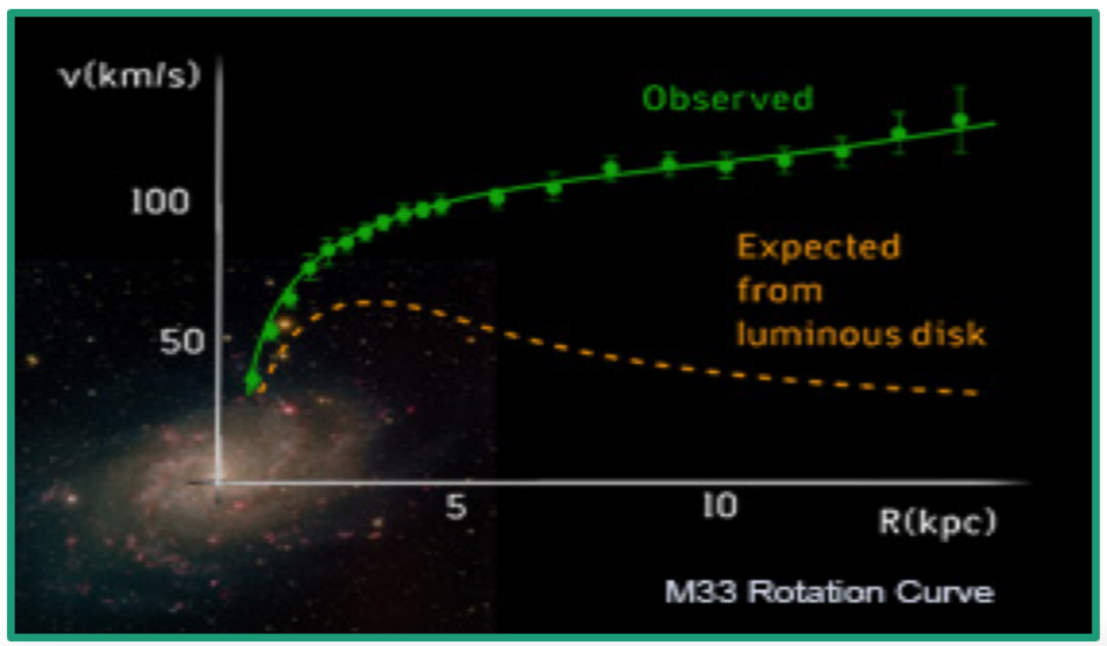
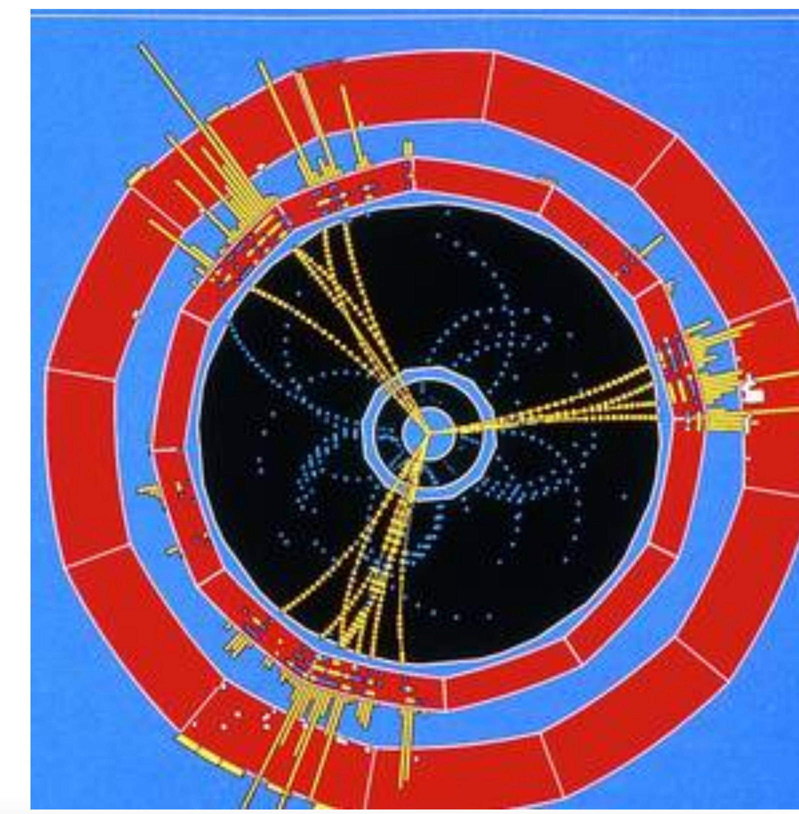
# CosmiXs: Cosmic messenger spectra for indirect dark matter searches



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GAMBIT XVI @LNF
Frascati, 16-20 September 2024

Based on 2312.01153 (JCAP)
w/ C. Arina, M. Di Mauro, N. Fornengo, J. Heisig, and R. Ruiz de Austri

# Existing tools in the market

CERN-PH-TH/2010-057 SACLAY–T10/025 IFUP-TH/2010-44

## PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

Marco Cirelli[a,b], Gennaro Corcella[c,d,e], Andi Hektor[f], Gert Hütsi[g], Mario Kadastik[f], Paolo Panci[a,h,i,j], Martti Raidal[f], Filippo Sala[d,e], Alessandro Strumia[a,e,f,k]

(arXiv: 1012.4515)

Will be denoted by PPPCDM

- Using PYTHIA version 8135, they have calculated the spectra of stable particles for DM masses from 5 GeV to 100 TeV.
- They included electroweak corrections (relevant for DM masses > 1 TeV)

Cons:

- Old version of PYTHIA8 was used (released nearly 13 years ago).
- Large cutoff on the minimum transverse momentum for photons emitted off lepton lines in the shower ($10^{-4} \to 10^{-6}$)
- Electroweak corrections were added by brute force (not resummed).
- Polarization information is absent.
- Off-shell effects were not taken into account.

