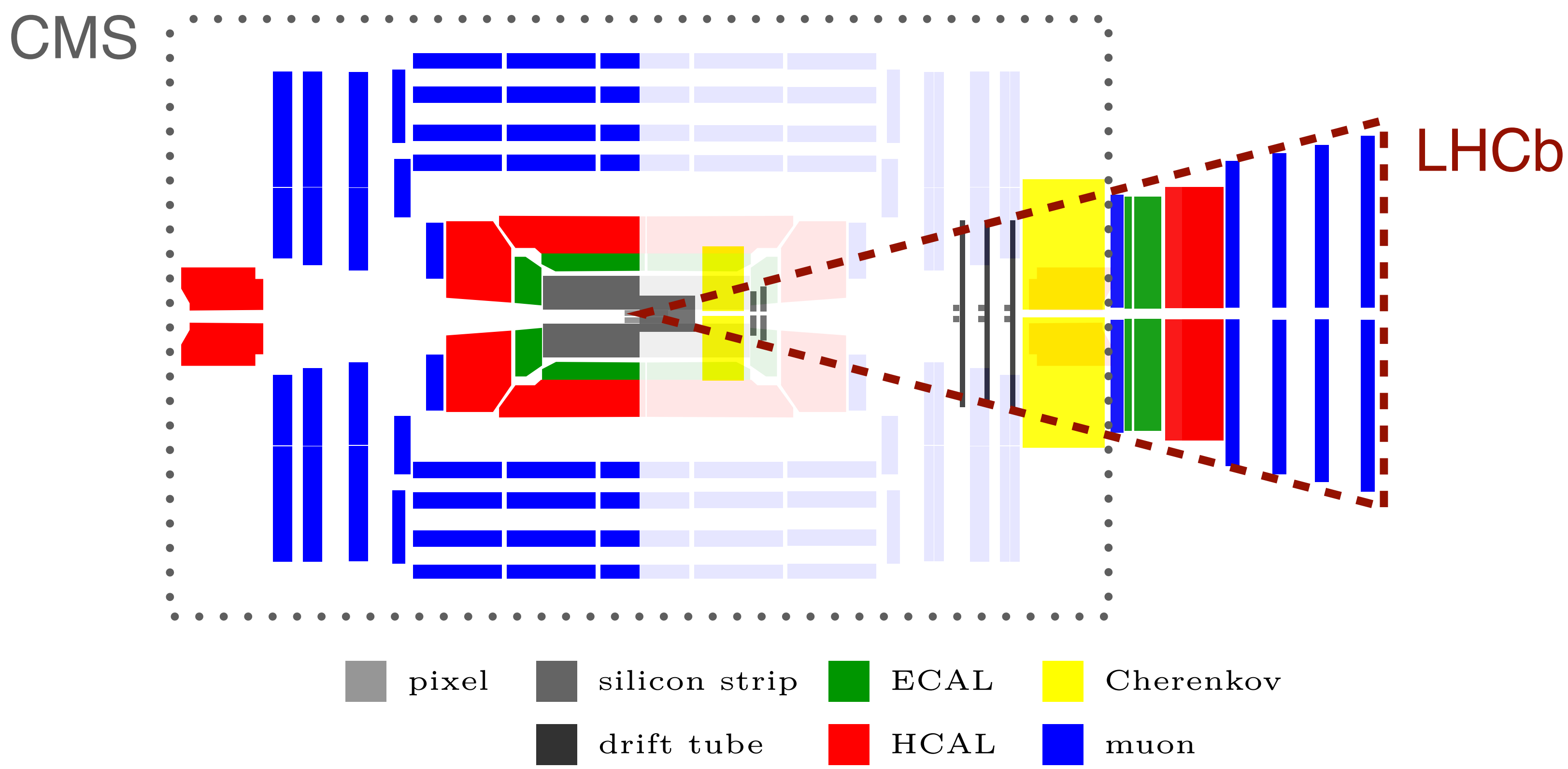
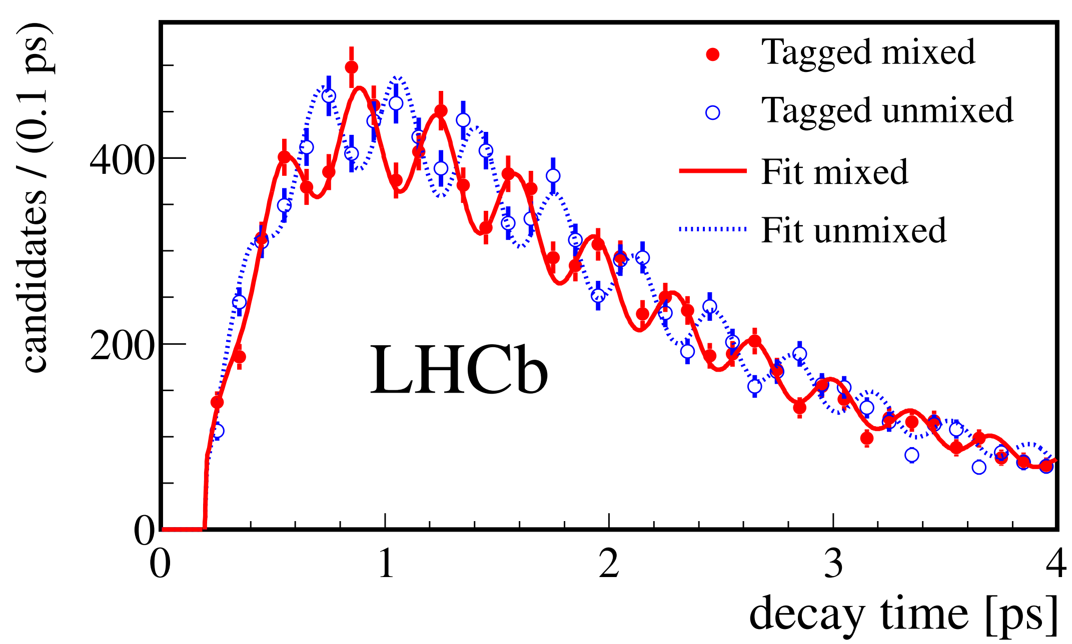
The LHCb detector

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

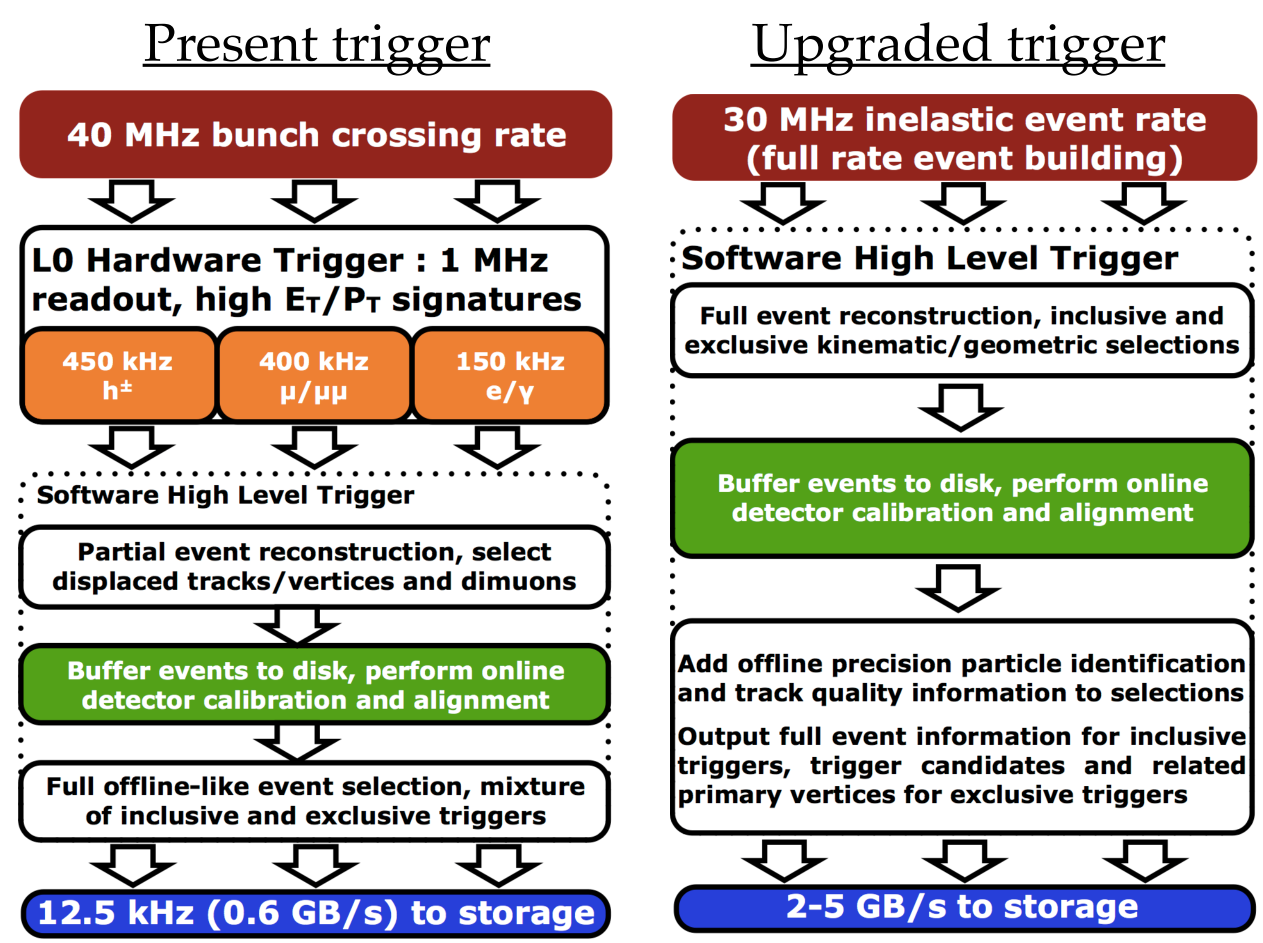
- Fully instrumented in forward region $2<\eta<5$
- Excellent vertex resolution
  - B_s oscillation at 40 fs (average boost $\beta\gamma \sim 3$)
- Excellent mass resolution
  - 0.5% at $m(\Upsilon \to \mu\mu)$
- Cherenkov PID capabilities
- Good jet reconstruction
  - 10-20% energy resolution for jets with $p_T > 10\,\mathrm{GeV}$
  - $b(c)$ tagging eff 65%(25%) for 0.3% contamination





The LHCb detector

- Lower luminosity (and low pile-up)
  - 1/8 of ATLAS/CMS in Run 1
- **Capable of very soft triggers!**
  - At hardware level (L0):
    - $\varepsilon = 95\%$ for detached $\mu\mu$ with $p_T > 1\,\mathrm{GeV}/c$
    - Calo trigger at ~3.5 (~2.5) GeV for hadrons (electrons)
  - At Software level (HLT):
    - Topological triggers on detached vertices
    - Also PID and jets in trigger!
- **Trigger-less upgrade (2020)**
  - Read-out detector in real time
  - **Will trigger on detached vertices at first level!**

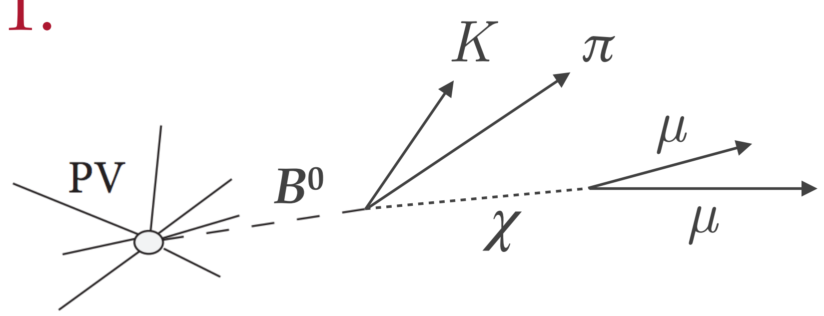


[LHCB-TDR-016]

Direct searches at LHCb

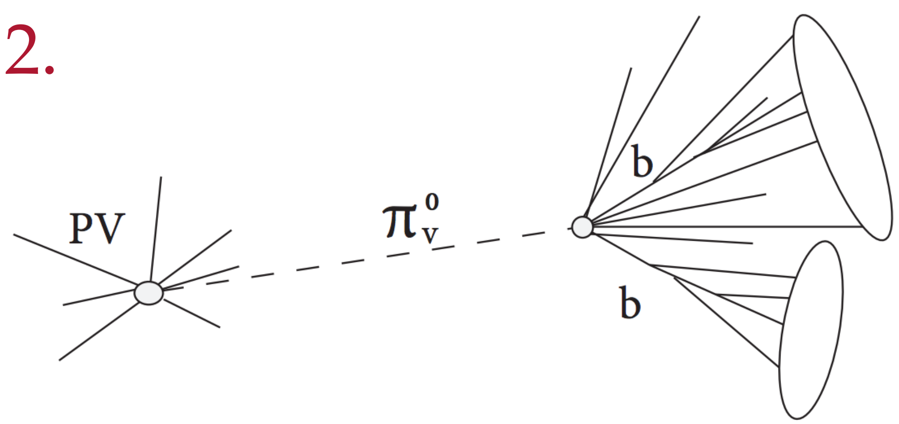
- **Complement** ATLAS / CMS searches in certain phase space regions :
  - **Light masses**
    - soft trigger and forward acceptance
  - **Low lifetimes** down to 1 ps
    - excellent vertexing and boost

1.

