Exotic B decays at CMS

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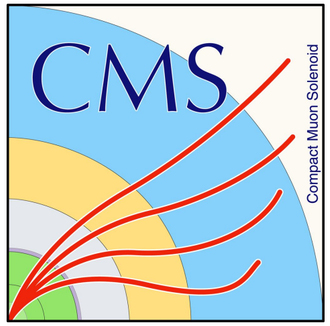
CMS Collaboration

ICNFP 2021



OUTLINE

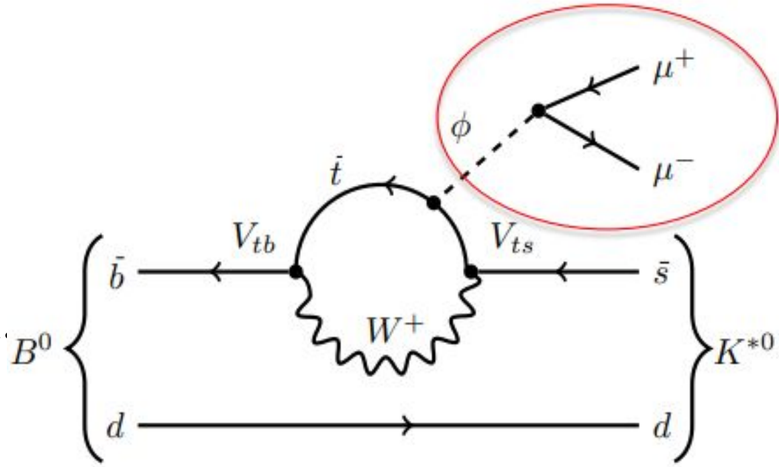
- Introduction: Singlet scalar field ϕ and a new dimuon resonance hiding below the B mass ?
- Search Strategy:
  - ϕ light and long lived ➢ Leverage dimuon displacements to reduce background.
  - Scouting Trigger ➢ Allows access to phase space of low mass and long lifetime.
- Search Results:
  - How current search compares with LHCb and how we push the existing boundaries ?
- Sensitivity Projections: Discovery potential with CMS phase 2 upgrades and high luminosity runs.

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}.

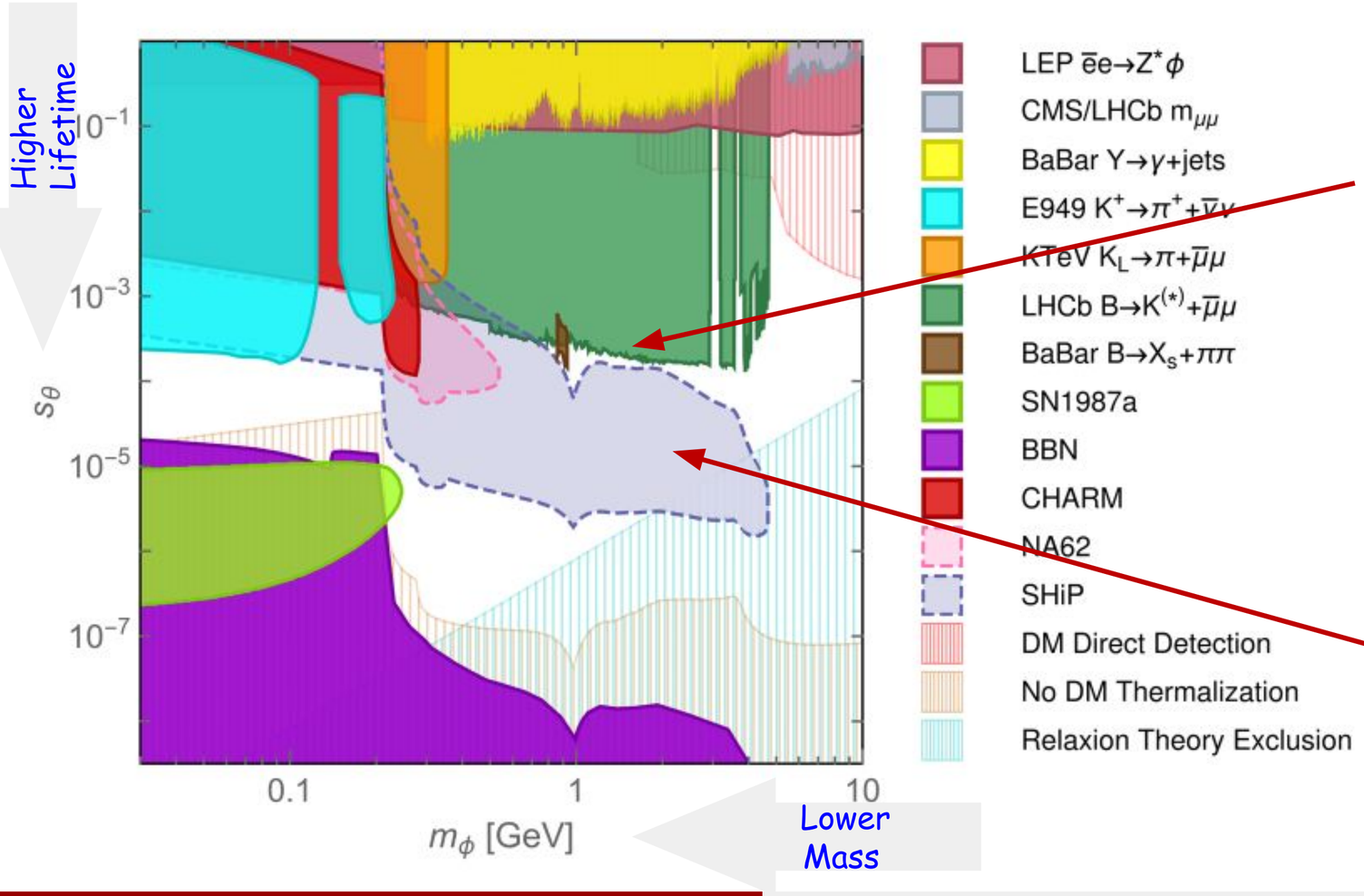
- Dominant production at LHC:
  - $B \rightarrow \phi X$ decays ➢ Flavor changing decays via an elecroweak penguin.
  - $\phi \rightarrow \mu\mu$ ➢ Branching ratio varies roughly between 0.1 to 0.01.



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

Existing Bounds on light scalars

Phys. Rev. D 99, 015018

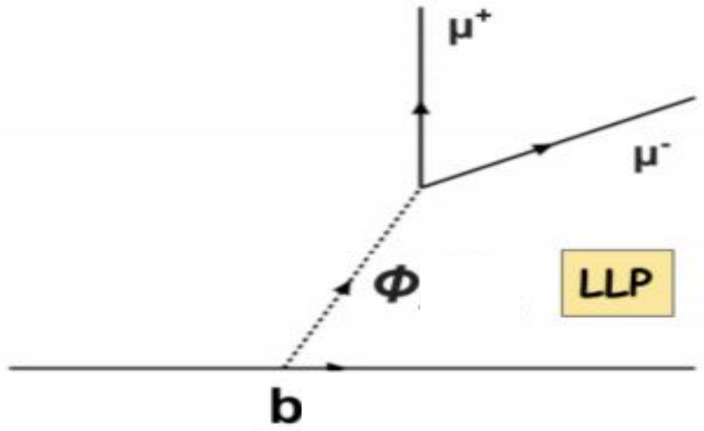


- LHCb constrains $s_\theta \sim 10^{-3}$ to 10^{-4} for $0.2\ \text{GeV} < m(\phi) < 5\ \text{GeV}$.
- Can CMS be competitive with LHCb ? Yes we are!
  - Results in the coming slides.
- Can we push into the unexplored phase space in future ? Yes we can!
  - Sensitivity projections in coming slides.

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

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

- CMS geometric acceptance for $B \rightarrow \phi X$ 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.

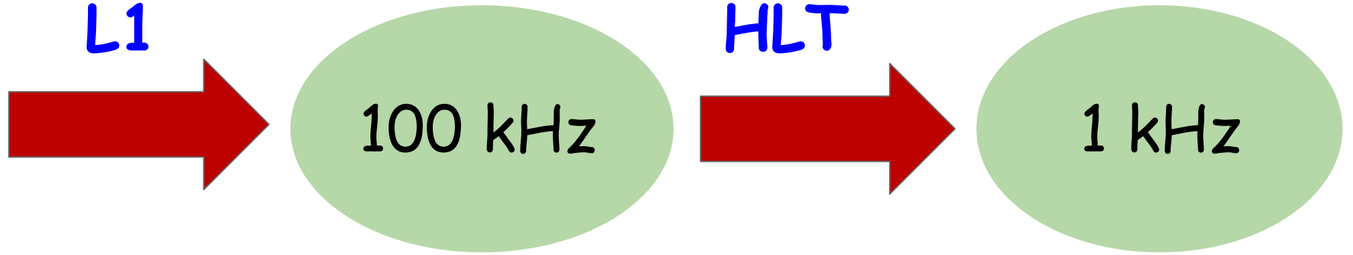


- In addition, the higher overall integrated luminosity gives CMS an edge.

CMS Trigger System

CMS Triggering selects mostly high p_T and prompt events

Proton Proton collisions at 40 MHz



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)

Trigger Bandwidth = Event Rate × Event Size

~1 kHz × ~1 MB

≈ **1 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.

