Long Lived Particles in LHCb Upgrade II

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on behalf of the LHCb collaboration

HL/HE LHC Meeting

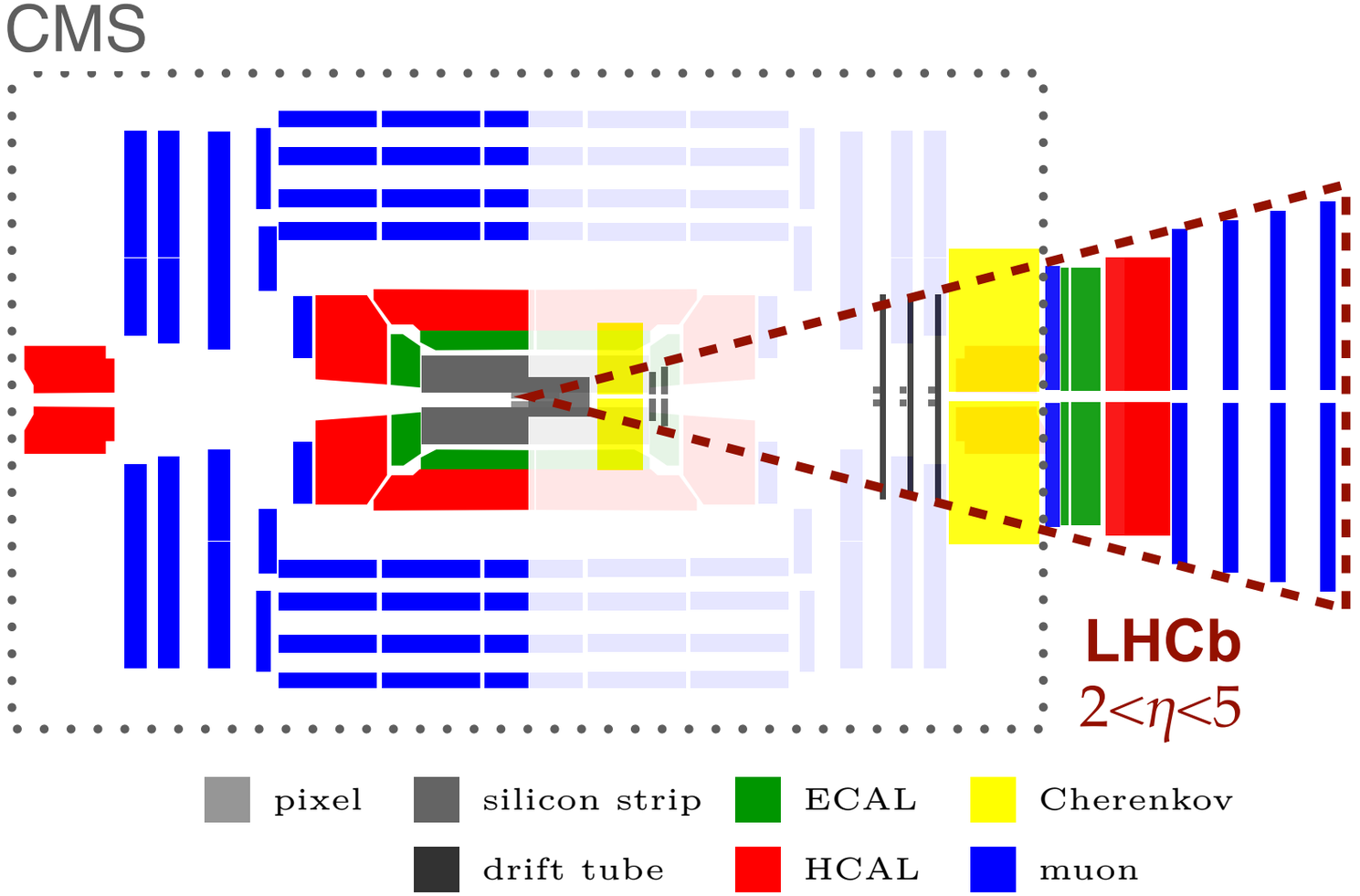
Fermilab 04-06/04/2018

LLPs at LHCb

Int.J.Mod.Phys. A 30,1530022 (2015)
JINST 10 (2015) P06013

- unique acceptance: $2 < \eta < 5$
- low pile-up (~1-2 visible interaction)
- excellent vertex resolution (σ_T~45 fs for B_s^0)
- excellent mass resolution (0.5% in μμ)

- good jet reconstruction
  - energy resolution ~10% for jets with $p_T > 10$ GeV
  - b(c) tagging efficiency ~65%(25%) for 0.3% light-parton contamination



LLPs at LHCb

- calibration + reconstruction in real time
- very soft triggers:

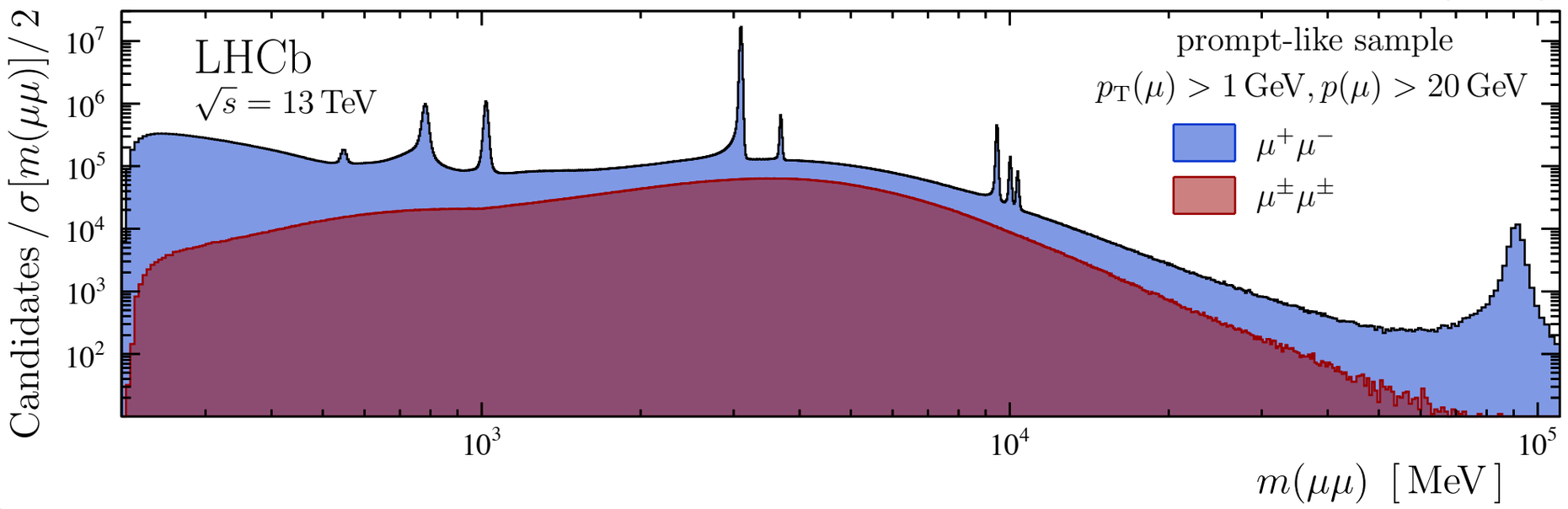
at **hardware** level (L0):
- muons with $p_T > 1.5$ GeV
- calo deposits with $E_T > 3$ GeV

at **software** level (HLT):
- topological triggers on detached vertices
- PID and jets in trigger
- excellent for light dimuons (prompt and detached)

see Mike's talk

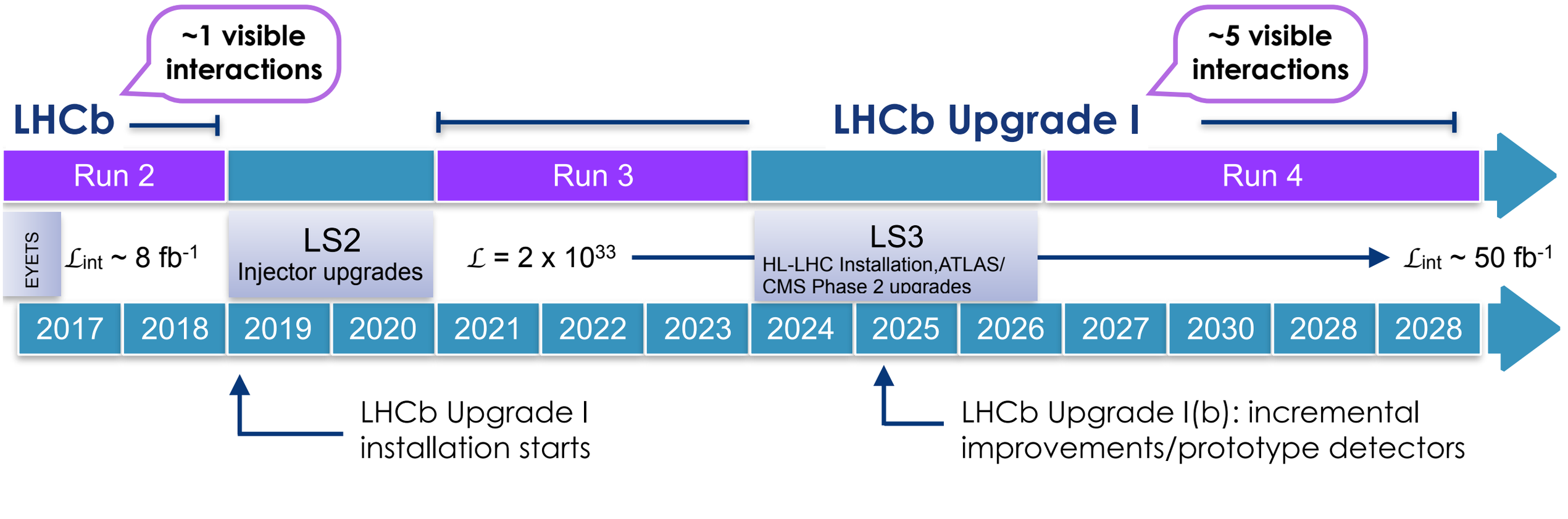
new μμ turbo trigger with online muon id requirement (no pre-scale)

Phys. Rev. Lett. 120, 061801 (2018)



Many searches for LLPs performed and ongoing!

LHCb Upgrades

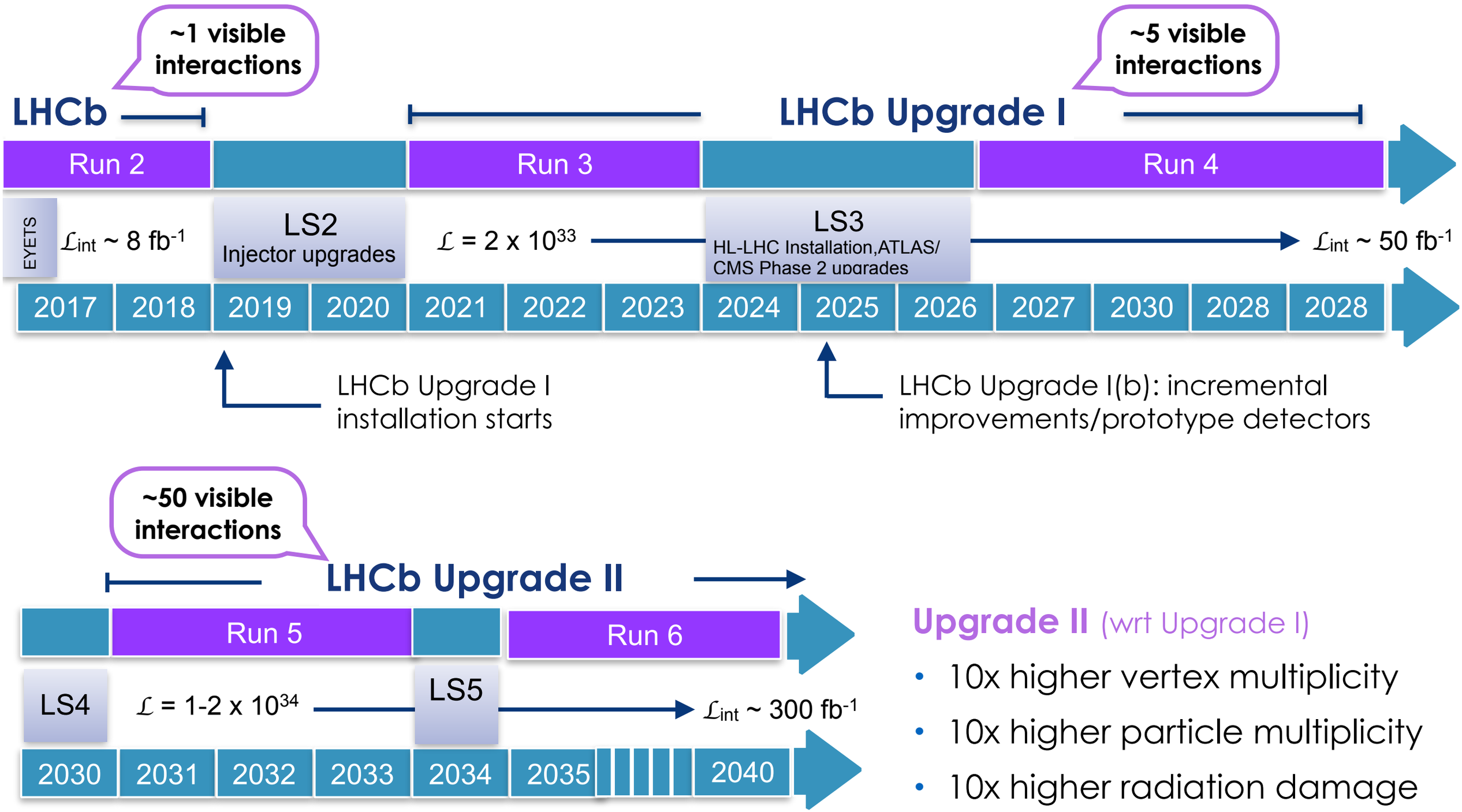


Upgrade I

- no hardware trigger, full software trigger with readout of the full event at 40 MHz
- improved vertex resolution
- momentum resolution of the tracking system ~10-20% better
- reduced ghost rate

➡ will extend LHCb reach for LLPs!

