Decay (& Production) of Light Vector Particles

Peter Reimitz
Instituto de Física, Universidade de São Paulo

4th Forward Physics Facility Meeting
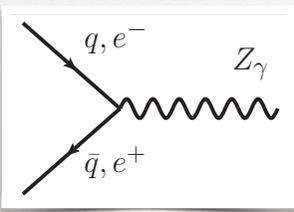**January 31, 2022**

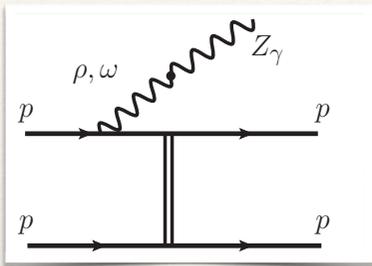**Ana Foguel (IFUSP), Renata Zukanovich (IFUSP), based on arXiv:2201.01788**

+ Aidin Masouminia (IPPP Durham), Simon Plätzer (Uni Graz)

Decay (& Production) of Light Vector Particles
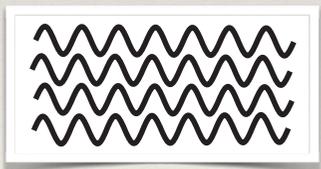
Drell-Yan

Proton bremsstrahlung

→ **BSM Sec. II.B.8** (Foroughi-Abari, Ritz)
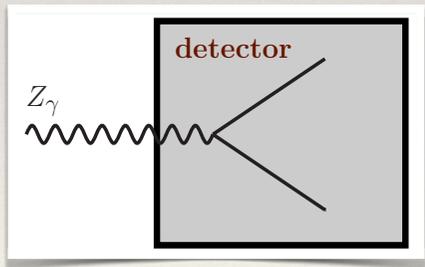
arXiv:2108.05900

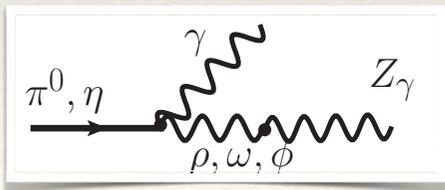**Vector Particle Production**

Vector particle "beam"

Decay

Meson decays

for $m_{Z_\gamma} < m_{\pi,\eta}$

- travelling through material
- Vector particle **lifetime** crucial

Decay (& Production) of Light Vector Particles

Drell-Yan

q, e^-
Z_γ
$\bar{q}, e^+$

Proton bremsstrahlung

ρ, ω
Z_γ
p — p
p — p

➡ **BSM Sec. II.B.8** (Foroughi-Abari, Ritz)

arXiv:2108.05900

Vector Particle Production

➡

Vector particle "beam"

➡

Decay ❗

Meson decays

π^0, η
γ
Z_γ
ρ, ω, ϕ

for $m_{Z_\gamma} < m_{\pi, \eta}$
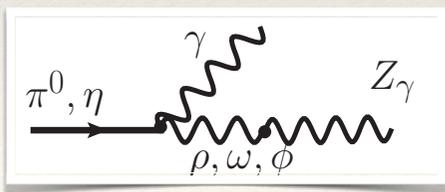

- travelling through material
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detector

Z_γ
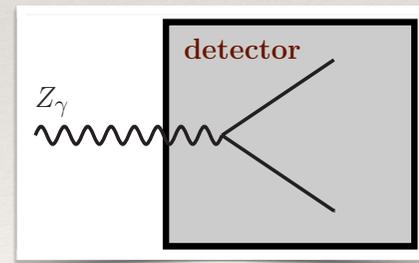
Success of the Dark Photon
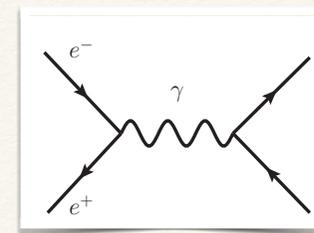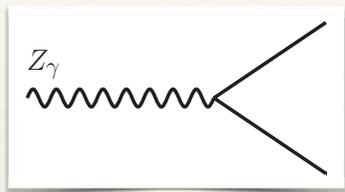

$$\sim \epsilon e J_{\text{em}}^{\mu}$$

$$J_{\text{em}}^{\mu} = \sum_{f} \bar{f} \gamma^{\mu} q_{\text{em}}^{f} f$$

Success of the Dark Photon

$$\sim L_\mu J^\mu_{\text{em}}$$

$$\sim \epsilon e J^\mu_{\text{em}}$$

$$J^\mu_{\text{em}} = \sum_f \bar{f} \gamma^\mu q^f_{\text{em}} f$$

Attractive Mass range: **MeV-GeV**

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$$\Gamma_{Z_\gamma \to \mathcal{H}} = \Gamma_{Z_\gamma \to \mu^+\mu^-} R^{\mathcal{H}}_\mu[\exp]$$

Most searches $e^+e^-, \mu^+\mu^-$!

- Branching ratio into leptons
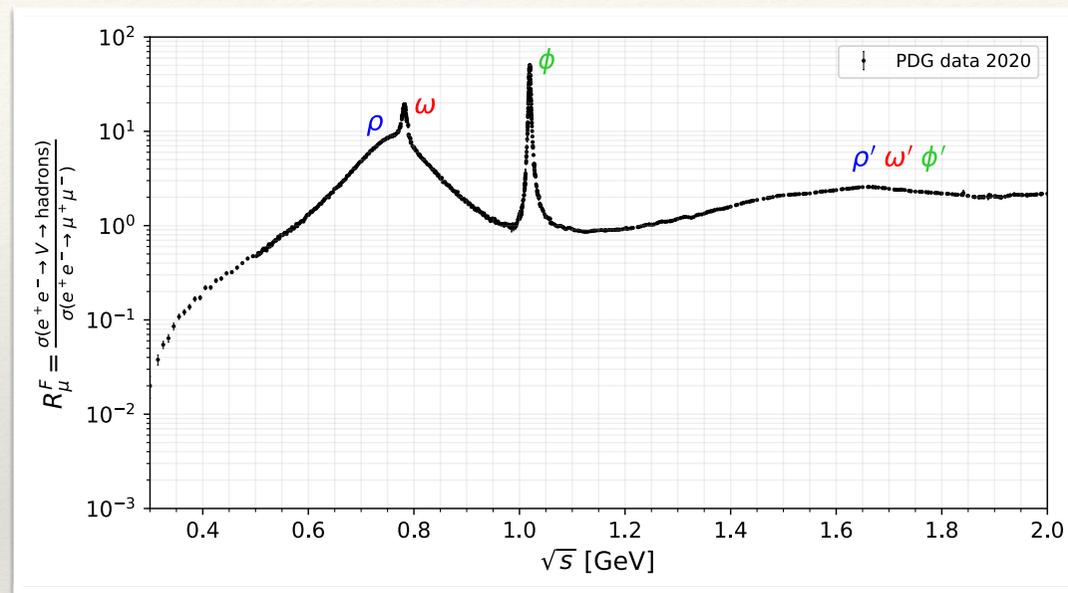- Lifetime of the dark photon
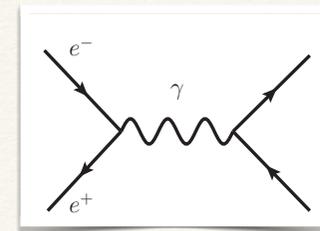
Description of Hadronic Current