Trigger Bandwidth = Event Rate ~1 kHz × Event Size ~1 MB

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

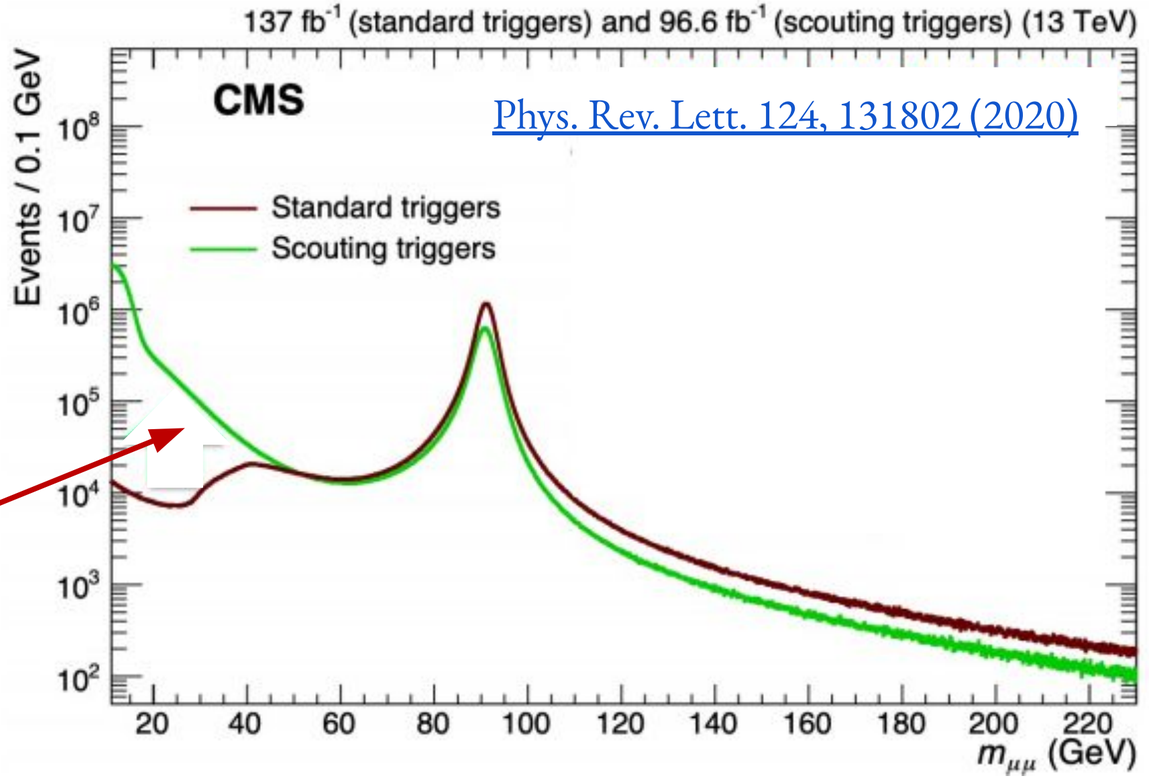
Scouting Data - I

Phase Space of interest:

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

$c\tau^{0}(\phi) > 0$

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



Scouting Data - II

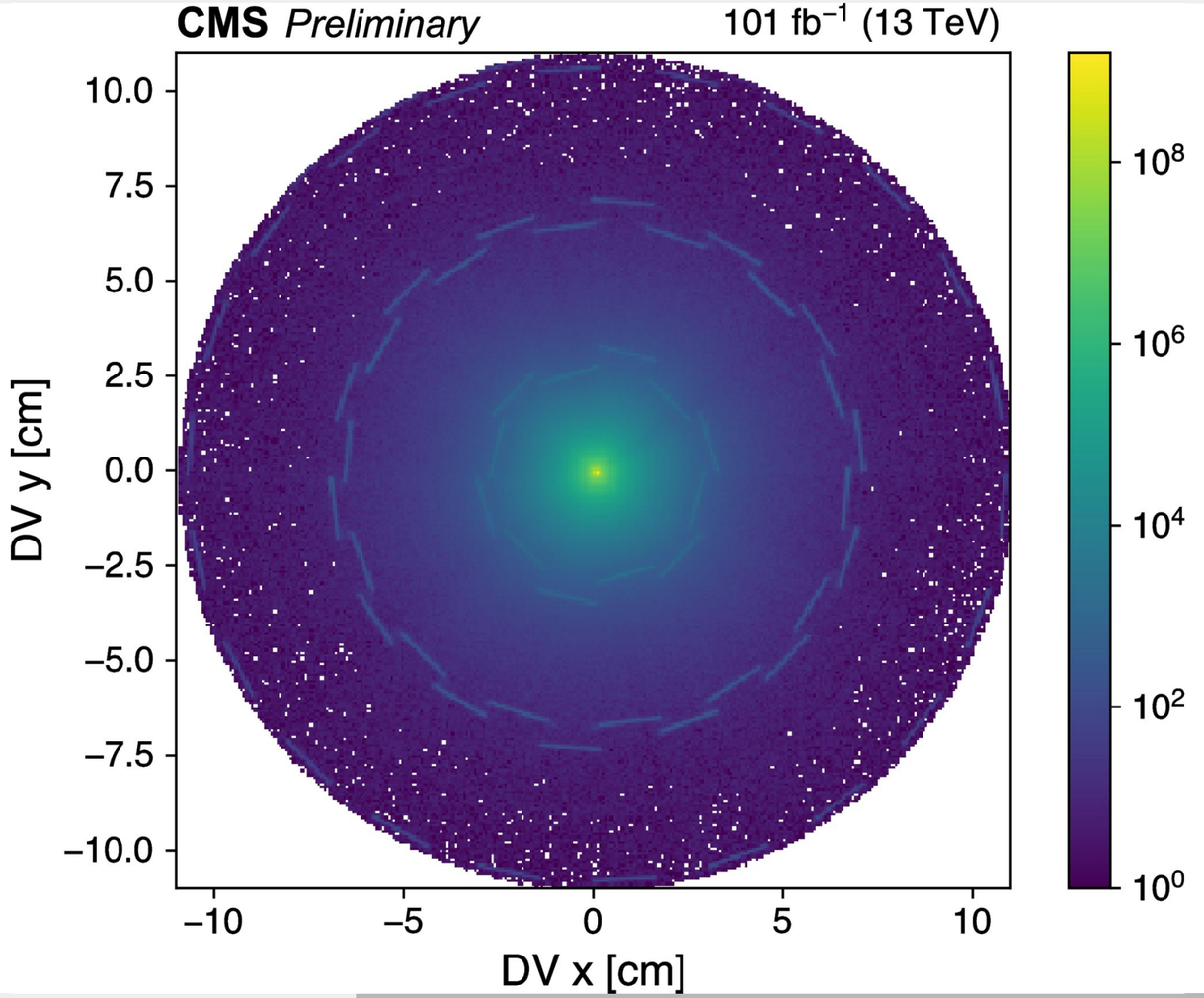
Phase Space of interest:

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

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

- 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, $|\eta| < 2.4$
- $\chi 2/ndf < 3$

DV

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

Isolation (binned)

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

- Isolation is not an explicit requirement due to the fact that μ'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 - Non B

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

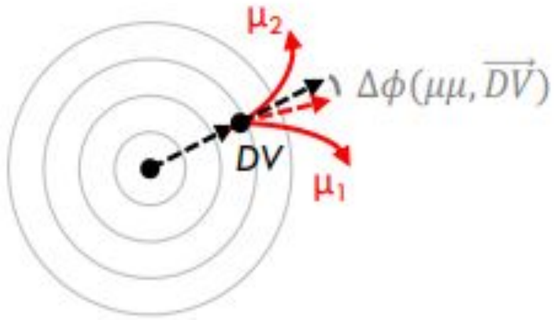
Background Suppression - Non B

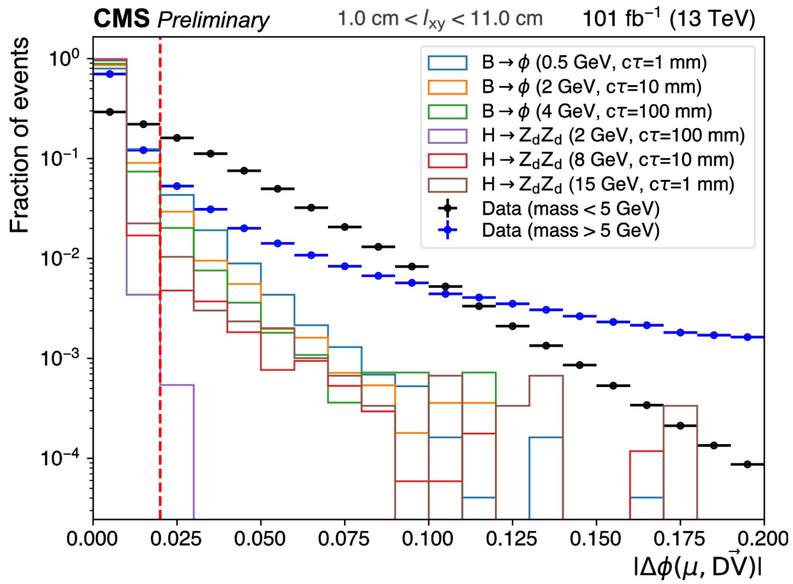
- **Fake vertices from accidental crossings of cosmic muons, PU tracks, QCD multijet events.**

➢ 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.

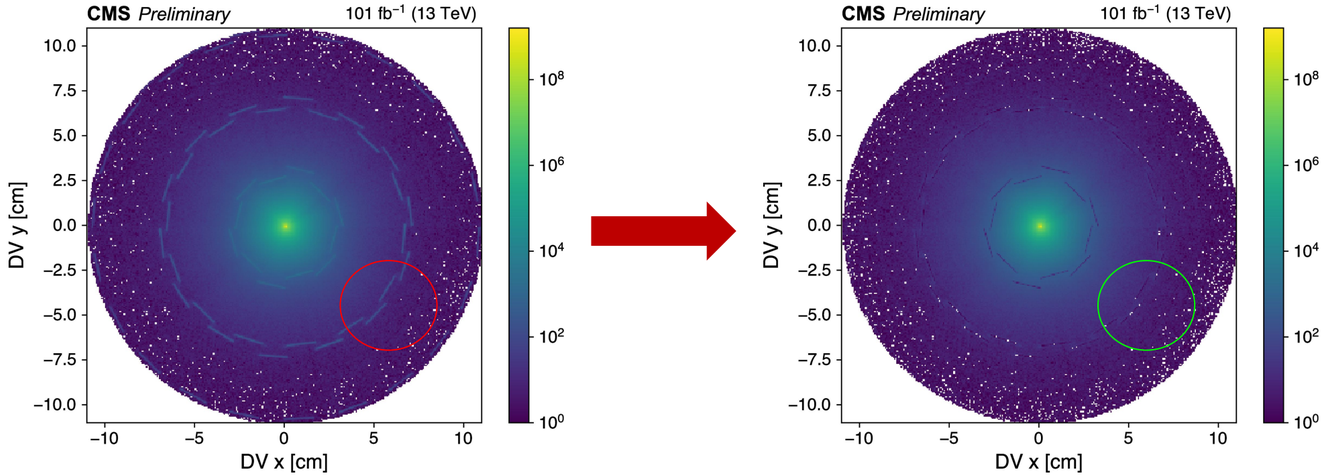
➢ Dimuon system collinear with DV vector for signal.
  - Require $\Delta\phi$ (**μμ**, DV) < 0.02 to to further suppress background.

