Dark sector and new ideas for LLP searches at LHCb

X. Cid Vidal (IGFAE)
on behalf of the LHCb collaboration

Anomalies and precision in Belle II era

8th of September 2021

LHCb
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
IGFAE Instituto Galego de Física de Altas Enerxías

Introduction

Dark sectors/LLPs → Stealth!

J. Zurita

- Electroweak naturalness (hierarchy) problem solved by New Physics (NP) at the TeV scale.
- Other fundamental questions (dark matter, CP asymmetry, neutrino masses, flavor, etc) can also be solved if the NP scale, Λ_{NP} is around the TeV scale.
- No New Physics at the LHC yet! (modulo flavour anomalies…)
  - 1) *collider-phobic* (axions, dark photons, sub-GeV dark matter, sterile neutrinos, …): "we'll need <another kind of experiment> " (e.g: FASER, MATHUSLA, ADMX, DUNE)
  - 2) Λ_{NP} higher than expected:
    - → "let's build a new collider!" [BSM-doer, energy]
    - → "let's compute more loops!" [QCD-doer, precision]
  - 3) $\Lambda_{NP} \sim$ 0.1-1 TeV, but it operates in *stealth mode*: heavy mediators, tiny couplings, compressed spectra, sequestered sectors, large backgrounds, …)

*Very long-lived, tiny couplings and/or ultra light new particles

Ideal territory for LHCb to explore!

Stealth @ LHCb

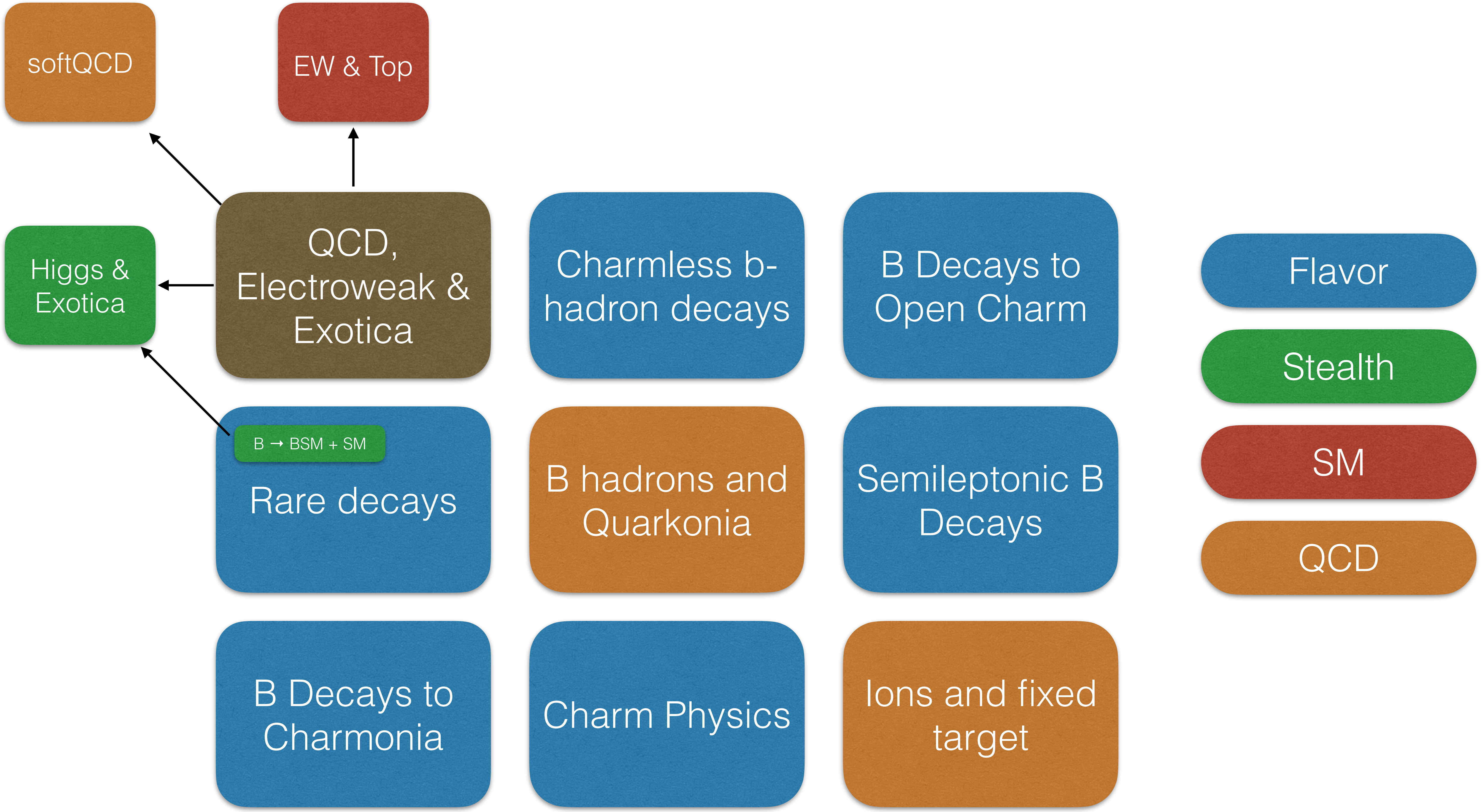
J. Zurita

- LHCb is usually considered *only good for flavour physics*. ATLAS&CMS have more luminosity and larger geometrical acceptance (central), so that's the ideal playground to hunt for new heavy degrees of freedom.

- But LHCb has several other advantages compared to ATLAS&CMS!!! e.g: trigger on soft objects, accurate vertex reconstruction, hadronic ID, precise mass resolution ($\Delta m \sim 0.5\%$ for $m \lesssim 10$ GeV), charged track reconstruction…

Can LHCb probe New Physics (besides flavor)?

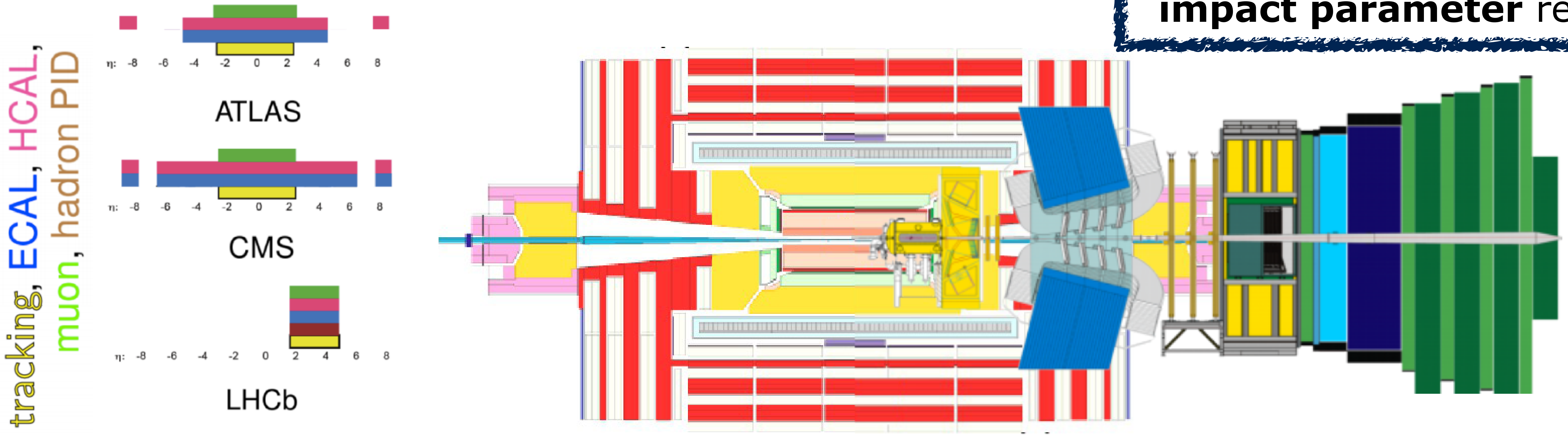
How does Stealth fit at LHCb?



Experimental considerations

- LHCb vs ATLAS/CMS
  - Obvious disadvantage: LHCb collects less data than ATLAS/CMS (factor ~10) and has a limited acceptance for several searches
  - But softer triggers (for instance, can trigger detached di-muons with p_T~1 GeV/c), also good vertexing, PID, *p* resolution…
  - In practice that means we can look into **complementary** phase space regions

Δp/p = 0.5 % at low momentum to 1% at 200 GeV/c
impact parameter resolution: (15 +29/p_T[GeV]) μm



LHCb detector papers:

JINST3(2008)S08005

Int J Mod Phys A30(2015)1530022

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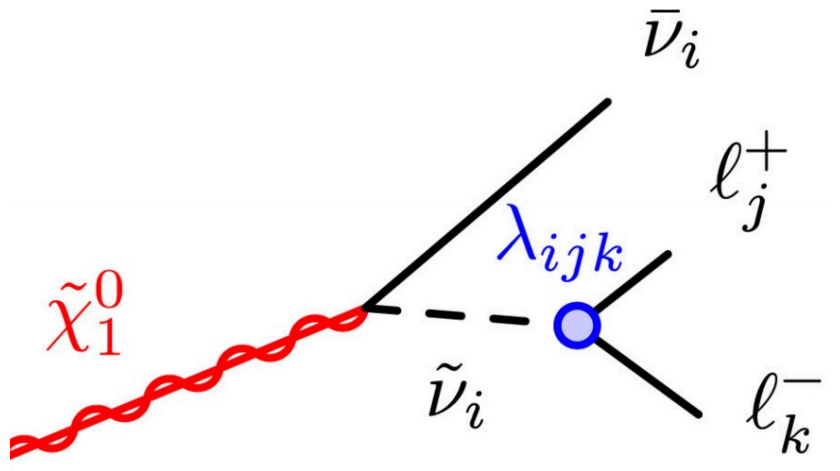
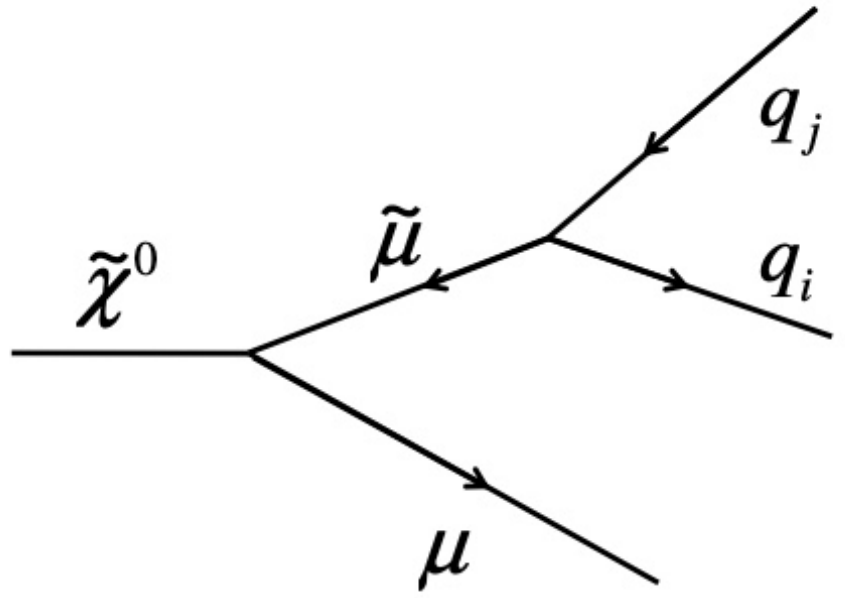
Review of LHCb results

Searches for LLPs

- Several searches for LLPs based on single theoretical benchmark: MSSM with R-parity violation

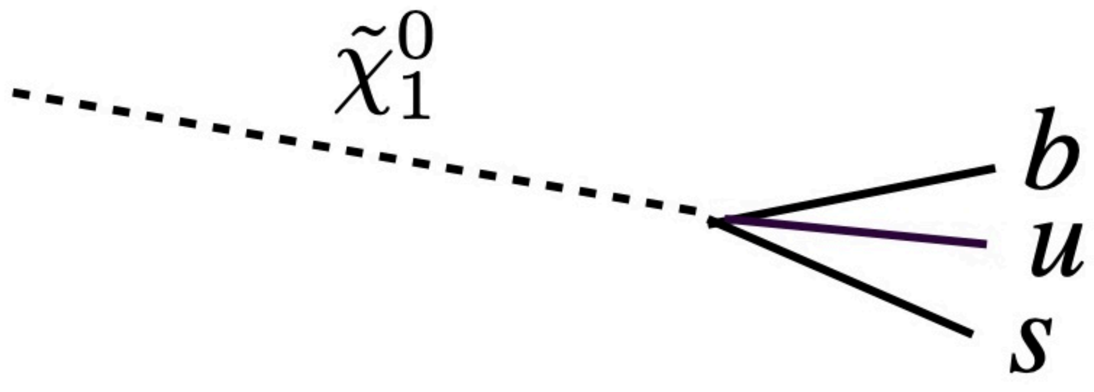


Run 2 dataset
Eur. Phys. J. C81 (2021) 261



New Run 2
LHCb-PAPER-2021-028

Run 1
Eur. Phys. J. C77 (2017) 224



Run 1 dataset
Eur. Phys. J. C (2016) 76664

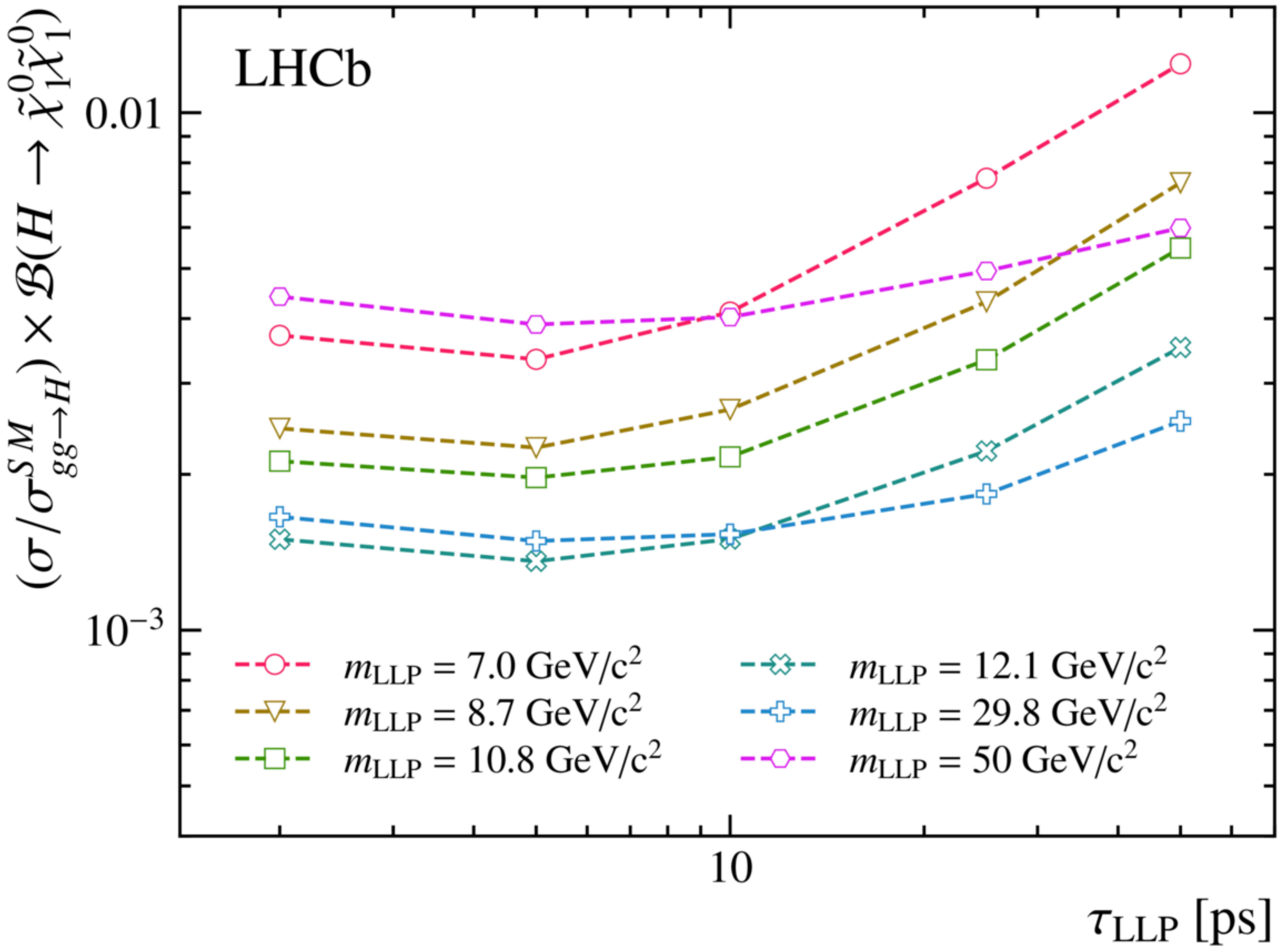
$$W \supset \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k$$

- Associated final states analyzed with different LHCb datasets
- Interpretations provided in different production models, e.g., Higgs portal, non-resonant, W decays

LLP → eμν

Eur. Phys. J. C81 (2021) 261

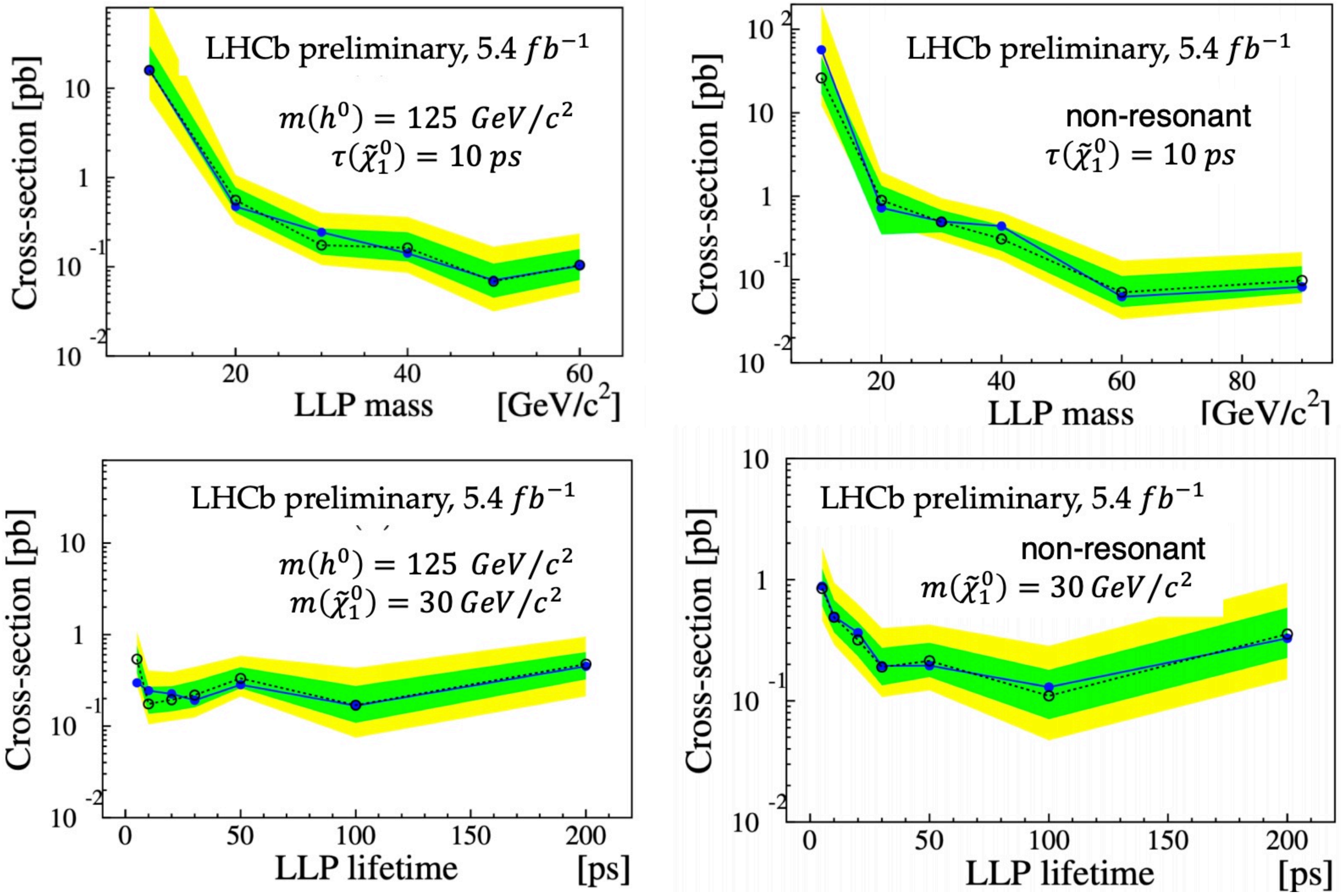
- Search using LHCb Run 2 dataset:
  - Main background, from QCD bb production
  - LLP masses down to 7 GeV
  - Correcting mass wrt flight direction!
  - Simultaneous fit to corrected mass and lifetime
  - No excess, but stringent limits in different production modes
  - For instance, excellent limits for an Exotic Higgs decay



LLP → μ+di-jet

LHCb-PAPER-2021-028 (NEW)

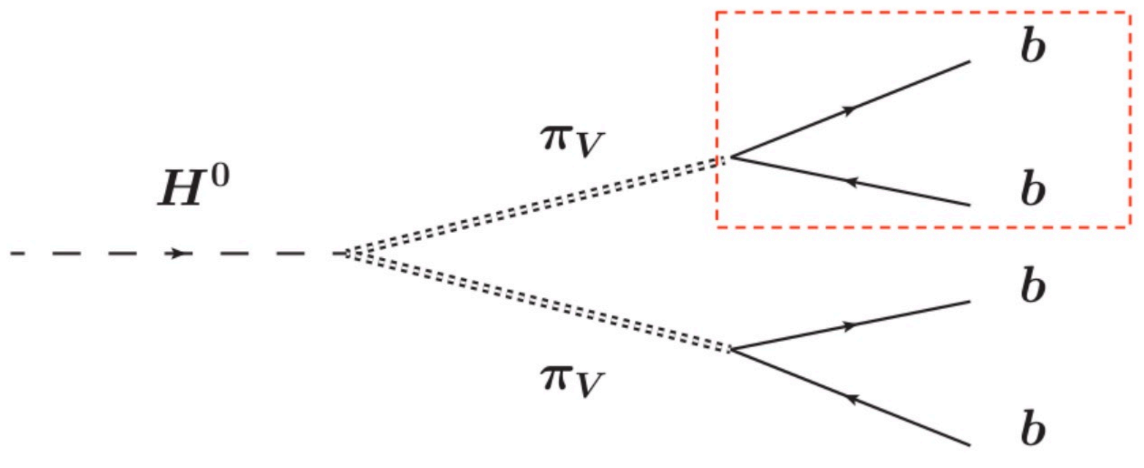
- Search using LHCb Run 2 dataset:
  - Again, main background QCD bb. Also, material interactions
  - LLP mass in [10,90] GeV, lifetime [5,200] ps
  - Fit to LLP mass for different LLP lifetimes
  - No excess, but excellent limits, with different production interpretations
  - Result updates Run 1 result (Eur. Phys. J. C77 (2017) 224)

