Search for heavy sterile neutrino from D_s^+ decay

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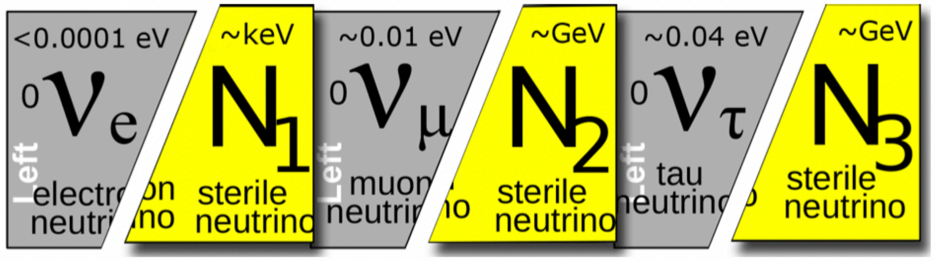
Introduction (heavy neutrinos)

- SM very successful but neutrino sector not completely accomodated (e.g. neutrino oscillations)
- Right-handed neutrinos missing in SM → added with neutrino Minimal Standard Model (νMSM)



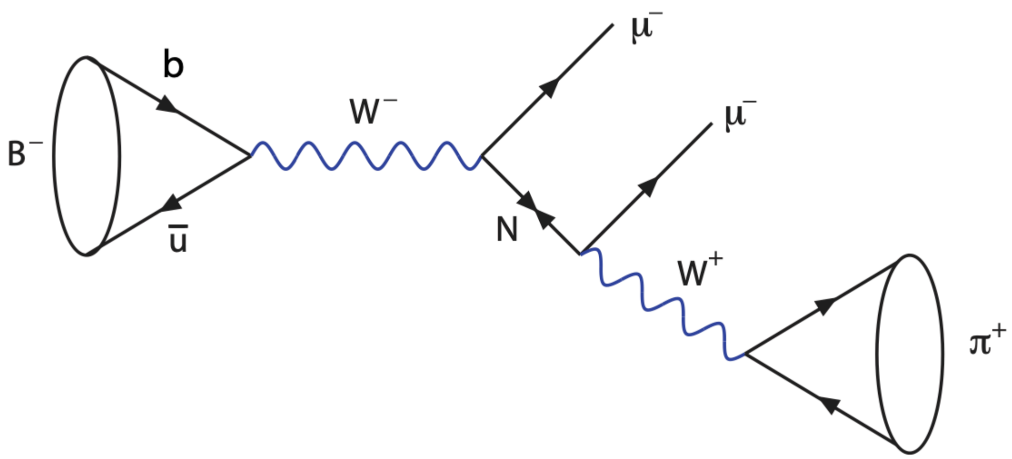
  - sterile heavy neutrinos
    - interact only with the light active ones through mixing $\theta^2 \sim m_\nu / m_N$
    - has **mixing angle** $V_{\ell N}$ to SM neutrino ν_ℓ
  - possible solution for long-standing puzzles :
    - origin of SM neutrino masses via seesaw mechanism $m_\nu \sim y^2 v^2 / m_N$
    - N_1 (m~keV) = dark matter candidate
    - degenerate N_2 and N_3 (1<m<100 GeV) = possible explanation for matter-antimatter asymmetry of the Universe

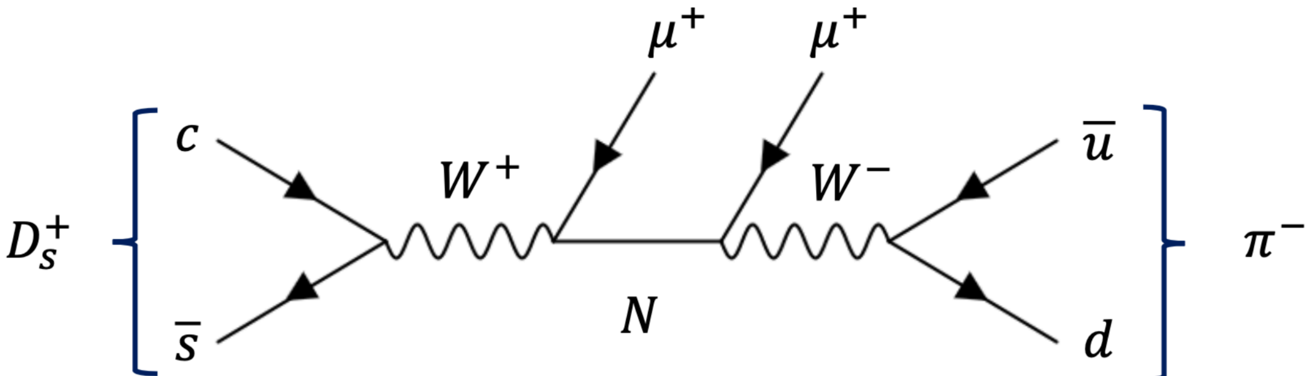
→ can be searched for at LHC

- HNL **lifetime** becomes longer with small masses or mixing

$$\tau \propto |V_{\ell N}|^{-2} m_N^{-5}$$

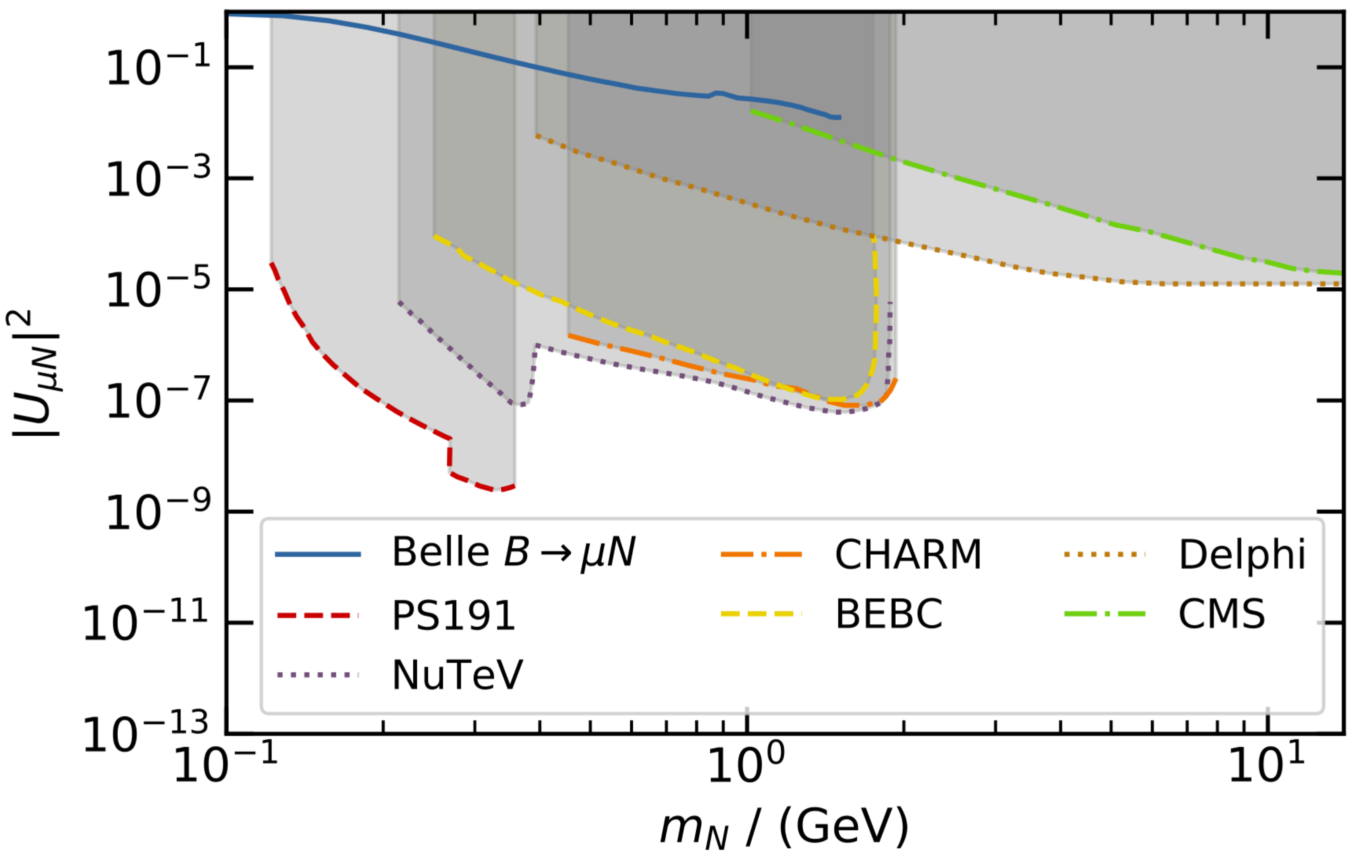
Searches of HNL in Heavy Flavour





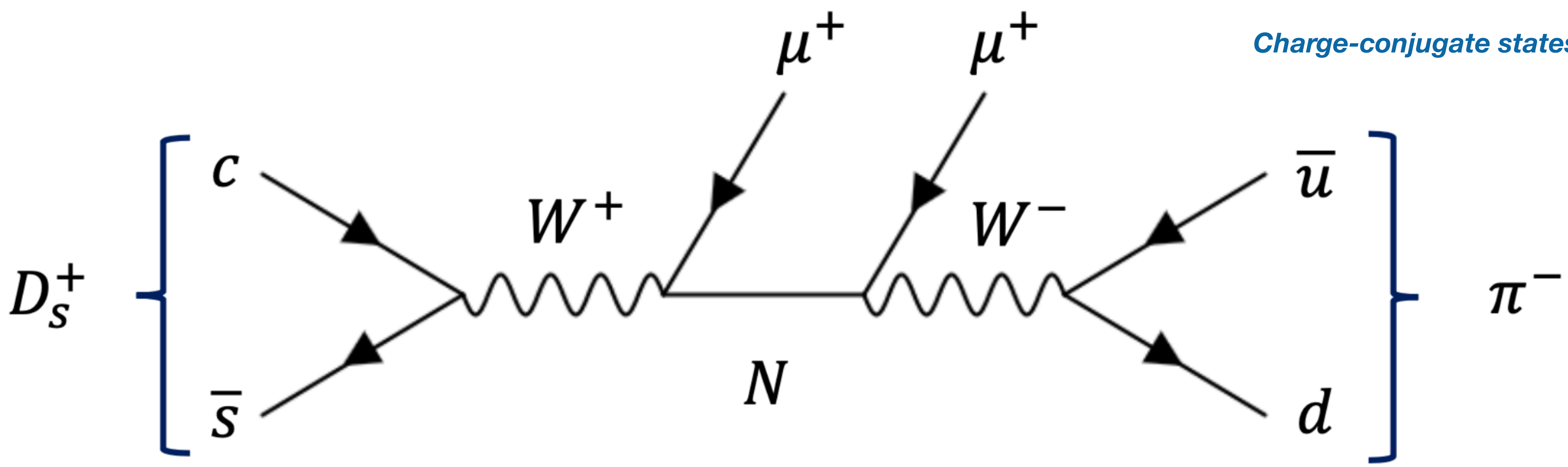
Charge-conjugate states are implied

Belle, Phys.Rev.D 101 (2020) 3, 032007



- It is also possible to search HNL in (heavy) hadrons decays: $B^{\pm} \to l^{\pm}N$, $D^{\pm}_{(s)} \to l^{\pm}N$,...
- Main idea: we have standard semi-leptonic decay to $W^- \to l\bar{\nu}_l$, then $\bar{\nu}_l$ oscillate to sterile N and then N again oscillate, but now to ν_l with the following decay to lW^+ —> final state is lepton number violating (LNV)
- Such LNV decay is strictly forbidden in SM, thus we expect negligible SM background processes and great opportunity to perform searches for N

Our goals



Charge-conjugate states are implied

- Subject of our study is search for decay $D_s^+ \to \mu^+ N \to \mu^+ \mu^+ \pi^-$ with normalisation channel $D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+$, where D_s^+ are originating from semi-leptonic B_s decay

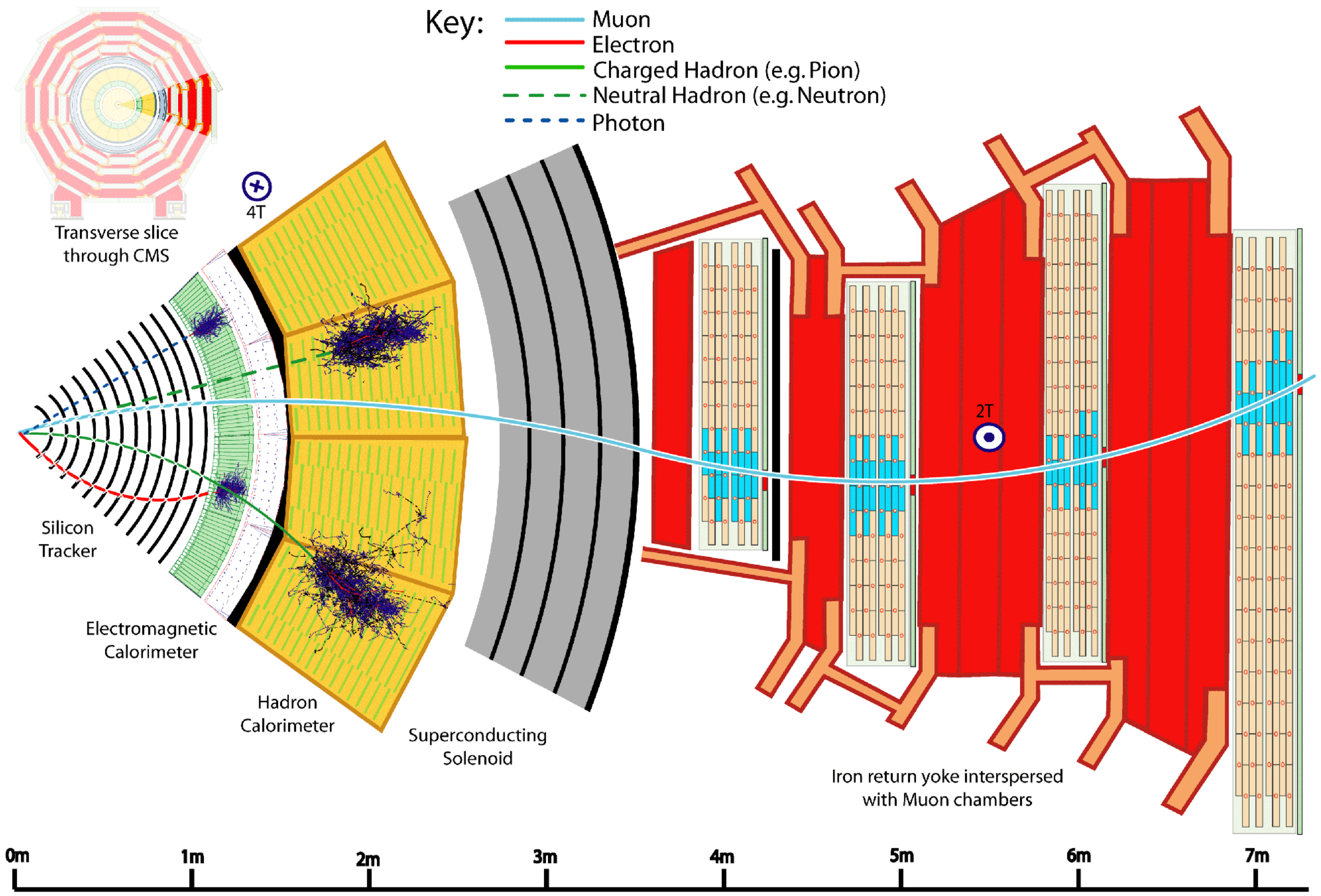
- This analysis is to be done at CMS Experiment data, using BParking dataset (see next slides)

