First flavor day at IJCLab - 27 Oct 2021

Dark sector searches in B-physics experiments

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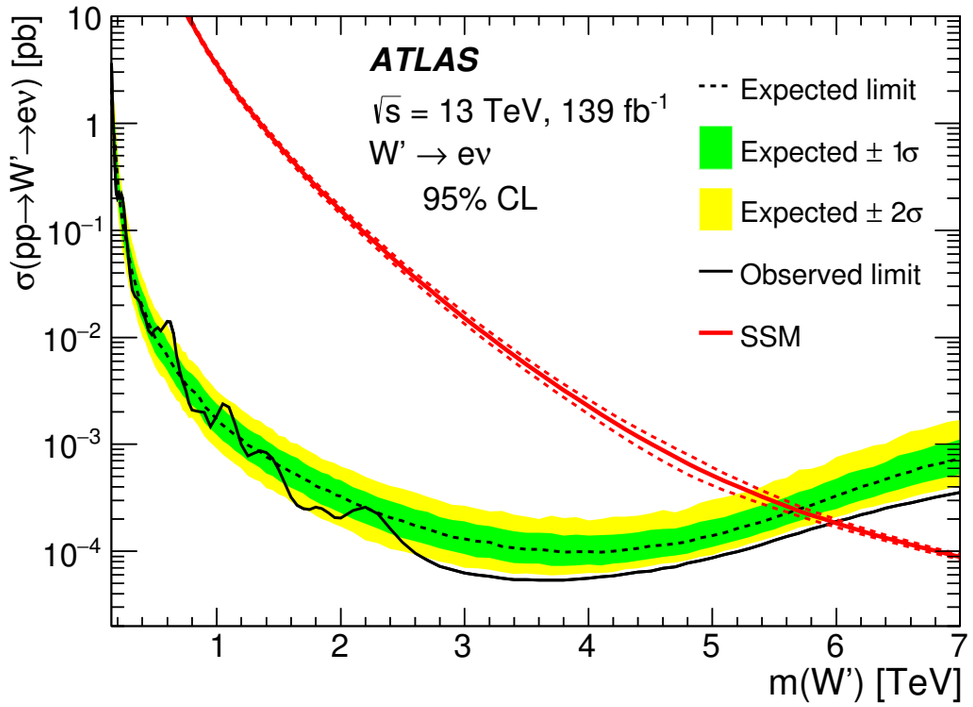
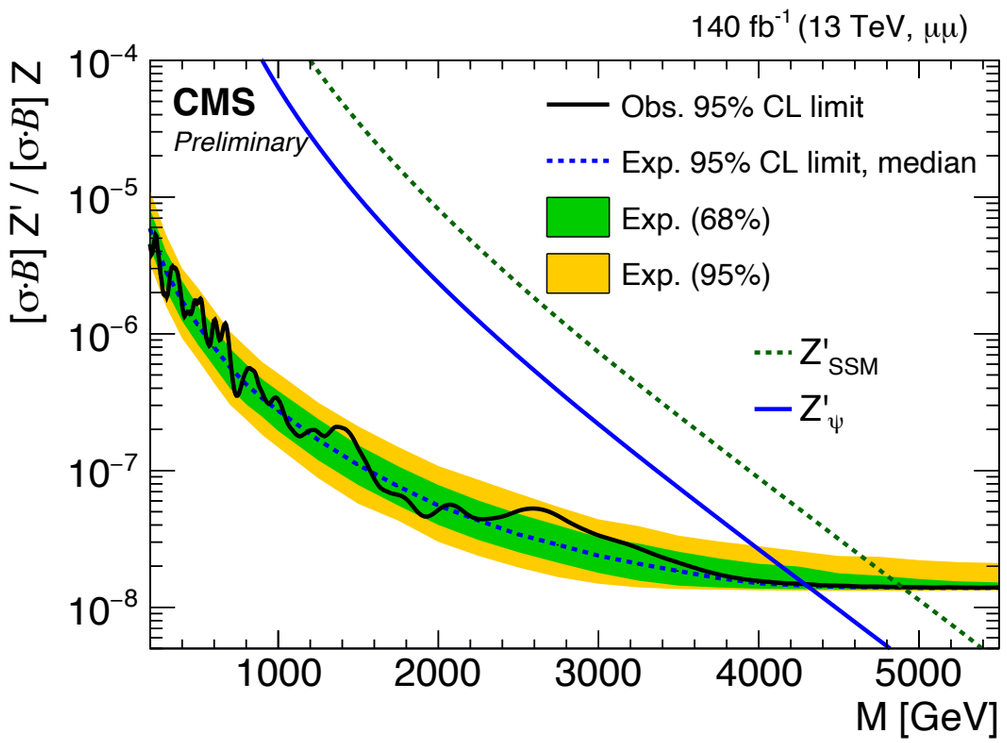
The energy frontier

- **Energy frontier exploration** has greatly advanced particle physics
  - Often guided by indirect signs in lower energy processes
- The LHC is our front runner
  - **Discovery of the Higgs**
  - First exploration of the multi-TeV range
  - So far no hint of new heavy objects
  - upper limits up to several TeV
- **What if the new particles have smaller couplings to the SM?**

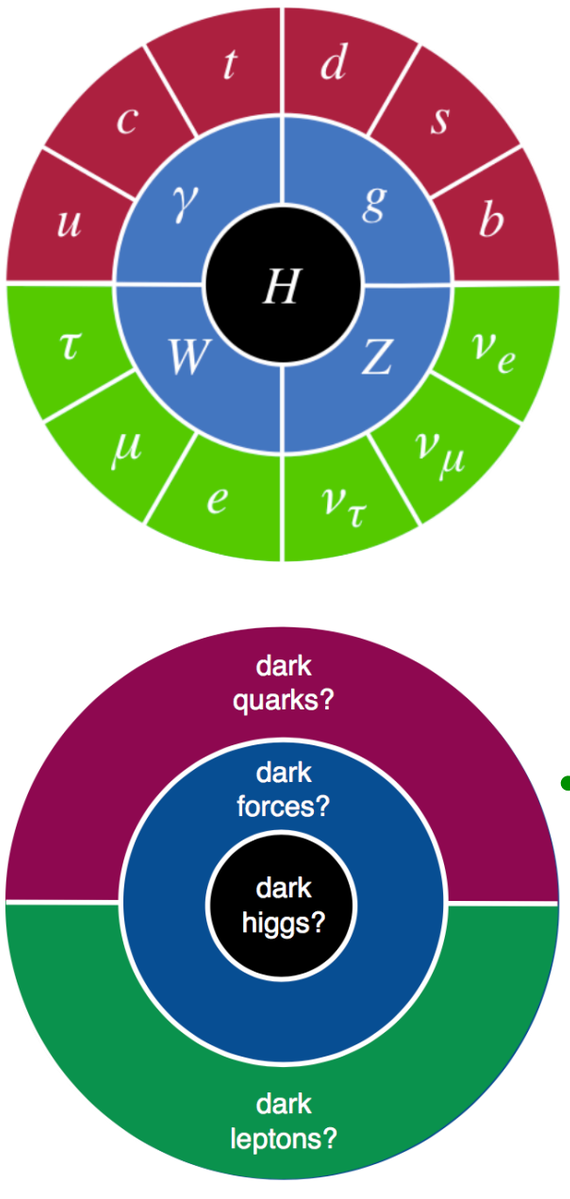




Dark sectors

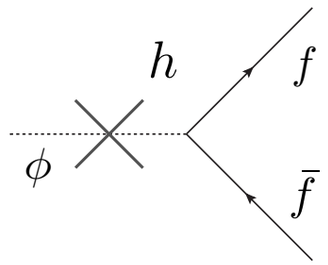
Dark Sectors

(neutral under SM forces)

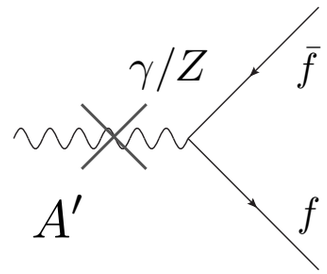


- Possible **portals** to the SM:

Scalar



Vector



Neutrino

…and more

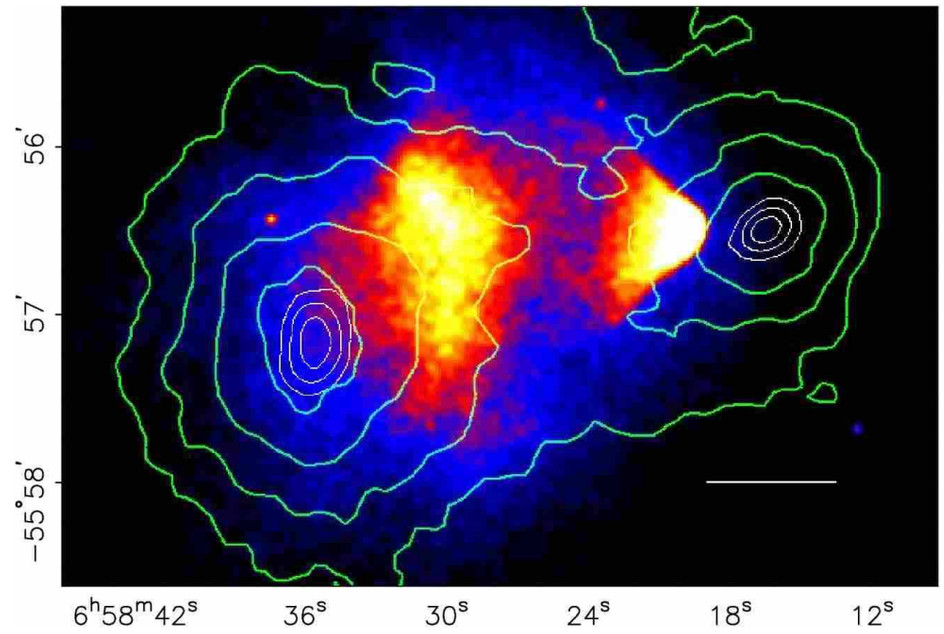
- Suppressed couplings to SM:
  - Low production rate
  - Decay with displaced vertex
- Can elude current limits
  - Even for very light masses
  - Especially if vertex is displaced

Nice review: arXiv:1608.08632

Example: Dark Photons

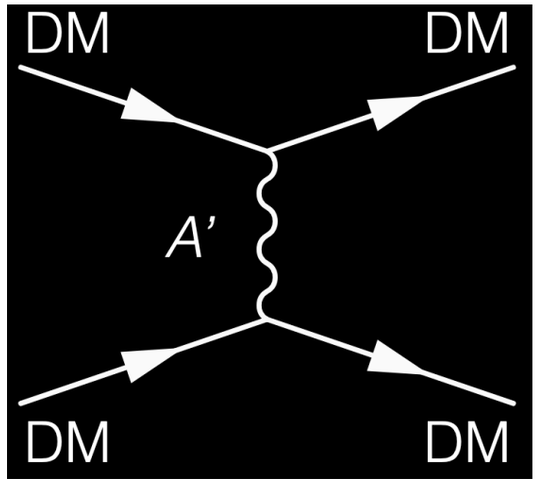
Explanation for Dark Matter:

- DM interacting through weak force (**WIMP**)
  - Weak scale mass and cross section give right DM relic ubundance (WIMP miracle)
- DM interacting through **different force**
  - Coupling only indirectly to SM
  - Keep it simple: add “dark" U(1) symmetry → dark photons mixing with SM photons



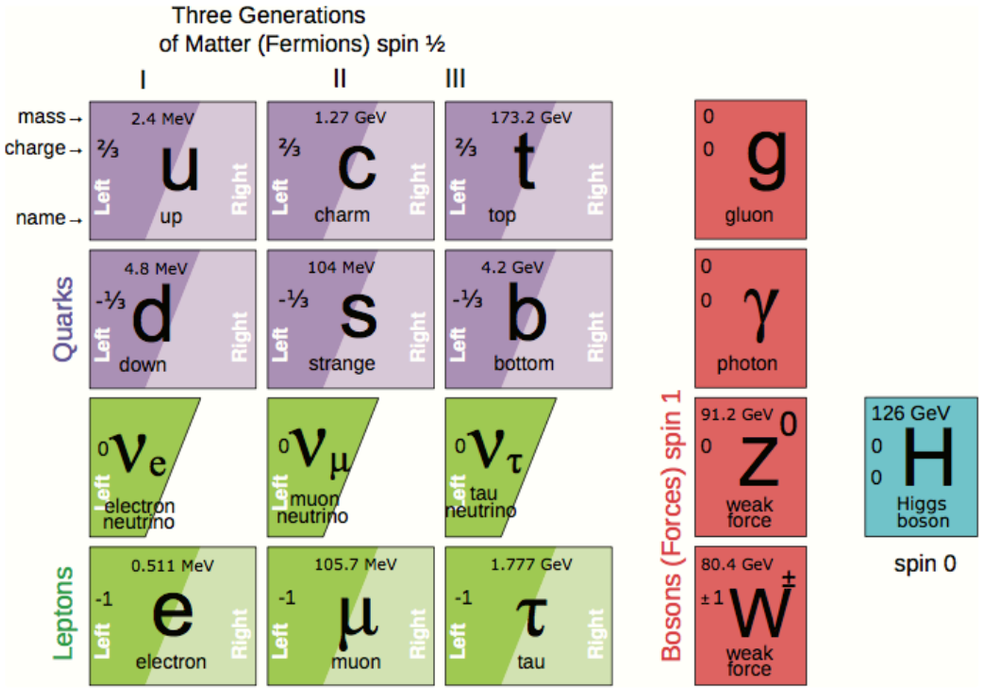
- Dark Photons interaction with SM and DM can give the right DM relic abundance:
  - e.g. if $m_{\rm DM} < m_{A'}$ you can get it if the mixing is:

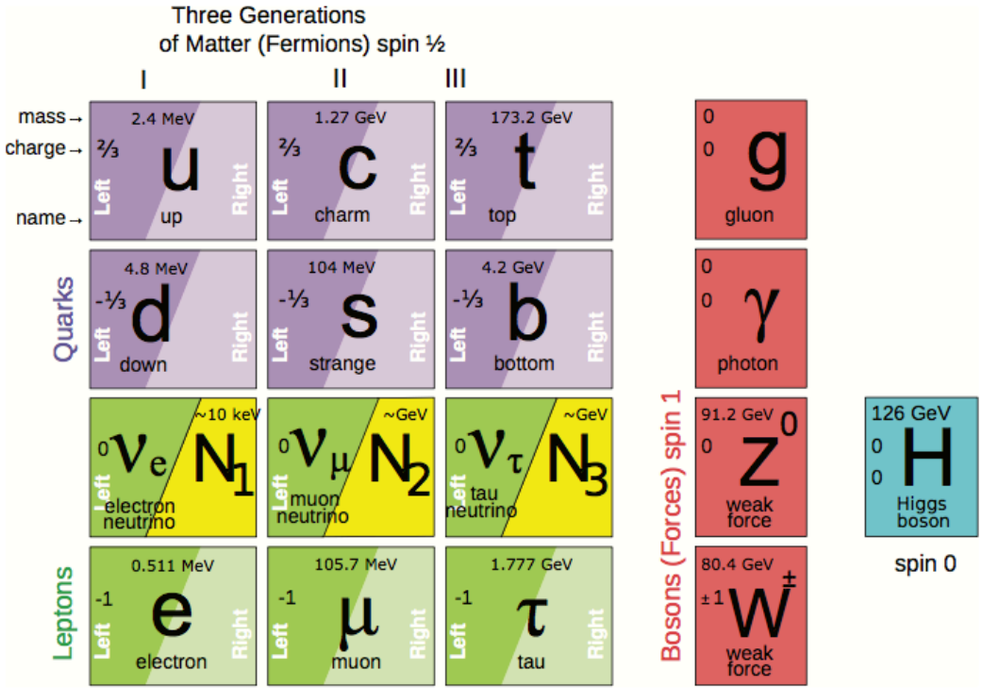
$$\epsilon \sim 10^{-7} \frac{m_{A'}^2}{m_{\rm DM}\,{\rm MeV}} \alpha_{\rm D}^{-1/2}$$



arXiv:1608.08632

Example: νMSM





- Driven by the need to explain neutrino masses
  - Minimal low scale see-saw with 3 singlet fermions
  - N_1 is the **dark matter candidate** (~keV range)
  - $N_{2,3}$ give **mass to neutrinos** (~GeV range)
    - Can also explain **baryon asymmetry** of the universe

T. Asaka, M. Shaposhnikov Phys.Lett. B620 (2005) 17-26
New νMSM paper this morning on arXiv:1806.06864!

Signature-first mindset

- No shortage of models → no precise guidance
  - Need to make sure we do not miss NP at our experiments!
- Shift to "*signature first model second*" mindset
  - Need to map signature space, including:
    → long-lived particles
    → masses below the EW scale
    → couplings much smaller than SM
  - Need shift in presentation of searches
    → model independent searches preferred
    → easy to reinterpret (long-lived results)

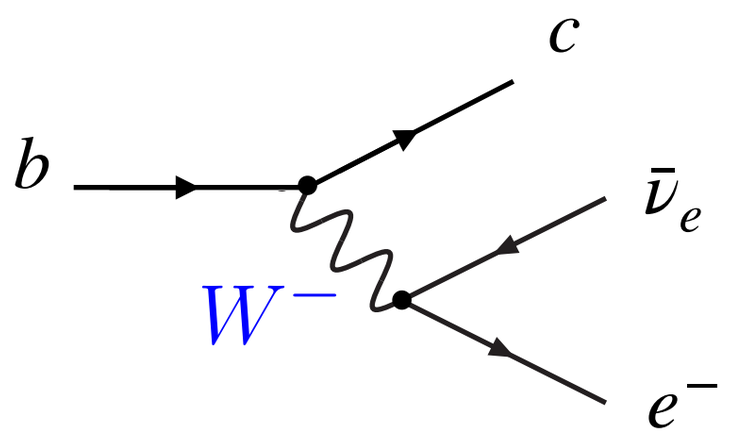
LHC(b) communities:

- LLP@LHC white paper
- LHC LLP WG
- LHC Dark Matter WG
- Stealth@LHCb workshop

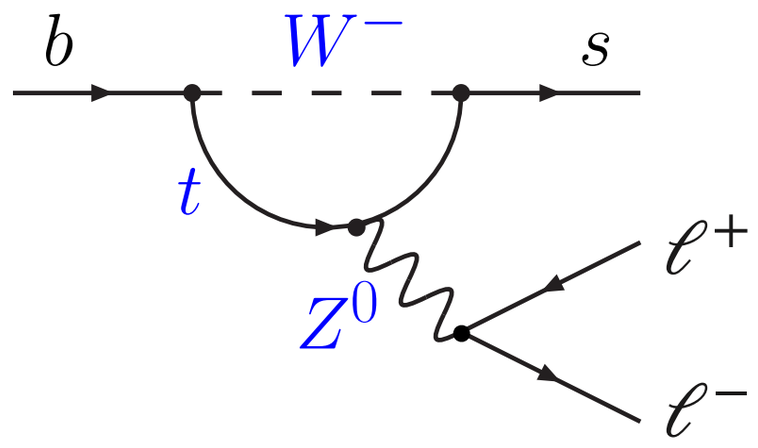
Dark sector searches in B decays

Dark sector searches in B decays

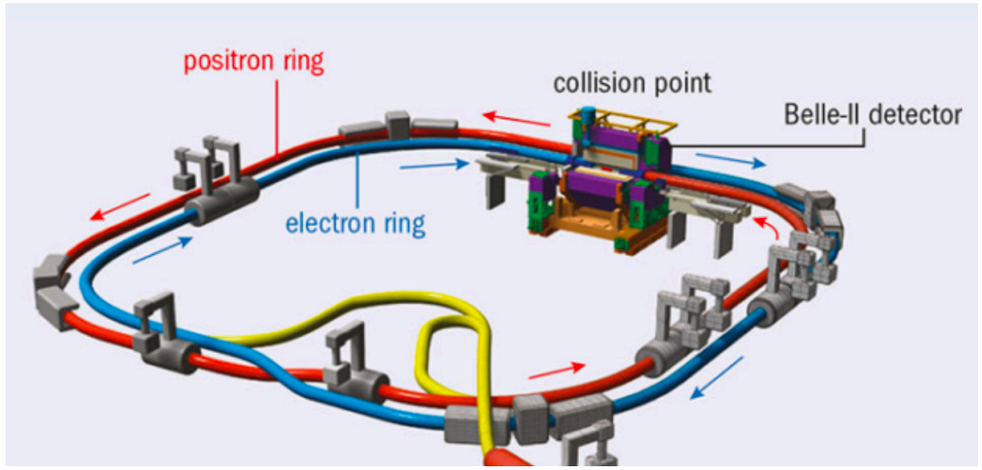
- Dedicated B-physics experiments
  - Precise probe of SM flavour structure, discrete symmetries, virtual NP contributions

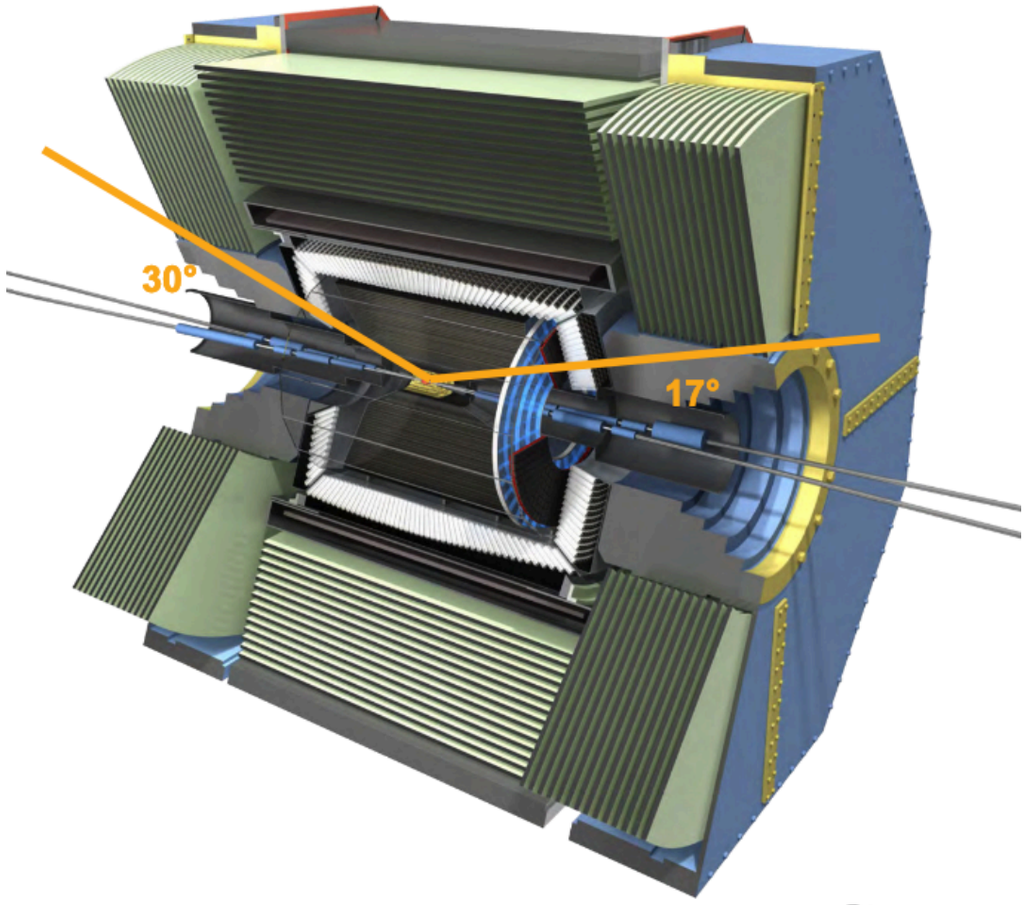


- B mesons decay weakly
  - Diagrams involving weak bosons $W^{\pm}$, Z^0 and top quark
  - Can radiate dark sector particles with $m < 5$ GeV (m_B)

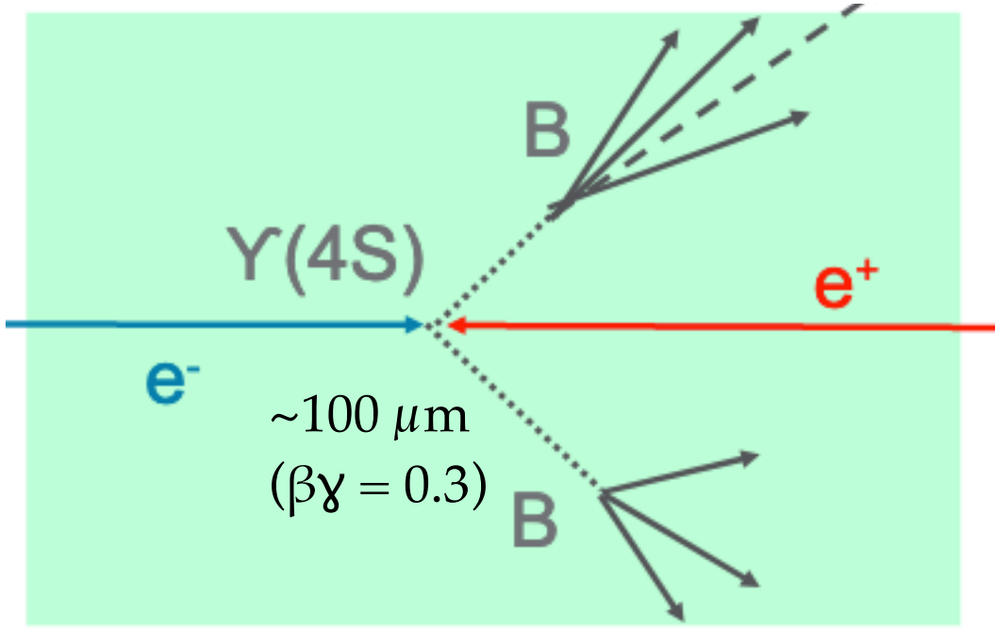


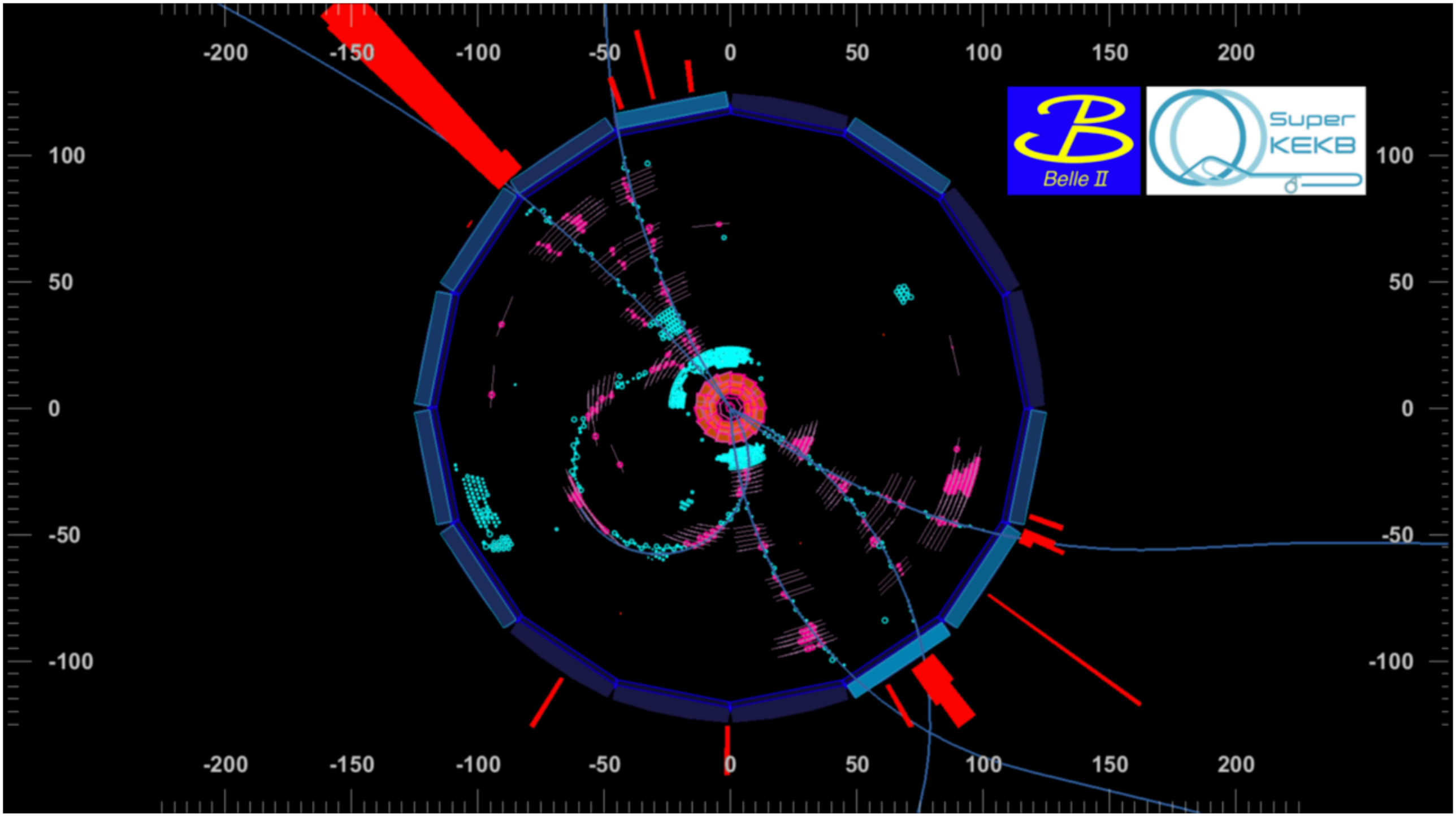
Belle II at SuperKEKB





- B-factories — SuperKEKB
  - Collider $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - Asymmetric beams (7 vs 4 GeV) to get boosted $B\bar{B}$
  - **Small cross section** — $\sigma(B\bar{B}) \sim 10^{-9}$ b
  - **Huge luminosity** — goal is 6×10^{35} cm^{-2}s^{-1}
- Belle II detector
  - Excellent hermeticity and precise ECAL
  - 1.5T magnet and drift chamber
  - Precise vertex detector
  - PID with Calo, ECAL, Cherenkov, KLM