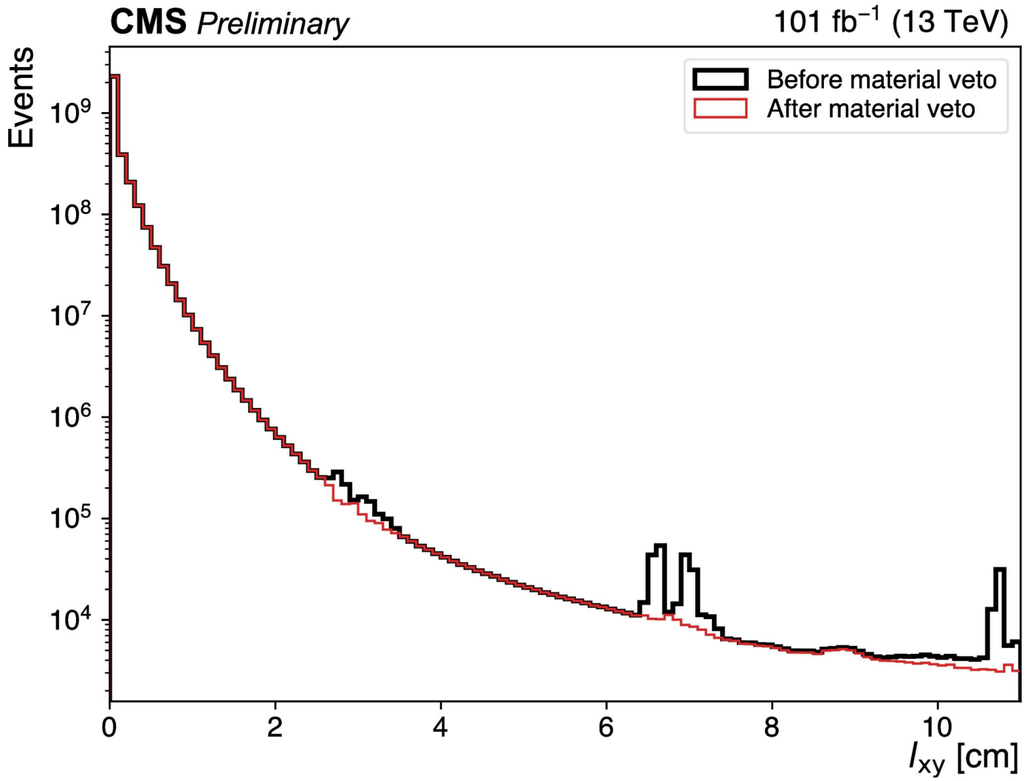




Background Suppression - Non B

- **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 - Non B

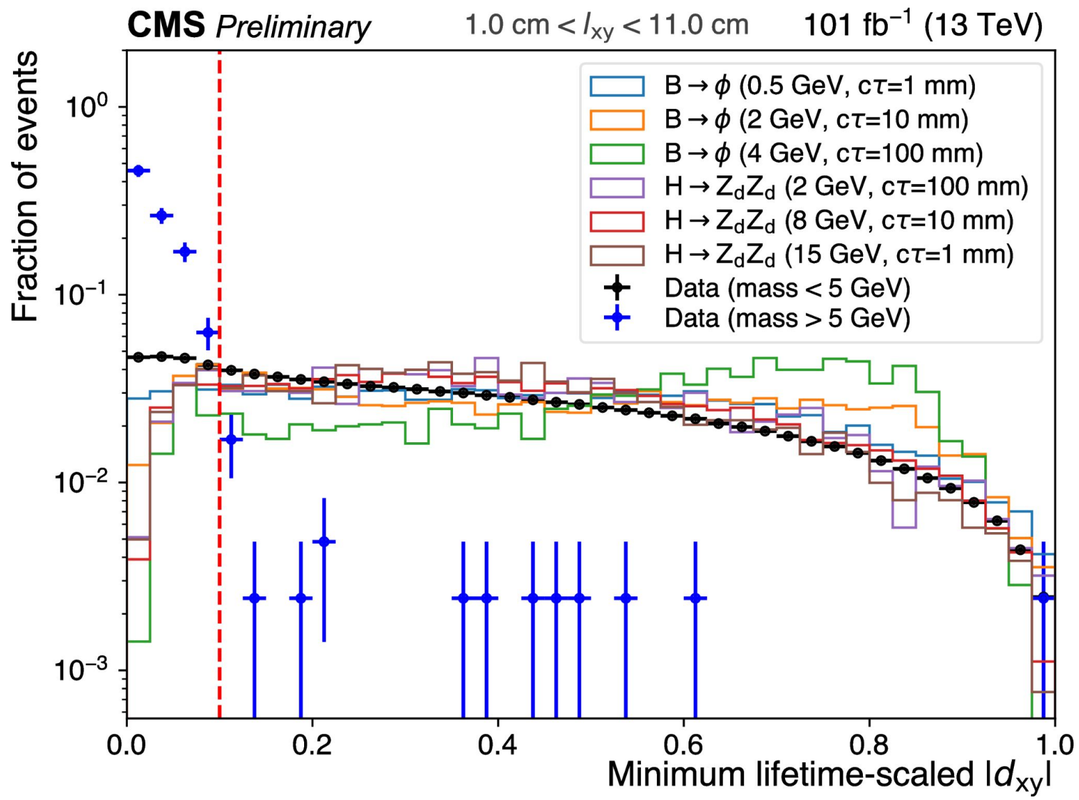
- **Prompt muons since we focus on a displaced search.**

➢ 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 ϕ lifetimes.



Background Sources - B

Dimuon signatures originating from b quark.

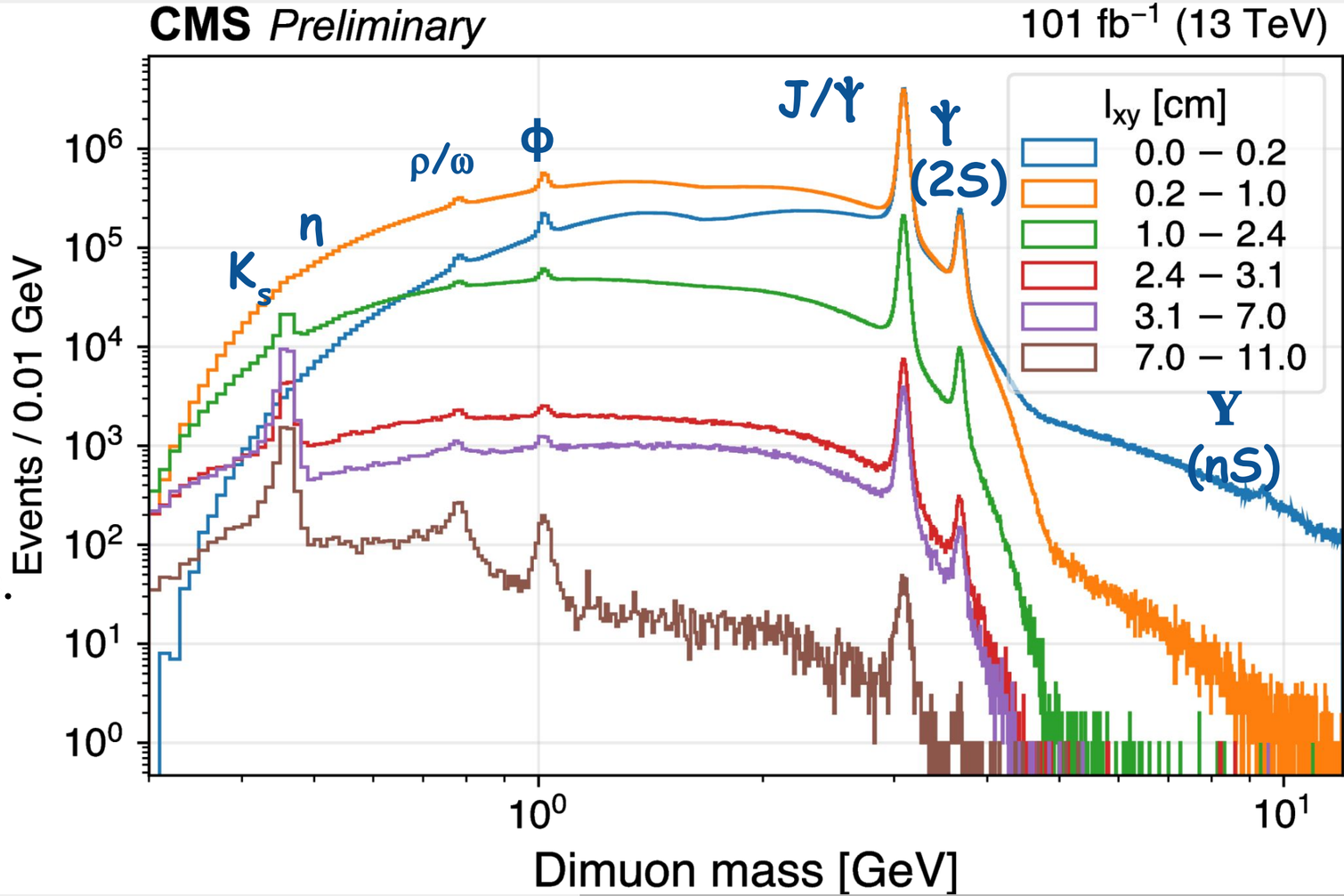
- Requiring IP selections reject prompt contribution.
- Harder selection on displacement would result in significant loss of signal efficiency.
- Do search in bins of displacement. (more info. in next slides)

- $b \rightarrow X + \Upsilon(nS) \rightarrow \mu\mu$
  - Veto J/Ψ and $\Upsilon(2S)$ resonances.
  - Also veto other known SM dimuon resonances.

- $b \rightarrow \mu\nu\,(X_c \rightarrow \mu\nu\, X_s)$
  - 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.

