
# Long Lived Particles and Dark Photons at LHCb

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*on behalf of the LHCb collaboration*

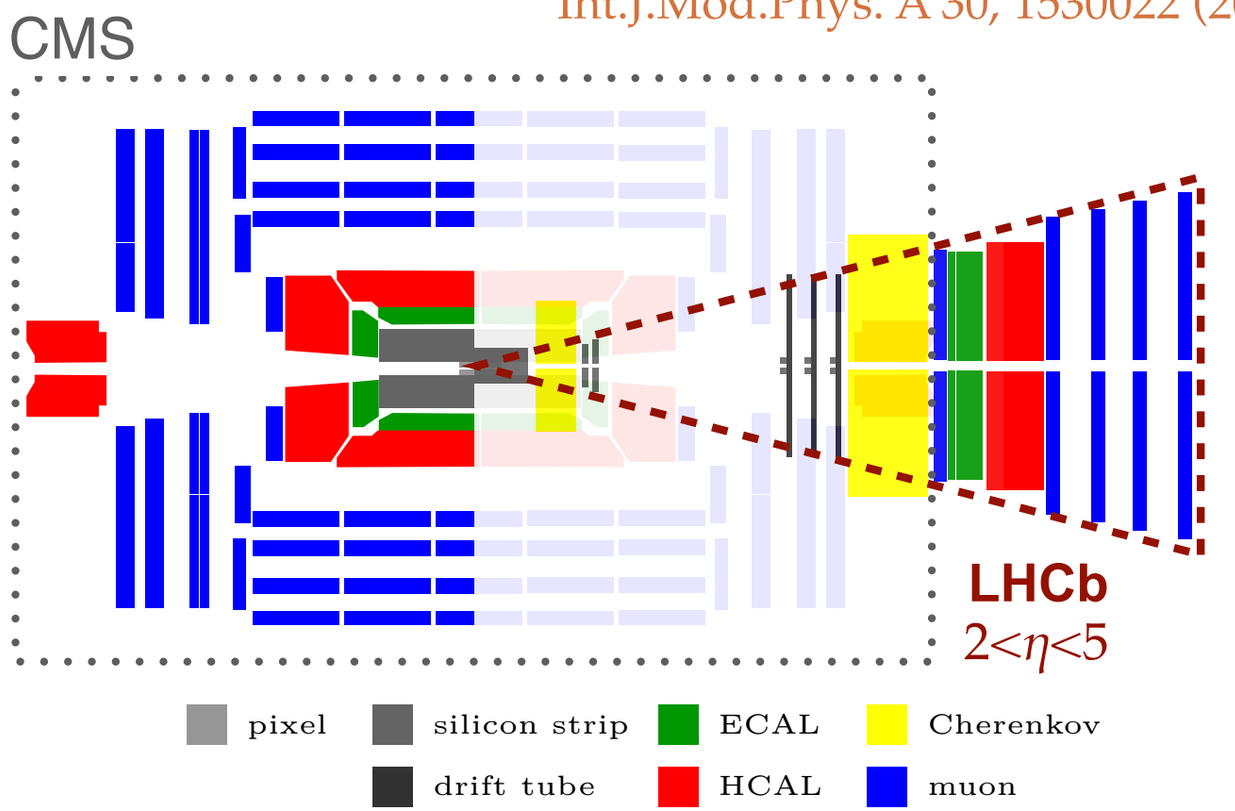
13/03/2018, La Thuile



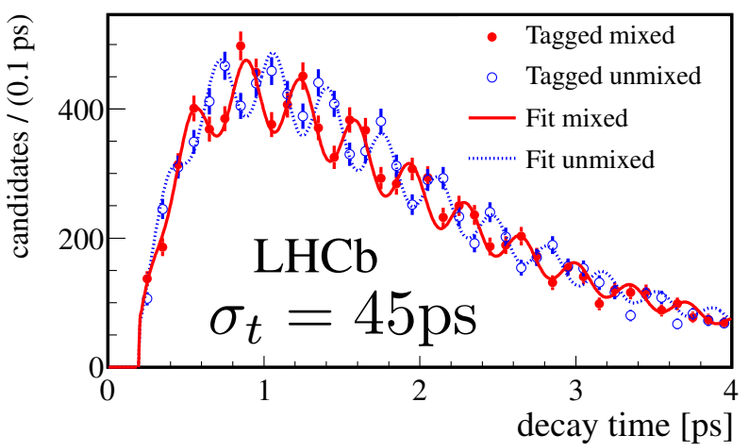

# The LHCb detector

- At LHC *pp* collisions (7-13 TeV)
- Only LHC detector fully instrumented in **forward** region
- Excellent **vertex resolution**
  - Able to measure $B_s$ oscillations (helped by large forward boost)
- Excellent **mass resolution**
  - Separating $B_d \to \mu\mu$ from $B_s \to \mu\mu$
- Good **jet reconstruction**
  - 10-20% energy resolution for jets with $p_T > 10\,\text{GeV}$
  - $b(c)$ tagging eff 65%(25%) for 0.3% contamination

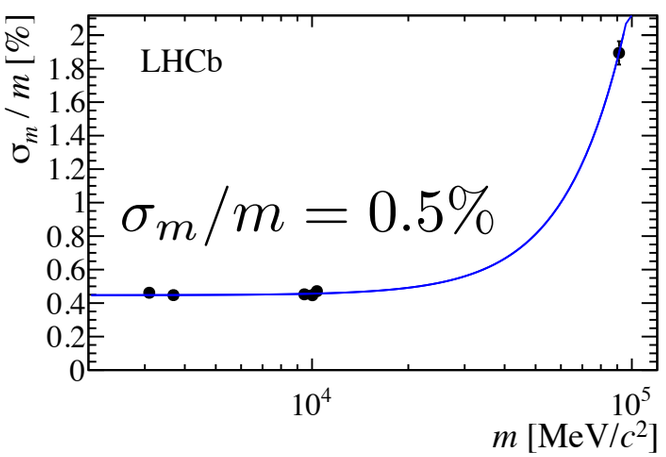
Int.J.Mod.Phys. A 30, 1530022 (2015)




vertex reconstruction



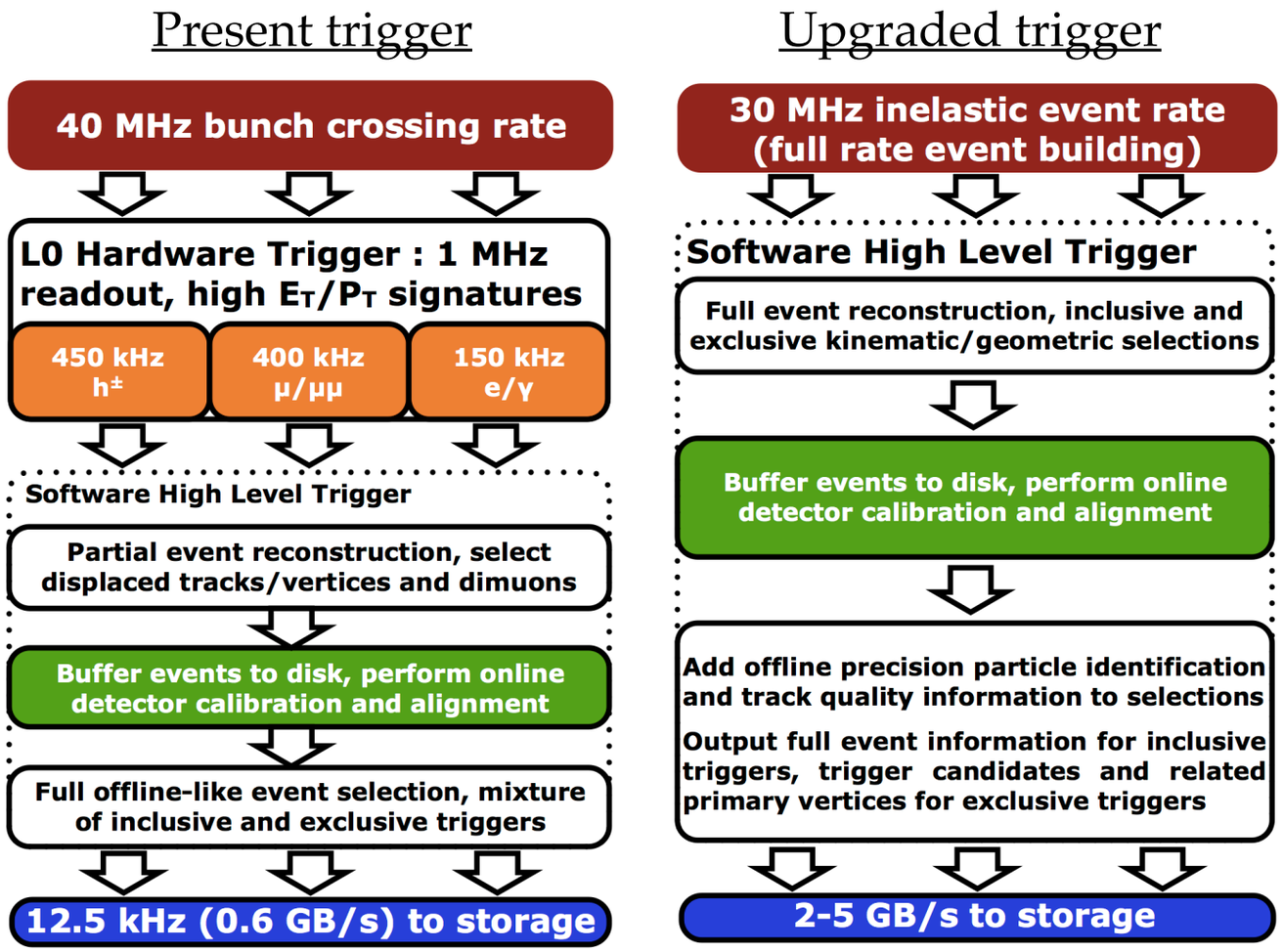

mass resolution



# The LHCb detector

[LHCB-TDR-016]

- **Lower luminosity** (and low pile-up)
  - ~1/8 of ATLAS/CMS in Run 1
  - ~1/20 of ATLAS/CMS in Run 2
- **Capable of very soft triggers!**
  - At hardware level (L0):
    - Muons with $p_T > 1.5\,\text{GeV}$
    - Calo deposits with $E_T > 3\,\text{GeV}$
  - At Software level (HLT):
    - Topological triggers on detached vertices

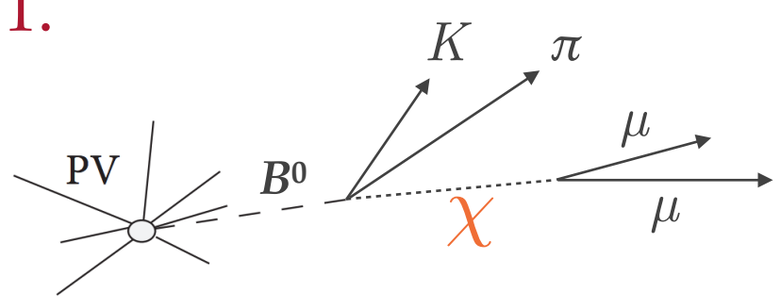



- **"Trigger-less" upgrade (2021)**
  - Read-out detector in *real time*
  - Can trigger on detached vertices and particle ID at first level!

# Direct Searches at LHCb

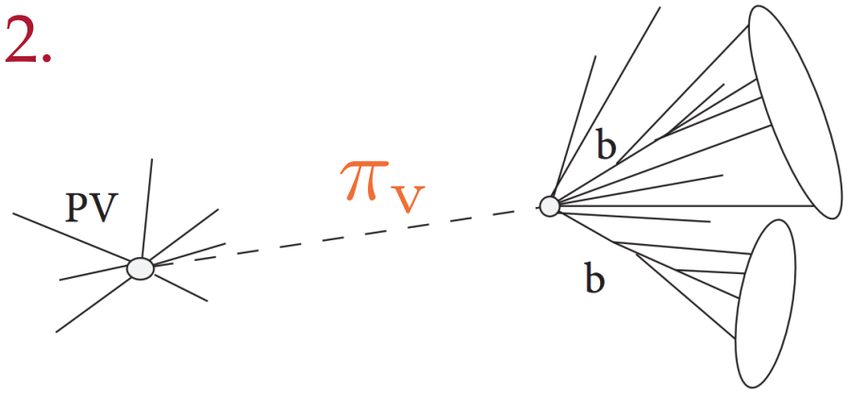
- LHCb has world-leading sensitivity at:
  - **Lighter masses** w.r.t. ATLAS/CMS
    - soft trigger and forward acceptance
  - **Low lifetimes** down to 1 ps
    - excellent vertexing and boost
- Signatures of several models e.g. dark sectors or extended Higgs sectors

1.




- Increasing interest in direct searches!
  1. **Produced in HF decays** (prompt / long-lived)
  2. **Produced in *pp* collision** (prompt / long-lived)

2.



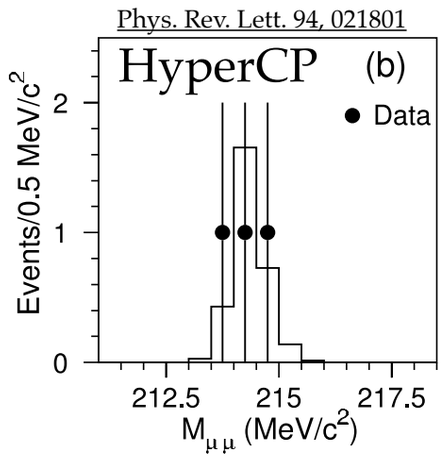
New

# Light Bosons from Heavy Flavour

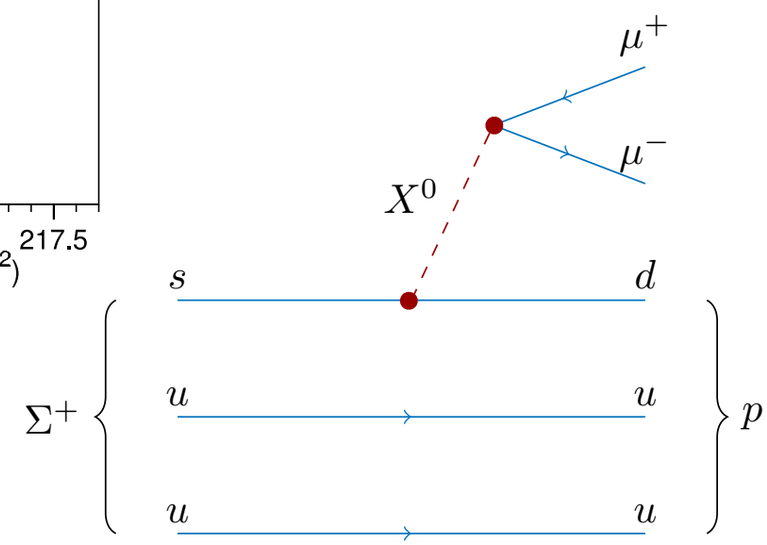
- LHCb searched for light bosons $X^0 \to \mu\mu$ in rare b→s transitions

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

- **Recently searched in rare *s*→*d***
  - Motivated by HyperCP anomaly at $m_X = 214.3 \pm 0.5$ MeV PRL 94,021801




