



Monte-Carlo studies of heavy sterile neutrino from D_s^+ decay

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Introduction (heavy neutrinos)

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

- **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

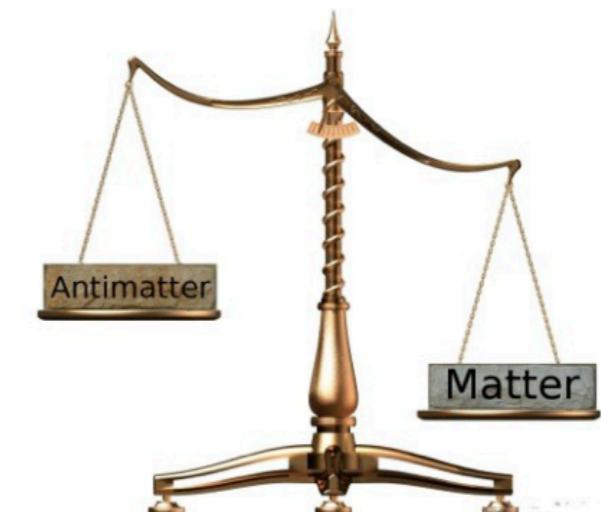
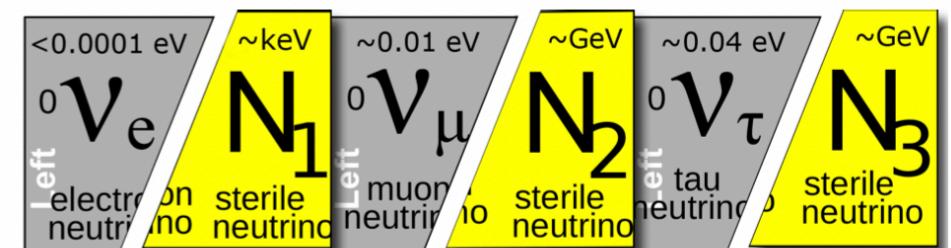
- possible solution for long-standing puzzles :

- origin of **SM neutrino masses** via **seesaw mechanism** $m_\nu \sim y^2 v^2 / m_N$

- N_1 ($m \sim \text{keV}$) = **dark matter candidate**

- degenerate N_2 and N_3 ($1 < m < 100 \text{ GeV}$) = possible explanation for **matter-antimatter asymmetry** of the Universe

- can be searched for at LHC

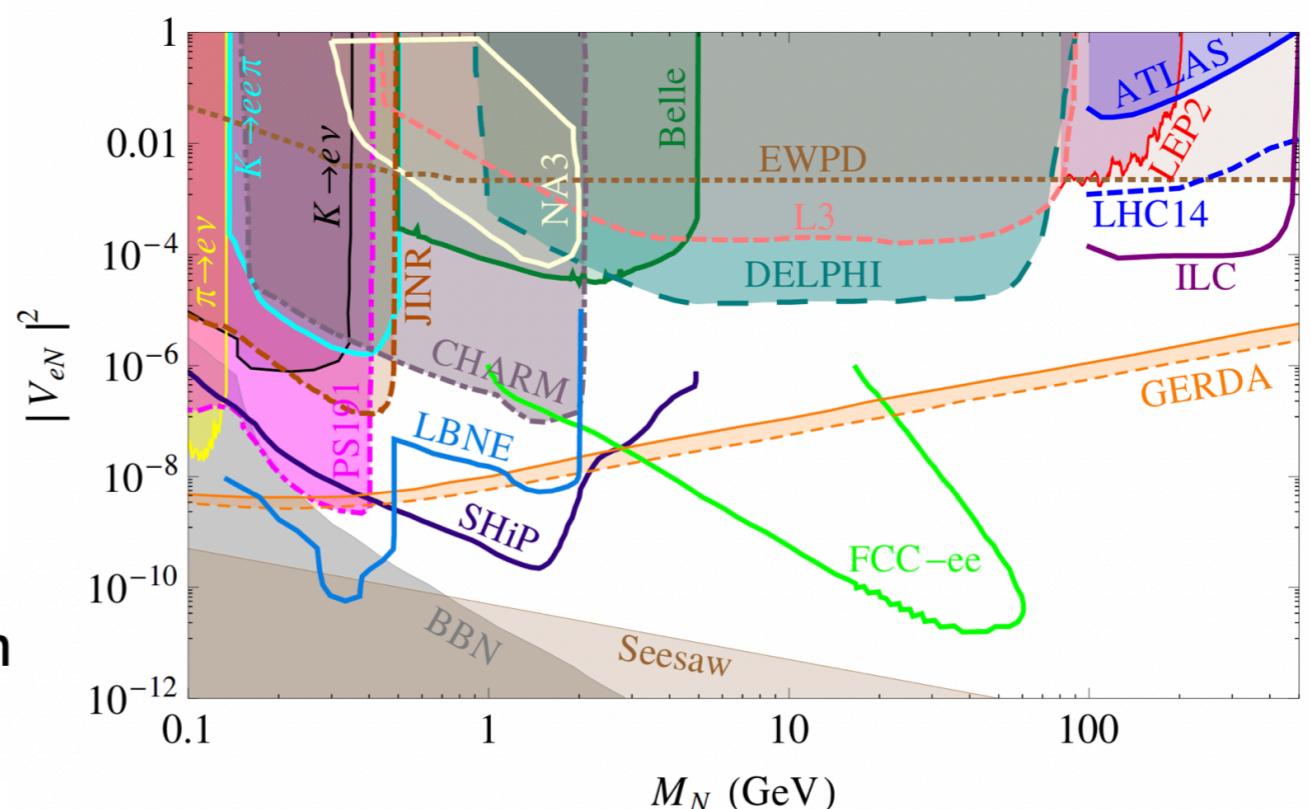
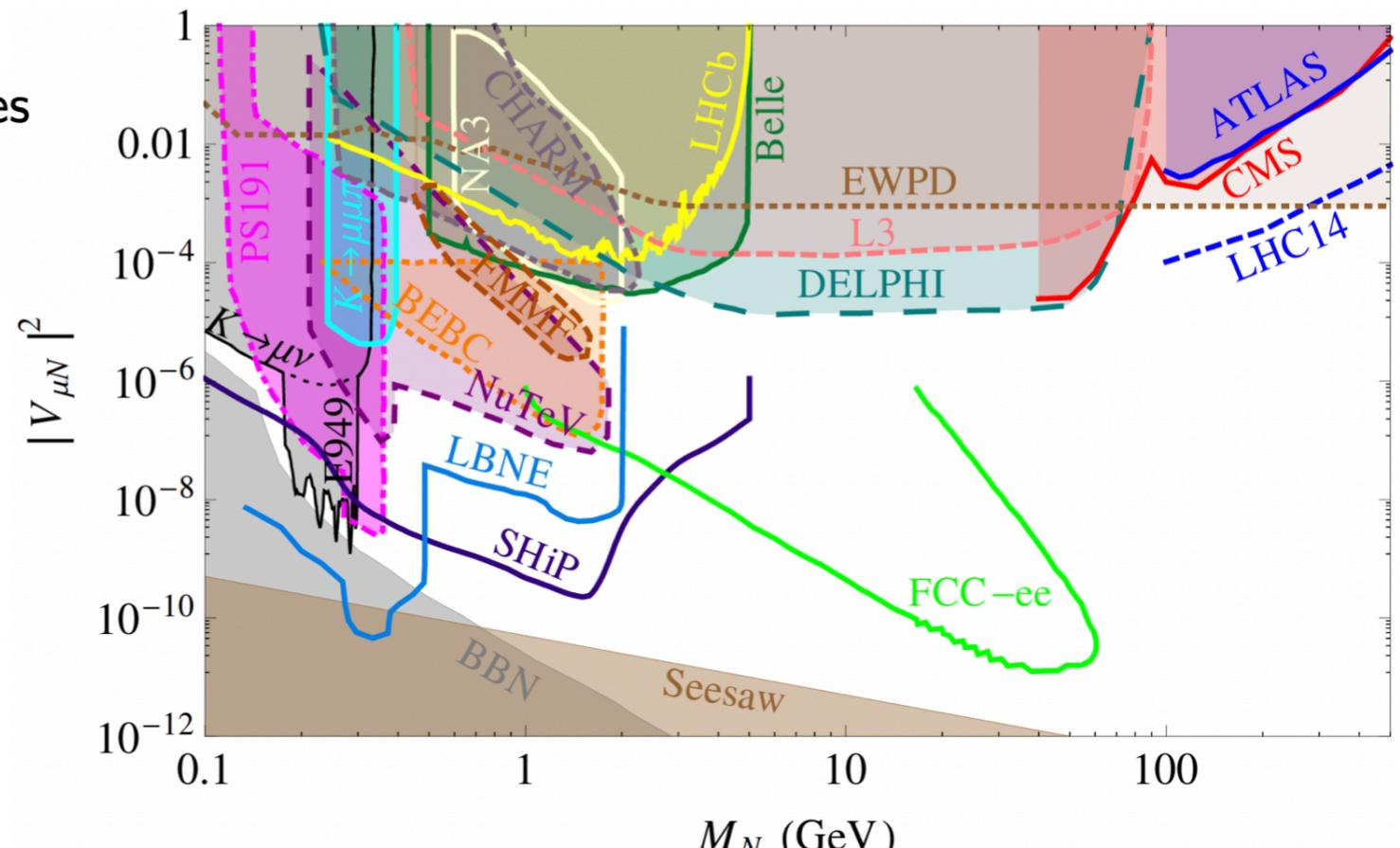


Heavy neutrinos

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

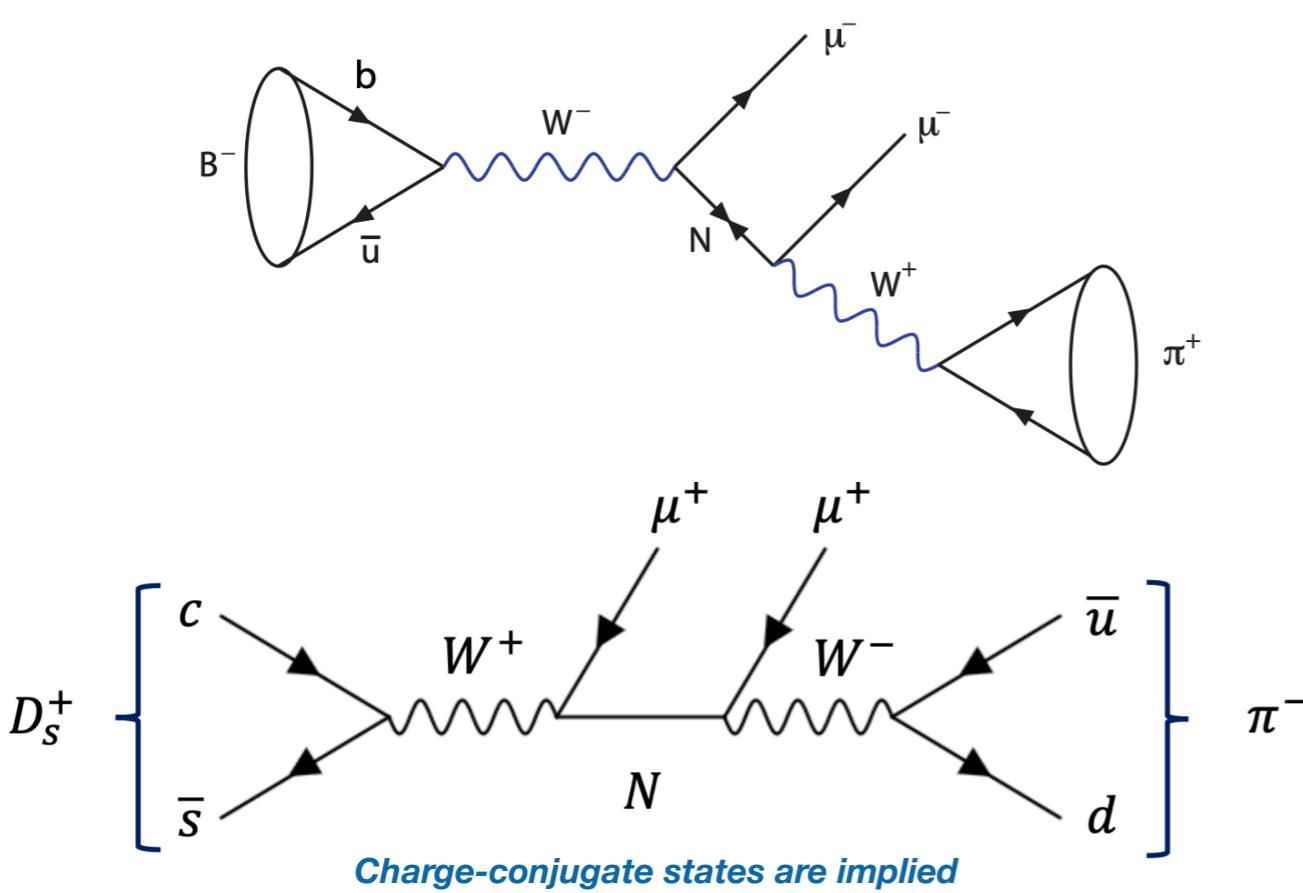
$$\tau \propto |V_{\ell N}|^{-2} m_N^{-5}$$

- 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:

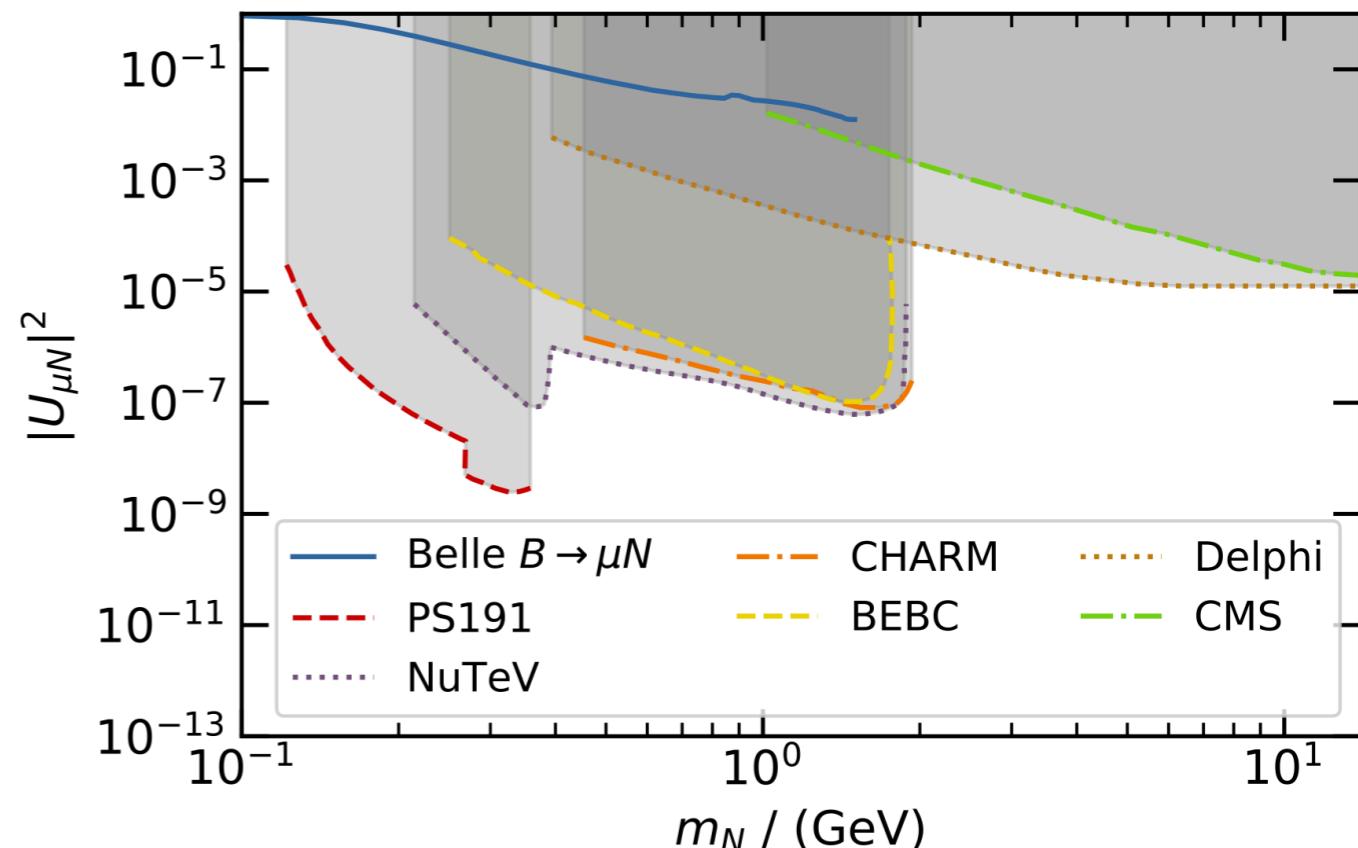


- **N are sterile** and interact only with ν through mixing

Searches of HNL in Heavy Flavour

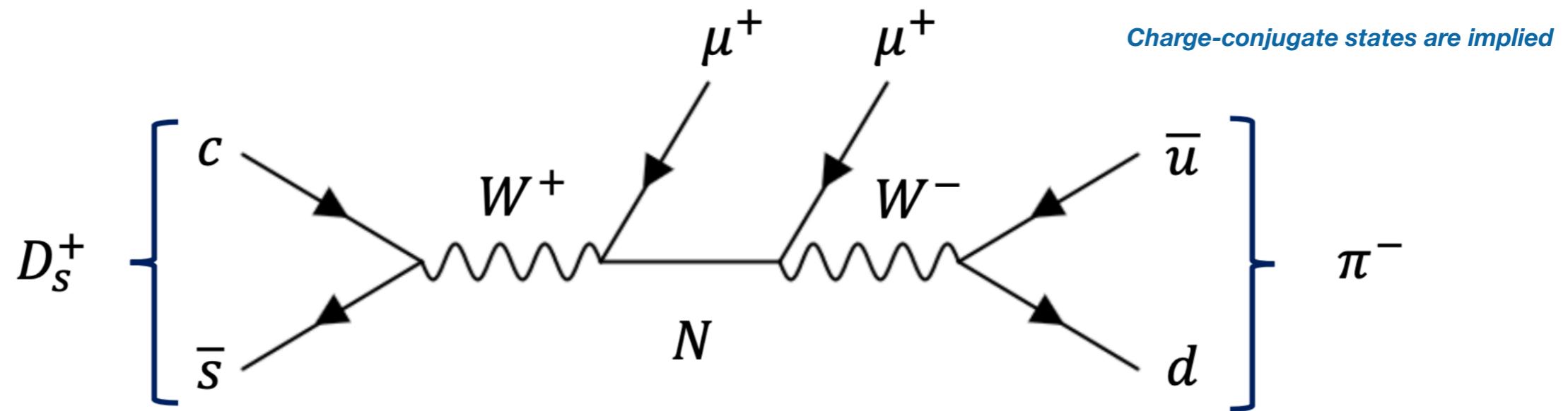


[Belle, Phys.Rev.D 101 \(2020\) 3, 032007](#)



