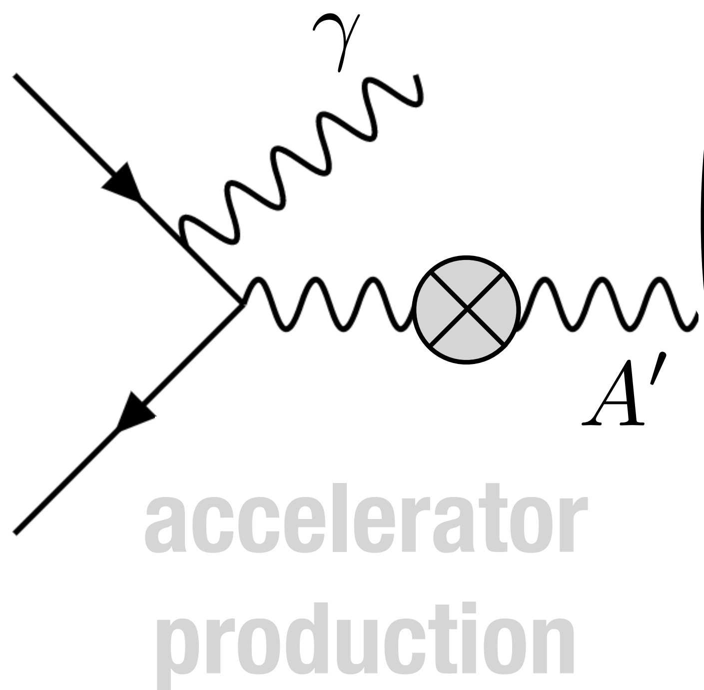


Flavour and Dark Matter

Karlsruhe 2018

Date: 24. - 26. September, 2018

Registration: https://indico.cern.ch/e/flavourdark2018

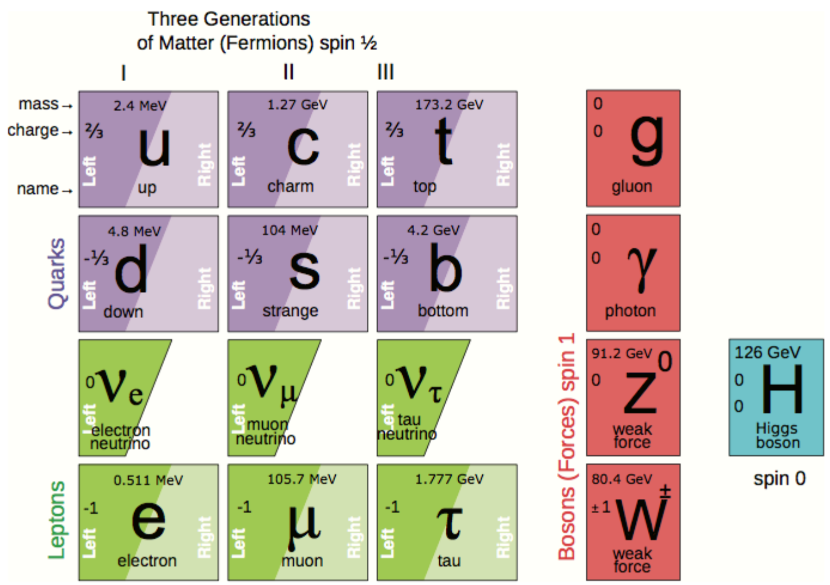
Organizers: Ulrich Nierste, Florian Bernlochner, Pablo Goldenzweig (KIT)
Stephanie Hansmann-Menzemer, Martin Bauer (UHD)

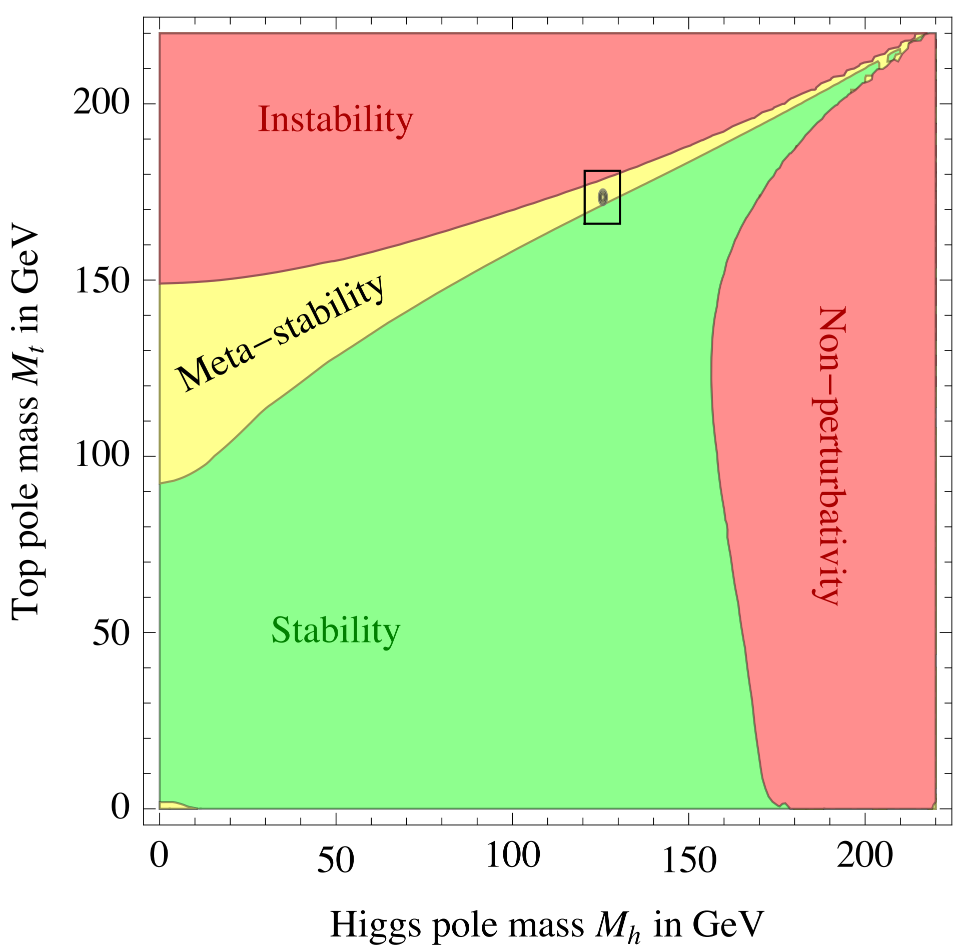
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Dark Sector Searches at LHCb

Martino Borsato†
†Universität Heidelberg
on behalf of the LHCb collaboration

New Physics scale





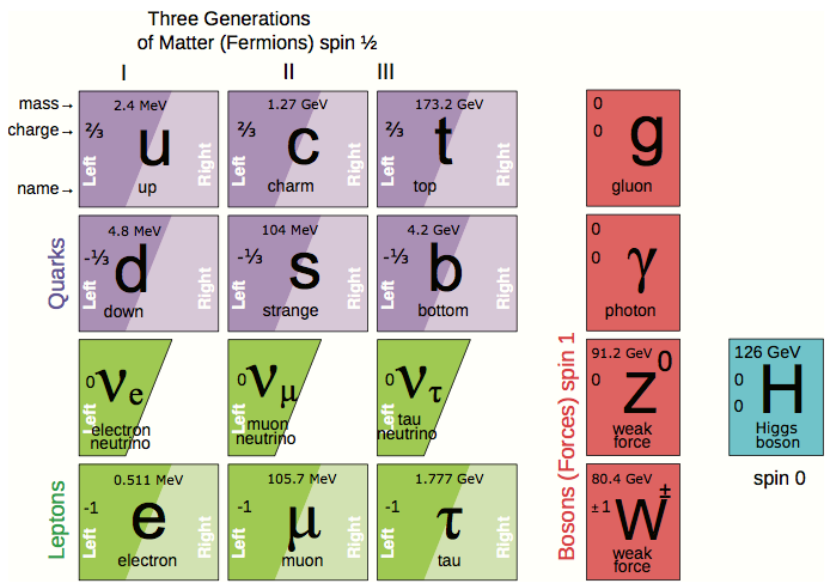
D.Buttazzo et al. JHEP 1312 (2013) 089

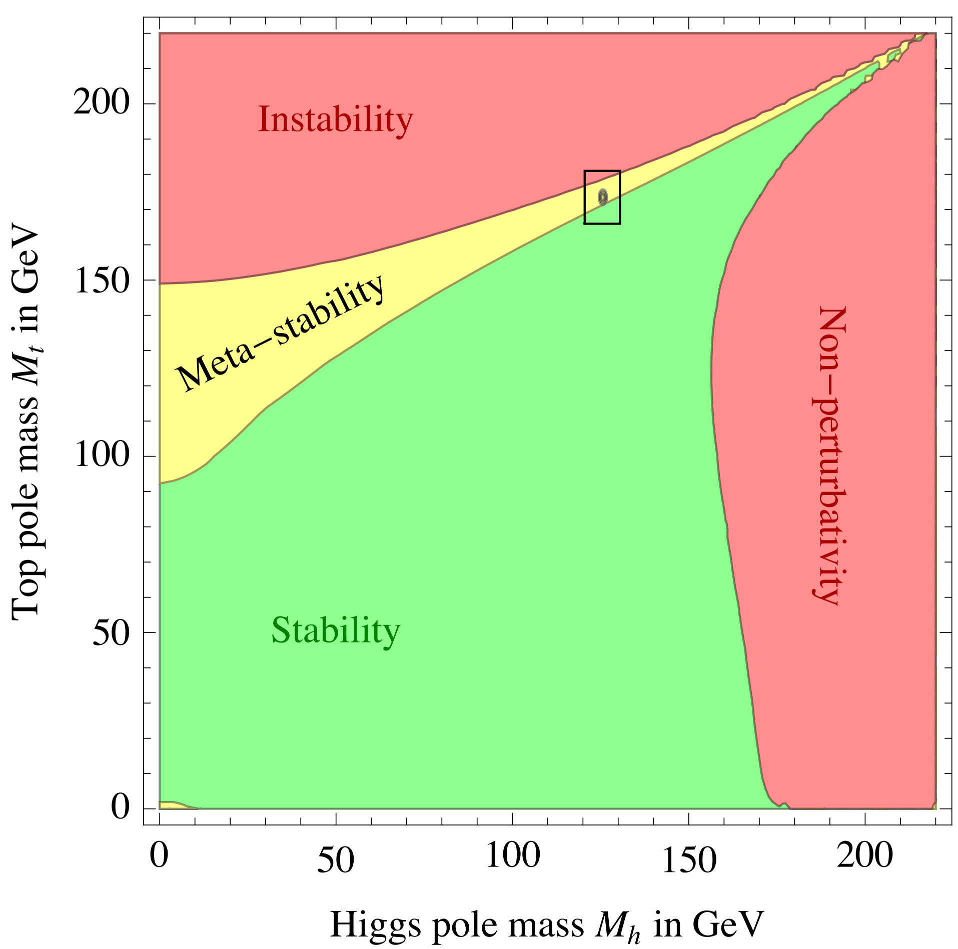
SM shortcomings:

- Experimental obs.:
  - **Dark Matter**
  - Neutrino masses
  - Baryon asymmetry
  - Inflation
- Theoretical prejudice:
  - Stability of m_H
  - Strong CP problem
  - Fermion hierarchy

Where is NP?

New Physics scale





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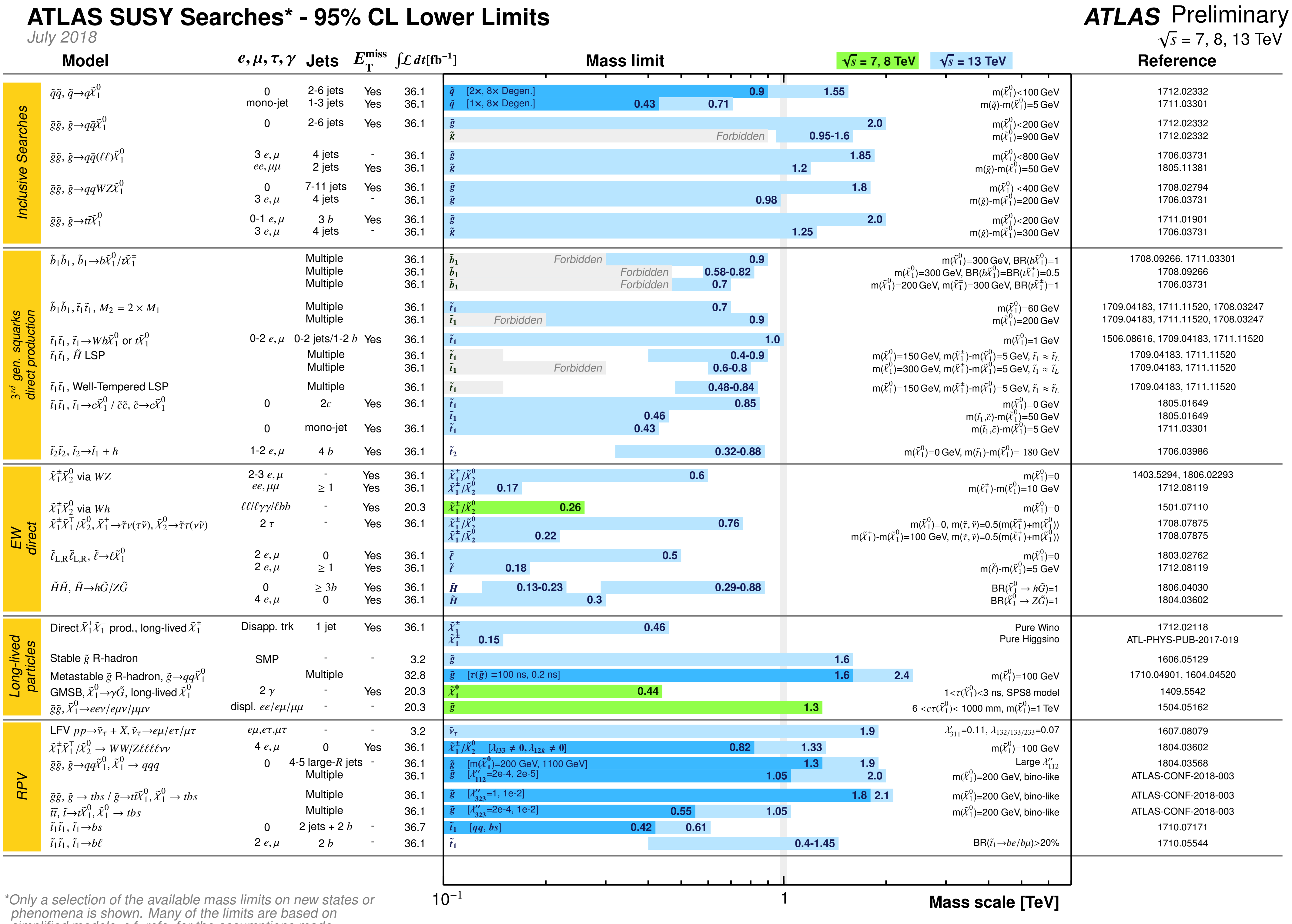
Where is NP?

Above the EW scale

- e.g. SUSY at TeV scale
- Can stabilise m_H and solve hierarchy problem
- New heavy particles → ***energy frontier***

Direct searches at energy frontier



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

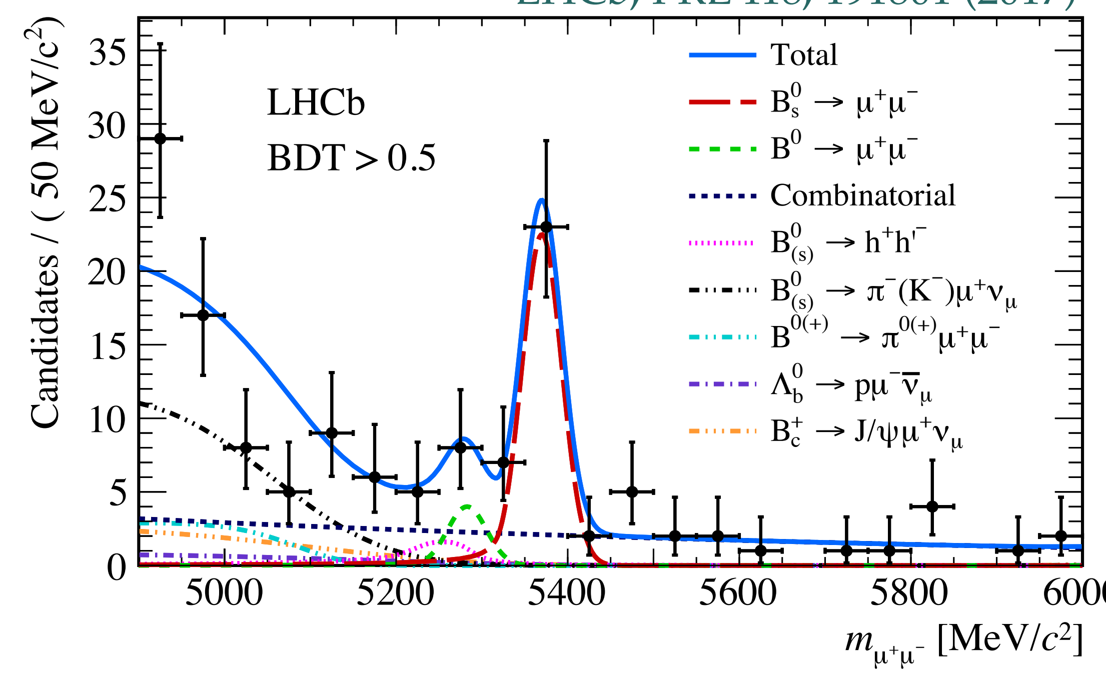
Indirect searches at energy frontier

- New heavy degrees of freedom can have an indirect effect on SM processes
- Choose experimental observables were the SM contribution is:
  - Very small (e.g. rare B decays)
  - Precisely predicted (e.g. CPV, BR ratios)
- Example: rare *b*→*s* FCNC transitions