LHCB-PAPER-2017-049

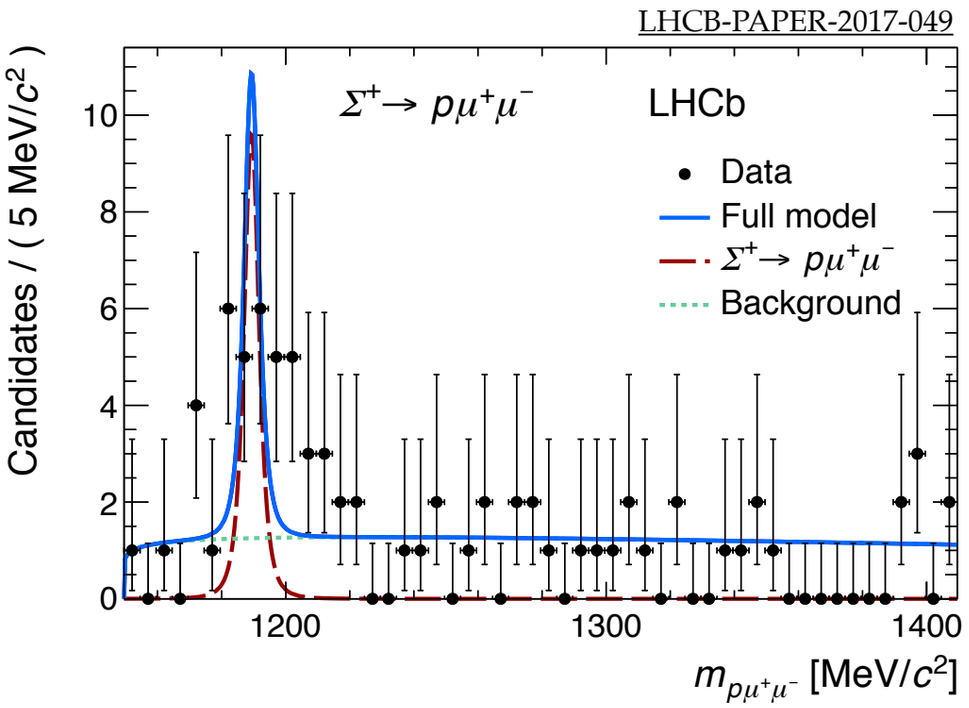



see M. van Veghel's talk

- Evidence for SM $\Sigma^+ \to p\mu\mu$ at 4.0 σ
  ⇒ searched in $\mu\mu$ spectrum

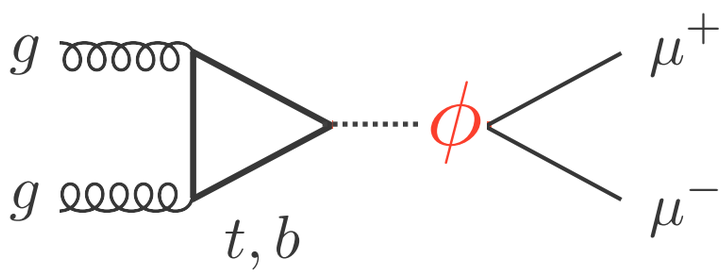
- No HyperCP anomaly observed:
  $\mathcal{B}(\Sigma^+ \to pX^0) < 9.5 \times 10^{-9}$ at 95% CL

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



# Light Bosons from $pp$

New

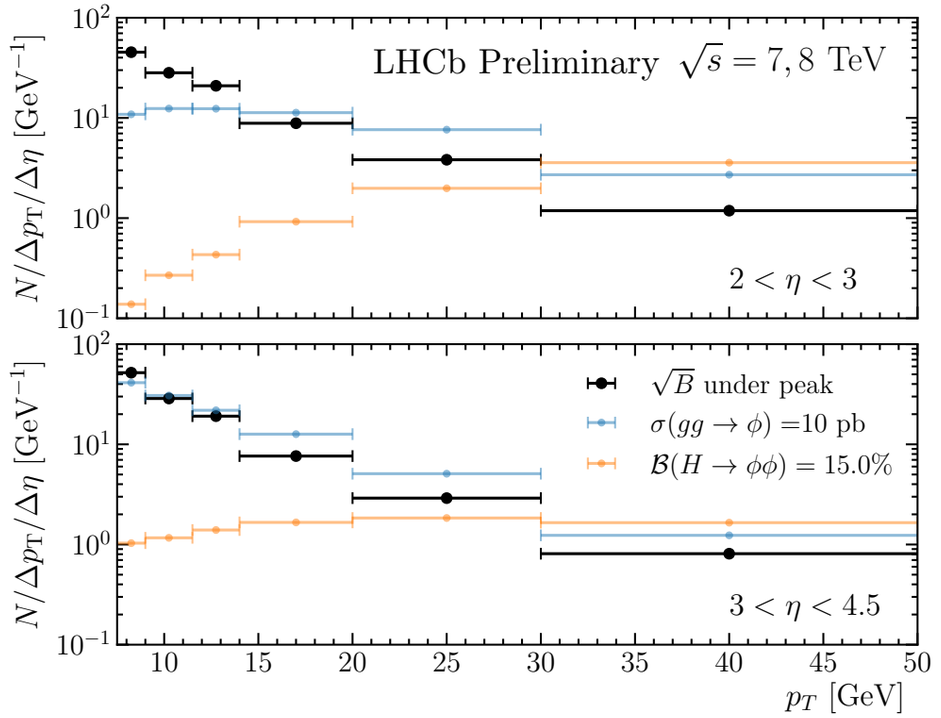


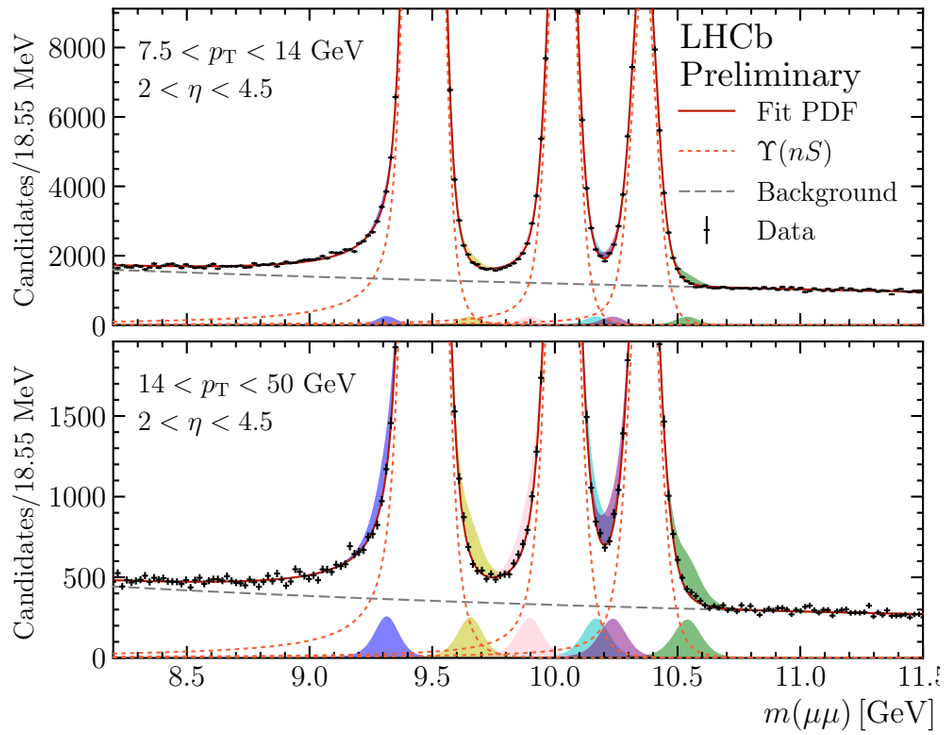

- Light spin-0 particles copiously produced in ggF
  - Many models: NMSSM, 2HDM+S
  - Extensive set of searches at the LHC

    *Recent review*: Haisch et al arXiv:1802.02156
- $m$~10 GeV difficult for $\gamma\gamma$ or $\tau\tau$ searches
  - Exploit dimuons: mass resolution is key
- Bins of kinematics to maximise sensitivity
- Mass-independent efficiency (uBDT technique)
- Precise modelling of $\Upsilon$(nS) tails to extend search range as close as possible

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

LHCb-PAPER-2018-008 in preparation



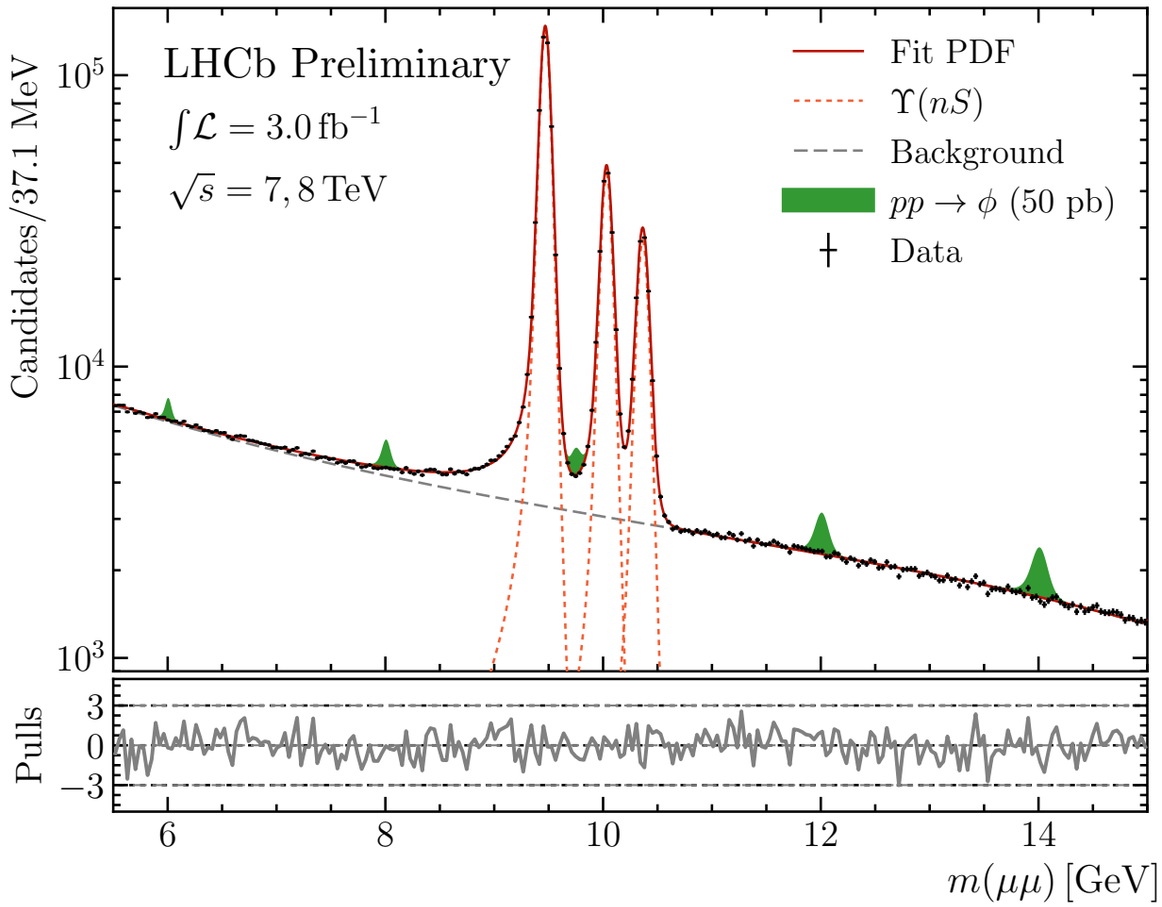
New

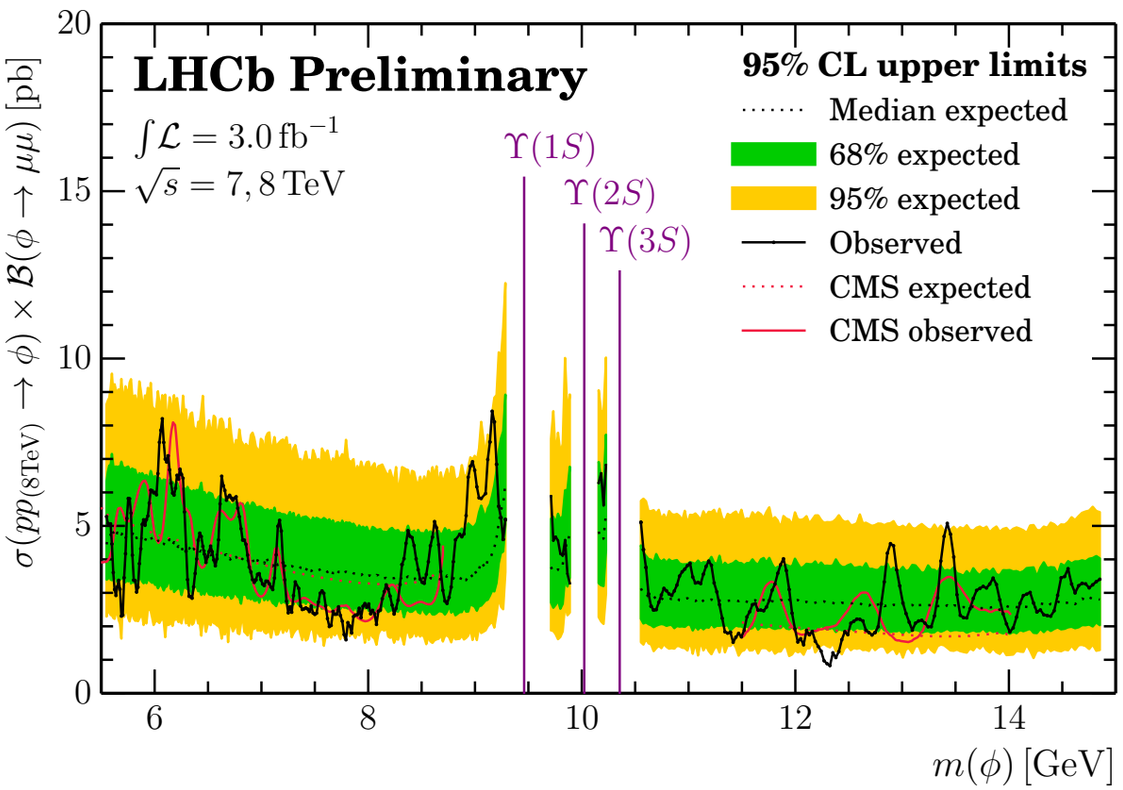
# Light Bosons from $pp$

LHCb-PAPER-2018-008 in preparation

- Search for dimuon resonance in $m_{\mu\mu}$ from 5.5 to 15 GeV (also between $\Upsilon$(nS) peaks)
- No signal: limits on $\sigma\times$BR
  - Limits on couplings require taking into account mixing with $bb$ states

