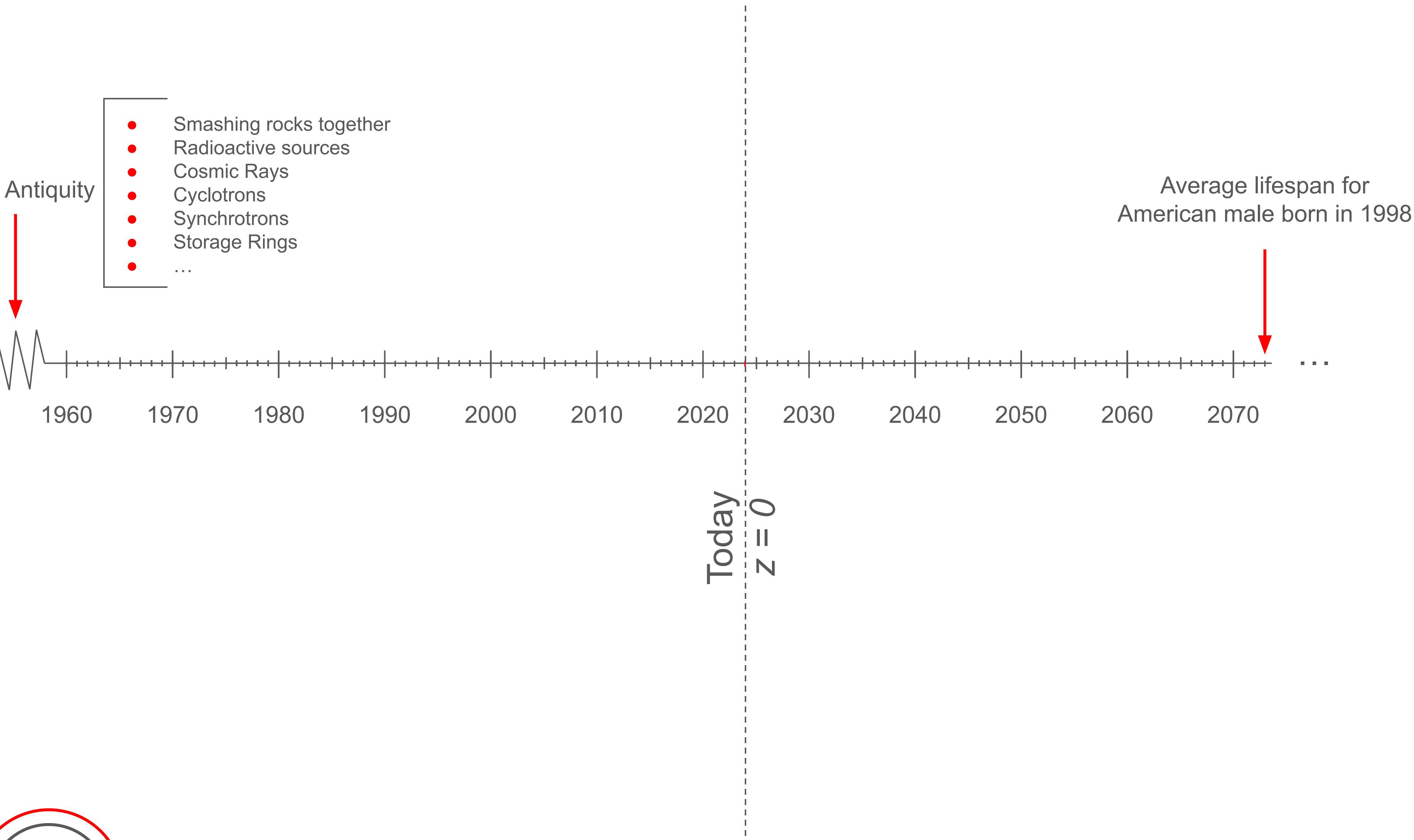
The New Physics Case for Muon Beam-Dump Experiments

Rikab Gambhir

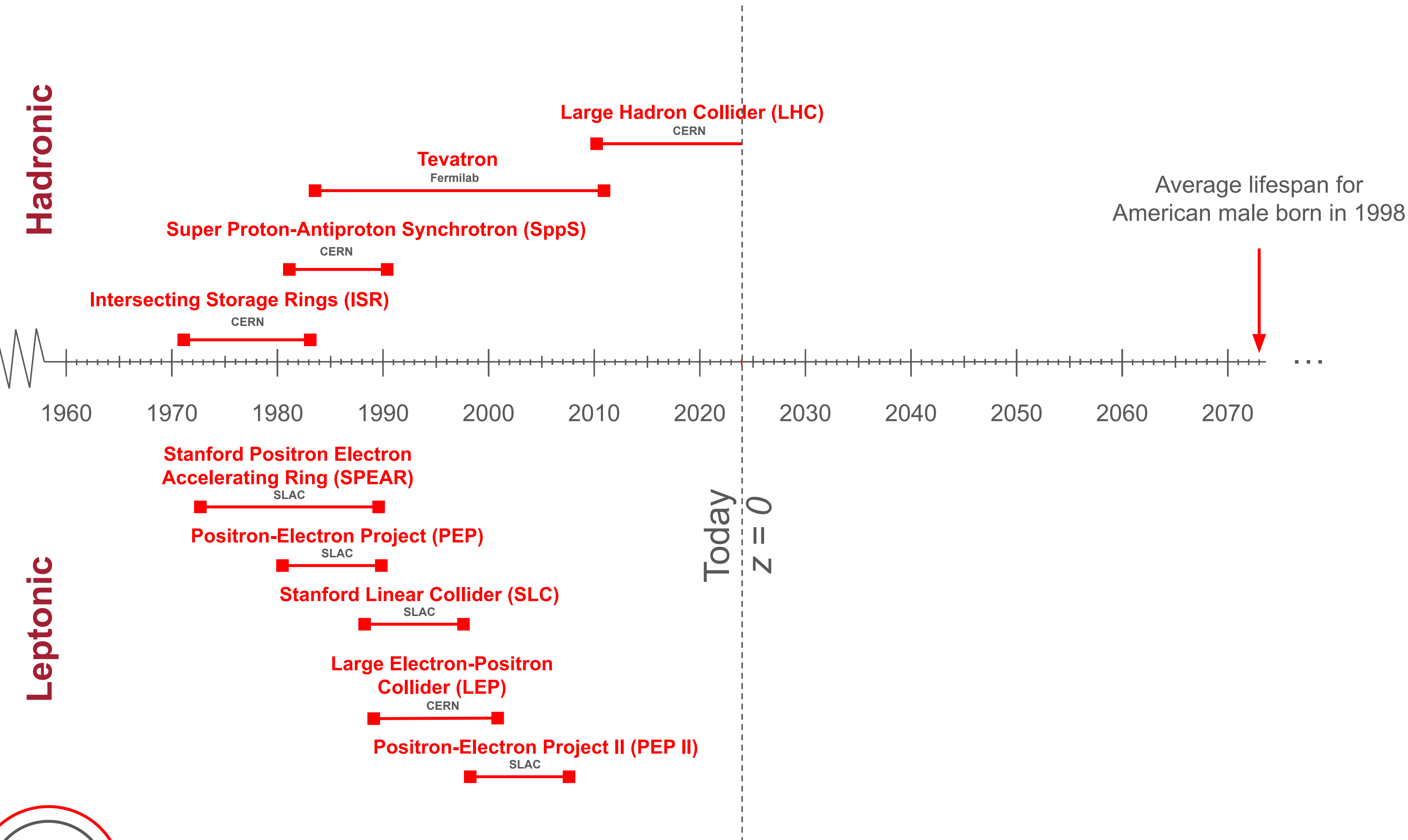
Email me questions at rikab@mit.edu!

Based on [Cesarotti, **RG**, 2310.16110]

