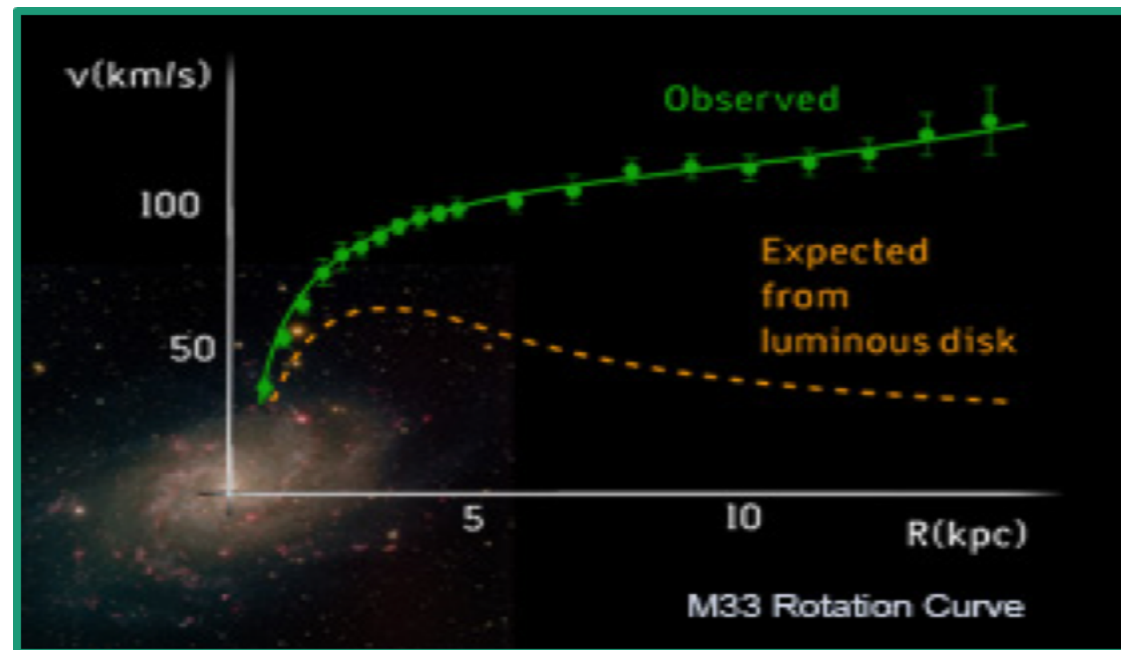
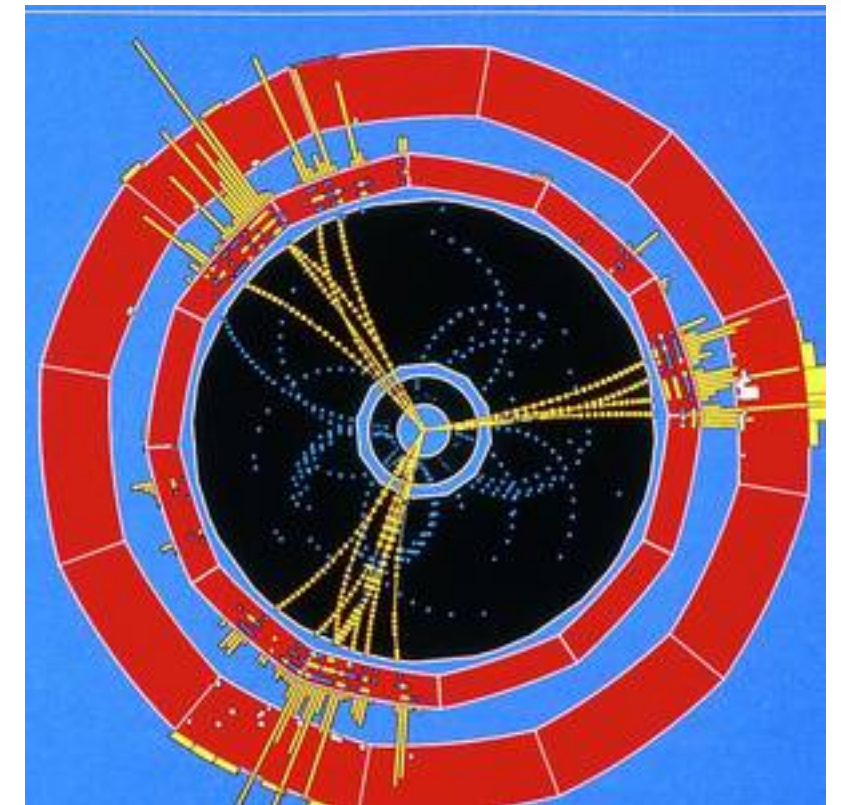


Impact of QCD uncertainties on dark-matter indirect searches



Adil Jueid



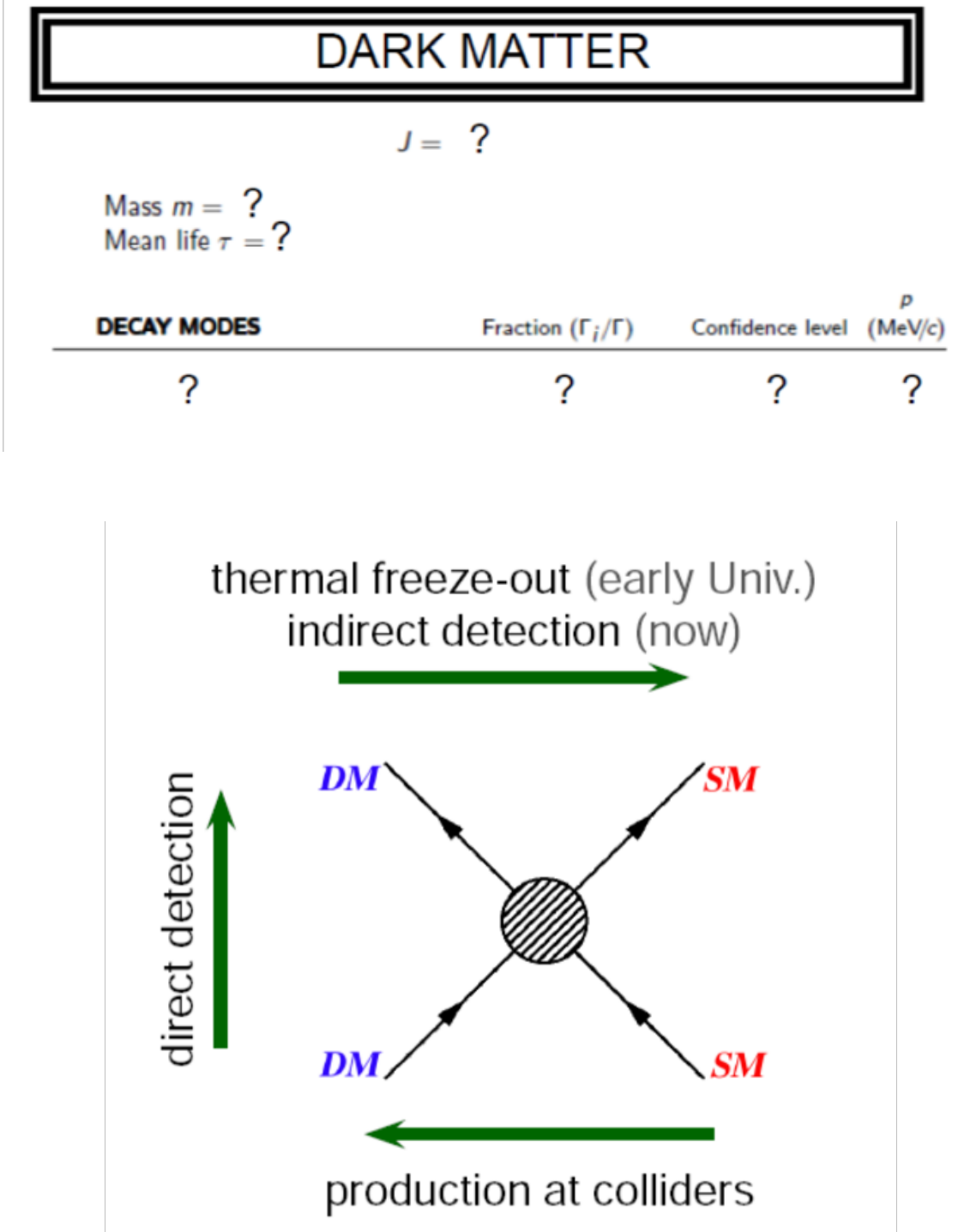
Talk based on:

- S. Amoroso, S. Caron, AJ, R. Ruiz de Austri, P. Skands, JCAP 05 (2019) 007
- AJ, J. Kip, R. Ruiz de Austri, P. Skands, e-Print: 2202.11456.
- AJ, J. Kip, R. Ruiz de Austri, P. Skands, in preparation.

APEC Seminar
Kavli IPMU, The University of Tokyo
03 February 2023

Introduction

- There is a tremendous evidence for the existence of new type of matter which forms about 85% of the matter content of the universe.
- From various observations, at different scales, the DM particle should be neutral, non-baryonic, non-relativistic and stable with a lifetime larger than the age of the universe.
- No SM particle can be a dark matter candidate.
- There are different types of DM (WIMPs, axions, ...).



Introduction

- 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, 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).

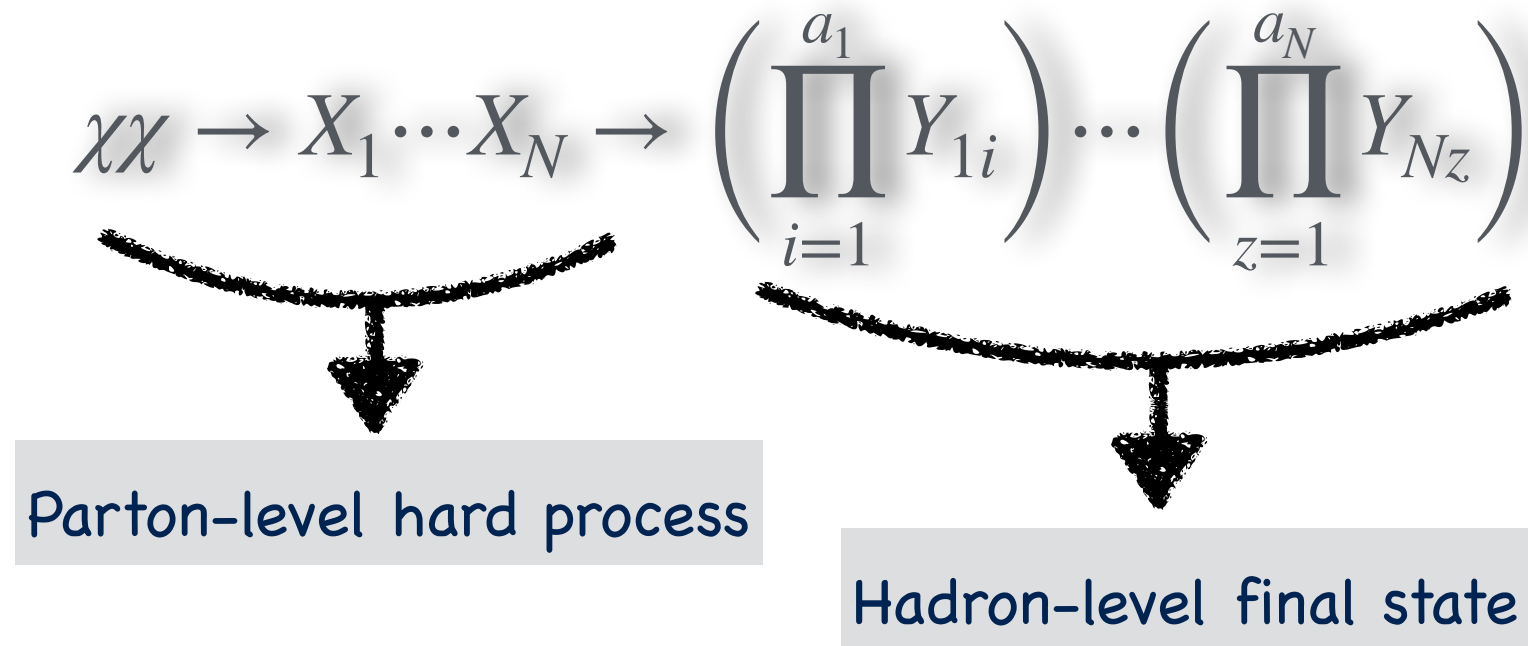
The role of precision

- 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

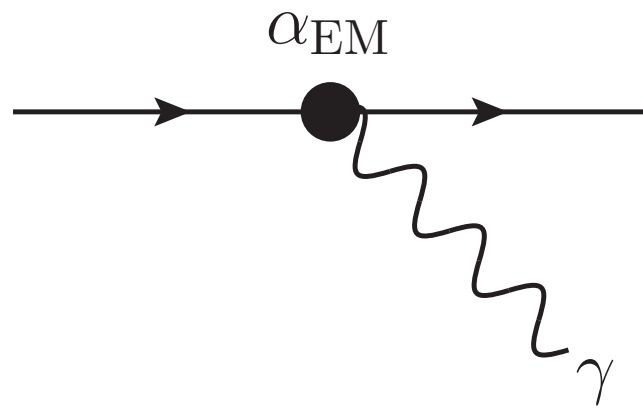


The underlying physics depends on the nature of the produced resonance X_i and the particles produced in its decay (Y_{ij}).

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 $X_i^\pm \rightarrow \gamma X_i^\pm$ and $\gamma \rightarrow f\bar{f}$.
- The former process ($X_i^\pm \rightarrow \gamma X_i^\pm$) is enhanced in both the soft ($E_\gamma \rightarrow 0$) and the collinear ($\theta_{X\gamma} \rightarrow 0$) regions. Therefore, the produced photon may take the whole energy of the parent provided that $\theta_{X\gamma} \rightarrow 0$.

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



- Dominate at high x_γ .
- Relevant for DM annihilation into photons and charged leptons.
- The corresponding coupling (α_{EM}) is measured with high precision.

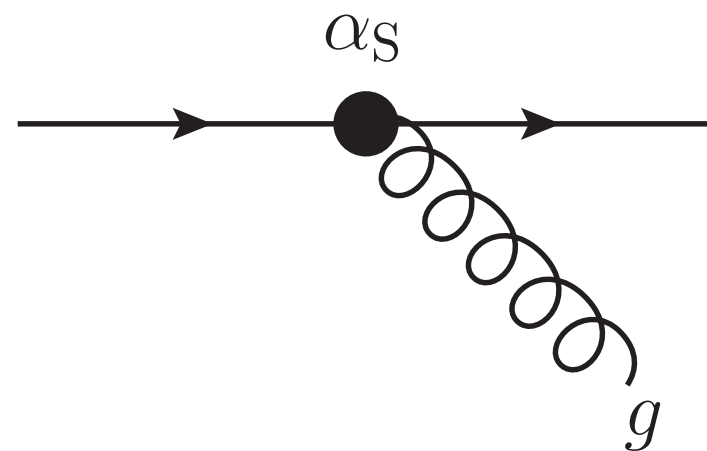


No need to assign uncertainties on the QED part.