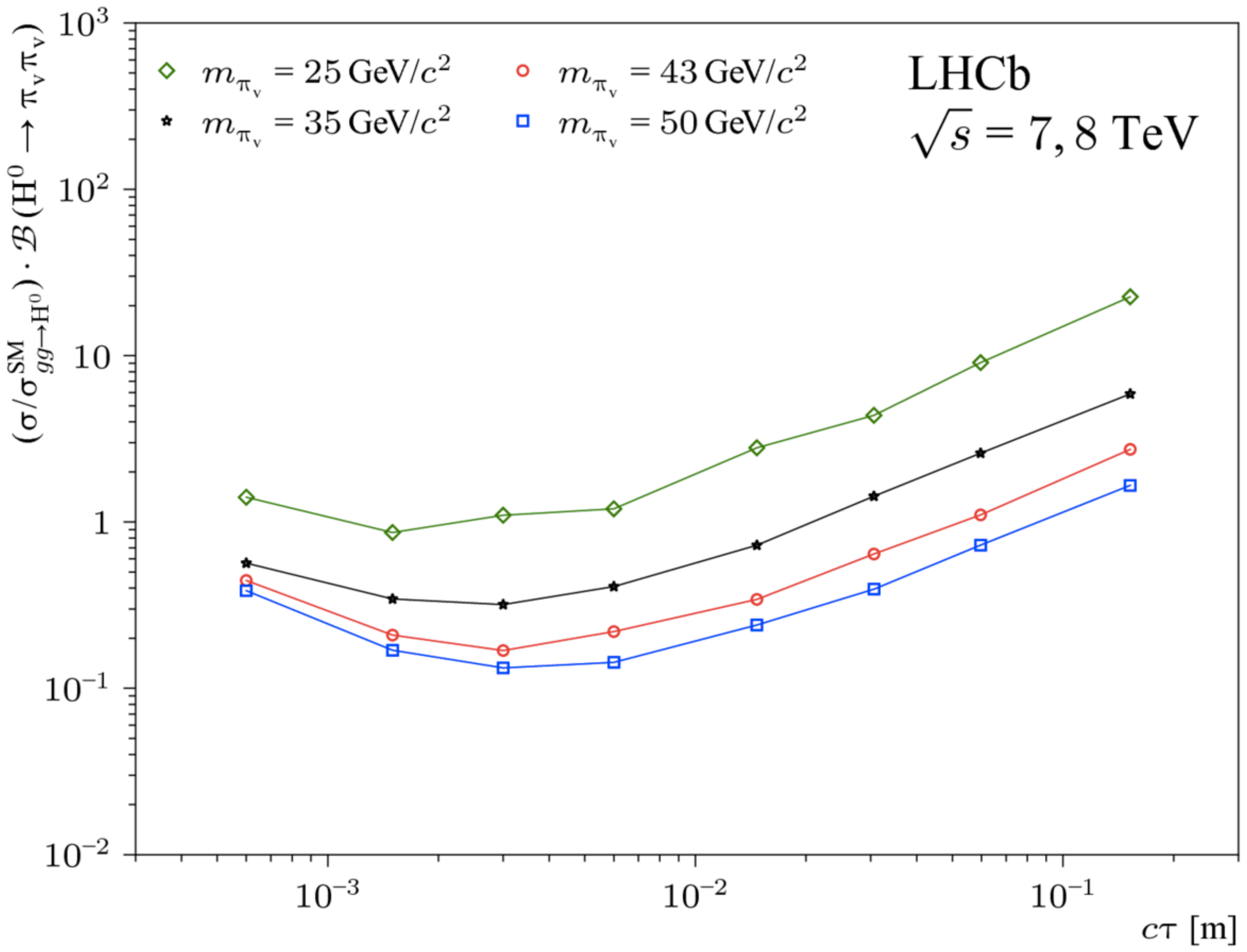


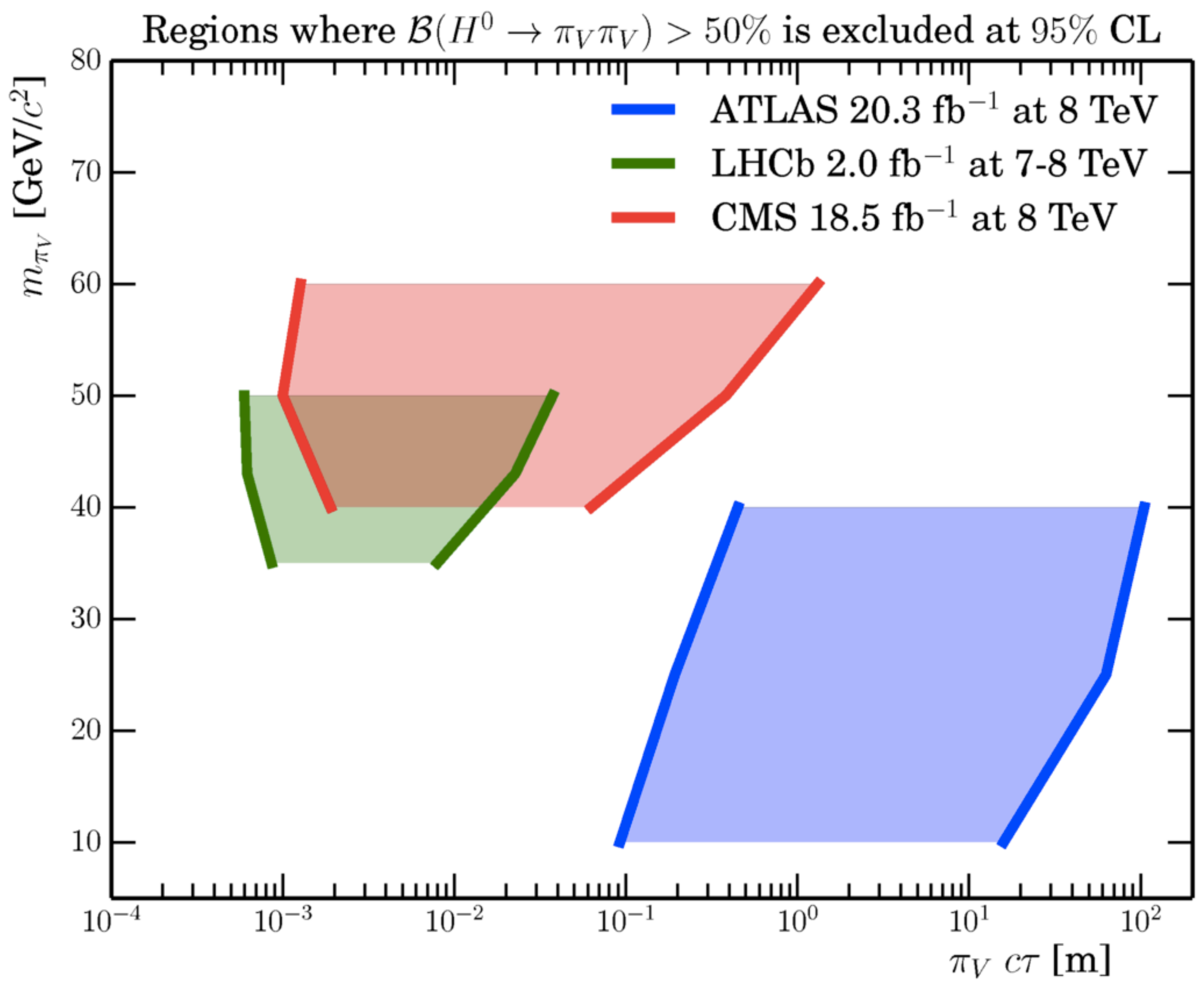
H→LLP→jet jet

Eur. Phys. J. C77 (2017) 812

- Correlated with previous searches (slightly different benchmark), but in this case single displaced vertex with two (b) jets. No excess found with Run 1 dataset
  - Tested the region: m_π =[25-50] GeV, τ=[2-500] ps
  - Interpretation as Higgs exotic decay allows comparisons!







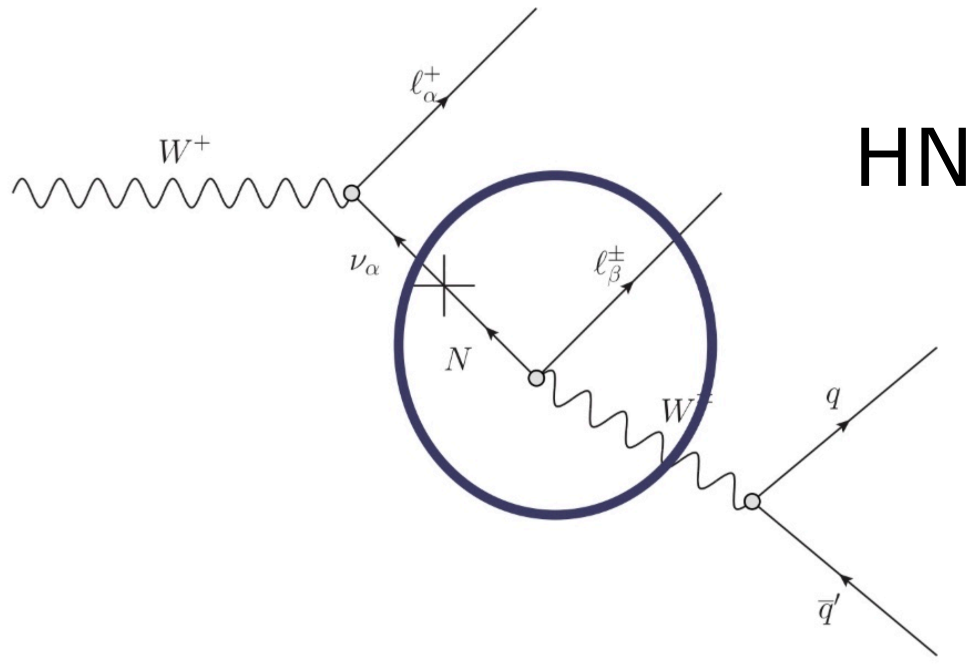
Example of complementarity with ATLAS/CMS

- Compatible search to Eur. Phys. J. C (2016) 76664 (both LLPs in the same event)

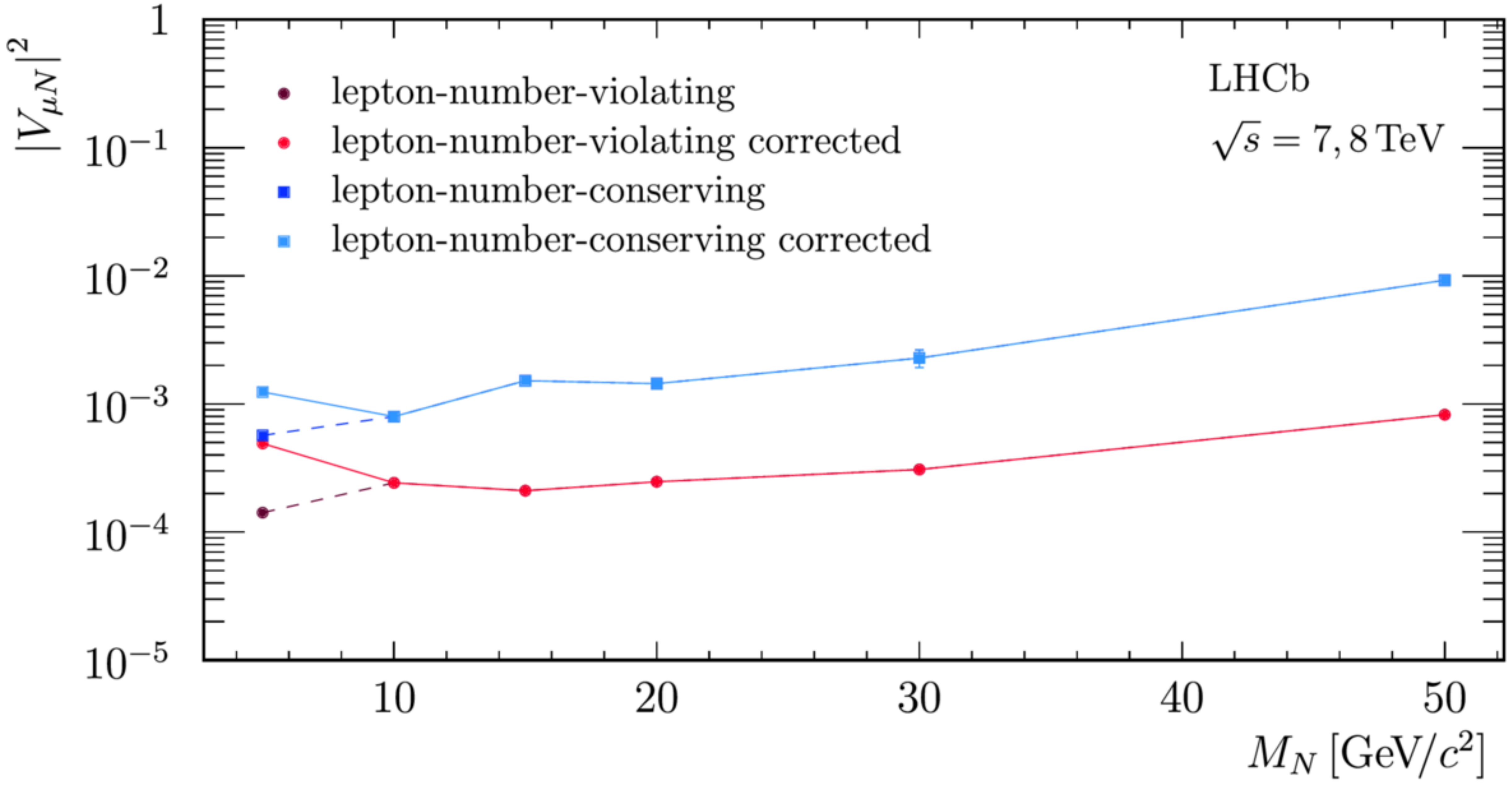
HNL in $W^\pm \rightarrow \mu^+\mu^\pm$ + jet

Eur. Phys. J. C81, (2021) 248

- Heavy neutral leptons could be found in W decays!
  - Search using LHCb Run 1 dataset: use same and opposite charge muons.
  - Background dominated by SM $W\rightarrow\mu\nu$ accompanied by other stuff
  - Example of results Upper limits on mixing with muon neutrino $|V_{\mu\nu}|^2$
  - Not yet competitive with ATLAS [JHEP 10 265], CMS [JHEP 01 122] and DELPHI [Z. Phys. C74 57] searches



HNL decay to μ and jet

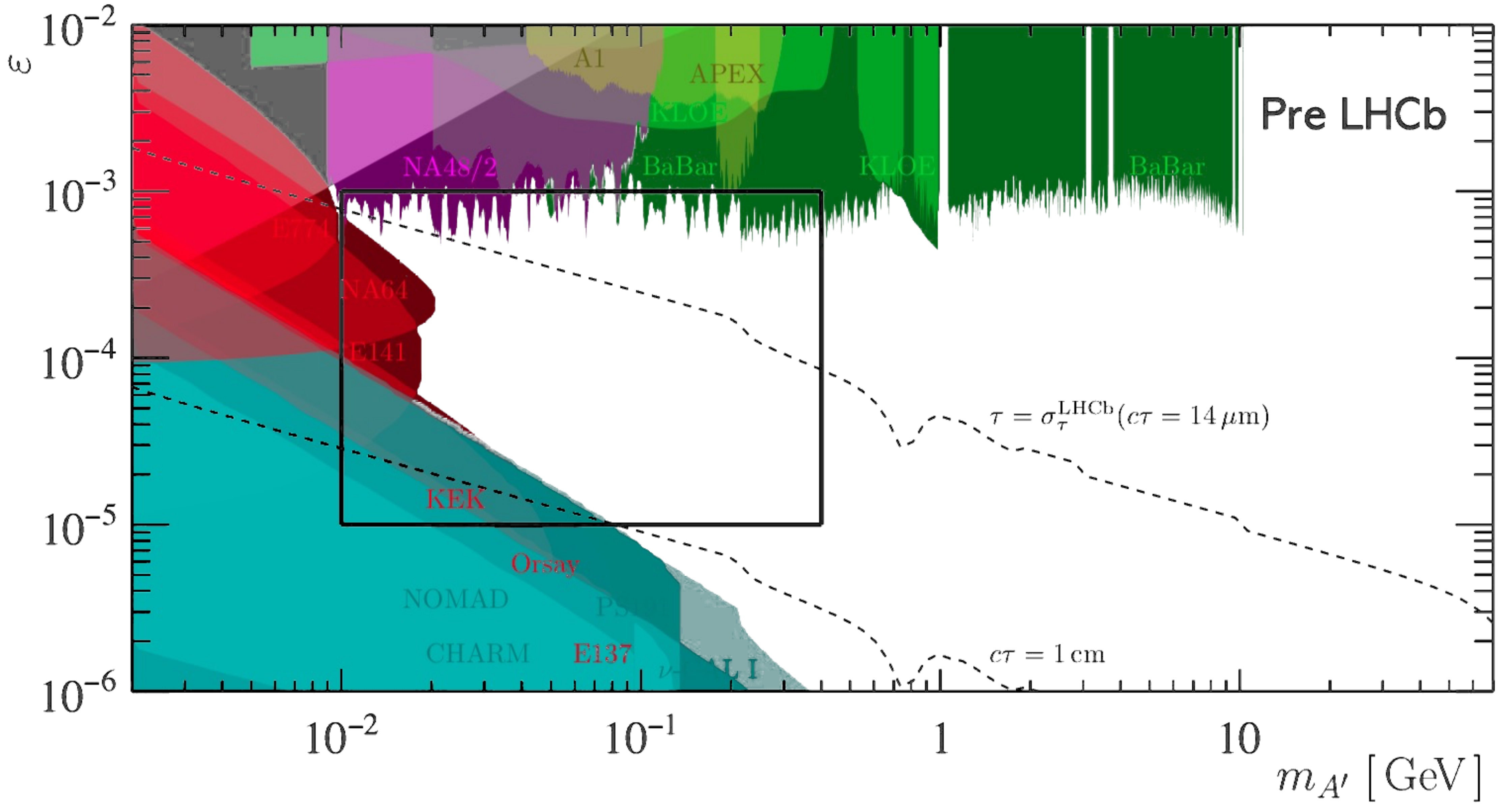


Dark photons

- Most spectacular example of vector portal, to connect dark sector with SM: **dark photon**
  - massive dark sector photon A' couples to SM photon via kinetic mixing
  - signature: resonance in (prompt or displaced) di-lepton spectrum
  - world wide effort for their detection: LHC, B-factories, fixed target experiments….
  - At LHCb, two proposals:
    - di-muon direct search

      [Phys. Rev. Lett. 116, 251803 (2016)]
    - look for $A' \to e^+e^-$ in $D^{*0} \to D^0 A'$ decays

      [Phys. Rev. D 92, 115017 (2015)]



Searches for dark photons at LHCb (I)

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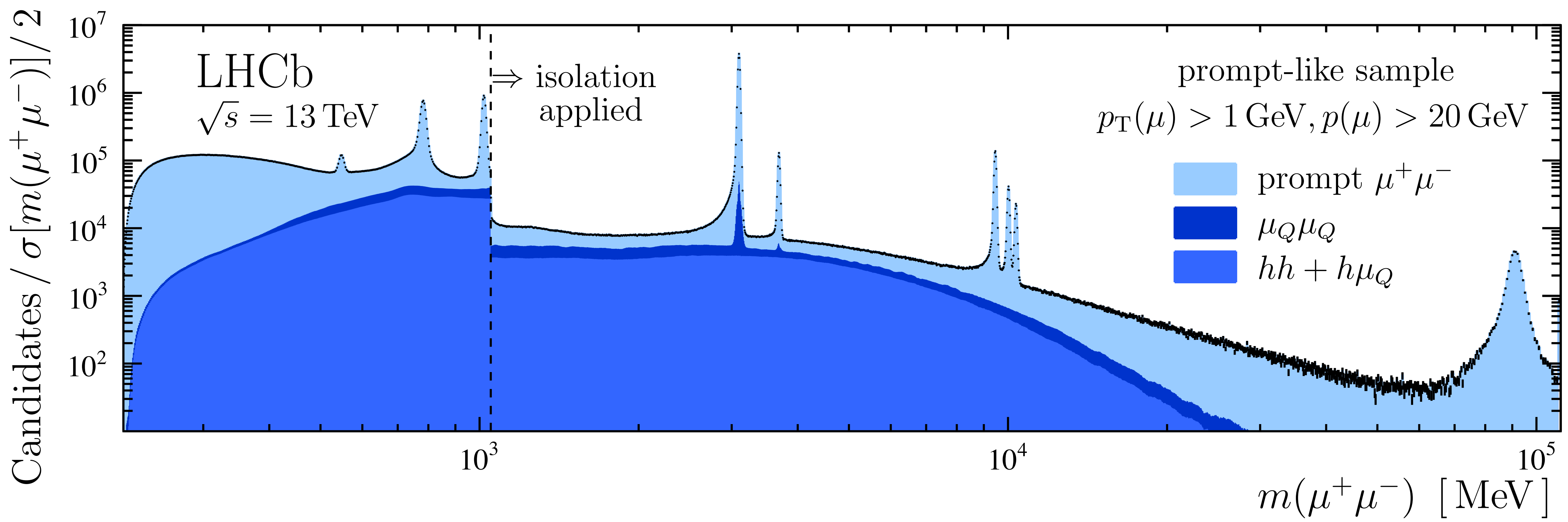
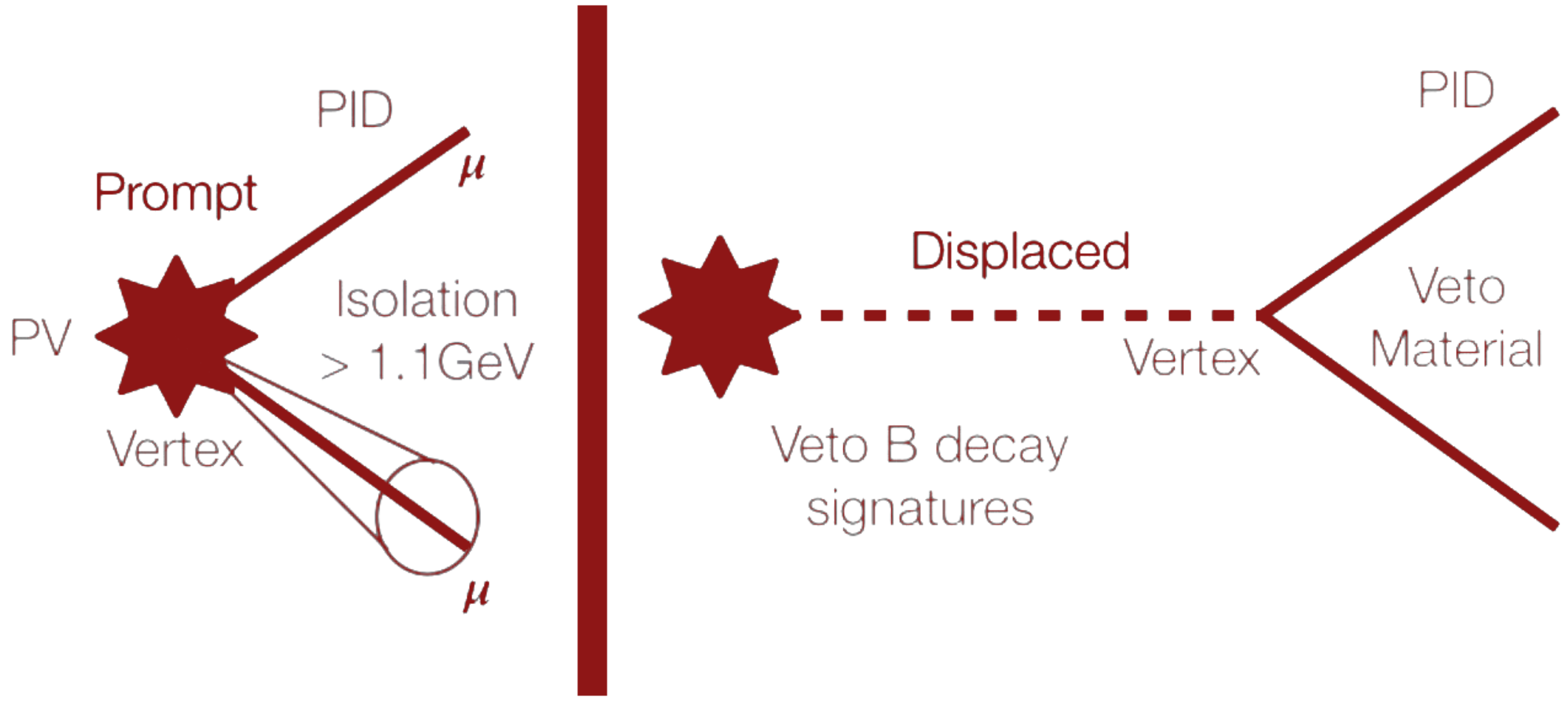
- Inclusive search for Dark Photons (A') in μμ with **LHCb** Run II dataset
  - A′ can be very light, produced as γ*
  - Large fraction in forward region, very soft p_T. Online reconstruction of candidates, no pre-scale down to threshold $2m_\mu$



