CosmiXs: Cosmic messenger spectra for indirect dark matter searches

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arXiv:2411.04815

CosmiXs

MadDM

Darktools, June 19th Torino 2025

https://theconversation.com/why-do-astronomers-believe-in-dark-matter-122864

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Dark matter search strategies

Gamma-ray flux from dark matter

Velocity averaged annihilation cross-section

Signal intensity:
[photon flux per steradian per energy]

Photon energy spectrum per annihilation

Source spectra

$$\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds\ \rho(\vec{r}[s,\Omega])^2$$

Dark matter mass

Dark matter mass density

Line-of-sight integral

Particle Physics

Astrophysics

Characteristic **Energy Spectrum**

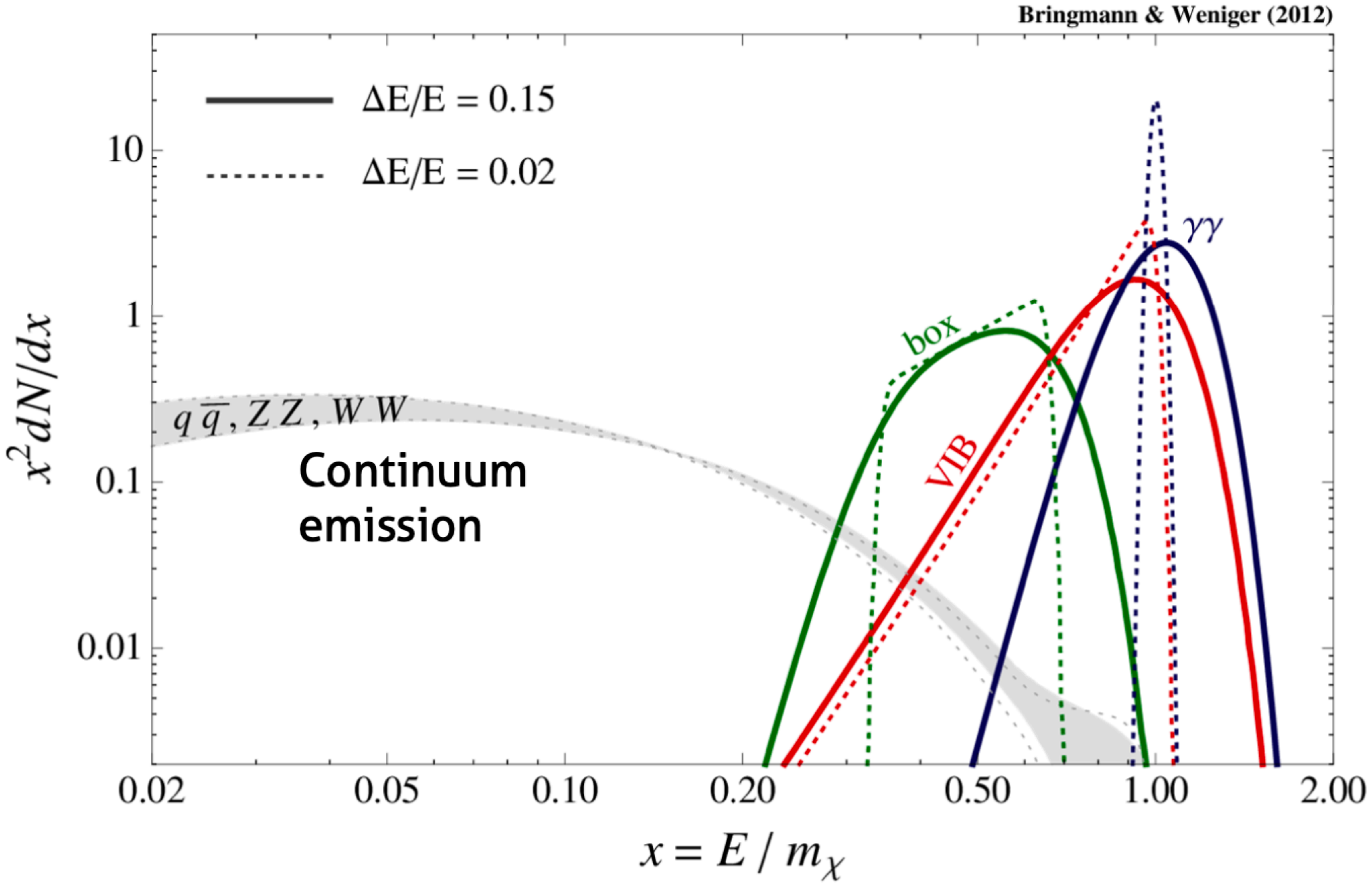
Characteristic **Morphology**
(point-like, extended or diffuse)

[review DM searches with gamma rays: Bringmann & Weniger (2012)]

It is convenient to define a "J-value":

$$J_{\Delta\Omega} \equiv \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} ds \rho(r[s, \vec{\Omega}])^2$$

Spectral features of gamma rays from dark matter



Box-shaped spectra
- Cascade-decay into monochromatic photons
- already at tree level

Internal Bremsstrahlung (IB)
- radiative correction to processes with charged final states
- Generically suppressed by O(α)

$$\chi\chi \to \bar{f}f\gamma$$

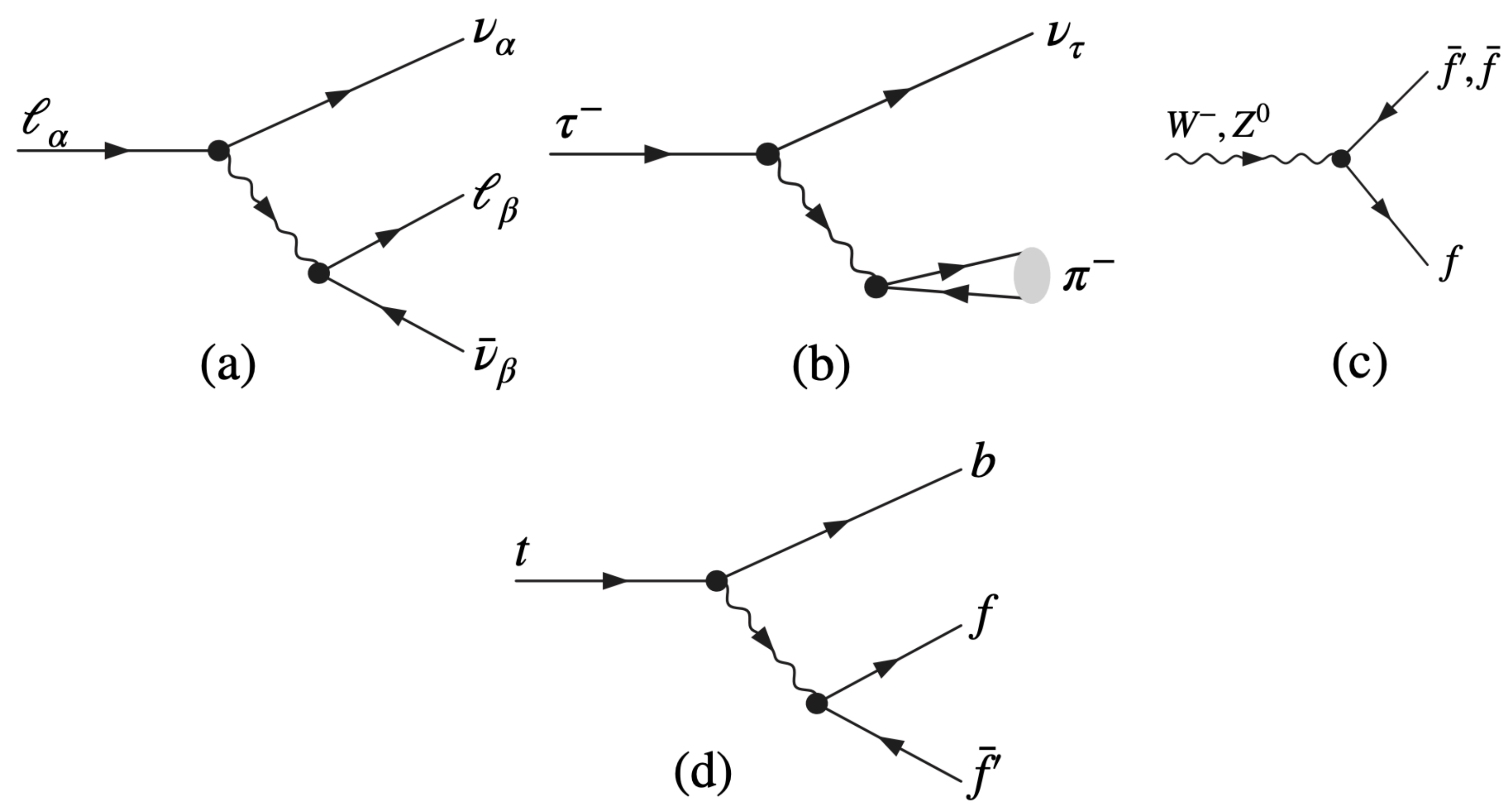
Gamma-ray lines
- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α^2)

$$\chi\chi \to \gamma\gamma$$

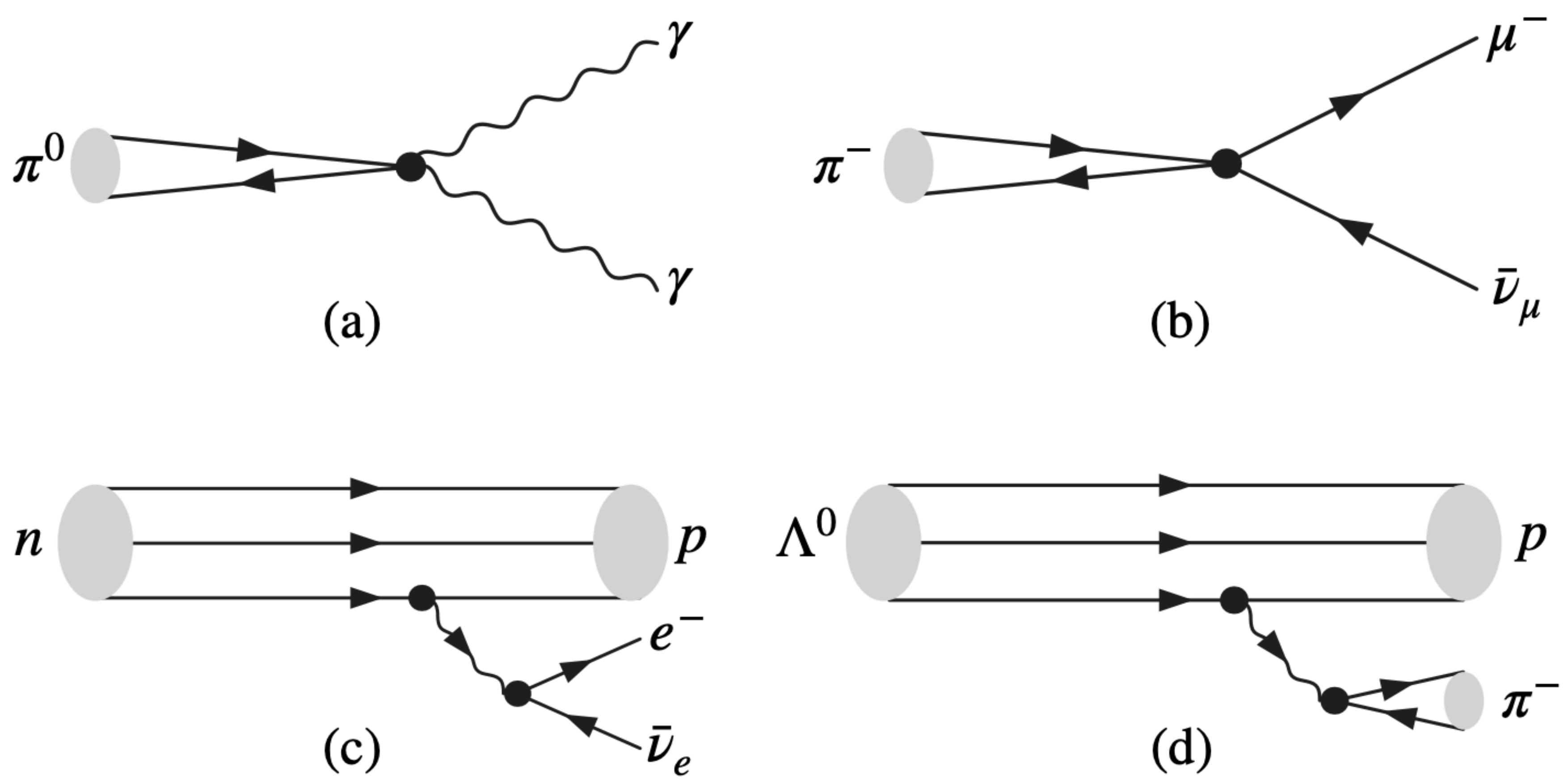
Summary of the possible processes

$$\chi\chi \to \underbrace{\Big[X_1 X_2 \dots X_N\Big]}_{\text{Intermediate states}} \to \overbrace{\Big(Y_{11}\dots Y_{1a_1}\Big)\dots\Big(Y_{N1}\dots Y_{Na_N}\Big)}^{\text{Stable particles}}.$$