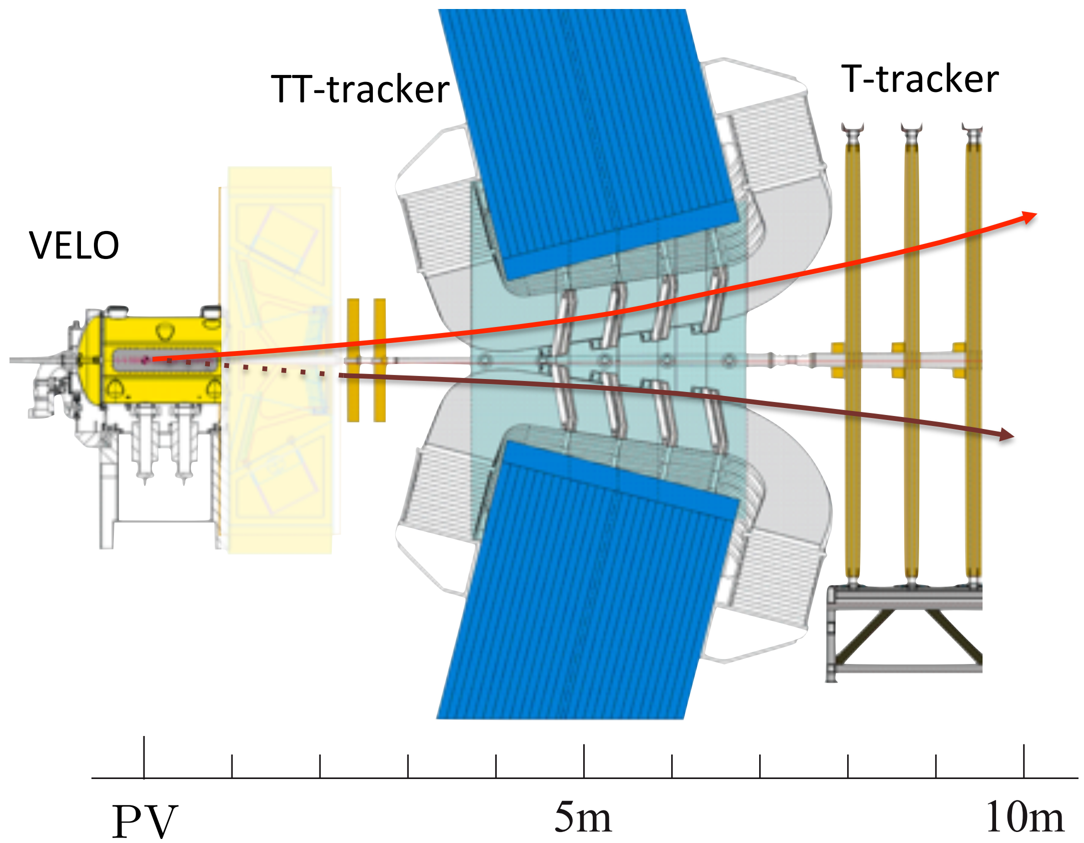


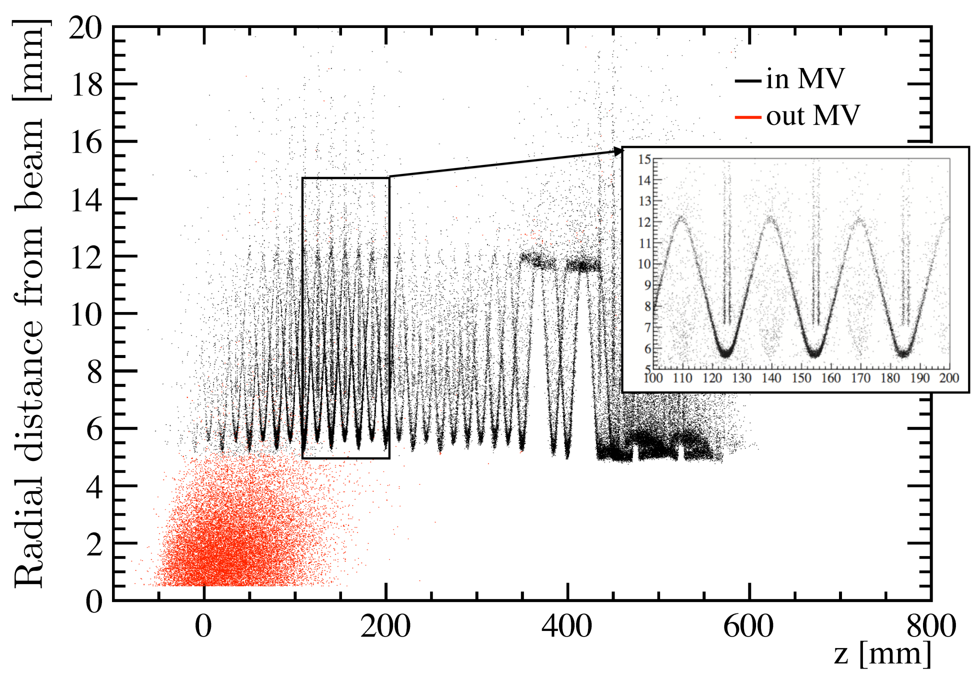
- Increasing interest in direct searches!
  1. **Produced in *B*/*D* decays** (prompt / long-lived)
  2. **Produced in *pp* collision** (prompt / long-lived)

2.



LLP at LHCb





<u>Tracks from long-lived in LHCb:</u>

- **Within VELO** (< 50 cm)
  - in reality more like < 20 cm
- **Up to TT** (<200 cm)
  - Worse vertex and p resolution ($K_S(\pi\pi)$ 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

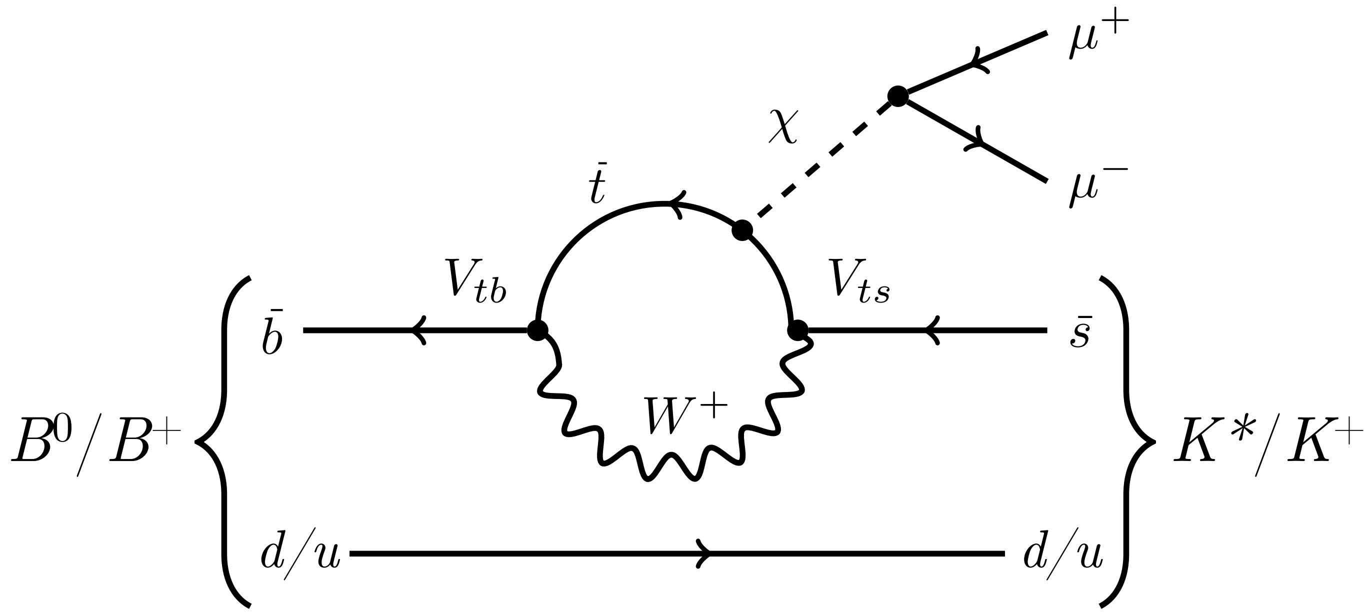
Direct searches in heavy flavour decays

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

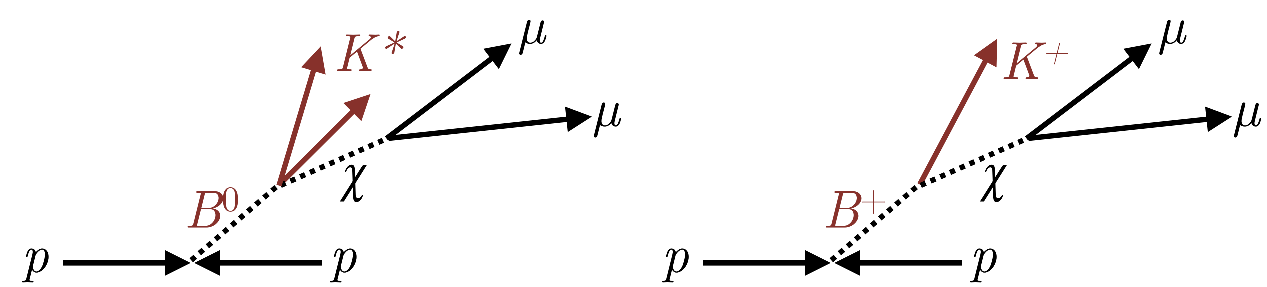
NEW

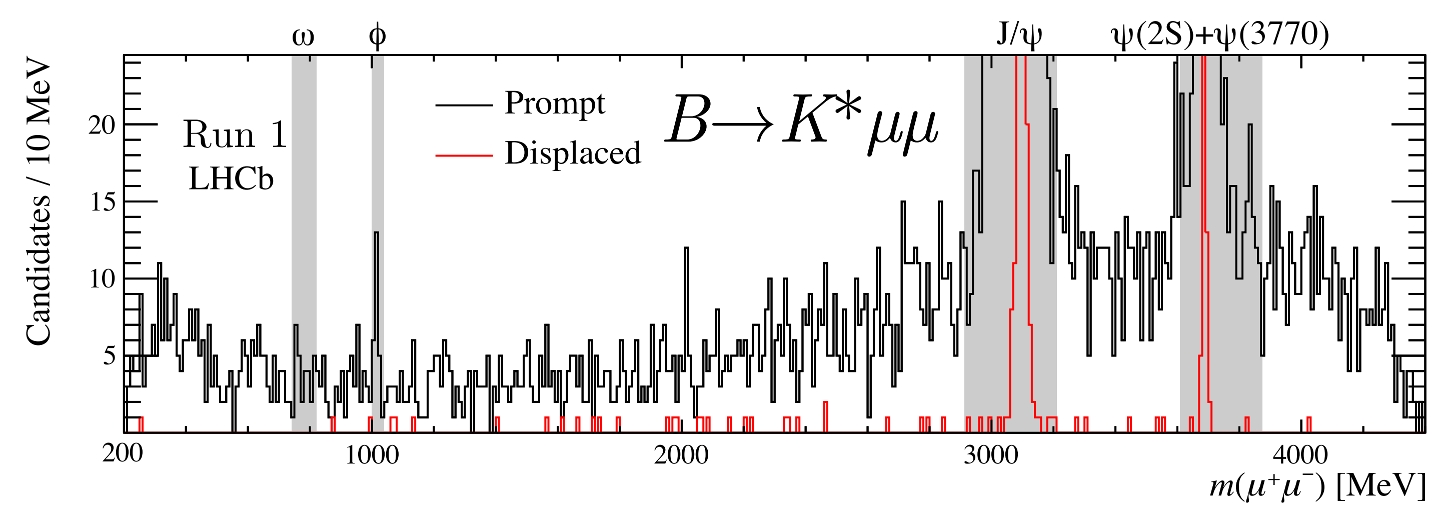
[Phys Rev Lett 115 161802 (2015)](#)
[Phys Rev D 95, 071101(R) (2017)](#)

- Look for new hidden-sector bosons in $b\to s$ penguin transitions
  - Can be axion or (long-lived) inflaton
- LHCb collected world record samples of rare decay $B\to K^{(*)}\mu\mu$



- Allow detached $\mu\mu$
- MVA selection independent of $m(\mu\mu)$ and τ (uBDT)
- Search for narrow peak in m($\mu\mu$), excluding QCD resonances





