Search for New Physics in current and future experiments

Mateusz Goncerz (KISD)

Motivation

The Standard Model is likely not the fundamental theory of particle physics, but can be replaced or extended in many equally valid ways.

It's important to:

- understand how it breaks
- plan future experiments and search methods accordingly
- search for particles and phenomena predicted by new theories

I want to talk about New Physics with these three perspectives.

MUonE collaboration

muon's anomalous magnetic moment

M. Goncerz et al., JINST 16 (2021) P06005

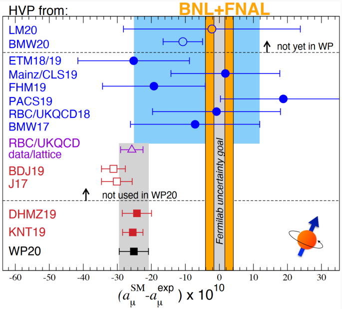
The current picture

$$a_\mu = \frac{g-2}{2},\ \ g - \text{magnetic g-factor}$$

$a_\mu^{SM} \neq 0$ due to self-interactions and shielding from virtual pairs, but exact value hard to estimate because of non-perturbative contributions.

Data-driven predictions in 5+ σ disagreement with measurement, lattice QCD calculations model dependent and with high uncertainties.

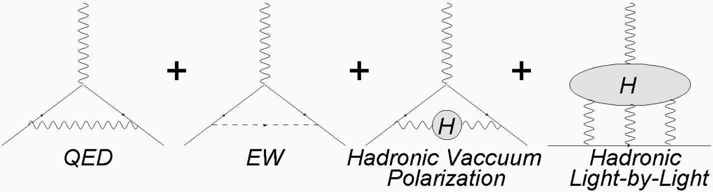
arXiv:2203.15810 (2021 result)



2023 result (arXiv:2308.06230) reduces the uncertainty by a factor of 2

circles – lattice, squares – data driven
triangle – combined

Structure of a_μ^{SM}

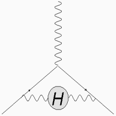


contribution	exact corrections	value $[\cdot 10^{-11}]$	σ	σ/σ_{total} [%]
QED	5 loops	116'584'718.931	0.104	0.001
EW	2 loops	153.6	1.0	0.2
HVP	non-perturbative	6'845	40	99.8
HLbL	non-perturbative	92	18	
Total SM		116'591'810	43	

The Leading Order Hadronic Vacuum Polarization (HVP) contribution dominates the Standard Model uncertainty.

$a_\mu^{\text{HVP, LO}}$ – standard data driven method

The Leading Order HVP term can be tied to experimental hadronic cross-sections (mostly pion production in electron-positron collisions):

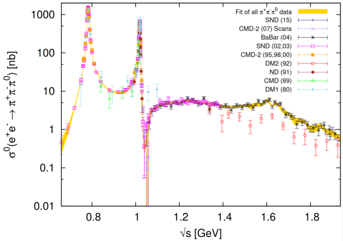


$$a_\mu^{HVP,LO} = \frac{1}{4\pi^3} \int_{m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{had}(s)$$

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)\left(s/m_\mu^2\right)}$$

Very challenging to integrate due to resonances and threshold effects.

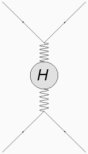
arXiv:1802.02995



Approx. 0.6% precision, preliminary suggestions of possible errors in the measurements used (Phys. Rev. Lett. 131, 251803).

$a_\mu^{\text{HVP, LO}}$ – MUonE experiment

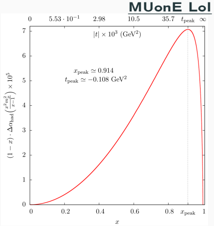
By inverting the order of integration, an equivalent space-like formulation can be obtained:



$$a_\mu^{HVP,LO} = \frac{\alpha}{\pi} \int_0^1 dx\ (1-x)\, \Delta\alpha_{had}\,[t(x)]$$

$$t\,(x) = \frac{x^2 m_\mu^2}{x-1}$$

The integrand now depends on the change of the hadronic part of the effective fine structure constant and is a smooth, well-behaved function.



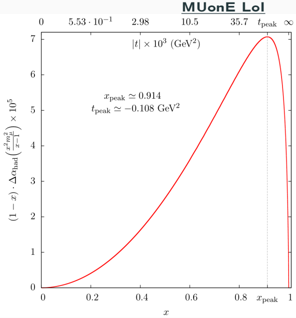
Approx. 0.3% precision achievable, much less prone to systematic errors and data problems.