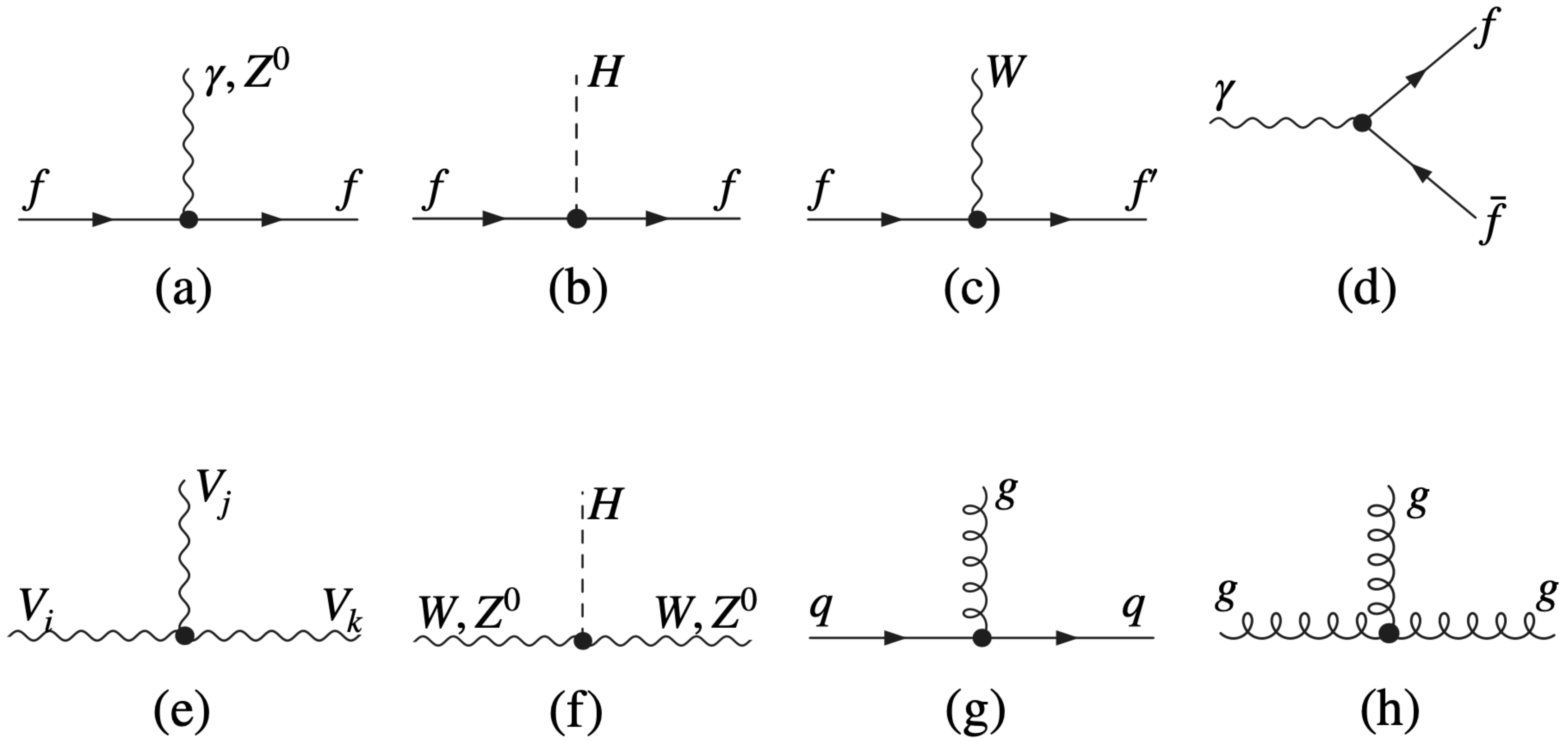
Leading order EW interactions



Baryon and meson decays

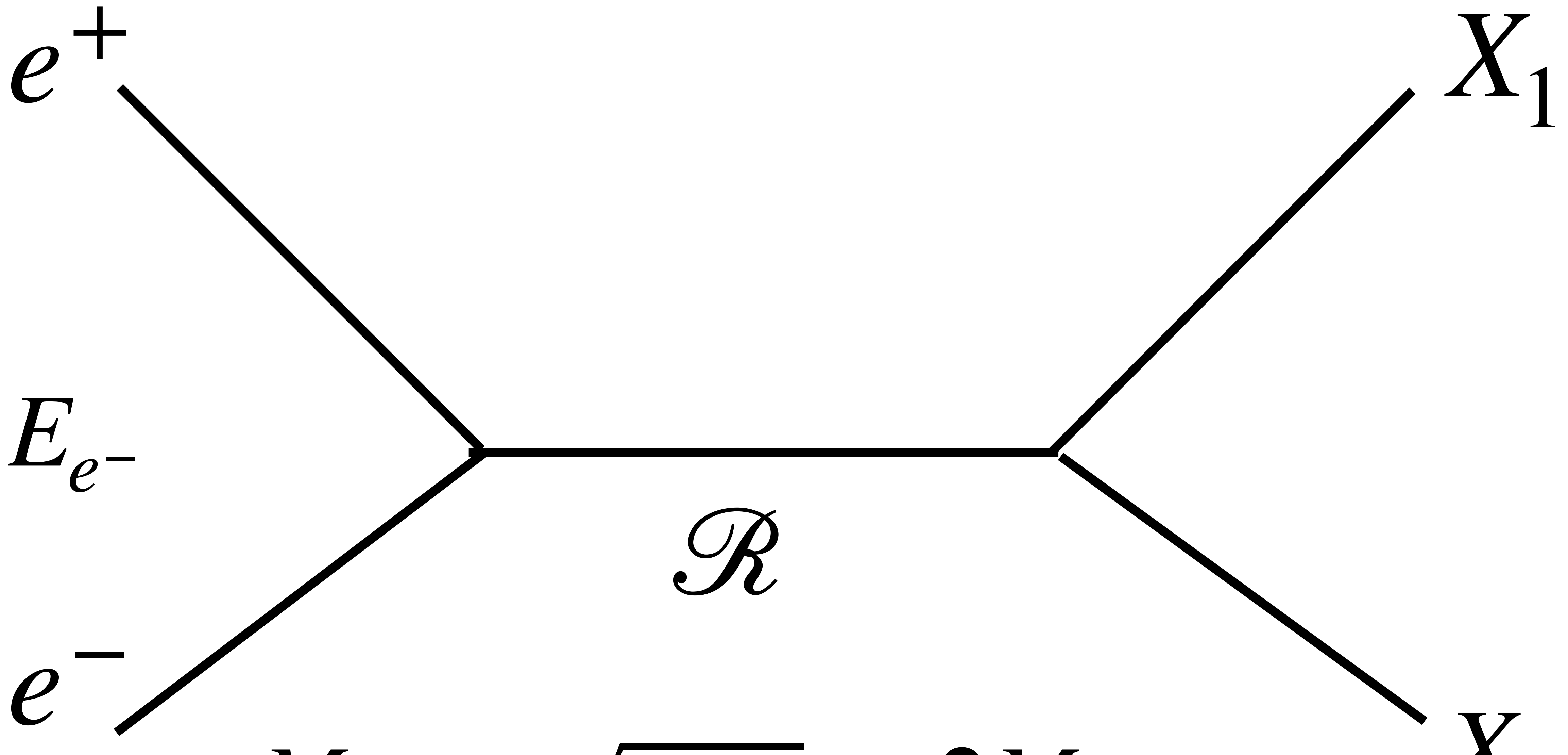


Bremsstrahlung and EW corrections



Spectra calculated with the *resonance approach*

- Standard tool to calculate the spectra using PYTHIA (PPPC4DMID).
- This case resemble the annihilation of fermionic DM (e.g. neutralinos).
- Spin information is lost as the outgoing particles do not have assigned helicities and polarisation.
- Electroweak corrections will not be taken properly into account.



$$M_\chi = E_{e^+} = E_{e^-}$$

$$M_{\mathscr{R}} = \sqrt{s_{e^+e^-}} = 2M_\chi$$

State of the art: PPPC 4 DM ID

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]

- They used Pythia 8.135 (about 13 years old) to calculate, with the resonance approach, DM spectra for different annihilation channels and masses from 5 GeV to 100 TeV.
- EW corrections are added, without resummation, by hand on top of Pythia results (matching issue?) (Ciafaloni et al. 2010).
- *Large cutoff on the minimum transverse momentum for photons emitted off lepton lines in the shower.*
- Polarization and helicity information is absent during the showering.
- Off-shell effects for the EW Gauge boson channels were not taken into account.

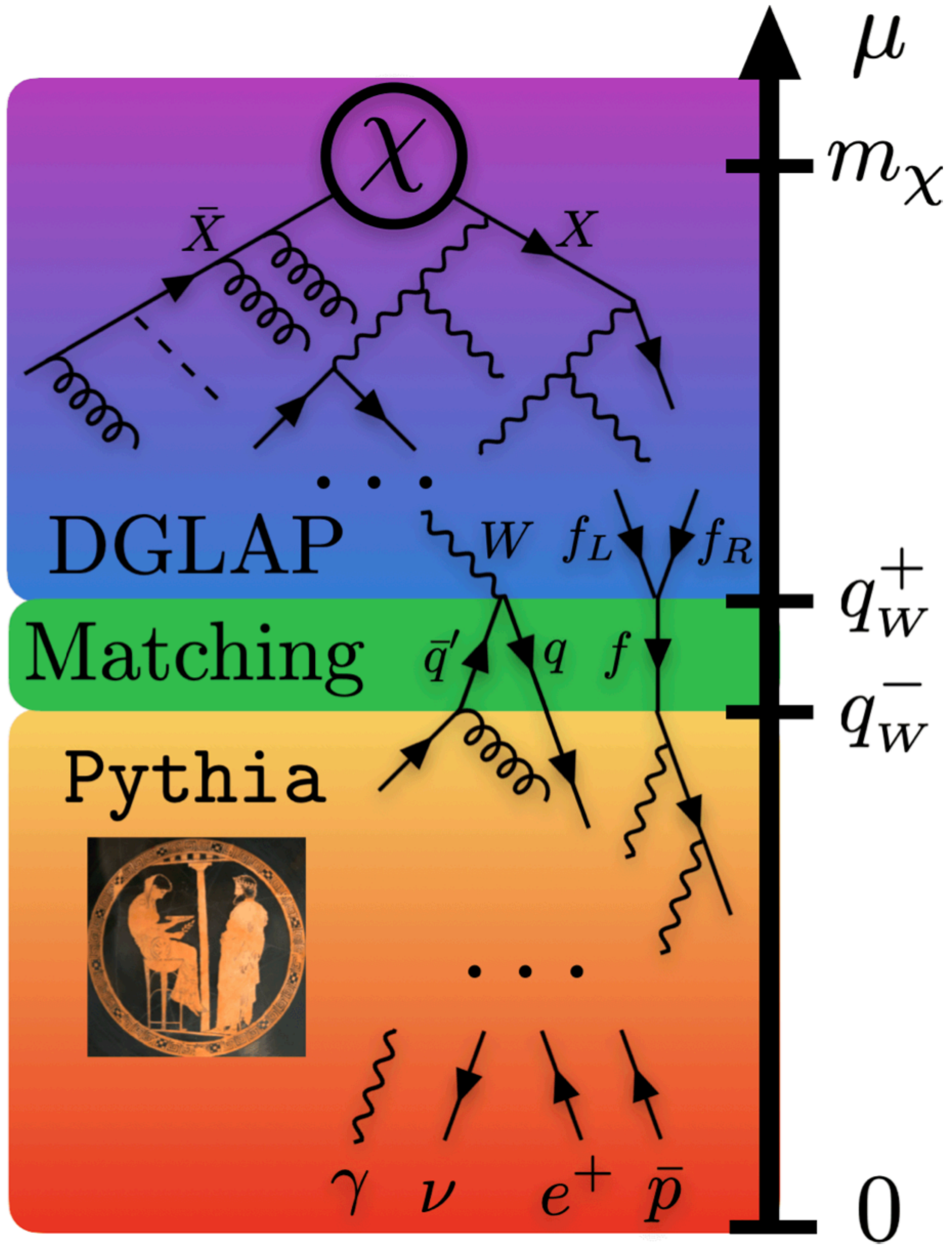
State of the art: HDMS

Dark Matter Spectra from the Electroweak to the Planck Scale

Will be denoted by HDMS in what follows

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

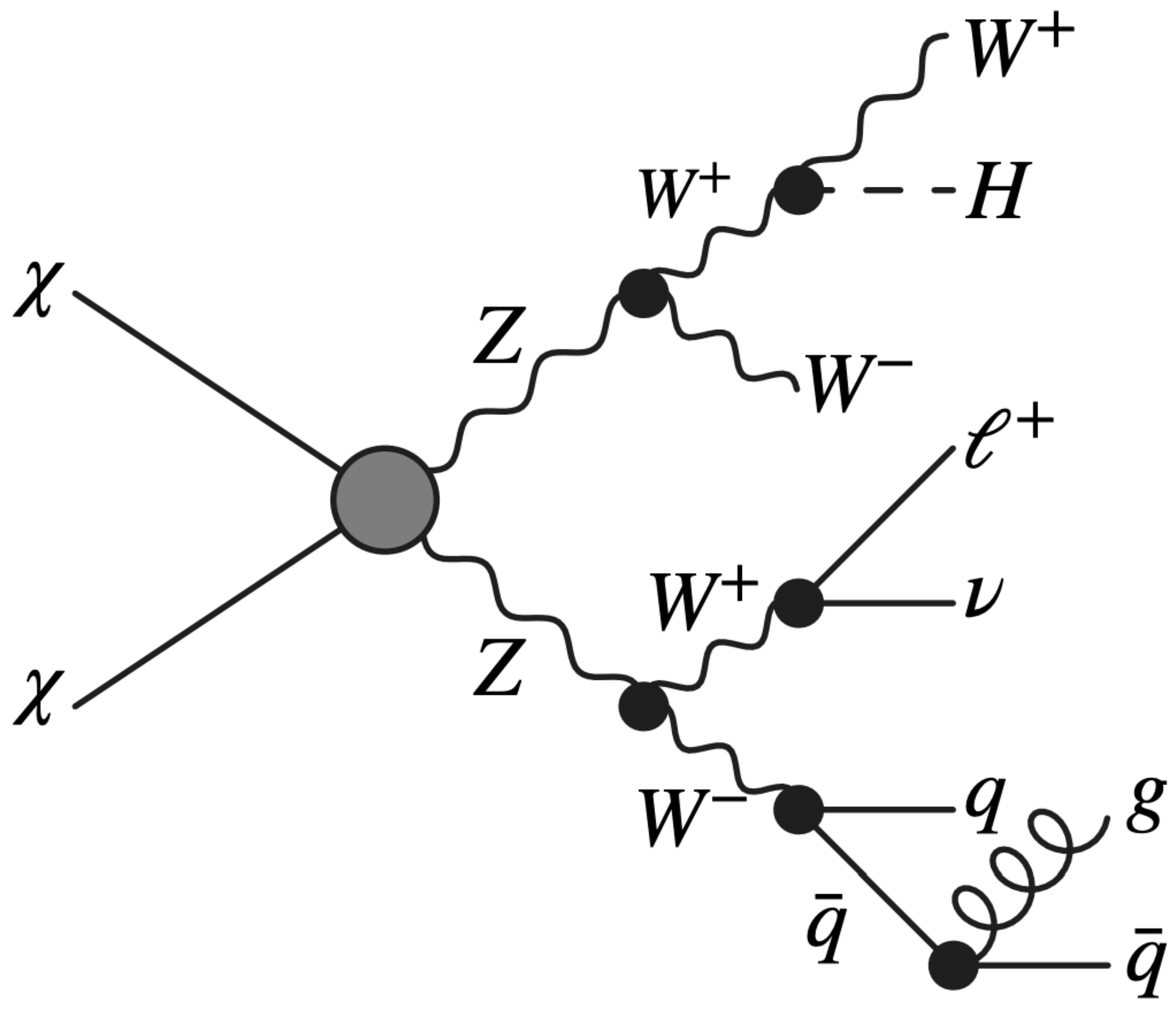
[1] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*
[2] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *University of Cambridge, Cavendish Laboratory, J.J. Thomson Avenue, Cambridge, UK*