LHCb Upgrades



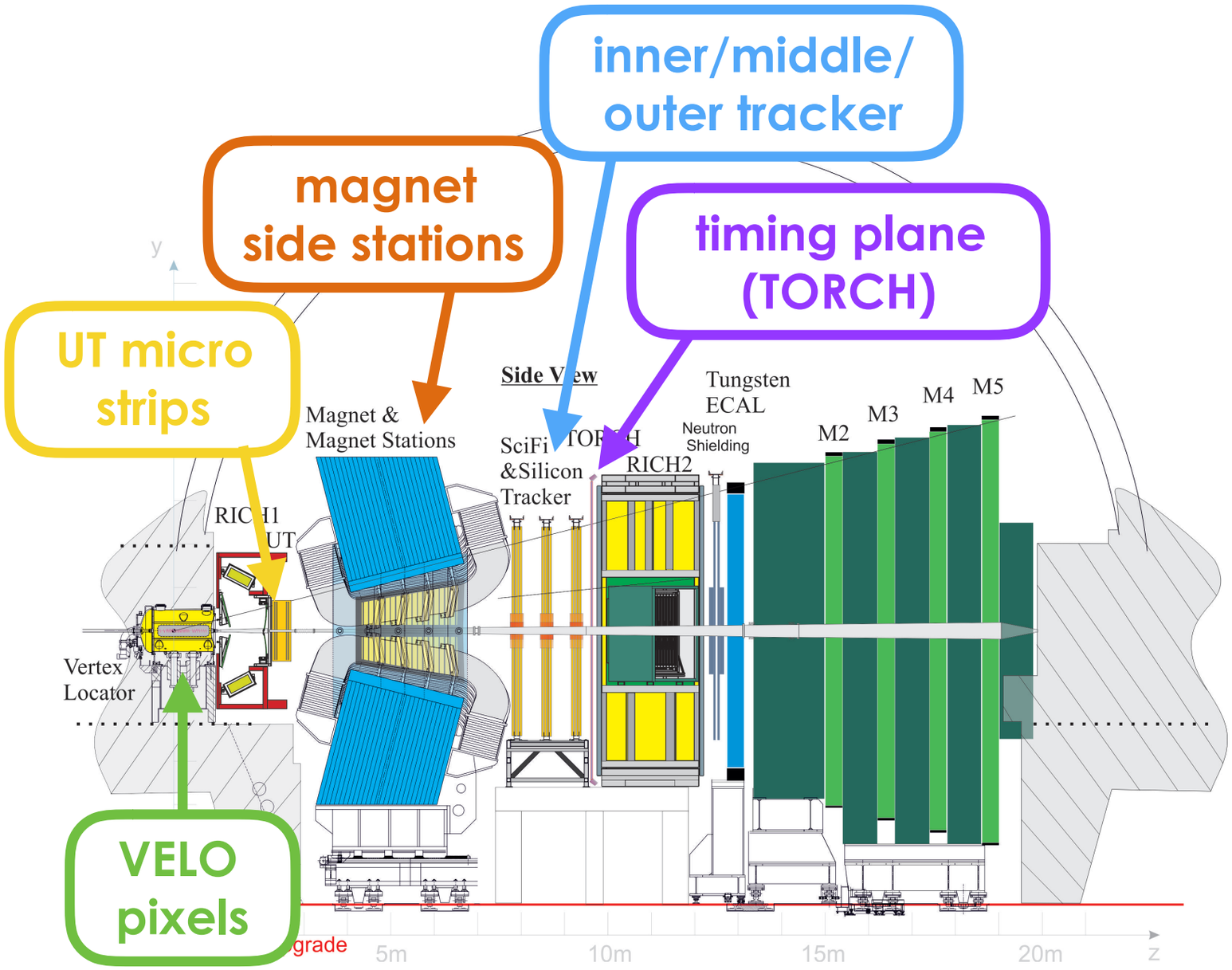
Upgrade II (wrt Upgrade I)

- 10x higher vertex multiplicity
- 10x higher particle multiplicity
- 10x higher radiation damage

Detector improvements for LLPs?

LHCb Upgrade II

CERN-LHCC-2017-003



How LHCb might look like…

- silicon and scintillating fibres based tracking detectors
- new sub-detectors (magnet stations, TORCH)
- high granularity ECAL with extended dynamic range
- HCAL removed

see Matt's talk tomorrow

Tracking system and trigger crucial for LLP searches!

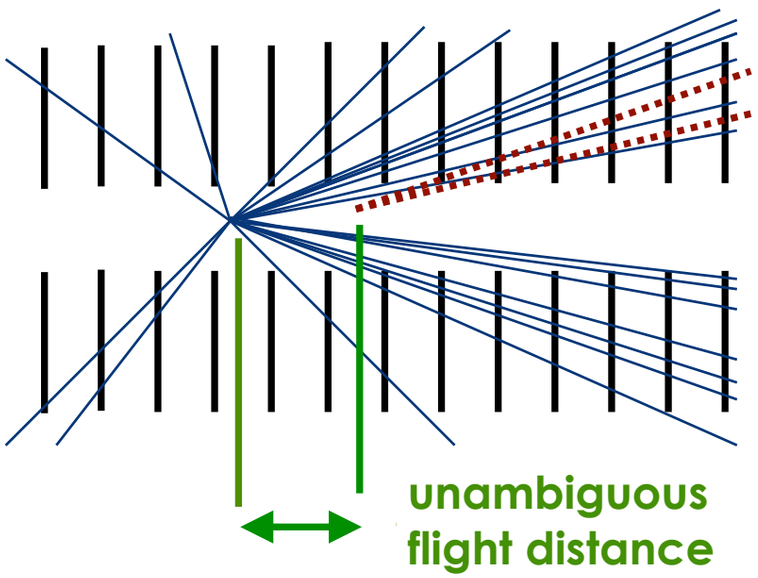
VELO

VELO plays a fundamental role in LLP searches:

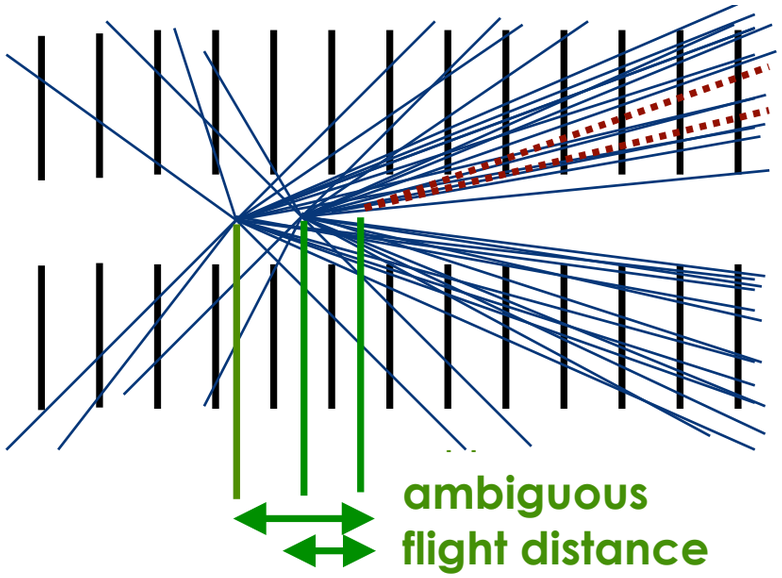
- reconstruction of primary and secondary vertices
- part of the tracking system
- decay length accessible by LHCb ~20 cm (decay in the VELO)

in upgrade II **pixel timing** becomes essential to reduce vertex mis-association in the high pile up environment!

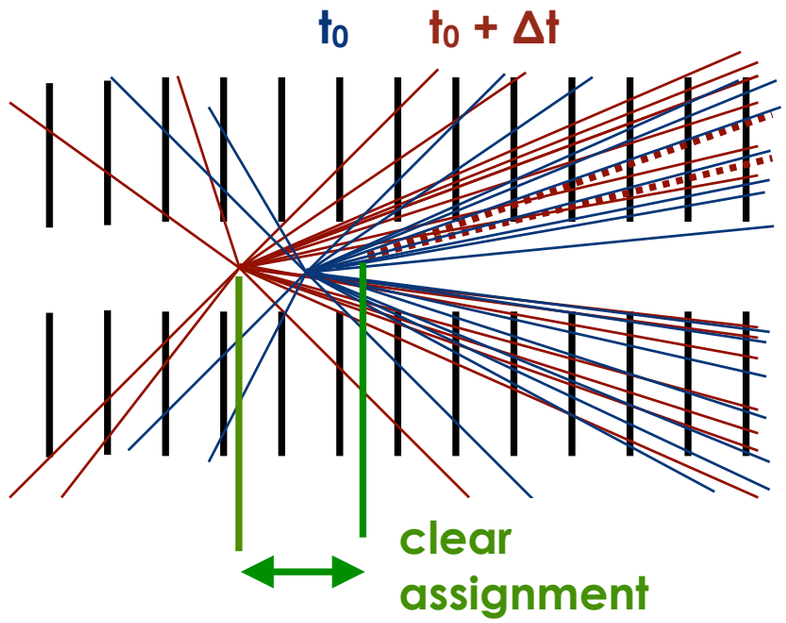
single PV



two PVs



two PVs + timing



VELO Material

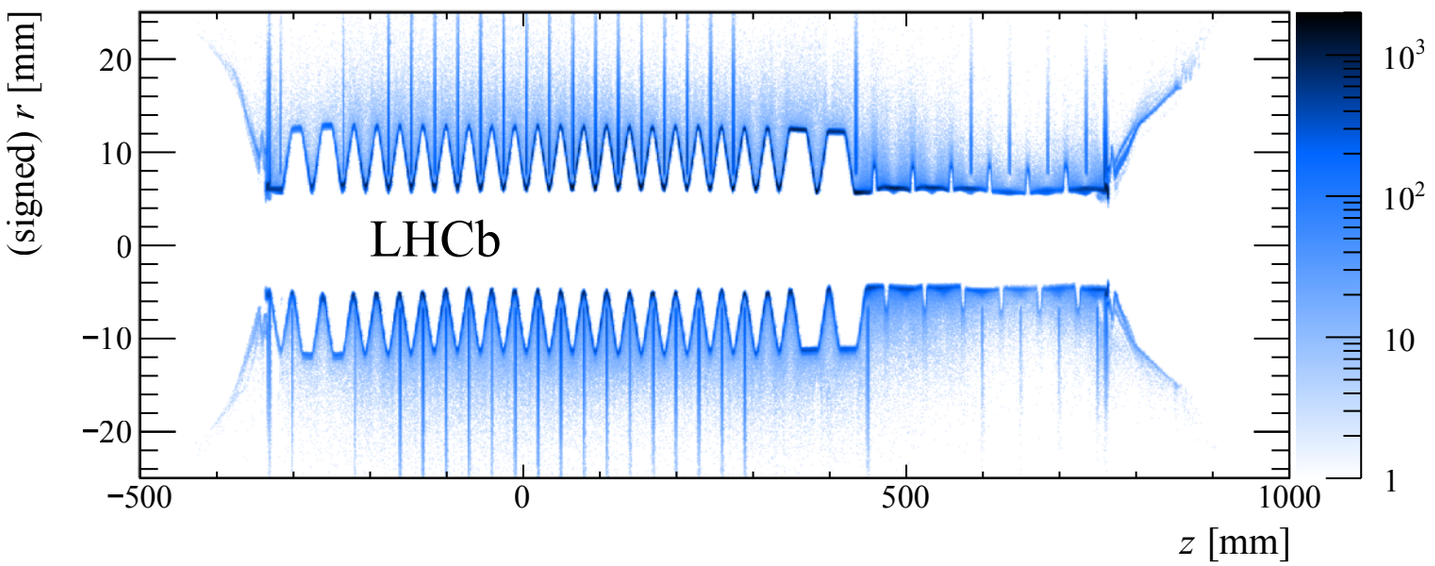
CERN-LHCb-DP-2018-002

RF box at ~5 mm from the beam:

- < 5 mm: background dominated by heavy flavour
- > 5 mm: background mainly from material interaction

- the removal of the RF foil is under study for upgrade II
- it would reduce the background and improve the IP resolution
- if not feasible it is crucial to veto the material interactions…

…a material map of the VELO is essential to reduce the background in LLP searches!



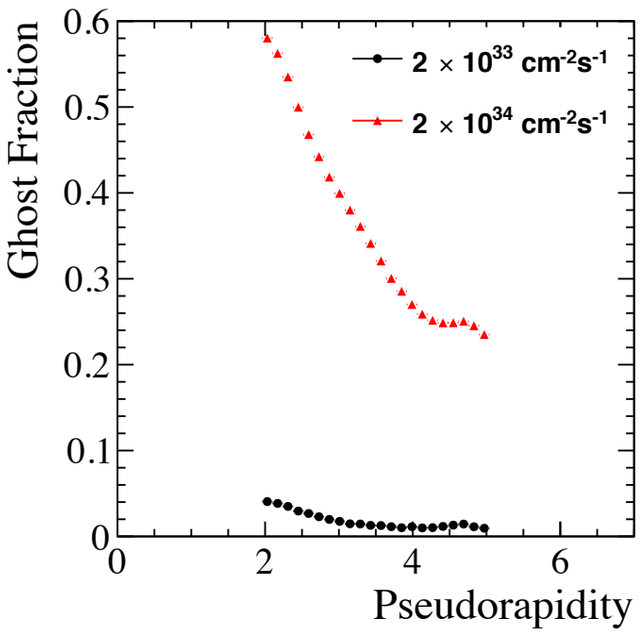
- beam-gas (helium) collisions
- material interaction along the full length of the VELO
- secondary interactions of hadrons used to map the material

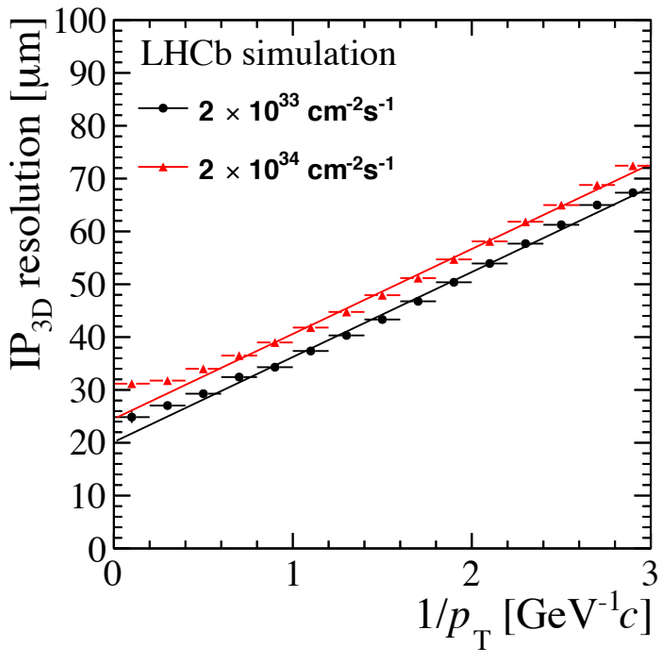
- analysis performed for Run1 and Run2
- method already applied successfully on a LLP analysis (Phys. Rev. Lett. 120, 061801 (2018))

…repeat for next runs?

