ assumed to be highly energetic
  - Measured in detector before decaying
  - Reconstructed as individual Particle-Flow candidates
  - Charge information available for offline reconstruction



Analysis Overview

- Objective: Agnostic search for h_{125} resonance in invariant four-kaon mass m_{4K}
- Considered data-taking periods: 2016 ($36.3\,\mathrm{fb}^{-1}$), 2017 ($41.5\,\mathrm{fb}^{-1}$), 2018 ($59.8\,\mathrm{fb}^{-1}$)
- Two signal regions based on the Z boson decay: $\mu\mu$, ee
- Control regions: Sidebands of the SRs, $e\mu$
- Selection for model building based on distribution of m_{4K}:

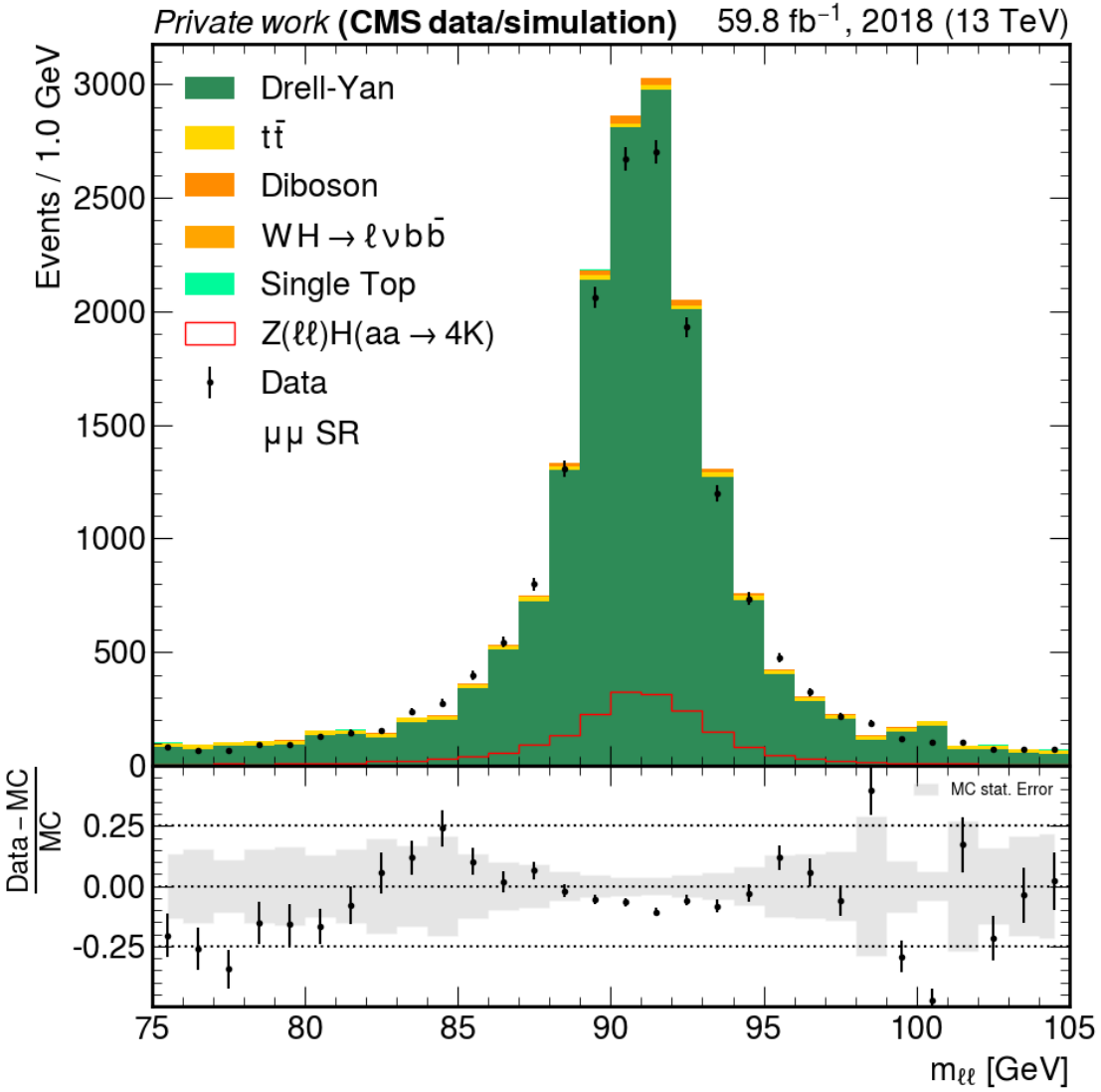
Cut Variable	$\mu\mu/ee$ SR
Dilepton mass $m_{\ell\ell}$	$75\,\mathrm{GeV} < m_{\ell\ell} < 105\,\mathrm{GeV}$
Dilepton $p_{\mathrm{T}}^{\ell\ell}$	$p_{\mathrm{T}}^{\ell\ell} > 30\,\mathrm{GeV}$
Four-kaon mass m_{4K}	$70\,\mathrm{GeV} < m_{4K} < 200\,\mathrm{GeV}$
Four-kaon η_{4K}	$\lvert\eta_{4K}\rvert < 2.4$
Leading constituent $p_{\mathrm{T}}^{K^\pm}$	$p_{\mathrm{T}}^{K^\pm} > 10\,\mathrm{GeV}$
Di-kaon mass $m_{K^+K^-}$	$m_{K^+K^-} < 3\,\mathrm{GeV}$
$\Delta m_{K^+K^-}$	$\lvert\Delta m_{K^+K^-}\rvert < 0.06\,\mathrm{GeV}$
Blinded region	$110\,\mathrm{GeV} < m_{4K} < 140\,\mathrm{GeV}$