Haisch et al PRD93 (2016) 055047




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

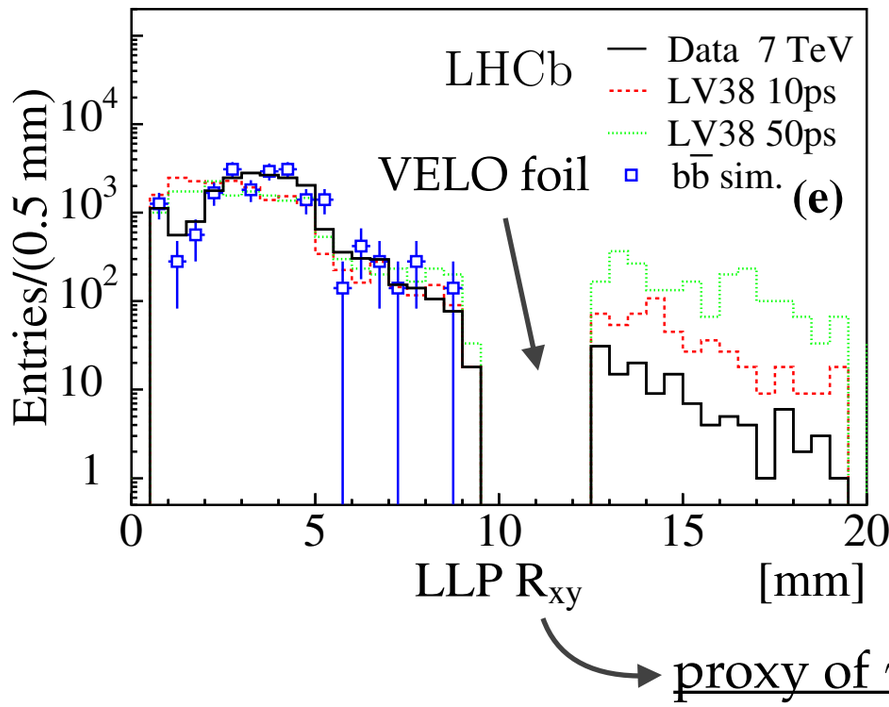
PRL 109(2012)121801

# Long Lived Particles → μ+jets

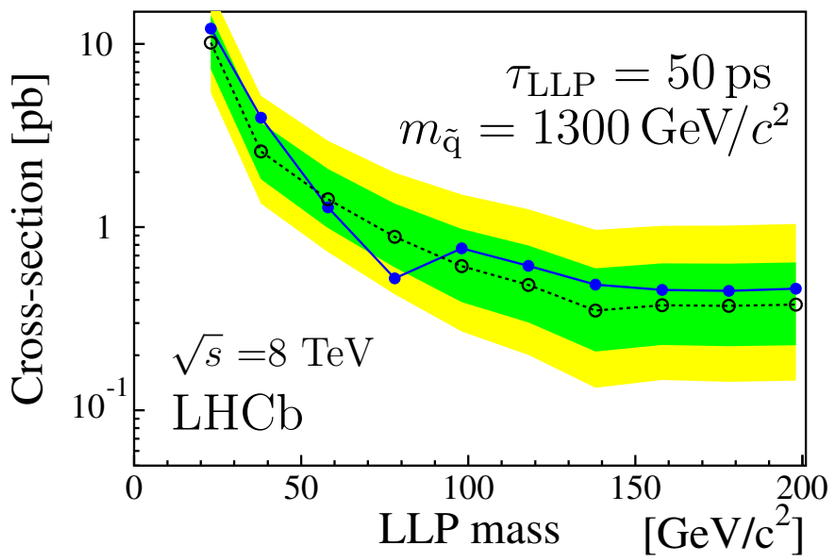
Eur. Phys. J. C (2017) 77:224

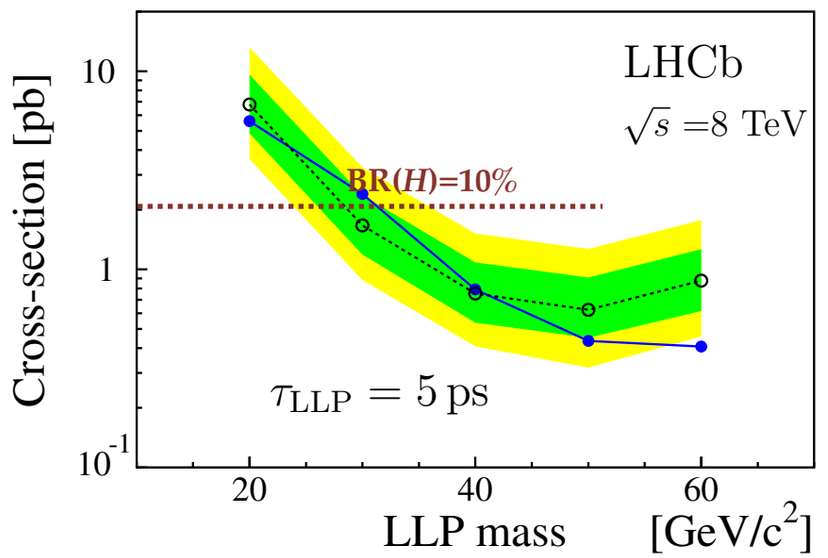
- **Signature**: single displaced vertex with several tracks and a high $p_T$ muon
- **Model**: RPV mSUGRA neutralino decaying to a lepton and two quarks

- Hardware trigger on muon
- Software trigger on displaced vertex
- Background dominated by *bb*
  - MVA classifier + fit to candidate LLP mass




- **Set upper limits** on:
  - RPV mSUGRA
  - Simplified topologies
- Can also be sensitive to sterile neutrinos
  Antusch et al. PLB774 (2017) 114-118



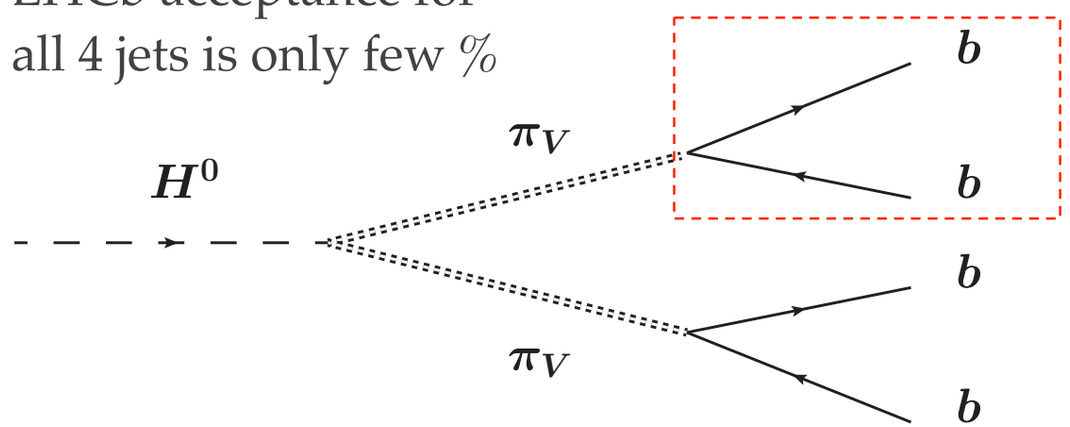



# Long Lived Particles → jet jet

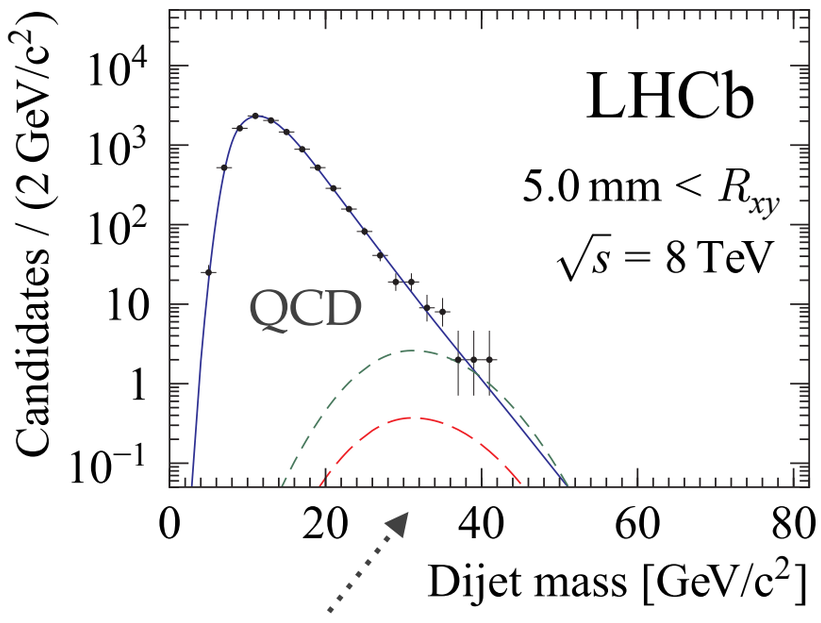
EUR. PHYS. J. C77 (2017) 812

- **Signature**: single displaced vertex with two (*b*-) jets (previously searched double)
  EUR. PHYS. J. C (2016) 76: 664
- **Model**: hidden-valley dark pions from 125 GeV Higgs decay

LHCb acceptance for all 4 jets is only few %




- Using 7 and 8 TeV *pp* data
- Software trigger on displaced vertex in the Vertex Locator
- Signal from di-jet mass fit in bins of transverse displacement $R_{xy}$

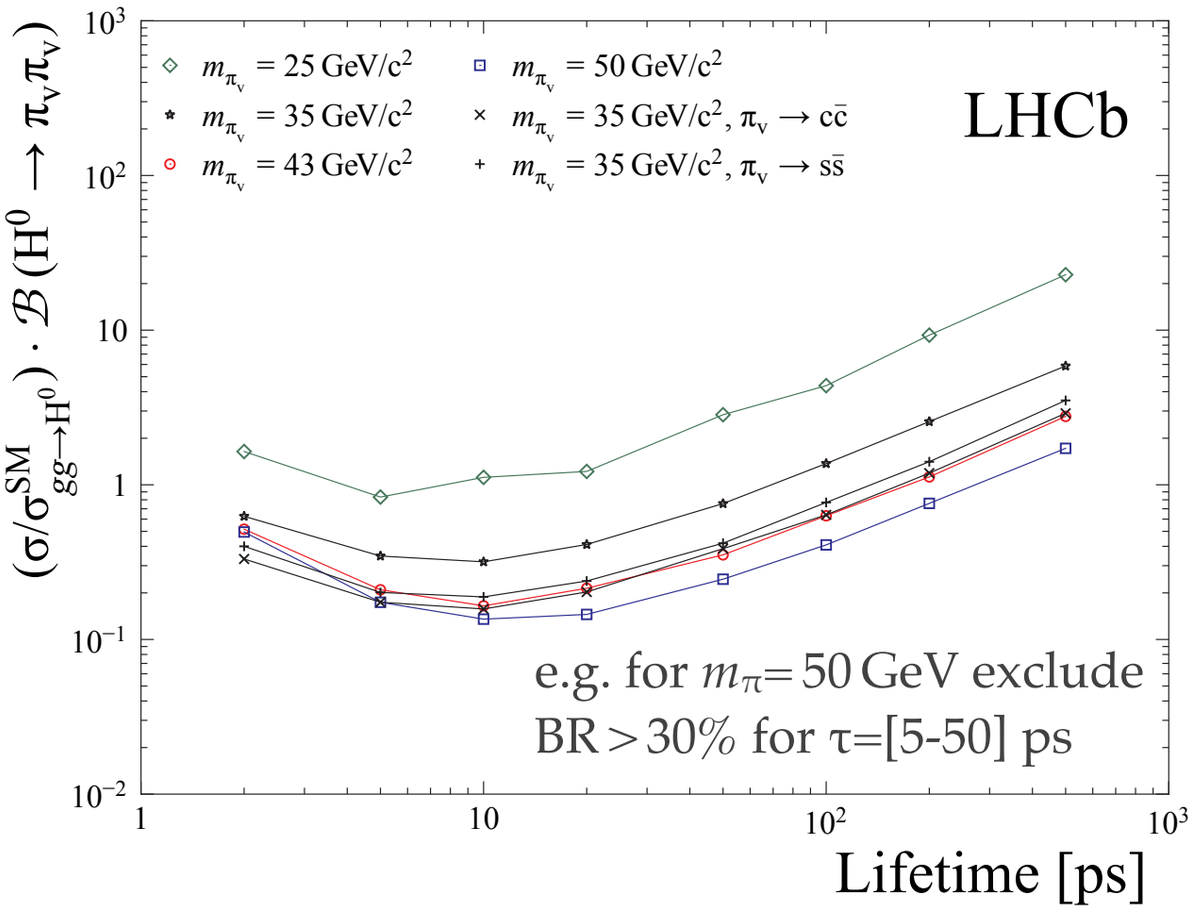



$\pi_V$ (35 GeV, 10 ps)
best fit, BR=1

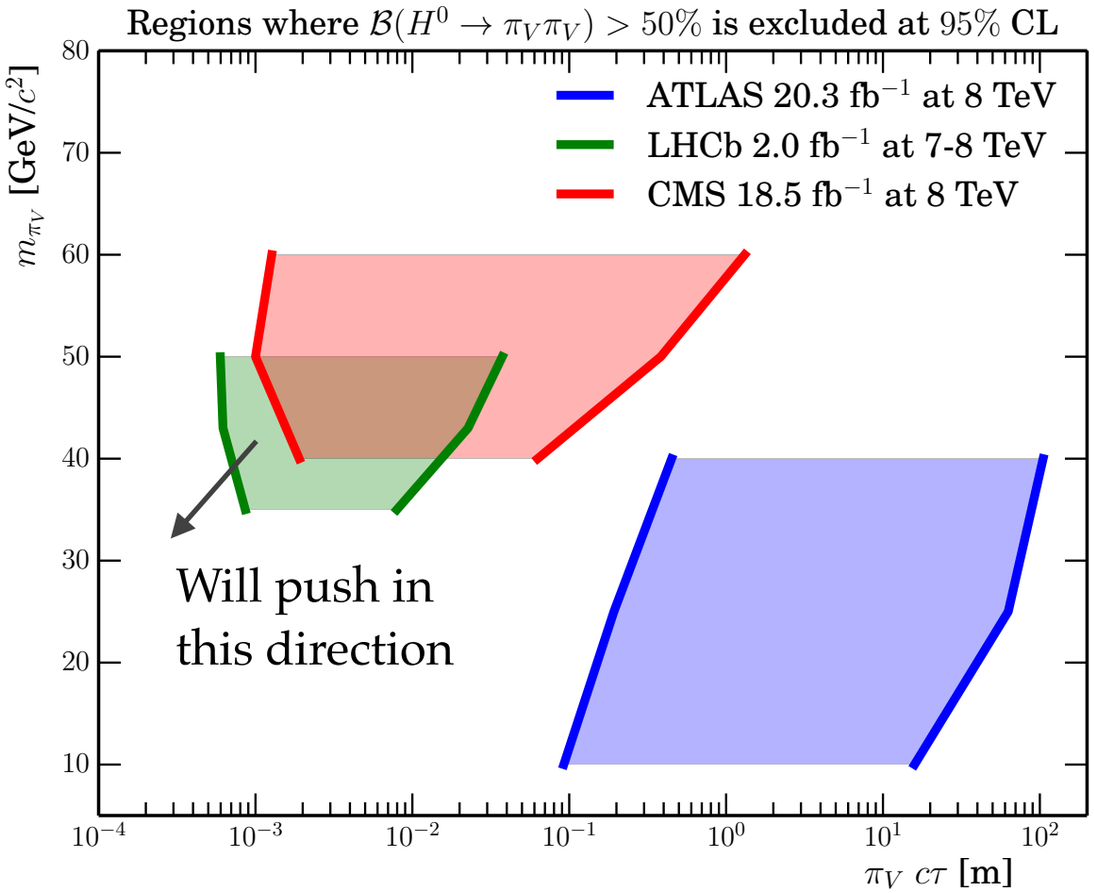
# Long Lived Particles → jet jet

EUR. PHYS. J. C77 (2017) 812

Limit on BR(H→$\pi_v\pi_v$) for a set of masses and lifetimes




Competitive limit with ATLAS/CMS despite factor 10 less luminosity!



