Search for long-lived Heavy Neutrinos in B decays

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Motivation

- Flavour oscillation of Standard Model (SM) neutrinos

  - At least two SM neutrinos are massive

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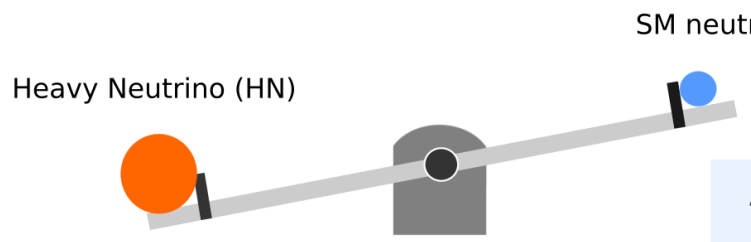
$\alpha, \beta = (e, \mu, \tau)$ $\quad \nu_\alpha \longrightarrow \nu_\beta$

  - At least two SM neutrinos are massive

- How to generate the SM neutrinos mass?
  - A possible mechanism is the Seesaw Mechanism
  - Introduction of **Heavy Neutrinos (HNs)**

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R^c\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix} + \text{h.c}$$

$m_D \ll M$



$m_\nu = \frac{m_D^2}{M}$

$\nu \approx (\nu_L + \nu_L^c)$

$m_{\text{HN}} = M$

$\text{HN} \approx (\nu_R + \nu_R^c)$

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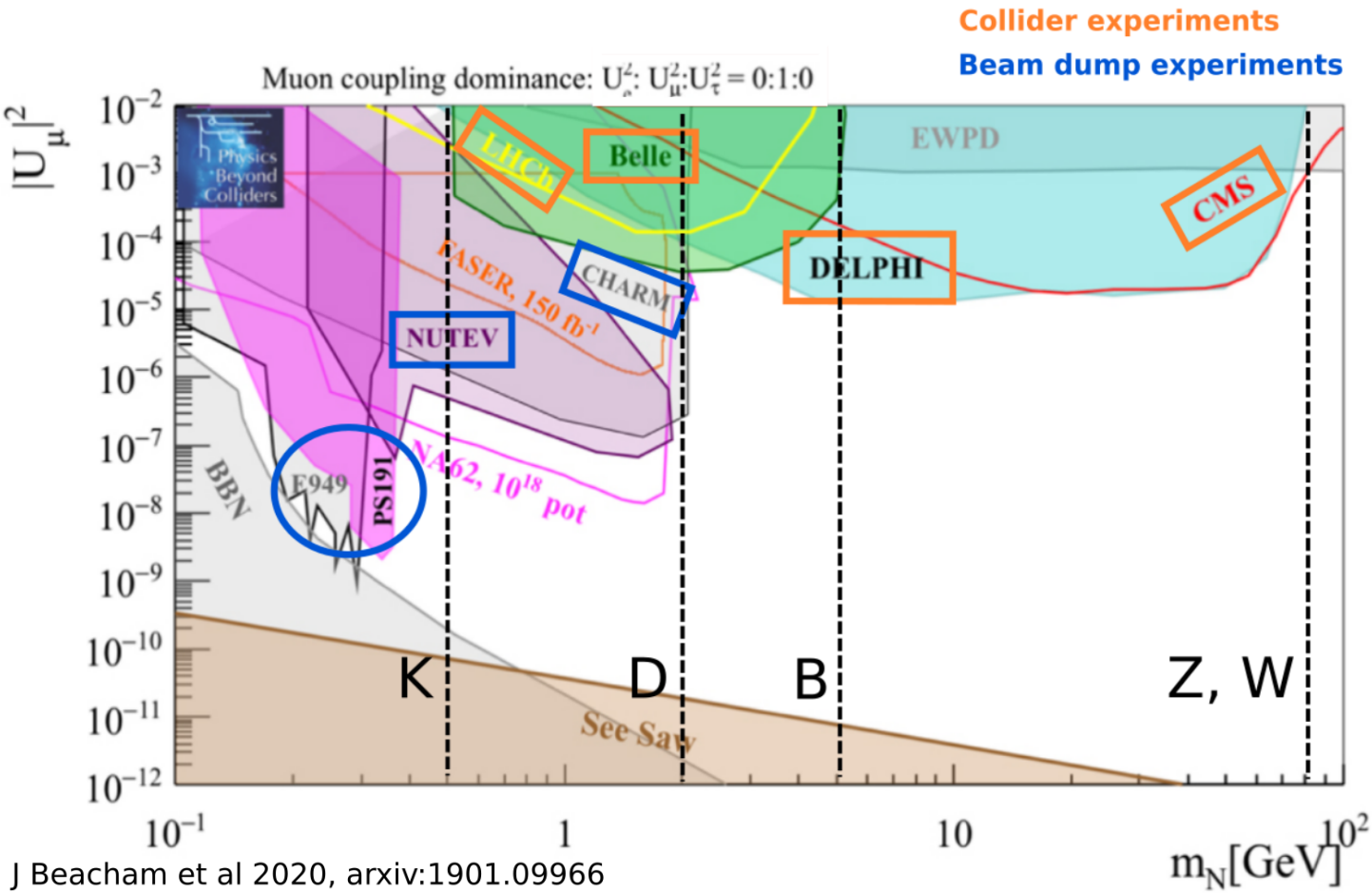
νMSM [1]

- Mechanism for baryogenesis
- Masses of Heavy Neutrinos below the EW scale ($\mathcal{O}$ (100GeV))
- Sterile particles: do not couple to the SM gauge bosons

[1] Asaka, T., Blanchet, S., & Shaposhnikov, M. (2005), arxiv:hep-ph/0503065

Experimental overview



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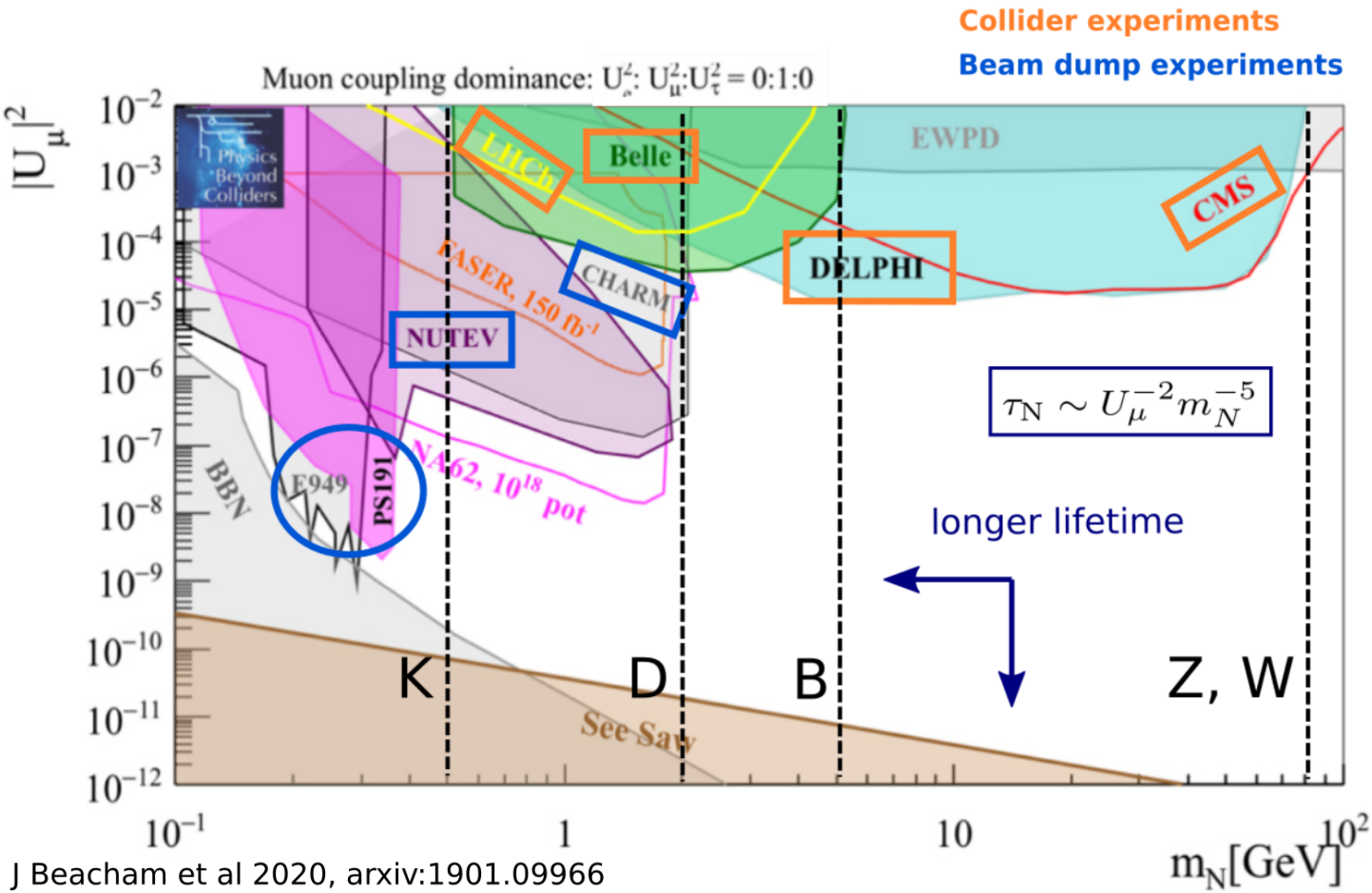

