

Estimating QCD uncertainties on anti-proton spectra from dark matter annihilation

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Talk based on

- A. Jueid, J. Kip, R. Ruiz de Austri, P. Skands, in preparation.

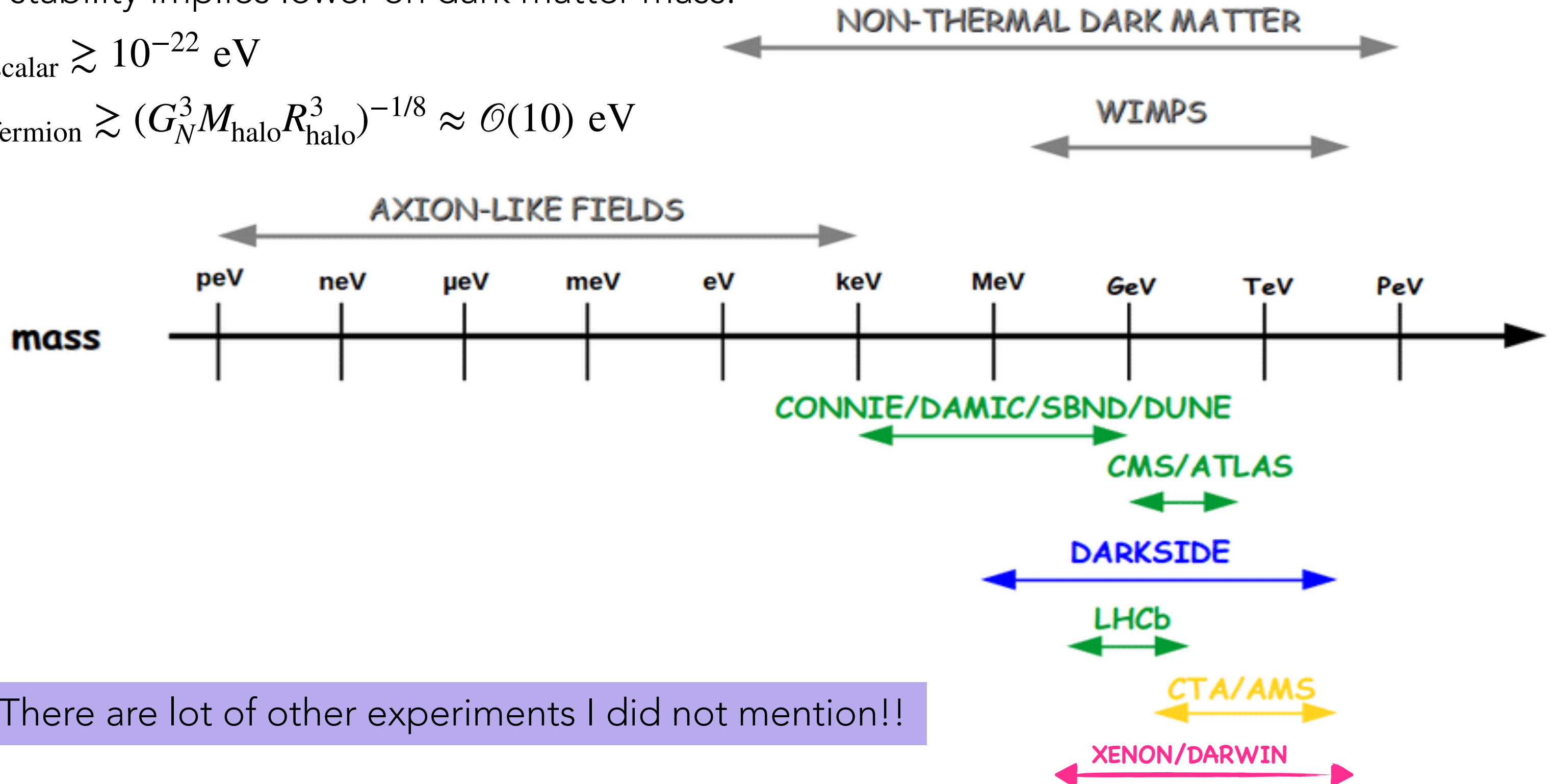
Is dark matter the aether of the twenty-first century?

- The existence of dark-matter in the universe is supported by various data at astronomical and cosmological scales.
- The measurement of anisotropies in the Cosmic Microwave Background (CMB) implies that about 80% of the matter budget in the universe is formed by dark-matter (Planck Experiment; 2015).
- Dark-matter is required to be (mostly) non-relativistic when the gravitational clustering started at the matter-radiation equality.
- The freeze-out mechanism can be straightforwardly realized by extending the Standard Model with Weakly Interacting Massive Particles (WIMPs).
- This scenario has driven multiple searches of dark matter through direct detection (Xenon, DAMA, LUX, PandaX), indirect detection (Fermi-LAT, IceCube, AMS) and collider experiments (LHC).
- No signals above the expected backgrounds have been observed (besides some mild excesses...)

The dark matter landscape

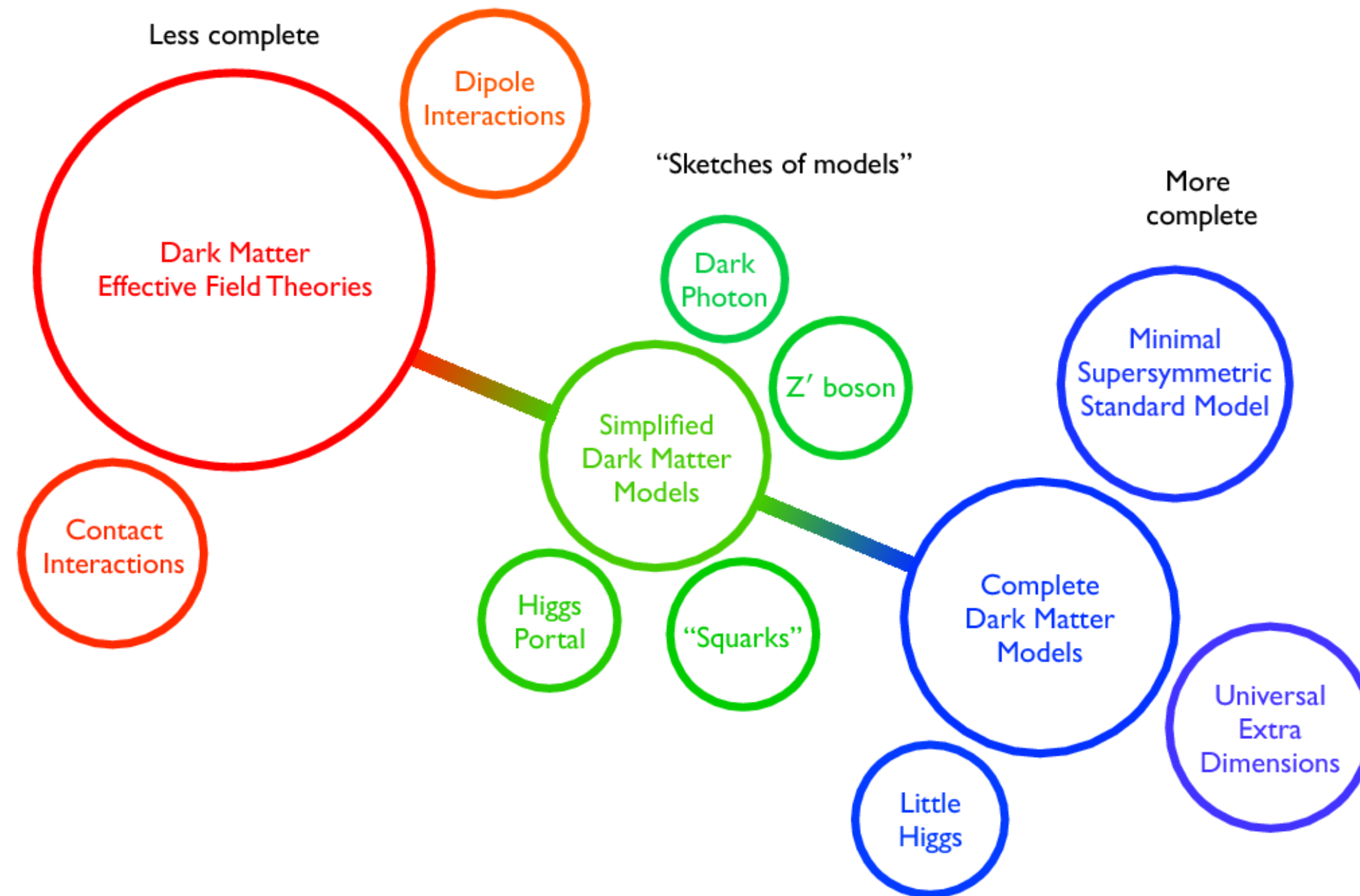
Halo stability implies lower on dark matter mass:

- $M_{\text{scalar}} \gtrsim 10^{-22} \text{ eV}$
- $M_{\text{fermion}} \gtrsim (G_N^3 M_{\text{halo}} R_{\text{halo}}^3)^{-1/8} \approx \mathcal{O}(10) \text{ eV}$



There are lot of other experiments I did not mention!!

The dark matter landscape



Introduction to particle physics modeling of dark matter annihilation

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

Impossible to predict the spectra from first principles.

