Long-lived light mediators from Higgs boson decays

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Based on

Long-Lived Light Mediators from Higgs boson Decay at HL-LHC, FCC-hh and a Proposal of Dedicated LLP Detectors for FCC-hh
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FCC physics meeting, 29th November 2021

Long-lived Particles (LLP)

Nature of the new physics is completely unknown
Probably very unconventional, exotic final states

Not yet searched for ?
Experimentally challenging ?

One such interesting possibility : Long-lived particles(LLPs)

Presence of LLP is not unnatural

- LLPs are present in the Standard Model
- Small coupling, and/or suppression in the phase space makes particles long-lived
- Many well motivated BSM models predict the presence of LLPs : SUSY, dark matter models

Unusual signatures of LLPs

Signatures of LLPs not only depend on the decay modes but also where these decay

Many unusual possibilities at the LHC :

See LLP White paper, 1903.04497, for the list of possible signatures

- **displaced vertex search**
- **Disappearing tracks/tracklets**
- **Randomly timed large energy response**
- **Non pointing objects….**
- **For slow moving LLPs, decay product can move in the backward direction !**
  (Banerjee, Bélanger, **BB**, Boudjema, Godbole and Mukherjee, *P hys.Rev.D* 98 (2018) 11, 115026)

Two possible ways to search:

A. Use standard trigger made for prompt analysis and try find the presence of LLP off-line

B. Use dedicated triggers for LLPs

Scalar Mediator : Production and decays

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \Phi)^2 - A_{\Phi H}\Phi|H|^2 - \frac{\lambda_{\Phi H}}{2}\Phi^2|H|^2 - \mu_1^3\Phi - \frac{\mu_\Phi^2}{2}\Phi^2 - \frac{\mu_3}{3!}\Phi^3 - \frac{\lambda_\Phi}{4!}\Phi^4 + \mathcal{L}_{\rm DS},$$

Minimal model of scalar mediator with a mixing With the SM Higgs boson

$\Phi|H|^2 \rightarrow$ Induces mixing between Φ and H -> Mass eigenstates : ϕ and h
Single production of ϕ possible,
Mixing highly constrained (For current bounds see 1811.03292)

$\Phi^2|H|^2 \rightarrow$ Not severely constrained so far, as it must be accompanied by an on-shell Higgs boson to probe it sensitively.

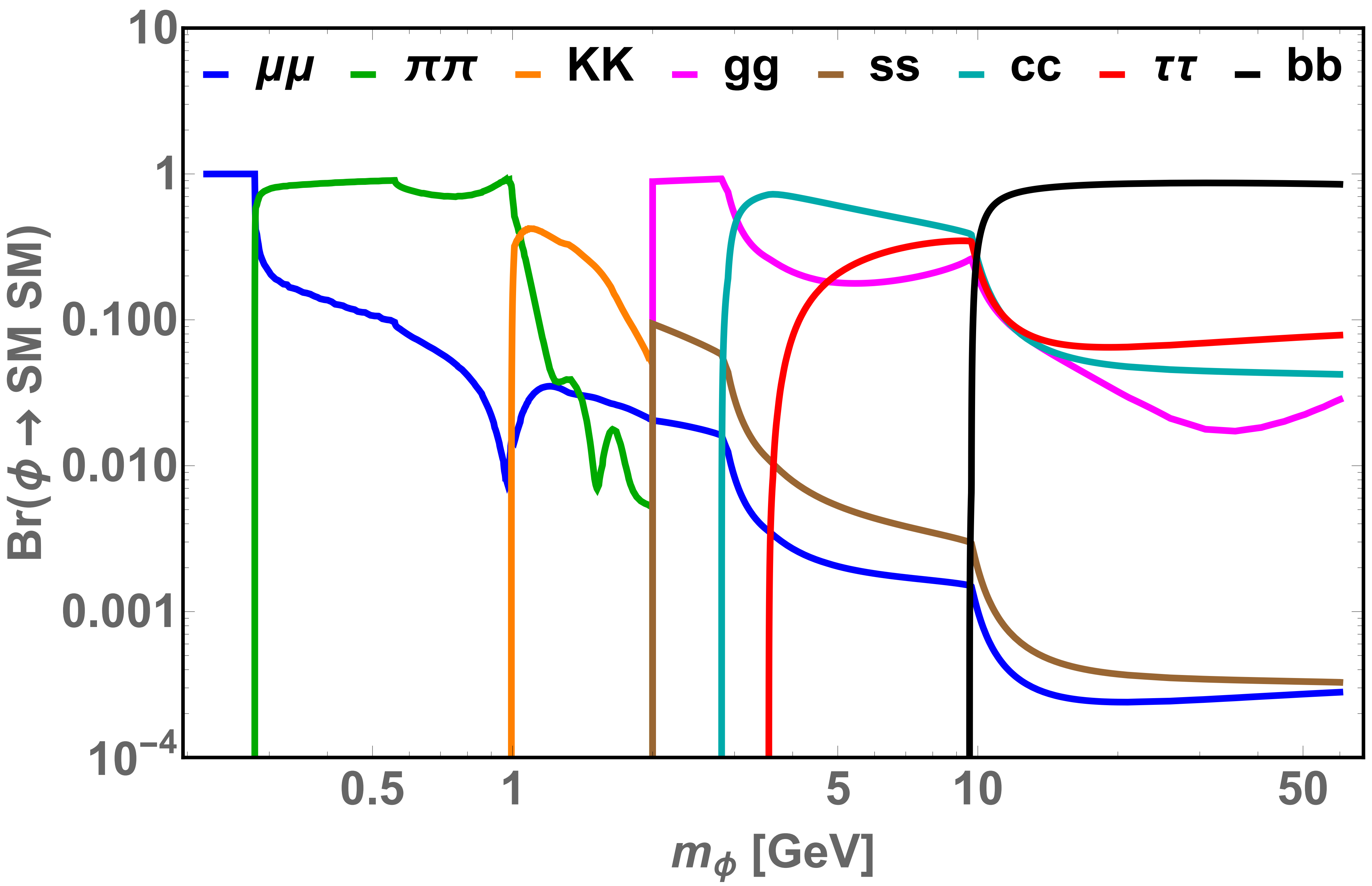
If $m_\phi < m_h/2$ the interaction induces the Higgs boson to decay into a pair of mediator particles, i.e. h → ϕϕ

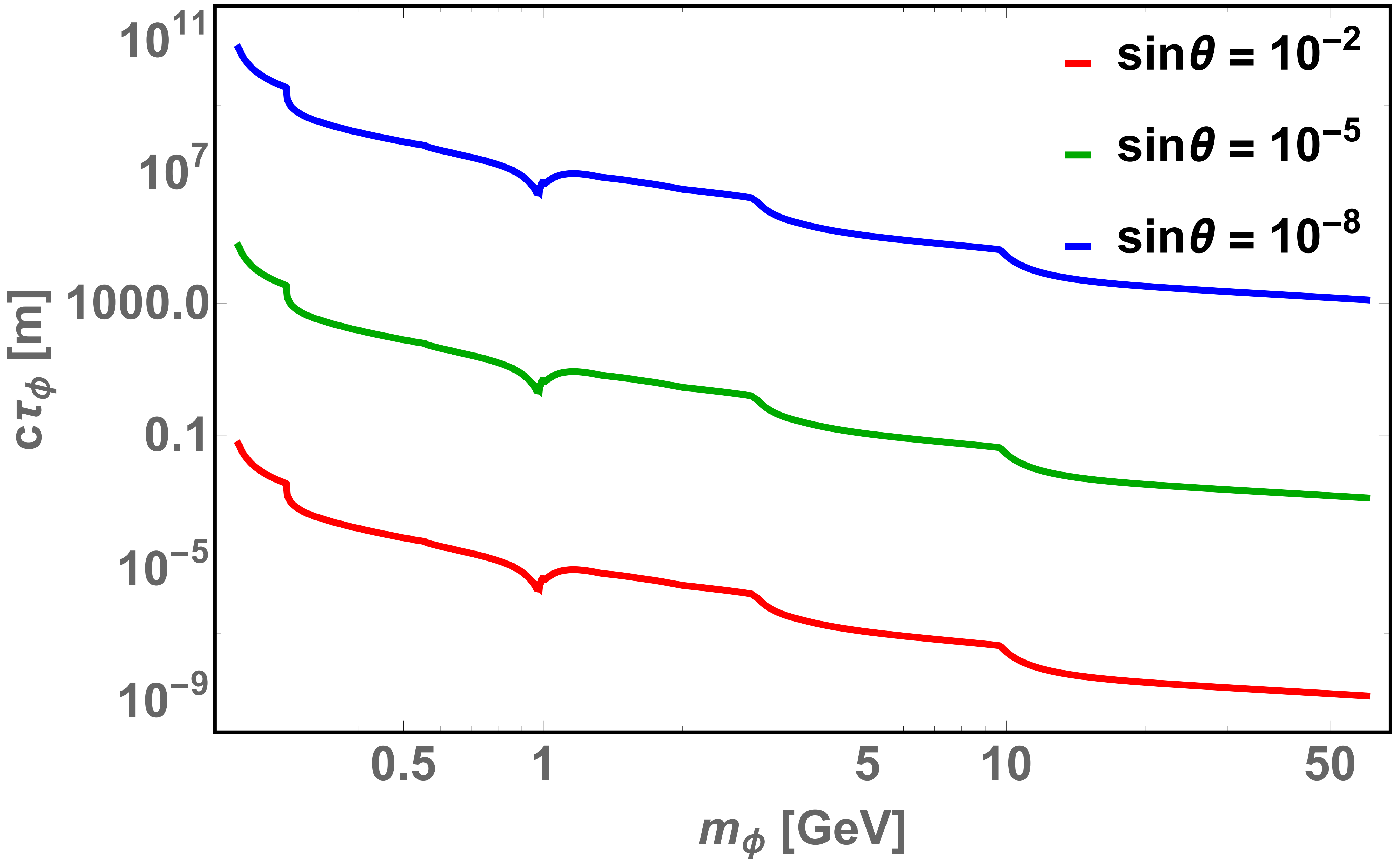
$$g_{SM\ SM\ \phi} \propto \sin\theta$$

Mixing angle θ determines the strength of the ϕ with SM particles

For heavy dark sector, ϕ will behave like SM Higgs boson with suppressed Decay width (suppression factor = $\sin^2\theta$

For very small θ, ϕ can be long-lived

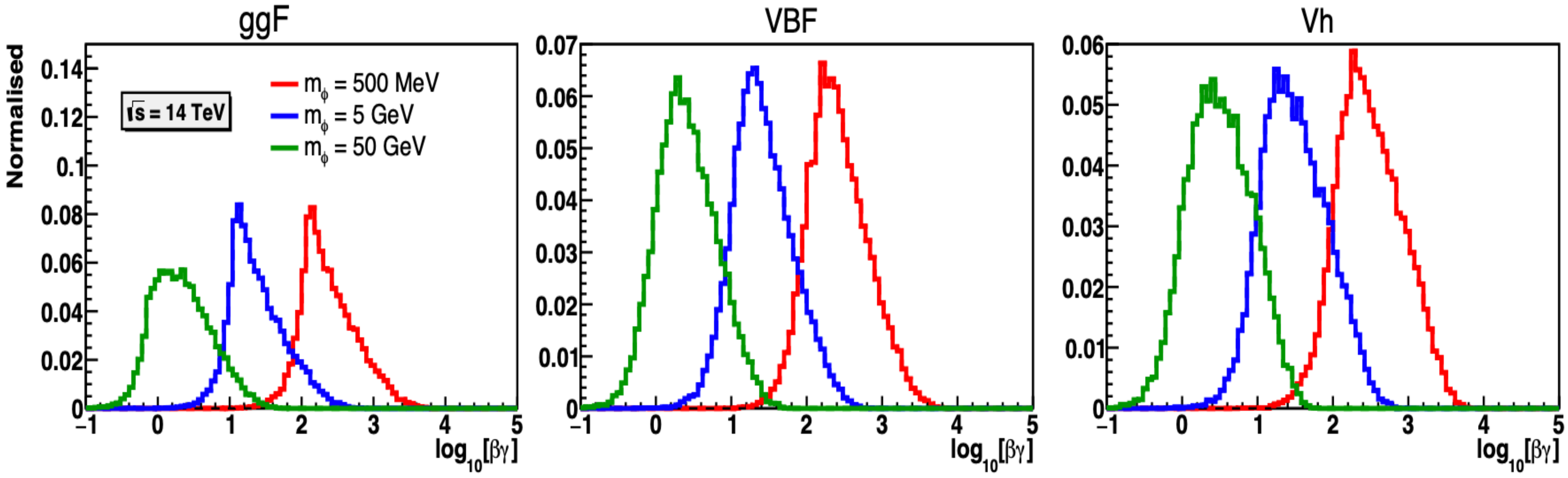




Scalar Mediator: Dominant production modes

$\sqrt{s}$ [TeV]	Process	Cross section [pb]
14	ggF	50.35
	VBF	4.172
	Vh	2.387 (Wh:1.504, Zh:0.8830)

Several production processes and many decay modes of ϕ—-> mostly studied in ggF channel

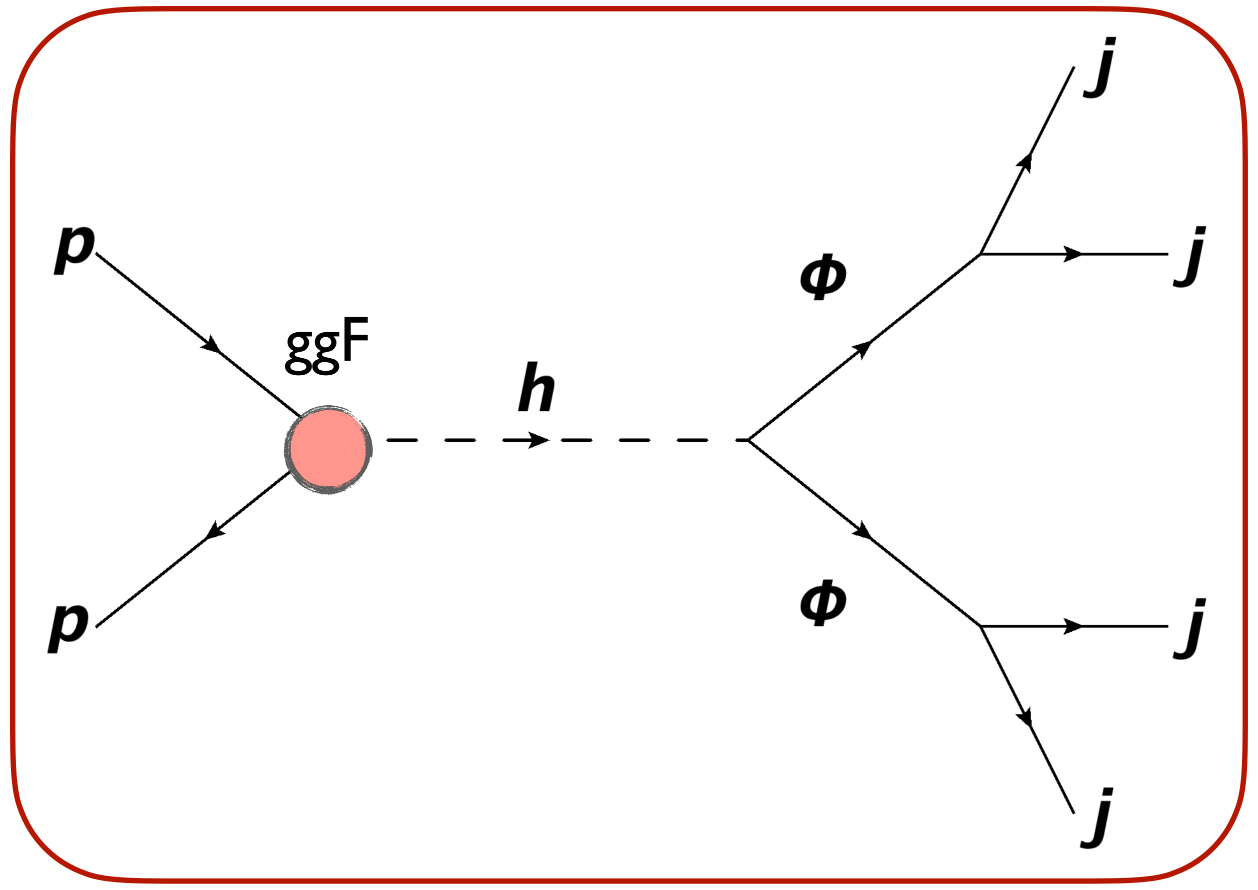


Boost distribution mildly depends on the production process

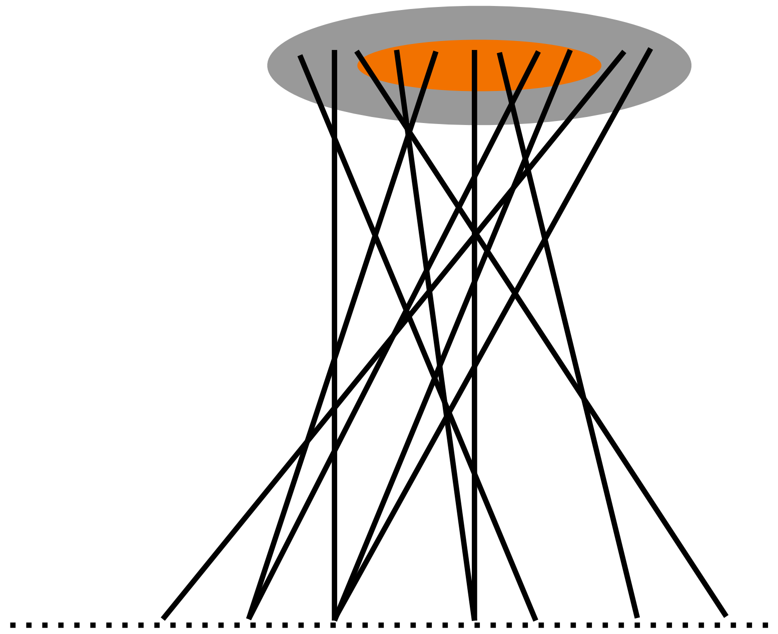
Mediator from Higgs decays: Tracker based search

ϕ mostly decays to jets unless it is very light.

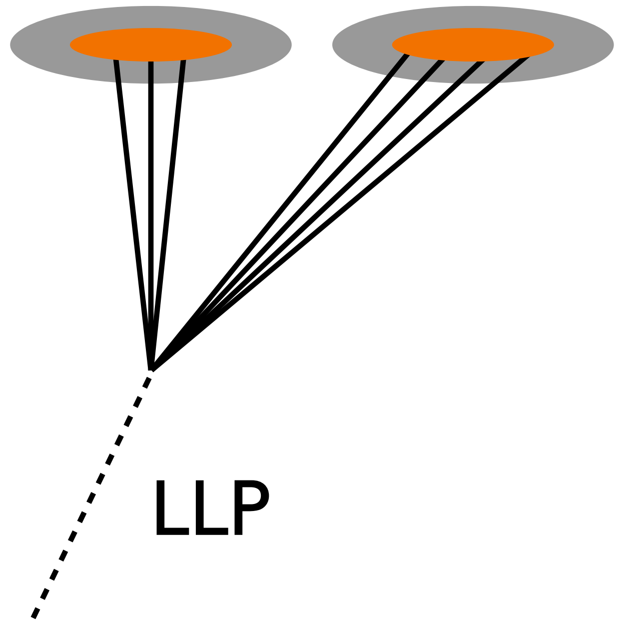
- We will always have some decays inside the Tracker for a large range of lifetimes
- The displaced vertex position can be identified most precisely in the Tracker.
- In Phase-II upgrade, some tracking will be available at L1.



- Highly affected by the increased amount of PU in HL-LHC



PU contribution, being more uniform, reduces with reduced cone-size

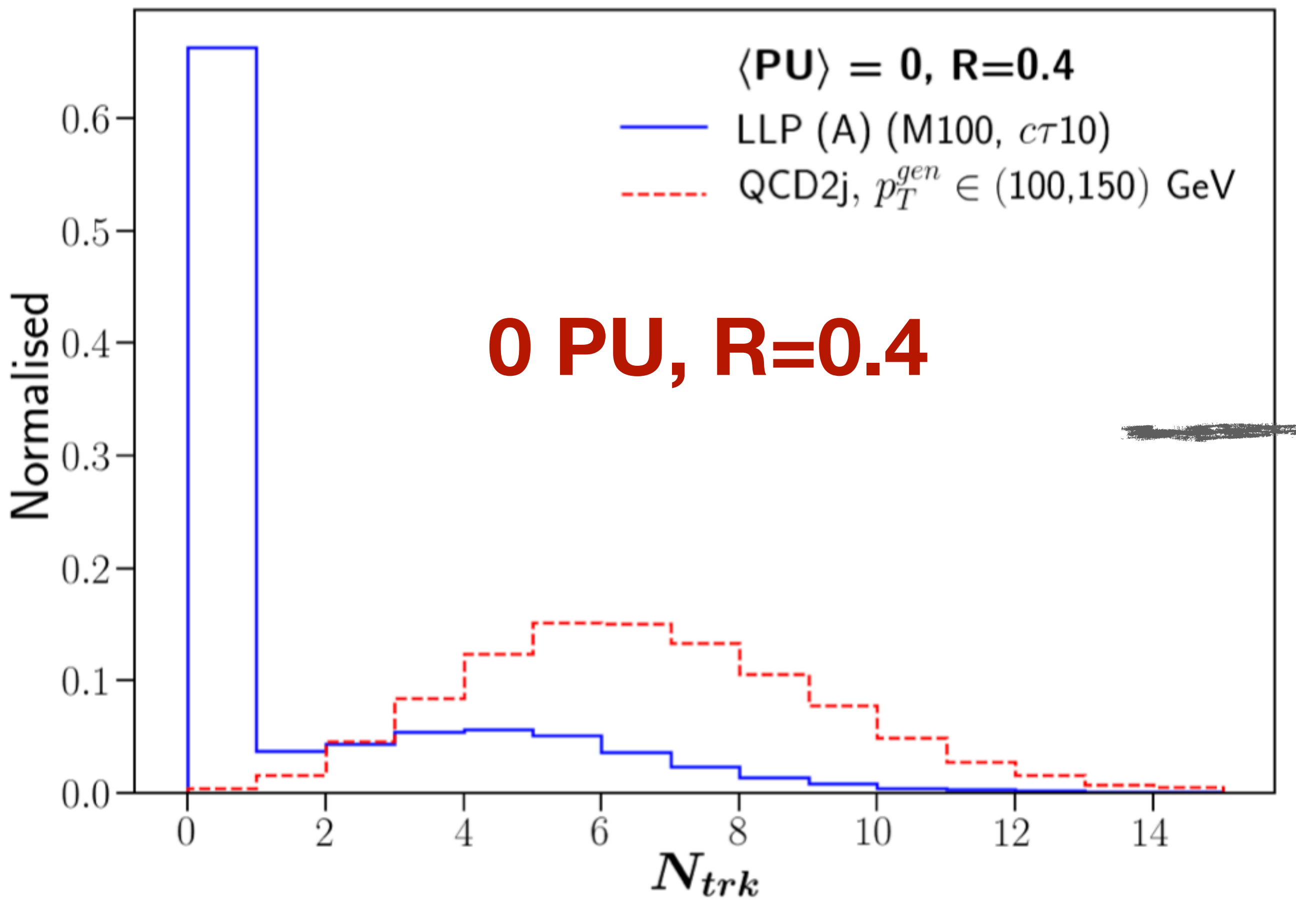


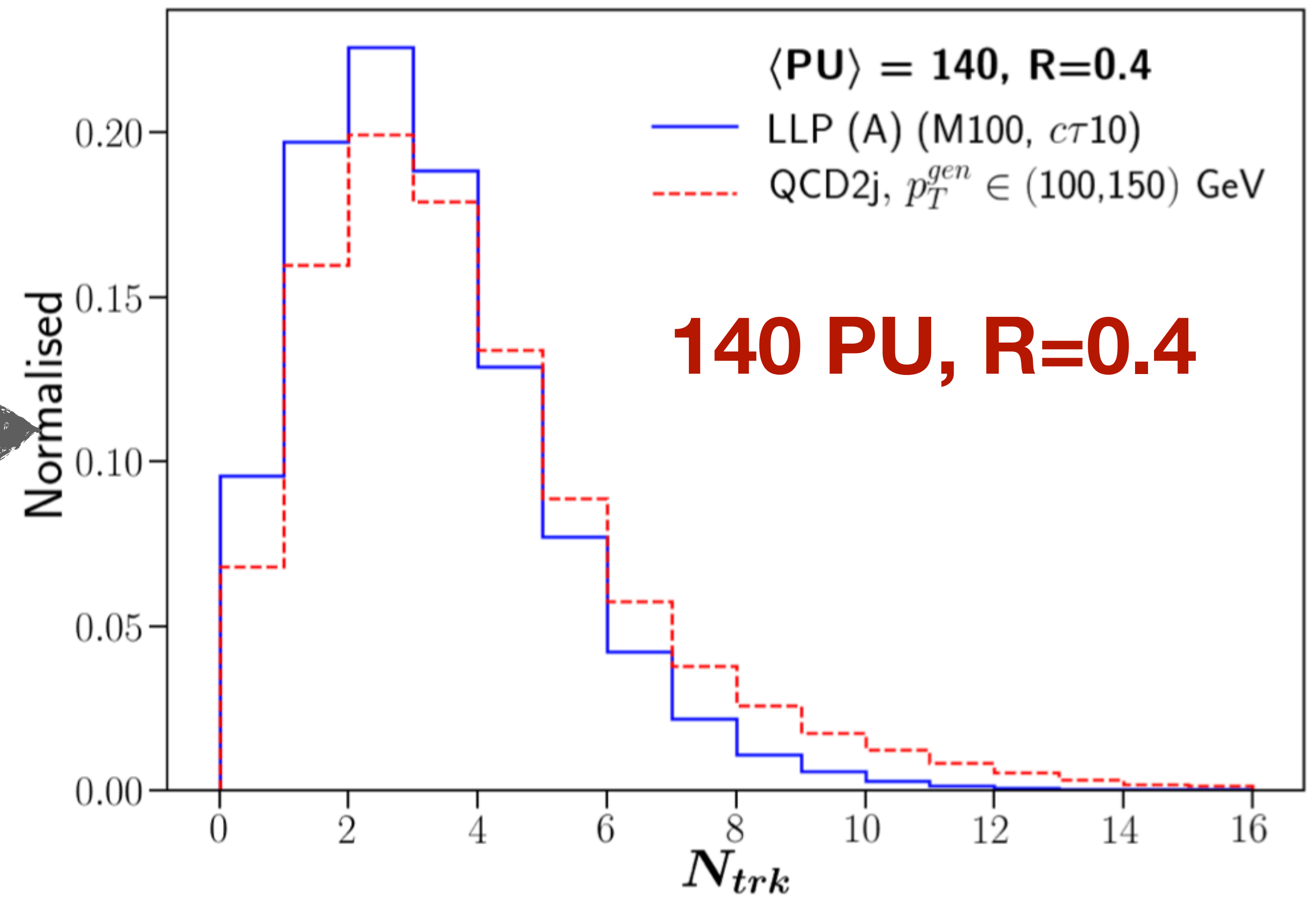
LLP signals not much affected with reduced cone-size