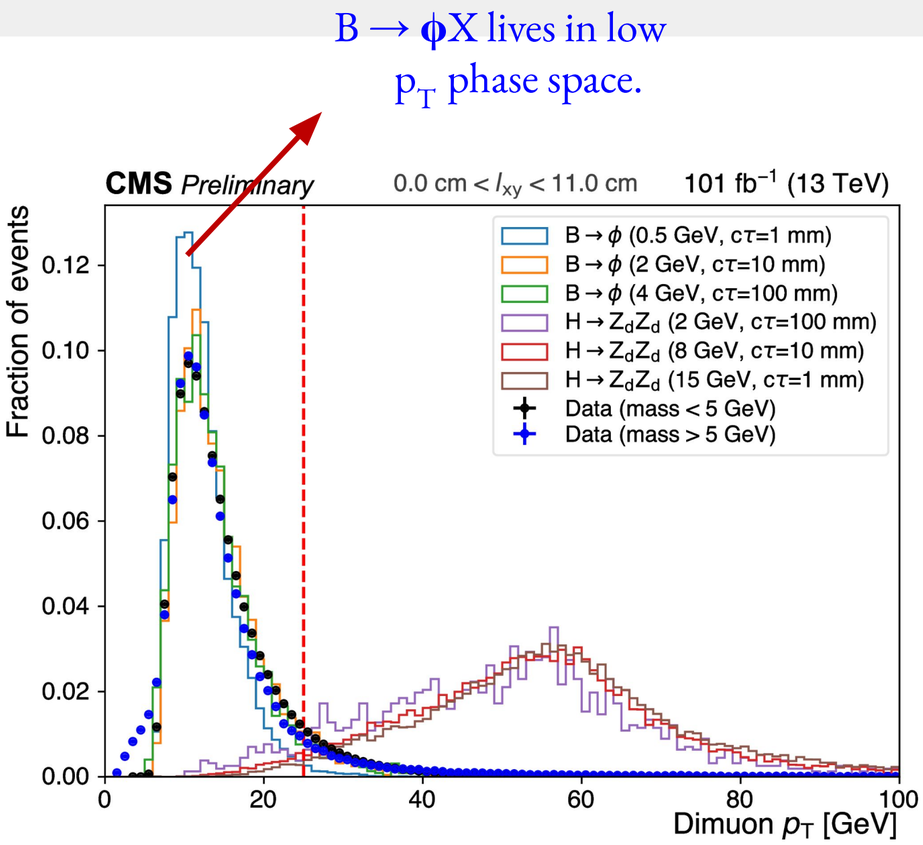
Dimuon Mass Spectrum

- 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 -> $\pi\pi$ where π mis-identified as μ appears at higher l_{xy} bins. ($c\tau^0 \sim 27$ mm)



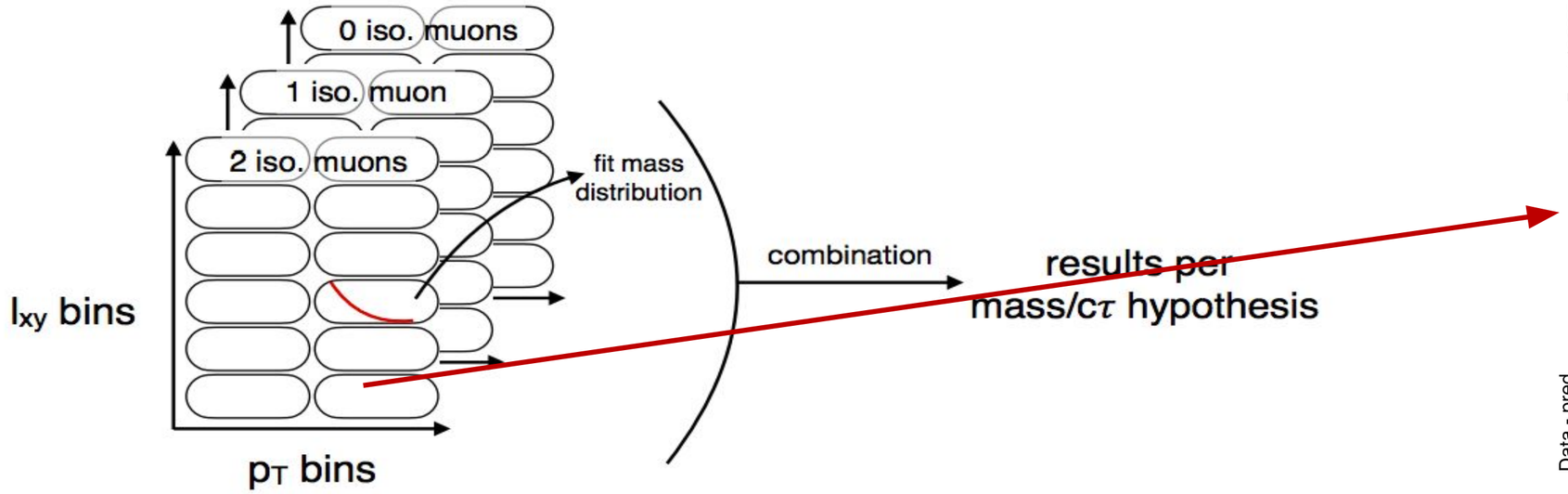
Search Strategy

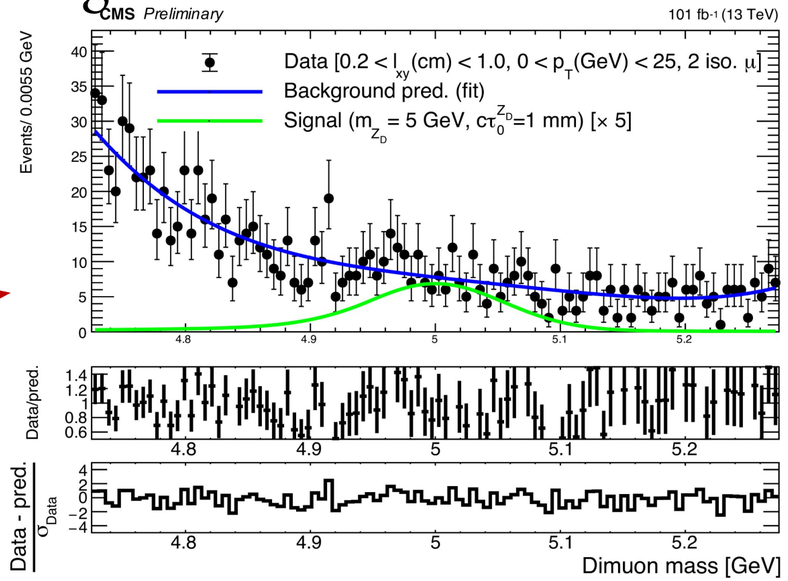
- Events categorized in 36 categories of $\mathbf{l_{xy}}$, $\mathbf{p_T}$ and **isolation** to maximize sensitivity to a wide range of mass/c$\boldsymbol{\tau}$ hypotheses.
- Six bins of l_{xy}: [0, 0.2, 1, 2.4, 3.1, 7, 11] cm based on tracker geometry.
- Further categorize events in bins of **dimuon** $\mathbf{p_T}$ [0, 25, ∞] and **isolation** bins.
- Look for narrow resonant peak over the background continuum by simultaneous fit in all event categories.



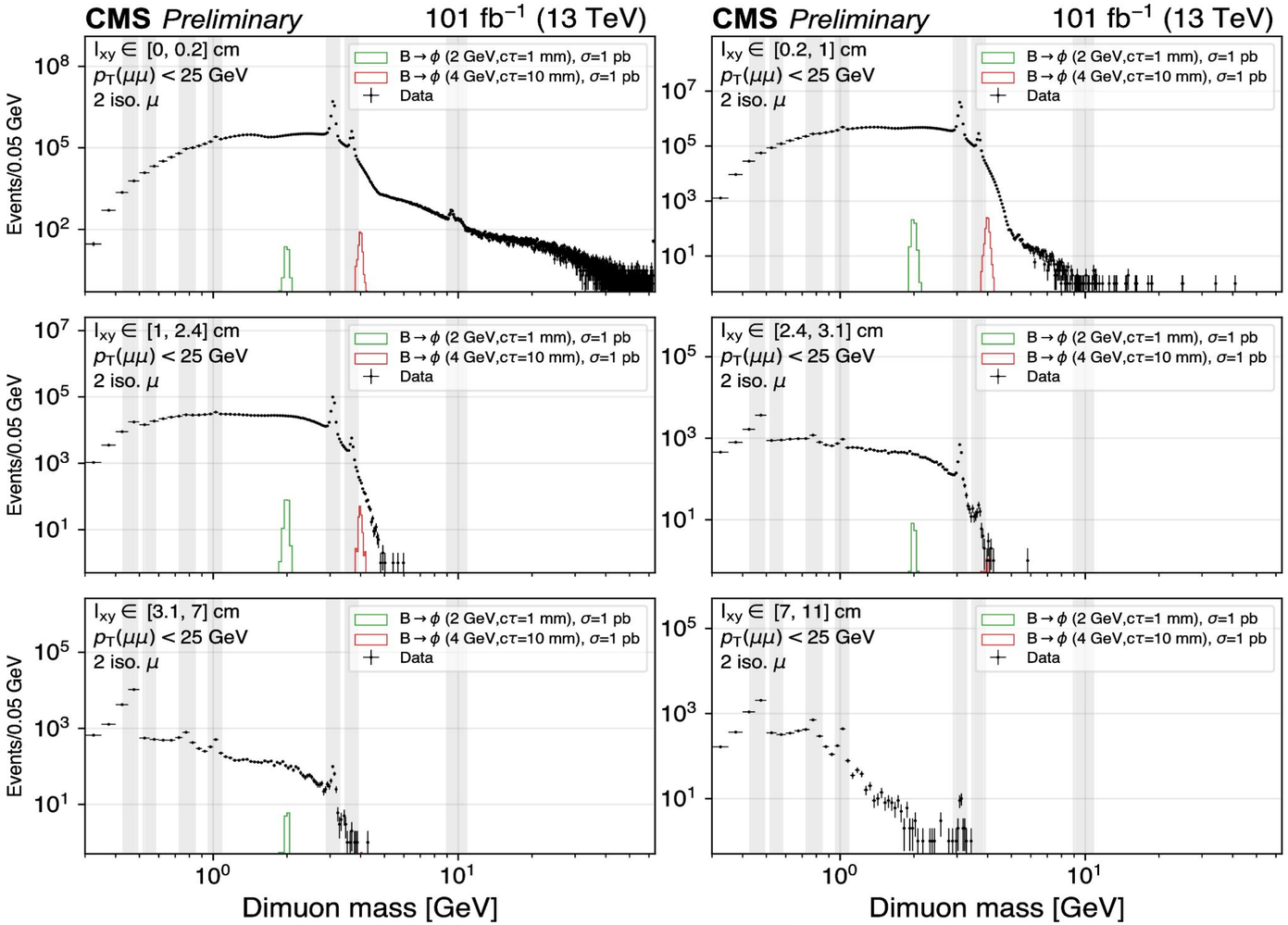
Search Strategy

- For B → ϕX signal, we scan in steps of ϕ mass and windows according to signal mass resolution σ.
  - σ ~ 1.1% of ϕ 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.