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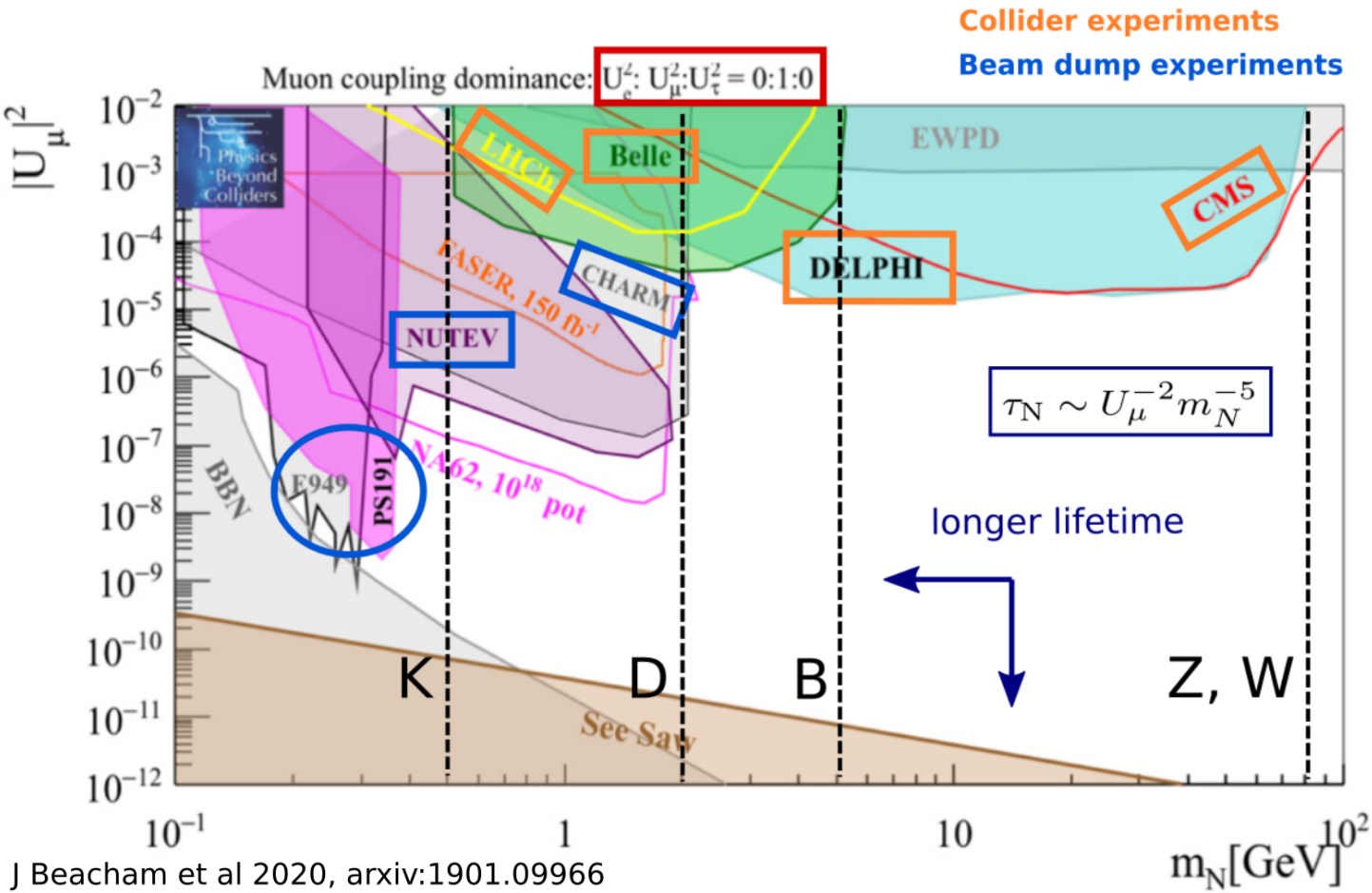

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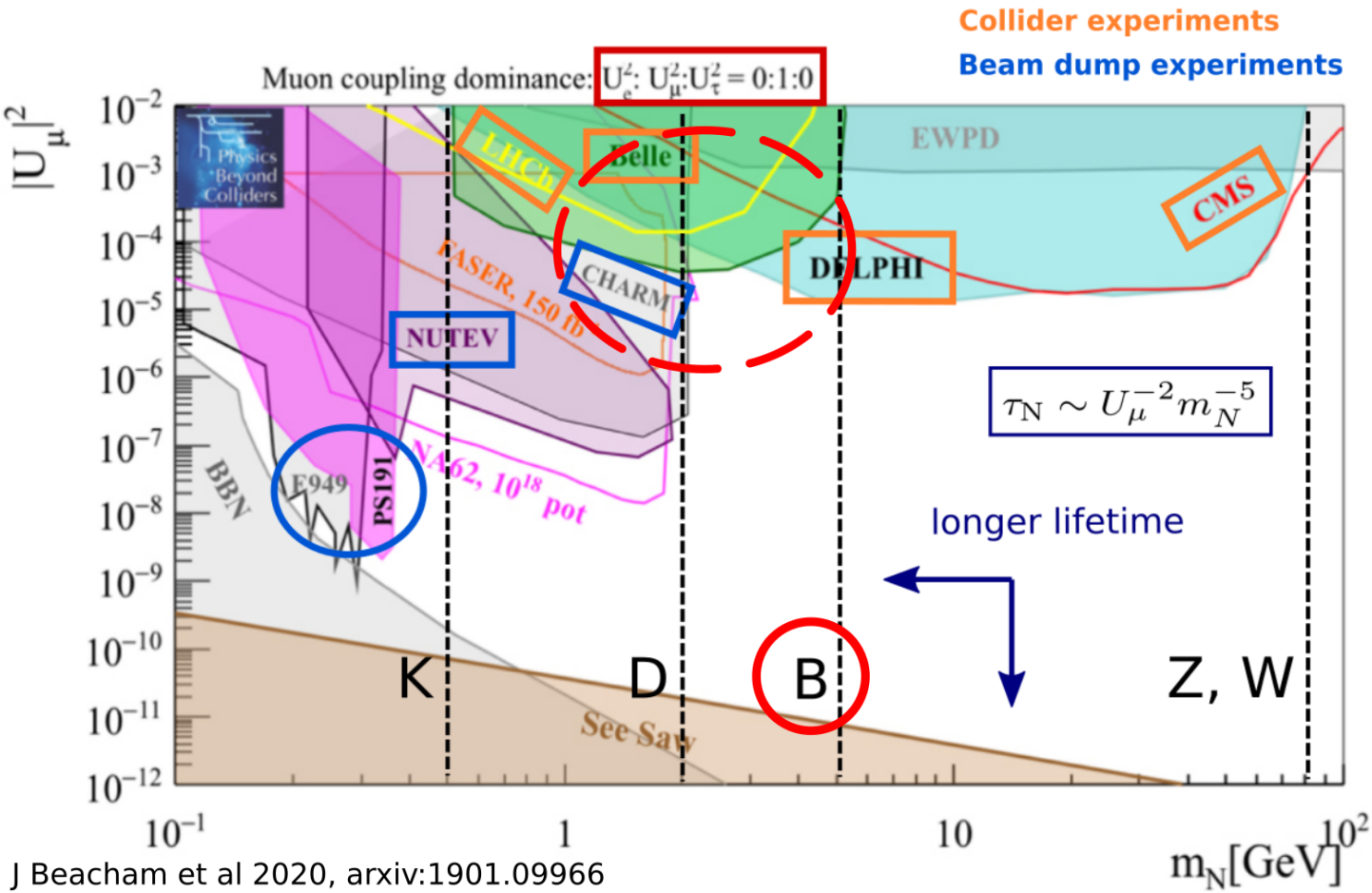

- Search for long-lived Heavy Neutrinos in B meson decays with CMS
  - Abundant source of SM neutrinos
  - Daughters of B meson less boosted than those of W ⇒ better acceptance

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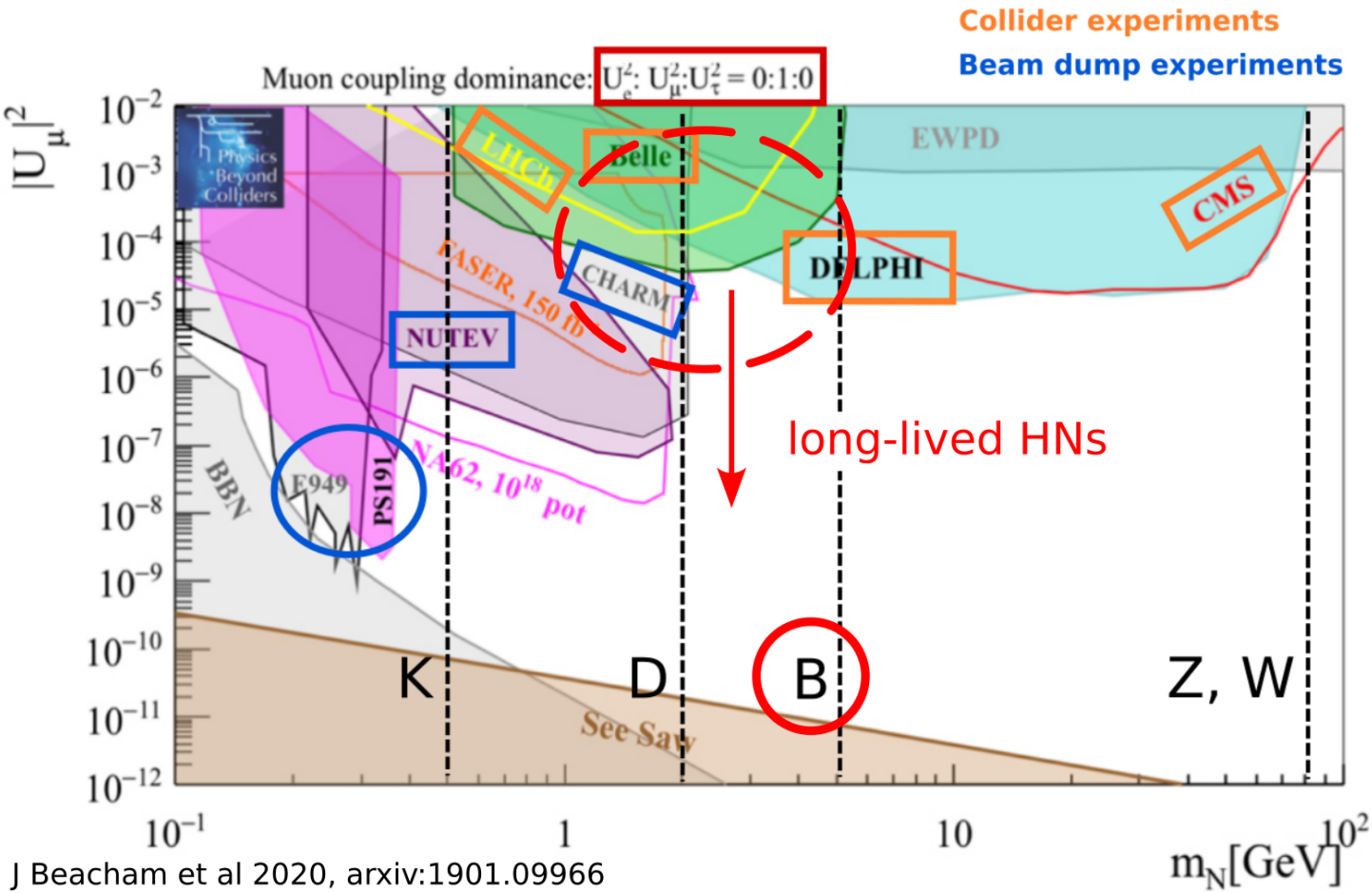