VELO

CERN-LHCC-2017-003



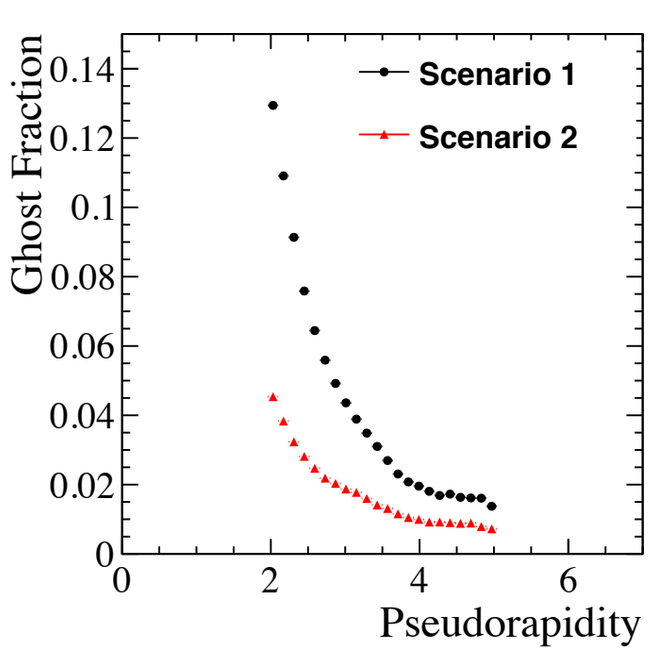


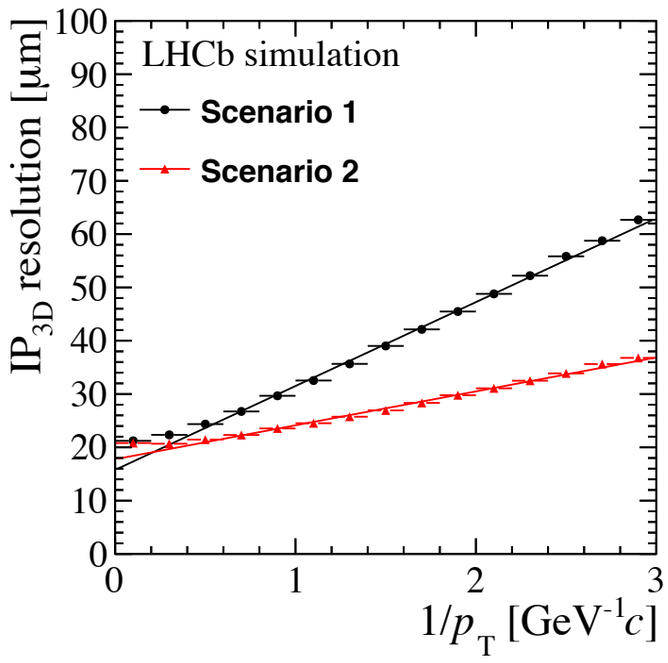
VELO Upgrade I performance at HL-LHC luminosity:

- ghost rate explodes
- tracking efficiency decreases
- spatial resolution degrades

potential design improvements to recover performance losses:

- smaller pixels and thinner silicon sensor
  scenario1
- removal of RF box (biggest contributor to material budget)
  scenario2

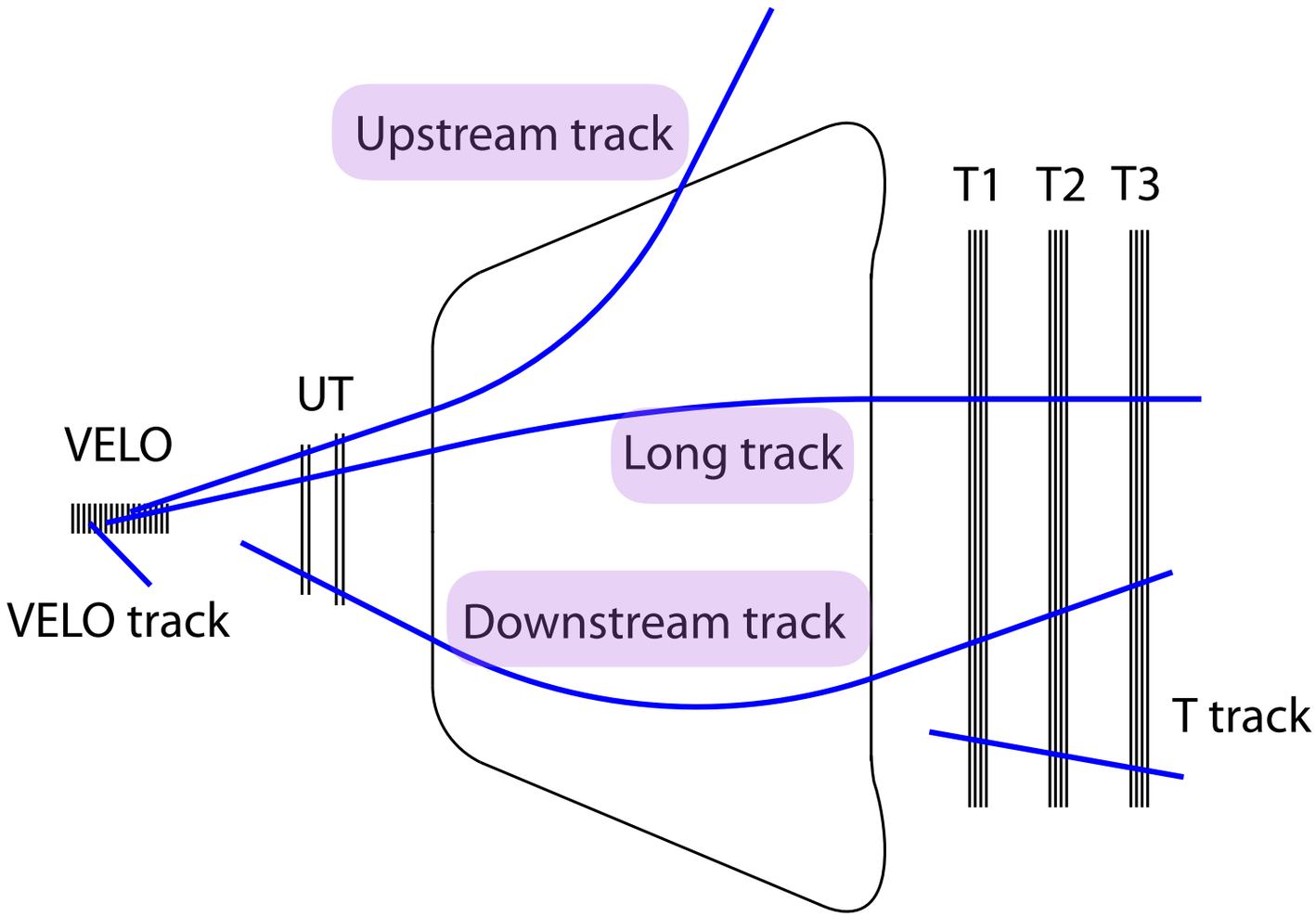




most likely to get additional gain (timing for reconstruction? timing for extrapolation?)

Tracks in LHCb Now

most relevant tracks for LLP searches



Long tracks

- excellent spatial resolution close to PV
- excellent momentum resolution in magnitude and direction

Downstream tracks

- reconstruction of daughters of LLPs that decay beyond VELO acceptance (20 cm<SV<200 cm)
- good momentum resolution

Upstream tracks

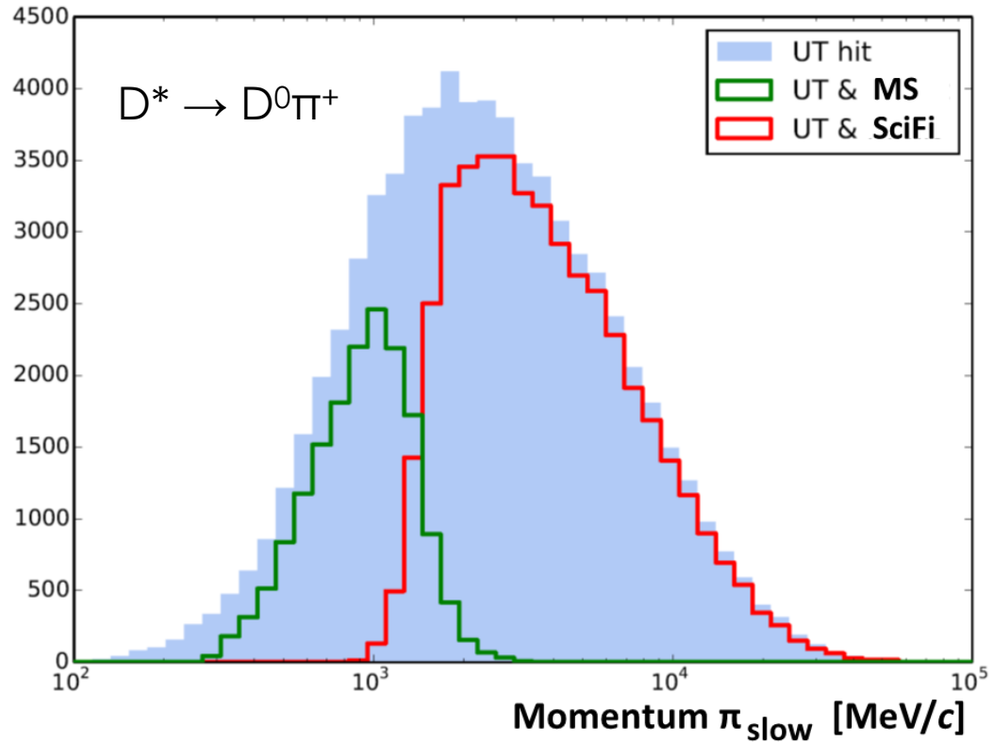
- reconstruction of charged particles bent out of the acceptance
- excellent directional resolution
- approximate estimation of the momentum possible

Tracks in LHCb Upgrade II

CERN-LHCC-2017-003

Upstream tracks

- tracking acceptance can be significantly increased for soft tracks by **tracking stations on the magnet**
- the momentum resolution will improve
- a large fraction of track now lost will be recovered



Downstream tracks

- downstream timing with **TORCH** (Time Of Internally Reflected CHerenkov light)
- target: precision per track ~15 ps
- track matching will improve with consequent suppression of ghosts
- it will allow to timestamp LLP decaying after the VELO and match it to the correct vertex
- it will provide particle id to lower momenta through the ToF

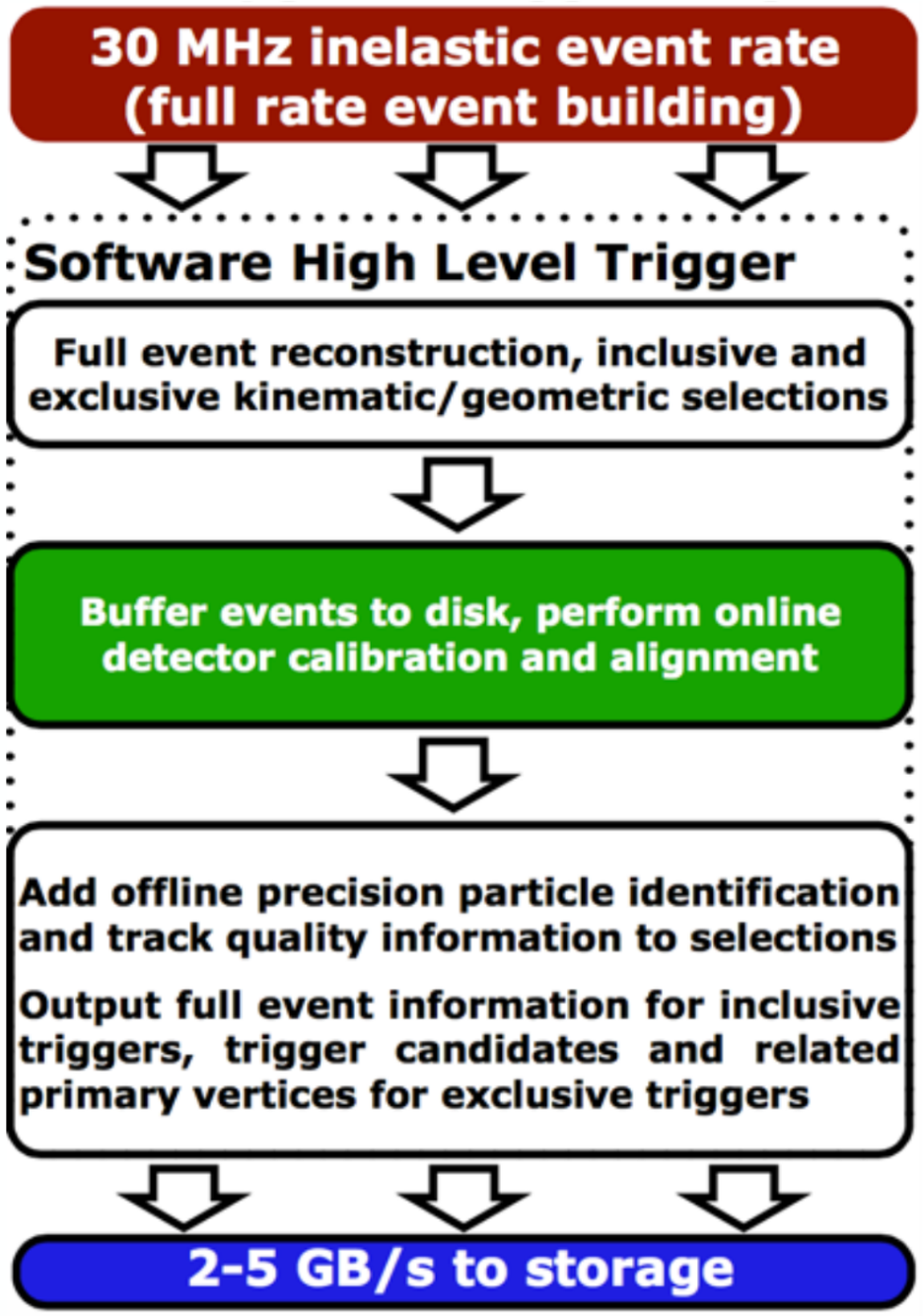
Trigger

CERN-LHCC-2017-003

same strategy as Upgrade I:

- no hardware trigger
- triggerless readout at the LHC bunch crossing rate
- fully software-based trigger with no further offline processing
- signal classification at the trigger level

- more flexibility
- higher efficiency for low mass searches and electron modes
- possibility to access lower jet masses (emerging jets, jet substructures…)



what can be further improved?

