Searching for Muon Force Carriers with ATLAS

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Motivation

- So far no discovery of BSM at the LHC
- We exhausted the vanilla flavored theories with nice theoretical motivations
- Further, we have excluded to the point where discovery is now less likely
  - Flavor universal theories
  - Electron related BSM
  -
  - Even LLP are now excluded to high masses

- But dark matter is still with us… (as are other SM issues)

- Time to look at corners of pheno-space that were less favored/easy
- A model where dark matter only couples through muons?
  - There is even a hint from g-2

The phenomenologic framework

- Muonic Force Carriers (MFCs) are non-universal mediators of a new force, which couples μ to a dark sector.
  - Could explain the long standing muon g-2 discrepancy.
- We are working on a novel search for these force carriers in ATLAS.
  - ATLAS is used as a fixed target experiment for μ from LHC collisions.
- We consider a scenario described by the spin, mass and coupling of the MFC to μ.
  - In this scenario the MFC emission process is rare and occurs in the calorimeter

From: Searching for muonic forces with the ATLAS detector, Galon et al, Phys.Rev.D 101 (2020) 1, 011701

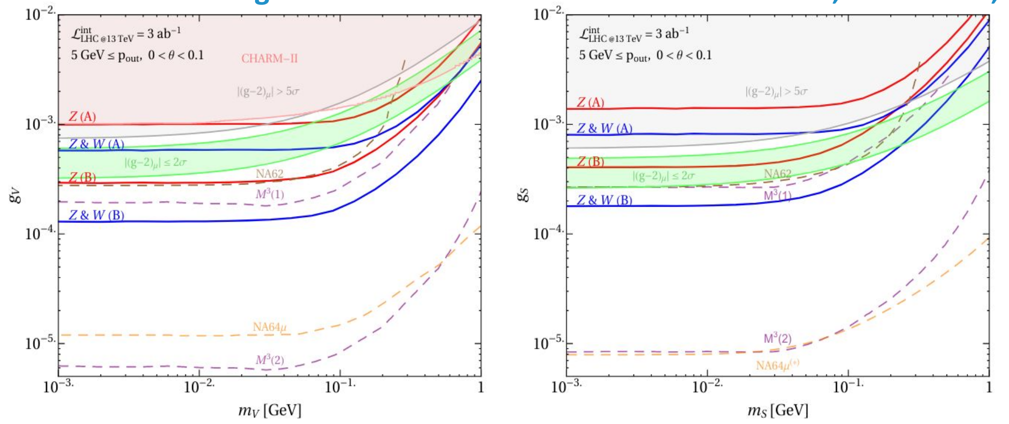
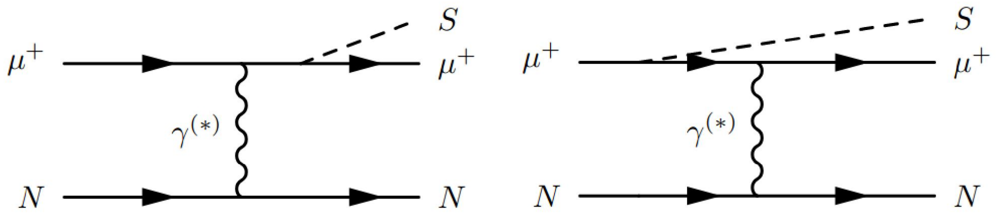


FIG. 4: The projections of the proposed ATLAS fixed-target like analysis to probe MFC at the HL-LHC comparing to current constraints from $(g-2)_\mu$ [5, 6] and CHARM-II [21, 22] as well as to the projection of $M^3(1)(M^3(2))$ [14] with $10^{10}(10^{13})$ μ on-Target, NA62 [16] with 10^{13} K^+, and $NA64_\mu$ [15, 18] with 5×10^{12} μ on-Target. Left: vector mediator; right: scalar mediator.



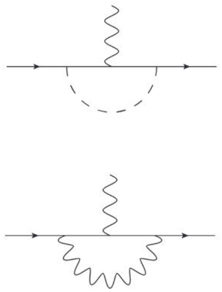
Production Feynman diagrams for the scalar benchmark

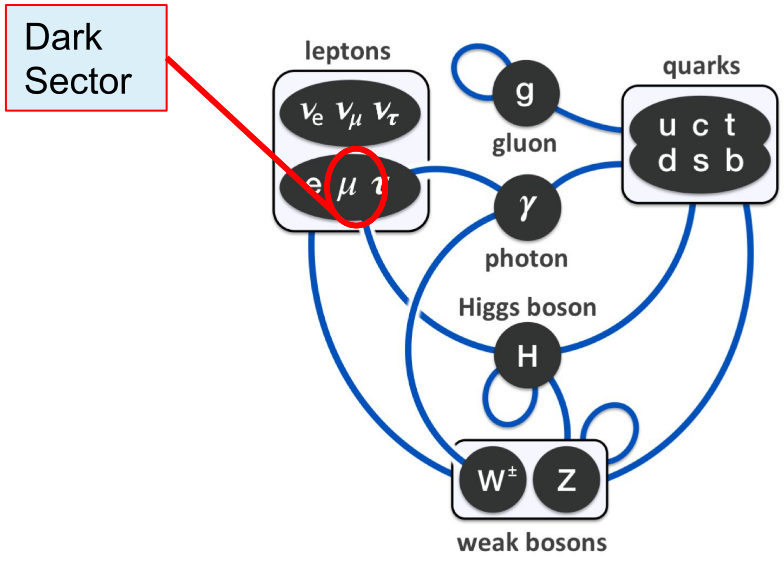
Muon Force Carriers

- Muonic Force Carriers (MFCs) are non-universal mediators of a new force, which couples μ to a dark sector

$$\mathcal{L}_V = g_V V_\alpha \bar{\mu} \gamma^\alpha \mu \,, \qquad \mathcal{L}_S = g_S S \bar{\mu} \mu \,,$$

