technische universität
dortmund

QCD, electroweak physics, and searches for exotic signatures in the forward region at LHCb

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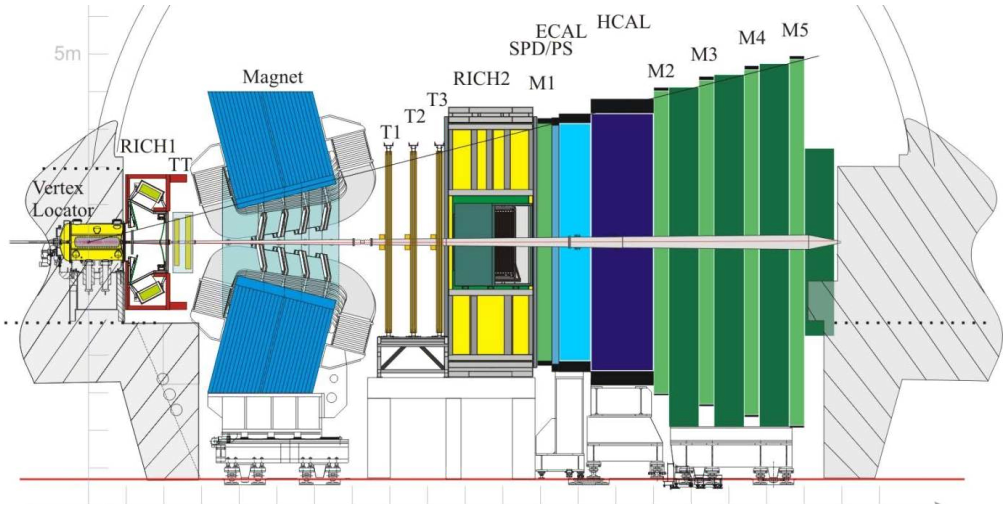
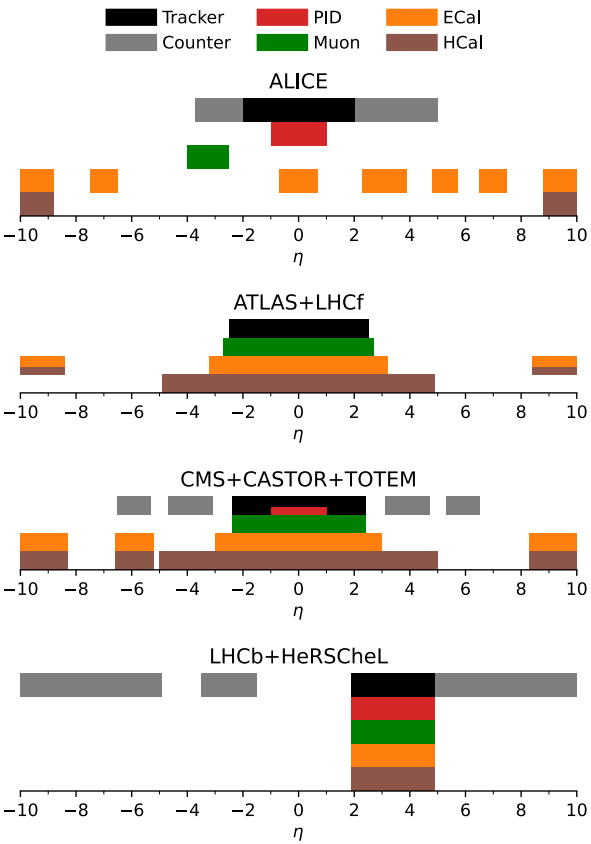
Rencontres de Blois
October 2021

LHCb detector

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



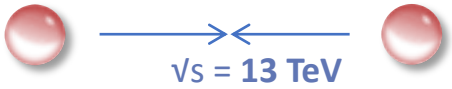


General purpose single-arm forward spectrometer

- Acceptance
  - $2 < \eta < 5$ with particle identification
  - $0.1 < p_T$ / GeV$c^{-1} < 10$
- Very good momentum and vertex resolution
  - Very good discrimination of prompt charm & beauty
- Very accurate luminosity (world record for *p-p* 7 TeV)
- PID optimal for μ, p, K, π
- Flexible software trigger

Overview

$p\text{-}p \ \sqrt{s} = 13 \text{ TeV}$

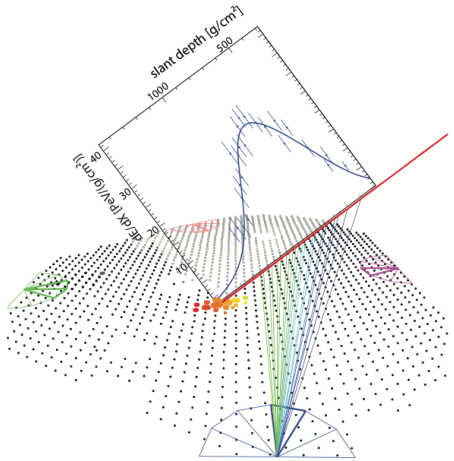


Legend
QCD
EW
Exotics

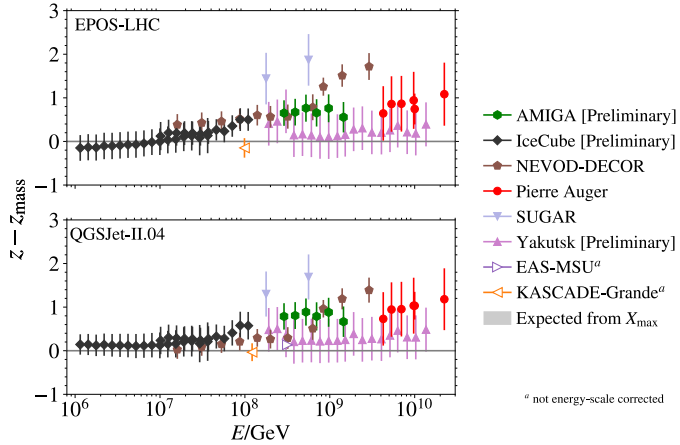
- Prompt charged particles
- Z bosons produced in association with charm
- W mass
- Search for neutral long-lived particles in semi-leptonic decays New!