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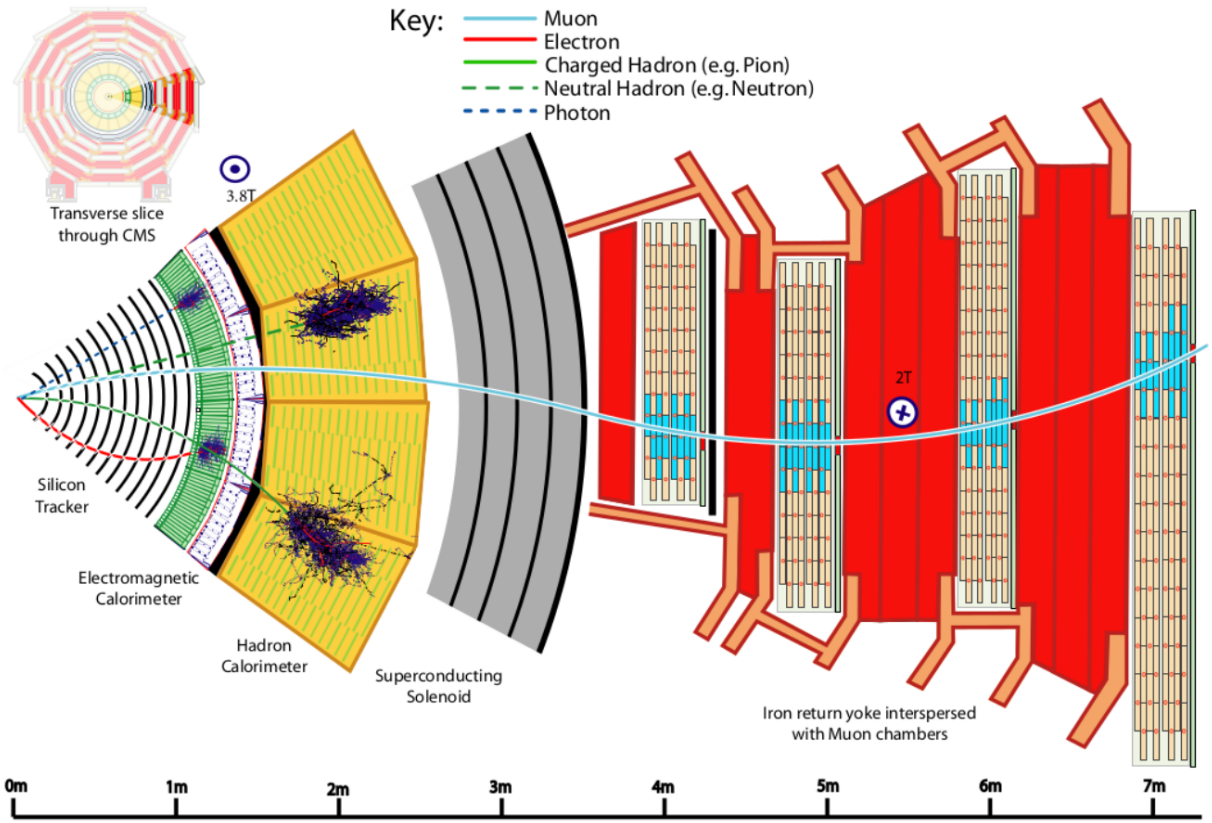
CMS experiment

- One of the four experiments at CERN-LHC
  - Proton-proton collisions, $\sqrt{s} = 13$ TeV
- General-purpose detector



Transverse slice of the CMS detector

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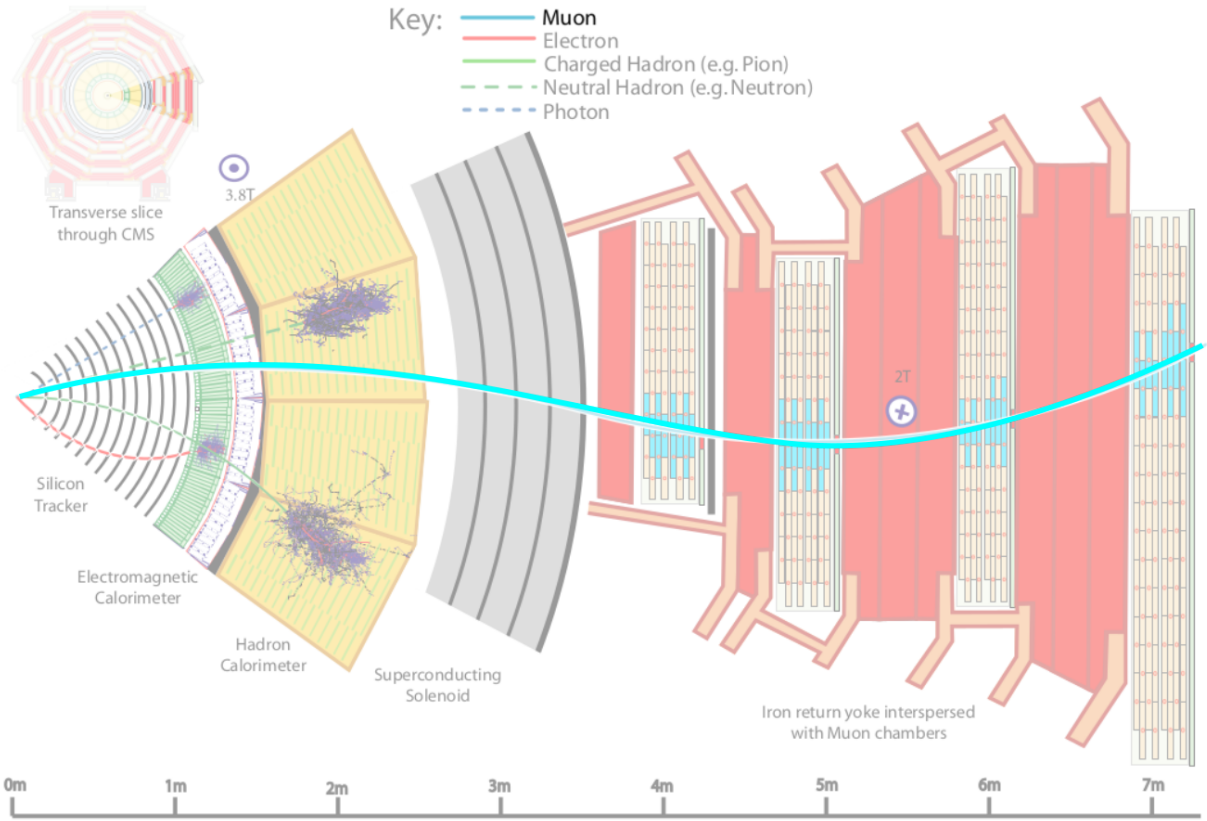

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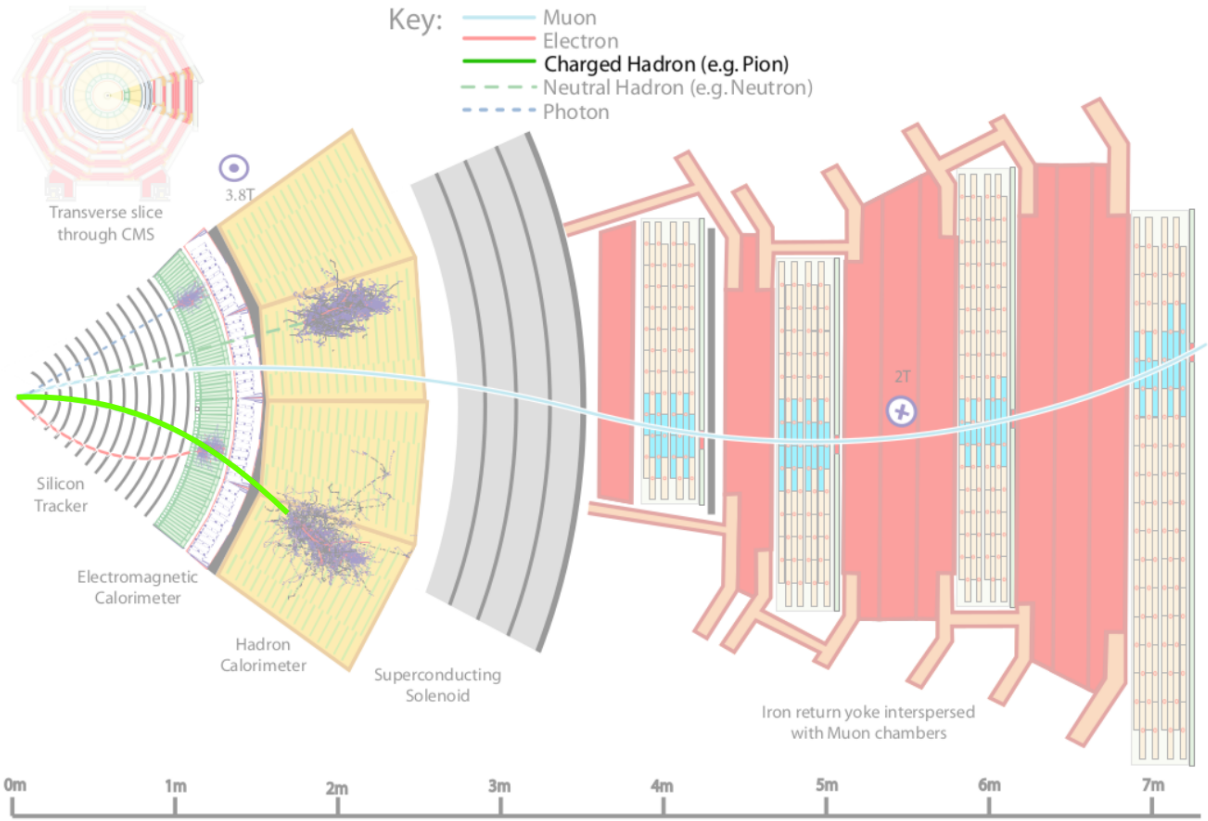

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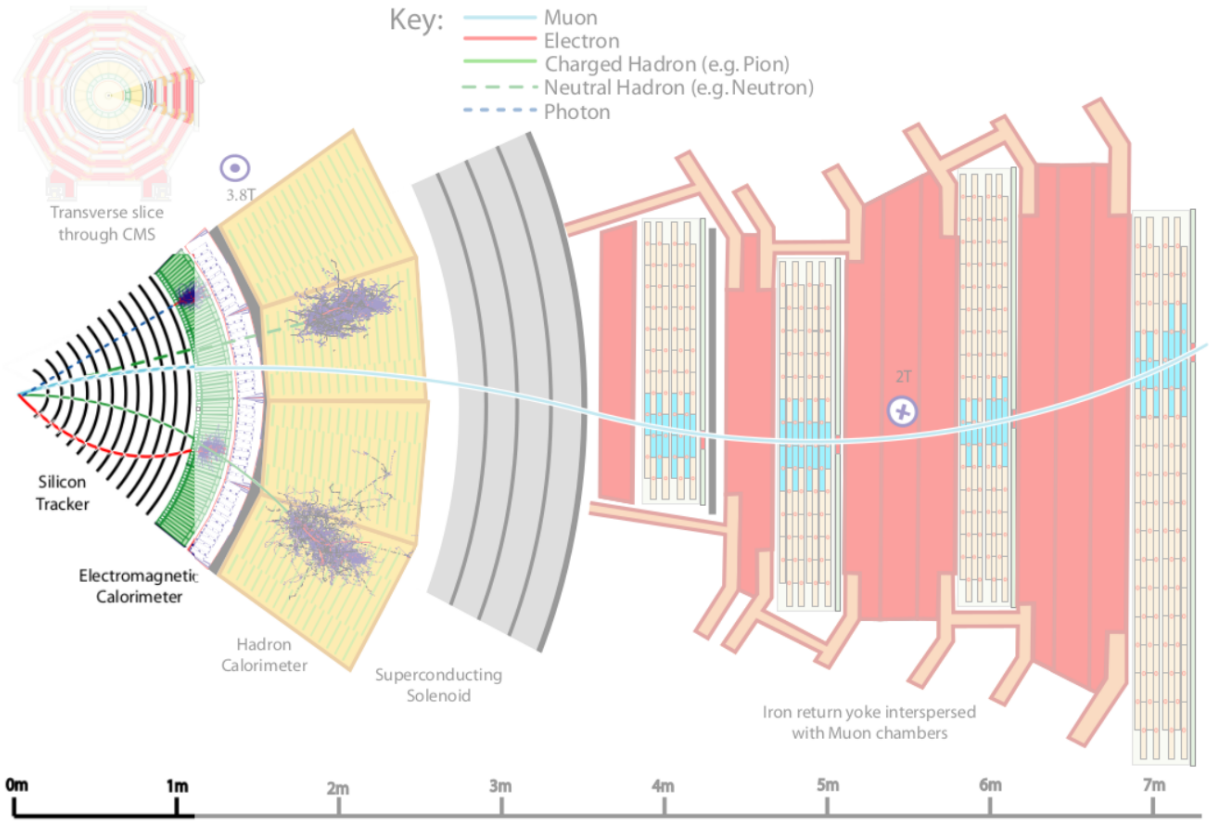
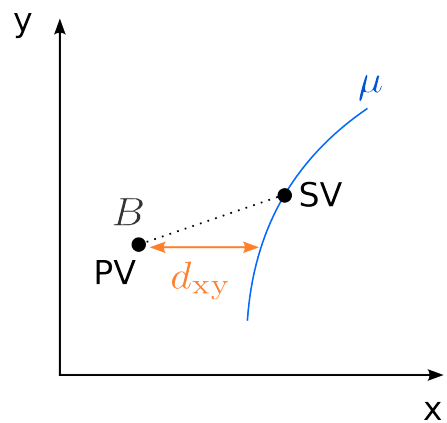


