Search for long-lived particles decaying into two muons using data collected with high-rate triggers at CMS

July 22nd, 2021

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- on behalf of the CMS collaboration -

Seminar - INFN (Padova)

The Standard Model: a story of success

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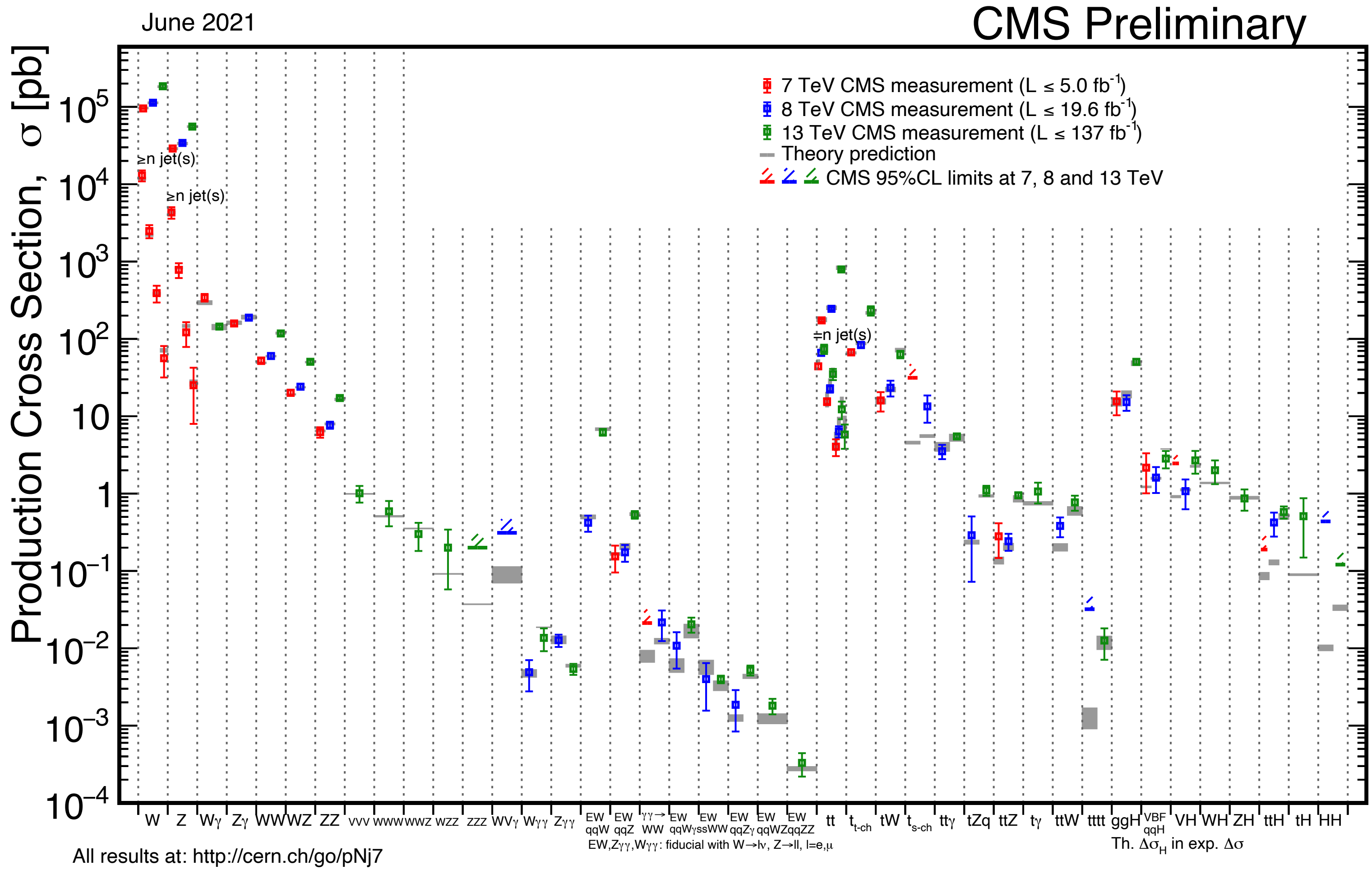
- The Standard Model (SM) has been probed over the years at the LHC (and before)
  - → With great success, ranging over many orders of magnitude
  - → Including prediction of Higgs boson



The Standard Model: a story of success, with its limitations

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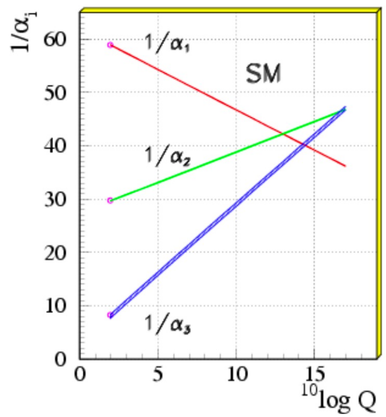
- **Gravitation** is not described by SM
  - Sizeable effects are expected at large energy scale
- EWK scale [O(1 TeV)] << Planck scale [$\simeq 2.4 \cdot 10^{15}$ TeV]
  - **Hierarchy problem**
  - With significant fine-tuning to achieve $m_{Higgs} \simeq 125$ GeV
- **Unification of forces** (Grand Unified Theories) is not supported
  - GUTs may explain inflationary dynamics of early Universe
- Why **matter-antimatter imbalance** in Universe?
- Why **three generations** of quarks and leptons?
- Why **flavor anomalies**?
- **Neutrinos** are predicted to be **massless**
  - Experimental observations imply nonzero mass
- Only *baryonic matter*, with no **dark matter** candidate
  - From astrophysical and cosmological observations:
    - Dark matter ~ 22% of energy in Universe
    - **Dark energy** ~ 74%



From Chin. Phys. C38 (2014) 090001

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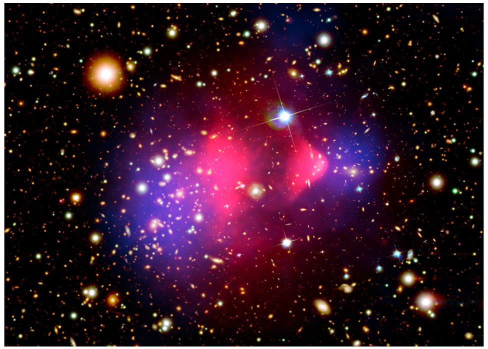

Going beyond the Standard Model

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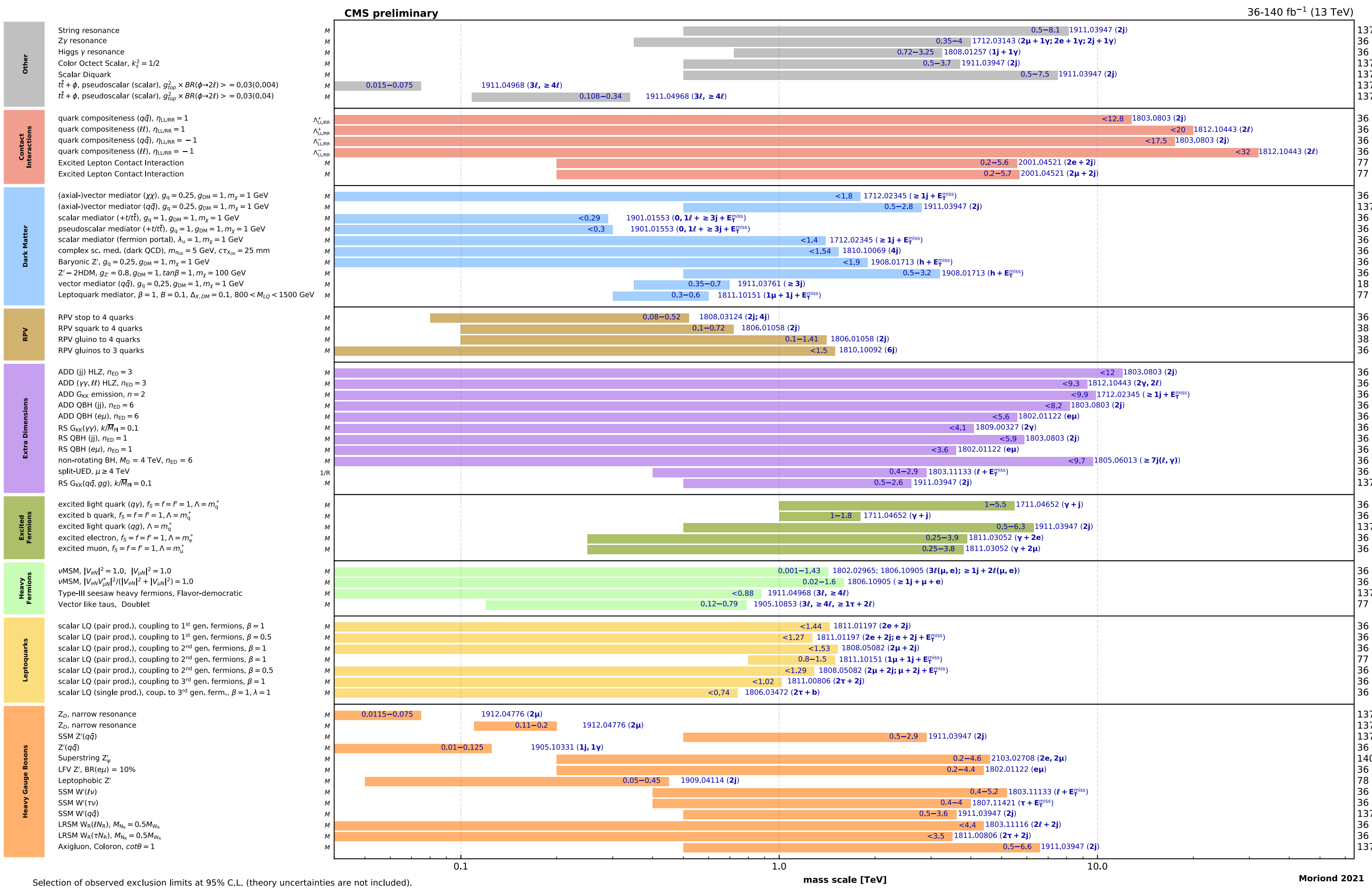
- Limitations to SM hint to physics **beyond the SM**

→ Searches at the LHC are extensively looking for signatures of BSM physics

Overview of CMS EXO results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

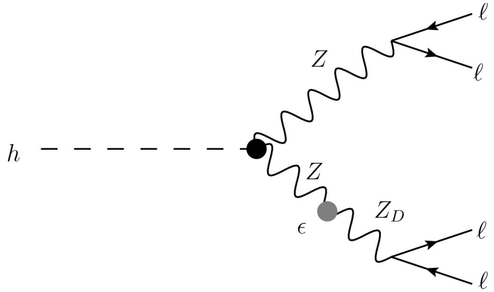
What are we looking for?

- Dark matter is expected to interact very weakly with SM, if at all

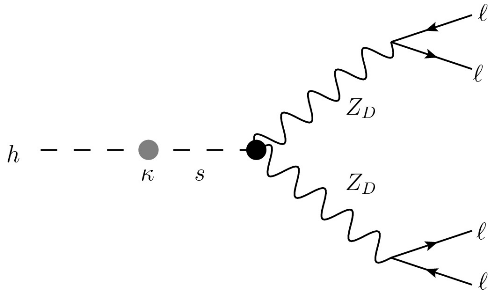
→ Possibility of **hidden/dark sector of matter** [1, 2]:
  - Dark particles can interact with SM via **weakly interacting mediators**
  - **Mass** and **lifetime** of mediators are not strongly constrained

1. Dark photon (Z_D):

- Interaction with SM through hypercharge portal
  - Via kinetic mixing coupling ε



- Interaction with SM through Higgs (h) portal
  - Via Higgs mixing κ



[1] arXiv:1311.0029; [2] JHEP 02 (2015) 157

What are we looking for?

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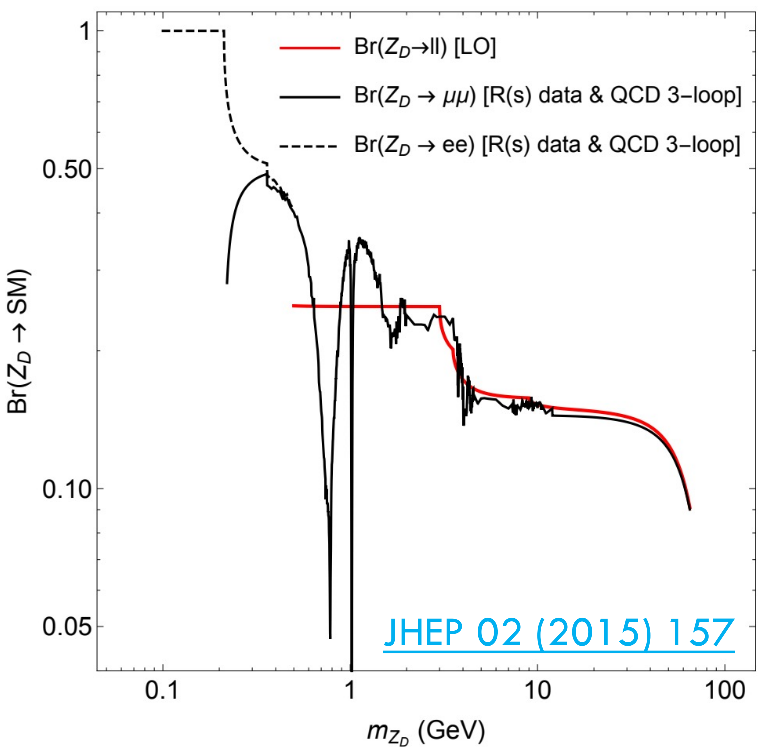
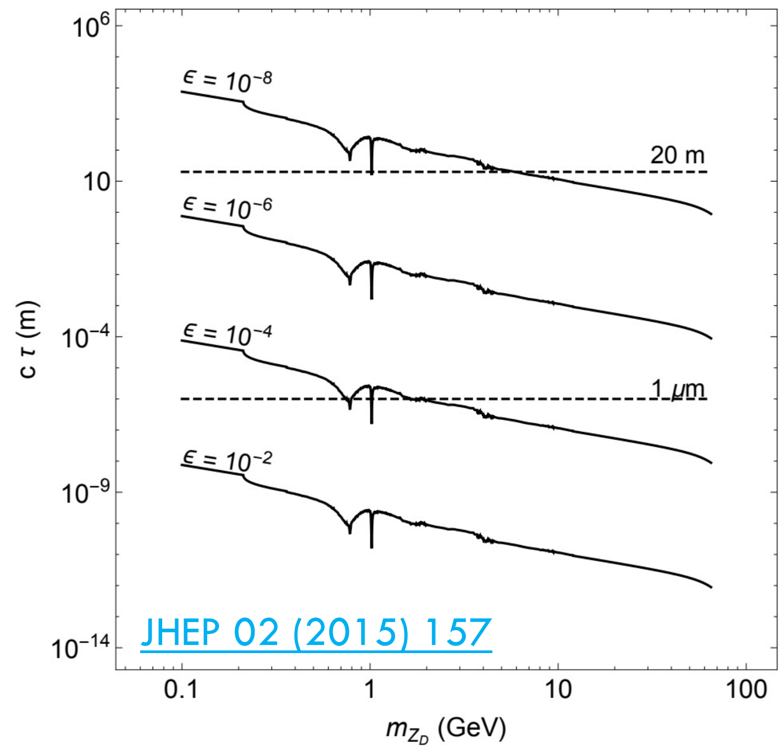
1. Dark photon (Z_D):

- In absence of hidden-sector states below its mass, Z_D will only decay to SM particles, with coupling of SM fermions to Z_D proportional to kinetic mixing coupling ε

❖ Sizeable **decay branching fraction of Z_D → μμ**



❖ If ε ≲10^{-4}, then Z_D will be **long-lived**



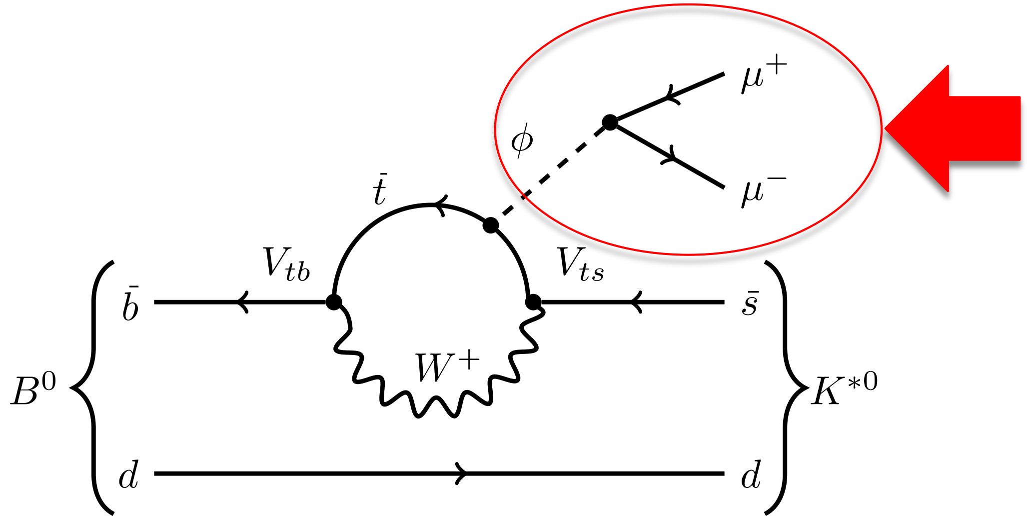
What are we looking for?

2. Singlet scalar field (ϕ):

- Minimal extension to the SM adds a singlet scalar field (ϕ) [3, 4]
  - ϕ is mixing with the SM-like Higgs boson
  - Coupling of SM fermions to ϕ is proportional to mixing angle (s_θ)
  - ϕ is likely long-lived (LL)

→ **Scalar resonance** produced in B hadron decay: **B→ϕX**

- With sizeable **decay** branching fraction of **ϕ→μμ**



[3] JHEP 1307 (2013) 140; [4] PRD 95 (2017) 115001

How do we look for it?
- The CMS detector

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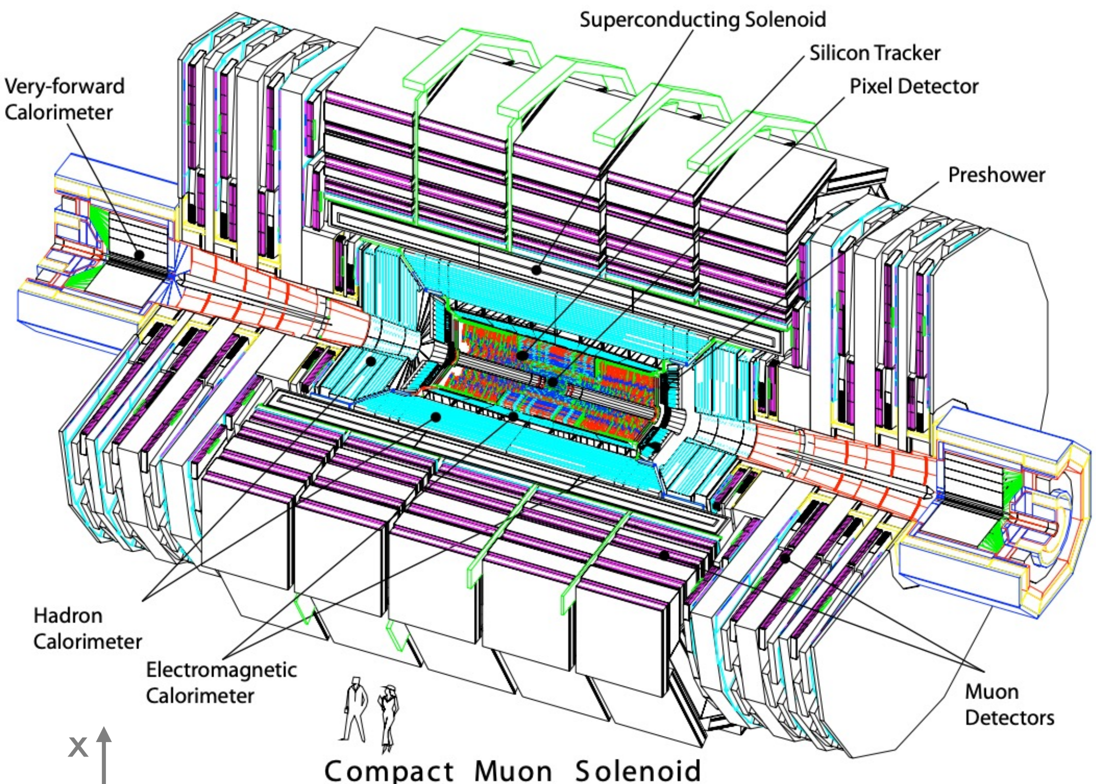
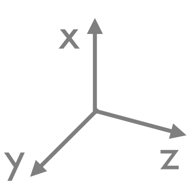
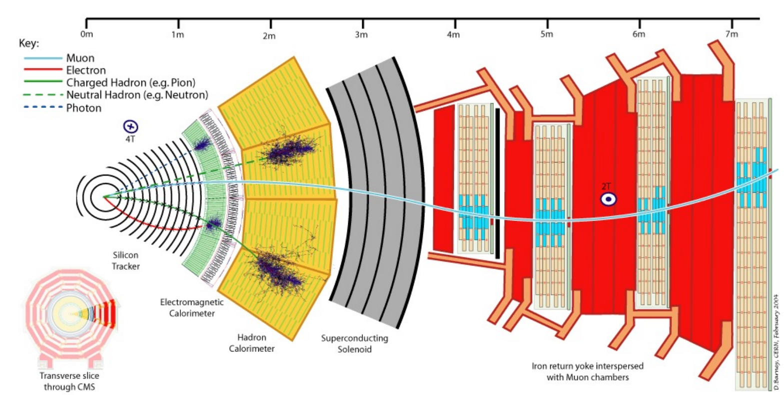
- Search for a **narrow long-lived dimuon resonance**
  - With $m_{LLP} \gtrsim 2m_{\mu}$ and $c\tau_0^{LLP} > 0$





From: CERN-LHCC-2006-001

→ Main features:
- Highly granular **tracking system**
- Electromagnetic+hadron calorimeter
- Superconducting solenoid (B = 3.8 T)
- Robust and redundant **muon system**



From: CMS-OUTREACH-2016-027

How do we look for it?
- The CMS trigger system

- Search for a **narrow long-lived dimuon resonance**
  - With $m_{LLP} \gtrsim 2m_{\mu}$ and $c\tau_0^{LLP} > 0$

- Collision data delivered by LHC and collected by the CMS detector are filtered by a two-level trigger system:
  1. Level-1 Trigger (L1T)
  2. High Level Trigger (HLT)