Muon Puzzle in air showers

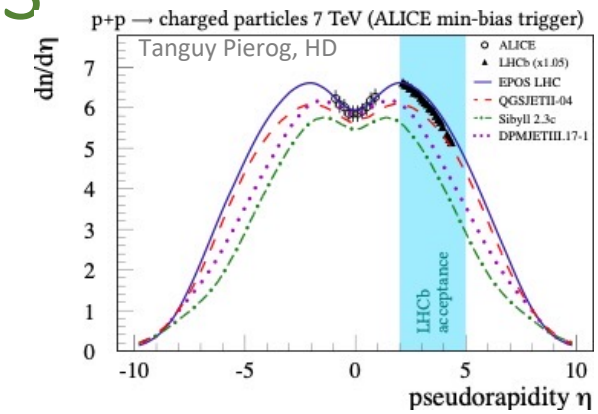
ALICE, EPJC 68 (2010) 345
LHCb, EPJC 72 (2012) 1947
CMS, PLB 751 (2015) 143-163

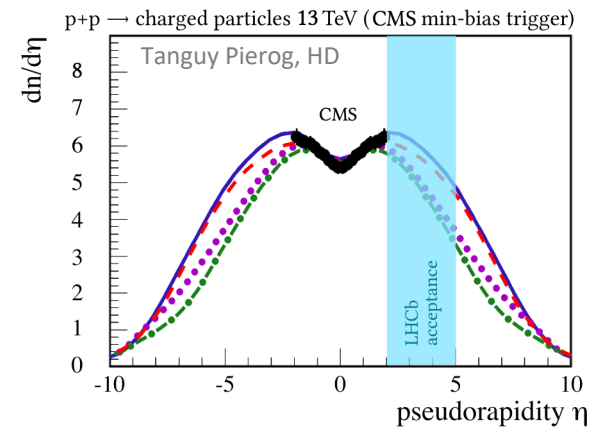


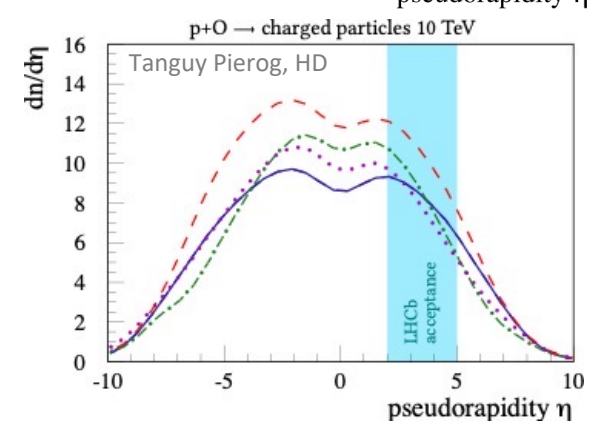
Example event from Pierre Auger Observatory



EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, Yakutsk EAS Array Collaborations (HD et al.), EPJ Web Conf. 210 (2019) 02004







- Air showers are hadronic cascades driven by soft-QCD interactions
- Muon Puzzle: μ deficit in simulated showers starting at $\sqrt{s_{NN}} \approx 8$ TeV
- Muon production quantitatively linked to forward hadron production and hadron composition Ulrich et al. PRD 83 (2011) 054026 Baur et al. arxiv:1902.09265
- Nuclear effects in target important, large interest in p+O

Prompt charged particles

***pp* 13 TeV** 5.4/nb

LHCb-PAPER-2021-010 arXiv:2107.10090, submitted to JHEP

- First double-differential forward charged particle spectrum at 13 TeV
- Fundamental measurement for (soft-)QCD, generator tuning, and astroparticle physics

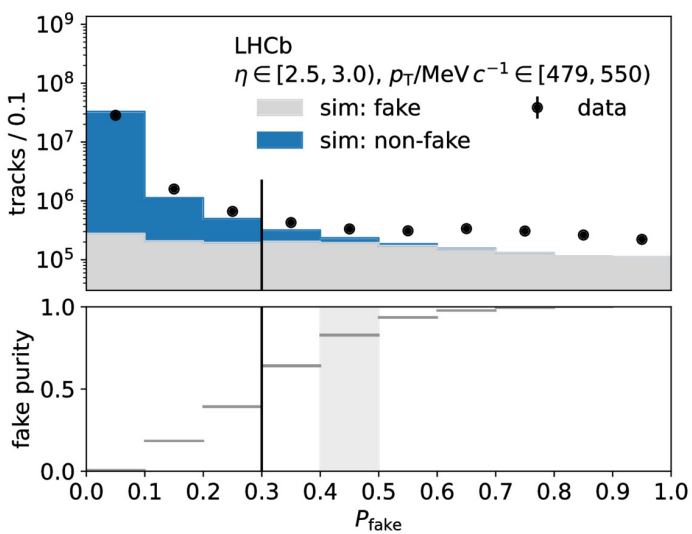
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\eta\,\mathrm{d}p_\mathrm{T}} \equiv \frac{n}{\mathcal{L}\,\Delta\eta\,\Delta p_\mathrm{T}}$$