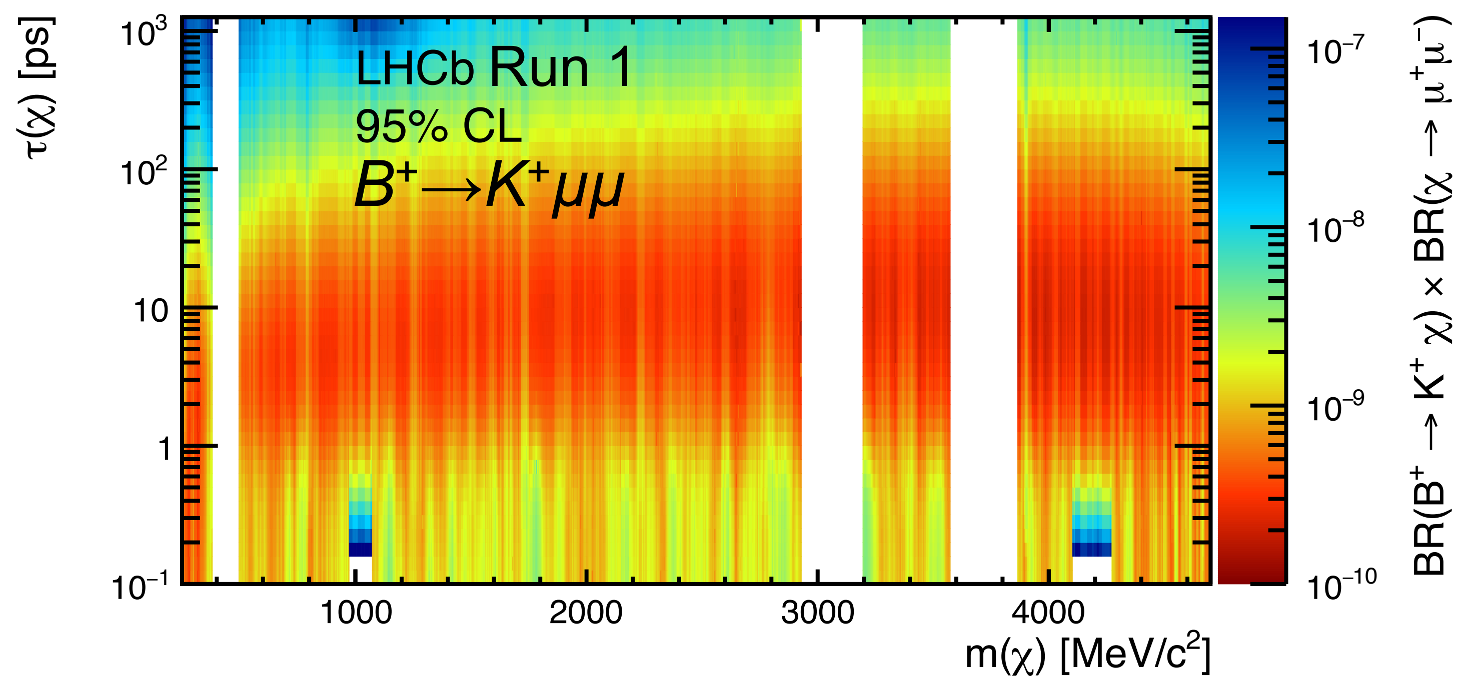
Hidden Sector in $B \to K^{(*)} \chi(\mu\mu)$

NEW

Phys Rev Lett 115 161802 (2015)

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

- BR normalised to *rare* SM decay
- Constraint set on lifetimes **[0.1-1000] ps (30μm to 30cm)**

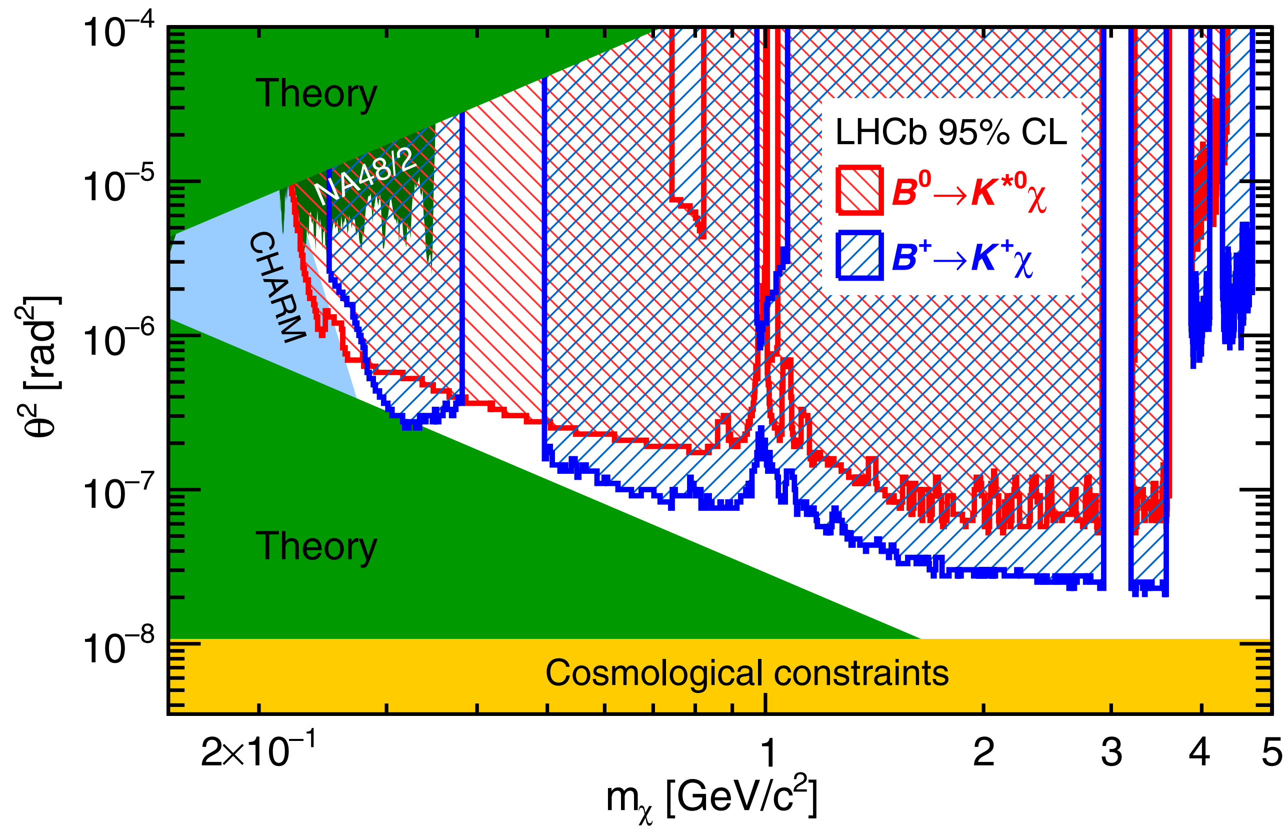


- Constrain on new scalar mixing with the Higgs

$$|\chi\rangle_{\text{phys}} = \cos\theta|\chi\rangle + \sin\theta|\text{Higgs}\rangle$$

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

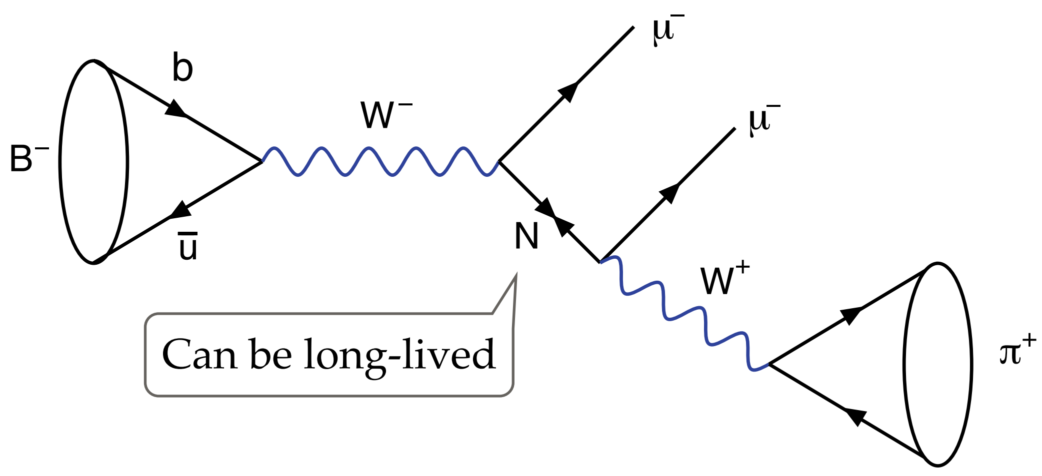
- Nearly rule out the inflaton parameter space below $2\,m_\tau$



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

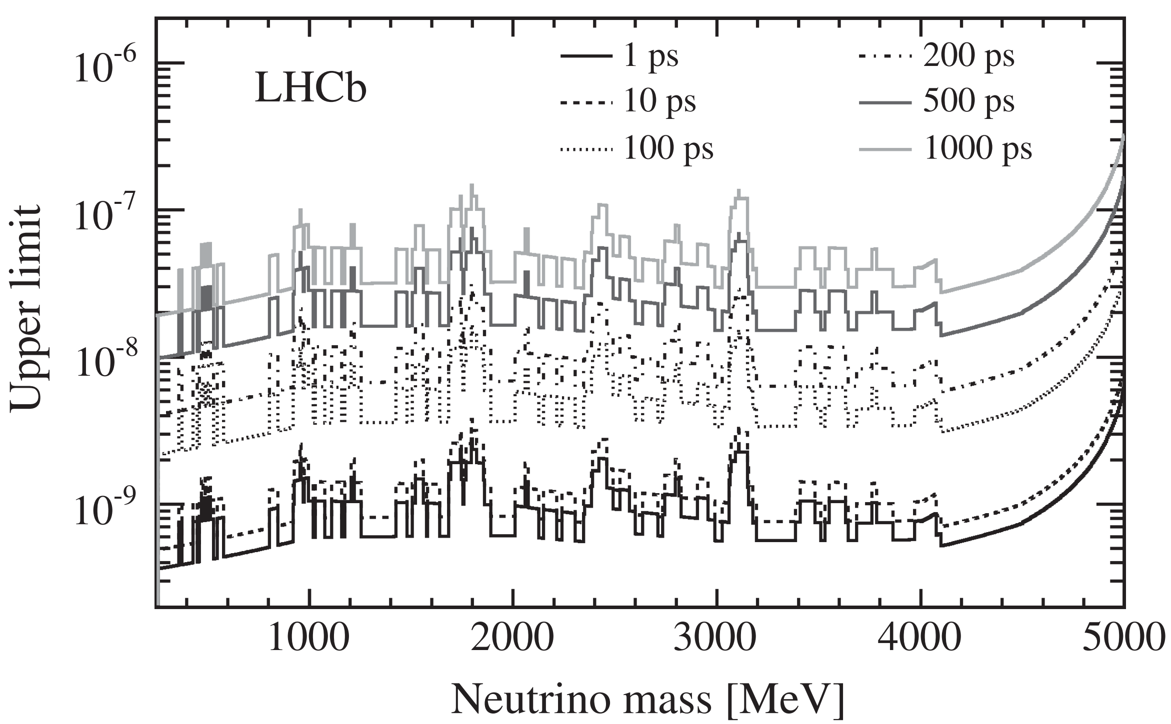
Phys Rev Lett 112 131802 (2014)

- 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 $\mu^-\mu^-$



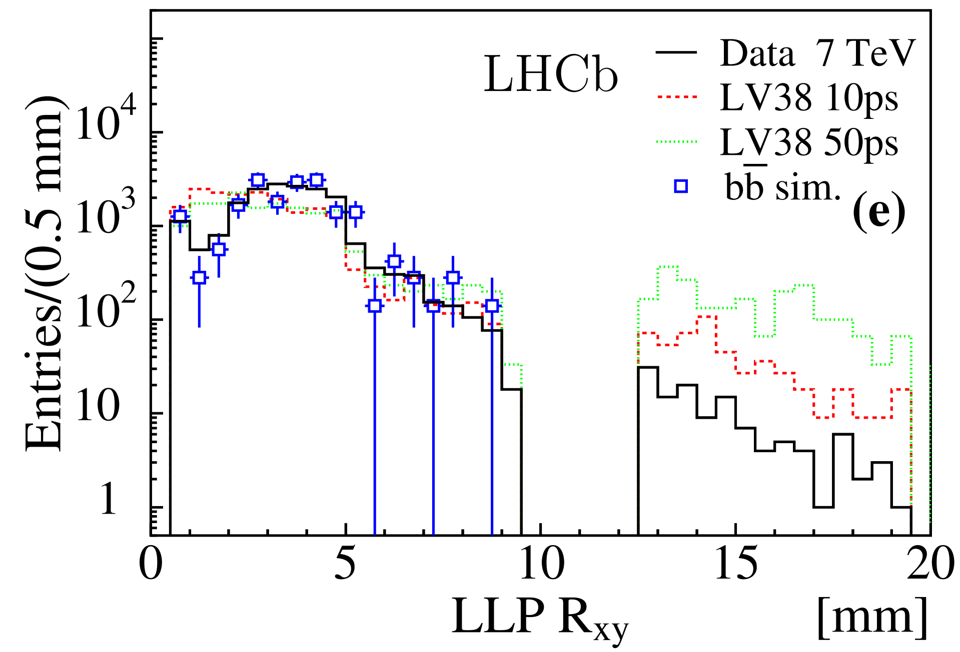
Produced in pp collisions

NEW

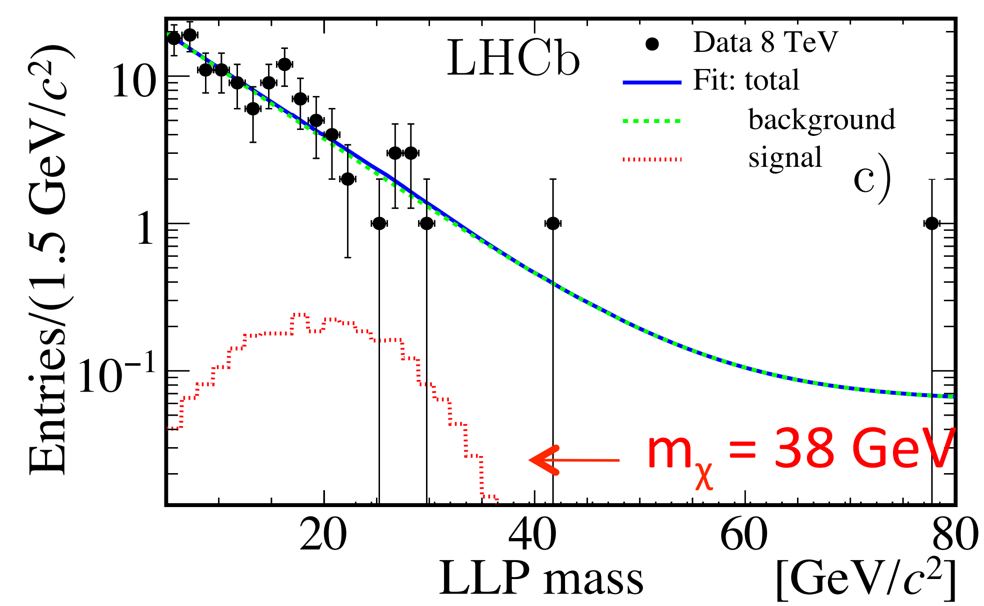
LLP → μ+jets

[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



- Using 3 /fb at 7 and 8 TeV
- LLP m=[20-80] GeV/c^2, τ=[5-100] ps
- Triggering on muon + displaced vertex
- Background dominated by bb
  - tight selection + MVA classifier
- Number of candidates from fit to LLP mass