Transverse slice of the CMS detector

CMS BParking dataset

- Large dataset of $B\bar{B}$ pairs
  - Data collected in 2018
  - $\mathcal{O}(10^{10})$ $B\bar{B}$ events
  - Total luminosity of 41.6 fb^{-1}
- Set of triggers designed to capture the signatures of a B meson decay
  - Single muon trigger
  - Low transverse momentum (p_T) requirement (from 7 GeV on)
  - Large transverse impact parameter significance



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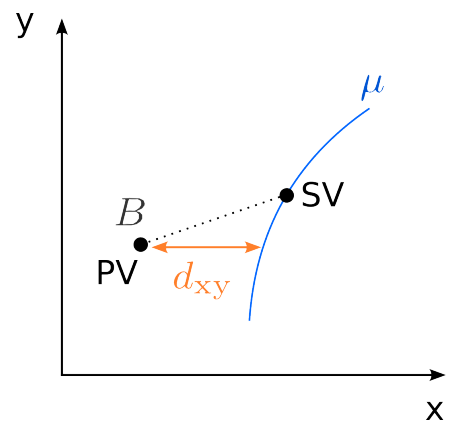

$\Rightarrow$ **Unprecedented possibility to study B-physics with CMS**

Strategy

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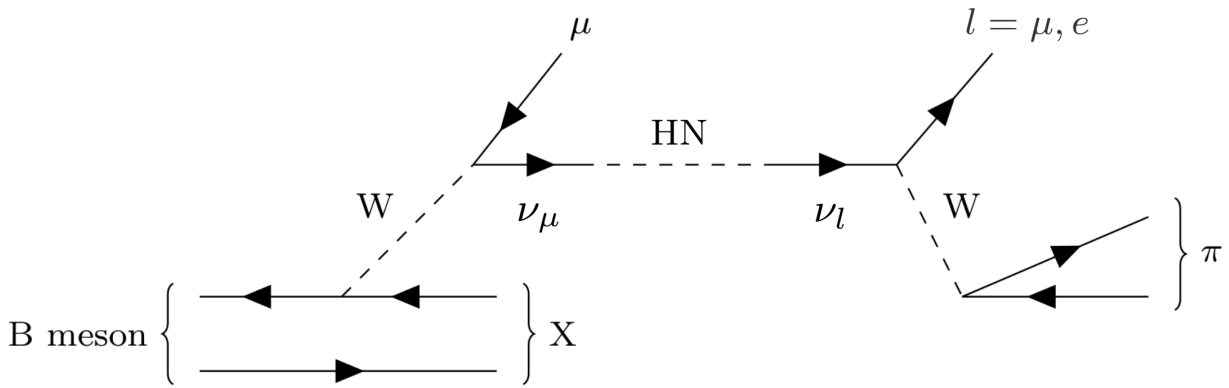
  - Restrict the search to HNs decaying within the tracker volume ($l_{xyz} < 1$ m)



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- Inclusive B meson decay

$B \to \mu\nu_R$
$B \to D^0\mu\nu_R$
$B^0 \to \pi\nu_R$
$B_s \to K\mu\nu_R$
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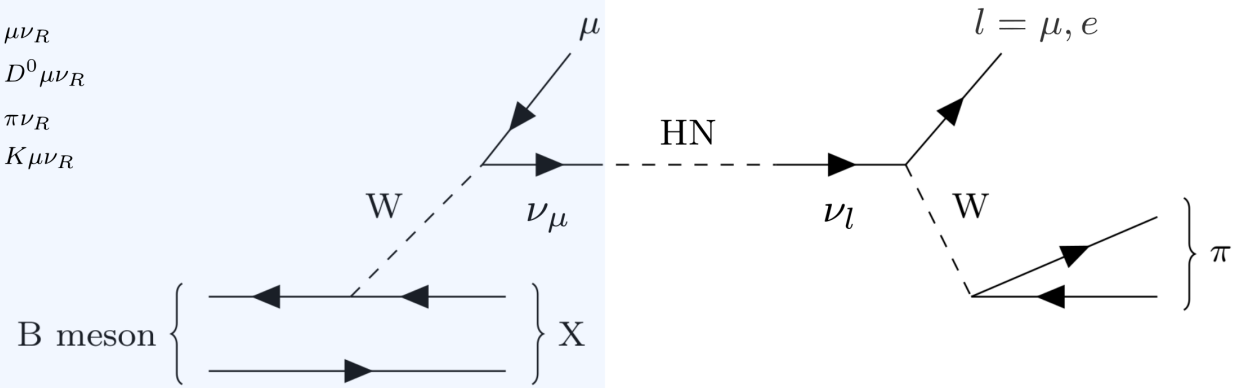

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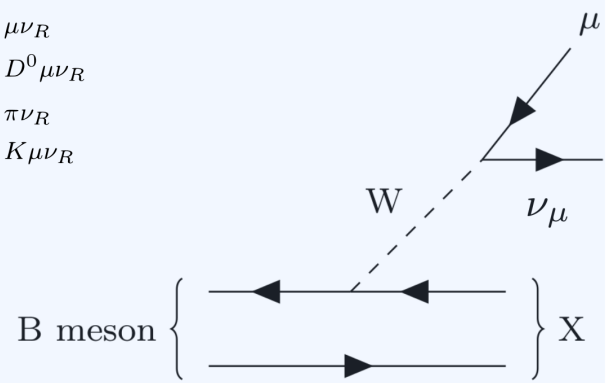
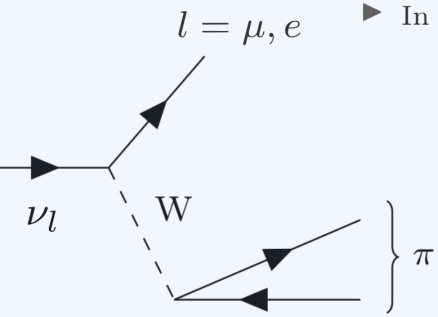
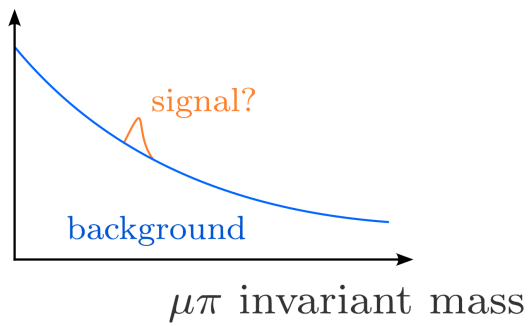


- Exclusive HN decay
  - In this talk: HN $\to \mu\pi$



- Inclusive B decay offers a better sensitivity
- Perform a **bump hunt** in the HN mass spectrum



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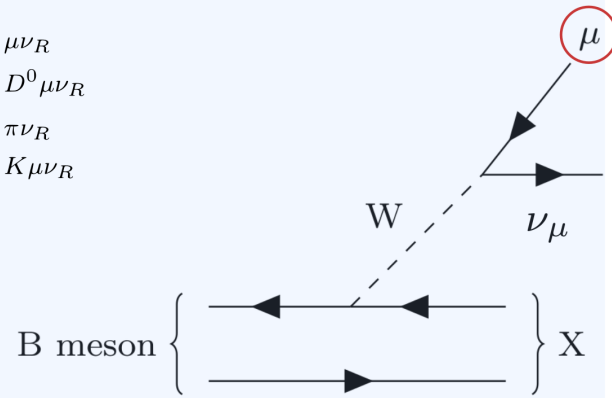

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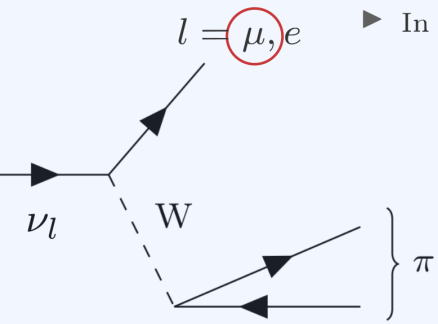
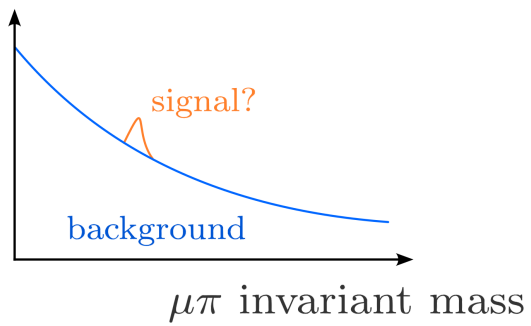


- Inclusive B decay offers a better sensitivity
- Perform a **bump hunt** in the HN mass spectrum
- At least one muon fires a BParking trigger line



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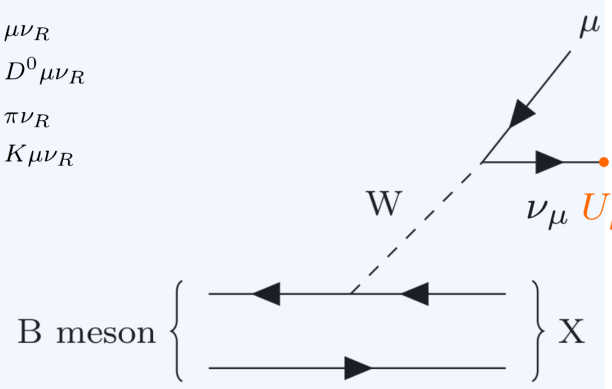