PRL 120 (2018) no.6, 061801

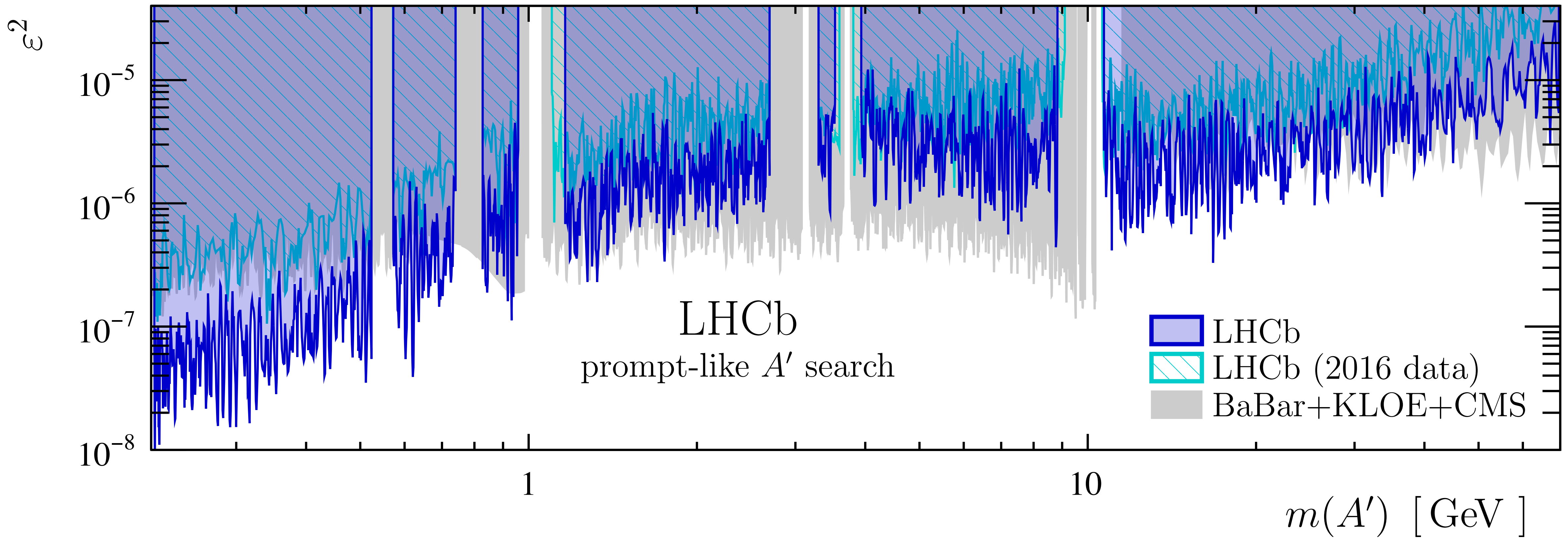
- Analysis flow (similar for prompt/displaced):
  - Self-normalize to $\gamma^* \to \mu\mu$
  - Prompt backgrounds from same sign μ, fits to $IP\chi^2$, isolation cut applied only above 1 GeV/c^2.
  - Displaced background: $K_s \to \pi\pi$, b-hadron decays + material interactions (vetos for all)



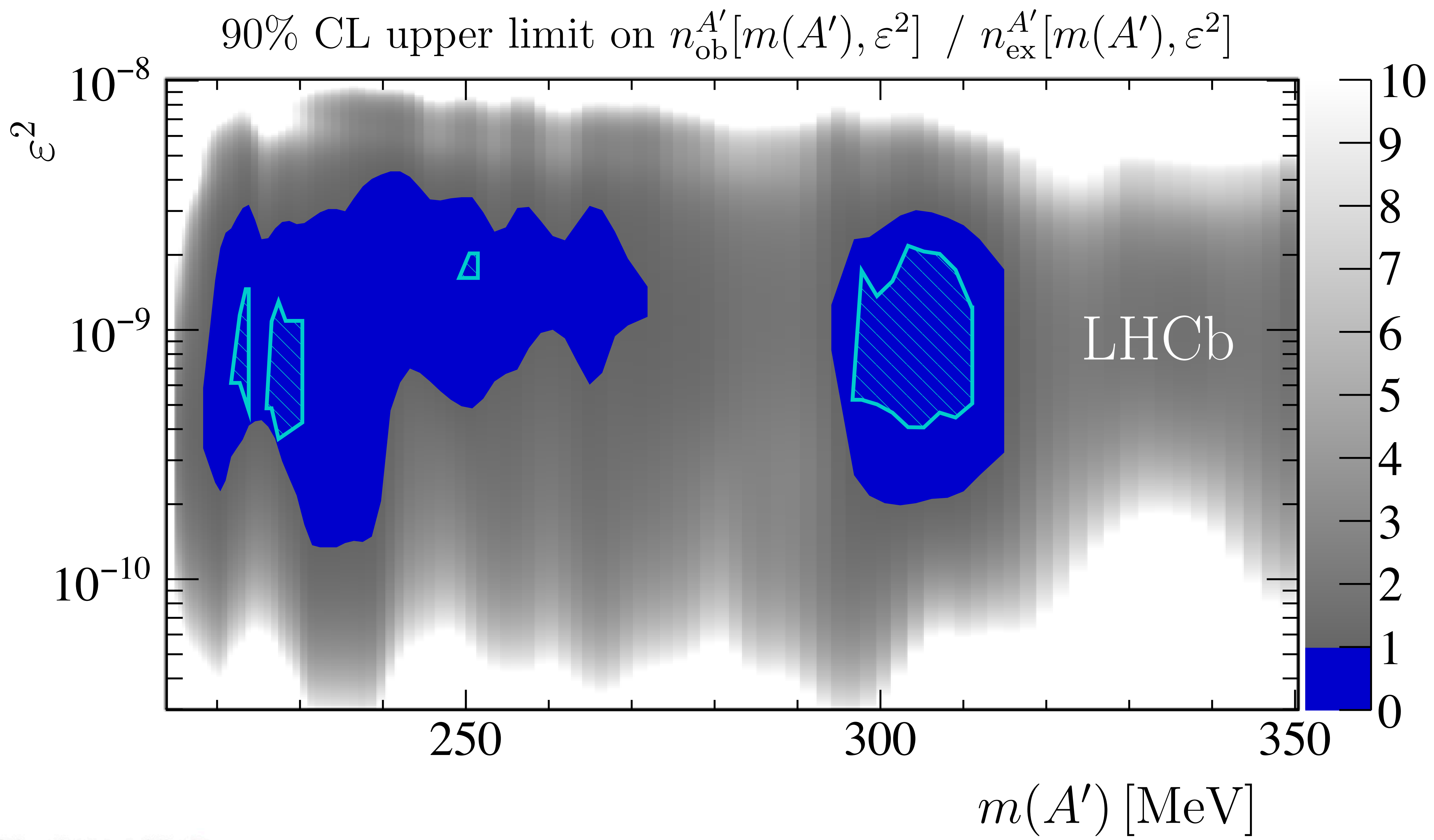
Searches for dark photons at LHCb (II)

PRL 124 (2020) 041801

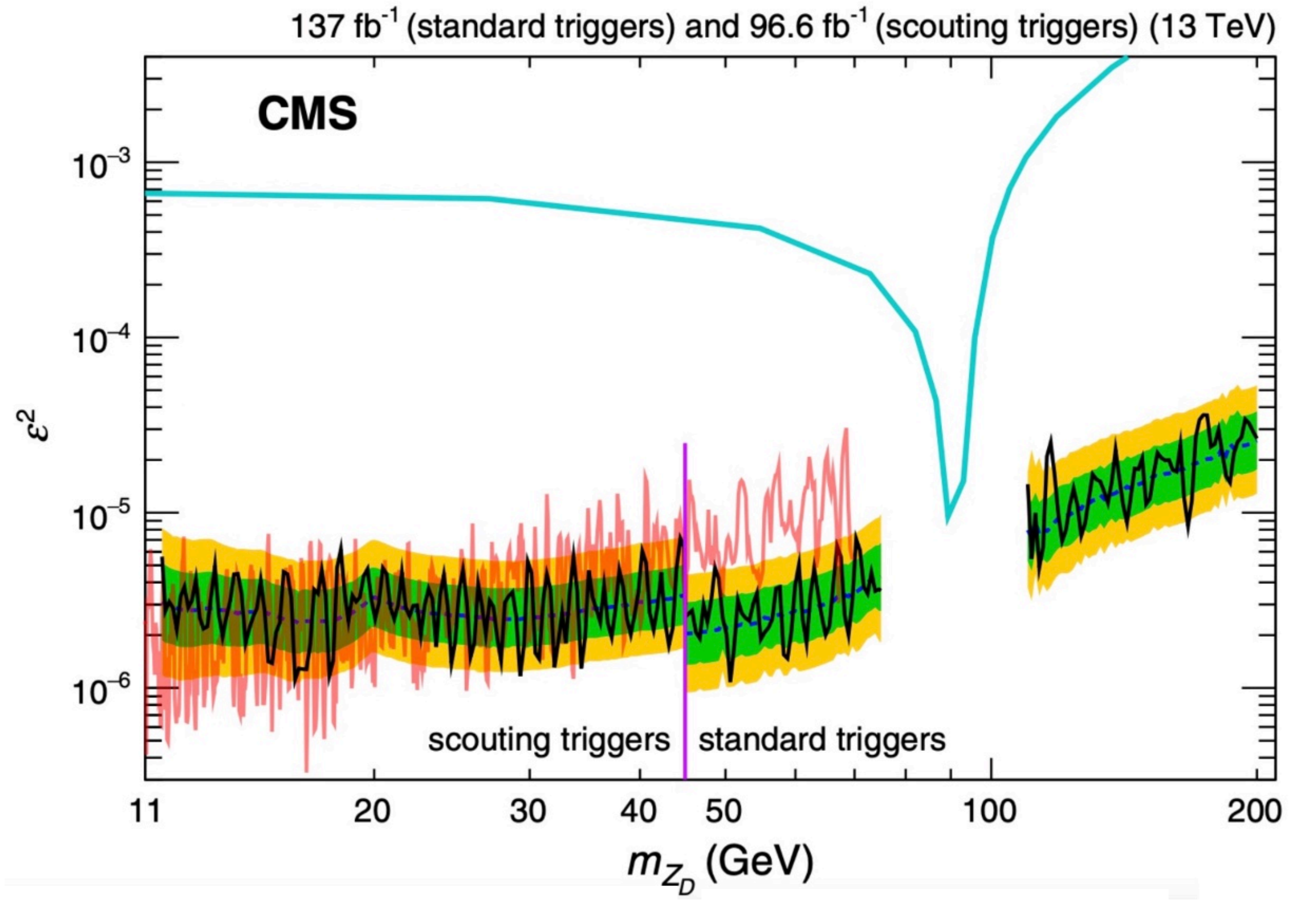
✦ Prompt results

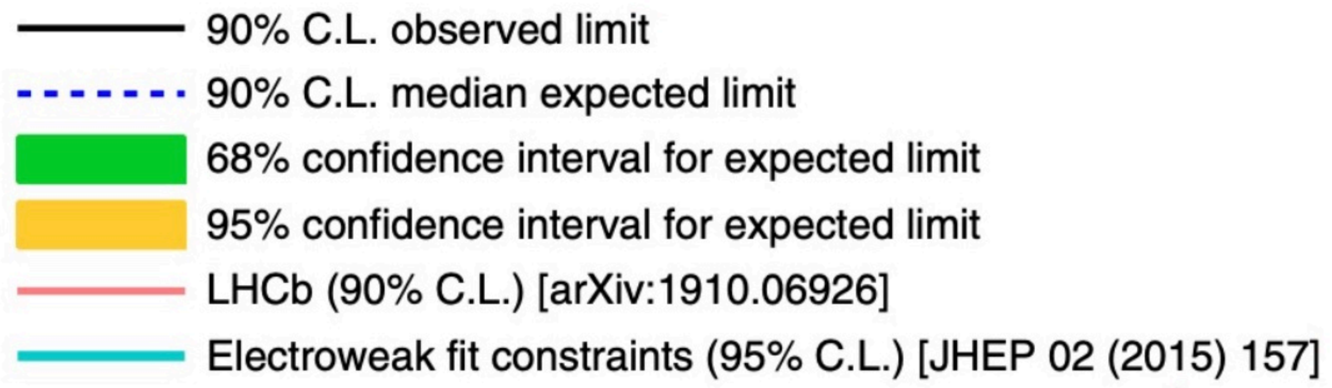


✦ Displaced results



Note new CMS limit above ~10 GeV/c²!





PRL 124, 131802 (2020)

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Searches for dark photons at LHCb (II)

PRL 124 (2020) 041801

- Prompt resul

Note new CMS limit above ~10 GeV/c²!

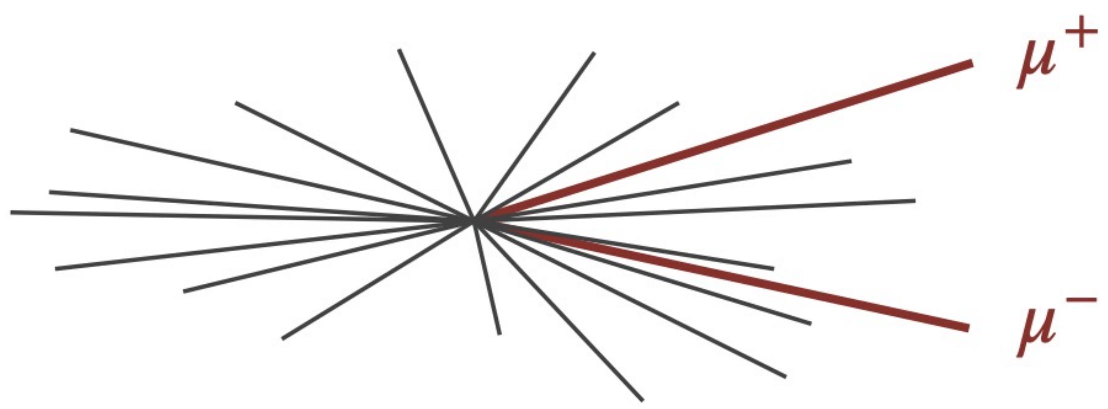
PRL 124, 131802 (2020)

Non-minimal searches

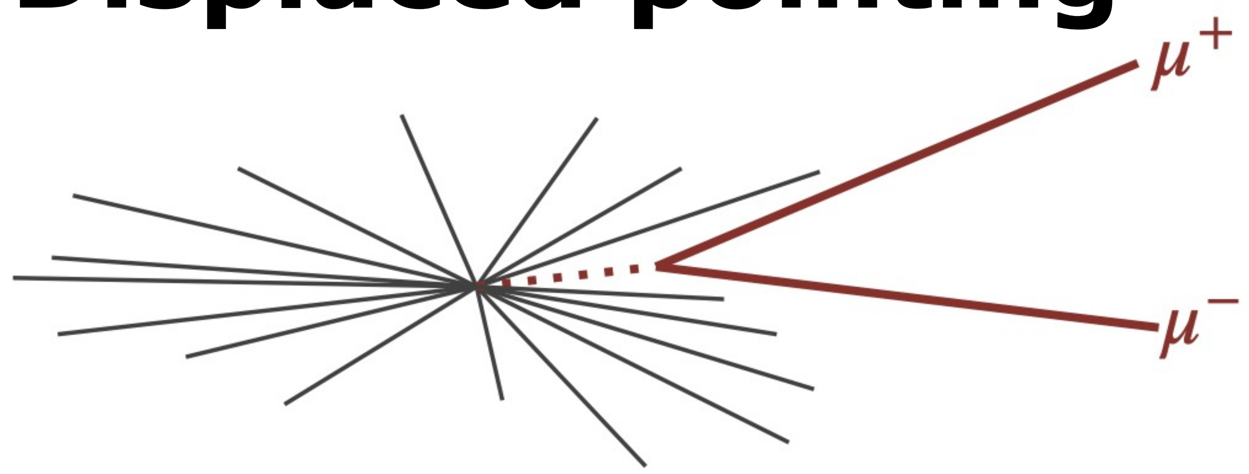
- Our μμ dataset can be sensitive to many more models, including dark-photon and similar topologies
  - ➡ Perform a model independent search, provide a few example interpretations

