Search for long-lived particles at LHCb

SUSY17

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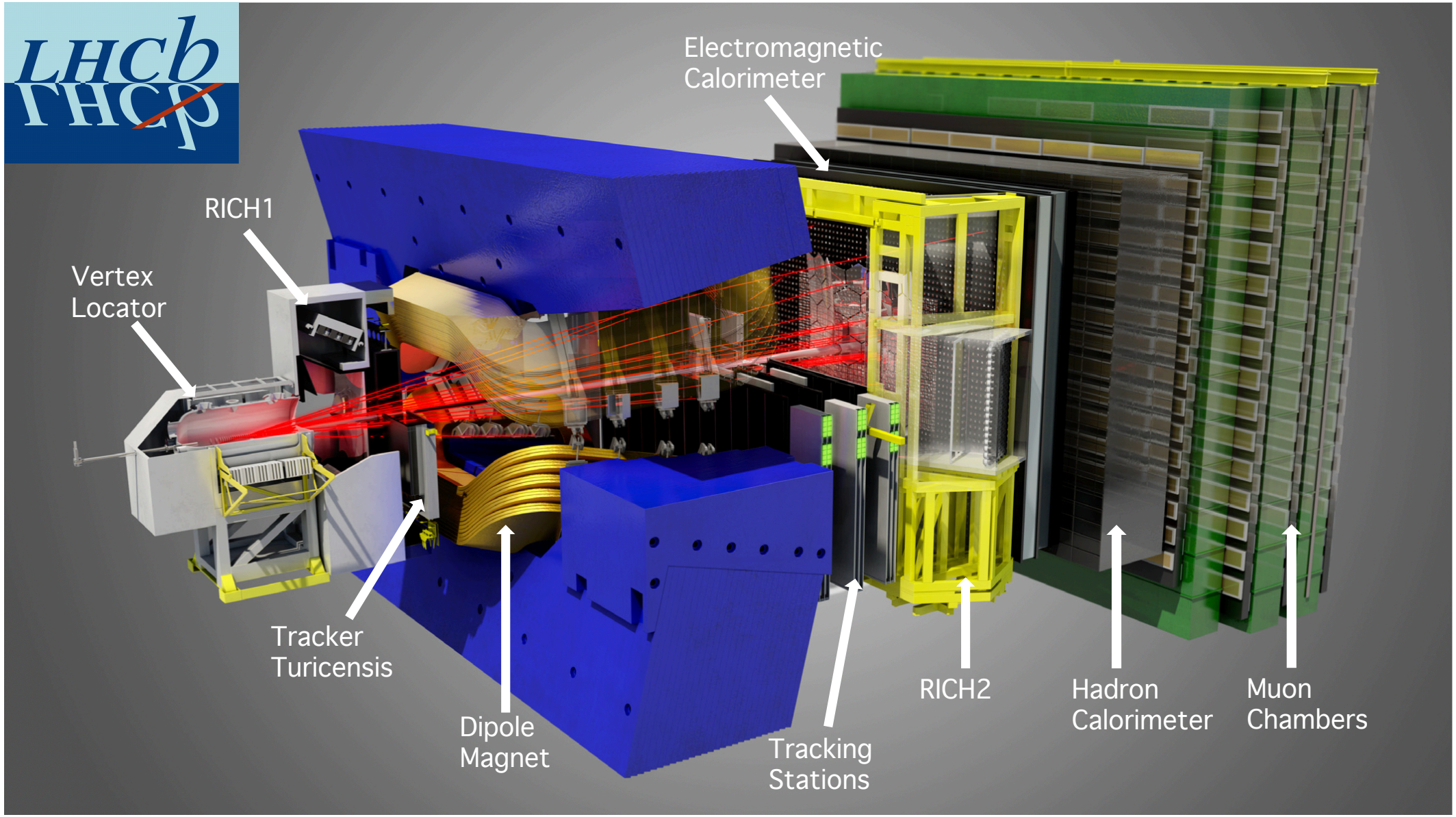
The LHCb detector

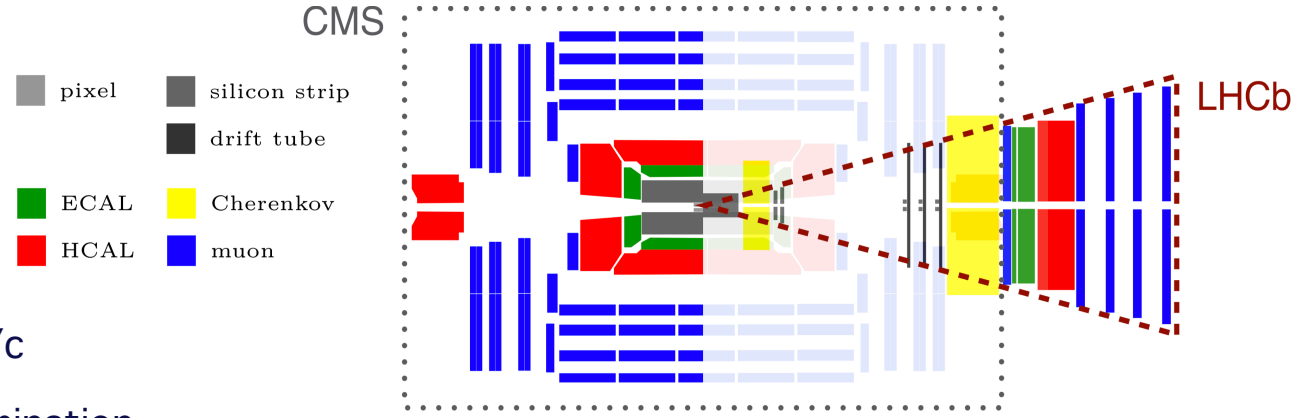
[JINST 3 (2008) S08005]



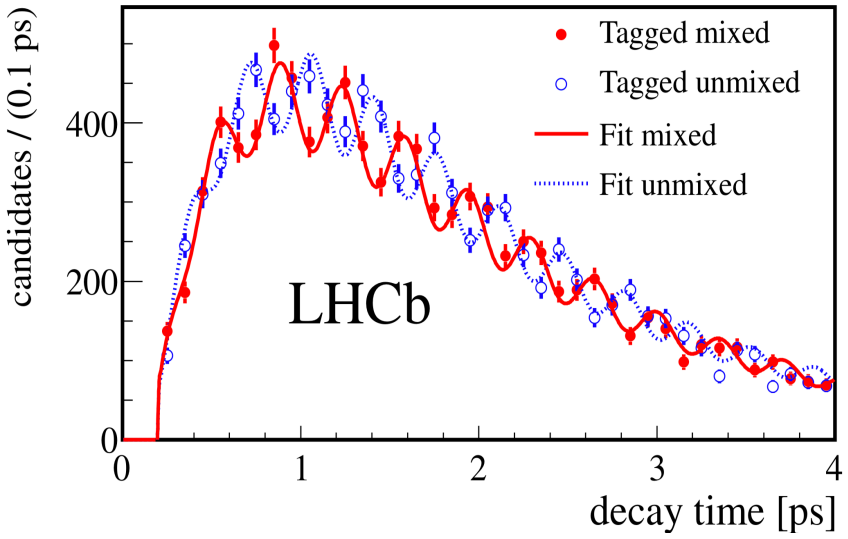
The LHCb detector

[IJMP A30 (2015) 1530022]

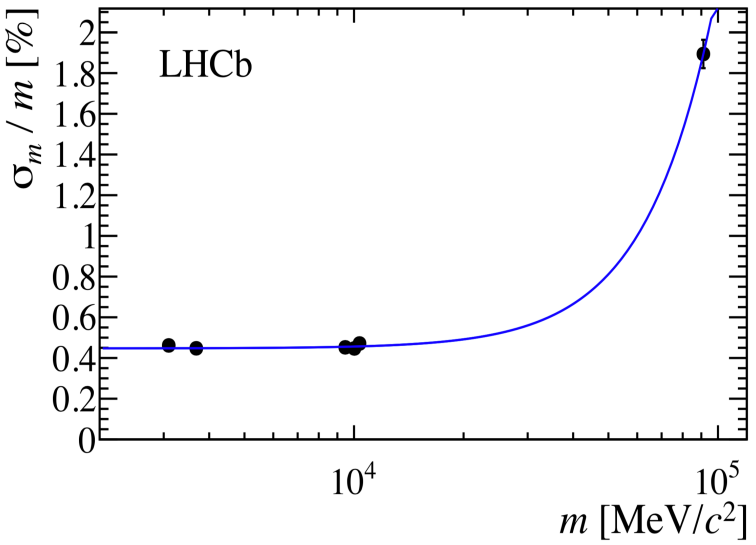
- fully instrumented in $2 < \eta < 5$
- excellent particle identification capabilities
- good jet reconstruction:
  - 10 to 20 % energy resolution for jets with $p_T > 10$ GeV/c [JHEP01 (2014) 033]
  - b(c) tagging efficiency of 65% (25%) with 0.3% contamination [JINST 10 (2015) P06013]



- excellent vertex resolution (B_s^0 decay time resolution ~40fs):



- excellent mass resolution (0.5 % for $J/\psi \to \mu\mu$, 2% for $Z \to \mu\mu$)



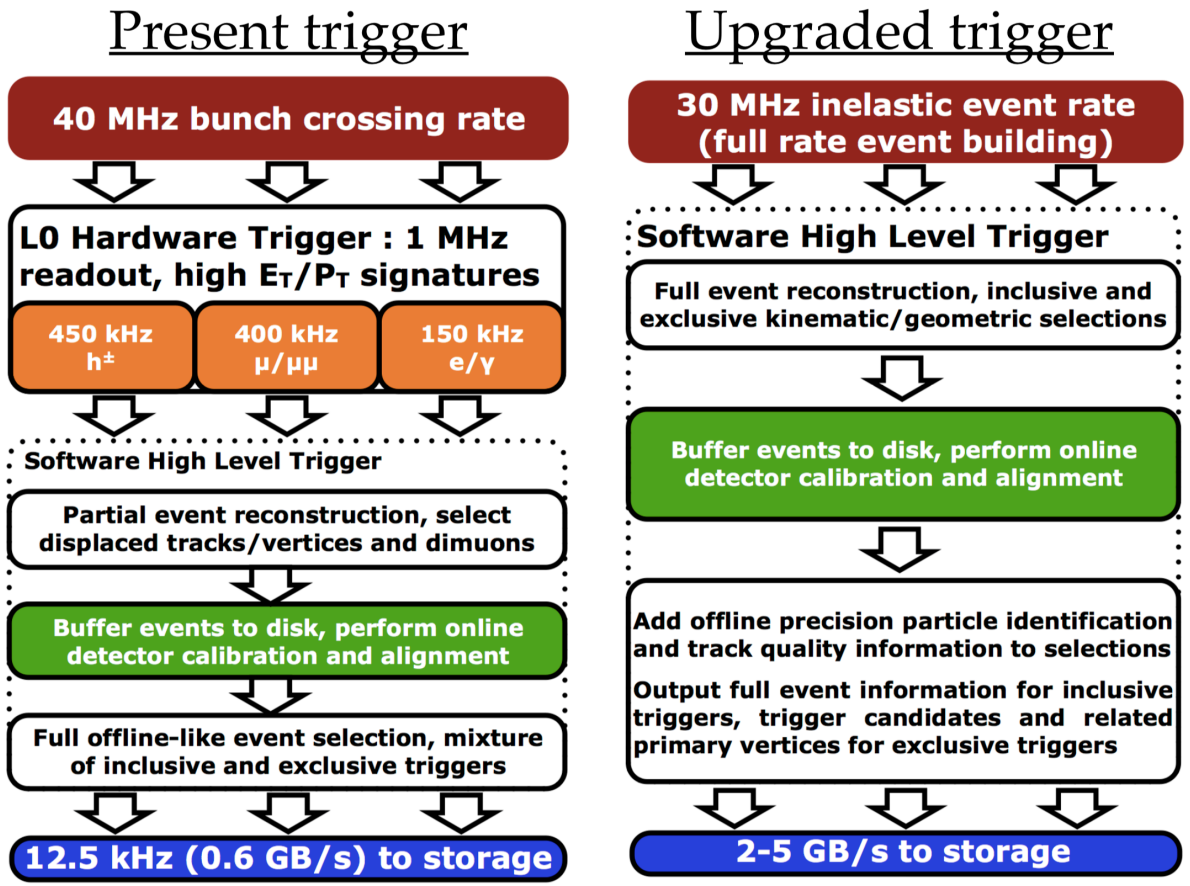
The LHCb detector

[IJMP A30 (2015) 1530022]

- **Constant instantaneous luminosity** (Run I: ~40 $mb^{-1}s^{-1}$) and **low pile-up** (~1.8 in 2011 and ~2.1 in 2012).

