

New Physics searches via Scattering at DarkQuest

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In collaboration with:

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PHYSICS AND
ASTRONOMY

What is DarkQuest?

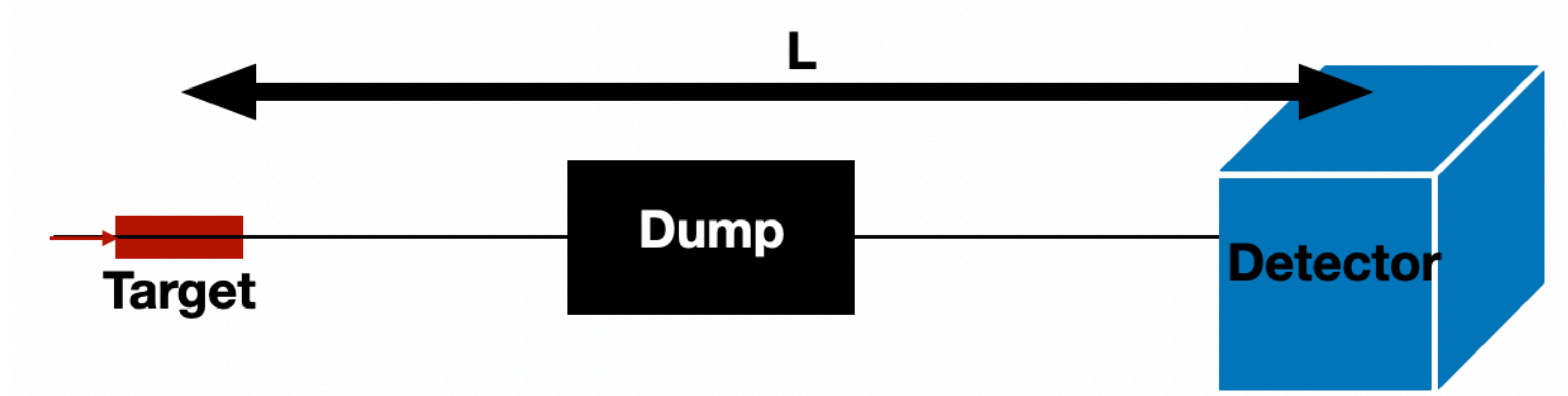
- Proton fixed target beam dump
- Spectrometer
- Present on the neutrino-muon beamline
- Receives protons from NuMI

Why DarkQuest?

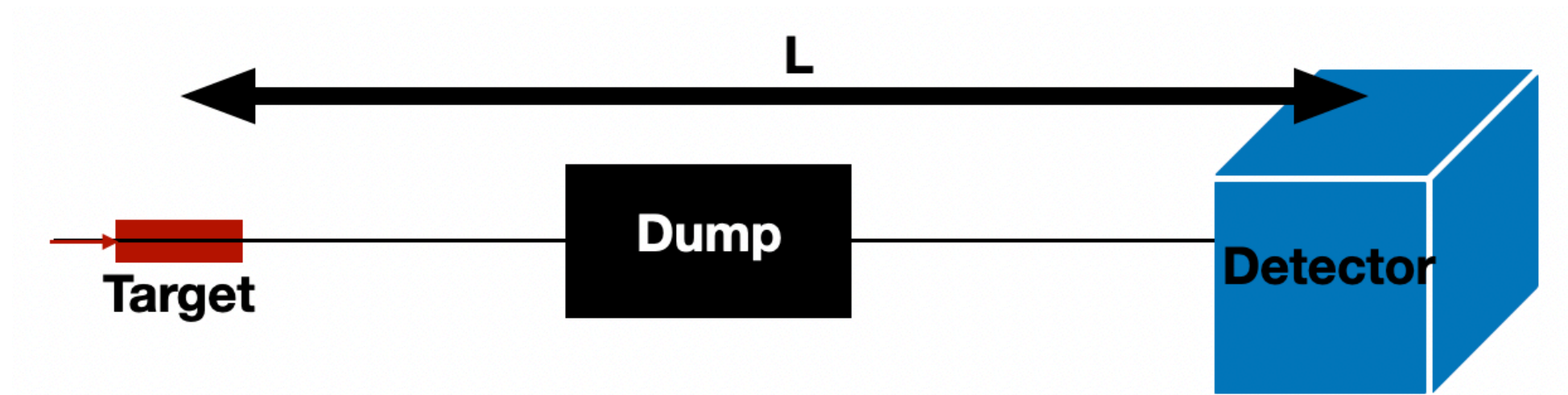
Why DarkQuest?

High energy, short lifetime, short-baseline setup

Beam dumps



Beam dumps



Experiments	COHERENT, CCM, JSNS2	SBND, MicroBooNE	ICARUS, DUNE ND
Proton K.E, Detector distance	0.8 GeV ~20 m	8 GeV 110 - 470 m	120 GeV 570 - 900 m
$\Delta\theta$	0.07	0.01 - 0.004	0.003 - 0.001
Target to dump [m]	-	50	250 - 600

Increasing energy & shorter lifetime

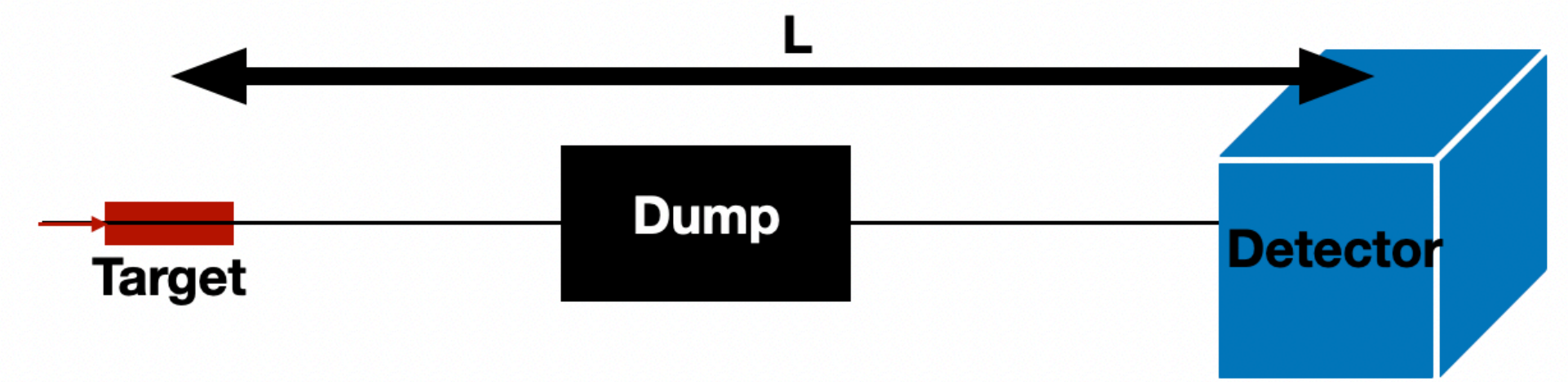


Decreasing flux

[arxiv:2008.08108](https://arxiv.org/abs/2008.08108)

[arxiv:1804.00661](https://arxiv.org/abs/1804.00661)

Beam dumps



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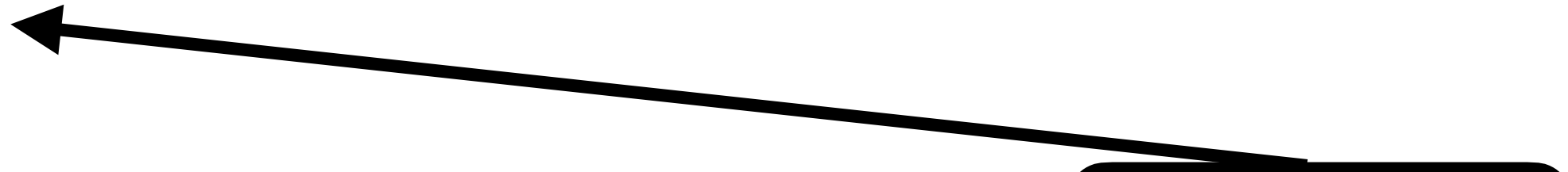
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Increasing energy & shorter lifetime



Decreasing flux

Short-baseline setup - *Scattering environment*



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Increasing energy & shorter lifetime

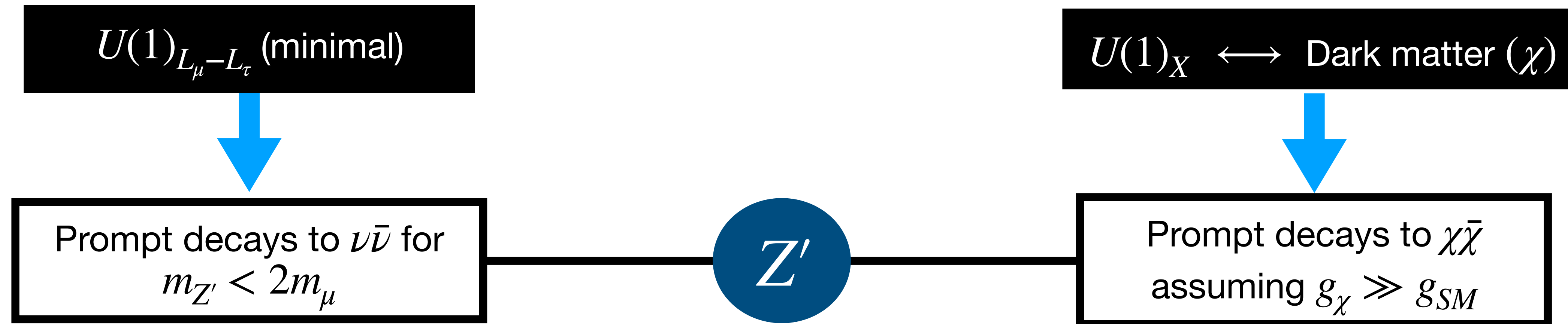
Decreasing flux

Short-lived Dark Gauge Boson

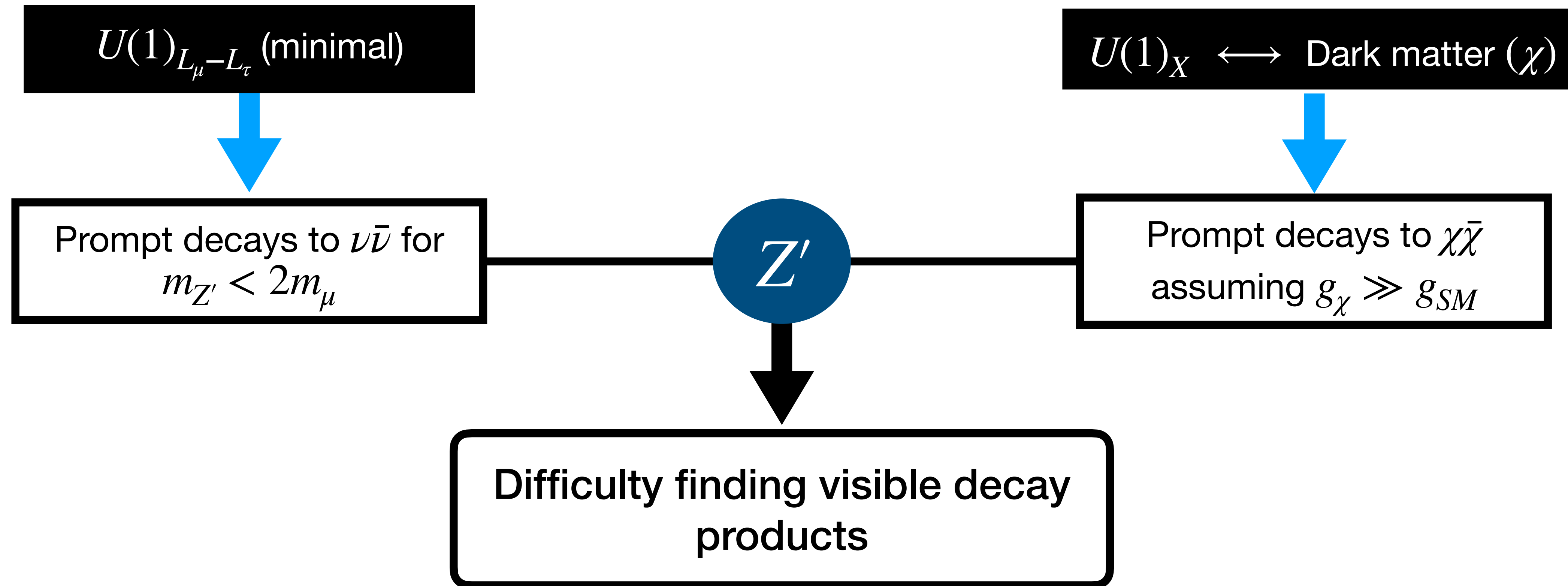
$U(1)_{L_\mu - L_\tau}$ (minimal)

$U(1)_X \longleftrightarrow$ Dark matter (χ)