Events (Low p_T and isolated)

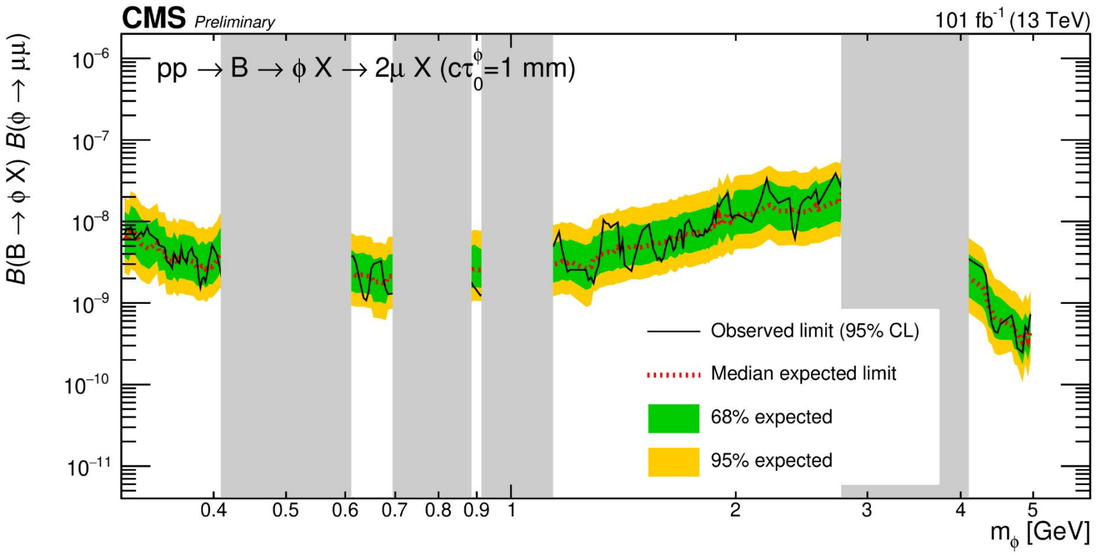


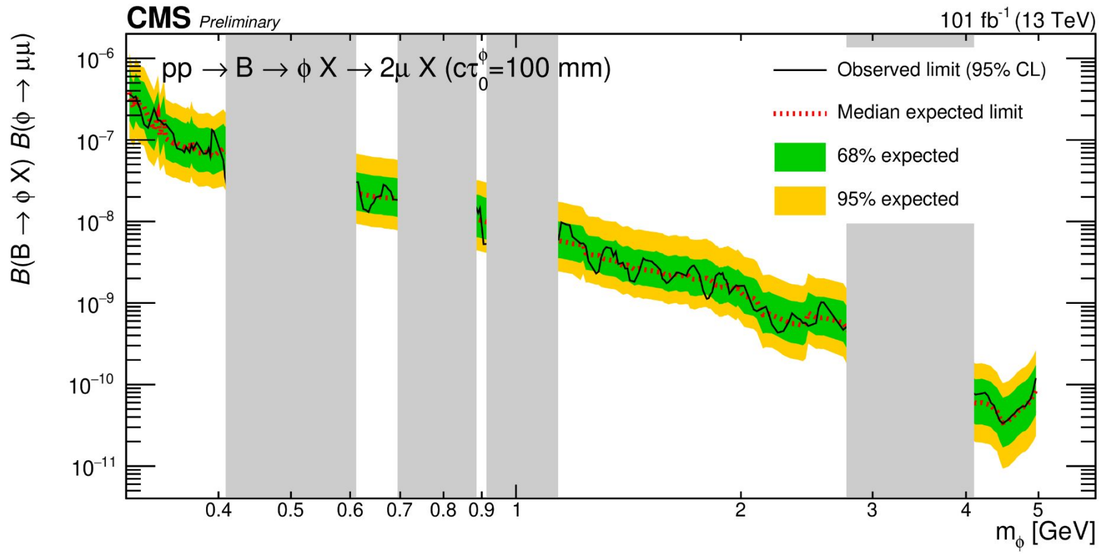
- Isolated 2**μ** events having dimuon $p_T(\mu\mu) < 25$ GeV in successive l_{xy} bins.
- Non isolated and partially isolated distributions in backup.

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

- Upper limits at 95% CL on BR(B → ϕX) . 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).

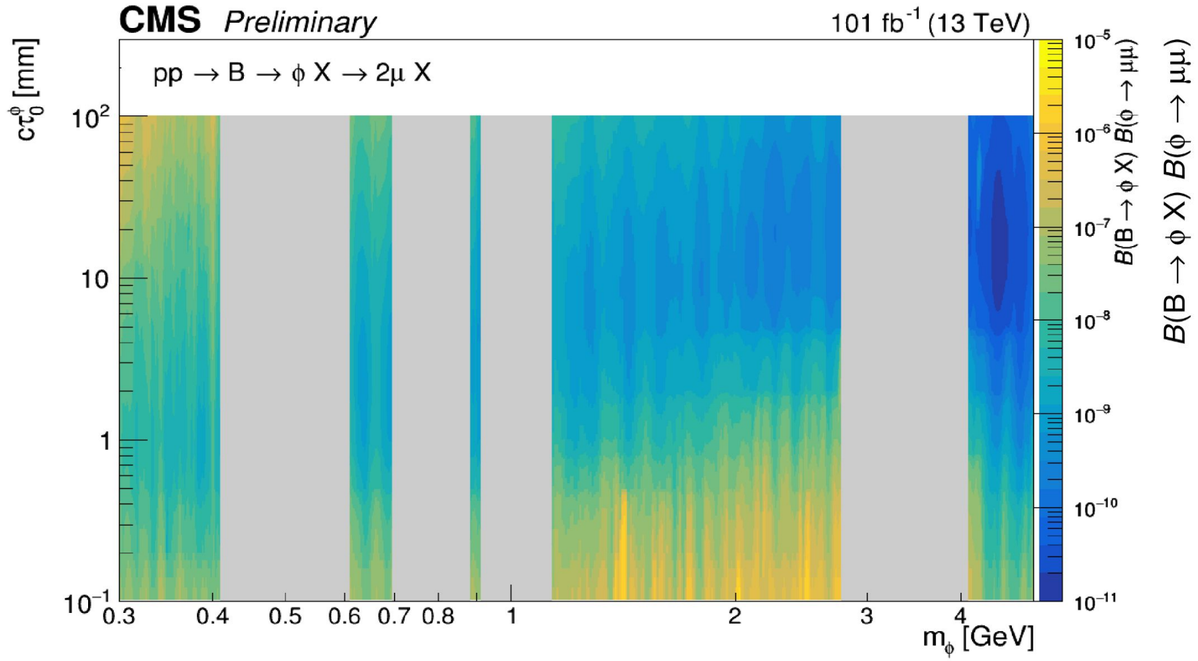
- No assumption on BR(ϕ → μμ) to keep it model independent.

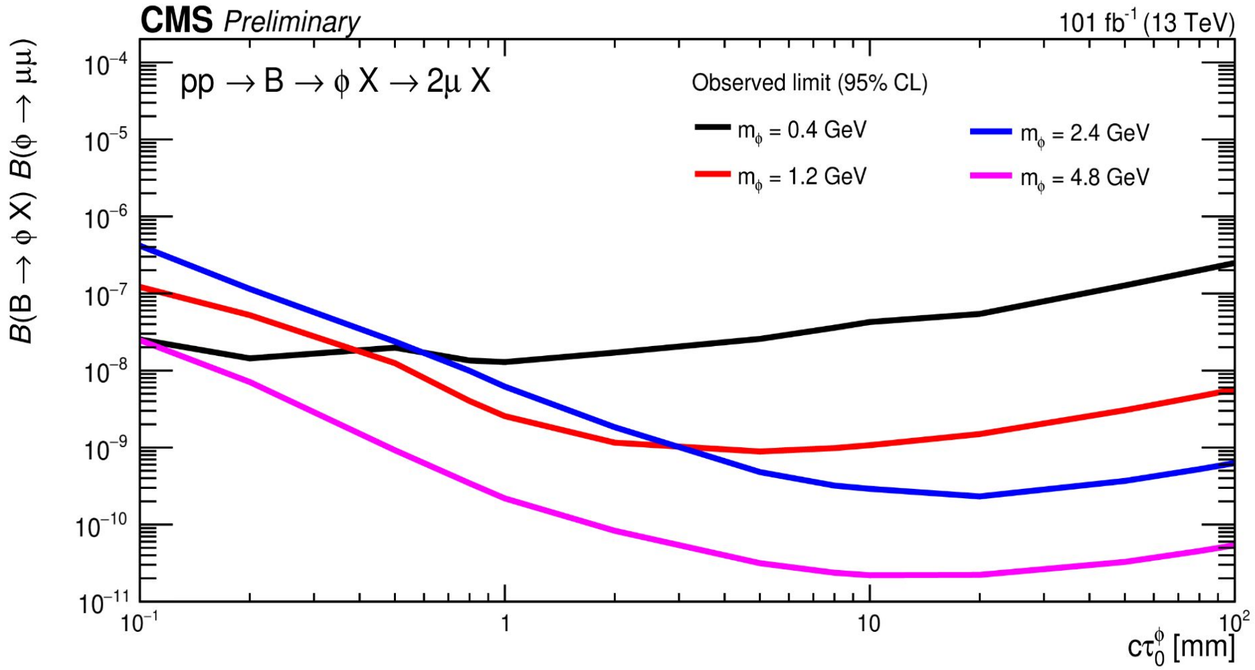




Results: UL on BR(B → ϕX) . BR(ϕ → μμ)

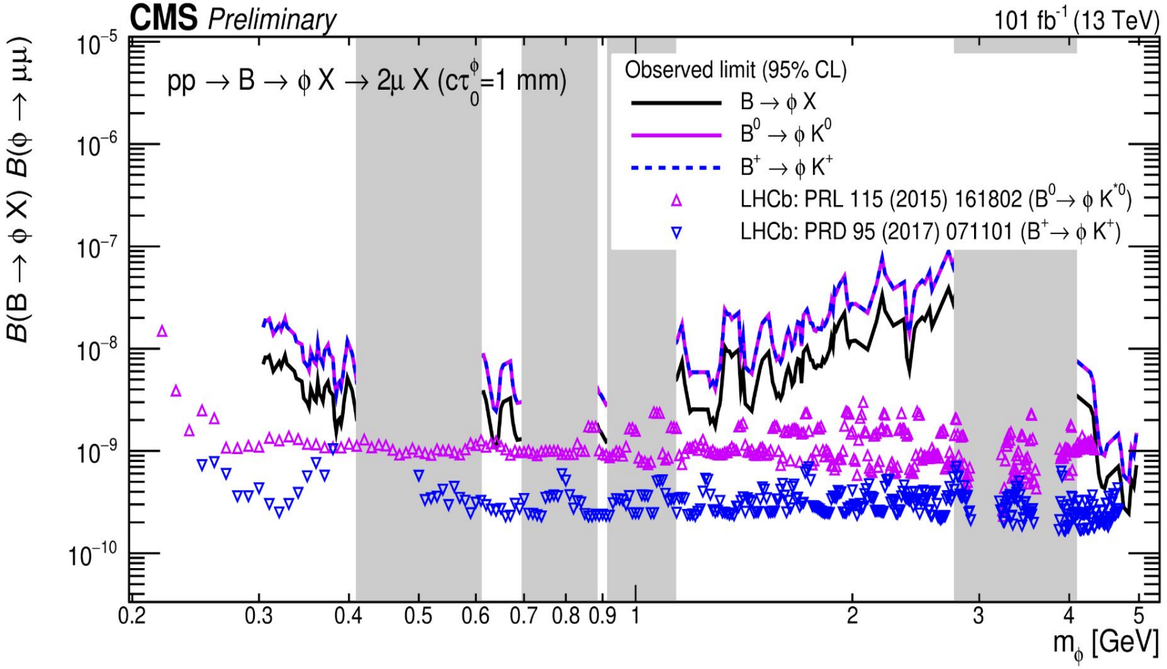
- Upper limits at 95% CL on BR(B → ϕX) . BR(ϕ → μμ) are shown in $c\tau^{\phi}_{0}$ - m_{ϕ} plane as well as a function of $c\tau^{\phi}_{0}$ for various mass hypotheses of ϕ.
  - At high m_{ϕ} and high $c\tau^{\phi}_{0}$, the constraints are stronger due to lower backgrounds at larger displacements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