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 $g \rightarrow q\bar{q}$ 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 $\alpha_S(Q)$



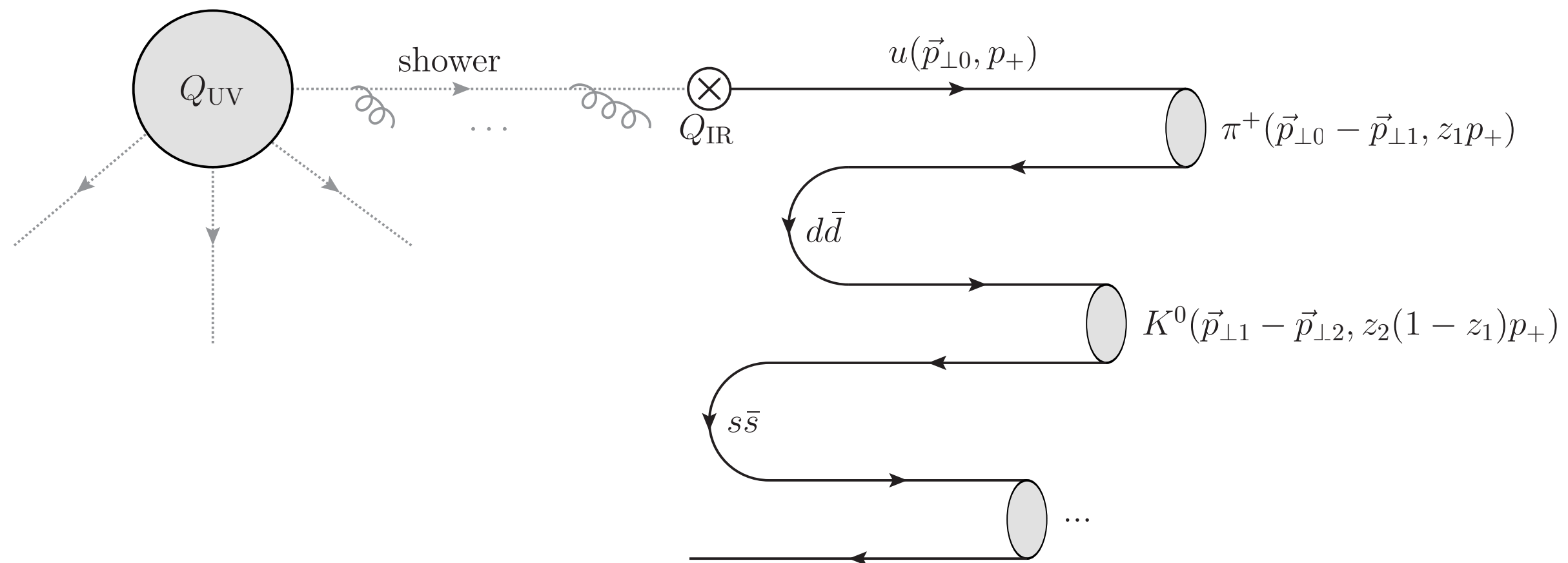
- Dominate at both the bulk and the peak.
- Relevant for DM annihilation into colored particles
- The corresponding coupling (α_S) in PYTHIA8 is different by about 20% from the $\alpha_S(M_Z)^{\overline{\text{MS}}}$.



Subject to uncertainty variations!

Modeling of the spectra: 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.



Review: Hadronisation in PYTHIA8

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.