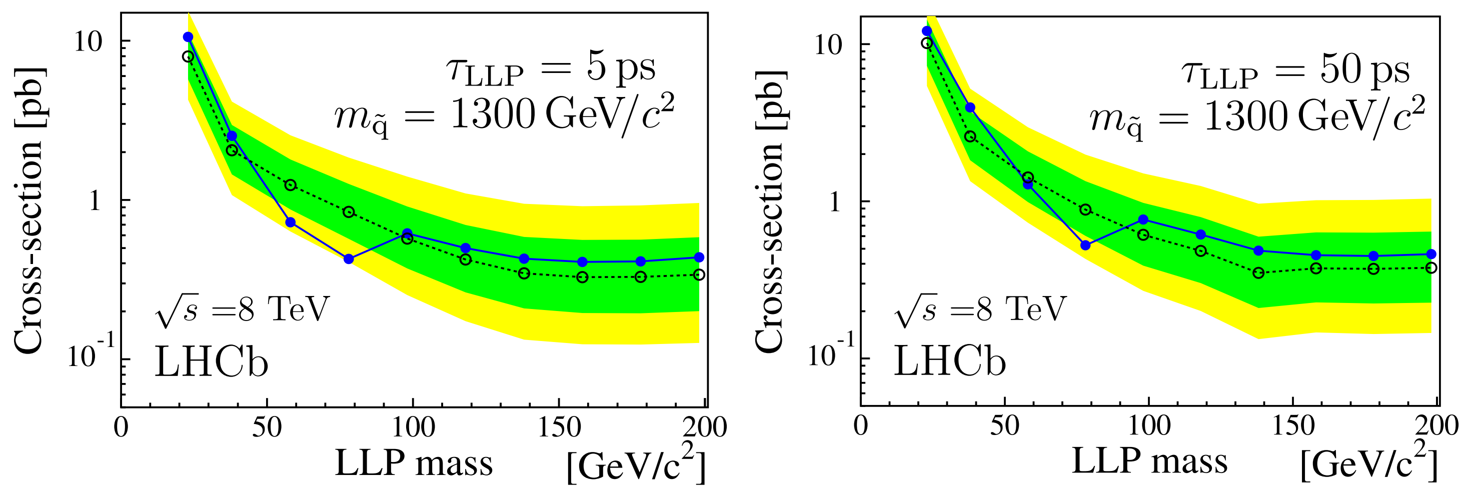
LLP → μ+jets

NEW

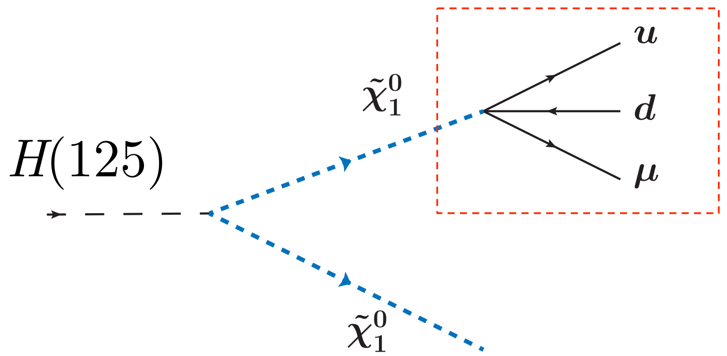
Eur. Phys. J. C (2017) 77:224

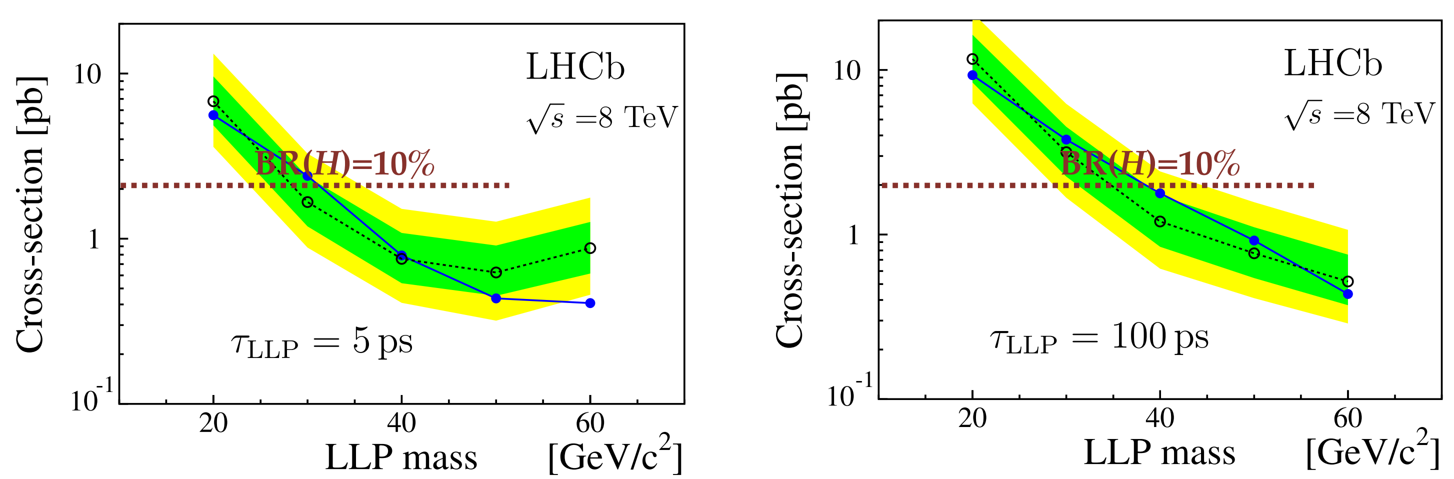
Result interpreted in various models:

- RPV mSUGRA from Pythia 6
  M_1= [40-200] GeV → m_χ = [38-198]
  M_2= 2 TeV, m_g= 2 TeV, m_q= 1.3 TeV
  τ_{LLP} = [5, 100] ps



- Simplified topologies:
  - Example: 125 GeV Higgs decay

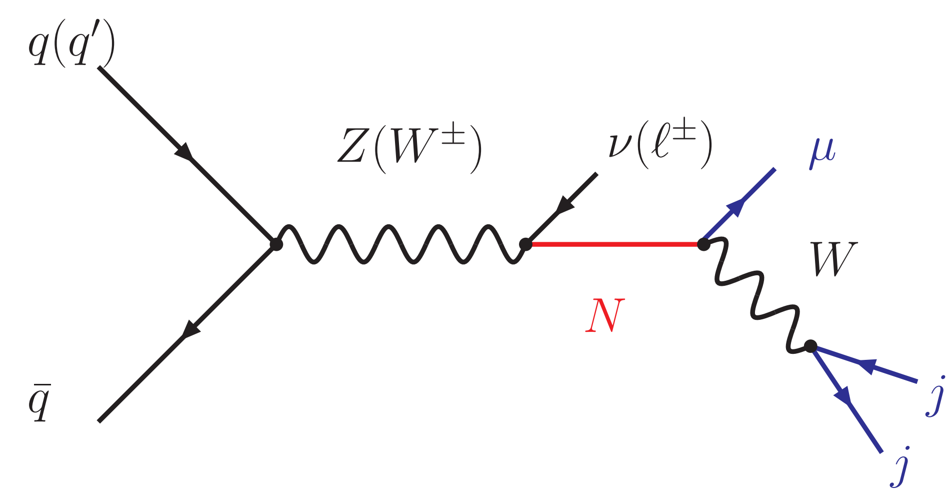


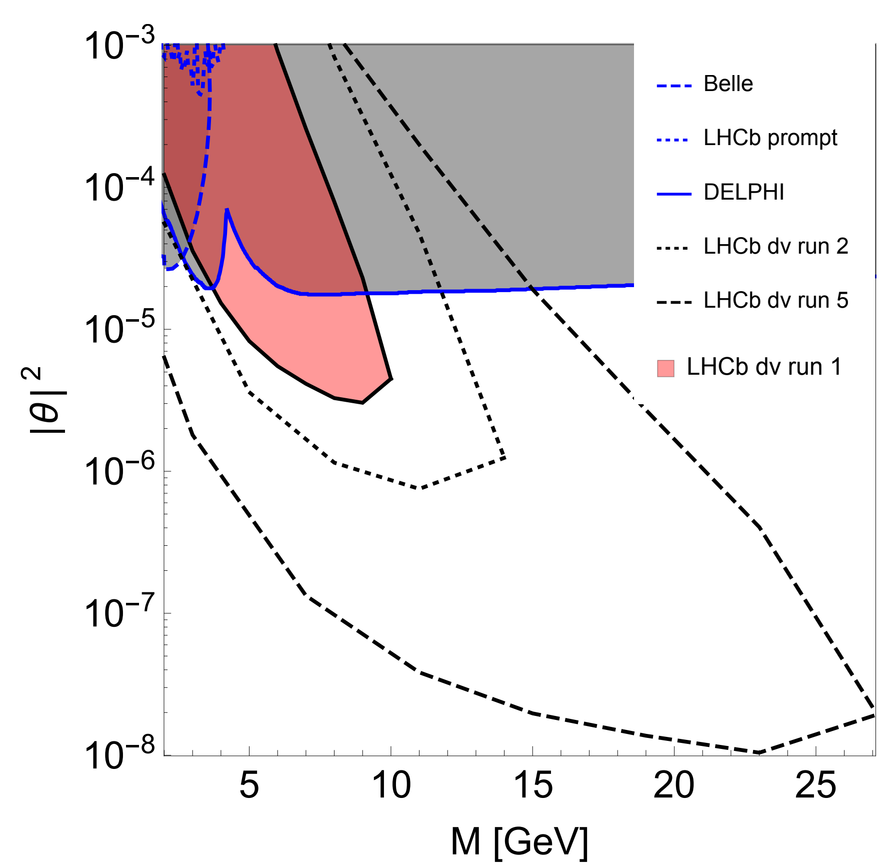


Rejecting BR(H→$\chi\chi$) > 10% down to m_χ= 30 GeV, τ_χ= 5 ps

LLP → μ+jets

- Re-interpreting in terms of Sterile Neutrinos
- Recasting search with simplified implementation of the analysis
- Limit is promising, but has to be taken with a pinch of salt
- Future searches:
  - can add prompt lepton for triggering
  - can look into e and τ as well





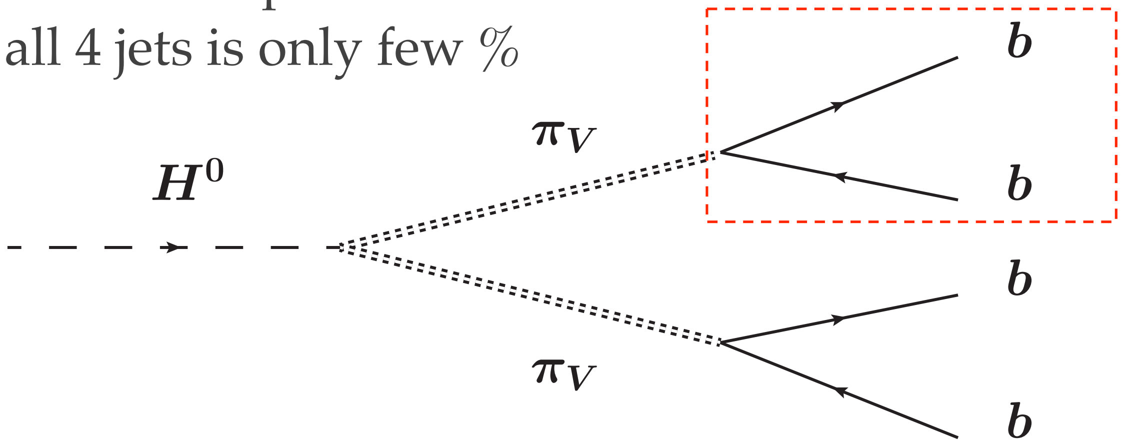
LLP → jet jet

NEW

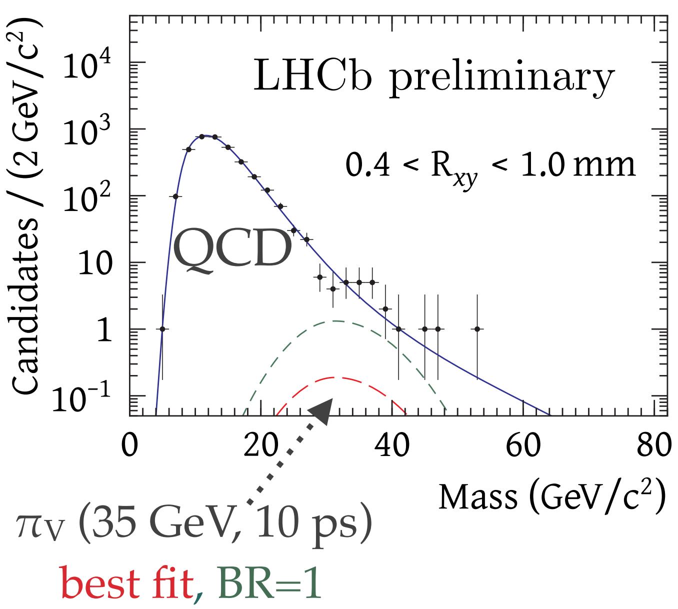
LHCb-PAPER-2016-065
very soon in ArXiv

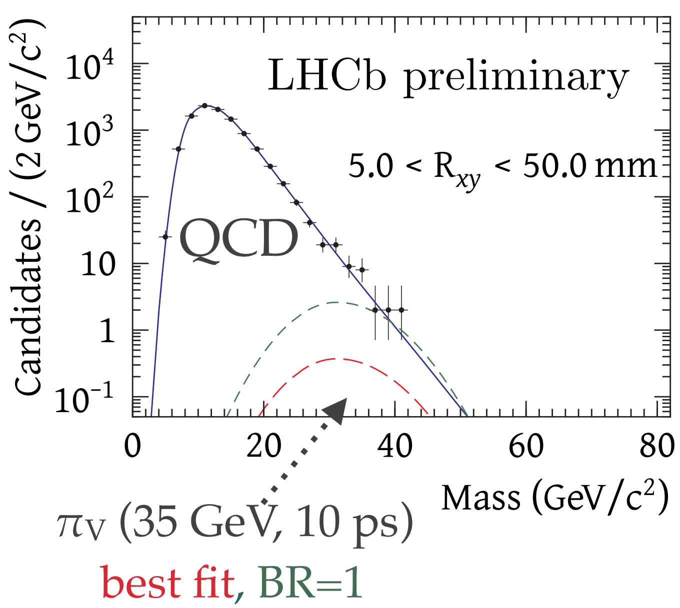
- **Signature**: single displaced vertex with two (*b*-) jets
- **Model**: hidden-valley pions from SM Higgs decay

