Search for long-lived particles using data scouting

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OUTLINE

- **What are we looking for ?**
  - A vector boson "dark photon" Z_D decaying to muons
  - A singlet scalar field **ϕ** and a new dimuon resonance hiding below the B mass ?

- **Search Strategy:**
  - Z_D, **ϕ** light and long lived ➢ Leverage dimuon displacements to reduce background.
  - Scouting Trigger ➢ Allows access to phase space of low mass and long lifetime.

- **Search Results (CMS-EXO-20-014):**
  - How current Z_D search compares with existing CMS/ATLAS results?
  - How current **ϕ** search compares with LHCb results?

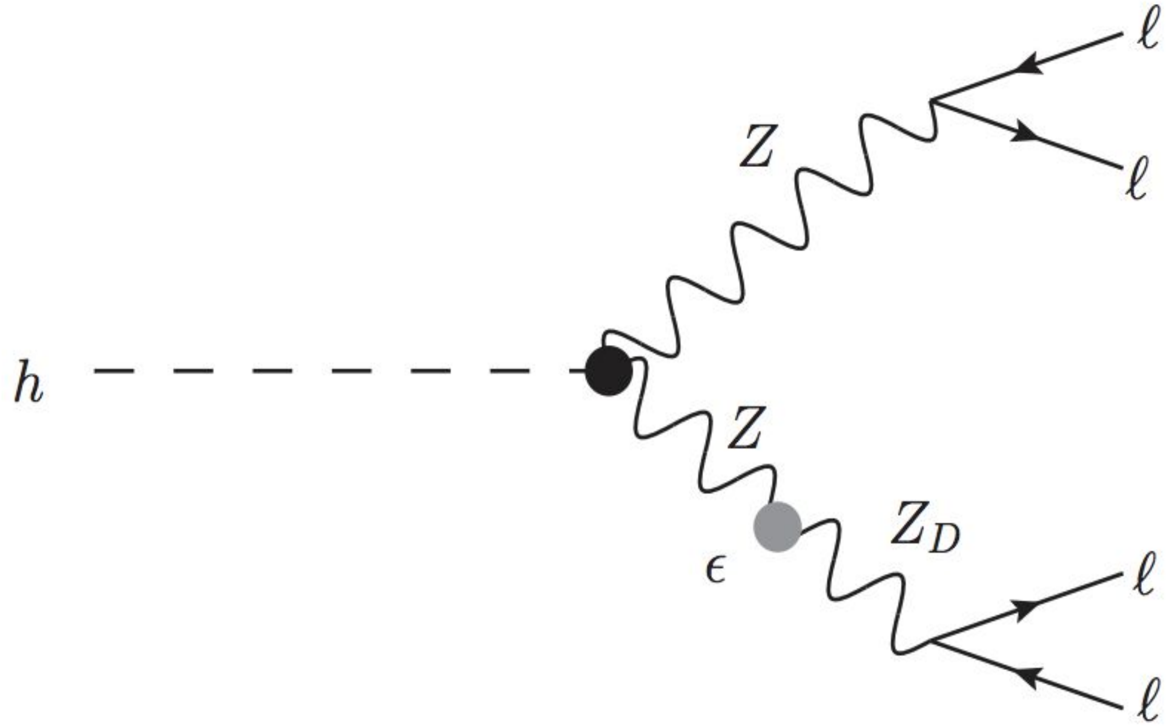
Dark Sector

JHEP 02 (2015) 157
arXiv:1311.0029

- Dark matter interaction with SM via weakly interacting mediators if at all
  - Dark photon Z_D decays to SM fermions in absence of lower-mass hidden sector states.
  - Coupling between Z_D and $\boldsymbol{\mu\mu}$ proportional to kinetic mixing coupling $\boldsymbol{\varepsilon}$.

- Production at LHC:
  - Exotic Higgs decays ➢ $H \rightarrow Z_D Z / Z_D Z_D$
  - $Z_D \rightarrow \boldsymbol{\mu\mu}$ ➢ Branching ratio varies roughly between 0.05 to 0.5

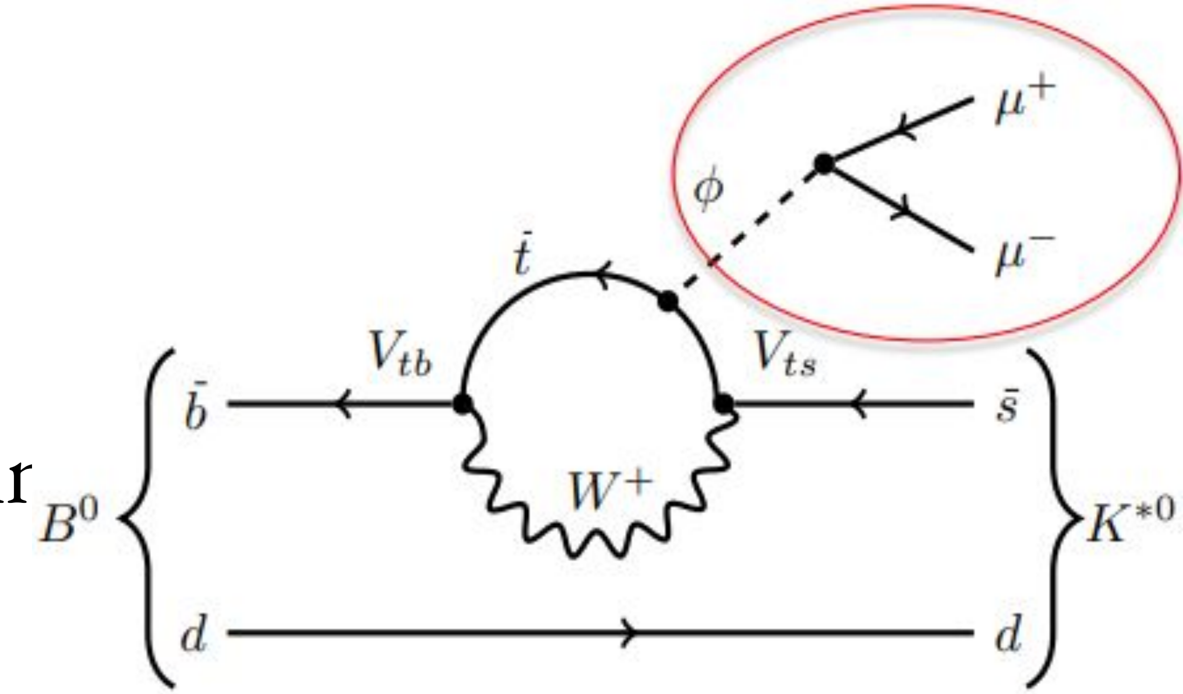
- Z_D can be long lived ($c\boldsymbol{\tau}^0 \; \alpha \; 1/\boldsymbol{\varepsilon}^2$) and warrants a displaced dimuon resonance search.



A new dimuon resonance below the B mass ?

[Phys. Rev. D 95, 115001](#)
[JHEP 1005:010, 2010](#)

- A minimal extension to the SM adds a singlet scalar field **ϕ** mixing with the SM Higgs.
  - **ϕ** couples with SM fermions proportional to their masses.
  - Coupling between **ϕ** and **μμ** suppressed by mixing angle s_{θ}.



- Dominant production at LHC:
  - B → **ϕ**X decays ➢ Flavor changing decays via an electroweak penguin
  - **ϕ** → **μμ** ➢ Branching ratio varies roughly between 0.01 to 0.1.

- **ϕ** likely to be long lived and warrants a ultra low mass and displaced dimuon resonance search.

CMS Trigger System

CMS Triggering selects mostly high p_T and prompt events

Proton Proton collisions at 40 MHz $\xrightarrow{\text{L1}}$ 100 kHz $\xrightarrow{\text{HLT}}$ 1 kHz — Sent for offline reconstruction

- Two level triggering system to manage such rate
- Kinematic thresholds kept high to decrease event rate ($p_T(\mu) > 17$ GeV)

$$\text{Trigger Bandwidth} = \text{Event Rate} \times \text{Event Size}$$

$$\sim 1\ \text{kHz} \times \sim 1\ \text{MB}$$

$$\approx 1\ \text{GB/sec}$$

Adapted from:
Swagata Mukherjee

Scouting Trigger System

Data Scouting: Gain sensitivity to low mass and long lived dimuons

- Select 2 muons with lower kinematic threshold: muon p_T of 3 GeV as well as no prompt requirement.

- No dimuon mass cut: down to 2m[μ].

- Online HLT objects.

$$\text{Trigger Bandwidth} = \boxed{\begin{array}{c}\text{Event Rate}\\ \sim 1\ \text{kHz}\end{array}} \times \boxed{\begin{array}{c}\text{Event Size}\\ \sim 1\ \text{MB}\end{array}}$$

If we want to **increase** rate (i.e. decrease threshold)

We need to **decrease** event size

Event size reduced by a factor of **~1000** in data scouting (4 kHz × 7 kB)

Adapted from:
Swagata Mukherjee

Scouting Data - I

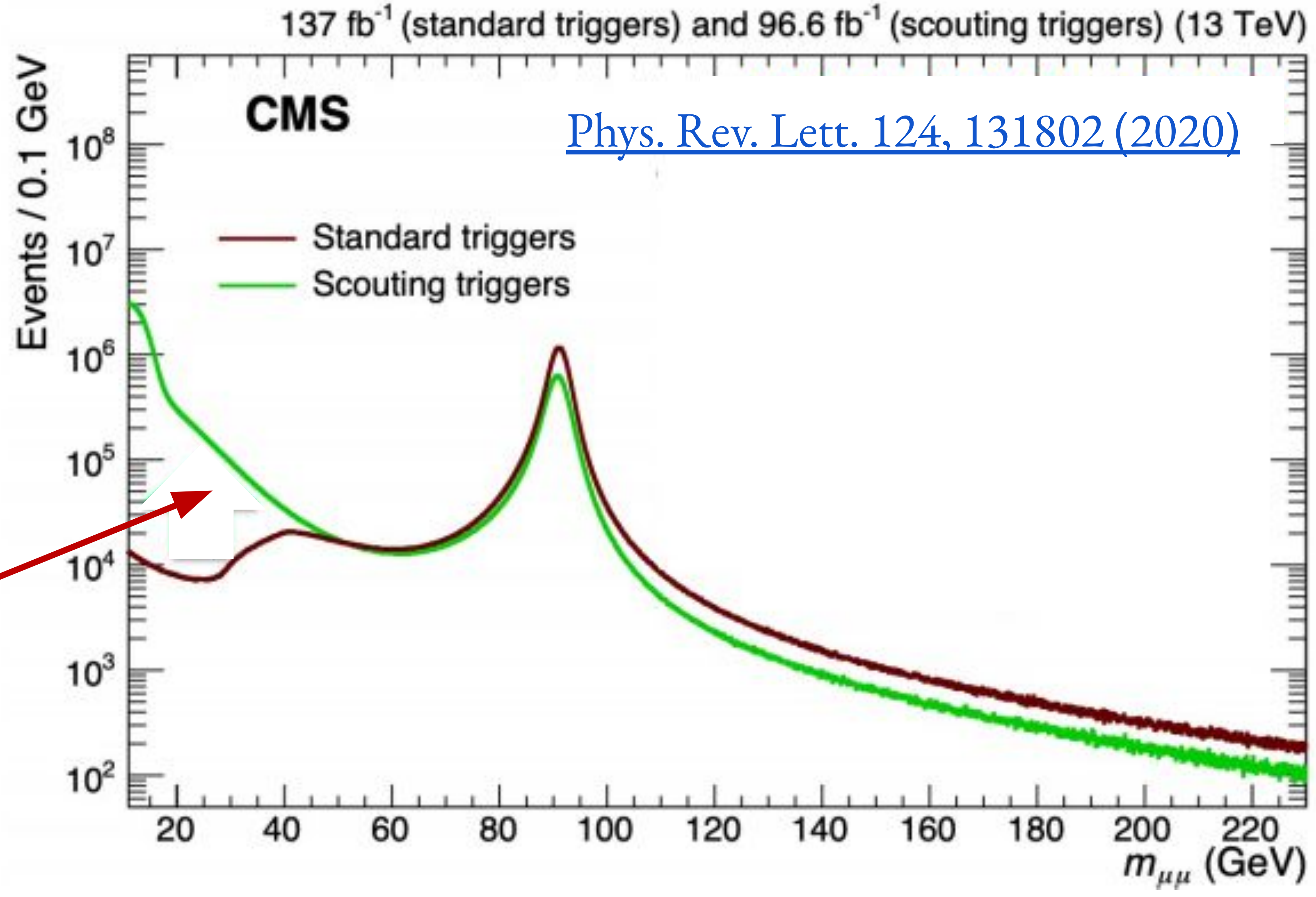
Phase Space of interest:

$2m[\mu] \leq m(Z_D) \leq 50$ GeV

$2m[\mu] \leq m(\phi) \leq 5$ GeV

$c\tau^0(Z_D/\phi) > 0$

- Standard triggers not ideal for such a search.
- CMS dimuon scouting trigger enables us to probe ultra low dimuon masses.



Scouting Data - II

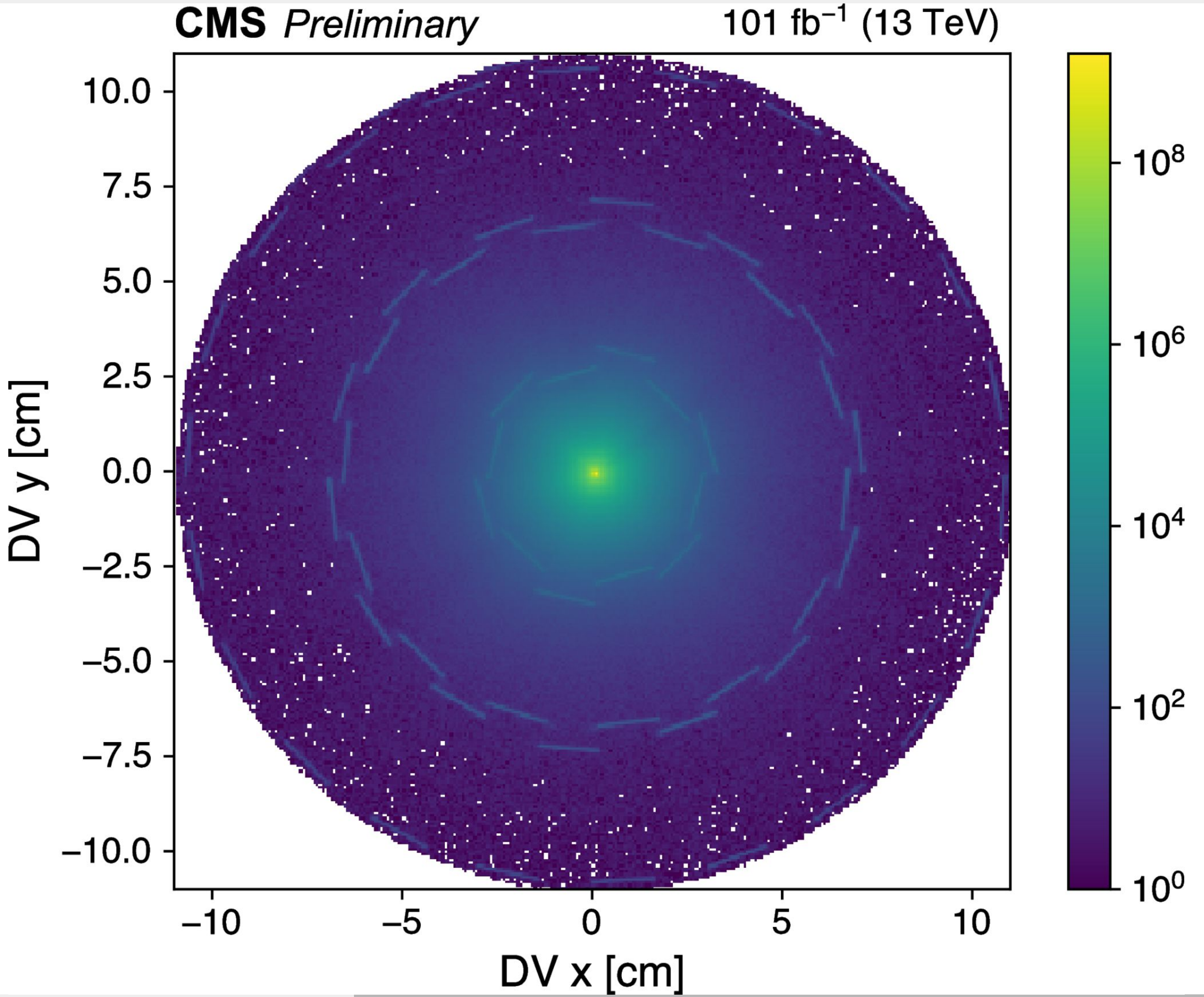
Phase Space of interest:

$2m[\mu] \leq m(Z_D) \leq 50$ GeV

$2m[\mu] \leq m(\phi) \leq 5$ GeV

$c\tau^0(Z_D/\phi) > 0$

- Scouting doesn't reject dimuons that are displaced.
- CMS pixel layers clearly visible in the displaced vertex (DV) plot shown alongside.
    - Requirement of ≥ 2 hits in pixel tracker in Run-2 restricts accessible transverse displacement (**l_{xy}**) of the dimuons to 11 cm



Event Selections

- Select events with 2 good muons and 1 associated displaced vertex (DV)

Muons

- [tracker + muon sys.]
- $p_T > 3$ GeV, $|\eta| < 2.4$
- $\chi 2/\text{ndf} < 3$

DV

- $\sigma(x), \sigma(y) < 0.01$ cm
- $\sigma(x) < 0.05$ cm
- $\chi 2/\text{ndf} < 5$, $l_{xy} < 11$ cm

Isolation (binned)

- Track Isolation < 0.01
  - Cone of $\Delta R = 0.3$
- Min ΔR ($\boldsymbol{\mu}$, jet) > 0.3
  - HLT calo-jets with $p_T > 20$

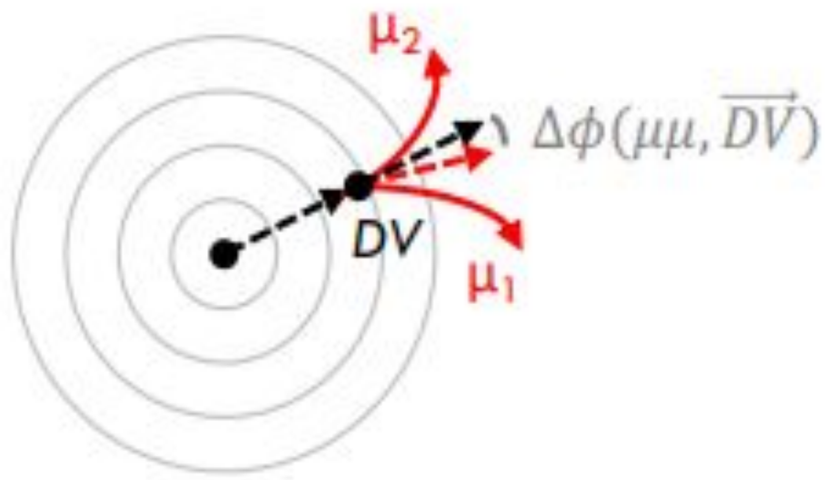
- Isolation is not an explicit requirement due to the fact that $\boldsymbol{\mu}$'s originate from $B \rightarrow \phi X$.
  - Events binned as fully isolated, partially isolated and non isolated.
  - Enables us to maximize sensitivity to the signal

Background Sources

- Fake vertices from accidental crossings of cosmic muons, QCD multijet events etc.
- Fake vertices from interaction with detector material.
- Fake vertices from overlapping PU tracks
- Prompt muons since we focus on a displaced search.