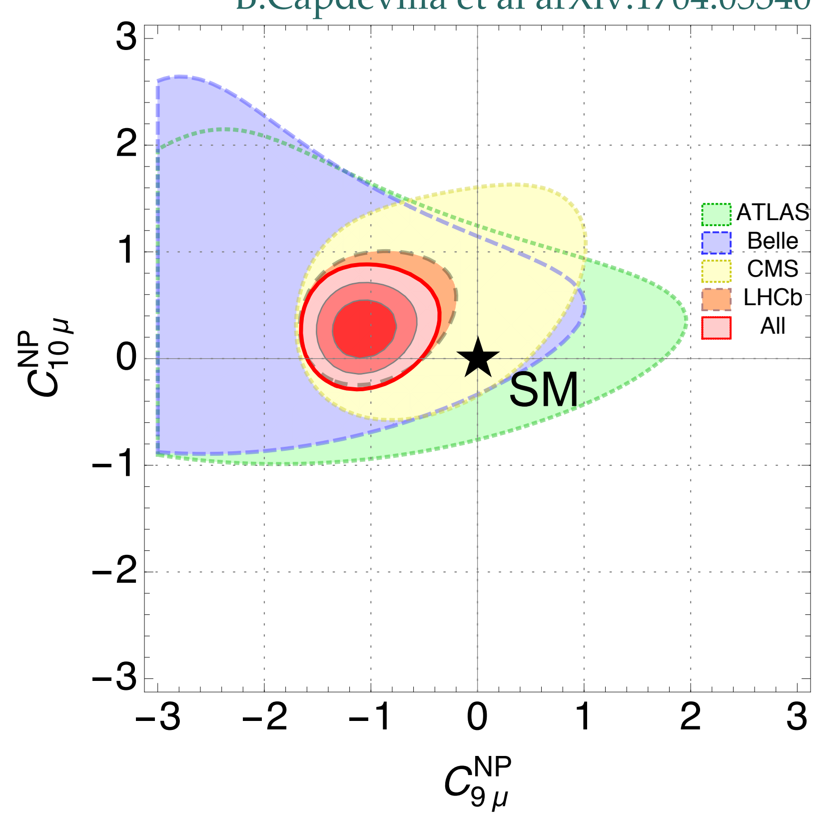
$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^{*}\frac{\alpha_e}{4\pi}\sum_i(\mathcal{C}_i\mathcal{O}_i + \mathcal{C}_i'\mathcal{O}_i') + \text{h.c.}$$

$$\Lambda_{\text{NP}} \times \sqrt{|\mathcal{C}^{\text{NP}}_{9,10}|} \sim \begin{cases} \frac{4\pi\,\sqrt{2}M_W}{ge\sqrt{|V_{tb}V_{ts}^{*}|}} = 36\,\text{TeV} & \text{(generic tree level)}, \\ \frac{\sqrt{2}M_W}{e\sqrt{|V_{tb}V_{ts}^{*}|}} = 2\,\text{TeV} & \text{(weak loop)}, \\ \sqrt{2}M_W/e = 400\,\text{GeV} & \text{(MFV, weak loop)}. \end{cases}$$

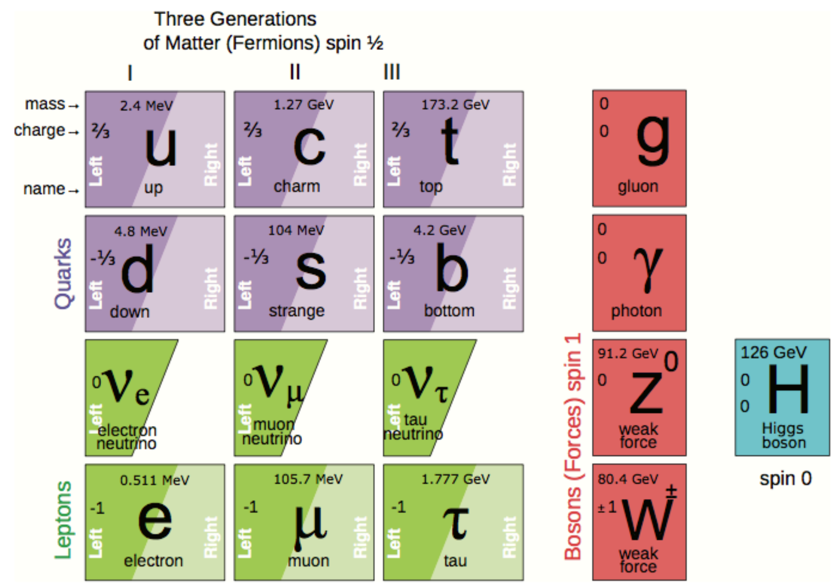
LHCb, PRL 118, 191801 (2017)

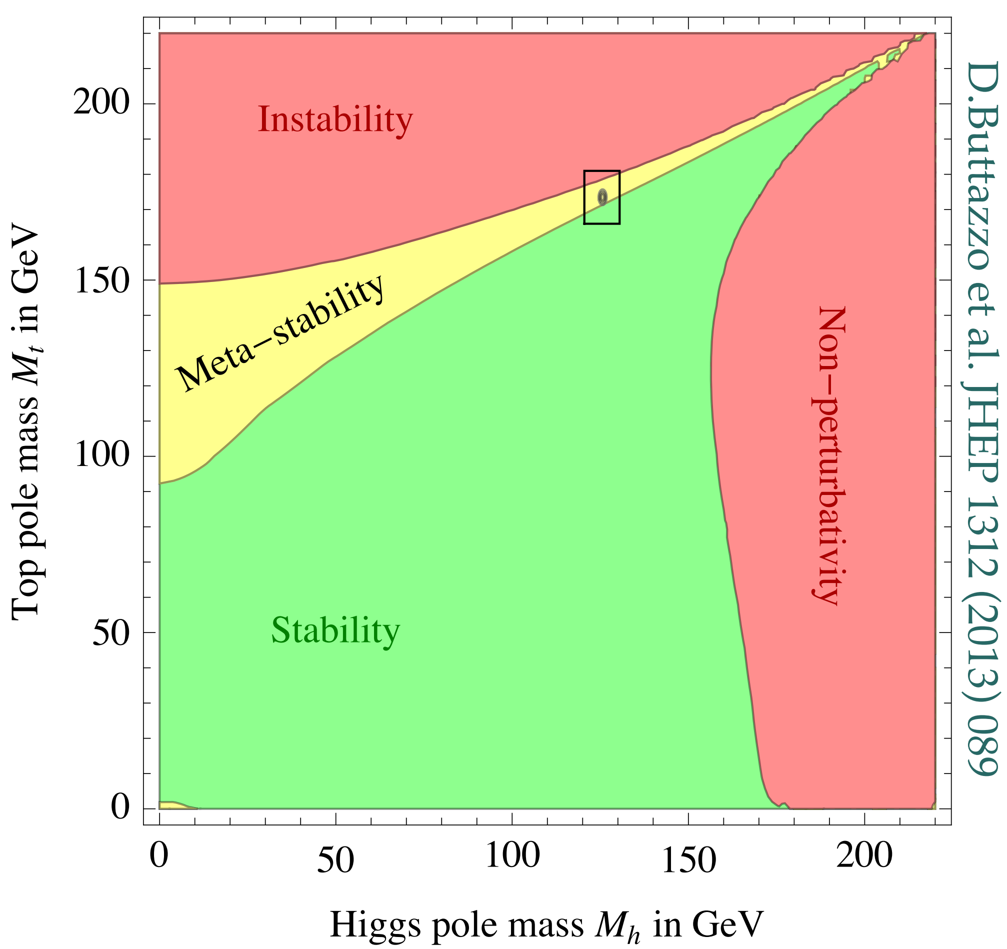


B.Capdevilla et al arXiv:1704.05340



New Physics scale





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Where is NP?

Above the EW scale

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- Can stabilise m_H and solve hierarchy problem
- New heavy particles

→ *energy frontier*

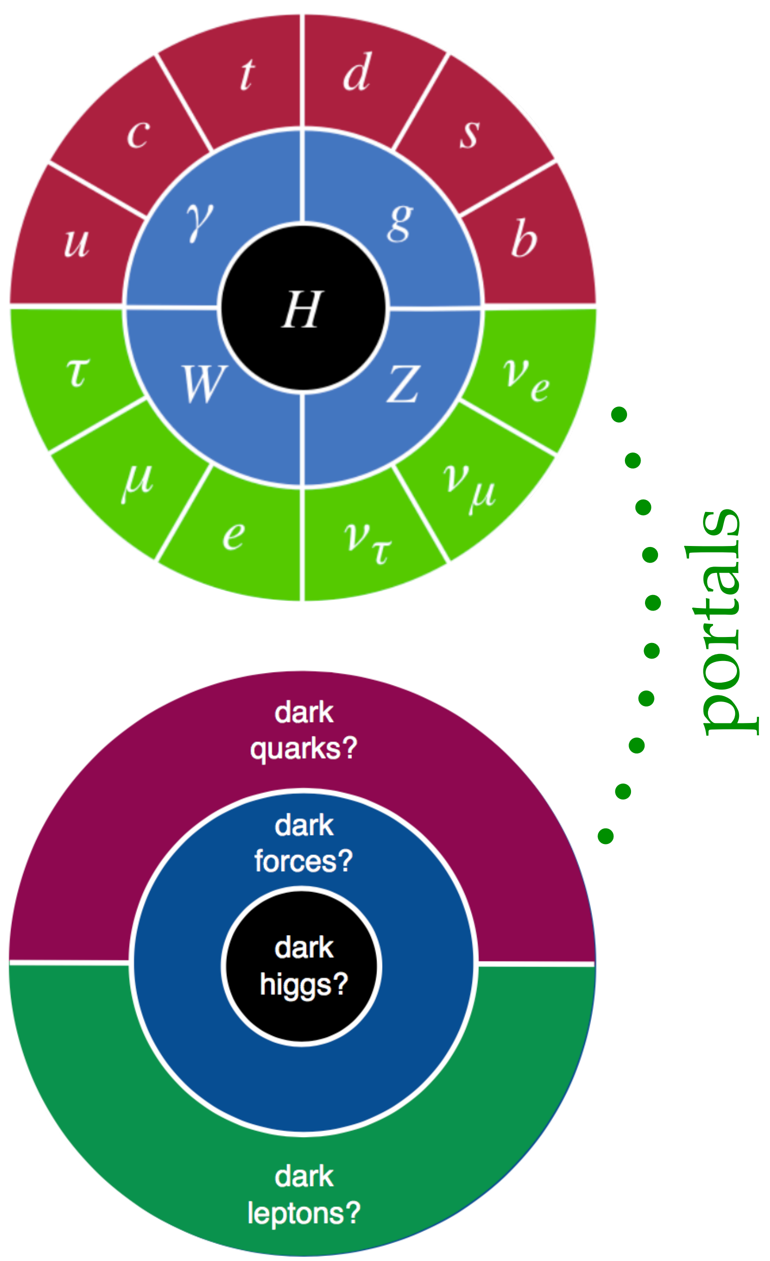
Below the EW scale

- SM valid up to Planck scale? NP is light?
- Still solve many SM issues
- New light particles weakly coupled to SM

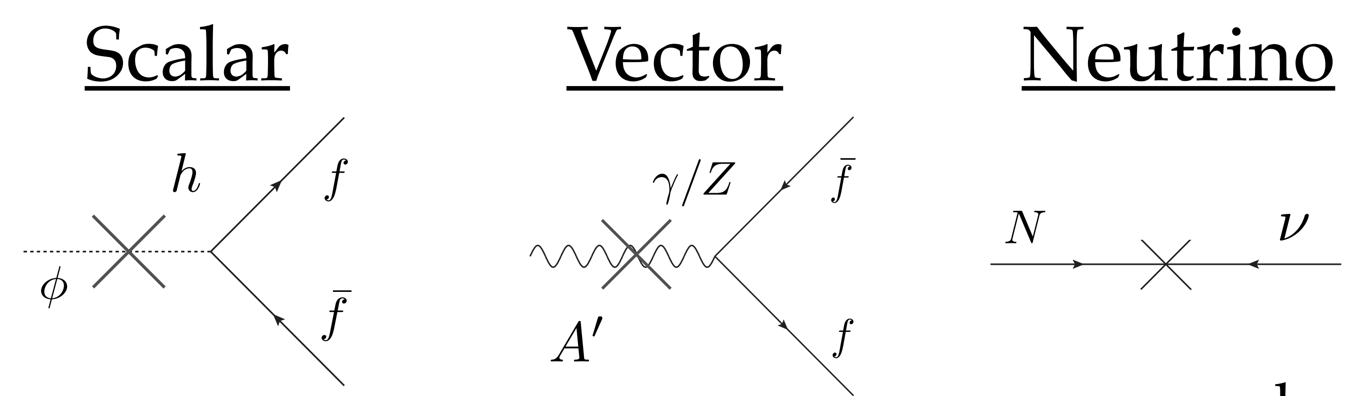
→ ***intensity frontier***

Direct searches at intensity frontier

Dark Sectors
(neutral under SM forces)



- Possible **portals** to the SM:



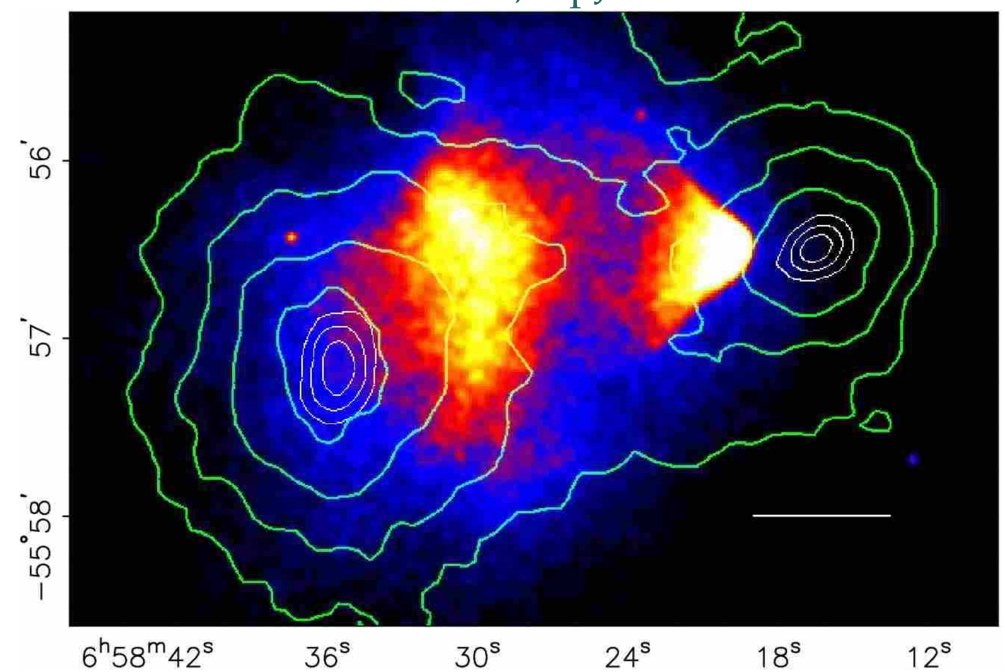
…and more

- Typical features:
  - Very weakly coupled to SM
  - Displaced vertex signature
- Can elude current limits
  - Even for very light masses
  - Especially if vertex is displaced

Nice review: arXiv:1608.08632

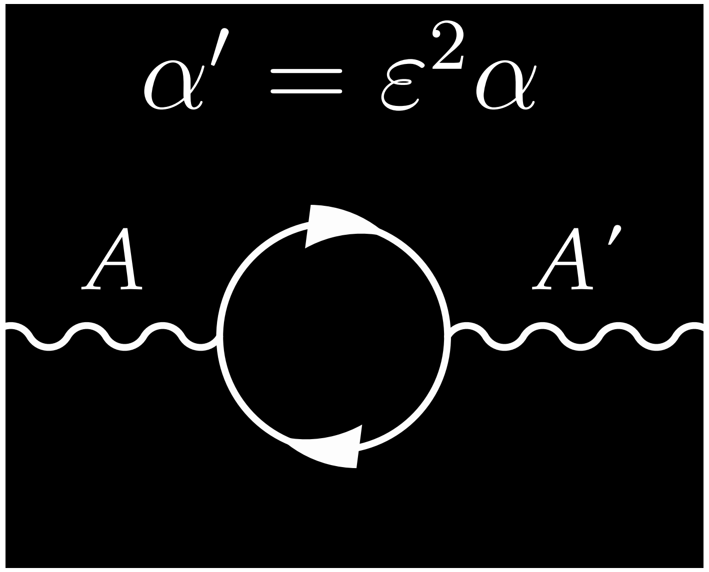
Example: Dark Photons

D. Clowe et al, ApJ 648 No 2 L109-L113



Explanation for Dark Matter:

- DM interacting through weak force (**WIMP**)
  - not found yet at LHC or Direct Detection
- DM interacting through **different force**
  - Coupling only indirectly to SM
  - Keep it simple: add “dark" U(1) symmetry
    → dark photons mixing with SM photons

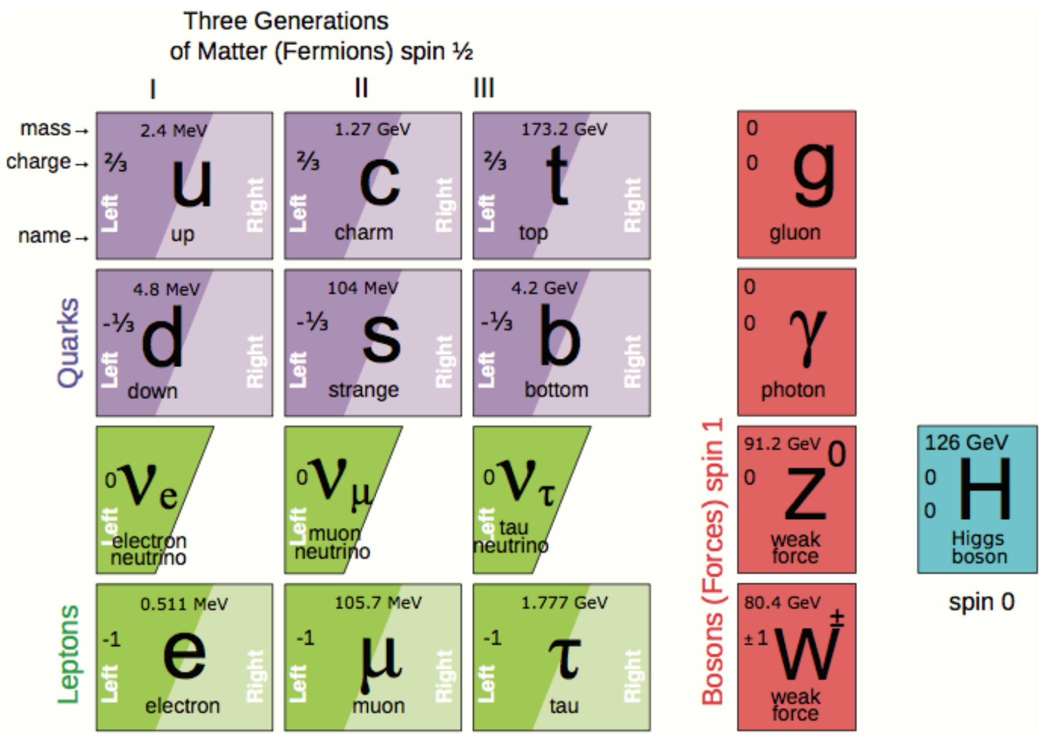


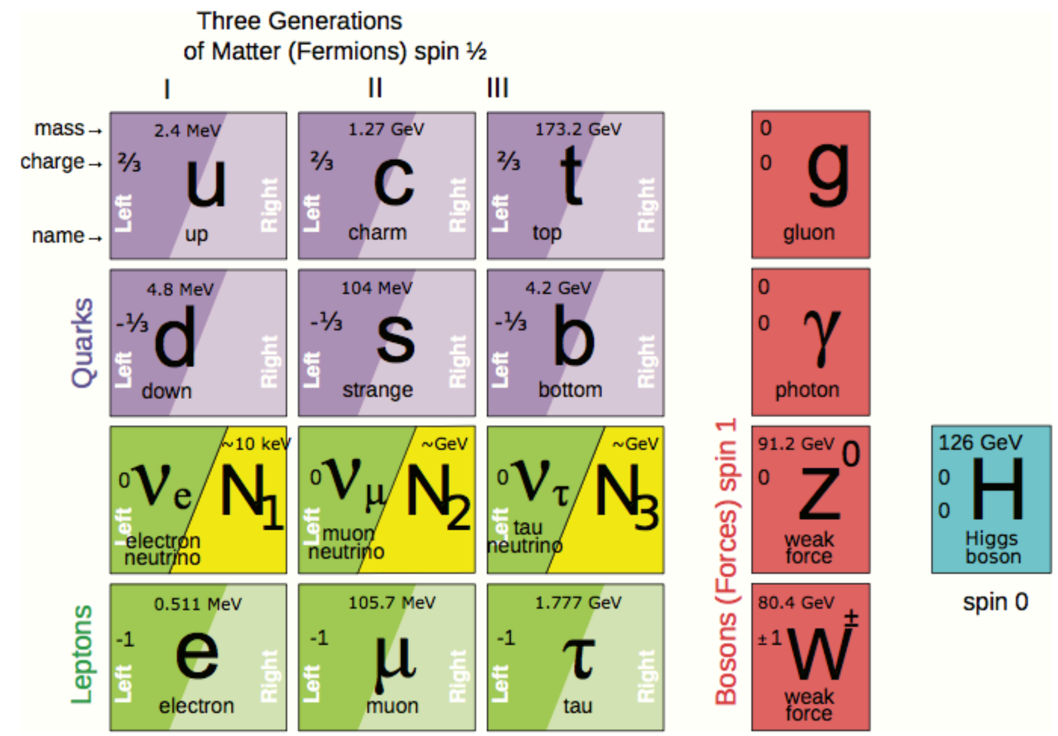
- Dark Photons interaction with SM and DM can give the right DM relic abundance:
  - e.g. if $m_{DM} < m_{A'}$ you can get it if the mixing is:

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

From Dark Sectors Community Report 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
Recent ννMSM model arXiv:1806.06864

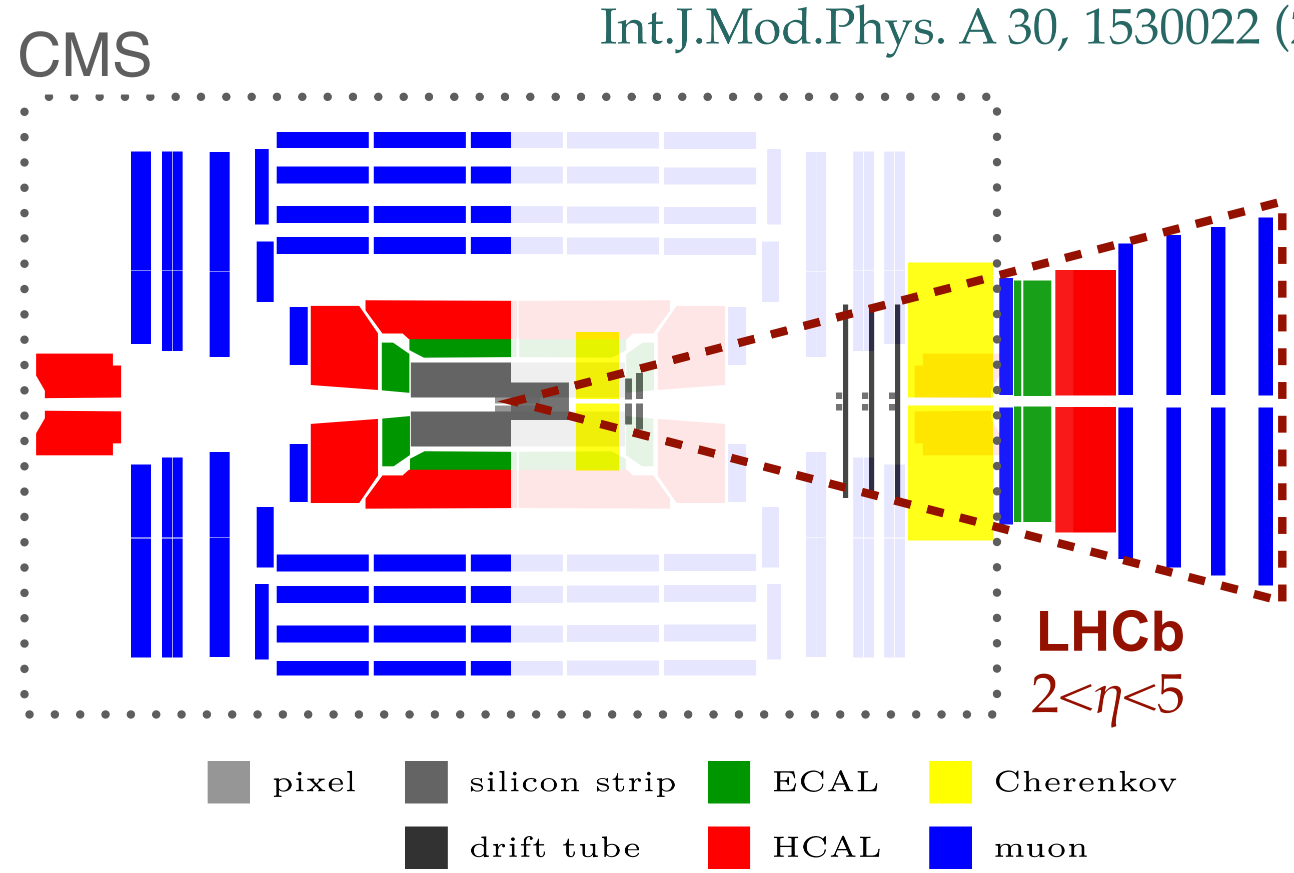
How can LHCb contribute?

The LHCb detector

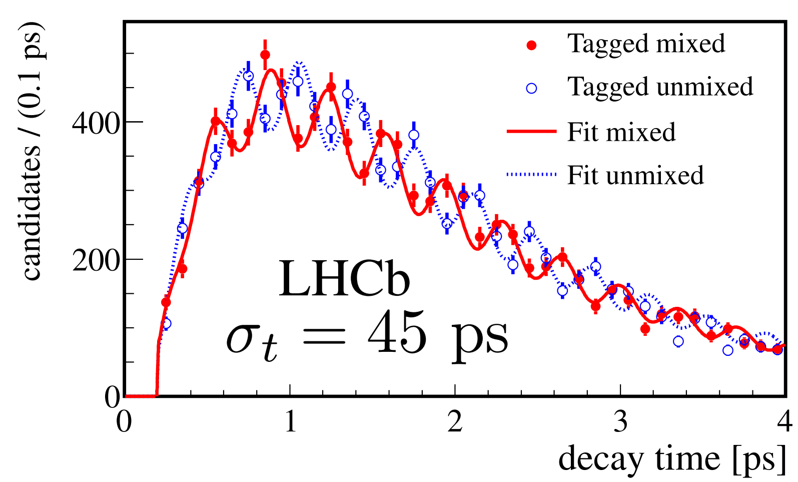
- Only LHC detector fully instrumented in **forward** region
- Excellent **vertex resolution**
  - Able to measure B_s oscillations (helped by forward boost)
- Excellent **mass resolution**
  - Separate partially and $B_{d/s}$
- Good **jet reconstruction**
  - 10-20% energy resolution for jets with $p_T > 10\,\text{GeV}$
  - $b(c)$ tagging eff 65%(25%) for 0.3% contamination

LHCb, JINST 10 (2015) P06013

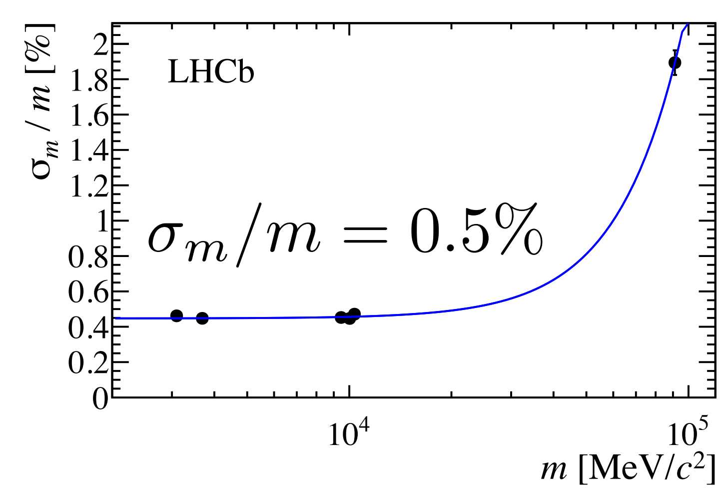
Int.J.Mod.Phys. A 30, 1530022 (2015)



vertex reconstruction



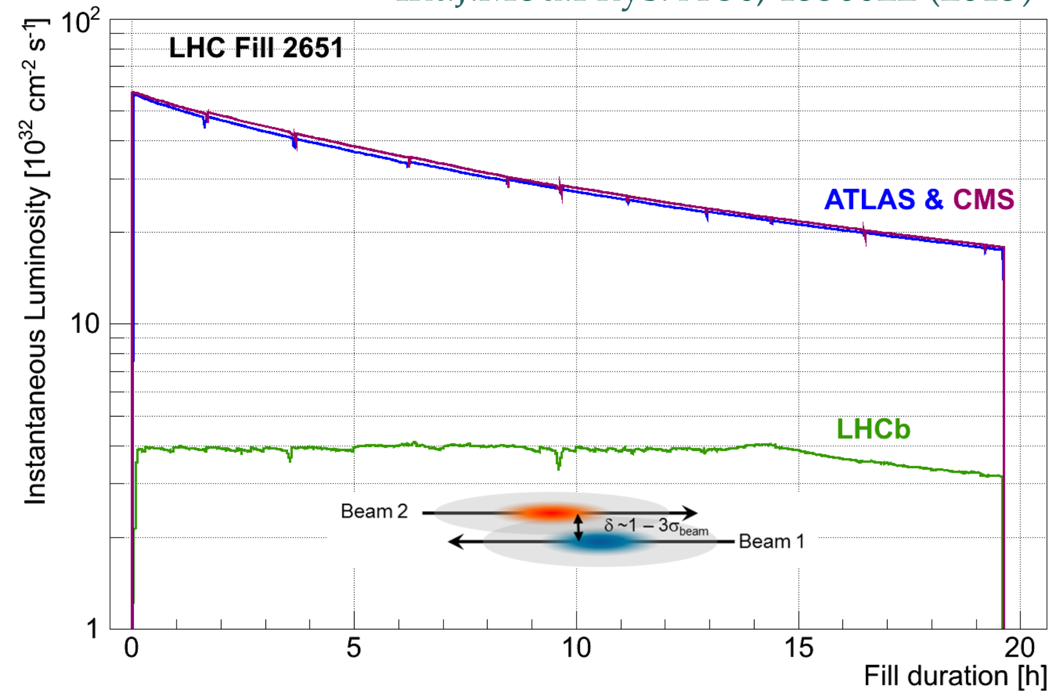
mass resolution



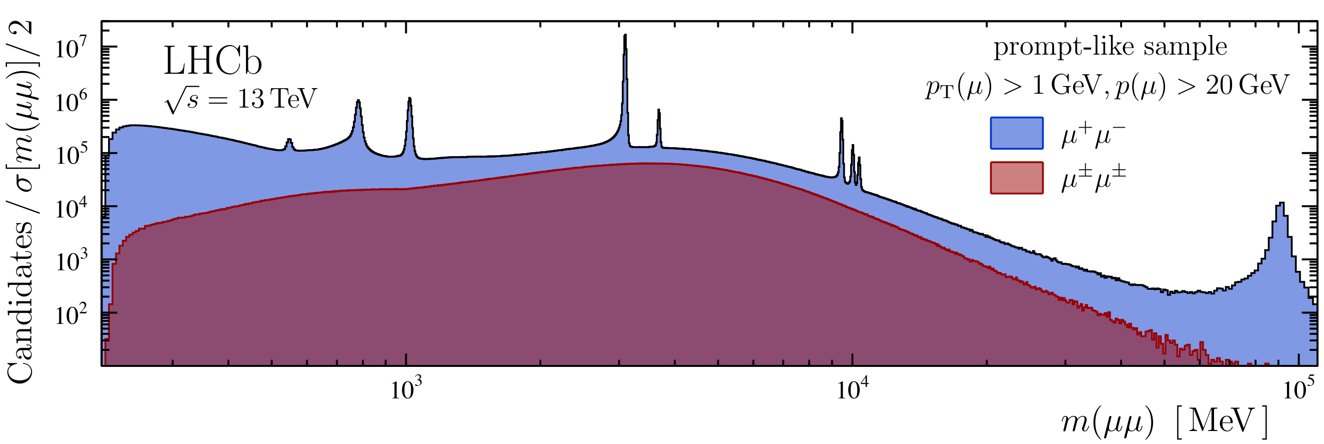
The LHCb detector

- **Lower luminosity** (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 $p_{\mathrm{T}} > 1.7\,\mathrm{GeV}$
    - Calo deposits with $E_{\mathrm{T}} > 3$ GeV
  - At Software level (HLT):
    - Topological triggers on detached vertices
  - Real-time calibration in Run 2:
    - Allowed "real time analysis" i.e. keep only interesting part of event

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



Dimuon spectrum from trigger output:

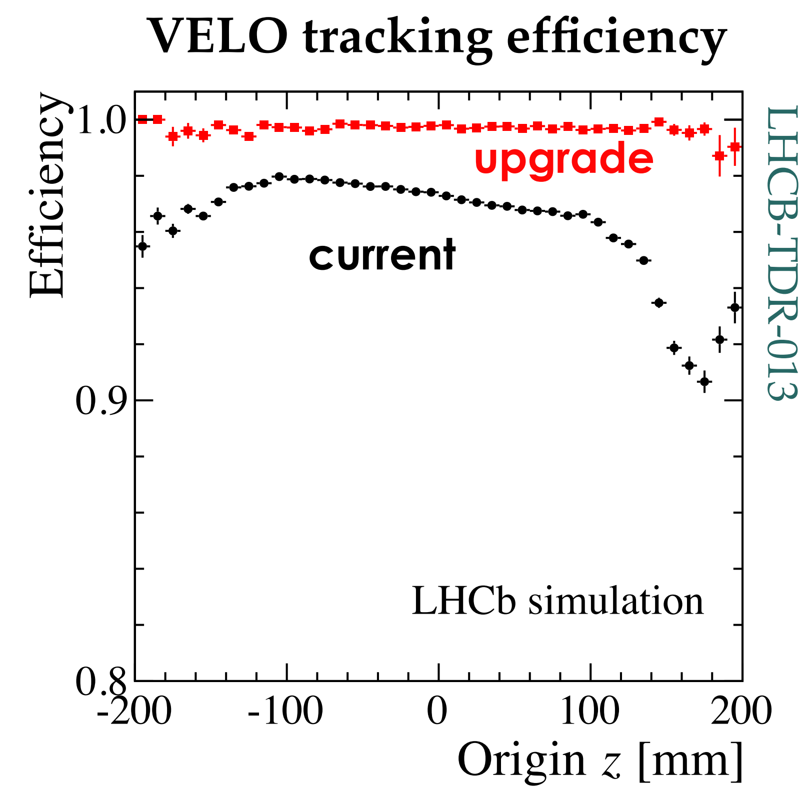


LHCb, PRL 120 (2018) no.6, 061801

The LHCb upgrade

	Current	Upgrade-Ia	Upgrade-Ib	Upgrade-II
$\mathcal{L}/(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	4×10^{32}	2×10^{33}	2×10^{33}	2×10^{34}
$\int \mathcal{L}$	$8\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$\sqrt{s}$	7, 8, 13 TeV	14 TeV	14 TeV	14 TeV
μ	~ 1	~ 5	~ 5	~ 50

CERN-LHCC-2018-026

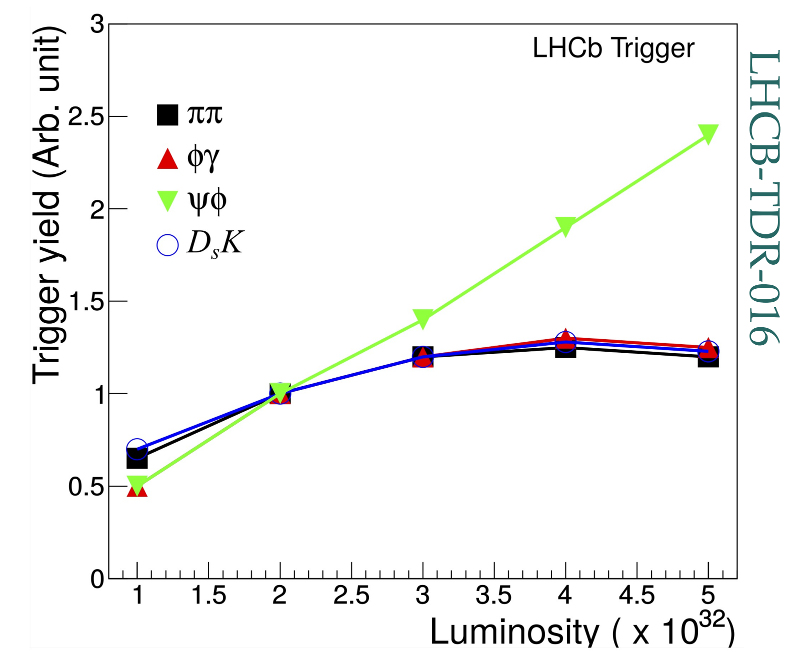


- Upgrade Ia LHCb detector:
  - Upgraded **VELO** with pixels and live readout
    - Lower fake rate and faster pattern recognition
    - Less material interaction (factor 3 better)
    - Better IP resolution (factor 2 better at p_T~0.5 GeV)