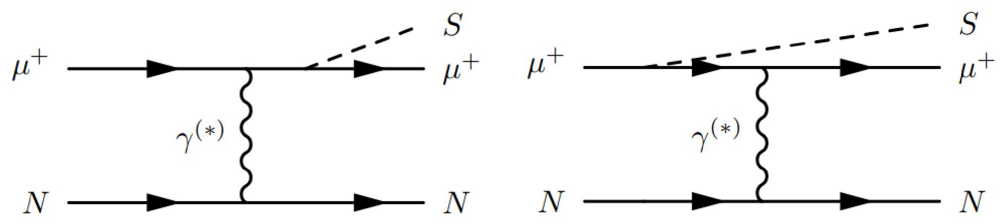
- Could explain the long standing muon g-2 discrepancy





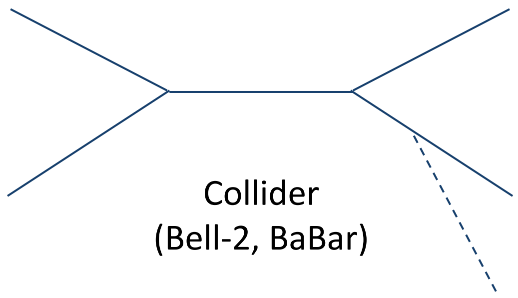
- **Tree level searches are important**
  - There are also models where they can exist with no discrepancy

Phenomenology



Fixed target experiments
(ATLAS,M3...)

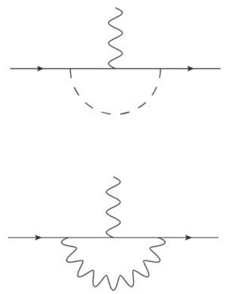
This talk



Collider
(Bell-2, BaBar)

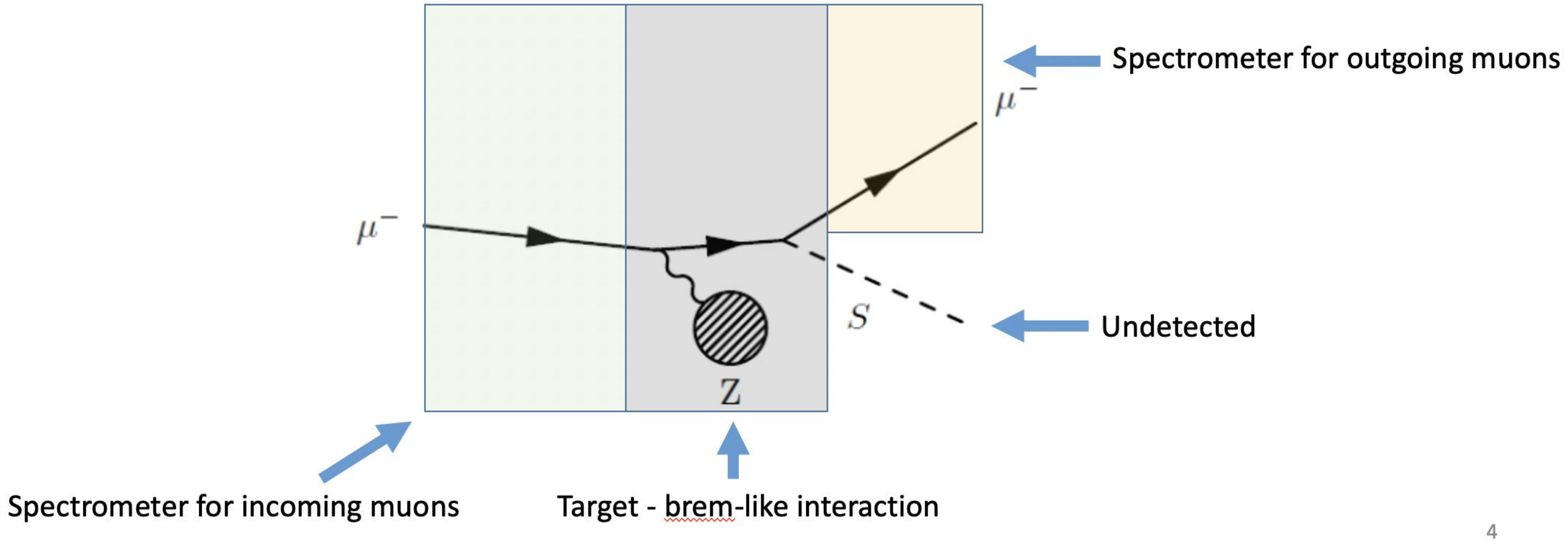
$$K \to \mu\nu X$$

Rare decays
(NA62)



g-2

Strategy for MFC in fixed target experiments



Observables:

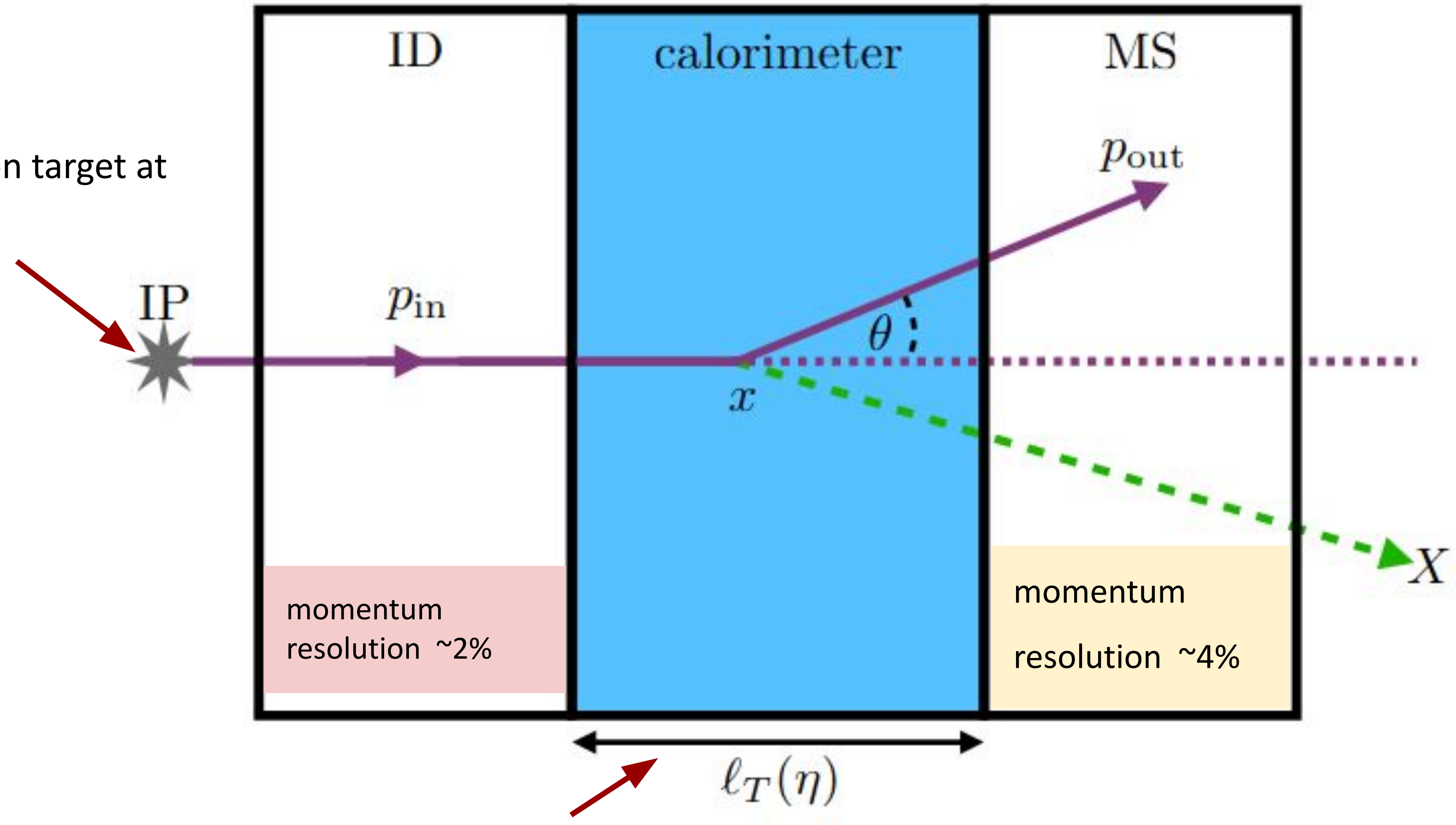
- **Missing muon momentum**
- **Scattering angle**

$$\frac{d\sigma_T}{dp_{\rm out}dc_\theta} = \frac{p_{\rm out}^2}{64\pi^3 p_{\rm in} E_{\rm out}|\vec{V}|}\int_0^{2\pi}\frac{d\phi_q}{2\pi}\int_{t_{\rm min}}^{t_{\rm max}}\frac{dt}{8m_A^2}\left|\overline{\mathcal{M}}_{2\to 3}\right|^2$$

* Taking into account the Nuclear form factor

ATLAS as a muon-beam fixed target experiment

10^9-10^{10} muons on target at high-luminosity



Approx 100 radiation lengths (fixed target M3 has ~ 60)
Resolution for the deposited energy by muons ~ 1%