- Very **soft** and **versatile** trigger system:
  - At Hardware Level (L0):
    - 95 % efficiency for detached $\mu\mu$ with P_T over 1 GeV/c.
    - ECAL (HCAL) triggers at 3.5 (2.5) GeV for electrons (hadrons).
  - At Software level (HLT):
    - Topological triggers on detached vertices.
    - Run-II onward particle ID and jets in trigger.

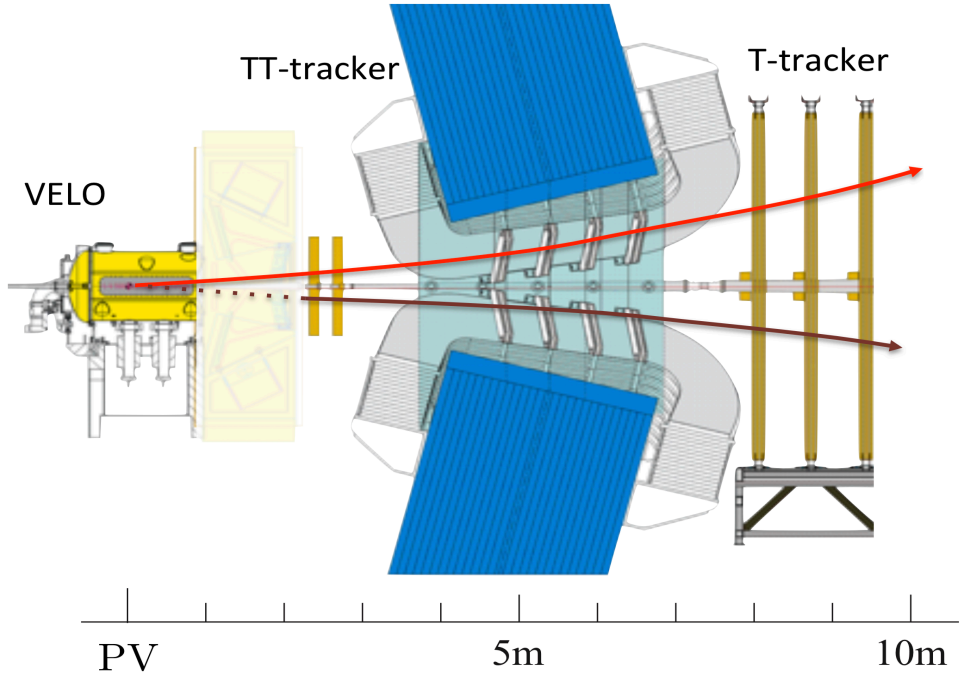
- "Software Trigger Only" upgrade (2021):
  - Read-out detector in real time.
  - Can trigger on detached vertices and particle ID at first level.

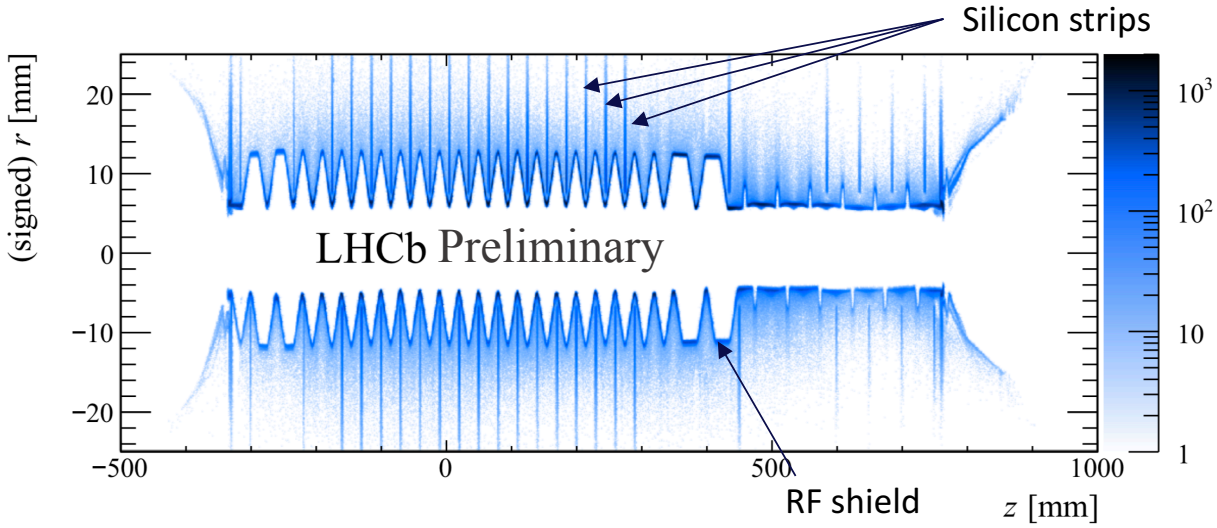


Long-lived particles in LHCb

How long-lived?

- Decay length < 50 cm → Tracks within VELO:
  - in reality more like 20 cm (~ 700 ps)
  - **VELO envelope at ~ 5 mm from beam**
    - < 5 mm mainly heavy-flavour background
    - > 5 mm mainly material interaction background
  - a detailed material veto map is used
- Decay length < 200 cm → Tracks up the to TT:
  - worse vertex and momentum resolution ($m(\pi\pi)$ resolution two times larger without VELO)
  - not available in trigger (under study)

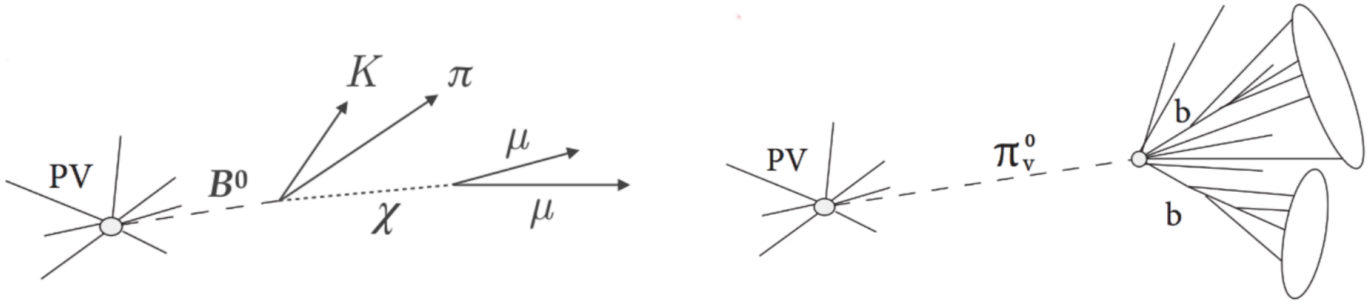




Long-lived particles in LHCb

- Coverage complementarity to ATLAS and CMS:
  - forward acceptance and soft trigger → masses down to few GeV/MeV for jets/leptons,
  - excellent vertexing capabilities → lifetimes down to 1 ps.

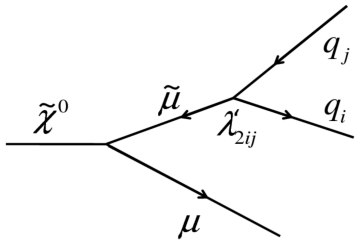
- LHCb capabilities for direct searches:
  - search for LLP produced in the *pp* collision,
  - search for LLP produced in B and D decays:



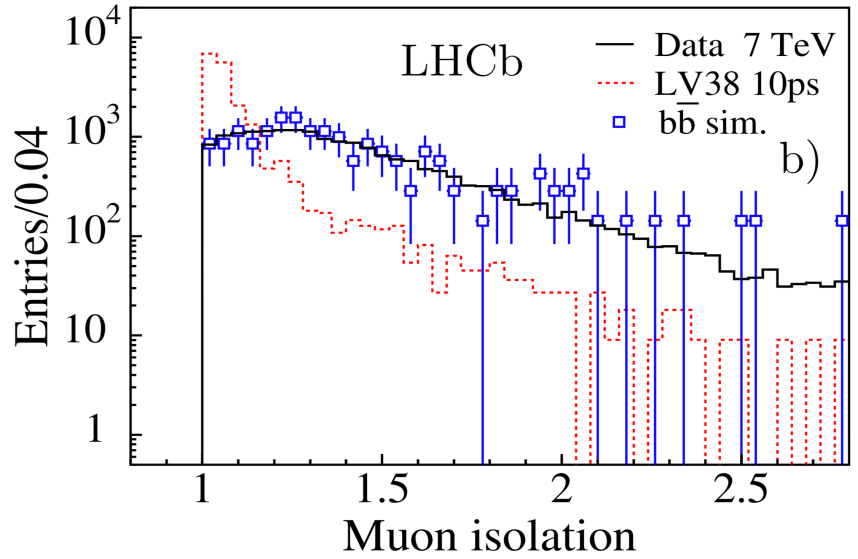
Massive LLPs decaying to μ + jets

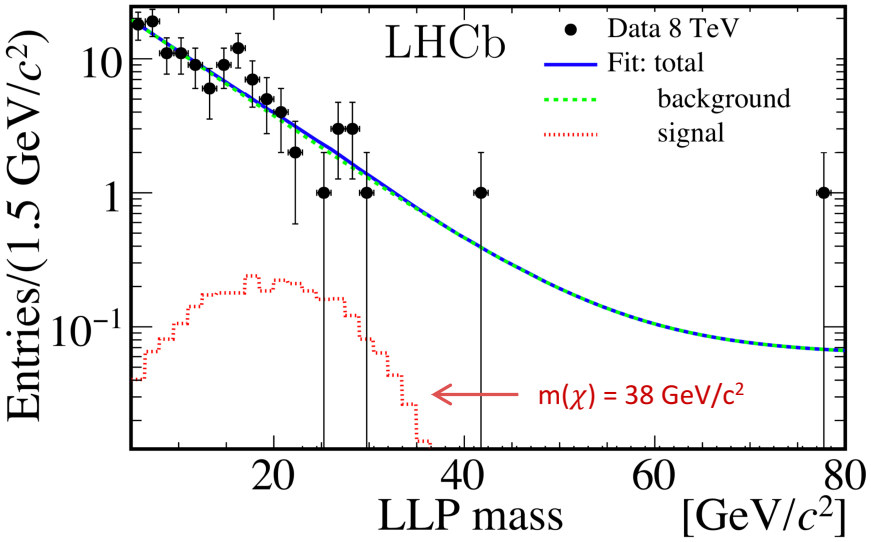
[EPJC (2017) 77:224]

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



- Study uses 3 fb^{-1} of data collected by LHCb at E_{CM} = 7 and 8 TeV
- LLP mass=[20-200] GeV/c^2 and lifetime=[5-100]ps
- Major background from $b\bar{b}$ events:
  - rejected with a tight selection + MLP classifier
- Muon isolation → very discriminant (top plot)
- Number of candidates extracted from fit to LLP mass (bottom plot)



