Searching for low-mass dark scalars through the Higgs portal using CMS

EOS be.h Winter Solstice Meeting

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HIGH-ENERGY PHYSICS
RESEARCH CENTRE

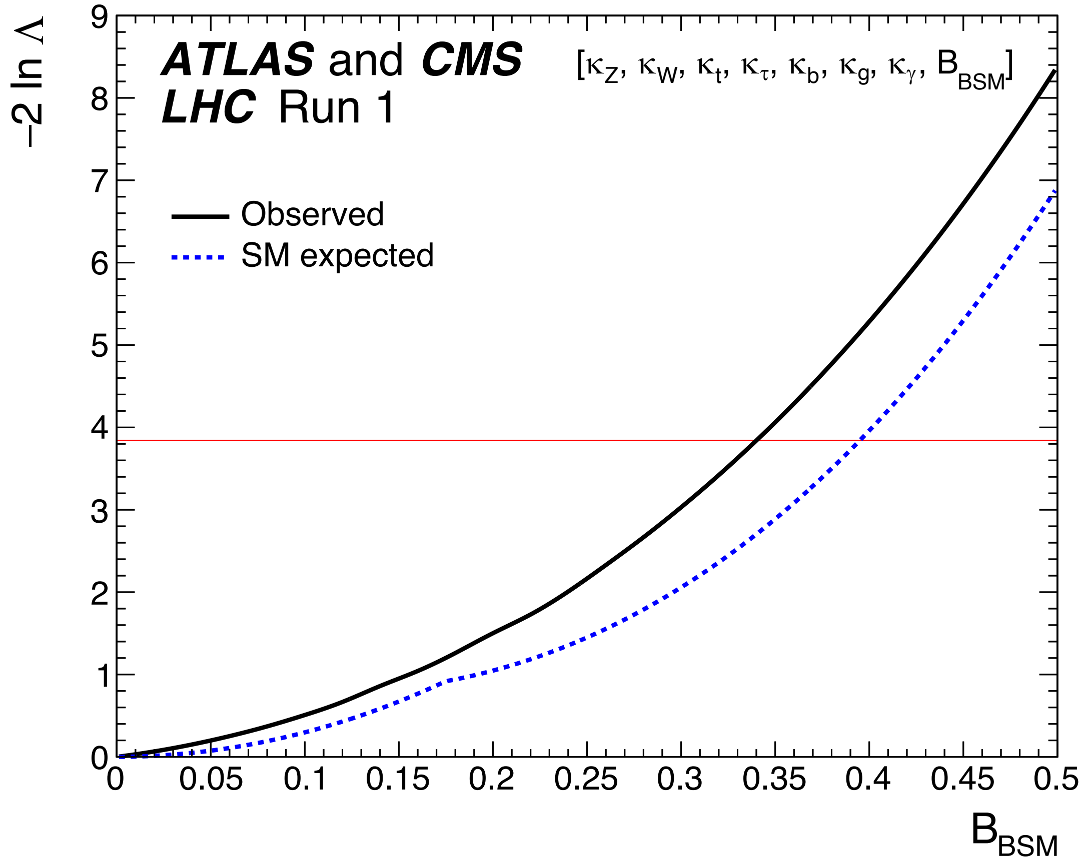
Higgs Exotic Decays

Higgs Standard Model (SM) decays:

- Efforts initially focused on five decay modes: $H \rightarrow \gamma\gamma, ZZ, WW, \tau\tau, bb$
- Shifting from "discovery mode" to precision and more challenging measurements.
  - Evidence for $H \rightarrow \mu\mu$ now!
- Other decays are even rarer!

Beyond the SM (BSM) decays:

- We only have an upper limit on Γ_{total}!
- Latest public ATLAS+CMS result: Branching fraction to BSM decays < 0.34 @ 95% CL
- Plenty of phase space where new physics could be hiding …



arXiv:1606.02266

Higgs Exotic Decays
Why search for $H \rightarrow aa$

- **The majority of BSM theories posit the existence of new particles:**
  - Simplest extension to SM involves introduction of a singlet scalar field that mixes with Higgs.
  - No shortage of theories adding such a field … dark matter candidates, NMSSM, SUSY with hidden sectors (*dark SUSY*), hidden valley models, and Neutral Naturalness …

- **Higgs is a portal through which we can hunt for exotic particles from hidden sectors!**
  - Through mixing with the Higgs, a light scalar inherits Higgs couplings to SM matter (suppressed) – we can use visible decay products!

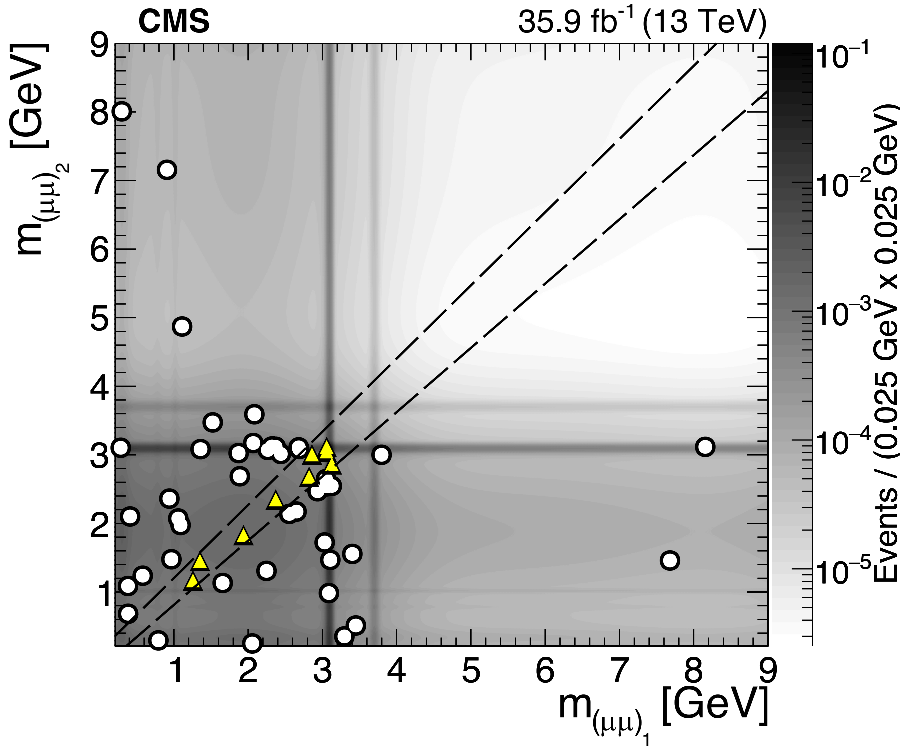
- **The Higgs-scalar mixing parameter *must be small* - otherwise we'd have seen it!**
  - Mixing is a free parameter though – lots of phase space to explore!
  - If the mixing is very small/suppressed, then the scalar may travel macroscopic distances before decaying … missing transverse energy or displaced vertices become relevant!

Low mass BSM Higgs Decays
Status of Prompt Decay Searches

Several searches for Higgs to promptly decaying scalars have been undertaken at the LHC.

Broadly two final states considered:

- 0μ + 4 heavy fermions or 2μ + 2 heavy fermions: 2μ + 2τ, 2μ + 2b, 2τ + 2τ, etc:
  - τ, and heavy quark masses restrict $m_a \gtrsim 3.5$ GeV
  - e.g. 2τ + 2τ/μ (*arXiv:1907.07235*): 4 GeV < m_a < 15 GeV & 2τ + 2b (*arXiv:1812.06359*): 20 GeV < m_a < 62.5 GeV
- 2μ + 2μ:
  - Lower mass range accessible, ie. $m_a \geq 2m_\mu$
  - Reliant on model predicting scalar has a substantial coupling to leptons.
  - Most recent CMS search sensitivity: 0.25 < m_a < 8.5 GeV



arXiv:1812.00380

Low mass BSM Higgs Decays
Status of Displaced Decay Searches

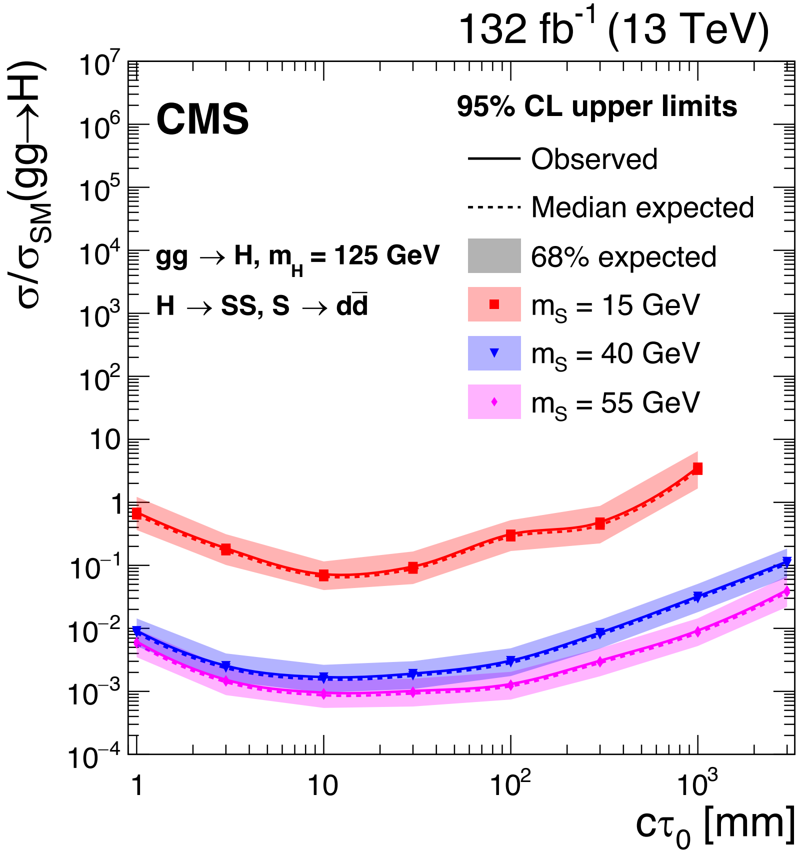
Several displaced searches have been done also …

Displaced jets:

- Latest CMS result: *arXiv:2012.01581*
- Optimal sensitivity: 10mm < $c\tau$ < 100mm:
    - Low backgrounds & tracker optimal for displacement.
- Sensitivity is lost even at 15 GeV due to collimation of multiple tracks from jets and low track multiplicity of secondary vertices.