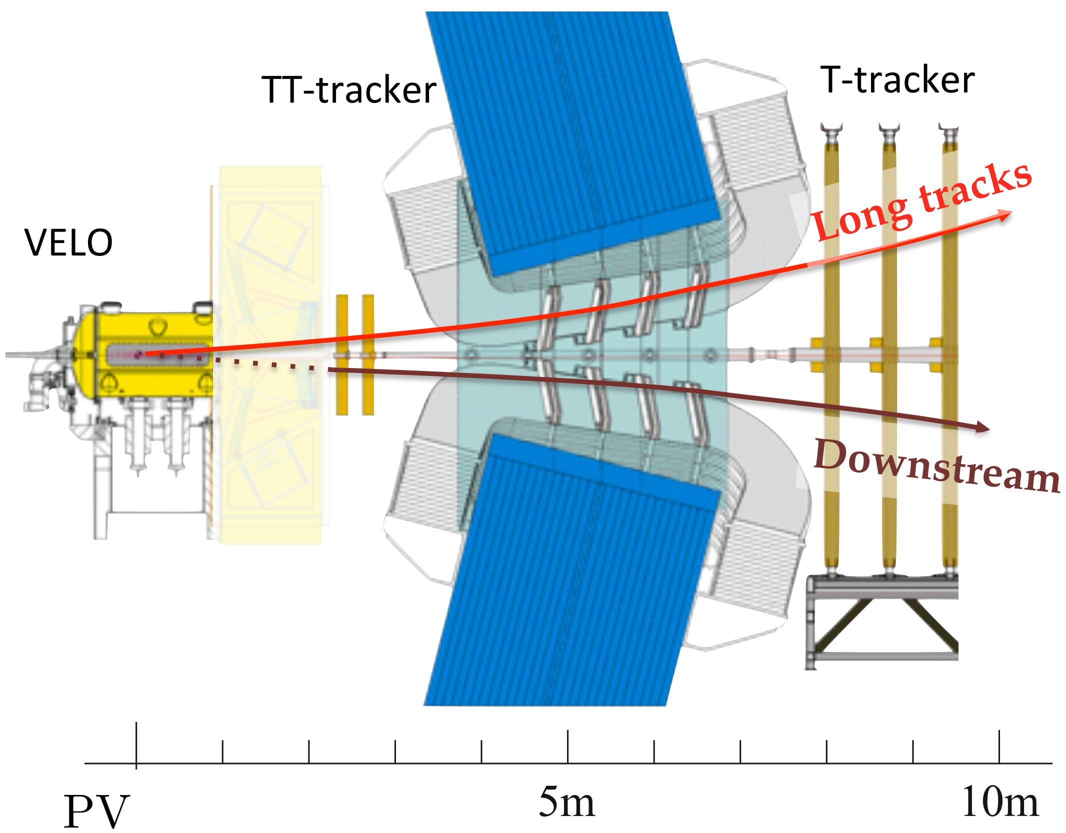
LHCB-TDR-013

  - Upgraded Trigger all in software
    - Reading out full detector in real time (40 MHz)
    - Lower p_T thresholds, displaced vertices at first level
    - Turbo stream with offline-quality calibration

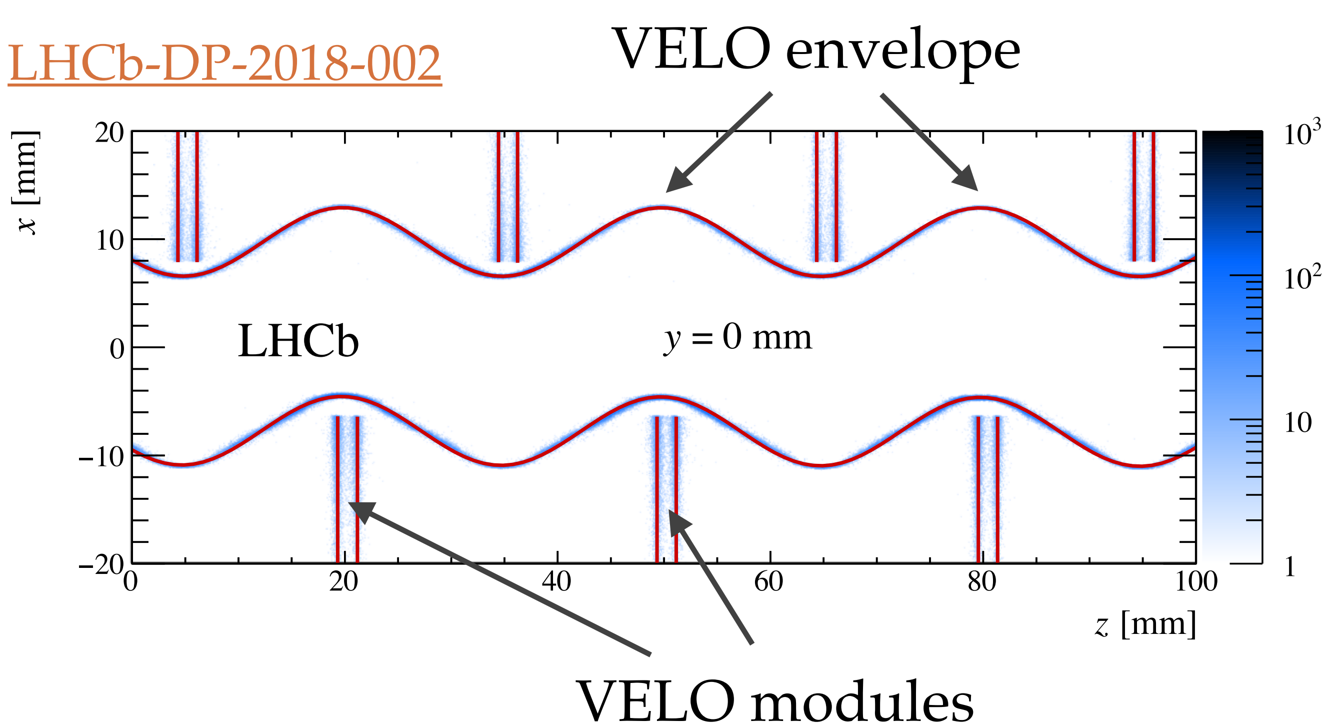
LHCB-TDR-016



Displaced Vertices at LHCb



LHCb-DP-2018-002



- Currently only **within VELO**
  - Displacement < 20 cm (but with boost)
- 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]

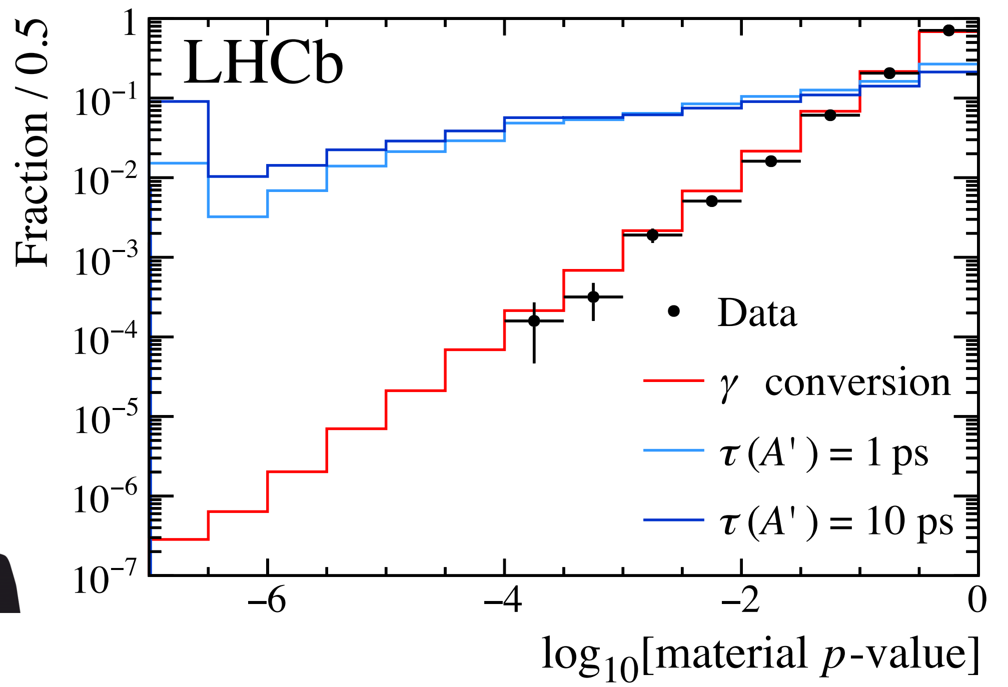
Backgrounds in VELO

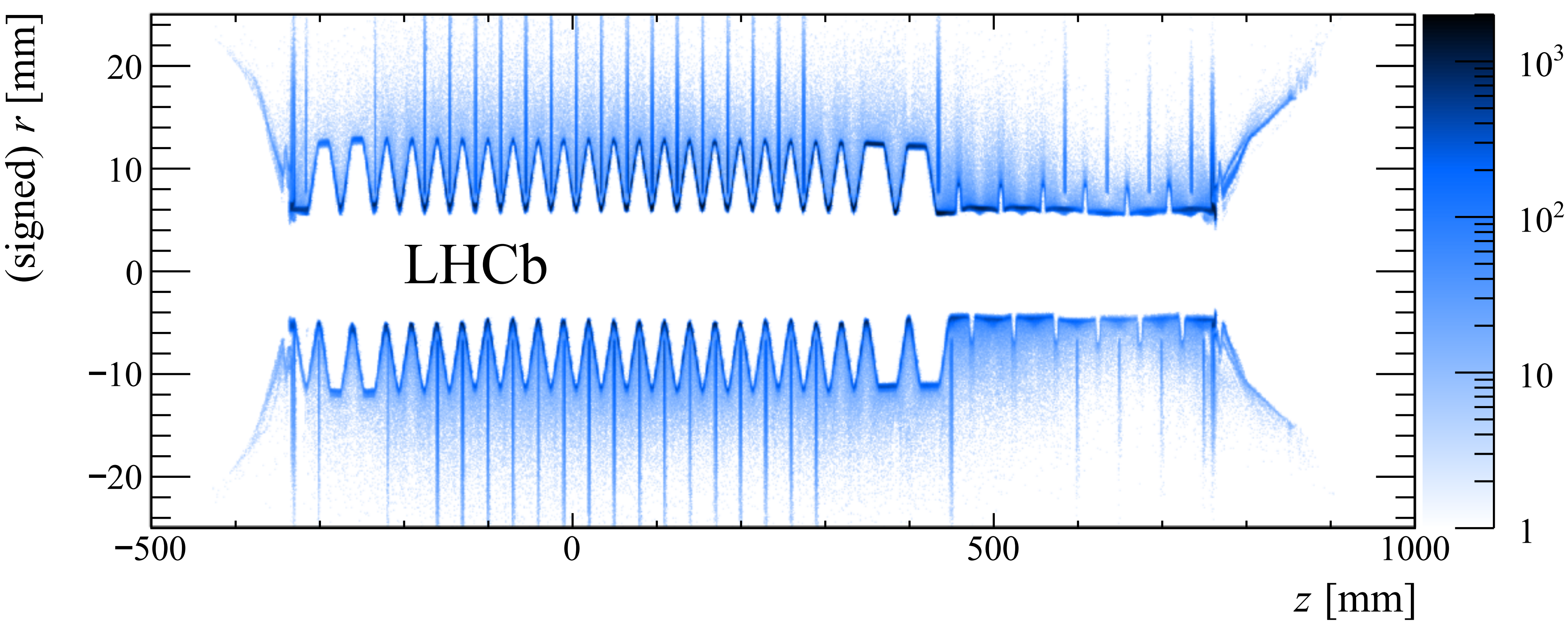
- Heavy Flavour displaced decays
  - $\tau(B)$~1.5 ps, $\beta\gamma$~10 ⇒ few mm
- Thin VELO envelope (RF foil)
  - **< 5 mm**: background mainly from heavy-flavour background
  - **> 5 mm**: background mainly from material interaction

VELO material map

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



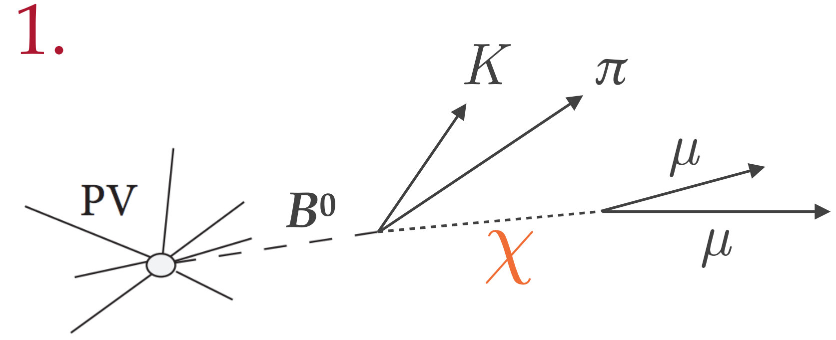


Overview of current results (and some future prospects)

Direct Searches at LHCb

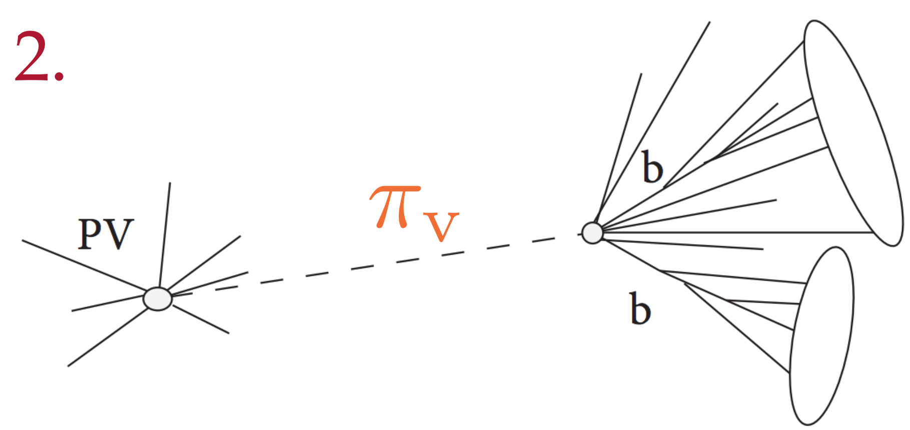
- LHCb can get world-leading sensitivity:
  - **Lighter masses** w.r.t. ATLAS/CMS
    - soft trigger and forward acceptance
  - **Low lifetimes** down to 1 ps
    - excellent vertexing and boost

1.



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

2.



Dark Bosons from $b \to s$

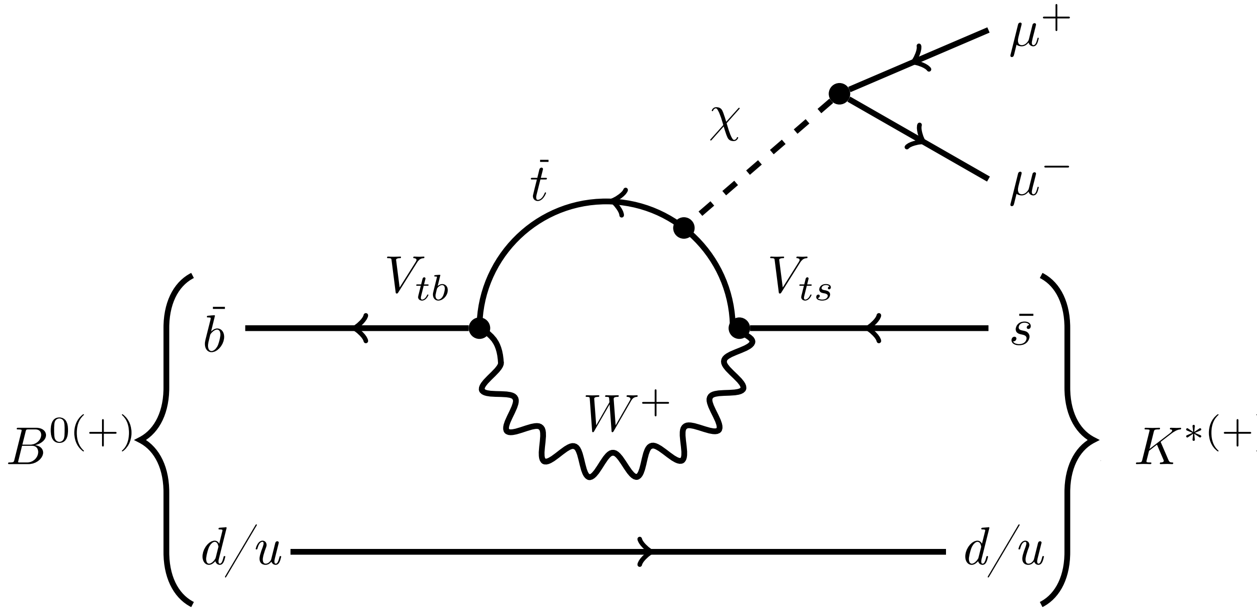
[Phys Rev Lett 115 161802 (2015)](#)
[Phys Rev D 95, 071101(R) (2017)](#)

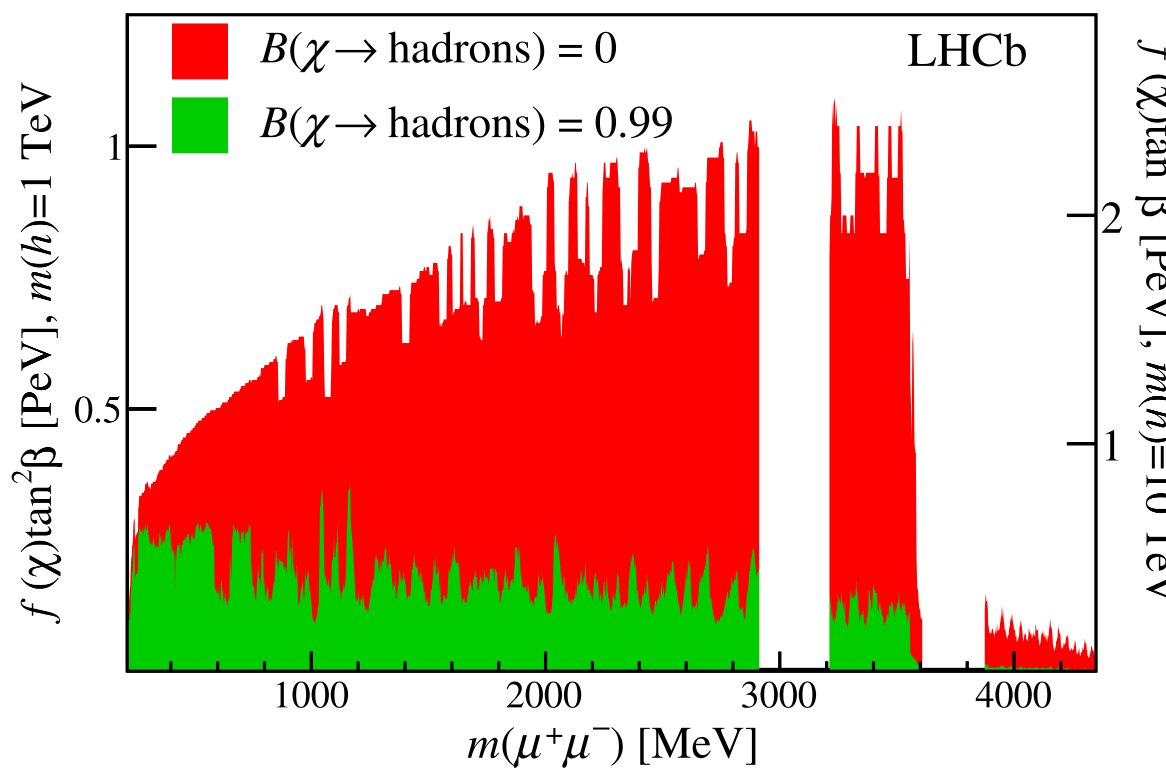
- Look for new hidden-sector bosons in $b \to s$ penguin transitions

- 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 models with **axion 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)