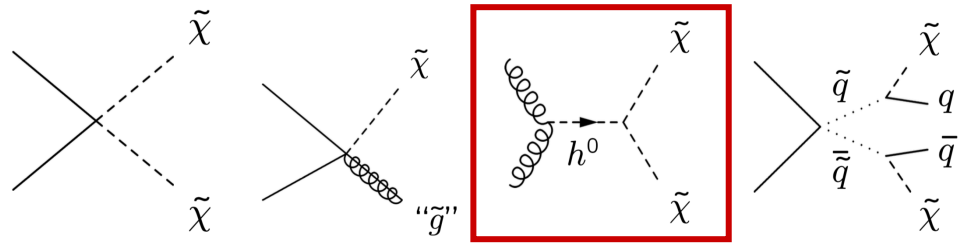


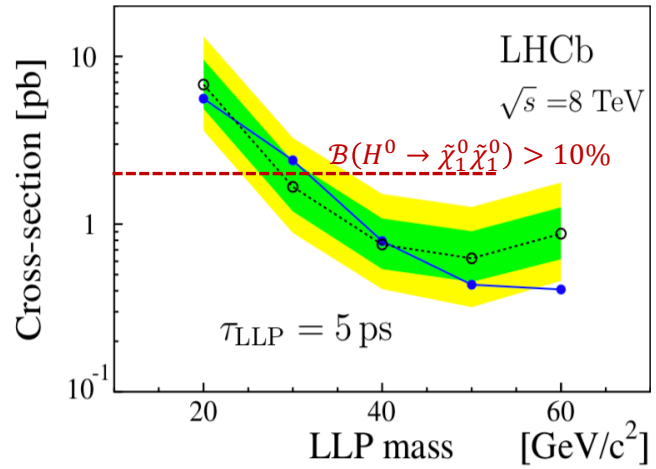
Massive LLPs decaying to μ + jets

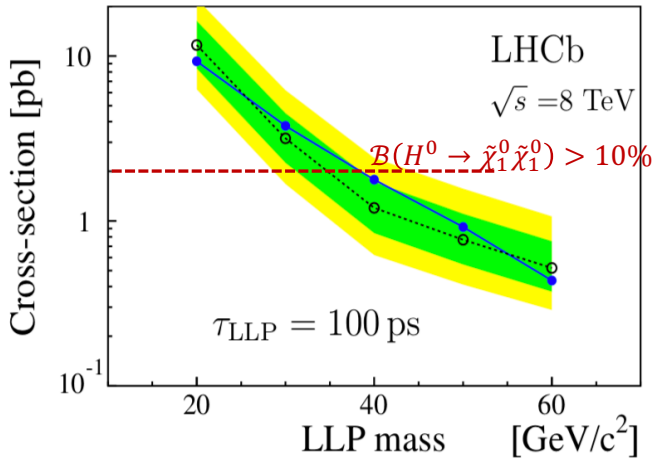
[EPJC (2017) 77:224]

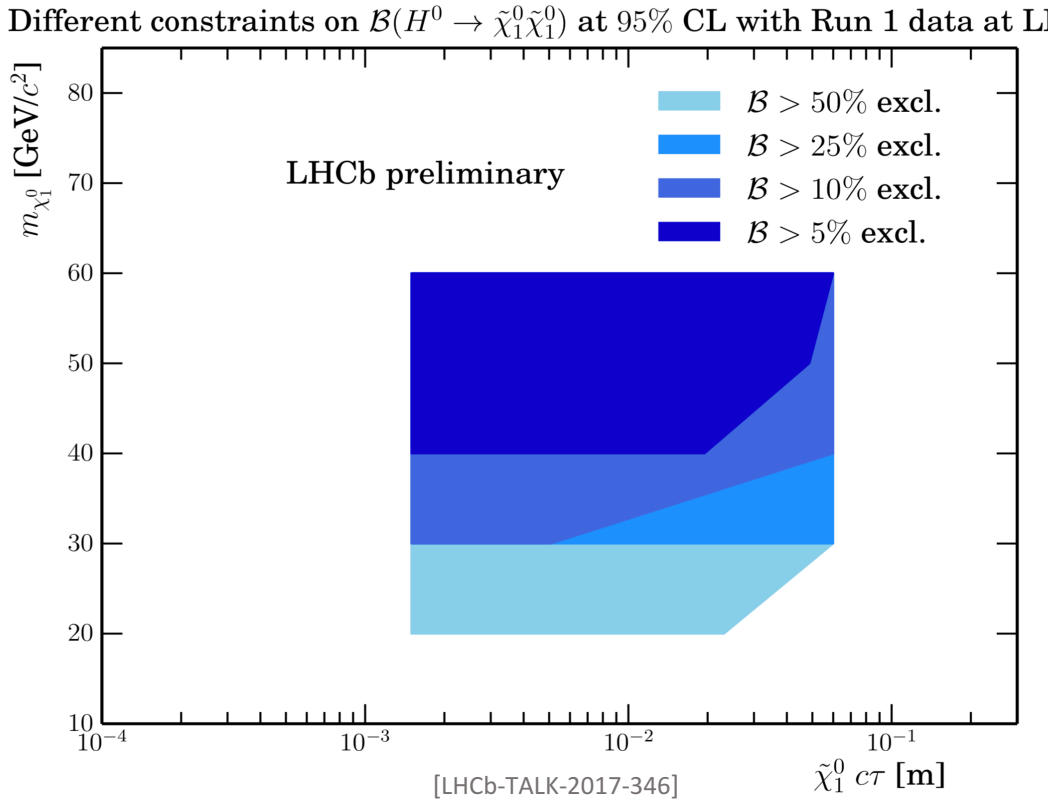
No excess found, interpretation in various production modes:

For example LLP pair production from $H^0(125)$





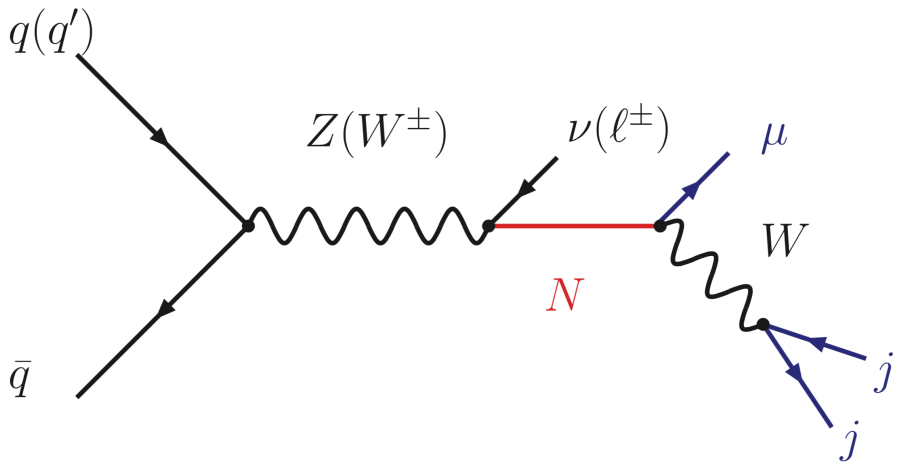


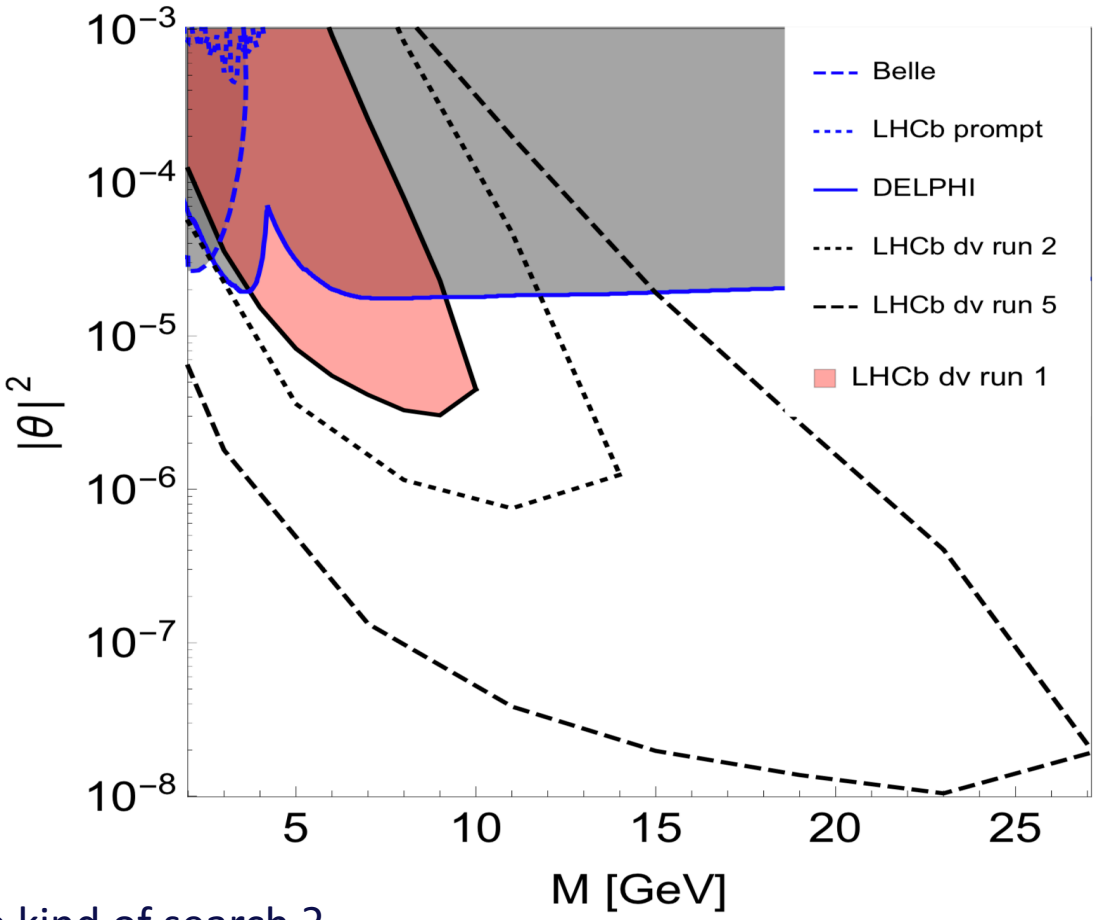


Stringent limits: $\mathcal{B}(H^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0) > 10\%$ rejected down to 30 GeV/c² ($\tau = 5\ ps$)

Massive LLPs decaying to μ + jets

Recast into sterile neutrinos scenario [arXiv:1706.05990, S. Antusch et al.]:





Could we get best world-limit (5 – 10 GeV/c^2) with the same kind of search ?