Displaced Leptons (2μ + 2μ):

- Prompt $H \rightarrow aa \rightarrow 2\mu + 2\mu$ searches have also considered small displacements for scalar decay.
- Recent CMS analysis is a solid basis to learn from …



arXiv:2012.01581

Low mass BSM Higgs Decays
Another possibility …

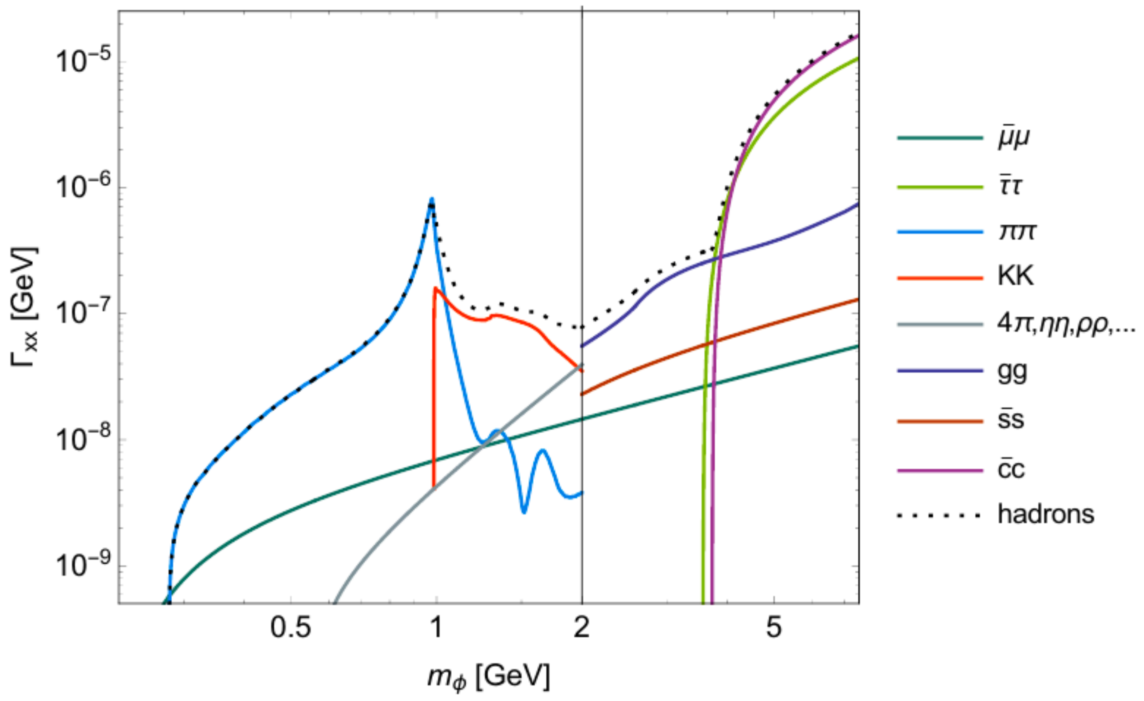
At very low mass there is insufficient phase space for the scalar to decay to a jet of multiple hadrons

Theoretical investigations of the decays of a light scalar mixing with the Higgs show that in the mass range 1-2 GeV, $a \rightarrow \pi\pi/KK$, dominates:

- At such low masses, the available decay phase space prevents the scalar decaying into jets of multiple hadrons

Final state of four hadrons will be drowned by backgrounds …

- Muon production is subdominant, but experimentally clean …



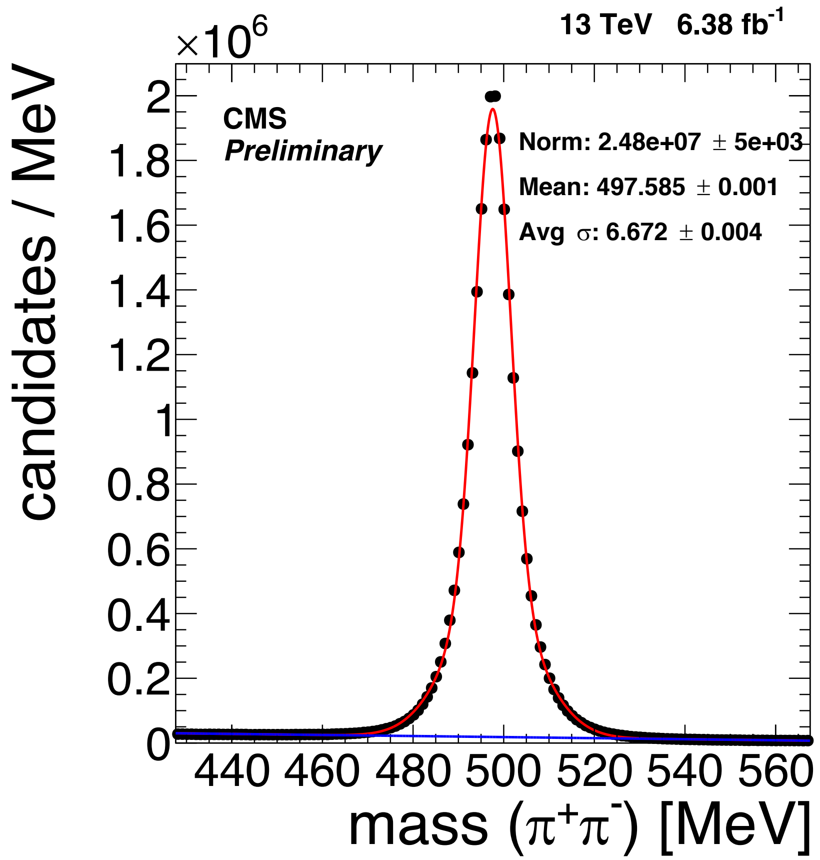
arXiv:1809.01876

Low mass BSM Higgs Decays

Cunning Plan: $H \rightarrow aa \rightarrow 2\mu + \pi\pi/KK$

Motivation:

- Can use subdominant muonic decay as a selection handle
    - Difficult to select/distinguish final state of four hadrons from backgrounds.
- CMS has excellent pion and K_S identification!



https://twiki.cern.ch/twiki/bin/view/CMSPublic/TrackingPOGPlotsICHEP2016

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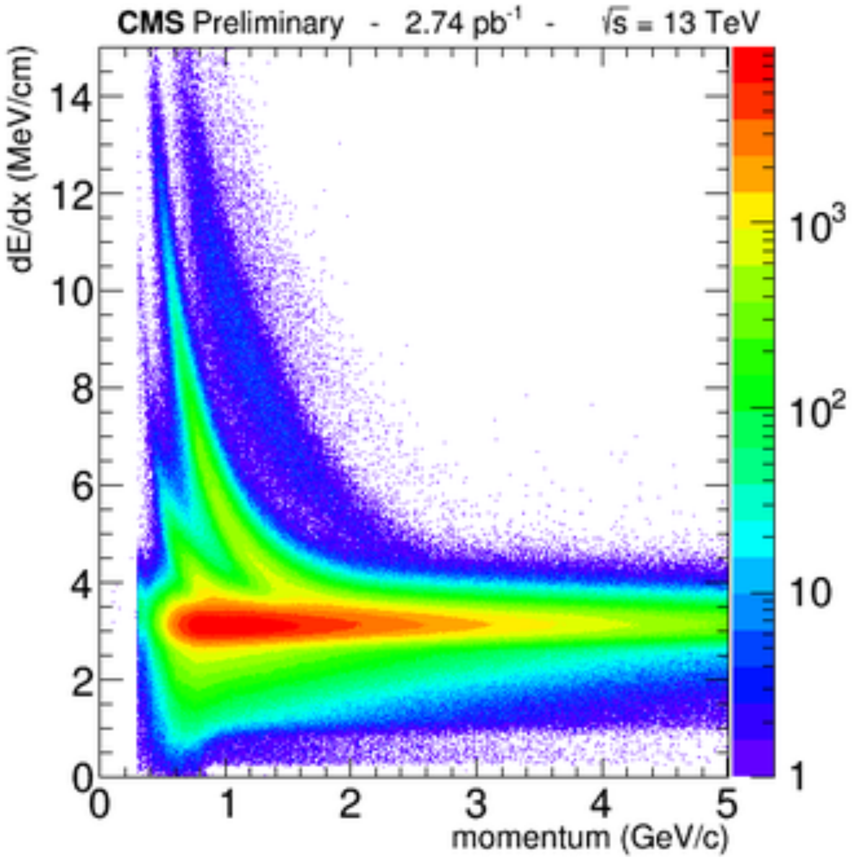
- Using charged Kaons was pointed for LHCb (*arXiv:1910.05225*) earlier …
    - CMS $K^{\pm}$ identification possible at low momenta ~1GeV



StripsOfflinePlots2015

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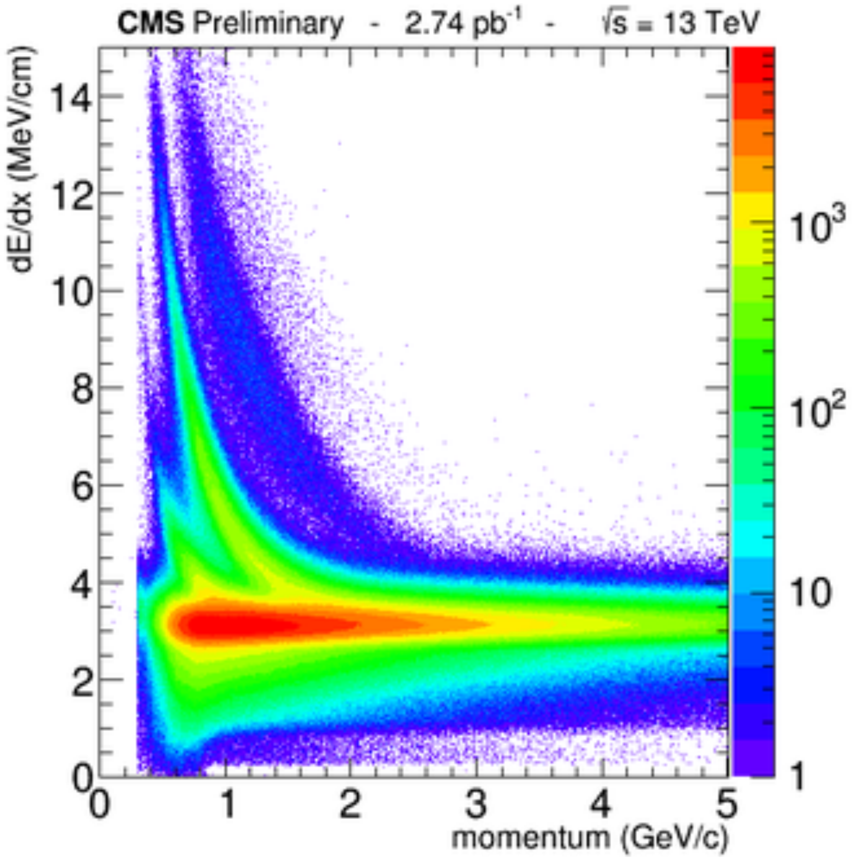
- CMS has excellent pion and K_S identification!
- Using charged Kaons was pointed for LHCb (*arXiv:1910.05225*) earlier …
  - CMS $K^{\pm}$ identification possible at low momenta ~1GeV
- Displaced vertex information can be used to reject backgrounds.
  - No complex variables should be required!



