

QCD uncertainties in dark-matter indirect searches: How large are they?

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Talk based on the following research:

- S. Amoroso, S. Caron, AJ, R. Ruiz de Austri, P. Skands, JCAP 05 (2019) 007
- AJ, J. Kip, R. Ruiz de Austri, P. Skands, 2202.11546
- AJ, J. Kip, R. Ruiz de Austri, P. Skands, in preparation

My research activities

I work on several research topics in particle physics phenomenology:

- Collider Physics: Electron-positron colliders (1507.03630, 2006.01348)
Electron-proton colliders (2102.12507 and in progress)
Heavy-Ion Collisions (1804.06858 and in progress)
Muon colliders (in progress on DM pheno and Pati-Salam models).
Proton-proton colliders (most of my papers).
- Top quark Physics: SMEFT and anomalous couplings (1606.05270 and 1805.07763) and charged Higgs bosons (1807.11306).
- Flavour physics (or the anomalies): Muon $g-2$ (2104.10175) and Leptoquarks (2111.08027, 2207.02879).
- QCD and event generators: QCD for dark-matter searches (1812.07424, 2202.11546) and global analysis of QCD in PYTHIA8 (in preparation).
- Machine Learning: Dark Machines Anomaly Score Challenges (2105.14027) and Simulation-based Inference (in preparation).
- Dark Matter and Neutrino Mass models: Scotogenic (1710.03842, 1811.00490, 2007.05845) and gravity portal (2007.09681).
- Models with extended Higgs and fermion sectors.

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...)

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 a sequence of complex phenomena: QED/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 hadronization 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).

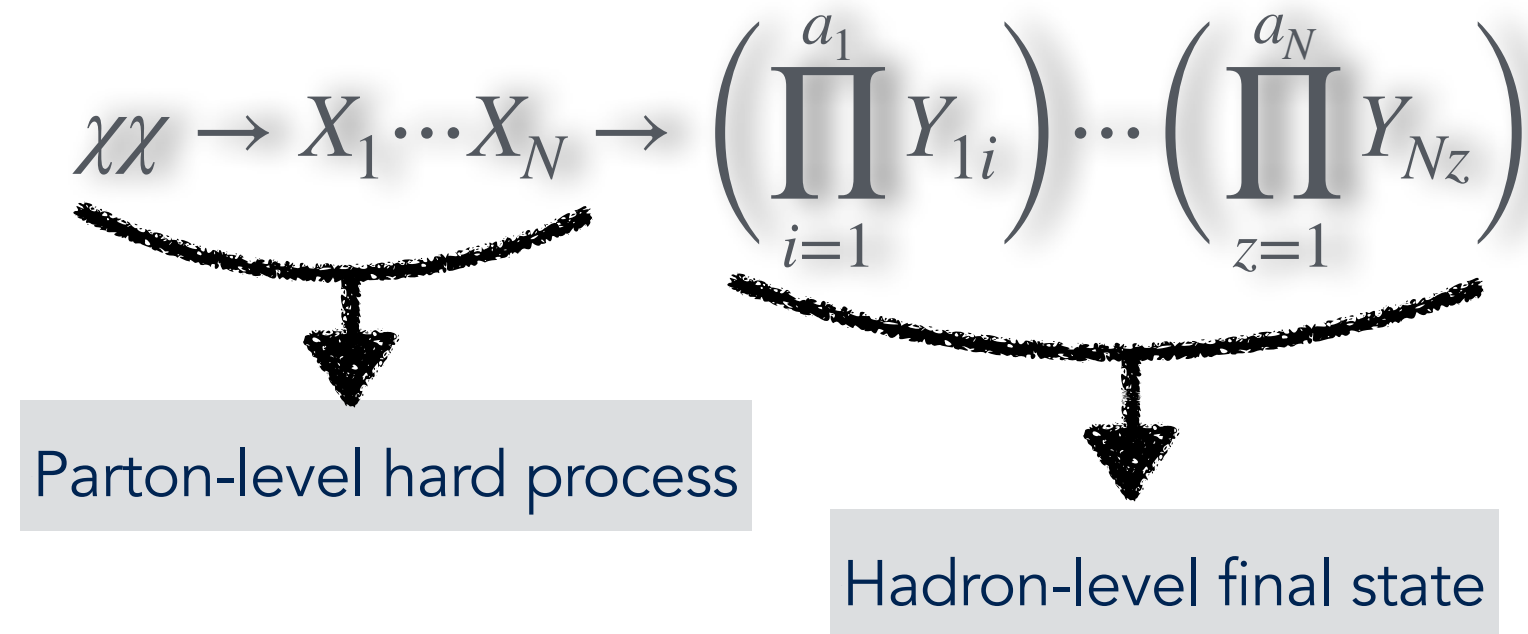
The role of precision

- 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

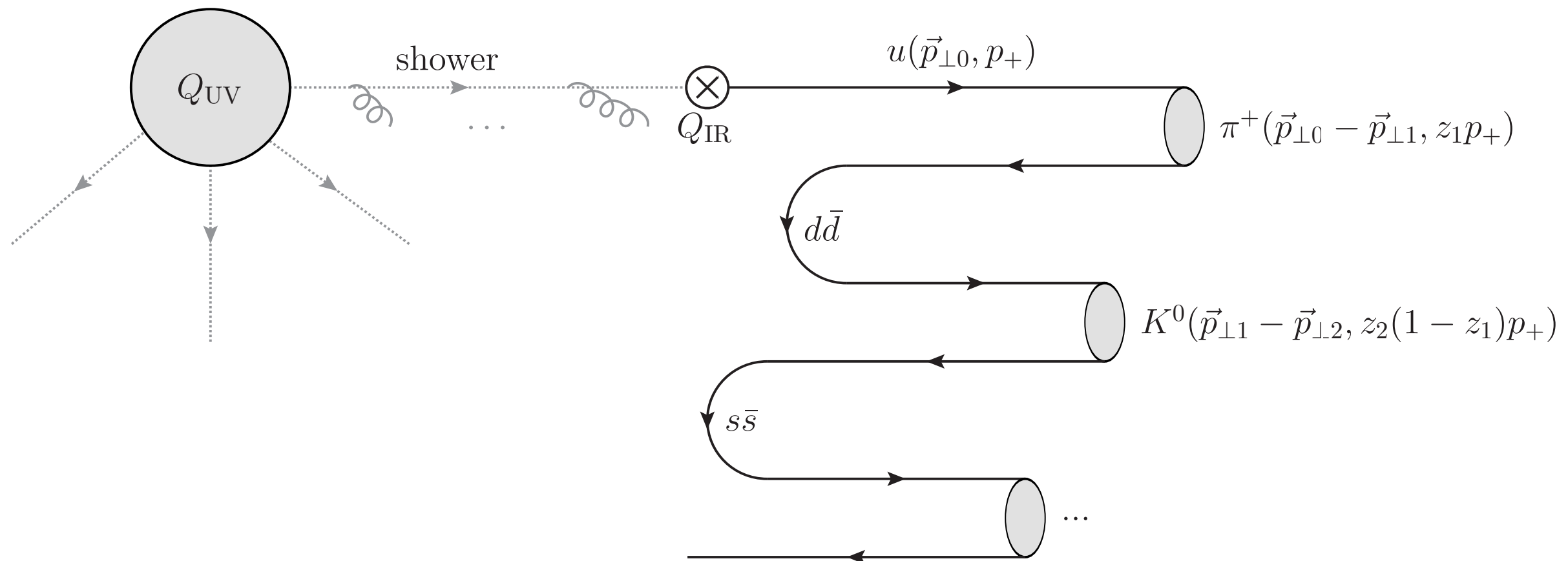


- X_i is electrically-charged or contain photons $\implies$ further QED emissions producing additional photons and charged fermions.
- X_i is colored particle $\implies$ cascade of QCD shower emissions will occur and treated in the same way as in QED emissions.
(the number and hardness of the emissions 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

- 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.

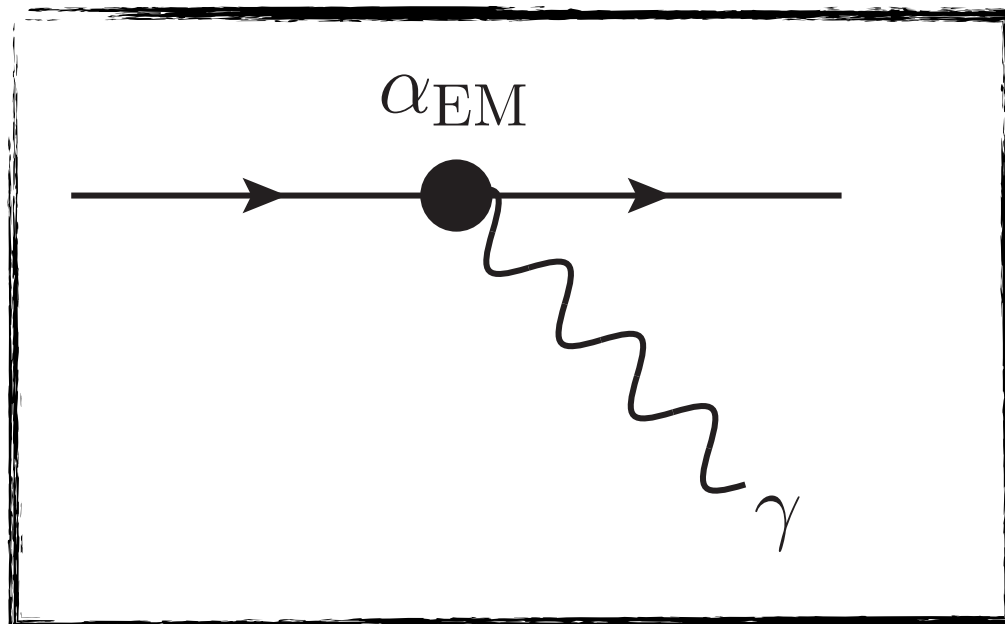


The Lund string model is based on the following symmetric function

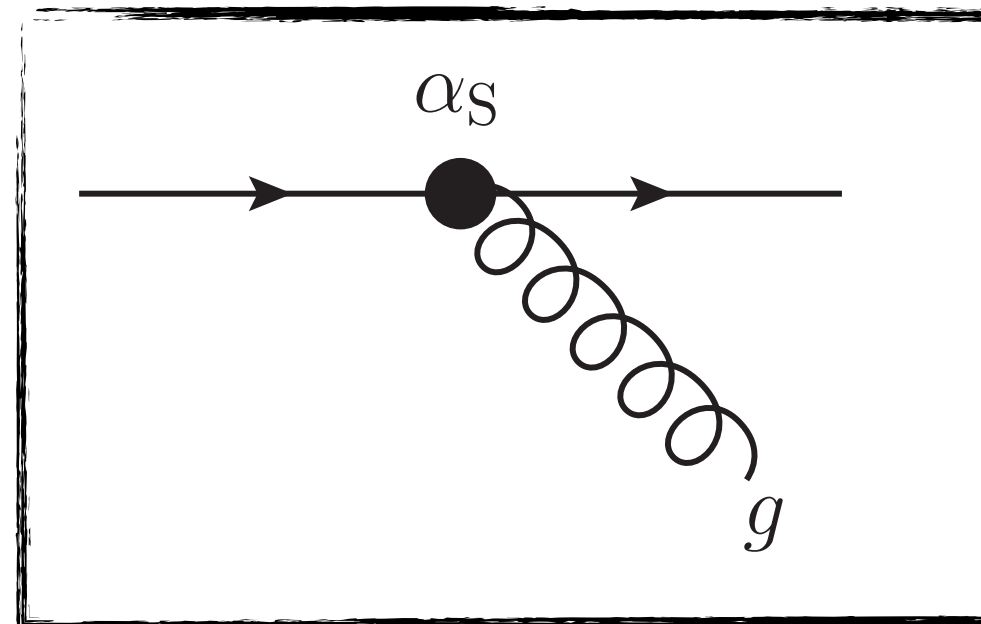
$$f(z, m_{\perp}) \propto N \frac{(1-z)^a}{z} \exp\left(\frac{-bm_{\perp}^2}{z}\right)$$

- 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 $\implies$ 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.