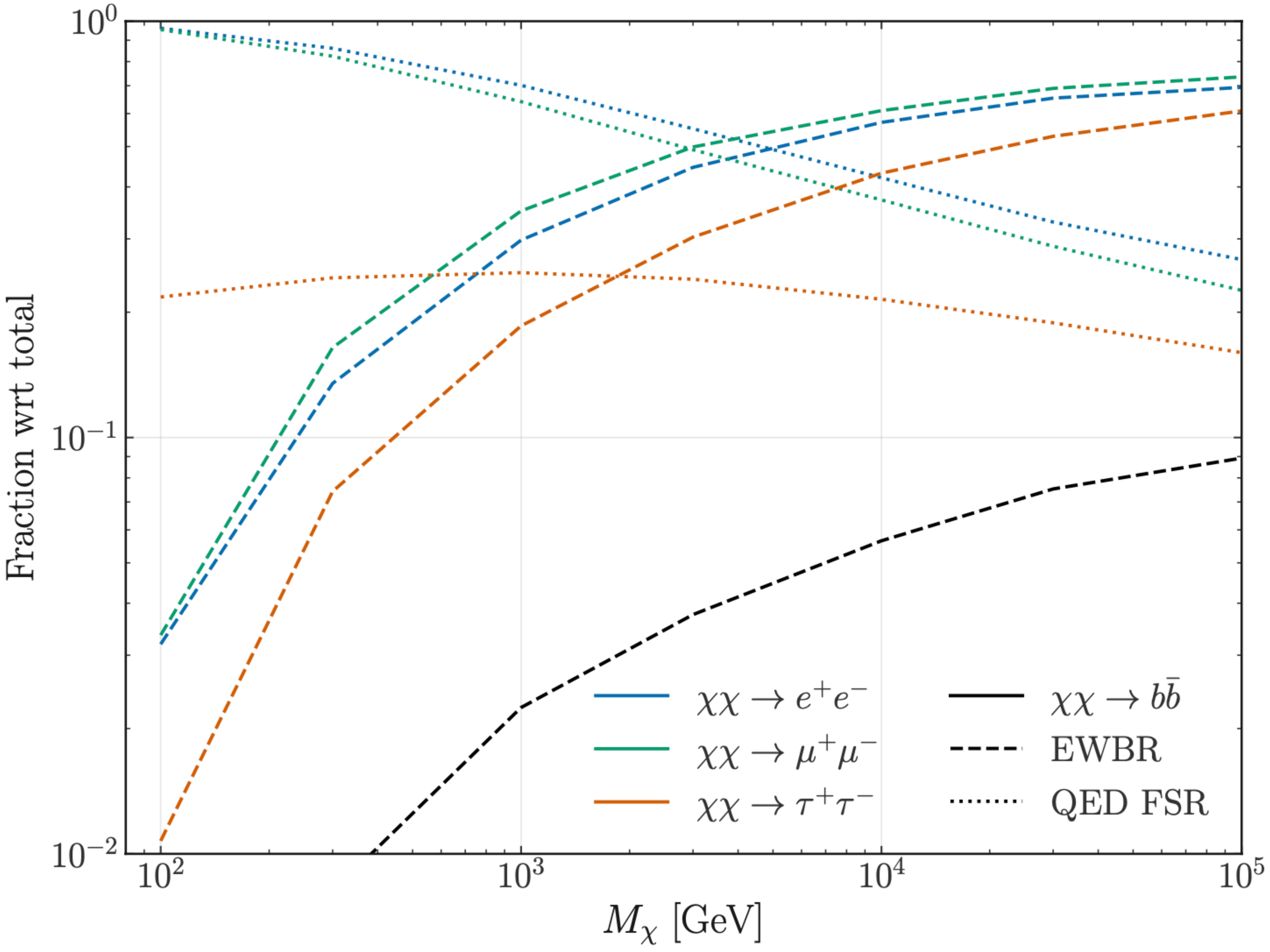


- They have provided decay spectra for DM with masses >500 GeV.
- Spectra of dark matter annihilation/decay were calculated using analytical methods (DGLAP evolution equations) and matched to PYTHIA at the electroweak scale.
- The results of HDMS can lead to theoretical problems in the matching between the physics generated by the DGLAP formalism in the unbroken phase and the physics described by Pythia

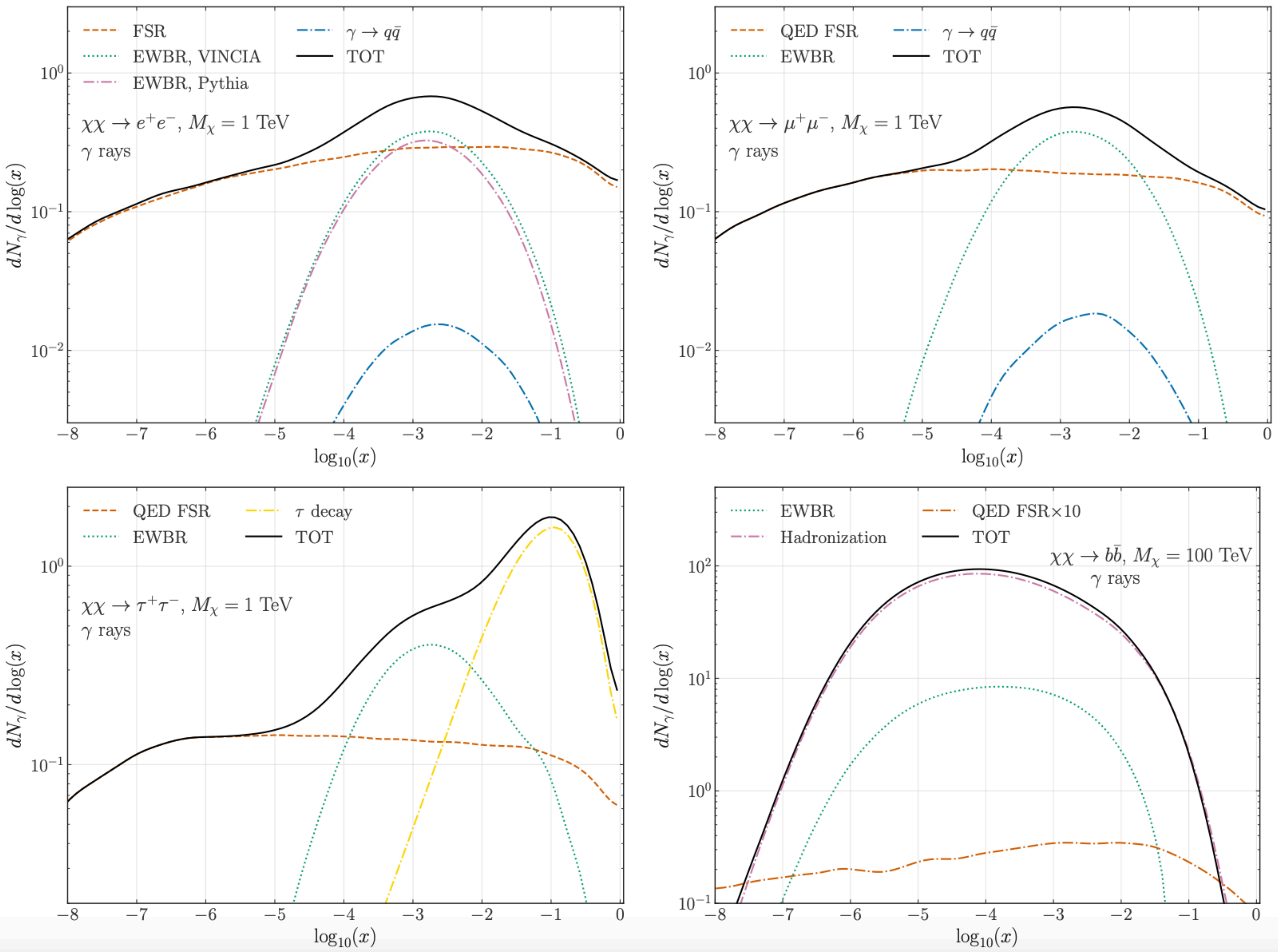
Electroweak boson radiation

- We use the Vincia algorithm (Pythia v. 8.309) which we interface with MadDM.
- We include contributions from triple gauge boson interaction.
  - We include subsequent radiation of Gauge bosons
  - Helicity and polarization info are considered across the entire showering.