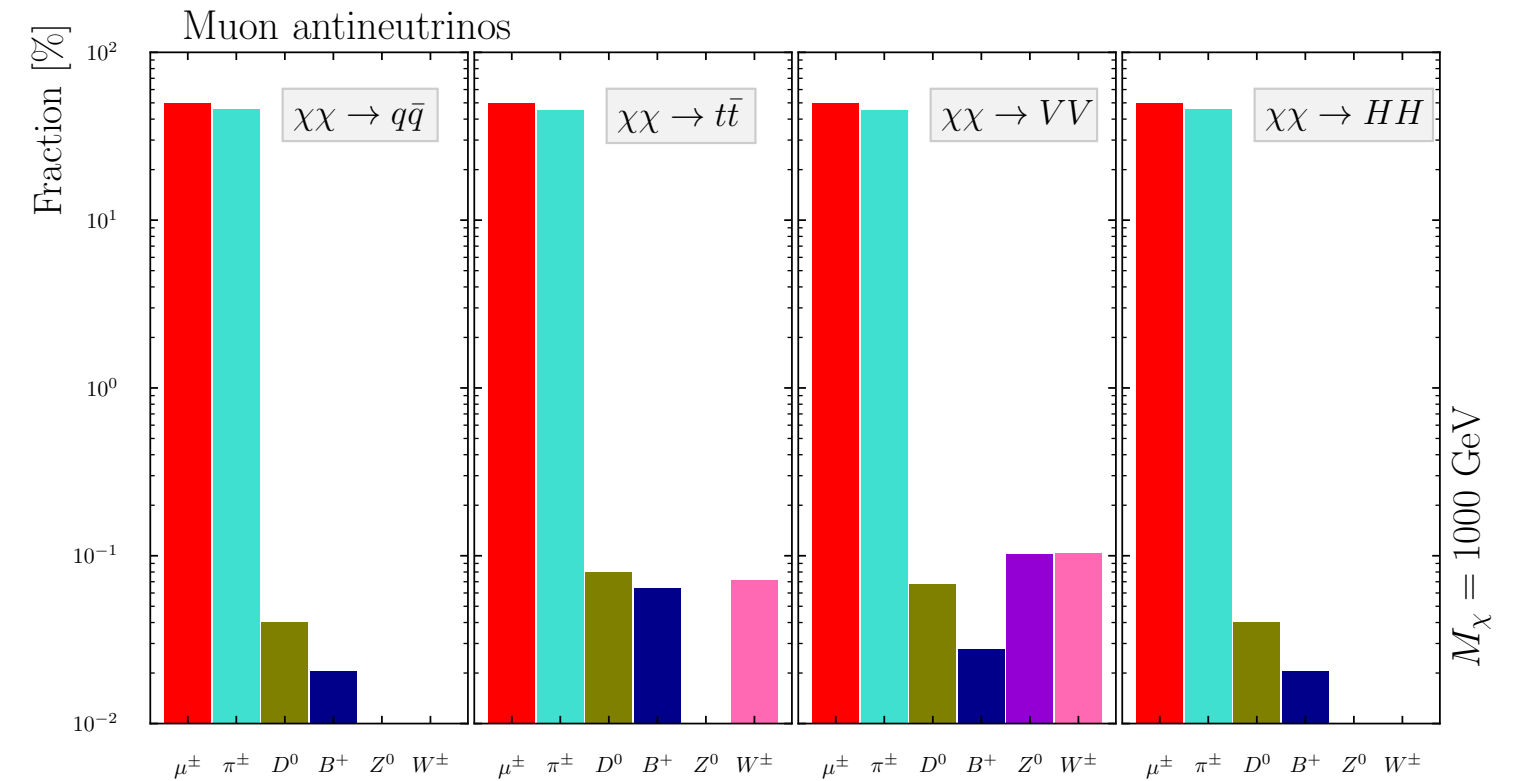
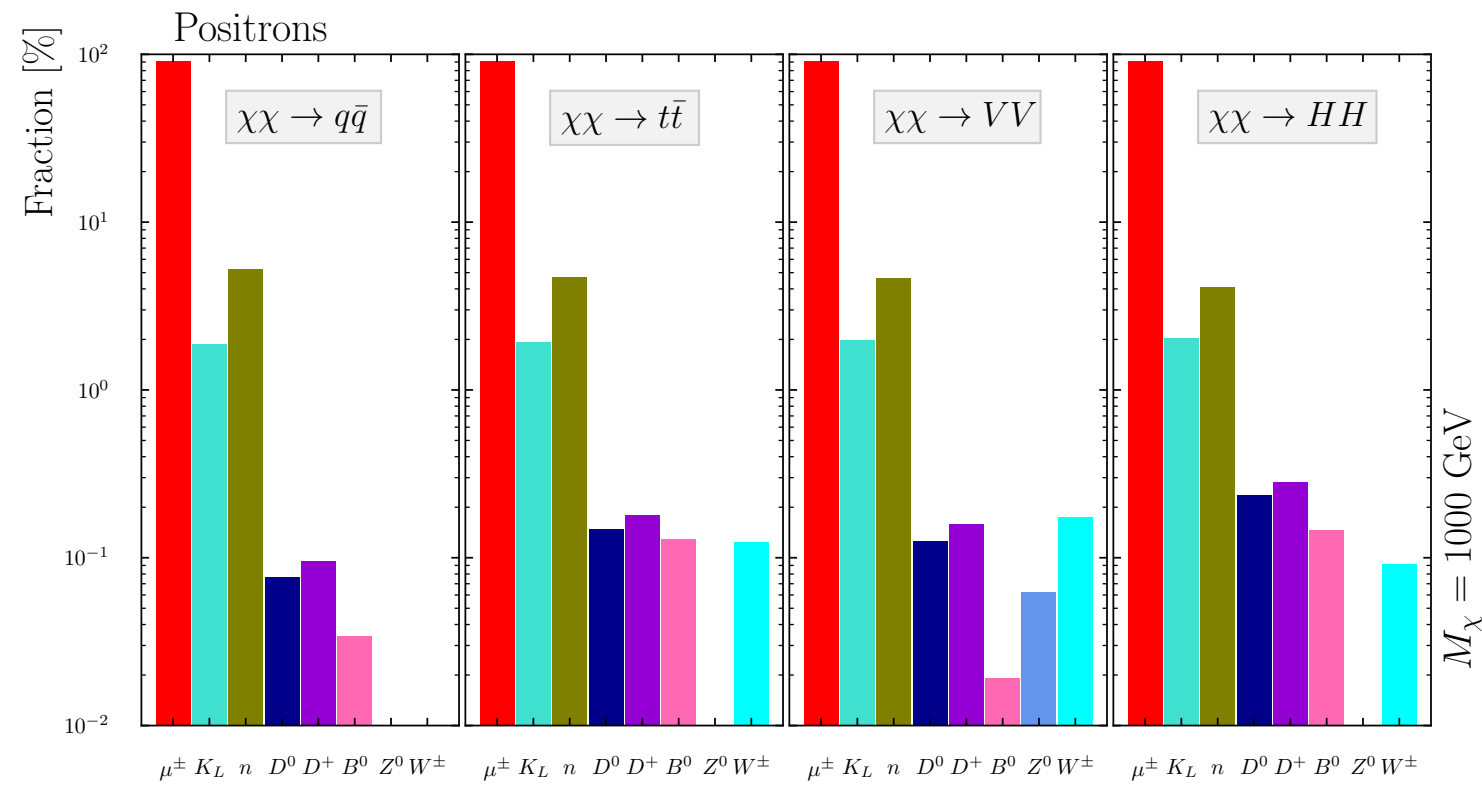
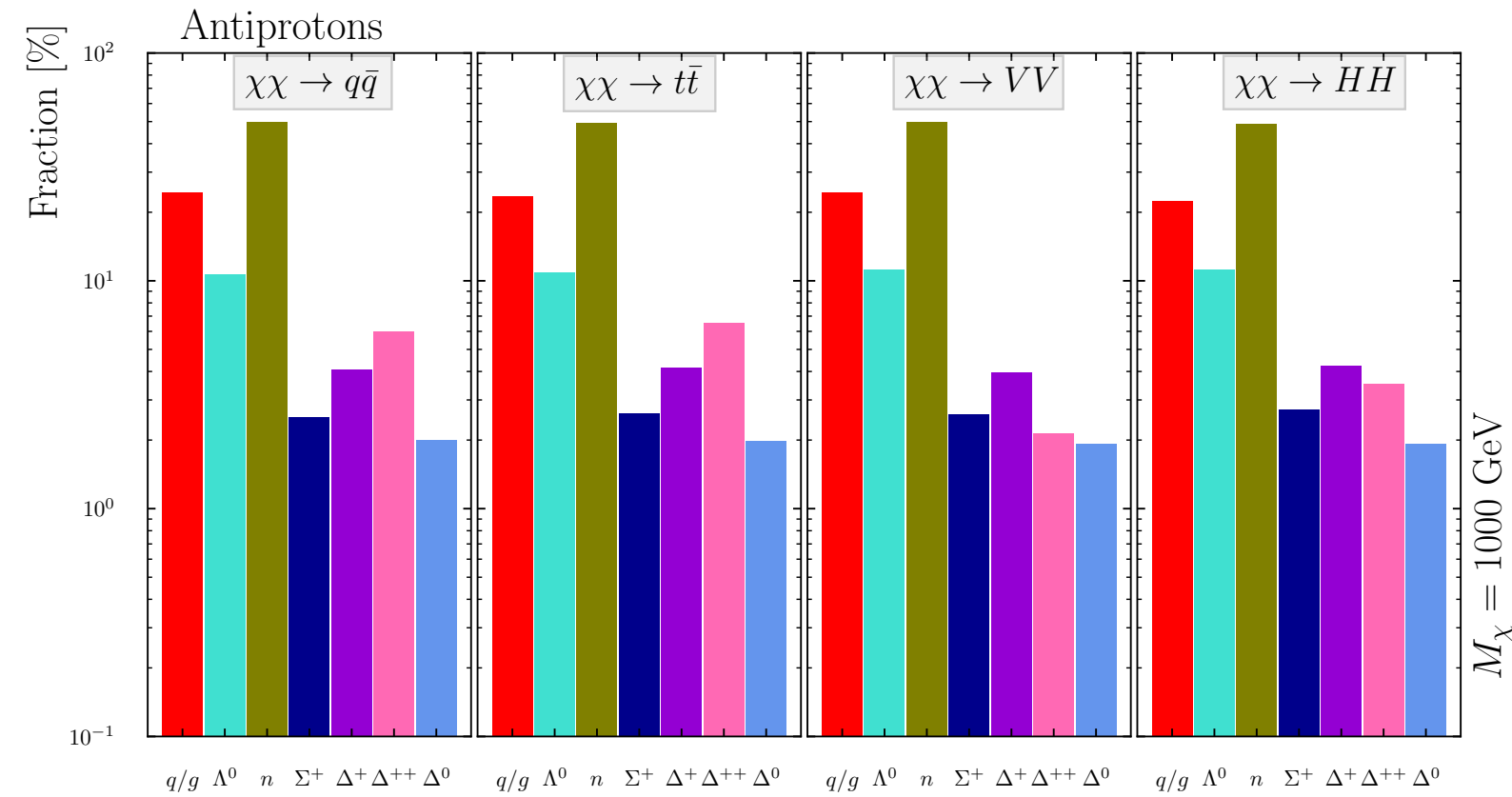
What about anti-protons?

- 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 performed by OPAL collaboration.
- To address this, the popcorn mechanism is introduced in which a set of $q\bar{q}$ pairs are produced between the diquark pairs — lead to the production of multiple mesons between a baryon and anti-baryon (therefore decreases the correlation).