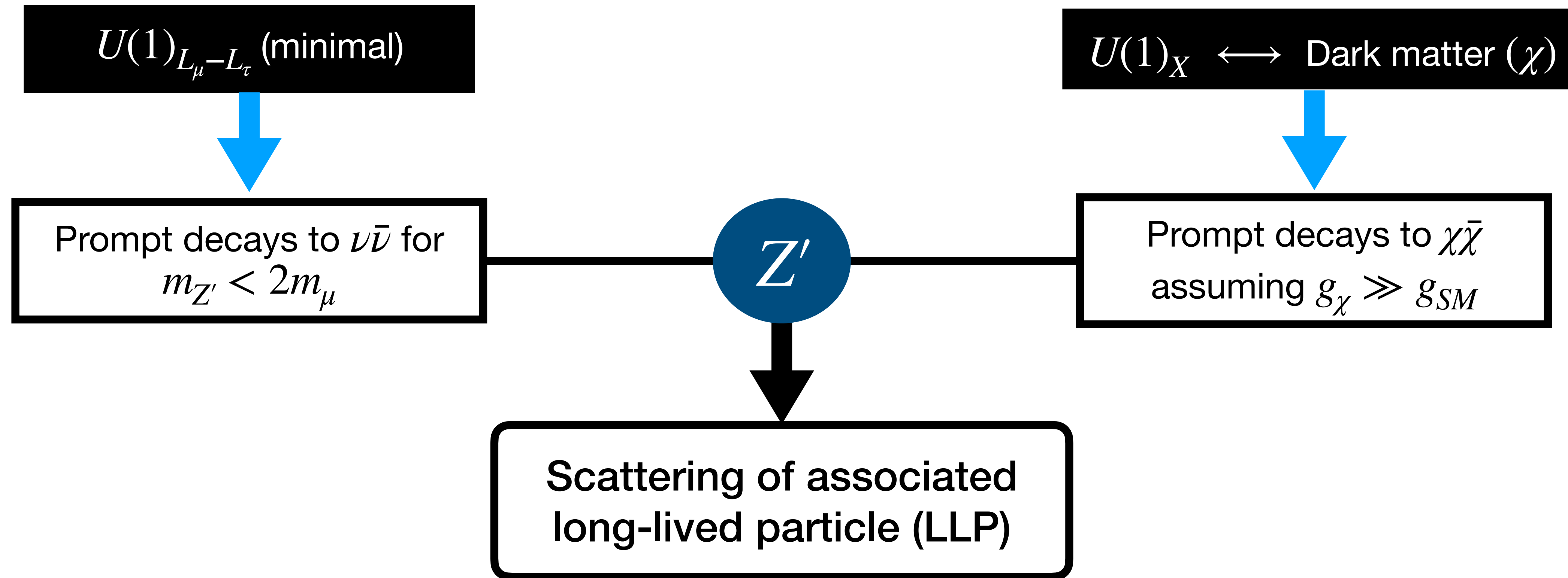
Short-lived Dark Gauge Boson



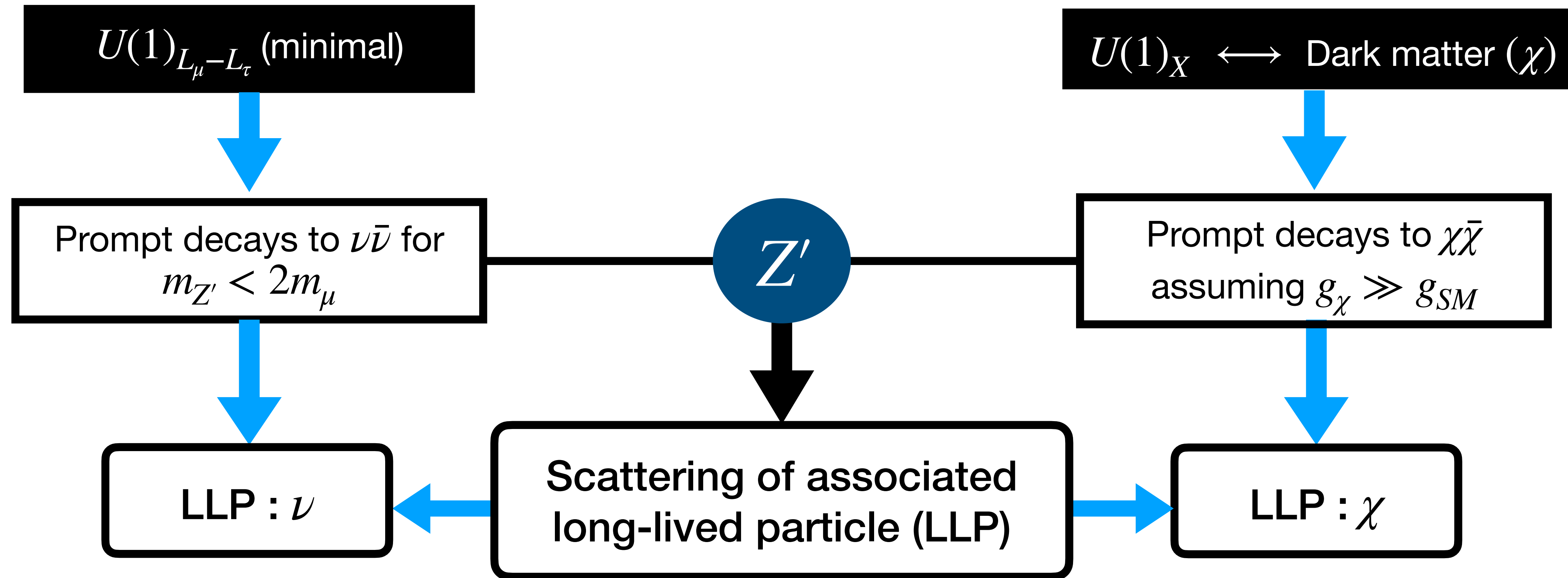
Short-lived Dark Gauge Boson



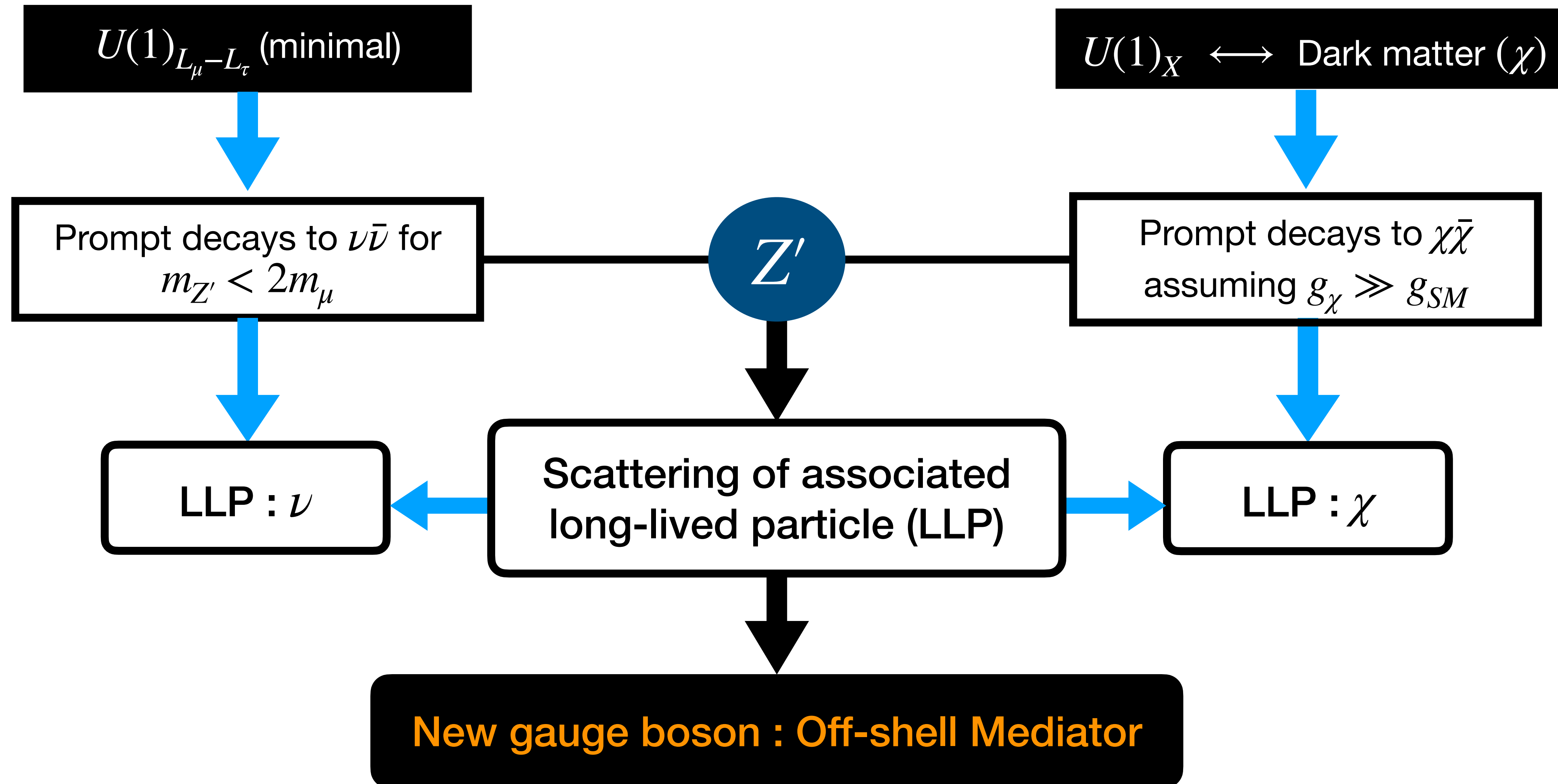
Short-lived Dark Gauge Boson



Short-lived Dark Gauge Boson

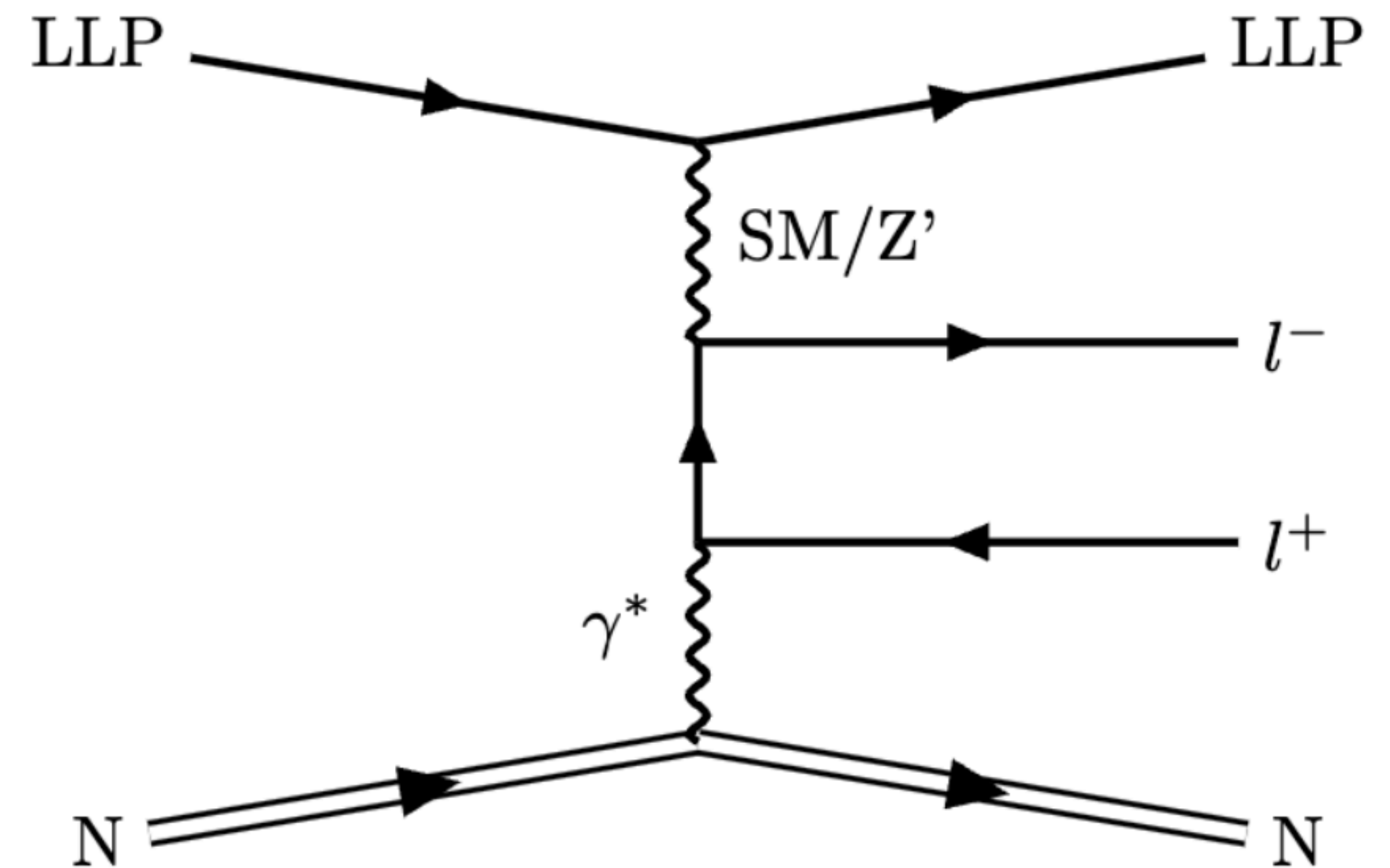


Short-lived Dark Gauge Boson



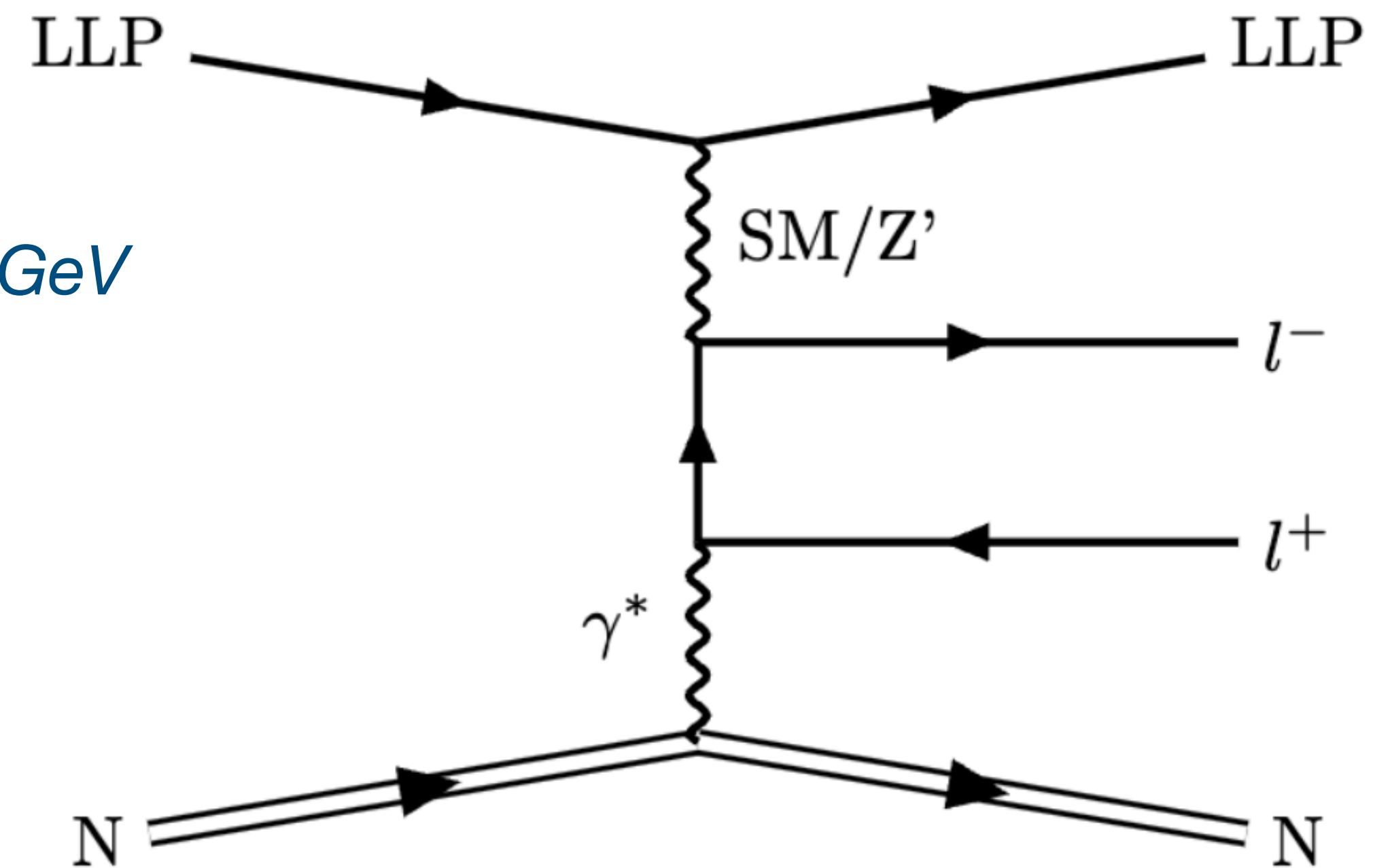
Trident scattering of LLP

1. Z^2 enhancement (coherence)
2. $\sigma_{trident}$ favors high energy
3. l^+l^- final states



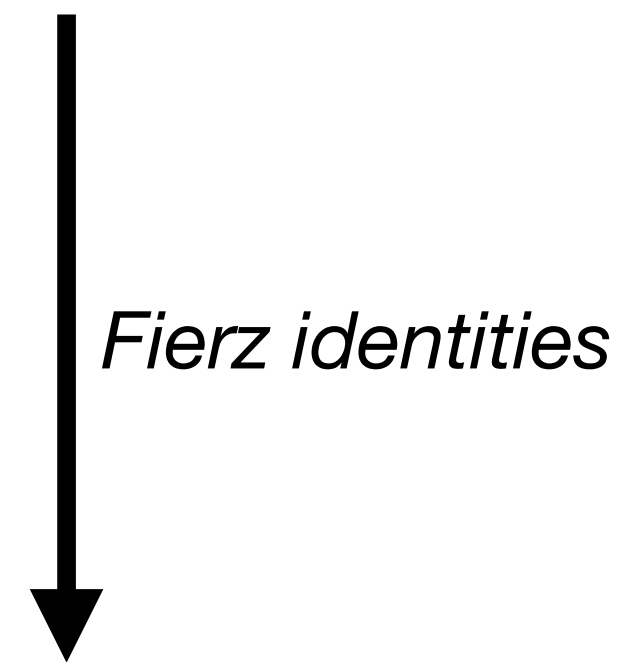
Trident scattering at *DarkQuest*

1. Z^2 enhancement - *High Z materials*
2. $\sigma_{trident}$ favors high energy - $1 \text{ GeV} < E_{LLP} < 50 \text{ GeV}$
3. l^+l^- final states - $\mu^+\mu^-$ detected within $\sim 20 \text{ m}$