Background Suppression

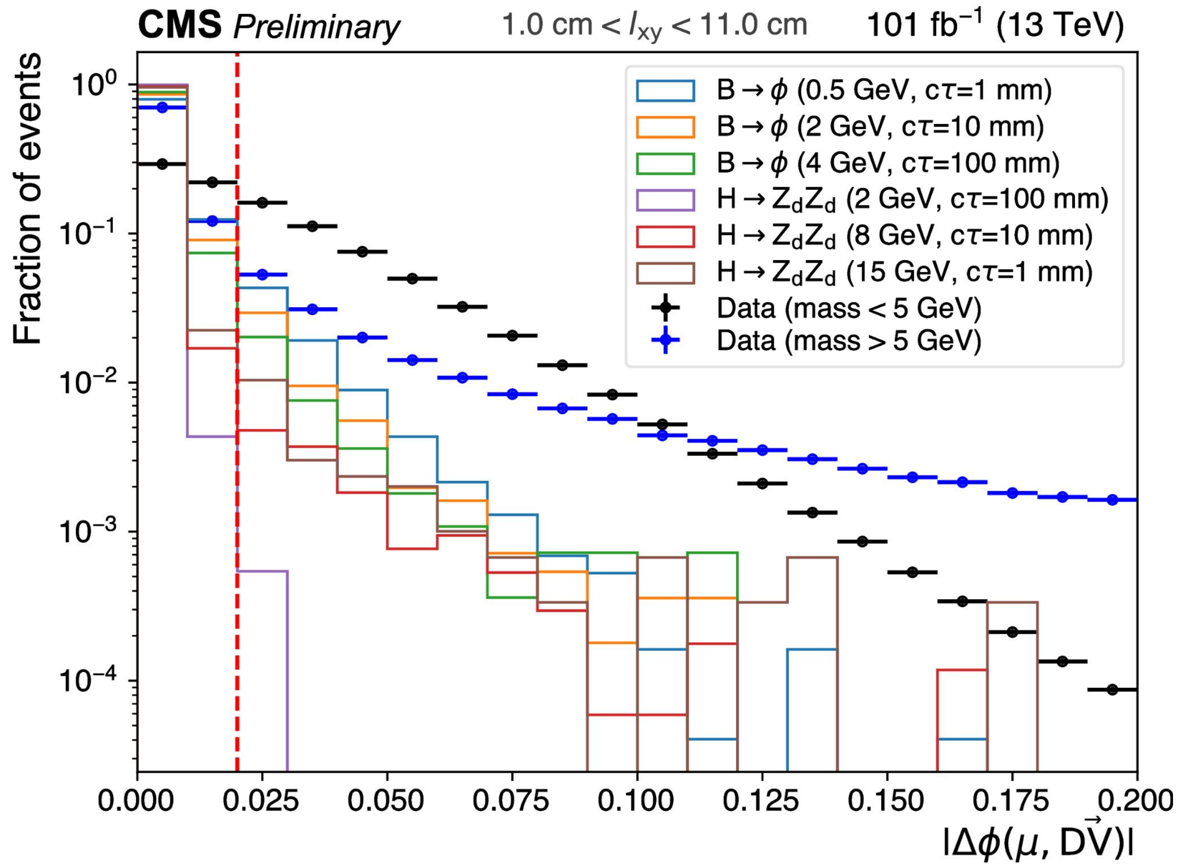
- **Fake vertices from accidental crossings of cosmic muons, QCD multijet events etc.**



➢ Exploit event topology of the decays.

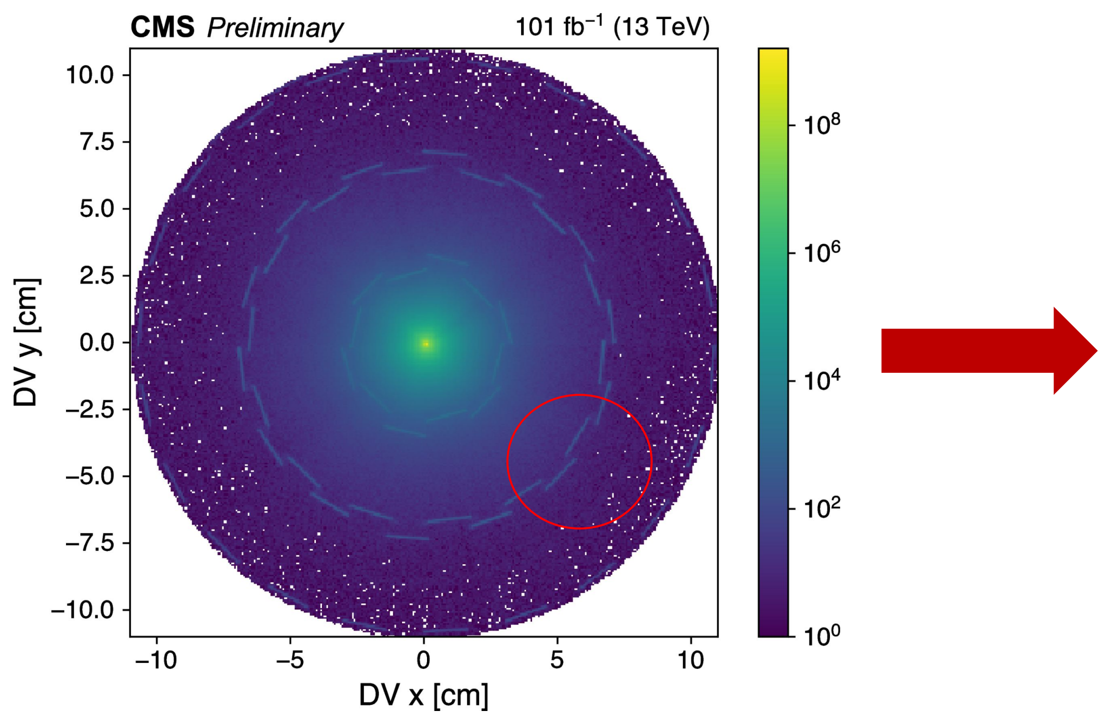
➢ Reject dimuon systems with large opening angles.
- Require $\Delta\phi$ (**μ,μ**) < 2.8 to suppress dimuons formed by accidental crossings.

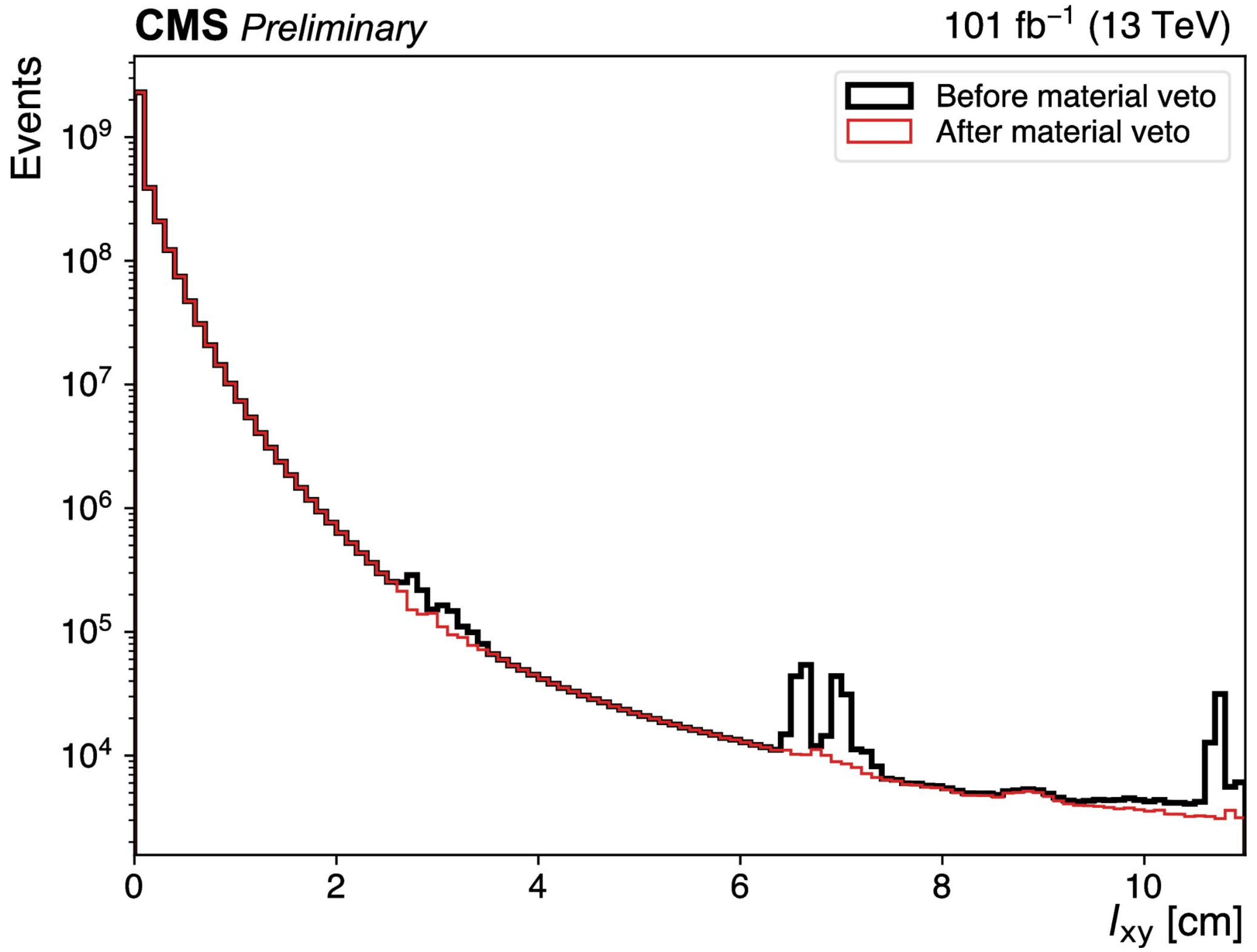
➢ Dimuon system collinear with DV vector for signal.
- Require $\Delta\phi$ (**μμ**, DV) < 0.02 to to further suppress background.



Background Suppression

- **Fake vertices from interaction with detector material.**
  - ➢ DV's in pixel module plane are vetoed to suppress material vertices.
    - ○ Require DV to be > 0.05 cm from the nearest pixel module plane

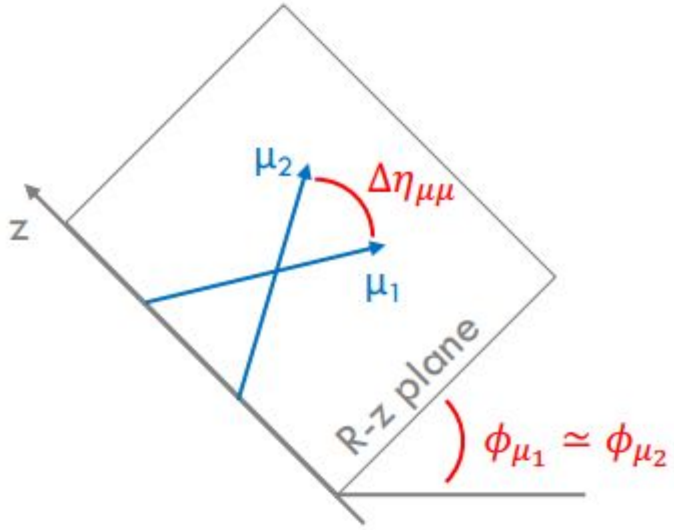


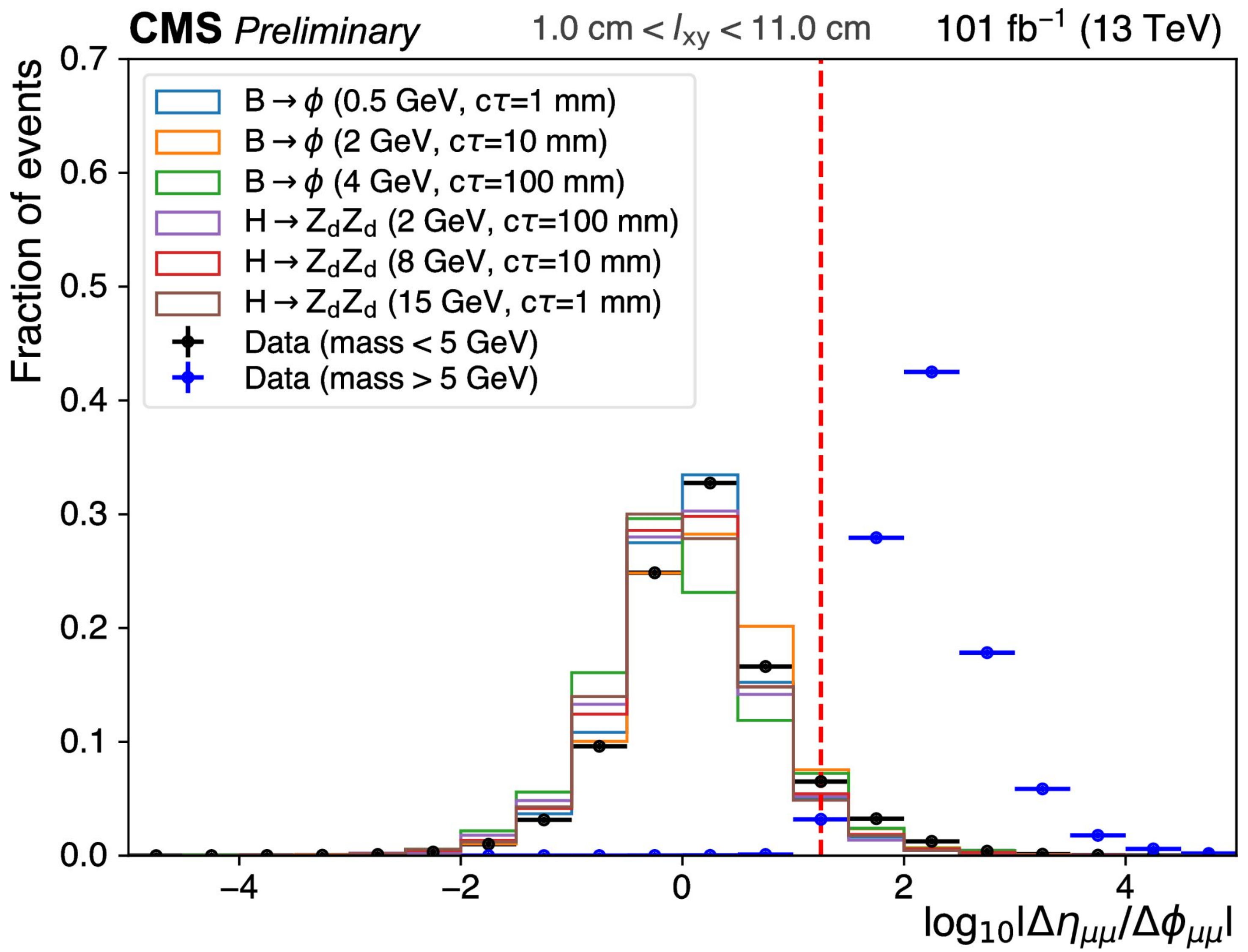


Background Suppression

- **Fake vertices from overlapping pileup (PU) muon tracks.**

➢ Pileup muon tracks are overlapping in R-ϕ plane ($\Delta\phi_{\mu\mu}$ ~ 0) and separated in R-z plane.
  - Require $\log_{10}(\Delta\eta / \Delta\phi) < 1.25$ to suppress PU background.





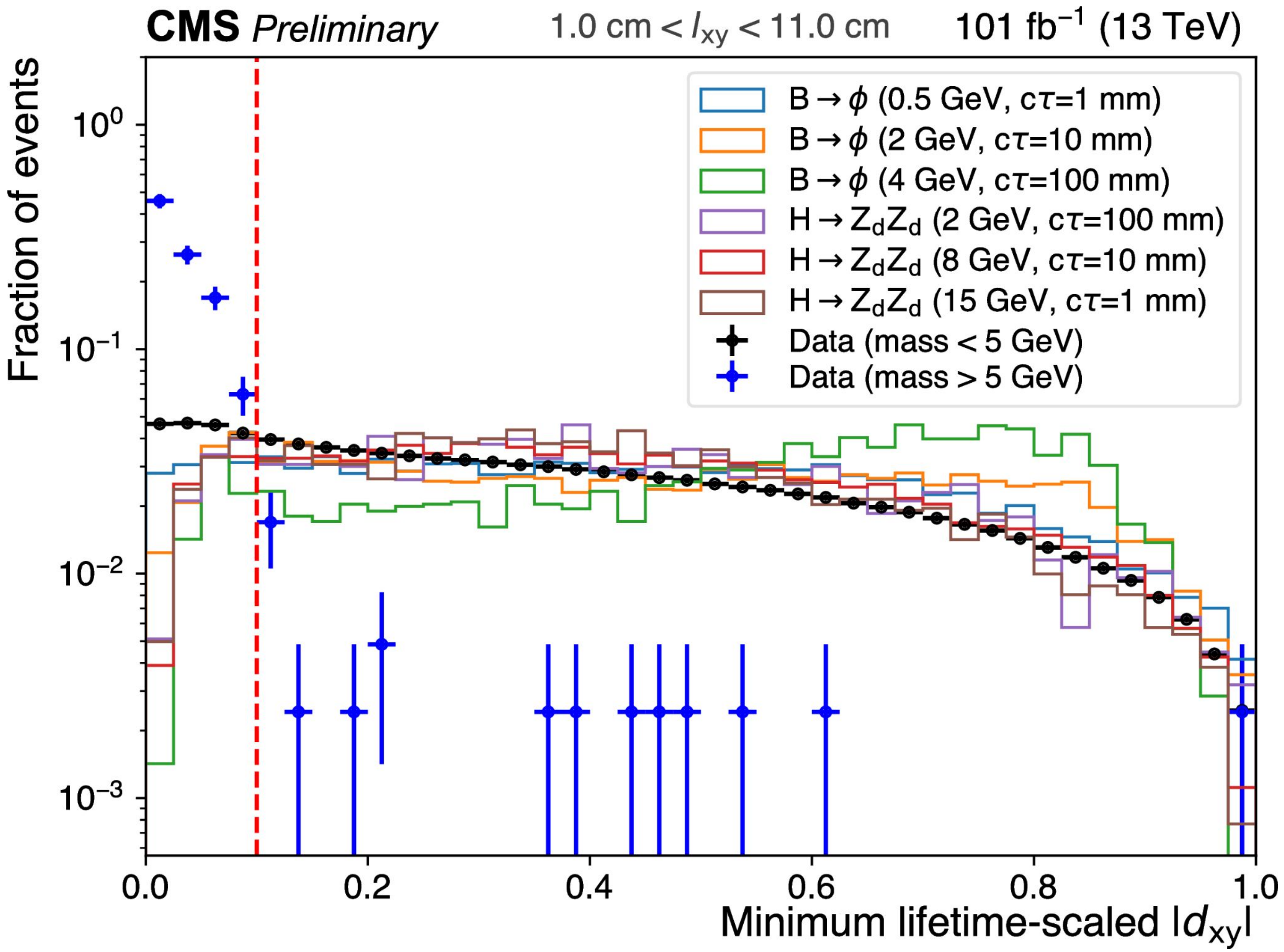
Background Suppression

- **Prompt muons since we focus on a displaced search.**

  ➢ Reject prompt muons using impact parameter (IP).

  ➢ Require IP significance $|d_{xy}/\sigma_{xy}| > 2$.

  ➢ Require lifetime scaled IP $|d_{xy}/(l_{xy}.m_{\mu\mu}/p_T^{\mu\mu})| > 0.1$.
  - IP scaled by lifetime to enable a single selection for different lifetimes.



Background Sources - B

Dimuon signatures originating from b quark.