L1 tracks:

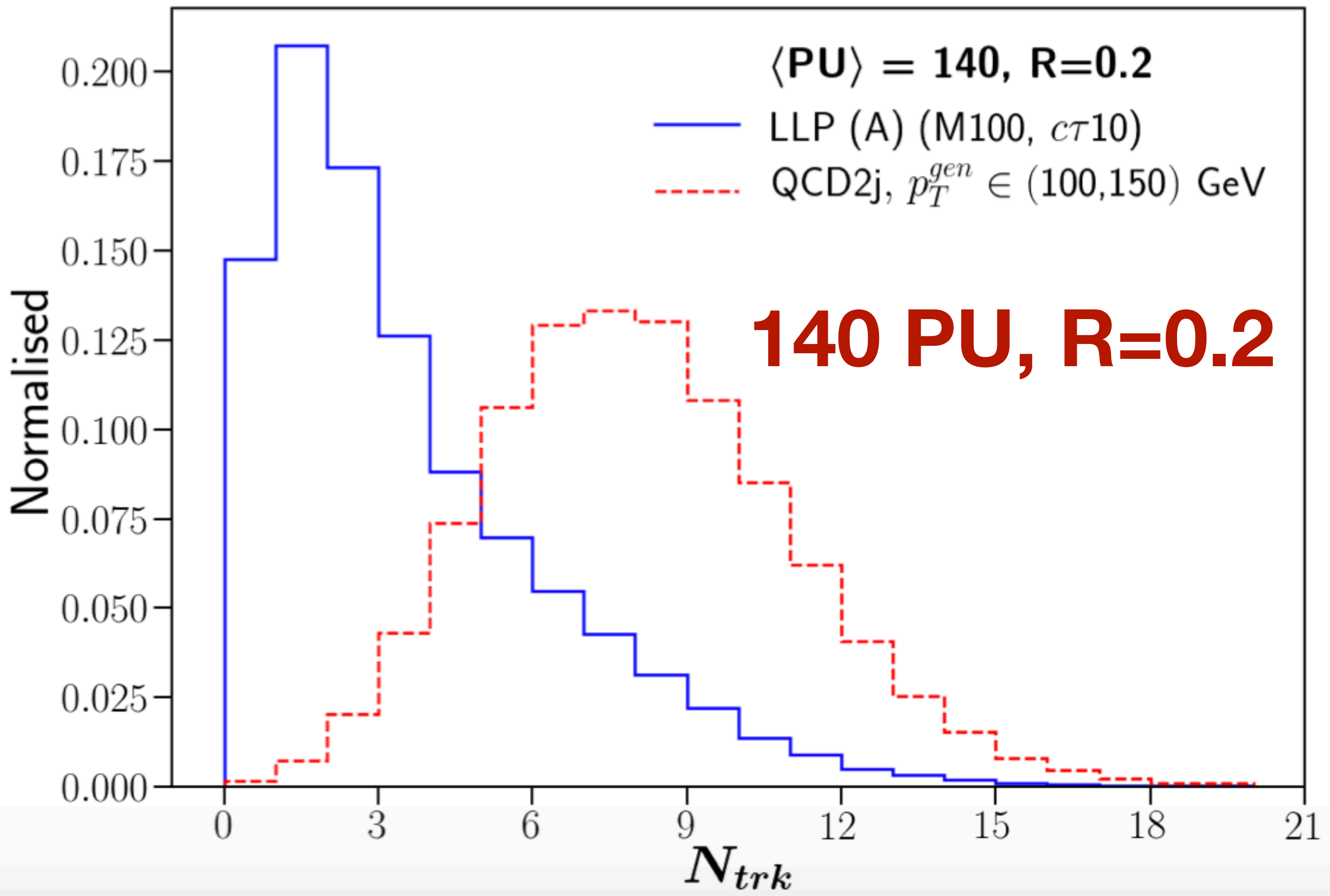
$$p_T > 2\ \text{GeV},\quad |\eta| < 2.5,\quad L_{xy} < 1\ \text{cm},\quad |z_0| < 30\ \text{cm}$$

T. James, CERN-THESIS-2018-241





Remedy:
NARROWER JETS
$(R = 0.2)$



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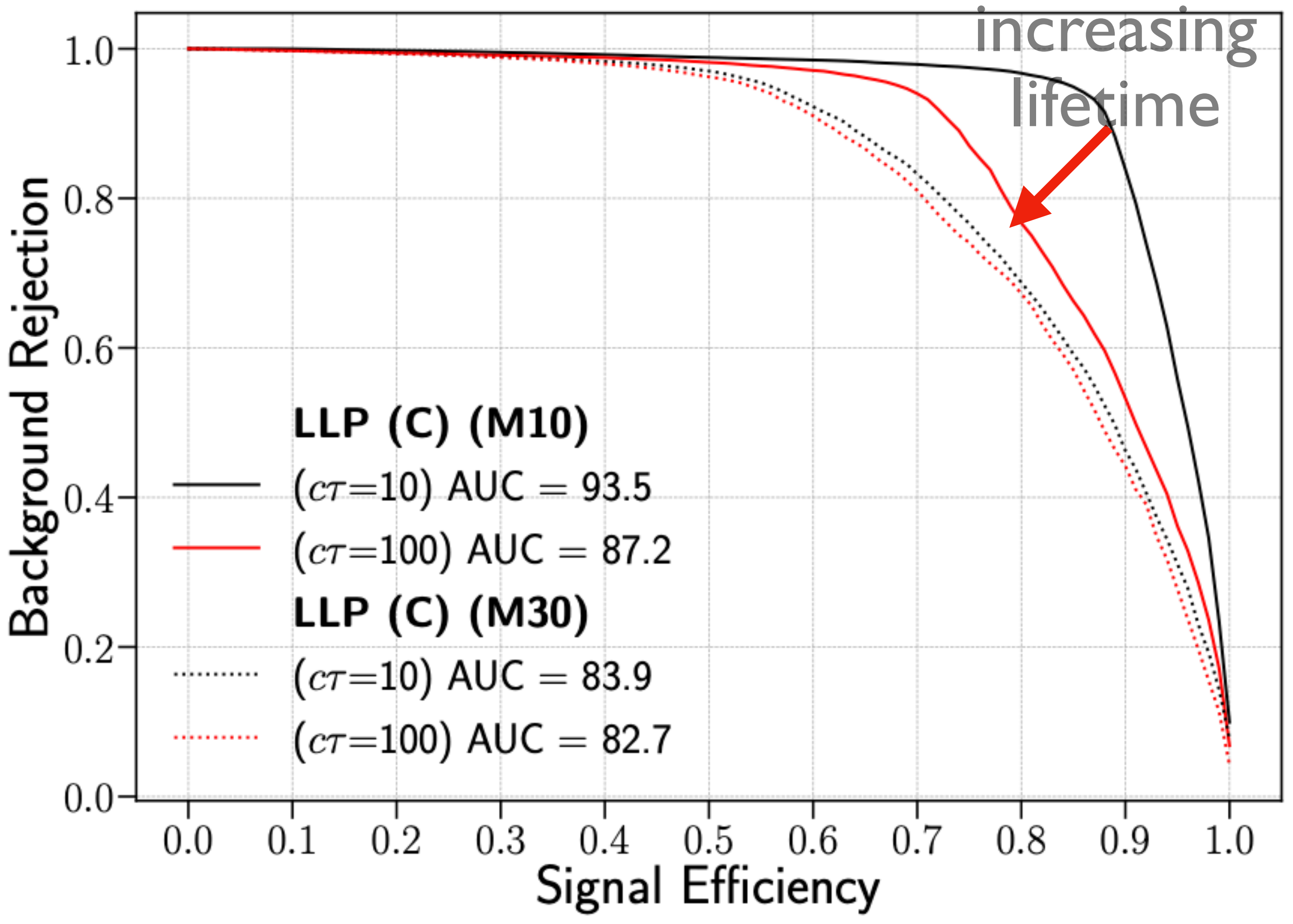
Tracker and MTD based search using classifiers

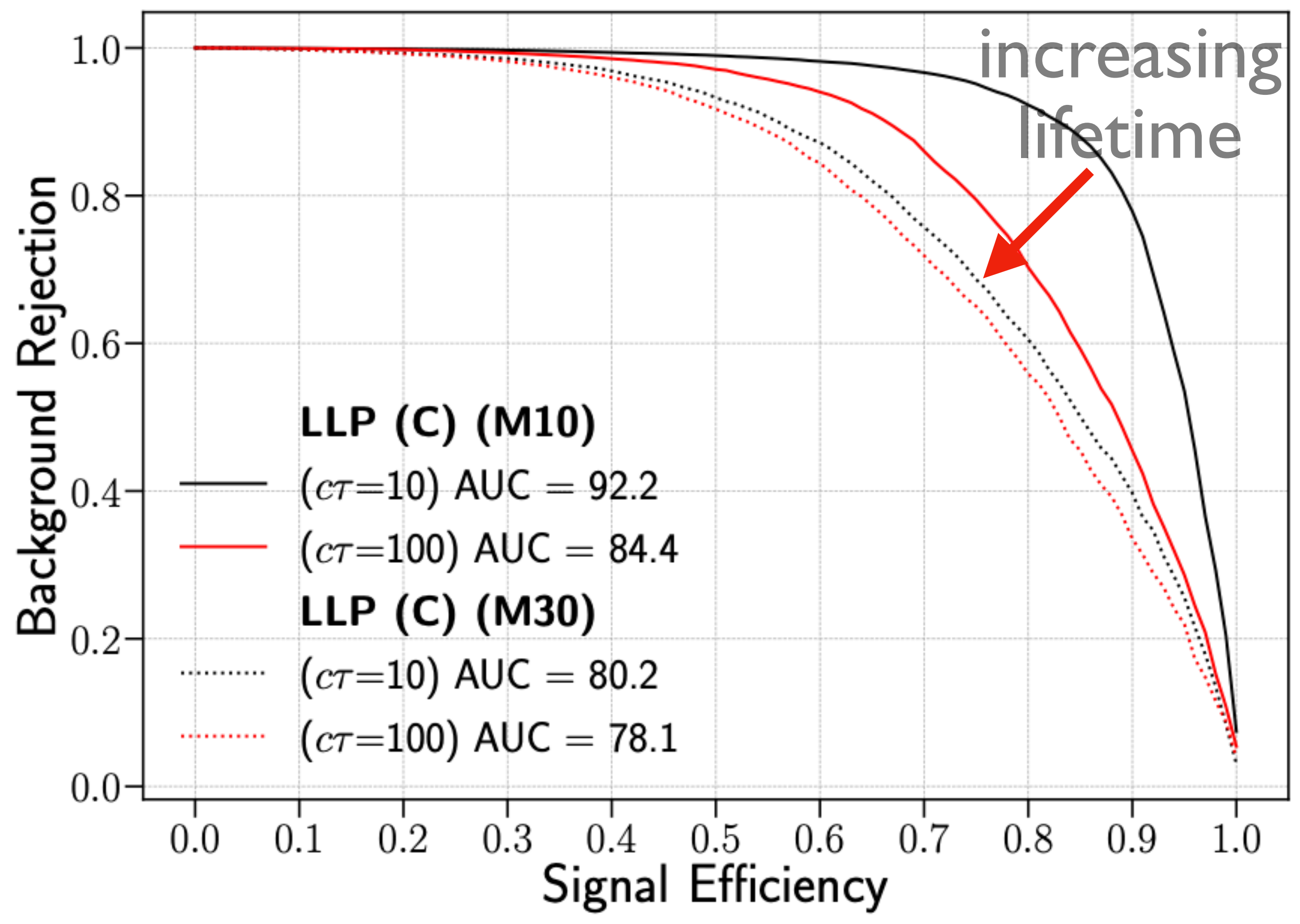
Tracking:

N_{trk} | $\sum p_T$ | $z_{\text{j\_vtx}}$ | $\Delta z_{\text{j\_vtx}}$ | $p_{T(\text{vtx})}^{\text{miss}}$ | $n_{z_{\text{trk\_max}}}$ | $\Delta z_{\text{trk\_max}}$ |
$\sum p_T^{z_{\text{trk\_max}}}$ | $\sum p_T^{z_a \neq z_{\text{trk\_max}}}$ | $\dfrac{\sum p_T^{z_{\text{trk\_max}}}}{\sum p_T}$ | $S(\dfrac{|z_i|}{\sum |z_i|})$ |
$S(z_i + 301)$ | $S(\dfrac{z_i + 301}{\sum (z_i + 301)})$ | $S(p_{T,i})$ | $S(\dfrac{p_{T,i}}{\sum p_{T,i}})$ |
Same vars with trks within $\Delta R = 0.2$ | $\dfrac{N_{\text{trk}}}{N_{\text{trk}}^{(0.2)}}$ | $\dfrac{\sum p_T}{\sum p_T^{(0.2)}}$



Timing:

- p_T
- η
- $N_{\text{MTD}}^{(0.2)}$
- $T_{\text{Med}}^{(0.2)}$
- $\Delta T_{\text{Med,PV}}^{(0.2)}$
- $N_{\text{MTD}}^{(0.2),\text{NT}}$
- $\Delta T_{\text{Med,PV}}^{(0.2),\text{NT}}$



- **Reasonable performance can be achieved, degrades with the lifetime of the mediator**
- **Similar performance of tracking and timing variables.**
- **More improvement possible using the tracking of displaced tracks at L1 (CMS-TDR-021)**
- **For higher decay length, ECAL timing provides good sensitivity (most sensitive decay length is cτ=50 cm for m_Φ = 10 GeV)**

BB, Swagata Mukherjee, Rhitaja Sengupta, Prabhat Solanki *JHEP* 08 (2020) 141

MIP timing detector (MTD): Timing of charged particles with $p_T > 0.7$ GeV up to $|\eta| = 1.5$; $p > 0.7$ GeV for $1.5 < |\eta| < 3.0$ with 30 ps resolution

Tracker vs CMS Muon spectrometer

$$\frac{\epsilon_{MS}}{\epsilon_{Tracker}}$$

$c\tau_\phi$ \ m_ϕ	0.5 GeV	5 GeV	50 GeV
0.01 m	0.09	0.00	0.00
0.1 m	1.10	0.09	0.00
1.0 m	1.68	1.07	0.07
10.0 m	2.04	1.67	0.85
100.0 m	-	1.59	1.53
1000.0 m	-	-	1.52

The ratio increases with the decay length

The ratio of efficiencies for the LLP (the mediator particle) which decays inside the muon spectrometer and the tracker of the CMS detector

MS volume : d_T > 4m or $|d_z|$ > 7m, and, d_T < 7m and $|d_z|$ < 10m

tracker volume : (d_T < 1.29m and $|d_z|$ < 3m)

<u>Why Muon spectrometer ?</u>

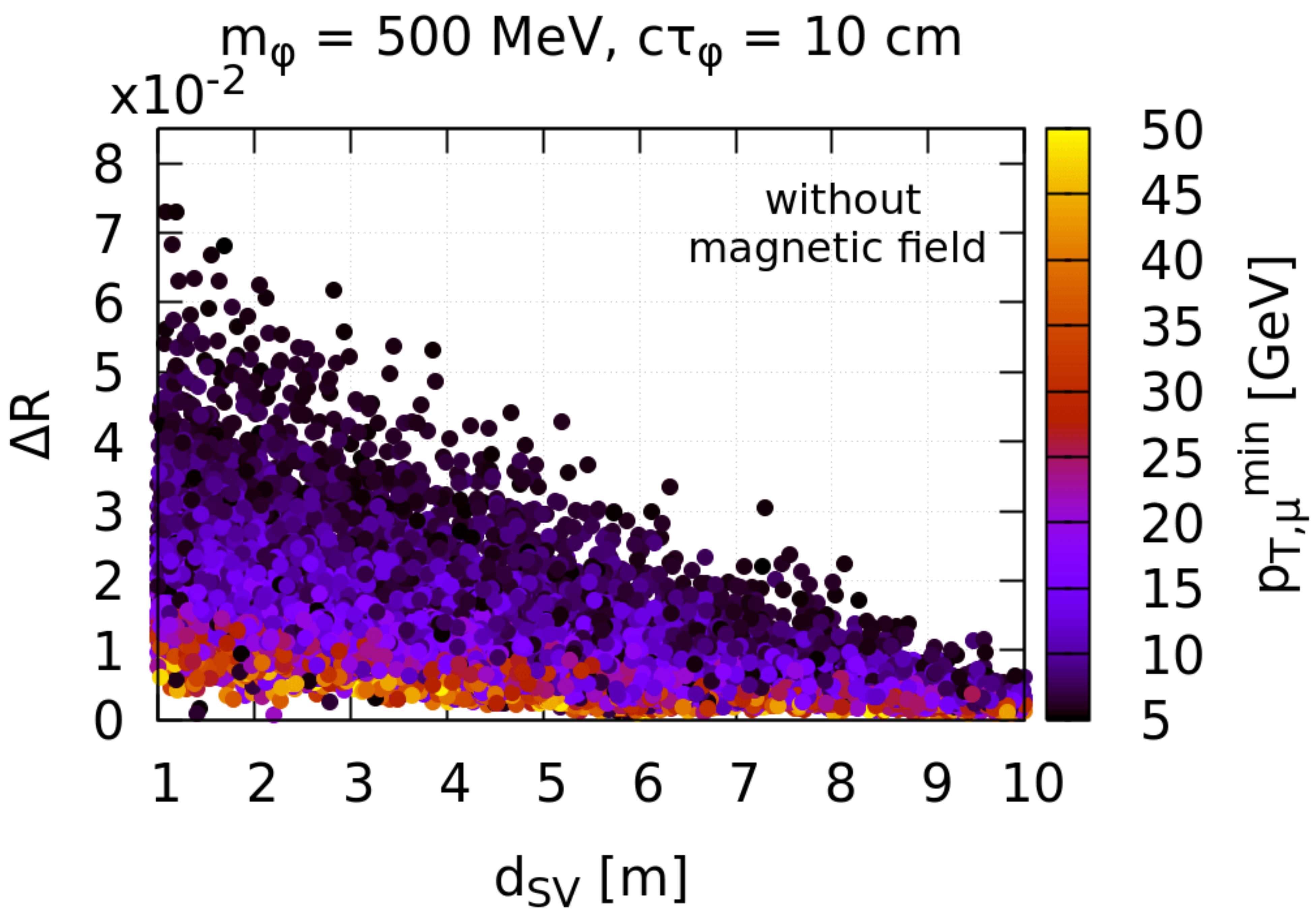
- **Muon spectrometer is least affected by the increased PU rate (farthest from the IP)**
- **Large decay volume, suitable for LLPs**
- **MS has the capability to detect various final states from the mediator decay other than muons**
- **There exists a range of decay lengths where this ratio is equal to or greater than one**

LLP searches using MS by CMS/ATLAS collaborations: 1811.07370, 1911.12575, CMS PAS EXO-20-015, 2107.04833

Fast detector level studies using Delphes

Two important effects

- The decay products of light LLPs can be boosted -> small opening angle
- For highly displaced LLPs -> the decay products will have small physical distance in the η-ϕ plane



