

Muon Colliders & Dark Sectors

Discussion Section

Cari Cesarotti & Yoni Kahn

How can we search for Dark Sectors at Muon Colliders?

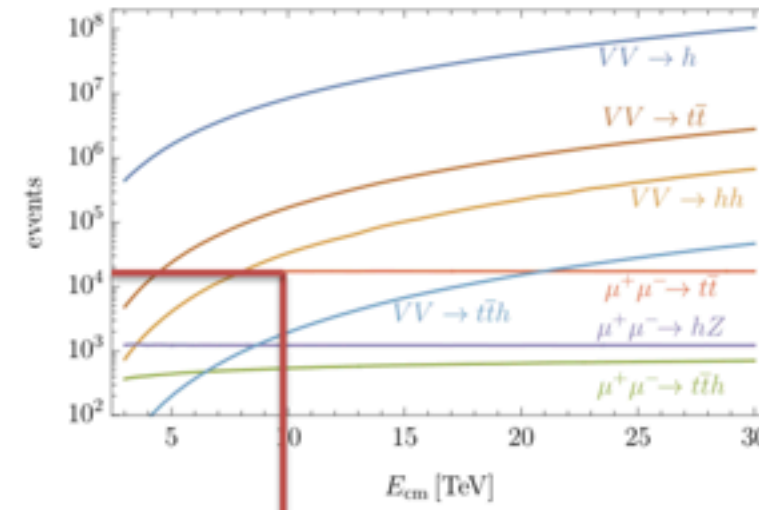
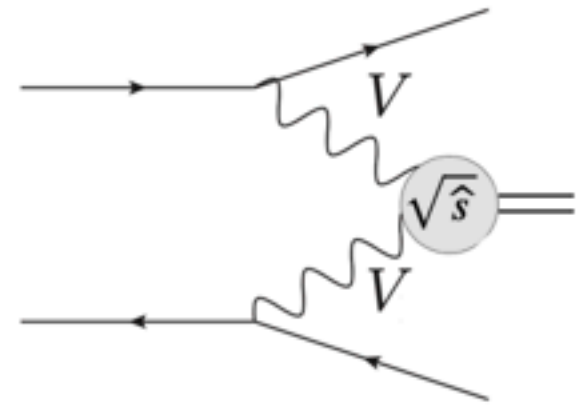
- *What can we do with higher energy? 3 TeV - 10 TeV - 100 TeV?*
- *How does the cleaner environment of the muon collider facilitate searches?*
- *What sort of beam intensity do we need to surpass other experiments?*
- *What can be done at beam dumps? At what energy? What material?*
- *Can we just use low energy things from the LINAC (400 MeV, 800 MeV, 8 GeV) or booster (8 GeV)?*

What Dark Sectors are of Interest?

- *What kind of portals are enhanced with muon colliders?*
- *What signals do we get from minimal models that can be seen at muon colliders?*
- *What models would couple more strongly to 2nd generation or EW bosons?*
- *What are the best production mechanisms for new physics?*