LHCb acceptance for all 4 jets is only few %



- Using 2 /fb of 7 and 8 TeV *pp* data
- Triggering on displaced vertex
- Quality requirement on jets, di-jet pointing, material veto
- Signal from di-jet mass fit in bins of beam-axis displacement R_{xy}





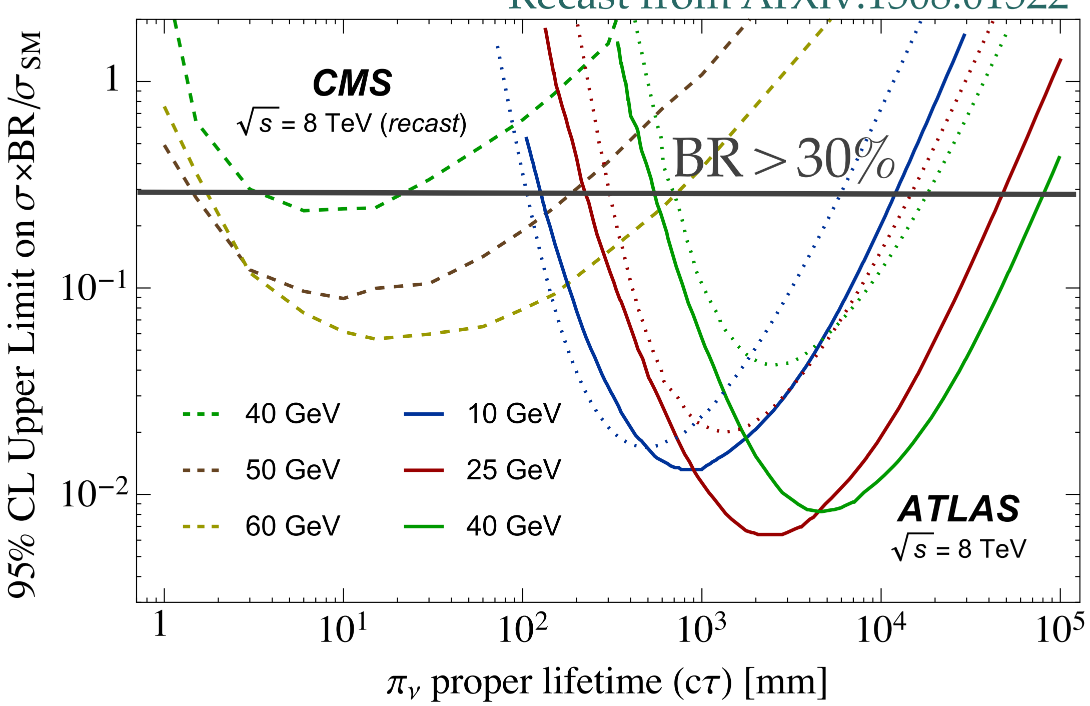
LLP → jet jet

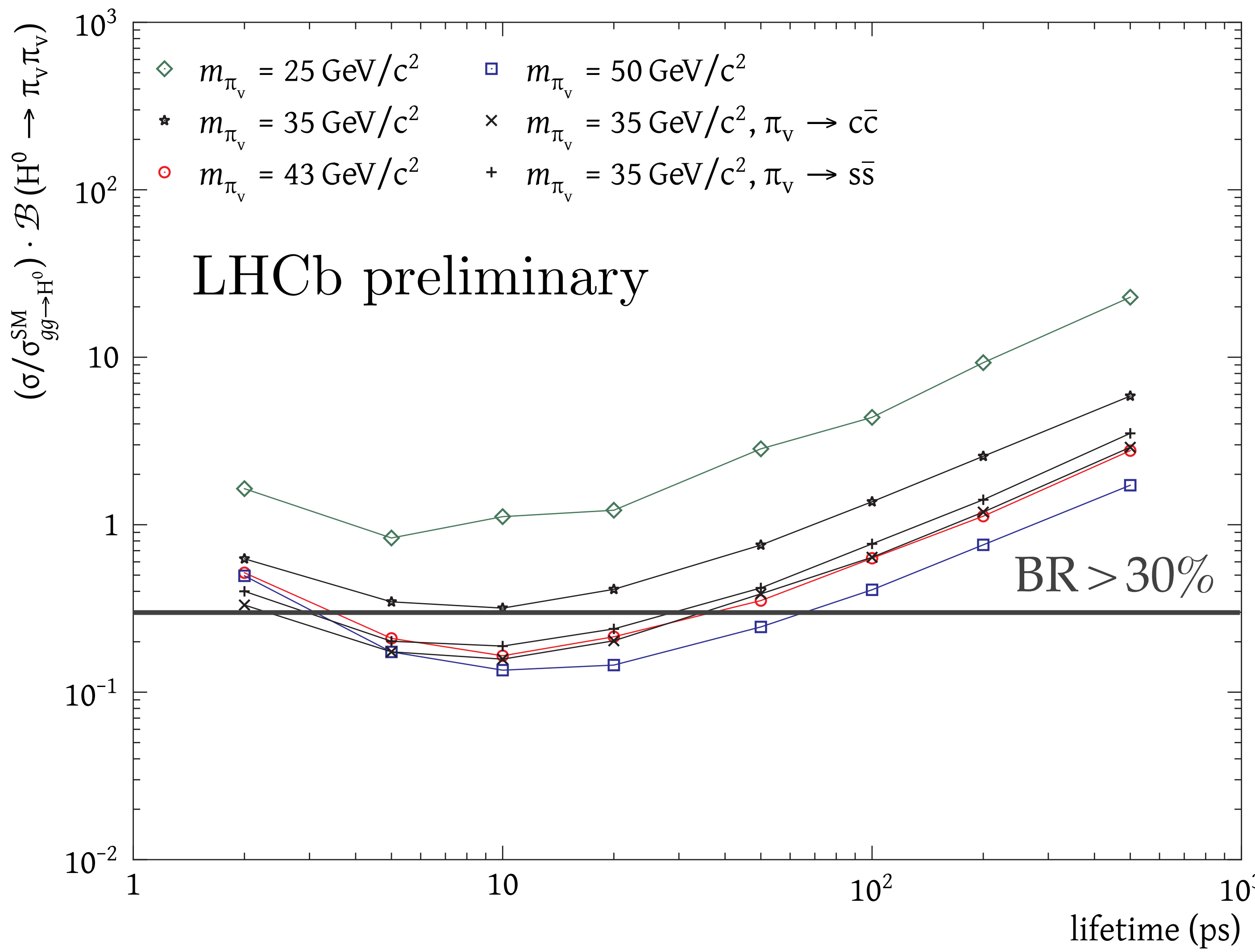
NEW

LHCb-PAPER-2016-065
very soon in ArXiv

- Tested the region: m_π=[25-50] GeV, τ=[2-500] ps
- Example: for $m_\pi = 50\,\text{GeV}$ exclude BR > 30% for τ=[5-50] ps (cτ = [1.5-15] mm)
- **Contributing at low lifetime and low mass despite lower luminosity and acceptance!**

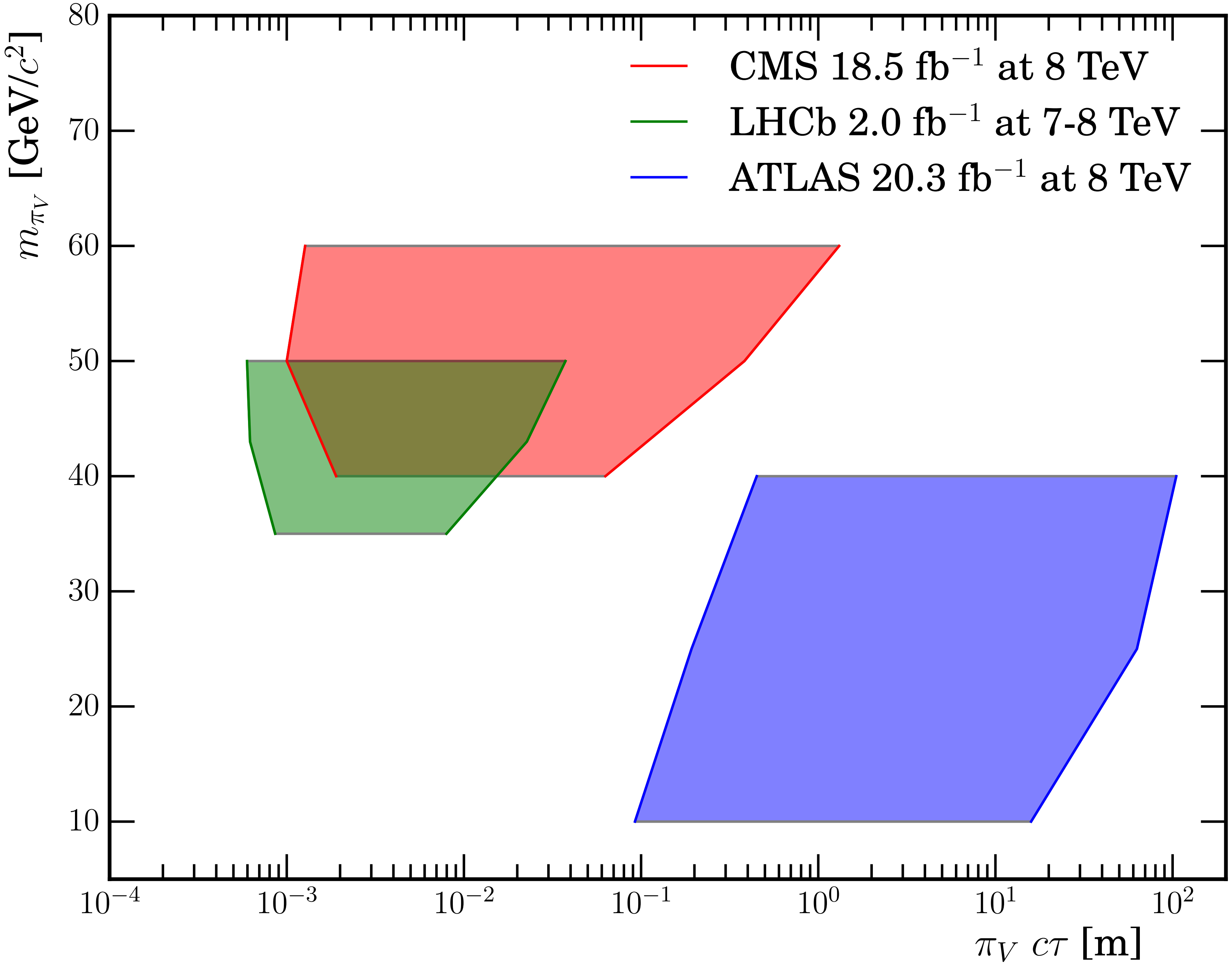
Recast from ArXiv:1508.01522





LLP to jetjet searches

Areas where $H \rightarrow \pi_V \pi_V$ BR is smaller than 50% (at 95% CL)



LLP at upgraded LHCb

- Removing L0 !!
  - Can trigger directly on displaced vertices (or even more complex signatures)
  - Also jets are in the trigger
  - No p_T requirements —> low masses
- Upgraded Vertex Locator
  - much faster —> vertices in the trigger
  - more precise —> less ghost tracks
  - thinner box —> less material interaction
- Will concentrate efforts in low mass, low lifetimes