$$\sim L_\mu J^\mu_{\text{em}}$$

$$\sim \epsilon e J^\mu_{\text{em}}$$

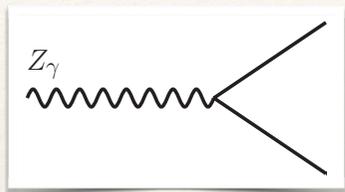$$J^\mu_{\text{em}} = \sum_f \bar{f}\gamma^\mu q^f_{\text{em}} f$$

Attractive Mass range: **MeV-GeV**

$$J^\mu_{\text{em}} = \frac{1}{\sqrt{2}} \underbrace{(q^u_{\text{em}} - q^d_{\text{em}})}_{=1} J^\mu_{I=1} + \frac{1}{\sqrt{2}} \underbrace{(q^u_{\text{em}} + q^d_{\text{em}})}_{=1/3} J^\mu_{I=0} + \underbrace{q^s_{\text{em}}}_{-1/3} J^\mu_s$$

Isospin states:

$$J^\mu_{I=1} = \frac{\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d}{\sqrt{2}}$$

$$J^\mu_{I=0} = \frac{\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d}{\sqrt{2}}$$

Strange quark current: $J^\mu_s = \bar{s}\gamma^\mu s$

$$\Gamma_{Z_\gamma \to \mathcal{H}} = \Gamma_{Z_\gamma \to \mu^+\mu^-} R^\mathcal{H}_\mu[\exp]$$

Most searches $e^+e^-, \mu^+\mu^-$ **!**

- Branching ratio into leptons
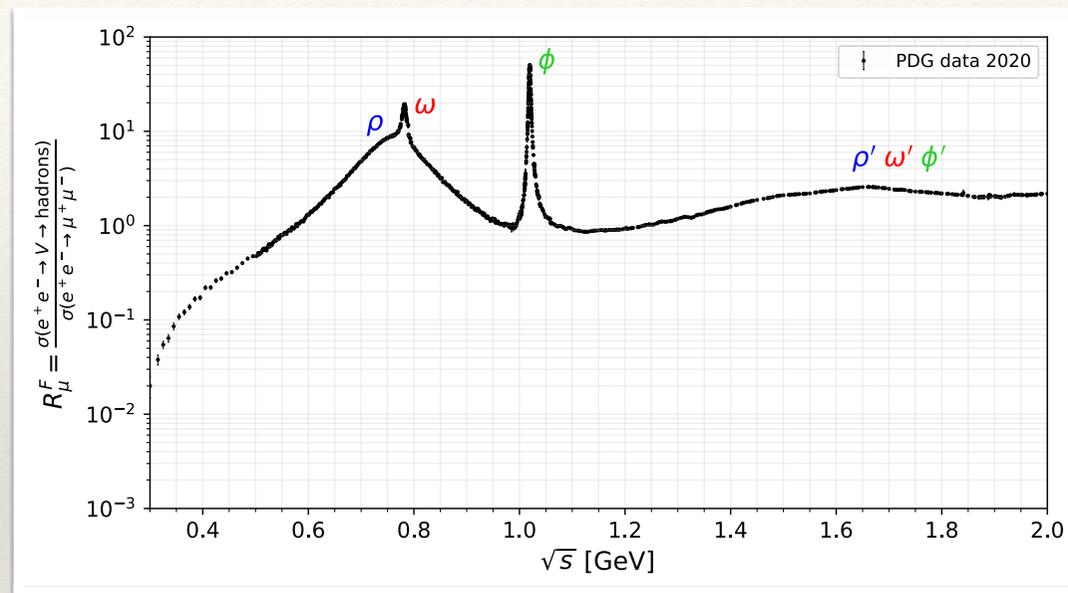- Lifetime of the dark photon