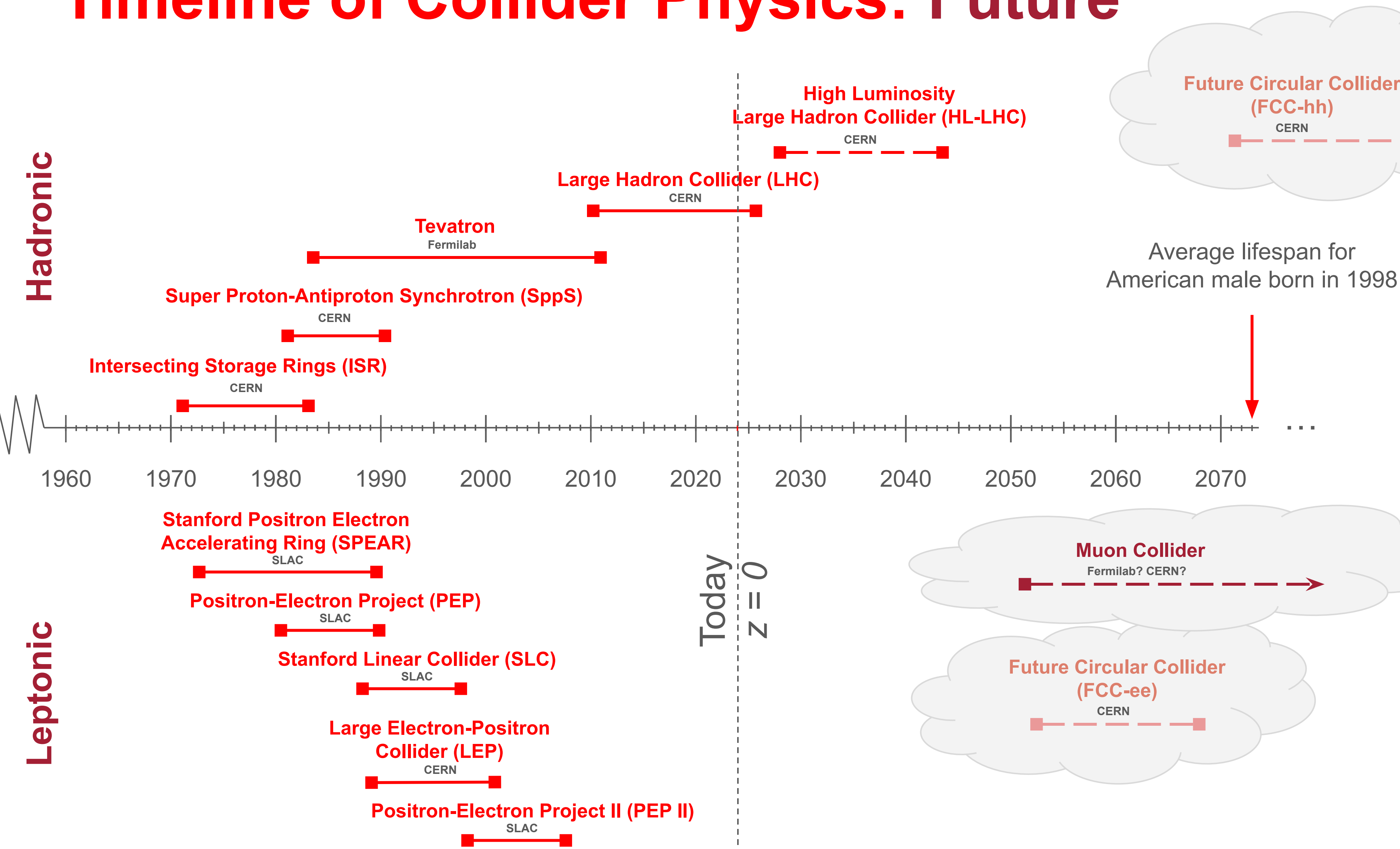
Timeline of Collider Physics



Timeline of Collider Physics: Past



Timeline of Collider Physics: Future

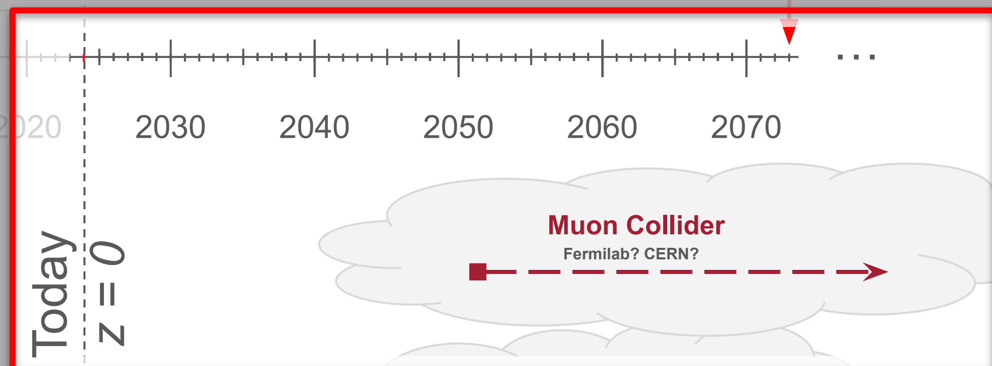


*Not an exhaustive list of potential futures!

Why Muons?

"This is our Muon Shot"

1. Achieve *much* **higher energies** than e^+e^-
2. **Cleaner*** than *pp* collisions
3. "**Electroweak** Boson Collider"
4. Direct probe of **2^{nd} gen physics**
5. "It's just [redacted]**ing cool**" – Nima Arkani-Hamed, APS 2023



Not included: Heavy ion experiments, neutrino experiments, *ep* experiments, astronomical or cosmological observations…

Timeline of Particle Physics

Why Muons?

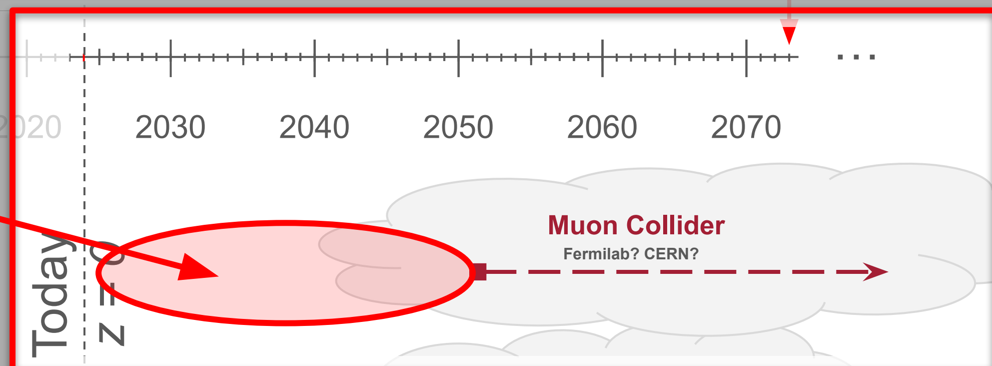
"This is our Muon Shot"

1. Achieve *much* **higher energies** than e^+e^-
2. **Cleaner*** than *pp* collisions
3. "**Electroweak** Boson Collider"
4. Direct probe of **2^{nd} gen physics**
5. "It's just [redacted]**ing cool**" – Nima Arkani-Hamed, APS 2023

Road to the Future

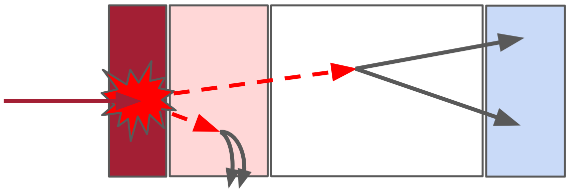
Lots of R&D needed! A huge undertaking …

This Talk: R&D is worth it, because **muon test beams** already have the potential for discovering **new physics**! Interesting results for muon beams as low as **10 GeV**!

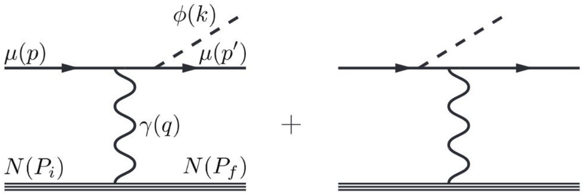


Outline

Beam Dump Fundamentals

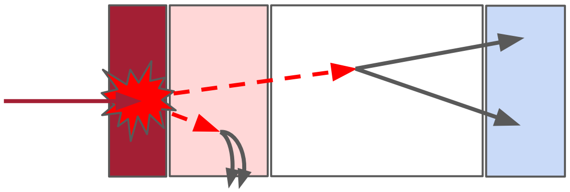


New Physics Searches

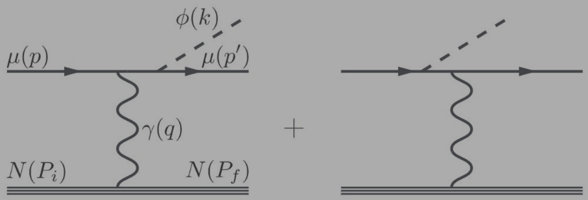


Outline

Beam Dump Fundamentals



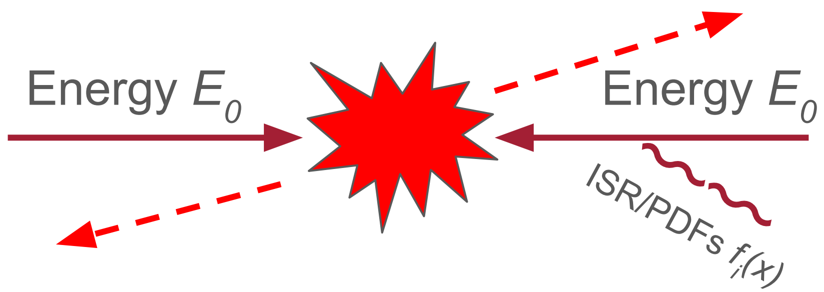
New Physics Searches



Beam Dump Fundamentals

Collider Setup

e.g. LHC, LEP, FCC

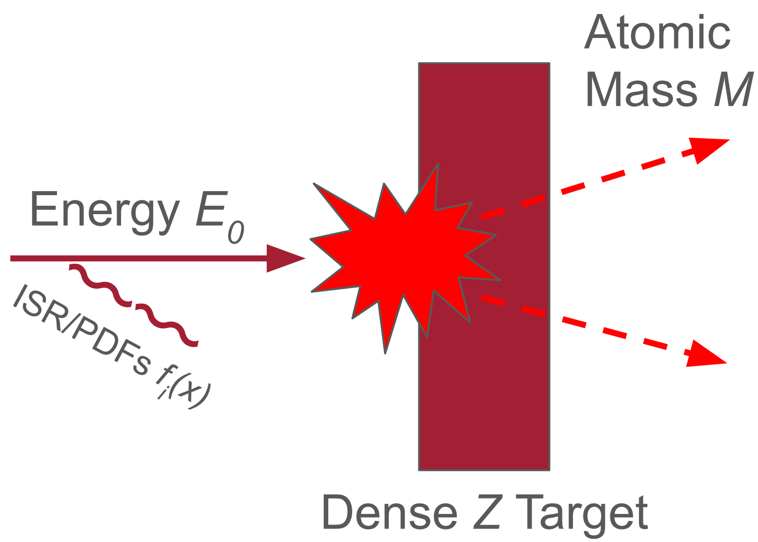


Nominal
Collision Energy: $\sqrt{s} = 2E_0$

✓ High Energies
✓ *s*-channel production

Beam Dump Setup

e.g. NA64, KEK, Orsay, E137, **Our Proposal**



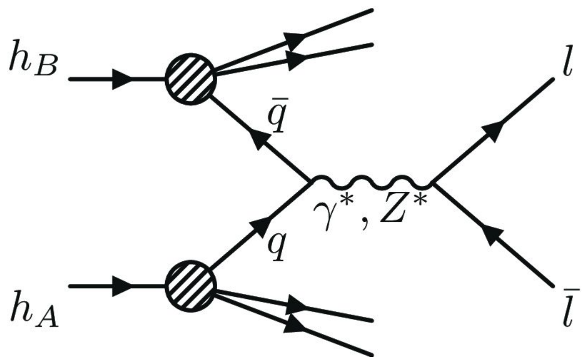
Nominal
Collision Energy: $\sqrt{s} = \sqrt{2E_0 M}$

✓ Large rate
✓ Low couplings
✓ More cost effective

*This is just the *nominal* energy – PDFs can *drastically* change the actual hard process energy, especially for hadrons!