prompt particles

$$n_\mathrm{cand} = \varepsilon n + \sum_i n_{\mathrm{backgr},\,i}$$

detection and selection efficiency

Control study on fake track probability

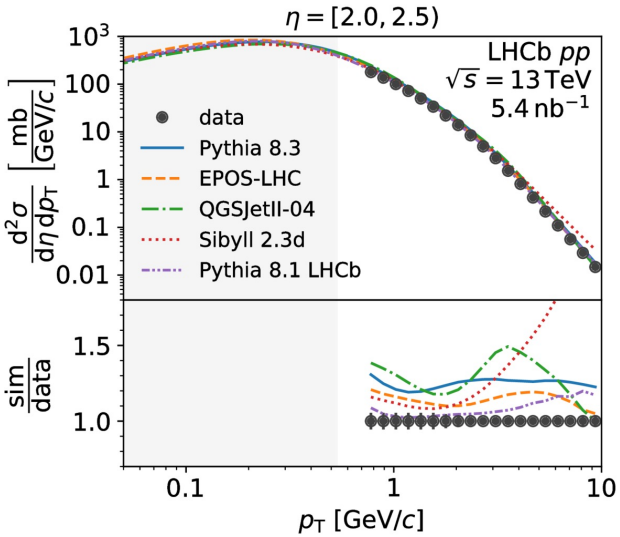


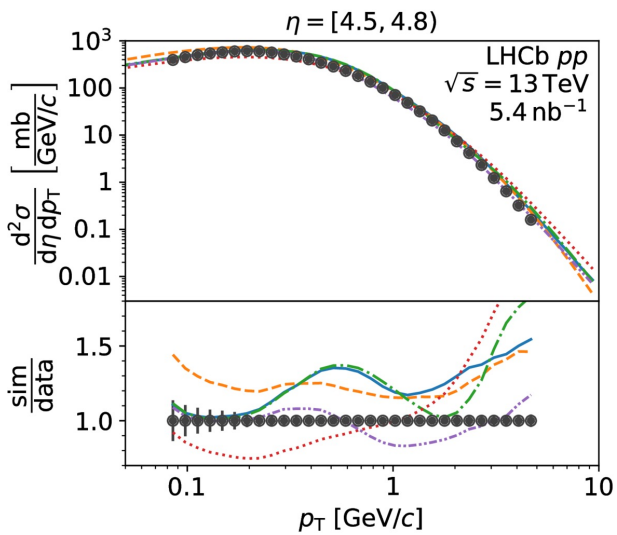
- Loose candidate selection with high efficiency
- Total efficiency from data-adjusted simulation
- Backgrounds subtracted using data-adjusted simulation; e.g. fake tracks, tracks from material interactions
- Analysis written completely in Python
  - Numerical code accelerated with Numba
  - Python scientific stack + Scikit-HEP tools