Description of Hadronic Current

$\sim L_\mu J^\mu_{\text{em}}$

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$$J^\mu_{\text{em}} = \sum_f \bar{f} \gamma^\mu q^f_{\text{em}} f$$
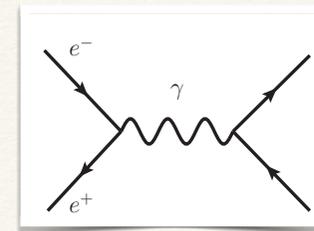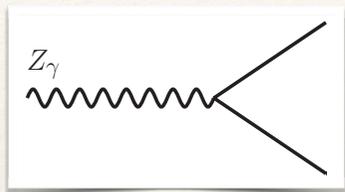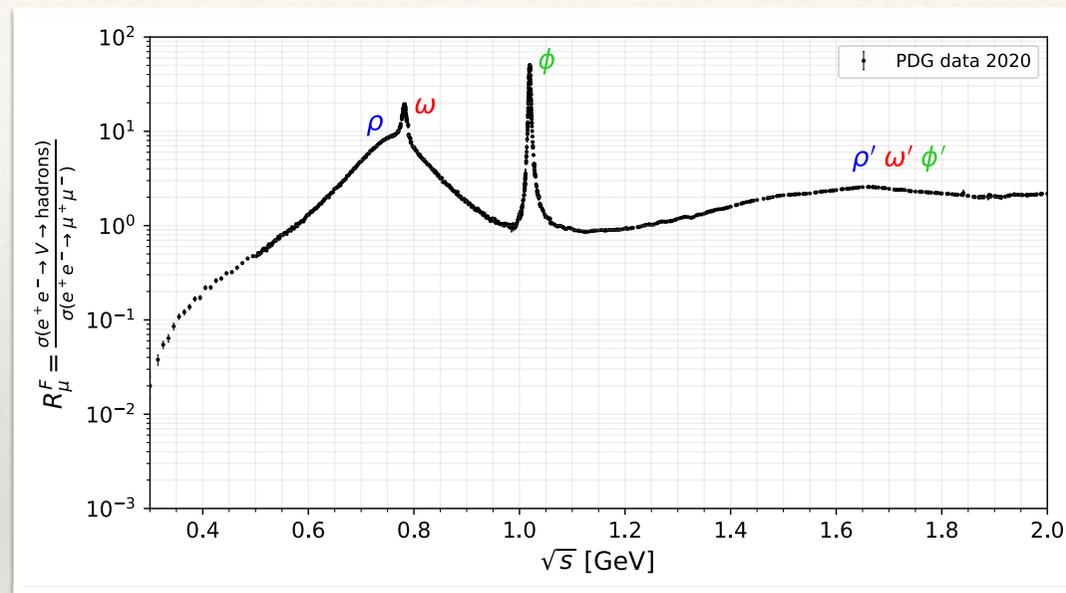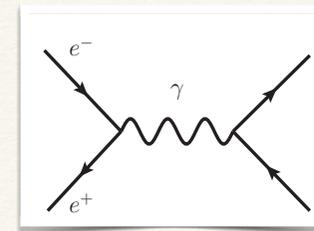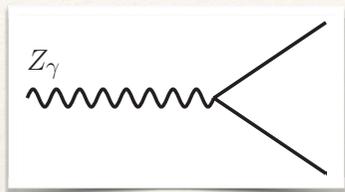
Attractive Mass range: **MeV-GeV**

$$J^\mu_{\text{em}} = \frac{1}{\sqrt{2}} \underbrace{(q^u_{\text{em}} - q^d_{\text{em}})}_{=1} J^\mu_{I=1} + \frac{1}{\sqrt{2}} \underbrace{(q^u_{\text{em}} + q^d_{\text{em}})}_{=1/3} J^\mu_{I=0} + \underbrace{q^s_{\text{em}}}_{-1/3} J^\mu_s$$

$\rho^\mu \qquad\qquad \omega^\mu \qquad\qquad \phi^\mu$

Vector meson dominance: $\quad V^\mu \sim J^\mu_{\text{had}}$

$$\Gamma_{Z_\gamma \to \mathcal{H}} = \Gamma_{Z_\gamma \to \mu^+ \mu^-} R^{\mathcal{H}}_\mu [\exp]$$

Most searches $\quad e^+ e^-, \mu^+ \mu^- \quad$ **!**

- Branching ratio into leptons
- Lifetime of the dark photon

Description of Hadronic Current

$\sim L_\mu J^\mu_{\text{em}}$

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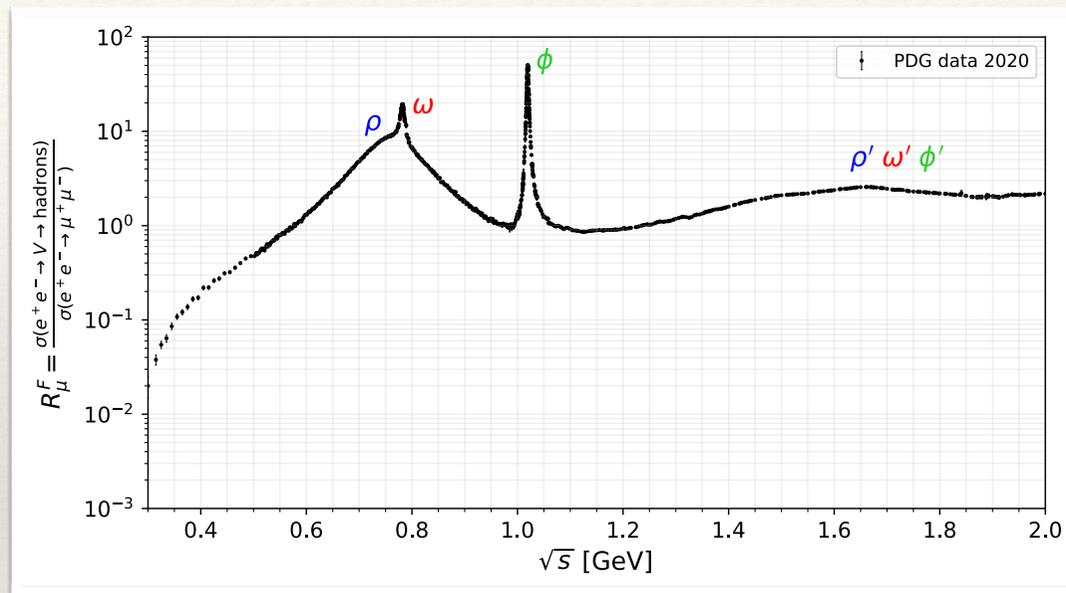
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$\rho^\mu \qquad\qquad \omega^\mu \qquad\qquad \phi^\mu$

<u>Chiral Perturbation Theory:</u>

SM: $\qquad \mathcal{L}_{VA} = e A^\mu 2 \text{Tr}[V_\mu Q_{\text{em}}]$

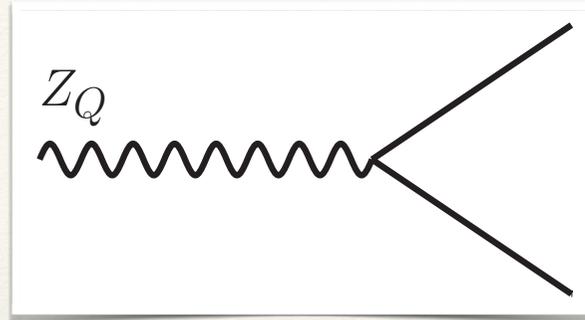BSM: $\qquad \mathcal{L}_{VZ_Q} = g_Q Z^\mu_Q 2 \text{Tr}[V_\mu Q^f]$

$$\Gamma_{Z_\gamma \to \mathcal{H}} = \Gamma_{Z_\gamma \to \mu^+ \mu^-} R^{\mathcal{H}}_\mu [\text{exp}]$$