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

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

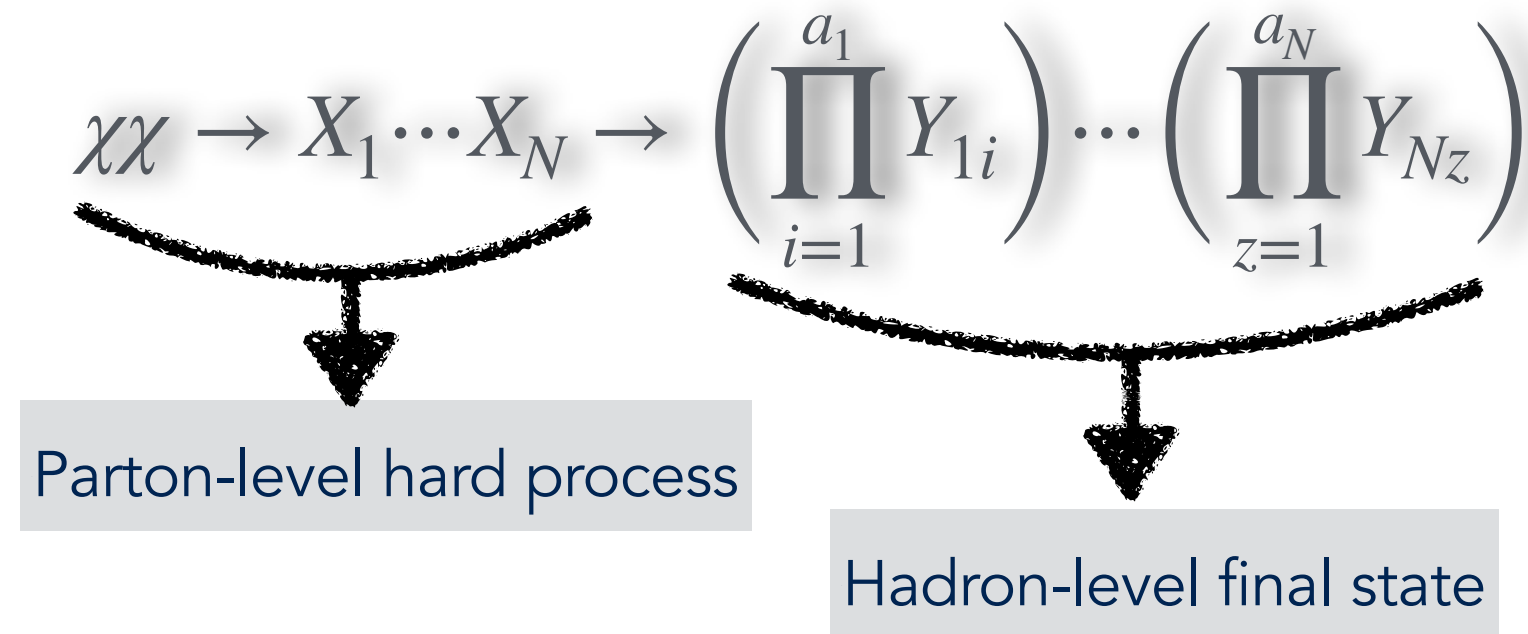
The role of precision

- There are hints for possible excess over the SM 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.
- The best-fit point is very sensitive to whether you choose a flat $X\%$ uncertainty or non uncertainty at all.

Determination of QCD uncertainties on the spectra is necessary

Modeling of the spectra

To simplify the discussion, we consider the generic annihilation process

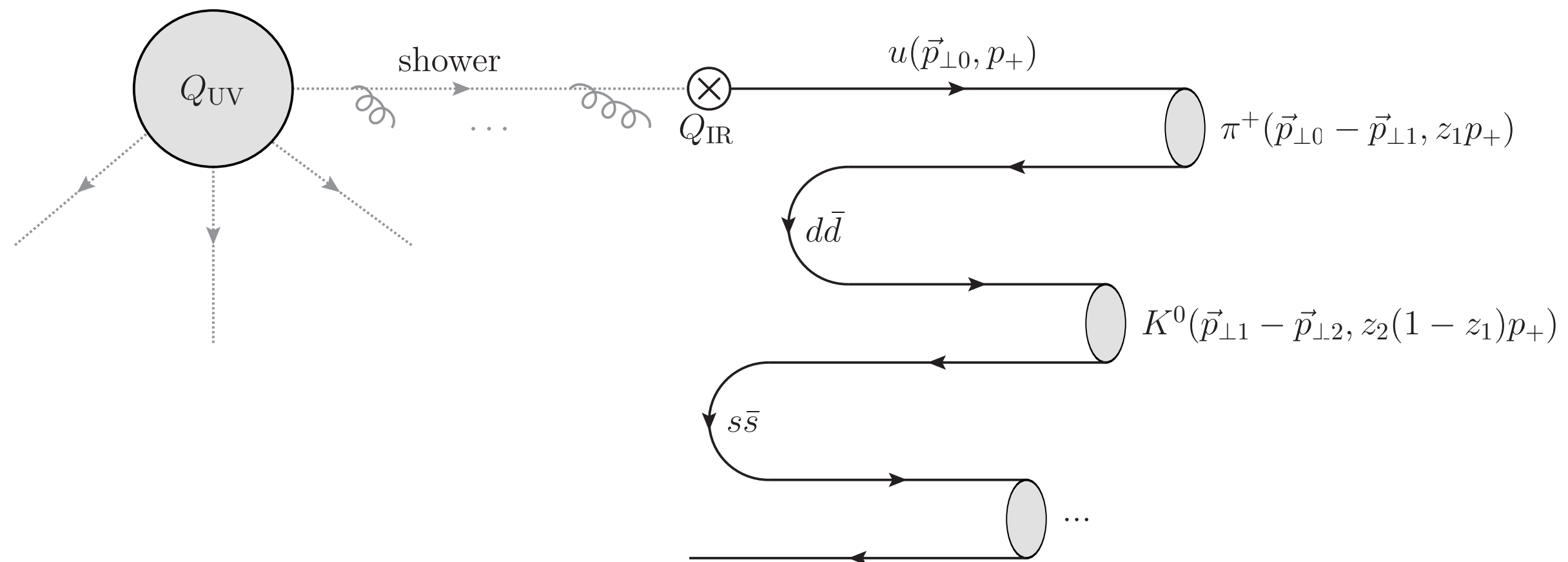


- X_i is electrically-charged or contain photons $\implies$ further *QED emissions* producing additional photons and charged fermions.
- X_i is colored particle $\implies$ cascade of *QCD shower emissions* will occur and treated in the same way as in QED emissions.
(the number and hardness of the emissions depend on how far from threshold the X_i particles are produced)

The top quark is very special as it can radiate photons, gluons, and decays to further jets and leptons.

Modeling of the spectra: Hadronisation

- Hadronisation 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.

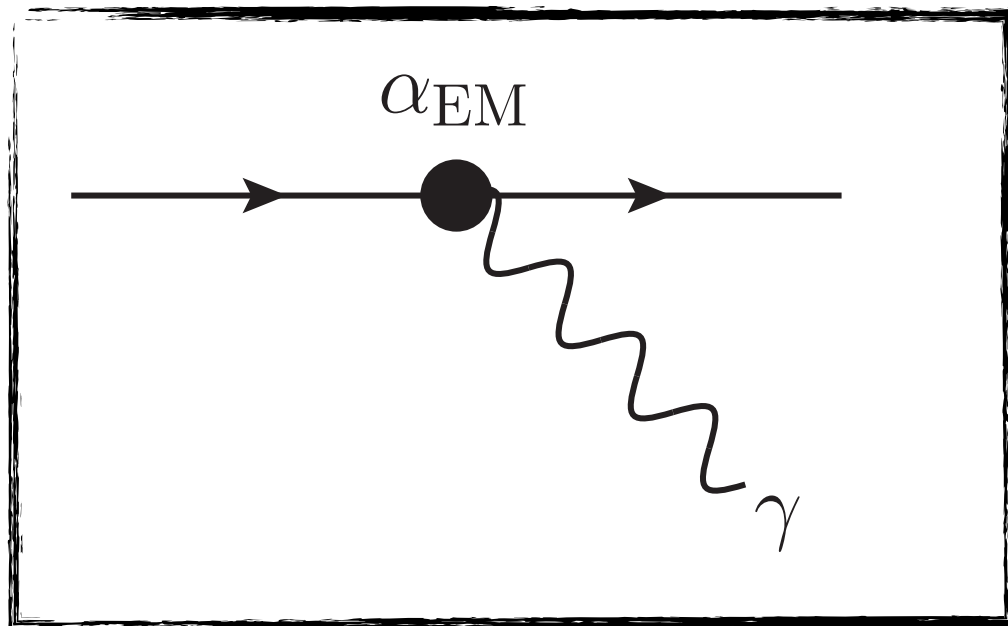


The Lund string model is based on the following symmetric function

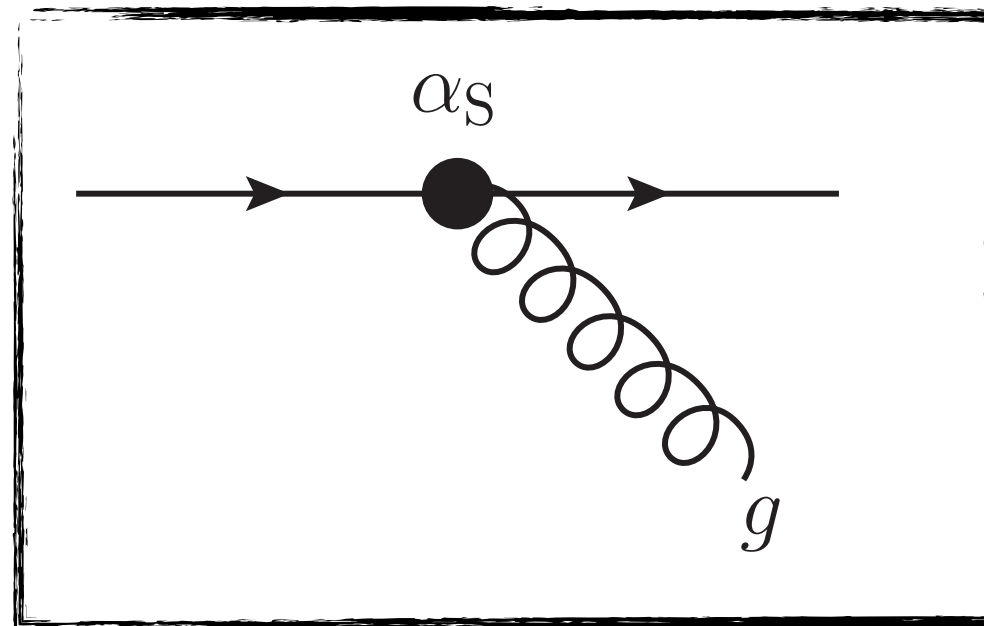
$$f(z, m_{\perp}) \propto N \frac{(1-z)^a}{z} \exp\left(\frac{-bm_{\perp}^2}{z}\right)$$

- 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 $\Rightarrow$ we introduce a new parametrization of the fragmentation function where the new parameter $\langle z_{\rho} \rangle$ has a lower correlation with the a parameter.