ΔR very small for light LLPs

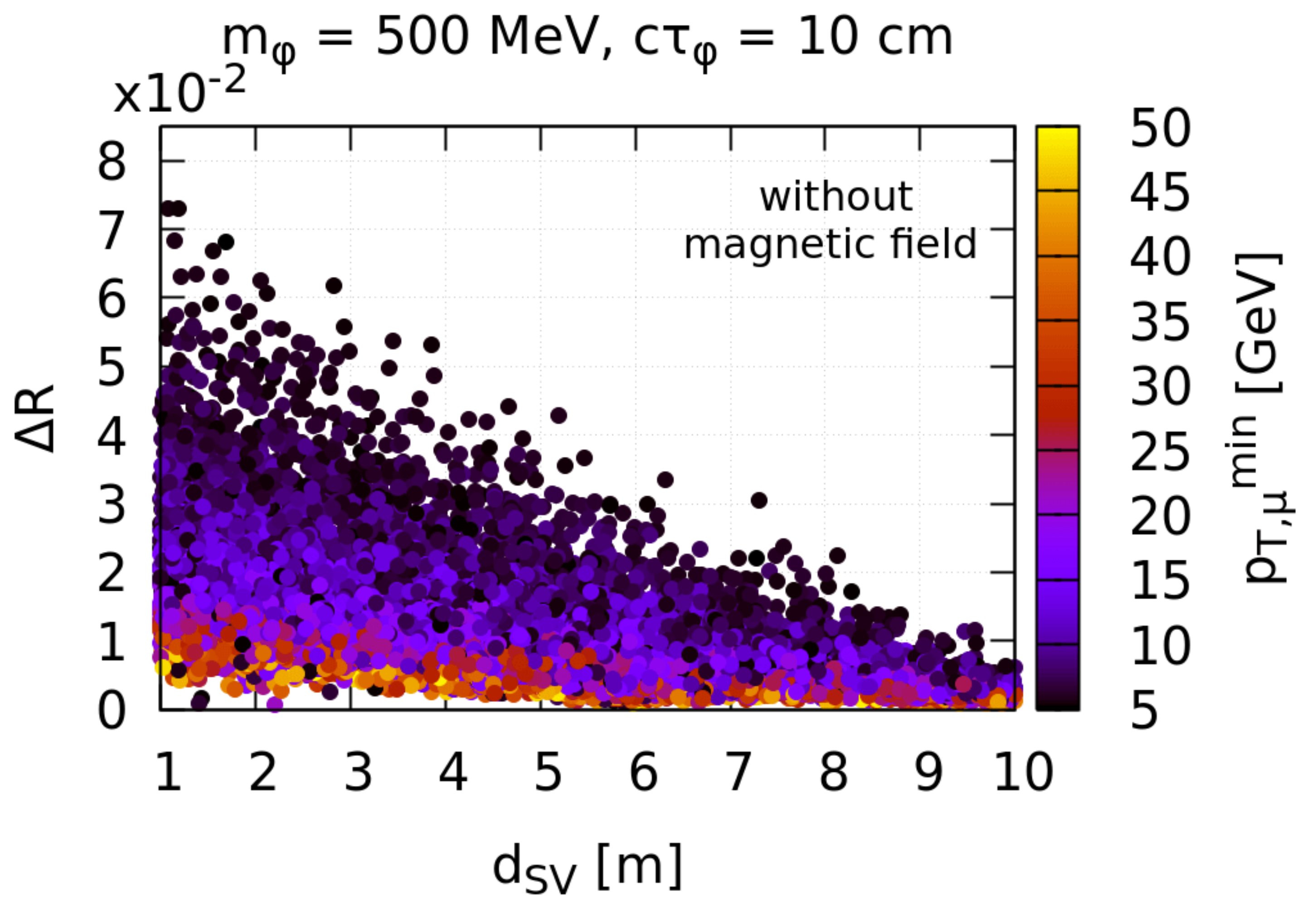
And it decreases

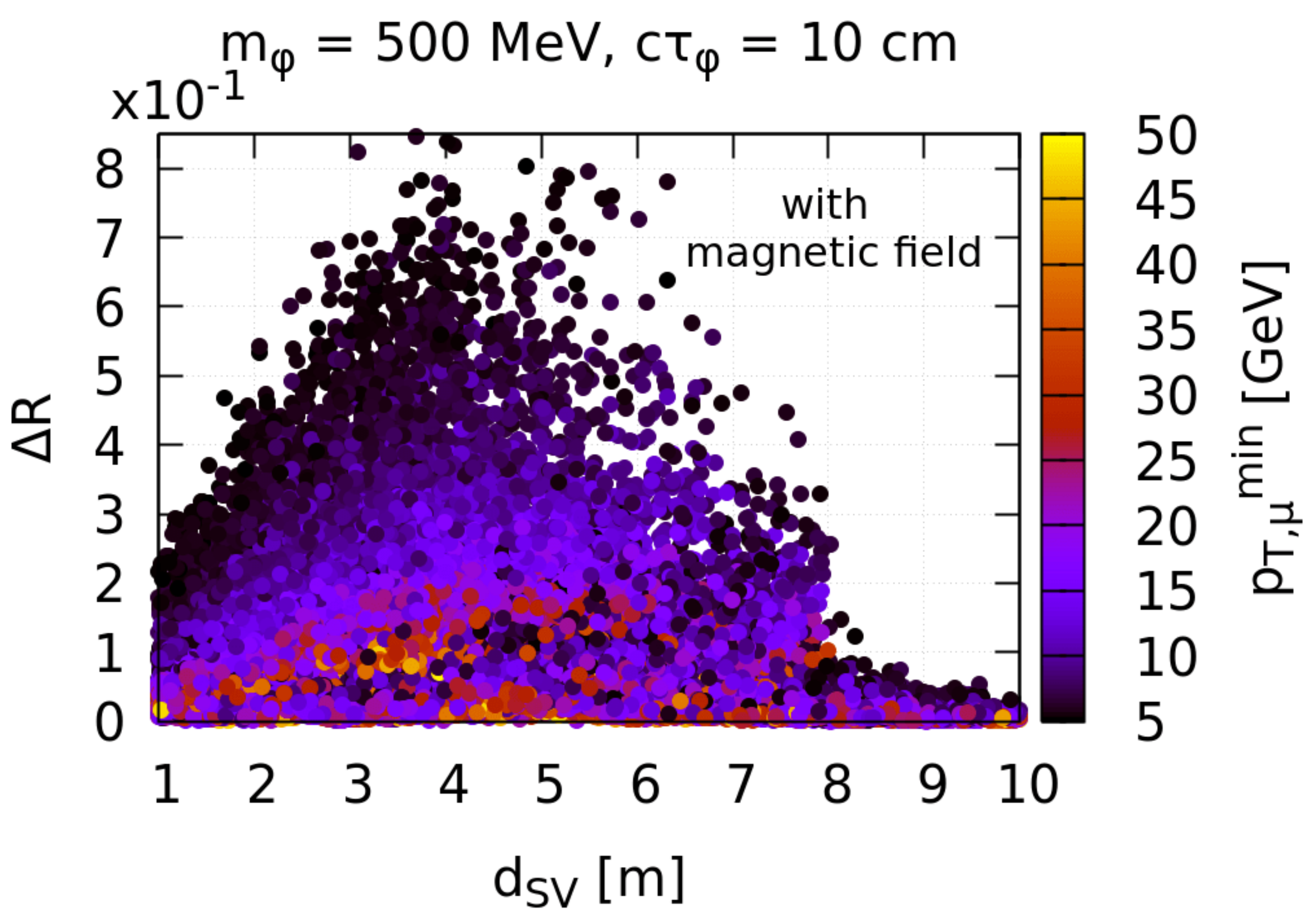
with displacements

It might create problems in the identification of the displaced vertex, isolation, etc

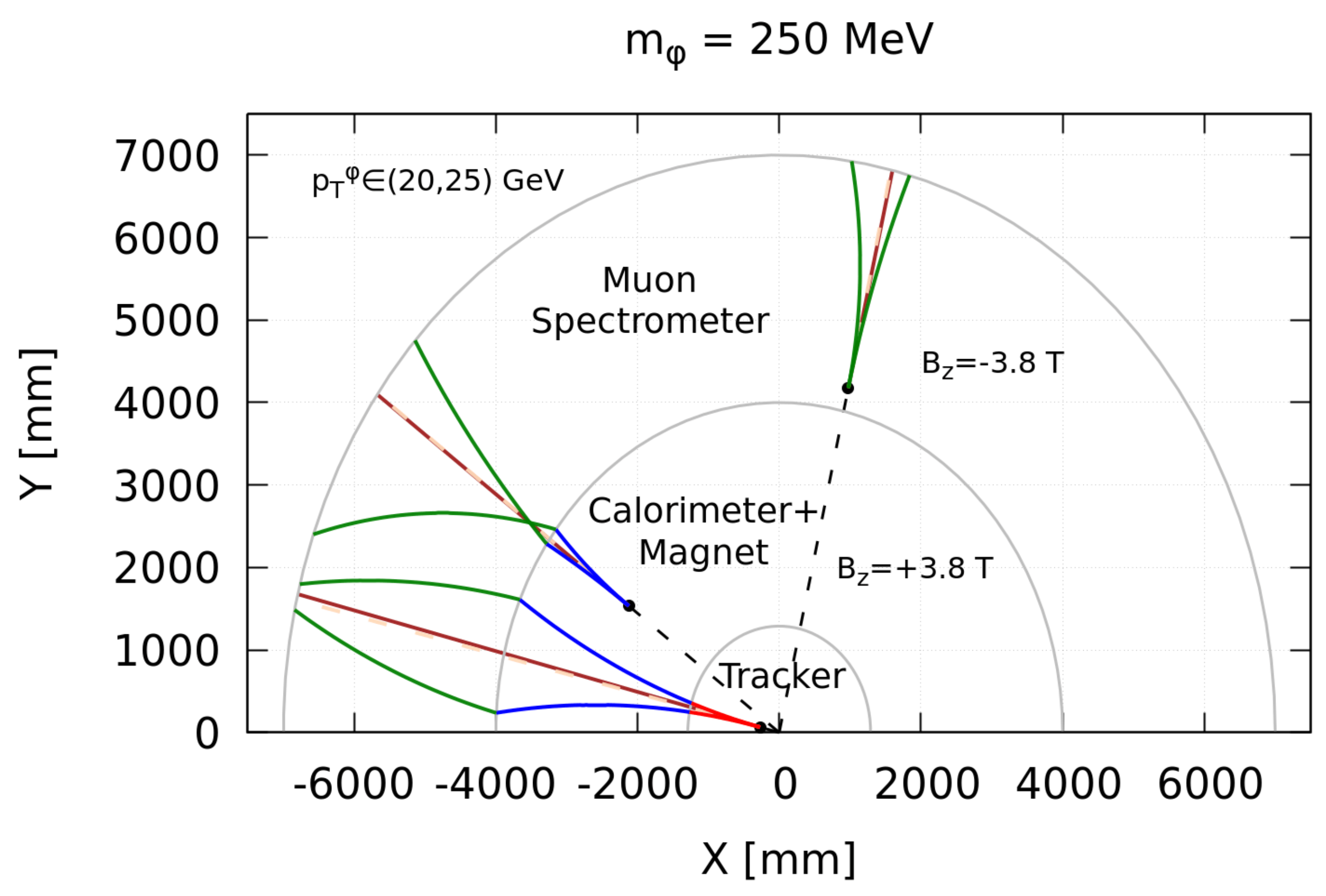
Fast detector level studies using Delphes

- **Presence of the magnetic field can modify the opening angle among charged decay products**
- **In the Delphes, a fast simulation package, magnetic field is implemented up to the tracker coverage**
- **We have modified the Delphes propagation part to implement the magnetic field up to the Muon spectrometer (assuming CMS geometry)**





Some examples



For heavy LLPs, the effect is not that strong

SIDE NOTE : Delphes calorimeter has η-ϕ segmentation, but no layered structure, and no segmentation in the physical z direction. Non-pointing nature of the jets can not be seen in the default settings. We have implemented this effect in Delphes and studied the signatures of LLPs decaying to jets

Study of energy deposition patterns in hadron calorimeter for prompt and displaced jets using convolutional neural network by BB, Swagata Mukherjee, Rhitaja Sengupta arXiv: 1904.04811, JHEP, 2019, 156 (2019)

Analysis strategies for HL-LHC

Trigger for Prompt objects

- We can trigger the event using the prompt associated objects like jets, leptons etc.
- Cuts on prompt objects motivated from CMS Level-1 trigger TDR to select events

Simple analysis

- We have not applied any efficiency for the HLT/offline analysis
- We have assumed SM and instrumental background is negligible
- On the other hand, we put limits assuming 50 signal events (This can take care of the above two points)

Activity in the Muon Spectrometer

Particles except muons will look different in the CMS MS due to their interactions with the iron yokes, i.e., they shower and give rise to a cluster of hits.

Experimental Questions : how they exactly look in the MS ? whether these hits can be reconstructed ? whether the position of the dSV can be identified with such clusters of hits .

We cannot address properly in a phenomenological study such as the one in this paper. —> However CMS and ATLAS collaborations have developed algorithms to identify such clusters.

We just devise our cuts to ensure that a cluster with a high multiplicity of hits can be detected in the MS for various final states other than muons.

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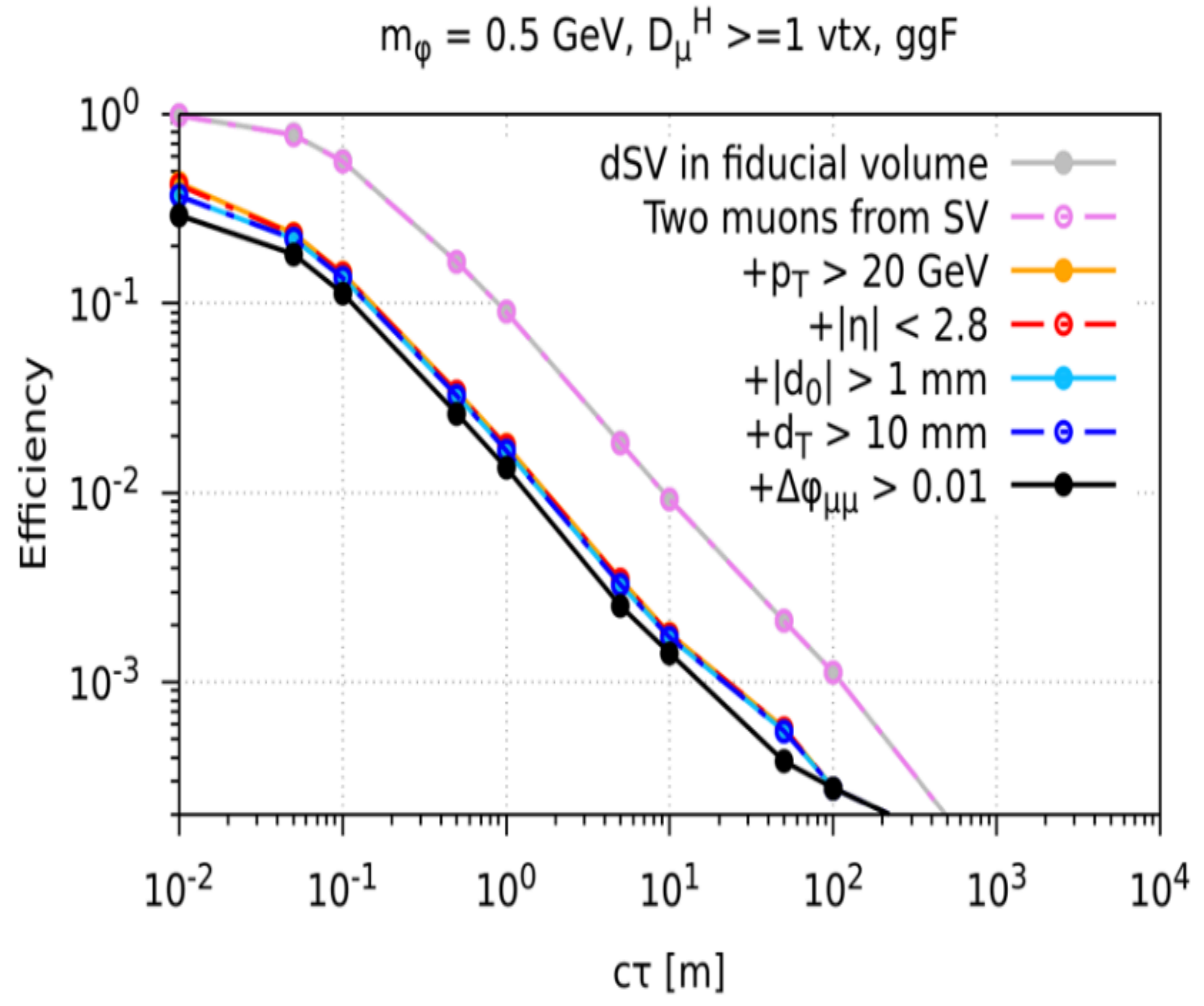
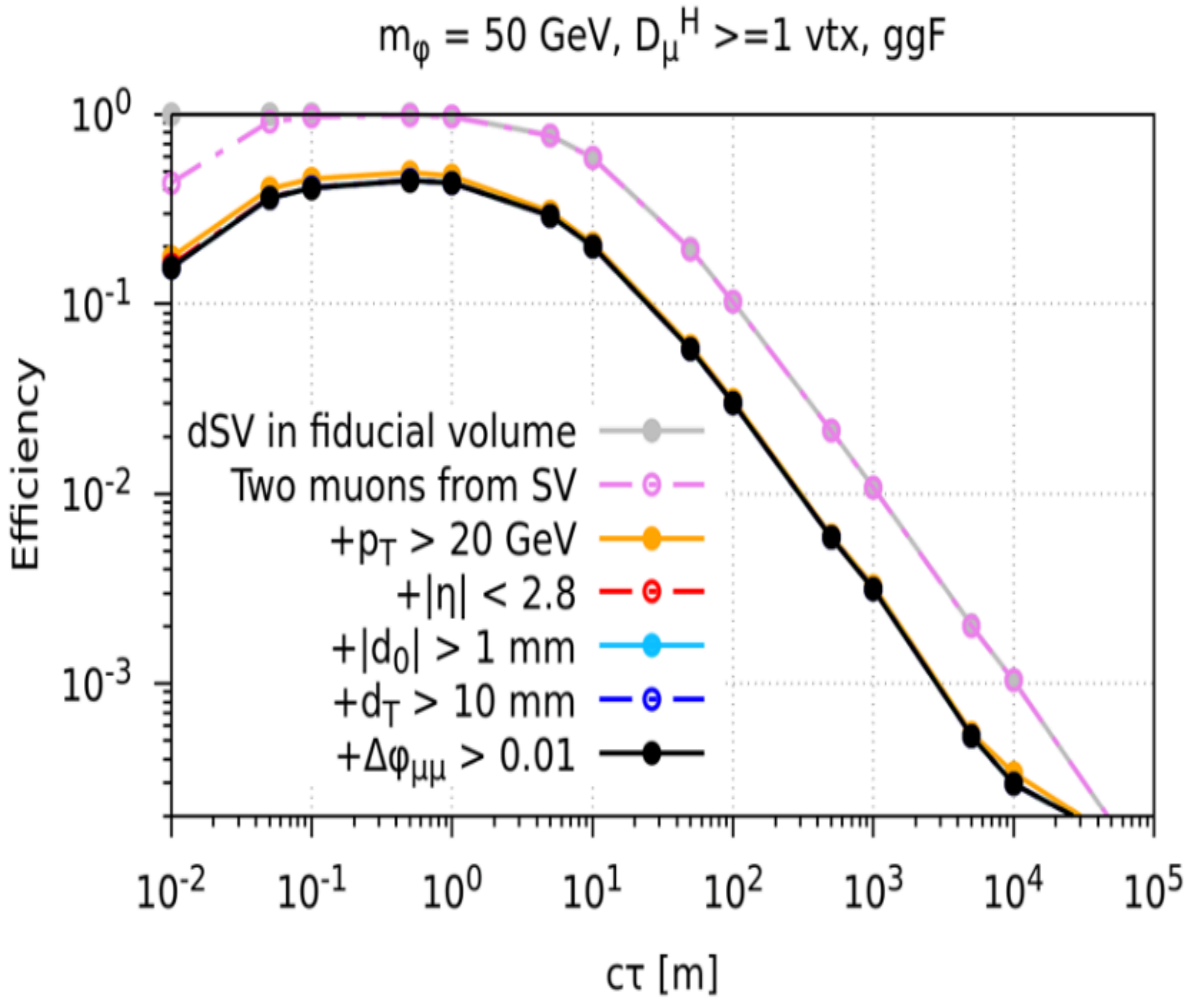
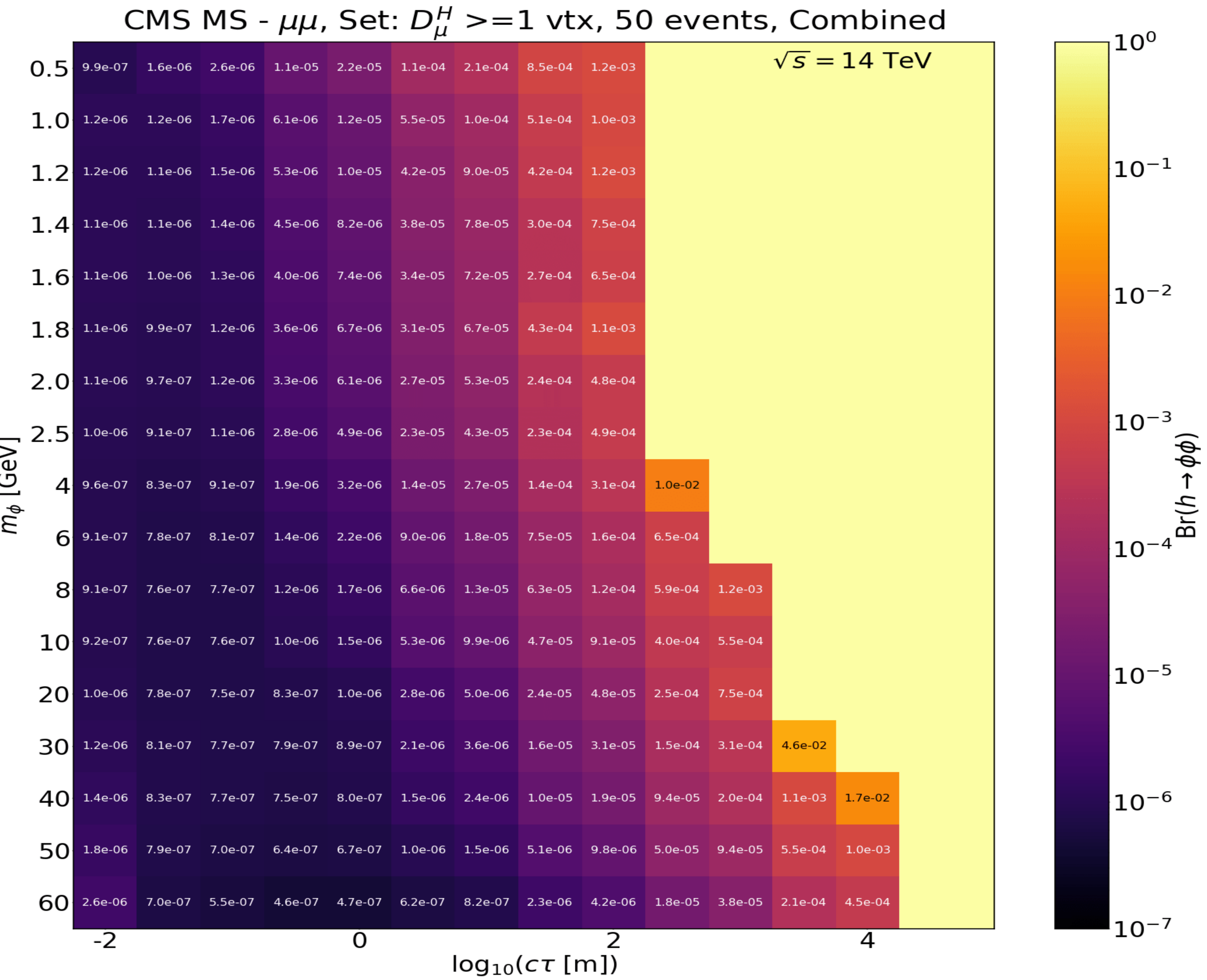
Φ -> μ μ channel

Cuts

	Hard cut $D^H_{\mu\mu}$	**Soft cut** $D^S_{\mu\mu}$
Muons	$p^\mu_T > 20\,\mathrm{GeV}$	$p^\mu_T > 10\,\mathrm{GeV}$
	$n_\mu \geq 2$	$n_\mu \geq 2$
	$\lvert\eta^\mu\rvert < 2.8$	$\lvert\eta^\mu\rvert < 2.8$
	$\lvert d^\mu_0\rvert > 1\,\mathrm{mm}$	$\lvert d^\mu_0\rvert > 1\,\mathrm{mm}$
Muon pair from the same dSV	$d_T > 1\,\mathrm{cm}$	$d_T > 1\,\mathrm{cm}$
	$d_T < 6\,\mathrm{m}$ & $\lvert d_z\rvert < 9\,\mathrm{m}$	$d_T < 6\,\mathrm{m}$ & $\lvert d_z\rvert < 9\,\mathrm{m}$
	$\Delta\phi_{\mu\mu} > 0.015$	$\Delta\phi_{\mu\mu} > 0.015$
Event	$n_{vtx} \geq 1$ or $n_{vtx} = 2$	$n_{vtx} \geq 1$ or $n_{vtx} = 2$







- **P_T cut on muons mostly affects the selection efficiency.**
- **For small mediator mass, Δϕ cut between muons mildly reduce the efficiency**
- **Data collection using soft cut may be achievable using di-muon scouting.**

Results

- **The limit grid is computed by combining ggF, VBF and Vh production process.**
- **For limit calculation, we assume Br(Φ -> μ μ) = 1 (translation to other model possible)**
- **Sensitivity shifts from 1cm for m_Φ = 0.5 GeV to 0.5 m for m_Φ = 50 GeV.**
- **The most sensitive limit on Br(h -> ΦΦ) = 9.9 10^{-7} for m_Φ = 0.5 GeV and cτ=1cm.**
- **For m_Φ = 60 GeV, very high cτ values ~ 10^4 m with Br(h -> ΦΦ) =5 10^{-4} accessible.**
- **If we try to identify both the vertices, no sensitivity above cτ=1m, for m_Φ = 0.5 GeV**

Φ -> b b channel

Trigger

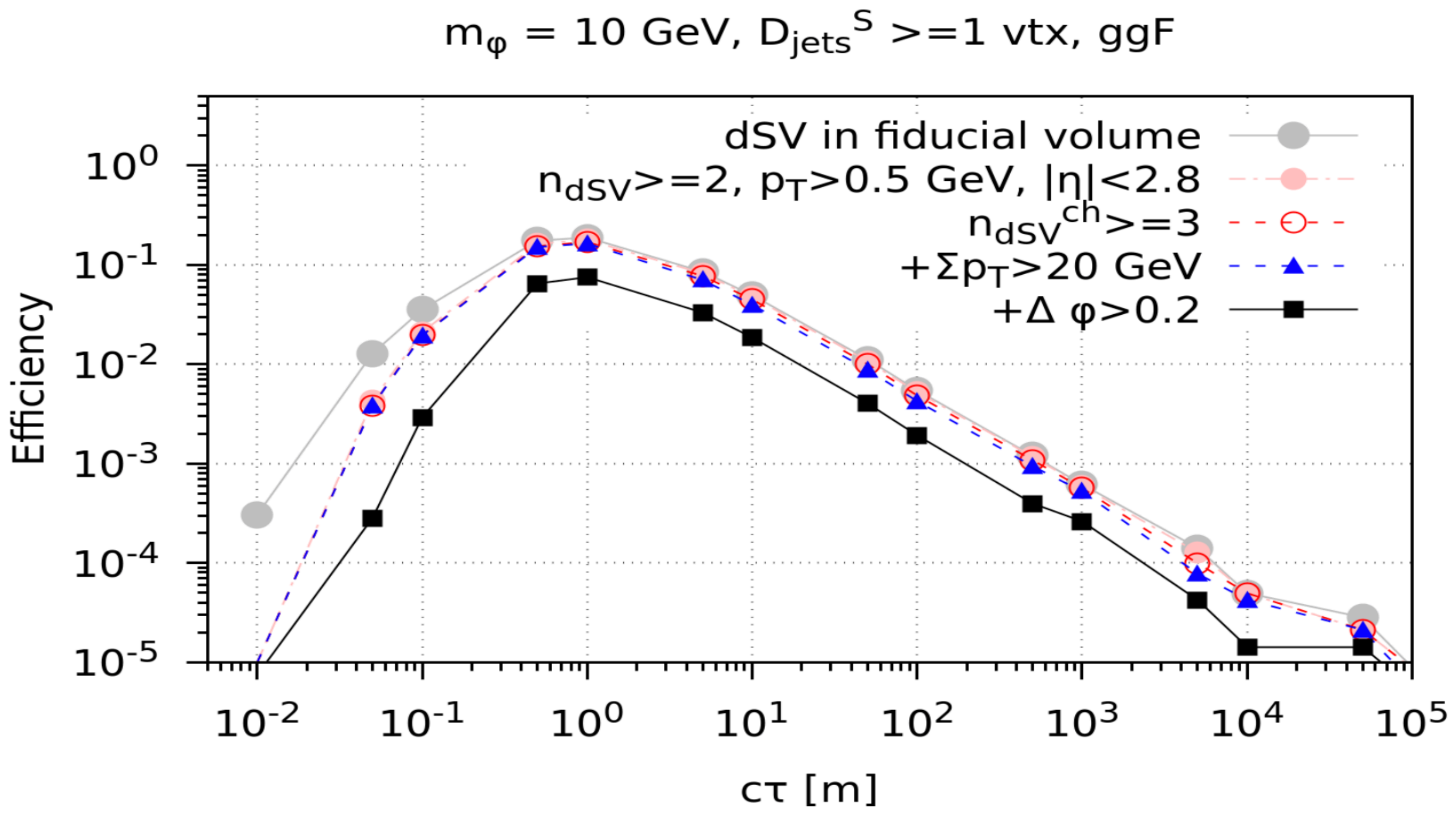
- We can trigger the event using the prompt associated objects like jets, leptons etc.
- We have applied a set of cuts on prompt objects motivated from CMS Level-1 trigger TDR to select events .
- It is possible to reduce the prompt threshold if we can consider activity in the MS.