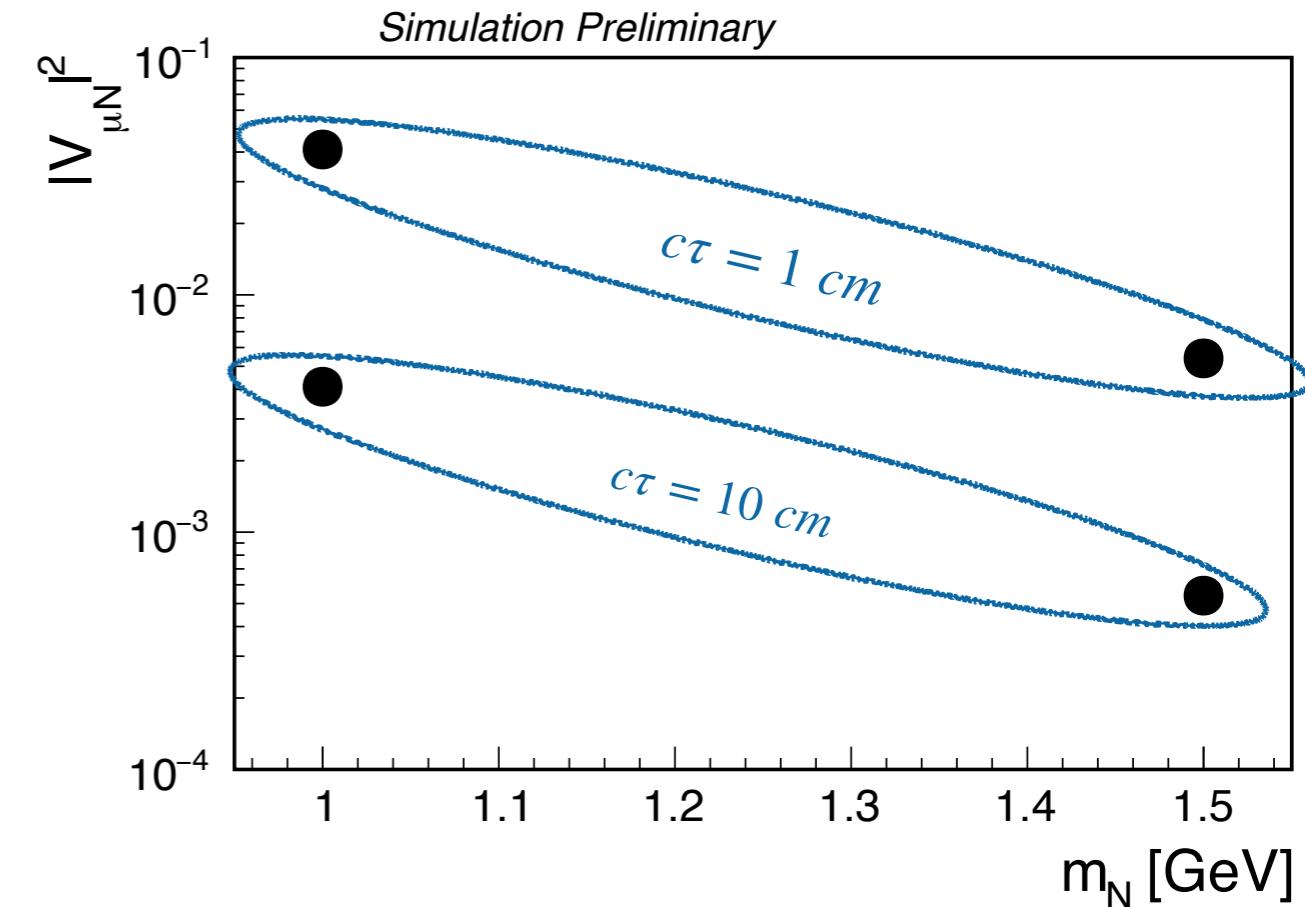
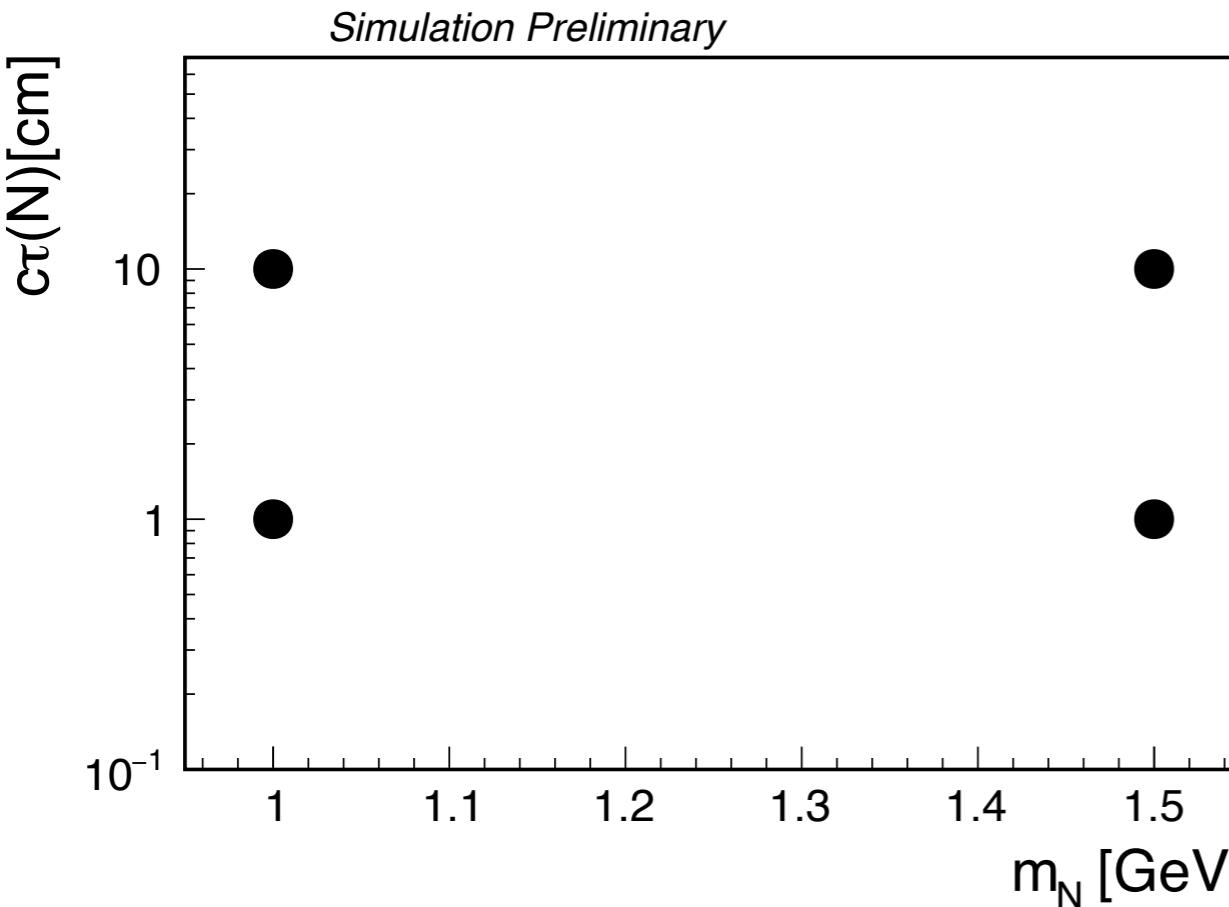
- It is also possible to search HNL in (heavy) hadrons decays: $B^\pm \rightarrow l^\pm N, D_{(s)}^\pm \rightarrow l^\pm N, \dots$
- Main idea: we have standard semi-leptonic decay to $W^- \rightarrow l \bar{\nu}_l$, then $\bar{\nu}_l$ oscillate to sterile N and then N again oscillate, but now to ν_l with the following decay to $l W^+ \rightarrow$ 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



- Subject of our study is search for decay $D_s^+ \rightarrow \mu^+ N \rightarrow \mu^+ \mu^+ \pi^-$ with normalisation channel $D_s^+ \rightarrow \phi \pi^+ \rightarrow \mu^+ \mu^- \pi^+$, where D_s^+ are originating from semi-leptonic B_s decay
- This analysis is to be done at CMS Experiment data, using BParking dataset (idea was to trigger displaced muon with large p_T and displacement — source of semi-leptonic b -hadron decay)
- Preparatory studies are divided into two parts:
 - studies of reference channel and reflections in BParking data
(see poster from Yakov Andreev)
 - prepare and study signal Monte-Carlo simulation samples (*this talk*)
- In the present talk I would provide our current status of MC signal samples studies

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}

	$m_N = 1.0 \text{ GeV}$	$m_N = 1.5 \text{ GeV}$
$c\tau = 1 \text{ cm}$	$1,52 \pm 0,03 \text{ \%}$	$1,45 \pm 0,03 \text{ \%}$
$c\tau = 10 \text{ cm}$	$1,50 \pm 0,03 \text{ \%}$	$1,49 \pm 0,03 \text{ \%}$

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 $p_T > 6.8 \text{ GeV}$ 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:
 $p_T(\mu) > 0.5 \text{ GeV}$, $|\eta(\mu)| < 2.5$
 $p_T(\pi) > 0.5 \text{ GeV}$, $|\eta(\pi)| < 2.5$
- In result we have $\epsilon^{gen} \sim 1.5 \text{ \%}$, 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

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

Muon selection

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

BParking trigger

D_s^+ selection

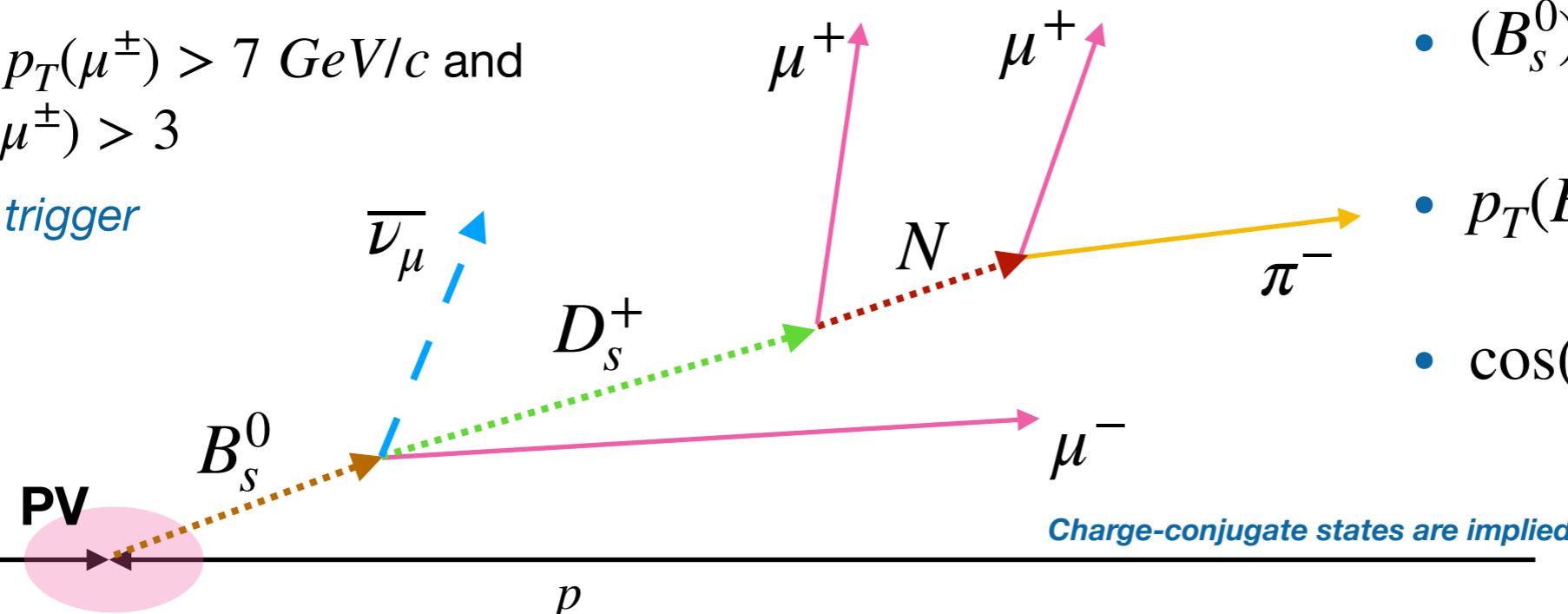
- $|m_{D_s^+} - m_{D_s^+}^{PDG}| < 60 \text{ MeV}$
- $D_{svtxprob}^+ > 0.01$

N selection

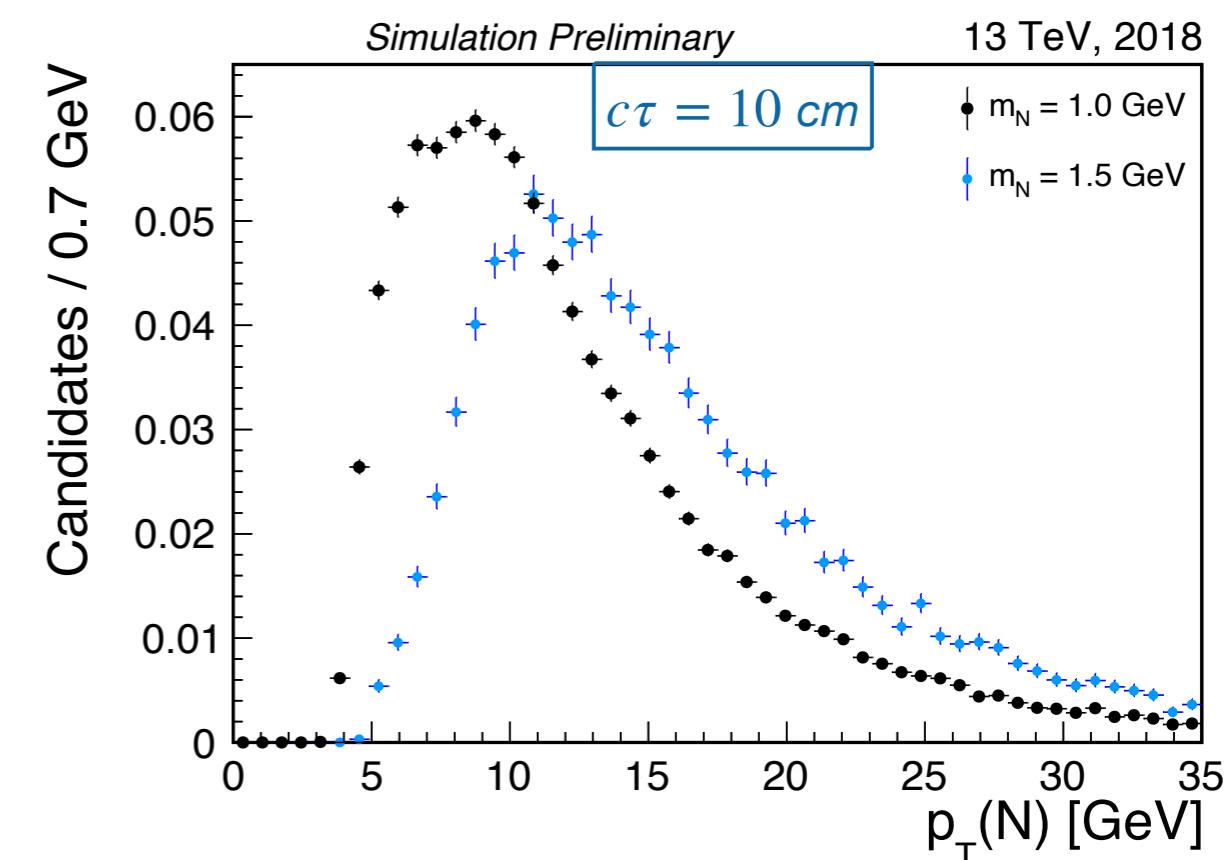
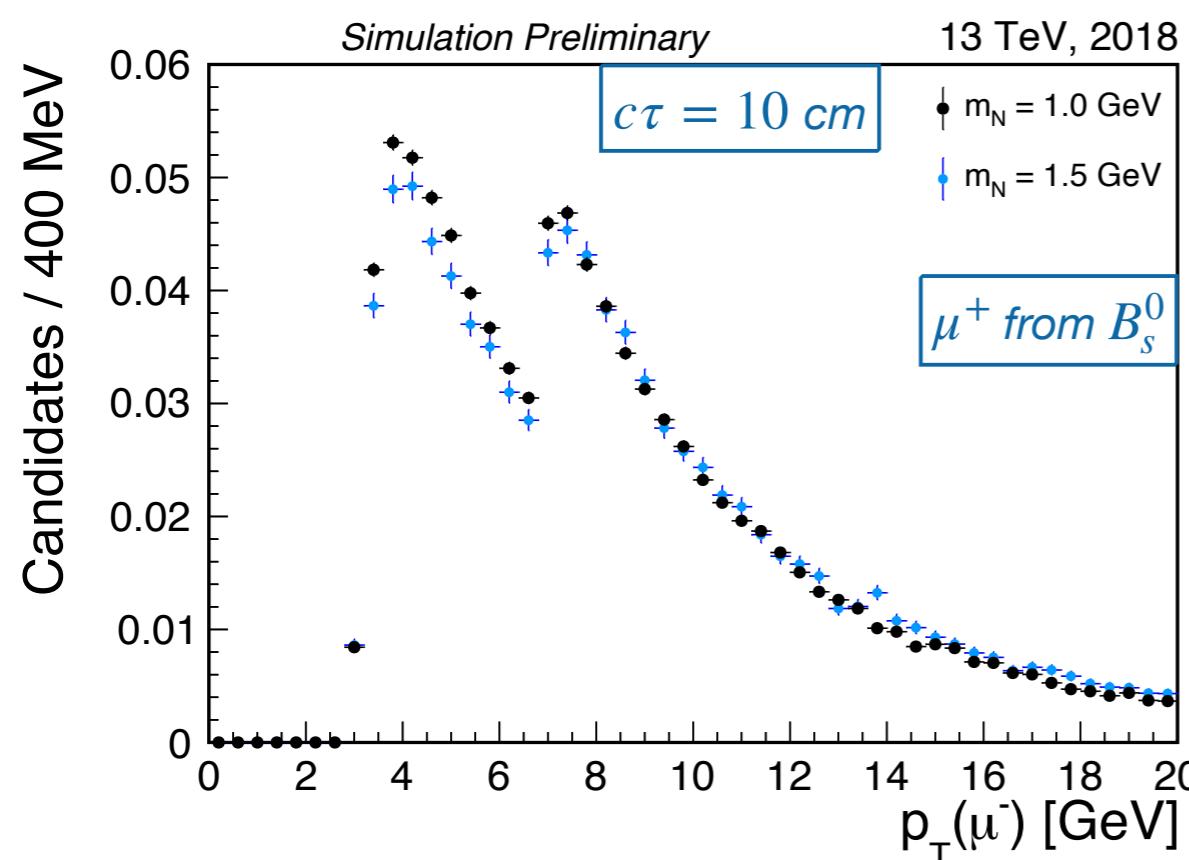
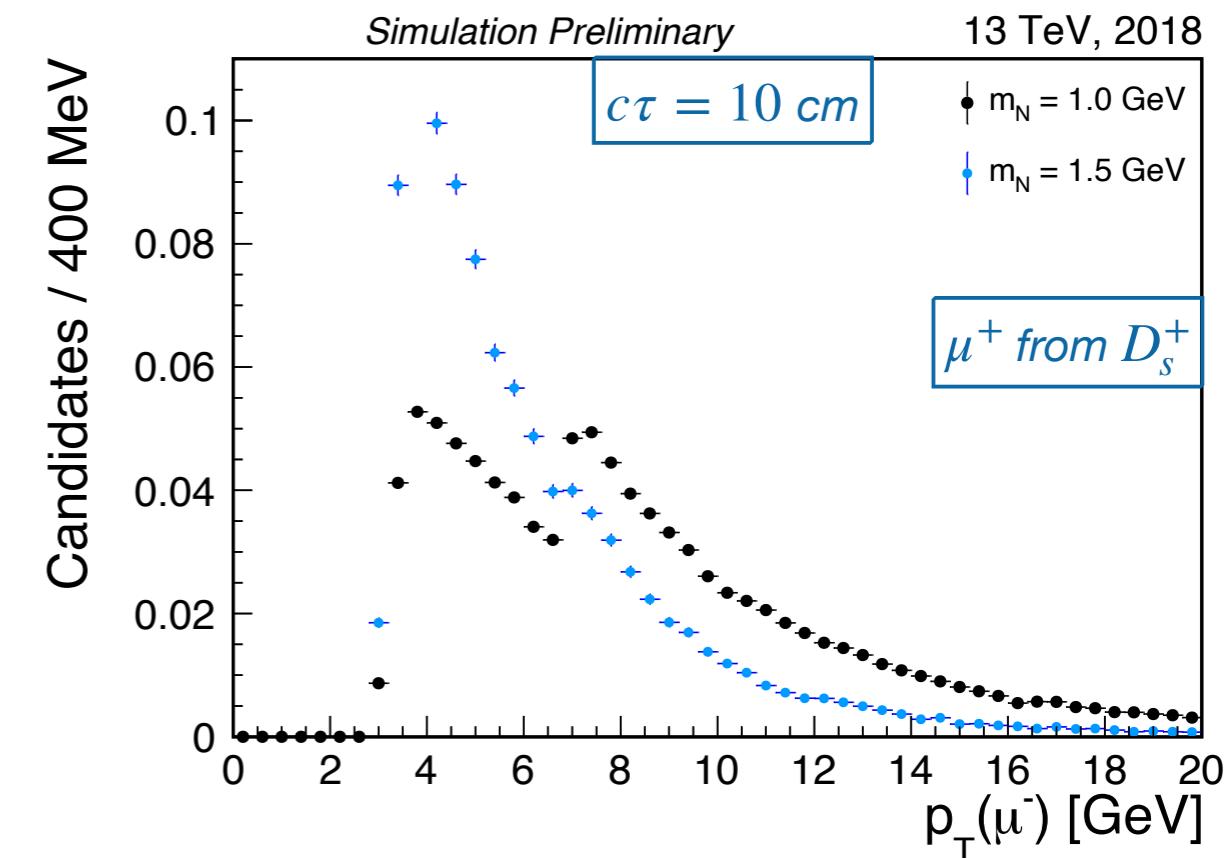
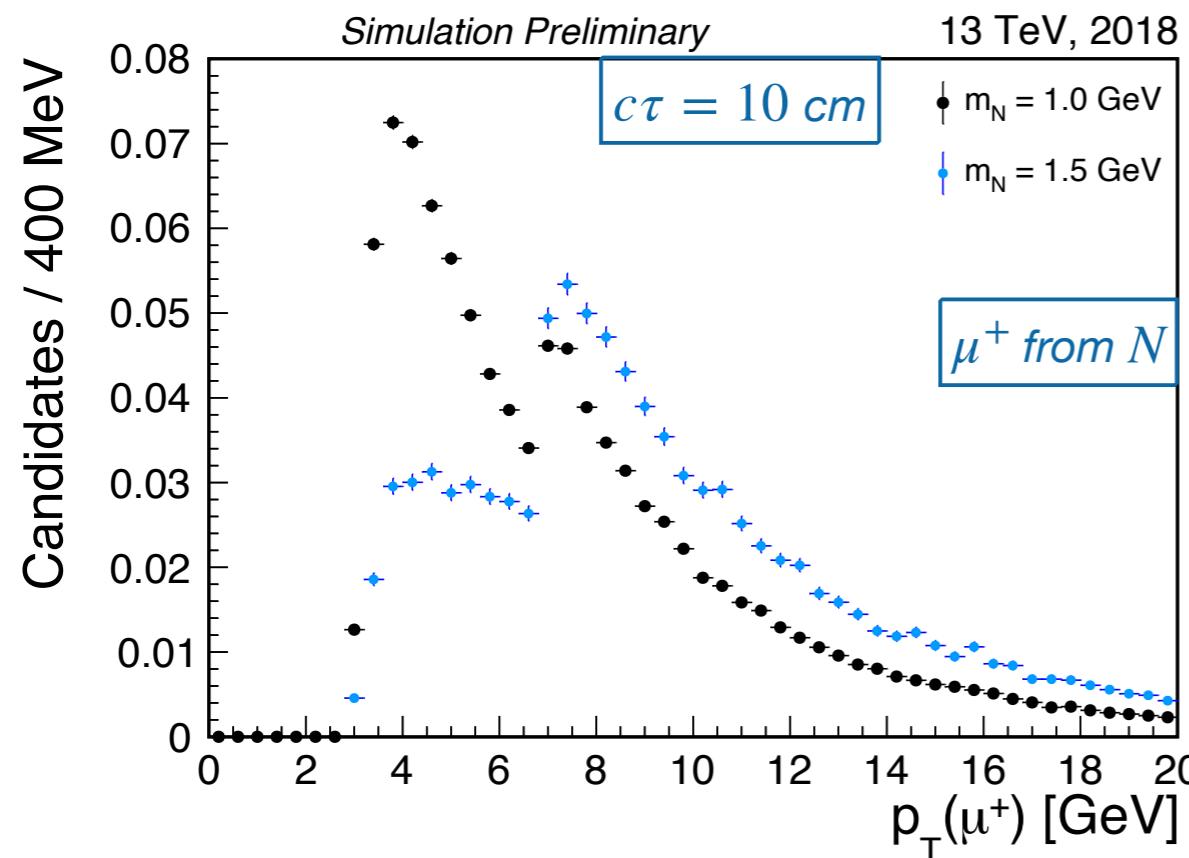
- $N_{vtxprob} > 0.01$
- $(D_s^+, N)_{\text{detach significance}} > 1$