  } ⇨ Total rate reduction by ~ 10^6

  ➢ Only events selected at HLT are then fully reconstructed offline, due to constraints on computing and storage resources

→ **Standard triggers** do **not** allow to access full phase-space of interest due to limitations in acceptance rate

How do we look for it? - The CMS scouting triggers

- Standard triggers do <u>not</u> allow to access full phase-space of interest
  - ❖ Events not selected by trigger system are lost, forever

➢ **<u>Data scouting</u>**, used in CMS since 2011:

- **Idea:** "<u>Do more, with less</u>"
  1. Increase of trigger acceptance rate
     - ❖ Looser (more inclusive) selections
  2. Decrease of event size, to compensate
     - ❖ Keep only HLT-level information

- Similar streams were used by ATLAS and LHCb during LHC Run-2

The CMS scouting triggers: a successful example

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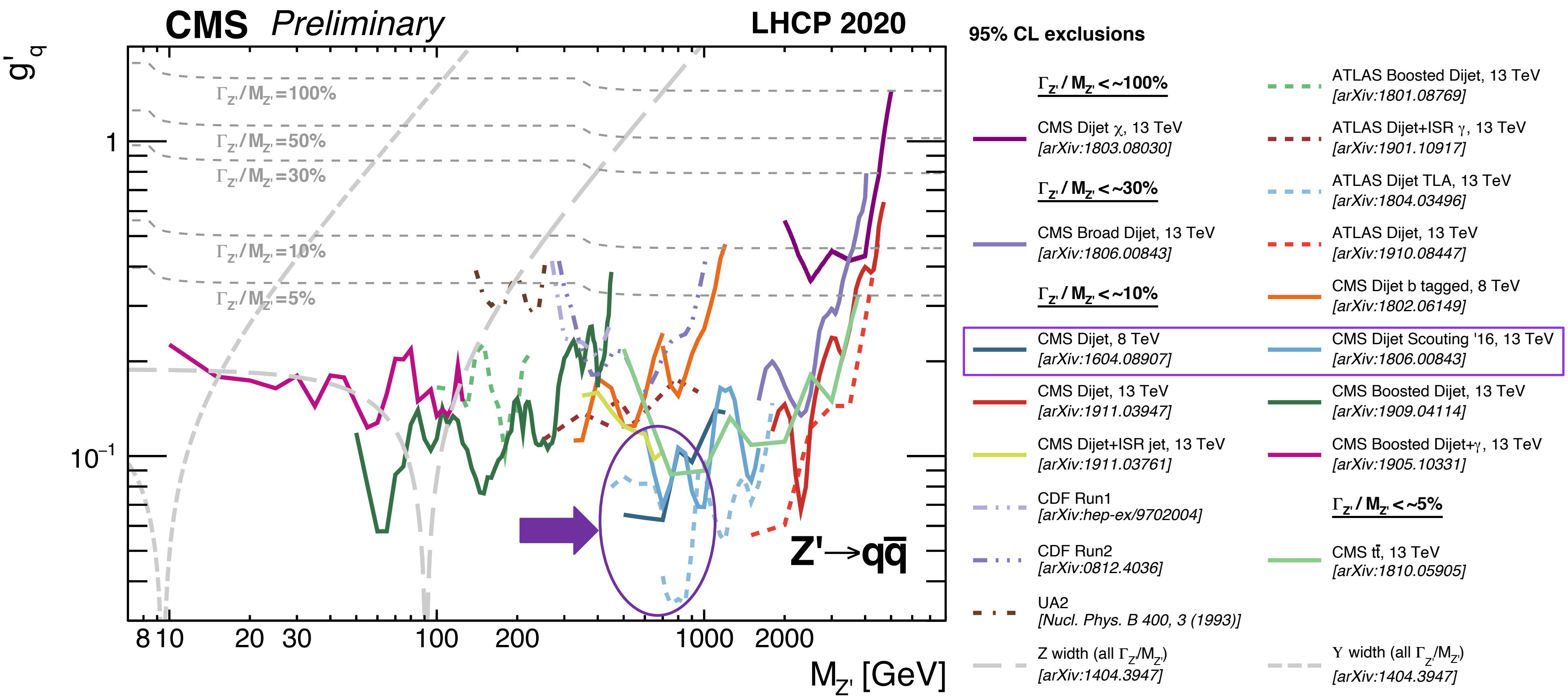
- First successful applications in CMS: **low-mass dijet resonances**



→ Allowed to **probe otherwise inaccessible parameter space,** at low coupling g'_q (between leptophobic Z' boson and quarks) and mass in range [500, 1000] GeV

How do we look for it?
- The CMS **dimuon** scouting triggers

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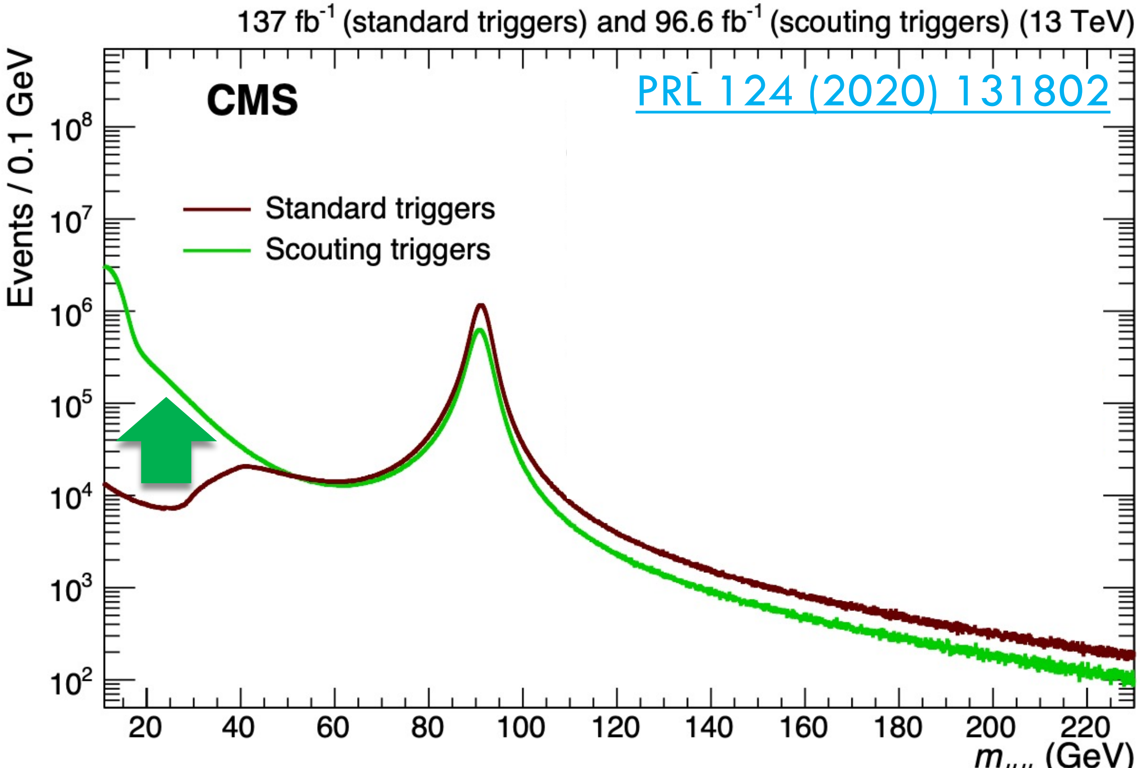
- Search for a **narrow long-lived dimuon resonance**
  - With $m_{LLP} \gtrsim 2m_{\mu}$ and $c\tau_0^{LLP} > 0$

❖ Standard triggers do not allow to access phase-space of interest

→ Use CMS **dimuon scouting triggers** (instead of standard triggers)



How do we look for it?
- The CMS dimuon scouting data, in detail

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- Search for a **narrow long-lived dimuon resonance**
  - With $m_{LLP} \gtrsim 2m_{\mu}$ and $c\tau_0^{LLP} > 0$

❖ Standard triggers do not allow to access phase-space of interest

→ Use CMS **dimuon scouting data** collected in 2017-2018 (101 fb^{-1})

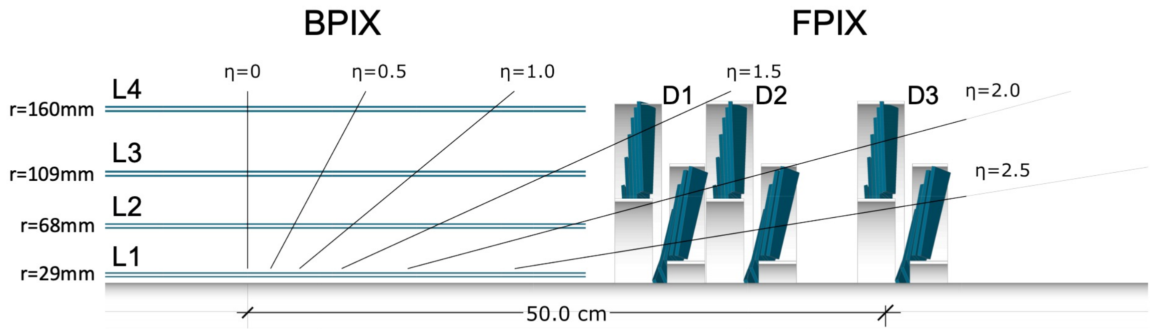
❖ Content of 2016 scouting data is different

➢ Data collected at high rate with limited information as at HLT

➢ Low p_T thresholds on μ's and ~no constraint on displacement

❖ Presence of ≥ 2 hits in pixel tracker was required in Run-2

→ Range of accessible transverse displacement: $\mathbf{0 \leq l_{xy} < 11}$ **cm**



From JINST 16 (2021) 02

A brief digression:
B physics parking program at CMS

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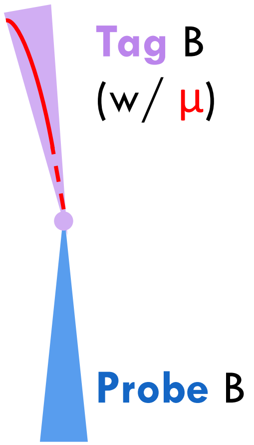
- Alternative/complementary approach to scouting data to cope with limited trigger acceptance, with focus on **B physics anomalies**
- **Unbiased** sample of $O(10^{10})$ B's was collected during LHC Run-2
  1. Trigger on muon from "tag" B
  2. Collect unbiased sample of "probe" B's

  - Collected data are "**parked**"

  → Undergo full offline reconstruction at later stage, to deal with limited computing resources



➢ **Unprecedented potential for B physics in CMS**
  - Including searches for BSM (LLP) signatures

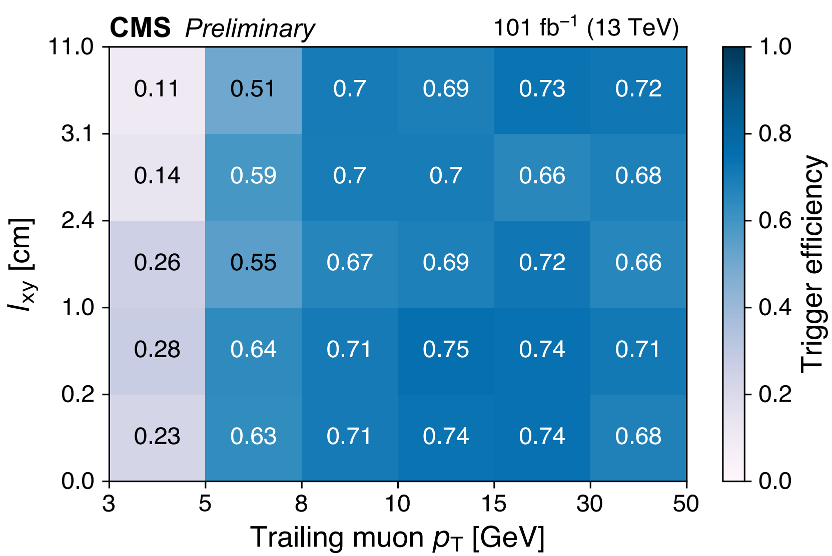
❖ For present search, choice to use **dimuon scouting data**
  - Due to enhanced inclusiveness of dimuon scouting triggers
  - Due to higher total integrated luminosity of scouting data set

An inclusive trigger selection

- Events are selected with at least two opposite-charge (OS) muons
  - With $p_T^{\mu} > 3$ GeV & $|\eta^{\mu}| < 2.4$
  - No explicit constraint on displacement
  - No explicit constraint on dimuon invariant mass ($m_{\mu\mu}$)

→ **Trigger selection allows for very inclusive & general search, including low-mass LLP signatures**

❖ Trigger efficiency is measured in data:



Muons and displaced vertices

- Events w/ at least a pair of μ's associated to a displaced vertex (DV)

DV selection:
- $\sigma(x) < 0.05$ cm
- $\sigma(y) < 0.05$ cm
- $\sigma(z) < 0.10$ cm
- $\chi^2/\text{dof} < 5$
- $l_{xy} < 11$ cm

μ identification:
- ❖ Tracker+muon system
- # tracker layers > 5
- $\chi^2/\text{dof} < 3$

μ isolation:
- Track isolation [$\Delta R<0.3$] < 0.1 (0.2) p_T^{μ}
  - ❖ Relaxed for 2nd μ-pair
- min $\Delta R(\mu, \text{jet}) > 0.3$
  - ❖ All HLT calo-jets (p_T>20 GeV)

→ If >1 pairs of OS μ's are selected:
- Ranking by χ^2(DV)
- ➢ Use first (**2μ**) or first two μ-pairs (**4μ**)
- ❖ For 2nd μ-pair, few selection criteria are relaxed to maximize sensitivity

→ Explore isolated, partially isolated and non-isolated 2μ topologies
- ❖ Exploit ability to search for non-isolated signatures, too

Sources of background

- Due to inclusiveness & generality of search and of scouting triggers, **background suppression** is fundamental

➢ Main **sources of background**:
  - Accidental crossing of **cosmic μ's**
  - Accidental crossing of **μ's from pileup** (PU)
  - Accidental crossing of **μ's from QCD** multijet events
  - **Material vertices**, from interactions with detector material
  - **Prompt** (non-displaced) **μ's**
  - Known dimuon mass resonances

  ❖ In the following, will refer to erroneously formed DVs as "fake"

→ Dedicated selection criteria are applied to **suppress background**, while **retaining BSM signal acceptance** for wide **range of signals**

Background suppression: event topology

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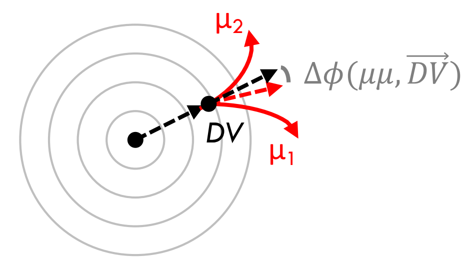
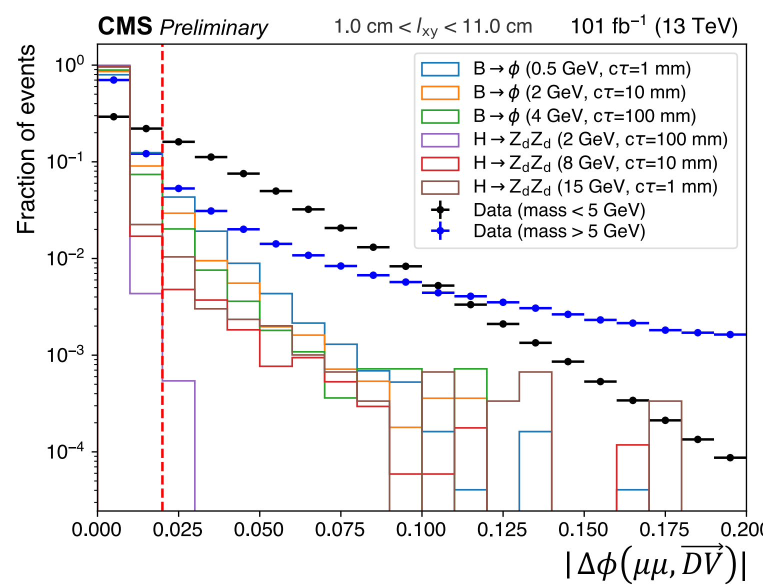
- For BSM signal, expect dimuon system vector to be collinear with DV vector

→ Require **$\Delta\phi(\mu\mu, \overrightarrow{DV}) < 0.02$ (0.1)**

  - To suppress backgrounds with DV formed from accidental crossing of μ-trajectories
  - Relaxed for 2nd μ-pair

- To further suppress backgrounds with fake DVs from cosmic μ's, μ's from PU, or μ's from QCD, also require **$\Delta\phi(\mu_1, \mu_2) < 2.8$**





Background suppression: vs. pileup muons

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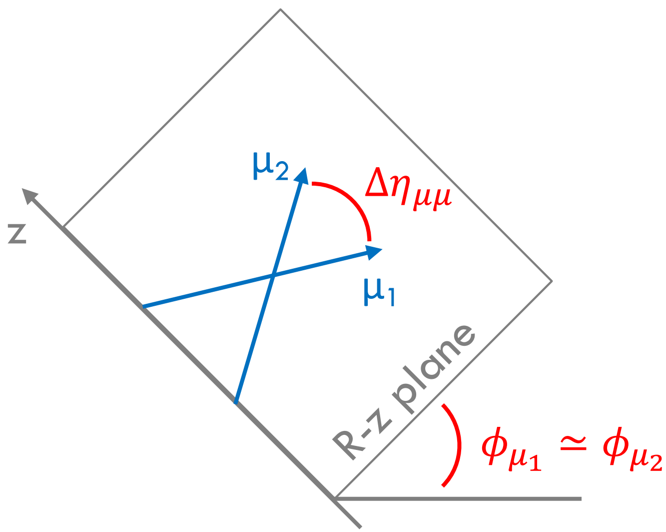
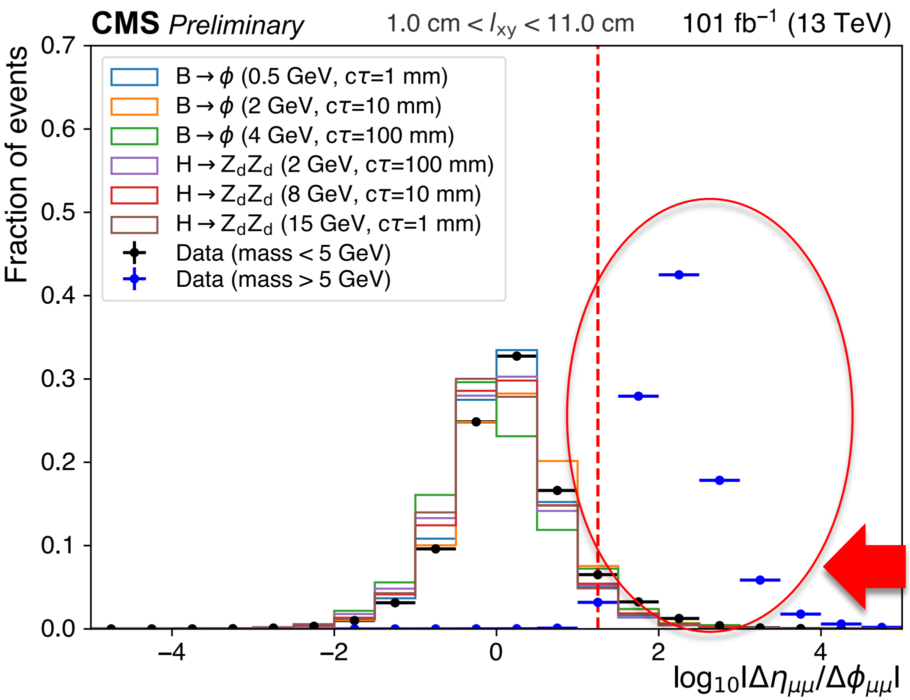
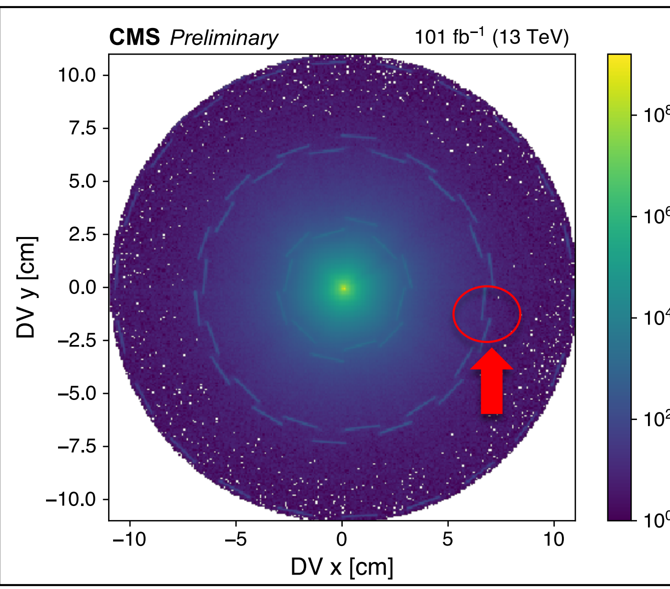
- Reject **fake DV's from overlapping pileup** (PU) μ-tracks
  - Require **$\log_{10}(|\Delta\eta_{\mu\mu}|/|\Delta\phi_{\mu\mu}|)<1.25$**
    - Fake DV's from PU μ-tracks overlapping in R-ϕ plane and far in R-z plane

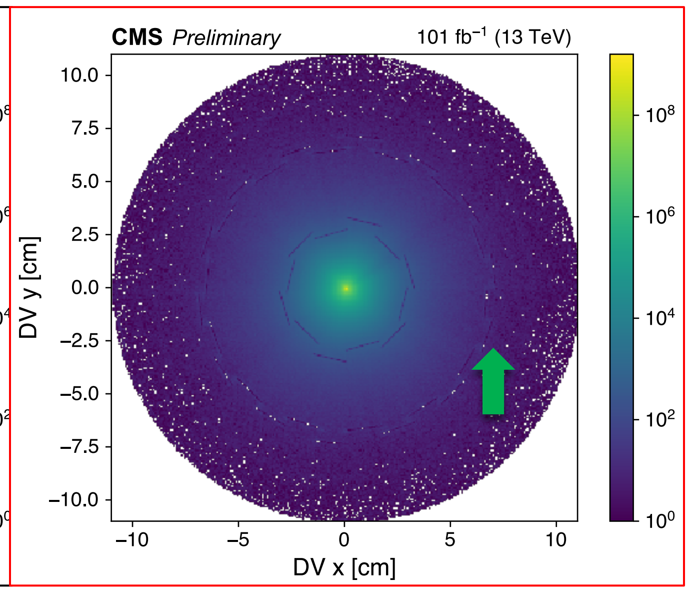


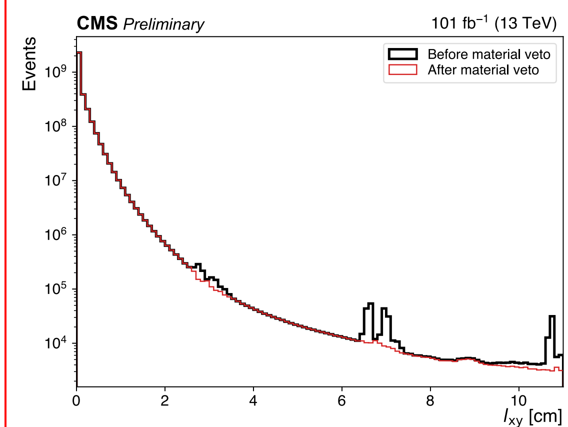


Background suppression: vs. material vertices

- Reject DV's near pixel modules, **to suppress material effects**
  - **DV** is required to be at **>0.05 cm from nearest pixel module**
    - Position of module plane is extracted directly from detector geometry