Most searches $\quad e^+ e^-, \mu^+ \mu^- \quad$ **!**

- Branching ratio into leptons
- Lifetime of the dark photon

Other models?

$$\sim g_Q J^\mu_\mathcal{H}$$

$$J^\mu_\mathcal{H} = ?$$

Focus on B-coupled models

$$J^\mu_Q = \sum_f \bar{f} \gamma^\mu q^f_Q f \qquad \Rightarrow \qquad J^\mu_B = \frac{1}{3} \sum_q \bar{q} \gamma^\mu q$$

Hadronic current:

$$J^\mu_B = \frac{1}{\sqrt{2}} \underbrace{(q^u_B - q^d_B)}_{=0} J^\mu_{I=1} + \frac{1}{\sqrt{2}} \underbrace{(q^u_B + q^d_B)}_{=2/3} J^\mu_{I=0} + \underbrace{q^s_B}_{1/3} J^\mu_s$$

$$\downarrow \qquad\qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$\rho^\mu \qquad\qquad\qquad \omega^\mu \qquad\quad \phi^\mu$$

Workflow

Individual hadronic channels have the form:

$$J^{\mu}_{KK} = -(p_1 - p_2)^{\mu} F_{KK}(\hat{s})$$

$$F_{KK}(\hat{s}) \propto \sum_{V=\rho,\omega,\phi,\dots} \frac{a_V m_V^2 e^{i\varphi_V}}{m_V^2 - \hat{s} - i m_V \Gamma_V}$$

e^+e^- data to describe the SM current J^{μ}_{em}

Description for individual channels

$2\pi, 3\pi, 4\pi, KK, KK\pi, \dots$

Separate ρ, ω, ϕ contributions
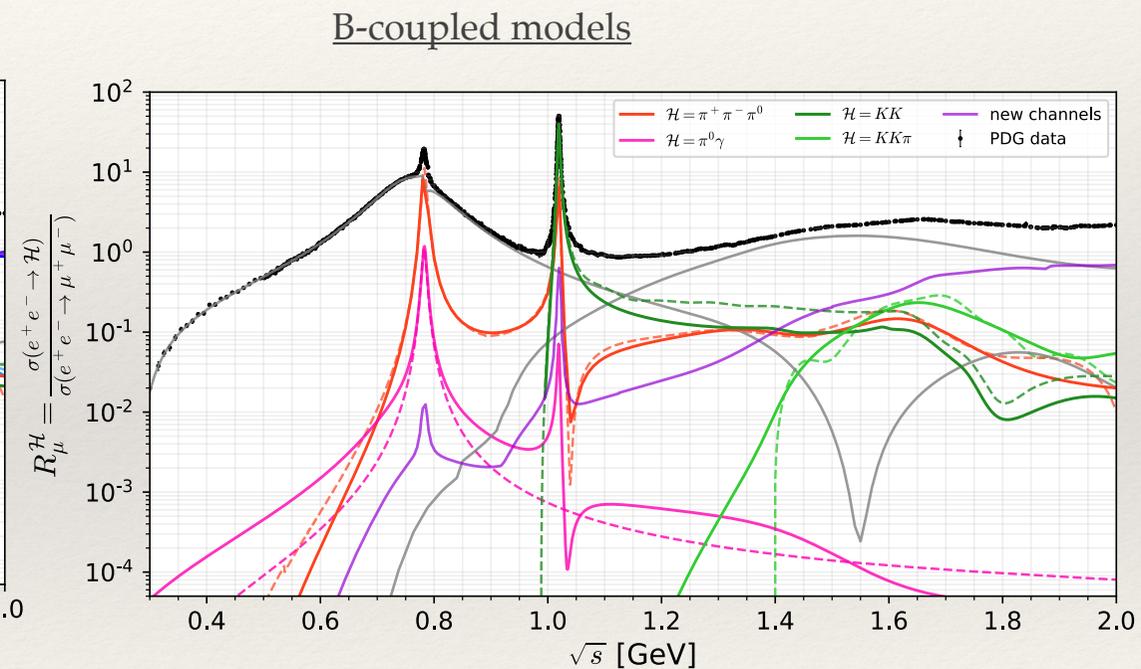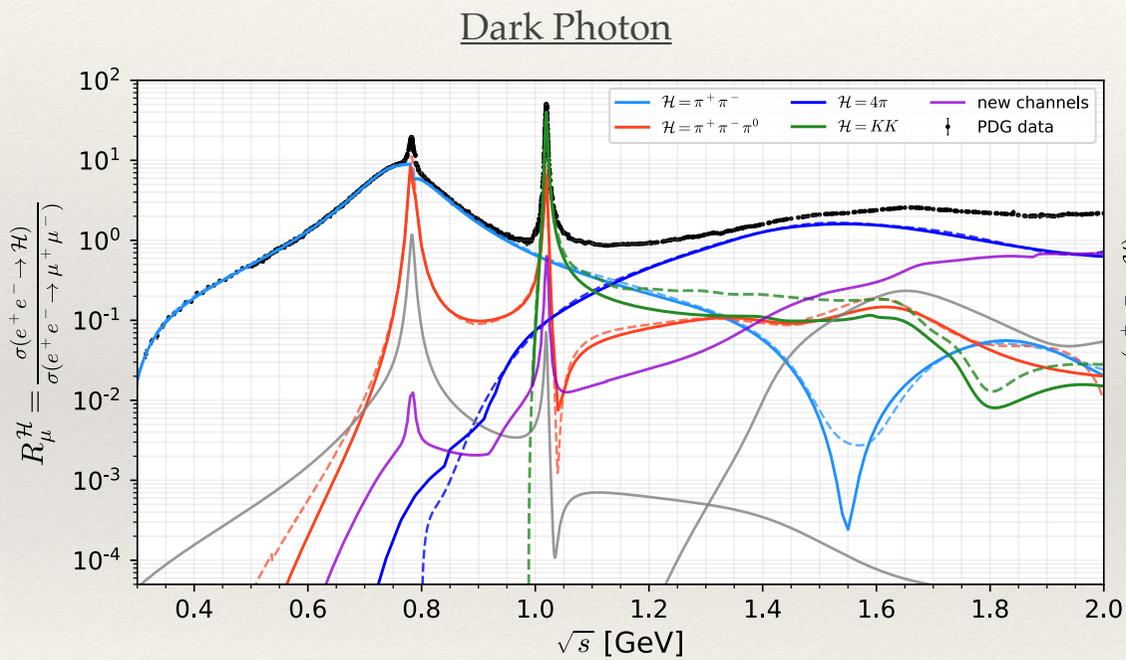
Put together pieces for hadronic current of model