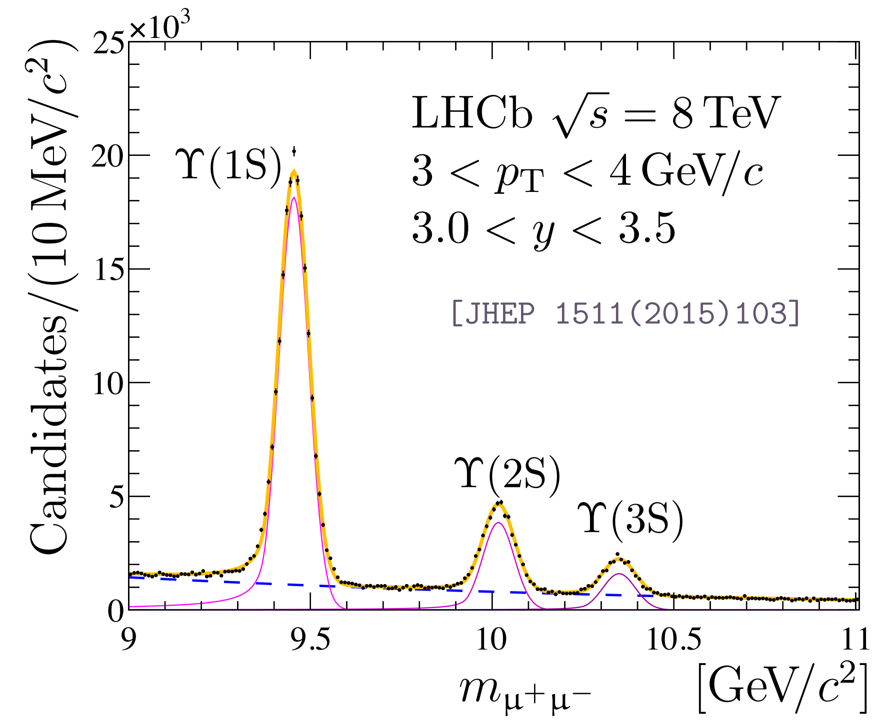
Low mass di-lepton program

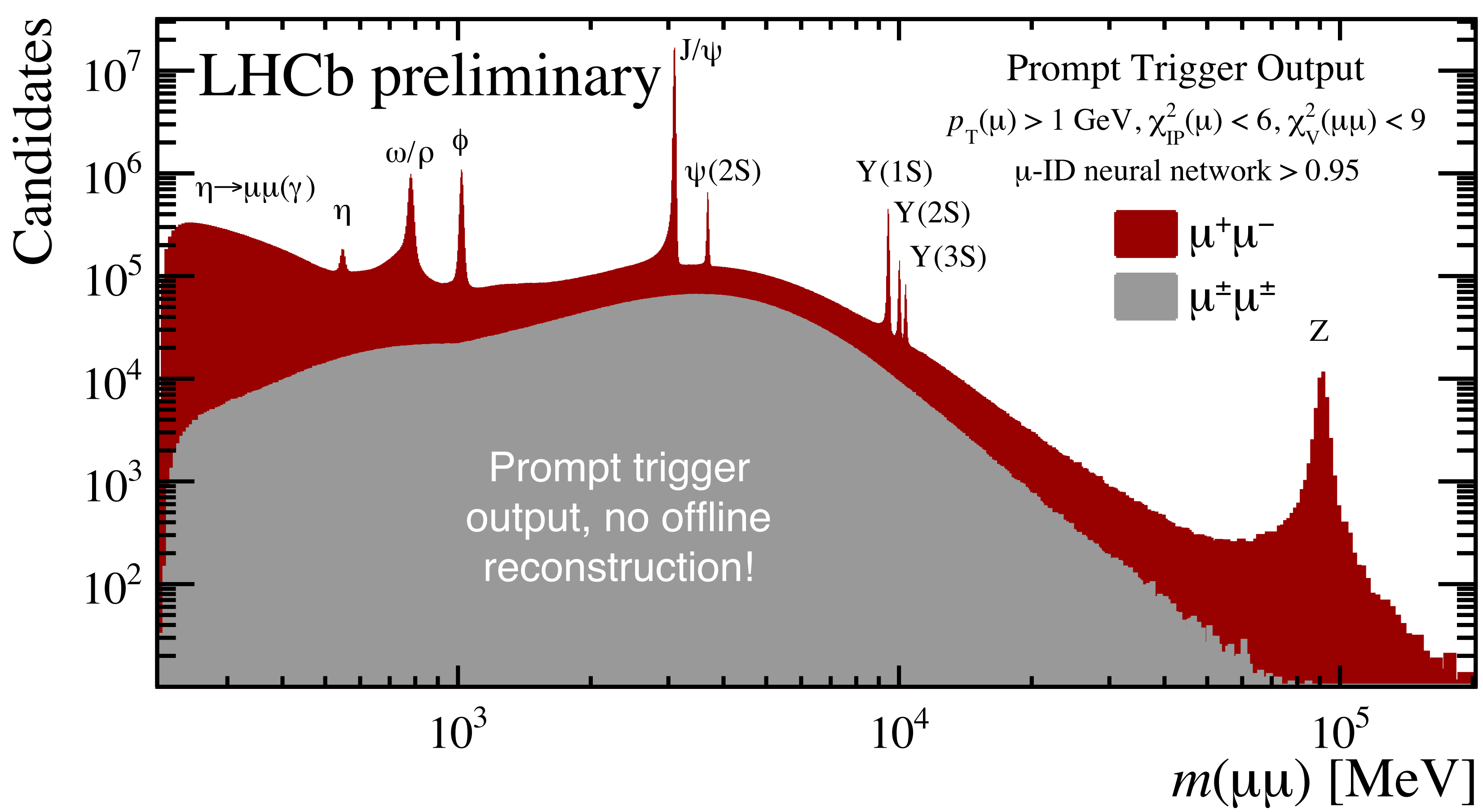
- Excellent mass resolution
  - is key when background is irreducible
- Soft triggers on μ p_T (even softer after upgrade)

Ilten, Soreq, Thaler, Williams, Xue [1603.08926]

- New $\mu\mu$ trigger with online μ-ID
  - Online calibration of μ-ID —> soften p_T cut
  - Only interesting part of the event to disk (turbo)

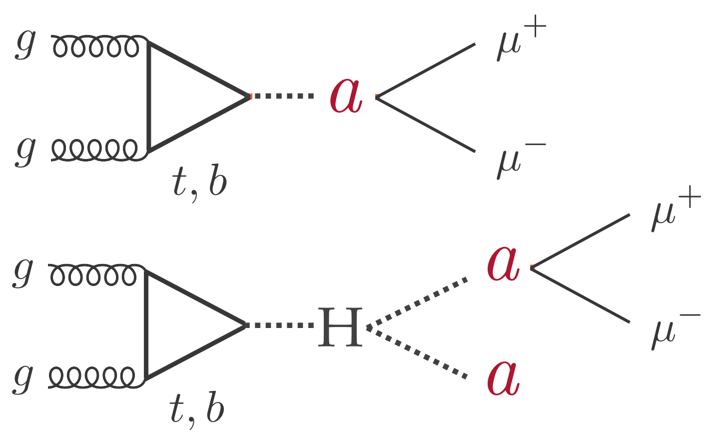
  → **no pre-scale down to threshold 2 m_μ**

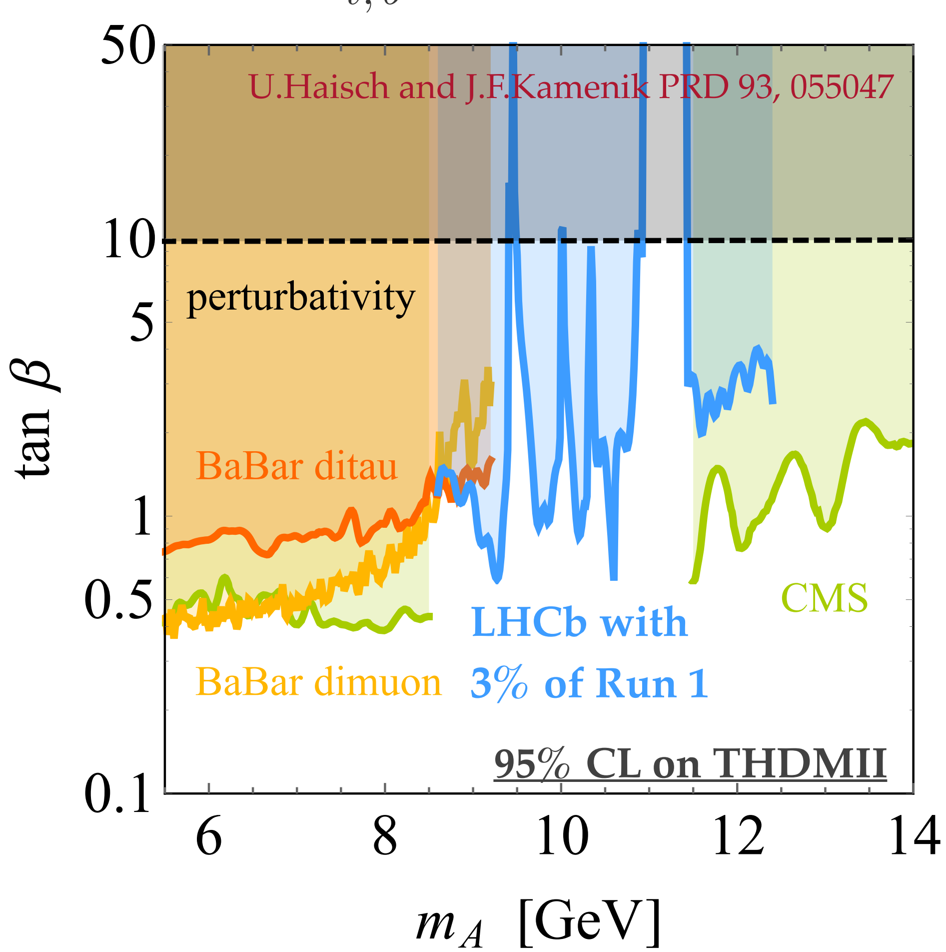




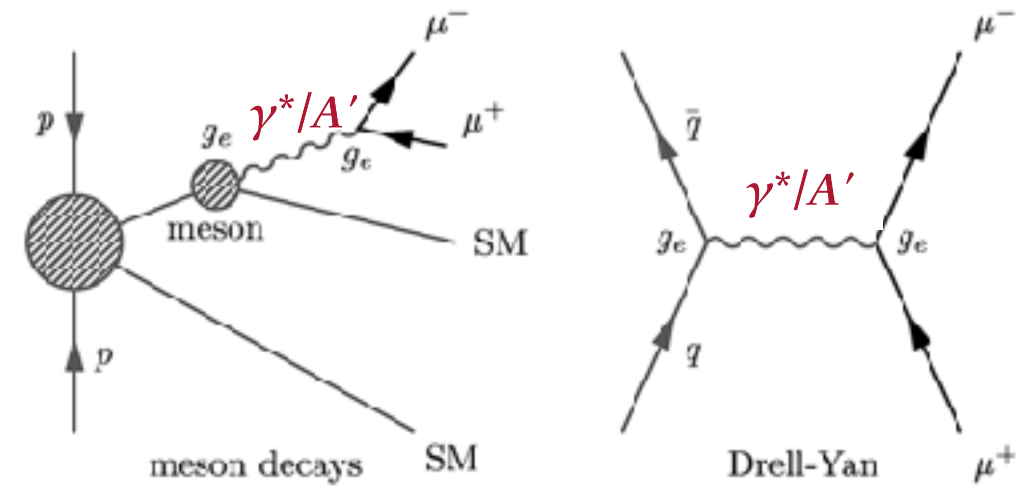
Low mass di-lepton program

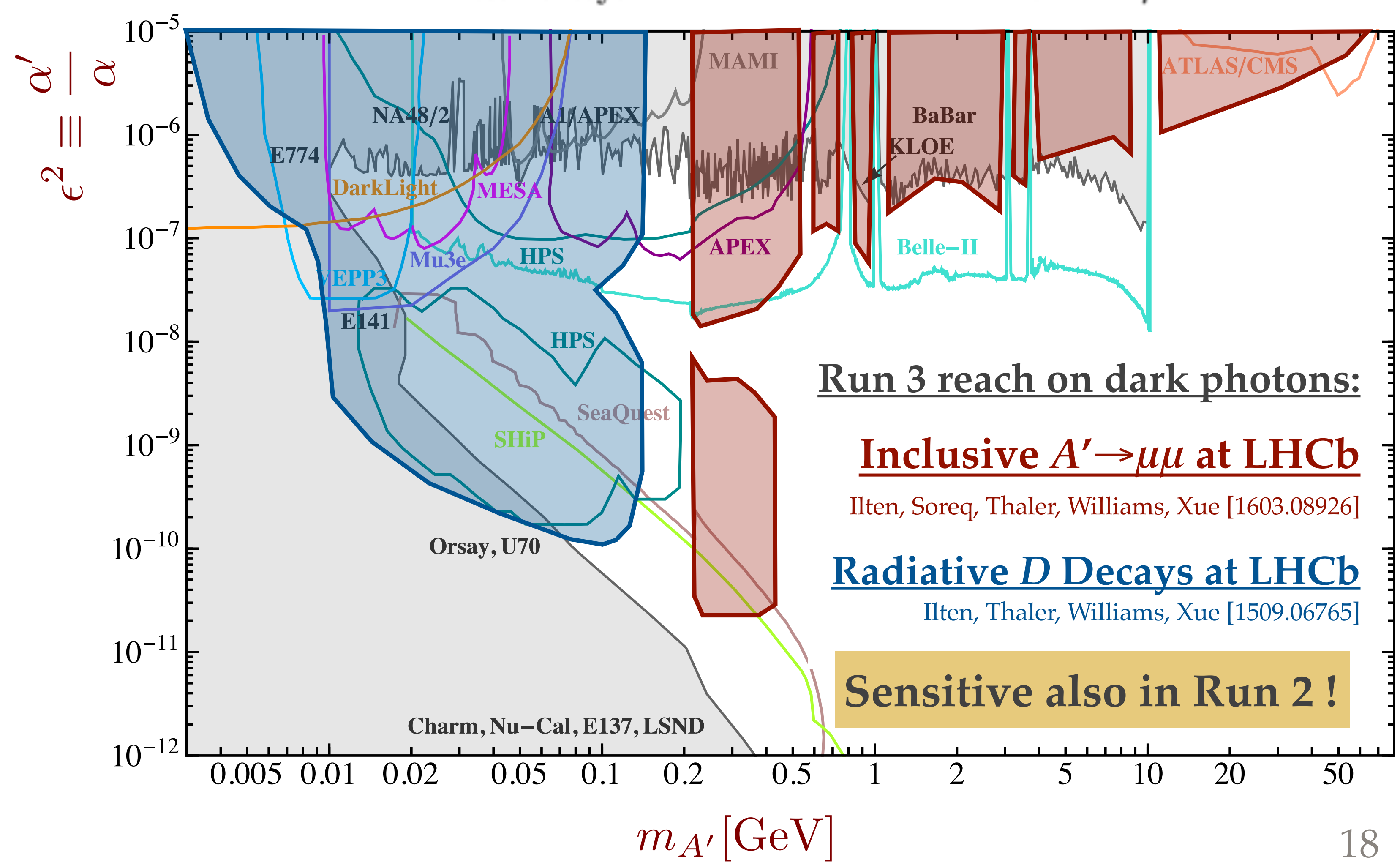
Low-mass CP-odd Higgs (a)