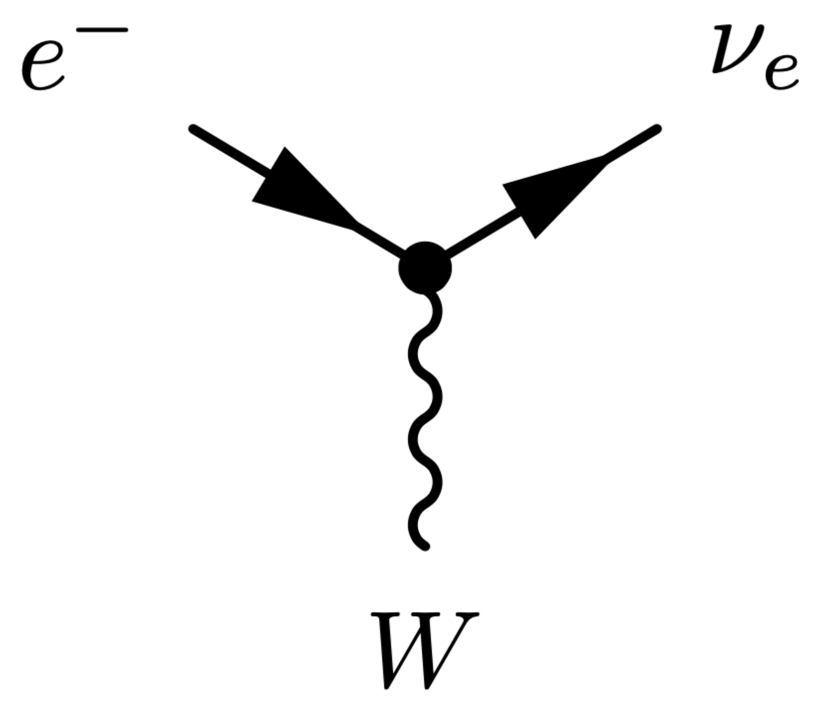
Components in the spectra



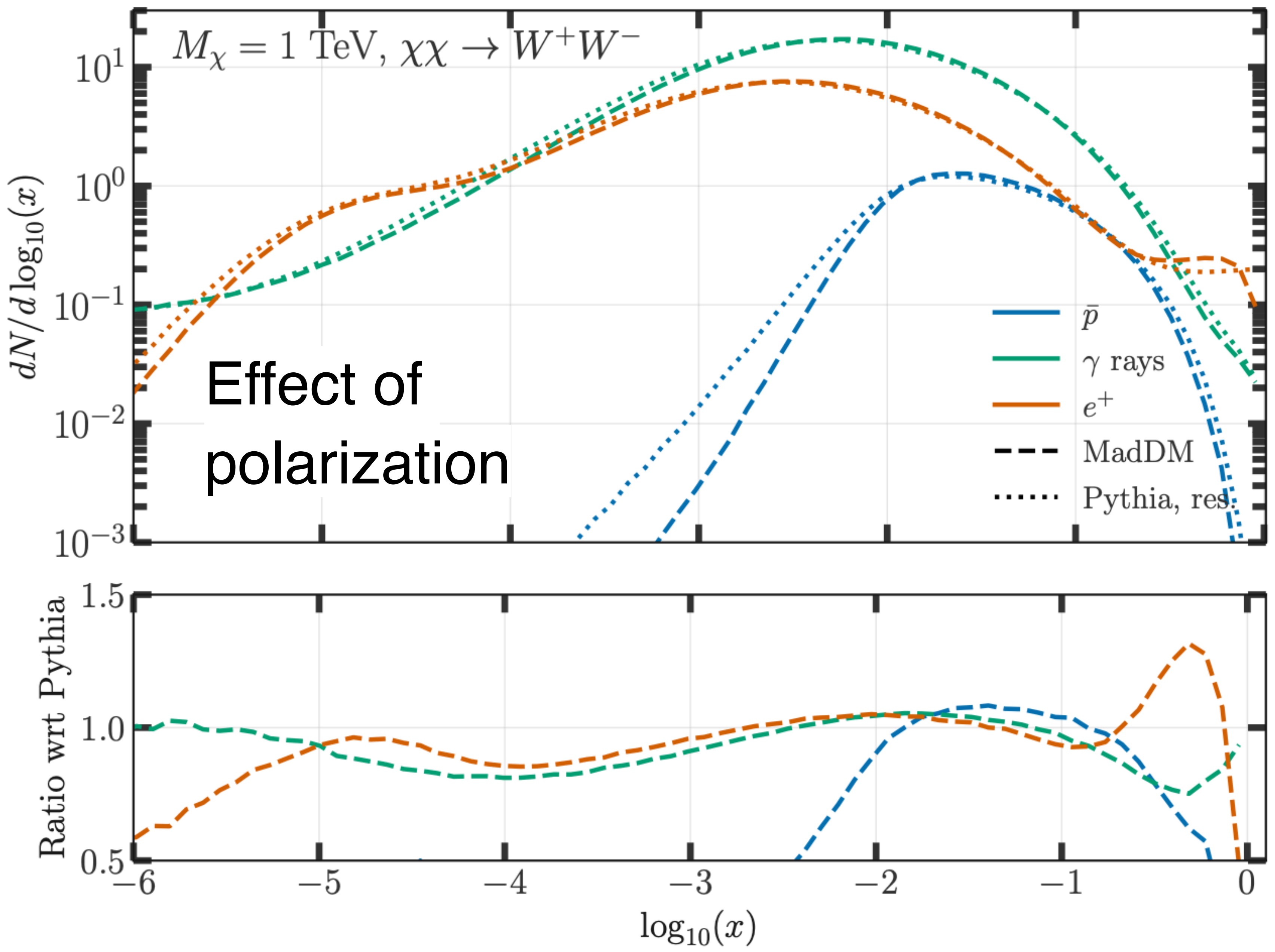
Polarisation and helicity information

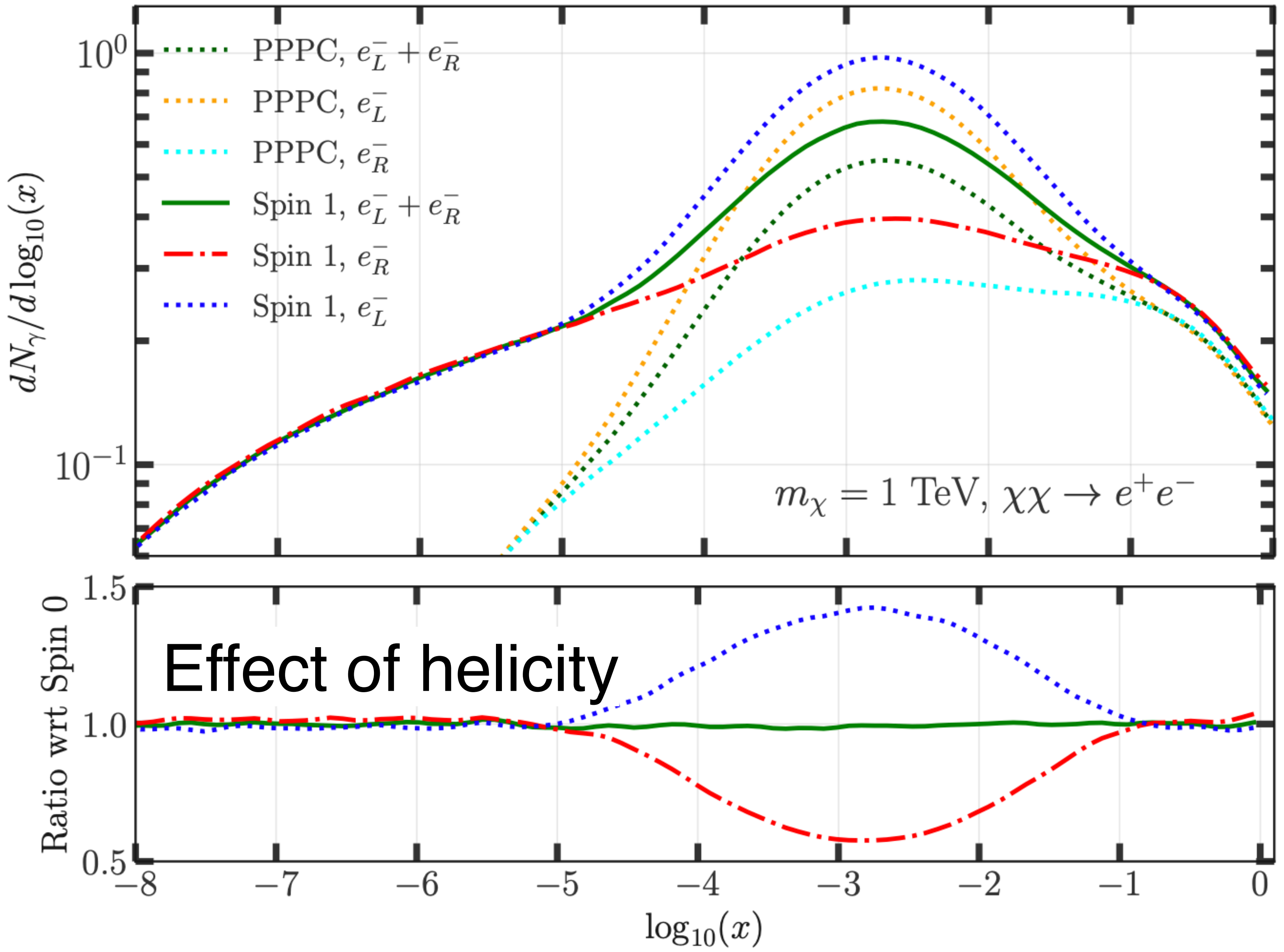
- We include polarisation and helicity of particles.
- We include annihilation channels with off-shell gauge bosons.

$$\mathscr{L}_{\rm I,L}^{\rm (CC)} = -\frac{g}{\sqrt{2}}\{\overline{\nu_{eL}}\not{W} e_L + \overline{e_L}\not{W}^\dagger \nu_{eL}\}$$
$$= -\frac{g}{2\sqrt{2}}\,\overline{\nu_e}\,\gamma^\mu\left(1-\gamma^5\right) e W_\mu + \text{H.c.}$$



$$\bar{\chi}\gamma_\mu(g^V_\chi + \gamma_5 g^A_\chi)\chi Y_1^\mu + \sum_i^{N_f} \bar{F}_i\gamma_\mu(g^V_{ij} + \gamma_5 g^A_{ij})F_j Y_1^\mu,$$

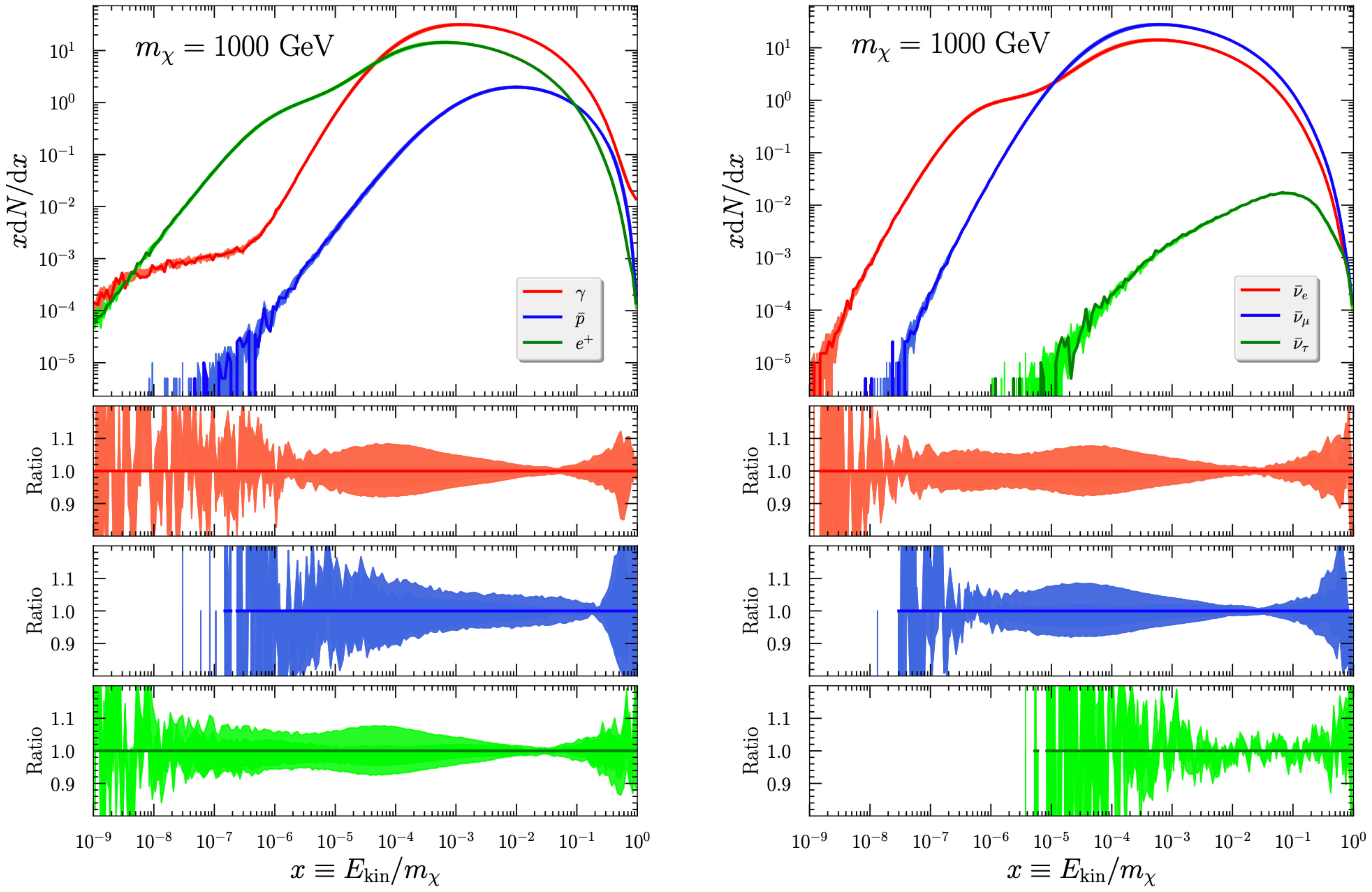




VINCIA Tuning

Measurement	Experiment	χ^2/N_{bins}	Measurement	Experiment	χ^2/N_{bins}
$1-T$	ALEPH [54]	0.13	C–parameter	ALEPH [54]	0.39
$\log(1/x_p)$	ALEPH [54]	0.19	$\langle N_{\text{ch}} \rangle$	ALEPH [54]	0.028
$\langle N_{\text{ch}} \rangle$ ($\lvert Y \rvert < 0.5$)	ALEPH [54]	0.012	$\langle N_{\text{ch}} \rangle$ ($\lvert Y \rvert < 1.0$)	ALEPH [54]	0.028
$\langle N_{\text{ch}} \rangle$ ($\lvert Y \rvert < 1.5$)	ALEPH [54]	0.030	$\langle N_{\text{ch}} \rangle$ ($\lvert Y \rvert < 2.0$)	ALEPH [54]	0.040
$\pi^{\pm}$ spectrum	ALEPH [54]	0.67	π^0 spectrum	ALEPH [54]	0.24
Λ^0 spectrum	ALEPH [55]	1.24	Λ^0 spectrum (2–jet events)	ALEPH [55]	1.31
Thrust	ALEPH [56]	0.097	C–parameter	ALEPH [56]	0.35
N_{ch} ($y_{\text{cut}} = 0.01$)	DELPHI [57]	5.99	N_{ch} ($y_{\text{cut}} = 0.02$)	DELPHI [57]	4.88
Λ^0 spectrum	DELPHI [58]	1.34	$\langle N_{\Lambda^0} \rangle$	DELPHI [58]	0.53
π^0 momentum	DELPHI [59]	0.41	$\log(1/x_p)$	DELPHI [59]	0.33
$1-T$	DELPHI [59]	0.18	C–parameter	DELPHI [59]	0.34
$\langle N_{\text{ch}} \rangle$	DELPHI [59]	0.031	$\langle N_{\pi^{\pm}} \rangle$	DELPHI [59]	0.063
$\langle N_{\pi^0} \rangle$	DELPHI [59]	0.39	$\langle N_{\rho} \rangle$	DELPHI [59]	3.40
$\langle N_p \rangle$	DELPHI [59]	2.30	$\langle N_{\Lambda^0} \rangle$	DELPHI [59]	1.54
$\langle N_{\text{ch}} \rangle$	DELPHI [60]	0.005	$\langle N_{\pi^{\pm}} \rangle$	DELPHI [60]	0.10
$\langle N_p \rangle$	DELPHI [60]	0.05	$N_{p/\bar{p}}/N_{\text{ch}}$	DELPHI [60]	0.27
$\pi^{\pm}$ momentum	DELPHI [60]	0.46	$p/\bar{p}$ momentum	DELPHI [60]	0.43
Thrust (udsc events)	L3 [61]	0.34	C–parameter (udsc events)	L3 [61]	0.22
Charged multiplicity	L3 [61]	3.39	$\log(1/x_p)$	L3 [61]	0.96
x_p (udsc events)	L3 [61]	0.78			
$\langle N_{\text{ch}} \rangle$	OPAL [62]	0.37	$\pi^{\pm}$ spectrum	OPAL [63]	0.25
Λ^0 scaled energy	OPAL [64]	1.49	π^0 scaled momentum	OPAL [65]	0.12
All events $\log(1/x_p)$	OPAL [66]	0.38	$\langle N_{\text{ch}} \rangle$	OPAL [66]	0.16
$1-T$	OPAL [67]	0.10	C–parameter	OPAL [67]	0.35

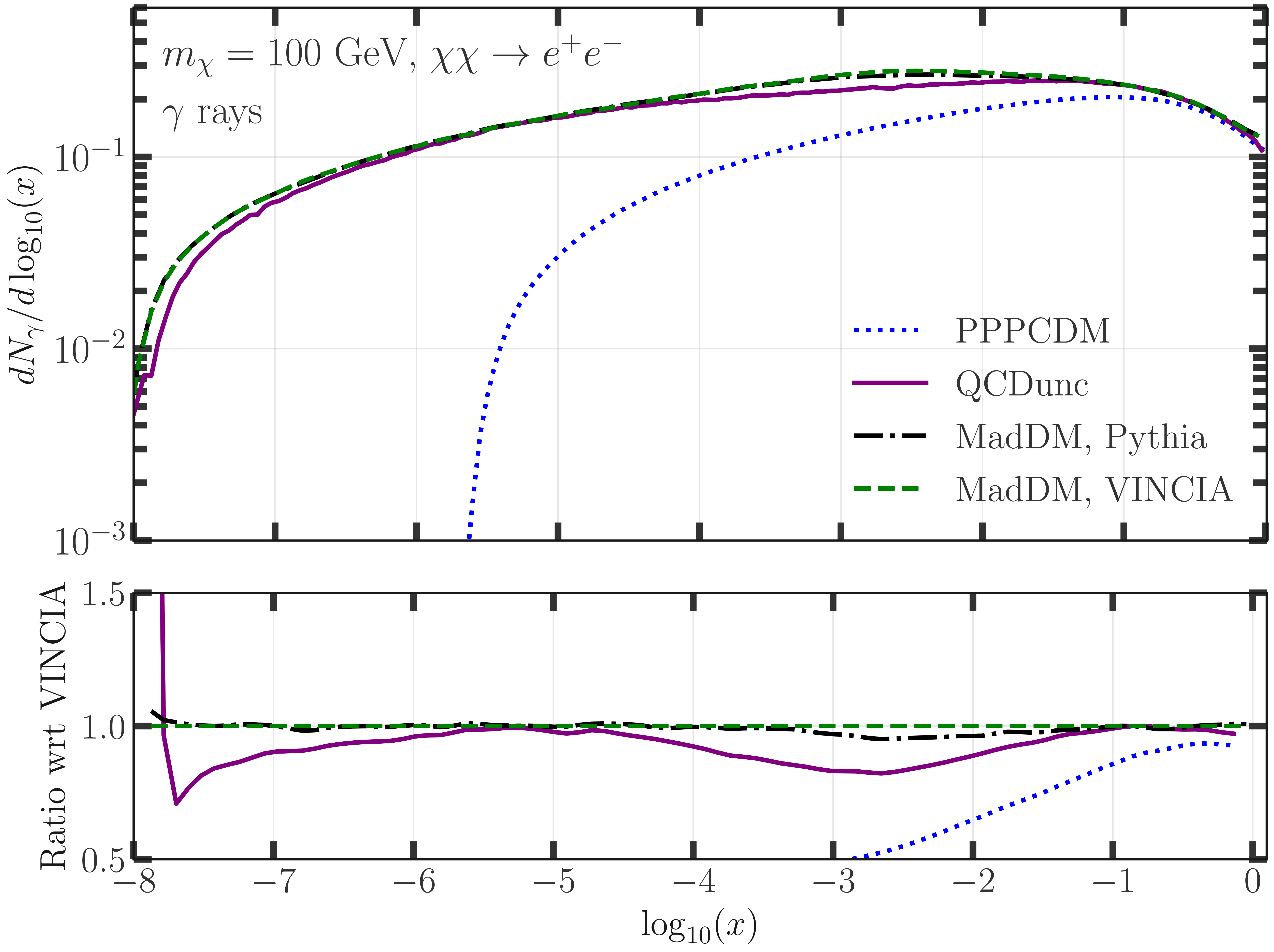
Parameter	MONASH	VINCIA (default)	PYTHIA [17, 18]	This work
a_L	0.68	0.45	0.601	0.337 ± 0.015
b_L	0.98	0.80	0.897	0.784 ± 0.020
$\sigma_{\perp}$ (GeV)	0.335	0.305	0.307	0.296 ± 0.003
a_{QQ}	0.97	0.90	1.671	1.246 ± 0.082
χ^2/N_{df}	1034.52/852	786.11/852	676.69/852	660.21/852