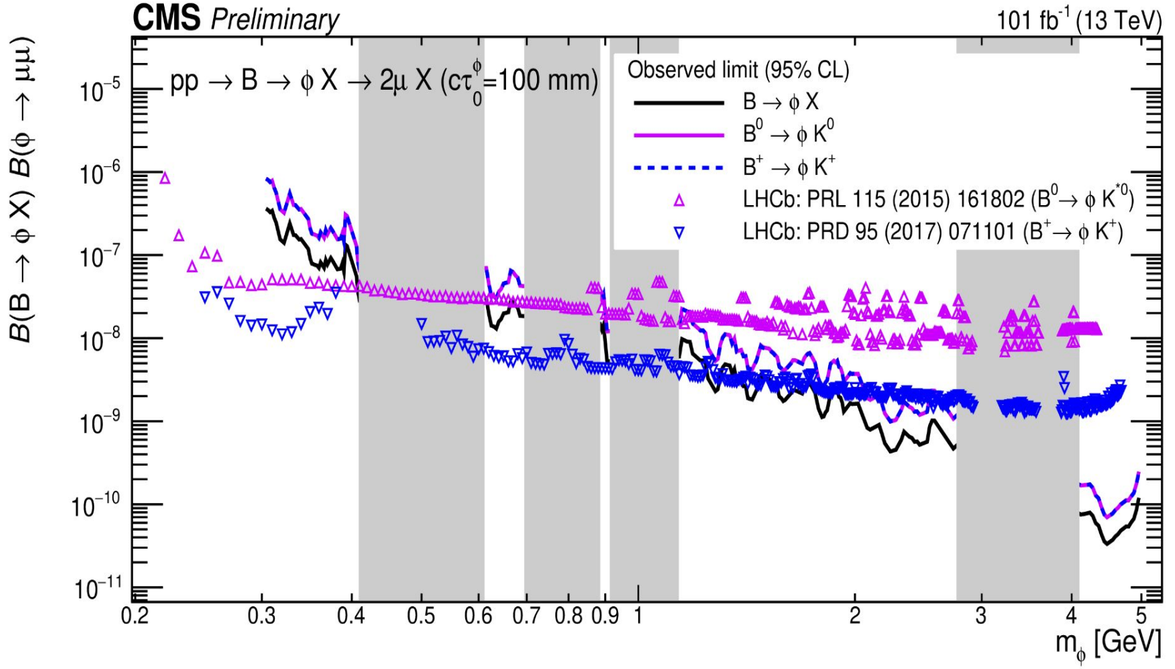




Comparison with LHCb

- 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.





Run -2 Summary for $B \rightarrow \phi X$

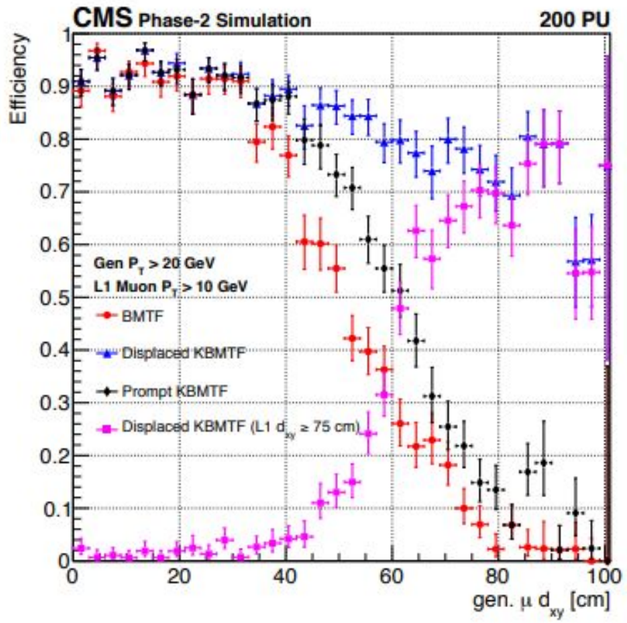
- We perform a first search for light scalars decaying to dimuons arising from flavor changing B decays at CMS using Run-2 data. Preliminary results can be viewed here.
- Scouting enabled us to probe into this otherwise inaccessible phase-space.
- The results from the search are motivating and CMS is competitive with LHCb.

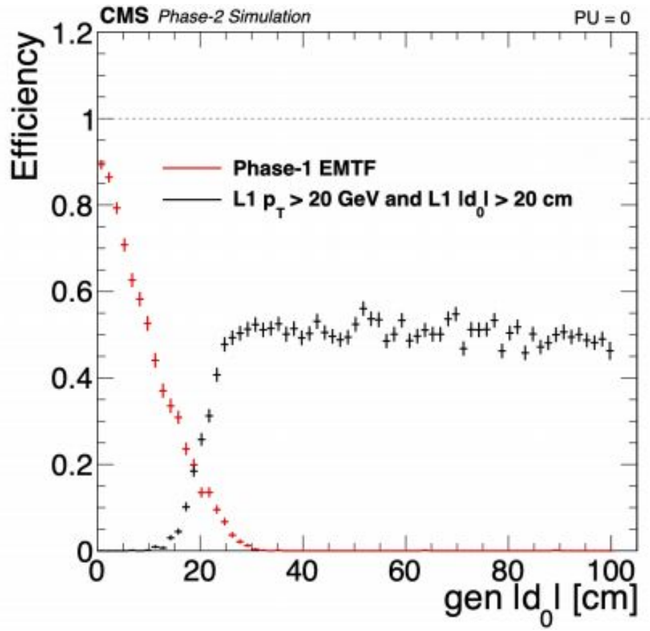
Sensitivity projections on B → ϕX at CMS

- HL-LHC expected to deliver overwhelmingly large number ~10^{15} B mesons.
- Phase-2 CMS upgrades expected to enable displaced tracking at L1 level providing opportunity to trigger on displaced objects.

CMS-TDR-021

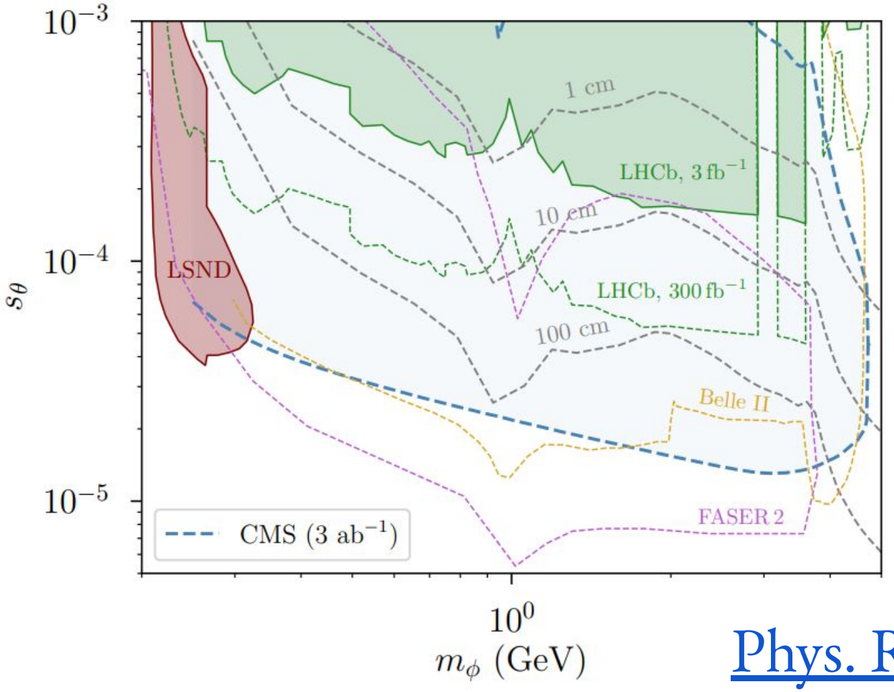
- Efficiency increased to ~95% - 50% for L1 barrel muons and ~50% for L1 endcap muons with displacements till 100 cm.
- Enormous capability with low threshold dimuon trigger like scouting.

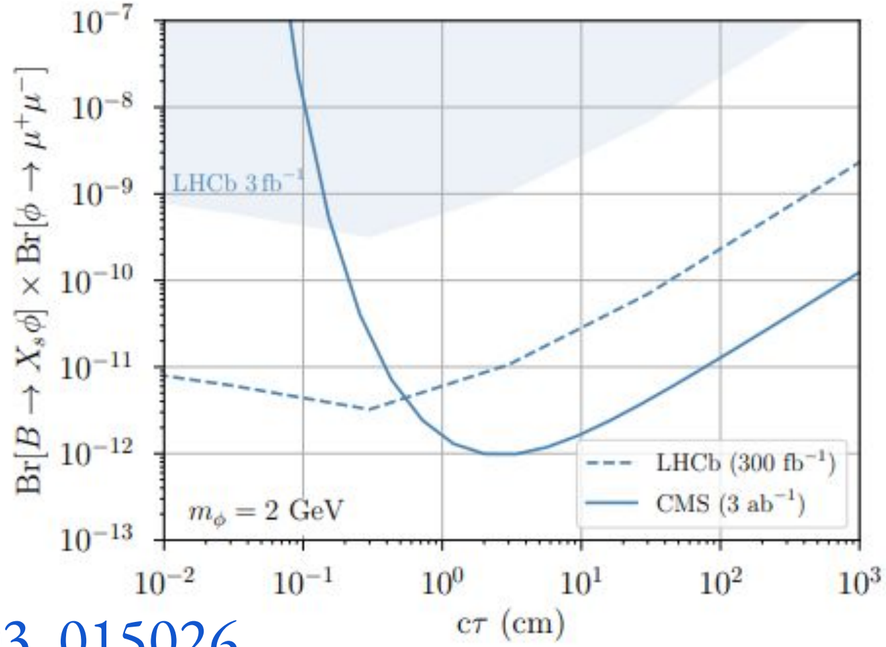




Sensitivity projections on B → ϕX at CMS

- Projected reach of CMS at HL-LHC shows improvement in existing limits by orders of magnitude.
- Expected to outperform LHCb HL-LHC's reach.
- Optimistic assumptions motivated by the current search.