Dedicated search with Run II in **preparation.**

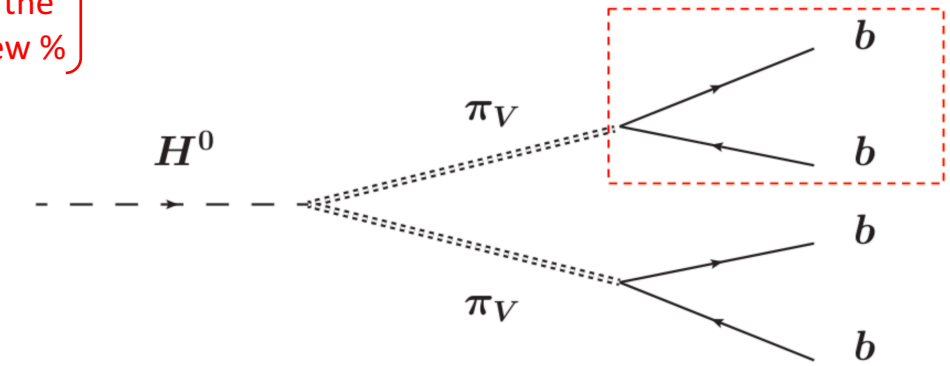
Massive LLPs decaying to jet pairs

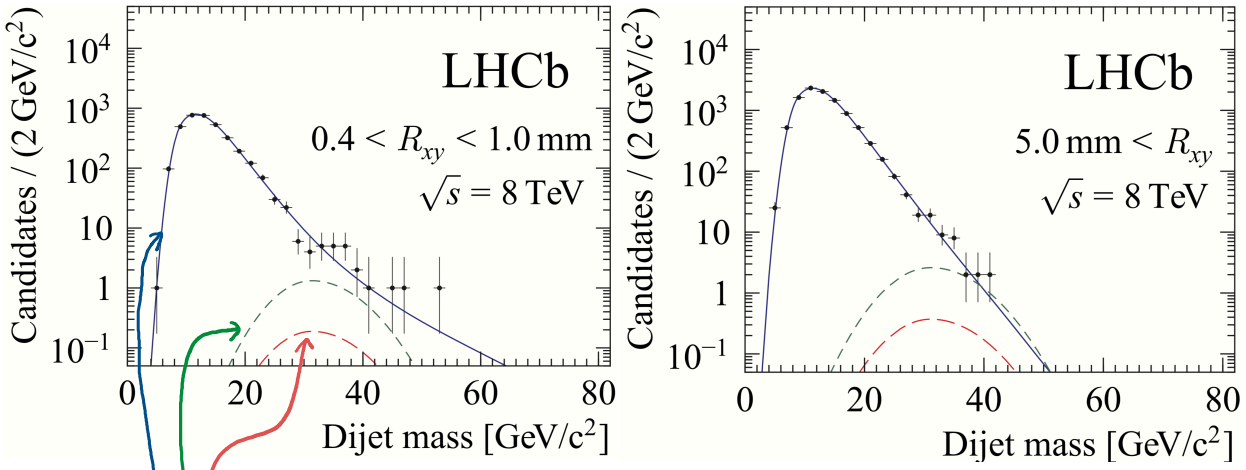
NEW [EPJC (2017) 77:812]

- **Signature**: single displaced vertex with two b-jets

Efficiency to have 4 jets in the LHCb acceptance is only few %

- Model: Hidden Valley pions from $H^0(125)$ decay
- Study uses 2 fb^{-1} of data collected by LHCb at E_{CM} = 7 and 8 TeV
- LLP mass=[25-50] GeV/c^2 and lifetime=[2-500]ps
- Analysis procedure:
  - trigger on displaced vertices,
  - reconstruct the displaced vertex and find two associated jets,
  - quality cuts on jets – dijets should points back to candidate vertex,
  - exclusion of material interactions and displaced vertices from heavy flavour.
- Fit the di-jet invariant mass in 6 bins of the radial vertex position R_{xy} (0.4 – 50 mm)





Background model: material + heavy-flavour + SM dijets

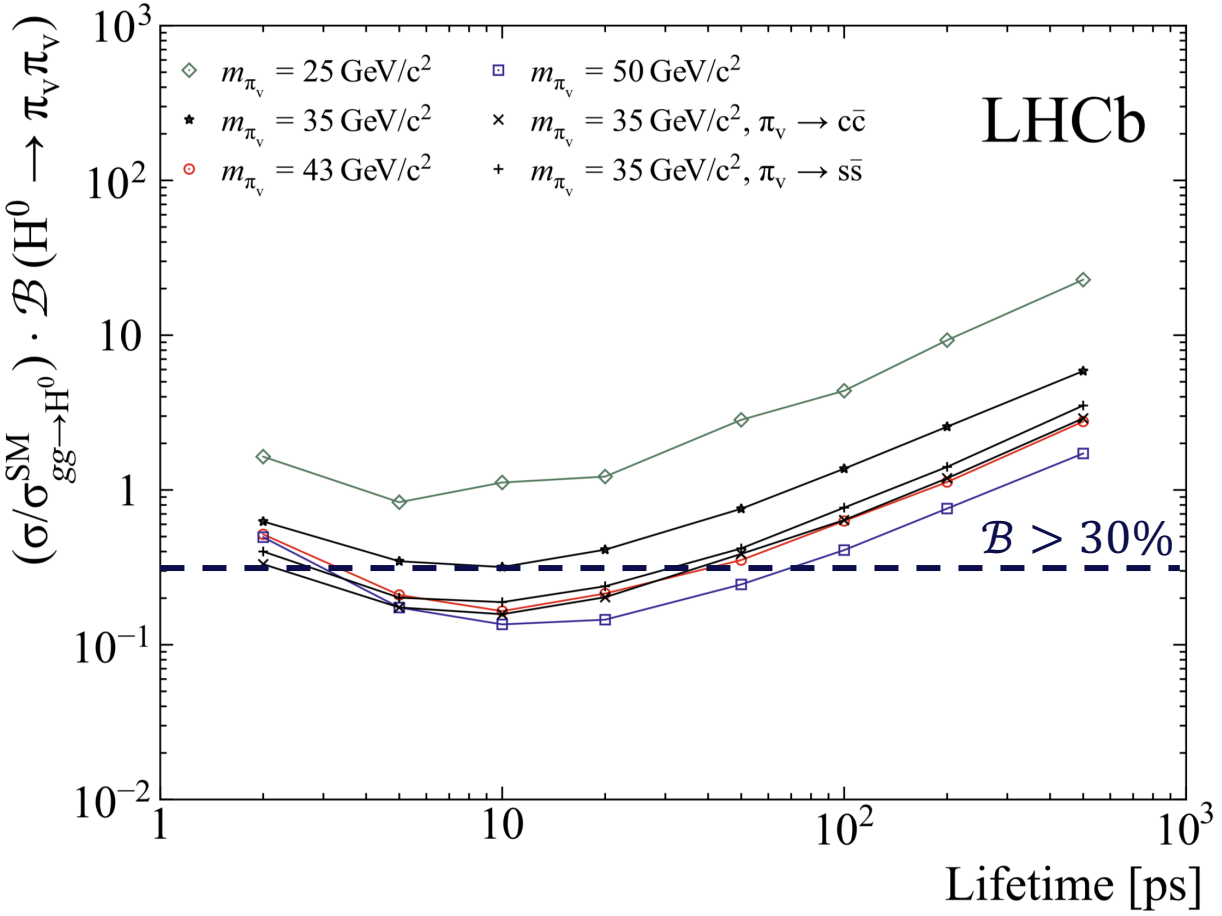
Expected signal(**35 GeV/c^2, 10 ps**) for $\mathcal{B}(H^0 \to \pi_V \pi_V) = 1$

Fitted signal model (**35 GeV/c^2, 10 ps**)

Massive LLPs decaying to jet pairs

NEW [EPJC (2017) 77:812]

- No excess found!
- Limits at 95% C.L. as a function of π_V lifetime for different masses.
- Also looking for $\pi_V \to c\bar{c}$ and $\pi_V \to s\bar{s}$ but only for m(π_V) = 35 GeV/c^2.
- If $\mathcal{B}(H^0 \to \pi_V\pi_V) > 30$ %, m(π_V) = 50 GeV/c^2 rejected for $5 < \tau(\pi_V) < 50$ ps.
- Plan to analyse LHCb Run II and go to lower π_V masses:
  - → new dedicated trigger lines for displaced jets are on development,
  - → development of a **jet substructure tools** to study multi-jets at lower masses.



Dark photon

[arXiv:1710.02867]

- **Search for dark photons decaying into a pair of <u>muons</u>**

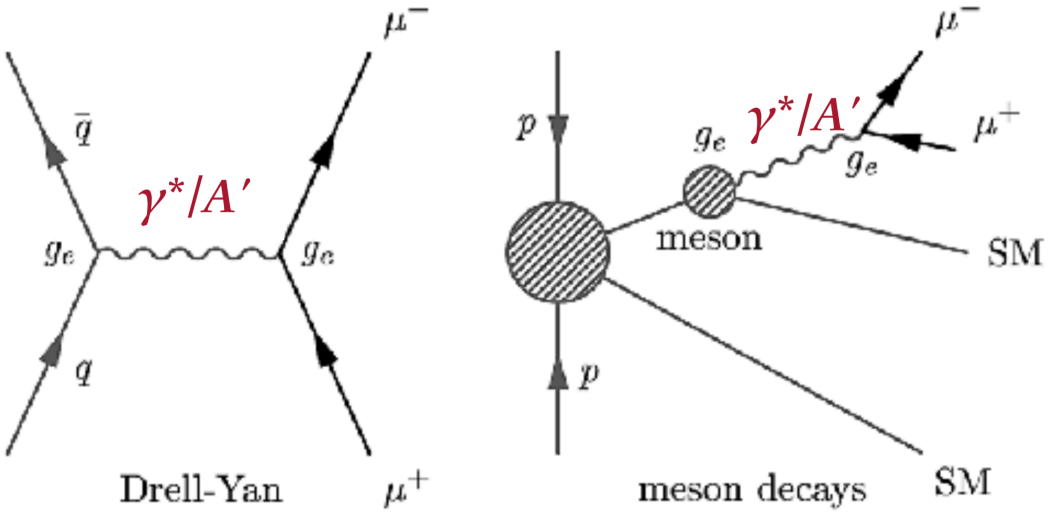
- Dark sector scenario involving a massive dark photon ***A'*:**
  - mixing of the dark photon with off-shell photon γ^* by a factor **ε** (ε^2 can be as small as 10^{-14})
  - dark photon mass can be low
  - dark photon inherits production mechanisms from SM photon

- $A' \to \mu^+\mu^-$ can be normalised to $\gamma^* \to \mu^+\mu^-$

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

expected dark photon; off-shell photon; phase space; γ^*/A' efficiency ratio, <u>ϵ = 1 for prompt</u>

- data-driven analysis

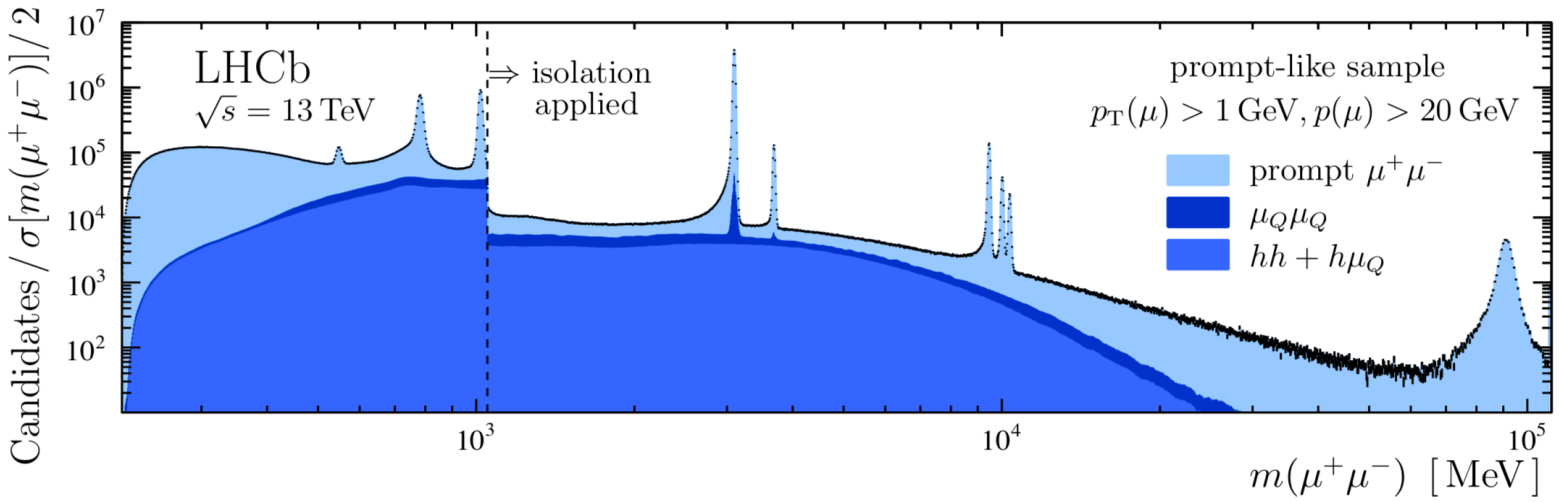


- Study uses 1.6 fb^{-1} of data collected by LHCb at E_{CM} = 13 TeV :
  - **Prompt-like** search ($2m_\mu < m(\mu\mu) < 70$ GeV/c^2)
  - **Displaced-like** search ($214 < m(\mu\mu) < 350$ MeV/c^2), *A'* is long-lived when ε is small

