7. miniworkshop difrakce a ultraperiferních srážek

Děčín, September 19, 2020

Dark photons from light and white colour

Guillermo Contreras, Jan Čepila

Czech Technical University in Prague

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Paper in preparation with Honza

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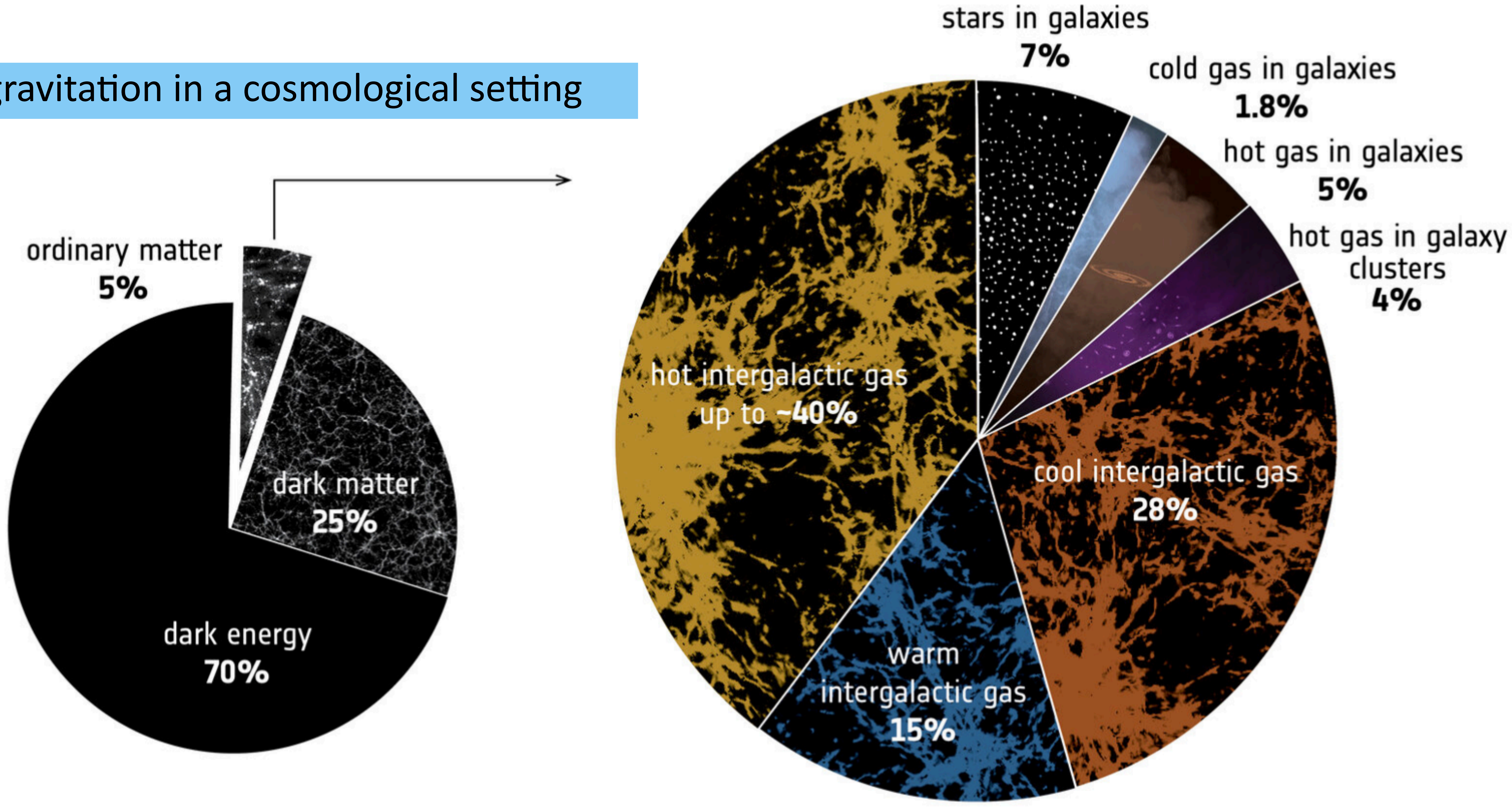
Composition of the universe

From gravitation in a cosmological setting



https://www.esa.int/ESA_Multimedia/Images/2018/06/The_cosmic_budget_of_ordinary_matter

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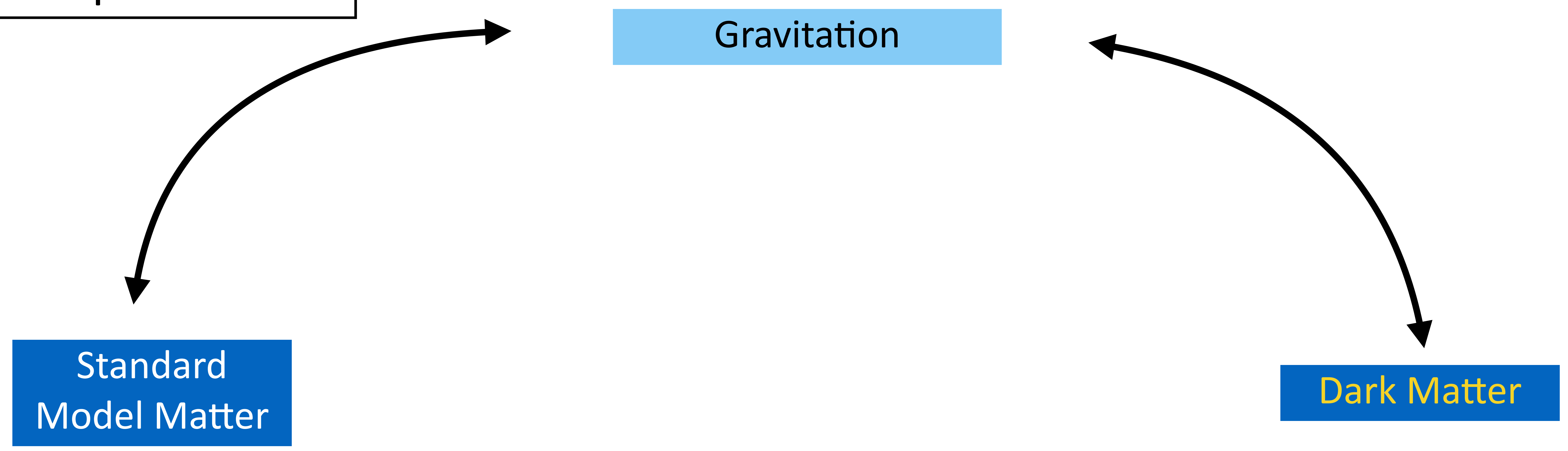
Dark matter and portals



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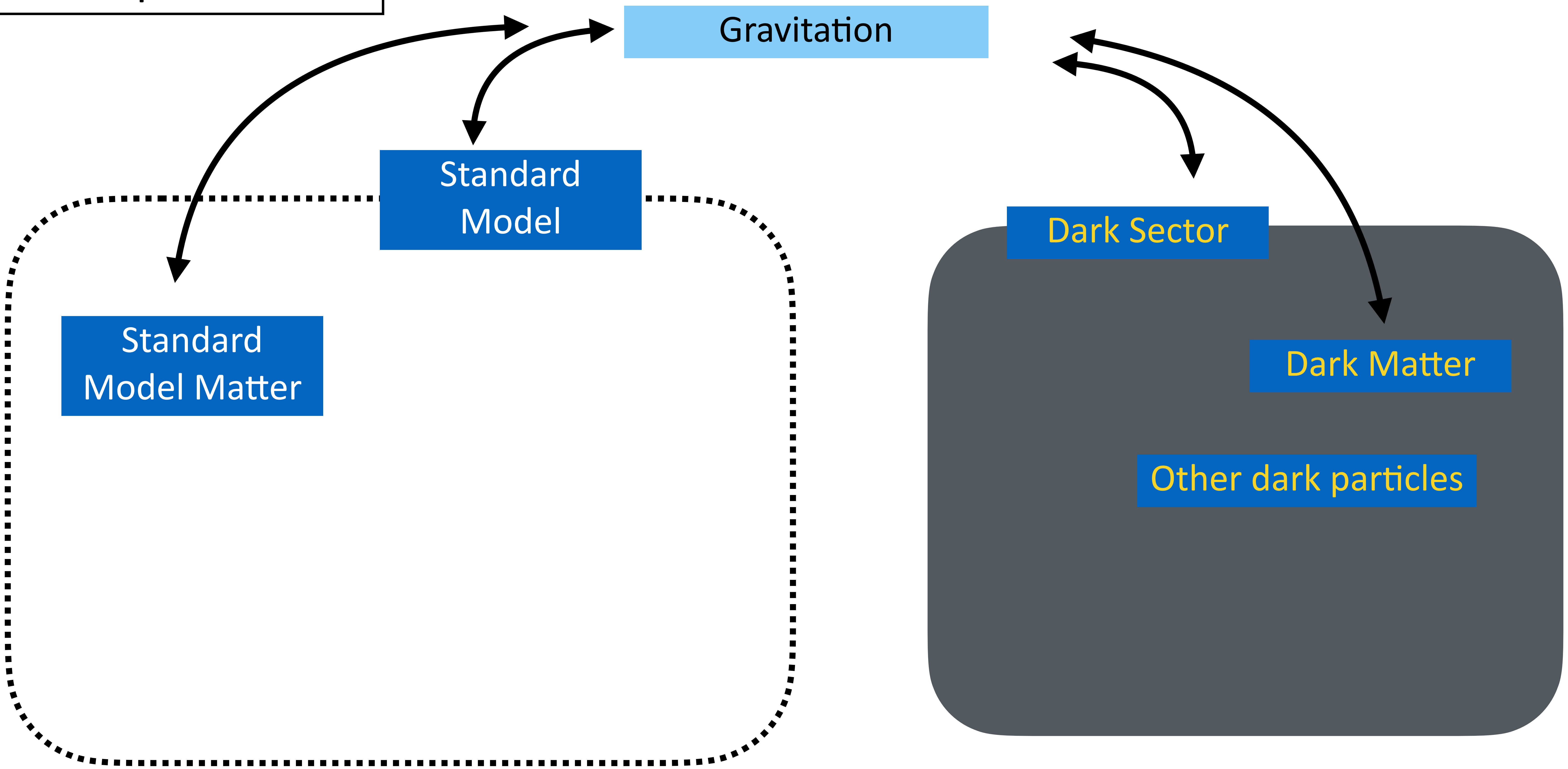

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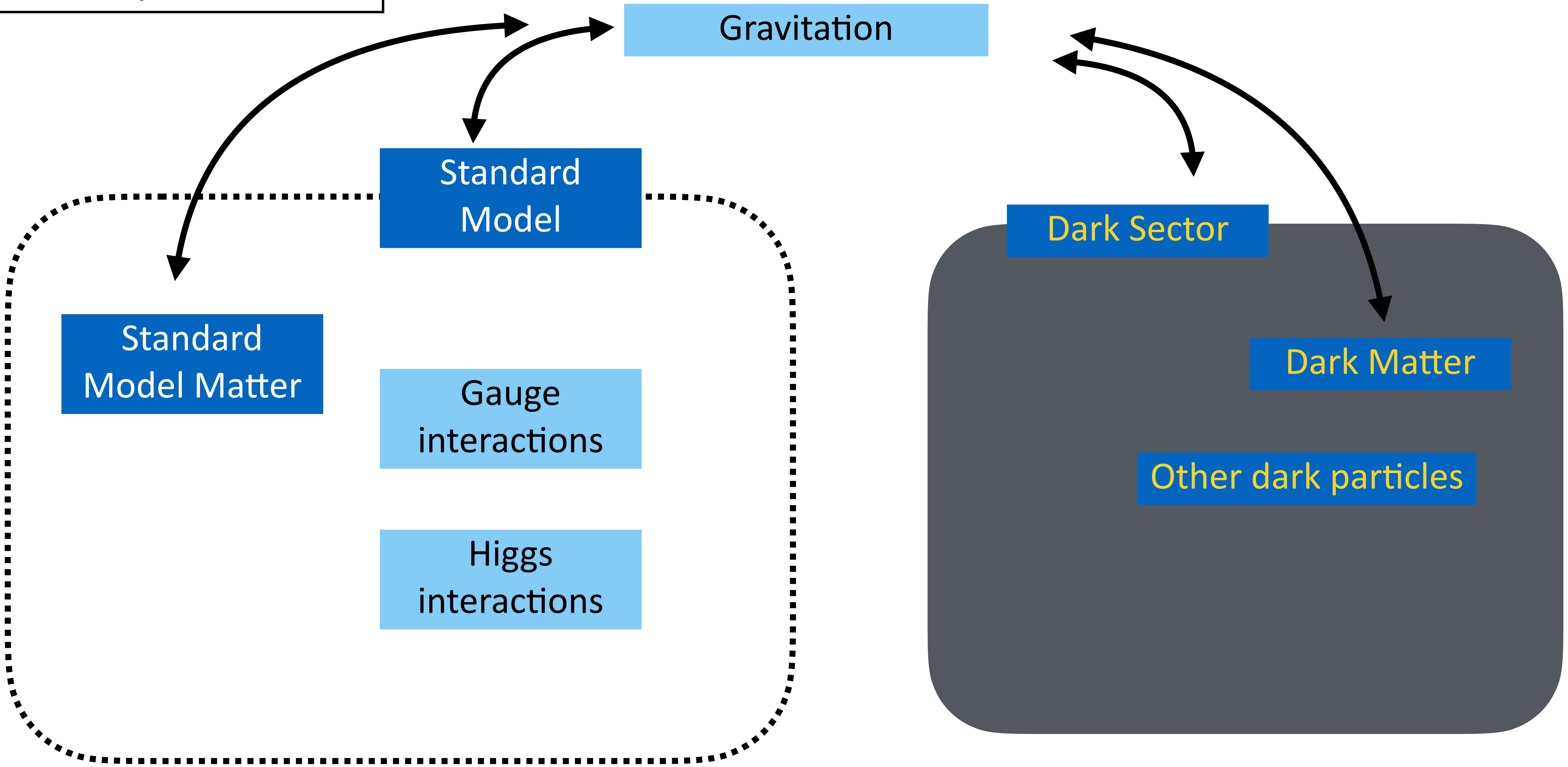