B_s^0 selection

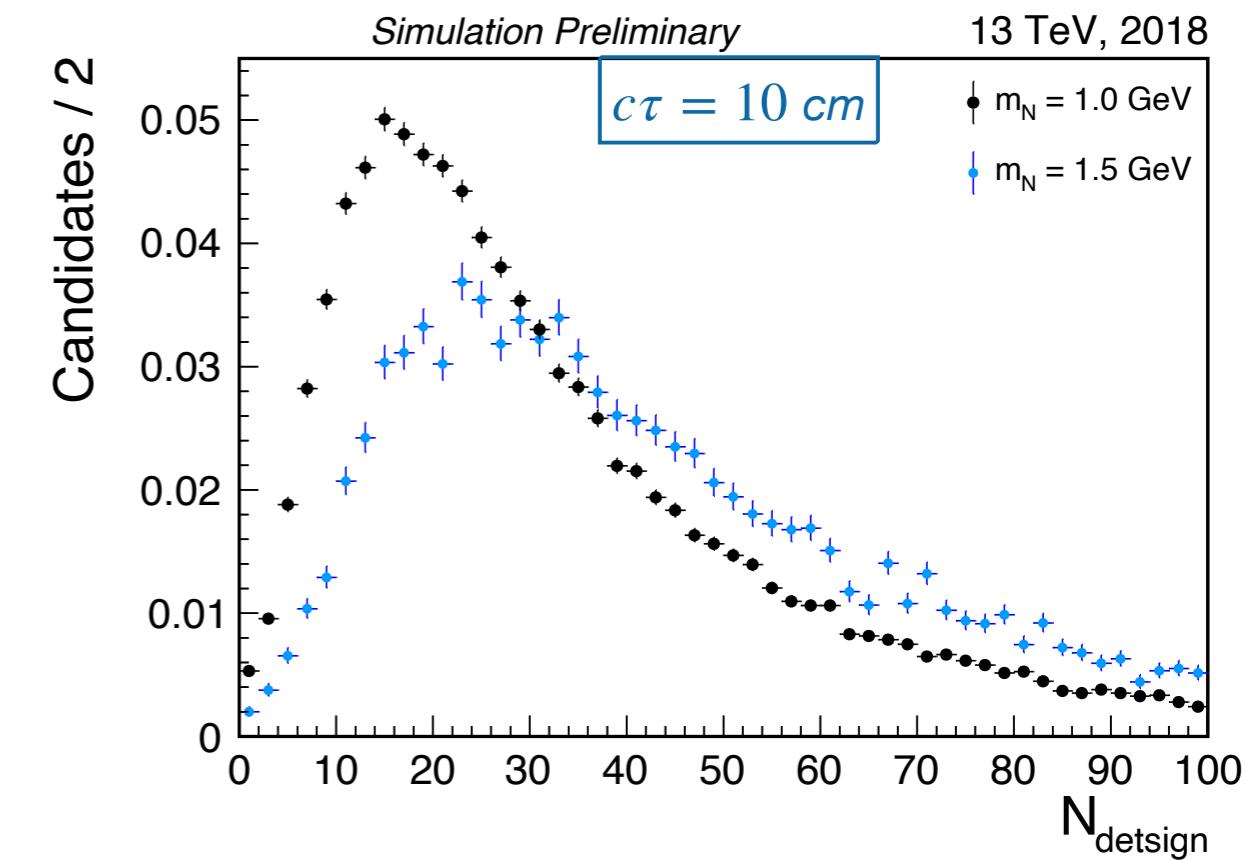
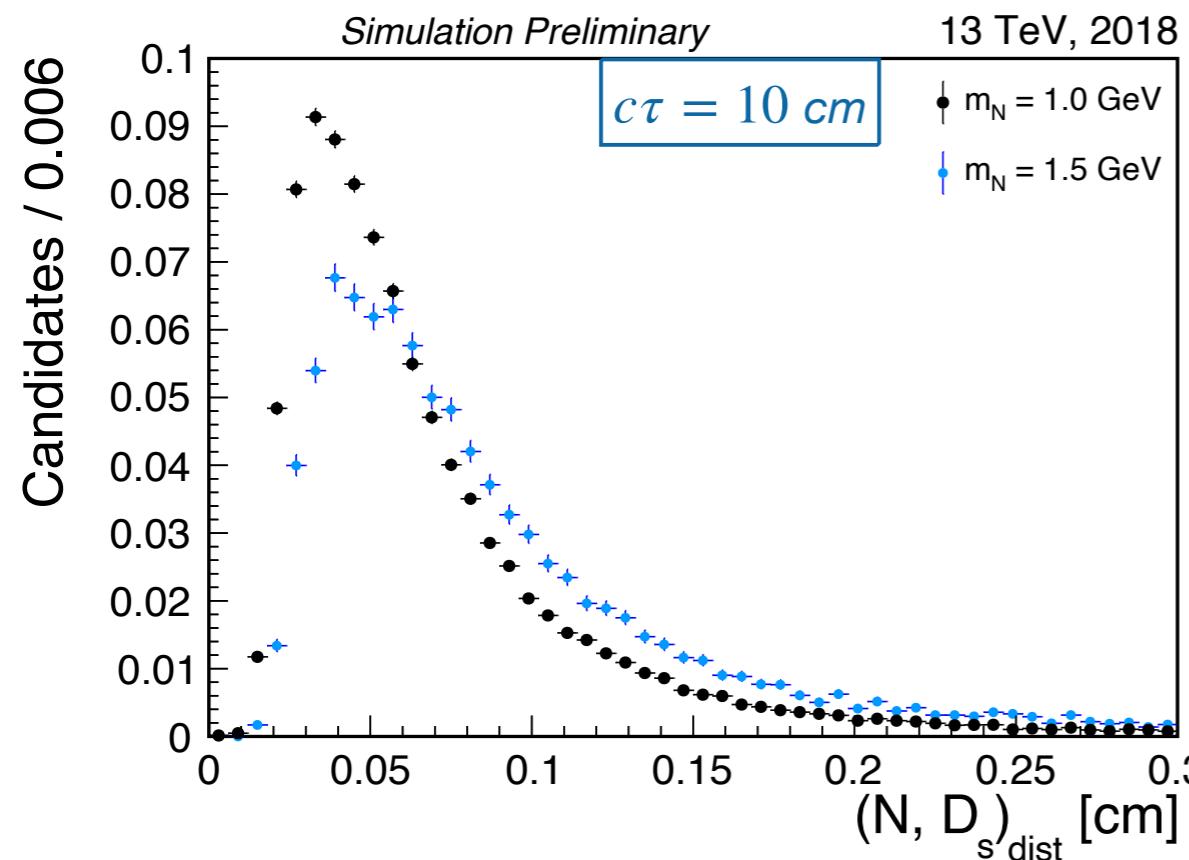
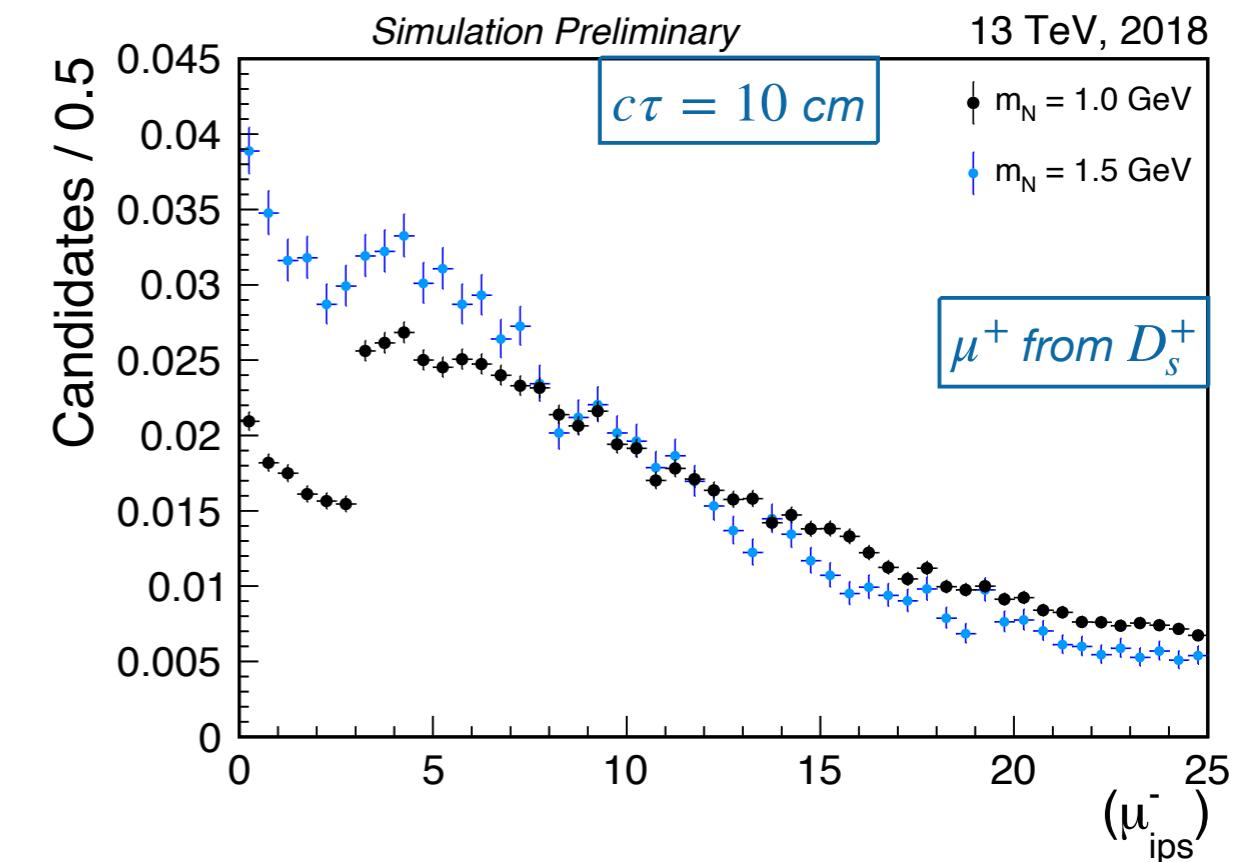
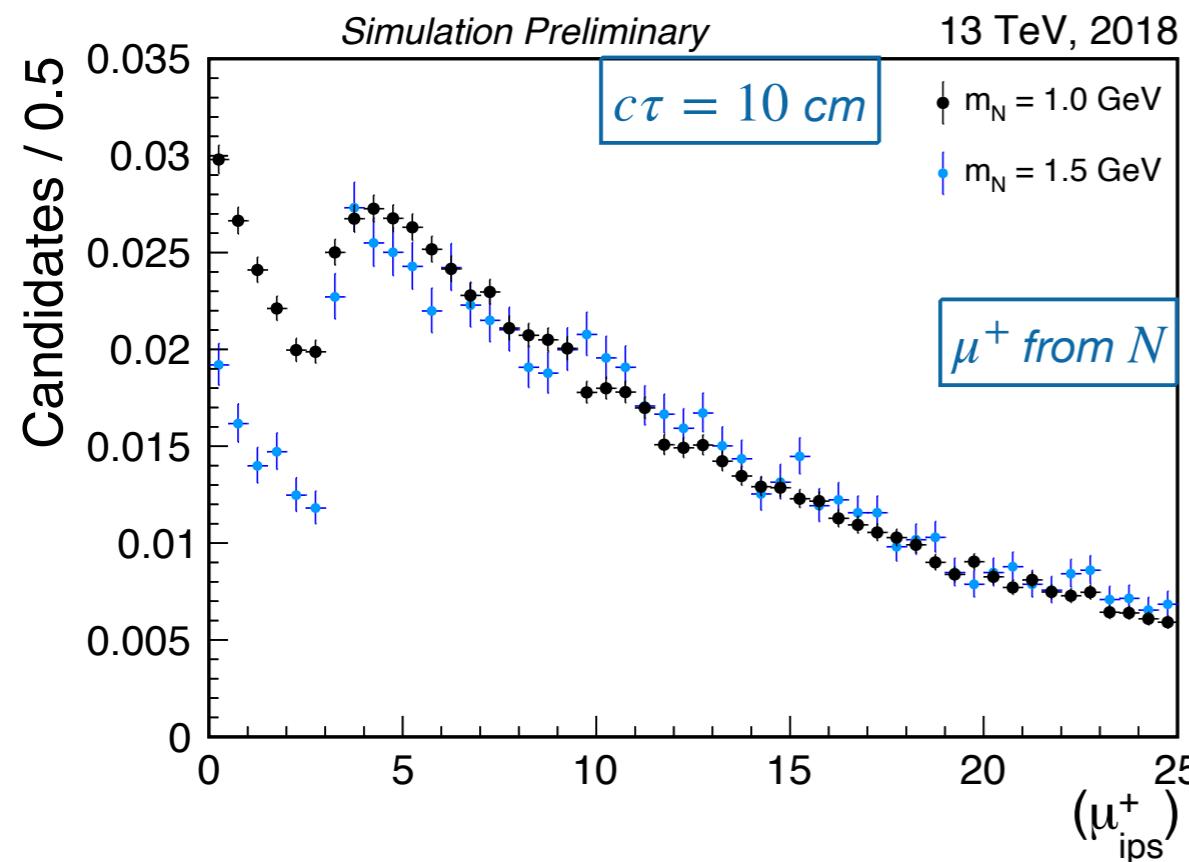
- $(B_s^0)_{vtxprob} > 0.01$
- $(B_s^0)_{\text{detach significance}} > 3$
- $p_T(B_s^0) > 12 \text{ GeV}/c$
- $\cos(PV, B^0) > 0.9$