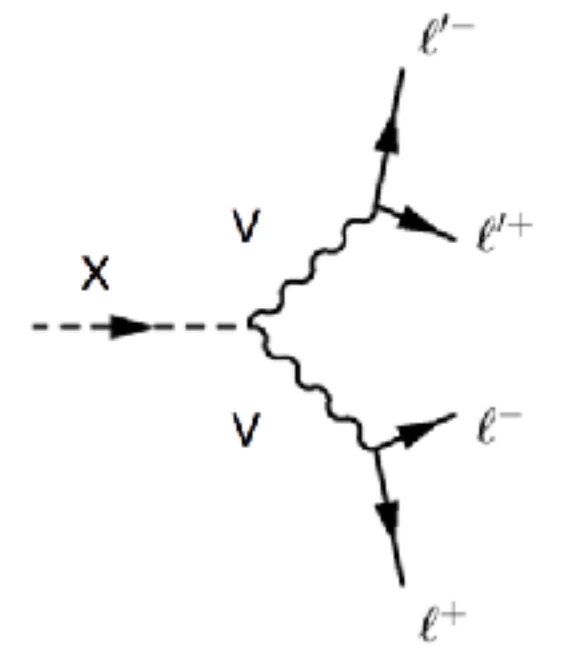


Dark Photon A' (auto-normalising to γ^*)

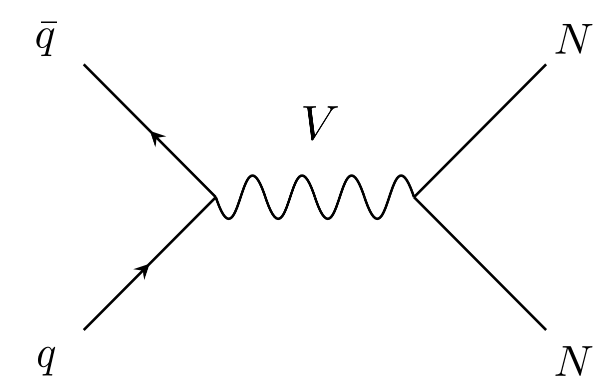


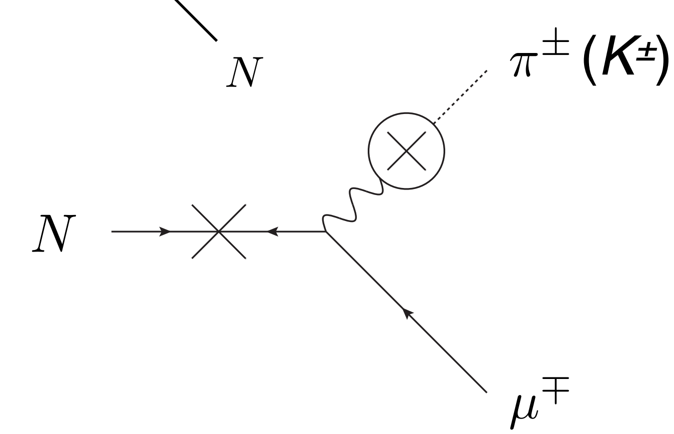


Other low-p_T leptons



- Four muons (low mass)
  - 2016 HLT line with $p_T > 0.5$ GeV
  - Much lower background





- Pair of right-handed neutrinos (low mass) Batell, Pospelov, Shuve [1604.06099]
  - 2 displaced $h\mu$ vertices

Conclusions

- Limited acceptance, smaller luminosity, no MET
- LHCb demonstrated to be extremely good at:
  - **Looking for on-shell new physics from B/D decays**
  - **Looking for long-lived particles with low mass and short lifetime**
- Big potential in low mass di-leptons: light Higgs, dark photons, …
- Bright future ahead:
  - 3/fb in Run 1, expect 5/fb in Run 2 (low pile-up)
  - A lot of potential in "trigger-less" upgrade (also 5× luminosity!)

LHC era → HL-LHC era →

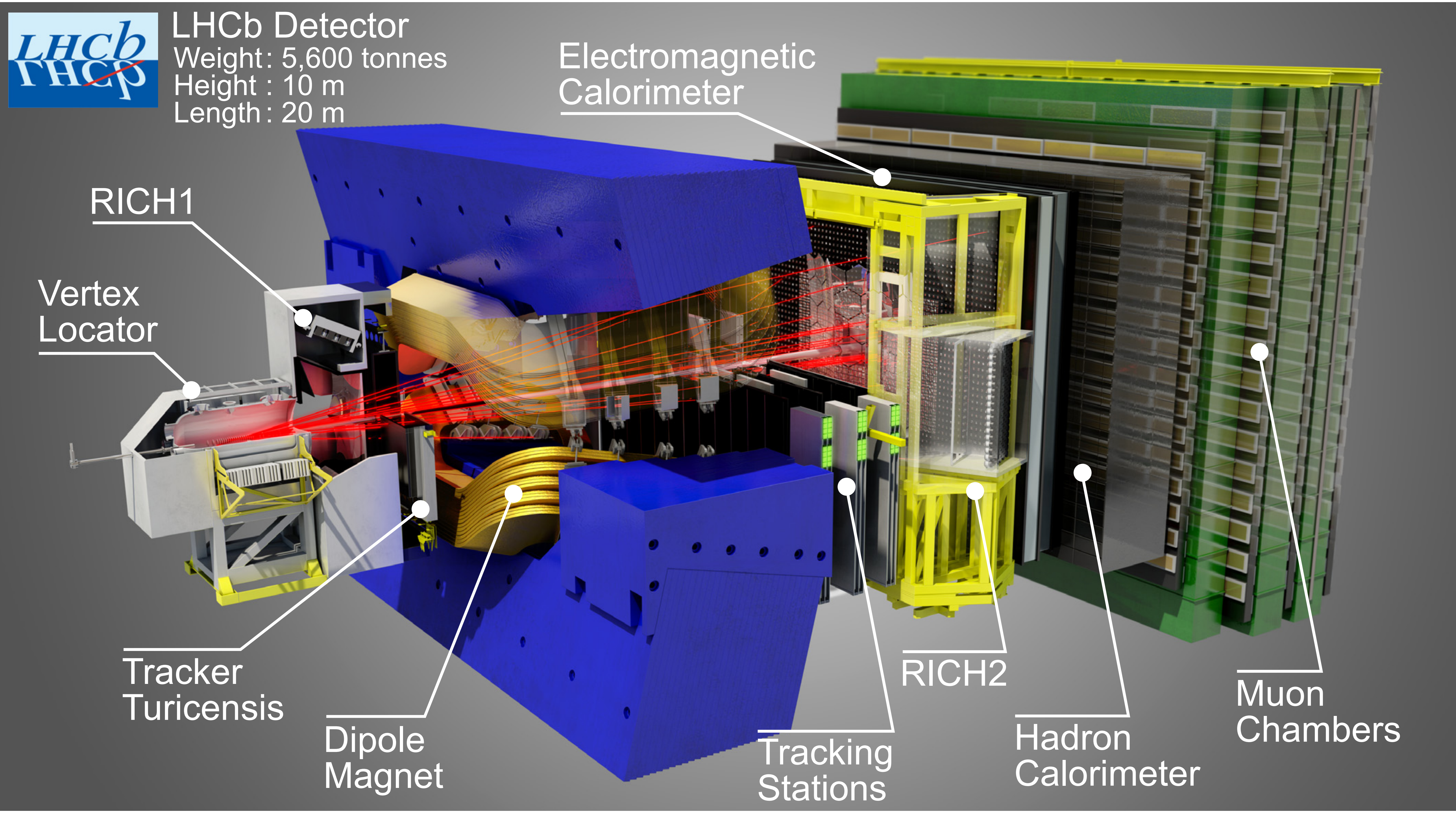
Run (years)	Run 1 (2010-2012)	Run 2 (2015-2018)	Run 3 (2021-2023)	Run 4 (2027-2029)
Integrated luminosity	3 fb^{-1}	8 fb^{-1}	25 fb^{-1}	50 fb^{-1}
Instantaneous luminosity	4×10^{32} $cm^{-2}s^{-1}$		2×10^{33} $cm^{-2}s^{-1}$	