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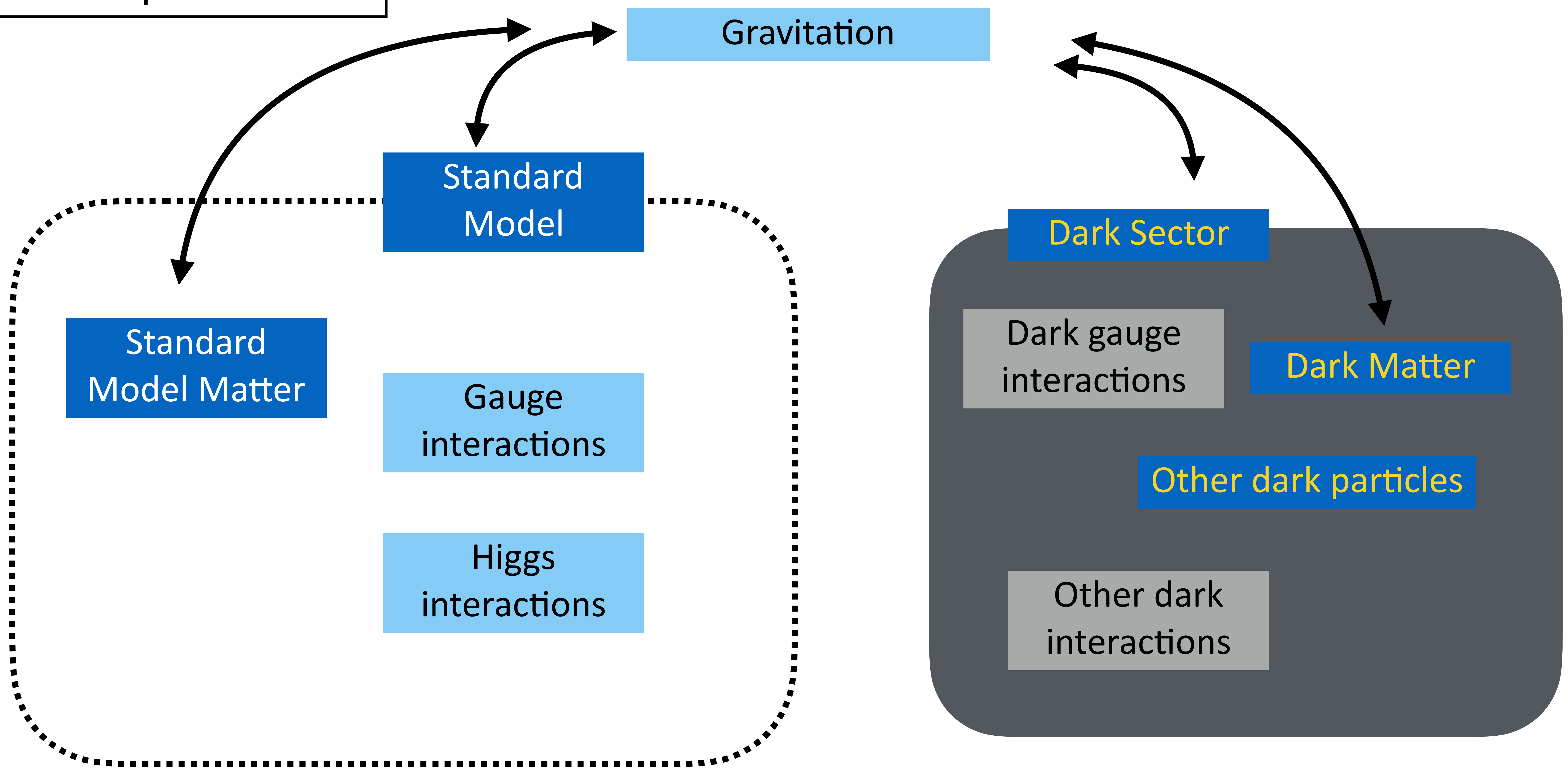

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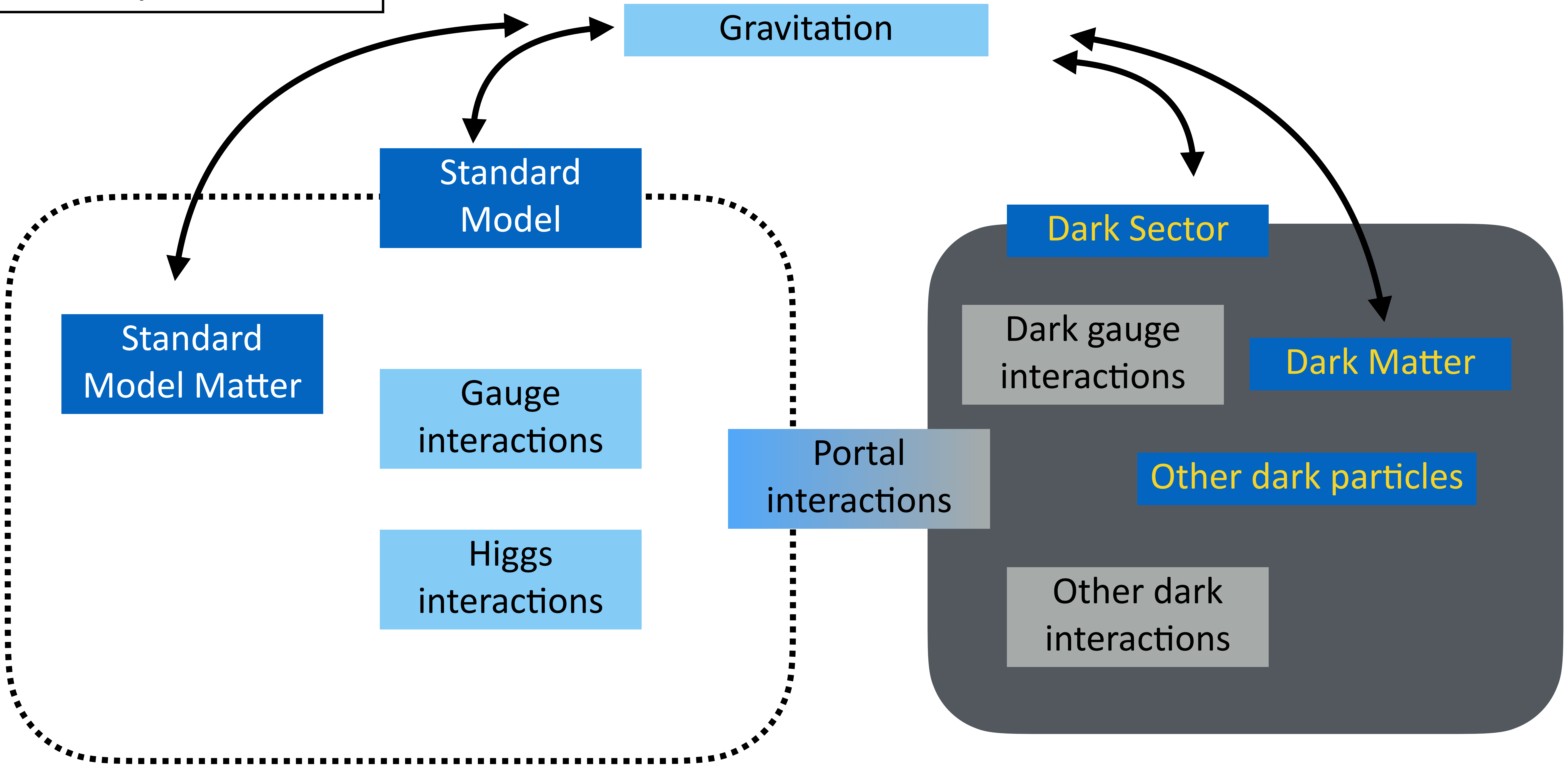

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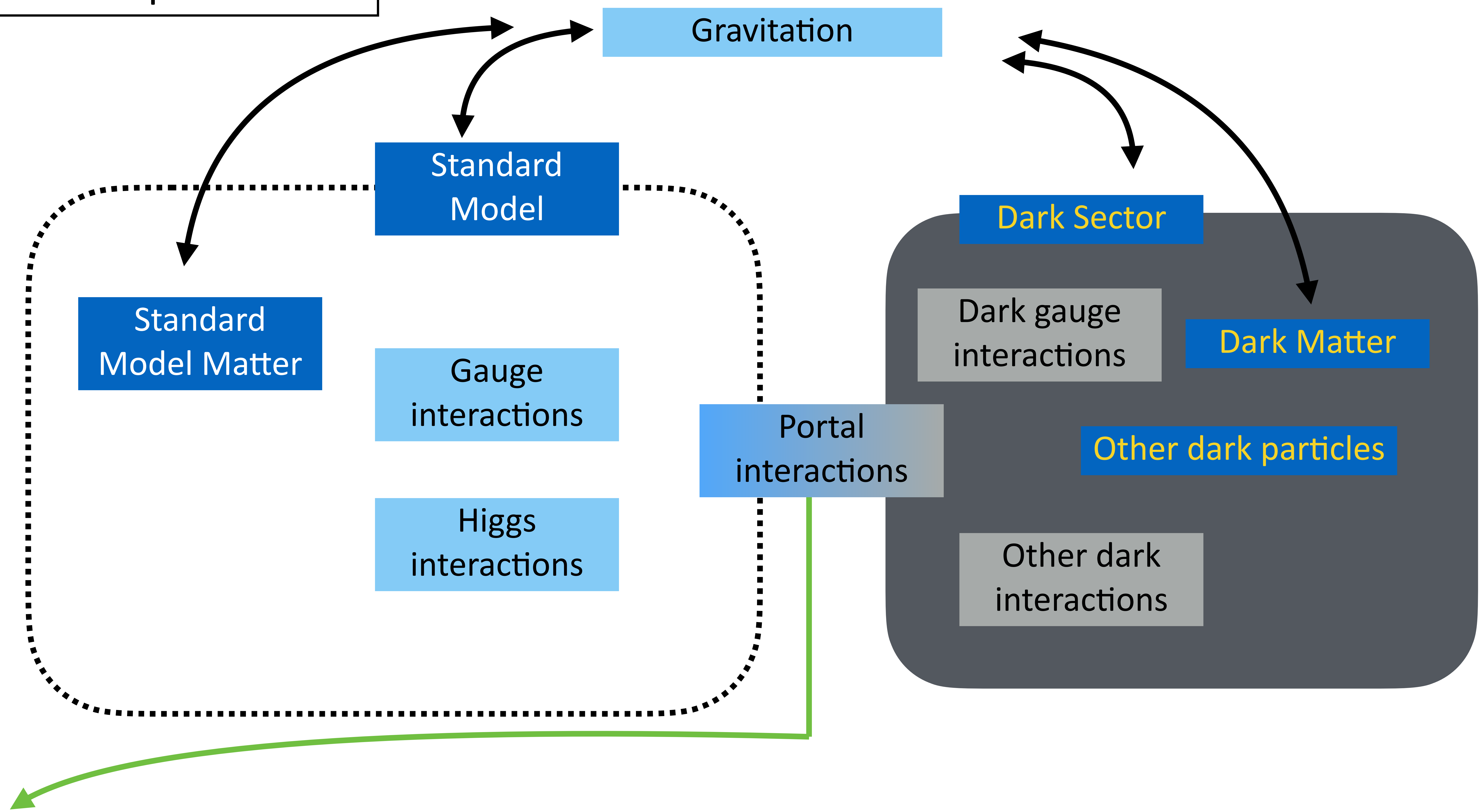
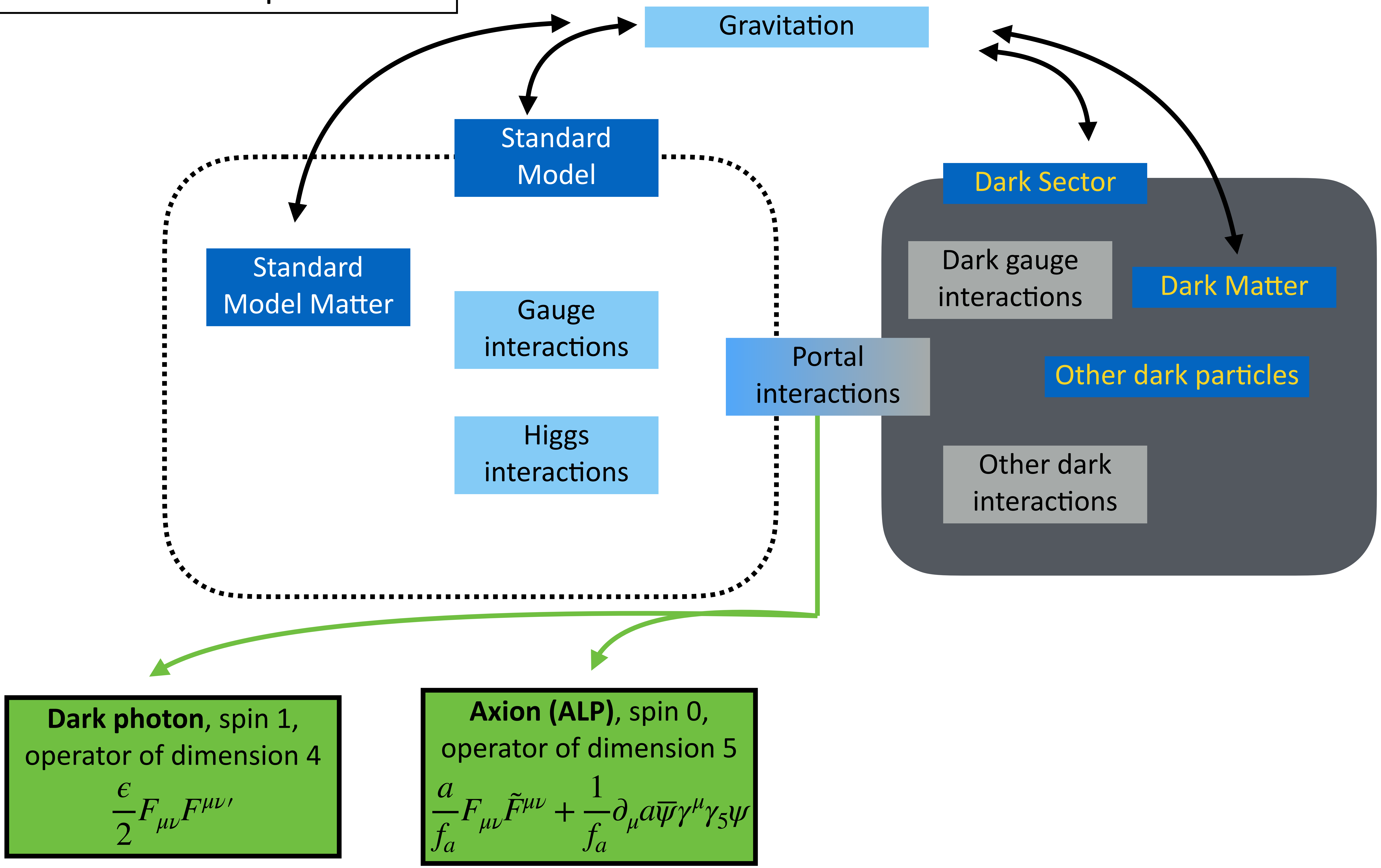
Dark matter and portals