# Existing tools in the market

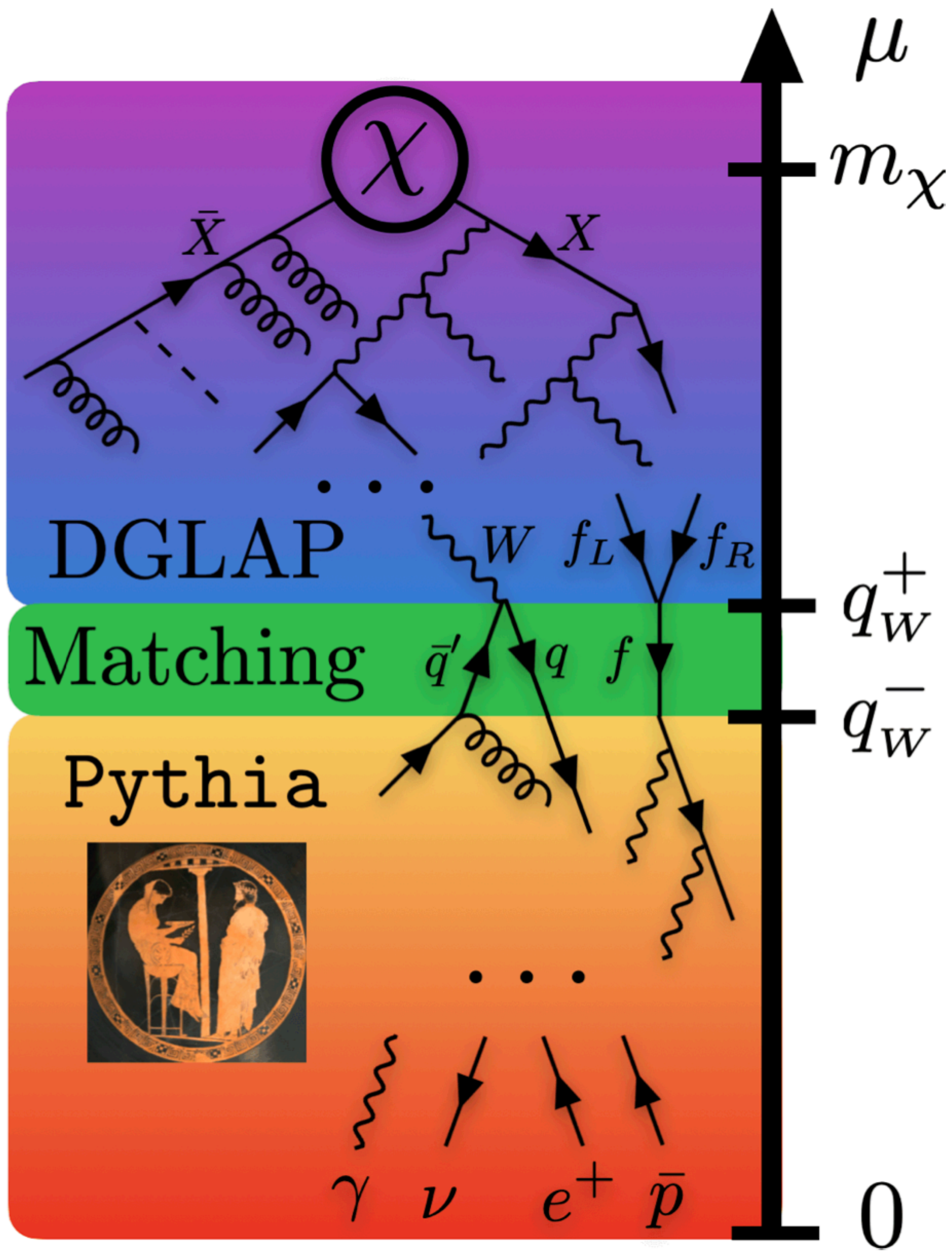
**Dark Matter Spectra from the Electroweak to the Planck Scale**

Christian W. Bauer,[1,2] Nicholas L. Rodd,[1,2] Bryan R. Webber[3]

[1] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*
[2] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *University of Cambridge, Cavendish Laboratory, J.J. Thomson Avenue, Cambridge, UK*

(arXiv: 2007.15001)

Will be denoted by HDMSpectra




- Spectra of dark matter annihilation/decay were calculated using analytical methods and matched to PYTHIA at the electroweak scale (including electroweak corrections).
- Lack mass effects which influence their results for small energies.
- The decays of heavy resonances is handled by HDMS (there is no interleaving with the rest of the shower).

# Existing tools in the market

Prepared for submission to JHEP

## Estimating QCD uncertainties in Monte Carlo event generators for gamma-ray dark matter searches

Simone Amoroso,[a] Sascha Caron,[b,c] Adil Jueid,[d] Roberto Ruiz de Austri[e] and Peter Skands[f]

(arXiv: 1812.07424)

Prepared for submission to JHEP — CTPU-PTC-23-08

## The Strong Force meets the Dark Sector: a robust estimate of QCD uncertainties for anti-matter dark matter searches

Adil Jueid,[a] Jochem Kip,[b] Roberto Ruiz de Austri[c] and Peter Skands[d]

(arXiv: 2303.11363)

Will be denoted by QCDUnc

Prepared for submission to JCAP

## Impact of QCD uncertainties on antiproton spectra from dark-matter annihilation

Adil Jueid,[a] Jochem Kip,[b] Roberto Ruiz de Austri[c] and Peter Skands[d]

(arXiv: 2202.11546)

- New spectra of DM cosmic messengers using new tunes of PYTHIA 8 (version 2.19 and 3.07)
- Estimated QCD uncertainties using parametric variations of the hadronization parameters.
- Estimated the impact on the best-fit point of the fitted DM mass and thermally-averaged annihilation cross section (in a two-parameter model).

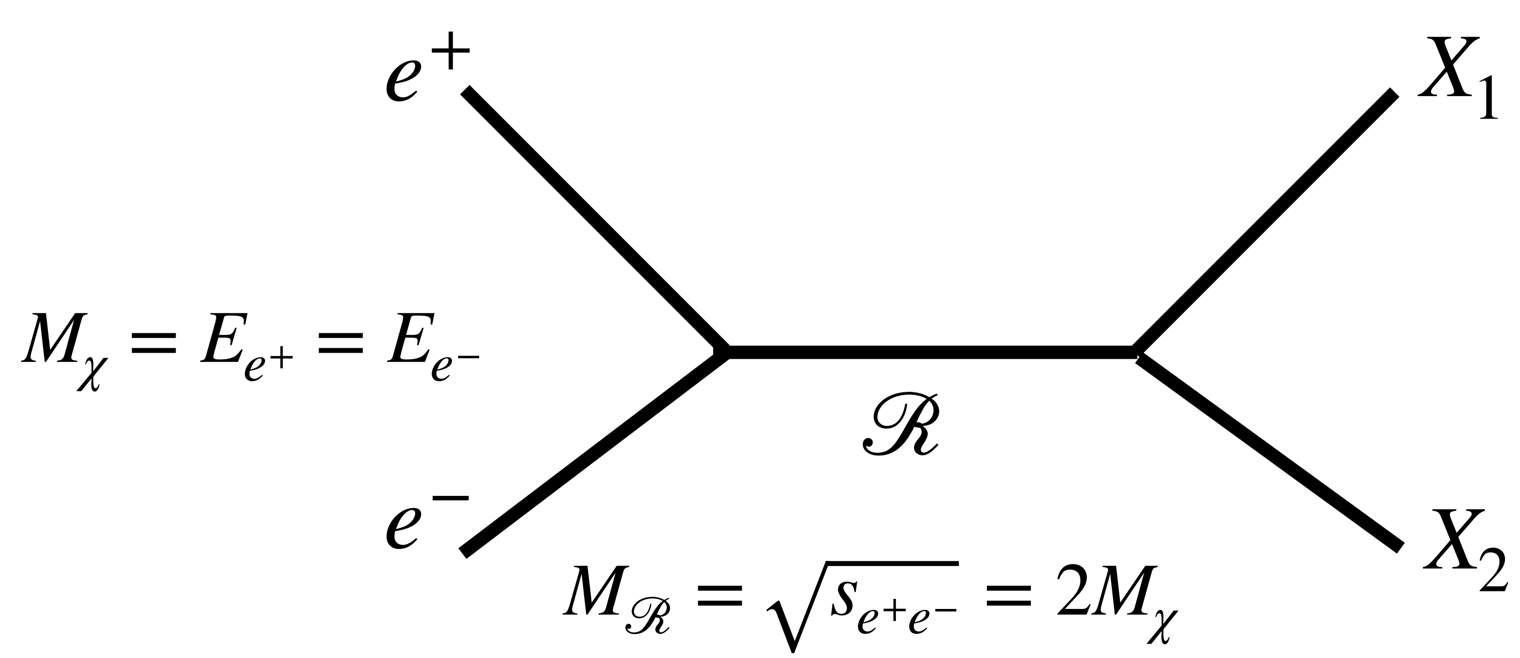
Cons:

- No electroweak corrections were included.
- Can only be used reliably for hadronic channels.