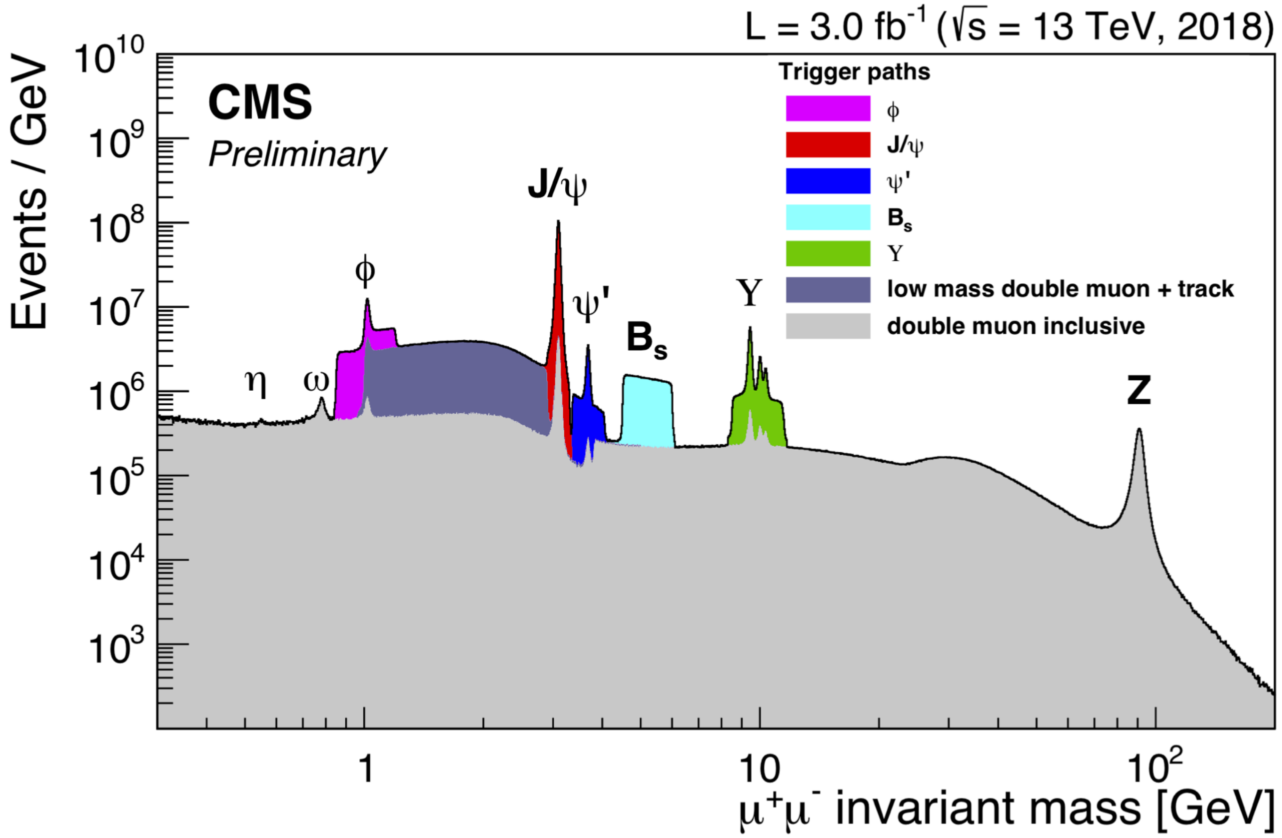
- Today we report our preparatory studies, divided into two parts:

  - studies of possible D_s^+ sources and normalisation channel on BParking data (we use $D_s^+ \to \phi\pi^+$, $\phi \to K^+K^-$ mode)

  - studies of signal Monte-Carlo simulation samples

The CMS Experiment





- The CMS Experiment at the LHC was designed mainly for high-p_T physics (Higgs, top-quark, SM precision measurement, New Physics searches etc)

- However, robust muon system, good p_T resolution and perfect vertex reconstruction provide promising opportunities for heavy flavour and quarkonia-related analyses

Motivation: CMS B-parking dataset

Trigger strategy

During June–Nov 2018, approximately 12 billion events were recorded with a trigger logic that requires the presence of a single, displaced muon. The sample comprises $b\bar{b}$ events with high purity. The muon candidate responsible for the positive trigger decision originates from the "tag-side" b hadron that undergoes a b→μX decay. The "signal-side" b hadron decays naturally as it is not biased by the trigger requirements.

Trigger: b hadron purity

$$N(b \to \mu X) = \frac{1}{F_{corr}} \frac{N(B^0 \to D^{*+}\mu\nu)}{\alpha(D^{*+}) \times \varepsilon(D^{*+}) \times \mathcal{B}(D^{*+} \to D^0(\to K\pi)\pi)}$$

$$f_d \frac{\mathcal{B}(B^0 \to D^{*+}\mu\nu)}{\mathcal{B}(b \to \mu X)} \frac{\alpha(B^0 \to D^{*+}\mu\nu)}{\alpha(b \to \mu X)}$$

From MC

Acceptance x efficiency of the D^{*+} decay chain. Computed on MC.

From data

From literature: 2.6%

$$P_b = \frac{N(b \to \mu X)}{N(\mu)}$$

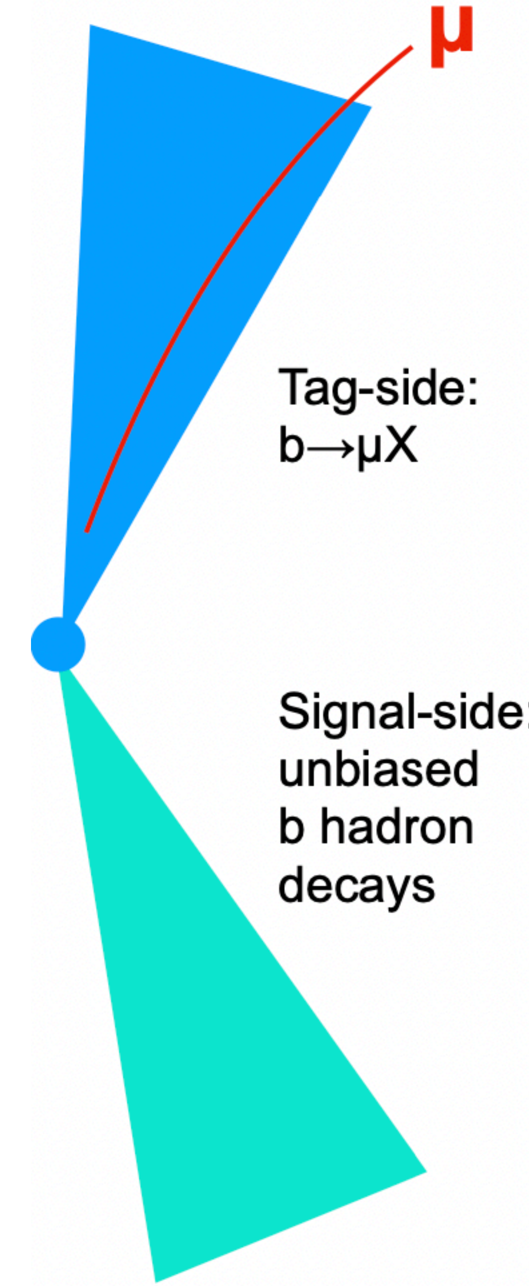
Modes of unbiased B hadron decays on tape

The table indicates the number of unbiased decays of different types of B hadrons recorded to tape in 2018 (N_{2018}). The fractions of B hadron type that are produced (f_B) and their branching fraction ($\mathcal{B}$) are also indicated.

Mode	N_{2018}	f_B	$\mathcal{B}$
Generic b hadrons			
B^0_d	4.0×10^9	0.4	1.0
$B^\pm$	4.0×10^9	0.4	1.0
B_s	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
B_c	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0

$B_s^0 \to D_s^+ \mu^- \bar{\nu}_\mu$

Source of D_s^+ mesons



Details are in CMS-DP-2019-043 Note

Using $\mathscr{B}(B_s^0 \to D_s^+ \mu^- \bar{\nu}_\mu)$, we have $> 3 \times 10^7$ D_s^+ in our BParking only on probe side

....and much more on trigger side

Reconstruction of two D_s^+ sources

Selection criteria are standard soft CMS B-physics cuts to provide robust reconstruction

Tracks selection

- $p_T(K^\pm) > 1.5\ GeV/c$
- $d_{xy}/\sigma_{d_{xy}}(K^\pm) > 0.8$
- $p_T(\pi^+) > 1\ GeV/c$
- $d_{xy}/\sigma_{d_{xy}}(\pi^+) > 0.8$

D_s^+ selection

- $|M(\phi) - m_\phi^{PDG}| < 10\ MeV$
- $1.8\ GeV < M(K^+K^-\pi^+) < 2.05\ GeV$
- $D^+_{s\,vtxprob} > 0.01$
- $\cos(PV, D_s^+) > 0.99$
- $(D_s^+)_{detach\ significance} > 5$

prompt only

- $(D_s^+, B_s^0)_{detach\ significance} > 4$
- $\cos(D_s^+, B_s^0) > 0.99$

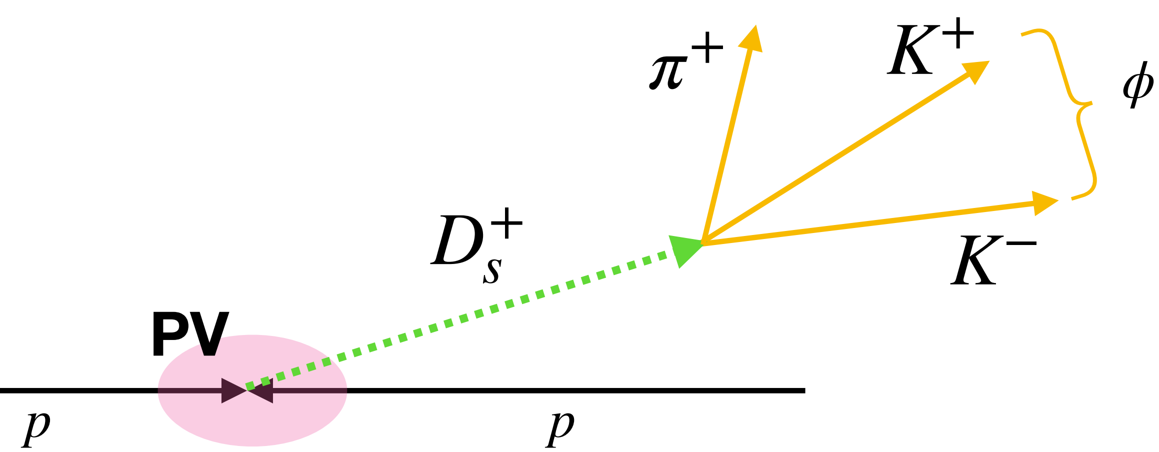
from B_s^0 only

B_s^0 selection

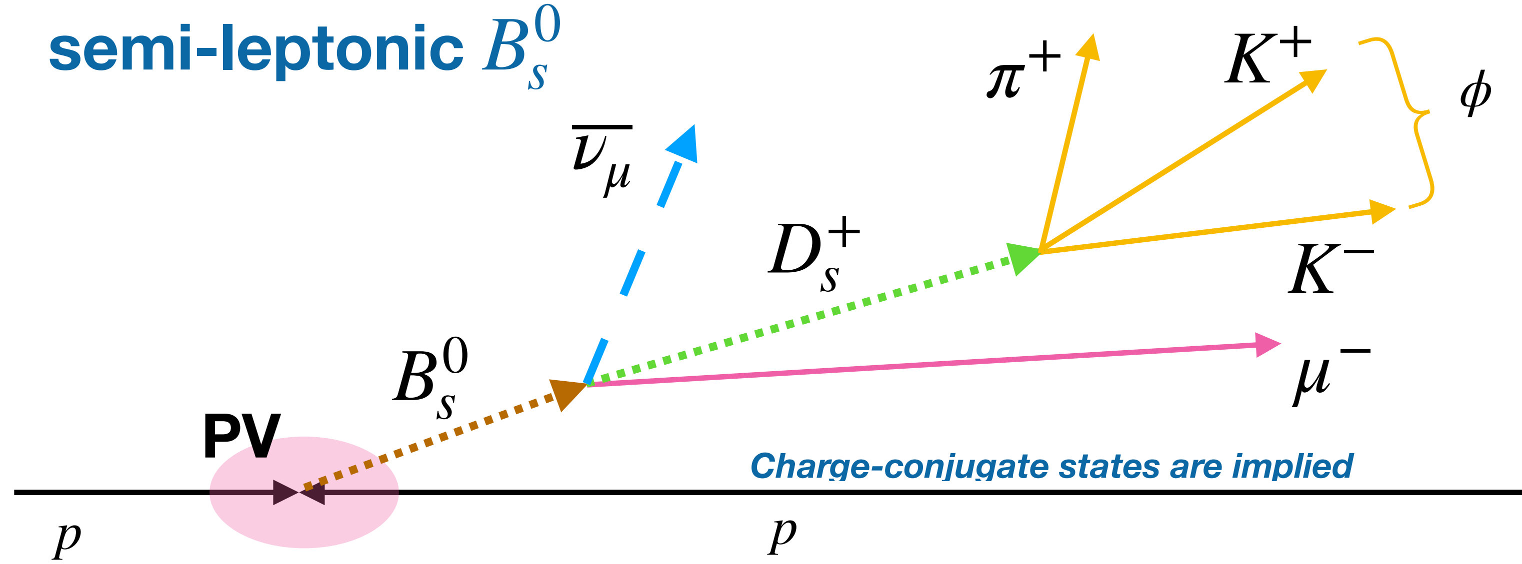
"BParking trigger"

- $p_T(\mu^\pm) > 7\ GeV/c$ and $d_{xy}/\sigma_{d_{xy}}(\mu^\pm) > 3$
- $(B_s^0)_{vtxprob} > 0.01$
- $(B_s^0)_{detach\ significance} > 4$
- $p_T(B_s^0) > 6\ GeV/c$
- $\cos(PV, B_s^0) > 0.9$