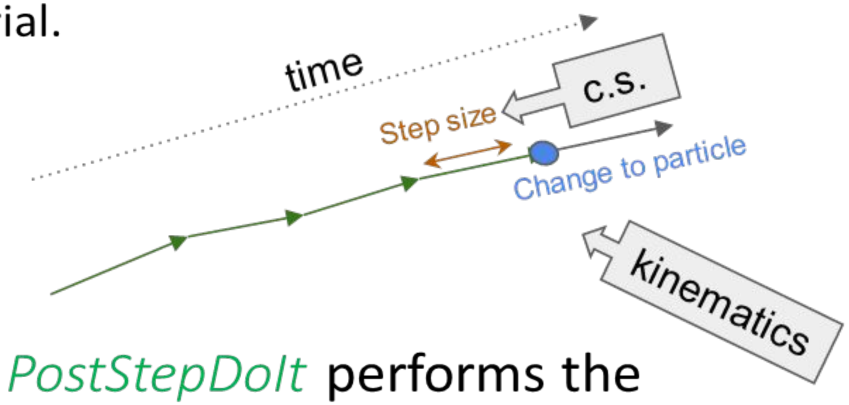
Simulating MFC production in ATLAS

- In most searches the BSM interaction occurs at the IP, and G4 simulates final state particles
- In this case the BSM interaction occurs with the ATLAS detector – G4 has to simulate it
  - MFC production is a discrete process, we also need to account for all the SM physics happening between the detector and the muon before and after the MFC production
- We added a G4 extension for this process
  - It’s rare, we can’t simulate trillions of events to get millions of MFC interactions
  - It’s rare so we can’t scale it to happen twice to the same muon, or have vertices distributed incorrectly along the muons’ path (“thin target”)
  - Modeling needs to include correct correlation between scattering angle and missing muon momentum
- Next I will describe how we do it

MFC extension for GEANT4

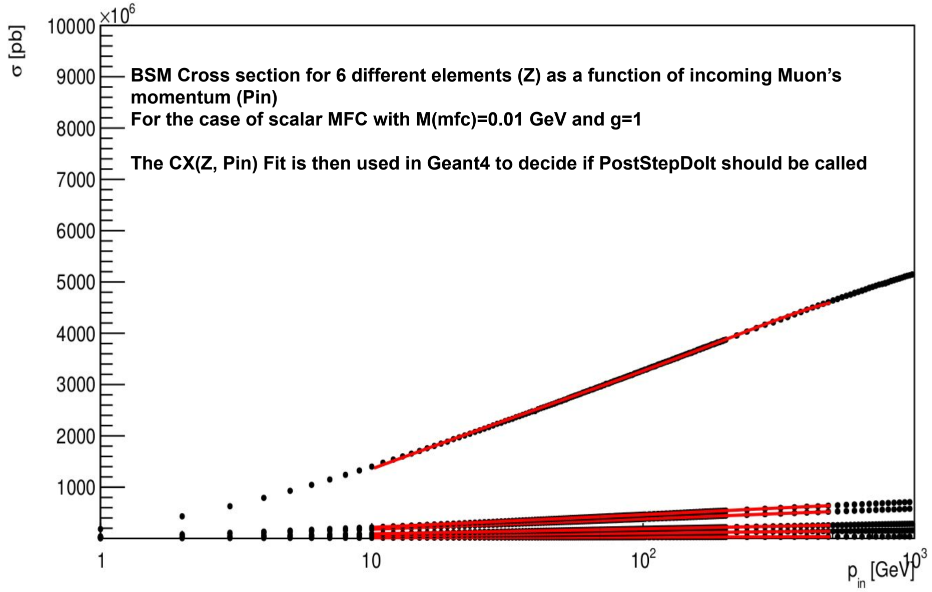
In GEANT4:

- A particle is defined in a class, e.g. *G4MuonMinus*, with its mass, width, charge etc.
- The particle interactions are defined in a *Physics list* of particle interactions.
- In order to simulate the MFC interaction, it is added to the muon processes
- When simulating a particle passing through a detector, G4 calculates steps
  - Depend on the mean free path of the particle in the current material.
- When defining *G4Mu1ForcesProcess*, the method *GetMeanFreePath* calculates σ
  - Depends on the process and the materials being traversed.
- At the end of each step, the method *G4VParticleChange* PostStepDoIt* performs the interaction $\mu T \rightarrow \mu T X$.
  - The kinematics of the outgoing muon and mediator are calculated from the differential cross section.



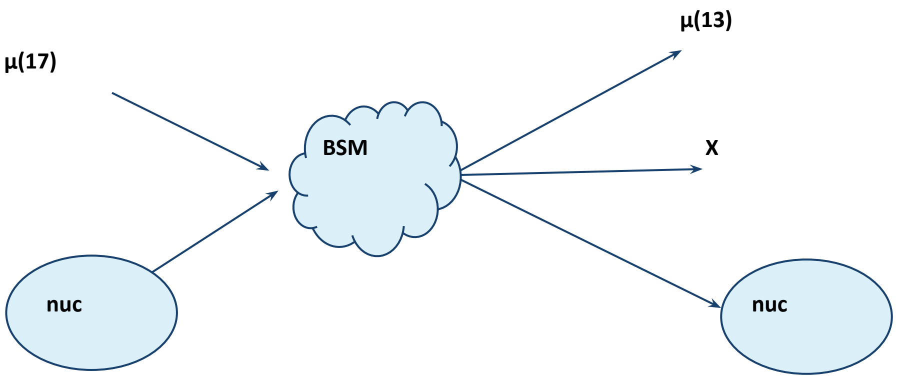
MFC Production cross section

- Production cross section is a function of
  - Target (Z)
  - Incoming momentum
  - Coupling (trivial scaling)
  - MFC (Mass,Spin)
- For a given MFC it is easy to parametrize the cross section per target and incoming muon momentum