Trigger	In P^H_{Mode}	In P^S_{Mode}	Mode
Single jet	$p_T^j > 180\,\mathrm{GeV}$, $\lvert\eta_j\rvert < 2.4$.	$p_T^j > 90\,\mathrm{GeV}$, $\lvert\eta_j\rvert < 2.4$.	
Di-jet	$p_T^j > 112\,\mathrm{GeV}$, $\lvert\eta_j\rvert < 2.4$, $\Delta\eta < 1.6$.	$p_T^j > 90\,\mathrm{GeV}$, $\lvert\eta_j\rvert < 2.4$, $\Delta\eta < 1.6$.	
VBF jet	$p_T > 70\,\mathrm{GeV}$ for Leading jet, $p_T > 40\,\mathrm{GeV}$ for Sub-leading jet, $\lvert\eta_j\rvert < 5$, $\eta_{j_1} \times \eta_{j_2} < 0$, $\Delta\eta > 4.0$, $\Delta\phi < 2.0$, $m_{jj} > 1000\,\mathrm{GeV}$.	$p_T > 60\,\mathrm{GeV}$ for Leading jet, $p_T > 30\,\mathrm{GeV}$ for Sub-leading jet, $\lvert\eta_j\rvert < 5$, $\eta_{j_1} \times \eta_{j_2} < 0$, $\Delta\eta > 4.0$, $\Delta\phi < 2.0$, $m_{jj} > 500\,\mathrm{GeV}$.	ggF, VBF, Vh-jet.
Single electron	$p_T^e > 36\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$.	$p_T^e > 18\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$.	
Double electron	$p_T^{e_1} > 25\,\mathrm{GeV}$, $p_T^{e_2} > 12\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$.	$p_T^{e_1} > 12\,\mathrm{GeV}$, $p_T^{e_2} > 12\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$.	Vh-lep.
Single muon	$p_T^{\mu} > 22\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$.	$p_T^{\mu} > 11\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$.	
Double muon	$p_T^{\mu_1} > 15\,\mathrm{GeV}$, $p_T^{\mu_2} > 7\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$.	$p_T^{\mu_1} > 7\,\mathrm{GeV}$, $p_T^{\mu_2} > 7\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.4$.	

P [H] : a hard set of cuts P [S] : a softer set of cuts

	D^H_{jj}	D^S_{jj}
Electrons, photons, hadrons	$p_T > 0.5\,\mathrm{GeV}$	$p_T > 0.5\,\mathrm{GeV}$
	$\lvert\eta\rvert < 2.8$	$\lvert\eta\rvert < 2.8$
MS cluster from same dSV ($< 1\,\mathrm{cm}$)	$d_T > 4\,\mathrm{m}$ or $\lvert d_z\rvert > 7\,\mathrm{m}$ $d_T < 6\,\mathrm{m}$ and $\lvert d_z\rvert < 9\,\mathrm{m}$	$d_T > 4\,\mathrm{m}$ or $\lvert d_z\rvert > 7\,\mathrm{m}$ $d_T < 6\,\mathrm{m}$ and $\lvert d_z\rvert < 9\,\mathrm{m}$
	$n^{\mathrm{ch}}_{\mathrm{dSV}} \geq 5$	$n^{\mathrm{ch}}_{\mathrm{dSV}} \geq 3$
	$\sum p_{T,dSV} > 50\,\mathrm{GeV}$	$\sum p_{T,dSV} > 20\,\mathrm{GeV}$
	$\Delta\phi_{\max} > 0.3$	$\Delta\phi_{\max} > 0.2$
Event	$n_{\mathrm{cluster}} \geq 1$, $n_{\mathrm{cluster}} = 2$	$n_{\mathrm{cluster}} \geq 1$, $n_{\mathrm{cluster}} = 2$

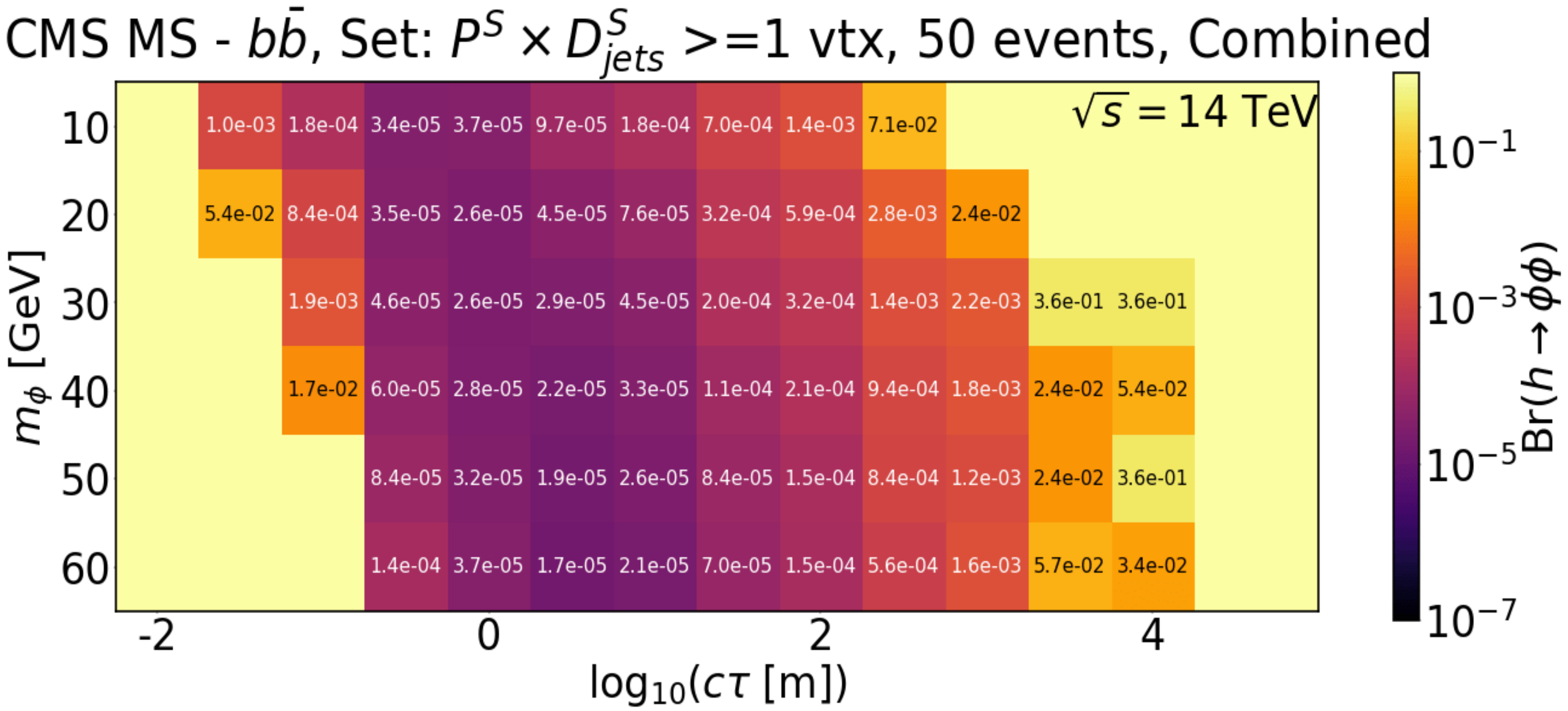
Activity in the Muon spectrometer

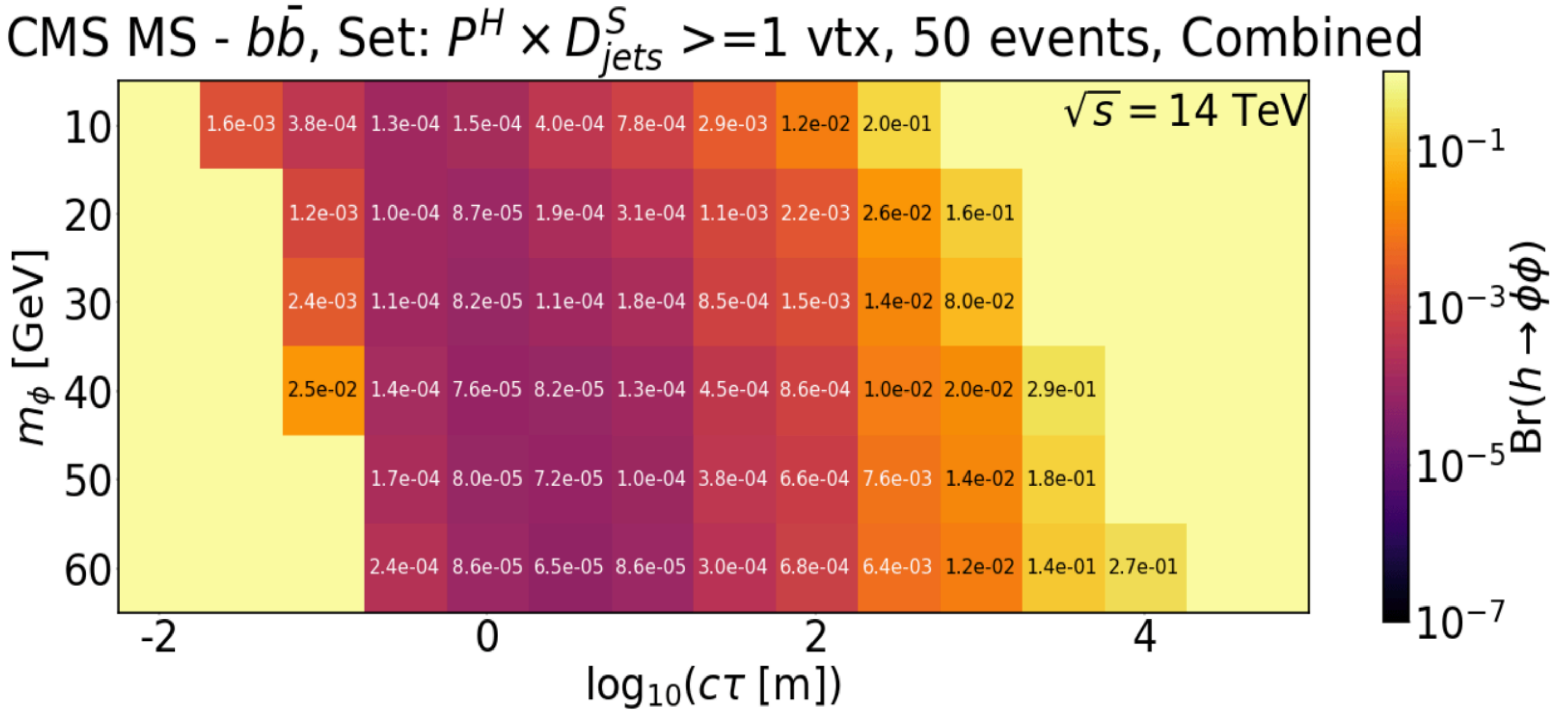


Observations

- Fraction of decays inside the fiducial volume ~ 10-15% at most
- Efficiency drops by about half if we apply Δϕ cut for m_ϕ = 10 GeV

Φ -> b b channel



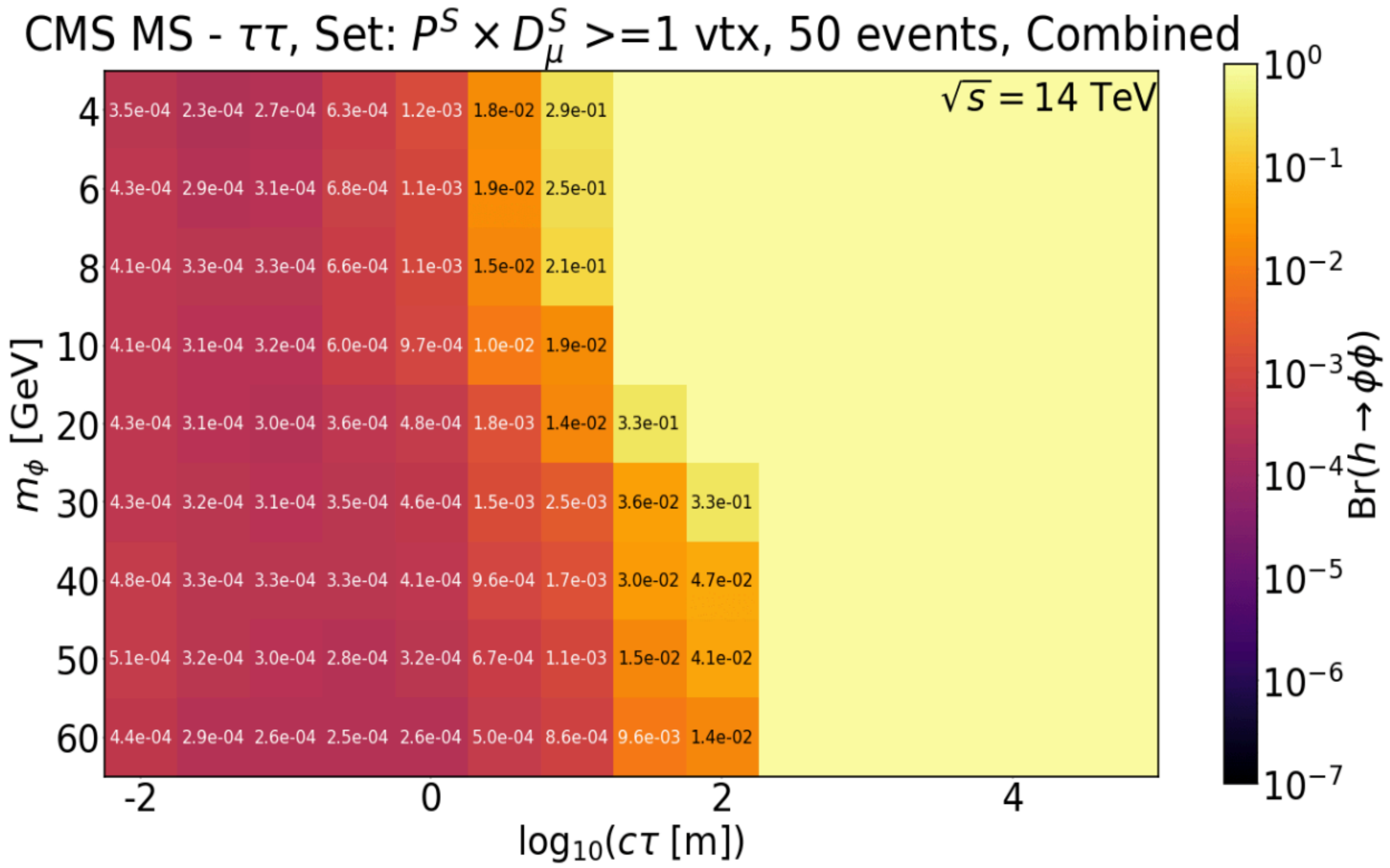


Results

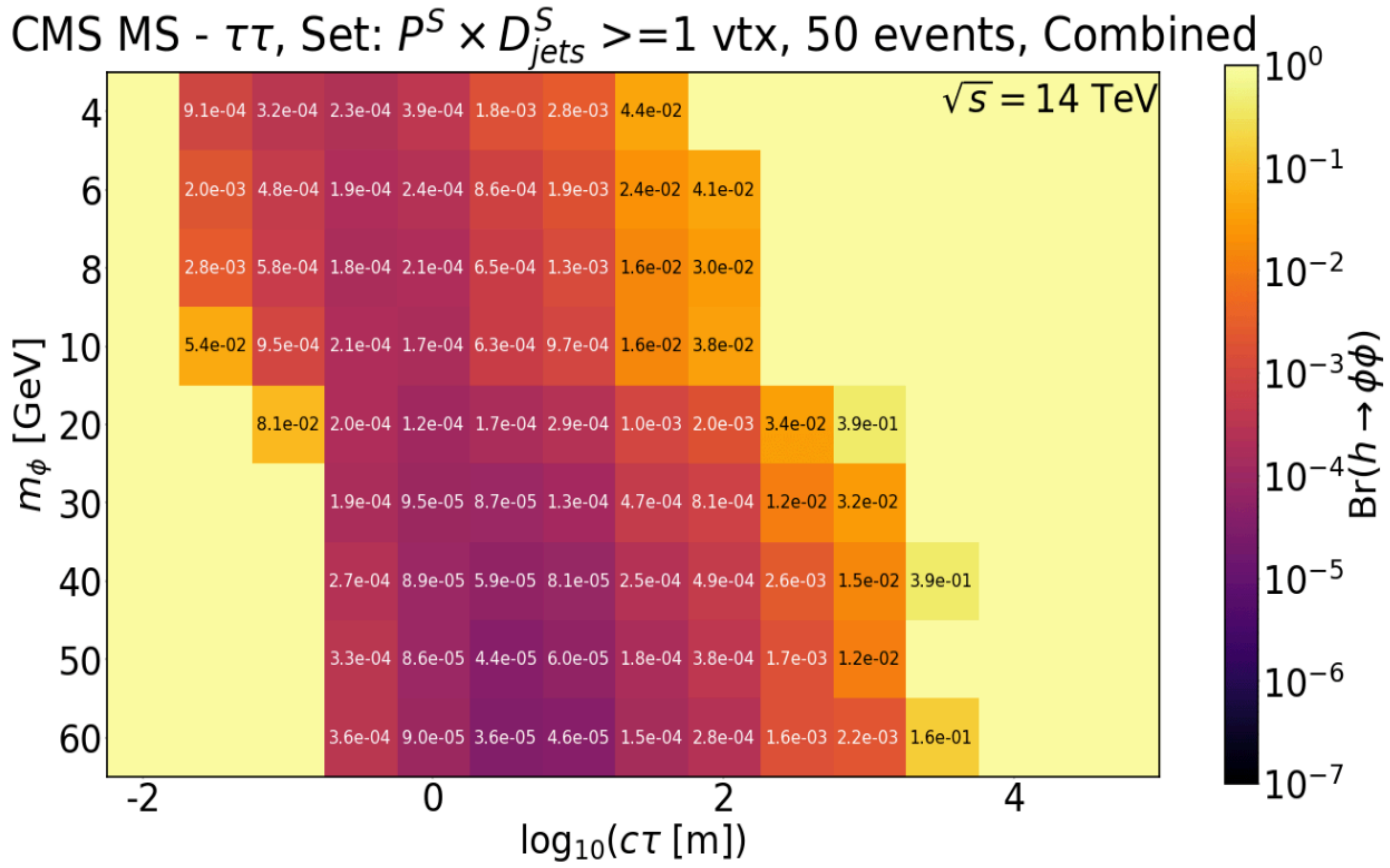
- **The limit grid is computed by combining ggF, VBF and Vh production process.**
- **For limit calculation, we assume Br(Φ -> b b) = 1 (translation to other model possible)**
- **Sensitivity shifts from 50 cm for m_Φ = 10 GeV to 5 m for m_Φ = 50 GeV.**
- **for m_Φ = 10 GeV : The most sensitive limit on Br(h -> ΦΦ) = 3.4 10^{-5} and cτ=50 cm.**
- **For m_Φ = 60 GeV: The most sensitive limit on Br(h -> ΦΦ) = 1.7 10^{-5} and cτ=5 m.**
- **Limit using P^H X D^S_{jet} is weaker than P^S X D^S_{jet} set ~ 5 in some cases**