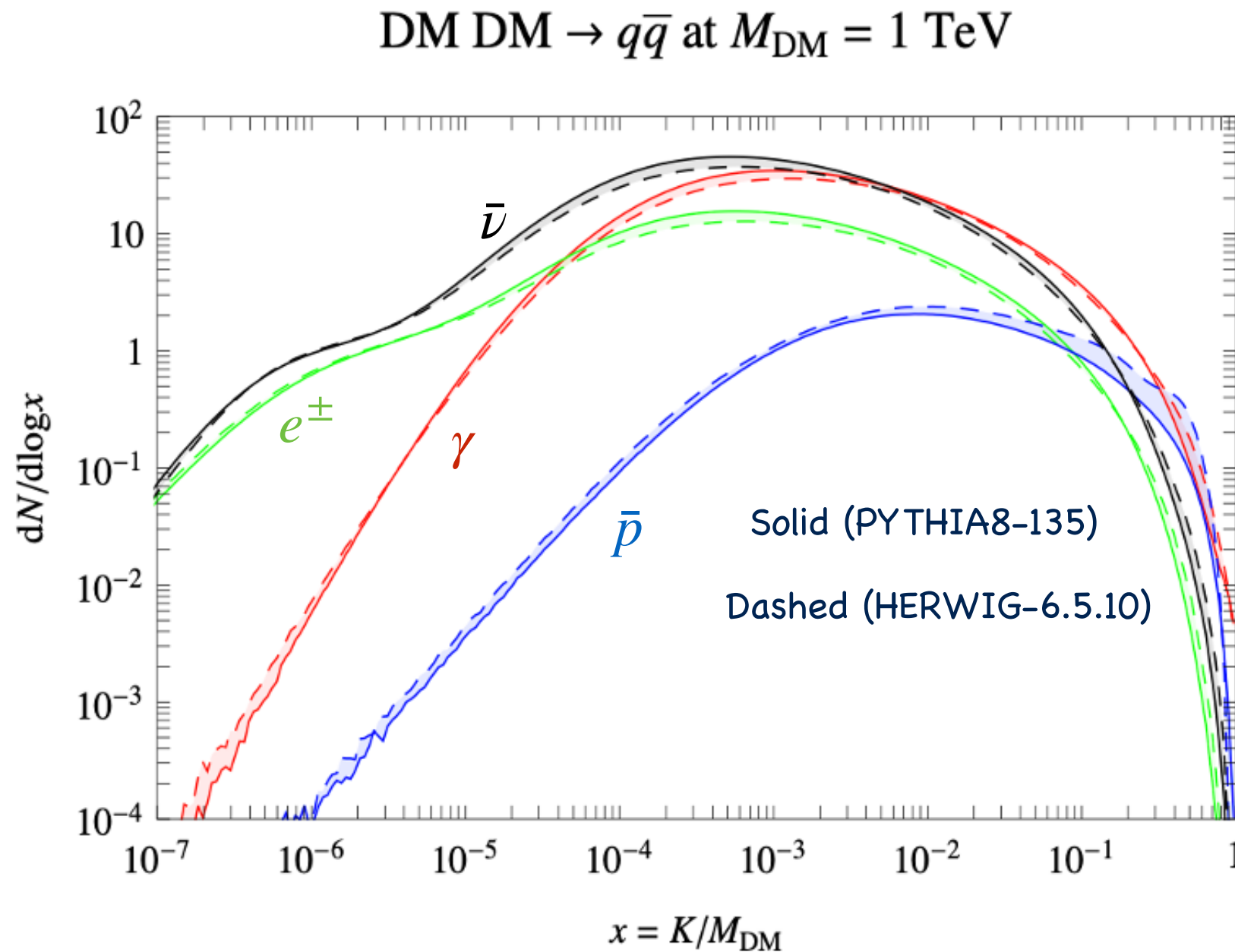
NOTE ONE: In the context of dark matter annihilation, correlations are lost as baryons travel long distances before reaching the detector.

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

Origin of stable particles in DM annihilation



The flux at production of stable particles: PPPC4DMID



- M. Cirelli et al. produced a complete recipe for the flux at production from DM annihilation in a wide range of DM masses (arXiv: 1012.4515) — called the Poor Particle Physics Cookbook for Dark Matter Indirect Detection (PPPC4 DMID).
- The study utilized PYTHIA-8.135 based on an old tune that is superseded by the most recent Monash tune.
- PYTHIA-8.135 lacks several capabilities such as QED radiation off heavy particles, EW showers among others.

Important question: What is the uncertainty on the predicted spectra?