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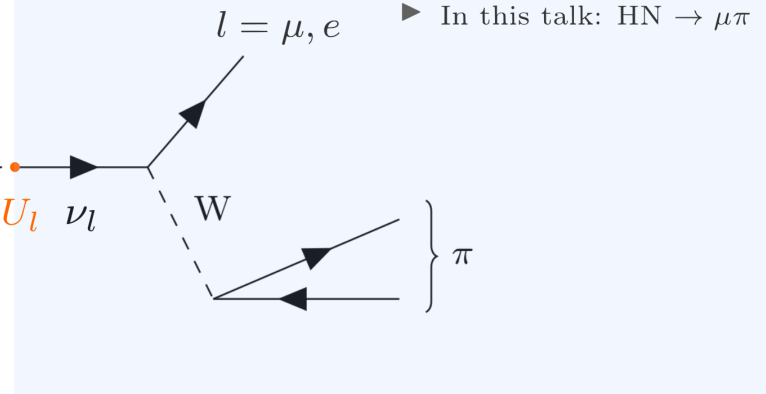
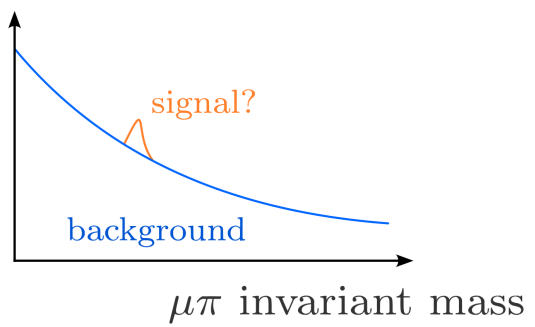
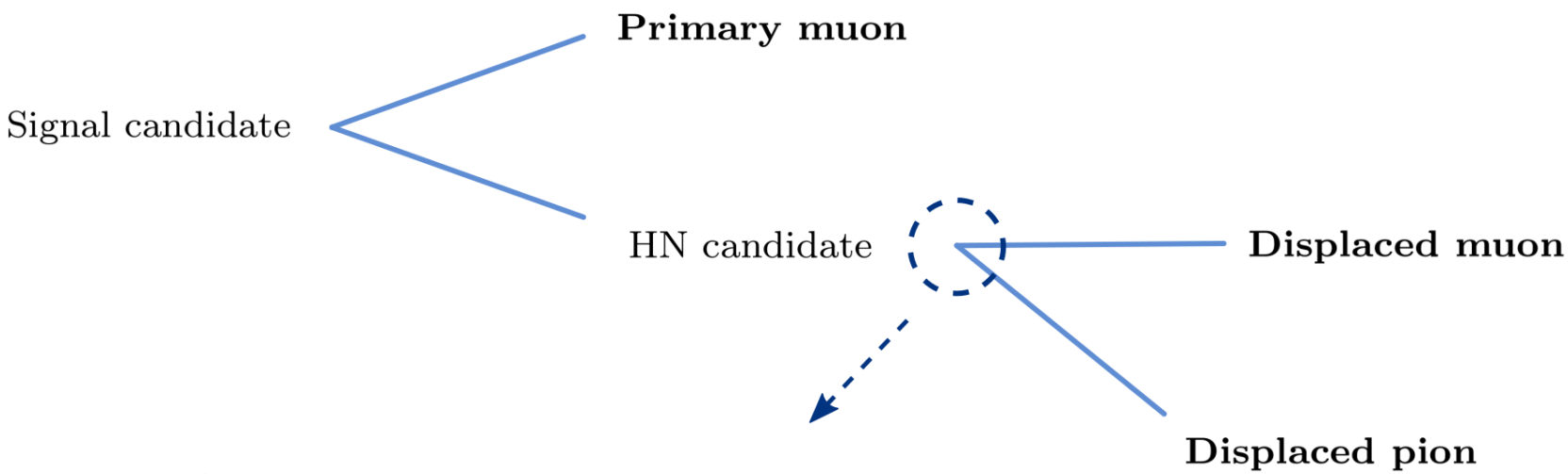


- Inclusive B decay offers a better sensitivity
- Perform a **bump hunt** in the HN mass spectrum
- At least one muon fires a BParking trigger line
- Interpret against mixed flavour scenarios



Reconstruction

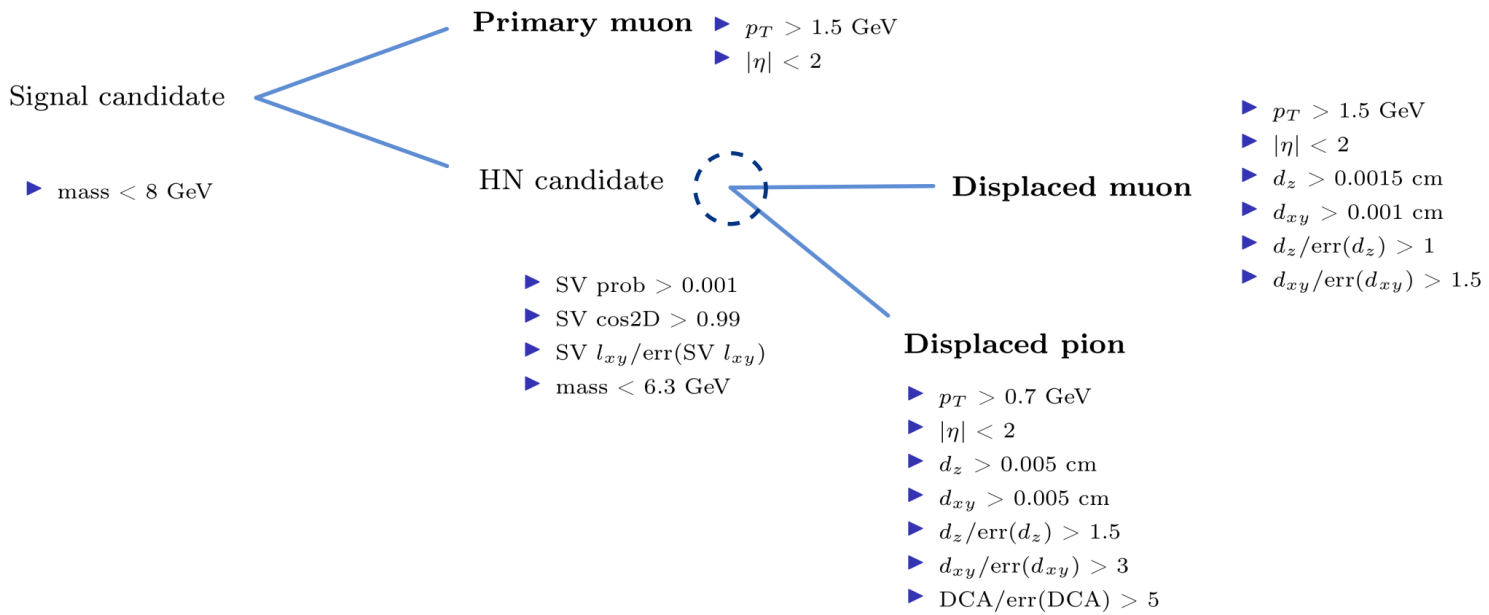
- Three objects in the final state
  - Primary muon
  - Displaced muon
  - Displaced pion



- Displaced pion and muon are fitted to a common vertex using a *kinematic vertex fitter*

Preselection

- Preselection based on
  - Particles kinematics
  - Displacement related quantities
  - Quality of the Secondary Vertex



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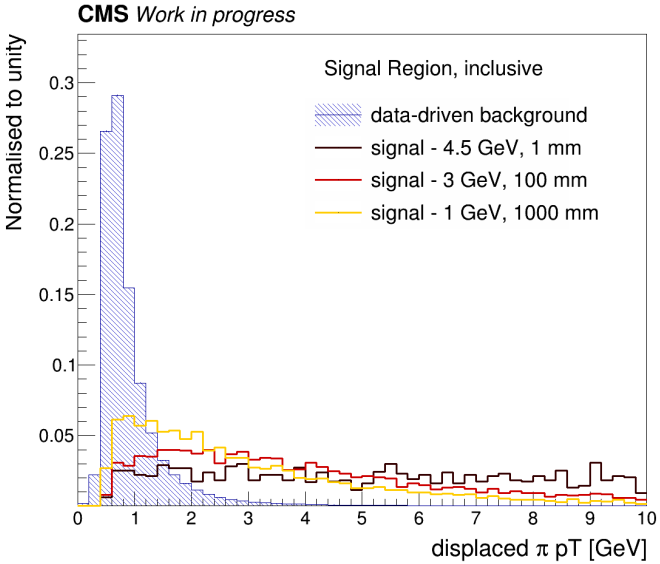

Signal candidate

- mass < 8 GeV

Primary muon

- $p_T > 1.5$ GeV
- $|\eta| < 2$

HN candidate

- SV prob > 0.001
- SV cos2D > 0.99
- SV $l_{xy}/\mathrm{err}(\mathrm{SV}\ l_{xy})$
- mass < 6.3 GeV

Displaced muon

- $p_T > 1.5$ GeV
- $|\eta| < 2$
- $d_z > 0.0015$ cm
- $d_{xy} > 0.001$ cm
- $d_z/\mathrm{err}(d_z) > 1$
- $d_{xy}/\mathrm{err}(d_{xy}) > 1.5$

Displaced pion

- $p_T > 0.7$ GeV
- $|\eta| < 2$
- $d_z > 0.005$ cm
- $d_{xy} > 0.005$ cm
- $d_z/\mathrm{err}(d_z) > 1.5$
- $d_{xy}/\mathrm{err}(d_{xy}) > 3$
- $\mathrm{DCA}/\mathrm{err}(\mathrm{DCA}) > 5$

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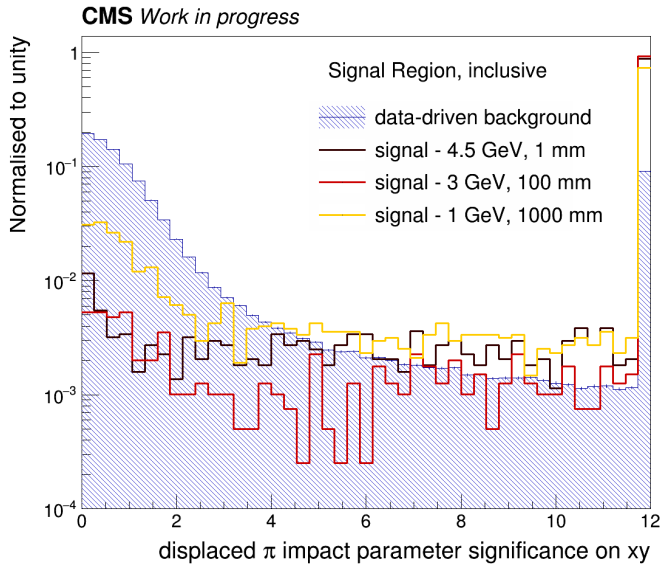

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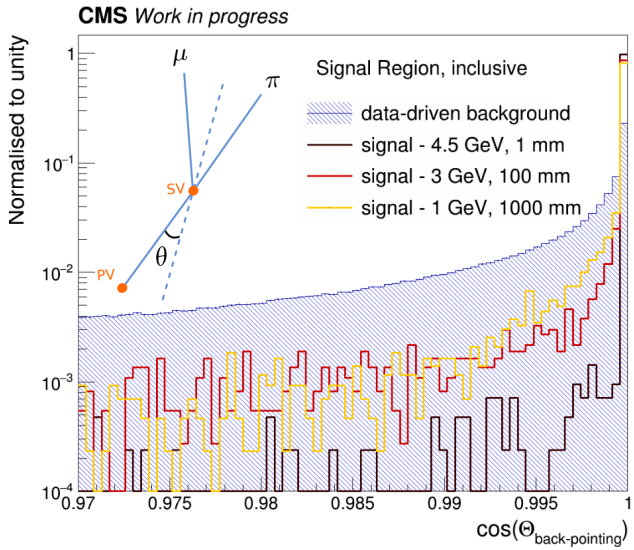