Φ -> τ τ channel

MS analysis



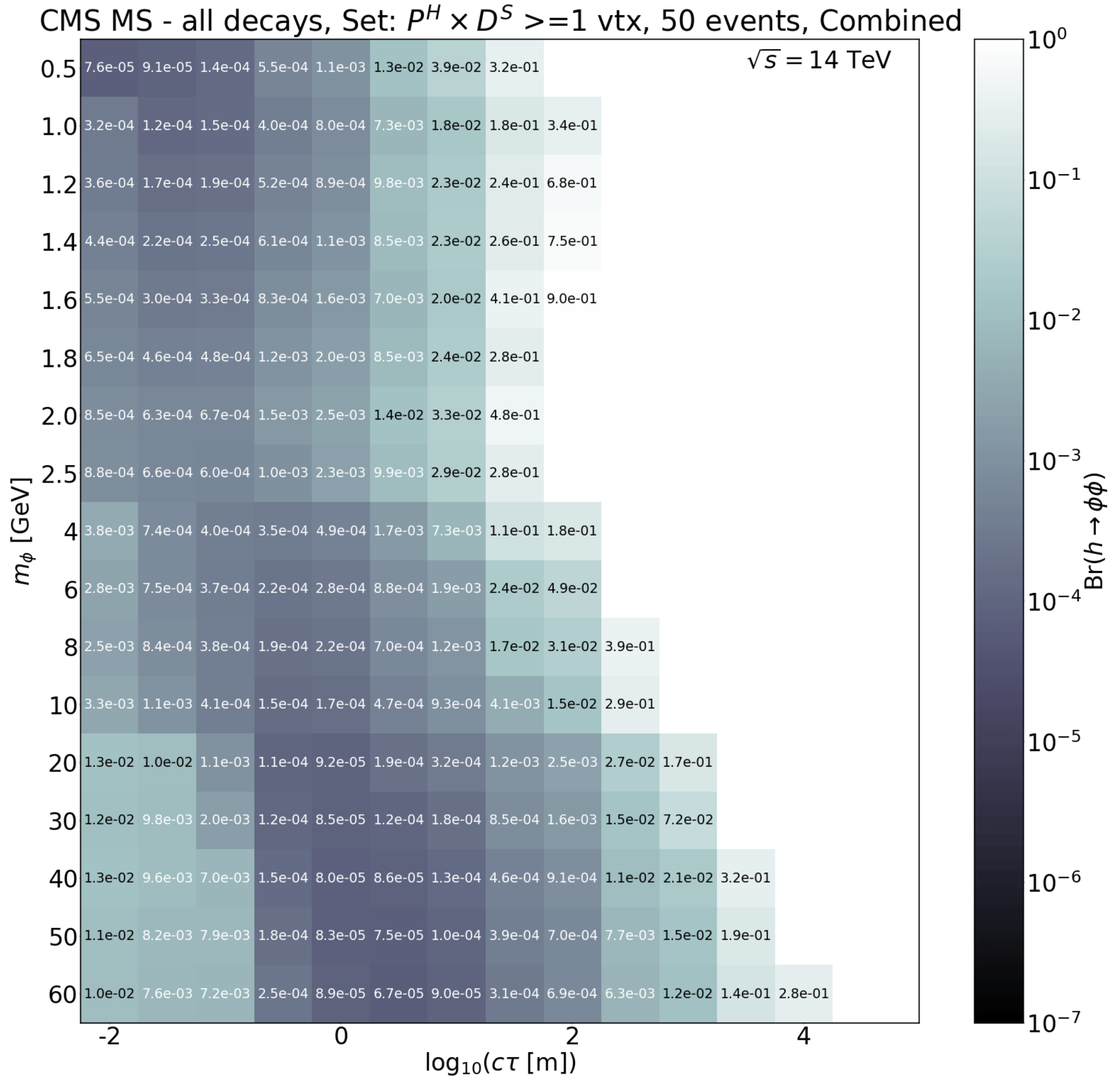
Di-muon analysis

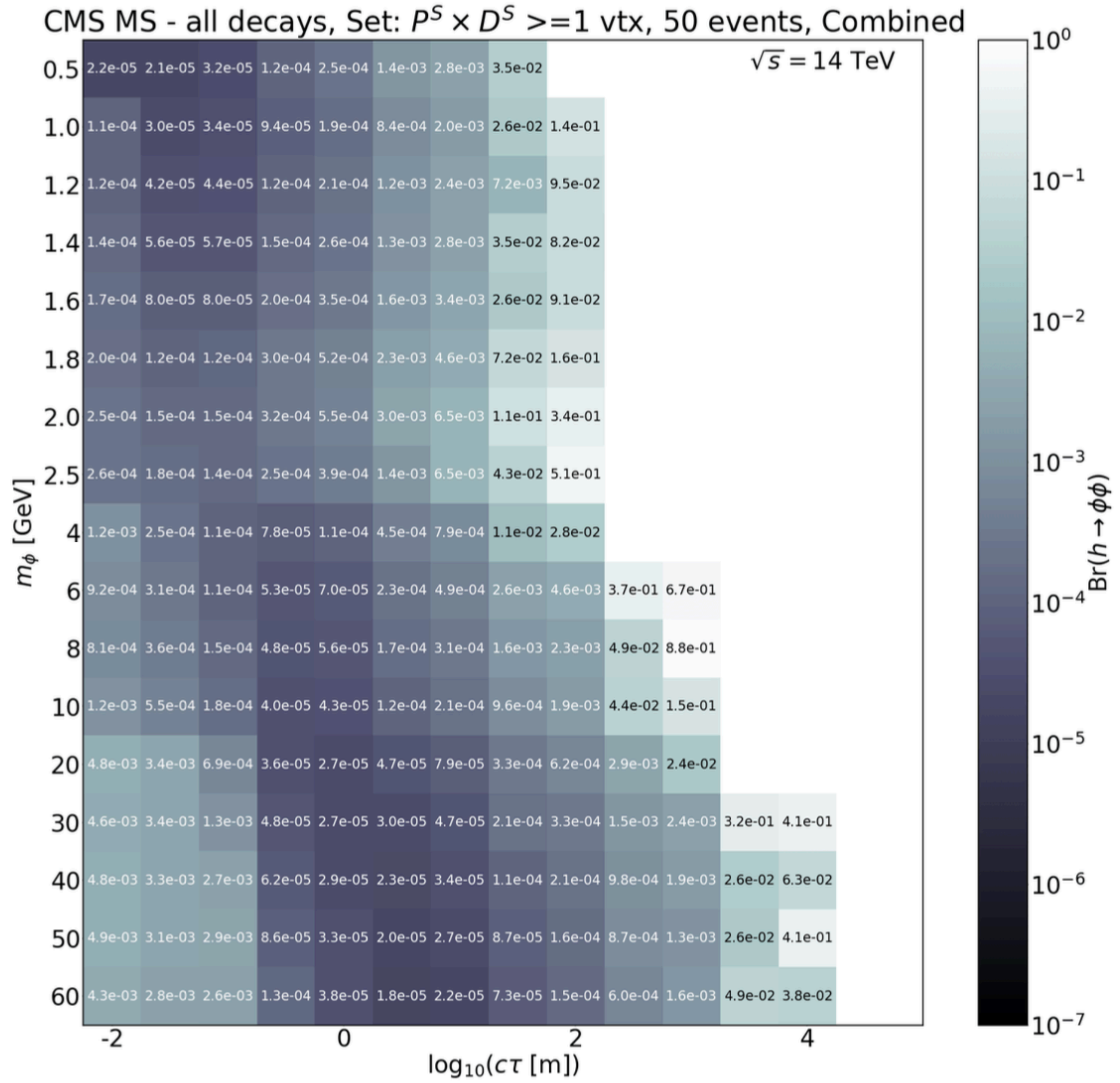


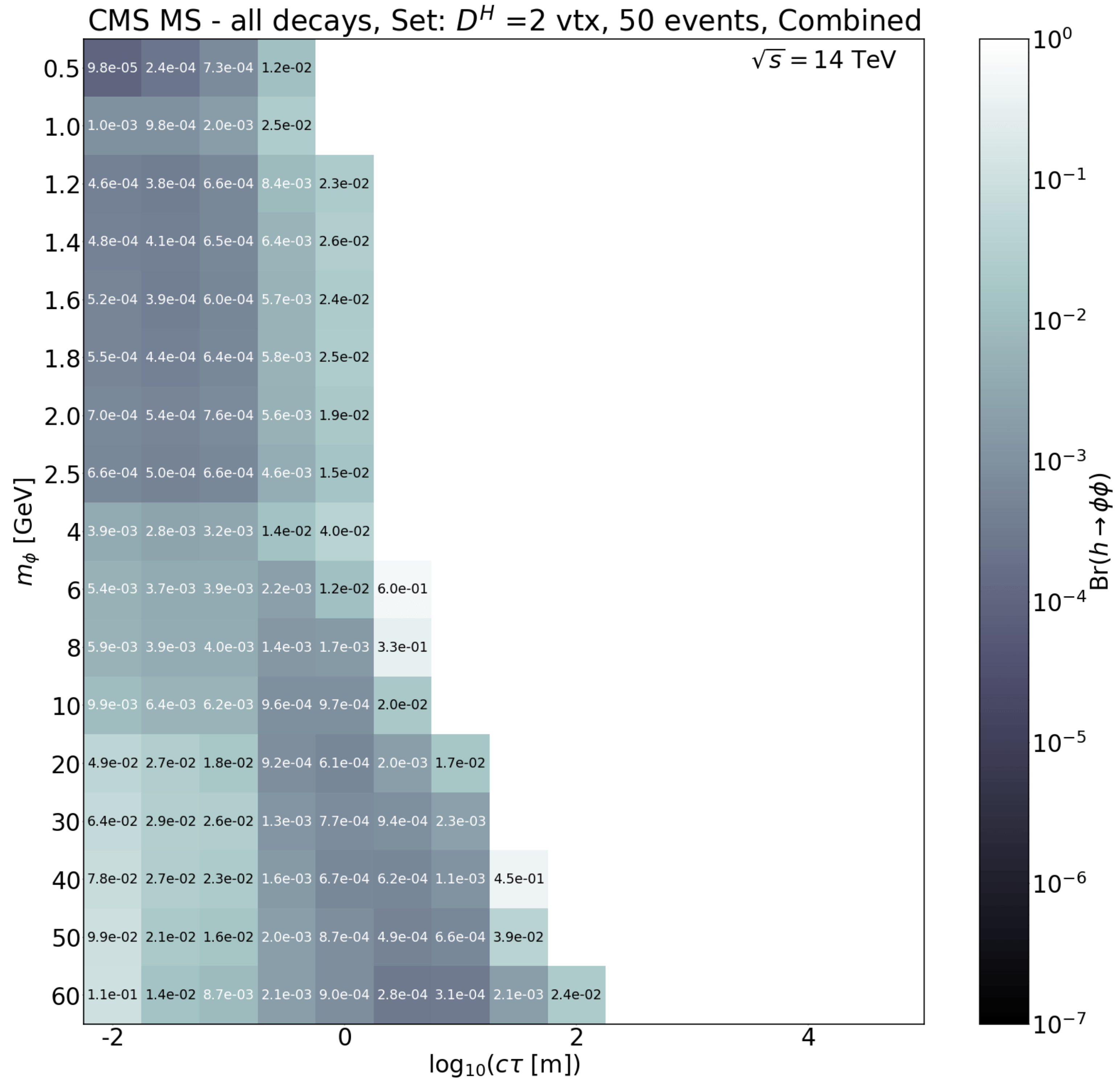
Results

- The τ lepton can decay hadronically, and leptonically
- Modified/relaxed Φ -> b b analysis is used as well as di-muon analysis
- Limits from displaced di-muon analysis and jet analysis in the MS is sensitive, although the branching to muon is small
- The most sensitive limit on Br(h -> ΦΦ) = 2.3 10^{-4} for m_Φ = 4 GeV and cτ=5 cm in di-muon channel.

Combination and Future Projections for HL-LHC with Integrated Luminosity =3000 ifb







Combined ggF, VBF, VH and several decay modes

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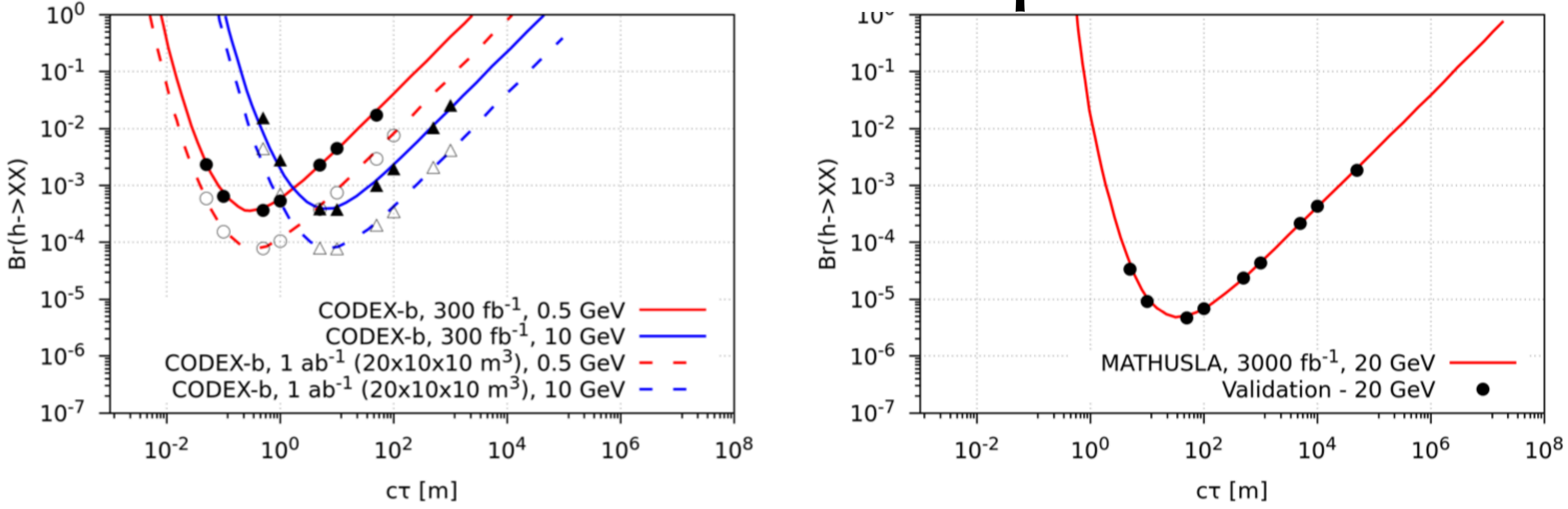
Results

- **We combine all these decay modes taking into account the branching ratios predicted in the minimal model (m_Φ = 0.5-60 GeV)**
- **We can probe Br(h -> ΦΦ) = 2 x 10^{-5} for m_Φ = 50 GeV for P^S X D^S_{jet} ≥ 1 vertex.**
- **combination of various production modes of Higgs boson as well as the decay modes of the mediator contribute non-trivially to the limits**

Dedicated LLP detectors : Mathusla and CODEX-b

- The dedicated detectors placed far away from the IP might be sensitive to a range of lifetimes which is complementary to the CMS MS.
- These proposed detectors will be placed a few tens of meters away from the IP of the pp collision.
- Enough shielding of rock or concrete as well as active veto to guarantee very little or almost no backgrounds.
- Therefore, observation of even a few events (~ 4) can be claimed as a discovery of displaced decays of particles.
- We have computed the limits assuming CODEX-b and Mathusla LLP detectors for our minimal model.

Our Validation plots



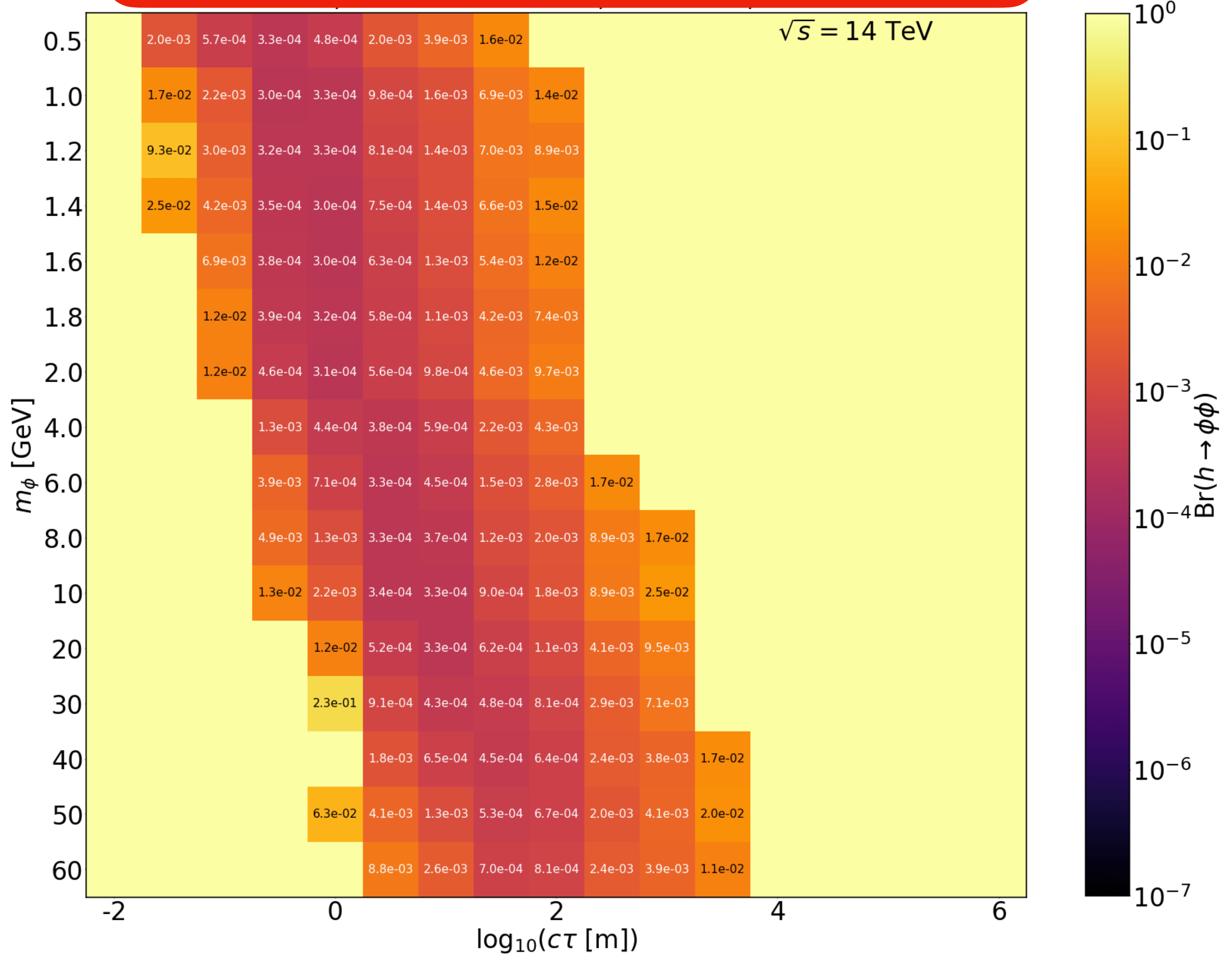
Compared with these two references

C. Alpigiani, "Exploring the lifetime and cosmic frontier with the MATHUSLA detector," JINST 15 no. 09, (2020) C09048, arXiv:2006.00788 [physics.ins-det].

V. V. Gligorov, S. Knapen, M. Papucci, and D. J. Robinson, "Searching for Long-lived Particles: A Compact Detector for Exotics at LHCb," Phys. Rev. D 97 no. 1, (2018) 015023, arXiv:1708.09395 [hep-ph].