Some taken from *1911.11147* (Herwig implementation)
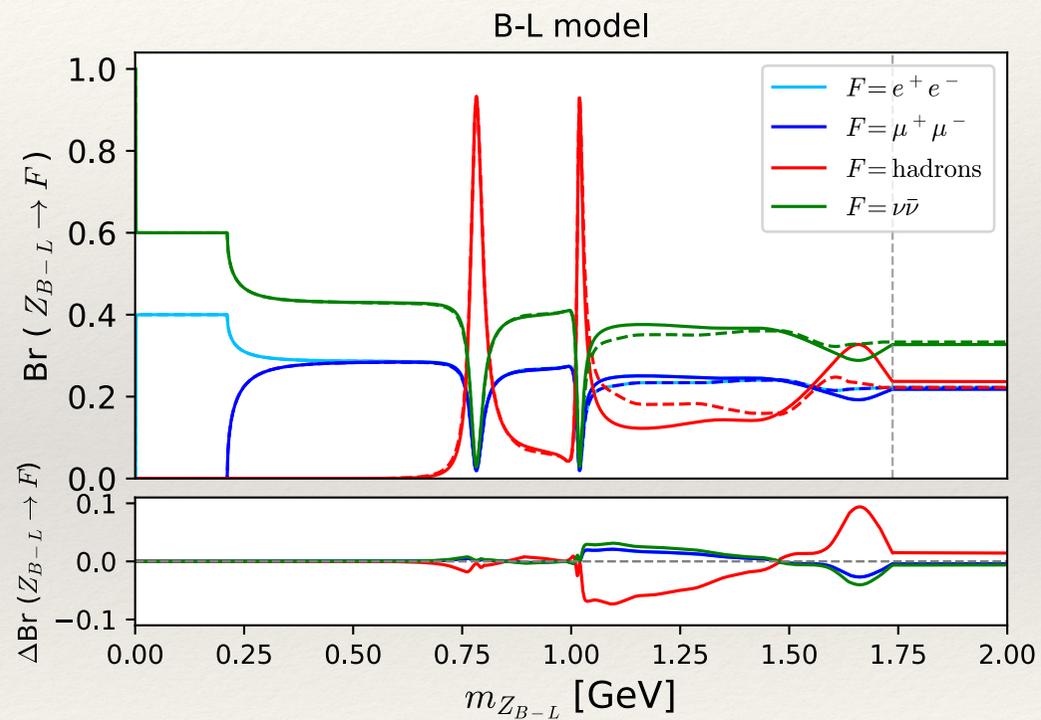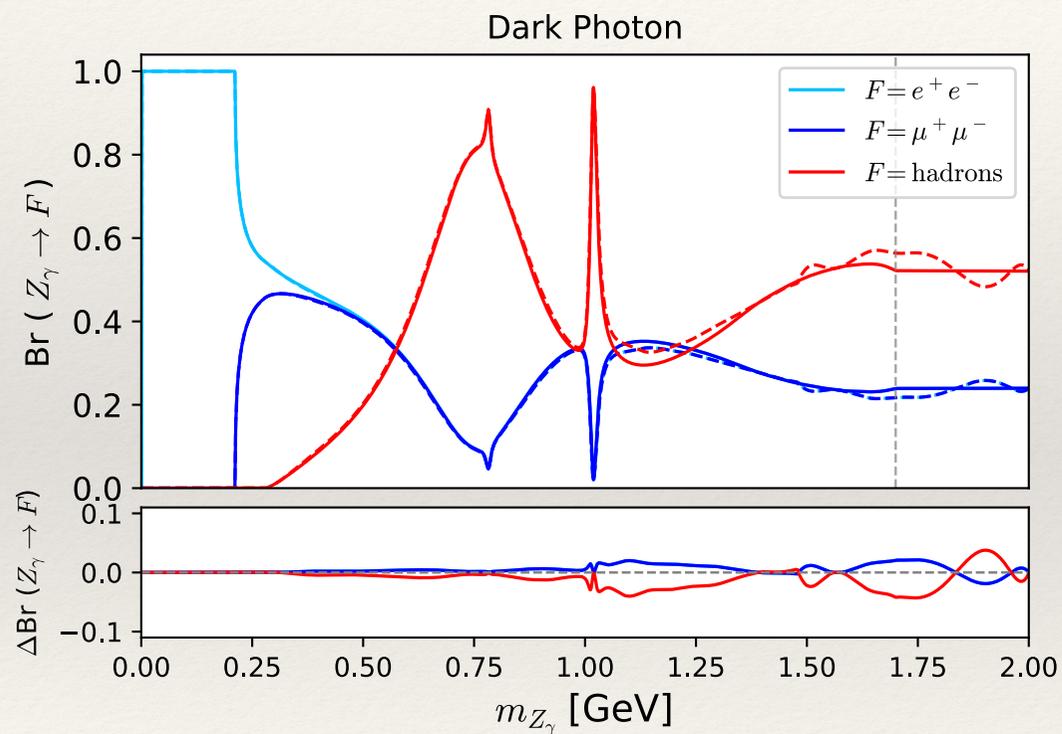
H7