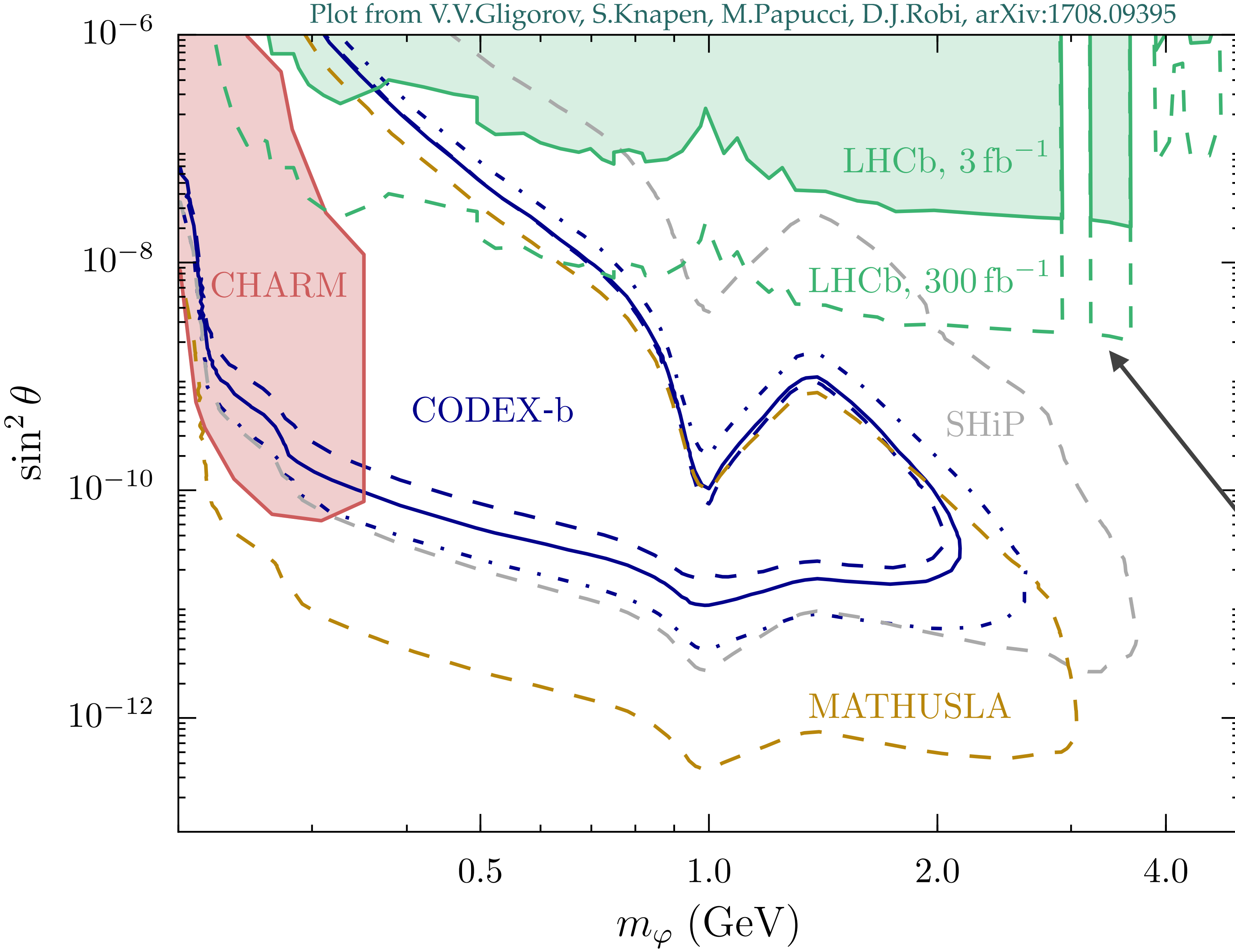


Dark Bosons from $b \to s$

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

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

Plot from V.V.Gligorov, S.Knapen, M.Papucci, D.J.Robi, arXiv:1708.09395



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

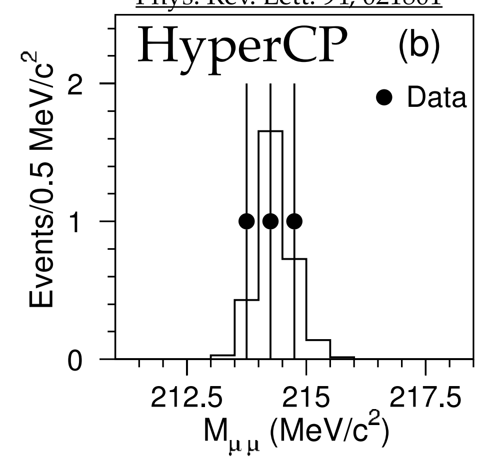
B.Batell, M.Pospelov, A.Ritz, PRD 83, 054005 (2011)
F.Bezrukov, D.Gorbunov, JHEP07(2013)140

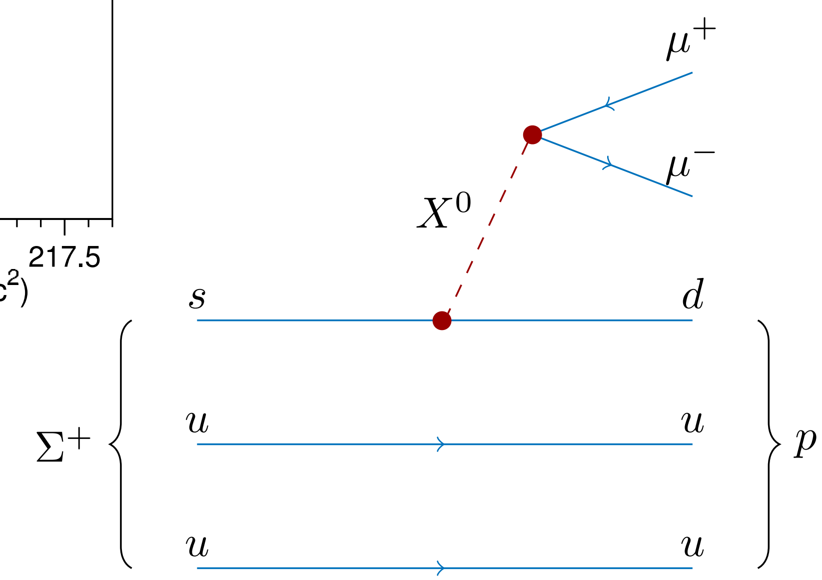
◉ Future sensitivity
- 300 fb^{-1} expected reach
- Phase space unexplored by other planned experiments

Dark Bosons from $s \to d$

LHCb, PRL 120, 221803 (2018)

- **Recently searched 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





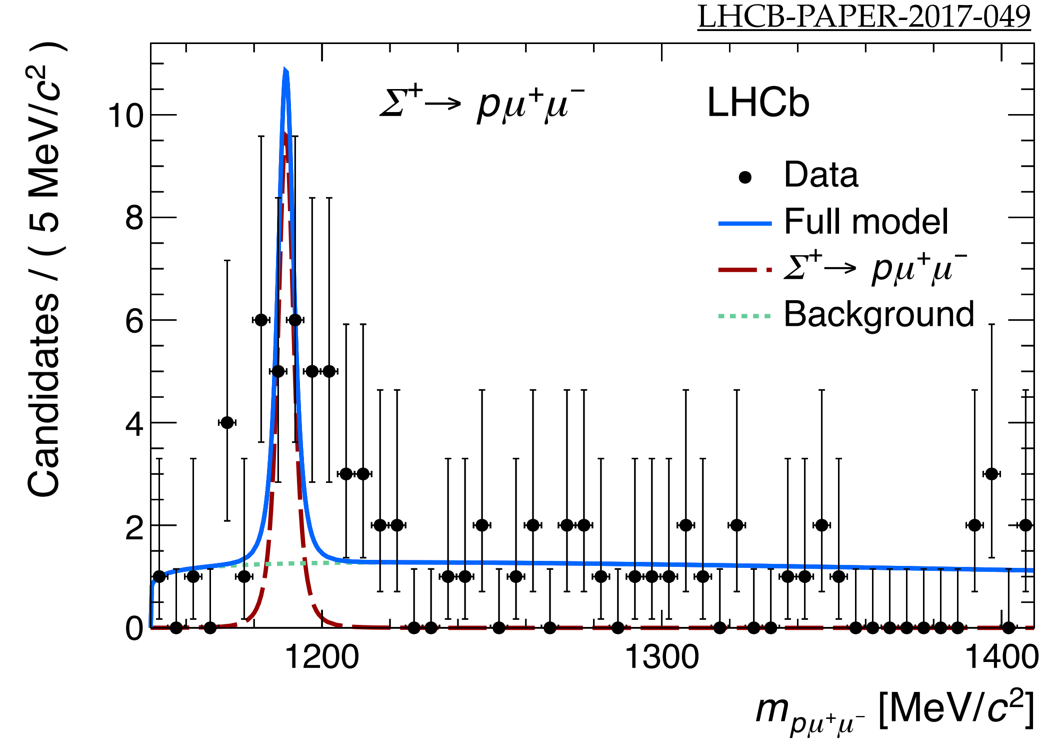
- Evidence for SM $\Sigma^+ \to p\mu\mu$ at 4.0 σ
  $\Rightarrow$ searched in $\mu\mu$ spectrum

- **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

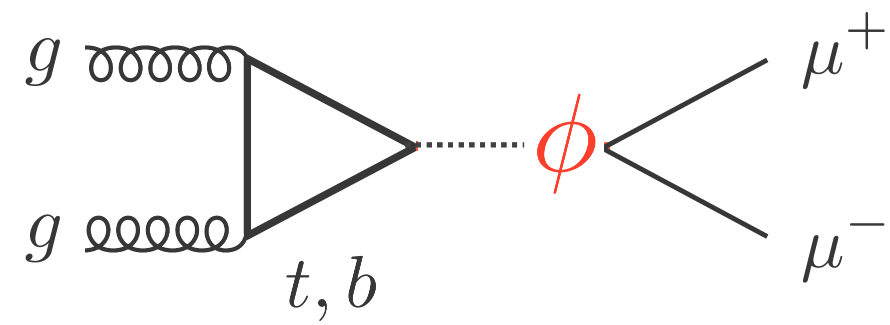
LHCb, arXiv:1805.09820

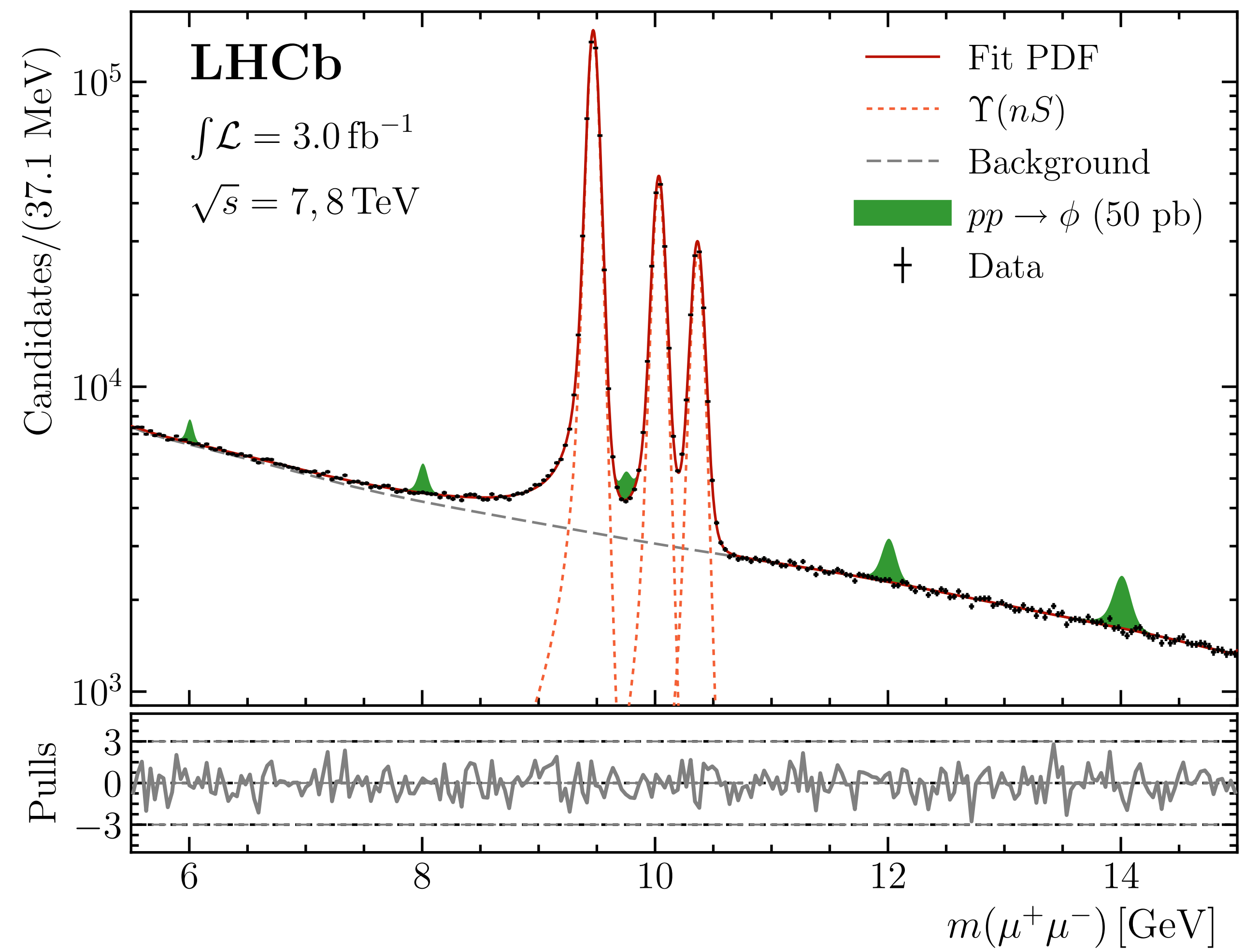
- Spin-0 particles copiously produced in ggF $\Rightarrow$ Extensive searches at the LHC