Aside: PDFs, ISR, and FSR

Since particles radiate or can be non-perturbative, it is a lot easier to think about colliding **partons** instead.



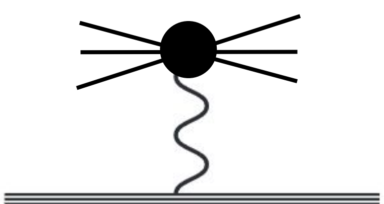
$$\sigma = \sum_{a,b} \int_0^1 \mathrm{d}x_a \mathrm{d}x_b \int f_{a/h_1}(x_a, \mu_F) f_{b/h_2}(x_b, \mu_F)\, \mathrm{d}\hat{\sigma}_{ab\to n}(\mu_F, \mu_R)$$

$f_a(x)$ = probability of finding parton *a* in the particle *h* with longitudinal momentum fraction *x*

Leptons are “cleaner” than hadrons because *f(x) ~* □*(x-1)**

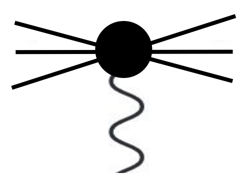
Useful Application: **Weizsäcker-Williams****

Process with a *t*-channel photon



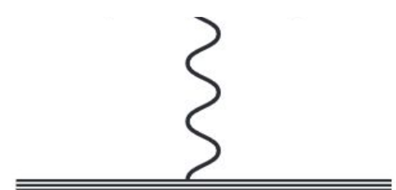
$\underset{t\to 0}{=}$

On-shell photon amplitude



× Propagator *1/t* ×

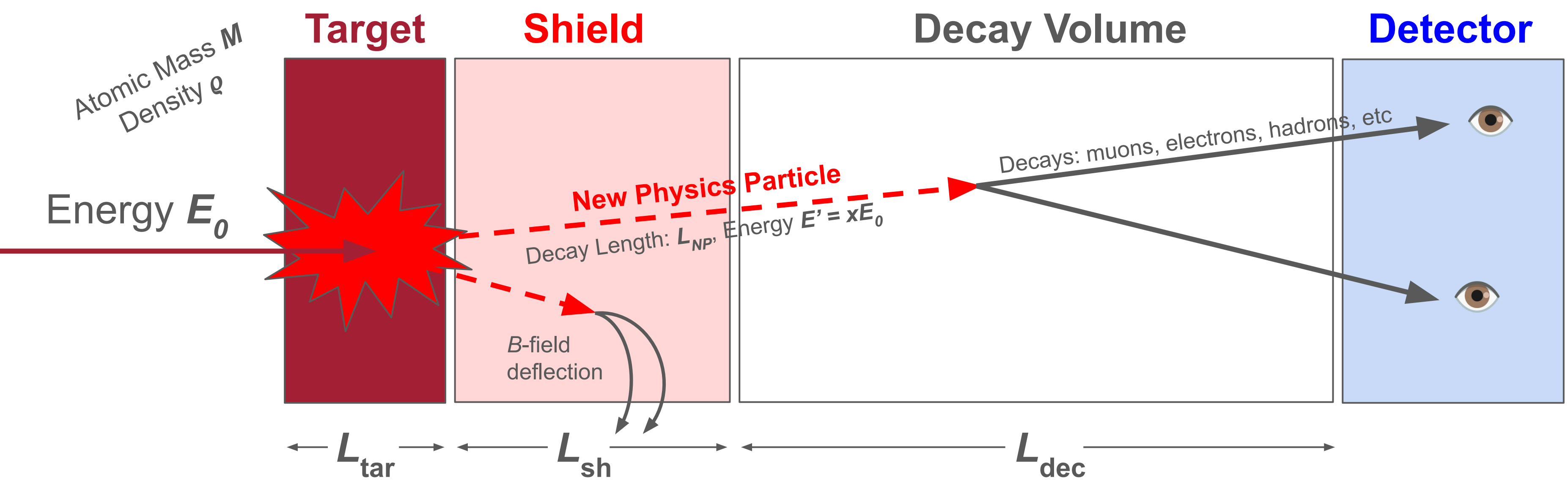
Photon PDF / “Flux Factor”



*But not exactly, which leads to lots of fun with gauge bosons and jets!

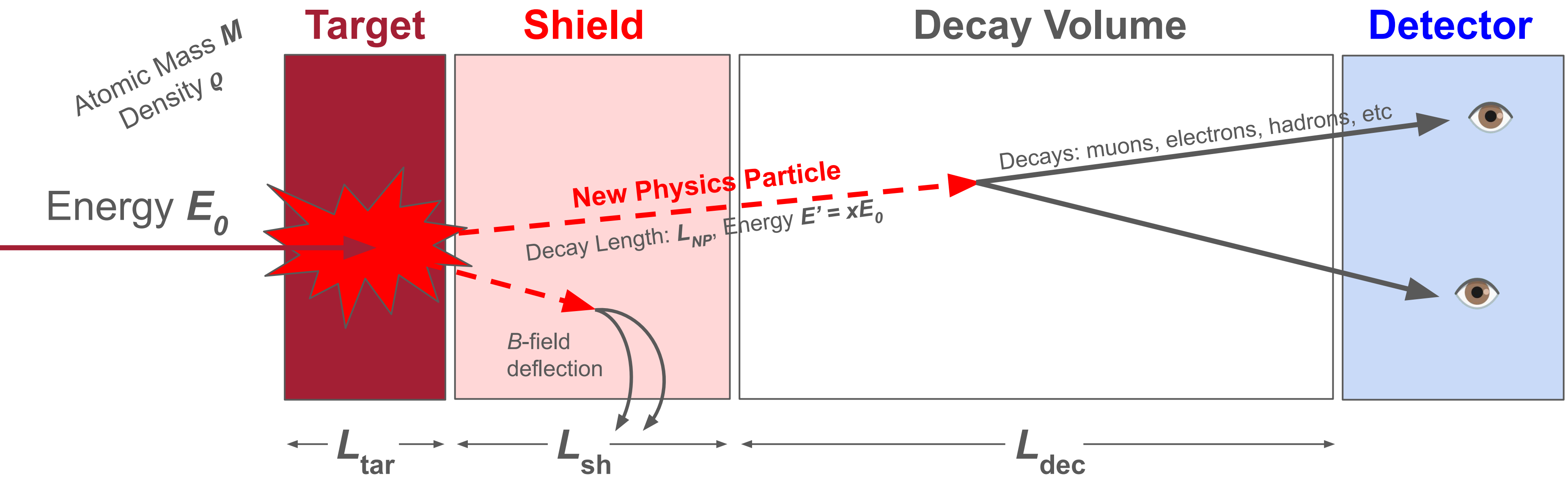
**Sometimes called the “Effective Photon Approximation” or “Effective Vector Approximation”

Beam Dump Fundamentals (Continued)



1. Dump a muon beam into a **fixed target**, produce new particles!
2. Junk (residual muons, SM decays, etc) deflected and/or absorbed by shield
3. New particles are boosted and collinear, fly for a distance L_{NP} before decaying to particles we can detect!

Beam Dump Fundamentals (Continued)



1. Dump a muon beam into a **fixed target**, produce new particles!
2. Junk (residual muons, SM decays, etc) deflected and/or absorbed by shield
3. New particles are boosted and collinear, fly for a distance L_{NP} before decaying to particles we can detect!

Particles can travel a long distance: $l_{\mathrm{NP}} \approx \left(\frac{E_0}{\mathrm{TeV}}\right) \times \left(\frac{g}{10^{-6}}\right)^{-2} \times \left(\frac{m_{\mathrm{NP}}}{10\ \mathrm{MeV}}\right)^{-2} \times 100\mathrm{m}$

Beam Dump Fundamentals (Details)

How many new particles should we expect to see*?

$$\frac{dN}{dx dz} = N_\mu \frac{N_0 X_0}{A} \times \mathcal{BR} \times \int_{E_\phi}^{E_0} \frac{dE'}{E'} \int_0^T dt \; I(E'; E_0, t) \times E_0 \frac{d\sigma}{dx'}\Big|_{x' \equiv E'/E_0} \frac{dP(z - \frac{X_0}{\rho} t)}{dz}$$

*Assuming that the detector is wide enough to capture all emitted particles – we have chosen geometries and cutoffs such that this is approximately true.
*Assuming 100% detection efficiency.
*Assuming no SM backgrounds, taken care of by shields and/or absorption.

Beam Dump Fundamentals (Details)

How many new particles should we expect to see*?

$$\boxed{\frac{dN}{dx\,dz}} = N_\mu \frac{N_0 X_0}{A} \times \mathcal{BR} \times \int_{E_\phi}^{E_0} \frac{dE'}{E'} \int_0^T dt\; I(E'; E_0, t) \times E_0 \frac{d\sigma}{dx'}\bigg|_{x' \equiv E'/E_0} \frac{dP(z - \frac{X_0}{\rho} t)}{dz}$$

Number of detected particles ***N*** as a function of their energy fraction ***x*** and decay length ***z***

*Assuming that the detector is wide enough to capture all emitted particles – we have chosen geometries and cutoffs such that this is approximately true.
*Assuming 100% detection efficiency.
*Assuming no SM backgrounds, taken care of by shields and/or absorption.