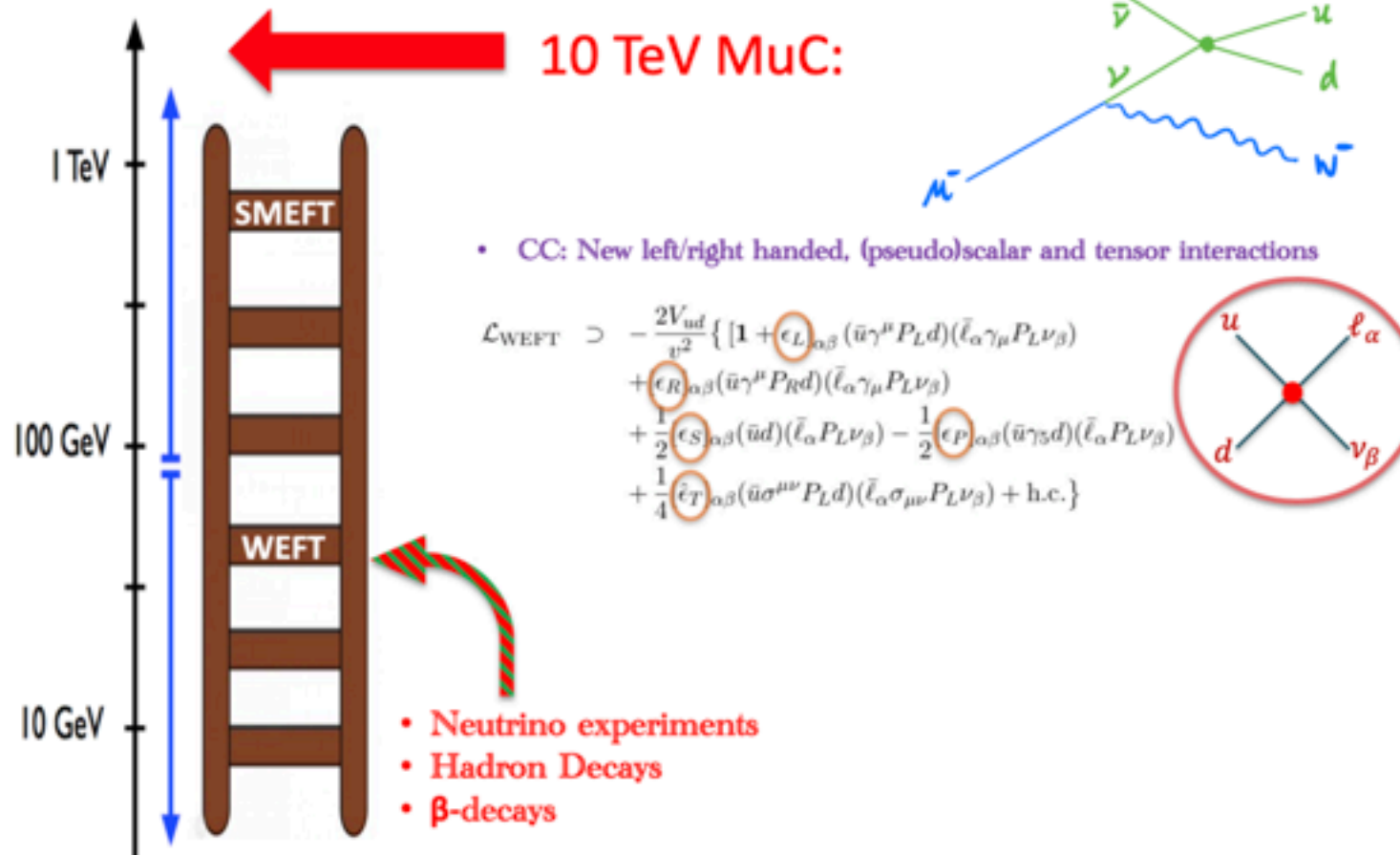
Slides from Talks

A 10 TeV muon collider would be a super-Higgs factory, producing ~ 10 million Higgs bosons with $10/\text{fb}$:



This would allow us to study the microscopic properties of the Higgs!
(By comparison, an "ordinary" Higgs factory produces ~ 1 million Higgses.)

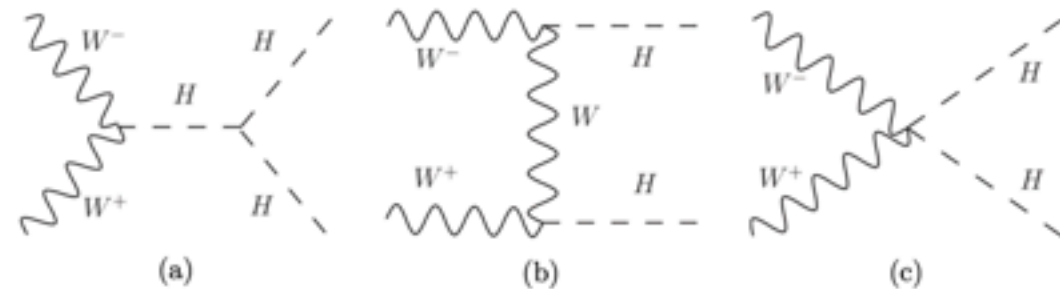
EFT ladder



Ian Low

Art work by Z. Tabrizi

- At a lepton collider, both the trilinear and quartic couplings can be probed in double Higgs production through VBF:



Notice the process is sensitive to **both** HHH and WWHH couplings!