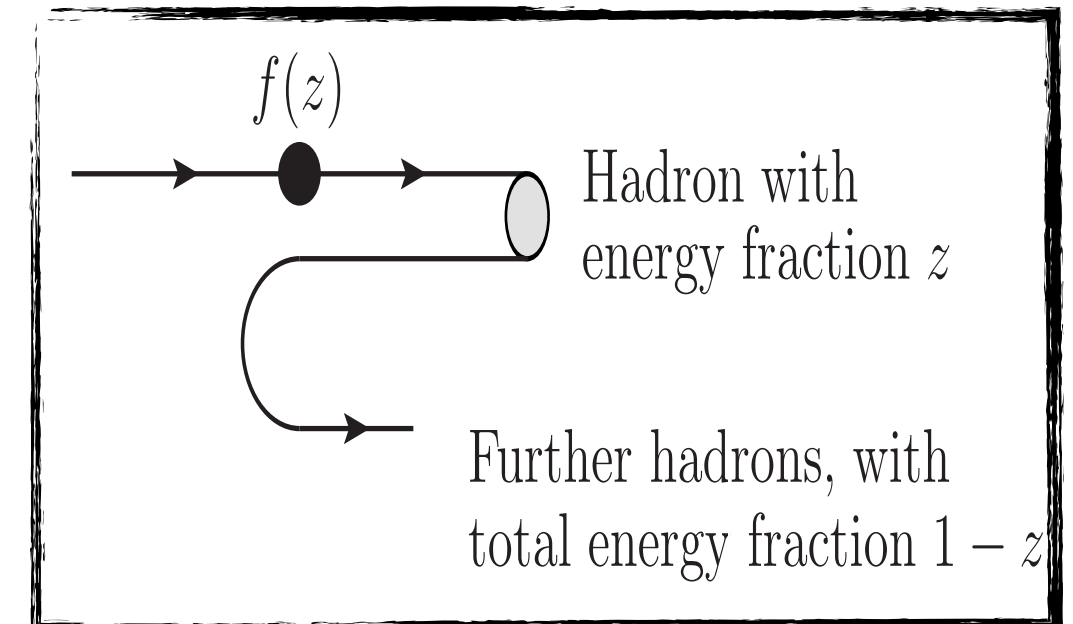
Modeling of the Particle Spectra: Recap



- 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 for mesons need 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 of angular correlations performed by OPAL collaboration.
- To address this, the popcorn mechanism is introduced in which a set of diquark pairs are produced between $q\bar{q}$ 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 parameter 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

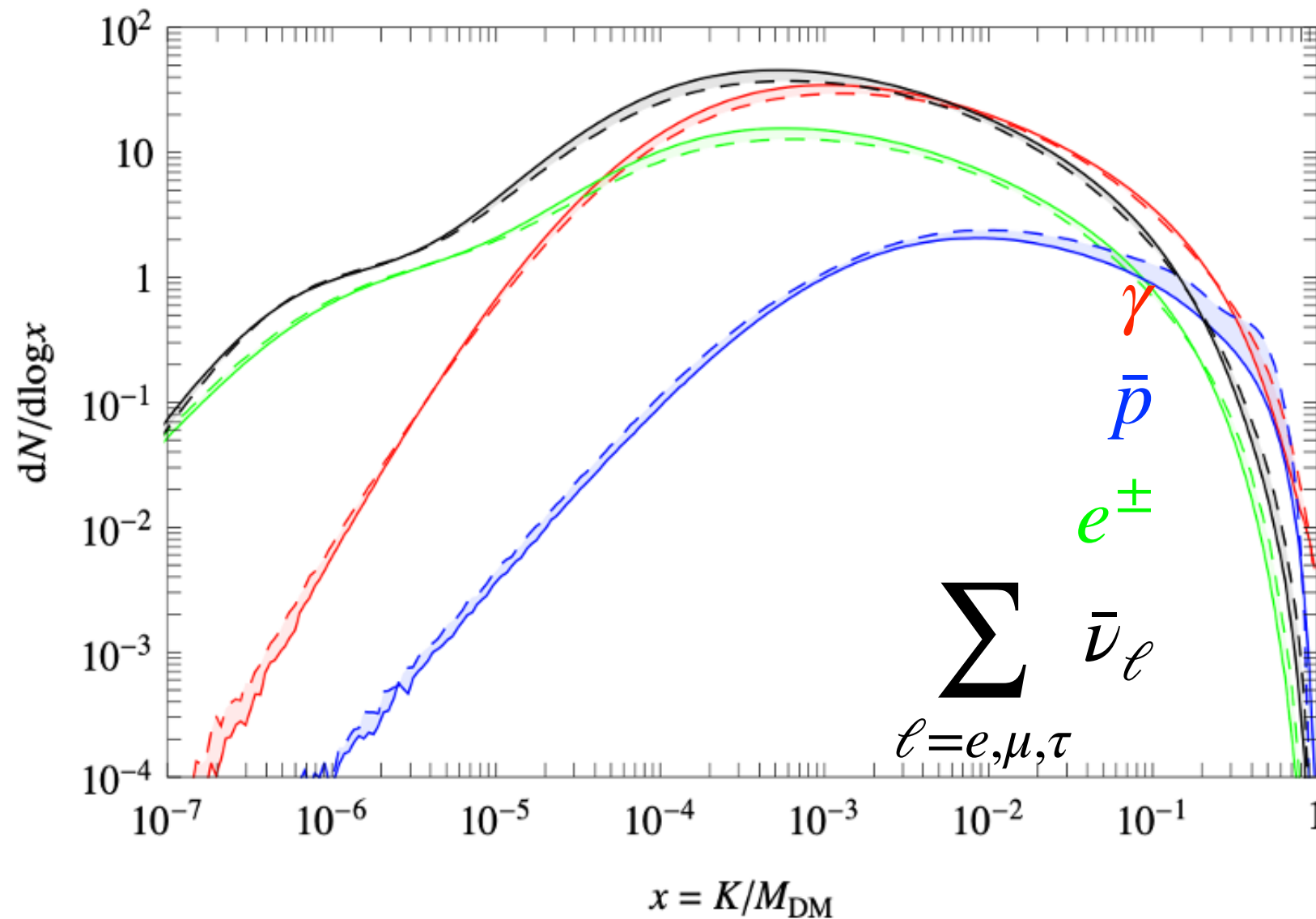
- Most of the positrons are produced from the decay of charged pions: – $\text{BR}(\pi^+ \rightarrow \mu^+ \nu_\mu) \approx 99.88\%$
- Some positrons are coming from photon splittings or from the decay of W or Z bosons.

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

DM DM $\rightarrow q\bar{q}$ at $M_{\text{DM}} = 1 \text{ TeV}$



Gamma-rays are in red.
Solid line (PYTHIA8),
dashed (HERWIG-6.5.10)