- 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



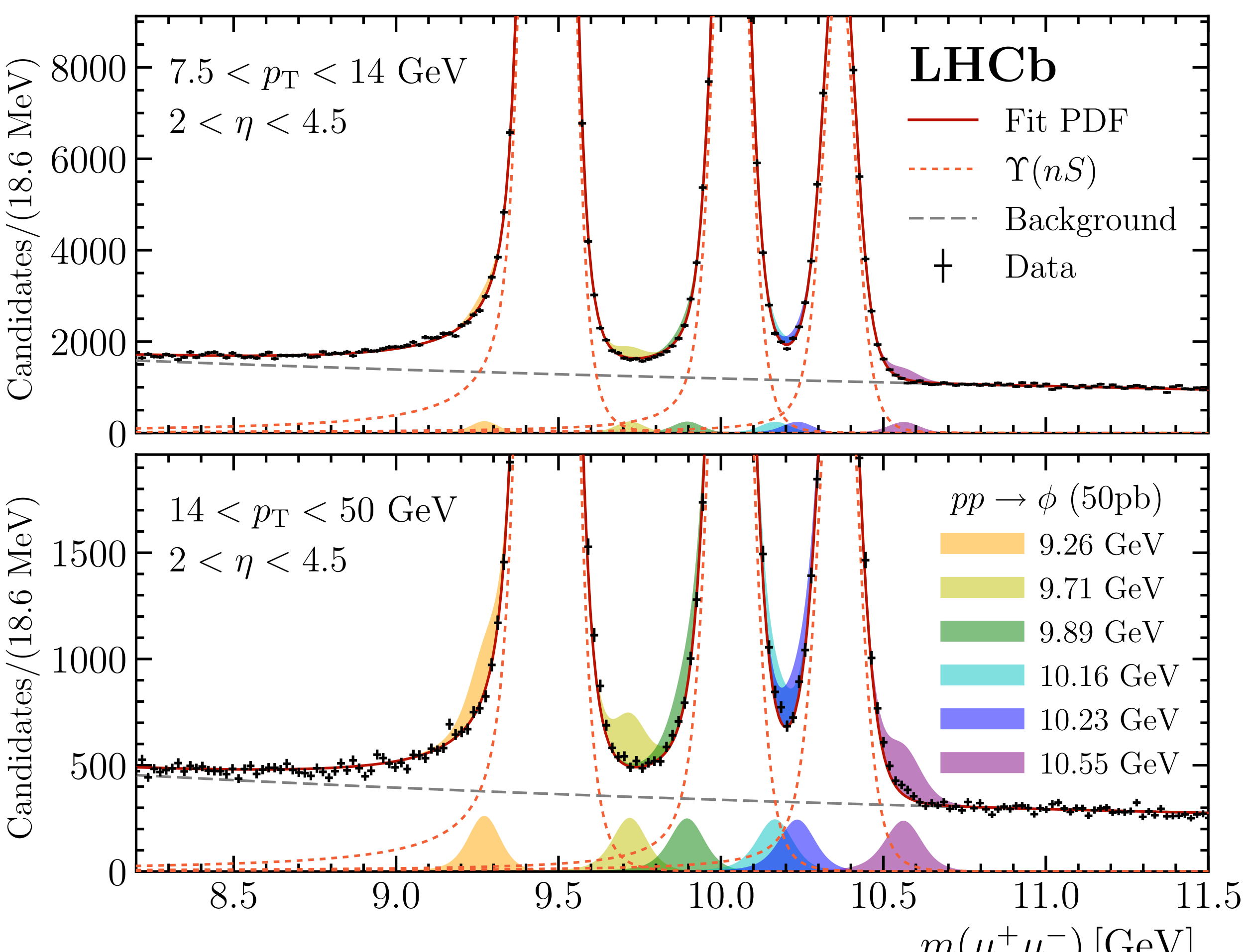


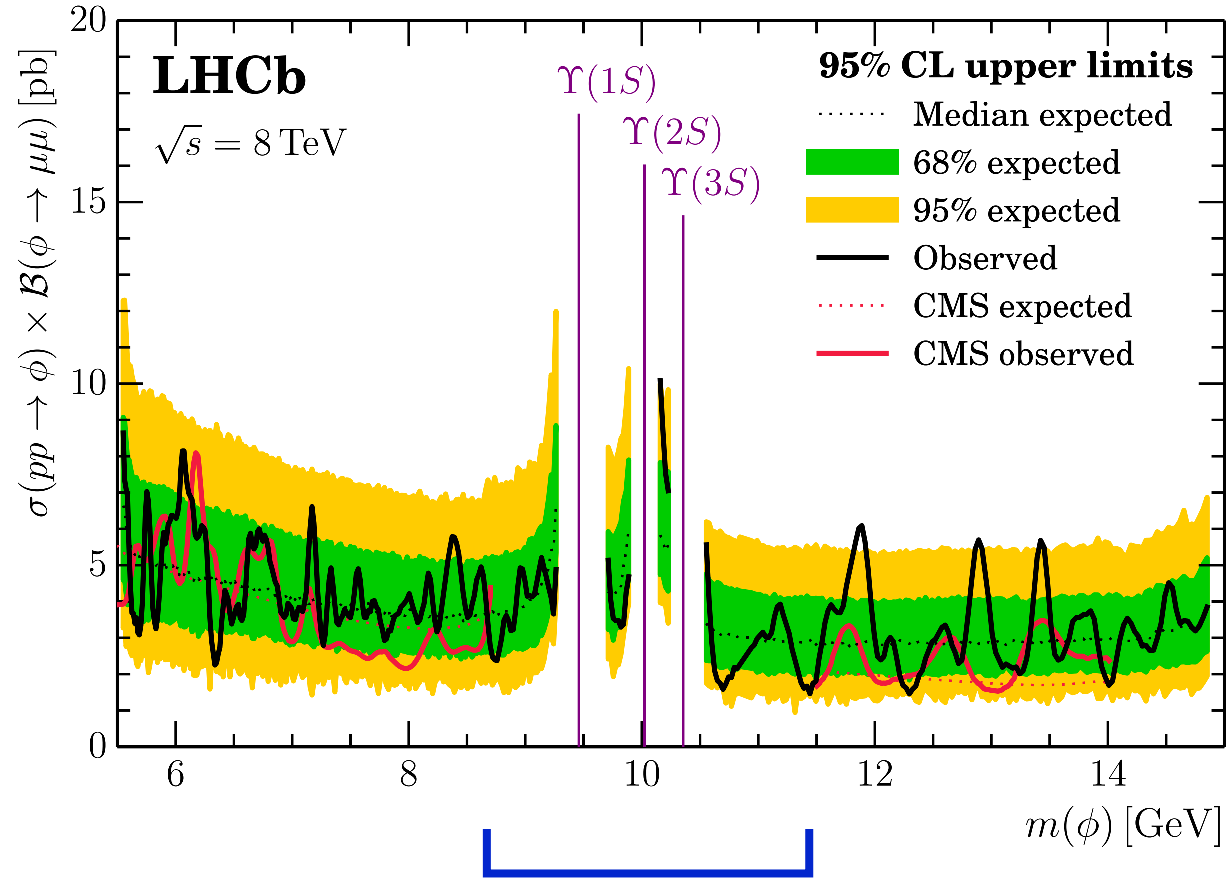
Dark Bosons from *gg*F

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





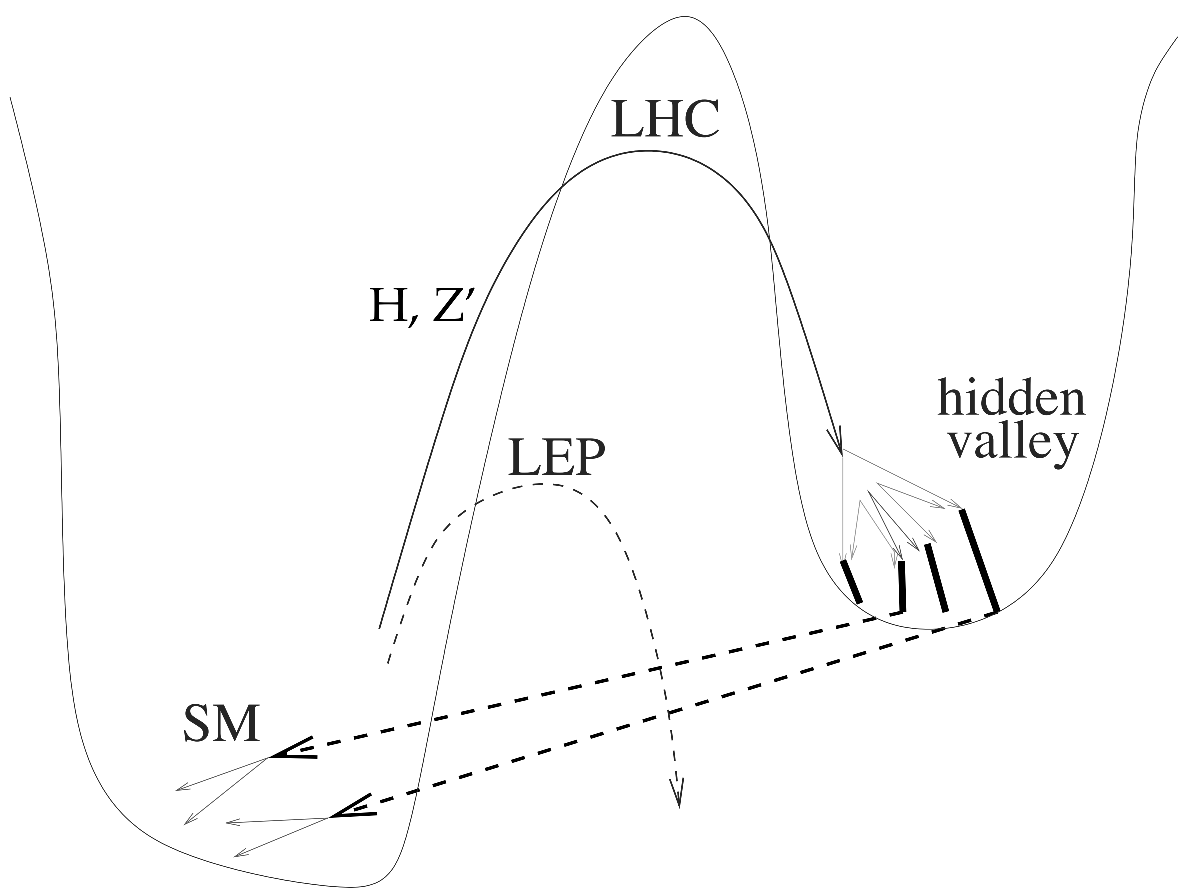
- First limits in **8.7-11.5 GeV region**
- Competitive with CMS elsewhere

CMS PRL 109(2012)121801

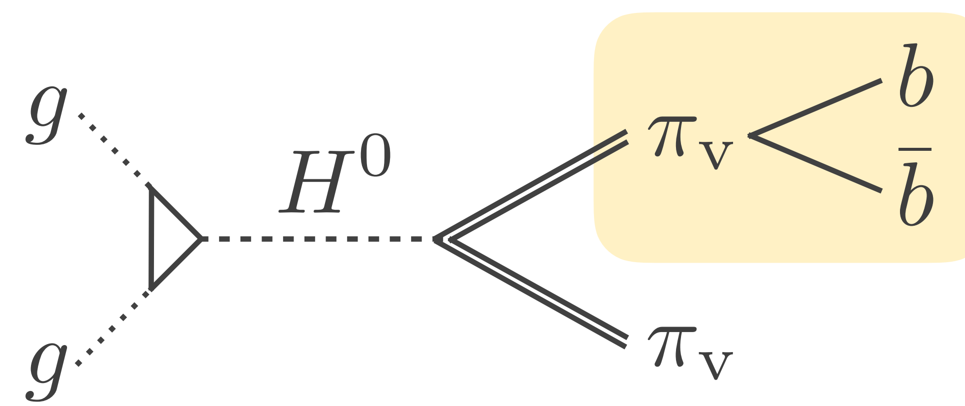
Dark Mesons → jet jet

EUR. PHYS. J. C77 (2017) 812

- **Dark sector with non-abelian group (QCD)**:
  - e.g. U(1)xSU(3) "hidden valley" model
    M.J.Strassler, K.M.Zurek, PLB651, 374-379, 2007
  - Some mesons (π_V) can decay back to SM
  - Stable meson gives DM candidate
  - Small coupling → long lifetimes



- Two $\pi^0{}_V$ produced from H^0 and decay to the highest mass fermion (helicity suppression)

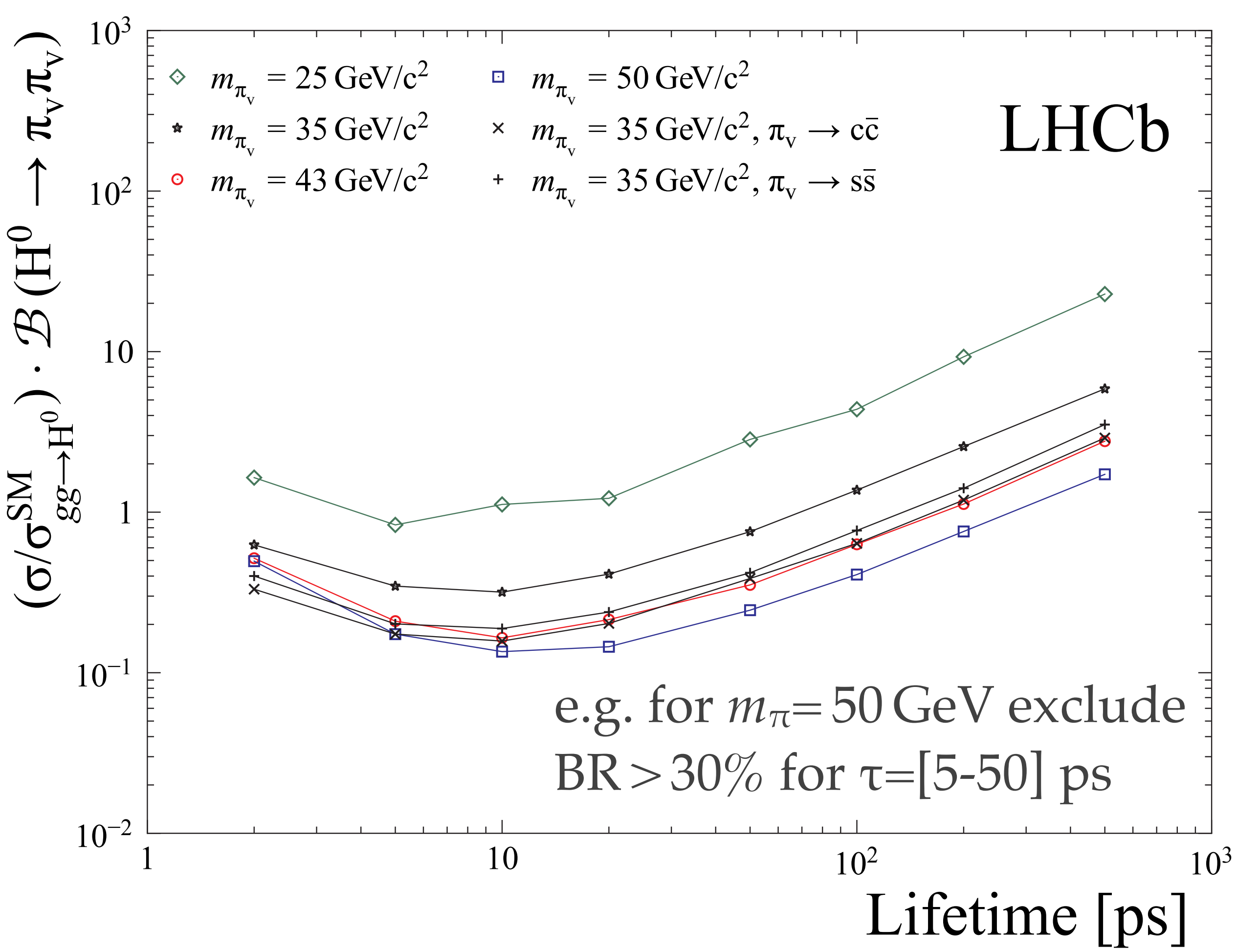


- **LHCb analysis (2/fb)**:
  - Software trigger on displaced vertex in VELO
  - Good di-jet mass resolution
  - Limited acceptance
    → reconstruct single $\pi^0{}_V$

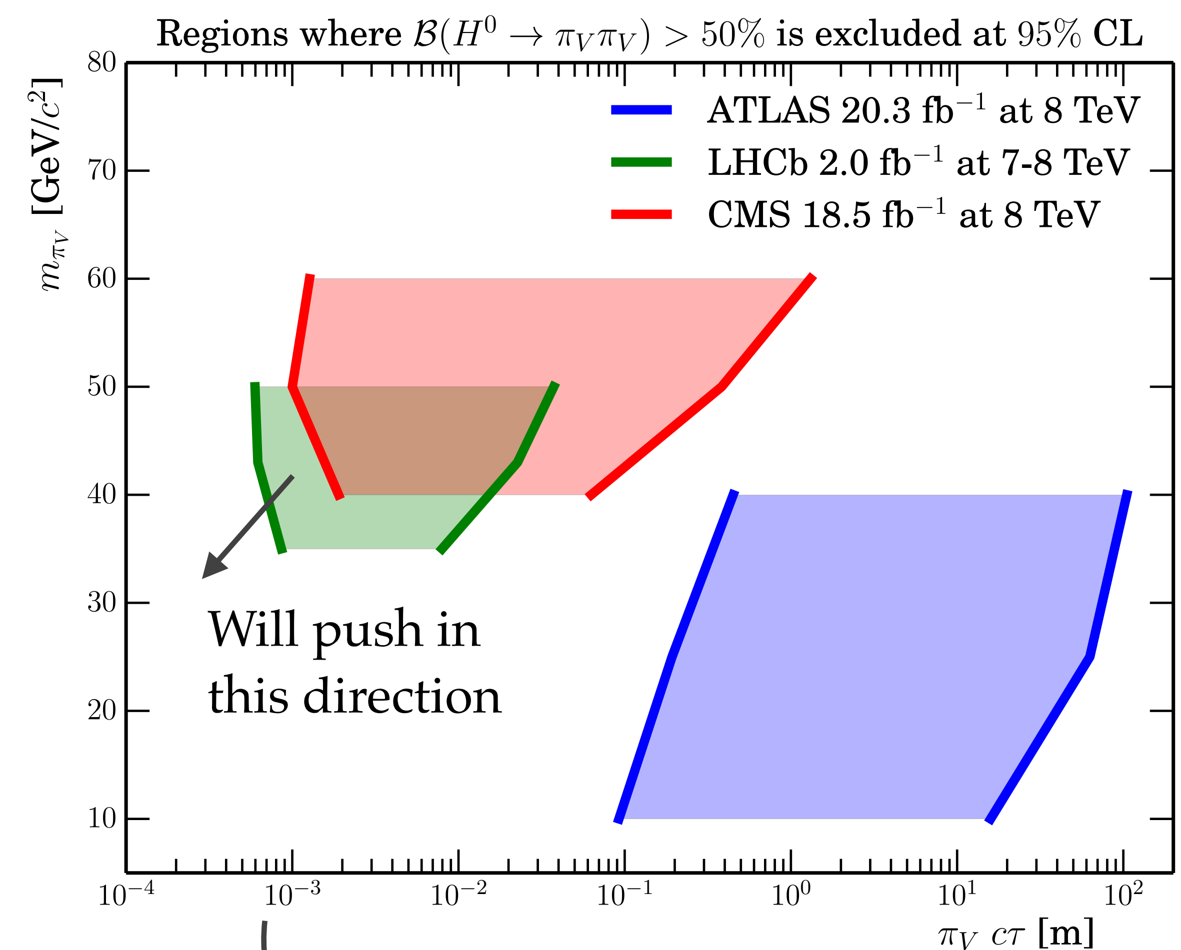
Dark Mesons → jet jet

EUR. PHYS. J. C77 (2017) 812

Limits on BR($H \to \pi_v \pi_v$) for a set of masses and lifetimes



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



Plot I've done for the LLP community
White paper out very soon!

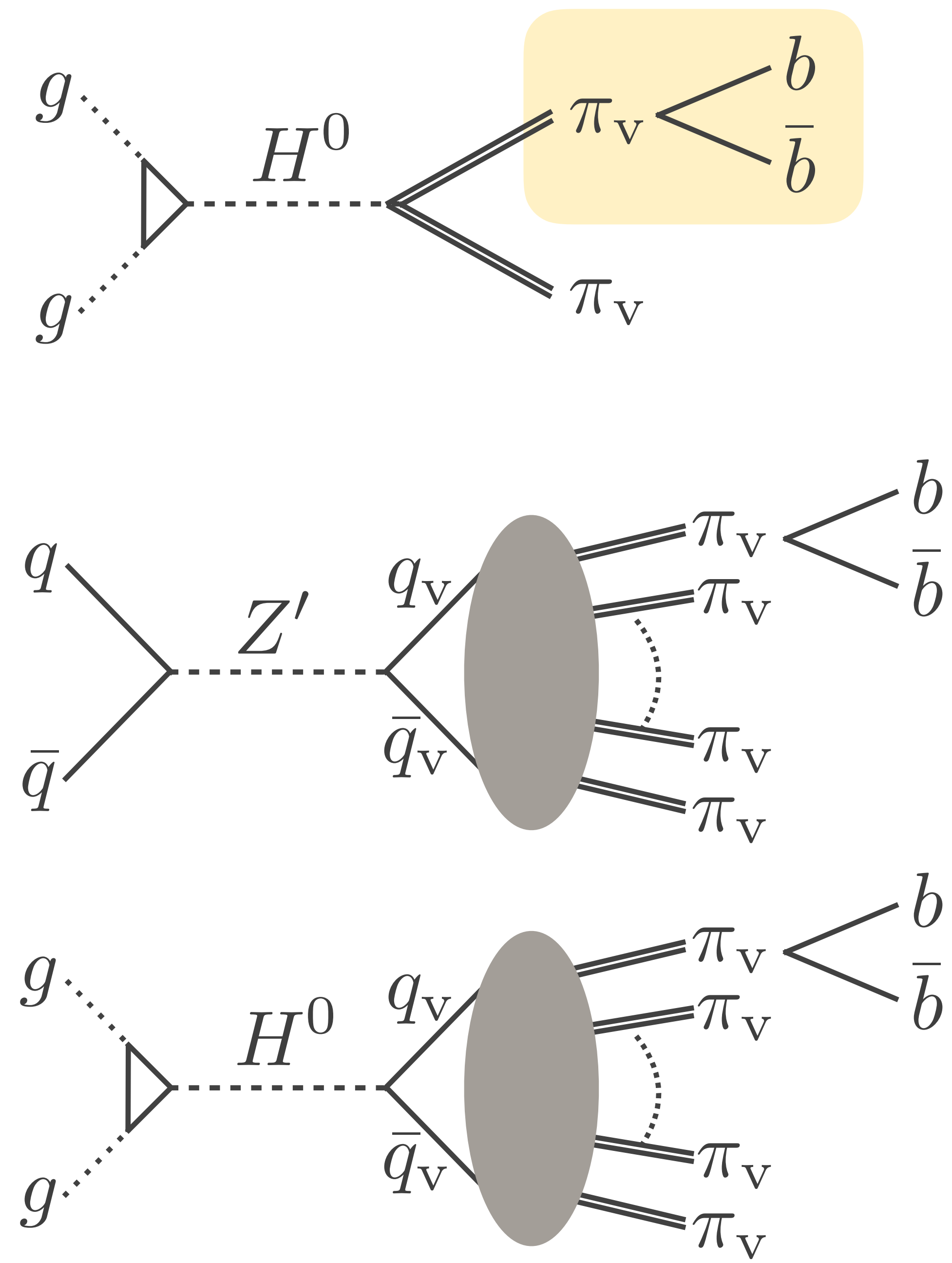
Dark Mesons → jet jet

- Target models for LLP to di-jet
  - So far focussed on $H(125) \to \pi_v \pi_v$ but LHCb signature is single π_v
  - Generically expect many soft π_v (Dark Showers)

A.Pierce et al. arXiv:1708.05389

- Lower masses are challenging
  - Use fat jet signature
  - Jet substructure tools
- New triggers being developed
  - Benefit from online identification of displaced dijets
- Can also look in B decays!
  - Dark pions decaying to 2-3 mesons
  - Need long lifetime to be competitive

