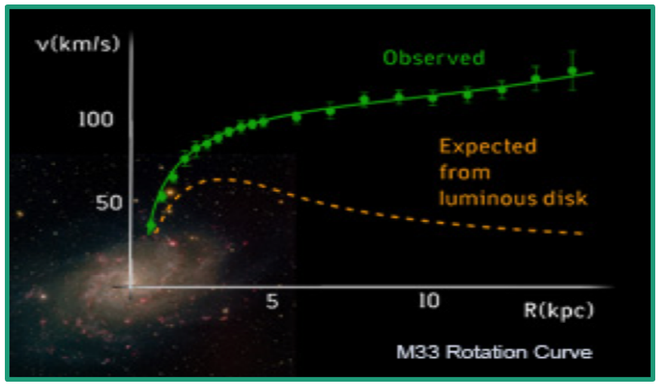
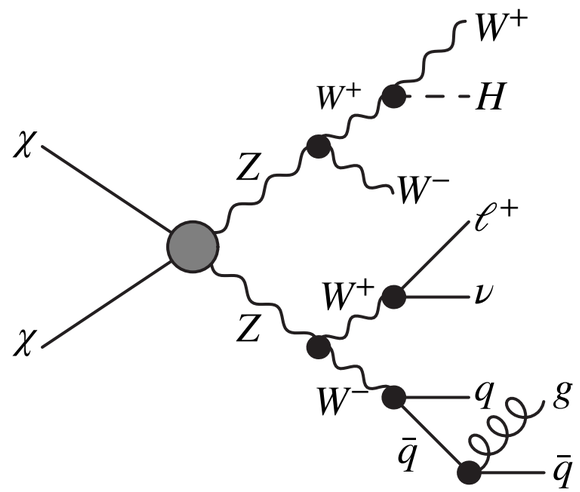
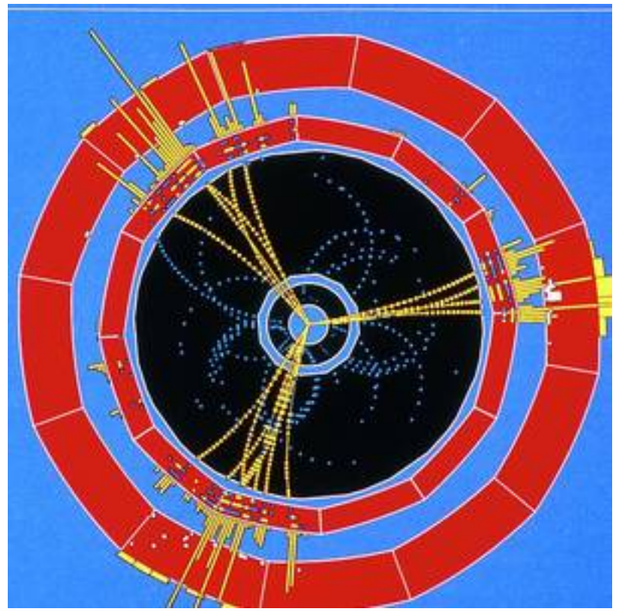
CosmiXs: Cosmic messenger spectra for indirect dark matter searches







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Institute for Basic Science

KIAS Workshop on Particle Physics and Cosmology
18-23 November 2024

w/ M. Di Mauro, N. Fornengo, R. Ruiz de Austri, F. Bellini (2411.04815)

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

w/ J. Kip, R. Ruiz de Austri, P. Skands (2303.11363, 2202.11546)

1. Introduction

Dark matter indirect detection

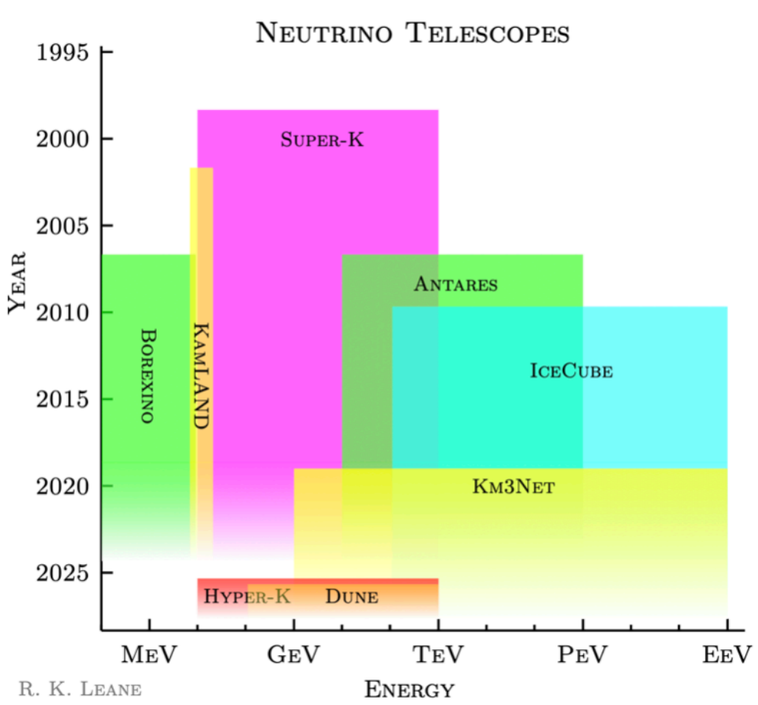
- WIMPs DM can annihilate or decay into a number final states: $W^+W^-; q\bar{q}, \ldots$ (depending on the model).
- Those final states will undergo of QED+EW+QCD showers, hadronization and hadron decays to produce stable particles; photons, positrons, anti-protons, and neutrinos.

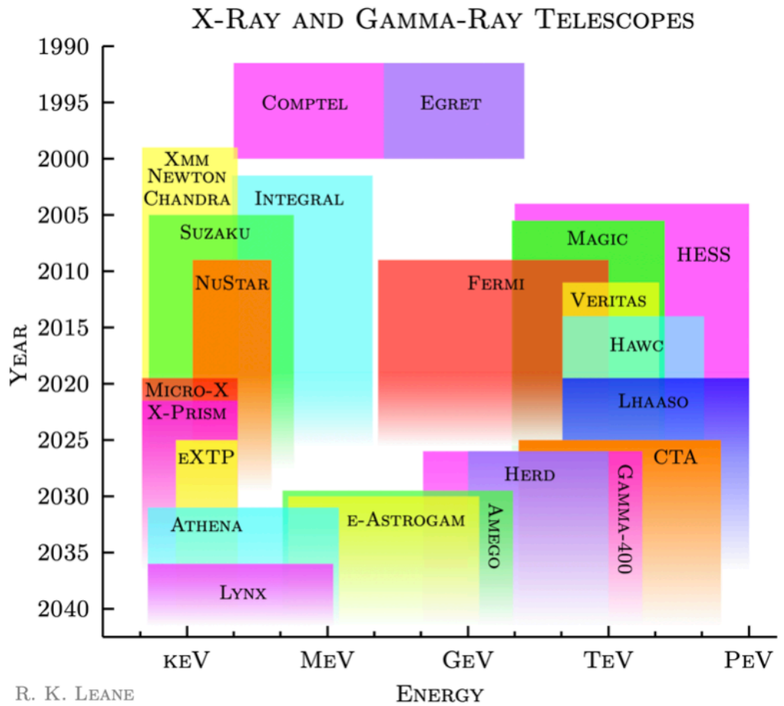
Impossible to predict the spectra from first principles.

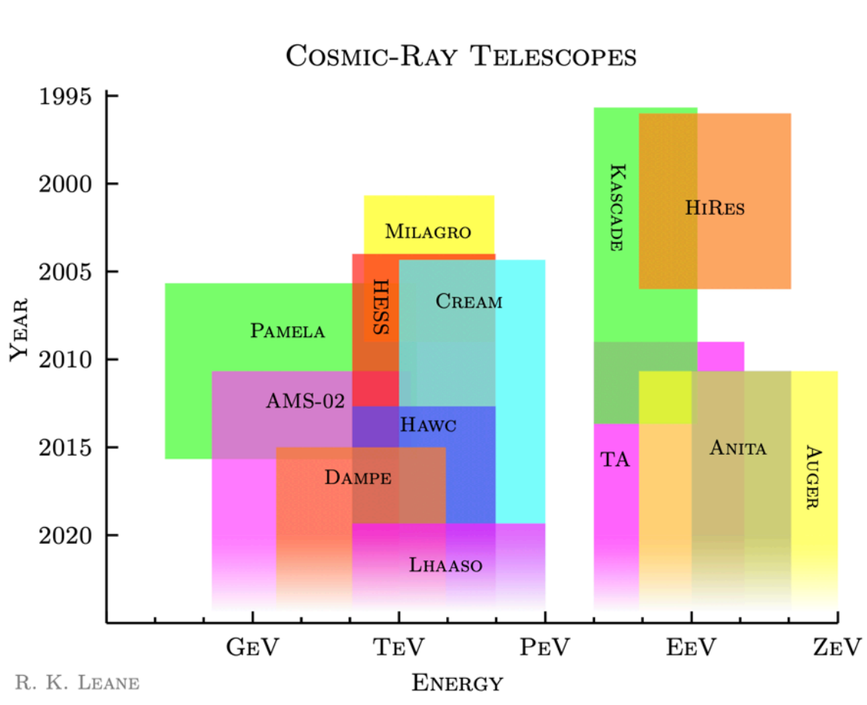
- Only phenomenological models can be used to solve the problem.

- IMPORTANT: hadronization occurs at longer distances compared to the scale of the hard process → The hadronization model can be constrained from fits to e.g. LEP data and used to make predictions for other processes (e.g. dark matter annihilation).

Past, Present and Future of DM ID







Taken from (R. K. Leane, 2006.00513)

Exciting times are awaiting for us in the next decade(s)!!

The flux of particles

For antiprotons, for example, the flux is given by

$$\frac{\mathrm{d}\Phi_{\bar{p}}}{\mathrm{d}E_{\mathrm{kin}}}(E_{\mathrm{kin}}, r_{\odot}) \equiv \frac{v_{\bar{p}}}{4\pi}\left(\frac{\rho_{\odot}}{M_{\chi}}\right)^{k} \mathcal{R}(E_{\mathrm{kin}}) \sum_{f} k^{-1} \mathcal{P}_{i\to f}(g_{\chi}; M_{\chi}) \left(\frac{\mathrm{d}N}{\mathrm{d}E_{\mathrm{kin}}}\right)_{f\to\bar{p}}$$

- $\mathscr{R}(E_{\mathrm{kin}})$ **encodes all the astrophysical information (e.g. propagation model).**

- $\mathscr{P}_{i\to f}(g_{\chi}; M_{\chi})$ **the transition rate (model dependent):**
  - $\mathscr{P}_{i\to f} \equiv \Gamma_{\chi\to f}$ **for decaying dark matter.**
  - $\mathscr{P}_{i\to f} \equiv \langle \sigma_{\chi\chi\to f} v \rangle$ **for annihilating dark matter.**

- $\left(\frac{\mathrm{d}N}{\mathrm{d}E_{\mathrm{kin}}}\right)_{f\to\bar{p}}$ **gives the differential probability to produce** $\bar{p}$ **from** f**.**

Our aim is to calculate $\mathrm{d}N/\mathrm{d}E_{\mathrm{kin}}$**!**

2. Existing tools

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

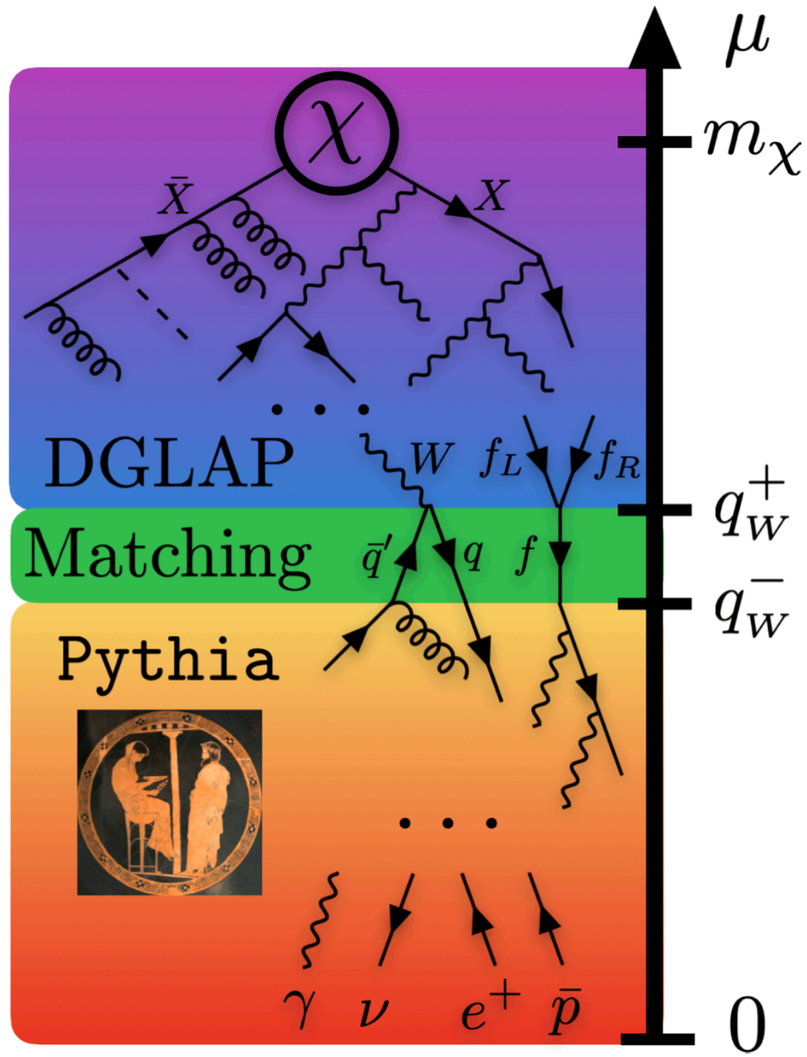
Christian W. Bauer,[1,2] **Nicholas L. Rodd,**[1,2] **Bryan R. Webber**[3]

[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?

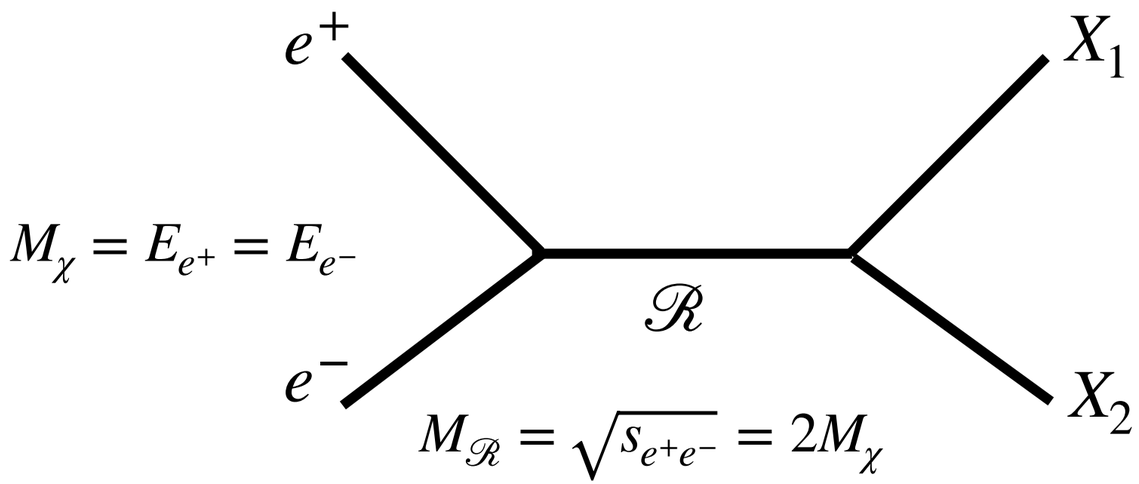
The standard tools calculate the spectra using PYTHIA 8 (can be found within the code).

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).