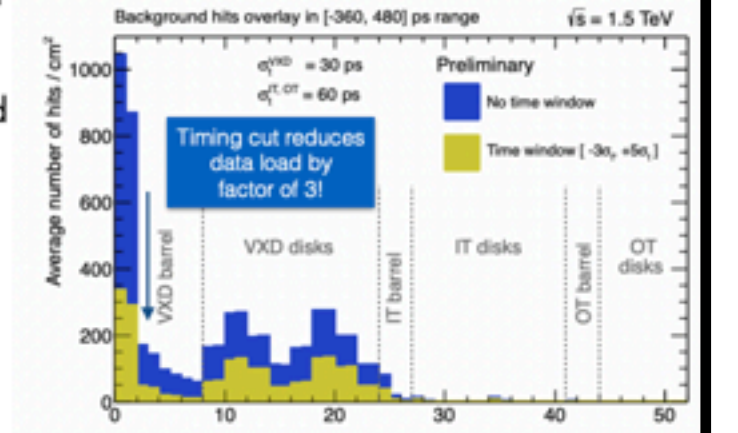
Tracking

From hits to particles

arXiv:2303.08533

- Tracking certainly the **biggest challenge**:
 - **Large hit occupancy** (1000 hits/cm²) implies high data volumes, large combinatorics.
- For 1% hit occupancy goal will need **high granularity silicon detector with timing capabilities**:
 - Optimal configuration found for pixels of size $25 \times 25 \mu\text{m}^2$ ($\sigma_t = 30\text{ps}$), $50 \times 100 \mu\text{m}^2$ ($\sigma_t = 60\text{ps}$) and strips of $50 \mu\text{m} \times 10\text{mm}$ ($\sigma_t = 60\text{ps}$).
 - **Promising R&D technologies**: hybrids, monolithic CMOS, LGADs, and more...

10x more hits than HL-LHC!



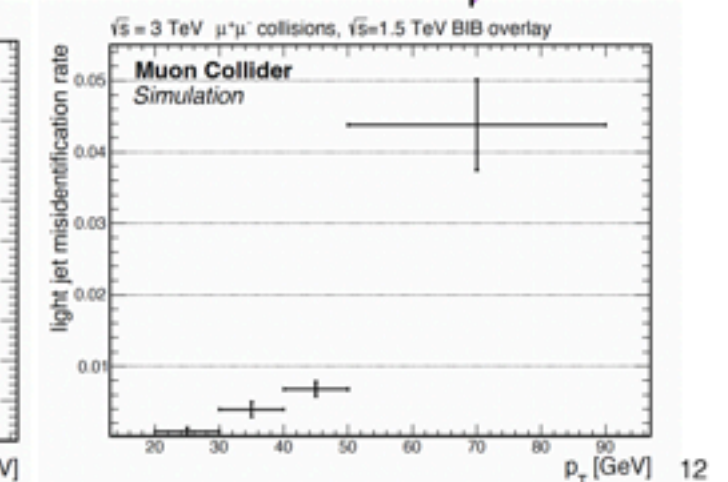
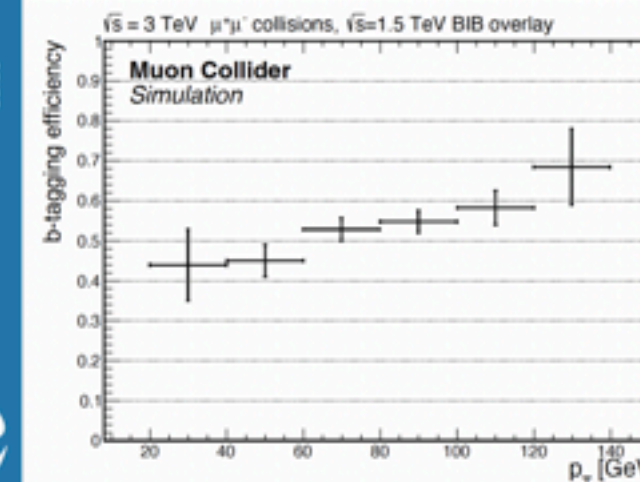
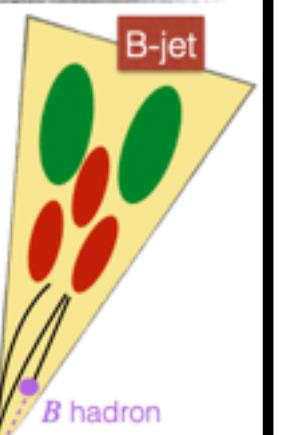
Marco Valente