Neutrino Tridents in SM

Five diagrams including W^+ and Z^*

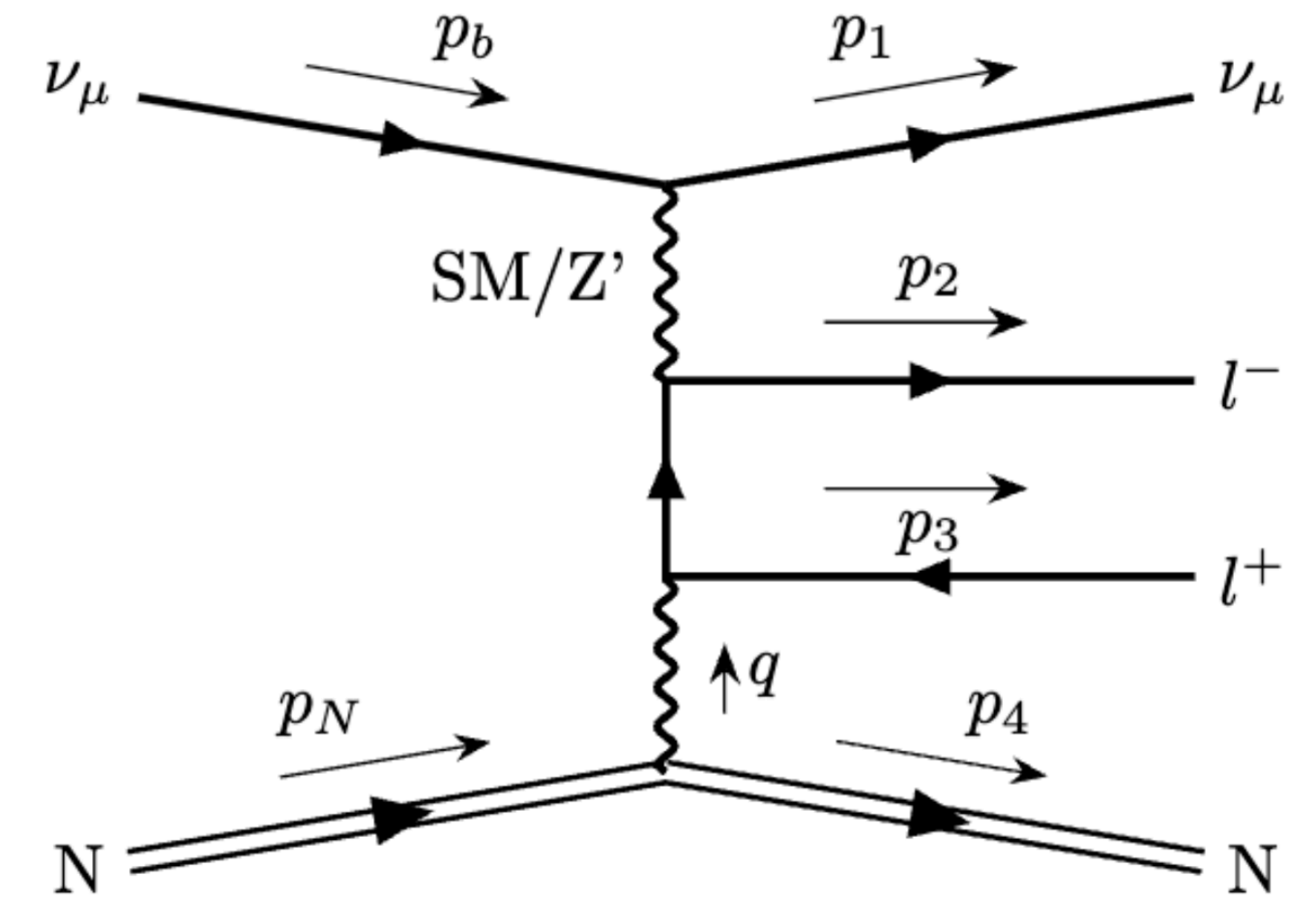


Reduced to two effective diagrams **

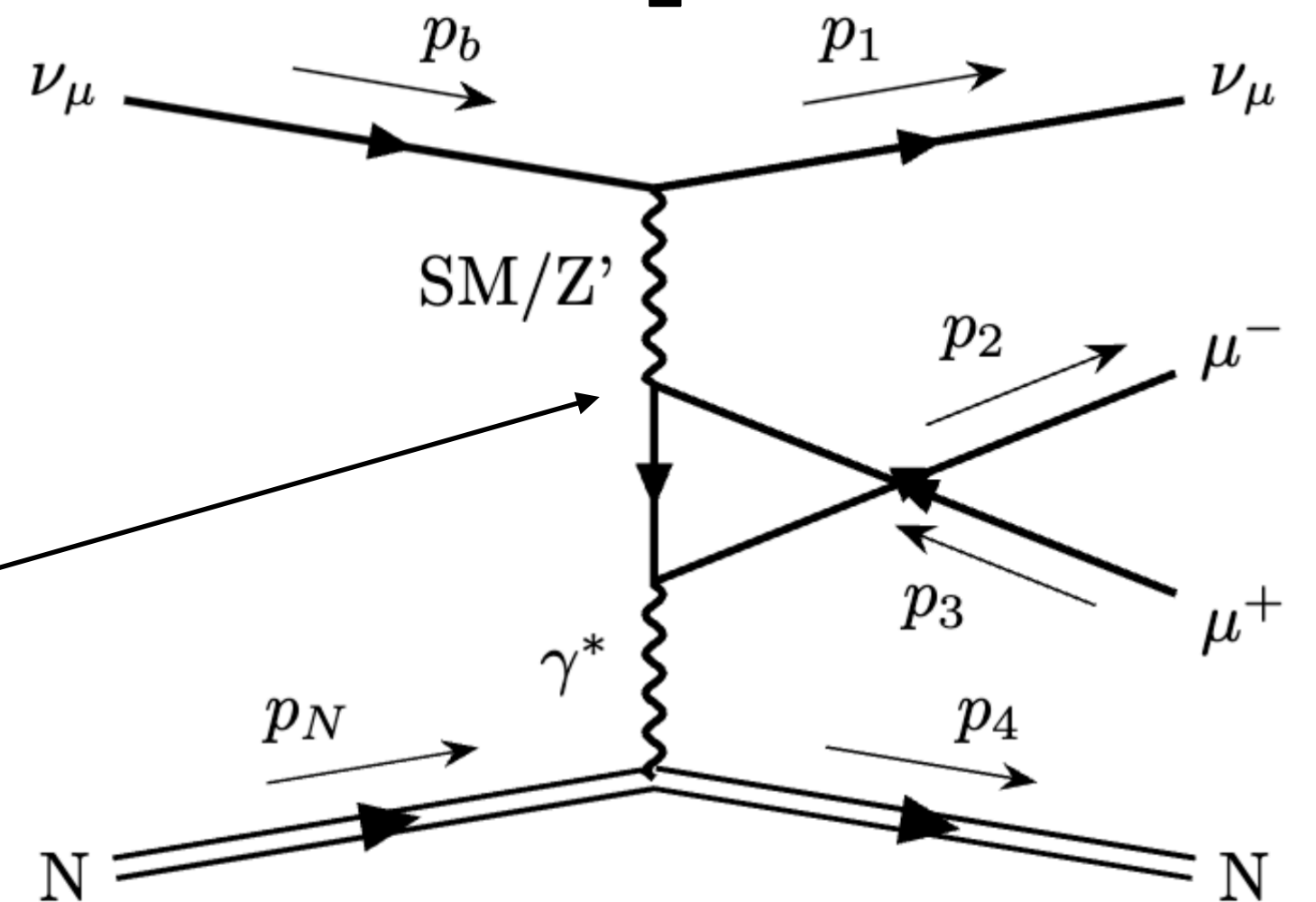
$$V_{\mu\mu} = \frac{1}{2} + 2 \sin^2 \theta_W \quad A_{\mu\mu} = \frac{1}{2}$$