-200
-150
-100
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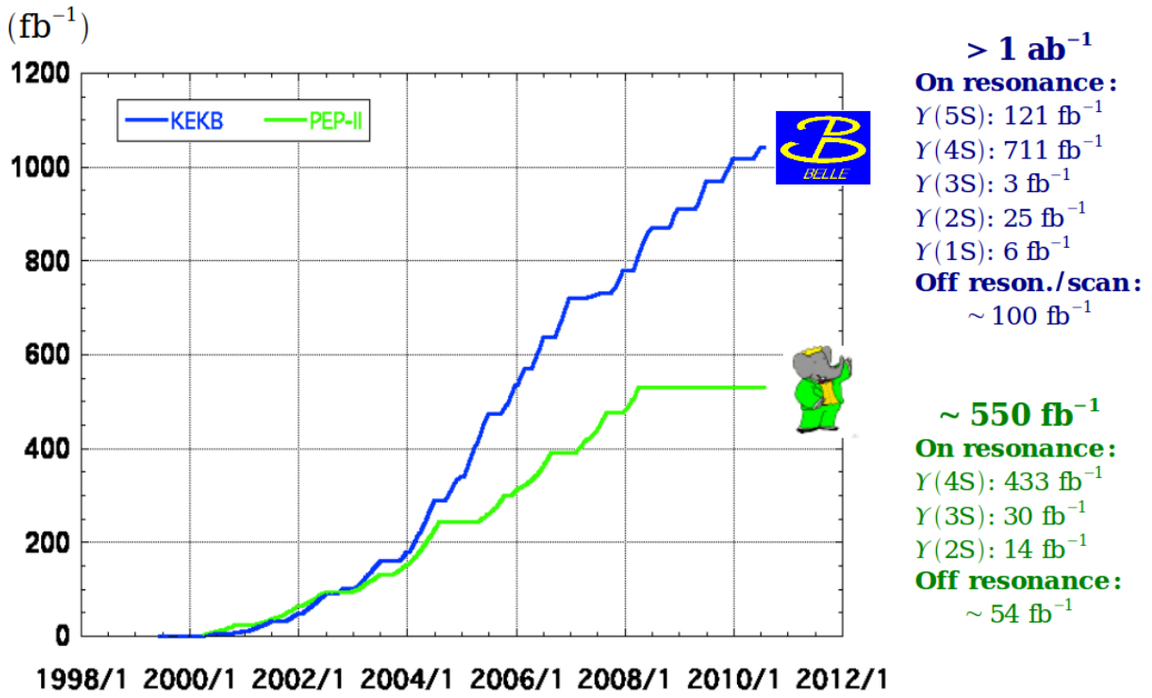
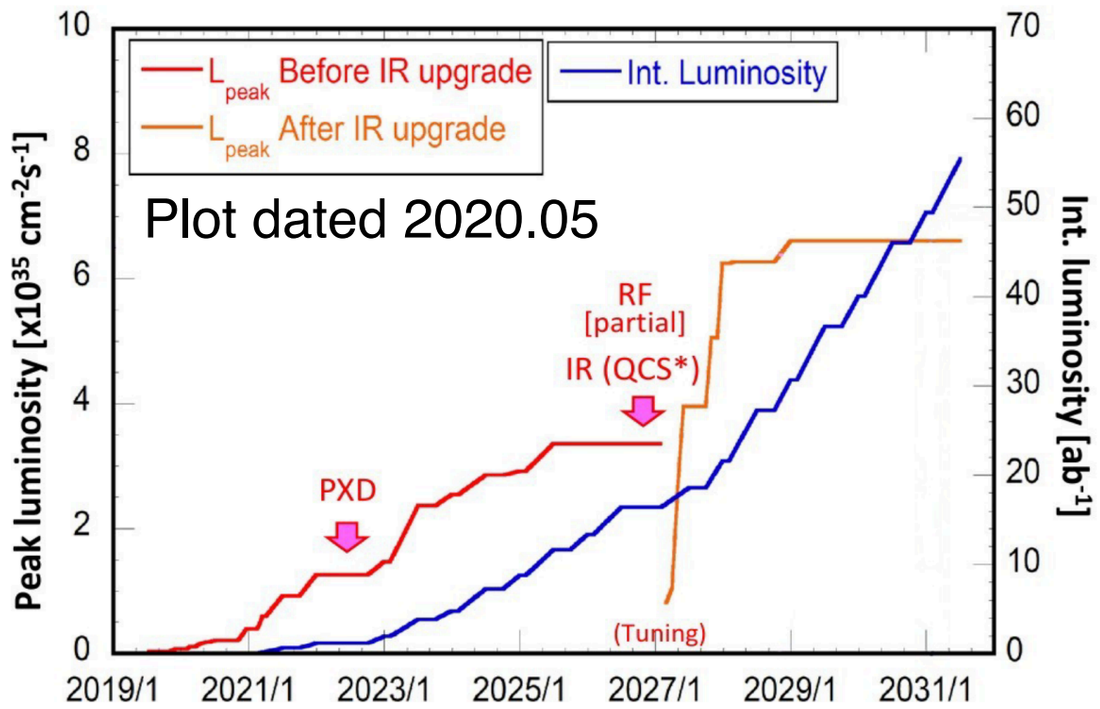
Belle II
Super KEKB

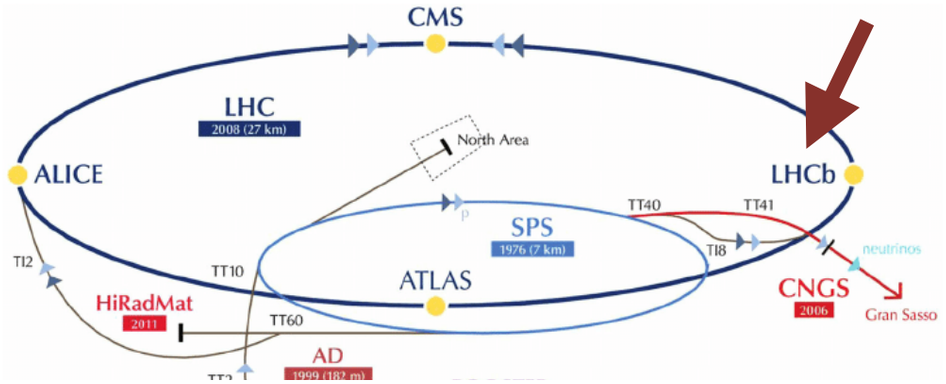
B-factories performance

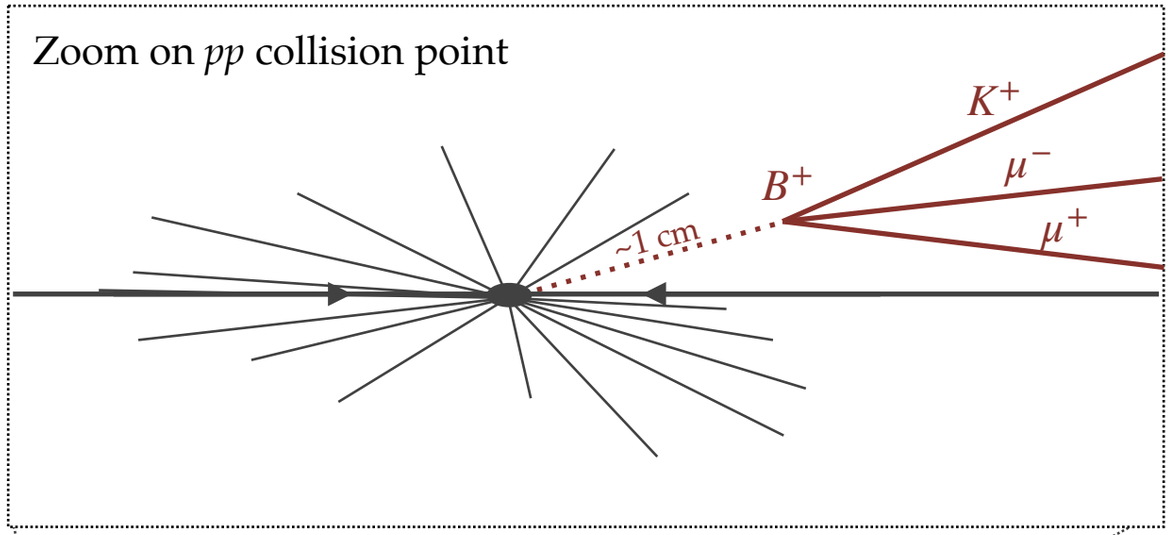
- BaBar and Belle have $L_{\text{int}} \simeq 1.5\ \text{ab}^{-1}$ on tape
- Belle II is ramping-up
  - $L_{\text{peak}} \simeq 0.3 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$ in June 2021
  - $L_{\text{int}} \simeq 0.2\ \text{ab}^{-1}$ in July 2021





The LHCb experiment

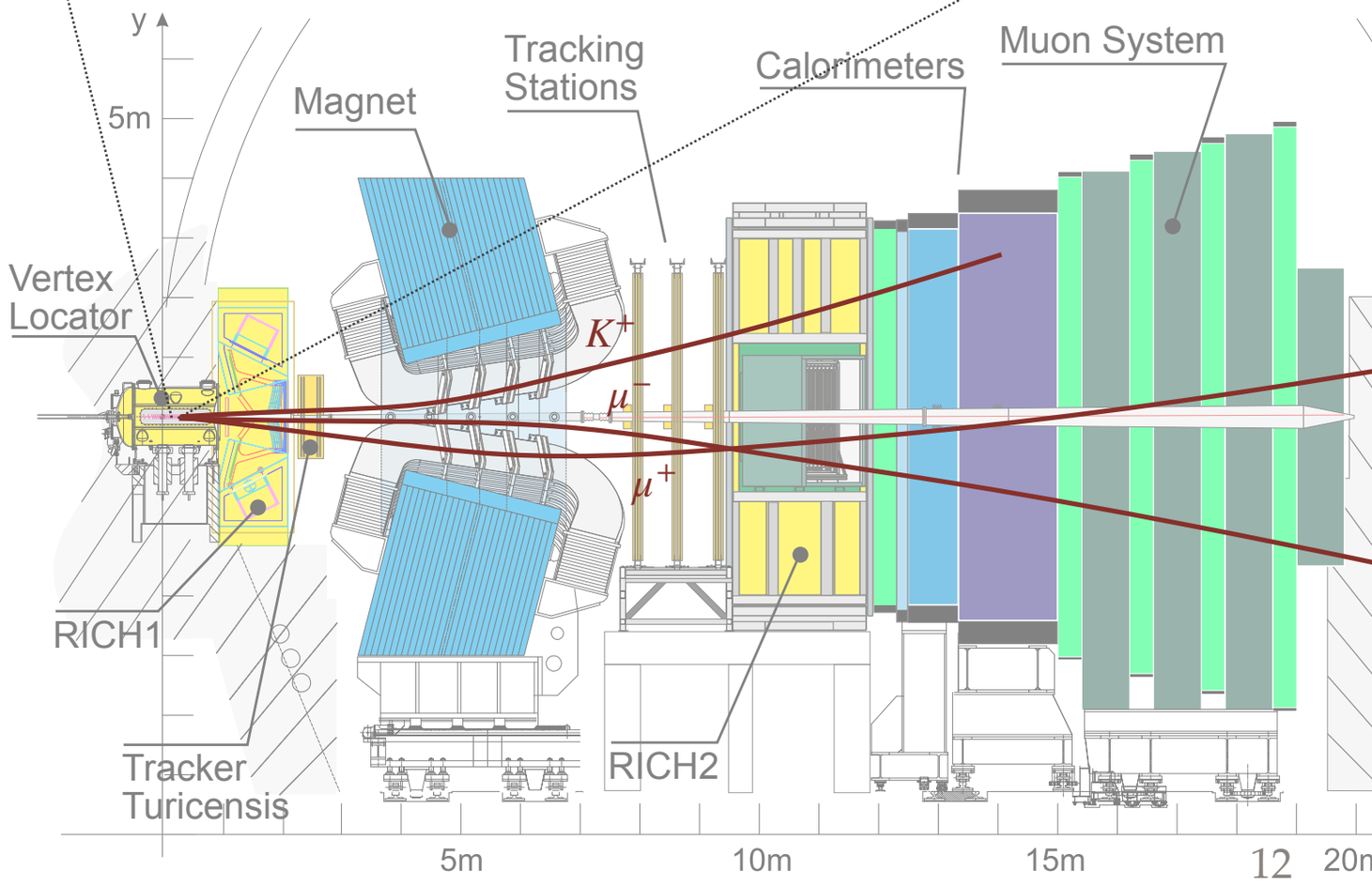




Int.J.Mod.Phys. A 30, 1530022 (2015)

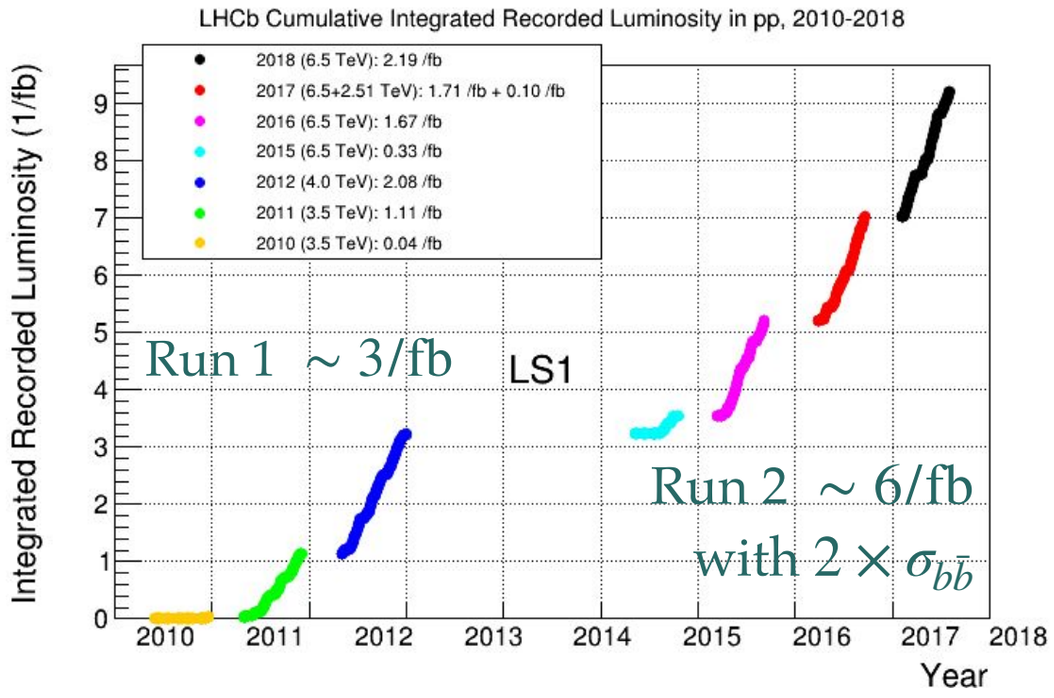
- Designed for *b*-hadrons:
  - **In the forward region** of LHC collisions where huge $\sigma_{b\bar{b}} \sim 0.5 \times 10^{-3}$ b
  - **Very displaced** *b* **vertices** thanks to large forward boost $\beta\gamma \sim 20$
  - **Low-p_T triggers** (lower than m_b)

- Running at lower luminosity and one *pp* collision per bunch crossing
- Spectrometer for precise momentum measurement $\sigma_p/p \sim 0.5\,\%$
- PID with calorimeters, muon system and Cherenkov detectors (RICH)

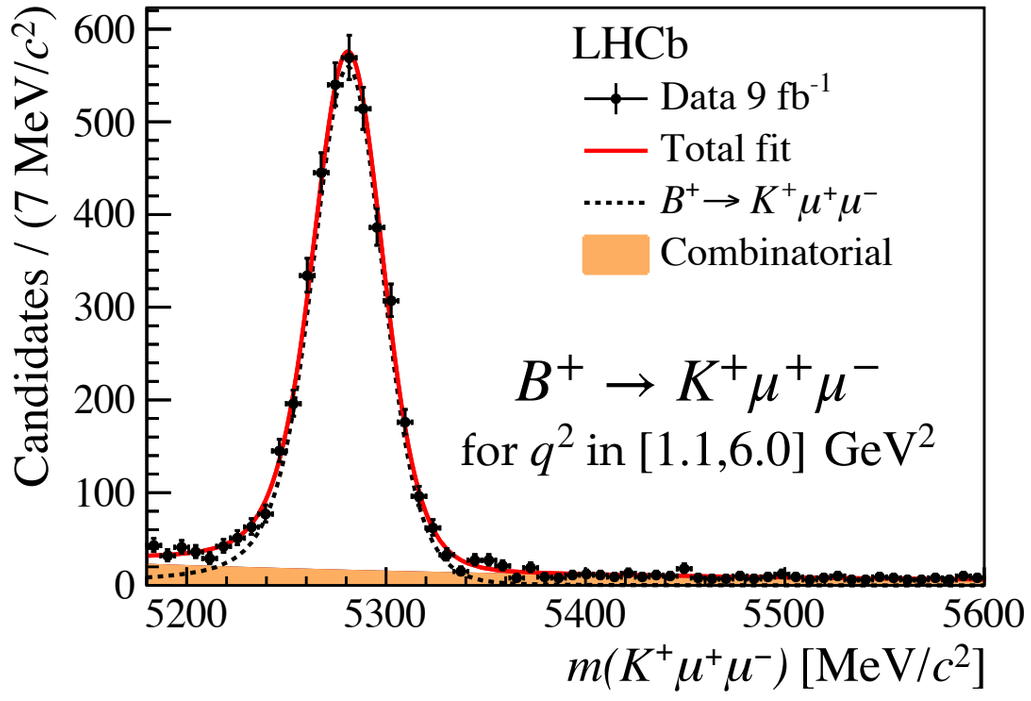


LHCb performance

- Excellent performance in LHC Runs 1 and 2
  - About 10^{12} $b\bar{b}$ in the acceptance (integrated $\mathscr{L} = 9$ fb^{-1})
- Best performance with fully charged final states
  - Even better if they include muons
  - e.g. $N(B^+ \to K^+\mu^+\mu^-) = 3850 \pm 70$ for a BR of about 1.2×10^{-7}



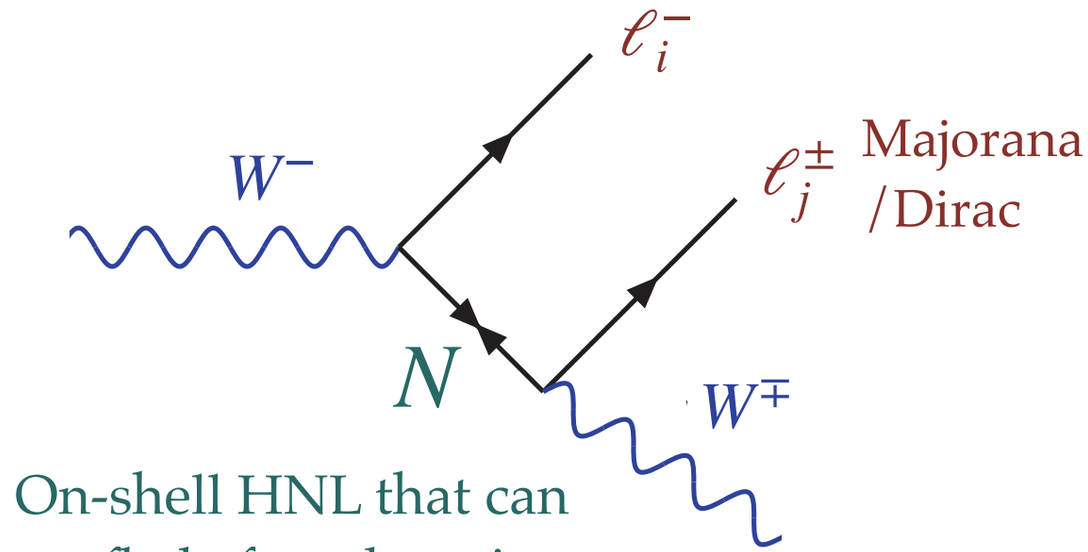
LHCb arXiv:2103.11769



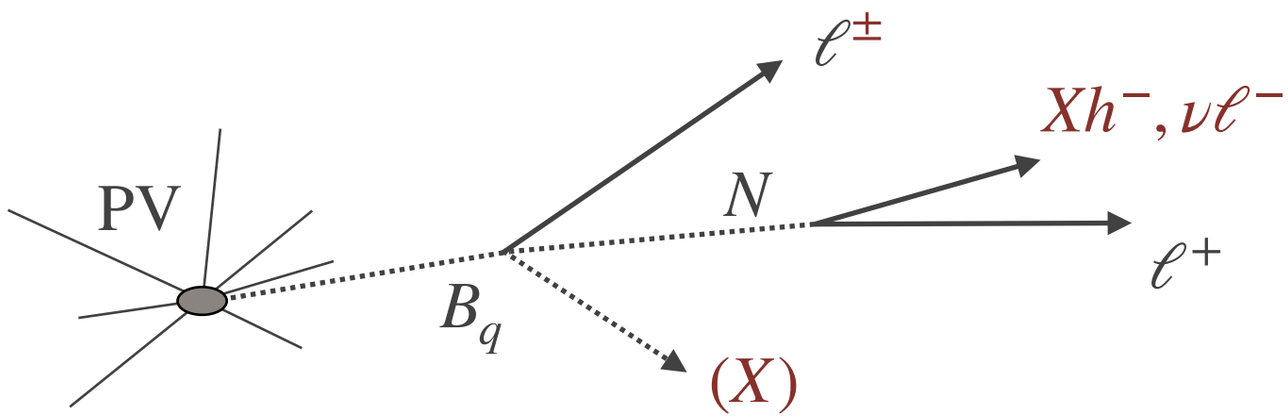
Example 1: heavy neutrinos

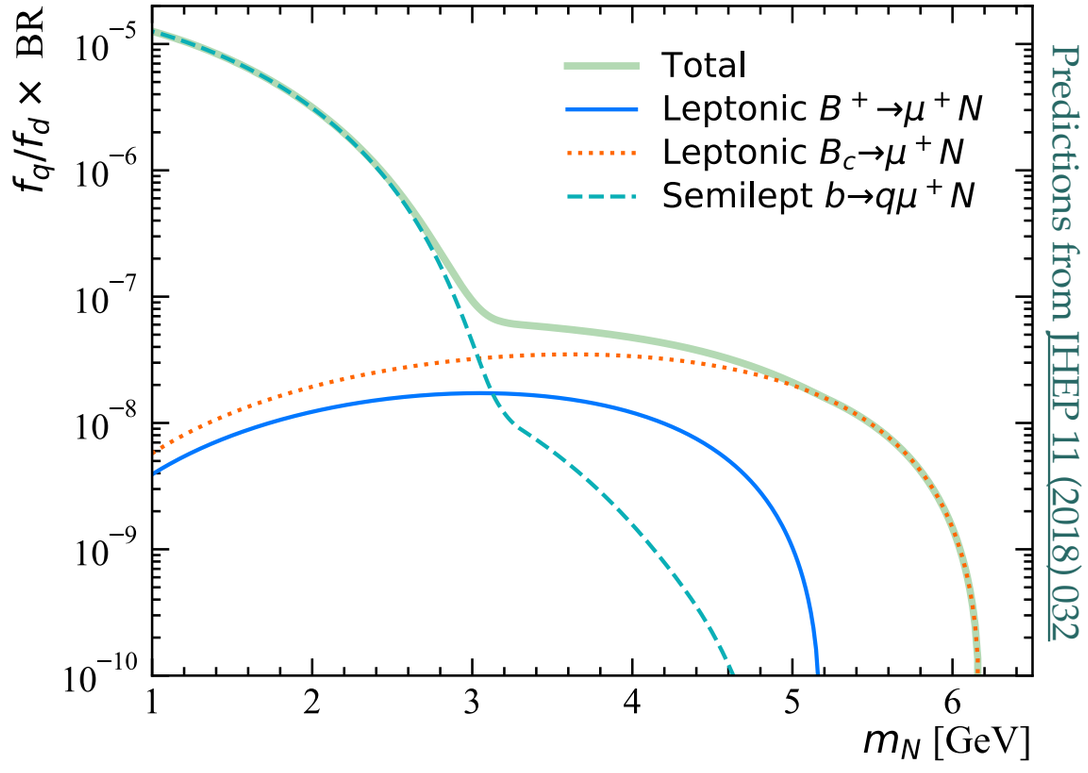
Heavy Neutrinos

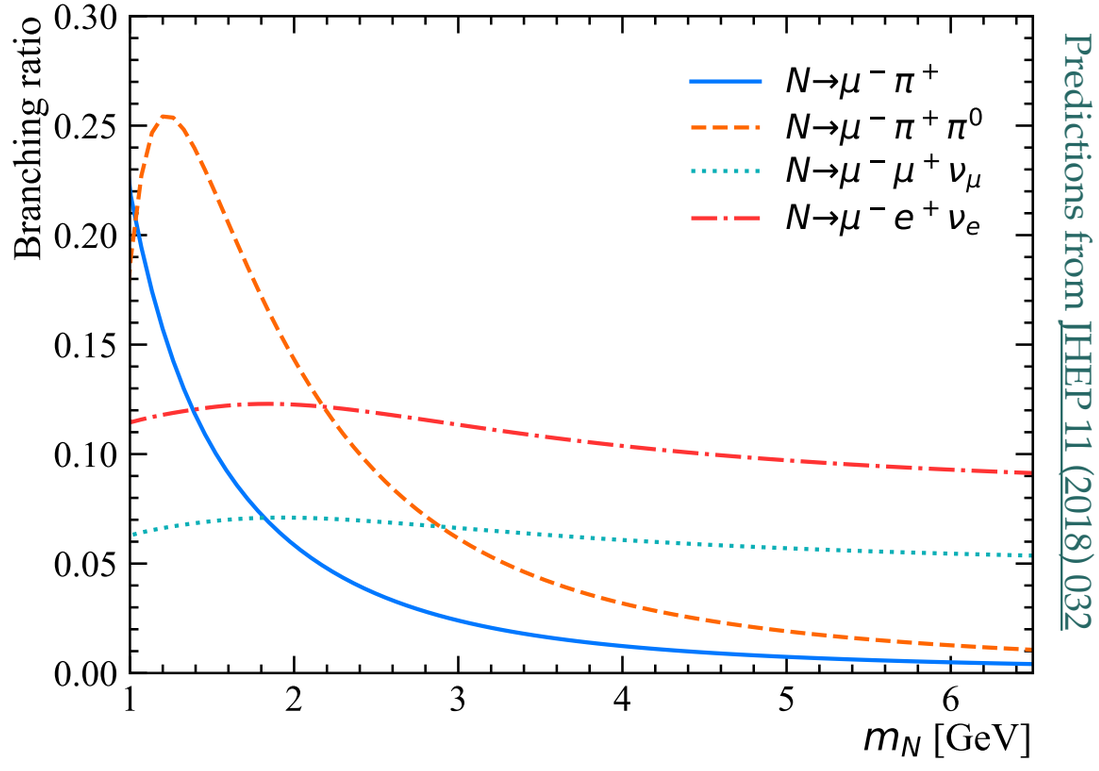
- **Neutrino mass models** can provide heavy neutral leptons (HNL) with masses in the GeV range
- Parameter $U^2_{\alpha N}$ gives HNL mixing with SM neutrino (flavour α)
  - Production rate is proportional to $U^2_{\alpha N}$
  - HNL lifetime τ is proportional to $U^{-2}_{\alpha N} \cdot m_N^{-5}$
- HNL can be a Majorana or Dirac particle $\rightarrow \ell^\pm$ in production and decay can have the same charge!



