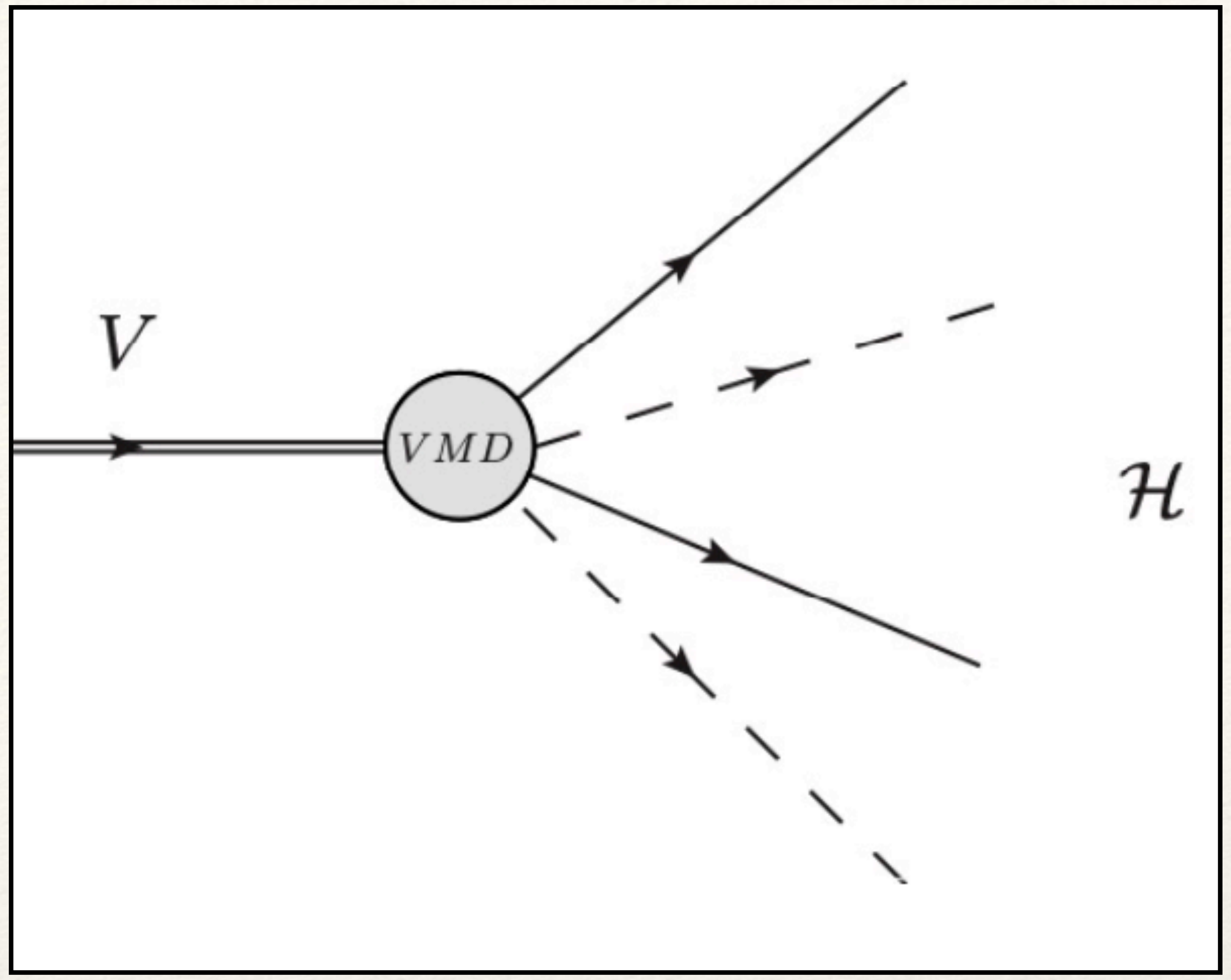


Peter Reimitz - Instituto de Física, Universidade de São Paulo (IFUSP)

Hadronic Footprint of Light Vector Particles

PLANCK 2022, May 30 - June 3

FAPESP

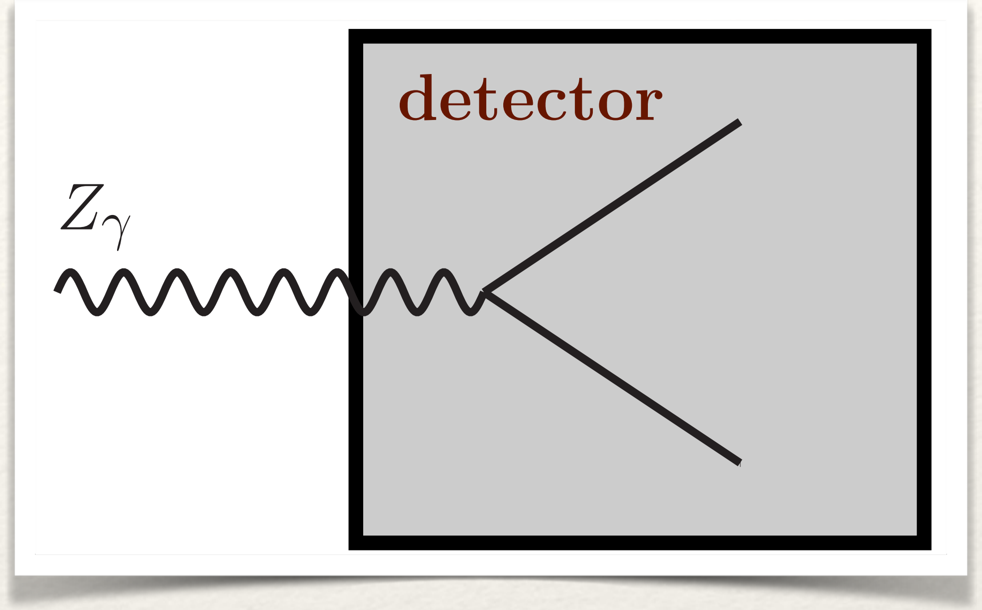
IFUSP
Instituto de Física da USP

Description of hadronic currents for Vector Particles

Long-Lived Vector Mediator Decays

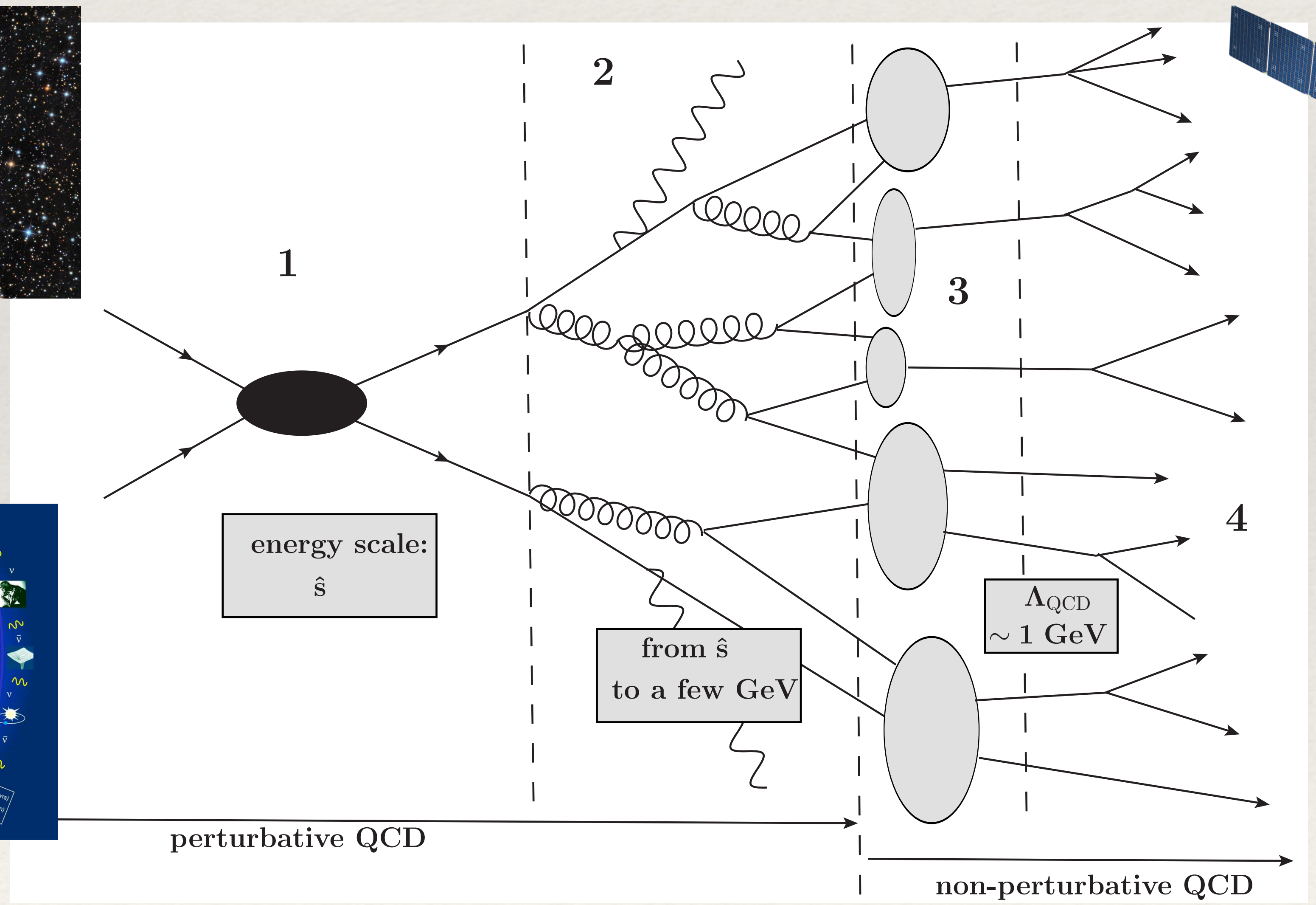
Vector Particle Production

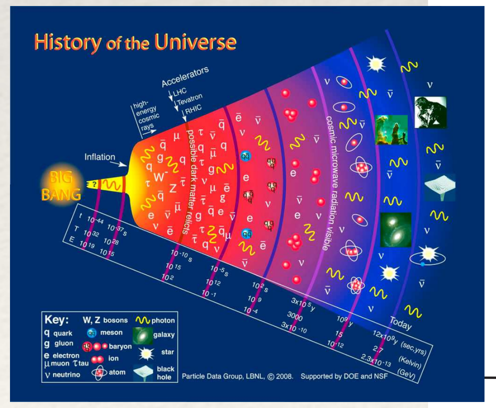
Dependent on lifetime



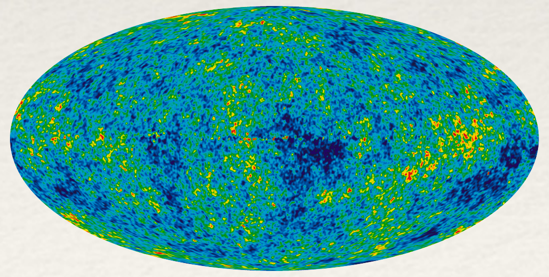
…and Branching ratios

Indirect Detection with Vector DM or Vector Mediator Models





$$\frac{\mathrm{d}N}{\mathrm{d}E_{\mathrm{kin}}}$$



http://wmap.gsfc.nasa.gov/media/101080

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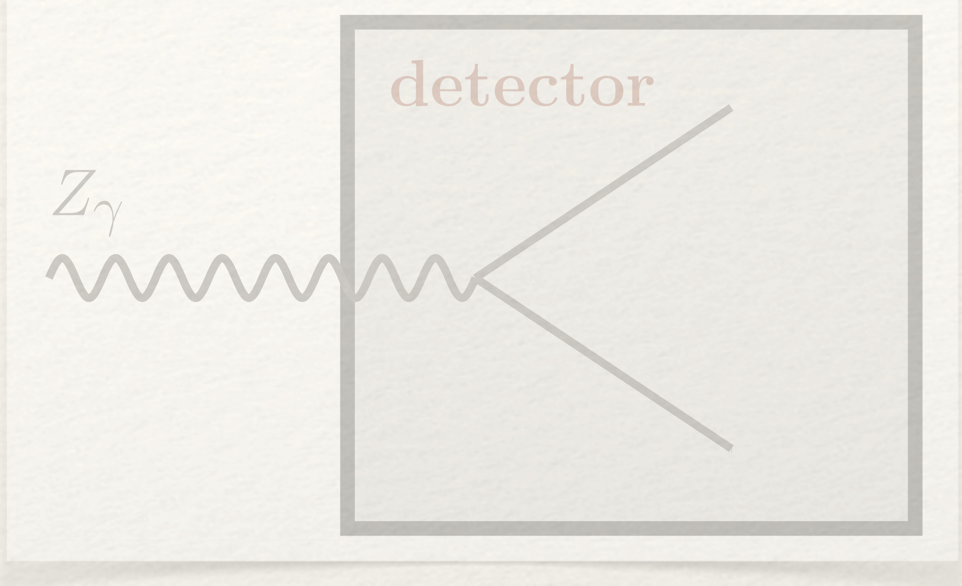