Background suppression: vs. prompt muons

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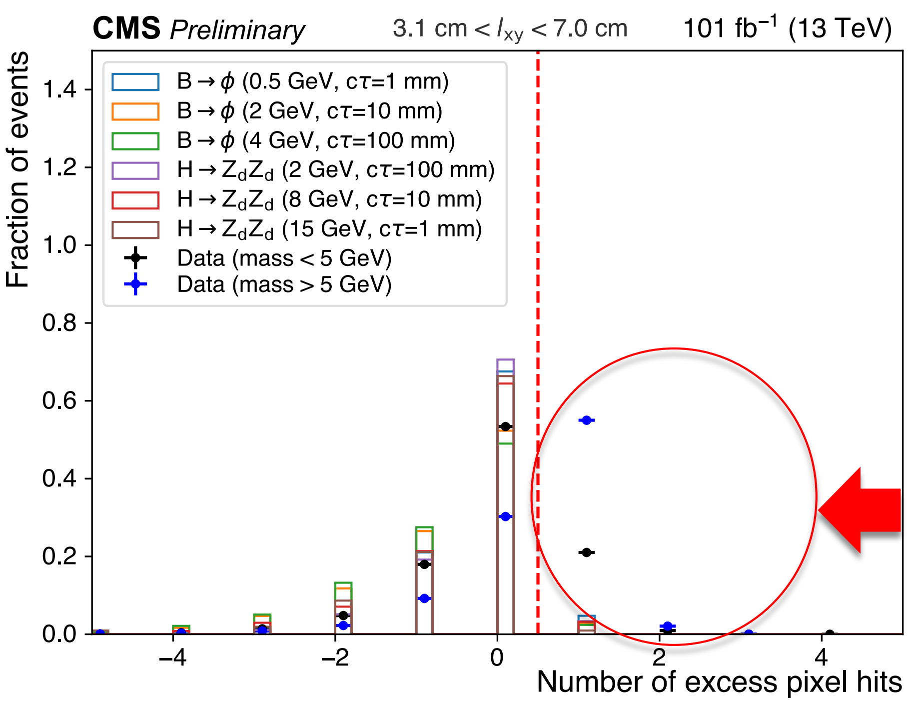
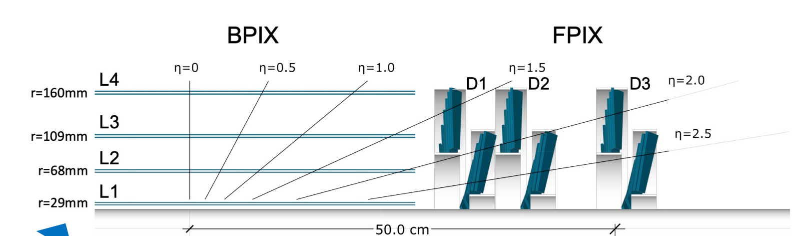
- Reject muons with **# observed pixel hits > # expected pixel hits**
  - To reject **"fake" displaced muons**
    - If a muon is truly displaced, no hits from beamspot to DV are expected
    - Only applied for l_{xy} > 3.5 cm [i.e., beyond 1st pixel layer (L1)]



1. Propagate μ's outwards from DV
2. Count # compatible pixel modules

→ Reject μ's with excess pixel hits



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Background suppression: explicit displacement requirement

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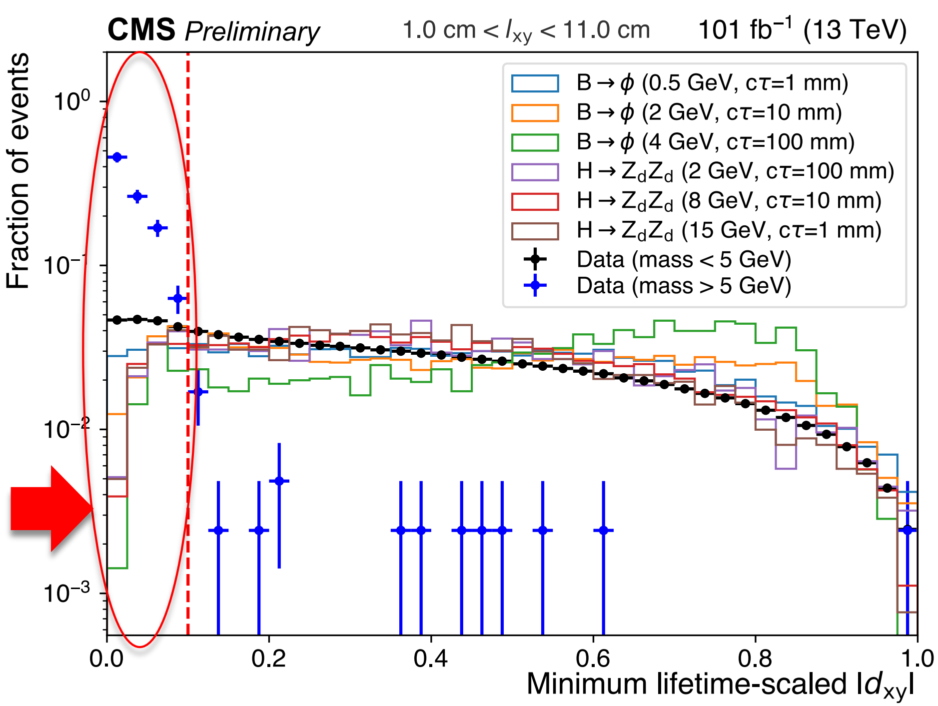
- Require each muon to be displaced wrt. primary vertex (PV)
  - Require $|d_{xy}/\sigma_{xy}| > 2$ (1)
    - Relaxed for 2nd μ-pair
  - Require $|d_{xy}|/(l_{xy}\, m_{\mu\mu}/p_T^{\mu\mu}) > 0.1$ (0.05)
    - Impact parameter is scaled by lifetime, for lifetime-independent cut
    - Relaxed for 2nd μ-pair



Known dimuon mass resonances

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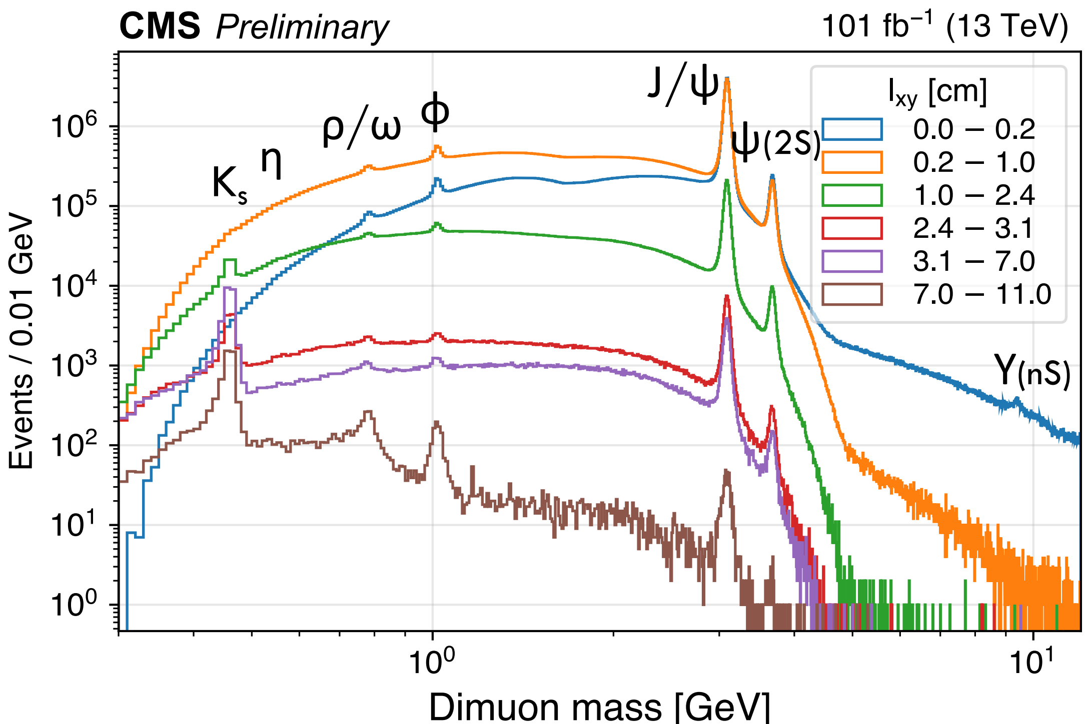
- **Known resonances** are clearly **visible** using CMS scouting data!
  - ❖ Here, shown in bins of transverse displacement (l_{xy})
  - ○ Known resonances, including those where π's are mis-ID'd as μ's, are treated as a signal: mass and width are determined by a fit
  - → A range of ±5σ around each known resonant peak is **masked**, i.e., it is required to not overlap with any search mass window



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

Looking for a range of BSM signals

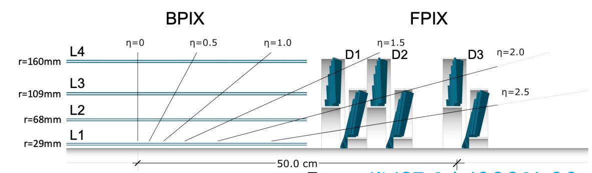
- As we do <u>not</u> target a specific BSM signal model, we can <u>not</u> apply too specific selection criteria

→ We rather **categorize events**, in the attempt to maximize sensitivity to a wide range of BSM signal models

- Aim at exploring a wide range of **lifetime hypotheses**
  - Categorize events according to **displacement** (l_{xy})
- Aim at exploring different **production topologies**
  - Categorize events according to $\mathbf{p_T}^{\mu\mu}$
  - Categorize events according to **muon isolation**
- Aim at exploring a wide range of **mass hypotheses**
  - Slide over dimuon mass spectrum in each category

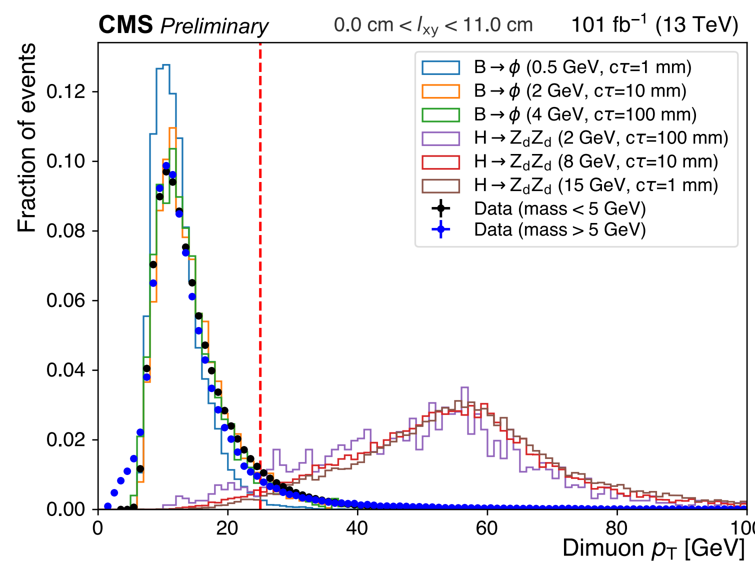
Categorization of dimuon events

- After selection, categorize dimuon events in multi-dimensional bins:
  - l_{xy}: [0.0, 0.2, 1.0, 2.4, 3.1, 7.0, 11.0] cm
    - Driven by geometry of CMS pixel tracker



From JINST 16 (2021) 02

  - $p_T^{\mu\mu}$: [0, 25, ∞] GeV
    - B→ϕX signal is mostly at low $p_T^{\mu\mu}$
    - h→$Z_D Z_D$ signal is mostly at high $p_T^{\mu\mu}$
  - **Isolation:**
    1. Fully isolated topologies
       - Both μ's are isolated
    2. Partially isolated topologies
       - Only one μ is isolated
    3. Non-isolated topologies
       - No μ is isolated



→ **Total of 36 dimuon event categories**

A look at selected dimuon events: $p_T^{\mu\mu} \geq 25$ GeV, isolated topologies

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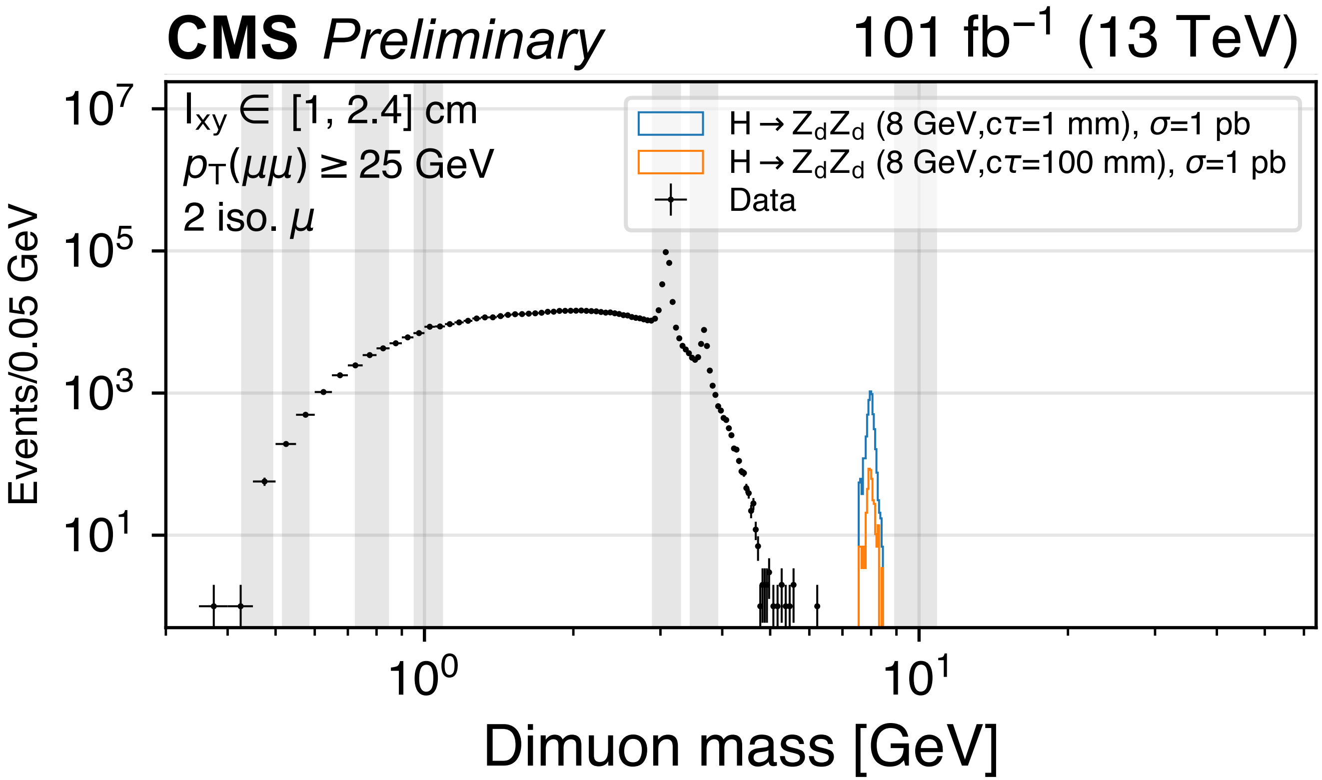
- After full event selection, for **isolated** 2μ events with $\mathbf{p_T^{\mu\mu} \geq 25}$ **GeV**
  - Here, shown for $1.0 < l_{xy} < 2.4$ cm
  - ❖ Other distributions/categories available in [backup]

→ Enriched in $\mathbf{h \rightarrow Z_D Z_D}$ signal



A look at selected dimuon events: $p_T^{\mu\mu}$ < 25 GeV, isolated topologies

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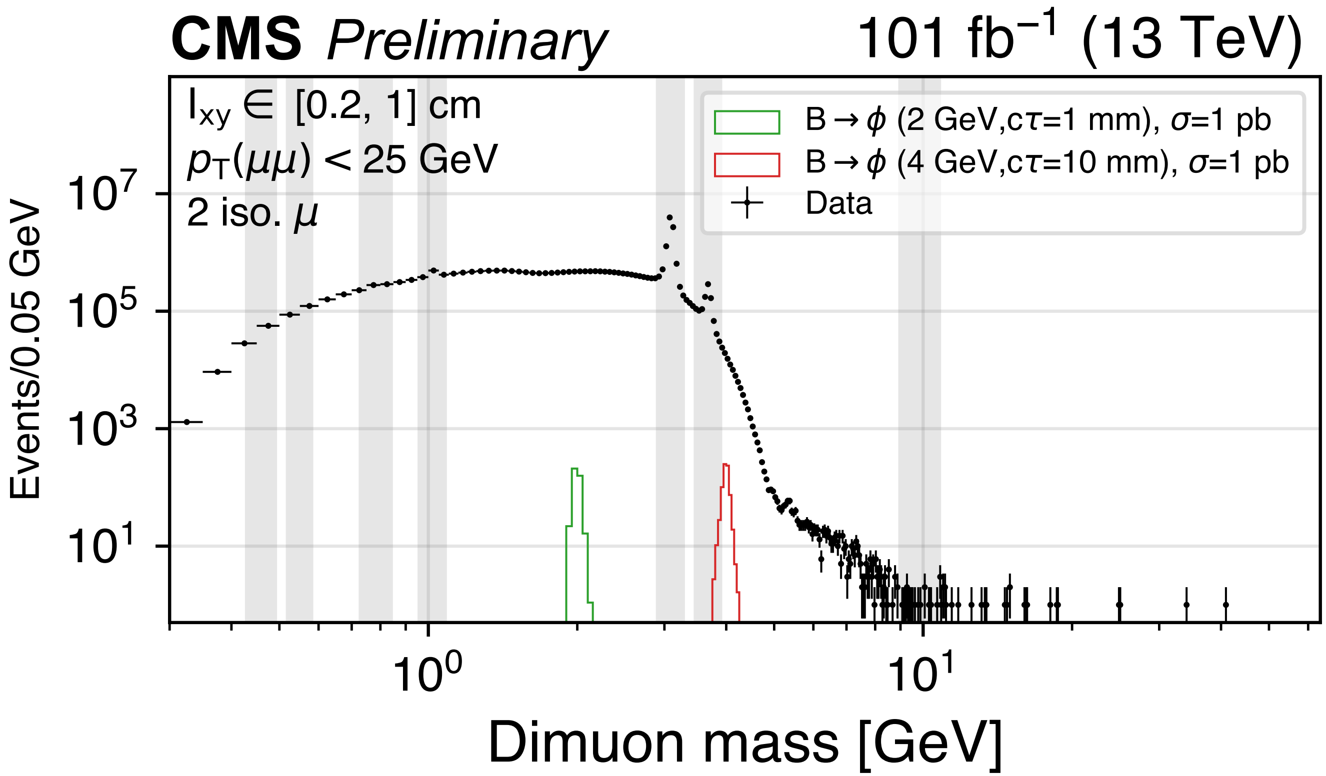
- For **isolated** 2μ events with **$p_T^{\mu\mu}$<25 GeV**
  - Here, shown for 0.2 < l_{xy} < 1.0 cm
  - ❖ Other distributions/categories available in backup
  - → Enriched in **B→ϕX** signal



A look at selected dimuon events: $p_T^{\mu\mu}$ < 25 GeV, **non**-isolated topologies

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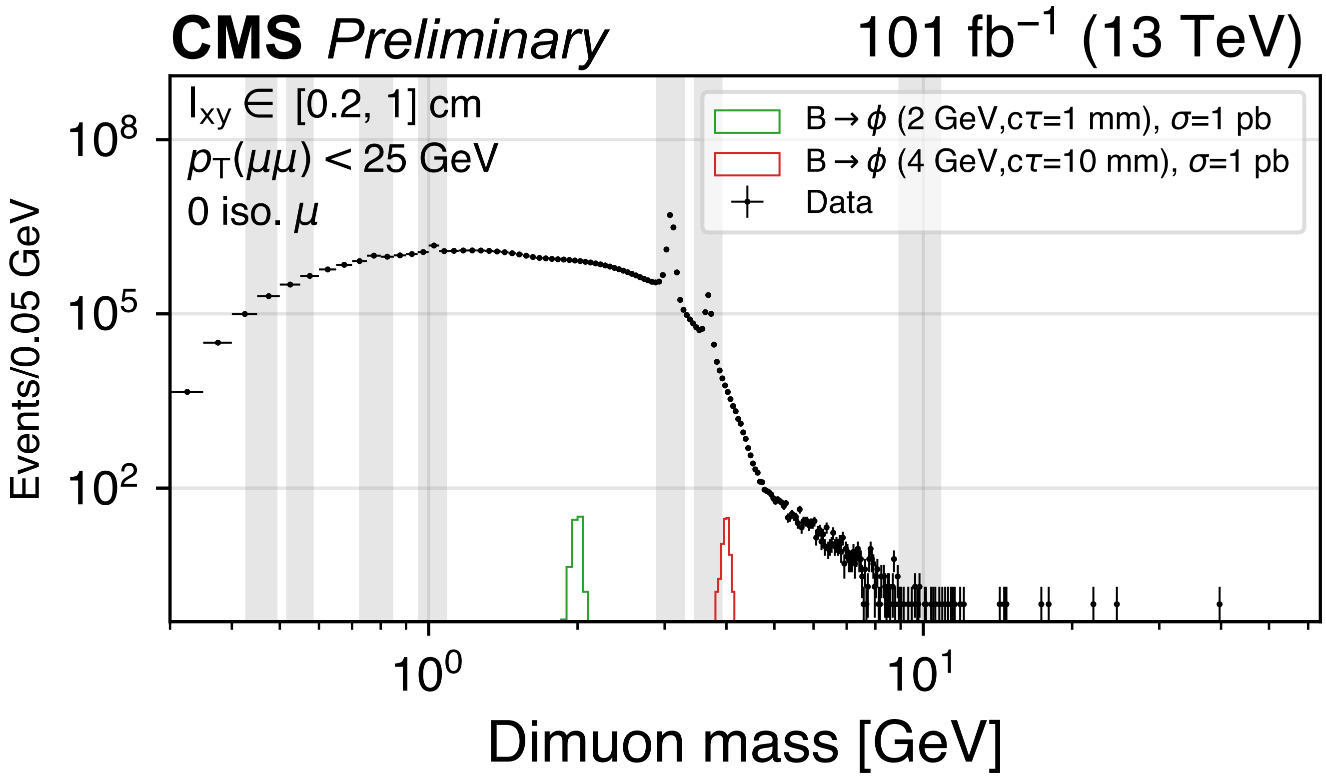
- For **non**-isolated 2μ events with **$p_T^{\mu\mu}$<25 GeV**
  - Here, shown for 0.2 < l_{xy} < 1.0 cm
  - ❖ Other distributions/categories available in backup
  - → Non-negligible contribution from **B→ϕX** signal