StripsOfflinePlots2015

Low mass BSM Higgs Decays
Production mechanisms

Higgs production (ggH):

- Dominant production mode at the LHC – cross section = 49pb
  - CMS Run II dataset = 135/fb → 6.6M Higgs events!
- Should this final state have been observed before?
  - Not necessarily as it is hidden by background muons from B and D meson decays and hadrons from jets.
  - A dedicated search utilising the reconstructed dimuon and dihadron masses is required.

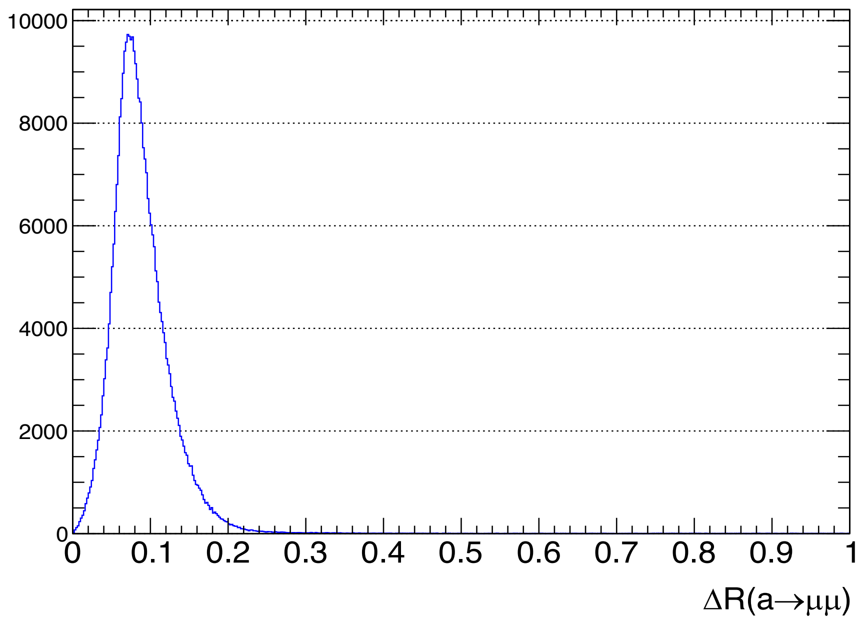
Higgs production with associated Z boson (ggHZ/ZH):

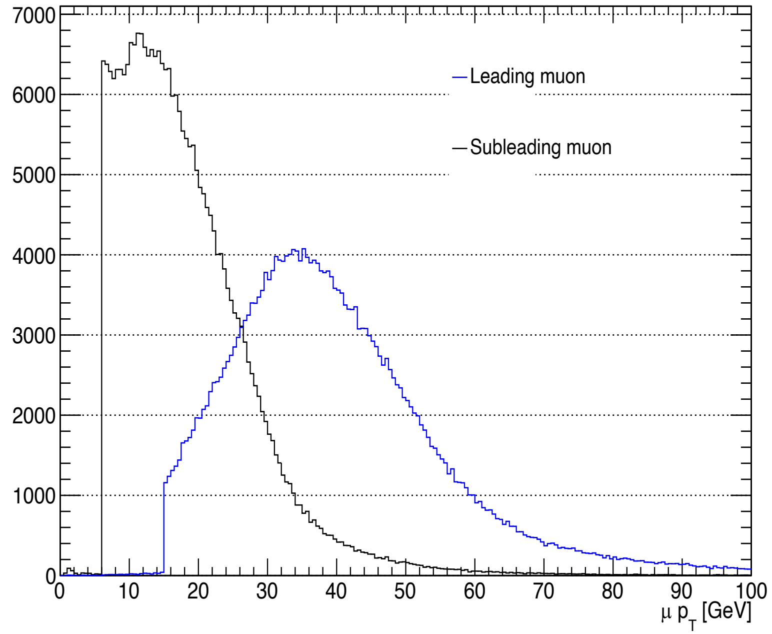
- Considered $Z \rightarrow \mu\mu; H \rightarrow 4$ hadrons, but …
  - Cross section gg→HZ ($Z \rightarrow \mu\mu$) = 0.88 pb x 3.4% = 0.03 pb
  - Factor of 1640 smaller than ggH!
  - Recall $BR(a \rightarrow \mu\mu) \sim 10^{-2} - 10^{-1}$ for $1\ GeV < m_a < 2\ GeV$, so *ggH production* always *dominates!*

Strategy
Understanding Trigger Performance

Final state relies on identification of 2μ naturally leads to considering muon triggers and datasets.

- Given momenta and collimation of the signal's muons, *ideally* we want the trigger to:
  - have as low a p_T threshold as possible;
  - be robust against increasingly displaced muon production;
  - and as loose a muon isolation requirement as possible.

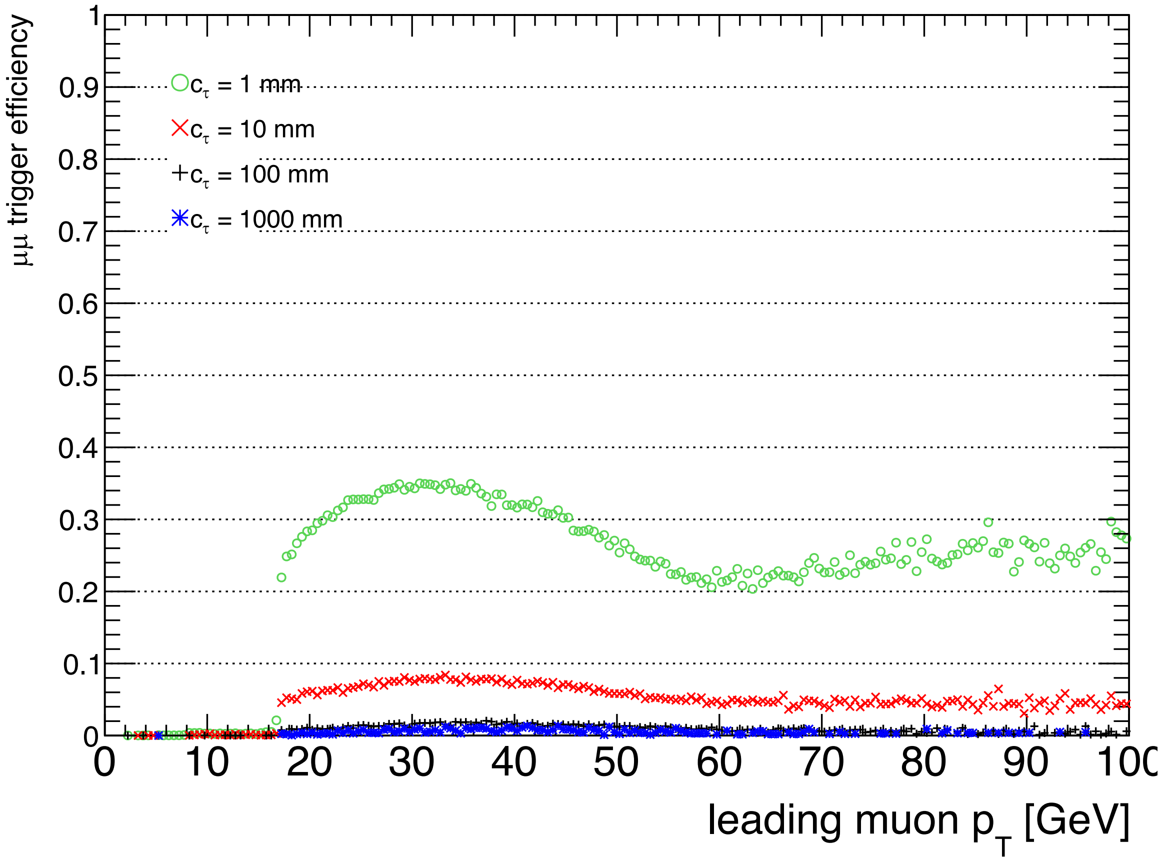




Strategy
Understanding Trigger Performance

Final state relies on identification of 2μ naturally leads to considering muon triggers and datasets.

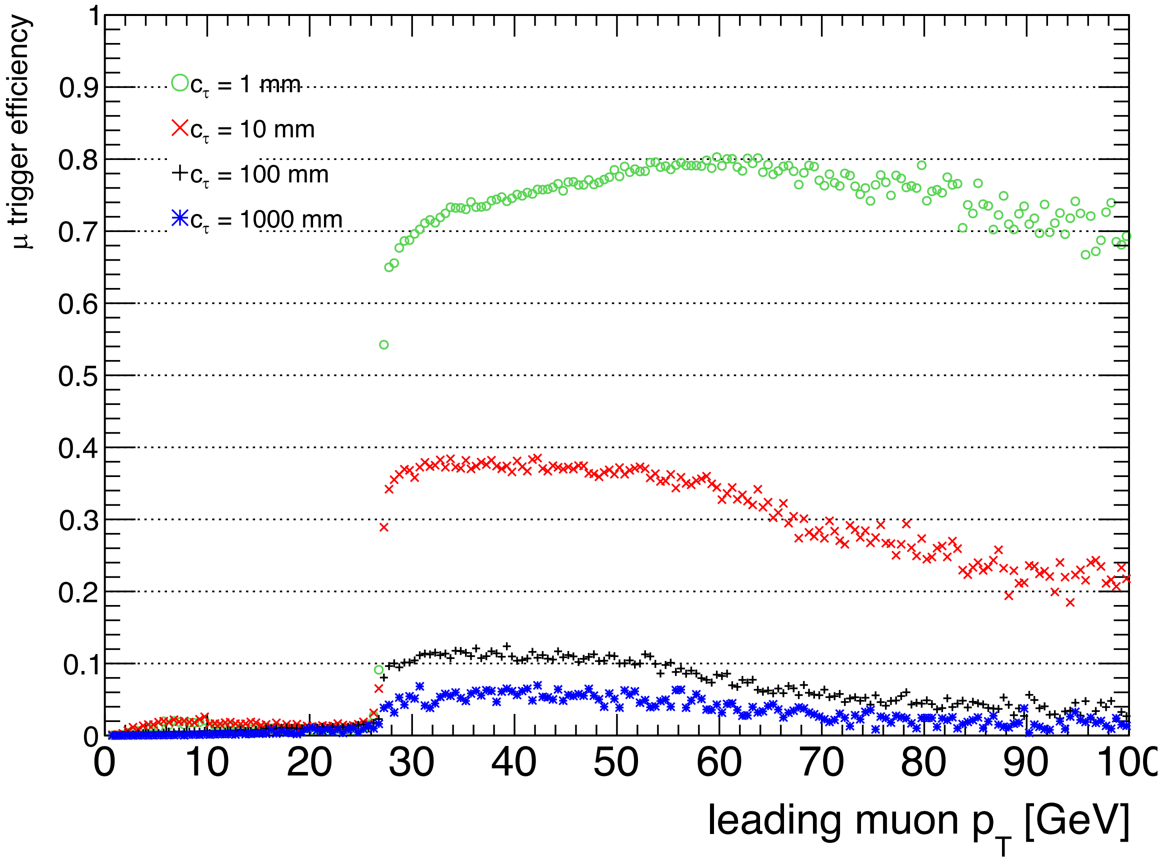
- **Double muon triggers?**
  - Trigger imposes a very very loose isolation and DZ requirements on the muons.
    - Highly collimated production results in subleading muon not being triggered.
    - Increasingly inefficient with increasing displacement …



Strategy
Understanding Trigger Performance

Final state relies on identification of 2μ naturally leads to considering muon triggers and datasets.