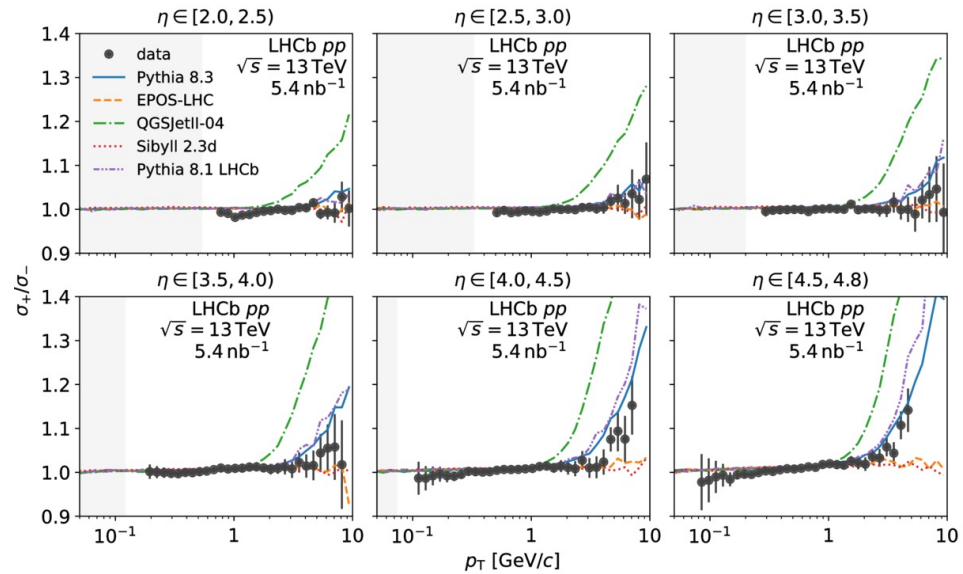
Prompt charged particles

***pp* 13 TeV** 5.4/nb

LHCb-PAPER-2021-010 arXiv:2107.10090, submitted to JHEP







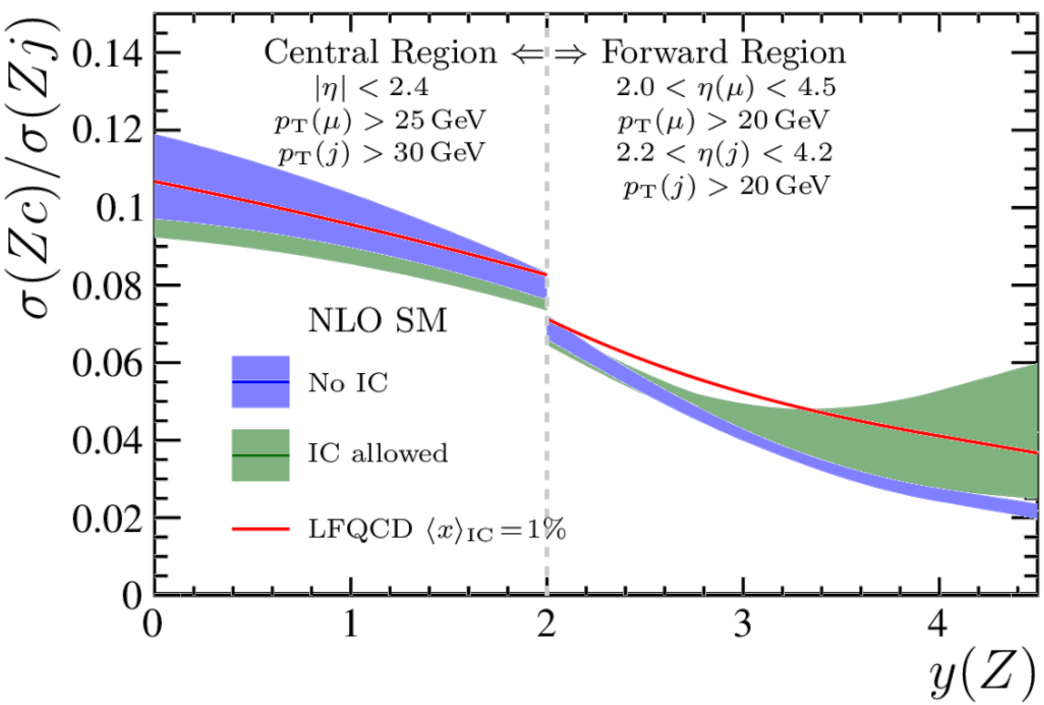
- Uncertainty (2.3 to 15) %
  - Fake tracks < 9.5 %
  - Material interactions < 12 %
  - Tracking efficiency < 5.1 %

  Outlook: reduce each with improved techniques
- Full covariance matrix will be published for first time for charge particle analysis in LHCb
- Comparison with QCD generators
  - Generators mostly overestimate forward density
  - Charge density: Best agreement with EPOS-LHC
  - Charge ratio: Best agreement with Pythia-8.3
- Outlook: Extend to p-Pb and identified hadron spectra

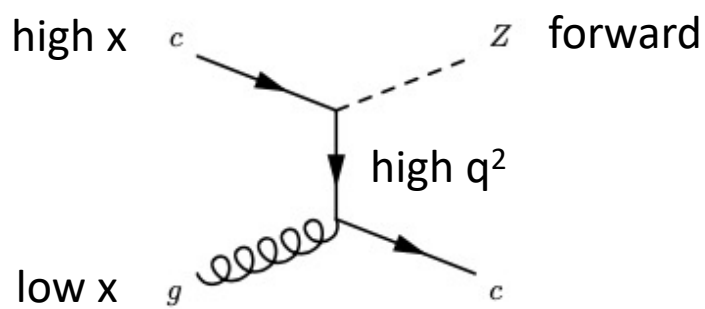
Z bosons produced in association with charm

LHCb-PAPER-2021-029 arXiv:2109.08084, submitted to PRL ***pp* 13 TeV** 6/fb

- Does proton PDF contain $|uudc\bar{c}\rangle$ component aka Intrinsic Charm (IC)?
- Predicted by Light Front QCD at percent level
- Predicted signature: enhanced production cross-section for charm at high *x*
- Important consequences for e.g. cosmic-ray interactions and atmospheric neutrino flux



- Observable $R_j^c = \sigma(Z\,c) / \sigma(Z\,j)$ should show enhancement at large rapidity
- First measurement of R_j^c at y > 2.5
- Low systematic uncertainties
  - Theory: associated production at high q^2, can use pQCD
  - Experiment: similar kinematics, efficiencies largely cancel



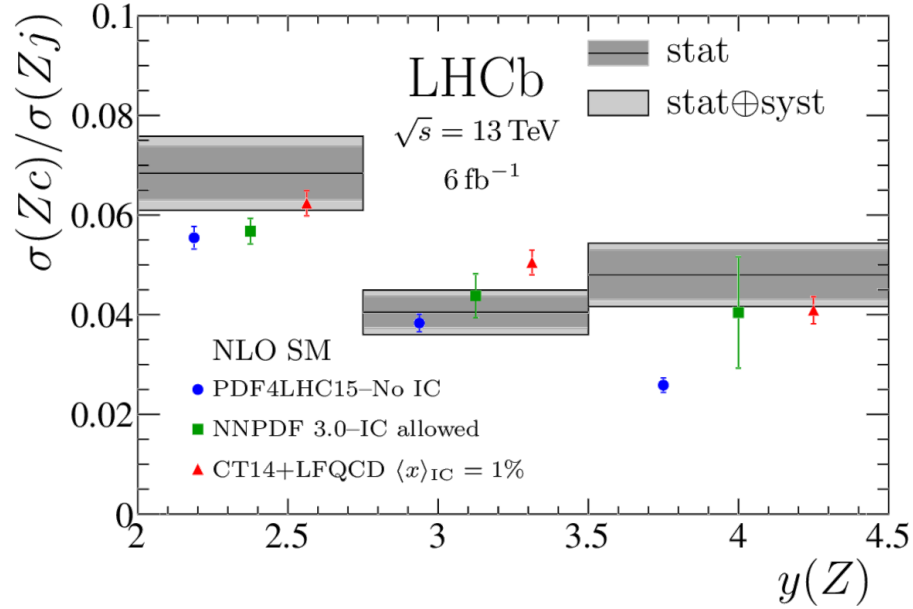
Z bosons produced in association with charm