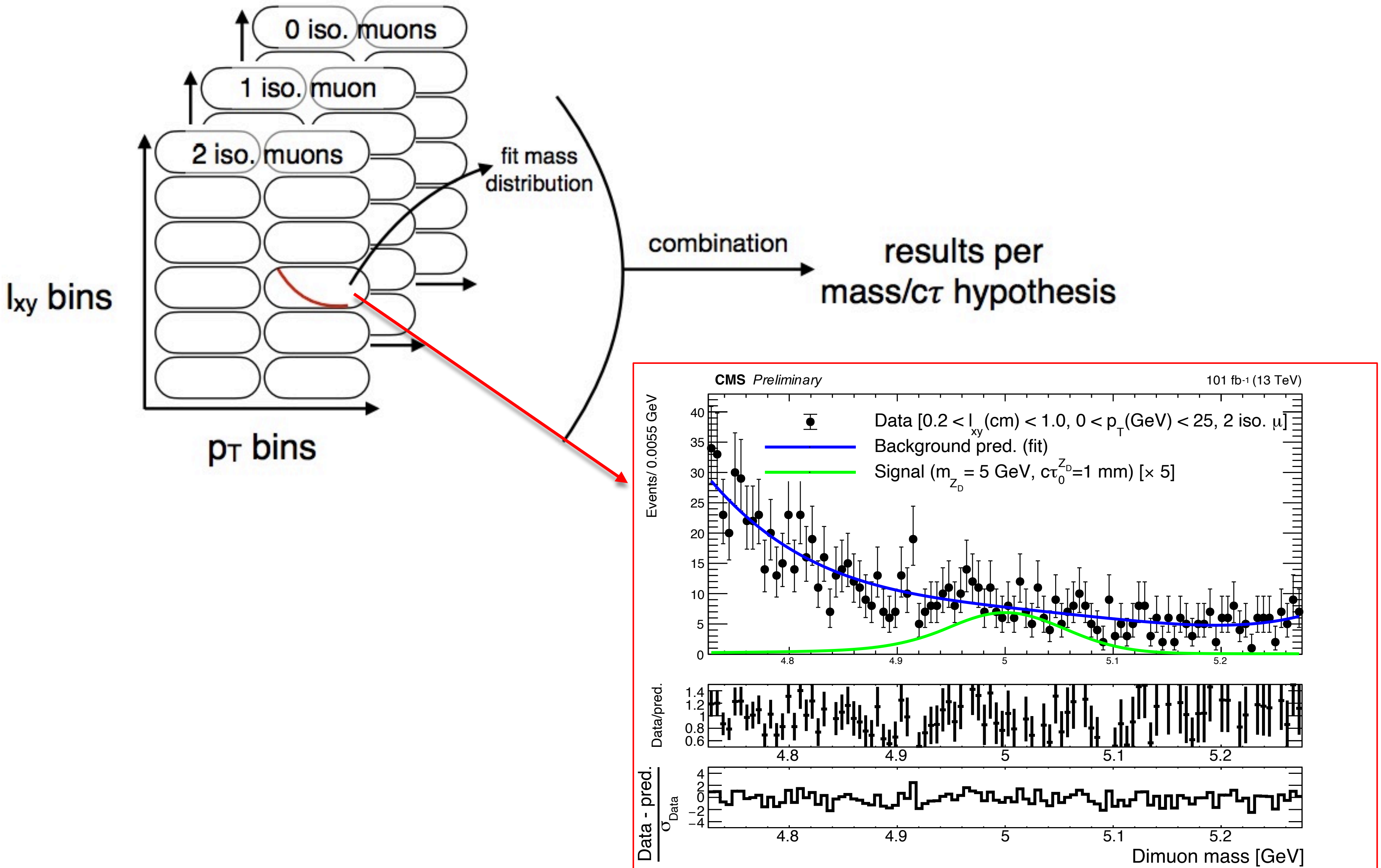
Analysis strategy

- In each dimuon event category, **slide over dimuon mass spectrum**
  - **Steps** and **windows** according to **signal mass resolution (σ)**:
    - **σ** is determined from **signal fit** (double Crystal Ball + Gauss)
      - ~1.1% of mass hypothesis and ~ constant
    - Mass window = ±5 σ around signal mass hypothesis
  - **Simultaneous fit of dimuon mass spectrum in all categories**
    - Use **polynomial + exponential functional forms** to fit $m_{\mu\mu}$
    - Determine best **order** via (modified) **F-test**
      - Systematic uncertainty to account for choice (**discrete profiling**)
    - Evaluate potential bias via extensive **bias tests**
    - Cross-check goodness of fit (GOF) via **GOF test**

→ **Search for narrow resonant peak over background continuum**

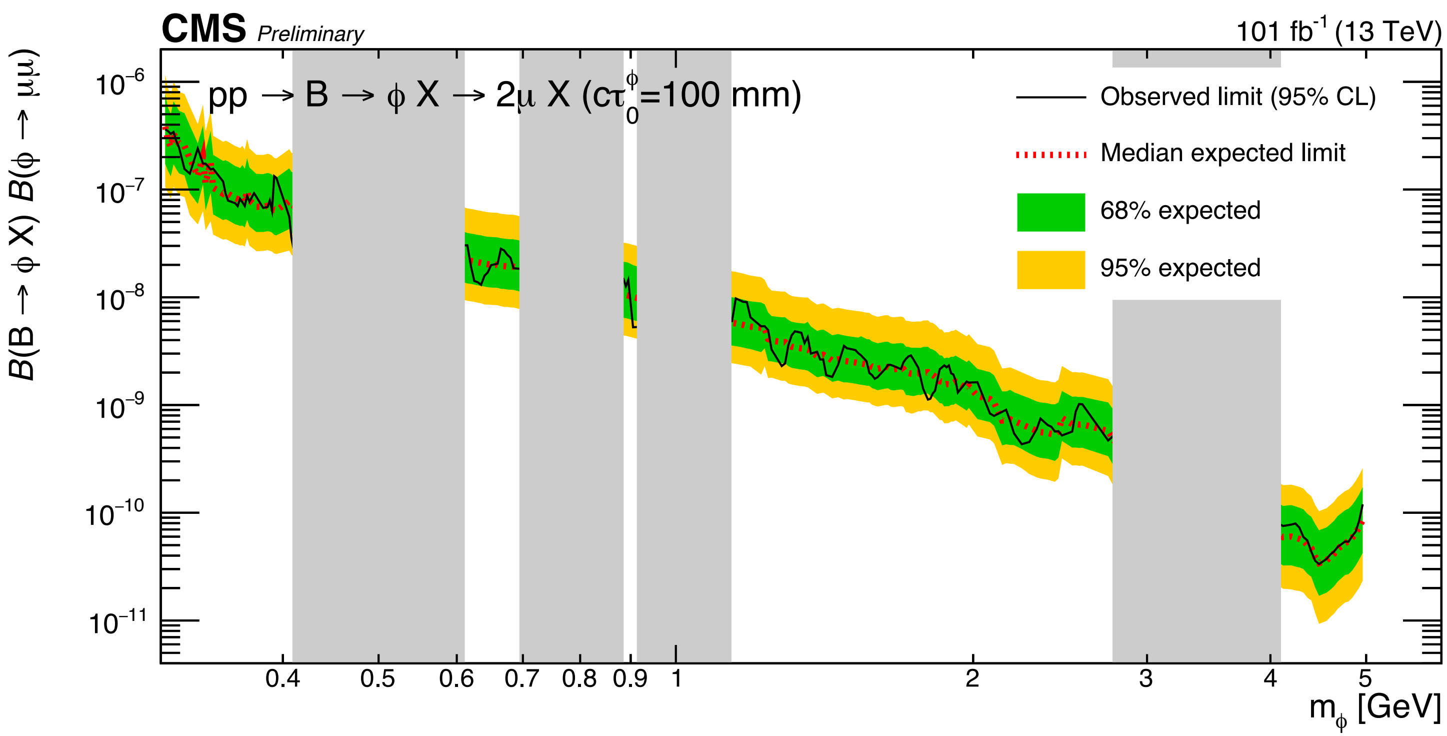
Analysis strategy, with a cartoon

Mario Masciovecchio (UCSD); July 22nd, 2021



Upper limits: $B(B \to \phi X) \cdot B(\phi \to \mu\mu)$

- Upper limits on $B(B \to \phi X) \cdot B(\phi \to \mu\mu)$, for B inclusive production
  - Using only dimuon events

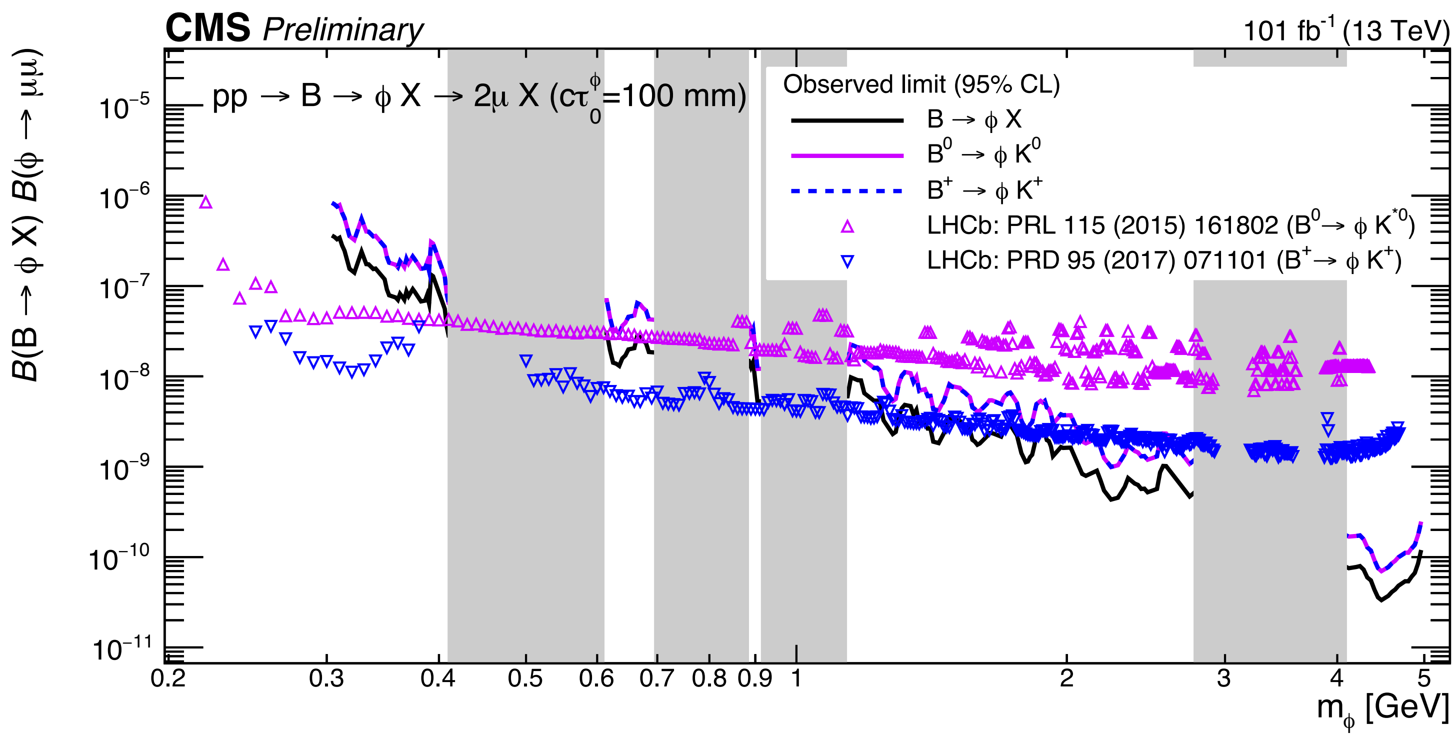


❖ Other lifetime hypotheses are available in backup

Upper limits: $B(B\to\phi X) \cdot B(\phi\to\mu\mu)$ - How do we compare to others?

- LHCb set limits on exclusive topologies ($B^0\to\phi K^{*0}$ or $B^{\pm}\to\phi K^{\pm}$)
  - Rescale our inclusive upper limits by fraction of B^0's / $B^{\pm}$'s

→ **Achieve better sensitivity than LHCb at increasing mass / lifetime**



❖ Other lifetime hypotheses are available in backup

Upper limits on $\mathcal{B}(B\rightarrow\phi X)\cdot\mathcal{B}(\phi\rightarrow\mu\mu)$: $c\tau_0^\phi - m_\phi$ + vs. $c\tau_0^\phi$

Mario Masciovecchio (UCSD); July 22nd, 2021

- Limits at 95% CL on $\mathcal{B}(B\rightarrow\phi X)\cdot\mathcal{B}(\phi\rightarrow\mu\mu)$ in $c\tau_0^\phi - m_\phi$ plane and vs. $c\tau_0^\phi$

○ For $B\rightarrow\phi X$ signal, we probe m_ϕ in range [0.3, 5] GeV and $c\tau_0^\phi$ in range [0.1, 100] mm

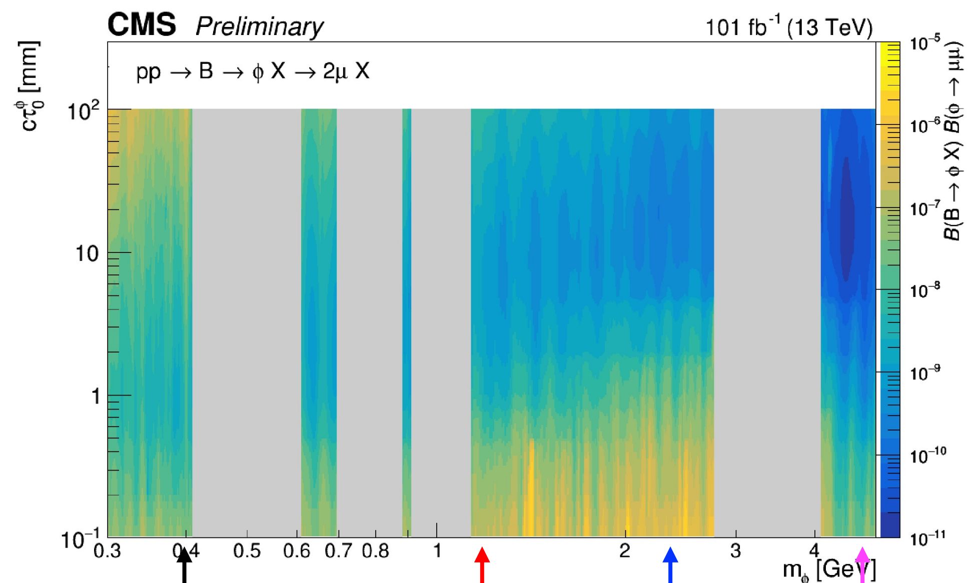
❖ Background is ~0 at dimuon mass ≳ 5 GeV, while it is larger at lower dimuon mass

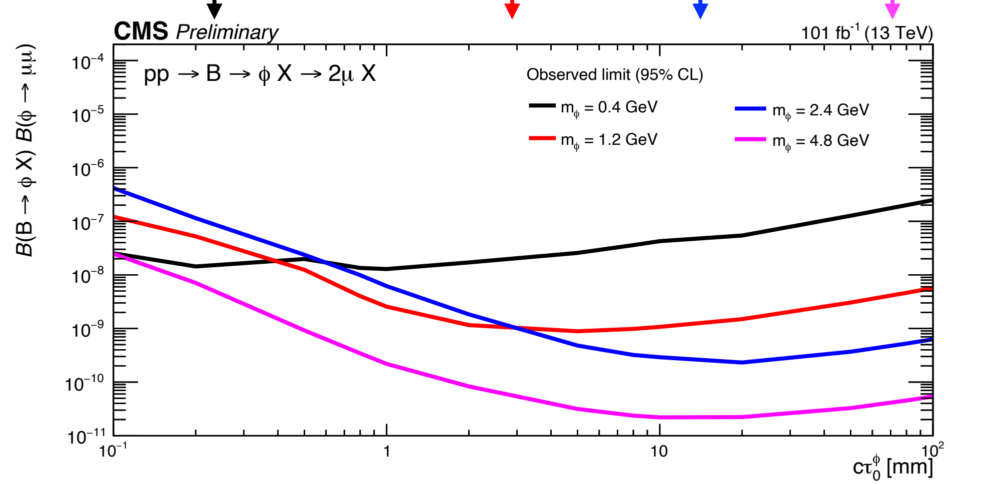
❖ Background is lower at increasing displacement from interaction point

❖ At low m_ϕ, signal acceptance decreases due to ϕ's boost

➢ At low m_ϕ, constraints are stronger at low $c\tau_0^\phi$

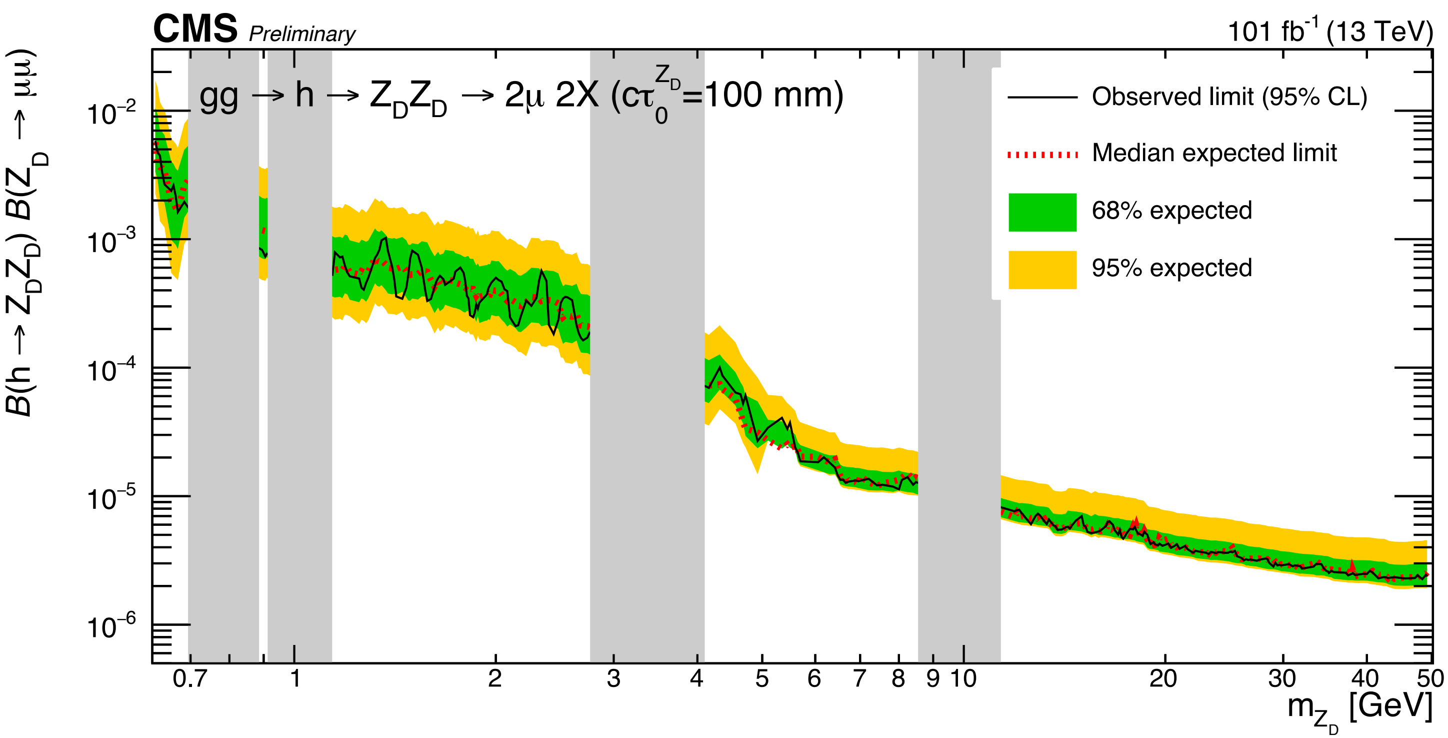
➢ At high m_ϕ, constraints are stronger at high $c\tau_0^\phi$





Upper limits: $B(h \rightarrow Z_D Z_D) \cdot B(Z_D \rightarrow \mu\mu)$

- Upper limits on $B(h \rightarrow Z_D Z_D) \cdot B(Z_D \rightarrow \mu\mu)$
  - Using only dimuon events
  - No assumption on $B(Z_D \rightarrow \mu\mu)$



❖ Other lifetime hypotheses are available in backup

Using events with two muon pairs (=4μ) to further constrain $h \to Z_D Z_D$ signal

Mario Masciovecchio; July 22nd, 2021

- Background is ~0 at $m_{\mu\mu} \gtrsim 5$ GeV in high $p_T^{\mu\mu}$ isolated 2μ categories, while it increases at lower masses
- 4μ channel is relatively free of background at low $m_{\mu\mu}$ wrt. 2μ

→ Can exploit selected **4μ events** to further constrain $h \to Z_D Z_D$ signal, despite acceptance penalty for $h \to Z_D Z_D \to 4\mu$ due to $\mathcal{B}^2(Z_D \to \mu\mu)$

- Require all 4 μ's to be **isolated**
- Require $m_{4\mu}$ to be consistent with Higgs boson (h): **$115 < m_{4\mu} < 135$ GeV**
- Require **$|m_{\mu\mu,1} - m_{\mu\mu,2}| / \langle m_{\mu\mu} \rangle < 5\%$**