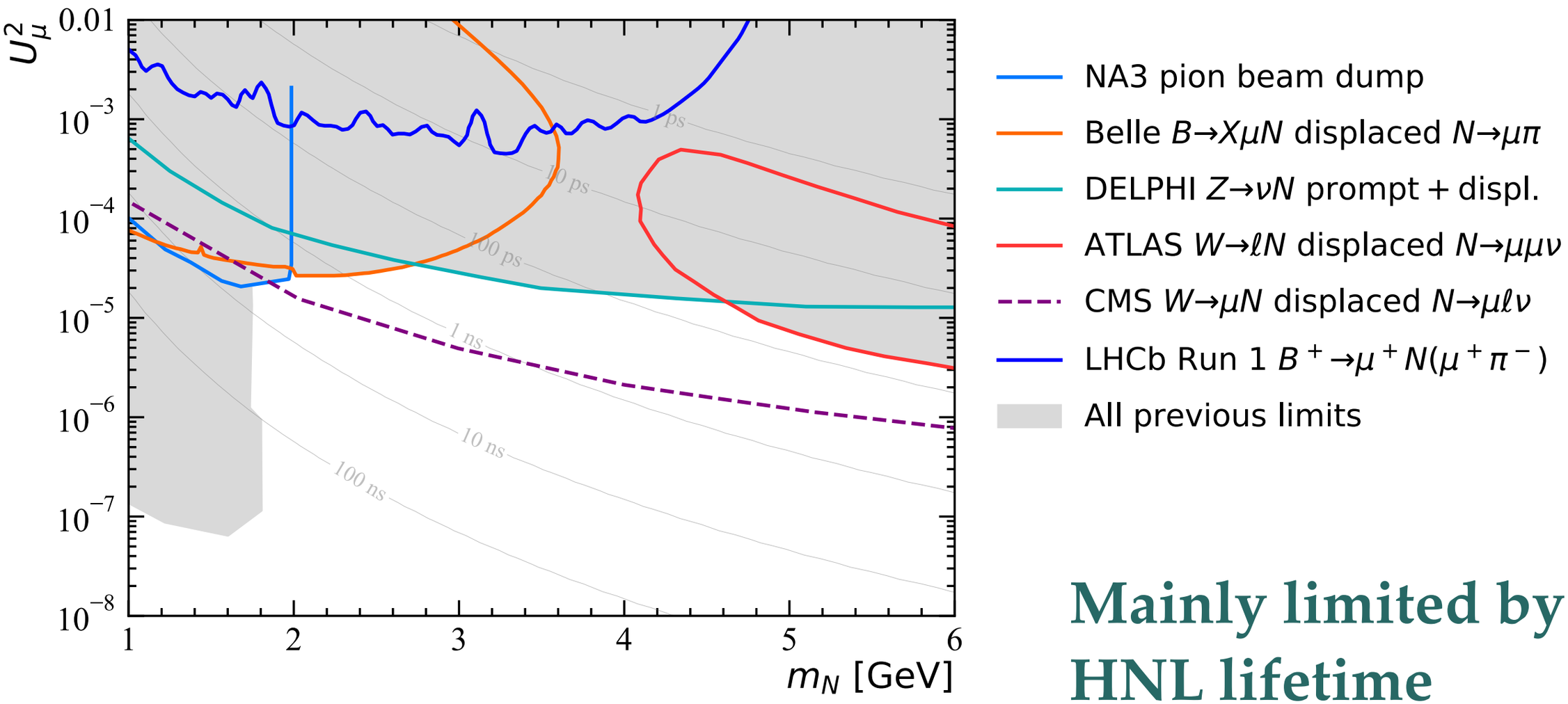
HNL in B decays







HNL searches in GeV range



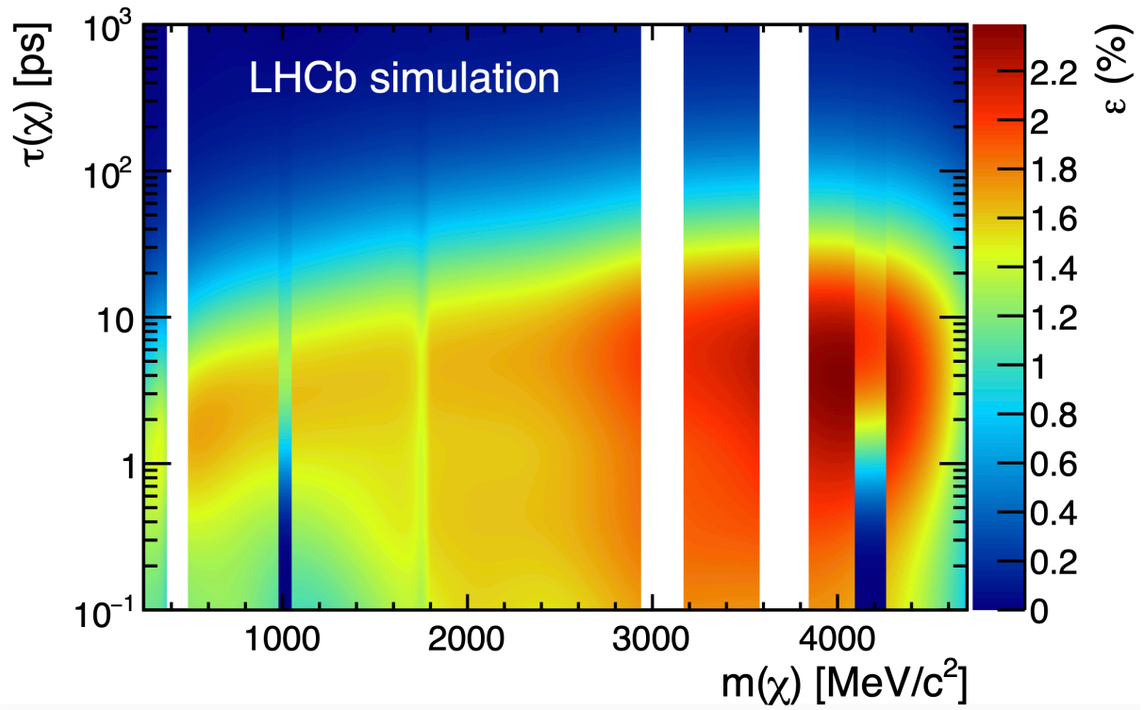
Mainly limited by HNL lifetime

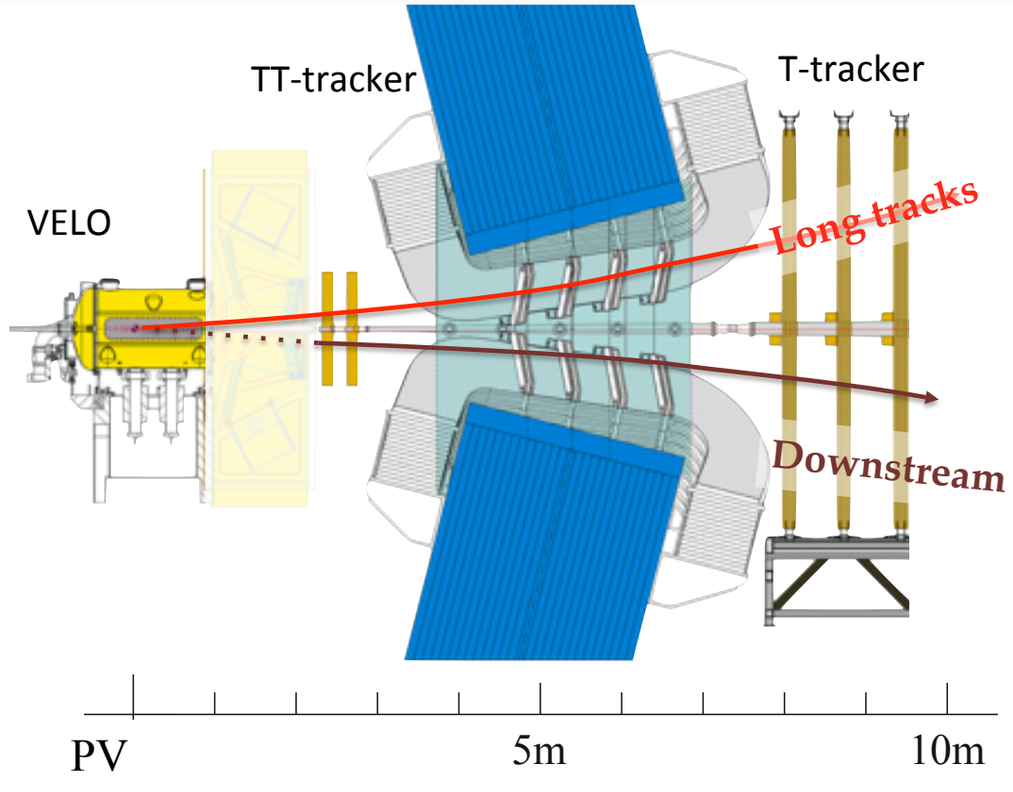
Displaced vertices at LHCb

- Currently only **within VELO**
  - Displacement roughly <20 cm
  - 2 GeV particle from B has $\beta\gamma \simeq 20$
- Could extend to ***downstream tracks***
  - Displacement <200 cm
  - Worse vertex and p resolution ($m(\pi\pi)$ resolution 2× larger)
  - Being optimised in the trigger

[LHCb-PUB-2017-005]

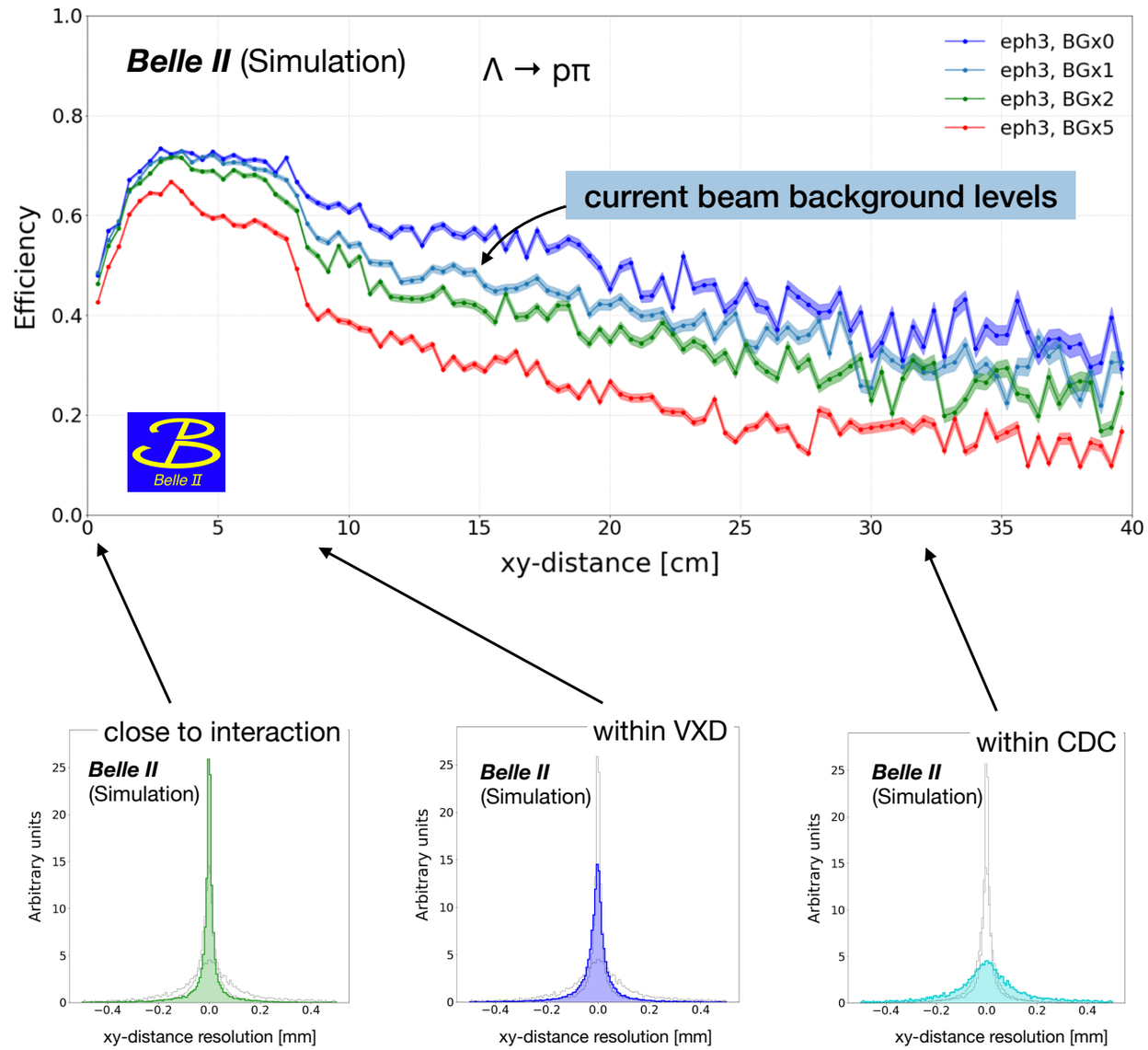
VELO acceptance for $B^+ \to K^+\chi(\mu\mu)$



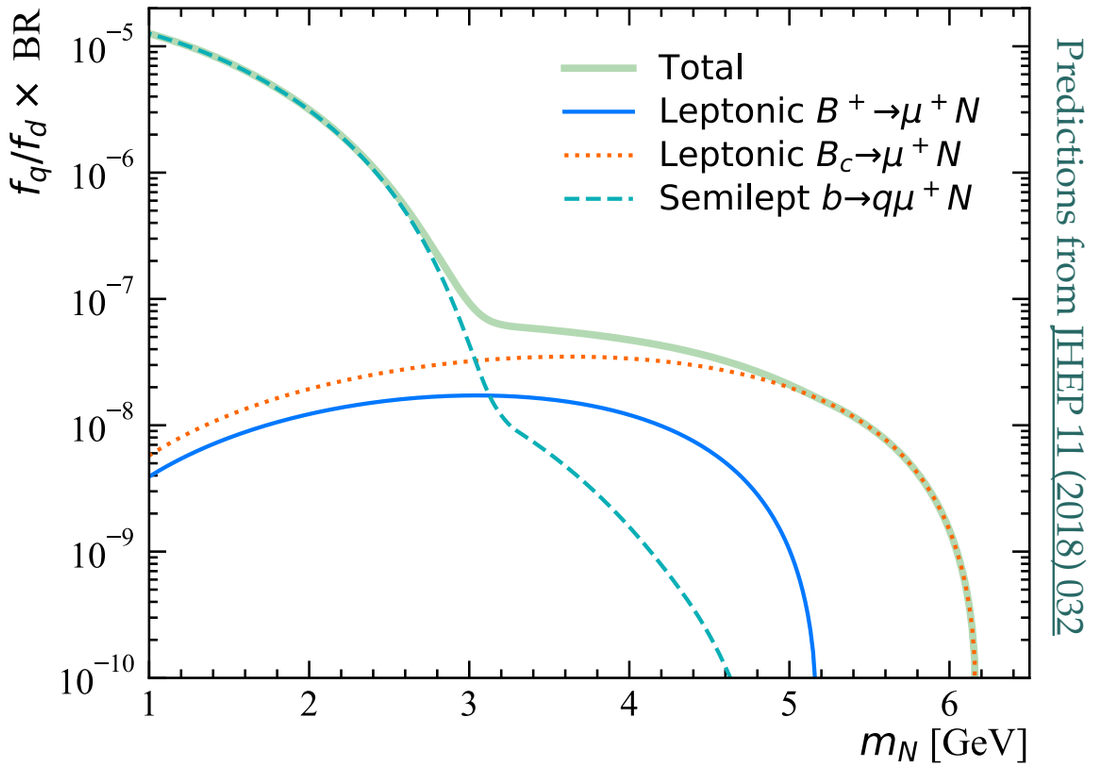


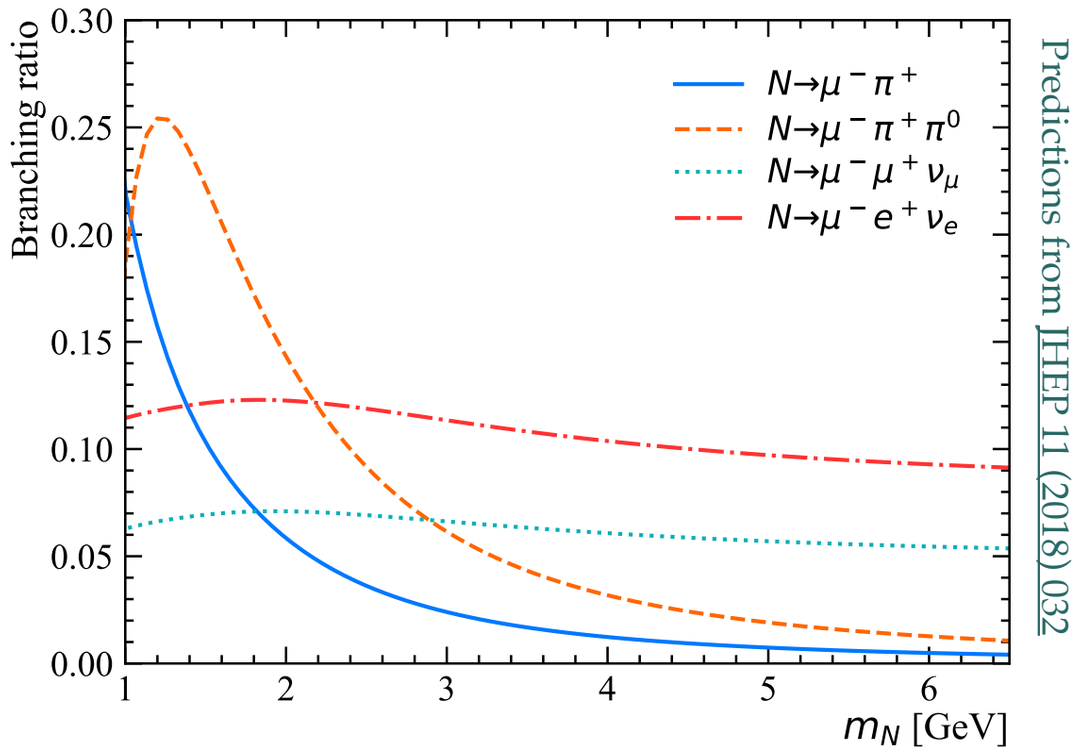
Displaced vertices at Belle II

- Vertex efficiency larger than 30% out to ~60 cm
  - But expect boost roughly 10 × smaller than LHCb
- Mass resolution worsens for more displaced vertices
- Efficiency depends on background level

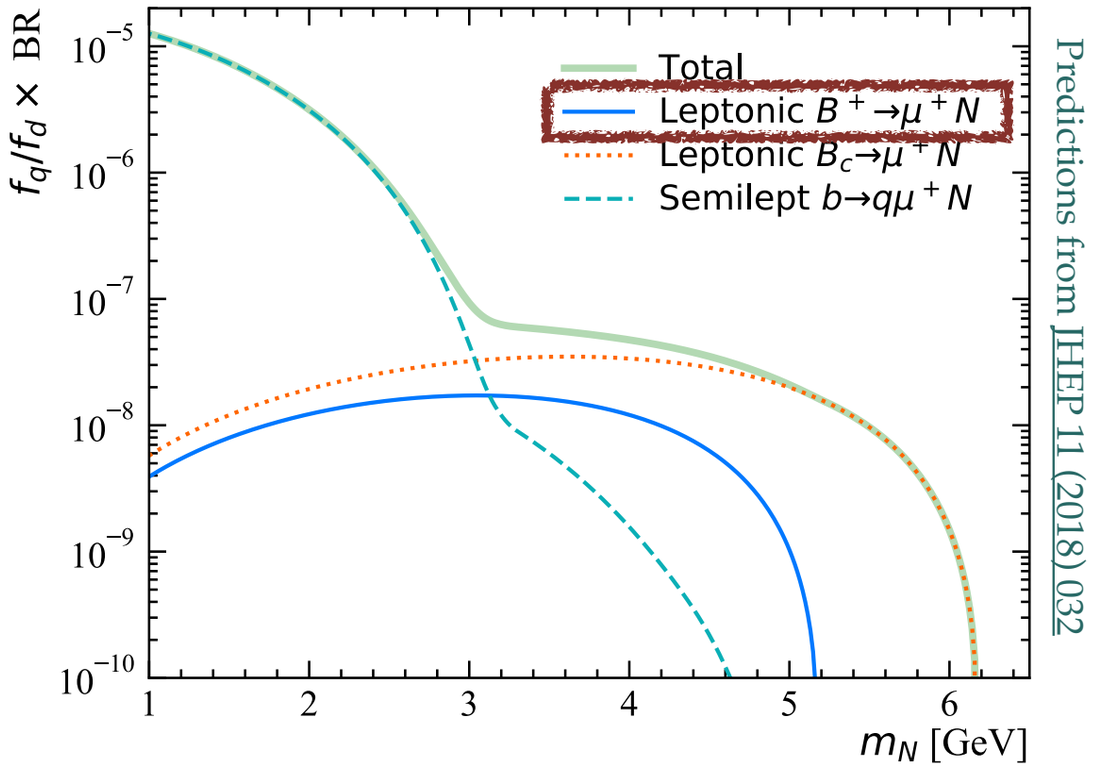


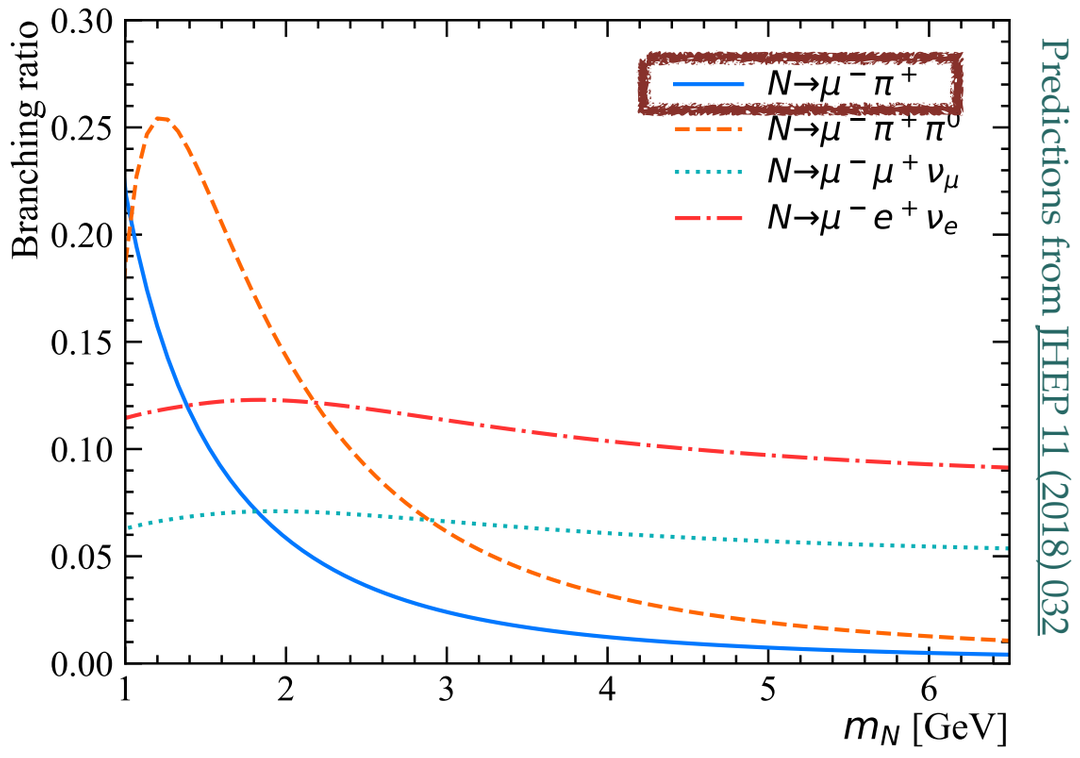
B→HNL


$f_q/f_d \times$ BR
Total
Leptonic $B^+ \to \mu^+ N$
Leptonic $B_c \to \mu^+ N$
Semilept $b \to q\mu^+ N$
m_N [GeV]
Predictions from JHEP 11 (2018) 032

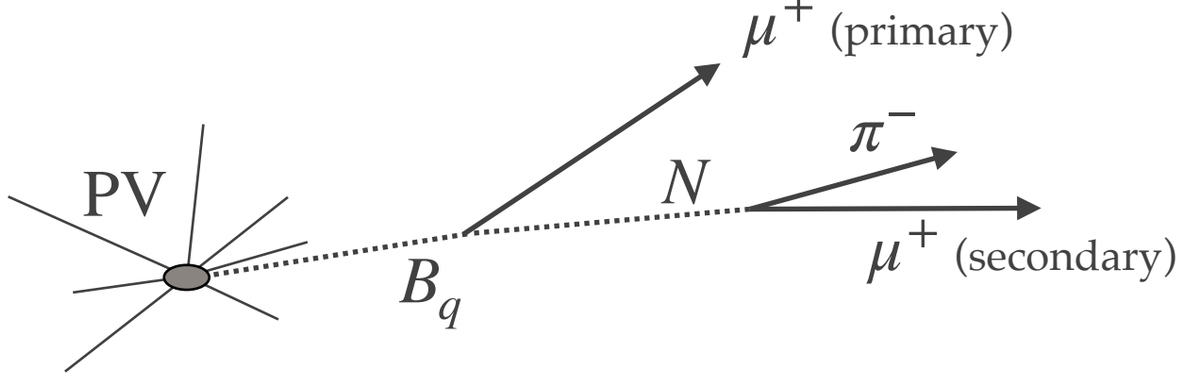

Branching ratio
$N \to \mu^- \pi^+$
$N \to \mu^- \pi^+ \pi^0$
$N \to \mu^- \mu^+ \nu_\mu$
$N \to \mu^- e^+ \nu_e$
m_N [GeV]
Predictions from JHEP 11 (2018) 032

B→HNL in LHCb Run 1

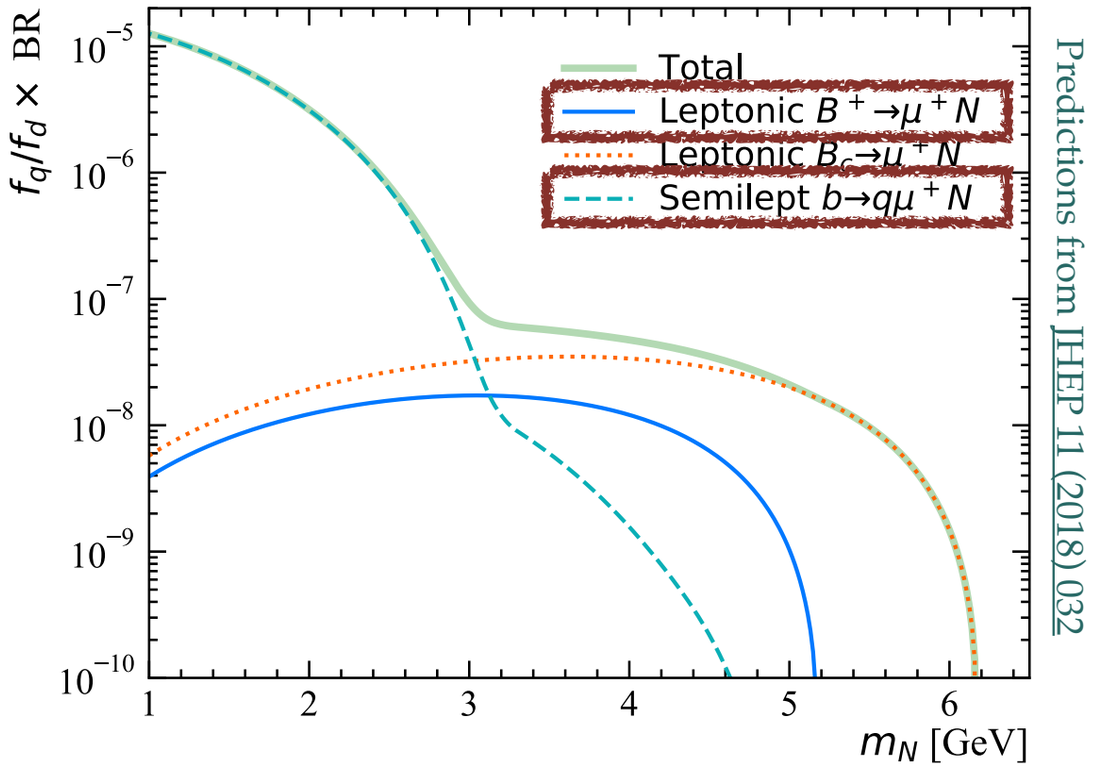


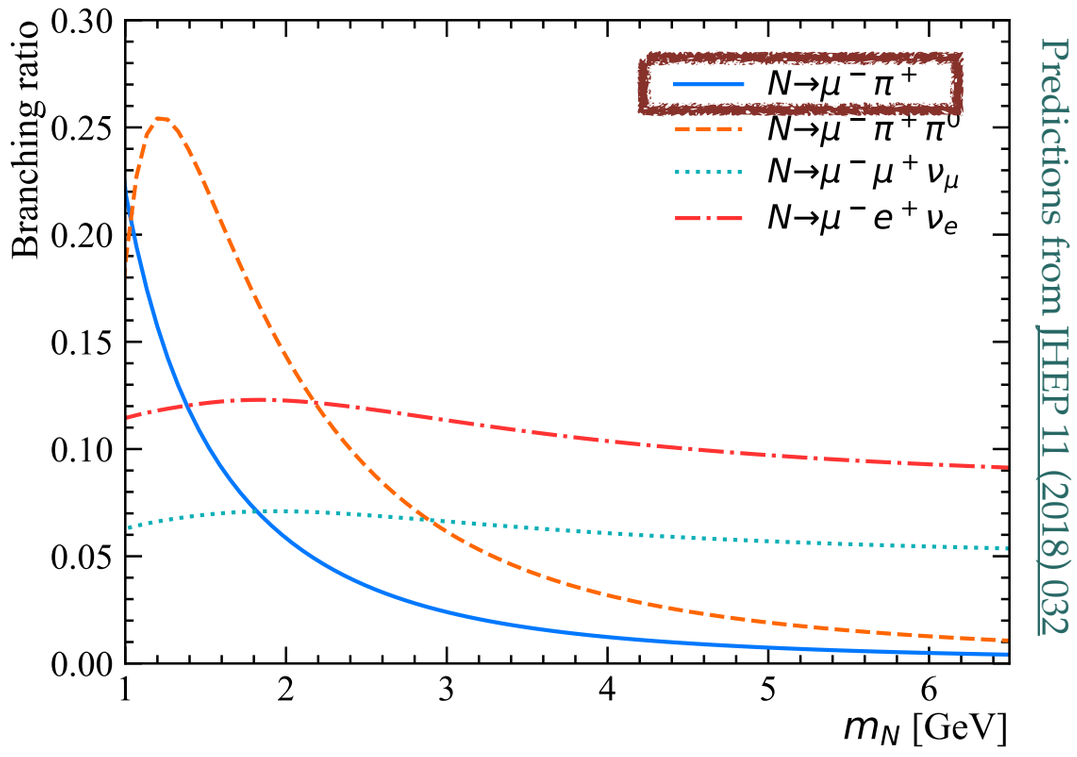


- LHCb Run 1:
  - Search in **leptonic channel** $B^+ \to \mu^+ N(\to \mu^+ \pi^-)$
  - Fully reconstructed LNV B decay
  - Search peak in $m(\mu\pi)$