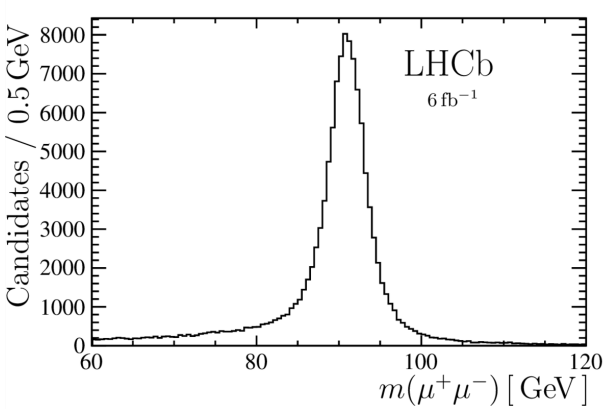
LHCb-PAPER-2021-029 arXiv:2109.08084, submitted to PRL

***pp* 13 TeV** 6/fb

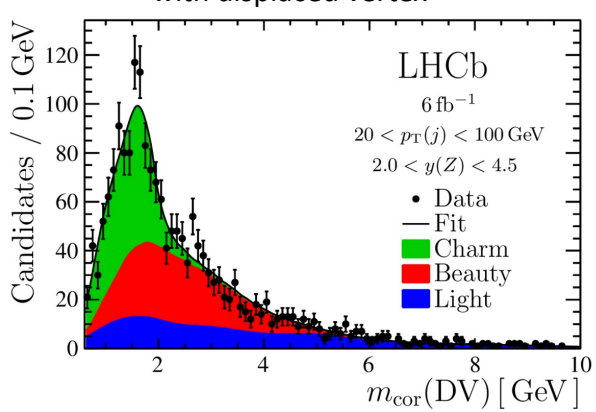
- Z bosons reconstructed from Z ⟶ μμ decays
- Jets reconstructed with anti-k_T algorithm (FASTJET)
- c-tagging via displaced-vertex inside jet
- Raw yields in (y, p_T) corrected via unfolding and integrated over p_T > 20 GeV/c
- Backgrounds from beauty and light-parton jets rejected via cuts on jet properties

- High-rapidity bin consistent with IC models
- Result expected to strongly constrain IC in global PDF fits

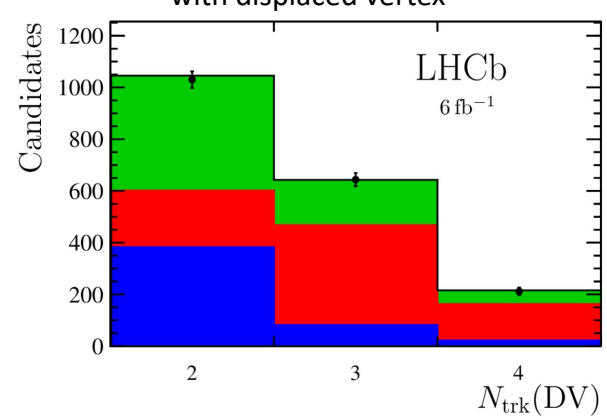




estimated mass of particle with displaced vertex



number of tracks in jet with displaced vertex



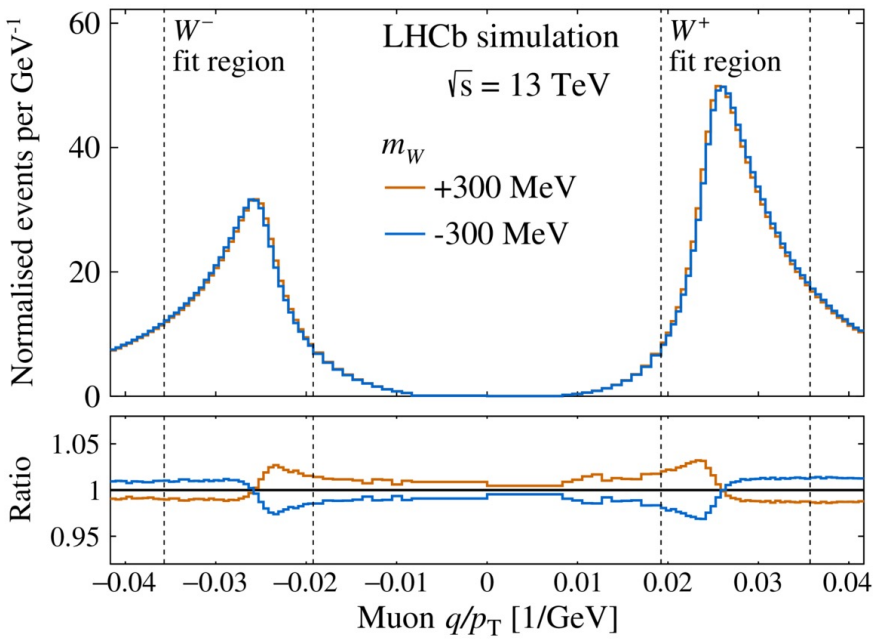
W boson mass

***pp* 13 TeV** 1.7/fb

c = 1

LHCb-PAPER-2021-024 arXiv:2109.01113, submitted to JHEP

- New physics may appear in loop corrections to W mass
- Compare direct with indirect measurements based on electroweak observables
- Accuracy limited by uncertainty of direct measurements
- Combining results from ATLAS/CMS and LHCb should boost accuracy (η coverage)



