Università degli Studi di Padova

INFN Padova

LHCb

Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13$ TeV

Davide Zuliani*

University and INFN of Padova

On behalf of the LHCb Collaboration

* for questions/comments: davide.zuliani@cern.ch

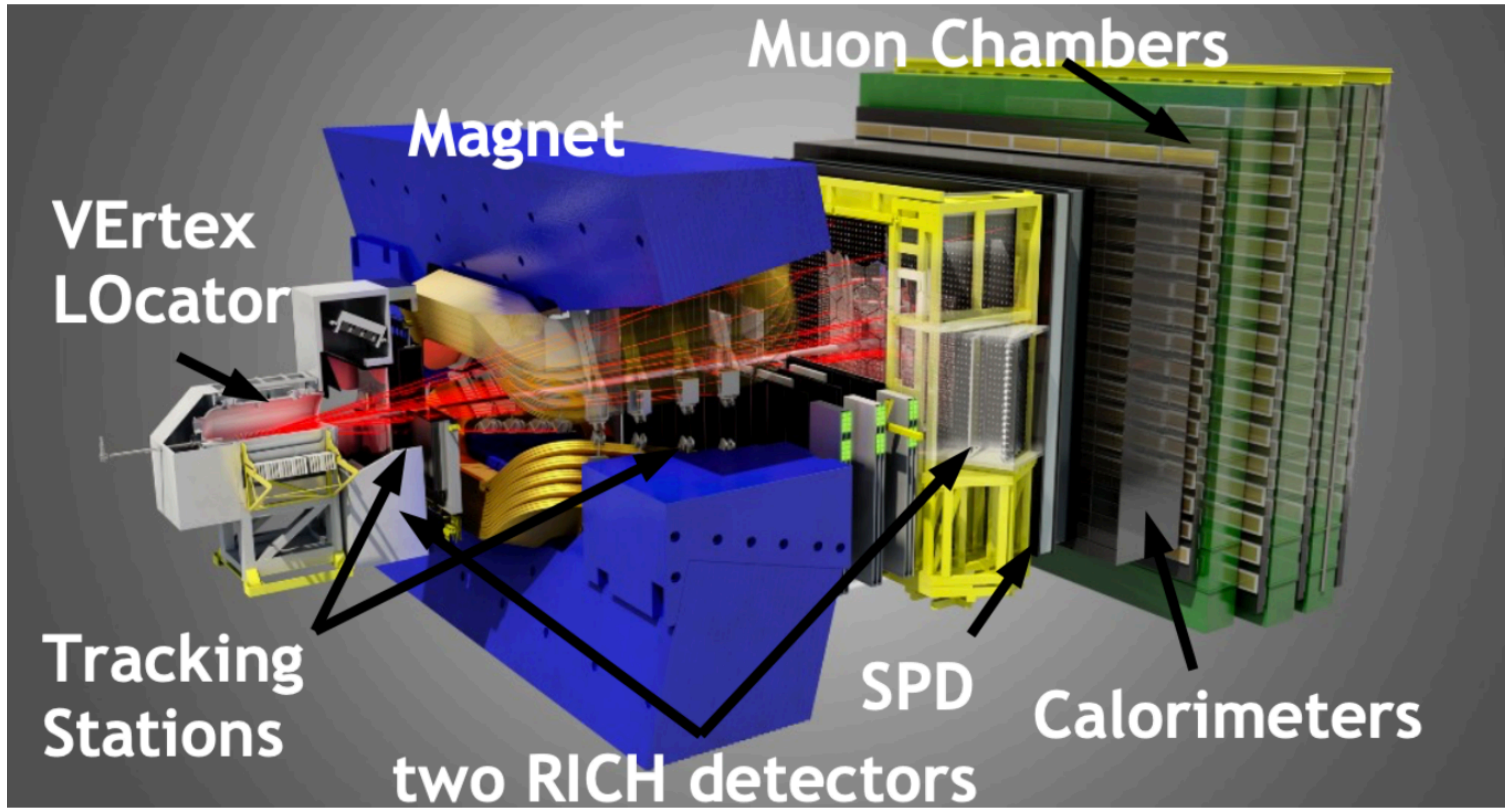
Outline

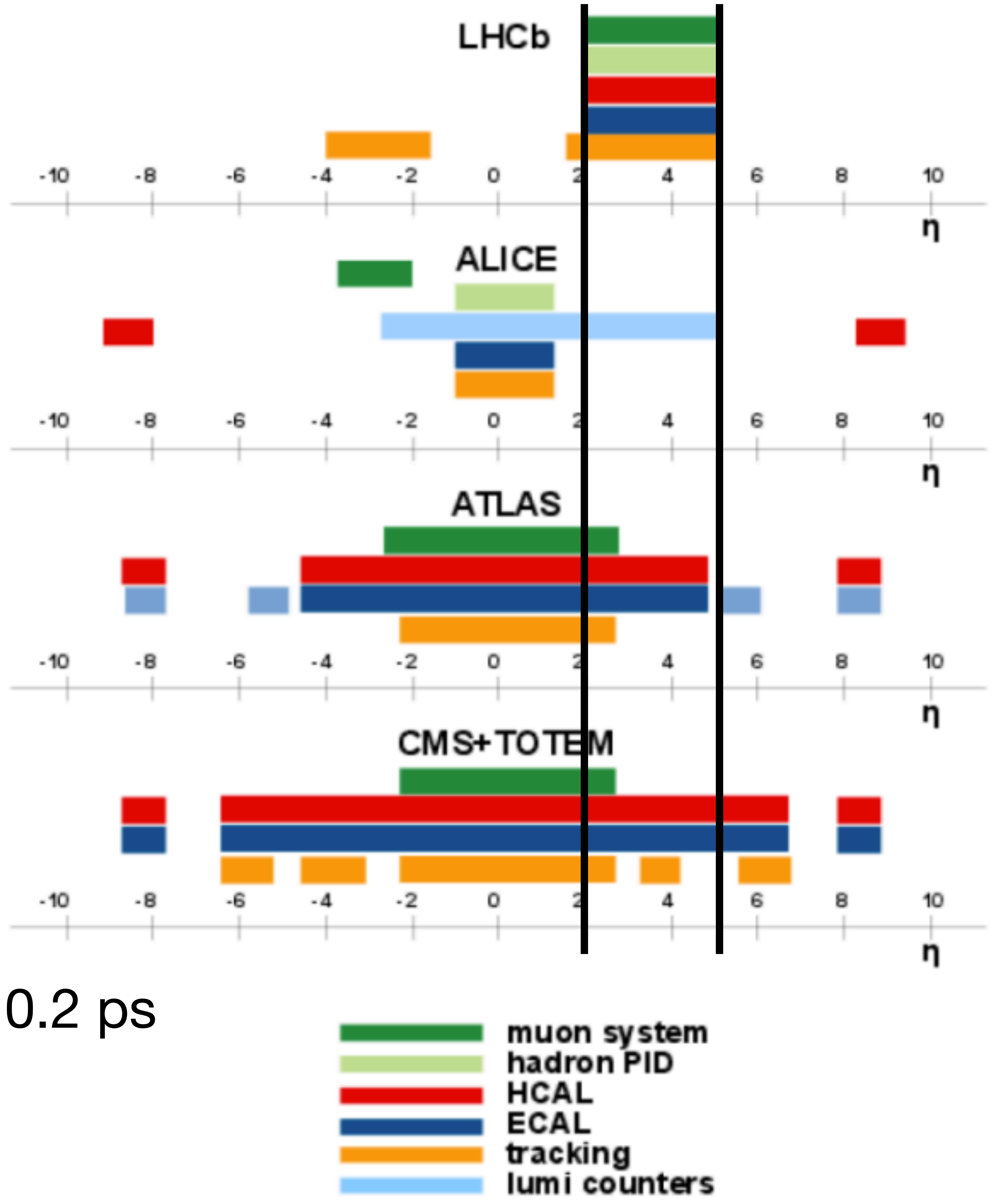
- LHCb experiment
- Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13$ TeV
- Conclusions