Prompt D_s^+ mesons

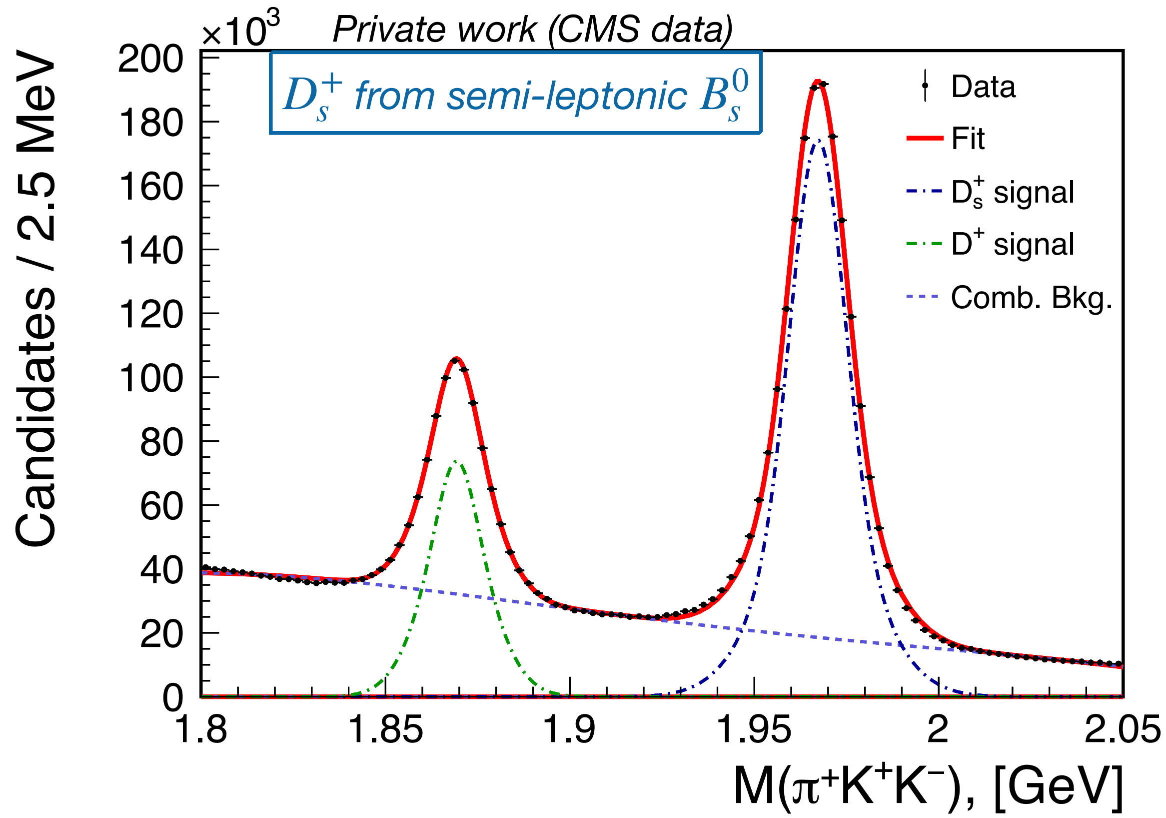


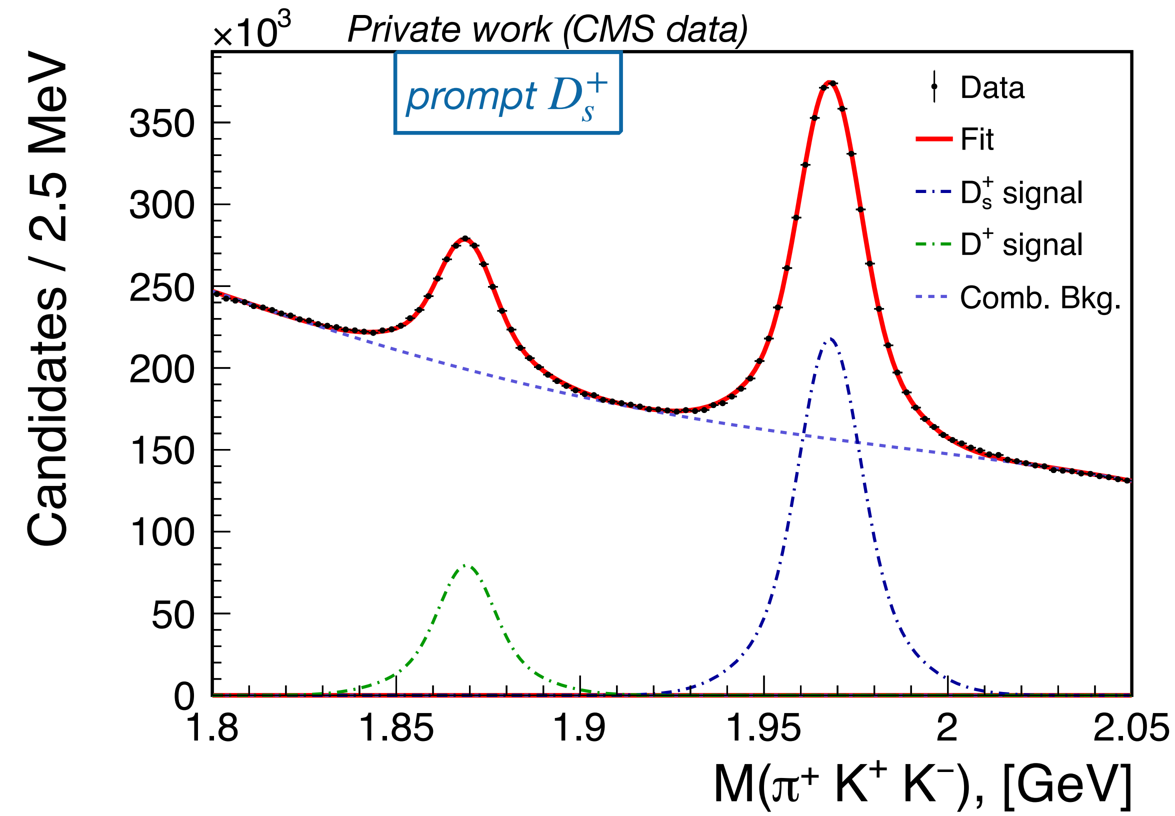
D_s^+ mesons from semi-leptonic B_s^0



Charge-conjugate states are implied

$D_s^+ \to \phi\pi^+$ fit results on data





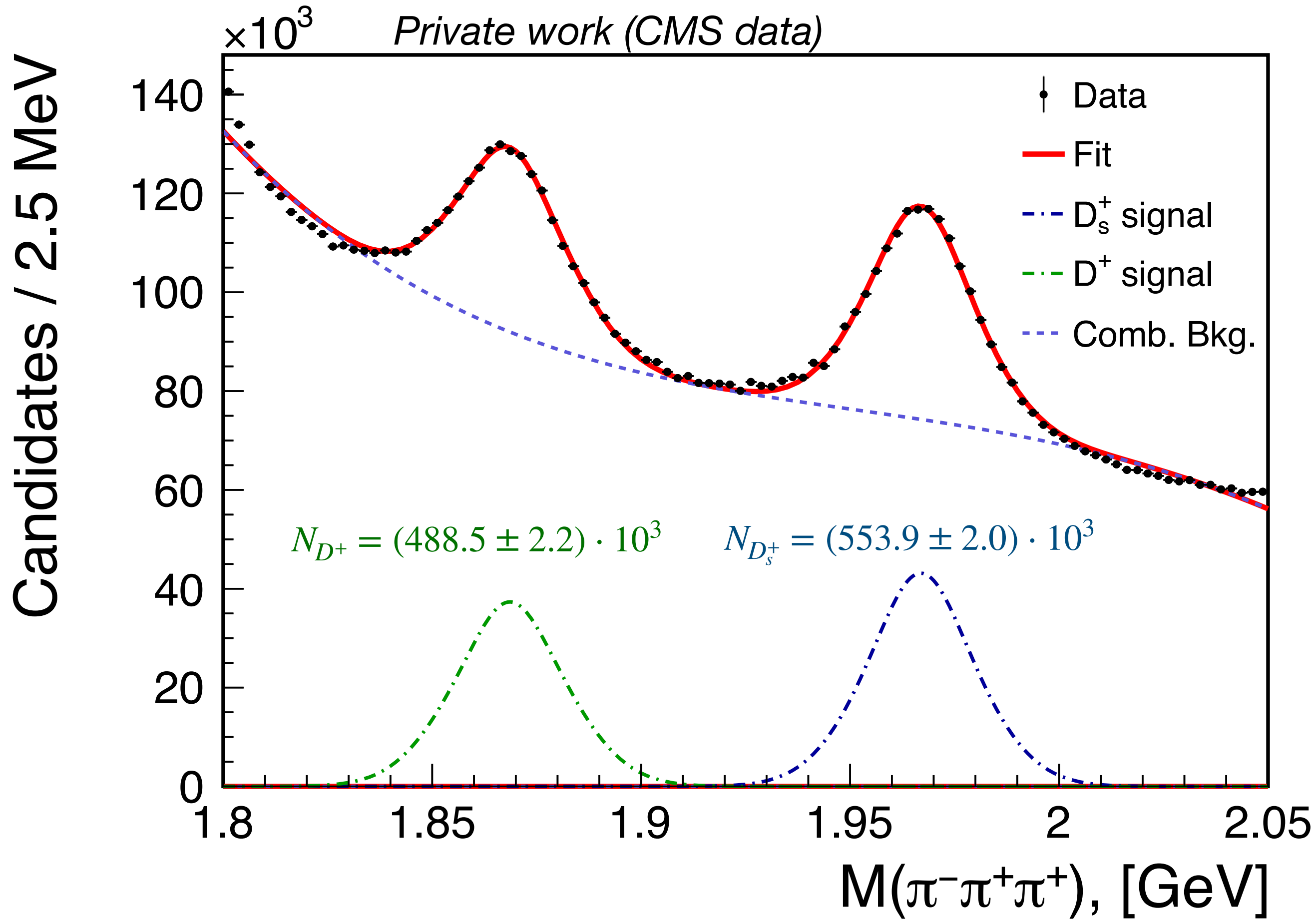
Fit model: *Double Gaussian for signal and polynomials for background*

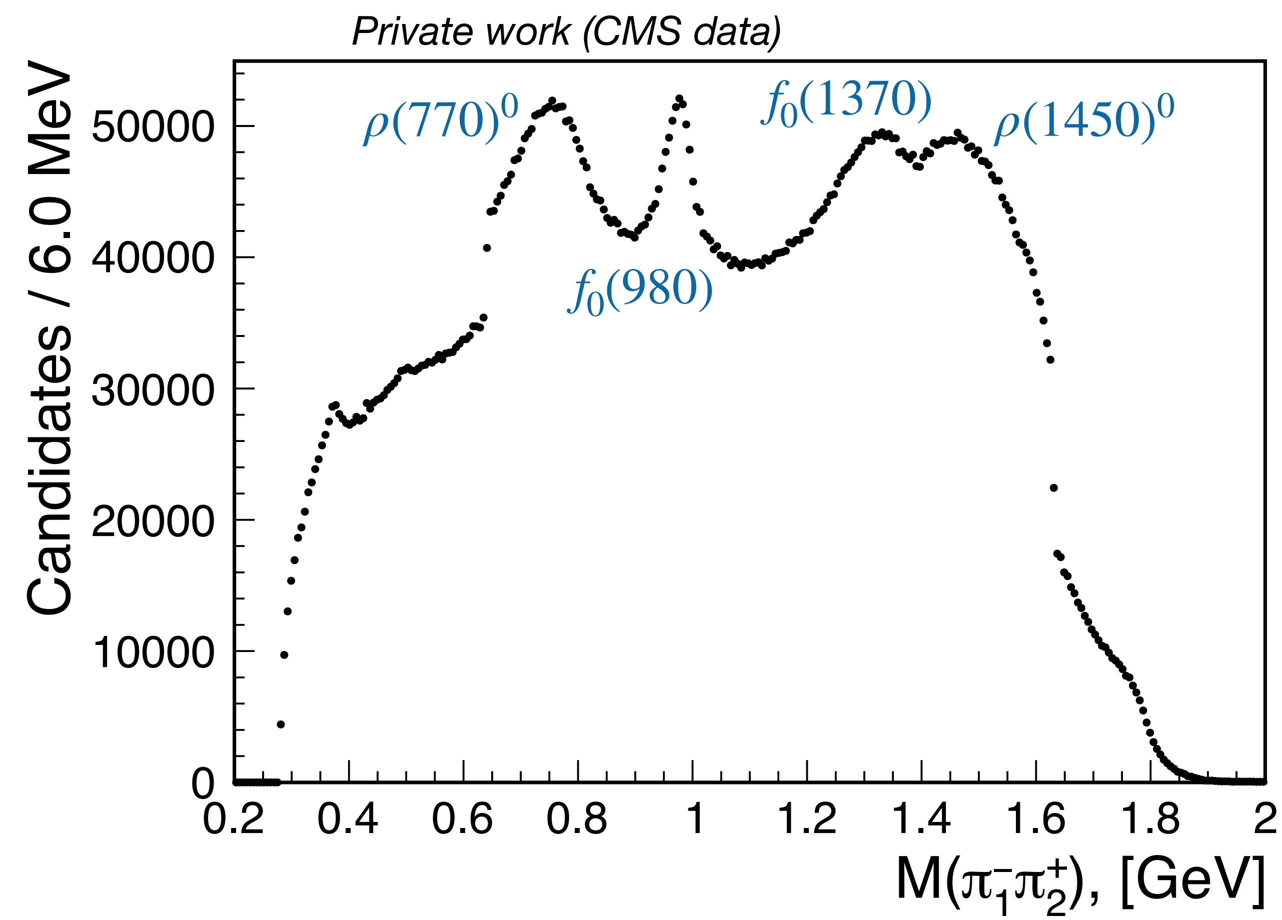
Signal	$N(D_s^+)$ $[10^3]$	S/B ratio	$N(D^+)$ $[10^3]$
$B_s^0 \to D_s^+ \mu^- \bar{\nu}_\mu$	1729 ± 3	3.500 ± 0.020	626 ± 2
prompt-D_s^+	2280 ± 10	0.509 ± 0.003	788 ± 12

- Robust and very large signals of D-mesons from both sources
  More than 1.7 and 2.2 millions of D_s^+ mesons are reconstructed

- $B_s^0 \to D_s^+ \mu^- \bar{\nu}_\mu$ channel with much larger purity (S/B ration in signal region) is selected as baseline for the further searches
  $N_{D_s^+}$ / $\mathscr{B}(D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+) \approx 8 \cdot 10^7$ of D_s^+ mesons from B_s^0 which could be used for $D_s^+ \to N\mu^+ \to \pi^-\mu^+\mu^+$ searches