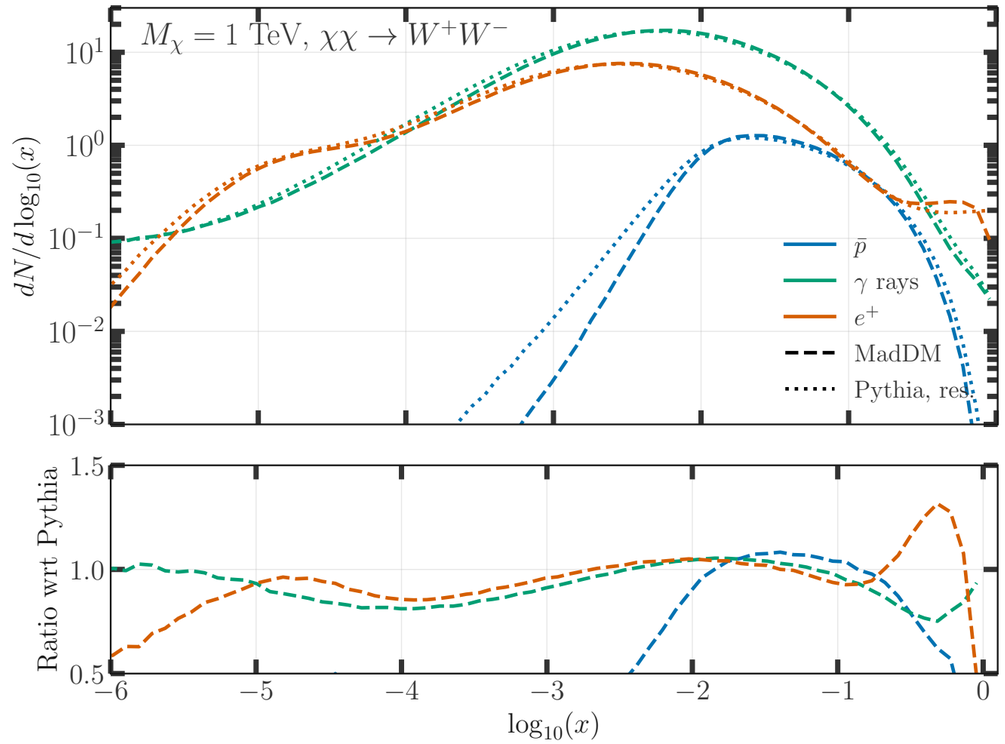
$\Longrightarrow$ Spin information is lost as the outgoing particles do not have assigned helicities.

$\Longrightarrow$ 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.



3. Particle production from dark matter

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

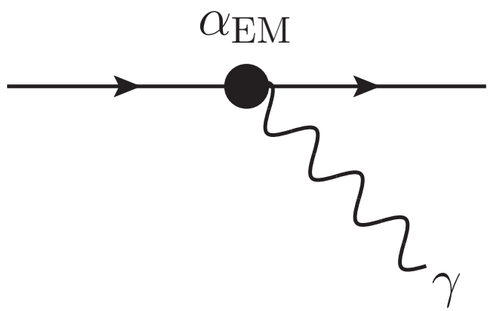
Stable particles

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

Modeling of the spectra: QED

- If X_i contains photons and/or electrically charged particles, then there are further QED emissions producing additional photons and charged fermions through $X_i^{\pm} \to \gamma X_i^{\pm}$ and $\gamma \to f\bar{f}$.
- The former process ($X_i^{\pm} \to \gamma X_i^{\pm}$) is enhanced in both the soft ($E_\gamma \to 0$) and the collinear ($\theta_{X\gamma} \to 0$) regions. Therefore, the produced photon may take the whole energy of the parent provided that $\theta_{X\gamma} \to 0$.

The rate of these processes is controlled by the effective value of $\alpha_{\rm EM}(Q)$

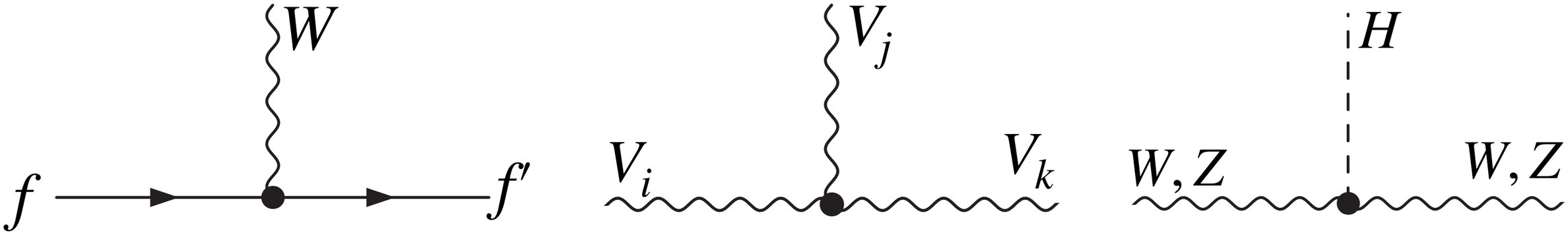


- Dominate at high (and also very low) x_γ.
- Relevant for DM annihilation into photons and charged leptons.
- The corresponding coupling ($\alpha_{\rm EM}$) is measured with high precision.

No need to assign uncertainties on the QED part.

Modeling of the spectra: EW

- All the particle species but the gluons can emit massive weak gauge bosons when phase space is permitting ==> Can cause significant contribution to the particle rates for heavy dark matter.
- In the standard PYTHIA shower, there are only two types of emissions: $f \to f'W$ and $f \to fZ$.
- VINCIA (based on helicity-dependent shower) contains all the possible weak shower emissions including those based on the triple-gauge interactions and Higgs-gauge interactions.



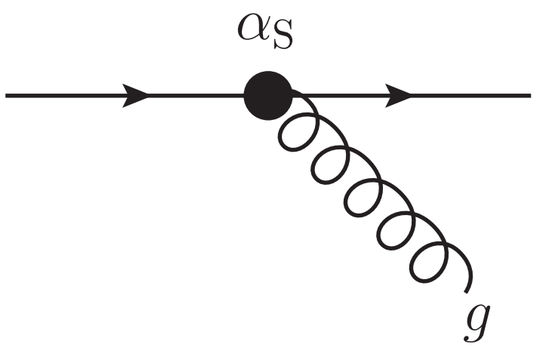
VINCIA takes the helicity information of the annihilation products into account.

(see e.g. 2108.10786, 2108.07133, 2106.10987, 1907.08980)

Modeling of the spectra: QCD

- If X_i contains colored particles (such as gluons or quarks), then a cascade of QCD shower emissions will occur.
- The QCD shower is treated the same way as in QED (enhancement of $g \to q\bar{q}$ splitting at low virtuality) with a probability that depends on how far from threshold the colored particle is produced.

The rate of these processes is controlled by the effective value of $\alpha_{\rm S}(Q)$

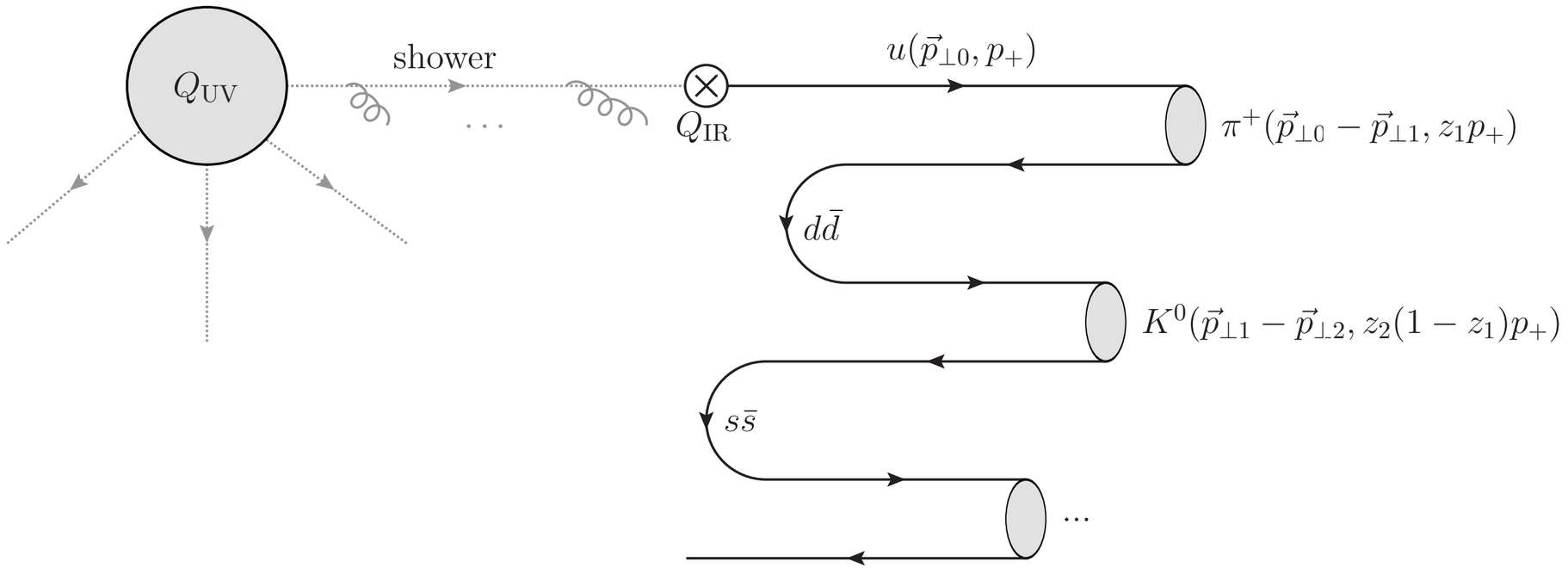


- Dominate at both the bulk and the peak.
- Relevant for DM annihilation into colored particles
- The corresponding coupling ($\alpha_{\rm S}$) in PYTHIA8 is different by about 20% from the $\alpha_{\rm S}(M_Z)^{\overline{\rm MS}}$.

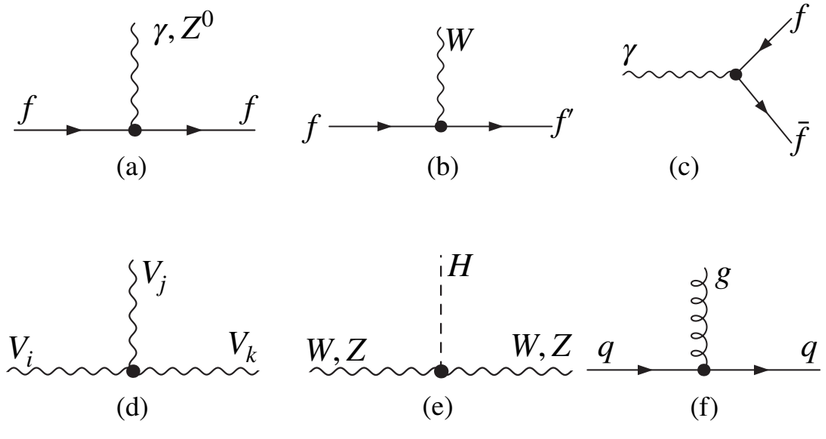
Subject to uncertainty variations!

Modeling of the spectra: Hadronization

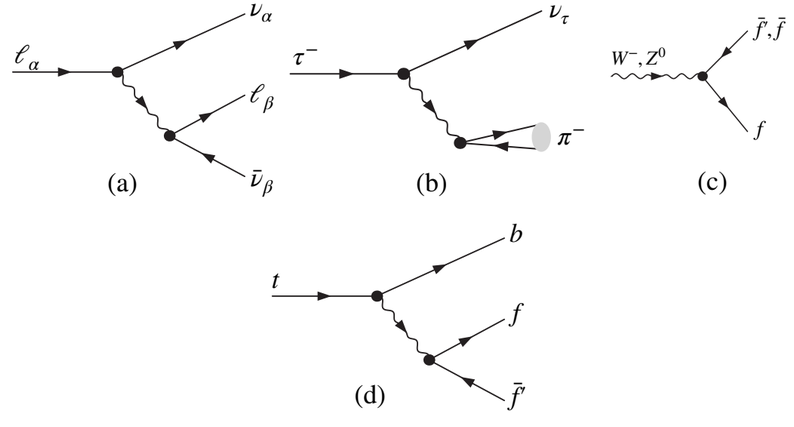
- Hadronization is a process where color triplets and octets (i.e. quarks and gluons) will fragment to form *color singlet hadrons.*
- This process occurs at low scales (at the shower cut-off).
- Two main models: Cluster and String models.