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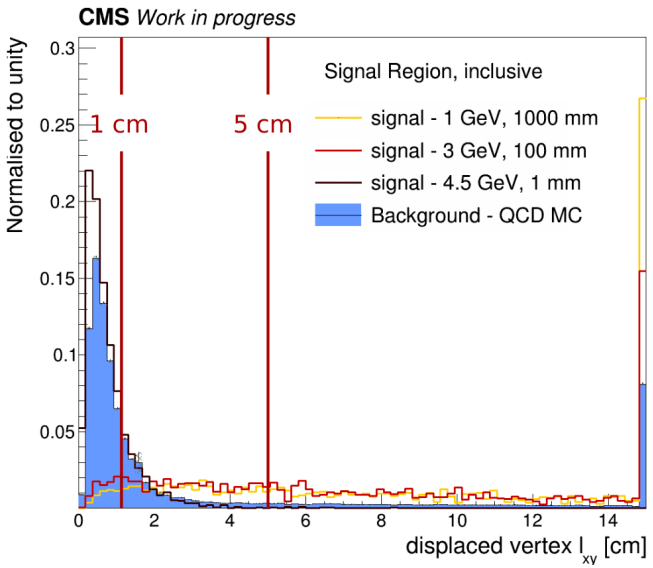
- Categorise the phase space to enhance the sensitivity on different signal hypotheses

1) Categorise in displacement

- Enhance sensitivity on signal with different lifetimes
- Handle to further reduce the background at large displacement



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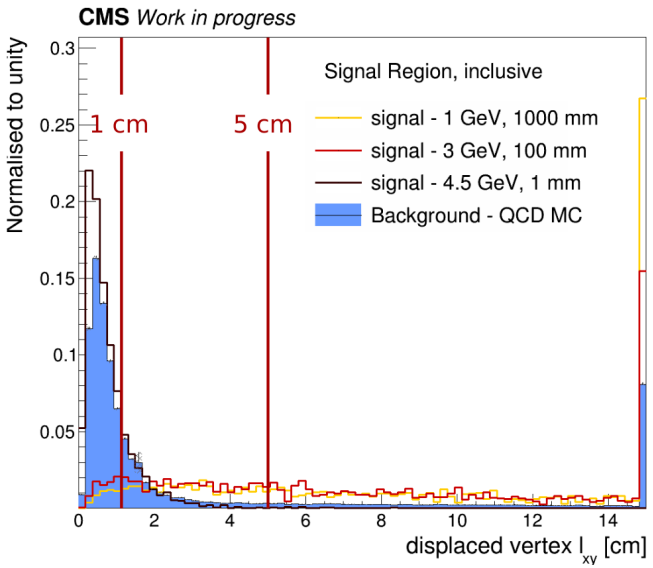
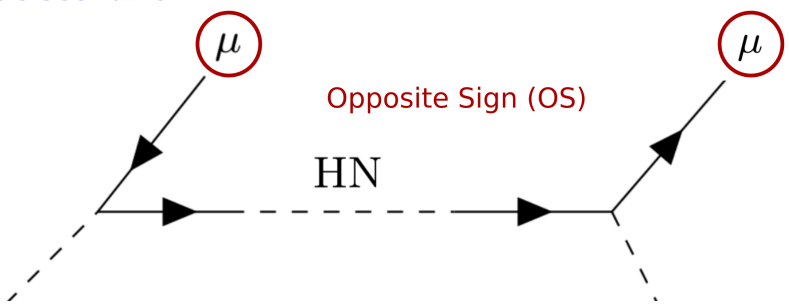


2) Categorise in relative lepton sign

- Enhance discrimination between Dirac and Majorana HNs
  - Dirac neutrinos: lepton number violation forbidden

Dirac scenario



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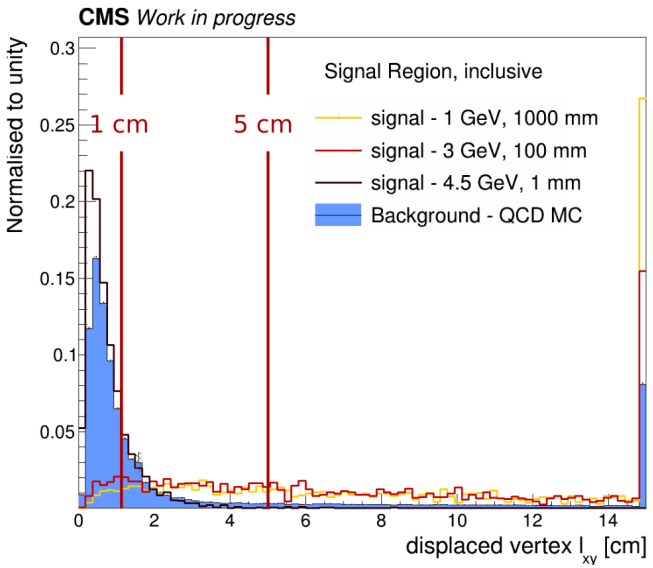

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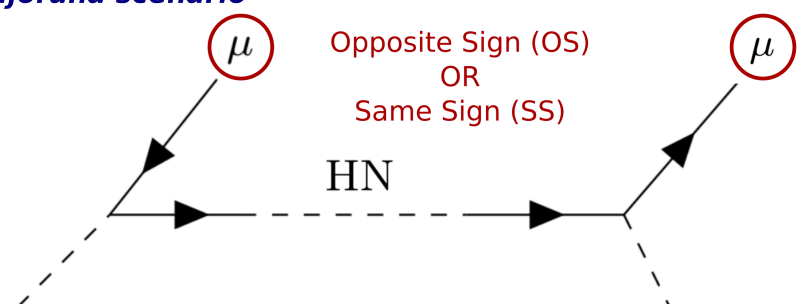
Majorana scenario



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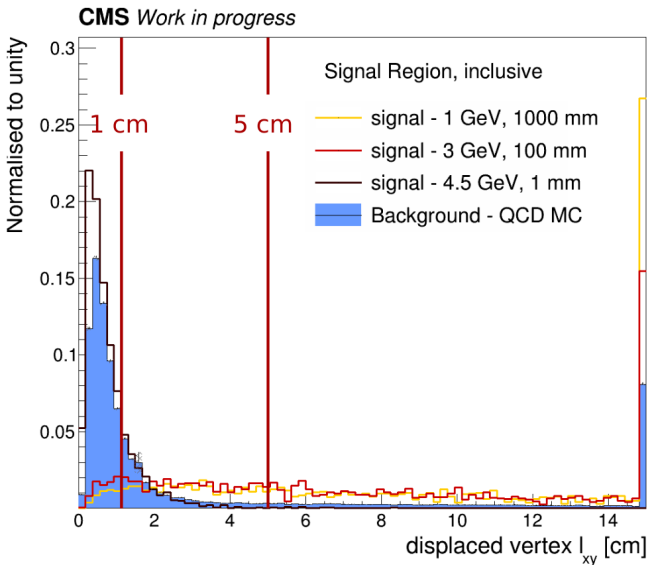

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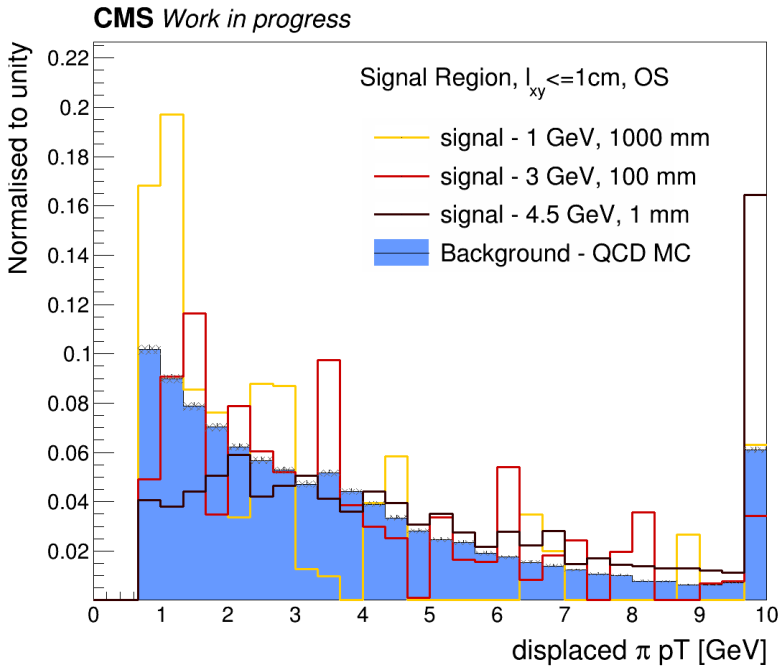
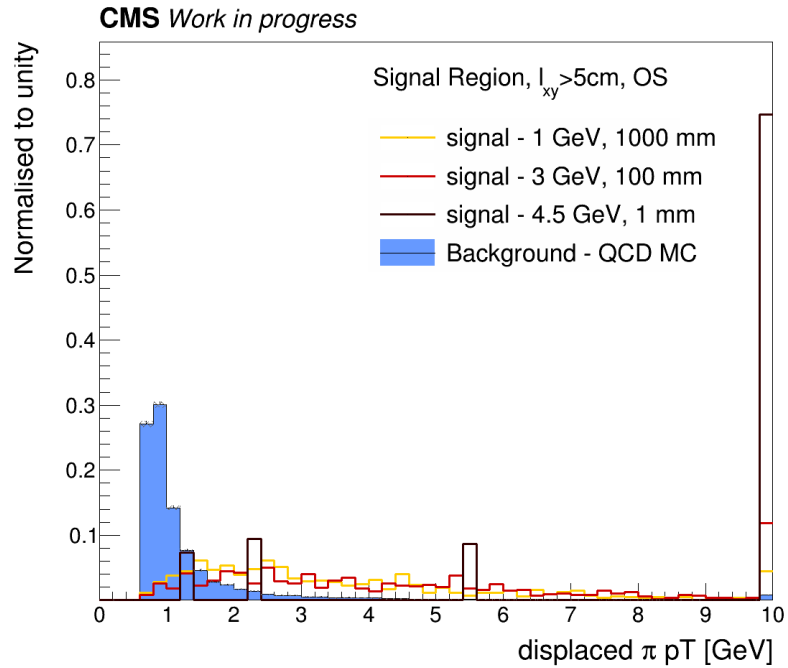
l_{xy}<=1cm, OS	(1<l_{xy}<=5)cm, OS	l_{xy}>5cm, OS
l_{xy}<=1cm, SS	(1<l_{xy}<=5)cm, SS	l_{xy}>5cm, SS

⇒ 6 categories in total

Selection

- Selection cutflow optimised
  - **In each category**
  - In three different mass regimes
  - Based on the significance gain
- The higher the displacement, the more background can be removed