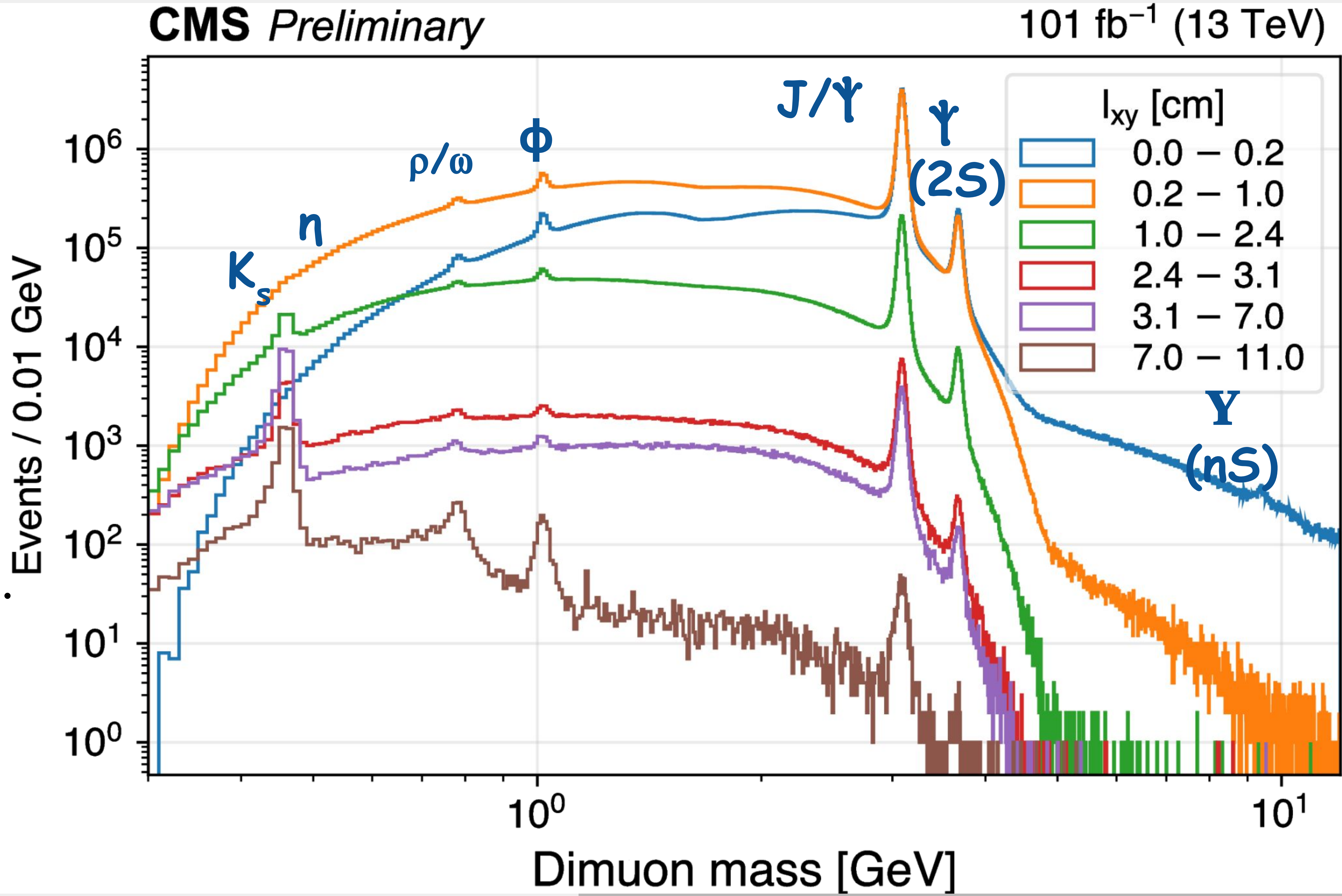
- ➢ Requiring IP selections reject prompt contribution.
- ➢ Harder selection on displacement would result in significant loss of signal efficiency.
- ➢ Do search in bins of displacement. (more info. in next slides)

- ❖ $b \rightarrow X + \Upsilon(nS) \rightarrow \boldsymbol{\mu\mu}$
    - ■ Veto J/ϒ and ϒ(2S) resonances.
    - ■ Also veto other known SM dimuon resonances.

- ❖ $b \rightarrow \boldsymbol{\mu\nu}\ (X_c \rightarrow \boldsymbol{\mu\nu}\ X_s)$
    - ■ Cascade B decays: semi-leptonic B decay followed by a semi-leptonic D decay.
    - ■ Requiring vertexing quality cuts already reject such fake pairs from cascade decays.
    - ■ p_T of the second muon from D decay very soft and usually fall outside our threshold.

Dimuon Mass Spectrum

- Dimuon mass distributions inclusive in dimuon p_T and isolation shown on the right in successive l_{xy} bins.
- Background mostly at $m_{\mu\mu} < 5$ GeV dominated by cascade B-decays.
- Background suppressed at higher l_{xy} bins.
- $K_s \to \pi\pi$ where π mis-identified as $\boldsymbol{\mu}$ appears at higher l_{xy} bins. ($c\boldsymbol{\tau}^0 \sim 27$ mm)



Search Strategy

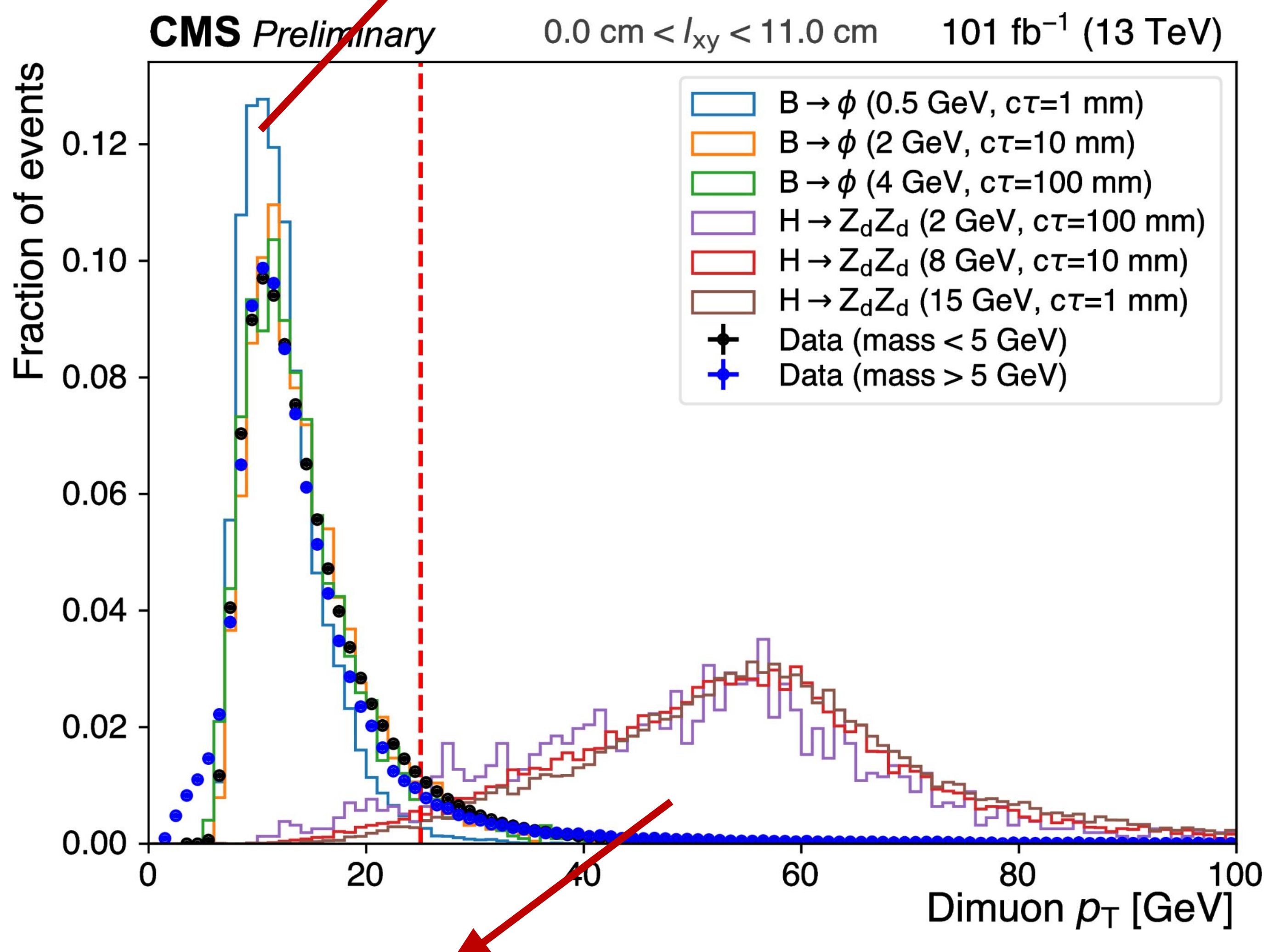
- Events categorized in 36 categories of $\mathbf{l_{xy}}$, $\mathbf{p_T}$ and **isolation** to maximize sensitivity to a wide range of mass/c$\boldsymbol{\tau}$ hypotheses.

- Six bins of l_{xy}: [0, 0.2, 1, 2.4, 3.1, 7, 11] cm based on tracker geometry.

- Further categorize events in bins of **dimuon** $\mathbf{p_T}$ [0, 25, ∞] and **isolation** bins.

- Look for narrow resonant peak over the background continuum by simultaneous fit in all event categories.

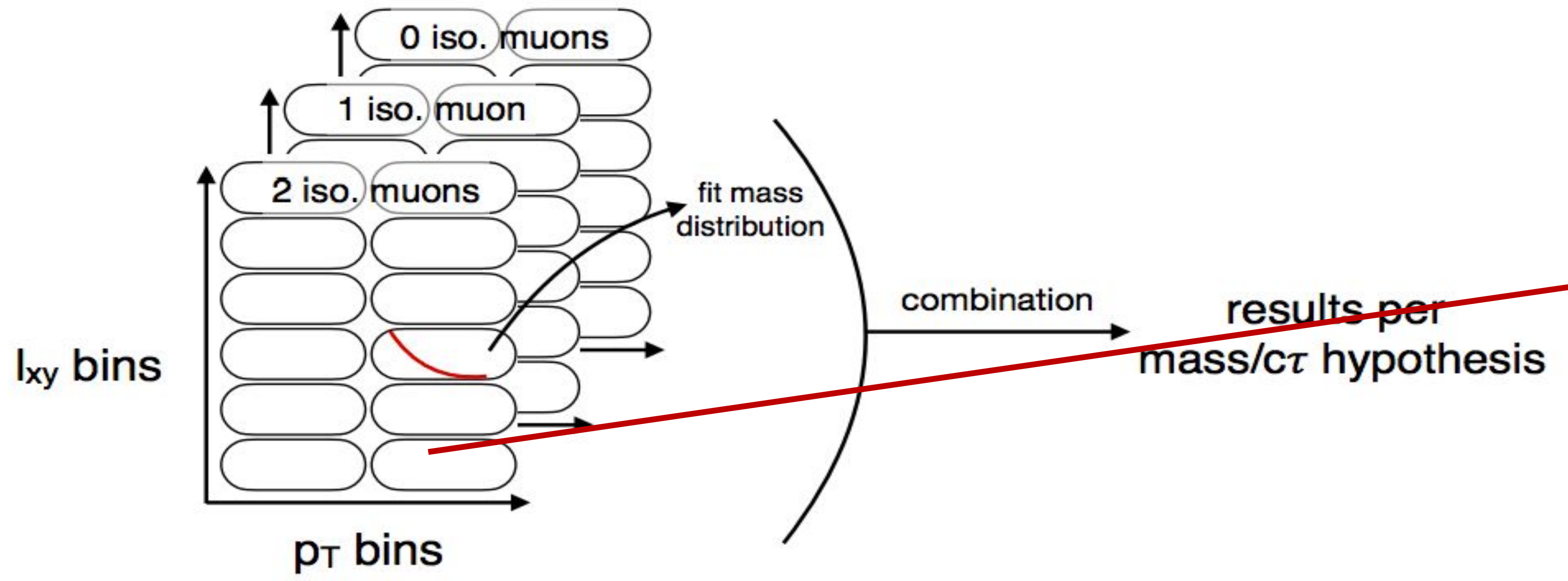
$B \rightarrow \phi X$ lives in low p_T phase space.

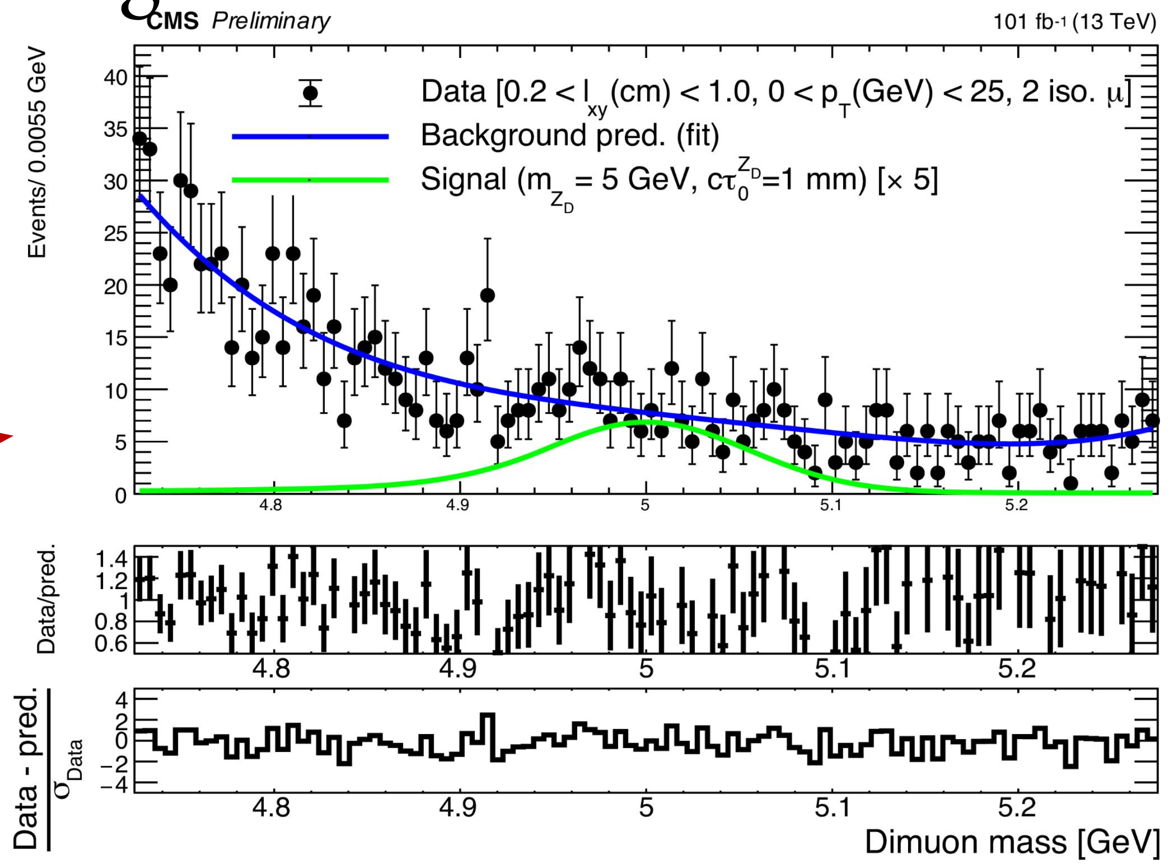


$H \rightarrow Z_D Z_D$ lives in high p_T phase space.

Search Strategy

- Scan in steps of Z_D/ϕ mass and windows according to signal mass resolution σ.
    - σ ~ 1.1% of mass and window = +/- 5 σ about the mass hypothesis (signal shape: dCB+Gaus).
- Polynomial + Exponential functional forms used fit the dimuon mass spectrum.
    - Best order chosen by modified F-Test.
    - Discrete profiling used to account for uncertainties in choice of background function.

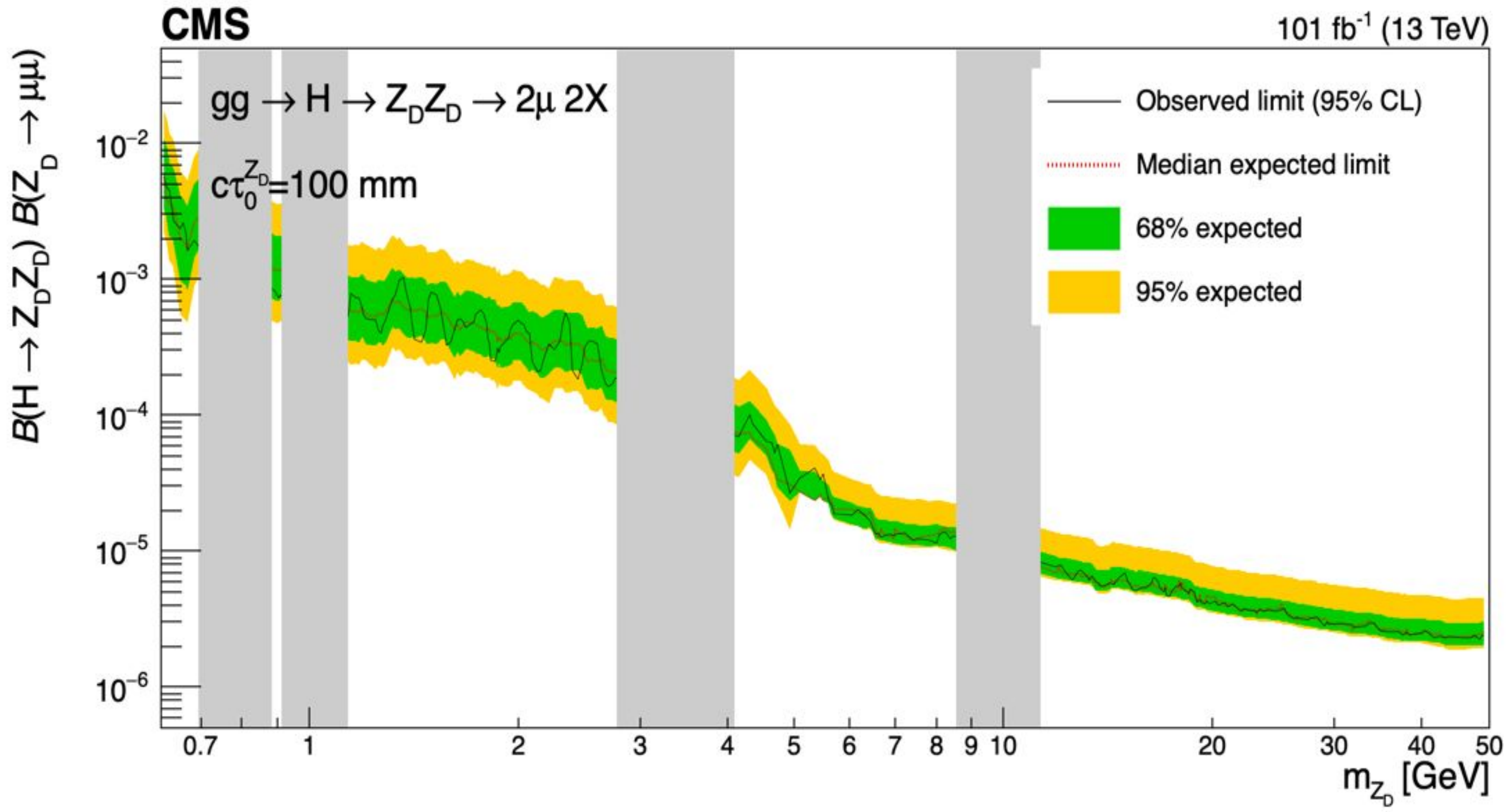




Results: UL on $BR(H \rightarrow Z_D Z_D) \cdot BR(Z_D \rightarrow \boldsymbol{\mu\mu})$

- Upper limits at 95% CL on $BR(H \rightarrow Z_D Z_D) \cdot BR(Z_D \rightarrow \boldsymbol{\mu\mu})$ are shown as a function of mass for $c\boldsymbol{\tau}^{ZD}{}_0 = 100$ mm.

- Only dimuon events used. No assumption on $BR(Z_D \rightarrow \boldsymbol{\mu\mu})$ to keep it model independent.