Current LHCb → Upgraded LHCb →

BACKUP

The LHCb detector

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

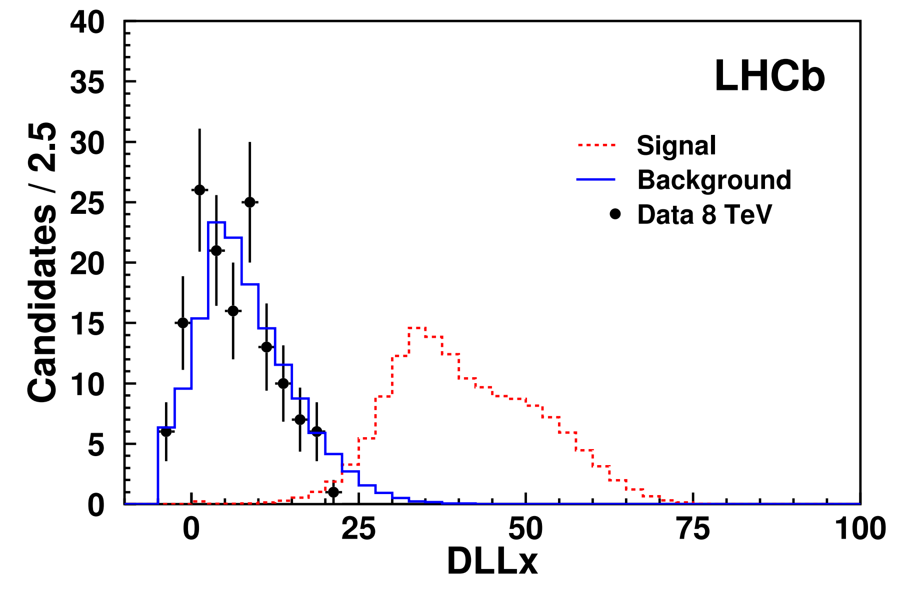


Charged Massive Stable Particles

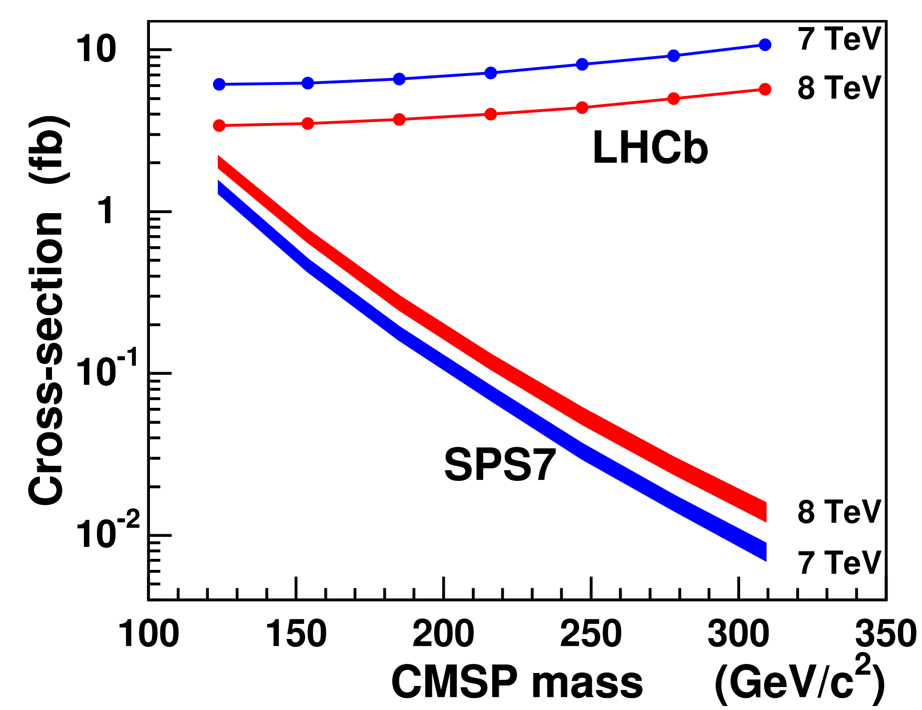
EPJC 75 (2015) 595

- 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



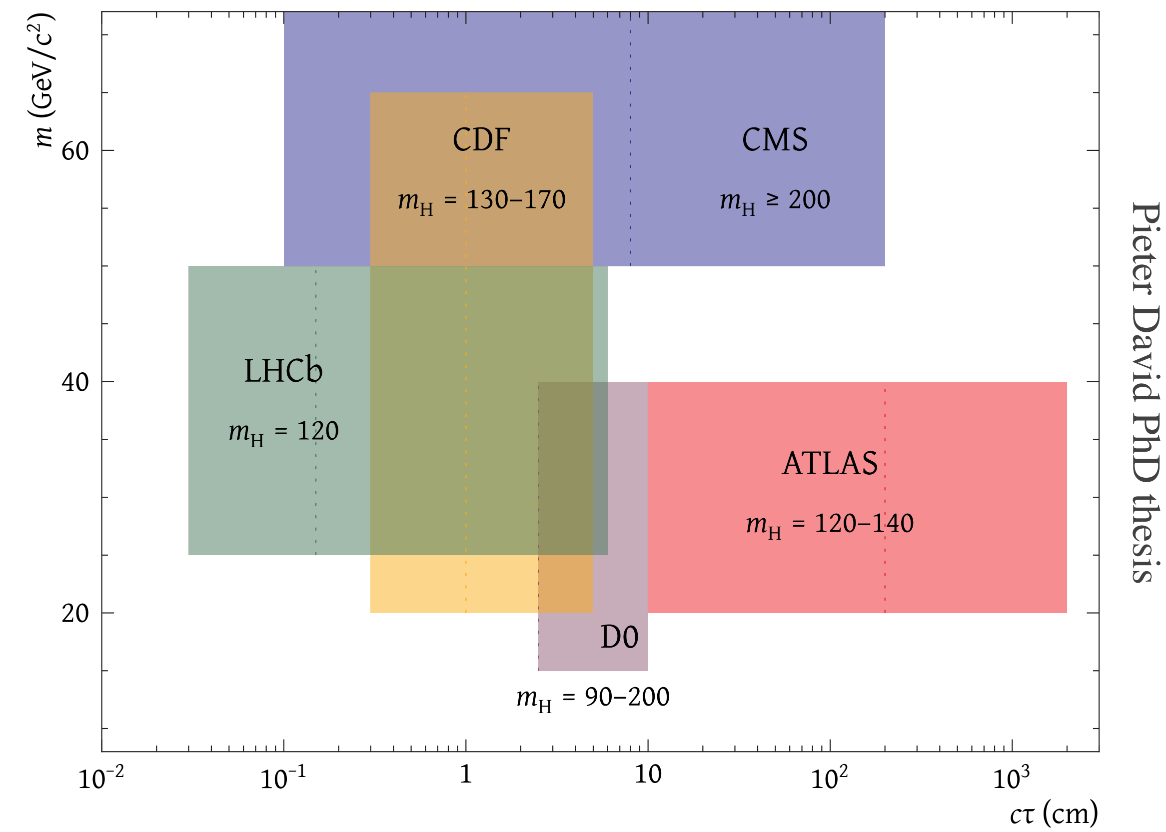
- Limit is not competitive with D0 (low mass) and ATLAS (high mass)
- Proof of concept for future searches!
- Possibly move to
  - single CMSP signature (3 times eff)
  - and/or to lower masses (??)

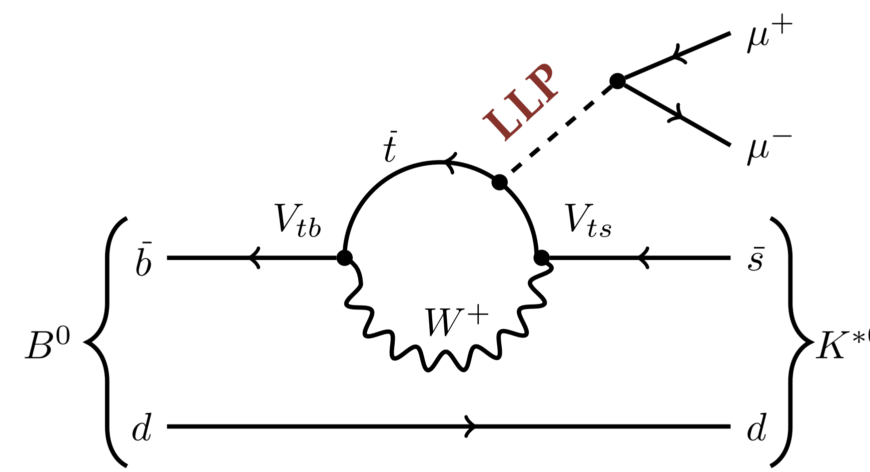


Long-Lived Particles at LHCb

- **Coverage complementary** to ATLAS and CMS:
  - Shorter lifetimes (down to ~1 ps)
  - Lighter masses (down to ~25 GeV for di-jets)
- **Bonus for LHCb**:
  - can look for LLP from (rare) decays of heavy-flavour
  - can use the RICH to identify charged massive stable particles

Regions with (subset of) published limits for the LLP→di-jet analysis





FCNC penguin b→s transition

Charged Massive Stable Particles

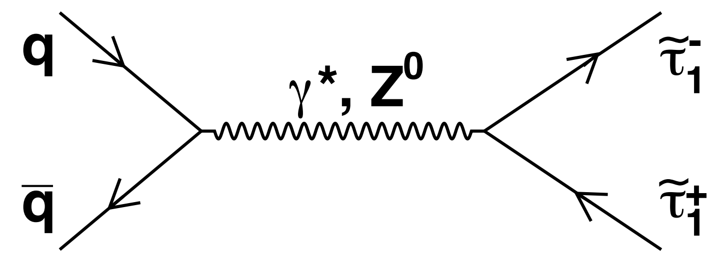
EPJC 75 (2015) 595

- 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

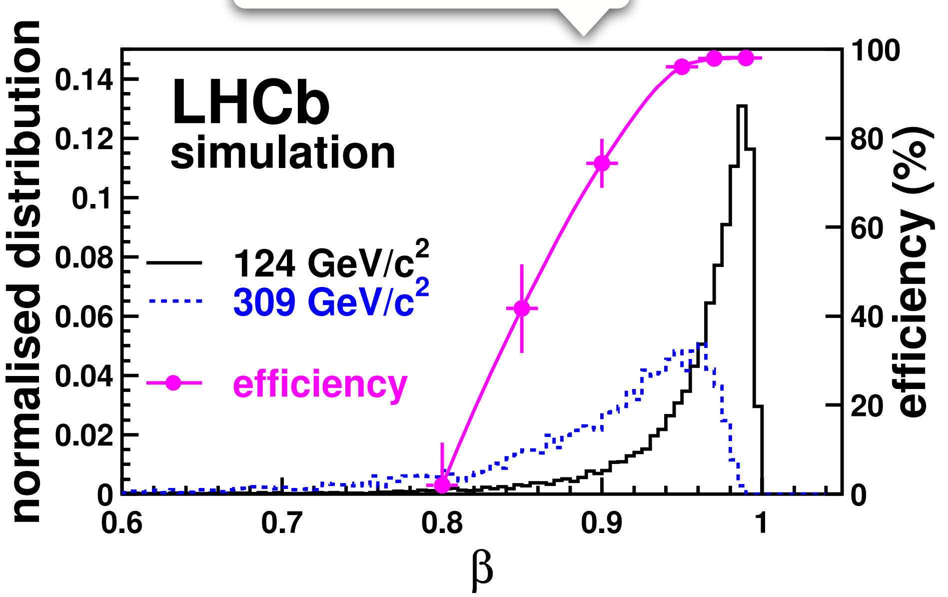
S Dimopoulos et al [NPB488(1997)39]
GF Giudice and R Rattazzi [Phys.Rep. 332(2011)419]

- 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

Drell-Yan produced stau pairs



β as low as 0.8

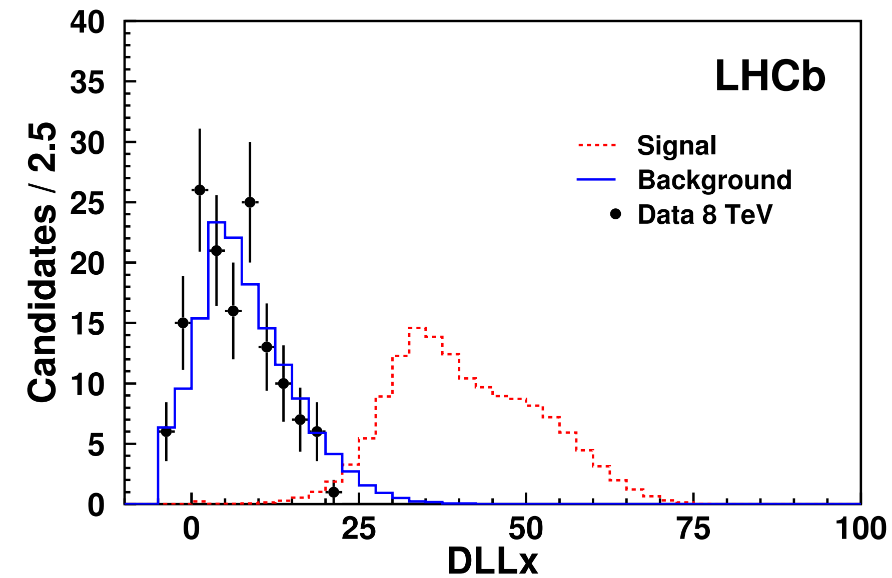


Charged Massive Stable Particles

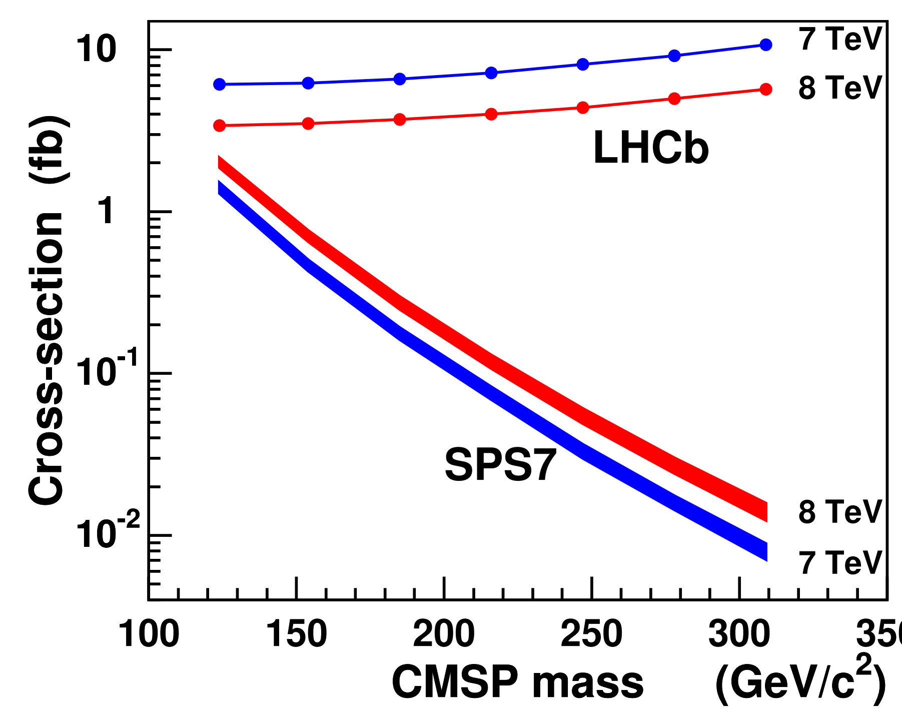
EPJC 75 (2015) 595

- 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



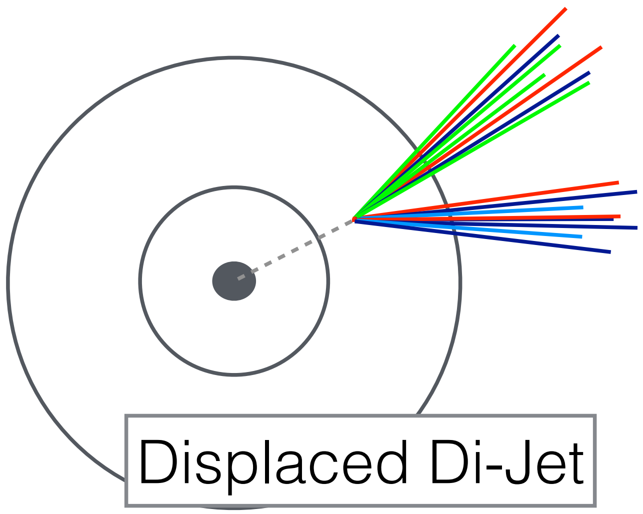
- Limit is not competitive with D0 (low mass) and ATLAS (high mass)
- Proof of concept for future searches!
- Possibly move to single CMSP signature and/or to lower masses

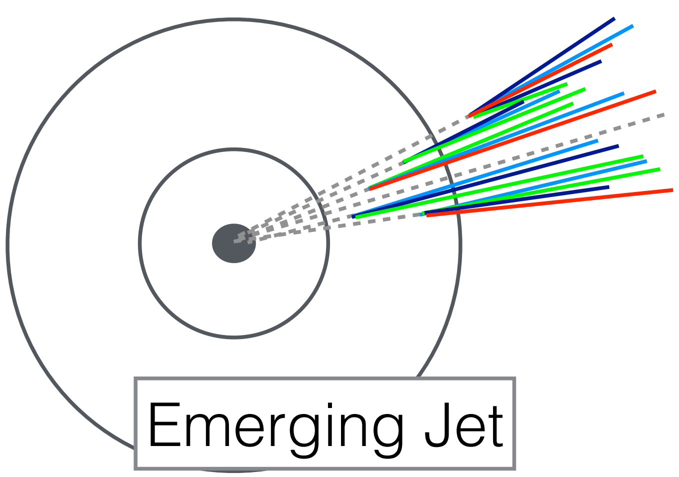


Future: Emerging Jets

- "Emerging jets":
  - Jets with many displaced vertices are smoking gun for dark parton 'shower' (models with composite dark sector)

Schwaller, Stolarski, Weiler, [arXiv:1502.05409]





- LHCb has potential
  - precise jet vertexing
  - sensitive to low mediator mass