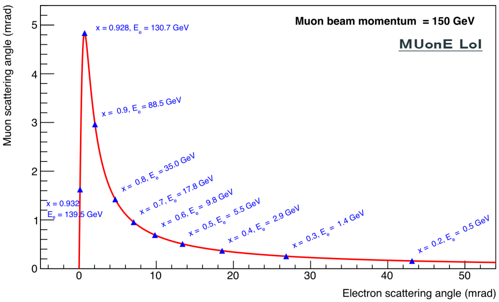
Experimentally, the problem is reduced to a measurement of the running of α via the cross-section of a single scattering process – $\mu + e \to \mu + e$.

$$\frac{\alpha(t)}{\alpha(0)} = \frac{1}{1 - \Delta\alpha(t)}, \quad \Delta\alpha(t) = [\Delta\alpha_{lepton} + \Delta\alpha_{hadron} + \Delta\alpha_{top} + \Delta\alpha_{weak}](t)$$

$$\frac{d\sigma}{dt} = \frac{d\sigma_{\text{born}}}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \Longrightarrow \Delta\alpha_{hadron} \propto \frac{\sigma_{\text{signal}}}{\sigma_{\text{reference}}}, \ \theta_e^{\text{signal}} \in (0, 15) \text{ mrad}$$

where all contributions, except $\Delta\alpha_{hadron}$, are perturbative.

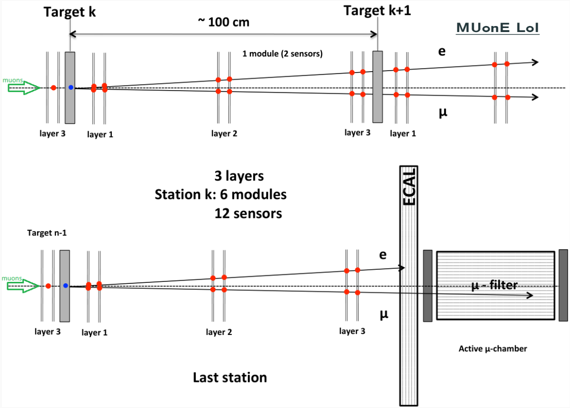




88+% of integral covered with $E_\mu^{\text{beam}} \geq 150$ GeV, rest can be linearly extrapolated. Most systematics canceled by ratio.

MUonE detector

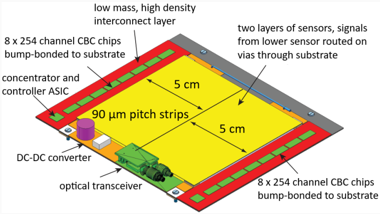
The detector has to be as simple as possible to keep the systematics low.

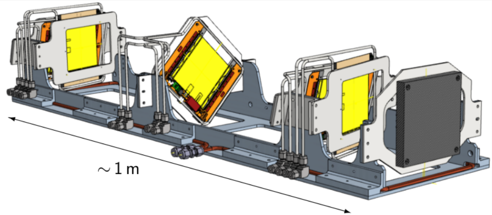


40 tracking stations planned in total, each with a thin target made of low Z material to reduce multiple scattering.

MUonE will be utilizing the M2 line at CERN (160 GeV muons).

Each station comprises 6 two-sensor silicon strip modules designed for the CMS upgrade (CMS-TDR-014) in an Invar (Fe/Ni alloy) frame.





4 define the X-Y plane at both ends of the station and are tilted around the strip axis to increase the position resolution.

The remaining 2 form a rotated stereo plane halfway through the station to solve combinatorial ambiguities.

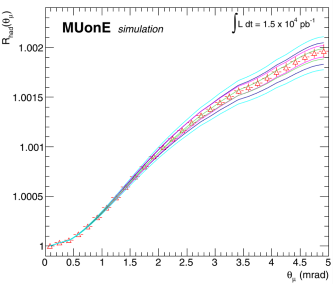
Analysis strategy

The hadronic running of α can be extracted from the ratio of elastic scattering cross-section in the signal and reference region, where we do not expect elastic scattering.

$$R^{LO}_{had}(t) = \frac{d\sigma(\Delta\alpha_{had})}{d\sigma(\Delta\alpha_{had} = 0)} \simeq 1 + 2\Delta\alpha_{had}(t)$$

The analysis will employ a template fit to the 2D distribution of scattering angles (θ_μ, θ_e) using a parametrization of $\Delta\alpha_{had}$.