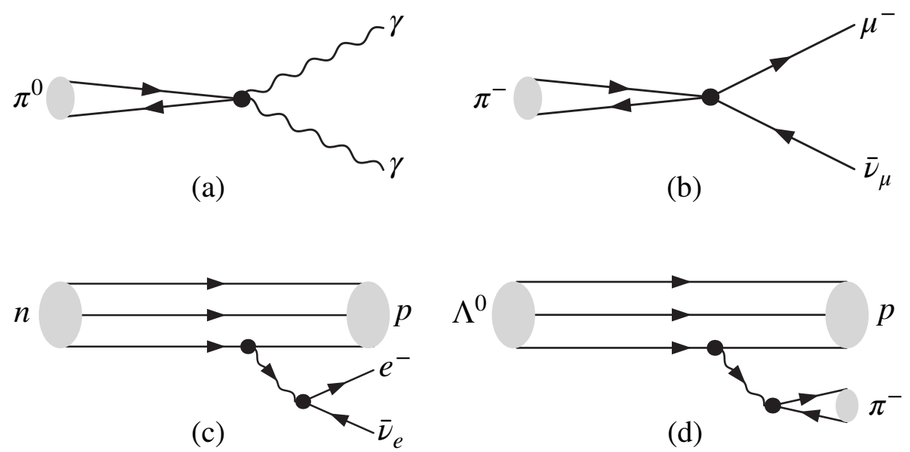
Summary of leading contributions



QED+QCD+EW showers

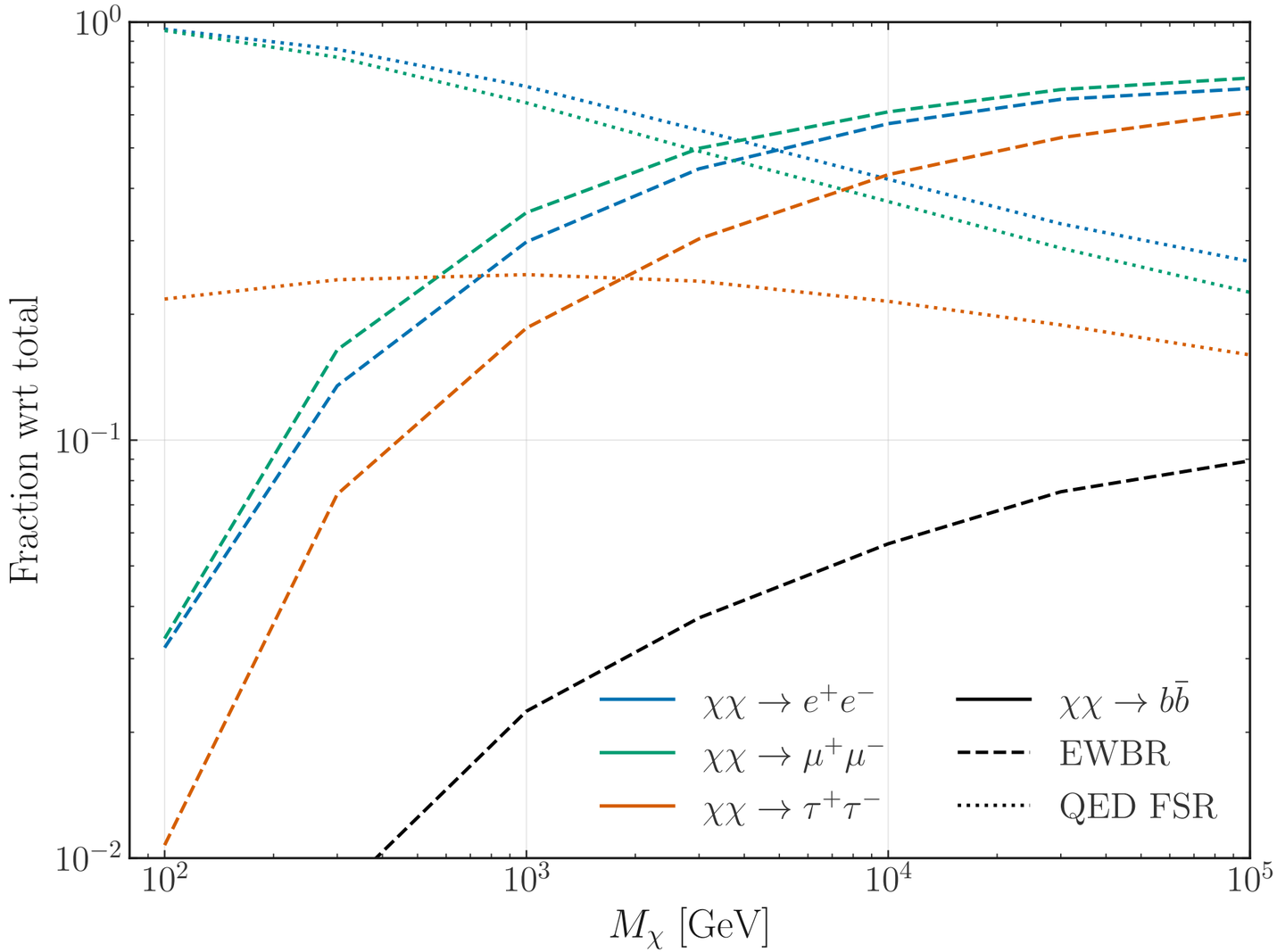


Weak decays



Meson and baryon decays

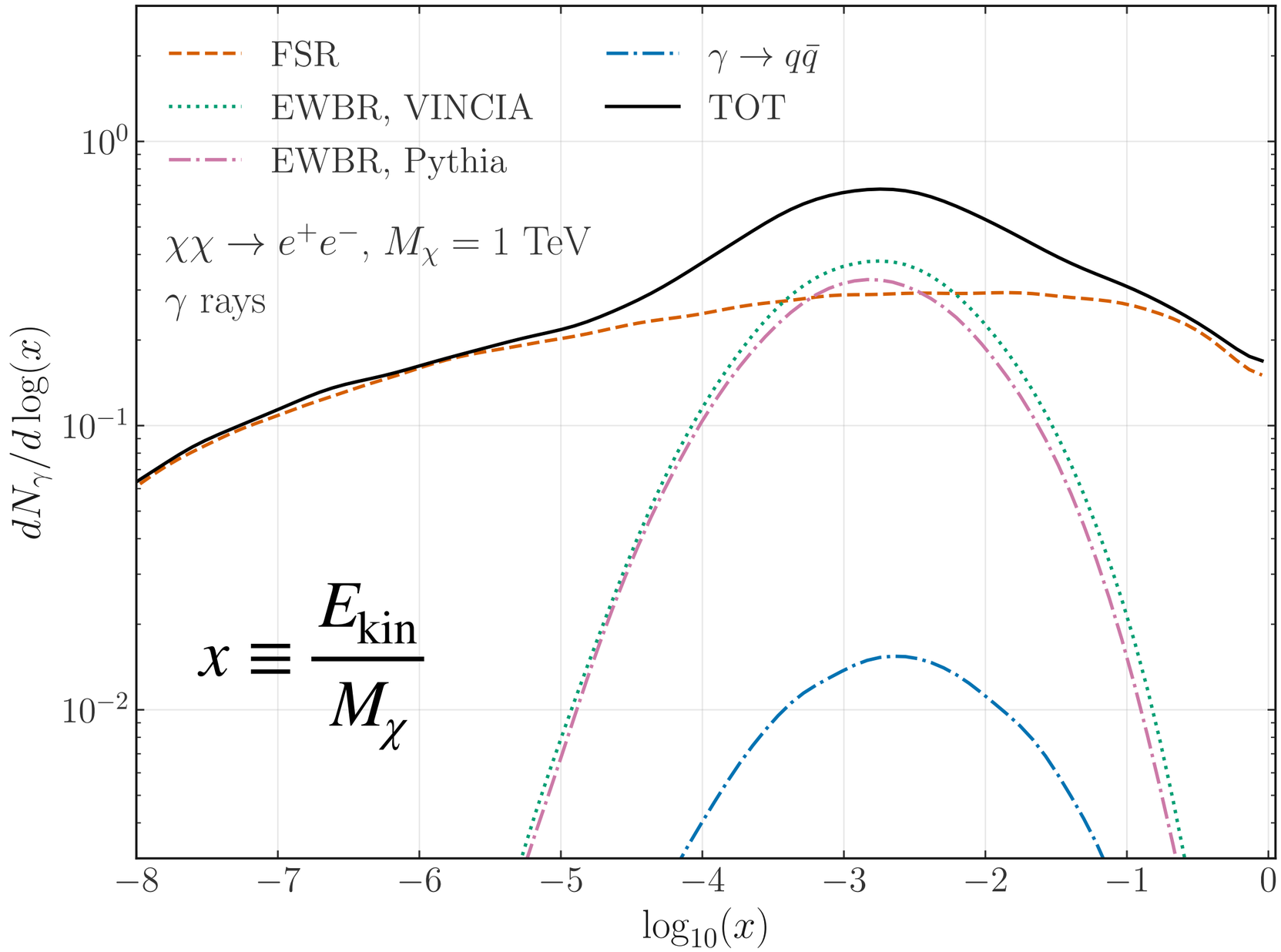
Generic features of particle production



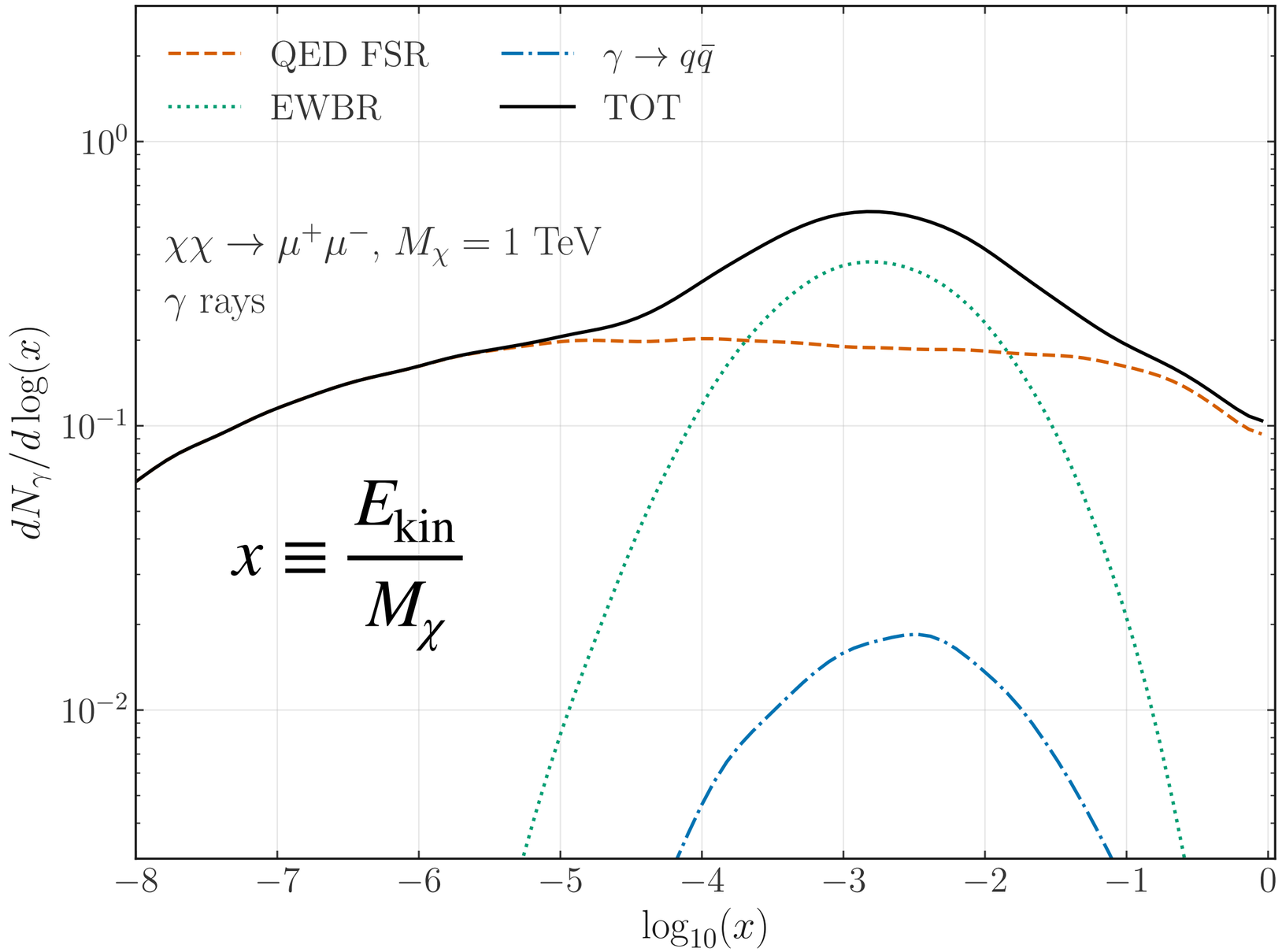
Fraction with respect to the total number of photons.

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.

4. Hadronization model

Review: Hadronization in PYTHIA8

The Lund string model is based on the following symmetric function

$$f(z, m_\perp) \propto N \frac{(1-z)^{a_L}}{z} \exp\left(\frac{-b_L m_\perp^2}{z}\right)$$

- **It gives the *probability* to produce a hadron with energy fraction z and transverse mass $m_\perp$**
- **a and b are tunable parameters with the former controls the number of high energy hadrons while the latter controls the number of low energy hadrons.**
- **These parameters can be highly strongly correlated causing both problems in the fits and/or in the interpretation of the $\pm$ uncertainties on them.**

Generalities

Including the baryon production and heavy quark effects, the fragmentation function becomes:

$$f(z) \propto N \frac{1}{z^{1+r_Q b_L m_Q}} z^{a_{\rm eff}} \left(\frac{1-z}{z}\right)^{a_{\rm eff}} \exp\left(\frac{-b_L m_{\perp h}^2}{z}\right)$$

r_Q $(Q = c, b)$ **are Bowler modification parameters** (X. Artru, 1974; M. G. Bowler, 1981)**.**

$$a_{\rm eff} \equiv a_L + a_{QQ}$$

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

We do not tune r_c and r_b

Tuning

- Different tunings of the parameters $a_L, b_L, \sigma(=\sqrt{\langle m_\perp^2 \rangle/2}),$ and a_{QQ} of the Lund fragmentation function are performed using a set of measurements at LEP-I at the Z-pole — ALEPH, DELPHI, L3, OPAL.

- Include the most sensitive measurements; mean multiplicities, identified particle momenta $(\pi^{\pm}, \pi^0, \eta, \gamma, \bar{p}, \Lambda)$, event shapes, jet rates and charged particle momenta.

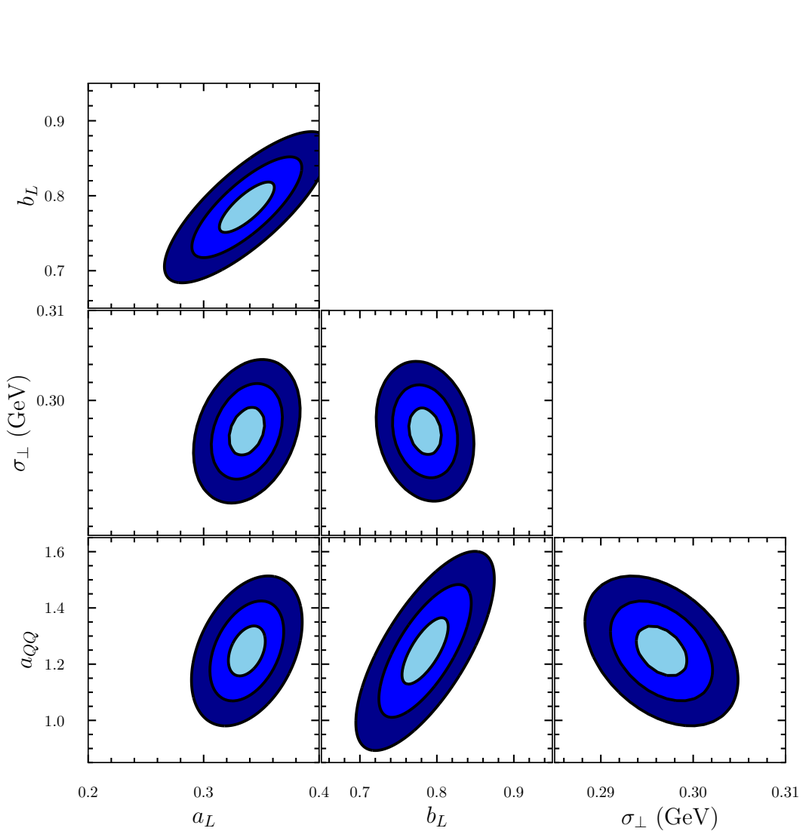
- We use Professor version 2.3.3 (arXiv: 0907.2973) for optimization of the parameters of the fragmentation function in Pythia8.309 assuming the VINCIA shower plugin and Rivet 3.1.7 for the experimental analyses.

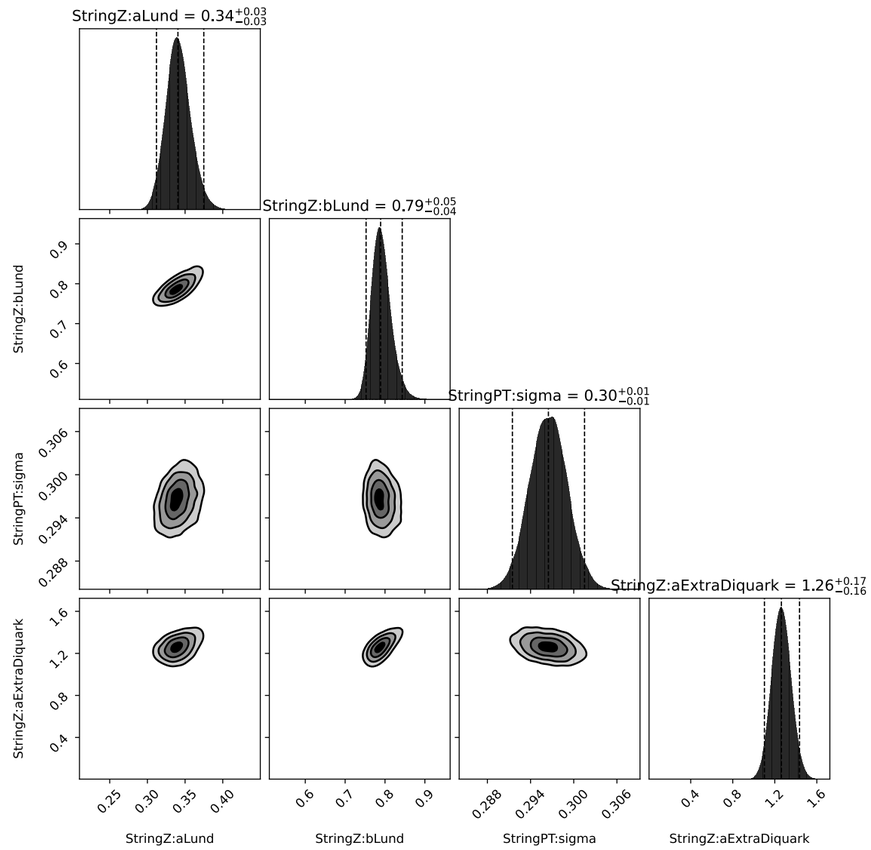
- We modify slightly the definition of the Goodness-of-Fit in Professor to account for a flat 5% uncertainty in the MC predictions

$$\chi^2 = \sum_{\mathcal{O}} \sum_{b \in \mathcal{O}} \left(\frac{\mathrm{MC}_{(b)}(\{p_i\}) - \mathrm{Data}_{(b)}}{\Delta_b} \right)^2 \qquad \Delta_b = \sqrt{\Delta_{\mathrm{exp}}^2 + \Delta_{\mathrm{MC}}^2 + (0.05\ \mathrm{MC}_{(b)})^2}$$