S.Renner and P.Schwaller arXiv:1803.08080

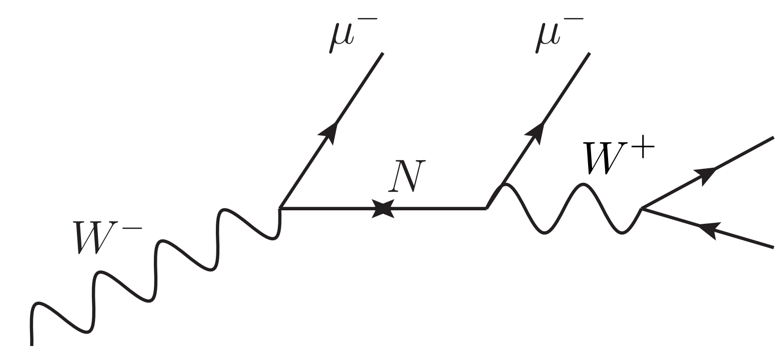


Future Prospects

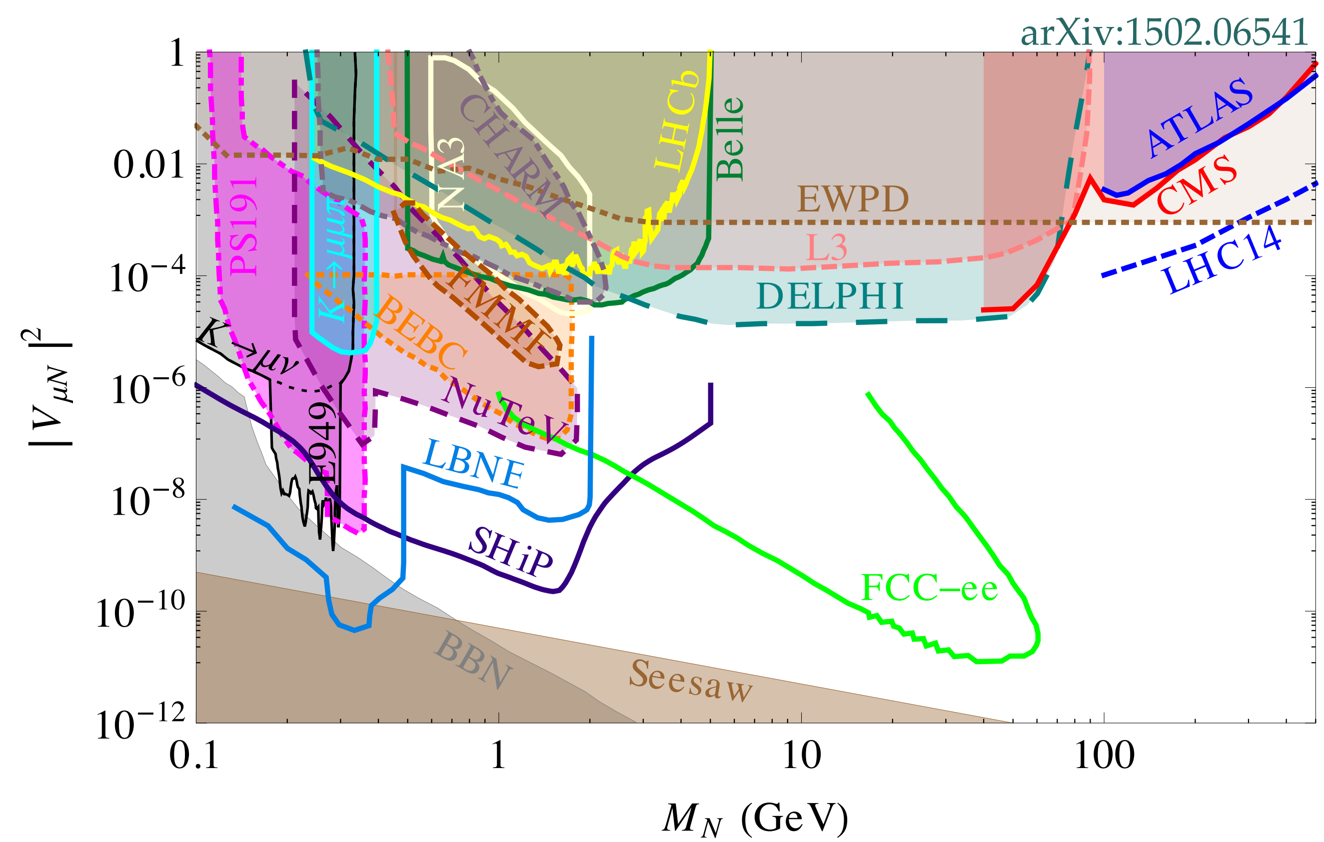
Dark Neutrinos

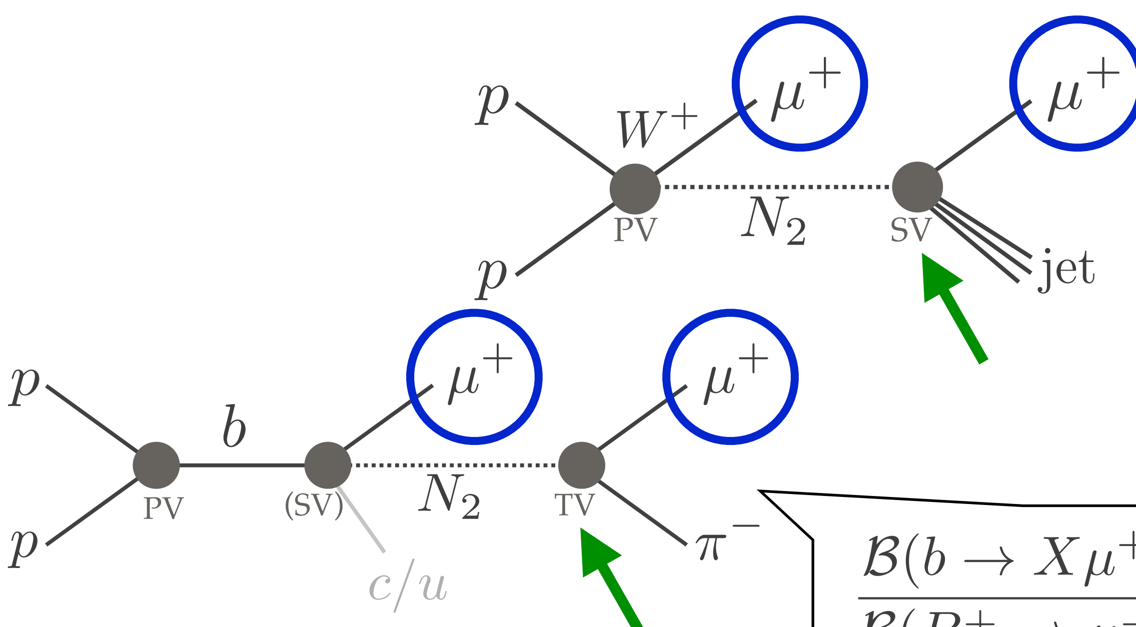
LHC prospects: B.Batell et al. JHEP 1608 (2016) 052

- Compelling models (e.g. νMSM) predict Heavy Neutral Leptons (HNL) to address neutrino masses (and more…)
- Large range of masses and mixing $V_{\ell N}$
- Characterised by ***$\ell^+\ell^+$* final states** and ***ℓ^+h^- displaced vertices***



- LHCb has searched HNL's using $B^-\to N(\pi^+\mu^-)\mu^-$ and $D^-\to N(\pi^+\mu^-)\mu^-$ LHCb, PRL 112, 131802 (2014)
- Plan to search in on-shell W decays (ongoing) and with inclusive B decays (trigger in 2017)



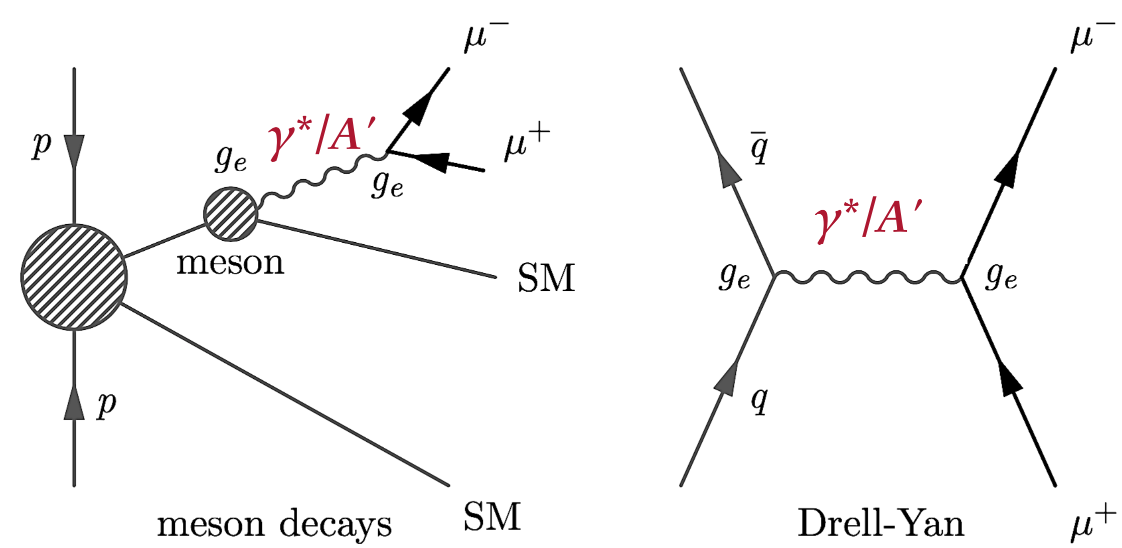


$$\frac{\mathcal{B}(b\to X\mu^+\nu)}{\mathcal{B}(B^+\to\mu^+\nu)} > 10^5 \;\; !!$$

Dark Photons

PRL 120 (2018) no.6, 061801

- LHCb can search for **Dark Photons** (A') in $\mu\mu$
  - Case for upgrade in `arXiv:1603.08926`
  - **First results** with 1.6/fb at 13 TeV
    - New $\mu\mu$ trigger with **online μ-ID**
    - Only interesting part of the event to disk
      → **no pre-scale down to threshold 2 m_μ**



- Kinetic mixing with off-shell photon (ε^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, ϵ=1 for prompt

Need to separate from background

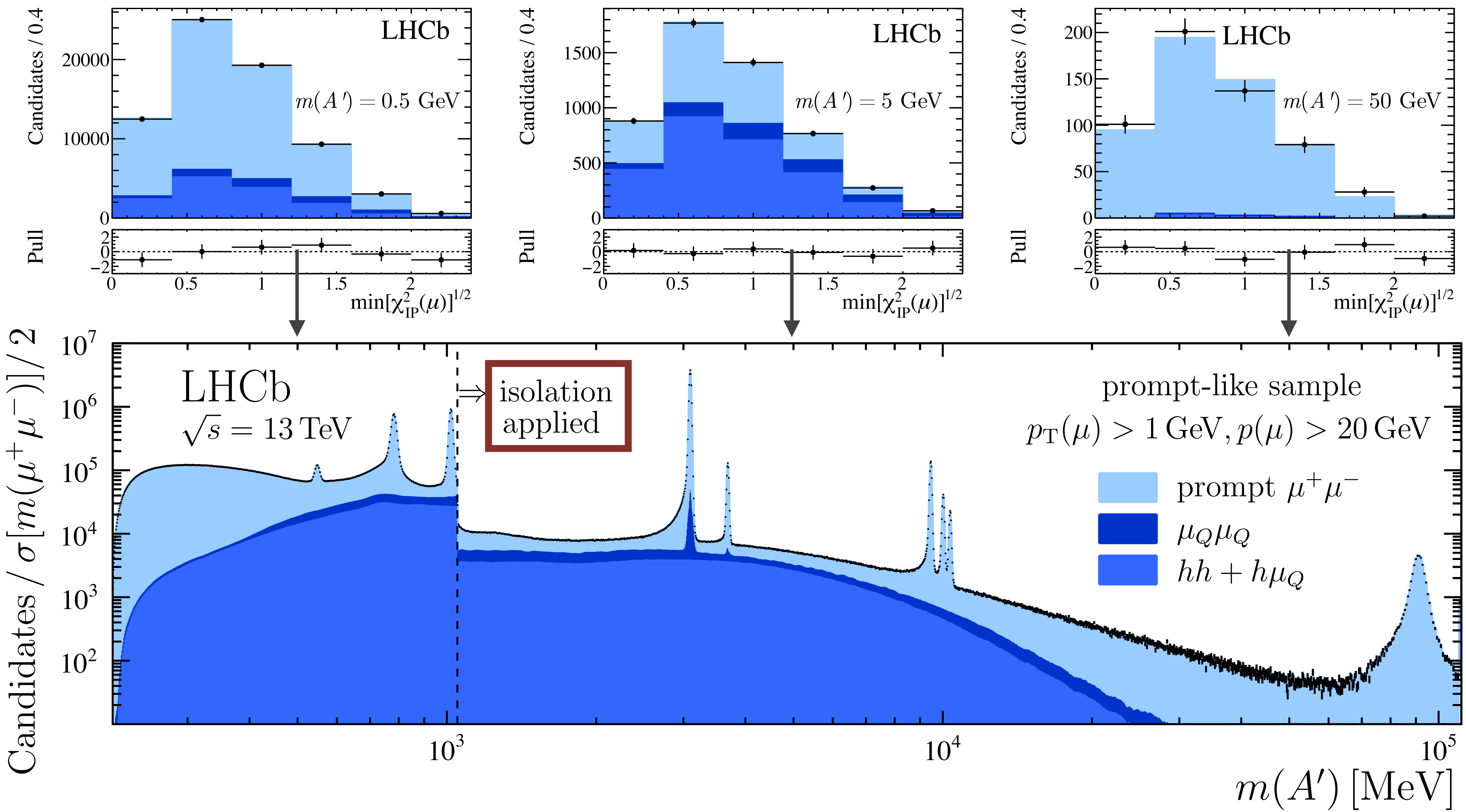
Dark Photons

PRL 120 (2018) no.6, 061801

Using templates for min[χ^2_{IP}] (small mass dep)

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

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

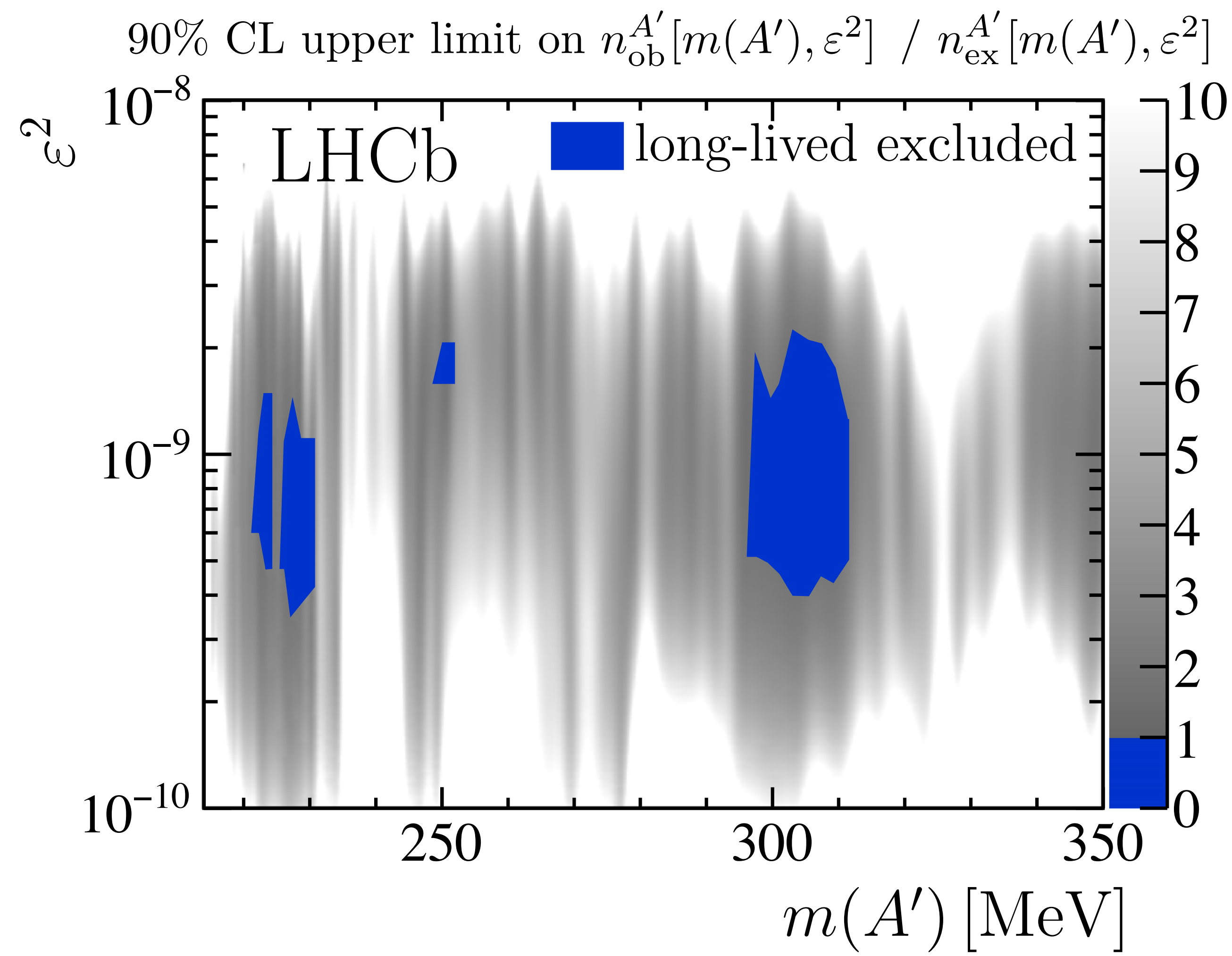


Dark Photons

PRL 120 (2018) no.6, 061801

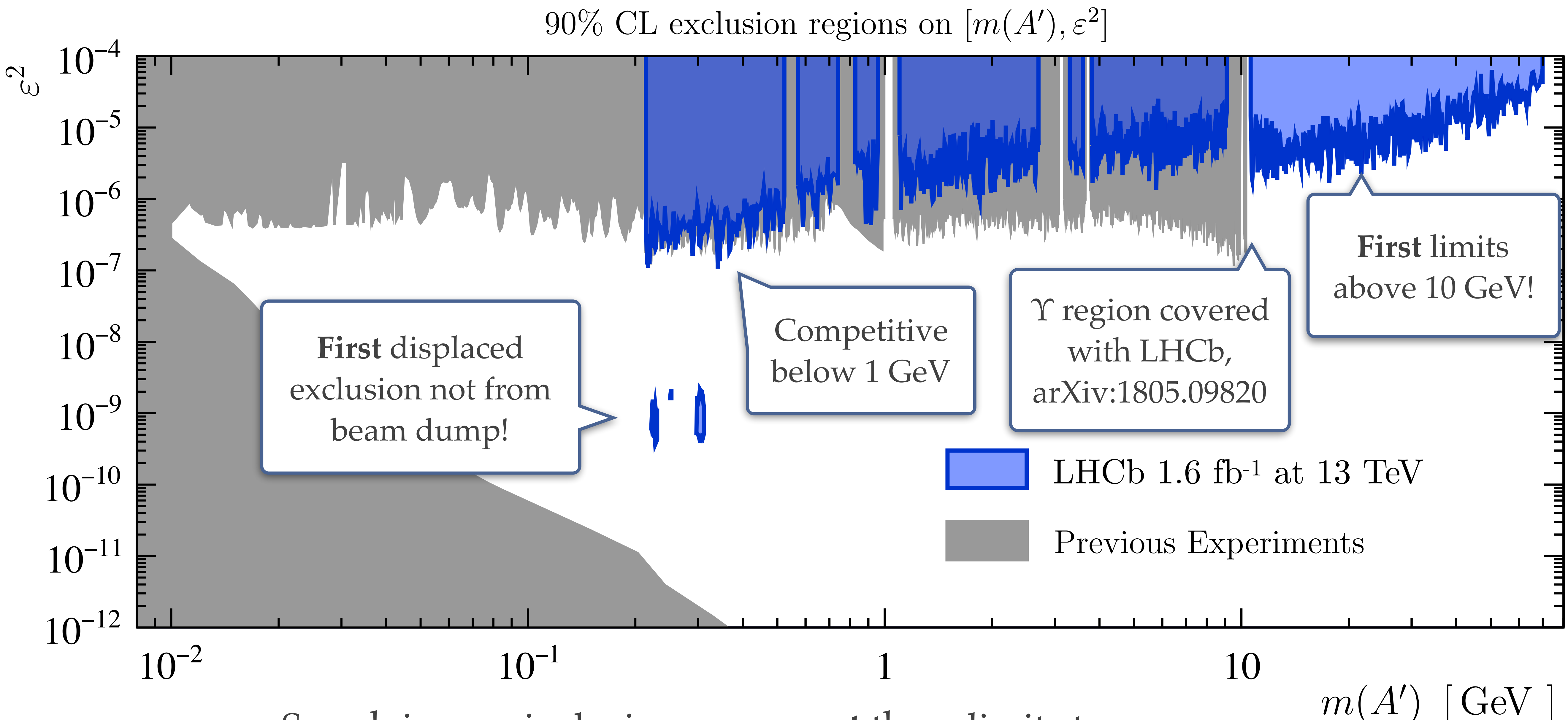
- **Displaced search** in low mass region $214 < m(A') < 350$ MeV
- Even looser online requirements on $p_T(\mu)$
- Main background from γ conversions in the VELO, material map buys factor 10 in sensitivity

- Fit in bins of mass and lifetime
- **No significant excess is found**
  - Already excluding a small region of phase space (ε^2, m)
  - First limit ever not from beam-dump!