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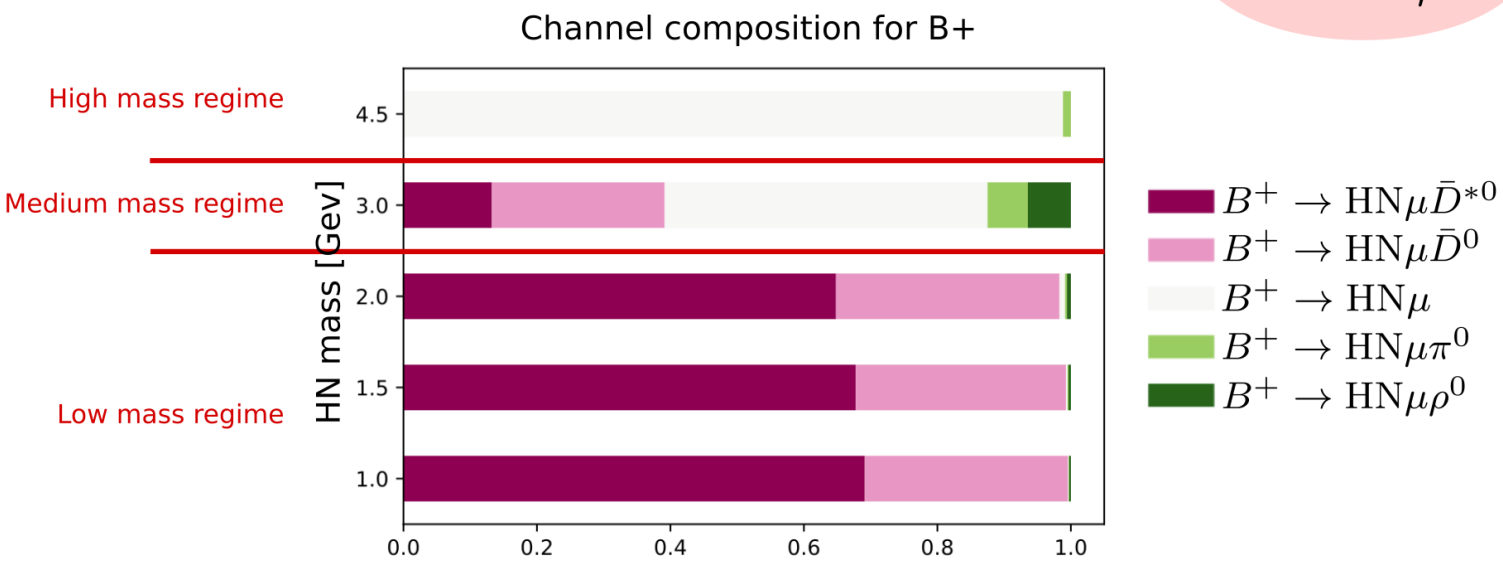
  - **In three different mass regimes**
  - Based on the significance gain
- Different masses yield different kinematics
  - Largely follows from that the B decays to different channels depending on the HN mass

Inclusive B decay
$B \to \mathrm{HN}\mu\mathrm{X}$



Selection

- Selection cutflow optimised
  - In each category
  - In three different mass regimes
  - **Based on the significance gain**

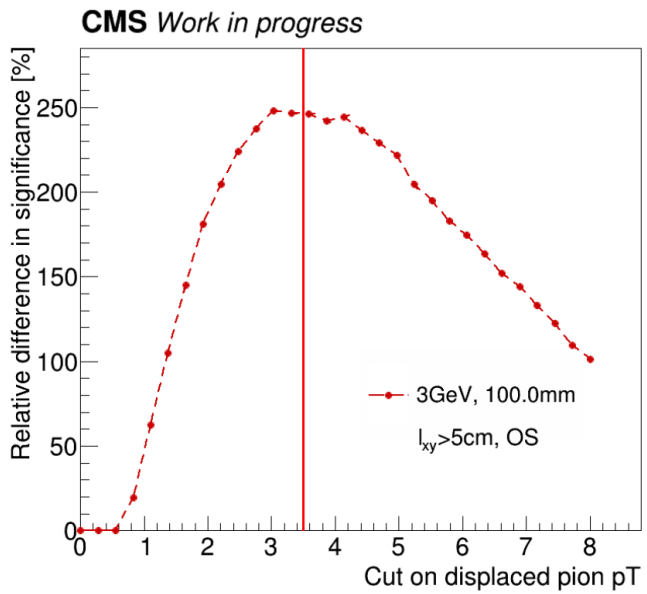
- Median of the significance $\mathcal{S}$ computed in the asymptotic approximation

$$\mathcal{S} = \sqrt{2\left((S+B)\ln\left(1+\frac{S}{B}\right)-S\right)}$$

with S and B the number of signal and background events respectively

Discriminating quantities

- pion p_T
- SV displacement significance (lxysig)
- min of the muon and pion transverse impact parameter significance (dxysig)
- difference of the $\cos(\Theta_{\mathrm{back-pointing}})$ with 1



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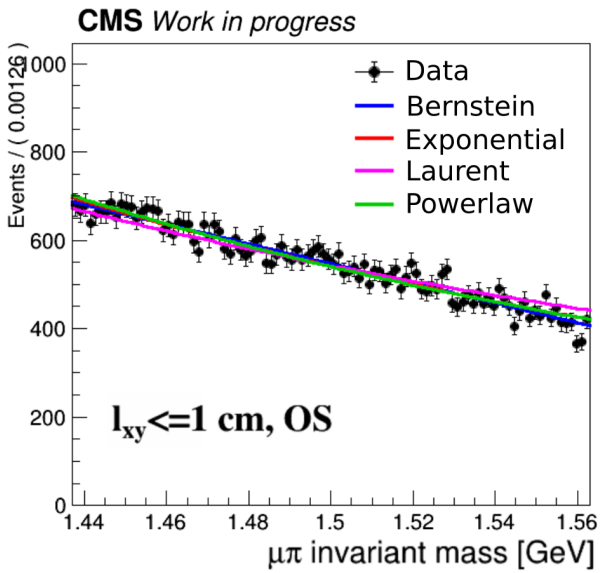
  - Can vary in the different mass windows and categories
  - How to assign the systematic uncertainty on the choice of the function?



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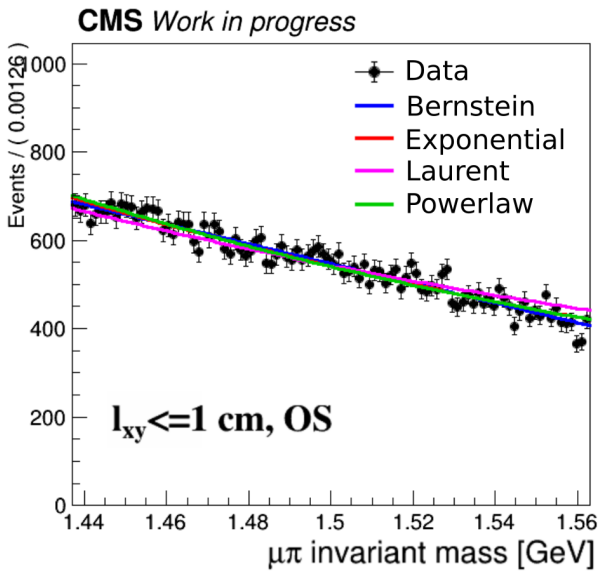
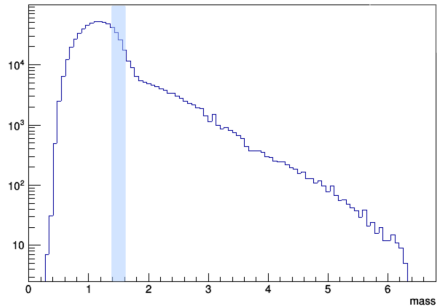
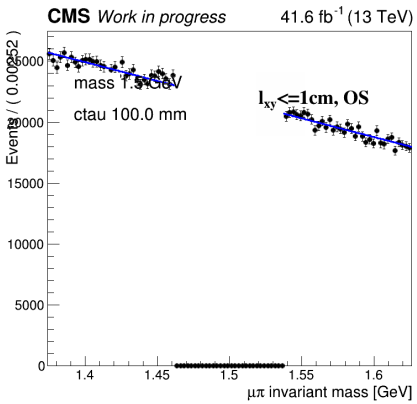


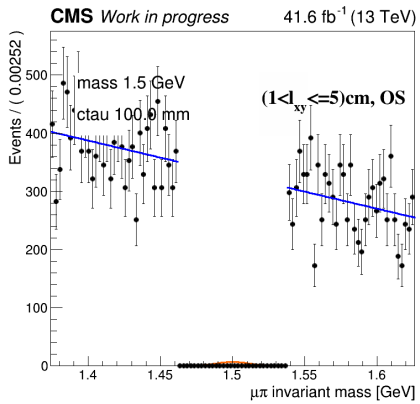
- Use the discrete profiling method
  - Consider a set of functions that provide a good description of the background
  - Treat the choice of the function as a discrete nuisance parameter (profiled)

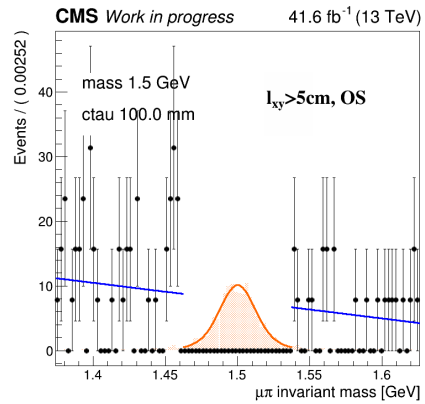
Sensitivity

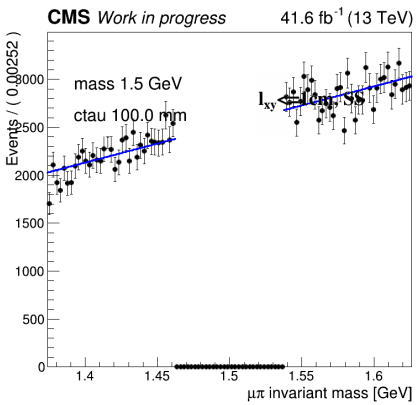
- Perform a bump hunt in the $\mu\pi$ invariant mass spectrum
- In each window, in each category
  - Build the signal model, and normalise it
  - Fit the background in the sidebands

