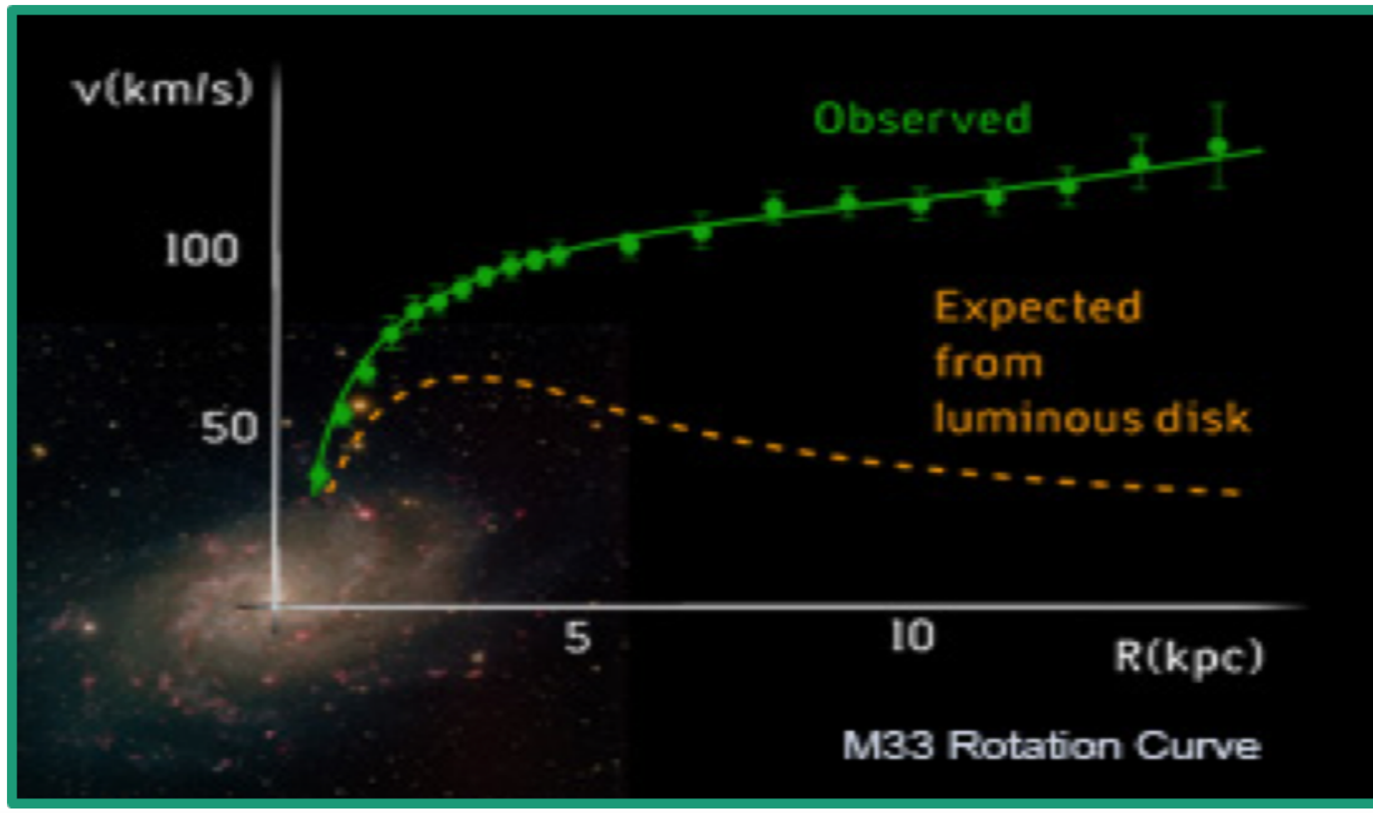
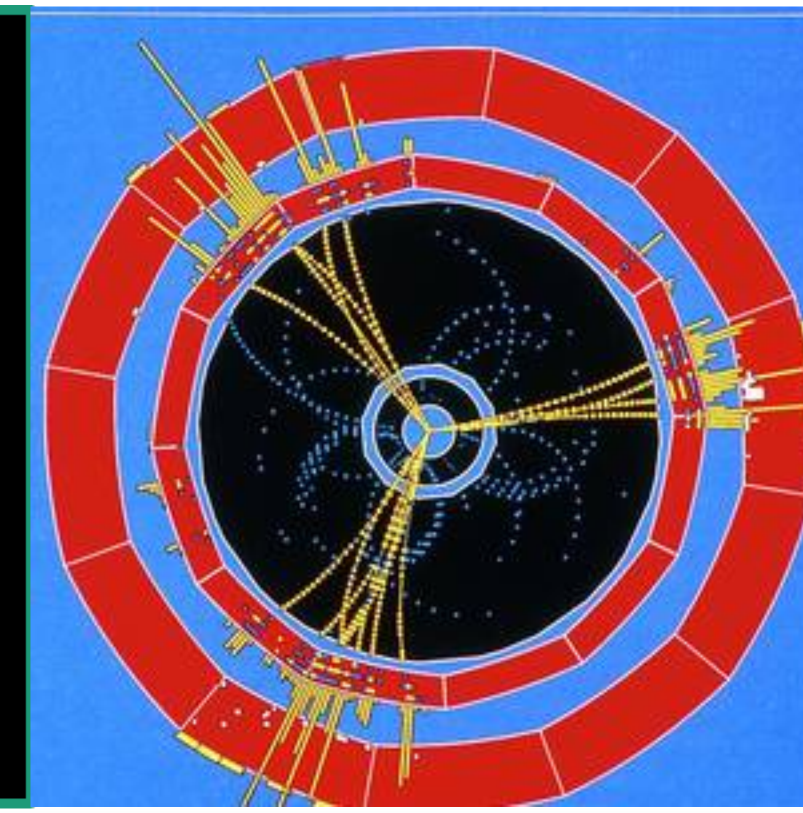
Toward Precision $\overline{\mathrm{D}}$ Spectrum from Dark Matter: Percent-Level Uncertainty Control





Adil Jueid
IBS CTPU-PTC

GNU-IBS workshop on Particle Physics and Cosmology
25-27 September, 2025

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)

PHYSICAL REVIEW LETTERS **135,** 131002 (2025)

Nailing Down the Theoretical Uncertainties of $\overline{\mathrm{D}}$ Spectrum Produced from Dark Matter

Mattia Di Mauro,[1,*] Nicolao Fornengo,[2,†] Adil Jueid,[3,‡] Roberto Ruiz de Austri,[4,§] and Francesca Bellini[5,6,∥]

[1]*Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy*
[2]*Department of Physics, University of Torino, Via Pietro Giuria 1, 10125 Torino, Italy*
[3]*Particle Theory and Cosmology Group, Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), Daejeon 34126, Republic of Korea*
[4]*Instituto de Física Corpuscular, CSIC-Universitat de València, E-46980 Paterna, Valencia, Spain*
[5]*Dipartimento di Fisica e Astronomia "Augusto. Righi", University of Bologna, Viale C. Berti Pichat 6/2, Bologna, 40127, Italy*
[6]*Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Viale C. Berti Pichat 6/2, Bologna, 40127, Italy*

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The detection of cosmic antideuterons ($\overline{\mathrm{D}}$) at kinetic energies below a few GeV$/n$ could provide a smoking gun signature for dark matter (DM). However, the theoretical uncertainties of coalescence models have represented so far one of the main limiting factors for precise predictions of the $\overline{\mathrm{D}}$ flux. In this Letter, we present a novel calculation of the $\overline{\mathrm{D}}$ source spectra, based on the Wigner formalism, for which we implement the Argonne v_{18} antideuteron wave function that does not have any free parameters related to the coalescence process. We show that the Argonne-Wigner model excellently reproduces the $\overline{\mathrm{D}}$ multiplicity measured by ALEPH at the Z-boson pole, which is usually adopted to tune the coalescence models based on different approaches. Our analysis is based on the Pythia 8 Monte Carlo event generator and the state-of-the-art shower algorithm. We succeed, with our model, to reduce the current theoretical uncertainty on the prediction of the $\overline{\mathrm{D}}$ source spectra to a few percent, for $\overline{\mathrm{D}}$ kinetic energies relevant to DM searches with the General Antiparticle Spectrometer and Alpha Magnetic Spectrometer, and for DM masses above a few tens of GeV. This result implies that the theoretical uncertainties due to the coalescence process are no longer the main limiting factor in the predictions. We provide the tabulated source spectra for all the relevant DM annihilation and decay channels and DM masses between 5 and 100 TeV, on the CosmiXs GitHub repository.

DOI: 10.1103/w6n5-vs4d

1. Introduction

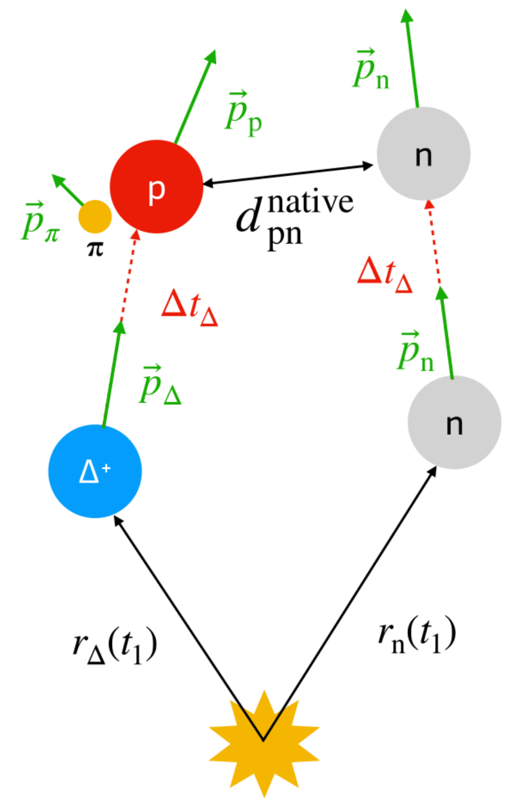
Dark matter indirect detection

- WIMPs DM can annihilate or decay into a number final states: $W^+W^-, q\bar{q}, \cdots$.
- Due to the weak interaction with ordinary matter, the produced cosmic ray signature is low $\Longrightarrow$ channels with small small associated backgrounds.
  - Neutral cosmic rays: gamma-rays and neutrinos.
  - Charged cosmic rays: positrons and antiprotons.
- Stable channels are produced after a complex sequence of phenomena: QED+EW+QCD showers, hadronization and hadron decays (and coalescence for anti-nuclei).
- Excesses have been observed in positrons, gamma-ray and antiproton searches.
  - What about anti-deuterons ($\overline{\mathrm{D}}$) and anti-helions ($^3\overline{\mathrm{He}}$)?

What about $\overline{\mathrm{D}}$?

- Antideuterons represent a clean 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 samples.
- Coalescence process depends on at least one extra parameter called coalescence momentum (p_0).

$$\overline{p} : \overline{\mathrm{D}} : {}^{3}\overline{\mathrm{He}} \sim 1 : 1.4 \times 10^{-4} : 3.4 \times 10^{-8}$$

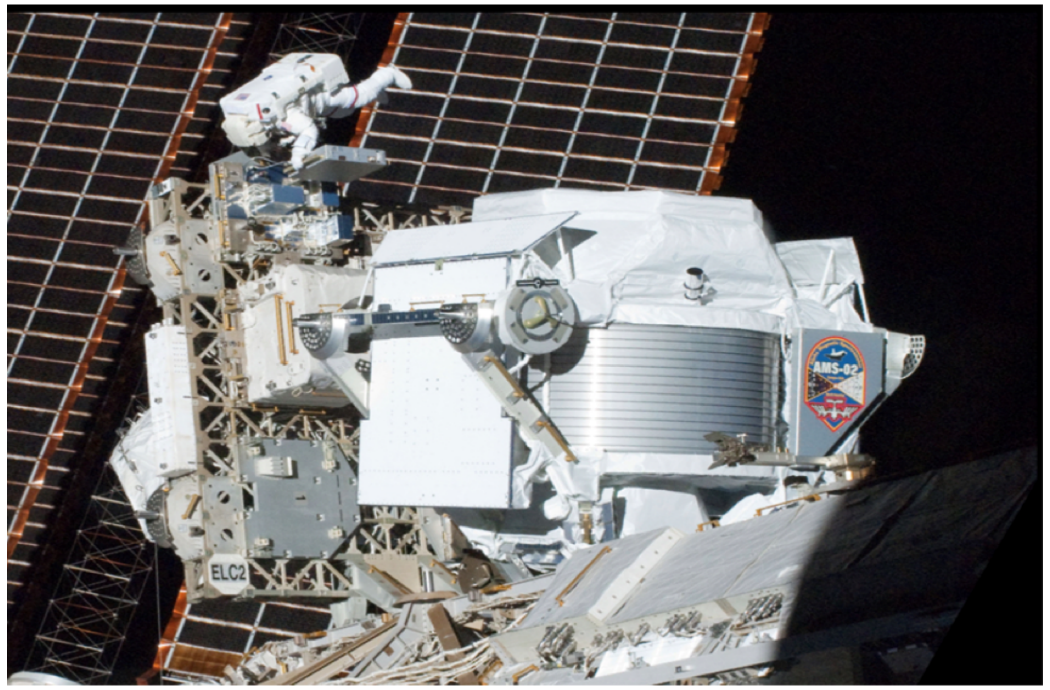
$\overline{\mathrm{D}}$: past, present and future

BESS

- Operation: 1993-2008
- Purpose: $\bar{p}, \overline{\mathrm{D}}$, solar modulation.
- Best Limit:

$\Phi_{\overline{\mathrm{D}}} < 6.7 \times 10^{-5}\ (\mathrm{m}^2 \times \mathrm{s} \times \mathrm{sr} \times \mathrm{GeV}/n)^{-1}$
for $E_{\mathrm{kin}} \in [0.163, 1.1]\ \mathrm{GeV}/n$