- First LHCb measurement of m_W with $W \longrightarrow \mu\nu$ decays

- Distribution of muon q/p_T sensitive to m_W
- Also sensitive to p_T^W of W boson
- Measure proxy ϕ^* for p_T^Z distribution to validate predictions of p_T^W distribution

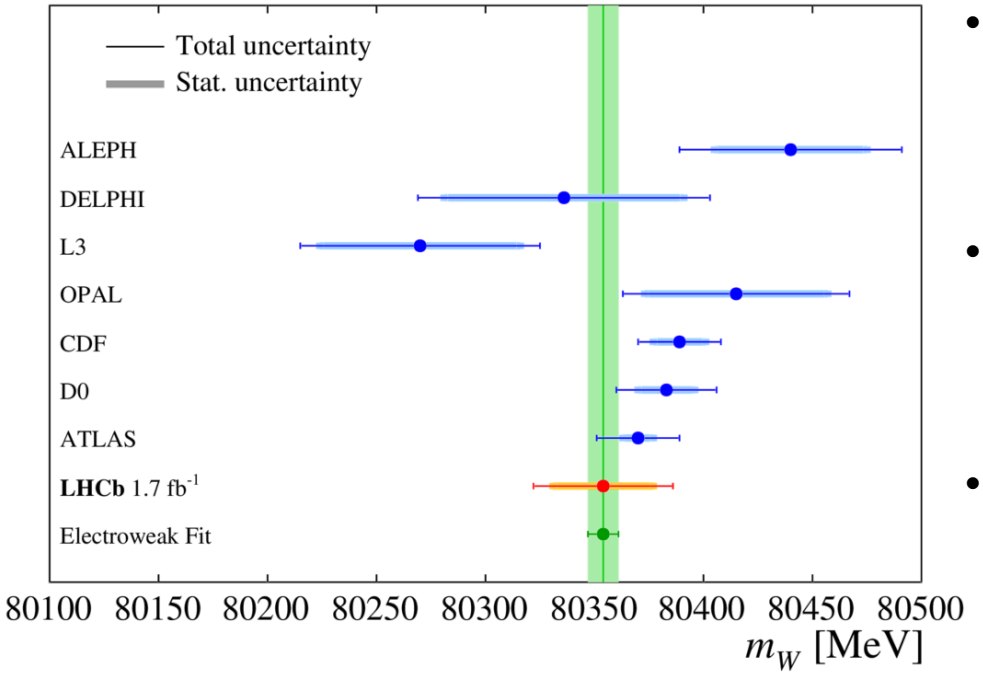
$$\phi^* \sim \frac{p_T^Z}{M}$$

W boson mass

***pp* 13 TeV** 1.7/fb

c = 1

LHCb-PAPER-2021-024 arXiv:2109.01113, submitted to JHEP



- Momentum and efficiency corrections with control measurements Z, J/ψ, Υ(1S) ⟶ μμ decays
- Theory uncertainty from modelling W and Z boson production studied with different generators in Z ⟶ μμ
- W mass determined in simultaneous fit to q/p_T and ϕ^* distributions

11 MeV from transverse momentum model

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Plan to reduce with larger sample in Run 3

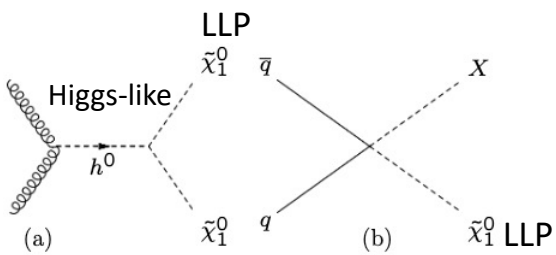
Plan to reduce with *in situ* constraints from analyzing 2D (η, p_T) distribution

Search for neutral long-lived particles (LLP)

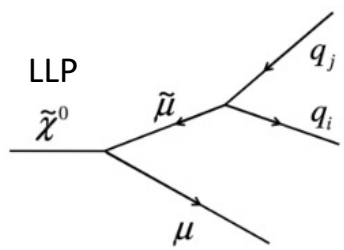
LHCb-PAPER-2021-028 arXiv:2110.07293, submitted to EPJ C New!