LHCb experiment
A General Purpose Forward Detector

JINST 3 (2008) S08005
Int. J. Mod: Phys. A 30, 1530022 (2015)
CERN-LPCC-2018-04

- LHCb, originally designed for b- and c-hadron physics, is now considered a **general purpose forward detector**
- Unique phase space region $(2 < \eta < 5)$ **complementary to General Purpose Detectors** (ATLAS & CMS)



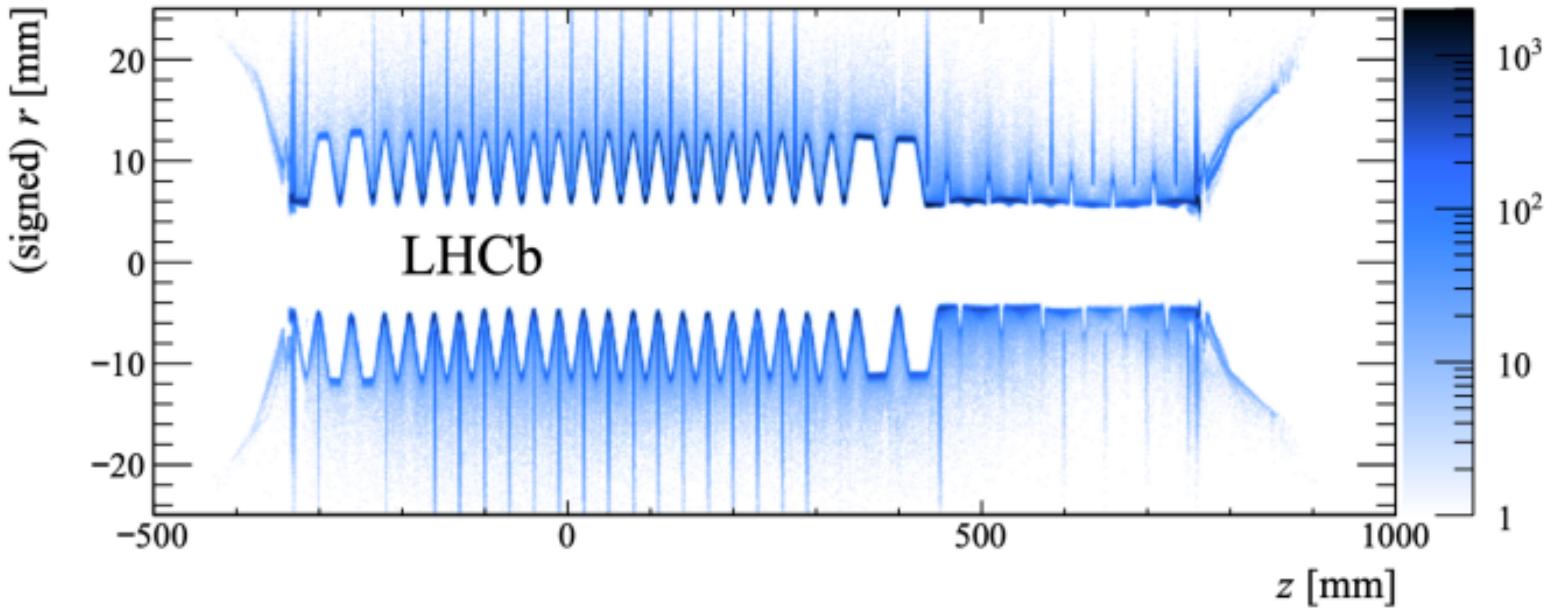


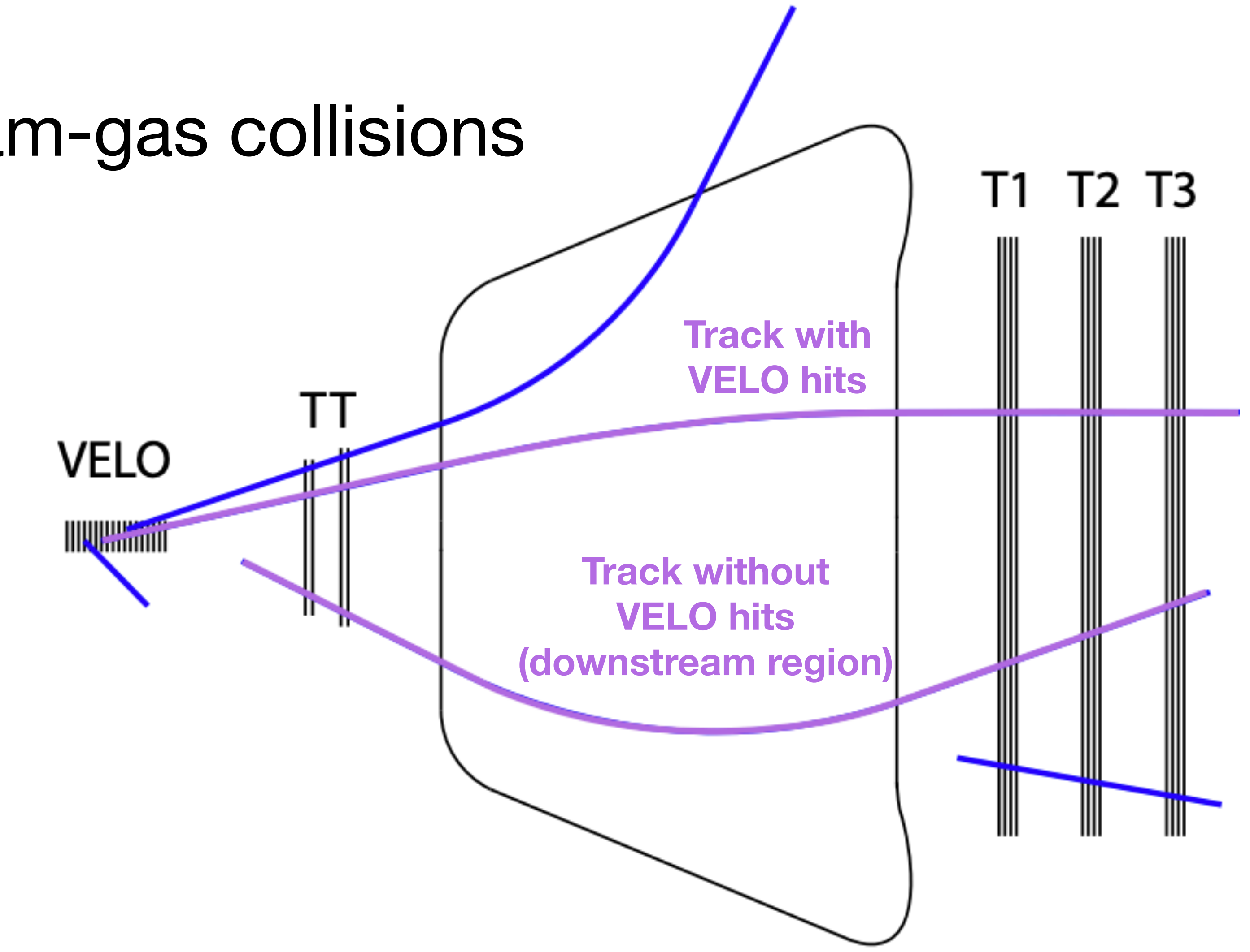
- **Excellent track momentum resolution**: 0.4% at 5 GeV to 1.0% at 200 GeV
- Impact Parameter resolution $\sigma_{IP} = 20\ \mu$m for high-p_T tracks, lifetime resolution of $\sigma_\tau = 0.2$ ps
- Muon ID efficiency: 97% with 1-3% $\mu \rightarrow \pi$ misidentification
- Electron ID efficiency: 90% with 5% $h \rightarrow e$ misidentification