+ no isolation requirement
+ non-zero width considered

Inclusive Prompt

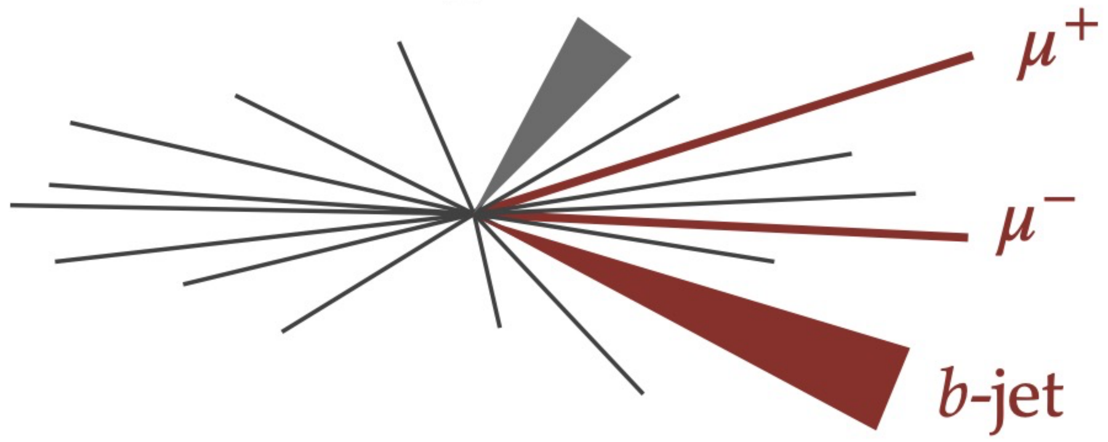


Displaced pointing

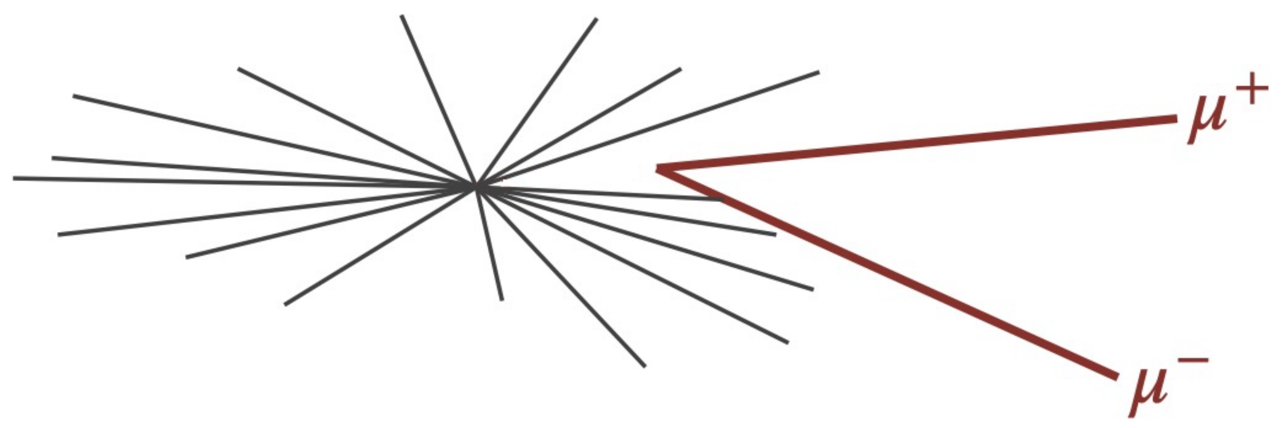


+ non-zero width considered

Prompt + b-jet



Displaced non-pointing

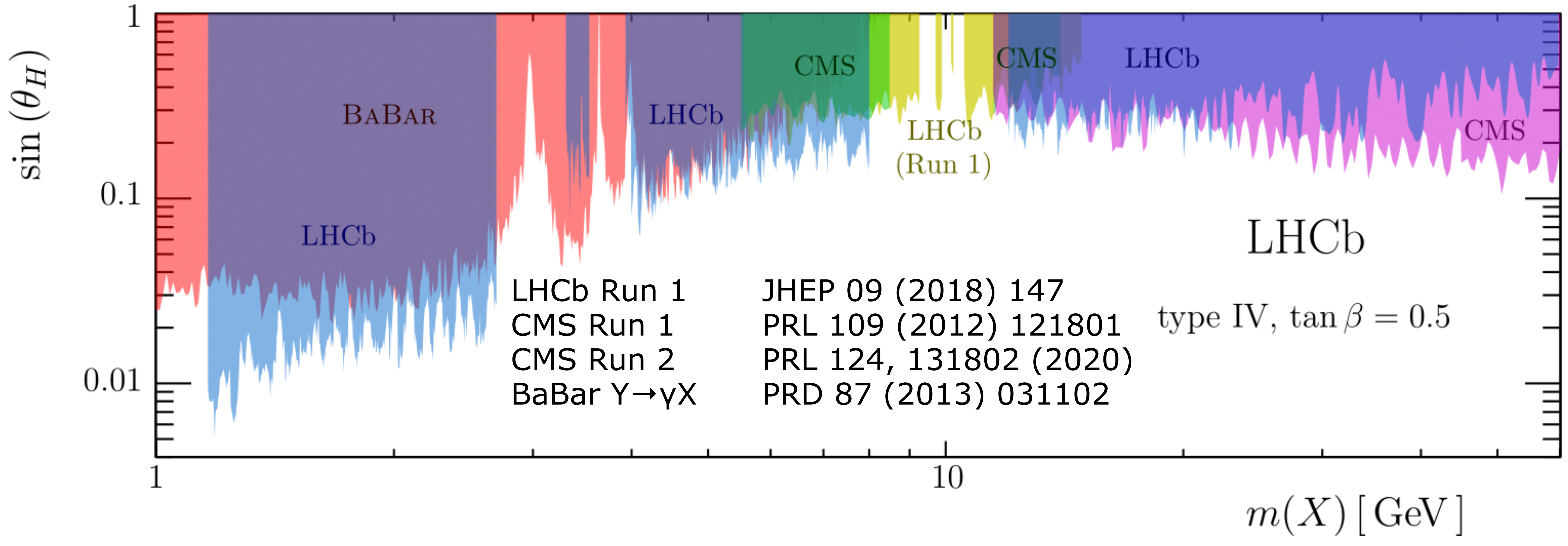


Interpretations

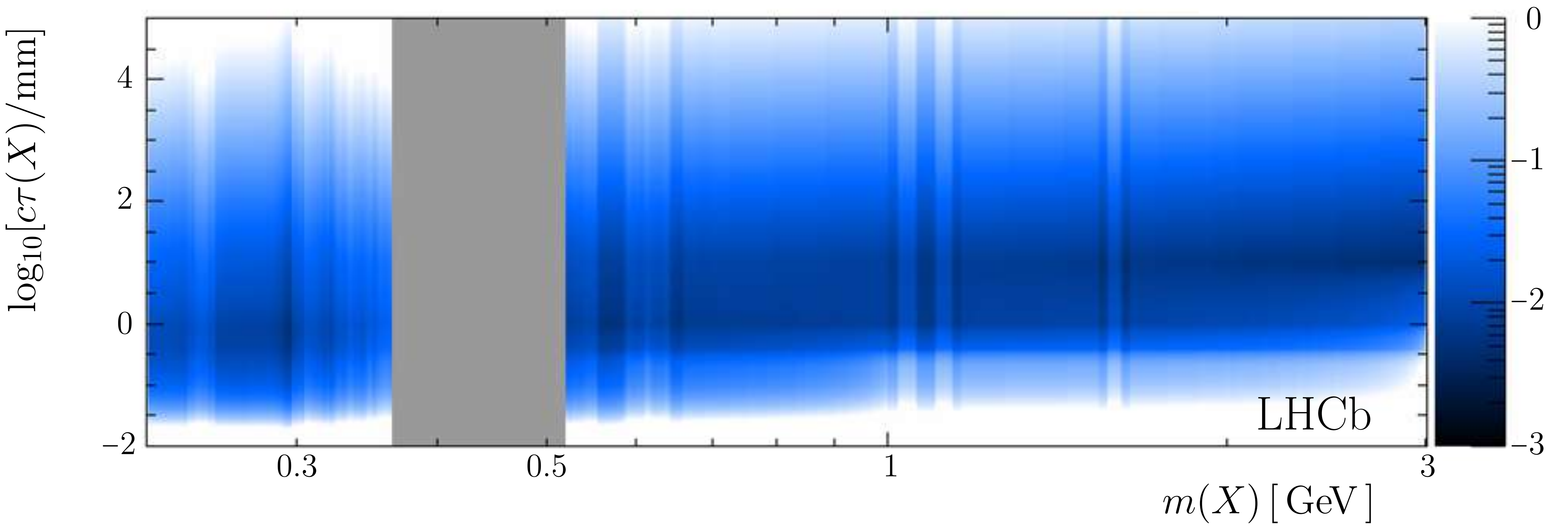
- Example of model-interpretations (upper limits at 90% CL). Model dependent in backup!

JHEP 10 (2020) 156

X-Higgs mixing angle for the 2HDM scenario: world best upper limits!
Note in this scenario, excess seen by CMS [JHEP 11 (2018) 161)] excluded with 20 times lower σ
Theoretical model from:
PRD 93, 055047 (2016)



HV scenario: upper limits on γ - Z_{HV} kinetic mixing. Results depend on hidden hadron multiplicity (here $< N_{HV} > \sim 10$)
Theoretical model from:
PRD 97 (2018) 095033



New ideas (non-LHCb papers)

Long-lived particles

Exclusive Displaced Hadronic Signatures (I)

XCV et al, JHEP 01 (2020)

Portals into New Physics

- How to couple light degrees of freedom to the SM while being consistent with all possible constraints (e.g: LEP, Tevatron, EDMs, LHC, flavor…)?
- Idea: add new particle weakly coupled to the SM via a portal term.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{portal} + \mathcal{L}_{\mathcal{NP}}$$

Encodes interaction of SM fields and new particles

Field	Lagrangian	Phenomenology
Scalar S:	$\mathcal{L}_S \supset \mu S H^\dagger H + \lambda S^2 H^\dagger H$	Exotic Higgs decays
Vector A′:	$\mathcal{L}_{A'_\mu} \supset \epsilon F'_{\mu\nu} B_{\mu\nu}$	Dark photon/Z′
Fermion N:	$\mathcal{L}_N \supset y_{ai}(L_a H) N^i$	HNL (ν masses)
Pseudoscalar a:	$\mathcal{L}_a \supset a \left(\frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{4 f_\gamma} + \frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{4 f_g} \right) + \frac{\partial^\mu a}{f_f} \bar{f}_i \gamma^\mu \gamma^5 f^i$	ALPs

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Exclusive Displaced Hadronic Signatures (I)

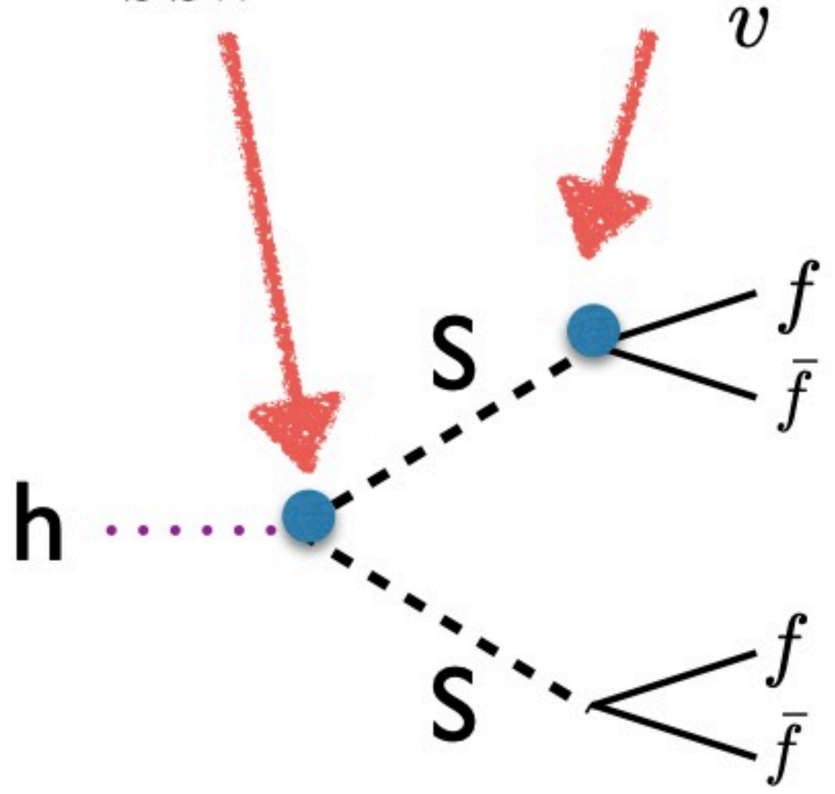
XCV et al, JHEP 01 (2020)

Portals into New Physics

- How to couple light degrees of freedom to the SM while being consistent with all possible constraints (e.g: LEP, Tevatron, EDMs, LHC, flavor…)?

Decay:

$$\mathcal{L} \supset -\lambda_{SSh} h S^2 - \sin\theta \frac{m_f}{v} S \bar{f} f$$



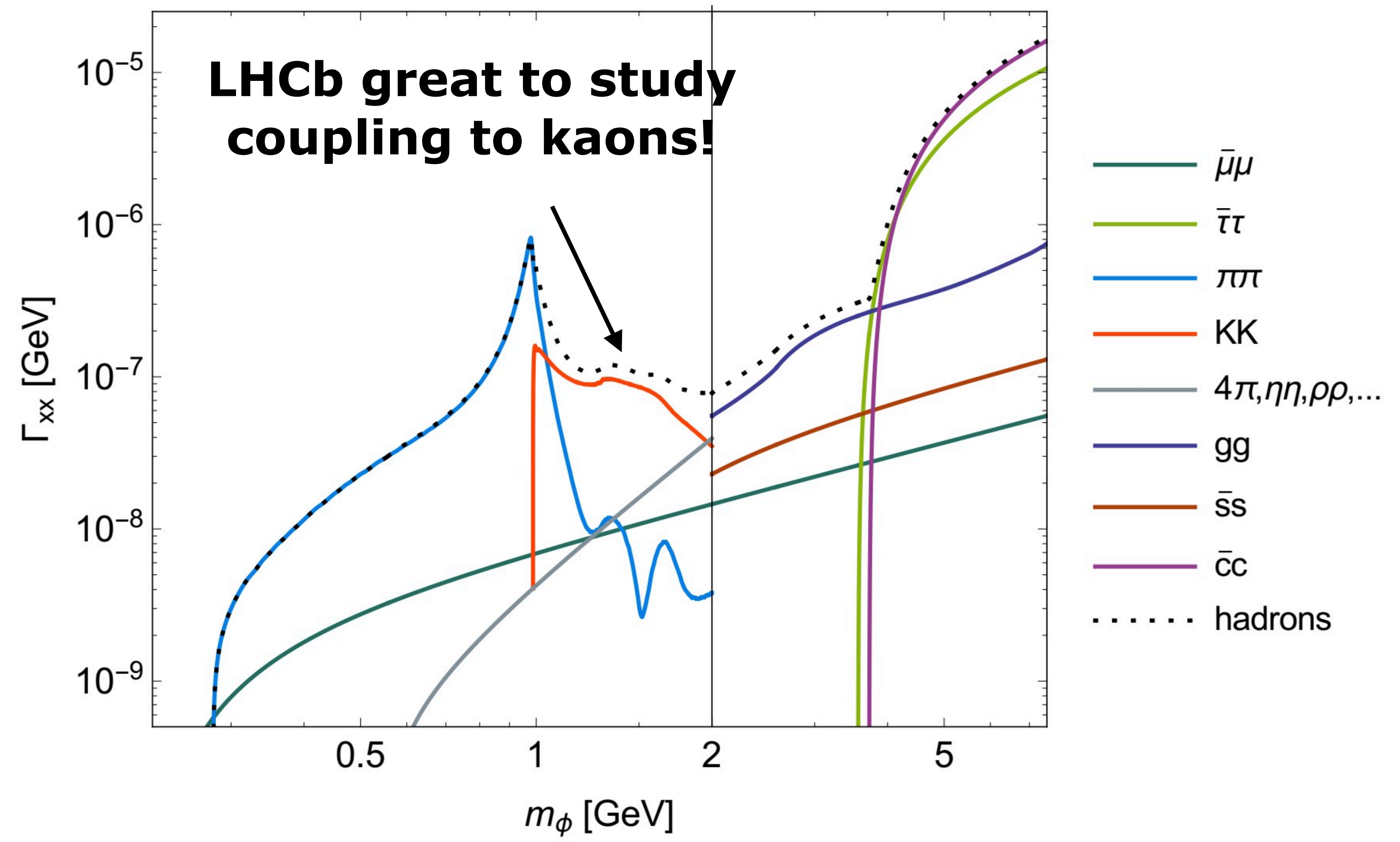
oup … es int … P … $H^\dagger H$ …

Sc…

Ve…

Fermion N: $\mathcal{L}_N \supset y_{ai}(\bar{L}_a H) N$ …

MW Winkler, Phys. Rev. D 99, 015018 (2019)



Pseudoscalar a: $\mathcal{L}_a \supset a\left(\frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{4f_\gamma} + \frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{4f_g}\right) + \frac{\partial^\mu a}{f_f}\bar{f}_i\gamma^\mu\gamma^5 f^i$ ALPs

Exclusive Displaced Hadronic Signatures (II)

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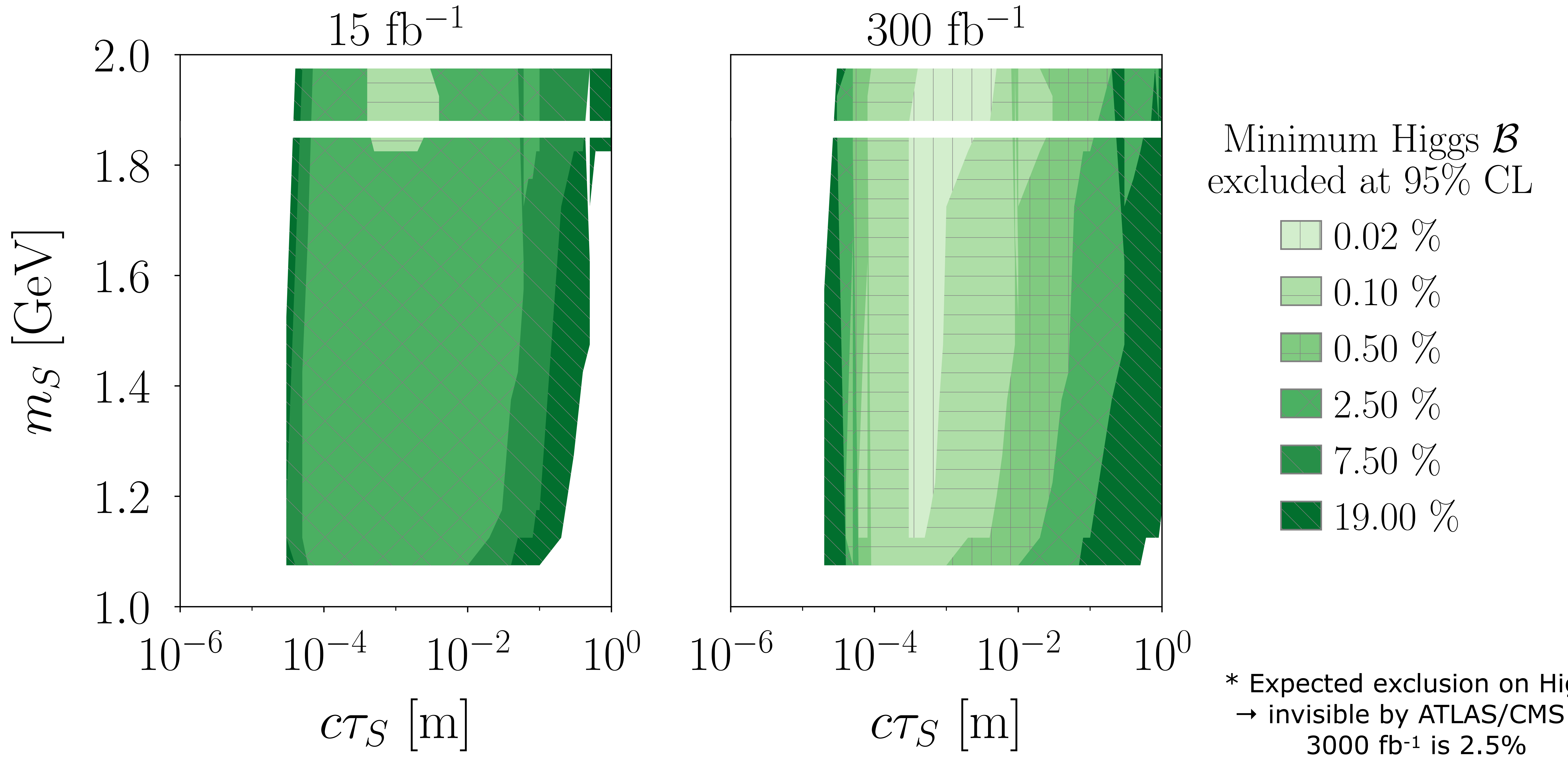
XCV et al, JHEP 01 (2020)

- LHCb prospects for model independent limits on BR(H→SS), assuming BR(S→KK) = 100%



* Expected exclusion on Higgs → invisible by ATLAS/CMS @ 3000 fb^{-1} is 2.5%

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True Muonium (I)

XCV et al, Phys. Rev. D 100, 053003

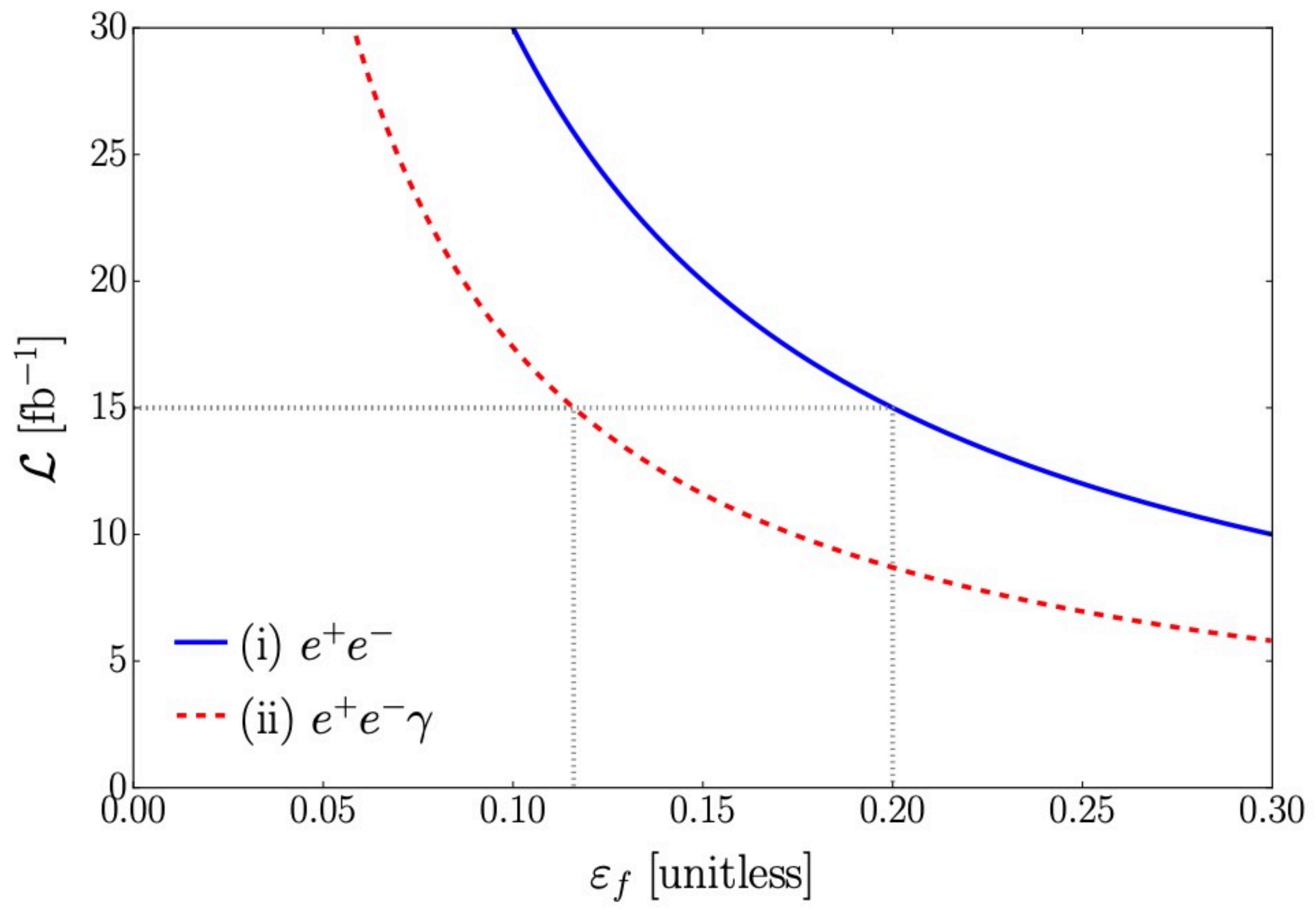
- $(\mu^+\mu^-)$ bound state exists in the SM. Studying properties would be a very clean test to QED!
  - Also, potential to BSM physics (e.g., modifications to the TM decay rate)
- Expected properties of an $^3S_1$ (ortho-TM) state
  - Mass ~210 MeV/c^2, $c\tau$ ~ 0.5 mm (5 times a τ lepton, for instance), way larger boost. Decays to e^+e^-!
  - Fragile state: Material interactions would produce $\mu\mu$ separation
  - Predominantly produced in $\eta \rightarrow (\mu\mu)\gamma$ decays. BR~10^{-9}
  - But huge η production cross section at the LHC. Decay too soft in p_T for ATLAS/CMS
- Signature: LLP decaying to e^+e^- not having traversed any detector layer or material (challenging). At LHCb, similar to a dark photon!