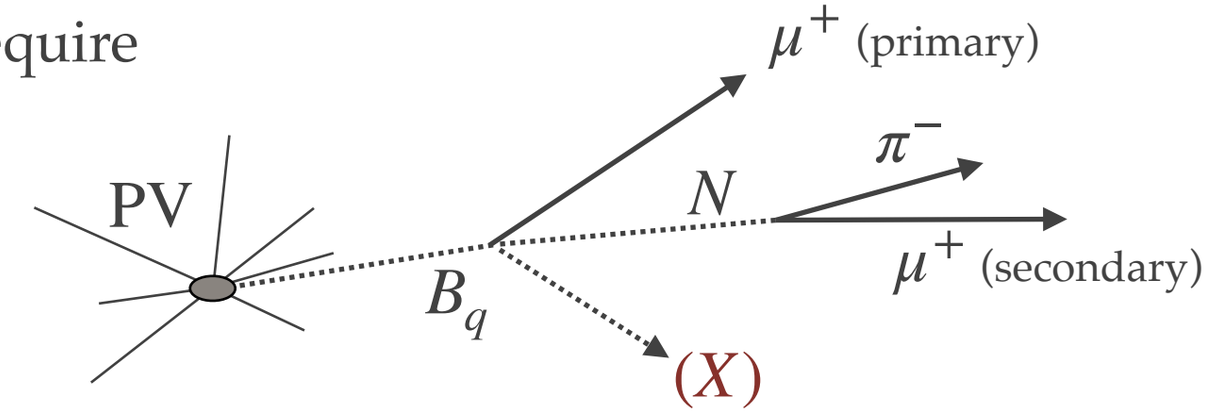


B→HNL in Belle



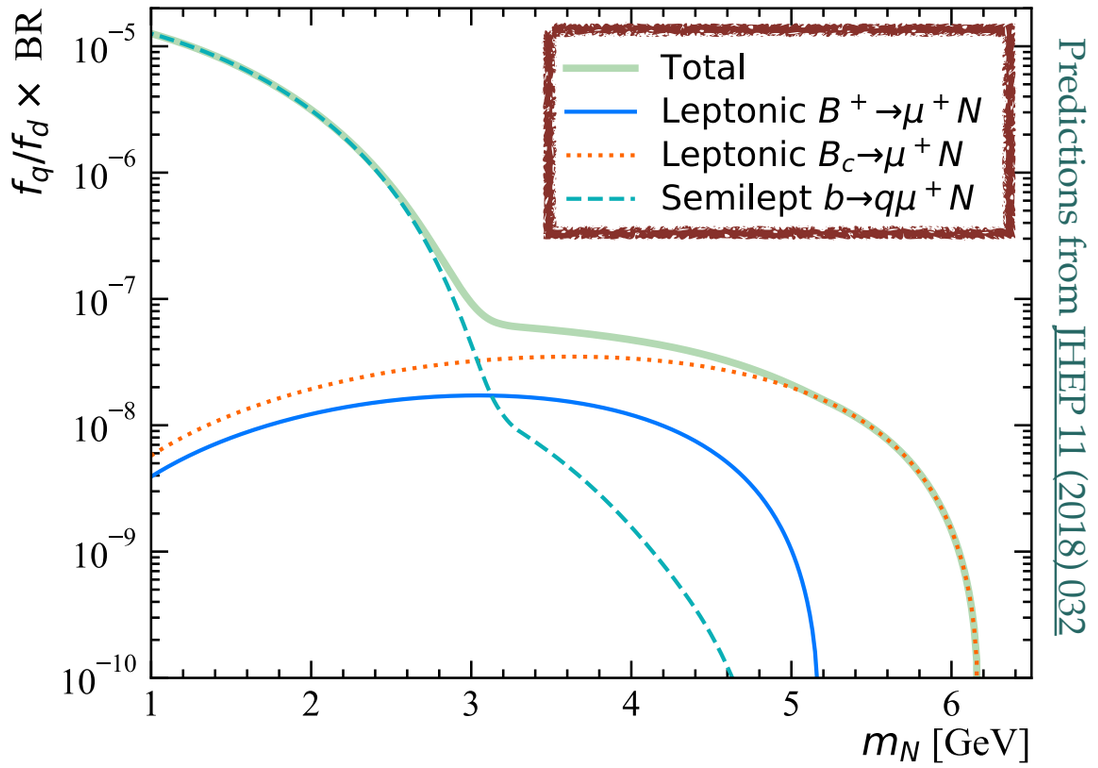


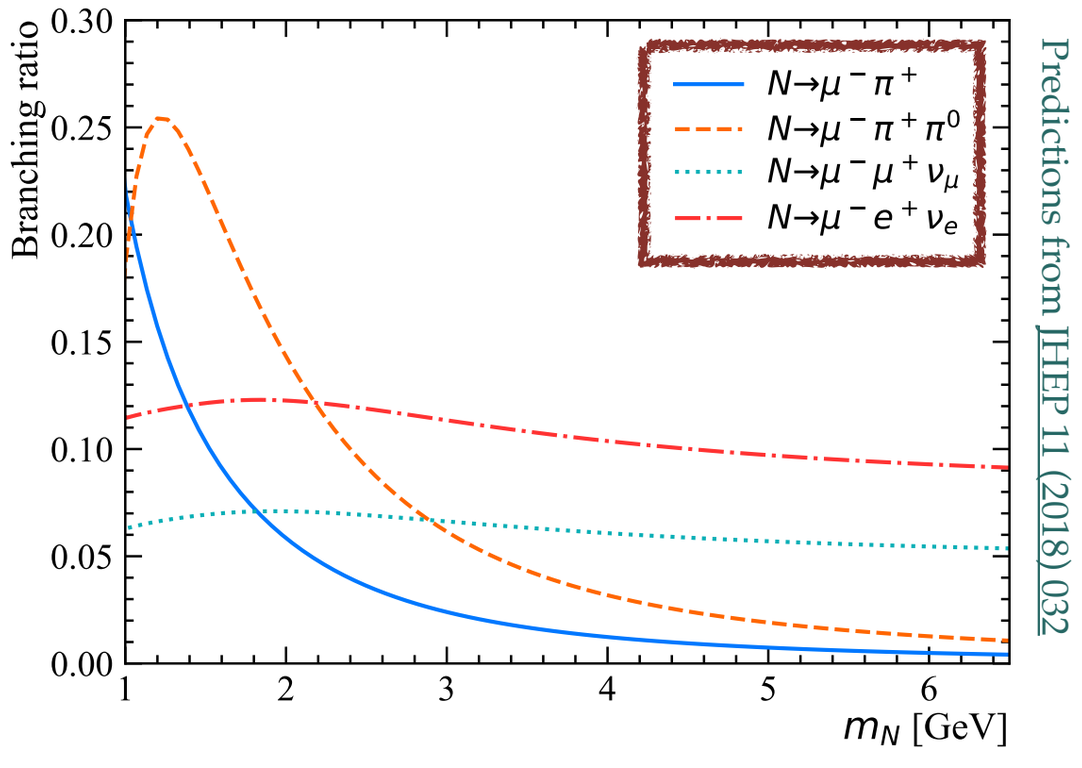
- Belle search:
  - Search in **leptonic and semileptonic channels**
  - Partially reconstructed LNV B decay, require displacement to reduce background
  - Search peak in $m(\mu\pi)$



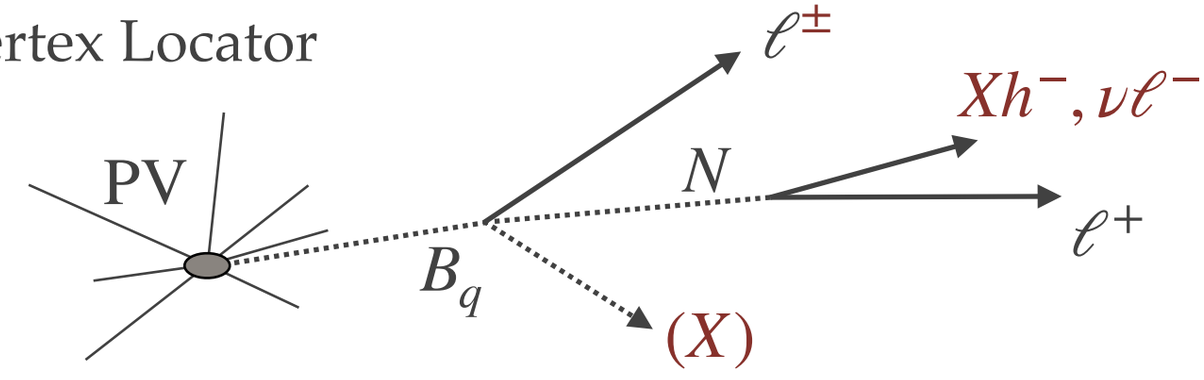
Future Prospects

B→HNL in future LHCb





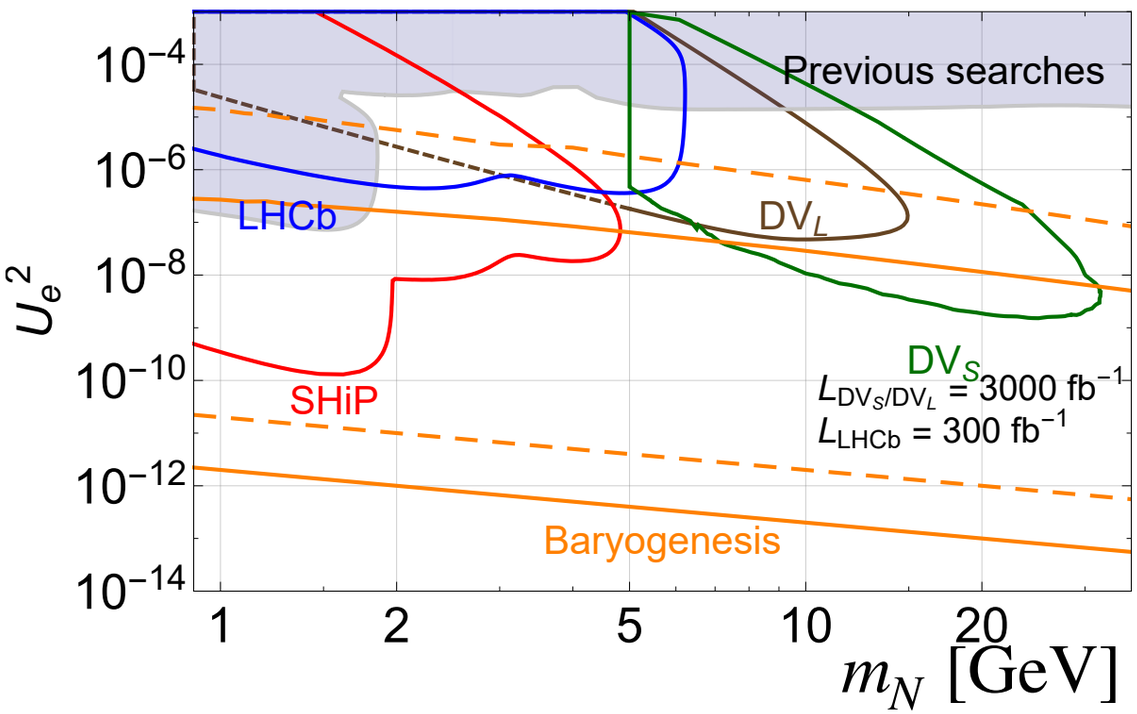
- Future LHCb strategy:
  - Include $B_c \to \ell N$ and $B_q \to X\ell N$
  - Include partially reconstructed N decays
  - Include N decays downstream of the Vertex Locator (10x longer decay time)
  - Search in all lepton flavours (also τ?)
  - Search both LNC and LNV decays

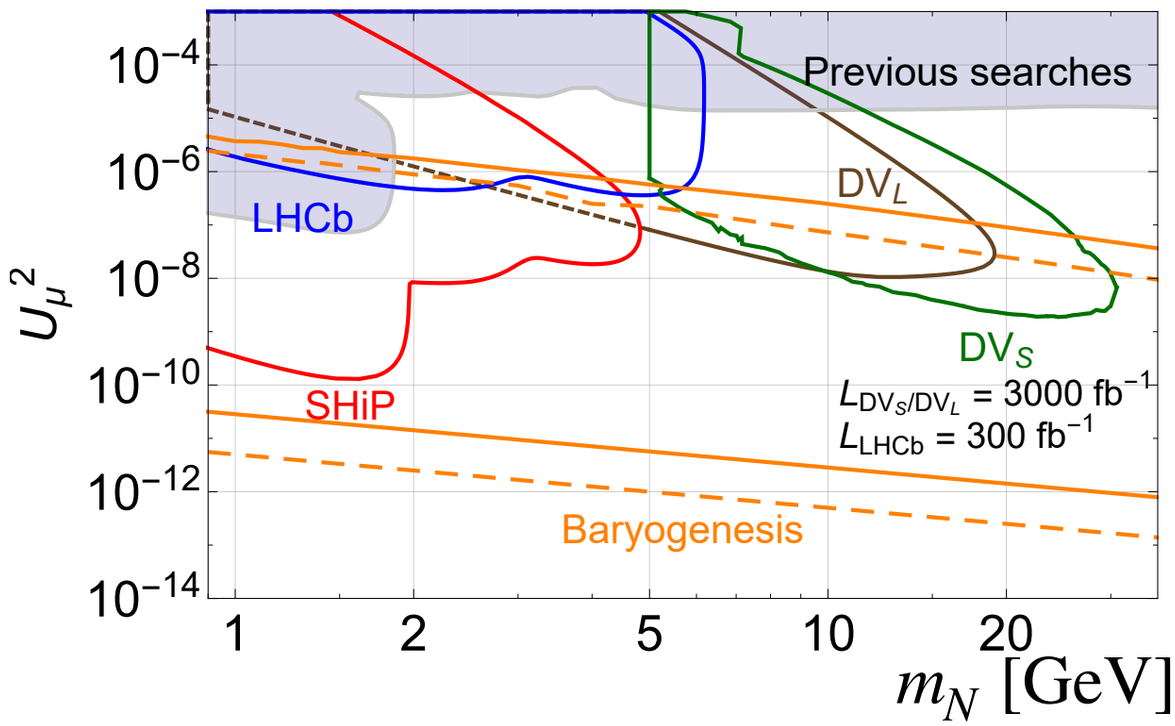


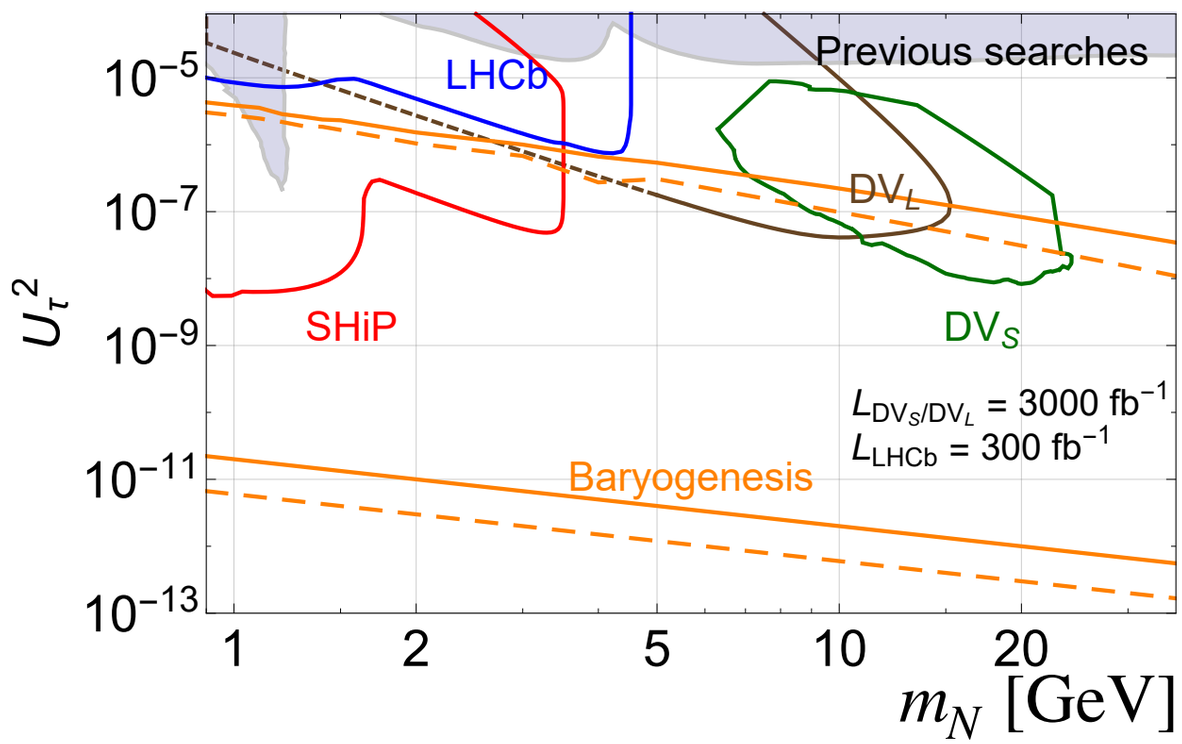
Future Prospects

B→HNL in future LHCb

arXiv:1902.04535







Example 2: light scalars

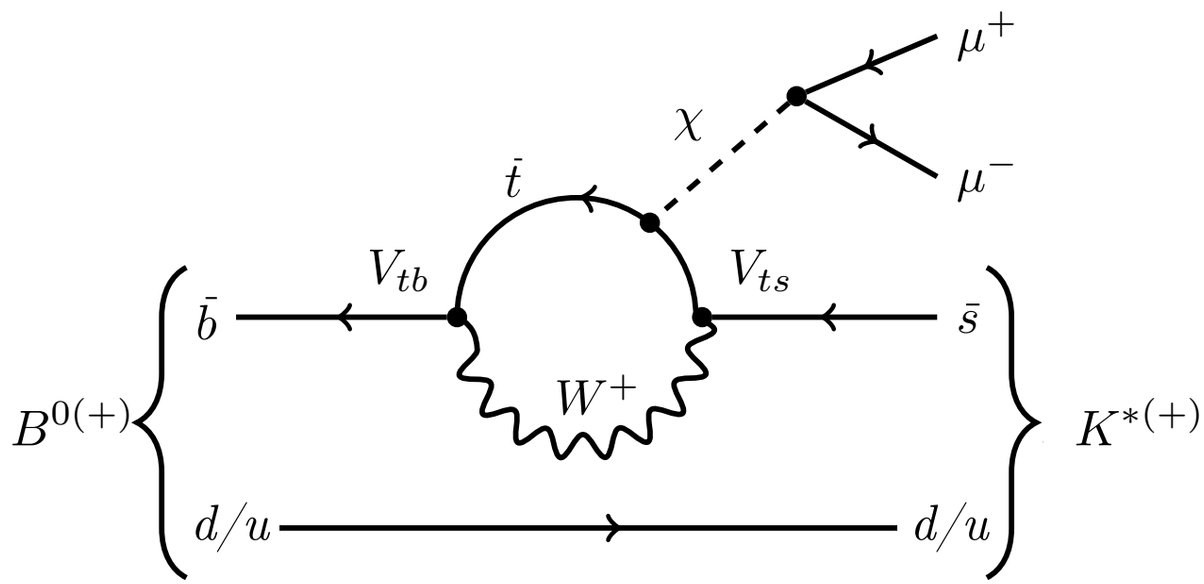
Light scalar from $b \to s$

Phys Rev Lett 115 161802 (2015)
Phys Rev D 95, 071101(R) (2017)

- Flavour-changing neutral currents $b \to s$ involve top loop (GIM mechanism)
  - Scalars prefer heavier quarks, can be radiated from virtual top
  - Rate and lifetime controlled by θ mixing angle with SM Higgs

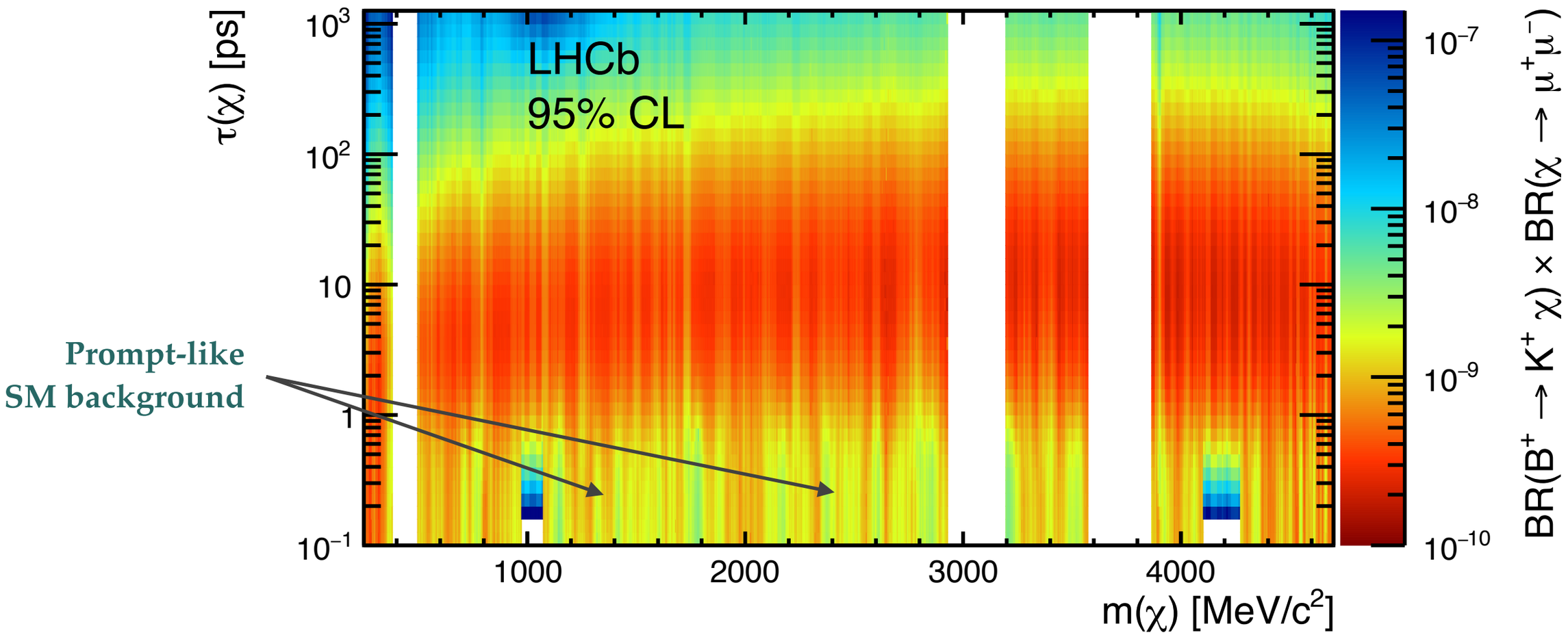
$$\tau \propto 1/\theta^2 \qquad \mathcal{B}(B^+ \to K^+\chi) \propto \theta^2$$

- LHCb has world-record samples of rare $B \to K^{(*)}\mu\mu$ decays (BR~10^{-7})
  - search for narrow $\mu\mu$ peak
- Allow detached $\mu\mu$ (within VELO)
  - small SM mixing can give significant lifetime



Light scalar from $b \to s$

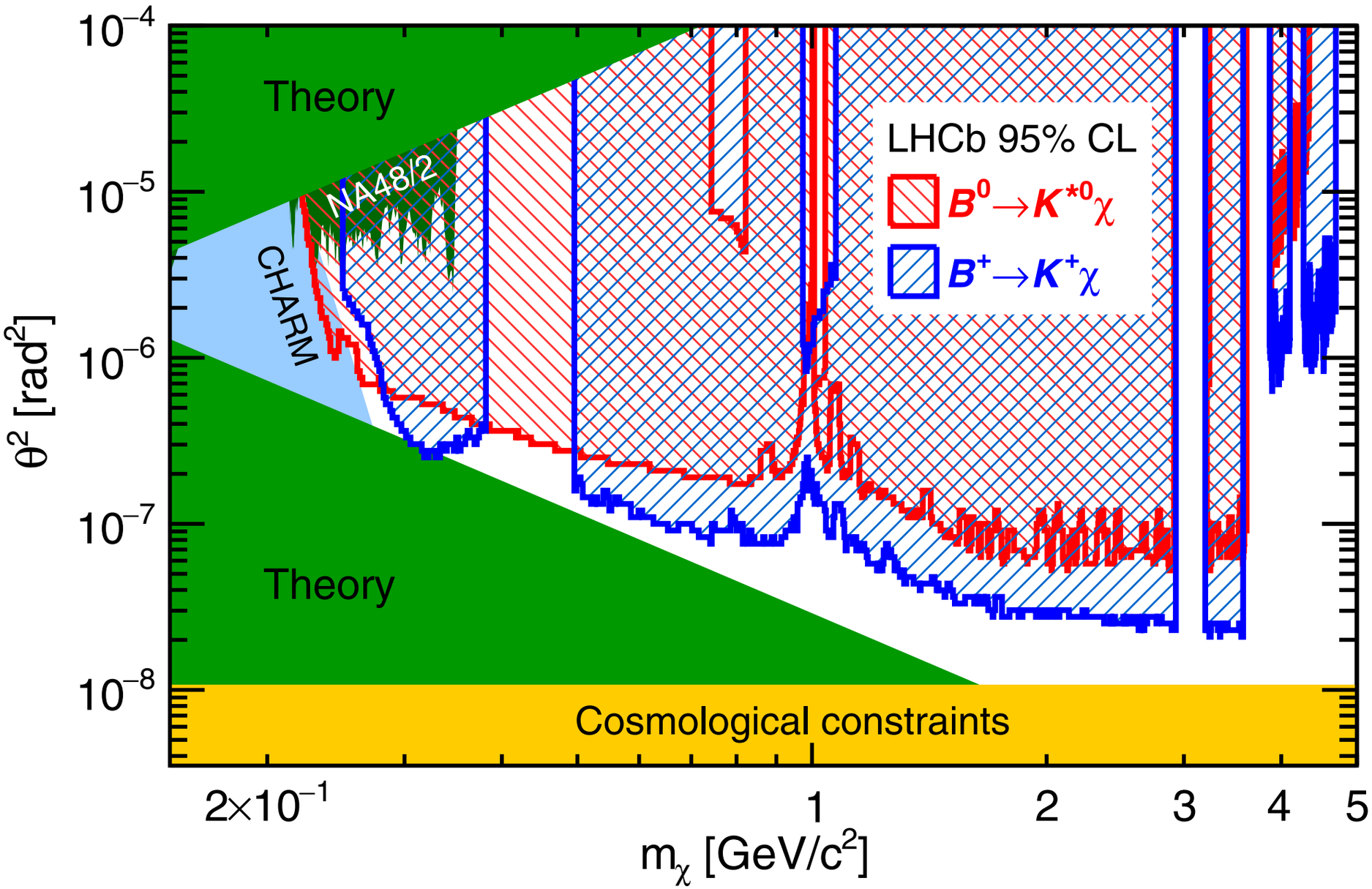
Phys Rev Lett 115 161802 (2015)
Phys Rev D 95, 071101(R) (2017)