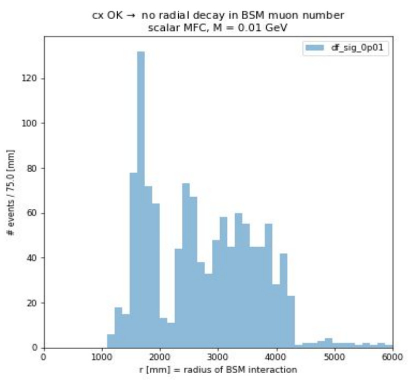


Thin target "trick"

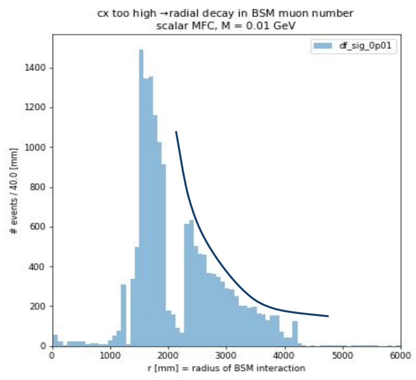
- Since the process is rare, G4 scale up the cross section in the simulation
  - Avoid multiple interactions of the same incoming muon, we introduce a new particle, a muon with the addition of the MFC interaction.
- This particle, with PDGID=17, the 'BSM Muon' has the MFC interaction resulting in a regular muon, that has no MFC interaction, in the final state.
- The 'SM muon' that came out of the MFC interaction continues to progress through the detector



- The scale for σ has to preserve reasonable vertex distribution



Scale OK



Scale too large

Outgoing muon kinematics

- It is difficult to parametrize the double differential cross section (muon and mediator kinematics)
- MadGraph5 simulates the outgoing kinematics based on first-principles calculation
- Per each muon MFC process in GEANT we draw the outgoing kinematics from a large set of reference events (generated by MG5 per (Z, P_{in}, M)).
- The sets are generated at discrete incoming momenta (P_{in}) and linear weighing allows us to recreate the in-between statistics.
- **Need to code an approximation that will be calculated in G4**

- Also – **we only simulated (and analyzed) single particle signal events so far**
- **Need to find a way to replace muons in full events**

Recap: Muon Reconstruction within ATLAS

Types of muons:

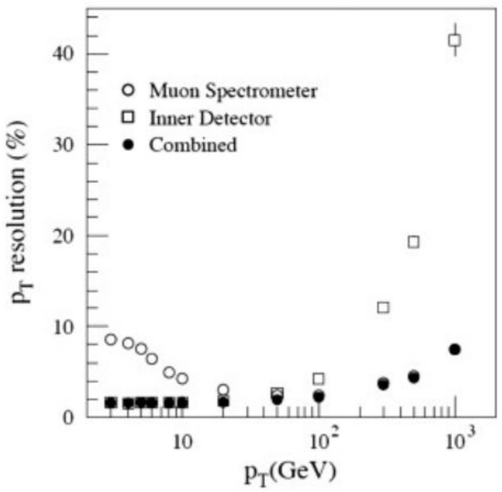
- Combined: ID+MS fitted together
- Inside out (Mugirl): also combined
- MS standalone
- ME = MS extrapolate to IP using calo E
- Segment tagged = ID points to MS segment
- Calo muons

- Mostly the first 2 used in analysis
- Quality selection includes agreement between ID and MS tracks

$$q/p \text{ compatibility} = \frac{|q/p_{\mathrm{ID}} - q/p_{\mathrm{MS}}|}{\sqrt{\sigma^2(q/p_{\mathrm{ID}}) + \sigma^2(q/p_{\mathrm{MS}})}},$$