Dark photon, spin 1, operator of dimension 4

$$\frac{\epsilon}{2} F_{\mu\nu} F^{\mu\nu\prime}$$

Dark matter and portals



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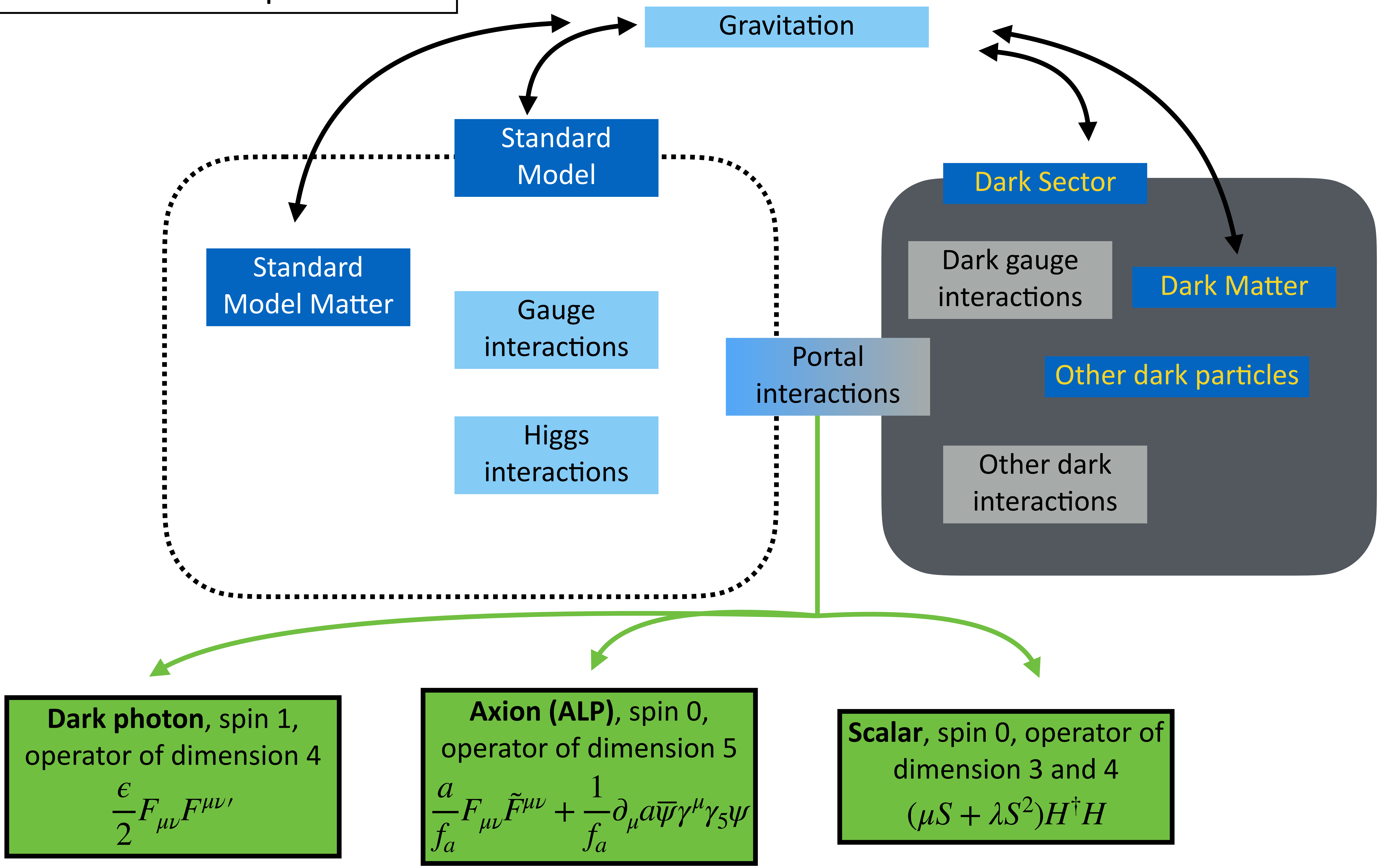

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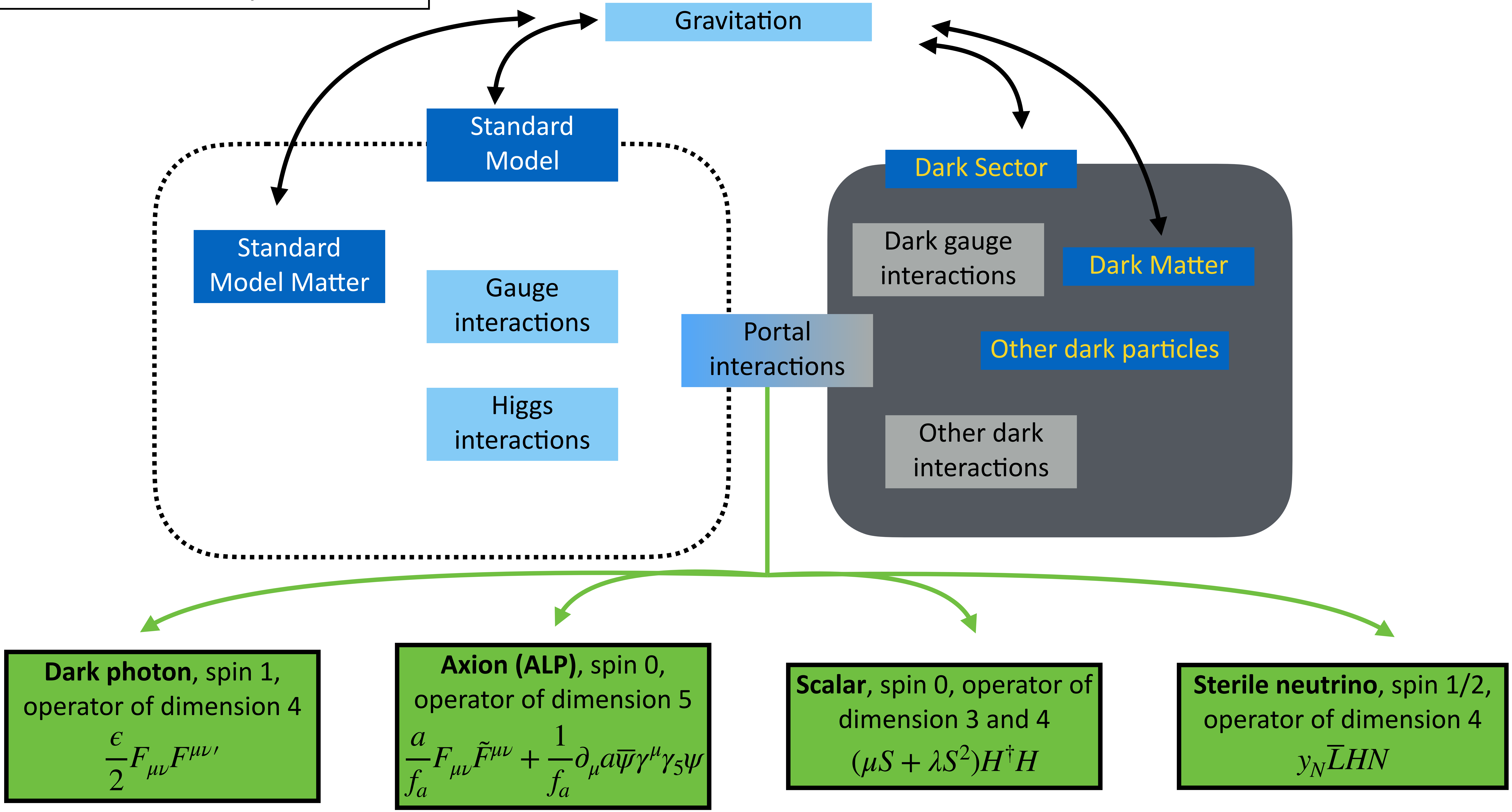
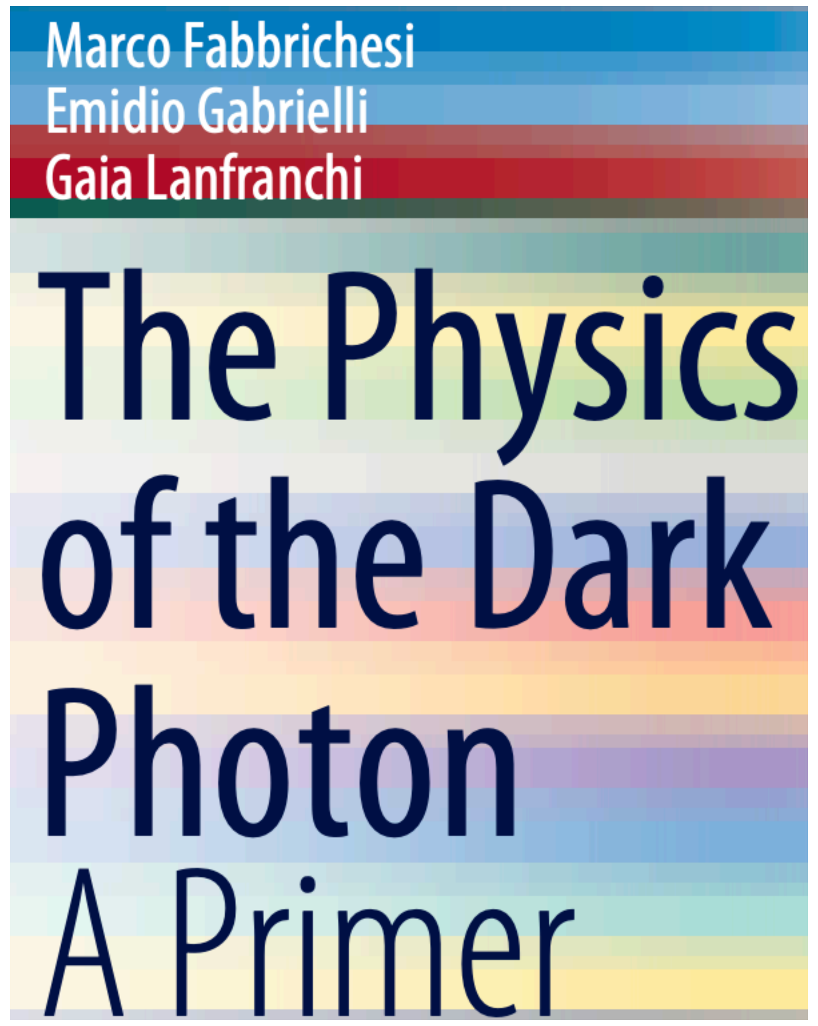


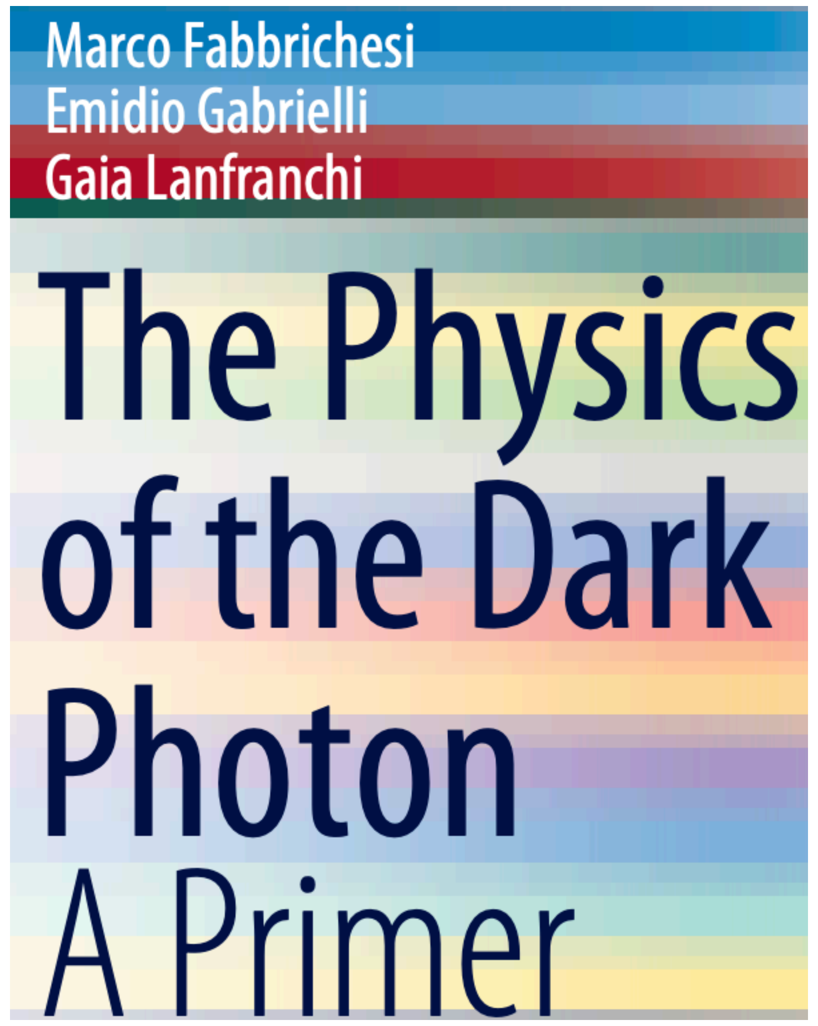
Dark photon



https://inspirehep.net/literature/1794152

Dark photon

Consider a new U(1) interaction



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Dark photon

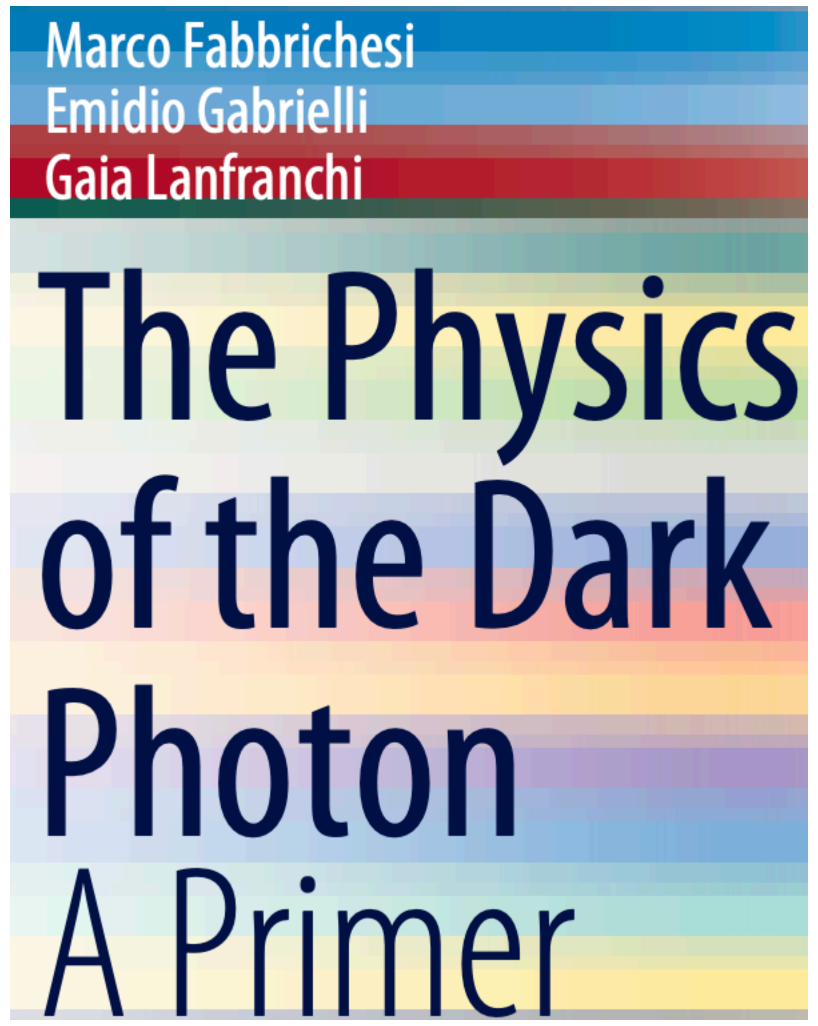
Consider a new U(1) interaction

$$\mathcal{L}_0 = -\frac{1}{4} F_{a\mu\nu} F_a^{\mu\nu} - \frac{1}{4} F_{b\mu\nu} F_b^{\mu\nu} - \frac{\varepsilon}{2} F_{a\mu\nu} F_b^{\mu\nu}$$