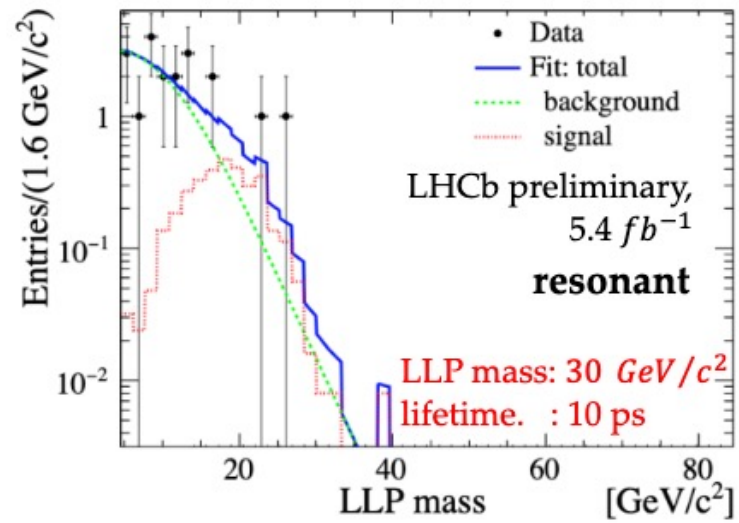
***pp* 13 TeV** 5.4/fb

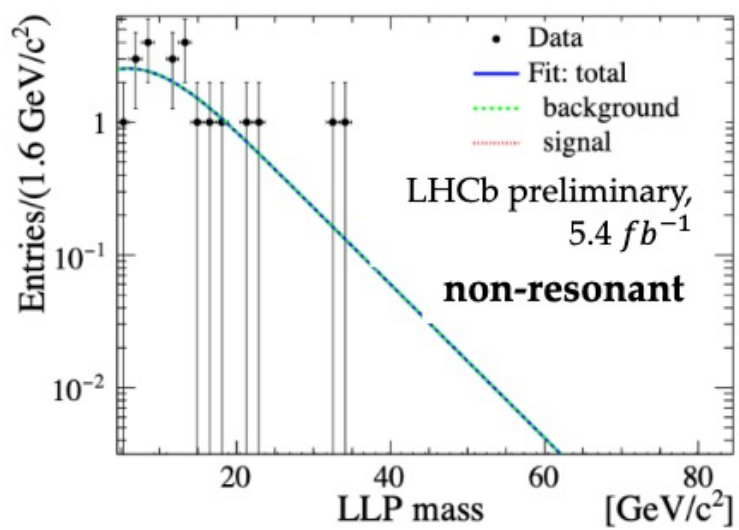
- Heavy long-lived particles may appear in SUSY
- Benchmark model: mSUGRA with R-parity violation, where neutralino decays (LLP)
- Search via semi-leptonic decays, extending previous LHCb analysis with 3/fb
  LHCb, EPJ C77 (2017) 812



resonant non-resonant





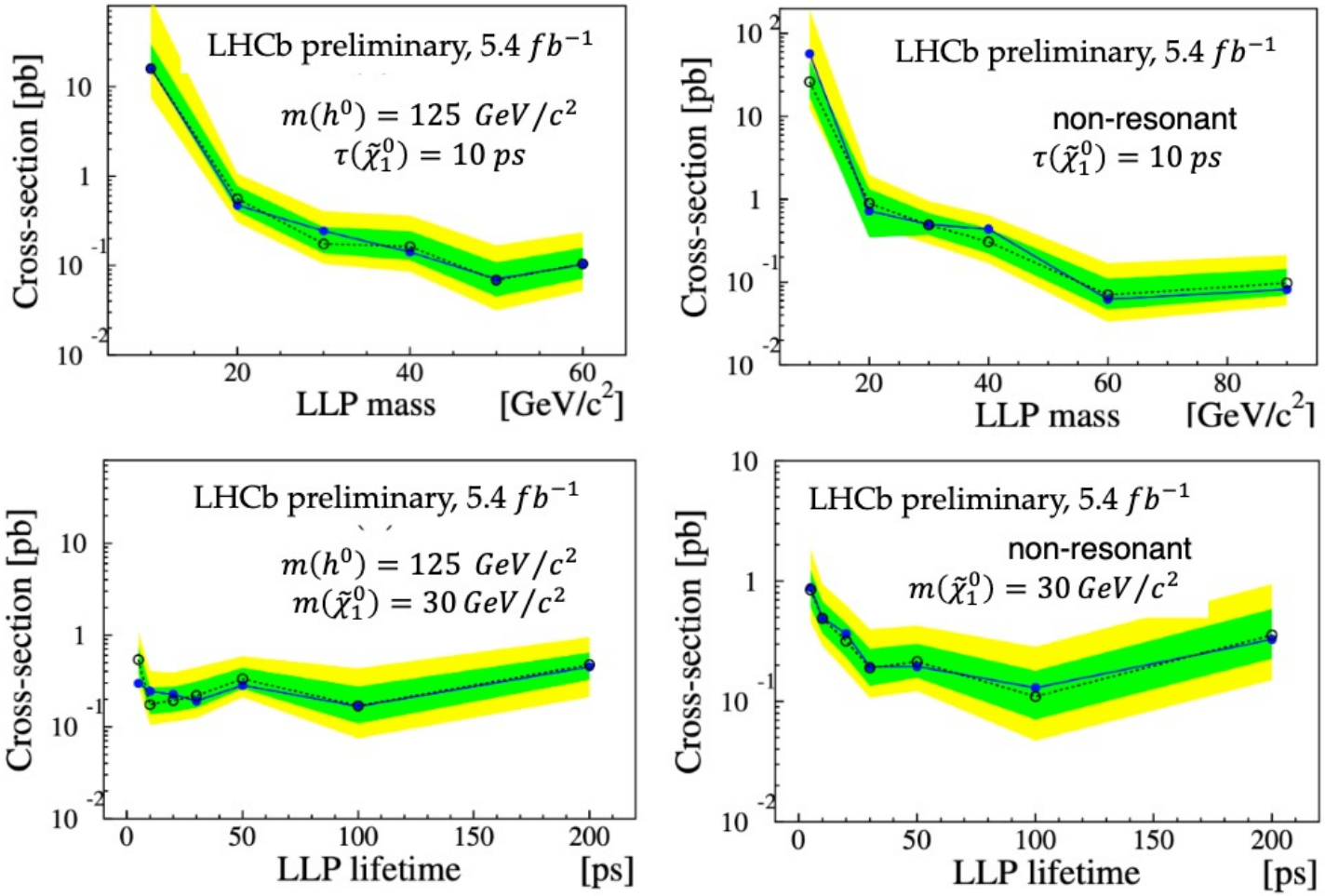


- Selection
  - High p_T muon from secondary vertex and 2+ tracks
  - SV in vertex locator vetoed
  - Multi-variate kinematical selection for each model, background sample taken from real data