Beam Dump Fundamentals (Muon Source)

How many new particles should we expect to see?

$$\frac{dN}{dxdz} = \boxed{N_\mu} \frac{N_0 X_0}{A} \times \mathcal{BR} \times \int_{E_\phi}^{E_0} \frac{dE'}{E'} \int_0^T dt \; I(E'; E_0, t) \times E_0 \frac{d\sigma}{dx'}\bigg|_{x' \equiv E'/E_0} \frac{dP(z - \frac{X_0}{\rho} t)}{dz}$$

Number of **muons on target**, 10^{18} - 10^{22} / year

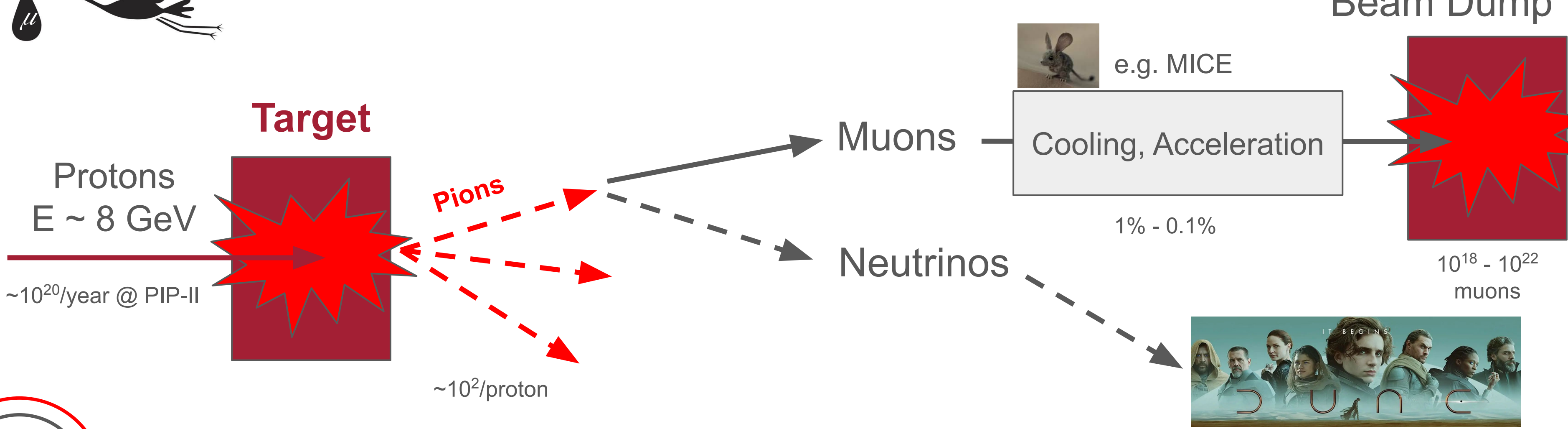
Beam Dump Fundamentals (Muon Source)

How many new particles should we expect to see?

$$\frac{dN}{dx\,dz} = \boxed{N_\mu} \frac{N_0 X_0}{A} \times \mathcal{BR} \times \int_{E_\phi}^{E_0} \frac{dE'}{E'} \int_0^T dt\; I(E';E_0,t) \times E_0 \frac{d\sigma}{dx'}\Big|_{x'\equiv E'/E_0} \frac{dP(z-\frac{X_0}{\rho}t)}{dz}$$

Number of **muons on target**, 10^{18} - 10^{22} / year

How are muons born?



Beam Dump Fundamentals (Target)

How many new particles should we expect to see?

$$\frac{dN}{dx\,dz} = N_\mu \boxed{\frac{N_0 X_0}{A}} \times \mathcal{BR} \times \boxed{\int_{E_\phi}^{E_0} \frac{dE'}{E'} \int_0^T dt\; I(E'; E_0, t)} \times E_0 \frac{d\sigma}{dx'}\bigg|_{x' \equiv E'/E_0} \frac{dP(z - \frac{X_0}{\rho} t)}{dz}$$

N_0: Avogadro's Number, ~10^{23}/mol
X_0: Material Decay Length
A: Material atomic mass, ~10-100 g/mol

$I(E'; E_0, t)$ = Radiative losses as the muon transverses a distance *t* through the target

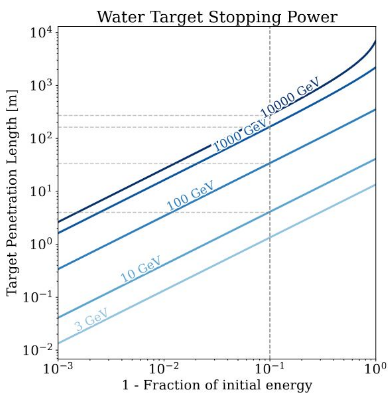
Beam Dump Fundamentals (Target)

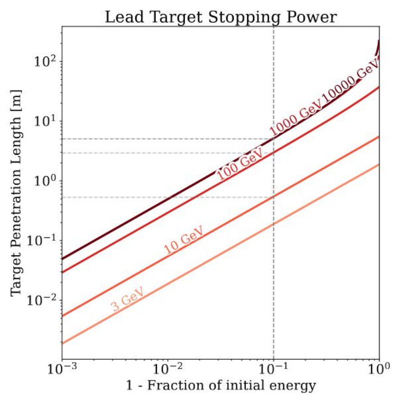
How many new particles should we expect to see?

$$\frac{dN}{dx\,dz} = N_\mu \boxed{\frac{N_0 X_0}{A}} \times \mathcal{BR} \times \boxed{\int_{E_\phi}^{E_0} \frac{dE'}{E'} \int_0^T dt\, I(E'; E_0, t)} \times E_0 \frac{d\sigma}{dx'}\bigg|_{x' \equiv E'/E_0} \frac{dP(z - \frac{X_0}{\rho} t)}{dz}$$

N_0: Avogadro's Number, $\sim 10^{23}$/mol
X_0: Material Decay Length
A: Material atomic mass, ~10-100 g/mol

$I(E'; E_0, t)$ = Radiative losses as the muon transverses a distance *t* through the target





Radiative losses for water and lead

Thin Target Approximation: No losses

$$I(E'; E_0, t) = \delta(E' - E_0)$$

Fixes the size of L_{tar}, otherwise requires more sophisticated material modeling …

Beam Dump Fundamentals (Decays)

How many new particles should we expect to see?

$$\frac{dN}{dxdz} = N_\mu \frac{N_0 X_0}{A} \times \boxed{\mathcal{BR}} \times \int_{E_\phi}^{E_0} \frac{dE'}{E'} \int_0^T dt\, I(E'; E_0, t) \times E_0 \frac{d\sigma}{dx'}\Big|_{x' \equiv E'/E_0} \boxed{\frac{dP(z - \frac{X_0}{\rho} t)}{dz}}$$

Branching ratio into ***visible* final states** (electrons, muons, hadrons)*

Probability of the new particle decaying at a (normalized) position *z*

$$\frac{dP(l)}{dl} = \frac{1}{L_{\mathrm{NP}}} e^{-l/L_{\mathrm{NP}}}$$

*Photons not considered, but definitely possible to do in other setups!
*Hadrons obtained by using *R*-ratio measurements, OK below *Z* pole.
* Tau decays are possible, but to be conservative we will assume we can't reconstruct them.

Beam Dump Fundamentals (Decays)

How many new particles should we expect to see?

$$\frac{dN}{dxdz} = N_\mu \frac{N_0 X_0}{A} \times \boxed{\mathcal{BR}} \times \int_{E_\phi}^{E_0} \frac{dE'}{E'} \int_0^T dt\, I(E'; E_0, t) \times E_0 \frac{d\sigma}{dx'}\Big|_{x' \equiv E'/E_0} \boxed{\frac{dP(z - \frac{X_0}{\rho} t)}{dz}}$$

Branching ratio into ***visible* final states** (electrons, muons, hadrons)*

Probability of the new particle decaying at a (normalized) position *z*

$$\frac{dP(l)}{dl} = \frac{1}{\boxed{L_{\rm NP}}} e^{-l/\boxed{L_{\rm NP}}}$$

$$\Gamma_{\phi \to l^+ l^-} = g_S^2 \frac{m_\phi}{8\pi} \left(1 - \frac{4m_l^2}{m_\phi^2}\right)^{3/2}$$

$$\Gamma_{a \to l^+ l^-} = g_P^2 \frac{m_\phi}{8\pi} \left(1 - \frac{4m_l^2}{m_\phi^2}\right)^{1/2}$$

$$\Gamma_{V \to l^+ l^-} = g_V^2 \frac{m_\phi}{12\pi} \left(1 + \frac{2m_l^2}{m_\phi^2}\right) \left(1 - \frac{4m_l^2}{m_\phi^2}\right)^{1/2}$$

$$\Gamma_{A \to l^+ l^-} = g_A^2 \frac{m_\phi}{12\pi} \left(1 - \frac{4m_l^2}{m_\phi^2}\right)^{3/2}.$$

Decay lengths and branching ratios depend on new particle mass, coupling, and spin/parity

*Photons not considered, but definitely possible to do in other setups!
*Hadrons obtained by using *R*-ratio measurements, OK below *Z* pole.
*Tau decays are possible, but to be conservative we will assume we can't reconstruct them.

Beam Dump Fundamentals (Cross Section)

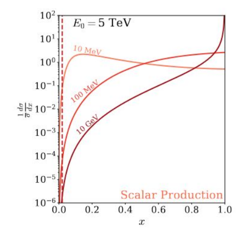
How many new particles should we expect to see?

$$\frac{dN}{dx\,dz} = N_\mu \frac{N_0 X_0}{A} \times \mathcal{BR} \times \int_{E_\phi}^{E_0} \frac{dE'}{E'} \int_0^T dt\, I(E'; E_0, t) \times E_0 \boxed{\left.\frac{d\sigma}{dx'}\right|_{x' \equiv E'/E_0}} \frac{dP(z - \frac{X_0}{\rho} t)}{dz}$$

Cross section to produce new particle with an energy fraction *x*
Assumed to be produced collinearly, with characteristic angle:

$$\theta_0 \lesssim \frac{m_\phi \sqrt{\max\left(\frac{m_\mu}{m_\phi}, \frac{m_\phi}{E_0}\right)}}{E_0}$$

Explored more in the next section!