Tunes: Results

Parameter	MONASH	VINCIA (default)	PYTHIA	(QCDUnc)	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



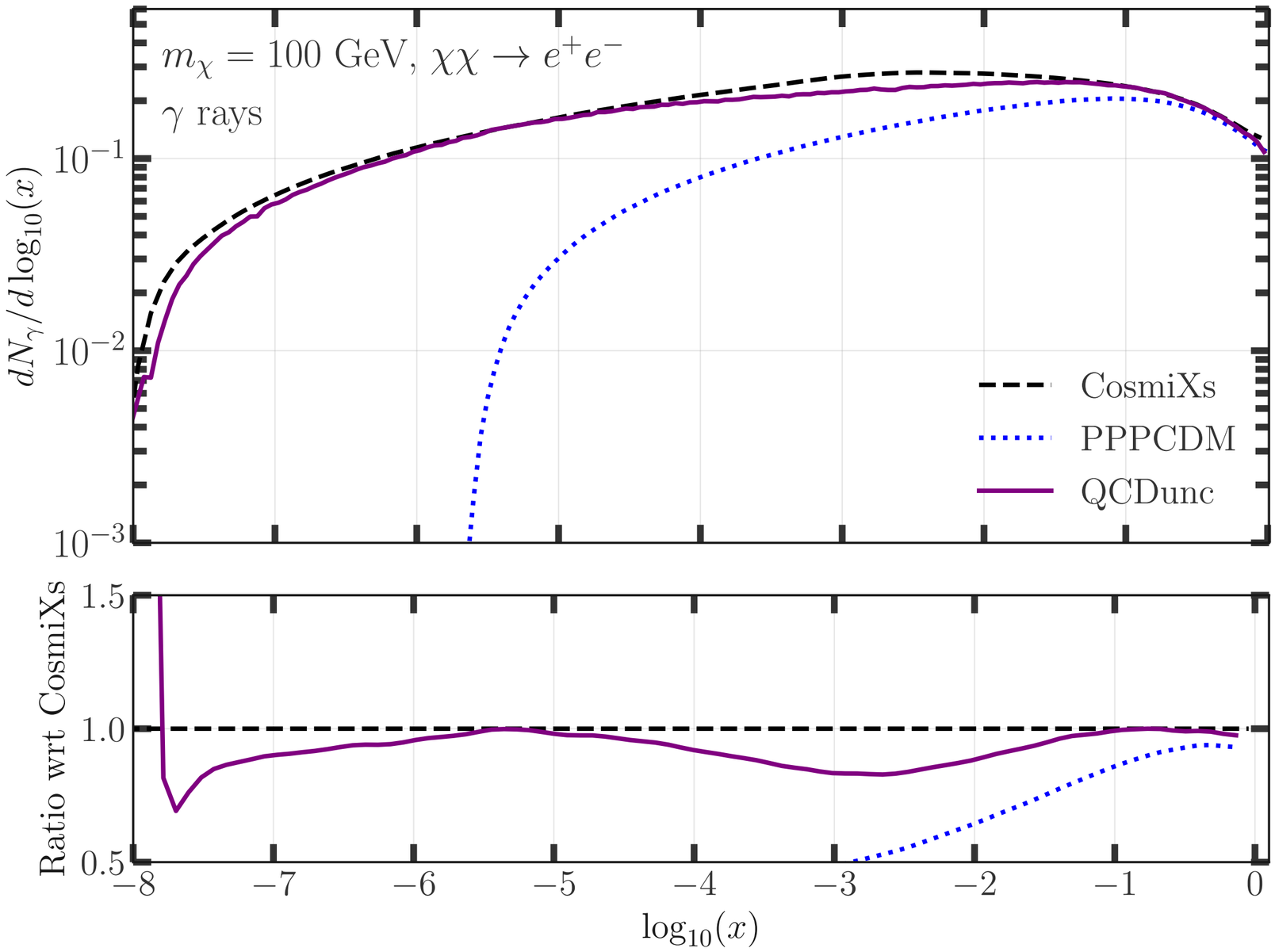


Tunes: Results

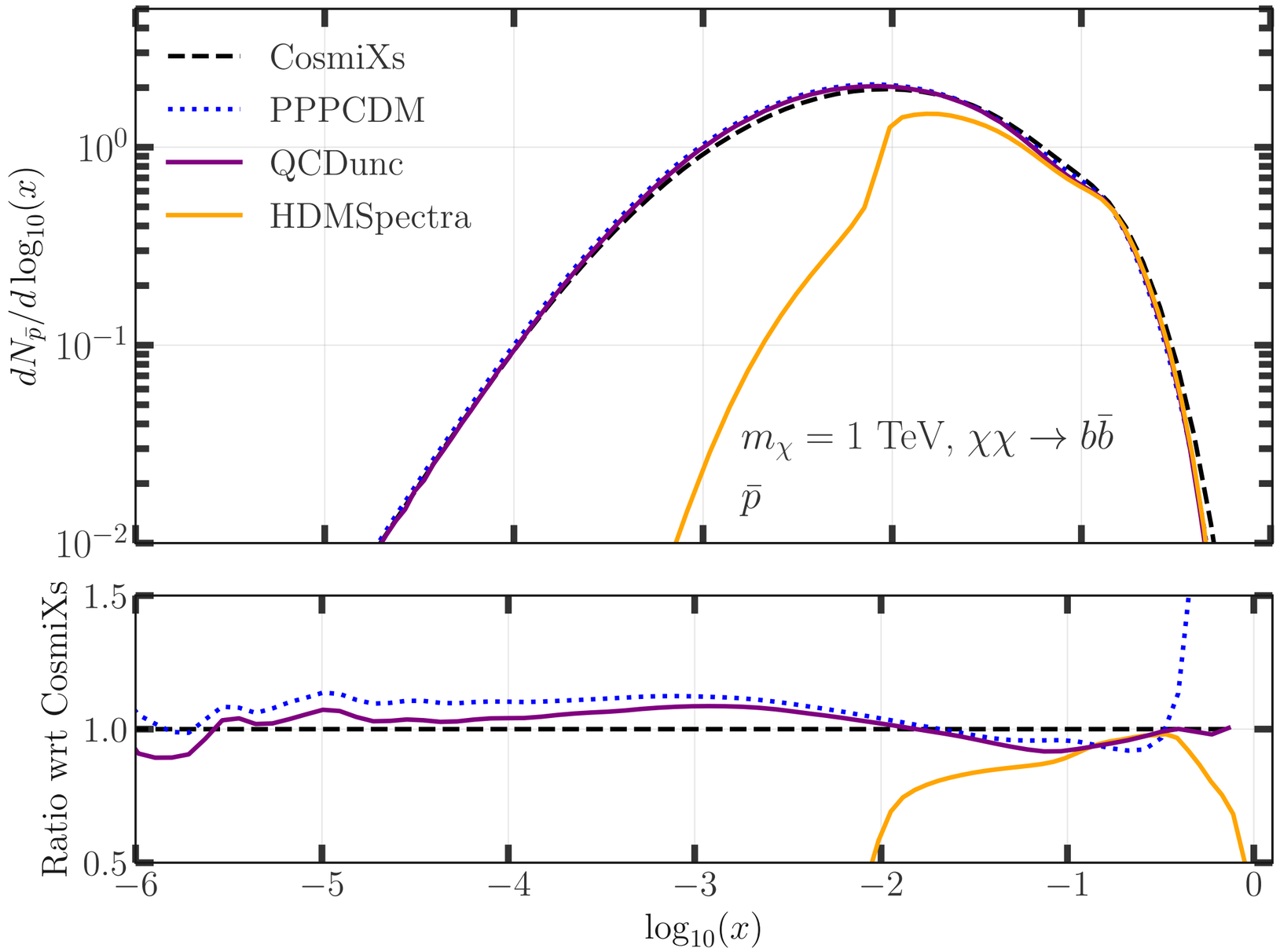
Measurement	Experiment	χ^2/N_{bins}	Measurement	Experiment	χ^2/N_{bins}
$1-T$	ALEPH [49]	0.13	C–parameter	ALEPH [49]	0.39
$\log(1/x_p)$	ALEPH [49]	0.19	$\langle N_{\text{ch}} \rangle$	ALEPH [49]	0.028
$\langle N_{\text{ch}} \rangle$ ($\lvert Y \rvert < 0.5$)	ALEPH [49]	0.012	$\langle N_{\text{ch}} \rangle$ ($\lvert Y \rvert < 1.0$)	ALEPH [49]	0.028
$\langle N_{\text{ch}} \rangle$ ($\lvert Y \rvert < 1.5$)	ALEPH [49]	0.030	$\langle N_{\text{ch}} \rangle$ ($\lvert Y \rvert < 2.0$)	ALEPH [49]	0.040
$\pi^{\pm}$ spectrum	ALEPH [49]	0.67	π^0 spectrum	ALEPH [49]	0.24
Λ^0 spectrum	ALEPH [50]	1.24	Λ^0 spectrum (2–jet events)	ALEPH [50]	1.31
Thrust	ALEPH [51]	0.097	C–parameter	ALEPH [51]	0.35
N_{ch} ($y_{\text{cut}} = 0.01$)	DELPHI [52]	5.99	N_{ch} ($y_{\text{cut}} = 0.02$)	DELPHI [52]	4.88
Λ^0 spectrum	DELPHI [53]	1.34	$\langle N_{\Lambda^0} \rangle$	DELPHI [53]	0.53
π^0 momentum	DELPHI [54]	0.41	$\log(1/x_p)$	DELPHI [54]	0.33
$1-T$	DELPHI [54]	0.18	C–parameter	DELPHI [54]	0.34
$\langle N_{\text{ch}} \rangle$	DELPHI [54]	0.031	$\langle N_{\pi^{\pm}} \rangle$	DELPHI [54]	0.063
$\langle N_{\pi^0} \rangle$	DELPHI [54]	0.39	$\langle N_{\rho} \rangle$	DELPHI [54]	3.40
$\langle N_p \rangle$	DELPHI [54]	2.30	$\langle N_{\Lambda^0} \rangle$	DELPHI [54]	1.54
$\langle N_{\text{ch}} \rangle$	DELPHI [55]	0.005	$\langle N_{\pi^{\pm}} \rangle$	DELPHI [55]	0.10
$\langle N_p \rangle$	DELPHI [55]	0.05	$N_{p/\bar{p}}/N_{\text{ch}}$	DELPHI [55]	0.27
$\pi^{\pm}$ momentum	DELPHI [55]	0.46	$p/\bar{p}$ momentum	DELPHI [55]	0.43
Thrust (udsc events)	L3 [56]	0.34	C–parameter (udsc events)	L3 [56]	0.22
Charged multiplicity	L3 [56]	3.39	$\log(1/x_p)$	L3 [56]	0.96
x_p (udsc events)	L3 [56]	0.78			
$\langle N_{\text{ch}} \rangle$	OPAL [57]	0.37	$\pi^{\pm}$ spectrum	OPAL [58]	0.25
Λ^0 scaled energy	OPAL [59]	1.49	π^0 scaled momentum	OPAL [60]	0.12
All events $\log(1/x_p)$	OPAL [61]	0.38	$\langle N_{\text{ch}} \rangle$	OPAL [61]	0.16
$1-T$	OPAL [62]	0.10	C–parameter	OPAL [62]	0.35

5. Comparison with HDMS and PPPC

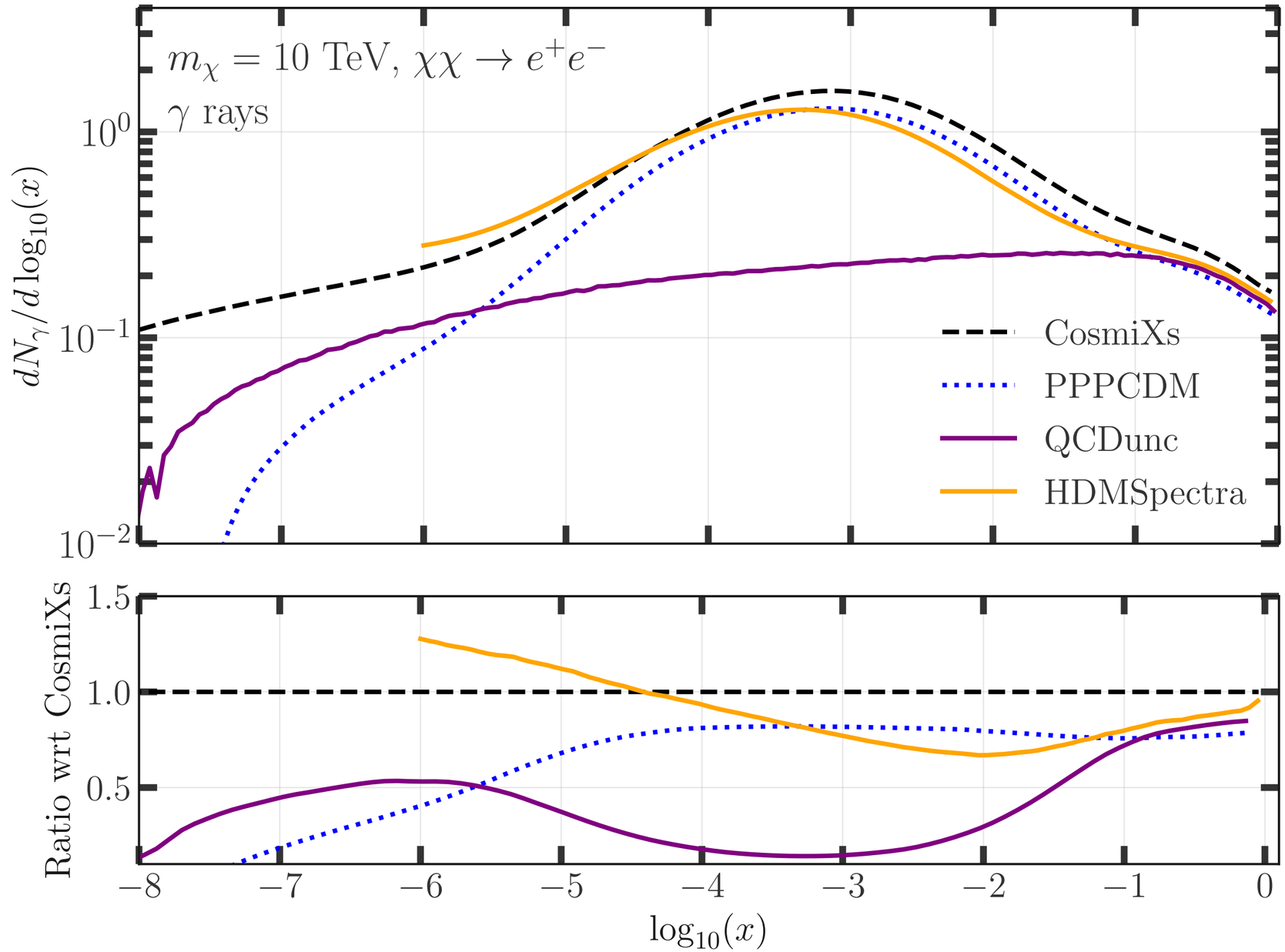
Comparison


$m_\chi = 100$ GeV, $\chi\chi \to e^+e^-$
γ 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
$\log_{10}(x)$