# How to calculate the spectra?

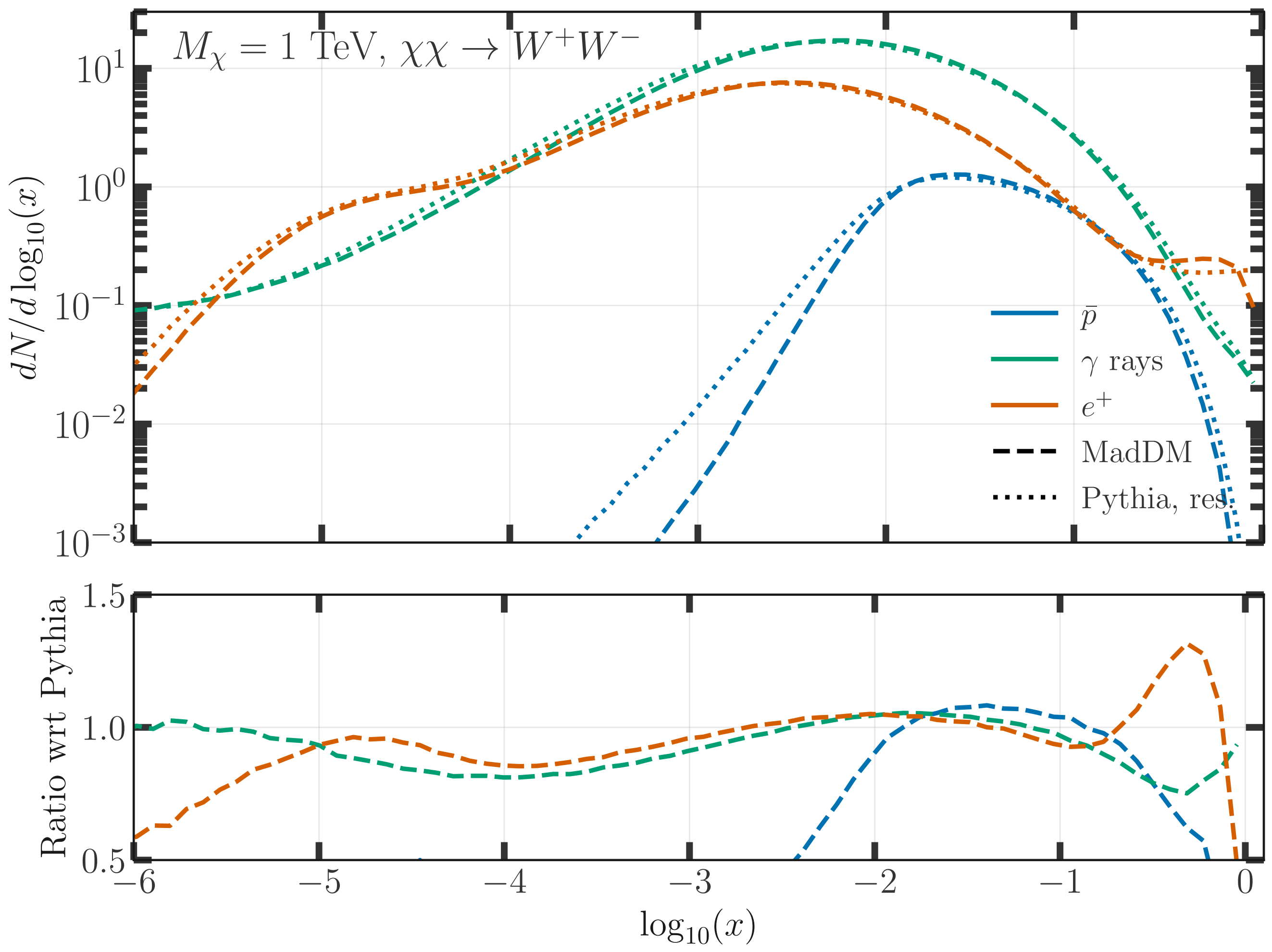
The standard tools calculate the spectra using PYTHIA 8 (can be found within the code).

In the calculation, the DM annihilation via a $2 \to 2$ process assuming $e^+e^-$ as incoming beams which produce a resonance $\mathscr{R}$ (spinless) with a mass equal to twice the DM mass and removing all the QED radiation.
$\Longrightarrow$ this case resemble the annihilation of fermionic DM (e.g. neutralinos).
$\Longrightarrow$ Spin information is lost as the outgoing particles do not have assigned helicities.
$\Longrightarrow$ Electroweak corrections will not be taken properly into account.



# What is missing?

- We use instead MadDM (arXiv: 1804.00044) to calculate the spectra.
- MadDM is a DM calculator based on Madgraph5_aMC@NLO which therefore produces LHEF that are interfaced to any shower program to add Parton showering and hadronization.
- We interface MadDM to VINCIA shower plugin to add electroweak corrections.
- For the models, we assume three classes of simplified models: Higgs portal at NLO, spin-0 pseudo scalar mediator and spin-1 mediator.



# Modeling of the spectra

## To simplify the discussion, we consider the generic annihilation process

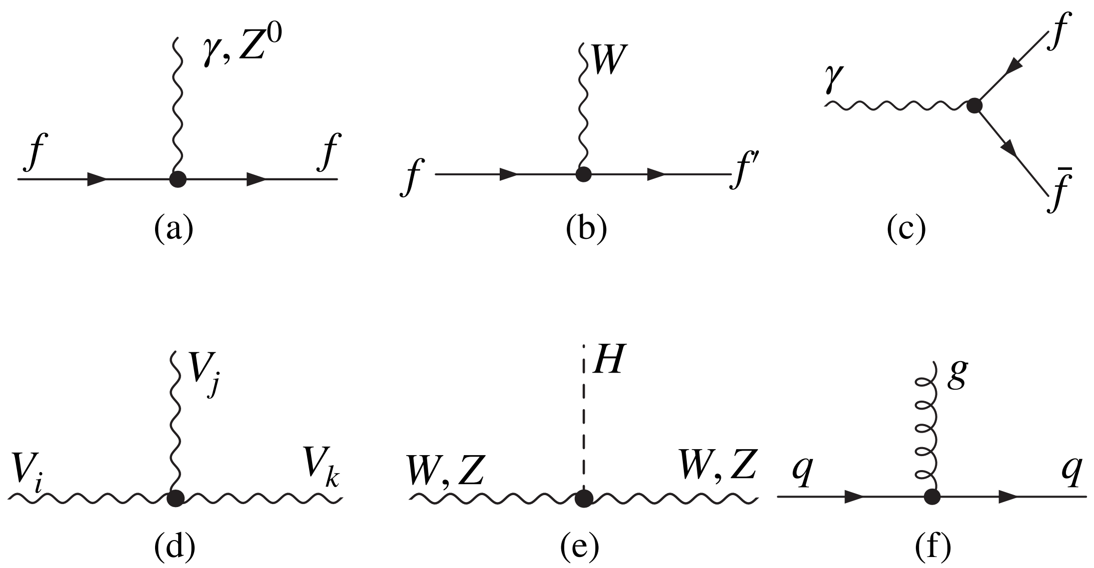
$$\chi\chi \to X_1 \cdots X_N \to \left(Y_{11} \cdots Y_{1a_1}\right) \cdots \left(Y_{N1} \cdots Y_{Na_N}\right)$$