Kinematic distributions: p_T of muons and N

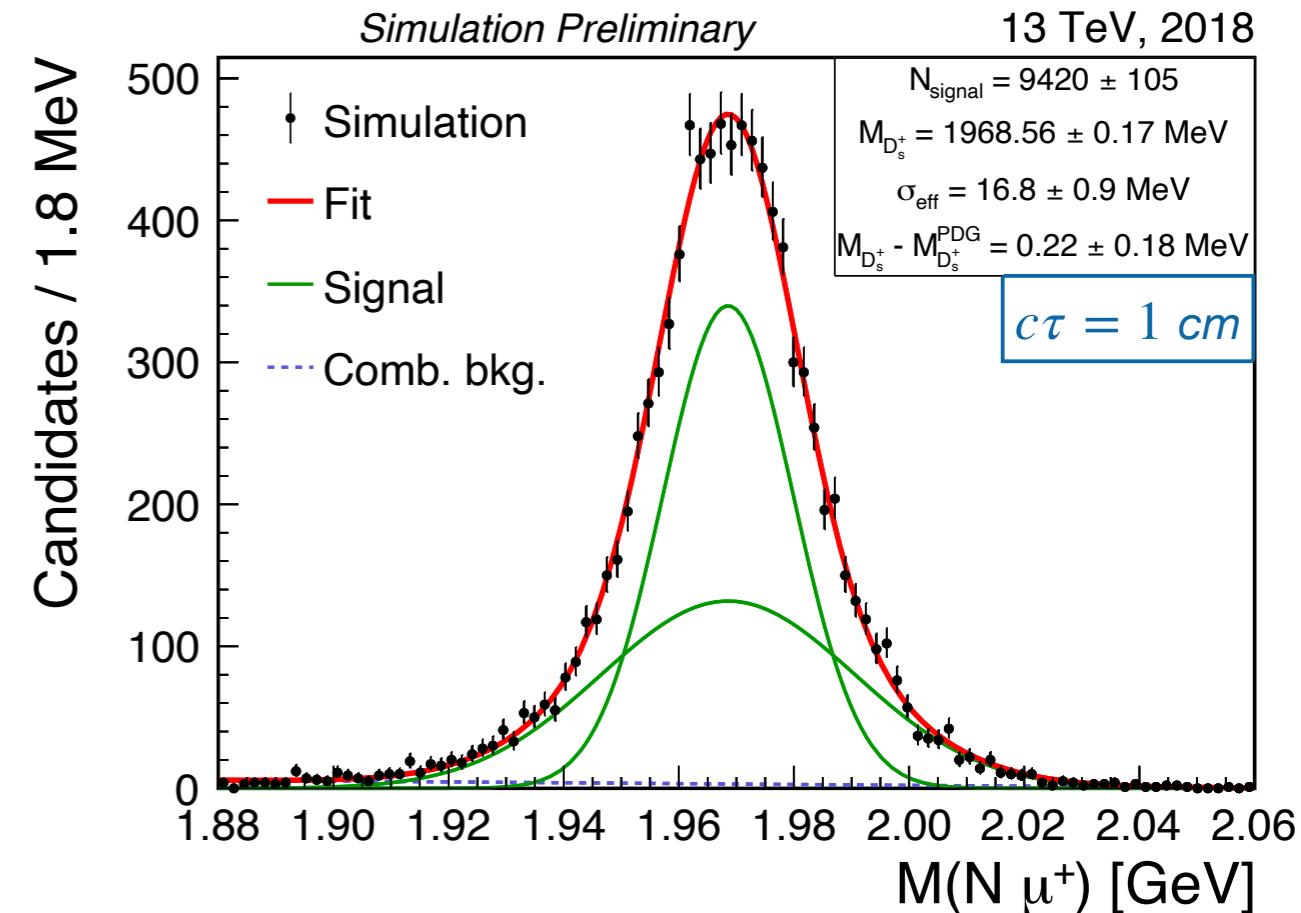
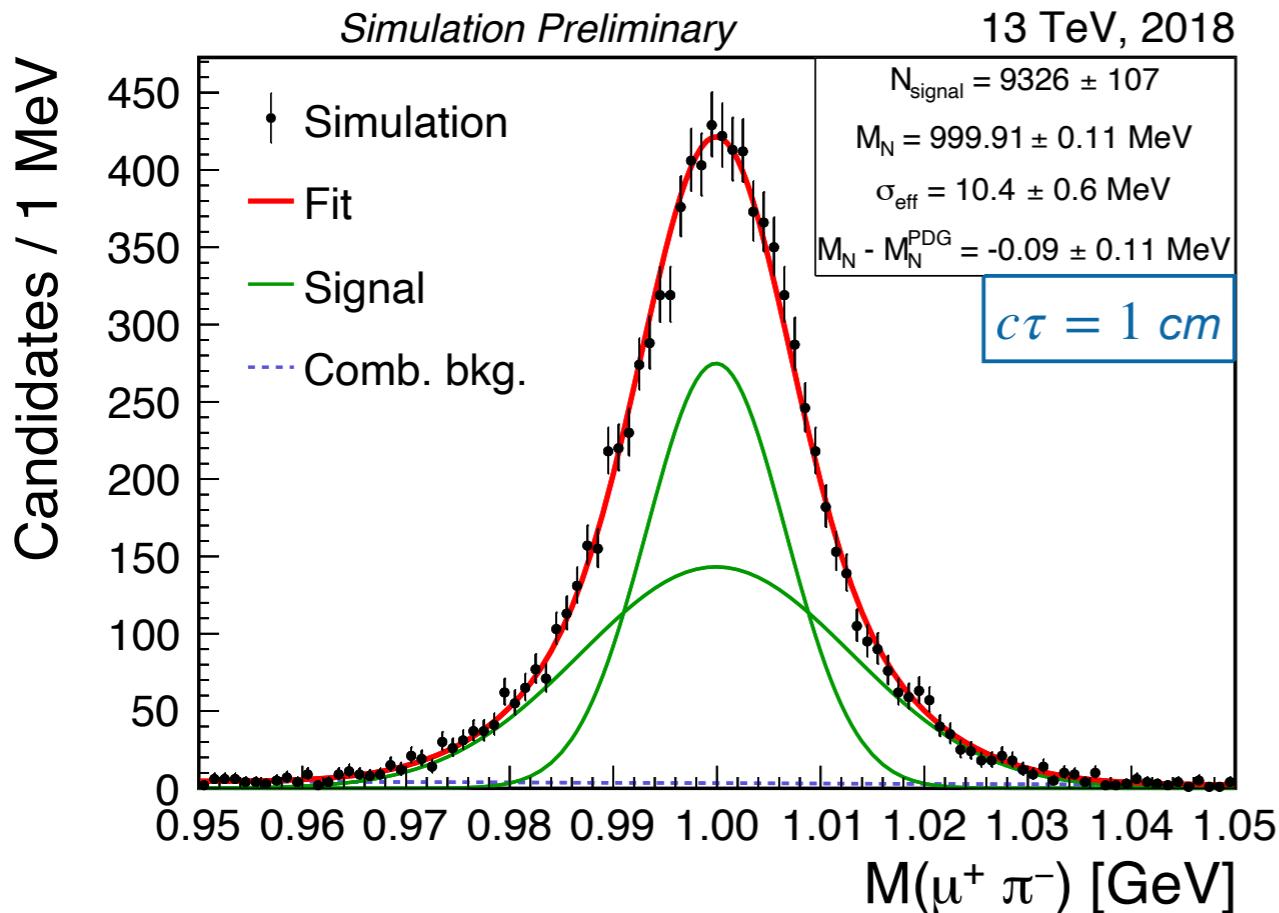


Topological distributions



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

Example of fits for one MC sample



- After reconstruction, clear peaks are visible in invariant masses of $\mu^+\pi^-$ and $\mu^+\mu^+\pi^-$ (corresponding to N and D_s^+ signals)
- To obtain number of signal events and estimate detector resolution, we perform fits to these distributions, using Double Gaussian (or Gaussian + Crystal Ball) for signal and 1st order polynomial for background

Detector resolution and reconstruction efficiency

HNL detector resolution

	$m_N = 1.0 \text{ GeV}$	$m_N = 1.5 \text{ GeV}$
$c\tau = 1\text{cm}$	10.4 ± 0.6	16.1 ± 0.7
$c\tau = 10 \text{ cm}$	11.0 ± 0.3	14.9 ± 1.1

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

	$m_N = 1.0 \text{ GeV}$	$m_N = 1.5 \text{ GeV}$
$c\tau = 1\text{cm}$	$9,03 \pm 0,10$	$6,64 \pm 0,18$
$c\tau = 10 \text{ cm}$	$8,00 \pm 0,04$	$5,26 \pm 0,06$

Resolution is in MeV

Efficiency is in $[10^{-3}]$ units

- Here we provide estimations for our 4 simulated samples
- 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
- $\epsilon^{rec-sel}$ is an efficiency of the reconstruction and selection requirements applied; calculated as ratio of the number of events from fit of $N \rightarrow \mu^+ \pi^-$ 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 ϵ and sensitivity

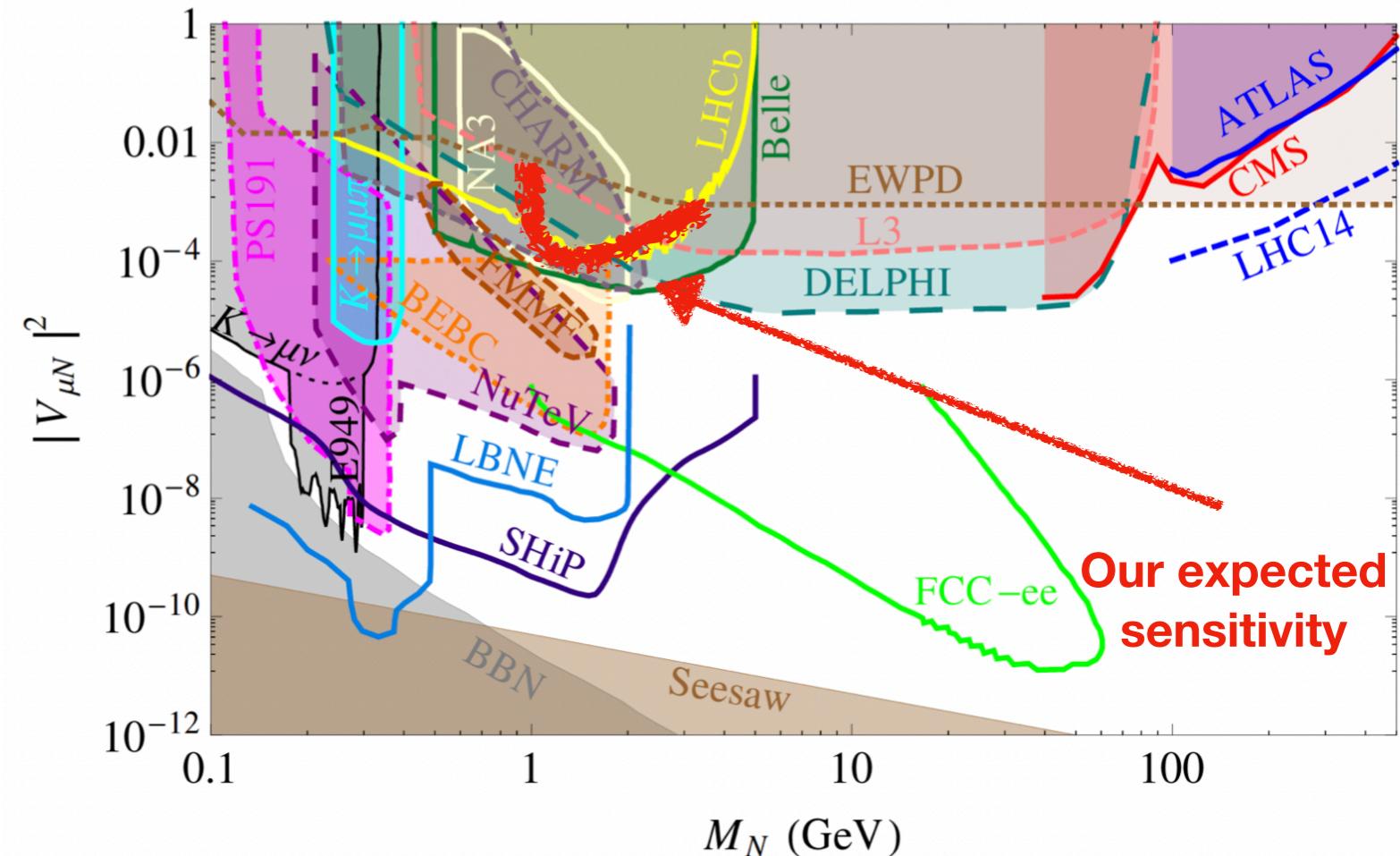
	$m_N = 1.0 \text{ GeV}$	$m_N = 1.5 \text{ GeV}$
$c\tau = 1 \text{ cm}$	13.72 ± 0.31	9.63 ± 0.32
$c\tau = 10 \text{ cm}$	12.00 ± 0.25	7.84 ± 0.18

Efficiency is in $[10^{-5}]$ units

- Total efficiency is $\epsilon = \epsilon^{gen} \times \epsilon^{recsel}$
The results are about $10^{-4} \div 10^{-5}$ depending on HNL parameters
- The expected number of signal on data could be estimated as
$$N_{sig} = N(D_s^+) \times (\mathcal{B}(D_s^+ \rightarrow N[\rightarrow \mu^+ \pi^-] \mu^+) \times \epsilon)$$
- 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 is expected to be quite humble and unpretentious

Conclusion and summary

- Monte-Carlo studies of decay $B_s^0 \rightarrow D_s^+ \mu^- \bar{\nu}_\mu$, $D_s^+ \rightarrow N\mu^+ \rightarrow \mu^+\mu^+\pi^-$ are reported
- Efficiencies are estimated for 4 points in $(m_N, |V_{\mu N}|^2)$ plane for possible HNL parameters
- We are going to proceed detailed studies of MC simulation, including better understanding of topological parameters (lifetime and proper decay length)
- Our next plans are to perform selection optimisation (using both data and MC) and blind analysis for the search of $D_s^+ \rightarrow N\mu^+ \rightarrow \mu^+\mu^+\pi^-$ and measuring its branching fraction (or its upper limit)



Thank you for your attention!

Do you have any questions?

Backup slides

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 $b \rightarrow \mu X$ decay. The "signal-side" b hadron decays naturally as it is not biased by the trigger requirements.

Trigger: b hadron purity

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

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

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

From MC

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

From data

From literature:
2.6%

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.

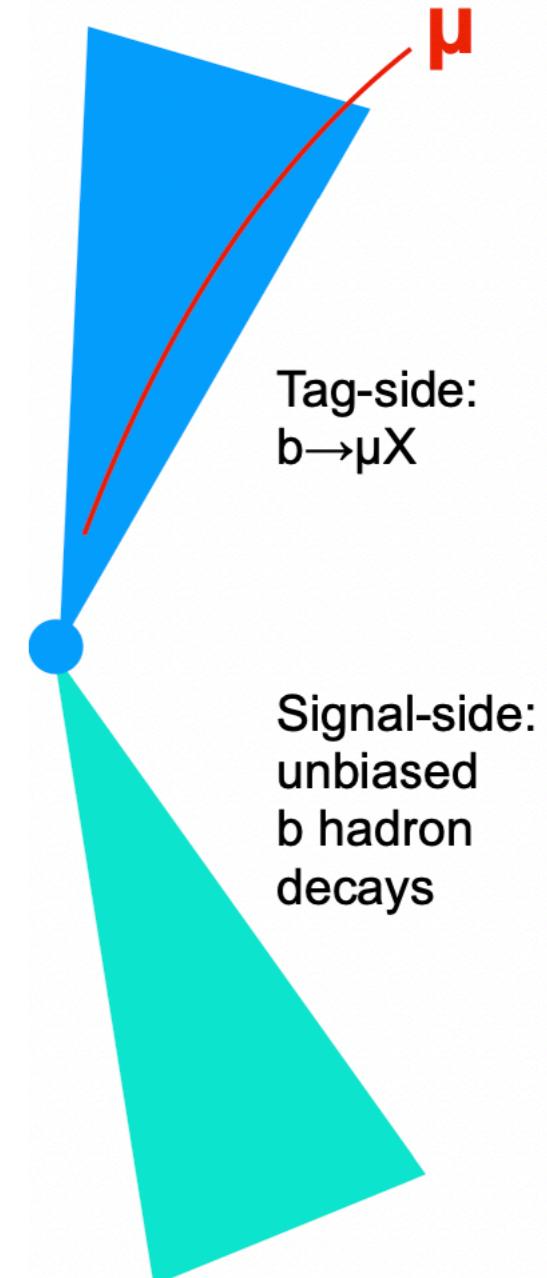
Mode	N_{2018}	f_B	\mathcal{B}
Generic b hadrons			
B_d^0	4.0×10^9	0.4	1.0
B^\pm	4.0×10^9	0.4	1.0
B_s	1.2×10^9	0.1	1.0
b baryons	1.2×10^9	0.1	1.0
B_c	1.0×10^7	0.001	1.0
Total	1.0×10^{10}	1.0	1.0

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

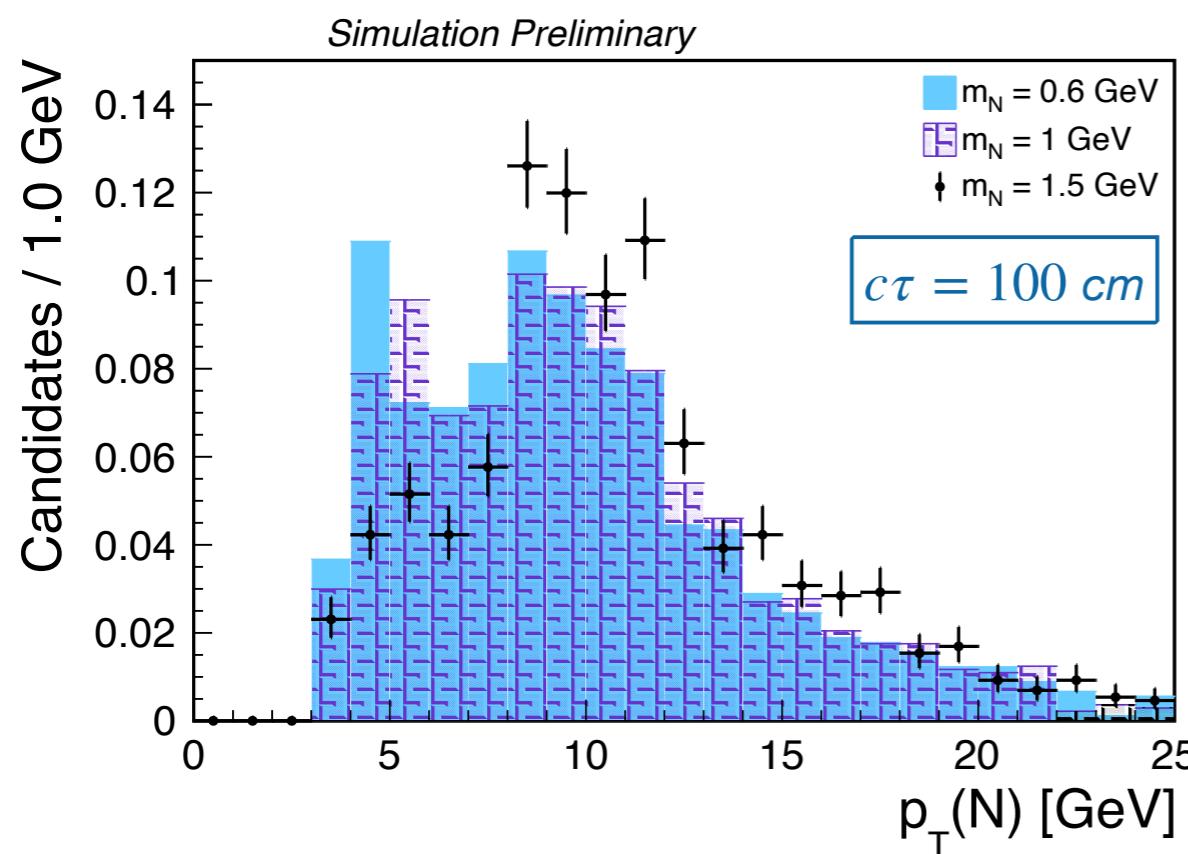
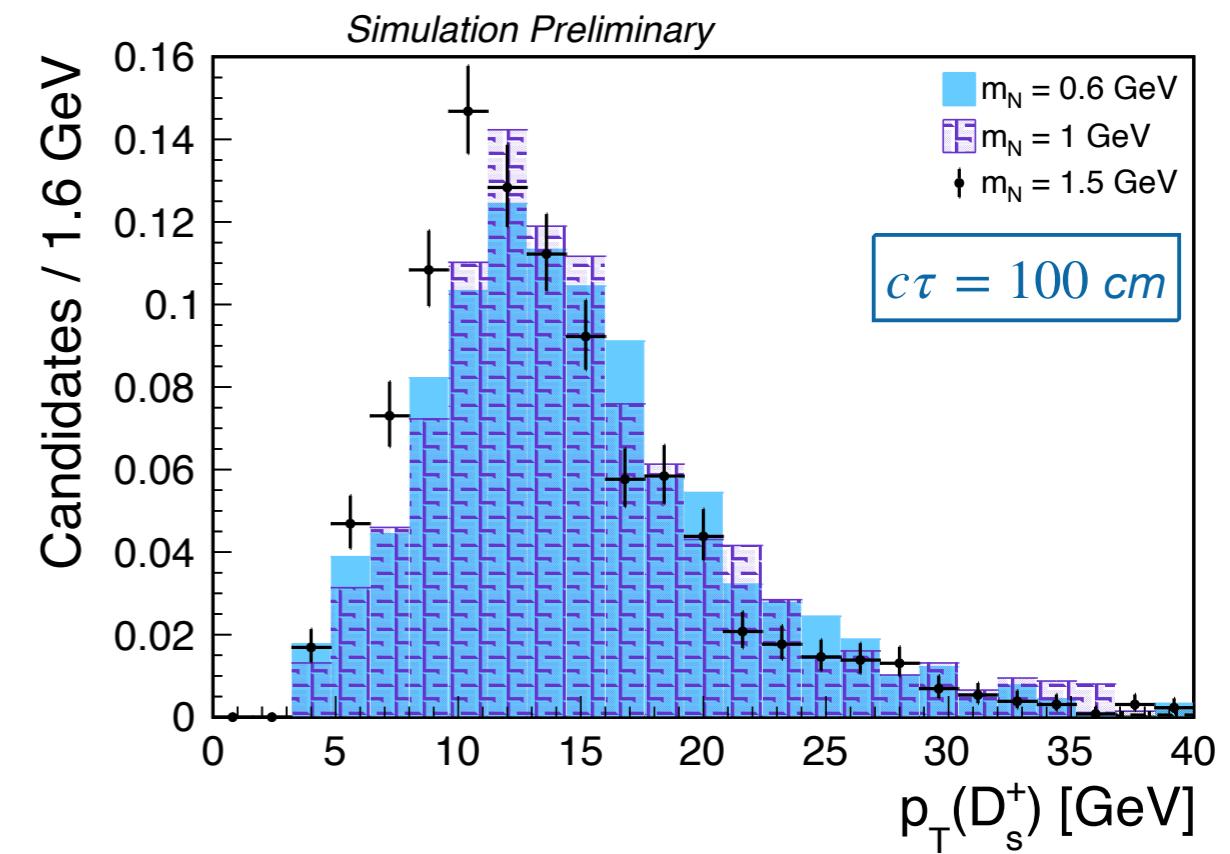
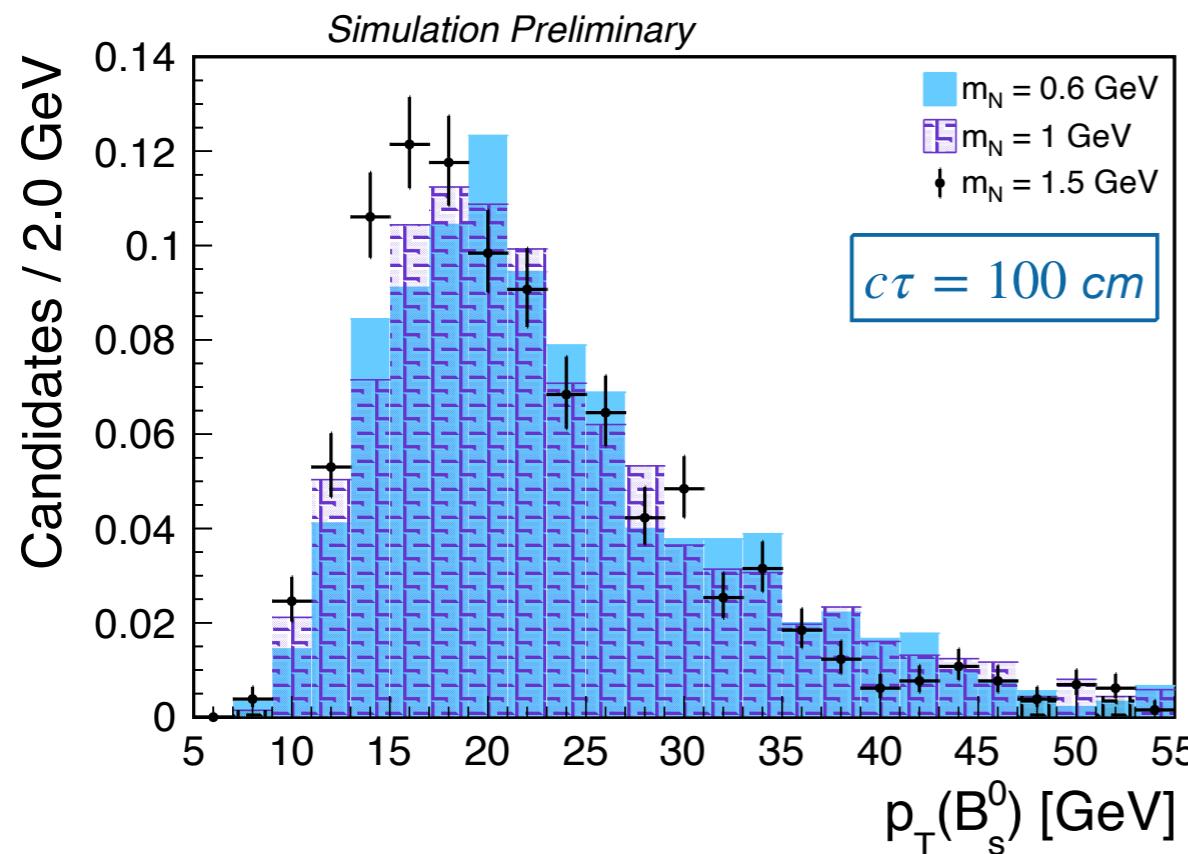
Source of D_s^+ mesons