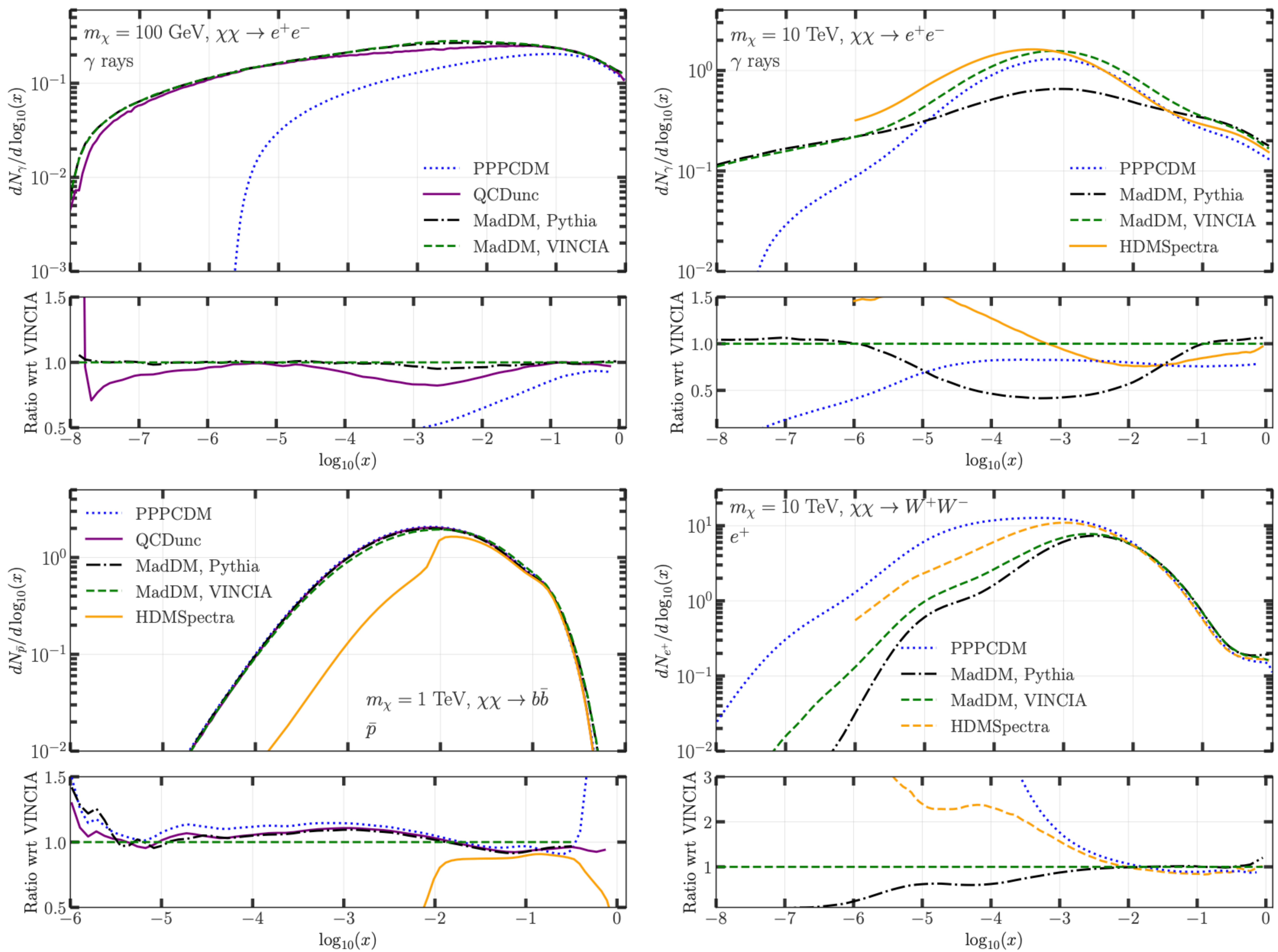
Summary of the novelties

- **Polarization and helicity effects:** We use MadDM which we interface with PYTHIA 8 and VINCIA shower plugin being the default option.
- **Resummed electroweak corrections and interleaved resonance decays:** The electroweak corrections are modeled with helicity-dependent Antenna showers and Sudakov form factors.
- **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 with PPPC and HDMS