LHCb experiment
VELO material map

JINST 13 (2018) 06, P06008

- Material map of VErtex LOcator (VELO) is fundamental for LLP searches:
    - Displacement up to 20 cm
    - Thin VELO envelope (RF foil) - background dominated by
        - heavy flavour decays at < 5 mm
        - material interactions at > 5 mm
- Precise material VELO map by secondary interactions of hadrons produced in beam-gas collisions

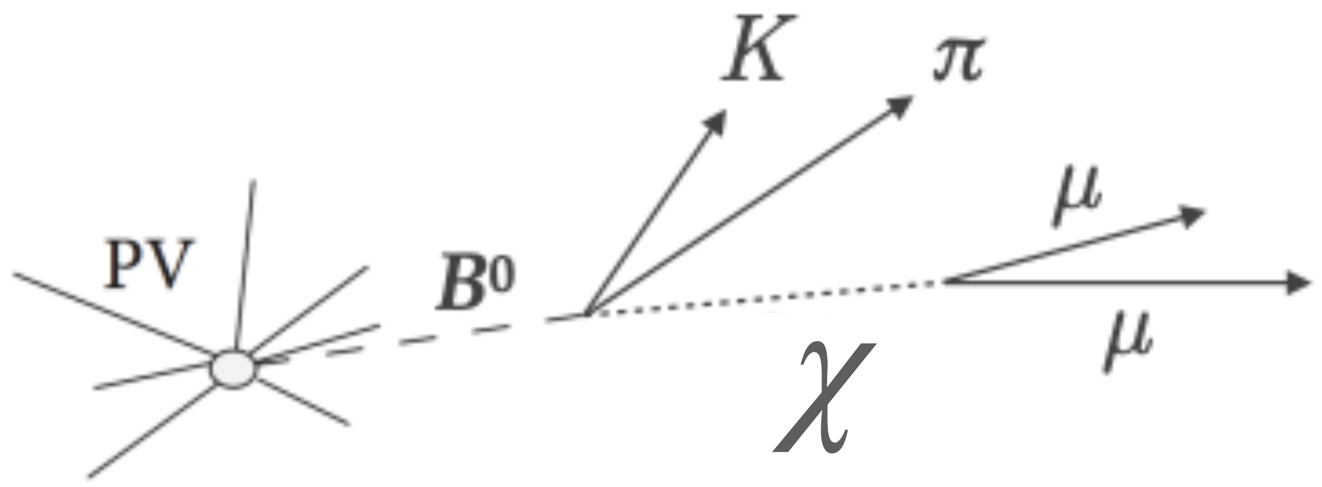




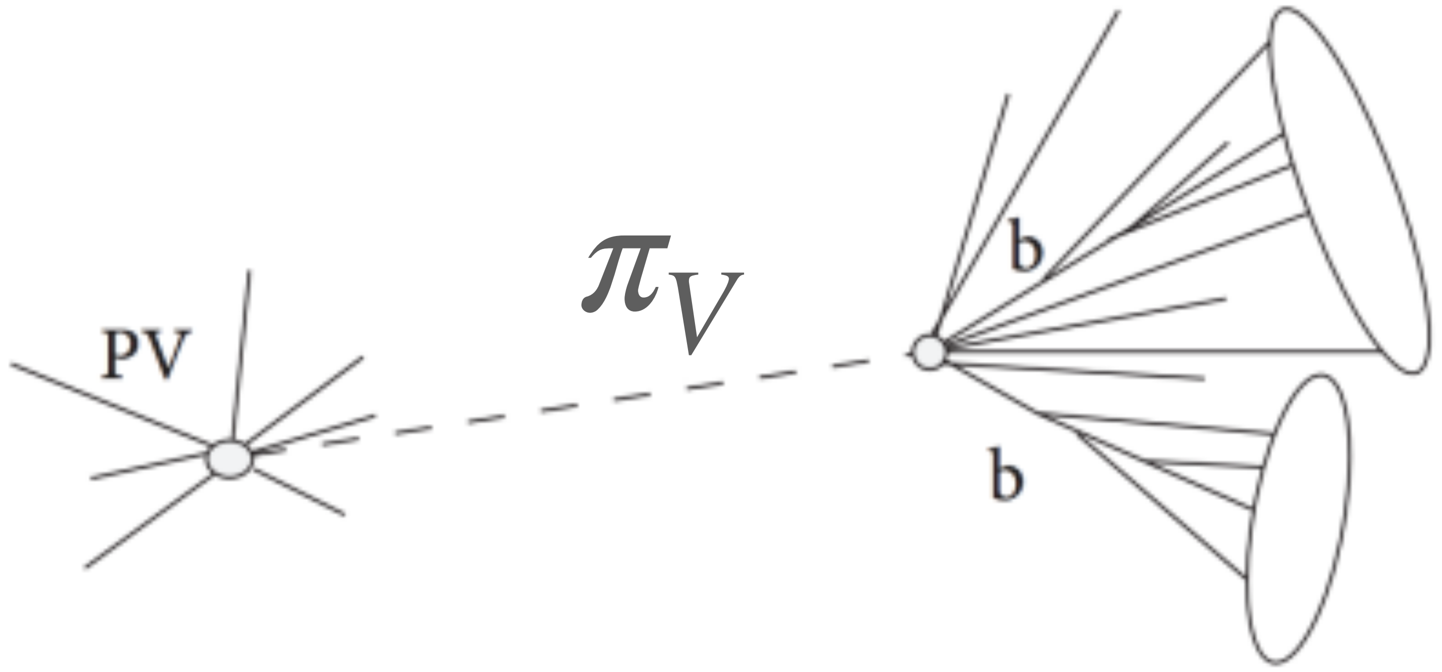
- So far only performed analyses on Run 1 and Run 2 data with LLPs decaying within the VELO
- Searches could be extended to LLPs decaying downstream of the VELO (displacement up to 200 cm) → much worse momentum resolution