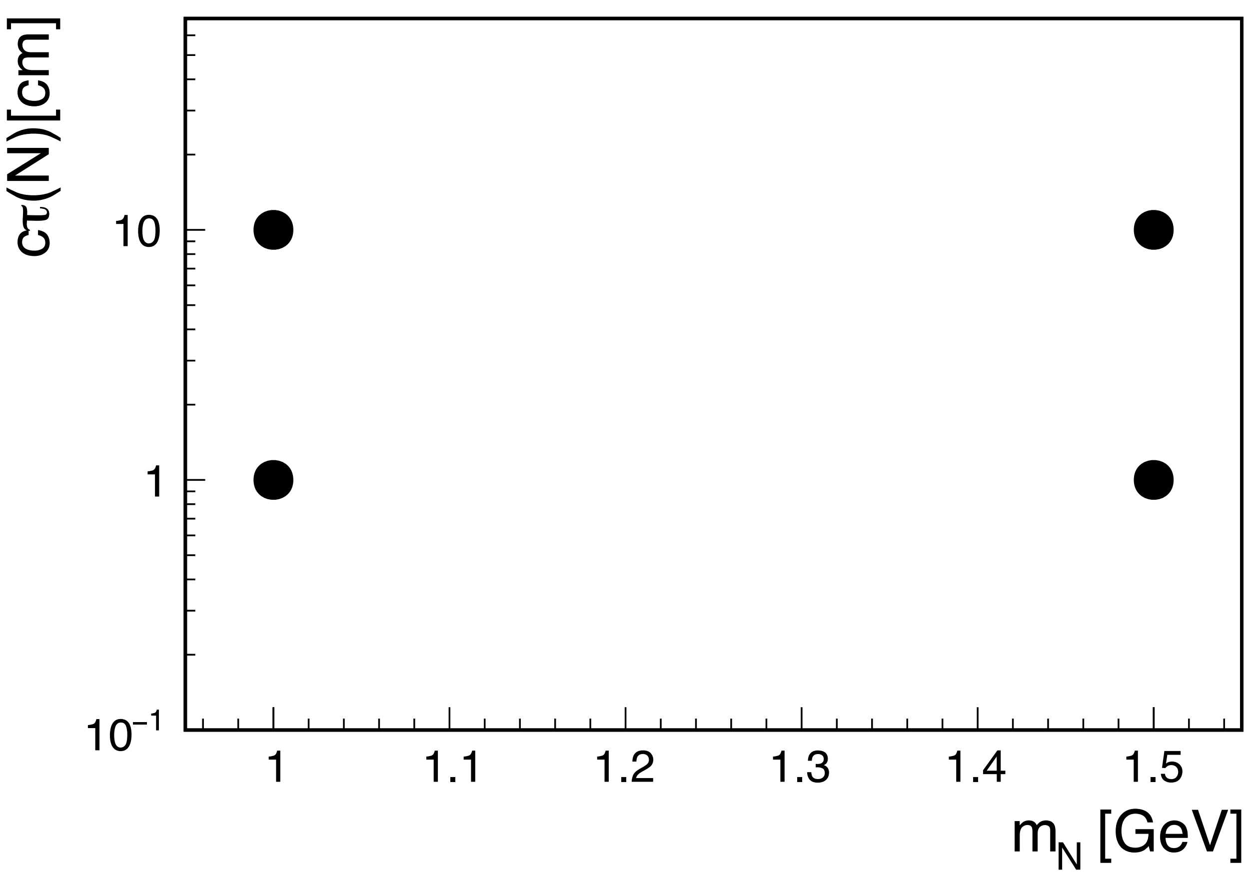
Studies of $D_s^+ \to \pi^+\pi^-\pi^+$

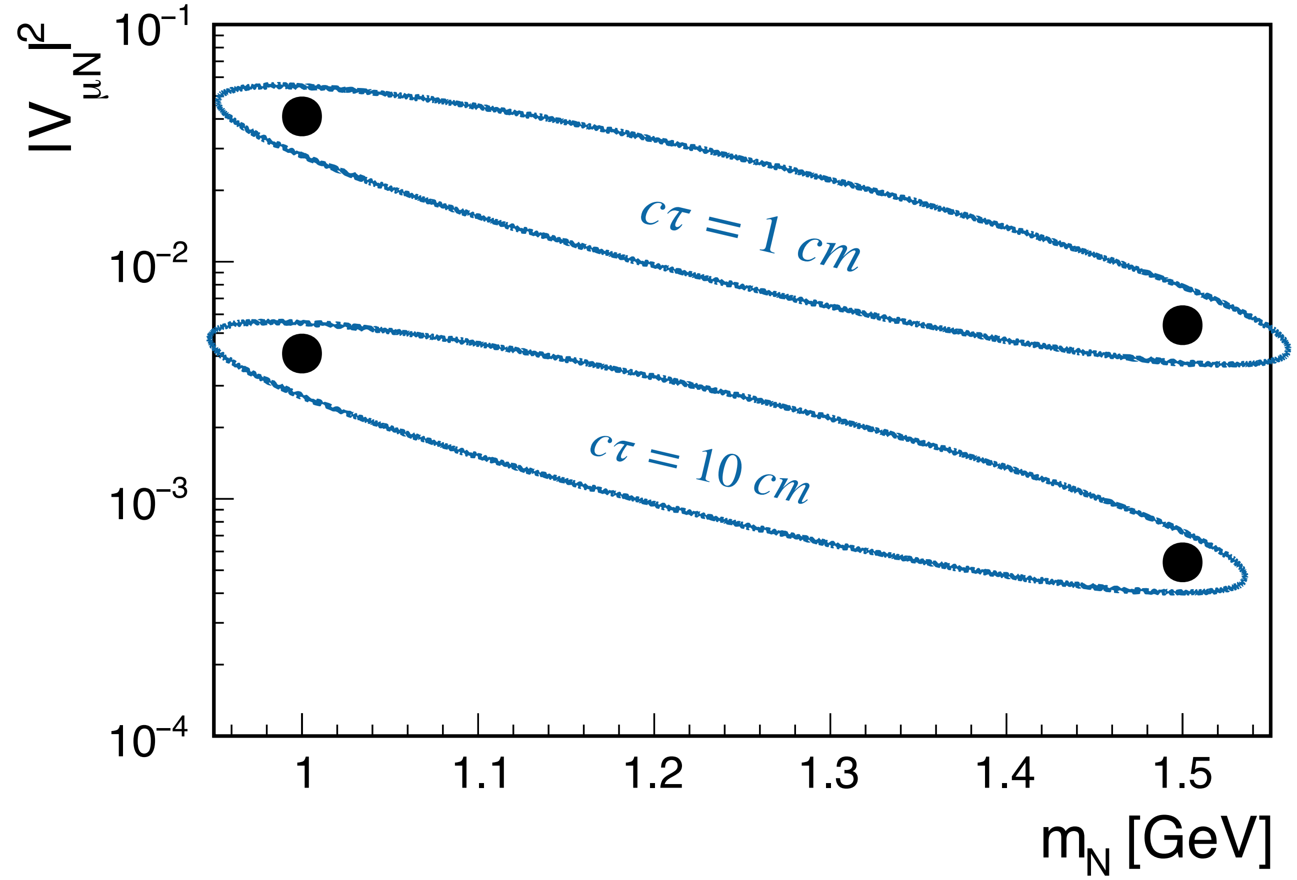




- Signal of $B_s^0 \to D_s^+\mu^-\bar{\nu}_\mu$ with $D_s^+ \to \pi^+\pi^-\pi^+$ is also accessible via CMS BParking dataset
- While $D_s^+ \to \phi\pi^+$ is considered to be the normalisation channel, $D_s^+ \to \pi^+\pi^-\pi^+$ mode could be important background contribution (with $\mu^\pm$-$\pi^\pm$ misID)
- Very rich resonant structure in $M(\pi, \pi)$ invariant masses is present

MC simulation intro





- Using official CMS MC production, we have generated 4 points in $(m_N, |V_{\mu N}|^2)$ plane for possible HNL parameters

- For theoretical calculation of HNL parameters and their relations (N lifetime $\tau \sim m_N^{-5} |V_{\mu N}|^{-2}$) we used approach from Phys.Rev.D 94 (2016) 11, 113007:

$$\Gamma_N \approx \frac{G_F^2 m_N^5}{96\pi^3} \left| V_{\mu N} \right|^2 \cdot 10.95 \longrightarrow |V_{\mu N}|^2 = \frac{0.41}{m_N^5[\text{GeV}] \cdot c\tau[\text{mm}]}$$

Gen-filter efficiency ϵ^{gen}

	m_N = 1.0 GeV	m_N = 1.5 GeV
ctau = 1cm	1,52 ± 0,03 %	1,45 ± 0,03 %
ctau = 10 cm	1,50 ± 0,03 %	1,49 ± 0,03 %

Efficiency is in $[10^{-2}]$ ***units***

- ϵ^{gen} is an efficiency of soft requirements applied at the generator level on the p_T and η of the particles (gen-filters).
  For our MC samples, GEN-filter includes:

- 1) *"BParking trigger"* filter:
  at least one muon has $p_T > 6.8$ GeV and $|\eta| < 1.55$

- 2) Filter, related with CMS detector acceptance on p_T and η (restrictions on possibilities of adequate particles reconstructions) for HNL daughters:
  $p_T(\mu) > 0.5$ GeV, $|\eta(\mu)| < 2.5$
  $p_T(\pi) > 0.5$ GeV, $|\eta(\pi)| < 2.5$

- In result we have $\epsilon^{gen} \sim 1.5\ \%$, similar for all samples

Reconstruction and selection criteria

Selection criteria are standard soft CMS B-physics cuts to provide robust reconstruction
MC Truth (matching the reconstructed particles with the generated ones) is applied.

Pion selection

- $|\eta(\pi^{\pm})| < 2.4$
- $p_T(\pi^{\pm}) > 0.5\ GeV/c$

Muon selection

- $p_T(\mu^{\pm}) > 3\ GeV/c$
- $|\eta(\mu^{\pm})| < 2.4$
- One has $p_T(\mu^{\pm}) > 7\ GeV/c$ and $d_{xy}/\sigma_{d_{xy}}(\mu^{\pm}) > 3$
  BParking trigger

D_s^+ selection

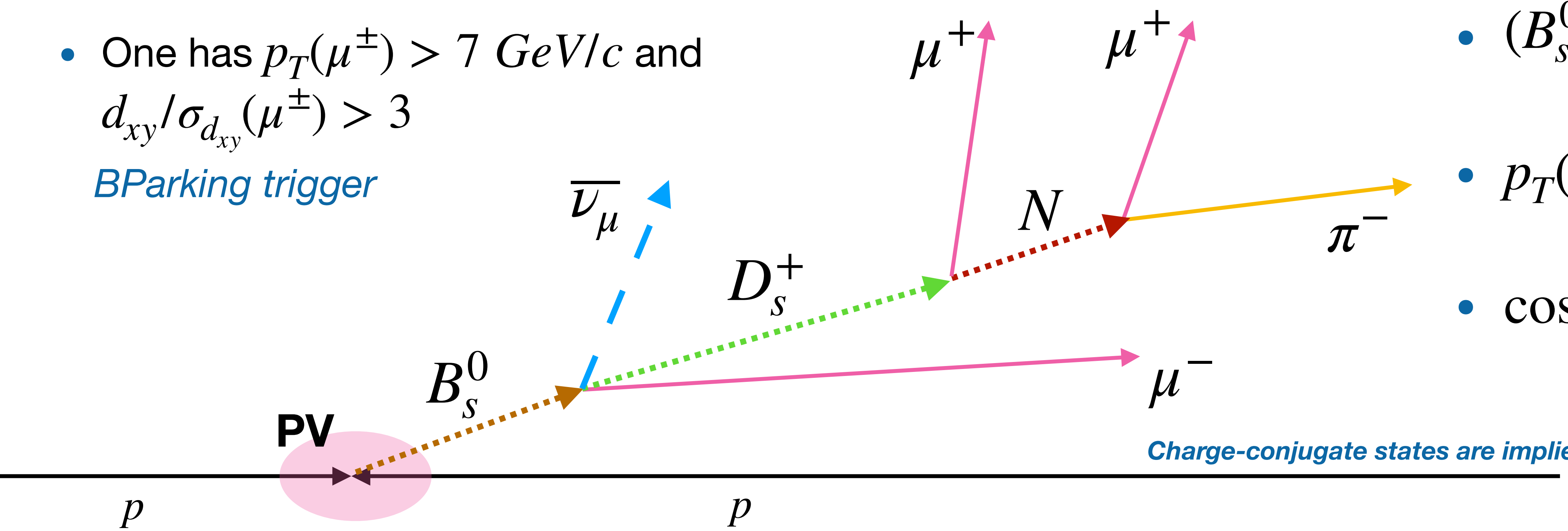
- $|m_{D_s^+} - m_{D_s^+}^{PDG}| < 60\ MeV$
- $D^+_{s\,vtxprob} > 0.01$
- $p_T(D_s^+) > 8\ GeV/c$
- $(B_s^0, D_s^+)_{detach\ significance} > 3$