Free part of the (classical) Lagrangian

Interaction part of the Lagrangian

$$\mathcal{L} = e\, J_\mu A_b^\mu + e' J'_\mu A_a^\mu \,,$$



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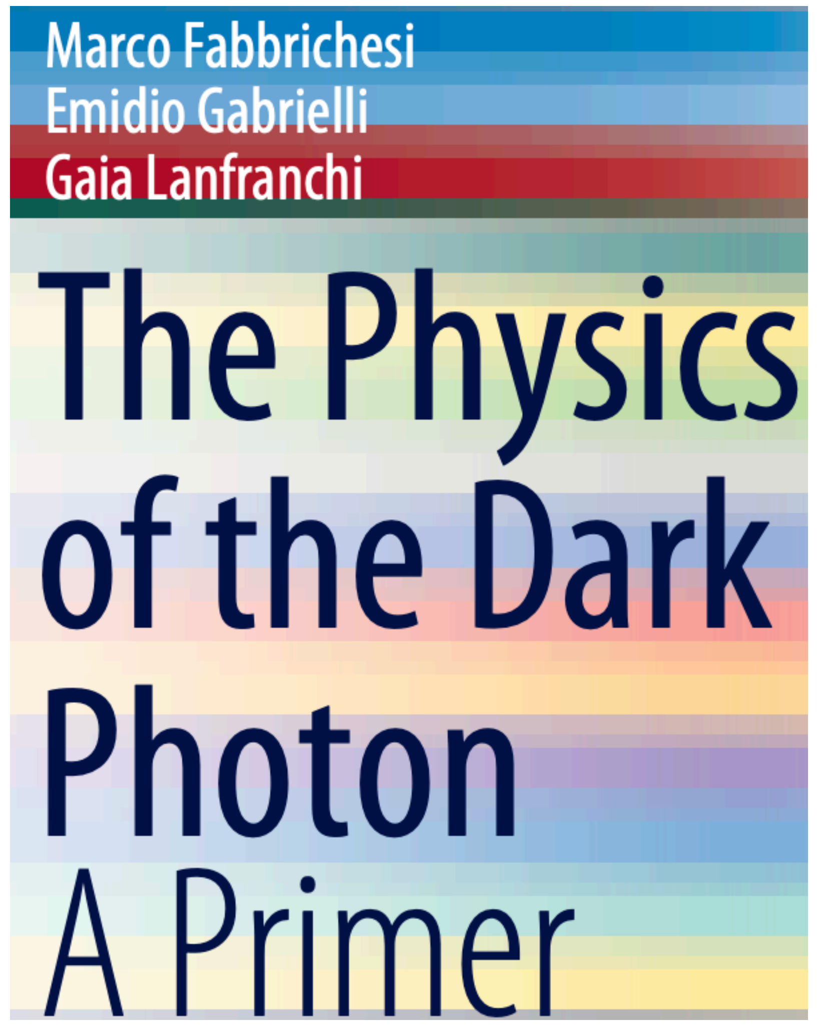
Diagonalise:

$$\begin{pmatrix} A_a^\mu \\ A_b^\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\frac{\varepsilon}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A'^\mu \\ A^\mu \end{pmatrix},$$

Dark photon

SM photon



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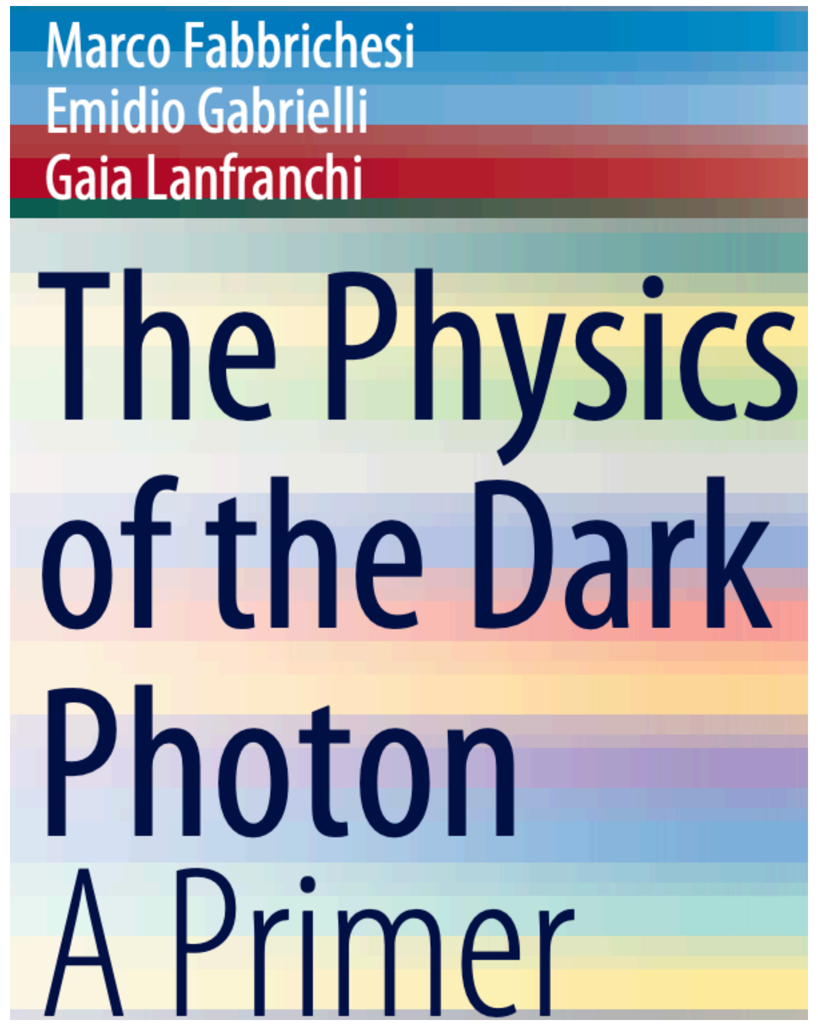
Dark photon

SM photon

$$\mathcal{L}' = \left[\frac{e' \cos\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e \left(\sin\theta - \frac{\varepsilon \cos\theta}{\sqrt{1-\varepsilon^2}} \right) J_\mu \right] A'^\mu + \left[-\frac{e' \sin\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e \left(\cos\theta + \frac{\varepsilon \sin\theta}{\sqrt{1-\varepsilon^2}} \right) J_\mu \right] A^\mu$$

Dark photon can be massless or massive

If massive, the angle θ is fixed.
Mass can be obtained by the Higgs or the Stueckelberg mechanisms



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Massive dark photon

Massive dark photon

$$\sin\theta = \frac{\delta\sqrt{1-\varepsilon^2}}{\sqrt{1-2\delta\varepsilon+\delta^2}} \quad \cos\theta = \frac{1-\delta\varepsilon}{\sqrt{1-2\delta\varepsilon+\delta^2}}$$

$$\delta = M_b/M_a$$

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$$\delta = M_b/M_a$$

$$\mathcal{L}'' = \frac{1}{\sqrt{1-2\delta\varepsilon+\delta^2}}\left[\frac{e'\,(1-\delta\varepsilon)}{\sqrt{1-\varepsilon^2}}J'_\mu + \frac{e\,(\delta-\varepsilon)}{\sqrt{1-\varepsilon^2}}J_\mu\right]A'^\mu + \frac{1}{\sqrt{1-2\delta\varepsilon+\delta^2}}\left[e J_\mu - \delta e' J'_\mu\right]A^\mu\,.$$

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Massive dark photon

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$$\mathcal{L}'' = \frac{1}{\sqrt{1-2\delta\varepsilon+\delta^2}}\left[\frac{e'(1-\delta\varepsilon)}{\sqrt{1-\varepsilon^2}}J'_\mu + \frac{e(\delta-\varepsilon)}{\sqrt{1-\varepsilon^2}}J_\mu\right]A'^\mu + \frac{1}{\sqrt{1-2\delta\varepsilon+\delta^2}}\left[eJ_\mu - \delta e' J'_\mu\right]A^\mu .$$

$M_b = 0$

$$\mathcal{L} \supset -\frac{e\varepsilon}{\sqrt{1-\varepsilon^2}}J_\mu A'^\mu \simeq -e\,\varepsilon\,J_\mu A'^\mu ,$$

SM photon couples to SM matter,
dark photon couples to both, dark and SM matter

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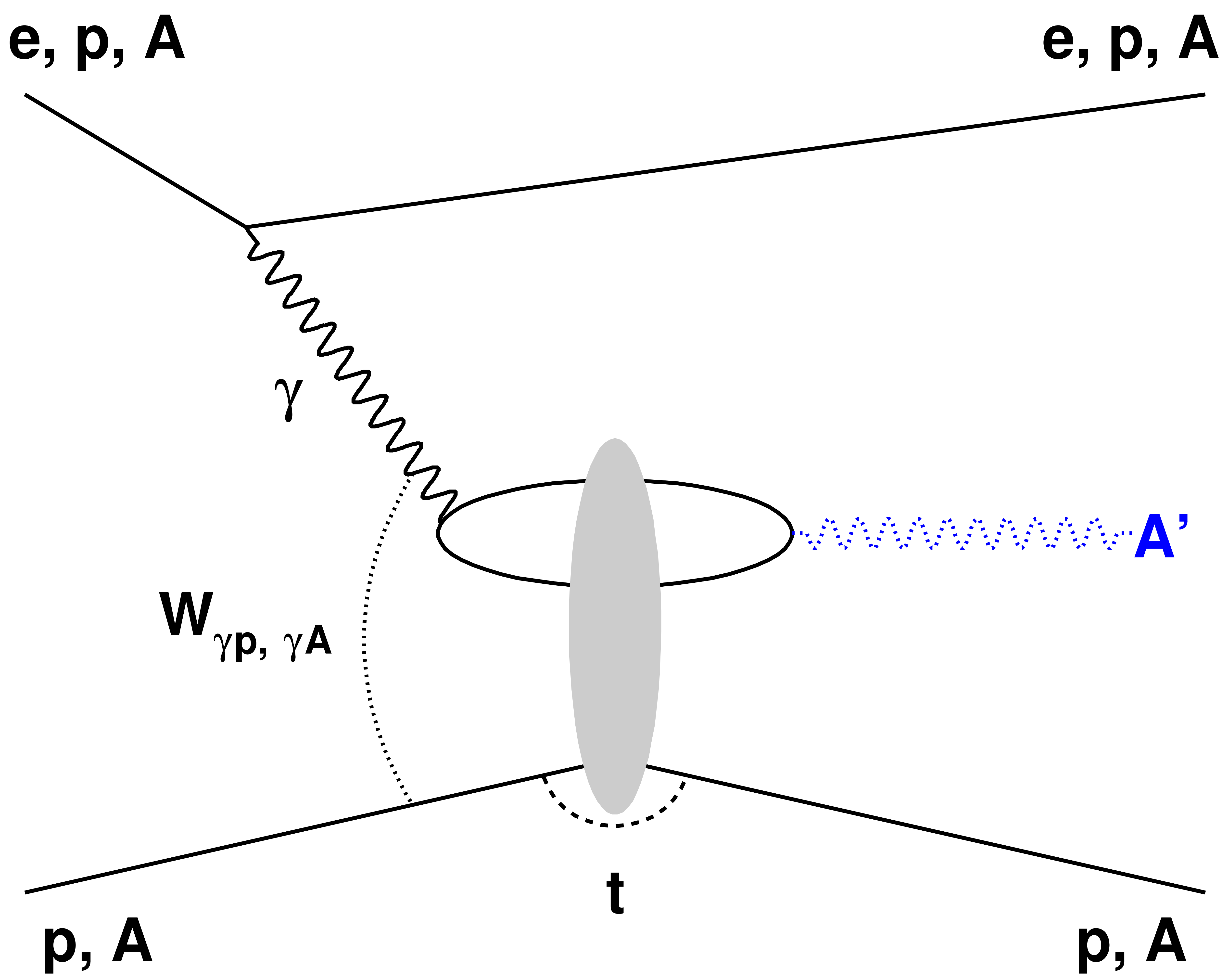
Massive dark photon: bottom line

In this case the interaction of the dark photon with electrically charged SM particles is the **same** as for the normal photon, but scaled by a factor of ε

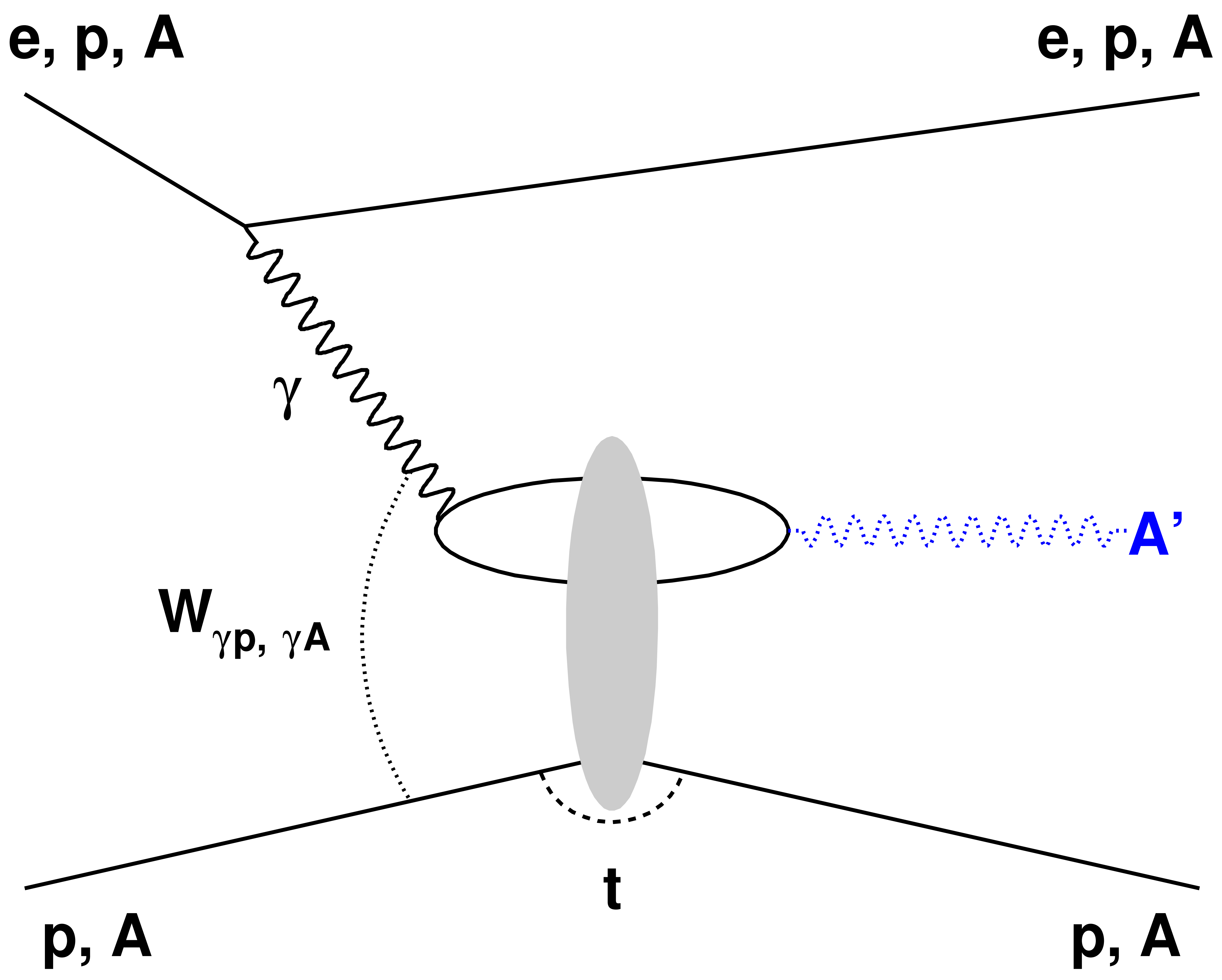
$$\mathcal{L} \supset -\frac{e\varepsilon}{\sqrt{1-\varepsilon^2}} J_\mu A'^\mu \simeq -e\,\varepsilon\, J_\mu A'^\mu \,,$$

In the simplest model there are thus **two** parameters:
the dark photon mass and ε
(In addition, one needs to consider the branching rations ...)