Dark photon: prompt-like search

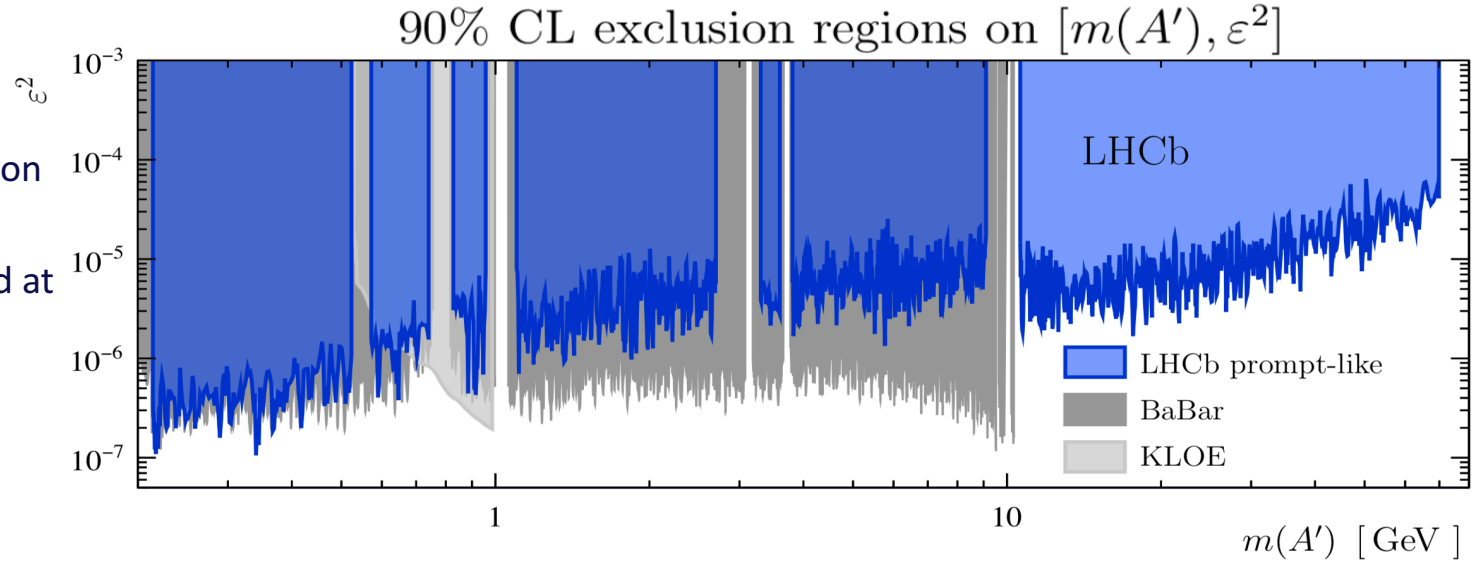
[arXiv:1710.02867]

- Know the $\gamma^* \to \mu^+\mu^-$ yield in order to get the $A' \to \mu^+\mu^-$ **expected yield** using the normalization equation (previous slide):



- Get the **observed $A' \to \mu^+\mu^-$ yield** from fits of $\mu^+\mu^-$ invariant mass. **No significant excess found**

Regions where upper limit on $n_{obs}^{A'}[m(A')]$ is less than $n_{ex}^{A'}[m(A'), \varepsilon^2]$ are excluded at 90% C.L.



- First limits above dark photon masses of 10 GeV/c².
- Competitive limits below 0.5 GeV/c² as well.

Dark photon: displaced-like search

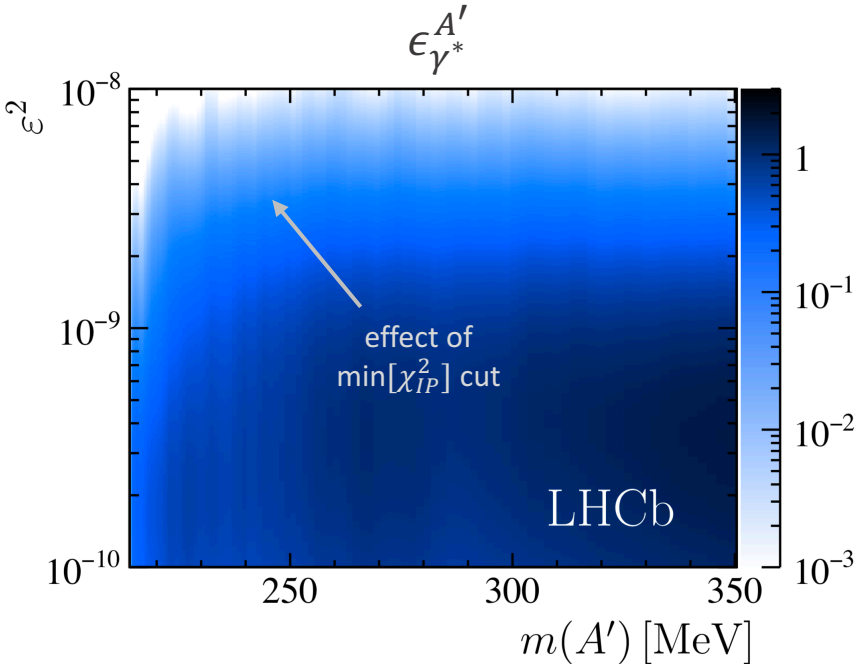
[arXiv:1710.02867]

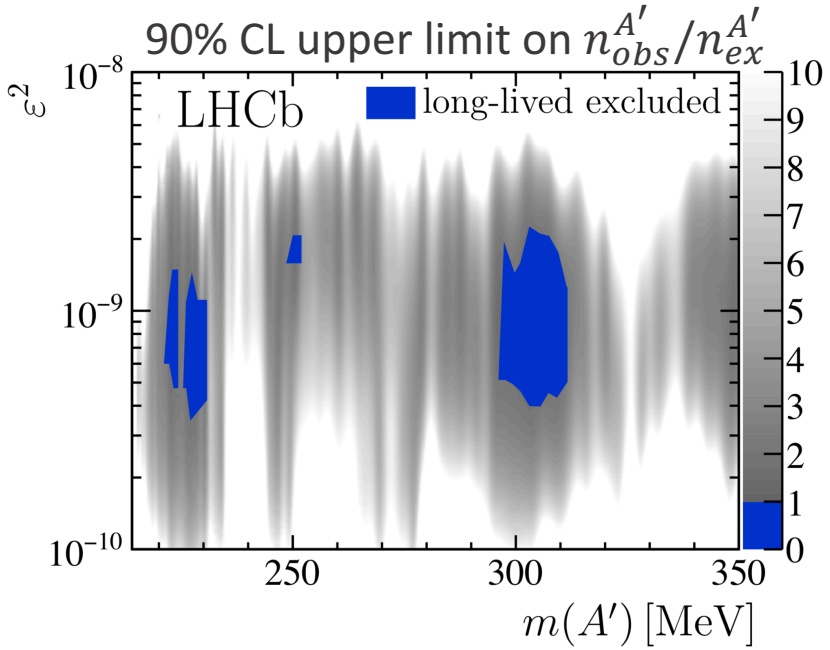
- Backgrounds:
  - photon conversions to $\mu^+\mu^-$ at the VELO region —> suppressed using material veto map
  - b-hadron decays
  - low mass tail of $K_s^0 \to \pi^+\pi^-$, π misidentified as μ

  } suppressed by an isolation decision tree

- Determination of the $A' \to \mu^+\mu^-$ **expected** yield:
  - get the prompt $\gamma^* \to \mu^+\mu^-$ yield in the fiducial region of the displaced search
  - get the efficiency ratio $\epsilon_{\gamma^*}^{A'}$

- Determination of the **observed** $A' \to \mu^+\mu^-$ yield from fits of m($\mu^+\mu^-$) (in bins of mass and lifetimes)





- **No significant excess found;** small parameter space region excluded
- First limit ever **not from beam dump experiment!**
- First limit for **non prompt production.**

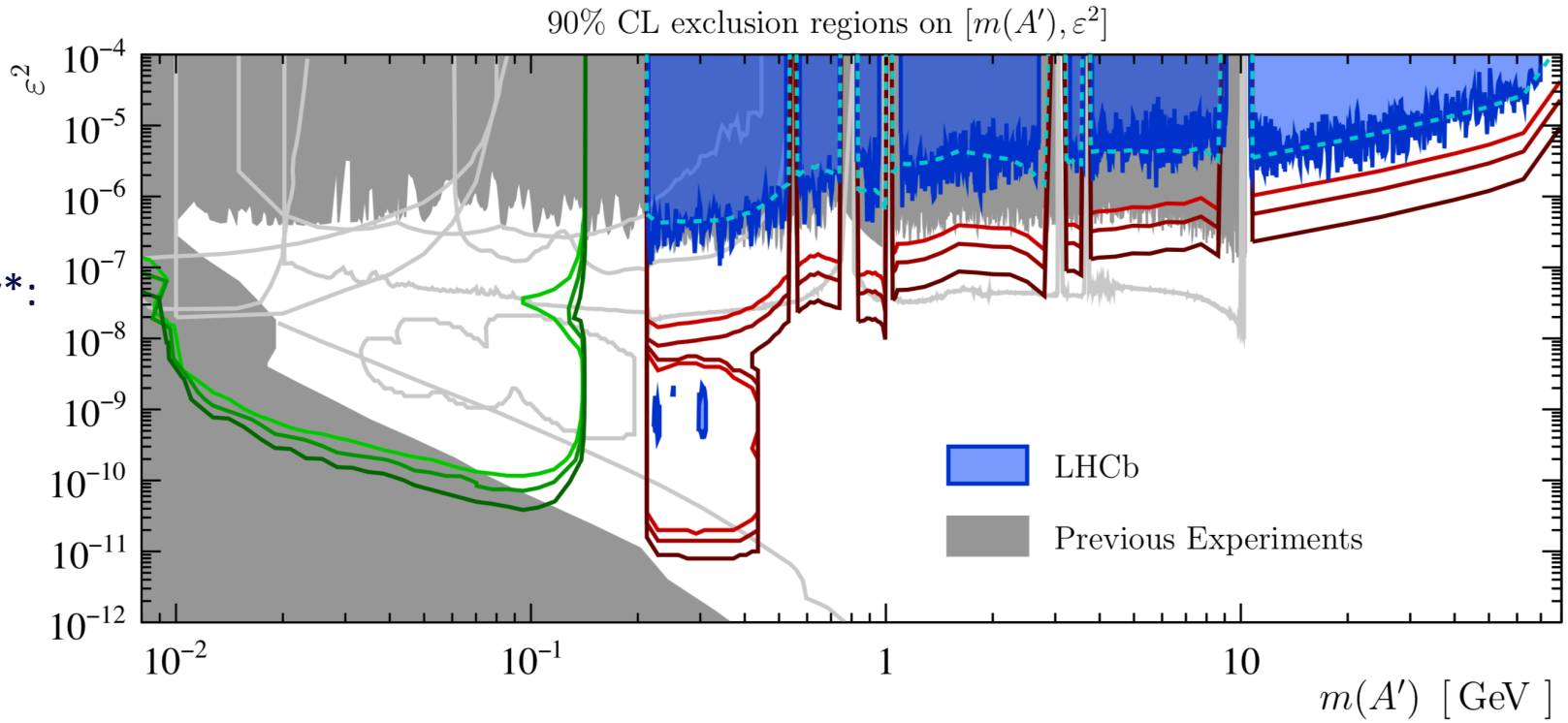
Dark photon: future

[arXiv:1710.02867]

- Continue to contributes ⟶ more sensitivity coming with more Run-II data.
- Extend searches model-independently ⟶ i.e light NMSSM Higgs via ggF [PRD 93 (2016) 055047, U. Haisch, et al.]
- Prospected search for **Run III**: [PRL 116 (2016) 251803, P. Ilten et al.] [PRD 92 (2015) 115017, P. Ilten et al.]

Charm mesons decay*:

- 15 fb^{-1}
- 50 fb^{-1}
- 500 fb^{-1}



Drell-Yan:

- 15 fb^{-1}
- 50 fb^{-1}
- 500 fb^{-1}

* Dark photons from charm mesons decays will be searched for in LHCb in di-electron final state.