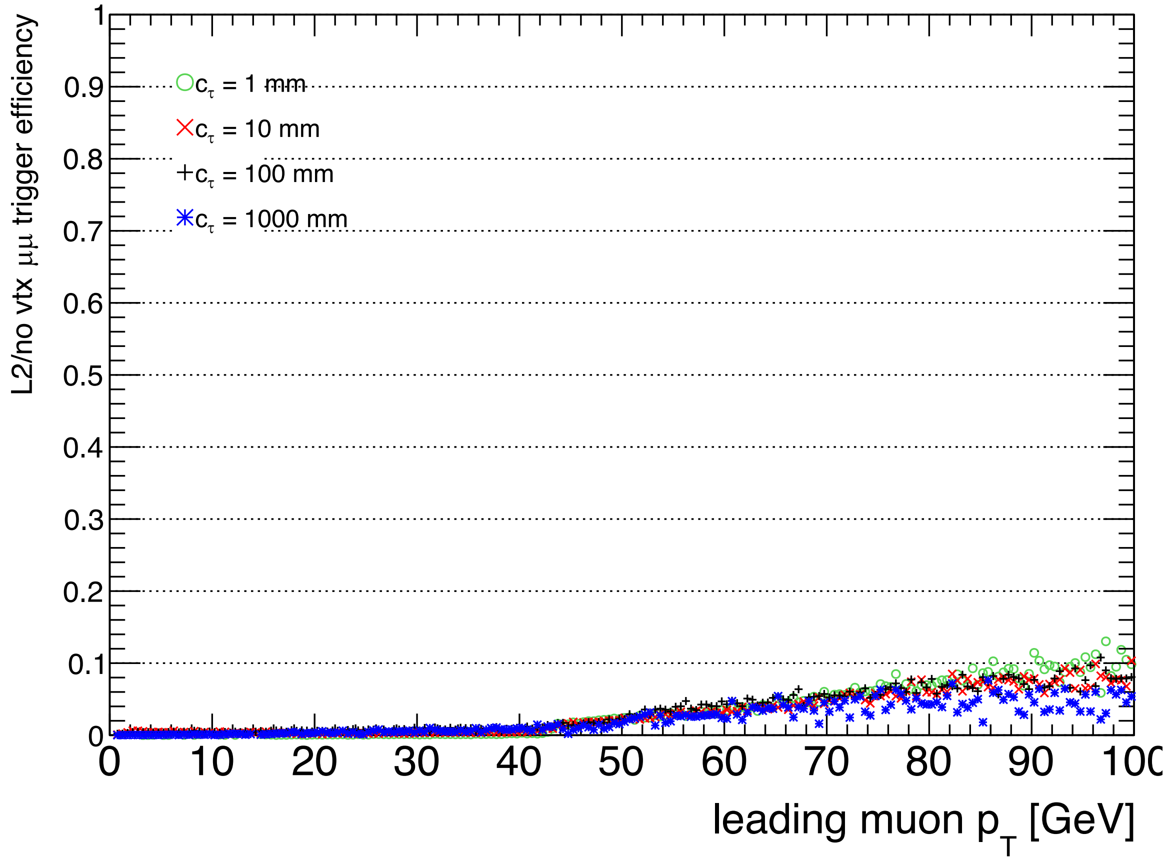
- **Double muon triggers**
- **Single muon triggers?**
  - Higher p_T threshold but more highly efficient with no isolation requirement on the subleading muon
  - Trigger efficiency also suffers as displacement increases.



Strategy
Understanding Trigger Performance

Final state relies on identification of 2μ naturally leads to considering muon triggers and datasets.

- **Double muon triggers**
- **Single muon triggers**
- **L2 only muon/no muon vertex triggers?**
  - Very inefficient!
  - Requiring no vertex/only L2 muons does mitigate against losses from displacement.
  - Higher p_T requirements discard significant fraction of signal.



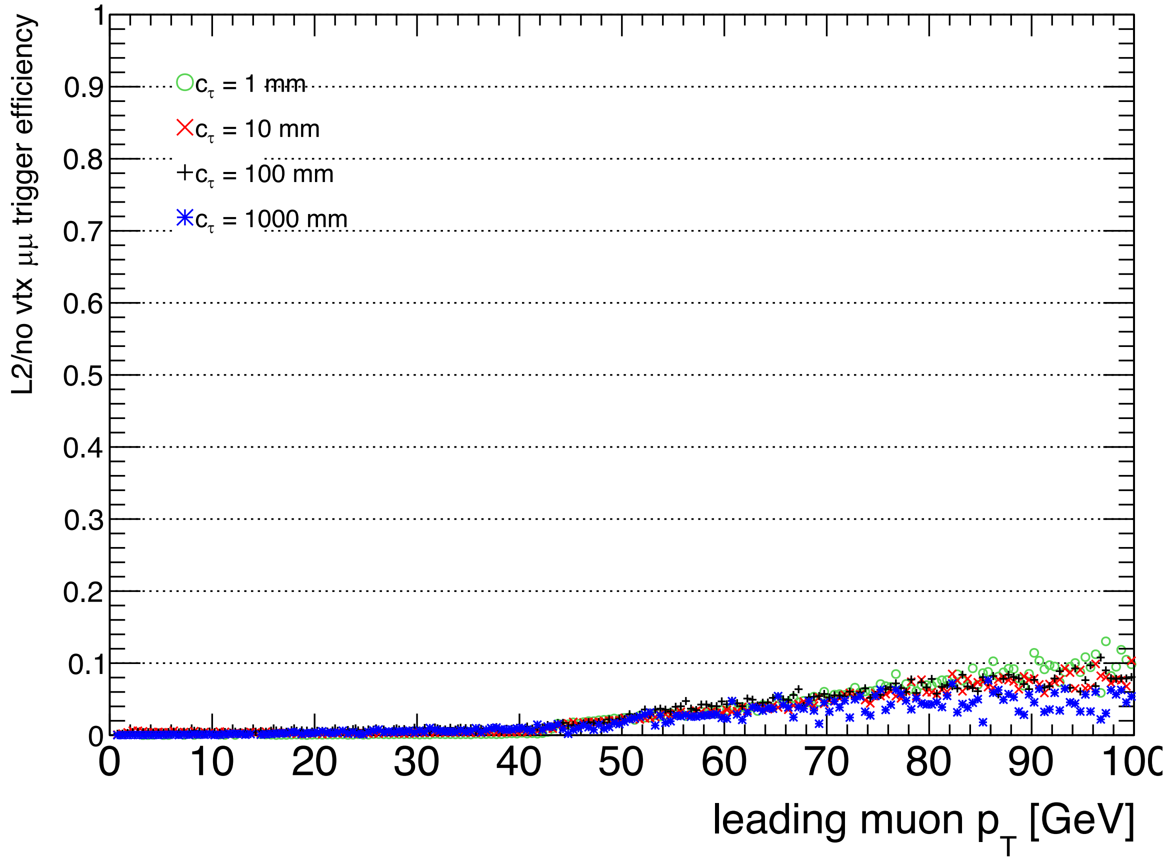
Strategy
Understanding Trigger Performance

Final state relies on identification of 2μ naturally leads to considering muon triggers and datasets.

- **Double muon triggers**
- **Single muon triggers**
- **L2 only muon/no muon vertex triggers**

Single muon trigger is the most optimal trigger available:

- **No isolation on 2nd muon.**
- **Need to better understand how displacement impacts trigger turn-on for signal processes.**



Strategy

Strategy: Background discrimination

Currently: working to understand both signal and backgrounds processes using 2017 conditions, before progressing making a data-driven estimate at the background and considering looking at the complete Run-2 dataset.