Search for neutral long-lived particles (LLP)

LHCb-PAPER-2021-028 arXiv:2110.07293, submitted to EPJ C New! ***pp* 13 TeV** 5.4/fb

No signal, 95% CL upper limits on cross-section × branching fraction as function of LLP mass, LLP life-time, h^0 mass (in case of resonant production)

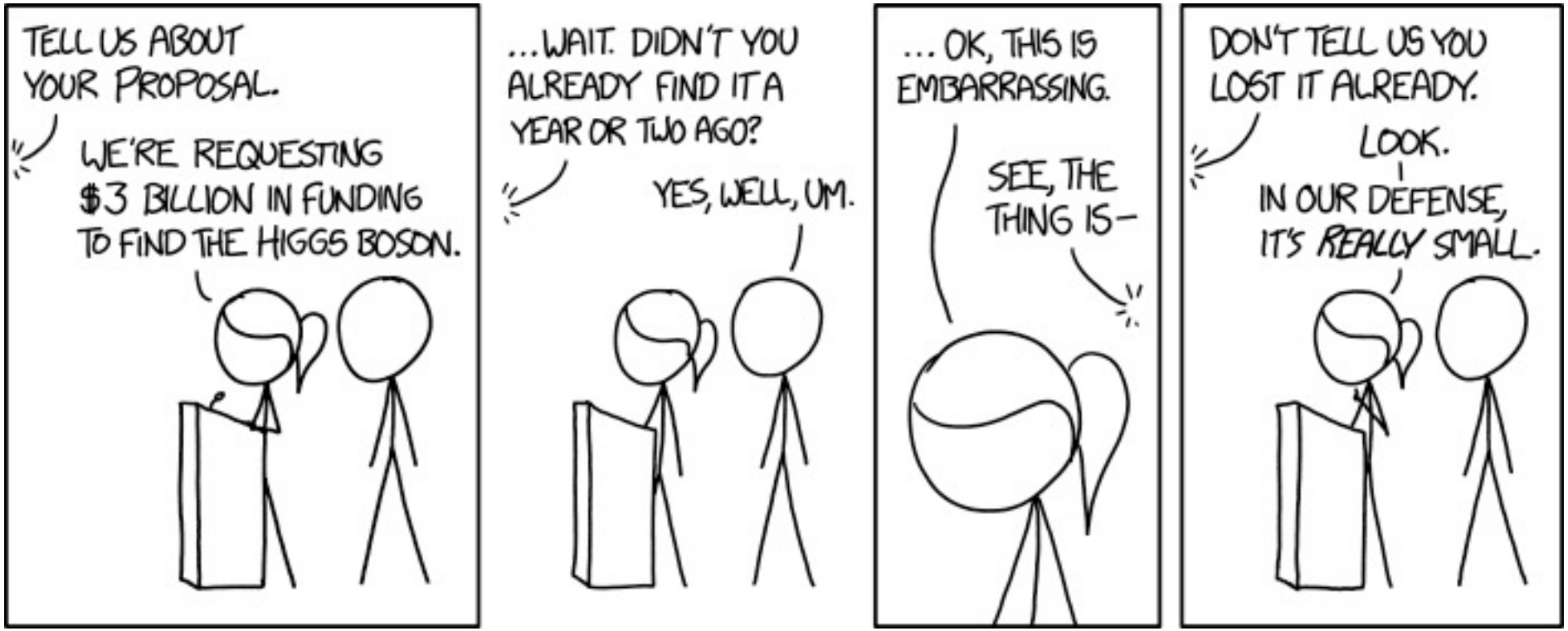


Summary

- LHCb offers unique opportunities for QCD+EW measurements and searches for exotics in forward region

- *p-p* $\sqrt{s} = 13$ TeV
  - Prompt charged particles
    LHCb-PAPER-2021-010 arXiv:2107.10090
    - First measurement of double differential cross-section in forward region at 13 TeV
    - Input for the Muon Puzzle in astroparticle physics
  - Z bosons produced in association with charm
    LHCb-PAPER-2021-029 arXiv:2109.08084
    - Hints for intrinsic charm in the proton PDF
    - Input for calculation of atmospheric background to astro-neutrinos
  - Direct measurement of W mass
    LHCb-PAPER-2021-024 arXiv:2109.01113
    - High-precision measurement with further room for improvement
    - Complementary to ATLAS/CMS, will boost accuracy of global fits
  - Search for neutral long-lived particles in semi-leptonic decays New!
    LHCb-PAPER-2021-028 arXiv:2110.07293
    - Upper limits on cross-section × branching fraction at level of 0.1-1 pb

Thank you!



Randall Munroe, https://xkcd.com/1437/