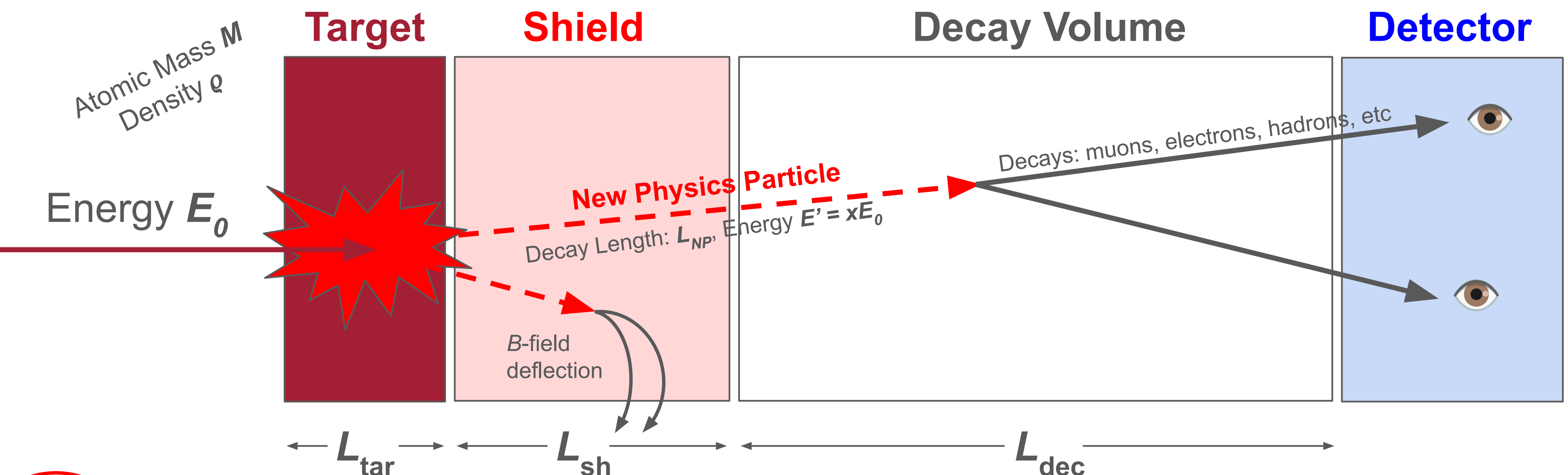


Beam Dump Fundamentals (Simplification)

Under thin target approximation, we can simplify:

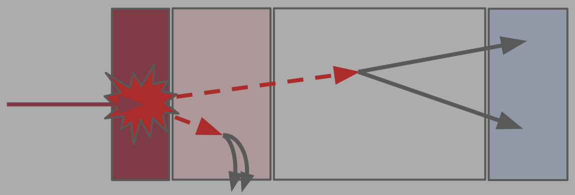
$$\frac{dN}{dx} = N_\mu \frac{N_0 \rho l_0}{A} \frac{d\sigma}{dx} \left(e^{\frac{L_{\rm tar}}{l_0}} - 1 \right) e^{-(L_{\rm tar} + L_{\rm sh})} \left(1 - e^{-L_{\rm dec}/l_0} \right)$$

Explicit dependence on experiment geometry! Needs to be optimized.
Final results obtained by numerical integration over *x*

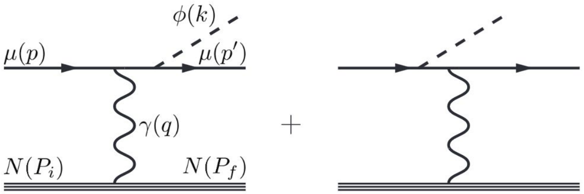


Outline

Beam Dump Fundamentals



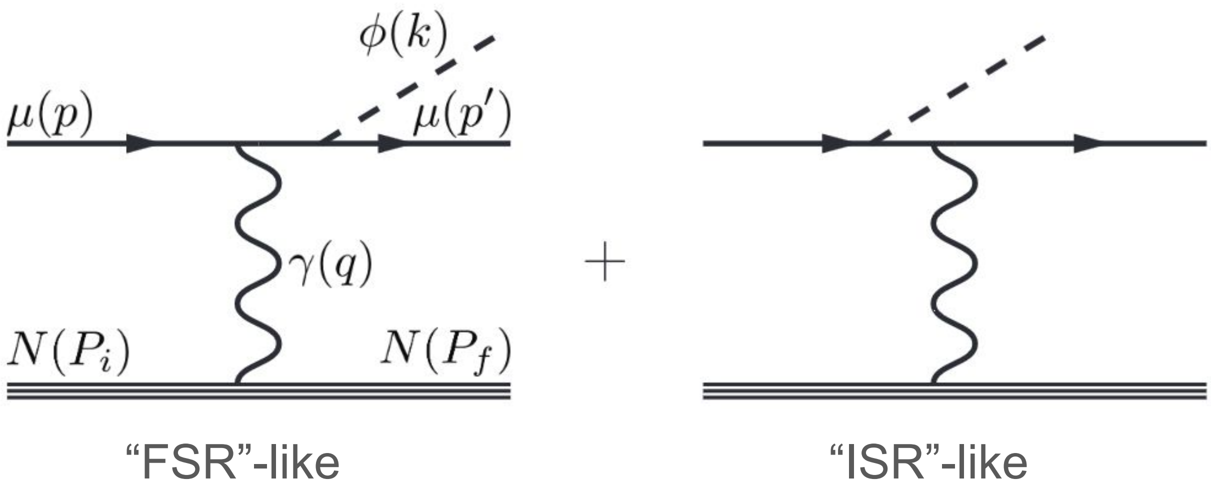
New Physics Searches



New Physics – Bremsstrahlung Production

Given a beam dump, what kind of new physics ϕ can we search for?

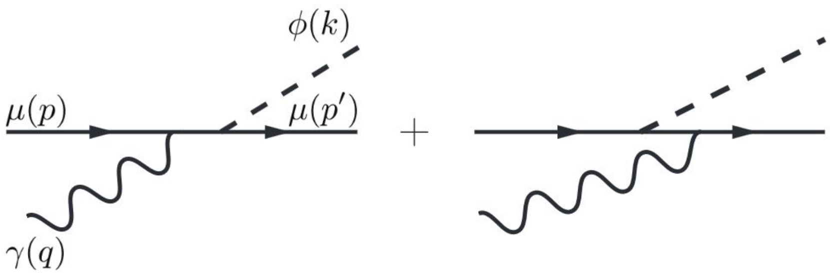
$$\mu(p) + N(P_i) \to \mu(p') + N(P_f) + \phi(k)$$



Cross Sections – Weizsäcker-Williams

2→3 scattering is hard, and nuclear physics is even harder … use Weizsäcker-Williams!

$$\mu(p) + \gamma(q) \to \mu(p') + \phi(k)$$



Approximation works best when the photon (virtuality *t*) is nearly on shell:

$$t_{\min} \approx \left(\frac{m_\phi^2}{2E}\right)^2$$

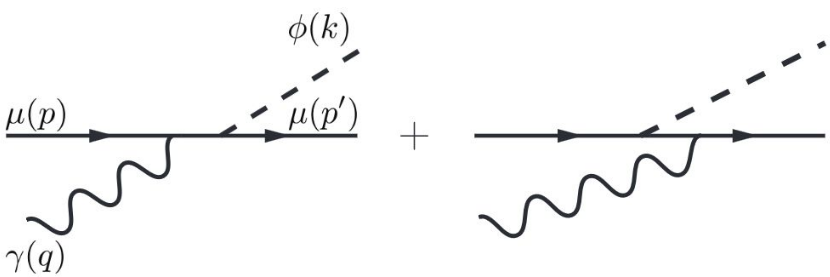
Sets the minimum beam energy we consider

*Fully collinear approximation begins to fails for E < 100 GeV – see 2310.16110 for the full treatment and long formulas.

Cross Sections – Weizsäcker-Williams

2→3 scattering is hard, and nuclear physics is even harder … use Weizsäcker-Williams!

$$\mu(p) + \gamma(q) \to \mu(p') + \phi(k)$$



Approximation works best when the photon (virtuality t) is nearly on shell:

$$t_{\min} \approx \left(\frac{m_\phi^2}{2E}\right)^2$$

Sets the minimum beam energy we consider

Enhanced production when t is small – collinear emission, regulated by masses

$$\left(\frac{d\sigma_{2\to3}}{dx}\right)_{\mathrm{IWW}} = \frac{g^2}{2\pi}\alpha\chi\frac{|\vec{k}|}{E}\frac{(1-x)}{x}\int_{-\infty}^{\tilde{u}_{\max}} d\tilde{u}\,\frac{\mathcal{A}^{22}_{t=t_{\min}}}{\tilde{u}^2}$$

Spin-averaged squared amplitude evaluated at $t_{\min}$

Integrated Photon Flux

$$\chi \equiv \int_{t_{\min}}^{t_{\max}} dt\,\frac{t-t_{\min}}{t^2}G(t)$$

$$\tilde{u}(x,\theta) \approx -xE_0^2\theta^2 - m_X^2\frac{1-x}{x} - m_\mu^2 x$$

Experiment Parameters

Target Materials	Beam Energy E_0 [GeV]	Muons On Target (μ)
Lead	10	10^{18}
Water	$63\ (m_h/2)$	10^{20}
	1.5×10^3	10^{22}
	5×10^3	

- Minimum beam energy chosen such that WW approximation is good
- L_{tar} chosen such that the muons lose no more than 90% of their energy
- L_{sh} and L_{dec} process-dependent
- Detector radius should be chosen such that an order 1 factor of decays are captured – most are collinear, typically 10^{-2} rad

All of these parameters should be optimized!