Flavour tagging

From hits to particles

arXiv:2303.08533

- B-jet identification very important for physics case (in particular for Higgs physics).
 - B-tagging relies on secondary vertices reconstructed through tracks not associated to the Primary vertex.
- **B-tagging efficiency found to be within 50-70%** for light-jet mis-tagging rate between 0.1% and 5%



Slides from Talks

Example CERN Locations

Consider nTOF-like beam from P5 for cooling experiment:

- 1 pulse of 10^{13} p at 20 GeV per 1.2 s
- i.e. 27 kW, maybe O(100kW) possible

If SPL were, installed could use its beam, e.g. 5 GeV, 4 MW

What could be done at FNAL?

D. Schulte

Daniel Schulte

CDR Phase, R&D and Demonstrator Facility

Broad R&D programme required and can be distributed world-wide

- Models and prototypes
 - Magnets, Target, RF systems, Absorbers, ...
- CDR development
- Integrated tests, also with beam

Integrated cooling demonstrator is a key facility

- look for an existing proton beam with significant power

Different sites are being considered

- CERN, FNAL, ESS are being discussed
- J-PARC also interesting as option

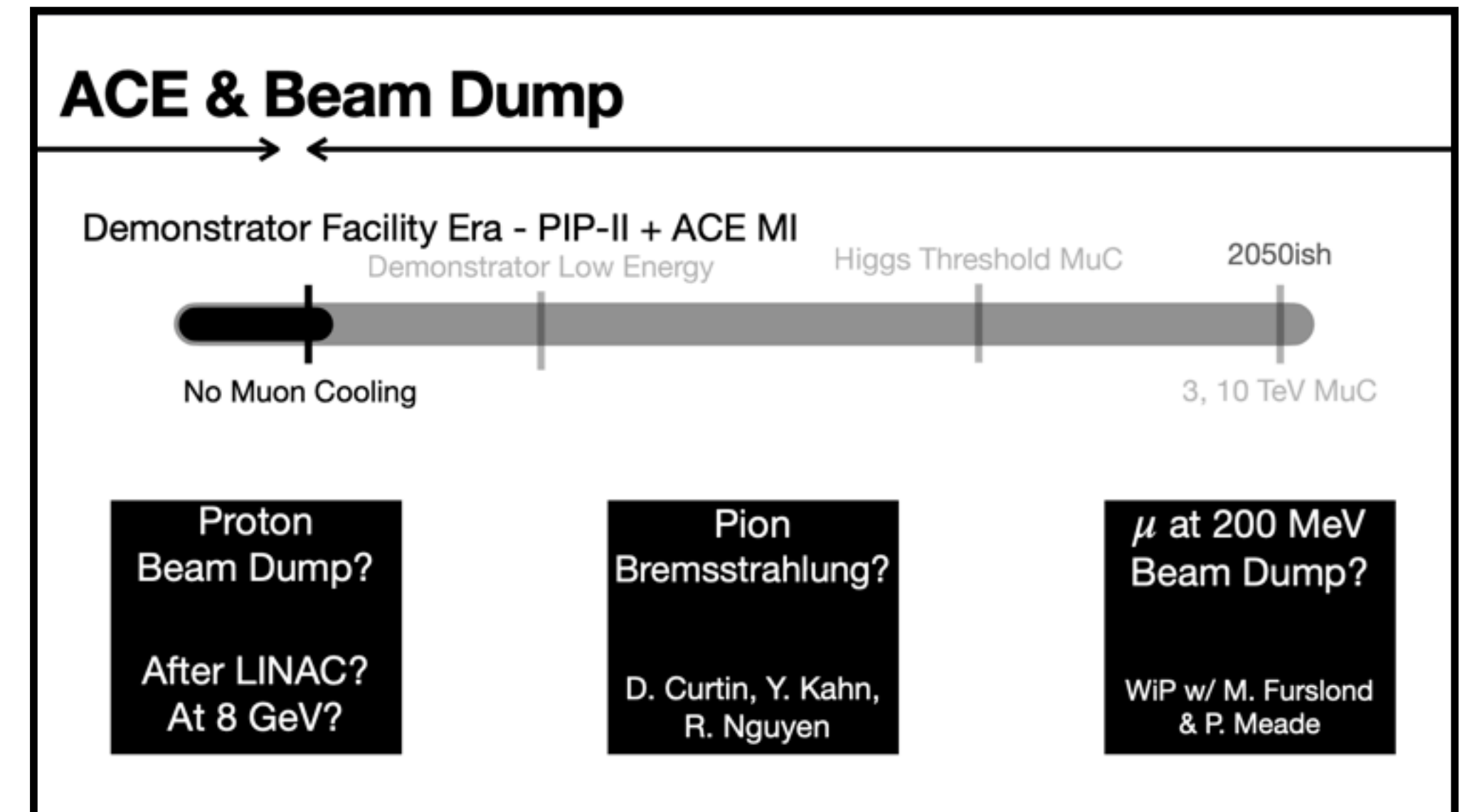
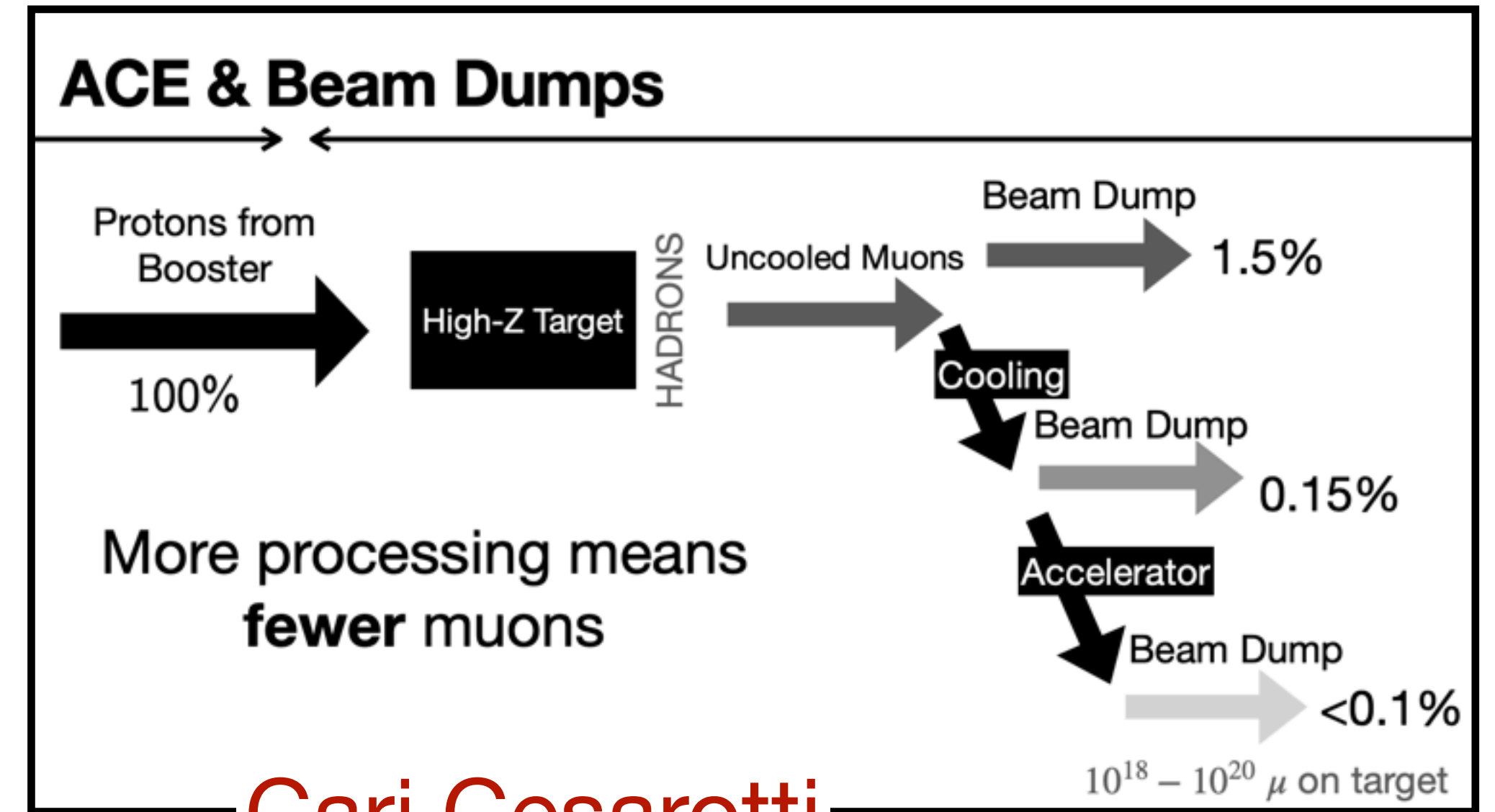
Could be used to house physics facility