LLPs searches at LHCb so far…

- Displaced leptons:
  - Dark photon — PRL 124(2020) 041801
  - Low-mass di-muon resonances — LHCb-PAPER-2020-013
  - Majorana neutrino — PRL 112 (2014) 131082
  - LLPs decaying to $e^{\pm}\mu^{\mp}\nu$ — EPJC 81 (2021) 261
  - Light boson from $b \to s$ decays — PRD 95 (2017) 071101



- Displaced jets:
  - HNL in $W^{\pm} \to \mu^{+}\mu^{\pm}$ jet — EPJC 81 (2021) 248
  - LLP $\to$ jet jet — EPJC 77 (2017) 812
  - **LLP $\to \mu$ + jets** — LHCb-PAPER-2021-028



Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13$ TeV

Theory context

- Supersymmetry (SUSY) is one of the most popular extension of Standard Model (SM)
  - Solves the hierarchy problem
  - Unifies gauge couplings at Planck scale
  - Dark Matter candidates
- Subset of models for Minimal Supersymmetric Standard Model (MSSM) addresses long-lived particles
  - Main signature: measurable flight distance and displaced vertices
- If considering R-parity violation (RPV) processes a MSSM long-lived particle can decay into SM particles
- In this analysis the minimal SUper GRAvity (mSUGRA) theoretical model has been considered, with RPV
  - A “neutralino” $\tilde{\chi}_1^0$ can decay into a muon and two quarks: $\tilde{\chi}_1^0 \to \mu^+ q_i q_j (\mu^- \bar{q}_i \bar{q}_j)$

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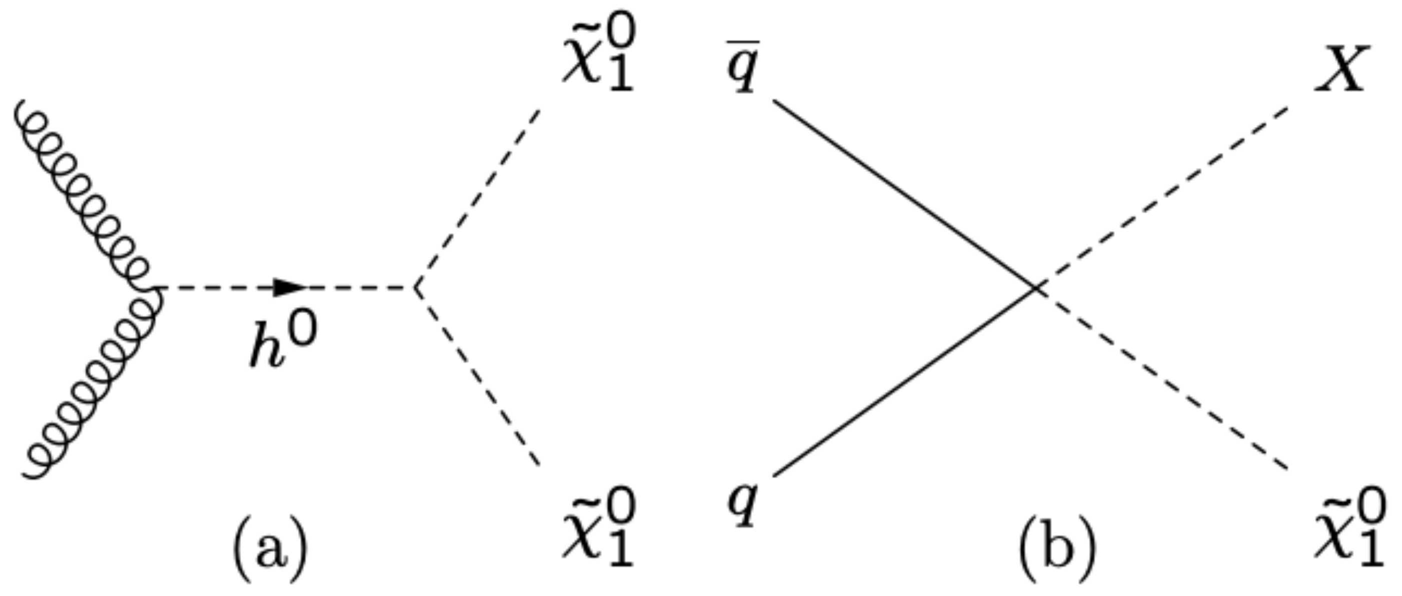
LLPs production mode

- In this analysis two productions mode have been considered:

Higgs-like boson decay



Direct production

- The Higgs-like decay analysis covers h^0 masses from 30 to 200 GeV/c²
- LLPs masses are in the range [10, $\sim m(h^0)$/2] GeV/c² and lifetimes in the range [5,200] ps
- The direct production mode address LLPs masses in the range [10, 90] GeV/c² and lifetimes in the range [5,200] ps

- Lifetime range well above b-hadron lifetime and vertices still within LHCb VELO
- Mass range to avoid SM b-quark states and to consider LHCb forward acceptance

- Relevant backgrounds: $b\bar{b}$ and $c\bar{c}$ direct production and Z, W, Higgs and top decays

Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13$ TeV

Signal Selection

- The LLP signature is a displaced vertex (charged particles tracks) + isolated muon with high p_T
- Muons are expected to be more isolated than muons in hadron decays (high LLP masses)

- PV selection:
  - Small radial distance from beam axis, $R_{xy} < 0.3$ mm
- Muon selection:
  - Online trigger selects muon with $p_T > 10$ GeV/c
  - Offline selection: impact parameter IP$^{\mu} > 0.25$ mm and $p_T > 12$ GeV/c
  - Isolation: sum of energy tracks around muon (with muon) in a cone of radius $R_{\eta\phi} = 0.3$
- LLP selection:
  - Once PVs are found, geometric veto on displaced vertices (remember VELO material map)
  - A LLP candidate is formed by 3 or more tracks + muon, and $m_{inv}(\text{LLP}) > 4.5$ GeV/c^2