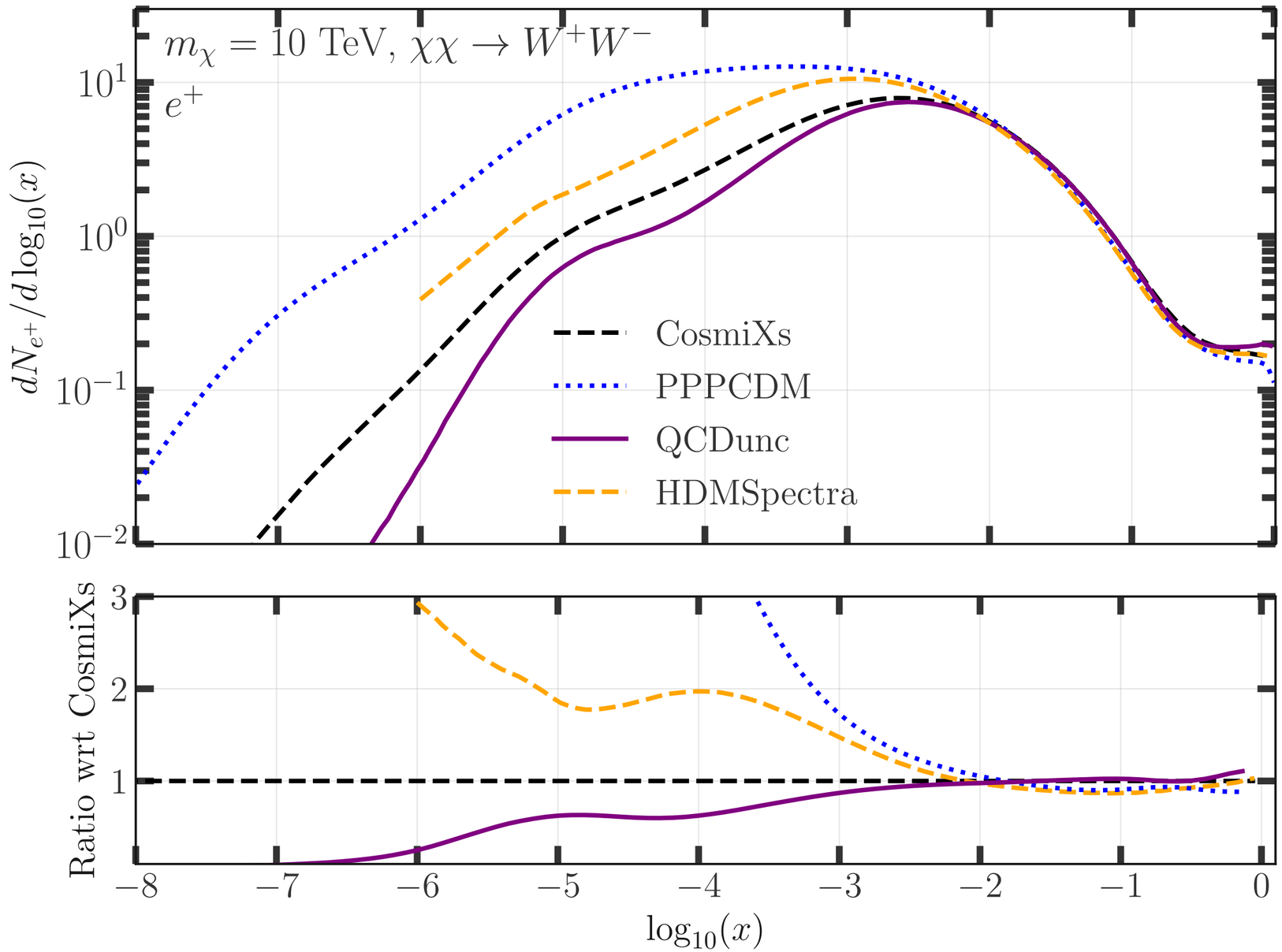
Comparison


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

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
$\log_{10}(x)$

CosmiXs Public

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ajueid Update README.md 25fc82e · last week 90 Commits

AntiDeuterons	Added spectra of antideuterons	2 weeks ago
Data	Minor change on notation	10 months ago

README

https://github.com/ajueid/CosmiXs



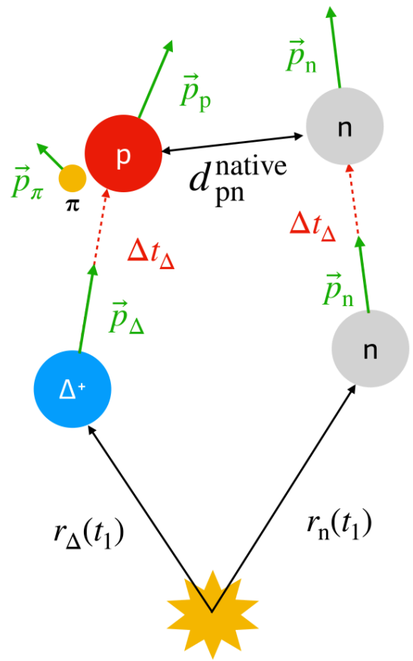
CosmiXs: Cosmic messenger spectra for indirect dark matter searches

6. Antideuterons

Introduction

- Antideuterons represent a clean and smoking-gun signature for DM indirect detection.
- Secondary production is at least one order of magnitude smaller than DM one for energy range of 0.1 to 1 GeV/n.

  A. Ibarra et al. (1209.5539), N. Fornengo et al. (1306.4171), J. Herms et al. (1610.00699)
- Modeling depending on phenomenological models called coalescence models.



M. Mahlein et al. (2302.12696)

- Space-time distance can be obtained from MC simulations.
- Coalescence process depends on an extra parameter called coalescence momentum.

Coalescence Models

- *Spherical model:*

Most straightforward as it assumes spherical symmetry — Rates are proportional to the products of the antiproton and anineutron spectra. $\Longrightarrow$ Wrong answers!

- *Simple coalescence model:*

Select, for each annihilation event, the $\bar{n}$ and $\bar{p}$ pairs that have a difference in momentum $\Delta p = |\vec{p}_{\bar{p}} - \vec{p}_{\bar{n}}|$, in the $\overline{\mathrm{D}}$ rest frame, smaller than p_{coal}, which is the single parameter of the model.

Another variant is to use the same model with a sharp cutoff on distance ($\Delta r < 3$ fm)

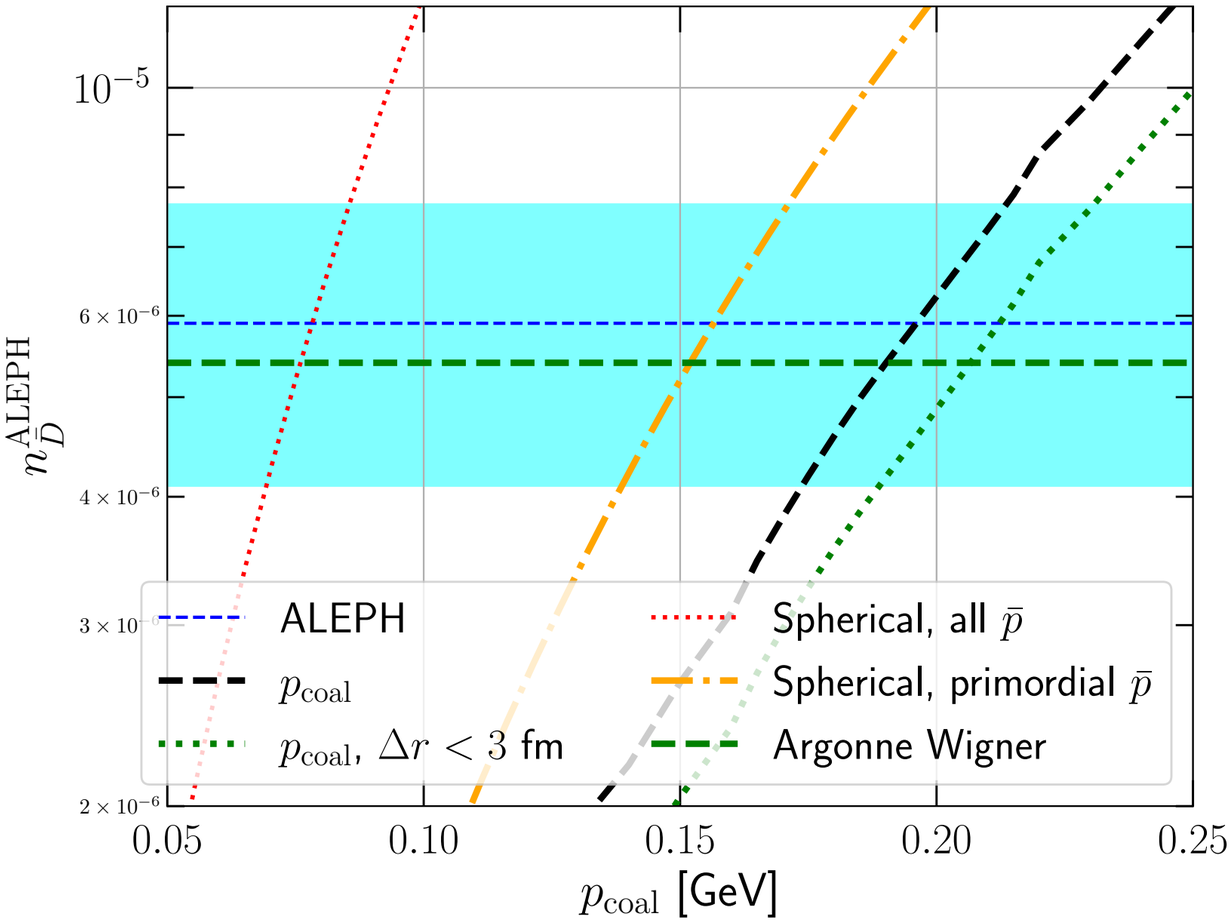
- *Wigner model:*

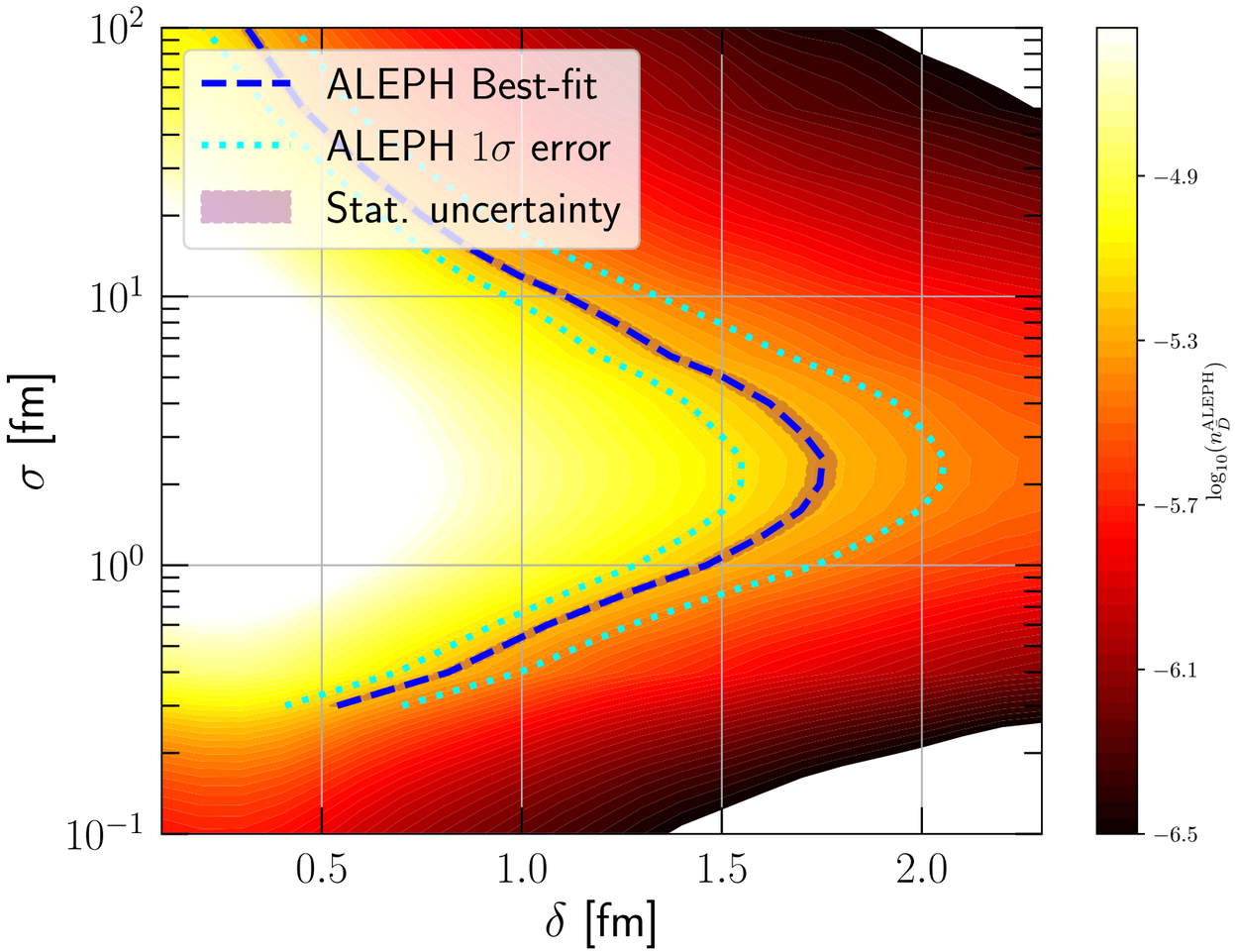
Use a quantum mechanical description of the wave functions of $\bar{n}, \bar{d},$ and $\overline{\mathrm{D}} \Longrightarrow$ Full space and charge correlations, ...

With a Gaussian wave function: $\mathscr{D}(\Delta r, \Delta p) \propto e^{-\Delta r^2/(2\sigma^2)} e^{-\Delta p^2 \delta^2/2}$

With an Argonne wave function (v_{18}) : has no free parameters (R. Wiringa et al., nucl-th/9408016).