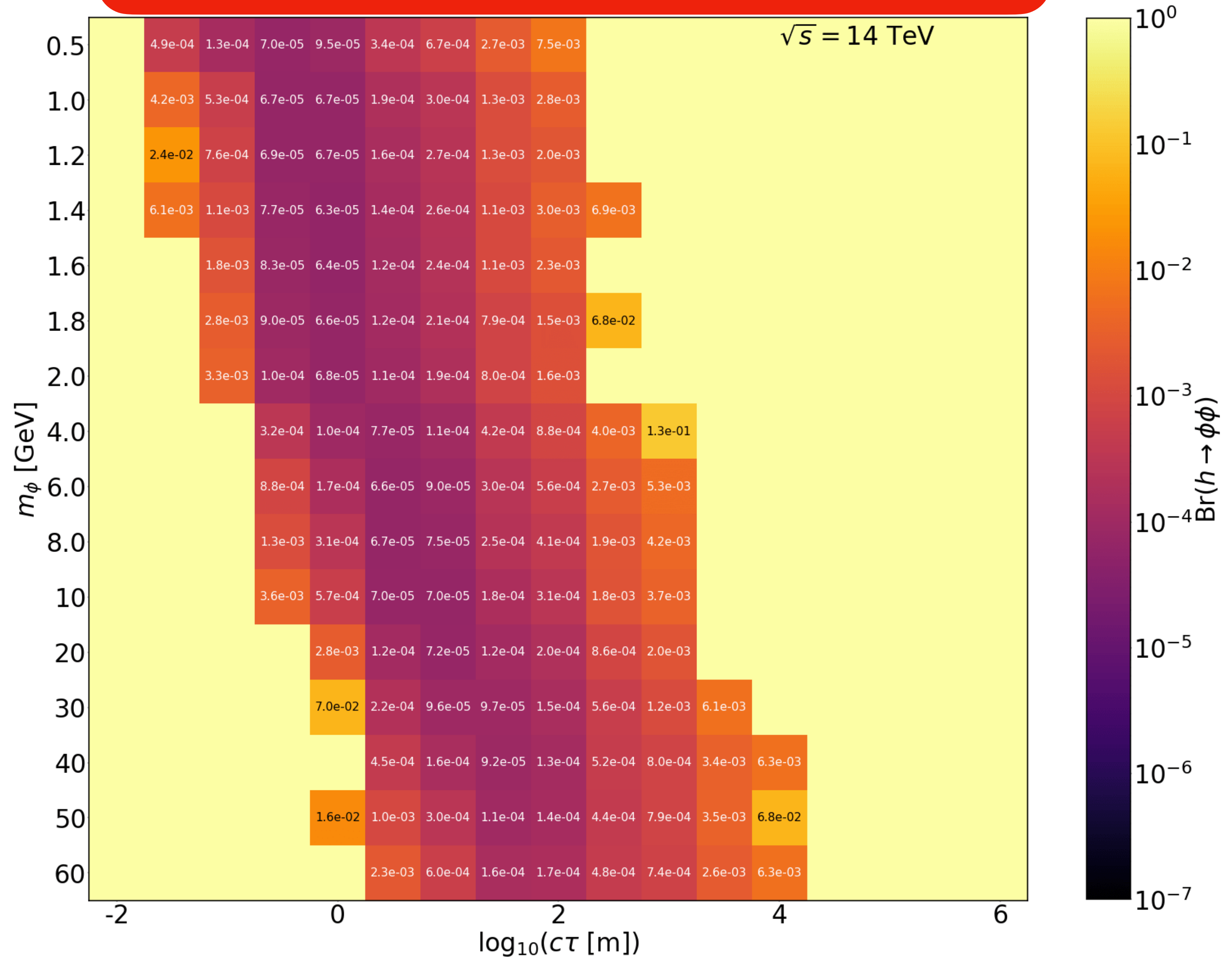
Sensitivities of CODEX-b and MATHUSLA

CODEX-b 10x10x10m³



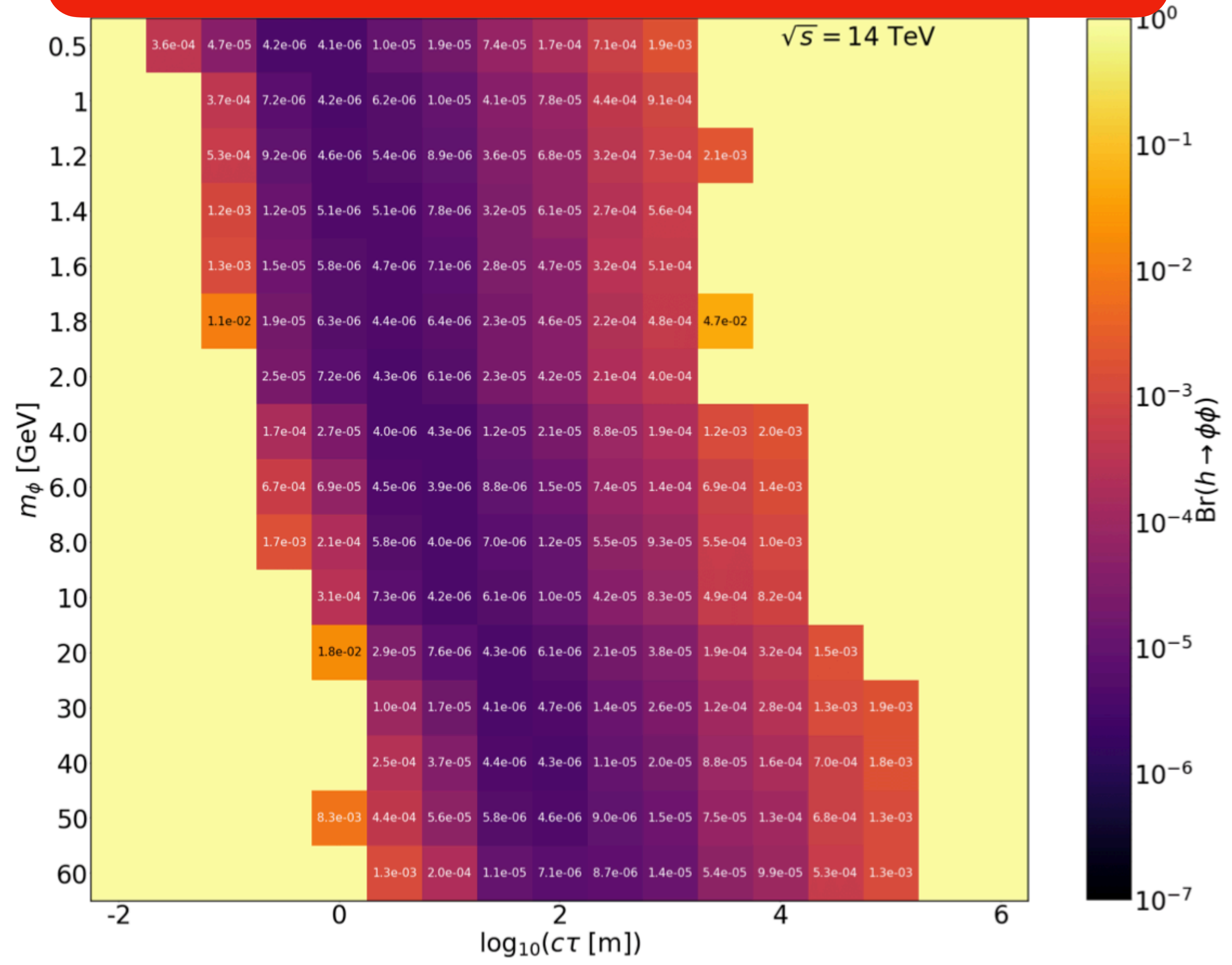
L = 300 fb⁻¹

CODEX-b 20x10x10m³



L = 1000 fb⁻¹

MATHUSLA 100x100x25m³

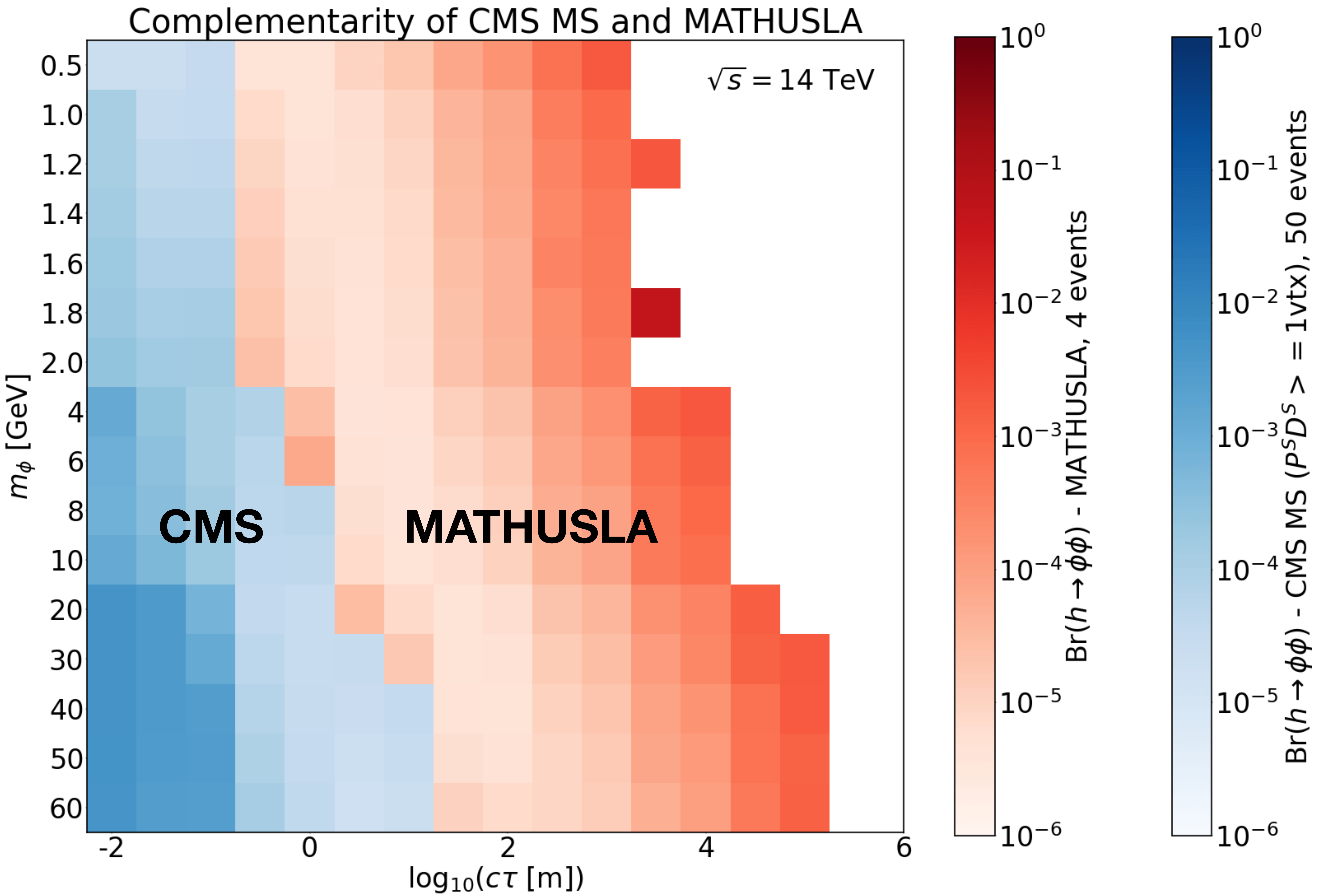


L = 3000 fb⁻¹

Results

- **The limits are obtained by combining the ggF, VBF and Vh channels for the production of the Higgs boson.**
- **Assumed 4 signal events (0 background) for discovery**
- **For the 50 GeV mediator, the most sensitive limit from MATHUSLA is $Br(h \to \phi\phi) < 4.6 \times 10^{-6}$ at $c\tau$ = 100 m**
- **The most sensitive decay length for CODEX-b detectors are always smaller than that of MATHUSLA, since CODEX-b is nearer to the IP**

Combination of results of CMS and dedicated LLP detectors



Complementarity of the CMS analyses using the muon spectrometer and the MATHUSLA LLP detector at 14 TeV with an integrated luminosity of 3000 ifb

FCC-hh

International FCC collaboration has been working on the design for PP collider at the CoM energy 100 TeV

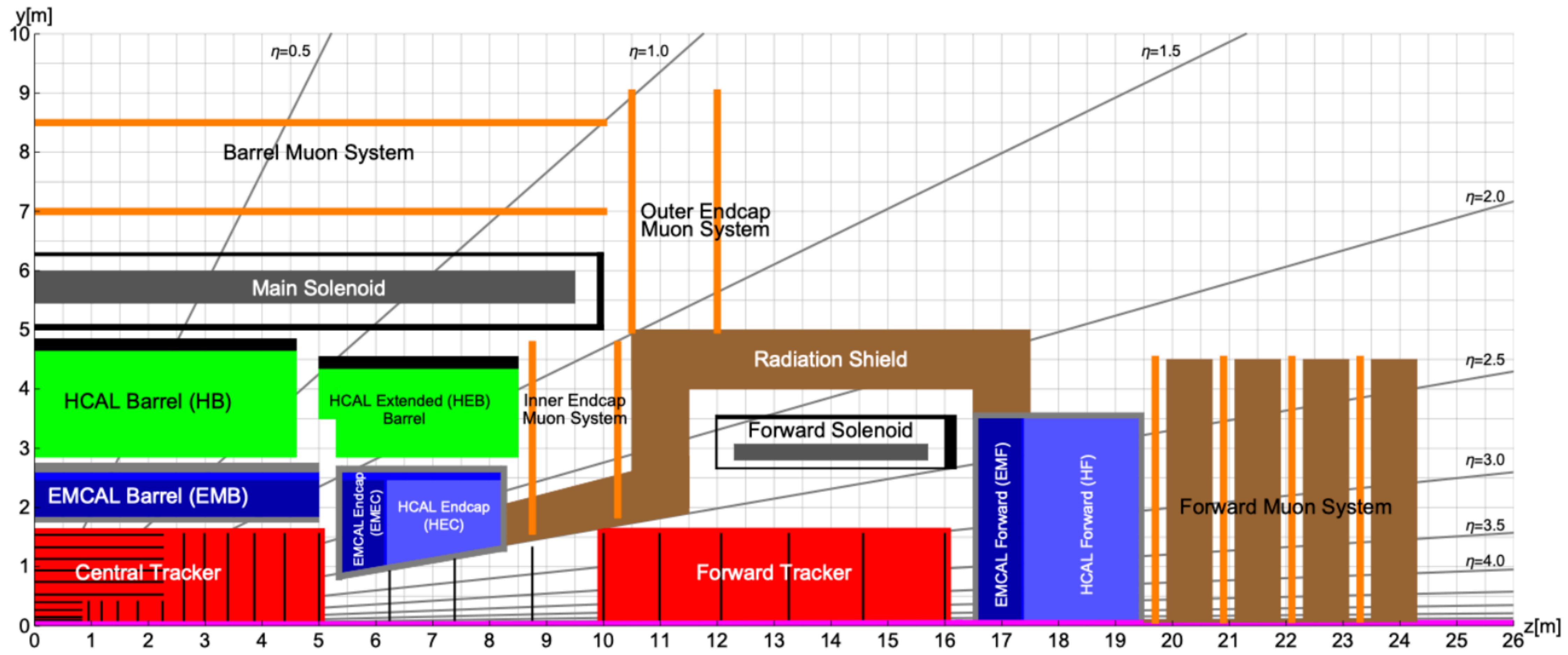
- Conceptual Design Report (CDR) published in 2019
- 25 years of run can accumulate 20k-30k ifb of data
- 2 main detectors will be placed (combination of results possible)
- For 125 GeV Higgs boson gain ~150 in the ggF channel and ~ 400 in the di-Higgs, ~ 500 in the ttH

$\sqrt{s}$ [TeV]	Process	Cross section [pb]
14	ggF	50.35
	VBF	4.172
	Vh	2.387 (Wh:1.504, Zh:0.8830)
100	ggF	740.3
	VBF	82.00
	Vh	27.16 (Wh:15.90, Zh:11.26)

$$\begin{aligned} \textbf{Tracker:} \quad & R \leq 1.5\,\text{m}, \quad |Z| \leq 5\,\text{m}, \\ \textbf{Barrel + Endcap MS:} \quad & 6\,\text{m} \leq R \leq 9\,\text{m}, \quad 9\,\text{m} \leq |Z| \leq 12\,\text{m}, \quad \eta \leq 2.5, \\ \textbf{Forward MS:} \quad & 12\,\text{m} \leq |Z| \leq 23\,\text{m}, \quad 2.5 \leq \eta \leq 5.0. \end{aligned} \tag{4.1}$$

FCC-hh Reference Detector

50m long, 20m diameter
Cavern length 66m
L* of FCC 40m.



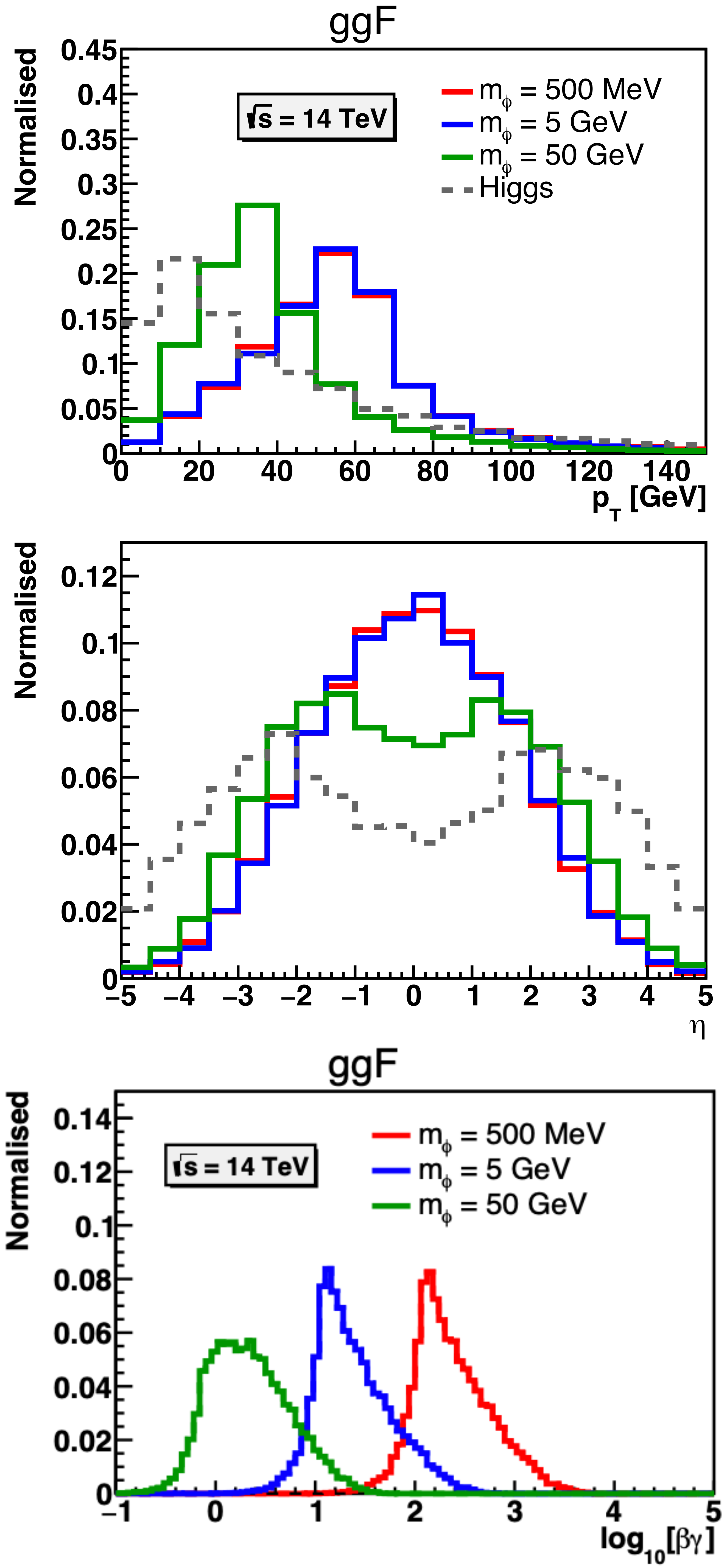
90% of 'heavy' physics will take place in η<2.5.

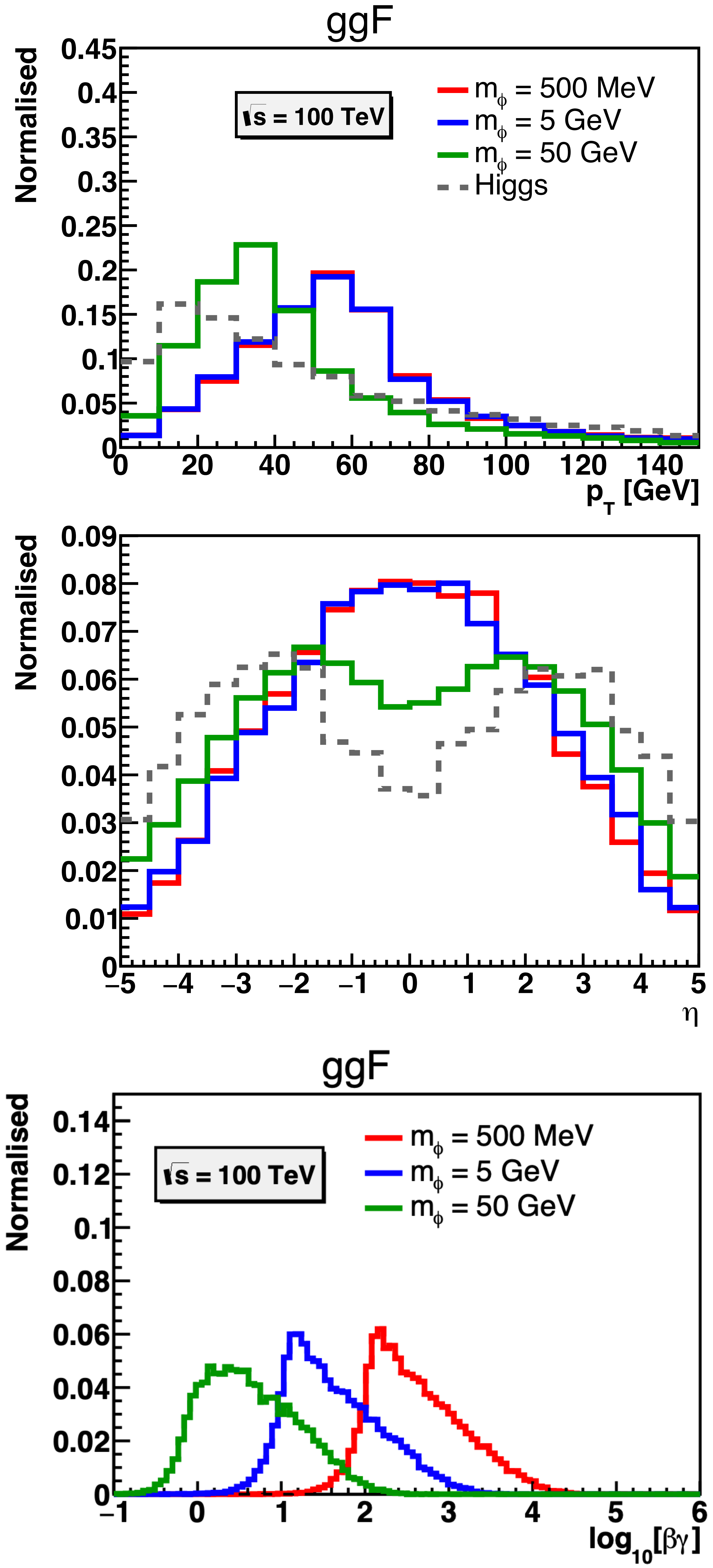
Increase of acceptance for precision spectroscopy and calorimetry from 2.5 at LHC to 3.8-4 for SM physics.

https://indico.cern.ch/event/789349/contributions/3298692/attachments/1805766/2946875/fcc_hh_detector_cdr_presentation_feb_2019.pdf

Comparison of distributions : LHC vs FCC-hh

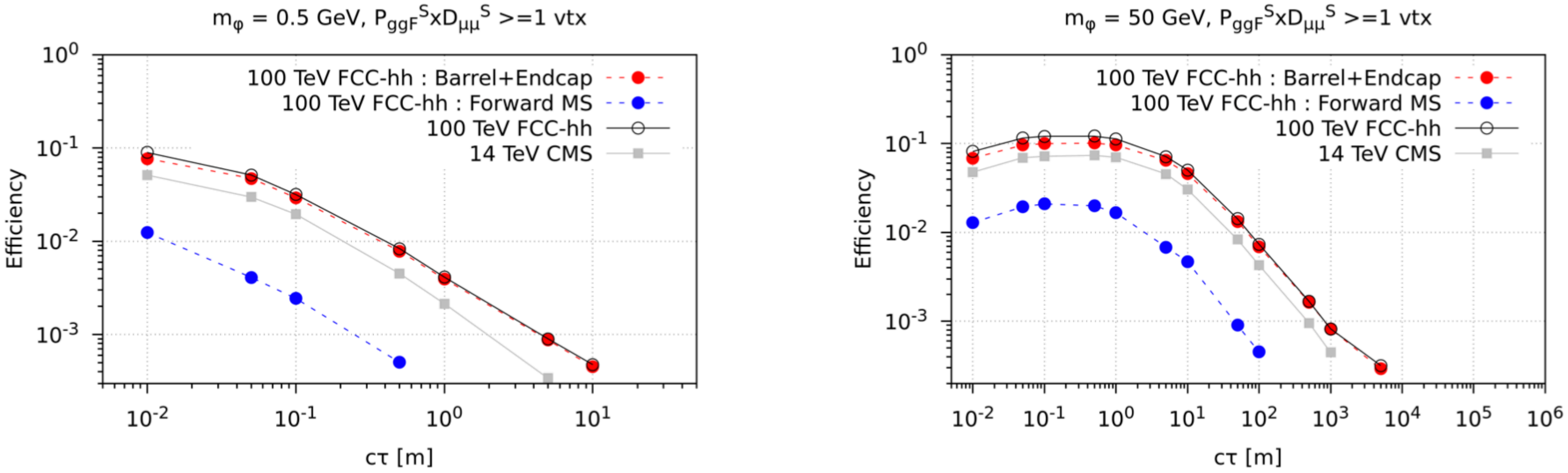
14 TeV





100 TeV

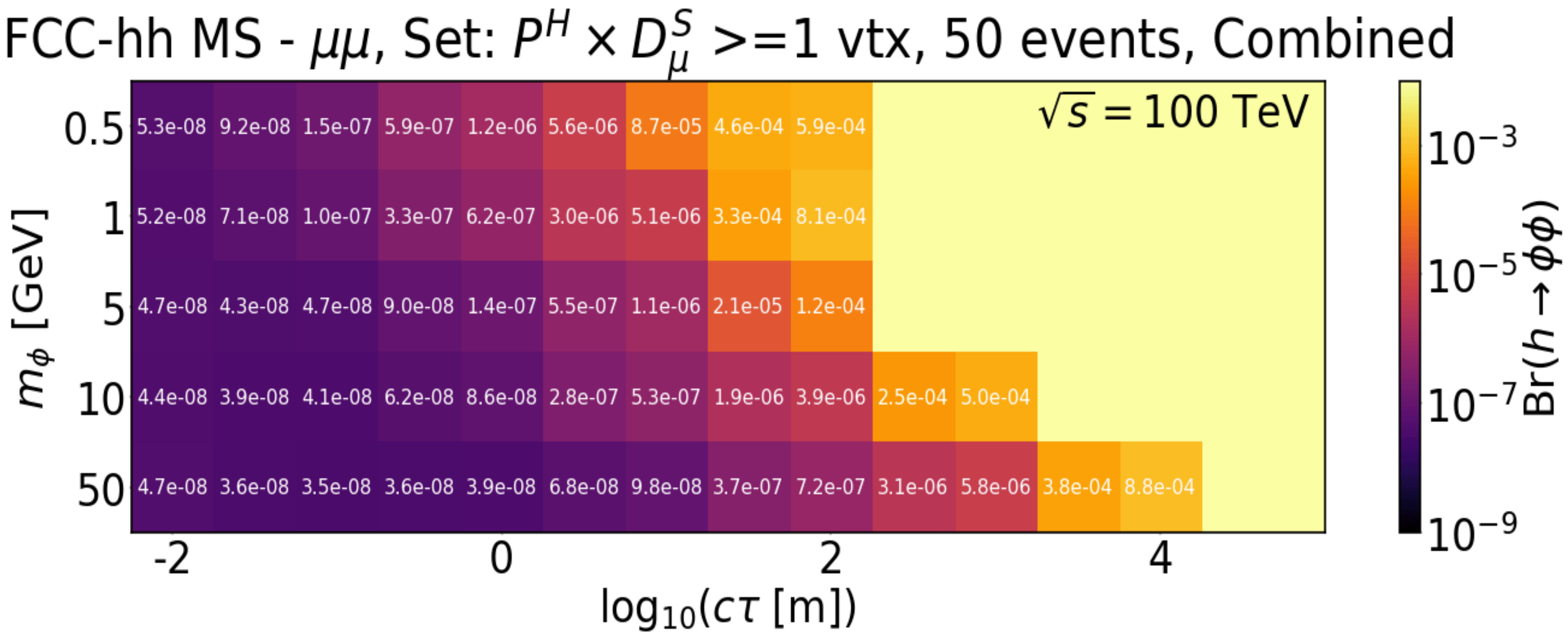
FCC-hh : φ->μ μ

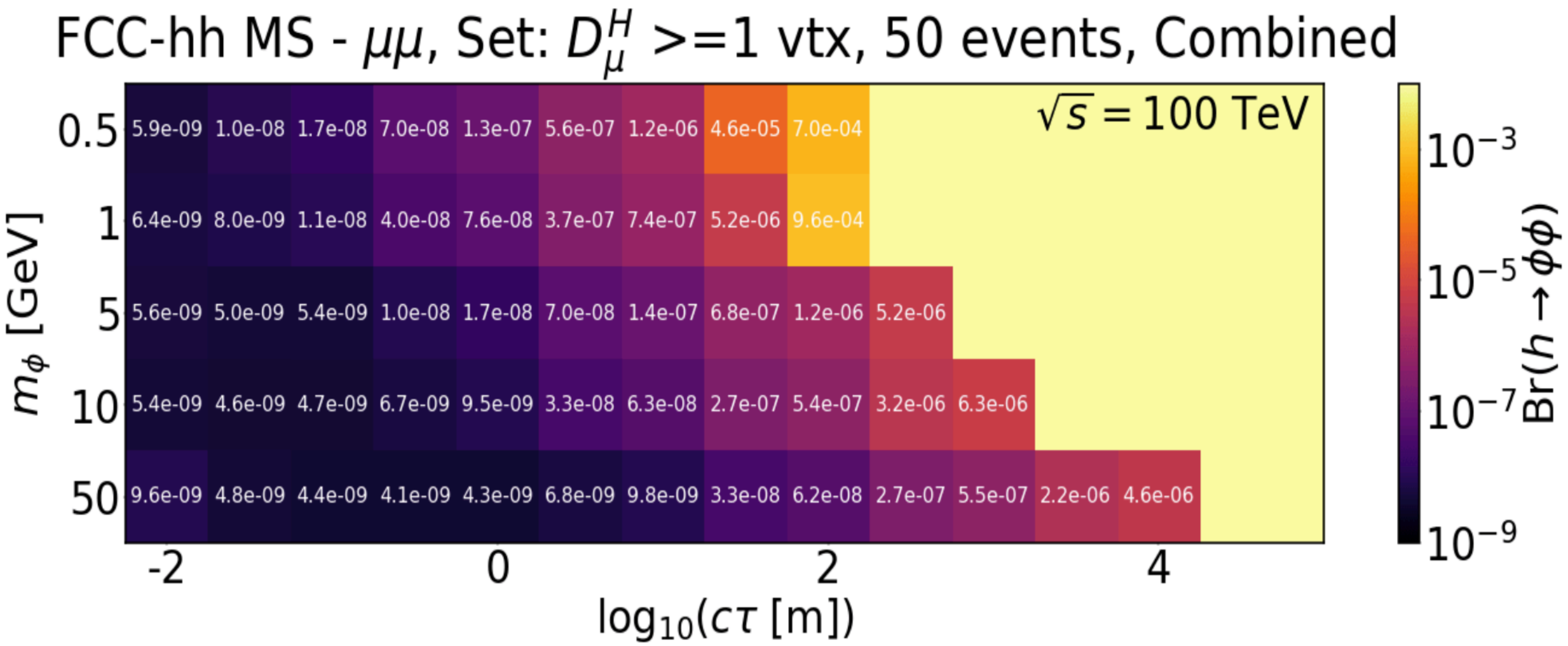


(Comparison of the efficiencies as a function of decay lengths)