Reconstruction of the Z Boson

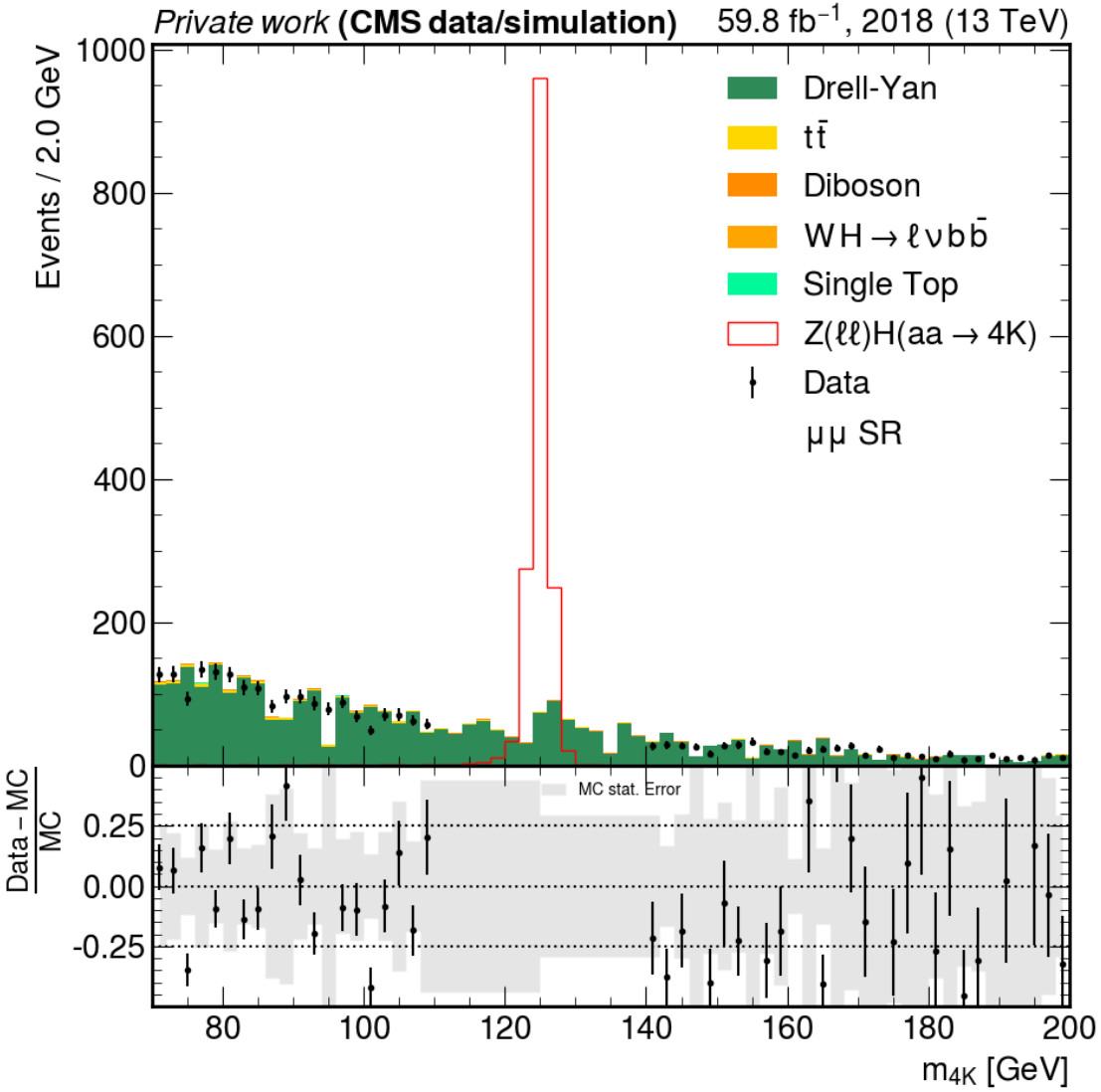
- Reconstructed from leptons that pass additional quality criteria
  - Isolation
  - Compatibility with the primary vertex
  - Criteria on p_{T}^{ℓ} and η_{ℓ}
- Lepton pair chosen that
  - passes separation requirement $\Delta R > 0.5$
  - has the invariant dilepton mass $m_{\ell\ell}$ closest to the Z boson mass