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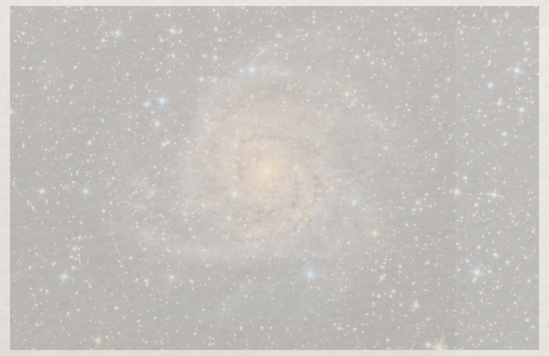
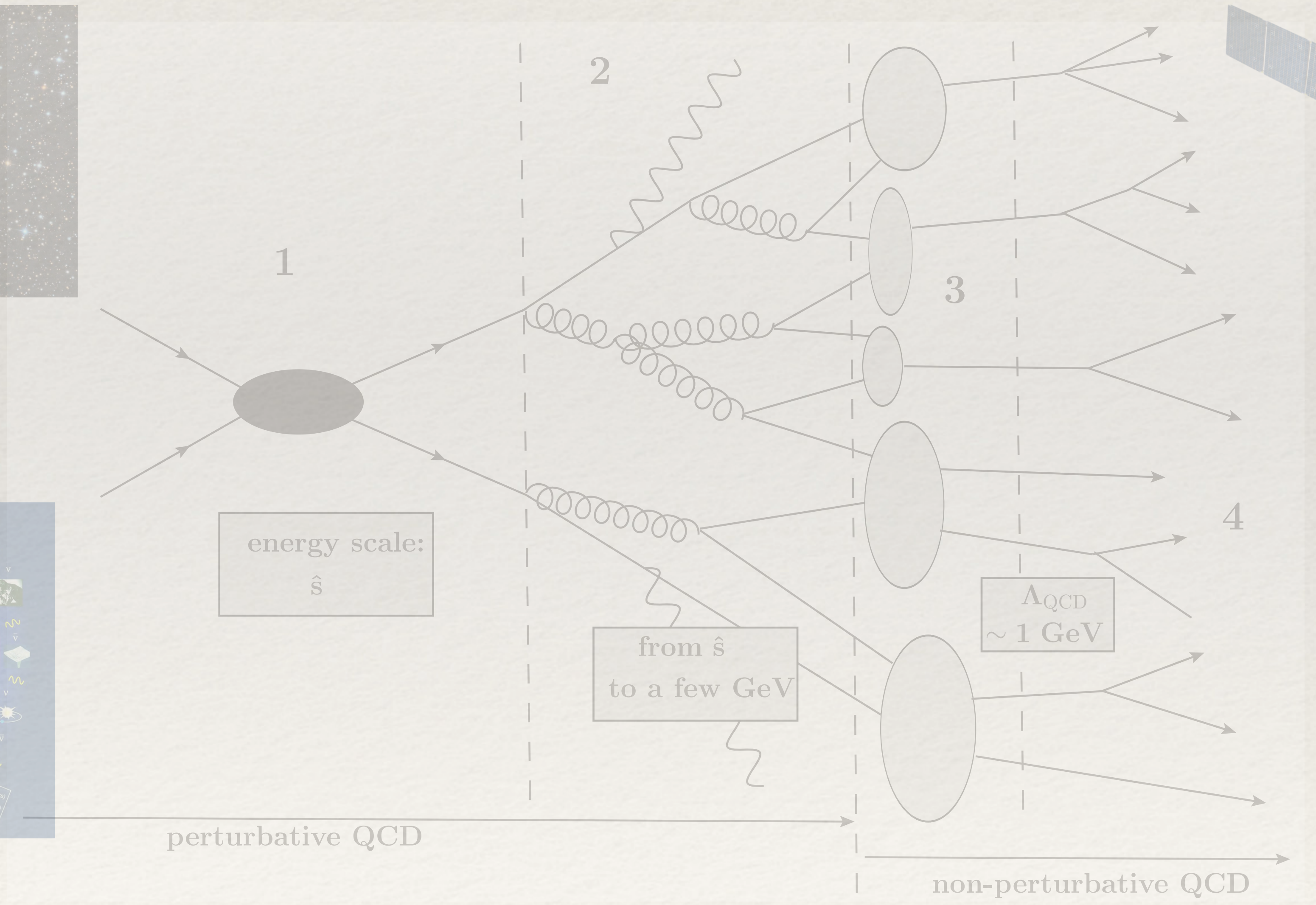
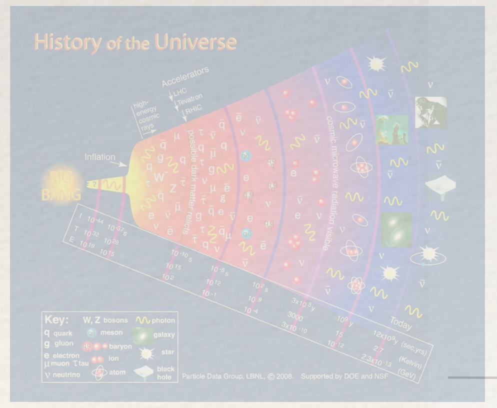
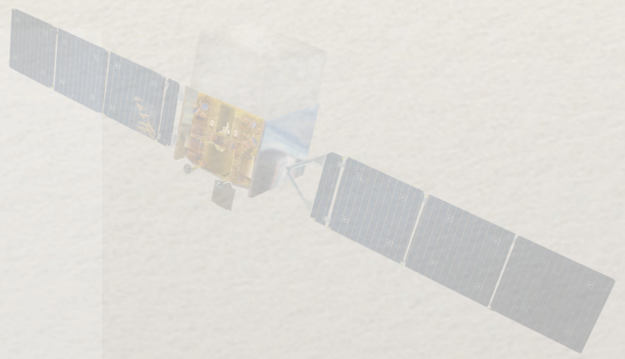
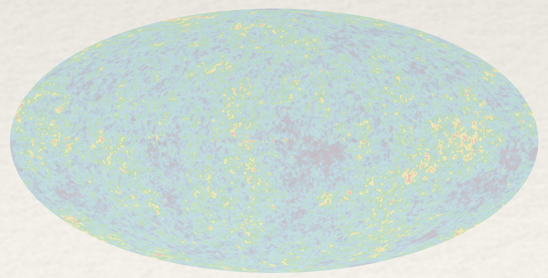








$$\frac{\mathrm{d}N}{\mathrm{d}E_{\rm kin}}$$

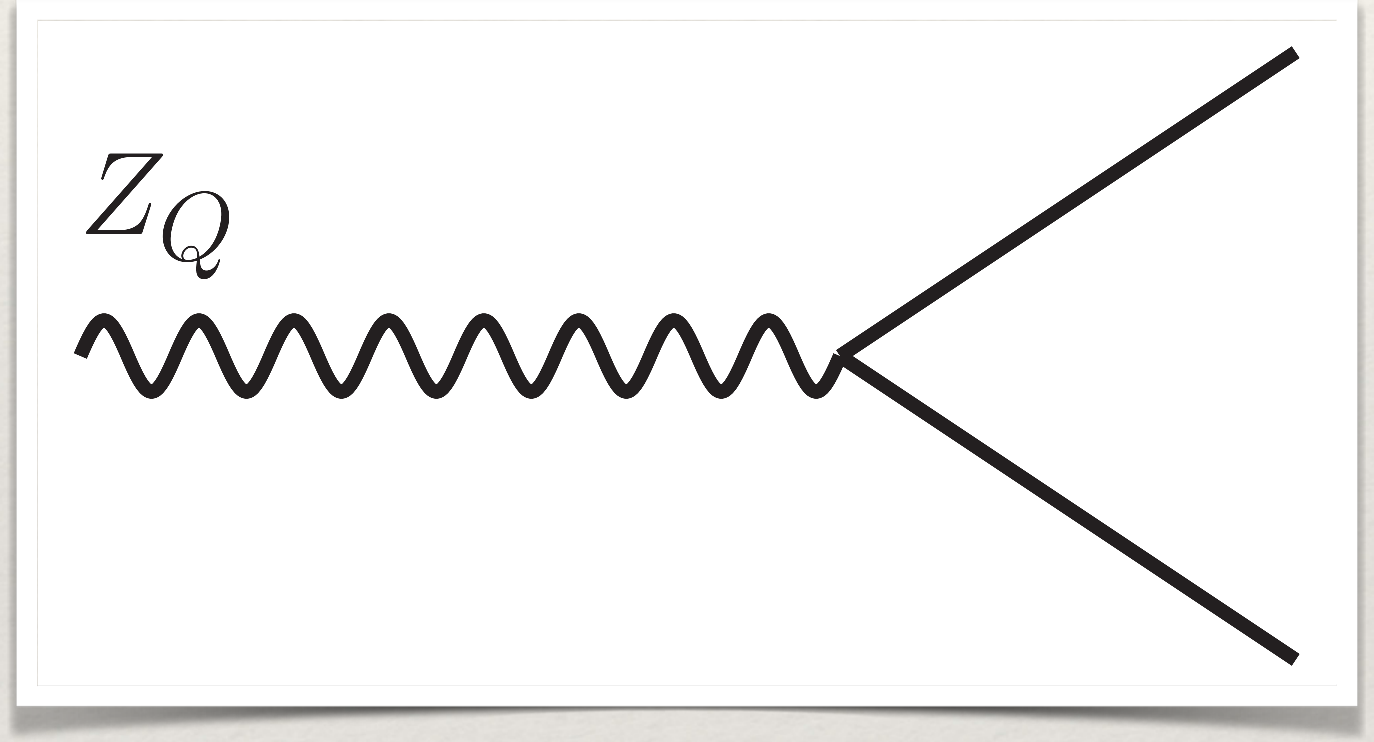


http://wmap.gsfc.nasa.gov/media/101080

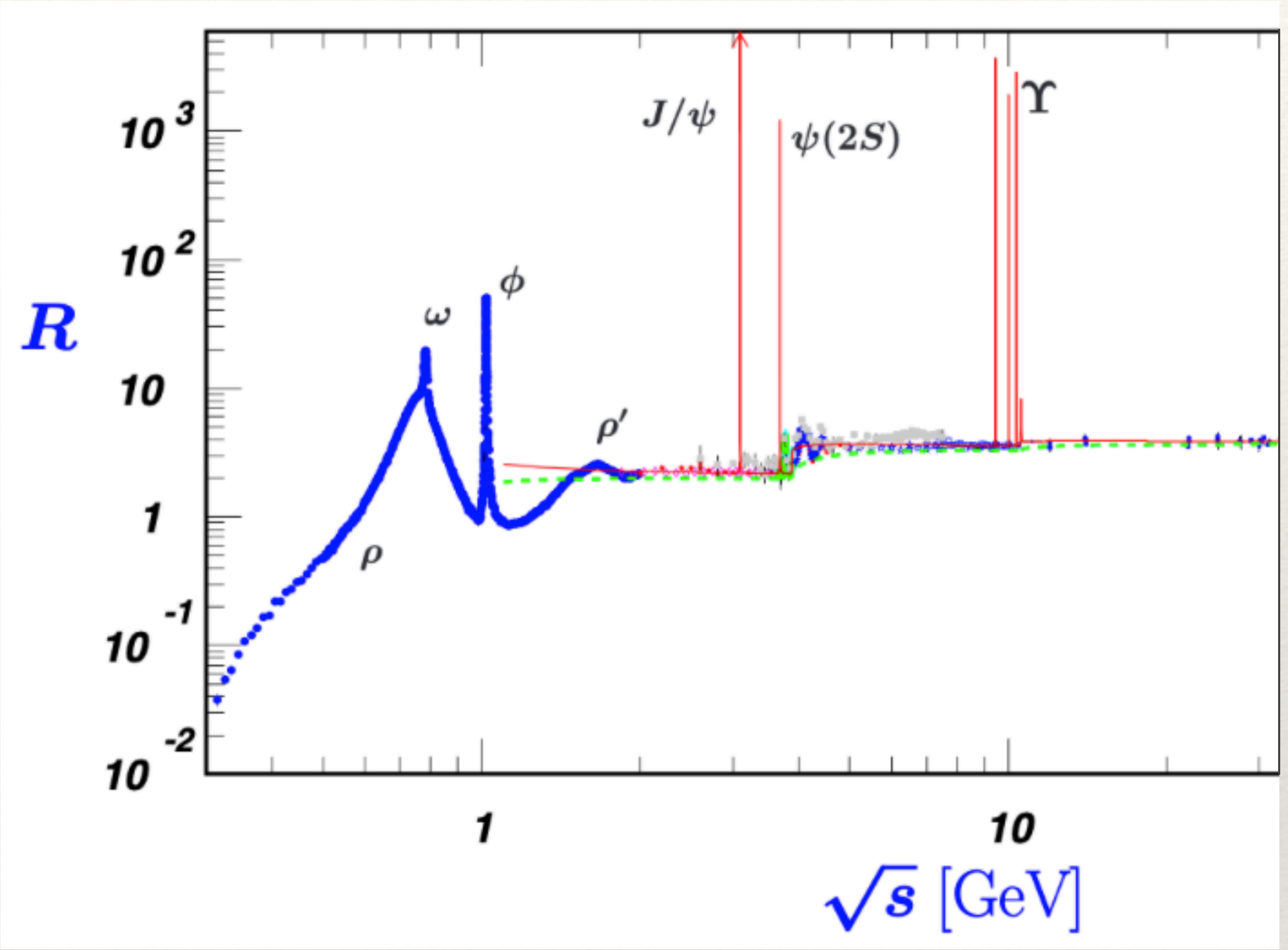
Description of hadronic currents for Vector Particles

- Data-driven approach based on e^+e^-- low-energy data
- Theory:
    - ChPT, valid up to $\sqrt{s} \lesssim 500$ MeV

$$R_\mu^{\mathcal{H}}[\text{exp}] \equiv \frac{\sigma(e^+e^- \to \mathcal{H})}{\sigma(e^+e^- \to \mu^+\mu^-)} .$$