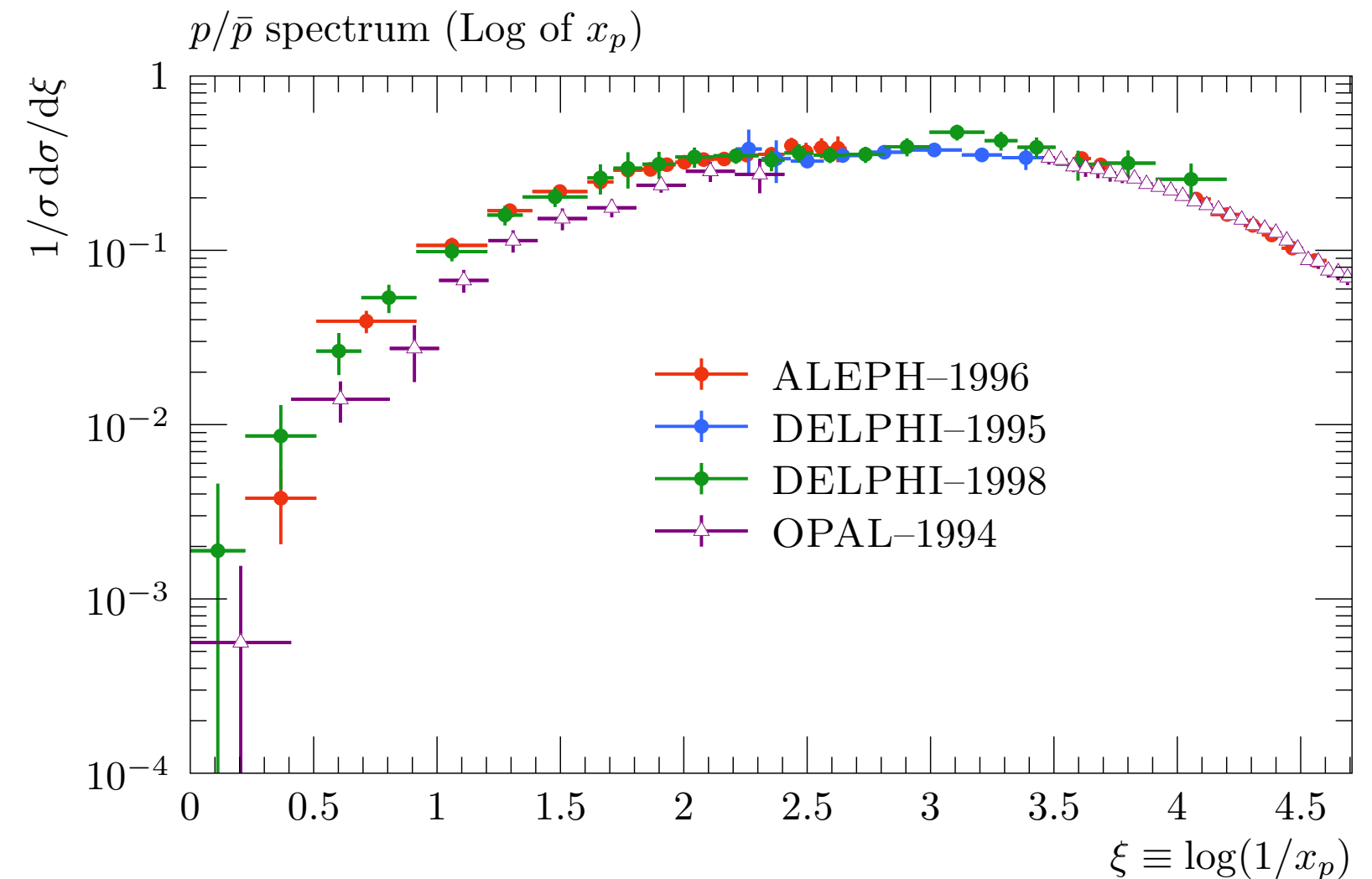
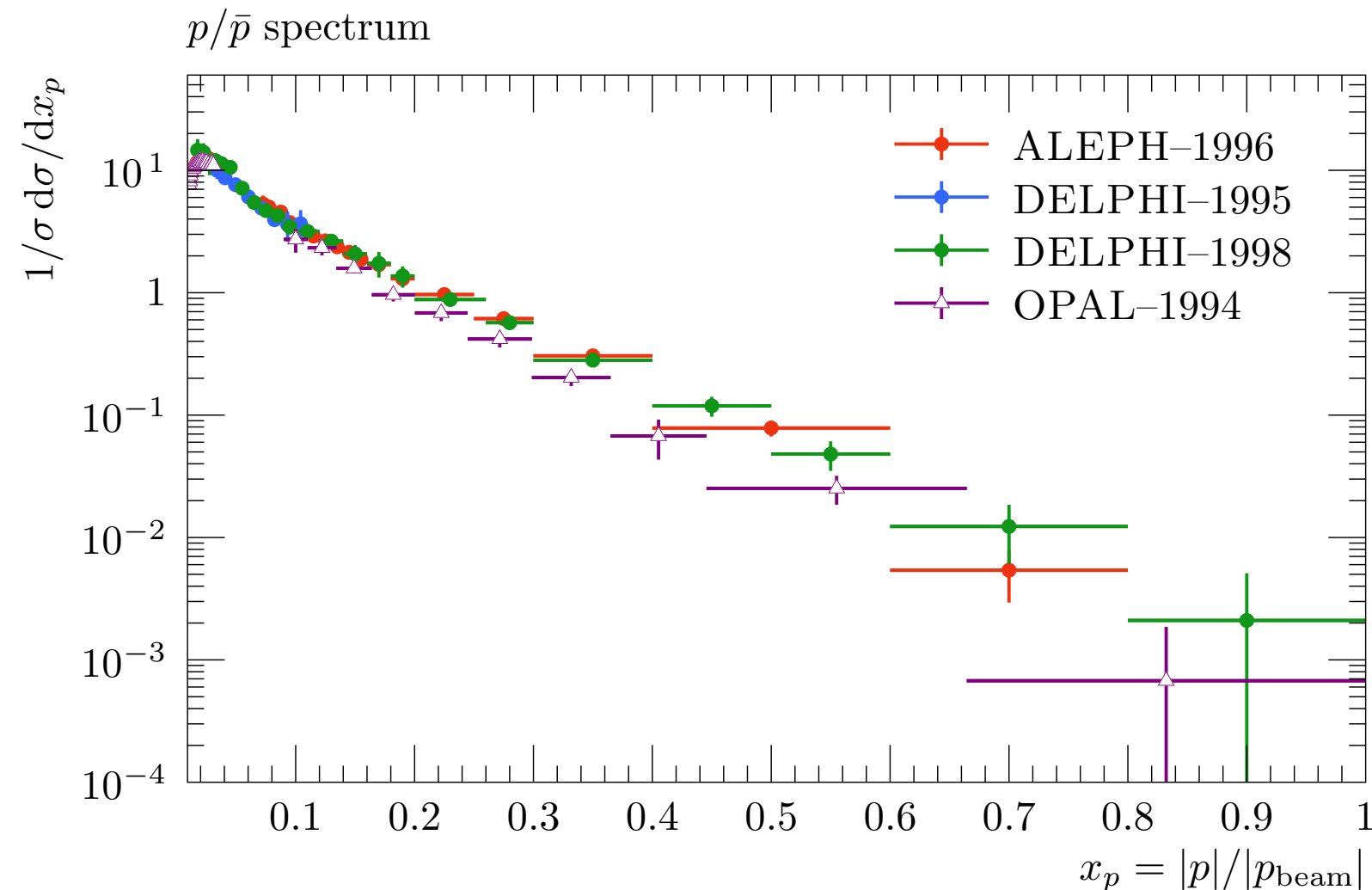
- o M. Cirelli et al. produced a complete recipe for the flux at production from dark matter annihilation in a wide range of masses (arXiv:1012.4515) – called Poor Particle Physics Cookbook for Dark Matter Indirection Detection (PPPC 4 DM ID) –.
- o The study used Pythia8-135 based on an old tune that is replaced by the most recent Monash tune.
- o 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

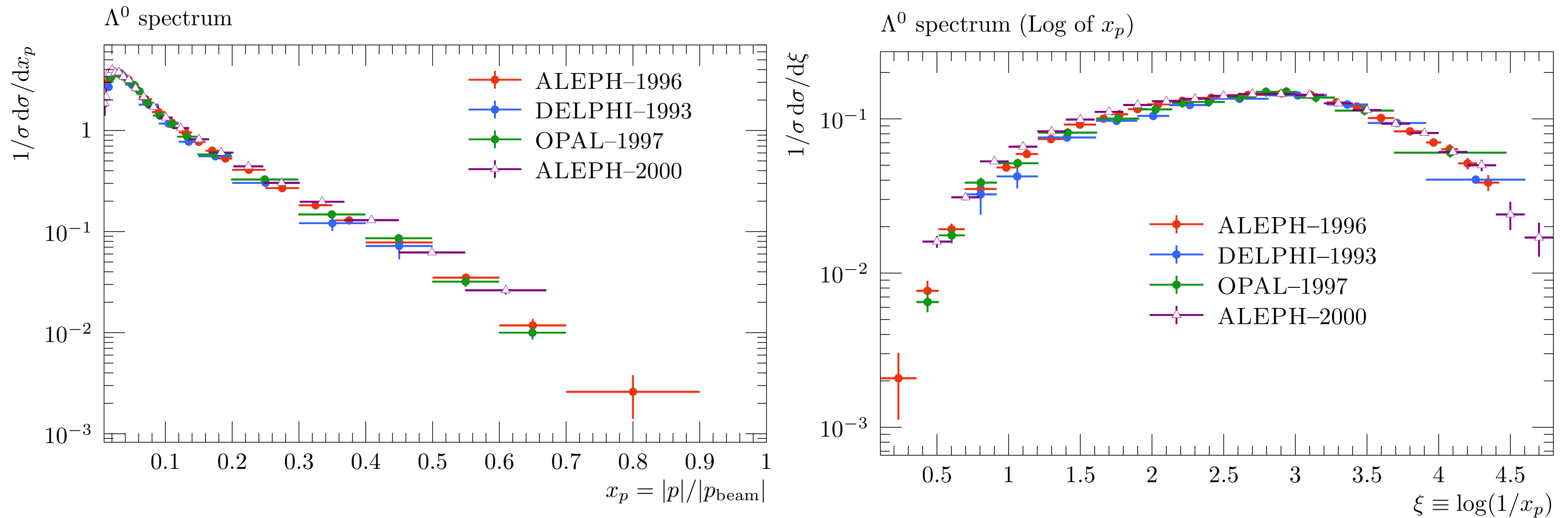
- Different tunings of the parameters a , $\langle z_\rho \rangle$, $\sigma(= \sqrt{2\langle m_\perp^2 \rangle})$, and a_{Diquark} of the Lund fragmentation function are performed using a set of measurements at LEP-I at the Z-pole — ALEPH, DELPHI, L3, OPAL.
- Include the most sensitive measurements; 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.
- We modify slightly the definition of the Goodness-of-Fit in Professor to account for a flat 5% uncertainty in the MC predictions