Models

Scalar

$$\mathcal{L}^S_{\text{int}} \supset -ig_S \phi \bar{\psi} \psi$$

e.g. muonphilic, leptophilic scalars

Pseudoscalar

$$\mathcal{L}^P_{\text{int}} \supset -ig_P a \bar{\psi} \gamma^5 \psi$$

e.g. muonphilic, leptophilic pseudoscalars*

Vector

$$\mathcal{L}^V_{\text{int}} \supset -ig_V V_\mu \bar{\psi} \gamma^\mu \psi$$

e.g. Dark Photons, L_μ - L_τ

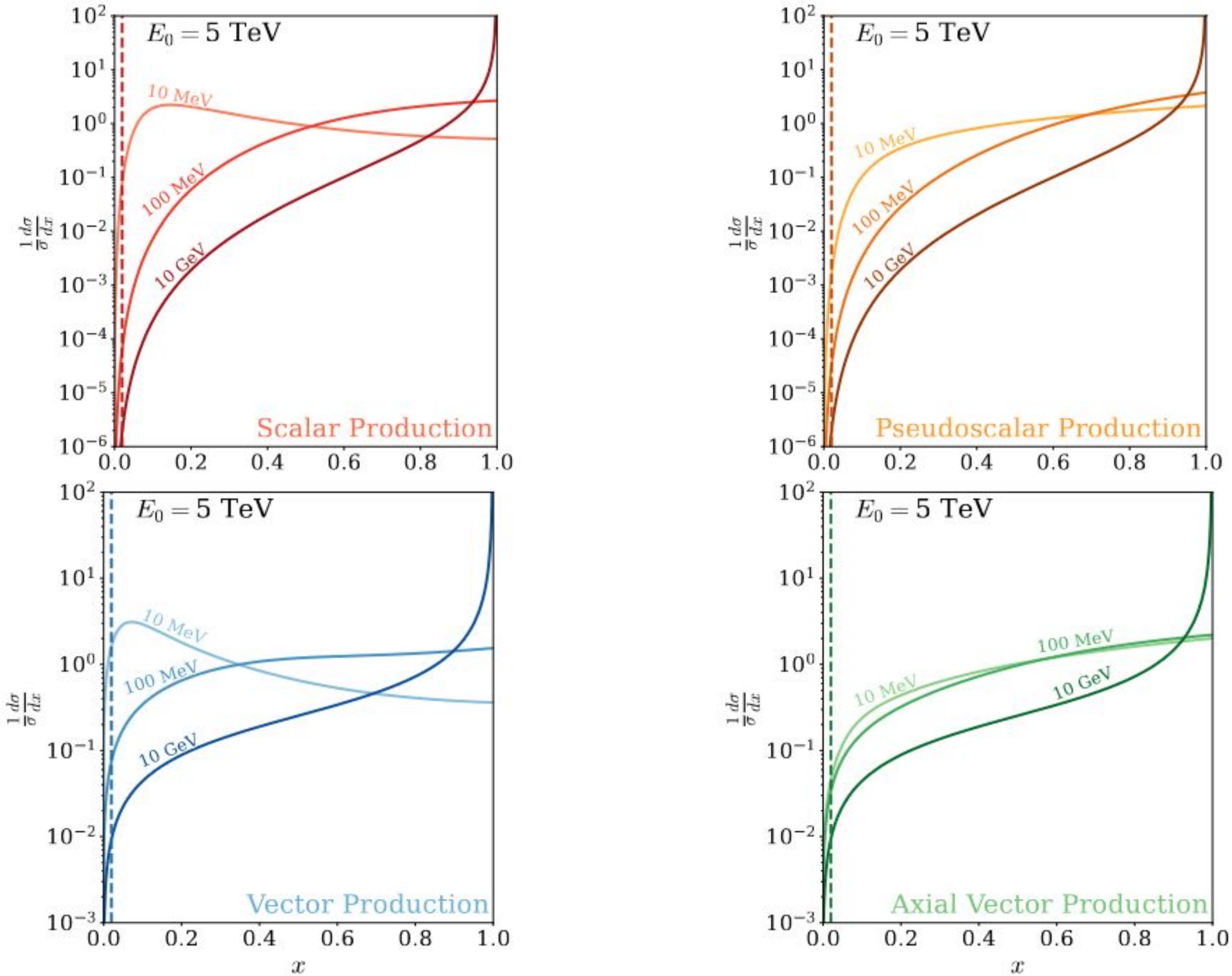
Axial Vector

$$\mathcal{L}^A_{\text{int}} \supset -ig_A A_\mu \bar{\psi} \gamma^\mu \gamma^5 \psi$$

e.g. muonphilic axial vectors

*ALPs are funny in our setup.

Models – Cross Sections



Models

Scalar

$$\mathcal{L}^S_{\text{int}} \supset -i g_S \phi \bar{\psi} \psi$$

e.g. muonphilic, leptophilic scalars

Vector

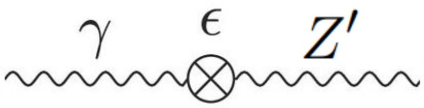
$$\mathcal{L}^V_{\text{int}} \supset -i g_V V_\mu \bar{\psi} \gamma^\mu \psi$$

e.g. Dark Photons, L_μ - L_τ

Dark Photons

Extend the SM with a broken *U*(1)' symmetry with a gauge boson *Z*'.

Couples to SM charged particles via kinetic mixing with the photon with parameter ε.



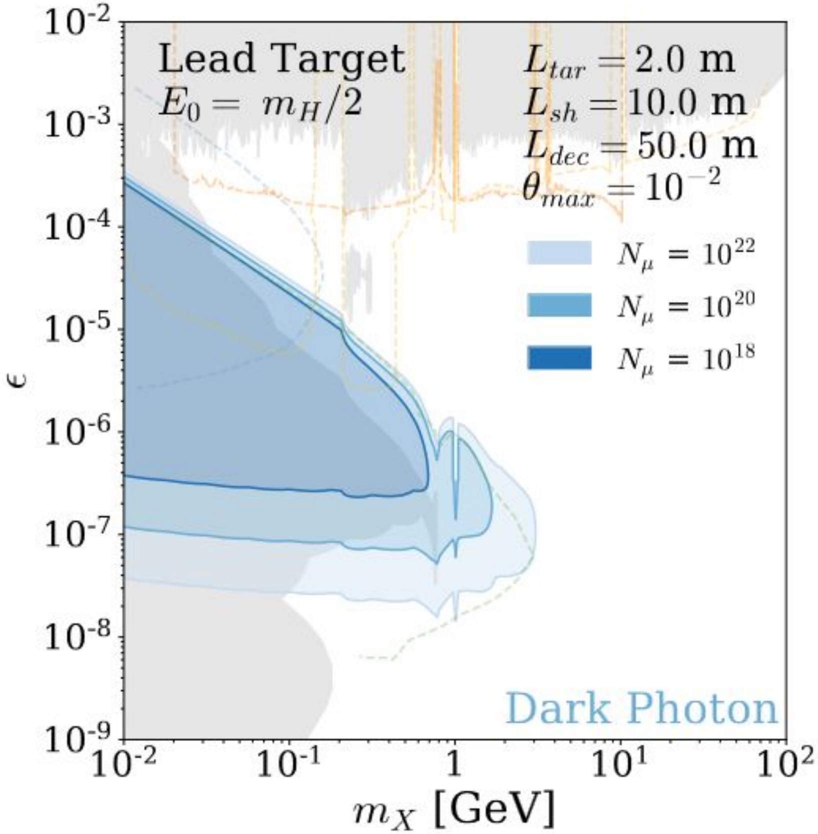
$$\mathcal{L} \supset \frac{1}{2} m^2_{Z'} Z'^\mu Z'_\mu - \sum_{l \in e,\mu,\tau} i\epsilon e \left(\bar{l}\gamma^\mu l\right) Z'_\mu$$

Classic DM candidate!

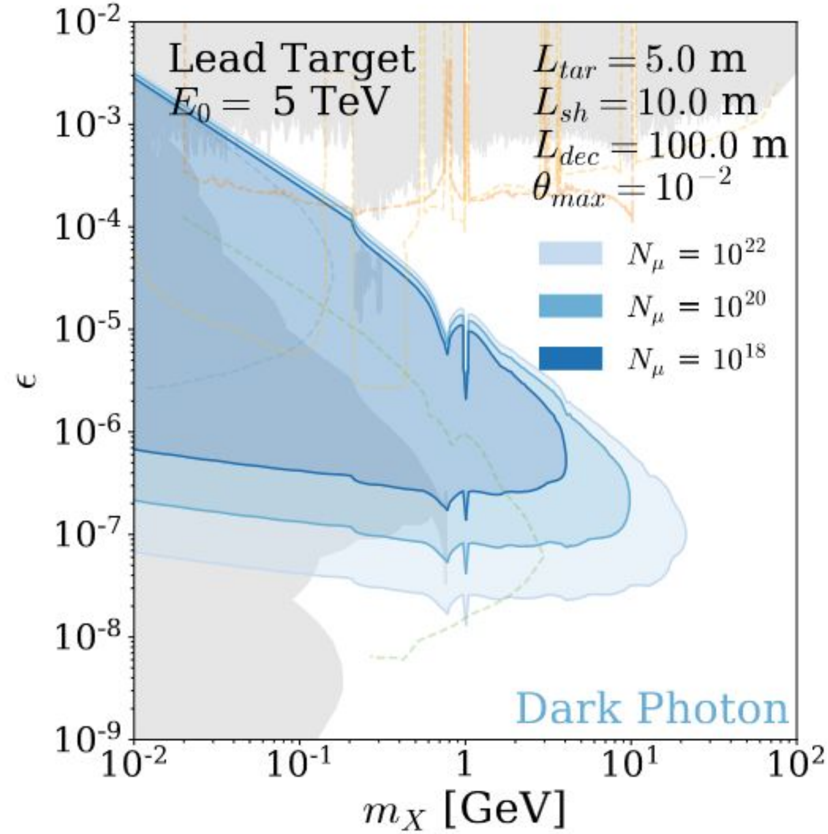
Dark photons are like light, except they're dark instead of light, and heavy instead of light

*ALPs are funny in our setup.

Results – Dark Photons



(a) Dark photon limits at $E_0 = m_h/2$.



(b) Dark photon limits at $E_0 = 5$ TeV.