Our signal will fail this criteria

ID and MS resolutions



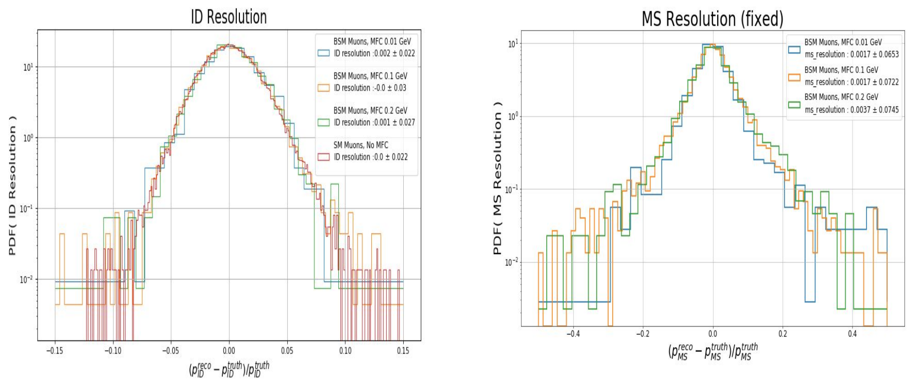
Muon quality / Working Points

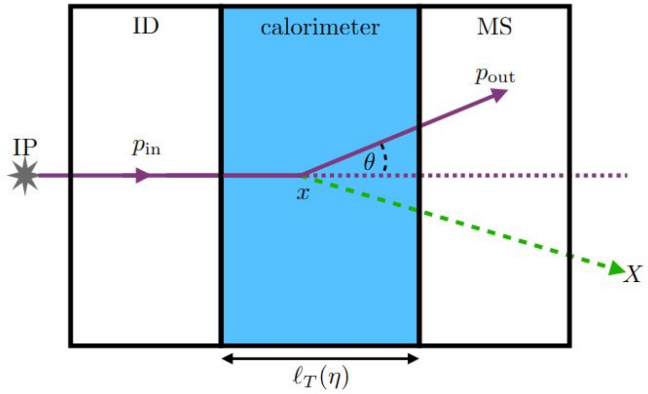
	$4 < p_T < 20$ GeV		$20 < p_T < 100$ GeV	
Selection	ε_μ^{MC} [%]	$\varepsilon_{Hadrons}^{MC}$ [%]	ε_μ^{MC} [%]	$\varepsilon_{Hadrons}^{MC}$ [%]
Loose	96.7	0.53	98.1	0.76
Medium	95.5	0.38	96.1	0.17
Tight	89.9	0.19	91.8	0.11

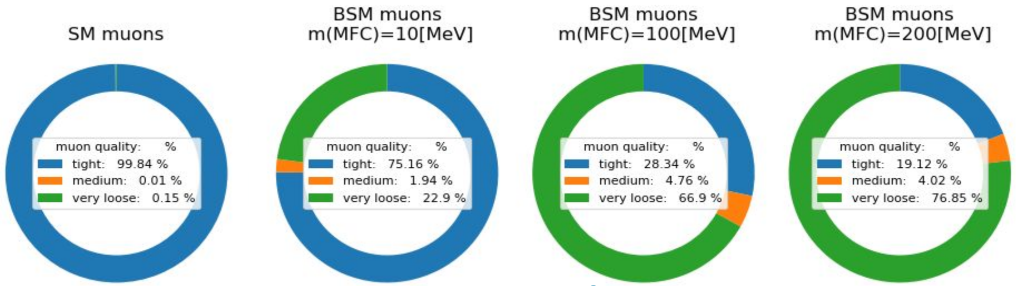
Reconstruction of MFC emission in ATLAS

- ATLAS muon reco finds a “muon” with the associated MS and ID tracks
- Momentum resolution in each (ID,MS) system is consistent with μ reconstruction performance
- Interacting muons fail quality requirement of consistency between ID and MS momentum
- The combined track fails quality selections
- The efficiency for reconstruction is close to 100%

Momentum resolutions







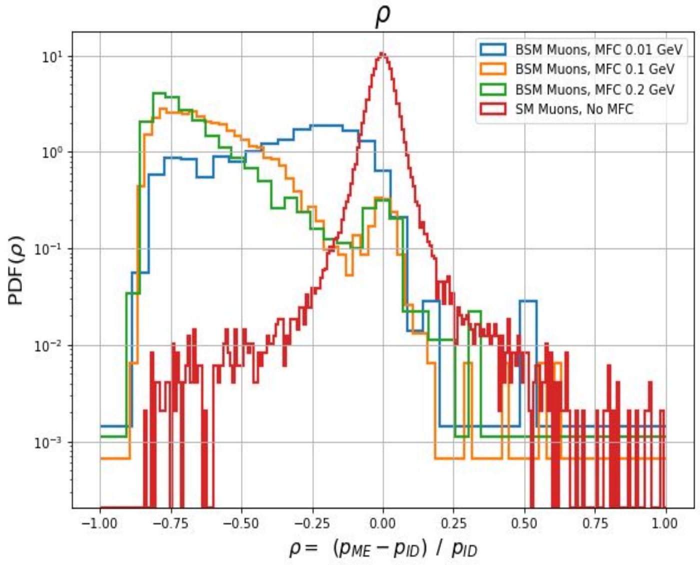
Muon quality tags

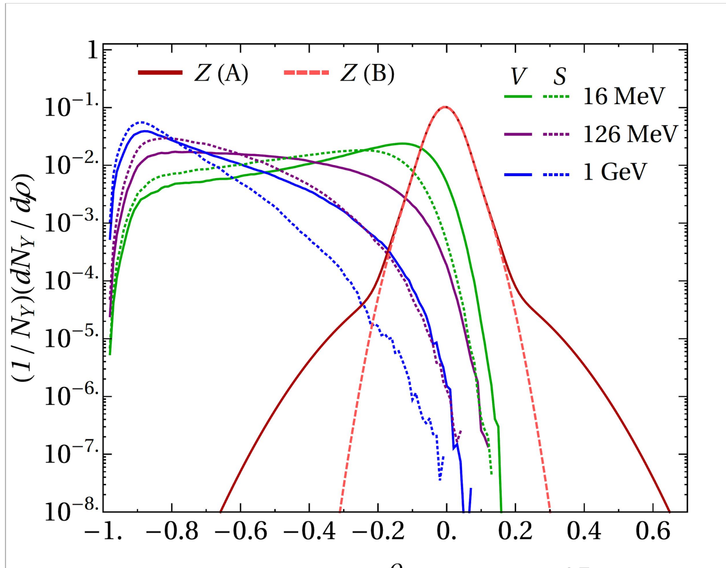
An observable that is sensitive to the MFC production

- The MFC interaction is characterized by unaccounted momentm-loss of the muon between the Inner-Detector and Muon-Spectrometer
- The observable of choice, ρ, is the fraction of missing muon mometum between the ID and MS measurements, $\rho = \frac{p_{ME} - p_{ID}}{p_{ID}}$
  - p_{ME} is the muon momentum at the IP estimated by extrapolating the measured MS muon momentum, using the estimated energy loss in the calorimeter.