True Muonium (II)

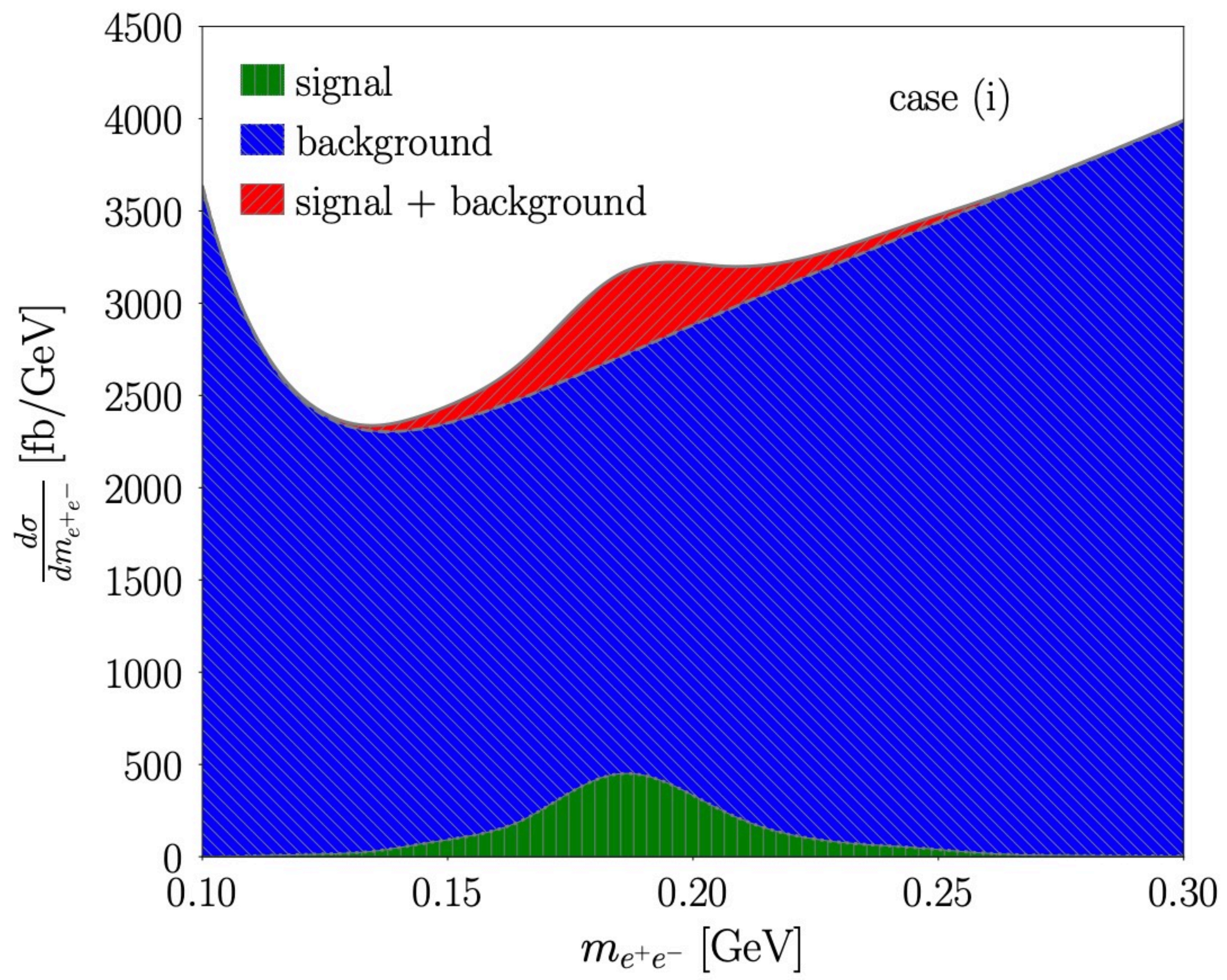
XCV et al, Phys. Rev. D 100, 053003

- Potential reconstruction strategies at LHCb: inclusive (ignore γ) or exclusive (reconstruct γ and get η mass)
  - Assess prospects for LHCb upgrade(s). Different assumptions for reconstruction efficiencies. Assume *ee* mass resolution at 210 MeV/c^2 close to current (σ~20 MeV/c^2)

$5\sigma_{stat}$ discovery potential: Discovery possible with inclusive search at the end of Run 3!



Inclusive search, background dominated by QCD



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Other proposals (non-LHCb papers)

ALPs

Axion-like particles through photons (I)

XCV et al, JHEP 2019 (113)

- Axion-like particles (or ALPs) are Pseudo Nambu Goldstone Bosons, associated to spontaneously broken approximate symmetries.

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \sum_{i,\mu,\nu} \frac{a}{f} c_i \frac{\alpha_i}{4\pi} F_{i,\mu\nu}\tilde{F}^{i,\mu\nu} - \frac{g^* f}{\sqrt{2}}\psi\tilde{\psi}$$

  - Their mass, $\mathbf{m_a}$, can be arbitrarily below the NP scale
  - Their coupling to the SM goes as 1/f, while the m_{NP}(=g*f) goes with f → exploring the intensity frontier implies exploring the energy frontier!
  - In the SM sector, ALPs couple to gluons (LHC production) or photons (LHC decay). Decay to gluons possible but way harder experimentally

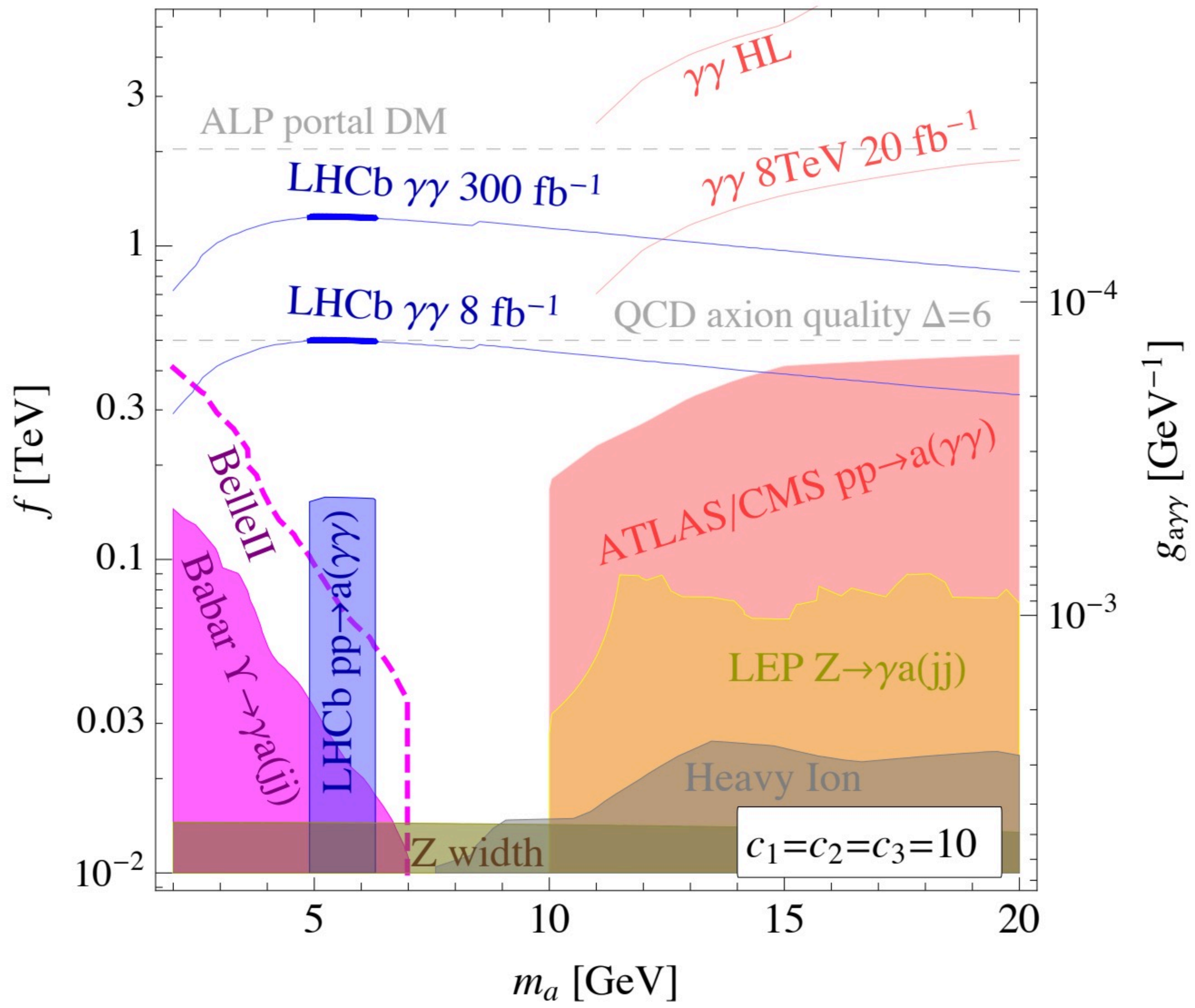
Axion-like particles through photons (II)

XCV et al, JHEP 2019 (113)

- Light ALPs impossible for ATLAS and CMS
  - Photons too soft. Different at LHCb :-)
- Exploratory pheno study: use 80 pb^{-1} of public LHCb data. This is ~1% of what we have on tape!
  - Existing trigger for $B_s \to \gamma\gamma$, for a while (analysis is relatively similar and could be done in parallel)
  - Trigger mass range extended in 2018 to cover all the gap. Before 2018, just sensitive to $m_a \sim B$

SciPost Phys. 7, 062 (2019)

  - Experimental analysis ongoing, potential to include photon conversions (should improve sensitivity, but not by a lot)



Alternatives to discover an ALP

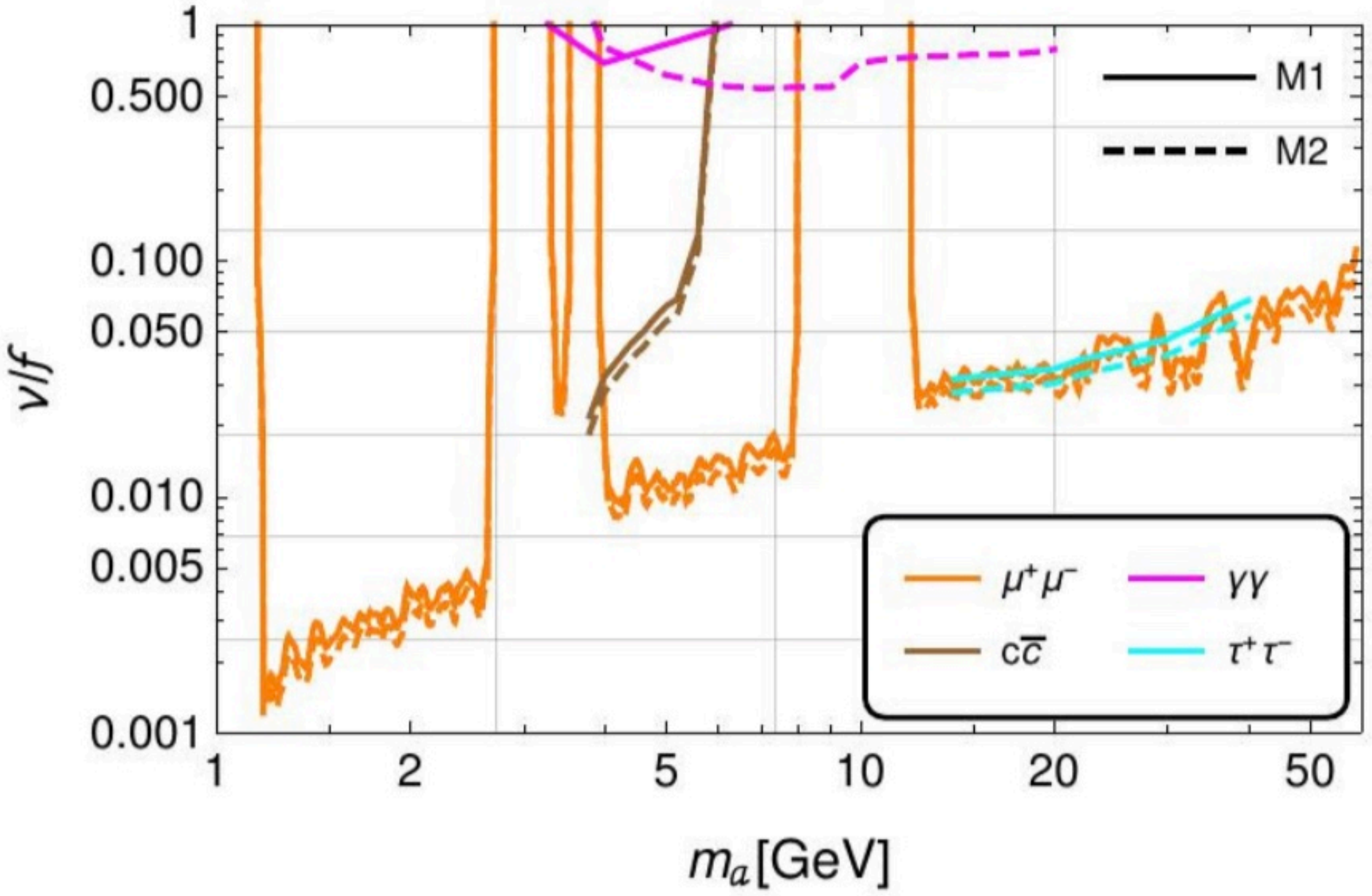
D. Buarque et al, arXiv:2106.12615

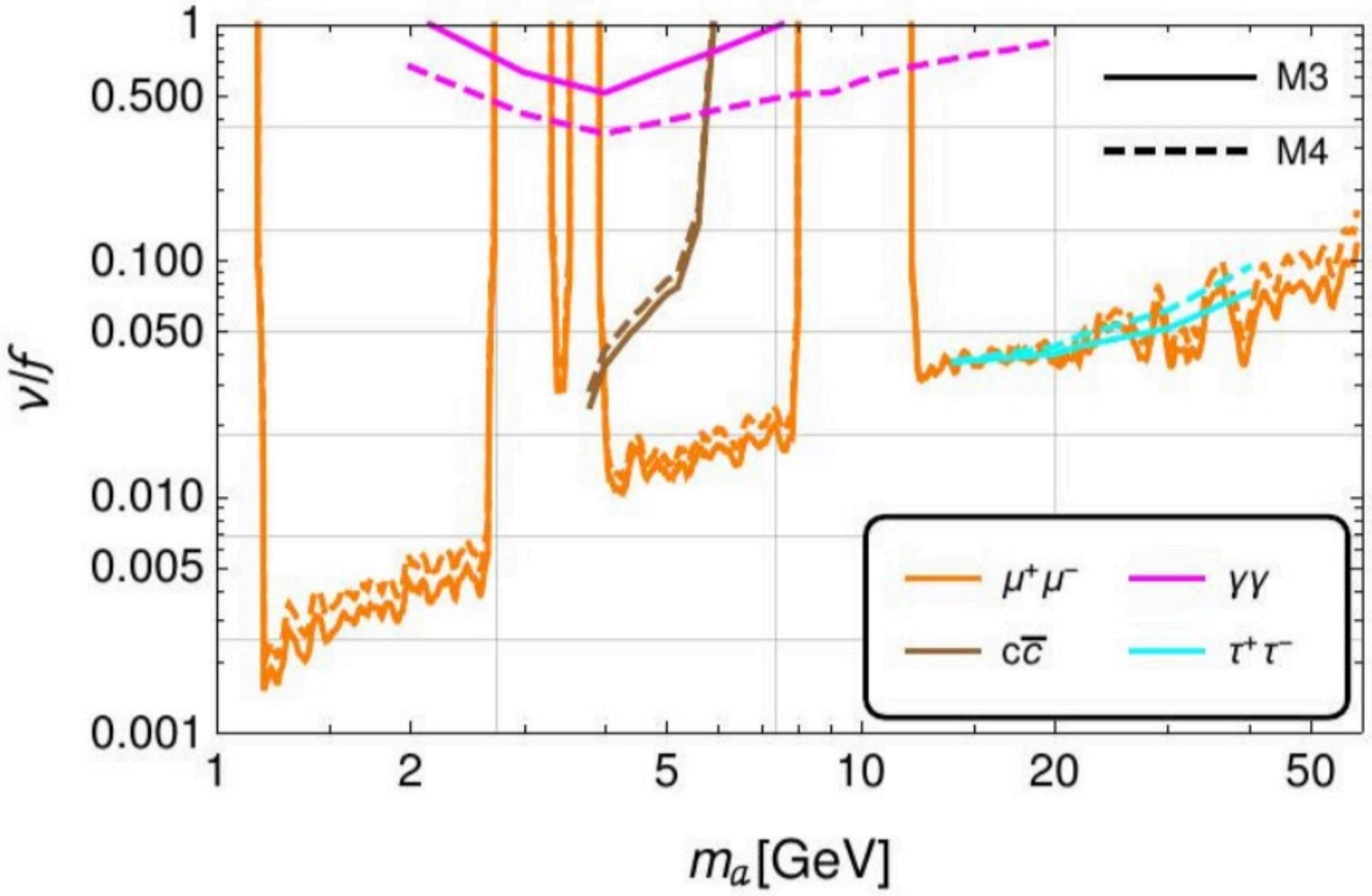
- There is a bit of a blind spot in searches for (neutral colorless) BSM well-motivated resonances in the mass regime O(5-10 GeV) - O(100 GeV).
  - Backgrounds at the LHC for such light resonance searches are huge. Difficult to trigger… How about LHCb?
  - Use set of 12 models with a composite Higgs as a benchmark. Very predictive models, only free parameter is mass of the (prompt) ALP.
  - Focus on μμ, γγ (again) and two **new proposals**: ττ and exclusive cc (two D mesons)
  - For the first two, recast LHCb results or prospects shown in previous slides. For the others, perform simplified study based on simulation of LHCb signal and backgrounds

Alternatives to discover an ALP

D. Buarque et al, arXiv:2106.12615

- Results promising: interesting alternatives in leptophobic or non-universal lepton coupling scenarios





* rest of models avaliable in paper

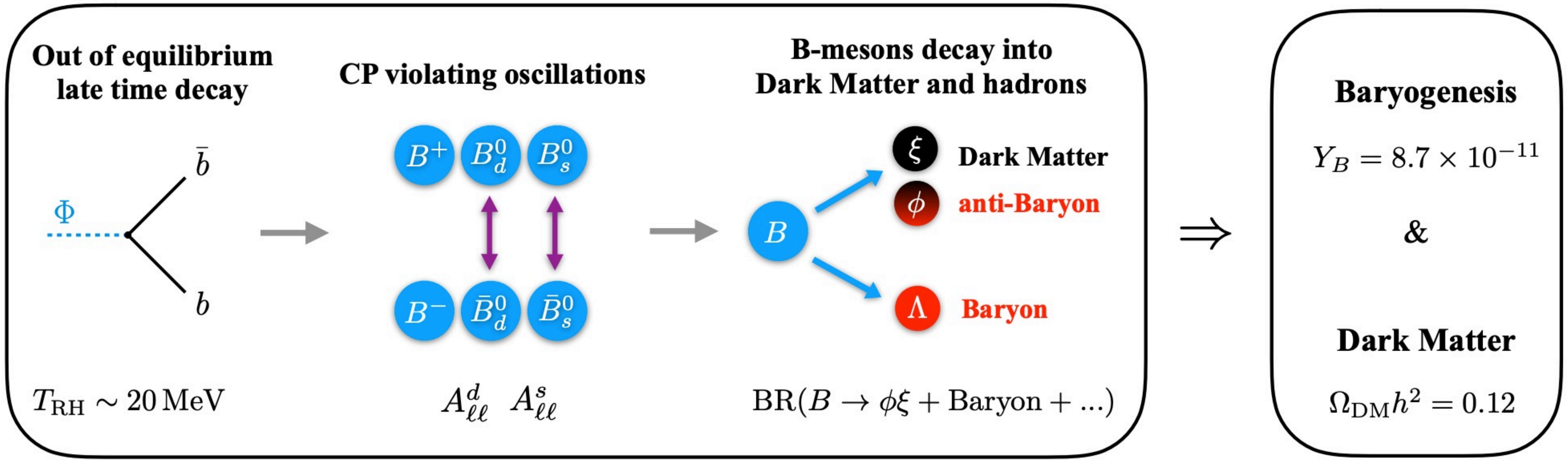
Other proposals (non-LHCb papers)

DM related

Baryogenesis & DM from B Mesons

G. Elor et al, Phys. Rev. D 99, 035031 (2019)

- Novel mechanism to explain DM and baryogenesis at once
  - DM has baryonic number! Can be realized in different ways



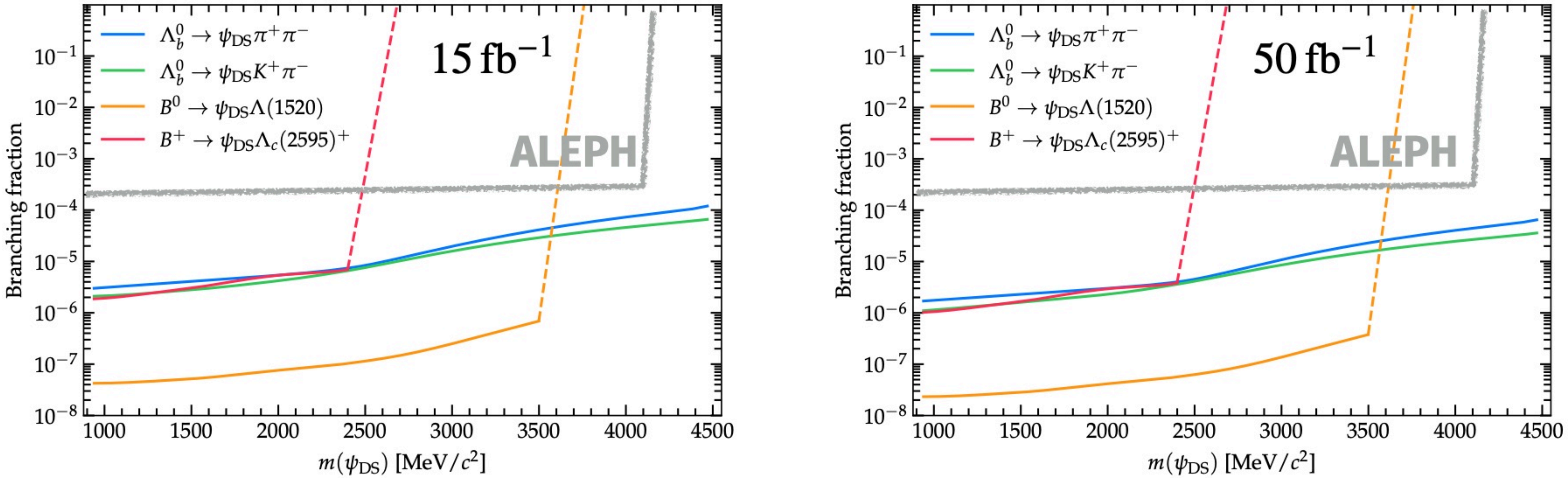
  - Long lived Φ meets two of Sakharov conditions
  - This can be achieved **even with the CPV of the SM**
  - Key aspect: DM charged under baryon number. Total baryon of the Universe is conserved, relaxed baryon number violation only in visible sector. **Proton becomes stable**!

Baryogenesis & DM from B Mesons

A. Brea et al, arXiv:2106.12870

- Prospects at LHCb recently assessed
  - Search for exclusive B or Λ_b decays, with MET in the final state
  - Develop selection and estimate background with fast simulation
  - Potential to exclude most of interesting phase space: overlap with Belle/BaBar

LHCb Upgrade (Phase I)



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Conclusions

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Conclusions

- LHCb can be the ***new*** detector to directly discover BSM physics (à la SHIP or MATHUSLA)
  - It has the **big** advantage that it is already built!
- Plethora of searches performed in this area.
  - For instance, results in μμ searches: dark photon and model independent. Show LHCb potential for dark sector/Stealth physics
- Plenty of very **well motivated** ideas already there: would probably need an order of magnitude more people to do all the searches proposed!
- New detector ready from Run 3, trigger-less readout, more luminosity taken: **stay tuned**!