Issues in measurements of baryon spectra at LEP



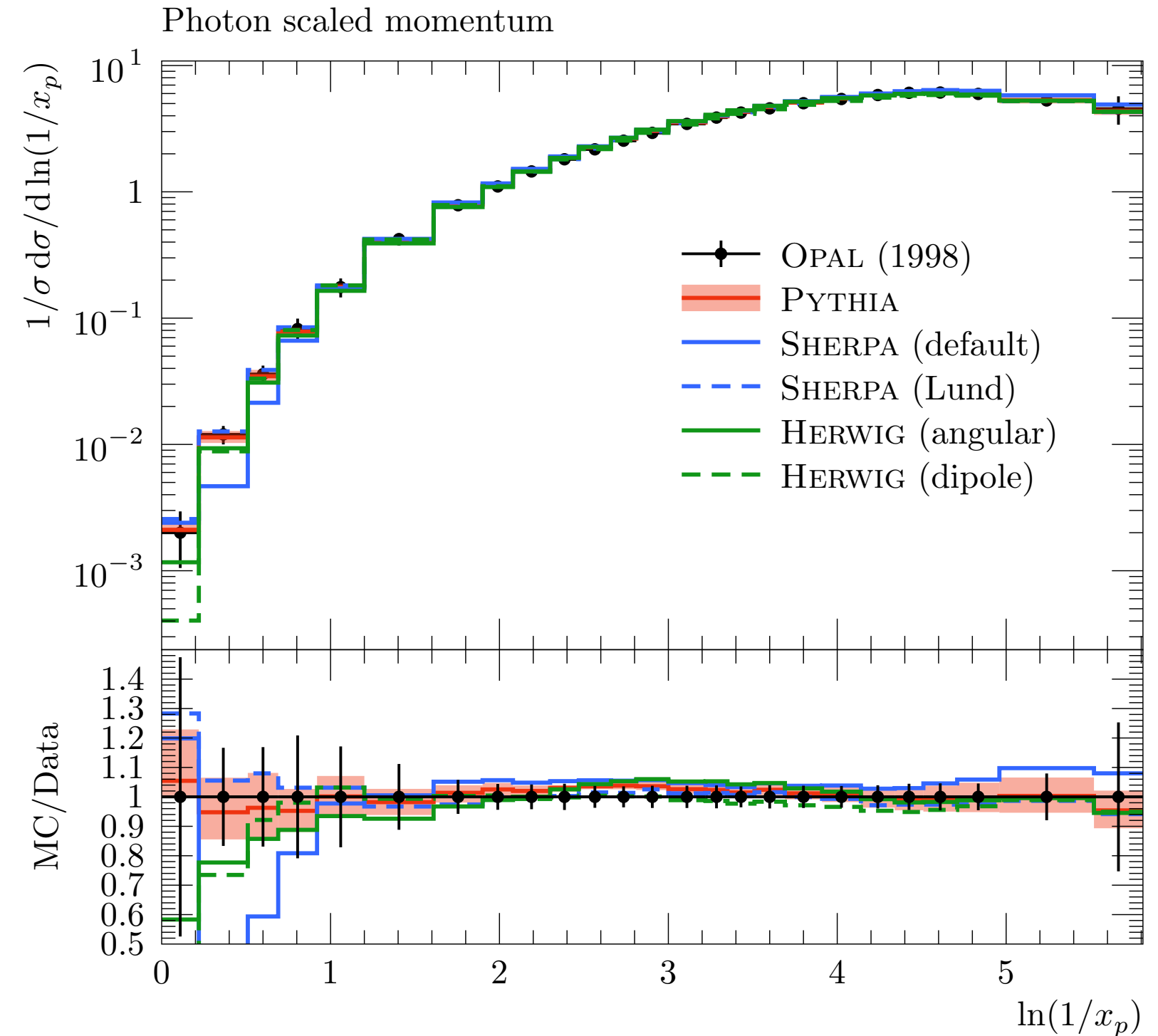
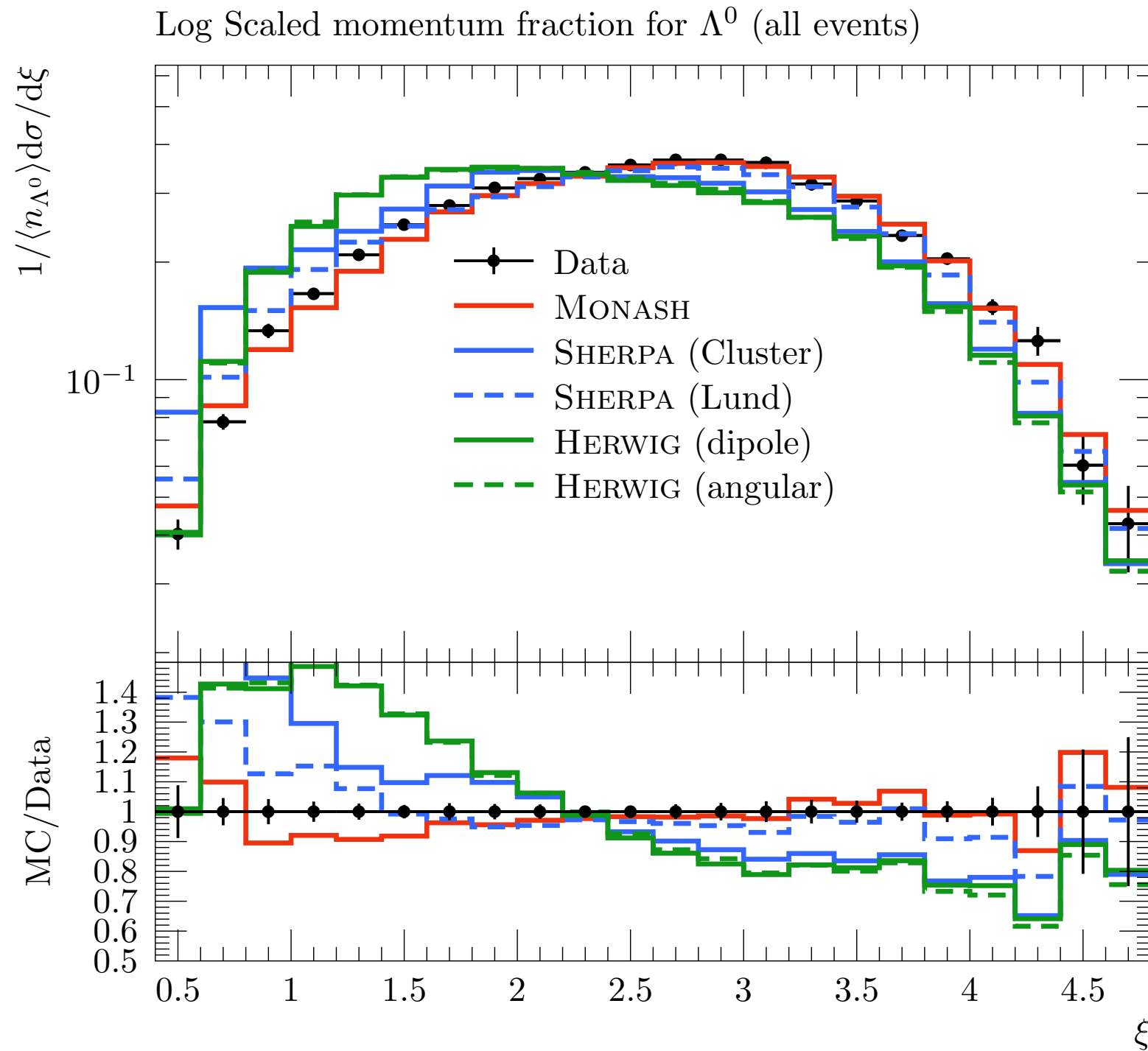
OPAL-1994 is not consistent with the other measurements for $x_p \geq 0.1$

Issues in measurements of baryon spectra at LEP



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

How good are the current theory predictions?



$$\xi = \log(1/x_p); x_p = |p|/|p_{\text{beam}}|$$

Tunes: Results

$$\chi^2/N_{\text{df}} = \sum_{\mathcal{O}} \omega_{\mathcal{O}} \sum_{b \in \mathcal{O}} \left(\frac{f_{(b)}(\{p_i\}) - \mathcal{R}_b}{\Delta_b} \right)^2$$

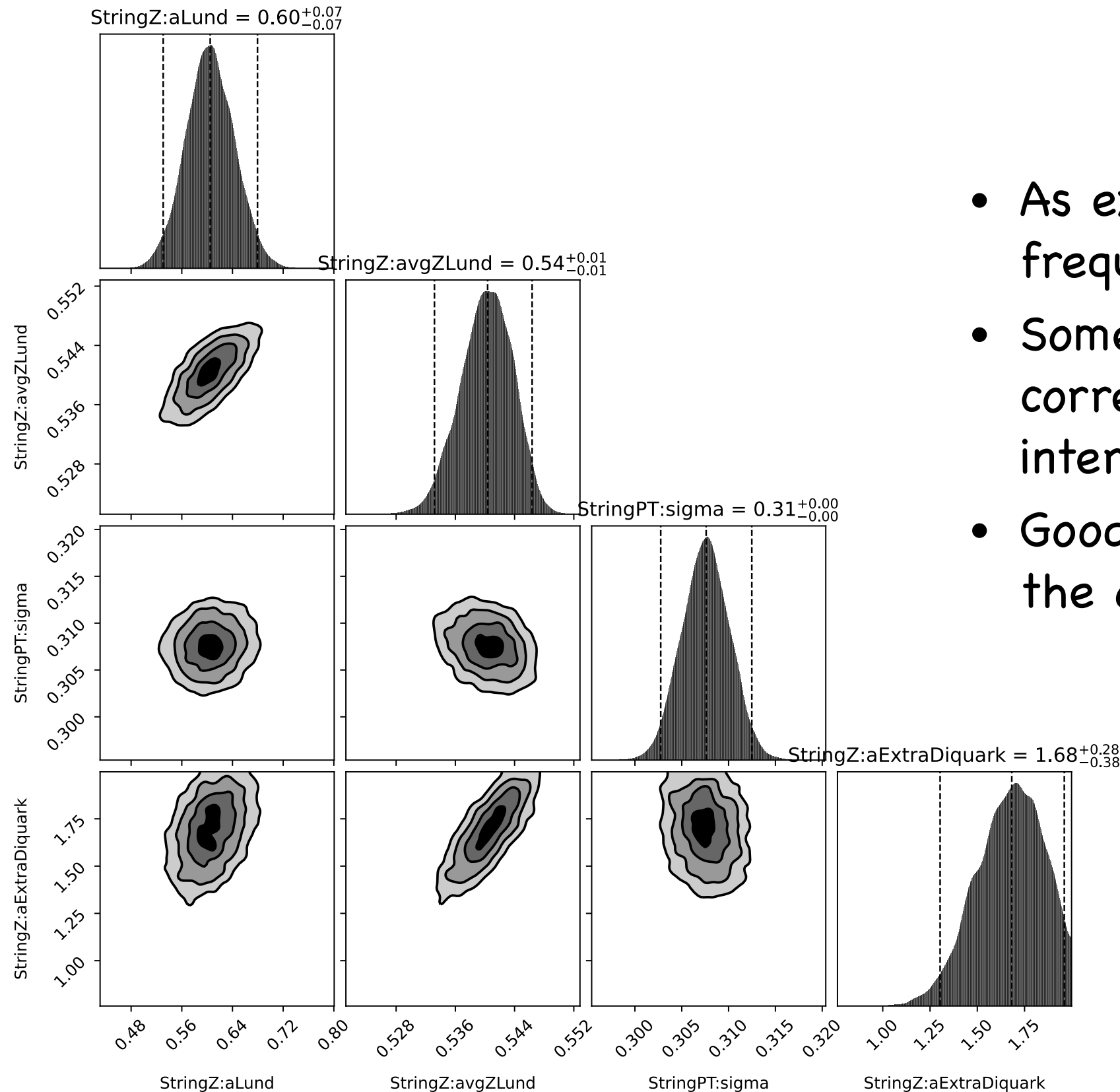
$\omega_{\mathcal{O}}$ → weight factor
 $f_{(b)}(\{p_i\})$ → MC prediction
 Δ_b → Total error:
 $\sqrt{\sigma_{b,\text{exp}}^2 + \sigma_{b,\text{MC}}^2 + \sigma_{b,\text{th}}^2}$

Experimental measurement

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.

Results: Bayesian analysis



- As expected, good agreement with the frequentist fit (Gaussian unimodal PDF)
- Some parameters are extremely highly correlated $\rightarrow$ We need to be careful in the interpretation of the uncertainties.
- Good coverage: 95% has covers most of the area under the histogram.

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.