Parton-level hard process

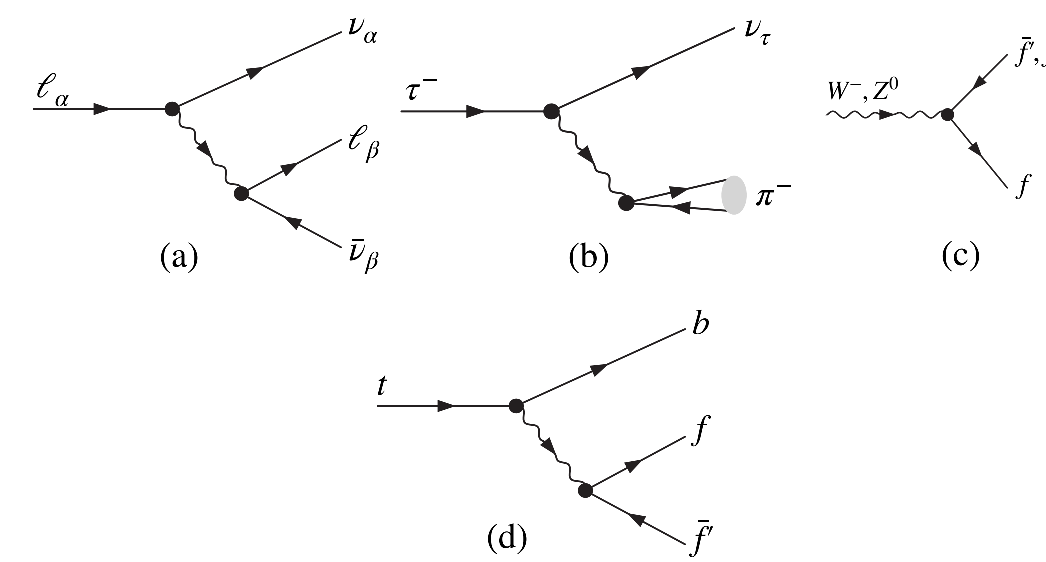
Stable particles

The underlying physics depends on the nature of the produced resonance $X_i$ and the particles produced in its decay ($Y_{ij}$).