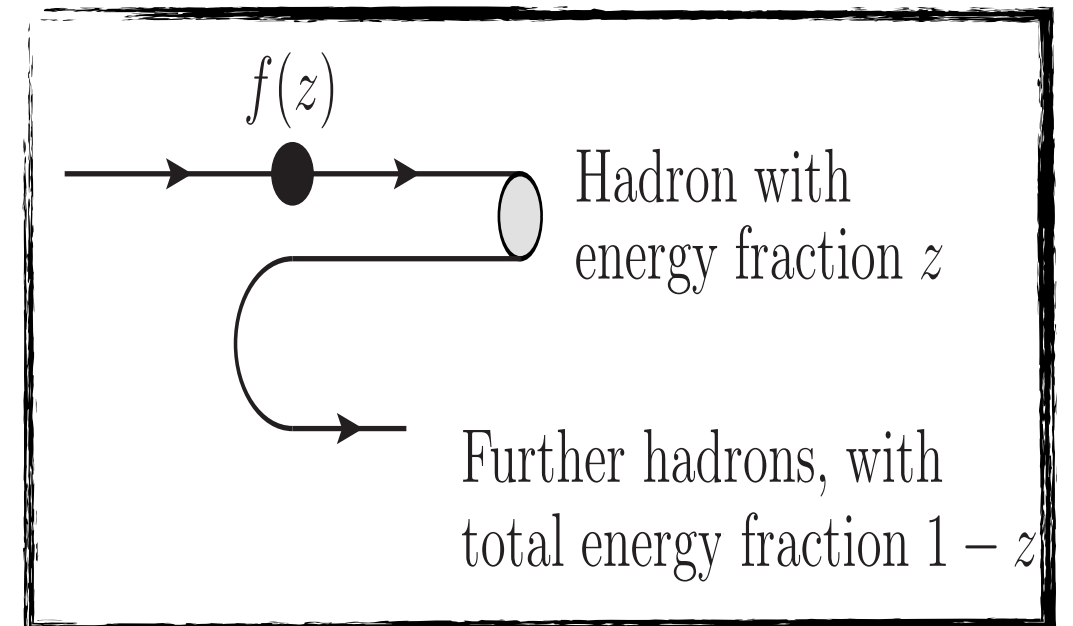
Modeling of the Particle Spectra: Recap



- Dominates at high x_γ .
- Relevant for DM annihilation into charged leptons and photons as well.
- The corresponding coupling is measured with very high precision.



- Dominates at the bulk and the peak of the photon energy.
- The main parameter controlling the QCD showers is α_S .
- Very different value from the $\overline{\text{MS}}$ scheme; $\alpha_S(M_Z) \sim 0.139$



- Dominate at the bulk and the peak of the photon energy.
- Three parameters are relevant for this process (flavor-independent part).
- Can be subjected to uncertainty estimates.

What about anti-protons?

- The basic picture of fragmentation process for mesons needs to be modified.
- As baryons consist of three quarks or three anti-quarks, their production occurs through the breaking of strings by the production of diquark pairs (bound states of two quarks).
- In this case, there is a strong correlation between the produced baryons and anti-baryons — which was challenged by a measurement performed by OPAL collaboration.
- To address this, the popcorn mechanism is introduced in which a set of $q\bar{q}$ pairs (one pair or more...) are produced between the diquark pairs — lead to the production of multiple mesons between a baryon and anti-baryon (therefore decreases the correlation).

NOTE ONE: In the context of dark matter annihilation, correlations are lost as baryons travel long distances before reaching the detector.

NOTE TWO: In the case of baryon production, the a is changed into $a_{\text{eff}} = a_{\text{light}} + a_{\text{diquark}} \implies 4$ parameters to tune.

Origin of Photons, Positrons and Anti-protons

Photons

- Most of the photons are produced from the decay of neutral pions — $\text{BR}(\pi^0 \rightarrow \gamma\gamma) \approx 100\%$
- Some photons are produced from the decay of η mesons while a sub-leading contribution to photons is from bremsstrahlung.

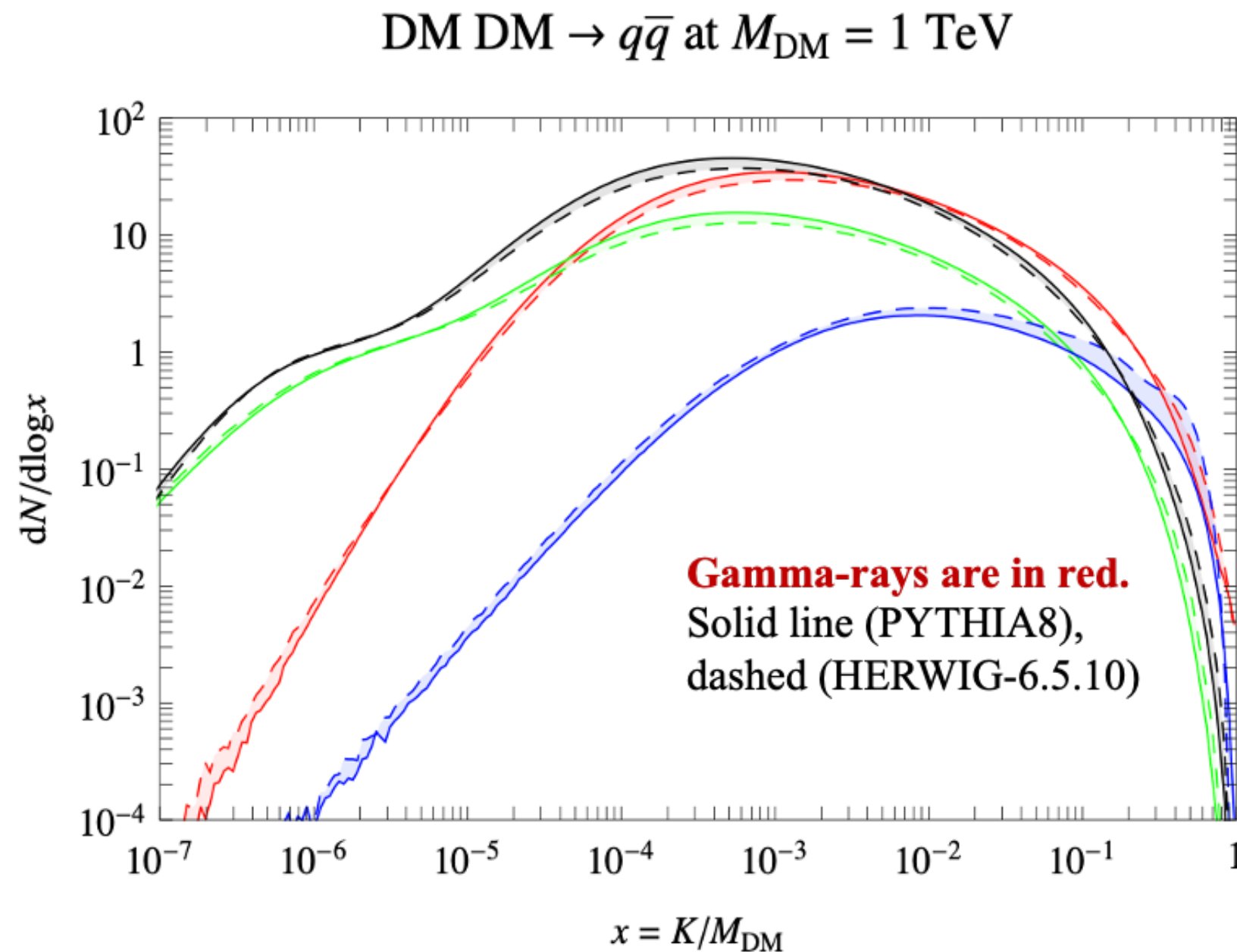
Positrons

- Most of the positrons are produced from the decay of charged pions: — $\text{BR}(\pi^+ \rightarrow \mu^+ \nu_\mu) \approx 99.88\%$
- Some positrons are coming from photon splittings or from the decay of W or Z bosons.

Anti-protons

- Antiprotons are usually produced from q/g fragmentation (called primary) or from the decay of heavier baryons (called secondary).
- The most important baryons that contribute to antiproton production are: neutrons, Λ^0 , Δ^{++} , and, $\Sigma^\pm$

The flux at production of stable particles: PPPC4DMID



- M. Cirelli et al. produced a complete recipe for the flux at production from dark matter annihilation in a wide range of masses (arXiv:1012.4515) – called Poor Particle Physics Cookbook for Dark Matter Indirection Detection (PPPC 4 DM ID) –.
- The study used Pythia8-135 based on an old tune that is replaced by the most recent Monash tune.
- That version of Pythia8 lacks several capabilities such as QED radiation off heavy-particles, EW showers, among others.

Important Question: what is the uncertainty on the derived spectra?

Tuning

- Different tunings of the parameters $a, \langle z_p \rangle, \sigma (= \sqrt{2\langle m_{\perp}^2 \rangle})$, and a_{Diquark} 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 (0907.2973) for optimization of the parameters of the fragmentation function in Pythia8.244 and Rivet 3.1.1 for the experimental analyses.