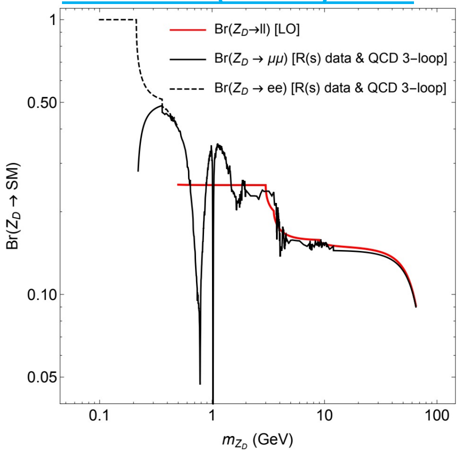
→ **Observe exactly zero events in 4μ event category**

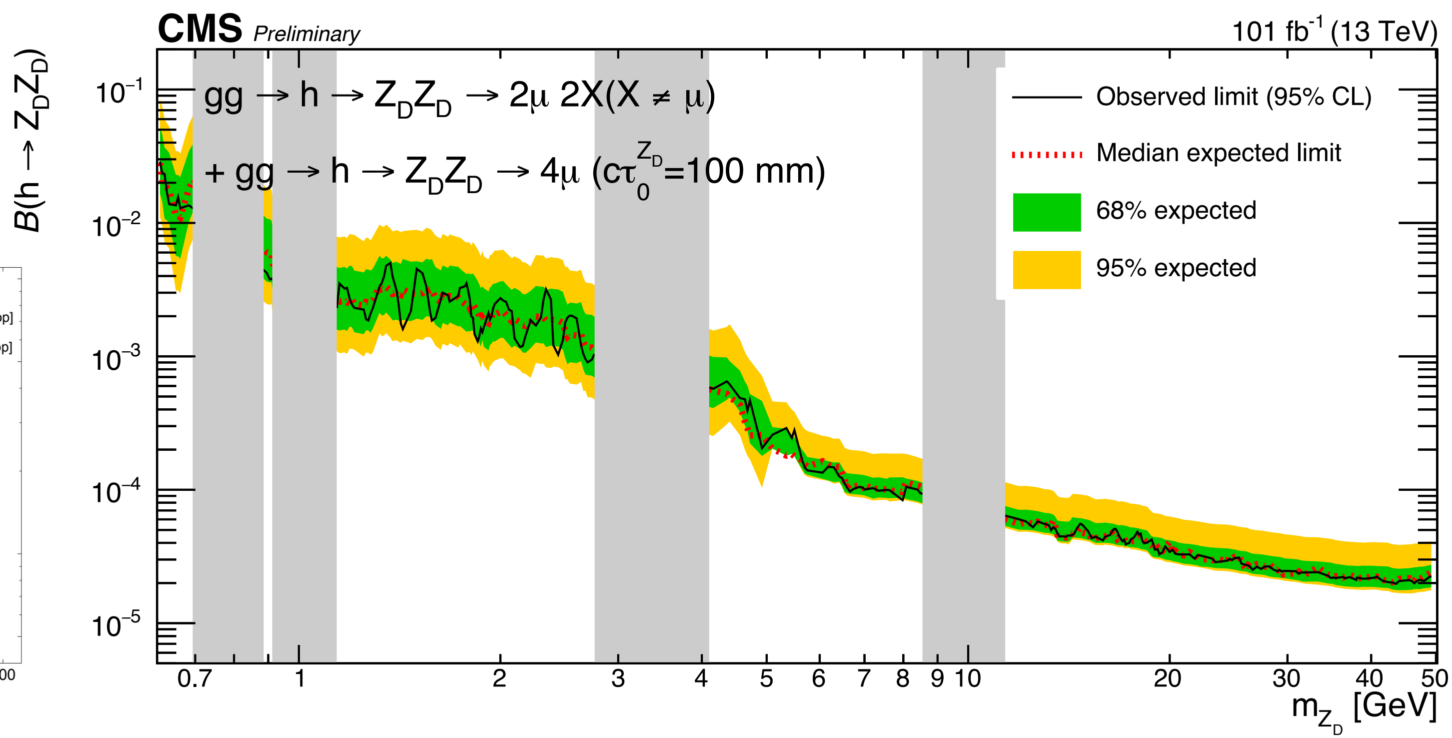
Upper limits: $B(h \rightarrow Z_D Z_D)$

Mario Masciovecchio (UCSD); July 22nd, 2021

- Upper limits on $B(h \rightarrow Z_D Z_D)$
  - Using both **2μ and 4μ events**
  - Using $B(Z_D \rightarrow \mu\mu)$ from JHEP 02 (2015) 157

JHEP 02 (2015) 157





❖ Other lifetime hypotheses are available in backup

Upper limits on $B(h \rightarrow Z_D Z_D)$: $c\tau_0^{Z_D} - m_{Z_D}$ + vs. $c\tau_0^{Z_D}$

Mario Masciovecchio (UCSD); July 22nd, 2021

- Limits at 95% CL on $B(h \rightarrow Z_D Z_D)$ in $c\tau_0^{Z_D} - m_{Z_D}$ plane and vs. $c\tau_0^{Z_D}$

  - For $h \rightarrow Z_D Z_D$ signal, we probe m_{Z_D} in range [0.6, 50] GeV and $c\tau_0^{Z_D}$ in range [0.1, 10^4] mm

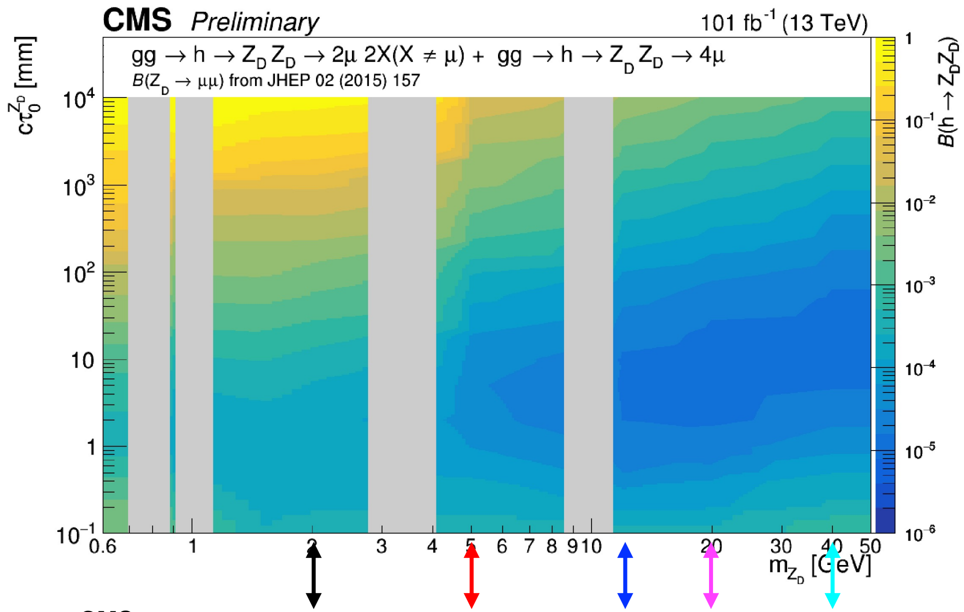
  - Background is ~0 at dimuon mass $\gtrsim$ 5 GeV, while it is larger at lower dimuon mass

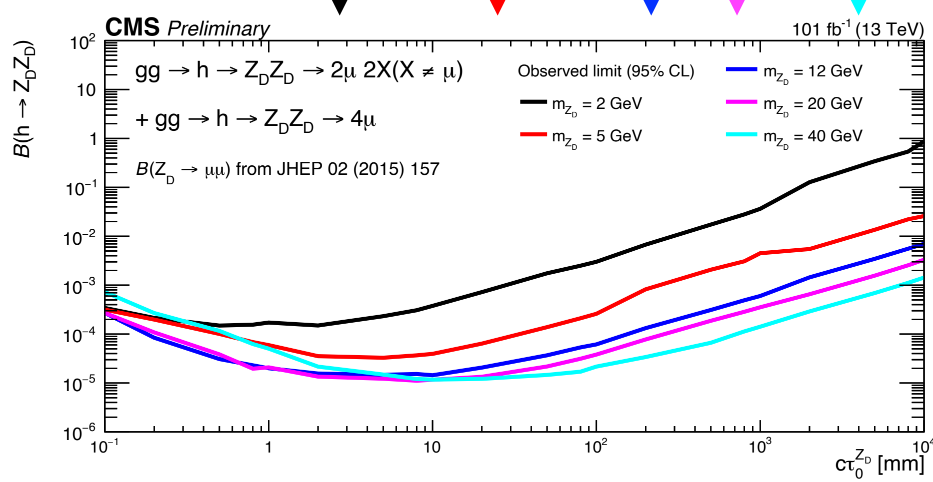
  - Background is lower at increasing displacement from interaction point

  - At low m_{Z_D}, signal acceptance decreases due to Z_D's boost

  - At low m_{Z_D}, constraints are stronger at low $c\tau_0^{Z_D}$

  - At high m_{Z_D}, constraints are stronger at intermediate $c\tau_0^{Z_D}$

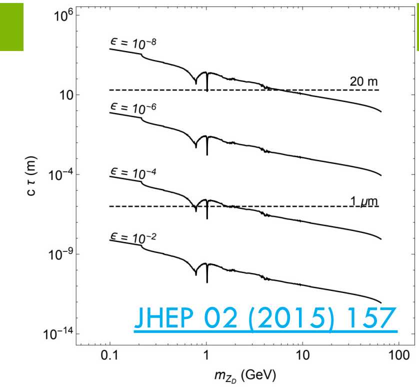




Upper limits on $B(h \rightarrow Z_D Z_D)$: ε vs. m_{Z_D} - A sample of previous results

Mario Masciovecchio (UCSD); July 22nd, 2021

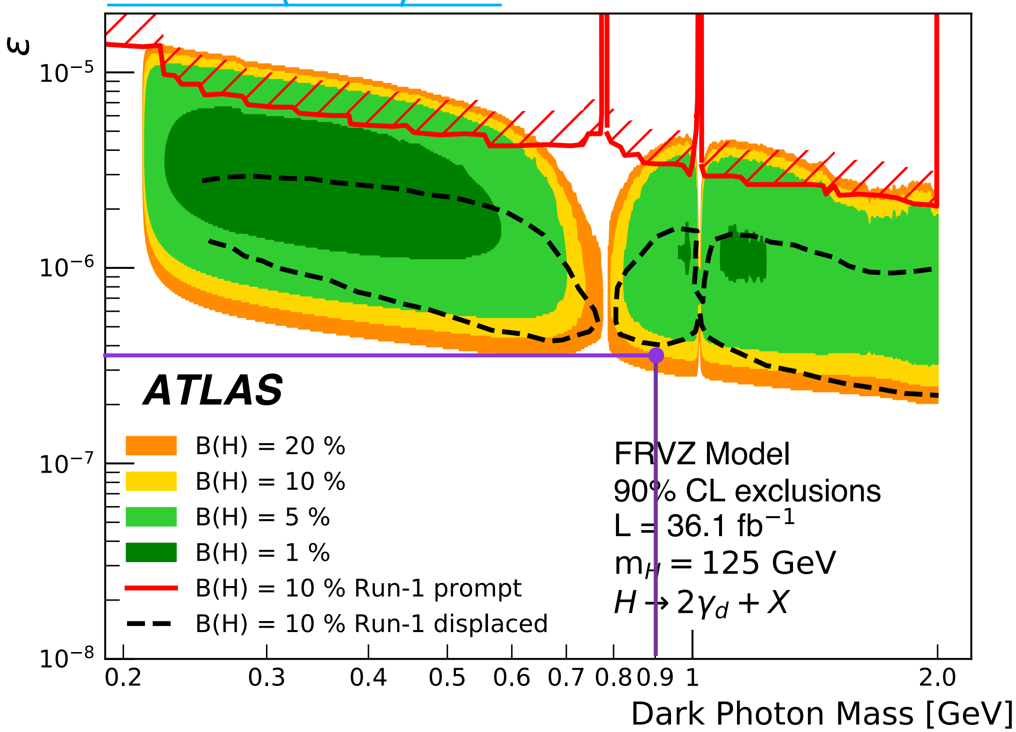
- Previous results from ATLAS and CMS, at $\sqrt{s}$ =13 TeV
  - **$B(h \rightarrow Z_D Z_D)$ = 10% at 90% CL:**
    - Exclude ε ≳ **$3.5 \cdot 10^{-7}$** for m_{Z_D} ≳ 0.9 GeV (ATLAS)
    - Exclude ε ≳ **10^{-7}** for m_{Z_D} ≳ 7 GeV (CMS)

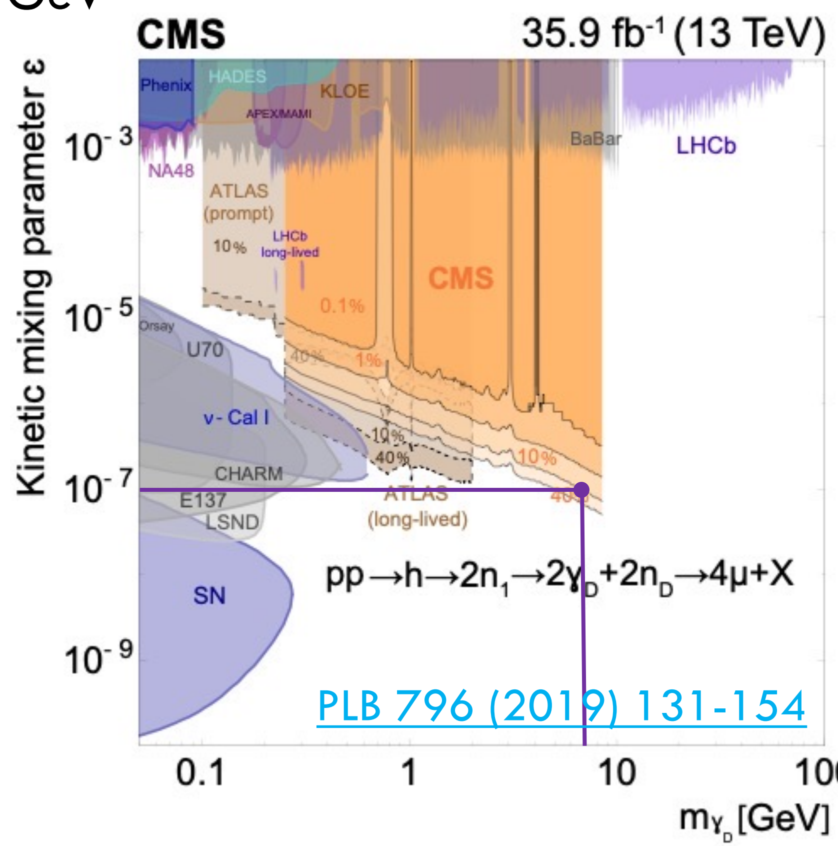


JHEP 02 (2015) 157

- A 2nd search by ATLAS covers m_{Z_D} ∈ [20, 60] GeV

EPJC 80 (2020) 450





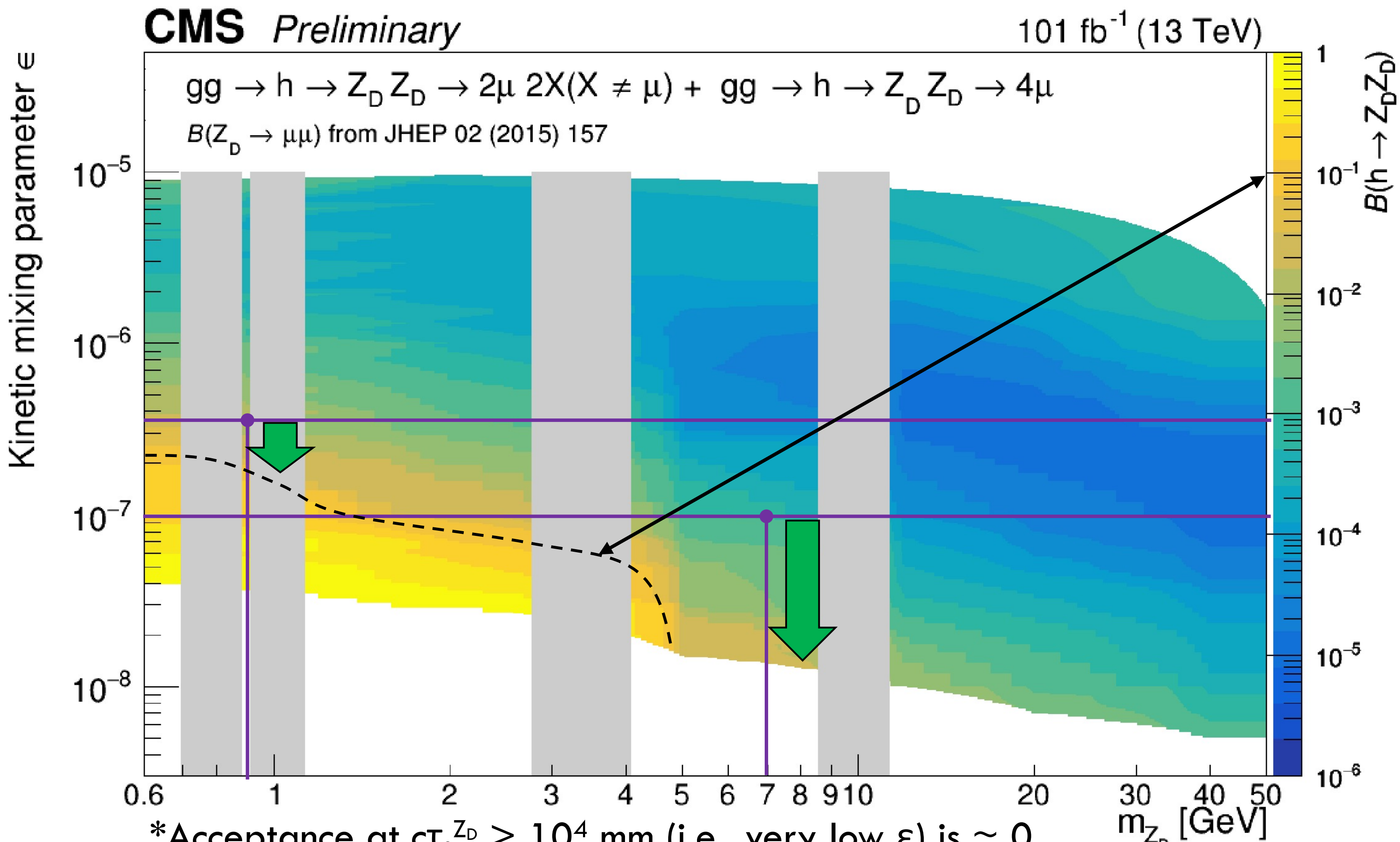
PLB 796 (2019) 131-154

Upper limits on $B(h \rightarrow Z_D Z_D)$: ε vs. m_{Z_D} - How do we compare to previous results?

Mario Masciovecchio (UCSD); July 22nd, 2021

- Compare upper limits at 95% CL to 90% CL limits from ATLAS and CMS

→ Achieve stronger constraints by **~2x to ~10x**



*Acceptance at $c\tau_0^{Z_D} > 10^4$ mm (i.e., very low ε) is ~ 0

Model-independent constraints

- We provide **model-independent upper limits on number of events** in each of 20 non-exclusive dimuon **aggregate regions**

  → To favor **reinterpretations of our results**

  ❖ CAVEAT: constraints are less stringent than full analysis

l_{xy} range [cm]	$p_T^{\mu\mu}$ [GeV]	Number of isolated muons
0.2 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2
1.0 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2
2.4 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2
3.0 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2
7.0 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2

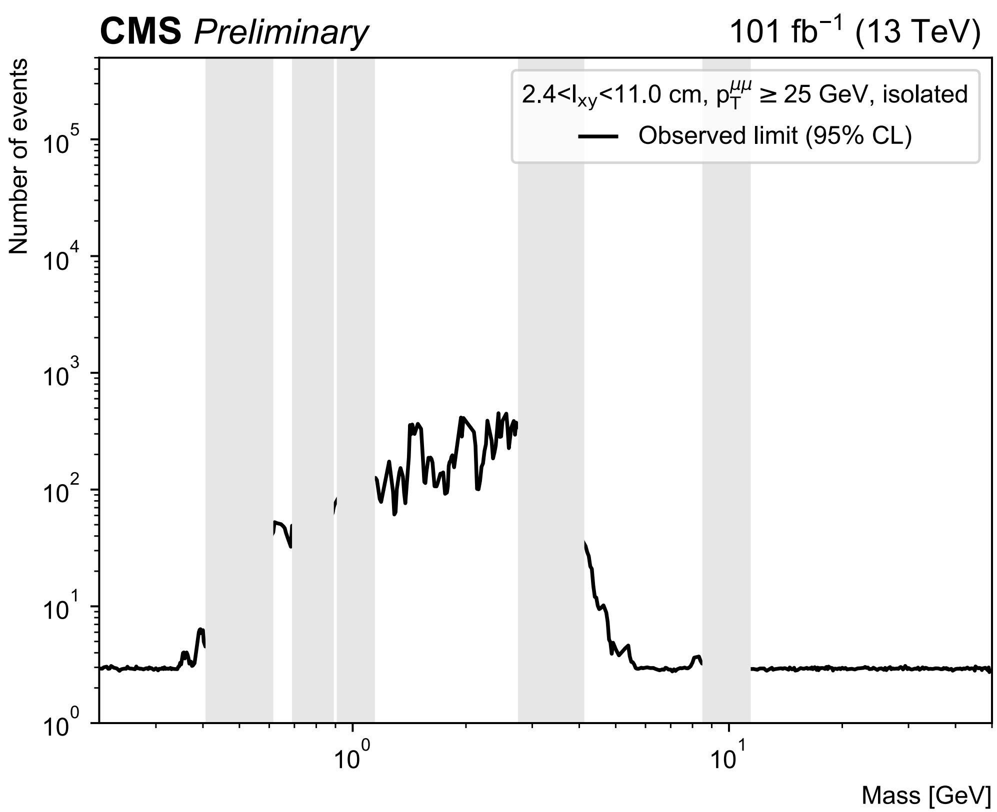
- Using scouting data, this search can probe otherwise/previously inaccessible phase-space
  - At low dimuon mass
  - With nonzero displacement
- Unprecedented sensitivity is achieved to range of BSM long-lived physics signatures