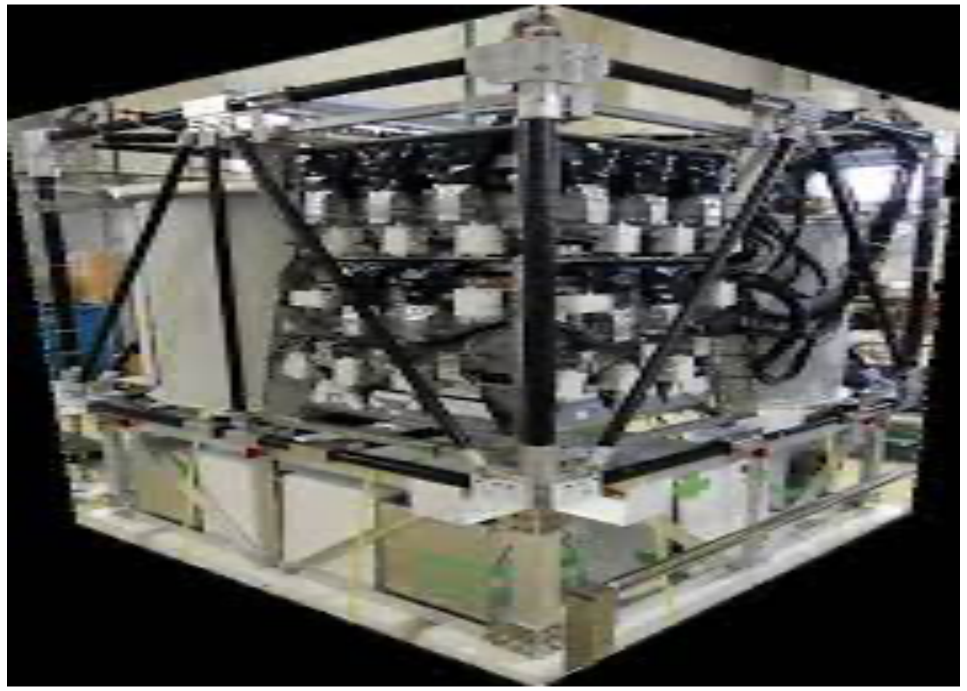
AMS-02



- Operation: 2011-present
- Purpose: $e^{\pm}, \bar{p}, \overline{\mathrm{D}}, {}^3\overline{\mathrm{He}}, \cdots$.
- Expected Limit:

$\Phi_{\overline{\mathrm{D}}} < 5 \times 10^{-7}\ (\mathrm{m}^2 \times \mathrm{s} \times \mathrm{sr} \times \mathrm{GeV}/n)^{-1}$
for $E_{\mathrm{kin}} \in [0.2, 1.0]\ \mathrm{GeV}/n$

GAPS



- Operation: ~2025 or 2026
- Purpose: $\bar{p}, \overline{\mathrm{D}}, {}^3\overline{\mathrm{He}}, \cdots$.
- Expected Limit:

$\Phi_{\overline{\mathrm{D}}} < 2 \times 10^{-6}\ (\mathrm{m}^2 \times \mathrm{s} \times \mathrm{sr} \times \mathrm{GeV}/n)^{-1}$
for $E_{\mathrm{kin}} \in [0.05, 0.2]\ \mathrm{GeV}/n$

The flux of particles

For antideuterons, for example, the flux is given by

$$\frac{\mathrm{d}\Phi_{\overline{\mathrm{D}}}}{\mathrm{d}E_{\mathrm{kin}}} \equiv \left(\frac{\rho^k_{\mathrm{DM}}}{m^k_{\mathrm{DM}}}\right)\mathscr{R}(E_{\mathrm{kin}})\sum_f k^{-1}\mathscr{P}_{i\to f}(g_{\mathrm{DM}}; m_{\mathrm{DM}})\left(\frac{\mathrm{d}N}{\mathrm{d}E_{\mathrm{kin}}}\right)_{f\to\overline{\mathrm{D}}}$$

$\mathscr{R}(E_{\mathrm{kin}})$ 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.

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

Our aim is to reduce the theory errors on $\mathrm{d}N/\mathrm{d}E_{\mathrm{kin}}$!

2. Existing tools

Existing tools in the market: PPPCDM

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 15 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

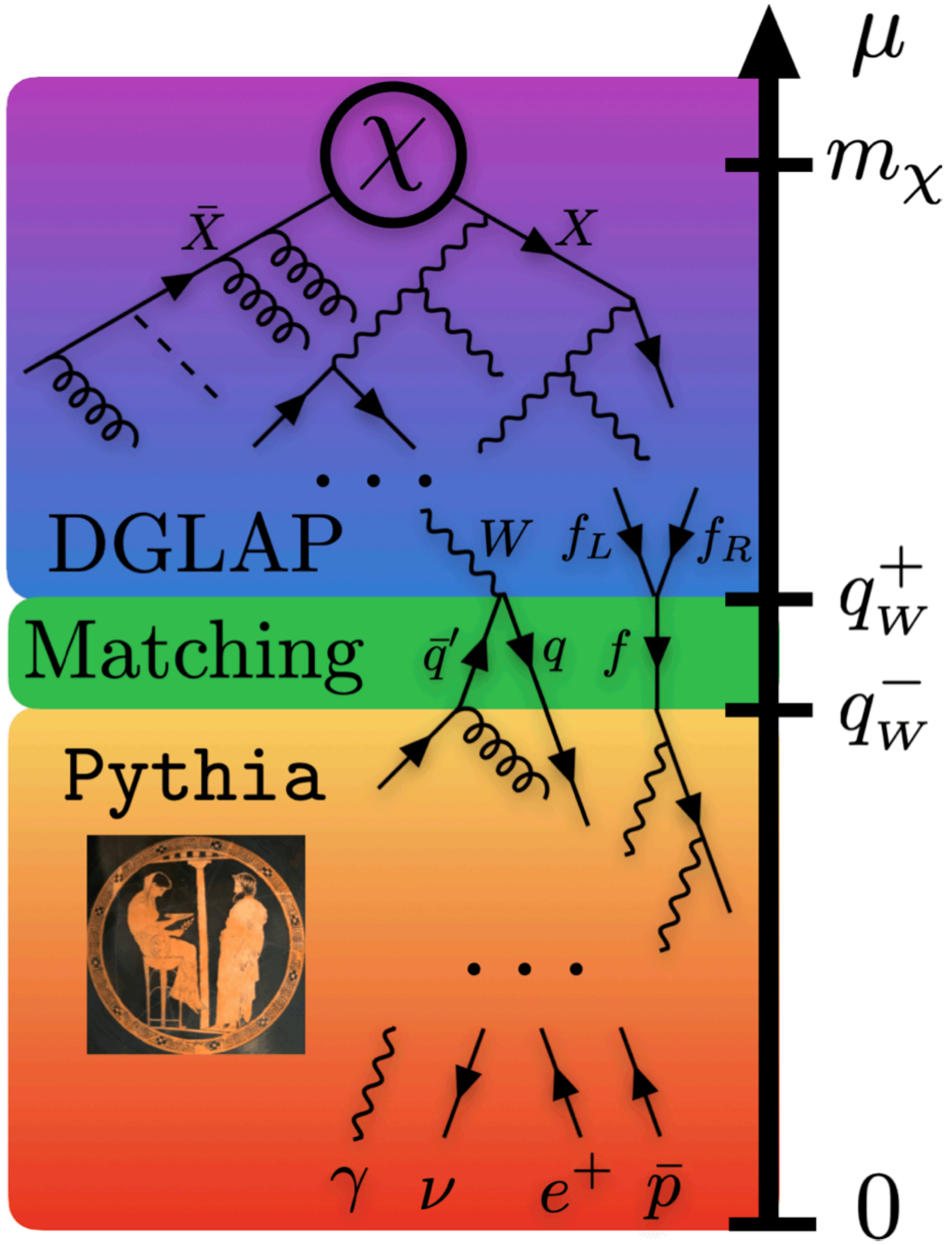
Christian W. Bauer,[1,2] Nicholas L. Rodd,[1,2] Bryan R. Webber[3]

[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.

3. Particle production from dark matter

Modeling of the spectra

To simplify the discussion, we consider the generic annihilation process

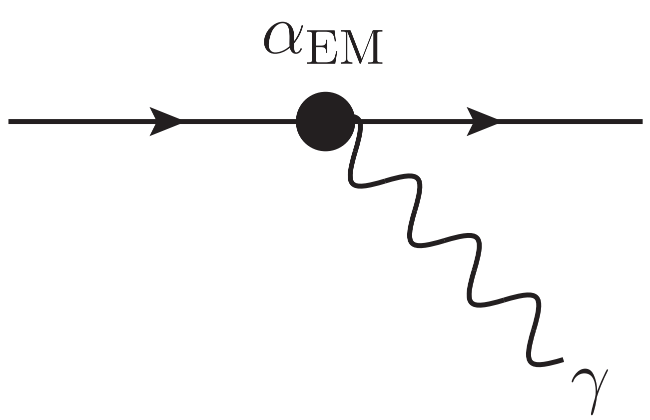
$$\underbrace{\chi\chi \to X_1 \cdots X_N}_{\text{Parton-level hard process}} \to \underbrace{\left(Y_{11} \cdots Y_{1a_1}\right) \cdots \left(Y_{N1} \cdots Y_{Na_N}\right)}_{\text{Stable particles}}$$

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 $\alpha_{\rm EM}(Q)$

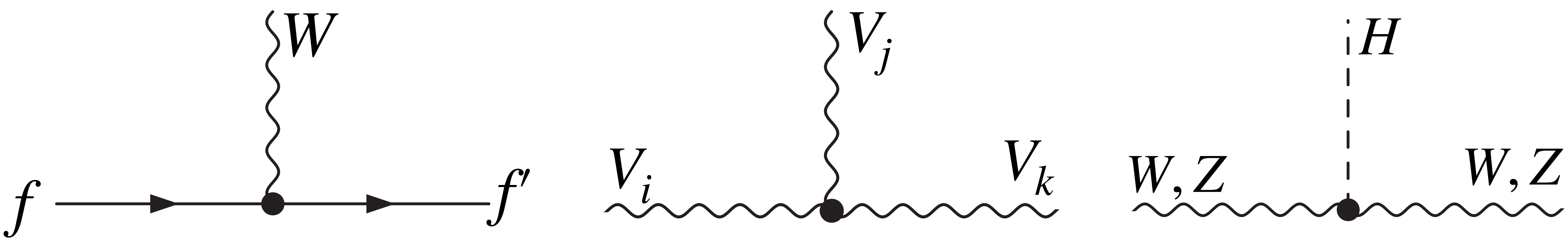


- Dominate at high (and also very low) x_γ.
- Relevant for DM annihilation into photons and charged leptons.
- The corresponding coupling ($\alpha_{\rm EM}$) is measured with high precision.

→ 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.

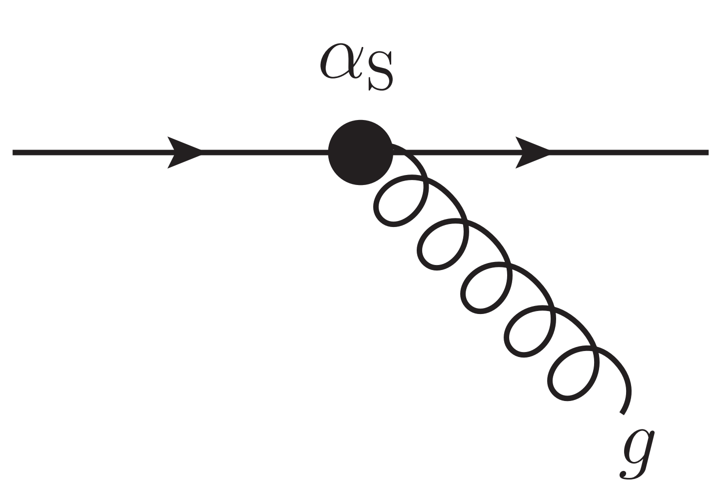


VINCIA takes the helicity information of the annihilation products into account.
(see e.g. 2108.10786, 2108.07133, 2106.10987, 1907.08980)

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 $\alpha_S(Q)$

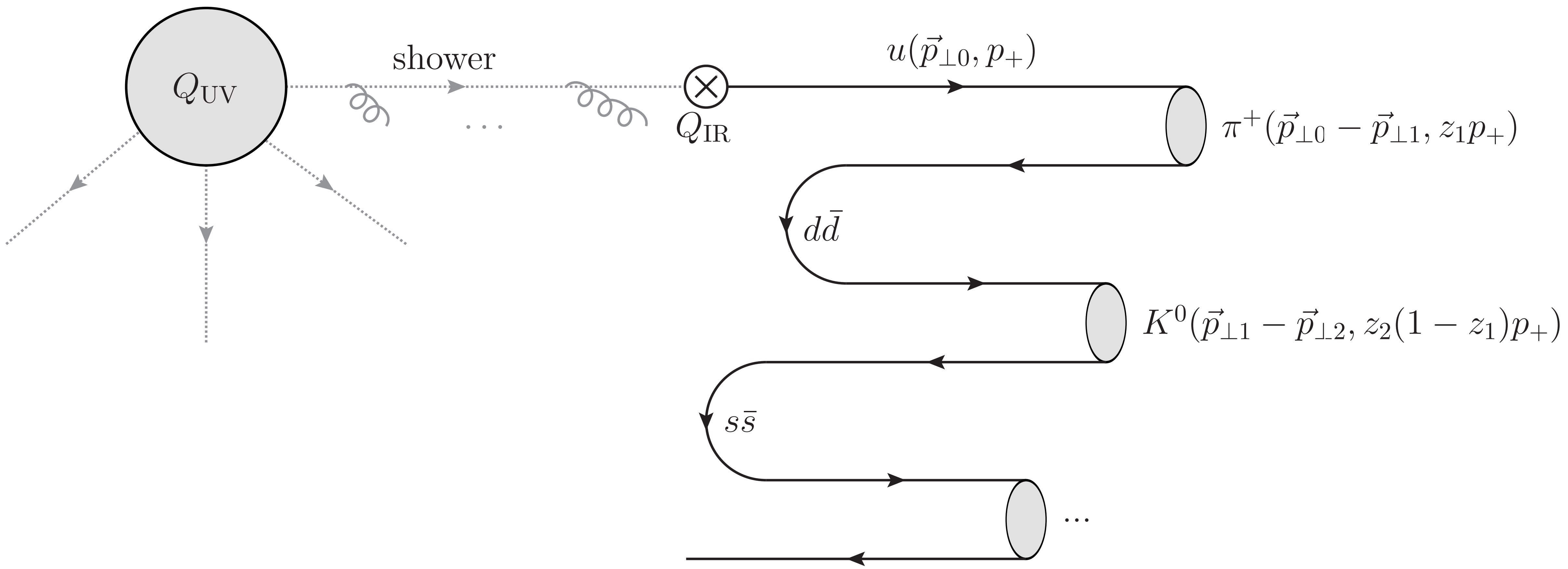


- Dominate at both the bulk and the peak.
- Relevant for DM annihilation into colored particles
- The corresponding coupling (α_S) in PYTHIA8 is different by about 20% from the $\alpha_S(M_Z)^{\overline{\text{MS}}}$.