Strategy
Background discrimination

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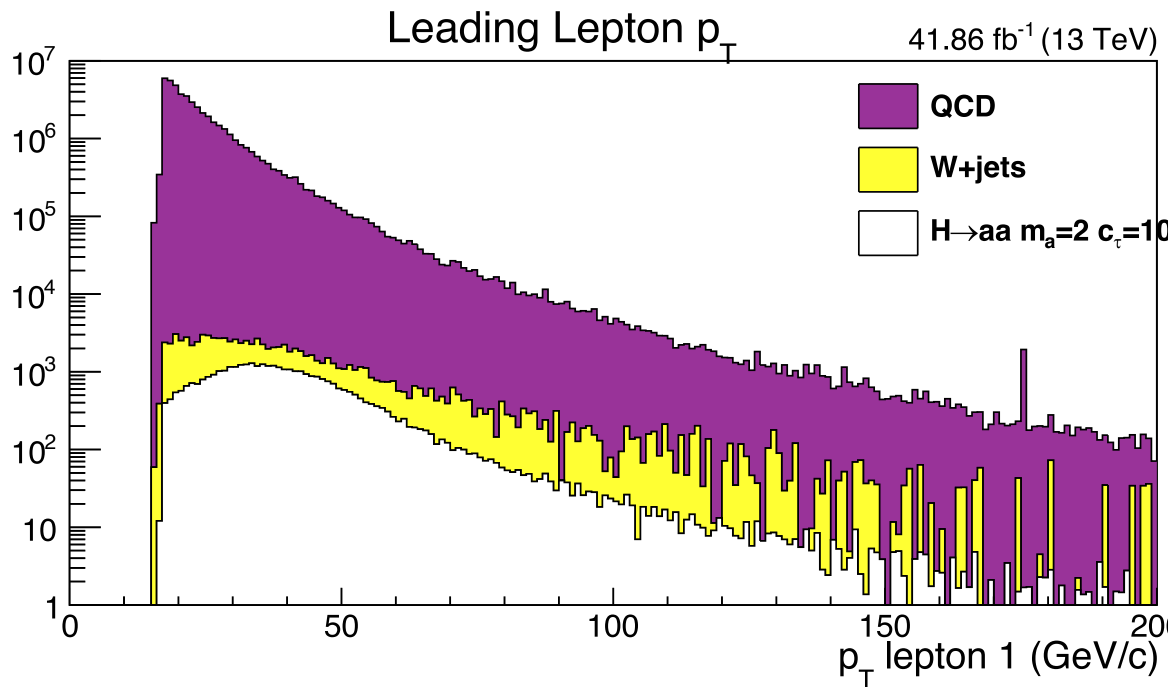
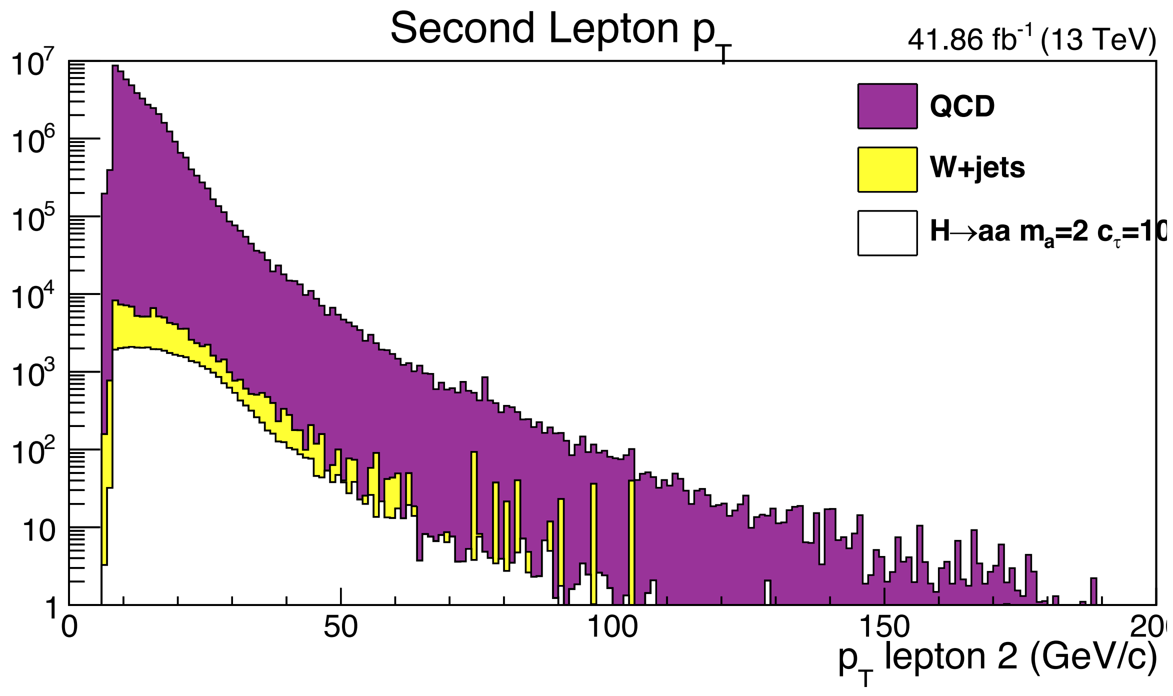
So:

- What are the main backgrounds?
  - QCD, EW 2μ + jets, 1μ + 1μ (non-prompt) + jets,
- Can scalar decay products and vertex information be used to distinguish against backgrounds?

Strategy
Background discrimination

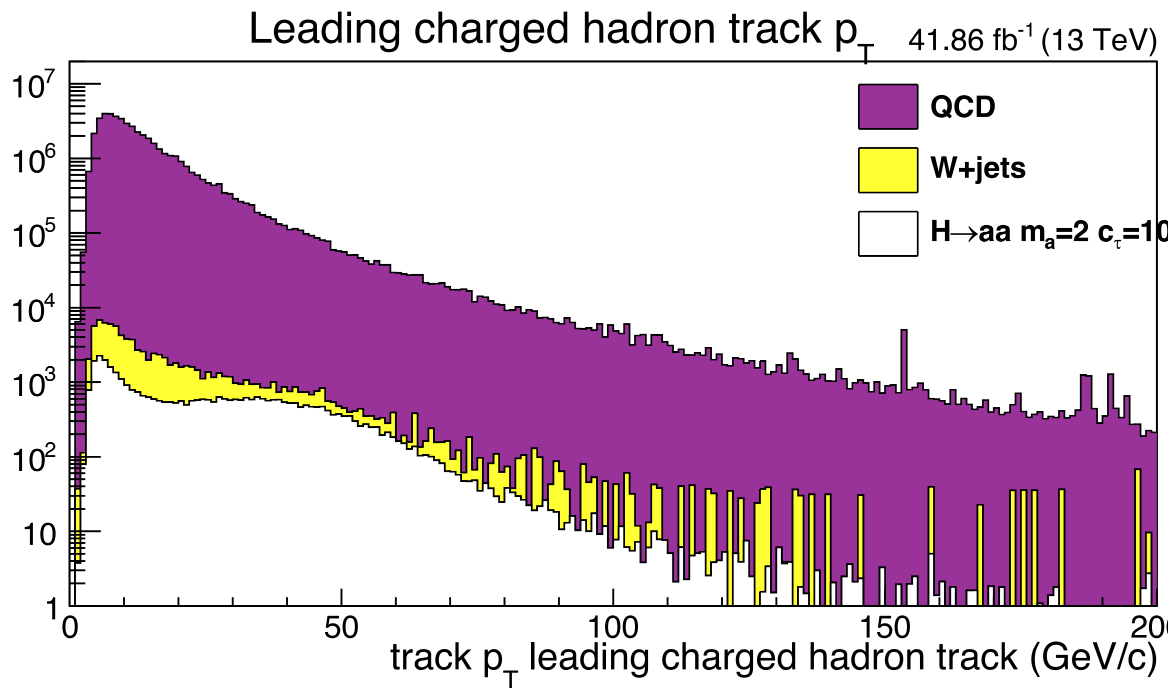
Post-loose offline muon selection (PF muon + tracks), reconstructed muons' physics well describes the signal muons' physics seen at the generator level.

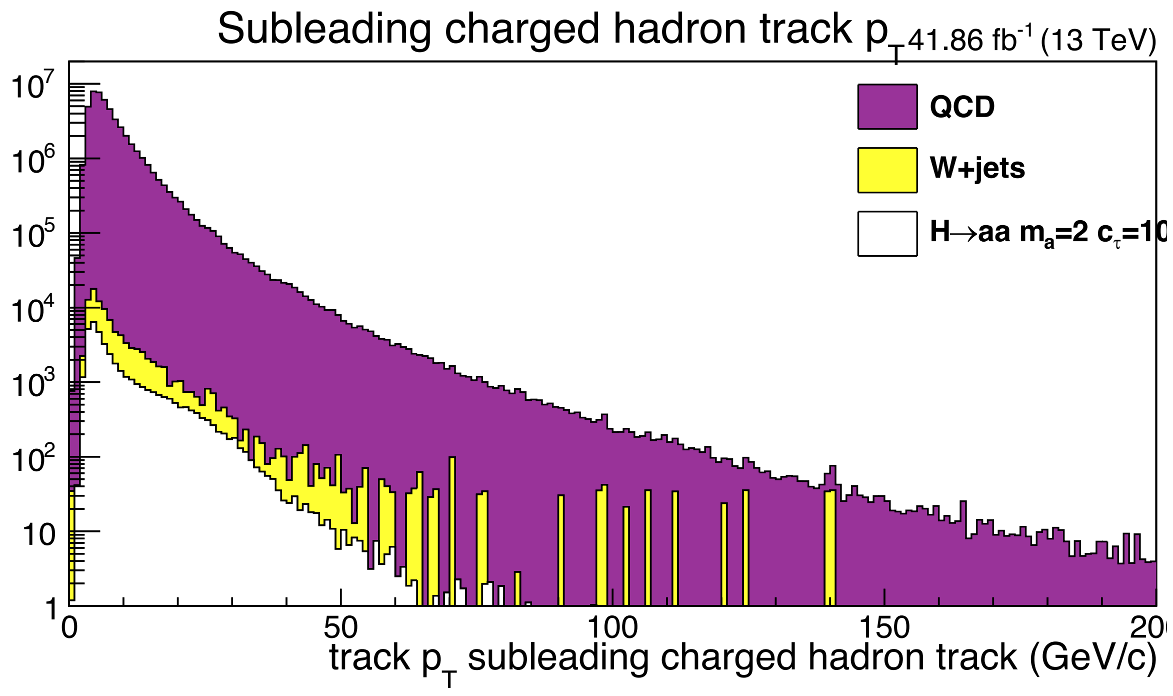




Strategy
Background discrimination

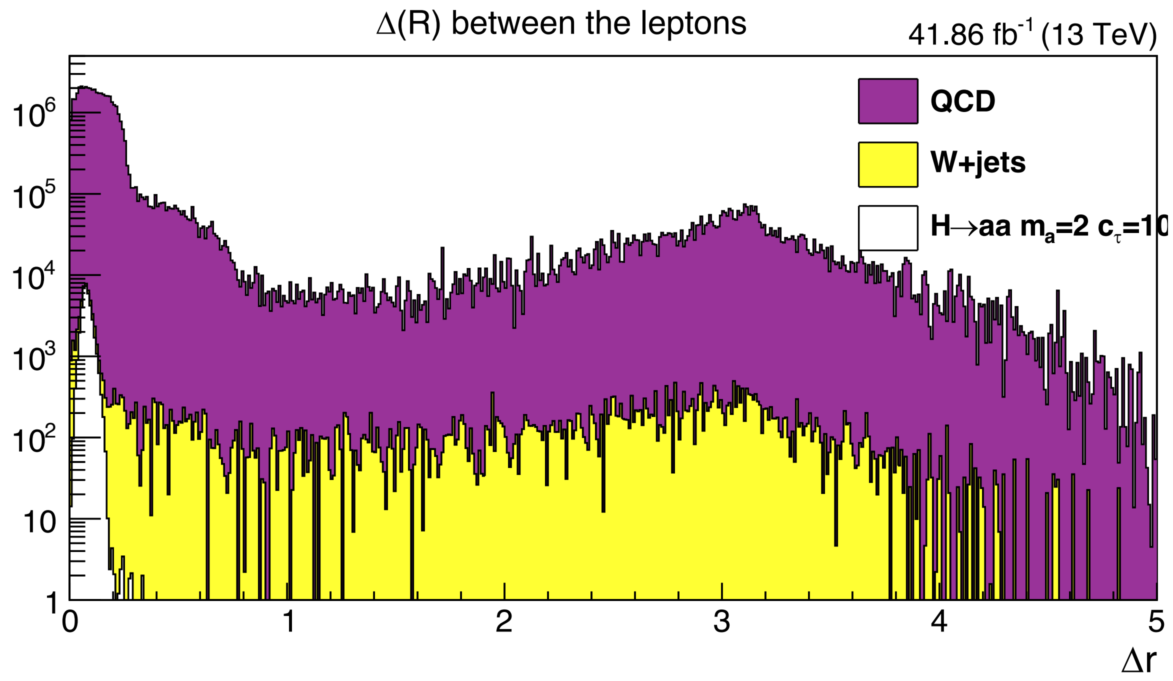
A lower pT spectra observed for selected charged hadron tracks is not unexpected given that these objects are not as experimentally clean as muons.