Conclusions: today

- LHCb has collected 3.0 fb^{-1} during the full Run I.
- LHCb has collected 3.7 fb^{-1} collected so far in Run II (2015 – November 2017).
- Current long-lived particle searches results:
  - Neutralinos (mSUGRA RPV, from SM-like Higgs decay),
  - Hidden Valley π_V from SM-like Higgs decay, ← shown today
  - Dark photon from Drell-Yan,
  - Hidden-sector bosons (inflatons) from B decays,
  - Charged Massive Stable Particles (SUSY mGMSB),
  - Majorana neutrinos in B decays.

Conclusions: future

- Expect to collect more than 5.0 fb^{-1} during the full Run II.
- A lot of potential in Run III: new triggers and 5 x instantaneous luminosity.
- Plan to extend the LLPs programme to complementary regions w.r.t other experiments.
- Prospects and new ideas:
  - HV π_V at lower masses, lower lifetimes, using confining HV models (arXiv:1708.05389)
  - Extend dark photon searches model-independently, inclusive searches,
  - Majorana neutrinos in B decays, u → c transitions,
  - Majorana neutrinos in W decays (already ongoing),
  - electrons in final states, sensitive to lower masses (no sensitivity anywhere else at LHC),
  - fractional particles, monopoles, quirks (sensitivity studies needed).
- **We are open to new ideas for new signatures and techniques, don't hesitate!**

Dark photon: prompt-like search

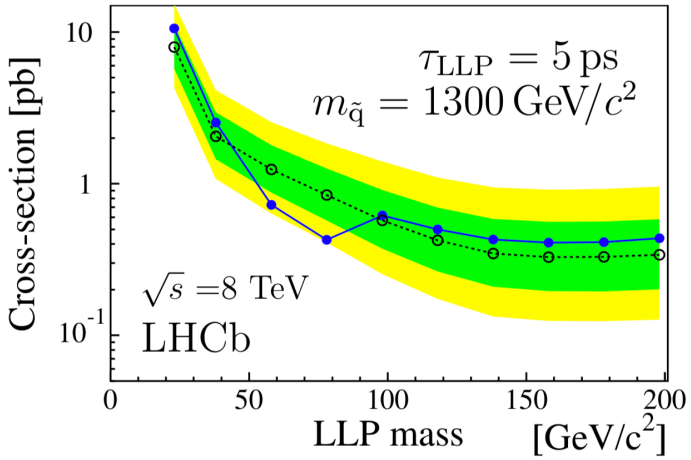
Backup

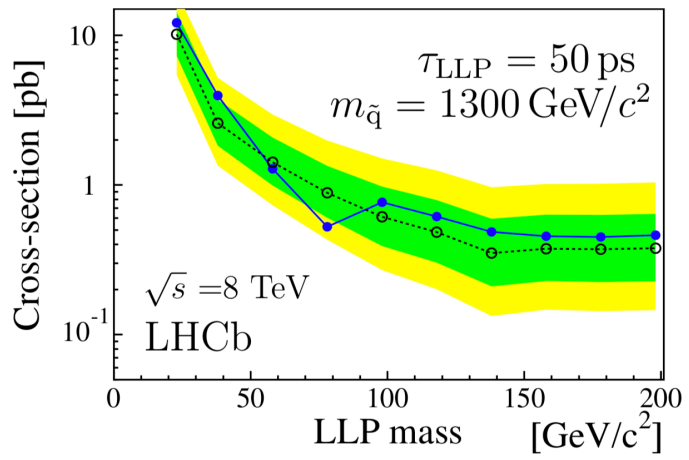
Massive LLPs decaying to μ + jets

[EPJC (2017) 77:224]

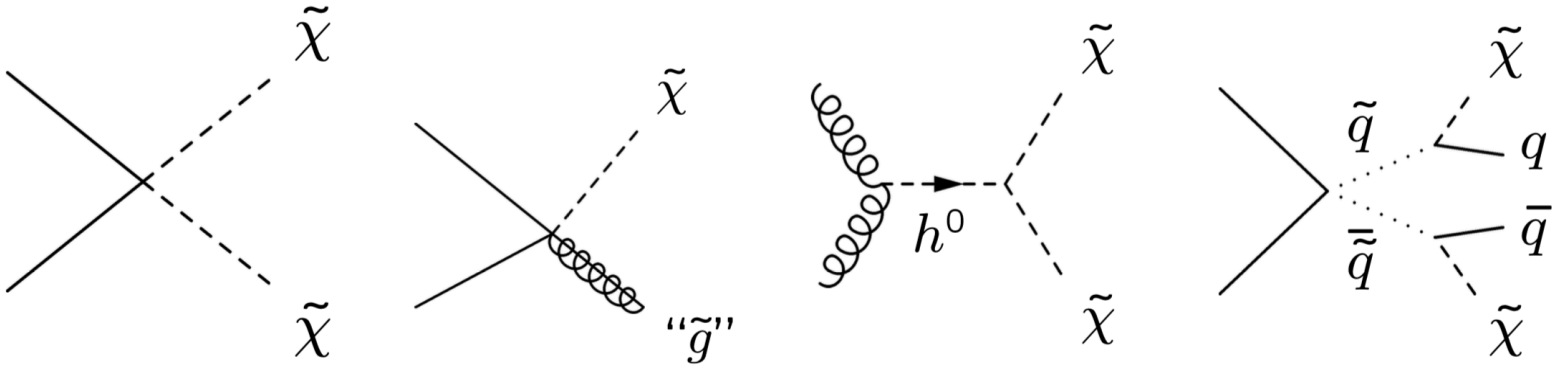
No excess found, interpretation in various models:

- **RPV mSUGRA from pythia6:**
  M_1 = [40-200] GeV/c^2 ➞ m_χ = [38-198] GeV/c^2
  M_2 = 2 TeV/c^2, $m_{\tilde{g}}$ = 2 TeV/c, $m_{\tilde{q}}$ = 1.3 TeV/c
  τ_{LLP} = [5-100] ps





- **Simplified MSSM topologies:**

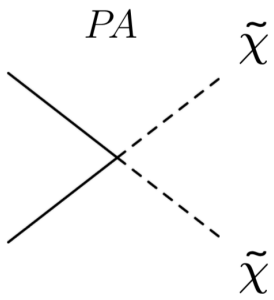


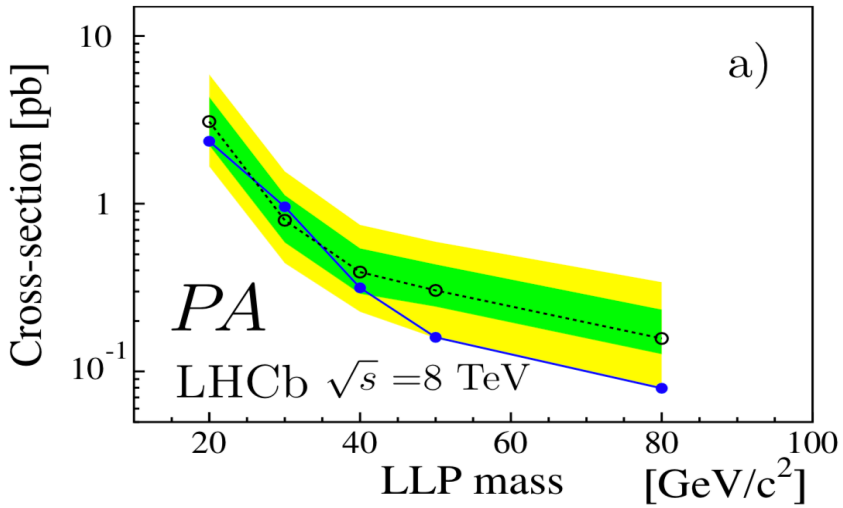
Massive LLPs decaying to μ + jets

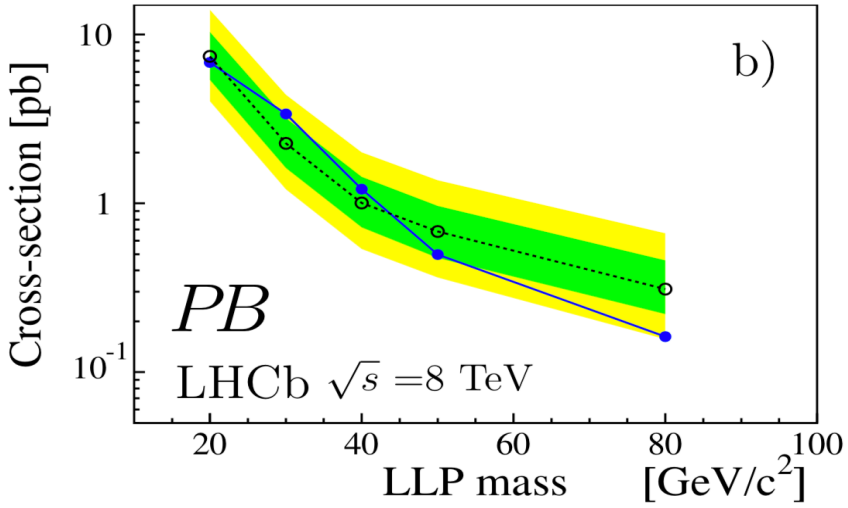
[EPJC (2017) 77:224]

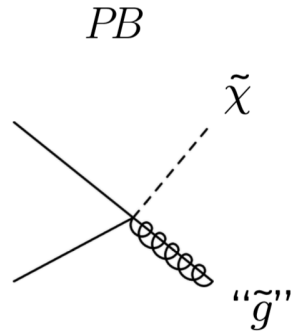
No excess found, interpretation in various models:

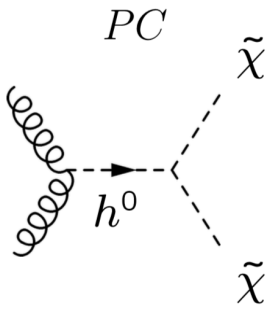
$\tau = 10\ ps$

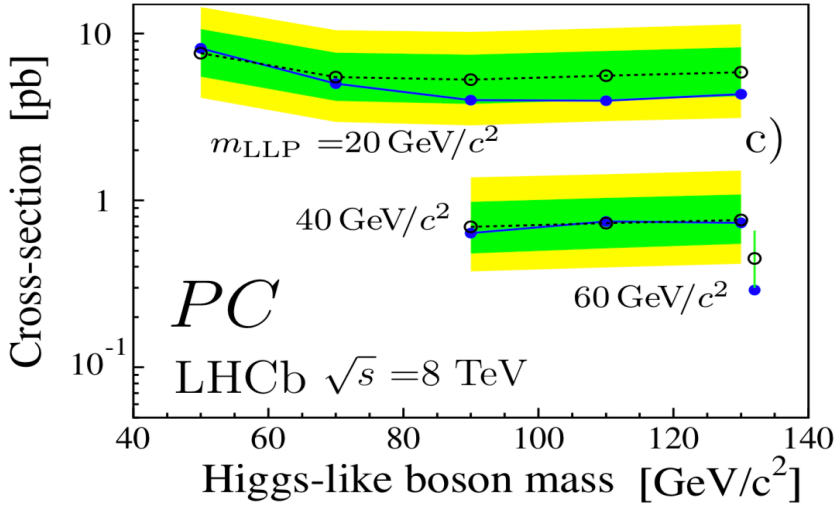


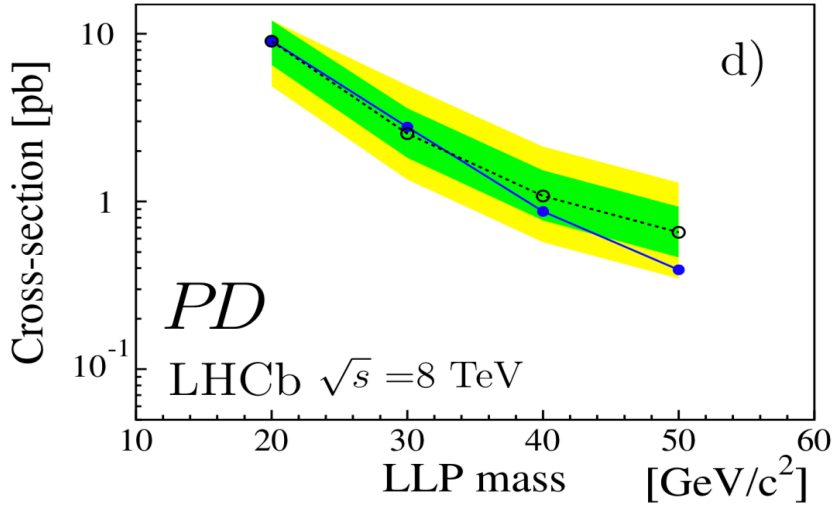


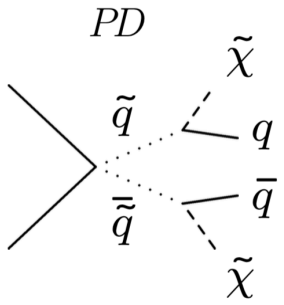








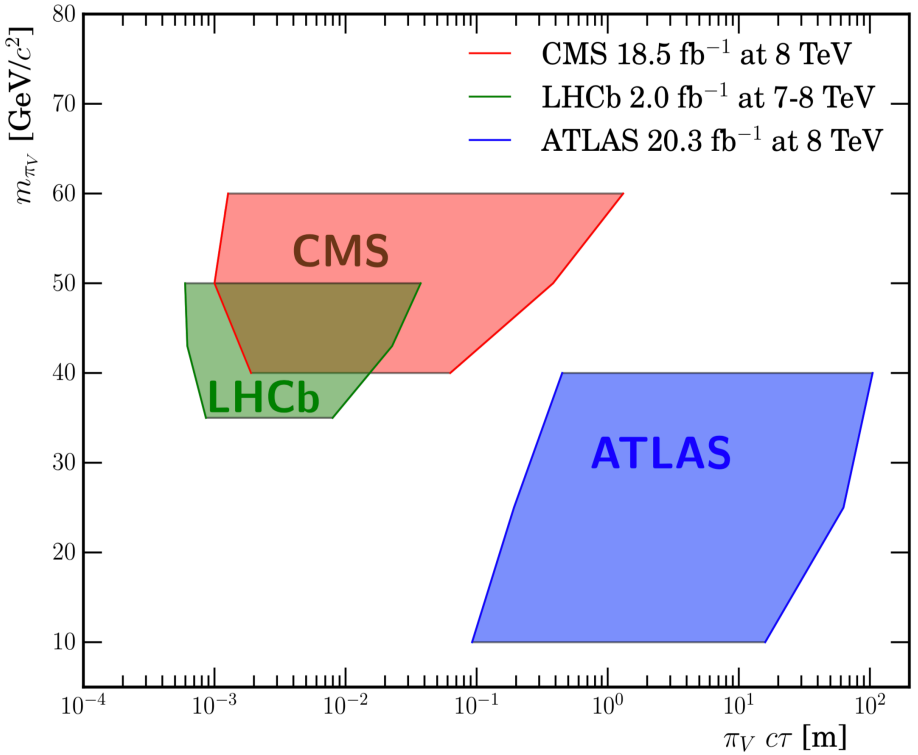




Massive LLPs decaying to jet pairs

[arXiv:1705.07332]

Comparison with results from ATLAS and CMS (recast), where $\mathcal{B}(H^0 \rightarrow \pi_V \pi_V) > 50$ % is excluded at 95% C.L:



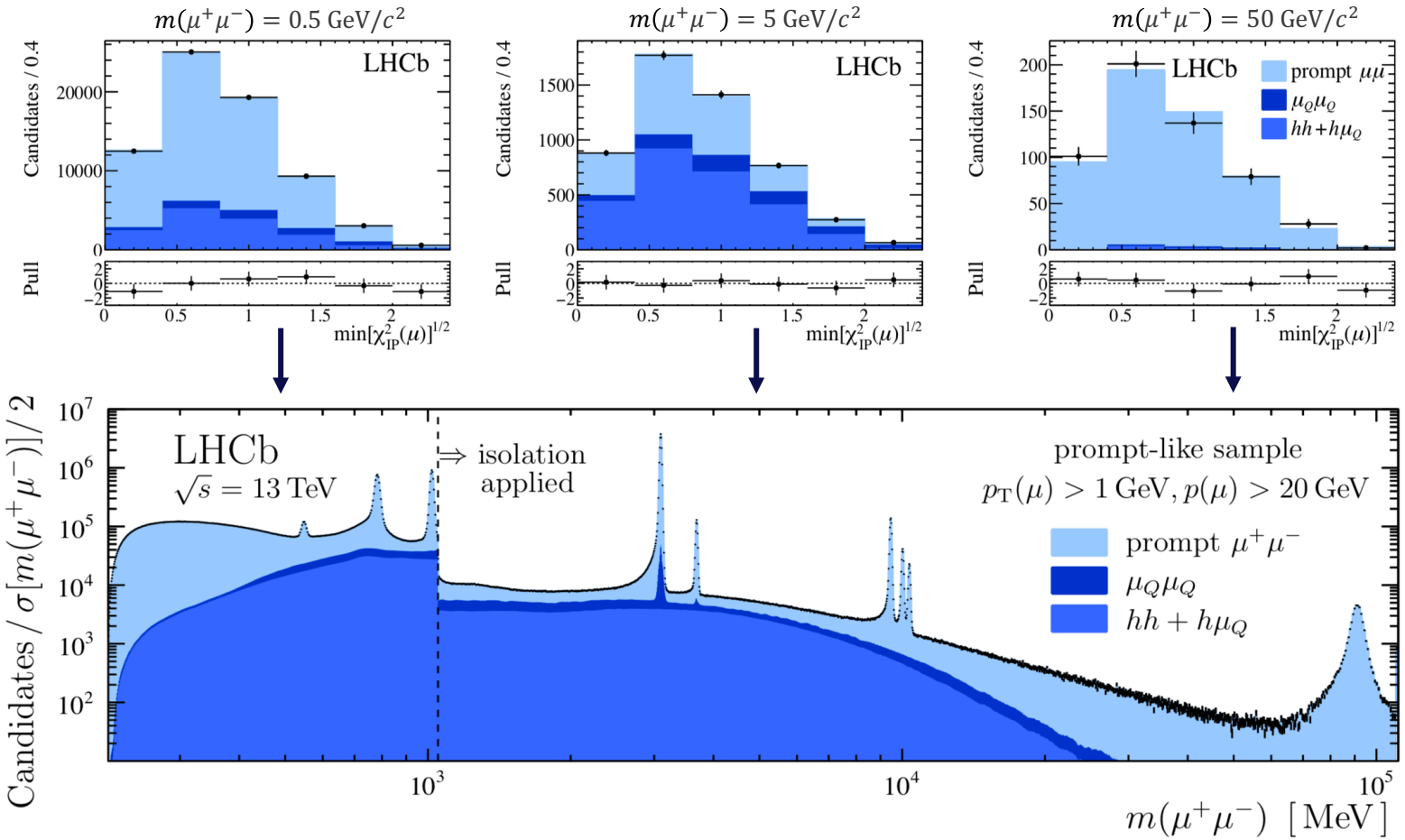
(Plot by M. Borsato)

- CMS: 18.5 fb^{-1} [PRD 91 (2015) 012007], recast [PRD 92 (2015) 073008]
- ATLAS: 20.3 fb^{-1} [PRD 92 (2015) 012010], [PLB 743 (2015) 15-34]
- Disclaimer: new CMS results at 13 TeV not included in the recast [CMS-PAS-EXO-16-003]

Dark photon: prompt-like search

[LHCB-PAPER-2017-038]

- determine the $\gamma^* \to \mu^+\mu^-$ rate from fits of $\min[\chi^2_{IP}(\mu^\pm)]$ [1] :



prompt $\mu^+\mu^-$ ⟶ from data at m(J/ψ) and m(Z)

$\mu_Q\mu_Q$ ⟶ from simulation (validated)

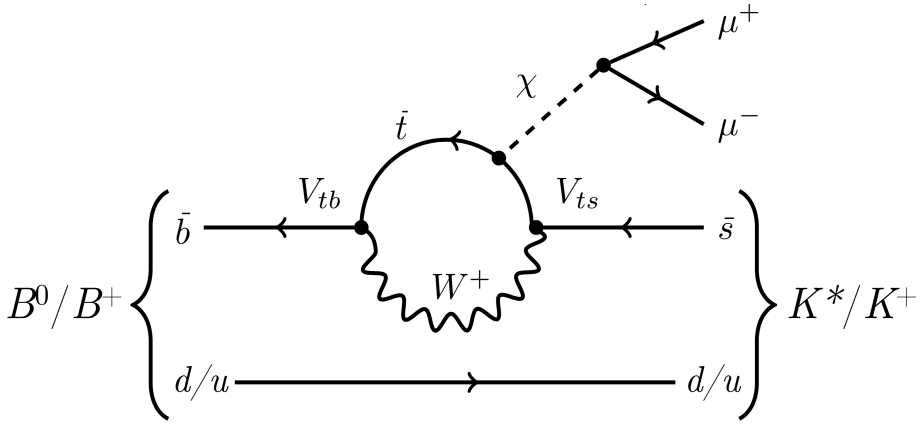
$hh + h\mu_Q$ ⟶ from same-sign dimuons (corrected)

$\chi^2_{IP}(\mu^\pm)$: difference in $\chi^2_{VF}(PV)$ when the PV is reconstructed with and without the muon track

Hidden-sector bosons in $B \to K^{(*)}\chi(\mu^+\mu^-)$

[PRL 115 (2015) 161802]
[PRD 95 (2017) 071101(R)]

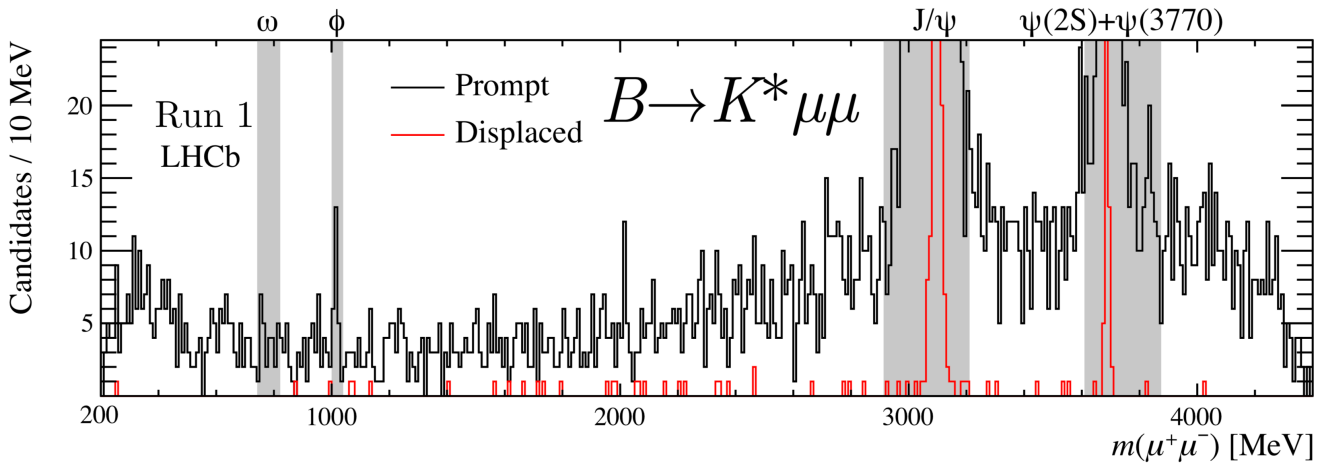
- Search for hidden-sector boson $\chi \to \mu^+\mu^-$ in $b \to s$ penguin decays:
  - Axial-vector portal (χ as axion) **[LNP 741 (2008) 3]**
  - Scalar (Higgs) portal (χ as inflaton) **[JHEP 05 (2010) 10]**
  - $B^0 \to K^{0*}\chi$ **[PRL 115 (2015) 161802]:**
    - $K^{*0} \to K^+\pi^-$ vertex leads to a better $\tau(\chi)$ resolution and less background
  - $B^+ \to K^+\chi$ **[PRD 95 (2017) 071101 (R)]:**
    - $B^+ \to K^+\chi$ has a larger branching fraction