Diffractive dark photon production

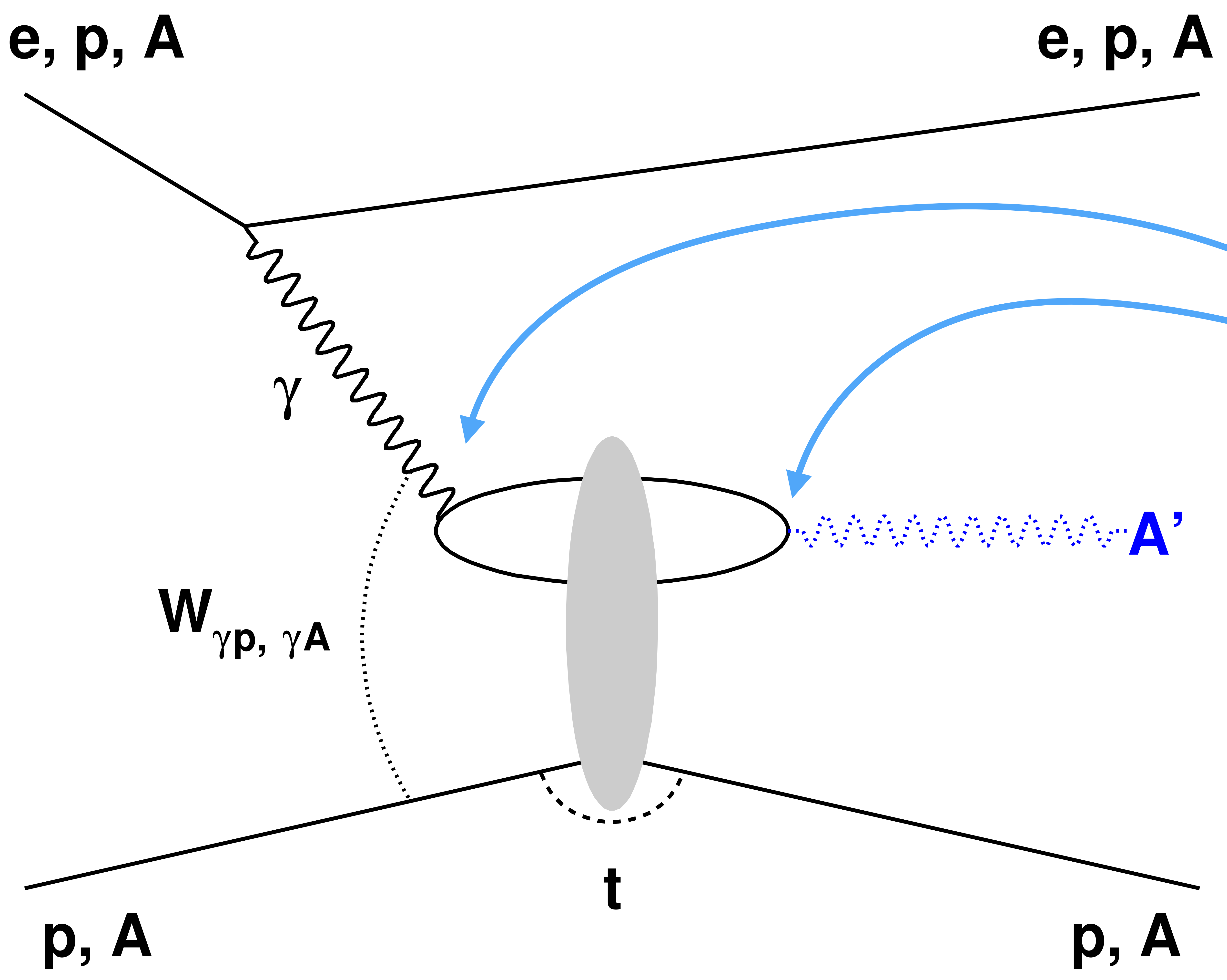


Diffractive dark photon production



$$\mathcal{A}(t,Q^2,W)_{T,L} = i\int \mathrm{d}\vec{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\vec{b} \times \left(\Psi^{\dagger}_{A'}\Psi\right)_{T,L} e^{-i[\vec{b}-(\frac{1}{2}-z)\vec{r}]\vec{\Delta}} \times 2N(\vec{r},\vec{b},x), \qquad (2)$$

Diffractive dark photon production



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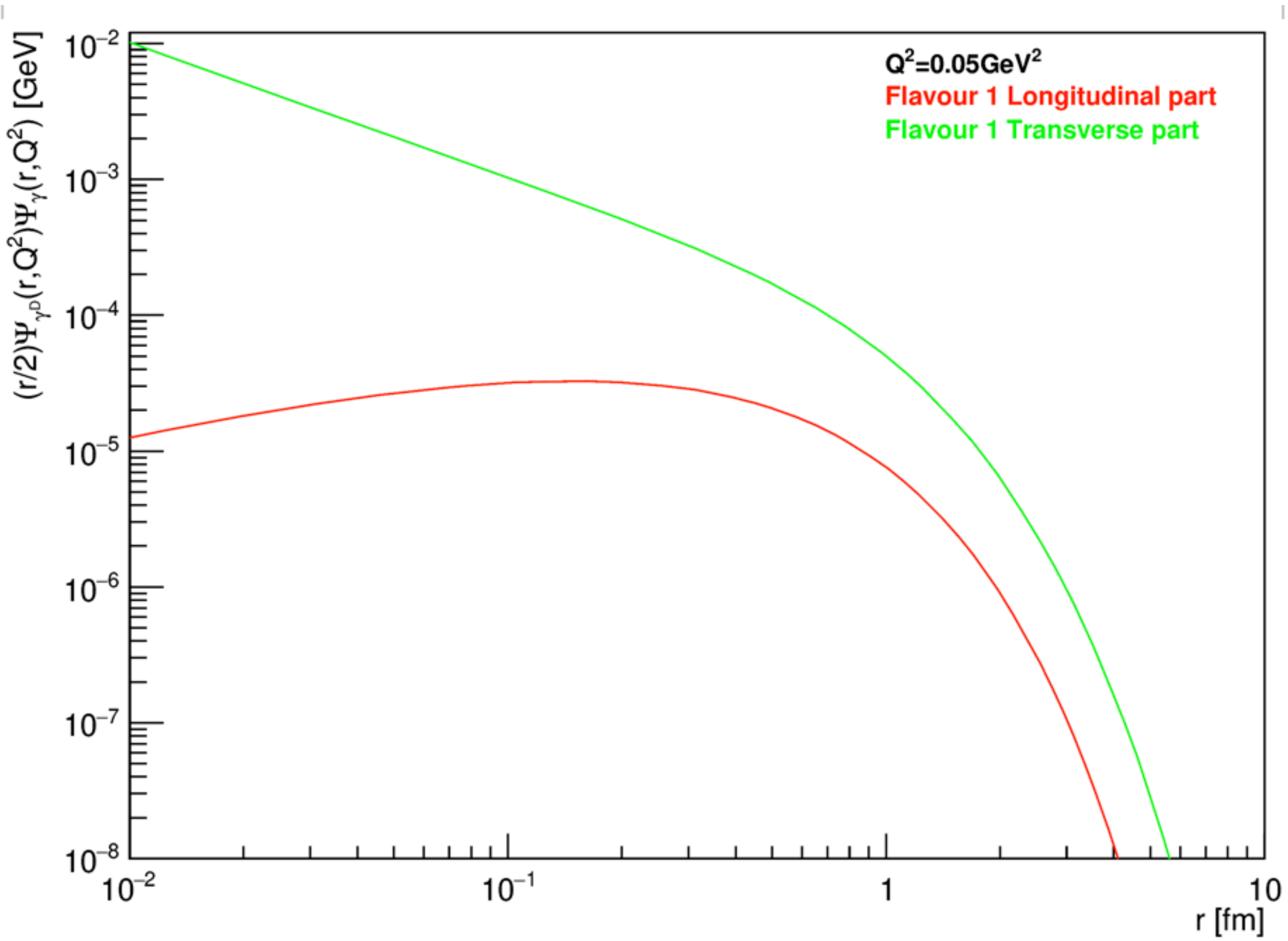
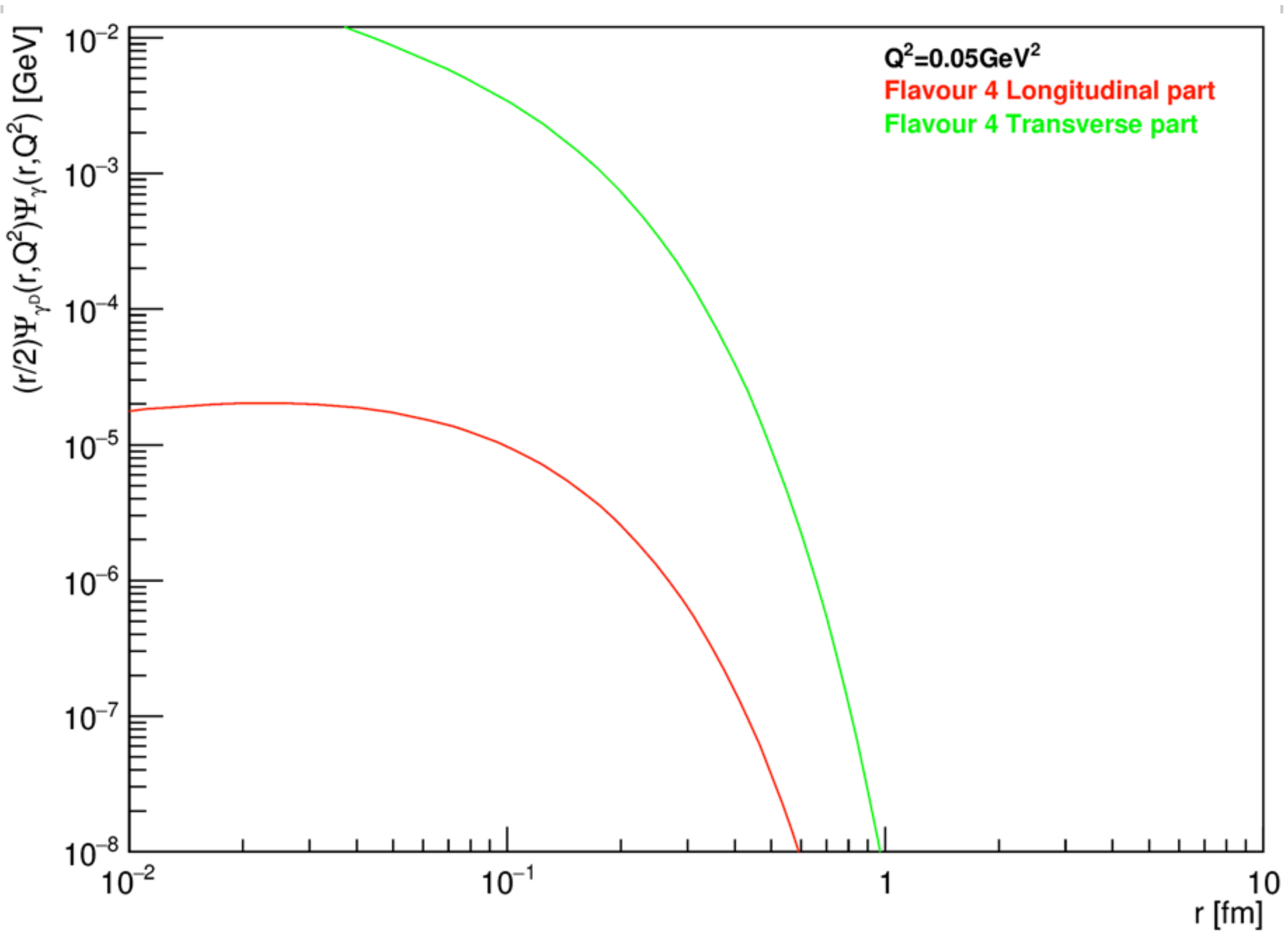
$$\left(\Psi^\dagger_{A'}\Psi\right)^f_L = \frac{8N_\mathrm{C}}{\pi}\epsilon\alpha_\mathrm{em}e_f^2 Q m_{A'} z^2(1-z)^2 \times K_0\left(r\epsilon_\gamma\right)K_0\left(r\epsilon_{A'}\right), \quad (3)$$

$$\left(\Psi^\dagger_{A'}\Psi\right)^f_T = \frac{2N_\mathrm{C}}{\pi}\epsilon\alpha_\mathrm{em}e_f^2 \{ \left[(z^2+(1-z)^2)\right] \times\epsilon_\gamma K_1\left(r\epsilon_\gamma\right)\epsilon_{A'}K_1\left(r\epsilon_{A'}\right) + m_f^2 K_0\left(r\epsilon_\gamma\right)K_0\left(r\epsilon_{A'}\right)\}, \quad (4)$$