- Are trying to explore what are good options

C. Rogers, R. Losito, et al.

D. Schulte

Muon Collider Collaboration, FNAL, June 2023



Slides from Talks

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Setup

Scalar Scenario, $E_{beam} = 15 \text{ GeV}$, W Target

outgoing energy distribution

acceptance

Unlike electron beam, invisible particle doesn't take all the beam energy:
low-mass invisibles are QED-like (and hard to distinguish from background)

M³ schematic

Similar in spirit to LDMX (electron beam missing momentum)

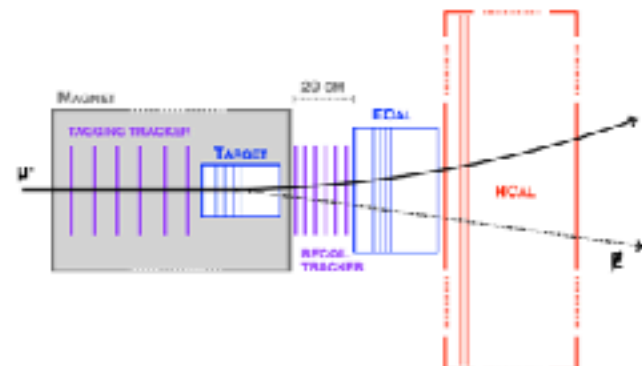
Main differences from LDMX:

- **thicker (50 X0) active target** (muon is a MIP)
- outgoing muon momentum measured **exclusively by recoil tracker** id HCal for veto only

Yoni Kahn

Beam requirements

- Lots of muons on target (MoT), i.e. high rep rate
- Identify and track each one so that we know they lost a significant amount of momentum ($p_{out} \lesssim 0.5 p_{in}$)
- Pion contamination = bad (esp. pions decaying in target). Estimate 10^{-6} will suffice for g-2 search
- $p_{in} > \sim$ several GeV - 10s of GeV:
 - lower boundary: need significant amount of lost momentum above detector thresholds to detect bkg processes
 - upper boundary: high momentum beam requires more B field lever arm, makes for a big and expensive detector with poor coverage



Reach

Phase 1 (10^{10} MOT): **complete coverage of g-2 region** for any invisibly-decaying particle lighter than the muon

Phase 2 (10^{13} MOT): can probe large parts of **well-motivated DM parameter space**

SM as an Effective Field Theory in the presence of FIPs

Typical BSM model-independent approach is to include all possible BSM operators + light new states explicitly.

$$\mathcal{L}_{SM+BSM} = -m_{ij}^2 (H_{SM}^\dagger H_{SM}) + \text{all dim 4 terms } (A_{SM}, \psi_{SM}, H_{SM}) + (\text{W.coeff.}/\Lambda^2) \times \text{Dim 6 etc } (A_{SM}, \psi_{SM}, H_{SM}) + \dots$$

all lowest dimension portals $(A_{SM}, \psi_{SM}, H, A_{DS}, \psi_{DS}, H_{DS}) \times$ portal couplings

+ dark sector interactions $(A_{DS}, \psi_{DS}, H_{DS})$

SM = Standard Model

DS – Dark Sector

Maxim Pospelov

Minimal portal interactions

Let us *classify* possible connections between Dark sector and SM

$H^\dagger H (\lambda S^2 + A S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$ “Kinetic mixing” with additional U(1)’ group (becomes a specific example of $J_\mu^i A_\mu$ extension)

LHN neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal...