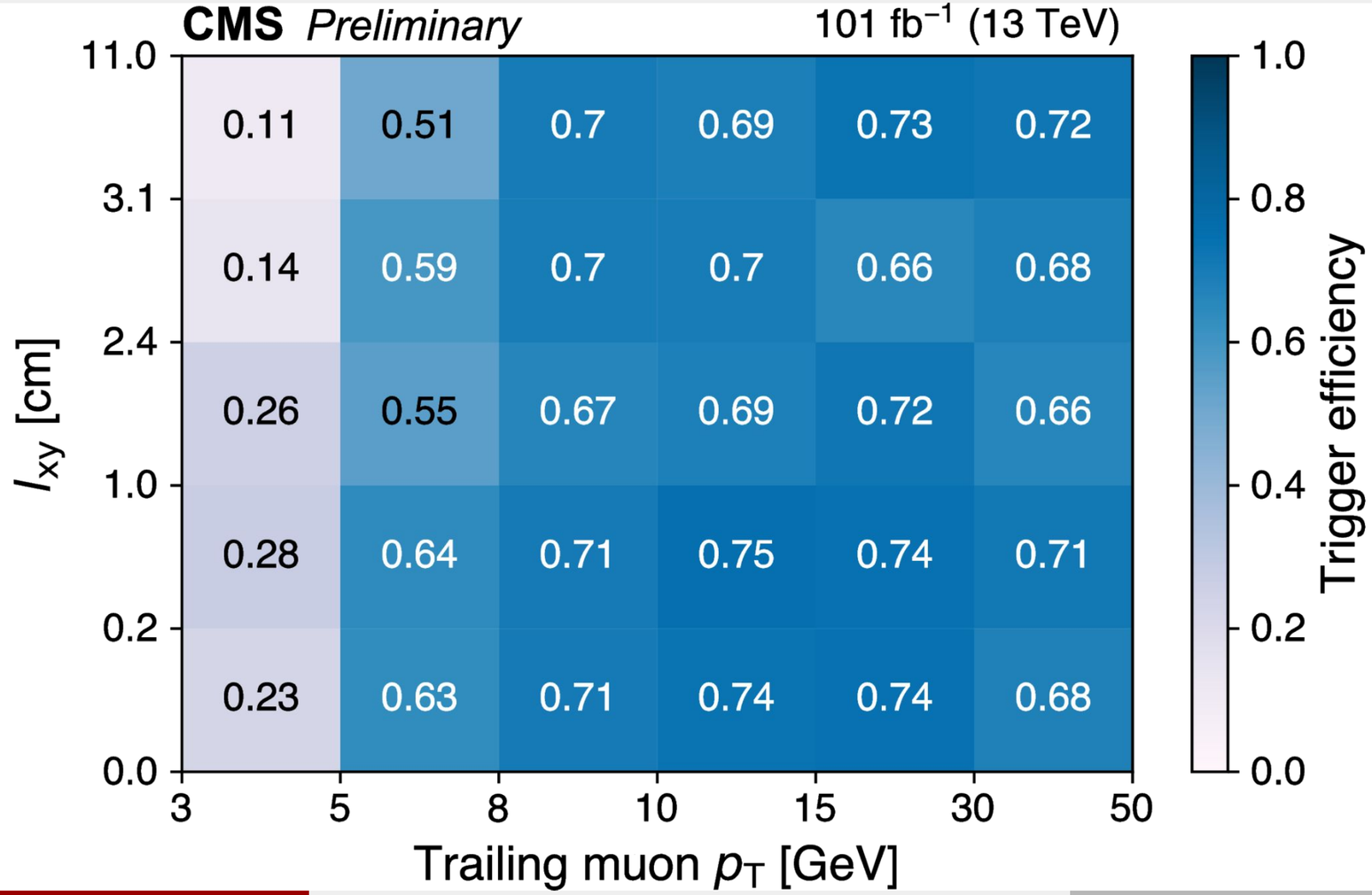


Phys. Rev. D 103, 015026

THANK YOU

BACKUP

Scouting Trigger Efficiency



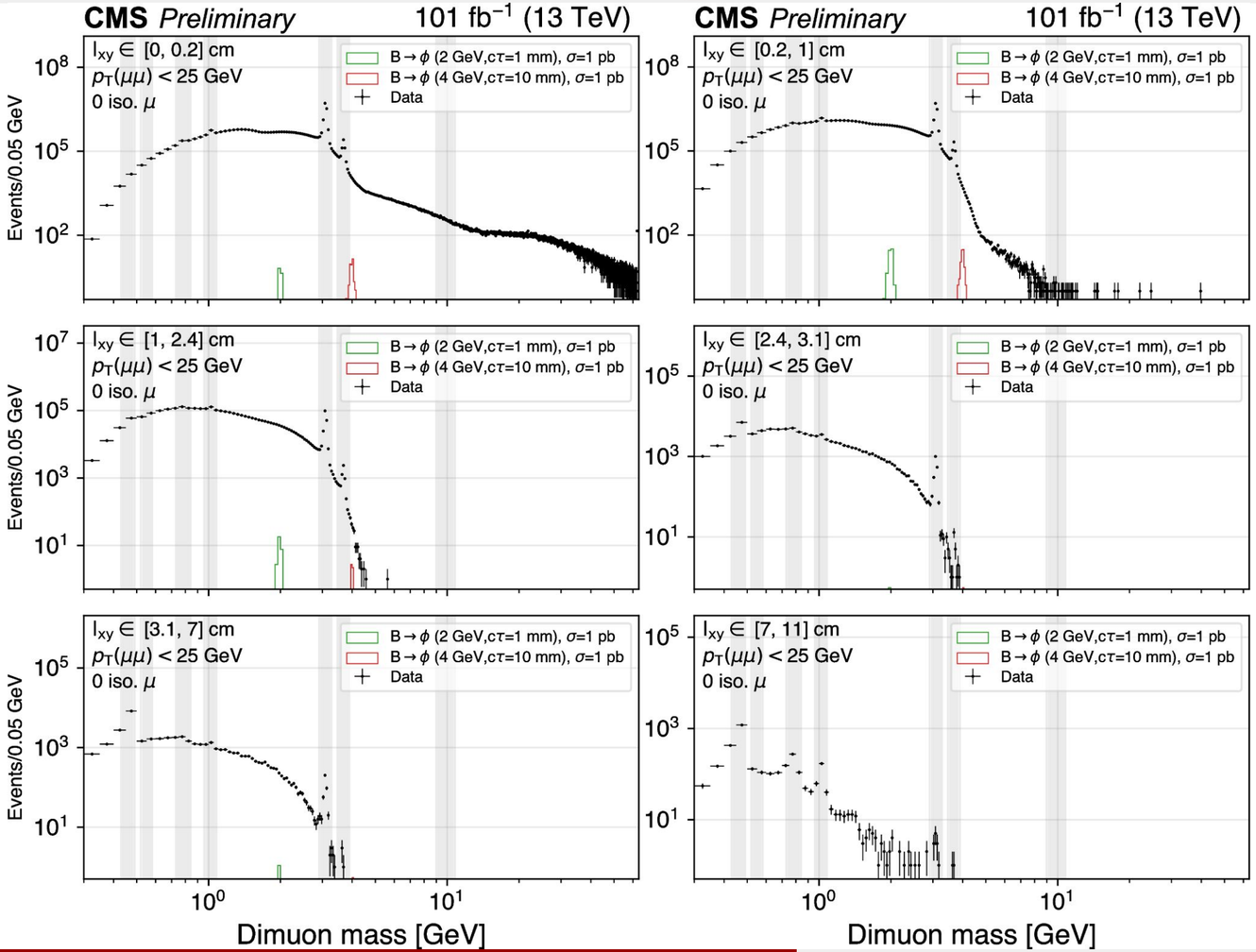
$B \rightarrow \phi X$ Monte Carlo

- $B \rightarrow \phi X$ 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

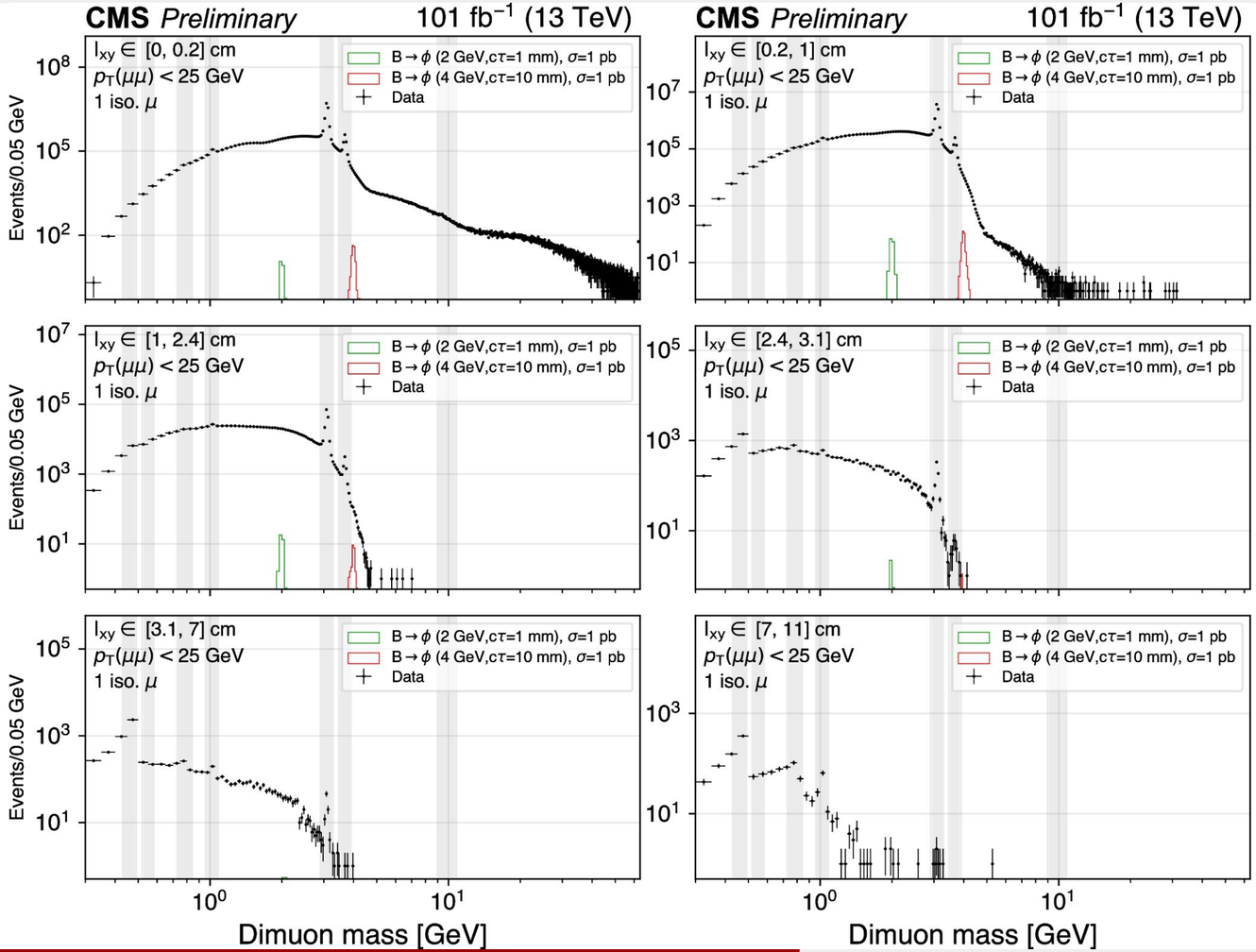
Resonance	Mean mass [GeV]	σ [MeV]	Lower bound [GeV] (mean -5σ)	Upper bound [GeV] (mean $+5\sigma$)
K_S	0.46	5	0.43	0.49
η	0.55	5	0.52	0.58
ρ/ω	0.78	10	0.73	0.84
$\phi(1020)$	1.02	10	0.96	1.08
J/ψ	3.09	40	2.91	3.27
$\Psi(2S)$	3.68	40	3.47	3.89
$\Upsilon(1S)$	9.43	90	8.99	9.87
$\Upsilon(2S)$	10.00	80	9.61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