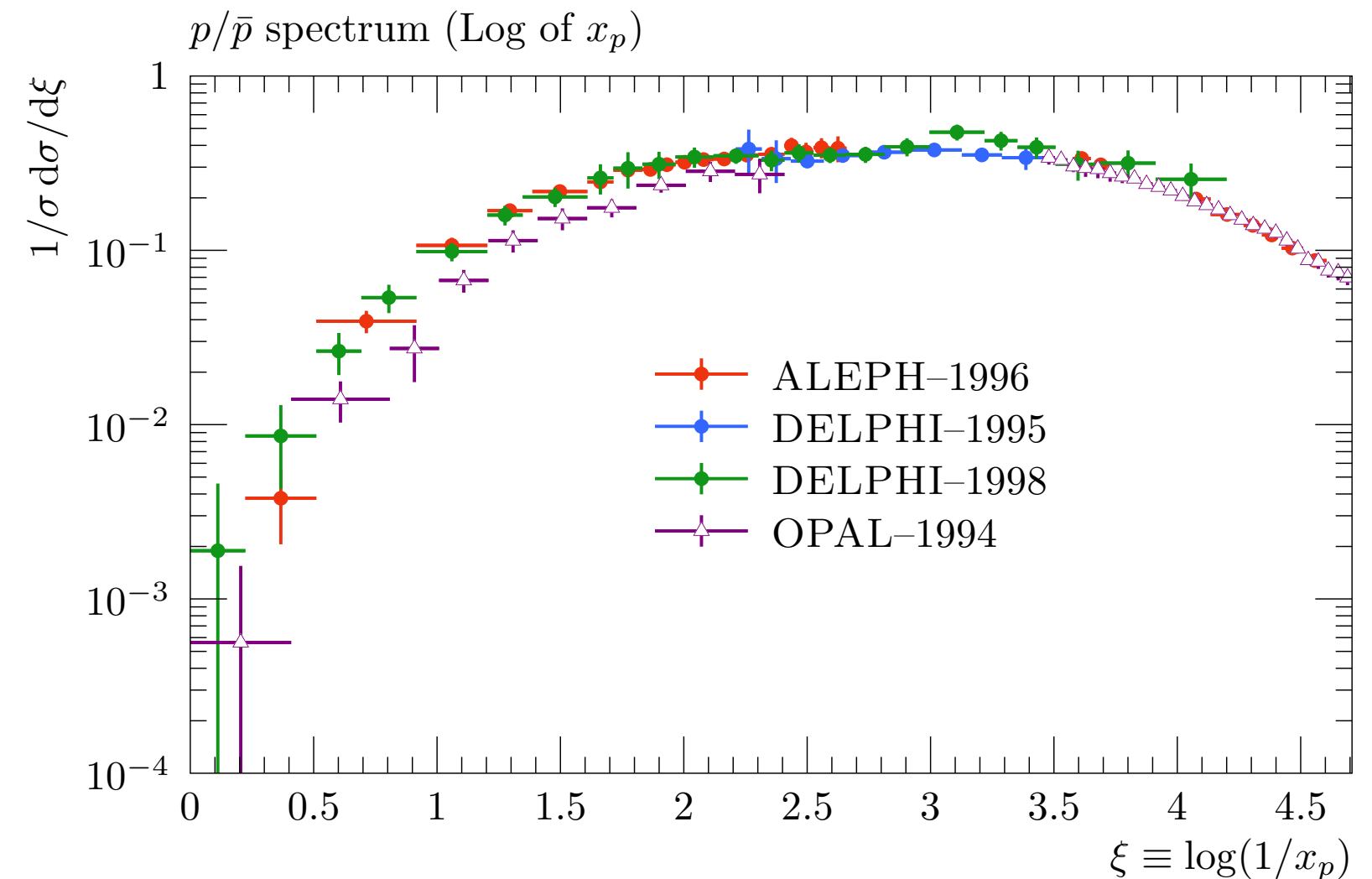
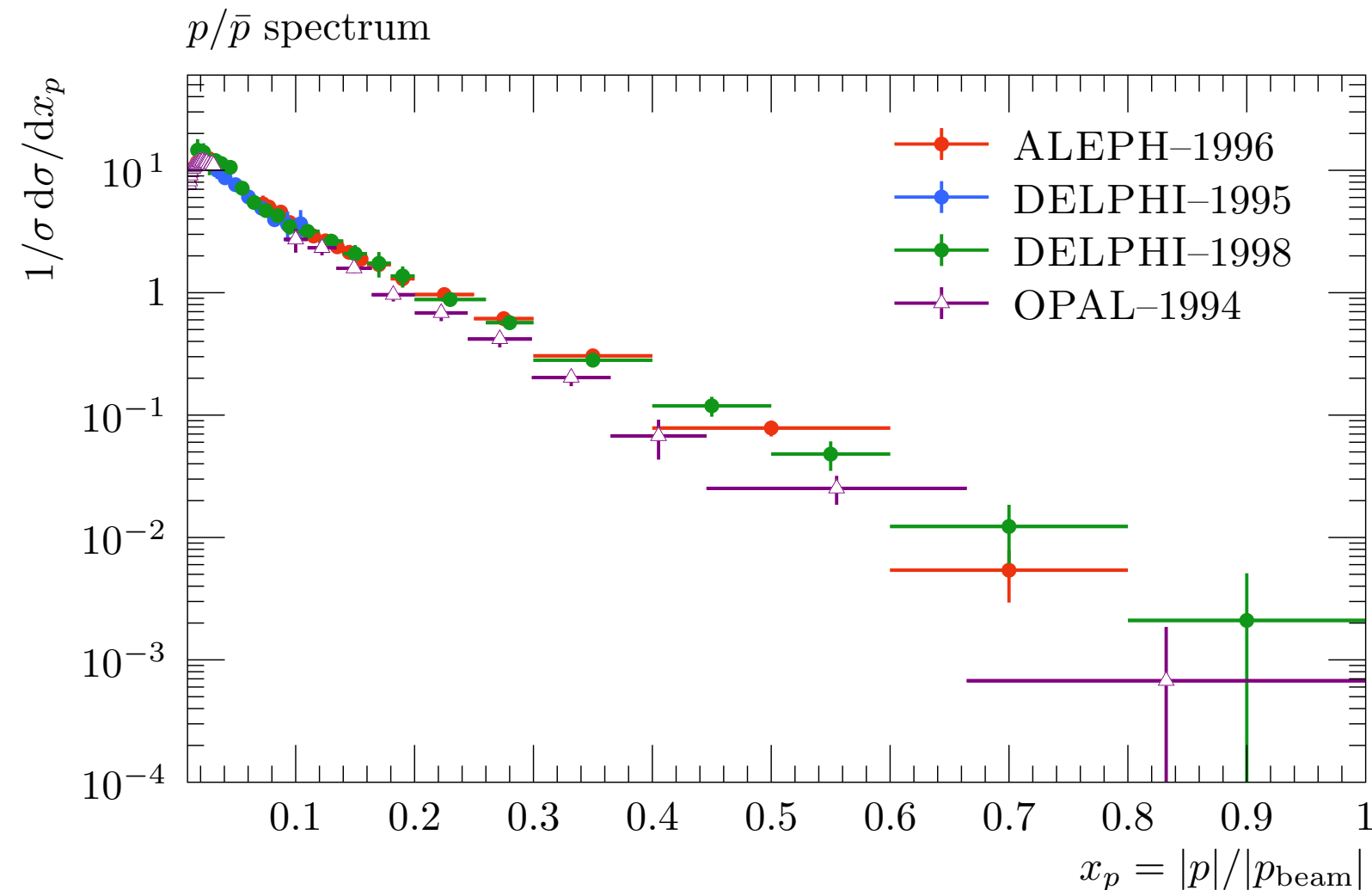
$$\chi^2 = \sum_{\mathcal{O}} \omega_{\mathcal{O}} \sum_{b \in \mathcal{O}} \left(\frac{f_{(b)}(\{p_i\}) - \mathcal{R}_{(b)}}{\Delta_{(b)}} \right)^2$$

Theory prediction
Experimental measurement

Weight for observable $\mathcal{O}$

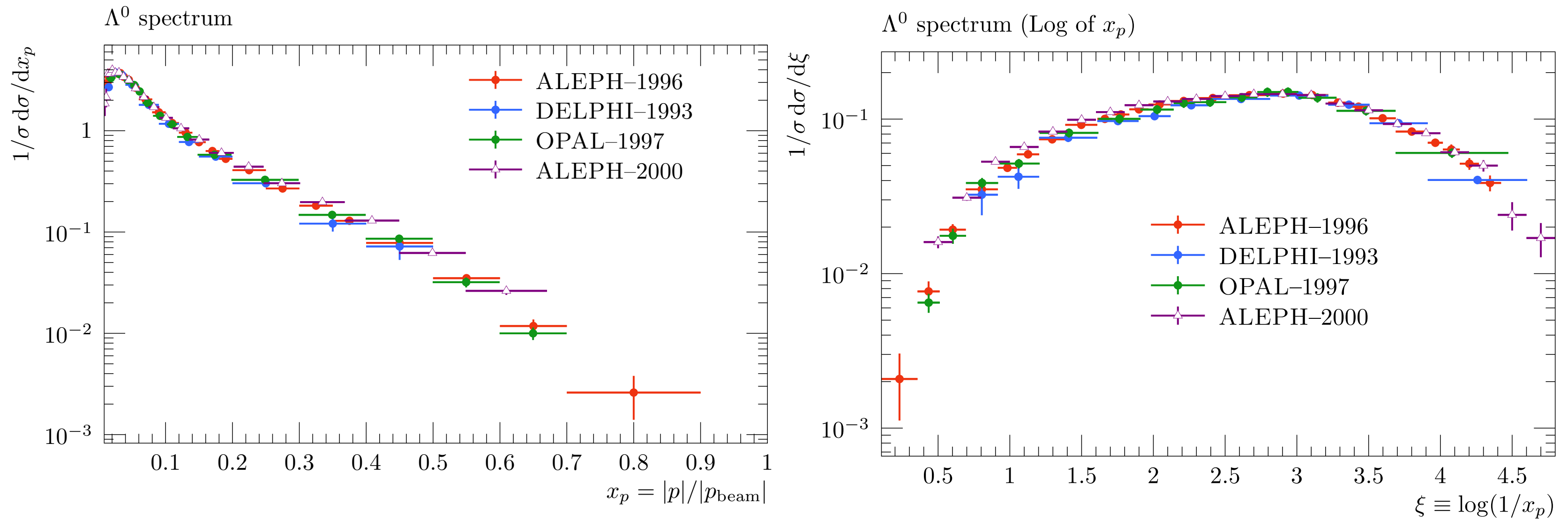
Total error: $\Delta_{(b)} = \sqrt{\Delta_{\text{exp}}^2 + \Delta_{\text{MC}}^2 + (0.05 \times f_{(b)}(\{p_i\}))^2}$

Issues in measurements of baryon spectra at LEP



OPAL—1994 is not consistent with the other measurements for $x_p \geq 0.1$

Issues in measurements of baryon spectra at LEP



ALEPH—2000 is slightly above the other measurements for high- x

Tunes: Results

Tune	aLund	avgZLund	sigma	aExtraDiquark	χ^2/N_{df}
ALEPH	$0.758^{+0.074}_{-0.074}$	$0.541^{+0.007}_{-0.007}$	$0.297^{+0.005}_{-0.005}$	$1.218^{+0.358}_{-0.358}$	116.22/296
DELPHI	$0.358^{+0.054}_{-0.054}$	$0.497^{+0.007}_{-0.007}$	$0.287^{+0.006}_{-0.006}$	$0.782^{+0.298}_{-0.298}$	144.37/268
L3	$0.478^{+0.063}_{-0.063}$	$0.557^{+0.006}_{-0.006}$	$0.315^{+0.007}_{-0.007}$	$1.998^{+0.049}_{-0.049}$	84.70/140
OPAL	$0.588^{+0.086}_{-0.086}$	$0.536^{+0.005}_{-0.005}$	$0.300^{+0.005}_{-0.005}$	$1.998^{+0.204}_{-0.204}$	53.54/136
COMBINED	$0.601^{+0.038}_{-0.038}$	$0.540^{+0.004}_{-0.004}$	$0.307^{+0.002}_{-0.002}$	$1.671^{+0.196}_{-0.196}$	676.69/852

Good agreement between theory and data.