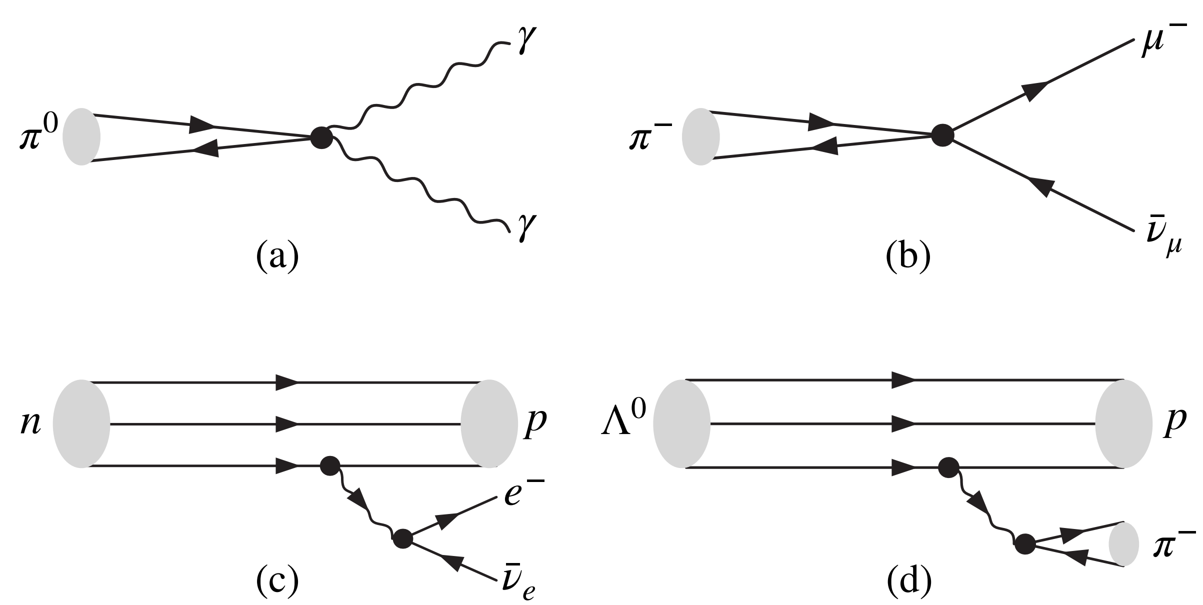
# Summary of leading contributions




QED+QCD+EW showers

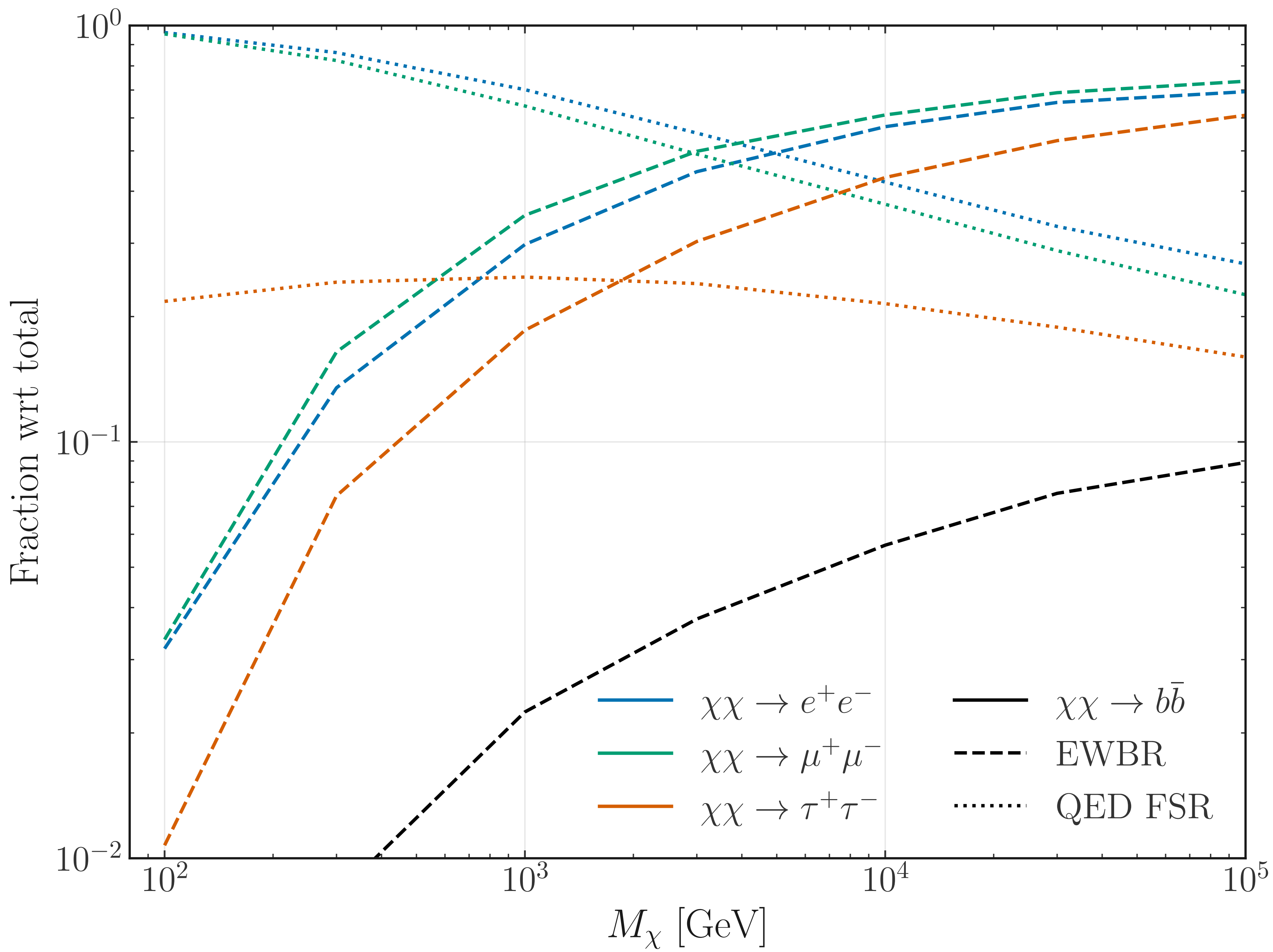



Weak decays




Meson and baryon decays

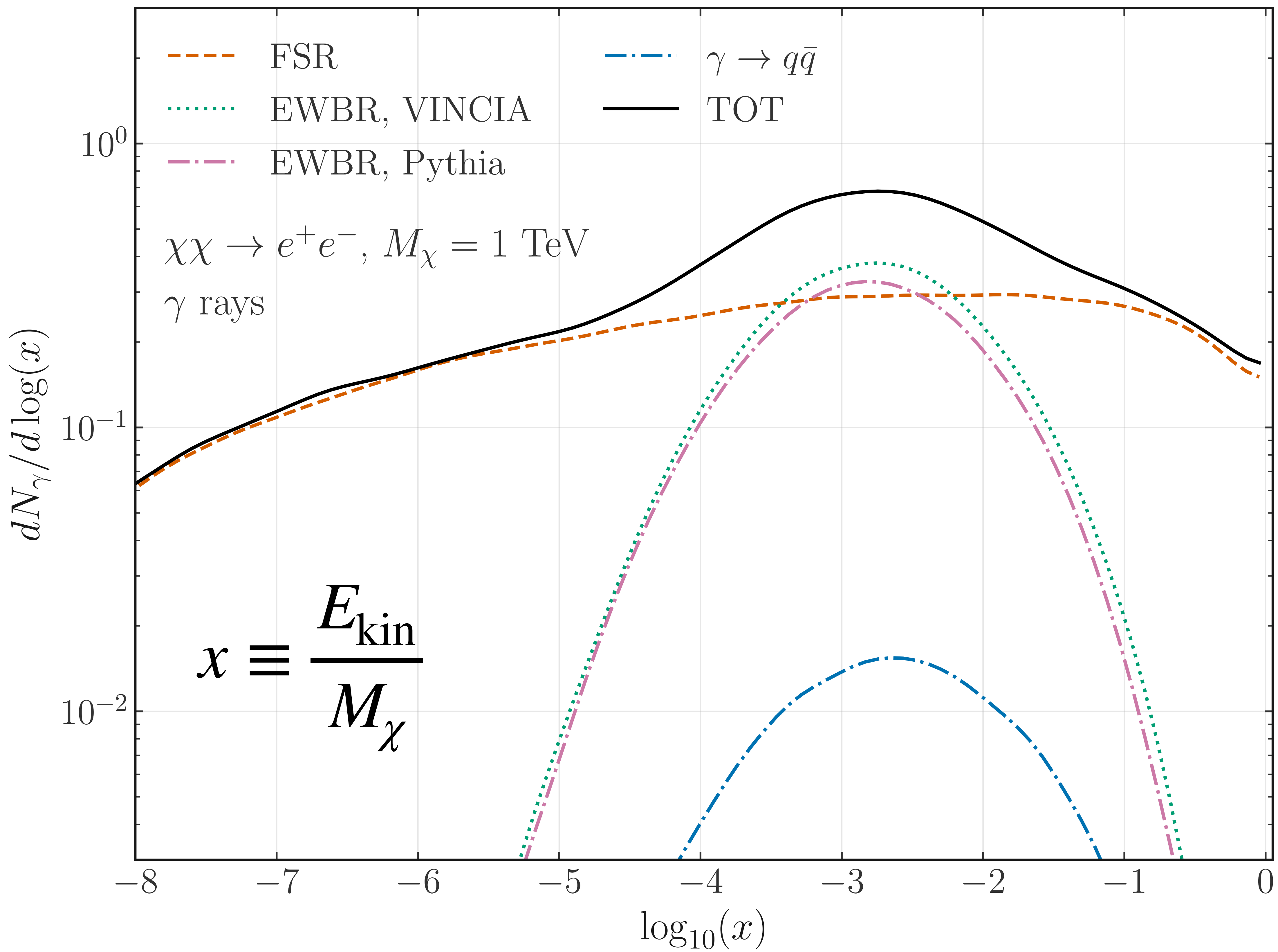
# Generic features of particle production



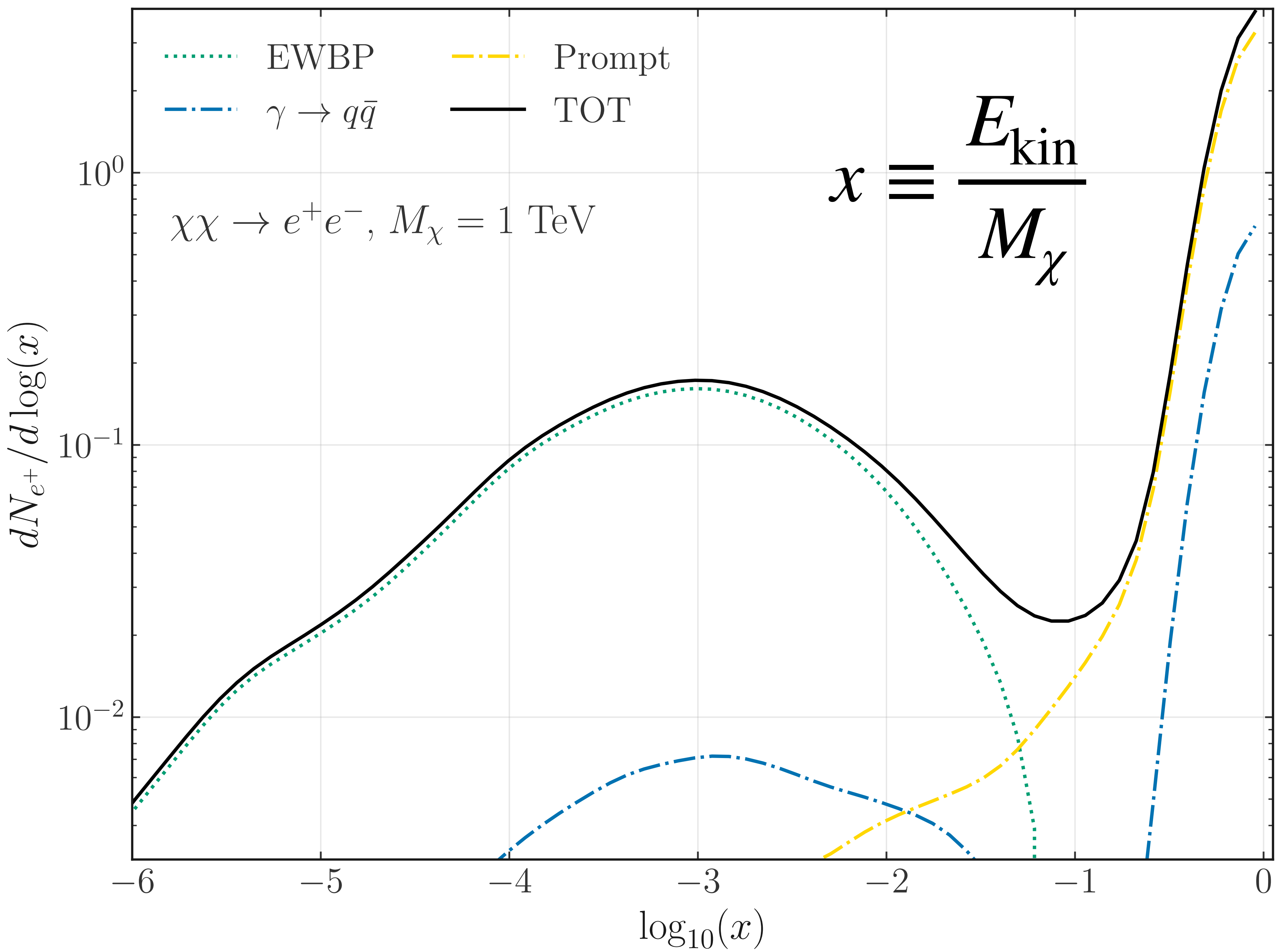

**Fraction with respect to the total number of photons.**

**Clearly EWBR dominates over QED FSR for heavy DM**

# Generic features of particle production



# Generic features of particle production



# Main Novelties of our analysis

- Polarization effects: We use MadDM which we interface with PYTHIA 8 with VINCIA shower plugin being the default option. MadDM produces LHEF where helicity information is written.