*arxiv.org/abs/1910.08090

**arxiv.org/abs/1612.05642

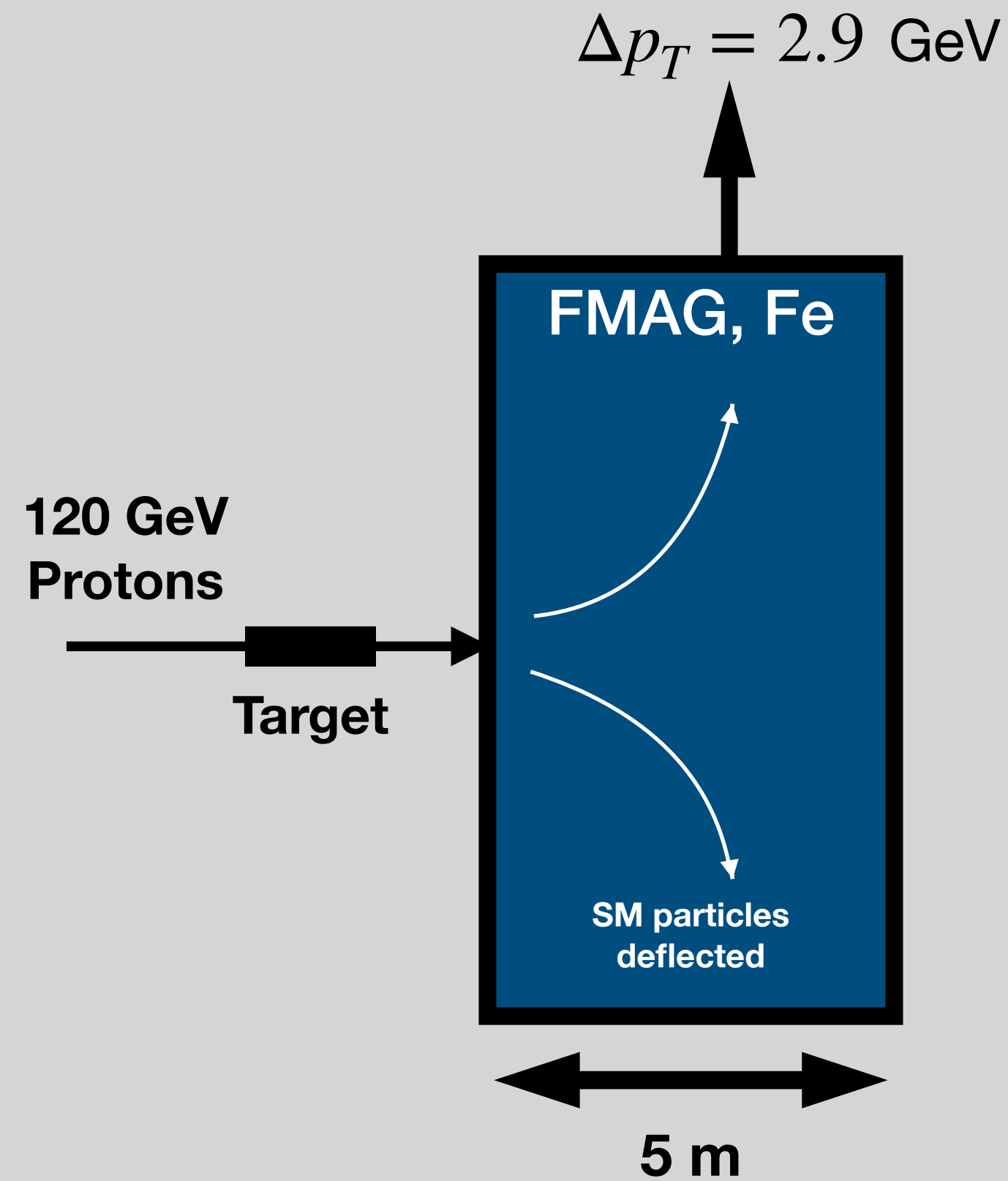


+



$$\propto (V_{\mu\mu} - A_{\mu\mu} \gamma^5)$$

DarkQuest

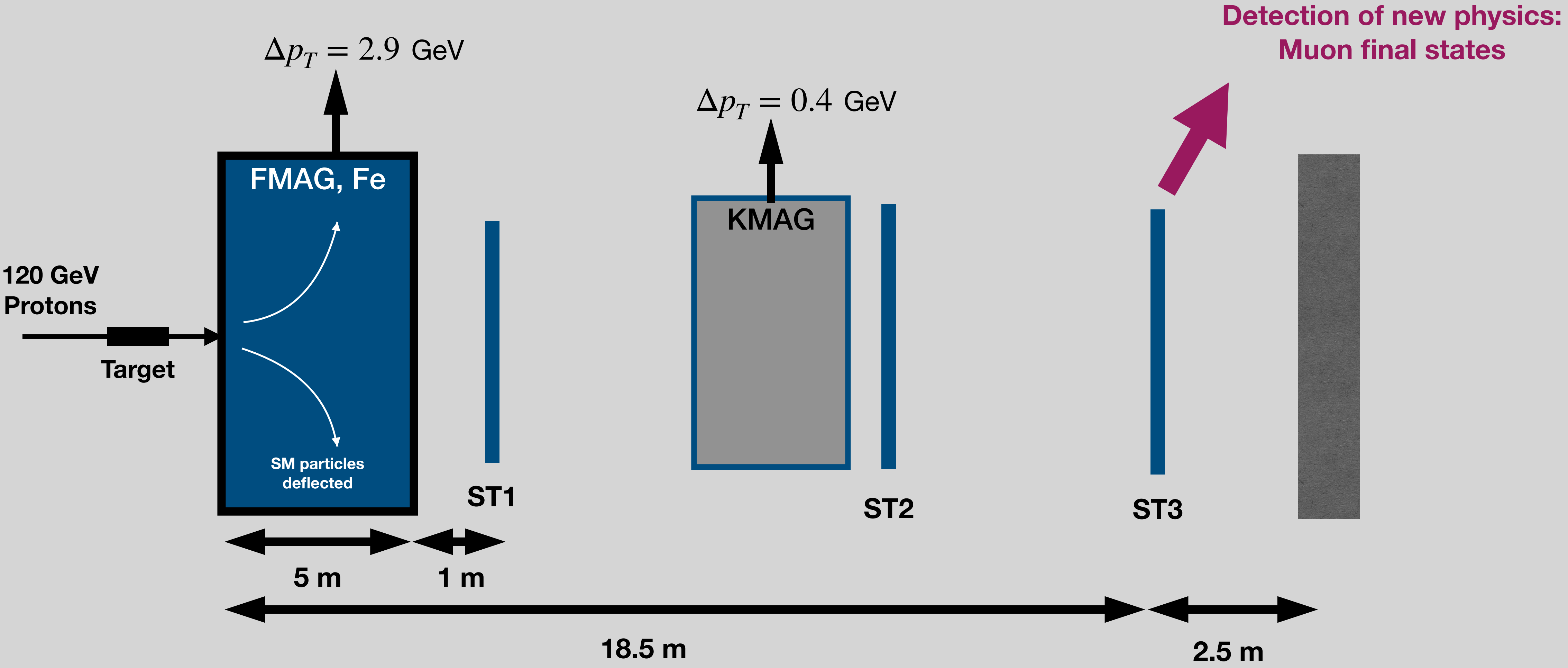


B. Batell, JA. Evans, S. Gori, M. Rai, [arxiv:2008.08108](https://arxiv.org/abs/2008.08108)

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DarkQuest

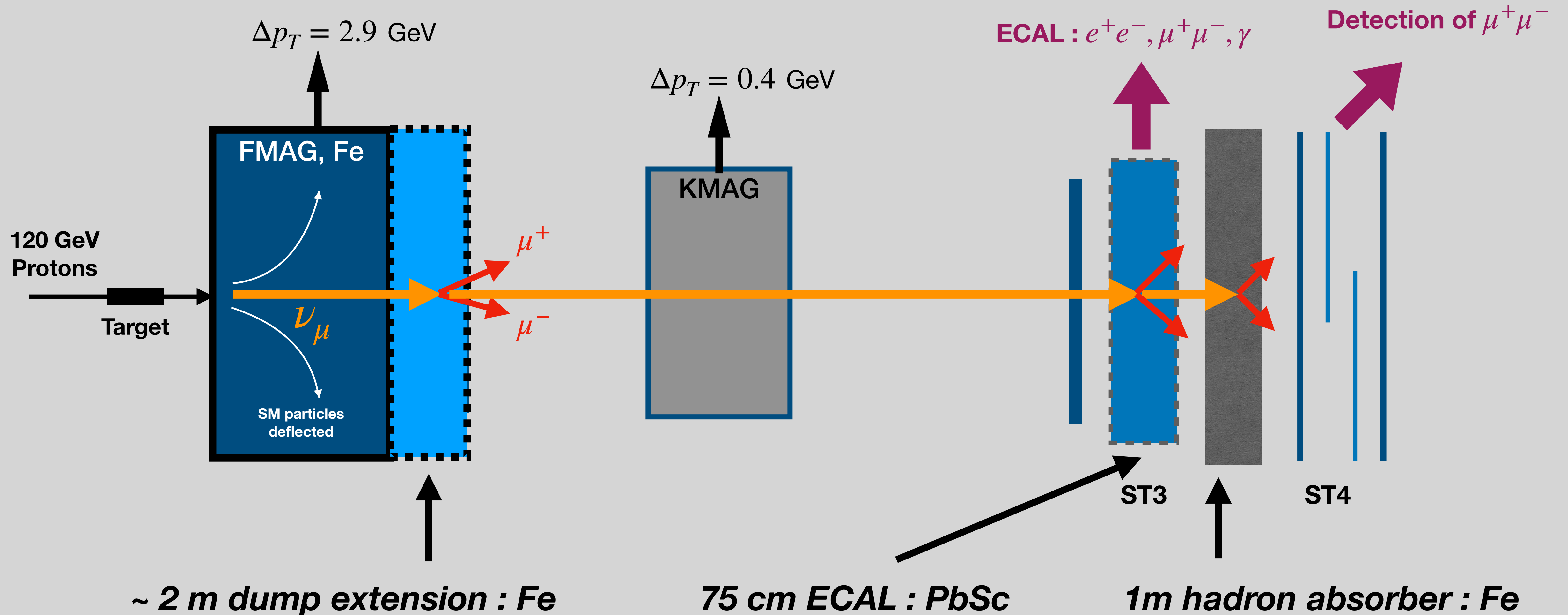


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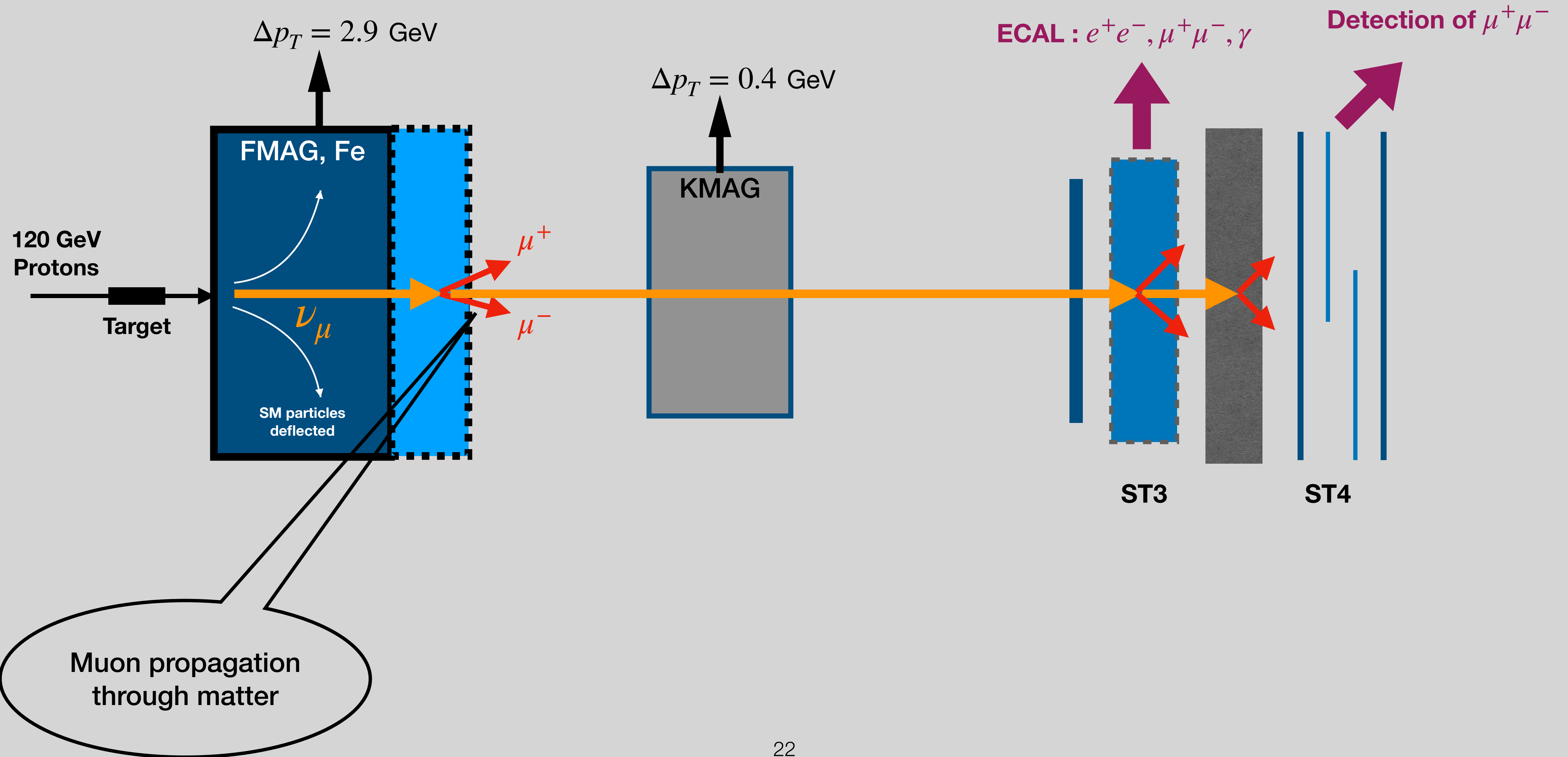
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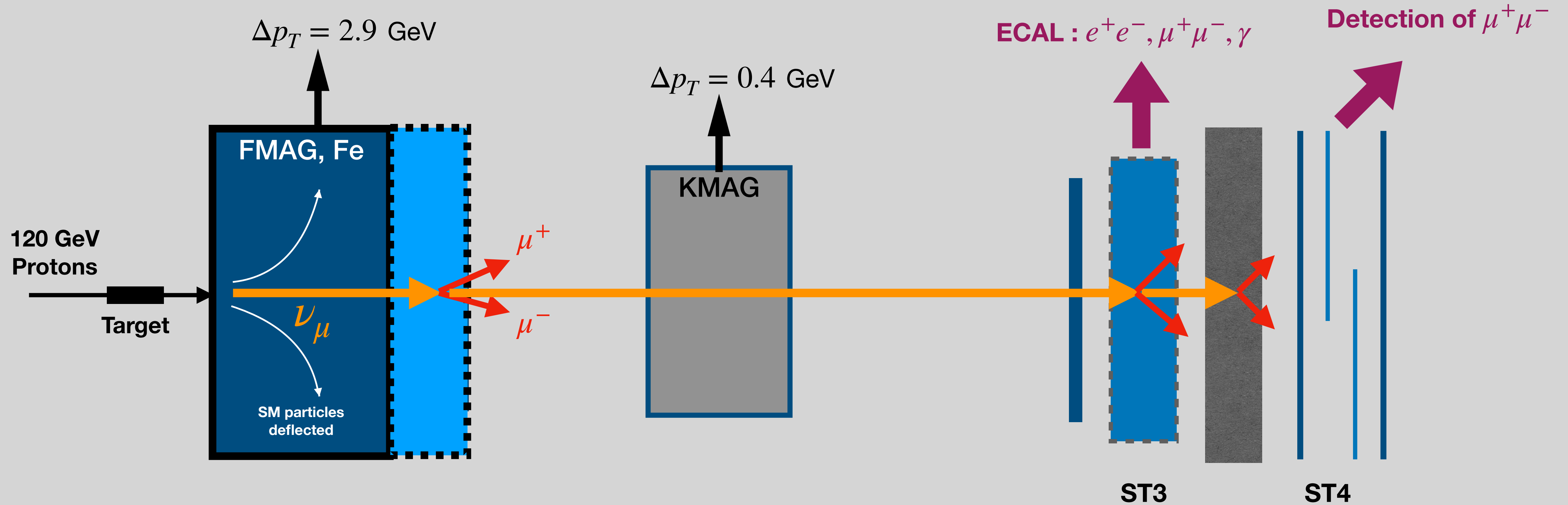
Neutrino Trident at DarkQuest- Phase 2



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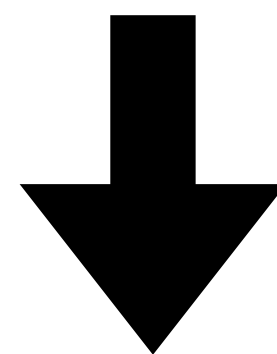
$d\sigma_{trident}/d(E_{\mu^+}, E_{\mu^-}, \theta_{\mu^+}, \theta_{\mu^-})$
 Used to determine sensitivity

SM neutrino tridents at DarkQuest

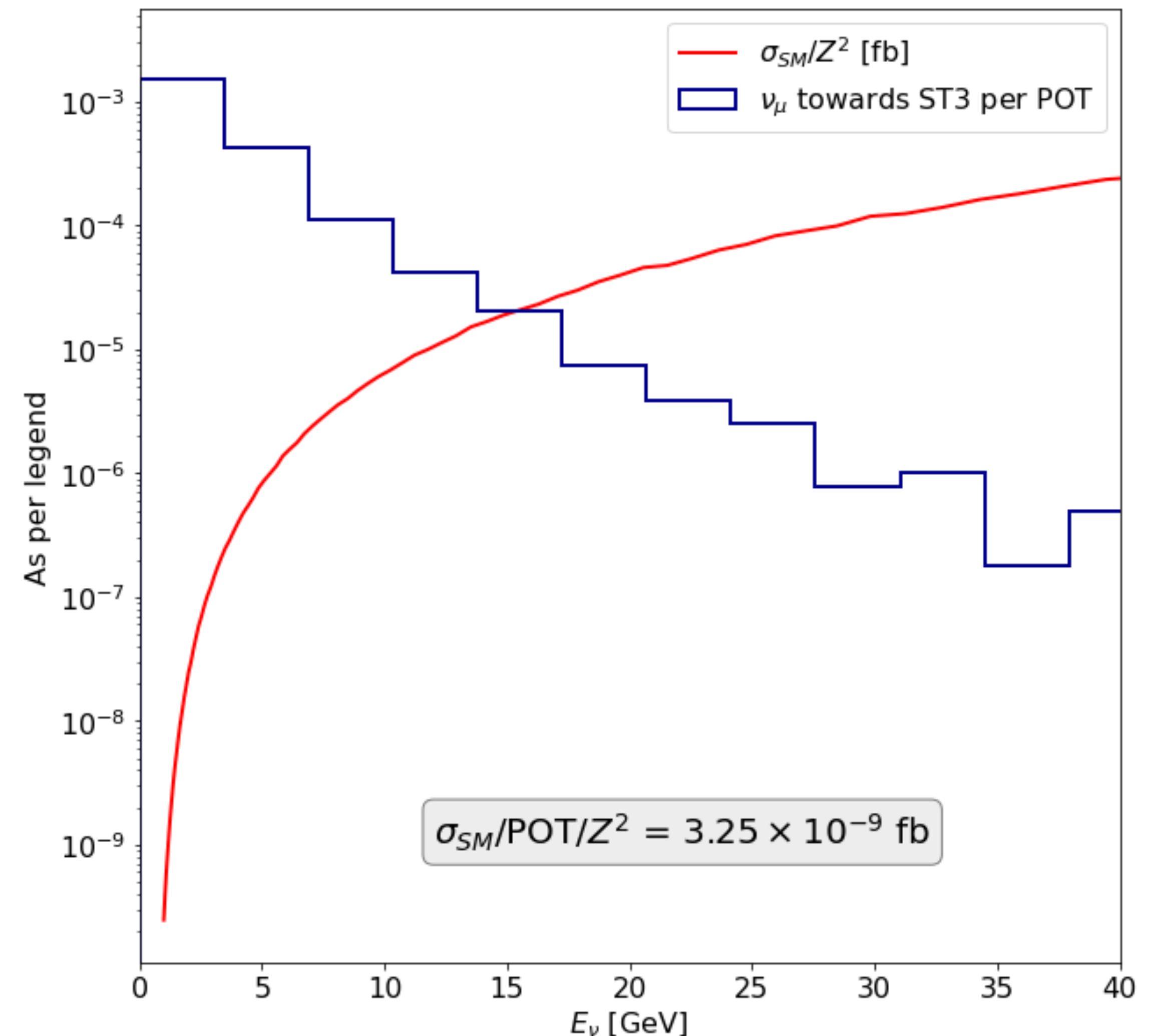
Scattering media:

- **FMAG** - 2m iron beyond magnetic field
- **ECAL** - 0.75 m PbSc
- **Absorber** - 1m iron

No. of $\mu^+ \mu^-$ from trident
~ 4 pairs



Observed at **ECAL** and **ST4**



$$L_\mu - L_\tau$$

Vanilla scenario :

$$\mathcal{L}_{\mu\tau}^V = -\frac{m_{Z'}^2}{2} Z'_\alpha Z'^\alpha + g_{\mu\tau} Z'_\alpha (\bar{\mu}\gamma^\alpha \mu + \bar{\nu}_\mu \gamma^\alpha \nu_\mu - \bar{\tau}\gamma^\alpha \tau - \bar{\nu}_\tau \gamma^\alpha \nu_\tau)$$

$$L_\mu - L_\tau$$

Vanilla scenario :

$$\mathcal{L}_{\mu\tau}^V = -\frac{m_{Z'}^2}{2} Z'_\alpha Z'^\alpha + \boxed{g_{\mu\tau} Z'_\alpha (\bar{\mu} \gamma^\alpha \mu + \bar{\nu}_\mu \gamma^\alpha \nu_\mu) - \bar{\tau} \gamma^\alpha \tau - \bar{\nu}_\tau \gamma^\alpha \nu_\tau}$$



**New contribution to
neutrino trident**

$$L_\mu - L_\tau$$

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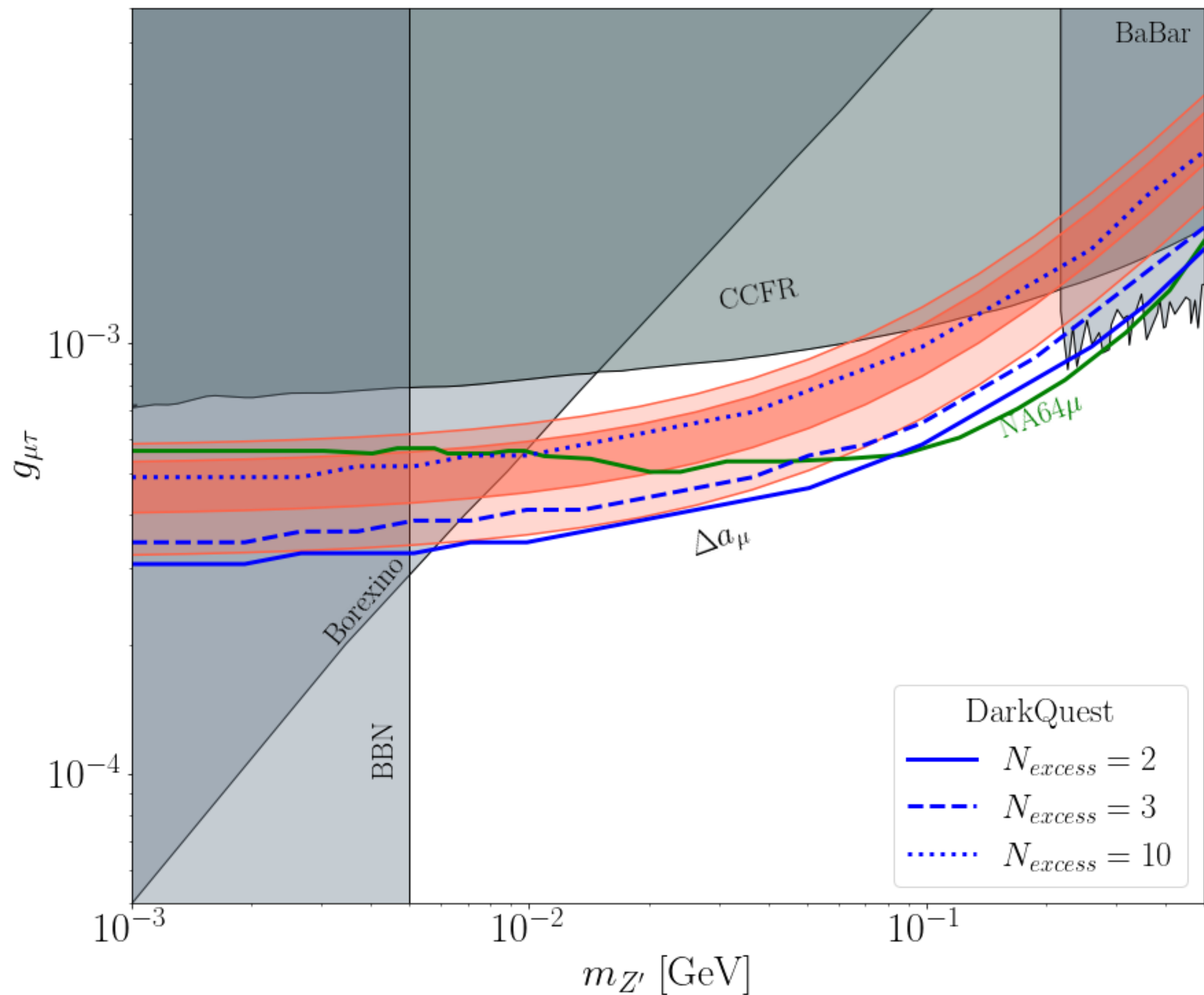
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$$N_{excess} = N_{tot} - N_{SM}$$

DarkQuest sensitivity:

$$N_{trident}^{excess} > 2$$

**New contribution to
neutrino trident**



DarkQuest limits for events **beyond SM:**

ECAL and absorber scattering : detected in ST4

Signal - $\mu^+\mu^-$ events

NA64 results : Paolo Crivelli's talk

Dark Matter

Assume : $g_D \gg g_q, g_l$

$$\mathcal{L} \supset -\frac{1}{2}m_{Z'}^2 Z'_\alpha Z'^\alpha + \left(g_q \sum_q x_q \bar{q} \gamma^\alpha q + g_l \sum_l x_l \bar{l} \gamma^\alpha l \right) Z'_\alpha + g_D \bar{\chi} \gamma^\alpha \chi Z'_\alpha$$

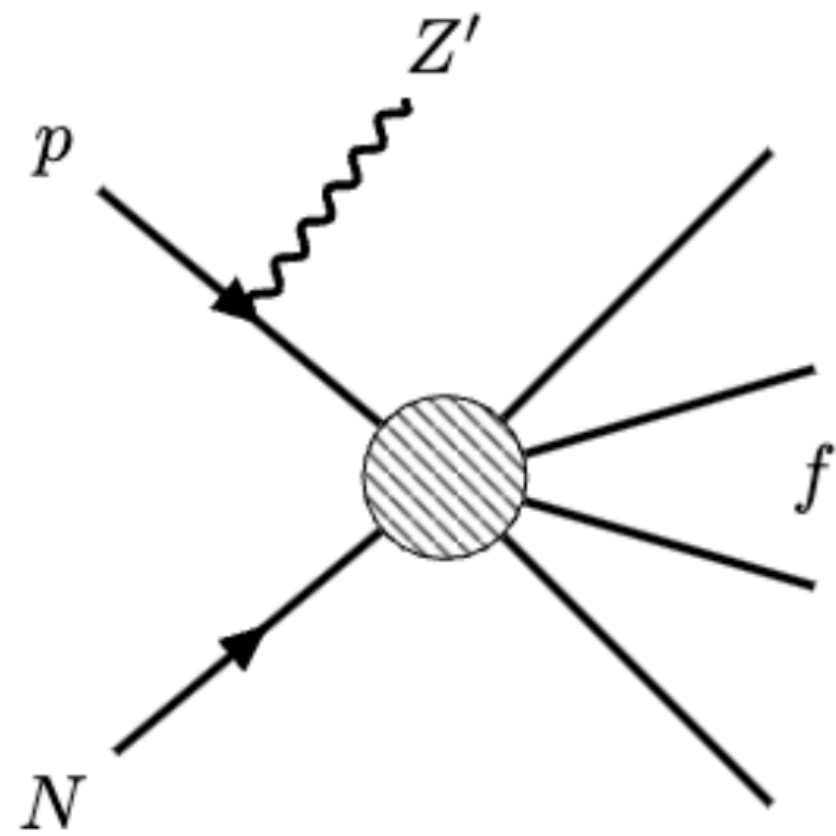
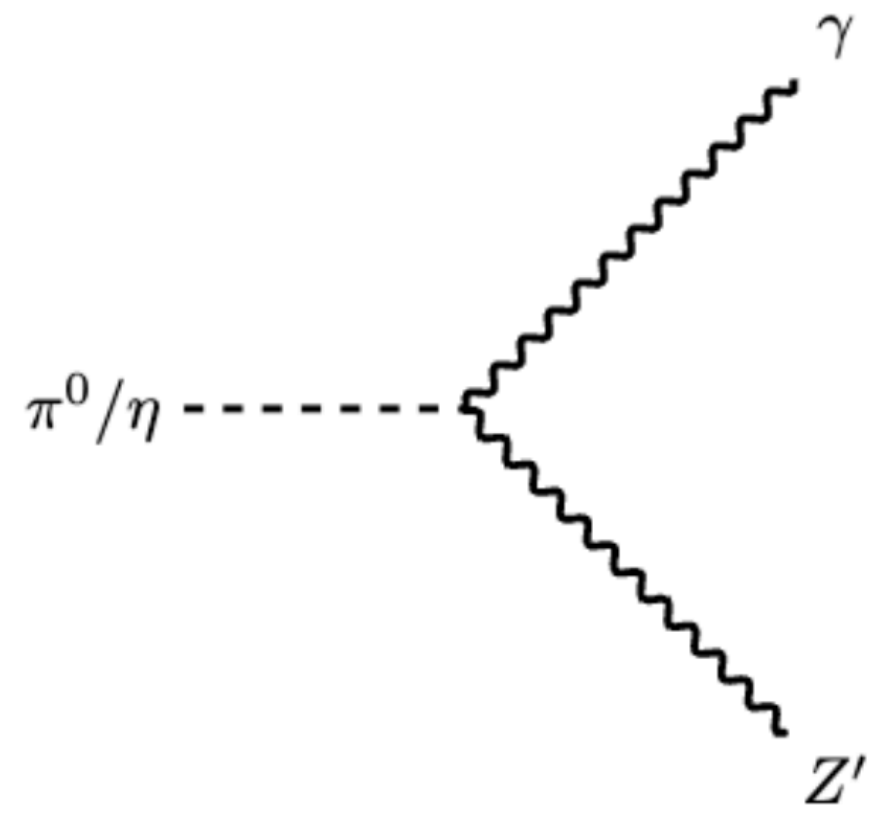
See also:

P. Fayet, Phys. Rev. D 70, 023514 (2004)

M. Pospelov, A. Ritz, M.M. Voloshin, Phys. Lett. B 662, 53 (2008)

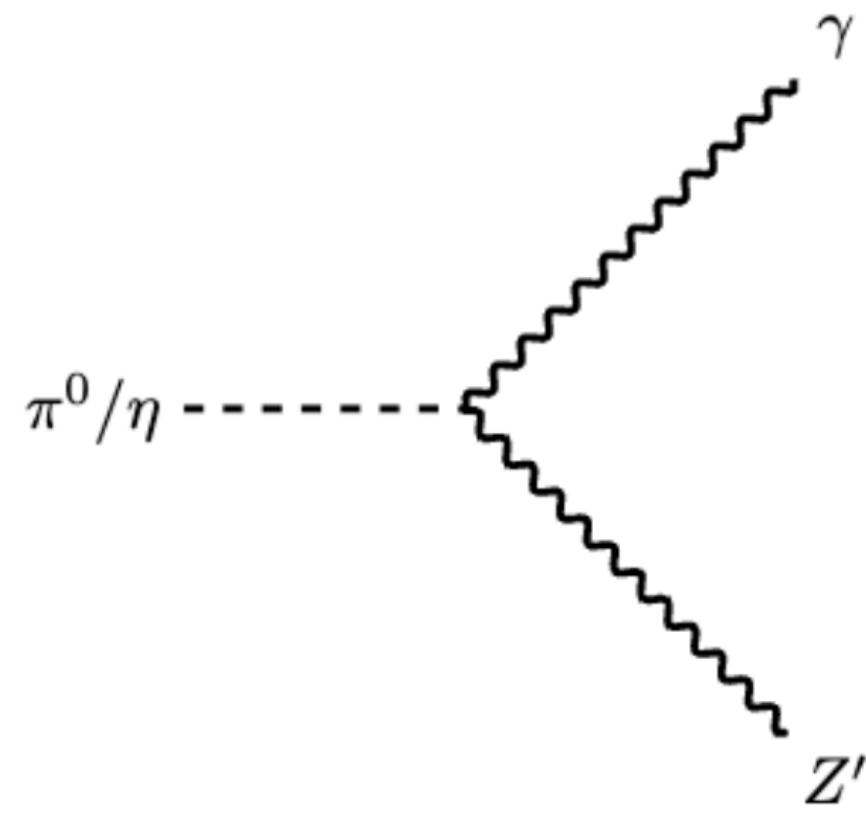
Dark Matter at DarkQuest

1. Production of $Z' \propto g_q^2$

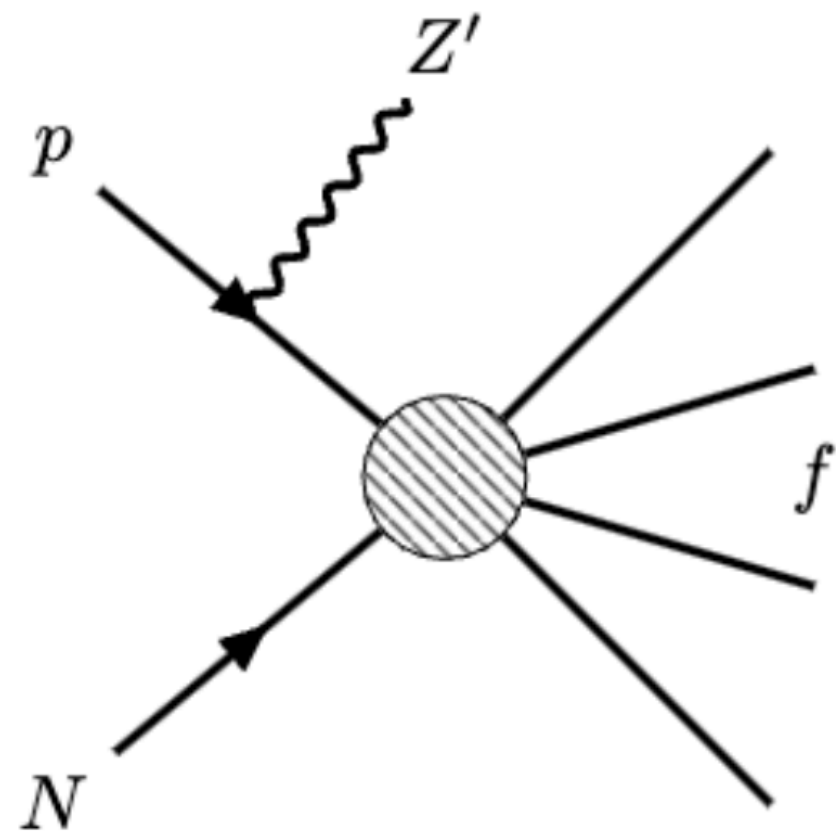
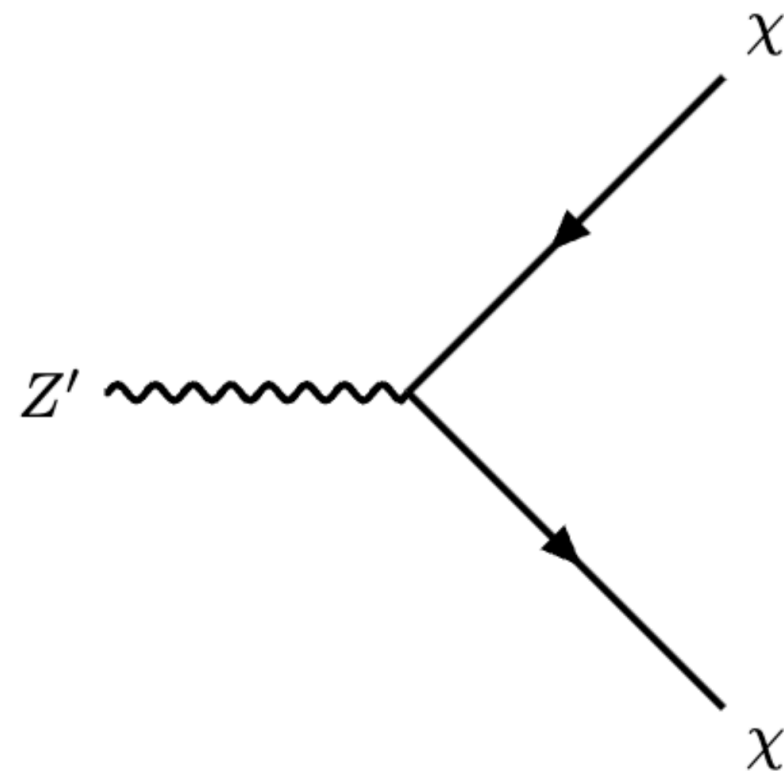


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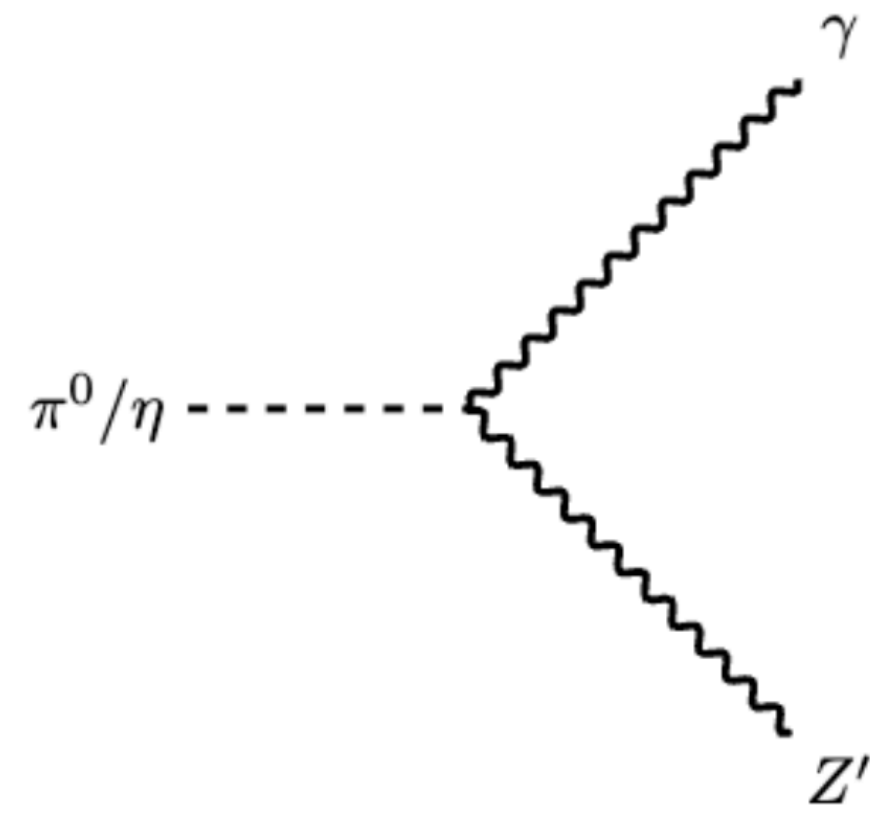


2. Production of χ ; $BR = 100\%$

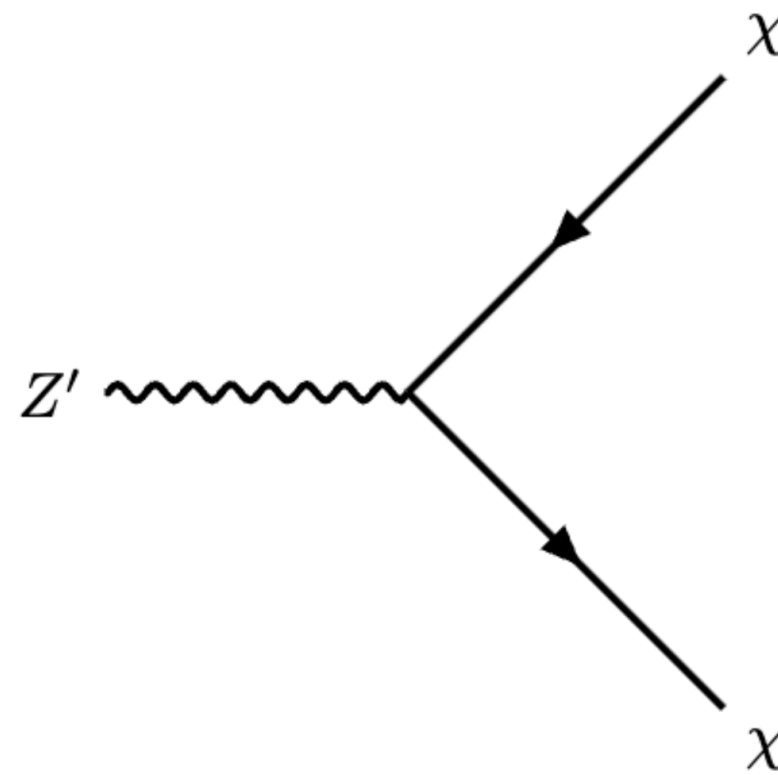


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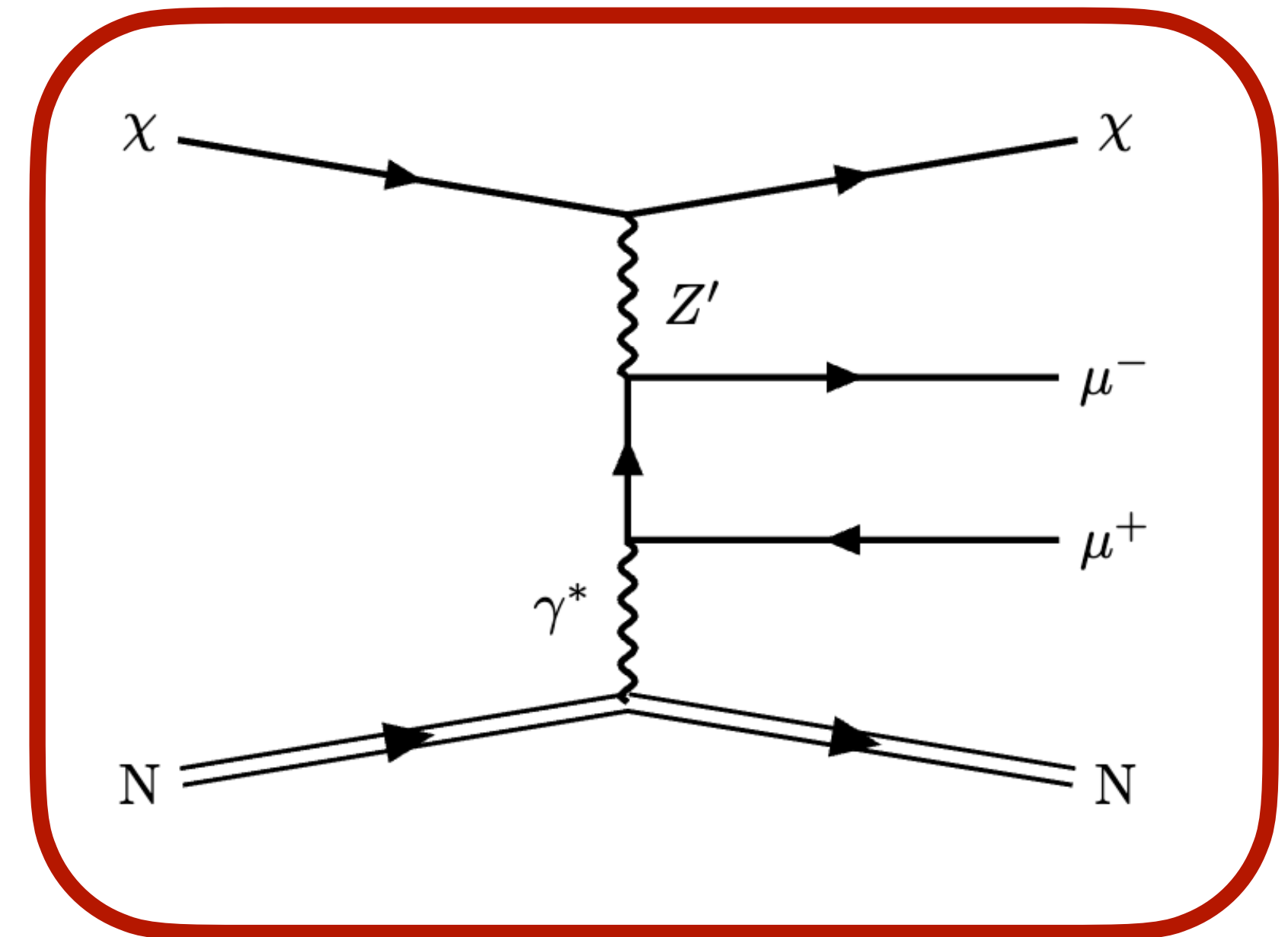
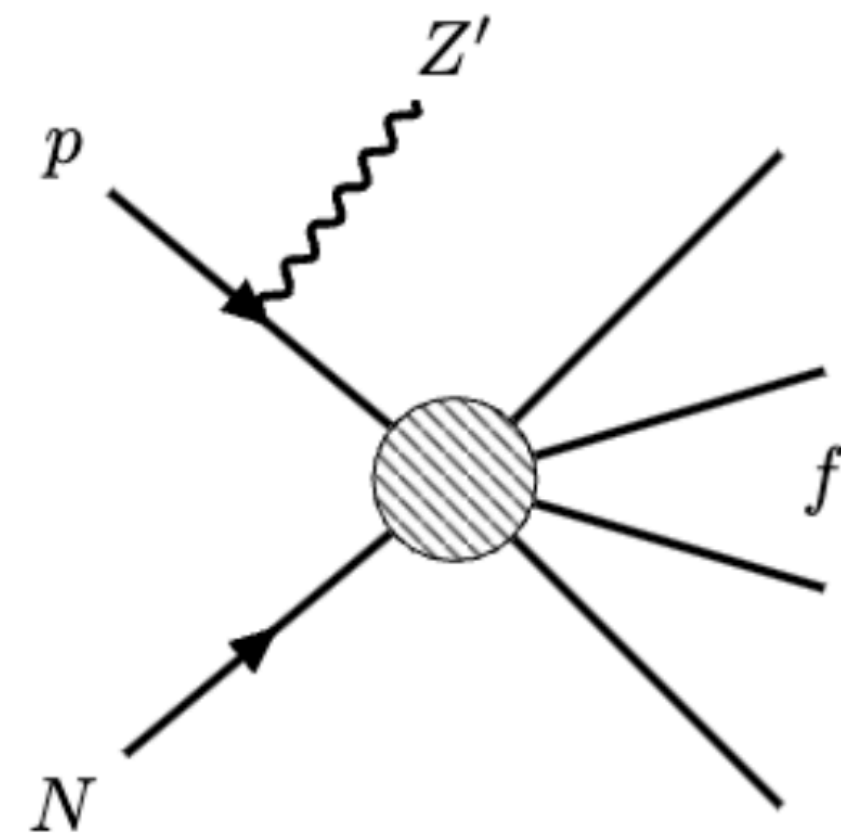
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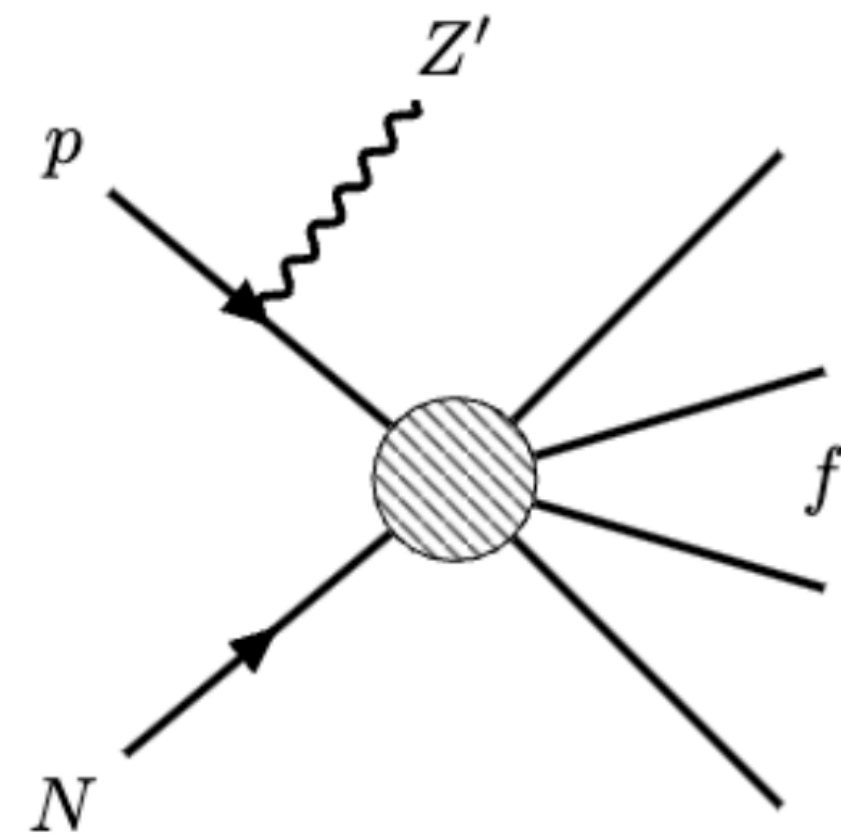
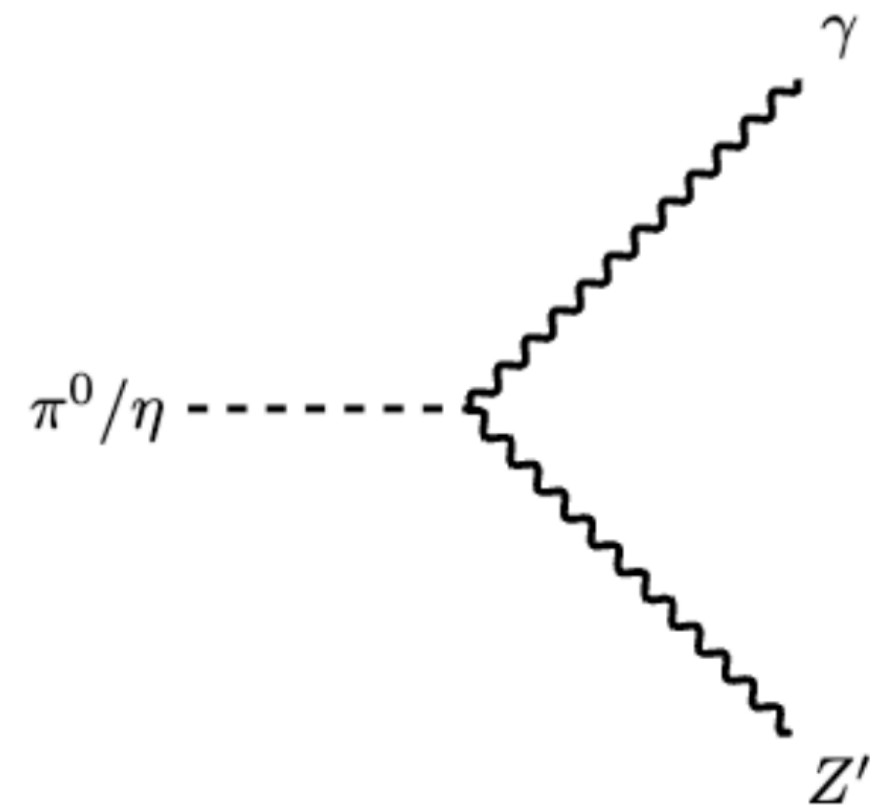