Estimate of Hadronization Uncertainties

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.

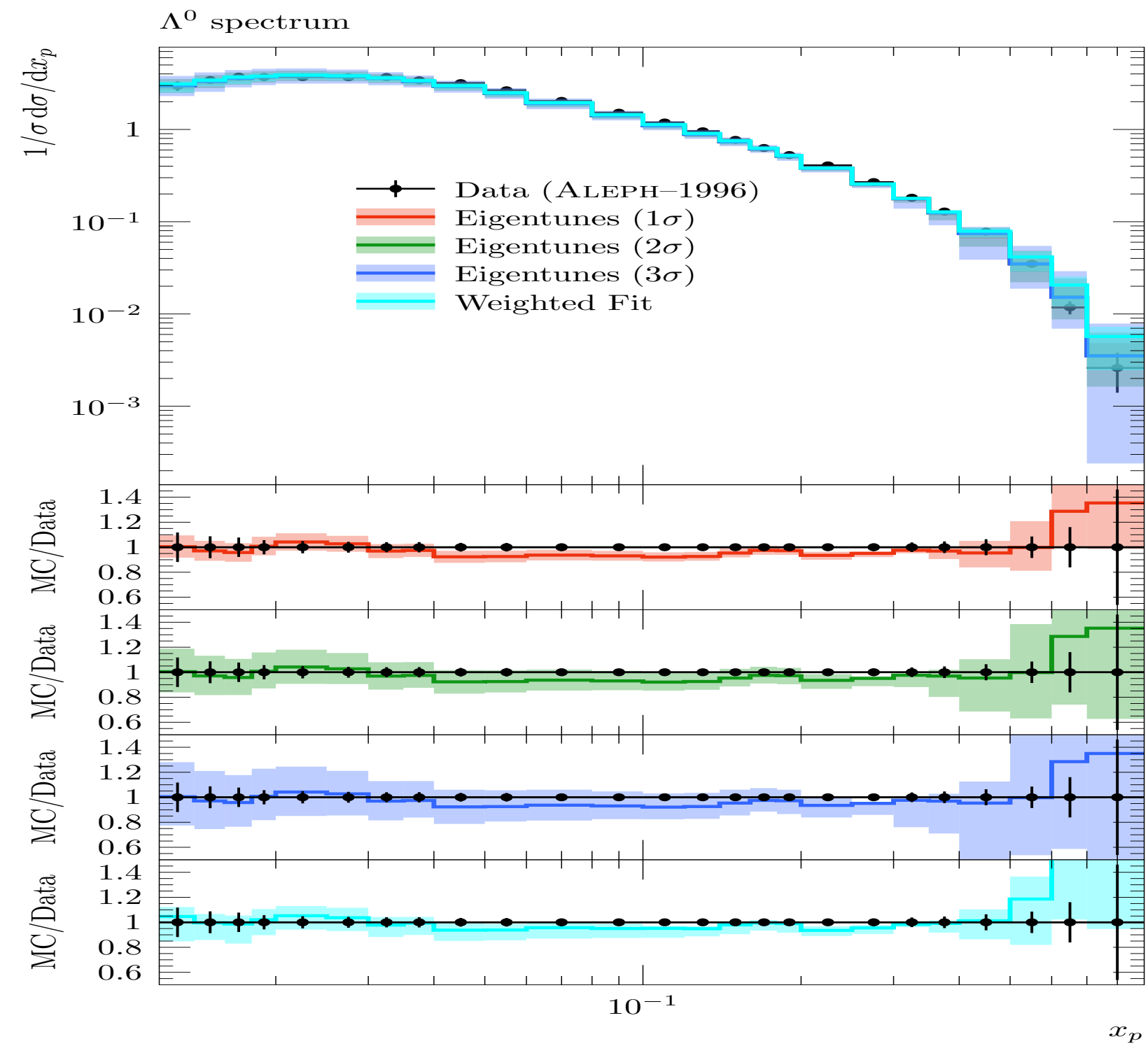
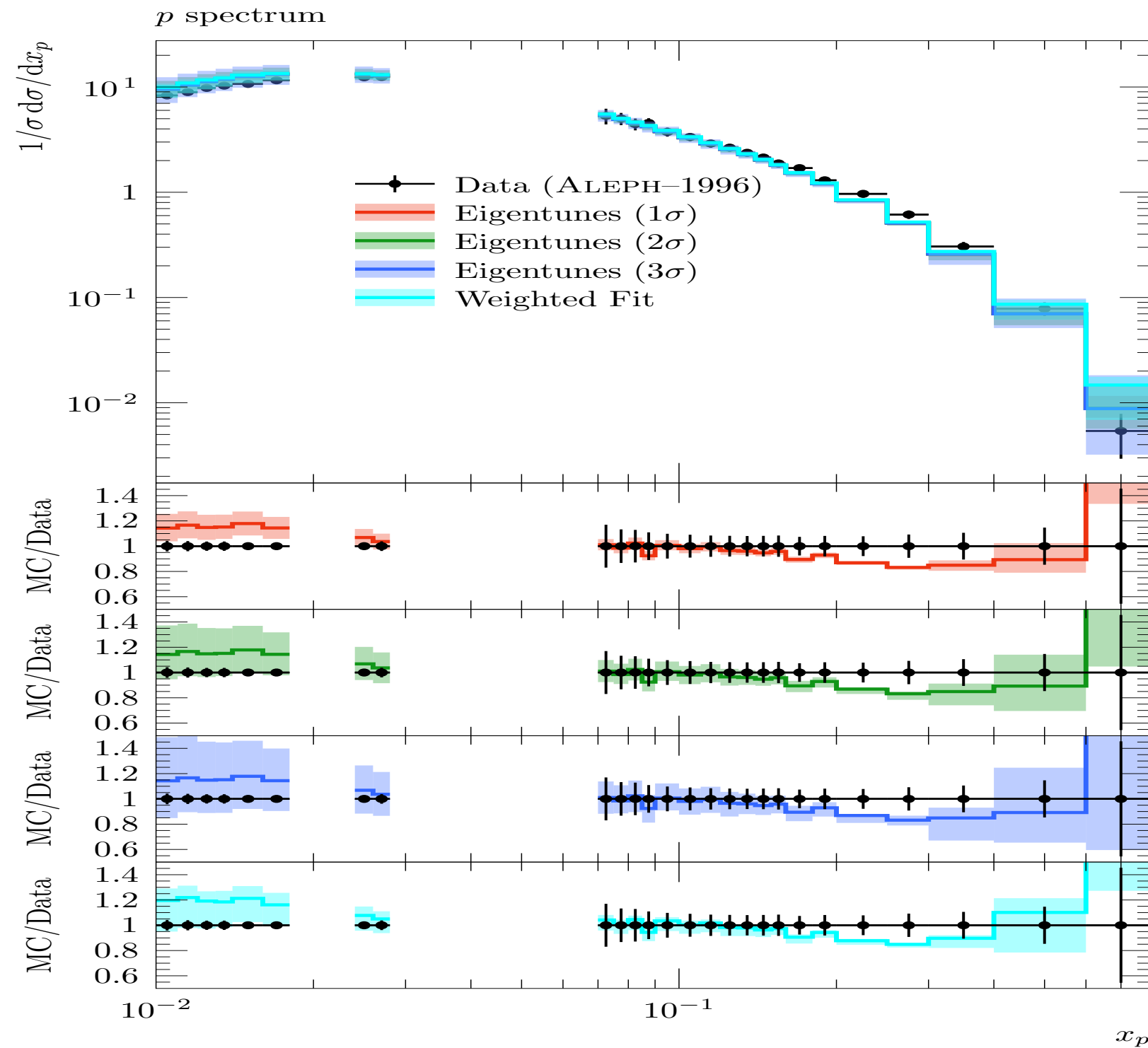
Eigentunes method:

- Diagonalization of the covariance matrix around the best fit point.
- Two set of variations are obtained; one in the positive and another one in the negative direction of the eigenvectors. For a four-dimensional tune, we get eight variations.