Expected signal size:



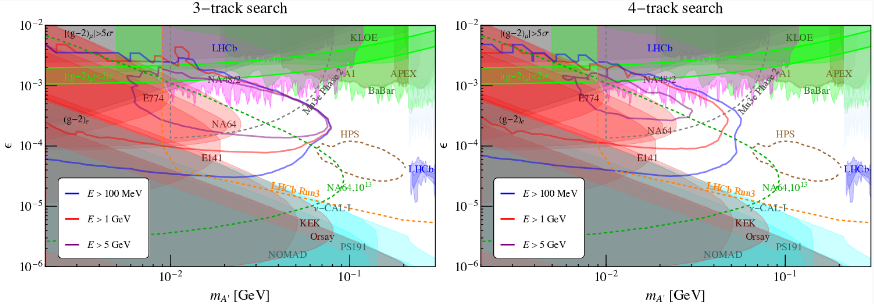
marks – central value with stat. uncert.
colored curves – representative templates

Long-lived particles – secondary measurement

The detector is sensitive to hypothetical particles, which decay between the target and the first tracking module, e.g. dark matter photons:

$$\mu + e \rightarrow \mu + e + A'(\rightarrow e^+e^-)$$

and covers parts of phase-space unreachable to other experiments.



My contribution – FairMUonE software

The software strictly reflects the character of MUonE collaboration.

- only one developer and maintainer
    - framework needed, but not too complex – FairRoot
    - everything in a single package – can't afford maintaining multiple
        - Monte Carlo generation to event reconstruction
- used by everyone, not just dedicated production team
    - steering with simple configuration files written in YAML
- modular detector
    - geometry defined in a nested YAML list of stations and modules
    - per-module parameter overriding, stations without targets
    - automatic translation to Geant4 objects
- New Physics calculations provided by other theory groups
    - standardized interface for interaction vertex generators

My contribution – event reconstruction

Very different measurement requirements:

- main – $1 \to 2$ vertex, precise scattering angle determination
- secondary – $1 \to N$ vertices, requires position estimation

Track reconstruction – very simple:

- 2D lines in XZ and YZ plane matched with stereo hits $\to$ 3D tracks

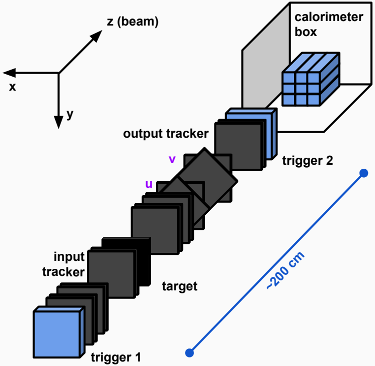
Interaction vertices – challenging:

- PID and multiple scattering correction for electron tracks
- kinematic fit anchoring electron on more stable muon tracks
  - simultaneous fit of all tracks with physics-based constraints
- position estimation with DOCA-based fit
- adaptive fit for displaced vertices with outgoing tracks selected by seeding procedure

My contribution – analysis of 2018 test beam data

M. Goncerz et al., JINST 16 (2021) P06005

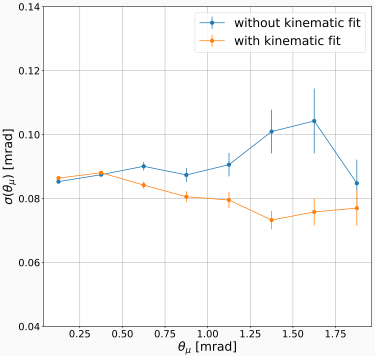
First proof of concept on the M2 beam line, using significantly worse tracking modules. Full analysis possible only after FairMUonE introduction.

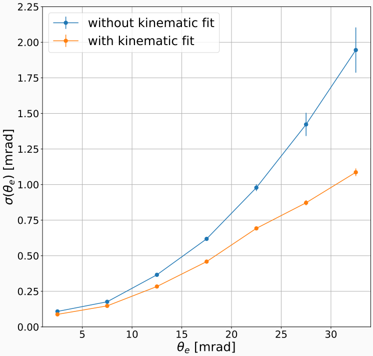


M. Goncerz et al., JINST 16 (2021) P06005

Kinematic fit concept validated.

Not quantitative – modules worse than final, limited selection.