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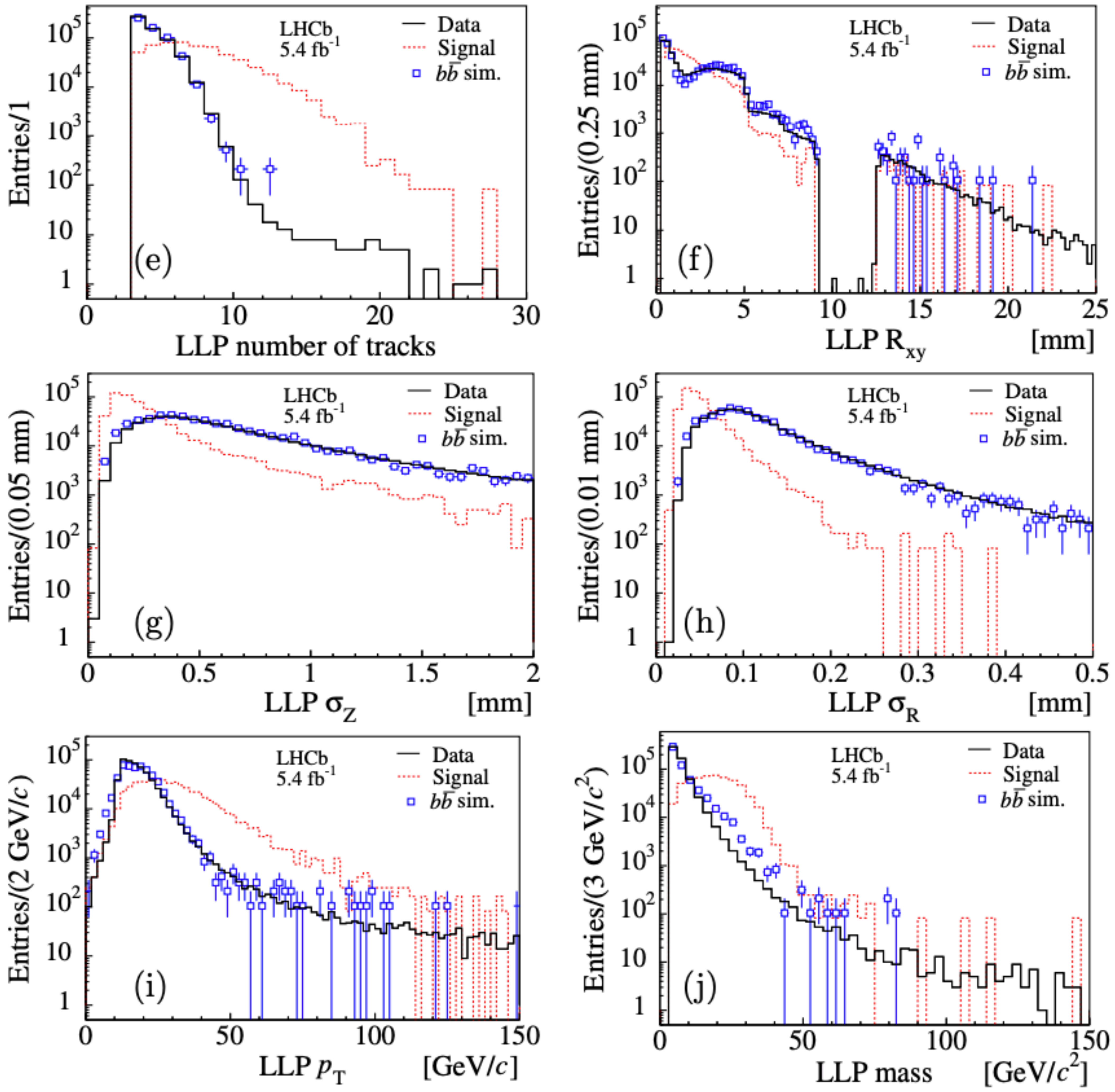
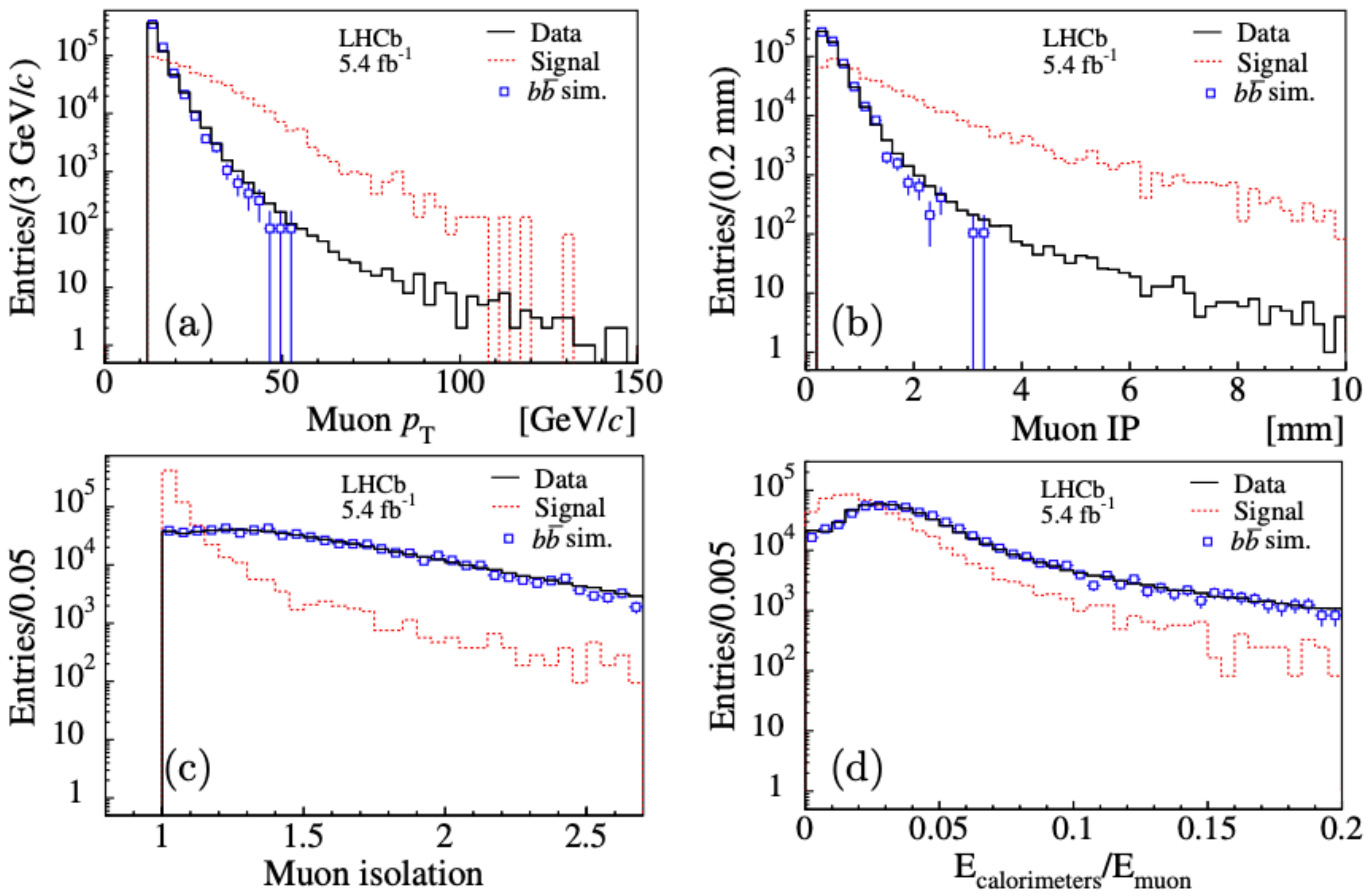
Signal Selection