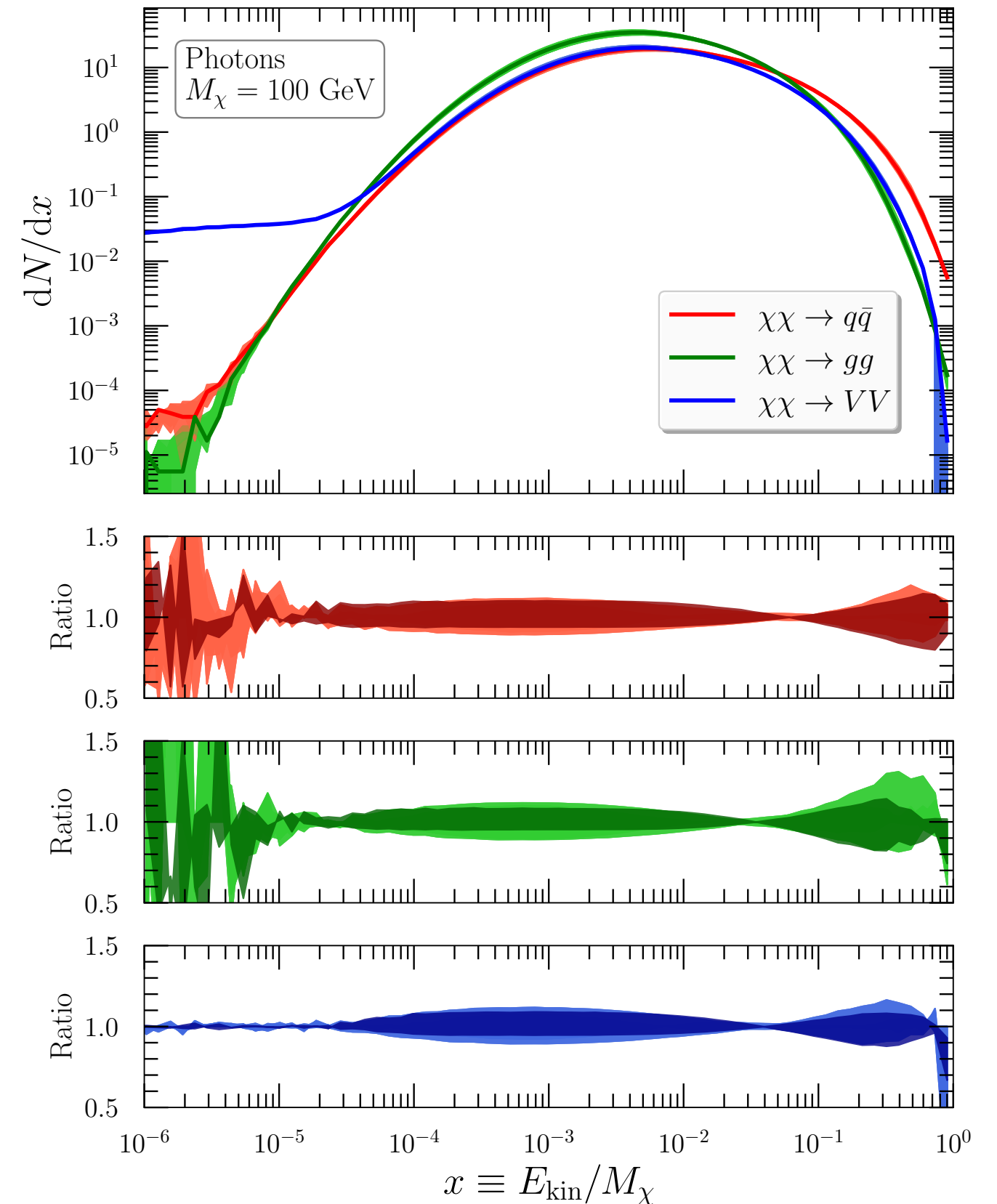
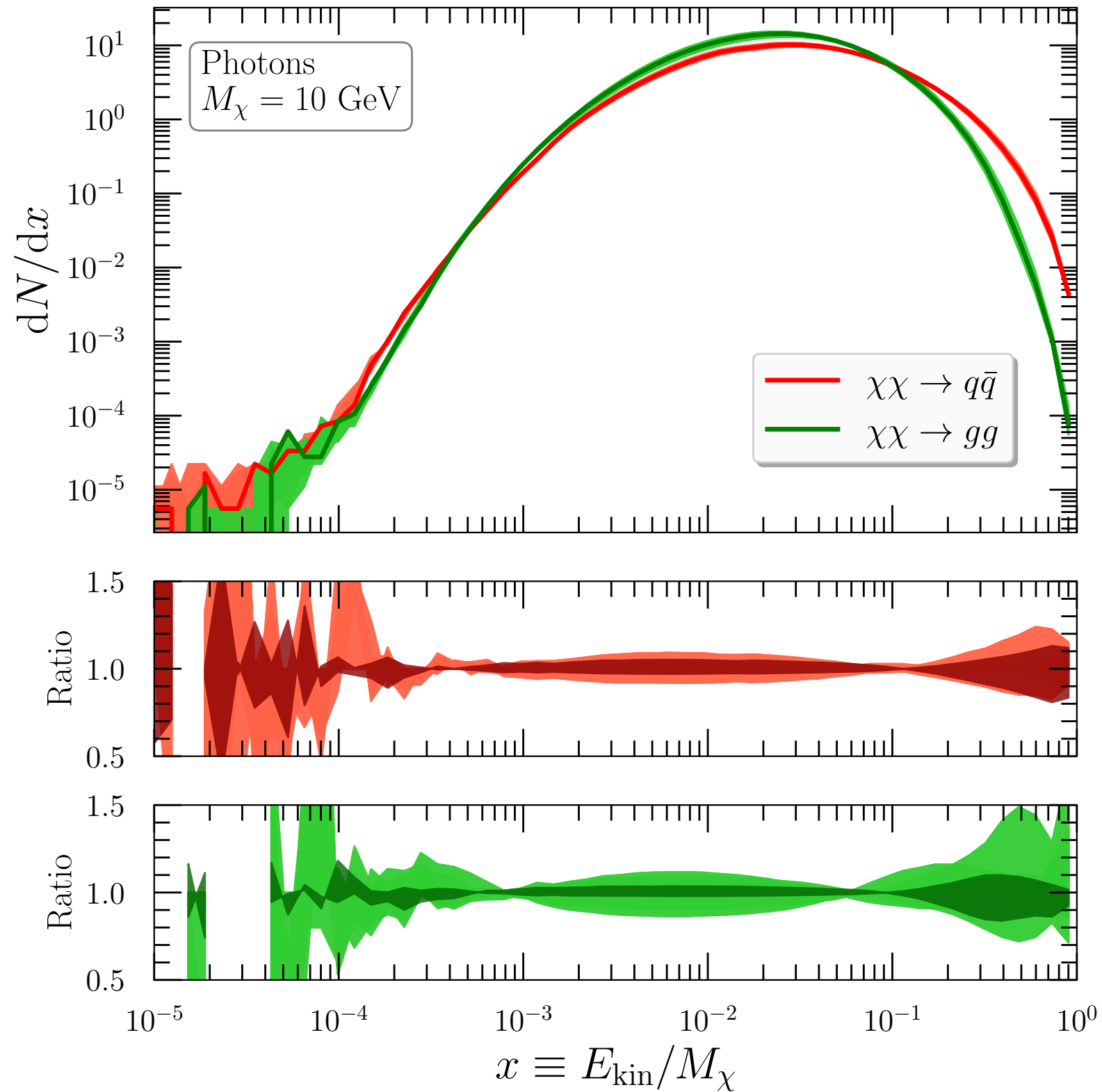
Manual method:

- Choose a set of the most sensitive observables (remove the outliers). We choose 15 observables sensitive to light quark fragmentation and 8 measurements for baryon production and perform a 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' estimate.