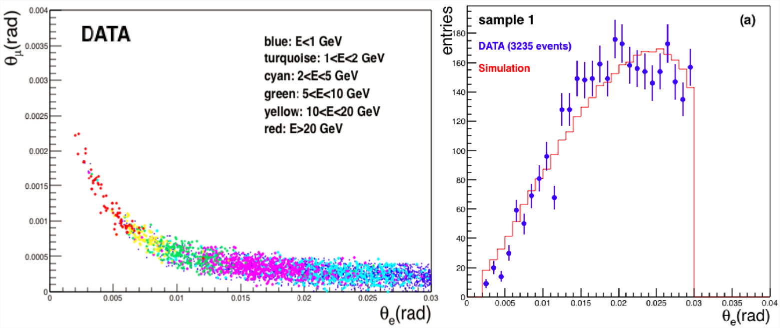




Significant reduction of multiple scattering impact on the electron scattering angle resolution.

M. Goncerz et al., JINST 16 (2021) P06005

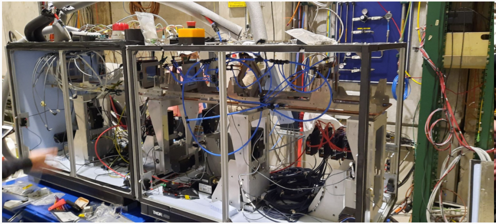
Preliminary study of signal extraction based on simple selection criteria (no background simulation available at the time).

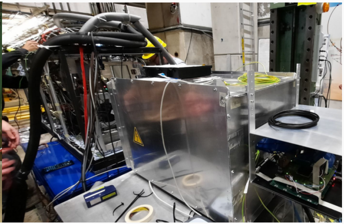


Very good results achievable even with worse modules and no multivariate analysis.

2022 and 2023 test beams

In 2022 (2023), a test involving single (two) full tracking station(s) with a calorimeter and using CMS modules were performed on the M2 beamline.





Data acquisition tested, successful and stable operation at high intensity.

Physical analysis in progress.

CLIC collaboration

sensitivity to long-lived particles

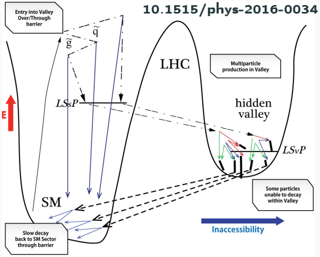
M. Kucharczyk, M. Goncerz, JHEP 03 (2023) 131

Hidden Valley

New particles with relatively long lifetimes and weakly coupled to the Standard Model sector emerge in many models (e.g. String Theory).

Hidden Valley – generalized framework for hidden gauge sectors

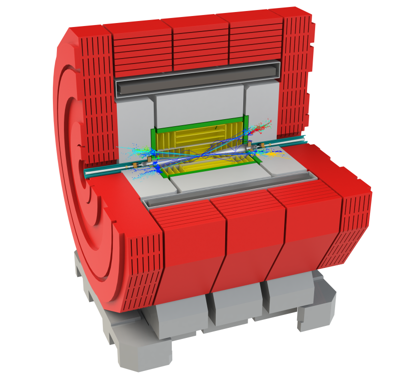
- separation by potential barrier – not crossable with current energies
- exact structure of hidden sector depends on theory
- communication via massive messenger particles (e.g. Z', Higgs)
- stable Hidden Valley particles good candidates for Dark Matter
- non-zero lifetimes → vertices displaced from the interaction point



Compact Linear Collider (CLIC)

One of two (with Future Circular Collider) most likely LHC successors:

- linear e^+e^- collider, Higgs/top factory
- 25-30 years nominal physics program
- 3 operation stages (length scaling) – 350 GeV, 1.5 TeV and 3 TeV
- dedicated system for reconstructing displaced vertices
- clean e^+e^- environment, no jet background