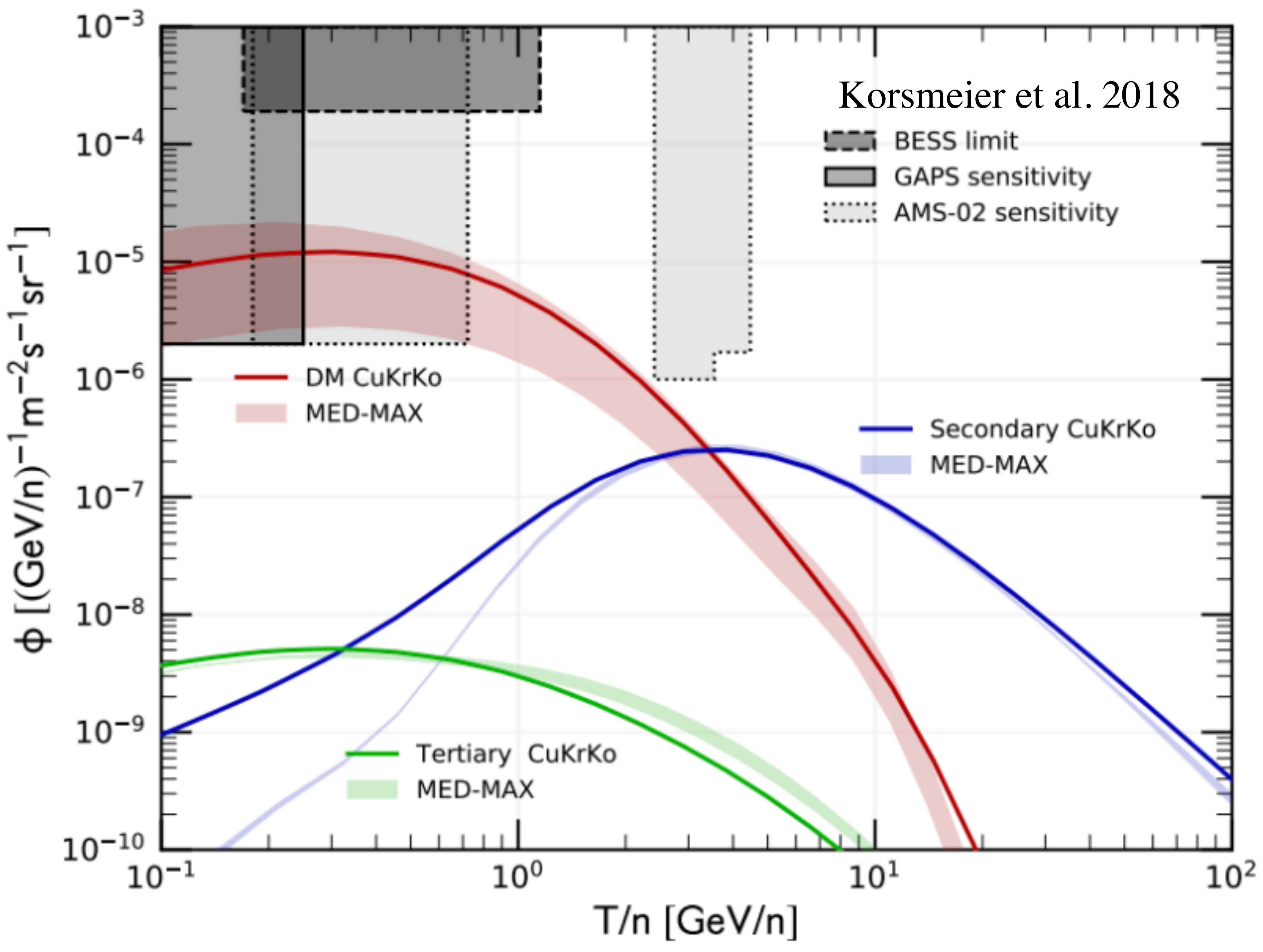
Comparison with PPPC and HDMS

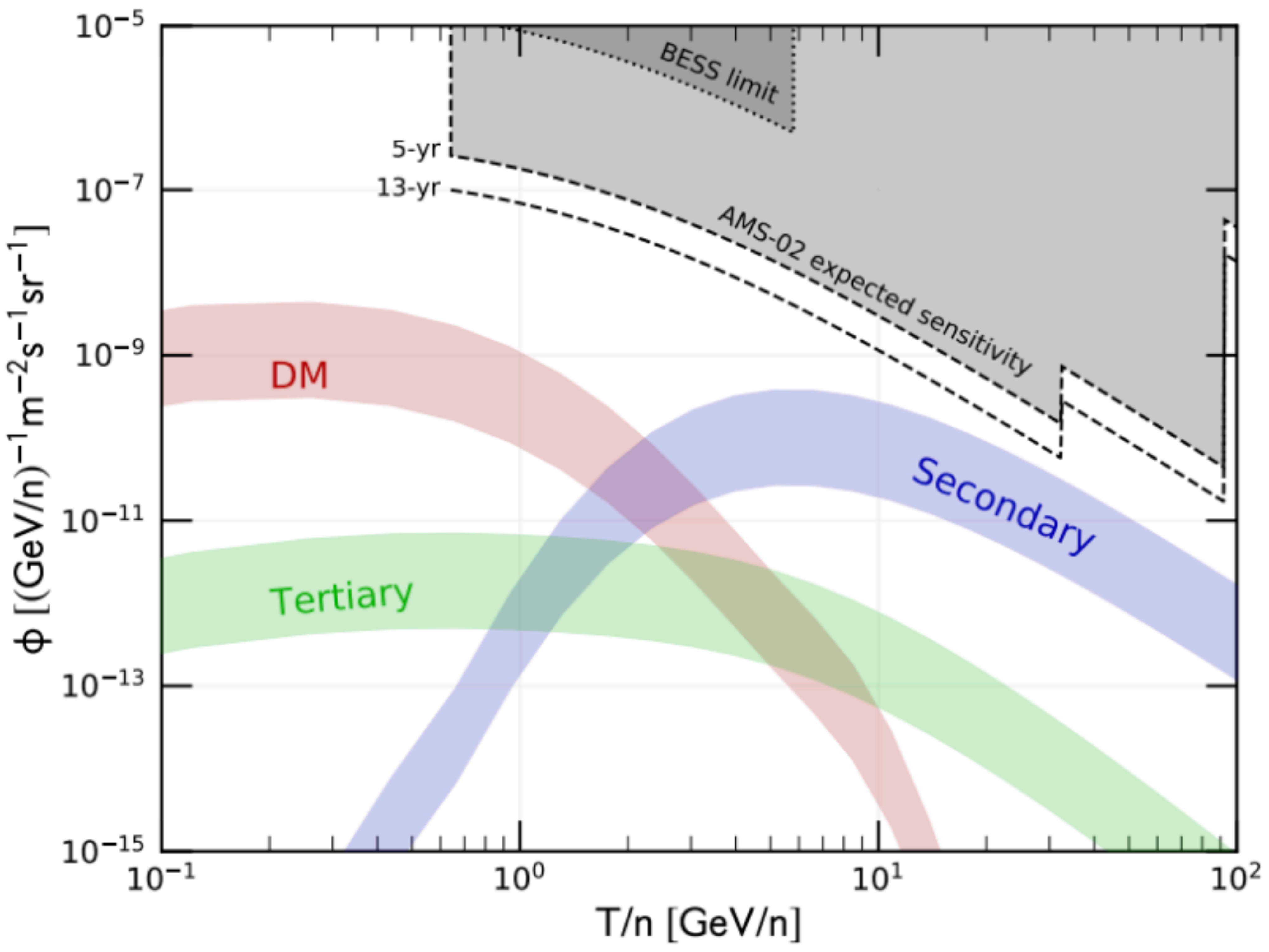


Dark matter search with cosmic antinuclei

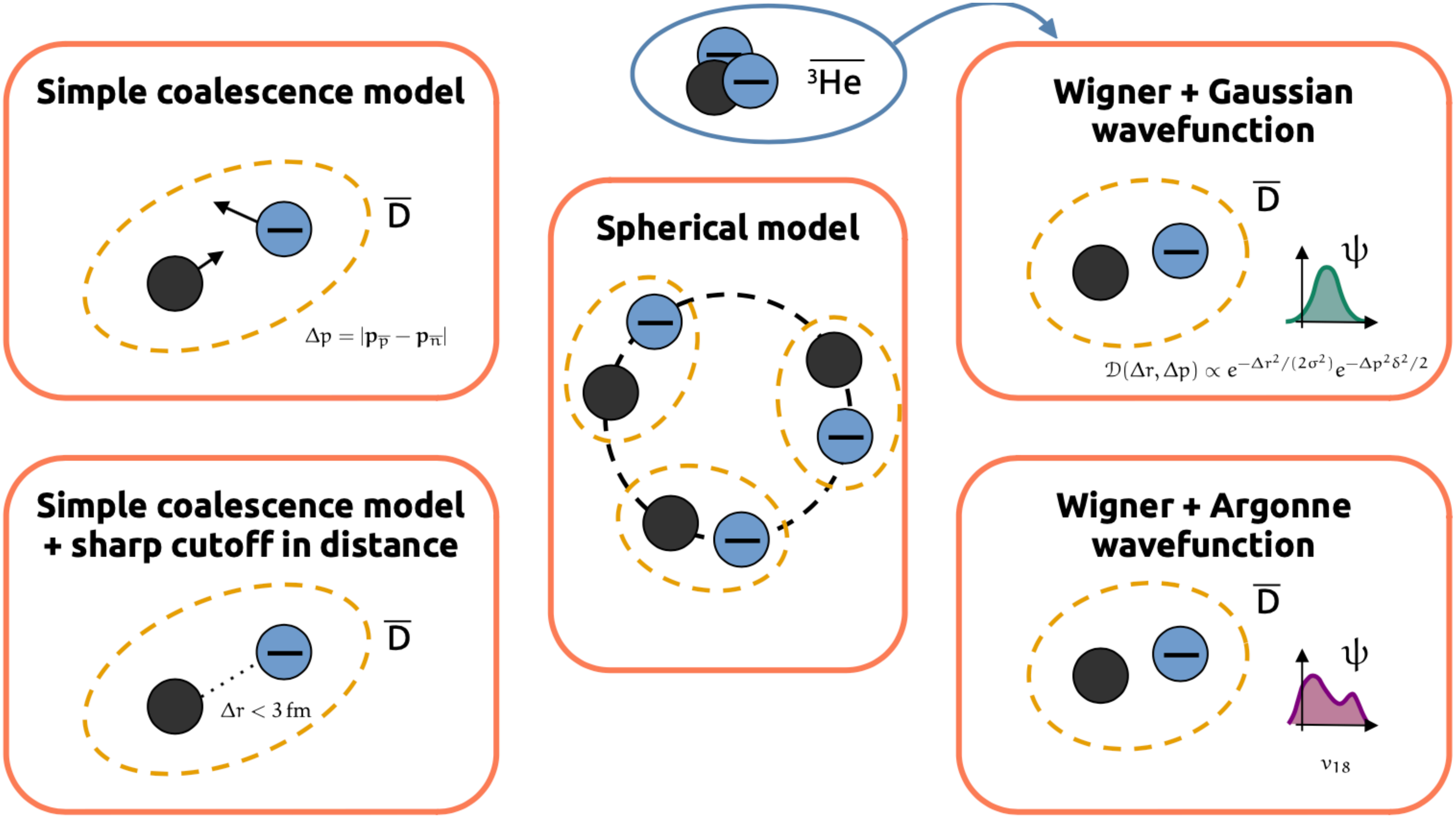
$$pp \rightarrow \bar{D}pppn$$

$$\sqrt{s} = 2E_{\mathrm{CM}} = \sqrt{2m_p \cdot (E_{\mathrm{LAB}} + m_p)} \geq 6m_p \rightarrow E_{\mathrm{LAB}} \geq 17m_p$$



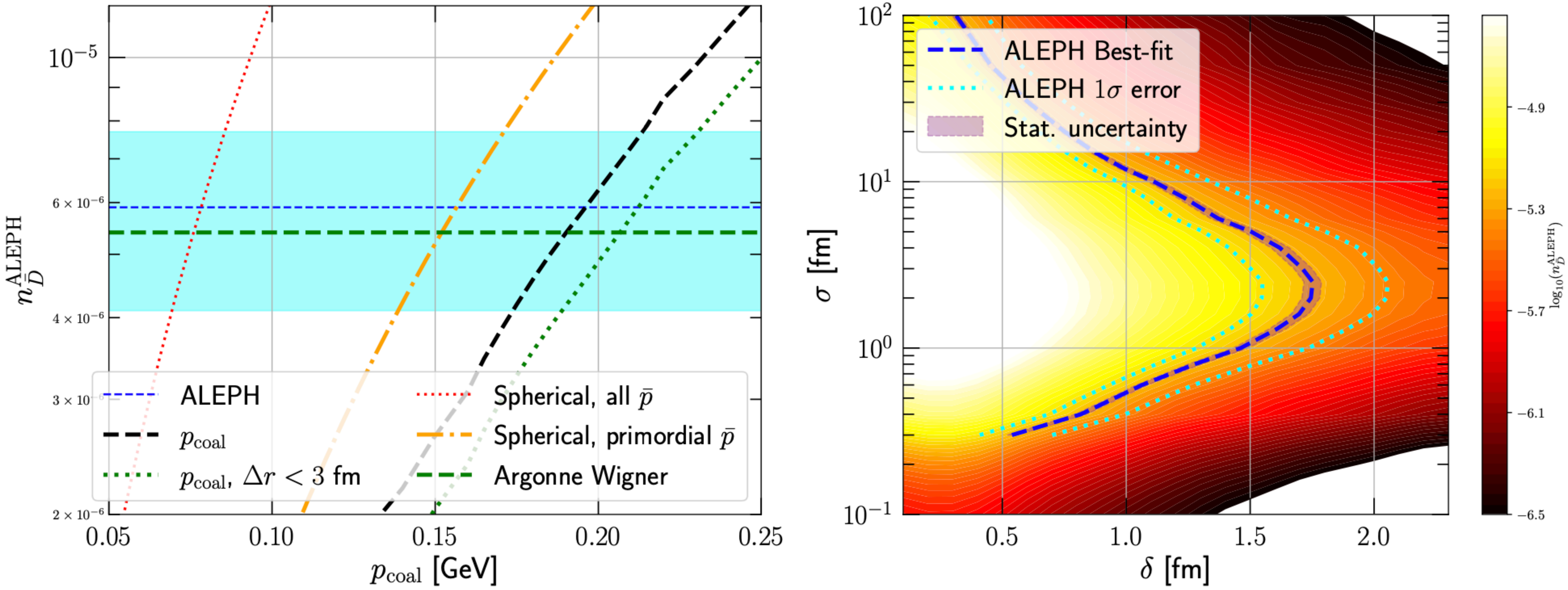


Coalescence models

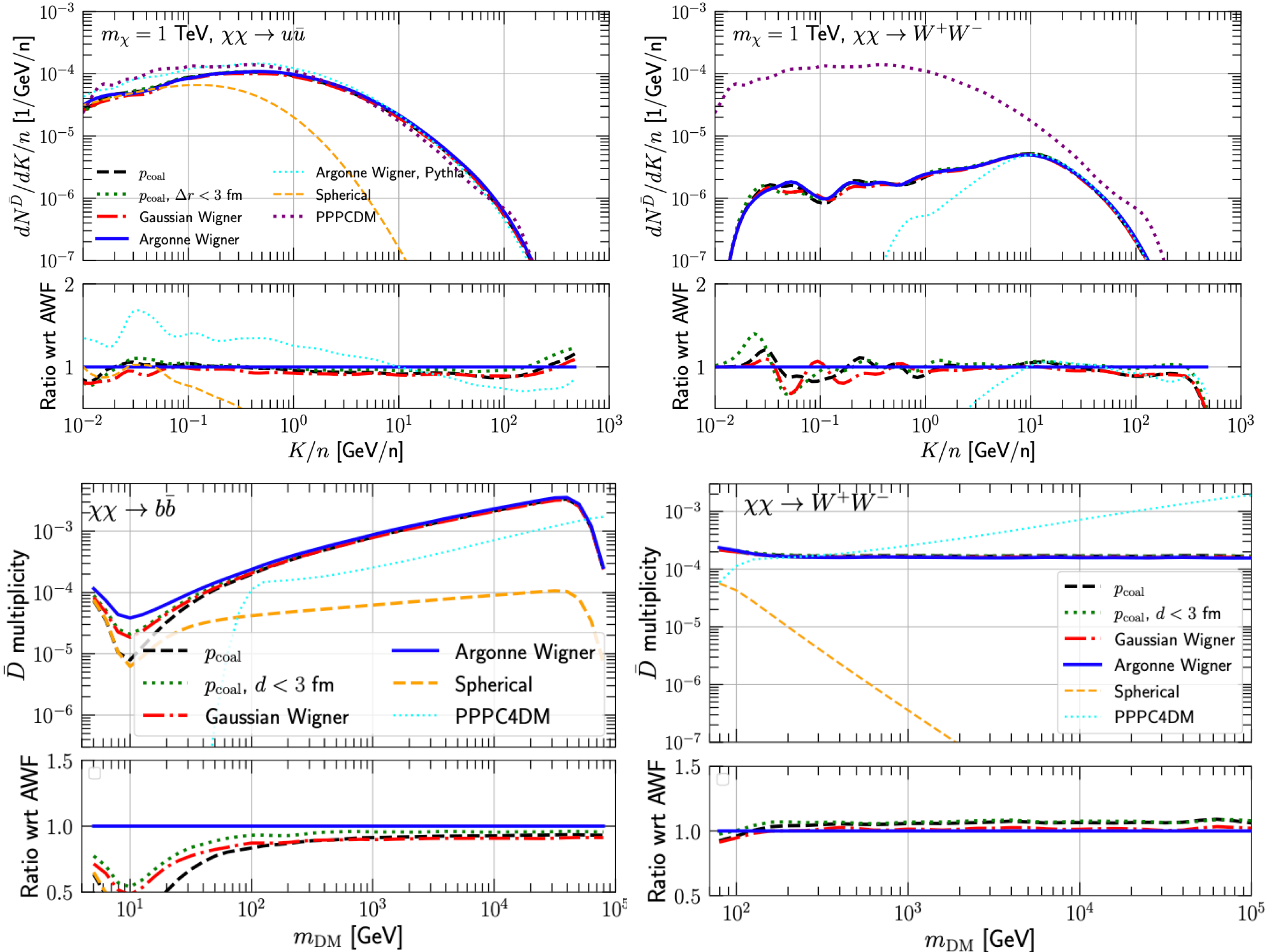


Courtesy of Daniele Massaro

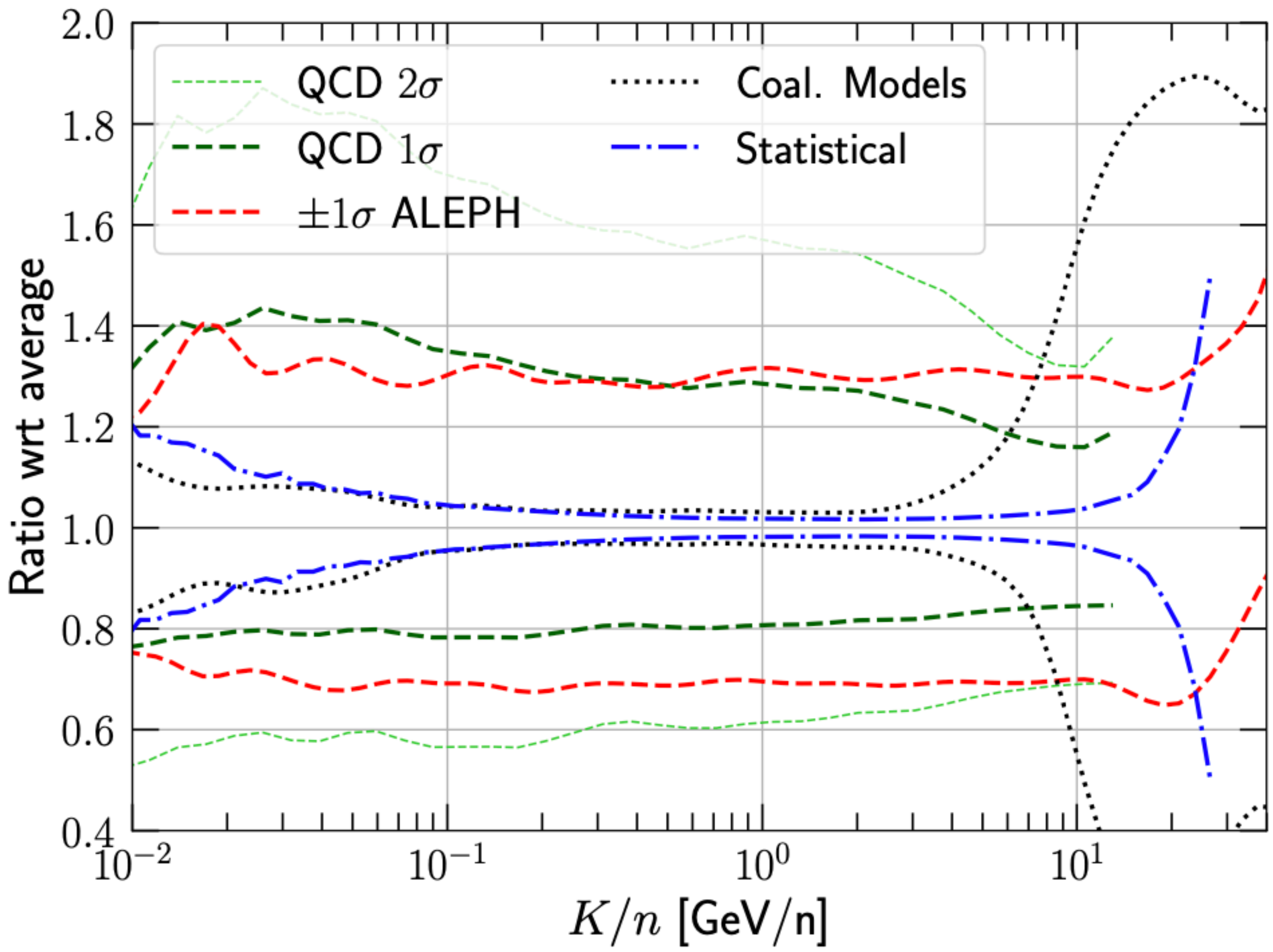
Tuning on ALEPH data point



Cosmixs predictions for Dbar



Current Uncertainties on Dbar source spectrum



Spectra are publicly available

$$e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-,\ \nu_e\nu_e,\ \nu_\mu\nu_\mu,\ \nu_\tau\nu_\tau,\ u\bar{u},\ d\bar{d},\ c\bar{c},\ s\bar{s},\ t\bar{t},\ b\bar{b},\ \gamma\gamma,\ gg,\ W^+W^-,\ ZZ, HH,\ ZH,\ \gamma Z.$$