- studies ongoing on adding downstream reconstruction at HLT1 ('retina' scheme with dedicated processors in the DAQ)
  EPJ Web Conf. 127 (2016) 00005

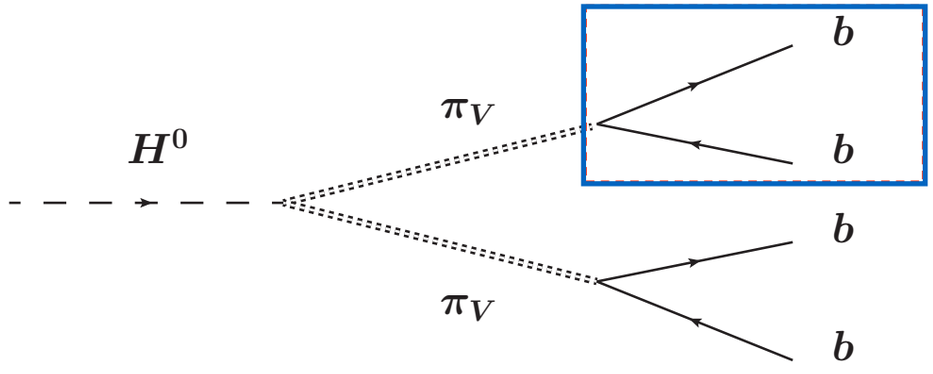
What sensitivity can we reach with HL-LHC?

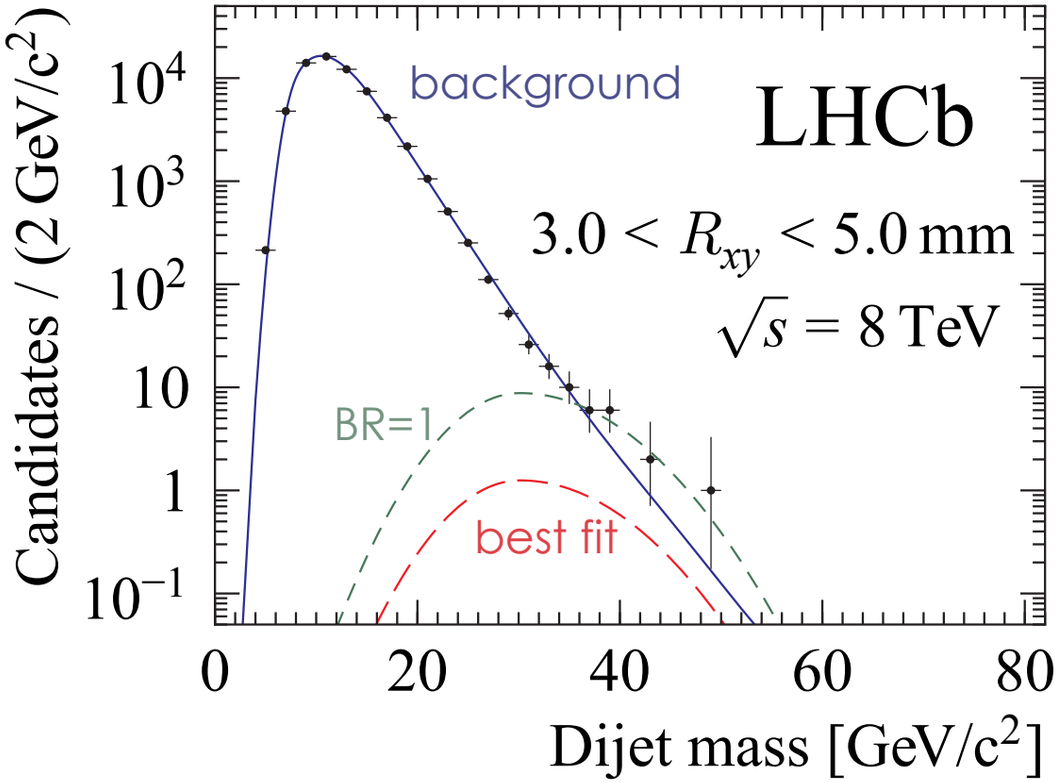
LLPs Decaying to Jet Pairs

Eur. Phys. J. C77 (2017) 812

- search for hidden sector LLP decays via SM Higgs portal
- **mass range:** 25-50 GeV
- **lifetime range:** 2-500 ps
- **dataset:** run I (2 fb^{-1})
- **signature:** single displaced vertex with 2 associated jets

in most cases only 1 π_V within LHCb acceptance





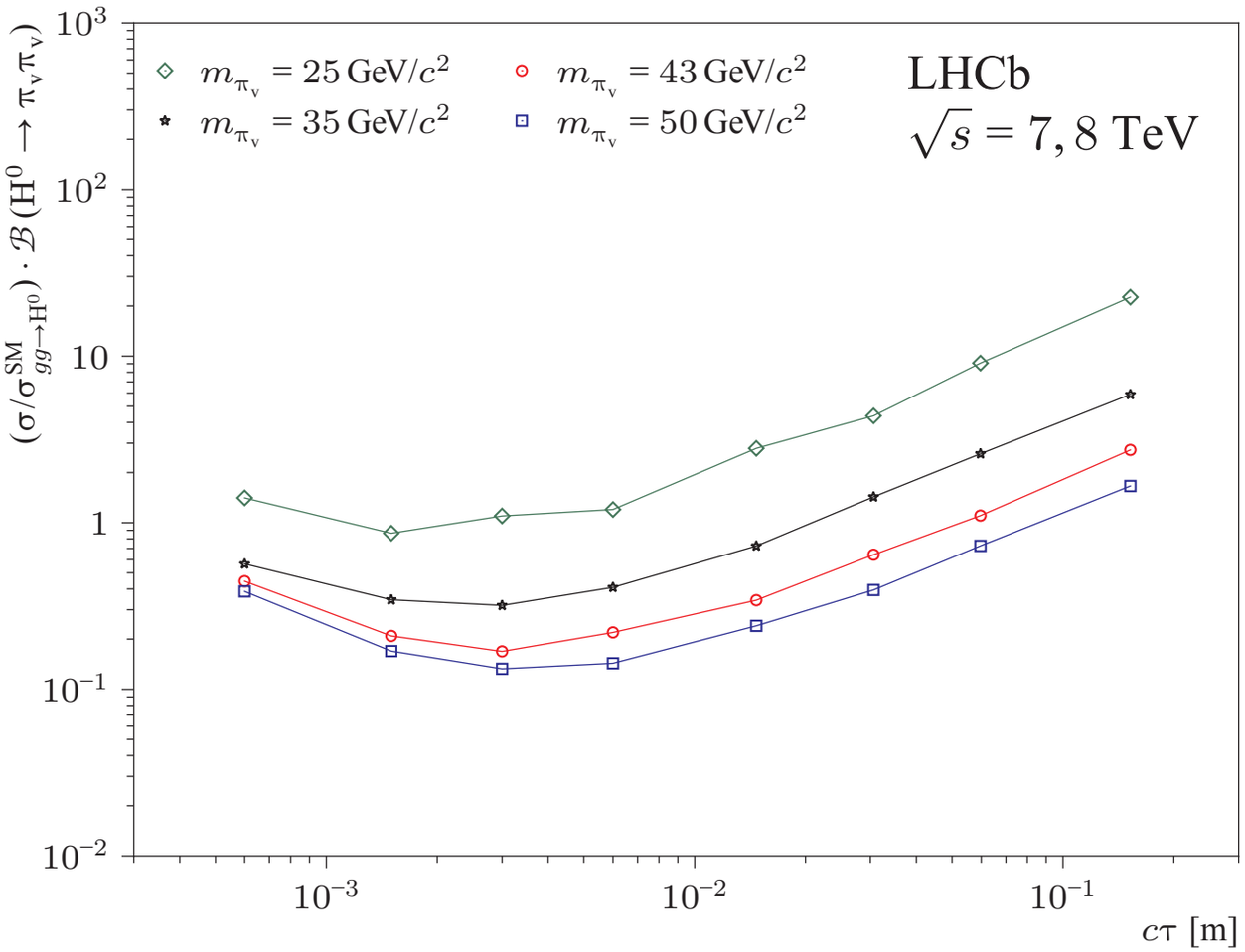
strategy

- trigger on displaced vertex
- requirements on jet pointing and material interaction veto to reduce main backgrounds:
  - vertex from heavy flavour decay or material interaction
  - SM dijet events
- fit of the di-jet mass in bins of lateral displacement R_{xy}

LLPs Decaying to Jet Pairs

Eur. Phys. J. C77 (2017) 812

upper limits set on SM-Higgs BR to dark pions



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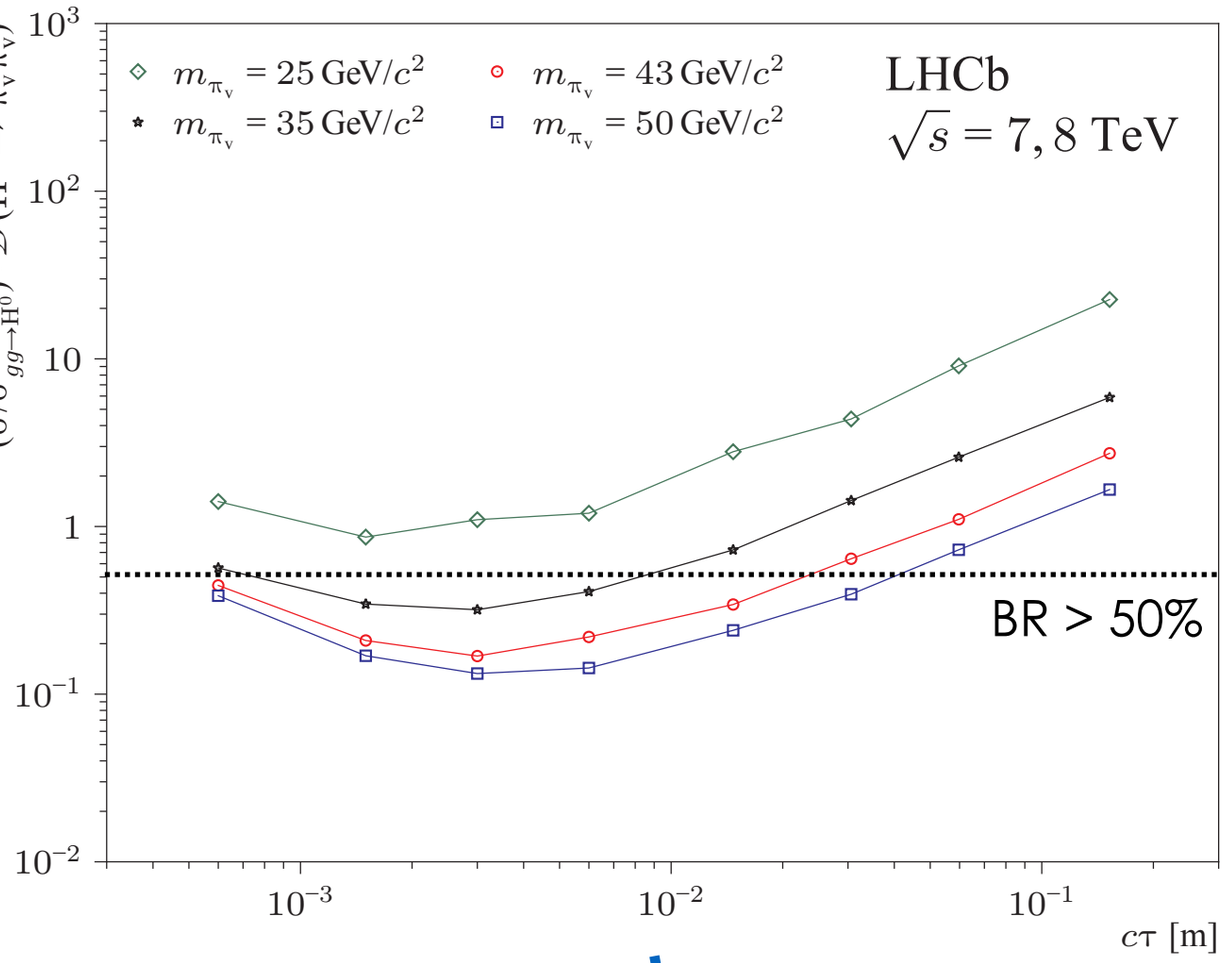
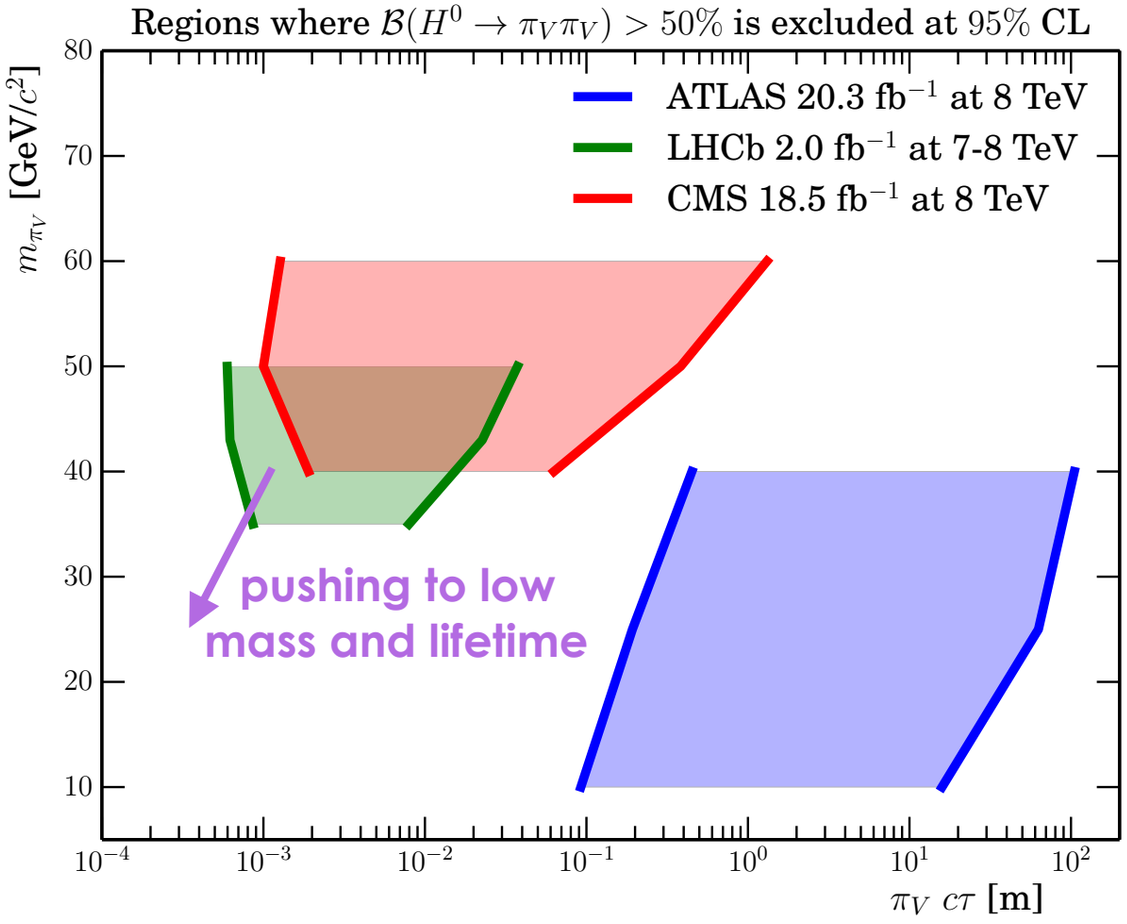


competitive and complementary limits to ATLAS and CMS!