- Distribution for simulated $b\bar{b}$ background samples and $h^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ with $m(h^0) = 125$ GeV/c² and $m(\tilde{\chi}_1^0) = 40$ GeV/c²
- Shapes are consistent with $b\bar{b}$ composition of background
- Background estimation used as cross-checks (see later)





Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13$ TeV

MVA analysis

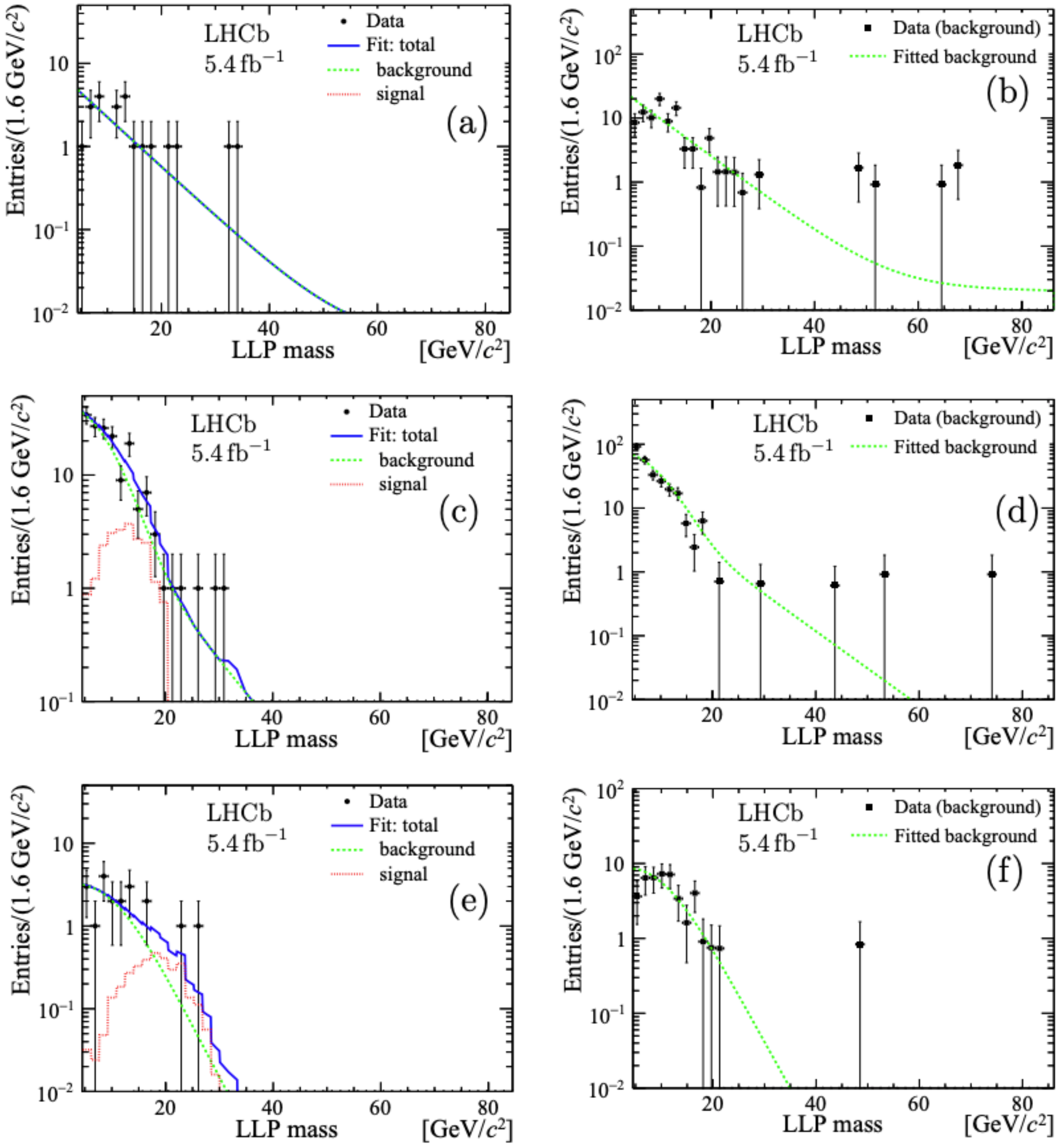
- A multivariate analysis (MVA) based on Boosted Decision Trees is used to further purify the data sample
- Ten MVA input variables are selected to perform signal-background separation
  - p_T and IP of the muon
  - Ratio of energies released in ECAL and HCAL normalized to muon energy
  - p_T and η of the LLP candidate
  - Number of tracks forming the LLP candidate
  - Vertex distance R_{xy}
  - Uncertainties of the vertex: σ_R, σ_z

- Muon-isolation variable and reconstructed LLP mass are used to get the LLPs yield
- Signal MVA training samples are obtained from simulation
- Background training sample is obtained from data
  - No bias on MVA performance

Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13$ TeV

Signal Extraction

- After MVA application no background events survive
- Background is obtained with a data-driven method
- Muon isolation is used to find a signal and a background region:
  - Signal region = muon-isolation variable < 1.2
  - Background region = muon-isolation variable > 1.2
- 80% of signal events are included in the signal region
- Fit to reconstructed LLP mass from background region
  - Constraints on fit on signal region



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Efficiencies and systematics

- Detector efficiency is estimated from simulations
- Several factor to be taken into account:
  - Efficiency increases with LLP mass (more particles are produced)
  - Loss of particles outside the detector when LLPs come from heavier states
  - Lower boost of heavier LLPs results in shorter flight distance (cut on radial distance R_{xy})
  - With increasing LLPs lifetime → material region VETO
  - Loss in efficiency due to MVA selection

- Systematic uncertainties take into account several aspects
  - Muon reconstruction
  - Vertex reconstruction
  - MVA discrimination
  - …