3. Detection: $\mu^+\mu^- \propto g_\mu^2 g_D^2$

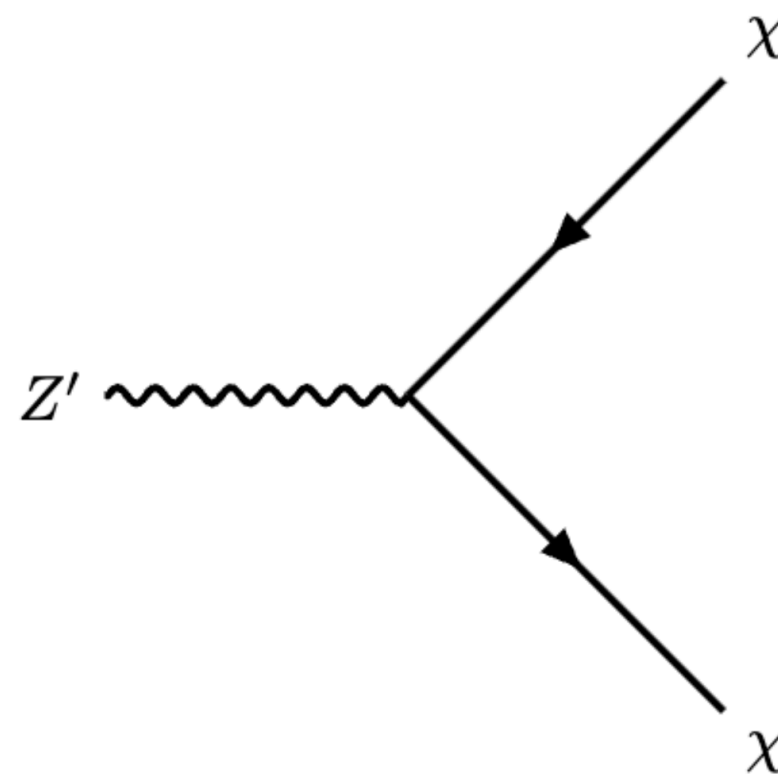


Dark Matter Trident

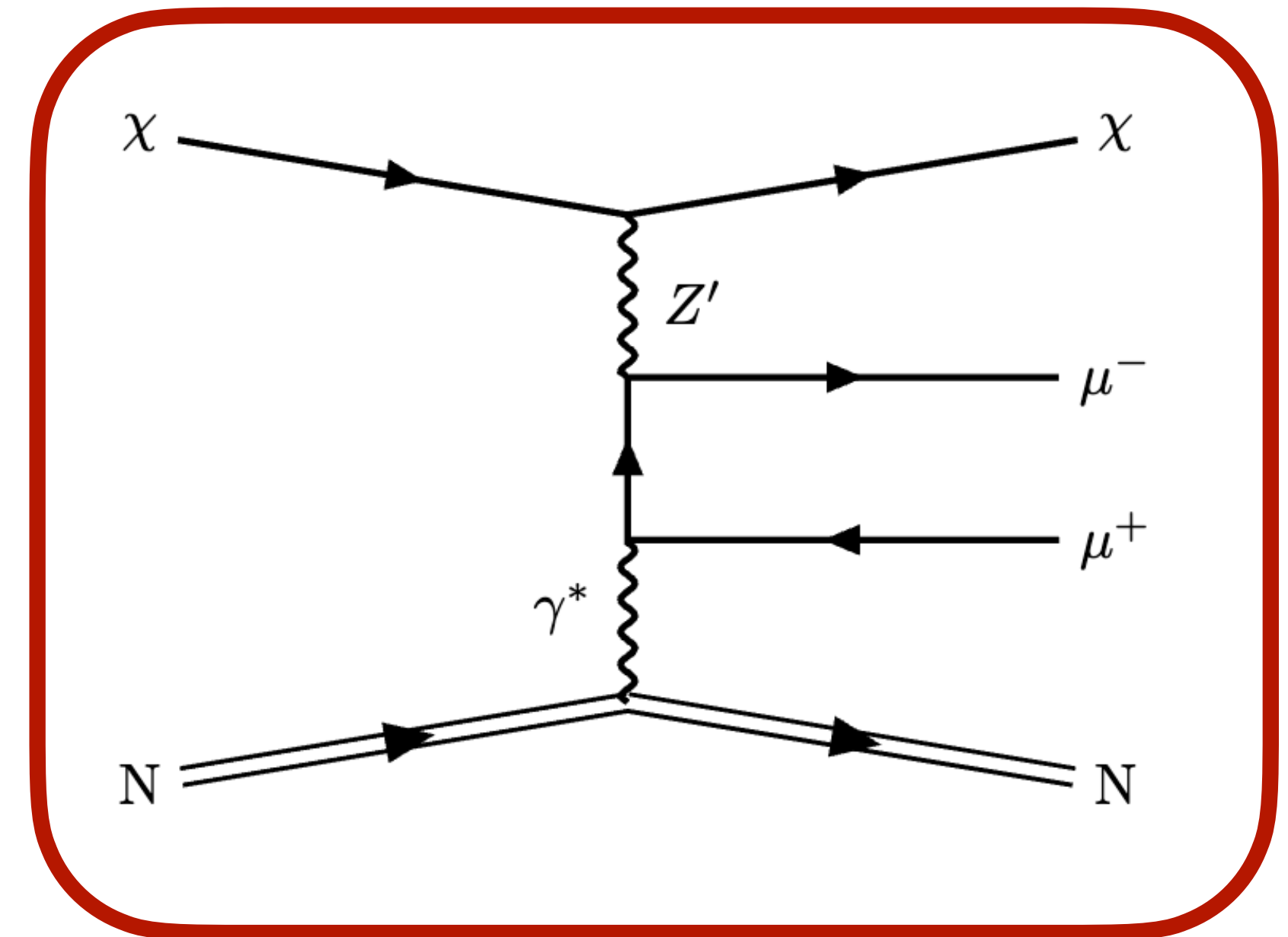
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Total event rate $\propto g_q^2 g_\mu^2 g_D^2$

COHERENT $\propto g_q^4 g_D^2$ (arxiv.org/abs/2110.11453)

NA64 $\propto g_\mu^2$ (Paolo Crivelli's talk)