- Resummed electroweak corrections and interleaved resonance decays: The electroweak corrections are modeled with helicity-dependent Antenna showers and Sudakov form factors. Decays of heavy resonances are interleaved with the rest of the shower machinery.

- Running quark masses and full mass effects: We use running quark masses instead of pole masses.

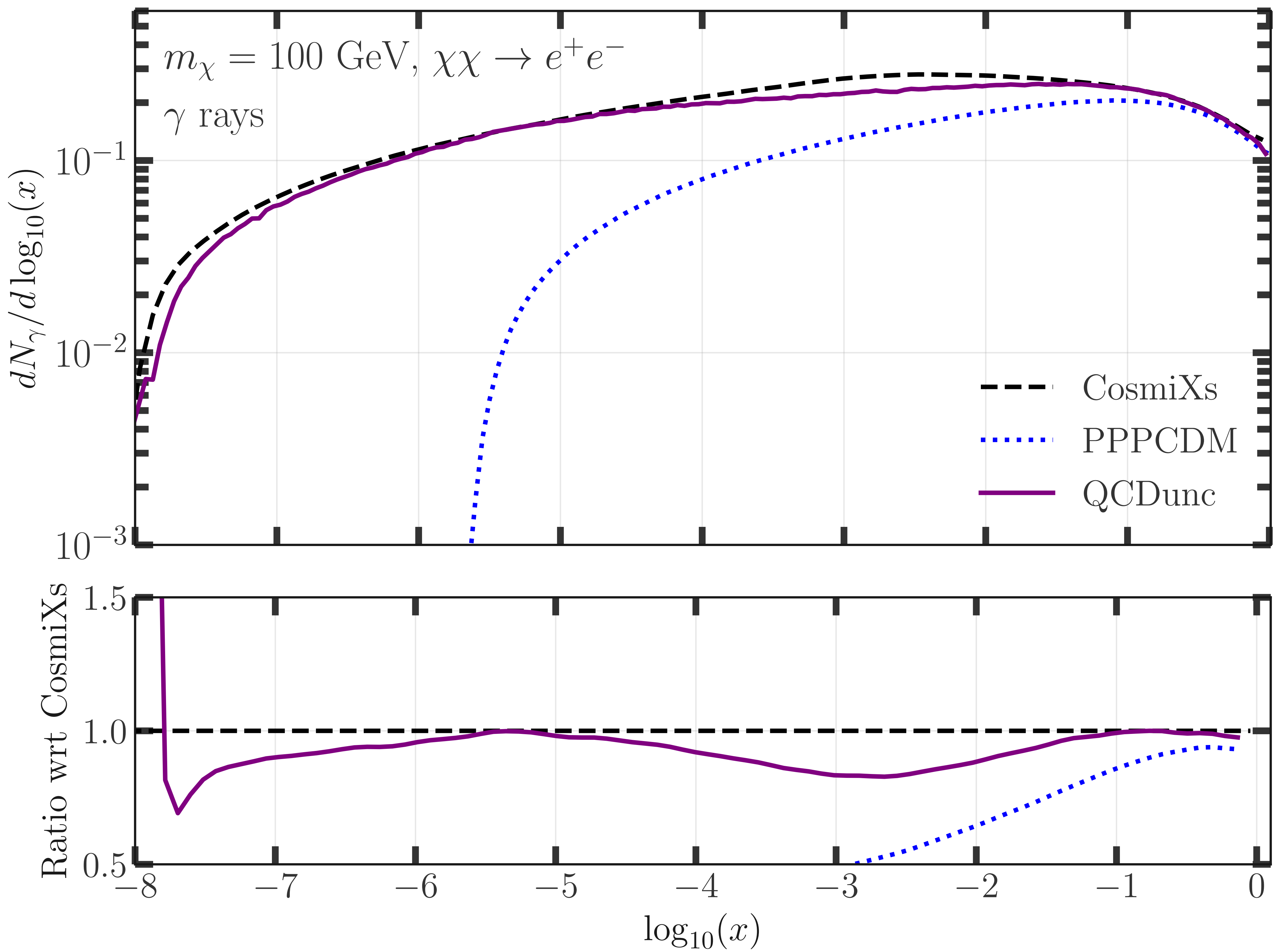
- New annihilation channels: We also calculate the spectra for two new annihilation channels ($\chi\chi \to \gamma Z, HZ$).

- Off-shell effects: We take into account off-shell effects. For the case of $WW, ZZ, HZ$ we generate the spectra of the four-body decays and DM masses down to 5 GeV.

- Full one-loop effects: For one-loop induced annihilation channels ($\gamma\gamma, \gamma Z, gg$), we take into account the full one-loop effects instead of effective couplings.

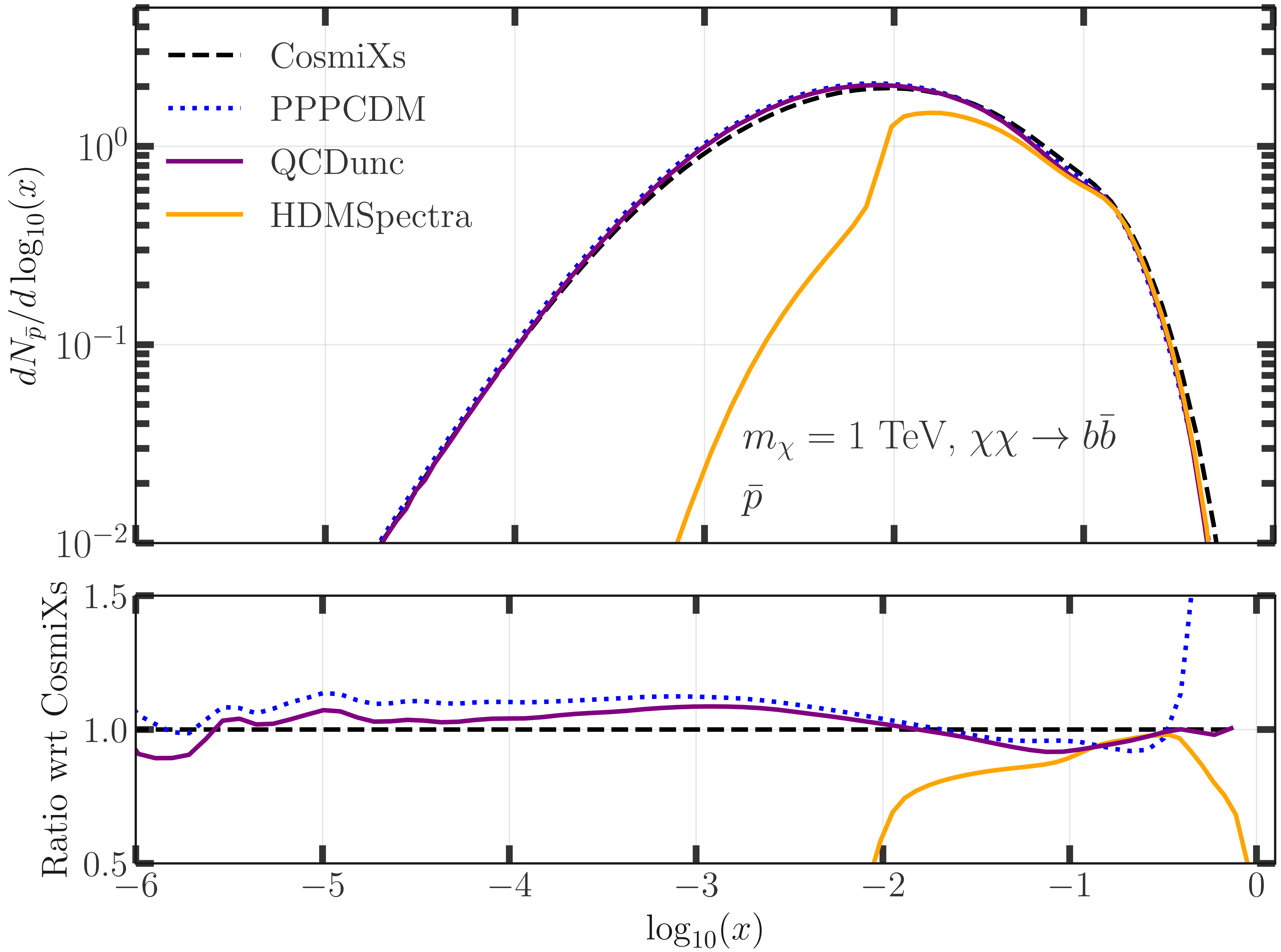
- Improved hadronization model: We carry out a new tuning of the hadronization model parameters using a set of measurements performed at the Z-boson pole.