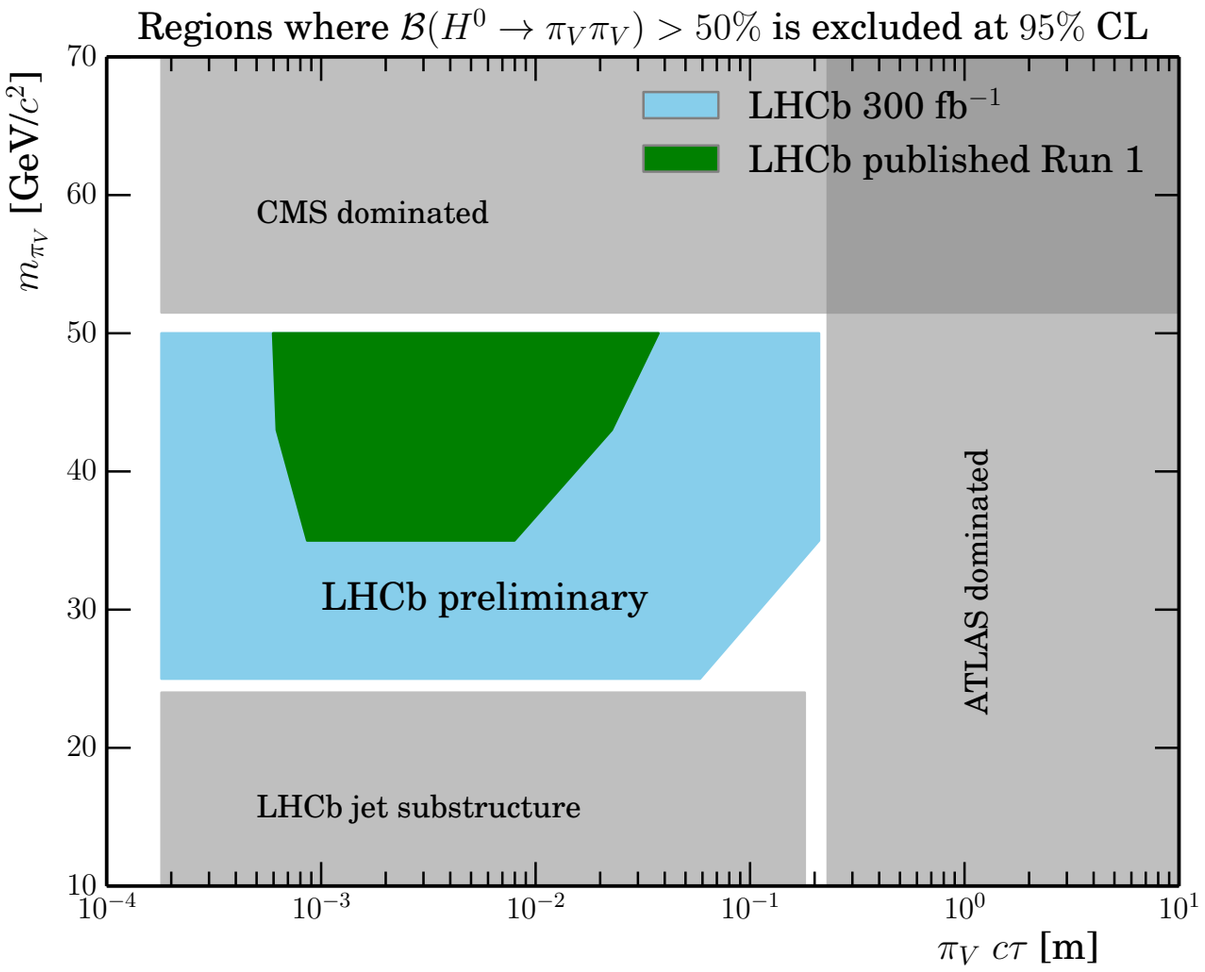
what about HL-LHC?

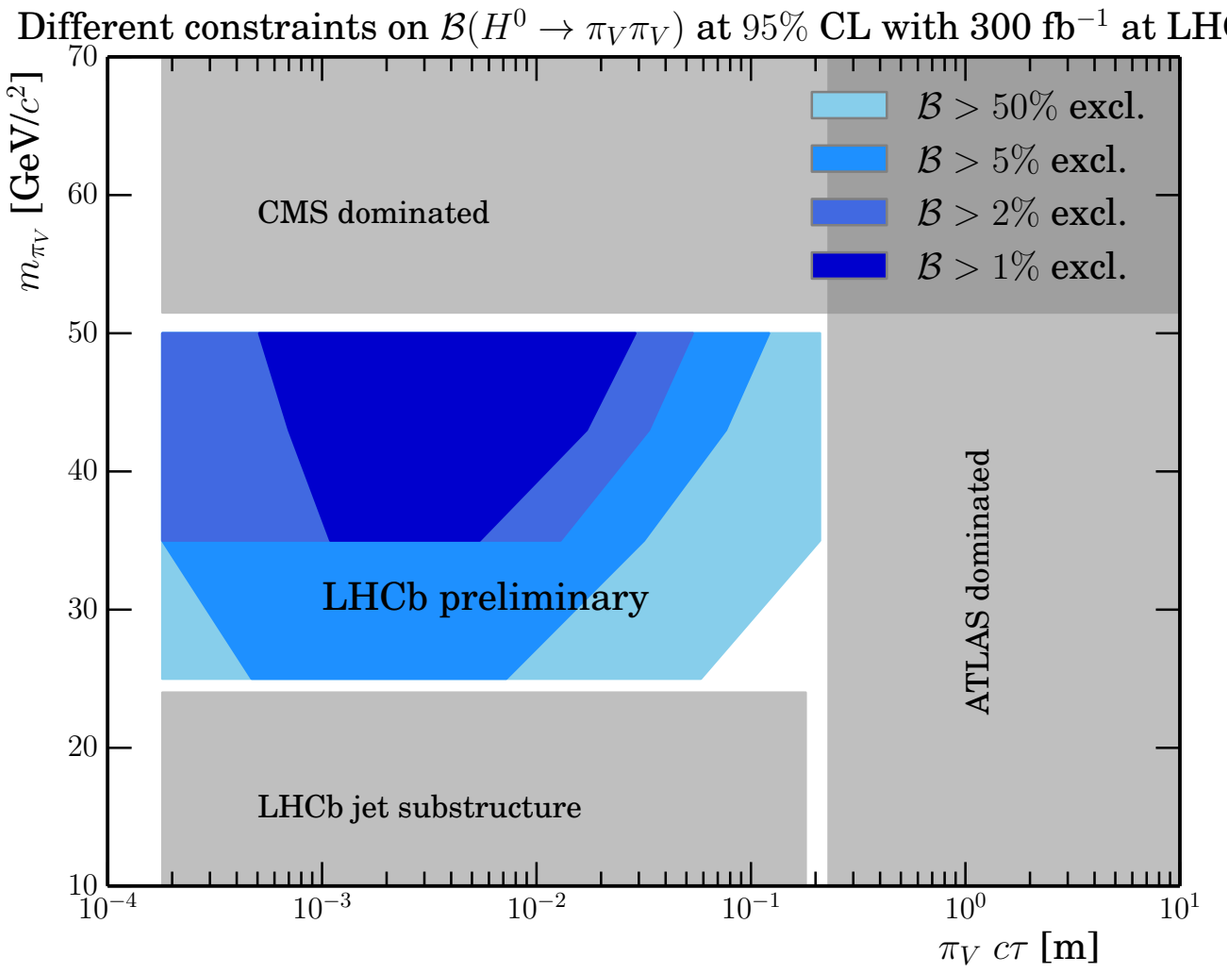


LLPs Decaying to Jet Pairs

extrapolation to 300 fb^{-1}

- signal and background scaled to 14 TeV
- conservative assumptions on detector performance (trigger, material interaction, jet reco)
- optimistic assumptions on the effect of pile-up





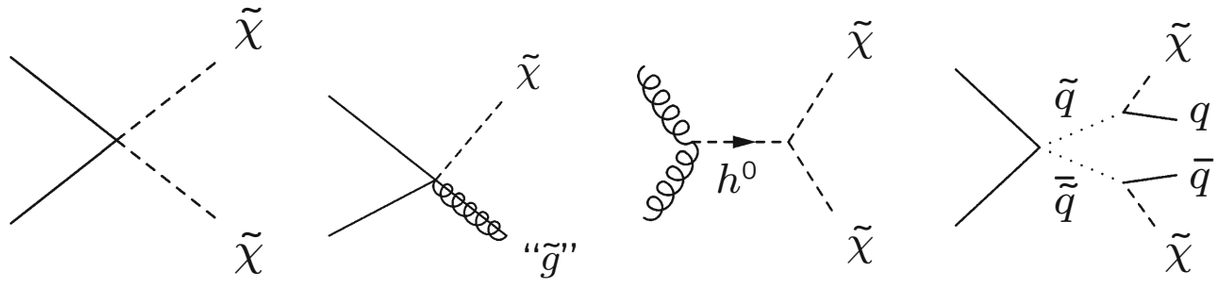
LLP Decaying Semileptonically

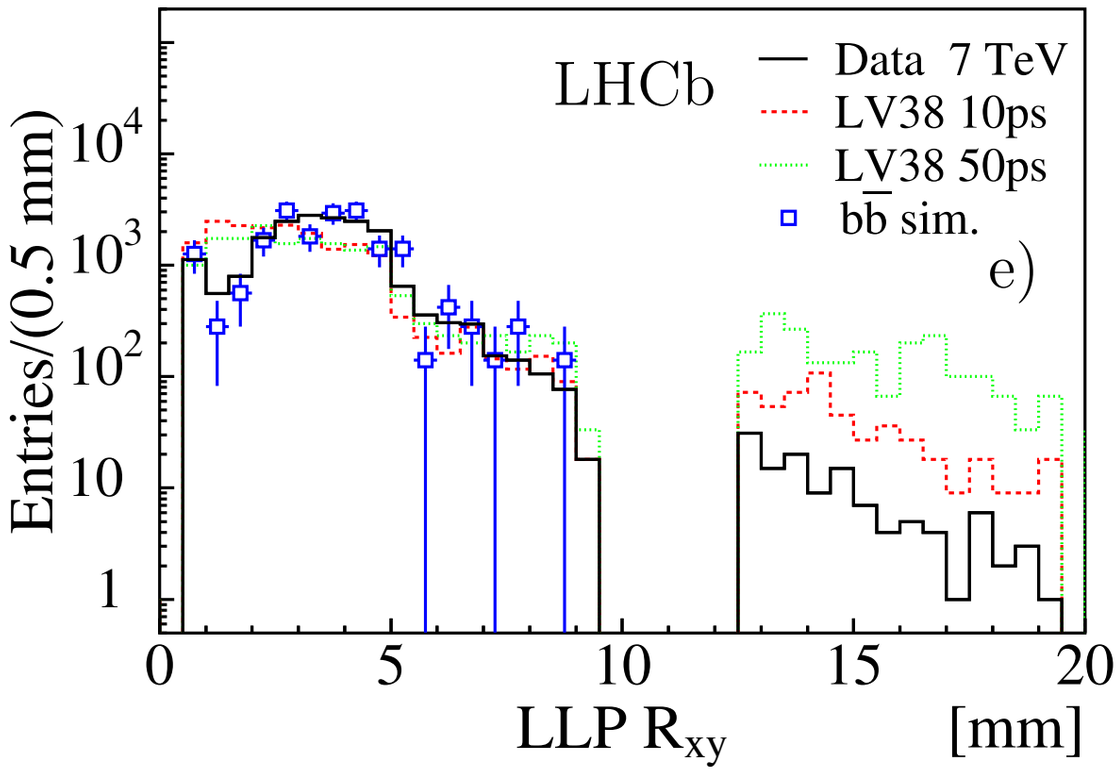
EPJC (2017) 77:224

- search for massive LLP decaying semileptonically into SM particles

- 2 approaches:
  - RPV mSUGRA neutralino as benchmark
    mass range: 23-198 GeV
  - simplified topologies, less model dependent
    mass range: 25-50 GeV

4 production mechanisms considered





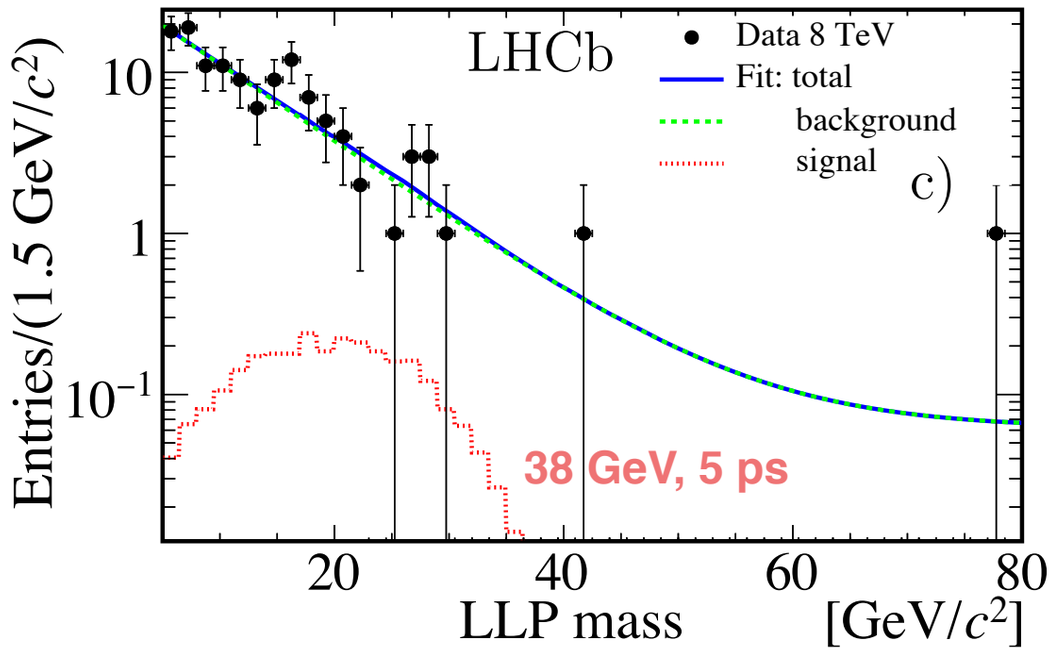
- **lifetime range:** 5-100 ps
- **dataset:** run I (1+2 fb^{-1})
- **signature:** single displaced vertex with several tracks and a high p_T μ
- background dominated by bb