Wave function convolution

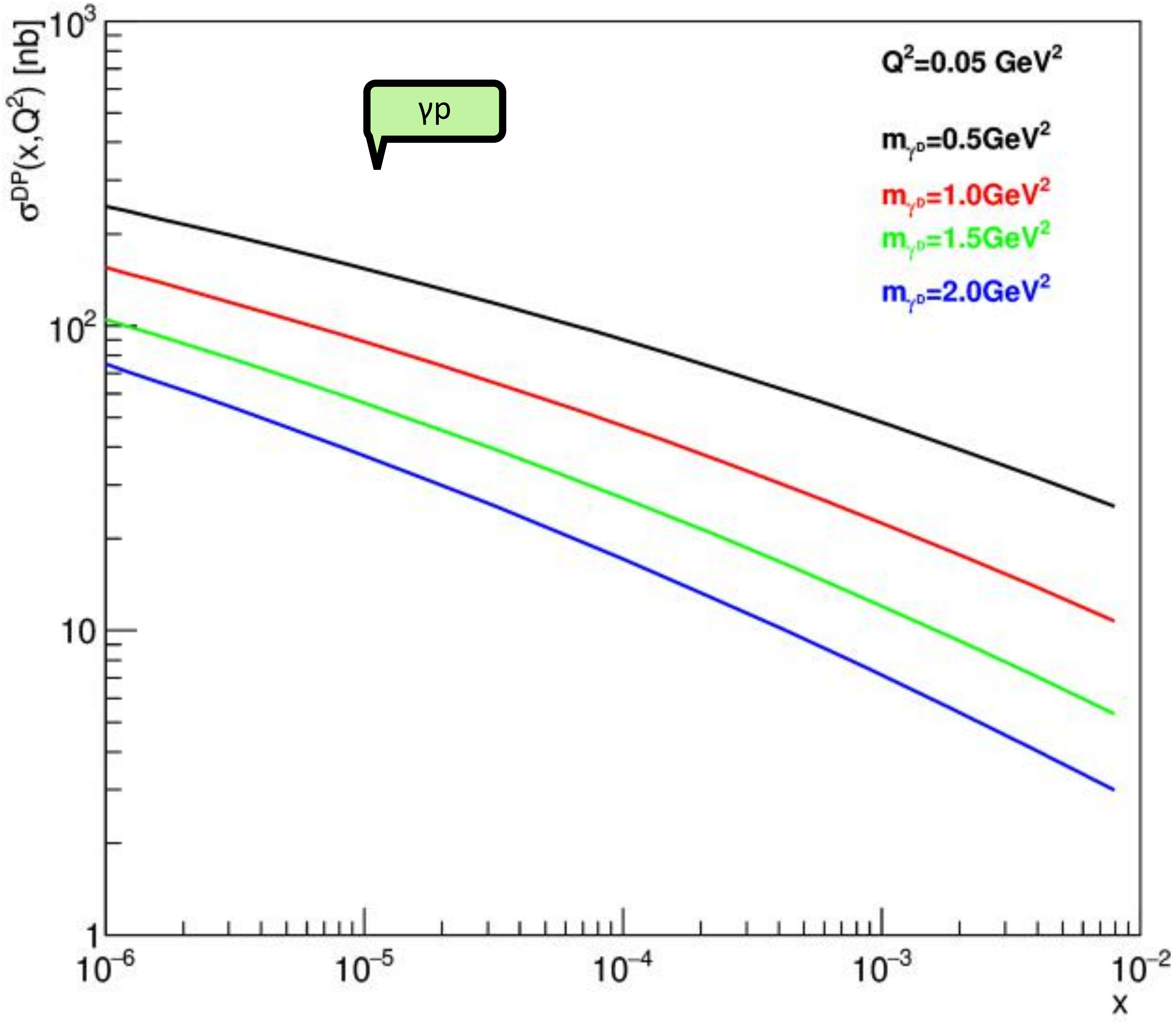
Plots by Honza

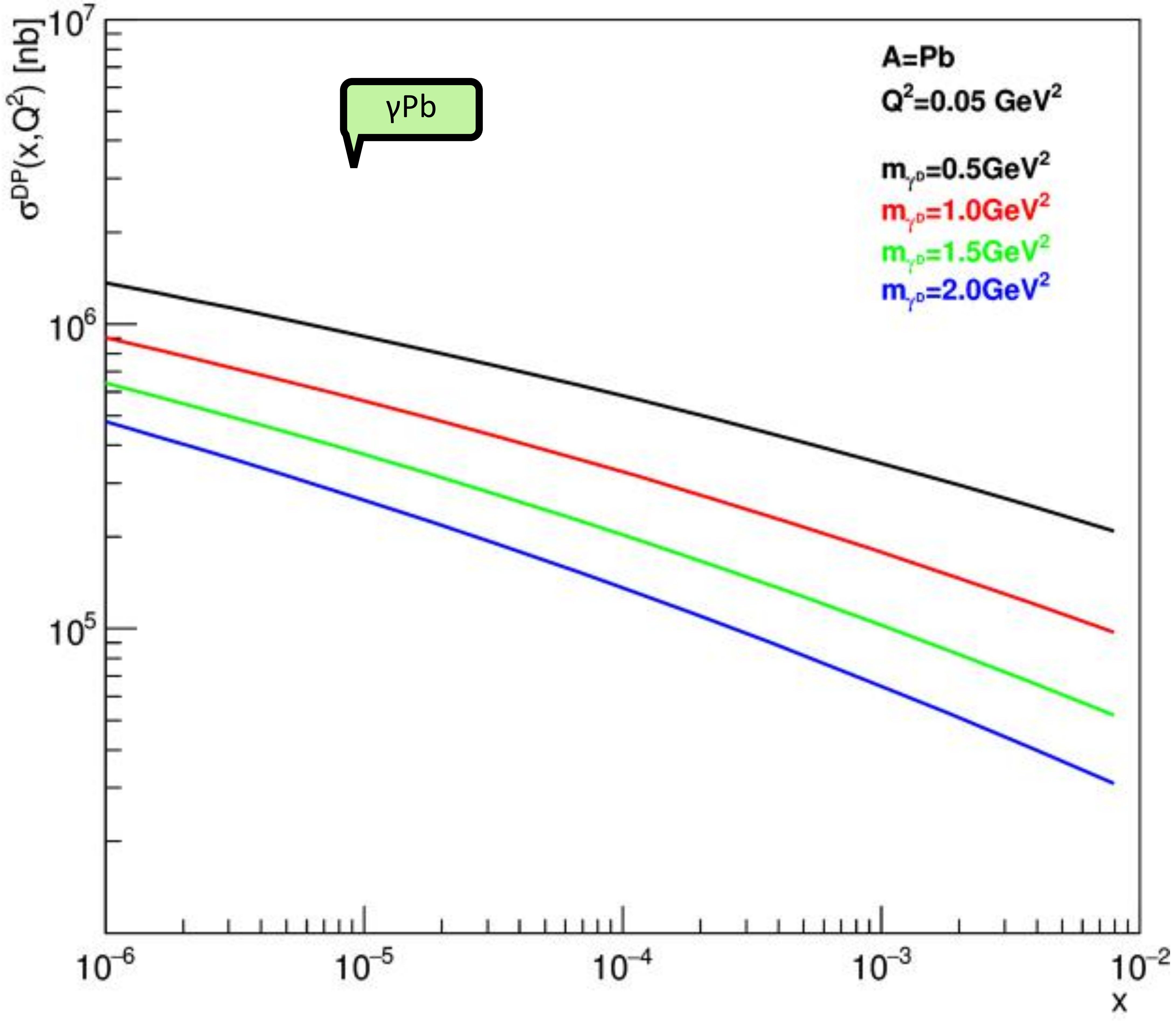




Photoproduction cross section (ε=1)

Plots by Honza





Large cross sections, but also for VM production and γγ interactions ....

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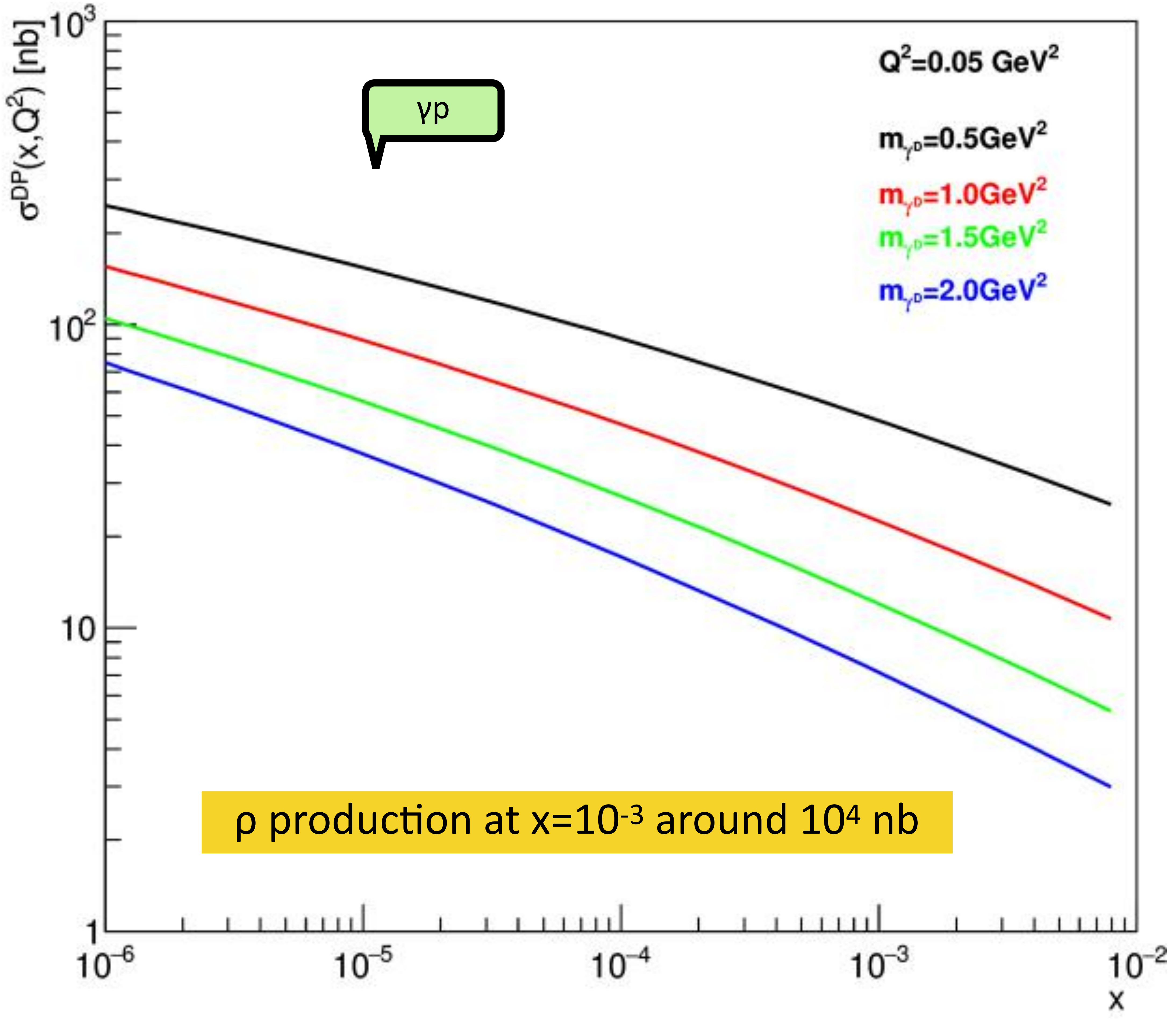

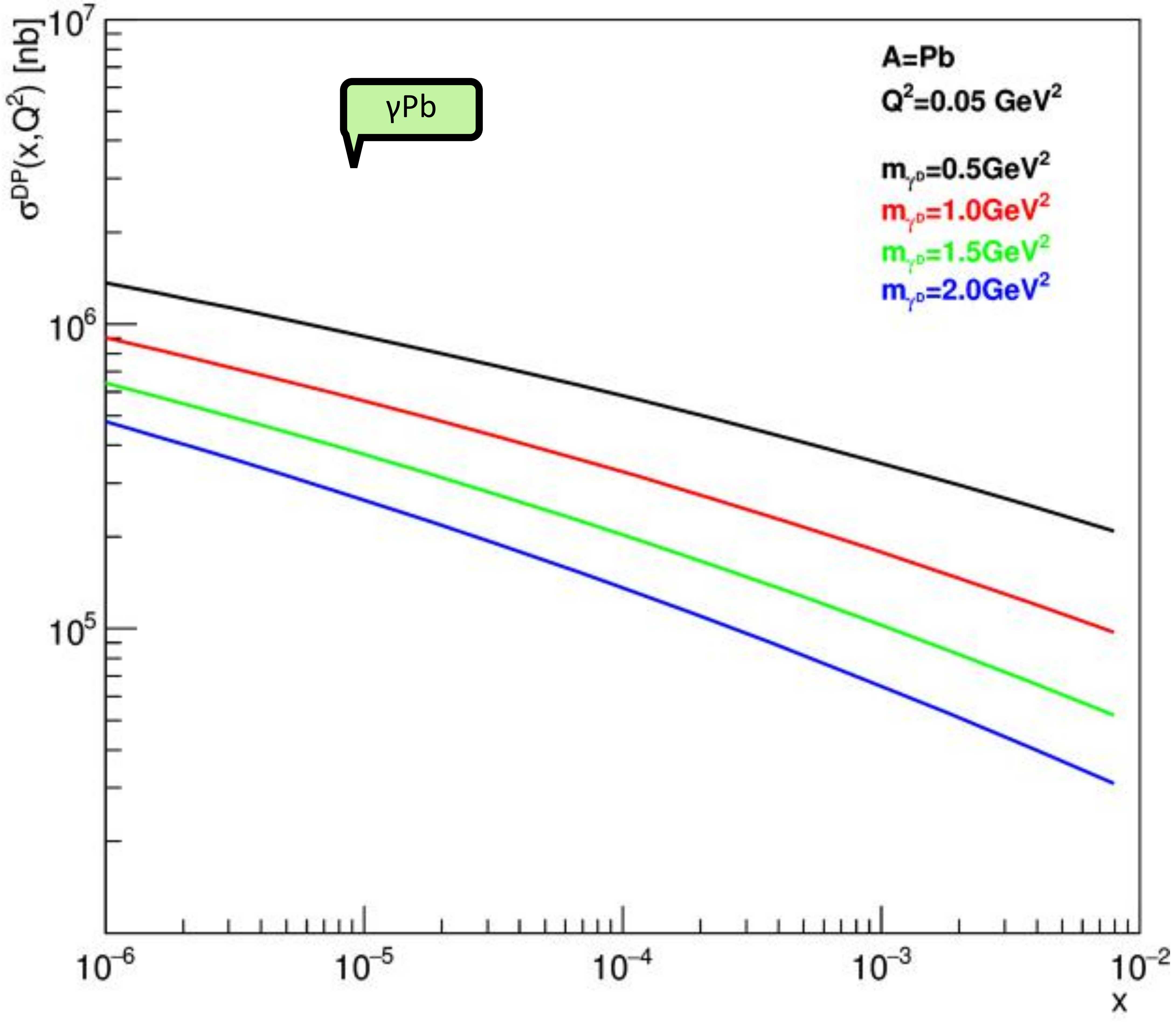

ρ production at $x=10^{-3}$ around 10^4 nb

Large cross sections, but also for VM production and γγ interactions ....