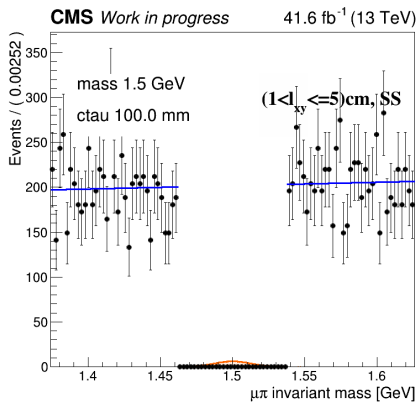


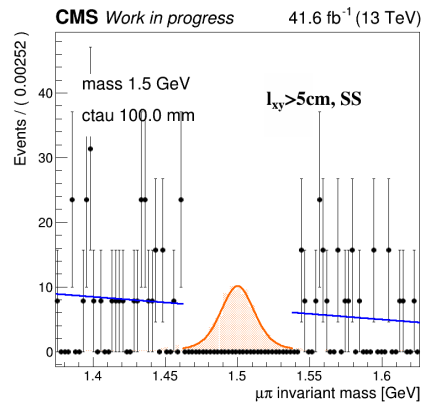












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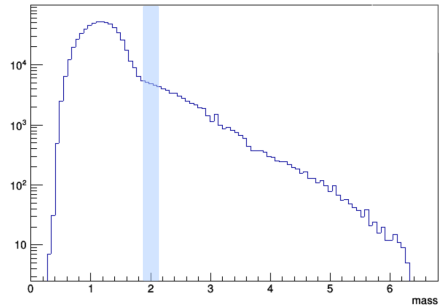
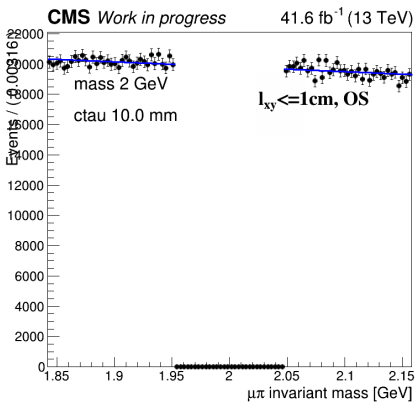
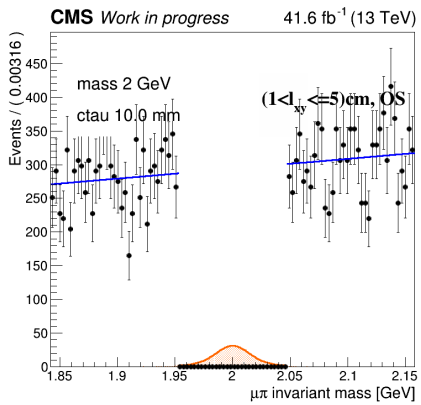
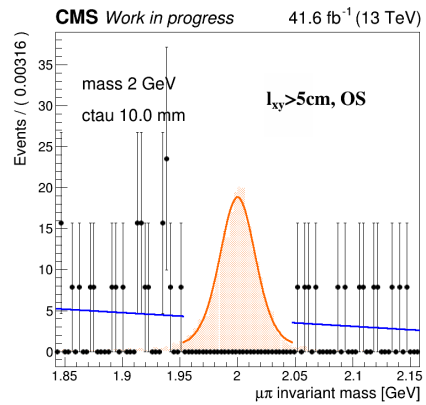
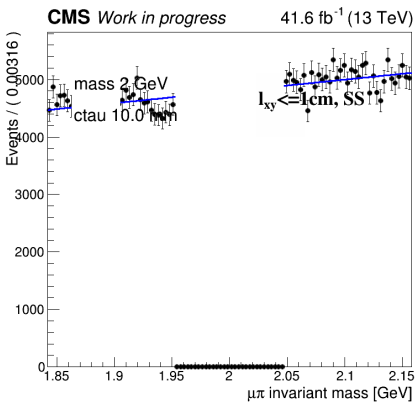
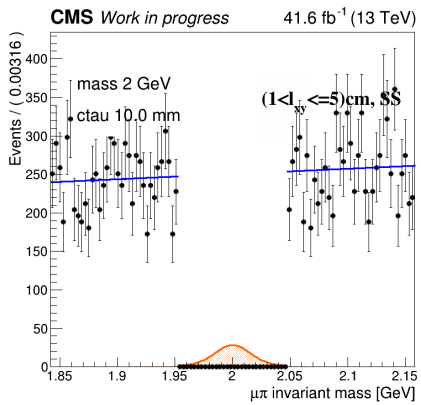


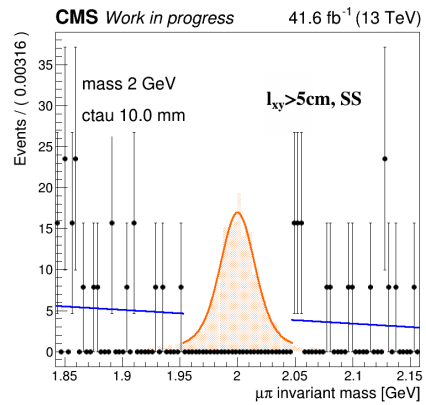












Summary

- First search for long-lived Heavy Neutrinos from B decays with CMS
- Possible thanks to the $B\bar{B}$ dataset collected in 2018
- Search designed to offer the best sensitivity
  - Inclusive B decay
  - Bump hunt in the HN mass spectrum
  - Categorisation of the phase space
- Interpretation against mixed-flavour coupling scenarios
- Results soon to be public
  - Competitive sensitivity

Backup

Backup

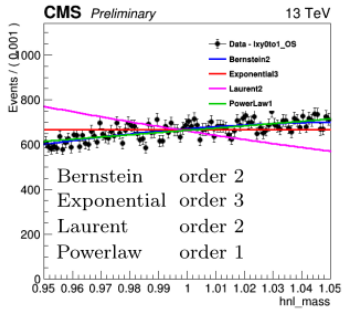
- Discrete profiling method

Consider 4 families of functions

Bernstein
Exponential
Laurent
Powerlaw

F-Test

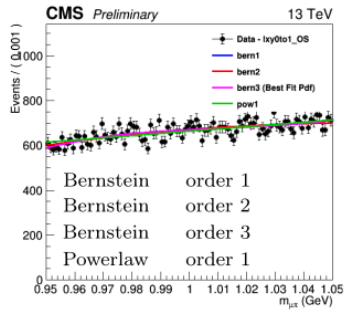
For each family, assess up to which order N a function should be considered*

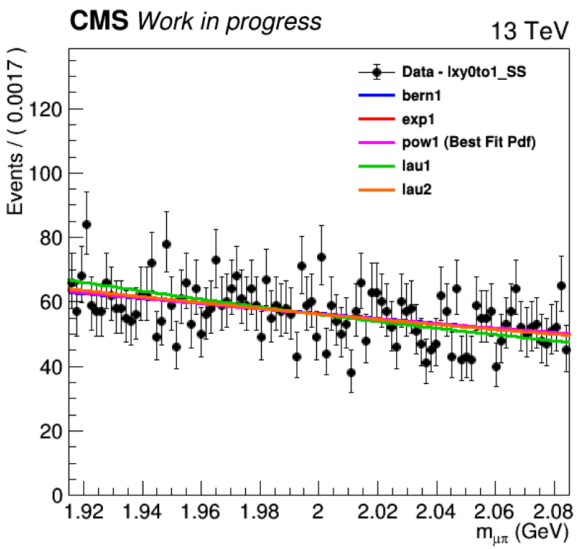


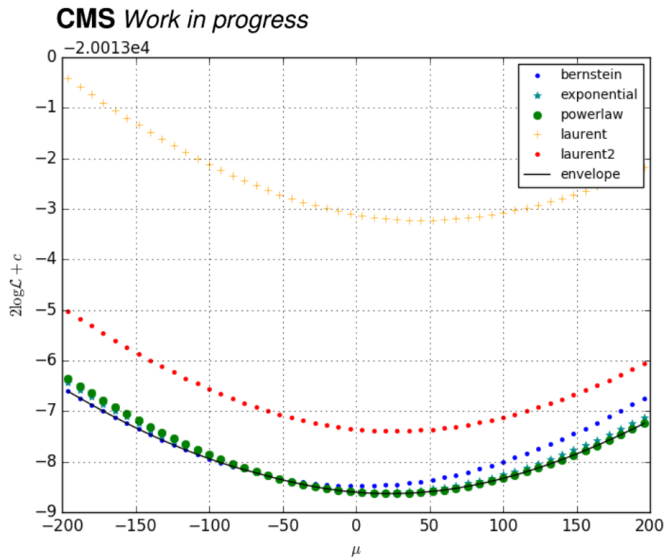
*Functions of order N+1 can still enter the envelope

Envelope

Determine which functions enter the envelope

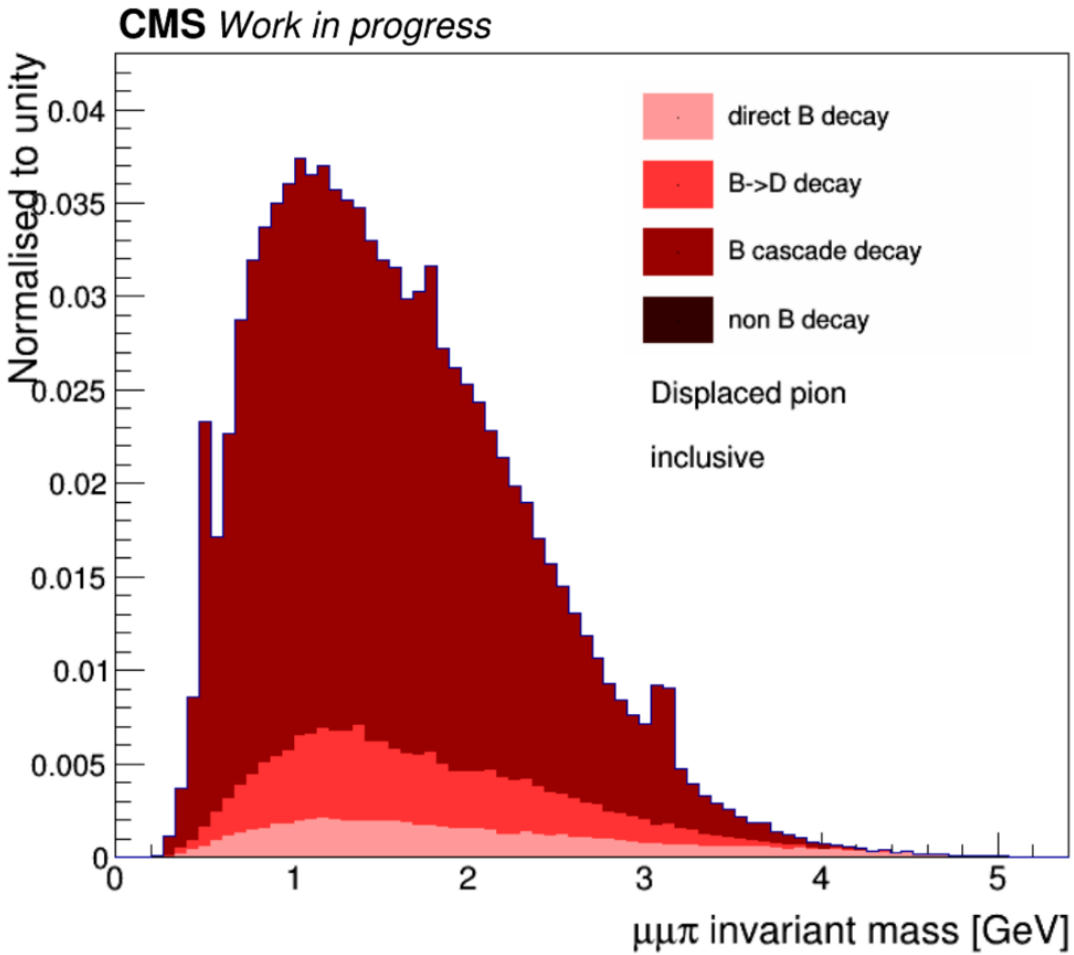






Backup

- Background sources



Backup

- Reconstruction efficiency