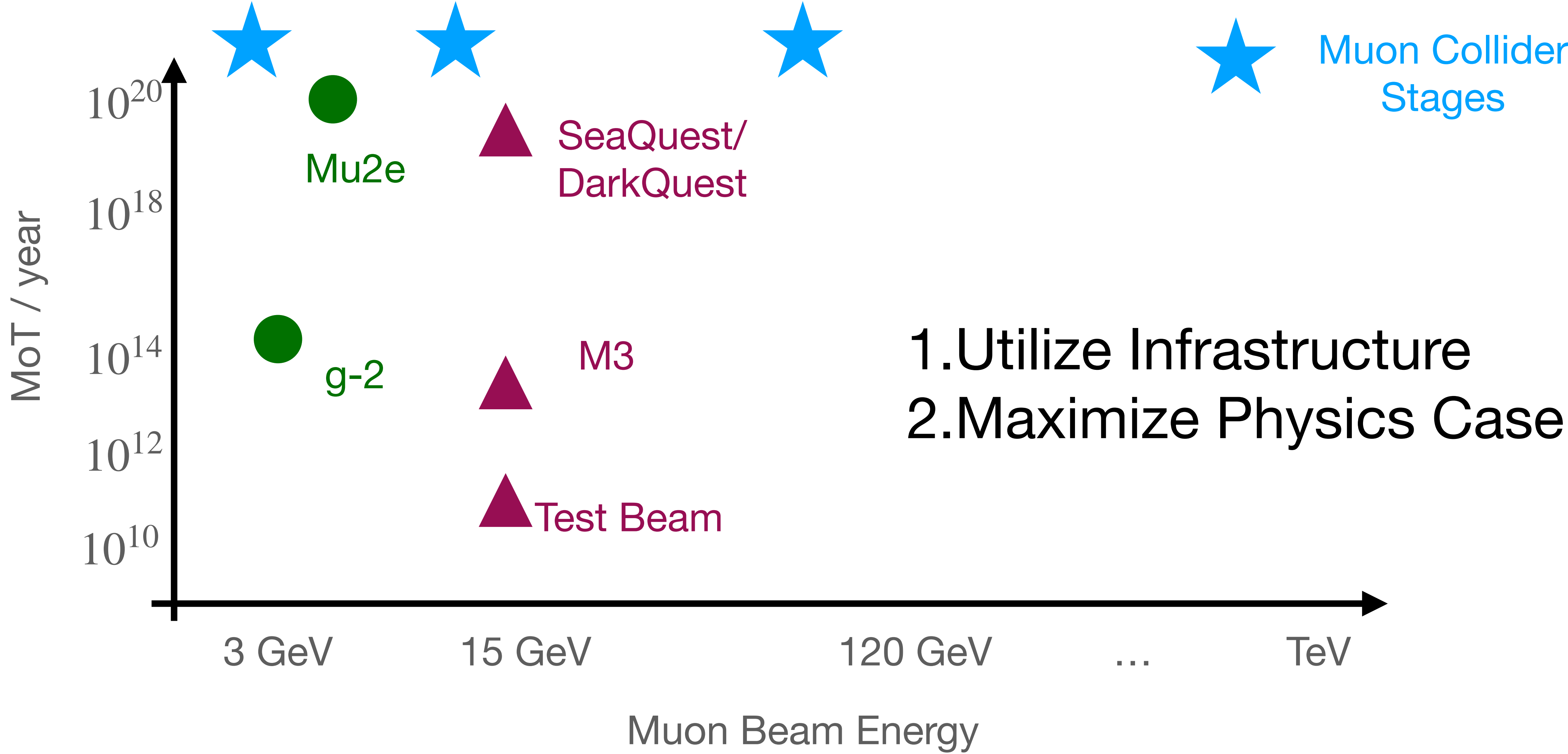
Dim>4

$J_\mu^A \partial_\mu a/f$ axionic portal

$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n} \frac{\mathcal{O}_{\text{med}}^{(k)} \mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n}$$

Owing to small couplings, such particles represent “dark sector”

Dark Sectors & Muon Colliders



- 1. Utilize Infrastructure
- 2. Maximize Physics Case

Dark Sectors & Muon Colliders

Things to Do:

1. Z' at muon Colliders: inclusive and semi-inclusive searches
2. Second generation right-handed neutrino production
3. Mu2e beams, beam dump infrastructure already in place!