Dark Matter mass between 5 GeV and 100 TeV

https://github.com/ajueid/CosmiXs

README.md

CosmiXs: Cosmic messenger spectra for indirect dark matter searches

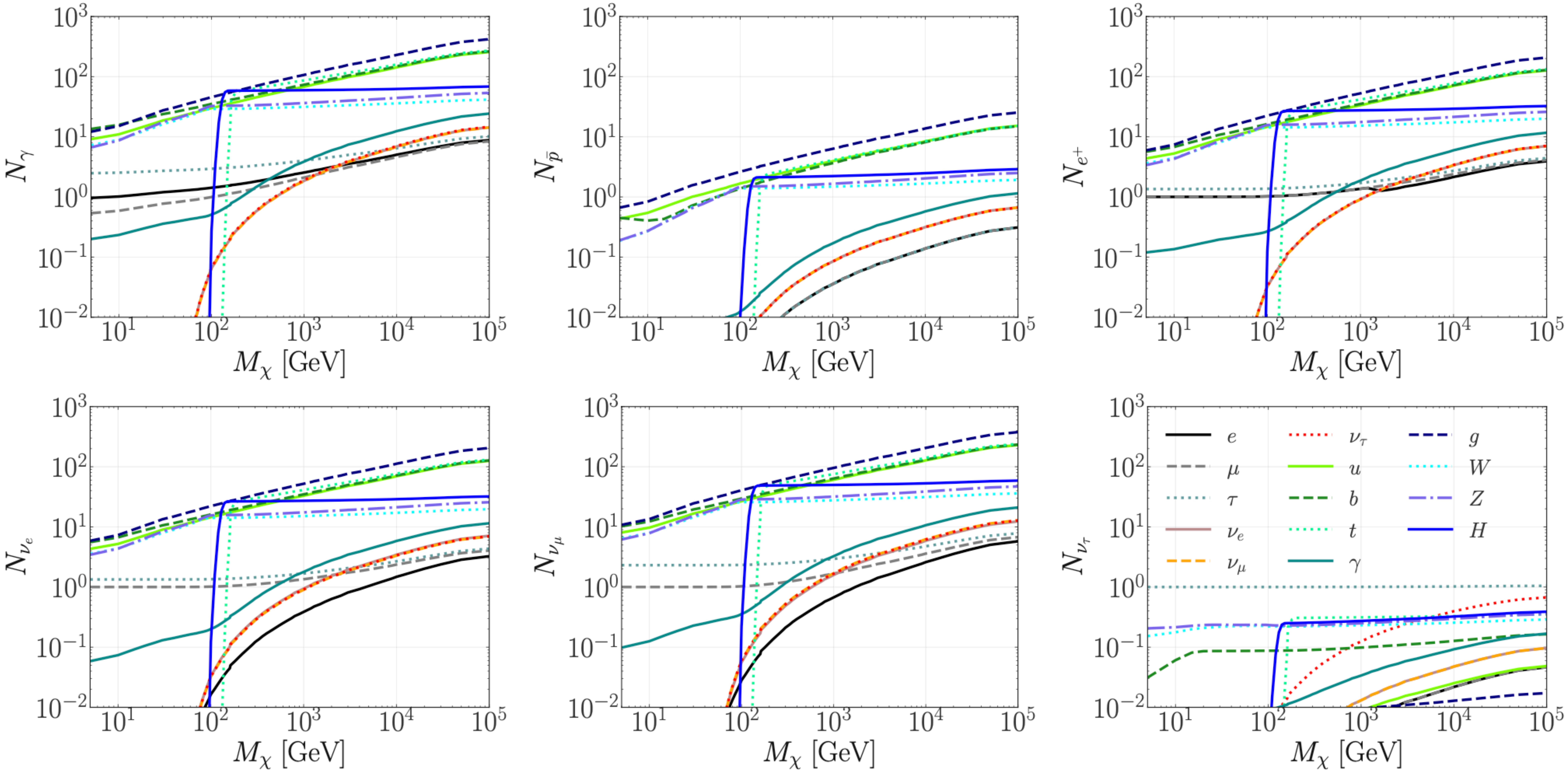
The Cosmixs code and repository provides the source spectra at production for the cosmic messengers relevant for dark matter indirect searches, namely $\bar{p}, e^+, \gamma$ or ν. The spectra have been generated with PYTHIA version 8.309 and the VINCIA antenna shower algorithm feeded by amplitudes generated by the MadDM code. The spectra are here provided for dark-matter masses between 5 GeV and 100 TeV (with a grid of 64 mass values) and for 29 annihilation channels. For each mass and each annihilation channel, five million events have been generated.

Conclusions

- We have significantly improved the predictions for particle spectra from dark matter annihilation.
- Our results include several effects not previously accounted for in PPPC4DMID.
- These improvements are relevant across all indirect detection strategies.
- CosmiXs tables are already implemented in *MadDM* and *MicrOMEGAs*, and will soon be adopted as the default in the *FermiTools*.
  - We encourage developers of other tools to adopt our results.
- We are extending CosmiXs up to 1 PeV in dark matter mass.
- The tables will be periodically updated, especially following major *Pythia* releases.

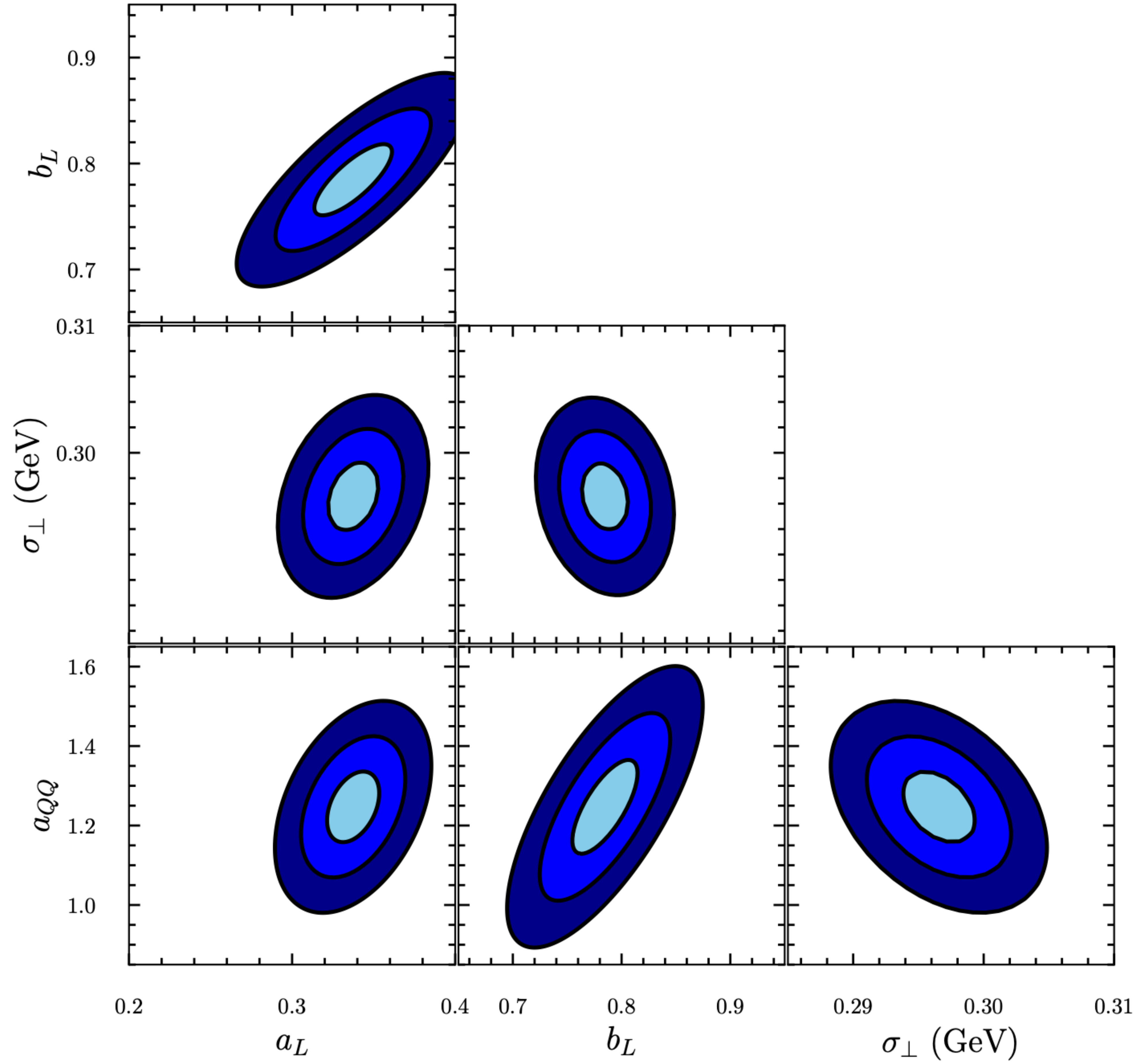
Backup slides

Multiplicities



Backup slides

parameter	PYTHIA 8 setting	Variation range	VINCIA
$\sigma_\perp$ (GeV)	StringPT:Sigma	0.0 – 1.0	0.305
a_L	StringZ:aLund	0.0 – 2.0	0.45
b_L	StringZ:bLund	0.2 – 2.0	0.80
a_{QQ}	StringZ:aExtraDiquark	0.0 – 2.0	0.90
r_c	StringZ:rFactC	0.0 – 2.0	0.85
r_b	StringZ:rFactB	0.0 – 2.0	1.15



State of the art: QCDUnc

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 in what follows

Prepared for submission to JCAP

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

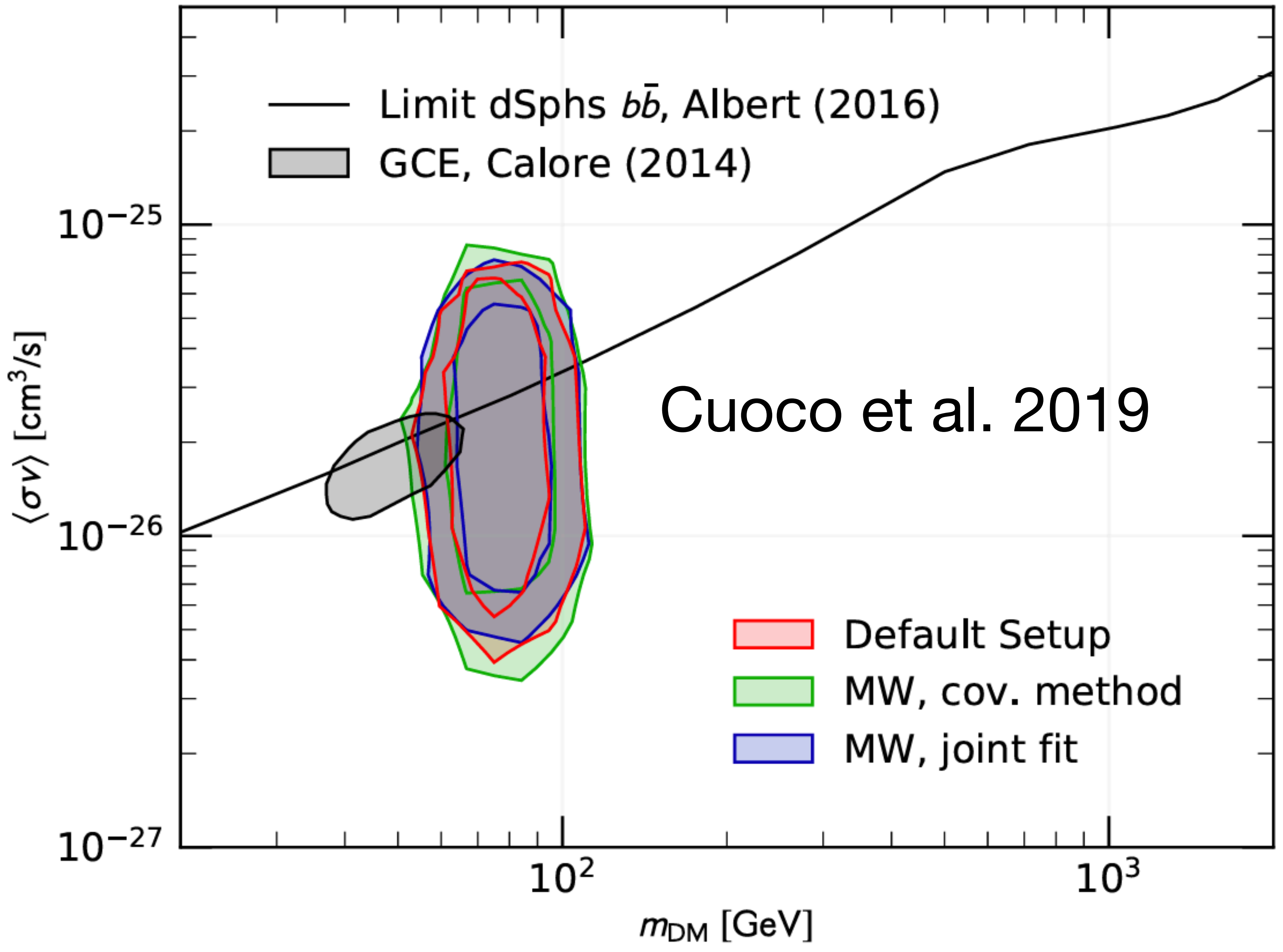
Adil Jueid,[a] Jochem Kip,[b] Roberto Ruiz de Austri[c] and Peter Skands[d]

(arXiv: 2202.11546)

- They 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 (about 10%).*
- Estimated the impact on the best-fit point of the fitted DM mass and thermally-averaged annihilation cross section (in a two-parameter model).