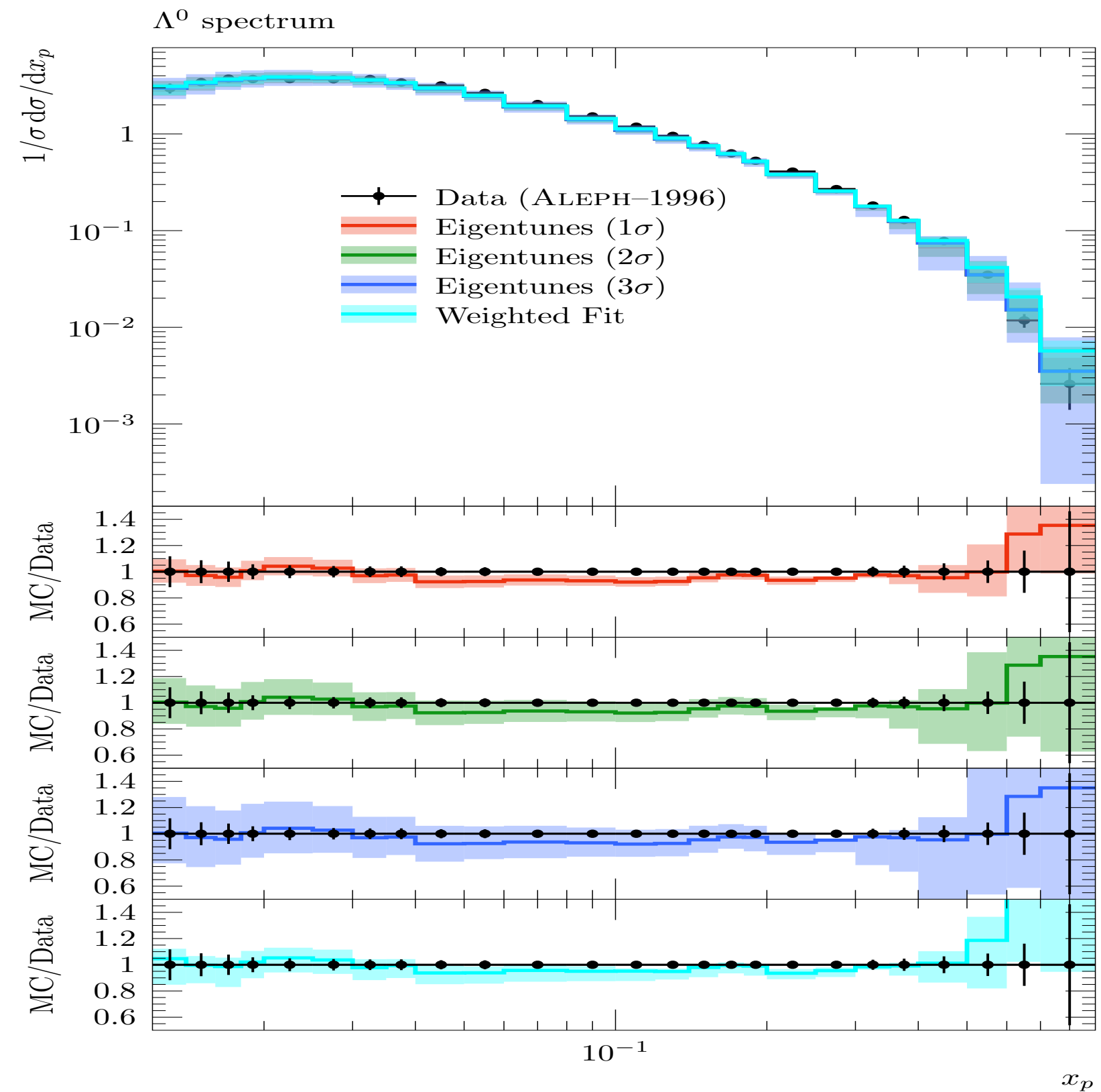
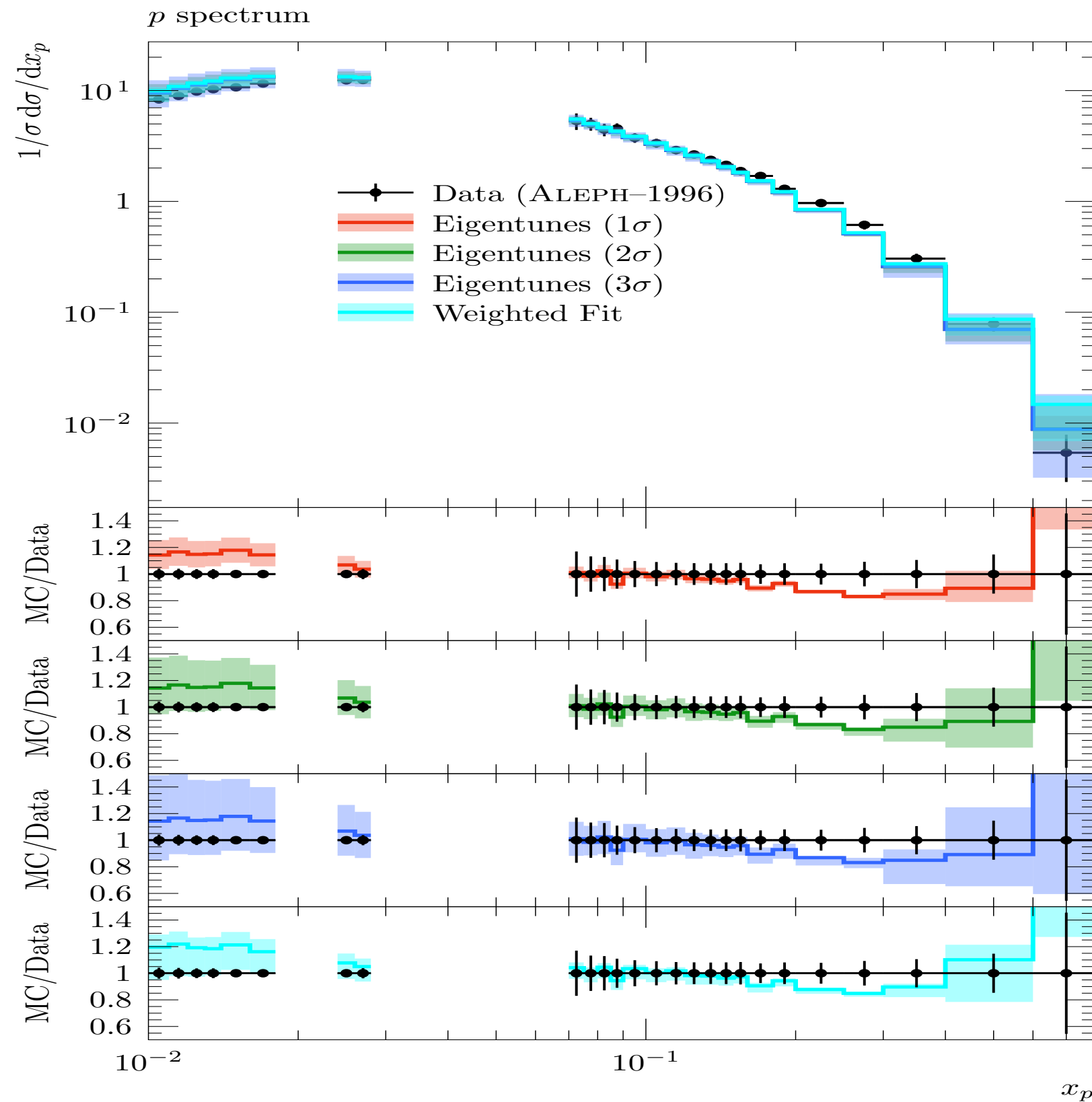
Eigentunes method:

- 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.

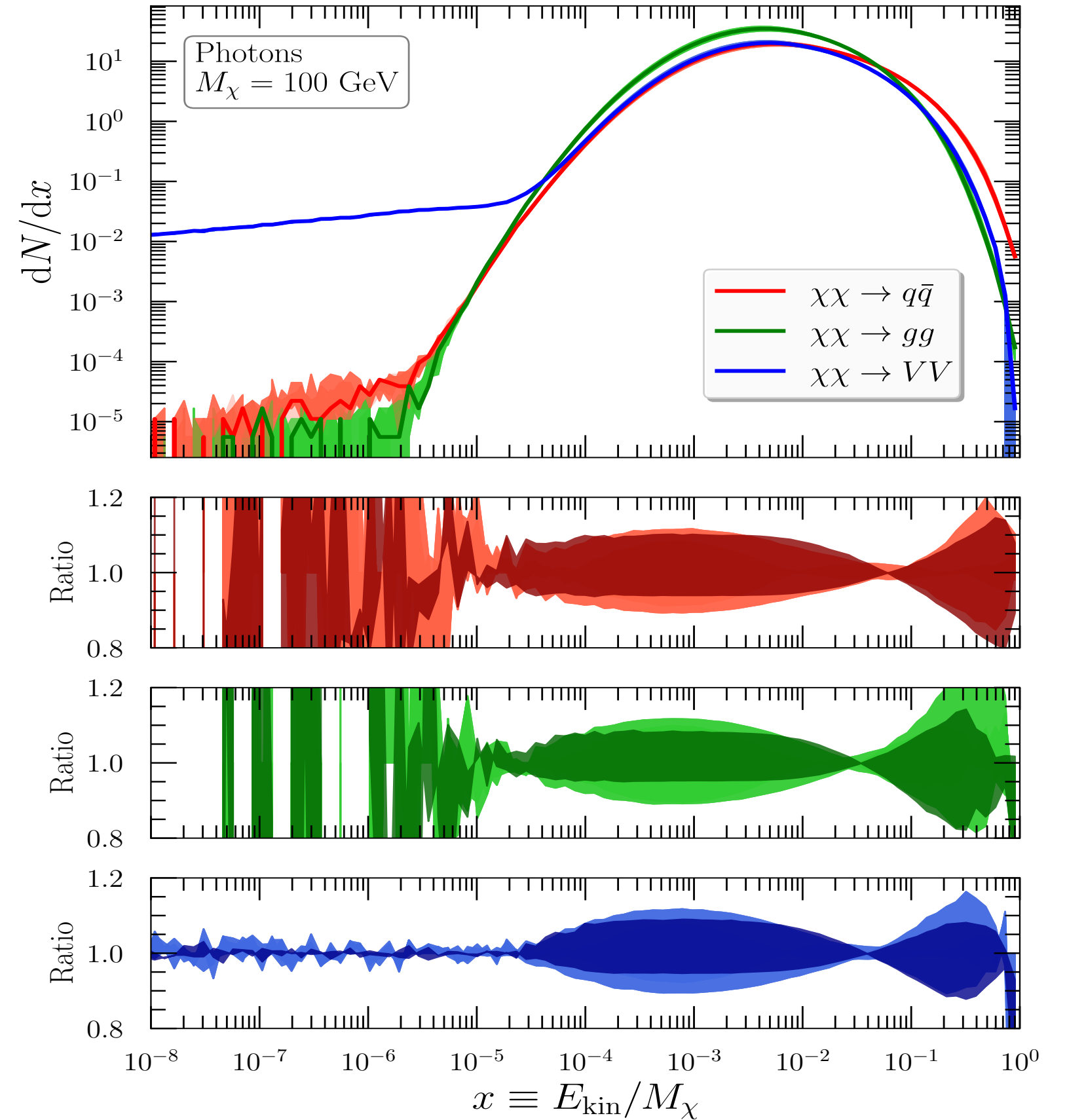
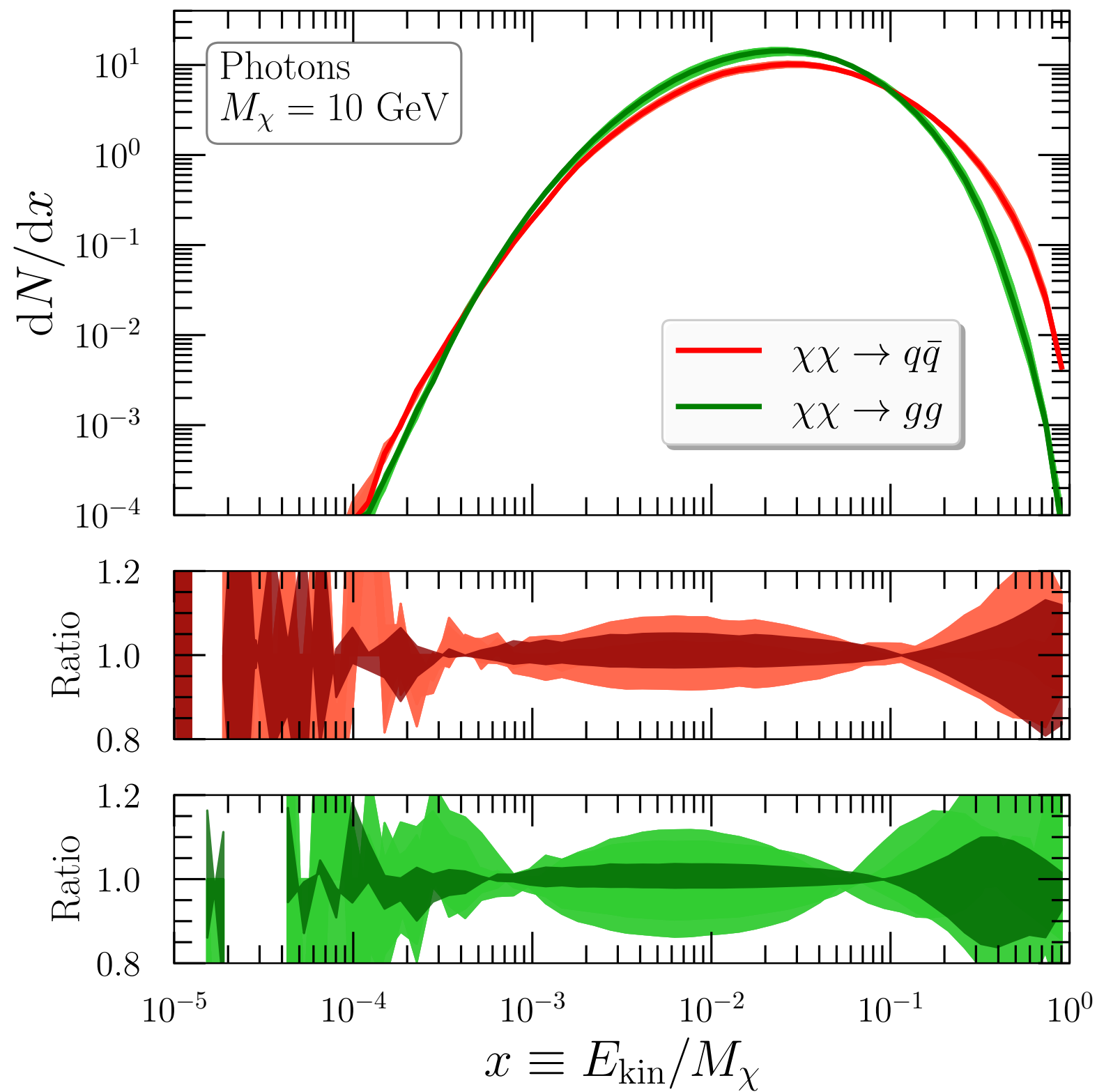
Manual method:

- 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.

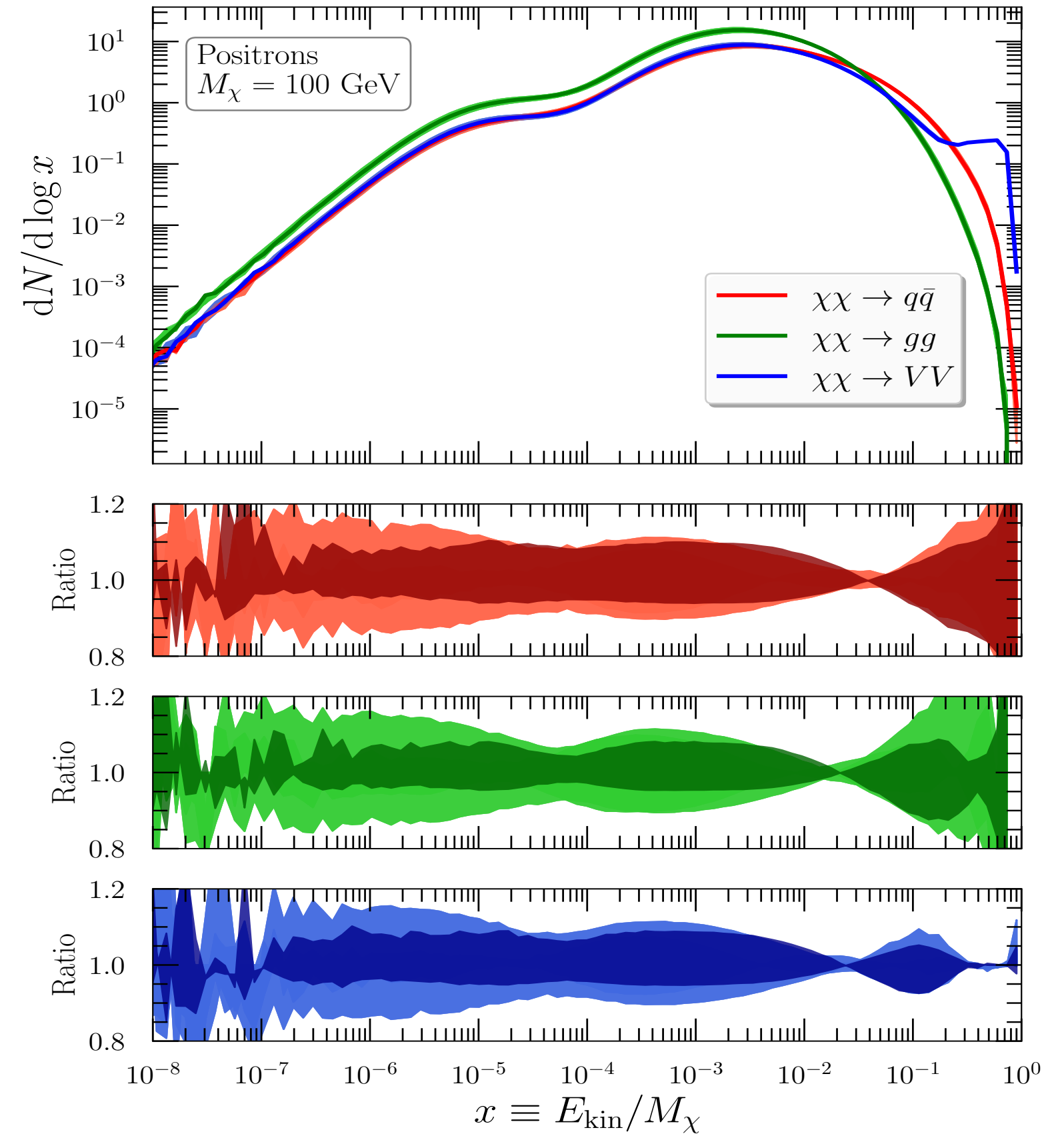
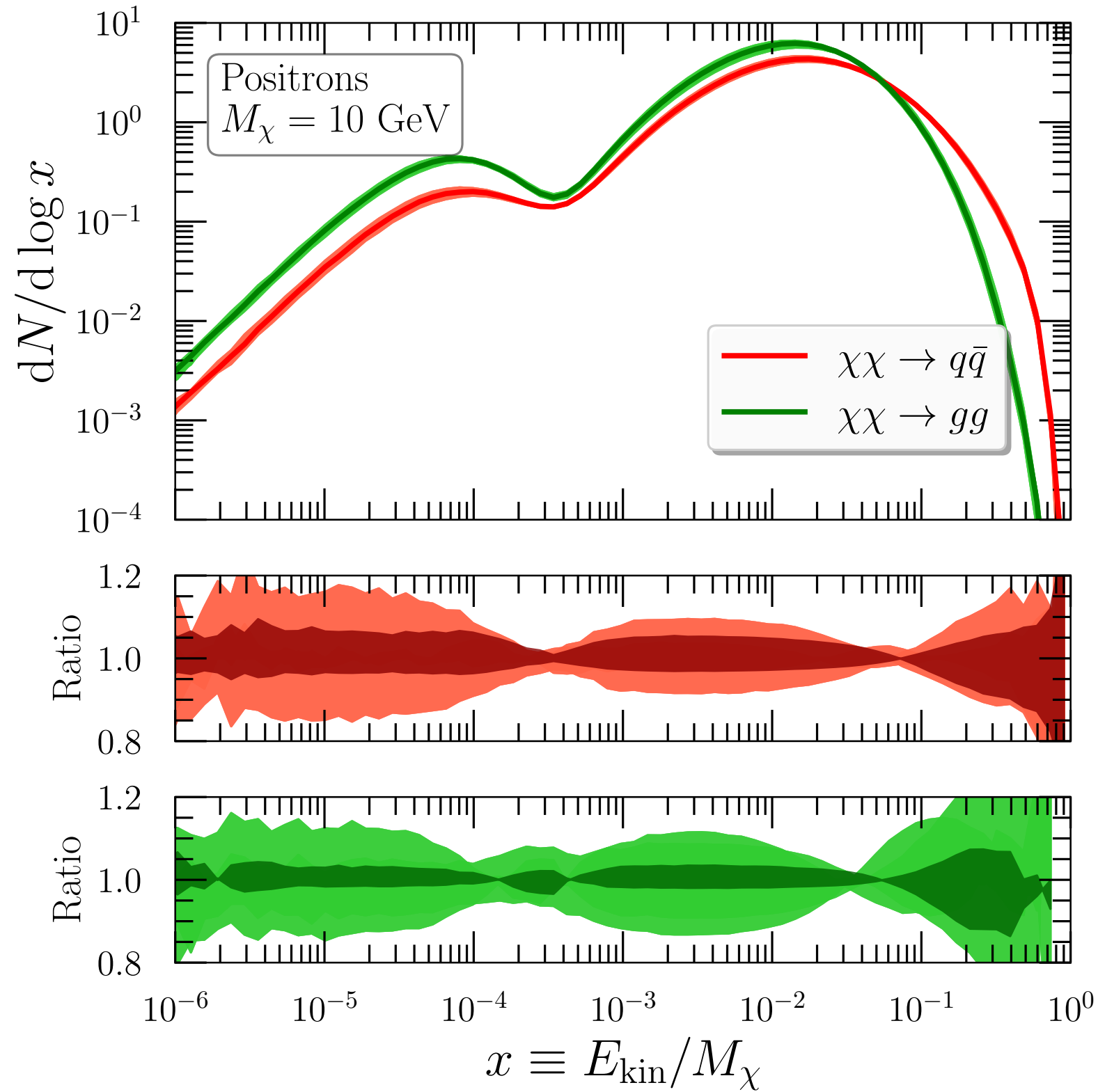
Hadronisation uncertainties: results