Direct couplings to $\pi^+\pi^-, \pi^0\gamma$



Description of hadronic currents for Vector Particles

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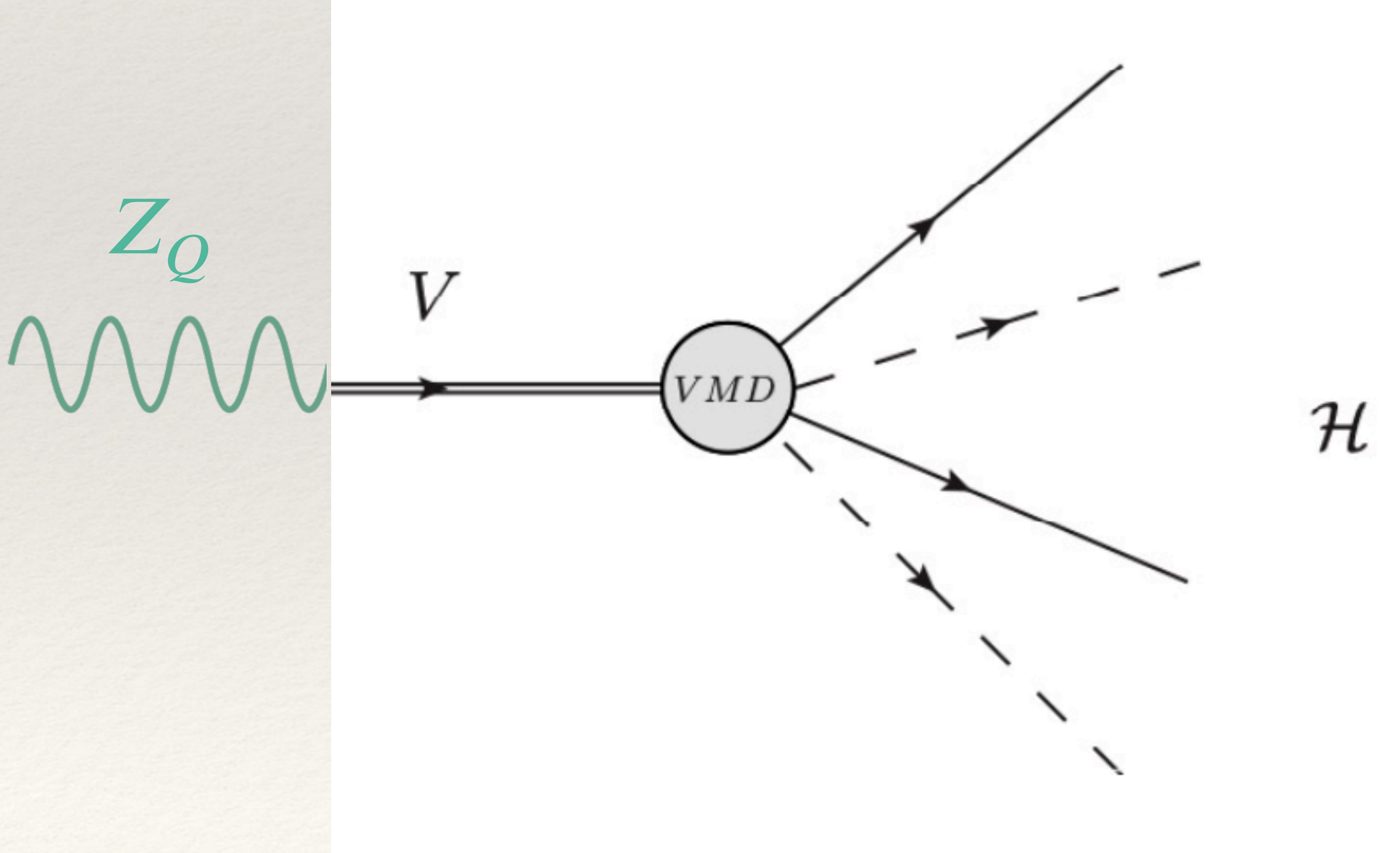
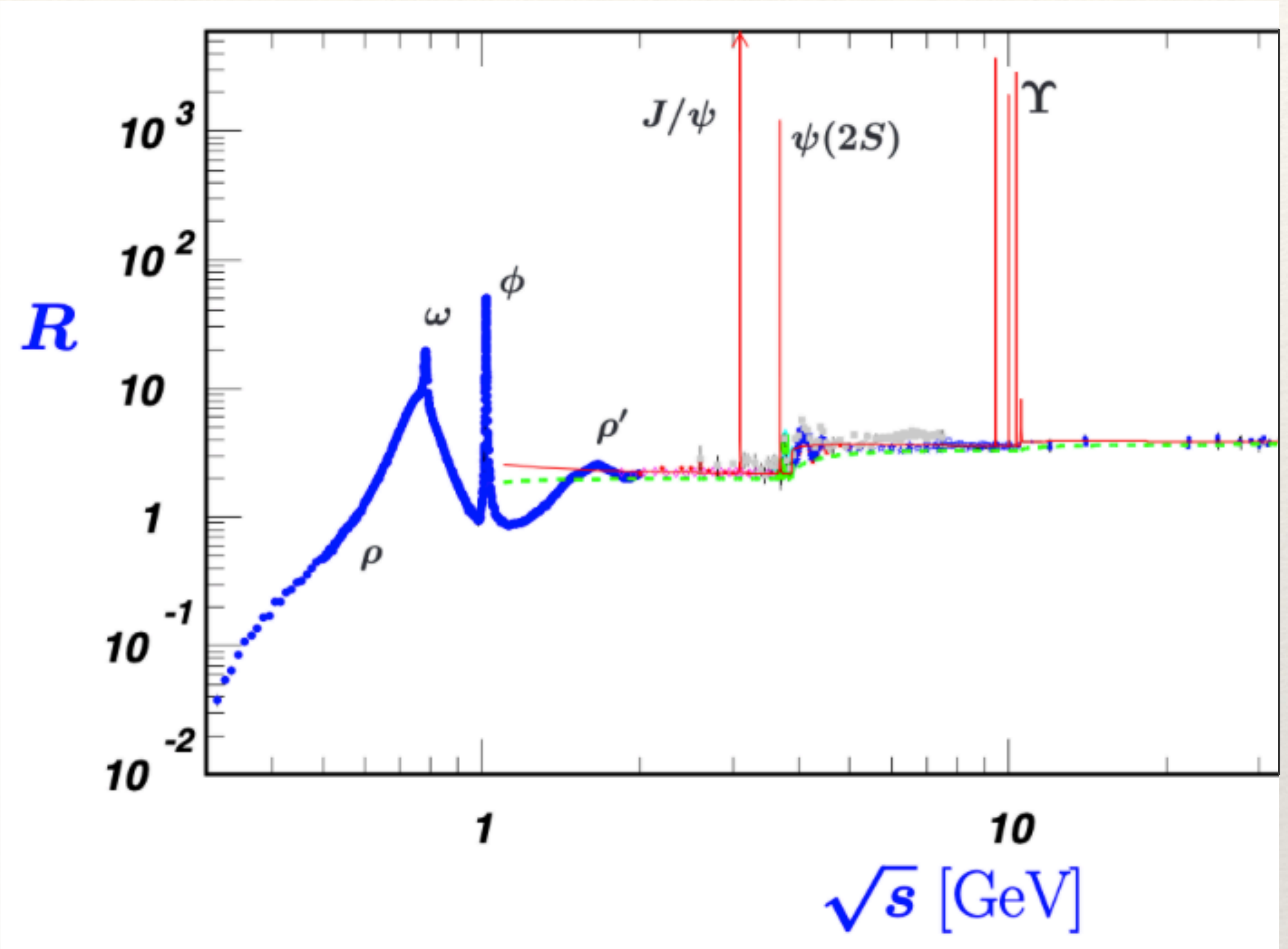


Decay to all sorts of hadrons through mixing with vector mesons



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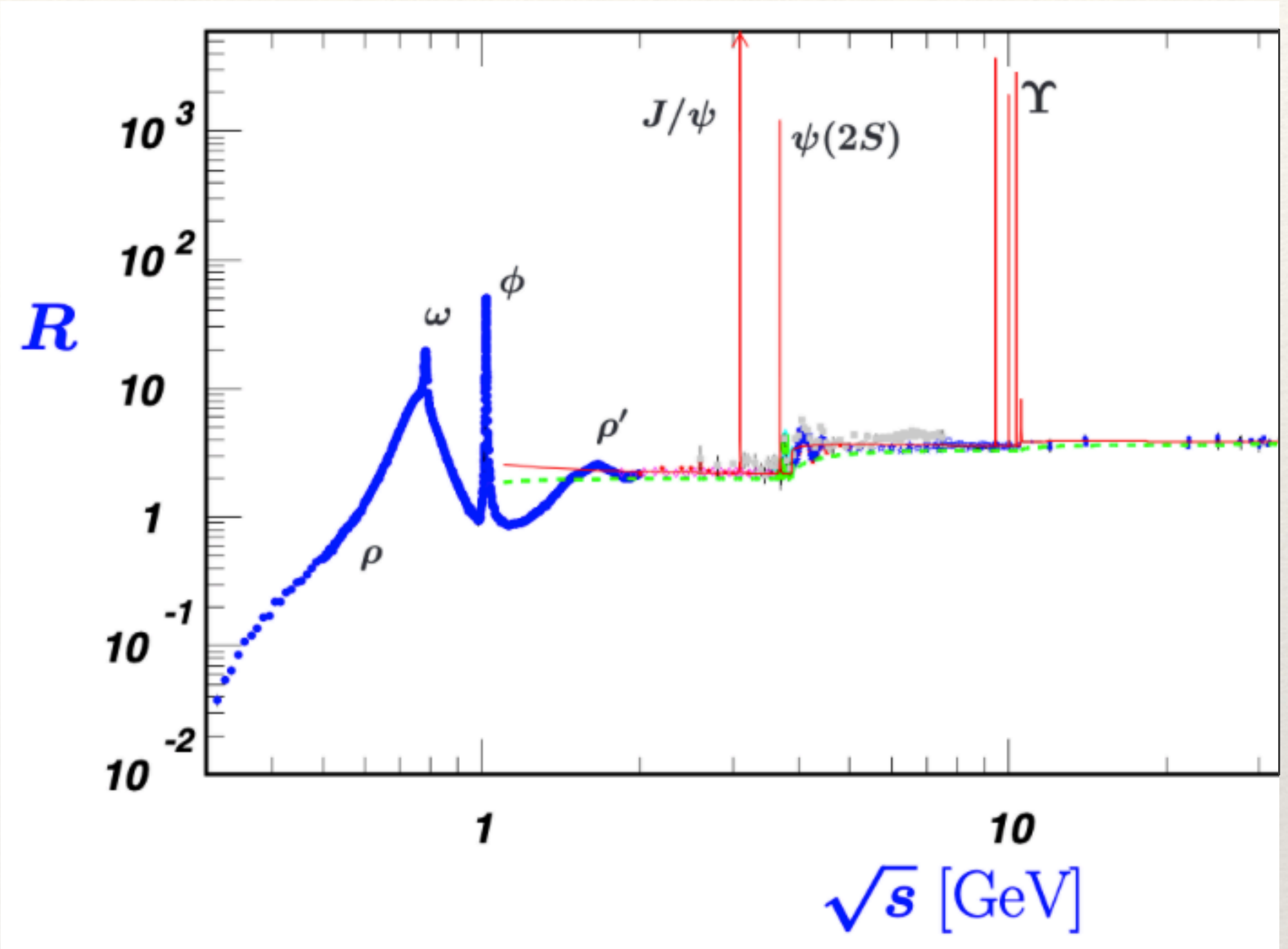

- Theory:
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Vector Meson Dominance (VMD) approach = vector mesons dominate hadronic currents

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

$J^{\mu}_{I=1} \downarrow \rho^{\mu}$, $J^{\mu}_{I=0} \downarrow \omega^{\mu}$, $J^{\mu}_{s} \downarrow \phi^{\mu}$

$\rho \to \pi^+\pi^-, \pi^0\pi^0\gamma$ $\eta\pi\pi, 4\pi, \ldots$	$\omega \to \pi^+\pi^-\pi^0, \pi^0\gamma$ $KK, KK\pi$	$\phi \to \pi^+\pi^-\pi^0, \pi^0\gamma$ $KK, KK\pi$

Description of hadronic currents for Vector Particles

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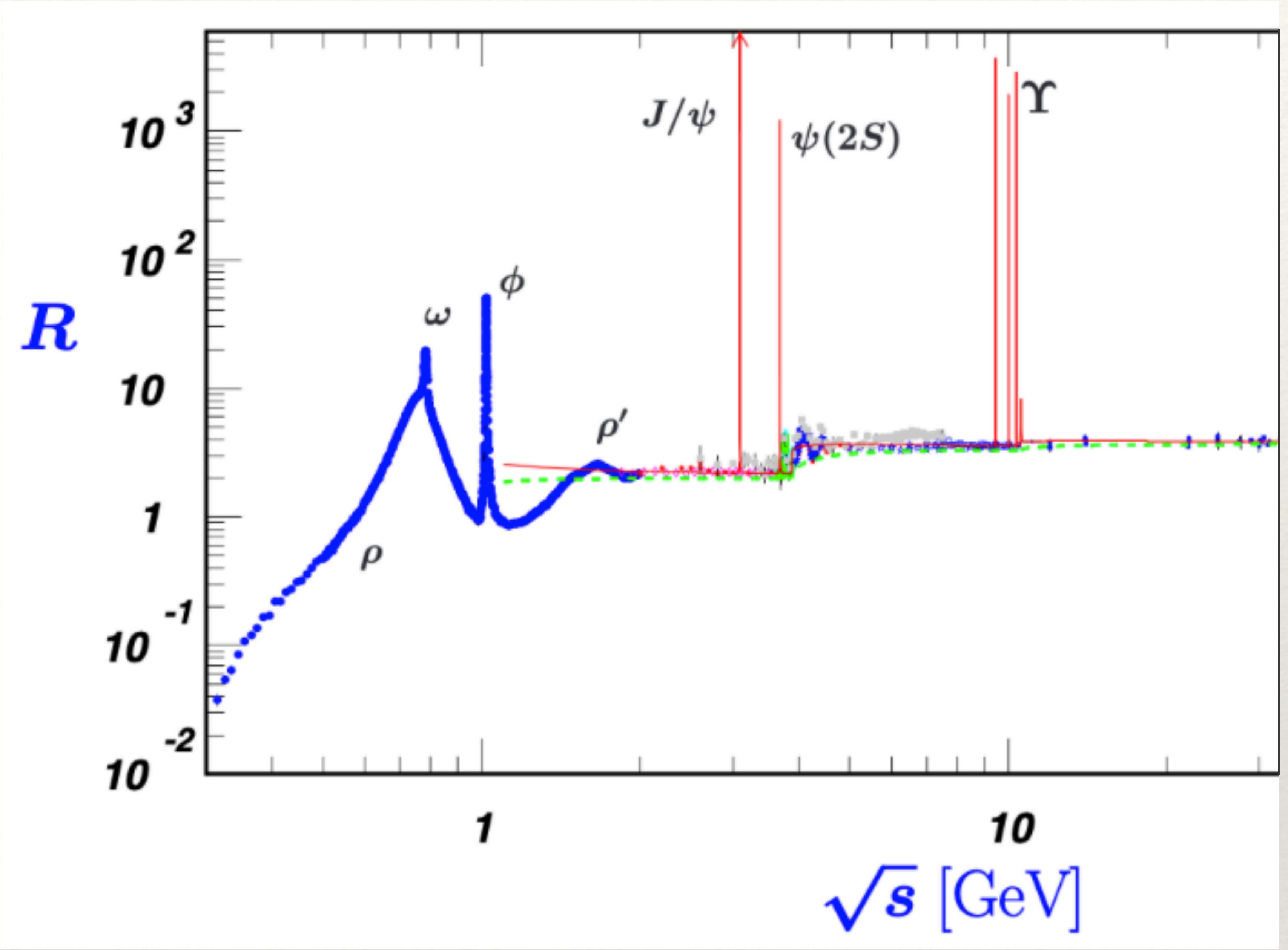