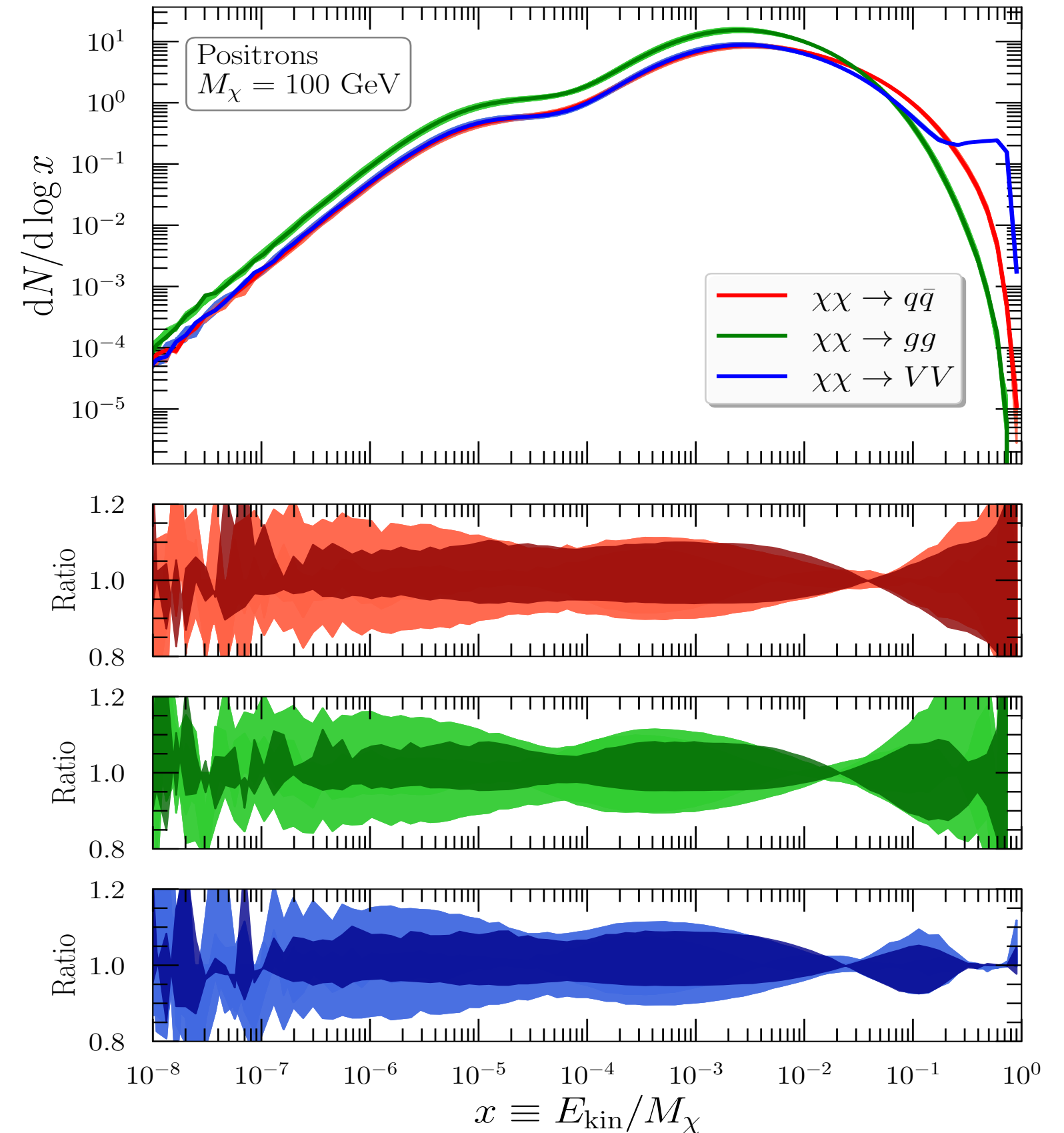
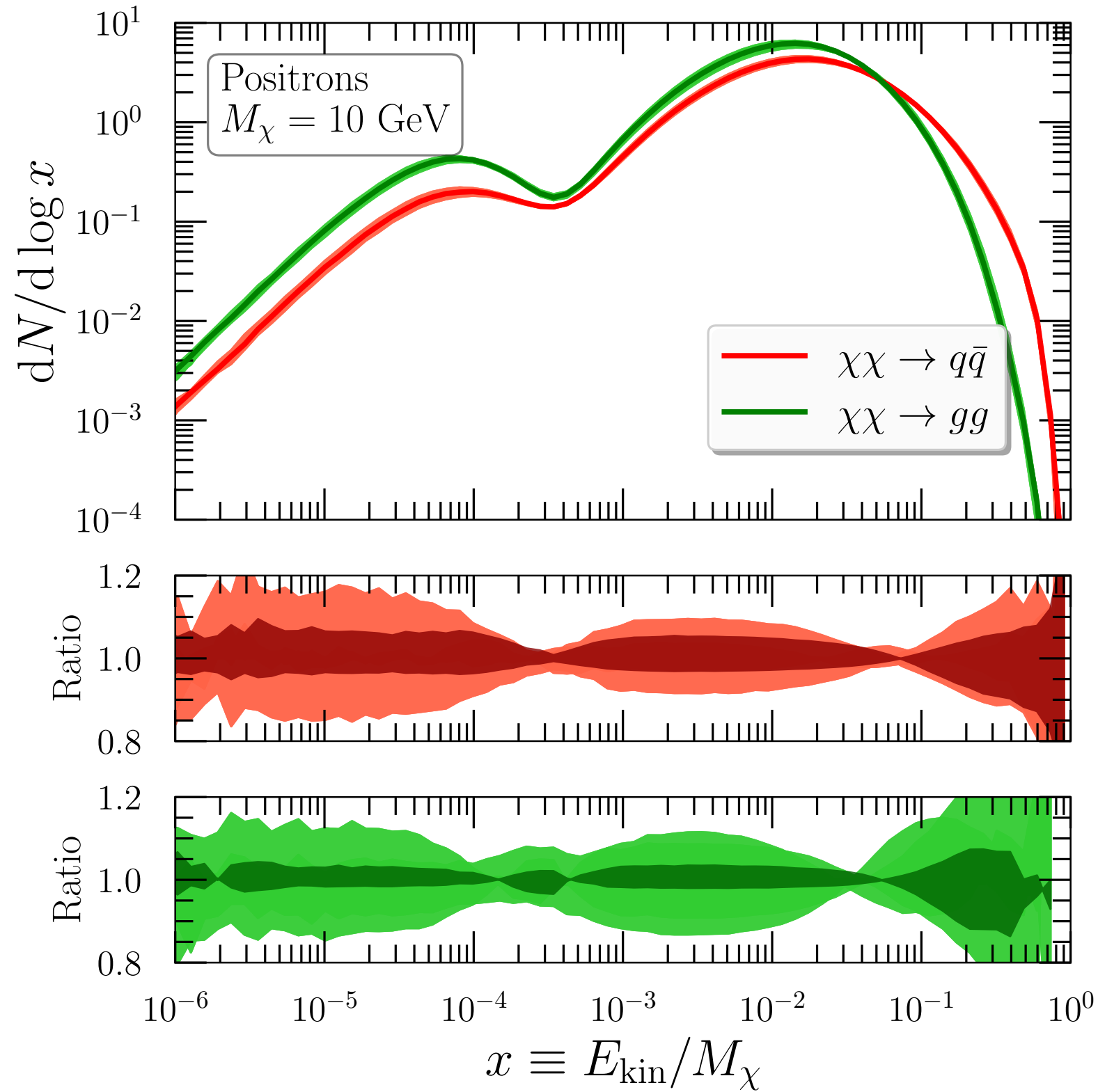
Hadronisation uncertainties: results



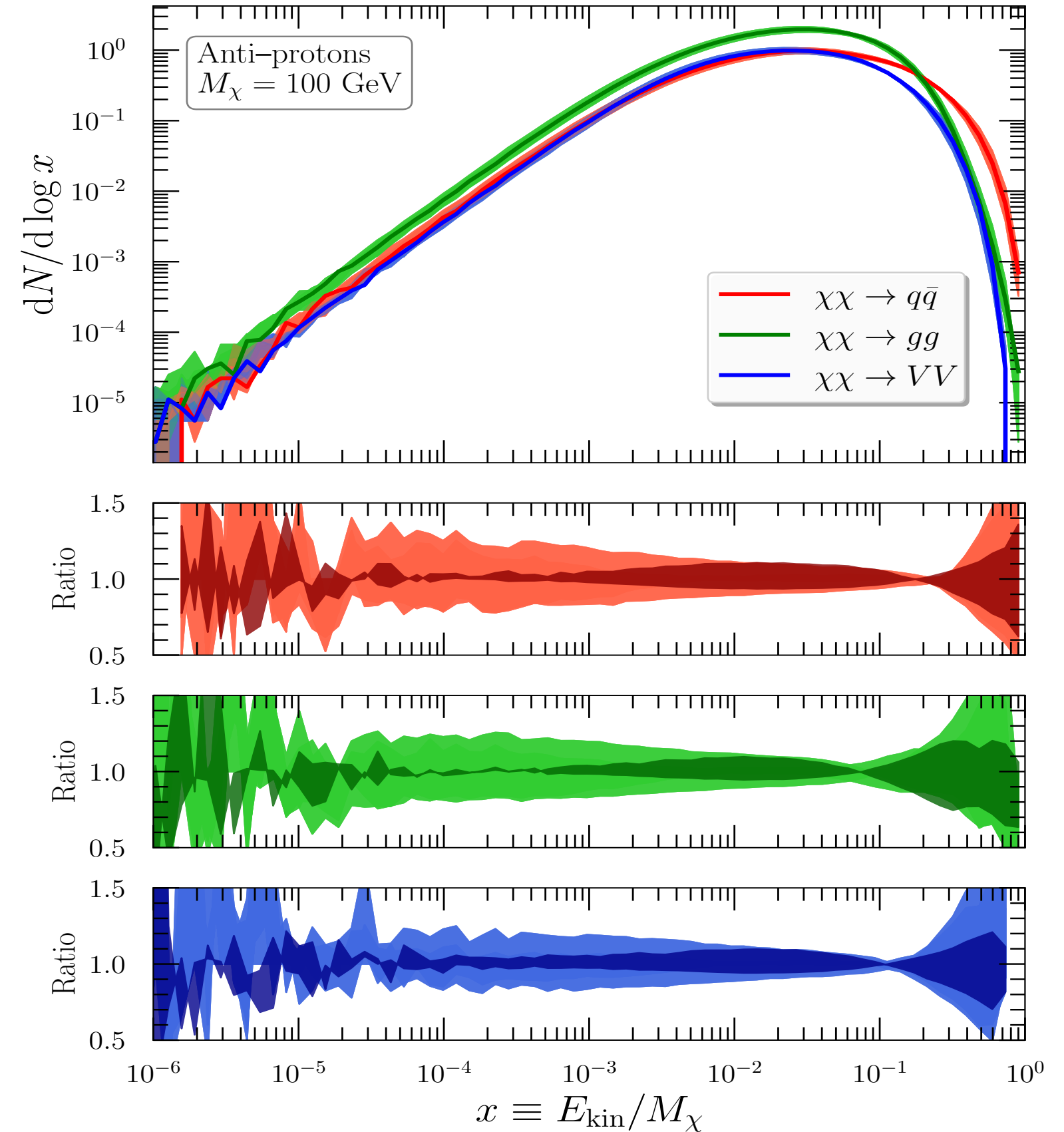
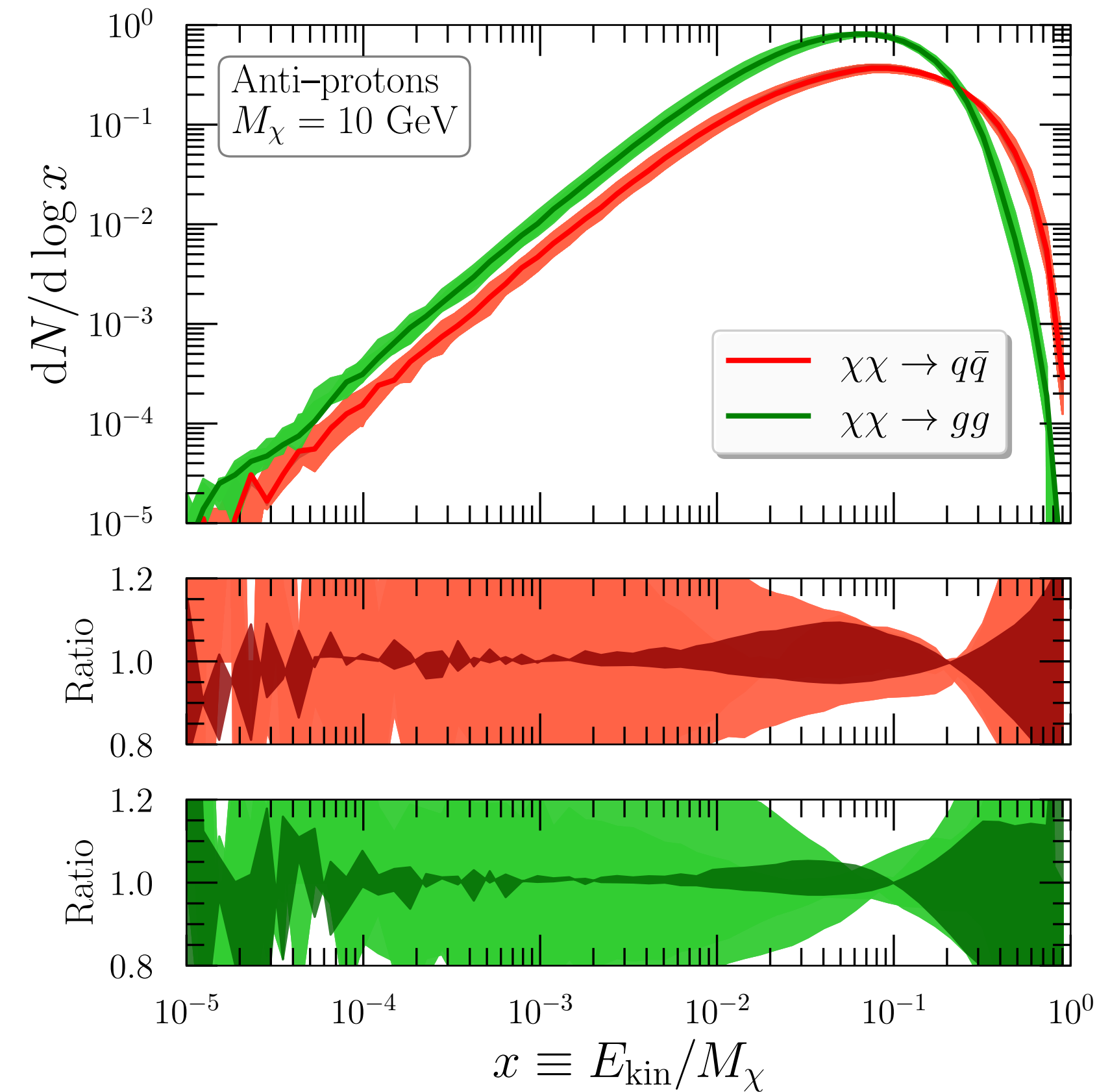
Particle spectra: Gamma rays