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Conclusions

- LHCb can be the ***new*** detector to directly discover BSM physics (à la SHIP or MAT
  - It has the
- Plethora of
  - For instanc independer sics
- Plenty of ve probably need an ord rches proposed!
- New detecto e luminosity t

arxiv:2105.12668

Unleashing the full power of LHCb to probe Stealth New Physics

Editors: M. Borsato[1], X. Cid Vidal[2], Y. Tsai[3,4], C. Vázquez Sierra[5], J. Zurita[6]

Authors: G. Alonso-Álvarez[7], A. Boyarsky[8], A. Brea Rodríguez[2], D. Buarque Franzosi[10,11], G. Cacciapaglia[12,13], A. Casais Vidal[2], M. Du[14], G. Elor[15], M. Escudero[16], G. Ferretti[10], T. Flacke [17], P. Foldenauer[18], J. Hajer[19,20], L. Henry[5], P. Ilten[21], J. Kamenik[22,23], B. Kishor Jashal[6], S. Knapen[5], F. L. Redi[24], M. Low[25], Z. Liu[14,26,27], A. Oyanguren Campos[6], E. Polycarpo[28], M. Ramos[29,30], M. Ramos Pernas[31], E. Salvioni[5], M. S. Rangel[28], R. Schäfer[9], L. Sestini[32], Y. Soreq [33], V. Q. Tran[14], I. Timiryasov[24], M. van Veghel[34], S. Westhoff[9], M. Williams[35], J. Zupan[21]

[hep-ph] 26 May 2021

Backup

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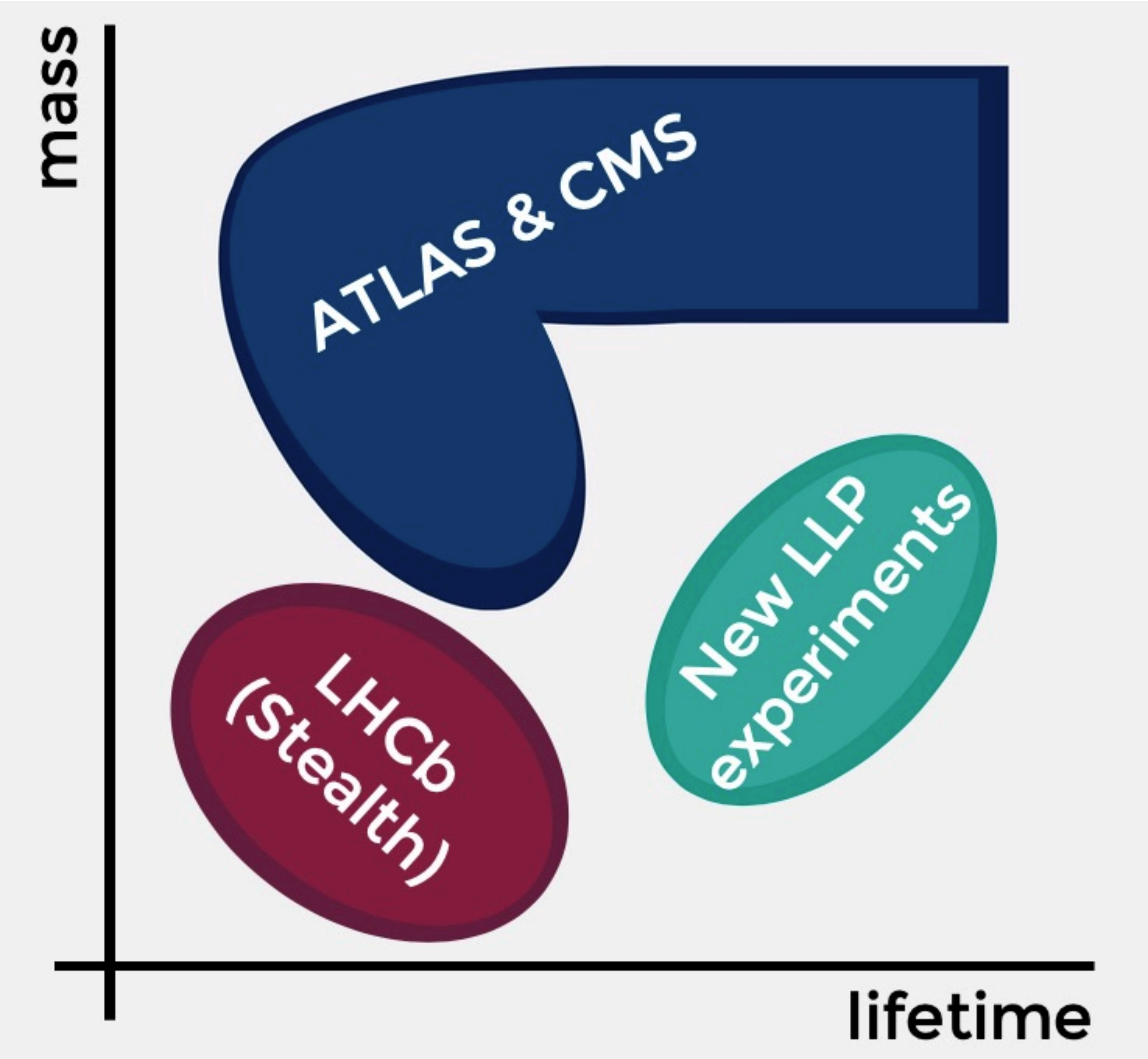
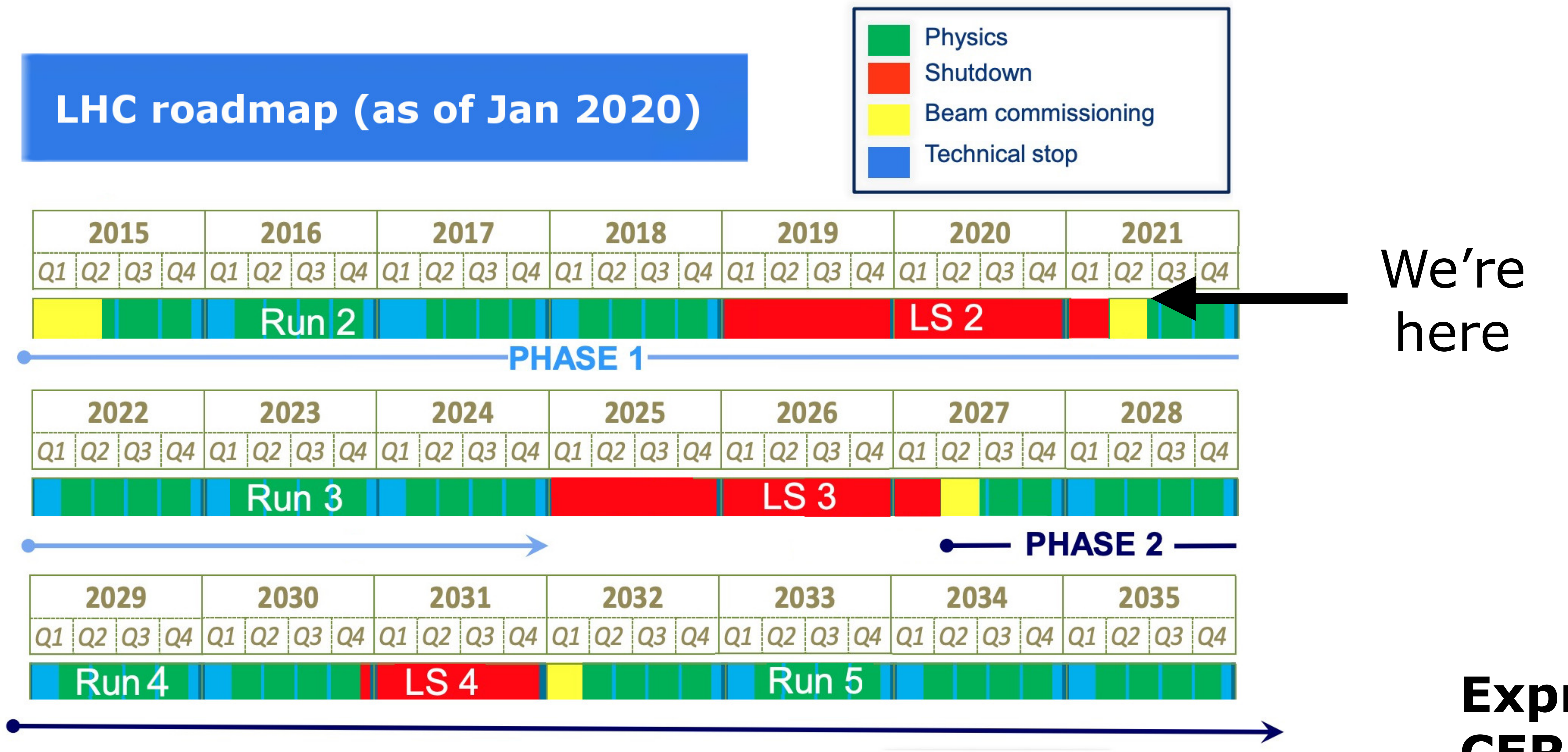
The parameter space

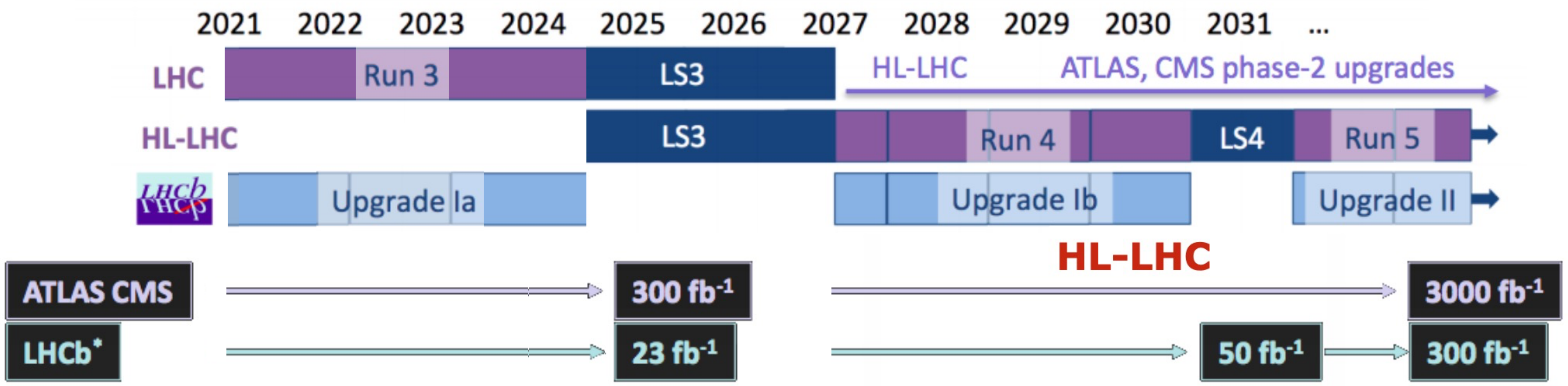


LHCb upgrade(s) (I)

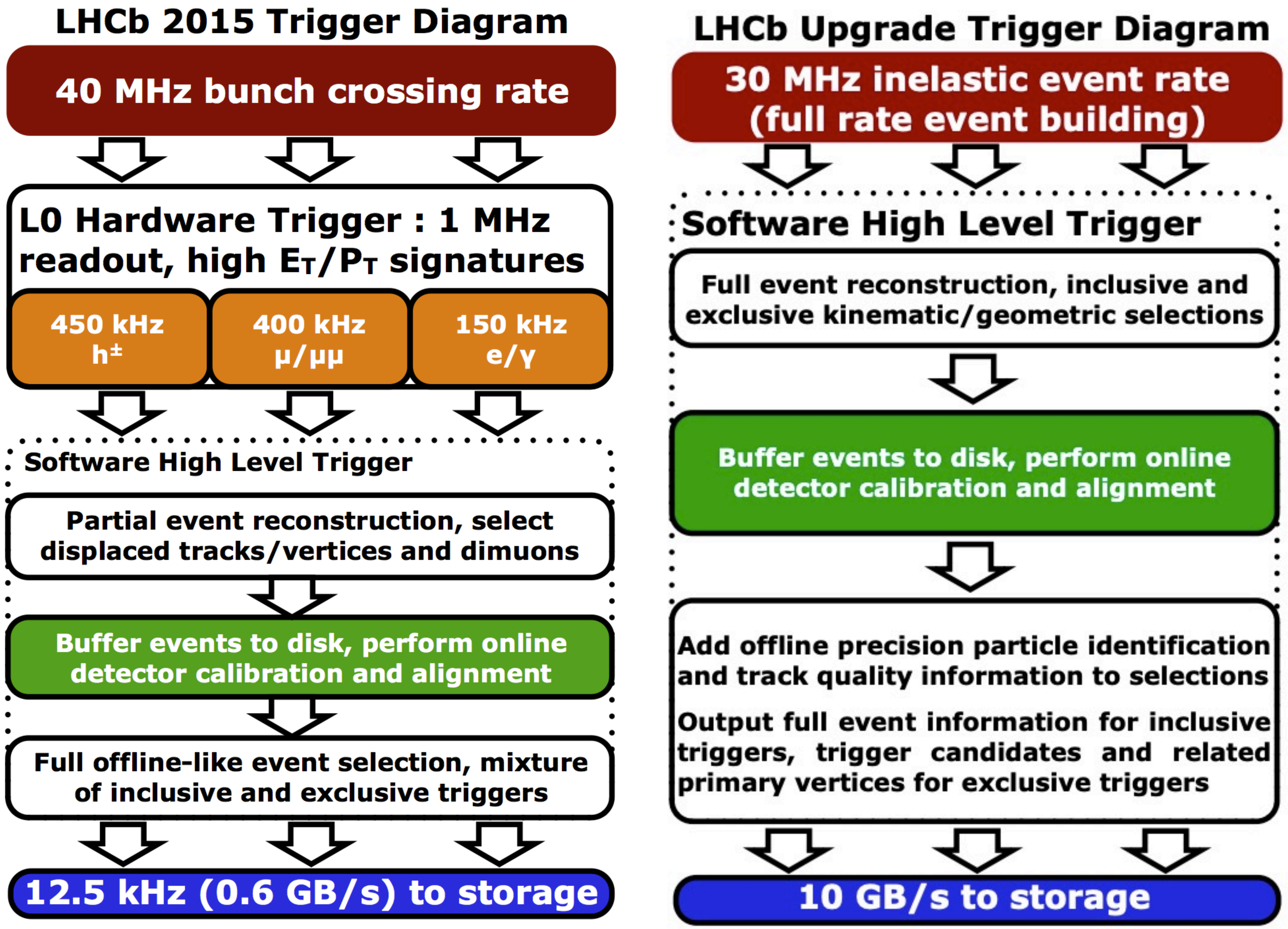


- We have ~9 fb^{-1} of data on tape
- Run guaranteed till 2030, currently upgrading the detector
- Submitted LoI for LHCb Upgrade II, to run beyond 2030
- Schedule being modulo COVID crisis!

Expression of Interest for a Phase-II LHCb Upgrade, CERN-LHCC-2017-003



LHCb upgrade(s) (II)



- At upgrade, almost **trigger-less readout**
  - Just software triggers, full event reconstruction at 30 MHz
  - Very convenient to trigger in non-standard signatures!
  - We shall be able to reconstruct even lowest momentum particles, e.g., very efficient on low mass muons for dark photon reconstruction
  - HLT1 level will be pure GPU-based! (Allen project)

arxiv:1912.09161

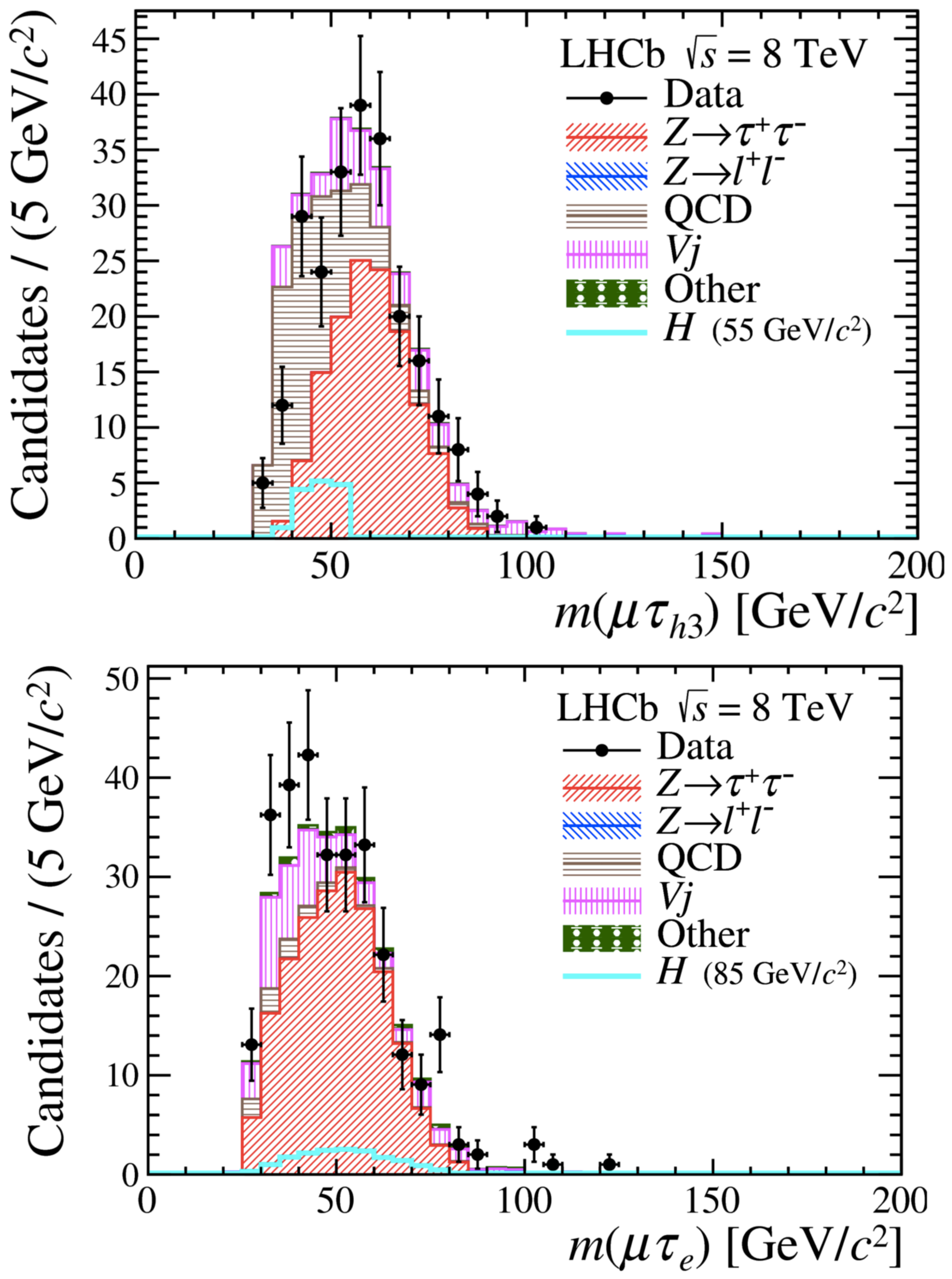
Search for LFV decays of Higgs-like bosons (I)

Eur. Phys. J. C78 (2018) 1008

- Search performed with Run 1 LHCb dataset, motivated by previously existing excess in $H \to \mu\tau$
  - Extended to large mass range (45-195 GeV/c^2)
- τ reconstructed in both leptonic and hadronic decay channels: 4 channels considered

  $\mu\tau_\mu$, $\mu\tau_e$, $\mu\tau_{h3}$, $\mu\tau_{h1}$
  - Different selections depending on the mass of the H searched for (e.g. different p_T cuts). Isolation applied on leptons
- Main backgrounds are $Z \to ll$, QCD and V+jet. First estimated from theory, second from same-sign data

(only **2** out of **12** plots shown!)



Search for LFV decays of Higgs-like bosons (II)

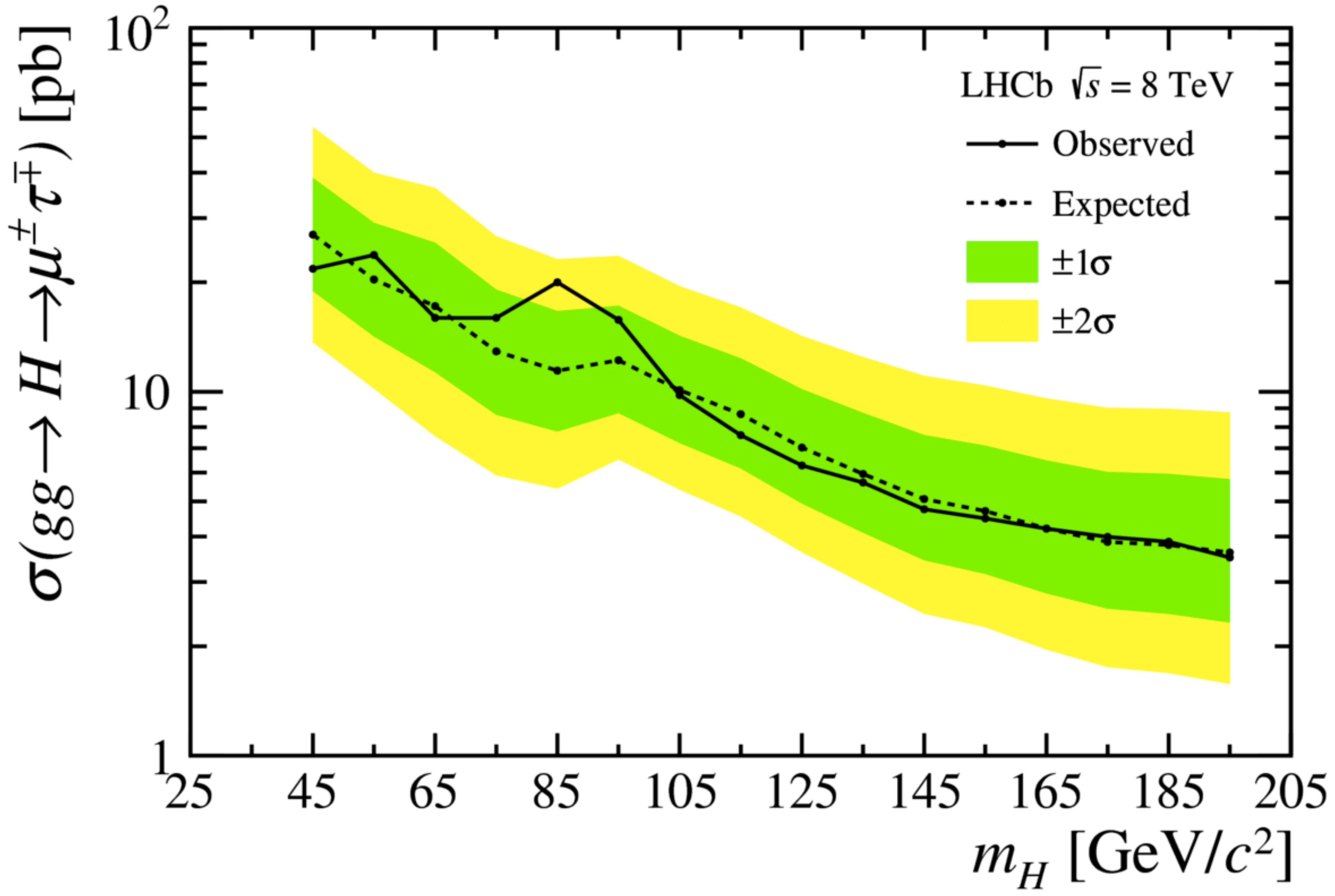
Eur. Phys. J. C78 (2018) 1008

✦ Results

- Fit data to obtain N_{sig} and determine efficiencies from simulation, corrected with data
- Main systematics, efficiency determination and PDFs
- No signal found, so upper limits set with the CL_S method. For each mass, use selection providing better expected upper limit
- Combine different channels into single measurement
- For the SM Higgs,