LLP Decaying Semileptonically

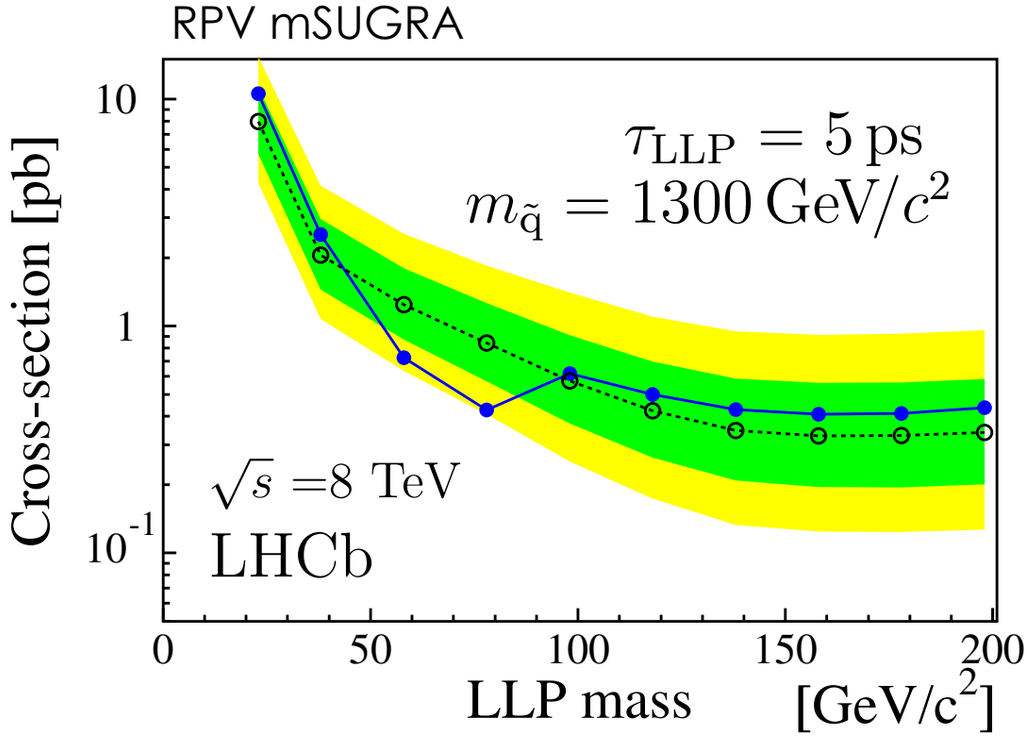
EPJC (2017) 77:224

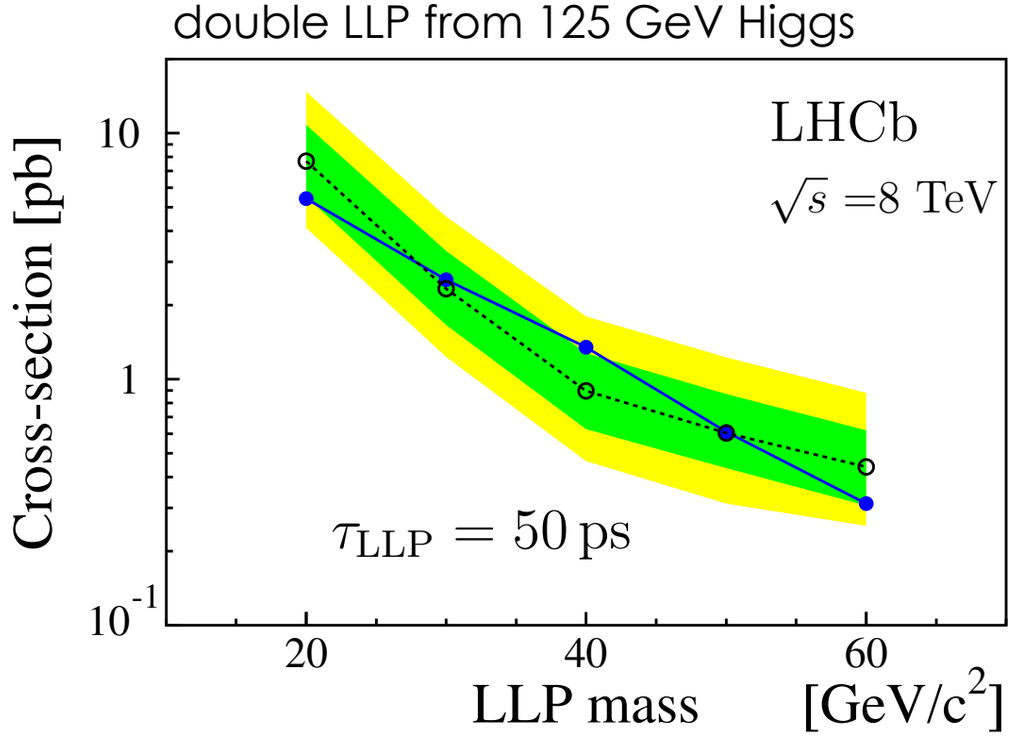
strategy

- trigger on μ + displaced vertex
- exploit μ isolation to define a signal and a control region enhanced in background
- simultaneous fit of the LLP candidate mass in the 2 regions to extract number of candidates



no significant excess observed





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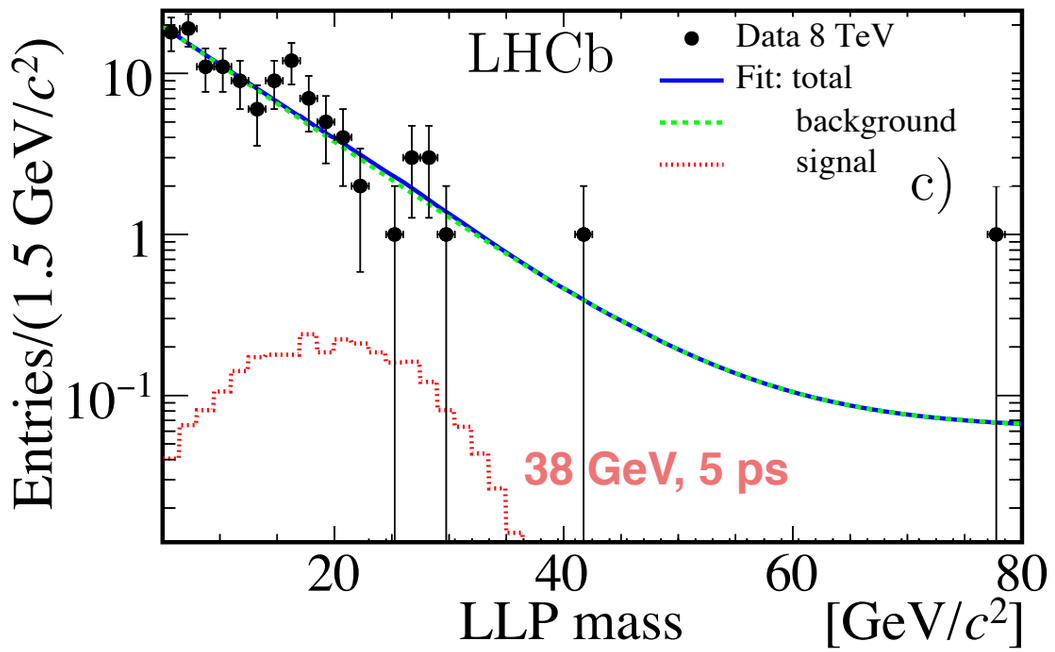