Expect:

- $\langle \rho \rangle = 0$ if no MFC production,
- $\langle \rho \rangle < 0$ for MFC-signal muons.



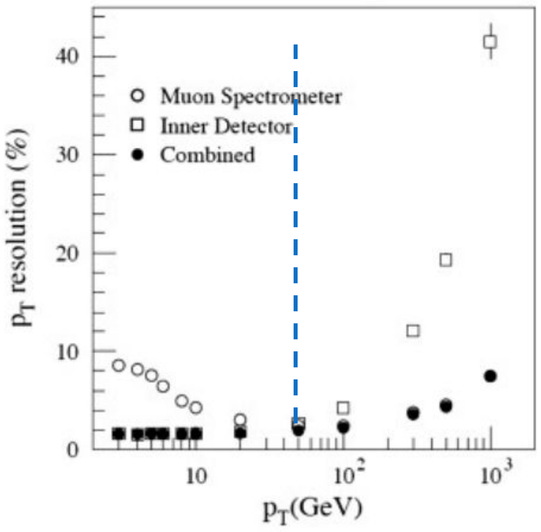


Analysis plan

- We started from $Z \rightarrow \mu\mu$ and will stay there for now
- It provides a clean, well understood sample of muons
  - Good, comparable, momentum resolution in ID and MS
- The Z tag-and-probe method, and ntuples, are a good tool

- Backgrounds
  - Instrumental - muon reconstruction resolution
  - Physics - hadronic sources (π and K decay, punch-through etc)

- Considering estimation methods from data
  - Like-sign pairs
  - Convolution of ID and MS resolutions



Tag-and-probe

- $(P_{CB}(\mu_{tag}) + P_{ID}(\mu_{probe}))^2 \sim m_Z^2$
- $Q(\mu_{tag}) + Q(\mu_{probe}) = 0$

Looks like a Z decay!

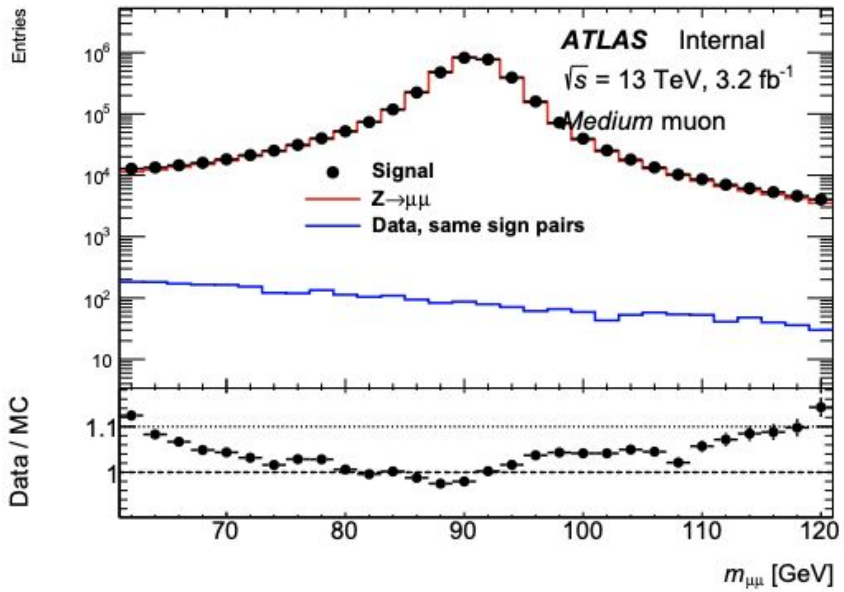
Tag:

- Medium muon
- Pt > 24GeV
- Trigger match

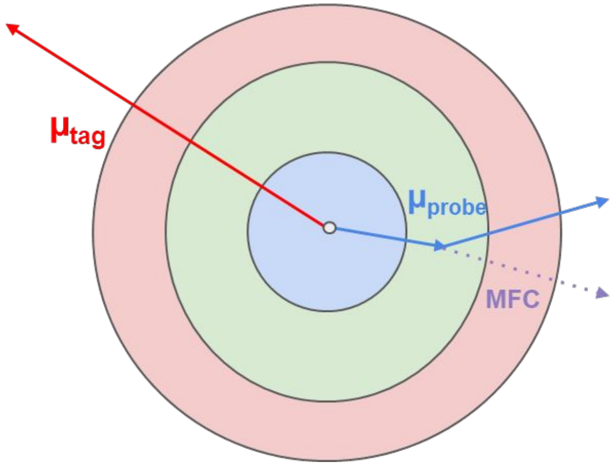
ID-Probe

- Inside mass window of Z->tag&probe (+-5 GeV)
- Pt>10[GeV]

Both have loose isolation (99% efficiency)