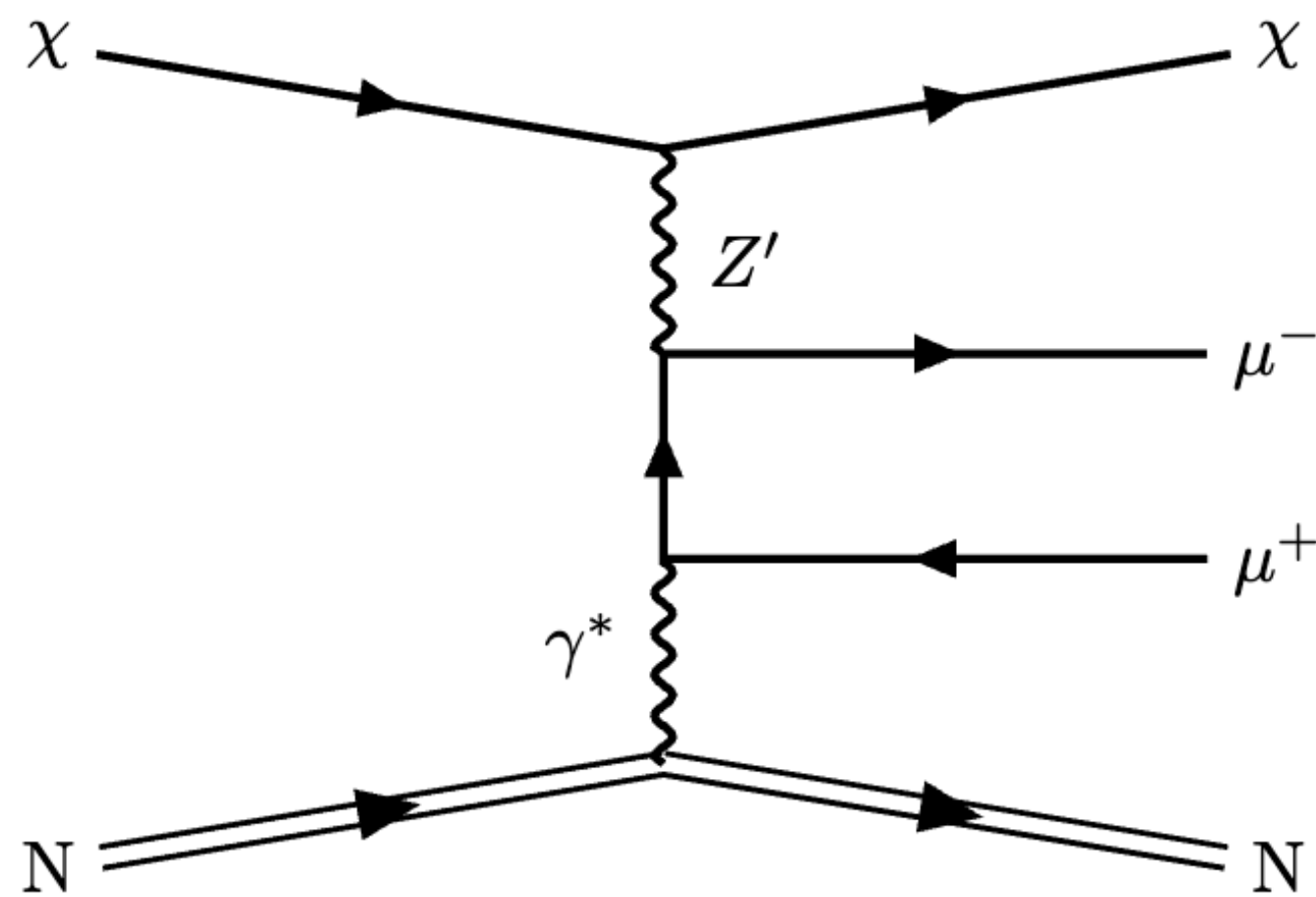
Dark Matter with Dark Photon

Signal - $\mu^+\mu^-$ events

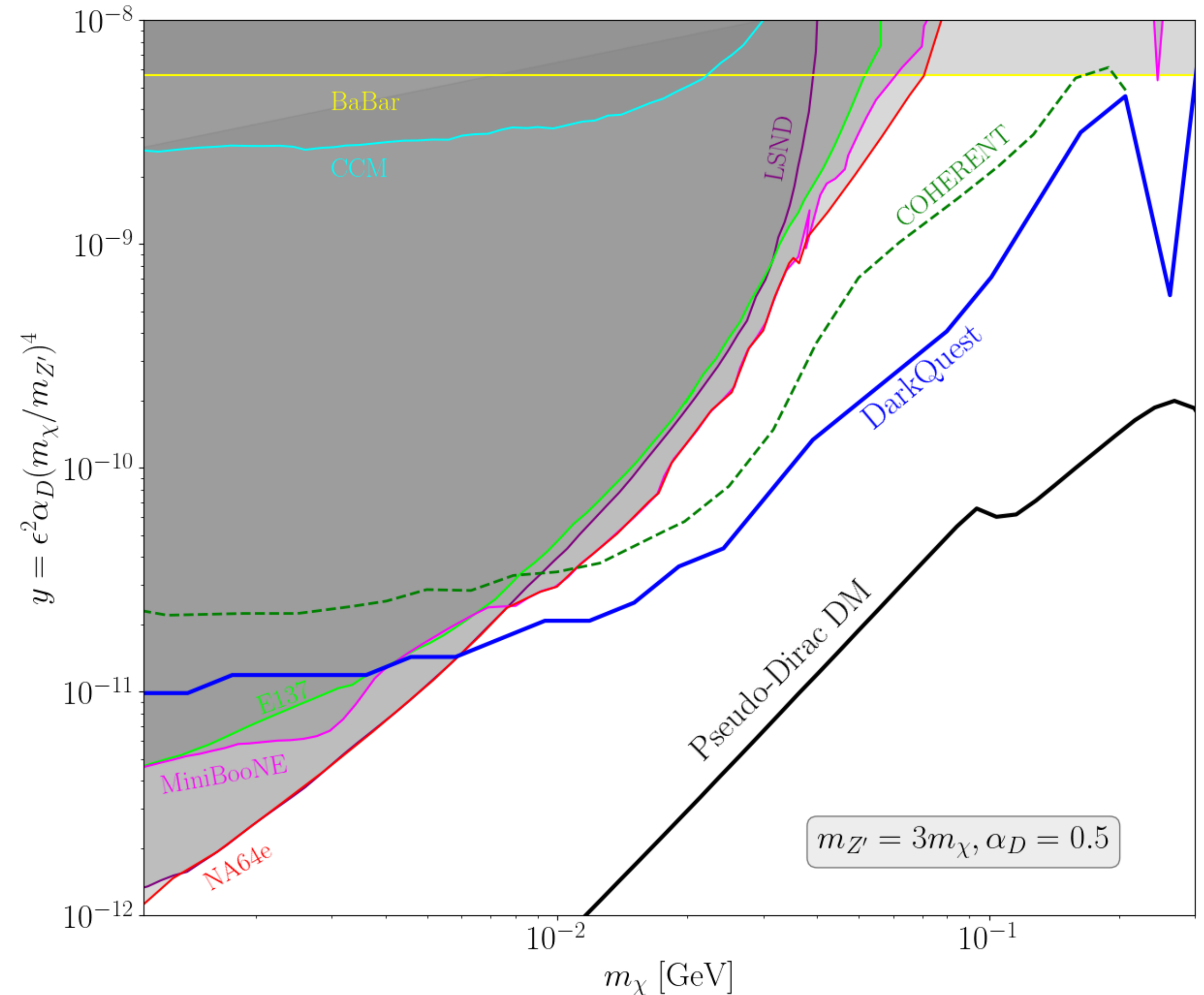
$$g_q = g_l = \epsilon e ; x_f = q_f$$

$$\text{COHERENT events} = N_C \times 1.2 \times 10^{18} g_q^2 g_D^2$$

$$\text{DarkQuest events} = 1.2 \times 10^{19} g_q^2 g_\mu^2 g_D^2$$



NA64 μ : Limits $\geq 2 \times 10^{-8}$



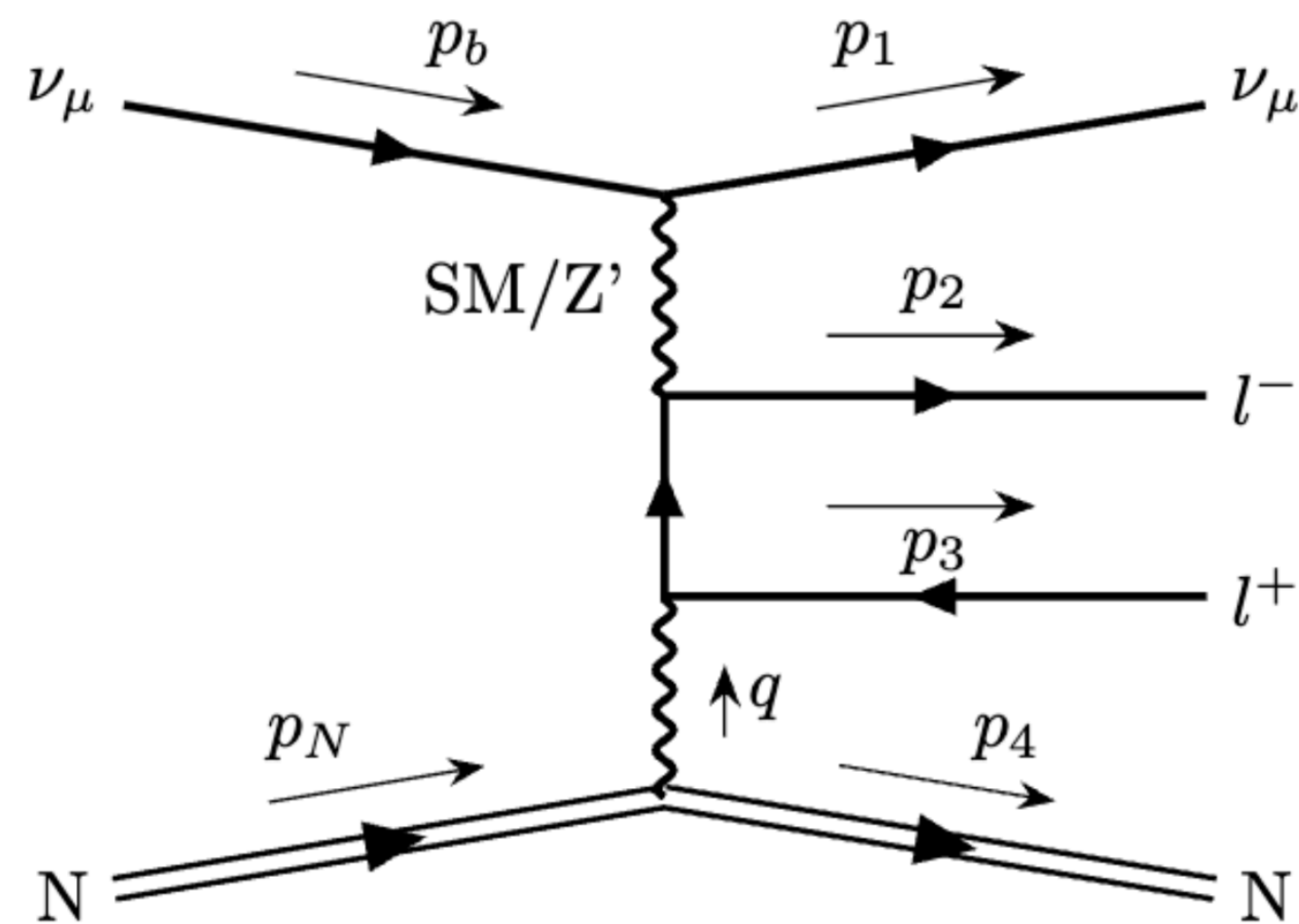
Dark Matter with $L_\mu - L_\tau$

Signal - $\mu^+\mu^-$ events

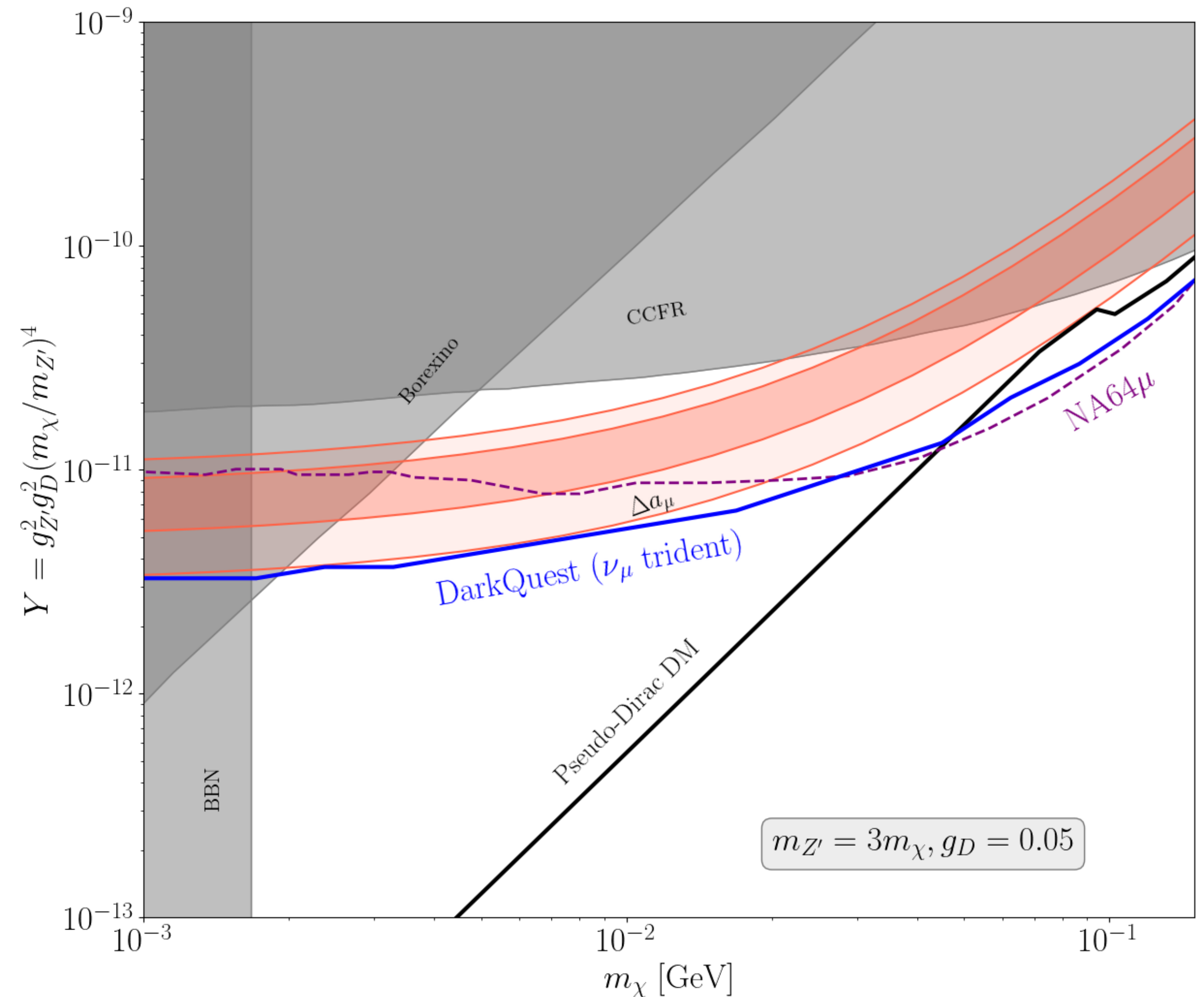
$$g_q = 0 ; x_\mu = 1 ; x_\tau = -1$$

$$\text{NA64mu events} = N_N \times 3.2 \times 10^6 g_\mu^2$$

$$\text{DarkQuest events} = 1.8 \times 10^{14} g_\mu^4 + 6.5 \times 10^6 g_\mu^2$$



COHERENT : Limits $\geq 3 \times 10^{-8}$



Conclusions

- Scattering at DarkQuest - many new physics opportunities
- Neutrino Trident - DarkQuest sensitivity in $(g - 2)_\mu$ band.
- Dark Matter Trident - Large cross section - lepton final states at DarkQuest
- New Physics via Trident - DM, HNLs via upscattering, Axions, etc.

Thank You

Backup

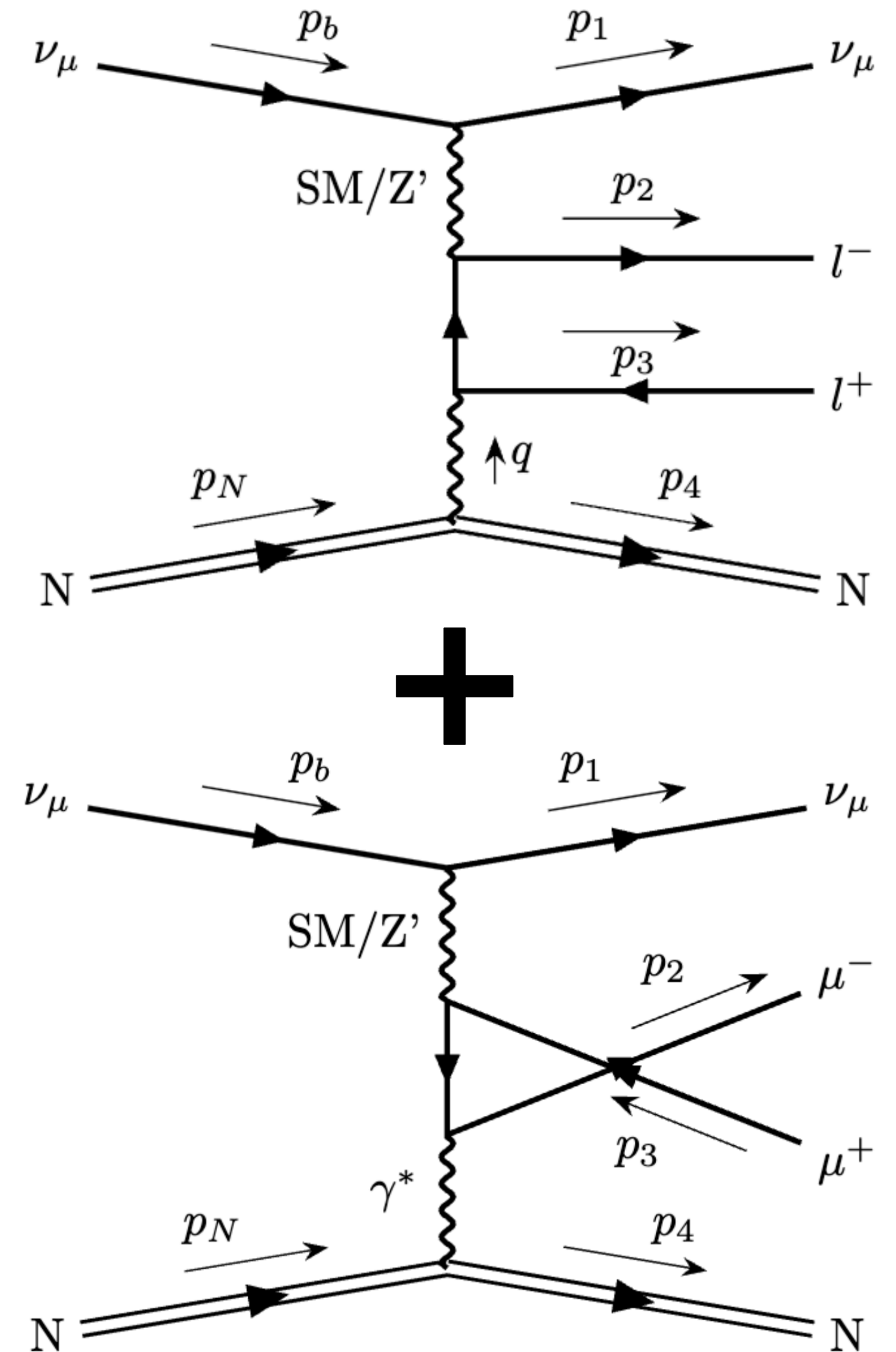
Neutrino Tridents in SM

Formalism used: **Beyond EPA**

- Find $\sigma(\nu\gamma \rightarrow \nu\mu^-\mu^+) = \sigma_{\nu\gamma}(Q^2, s)$
- $\sigma_{\nu\gamma}(Q^2, s) : \sigma_{\nu\gamma}^T(Q^2, s)$ and $\sigma_{\nu\gamma}^L(Q^2, s)$
- Total cross section : $\sigma_{\nu N}(E_\nu)$

$$\sigma_{\nu N} \propto h_N^T(Q^2, s)\sigma_{\nu\gamma}^T(Q^2, s) + h_N^L(Q^2, s)\sigma_{\nu\gamma}^L(Q^2, s)$$

$$h_N(\text{Hadronic current}) \propto Z^2 \text{ in coherent regime}$$



$L_\mu - L_\tau$ Neutrino Trident

- $\mathcal{M}^{SM,Z'} = \mathcal{M}_V^{SM} + \mathcal{M}_A^{SM} + \mathcal{M}_V^{Z'}$
- $\mathcal{M}_V^{Z'} = \left(-\frac{1}{\sqrt{2}G_F} \frac{g_{Z'}^2}{m_{Z'}^2} \frac{m_{Z'}^2}{k^2 - m_{Z'}^2} \right) \mathcal{M}_V^{SM}$
- $\frac{\sigma_{mix}}{\sigma_{SM}} \sim 10^7$; $\frac{\sigma_{Z'}}{\sigma_{SM}} \sim 10^{14}$

**DarkQuest sensitivity
to Z' for excess
events > 2**

$$N_{trident}^{tot} - N_{trident}^{SM} > 2$$

Backgrounds at DarkQuest

1. Decays $K_L^0 \rightarrow \pi^\pm \mu^\mp \nu_\mu$:

- Large in Phase 1 : $> \mathcal{O}(10^{2-3})$
- Can be reduced to $\mathcal{O}(10)$ in Phase 2

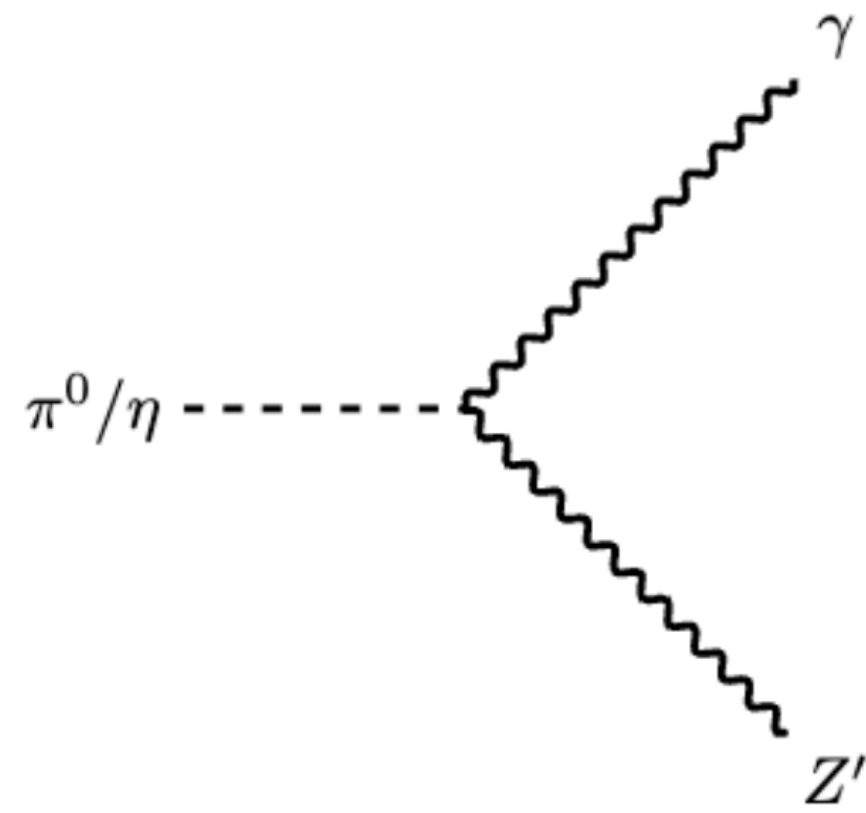
2. ν_μ CC:

- Single muon events - we look for muon-antimuon pairs.
- Yet to study in detail

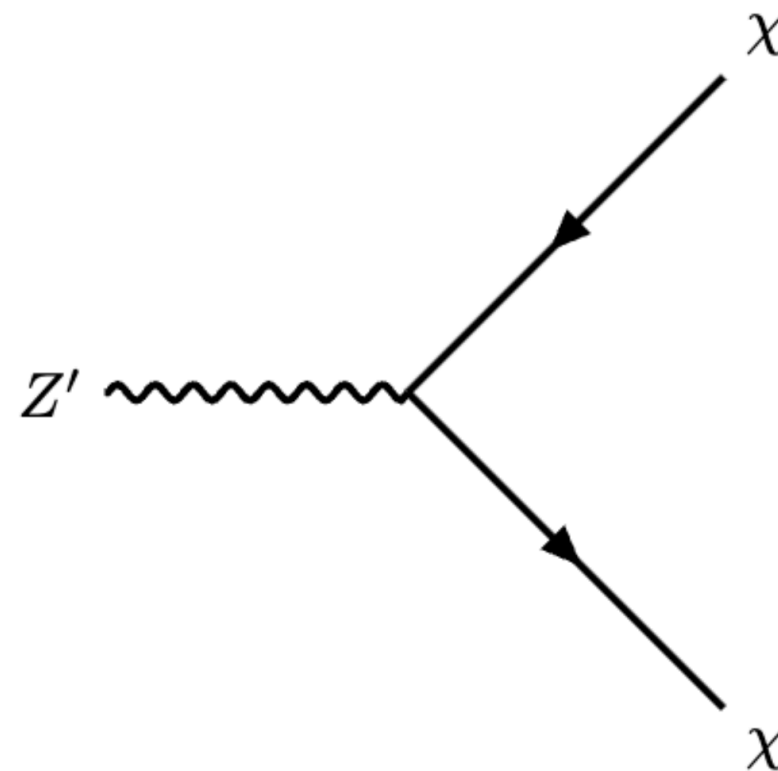
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Dark Matter at COHERENT

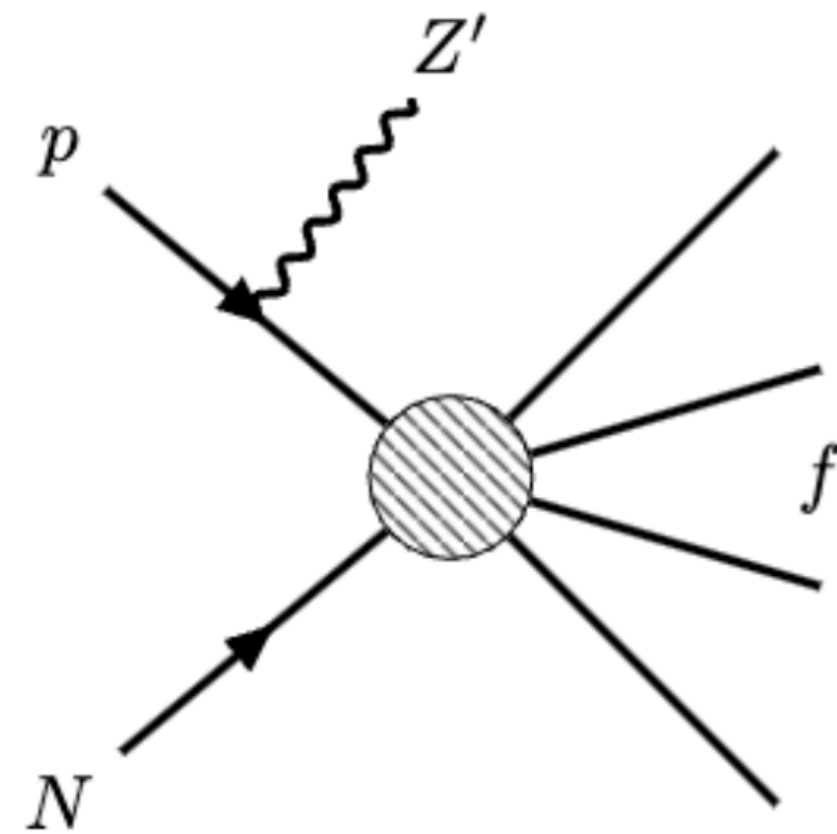
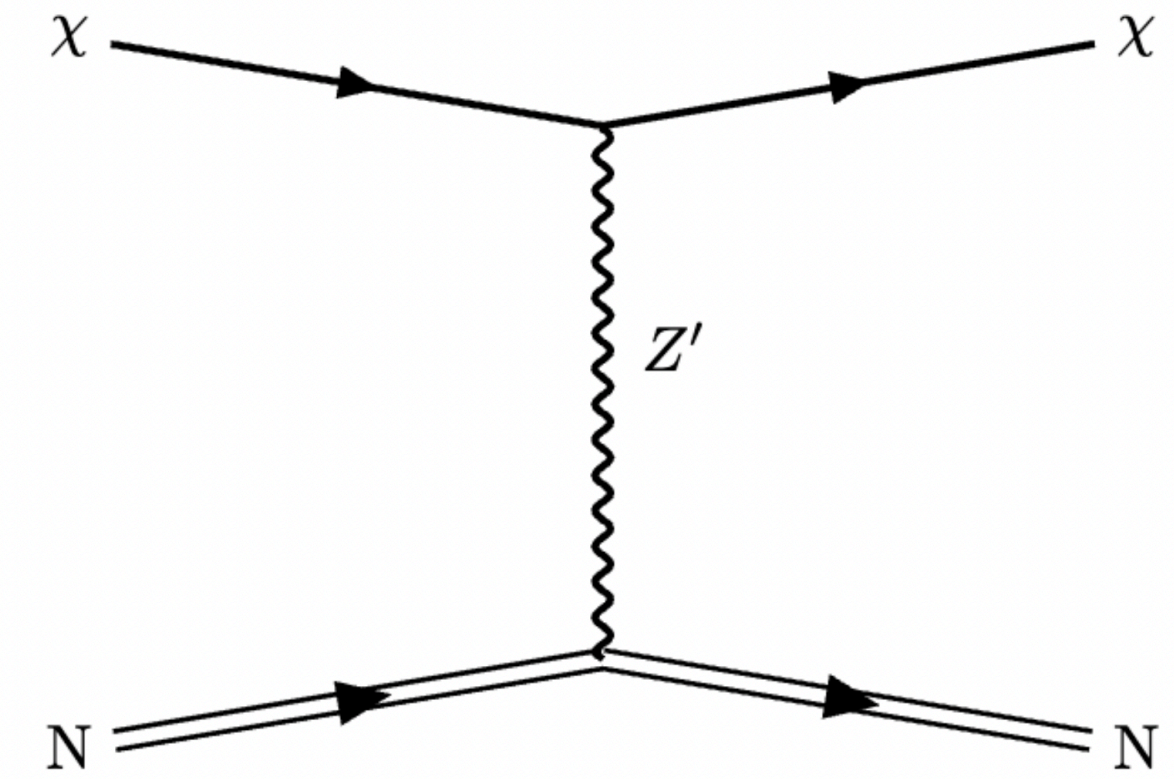
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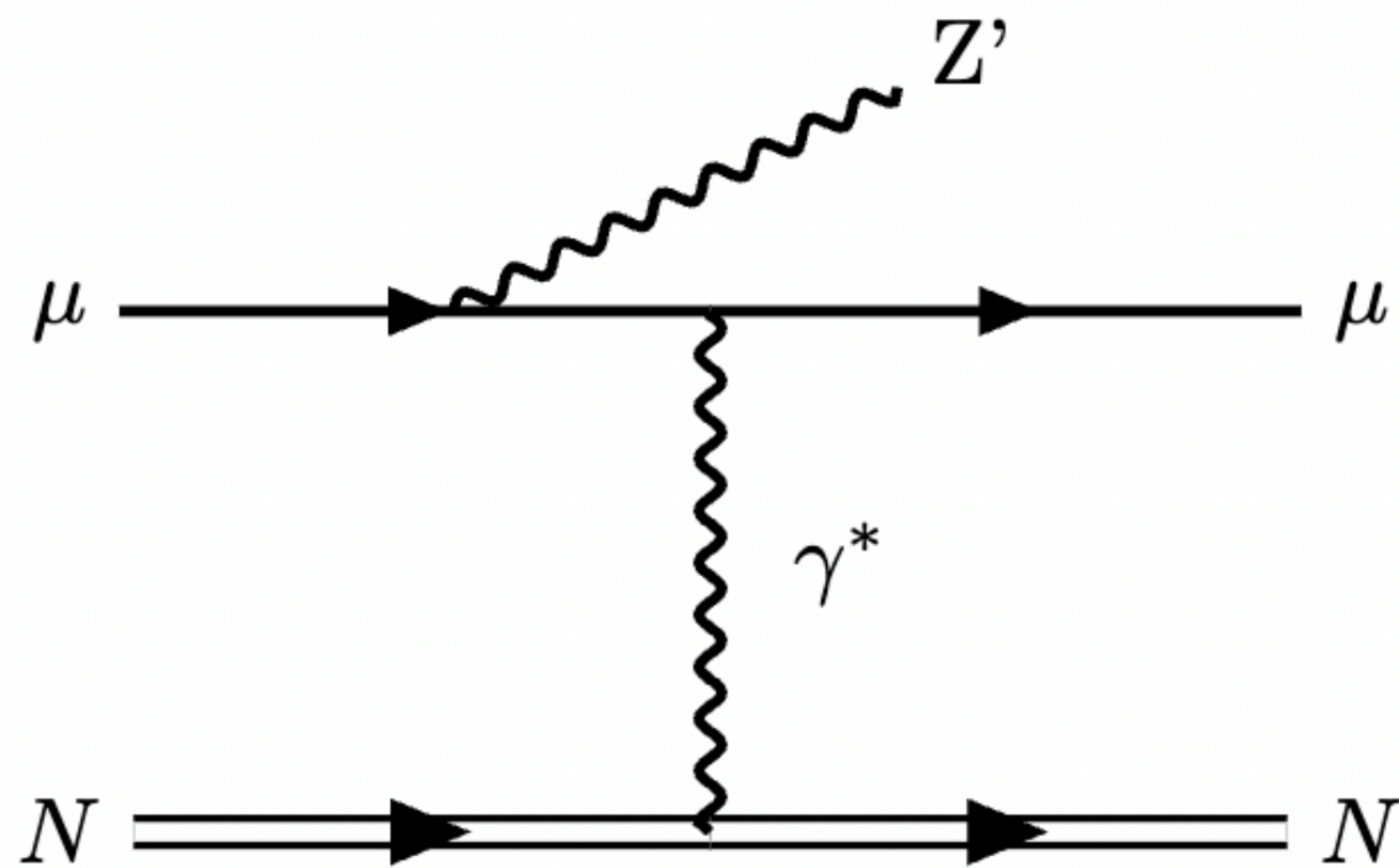
3. Nuclear recoil $\propto g_q^2 g_D^2$



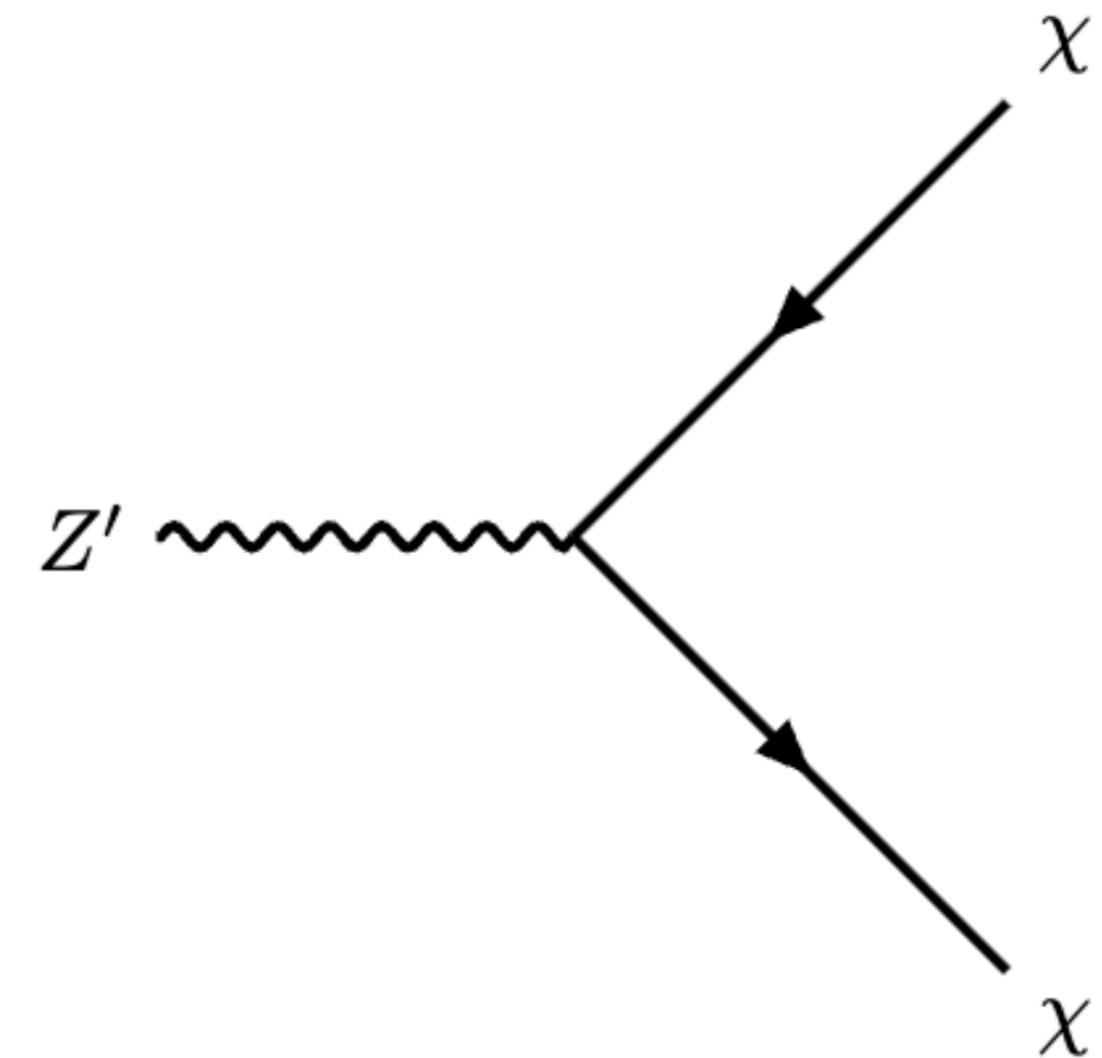
Total event rate $\propto g_q^4 g_D^2$

Dark Matter at NA64

1. Production of $Z' \propto g_\mu^2$



2. Production of χ ; $BR = 100\%$

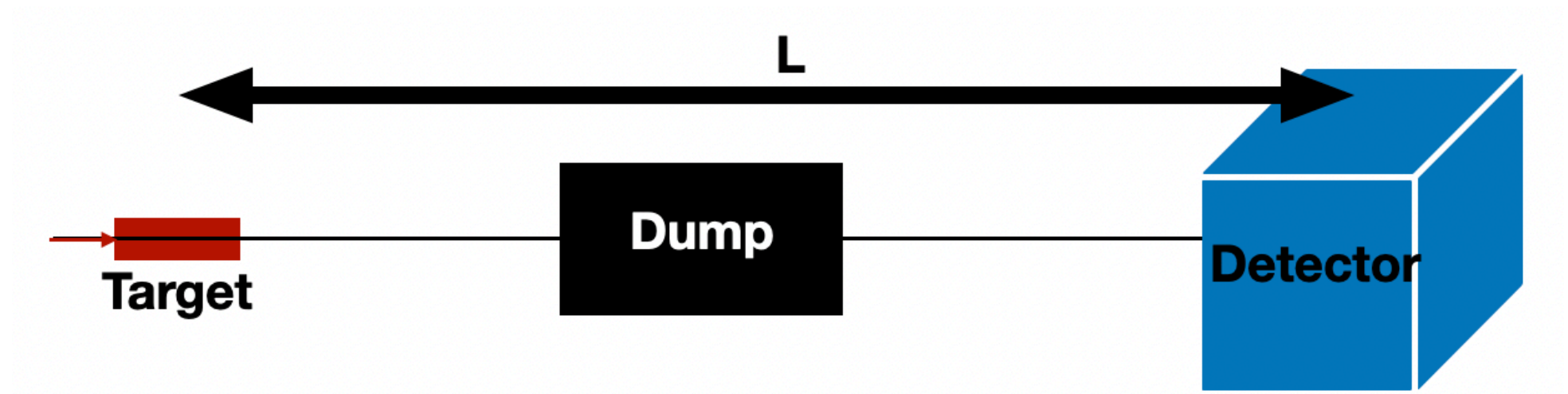


Missing energy $\propto g_\mu^2$

Prospective improvements

- Include ν_τ tridents and τ^+ , τ^- final states
- Better defined sensitivity from understanding tracking stations beyond ST4

Beam dumps



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Sensitivity : $B - 3L_\mu$

COHERENT events = $N_C \times 1.2 \times 10^{18} g_q^2 g_D^2$

DarkQuest events = $10.8 \times 10^{19} g_q^2 g_\mu^2 g_D^2$

- Additional enhancement from muon coupling compared to COHERENT