Photoproduction cross section (ε=1)

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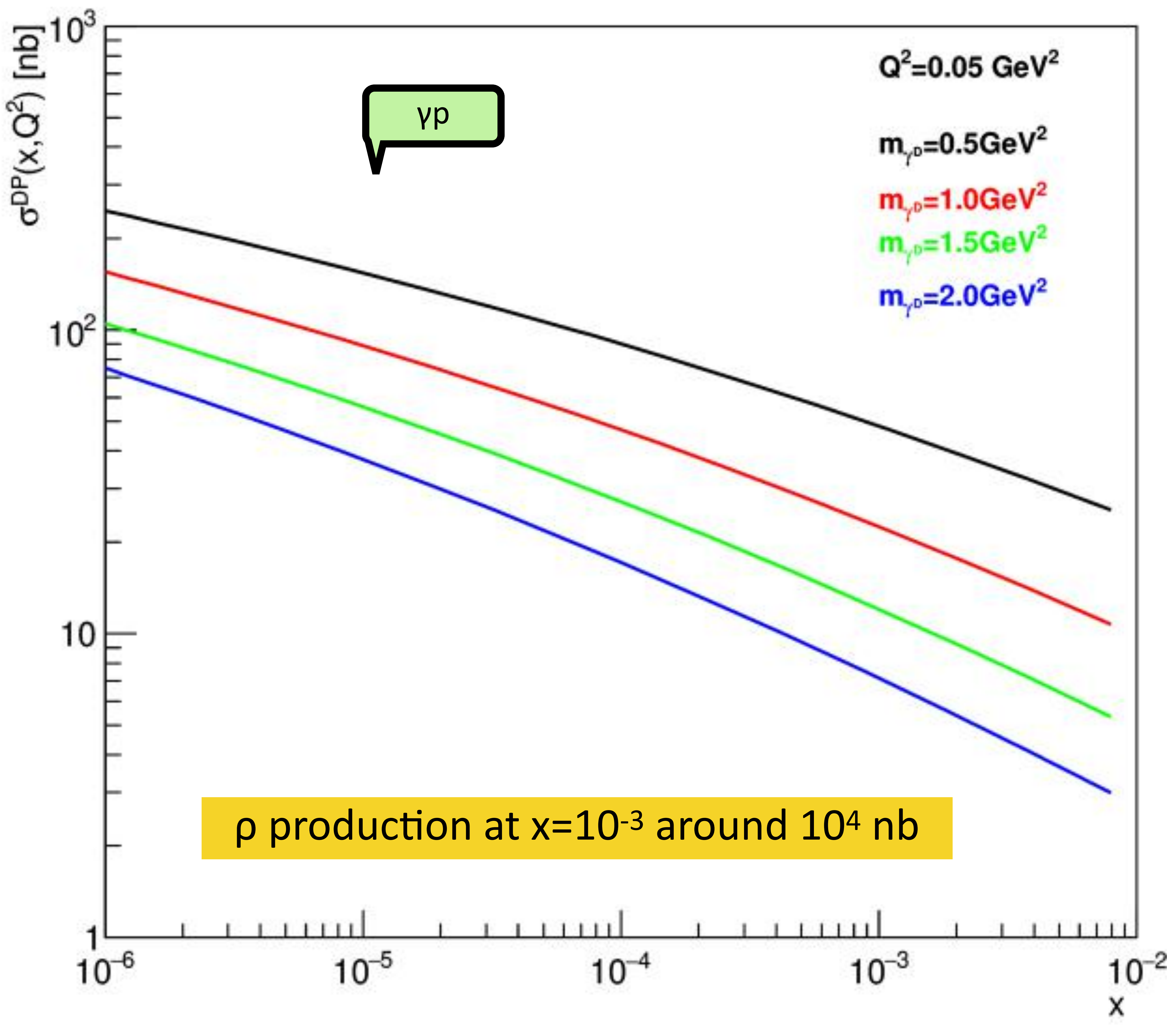
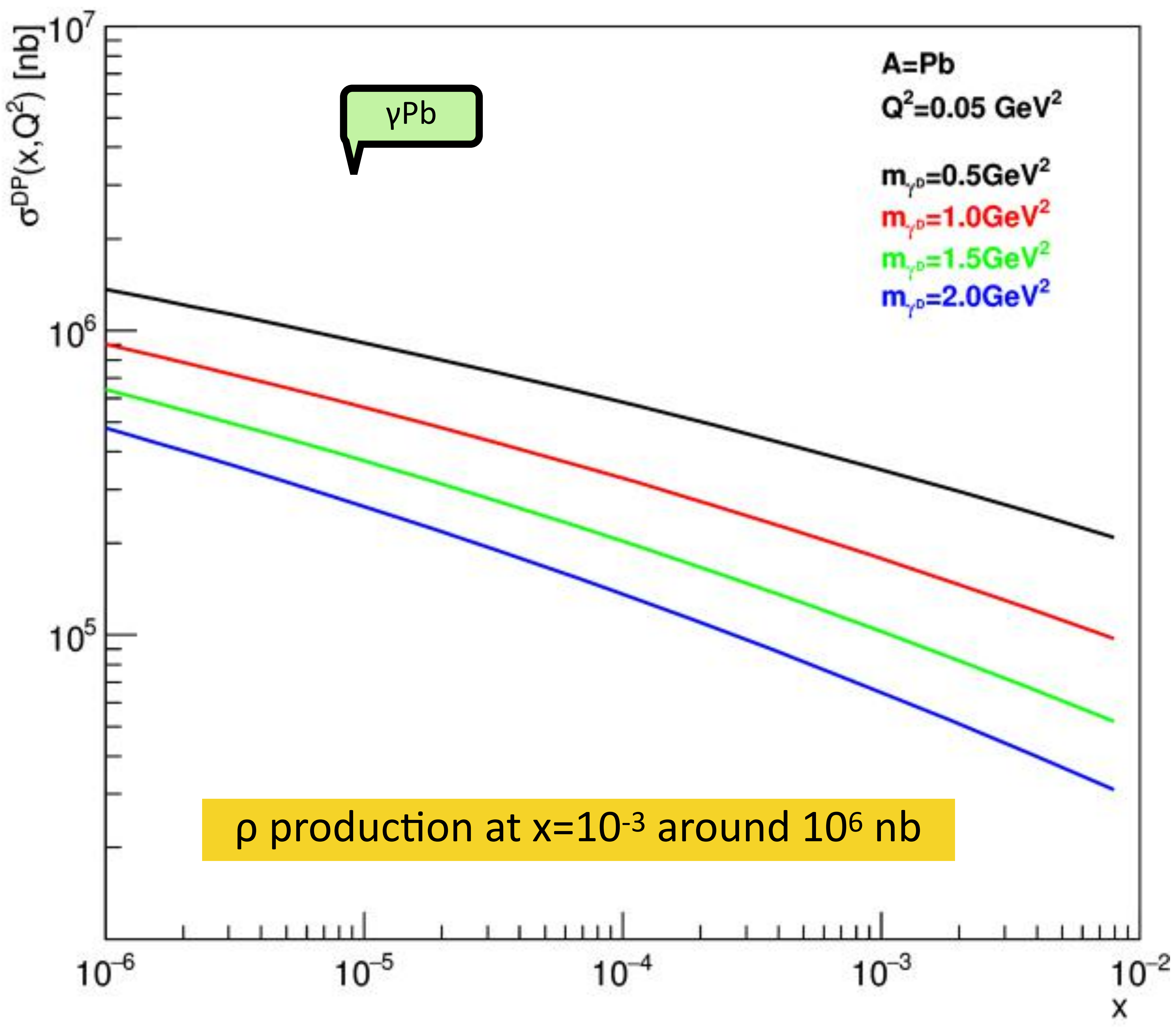
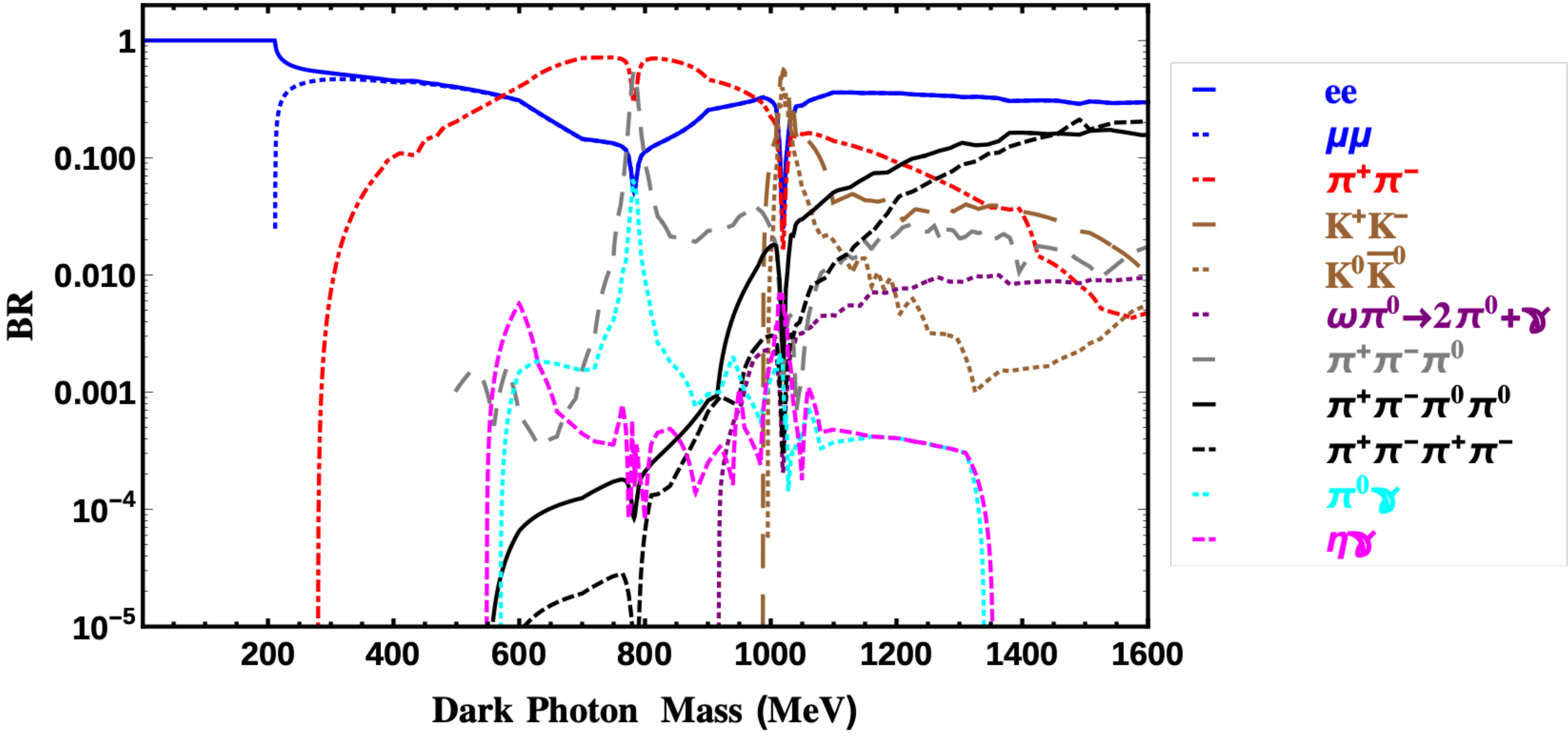




Large cross sections, but also for VM production and γγ interactions ....

Branching ratios



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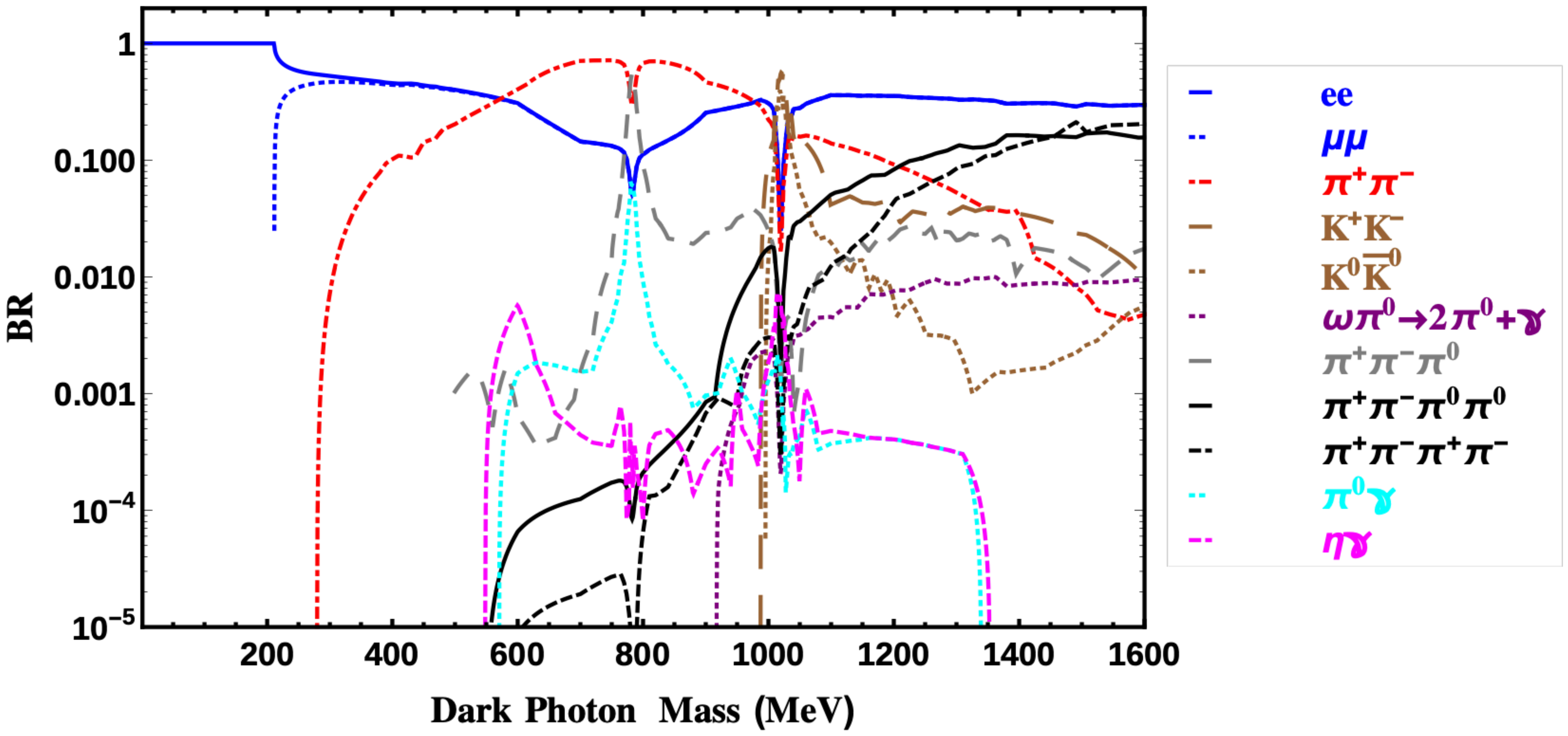
Branching ratios

Reasonably large branching ratios to electrons and muons, at higher masses to 4-pion state



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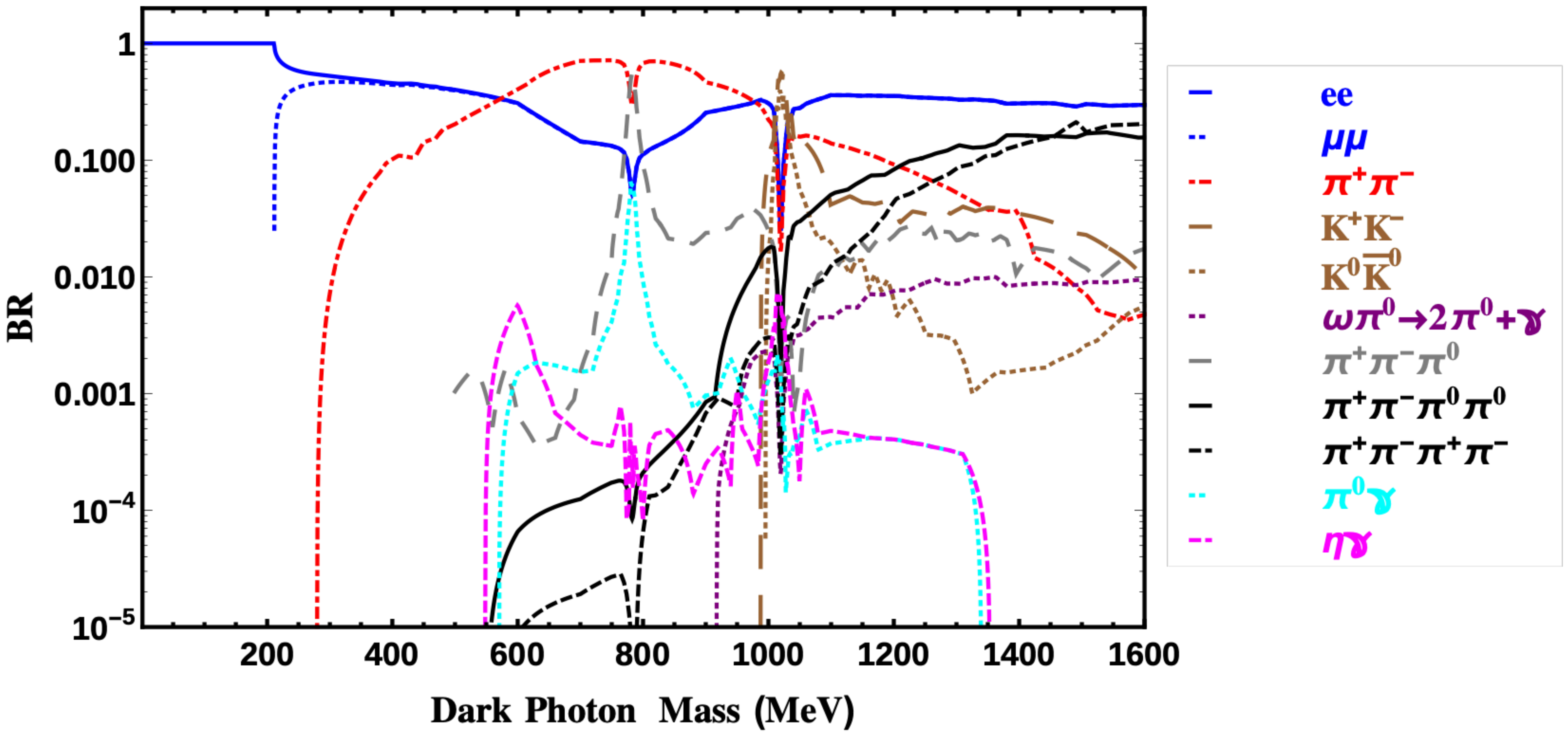
Branching ratios