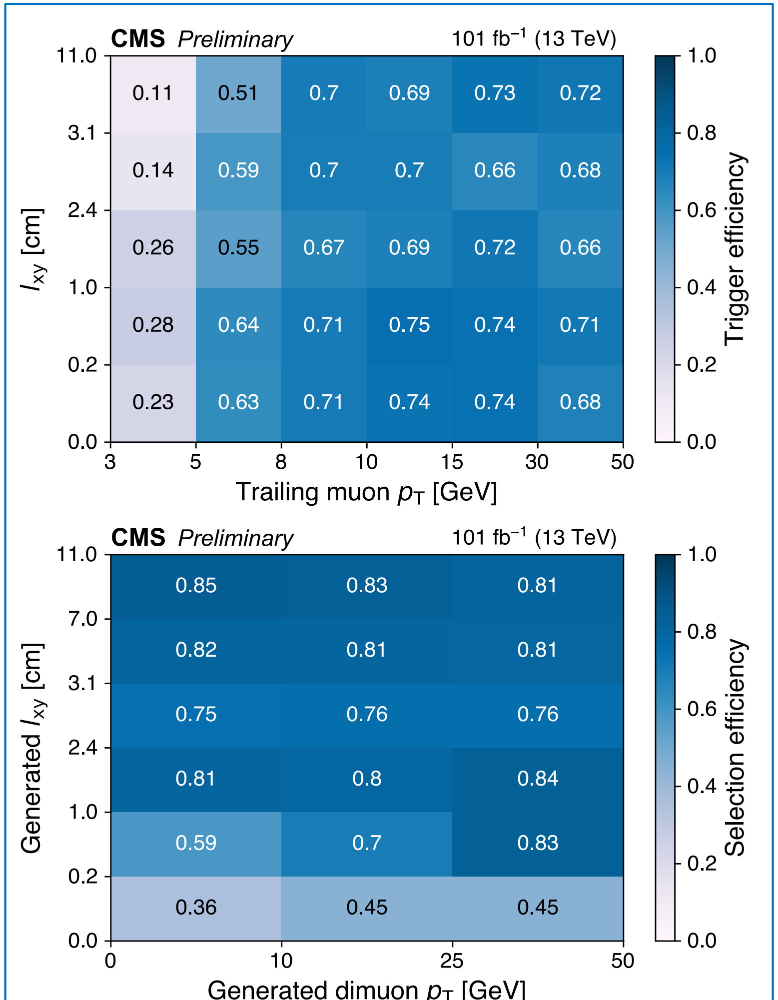
→ **Usage and reinterpretation of results is (hopefully) valuable**

Model-independent constraints: an example

Mario Masciovecchio (UCSD); July 22nd, 2021

- We provide model-independent upper limits on number of events in each of 20 non-exclusive dimuon aggregate regions
  - Together with efficiency maps
    - Instructions are available in backup





Outlook, towards the LHC Run-3

- Extensive R&D activity on scouting triggers towards LHC Run-3
  - **Goal(s):**
    - ➢ Collect scouting data at **higher rate** than in Run-2
    - ➢ Improve **object reconstruction** as much as possible
    - ➢ Enhance scouting data **event content** & **trigger selection**
    - → **Extend range of accessible physics signatures further**
  - **How can we achieve such goals?**
    - ➢ Accelerate event reconstruction
    - ➢ Use full detector information
    - ❖ Plan for CMS HLT farm to be heterogeneous (CPU+GPU)
    - → Perform faster pixel track reconstruction on GPU
    - → Use CMS Particle-Flow algorithm (with information from all CMS sub-detectors) to reconstruct all scouting physics objects

Summary

- Have presented preliminary results from CMS search EXO-20-014: search for **long-lived dimuon resonances** in CMS **scouting data**
  - **First** search for long-lived BSM signatures using scouting data
  - Preliminary results have recently become public
  - Additional material for reinterpretation of results is available

❖ **Scouting** data allowed to access otherwise inaccessible phase-space

→ Achieved **most stringent constraints on a range of BSM signatures**

➢ Paper is going to be submitted to JHEP, soon
  - Additional material will be uploaded to HEPData
  - In the meanwhile, please contact us for any input

- **Outlook**, towards the LHC **Run-3** (and beyond):

➢ Scouting triggers have been extensively developed towards Run-3
  - In terms of trigger **selection** and object **reconstruction**

➢ Unprecedented chance to search so far unexplored phase-space!

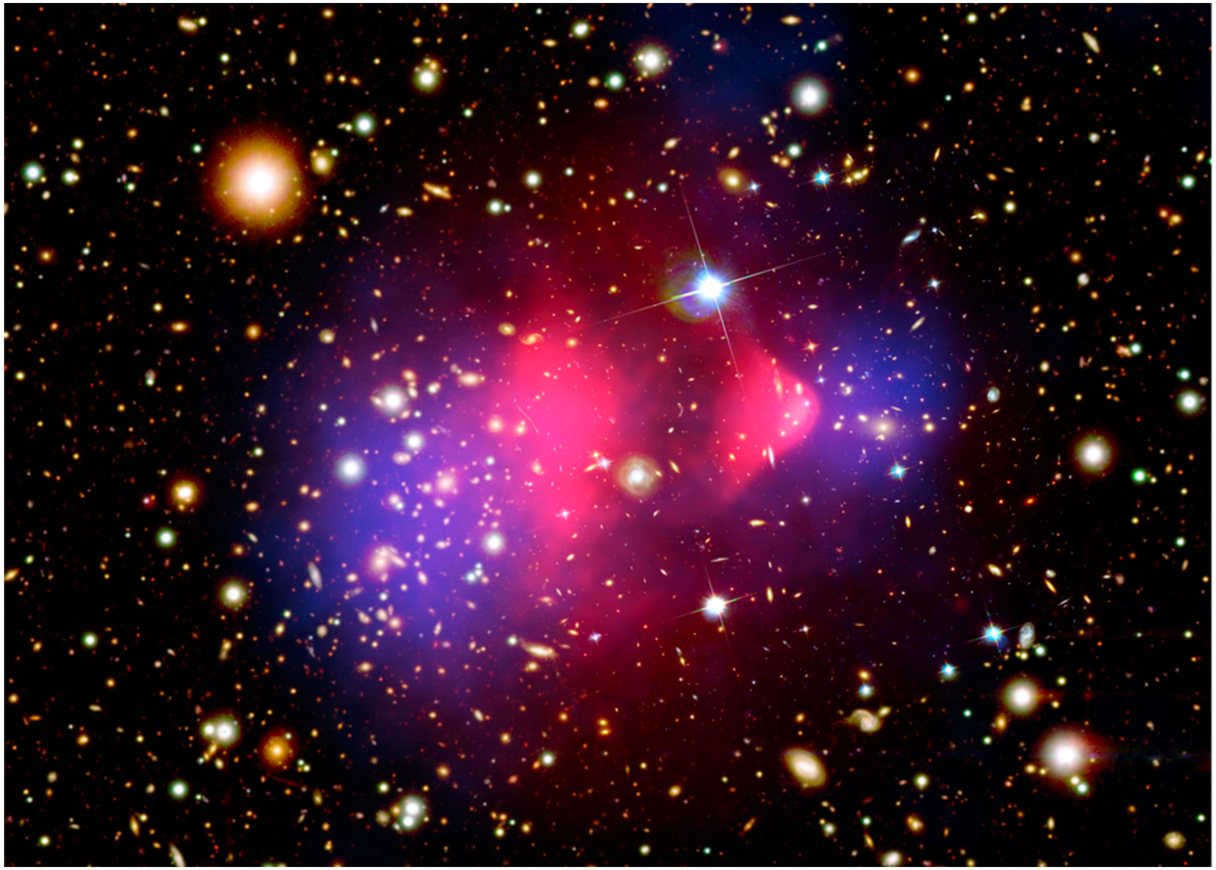
The end… till the LHC Run-3

THANK YOU!

Backup

The Standard Model: a story of success… with its limitations – Dark matter

- The SM fails to provide a particle candidate for **dark matter** (DM)
- From astrophysical and cosmological observations: DM ~22% of the Universe



CREDITS:
X-ray: NASA/CXC/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

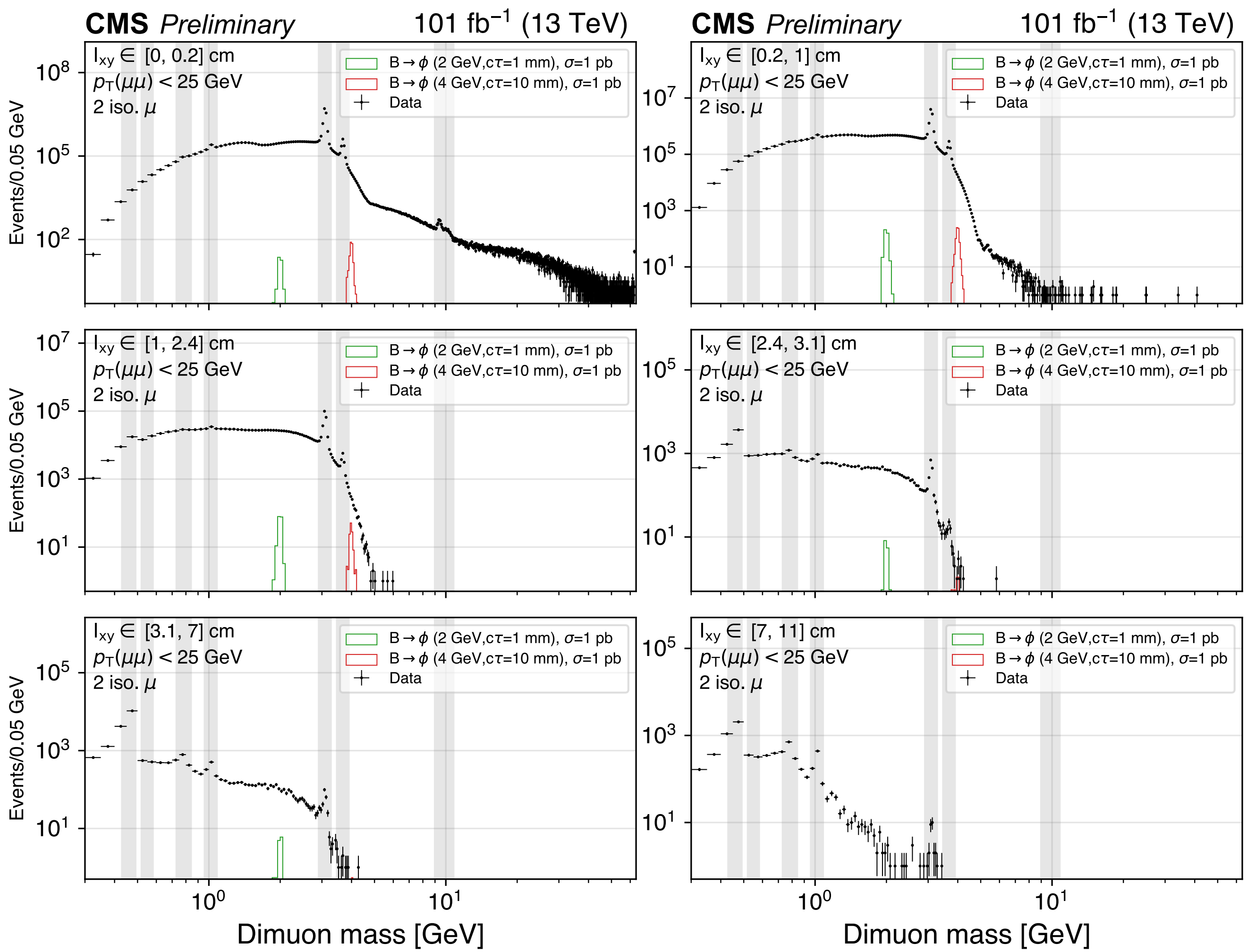
A note on B→ϕX MC simulation

- B→ϕX signal events are generated with PYTHIA 8.2
  - X = K^+, K^0 , ϕ(ss), Λ, D_s^+ for B = B^+, B^0 , B_s , Λ_b , B_c
- B signal MC is reweighted to FONLL
  - Absolute cross-section
  - p_T spectrum of the B hadron

A look at selected dimuon events: $p_T^{\mu\mu}$ < 25 GeV, **isolated** topologies [all]

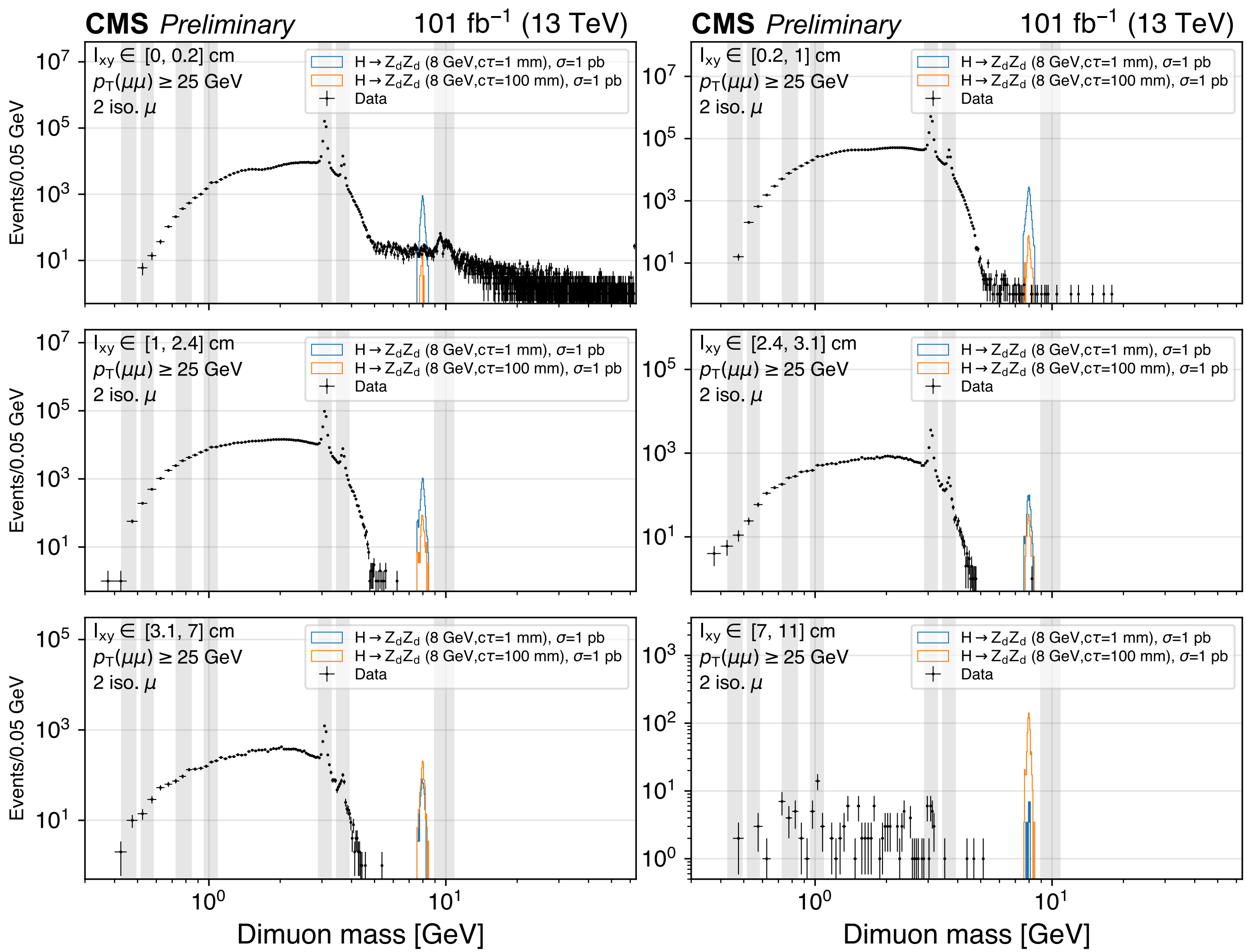
Mario Masciovecchio (UCSD); July 22[nd], 2021

- For isolated 2μ events with **$p_T^{\mu\mu}$<25 GeV**
  - Enriched in B→ϕX signal



A look at selected dimuon events: $p_T^{\mu\mu} \geq$ 25 GeV, **isolated** topologies [all]

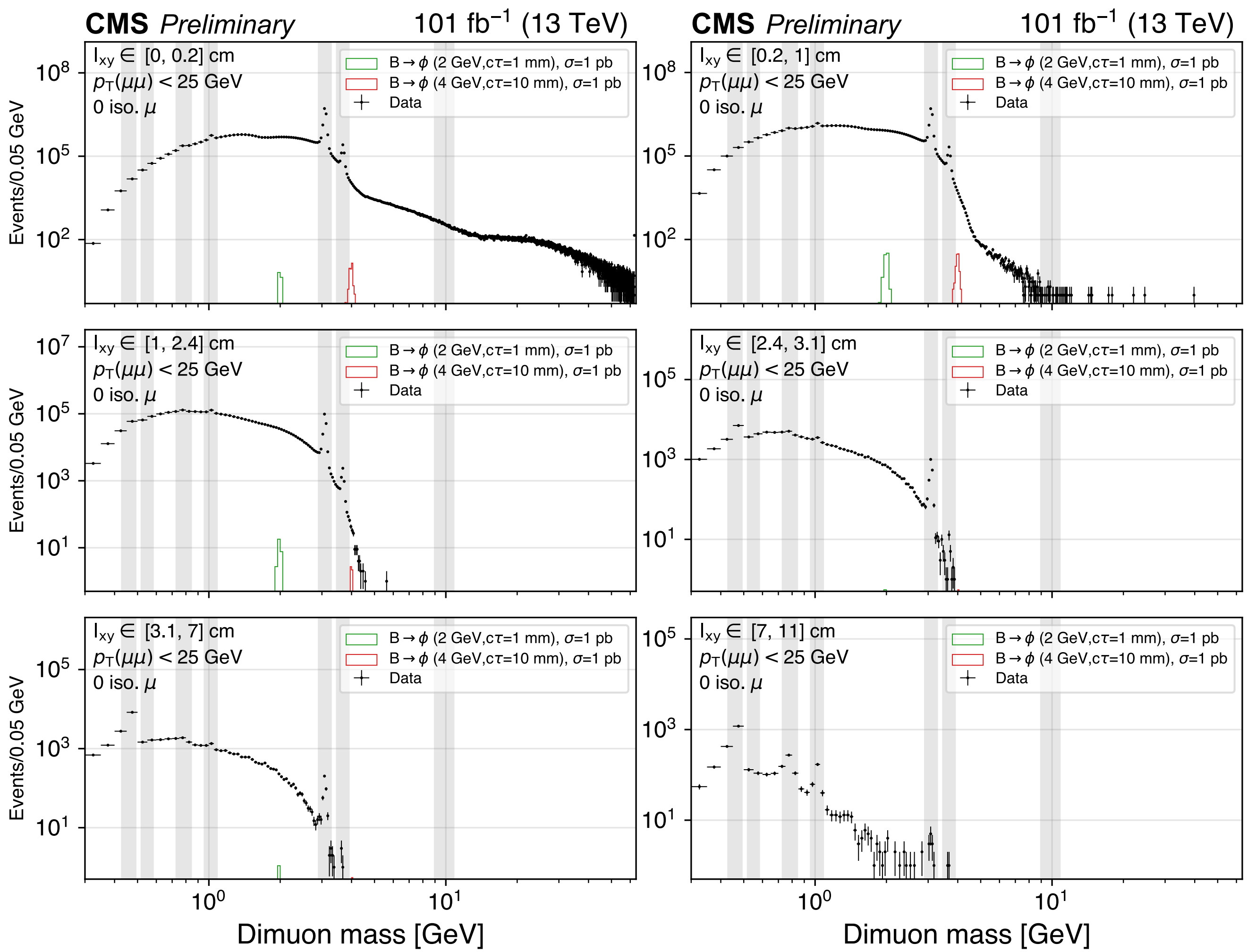
- For **isolated** 2μ events with **$p_T^{\mu\mu} \geq$25 GeV**
  - Enriched in h→$Z_D Z_D$ signal



A look at selected dimuon events: $p_T^{\mu\mu}$ < 25 GeV, **non**-isolated topologies [all]

Mario Masciovecchio (UCSD); July 22nd, 2021

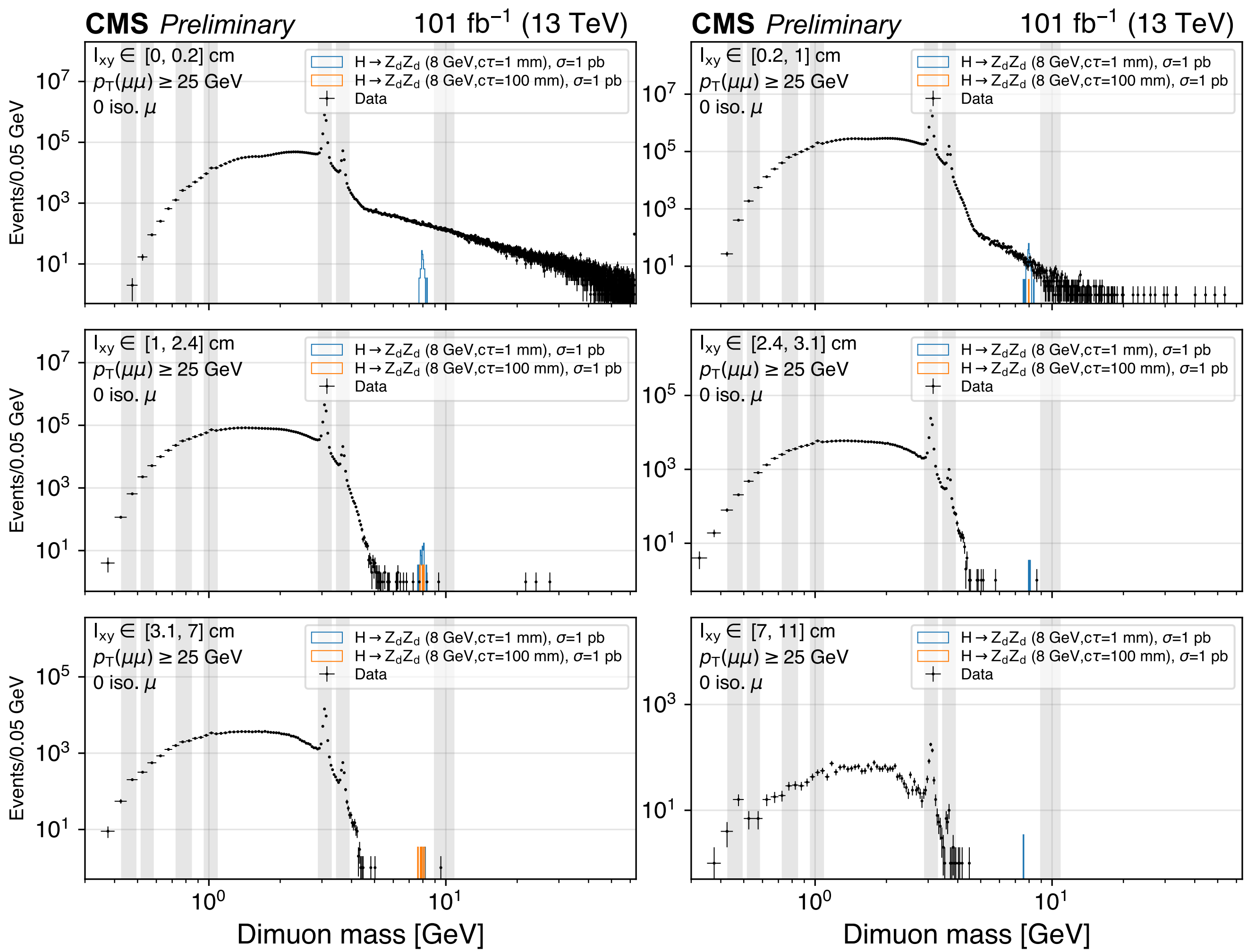
- For **non**-isolated 2μ events with $\mathbf{p_T^{\mu\mu}}$**<25 GeV**
  - Non-negligible contribution from B→ϕX signal