Events (Low p_T and non-isolated)



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

Events (Low p_T and partially-isolated)

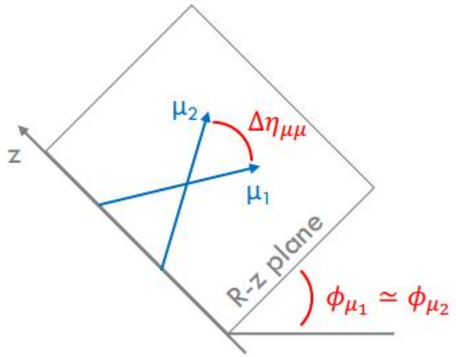


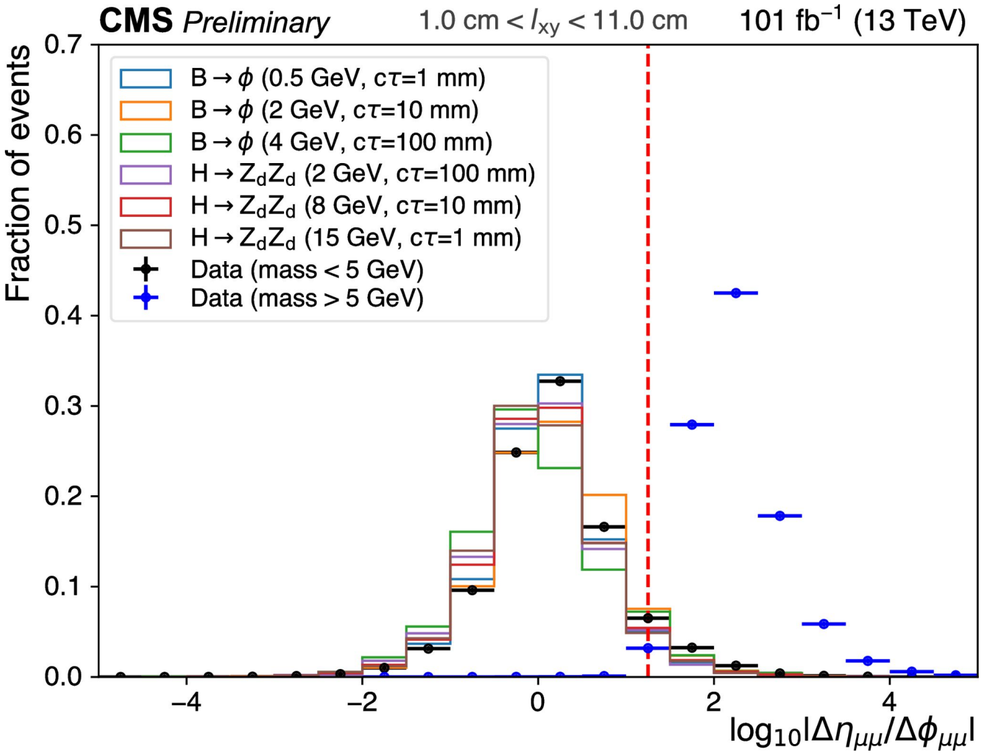
- Partially isolated 2**μ** events having dimuon $p_T(\mu\mu) < 25$ GeV in successive l_{xy} bins.

Background Suppression - Non B

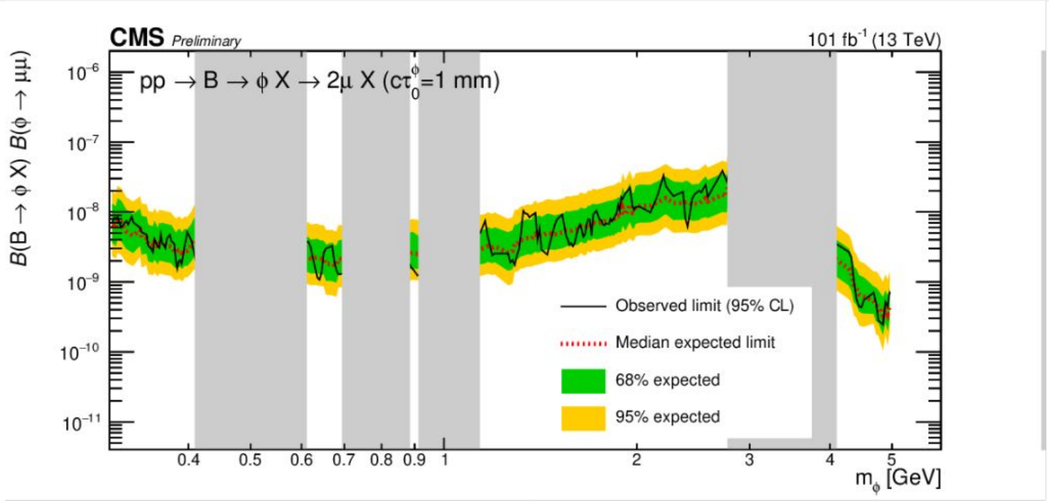
- **Fake vertices from overlapping pileup (PU) muon tracks.**

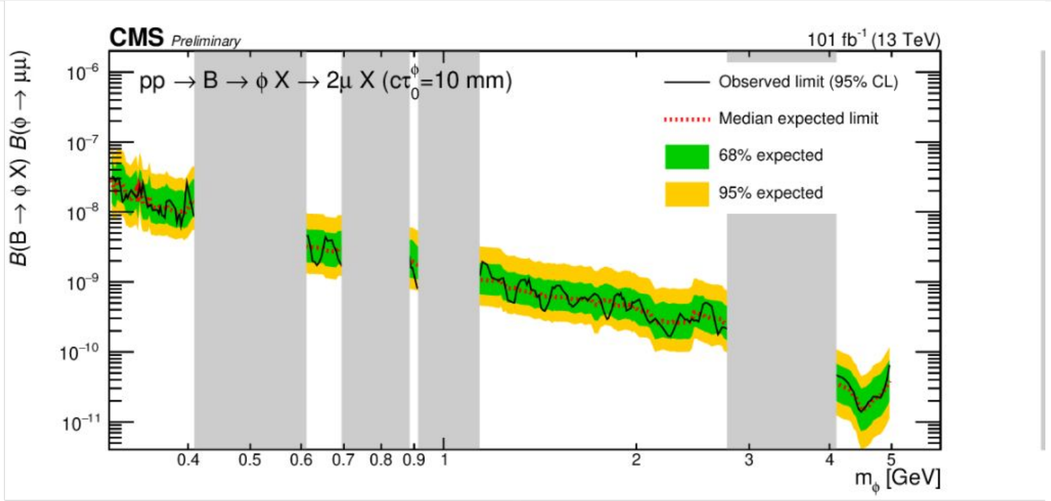
➢ Pileup muon tracks are overlapping in R-ϕ plane ($\Delta\phi_{\mu\mu}$ ~ 0) and separated in R-z plane.
  - Require $\log_{10}(\Delta\eta / \Delta\phi) < 1.25$ to suppress PU background.

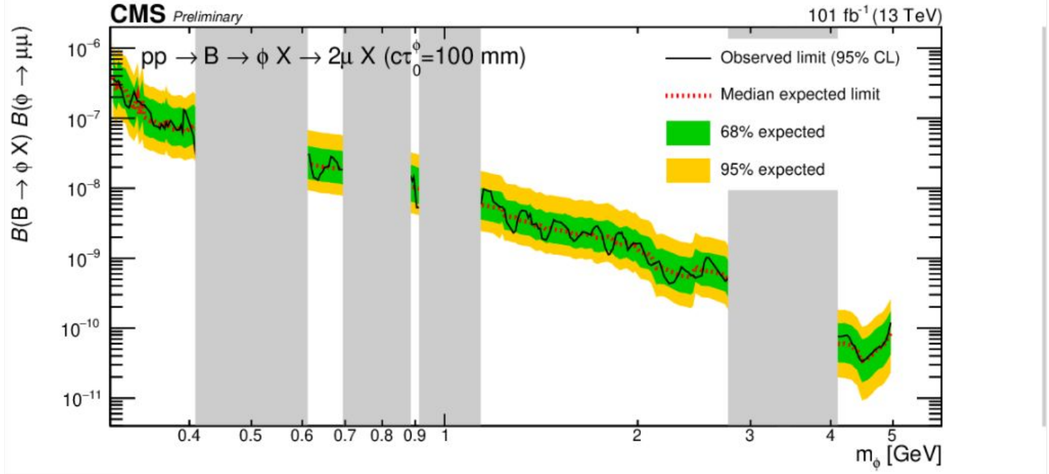




Results: UL on BR(B → ϕX) . BR(ϕ → μμ)







s_θ comparison placeholder

Comparison with LHCb