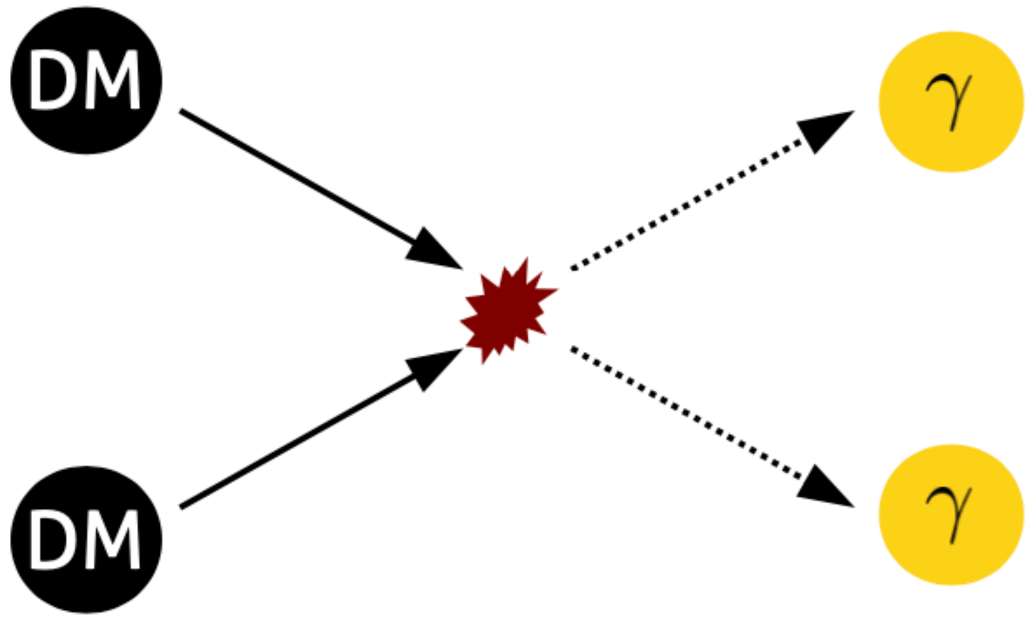
Importance of precise predictions

- There are hints for possible excess over the astrophysical backgrounds in various experiments, especially Fermi-LAT and AMS.
- These excesses triggered a plethora of phenomenological analyses aiming to explain it with dark matter.
- An important finding is that the precision in the determination of the particle spectra from DM annihilation is important in the fitting procedure.

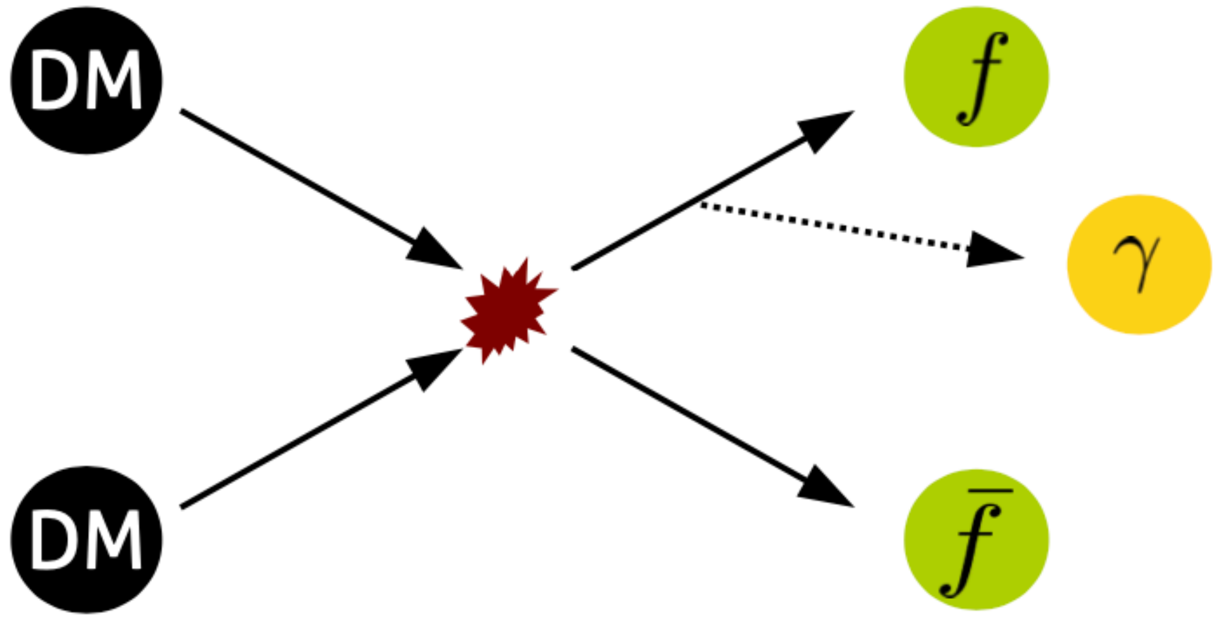


Gamma rays from dark matter annihilation

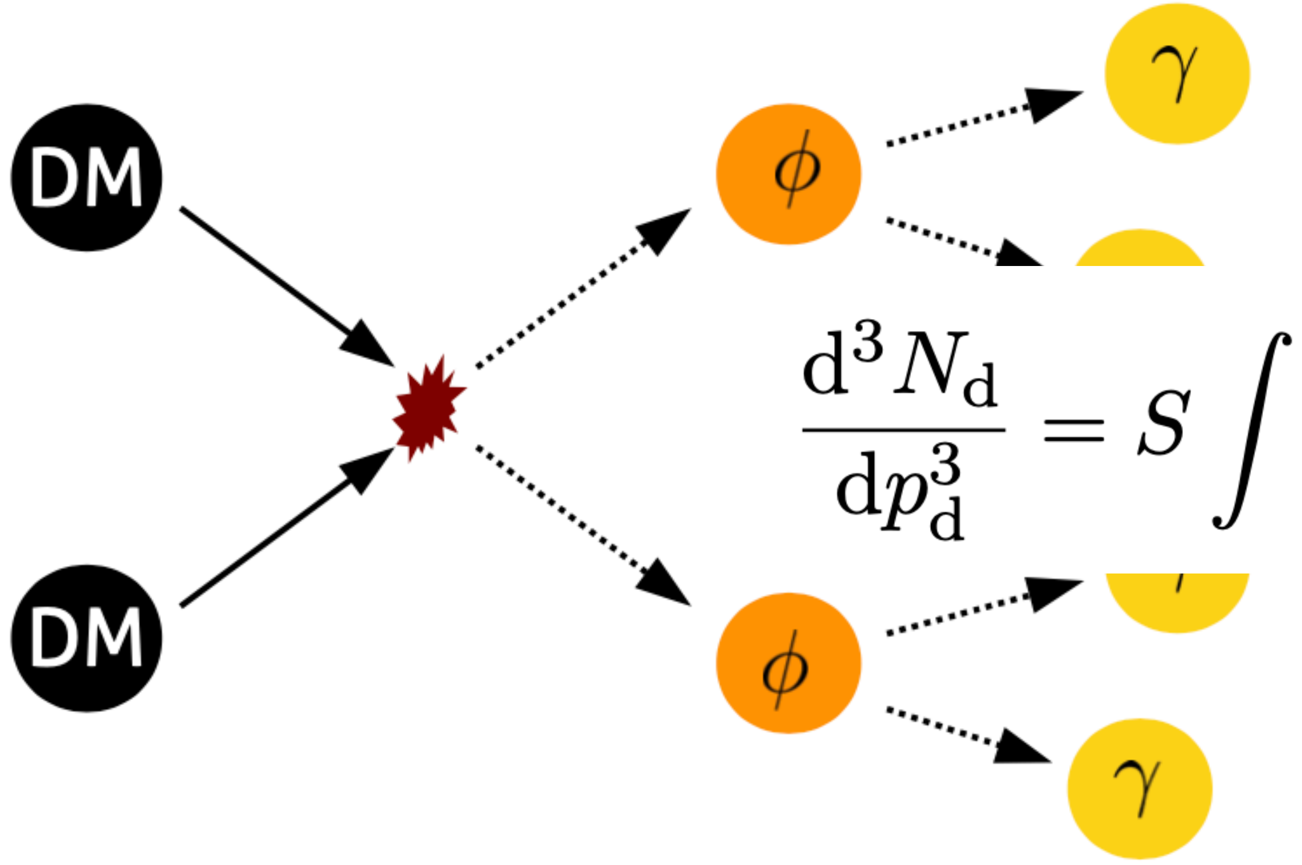
Gamma-ray lines:
Two-body annihilation into photons



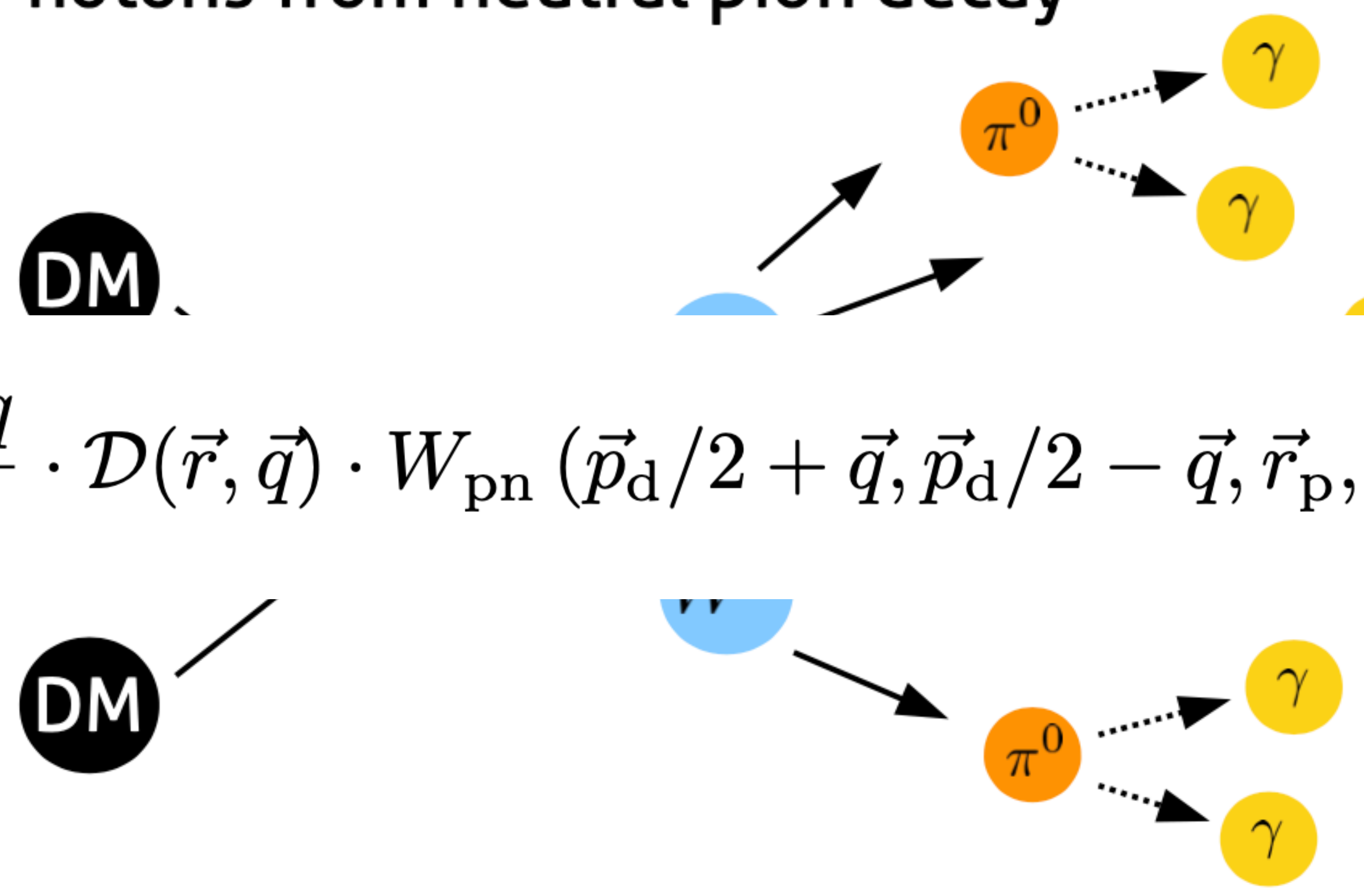
Bremsstrahlung:
Photon production in "hard process"



Box-shaped spectra:
Photons from cascade decay



Continuum emission: (Prompt)
Photons from neutral pion decay



$$\frac{\mathrm{d}^3 N_\mathrm{d}}{\mathrm{d}p_\mathrm{d}^3} = S \int \frac{\mathrm{d}^3 r_\mathrm{d} \mathrm{d}^3 r \, \mathrm{d}^3 q}{(2\pi)^6} \cdot \mathcal{D}(\vec{r}, \vec{q}) \cdot W_\mathrm{pn} \left(\vec{p}_\mathrm{d}/2 + \vec{q}, \vec{p}_\mathrm{d}/2 - \vec{q}, \vec{r}_\mathrm{p}, \vec{r}_\mathrm{n} \right)$$

Wigner approach

$$\frac{\mathrm{d}^3 N_\mathrm{d}}{\mathrm{d}p_\mathrm{d}^3} = S \int \frac{\mathrm{d}^3 r_\mathrm{d} \mathrm{d}^3 r\ \mathrm{d}^3 q}{(2\pi)^6} \cdot \mathcal{D}(\vec{r}, \vec{q}) \cdot W_\mathrm{pn}\left(\vec{p}_\mathrm{d}/2 + \vec{q}, \vec{p}_\mathrm{d}/2 - \vec{q}, \vec{r}_\mathrm{p}, \vec{r}_\mathrm{n}\right)$$

$$\mathcal{D}(\vec{r}, \vec{q}) = \int \mathrm{d}^3\xi e^{-i\vec{q}\cdot\vec{\xi}} \varphi_\mathrm{d}(\vec{r} + \vec{\xi}/2) \varphi_\mathrm{d}^*(\vec{r} - \vec{\xi}/2)$$

$$W_\mathrm{pn} = H_\mathrm{pn}\left(\vec{r}_\mathrm{p}, \vec{r}_\mathrm{n}\right) G_\mathrm{pn}\left(\vec{p}_\mathrm{d}/2 + \vec{q}, \vec{p}_\mathrm{d}/2 - \vec{q}\right)$$

$$\varphi_\mathrm{d}(r) = \left(\pi d^2\right)^{-3/4} e^{-r^2/(2d^2)}$$

$$\mathcal{D}(r, q) = 8 e^{-r^2/d^2} e^{-q^2 d^2} \qquad \frac{d^3 N_d}{dp_d^3} = \frac{3}{(2\pi)^6} \left(\frac{d^2}{d^2 + 4\sigma^2}\right)^{3/2} \int d^3 q\, e^{-q^2 d^2}\, G_{np}(\vec{p}_\mathrm{d}, \vec{q})$$

$$h(r_{p/n}) = \left(2\pi\sigma^2\right)^{-3/2} e^{-r_{p/n}^2/(2\sigma^2)}$$