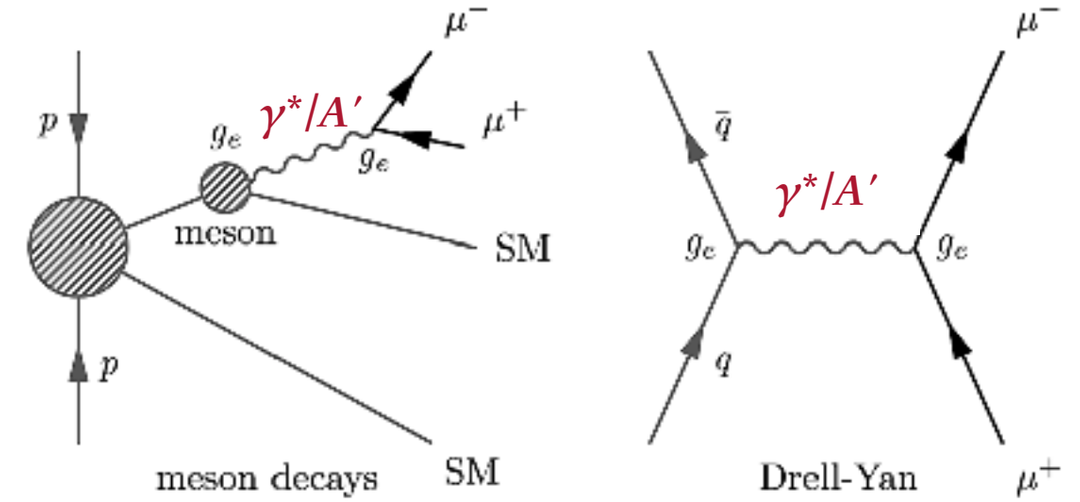

**Bright future at upgraded LHCb!**
expected benefit from online identification of displaced diets

New

# Dark Photons

PRL 120 (2018) no.6, 061801

- Can search for **Dark Photons** ($A'$) in $\mu\mu$
  - First results with 1.6/fb at 13 TeV
  - New $\mu\mu$ trigger with **online $\mu$-ID**
  - Only interesting part of the event to disk
    → **no pre-scale down to threshold $2\,m_\mu$**




- Kinetic mixing with off-shell photon ($\varepsilon^2$)
  - inherits production mode
  - can normalise to off-shell photon
  - data-driven analysis!

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

off-shell photon

phase-space

A′/γ* eff ratio, $\epsilon$=1 for prompt

Need to separate from background

New

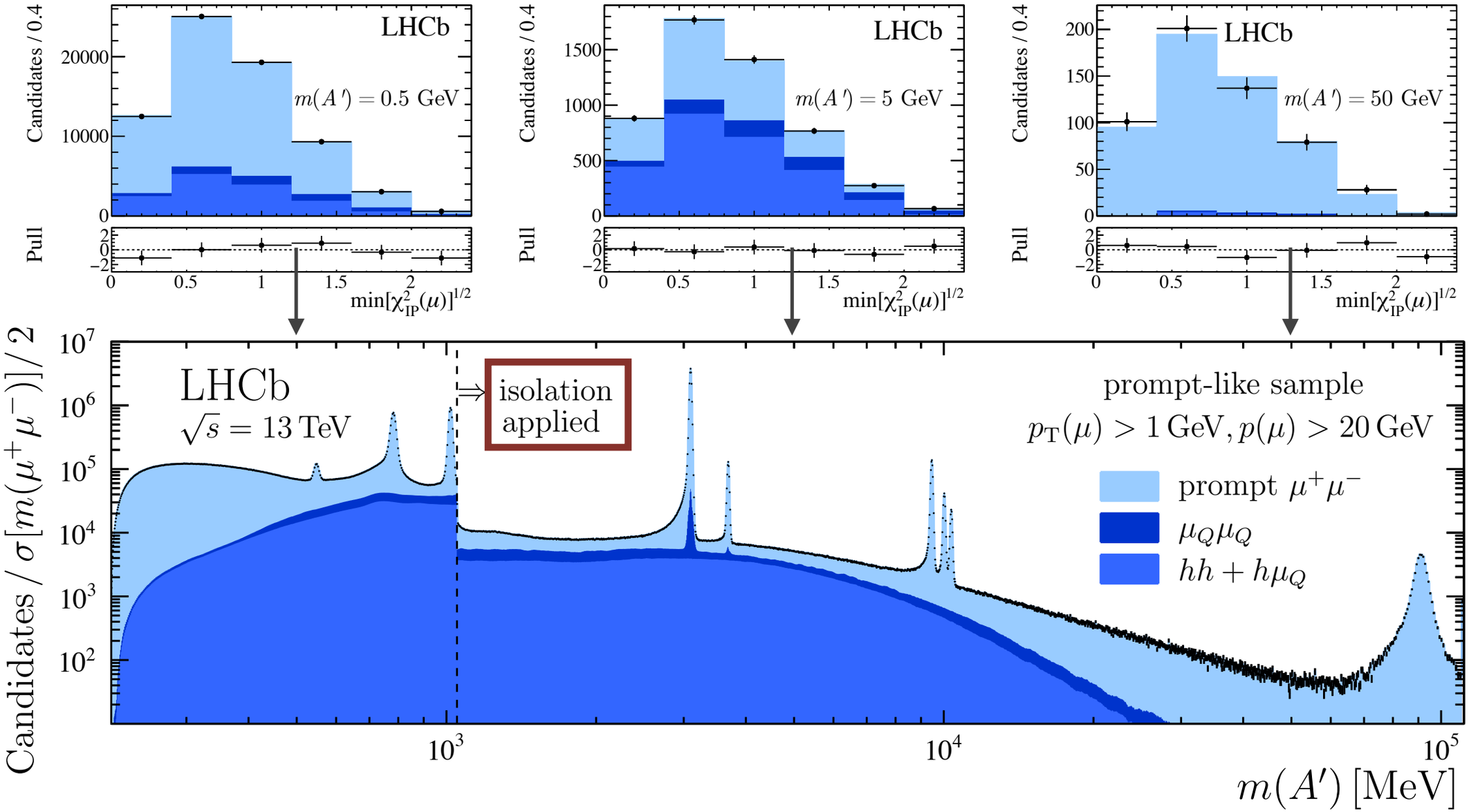
# Dark Photons

PRL 120 (2018) no.6, 061801

Using templates for $\min[\chi^2_{\text{IP}}]$ (small mass dep)

- prompt $\mu^+\mu^-$ → from data at $m(J/\psi)$ and $m(Z)$
- $\mu_Q\mu_Q$ → from simulation (validated)
- $hh + h\mu_Q$ → from same-sign dimuons (corrected)

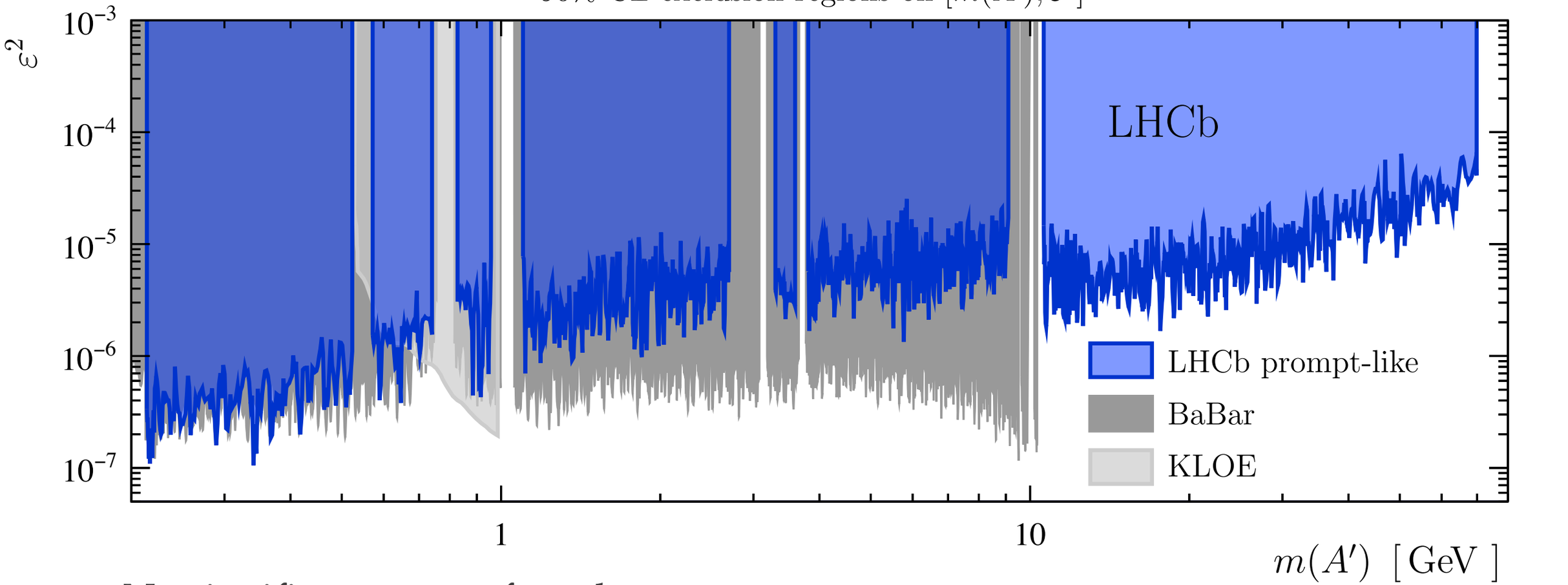
($\mu_Q$ is a muon from a heavy-flavour decay)



New

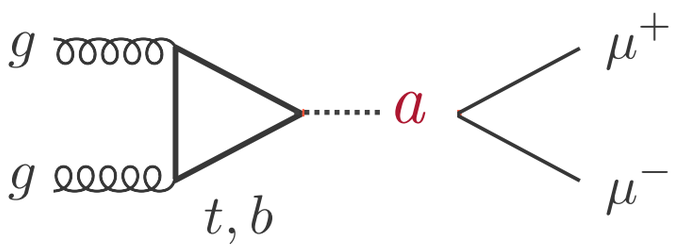
# Dark Photons

PRL 120 (2018) no.6, 061801




- No significant excess found
- Already competitive for $m(A') < 0.5\,\text{GeV}$
- First limit on dark photons for $m(A') > 10\,\text{GeV}$
  - Competitive limits on light pseudo-scalars as well