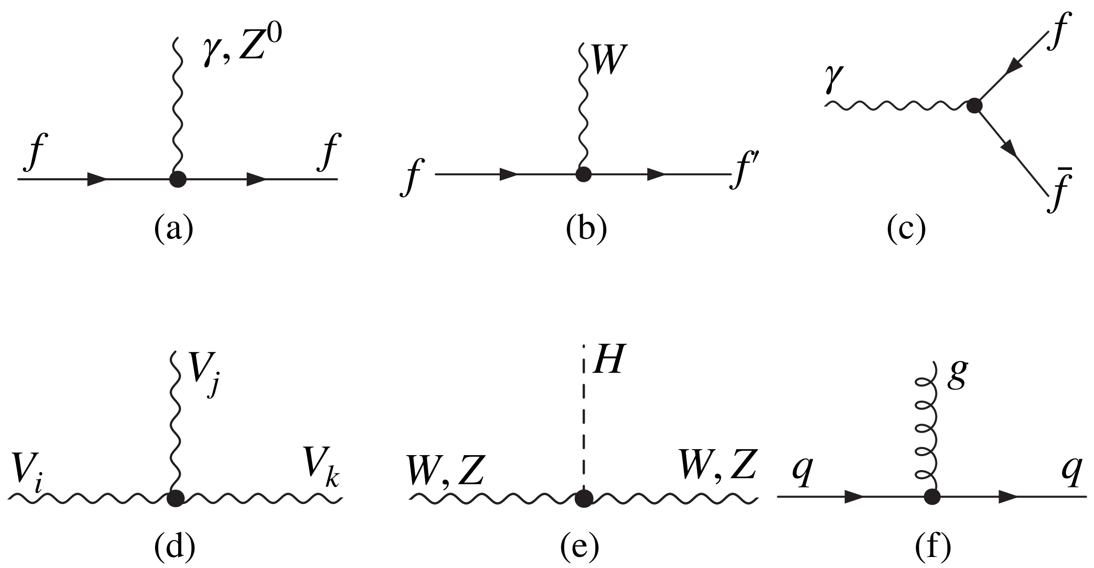
→ Subject to uncertainty variations!

Modeling of the spectra: Hadronization

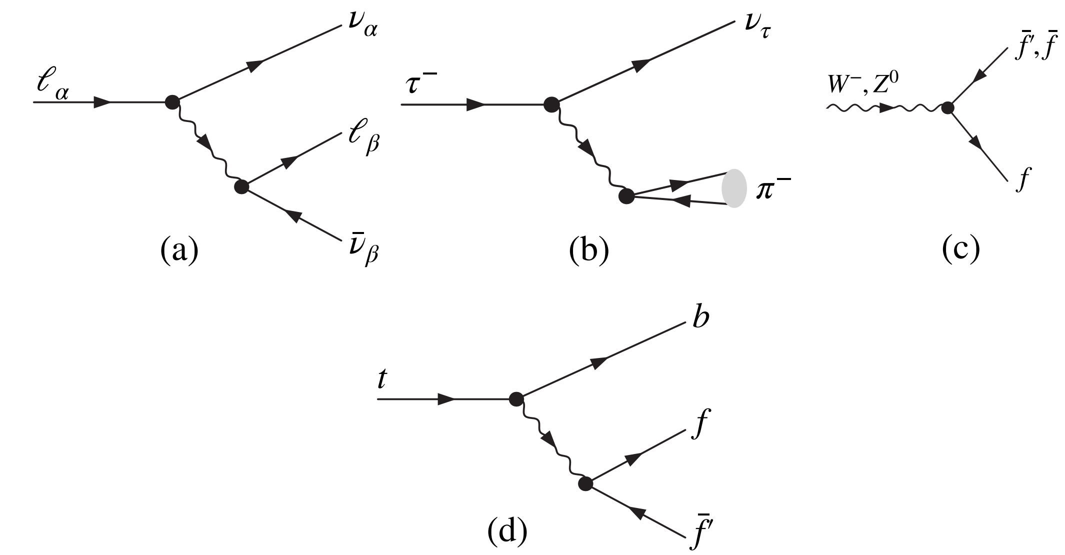
- Hadronization is a process where color triplets and octets (i.e. quarks and gluons) will fragment to form *color singlet hadrons.*
- This process occurs at low scales (at the shower cut-off).
- Two main models: Cluster and String models.



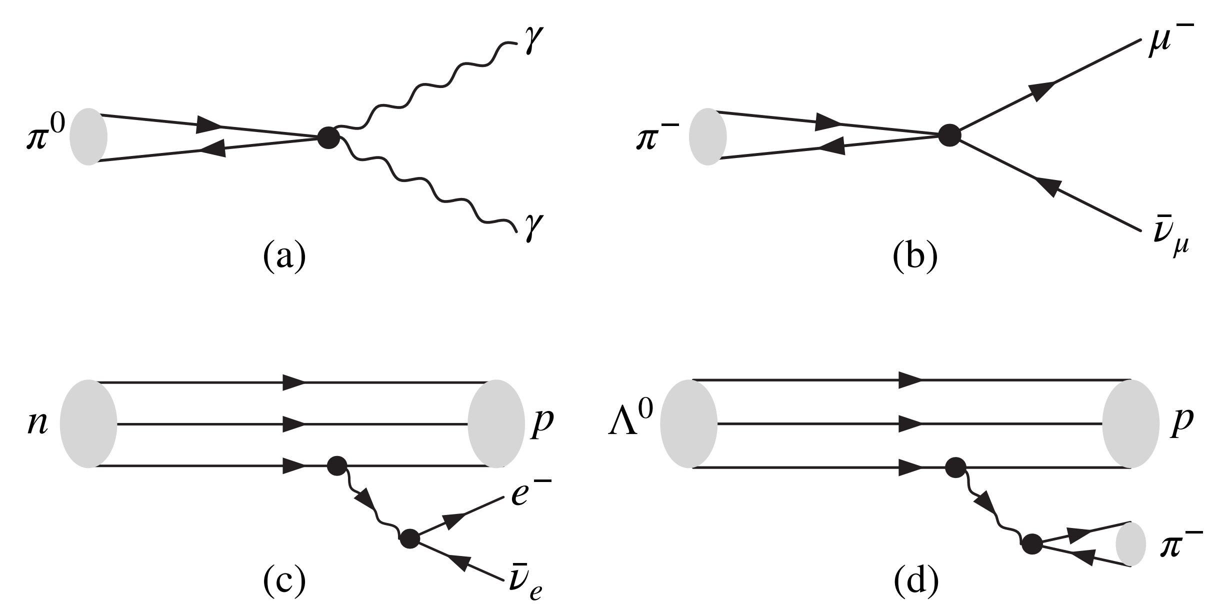
Summary of leading contributions



QED+QCD+EW showers

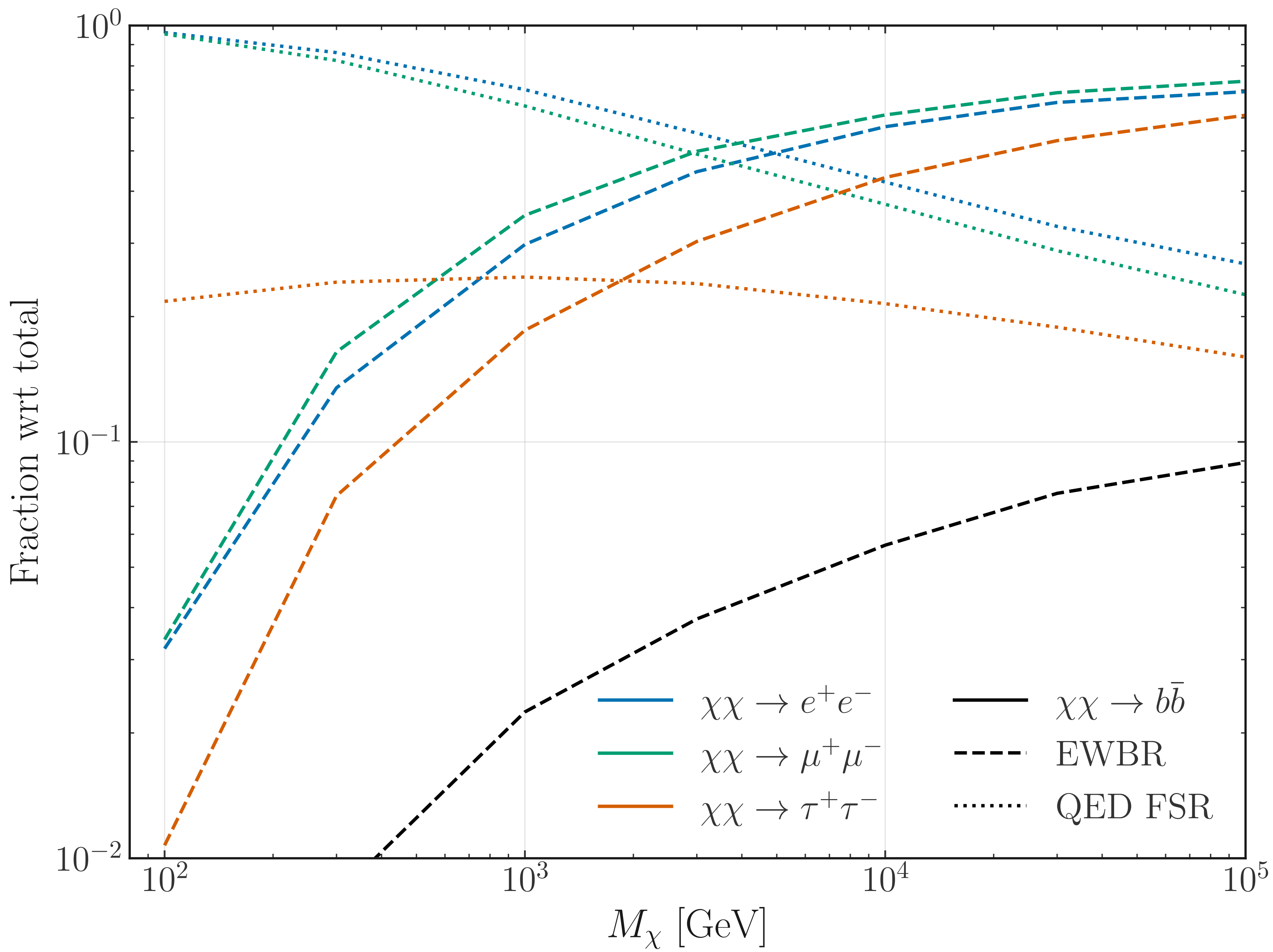


Weak decays



Meson and baryon decays

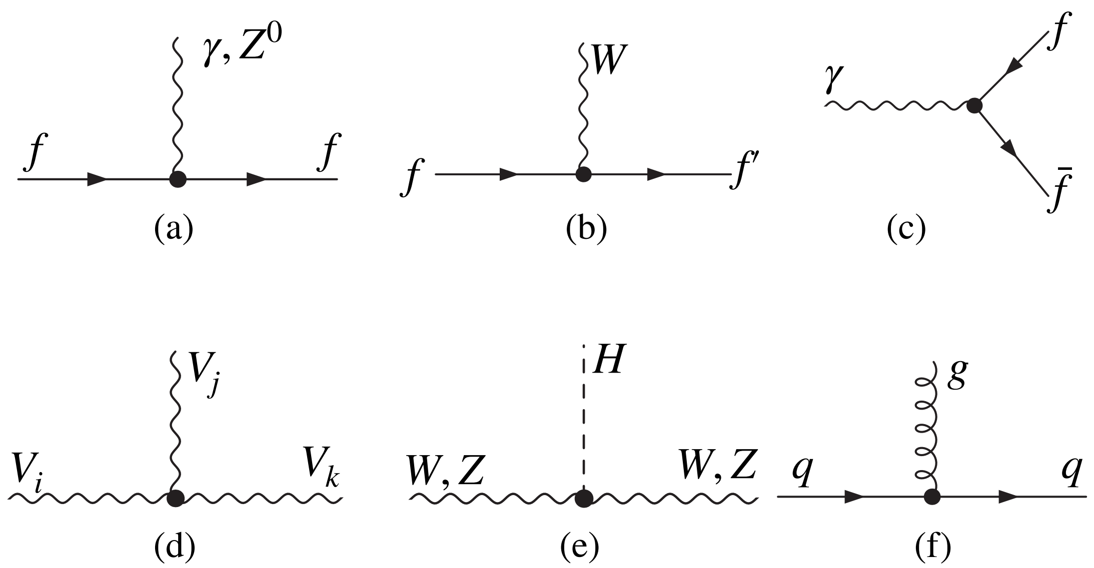
Generic features of particle production



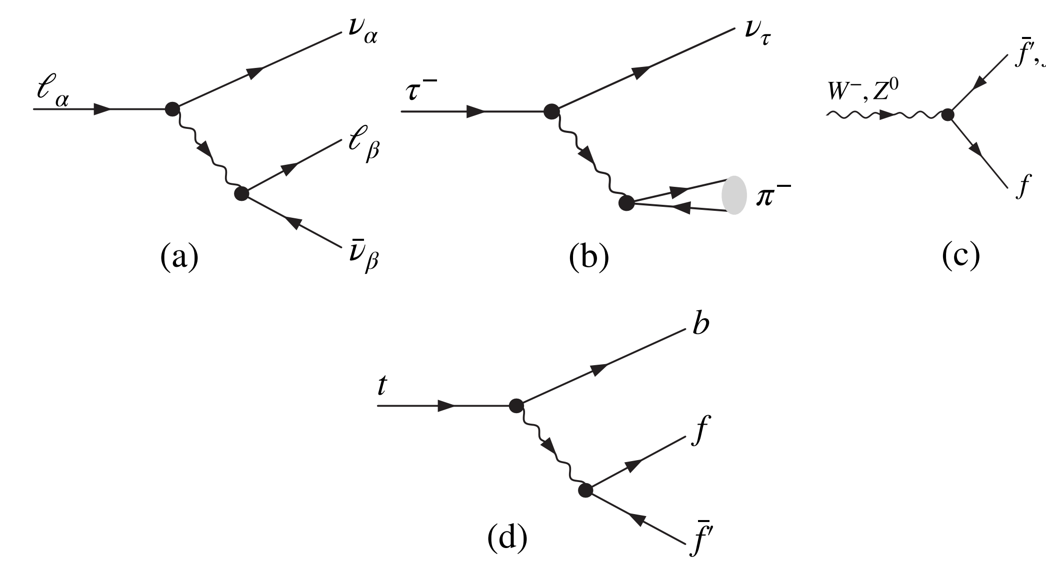
Fraction with respect to the total number of photons.