BR(H→τμ) < 26%

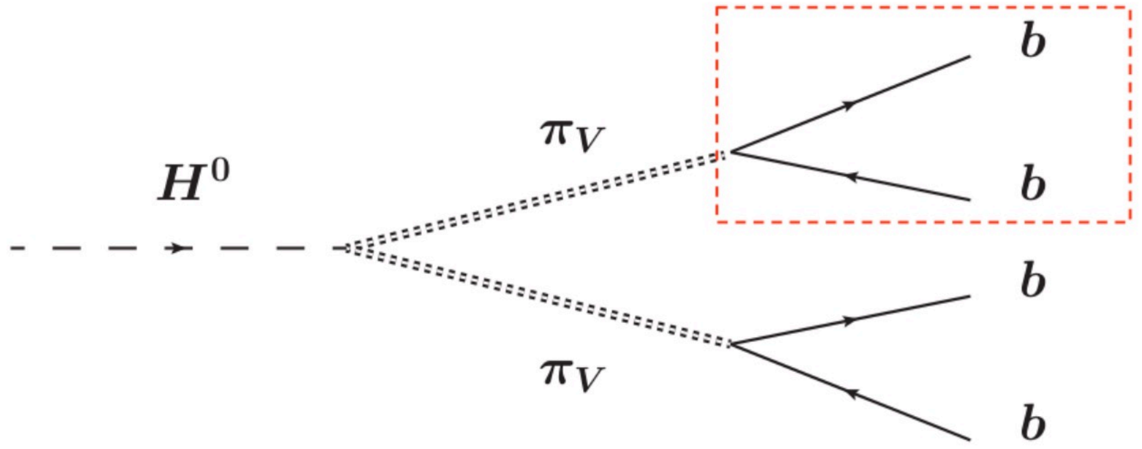
0.25% and 1.85% for CMS and ATLAS



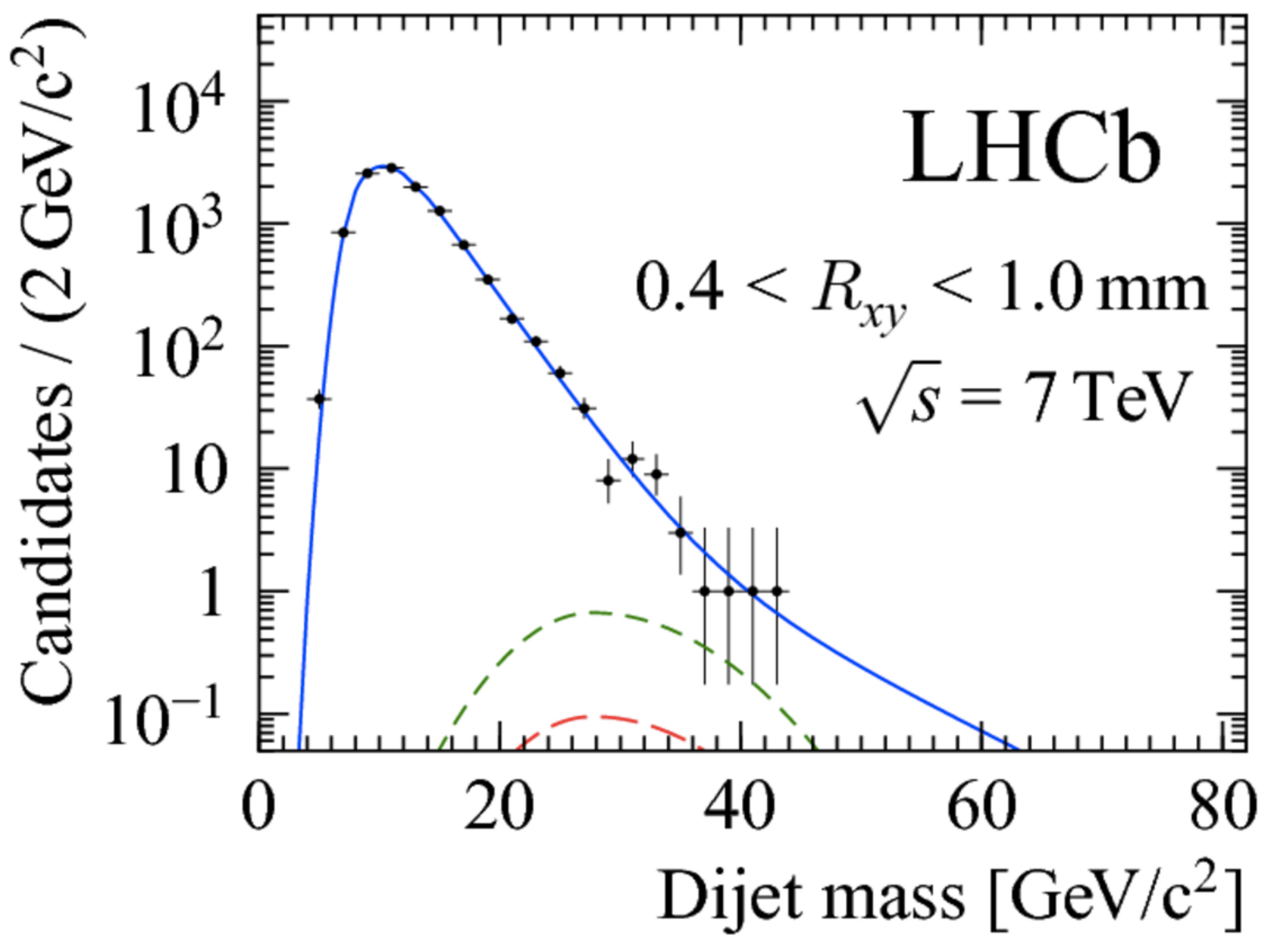
- Worse than ATLAS/CMS for high masses, but first search in low masses! Could be extended to even lower masses

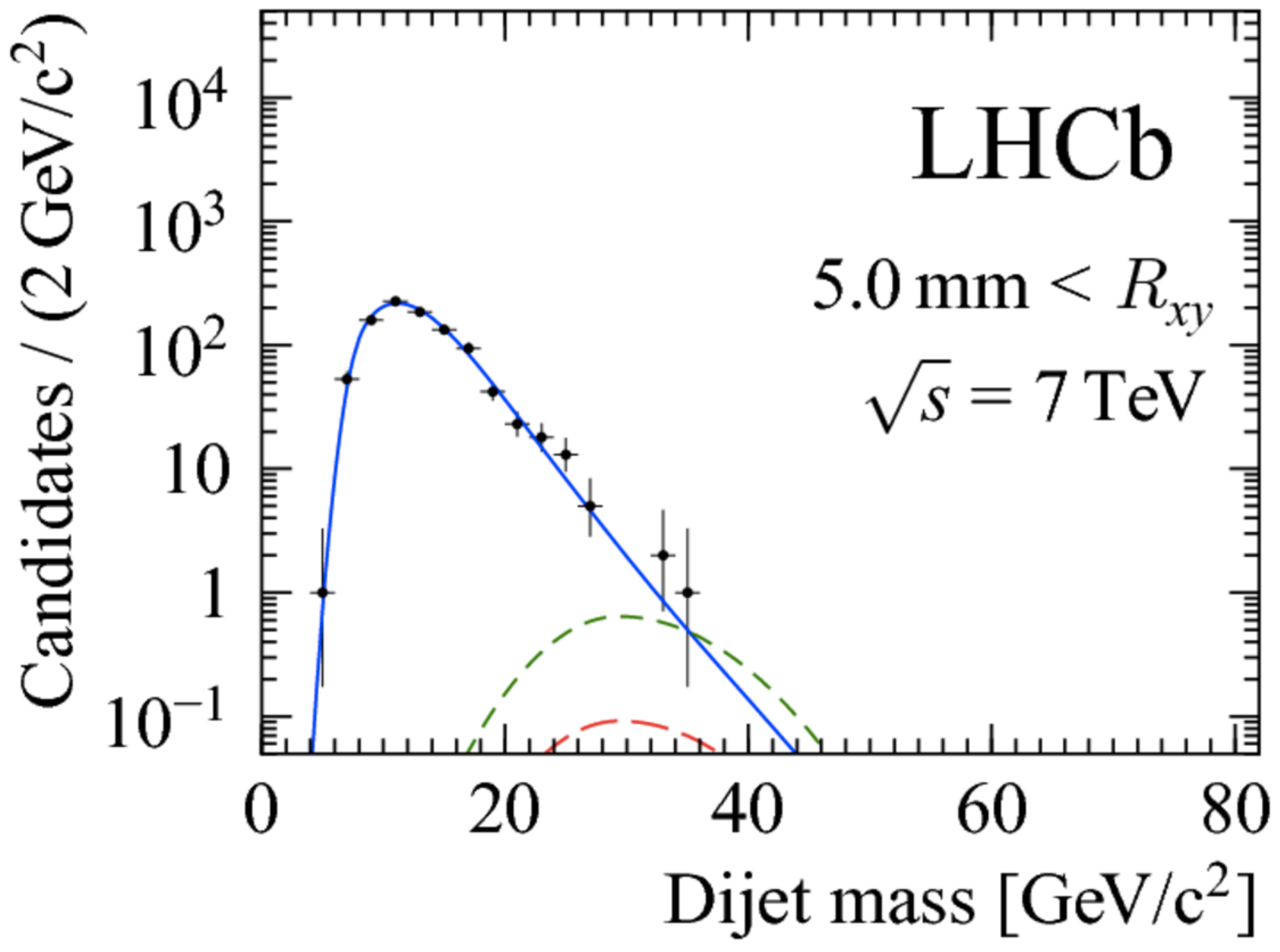
H→LLP→jet jet (I)

- **Signature**: single displaced vertex with two (b) jets
- Model: Hidden valley V-pions from SM Higgs decay
- Use Run 1 dataset, trigger on displaced vertex.
- **Selection**:
  - Find two associated jets, quality requirement on jets, di-jet pointing
  - Material veto + selection optimised as a function of R_{xy}
- Main remaining background: **QCD**
- Signal from di-jet mass fit in 6 bins of Rxy



Eur. Phys. J. C77 (2017) 812



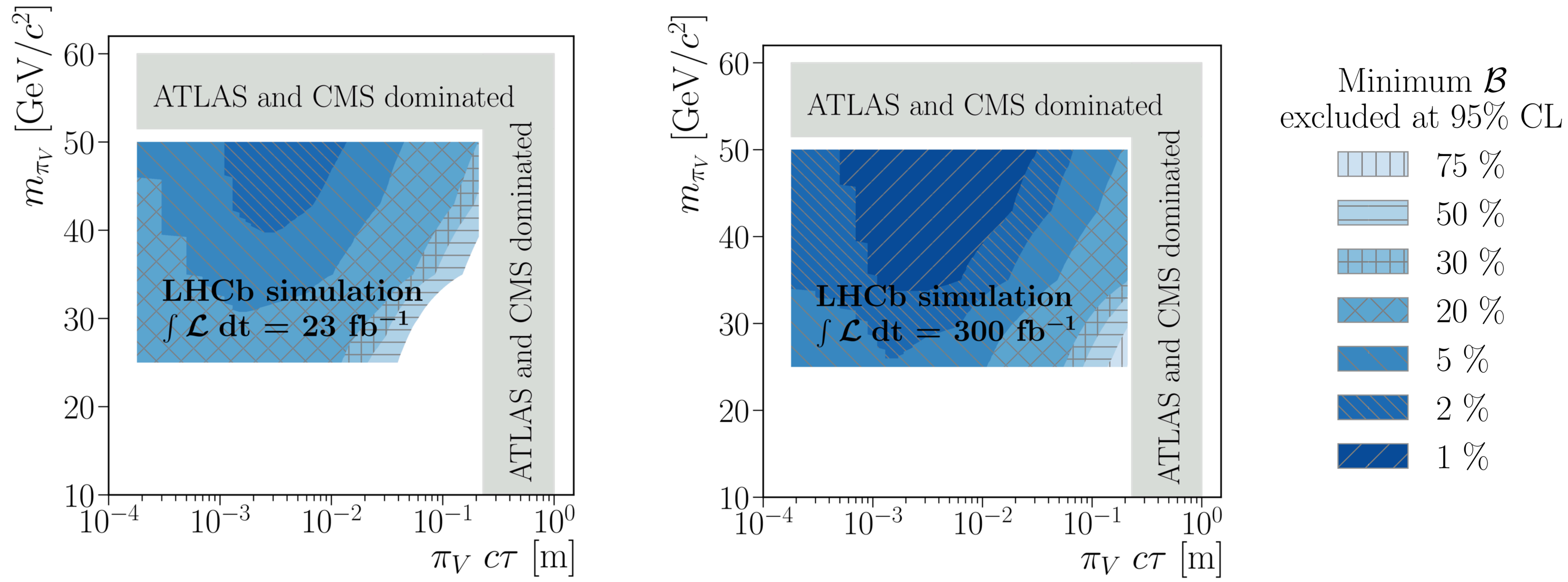


H→LLP→jet jet (II)

LHCB-CONF-2018-006

- Run I search presented above
  - Scale to the upgrade(s) luminosities, conservative assumptions
  - Reconstruction of displaced vertices and their associated tracks is crucial, also keep under control the dominant background contributions and pile-up effects.
  - Material interactions kept under control by the use of a very detailed veto map. Removal of VELO RF foil would further enhance the sensitivity!

H →LLP projected exclusions



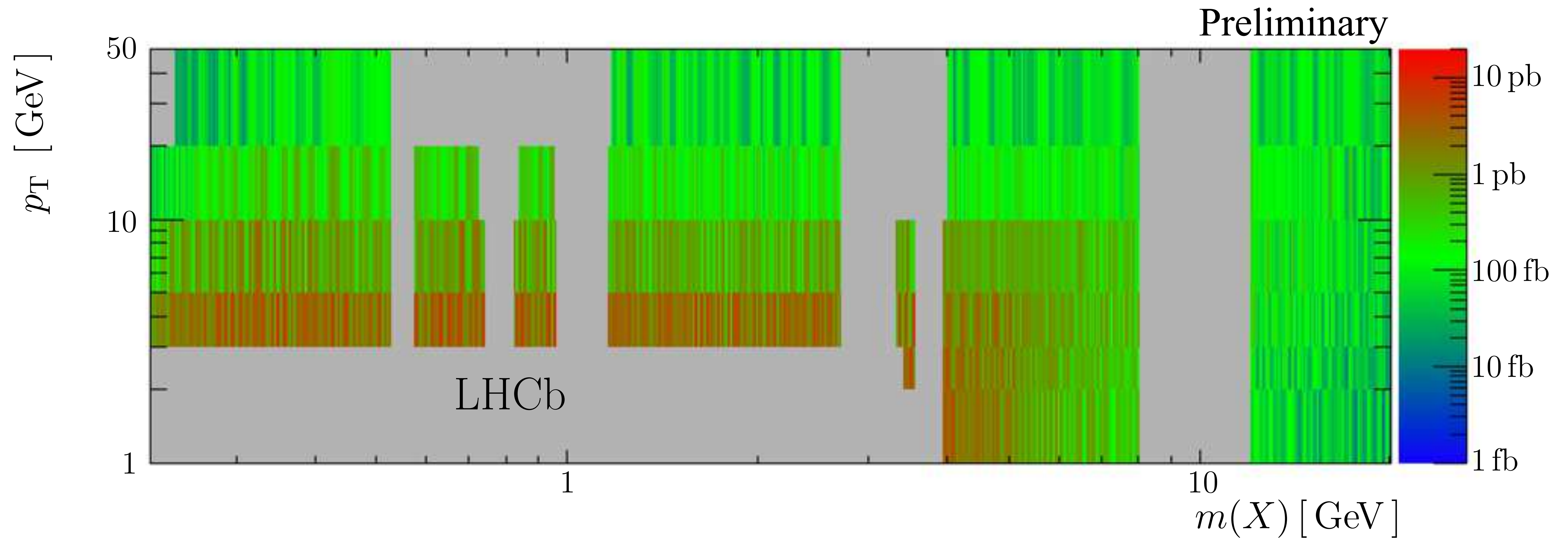
- Hopefully we'll cover the low mass region too: Jet substructure! Nothing more quantitative for the moment

Prompt non-minimal

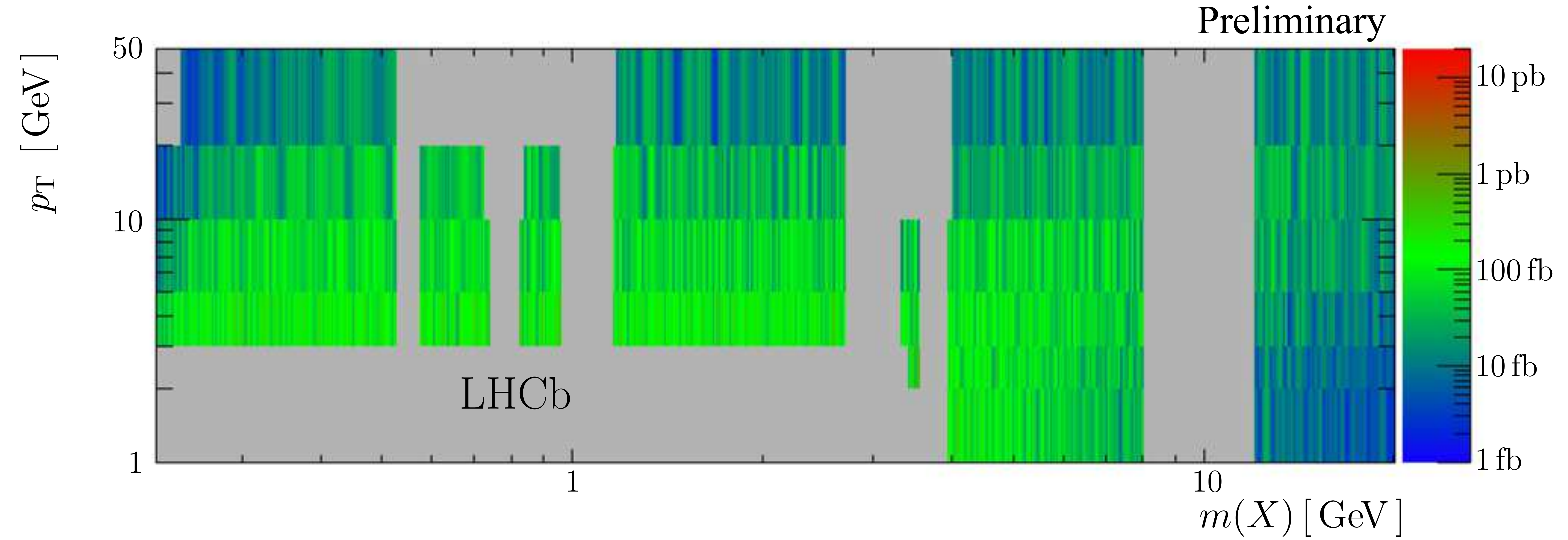
JHEP 10 (2020) 156

- Low mass upper limits at 90% CL on σ(X → μμ)