Haisch et al. arXiv:1802.02156

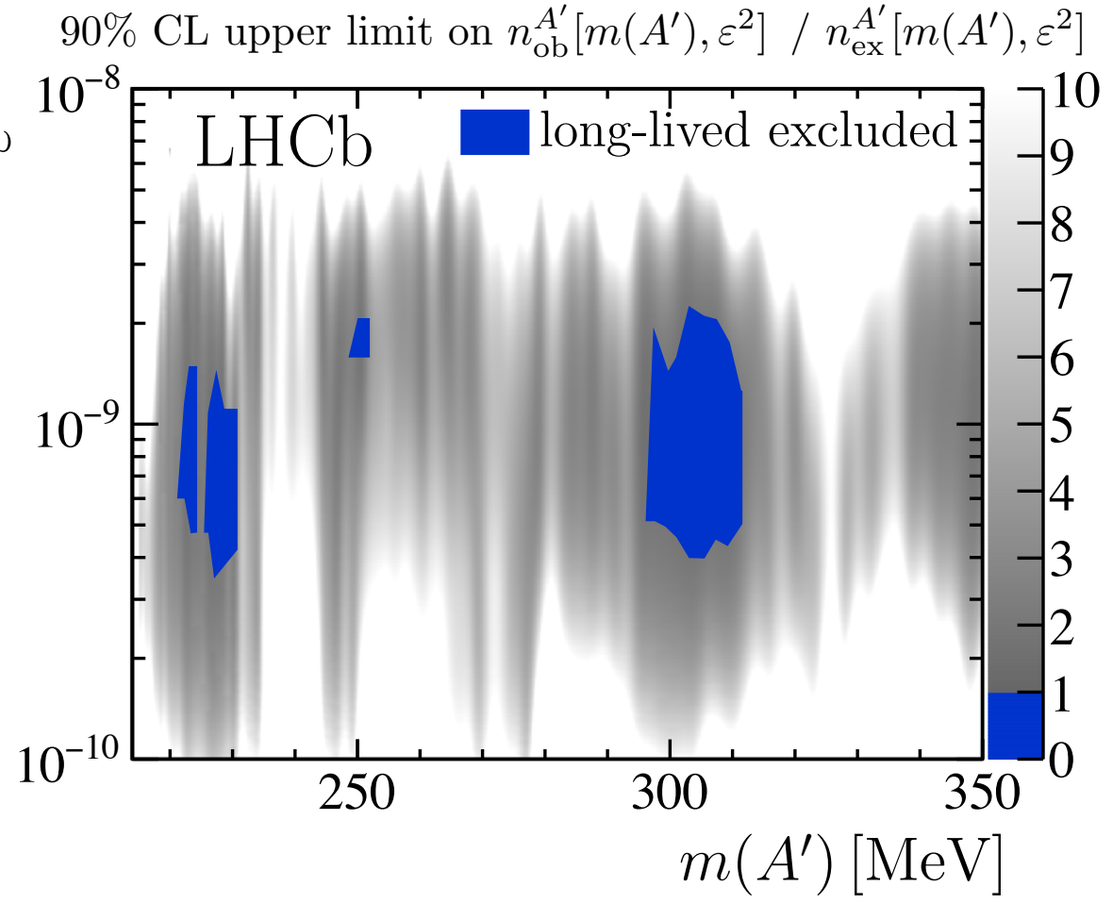


New

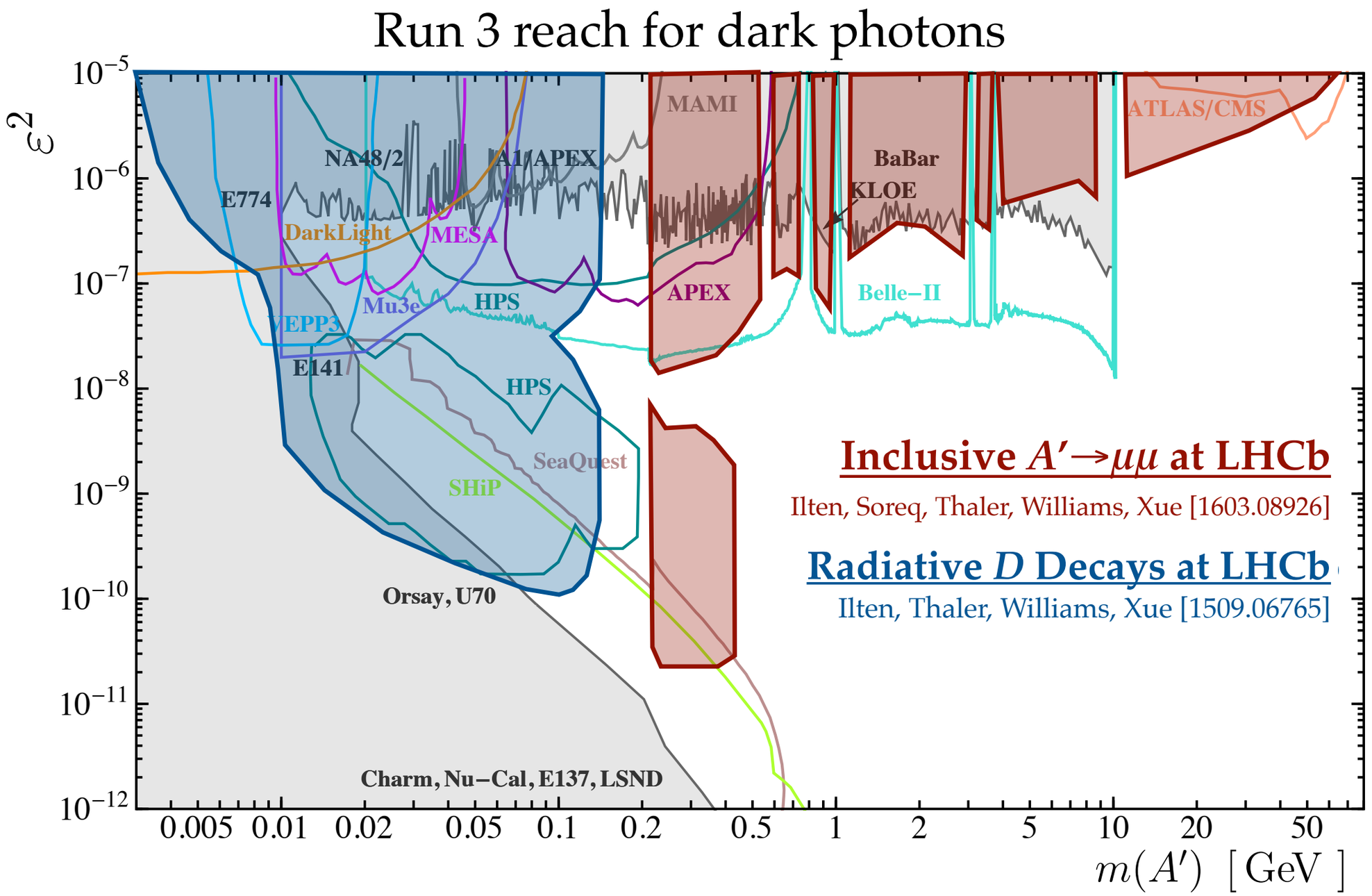
# Dark Photons

PRL 120 (2018) no.6, 061801

- **Displaced search** in region $214 < m(A') < 350$ MeV
- Even looser online requirements on $p_T(\mu)$
- Main backgrounds:
  - Dimuons from $\gamma$ conversions in the VELO
    → novel material map from beam-gas events
  - Mis-id pions from $K_S \to \pi\pi$ tail
    → modelled from PID sideband
- Fit in bins of mass and lifetime
  - Also using consistency of decay topology $\chi^2$
- **No significant excess is found**
  - Already excluding a small region of ($\varepsilon^2$, m)
  - First limit ever not from beam-dump!



# Future Reach




- Will also search for $4\mu$ and $N_{2,3} \to \pi^+\mu^-$

# Conclusions

- LHCb has an extensive program of searches
  - Searches for on-shell new physics from heavy flavour decays
  - Searches for long-lived particles with low mass and short lifetime
  - Searches for dimuon resonances in very broad parameter space
- Bright future ahead:
  - 3/fb in Run 1, expect 5/fb in Run 2 (with larger cross-sections)
  - A lot of potential in the upgraded trigger (also 5× luminosity!)

| 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 203+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Run III | | | | | | Run IV | | | | | Run V | |
| LS2 | | | | | | LS3 | | | | | LS4 | | | |
| LHCb 40 MHz UPGRADE Phase I | | $L = 2 \times 10^{33}$ | | | LHCb Consolidation | | | $L = 2 \times 10^{33}$ $50\ fb^{-1}$ | | | LHCb Ph II UPGRADE * | | $L = 2 \times 10^{34}$ $300\ fb^{-1}$ | |
| ATLAS Phase I Upgr | | $L = 2 \times 10^{34}$ | | | ATLAS Phase II UPGRADE | | | HL-LHC $L = 5 \times 10^{34}$ | | | ATLAS | | HL-LHC $L = 5 \times 10^{34}$ | |
| CMS Phase I Upgr | | $300\ fb^{-1}$ | | | CMS Phase II UPGRADE | | | | | | CMS | | $3000\ fb^{-1}$ | |
| Belle II | | $5\ ab^{-1}$ | $L = 8 \times 10^{35}$ | | $50\ ab^{-1}$ | | | | | | | | | |

LHCb Phase I TDR: [LHCB-TDR-016]
LHCB Phase II EOI: [CERN-LHCC-2017-003]

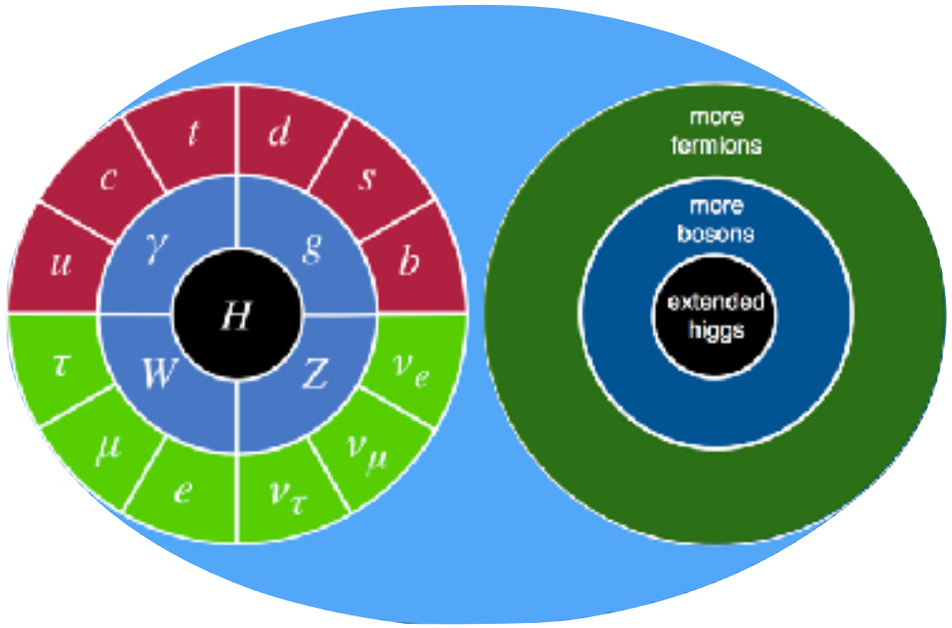
# *BACKUP*

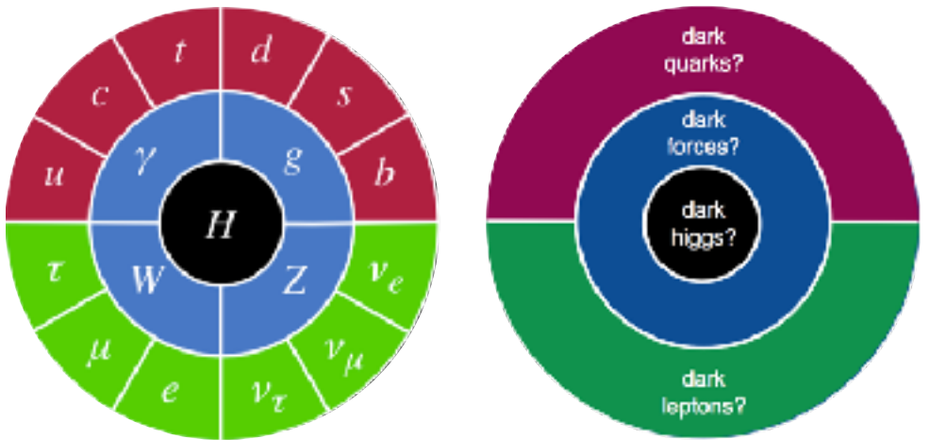
# Dark Sectors

diagrams are a courtesy of M.Williams

1. **Unified theory of DM and SM**
   at TeV scale (e.g. SuperSymmetry)
   - several talks in tomorrow's session
2. **Separated DM sector with portals to SM**
   - Scalar portal (e.g. inflaton)
   - Axial portal (e.g. ALPs)
   - Vector portal (e.g. dark photons)
   - Dark quarks (e.g. Hidden valley)

- **Small couplings to SM**
  - Small production cross-sections: weak limits at low masses
  - Long lifetimes: displaced objects missed by typical triggers

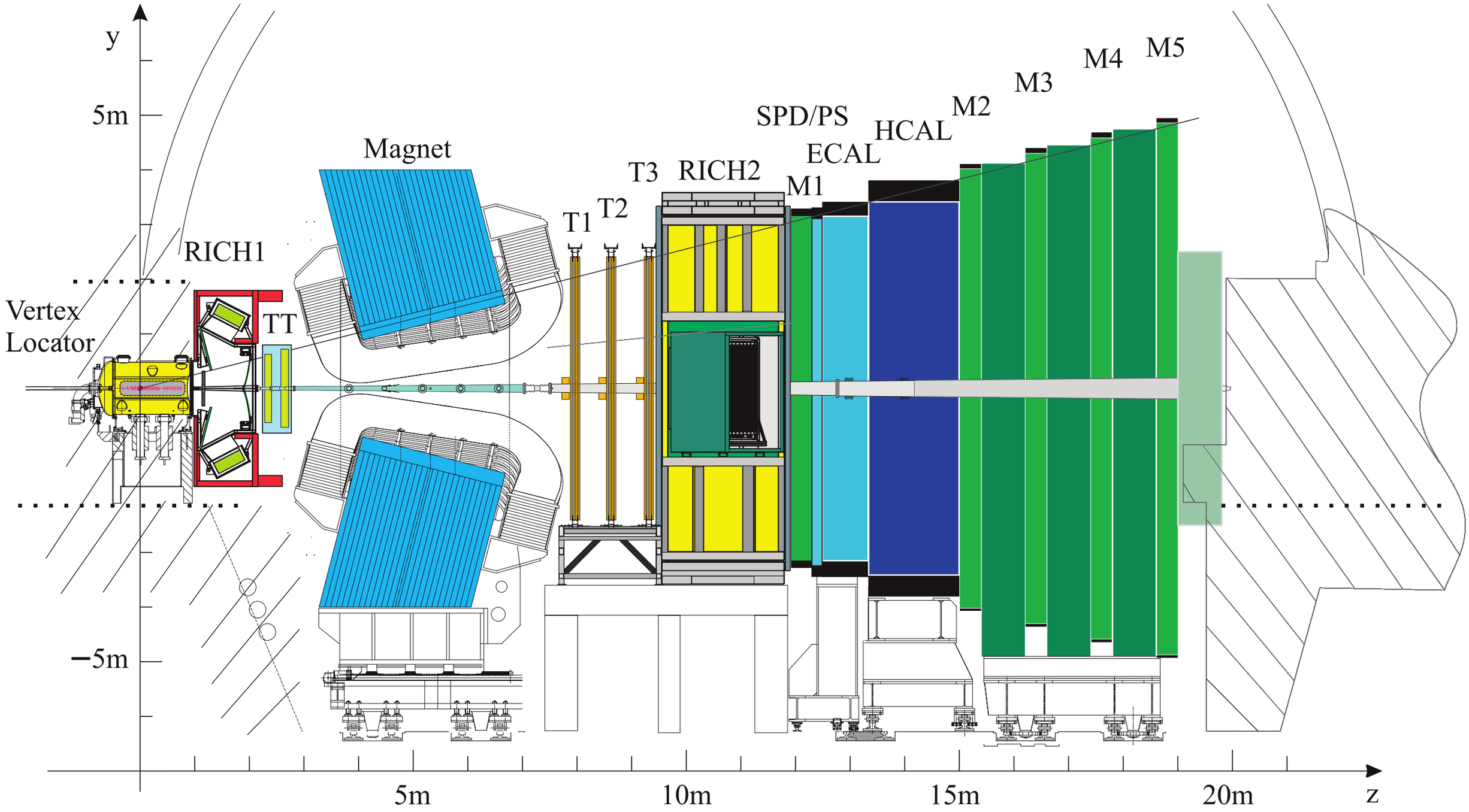


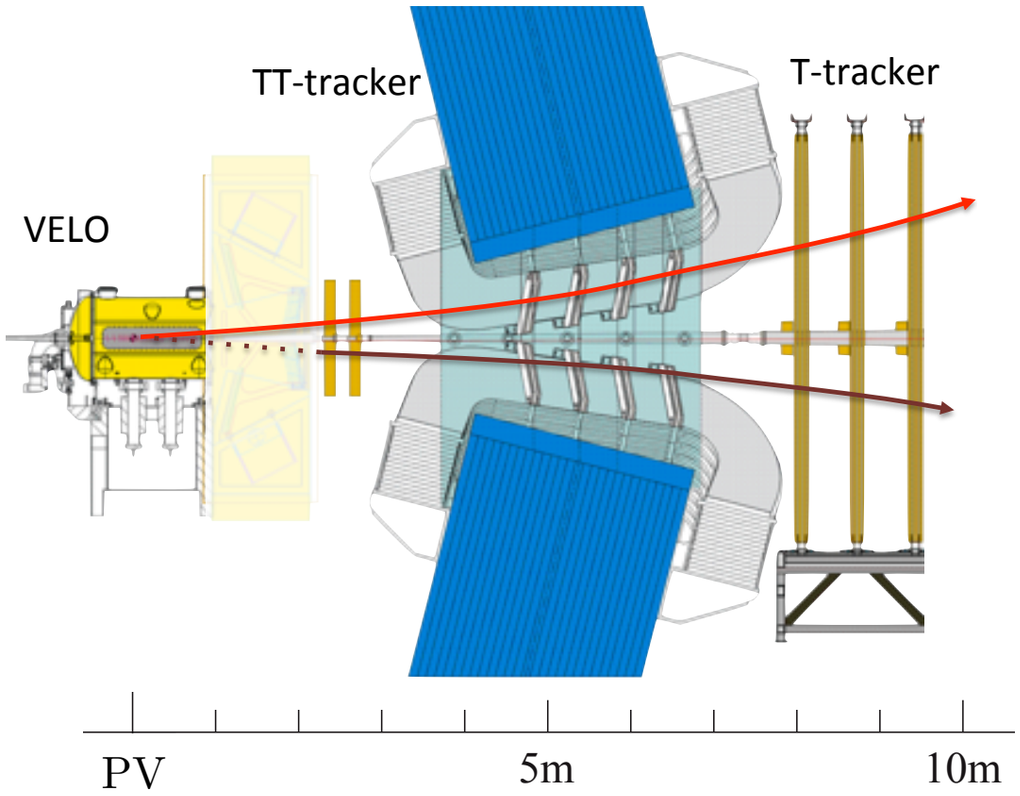

portals

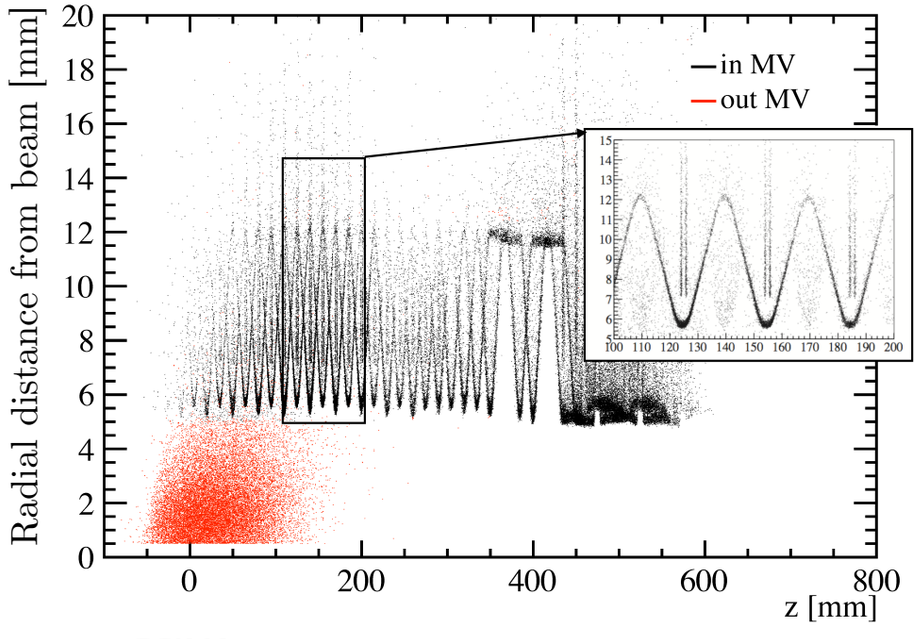
# The LHCb detector

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



# LLP at LHCb




## Tracks from long-lived in LHCb:

- **Within VELO** (<50 cm)
  - in reality more like <20 cm
- **Up to TT** (<200 cm)
  - Worse vertex and $p$ resolution ($m(\pi\pi)$ resolution 2× larger)
  - Not available in trigger (studies ongoing)