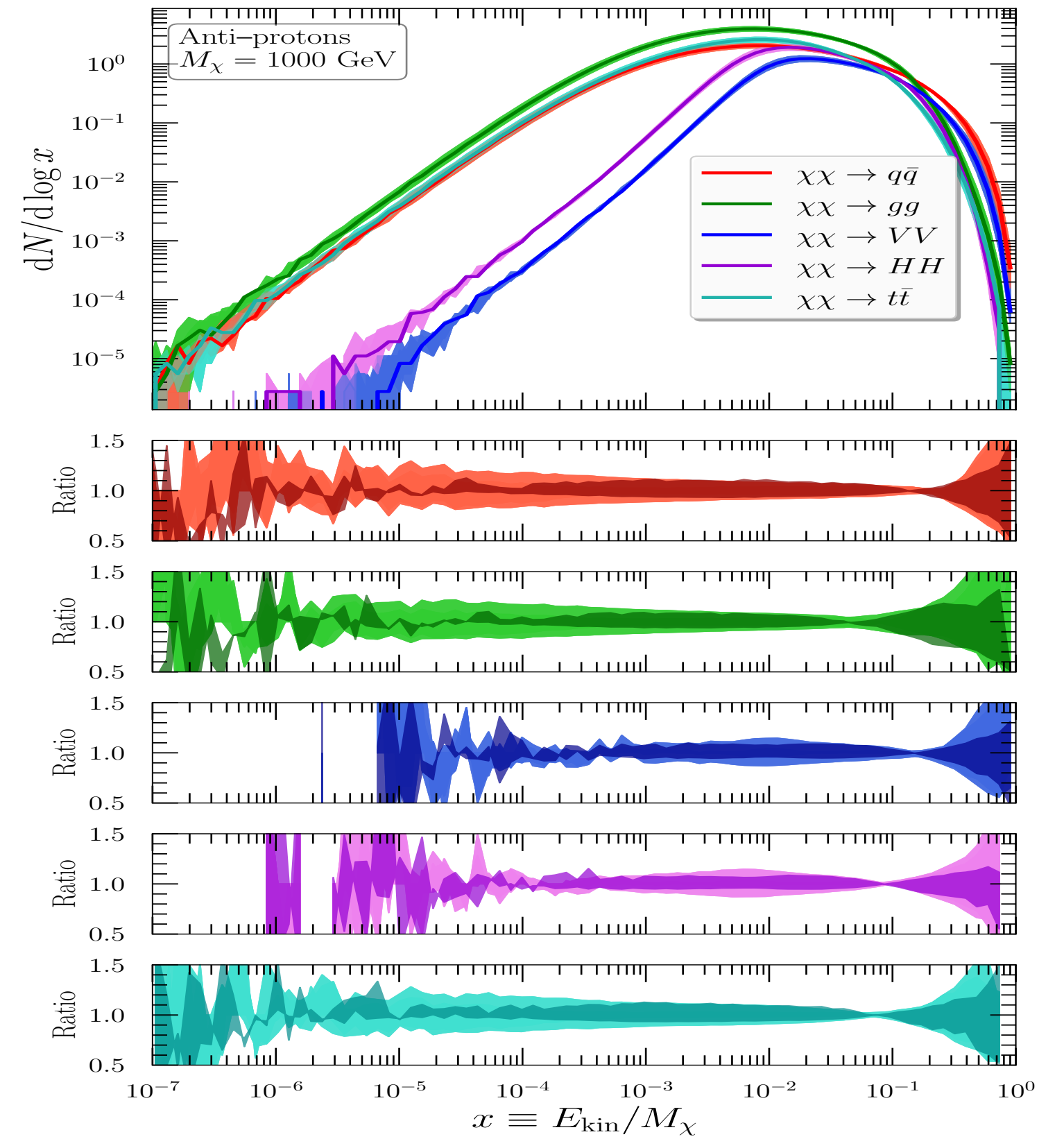
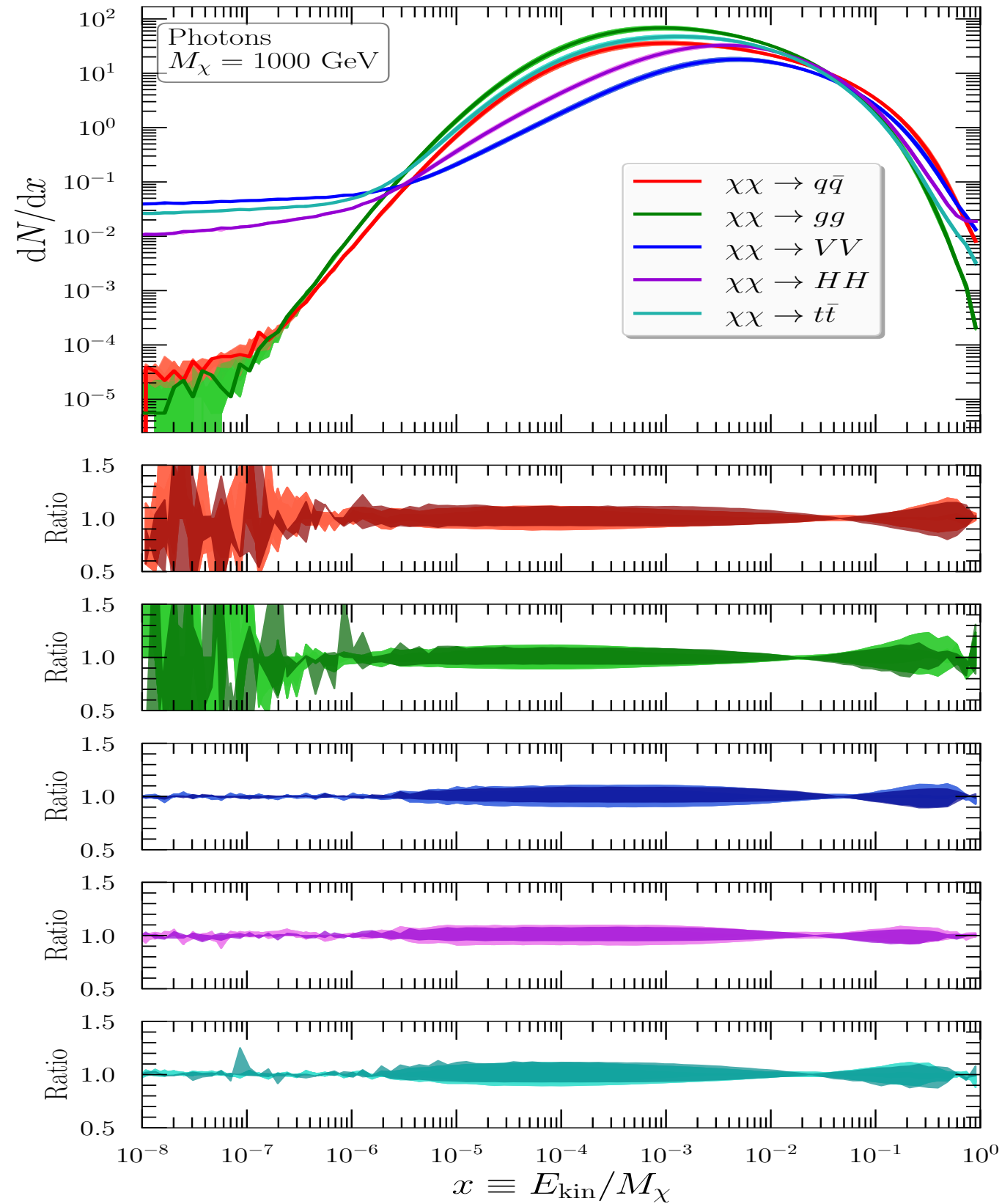
Particle spectra: Positrons



Particle spectra: Anti-protons



Particle spectra: Additional plots



The tables for the flux at production corresponding to gamma rays, positrons and anti-neutrinos (going to be updated with the new results) are now ready in Zenodo: <https://zenodo.org/record/3764809#.X59F4y8RpZ1>



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QCD Uncertainties in Particle Spectra from Dark Matter Annihilation

Amoroso, Simone;  Caron, Sascha;  Jueid, Adil; Ruiz de Austri, Roberto;  Skands, Peter

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Authors: Simone Amoroso, Sascha Caron, Adil Jueid, Roberto Ruiz de Austri, and Peter Skands

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S. Amoroso et al. arXiv: 1812.07424 [hep-ph], JCAP05(2019)007

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New tables for the flux at the production for the anti-protons will be released very soon.

Conclusions and Outlook

- As a follow up to our previous study, we have assessed for the first time the size of QCD uncertainties on the anti-matter spectra from dark matter indirect searches within PYTHIA 8.
- Surprisingly we have found that the QCD uncertainties that originate from the fragmentation function are sizable for a wide range of annihilation channels and dark matter masses (exemplified here for $M_\chi = 10, 100, 1000$ GeV)
- These results will be released in a new paper in a couple of months along with the new datasets to be used for future analyses.

Thank you for your attention