  $\rightarrow$ Reject events without a suitable lepton pair



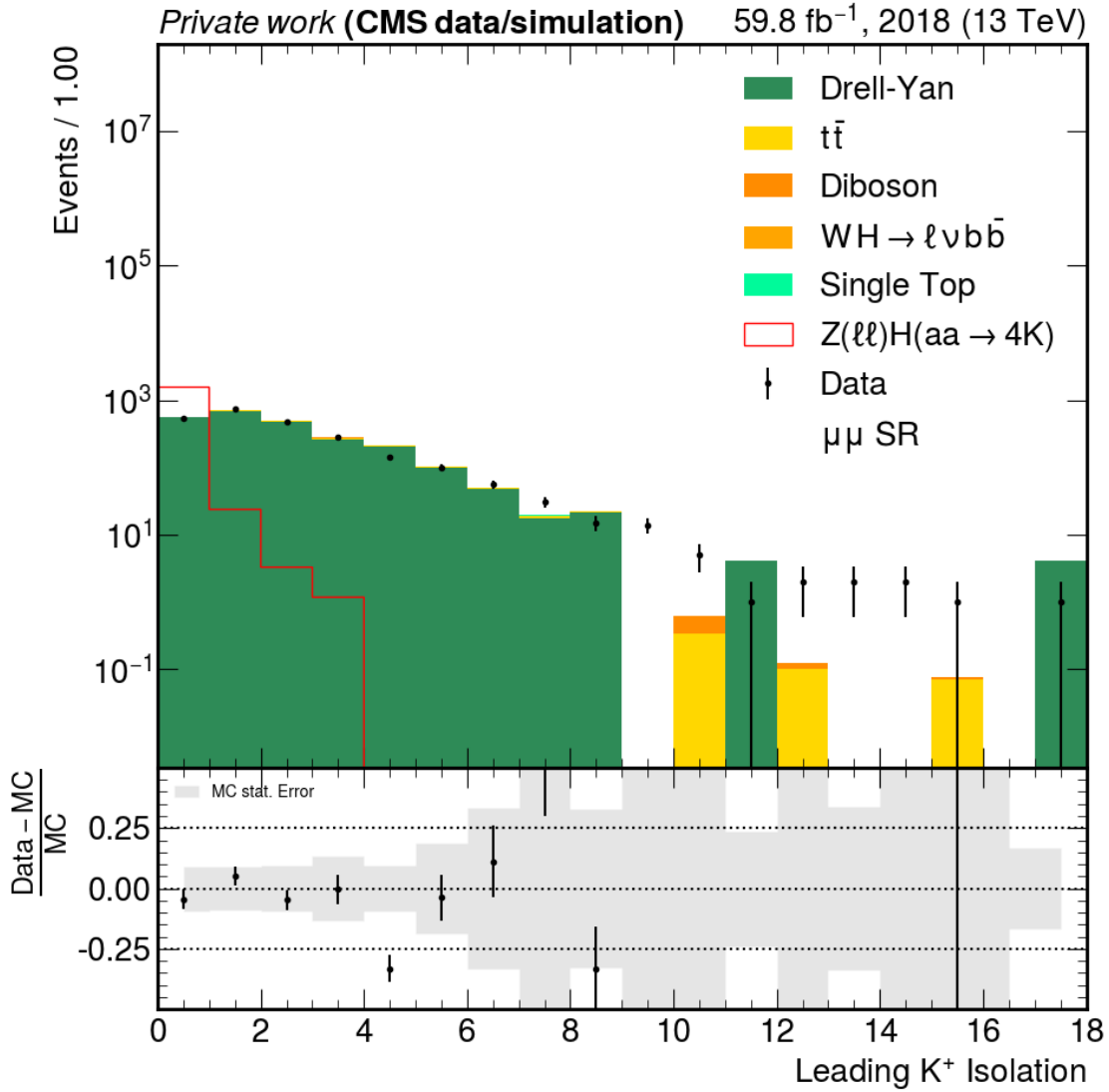
Reconstruction of the h_{125} Boson

- h_{125} candidate reconstructed by adding up four highest-p_T PF cands in an event
- Resulting distribution of m_{4K} after all cuts
  - Sharp signal resonance peak
  - SM backgrounds suppressed well
  - Good agreement between data and background simulation in sidebands