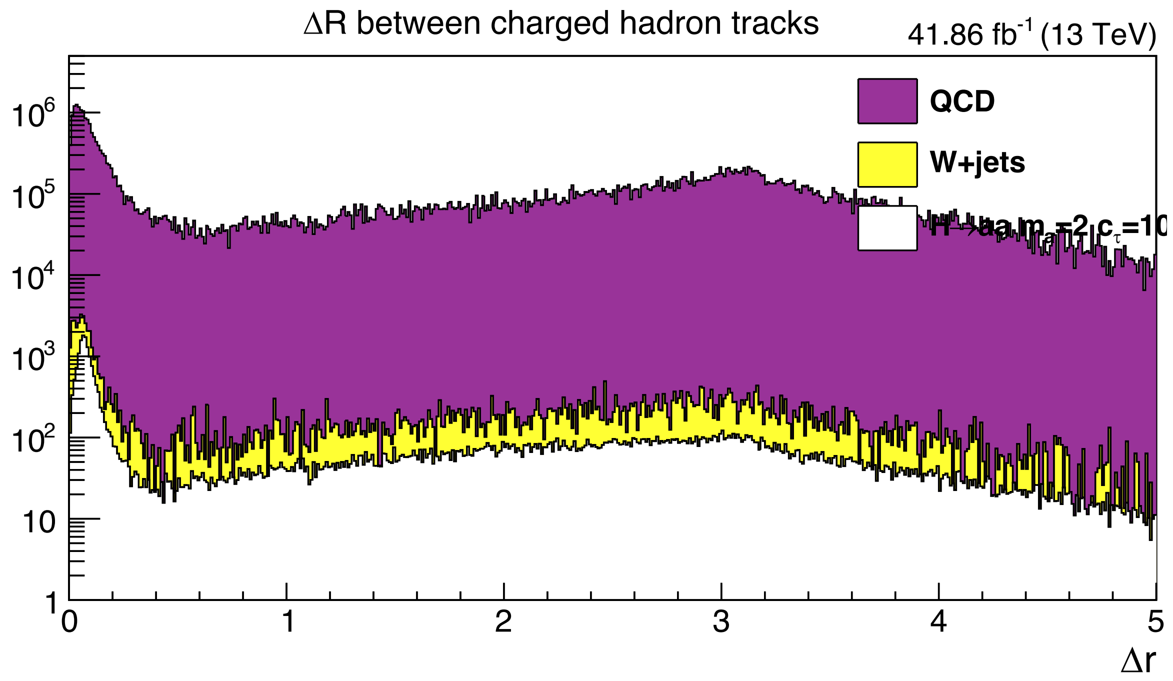




Strategy
Background discrimination

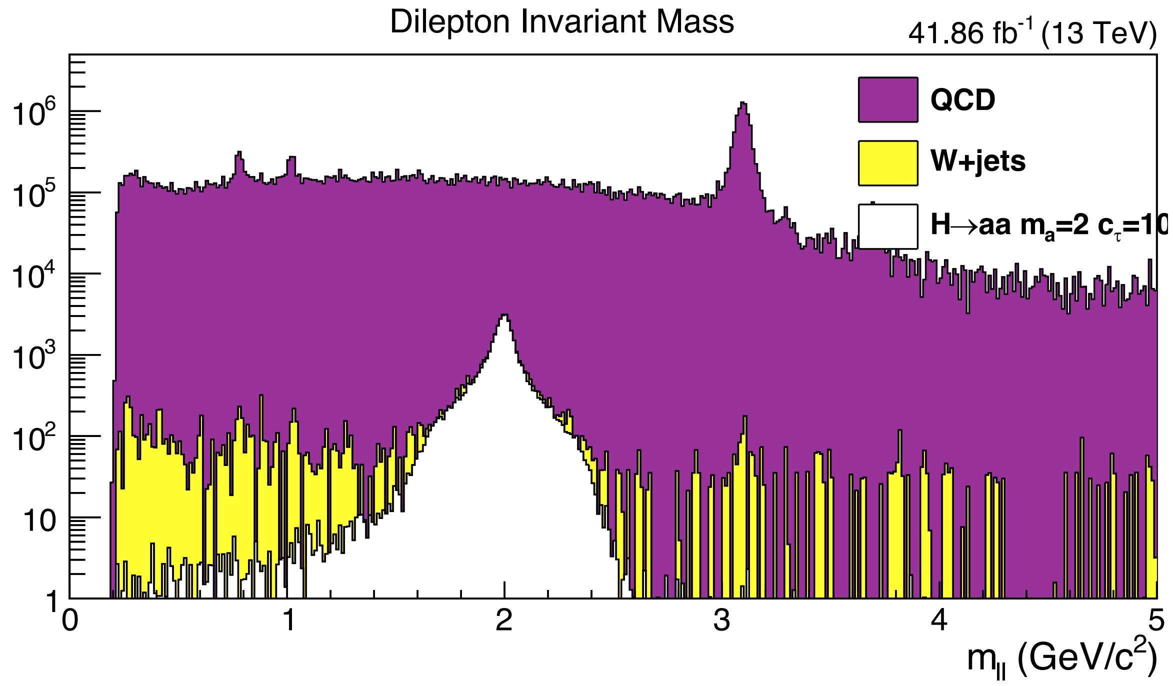
Muons/charged hadrons from scalar decays are highly collimated. The long tail observed for charged hadron tracks results an incorrect selecting charged tracks not from the scalar decay.

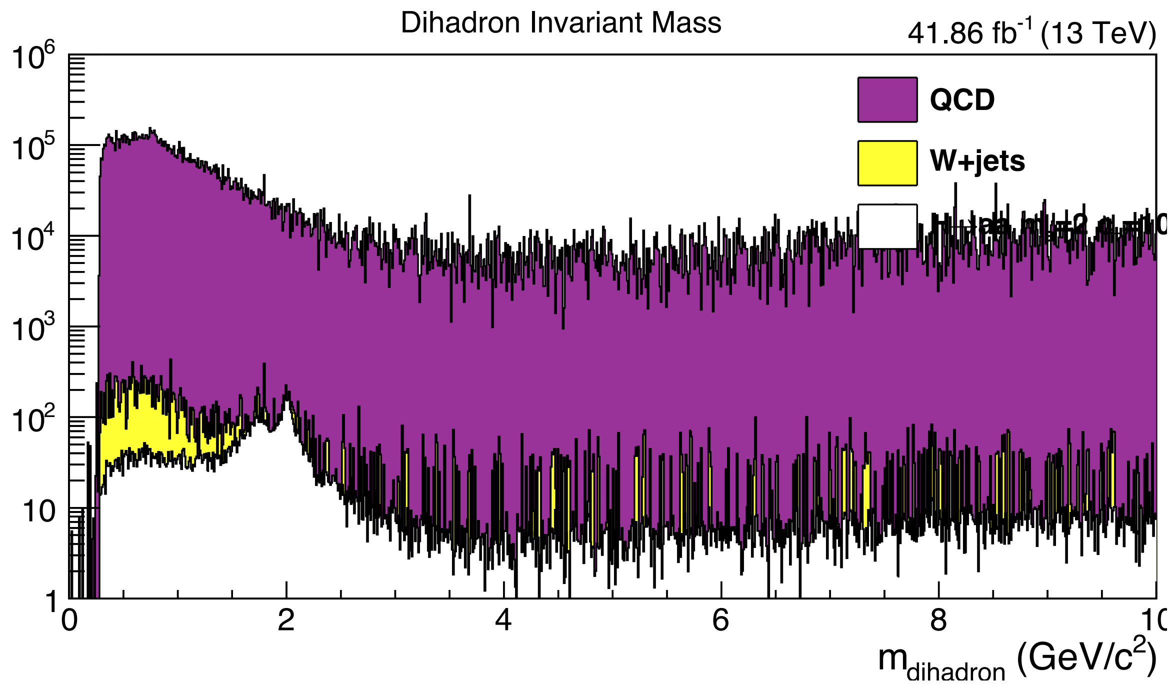




Strategy
Background discrimination

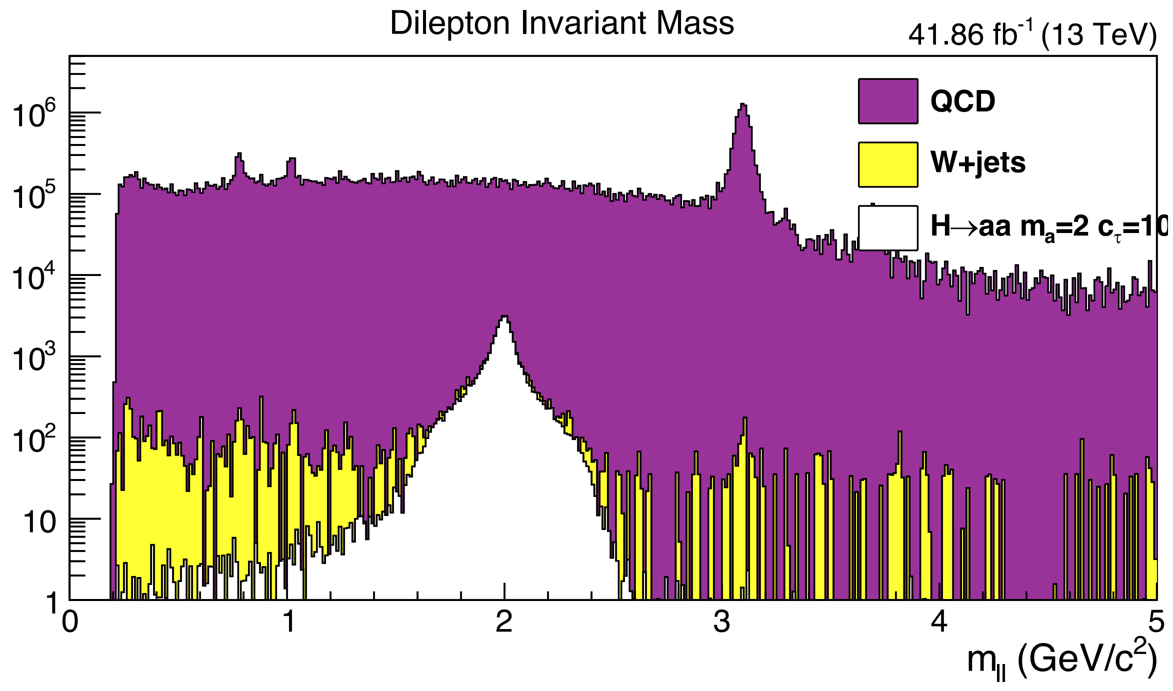
Clear scalar mass peaks are observed for both muons and charged tracks. A smaller secondary peak is observed to the left of the scalar mass peak for charged hadron tracks. Tracks assumed to be pions, but kaons also present in signal sample!