Vector Meson Dominance (VMD) approach = vector mesons dominate hadronic currents

$$J_B^\mu = \frac{1}{\sqrt{2}} \underbrace{(q_B^u - q_B^d)}_{=0} J_{I=1}^\mu + \frac{1}{\sqrt{2}} \underbrace{(q_B^u + q_B^d)}_{=2/3} J_{I=0}^\mu + \underbrace{q_B^s}_{1/3} J_s^\mu$$

$J_{I=1}^\mu \to \rho^\mu$, $J_{I=0}^\mu \to \omega^\mu$, $J_s^\mu \to \phi^\mu$

$\rho \to \pi^+\pi^-, \pi^0\pi^0\gamma$ $\eta\pi\pi, 4\pi, \ldots$	$\omega \to \pi^+\pi^-\pi^0, \pi^0\gamma$ $KK, KK\pi$	$\phi \to \pi^+\pi^-\pi^0, \pi^0\gamma$ $KK, KK\pi$

Workflow

Individual hadronic channels have the form:

$$J^{\mu}_{KK} = -(p_1 - p_2)^{\mu} F_{KK}(\hat{s}) \qquad F_{KK}(\hat{s}) \propto \sum_{V=\rho,\omega,\phi,\ldots} \frac{a_V m_V^2 e^{i\varphi_V}}{m_V^2 - \hat{s} - i m_V \Gamma_V}$$

e^+e^- data to describe the SM current $J^{\mu}_{\rm em}$

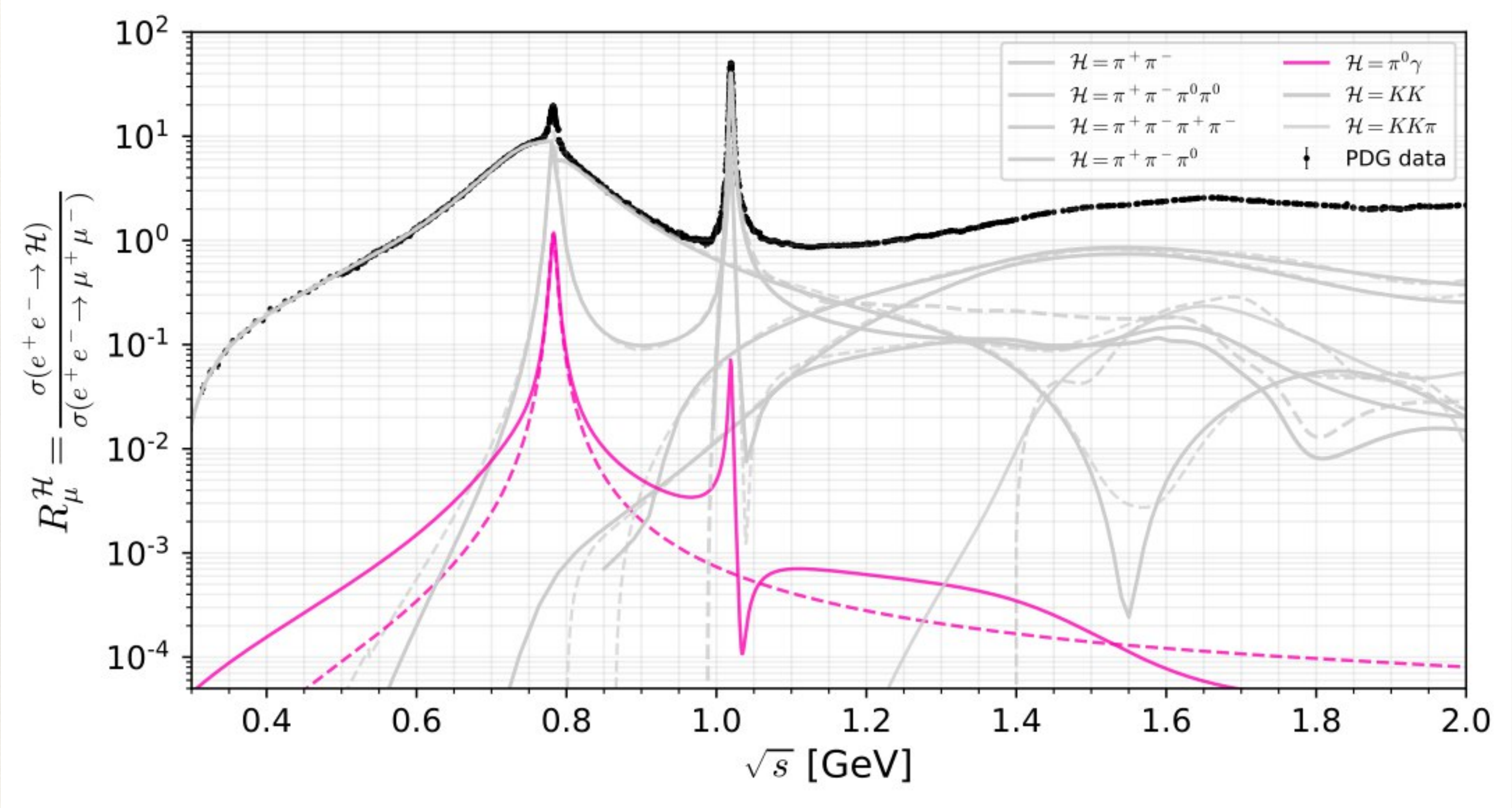
→ Description for individual channels $2\pi, 3\pi, 4\pi, KK, KK\pi, \ldots$

→ Separate ρ, ω, ϕ contributions

→ Put together pieces for hadronic current of model

Status and Improvements

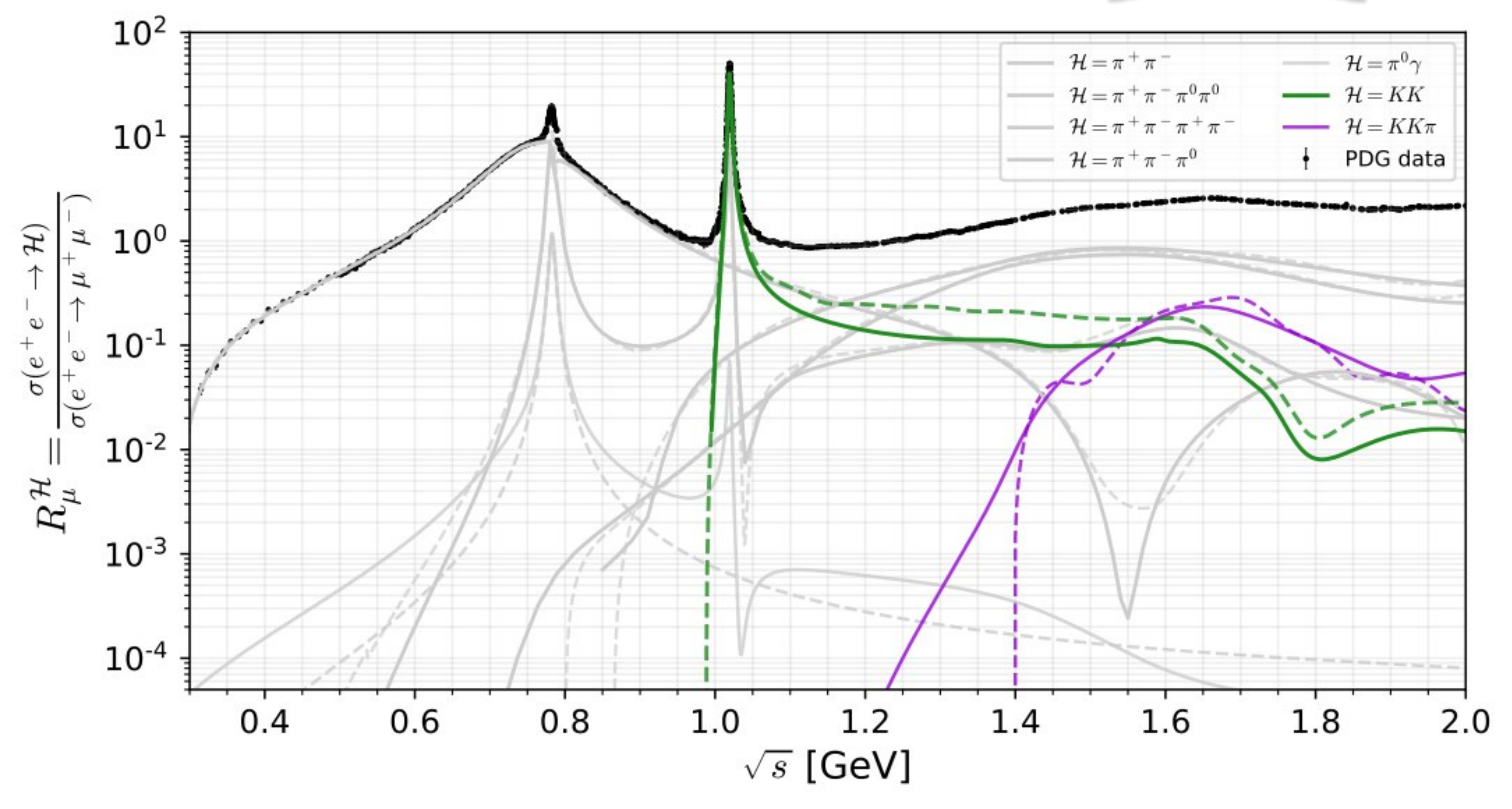
$\mathcal{H} = \pi^0\gamma$



- DarkCast only considers the ground-state ω peak
- We also include higher ω resonances, as well as a ρ and a ϕ (second peak) contribution
- This channel is very important since it is the only one below the two-pion threshold.