N selection

- $N_{vtxprob} > 0.01$
- $(D_s^+, N)_{detach\ significance} > 1$

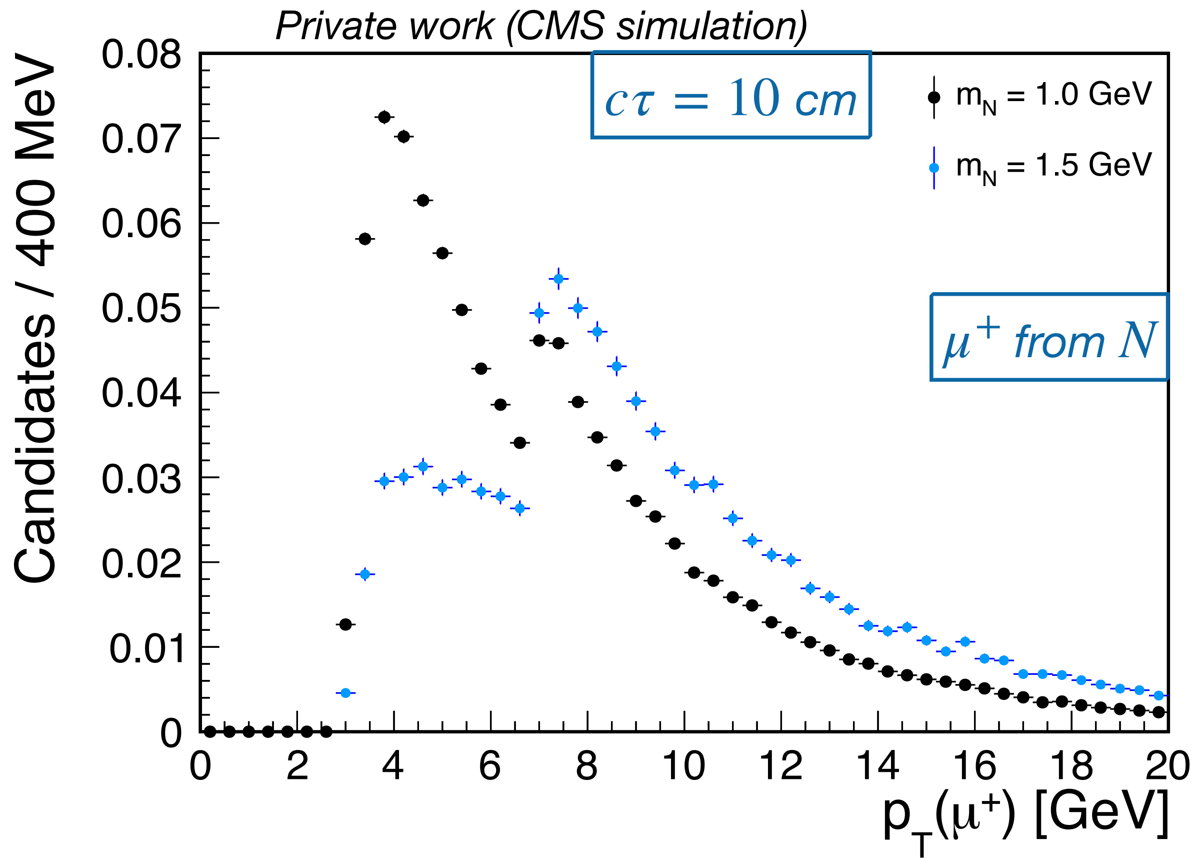
B_s^0 selection

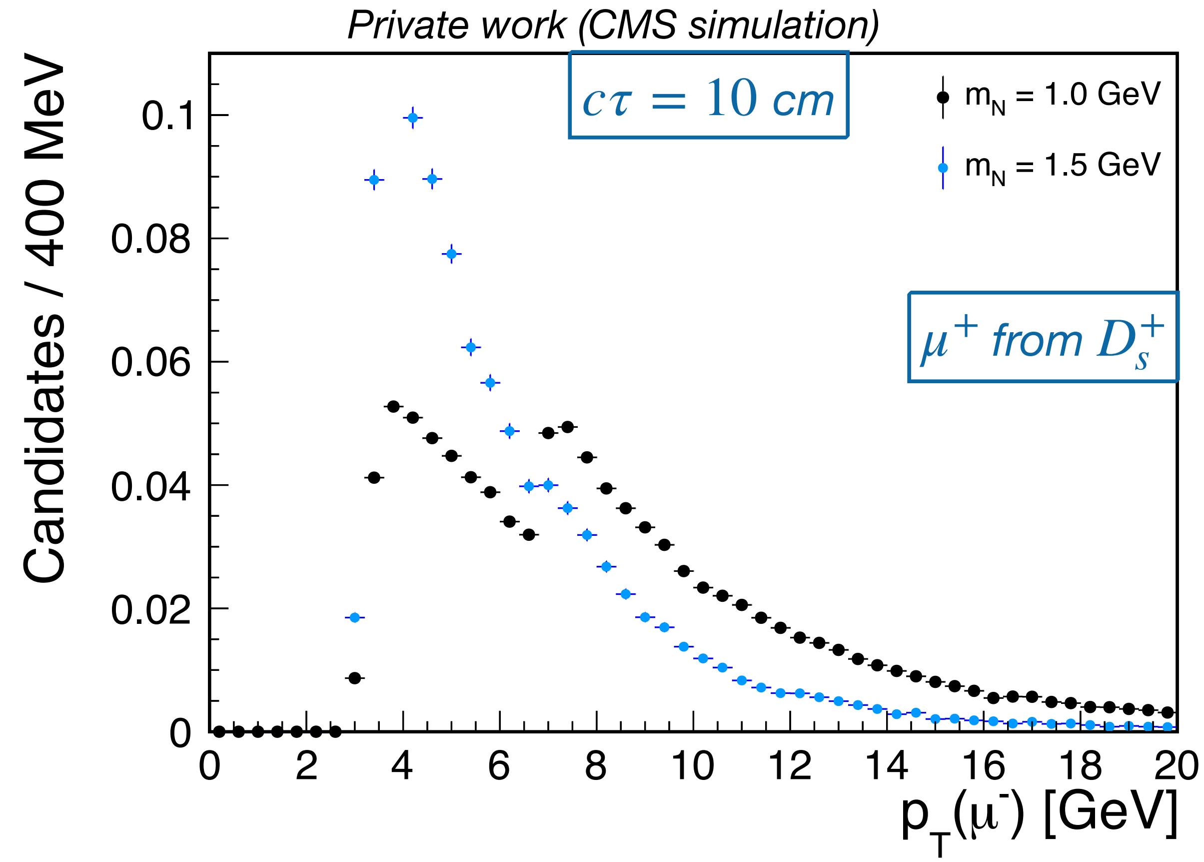
- $(B_s^0)_{vtxprob} > 0.01$
- $(B_s^0)_{detach\ significance} > 3$
- $p_T(B_s^0) > 12\ GeV/c$
- $\cos(PV, B^0) > 0.9$

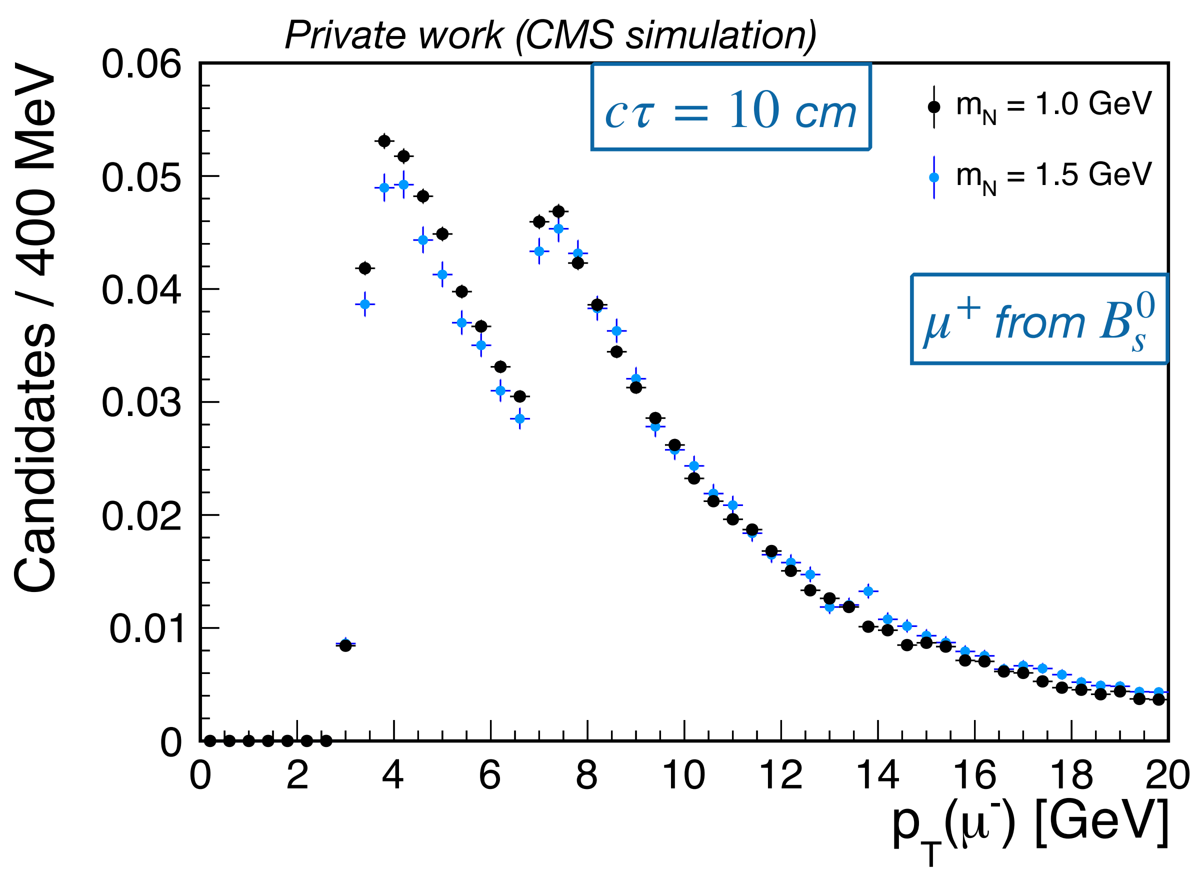


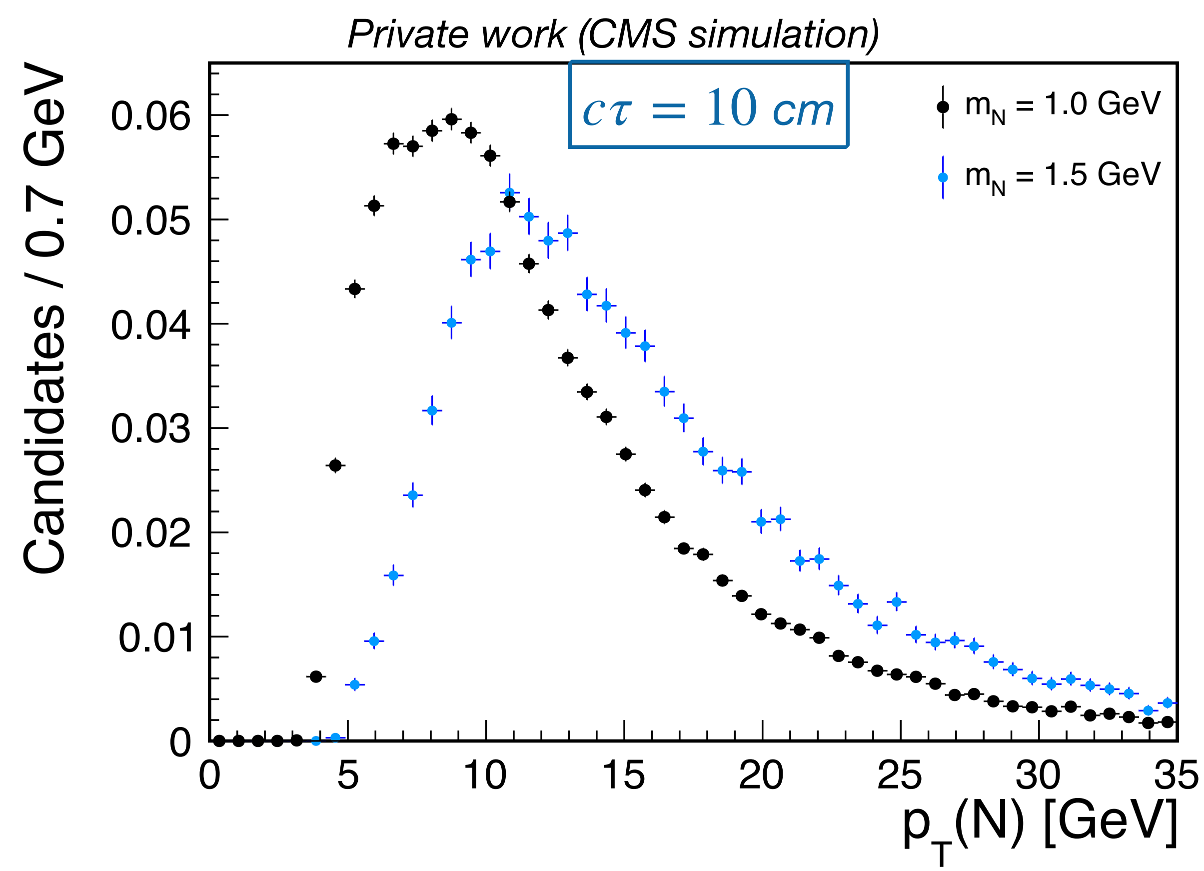
Charge-conjugate states are implied

Kinematic distributions: p_T of muons and N



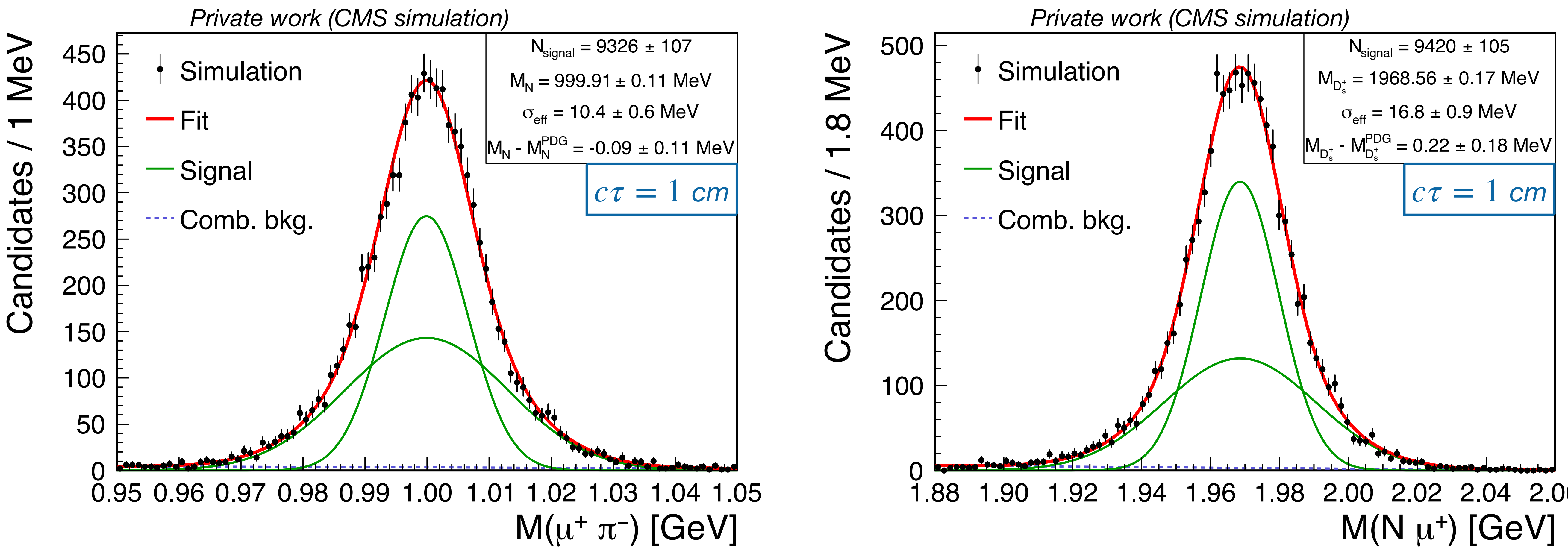






Fits of $\mu^+\pi^-$ and $\mu^+\mu^+\pi^-$ invariant masses

Example of fits for one MC sample



- Clear peaks are visible in reconstructed invariant masses of $\mu^+\pi^-$ and $\mu^+\mu^+\pi^-$ (corresponding to N and D_s^+ signals) Numbers of signal events and detector resolutions are extracted from fits with Double Gaussian (or Gaussian + Crystal Ball) for signal and 1st order polynomial for background

- HNL detector resolution is (as expected) better for lower mass, no clear dependence from lifetime is observed

- D_s^+ resolution was found to be independent from HNL parameters and is about 17-18 MeV for all samples

HNL detector resolution (in MeV)

	m_N = 1.0 GeV	**m_N = 1.5 GeV**
ctau = 1cm	10.4 ± 0.6	16.1 ± 0.7
ctau = 10 cm	11.0 ± 0.3	14.9 ± 1.1

Reconstruction and total efficiency

Reconstruction efficiency $\epsilon^{rec-sel}$

	m_N = 1.0 GeV	m_N = 1.5 GeV
ctau = 1cm	9,03 ± 0,10	6,64 ± 0,18
ctau = 10 cm	8,00 ± 0,04	5,26 ± 0,06

$[10^{-3}]$ ***units***

Total efficiency ϵ

	m_N = 1.0 GeV	m_N = 1.5 GeV
ctau = 1cm	13.72 ± 0,31	9,63 ± 0,32
ctau = 10 cm	12,00 ± 0,25	7,84 ± 0,18

$[10^{-5}]$ ***units***

- $\epsilon^{rec-sel}$ is an efficiency of the reconstruction and selection requirements applied; calculated as ratio of the number of events from fit of $N \to \mu^+\pi^-$ after all cuts to the number of generated events in MC-sample;
  $\epsilon^{rec-sel}$ seems to be better for both lower mass and lifetime