Tuning of Coalescence Models

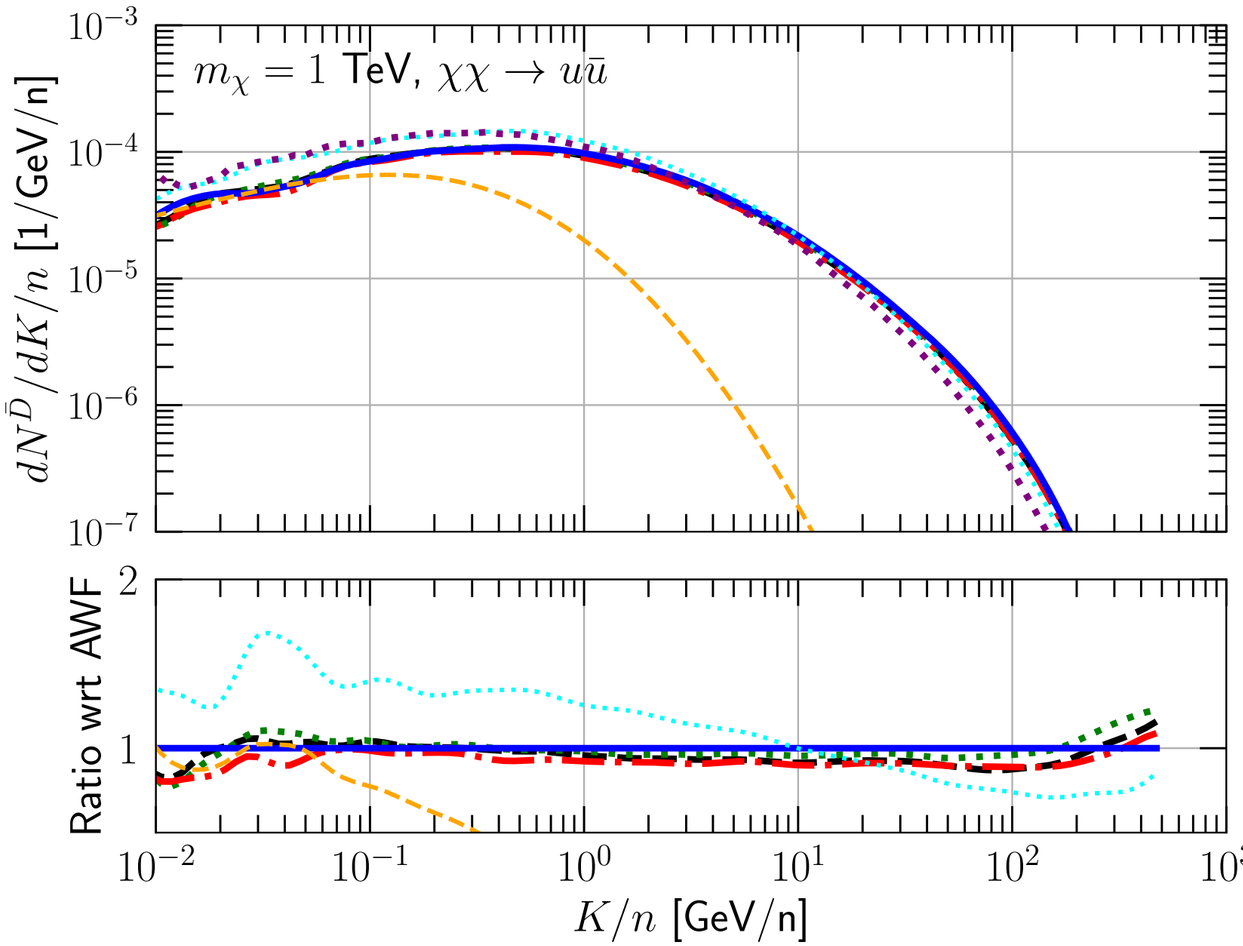


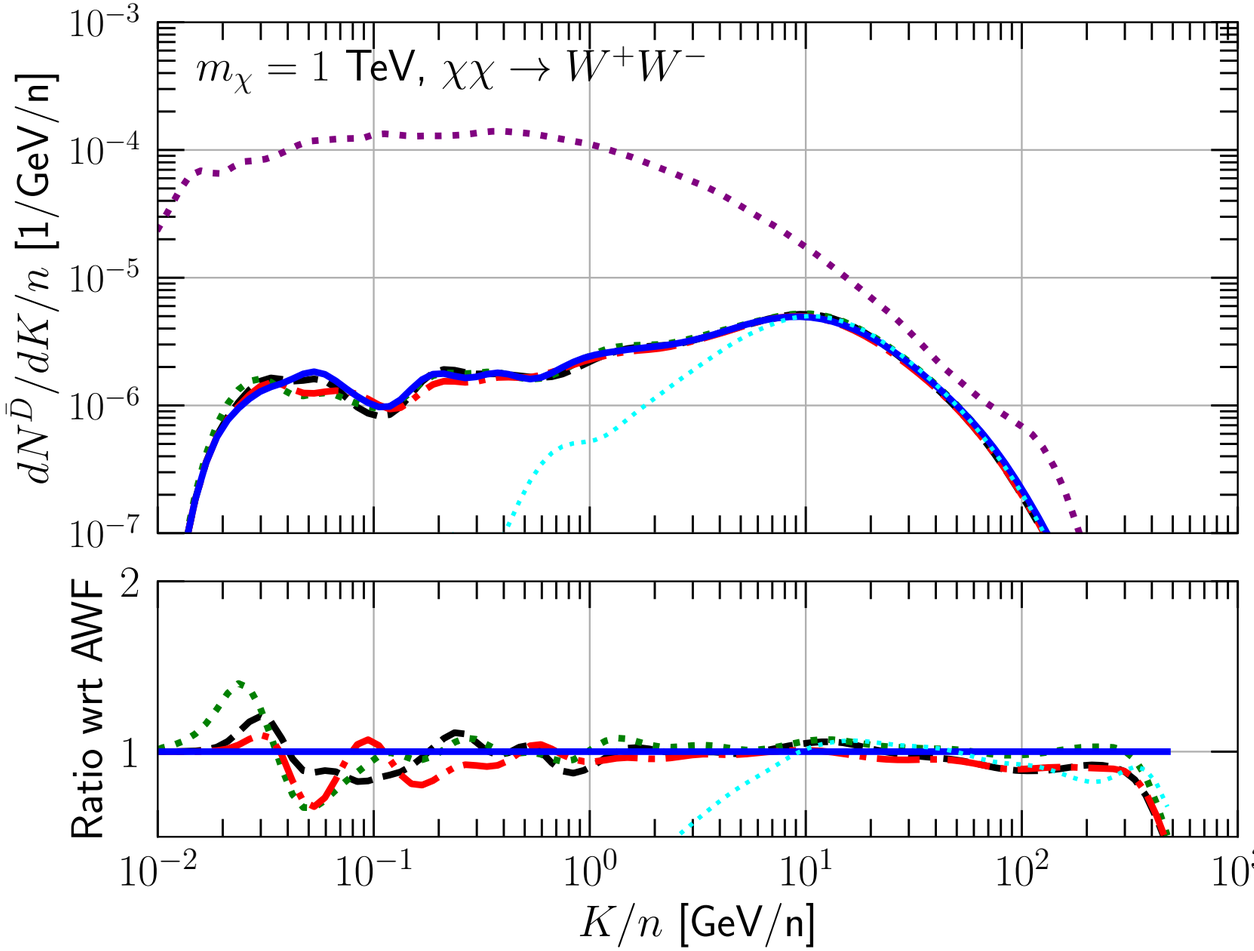


Use LEP data to tune the coalescence parameters ($n_{\overline{\mathrm{D}}}^{\mathrm{ALEPH}} = (5.9 \pm 1.8 \pm 0.5) \times 10^{-6}$)

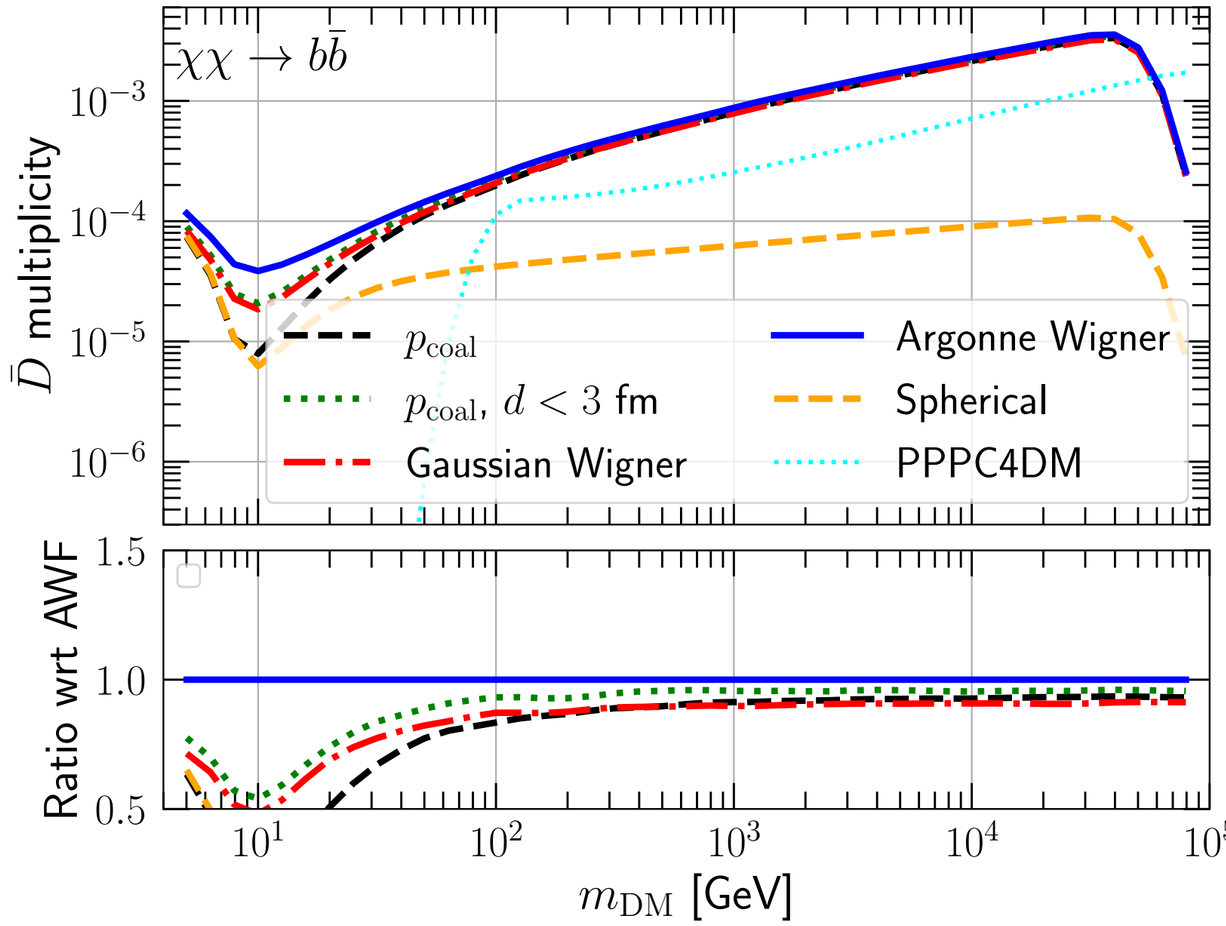
Use PYTHIA 8309 + VINCIA parton shower algorithm on the theory side.

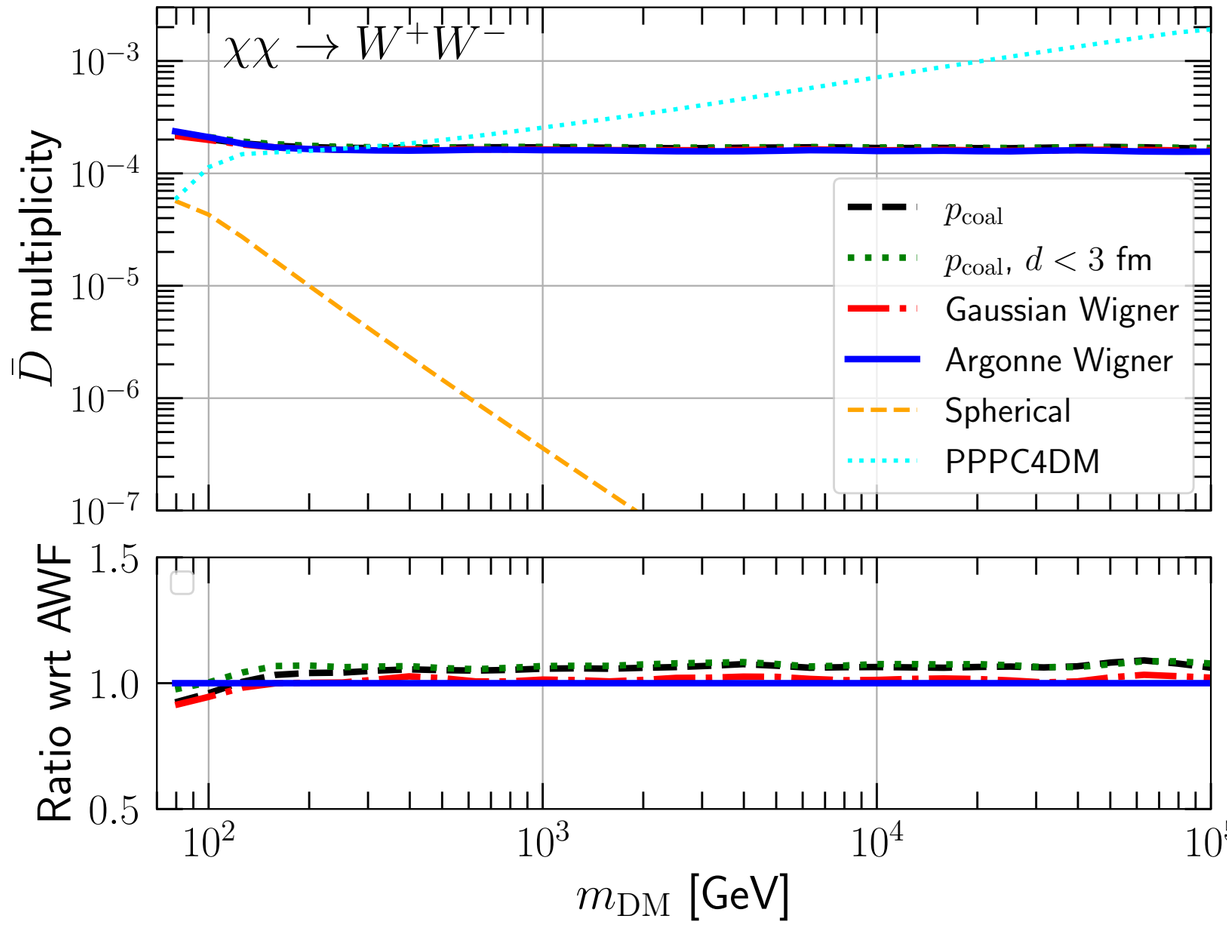
$\overline{\mathrm{D}}$ from DM: Some results



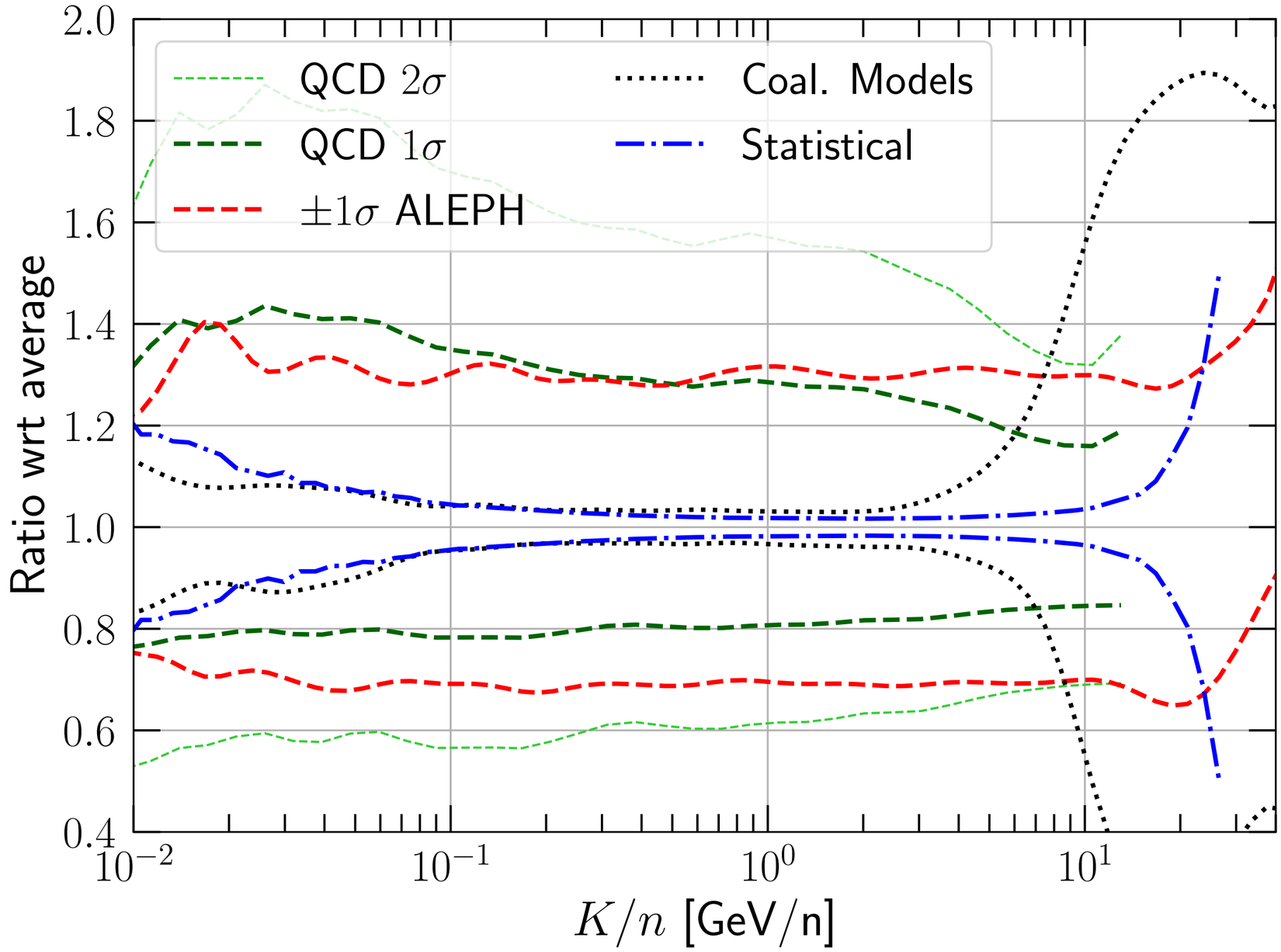


$\overline{\mathrm{D}}$ from DM: Some results





$\overline{\mathrm{D}}$ from DM: Uncertainties



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, improved resummations, matching or probably the use of new LHC data.