See more details about D_s^+ studies on data
on poster from Yakov Andreev

Using $\mathcal{B}(B_s^0 \rightarrow D_s^+ \mu^- \bar{\nu}_\mu)$, we have more than 3×10^7 pure D_s^+ in our BParking

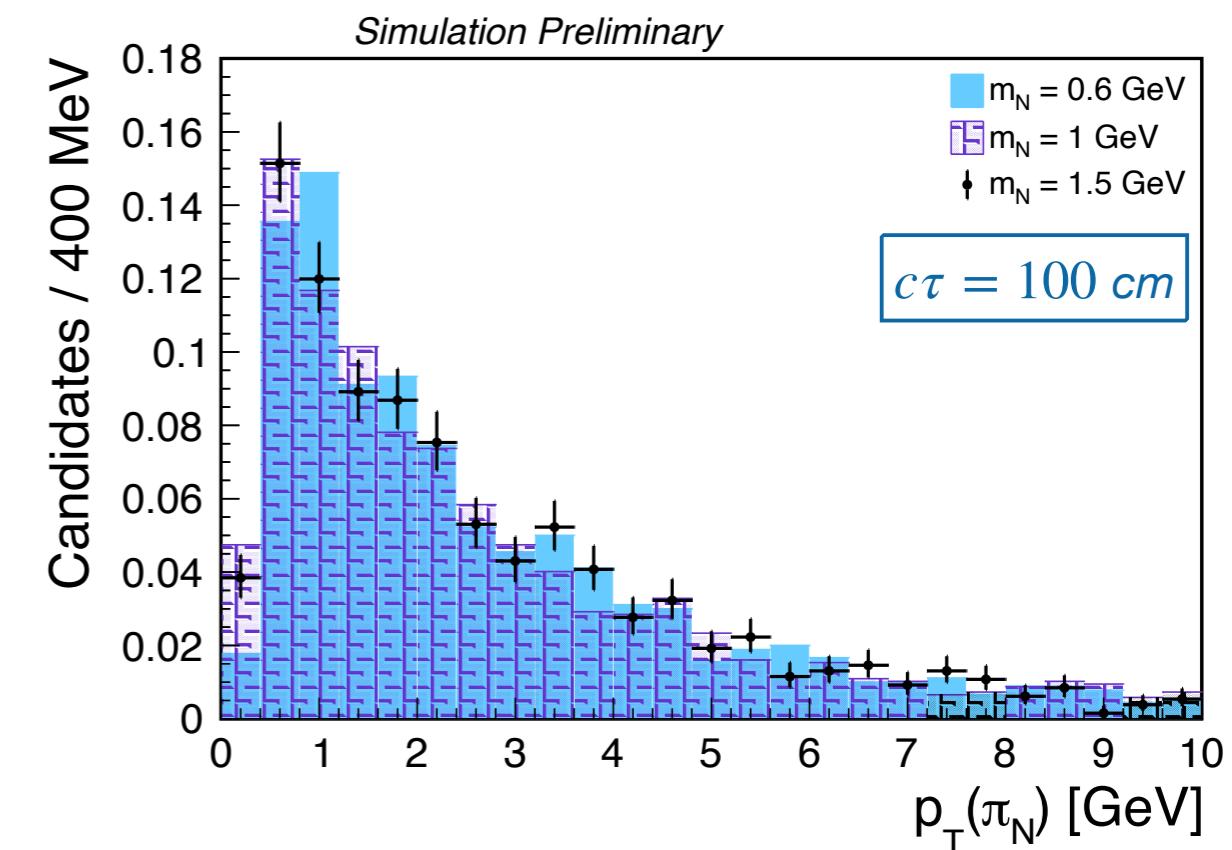
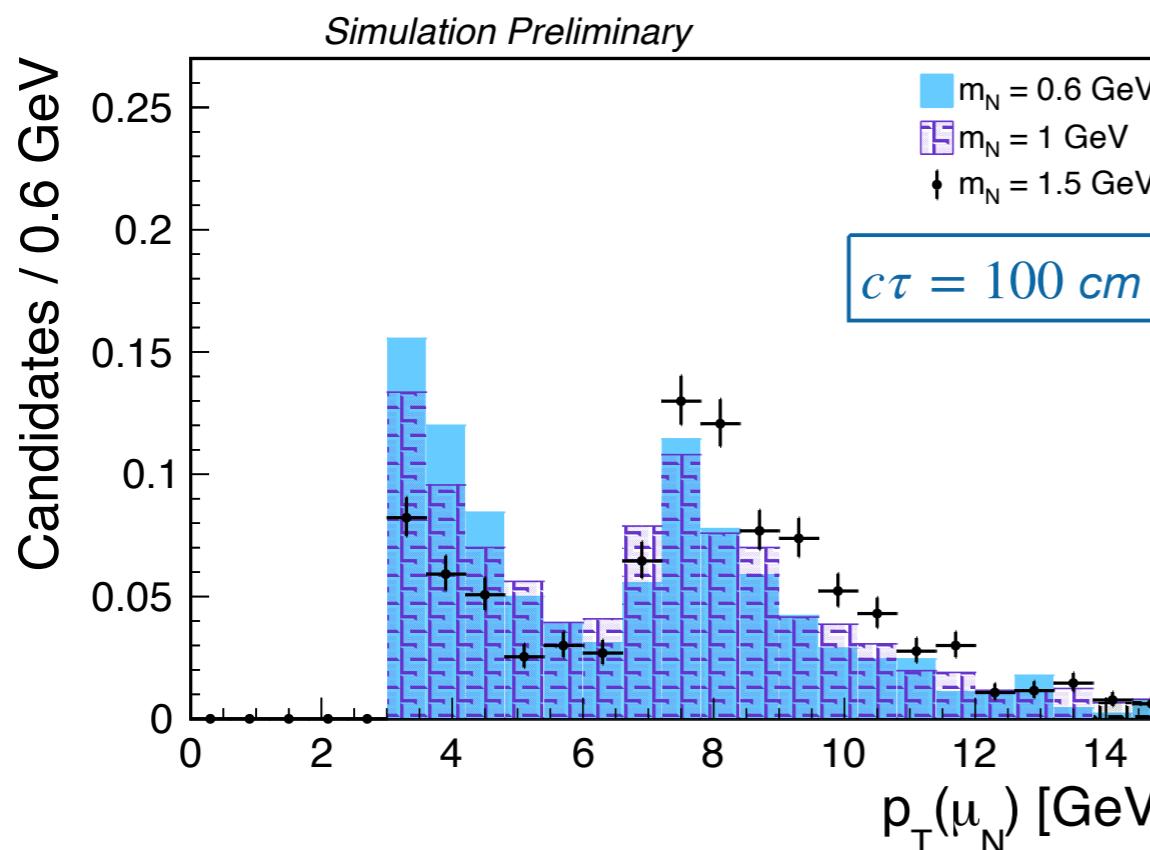
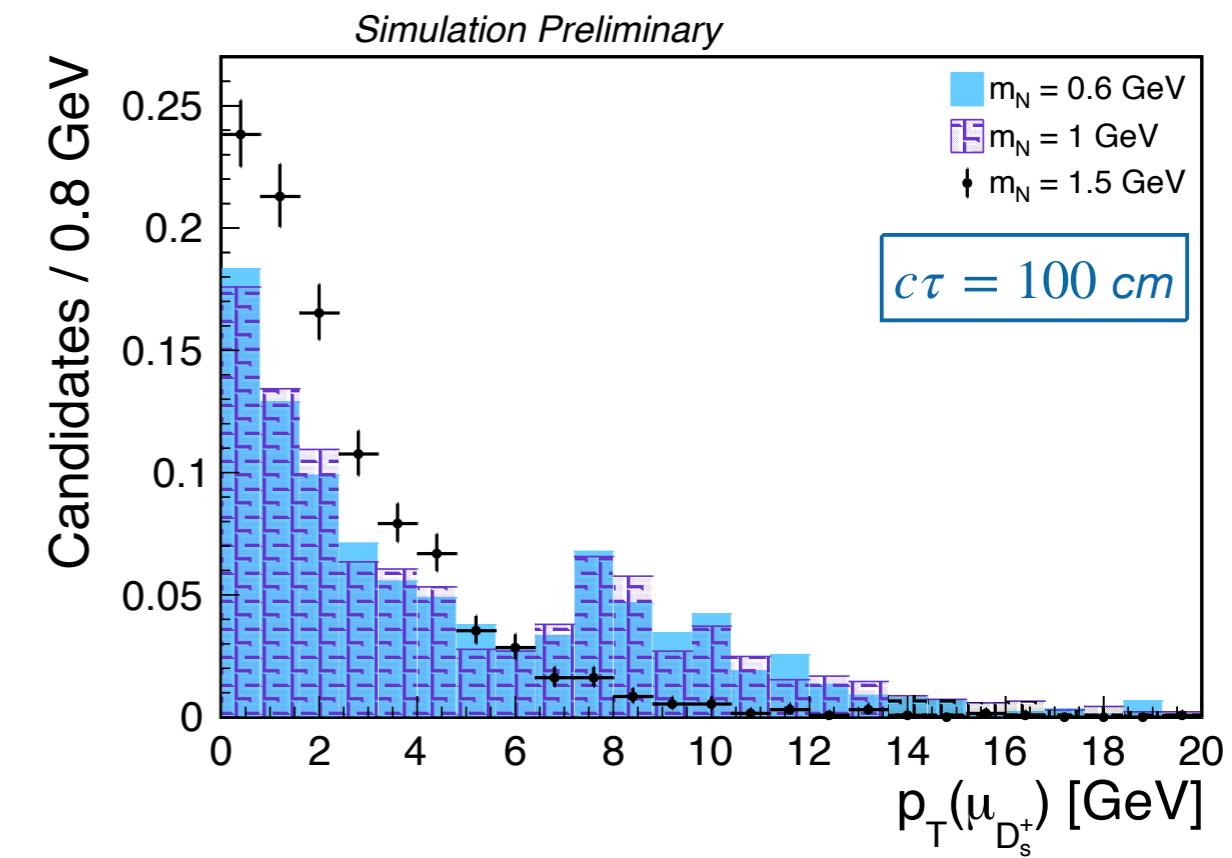
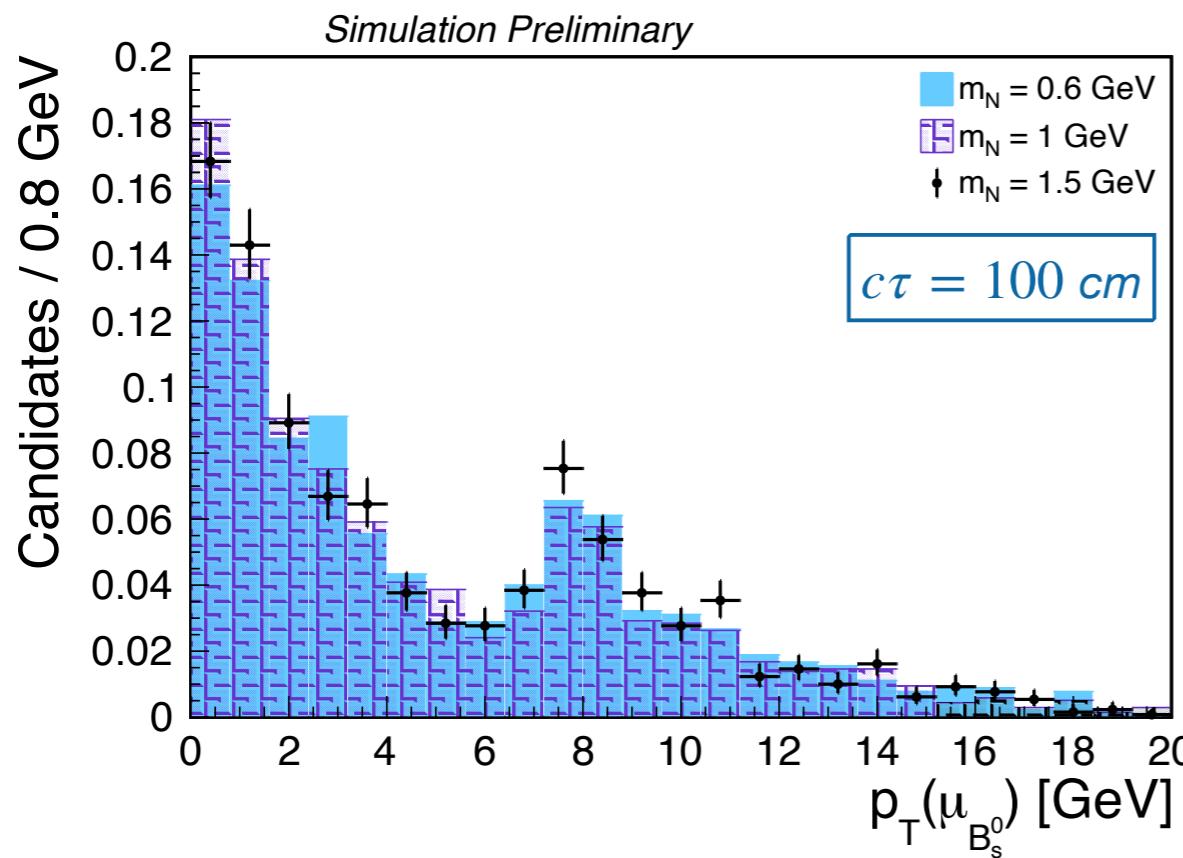