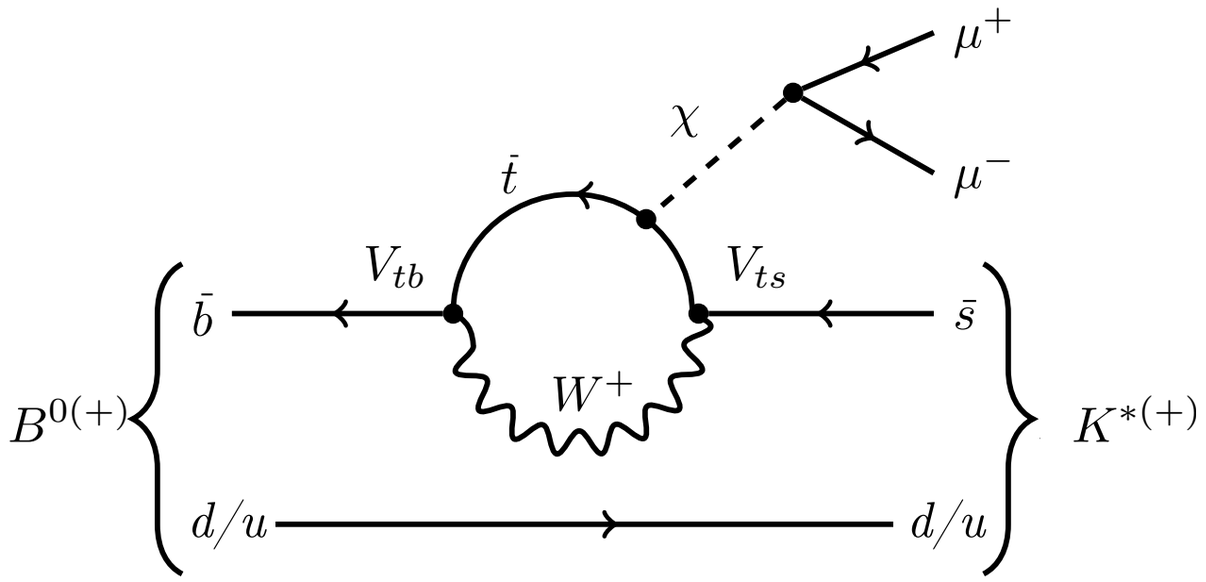
- VELO envelope at ~5 mm from beam
  - Detailed material veto is used
  - **<5 mm**: background mainly from heavy-flavour background
  - **>5 mm**: background mainly from material interaction

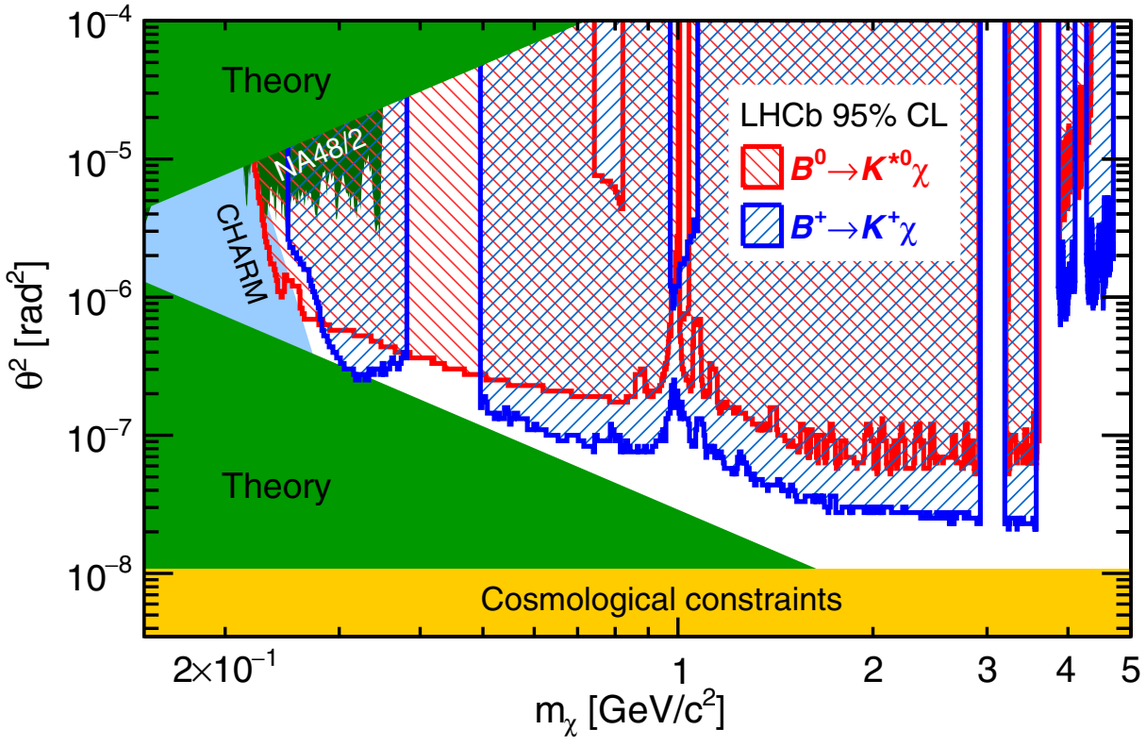
# Light Bosons from $b \to s$

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

- Look for new hidden-sector bosons in $b \to s$ penguin transitions
- World record samples of $B \to K^{(*)}\mu\mu$
  - search for narrow $\mu\mu$ peak
- Allow detached $\mu\mu$ (within VELO)
  - small SM mixing can give lifetime
- Constrain on **scalar portal** mixing with the SM Higgs (angle $\theta$)
  - Nearly rule out the inflaton parameter space below $2\,m_\tau$

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



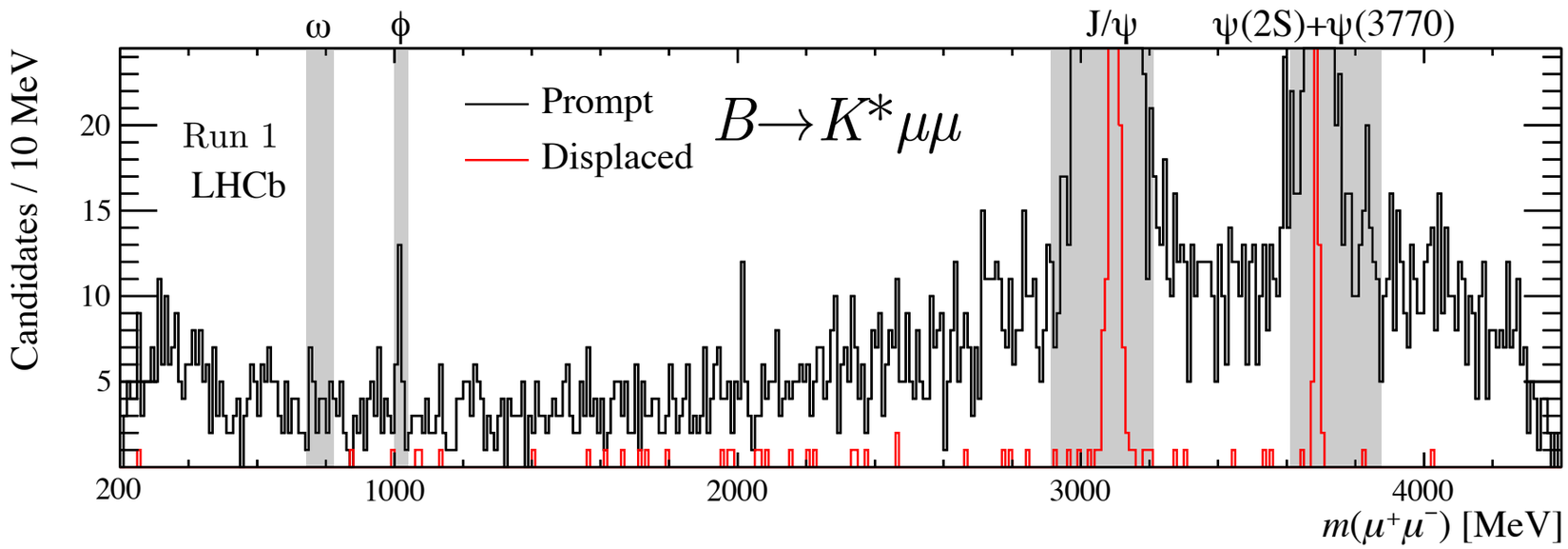

CHARM:
PL 157B, 458 (1985)
NA48/2:
PL B769, 67 (2017)
Cosmology:
JHEP 07(2013)140

# Light Bosons from $b \to s$

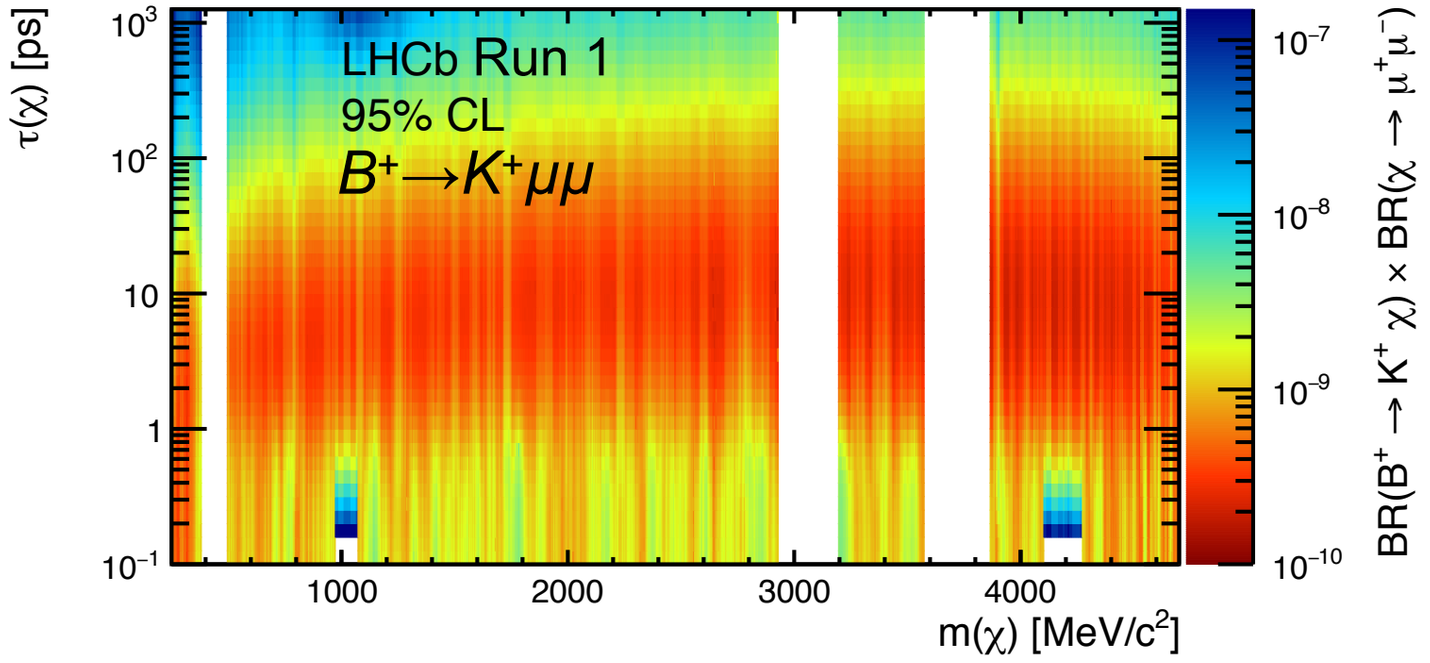
Phys Rev Lett 115 161802 (2015)

**Phys Rev D 95, 071101(R) (2017)**

- Search for narrow peak in m($\mu\mu$)
  - $\sigma(\mu\mu) \sim$ 3-9 MeV with $m_B$ constraint




- **Model independent limit**
  - BR limit normalised to *rare* SM decay (in $q^2$ range 1-6 GeV$^2$)
  - Constraint set on lifetimes [0.1-1000] ps (~ 30$\mu$m to 30cm)