4μ category

- $H \to Z_D Z_D \to 4\mu$ channel is background free at low masses compared to 2μ category but has an acceptance penalty due to $BR^2(Z_D \to \mu\mu)$

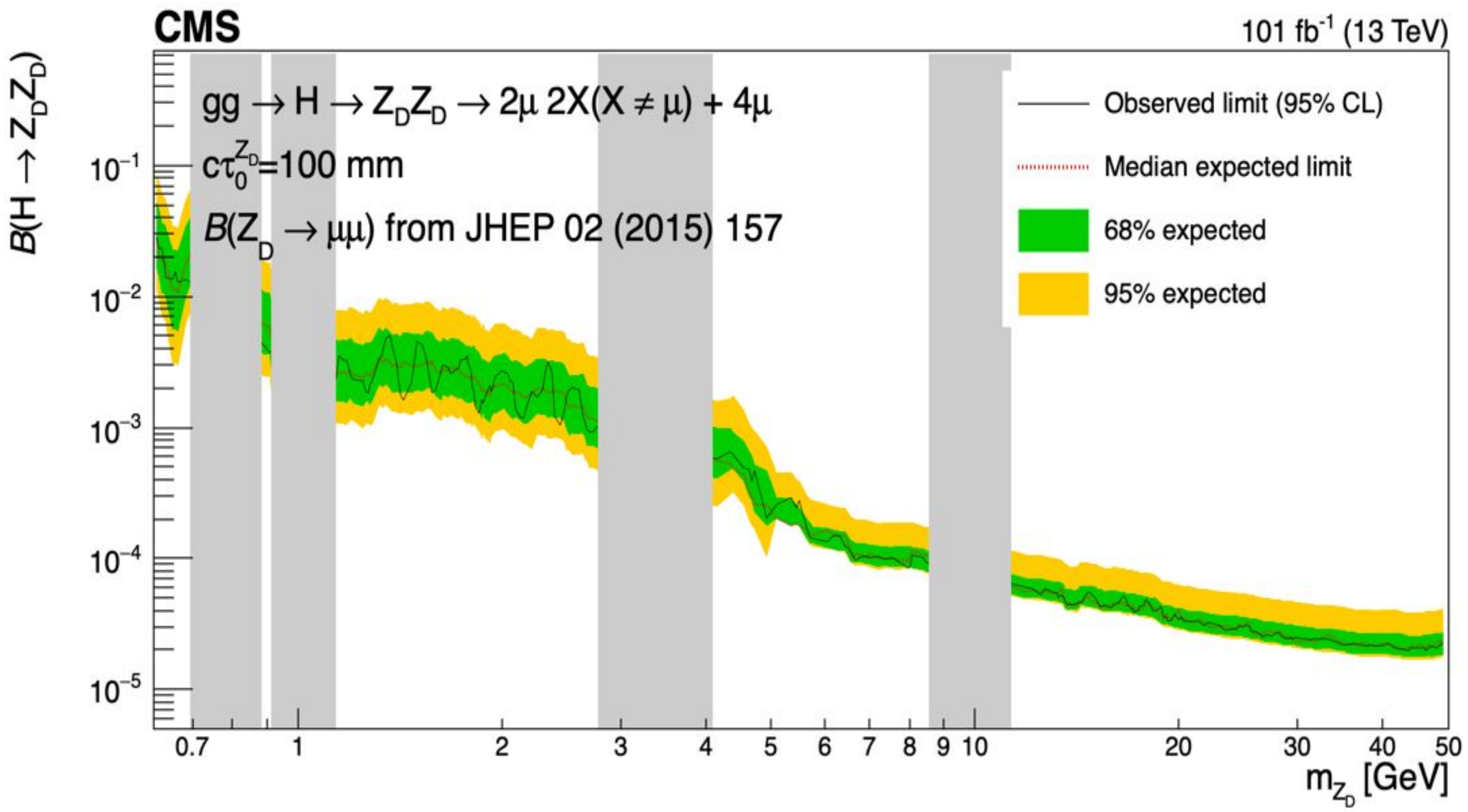
- Select events with good 4μ candidate($115 < M_{4\mu} < 135$)
  - Same selections on second muon pair as in slide 9,10 with few relaxed requirements
  - SR: Require mass difference between two dimuon pairs to be less than 5% of their average

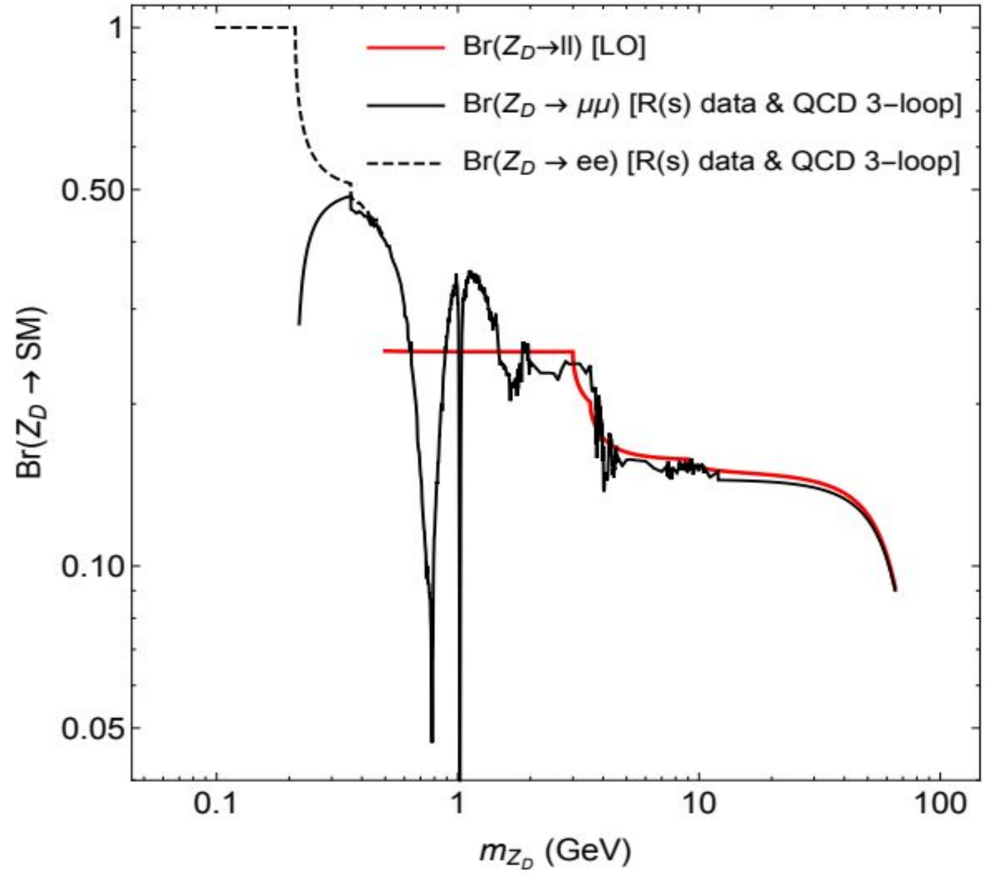
- One extra channel per ($m(Z_D)$, $c\tau(Z_D)$) point added to previous 36 channels from dimuon mass bins (6 lxy × 2 pT × 3 iso)

- We observe exactly 0 events in four muon mass distribution in [115 GeV , 135 GeV]

Results: UL on BR($H \rightarrow Z_D Z_D$)

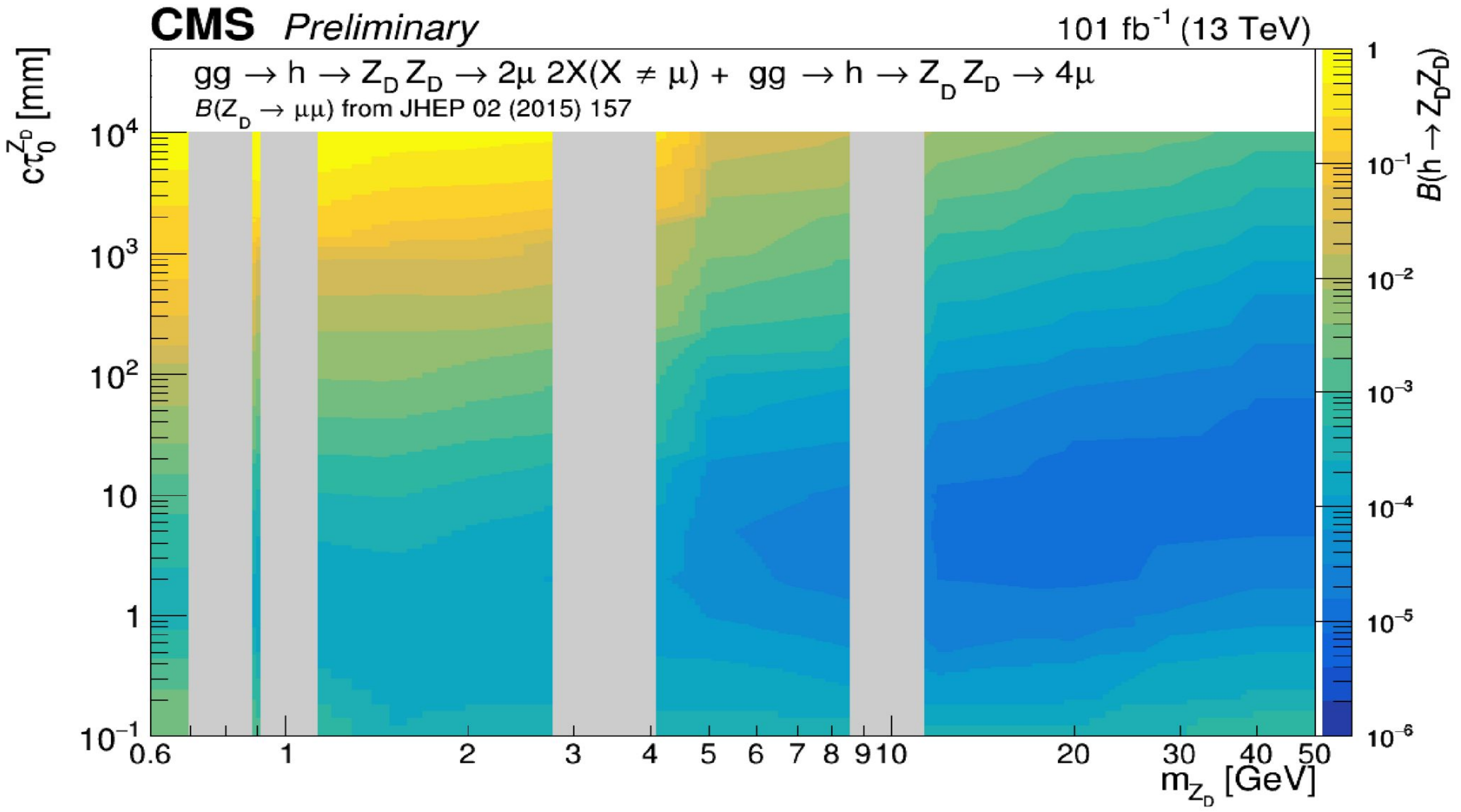
- Upper limits at 95% CL on BR($H \rightarrow Z_D Z_D$) are shown as a function of mass for $c\tau^{ZD}_0 = 100$ mm.
- 2μ and 4μ events used. BR($Z_D \rightarrow \mu\mu$) from [JHEP 02 (2015) 157]

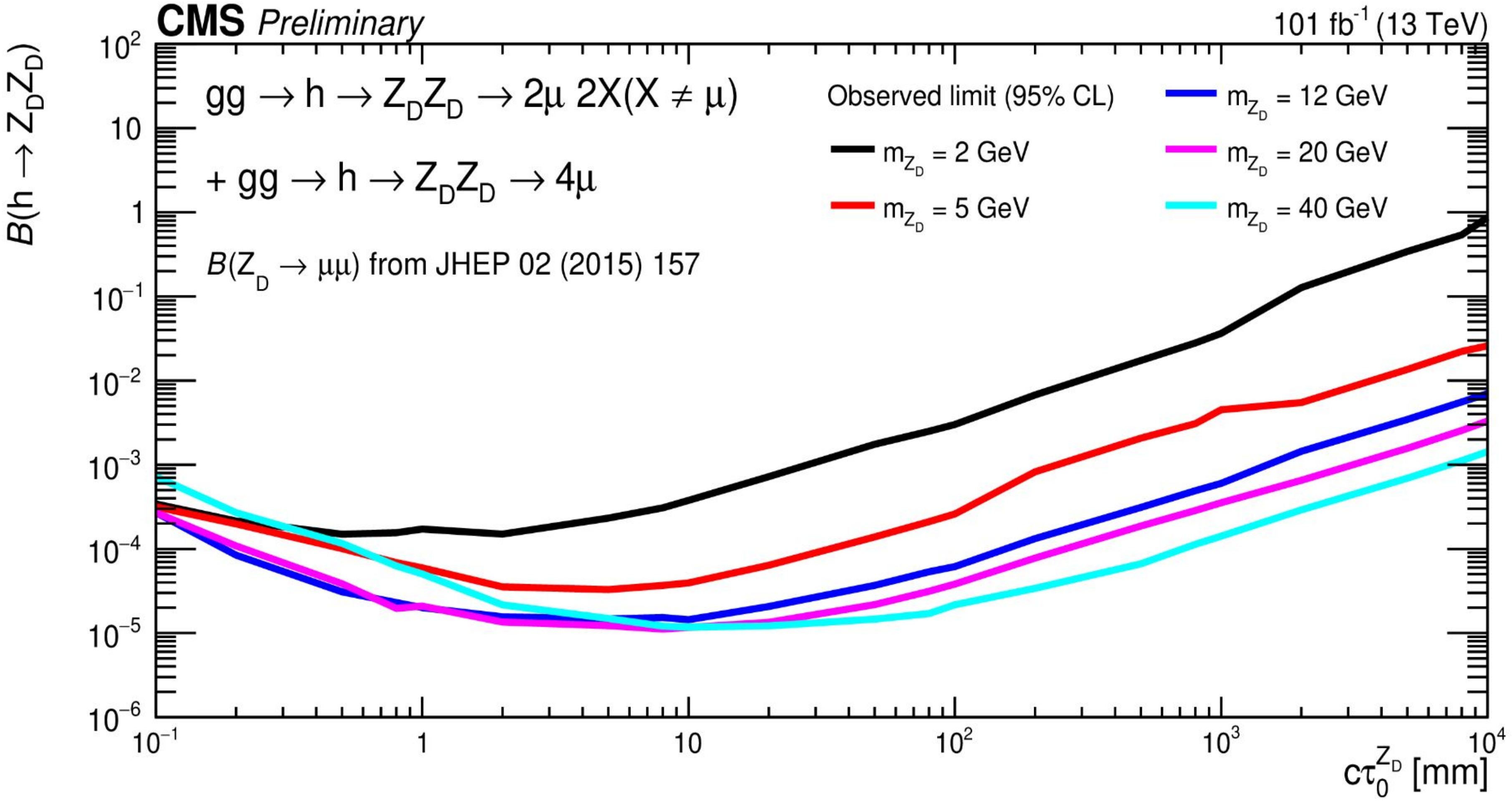




Results: UL on BR($H \rightarrow Z_D Z_D$)

- Upper limits at 95% CL on BR($H \rightarrow Z_D Z_D$) are shown in $c\tau^{ZD}_0$ - m_{ZD} plane as well as a function of $c\tau^{ZD}_0$ for various mass hypotheses of Z_D.
  - At low m_{ZD} and high $c\tau^{ZD}_0$, the constraints are weaker because of low signal acceptance due to Z_Ds boost.
  - At high m_{ZD} and intermediate $c\tau^{ZD}_0$, the constraints are stronger due to lower backgrounds at larger displacements

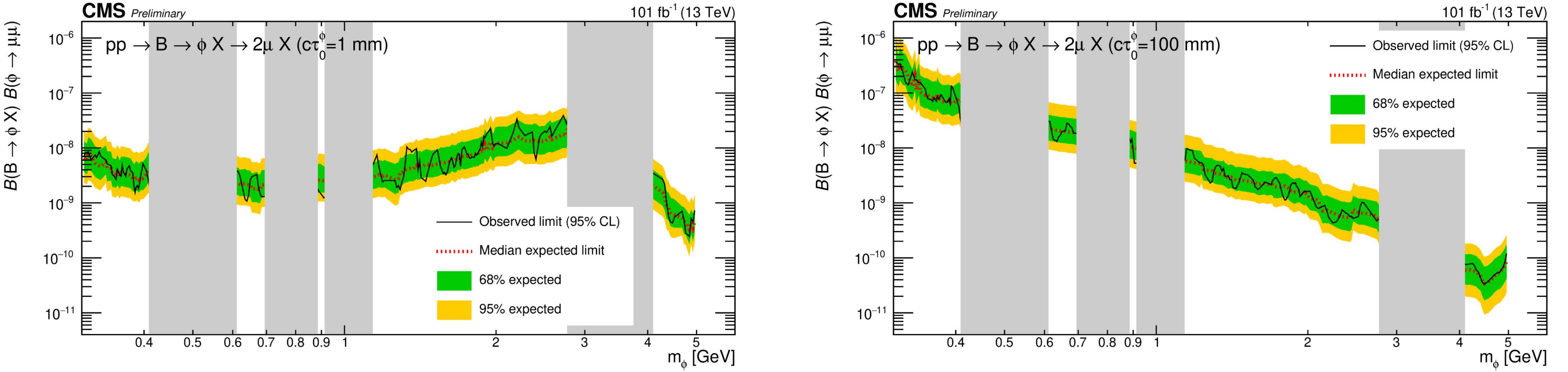




Results: UL on BR(B → ϕX) . BR(ϕ → μμ)

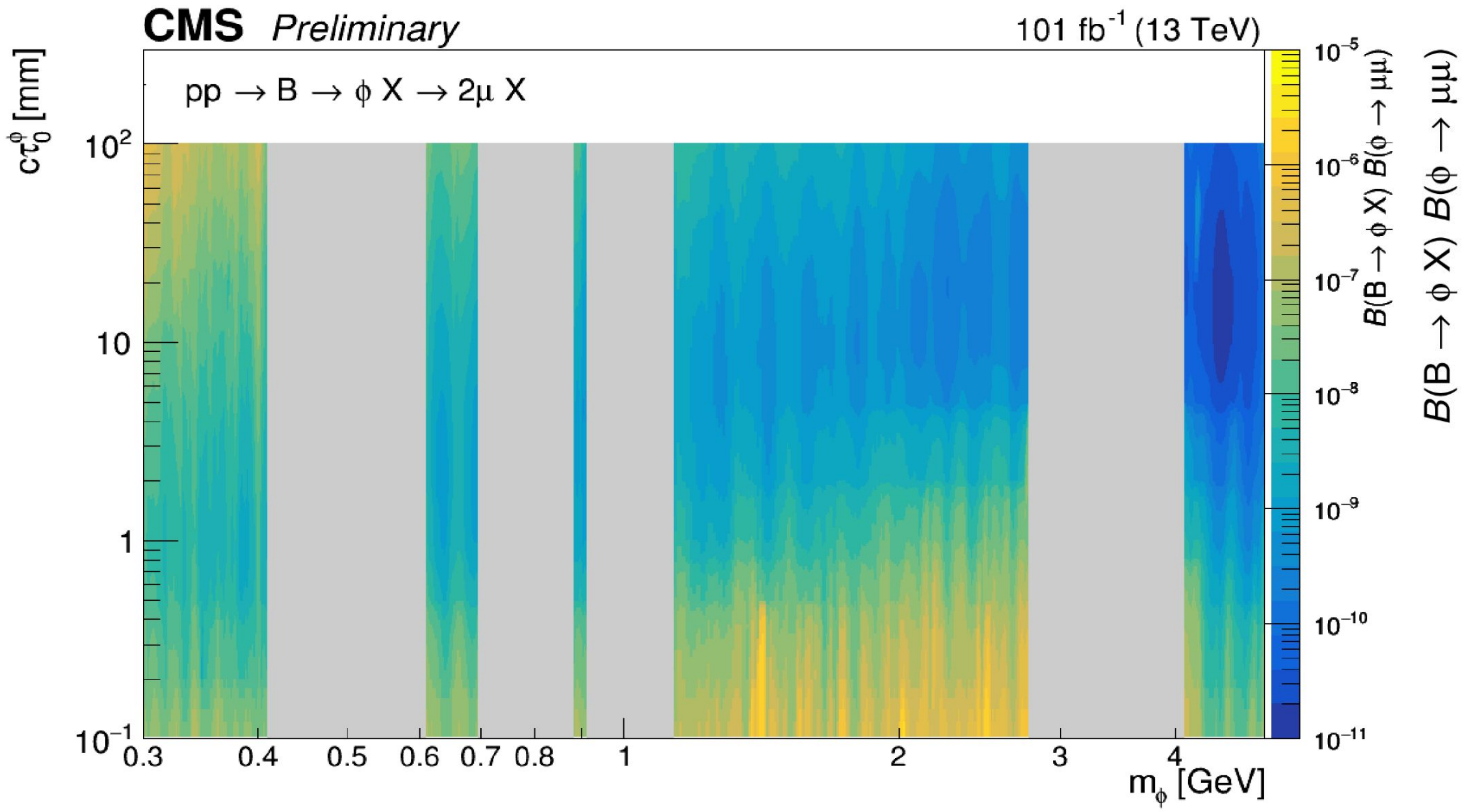
- Upper limits at 95% CL on BR(B → **ϕ**X) . BR(**ϕ** → **μμ**) are shown as a function of mass for two different lifetime hypotheses of **ϕ**. (Left: $c\tau^{\phi}_{0}$ = 1 mm , Right: $c\tau^{\phi}_{0}$ = 100 mm).