Status and Improvements

$\mathcal{H} = KK$ and $\mathcal{H} = KK\pi$

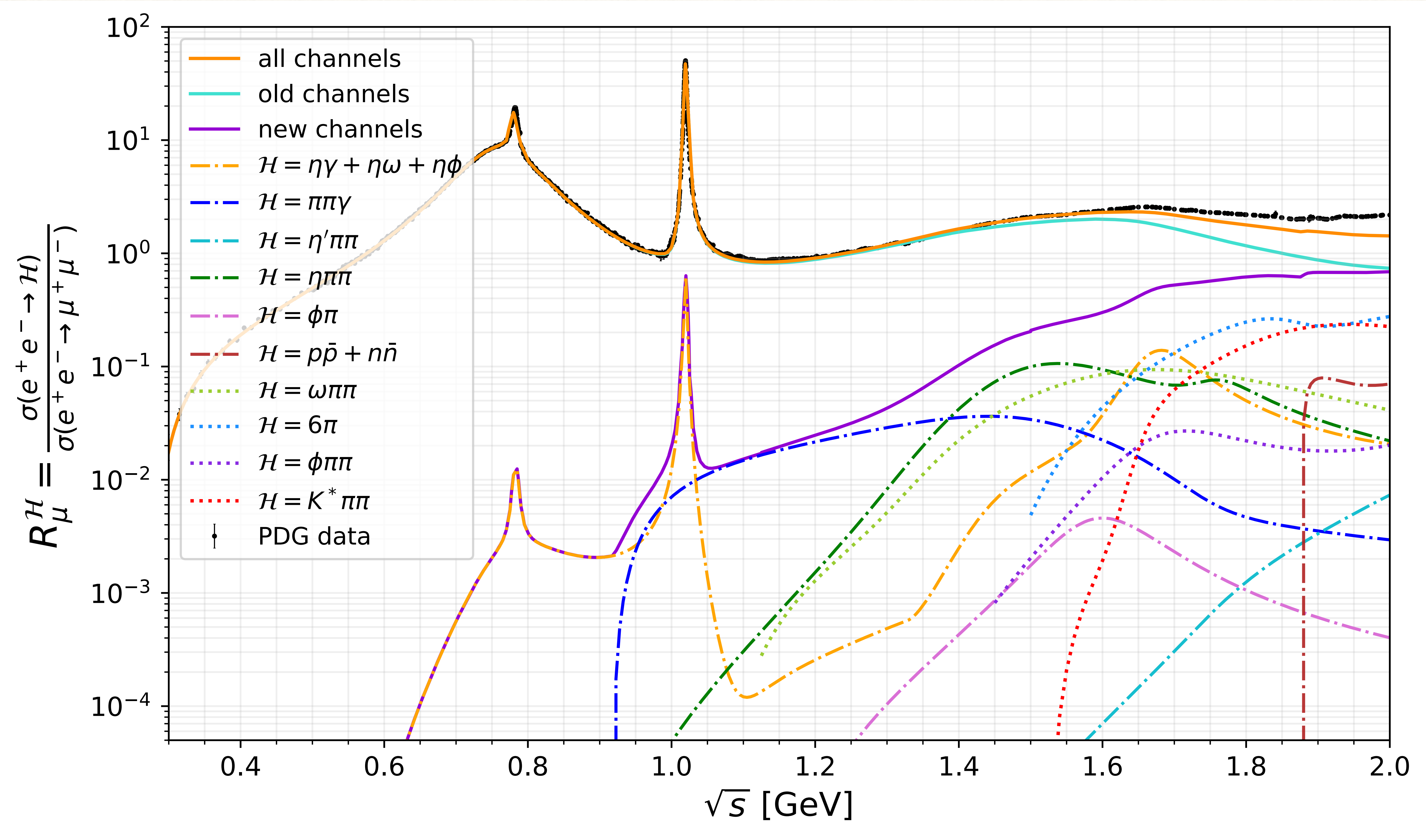


$$KK = K^0\bar{K}^0, K^+K^-$$

$$KK\pi = K^+K^-\pi^0, K^\pm K^0\pi^\mp, K^0K^0\pi^0$$

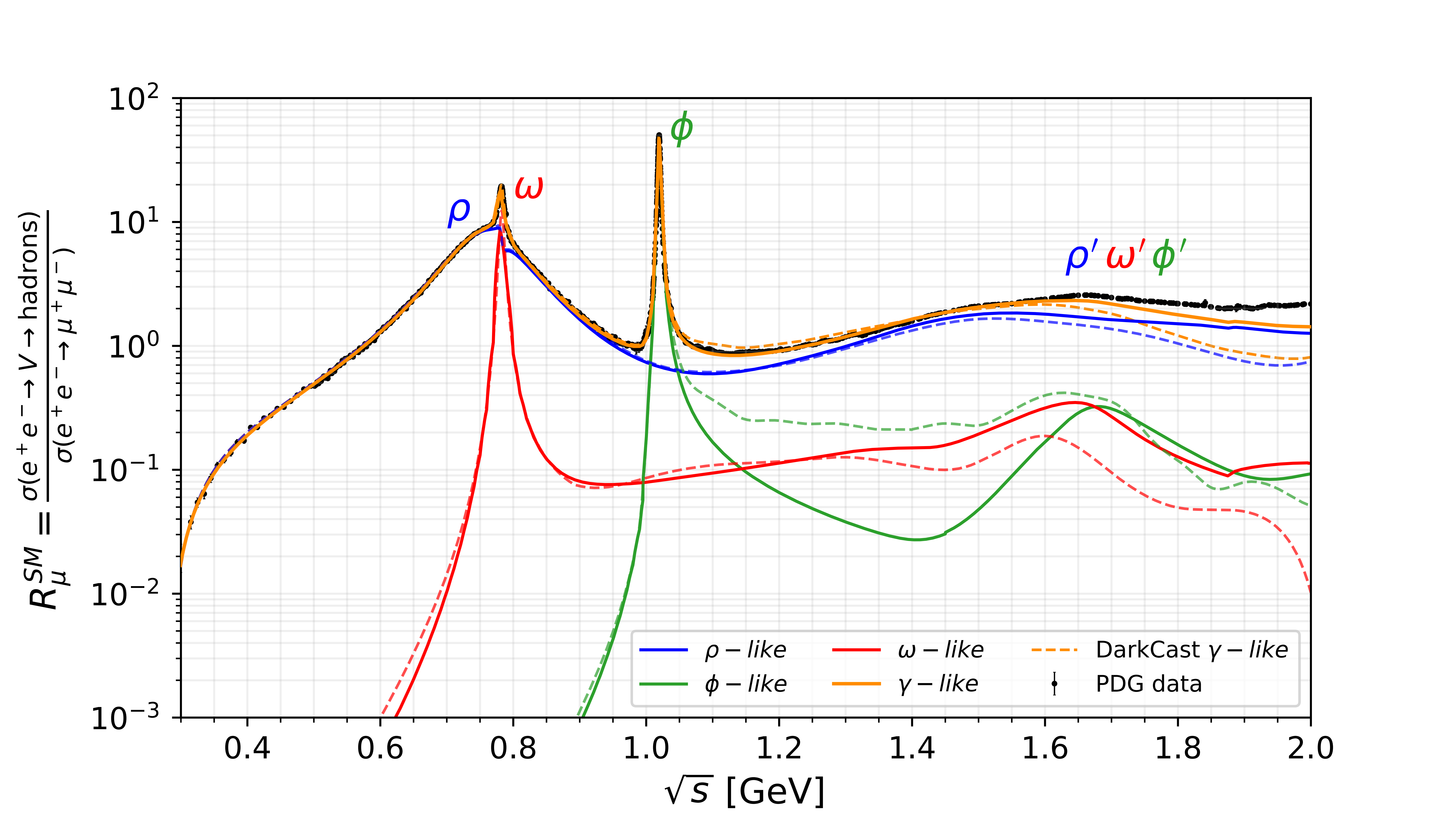
- We fit every separate component of each channel to recent data
- DarkCast considers channels as a ϕ contributions only

Status and Improvements



A lot of additional hadronic modes considered!

Status and Improvements



- ϕ and ω contribution differ above 1.0 GeV
- Sum of all hadronic contributions close to data up to higher energies

arXiv 2201.01788

Ana Foguel, Renata Zukanovich, **PR**

preimitz/**DeLiVeR**

Decays of Light Vectors Revised

DEcays of **LI**ght **VE**ctors **R**evised

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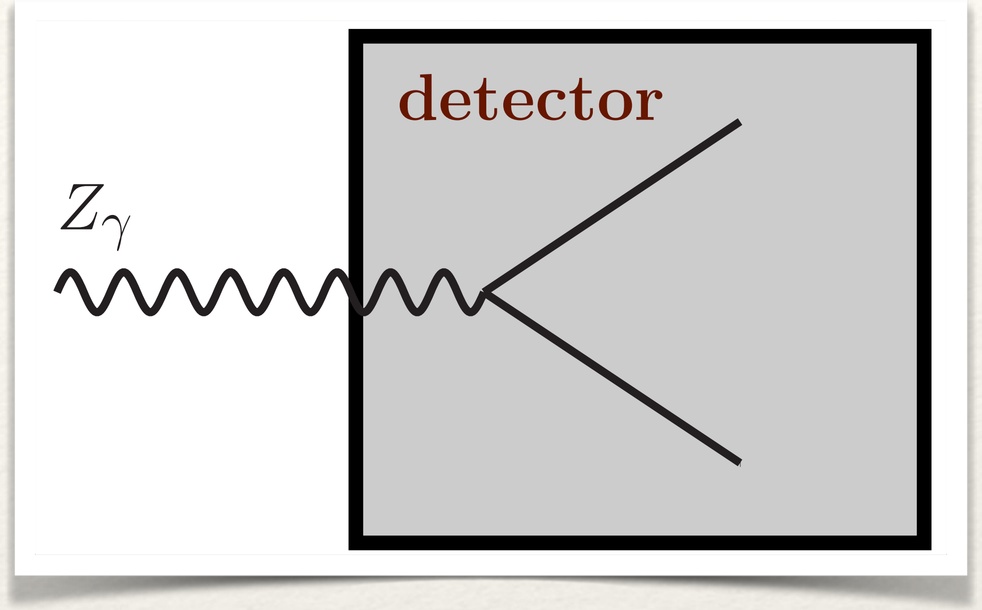
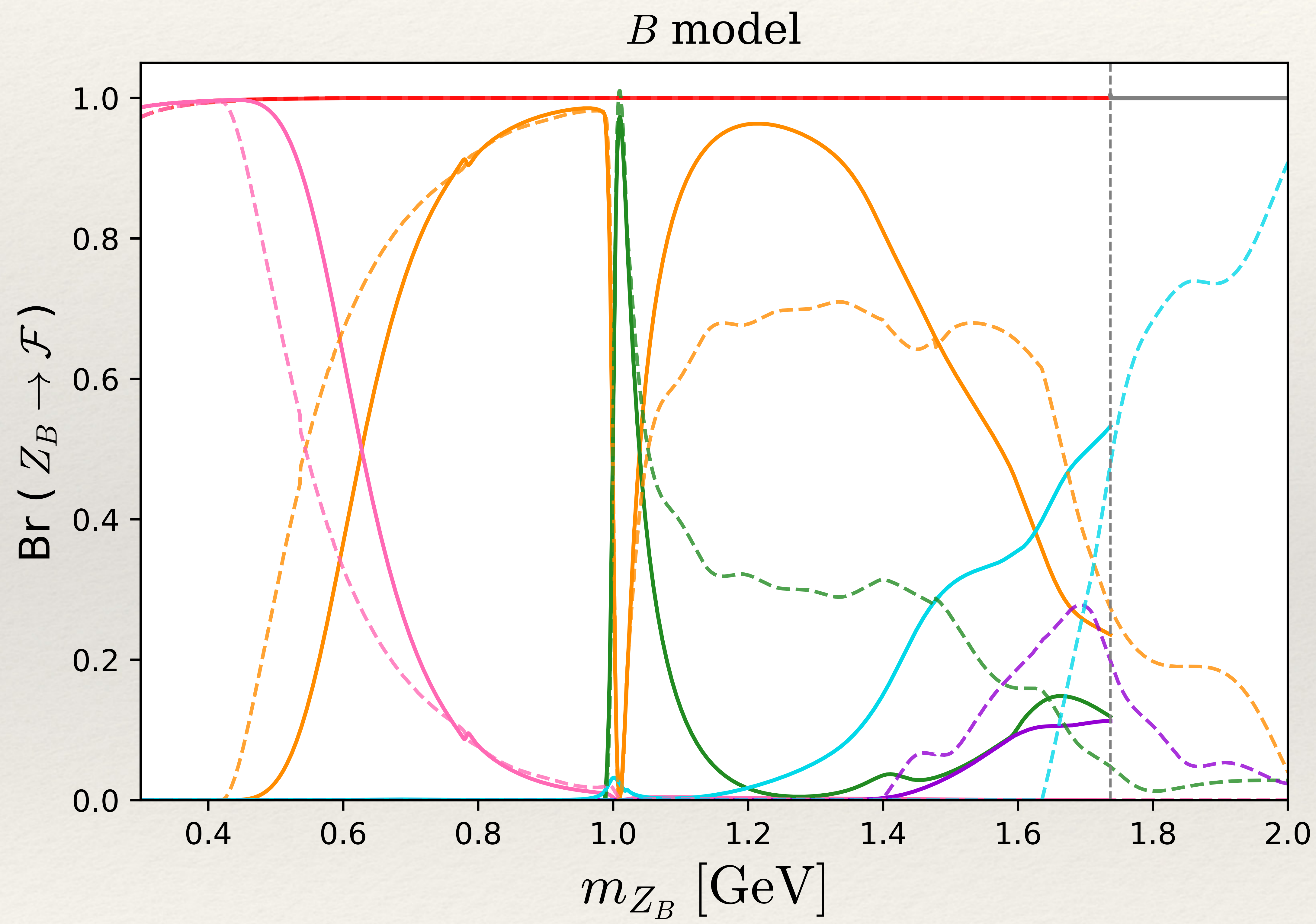
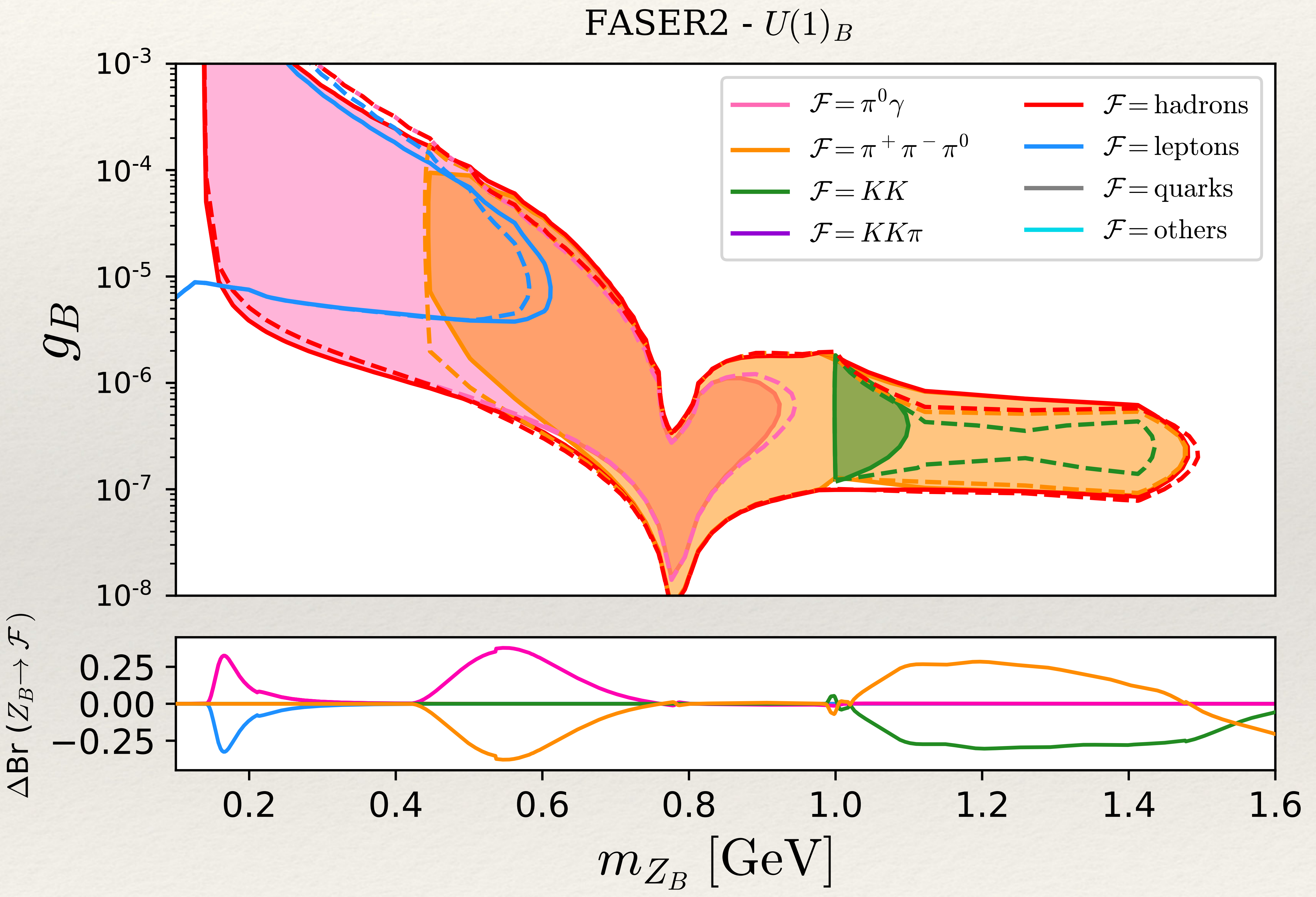