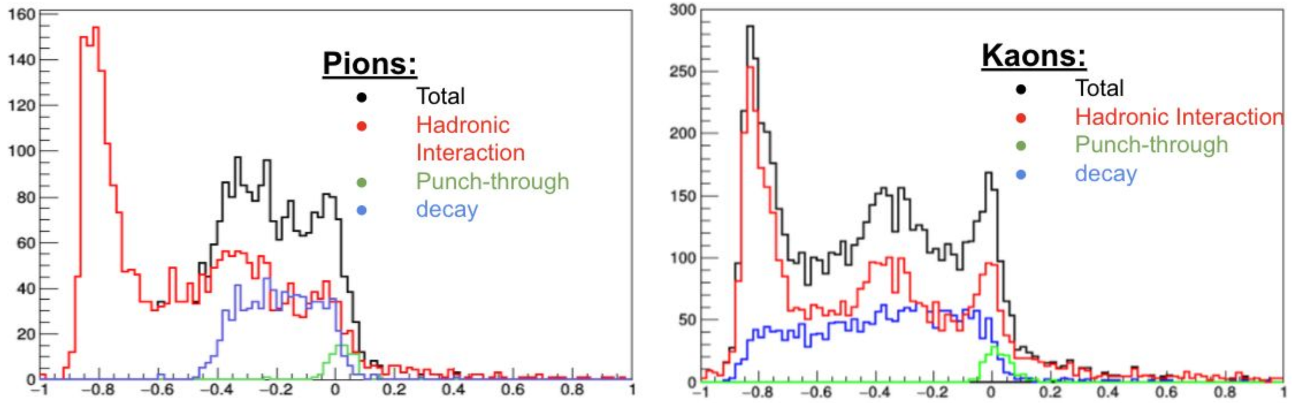


55M probes in 139/fb in barrel
0.05% background from K and π



Tiny bit on backgrounds

- Instrumental
  - Choice of fiducial region, requirements on quality of ID, MS tracks
  - Unavoidable: Long tails in ionization energy loss
- Physics
  - Decays: Pion - simple kinematics requirement is very effective, Kaon - more rare but also difficult
  - Hadronic Interactions
    - Punchthrough soft muons and hadrons
    - Isolation + additional requirements
    - **Need data-driven methods for estimation**
    - **Need to study in realistic events (as opposed to single-particle events)**



- Single particle events These distributions are not a "background expectation"

Simplified outlook on the sensitivity to MFC

For these plots we used a generous model for the instrumental background tails and assumed hadronic backgrounds based on the tag-and-probe estimates
Many possibilities to improve the signal selection
Including W is not trivial but may payoff due to much larger cross section
Other more complex states (J/Psi)

*If MFC decays it is easy to target with high multiplicity muon events

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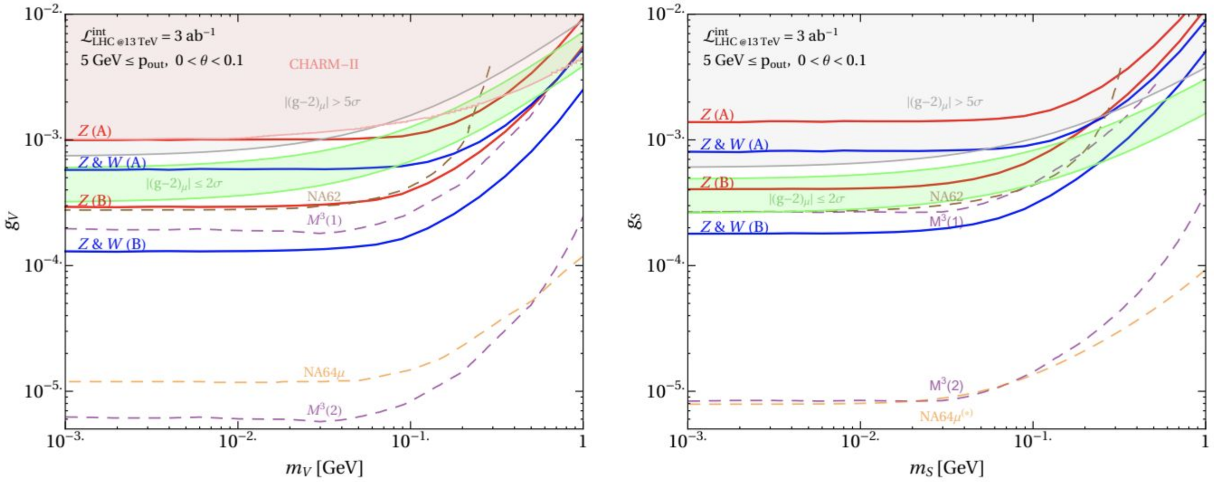

FIG. 4: The projections of the proposed ATLAS fixed-target like analysis to probe MFC at the HL-LHC comparing to current constraints from $(g-2)_\mu$ [5, 6] and CHARM-II [21, 22] as well as to the projection of $M^3(1)(M^3(2))$ [14] with $10^{10}(10^{13})$ μ on-Target, NA62 [16] with 10^{13} K^+, and $NA64_\mu$ [15, 18] with 5×10^{12} μ on-Target. Left: vector mediator; right: scalar mediator.

Status and plans

- We developed a Geant4 extension to simulate the MFC production
  - Currently relies on Mad-Graph events, plans to use an approximation to improve performance
- Work is needed towards the signal production request

- Standard muon reconstruction is efficient for signal
- Initial selection exists: tag-and-probe, additional criteria to reduce hadronic backgrounds
  - Further tuning is needed

- Background
  - Using simulation (single particle / full events) to characterize backgrounds
  - Technique for data-driven background estimation needs to be developed

- Analyzers are welcome, We are small team and lots of interesting challenges ahead