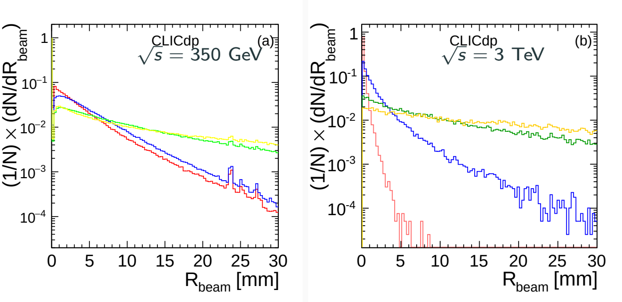
Analysis introduction

M. Kucharczyk, M. Goncerz, JHEP 03 (2023) 131

- focus on sensitivity to Hidden Valley pions
  - representative for relatively light long-lived particles
  - $H \to \pi_v^0(\to b\bar{b})\pi_v^0(\to b\bar{b})$ decays
  - $m_{\pi_v^0} \in (25, 35, 50)$ GeV, $\tau_{\pi_v^0} \in (1, 10, 100, 300)$ ps
  - $BR(\pi_v^0 \to b\bar{b}) = 100\%$
- dominant production mechanism assumed
  - $e^+e^- \to HZ(\to q\bar{q})$, $\sigma = 0.93$ pb at $\sqrt{s} = 350$ GeV
  - $e^+e^- \to H\nu_e\bar{\nu}_e$, $\sigma = 0.42$ pb at $\sqrt{s} = 3$ TeV
- background sources considered
  - $\mathrm{q\bar{q}}$, $\mathrm{q\bar{q}}\nu\bar{\nu}$, $\mathrm{q\bar{q}q\bar{q}}$, $\mathrm{q\bar{q}q\bar{q}}\nu\bar{\nu}$, $\mathrm{t\bar{t}}$, WWZ
  - more than 4 jets omitted due to low cross-section
  - beam induced $\gamma\gamma \to$ hadrons overlaid for each event
- assumed integrated luminosities
  - 1 ab^{-1} at $\sqrt{s} = 350$ GeV
  - 3 ab^{-1} at $\sqrt{s} = 3$ TeV
- study will be adapted to FCC

Reconstruction of signal vertices

M. Kucharczyk, M. Goncerz, JHEP 03 (2023) 131



$m_{\pi_v^0} = 50$ GeV, $\tau_{\pi_v^0} = 1$ (red), 10 (blue), 100 (green), 300 (yellow) ps

LCFI+ (Linear Collider Flavour Identification) algorithms found to be highly inefficient for displaced secondary vertices.

- designed primarily for B and D hadron decays
- not enough charged tracks assigned to displaced vertices
- hindering signal-background separation, especially in 1 ps samples
- not possible to solve using available (at the time) settings

M. Kucharczyk, M. Goncerz, JHEP 03 (2023) 131

Non-standard approach required:

- tracks and jets reconstructed using standard methods
    - longitudinally invariant k_t (FastJet), tagging based on decision trees
    - parameters optimized for Hidden Valley particles (jet radius etc.)
- dedicated track seeding to find $\pi_v^0 \to b\bar{b}$ vertex candidates
    - good quality charged tracks not coming from primary vertex
    - base tracks with at least 4 close tracks
    - other assigned based on distance of closest approach
- dedicated secondary vertex reconstruction starting from seeds
- jet-vertex matching maximizing number of common charged tracks
- assigned jets used to reconstruct di-jets (π_v^0) and four-jet (Higgs)
    - at $\sqrt{s} = 350$ GeV, the remaining two are used for the Z boson

Background rejection

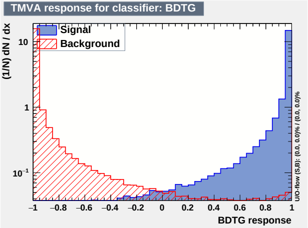
M. Kucharczyk, M. Goncerz, JHEP 03 (2023) 131

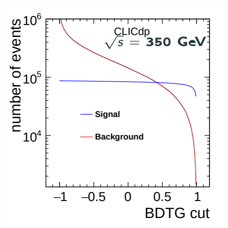
Background rejection based on matching signal signature:

- at least two displaced vertices
- at least 4 jets, probability of coming from a b-quark ≥ 0.95

and classifier trained on physical characteristics of signal and background

- properties of reconstructed vertices and kinematics of assigned jets
- distances where transition between 2, 3 and 4-jet events take place





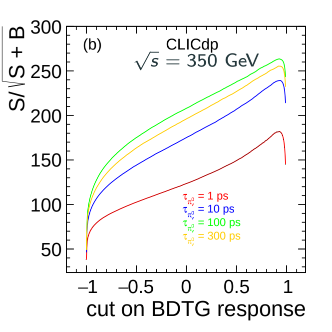
$m_{\pi_v^0} = 35$ GeV, $\tau_{\pi_v^0} = 10$ ps, normalized to assumed luminosity

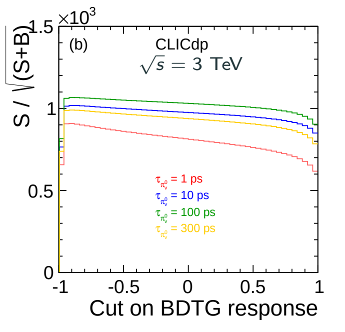
backgrounds combined with weights proportional to their contribution

Results

M. Kucharczyk, M. Goncerz, JHEP 03 (2023) 131

Threshold value chosen to maximize $S/\sqrt{S+B}$ ratio.