…and Branching ratios

B model

$$J_B^\mu = \frac{1}{3}\sum_q \bar{q}\gamma^\mu q$$





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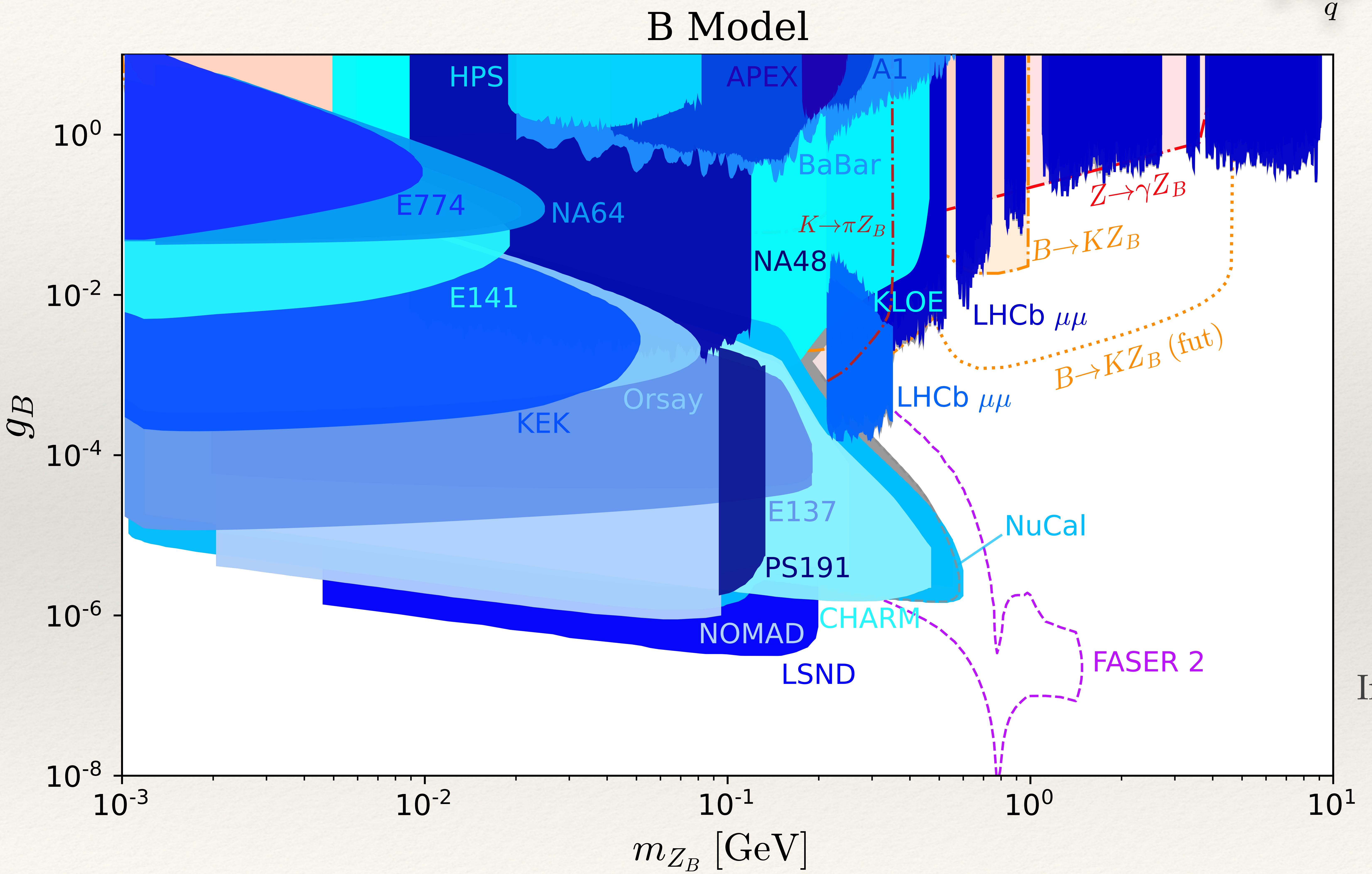


arXiv 2201.01788

Ana Foguel, Renata Zukanovich, **PR**

arXiv 2203.05090

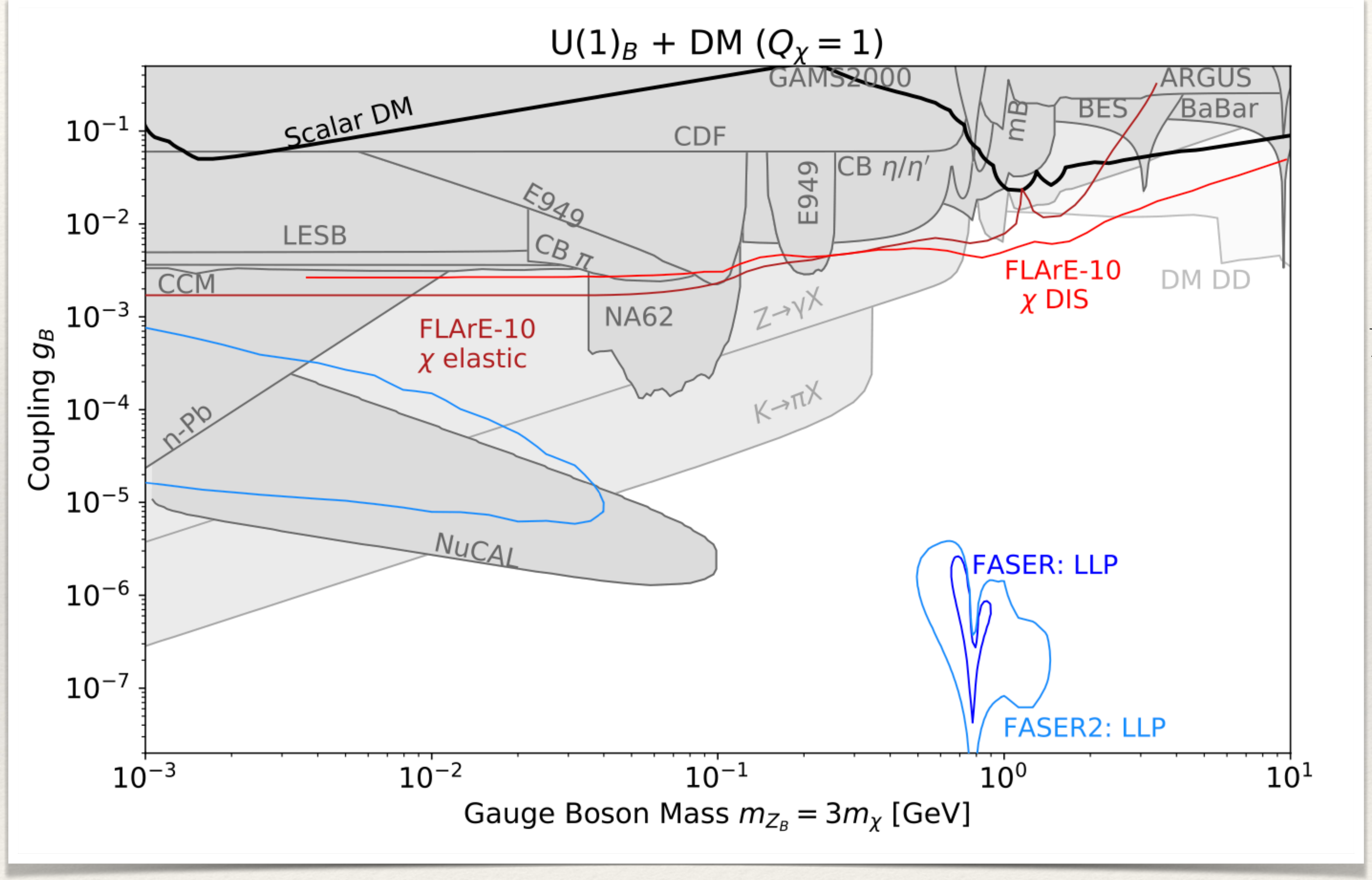
FPF Whitepaper

In blue: leptonic decays

B model

$$J_B^\mu = \frac{1}{3}\sum_q \bar{q}\gamma^\mu q$$

Including DM!



arXiv 2111.10343

Batell, Feng, Fieg, Ismail, Fling, Abraham, Trojanowski

arXiv 2203.05090

FPF Whitepaper

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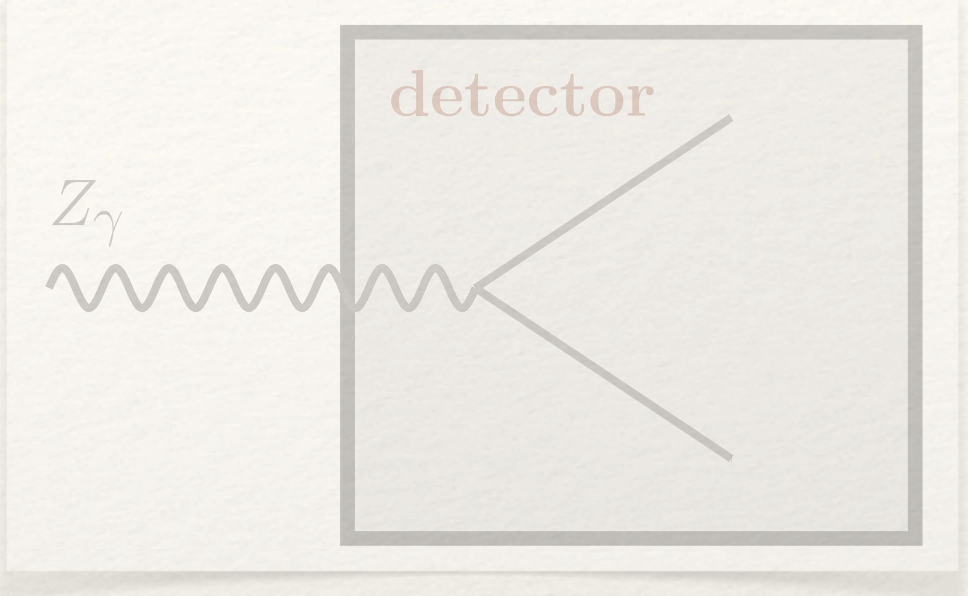

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…and Branching ratios

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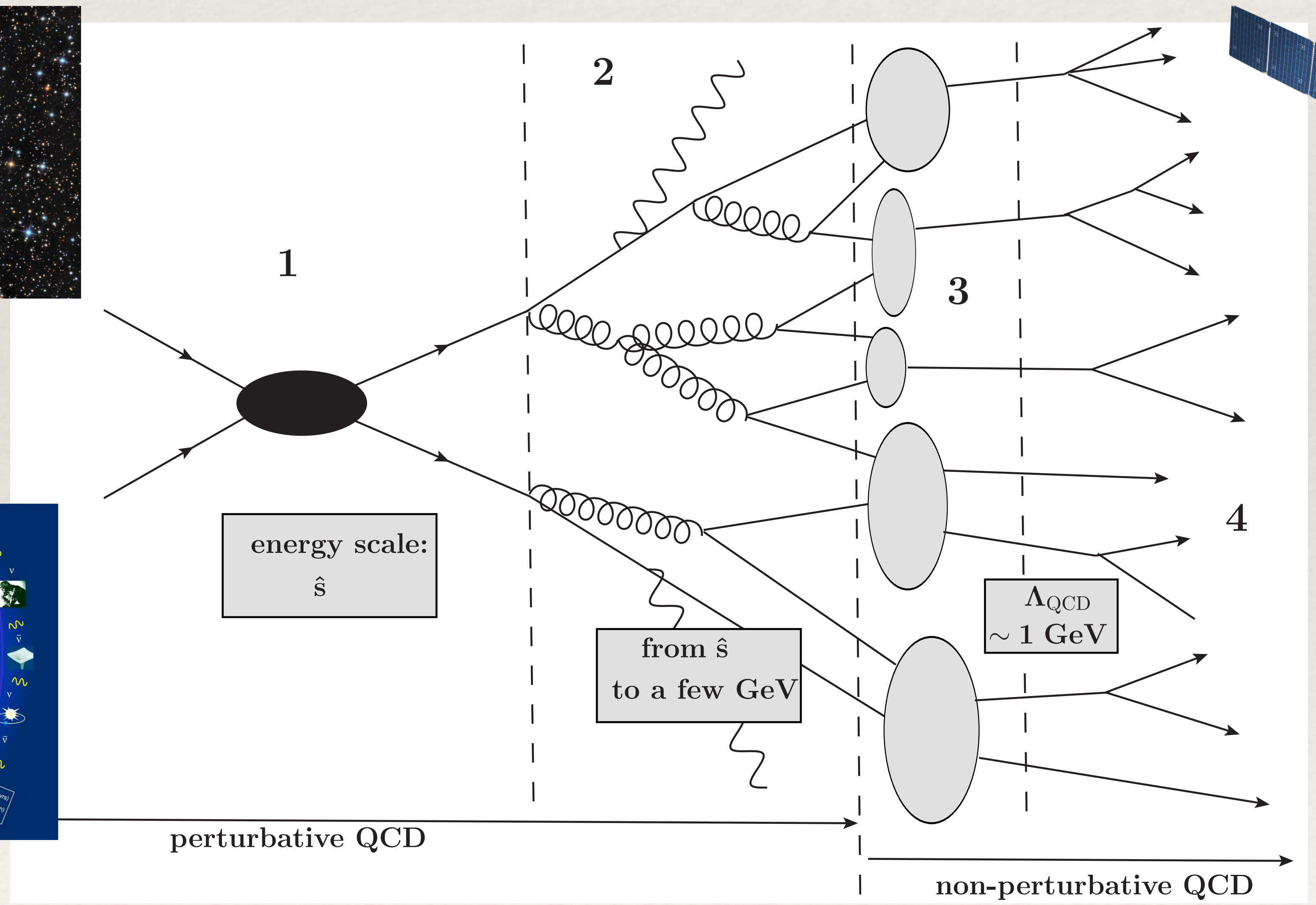
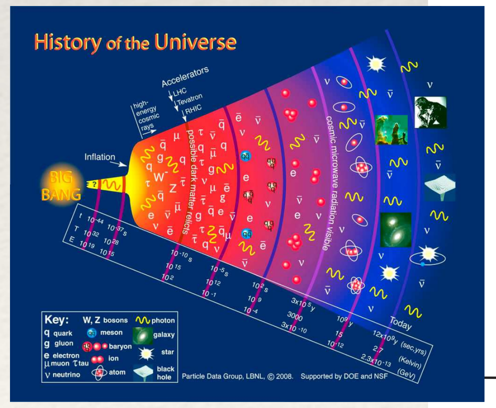
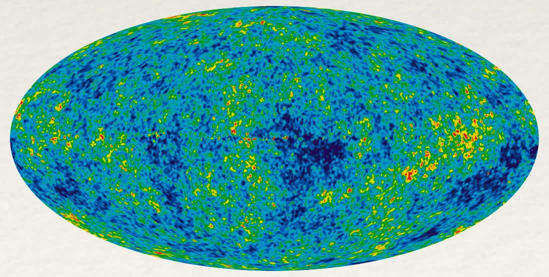