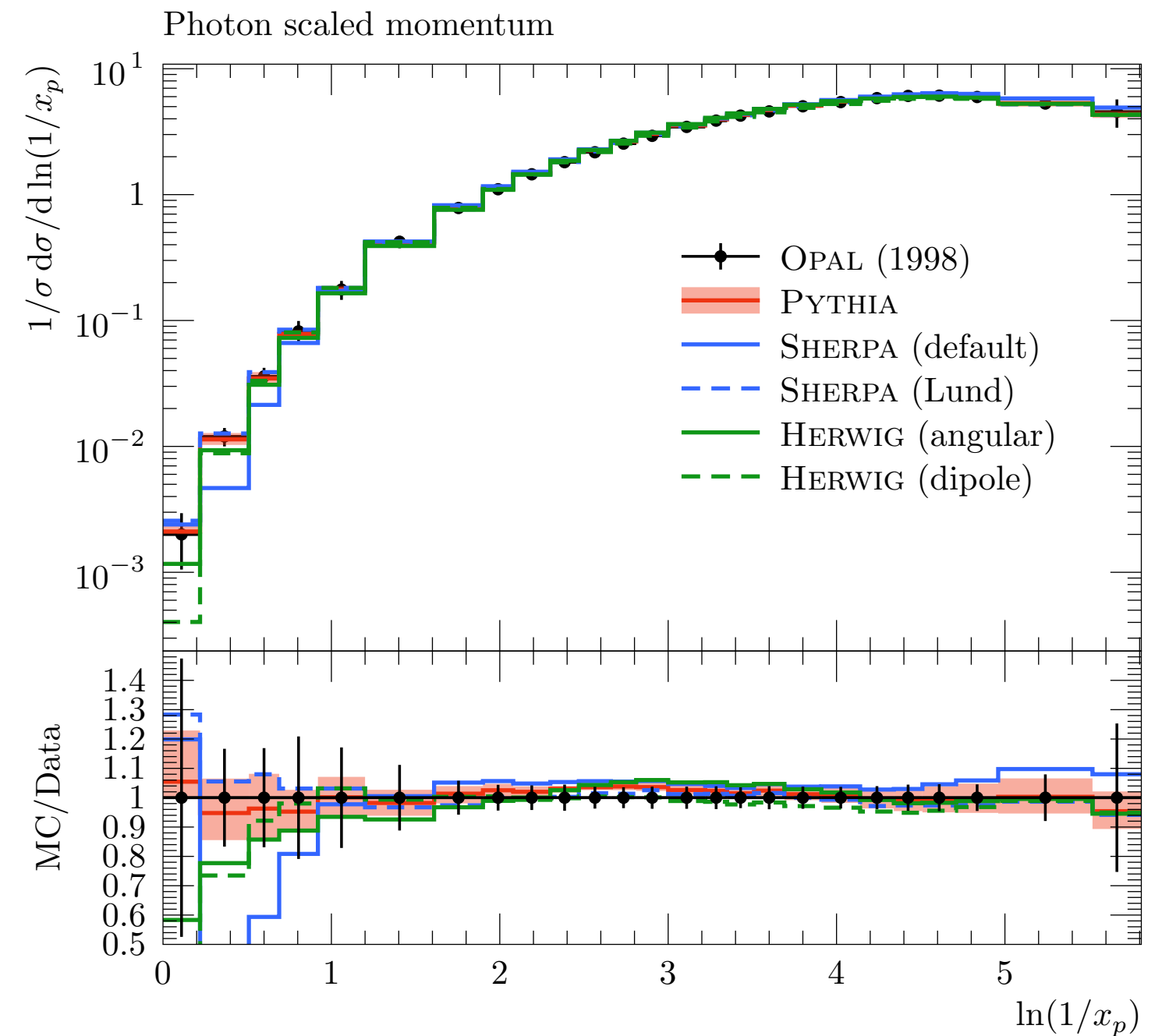
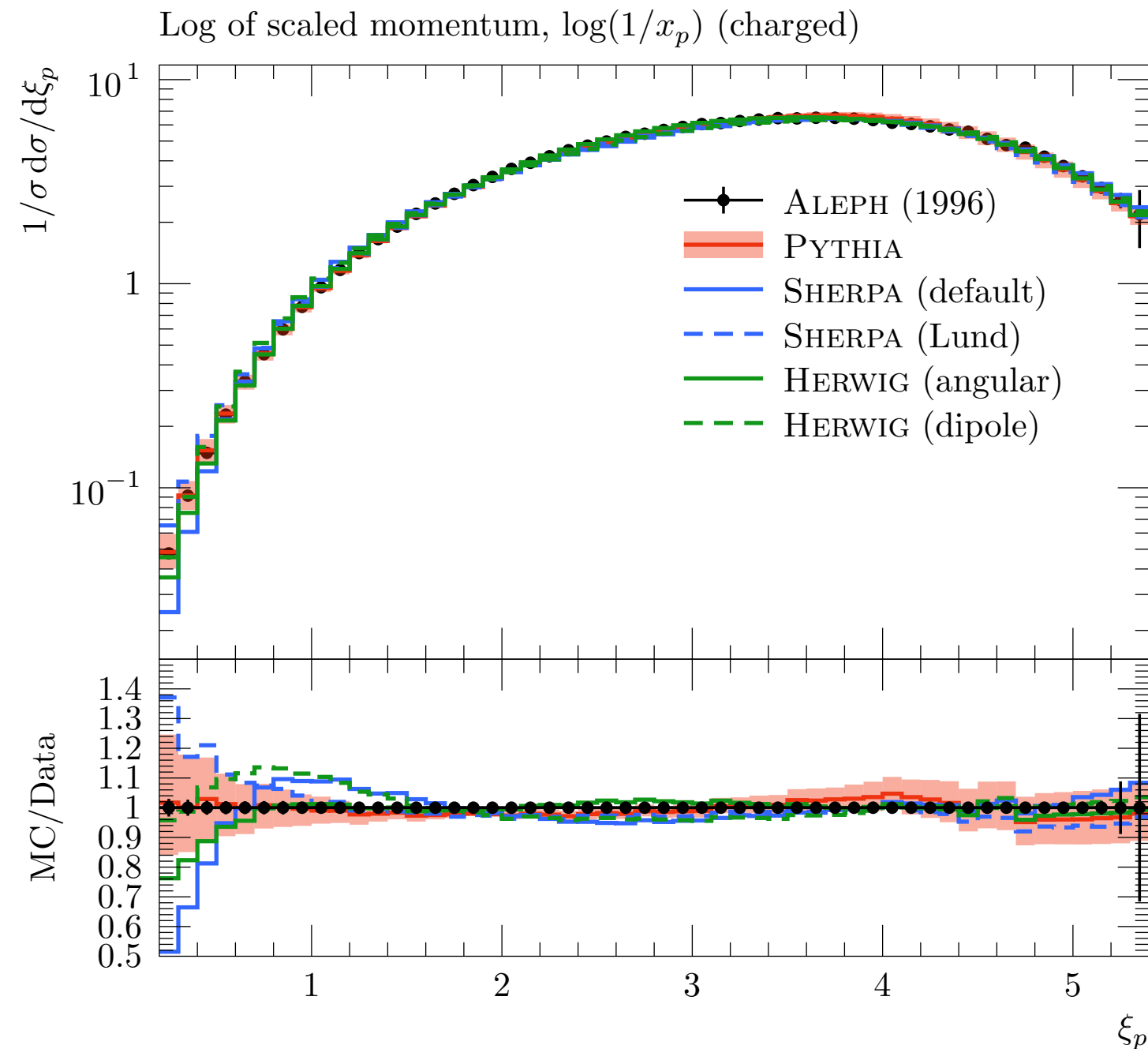
The modeling of the uncertainties: The old method

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 some regions, underestimate in the most important regions).