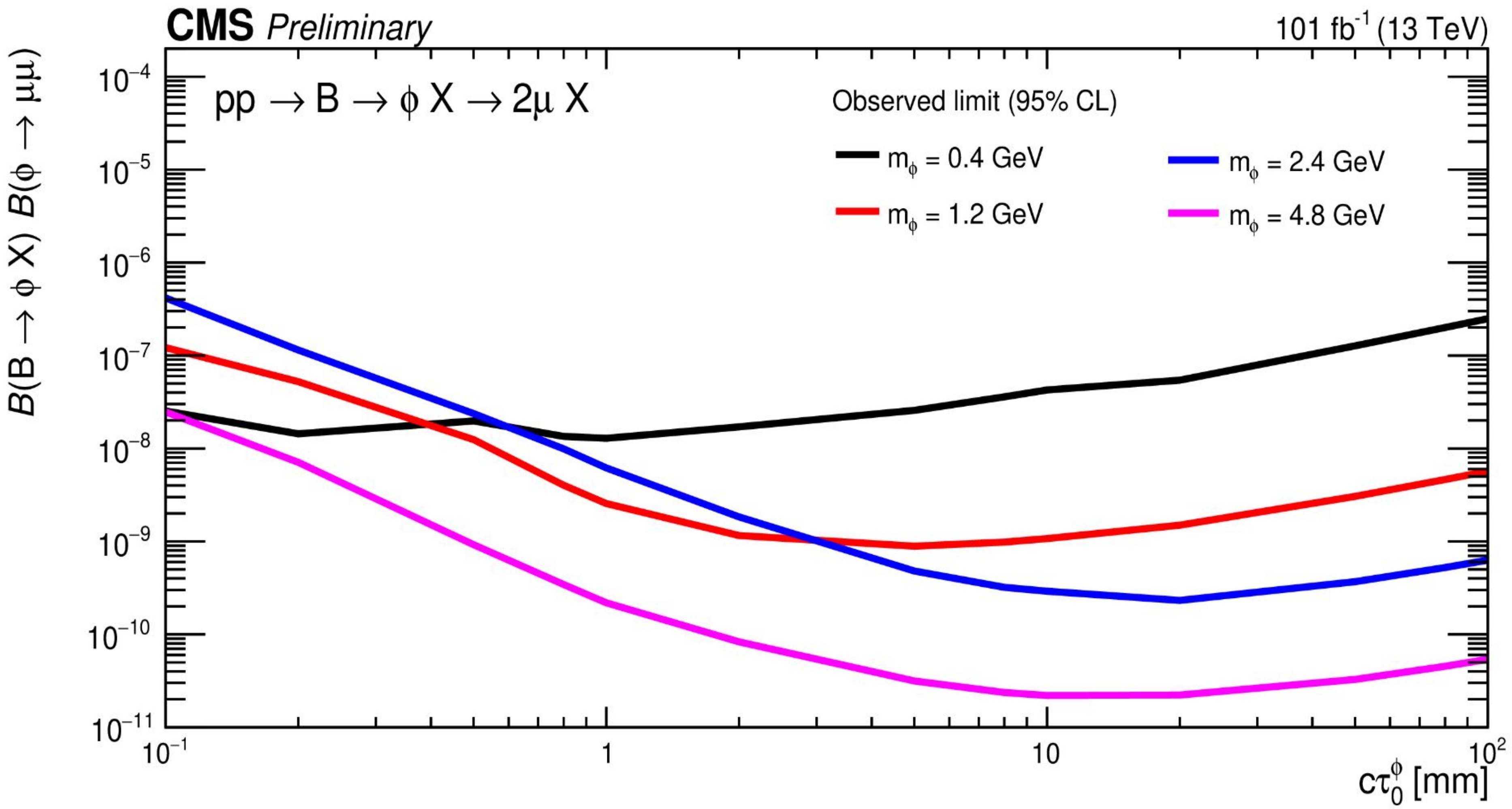
- No assumption on BR(**ϕ** → **μμ**) to keep it model independent.



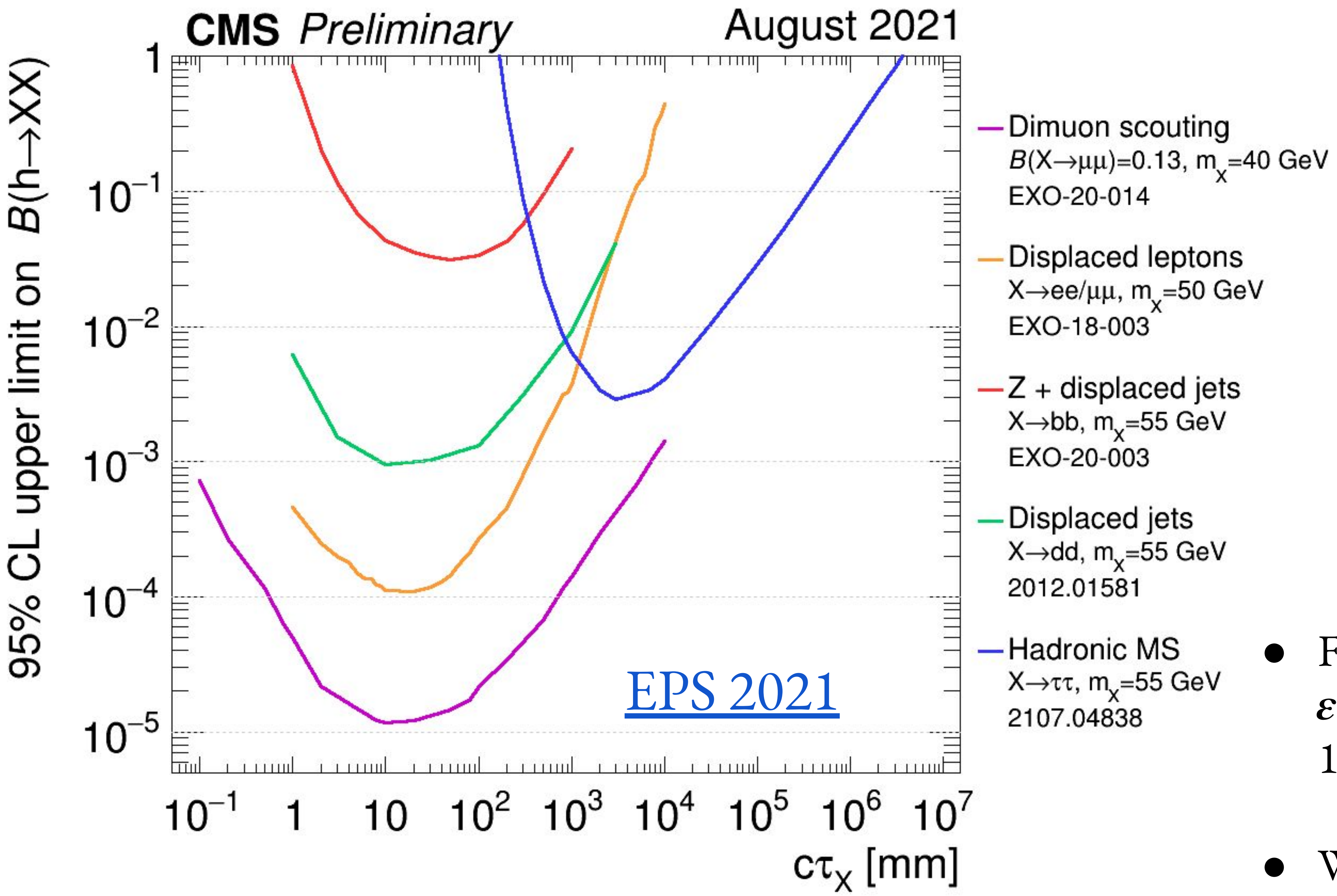
Results: UL on BR(B → ϕX) . BR(ϕ → $\mu\mu$)

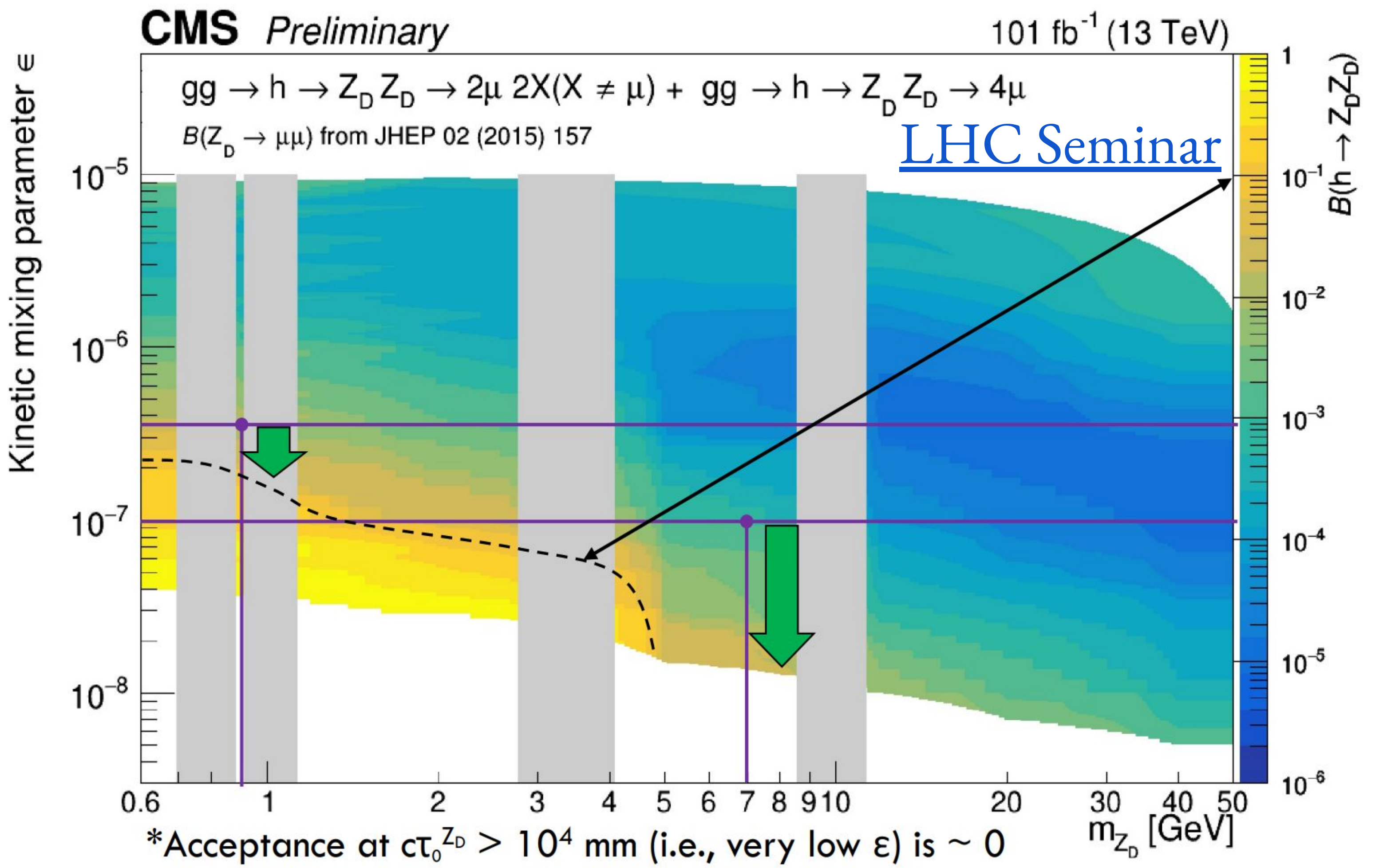
- Upper limits at 95% CL on BR(B → ϕX) . BR(ϕ → $\mu\mu$) are shown in $c\tau^{\phi}_{0}$ - m_{ϕ} plane as well as a function of $c\tau^{\phi}_{0}$ for various mass hypotheses of ϕ.
  - At high m_{ϕ} and high $c\tau^{\phi}_{0}$, the constraints are stronger due to lower backgrounds at larger displacements
  - At low m_{ϕ} and high $c\tau^{\phi}_{0}$, the constraints are weaker because of low signal acceptance due to ϕ's boost.





Comparison with CMS/ATLAS ($H \rightarrow Z_D Z_D$)



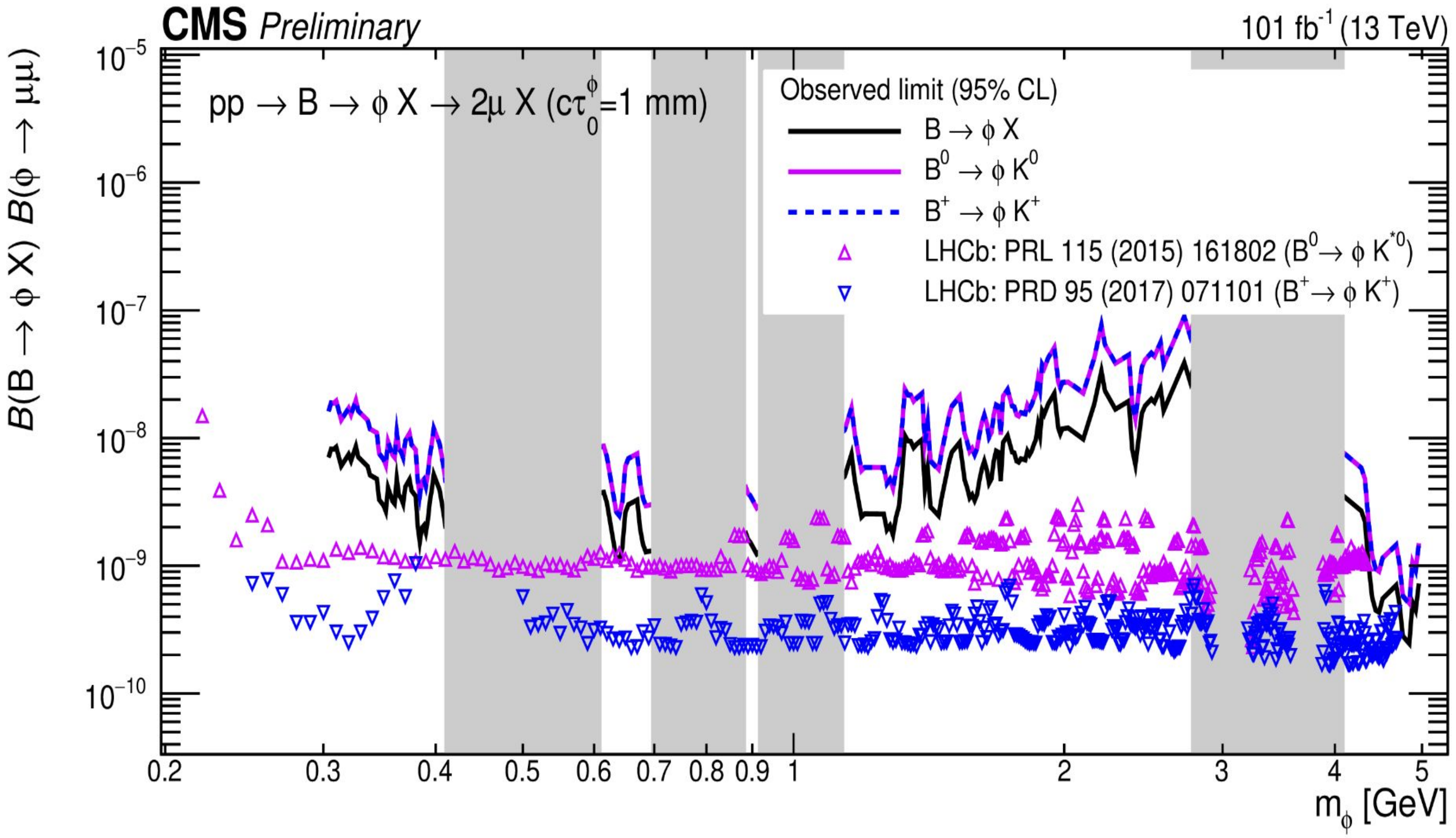


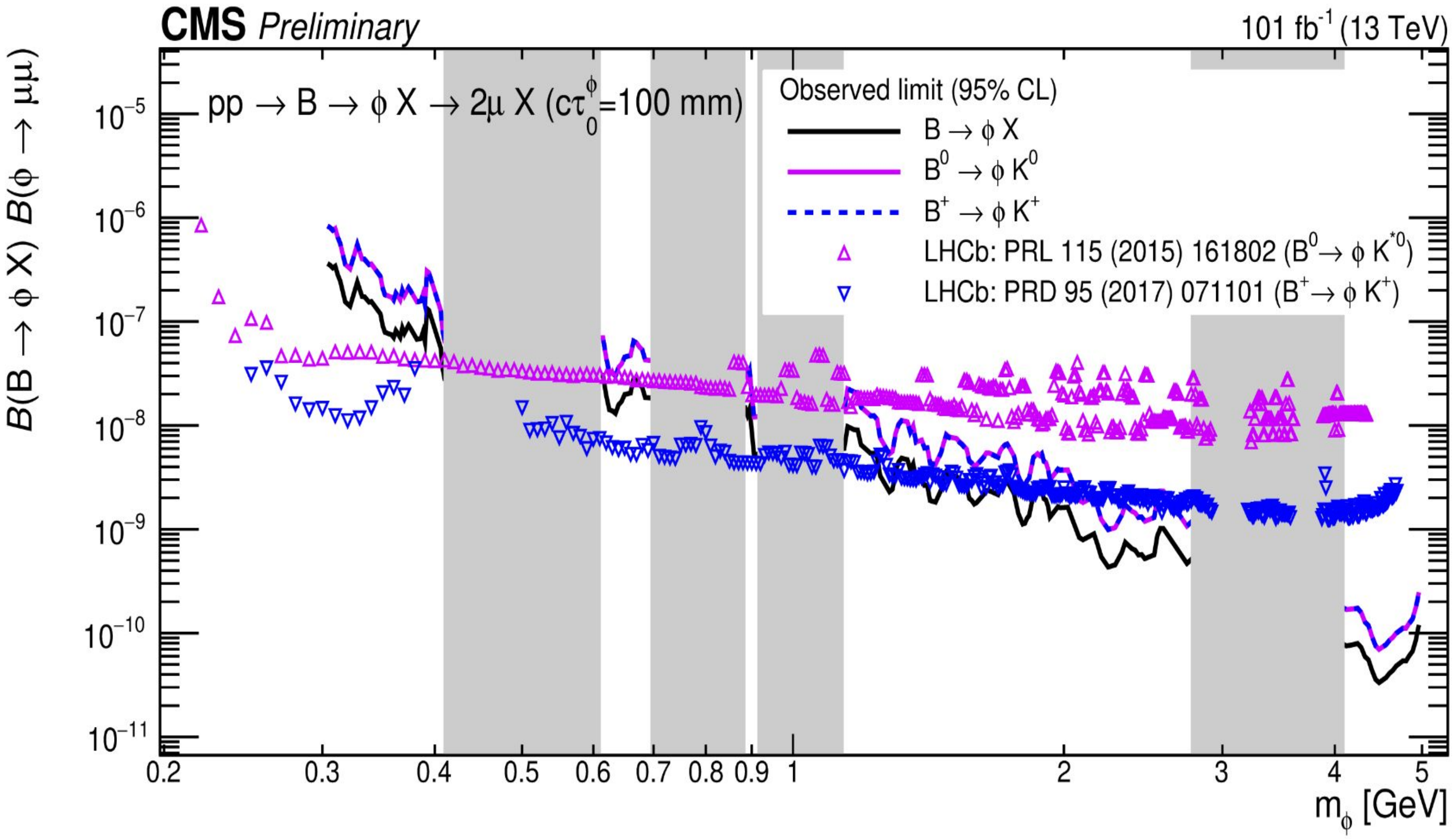
- For BR ($H \rightarrow Z_D Z_D$) = 0.1 at 90 % CL, ATLAS excludes $\varepsilon > 3.5 \cdot 10^{-7}$ for m(Z_D) ~ 0.9 GeV and CMS excludes $\varepsilon > 10^{-7}$ for m(Z_D) ~ 7 GeV

- We set stronger constraints by 2x ~ 10x

Comparison with LHCb ($B \to \phi X$)

- Inclusive and exclusive UL at 95% CL on BR($B \to \phi X$) . BR($\phi \to \mu\mu$).
  - CMS inclusive limits are rescaled by fraction of $B^0/B^{\pm}$ to compare with LHCb's UL on exclusive B decays, ($B^0 \to \phi K^{*0}$ / $B^{\pm} \to \phi K^{\pm}$).
  - CMS sets stronger constraints at higher masses and lifetimes of ϕ.