7. QCD uncertainties

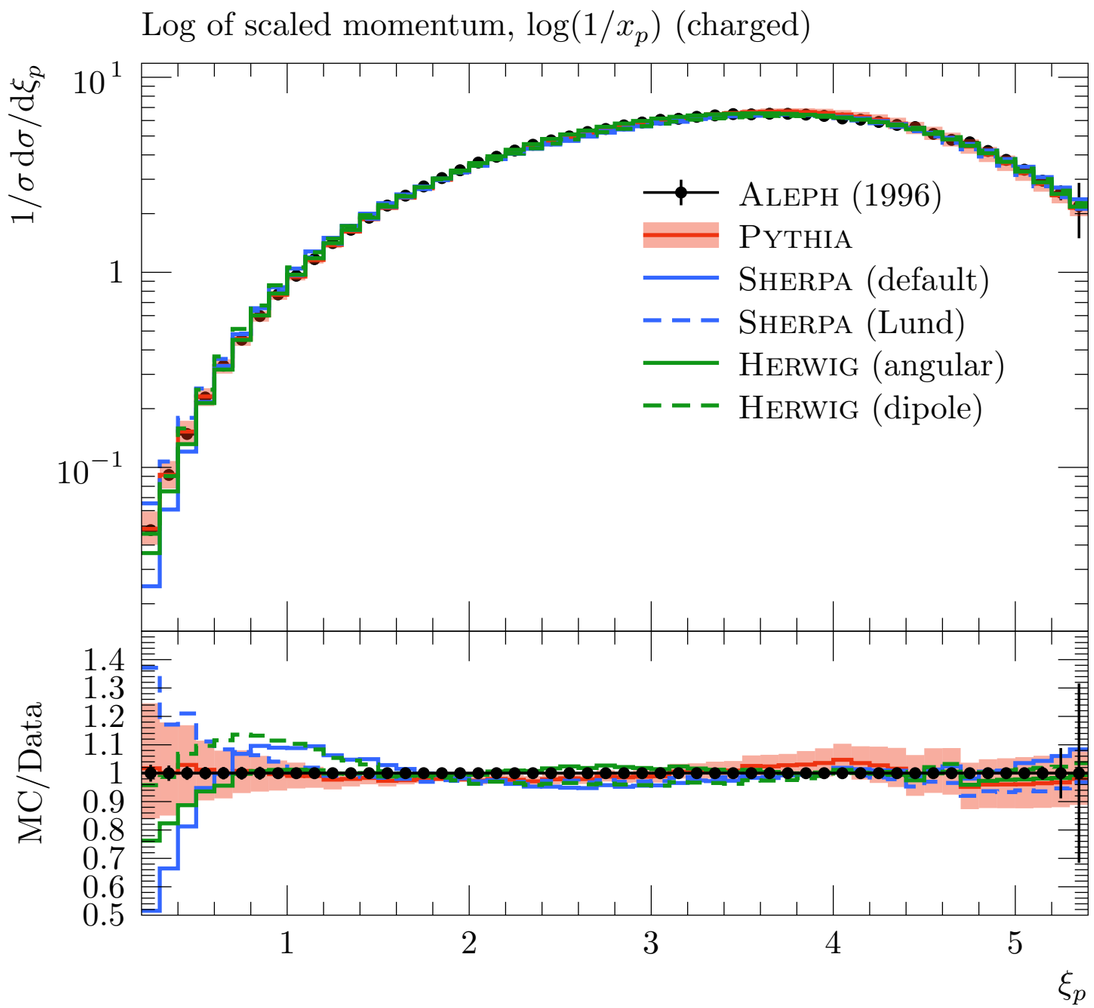
The modeling of the uncertainties: The old method

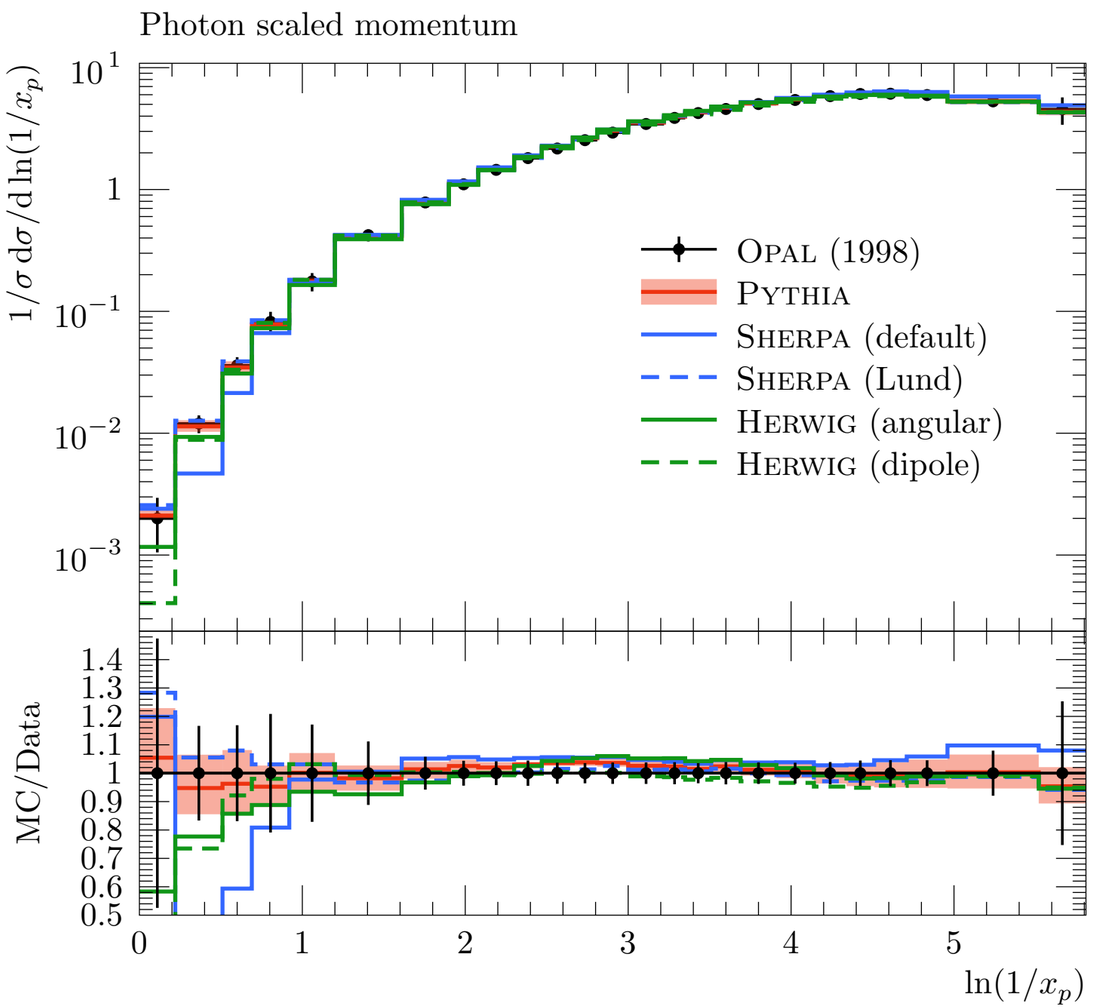
Take the predictions of different Monte Carlo event generators; define one as a central predictions and the envelope spanned by all is an estimate of the uncertainty:

- **At first glance, it seems like a reasonable approach due to the different modeling assumptions used in different Monte Carlo Event Generators.**
- **However, MC event generators are essentially tuned to the same set of constraining data.**
- **It was shown in a recent study (1305.2124) that different MC generators can have large differences in the extremes of the photon spectra (in which the modeling assumption and the lack of constraining data play an important role) while in the peak of the distribution, they have perfect agreement.**
- **This implies automatically that the envelope spanned by different MC generators cannot cover the range of the uncertainty allowed by data (overestimate in same regions, underestimate in the most important regions).**

We need to estimate QCD uncertainties within the same generator

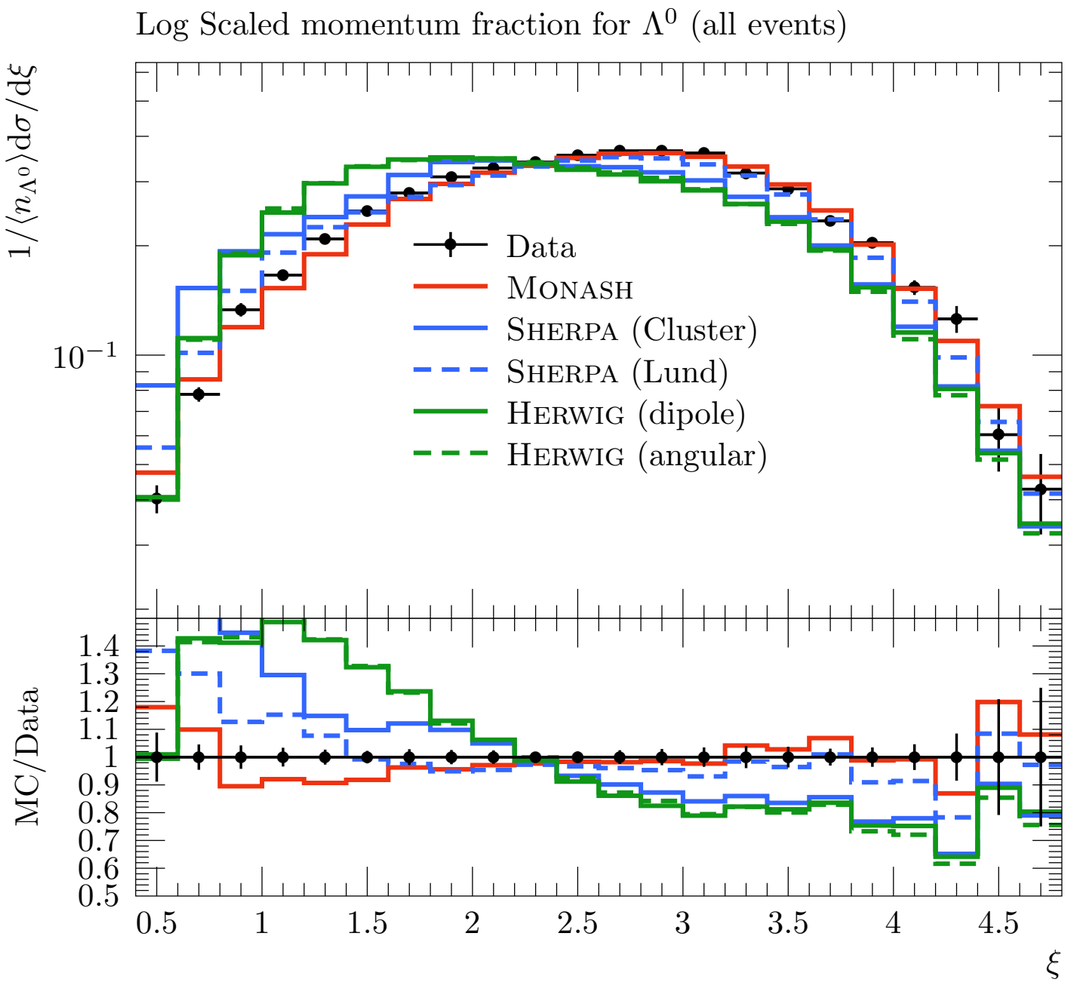
How good are the current theory predictions?

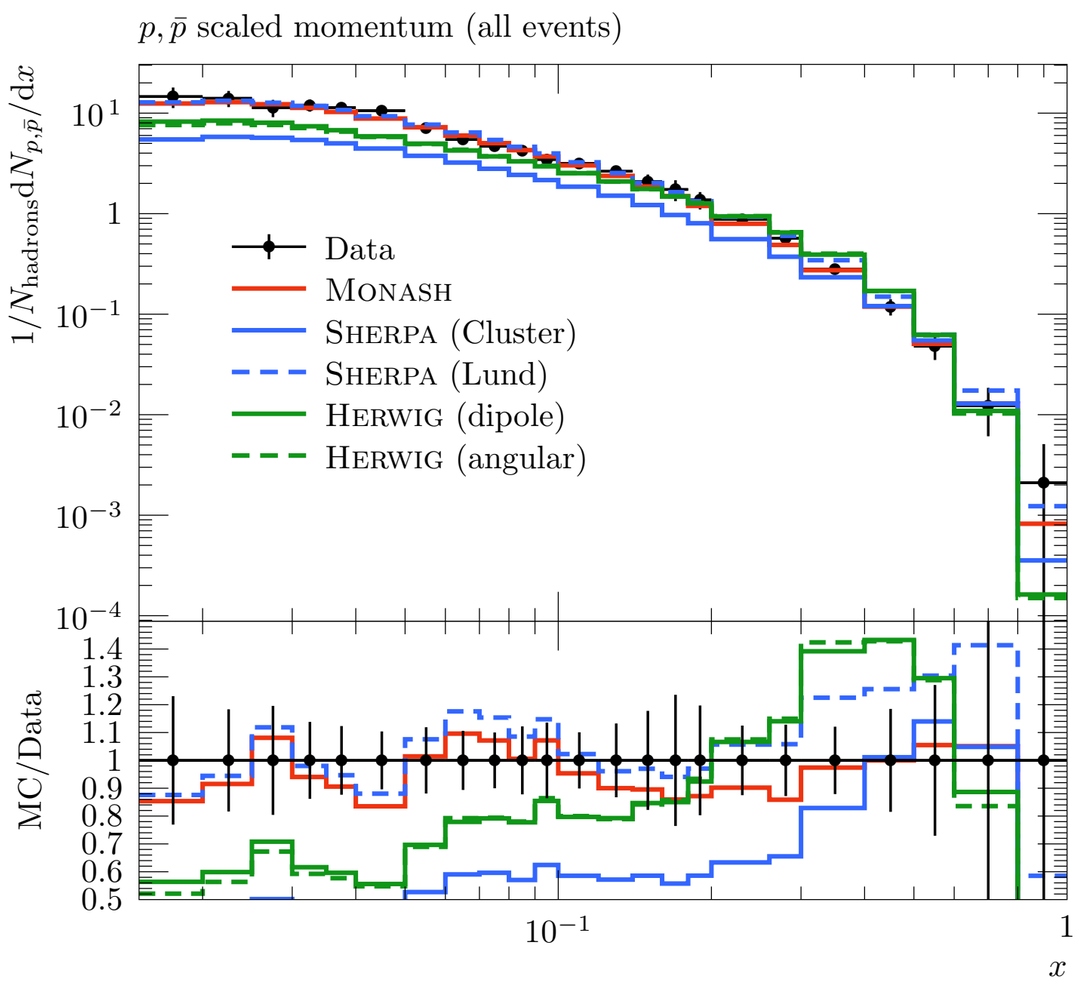




Good agreement for photon and meson spectra (some differences in the extreme)

How good are the current theory predictions?





Very important disagreement for the case of baryon spectra (cluster models do not agree with data)

Estimate of hadronisation Uncertainties

Eigentunes method (also Hessian)

- Diagonalization of the covariance matrix around the best-fit point of the fragmentation-function parameters.
- Two set of variations are obtained: one in the positive and another one in the negative directions of the eigenvectors (one sigma is for $\Delta\chi^2 \equiv \chi^2_{\rm var} - \chi^2_{\rm min} = N_{\rm df}$; two sigma for $\Delta\chi^2 \equiv \chi^2_{\rm var} - \chi^2_{\rm min} = 4N_{\rm df}$ and so on).
- Choose a variation that span the range of allowed uncertainties by data while in the same time being not very large.