- Use peaks in reconstructed m_B and $m(\mu\mu)$ to reduce background
- Upper limits down to $\mathbf{10^{-10}}$ on $\mathrm{BR}(B^+ \to K^+ \chi) \times \mathrm{BR}(\chi \to \mu\mu)$

Light scalar from $b \to s$

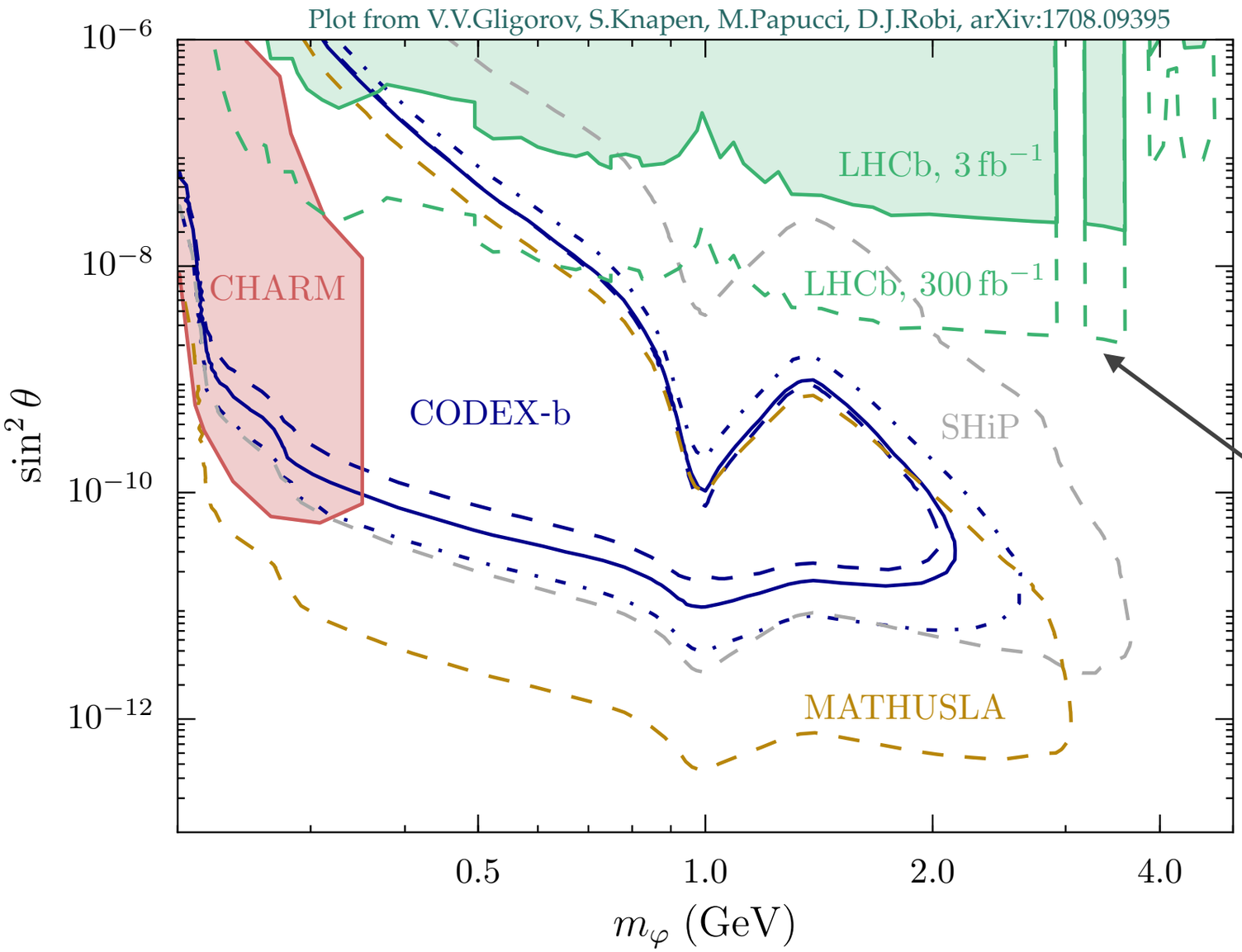
Phys Rev Lett 115 161802 (2015)
Phys Rev D 95, 071101(R) (2017)



Light scalar from $b \to s$

Phys Rev Lett 115 161802 (2015)
Phys Rev D 95, 071101(R) (2017)

$$\tau \propto 1/\theta^2 \qquad \mathcal{B}(B^+ \to K^+ \chi) \propto \theta^2$$



- Constraint on **light scalars**
  - mixing with SM Higgs
  - world-best limits below $2m_\tau$

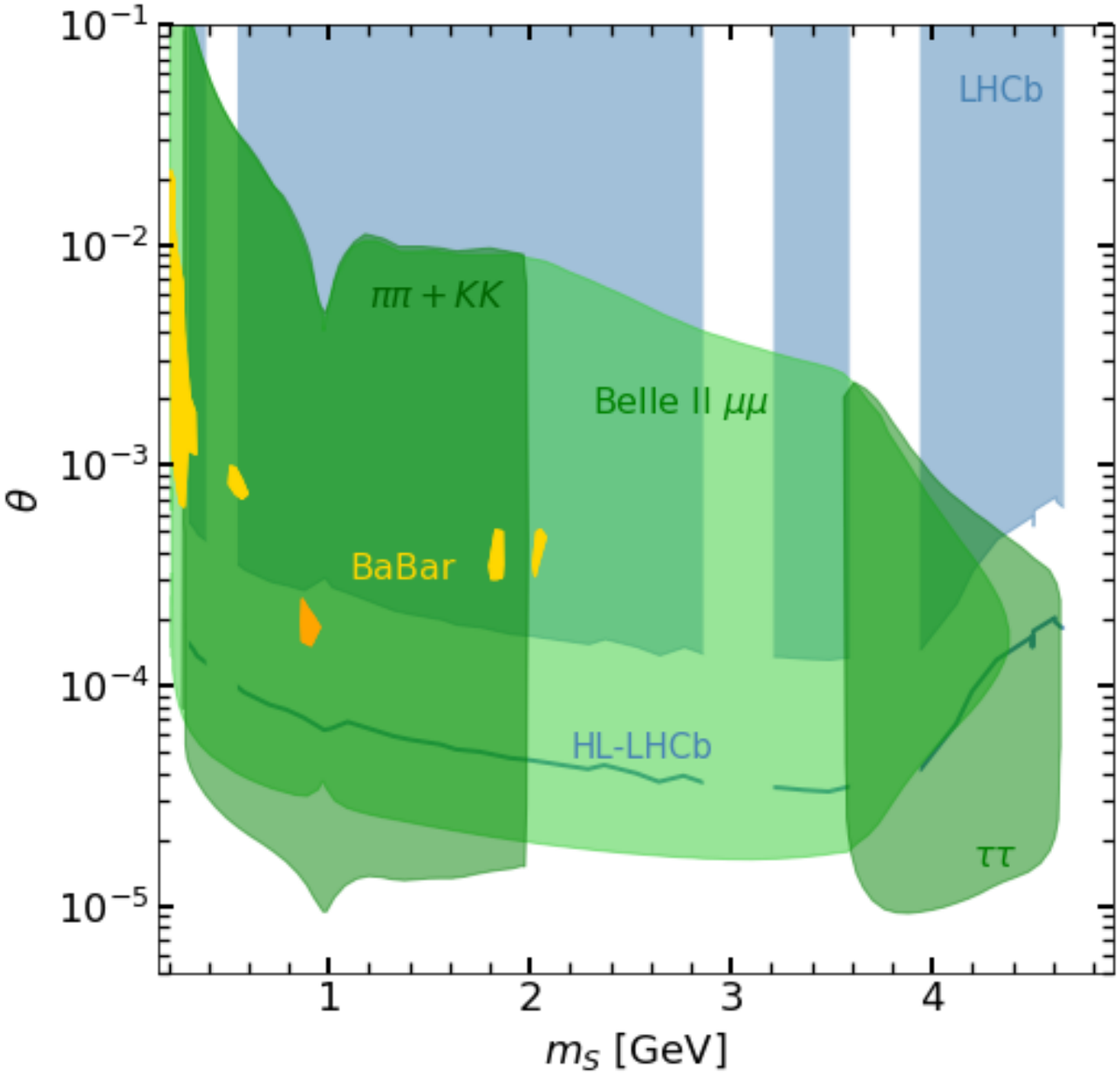
B.Batell, M.Pospelov, A.Ritz, PRD 83, 054005 (2011)
F.Bezrukov, D.Gorbunov, JHEP05(2010)010, JHEP07(2013)140

- LHCb upgrade II
  - 300 fb^{-1} expected reach
  - Phase space unexplored by other planned experiments

Light scalar → Belle II

- Belle II could have better reach thanks to lower boost
- Searches in displaced $\pi\pi$, KK and $\tau\tau$ can also contribute
  - We need to study that in LHCb too
- Belle II can also do:
  - $B \to K +$ invisible
  - $B \to Ka(\to \gamma\gamma)$

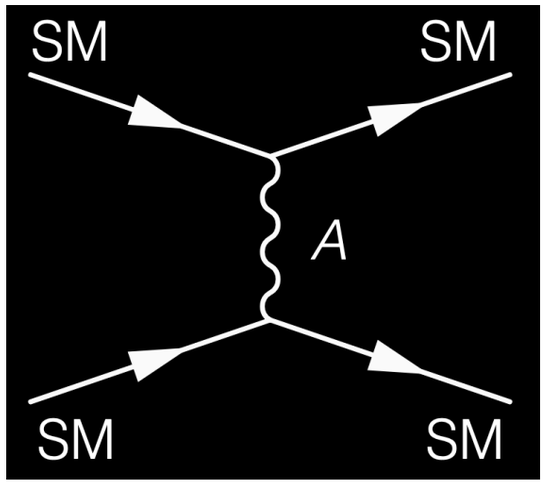
arXiv:1911.03490

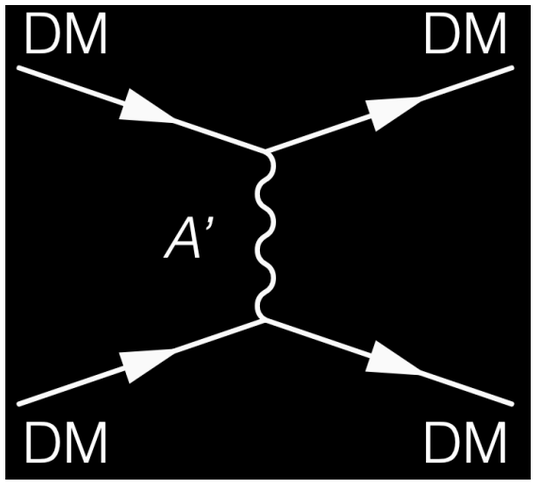


Searches beyond B decays

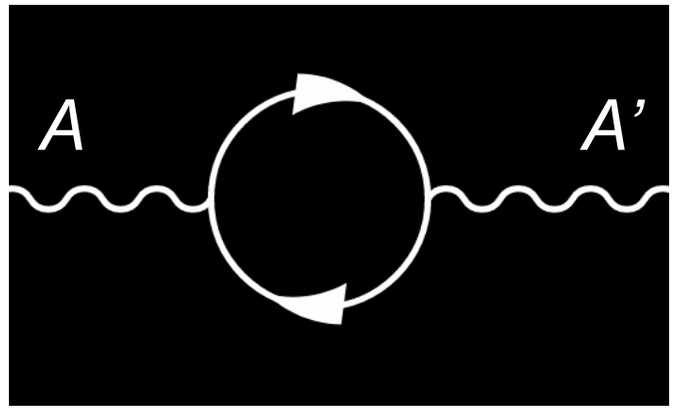
- *B*-physics experiments can contribute beyond B decays
  - In general sensitive to new particles of few-GeV with small production rates (and displaced vertices)
- A priori expect LHCb and Belle II to be very different
  - LHCb gets LHC pp collisions at 13 TeV
  - Belle II gets e^+e^- collisions at 10 GeV

Dark photons pheno





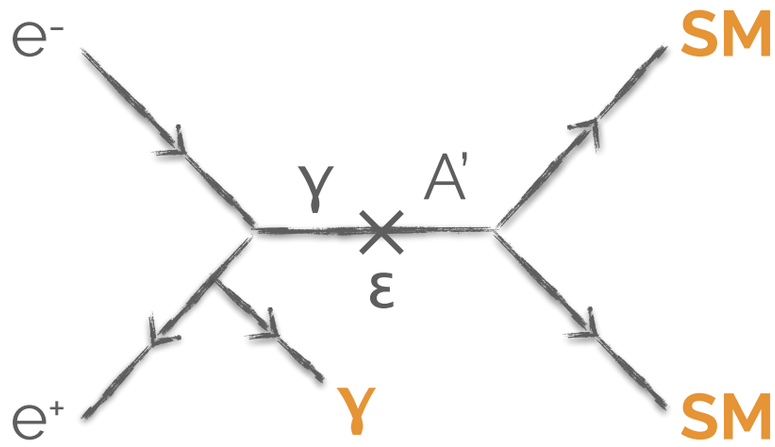
Kinetic mixing

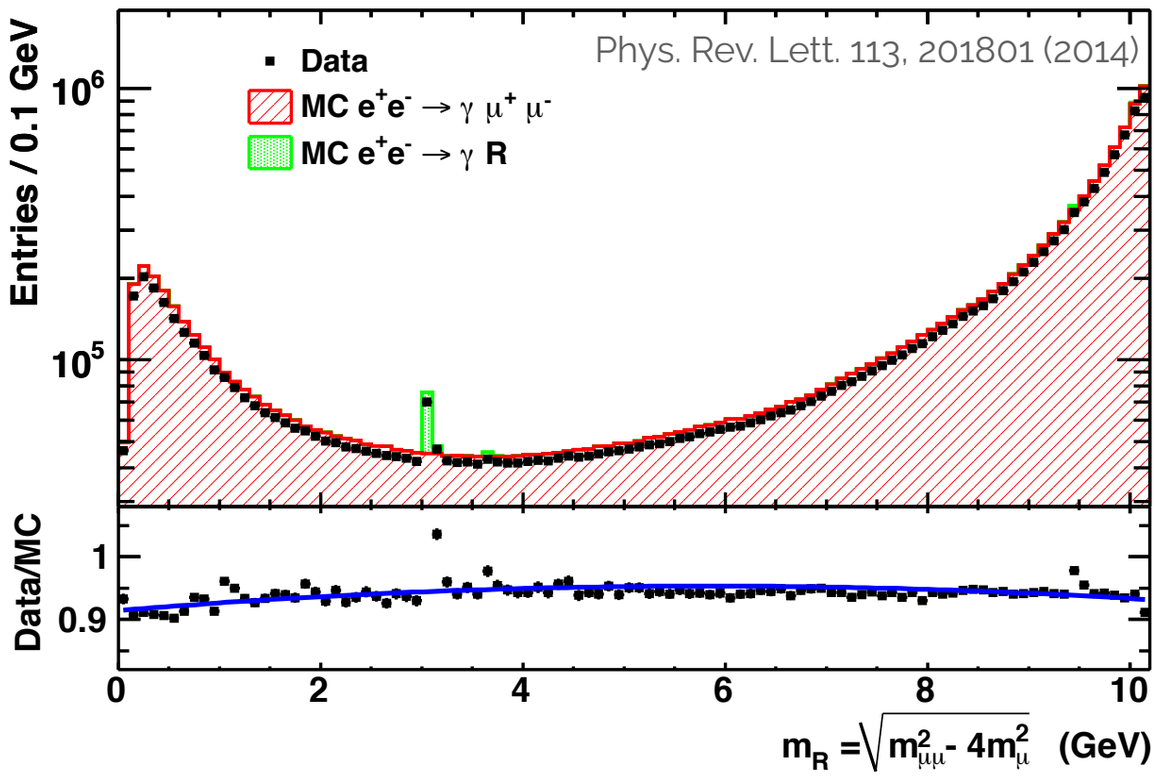


- Dark photon (A') mediates dark matter (χ) interaction
  - If $m(A') > 2m_\chi$ then **invisible decay** $A' \to \chi\chi$ dominant
  - If $m(A') < 2m_\chi$ then **visible decay** $A' \to \ell^+\ell^-$ dominant
- Production from mixing with virtual photon
  - Can oscillate to a dark photon with probability ϵ^2
- Dark photon lifetime proportional to $1/(\epsilon^2 m_{A'})$
  - Light, rarely produced dark photons are displaced

Visible $A' \longrightarrow B$-factories

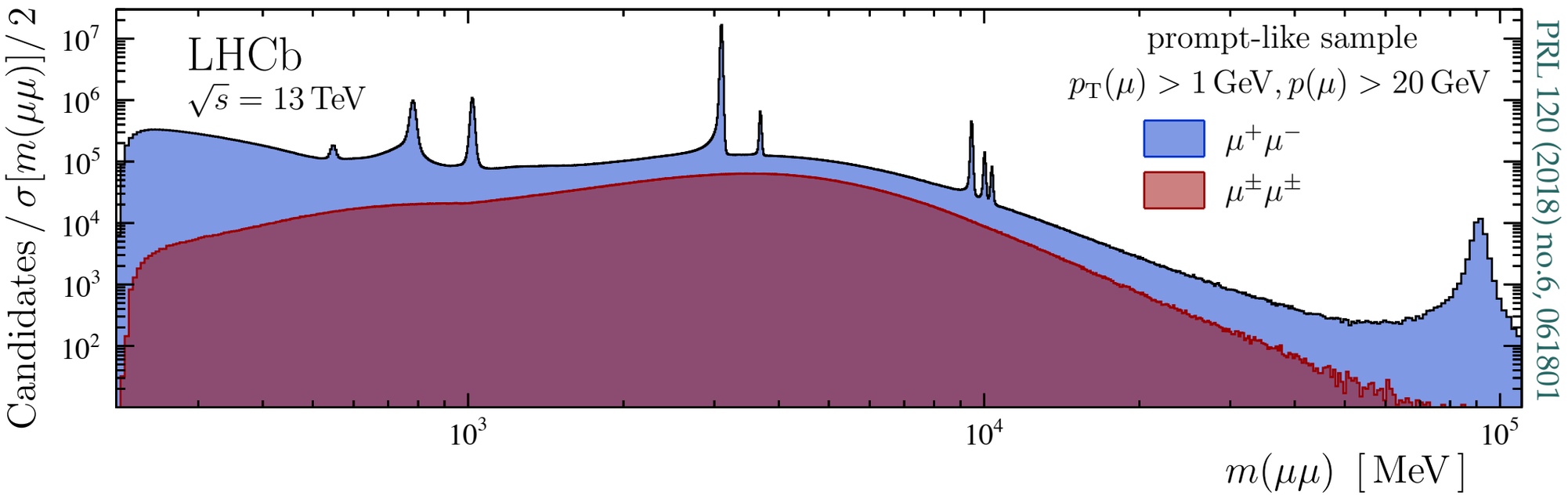
- Search for bump in $m(\ell^+\ell^-)$ spectrum
- Avoid SM resonances
- Large irreducible $\gamma^* \to \ell^+\ell^-$ continuum background
- BaBar placed world-leading bounds
- Belle II will need few years of data to lead sensitivity





Visible $A' \to$ LHCb

Dimuon spectrum from **trigger output**



- Started inclusive $A' \to \mu^+\mu^-$ searches in Run 2
  - Leveraging the online-analysis capabilities introduced in 2015
    → no pre-scale down to threshold $2m_\mu$
  - Great prospects for upcoming upgrade
- First $A' \to \mu^+\mu^-$ search published with 2016 dataset

  PRL 120 (2018) no.6, 061801
- **Now updated with full Run 2 dataset** (factor 3x luminosity)
  - Also greatly improved software trigger efficiency

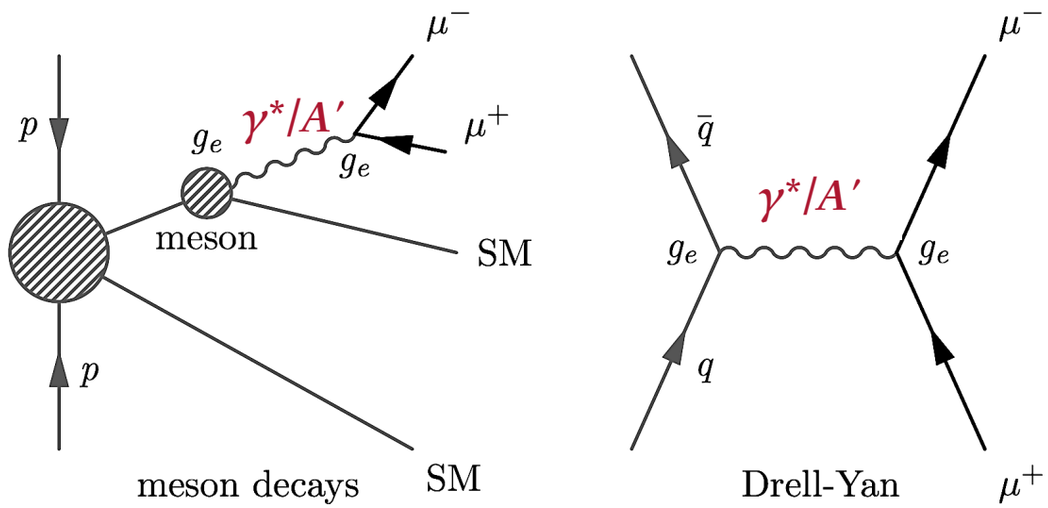
  PRL 124 (2020) 041801

Visible $A' \rightarrow$ LHCb

PRL 120 (2018) no.6, 061801
and PRL 124 (2020) 041801

Analysis strategy:

- inherits production mode of off-shell photon
  → Can normalise to $\gamma^* \rightarrow \mu\mu$ continuum
  → just need to separate non γ^* background
  - No need for efficiencies from simulation (only if displaced vertex)



$$n_{\rm ex}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\, \epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

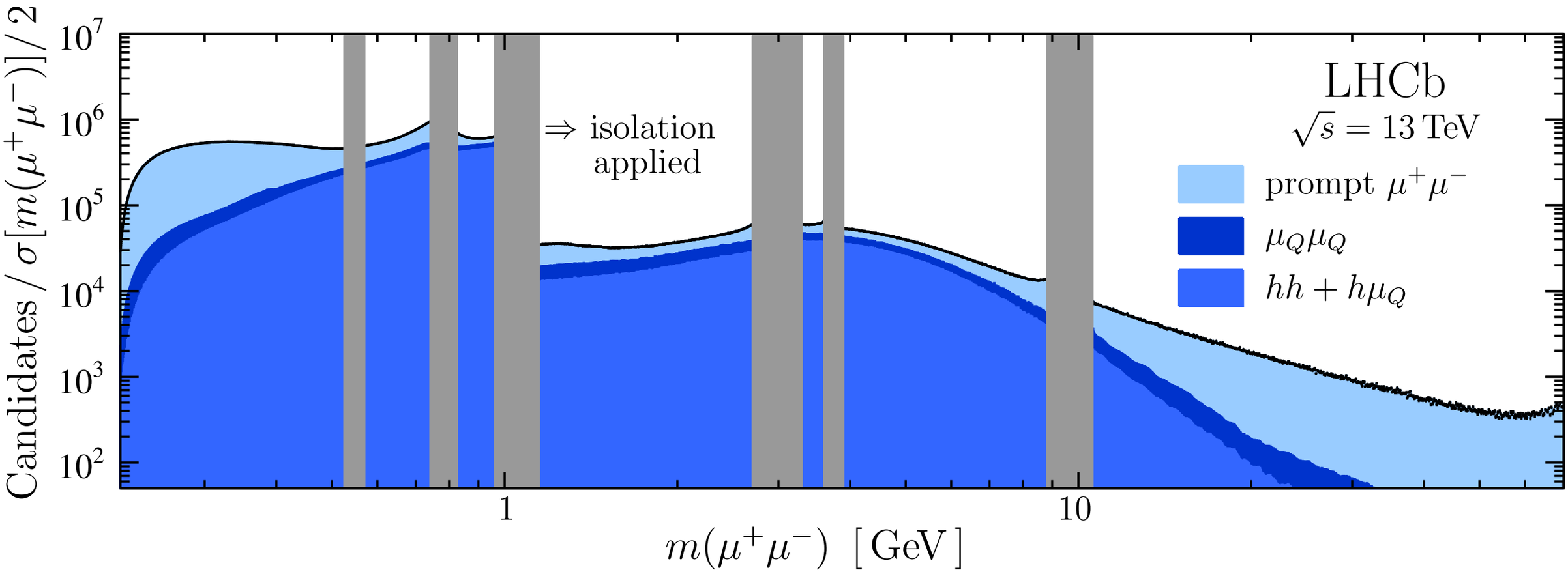
off-shell photon

phase-space

A′ / γ^* eff ratio,
ϵ**=1 for prompt**

Prompt-like $A' \to \mu^+\mu^-$

PRL 120 (2018) no.6, 061801
and PRL 124 (2020) 041801

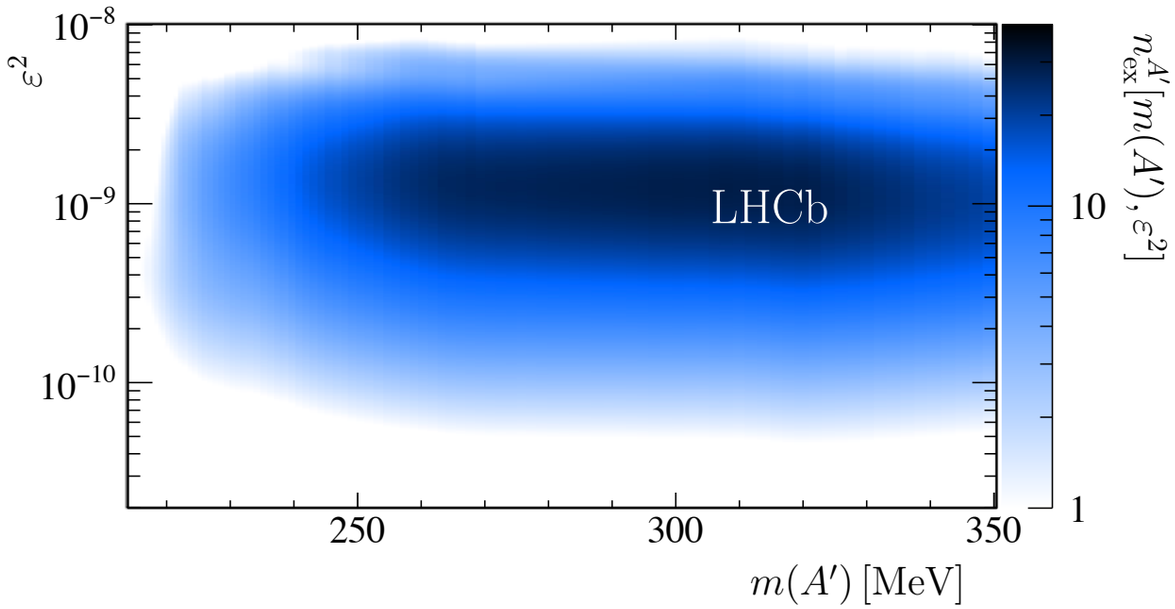


- $O(10^7 - 10^{11}) \times \epsilon^2$ dark photons expected
  - Peak hunt on top of large background
  - Remove regions with QCD resonances