Direct production mode

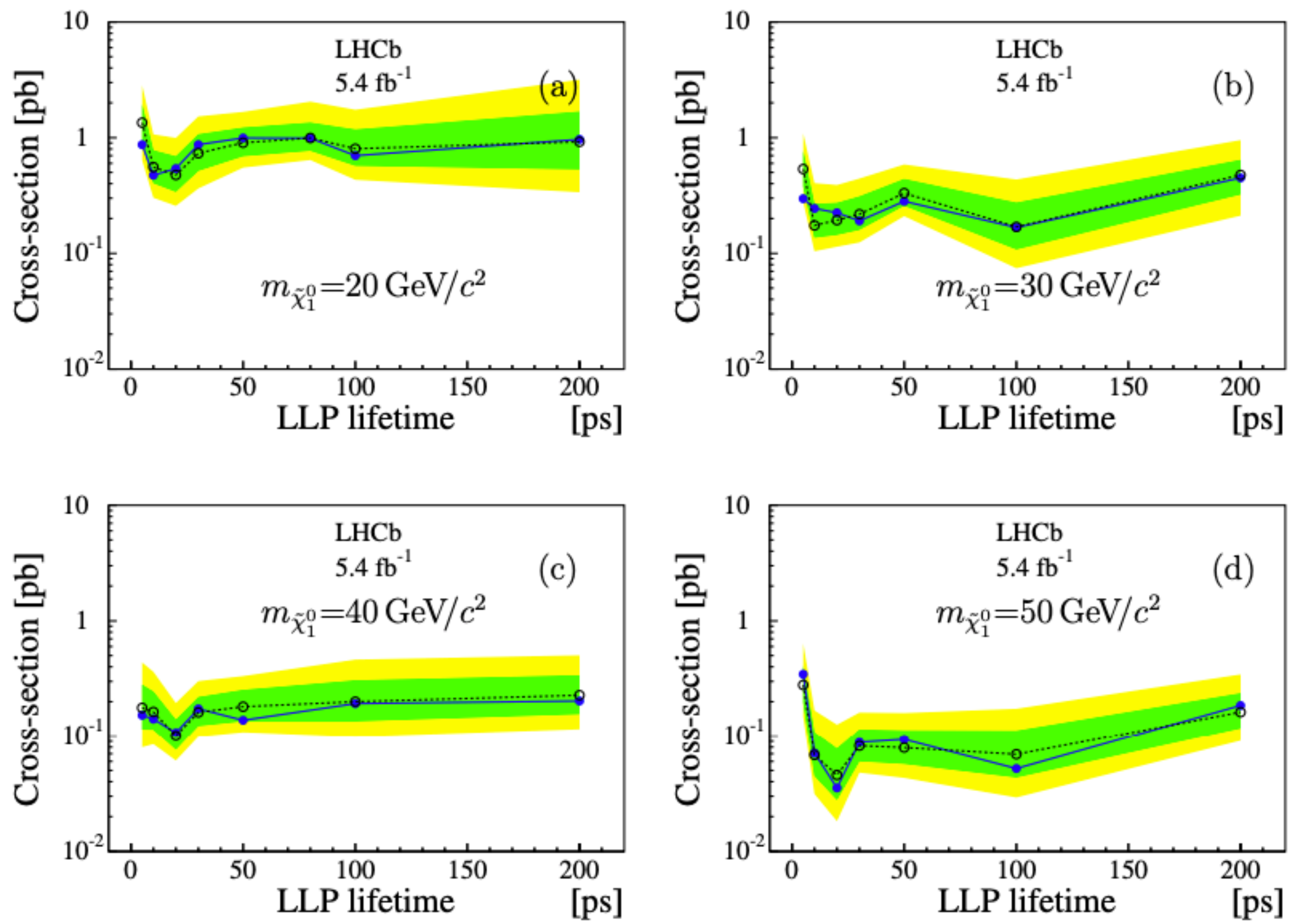
$m_{\tilde{\chi}_1^0}$	$\tau_{\tilde{\chi}_1^0}$	ε_{presel}	ε	N_b	N_s	χ^2/ndf
10	10	0.61	0.13	2767.9 ± 88.2	−141.8 ± 69.7	1.69
20	10	0.66	0.23	43.9 ± 40.1	−4.2 ± 5.0	0.67
30	10	2.29	0.47	15.7 ± 5.8	3.3 ± 5.2	0.90
40	10	2.49	0.52	1.1 ± 1.4	5.9 ± 2.8	0.96
60	10	3.81	1.97	45.1 ± 5.6	−8.0 ± 4.3	0.80
90	10	2.52	1.68	30.8 ± 2.2	−9.8 ± 5.0	1.04
30	5	1.44	0.21	11.0 ± 2.5	−1.0 ± 2.7	0.67
30	20	2.64	0.66	13.8 ± 4.4	3.2 ± 4.2	0.65
30	30	2.52	0.74	5.6 ± 2.2	2.4 ± 2.1	0.41
30	50	2.25	0.81	16.5 ± 16.1	−1.8 ± 3.2	0.69
30	100	1.68	0.61	9.9 ± 7.4	−1.7 ± 3.1	1.10
30	200	1.06	0.29	38.0 ± 6.3	0.0 ± 2.3	0.79

Source	Contribution [%]
Integrated luminosity	2.0
Parton luminosity gluons fusion (quarks)	6.0 (3.0)
Simulation statistics	2.0–4.0
Muon reconstruction	2.0–3.7
p_T^μ	1.0
IP^μ	1.0
Vertex reconstruction	2.0
Beam line uncertainty (R_{xy})	0.9
Muon isolation	1.7
MVA	1.7-16
Mass calibration	1.4
Total	7.3–18.9

Search for massive long-lived particles decaying semileptonically at $\sqrt{s} = 13$ TeV

95% CL upper limits

- No excess is found
- 95% CL upper limits are computed on $\sigma(\text{LLPs}) \times \mathscr{B}(\text{LLPs} \to q\bar{q}\mu)$ for both production modes
- Statistical and systematic uncertainties are included as nuisance parameters