Clearly EWBR dominates over QED FSR for heavy DM

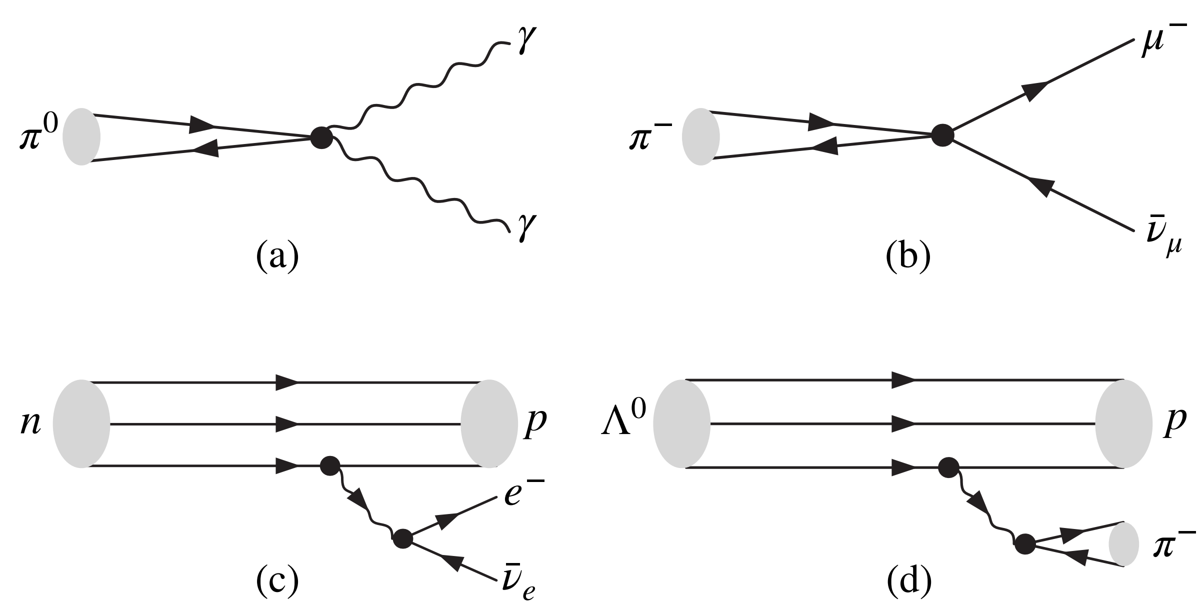
Leading contributions to particle spectra



QED+QCD+EW showers



Weak decays



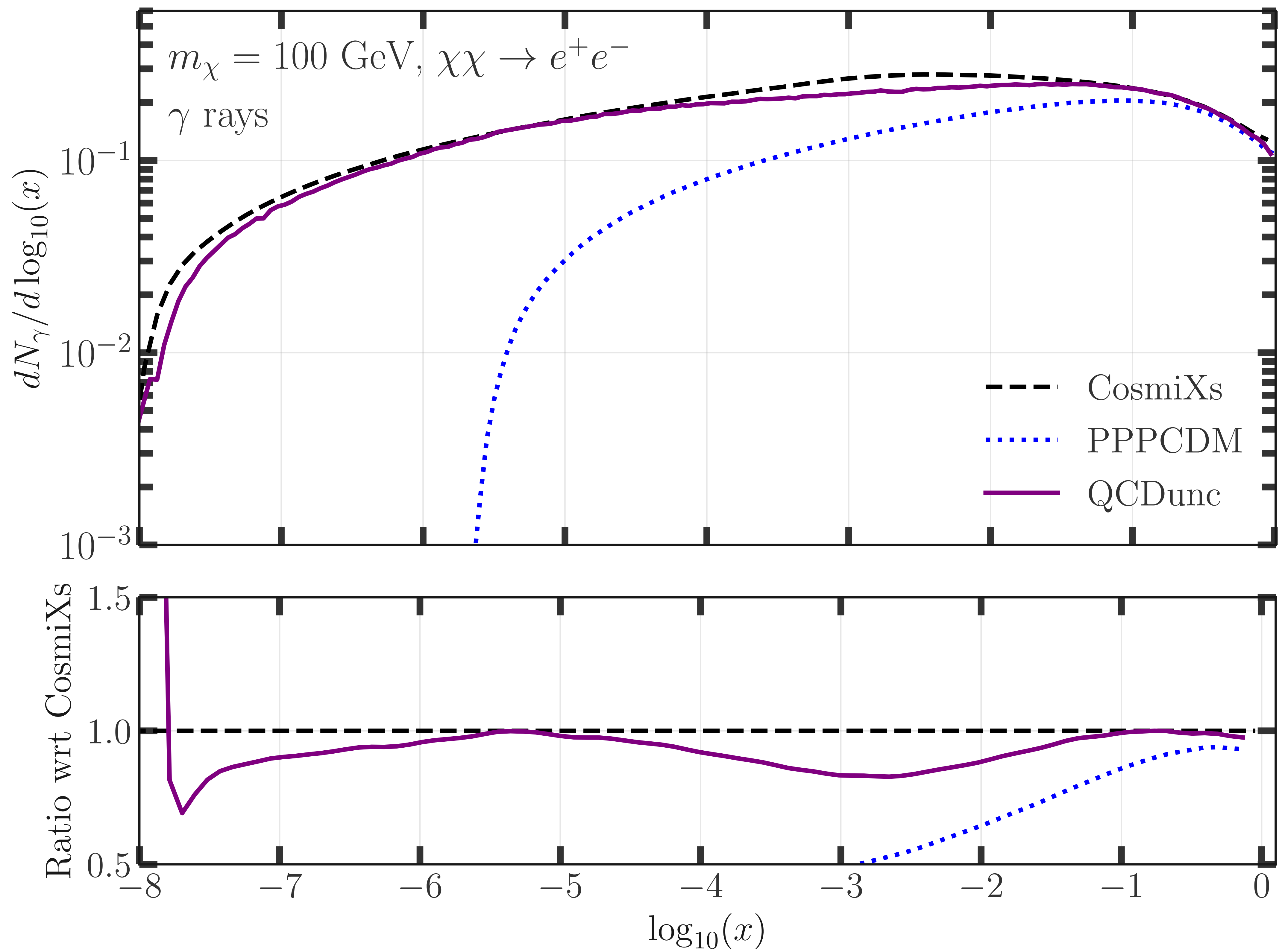
Meson and baryon decays

Main Novelties of our analysis

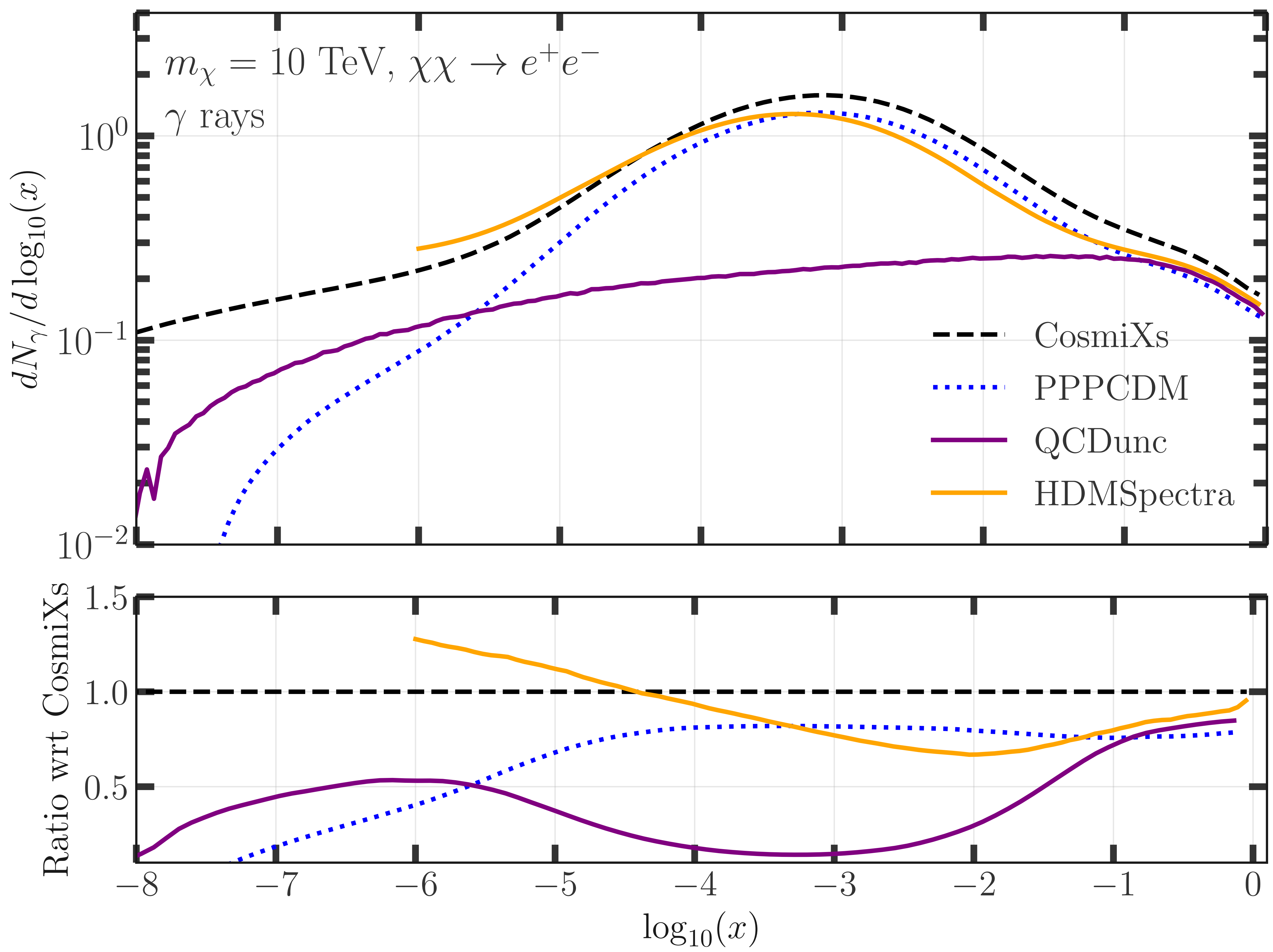
- **Polarization effects:** We use MadDM which we interface with PYTHIA 8 with VINCIA shower plugin being the default option. MadDM produces LHEF where helicity information is written.
- **Resummed electroweak corrections and interleaved resonance decays:** The electroweak corrections are modeled with 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.
- **Improved tuning of coalescence models.** (See the next slides)