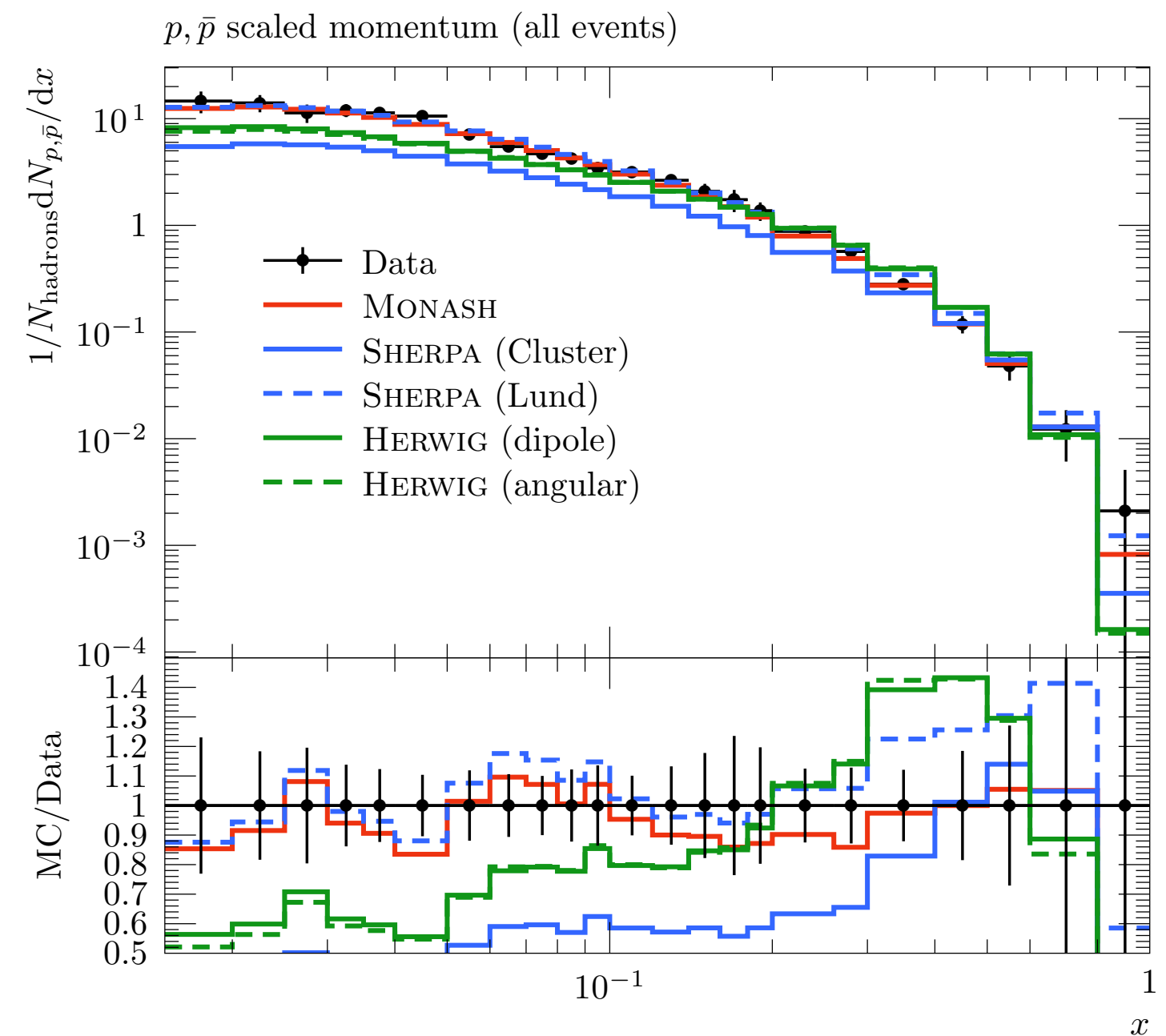
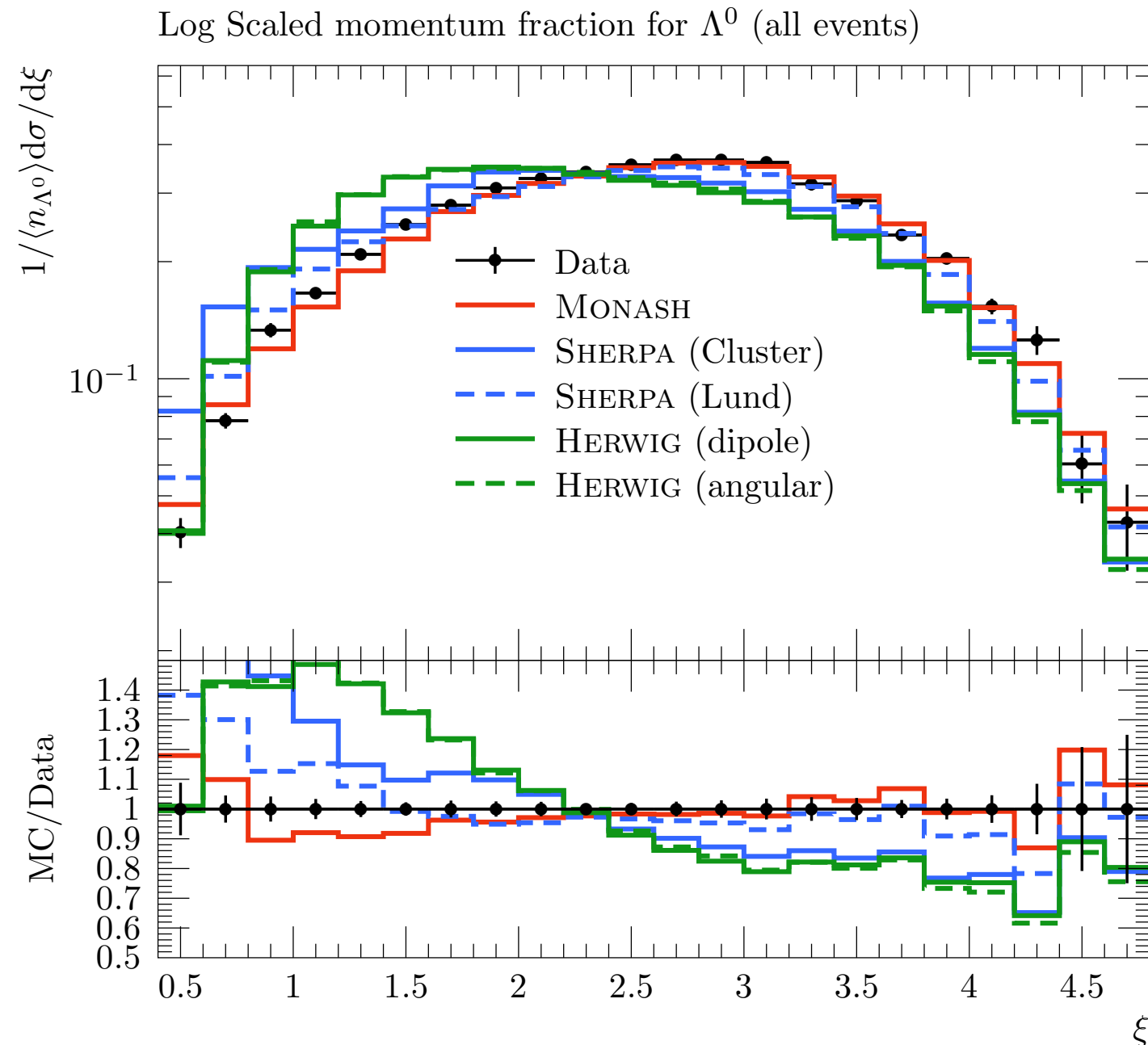
We need to estimate QCD uncertainties within the same generator

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)