$$\frac{dN}{dE_{kin}}$$



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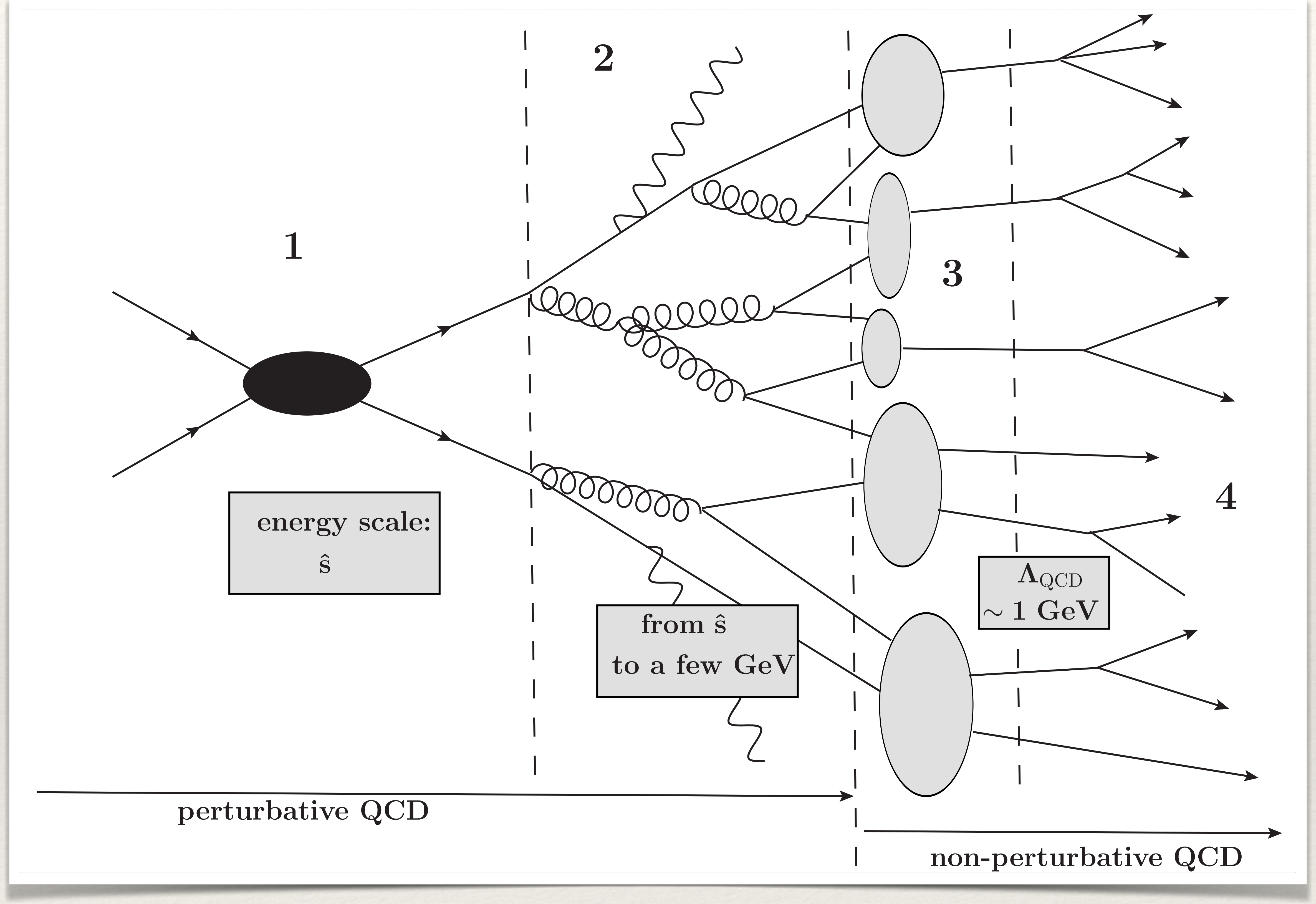


Detection of stable particles

$$e^{\pm}, \gamma, p/\bar{p}, \nu' s$$

$$\frac{\mathrm{d}N}{\mathrm{d}E_{\rm kin}}$$

So far:

- HEP tools: Herwig, Pythia
- Tabulated values: DarkSUSY, micrOmegas, PPPC4DMID, MadDM

$$\sqrt{s} \gtrsim 5 \text{ GeV}$$

Updates

arXiv 1907.11846

arXiv 2104.06168

Adam Coogan, Logan Morrison, Stefano Profumo

Herwig 7

Including error estimate!

arXiv 1911.11147 Tilman Plehn, **PR**, Peter Richardson

arXiv 2102.00041 **PR**

HAZMA

- computing spectra using ChPT
- Constraints from existing gamma-ray data + CMB
- Prospects for upcoming telescopes

2.0: Adam Coogan, Logan Morrison, Tilman Plehn, Stefano Profumo, **PR**

Extension to GeV range!

DarkSUSY

arXiv 2203.07439

Tabulated values
Limited to kinetic mixing, B-coupled models

Torsten Bringmann, Joakim Edsjö

Gamma rays

Sources:

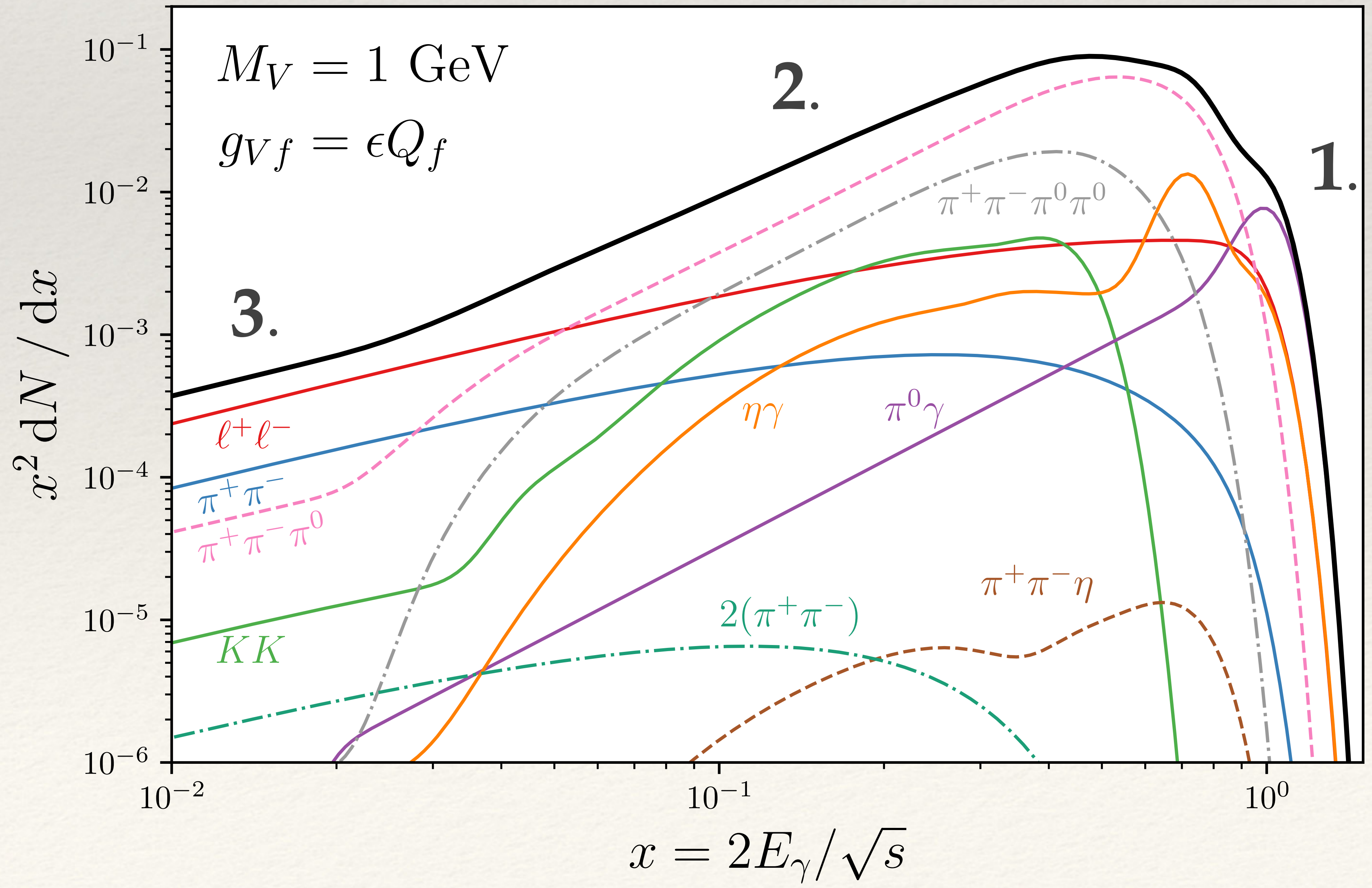
1. Monochromatic γ rays from $\pi^0\gamma$ and $\eta\gamma$

   ➞ Line-like spectrum at $E_\gamma = \dfrac{(E_{\text{c.m.}}^2 - m_P^2)}{2E_{\text{c.m.}}}$ with $P = \pi, \eta$

2. Decays of unstable particles, e.g. $\pi^0 \to \gamma\gamma,\ \eta \to \gamma\gamma$

   ➞ box spectrum in $\pi^0\gamma$, more complicated in consecutive decays, e.g. $K_L^0 \to 2\pi^0 \to 4\gamma$, or $\eta \to 3\pi^0 \to 6\gamma$