Some new ones *2201.01788* Python package **DeLiVeR**

Two models and comparison to DarkCast

DarkCast: P. Ilten, Y. Soreq, M. Williams, W. Wue
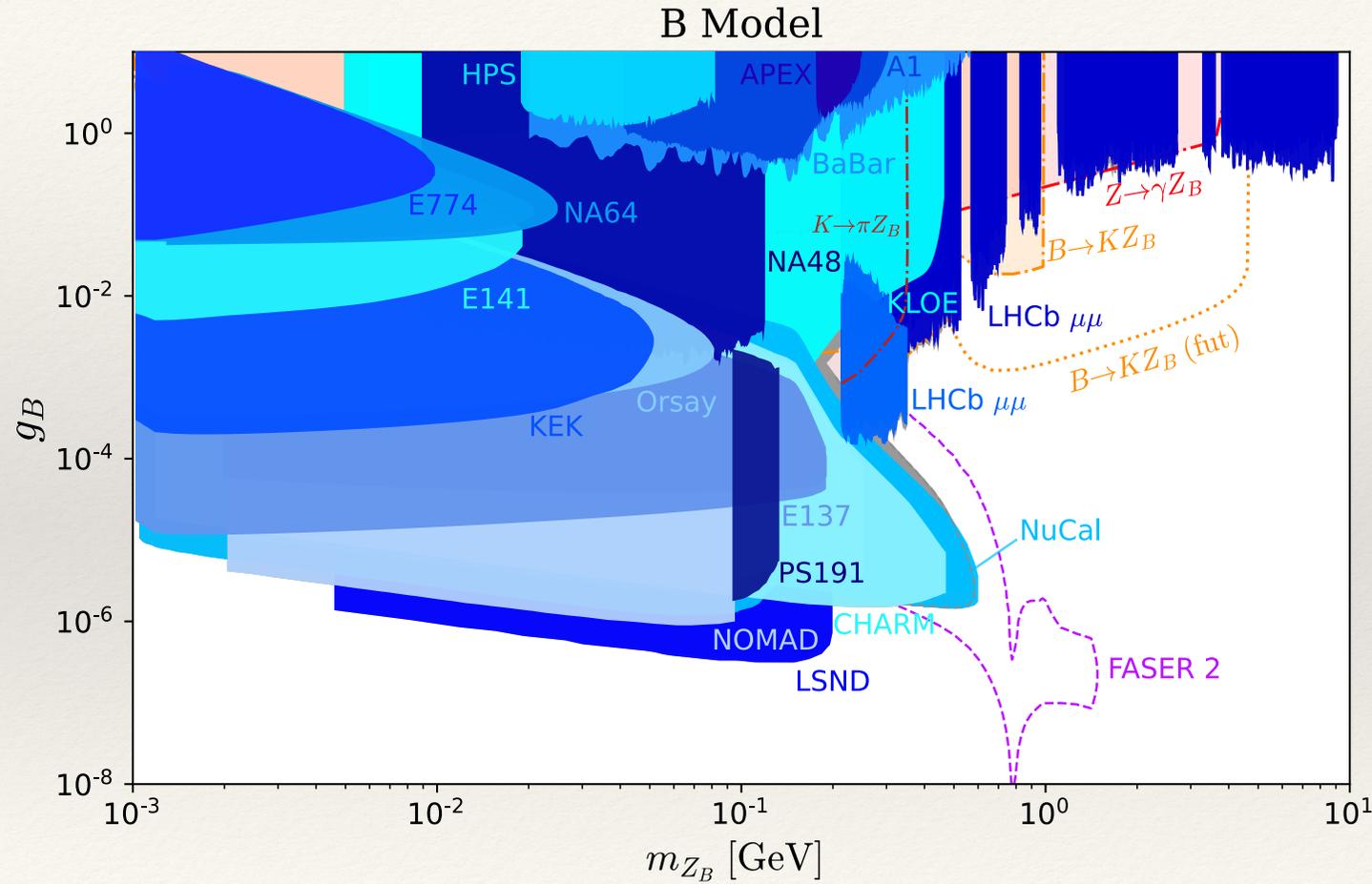*arXiv:1801.04847*

Dark Photon

B-coupled models

Two models and comparison to DarkCast

Dark Photon

B-L model

$\sim 10\%$ difference

B model

B Model

$$J_B^\mu = \frac{1}{3}\sum_q \bar{q}\gamma^\mu q$$
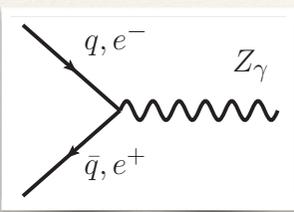
In blue: leptonic decays