A look at selected dimuon events: $p_T^{\mu\mu} \geq 25$ GeV, non-isolated topologies [all]

Mario Masciovecchio (UCSD); July 22nd, 2021

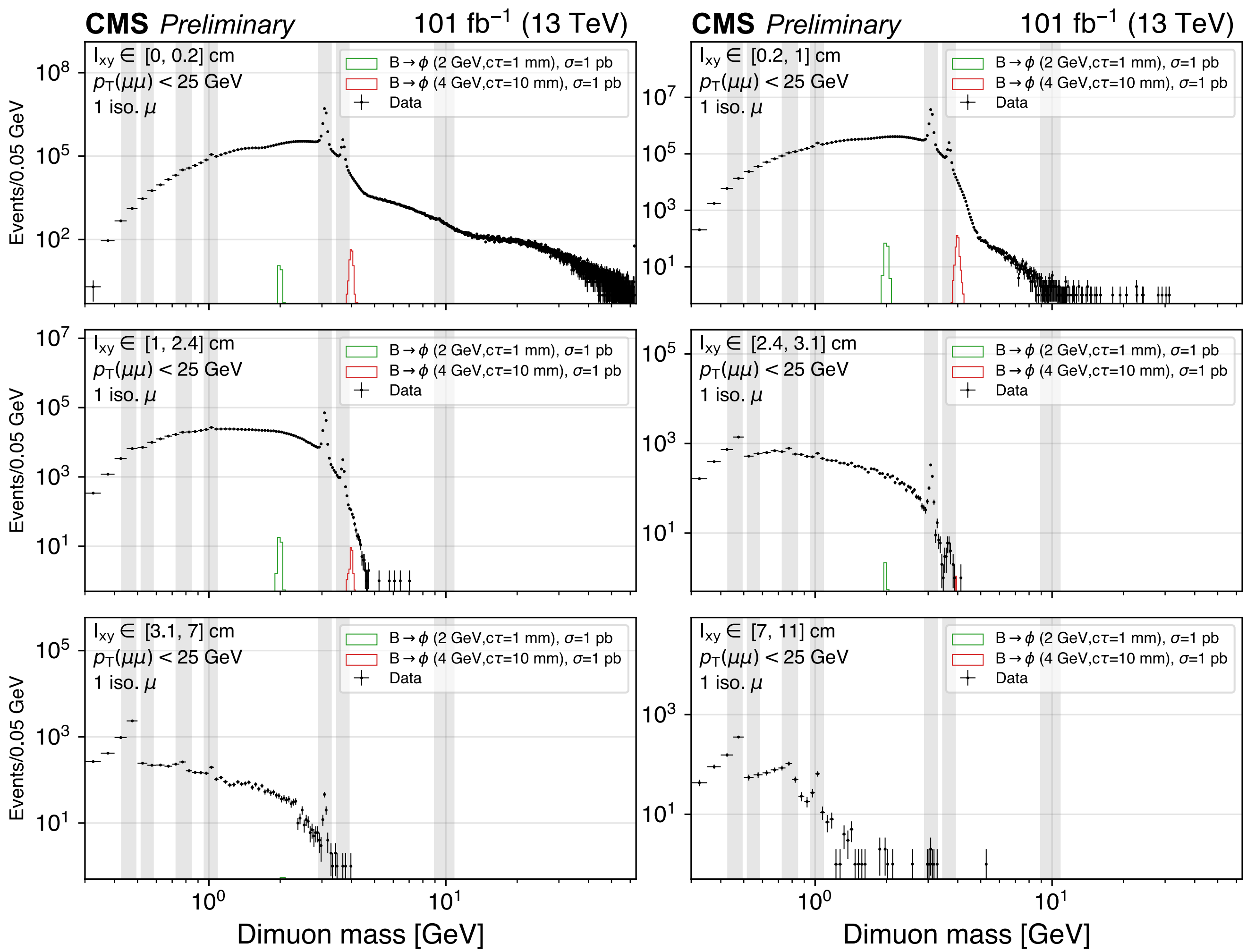
- For **non**-isolated 2μ events with **$p_T^{\mu\mu} \geq 25$ GeV**



A look at selected dimuon events: $p_T^{\mu\mu}$ < 25 GeV, **partially** isolated topologies [all]

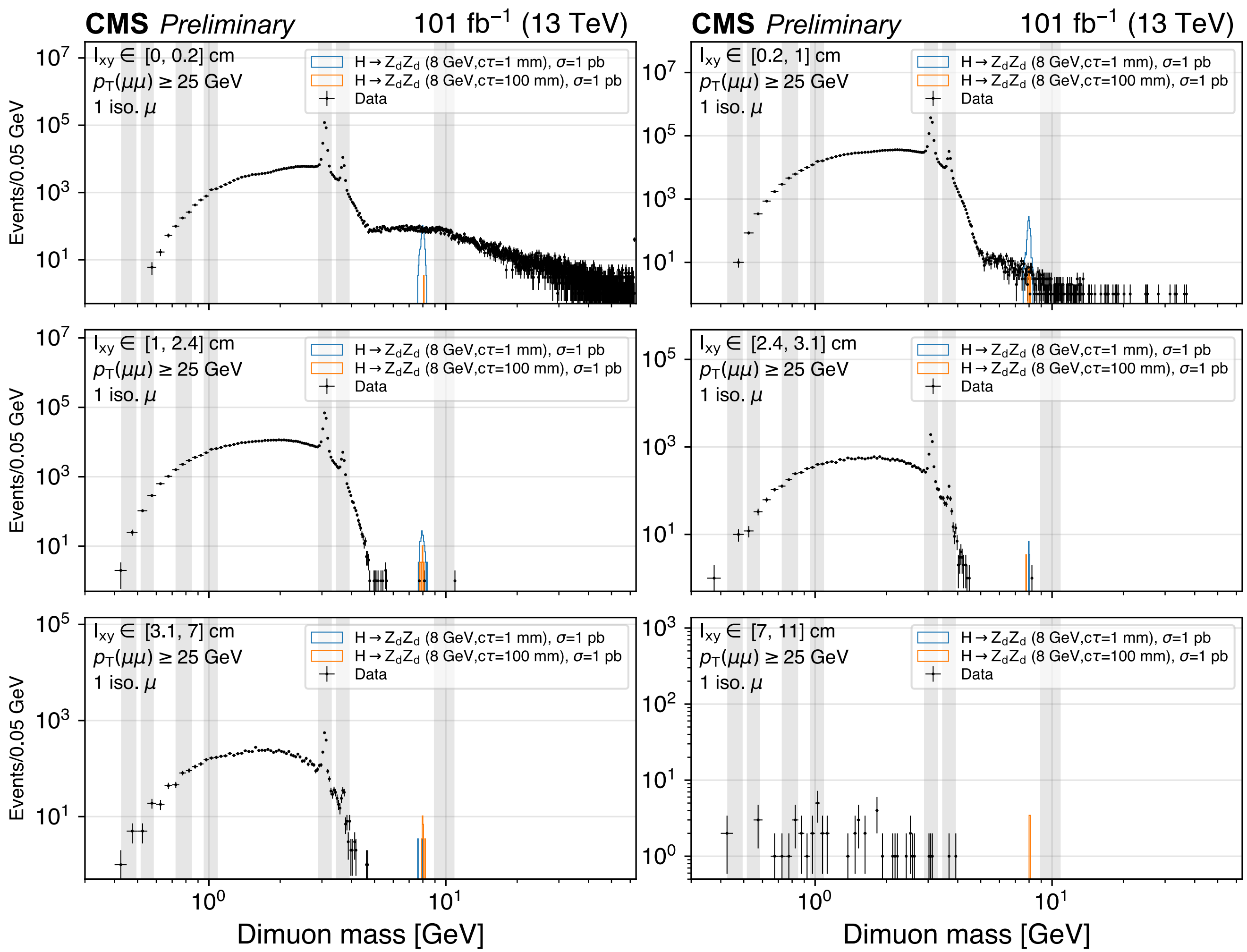
Mario Masciovecchio (UCSD); July 22nd, 2021

- For **partially** isolated 2μ events with $\mathbf{p_T^{\mu\mu}<25}$ **GeV**



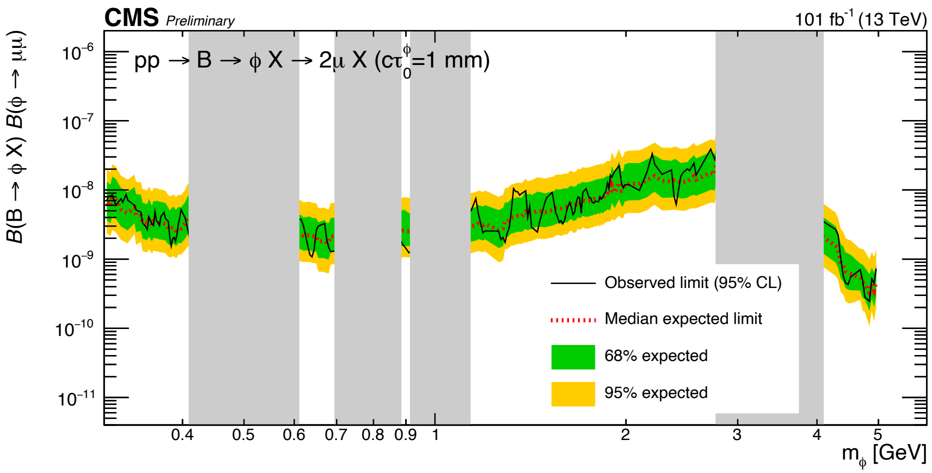
A look at selected dimuon events: $p_T^{\mu\mu} \geq$ 25 GeV, **partially** isolated topologies [all]

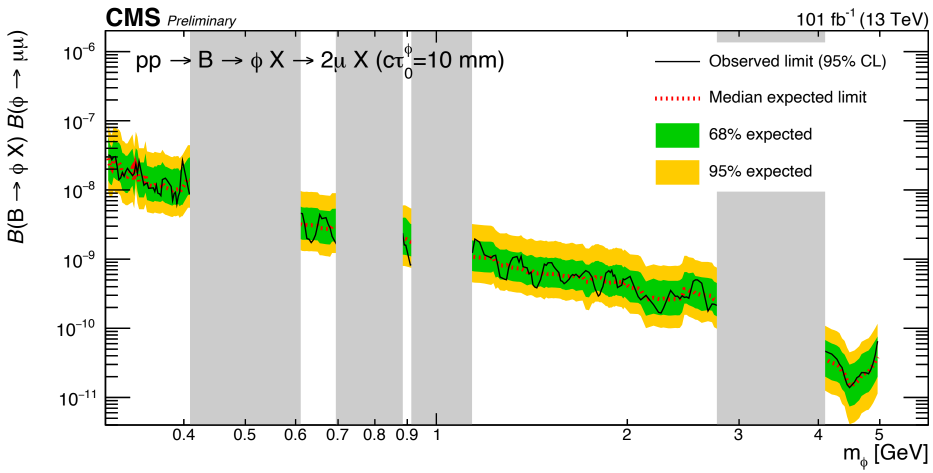
- For **partially** isolated 2μ events with $\mathbf{p_T^{\mu\mu} \geq 25}$ **GeV**

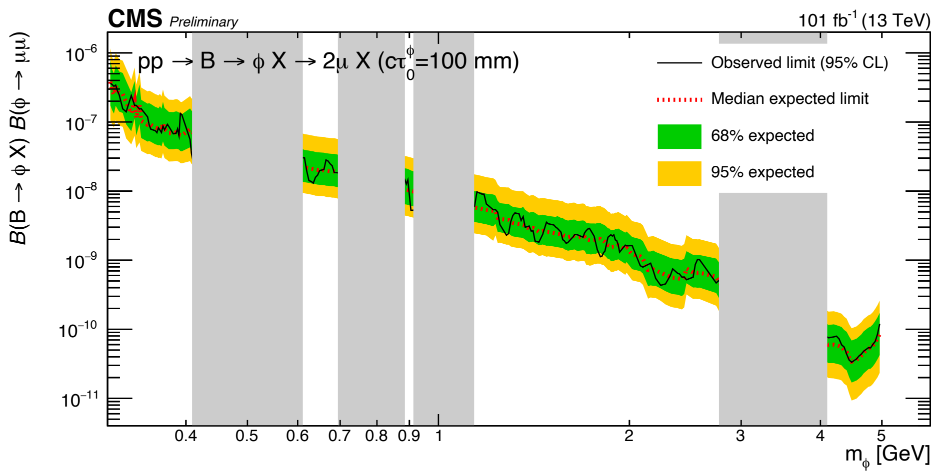


Upper limits: $B(B\to\phi X)\cdot B(\phi\to\mu\mu)$ [all]

- Inclusive limits on $B(B\to\phi X)\cdot B(\phi\to\mu\mu)$
  - Using only dimuon events





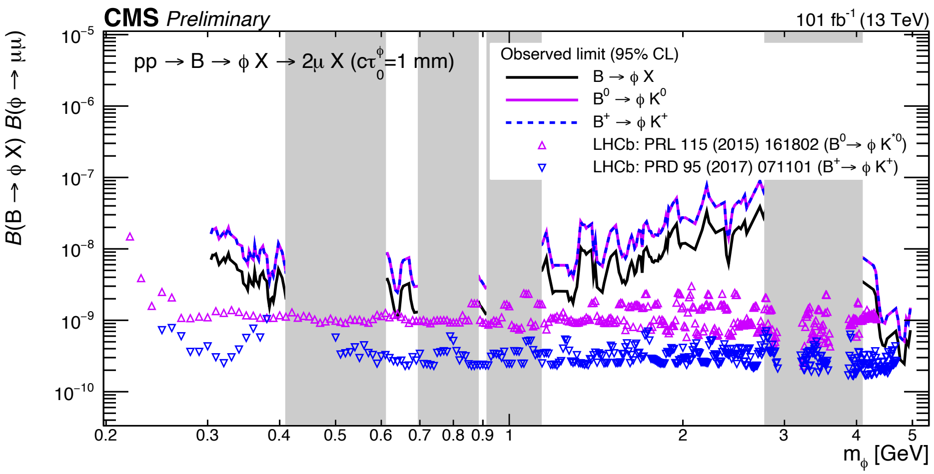


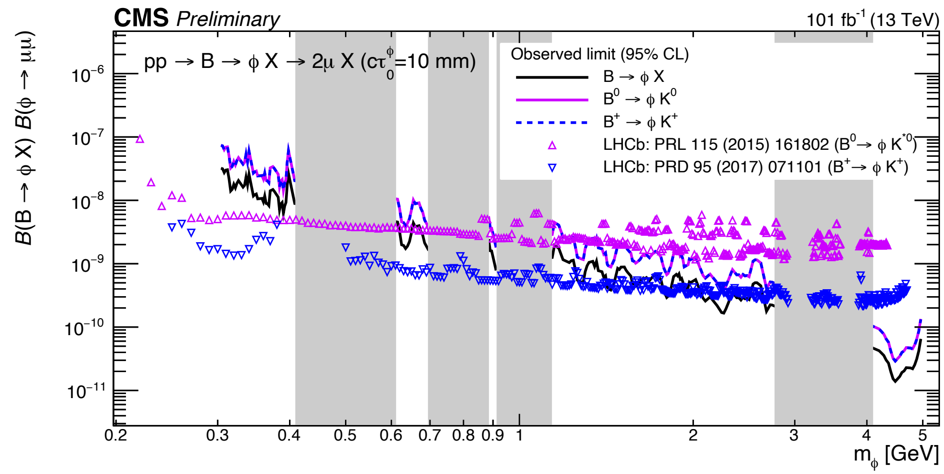
Upper limits: $\mathcal{B}(B \to \phi X) \cdot \mathcal{B}(\phi \to \mu\mu)$

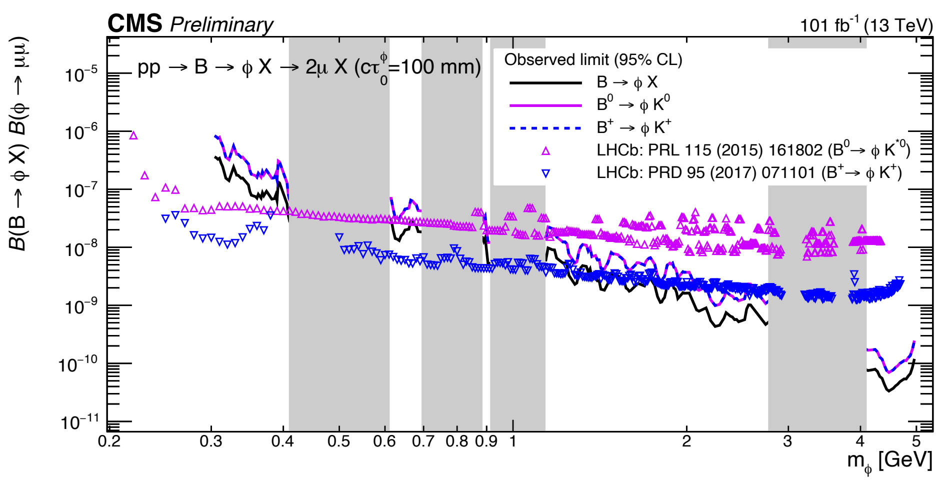
- How do we compare to others? [all]

- LHCb set limits on exclusive topologies ($B^0 \to \phi K^{*0}$ or $B^{\pm} \to \phi K^{\pm}$)
  - ➢ Rescale our inclusive upper limits by fraction of B^0's / $B^{\pm}$'s

→ **Achieve better sensitivity than LHCb at increasing mass / lifetime**







Upper limits: $B(h \rightarrow Z_D Z_D) \cdot B(Z_D \rightarrow \mu\mu)$ [all]

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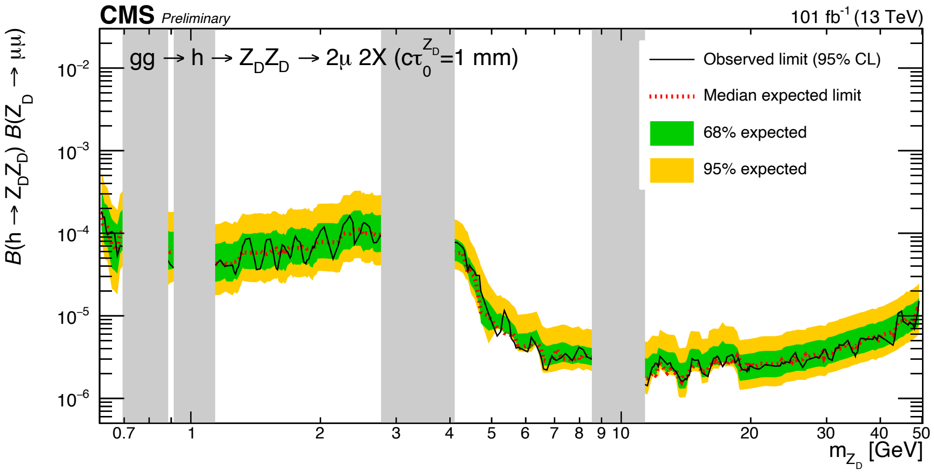
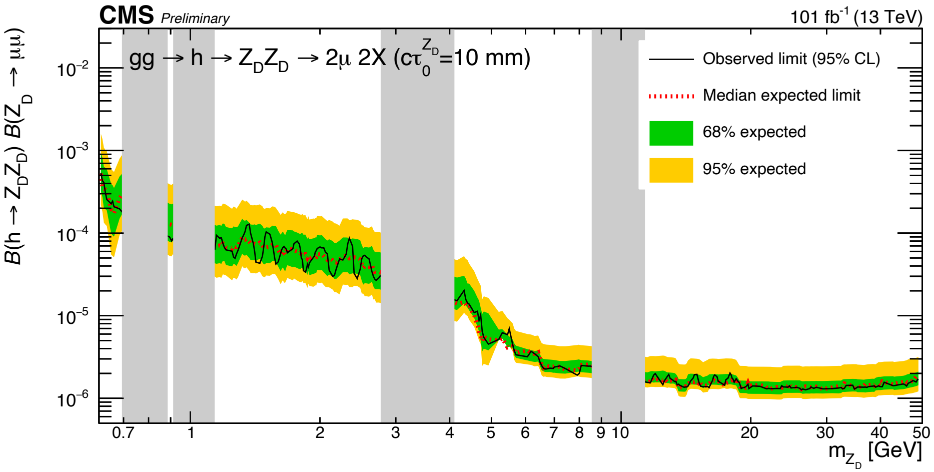
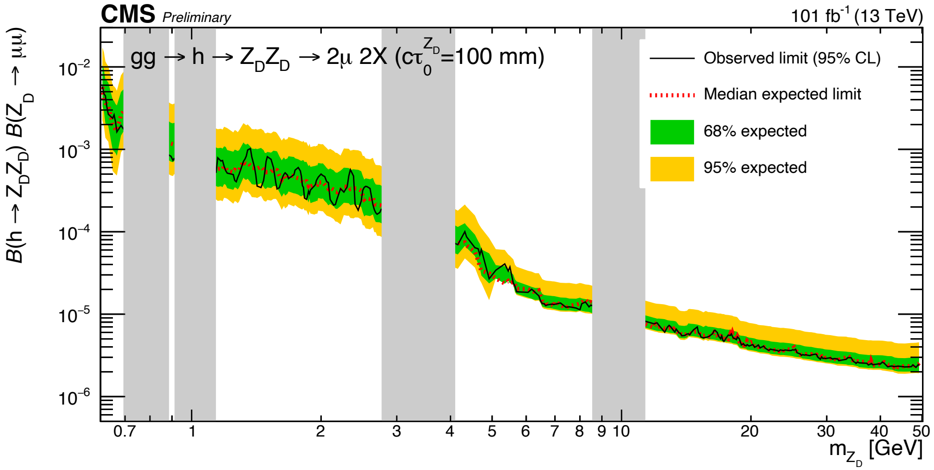
- Using only dimuon events