Models

Scalar

$$\mathcal{L}_{\text{int}}^{S} \supset -i g_S \phi \bar{\psi} \psi$$

e.g. muonphilic, leptophilic scalars

Vector

$$\mathcal{L}_{\text{int}}^{V} \supset -i g_V V_\mu \bar{\psi} \gamma^\mu \psi$$

e.g. Dark Photons, L_μ - L_τ

Muonphilic

Model where the new scalar *only* couples to muons.

$$\mathcal{L} \supset \frac{1}{2} m_\phi^2 \phi^2 - i \left[g_\mu \bar{\mu} \mu + \cancel{g_e \bar{e} e} + \cancel{g_\tau \bar{\tau} \tau} \right] \phi$$

Can be generated by the dim 5 operator:

$$\phi L H \mu^c$$

Can also arise as a Higgs-like coupling with $g_\ell \sim m_\ell / \Lambda$ with:

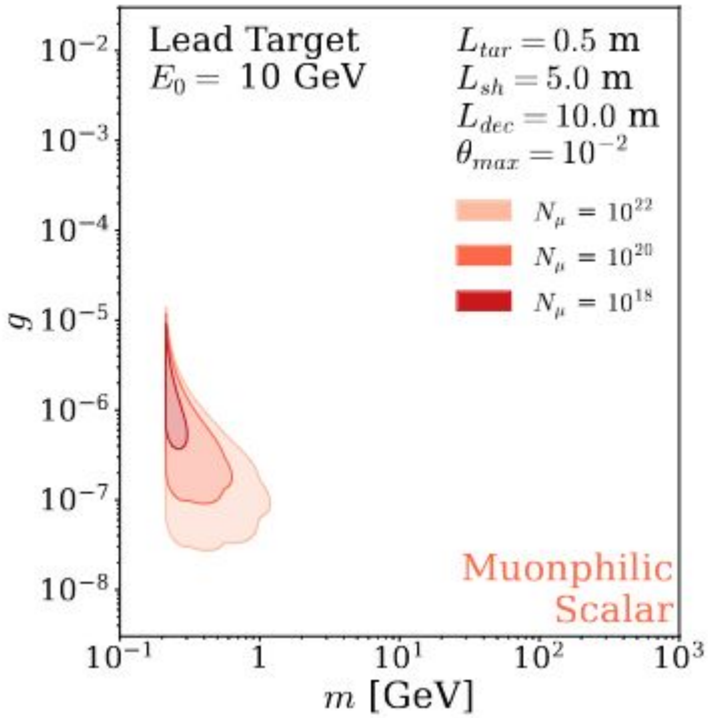
$$m_e \ll m_\mu \text{ and } m_\phi < m_\tau$$

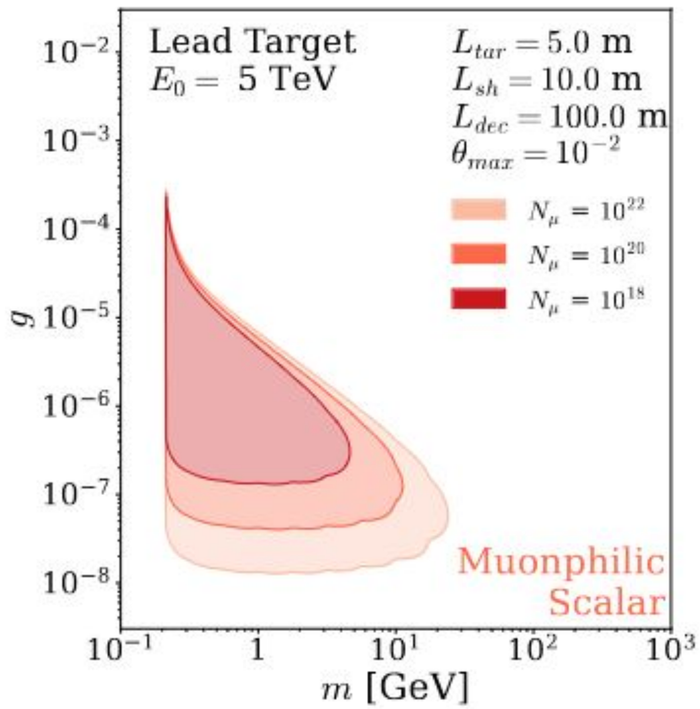
Muonic experiments probe muonic couplings!

See [1902.07715] for example UV completions
Can arise in e.g. Type III 2HDM

*ALPs are funny in our setup.

Results – Muonphilic

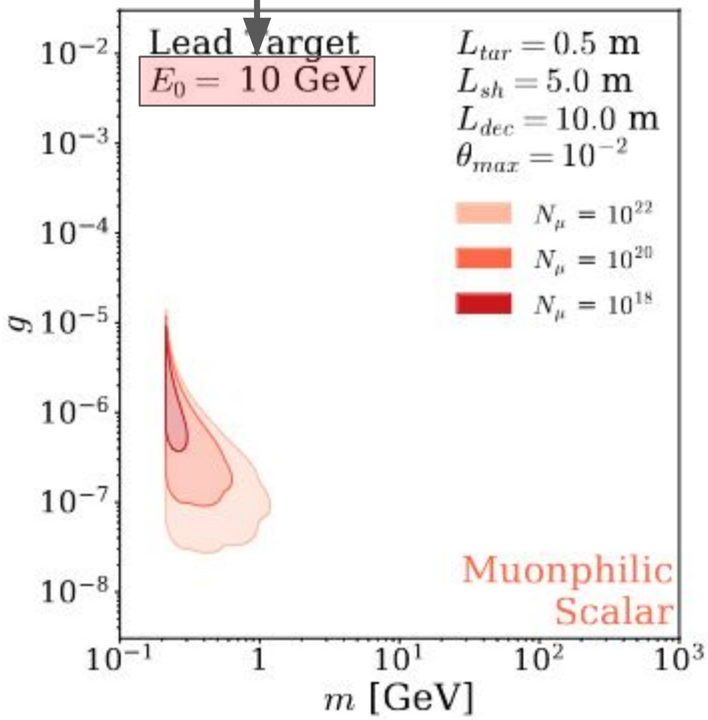


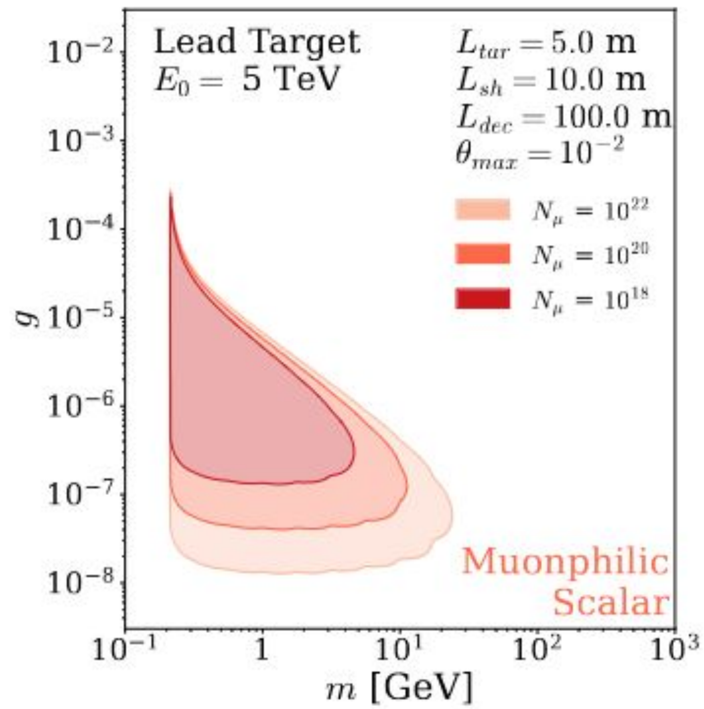


Muon specific coupling, no other limits in this range!

Results – Muonphilic

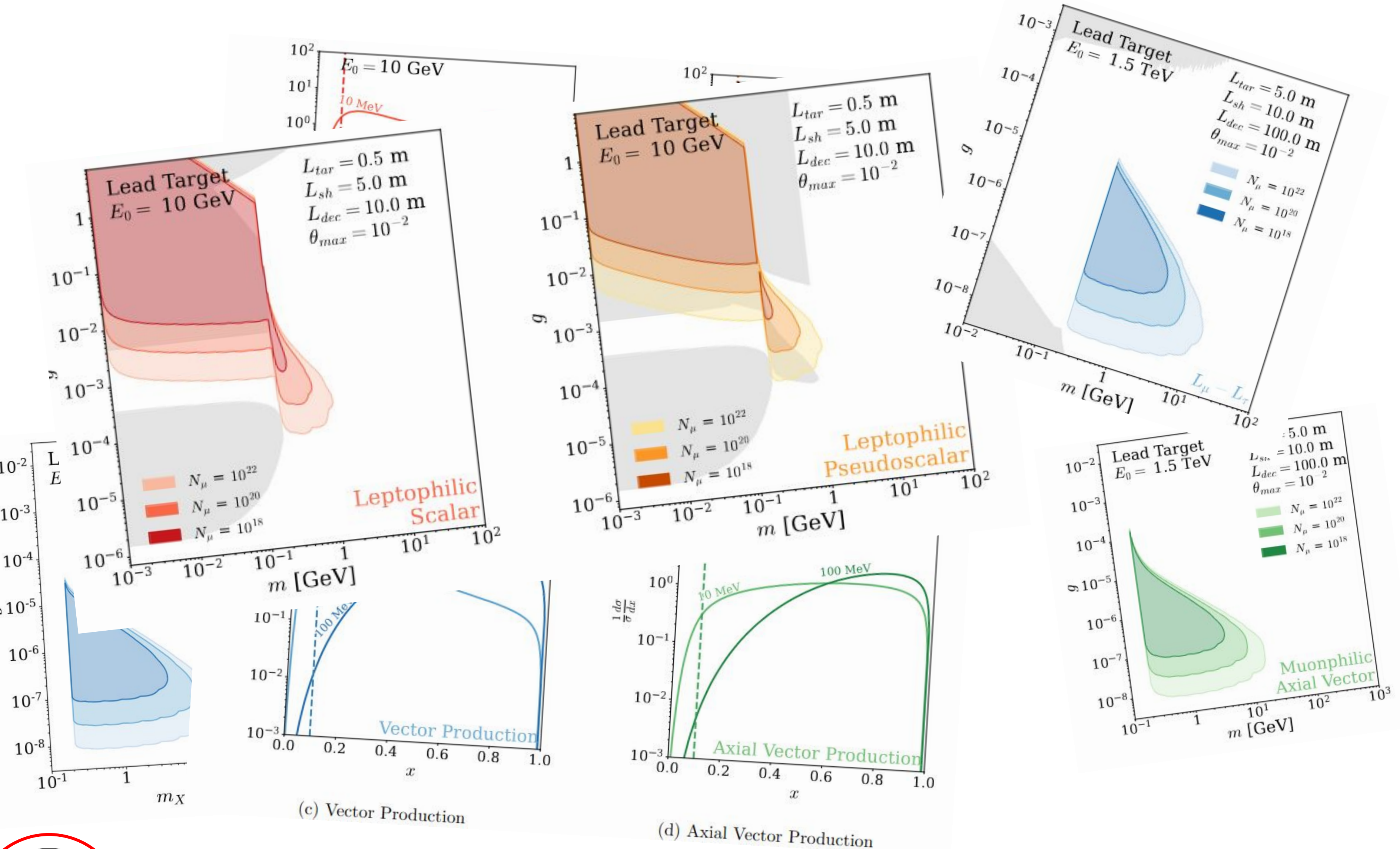
10 GeV … possible at a near-term **demonstrator facility**!