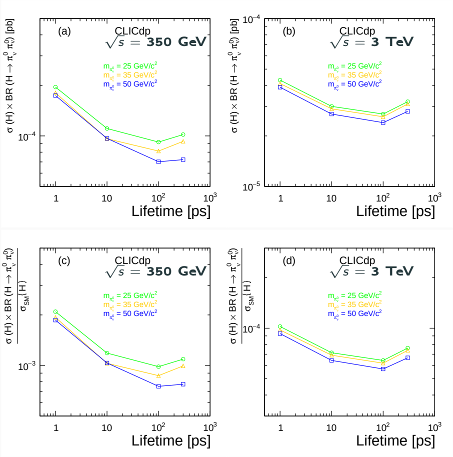
$m_{\pi_v^0} = 35$ GeV

Sensitivity roughly 4-6 times larger at $\sqrt{s} = 3$ TeV.

- with 3 times larger assumed luminosity
- consistent across all $m_{\pi_v^0}$ masses

M. Kucharczyk, M. Goncerz, JHEP 03 (2023) 131

Upper limits derived at 95% CL, assuming absence of signal observation.



Much better (few orders of magnitude) limits compared to ATLAS, CMS and LHCb results, even after upgrades planned for HL-LHC.

LHCb collaboration

$Zb\bar{b}$ production cross-section

$Zb\bar{b}$ coupling

Good channel to look for new physics:

- $\sigma_{NLO} \approx 2 \cdot \sigma_{LO}$ – sensitive to corrections from loop diagrams
- common final state for Beyond the Standard Model processes
  - $b' \to Zb$
  - ZZ'($\to b\bar{b}$)
- leptonic Z decay effective in suppressing hadronic backgrounds

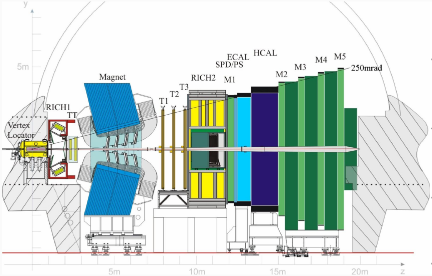
and important within the Standard Model:

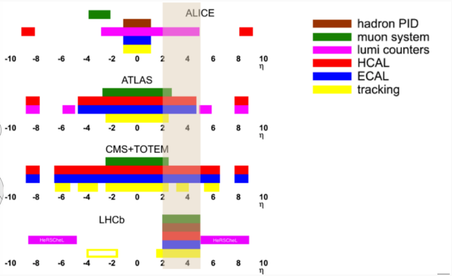
- test of calculation methods - 4 and 5 flavour scheme
  - include b-quark as *massive point* or Parton Distribution Function
- parametrization of Parton Distribution Functions
- background for Higgs studies
  - ZH($\to b\bar{b}$) – Z to suppress hadronic backgrounds

LHCb detector

One of the big experiments at the Large Hadron Collider:

- designed for b-quark physics – effective reconstruction and tagging of b-jets
- unique forward phase space coverage – approx. $2 < \eta < 5$
- very good mass resolution (15 MeV for J/ψ)
- very high muon reconstruction efficiency





Analysis introduction

- preliminary – one background Monte Carlo sample still missing
- on PRELUDIUM reserve list, should be accepted soon
- 2015-2018 data (Run 2 of LHC)
  - $\sqrt{s} = 13$ TeV
  - about 6 fb^{-1} of integrated luminosity
- focus on Z($\rightarrow \mu^+\mu^-$) channel, electrons in the future
- only total cross-section, yield too small for a differential study