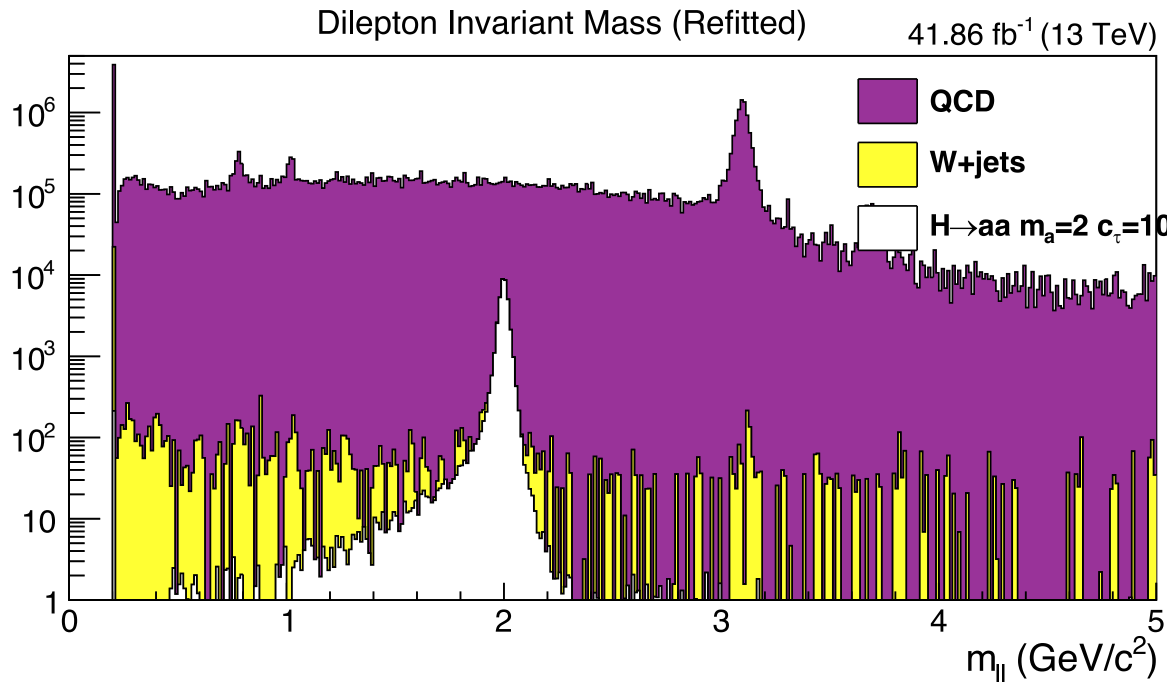




Strategy
Background discrimination

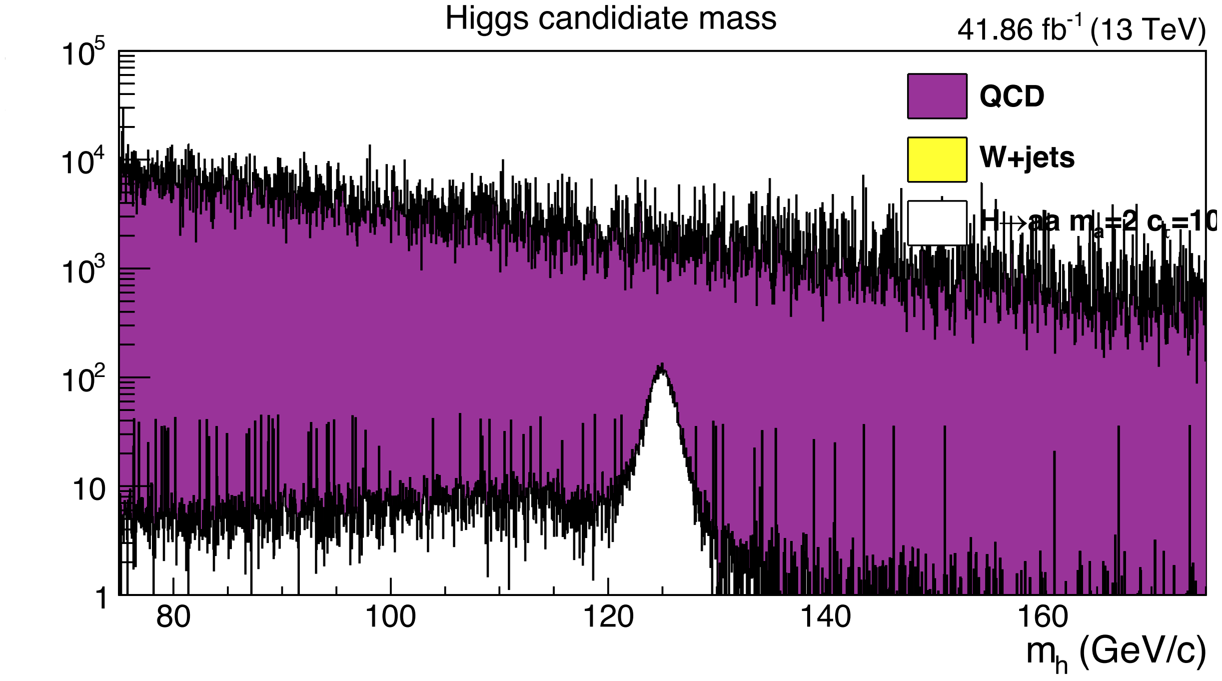
As it is known that scalar decay products will be produced from a displaced vertices, their tracks can be revertexed and refitted to improve the signal resolution.

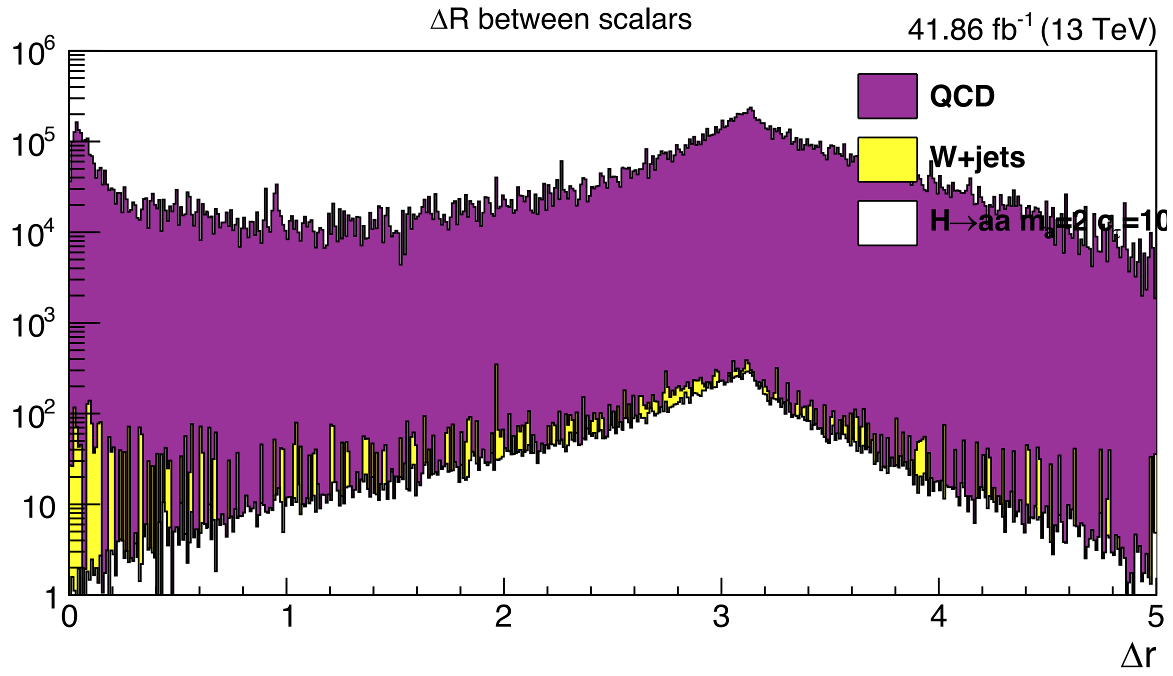




Strategy
Background discrimination

Similarly, a clear Higgs mass peak can be reconstructed from the scalar decay products and the scalars are, as expected, produced back-to-back. Long tails are the result of the incorrect charged track matching.