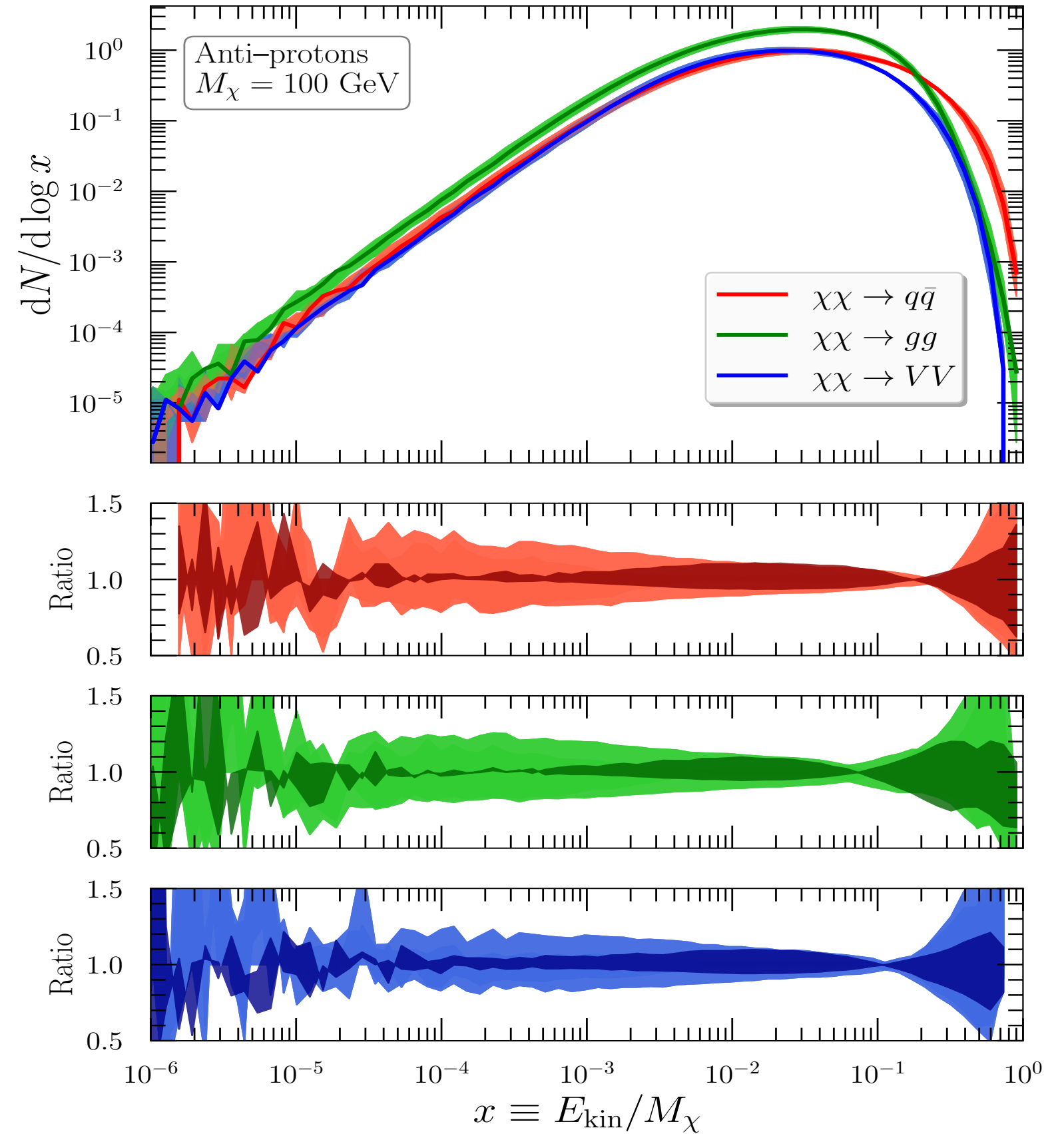
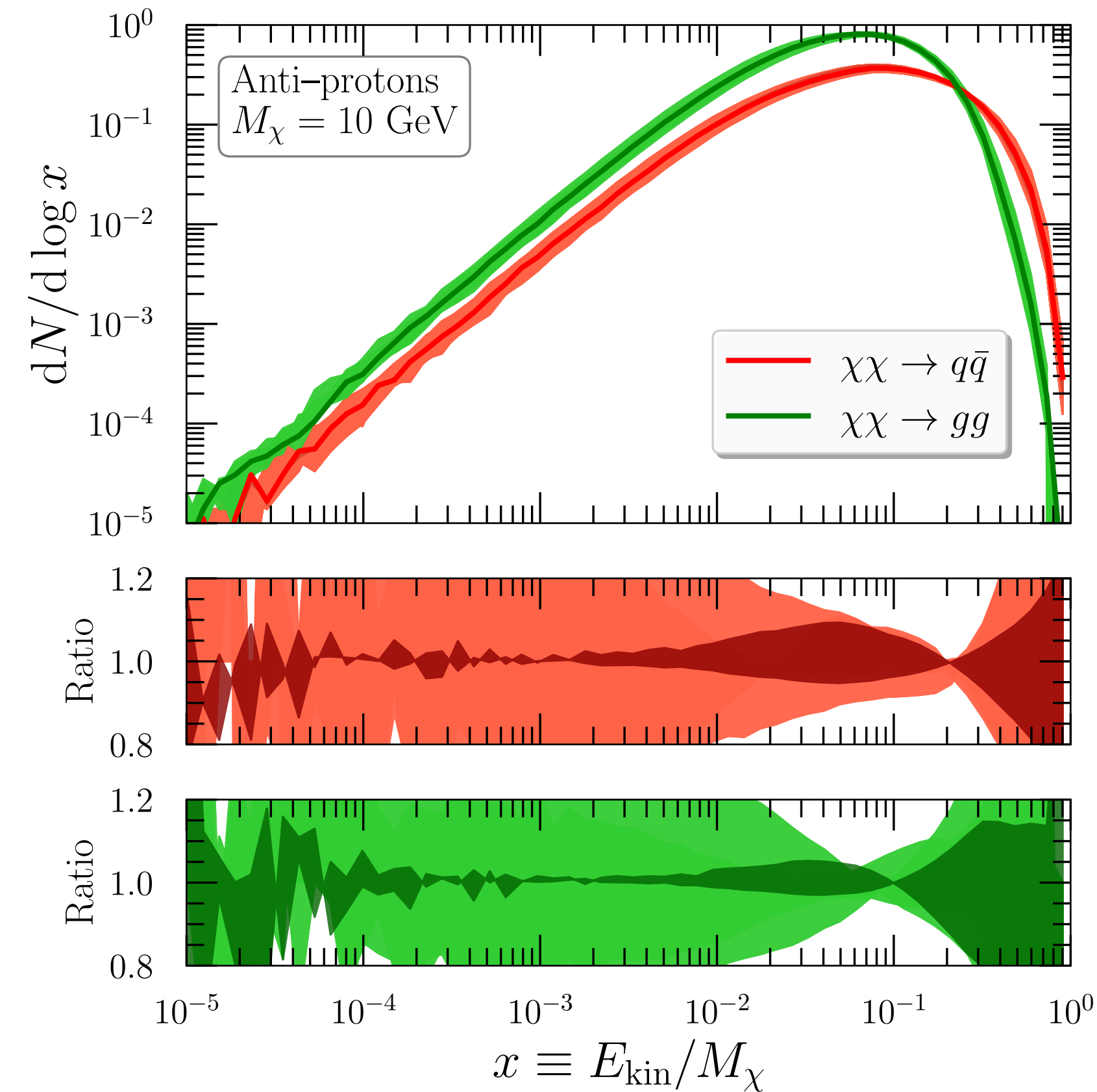
Particle spectra: Gamma rays



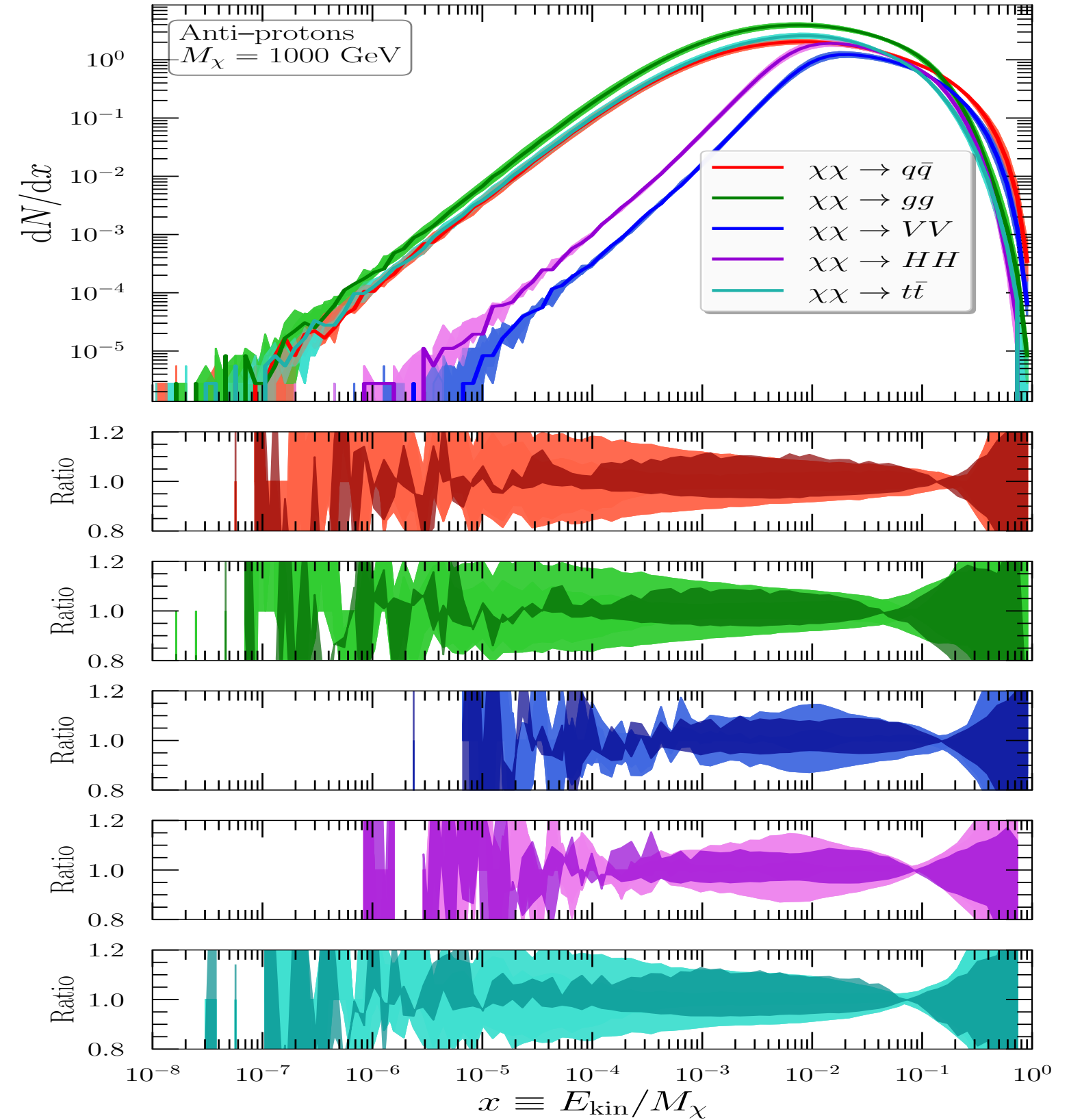
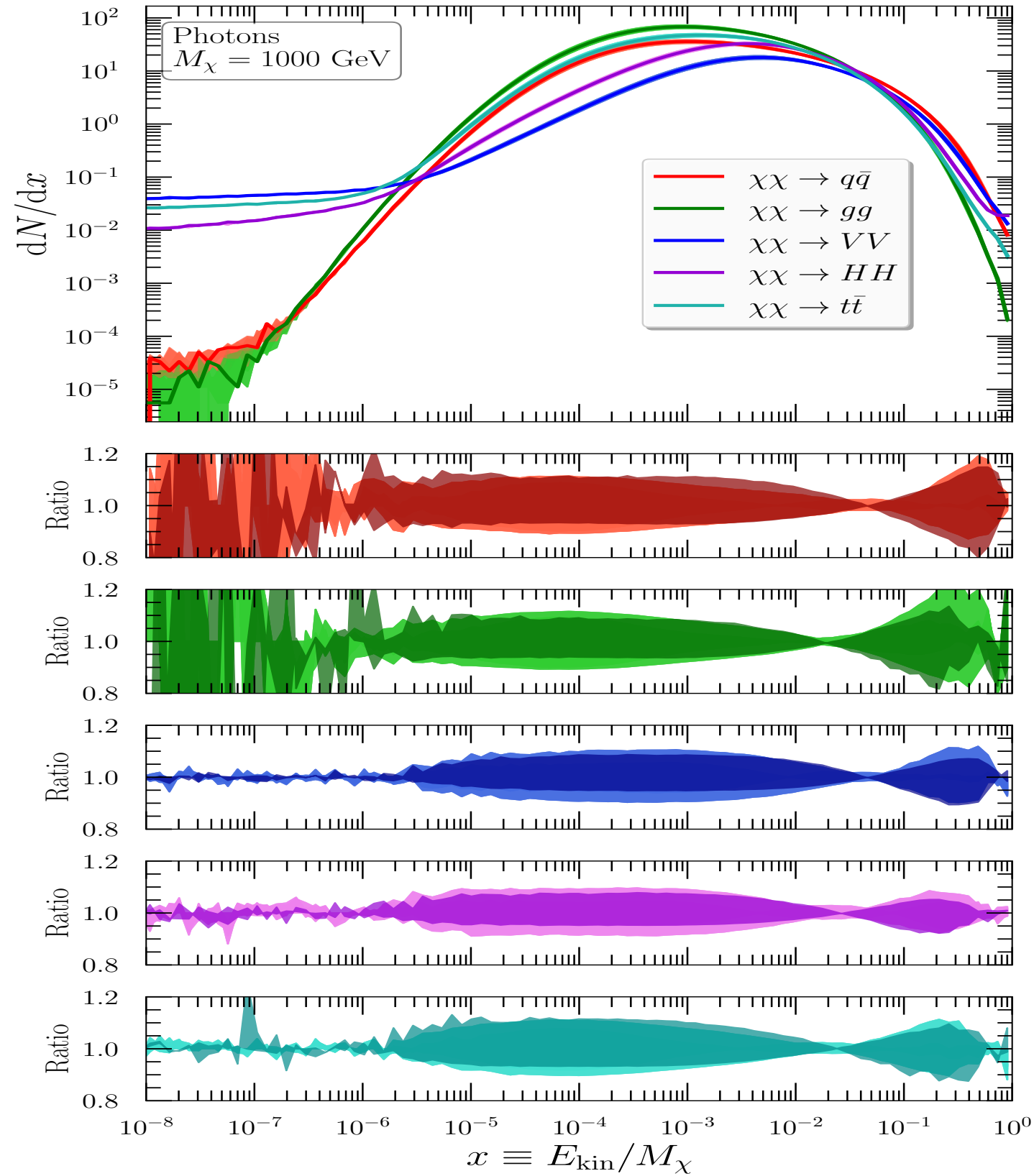
Particle spectra: Positrons