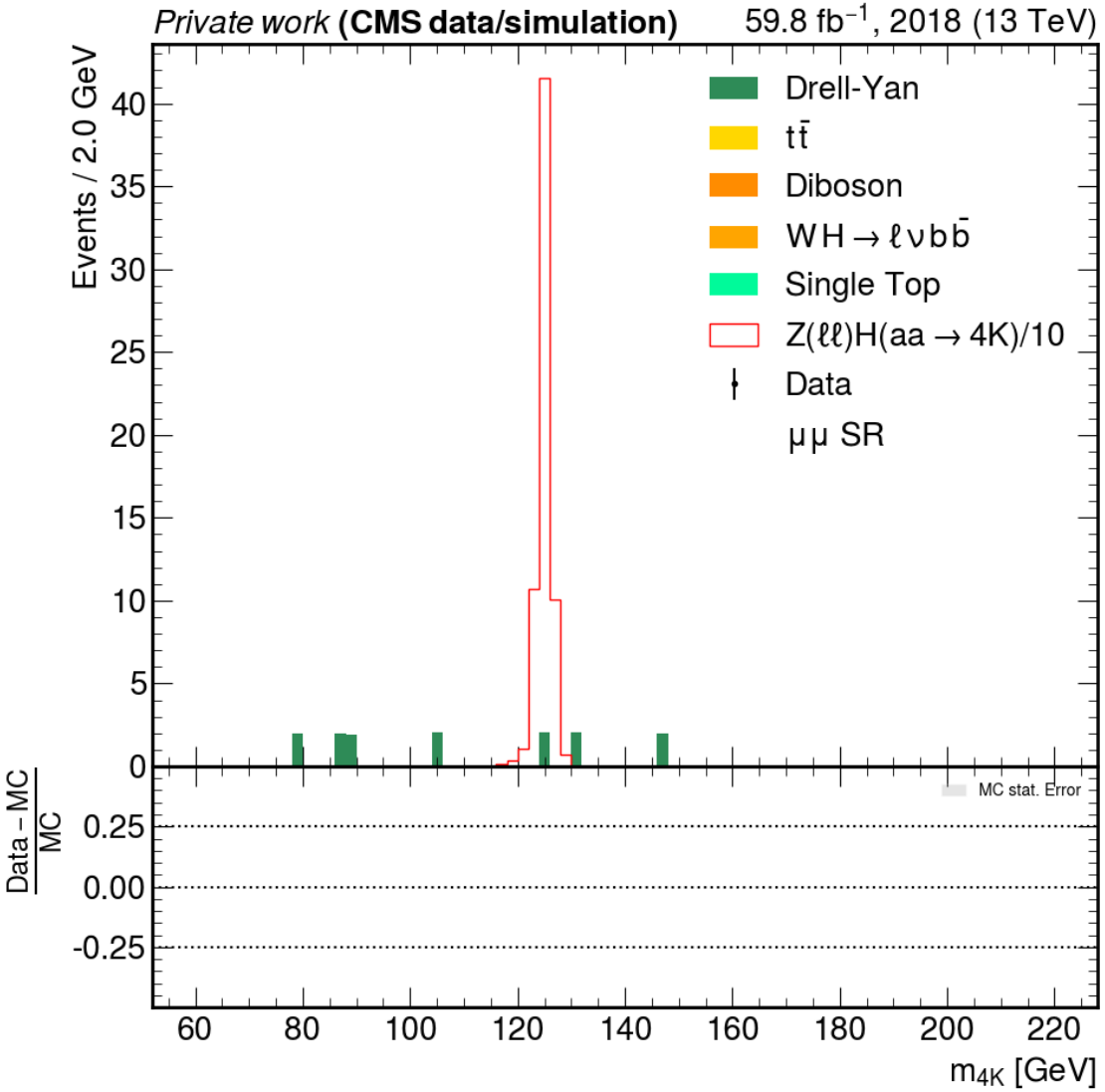
Relative Isolation of the Two Leading $K^{\pm}$ in the h_{125} System

- $K^{\pm}$ from h_{125} decay highly energetic
  - → More isolated than charged PF candidates from background events