4. Comparison with HDMS and PPPC

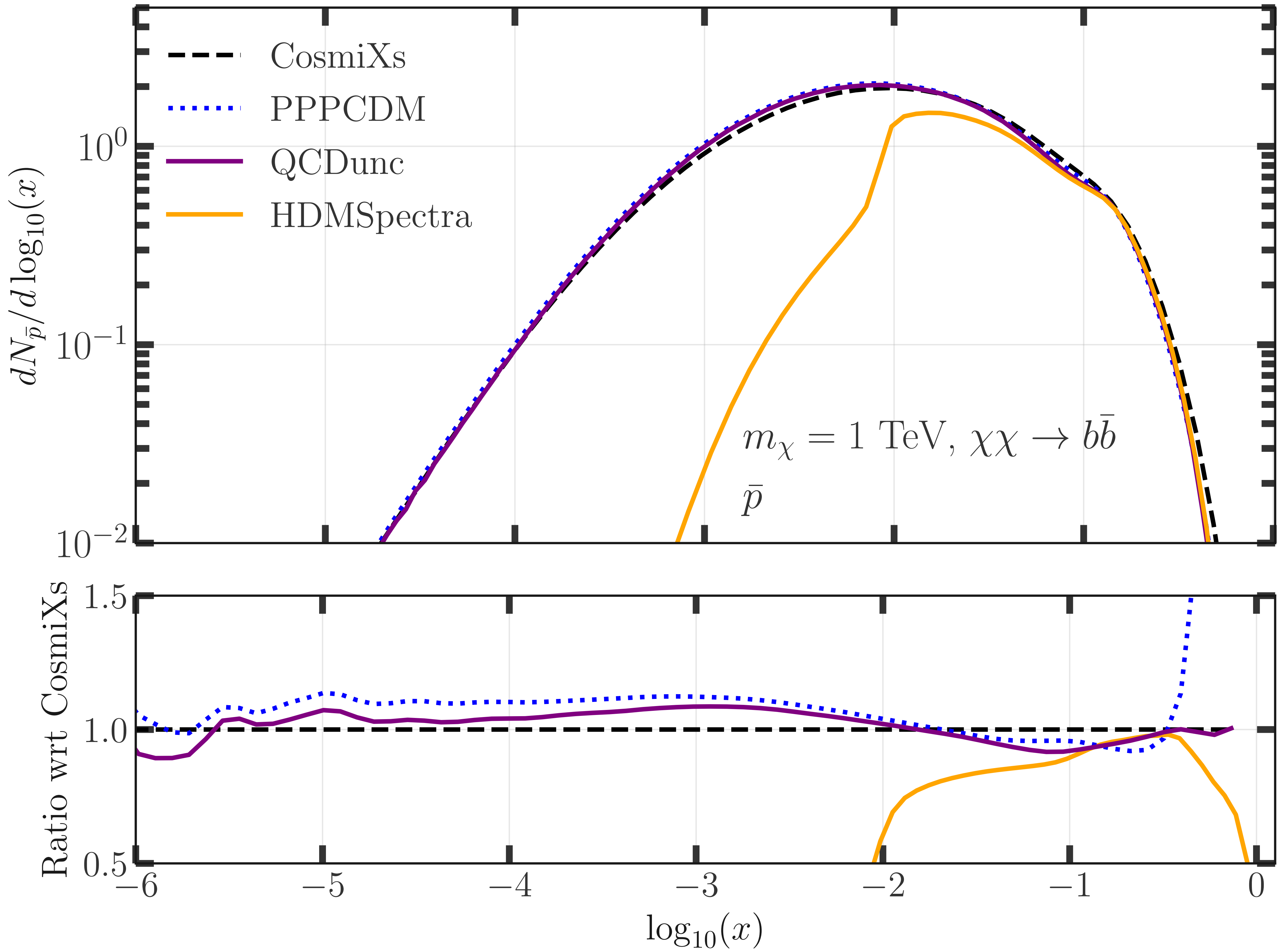
Comparison: γ rays



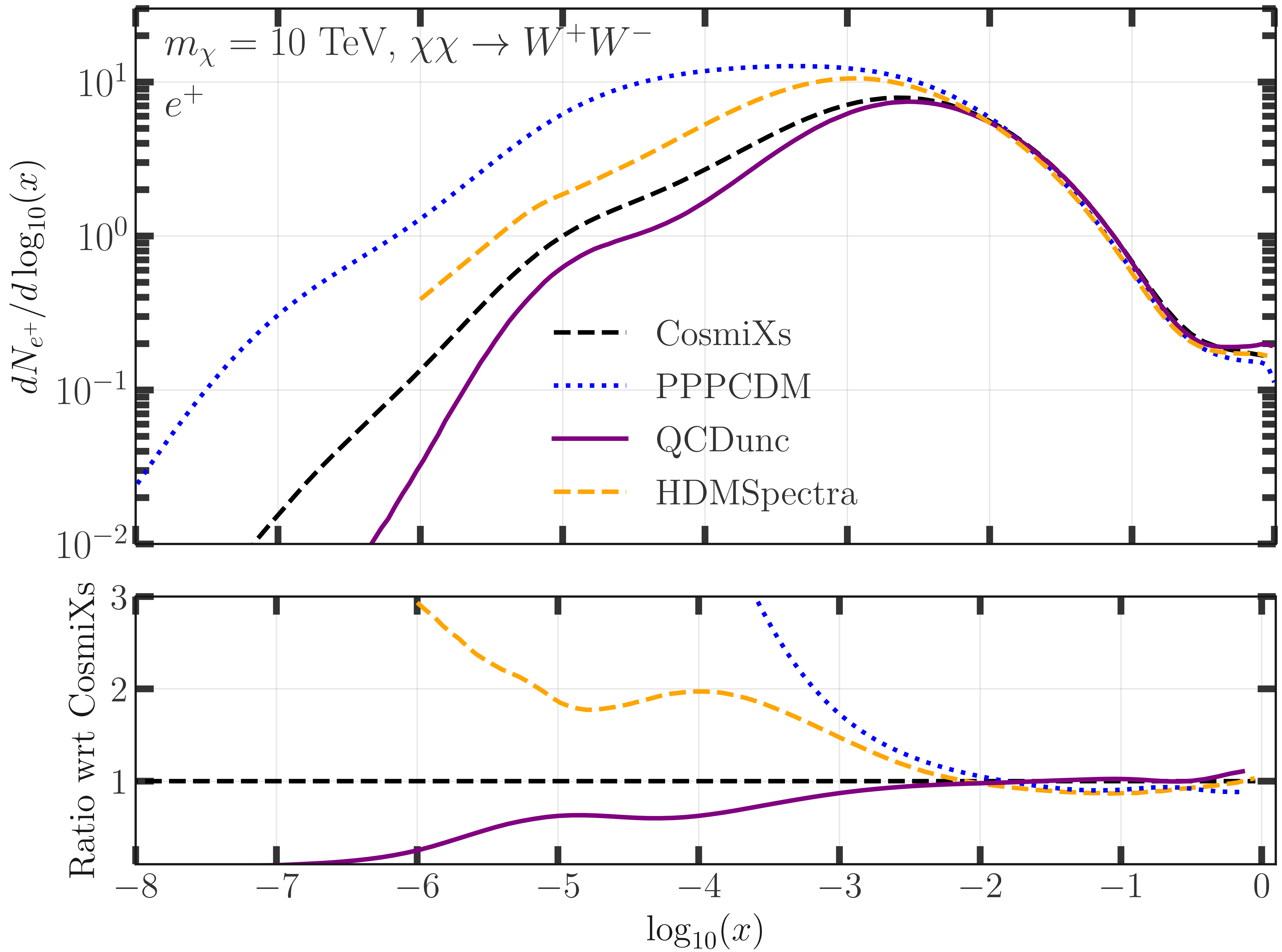
Comparison: γ rays



Comparison: $\bar{p}$



Comparison: e^+



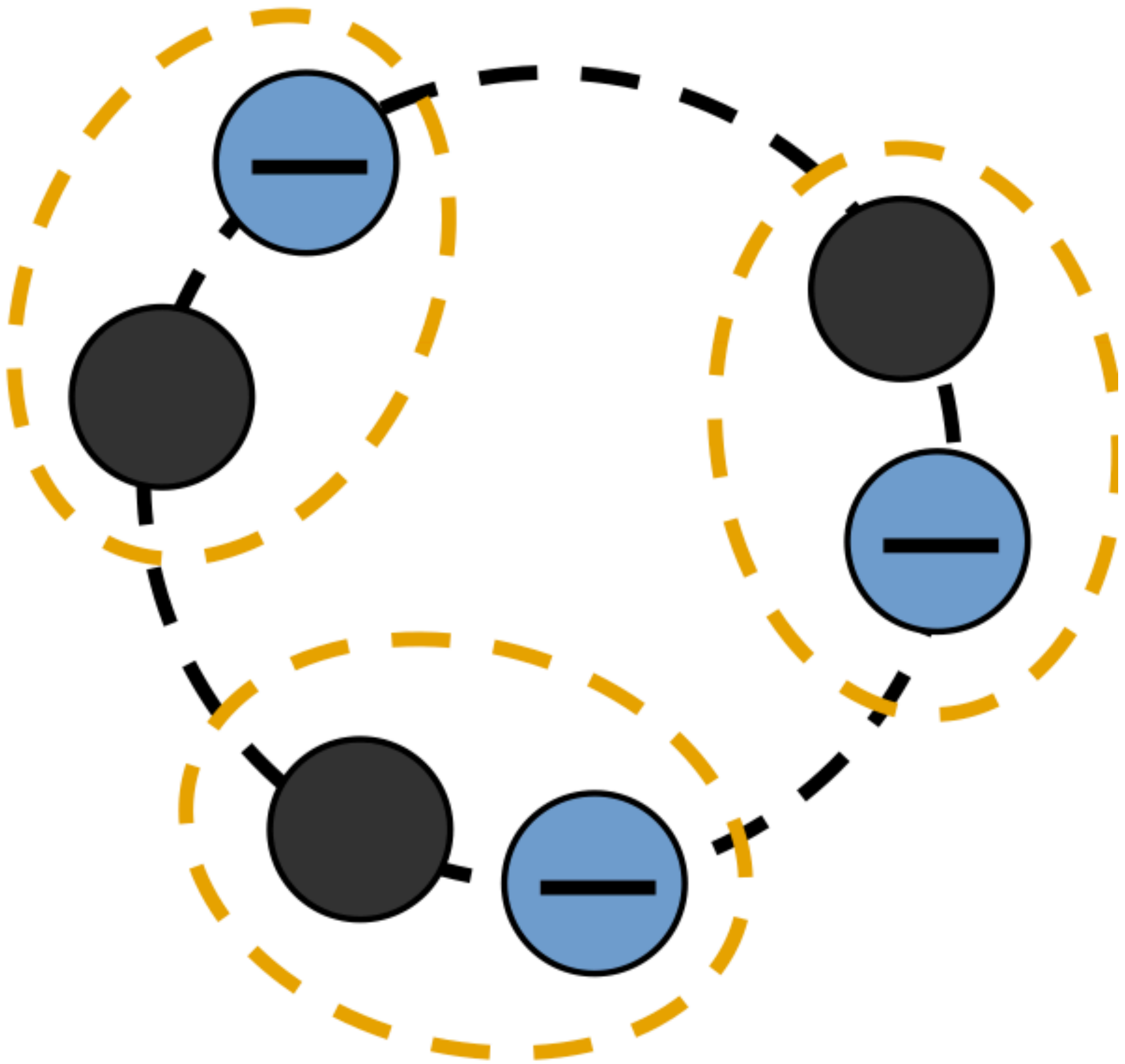
5. Antideuterons

Coalescence Models: Spherical model

Most straightforward as it assumes spherical symmetry — Rates are proportional to the products of the antiproton and anineutron spectra.

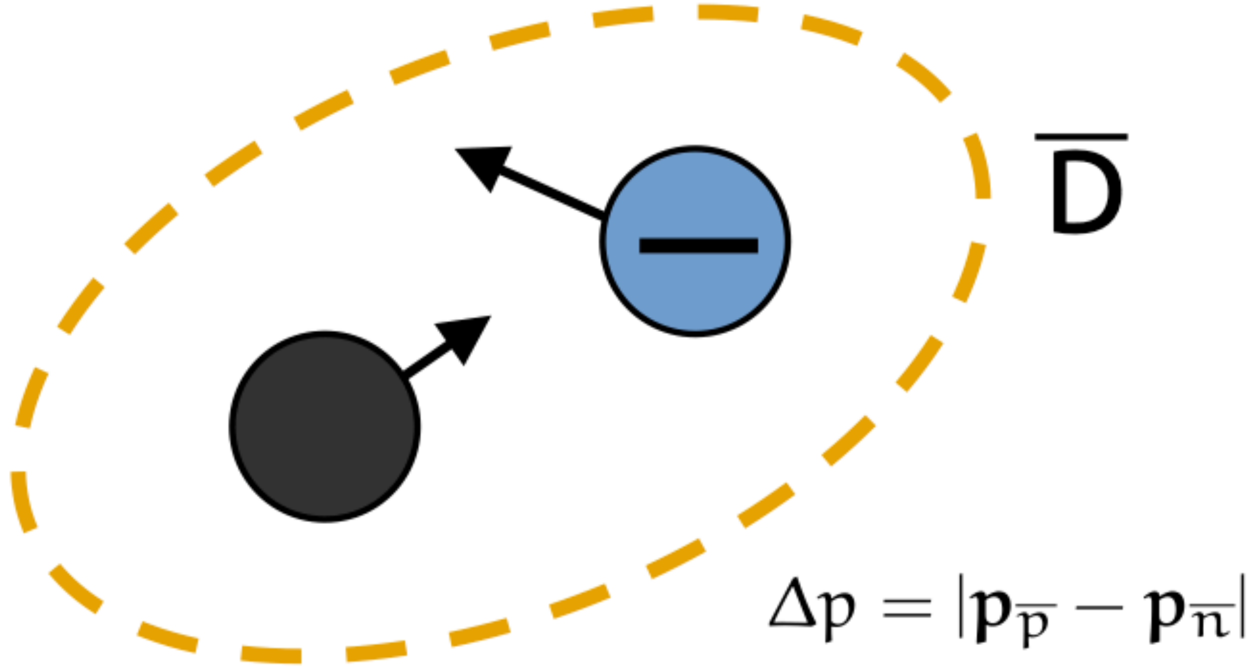
$\Longrightarrow$ Wrong answers!

$$\left(\frac{\mathrm{d}N}{\mathrm{d}T_{\overline{\mathrm{D}}}}\right) = \frac{p_0^3}{6}\frac{m_{\overline{\mathrm{D}}}}{m_{\bar{n}}m_{\bar{p}}}\frac{1}{\sqrt{T_{\bar{D}}^2 + 2m_{\overline{\mathrm{D}}}T_D}}\left(\frac{\mathrm{d}N_{\bar{n}}}{\mathrm{d}T_{\bar{n}}}\right)\left(\frac{\mathrm{d}N_{\bar{p}}}{\mathrm{d}T_{\bar{p}}}\right)$$

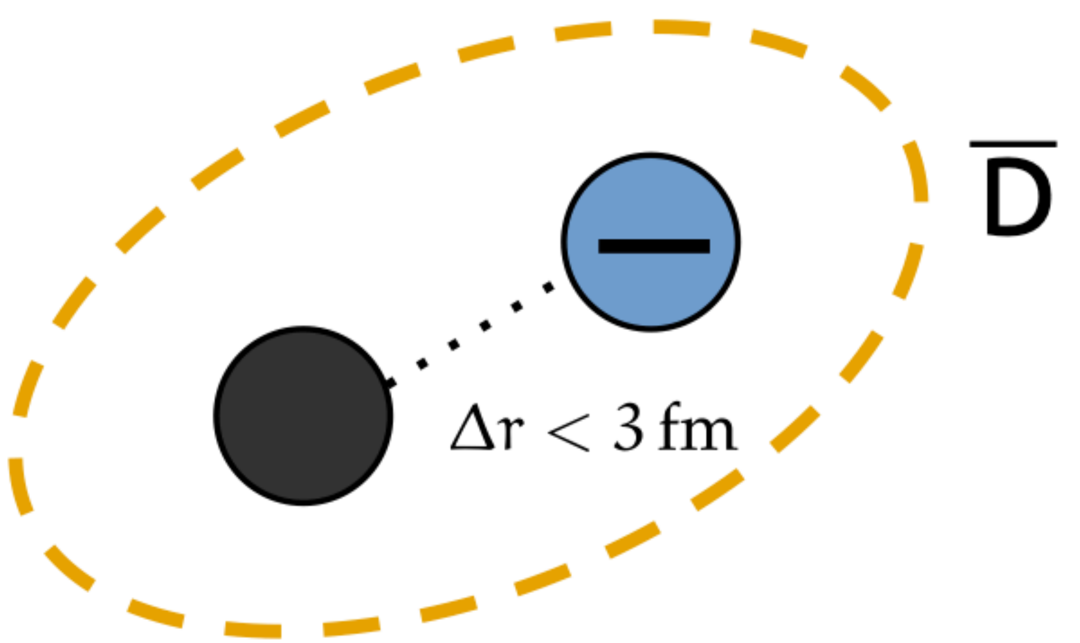


Coalescence Models: simple coalescence models

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)