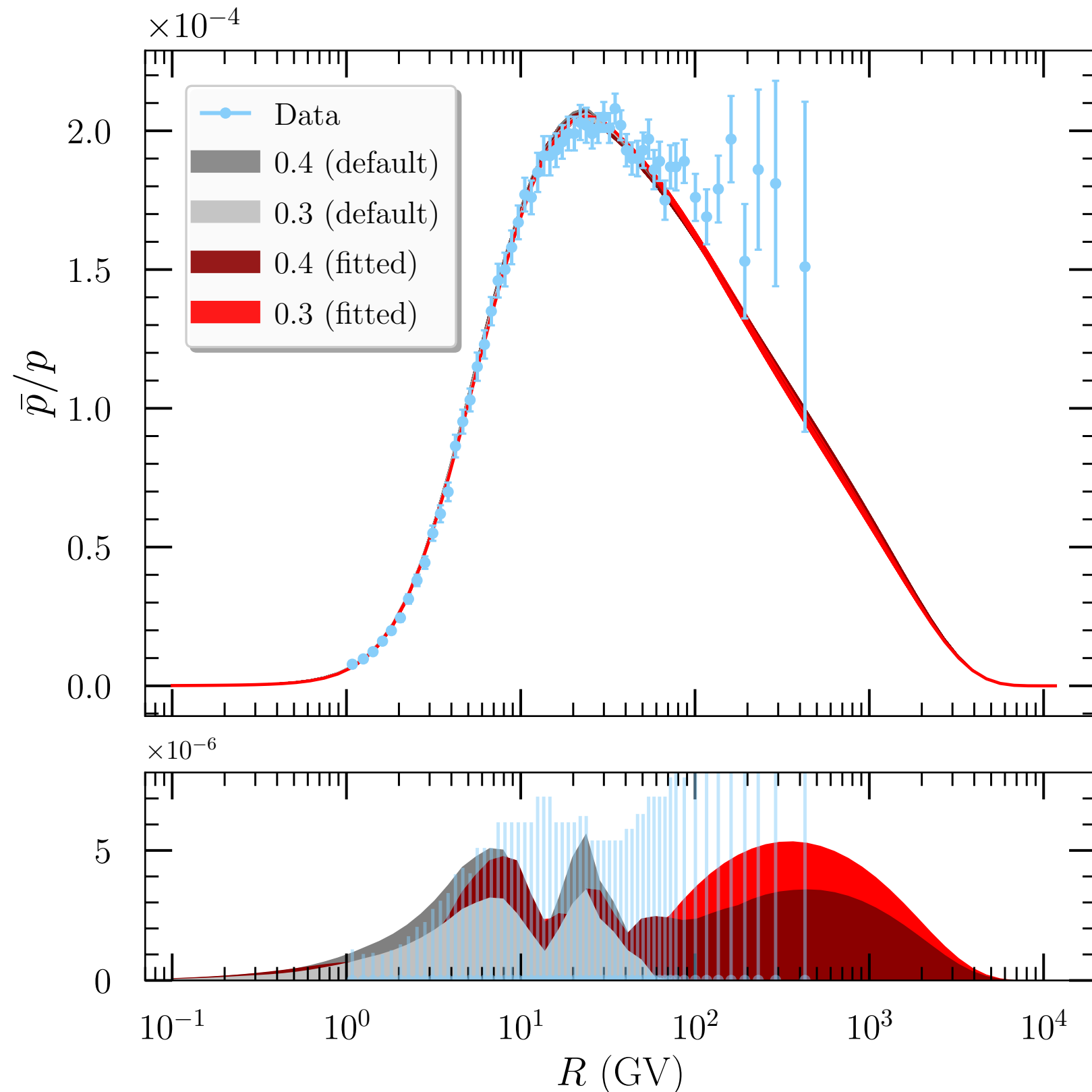
Particle spectra: Anti-protons



Particle spectra: Additional plots



Comparison to AMS data

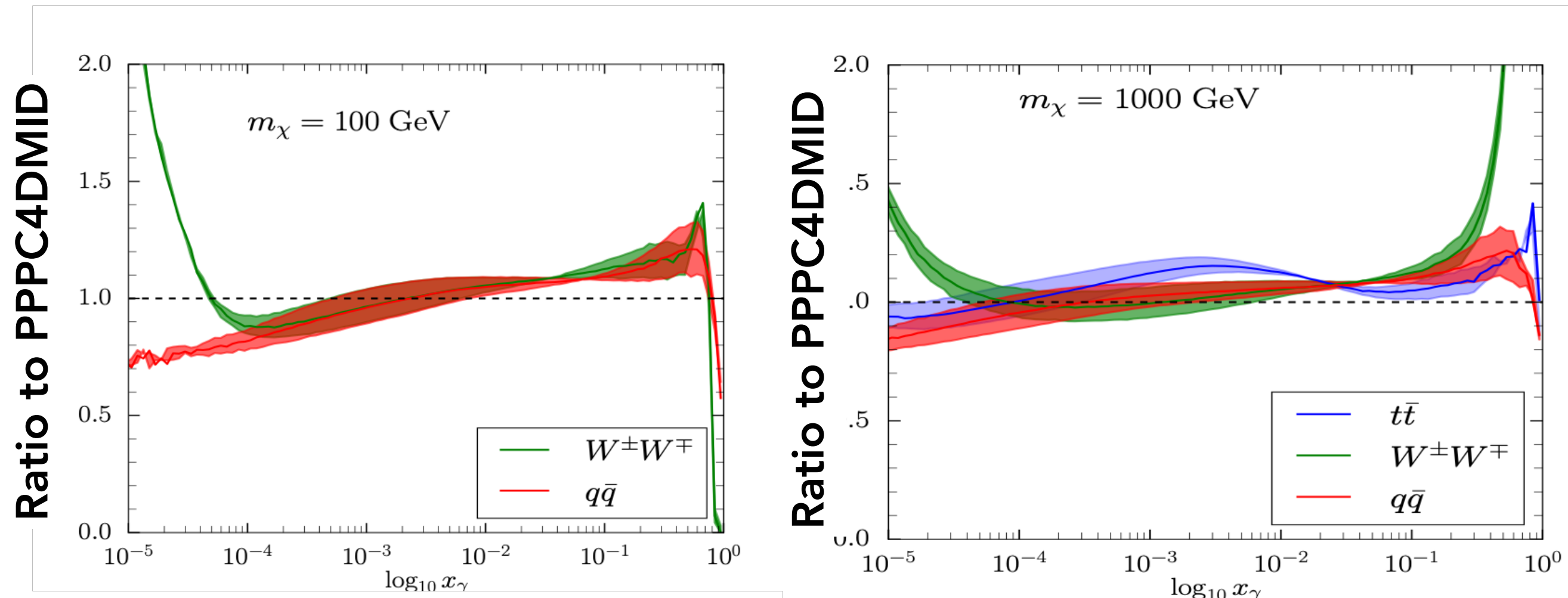


- Theoretical errors for QCD modeling are of similar size to the experimental errors in the peak region.
- Observation is quite independent of the dark-matter density and/or the way we fit the propagation parameters.
- Significant impact on the fits?

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

Our results compared to the PPPC4DMID

$$\chi\chi \rightarrow \gamma + X$$



$$x_\gamma = E_\gamma / m_\chi$$

Disagreement of order 10 – 20 % in the peak region.

Data & Code

We provide a public code on Github that contains the spectra and some snippets for interpolations and quick DM fits

The screenshot shows the GitHub repository page for 'ajueid / qcd-dm.github.io'. The repository is public and has 0 stars, 0 forks, and 1 watch. The main branch is 'main'. The repository contains a folder 'data' and files 'Interpolate.py', 'README.md', and 'Showcase.py'. The README.md file is selected, showing the title 'Toolbox for QCD uncertainties on particle spectra from dark-matter annihilation' and an introduction section. The introduction text states: 'We provide the spectra of stable particles in dark-matter (DM) annihilation or decay in a tabulated form using PYTHIA version 8306. In addition to the central prediction, we estimate the QCD uncertainties both due to hadronization as well as to the parton-shower variations. The DM masses considered here vary between 5 GeV and 100 TeV. We consider 14 primary annihilation channels:'. The right sidebar shows the 'About' section with no description, website, or topics provided, and the 'Releases' section with no releases published.

ajueid / qcd-dm.github.io Public

main 1 branch 0 tags

Go to file Add file Code

ajueid Update README.md d46635a on Apr 1 13 commits

File	Description	Updated
data	Tables for particle fluxes without uncertainties	8 months ago
Interpolate.py	Example for mass interpolation	8 months ago
README.md	Update README.md	7 months ago
Showcase.py	Example for mass interpolation	8 months ago

README.md

Toolbox for QCD uncertainties on particle spectra from dark-matter annihilation

Introduction

We provide the spectra of stable particles in dark-matter (DM) annihilation or decay in a tabulated form using PYTHIA version 8306. In addition to the central prediction, we estimate the QCD uncertainties both due to hadronization as well as to the parton-shower variations. The DM masses considered here vary between 5 GeV and 100 TeV. We consider 14 primary annihilation channels:

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