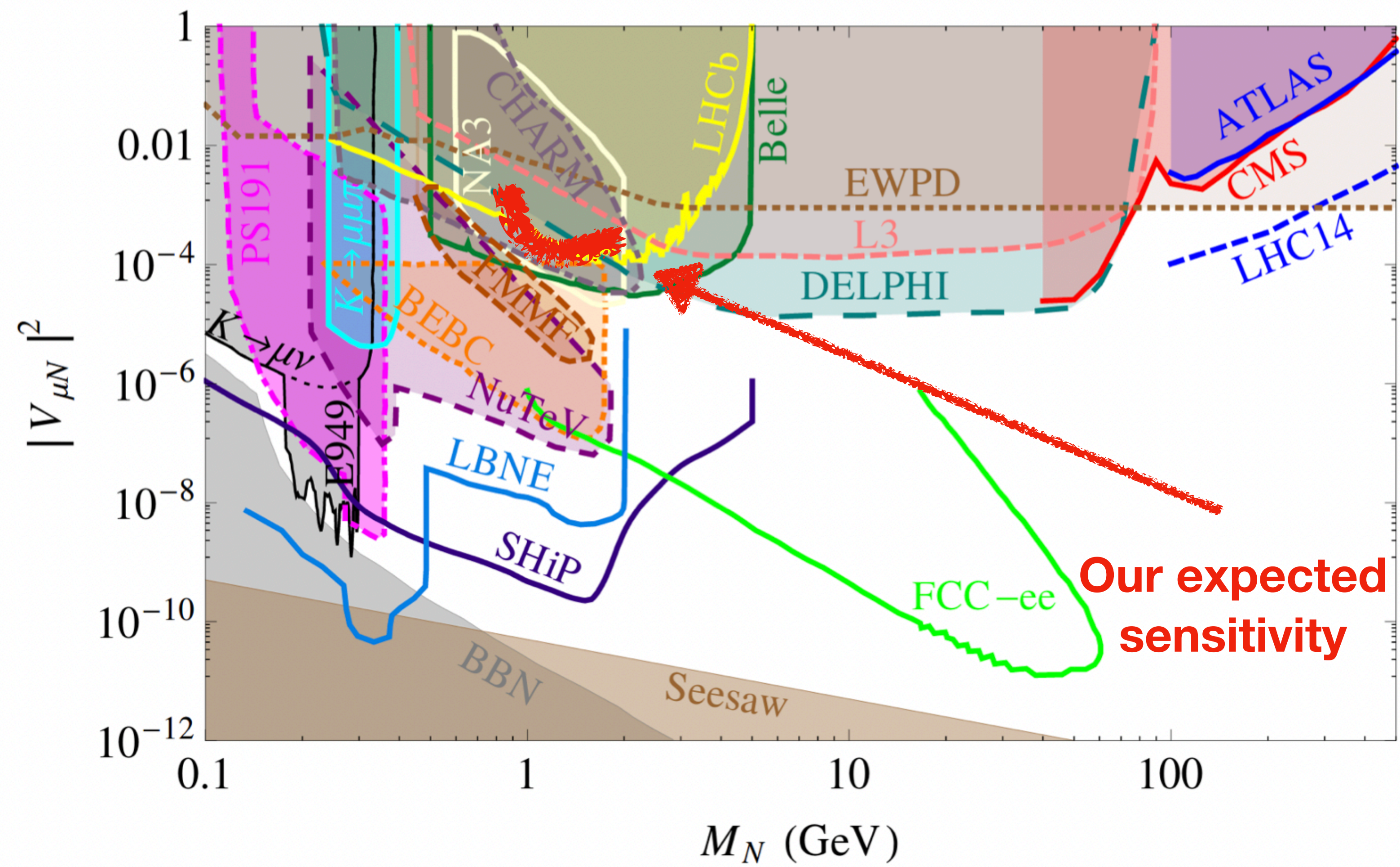
- Total efficiency is $\epsilon = \epsilon^{gen} \times \epsilon^{rec-sel}$
  The results are about $10^{-4} \div 10^{-5}$ depending on HNL parameters

- The expected number of signal on data could be estimated as
  $N_{sig} = N(D_s^+) \times (\mathscr{B}(D_s^+ \to N[\to \mu^+\pi^-]\mu^+) \times \epsilon$

- With $N(D_s^+) \sim 10^8$ (experimental estimate from BParking studies) and $\epsilon \sim 10^{-4}$, we need relatively high branching ($\gtrsim 10^{-3}$) to get any reasonable $N_{sig} \longrightarrow$
  our final upper limit could be measured to be quite humble and unpretentious

Conclusion and summary

- We report the studies of possibilities and prospects for the search for heavy sterile neutrino from D_s^+ decay
- Significant and robust signal with enormous D_s^+ statistics is observed on CMS 2018 data (BParking dataset)
- Monte-Carlo studies of signal decay $B_s^0 \to D_s^+ \mu^- \overline{\nu_\mu}$, $D_s^+ \to N\mu^+ \to \mu^+\mu^+\pi^-$ are provided



- Generator and reconstruction efficiencies are estimated for 4 points in $(m_N, |V_{\mu N}|^2)$ plane for possible HNL parameters
- Normalisation and background channels are to be studied in Monte-Carlo simulation
- As our next plans we consider to perform selection optimisation (using both data and MC) and then proceed blind analysis for the search of $D_s^+ \to N\mu^+ \to \mu^+\mu^+\pi^-$ and measuring its branching fraction w.r.t. $D_s^+ \to \phi\pi^+$ (or its upper limit)

Thank you for your attention!

Do you have any questions?

Backup slides

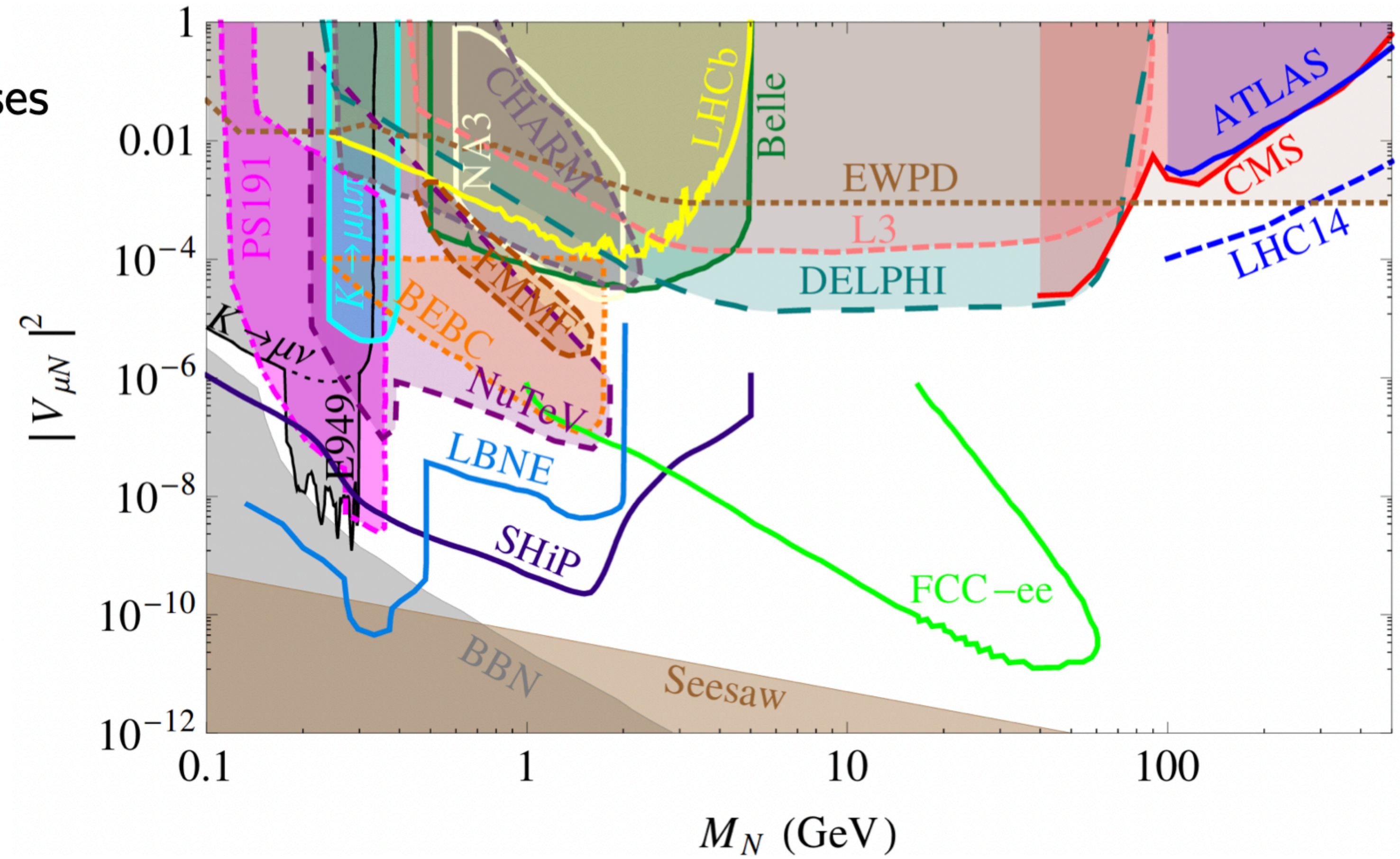
Heavy neutrinos

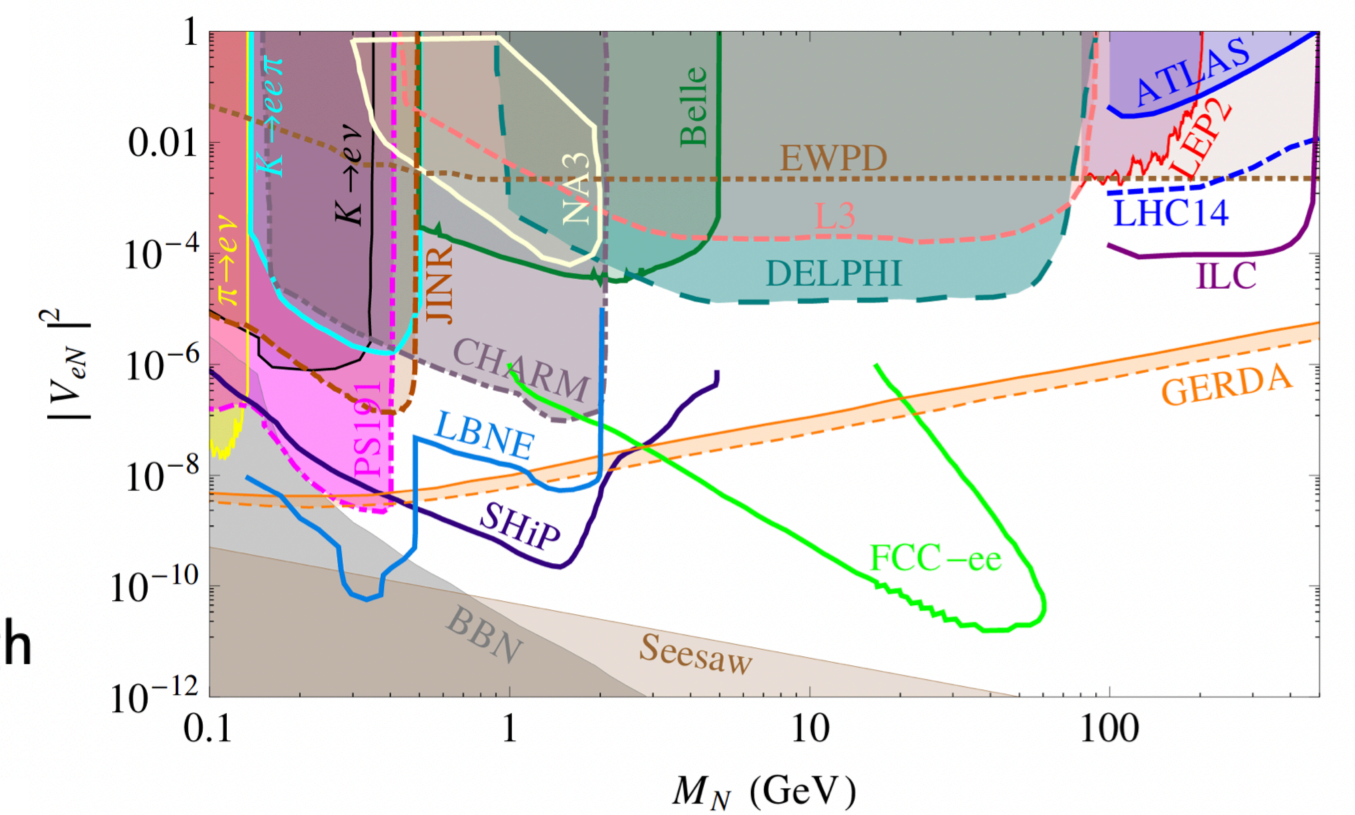
- HNL **lifetime** becomes longer with small masses or mixing

$$\tau \propto |V_{\ell N}|^{-2}\, m_N^{-5}$$

- Lifetime :
  - very small → prompt decays
  - macroscopic distances from production vertex

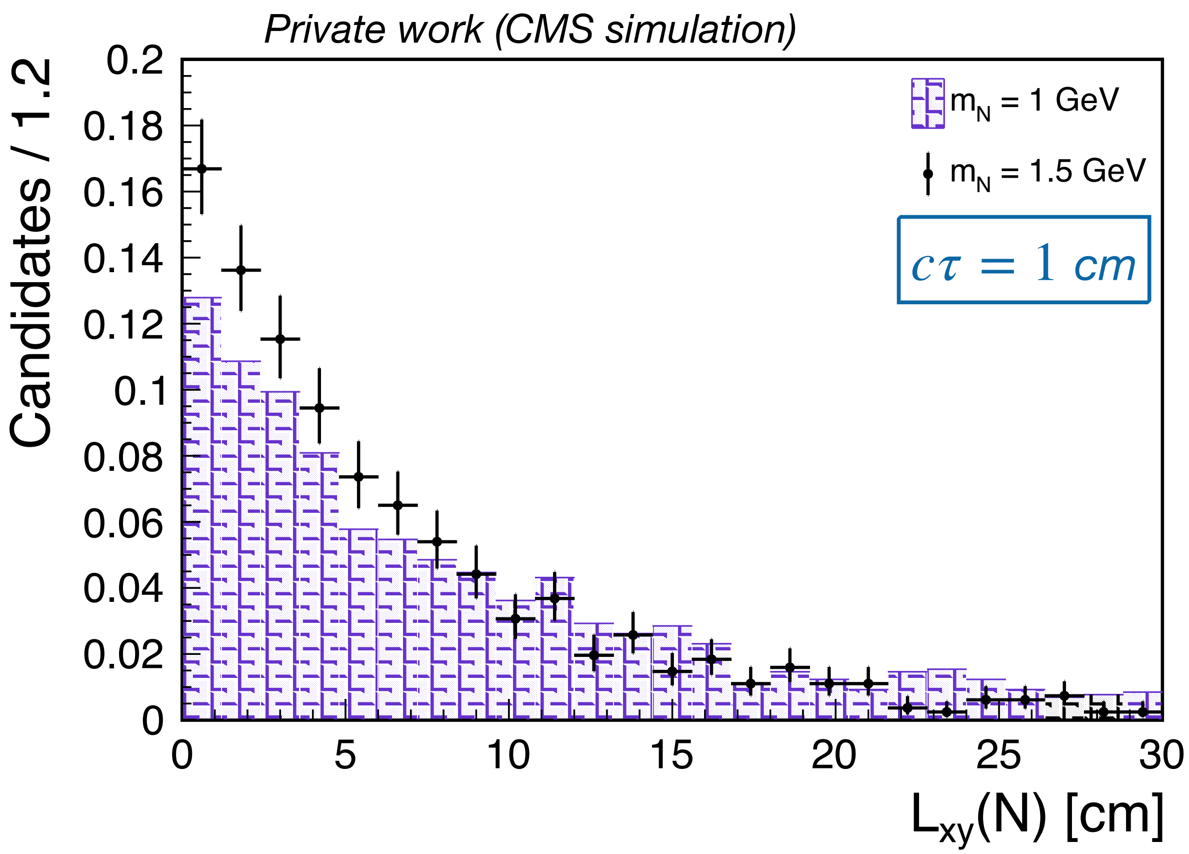
    → displaced decays for lower couplings at low masses
- Existing constraints (filled area) and future projections (contours) on mixing angle and mass:

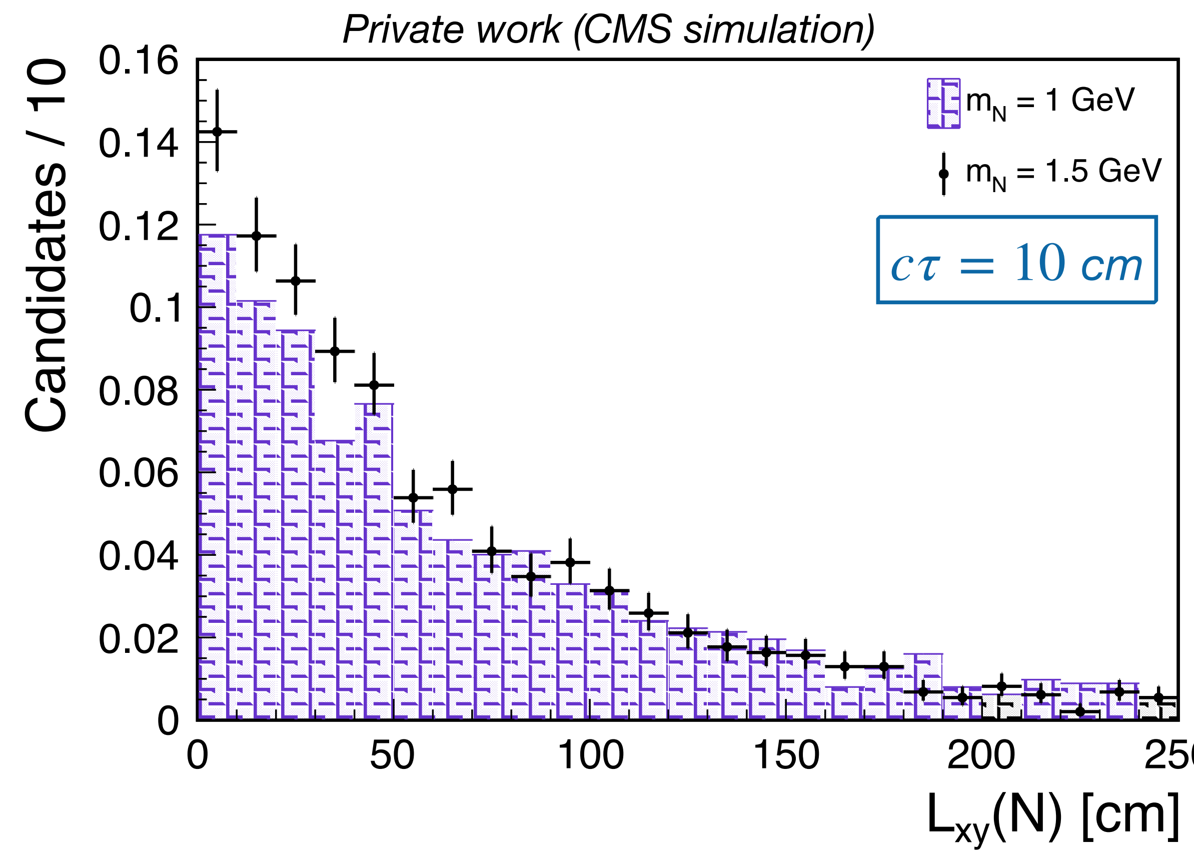


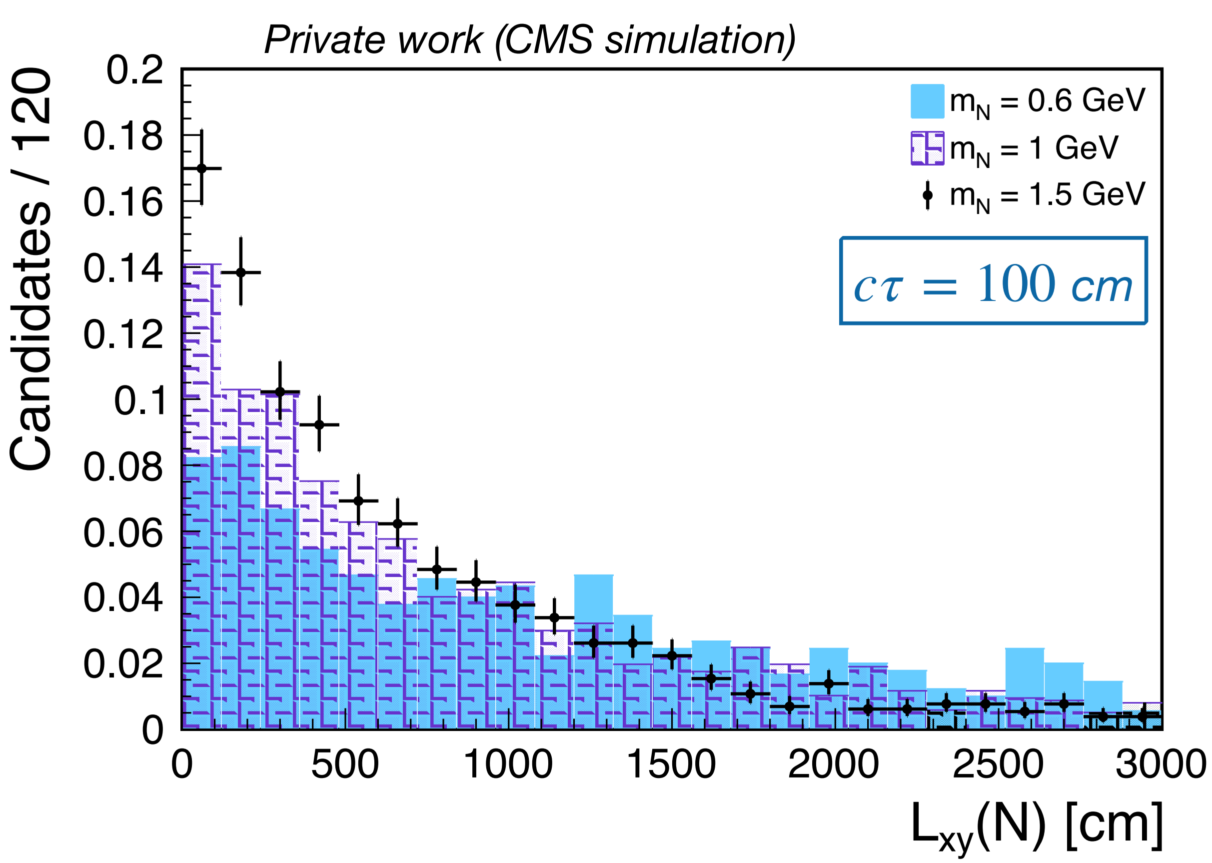


- **N are sterile** and interact only with ν through mixing

Gen-lvl $L_{xy}(N)$-distributions







Means of L_xy(N) distributions [cm]

	m_N = 0.6 GeV	m_N = 1.0 GeV	m_N = 1.5 GeV
ctau = 1 cm		11,1	7,4
ctau = 10 cm		109,2	73,9
ctau = 100 cm	1648,7	1115,2	772,0
ctau = 1000 cm	7388,6		

- Here we have clear dependence: Lighter N has larger displacement
- In agreement with obvious kinematic expectations

Acceptance

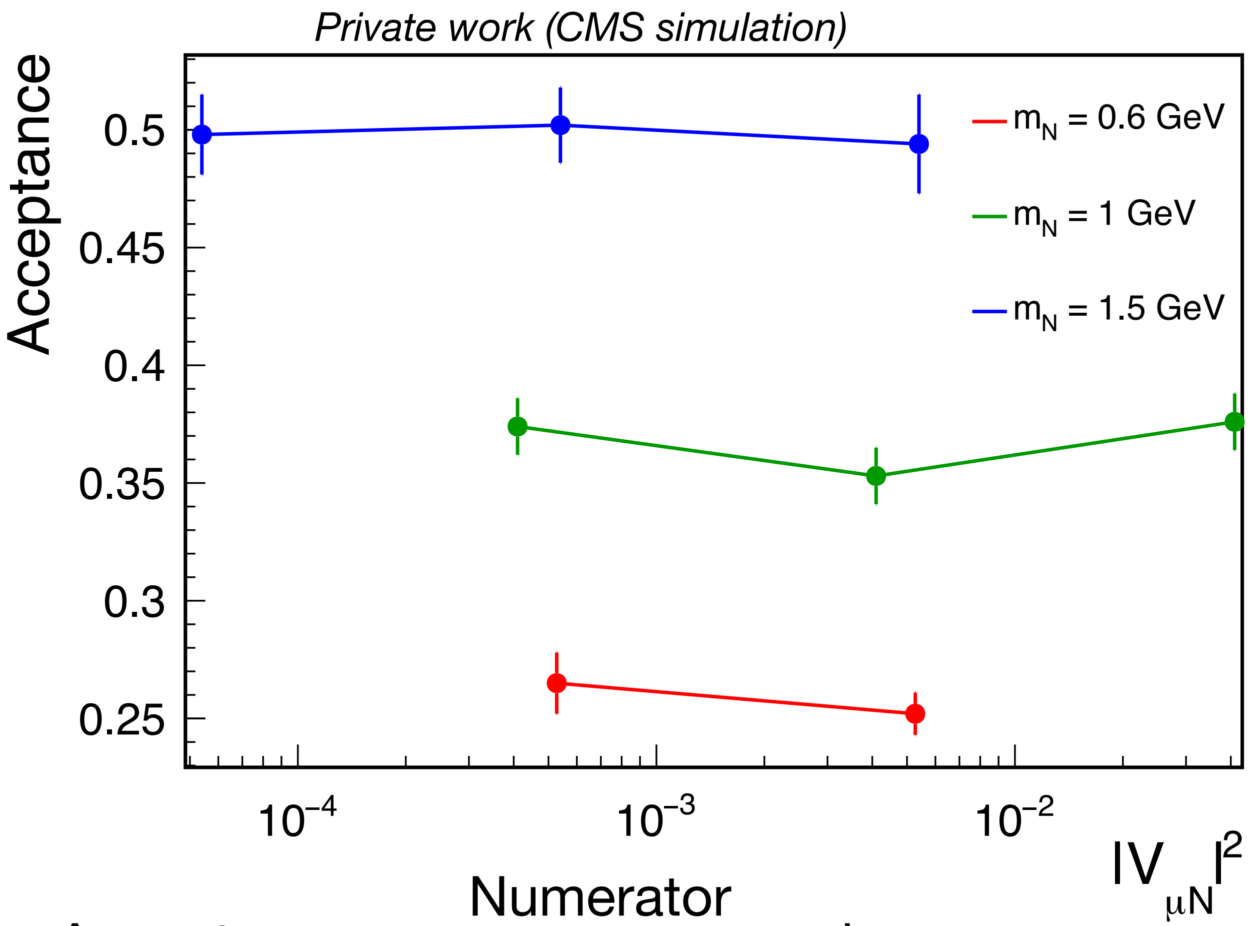
- Important parameter of our studies is acceptance, which is

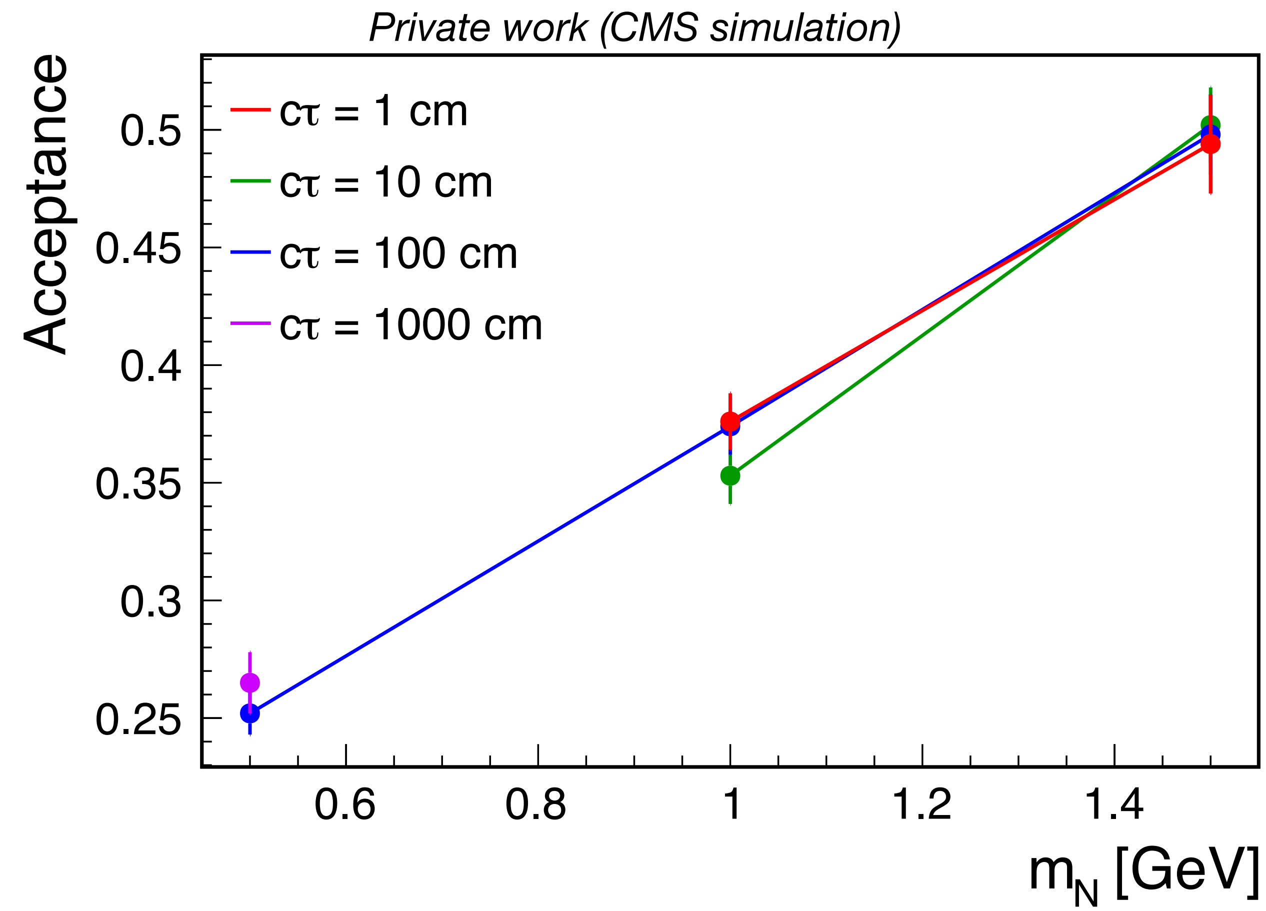
$$\text{Acceptance} = \frac{\text{Numerator}}{\text{Denominator}}$$

- Denominator is number of gen-events after *"BParking trigger"* filter: at least a muon with $p_T > 7$ GeV and $|\eta| < 1.55$

- Numerator is *"BParking trigger"* filter plus "CMS acceptance requirements" for HNL daughters:
  $p_T(\mu) > 3$ GeV, $|\eta(\mu)| < 2.5$
  $p_T(\pi) > 0.3$ GeV, $|\eta(\pi)| < 2.5$