# Comparison

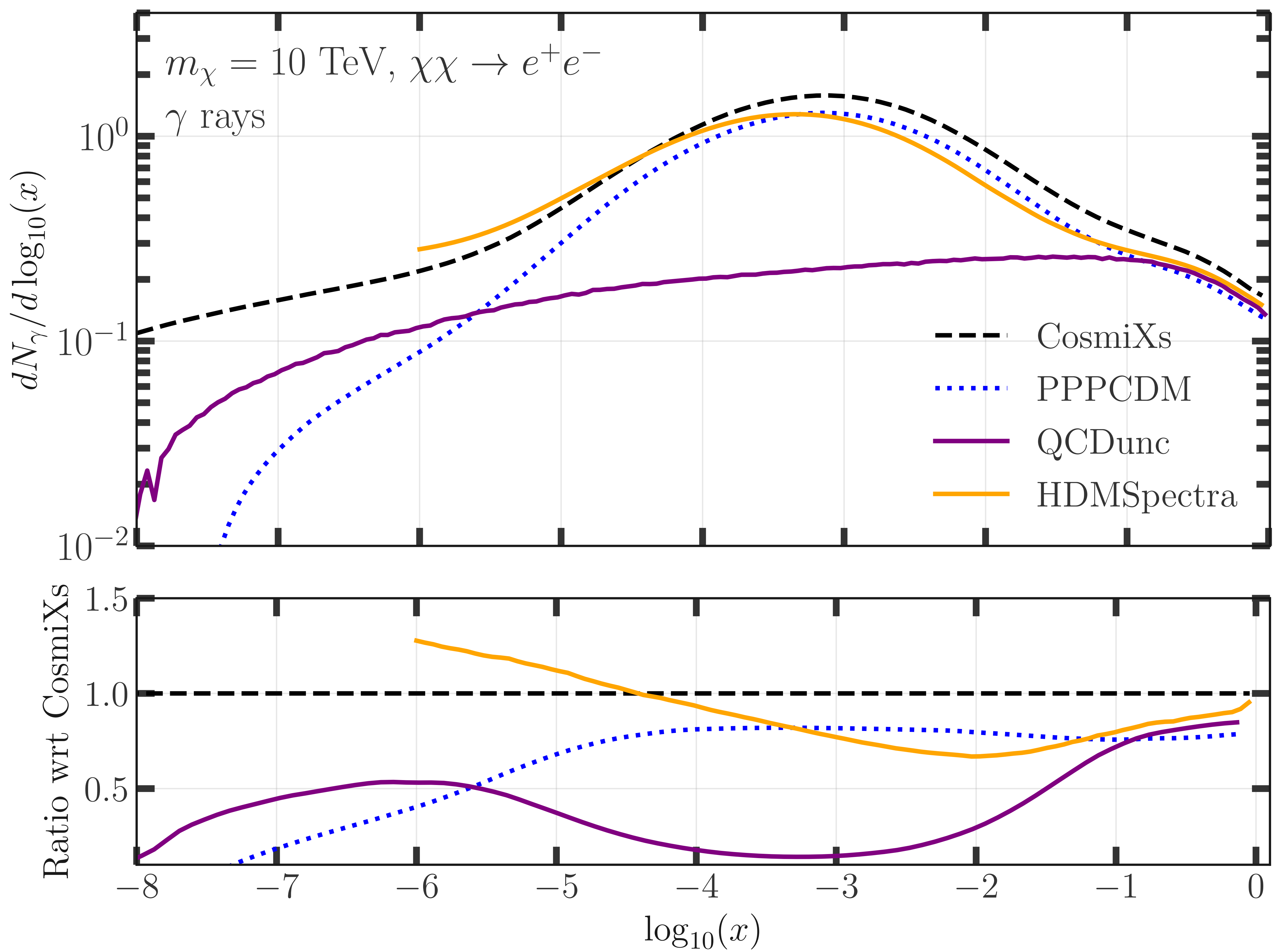


$m_\chi = 100$ GeV, $\chi\chi \to e^+e^-$
$\gamma$ rays
$dN_\gamma / d\log_{10}(x)$
$10^{-1}$
$10^{-2}$
$10^{-3}$
CosmiXs
PPPCDM
QCDunc
Ratio wrt CosmiXs
1.5
1.0
0.5
−8
−7
−6
−5
−4
−3
−2
−1
0
$\log_{10}(x)$

# Comparison


CosmiXs
PPPCDM
QCDunc
HDMSpectra
$m_\chi = 1$ TeV, $\chi\chi \to b\bar{b}$
$\bar{p}$
$dN_{\bar{p}}/d\log_{10}(x)$
$10^0$
$10^{-1}$
$10^{-2}$
Ratio wrt CosmiXs
1.5
1.0
0.5
−6
−5
−4
−3
−2
−1
0
$\log_{10}(x)$