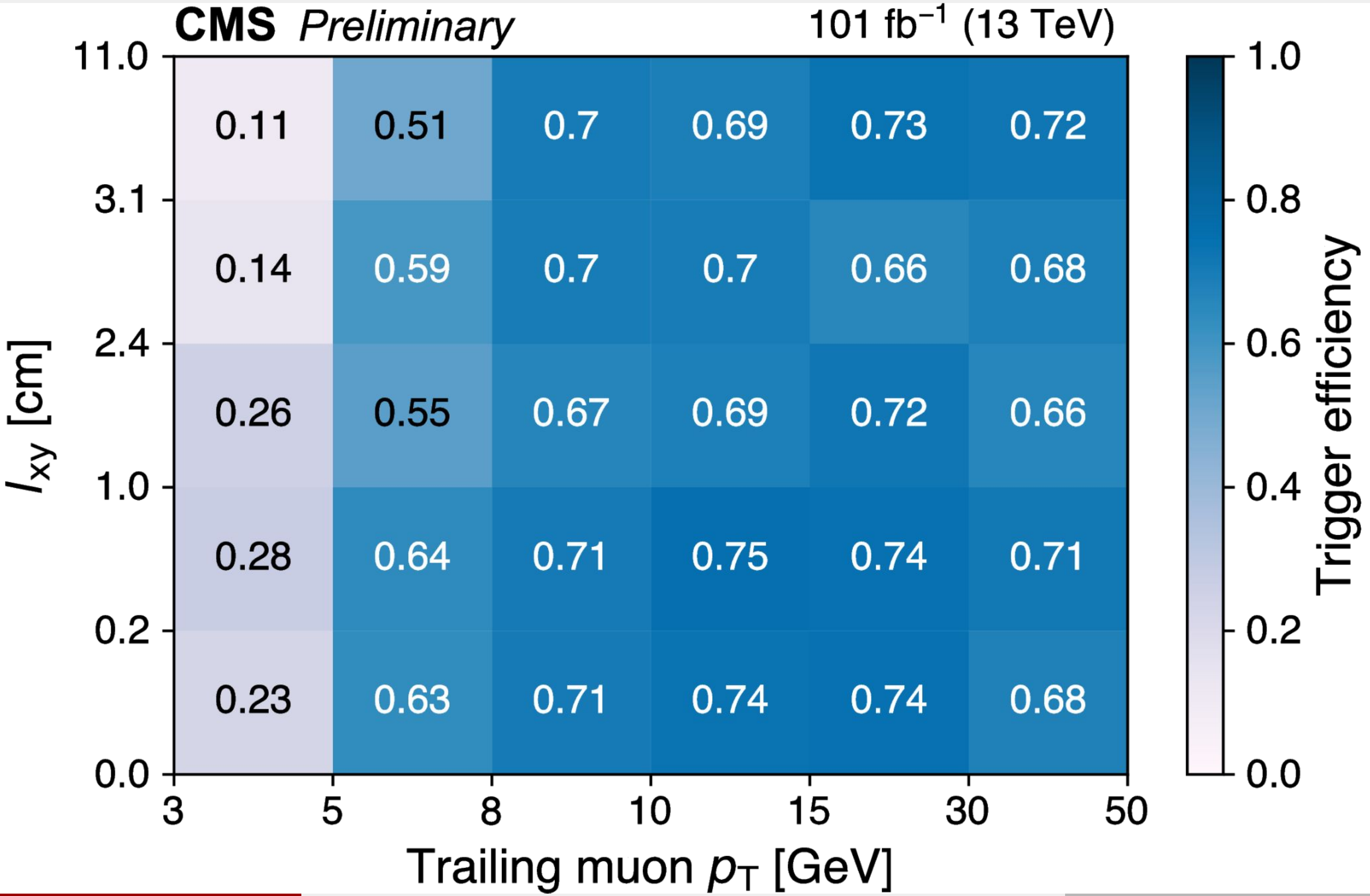
Summary

- We perform a first search for light scalars decaying to muons arising from flavor changing B decays at CMS using Run-2 data. We also set the most stringent constraints on $H \rightarrow Z_D Z_D$ in a large parameter space. (CMS-EXO-20-014)
- Data scouting enabled us to probe into this otherwise inaccessible low mass and long lived phase-space at CMS.
- The results from the search are motivating and CMS is competitive with LHCb.

THANK YOU

BACKUP

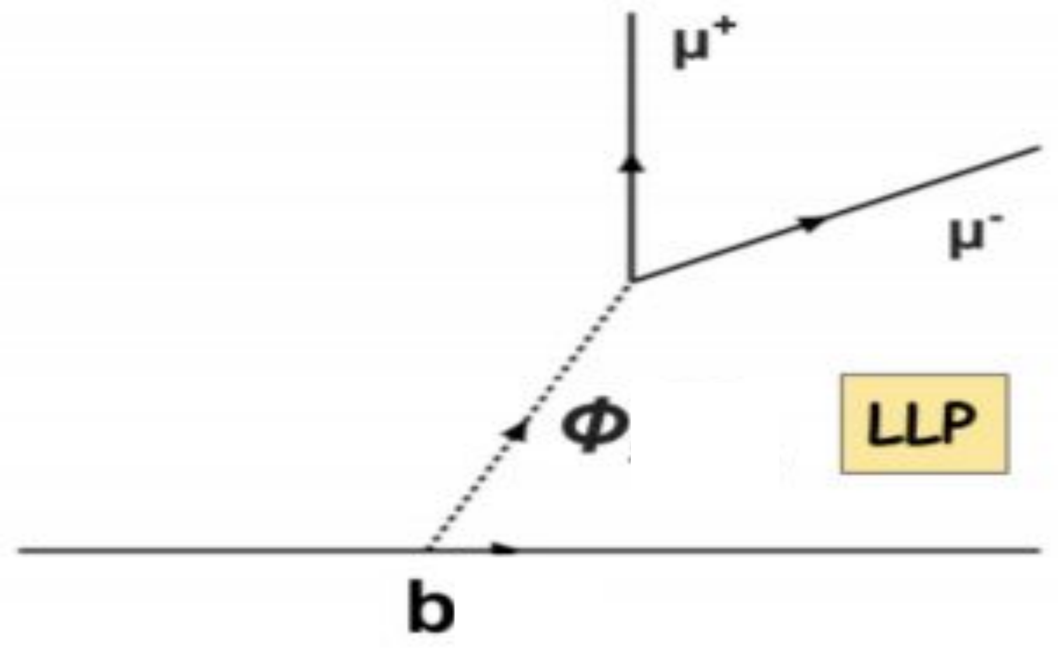
Scouting Trigger Efficiency



$B \to \phi X$ search strategy in CMS

- An inclusive search instead of focussing on exclusive B decay channels (e.g $B^+ \to \phi K^+$) to maximize signal acceptance.

- CMS geometric acceptance for $B \to \phi X$ higher than LHCb's vertex locator for dimuons with larger displacements.
  - Production of ϕ's not restricted to forward region.
  - ϕ could have significantly large lifetimes ($c\tau^0$ > few mm).
  - Expect comparable signal efficiency with LHCb even with stronger bkg. suppression in exclusive searches.



- In addition, the higher overall integrated luminosity gives CMS an edge.

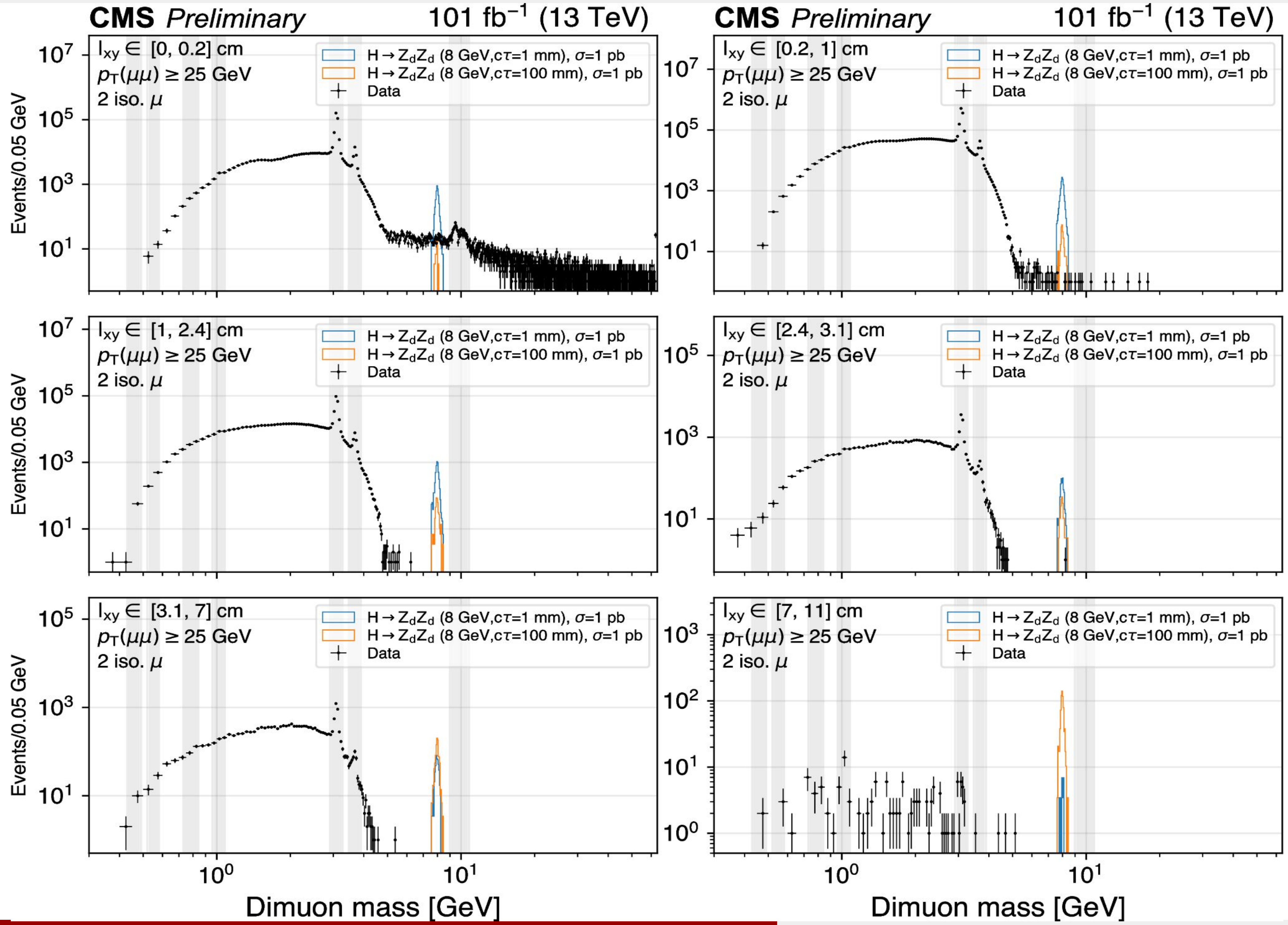
$B \to \phi X$ Monte Carlo

- $B \to \phi X$ events generated with PYTHIA 8.2 with $X = K^{+}, K^{0}, \varphi(ss), \Lambda, D_{s}^{+}$ for $B = B^{+}, B^{0}, B_{s}, \Lambda_{b}, B_{c}$
- B MC is reweighted to FONLL, both in terms of the absolute cross-section and the p_T of the B-hadron

Masked SM resonances

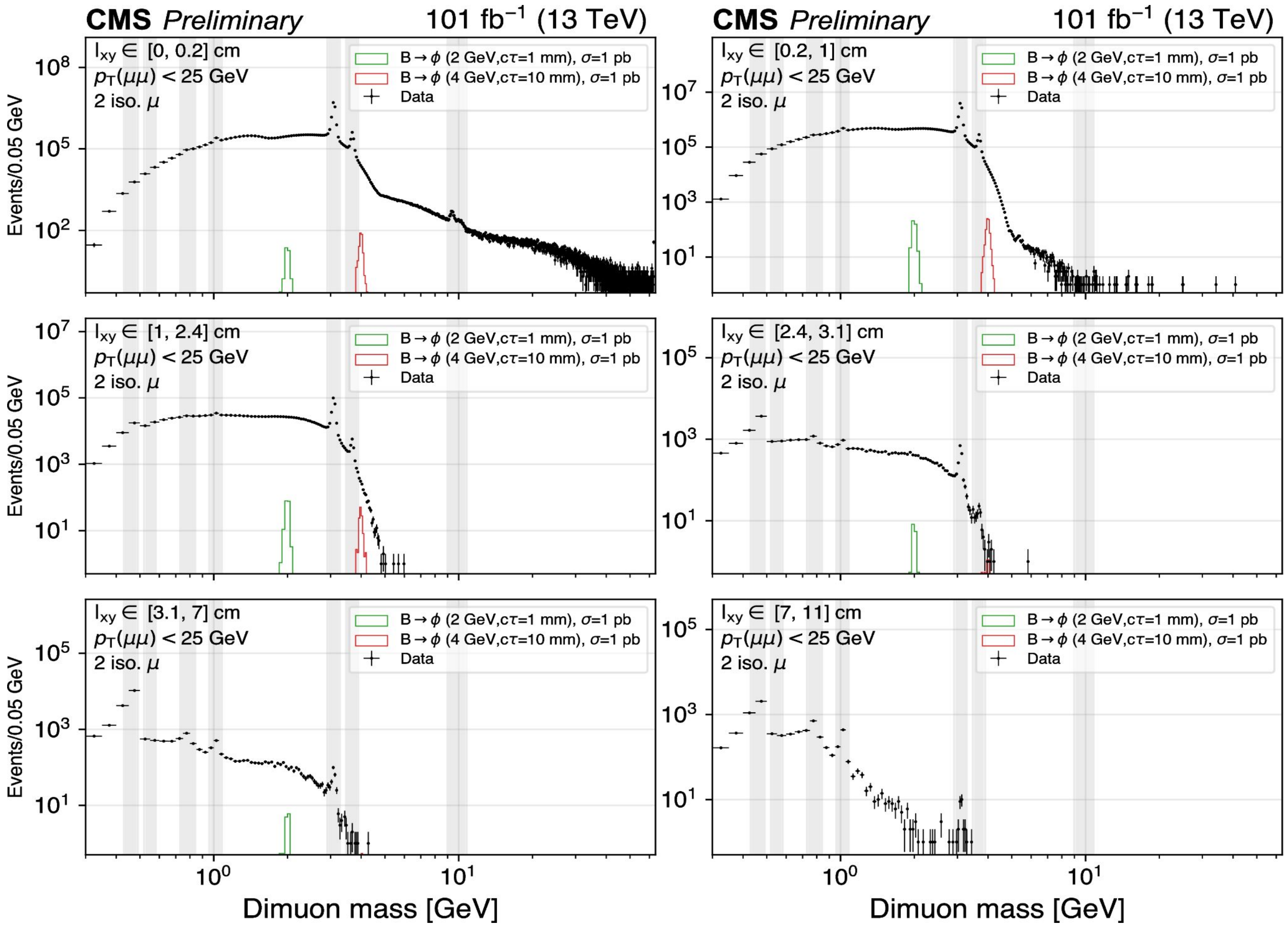
Resonance	Mean mass [GeV]	σ [MeV]	Lower bound [GeV] (mean -5σ)	Upper bound [GeV] (mean $+5\sigma$)
K_S	0.46	5	0.43	0.49
η	0.55	5	0.52	0.58
ρ/ω	0.78	10	0.73	0.84
$\phi(1020)$	1.02	10	0.96	1.08
J/ψ	3.09	40	2.91	3.27
$\Psi(2S)$	3.68	40	3.47	3.89
$\Upsilon(1S)$	9.43	90	8.99	9.87
$\Upsilon(2S)$	10.00	80	9.61	10.39
$\Upsilon(3S)$	10.32	90	9.87	10.77

Events (High p_T and isolated)



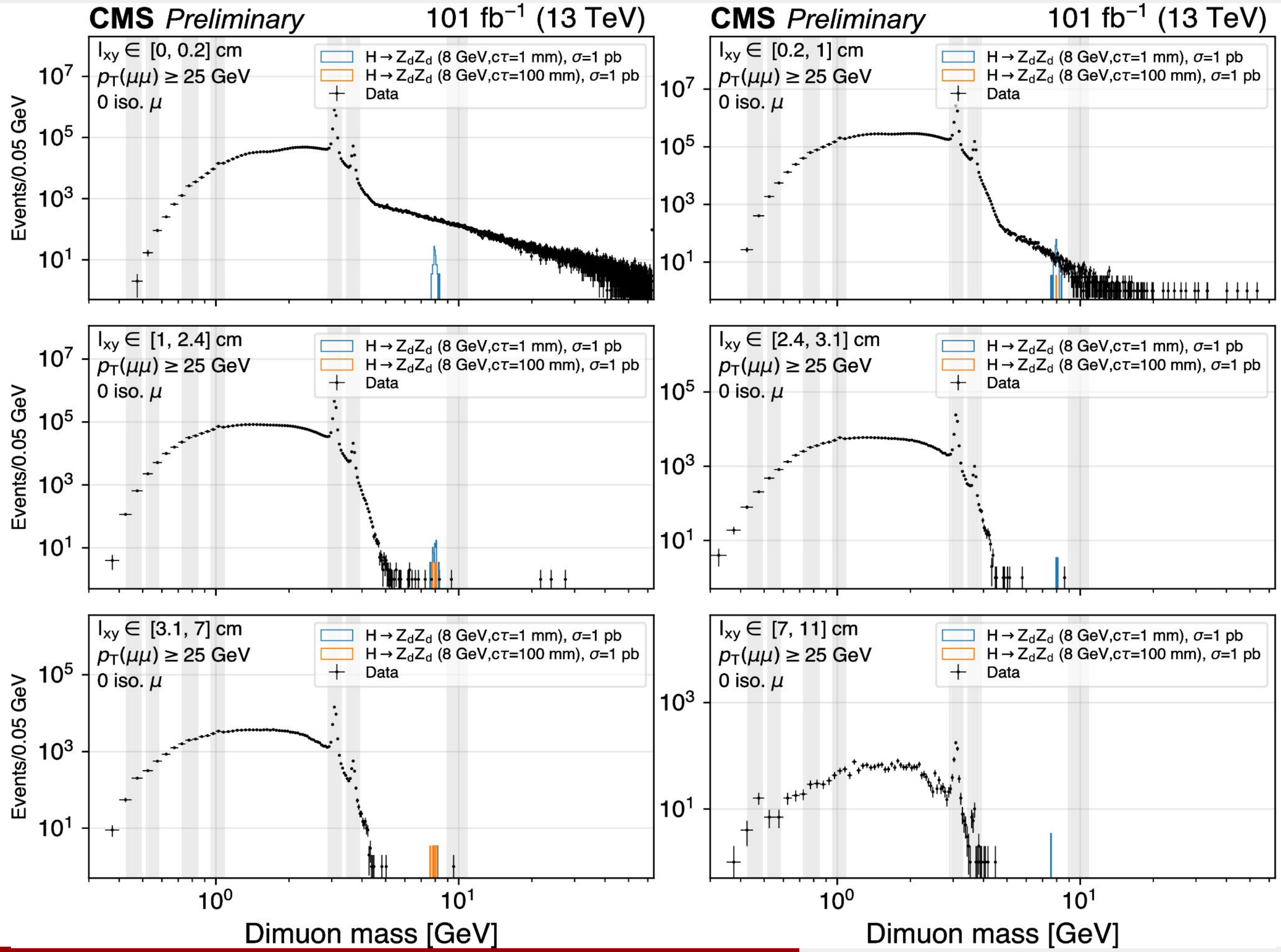
- Isolated 2**μ** events having dimuon p_T(**μμ**) > 25 GeV in successive l_{xy} bins.
- Non isolated and partially isolated distributions in backup.
- Significant fraction of $H \rightarrow Z_D Z_D$

Events (Low p_T and isolated)



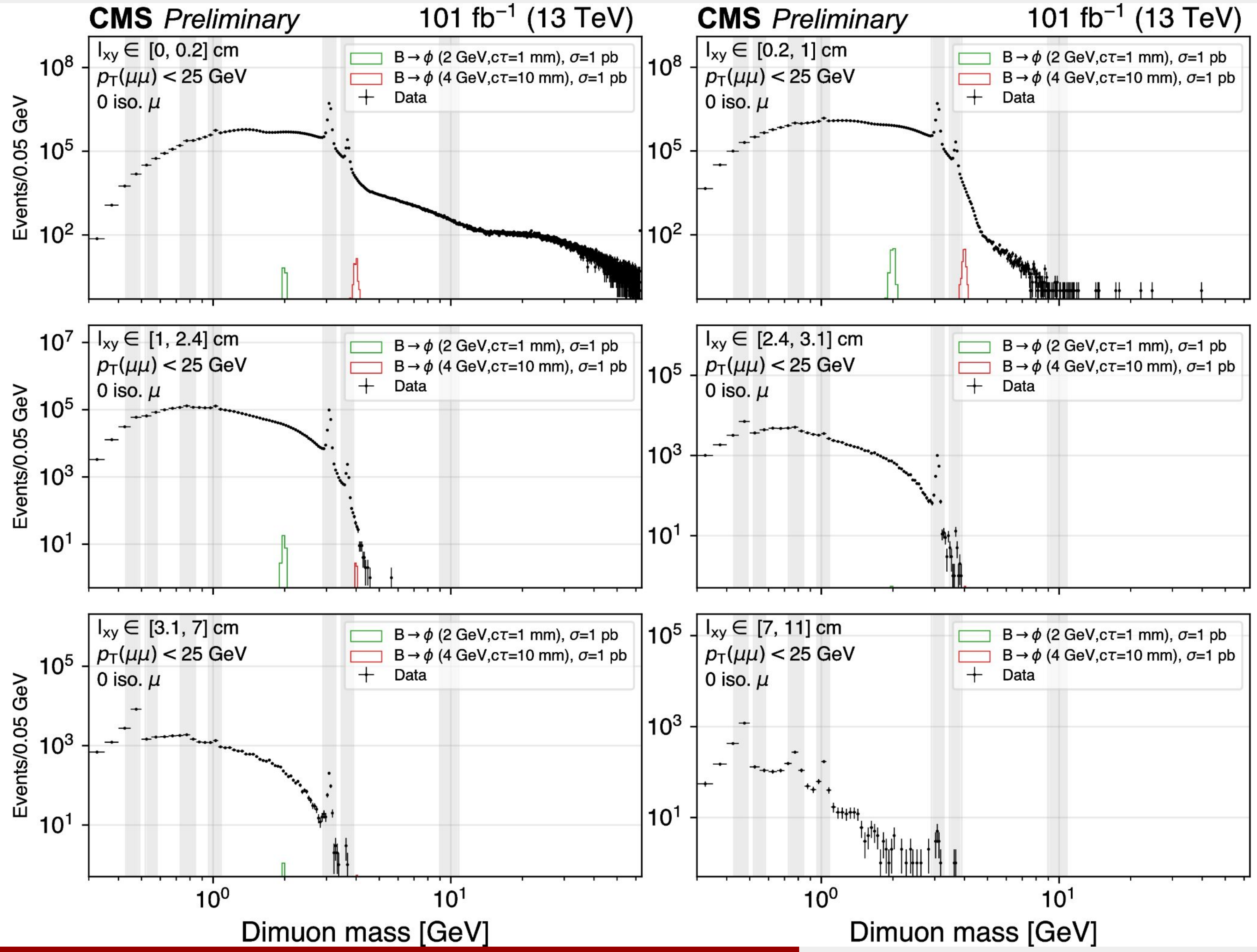
- Isolated 2μ events having dimuon $p_T(\mu\mu) < 25$ GeV in successive l_{xy} bins.
- Non isolated and partially isolated distributions in backup.
- Significant fraction of $B \to \phi X$