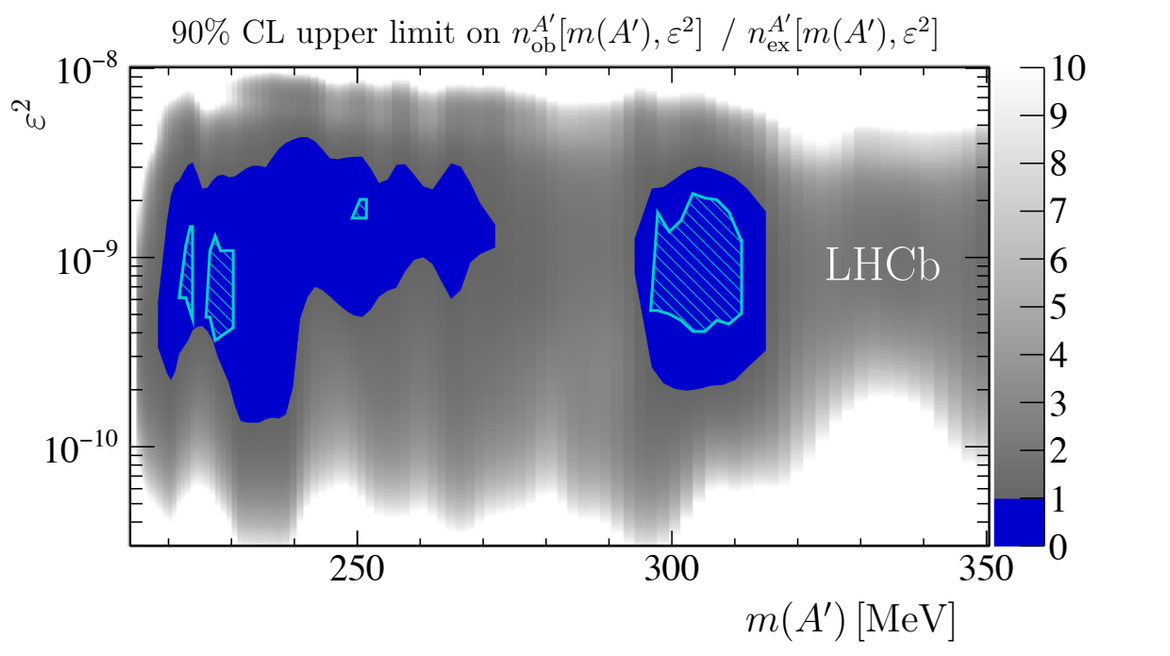
Displaced $A' \to \mu^+\mu^-$

PRL 120 (2018) no.6, 061801
and PRL 124 (2020) 041801

- **Displaced $\mu\mu$ in Vertex Locator** ($d \lesssim 20$ cm)
- Only region $m(A') < 350$ MeV is sensitive
- Even looser online requirements on $p_T(\mu)$
- Main background from γ conversions in the VELO (material map is key to reduce it)

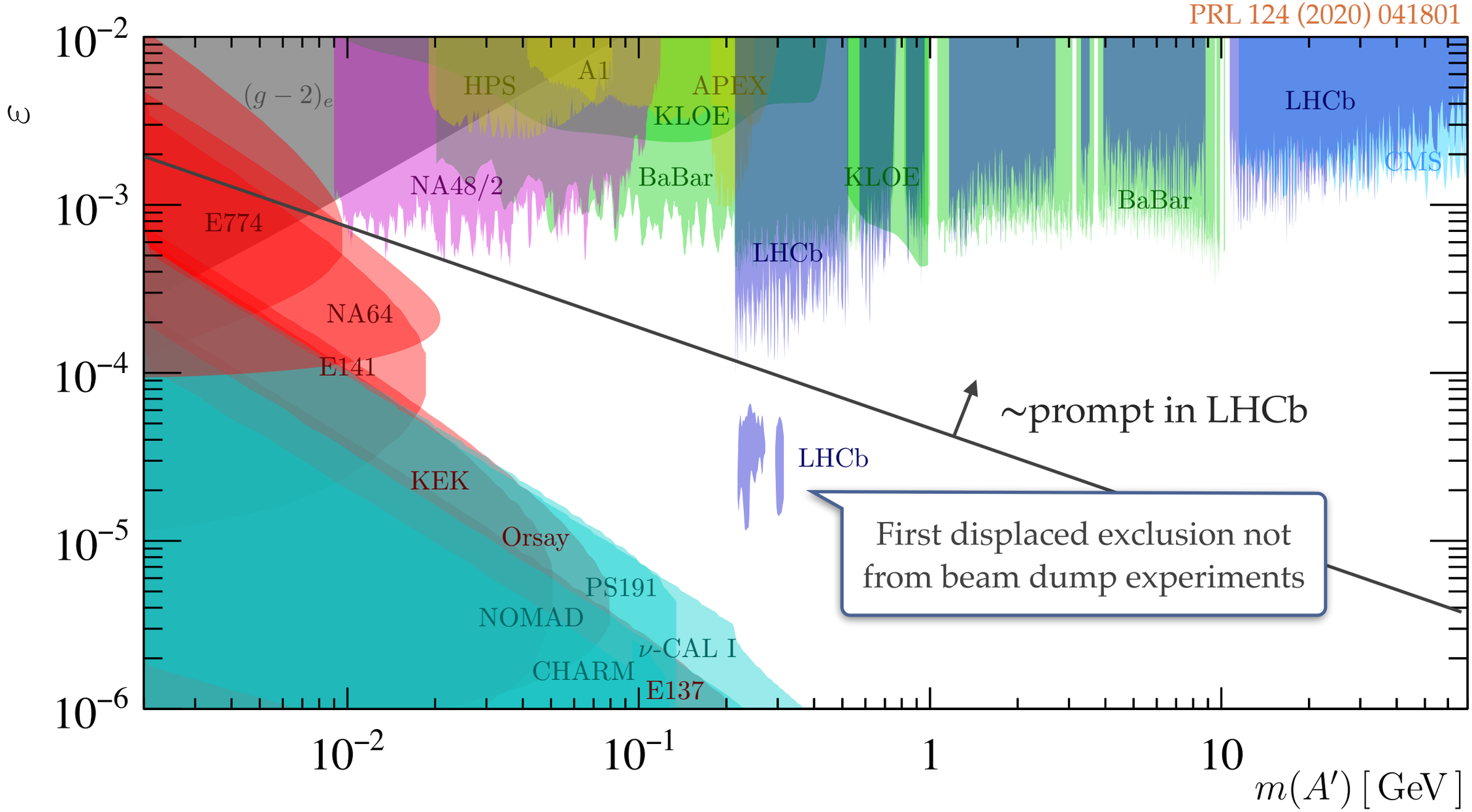


- Fit in bins of mass and lifetime
- **No significant excess is found**
  - Excluded region of phase space (ε^2, m) significantly larger than 2016
  - These are the only displaced limits not coming from beam-dump experiments!



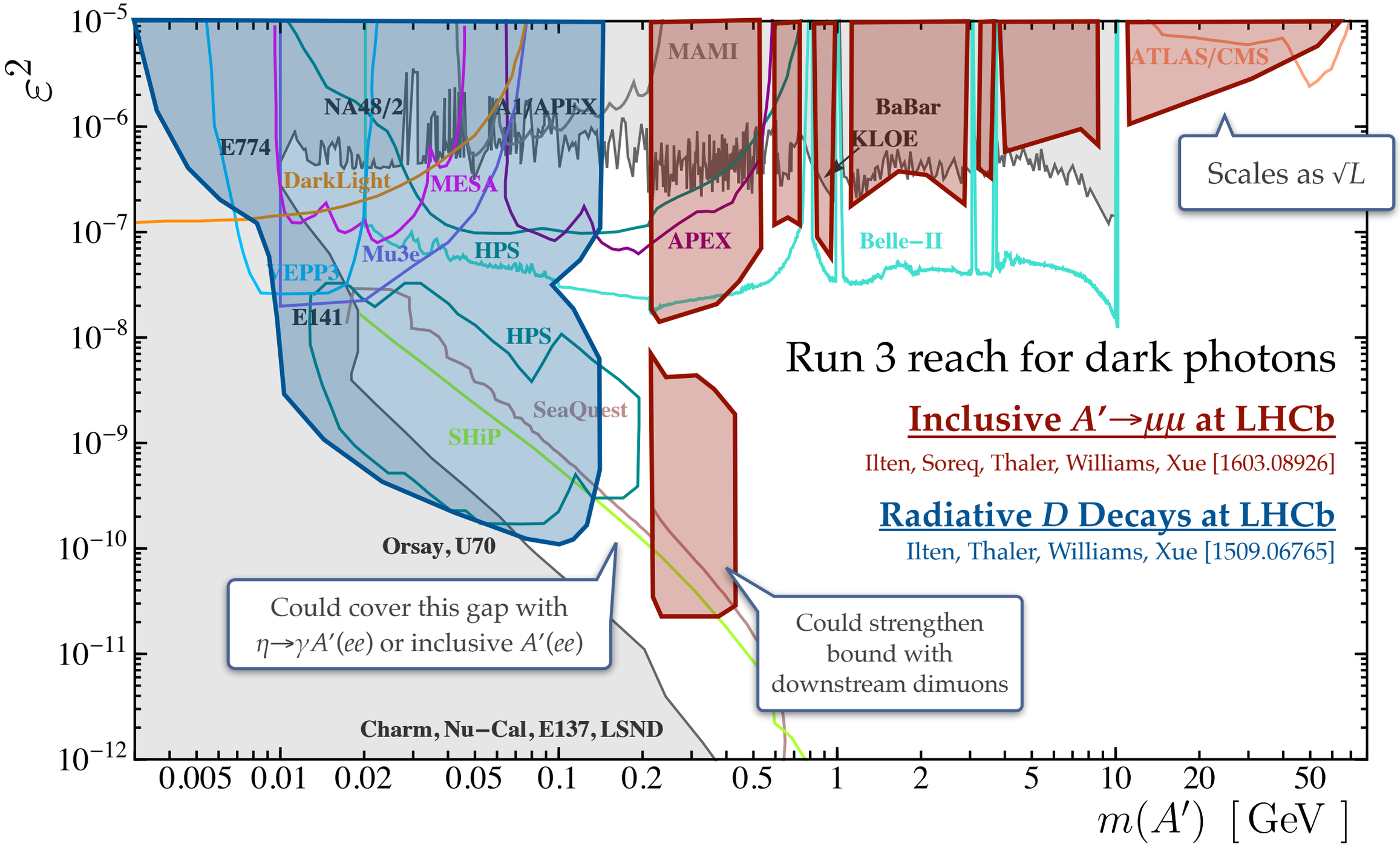
Visible A' limits

PRL 124 (2020) 041801



- Easy to recast to other vector models JHEP 06 (2018) 004
- In Run 3 can also use $D^* \to D^0 A'(e^+e^-)$ PRD 92, 115017 (2015)

Visible A' prospects

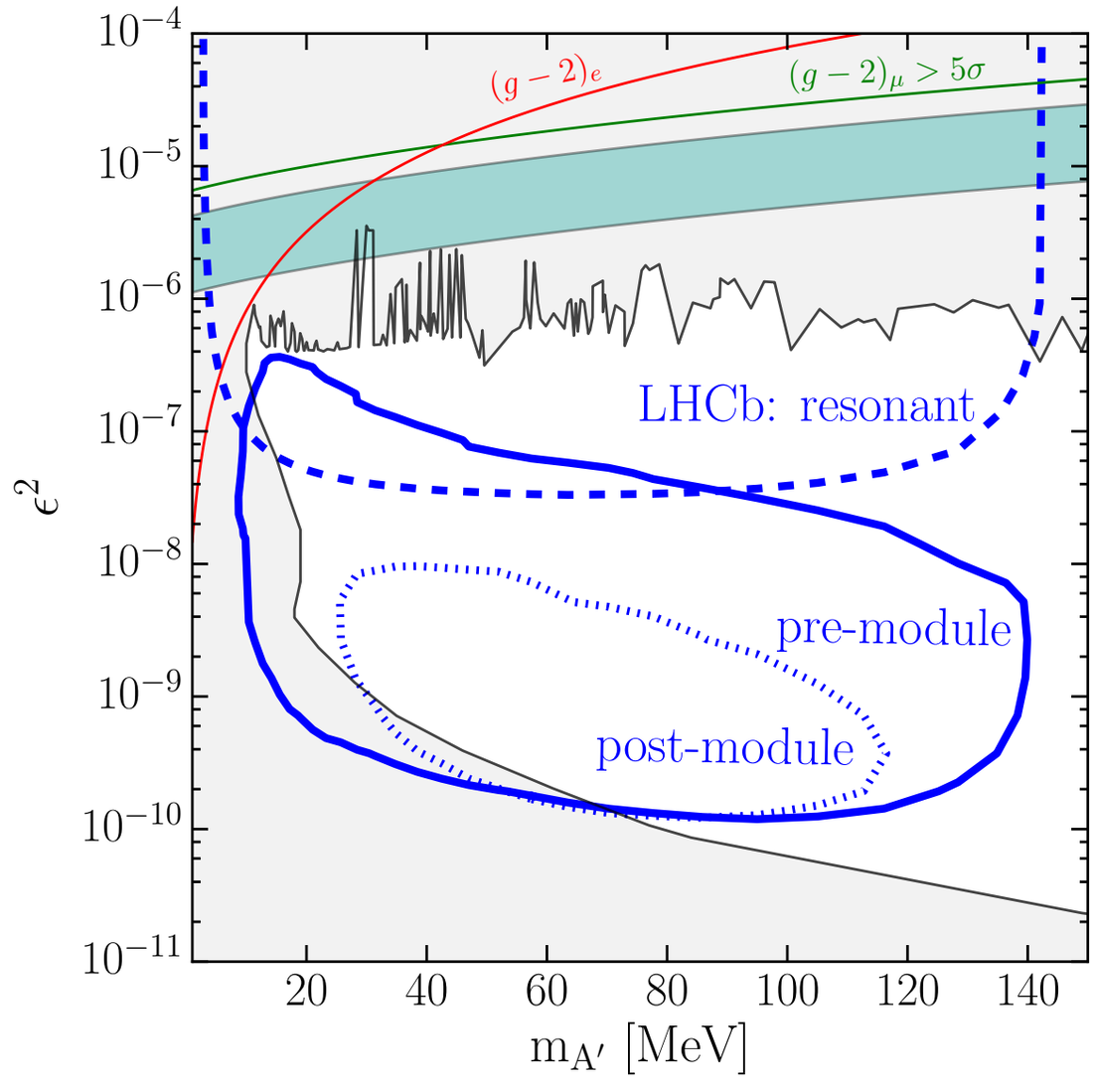


Future Prospects

Dark Photons below $2m_\mu$

Ilten, Thaler, Williams, Xue PRD 92 no.11, 115017 (2015)

- Can cover region below $2m_\mu$ using charm decays $D^{*0} \to D^0 A'(ee)$
  - Requires upgraded trigger to select efficiently soft final state
- Get **300×10⁹** $D^{*0} \to D^0\gamma$ **per fb⁻¹**
- Can use $D^{(*)}$ mass constraint to correct bremsstrahlung losses
- At these p electrons emit light in RICH while pions don't → excellent PID
- Both displaced and prompt searches

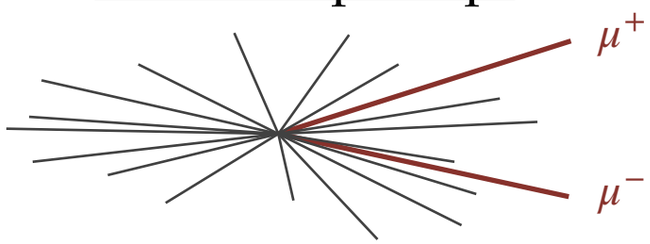


Inclusive $X \to \mu^+\mu^-$ search

LHCb JHEP10(2020)156

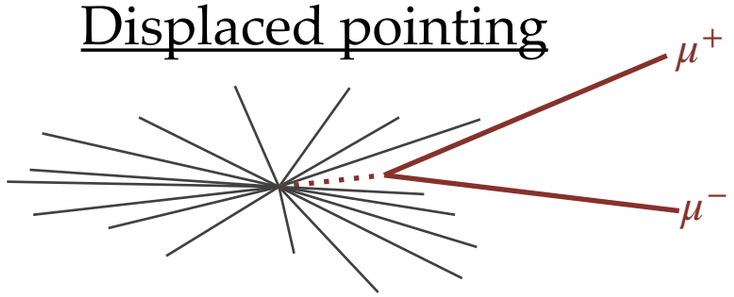
- Probe additional dark sectors in $\mu\mu$
  - Using same trigger as dark photon search
  - Drop assumption of kinetic mixing with γ^*
  - Minimise assumptions on production mechanism (tight fiducial regions and results in kinematic bins)