All these channels have been considered to search for vector mesons at previous, current and future colliders

Reasonably large branching ratios to electrons and muons, at higher masses to 4-pion state



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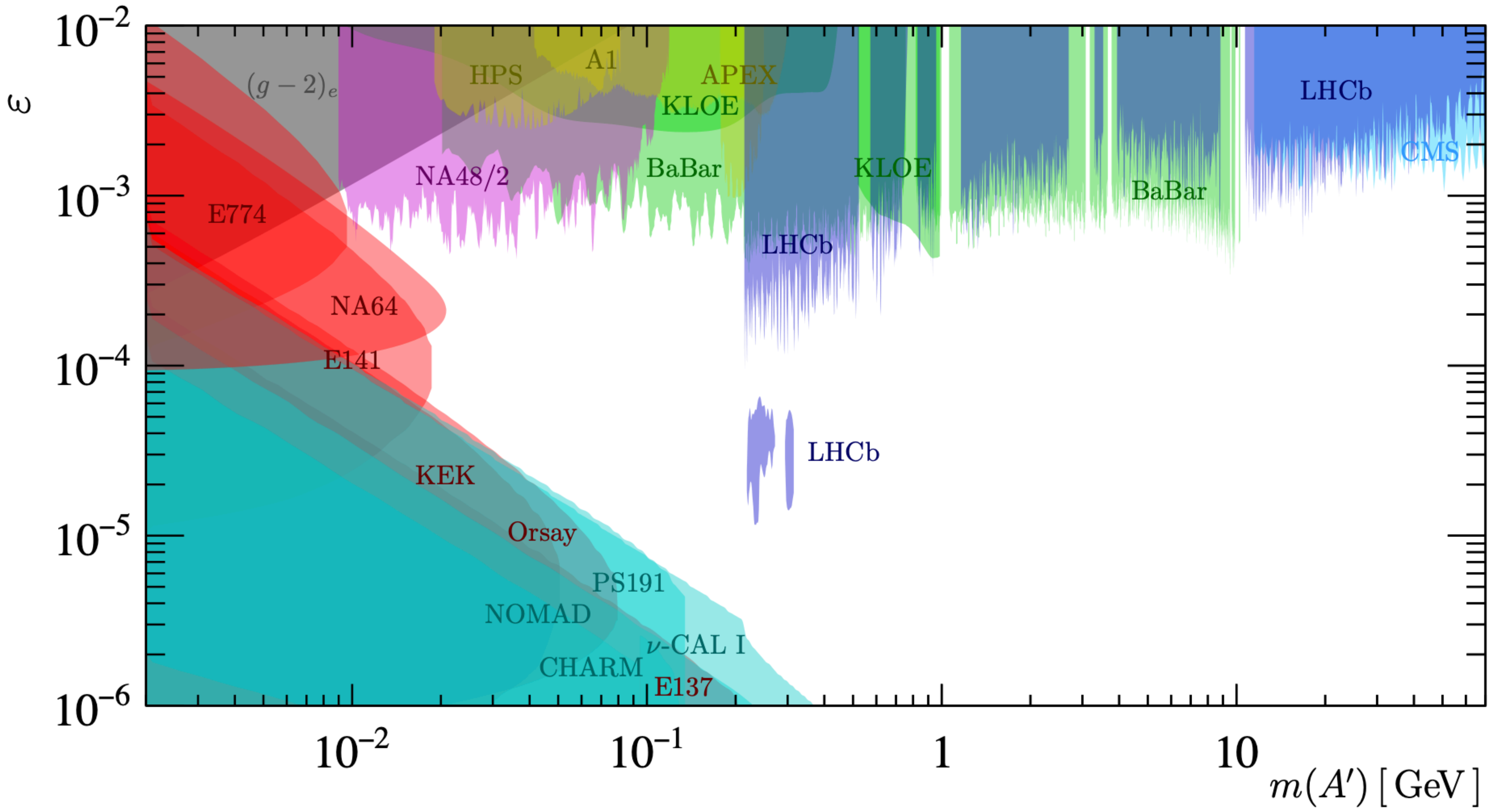
Existing limits



https://inspirehep.net/literature/1629161
(Supplementary material)

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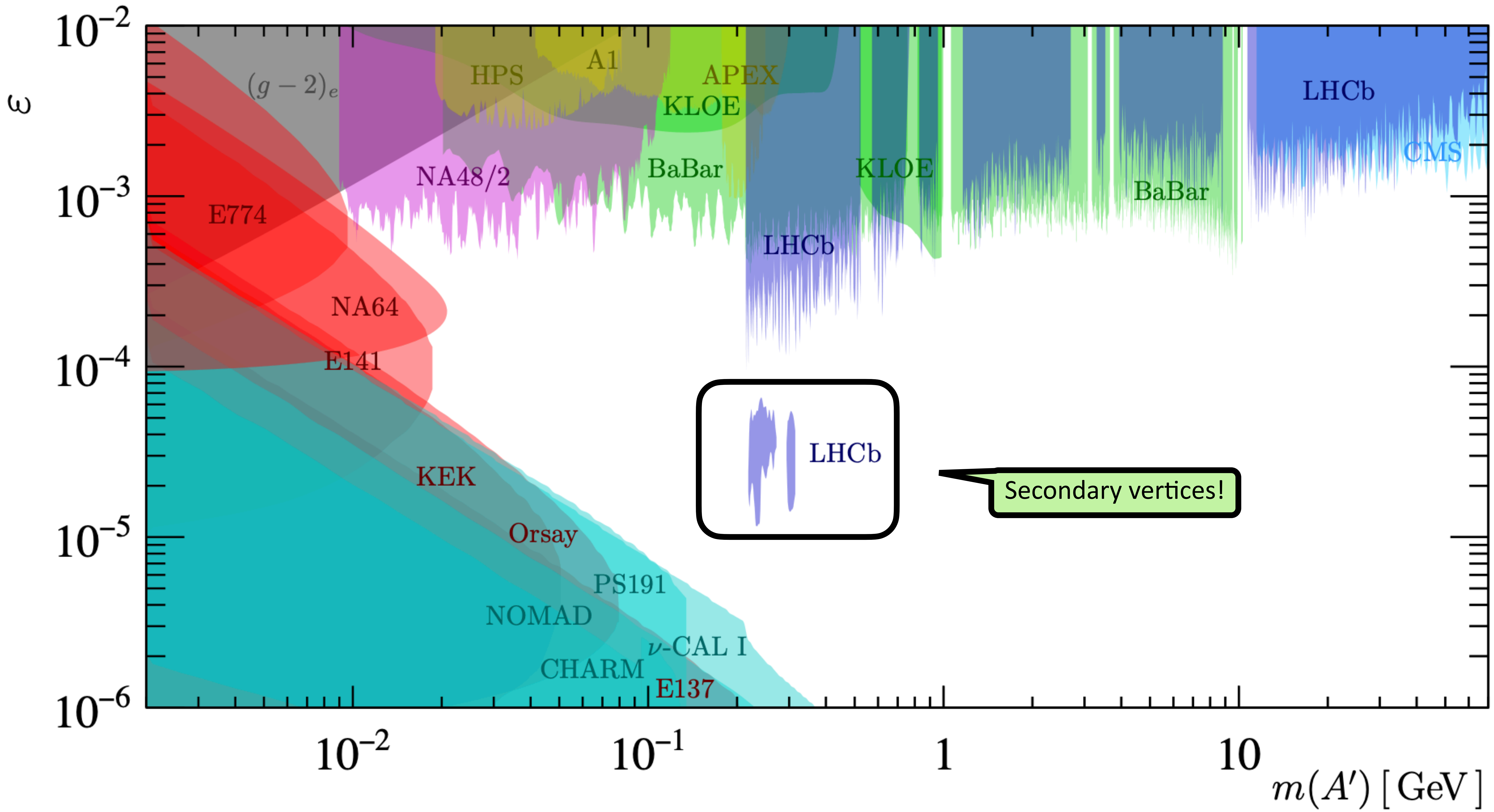
Existing limits



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(Supplementary material)

Decay width

Small coupling and small mass: long lived (τ~1/Γ)

Decay to leptons

$$\Gamma(A' \to \ell^+\ell^-) = \frac{1}{3}\alpha\,\varepsilon^2 m_{A'}\sqrt{1-\frac{4m_\ell^2}{m_{A'}^2}}\left(1+\frac{2m_\ell^2}{m_{A'}^2}\right),$$

https://inspirehep.net/literature/1794152

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In colliders, for masses around 1 GeV, a large boost is needed to be able to observe secondary vertex and thus reject the background

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LHCb demonstrated that it is possible

In colliders, for masses around 1 GeV, a large boost is needed to be able to observe secondary vertex and thus reject the background

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Expected luminosity and events

EIC

HL-LHC: Run 4-6

Expected luminosity and events

EIC	HL-LHC: Run 4-6

Luminosity

in ep collisions, 10/fb per month
in eA collisions, 1/fb per month

https://inspirehep.net/literature/1851258

Expected luminosity and events

Luminosity

EIC	HL-LHC: Run 4-6
in ep collisions, 10/fb per month in eA collisions, 1/fb per month	in pp collisions, 3000/fb in Pb-Pb collisions, 40/nb
https://inspirehep.net/literature/1851258	https://inspirehep.net/literature/2176715 https://cds.cern.ch/record/2749422

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Events/ε^2

γp(Pb) to ep(Pb): flux ~ 0.087(0.072) in 0<rap<2(3)

Events/ε^2 ep: 0.087*40 nb*10/fb ≈ 3.5e7

Events/ε^2 ePb: 0.072*3e5 nb*1/fb ≈ 2.2e10

Expected luminosity and events

	EIC	HL-LHC: Run 4-6
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Events/ε^2

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Not considered: BRs, detector acceptance nor efficiency, background ...

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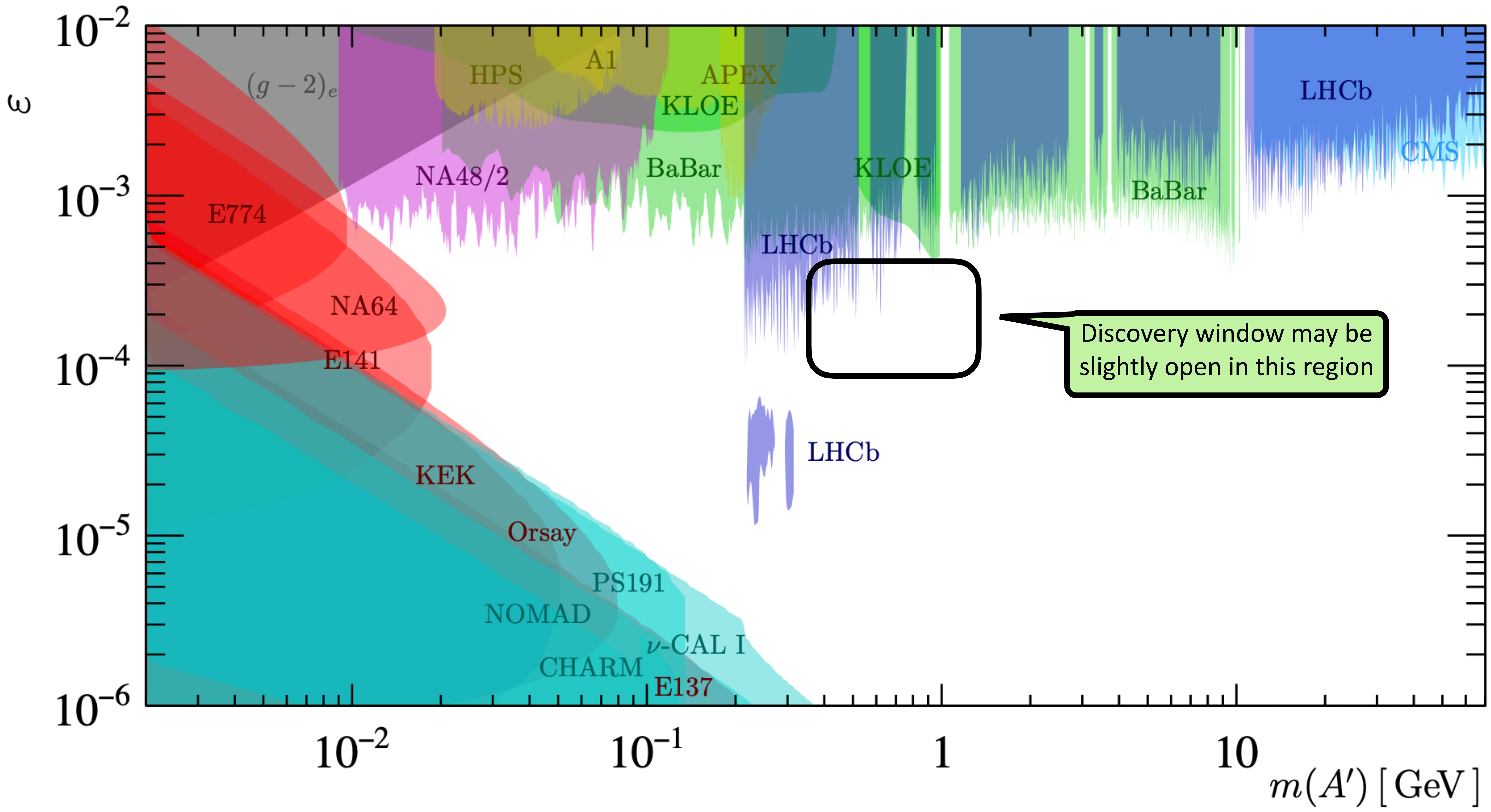
Bottom line



Discovery window may be slightly open in this region