Events (High p_T and non-isolated)



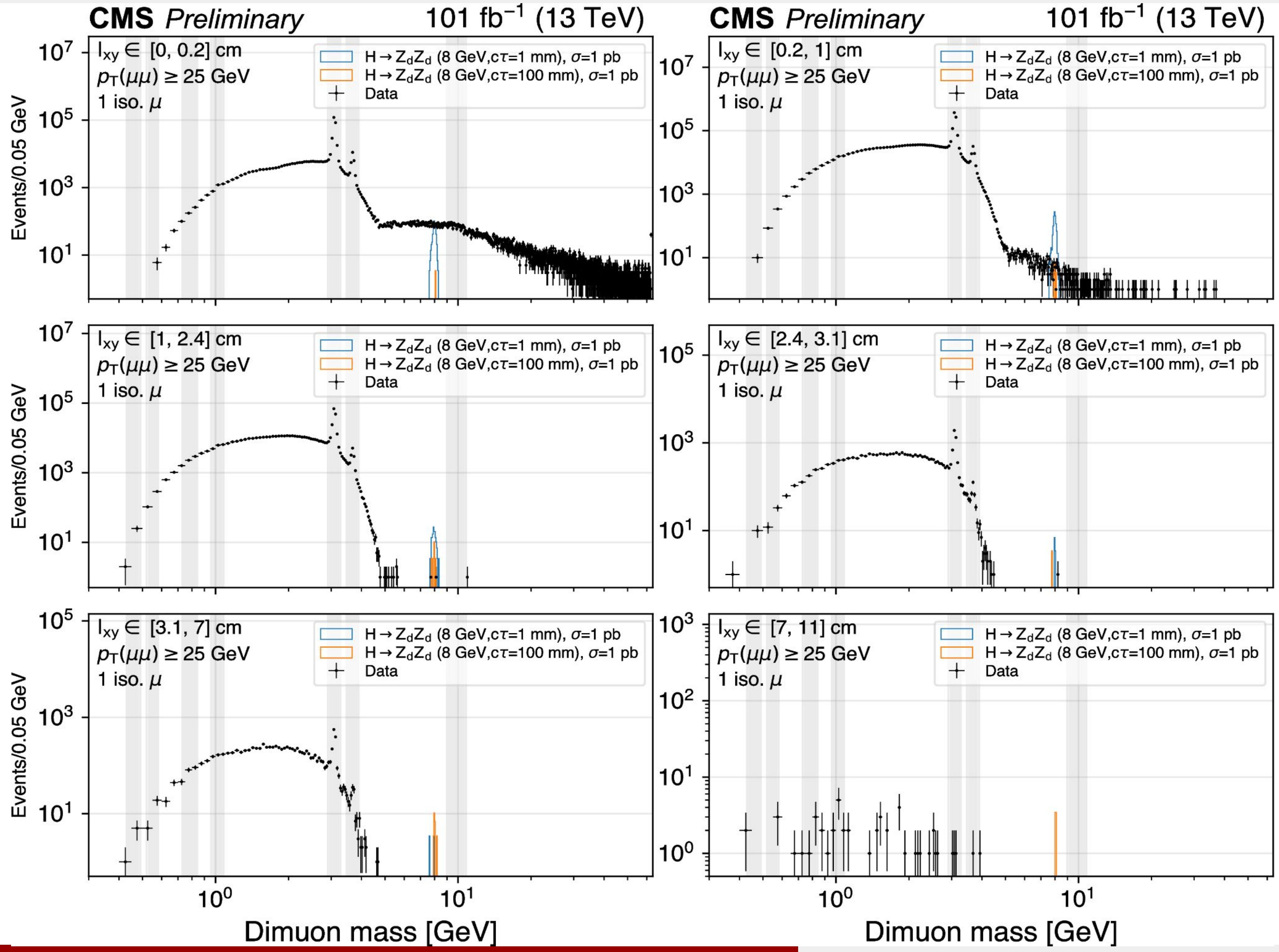
- Non-isolated $2\boldsymbol{\mu}$ events having dimuon $p_T(\boldsymbol{\mu\mu}) > 25$ GeV in successive l_{xy} bins.

Events (Low p_T and non-isolated)



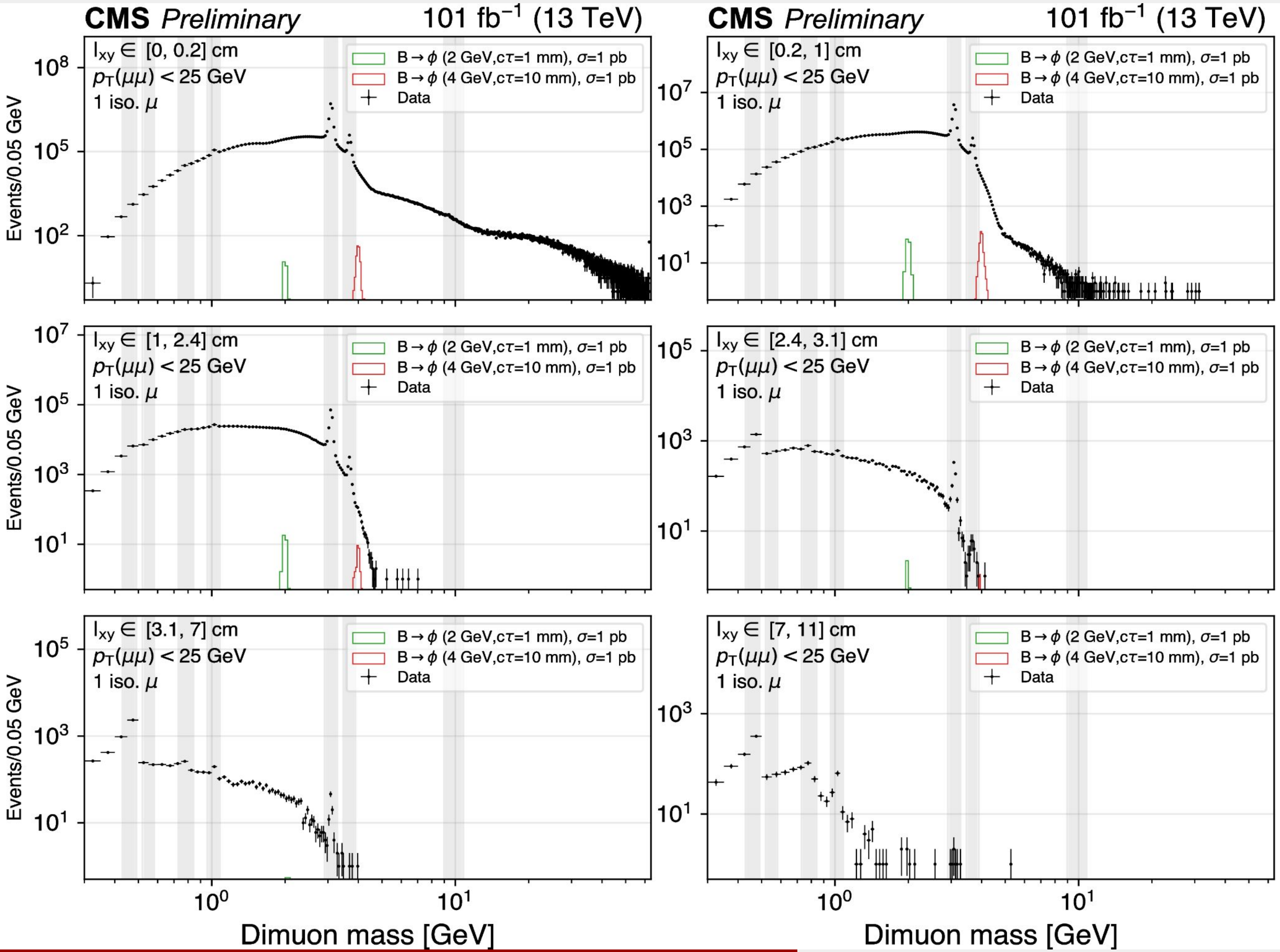
- Non-isolated 2**μ** events having dimuon p_T(**μμ**) < 25 GeV in successive l_{xy} bins.

Events (High p_T and partially-isolated)



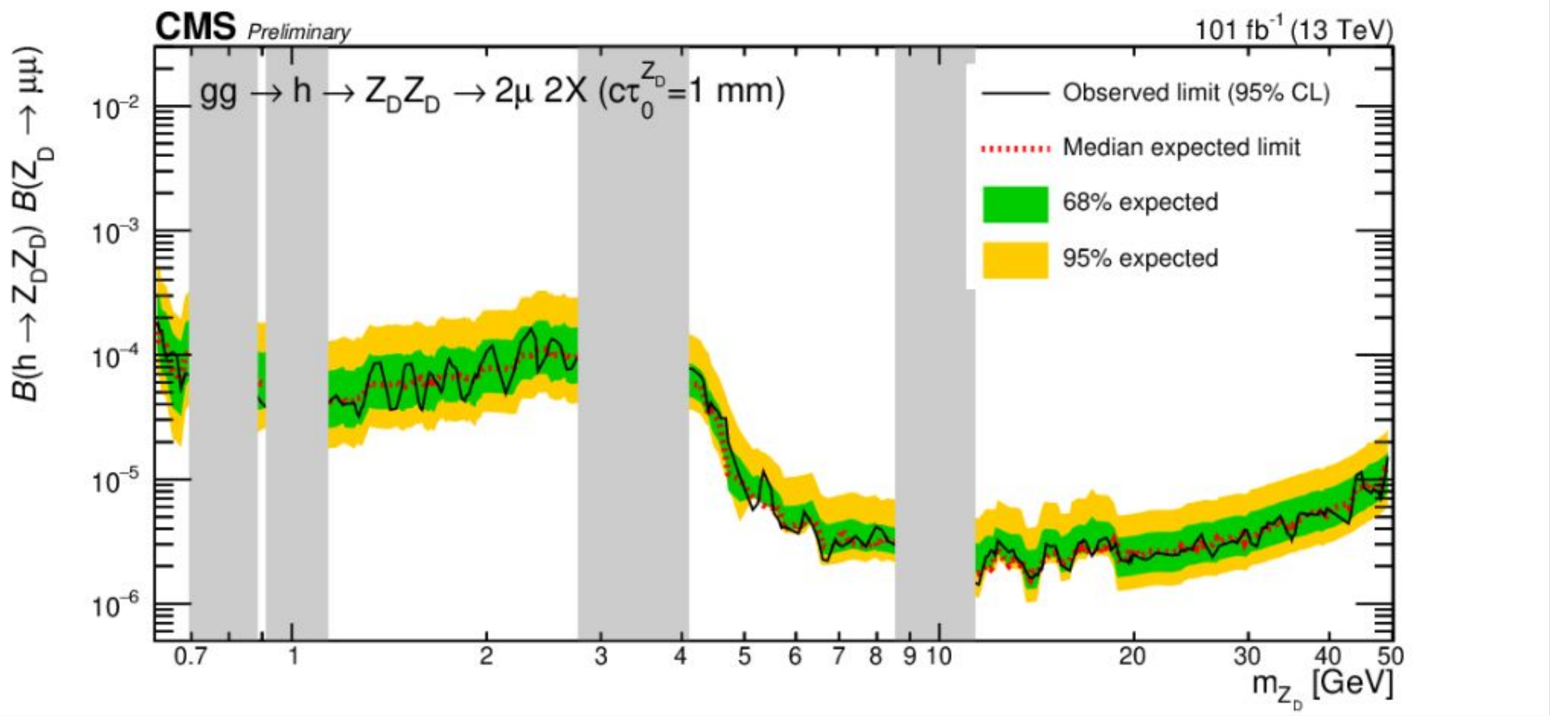
- Partially isolated 2**μ** events having dimuon p_T(**μμ**) > 25 GeV in successive l_{xy} bins.

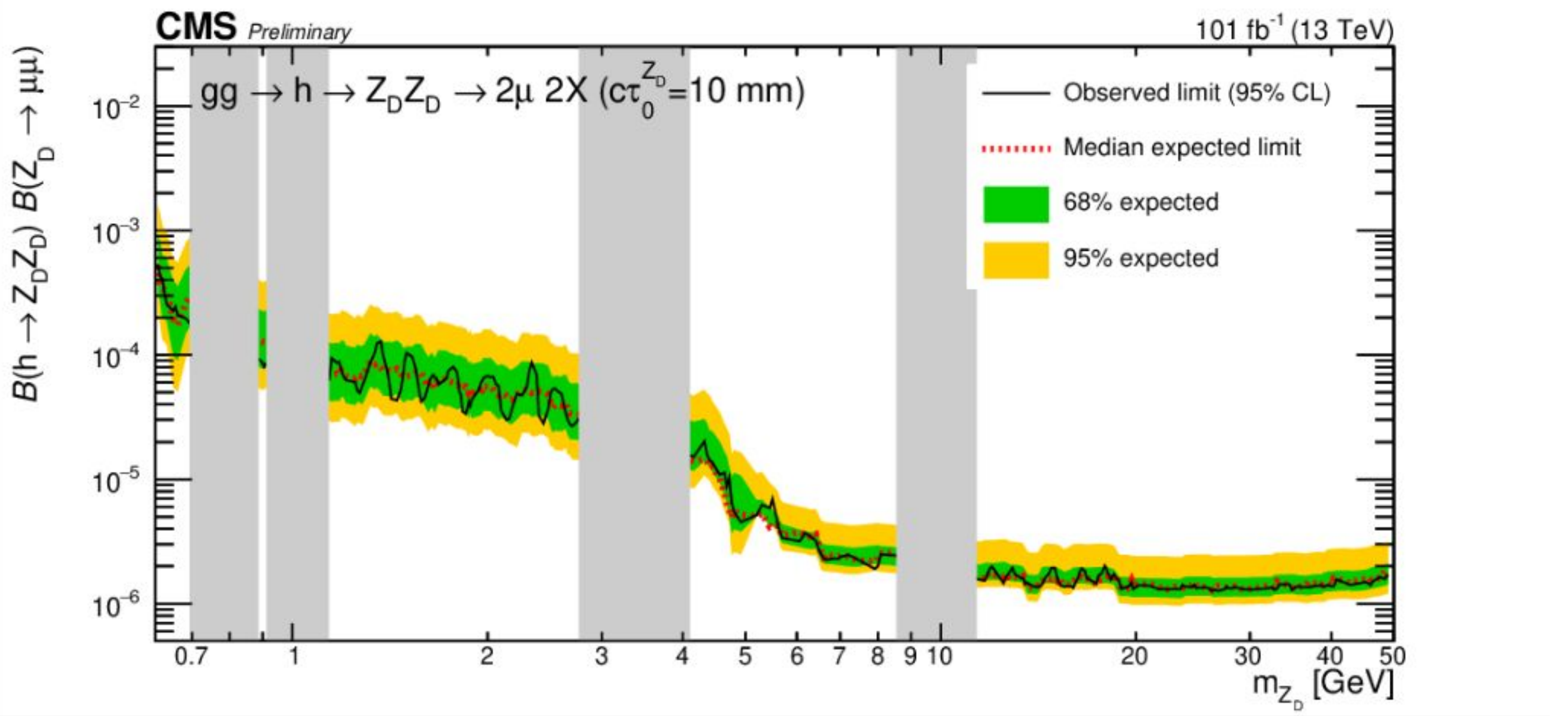
Events (Low p_T and partially-isolated)

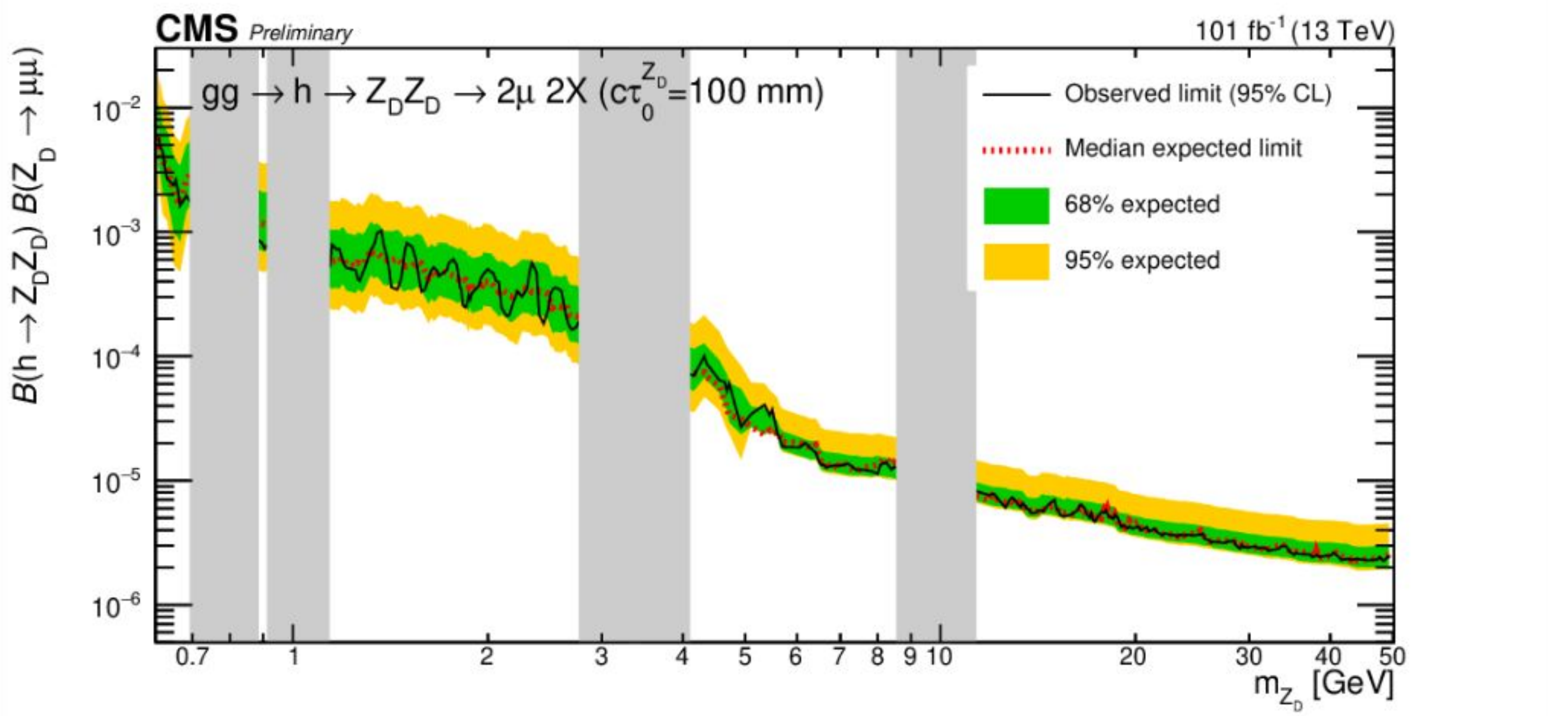


- Partially isolated 2**μ** events having dimuon p_T(**μμ**) < 25 GeV in successive l_{xy} bins.