Relative Isolation of the Two Leading $K^{\pm}$ in the h_{125} System

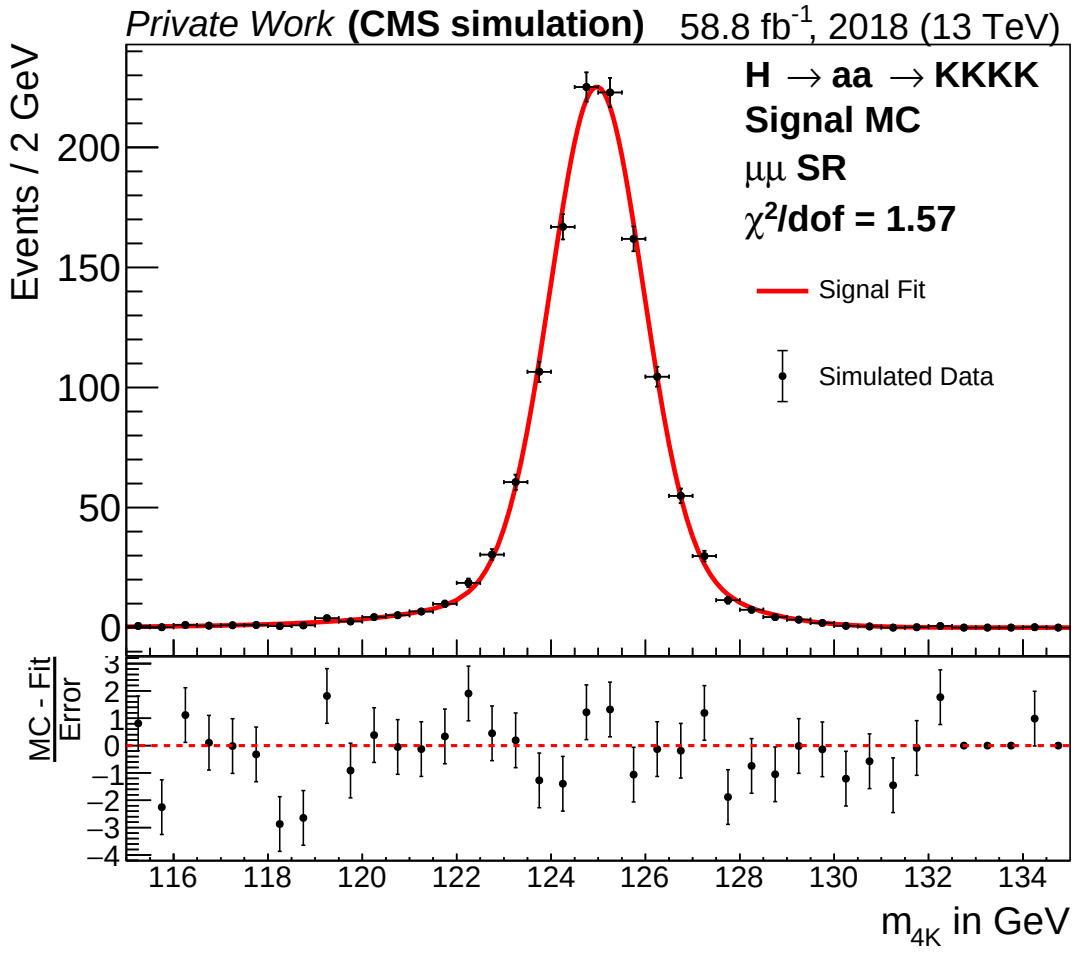
- $K^{\pm}$ from h_{125} decay highly energetic
  - → More isolated than charged PF candidates from background events
- Problem: In low relative isolation regime, statistics gets low for data and simulated background
- Solution:
  - Model the m_{4K} distributions for signal and background through parametric fits
  - Extrapolate the norm parameter of the parametric background model to the low relative isolation regime



Modeling of Signal and Background

Signal Model

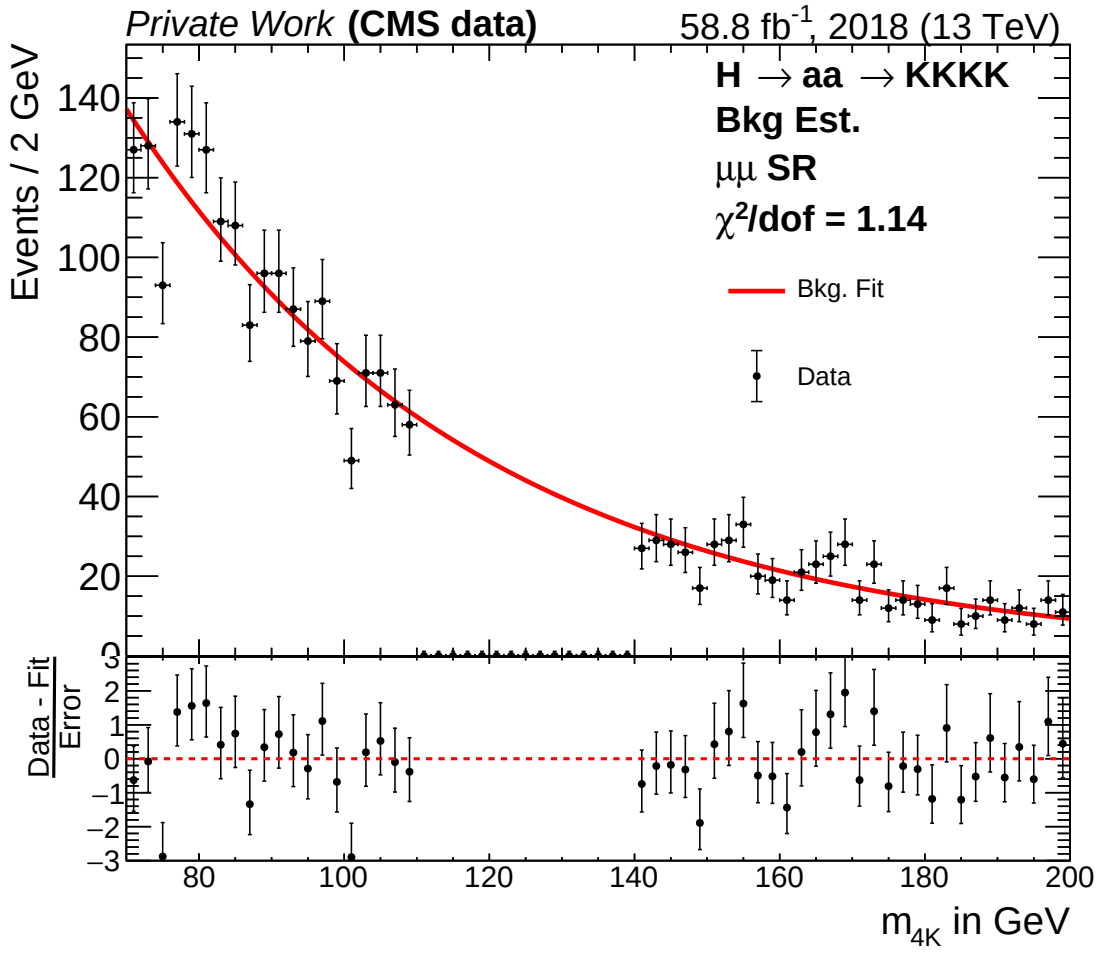
- Fit to data of signal simulation
- h_{125} resonance:
  Crystal ball function + Gaussian distribution