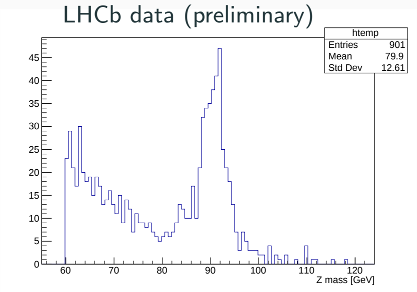
Signal event reconstruction

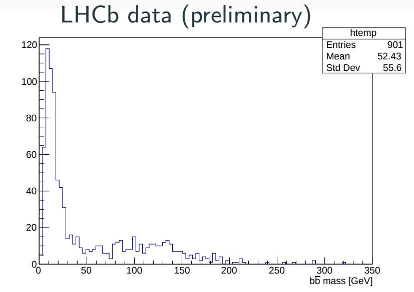
Z boson candidate

- well reconstructed muons with high transverse momenta
- 60 GeV $< M_{\mu^+\mu^-} <$ 120 GeV

$b\bar{b}$ dijet candidate

- loose selection to preserve efficiency, TBD when all samples available

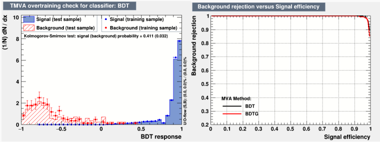




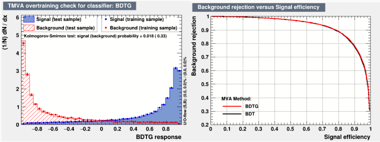
Background rejection

Three main background types:

- one or both muons in Z coming from jet(s)
  - dominated by $b\bar{b}$ production, easily removable



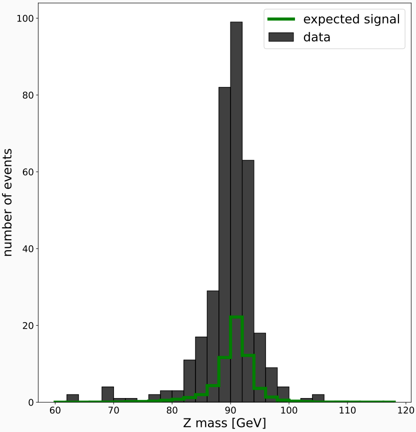
- $t(\to \mu^+ \nu_\mu b)\bar{t}(\to \mu^- \bar{\nu_\mu} \bar{b})$ and $Z(\to \mu^+\mu^-)Z(\to b\bar{b})$
  - reducible to negligible level without losing much signal

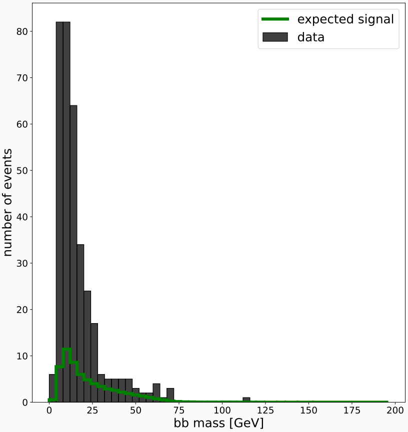


- $Zc\bar{c}$ and $Zj\bar{j}$ with j=udsg
  - $Zc\bar{c}$ negligible due to low cross-section
  - $Zj\bar{j}$ significant and irreducible

Signal yield

Signal yield (and cross-section) will be extracted using a template fit of $Zb\bar{b}$ and $Zj\bar{j}$ to the reconstructed $b\bar{b}$ dijet invariant mass, once the $Zj\bar{j}$ Monte Carlo sample becomes available. About 60 events are expected.





Conclusions

Looking for New Physics is important to validate and guide theories.

- MUonE experiment is expected to provide a new measurement of $a_\mu^{\text{HVP, LO}}$ (approx. 0.3% precision, 2 times better than current) in the next 4-5 years
  - 2018 data analysis – M. Goncerz et al., JINST 16 (2021) P06005
- sensitivity of CLIC detector to hypothetical long-lived particles is orders of magnitude better than in current experiments
  - M. Kucharczyk, M. Goncerz, JHEP 03 (2023) 131
  - study will be adapted to the FCC detector as well
- $Zb\bar{b}$ production cross-section measurement at 13 TeV and in the unique forward phase-space of LHCb is ongoing
  - likely timeframe for the paper to be published – 0.5 to 1 year

Other recent studies/grants:

- Bose-Einstein correlations of same-sign pions in proton-lead collisions – M. Goncerz et al., JHEP 09 (2023) 172
- STER, 2 months at CERN