Inclusive prompt

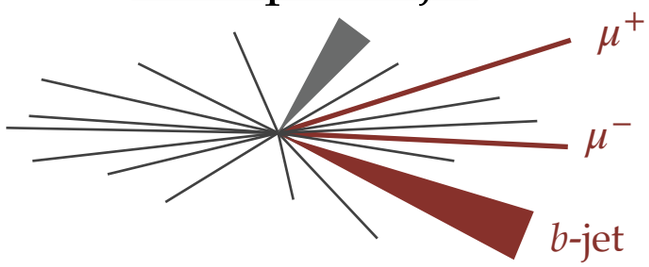


- No isolation requirements
- Non-zero width considered

Displaced pointing

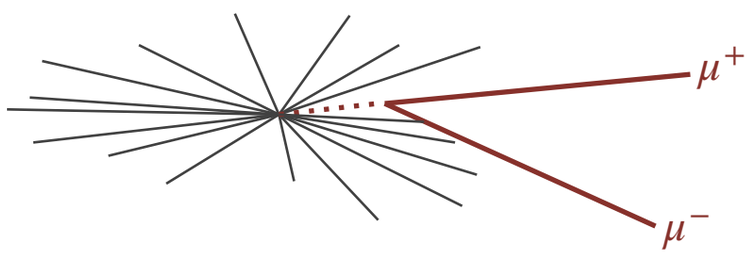


Prompt + b-jet



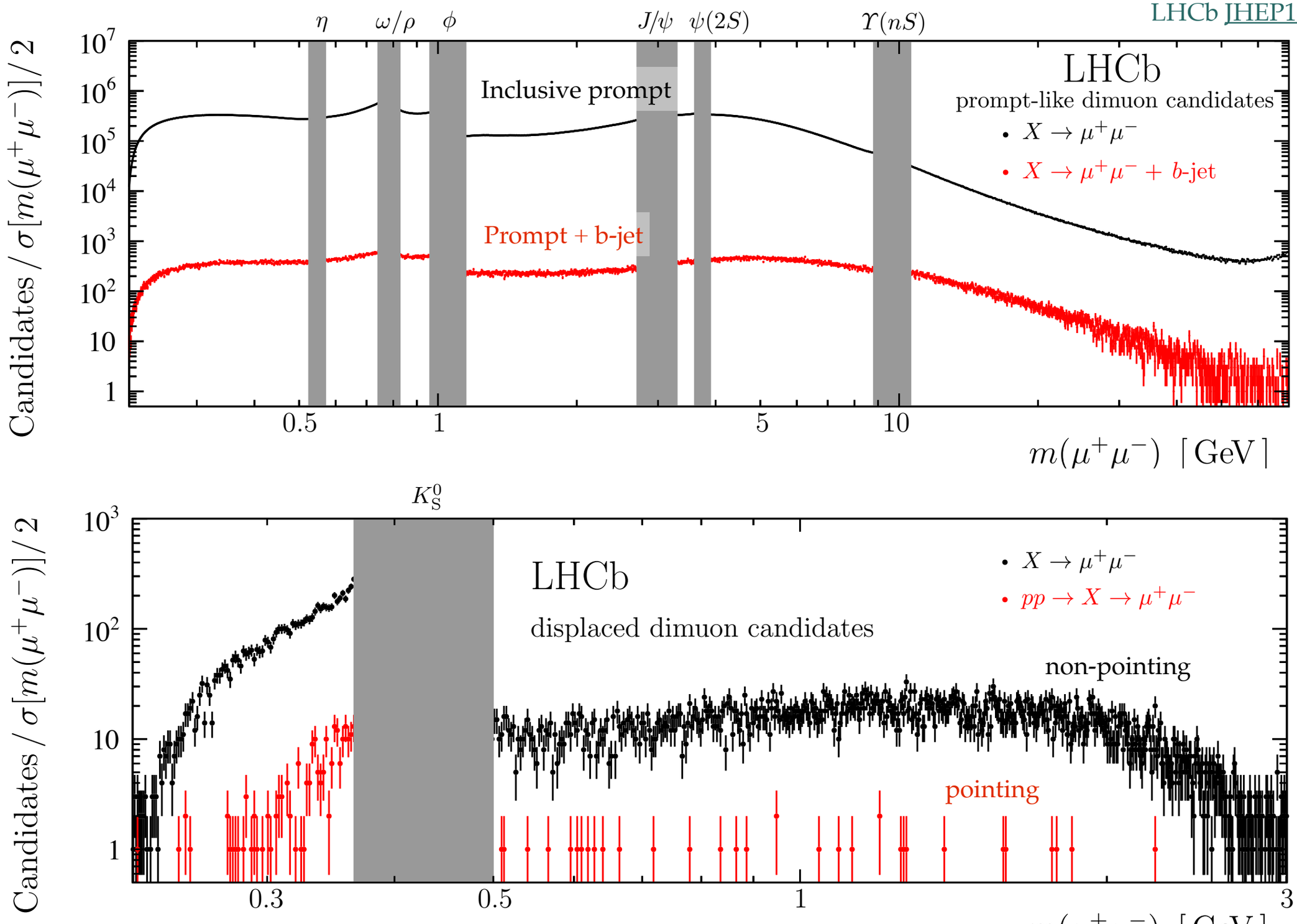
- Non-zero width considered

Displaced non-pointing

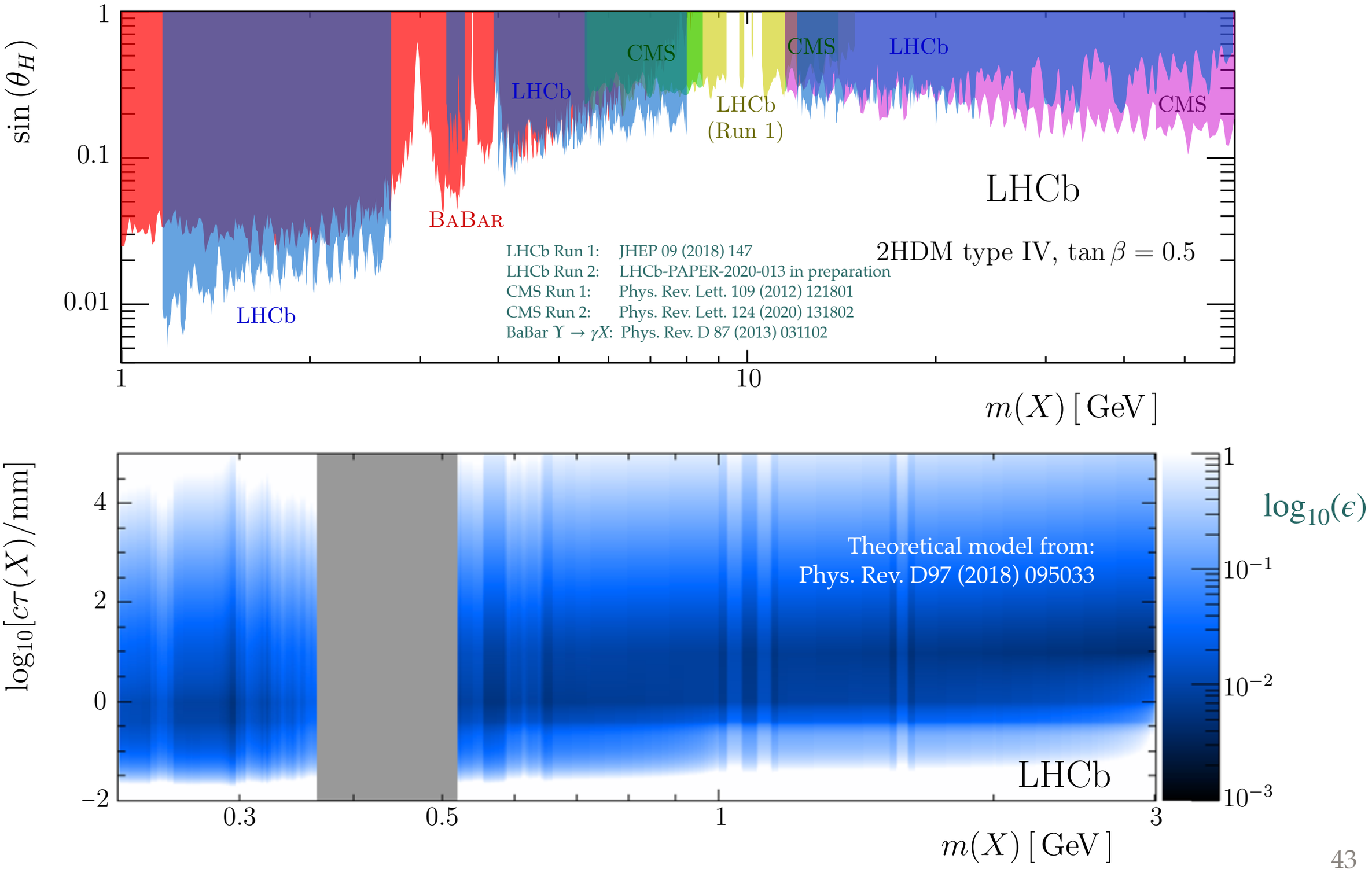


Inclusive $X \to \mu^+\mu^-$ search

LHCb JHEP10(2020)156

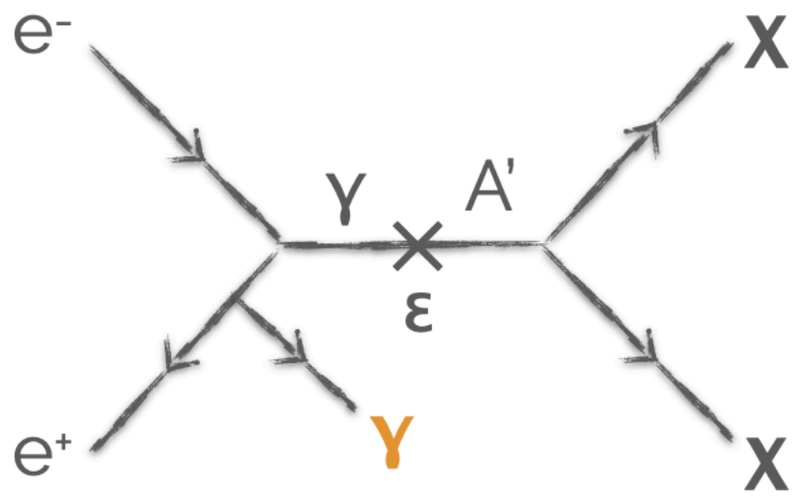


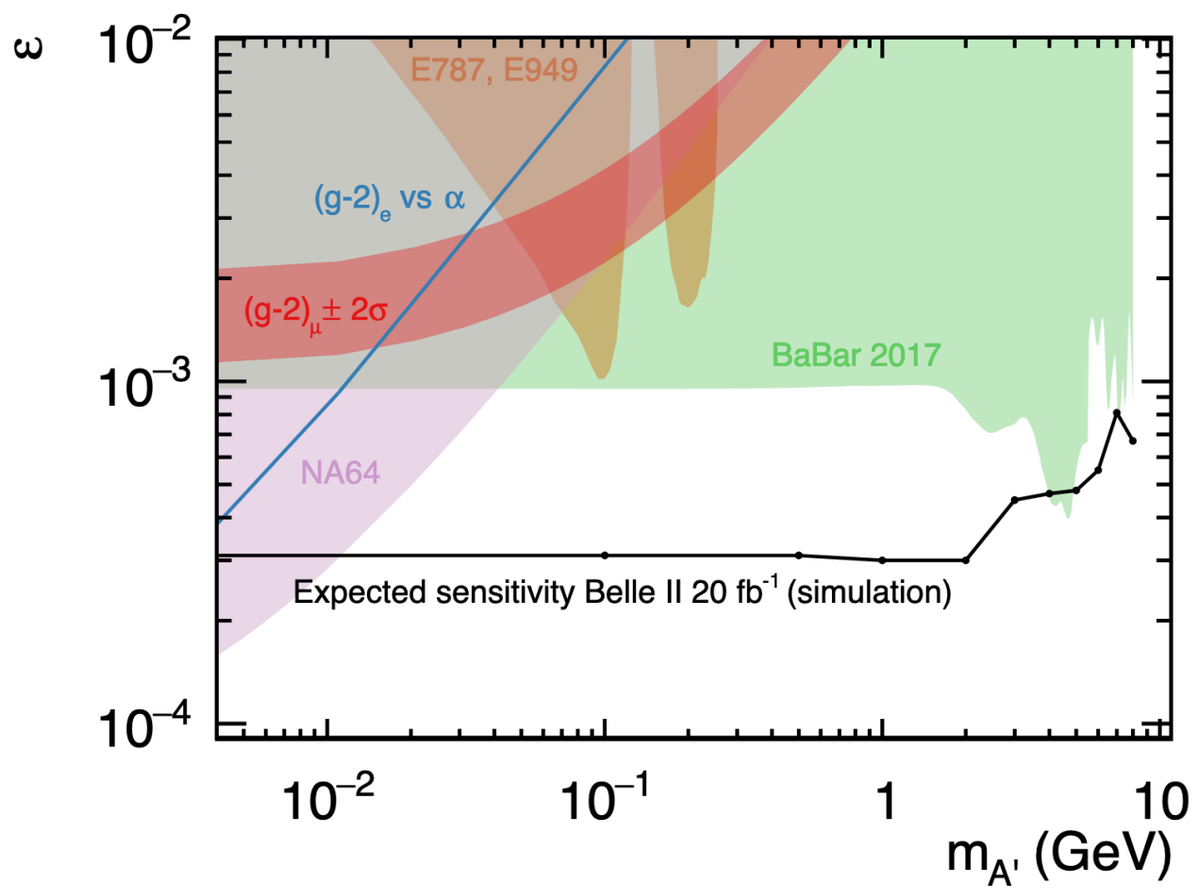
Inclusive $X \to \mu\mu$ interpretation



Invisible $A' \rightarrow$ Belle II

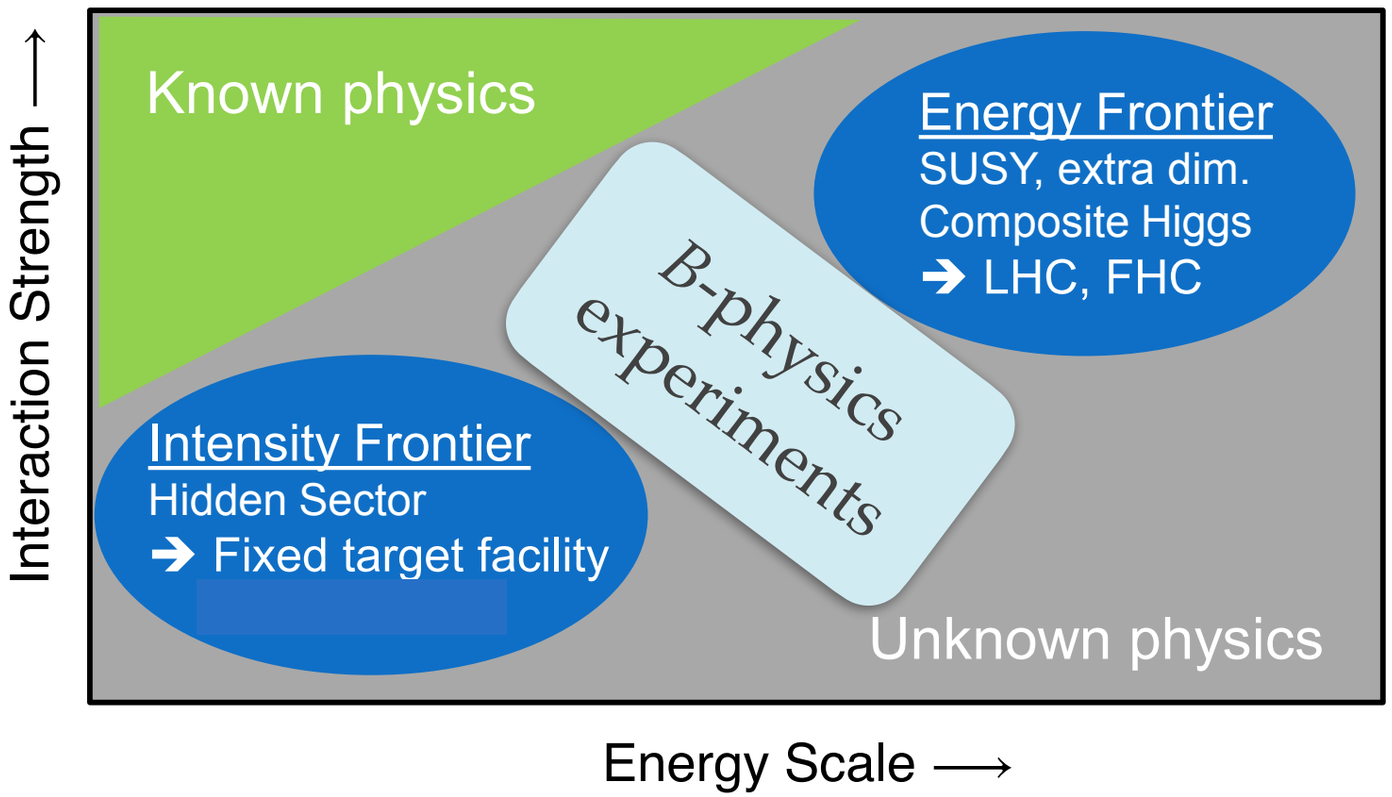
- Signature is only ISR mono-energetic photon
  $E_\gamma = \left(E_{\mathrm{CM}}^2 - m_{A'}^2\right) / \left(2E_{\mathrm{CM}}\right)$
- Implemented single-photon trigger
  - Only 50/fb from BaBar available
- Belle II has better calorimeter hermeticity than Belle/BaBar
- SM backgrounds from
  - $ee \rightarrow \gamma\gamma$ for low $m_{A'}$
  - $ee \rightarrow ee\gamma$ for high $m_{A'}$





Conclusions

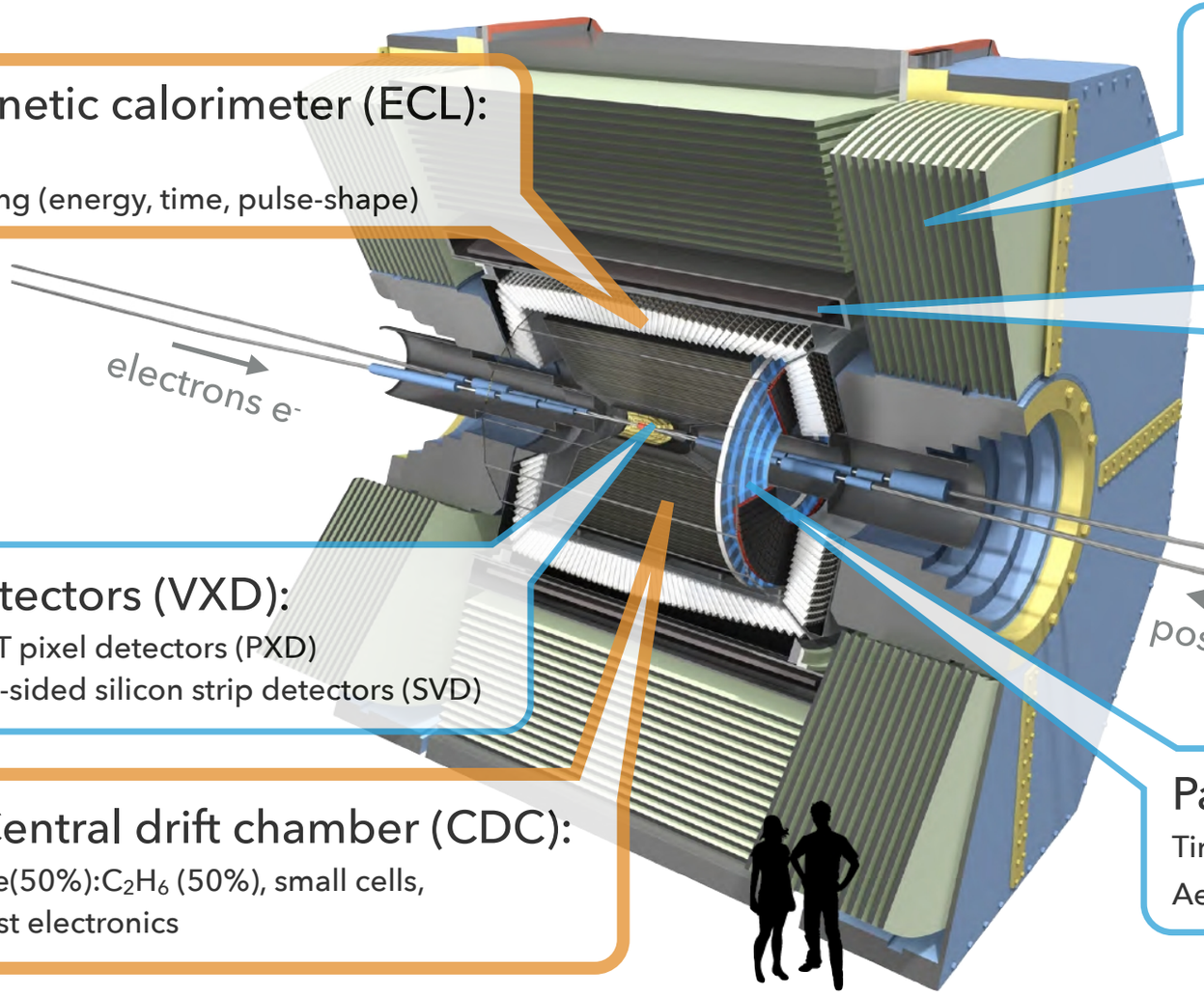
SHiP physics case Rept.Prog.Phys. 79 (2016) no.12, 124201



- Well motivated dark sectors with multiple portals
  - Light masses, small couplings, displaced vertices
- B-physics detectors can contribute to the hunt for dark sector particles!
  - Produced in B decays (virtual W, Z, top) and directly in collisions
- Lots of space for ideas to implement in LHCb Upgrade and Belle II

BACKUP

Belle II detector



Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

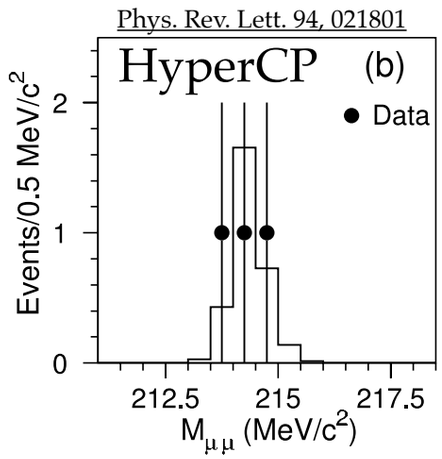
Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

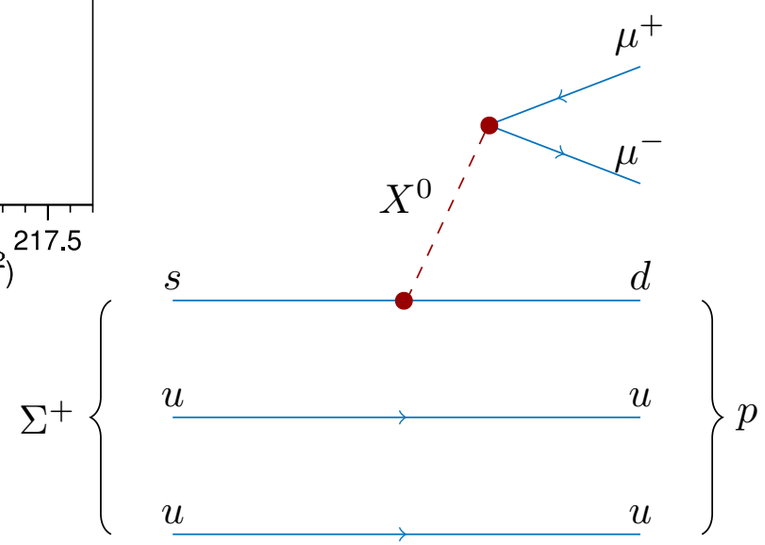
DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

Dark Bosons from $s \to d$

- **LHCb can search even in rare $s \to d$**
  - Motivated by HyperCP anomaly at $m_X = 214.3 \pm 0.5$ MeV PRL 94,021801
  - Various interpretations related to DM
    N.Arkani-Hamed, N.Weiner, JHEP 0812(2008)104
    M.Pospelov, Phys.Rev. D80 (2009) 095002



LHCb, PRL 120, 221803 (2018)



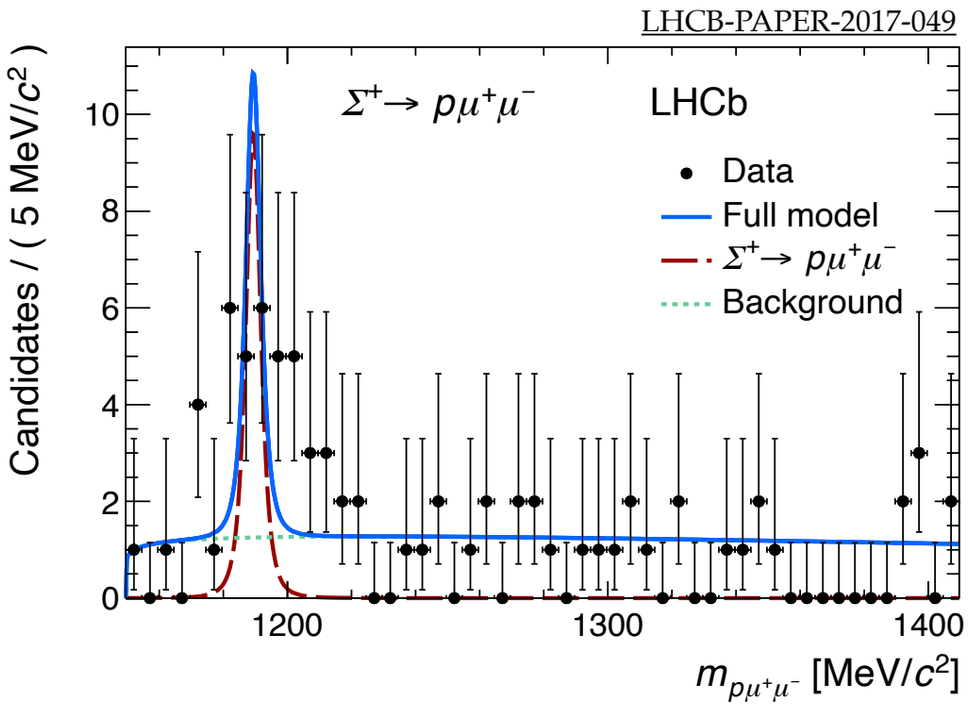
- LHCb got evidence for SM $\Sigma^+ \to p\mu\mu$ at 4.0 σ
  $\Rightarrow$ searched in $\mu\mu$ spectrum

- **No HyperCP anomaly observed**:

$$\mathcal{B}(\Sigma^+ \to pX^0) < 9.5 \times 10^{-9} \text{ at } 95\% \text{ CL}$$

- For comparison HyperCP observed:

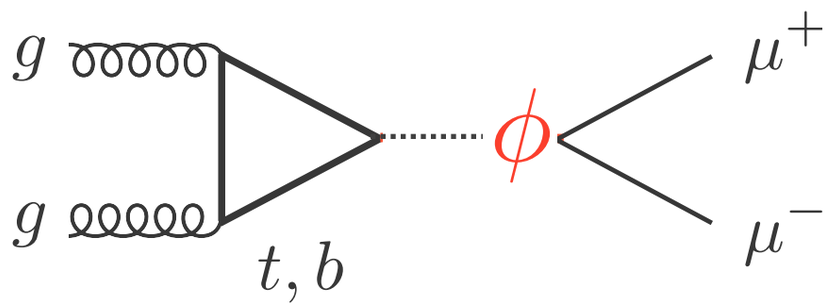
$$\mathcal{B}(\Sigma^+ \to pX^0) = (31^{+24}_{-19} \pm 15) \times 10^{-9}$$



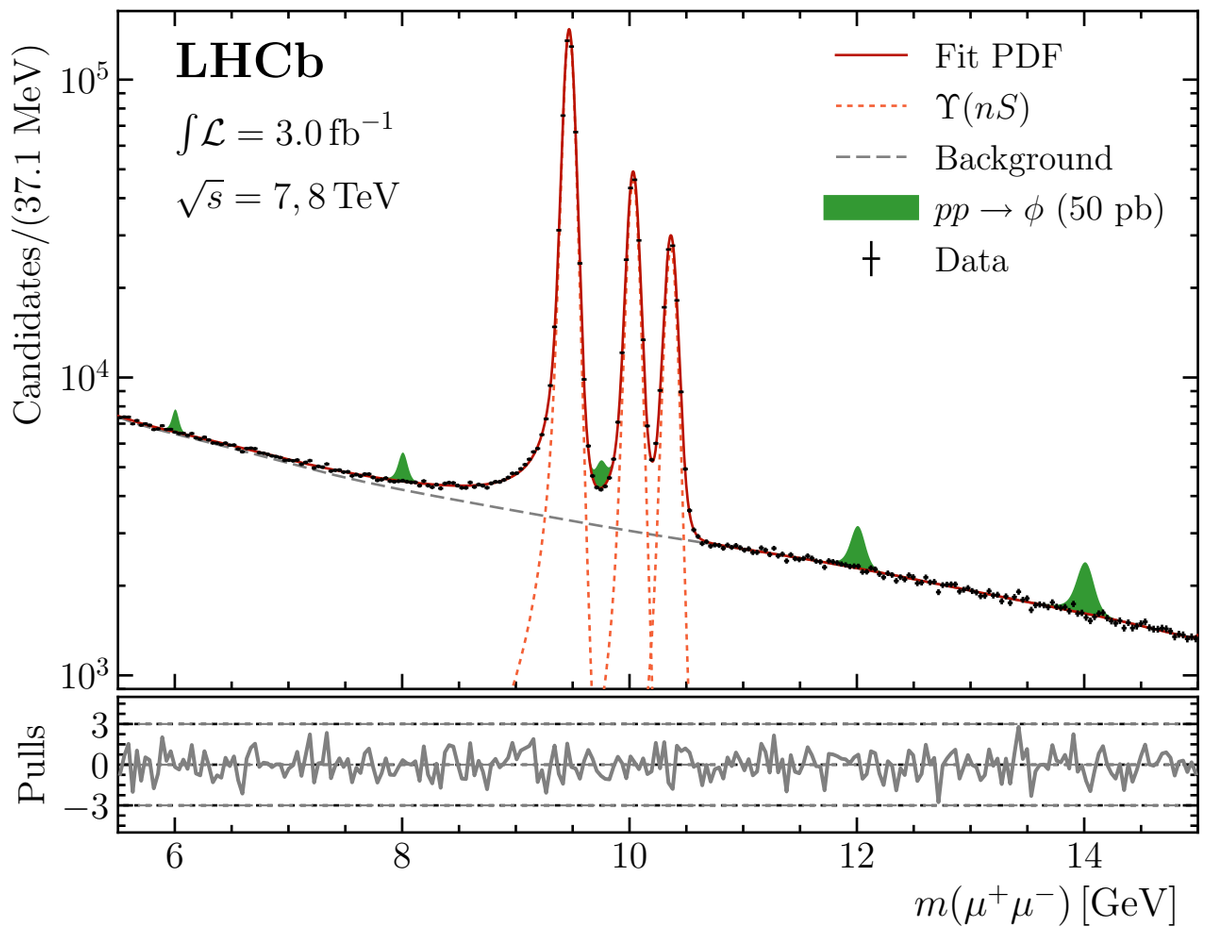
Dark Bosons from ggF

LHCb, arXiv:1805.09820

- Spin-0 particles copiously produced in ggF $\Rightarrow$ Extensive searches at the LHC



- m~10 GeV difficult for $\gamma\gamma$ or $\tau\tau$ searches
  Haisch et al arXiv:1802.02156
  - **Use $\mu\mu$: mass resolution is key**



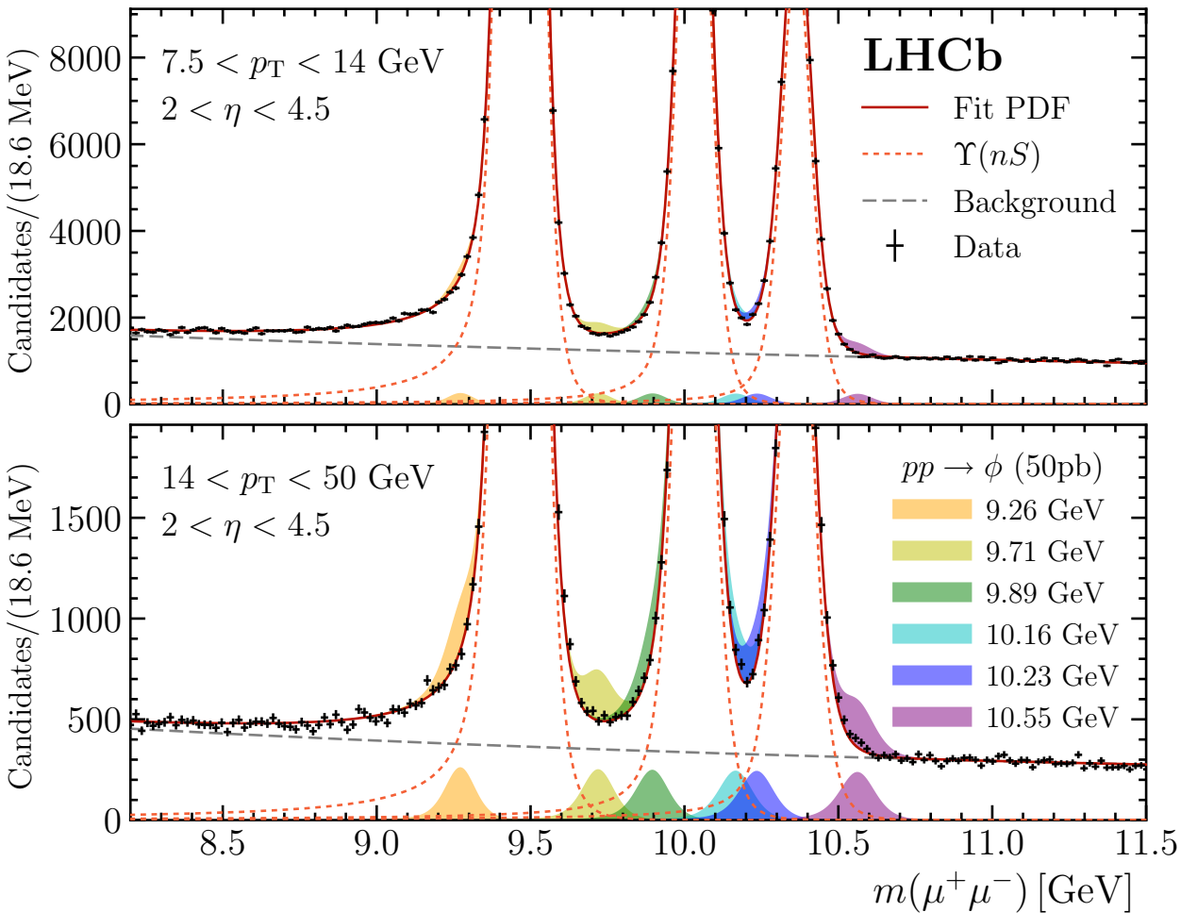
- Analysis features:
  - Mass-independent efficiency (using uniform BDT technique)
  - Bins of kinematics to maximise sensitivity model independently
  - Fit run in GPU to speed-up CLs method
    Santiago's framework arXiv:1706.01420

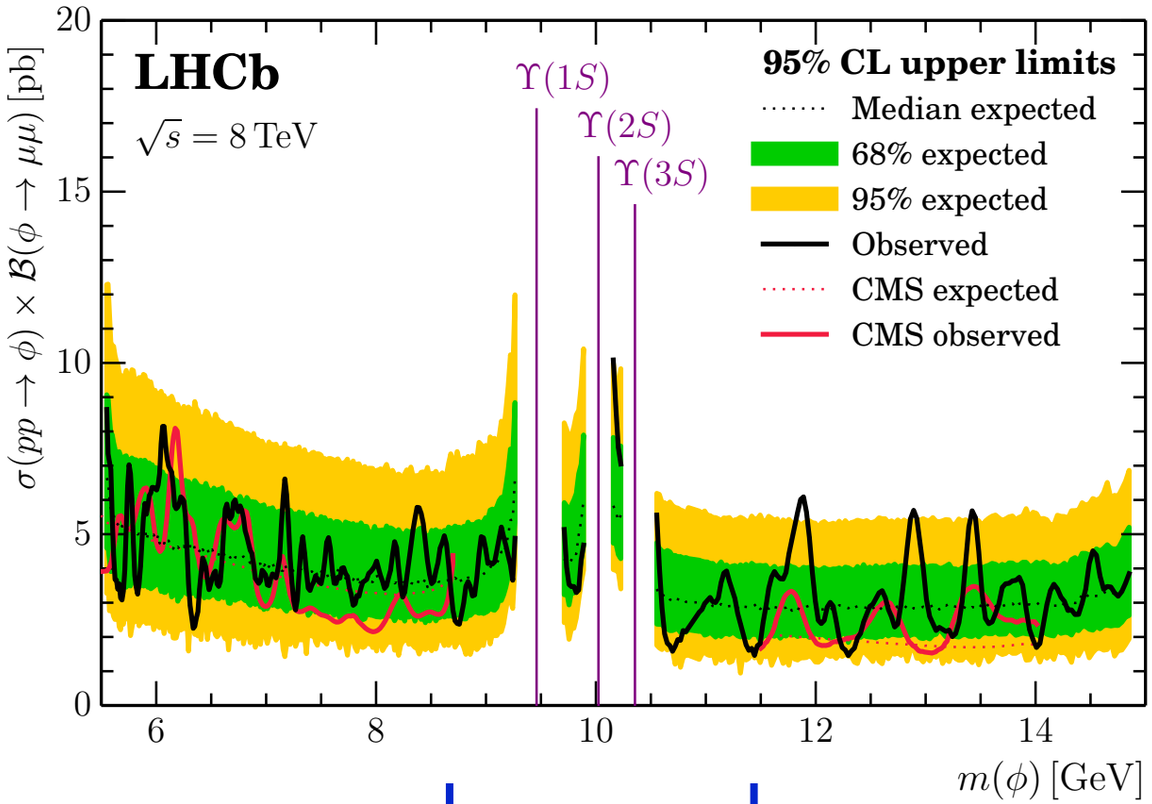
Dark Bosons from ggF

LHCb, arXiv:1805.09820

- Precise modelling of Υ(nS) tails to search as close as possible

D.Martinez Santos et al NIM A764(2014)150





- First limits in **8.7-11.5 GeV region**
- Competitive with CMS elsewhere

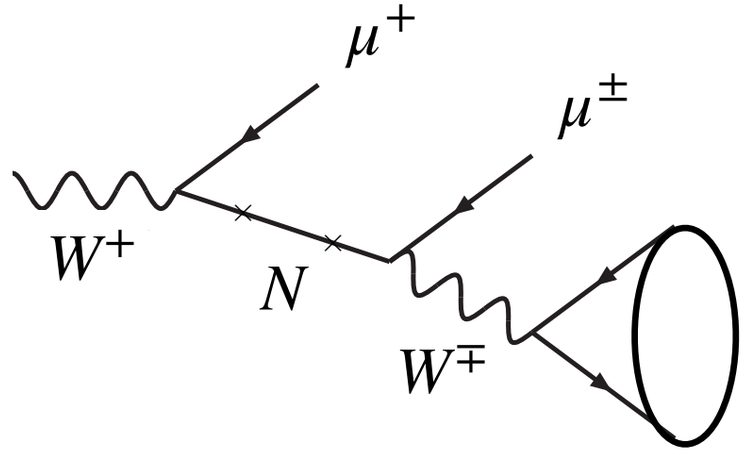
CMS PRL 109(2012)121801

Search for $W^+ \to \mu^+\mu^\pm$jet

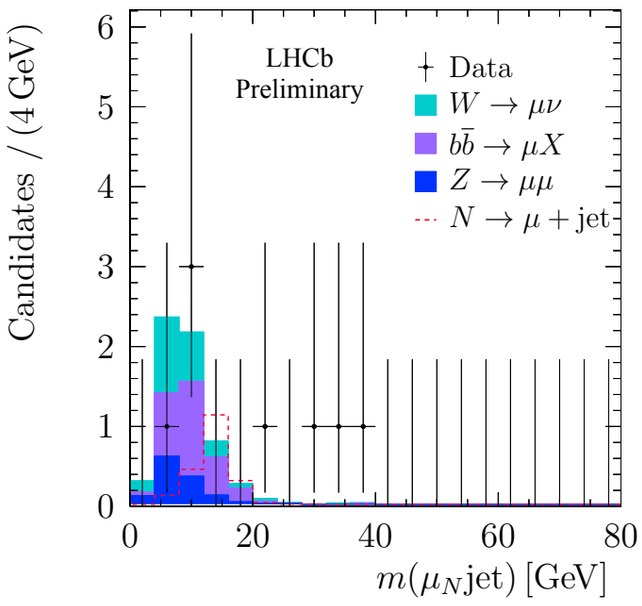
NEW

LHCb-PAPER-2020-022 in preparation

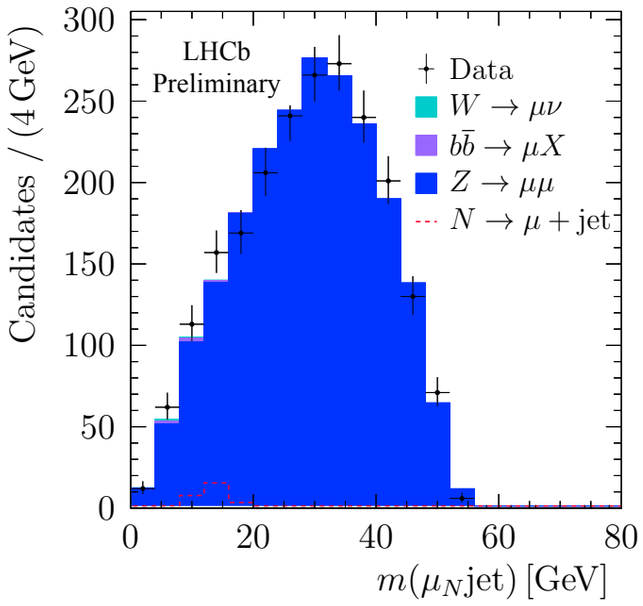
- Target is a heavy neutrino $N \to \mu^\pm$jet
  - Using Run 1 dataset (3/fb)
  - Searching both $\mu^+\mu^+$jet and $\mu^+\mu^-$jet
  - Limits not yet competitive (ATLAS, CMS, LEP)
    → interesting sensitivity in Upgrade