Gen-lvl p_T -distributions

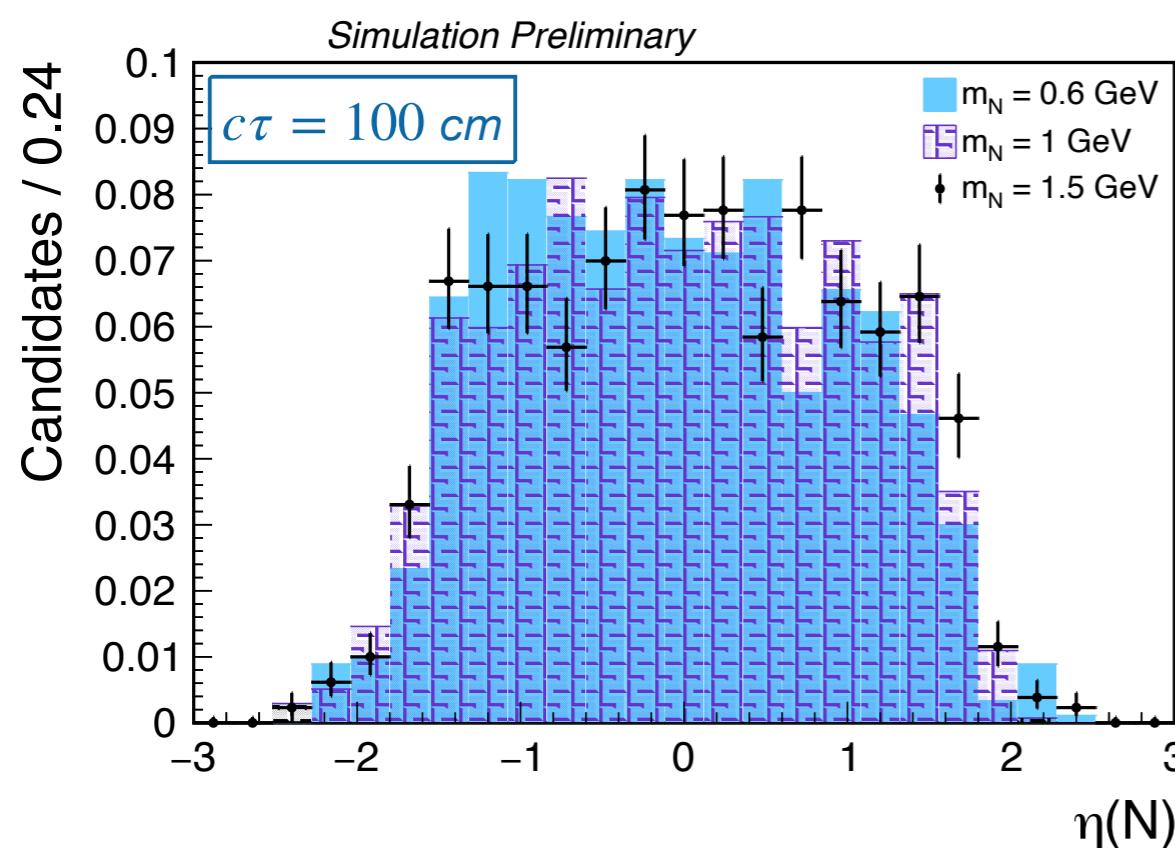
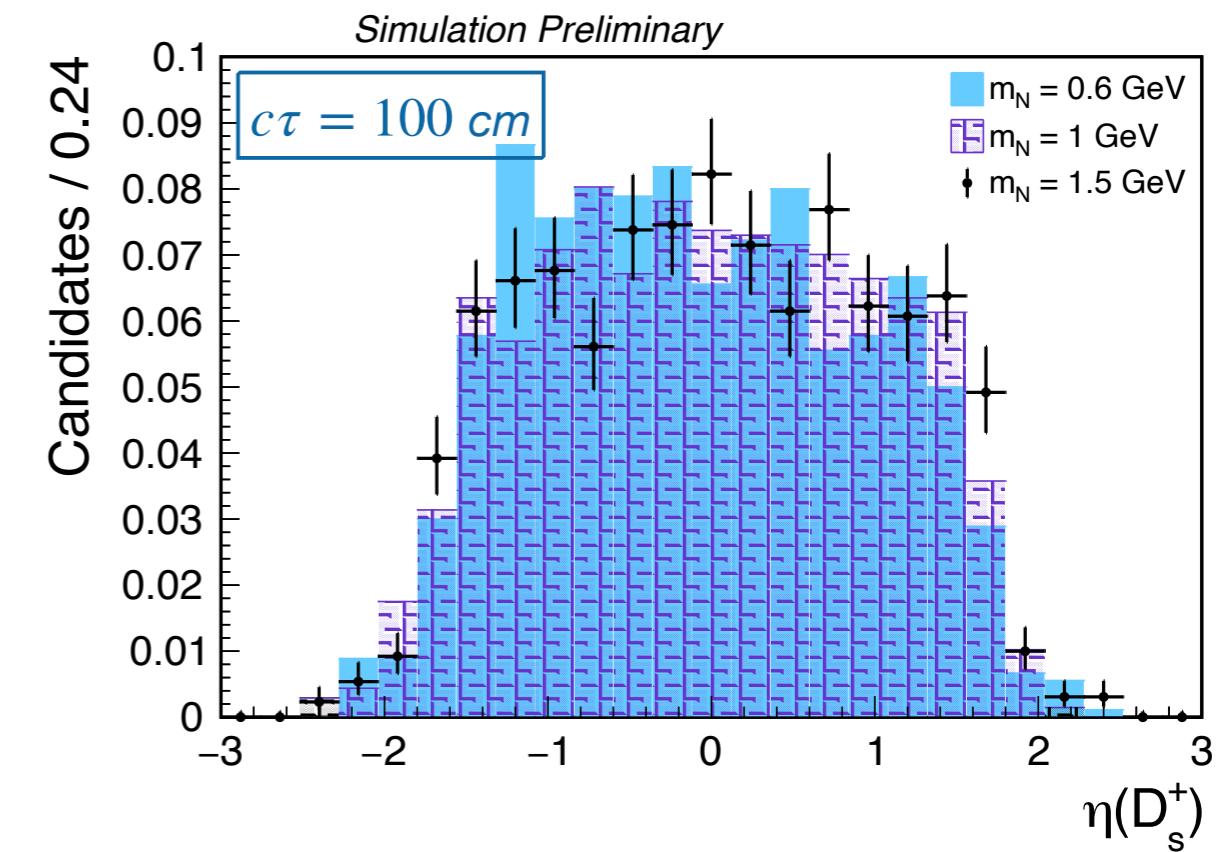
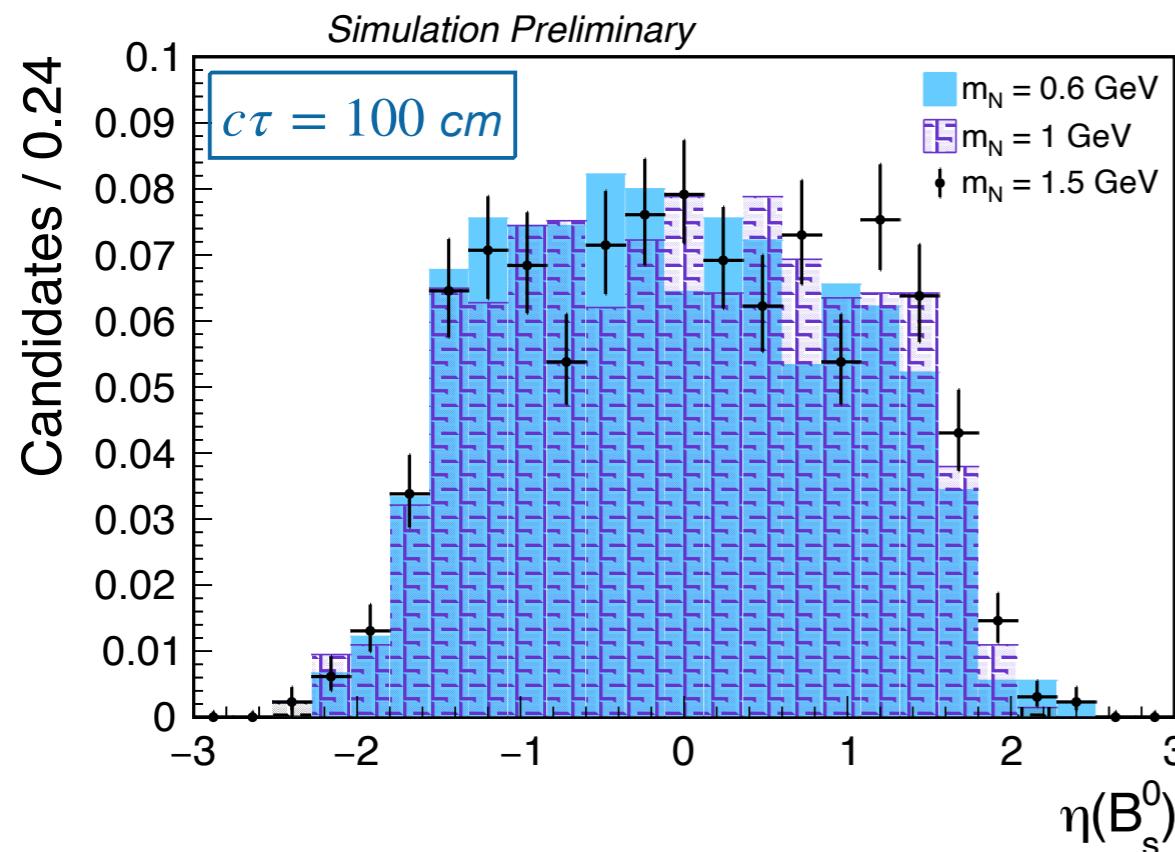


- We have clear dependence from mass: heavier HNL has larger p_T
- Because of selection bias (related with trigger BPark high- p_T muon) B_s^0 and D_s^+ distribution are also affected — for heavier N we select softer B_s^0 and D_s^+

Gen-lvl p_T -distributions

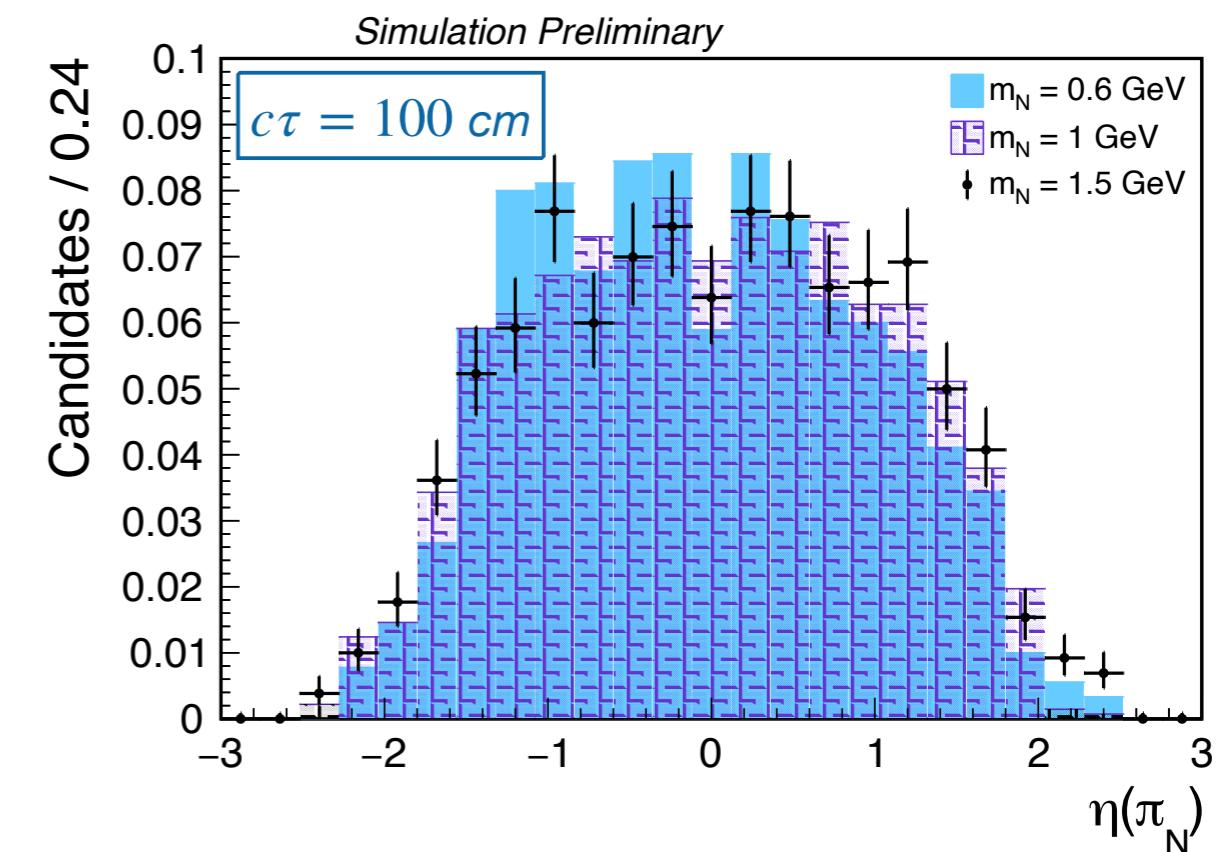
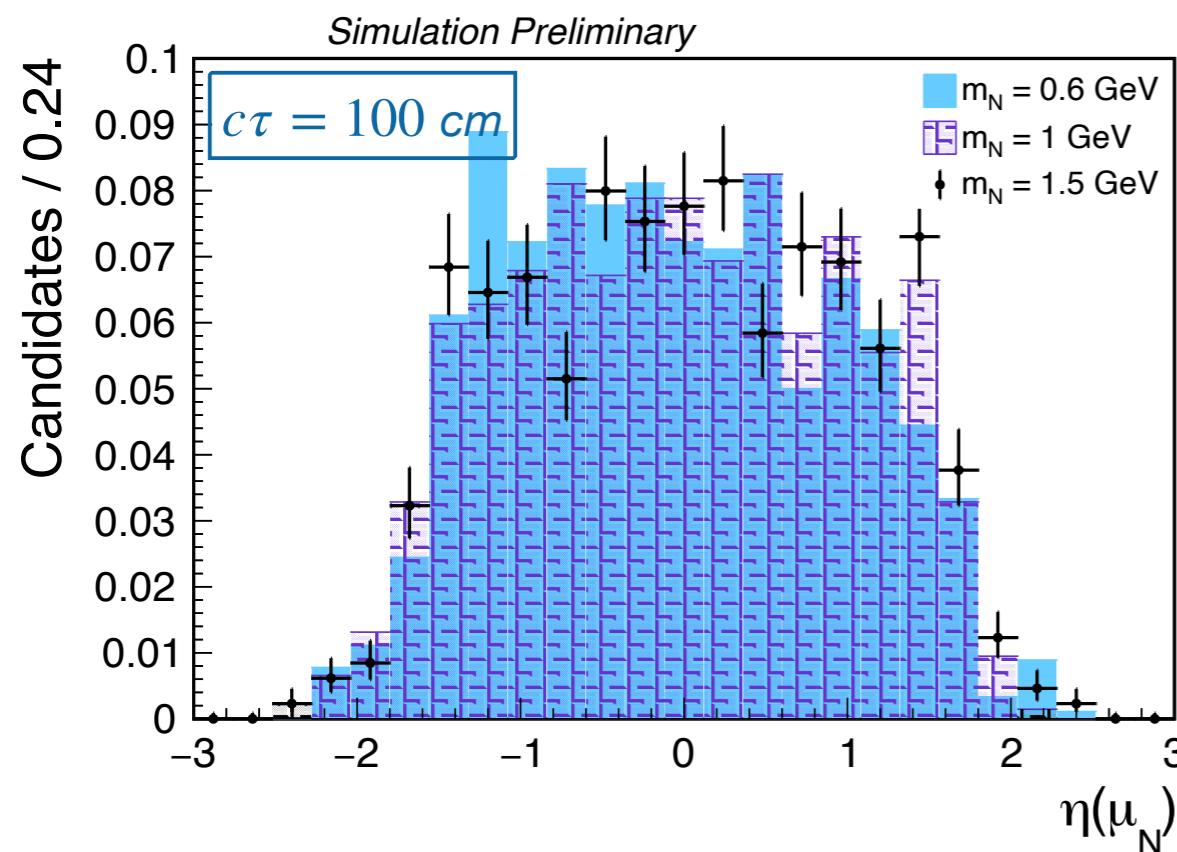
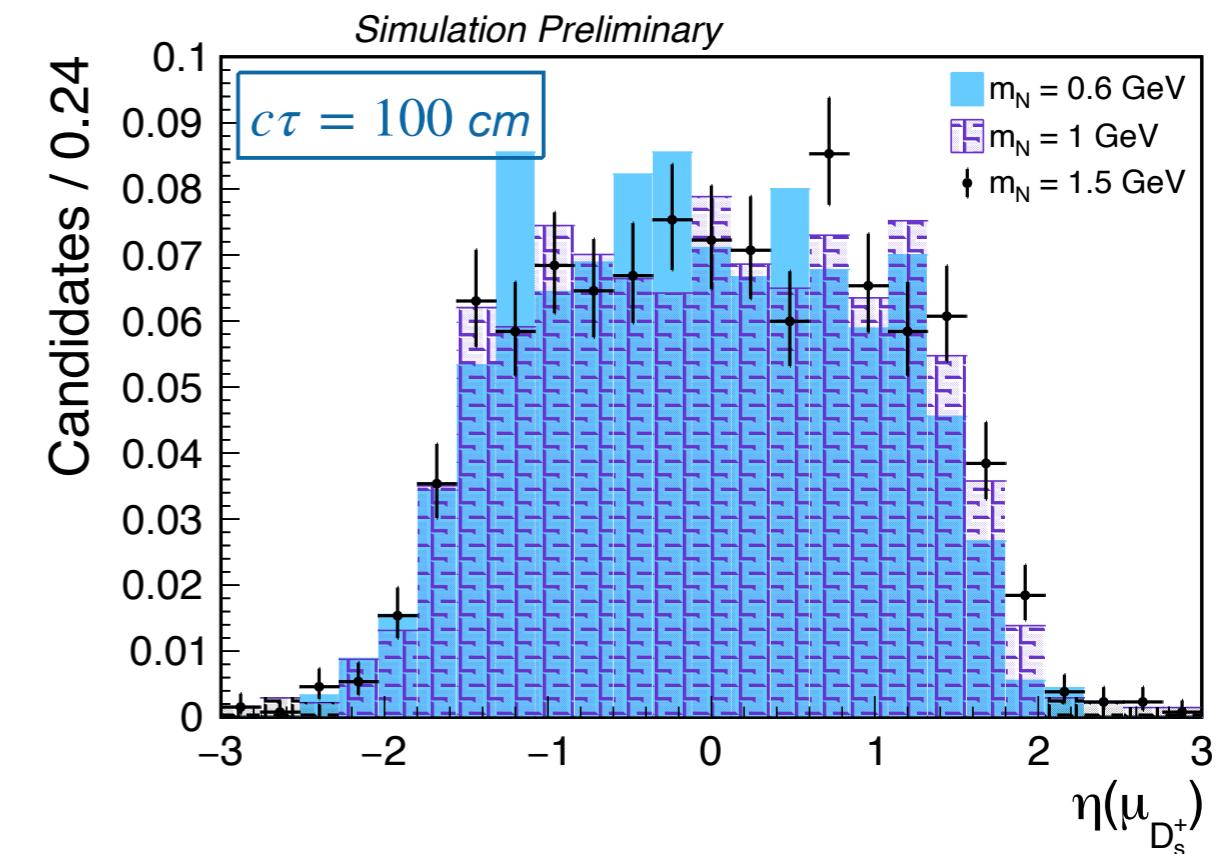
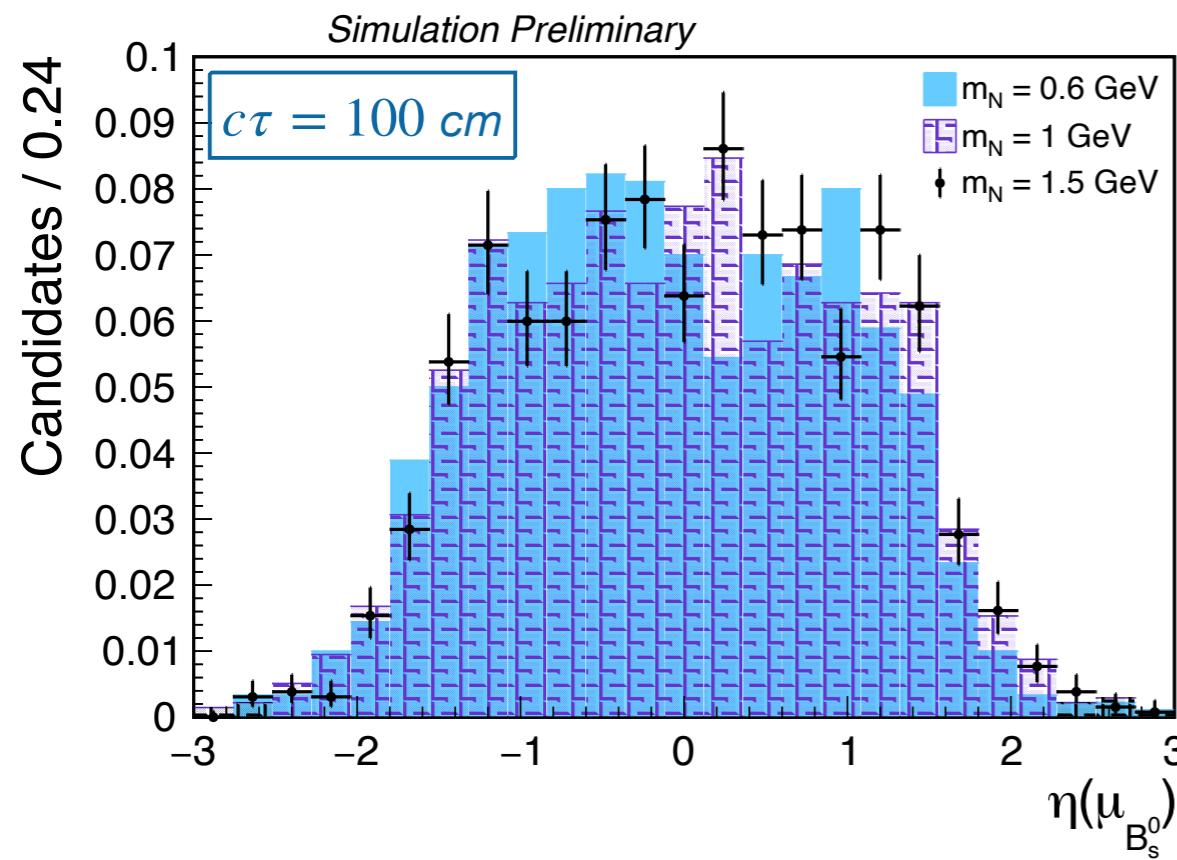