Muon specific coupling, no other limits in this range!

Results – Lots of models!



Results – Lots of models!

Lots of Possibilities!

Experimental Considerations

Lots of things to explore when doing this “for real” – these were first steps!

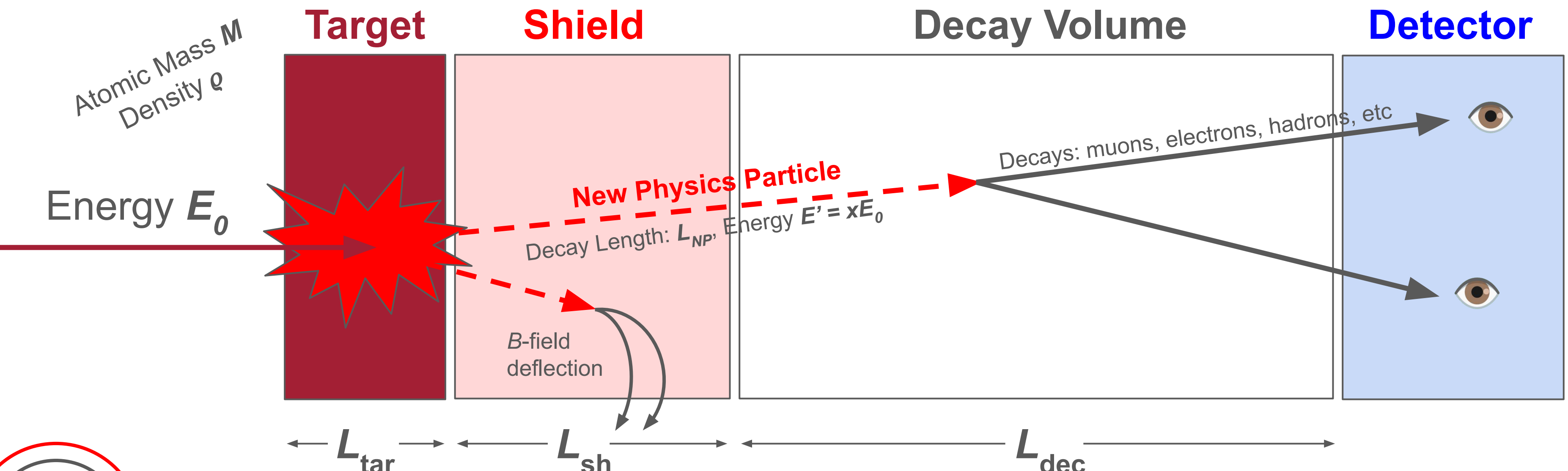
- **Backgrounds**: We assumed no backgrounds. A more sophisticated analysis would need to include these, and other techniques could be used to tag backgrounds without using shields.
- **Other Visible Signatures**: We do not consider photons, taus, MET, jet substructure, tracking, or any other visible signatures that can improve sensitivity.
- **Statistics**: Our contours are drawn assuming that 5 signal events over 0 background is a discovery. A more thorough limit setting procedure can be done.
- **Materials**: We use the thin target approximation and consider only lead and water – much more can be done with this!
- **Detector Effects**: Requires a thorough simulation.

Conclusion

"This is our Muon Shot"

A **muon beam-dump experiment** provides an excellent opportunity for **new physics** on the road to a **muon collider**

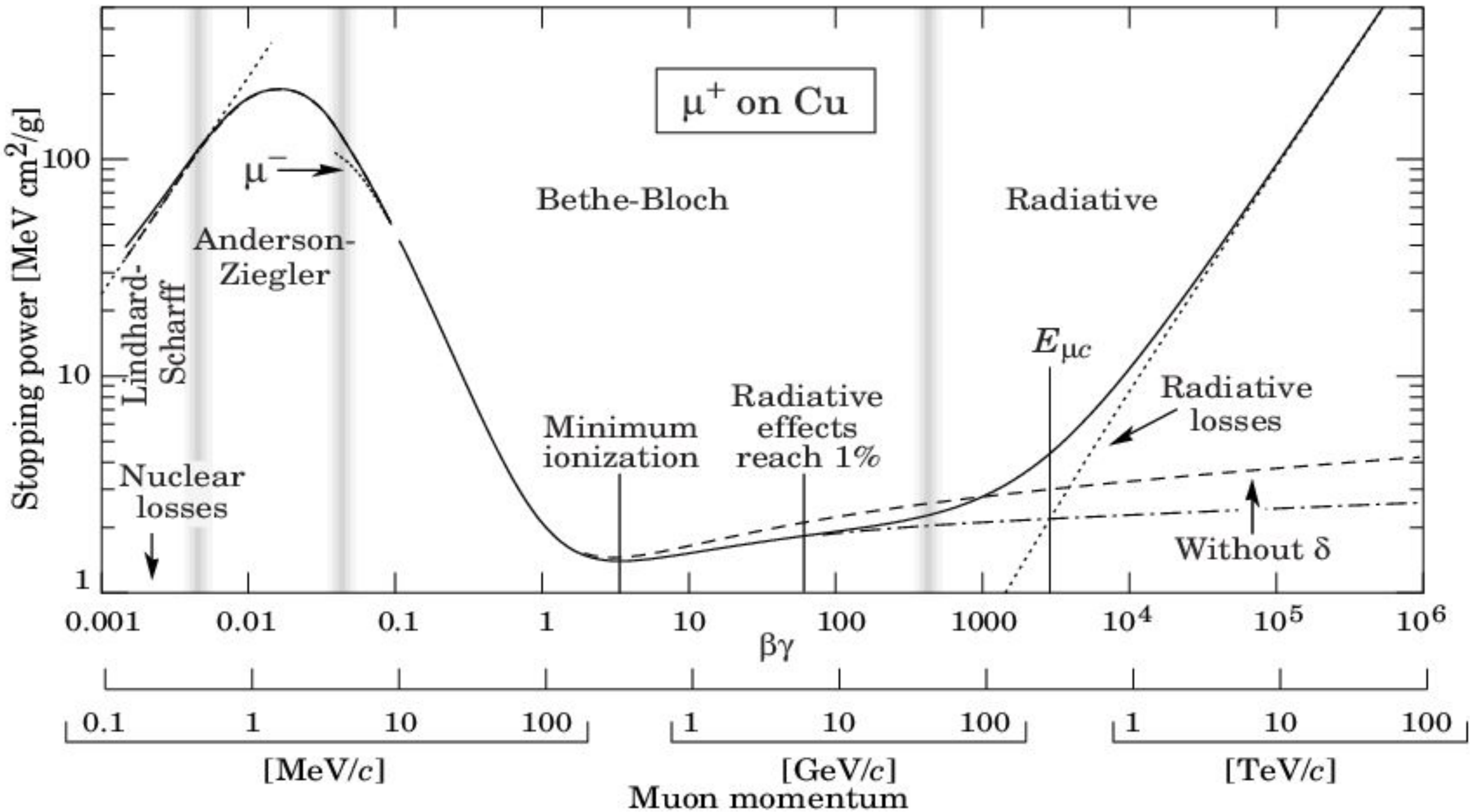
New physics is possible ***now*** with as low as a **10 GeV** muon beam at a demonstrator facility! We don't need to wait.



Backup

[PDG]

Muon Stopping Power



[PDG]

Full Cross Section Formulas

$$\left(\frac{d\sigma_{2\to3}(p+P_i\to p'+k+P_f)}{d(p\cdot k)d(k\cdot P_i)}\right)_{\mathrm{WW}}=\left(\frac{\alpha\chi}{\pi}\right)\left(\frac{E_0 x\beta_\phi}{1-x}\right)\times\left(\frac{d\sigma_{2\to2}(p+q\to p'+k)}{d(p\cdot k)}\right)_{t=t_{\mathrm{min}}}$$

$$\left(\frac{d\sigma_{2\to3}}{dx\,d\cos\theta}\right)_{\mathrm{WW}}=\frac{g^2}{2\pi}\alpha|\vec{k}|E(1-x)\frac{\mathcal{A}^{22}_{t=t_{\mathrm{min}}}}{\tilde{u}^2}\chi$$

$$\mathcal{A}^{2\to2}_{S,t=t_{\mathrm{min}}}\approx\frac{x^2}{1-x}+2(m_\phi^2-4m_\mu^2)\frac{\tilde{u}x+m_\mu^2(1-x)+m_\mu^2x^2}{\tilde{u}^2}$$

$$\mathcal{A}^{2\to2}_{P,t=t_{\mathrm{min}}}\approx\frac{x^2}{1-x}+2m_a^2\frac{\tilde{u}x+m_\mu^2(1-x)+m_\mu^2x^2}{\tilde{u}^2}$$

$$\mathcal{A}^{2\to2}_{V,t=t_{\mathrm{min}}}\approx2\frac{2-2x+x^2}{1-x}+4(m_V^2+2m_\mu^2)\frac{\tilde{u}x+m_\mu^2(1-x)+m_\mu^2x^2}{\tilde{u}^2}$$

$$\mathcal{A}^{2\to2}_{A,t=t_{\mathrm{min}}}\approx\frac{4m_\mu^2x^2}{(m_A^2)(1-x)}+2\frac{2-2x+x^2}{1-x}+4(m_A^2-4m_\mu^2)\frac{\tilde{u}x+m_\mu^2(1-x)+m_\mu^2x^2}{\tilde{u}^2}$$