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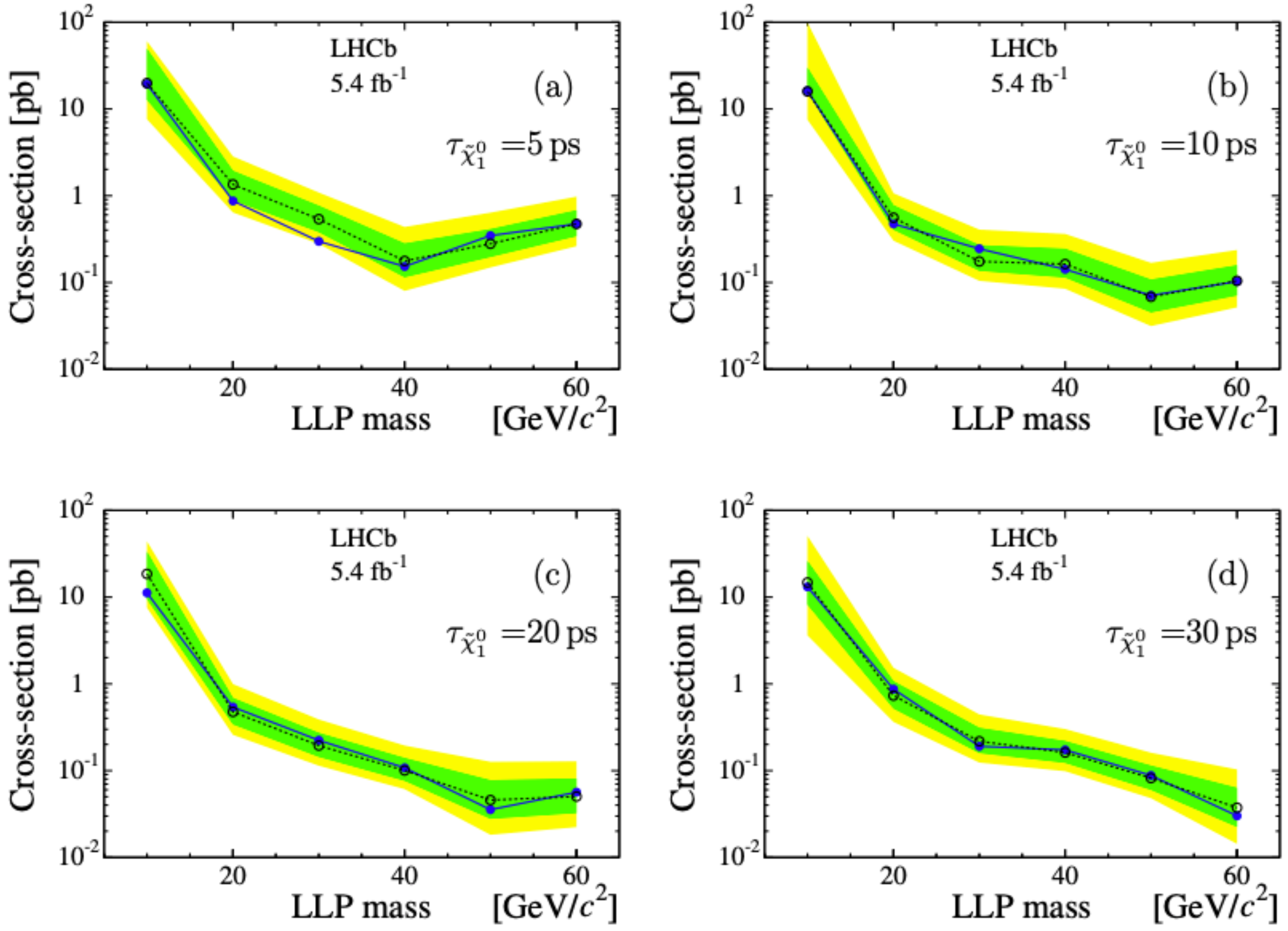

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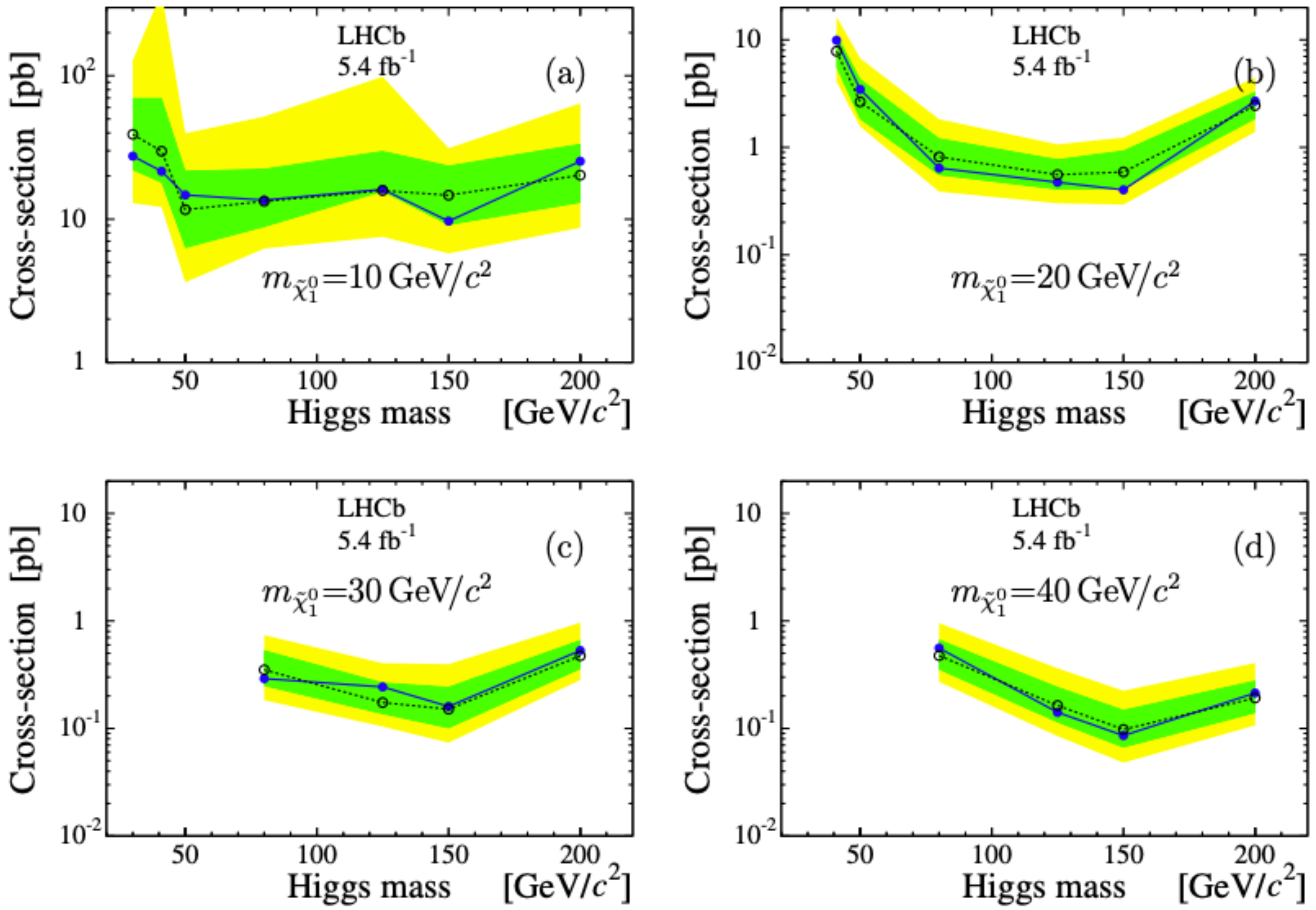

Conclusions
Wrap up

- LHCb is by all means a **general purpose forward detector**

- LHCb is a unique place to study LLPs:
  - Detection of low-mass particles and soft signatures
  - Studies on b- and c-decays
  - Phase space region complementary to ATLAS and CMS

- Here we studied massive LLPs decaying semileptonically into a muon and two quarks
  - Two production modes (direct production and Higgs like boson decay)
  - Different mass and lifetime ranges
  - Upper limits on $\sigma(\text{LLPs}) \times \mathcal{B}(\text{LLPs} \to q\bar{q}\mu)$ with sensitivity of the order $O(1\ \text{pb})$

- If you're interested in LLPs searches at LHCb go check yesterday's presentation

Thank you for your attention!