Dark Photons

PRL 120 (2018) no.6, 061801



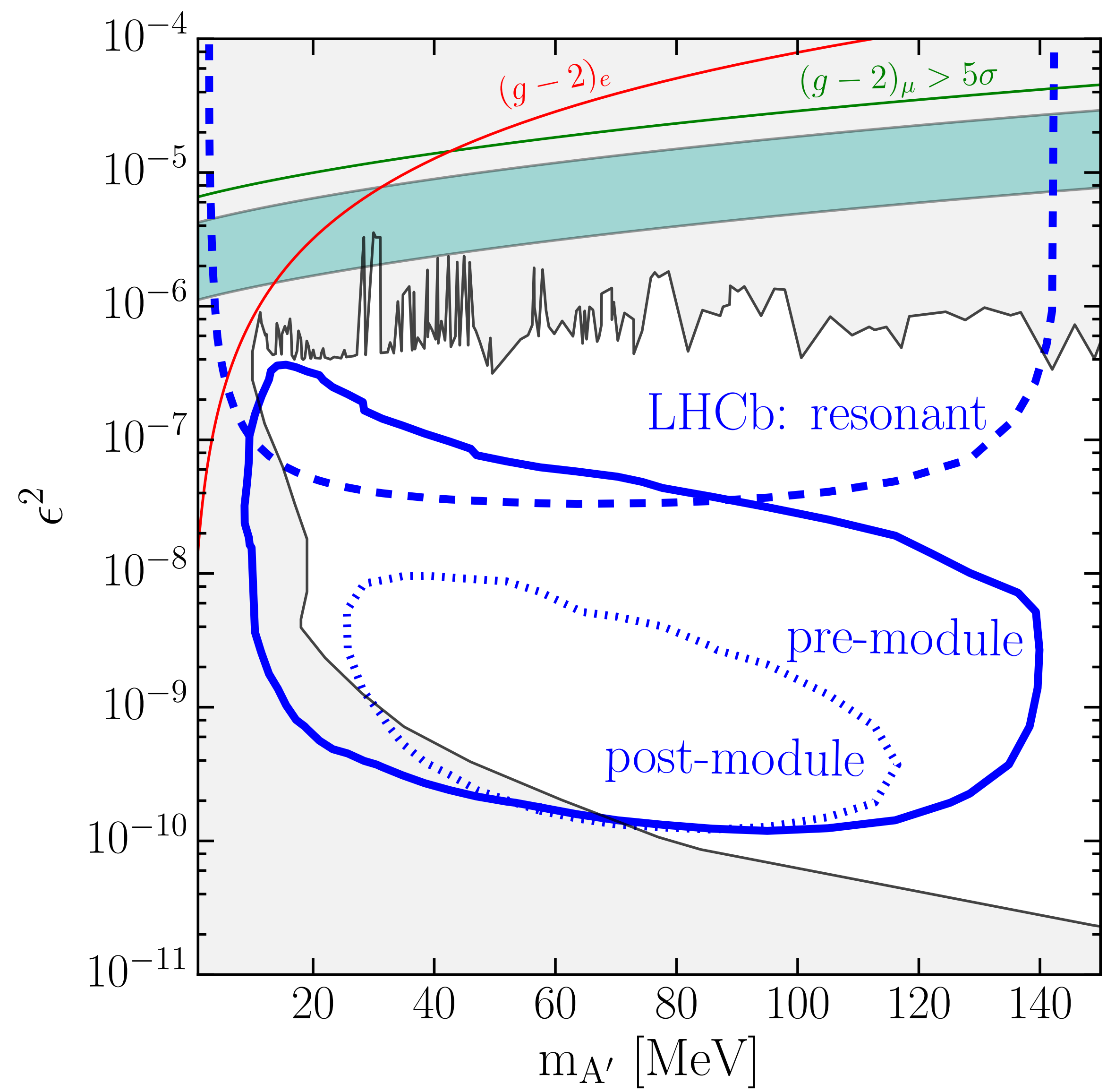
- Search is very inclusive, **can recast** these limits to
  - other vector models (P.Ilten et al. arXiv:1801.04847)
  - (pseudo-)scalar models (Haisch et al. arXiv:1802.02156)

Future Prospects

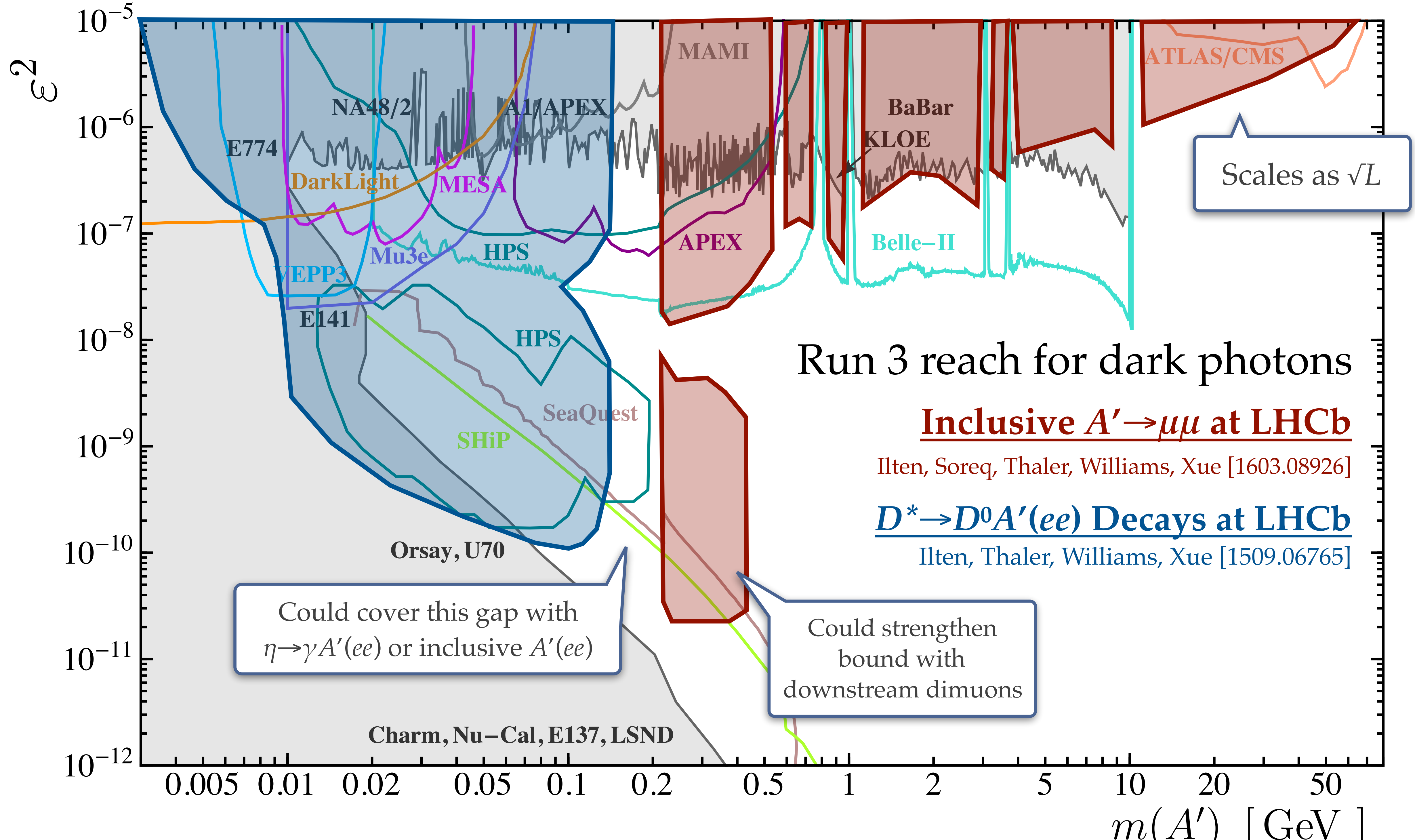
Dark Photons below $2m_\mu$

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 **300×10^9** $D^{*0} \to D^0\gamma$ **per fb^{-1}**
  - Both displaced and prompt searches

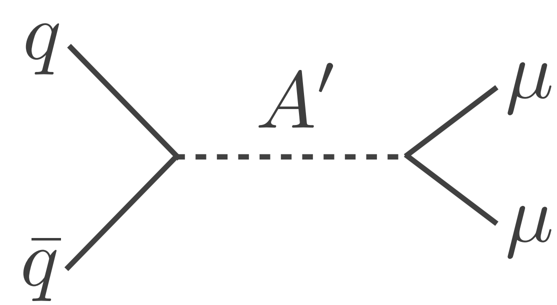


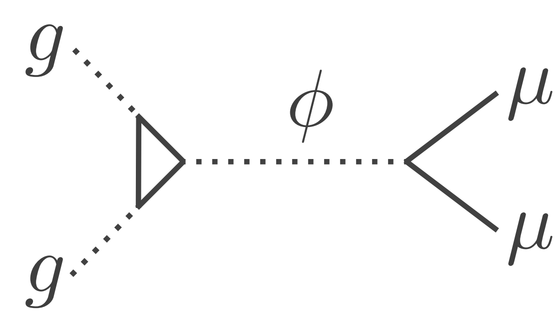
Upgrade Dark Photon Reach

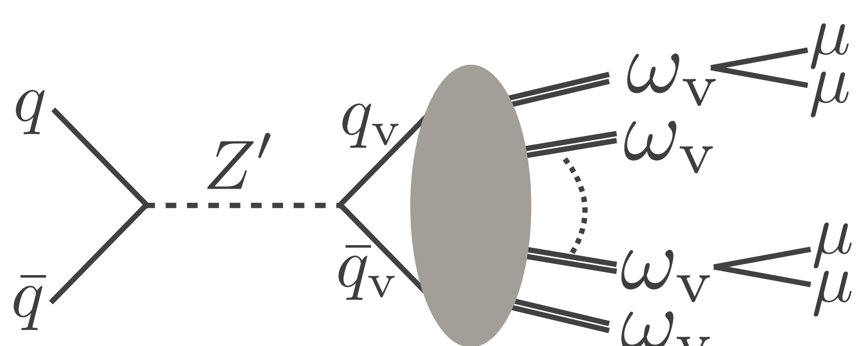


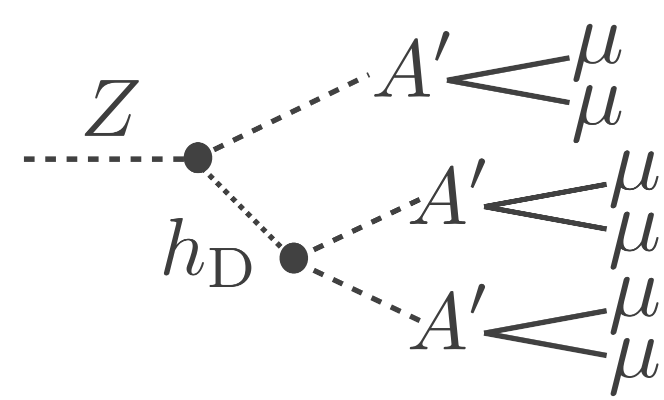
Extend dilepton searches

- **Extend dilepton searches**
  - Showers of displaced dileptons
    A.Pierce et al. arXiv:1708.05389
  - Rare Z boson decays to 6μ
    N.Blinov , PRD97 (2018) 015009
  - Also LFV decays μ^+e^-…



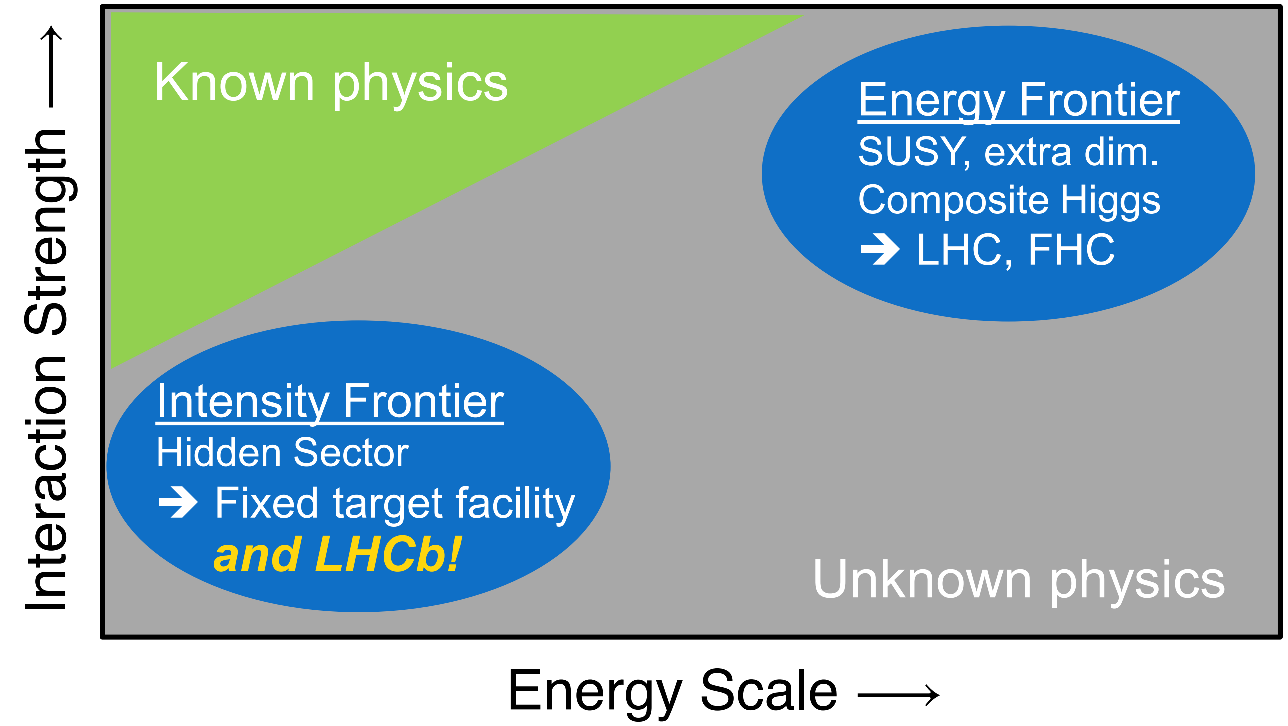






Conclusions

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



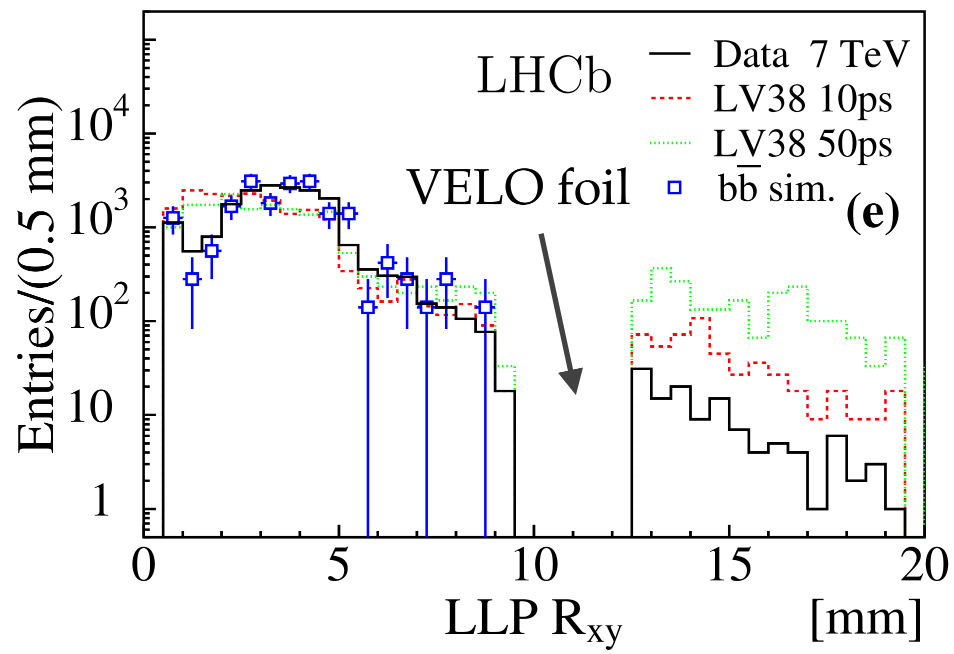
- **Intensity frontier** can be explored by LHCb in the LHC forward region
  - Not only the realm of fixed target
  - Can be used to **shed light on the Dark Sector**!
- **Broad program** of searches at LHCb
  - On-shell new physics from heavy flavour decays
  - Long-lived particles with low mass and short lifetime
  - Dilepton resonances in broad parameter space
- **Exciting prospects** for the future:
  - No lack of ideas for new/upgraded searches
  - 3/fb in Run 1, **5.7/fb in Run 2** so far (larger cross-sections)
  - A lot of potential in the **upgraded trigger** (also 5× luminosity!)

BACKUP

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

→ proxy of τ

- **Set upper limits** on:
  - RPV mSUGRA
  - Simplified topologies
- Can also be sensitive to sterile neutrinos

Antusch et al. PLB774 (2017) 114-118