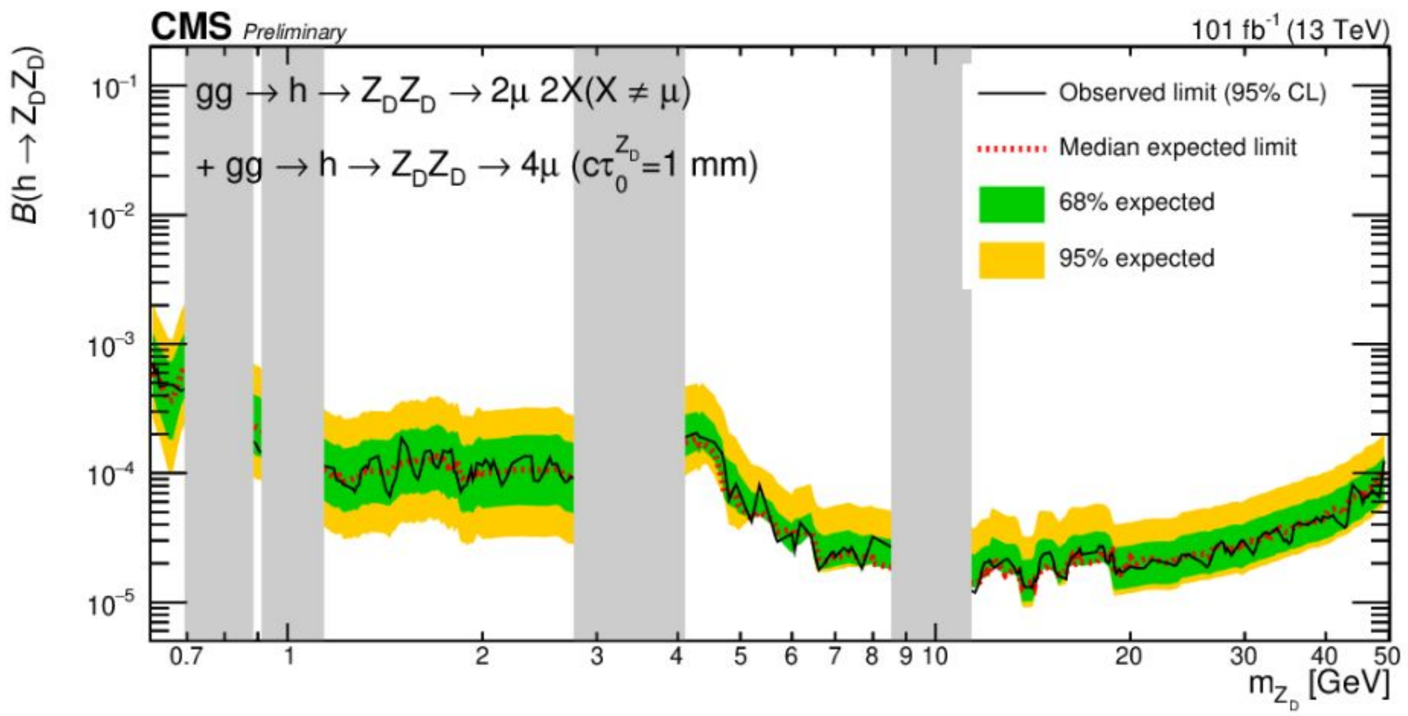
Results: UL on $BR(H \to Z_D Z_D) \,.\, BR(Z_D \to \mu\mu)$

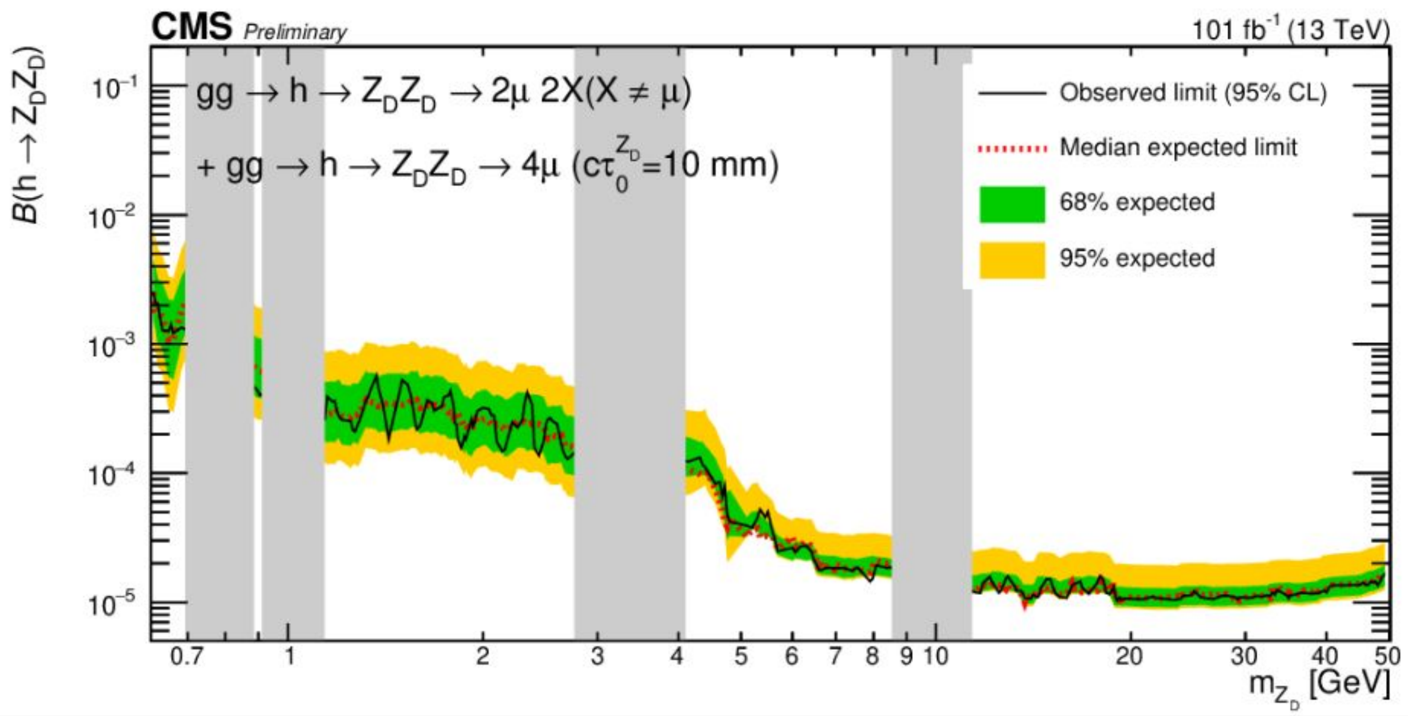


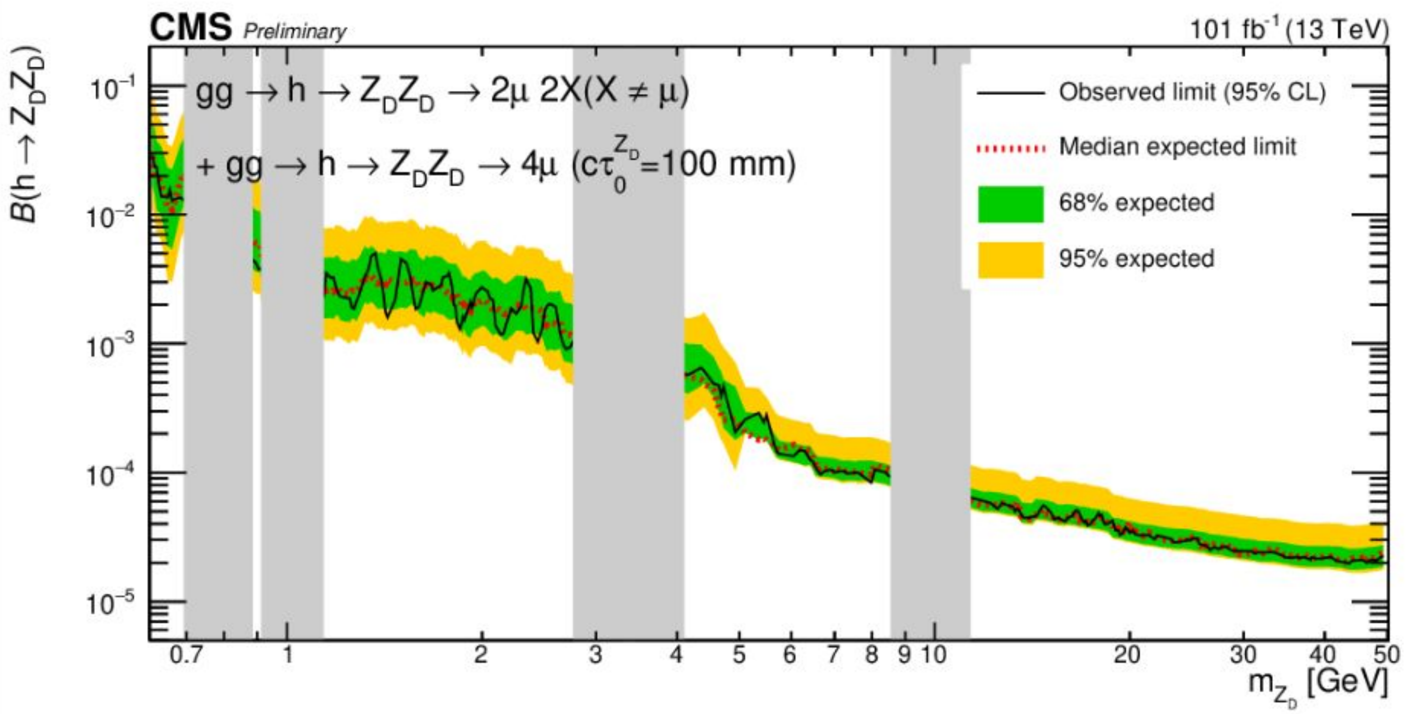




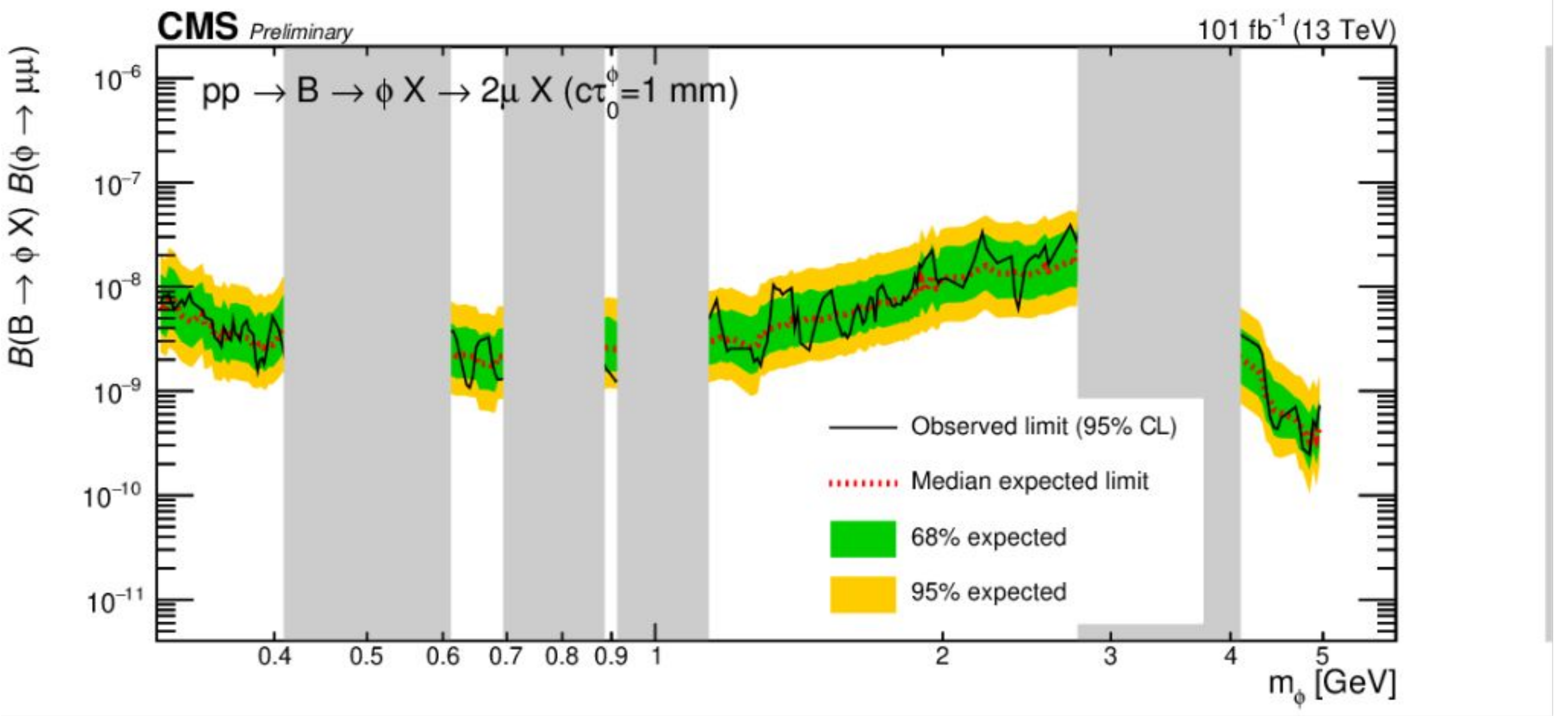
Results: UL on BR($H \rightarrow Z_D Z_D$)

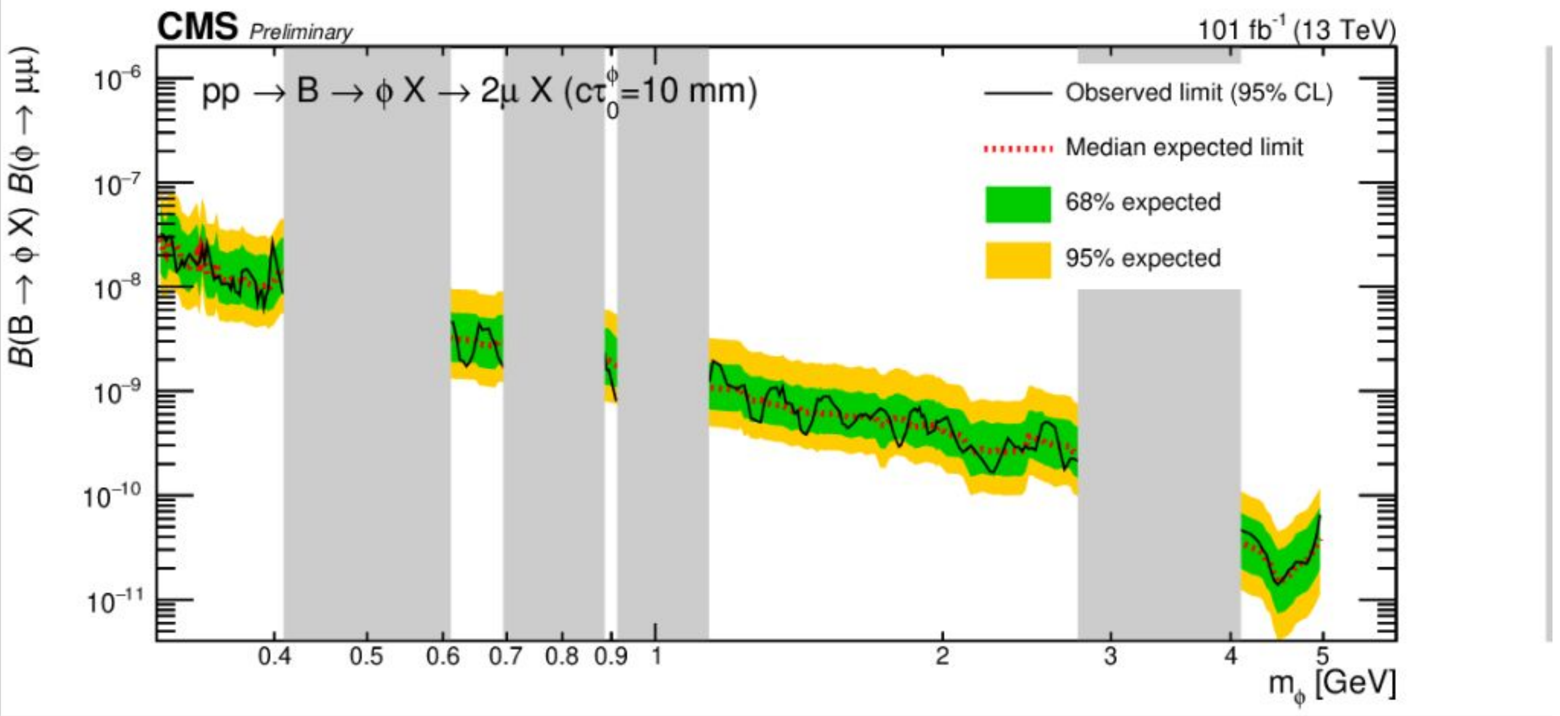


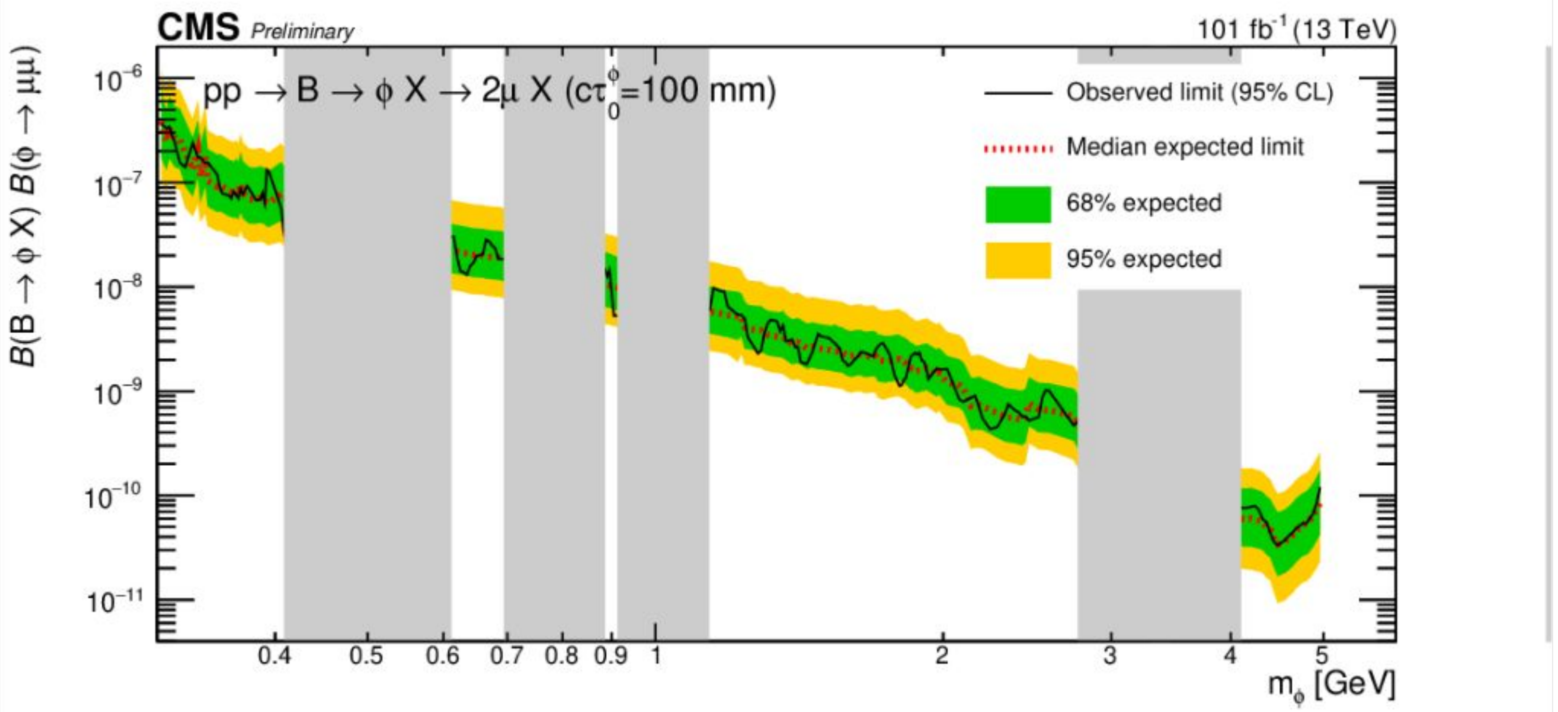




Results: UL on BR(B → ϕX) . BR(ϕ → μμ)







Comparison with LHCb