- We use the same cuts as we used for the CMS analysis
- Combined 100 TeV efficiency is larger than that achieved in 14TeV by a factor of ~ 1.4.
- Addition of forward MS with that in the barrel and endcap MS of FCC-hh, improves the limits by around 15-20%.
- The enhancement due to the forward MS is more for lower decay lengths

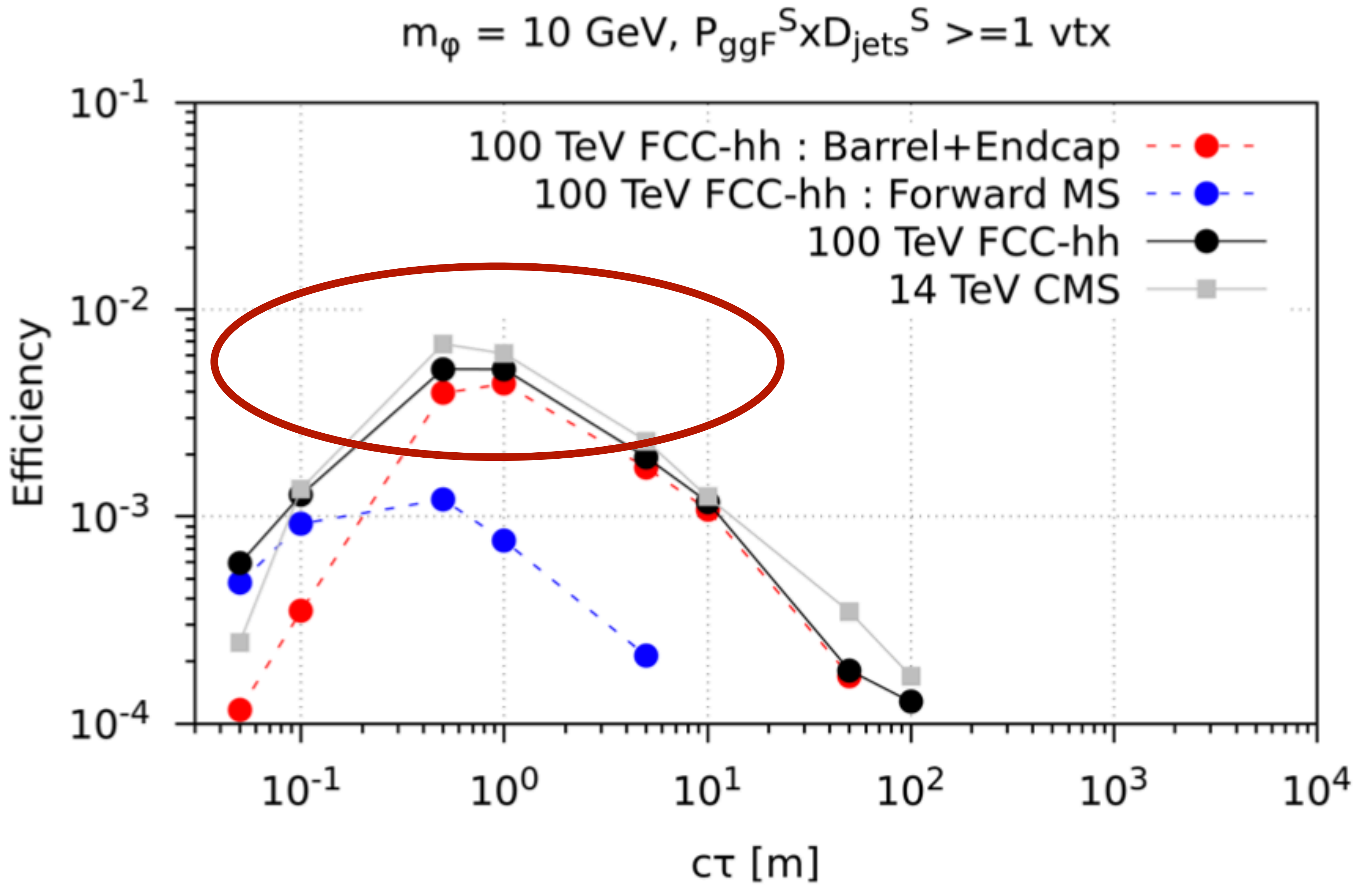
FCC-hh : φ->μ μ

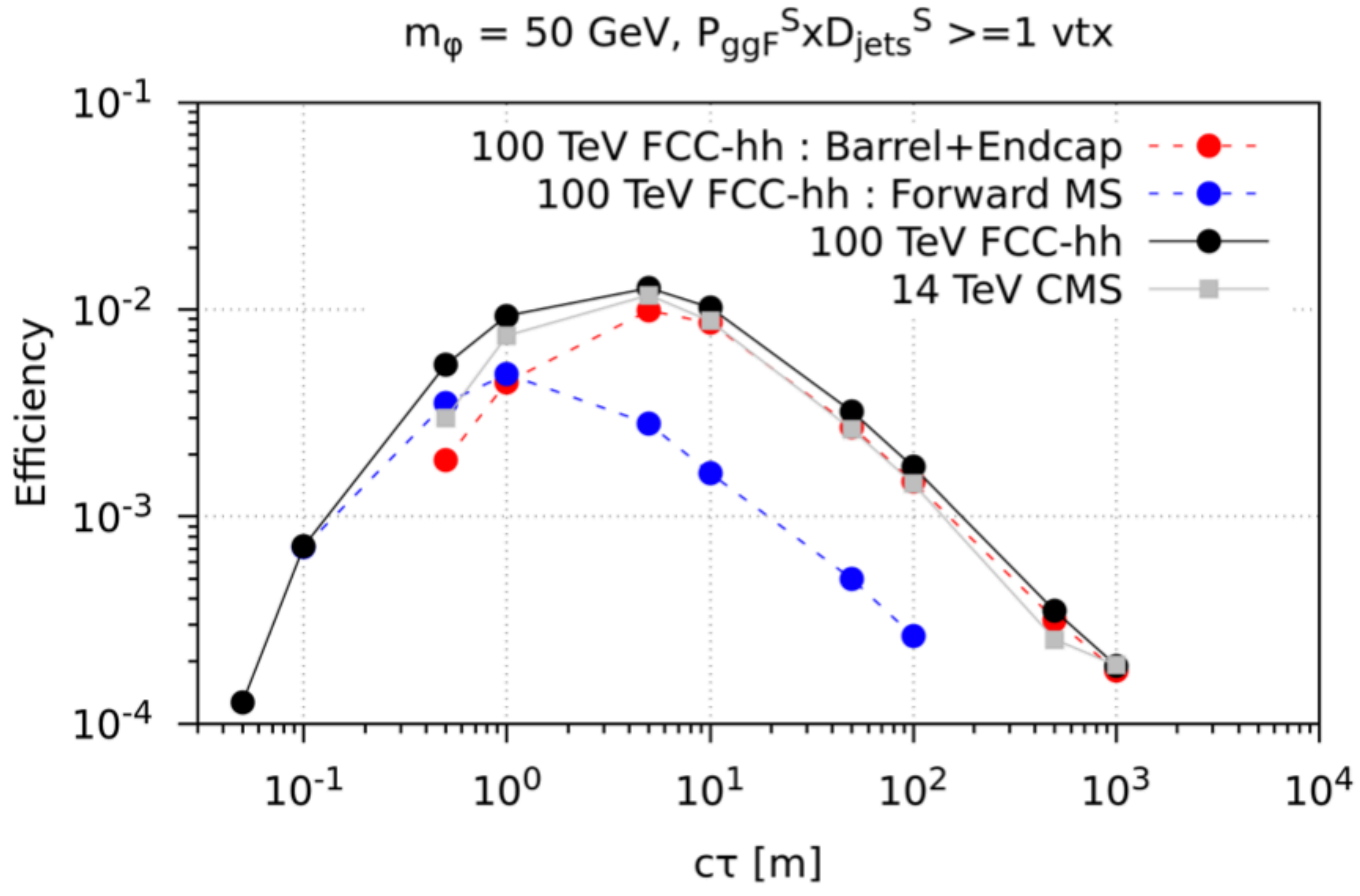




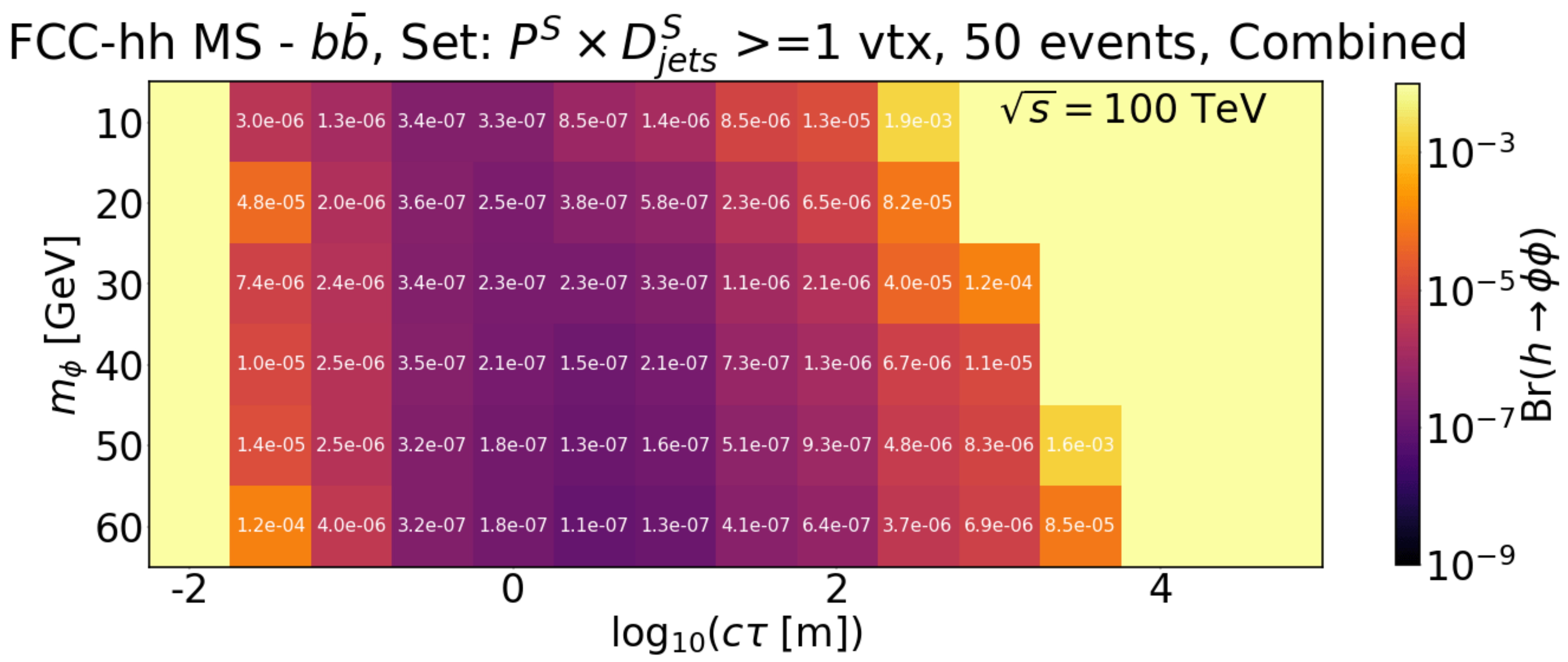
- We have an improvement by a factor of around 200 in the FCC-hh detector compared to the CMS detector.
- Increase in the cross-section and the luminosity alone accounts for a factor of ~ 150.
- An increase in the efficiency by a factor of ~ 1.4 in going from the CMS to the FCC-hh.

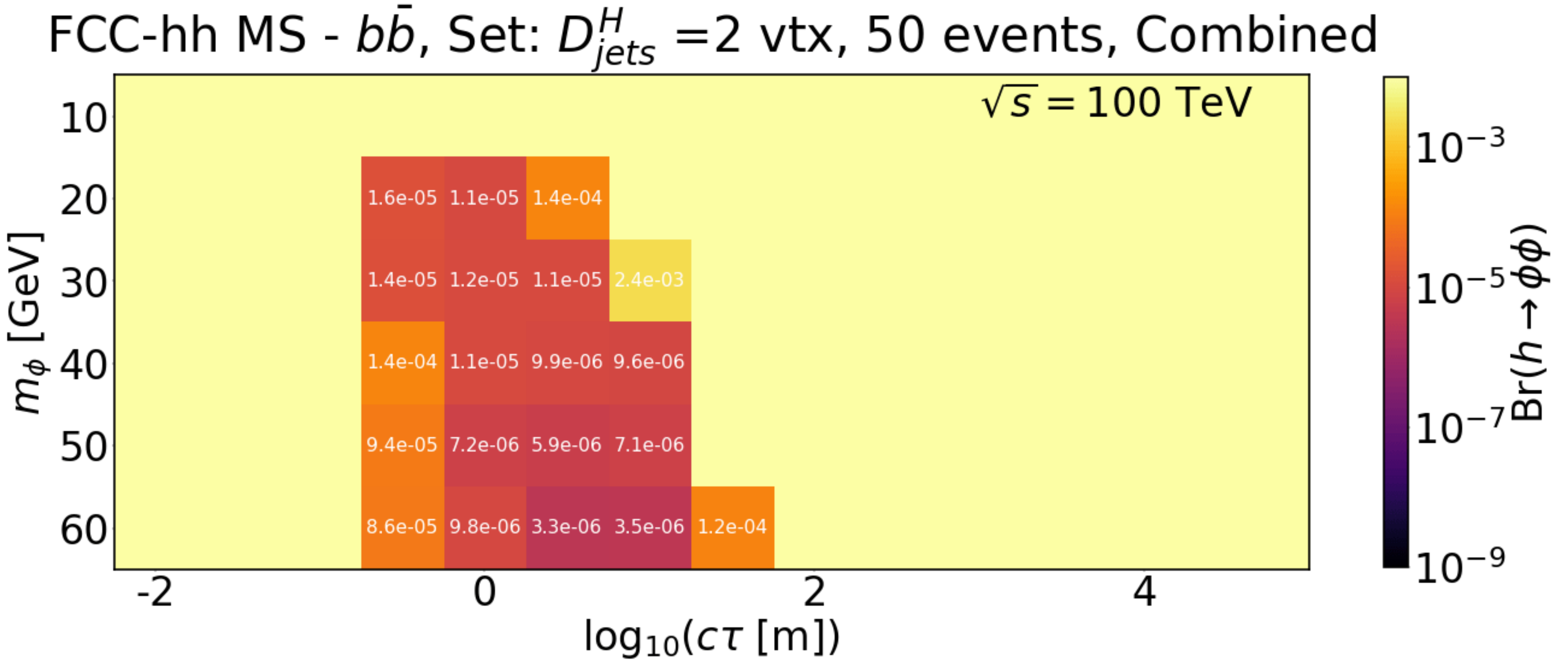
FCC-hh : φ->b b



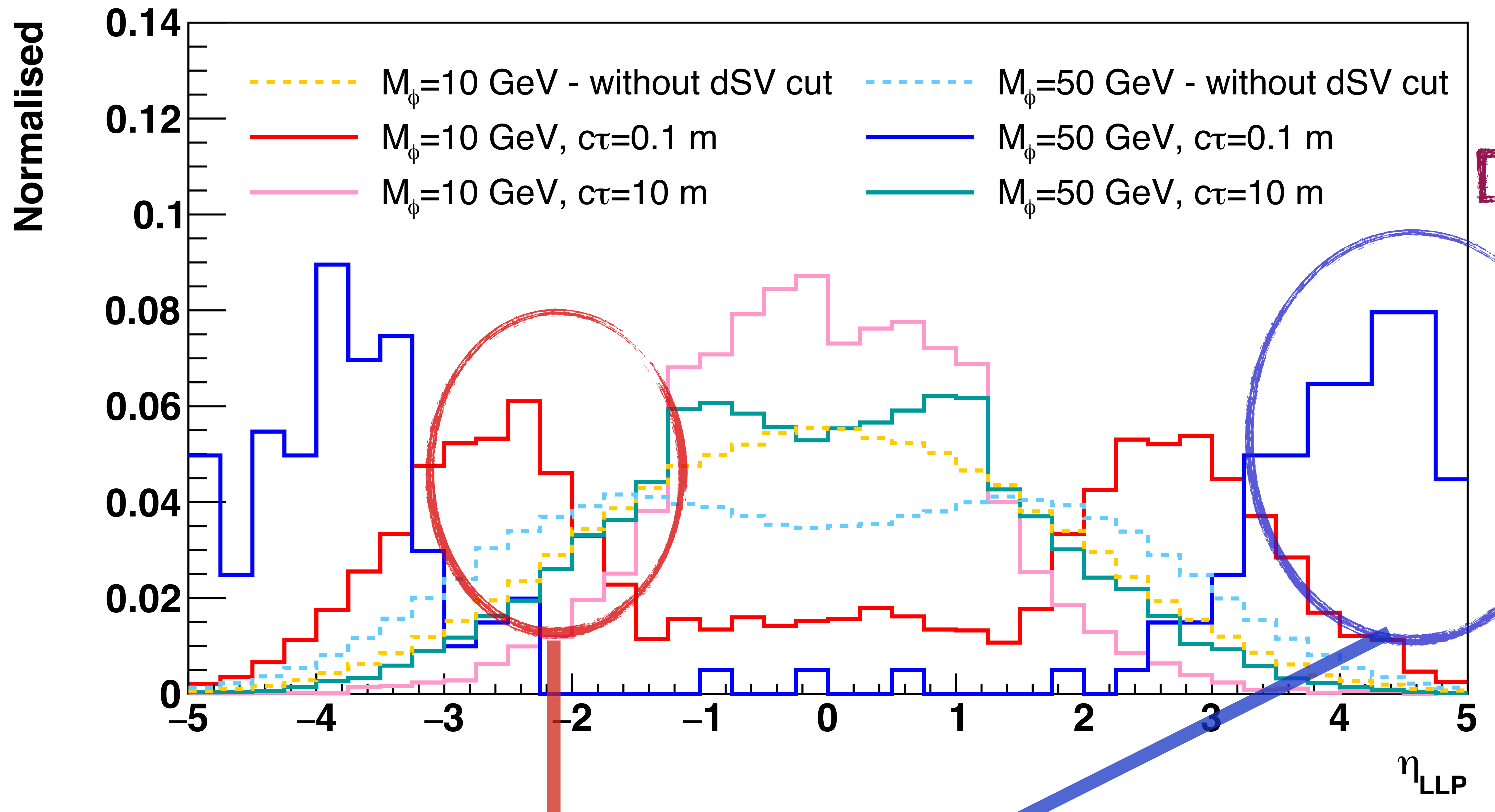


- **Slight reduction in efficiency for low mass region, improvement of the 14 TeV CMS results by a factor of~120-140 with the ≥ 1 vtx cuts for mediator mass of 10 GeV ⇒ mostly due to the $\Delta\phi$ cut.**

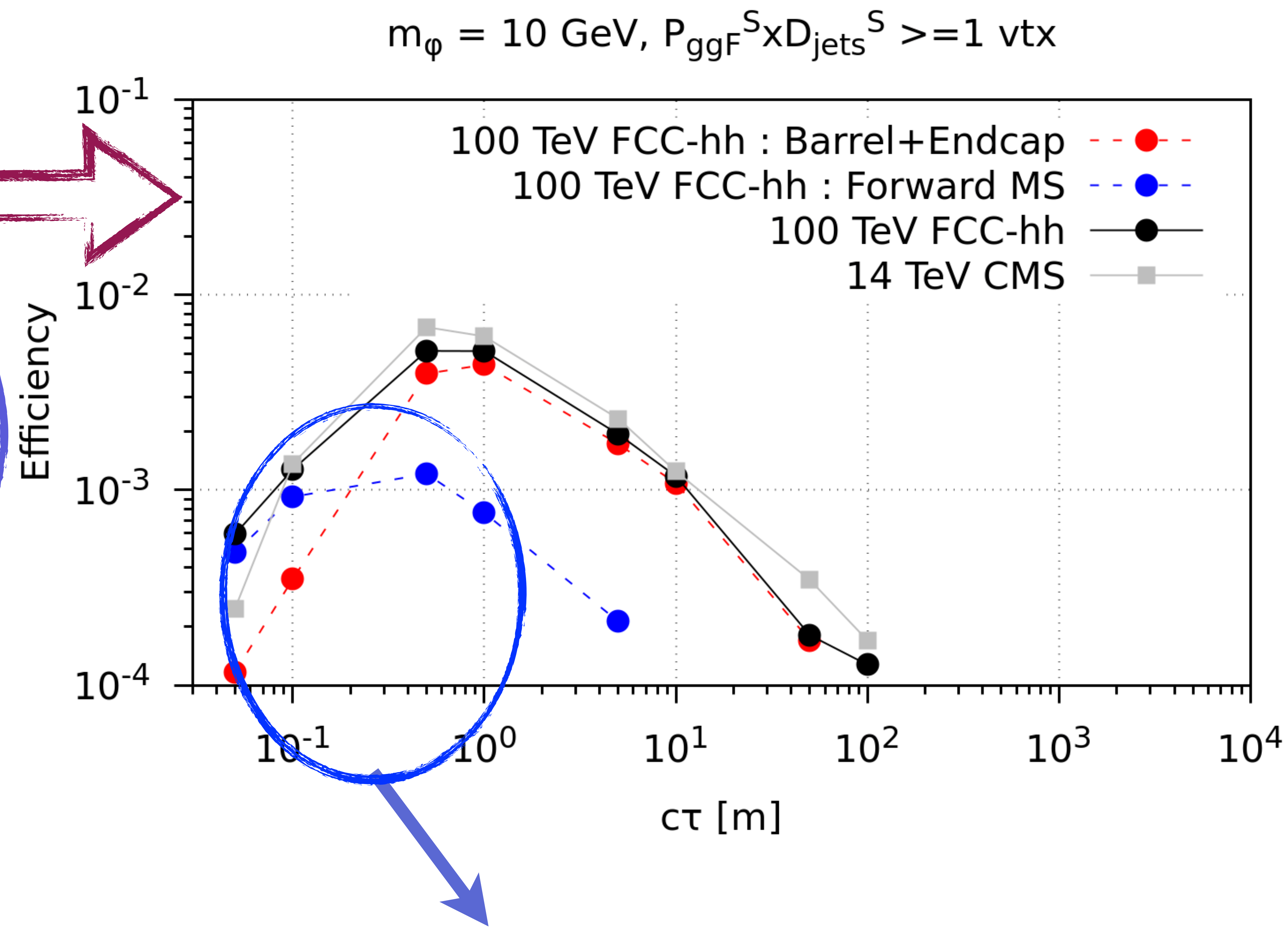




Role of forward MS at FCC-hh : φ->b b

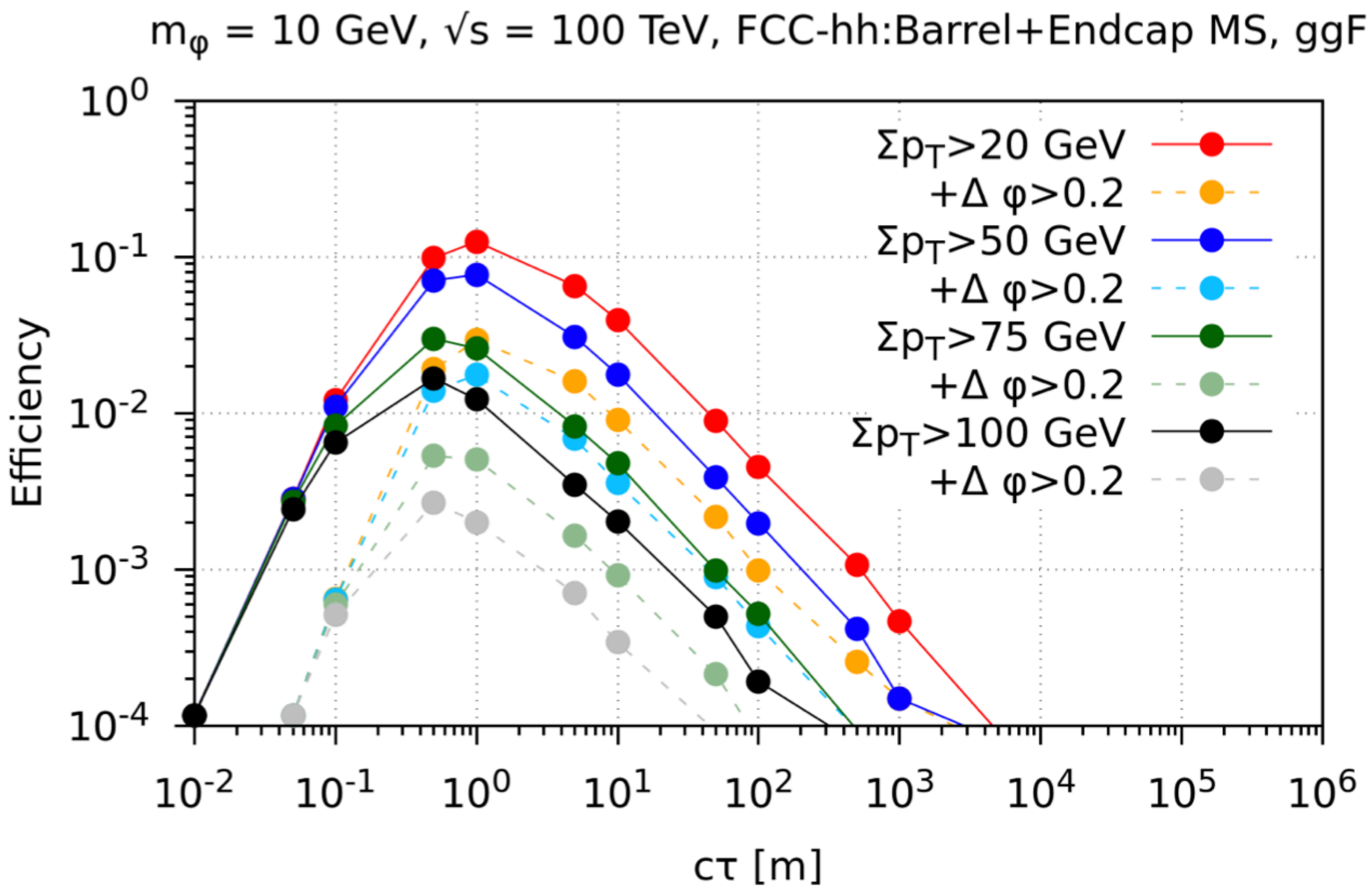


LLPs more in forward direction for lower $c\tau$ when decay is restricted within MS



Forward MS increases sensitivity to lower decay lengths

More stringent cuts at FCC-hh ?