Manual method

- Choose a set of the most sensitive observables (remove the outliers). In this case we have 15 measurements sensitive to light quark fragmentation and 8 measurements for baryon production.
- Perform a new tune of the parameters to every observable separately.
- The 68% CL interval of the spread of the different tunes can be defined as the uncertainty on the parameters (need to be inflated by some factor).

Estimate of parton-shower uncertainties

- Variations of the renormalization scale are also important. They correspond to the uncertainties on the singular part of the DGLAP splitting kernels.

  Usually (as in the context of scale variations of hard scattering cross sections), you can make a variation of a factor two in the two directions (up and down) with respect to the nominal scale.

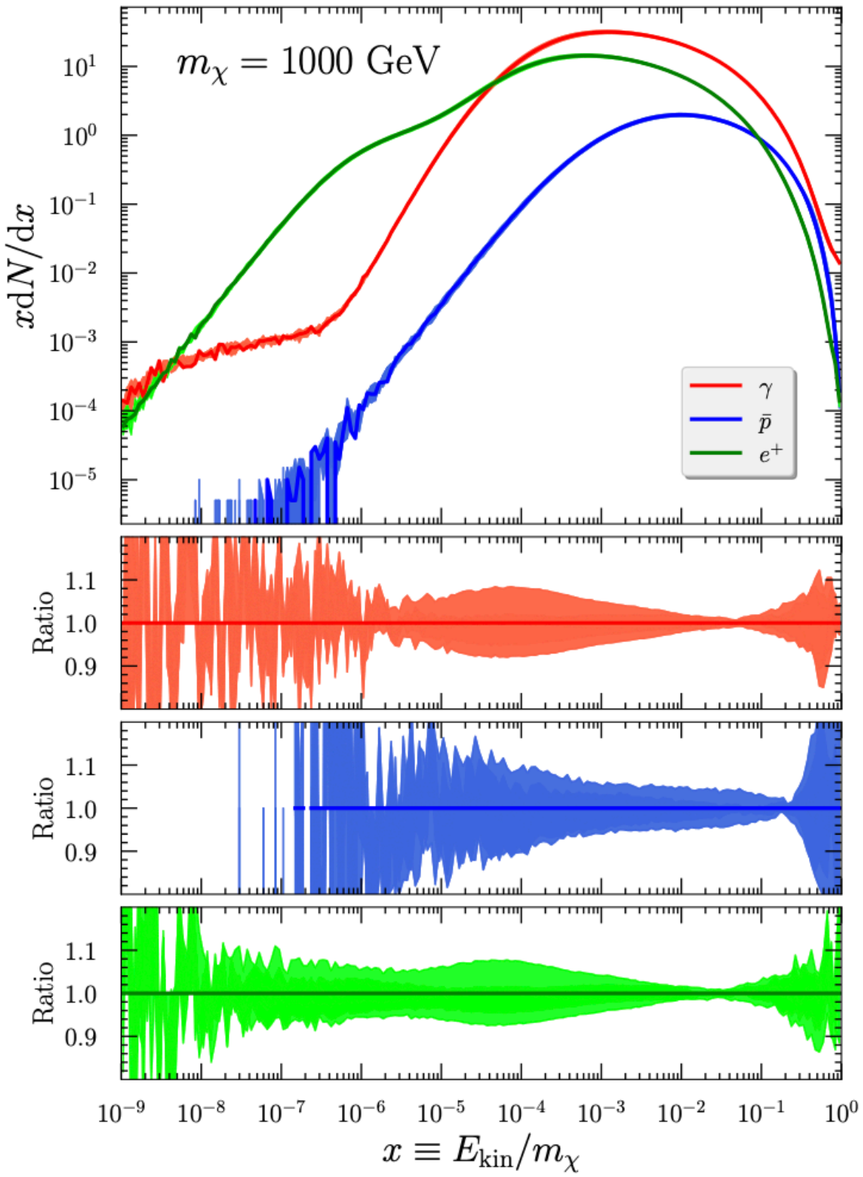
- Mrenna and Skands (1605.08352) developed an automatic method to estimate the shower uncertainties in PYTHIA.
- The method can be used as well to estimate the uncertainties on the non-singular parts of the DGLAP kernels.

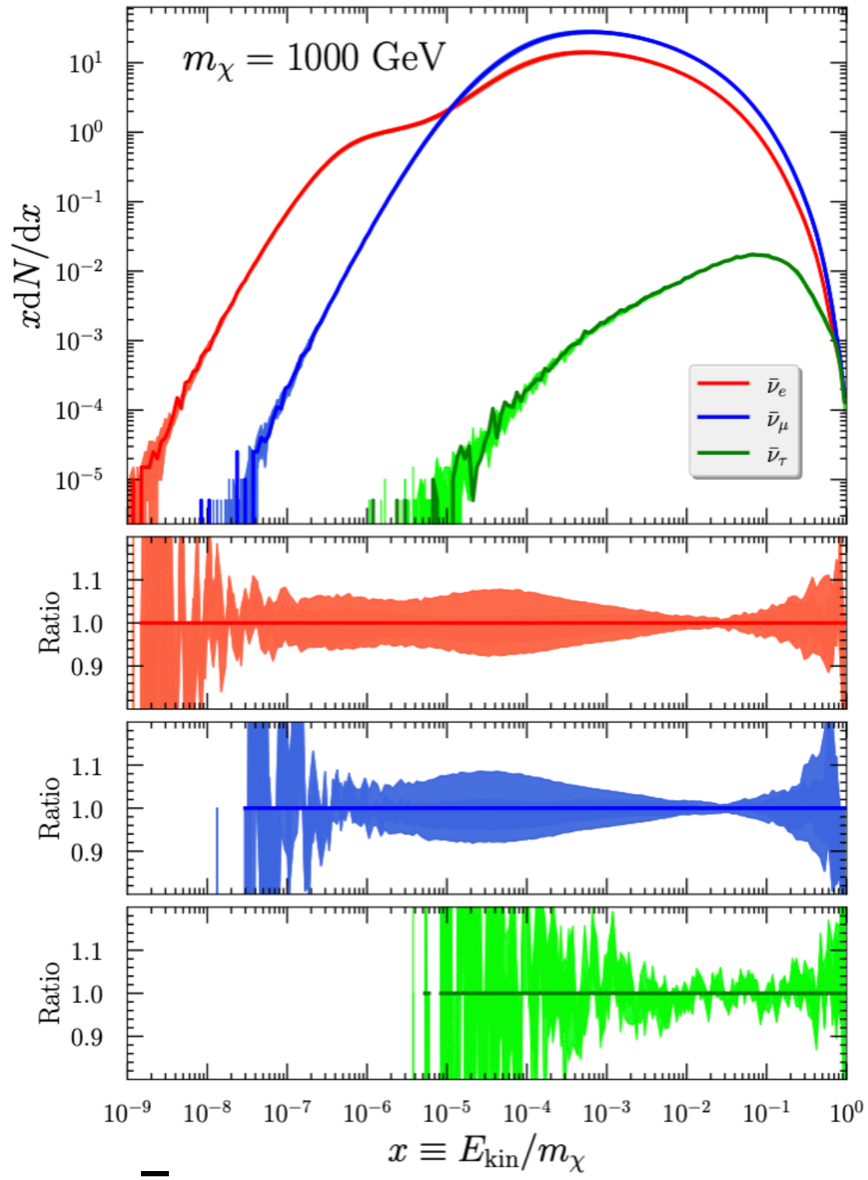
We will use this method to estimate parton-shower uncertainties

Hadronization uncertainties: eigentunes

Tune	a_L	b_L	$\sigma_\perp$ (GeV)	a_{QQ}
Central	0.337	0.784	0.296	1.246
1σ *eigentunes*				
Variation 1^+	0.345	0.803	0.295	1.345
Variation 1^-	0.329	0.766	0.297	1.149
Variation 2^+	0.968	1.444	0.339	1.074
Variation 2^-	0.047	0.482	0.277	1.326
Variation 3^+	0.207	0.907	0.255	1.233
Variation 3^-	0.476	0.652	0.340	1.262
Variation 4^+	0.327	0.791	0.346	1.247
Variation 4^-	0.346	0.778	0.250	1.246

Particle spectra with QCD uncertainties



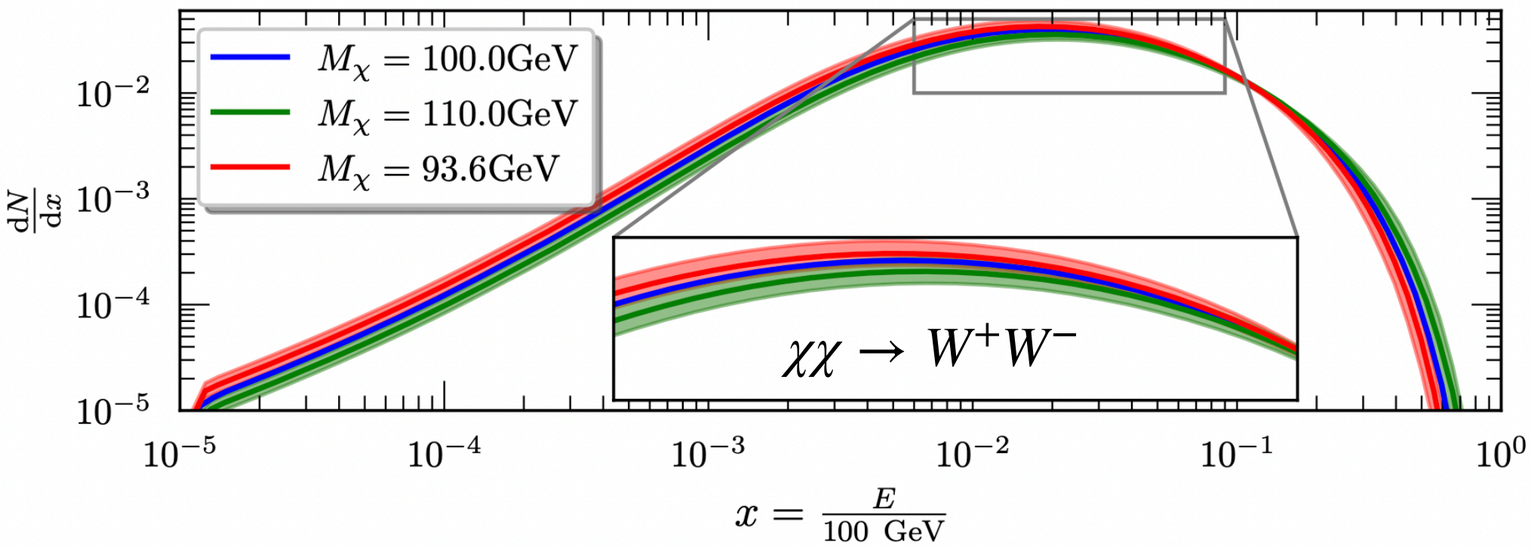


$$\chi\chi \to q\bar{q}$$

Application to DM indirect detection ($\chi\chi \to \bar{p} + X$)

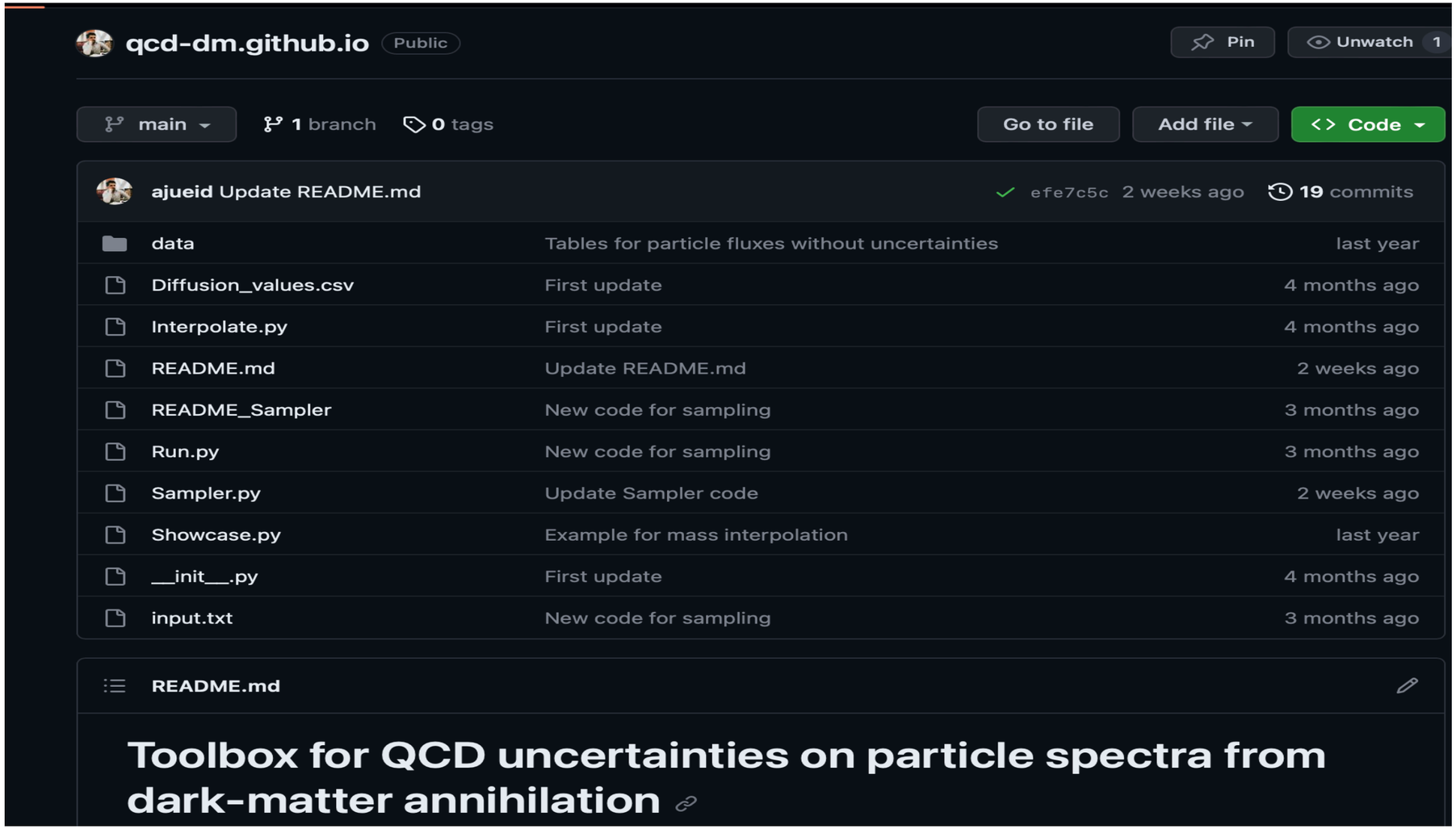
We quantify to what extent the QCD uncertainties affect two DM observables: the velocity-weighted cross section $\langle \sigma v \rangle$ and the DM mass M_χ for the case of antiprotons.

- **A total shift in the height of the spectrum, such that it is still contained within the QCD uncertainties of the spectrum, corresponds to an uncertainty on $\langle \sigma v \rangle$.**
- **The uncertainty on the DM mass, ΔM_χ, for a DM particle of mass M_χ can be determined by finding the masses of DM particles whose spectra including QCD uncertainties match the spectrum of the DM particle with mass M_χ.**



M	Channel	$\langle \sigma v \rangle$ [%]	ΔM_χ [GeV]
100	$b\bar{b}$	$^{+9.2}_{-7.0}$	$^{+12.8}_{-4.5}$
1000	$b\bar{b}$	$^{+7.9}_{-6.3}$	$^{+143.3}_{-65.5}$
100	W^+W^-	$^{+6.7}_{-9.4}$	$^{+10.0}_{-6.4}$
1000	W^+W^-	$^{+7.6}_{-9.3}$	$^{+63.0}_{-56.9}$

Public datasets



https://github.com/ajueid/qcd-dm.github.io