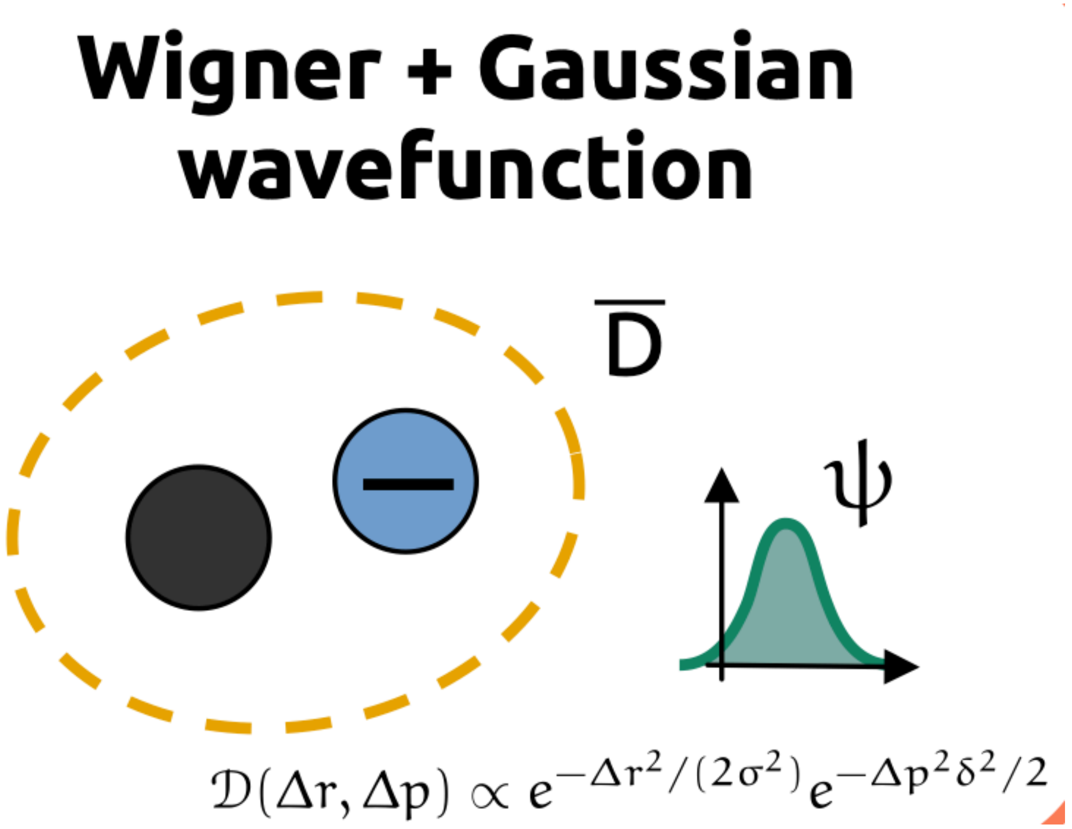


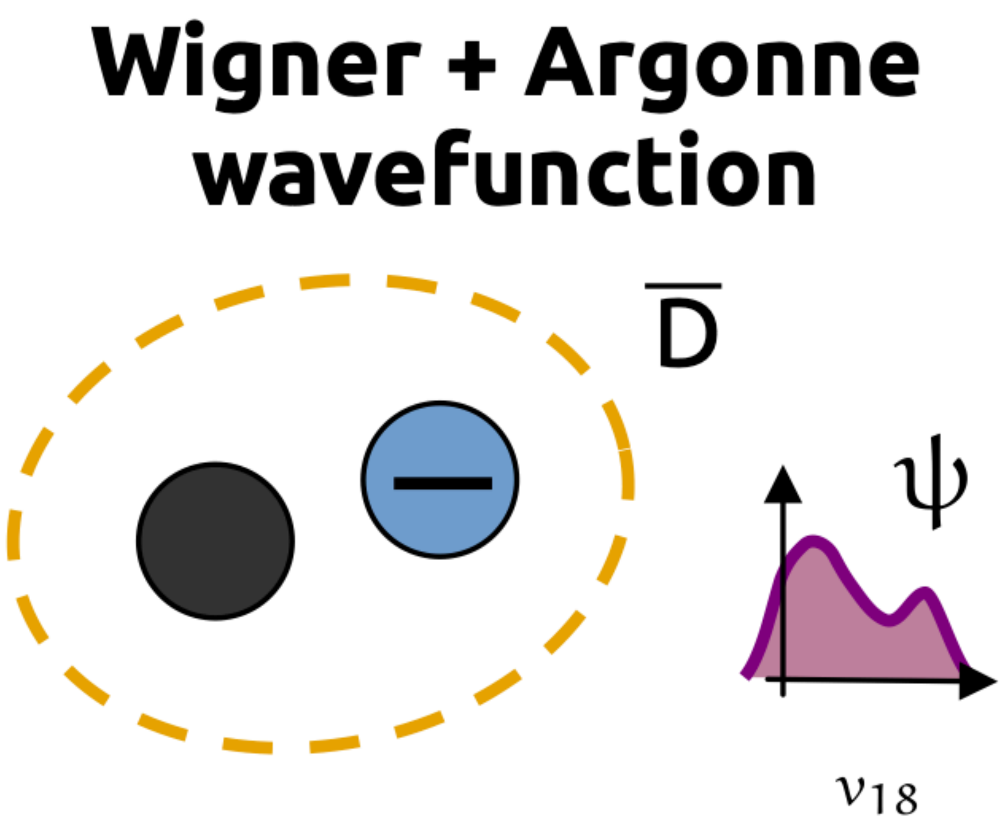
Models based on quantum mechanics (Wigner)

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

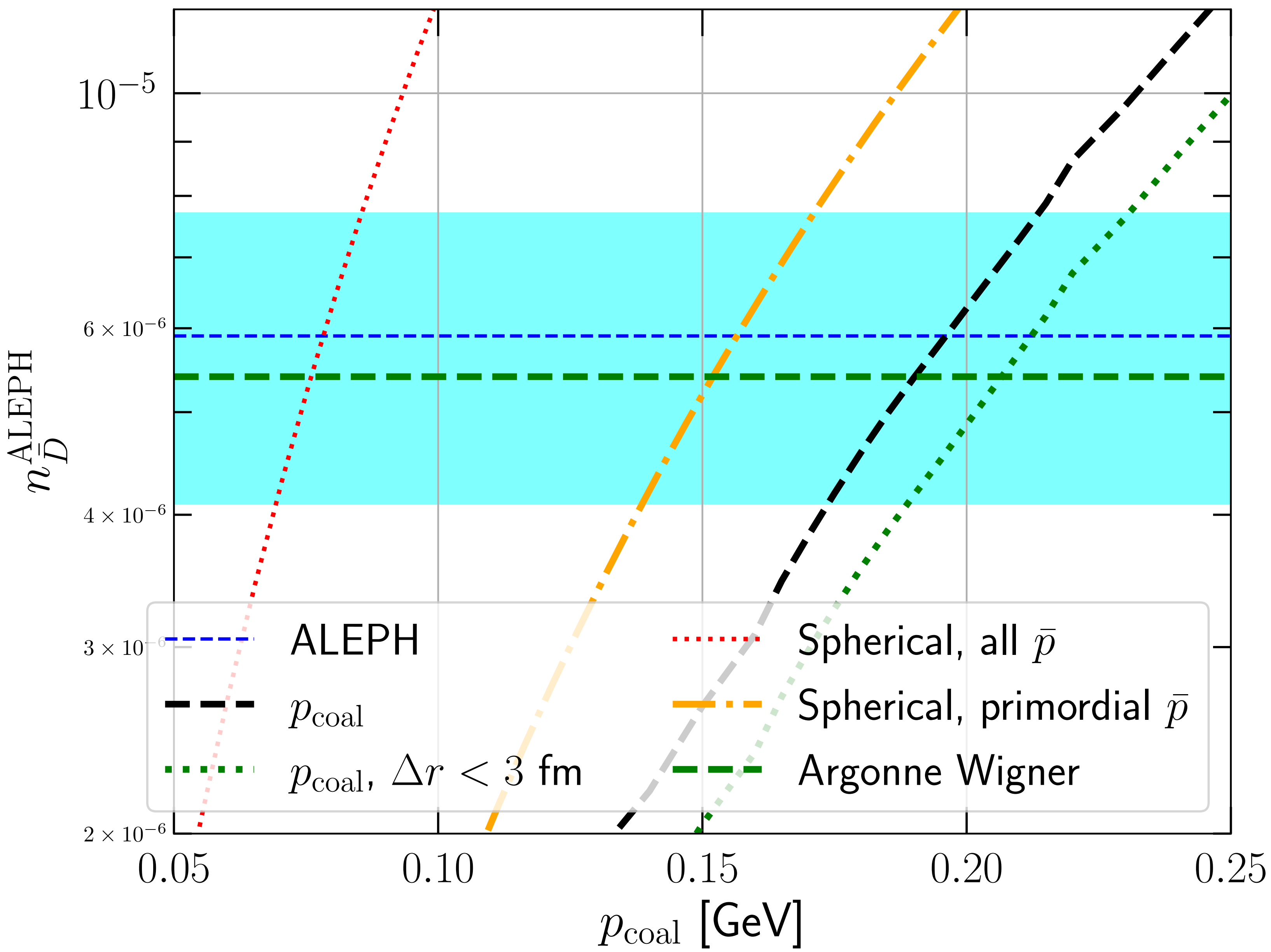
With a Gaussian wave function: $\mathscr{D}(\Delta r, \Delta p) \propto e^{-\Delta r^2/(2\sigma^2)} e^{-\Delta p^2 \delta^2/2}$

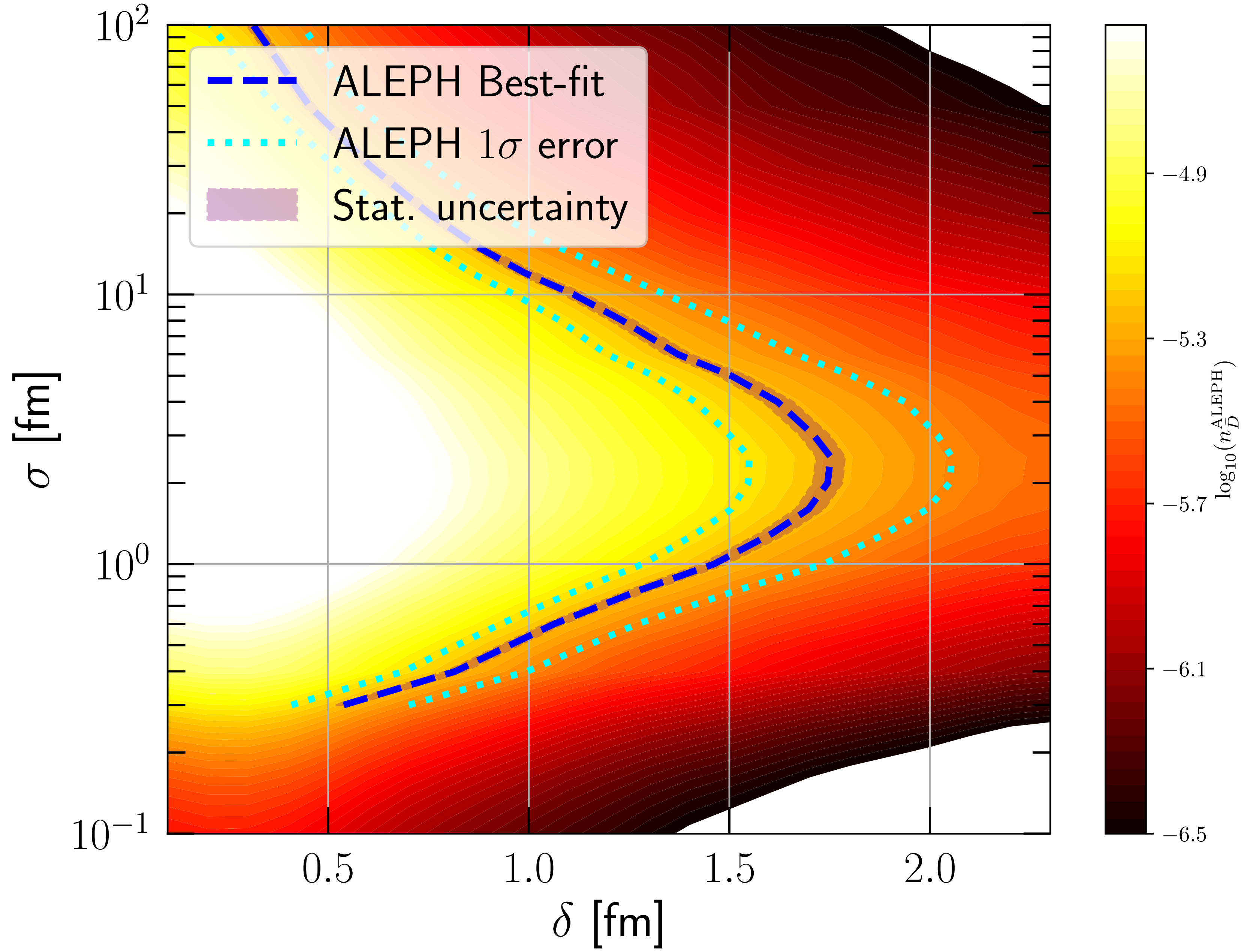
With an Argonne wave function (v_{18}) : has no free parameters (R. Wiringa et al., nucl-th/9408016).