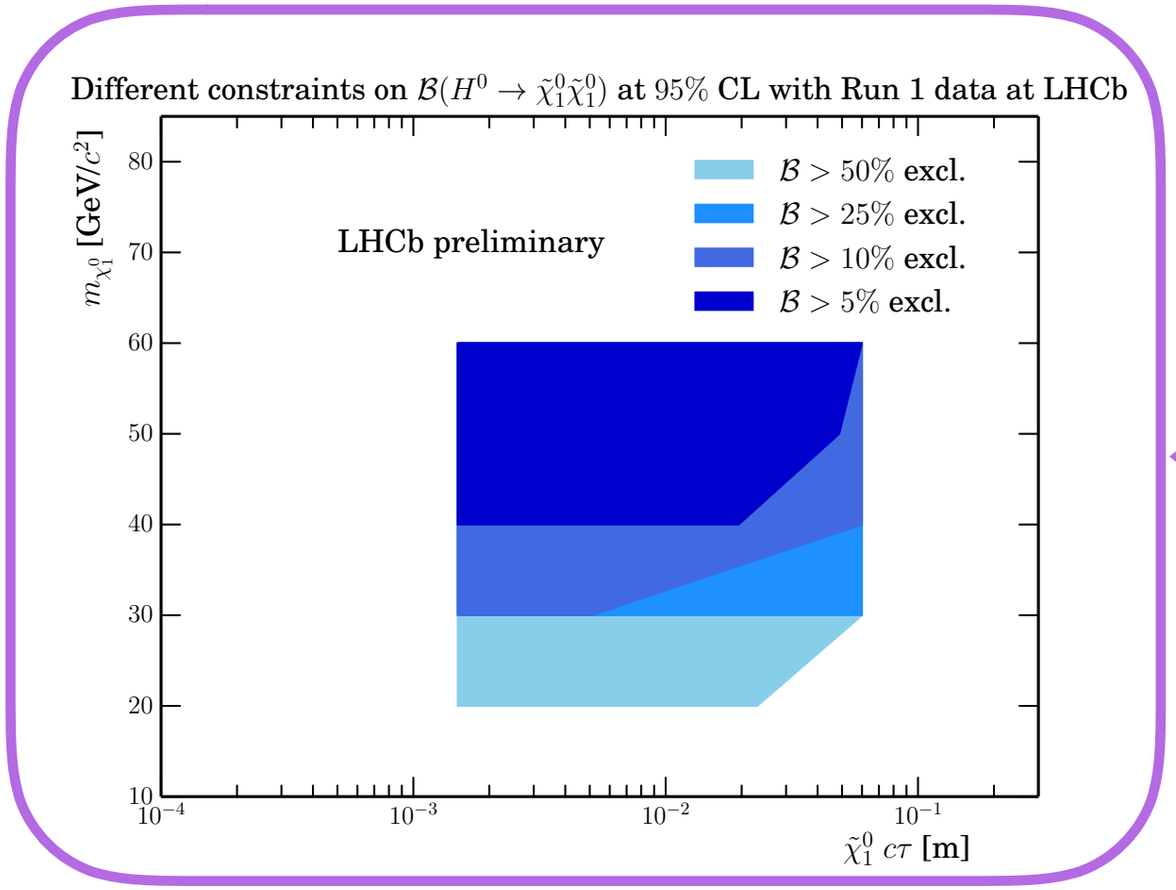

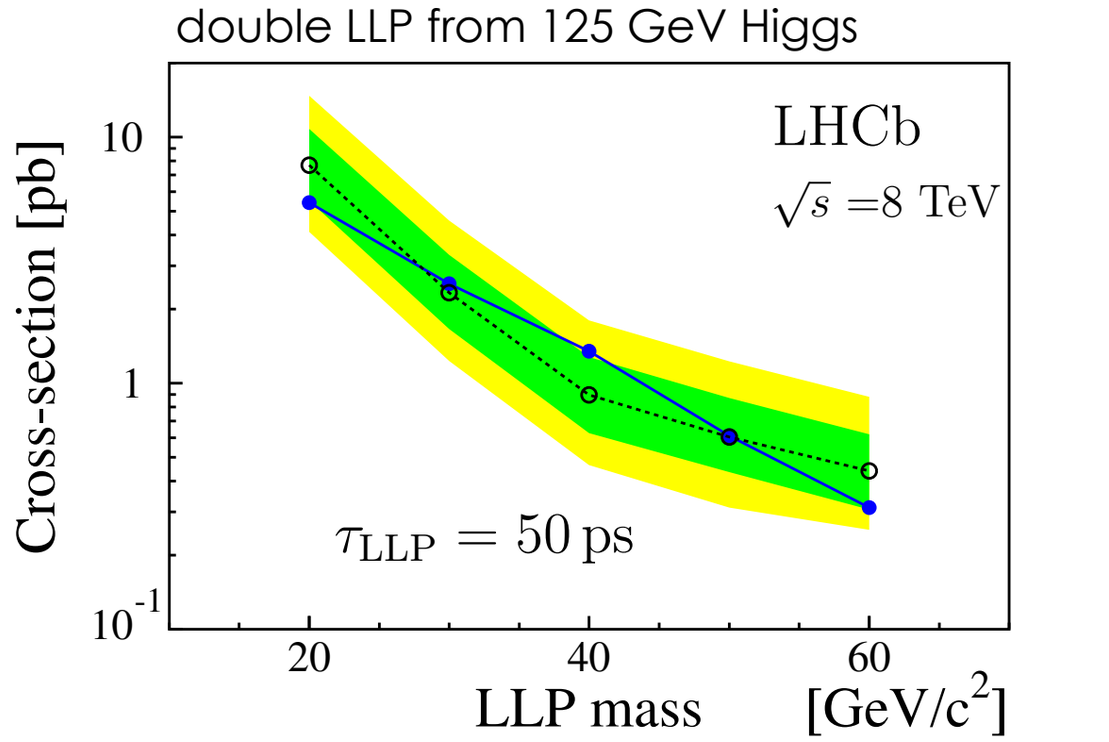

LLP Decaying Semileptonically

extrapolation to 300 fb^{-1}

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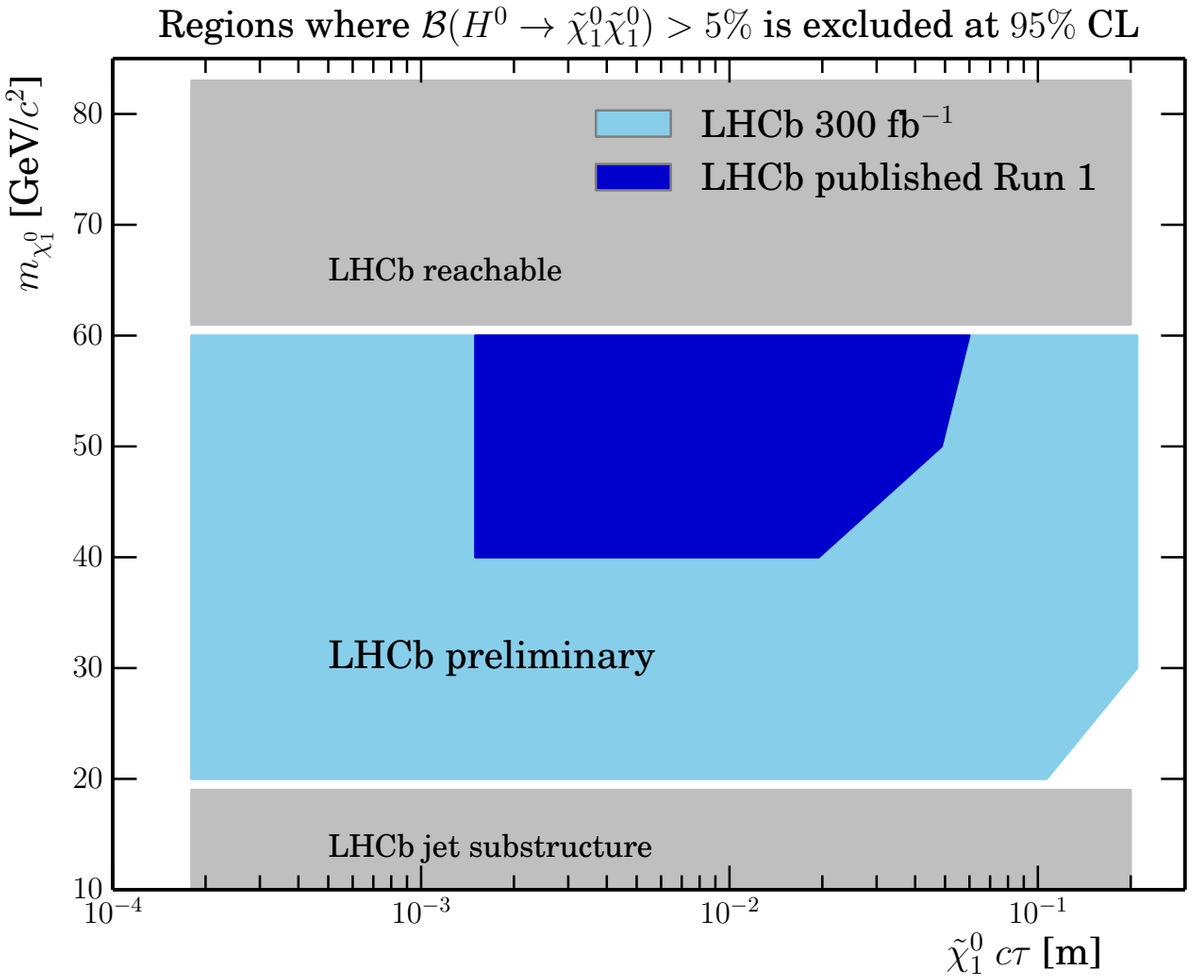
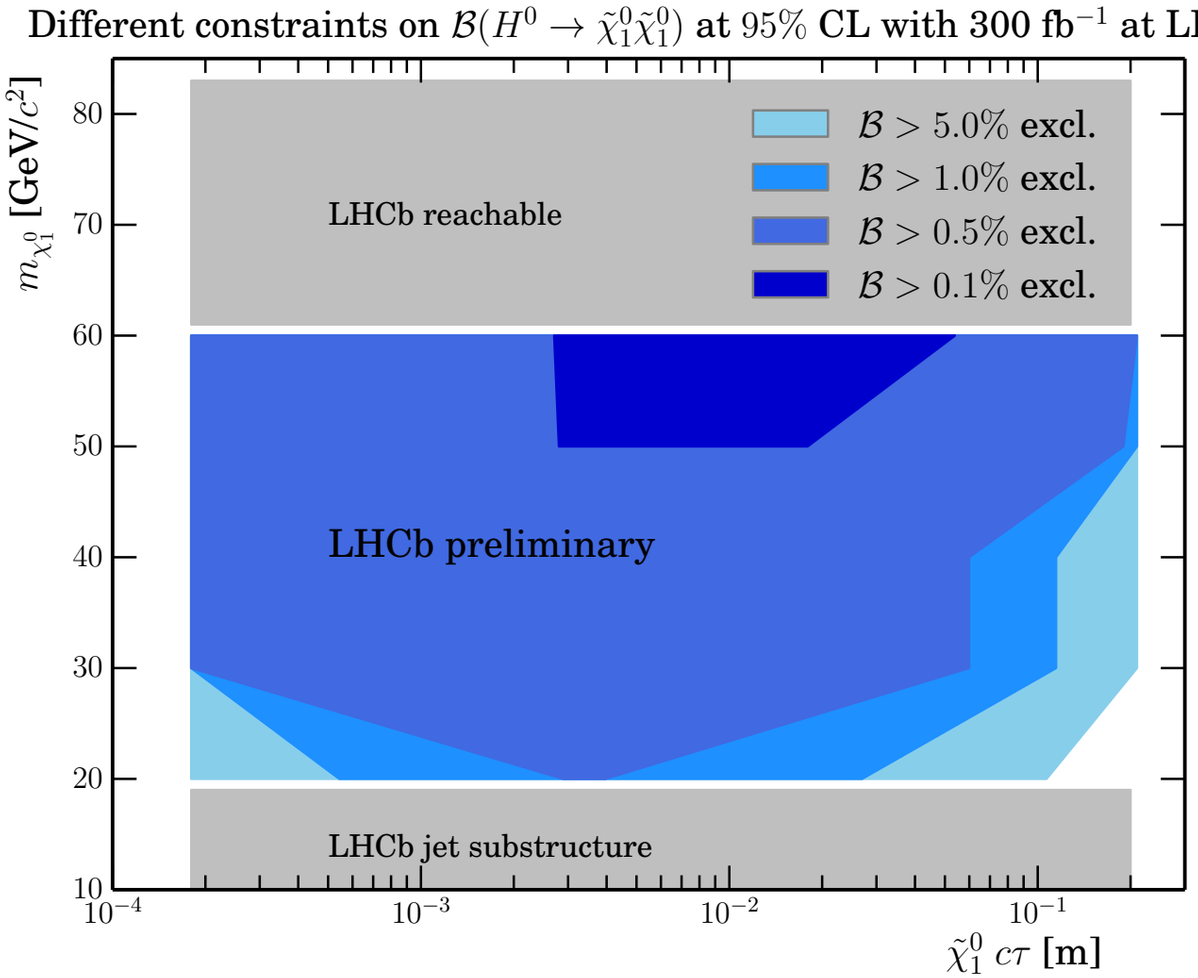




Summary

With the upgrade II we have…

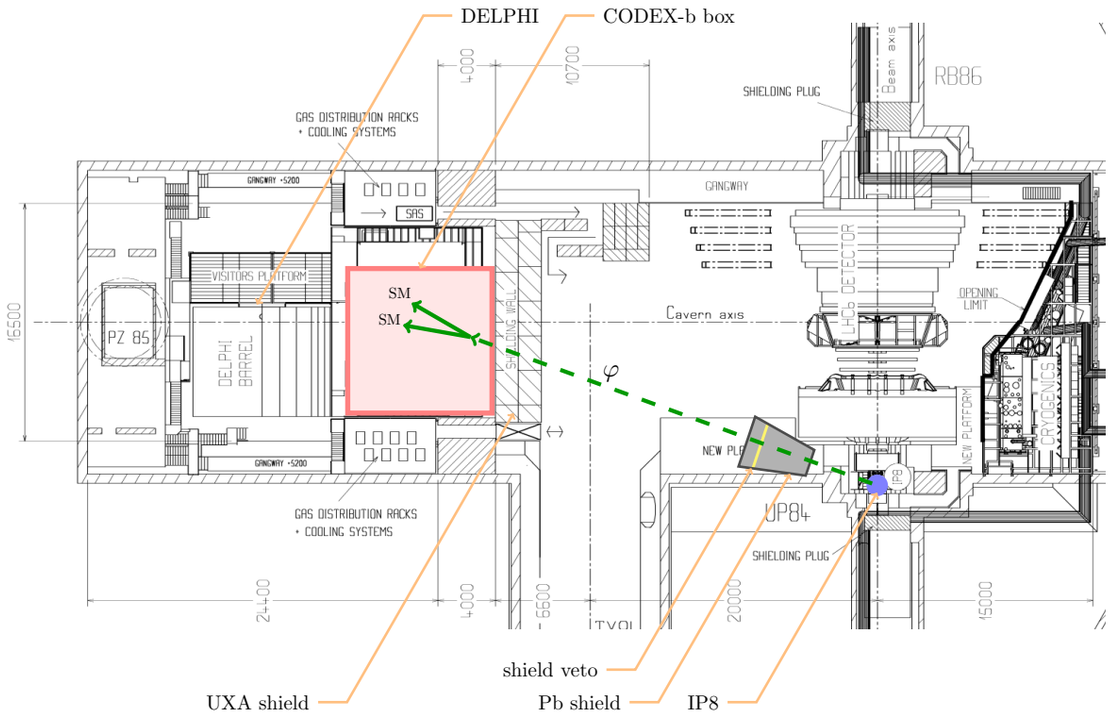
- 10x luminosity
- significant changes in the detector to cope with the challenging conditions: many proposals/ideas! (3rd Workshop on LHCb Upgrade II)
- LHCb reach for LLPs significantly improves beyond luminosity scaling: pushing towards low masses and low lifetimes
- proposal for a new dedicated detector (CODEX-b) to further extend physics reach and capabilities for LLPs (see Mike's talk)
- unique coverage complementary to ATLAS and CMS
- many inputs coming from the theory community:
  - confining Hidden Valley arXiv:1708.05389
  - soft bombs JHEP 08 (2017) 076
  - rare Z decays to a hidden sector arXiv:1710.07635

…growing interest for LLPs at LHCb!

Back Up

CODEX-b

arXiv:1708.09395

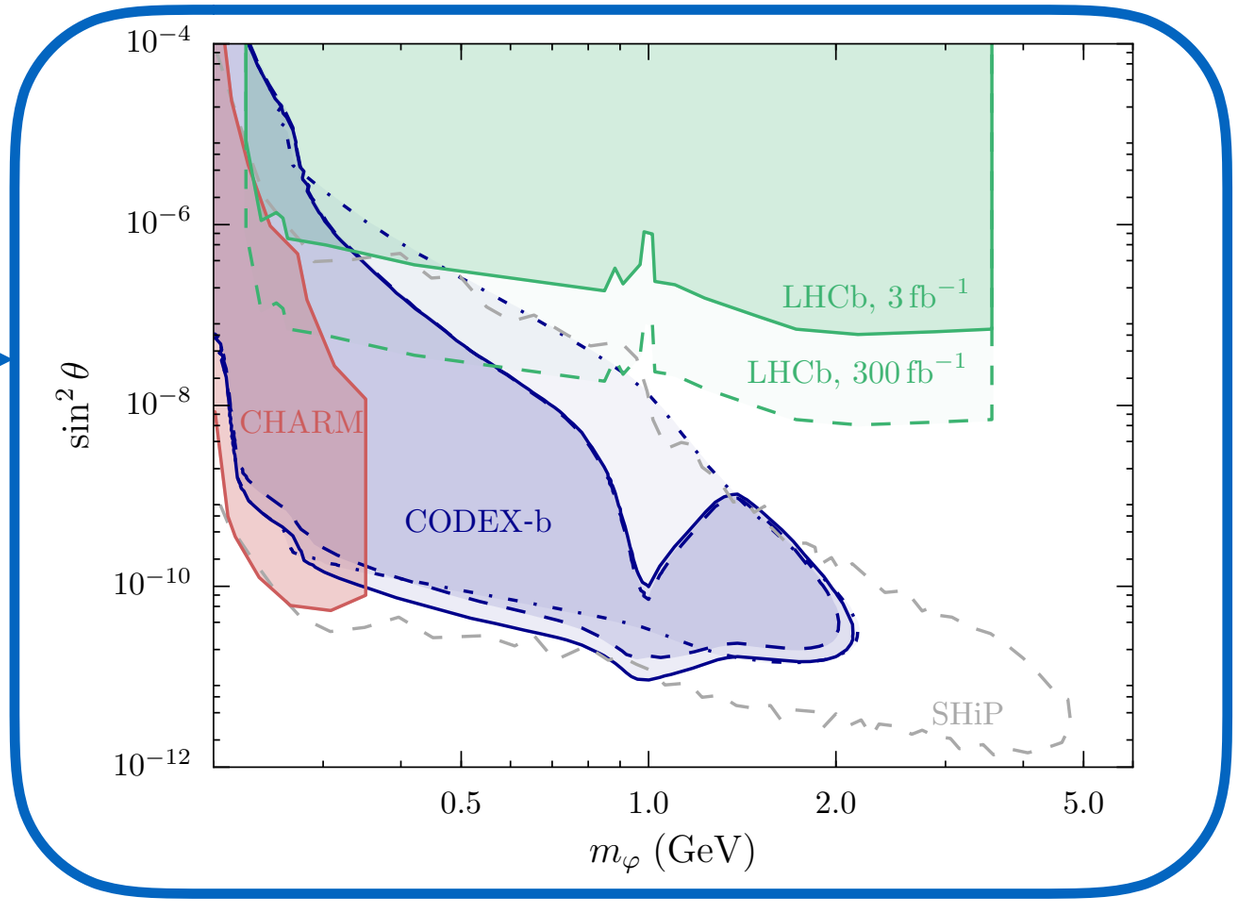


strategy:

look for decays-in-flight of LLPs from IP8

Five benchmark LLP scenarios:

- Massive dark photon γ_d (kinetic mixing)
- Light O(GeV) scalar φ (Higgs mixing)
- Heavy neutral lepton (mixing with the active neutrinos)
- $h \rightarrow$ dark glueballs (twin Higgs mixing portal)
- QCD coupled ALP $m_a < 3\pi$ (diphoton channel!)