Acceptance estimations





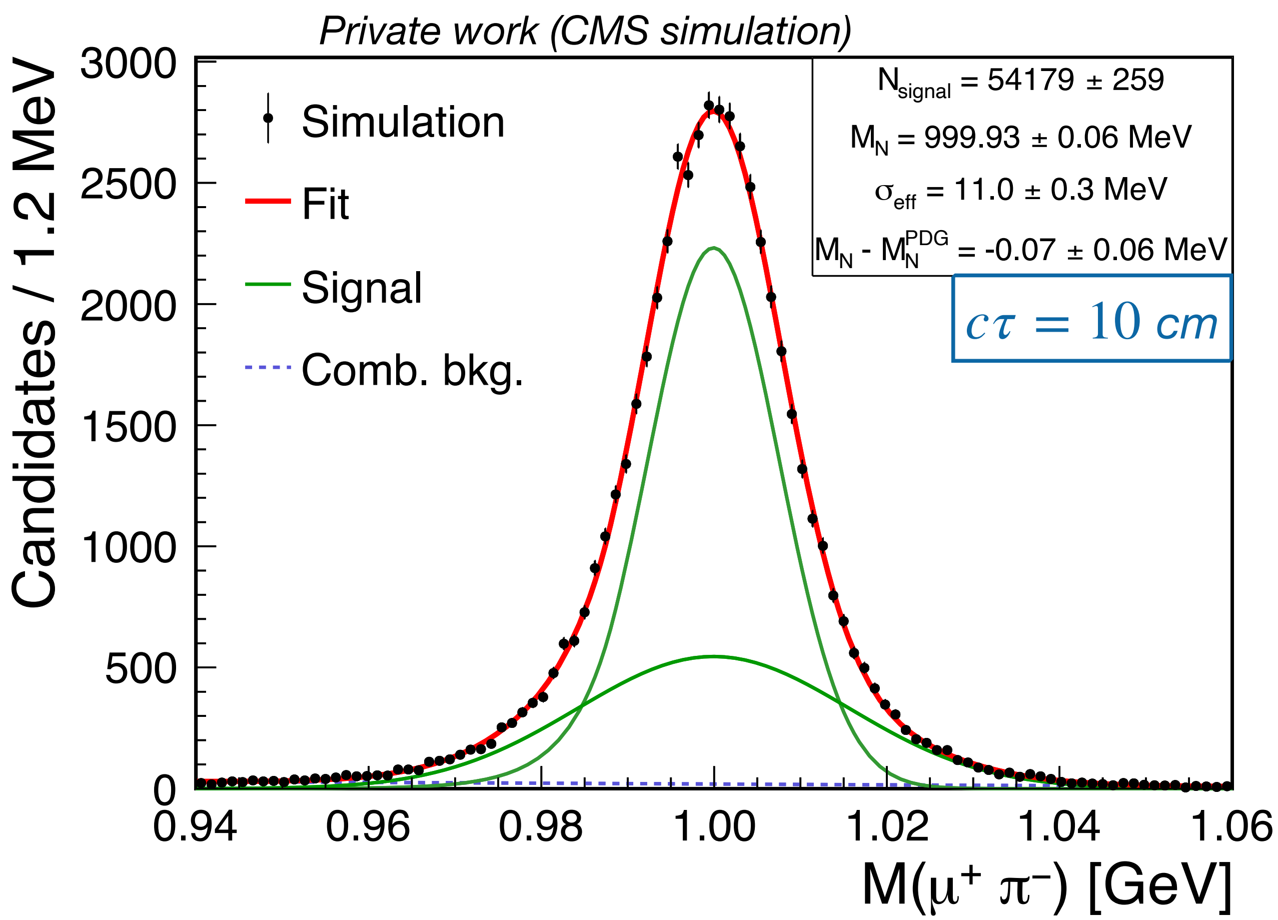
- Acceptance $= \dfrac{\text{Numerator}}{\text{Denominator}}$, where:

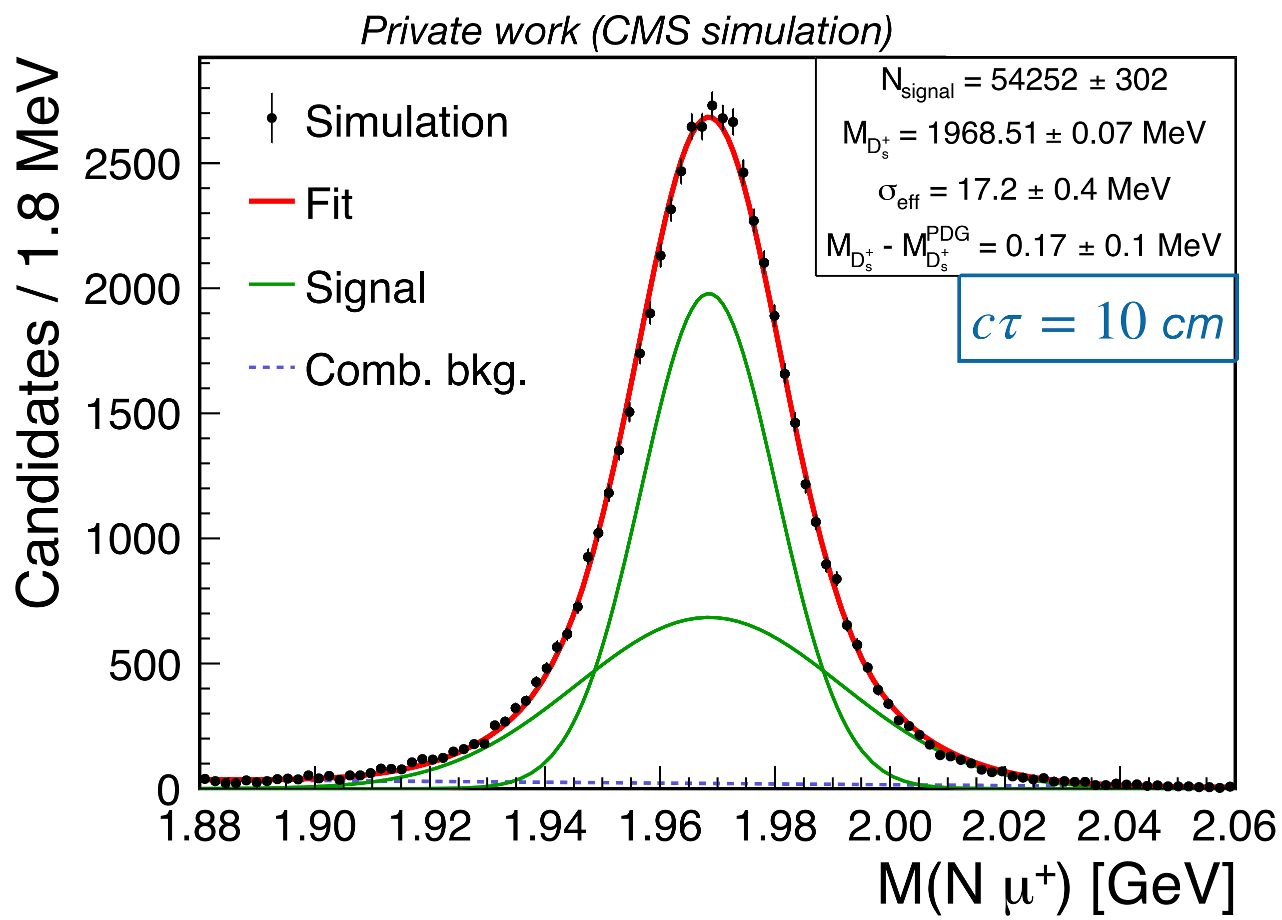
  - Denominator is number of gen-events after *"BParking trigger"* filter: at least a muon with $p_T > 7$ GeV and $|\eta| < 1.55$

  - Numerator is *"BParking trigger"* filter plus "CMS acceptance requirements" for HNL daughters: $p_T(\mu) > 3$ GeV, $|\eta(\mu)| < 2.5$, $p_T(\pi) > 0.3$ GeV, $|\eta(\pi)| < 2.5$

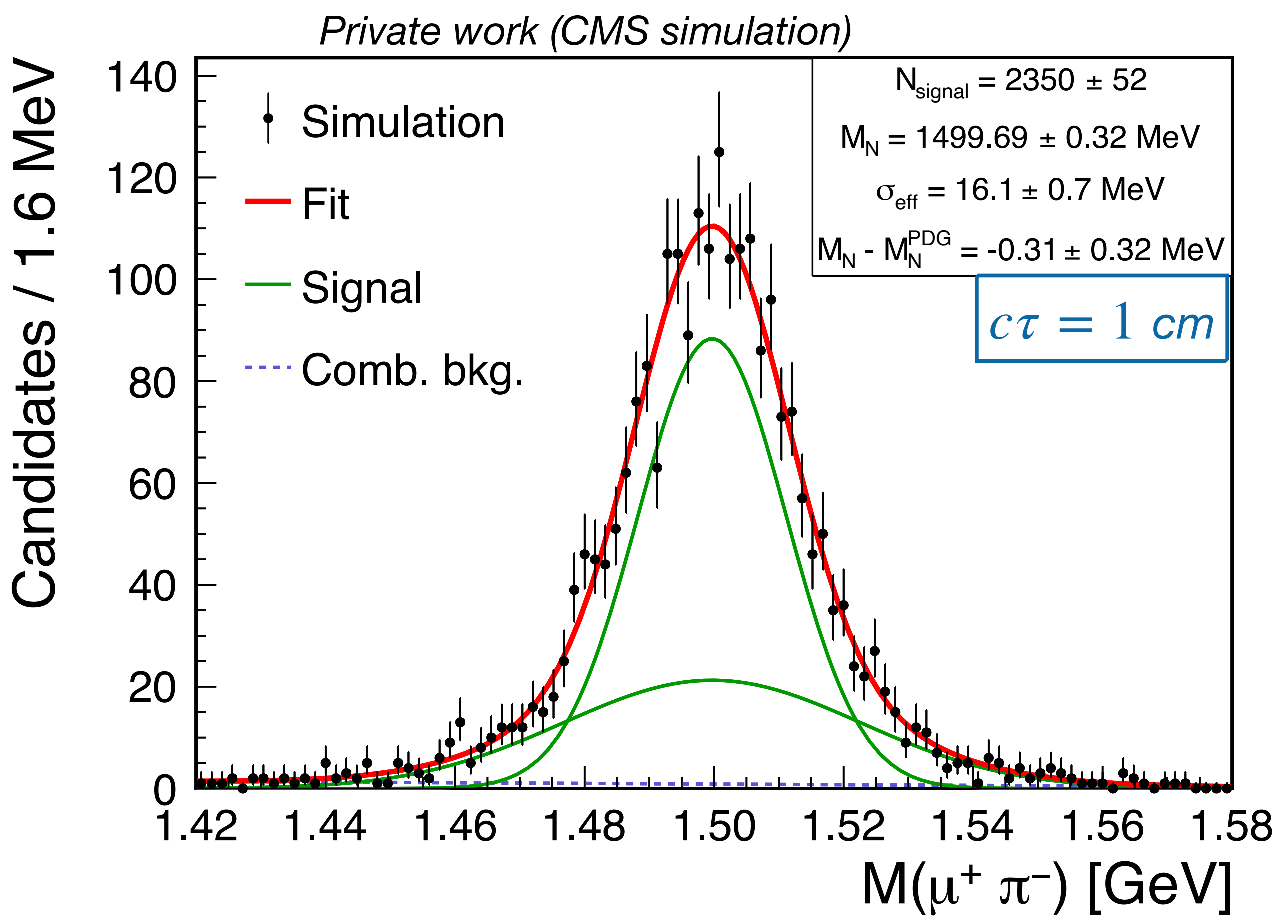
- The higher mass gives us higher acceptance
  No significant dependence of acceptance from coupling parameter $|V_{\mu N}|^2$ is observed

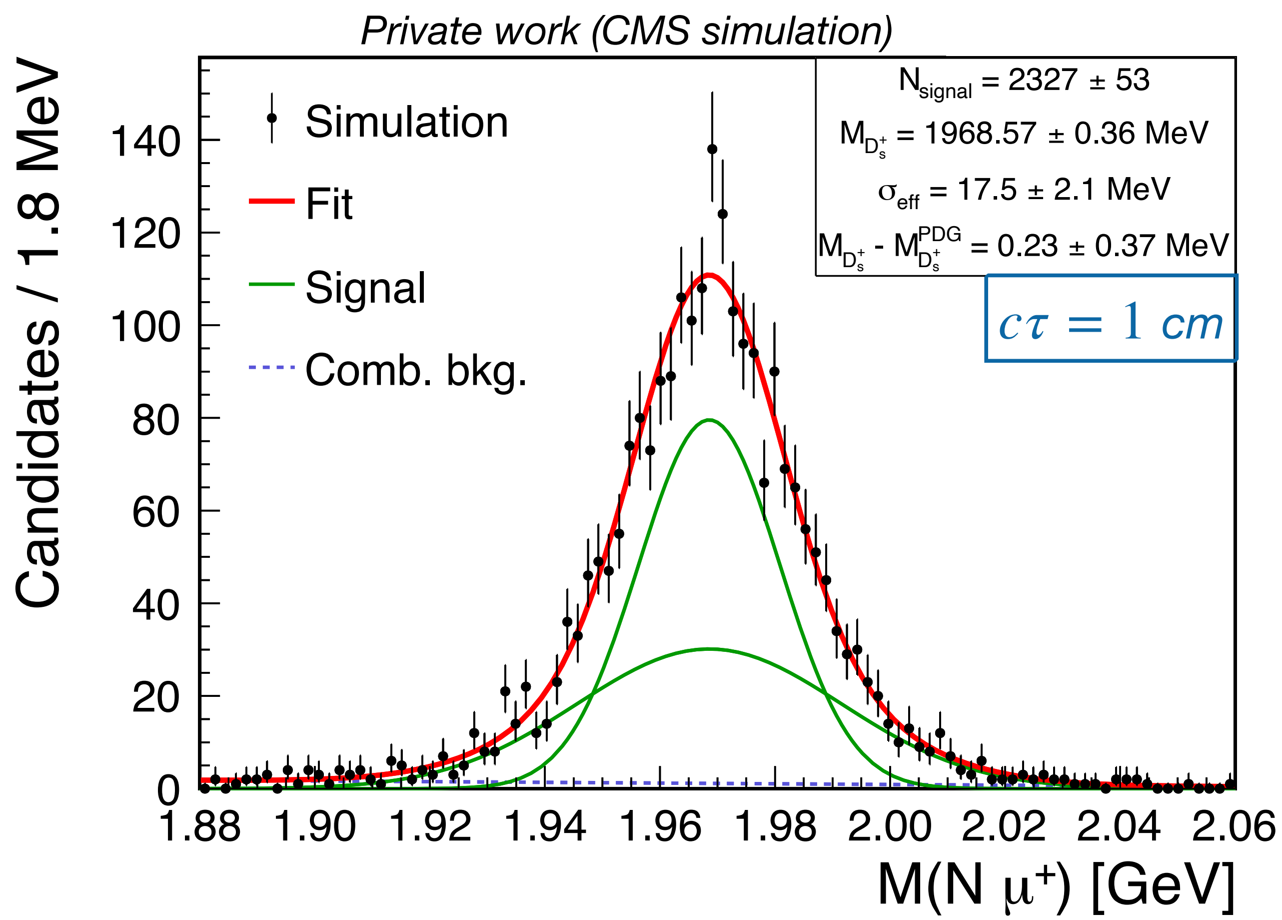
Fits of $\mu^+\pi^-$ and $\mu^+\mu^+\pi^-$ invariant masses





Fits of $\mu^+\pi^-$ and $\mu^+\mu^+\pi^-$ invariant masses





Fits of $\mu^+\pi^-$ and $\mu^+\mu^+\pi^-$ invariant masses