Tuning of coalescence models

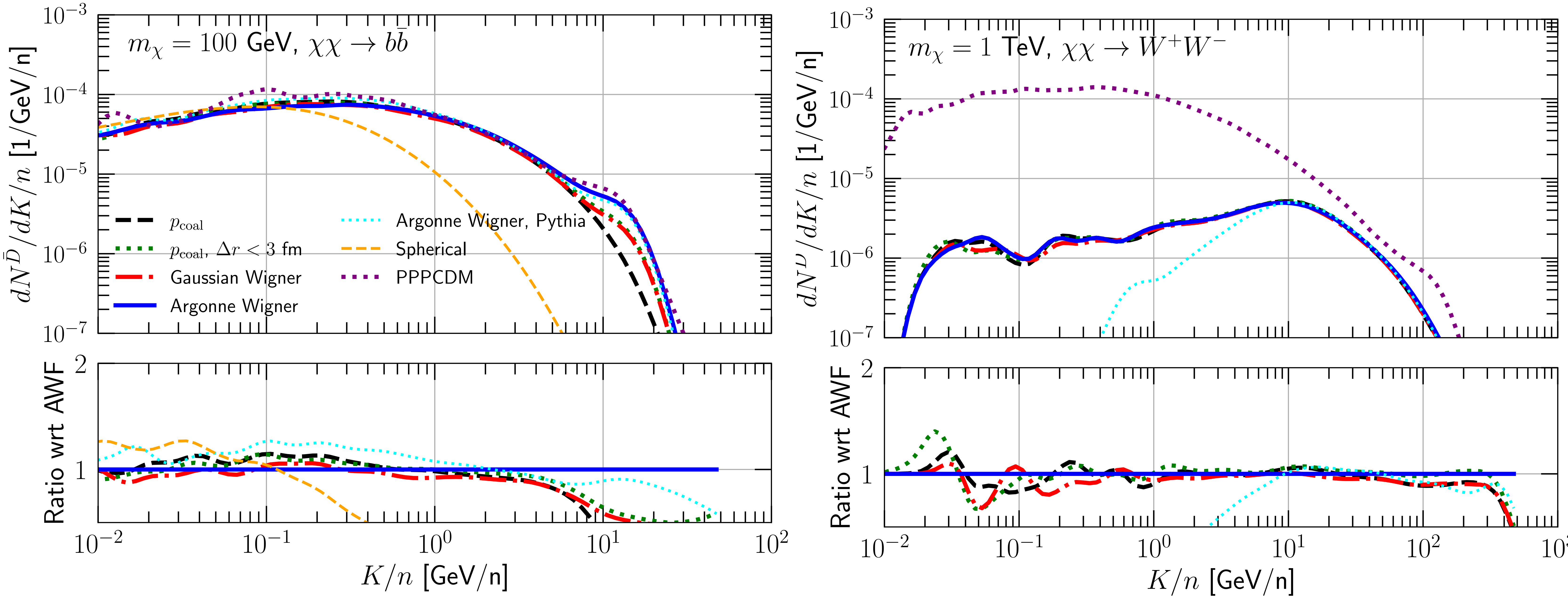




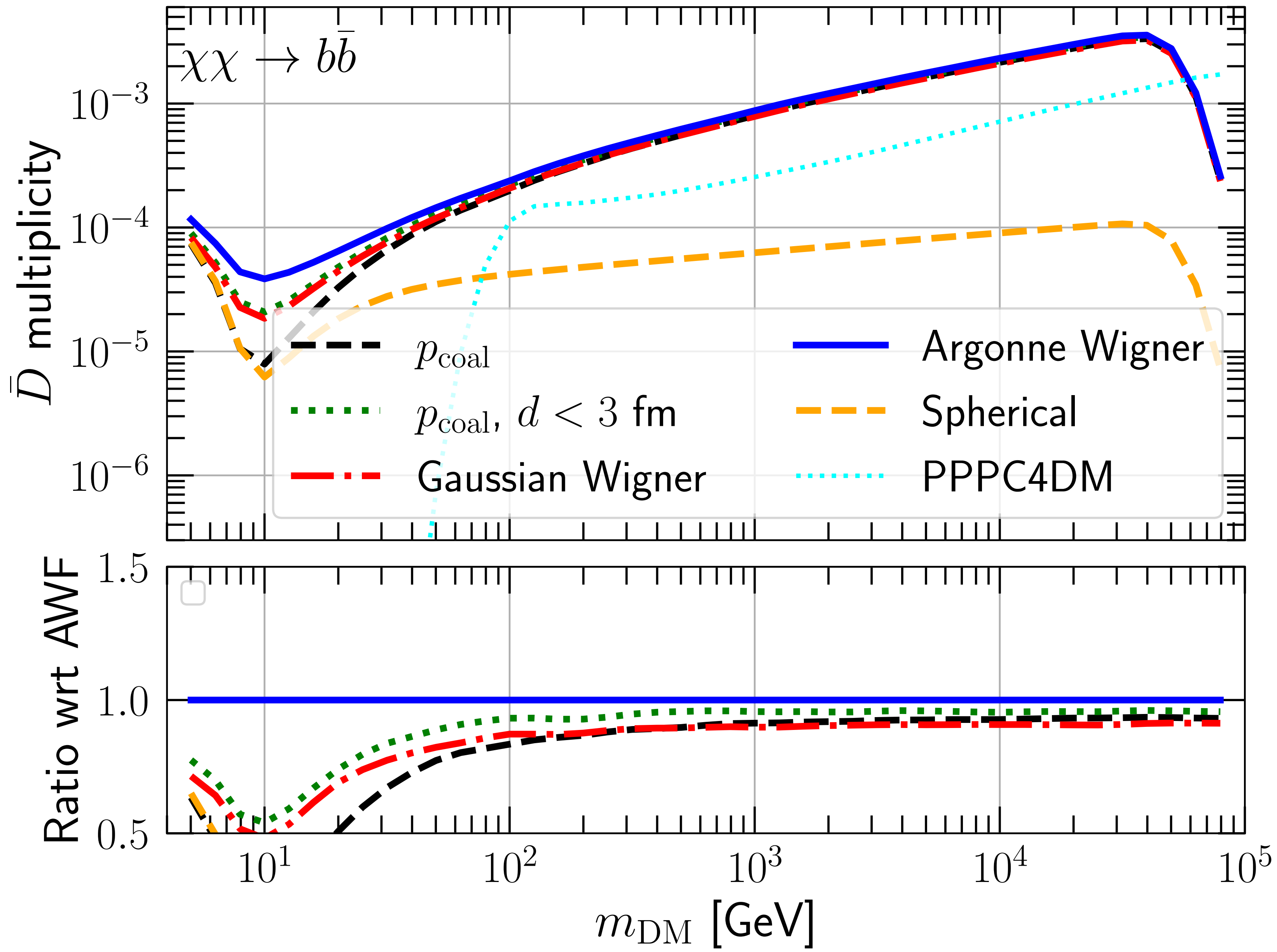
Use LEP data to tune the coalescence parameters ($n_{\bar{\mathrm{D}}}^{\mathrm{ALEPH}} = (5.9 \pm 1.8 \pm 0.5) \times 10^{-6}$)

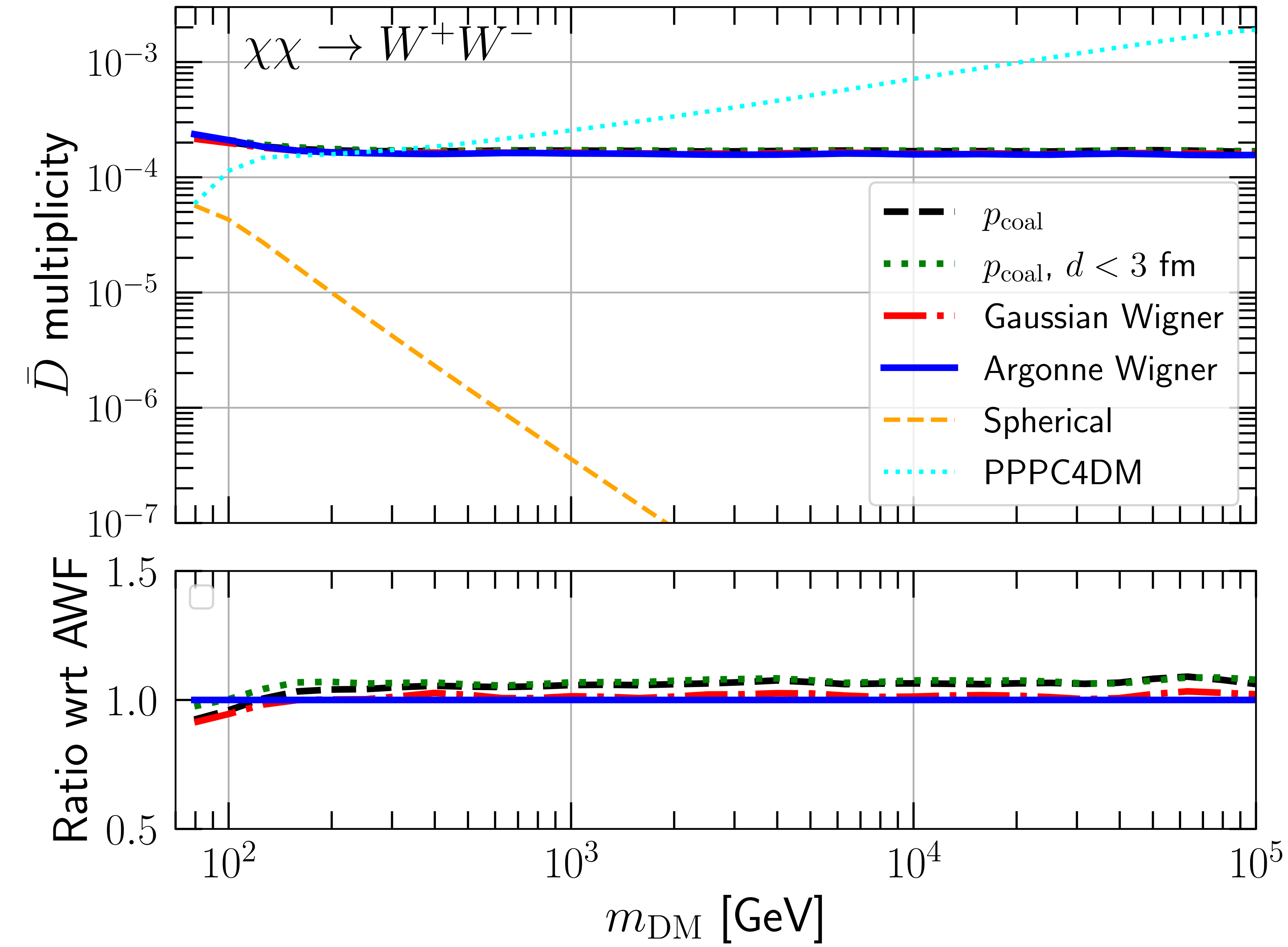
Use PYTHIA 8309 + VINCIA parton shower algorithm for the MC modeling.

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



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



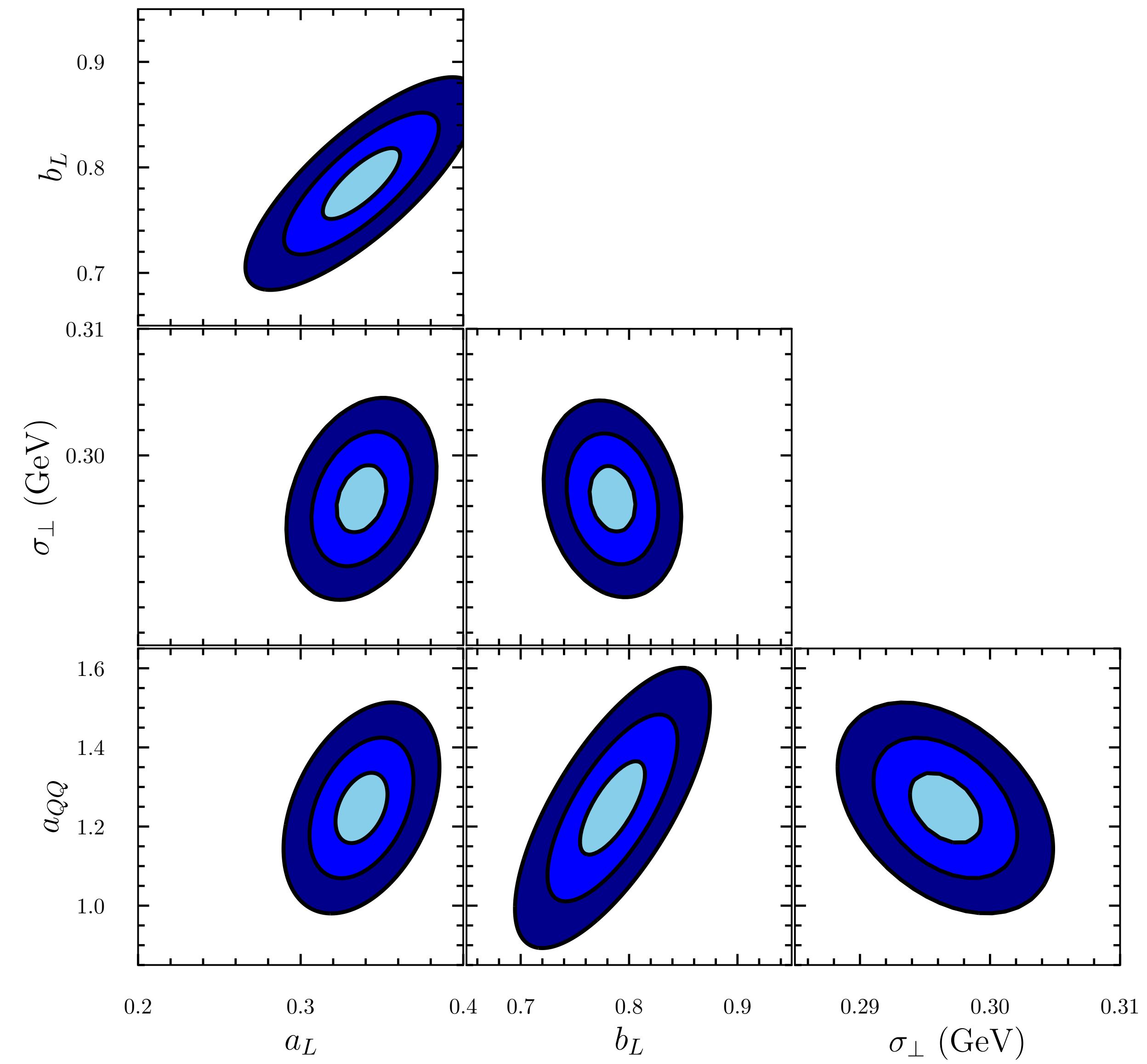


Improved Hadronization

The Lund string fragmentation function

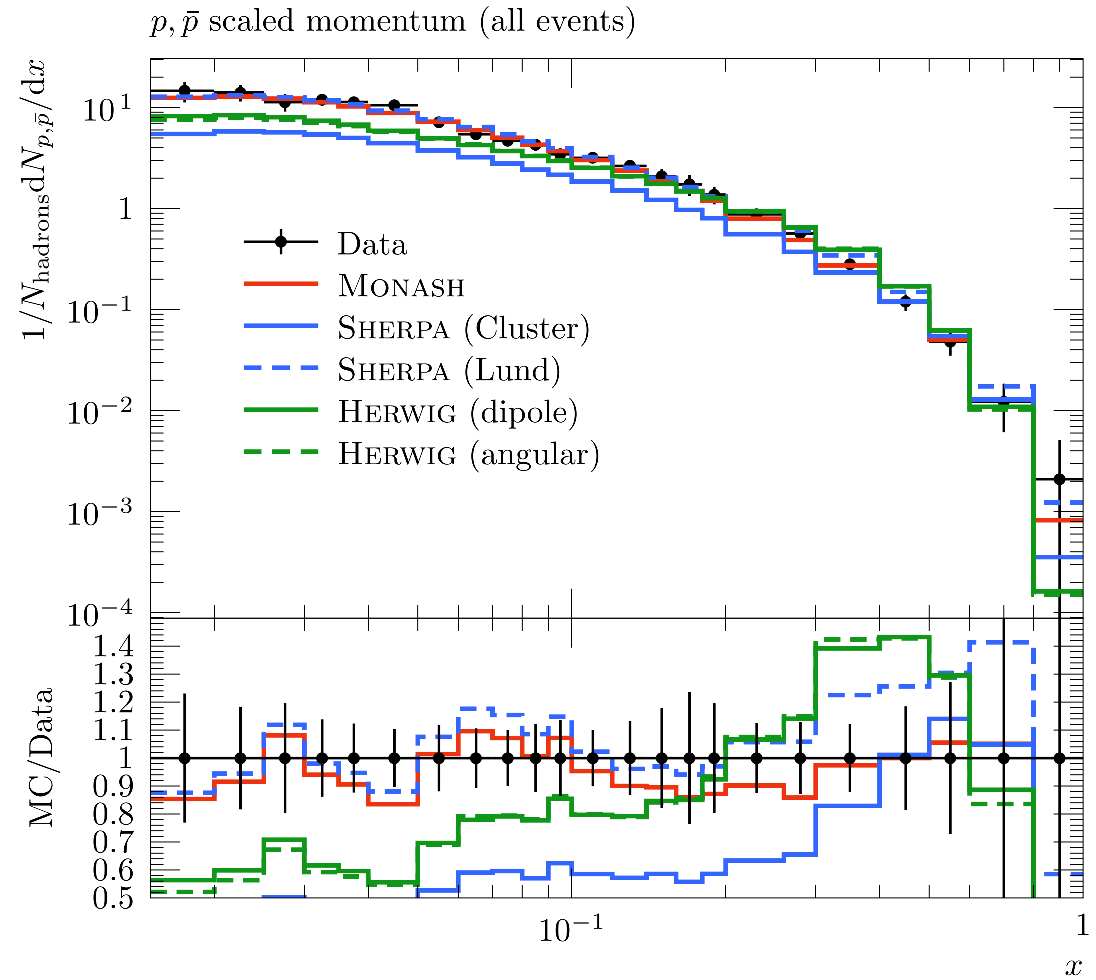
$$f(z, m_\perp) \propto N \frac{(1-z)^{a_L}}{z} \exp\left(\frac{-b_L m_\perp^2}{z}\right)$$