Extrapolation to HL-LHC

assumptions:

the pile-up won't affect much neither the jet reconstruction neither the backgrounds

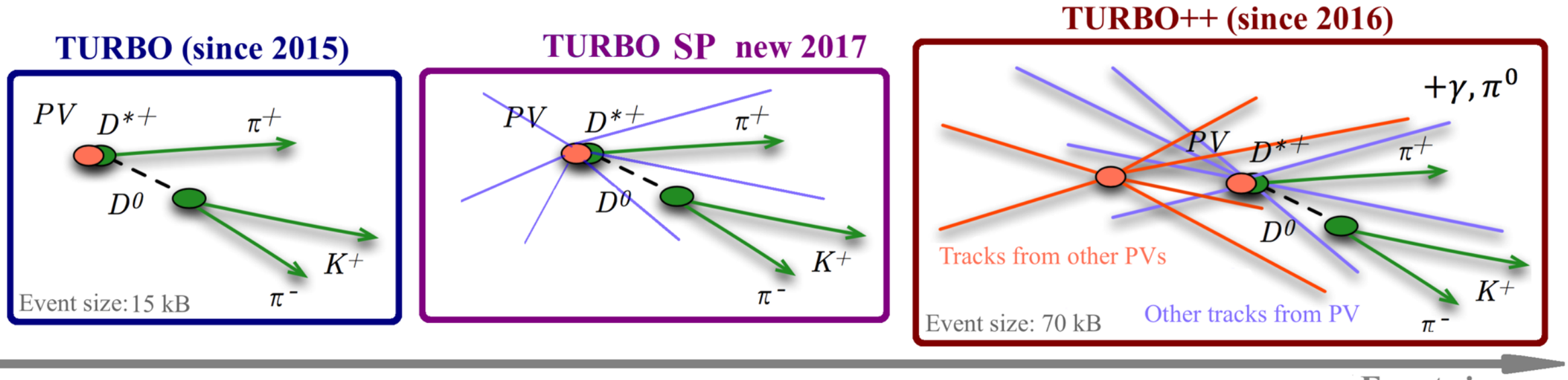
For **jet reconstruction**, we think we can have it under control by either:

- applying the same ML techniques to mitigate the pile up already used by ATLAS/CMS
- removing neutrals from jets (resolution would degrade but this is done already for Turbo jets)

For the **backgrounds**, for LLPs there are two main sources, heavy flavour and material interactions:

- heavy flavour should be about the same
- material interactions: the understanding of the VELO material significantly increased in the last year, and hopefully this will be also the case in the HL-LHC. If RF foil thinner or even completely removed, background drastically reduced

Turbo



only exclusive decays (nothing else saved)

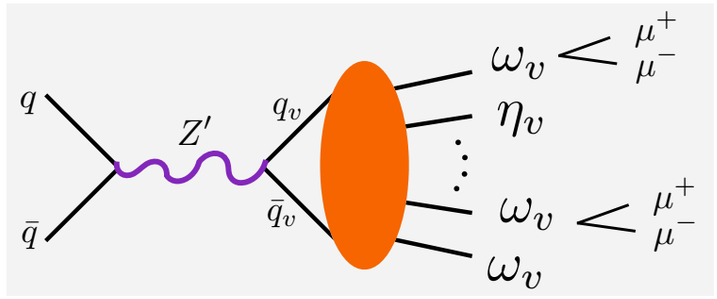
- new intermediate solution
- trigger candidate + subset of reconstruction saved

- full event reconstruction can be persisted
- variables such as isolation, objects for jet reconstruction can be saved

Confining Hidden Valley Model

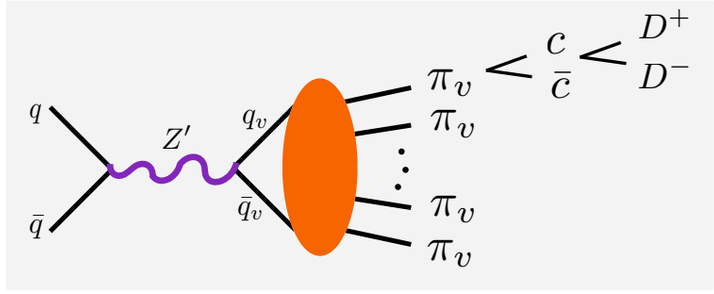
arXiv:1708.05389

di-muon channel

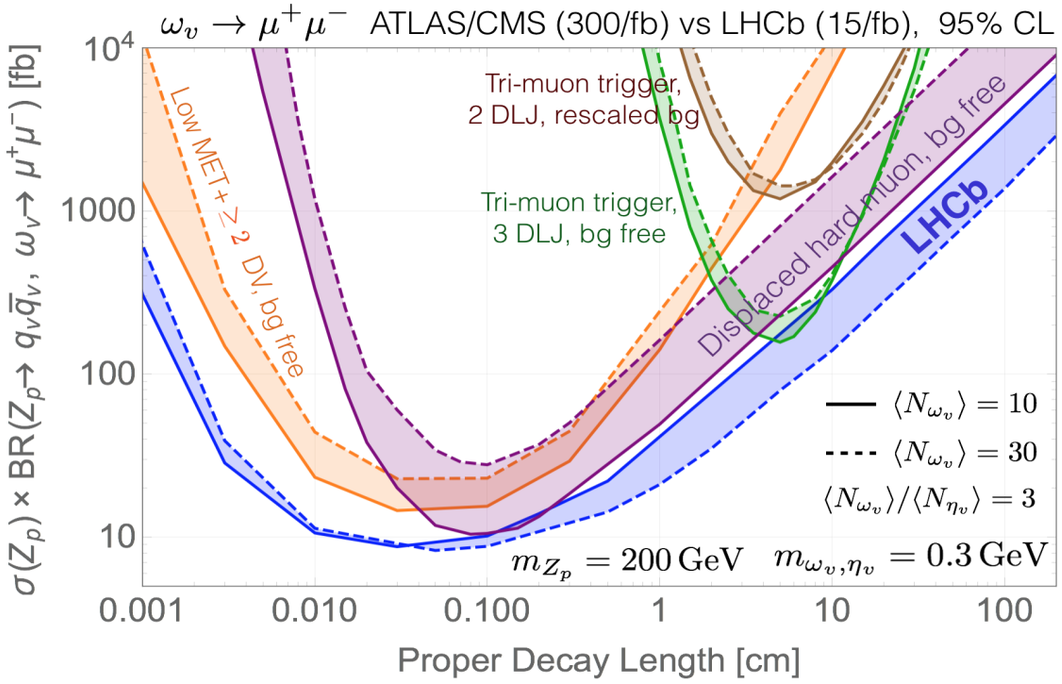


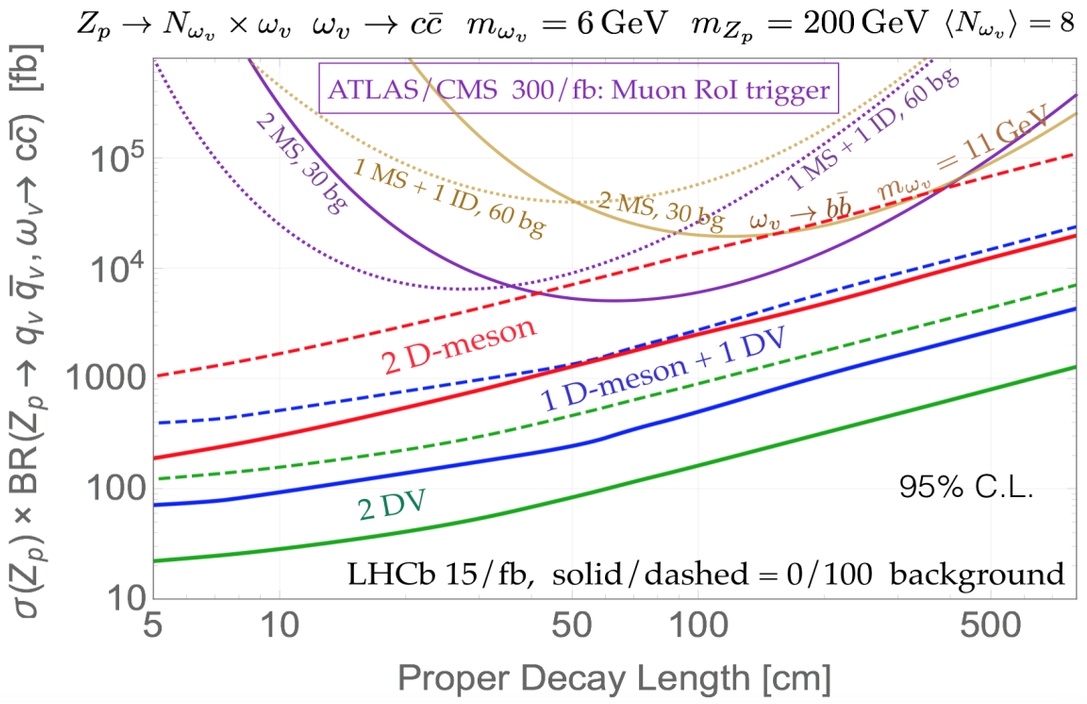
signature: a displaced vertex well separated from beamline

heavy flavour decay channel



signature: 2 vertices with large separation from PV and significant separation between each other





potential better sensitivity than ATLAS/CMS

Soft Bombs

JHEP 08 (2017) 076

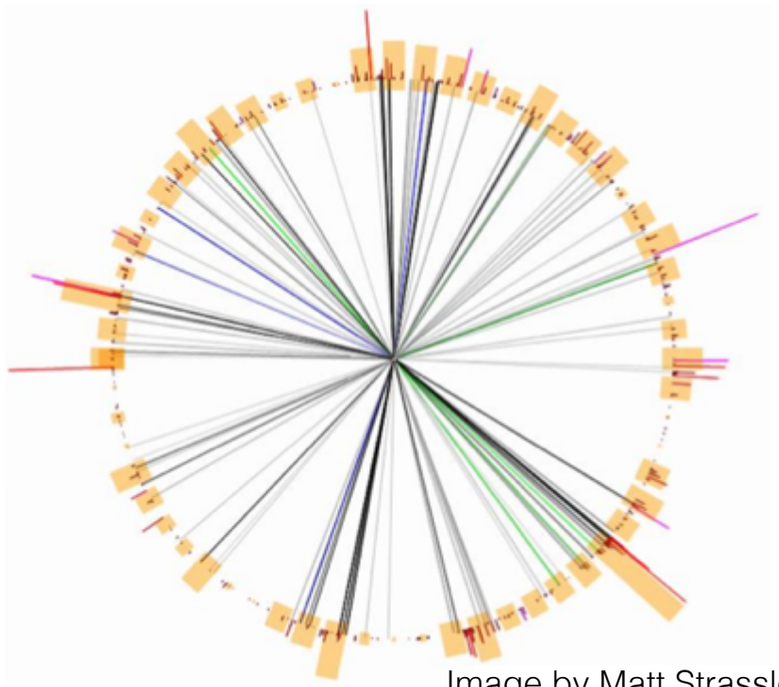


Image by Matt Strassler

- large multiplicity of soft particles
- spherical event shape
- multiplicity scales linearly with energy
- might be signature of strongly-coupled hidden valleys

"given that LHCb will eventually operate fully in the trigger-less mode, it will have unique sensitivity to soft signatures of new physics"

Rare Z Decays to a Hidden Sector

arXiv:1710.07635

- rare decays of the Standard Model Z boson are powerful probes of hidden sectors
- Z decays into hidden-sector particles typically give rise to large multiplicities of soft particles

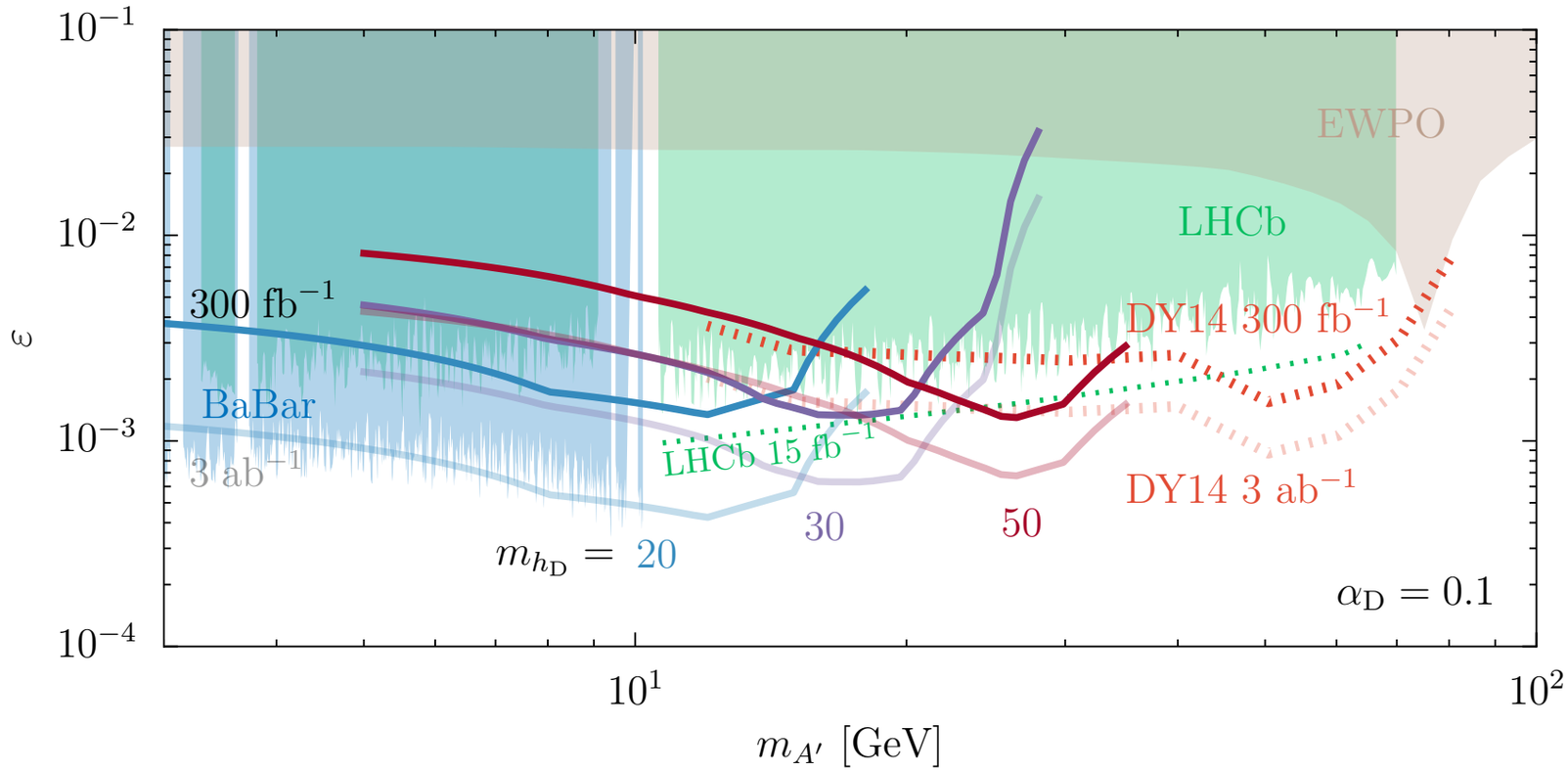


FIG. 4: Sensitivity projections for the $Z \to h_D A' \to 4\ell + X$ search for integrated luminosity of 300 fb^{-1} (upper dark lines) and 3000 fb^{-1} (lower faint lines) at $\sqrt{s} = 13$ TeV and $\alpha_D = 0.1$. The dotted green line shows the projected LHCb sensitivity with 15 fb^{-1} from Ref. [29], while the dashed lines show the projections for the proposed Drell-Yan search from Ref. [32]. Notation and existing bounds are the same as in Fig. 3.