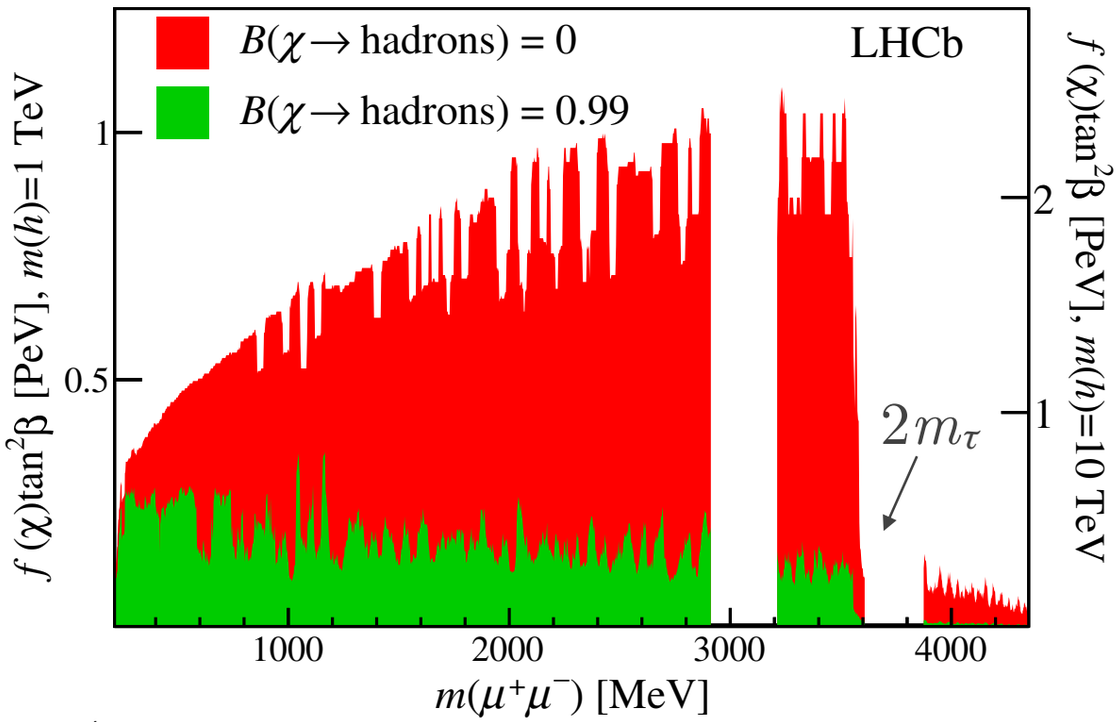
# Light Bosons from $b \to s$

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

## Model dependent limits

- On models with **axial portal**
  - Reaching PeV scale on axion decay constant $f(\chi)$

M.Dine, W.Fischler, M.Srednicki PL 104B 199-202 (1981)
A.R.Zhitnitsky Sov.J.Nucl.Phys. 31, 260 (1980)

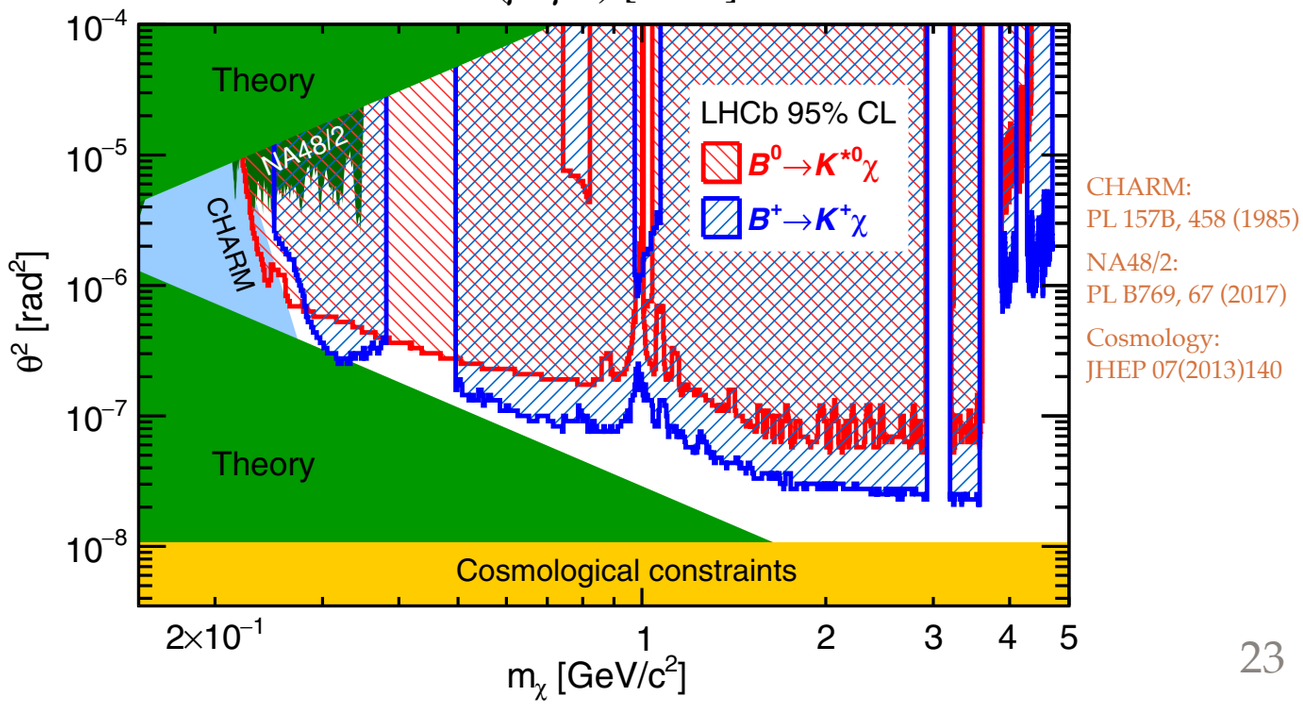



- Constrain on **scalar portal** mixing with the SM Higgs (angle $\theta$)

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

  - Nearly rule out the inflaton parameter space below $2\,m_\tau$

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

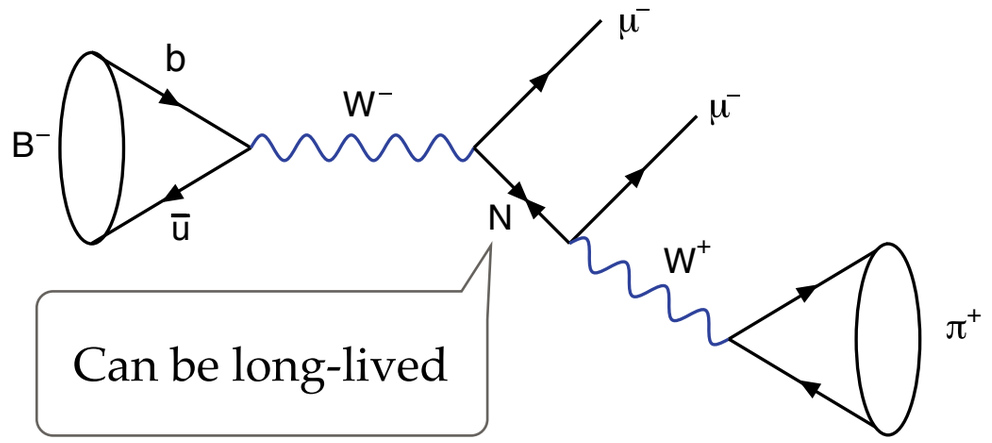



CHARM:
PL 157B, 458 (1985)
NA48/2:
PL B769, 67 (2017)
Cosmology:
JHEP 07(2013)140

# Majorana neutrinos in $B^- \to \pi^+ \mu^- \mu^-$

Phys Rev Lett 112 131802 (2014)

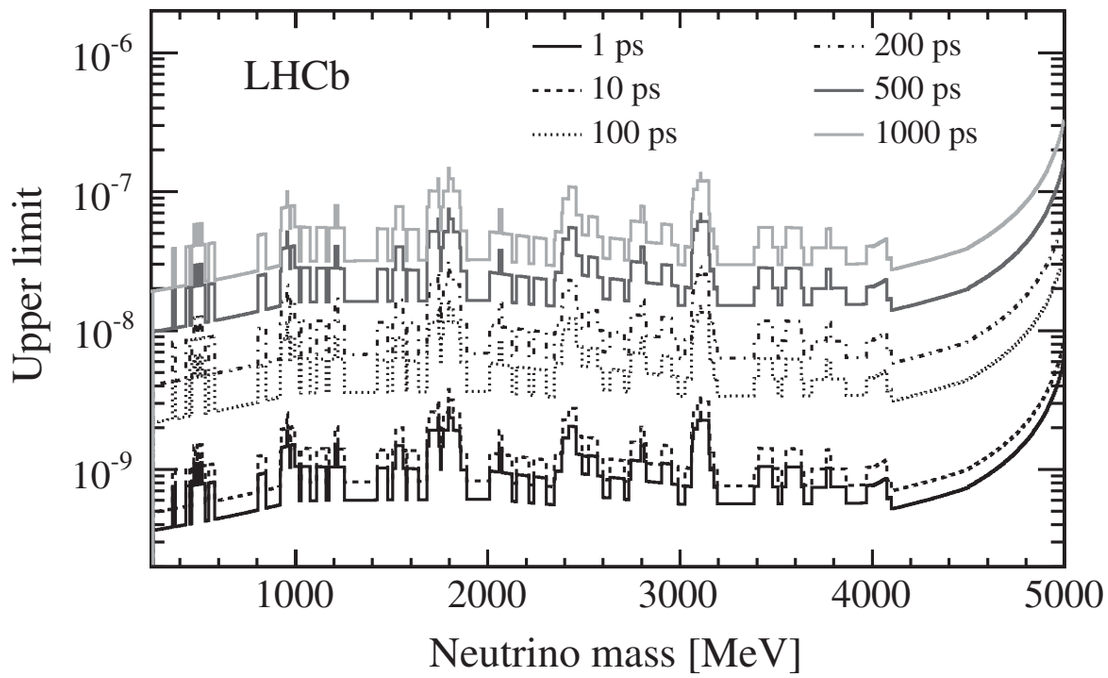
- Lepton number violating $B^- \to \pi^+ \mu^- \mu^-$ can proceed via on-shell Majorana neutrinos




- Look for $B$ mass peak, then extract limit as a function of $m_N$
- Limit set on N($\pi\mu$) lifetimes up to 1000 ps
- Constraints on mixing angle $V_{\mu 4}$
  - Recently revisited

B Shuve, ME Peskin, Phys.Rev. D94 (2016) no.11, 113007

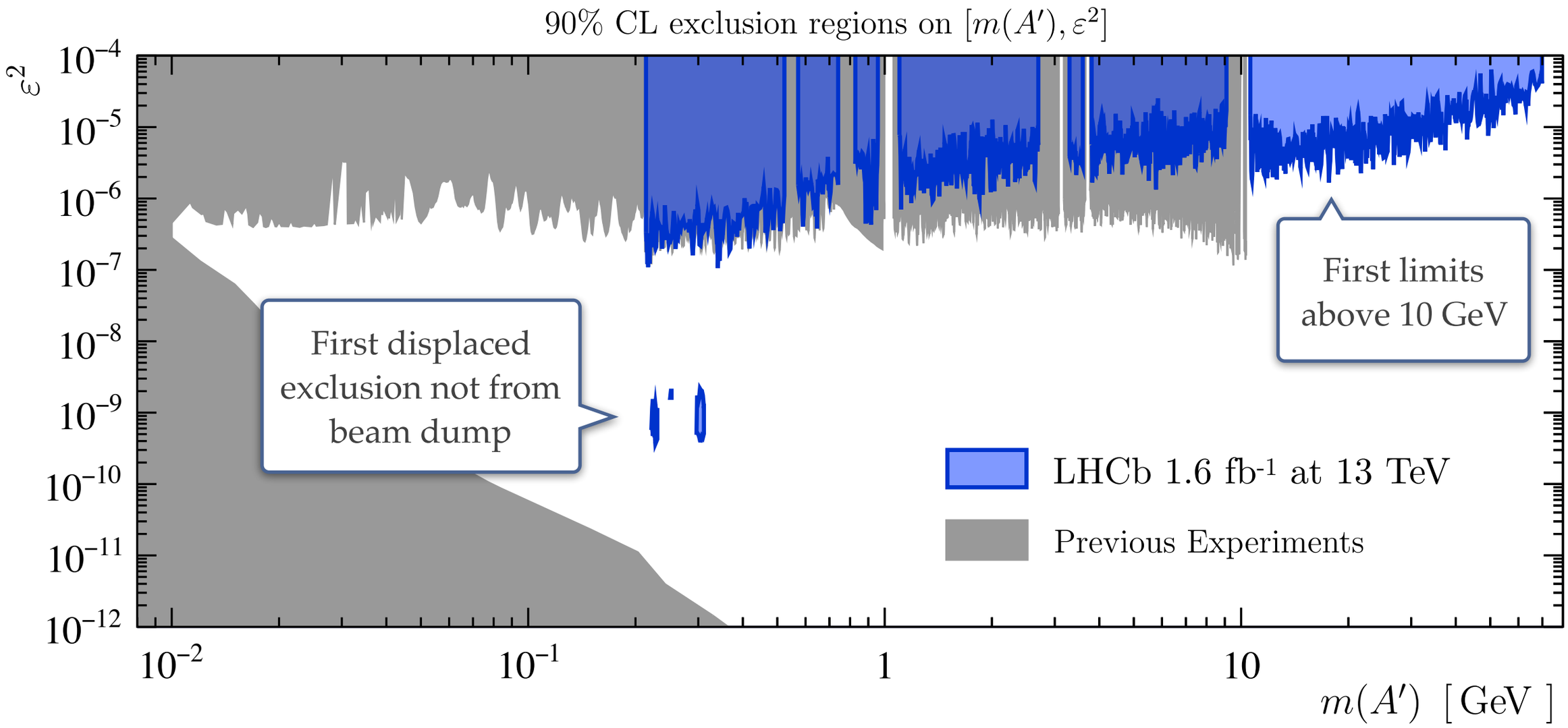
- Searches in other B/D channels foreseen
- Can also search using W→jet $\mu^-\mu^-$



# Dark Photons

LHCB, arXiv:1710.02867

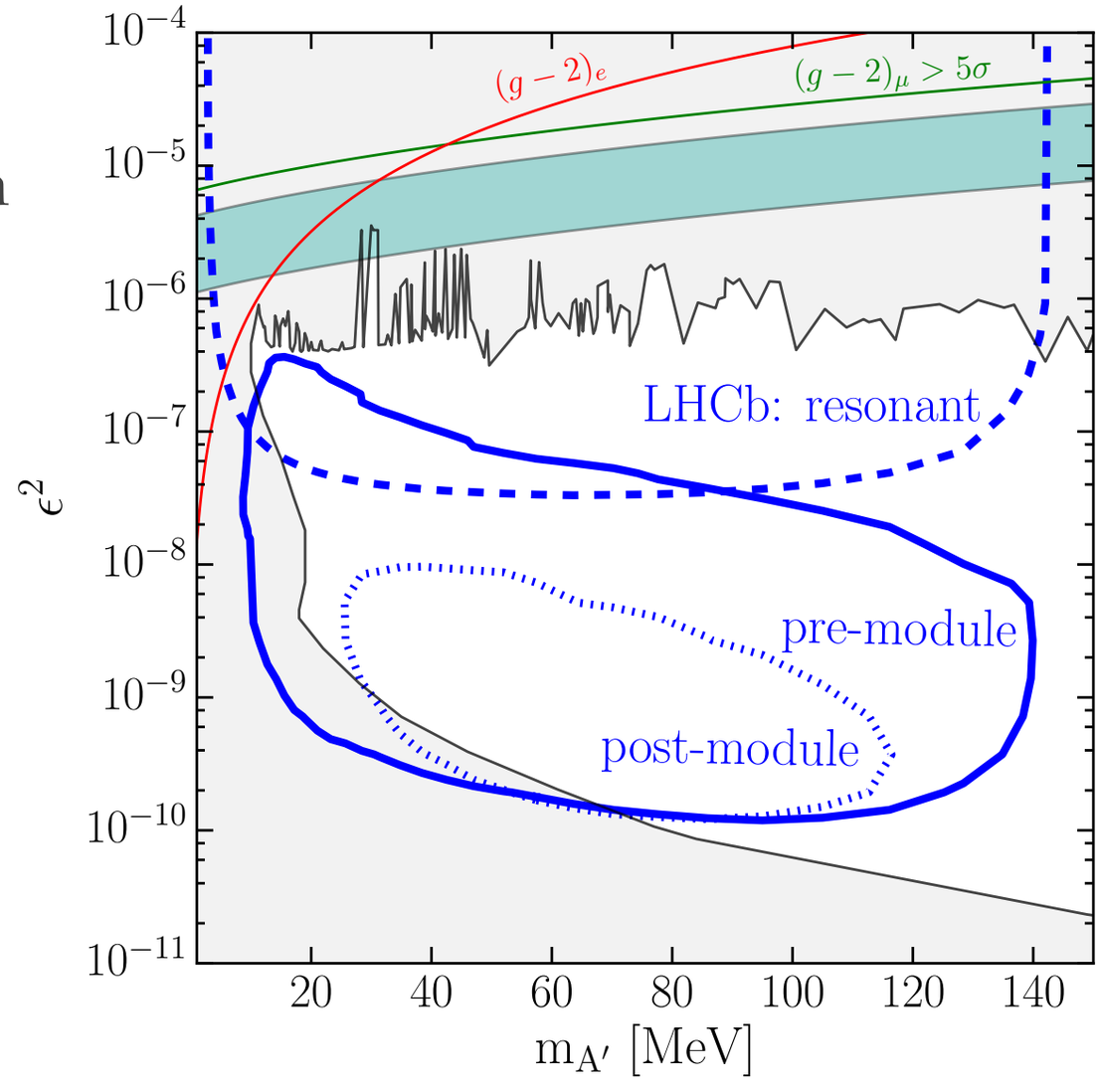
- **First results** already obtained with 1.6 fb$^{-1}$ at 13 TeV
  - **Prompt search** in large range $2\,m_\mu < m(\mu\mu) < m(Z)$
  - **Displaced search** in sensitive region $214 < m(A') < 350$ MeV