Gen-lvl η -distributions

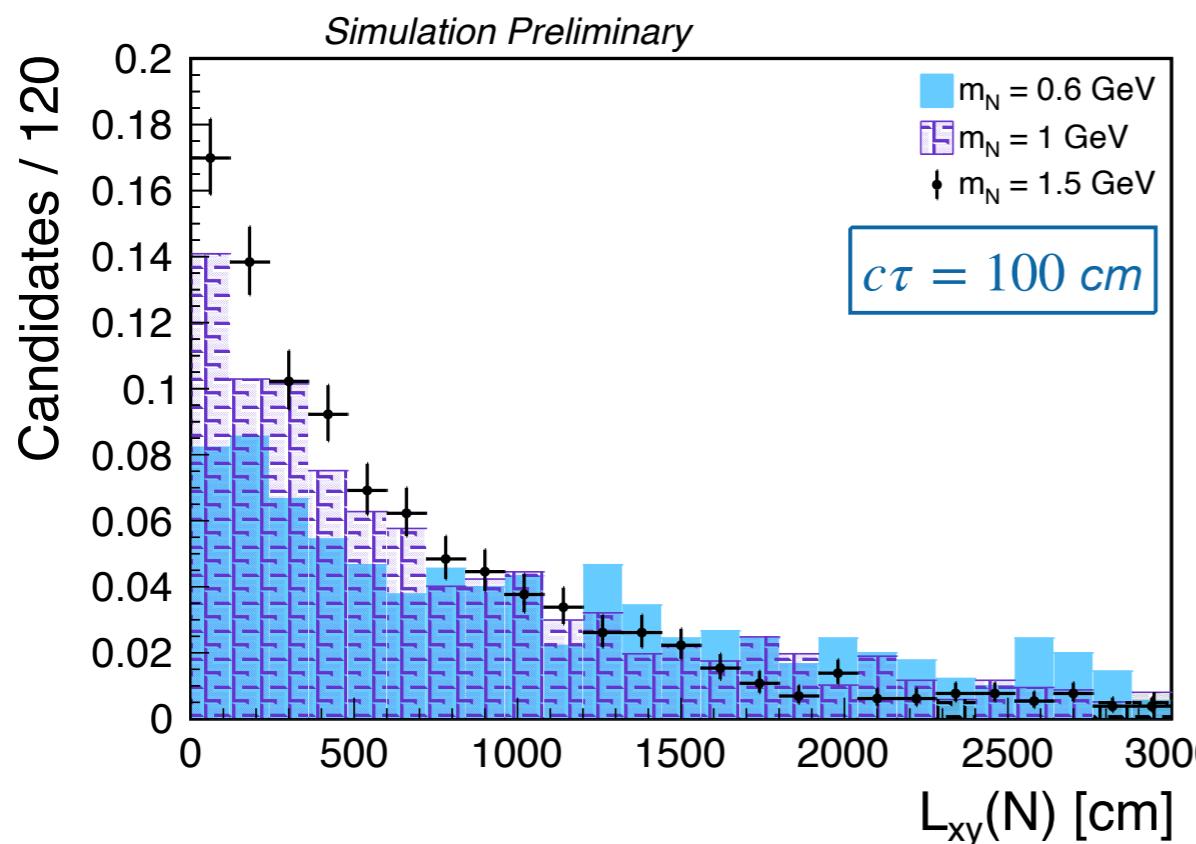
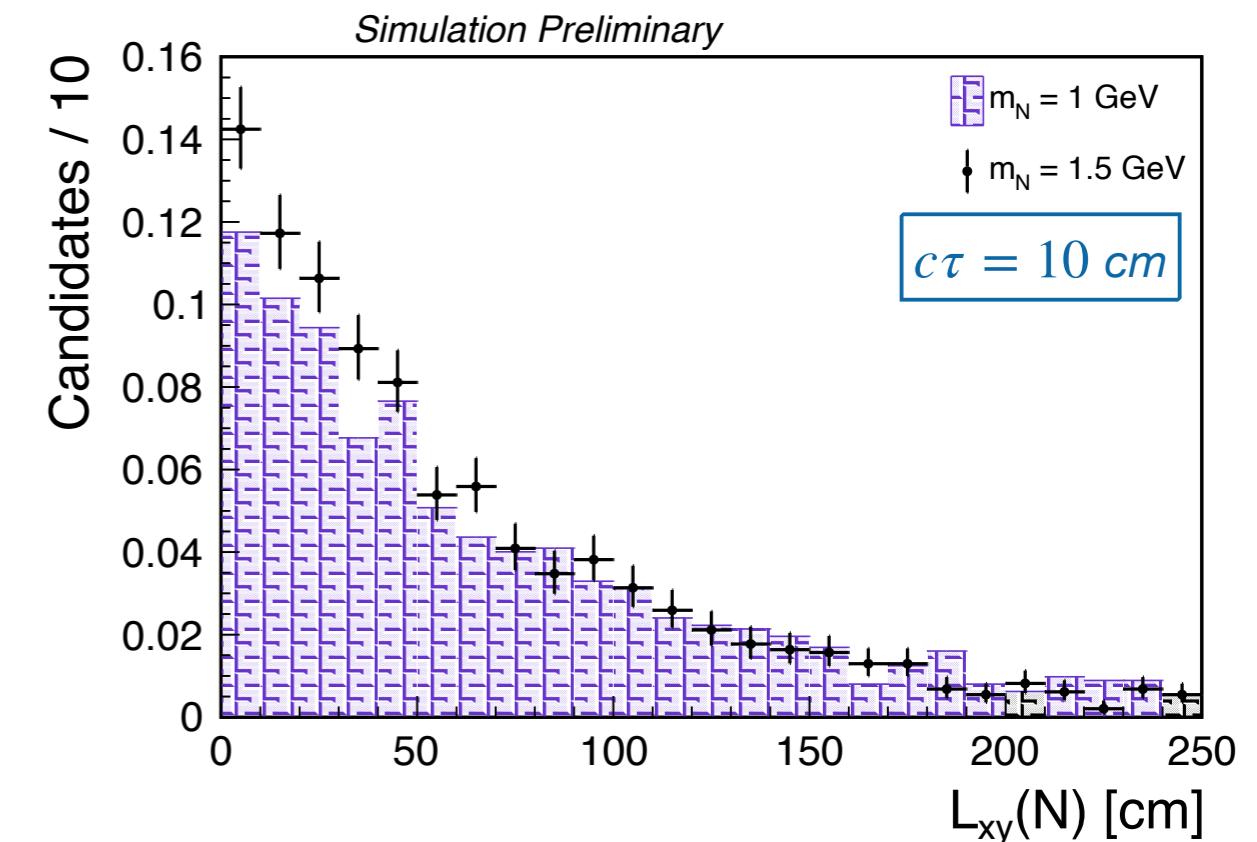
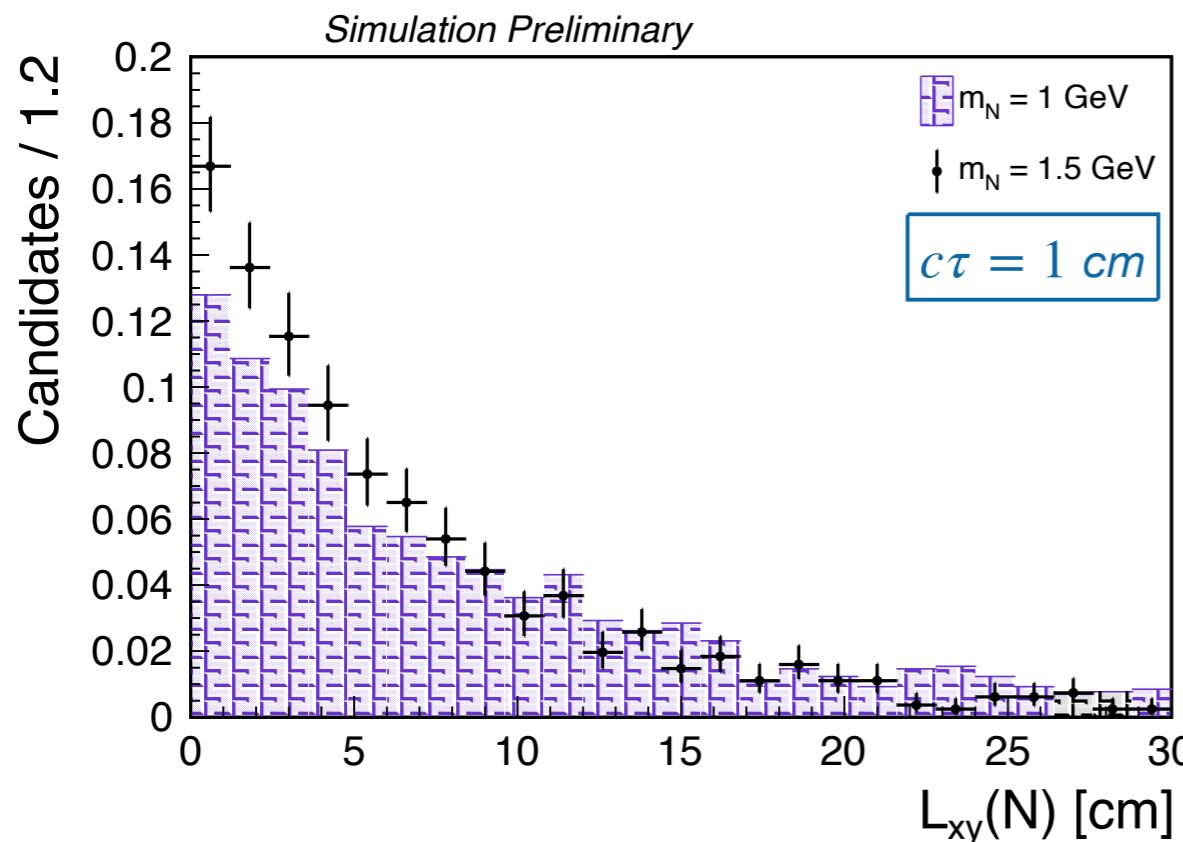


- η -distributions seem to be independent from mass, as expected

Gen-lvl η -distributions



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



	$m_N = 0.6 \text{ GeV}$	$m_N = 1.0 \text{ GeV}$	$m_N = 1.5 \text{ GeV}$
$c\tau = 1 \text{ cm}$		11,1	7,4
$c\tau = 10 \text{ cm}$		109,2	73,9
$c\tau = 100 \text{ cm}$	1648,7	1115,2	772,0
$c\tau = 1000 \text{ cm}$	7388,6		

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

Gen-filters efficiency — “BPark trigger” filter

	$m_N = 0.6 \text{ GeV}$	$m_N = 1.0 \text{ GeV}$	$m_N = 1.5 \text{ GeV}$
$c\tau = 1 \text{ cm}$		19,0	17,4
$c\tau = 10 \text{ cm}$		19,1	17,8
$c\tau = 100 \text{ cm}$	23,3	19,4	17,7
$c\tau = 1000 \text{ cm}$	23,2		

Efficiency is in $[10^{-3}]$ units

- We have MC gen-samples with zero filters (only decay topologies and correct PGD-IDs are required)
- We want to estimate gen-filters efficiency, which is number of events after filter (cut) divided by initial number of events
- Here we provide calculated efficiency for “BParking trigger” filter:
at least one muon has $p_T > 7 \text{ GeV}$ and $|\eta| < 1.55$

Gen filter efficiency – CMS acceptance

HNL daughters filters

	m_N = 0.6 GeV	m_N = 1.0 GeV	m_N = 1.5 GeV
ctau = 1 cm		7,1	8,6
ctau = 10 cm		6,7	8,9
ctau = 100 cm	5,9	7,2	8,8
ctau = 1000 cm	6,1		

All particles filters

	m_N = 0.6 GeV	m_N = 1.0 GeV	m_N = 1.5 GeV
ctau = 1 cm		1,8	1,5
ctau = 10 cm		1,7	1,6
ctau = 100 cm	1,6	2,0	1,4
ctau = 1000 cm	1,7		

Efficiency is in $[10^{-3}]$ units

“BPark trigger” filter is included in both cases

- CMS detector has p_T and η restrictions on possibilities of adequate particles reconstructions, and we need to account it in simulation productions
- First filter (left table) – we add “CMS acceptance” filter to HNL daughters:
 $p_T(\mu) > 3 \text{ GeV}, |\eta(\mu)| < 2.5$
 $p_T(\pi) > 0.3 \text{ GeV}, |\eta(\pi)| < 2.5$
- Second filter – we add these restrictions to μ from B_s^0 and D_s^+
- We have a tendency of higher mass \rightarrow higher efficiency

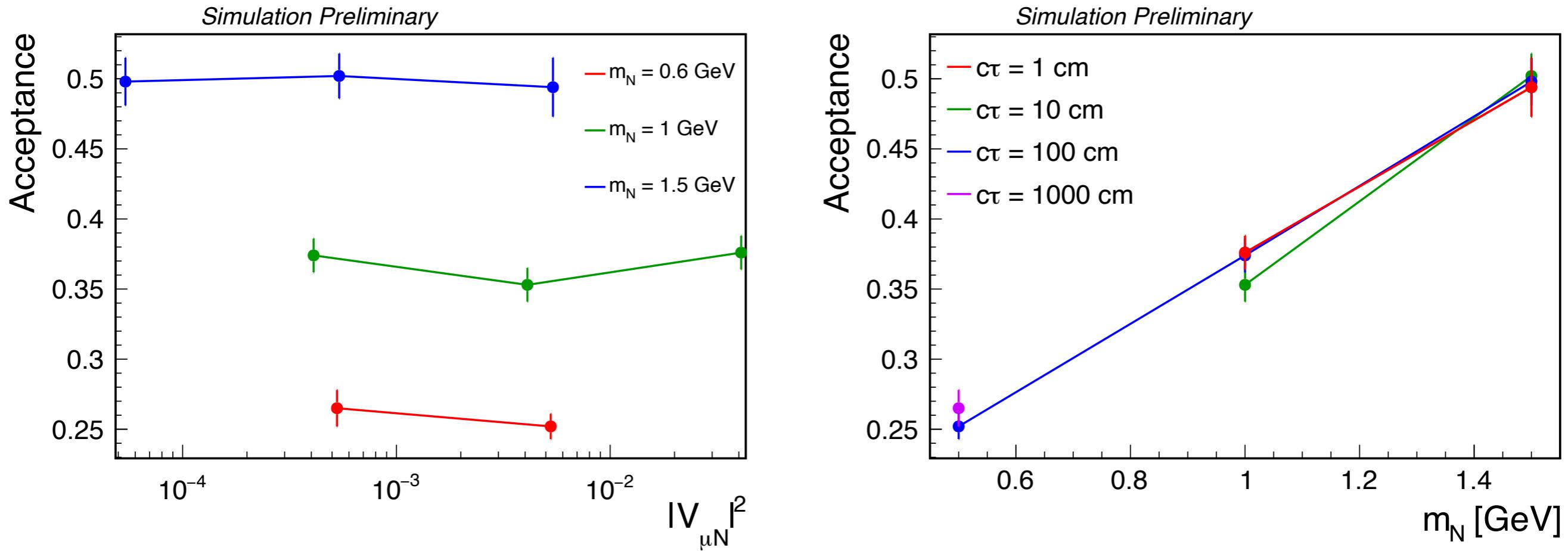
Acceptance

- Important parameter of our studies is acceptance, which is

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

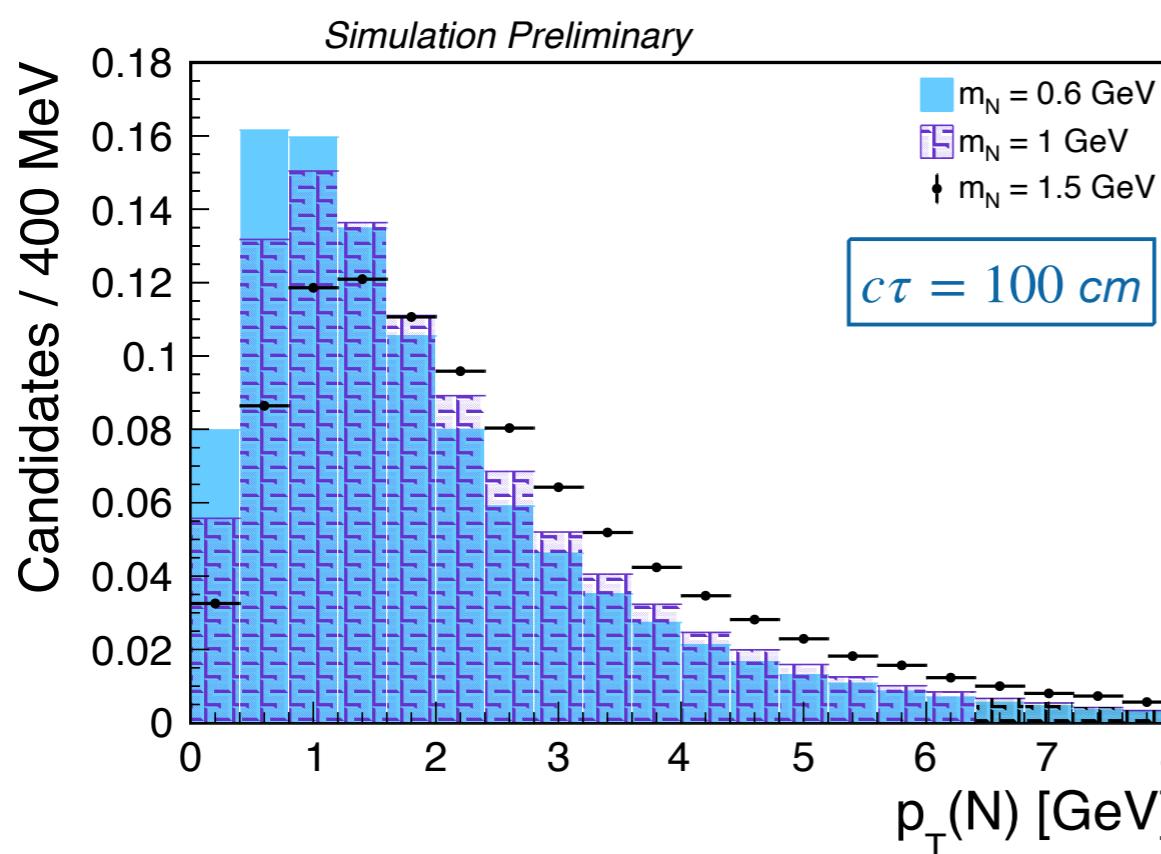
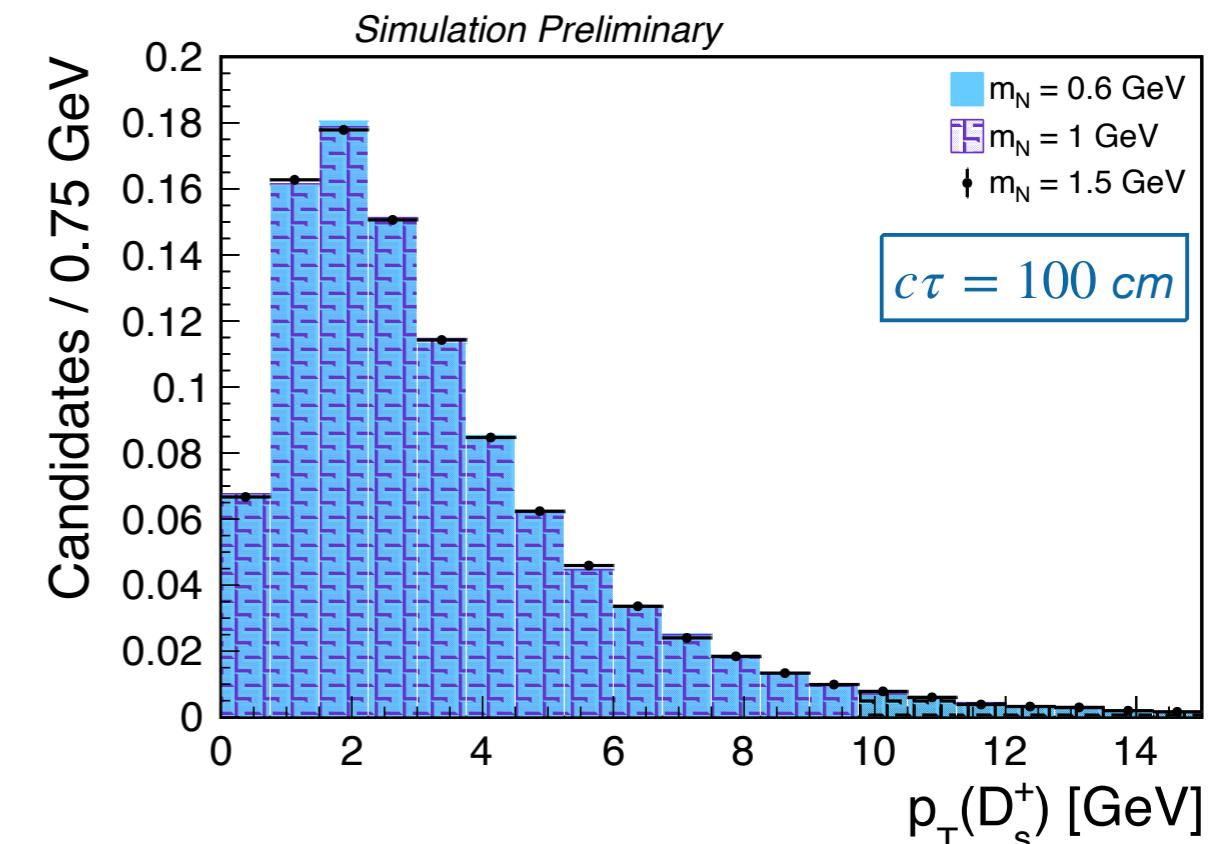
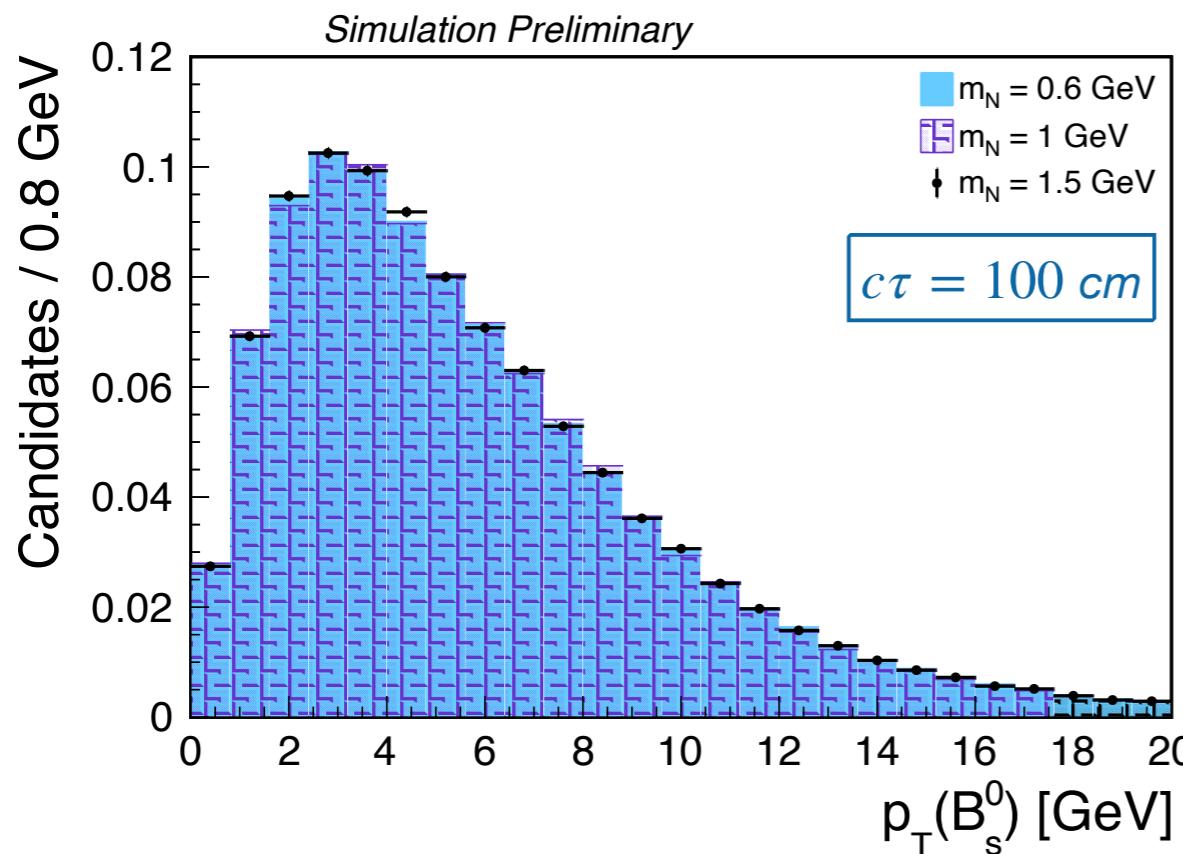
- Denominator is number of gen-events after “*BParking trigger*” filter:
at least a muon with $p_T > 7 \text{ GeV}$ and $|\eta| < 1.55$
- Numerator is “*BParking trigger*” filter plus “CMS acceptance requirements” for HNL daughters:
 $p_T(\mu) > 3 \text{ GeV}, \quad |\eta(\mu)| < 2.5$
 $p_T(\pi) > 0.3 \text{ GeV}, \quad |\eta(\pi)| < 2.5$