Modeling of Signal and Background

Background Model

- Fit to sidebands of experimentally recorded data
- Exponential function



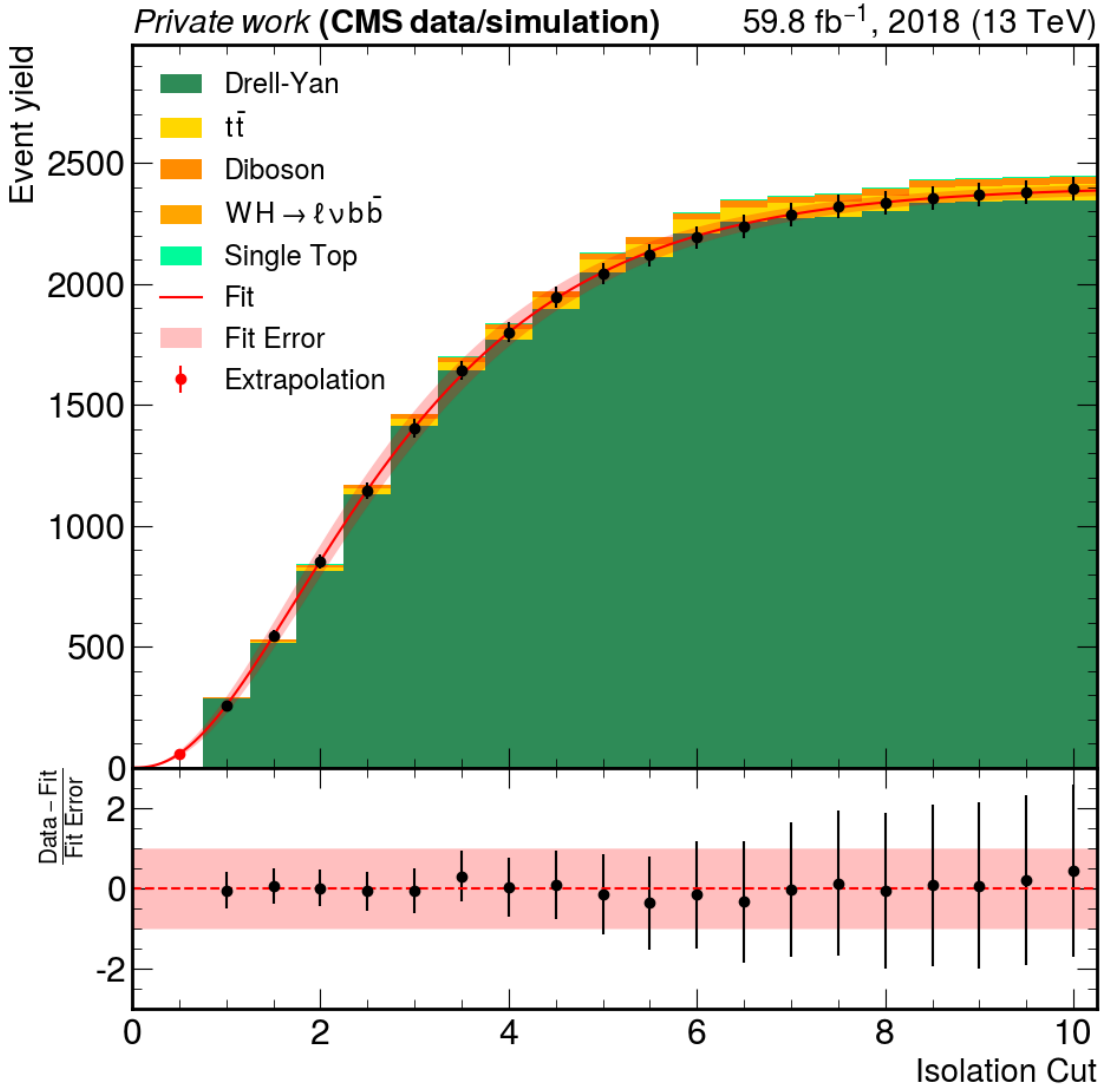
Extrapolation into Low Relative Isolation Regime