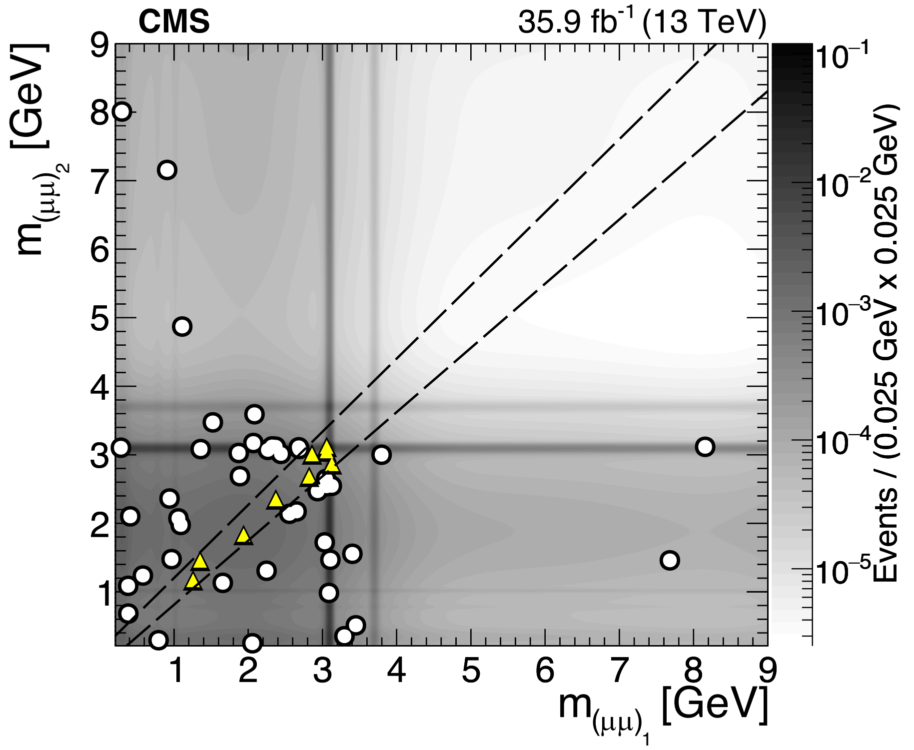


Strategy
Background Estimation

Considering potential background estimation methods …

One option takes inspiration from the previous CMS search for $H \rightarrow aa \rightarrow 2\mu + 2\mu$:

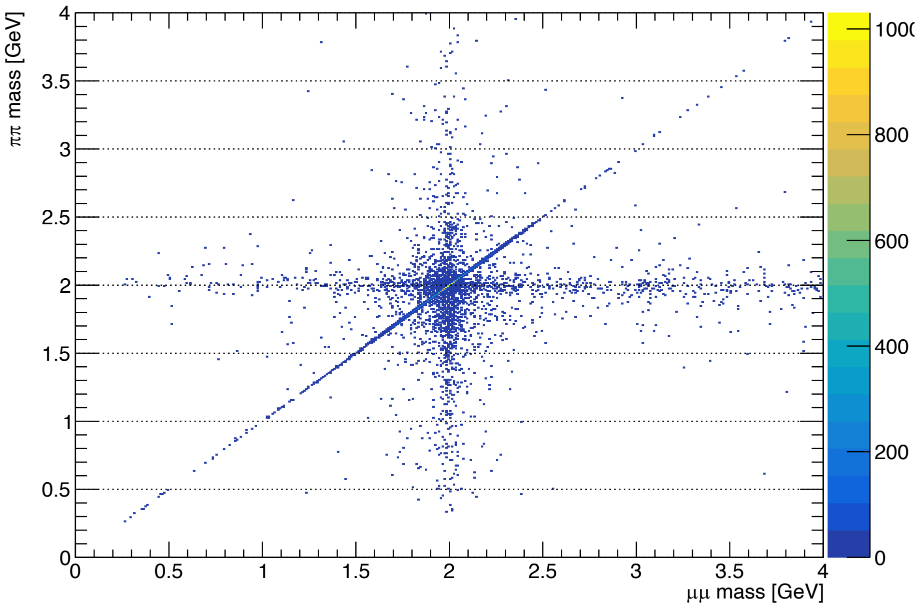
- Covers similar mass ranges and has similar backgrounds (QCD + EW 2μ + jets vs QCD + EW 4μ)
- Uses ABCD method:
    - Use isolation of each of the muon pairs as uncorrelated variables.
    - A (signal region) is bounded by $Iso_{\mu\mu} < 2$ GeV
    - B, C and D are non-isolated side band regions used to extrapolate into the signal region.



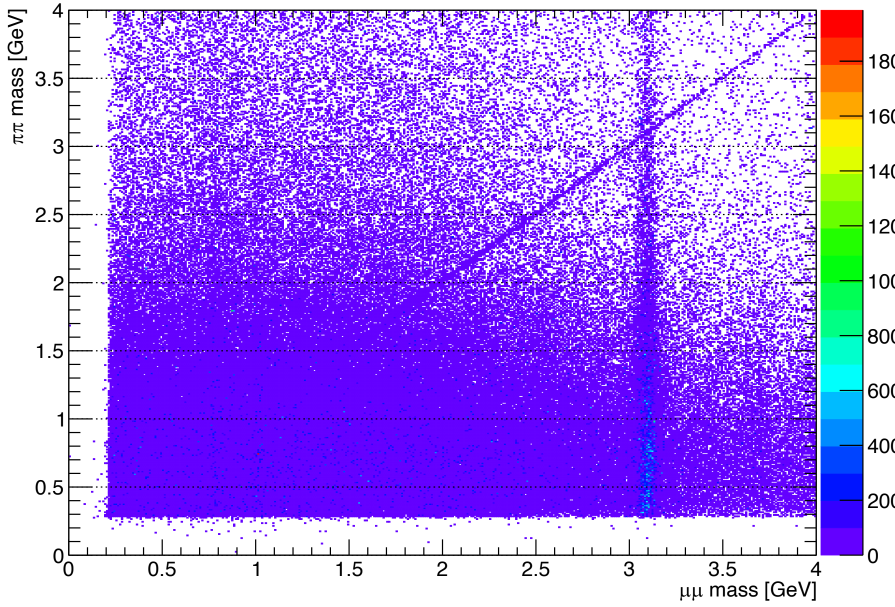
CMS-HIG-18-003 (arXiv:1812.00380)

Strategy
Background Estimation

- Signal for this search is similarly well bounded and defined by each reconstructed scalar mass.
- Whilst J/ψ and other light meson production can be clearly seen outside of the signal production window, a diagonal enhancement is present in both signal and background and needs understanding.
- Plan to investigate this methodology more thoroughly in the New Year!



Signal: m_a = 2 GeV; c_τ = 10mm

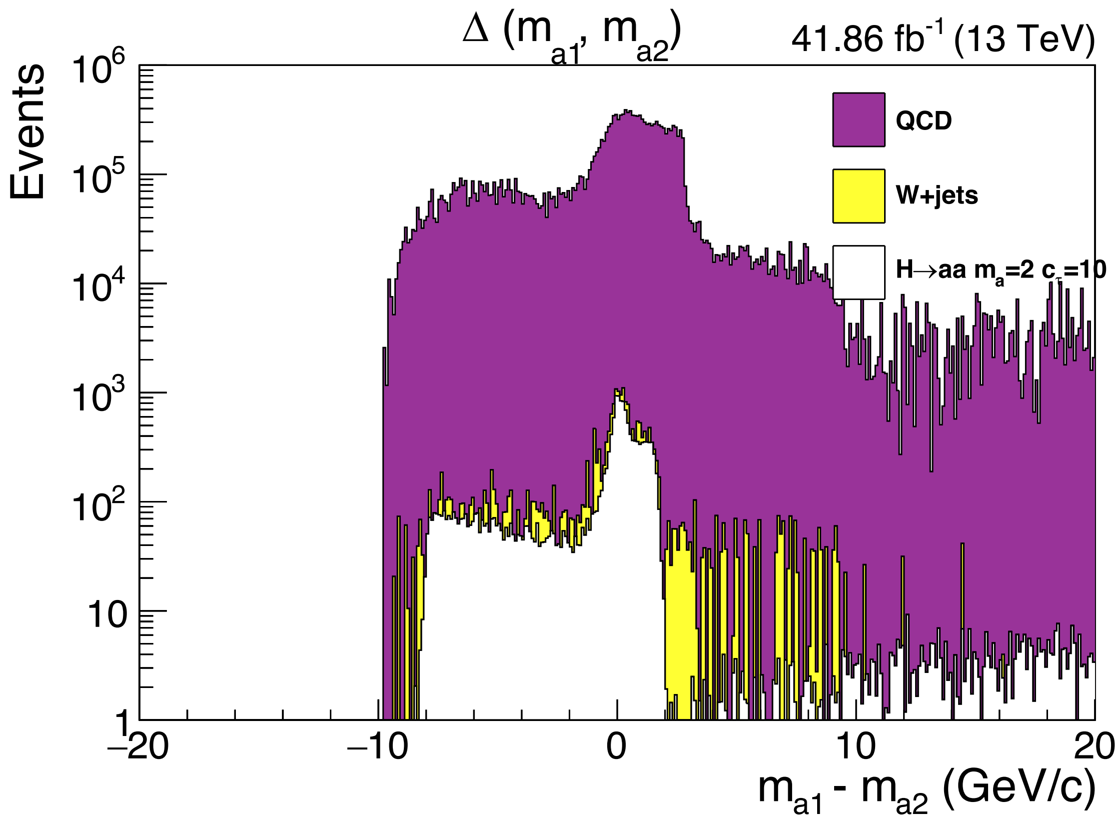


QCD

Strategy
Background Estimation

Another idea being considered for a background estimate involves:

- Signal region: window around a well-defined difference of scalar masses. Taking advantage of refitted vertices
- Side band regions: either side of the signal window.



Clear signal/background separation is observed, but impact of the "diagonal enhancement" on the previous slide needs quantifying.

Summary and Outlook

Plan:

- Undertake a unique first search for low mass scalars using a pair of muons and hadrons at CMS.
- Take advantage of experimentally clean muon decays and lack of hadronic decays into multiple jets to use precise tracking/vertexing information to distinguish against backgrounds.
- Determine an appropriate data-driven background estimation method to model backgrounds.
- Use full CMS Run-II dataset for this search and interpret results as appropriate.

Current Status:

- Flexible analysis framework established – quickly adaptable to needs as they develop.
- Masters student from University of Antwerp has been studying physics of the signal process.
- Established signal features can be used as a handle to supress backgrounds.

Outlook:

- Promising foundation needs to be swiftly built upon – finalise event selection and background estimation, and work on determining systematic uncertainties.
- New PhD student will join us in the New Year – plenty of opportunities to get involved, e.g $a \rightarrow K_S^0 \overline{K_S^0}$

Fin

BACKUP

BACKUP – Signal MC Details

Private MC (Full SIM) generated using POWHEG ggH gridpack

- Pythia 8 prescribes Higgs to decay to a pair of scalar bosons.
- One scalar *always* decays into a pair of *muons*.
- One scalar *always* decays into a *quark-antiquark pair*.
  - Generator filter only accepts charged pions, charged kaons, or k-shorts
- Samples produced:
  - Scalar masses: 1GeV or 2 GeV
  - Proper lifetimes: 1mm/c, 10mm/c, 100mm/c, 1000m/c (*0mm/c in production*)

BACKUP – Background MC Details

CMS 2017 MC re-miniAOD 12April2018

QCD (MuEnrichedPt5):

- p_T binned: 15-20, 20-30, 30-50, 50-80, 80-120, 120-170, 170-300, 300-470, 470-600, 600-800, 800-1000, 1000-Inf
- Total statistics: 265236163 events

Z+jets (p_T binnded):

- p_T binned: 0-50, 50-100, 100-250, 250-400, 400-650, 650-Inf
- Total statistics: 299620682 events

W+jets:

- Inclusive sample: 77700506 events

$t\bar{t}$:

- Hadronic decays: 130262440 events
- Semileptonic decays: 110014744 events
- Leptonic decays: 69155808 events