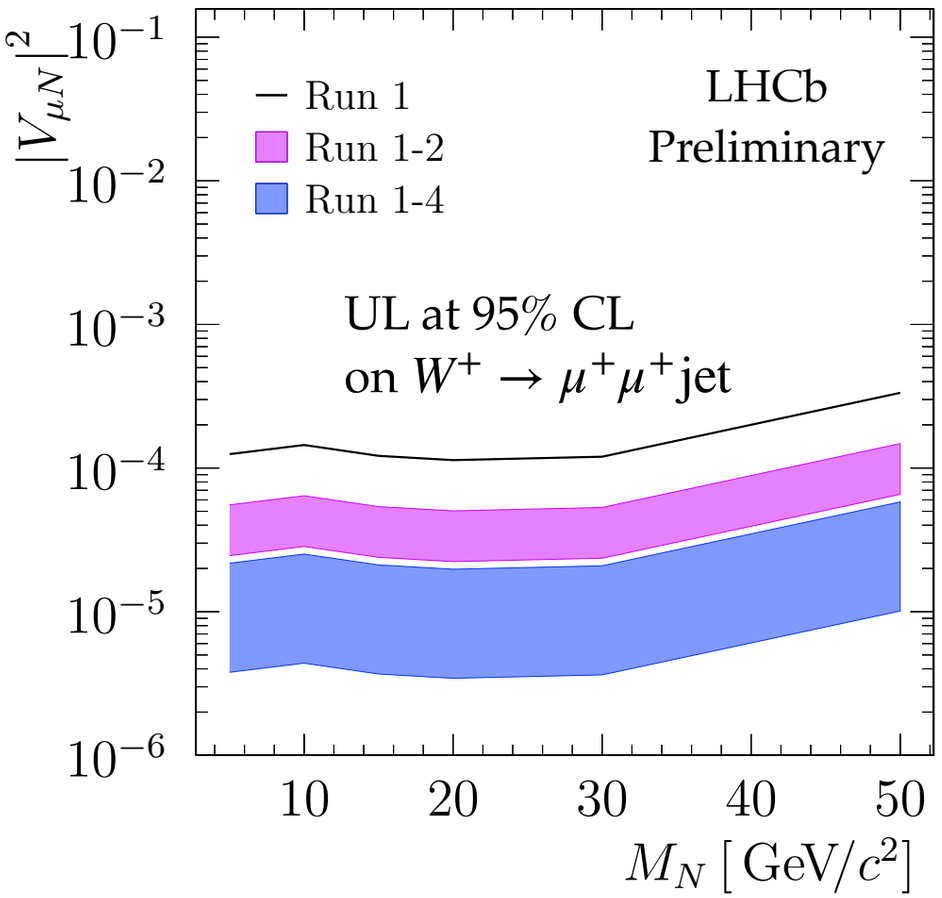


Same-sign muons



Opposite-sign muons



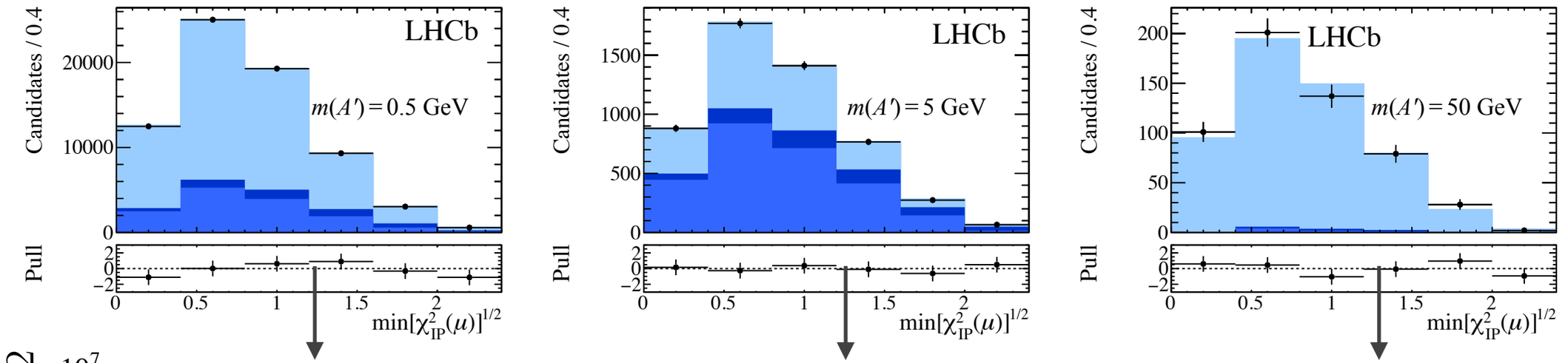


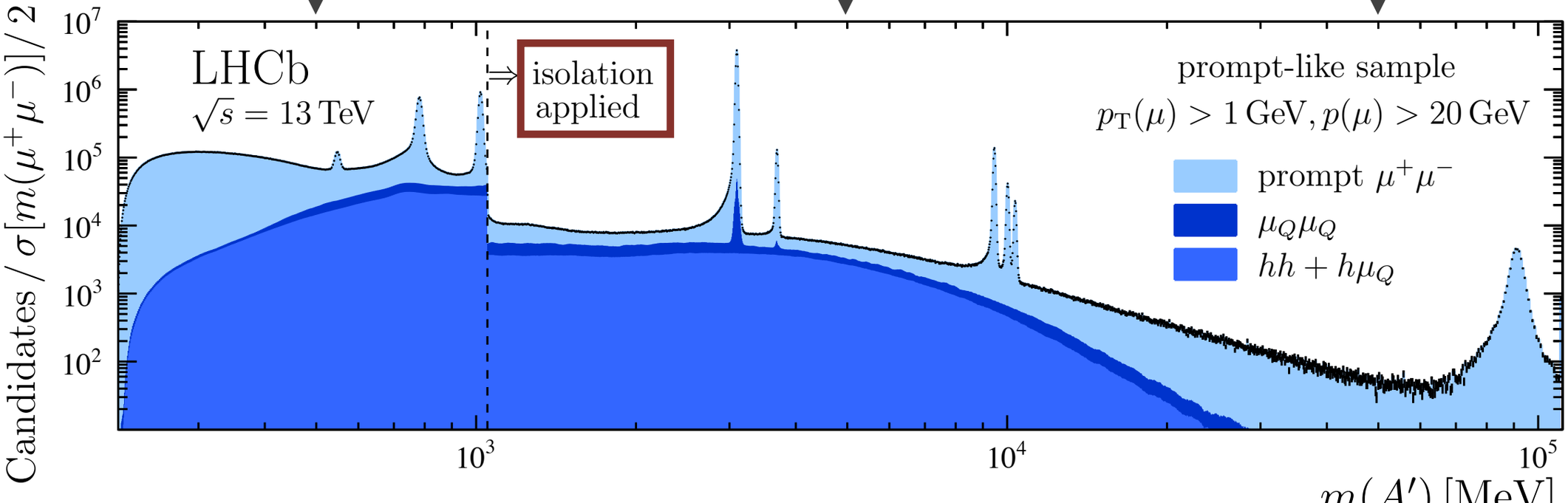
Strategy for prompt-like $A' \to \mu^+\mu^-$

PRL 120 (2018) no.6, 061801
and new arXiv:1910.06926

prompt $\mu^+\mu^-$ → from data at $m(J/\psi)$ and $m(Z)$
$\mu_Q\mu_Q$ → from min[χ^2_{IP}] template fit
$hh + h\mu_Q$ → from same-sign $\mu^+\mu^+$ (corrected)

(μ_Q is a muon from a heavy-flavour decay)





PRL 120 (2018) no.6, 061801

$X \to \mu^+\mu^-$ fiducial regions

LHCb arXiv:2007.03923

all searches

$$p_{\mathrm{T}}(\mu) > 0.5\,\mathrm{GeV}, \quad 10\,\mathrm{GeV} < p(\mu) < 1\,\mathrm{TeV}, \quad 2 < \eta(\mu) < 4.5, \quad \sqrt{p_{\mathrm{T}}(\mu^+) p_{\mathrm{T}}(\mu^-)} > 1\,\mathrm{GeV}$$

$$5 \leq n_{\mathrm{charged}}(2 < \eta < 4.5, p > 5\,\mathrm{GeV}) < 100 \text{ (from same PV as } X \to \mu^+\mu^-)$$

prompt-like $X \to \mu^+\mu^-$ decays

$$1 < p_{\mathrm{T}}(X) < 50\,\mathrm{GeV}, \quad X \text{ proper decay time} < 0.1\,\mathrm{ps}, \quad \alpha(\mu^+\mu^-) > 1\,\mathrm{mrad}$$

$$20 < p_{\mathrm{T}}(b\text{-jet}) < 100\,\mathrm{GeV}, \quad 2.2 < \eta(b\text{-jet}) < 4.2 \ (X + b \text{ only})$$

displaced $X \to \mu^+\mu^-$ decays

$$2 < p_{\mathrm{T}}(X) < 10\,\mathrm{GeV}, \quad 2 < \eta(X) < 4.5, \quad \alpha(\mu^+\mu^-) > 3\,\mathrm{mrad}, \quad 12 < \rho_{\mathrm{T}}(X) < 30\,\mathrm{mm}$$

Comments:

- $\alpha(\mu^+\mu^-) > 1(3)$ mrad so that $\varepsilon(\mu^+\mu^-) \simeq \varepsilon(\mu^+)\varepsilon(\mu^-)$
  - This is rarely satisfied at $p_{\mathrm{T}} > 50$ GeV
- Formed b-jets with anti-k_{T} using $R = 0.5$
- $12 < \rho_{\mathrm{T}} < 30$ mm results in minimal $\varepsilon(\rho_{\mathrm{T}})$ dependence
- Split in p_{T} bins for $m(\chi) < 20$ GeV to better model efficiency and $m(\chi)$resolution

$X \to \mu^+\mu^-$ systematics

LHCb Preliminary

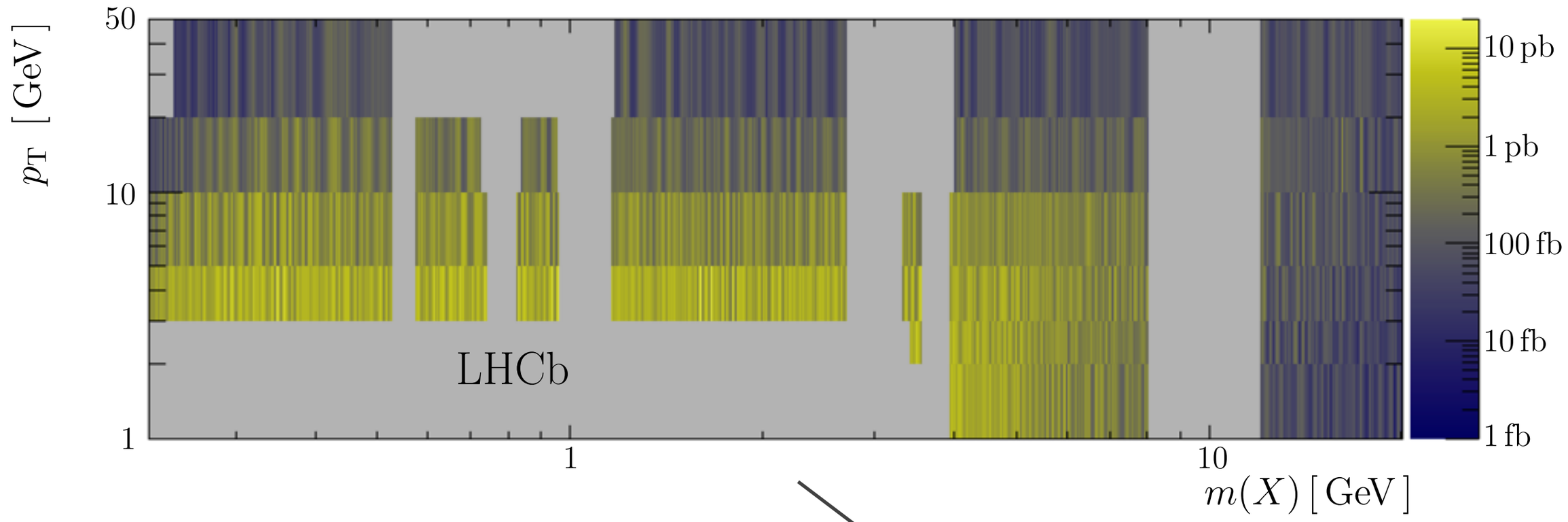
LHCb arXiv:2007.03923

source	relative uncertainty
signal model	5%
background model	data driven, see Sec. 4
trigger, reconstruction, selection	2–5% (bin dependent)
charged-particle multiplicity	5%
X kinematics	10–30% (bin dependent)
b-jet selection	11% ($X + b$ only)
SV selection	5% (SV-based only)
X SV distribution	10% (SV-based only)
luminosity	6%*
total	11–30% (bin dependent)

$X \to \mu^+\mu^-$ in [your model here]

LHCb JHEP10(2020)156

Example: UL at 90% CL on $\sigma(X \to \mu^+\mu^-)$ for prompt-like $X \to \mu^+\mu^-$



- Anyone is encouraged to reinterpret the results:
  - Get numbers from the supplementary material
  - Fiducial regions, plots and details in the paper

Corresponding fiducial region

All searches	$p_{\mathrm{T}}(\mu) > 0.5\,\mathrm{GeV}$ $10 < p(\mu) < 1000\,\mathrm{GeV}$ $2 < \eta(\mu) < 4.5$ $\sqrt{p_{\mathrm{T}}(\mu^+) p_{\mathrm{T}}(\mu^-)} > 1\,\mathrm{GeV}$ $5 \le n_{\mathrm{charged}}(2 < \eta < 4.5, p > 5\,\mathrm{GeV}) < 100$ (from same PV as X)
Prompt-like $X \to \mu^+\mu^-$ decays	$1 < p_{\mathrm{T}}(X) < 50\,\mathrm{GeV}$ X decay time $< 0.1\,\mathrm{ps}$ $\alpha(\mu^+\mu^-) > 1\,\mathrm{mrad}$ $20 < p_{\mathrm{T}}(b\text{-jet}) < 100\,\mathrm{GeV},\ 2.2 < \eta(b\text{-jet}) < 4.2$ ($X + b$ only)

$X \to \mu^+\mu^-$ in 2HDM+S

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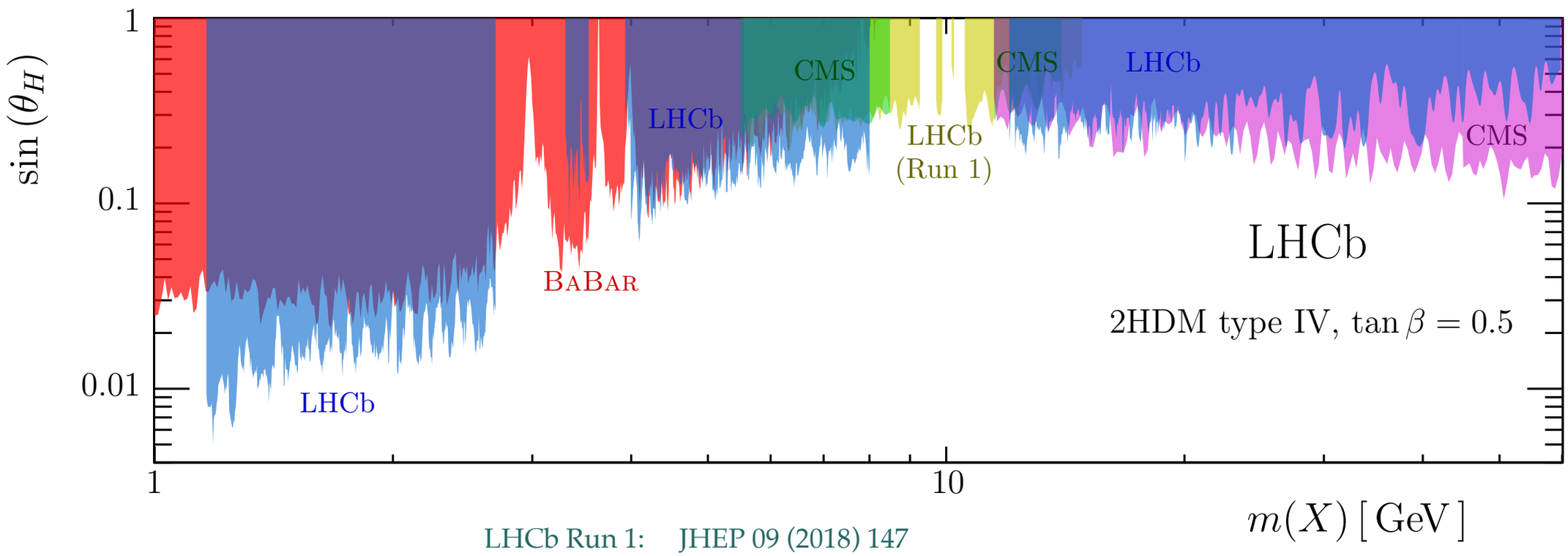
- Use **prompt search** to place limits on **2HDM** + complex scalar singlet
  - World-best upper limit on mixing angle with SM Higgs $\sin(\theta_H)$ PRD 93 (2016) 055047
  - In this scenario, $X + b\bar{b}$ excess seen by CMS (JHEP 11 (2018) 161) excluded with 20 times lower cross section

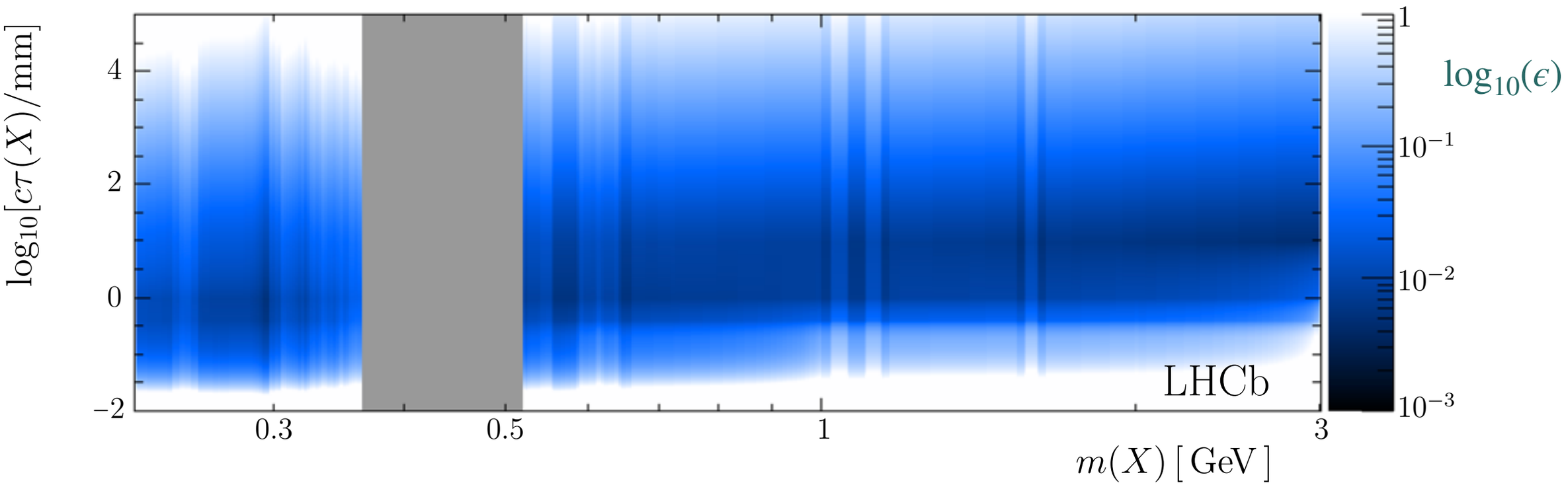


LHCb Run 1: JHEP 09 (2018) 147
LHCb Run 2: LHCb-PAPER-2020-013 in preparation
CMS Run 1: Phys. Rev. Lett. 109 (2012) 121801
CMS Run 2: Phys. Rev. Lett. 124 (2020) 131802
BaBar $\Upsilon \to \gamma X$: Phys. Rev. D 87 (2013) 031102

$X \to \mu^+\mu^-$ in Hidden Valley

LHCb JHEP10(2020)156

- Example: use **displaced search** results to place limits on Hidden Valley model with "dark showers" of light **hidden hadrons**
  - 90% upper limits on kinetic mixing between γ and heavy $Z_{\rm HV}$
  - Results depend on hidden hadron multiplicity (here $< N_{\rm HV} > \simeq 10$)
  - World-first constraints below unity for this mixing strength

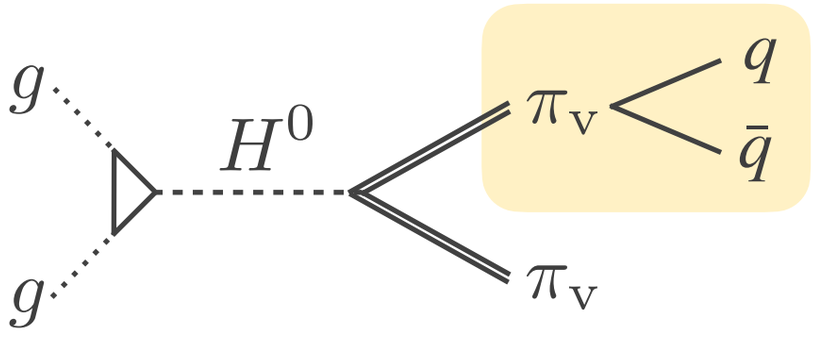


Theoretical model from:
Phys. Rev. D97 (2018) 095033

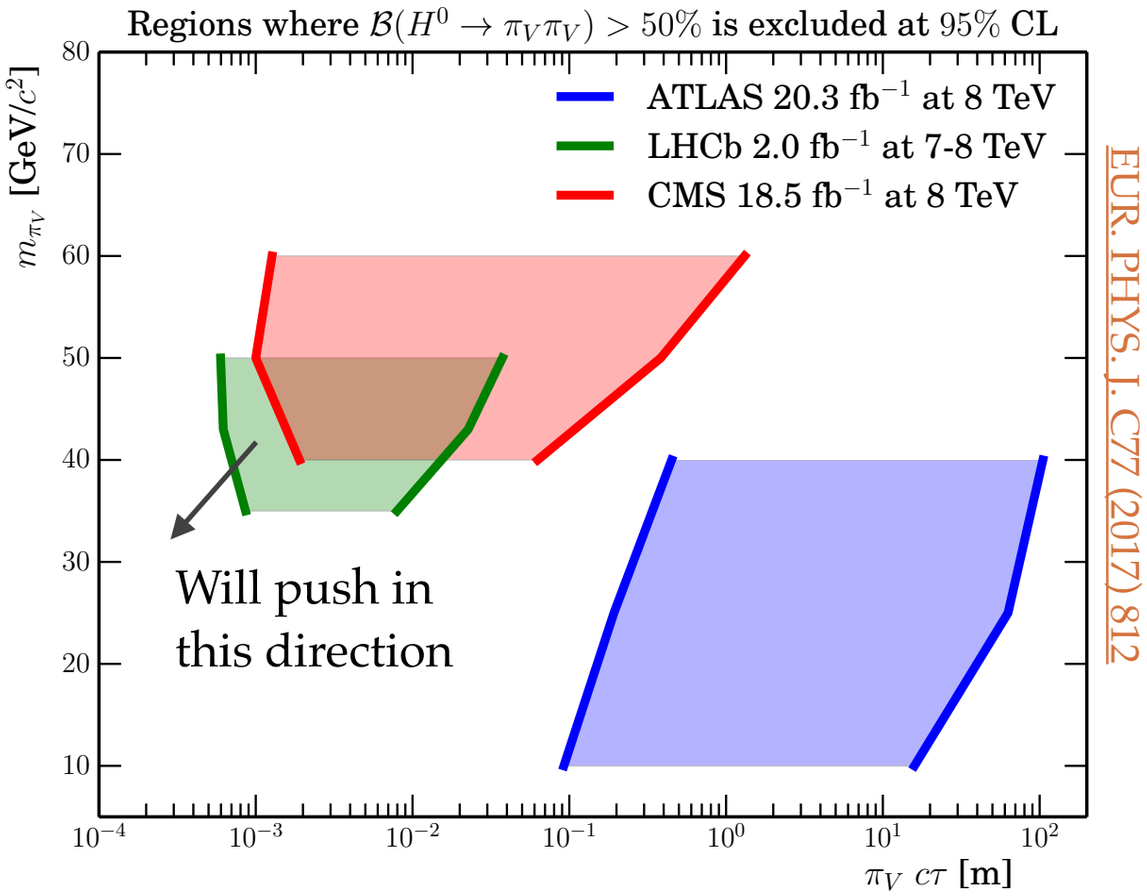
Searches in displaced quarks

- Run 1 searches with displaced dijet or jet+$\ell^{\pm}$
  - Competitive with ATLAS/CMS for low mass and short lifetime
- Now moving to pairs of hadrons
  - Large BR for low mass K^+K^-
  - Can exploit LHCb execellent mass resolution and hadron PID

arXiv:1910.05225



EUR. PHYS. J. C76 (2016) 664
EUR. PHYS. J. C77 (2017) 224
EUR. PHYS. J. C77 (2017) 812

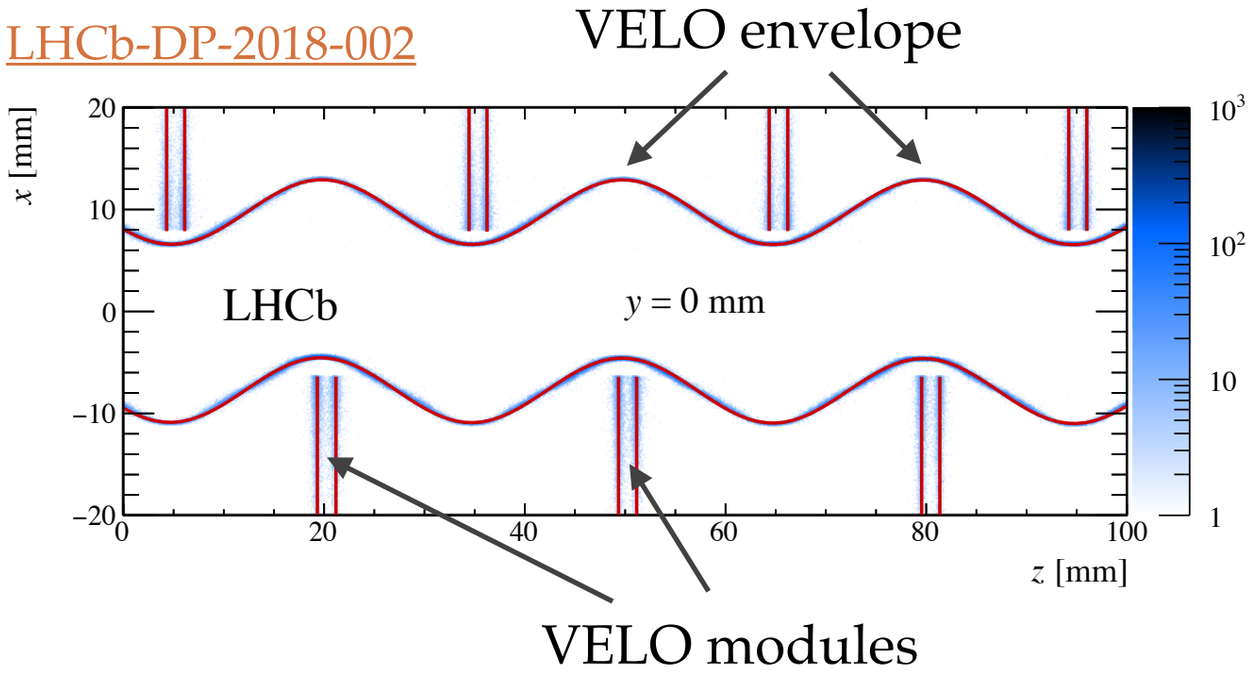


EUR. PHYS. J. C77 (2017) 812

LLP Backgrounds in VELO

- Heavy Flavour displaced decays
  - $\tau(B)$~1.5 ps, $\beta\gamma$~10 ⇒ few mm
- Thin VELO envelope (RF foil)
  - **< 5 mm**: background mainly from heavy-flavour background
  - **> 5 mm**: background mainly from material interaction

LHCb-DP-2018-002



- **VELO material map**
  - Based on material interactions from hadrons produced in beam-gas collisions
  - Can assign p-value to material interaction hypothesis
  - Very effective in vetoing photons conversions in the material

LHCb-DP-2018-002