# Comparison


$m_\chi = 10$ TeV, $\chi\chi \to e^+e^-$
$\gamma$ rays
$dN_\gamma/d\log_{10}(x)$
$10^0$
$10^{-1}$
$10^{-2}$
CosmiXs
PPPCDM
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Ratio wrt CosmiXs
1.5
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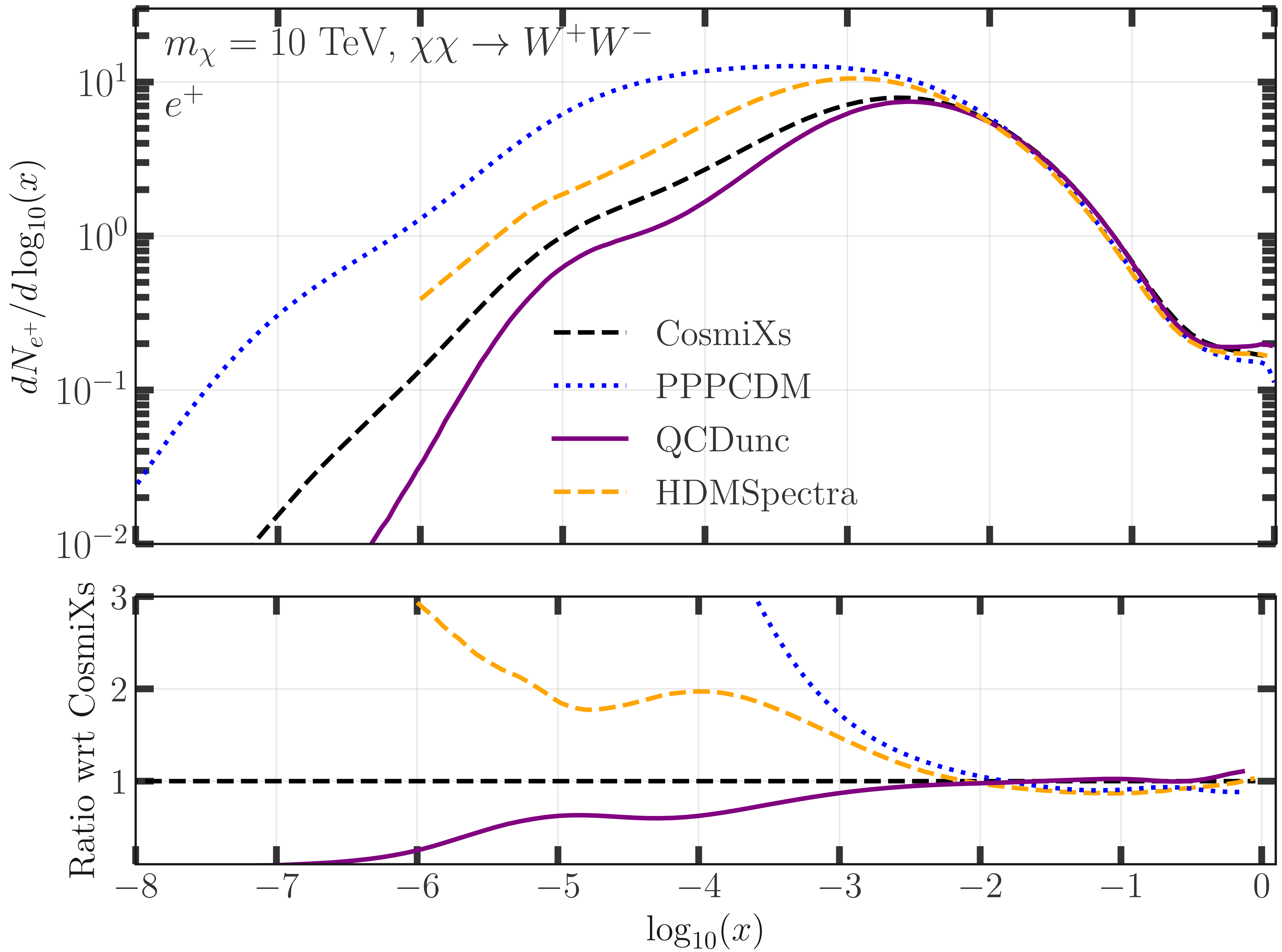
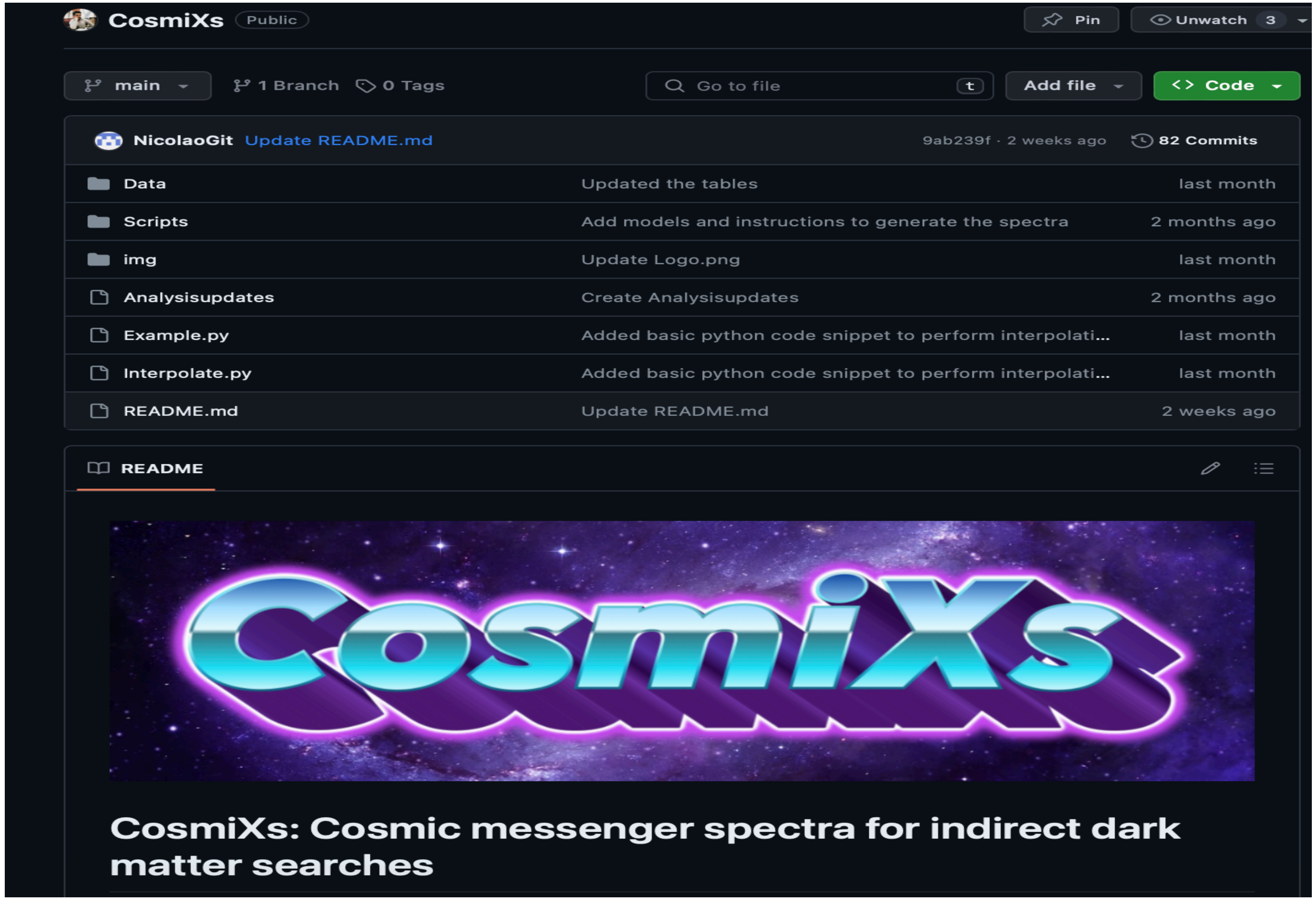
# Comparison



$m_\chi = 10$ TeV, $\chi\chi \to W^+W^-$
$e^+$
$dN_{e^+}/d\log_{10}(x)$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
CosmiXs
PPPCDM
QCDunc
HDMSpectra
Ratio wrt CosmiXs
3
2
1
$-8$ $-7$ $-6$ $-5$ $-4$ $-3$ $-2$ $-1$ $0$
$\log_{10}(x)$

# Public datasets




https://github.com/ajueid/CosmiXs.git

# Conclusions

- We have made significant improvements on the particle spectra from dark matter annihilation.
- These results are relevant for experiments like LHAASO, CTA and IceCube.
- Significant impact on the dark matter fits and beyond the SM analyses is foreseen as differences with the existing tools can not be accounted by any type of uncertainties especially for heavy dark matter.
- Further improvements can be made using e.g. higher order corrections or probably new LHC data.