Acceptance estimations



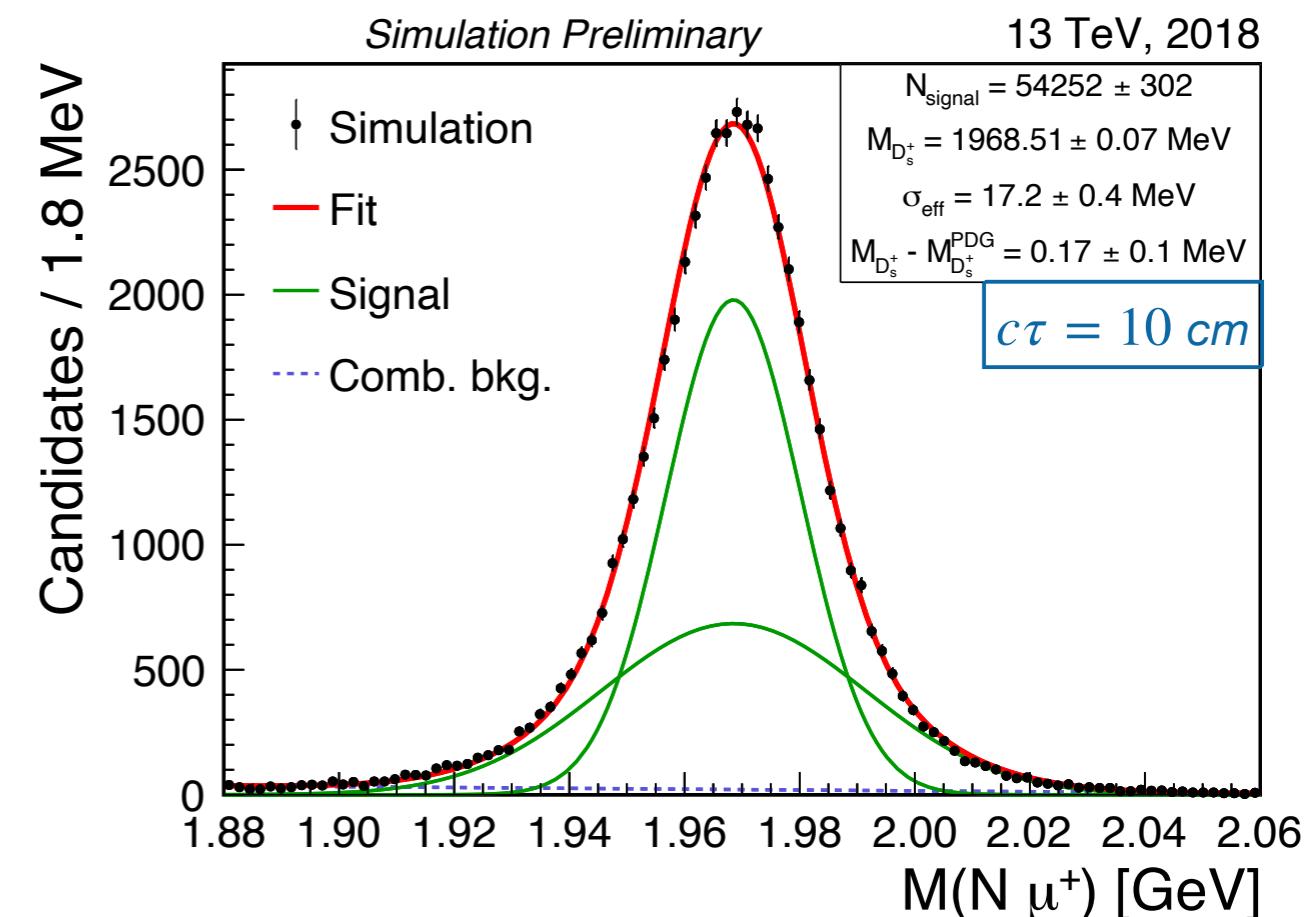
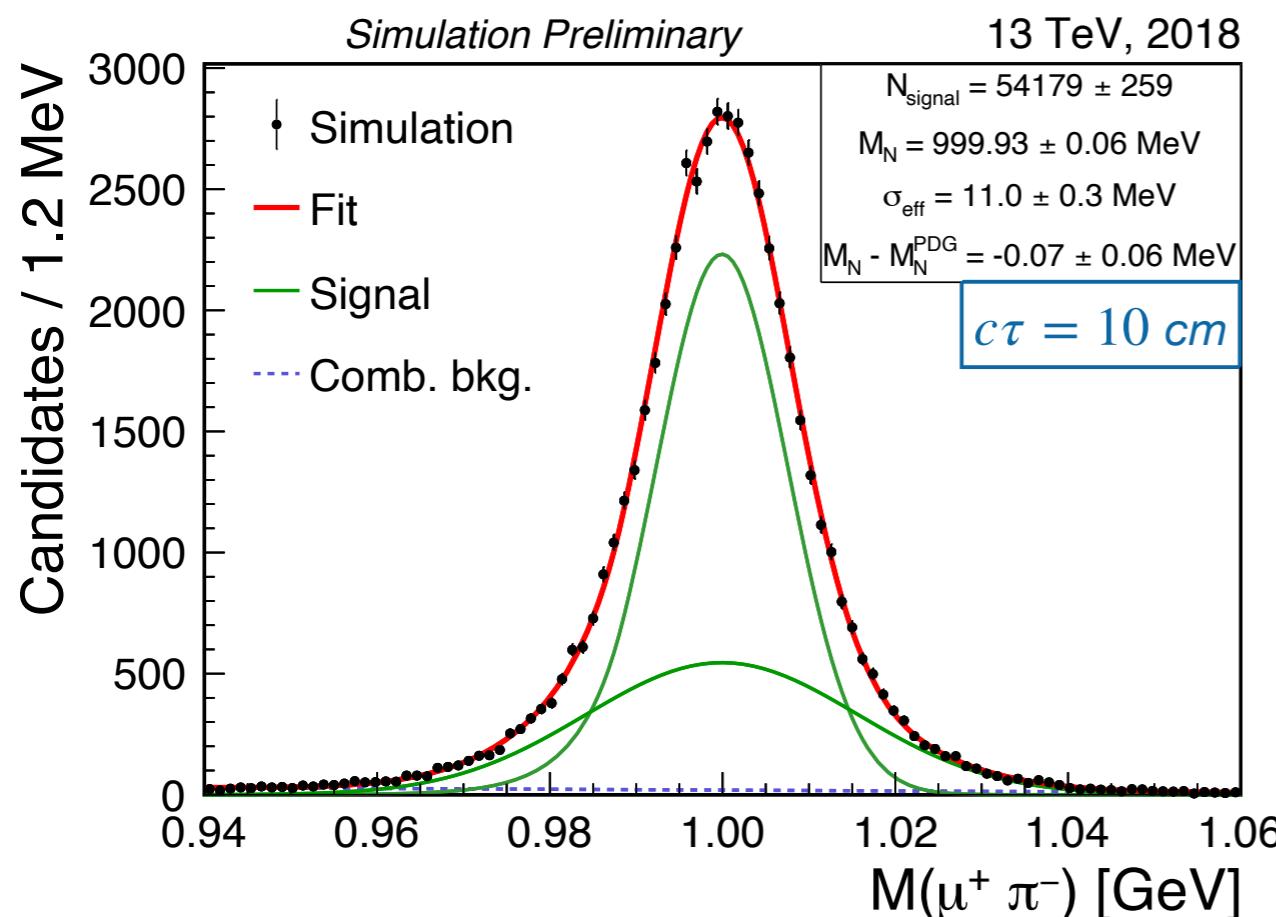
- The higher mass gives us higher acceptance
- No significant dependence of acceptance from coupling parameter $|V_{\mu N}|^2$ is observed

Gen-lvl p_T -distributions – no filters

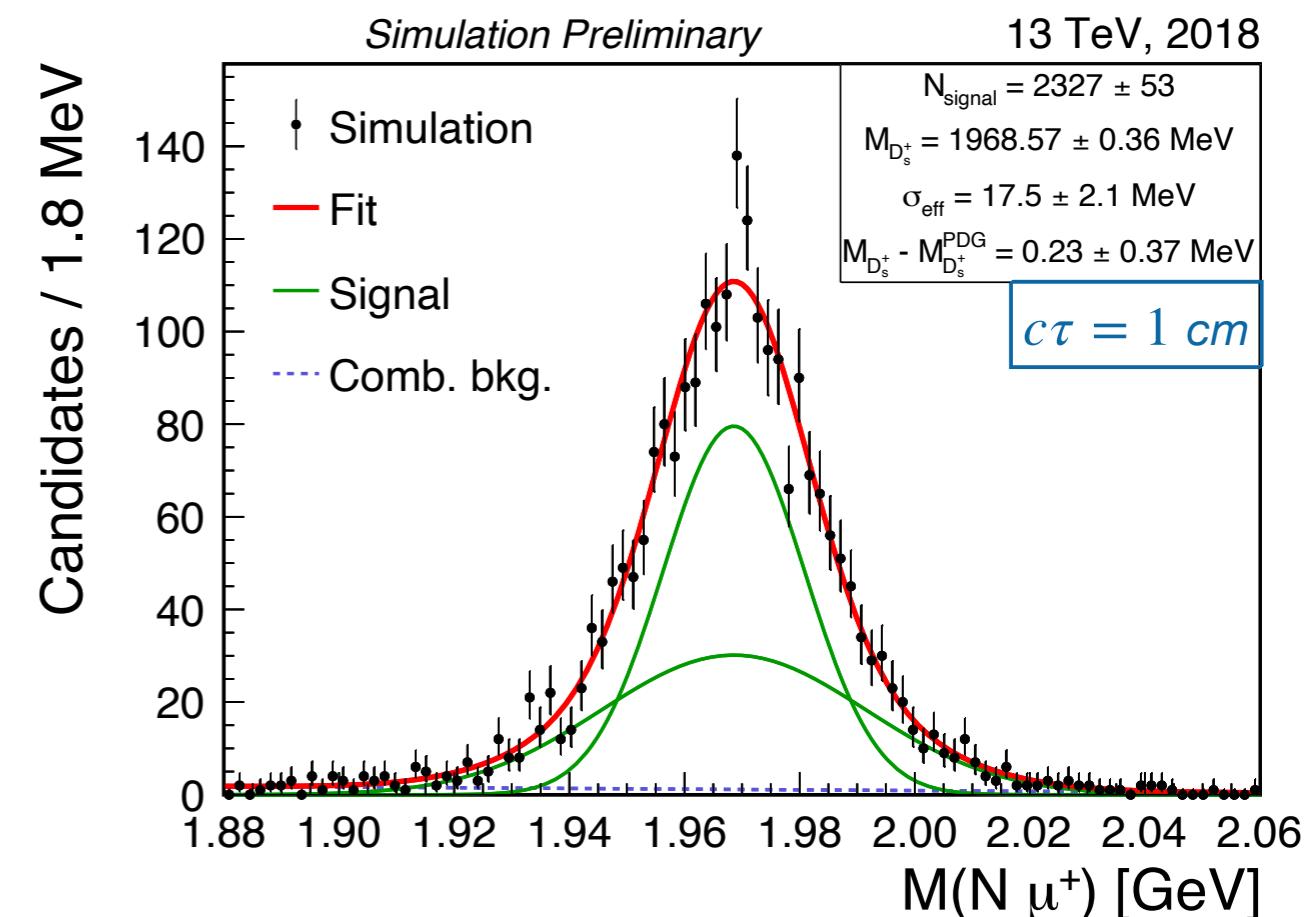
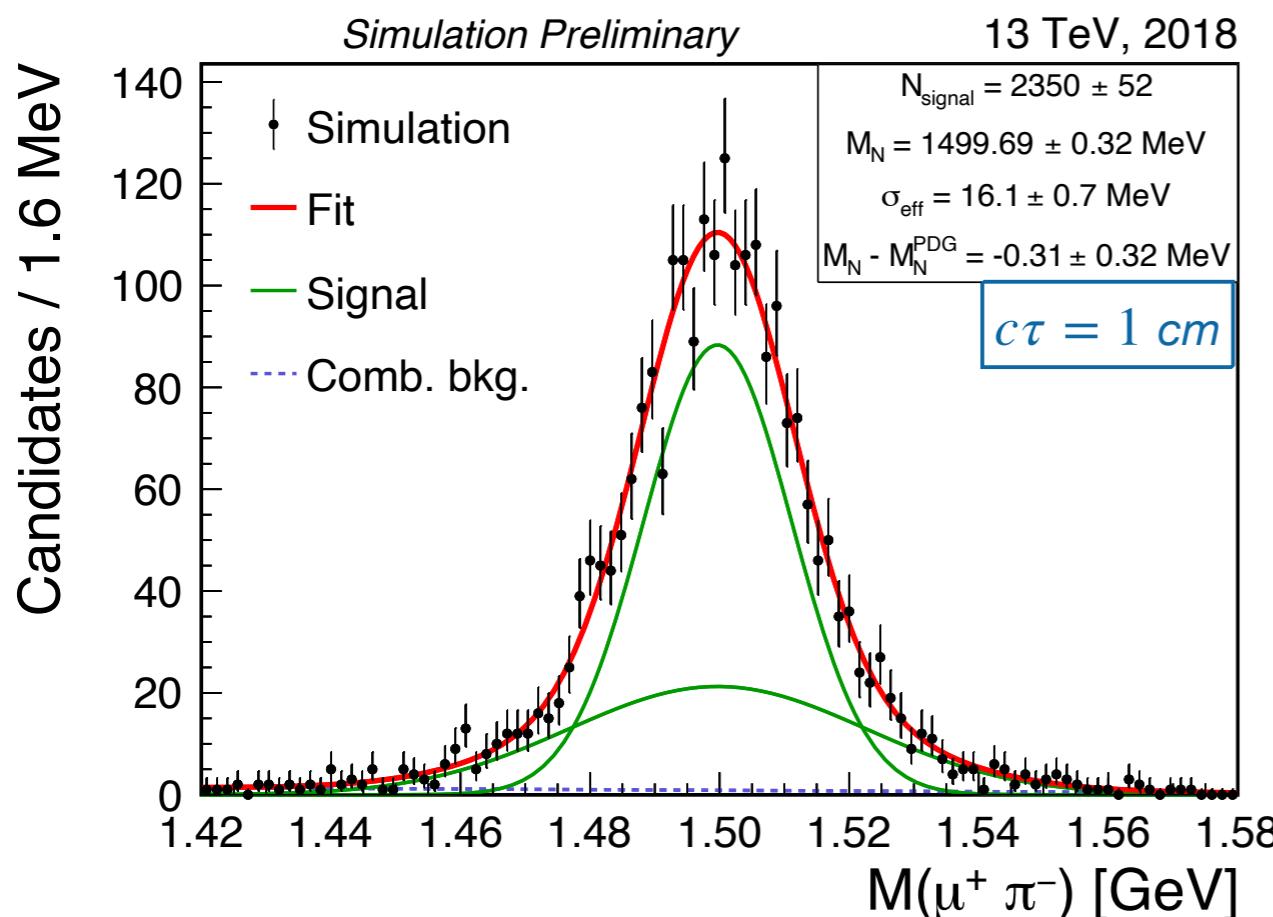


- With no selection (“zero” gen-filters) distributions of B_s^0 and D_s^+ p_T is independent from its daughter N mass

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