# Dark Photons from charm

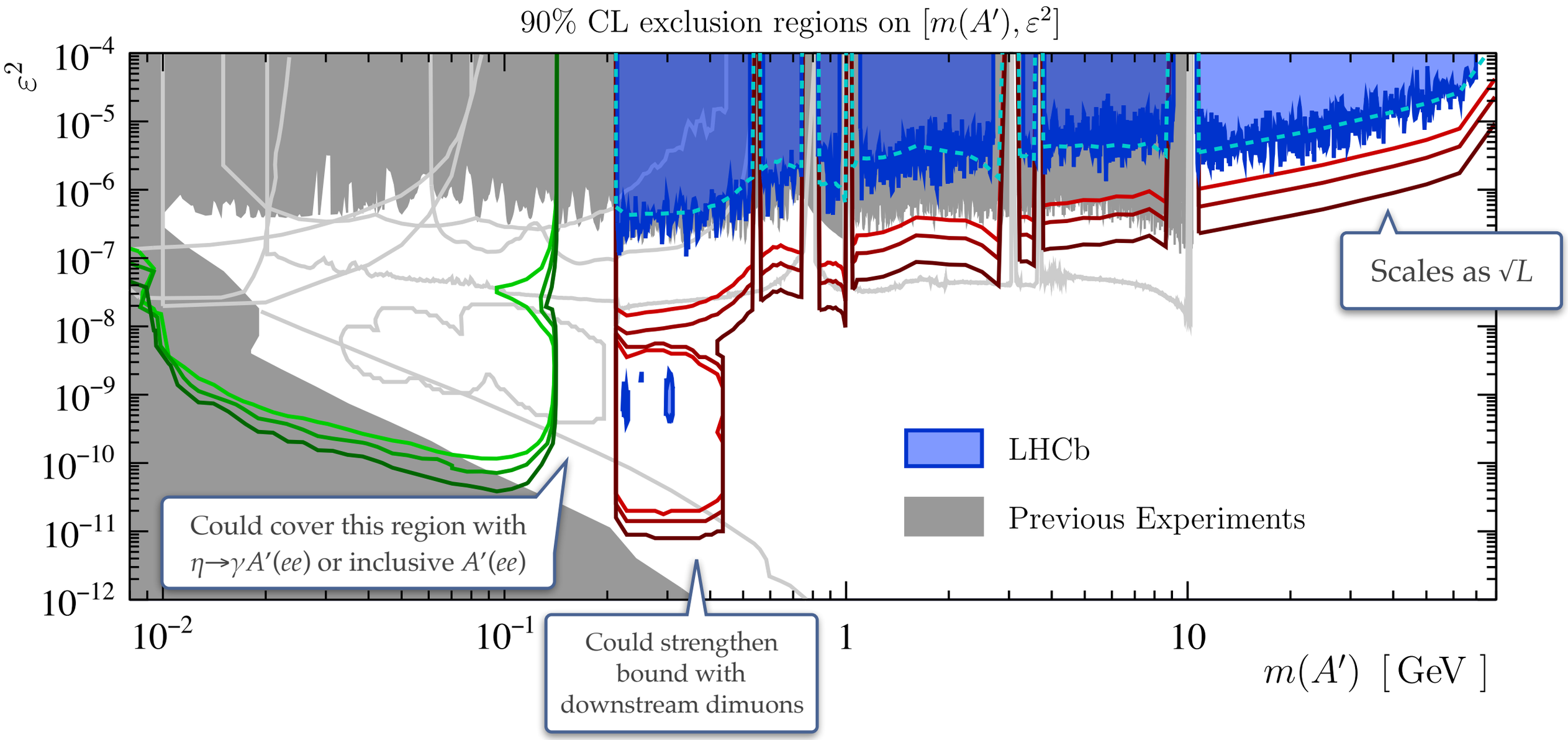
Ilten, Thaler, Williams, Xue PRD 92 no.11, 115017 (2015)

- 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 **$300\times10^9$ $D^{*0} \to D^0\gamma$ per fb$^{-1}$**
  - Both displaced and prompt searches



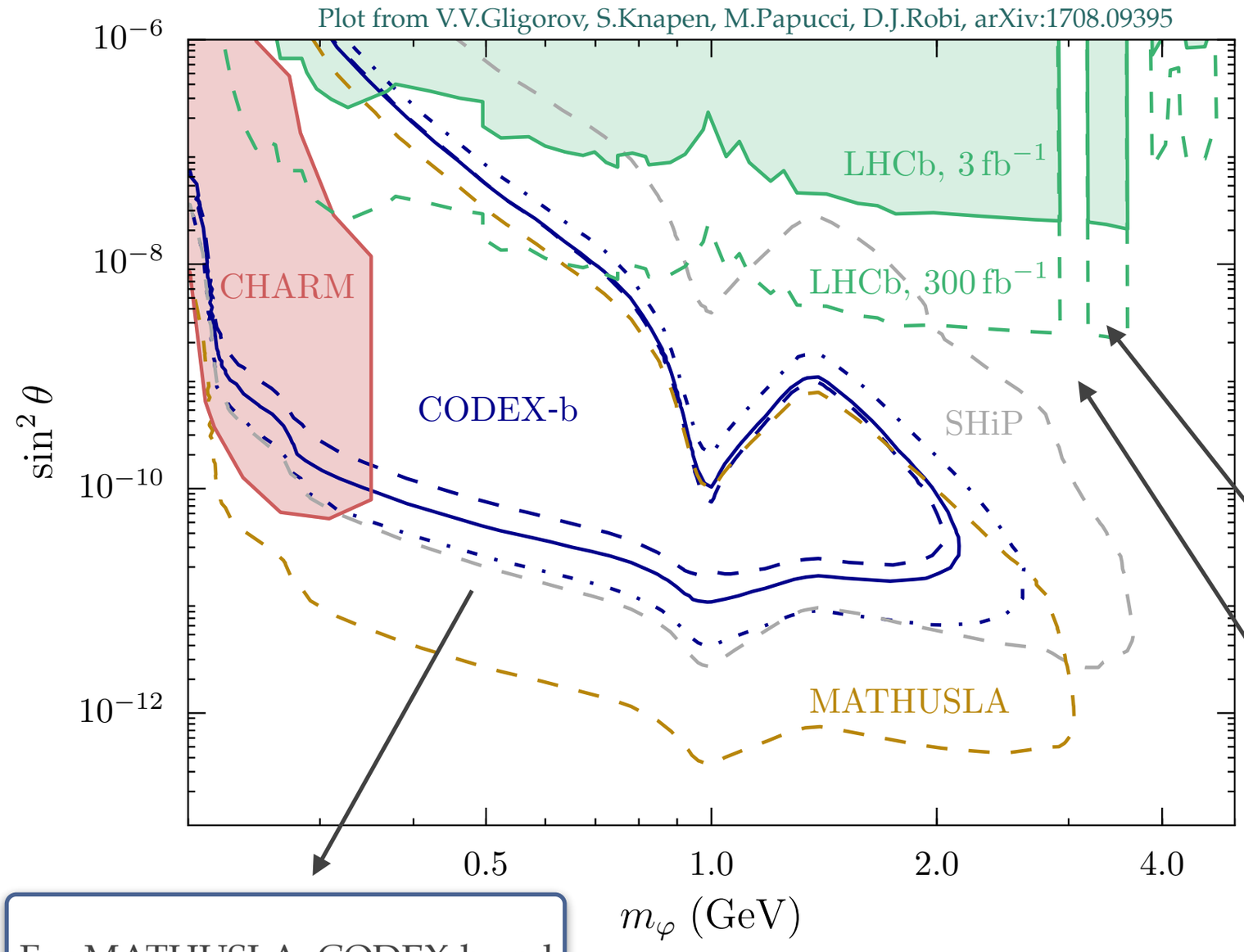
# Dark Photons reach

Ilten, Soreq, Thaler, Williams, Xue, PRL. 116 (2016) no.25, 251803



# Dark Sector in $B \to K^{(*)} \chi(\mu\mu)$

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




For MATHUSLA, CODEX-b and FASER see D.Curtin's talk

- **Constraint on light scalars mixing with the SM Higgs**

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

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

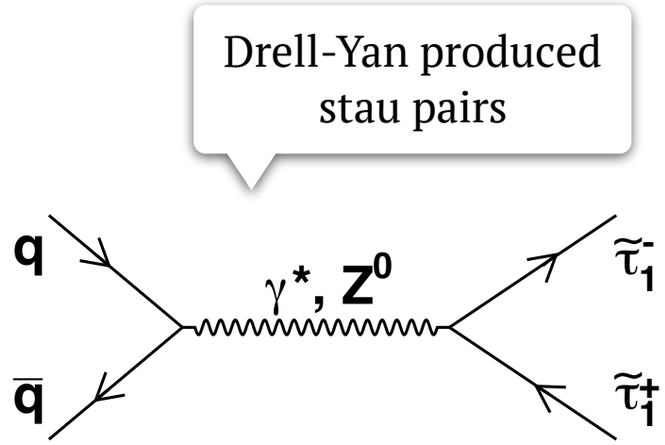
- **New parameter space is unexplored by current and future experiments**
  - 300 fb$^{-1}$ expected reach (no downstream dimuons)
  - Could significantly extend reach with downstream trigger

# Charged Massive Stable Particles

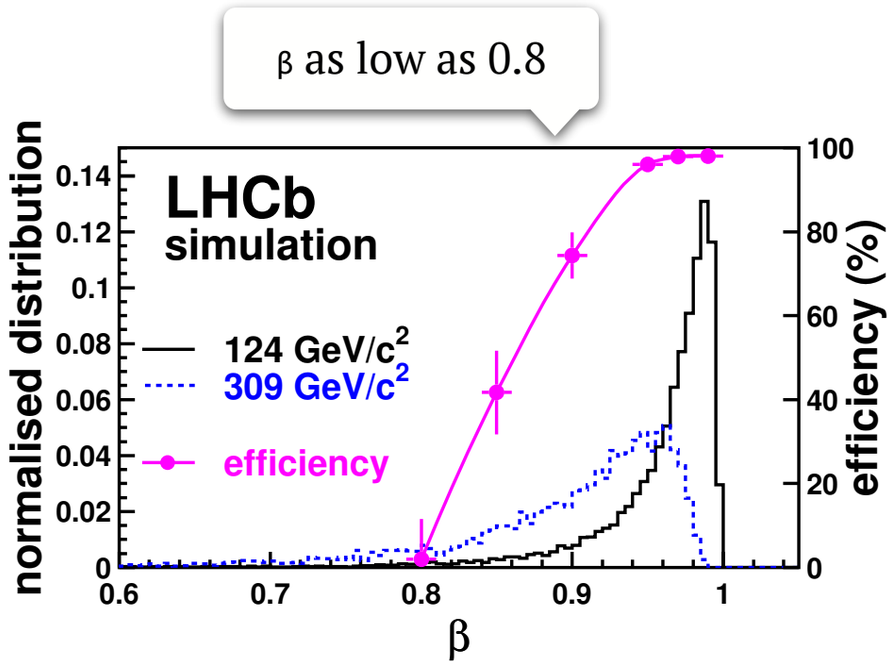
EPJC 75 (2015) 595

- Charged Massive Stable Particles
  - stable = can pass through the $\mu$-stations
- Model considered:
  - SUSY stau can be NLSP in mGMSB
  - long-lived with m>100 GeV/c2

S Dimopoulos et al [NPB488(1997)39]
GF Giudice and R Rattazzi [Phys.Rep. 332(2011)419]



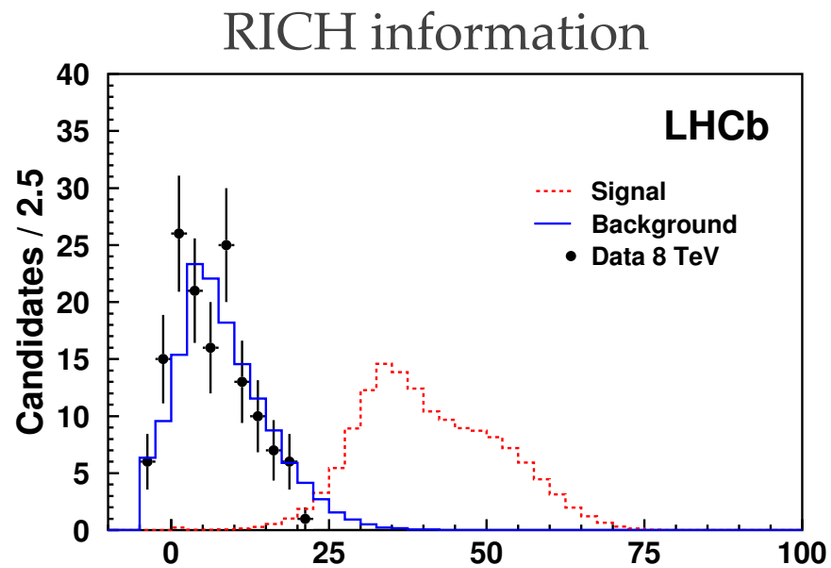

- CMSP can leave a signature as:
  - Smaller energy loss dE/dx
  - Longer Time of Flight
  - Absence of Cherenkov signal
- Several experiments searched for them
  - LEP, Tevatron, HERA, ATLAS/CMS



# Charged Massive Stable Particles

EPJC 75 (2015) 595

- Select pair of muon-like tracks in mass range [120, 300] GeV/$c^2$
- Train Neural Network to combine RICH information with d$E$/d$x$ from VELO and calorimeters




- Limit is not competitive with D0 (low mass) and ATLAS (high mass)
- Proof of concept for future searches!
- Possibly move to single CMSP signature and/or to lower masses