100 TeV - increase energy threshold

High granular detector - relax $\Delta\phi$ cut

	$\sum p_T > 20\,\mathrm{GeV}$	$50\,\mathrm{GeV}$	$100\,\mathrm{GeV}$
$\Delta\phi > 0.2$	$\times 75$	$\times 34.5$	$\times 4.5$
$\Delta\phi > 0.0$	$\times 250$	$\times 150$	$\times 24$

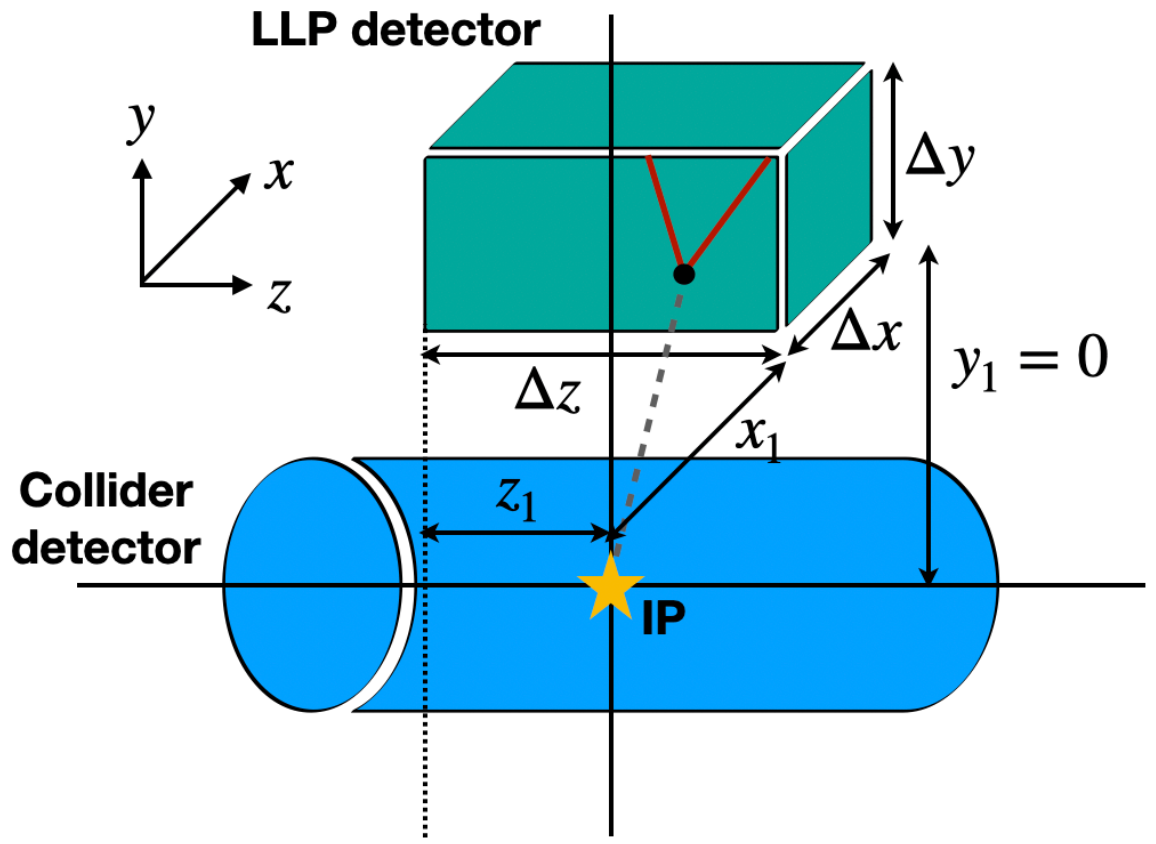
improvement factors w.r.t. HL-LHC

- With the computed efficiency of the $p_T > 100$ GeV (50 GeV) cut, we can improve the results only by a factor of ~4.5 (34.5) due to the loss in efficiency.
- The future detectors can be expected to have a higher granularity that can help in relaxing the Δϕ cut and regaining the improvement in sensitivity.

Dedicated LLP detector for FCC-hh

Advantage: **The collider, as well as the detectors, are not yet constructed, possible to optimise the position as well as the size of the detector to maximise its sensitivity, rather than finding empty spaces near the various IPs to place and fit the LLP detectors for the HL-LHC experiment.**

We here propose three designs of a dedicated LLP detector DELIGHT (Detector for long-lived particles at high energy of 100 TeV), a box-type detector in the periphery of the FCC-hh collider



DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (B): Four times bigger than the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.

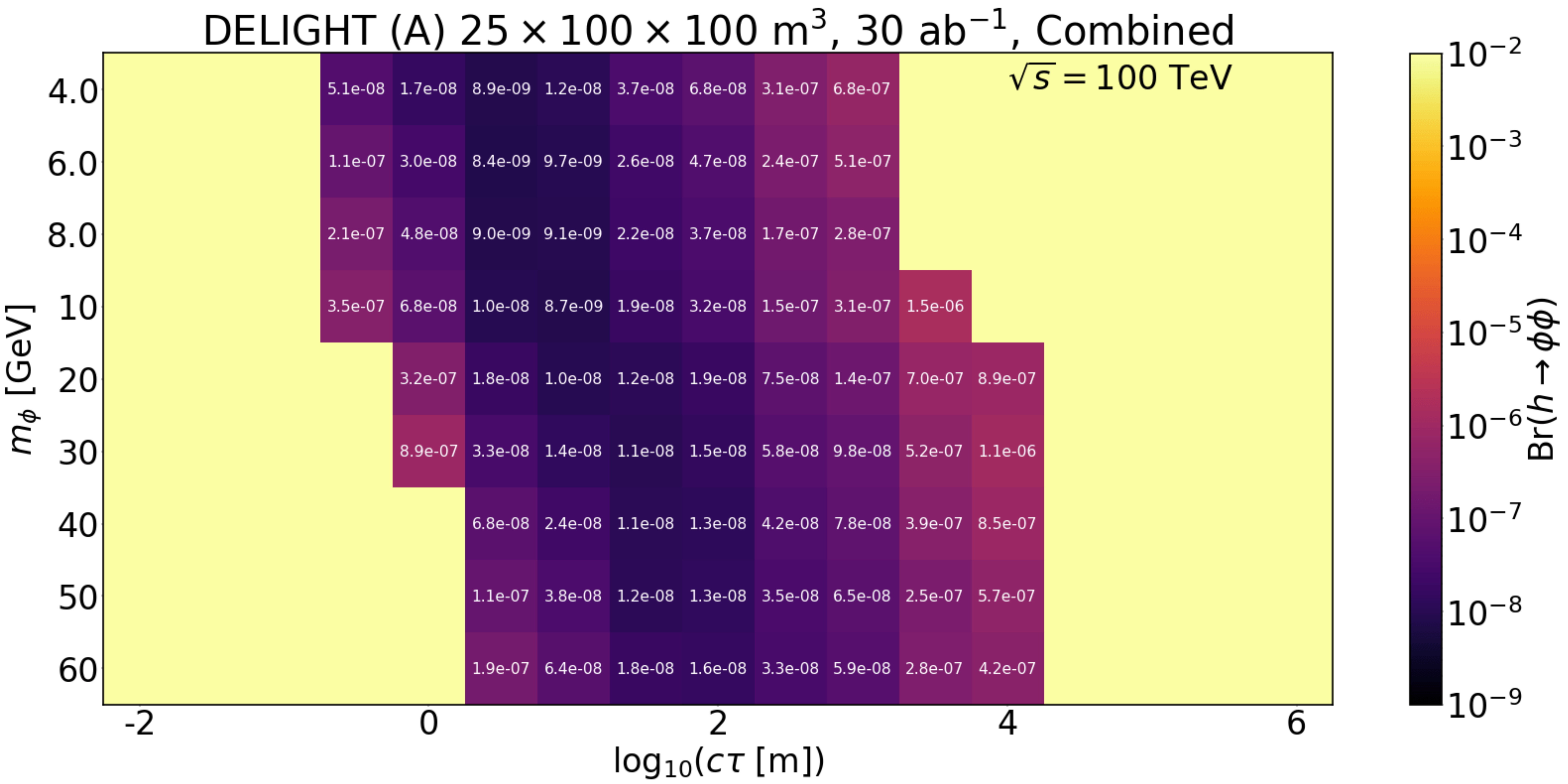
DELIGHT (C): The same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

A position starting at around 25 m in the x-direction around η = 0 region can be kept empty for placing a dedicated LLP detector.

LLP detectors for FCC-ee is proposed here : 2011.01005

DELIGHT (A)

DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.



DELIGHT(A) vs MATHUSLA: an improvement by a factor of ~ 540,

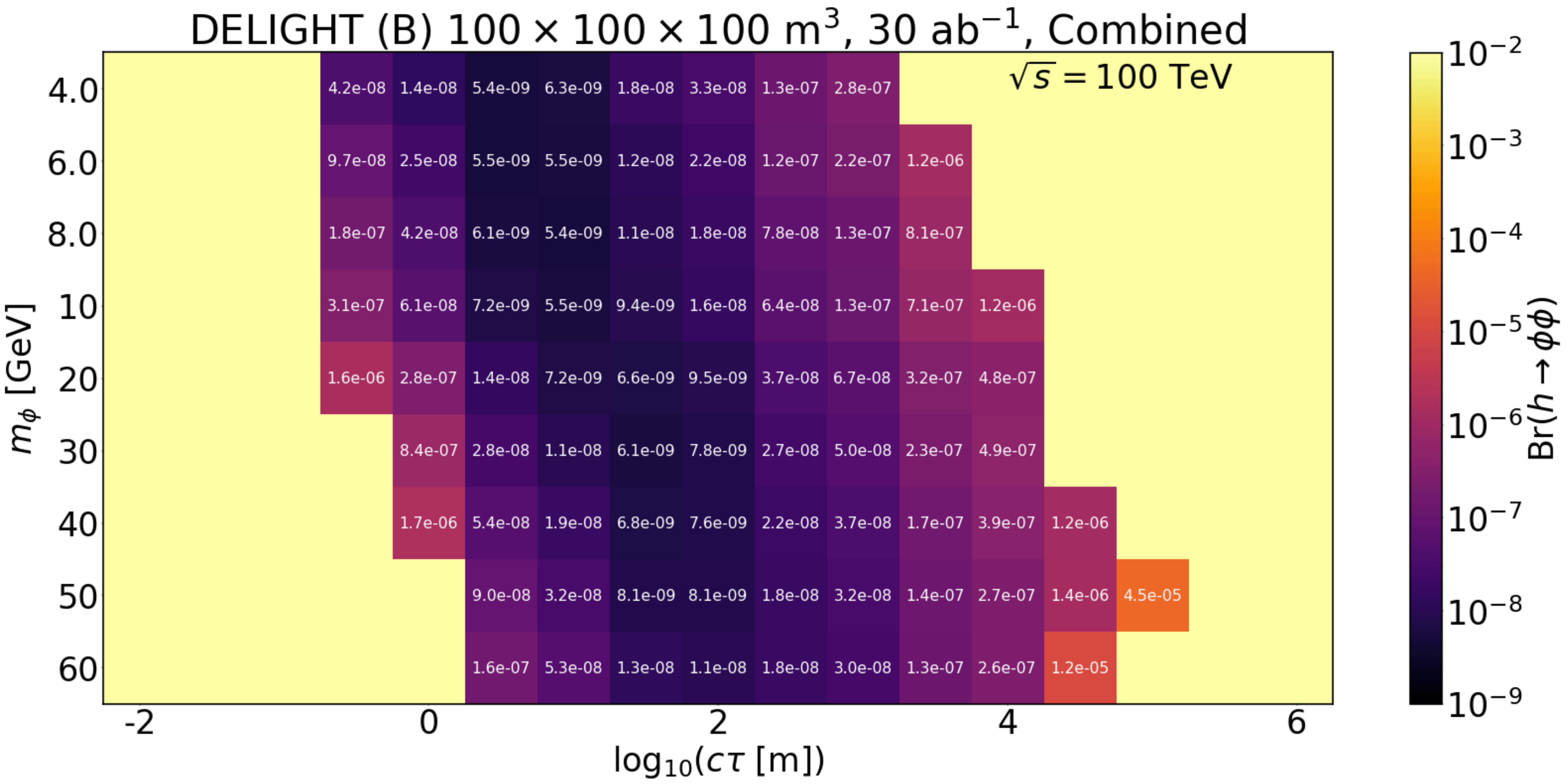
around ~ 150 from increased cross-section and integrated luminosity,

another factor of ~ 3–4 is gained by moving the detector close to the IP.

Central position of the detector can benefit light LLPs.

DELIGHT (B)

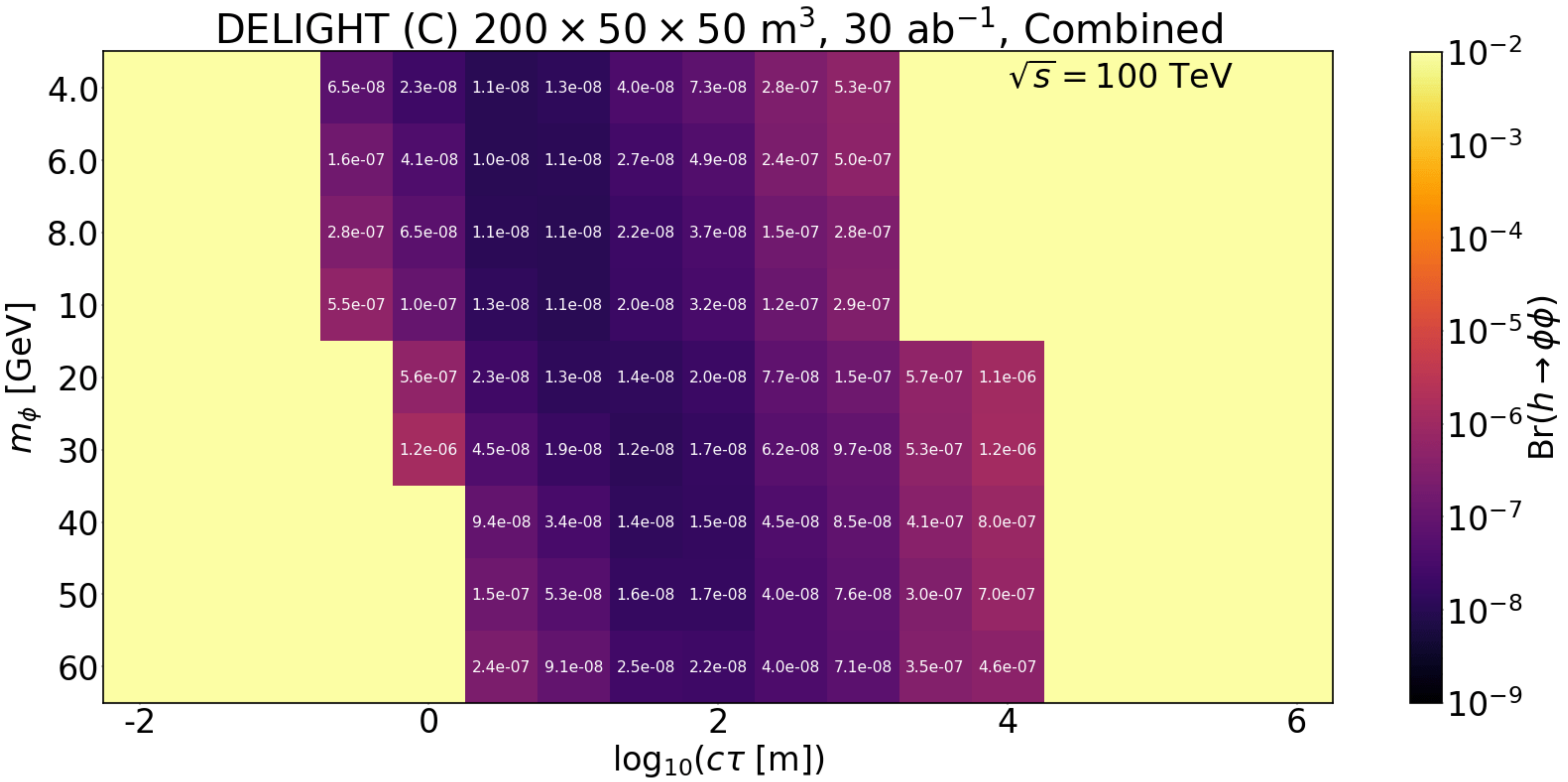
DELIGHT (B): Four times bigger than the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.



DELIGHT(B): The best limits come from DELIGHT(B), highest decay volume among the three (about four times bigger than the decay volume of MATHUSLA), and the performance is better by a factor of 2 compared to DELIGHT (A).

DELIGHT (C)

DELIGHT (C): The same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.



DELIGHT (A) vs DELIGHT(C): have the same decay volumes, lower $\Delta\eta\times\Delta\phi$ coverage, limits slightly weaker (factor of around 0.8 – 0.9), may have better shielding from cosmic rays, tunnel like structure might be useful for other LLP models (needs more detailed analysis) (A).

Some discussions on DELIGHT

- 100 TeV collider will have very high luminosity => a distance of 25 m might not seem enough to provide a background free environment.

- Still in the designing phase => significant shielding may be placed as well as active veto to reject backgrounds. It can be placed deep inside the ground to suppress cosmic ray backgrounds.

- Current RPC technology should provide adequate sensitivity => future technology can further improve the sensitivity.

- Presence of calorimeter can extend sensitivity to LLP decays to photons, and other neutral particles.

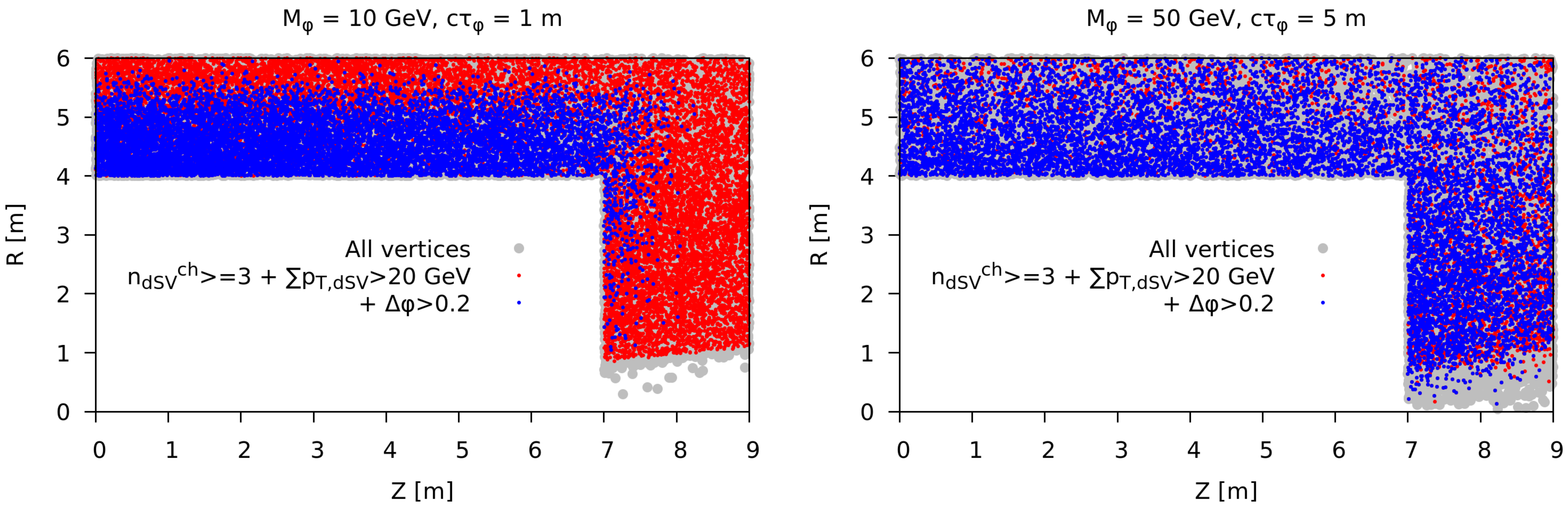
- The detector can be integrated with one of the detectors => coordinated triggers can be developed

Summary

- We have studied the production of the Long-lived scalar mediator from the on-shell decay of the SM Higgs boson at the LHC and future 100 TeV FCC-hh collider.
- Combined the dominant production modes of the Higgs as well as consider a variety of decay modes of the mediator particle. The Limits can be easily translated for different branching ratios.
- We study the sensitivity of the muon spectrometer of the proposed 100TeV hadronic collider experiment, FCC-hh.
- We propose detector designs for dedicated LLP searches in the periphery of the 100 TeV FCC-hh collider, named DELIGHT.
- We believe that our detailed analysis and findings will be useful for the a range of LLP models. Our analyses for the future 100 TeV collider can be a starting point for further detailed studies exploring their prospects for LLPs. The proposal put forth by us in this work for the DELIGHT detector near the FCC-hh collider shows promising results, motivating further studies in this direction for other LLP models.

Thank You

Effects of cuts : Extra Slides



The Δϕ cut selects only events with a much lesser displacement of the dSV for the 10 GeV mediator particle than the 50 GeV one.

- **The 10 GeV mediator particle has more boost and that combined with longer displacements, make the cluster of particles from the mediator particle decay more collimated.**
- **The 50 GeV mediator particle having less boost can satisfy the Δϕ cut even for longer displacements.**