3. Final State Radiation (FSR): goes like $\dfrac{\mathrm{d}N}{\mathrm{d}E_\gamma} \propto \dfrac{1}{E_\gamma}$



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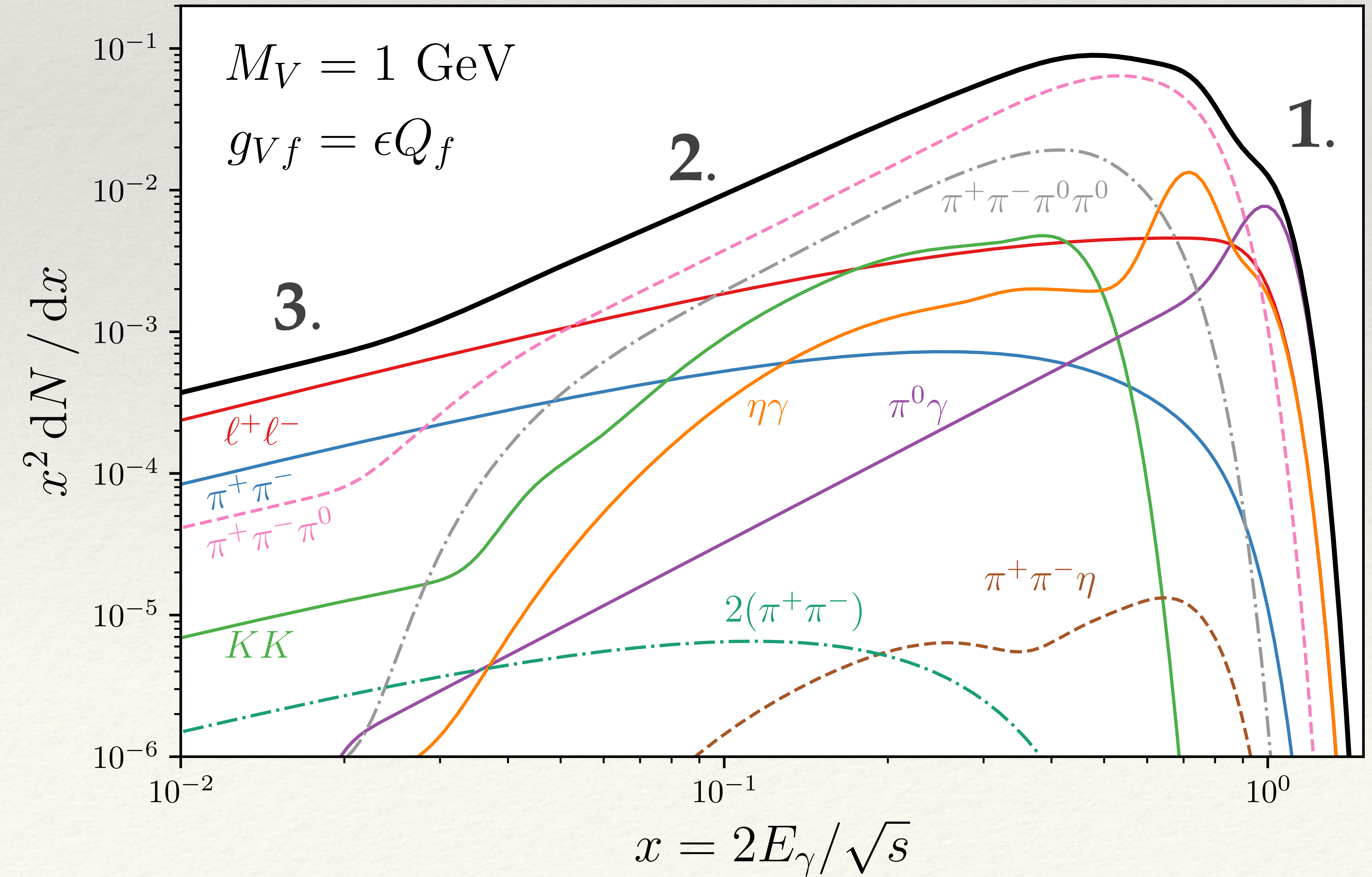
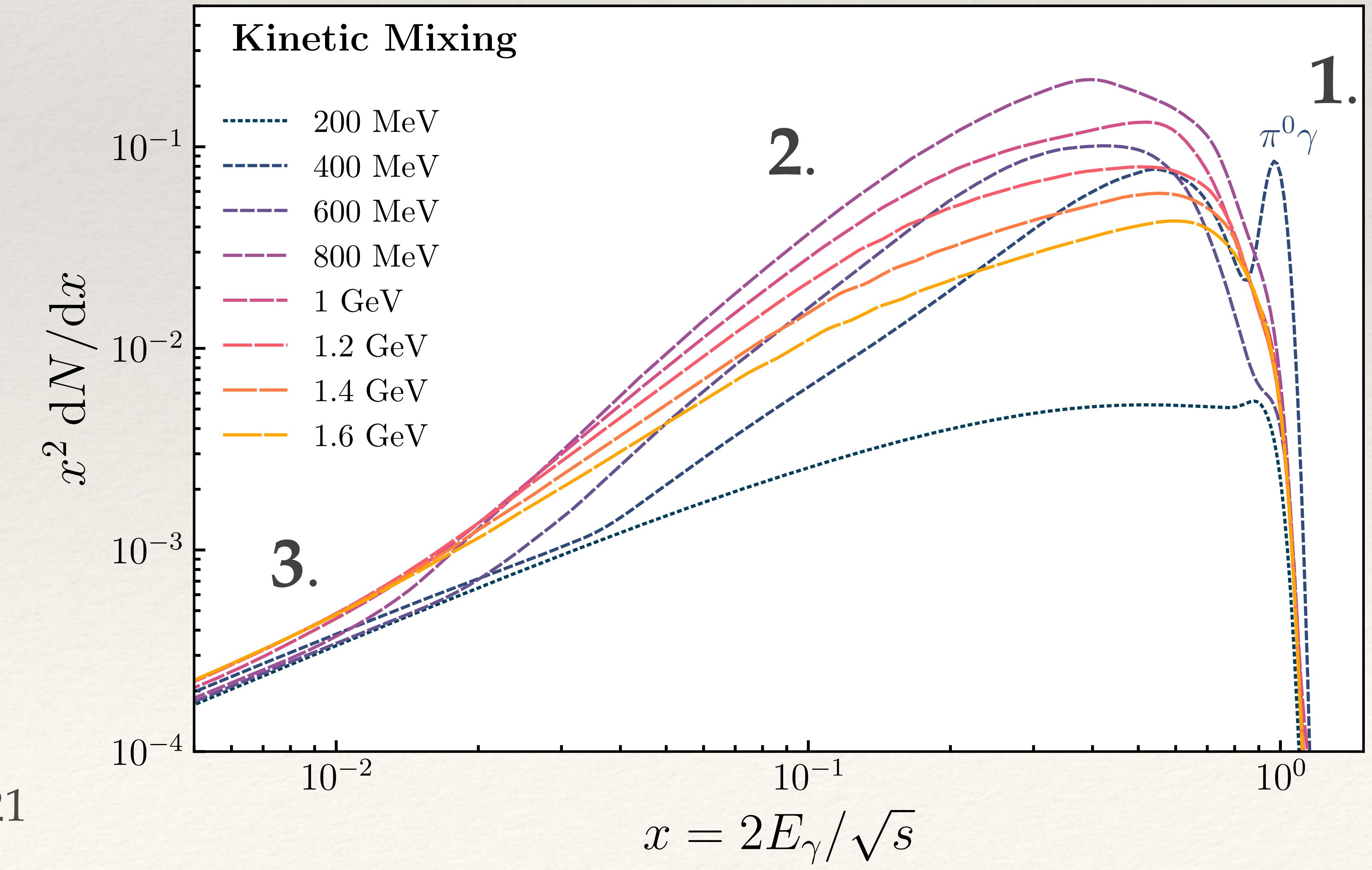
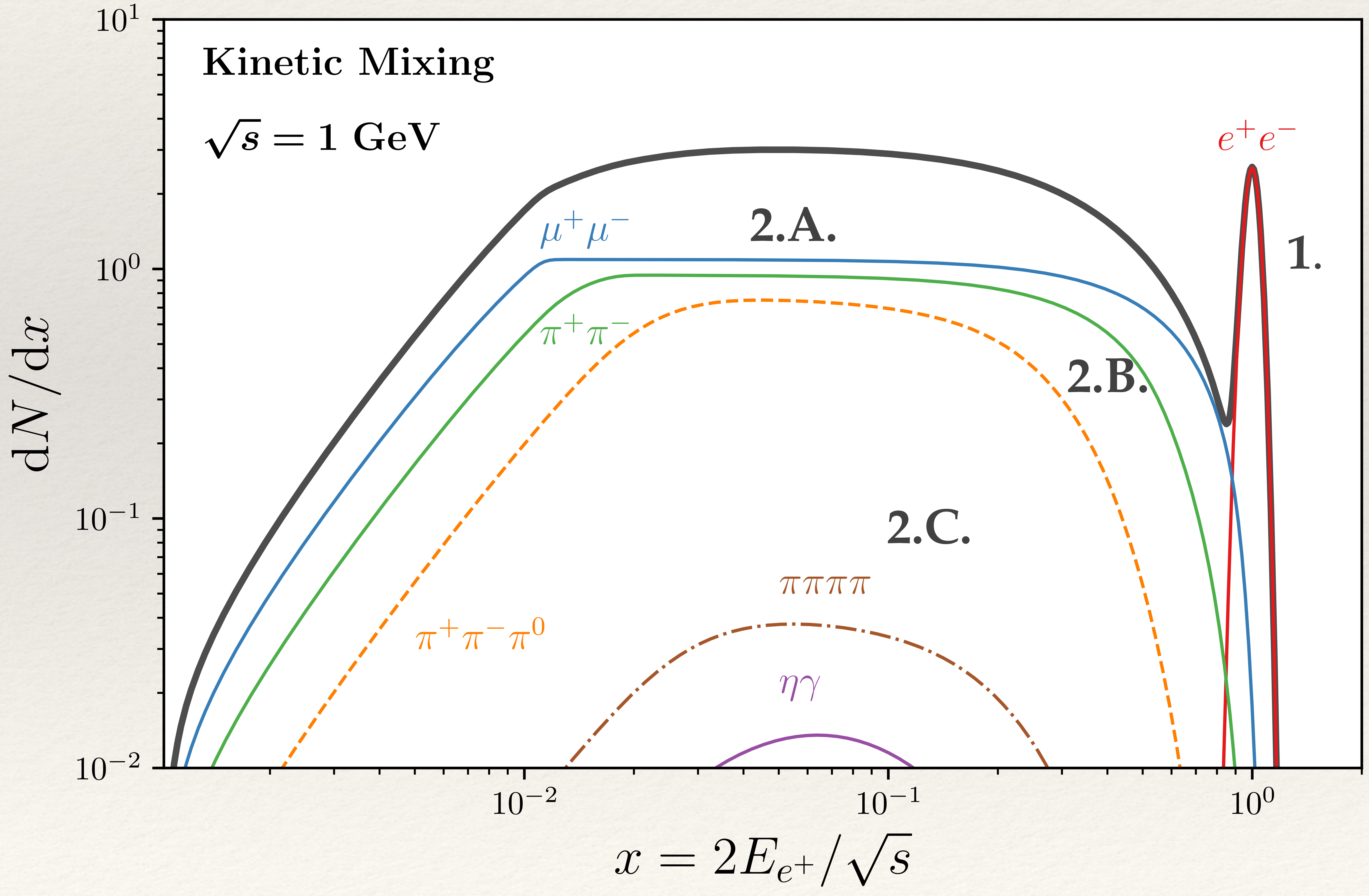




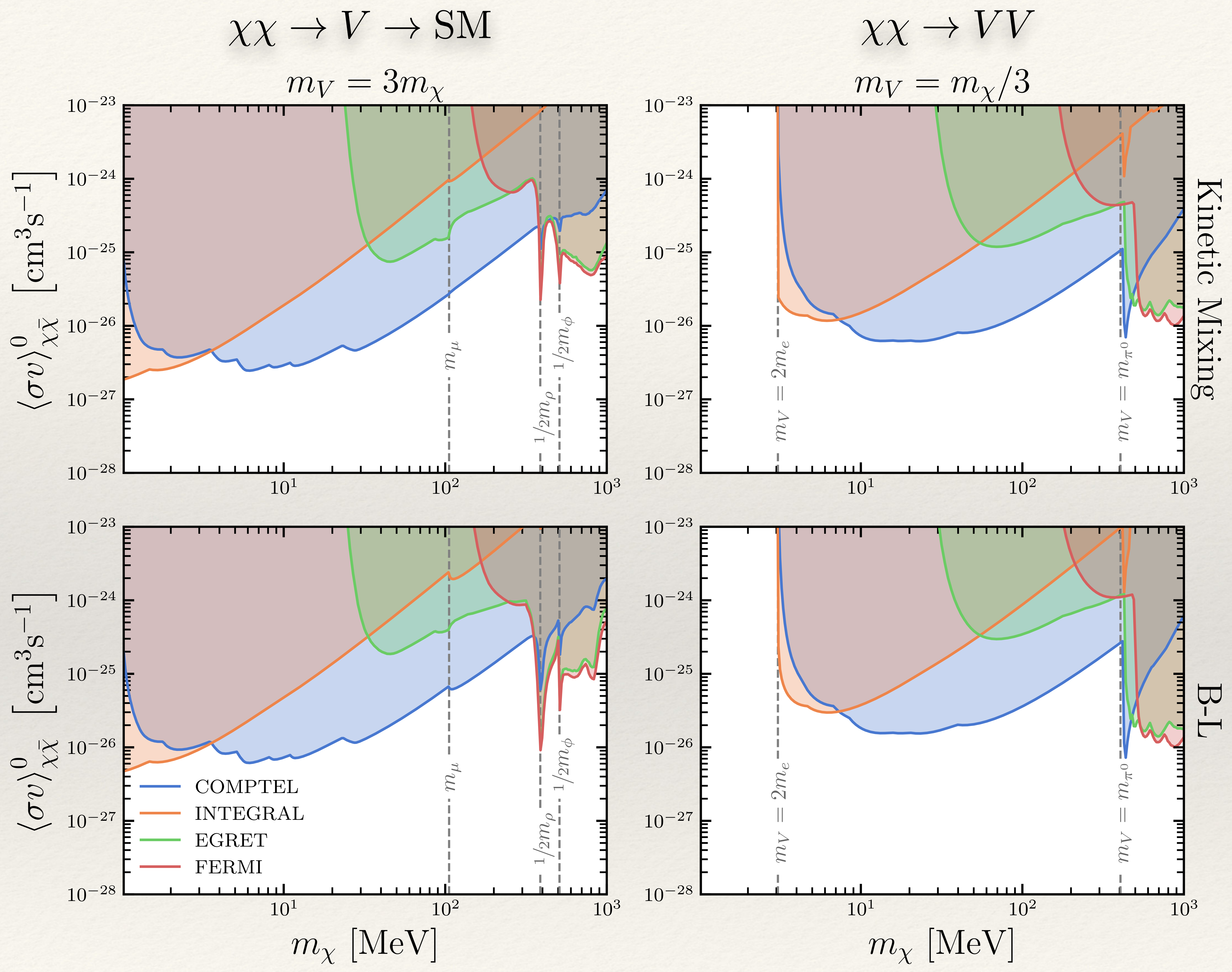
Positron

Sources:

1. Line-like spectrum from e^+e^- at $E_{e^+} = E_{\text{c.m.}}/2$
2. Decay from unstable particles:
   A. Muon decay spectrum: analytic form including bounds of integration from boost into lab frame
   B. Pion decay spectrum is boosted version
   C. Others more round



Limits:



$\chi\chi \to V \to \mathrm{SM}$
$m_V = 3m_\chi$
$\chi\chi \to VV$
$m_V = m_\chi/3$
Kinetic Mixing
B-L
$\langle\sigma v\rangle^0_{\chi\bar{\chi}}$ $[\mathrm{cm}^3\mathrm{s}^{-1}]$
m_χ [MeV]
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^1
10^2
10^3
m_μ
$1/2m_\rho$
$1/2m_\phi$
$m_V = 2m_e$
$m_V = m_{\pi^0}$
COMPTEL
INTEGRAL
EGRET
FERMI

Conclusions

- Robust description of decays into various hadronic final states for vector particles with arbitrary couplings
- Improvements compared to previous calculations of widths, branching ratios, lifetime
- **DE**cays of **LI**ght **VE**ctors **R**evised (DELIVER) Code available on Github
- Forward physics Facility: Important for experiments like FASER2
- Indirect Detection: Energy spectra can now be calculated for models with vector particles in the GeV and sub-GeV region
    1. with Herwig (MC generation), DarkSUSY (tabulated spectra)
    2. with Hazma: Full Indirect Detection pipeline from process to limit

2.0

Publicly available soon!