- Perform successive cuts on relative isolation of two leading $K^{\pm}$
- Fit parametric function

$$f(x) = \frac{a}{\left(1 - \exp\left(-\frac{x}{x_0}\right)\right)^b}$$

to recorded event yields

- Extrapolate this model to $f(0.5)$ to get the norm for the background model



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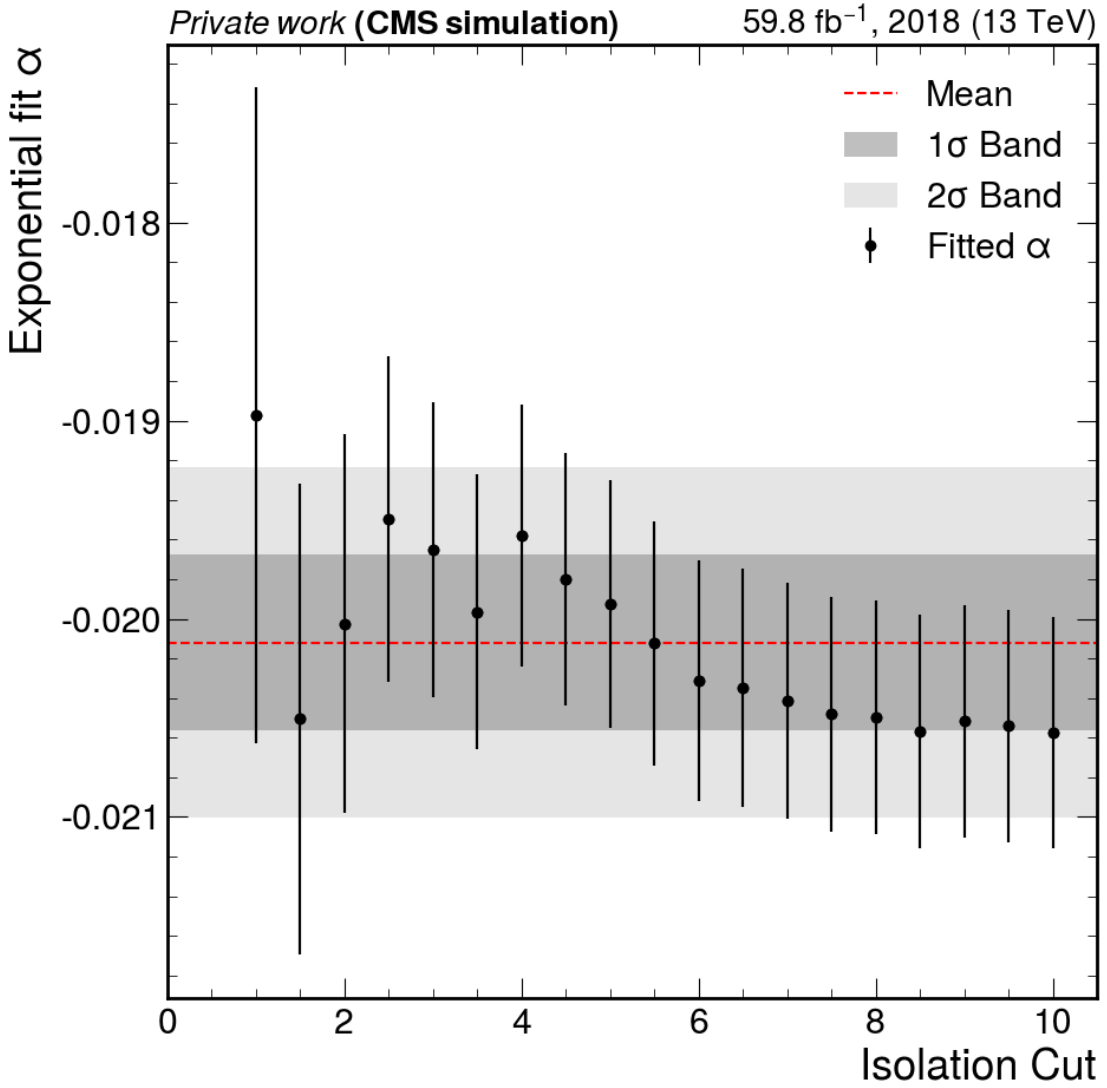
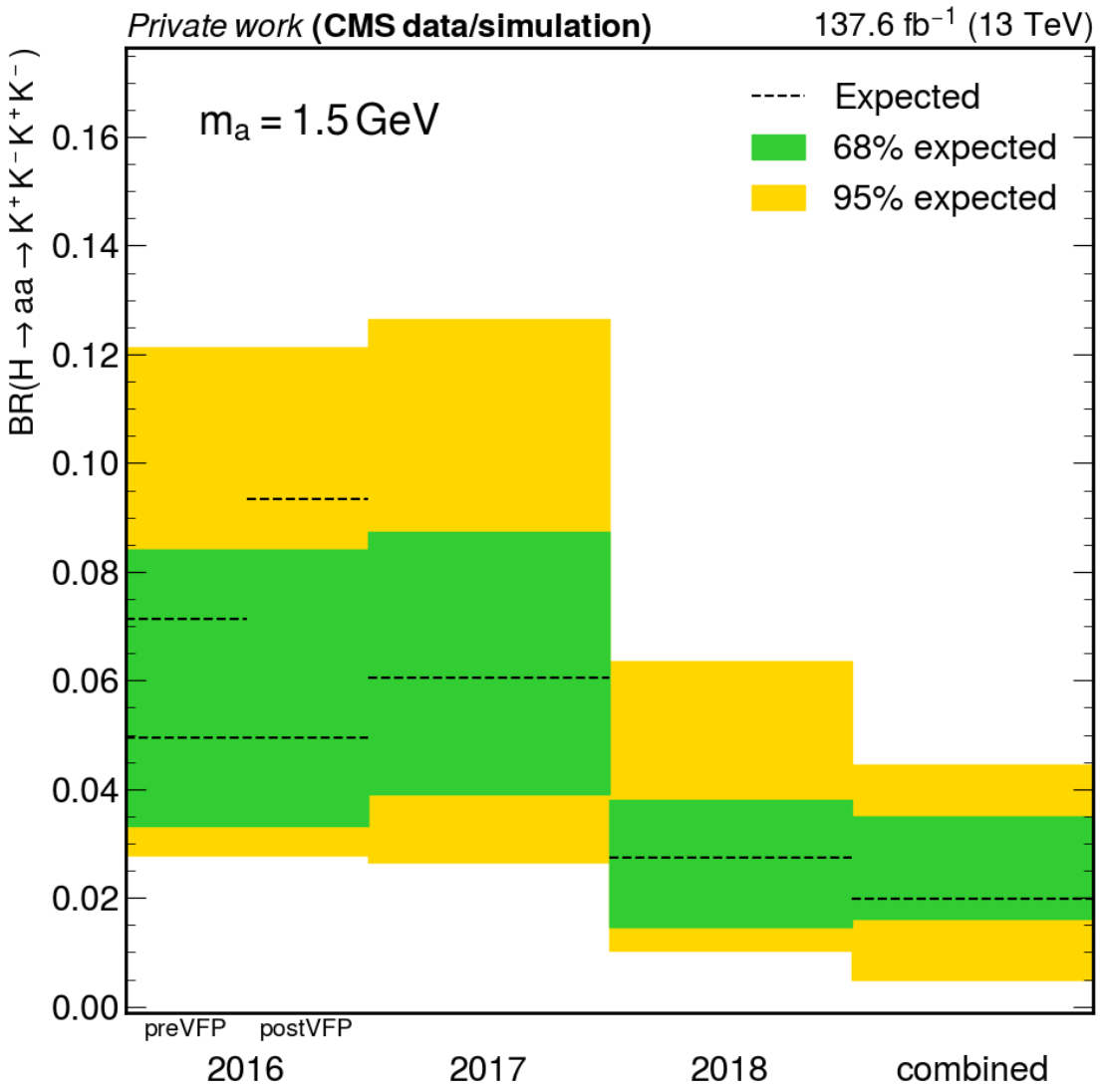
- Exponential parameter α unaffected by cuts on the relative $K^{\pm}$ isolation



Limits



2016: 0.049
2017: 0.060
2018: 0.027

combined: 0.019

Summary and Outlook

Summary

- First look into $h_{125} \to aa \to K^+K^-K^+K^-$
  - Data from 2016 ($36.3\,\mathrm{fb}^{-1}$), 2017 ($41.5\,\mathrm{fb}^{-1}$) and 2018 ($59.8\,\mathrm{fb}^{-1}$) processed
  - Zh_{125} as production mode of h_{125}
  - $m_a = 1.5\,\mathrm{GeV}$
- Combined expected limit on $\mathrm{BR}(h_{125} \to aa \to K^+K^-K^+K^-)$ 0.019 at 95 % CL

Outlook

- Scan m_a values: $1\,\mathrm{GeV} \leq m_a \leq 2\,\mathrm{GeV}$
- Process Run 3 ($> 180\,\mathrm{fb}^{-1}$) data
- Incorporate machine learning techniques
- Expand analysis to different production modes using scouting data
- Search for long lived a bosons

Thank you for your attention!

Google Doc for questions.