Parameter	Monash	Vincia (default)	Pythia [13, 14]	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
$\chi^2/N_{\rm df}$	1034.52/852	786.11/852	676.69/852	660.21/852



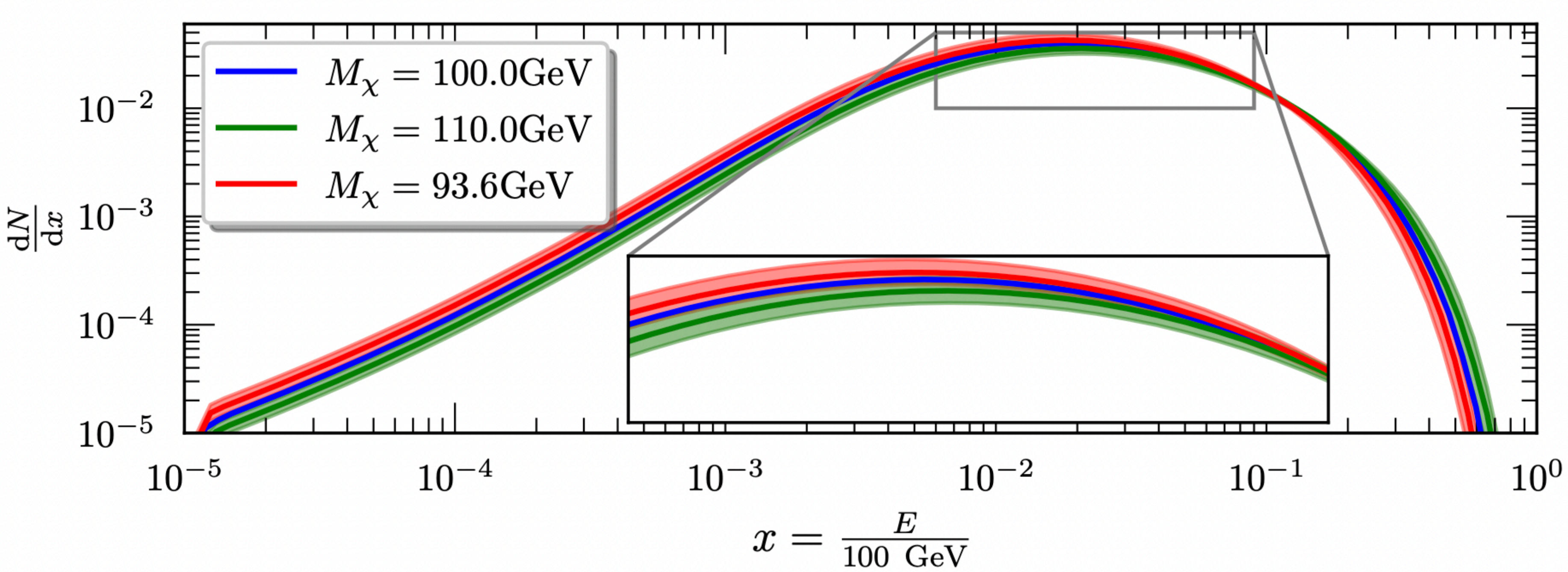
C. Arina, M. Di Mauro, N. Fornengo, A.J, J. Heisig, and R. Ruiz de Austri (2312.01153)

QCD uncertainties



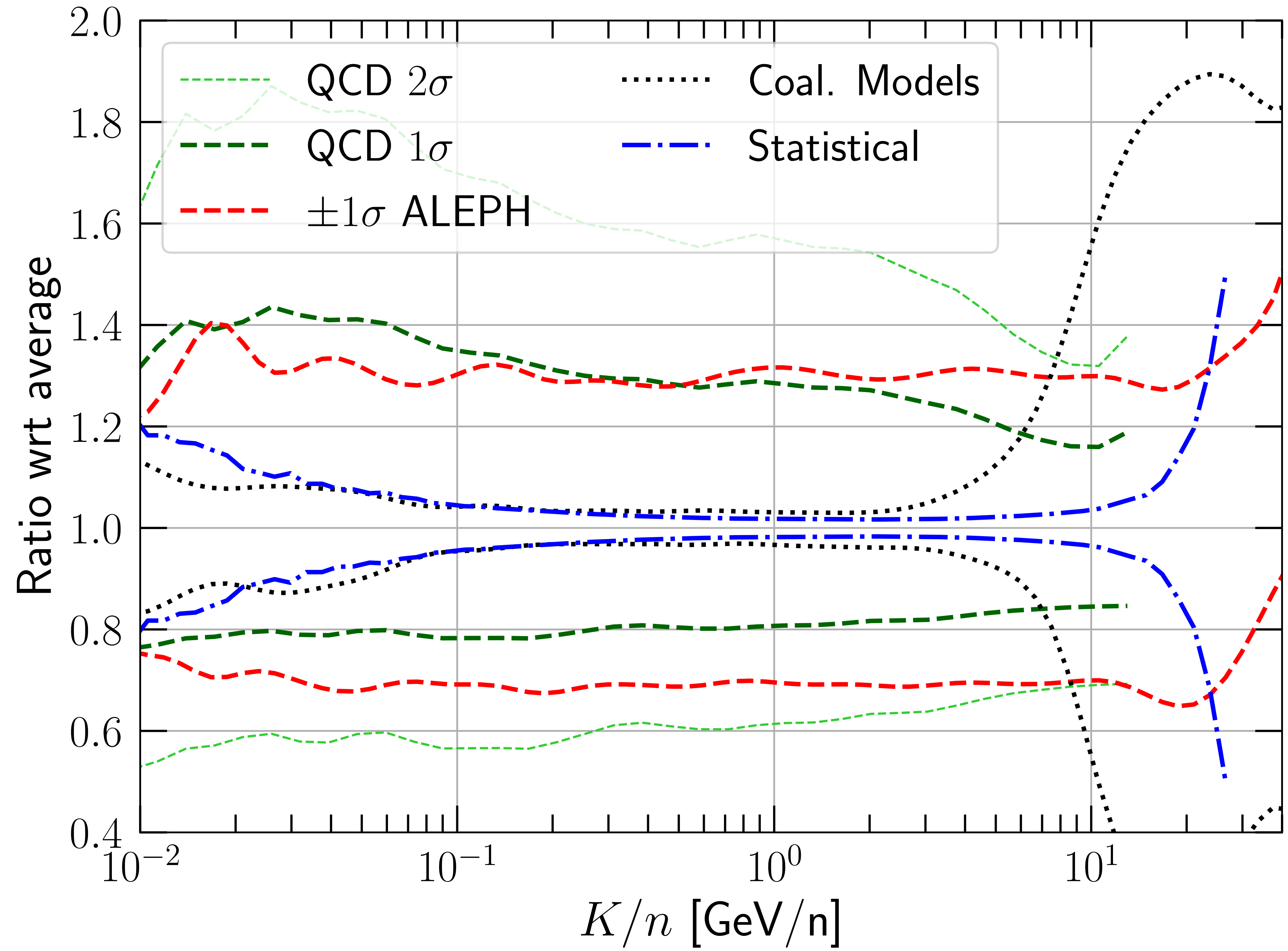
- Diagonalization of the covariance matrix around the best-fit point of the fragmentation-function parameters.
- One sigma is for $\Delta\chi^2 \equiv \chi^2_{\mathrm{var}} - \chi^2_{\mathrm{min}} = N_{\mathrm{df}}$; two sigma for $\Delta\chi^2 \equiv \chi^2_{\mathrm{var}} - \chi^2_{\mathrm{min}} = 4N_{\mathrm{df}}$ and so on).
- Choose a variation that span the range of allowed uncertainties by data while in the same time being not very large.

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



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^-	$^{+7.6}_{-9.3}$	$^{+63.0}_{-56.9}$

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



$$\chi\chi \to b\bar{b} \; [m_{\mathrm{DM}} = 100 \text{ GeV}]$$

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

Bonus: Some news

PHYSICAL REVIEW LETTERS **126,** 101101 (2021)

Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays

Martin Wolfgang Winkler[*] and Tim Linden[†]
Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden

(Received 10 July 2020; accepted 11 February 2021; published 8 March 2021)

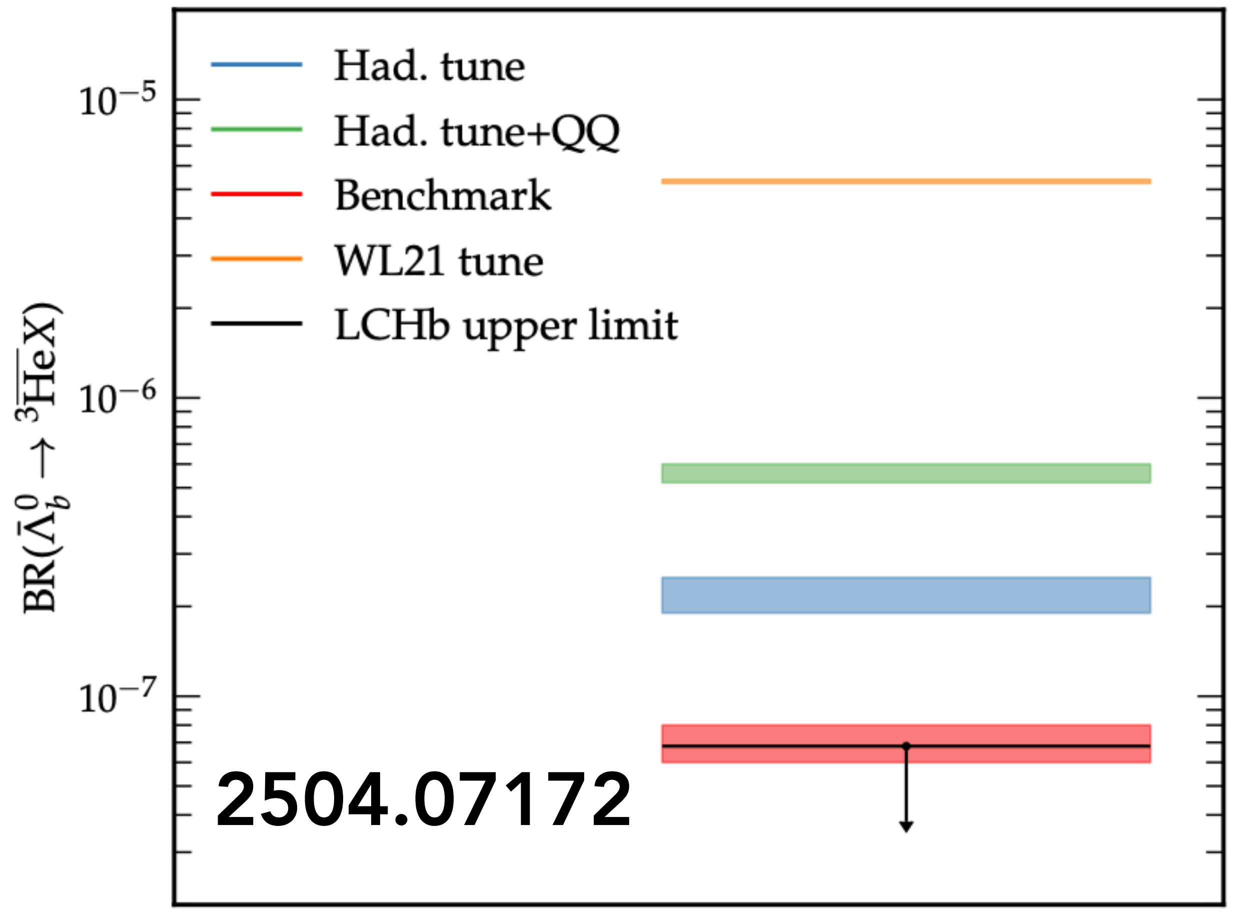
Recent observations by the Alpha Magnetic Spectrometer (AMS-02) have tentatively detected a handful of cosmic-ray antihelium events. Such events have long been considered as smoking-gun evidence for new physics, because astrophysical antihelium production is expected to be negligible. However, the dark-matter-induced antihelium flux is also expected to fall below current sensitivities, particularly in light of existing antiproton constraints. Here, we demonstrate that a previously neglected standard model process—the production of antihelium through the displaced-vertex decay of $\bar{\Lambda}_b$-baryons—can significantly boost the dark matter induced antihelium flux. This process can entirely dominate the production of high-energy antihelium nuclei, increasing the rate of detectable AMS-02 events by 2 orders of magnitude.

- **Challenged by a recent upper bound from LHCb**
- **Leads to results that disagree with LEP measurements of meson/baryon spectra.**

A Robust Determination of Antinuclei Production from Dark Matter via Weakly Decaying Beauty Hadrons

Mattia Di Mauro,[1,*] Adil Jueid,[2,†] Jordan Koechler,[1,‡] and Roberto Ruiz de Austri[3,§]
[1]*Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy*
[2]*Particle Theory and Cosmology Group, Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), Daejeon, 34126, Republic of Korea*
[3]*Instituto de Física Corpuscular, CSIC-Universitat de València, E-46980 Paterna, Valencia, Spain*

Recently, the Alpha Magnetic Spectrometer (AMS-02) Collaboration presented tentative evidence for the detection of cosmic antihelium-3 ($^3\overline{\mathrm{He}}$) events, alongside a comparable number of antideuterons ($\overline{\mathrm{D}}$). If confirmed, these observations could revolutionize our understanding of cosmic-ray production and propagation and/or serve as compelling indirect evidence for dark matter. Given that the detection of cosmic $\overline{\mathrm{D}}$ is already at the limit of AMS-02 sensitivity, explaining the observation of $^3\overline{\mathrm{He}}$ even within the standard coalescence framework poses a significant challenge. It has recently been shown that a previously overlooked mechanism within the Standard Model of particle physics—namely, the production of antihelion via the displaced-vertex decay of $\bar{\Lambda}^0$ baryons—could



Conclusions

- We have made significant improvements on the particle spectra from dark matter annihilation: CosmiXs.
- Reducing the theory uncertainties from coalescence to the few-percent level.
- These results are relevant for experiments like AMS-02 and GAPS.
- Further improvements can be made using e.g. higher order corrections, improved resummations, hadron spin correlations and different hadronization models, improved jet matching or probably the use of new LHC data.
- Challenges due to the high computational cost:
    - 15 million annihilation events per DM mass were simulated for $\chi\chi \to \ell^+\ell^-, \nu\bar{\nu}, \gamma\gamma$.
    - Between 11.2 million and 2.29 billion annihilation events for the other channels.