❖ No assumption on $B(Z_D \rightarrow \mu\mu)$





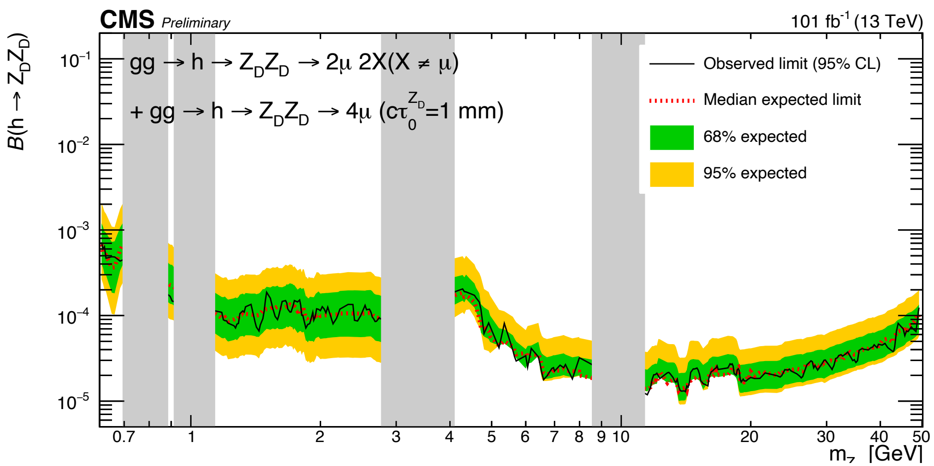


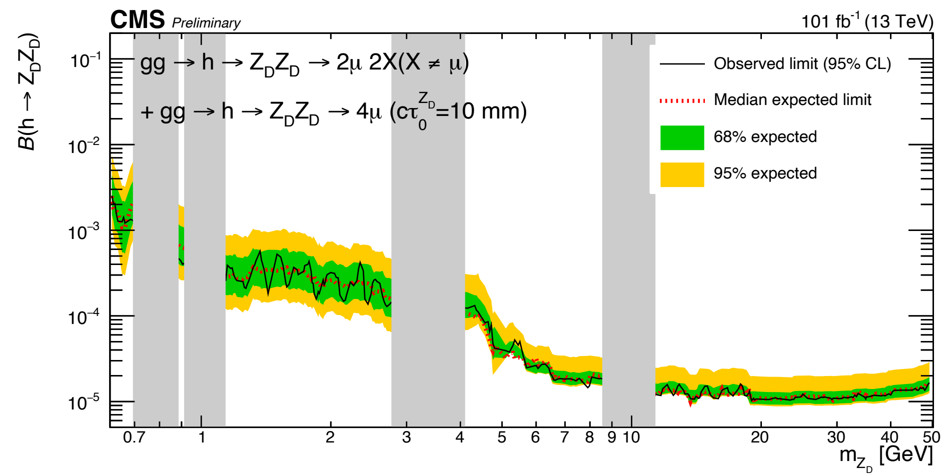
Upper limits: $B(h \rightarrow Z_D Z_D)$ [all]

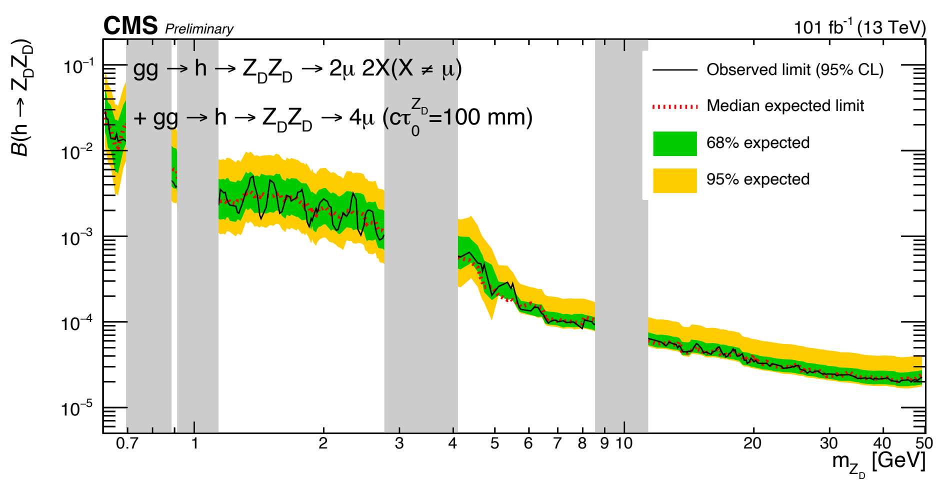
Mario Masciovecchio (UCSD); July 22nd, 2021

- Using both **dimuon and 4μ events**

❖ Using $B(Z_D \rightarrow \mu\mu)$ from [JHEP 02 (2015) 157]







Material for reinterpretation: instructions

Mario Masciovecchio (UCSD); July 22nd, 2021

- We provide model-independent upper limits on number of events in each of 20 non-exclusive dimuon **aggregate regions**
  - Together with efficiency maps

l_{xy} range [cm]	$p_T^{\mu\mu}$ [GeV]	Number of isolated muons
0.2 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2
1.0 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2
2.4 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2
3.0 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2
7.0 – 11.0	≥ 0	≥ 0
		2
	≥ 25	≥ 0
		2

How to use:

1. Select "best" aggregate signal region, based on signal of interest
2. Evaluate trigger selection efficiency
3. Evaluate signal selection efficiency
4. Use selected aggregate signal region and selection efficiency for reinterpretation of our results

Material for reinterpretation: selection efficiency maps

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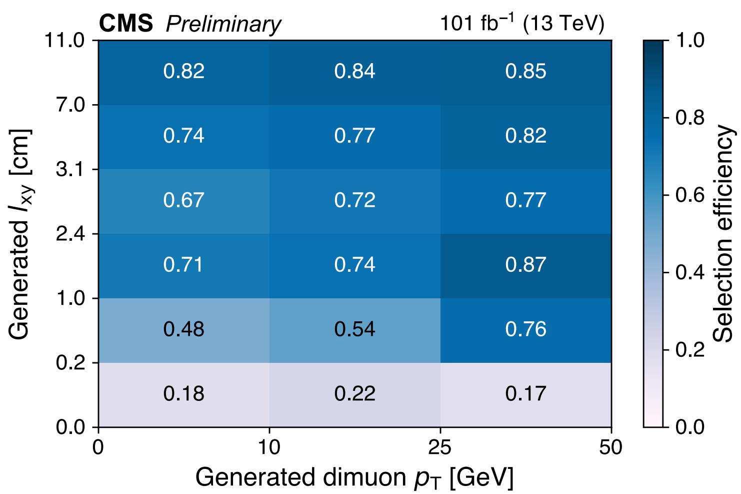
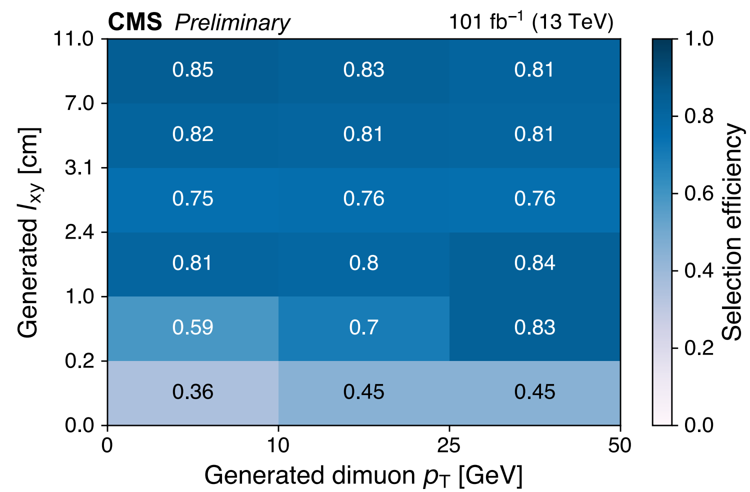
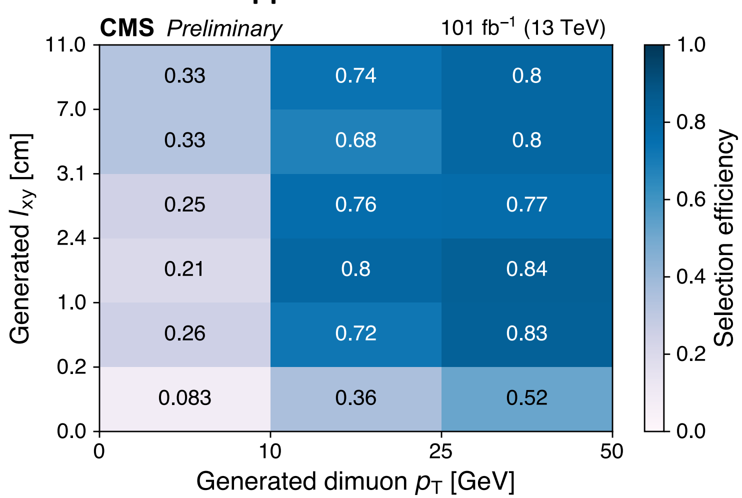
$0 < m_{\mu\mu} < 3$ GeV



$3 < m_{\mu\mu} < 10$ GeV



$m_{\mu\mu} > 10$ GeV



Model-independent upper limits: no μ isolation requirement, $p_T^{\mu\mu} \geq 0$ GeV

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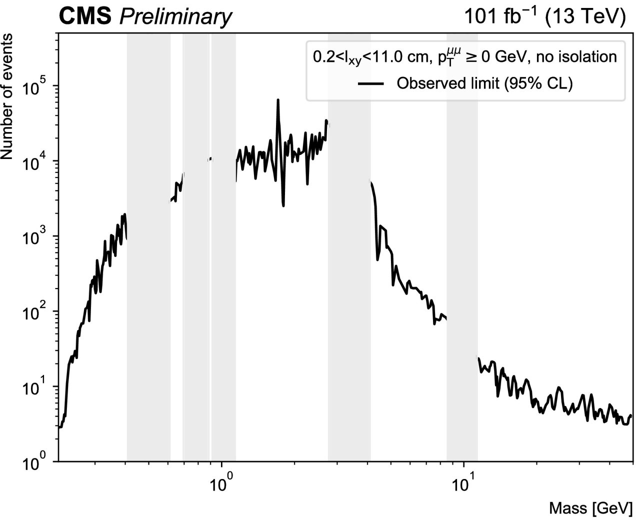
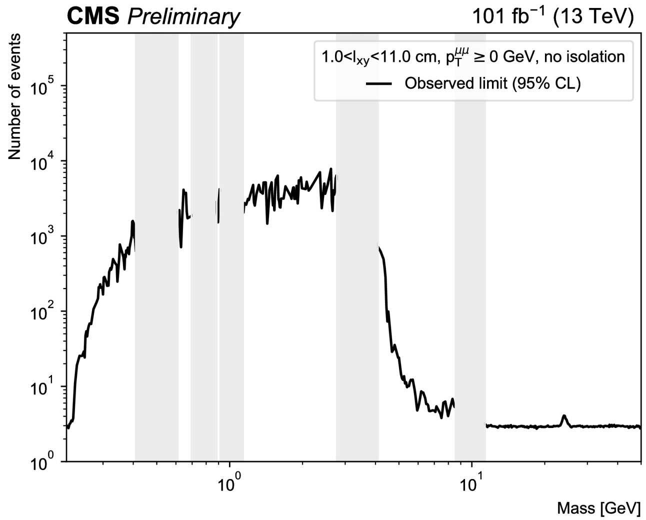
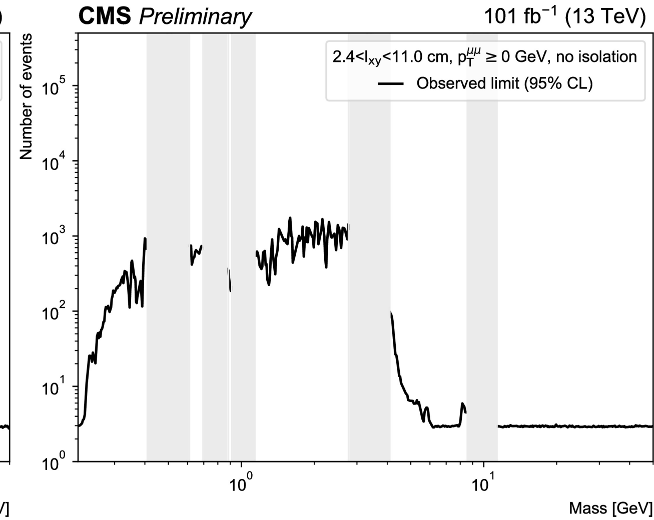
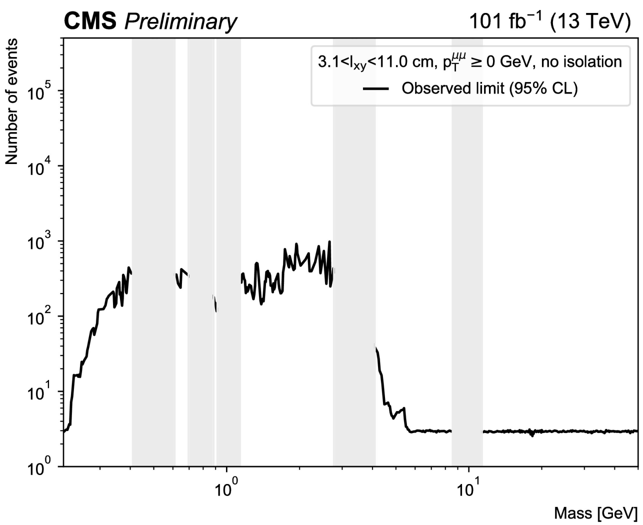
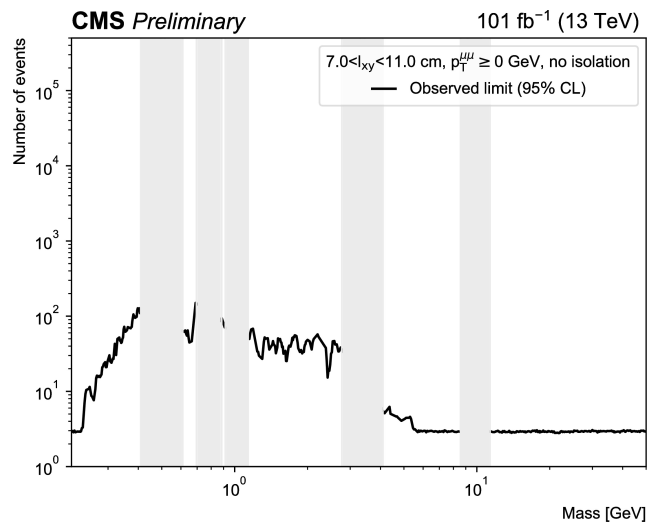


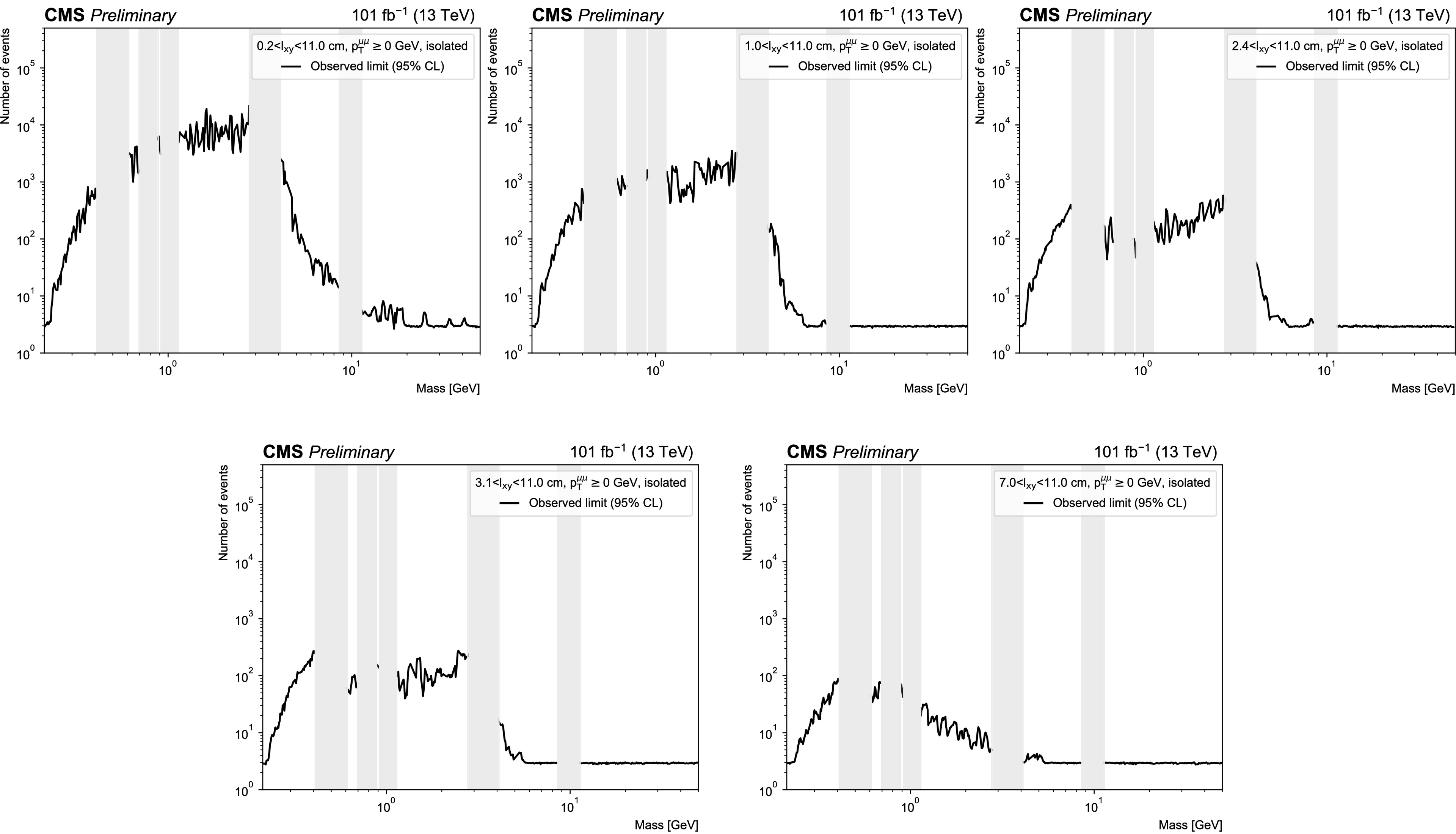








Model-independent upper limits: with two isolated μs, $p_T^{\mu\mu} \geq 0$ GeV



Model-independent upper limits: no μ isolation requirement, $p_T^{\mu\mu} \geq 25$ GeV

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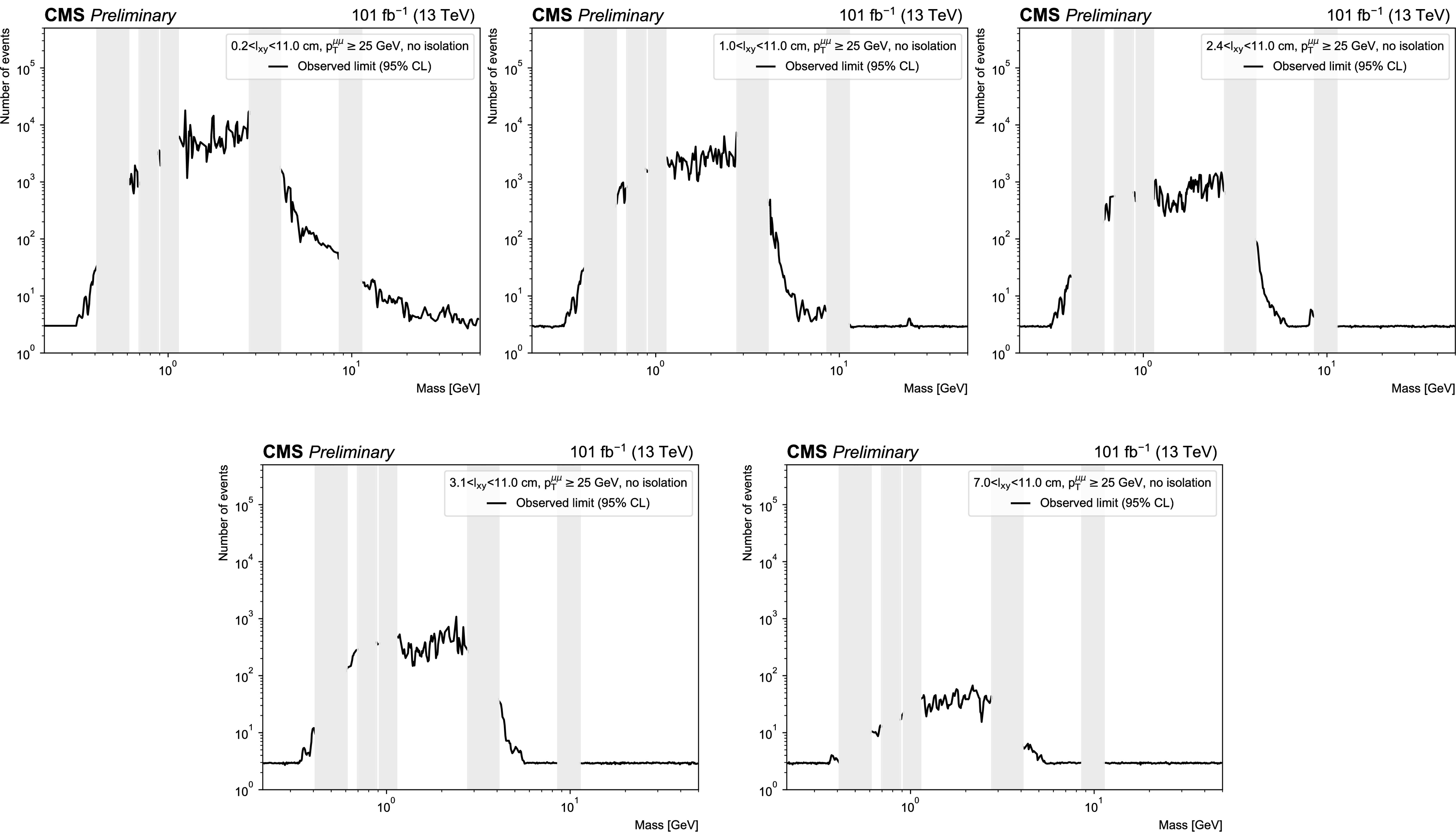

Model-independent upper limits: with two isolated μs, $p_T^{\mu\mu} \geq 25$ GeV

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