B model

B model

FASER2 - $U(1)_B$

Legend:
$\mathcal{F} = \pi^0\gamma$
$\mathcal{F} = \pi^+\pi^-\pi^0$
$\mathcal{F} = KK$
$\mathcal{F} = KK\pi$
$\mathcal{F} = $ hadrons
$\mathcal{F} = $ leptons
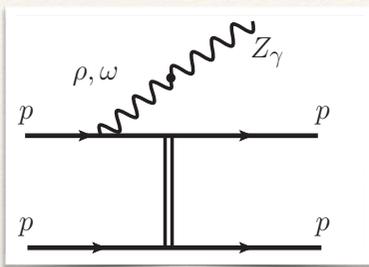$\mathcal{F} = $ quarks
$\mathcal{F} = $ others
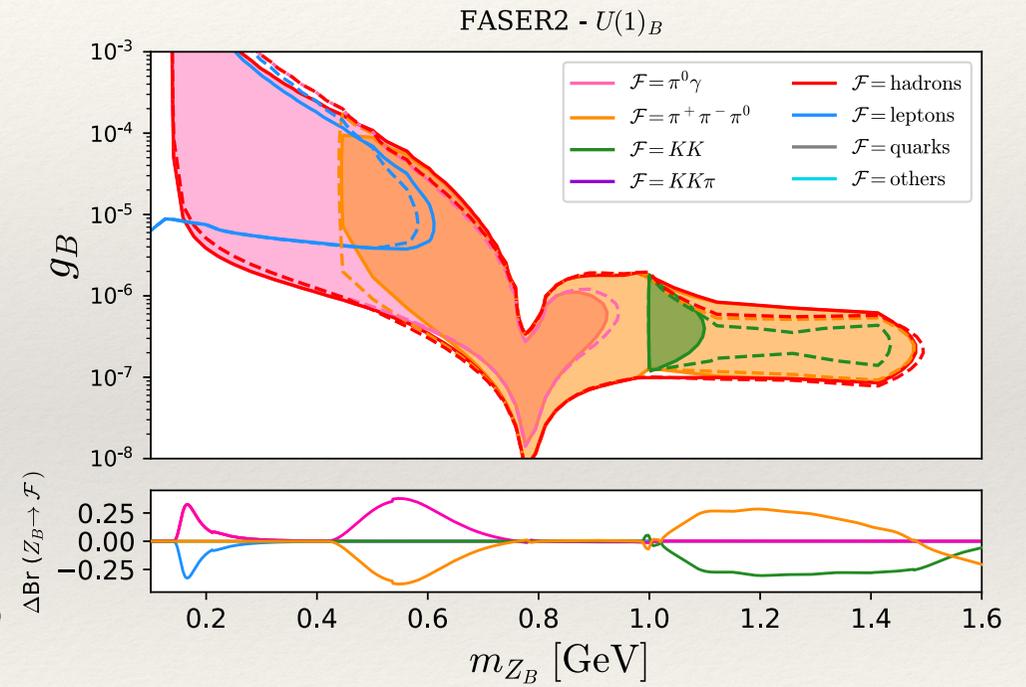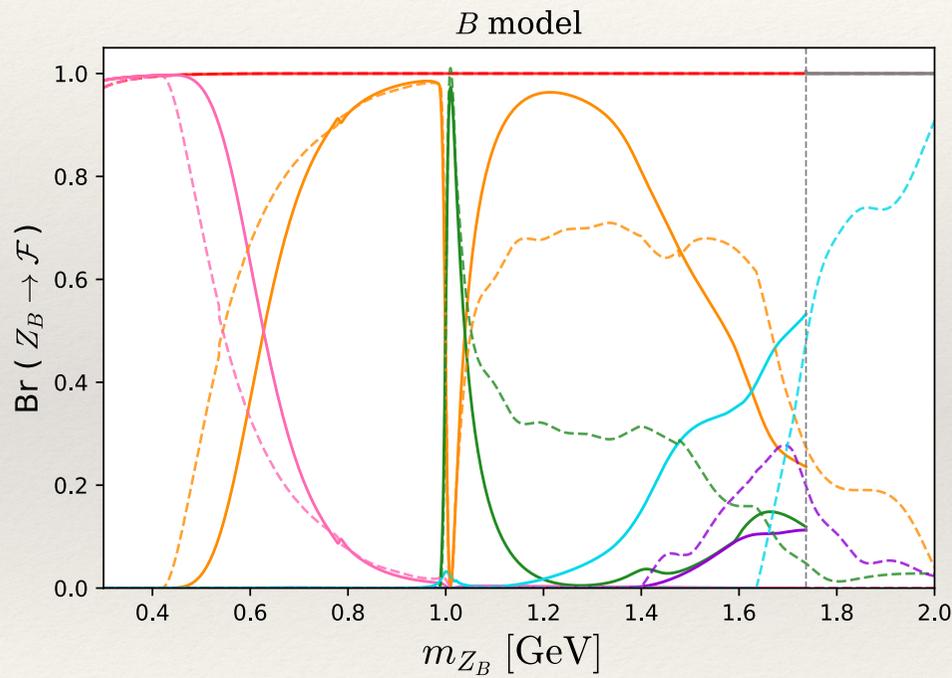
Using FORESEE   **BSM Sec. I.A.1**

arXiv:2105.07077

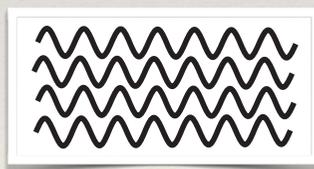# Decay (& Production) of Light Vector Particles

Drell-Yan

Proton bremsstrahlung

$\Rightarrow$ **BSM Sec. II.B.8** (Foroughi-Abari, Ritz)

arXiv:2108.05900

Vector Particle Production

$\Rightarrow$ **Vector particle "beam"**

$\Rightarrow$ **Decay**

Meson decays

for $m_{A'} < m_{\pi,\eta}$

- travelling through material
- Vector particle **lifetime** crucial

Decay (& Production) of Light Vector Particles

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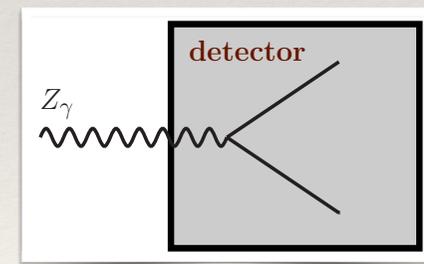
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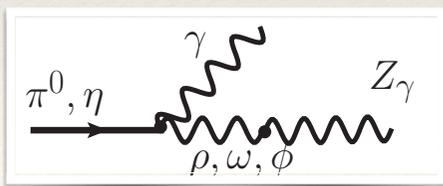
Vector Particle Production

→ **Vector particle "beam"**

- travelling through material
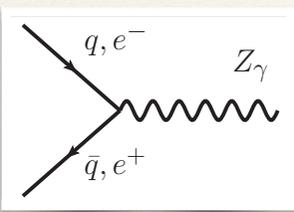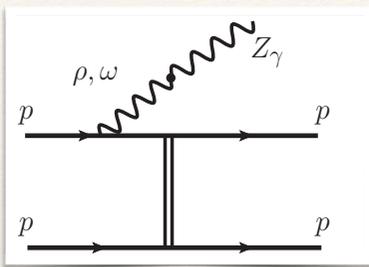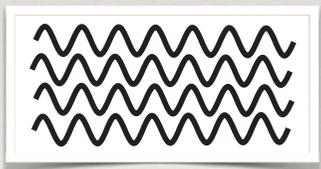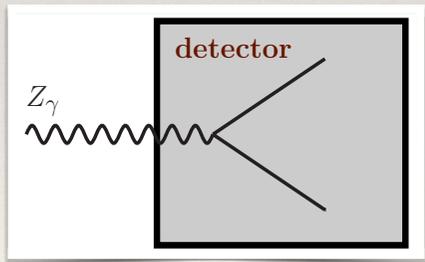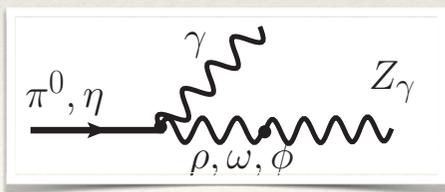- Vector particle **lifetime** crucial