Inclusive



Beauty associated

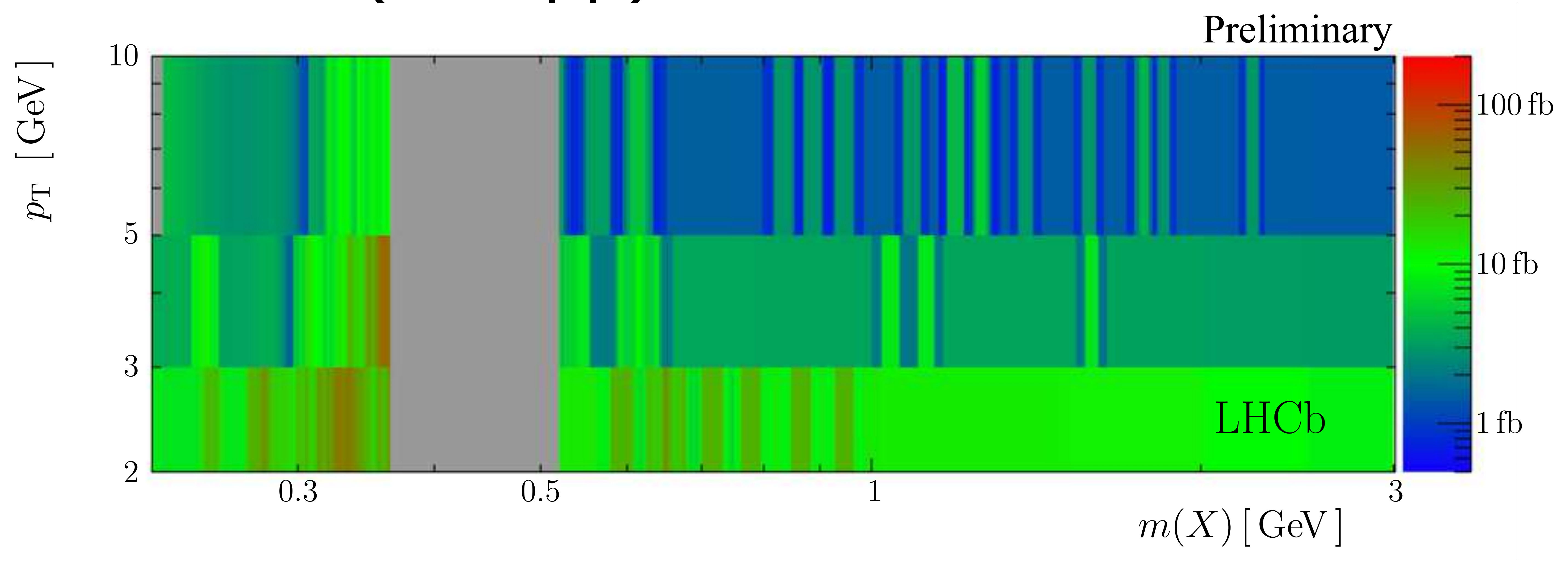


Displaced non-minimal

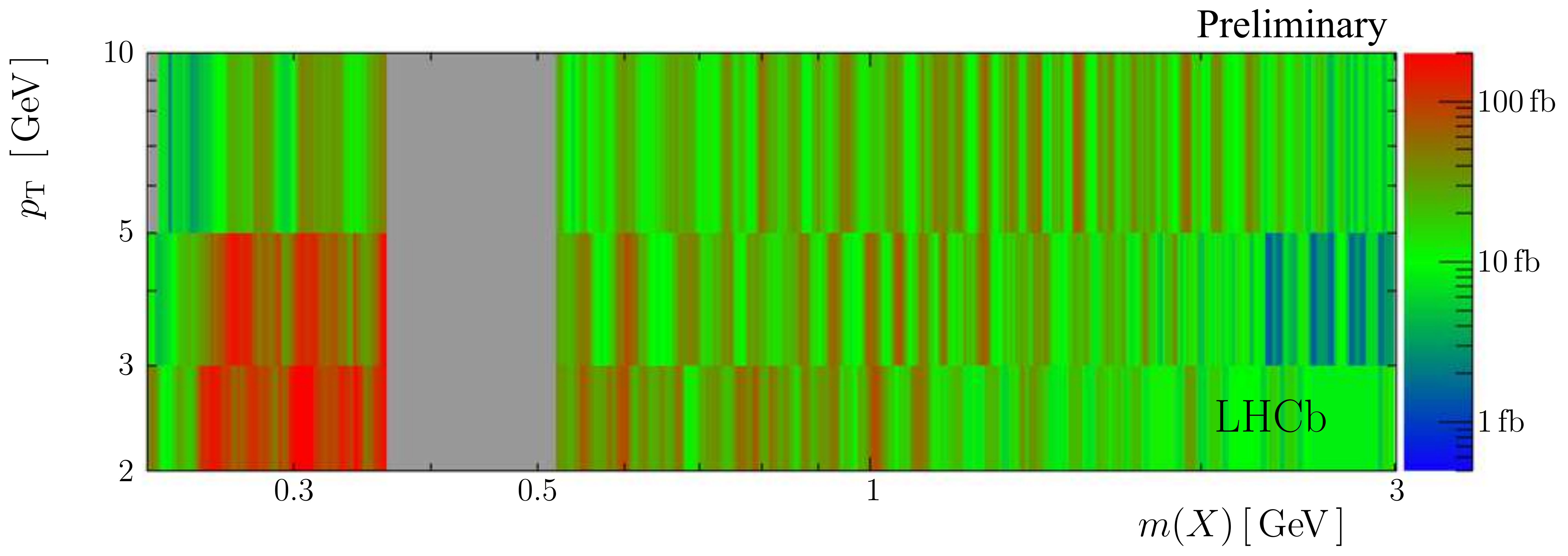
JHEP 10 (2020) 156

- Upper limits at 90% CL on $\sigma(X \rightarrow \mu\mu)$

Inclusive



Beauty associated

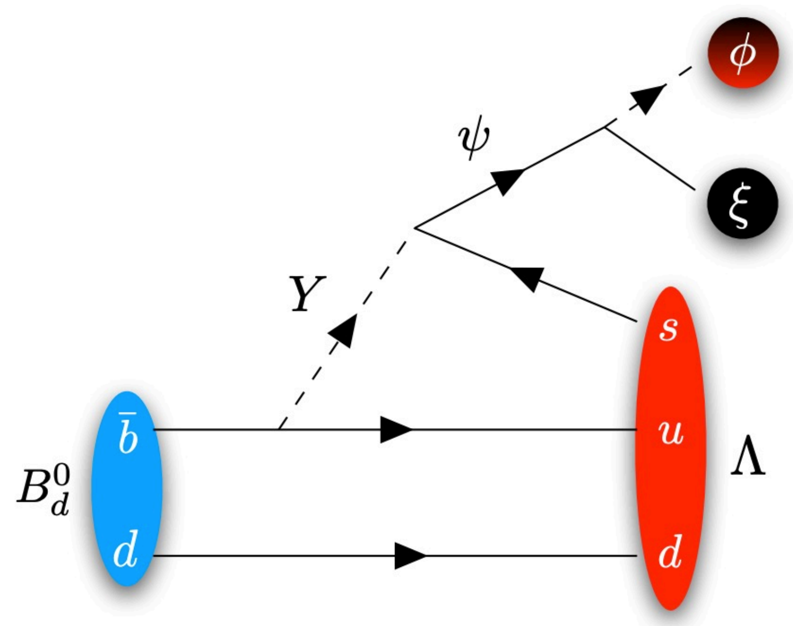


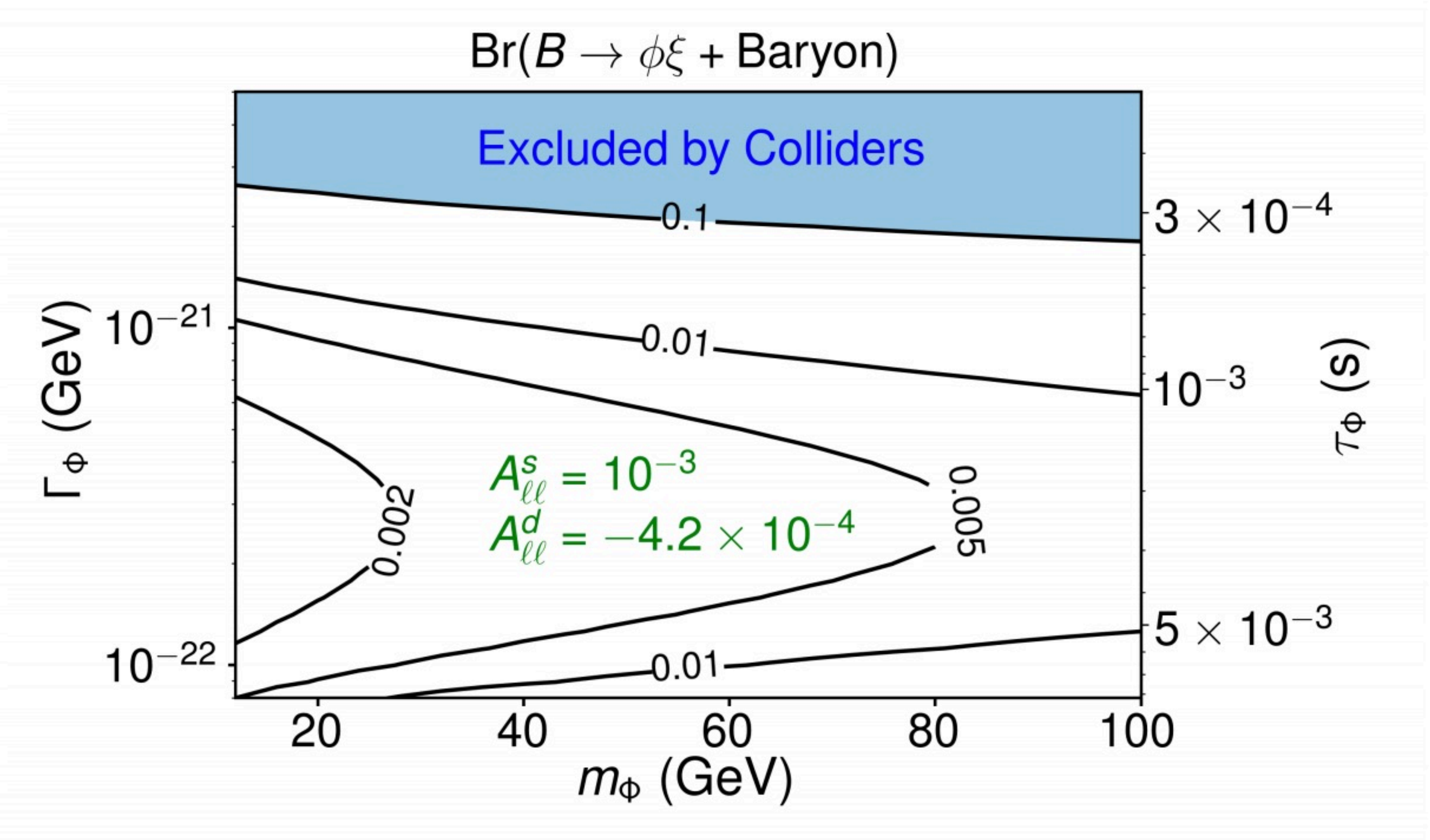
Baryogenesis & DM from B Mesons

- Summary of decay modes:

G. Elor et al, Phys. Rev. D 99, 035031 (2019)

  - ψ produced on-shell: ϕ (note small cap) and ξ DM candidates





Operator	Initial State	Final state	ΔM (MeV)
$\psi\, b\, u\, s$	B_d	$\psi + \Lambda\,(usd)$	4163.95
	B_s	$\psi + \Xi^0\,(uss)$	4025.03
	B^+	$\psi + \Sigma^+\,(uus)$	4089.95
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\psi\, b\, u\, d$	B_d	$\psi + n\,(udd)$	4340.07
	B_s	$\psi + \Lambda\,(uds)$	4251.21
	B^+	$\psi + p\,(duu)$	4341.05
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\psi\, b\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$	2807.76
	B_s	$\psi + \Omega_c\,(css)$	2671.69
	B^+	$\psi + \Xi_c^+\,(csu)$	2810.36
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2
$\psi\, b\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$	2853.60
	B_s	$\psi + \Xi_c^0\,(cds)$	2895.02
	B^+	$\psi + \Lambda_c\,(dcu)$	2992.86
	Λ_b	$\bar{\psi} + \bar{D}^0$	3754.7

  - BRs can be **very** large

Baryogenesis & DM from B Mesons

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G. Elor et al, Phys. Rev. D 99, 035031 (2019)

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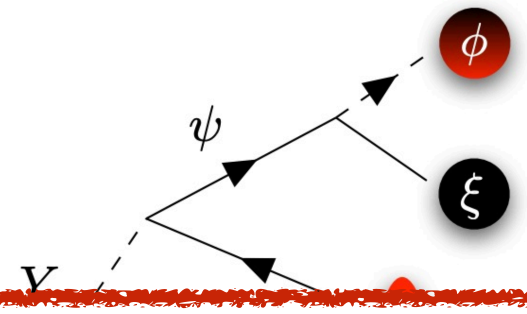
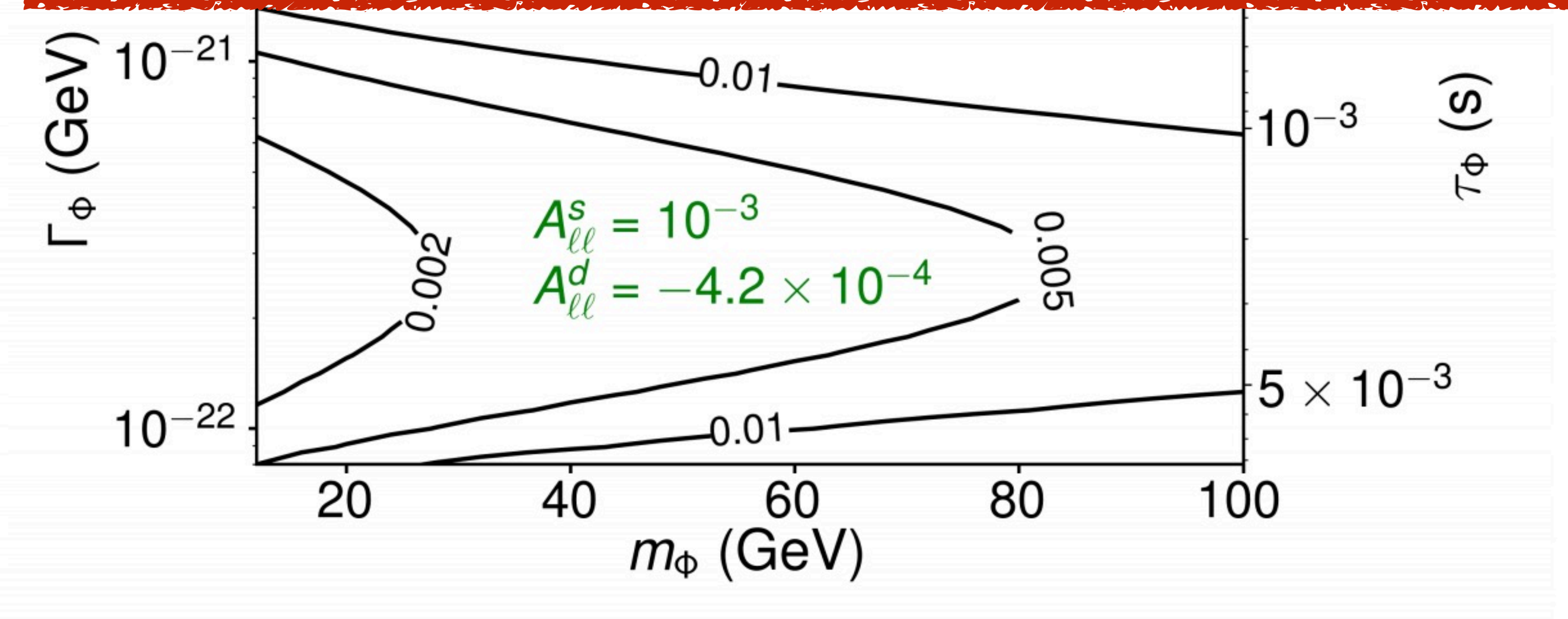


Probe this model also by measuring ϕ_s or A^d_{SL} and A^s_{SL} (semi-leptonic asymmetries), although this model can work even if these correspond to the SM values



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Baryogenesis & DM from B Mesons

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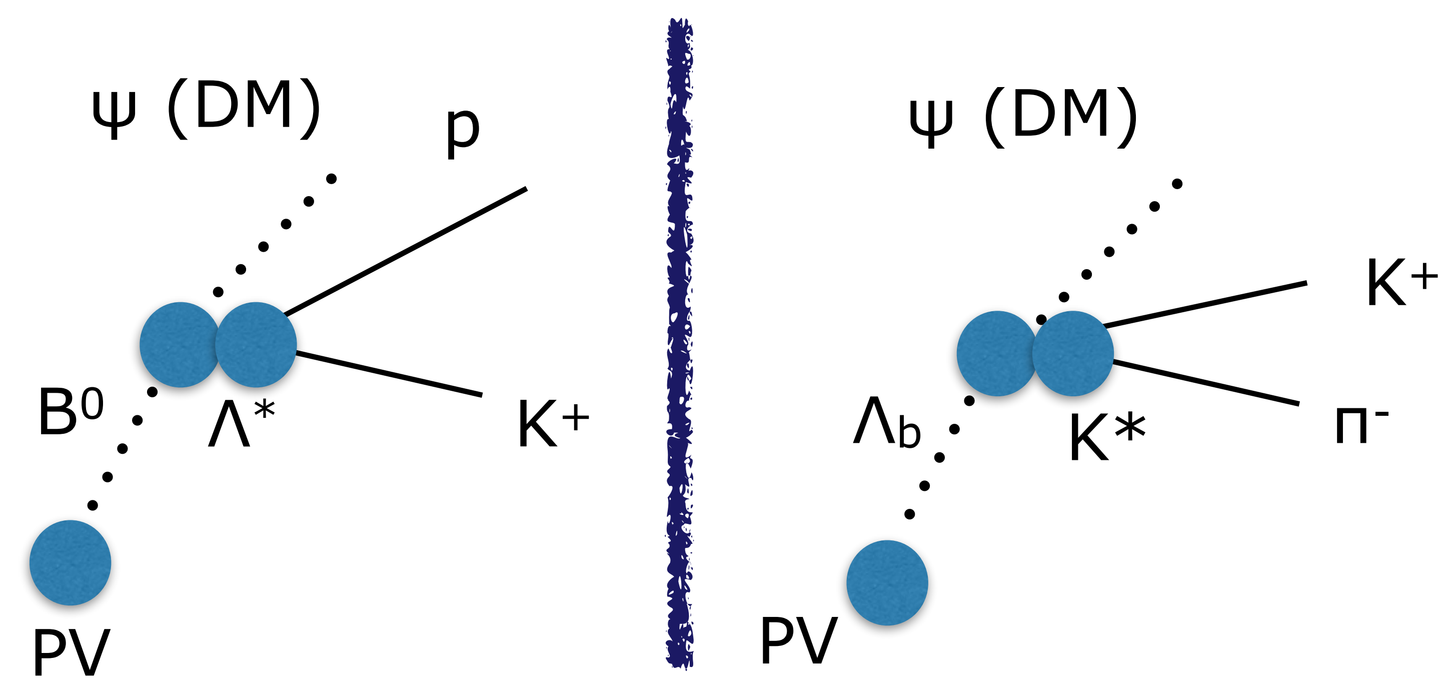
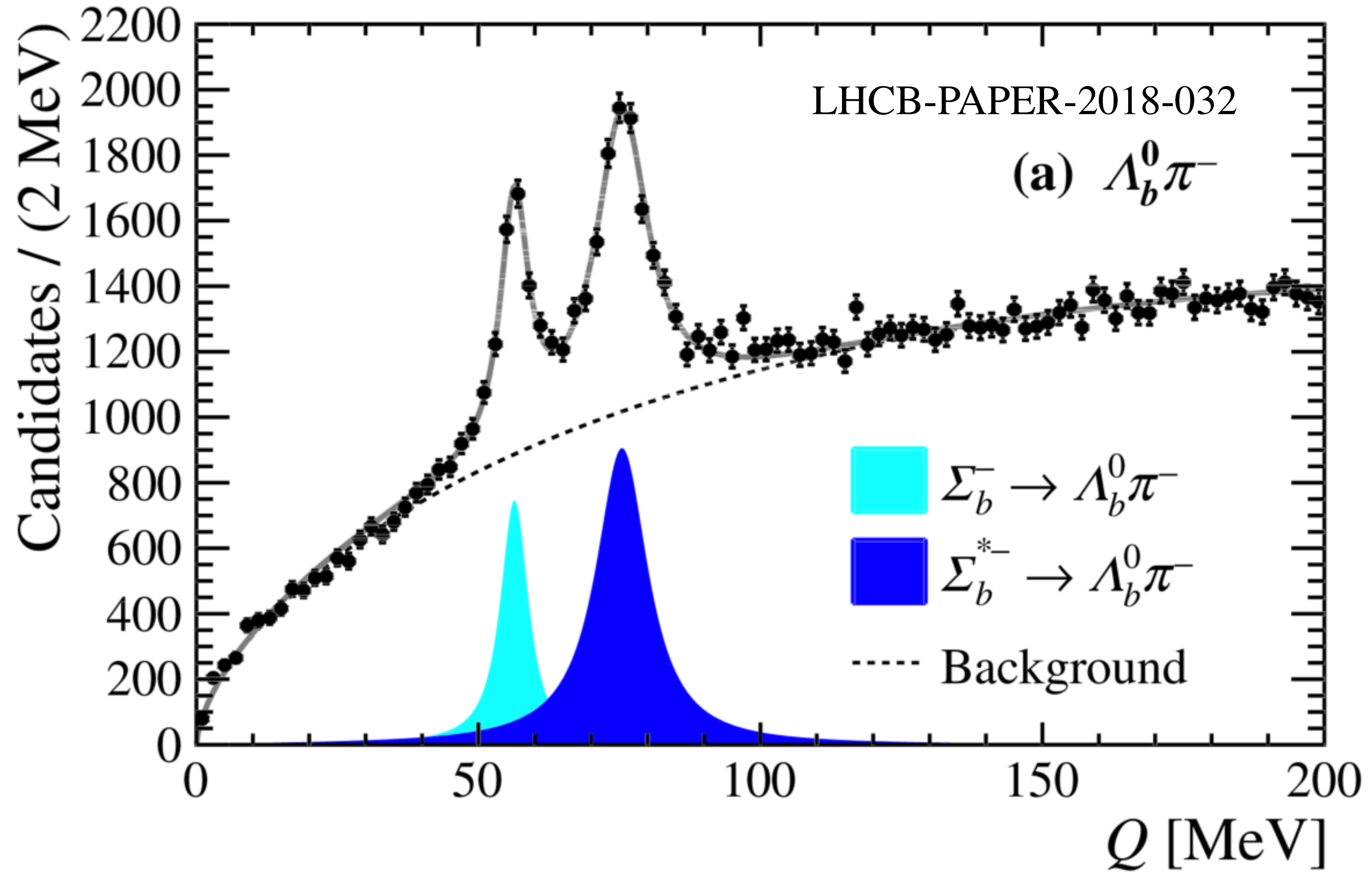
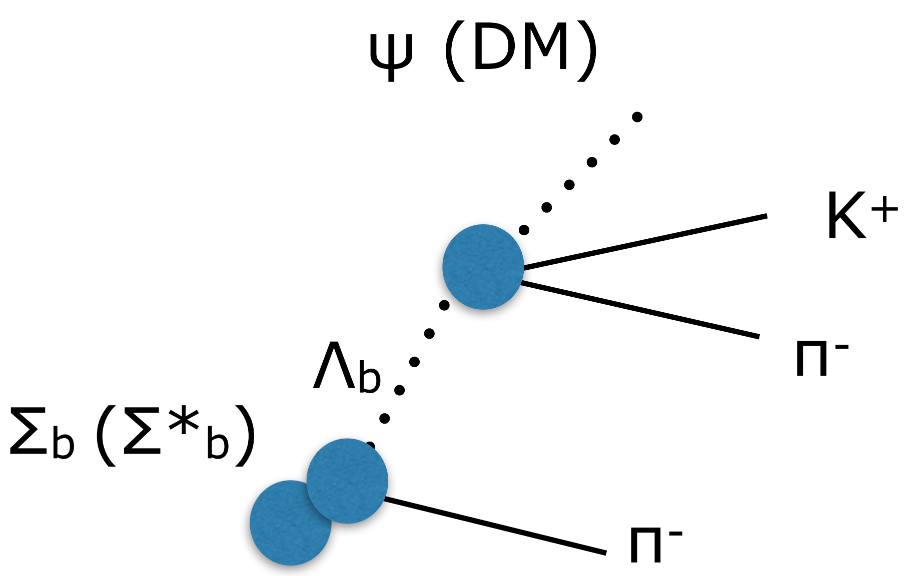
- Most promising modes at LHCb?
  - Possible to study B decays, but competence from B factories there!
  - Also possible to reconstruct Λ_b decay vertex. Additional kinematic constraint from Σ_b decay!
  - The whole decay chain has already **been observed** at LHCb
  - Yet another alternative; B^*_{s2} decays

G. Elor et al, Phys. Rev. D 99, 035031 (2019)

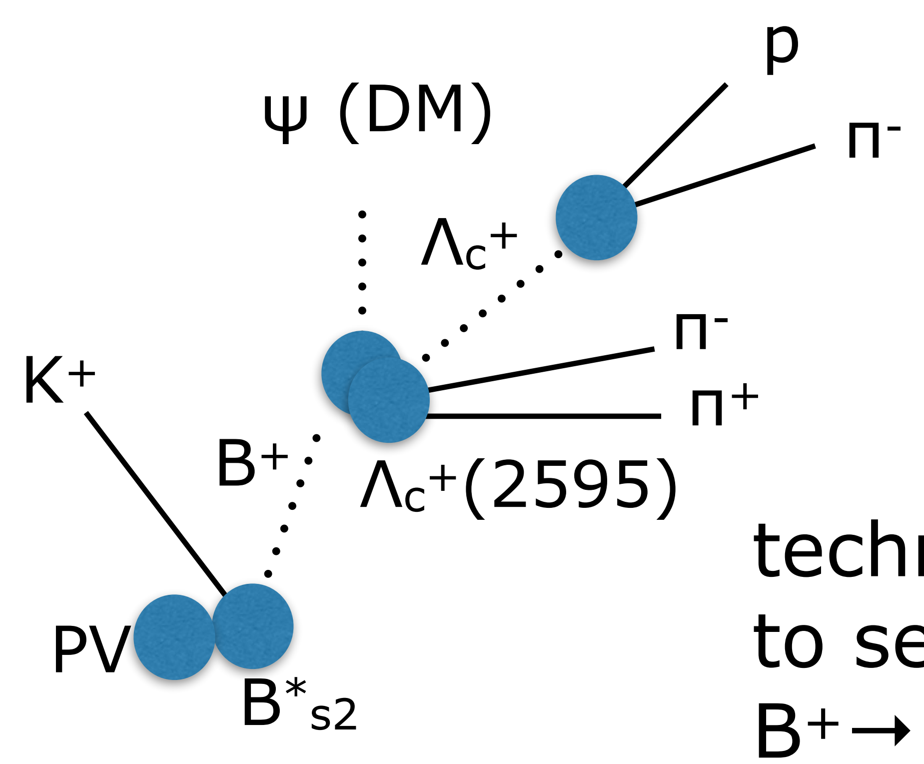




S. Stone and L. Zhang, Adv. High Energy Phys. 2014, 931257 (2014)



LHCb Collaboration, arxiv:2003.04352



technique used to search for $B^+ \to K^+\mu^-\tau^+$