- Study done on 3 fb^{-1} of data collected by LHCb at E_{CM} = 7 and 8 TeV

- $\mu\mu$ candidates are allowed to be **prompt** or **detached,** up to 1000 ps (~ 30 cm)

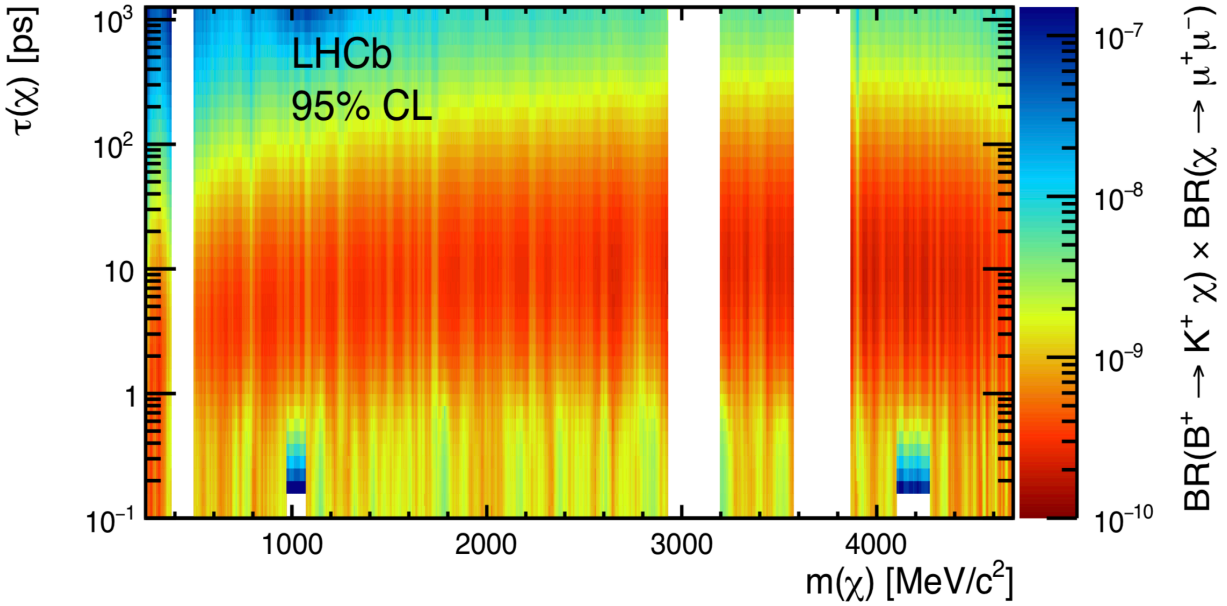
- Search for a narrow in peak in m($\mu\mu$):
  - B mass constrain → mass resolution 2-9 MeV/c^2
  - excluding QCD resonances



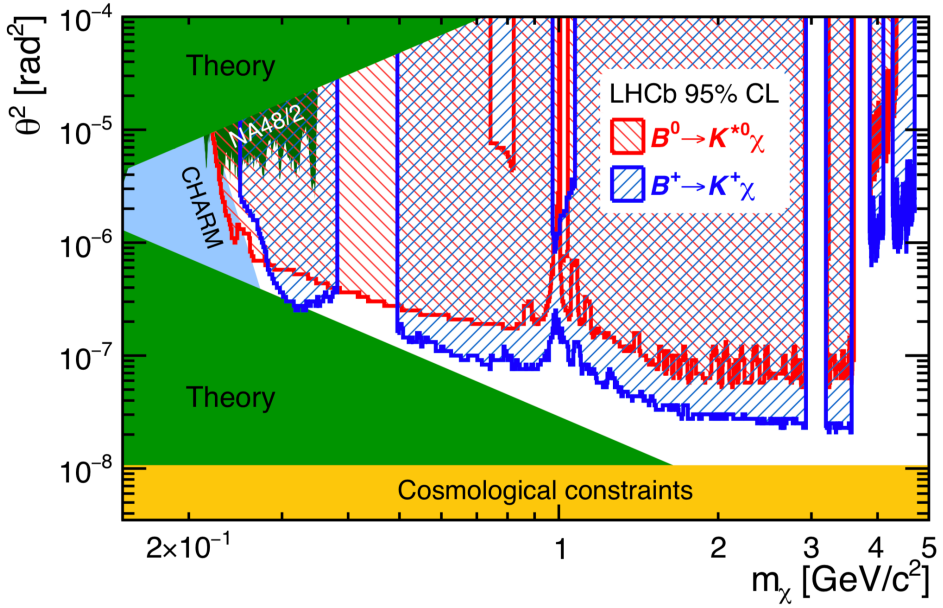
Hidden-sector bosons in $B \rightarrow K^* \chi(\mu^+\mu^-)$

[PRL 115 (2015) 161802]
[PRD 95 (2017) 071101(R)]

- No evidence for signal observed.
- Branching ratio $\mathcal{B}(B^+ \rightarrow K^+\chi)$ normalised to $\mathcal{B}(B^+ \rightarrow K^+ J/\psi)$ $(\sim 10^{-4})$, $\mathcal{B}(B^0 \rightarrow K^{*0}\chi)$ to $\mathcal{B}(B^0 \rightarrow K^{*0}\mu\mu)$ $(\sim 10^{-7})$.
- Constraints on $\tau(\chi)$ between 0.1 and 1000 ps.



- Constraints on mixing angle θ^2 between the Higgs and χ in the inflaton model.



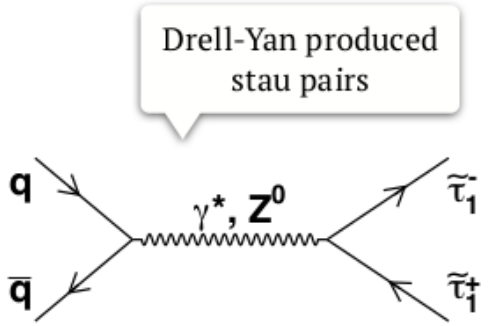
- **Large fraction of allowed inflaton parameter space ruled out.**

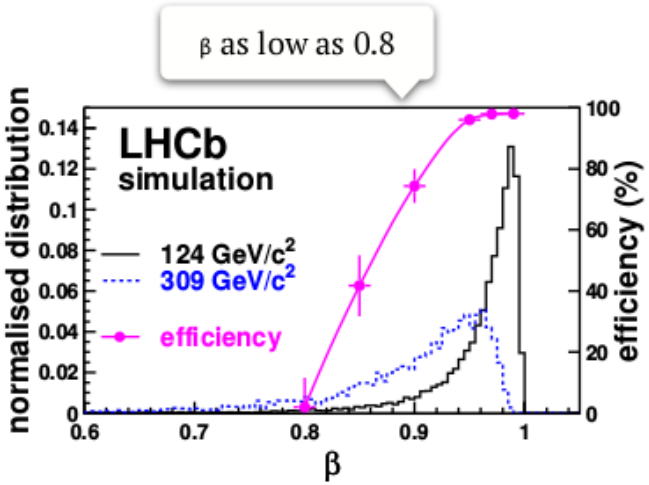
Charged Massive Stable Particles

EPJC 75 (2015) 595

- Charged Massive Stable Particles
  - stable = can pass through the μ-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





(shamelessly stolen from Martino's talk at previous LLP workshop)

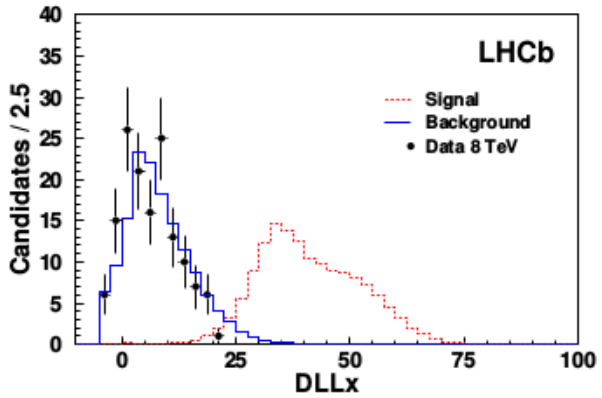
(Shamelessly stolen from Carlos Vázquez Sierra)

Charged Massive Stable Particles

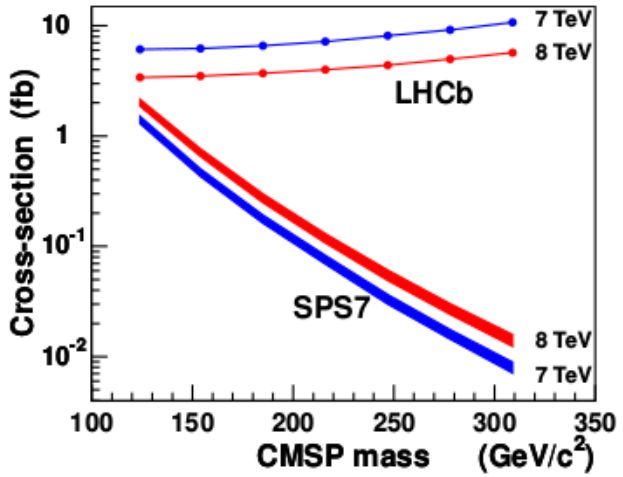
EPJC 75 (2015) 595

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

RICH information



- 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



(shamelessly stolen from Martino's talk at previous LLP workshop)

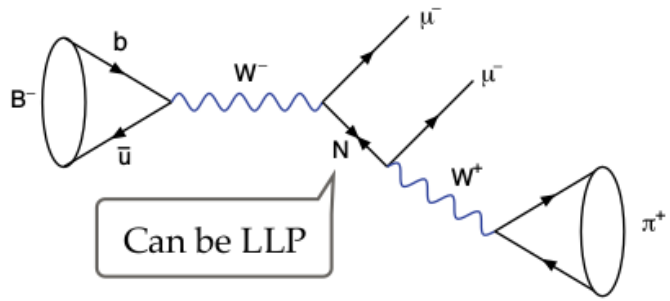
(Shamelessly stolen from Carlos Vázquez Sierra)

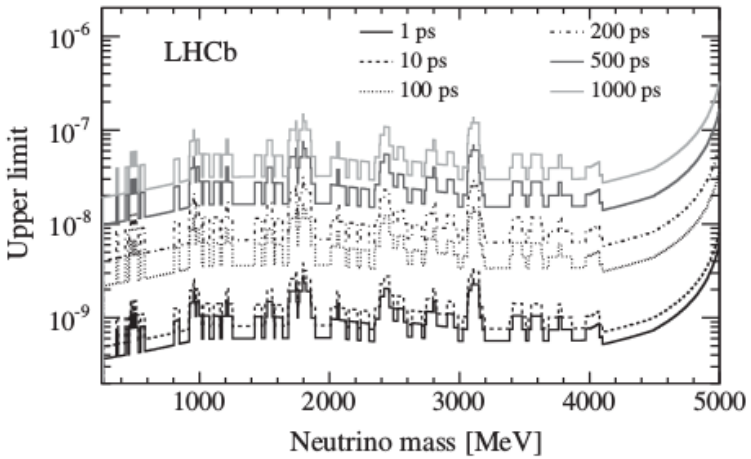
Majorana neutrinos in $B \to \pi\mu^+\mu^+$

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 $\mu^+\mu^+$





(shamelessly stolen from Martino's talk at previous LLP workshop)

- "Revision of the LHCb Limit on Majorana Neutrinos" **[arXiv:1607.04258]**

(Shamelessly stolen from Carlos Vázquez Sierra)