→ **Decay**

Meson decays

for $m_{Z_\gamma} < m_{\pi,\eta}$

→ **More Production Modes?**

Additional Production Modes
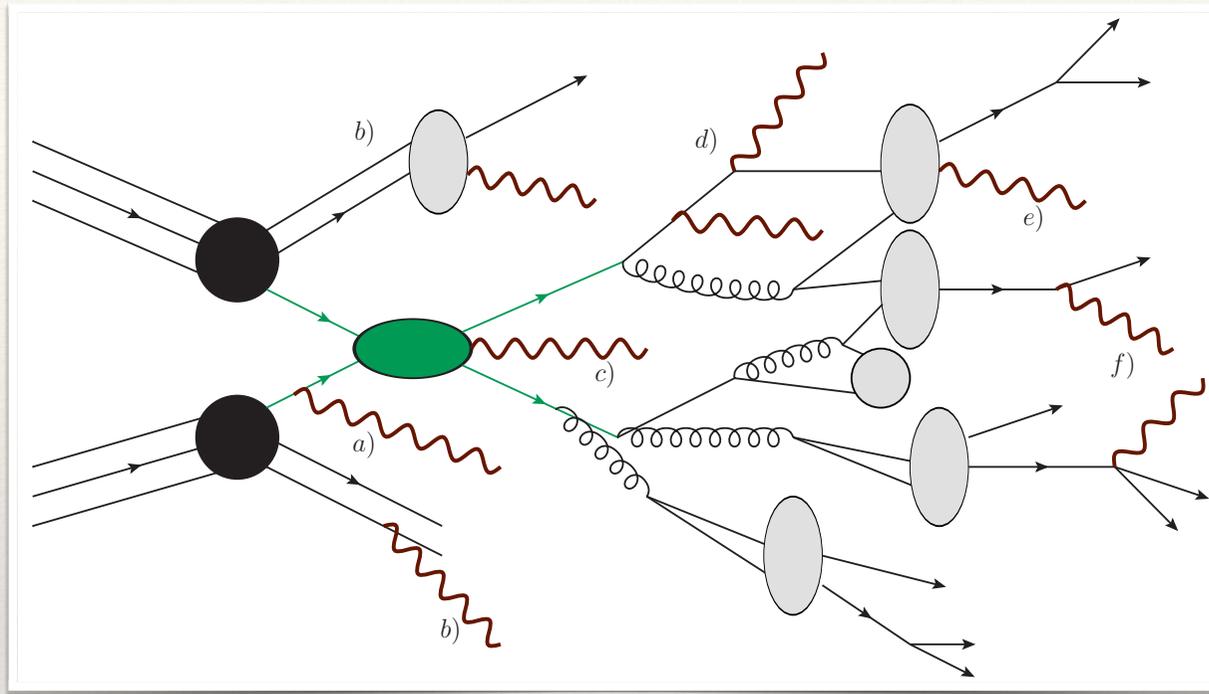
BSM Sec. II.B.9
(M.R.Masouminia, P.R., S.Plätzer)

a)   ISR
b)   Beam remnants
c)   Hard process
d)   FSR
e)   Hadronization
f) Decays of hadrons

Start with ISR, FSR

ISR & FSR in HERWIG

Splitting function:
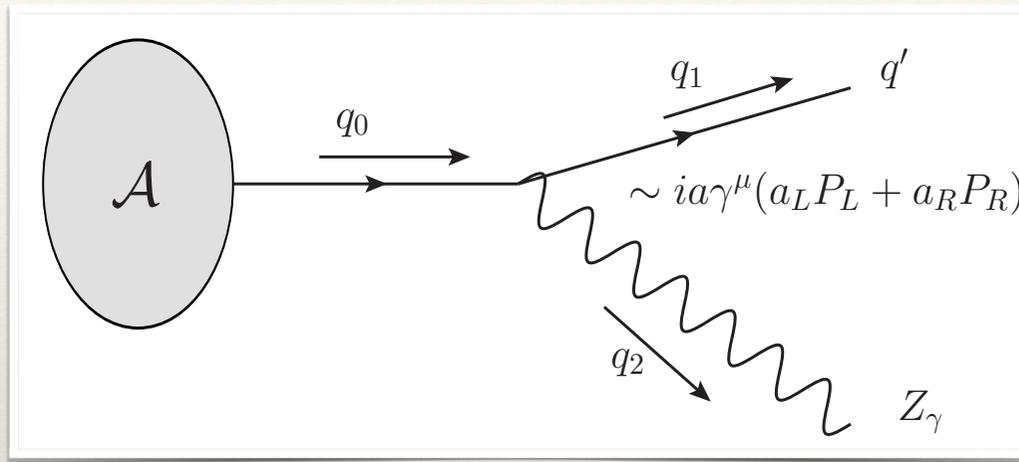
$$P_{q \to q' Z_\gamma}(z, \tilde{q}) = \frac{a^2}{1-z}\left[1 + z^2 - \frac{2m_q^2 + m_{Z_\gamma}}{z\tilde{q}^2}\right]$$

General vector splittings found in

arXiv:2108.10817 M.R. Masouminia, P. Richardson
arXiv:2112.15487 N. Darvishi, M.R. Masouminia

➡ Advantage of Herwig: Vector decays already implemented

Conclusions

<u>Decays of Vector Particles:</u>

- Robust calculation of Hadronic decays of Vector particles
- Especially useful for baryophilic models   **https://github.com/preimitz/DeLiVeR**
- Leading constraints coming from hadronic signatures in FPF experiments
- Available in python package DeLiVeR (Decays of Light Vectors Revised)

<u>Production of Vector Particles:</u>

- several possibilities for additional production modes
- Start with adding ISR&FSR to HERWIG
- Towards complete implementation of Vector Particles in Herwig (Production and Decay)