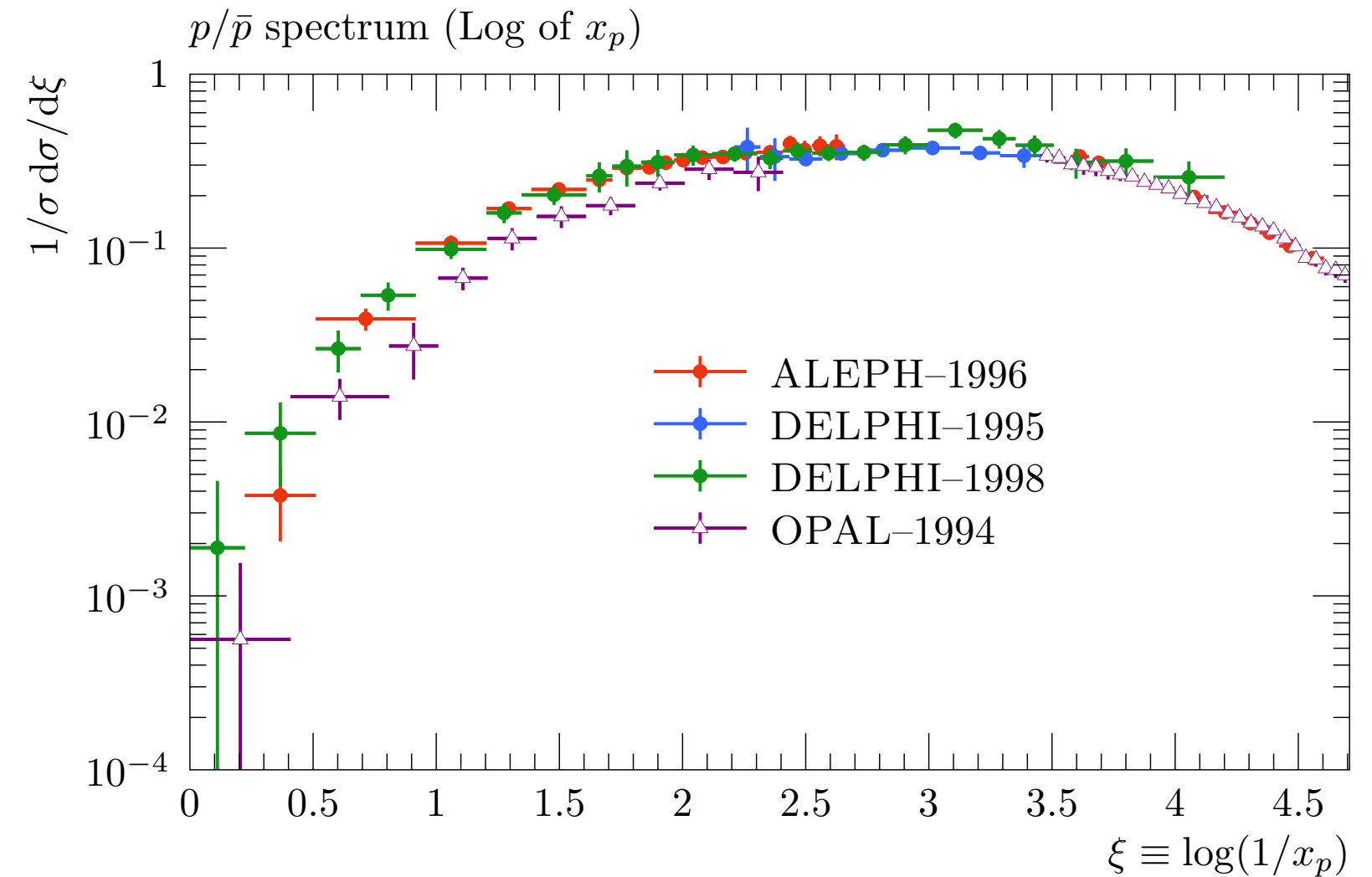
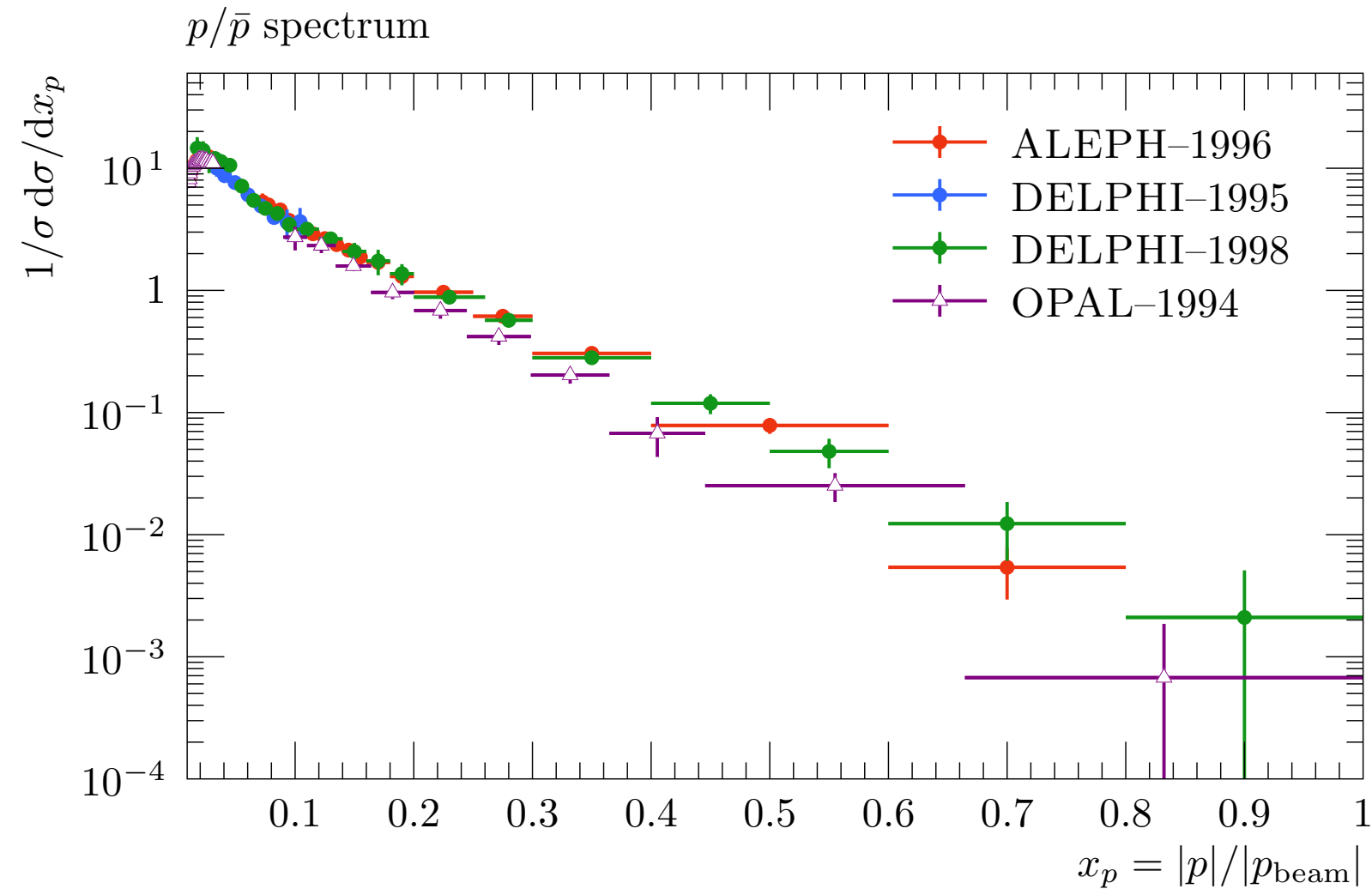
Tuning

- Different tunings of the parameters $a, \langle z_\rho \rangle, \sigma(= \sqrt{\langle m_\perp^2 \rangle / 2})$, 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 (0907.2973) for optimization of the parameters of the fragmentation function in Pythia8.307 and Rivet 3.1.6 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

$$\chi^2 = \sum_{\mathcal{O}} \sum_{b \in \mathcal{O}} \left(\frac{\text{MC}_{(b)}(\{p_i\}) - \text{Data}_{(b)}}{\Delta_b} \right)^2$$

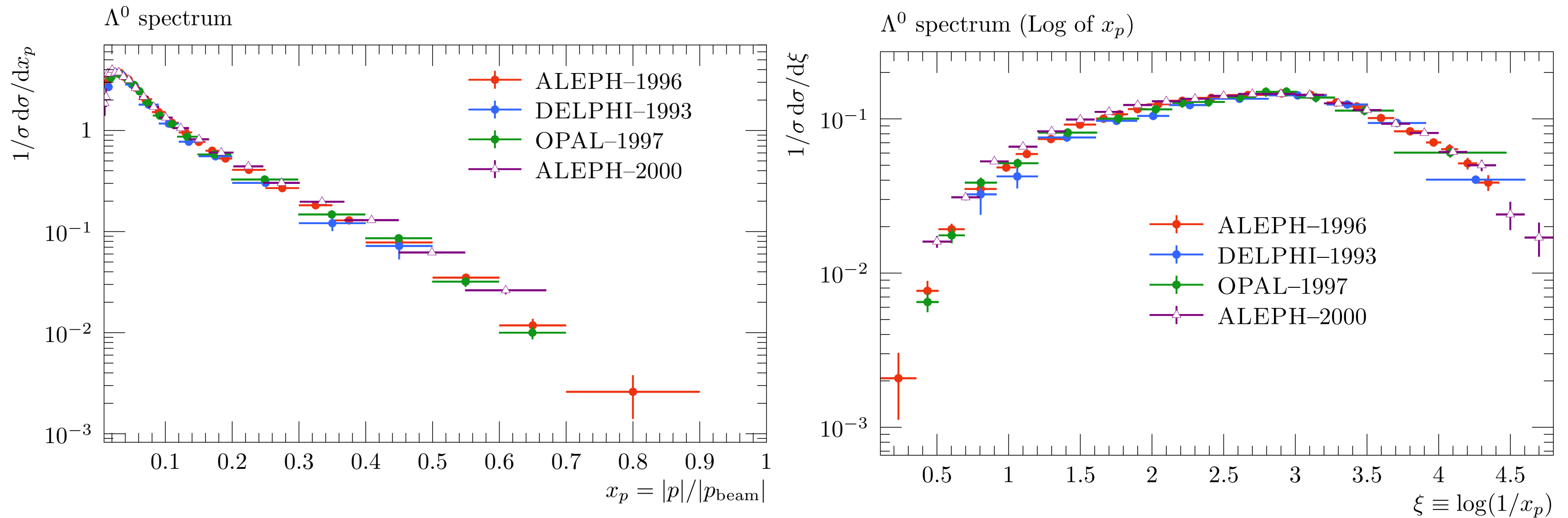
$$\Delta_b = \sqrt{\Delta_{\text{exp}}^2 + \Delta_{\text{MC}}^2 + (0.05 \text{ MC}_{(b)})^2}$$

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

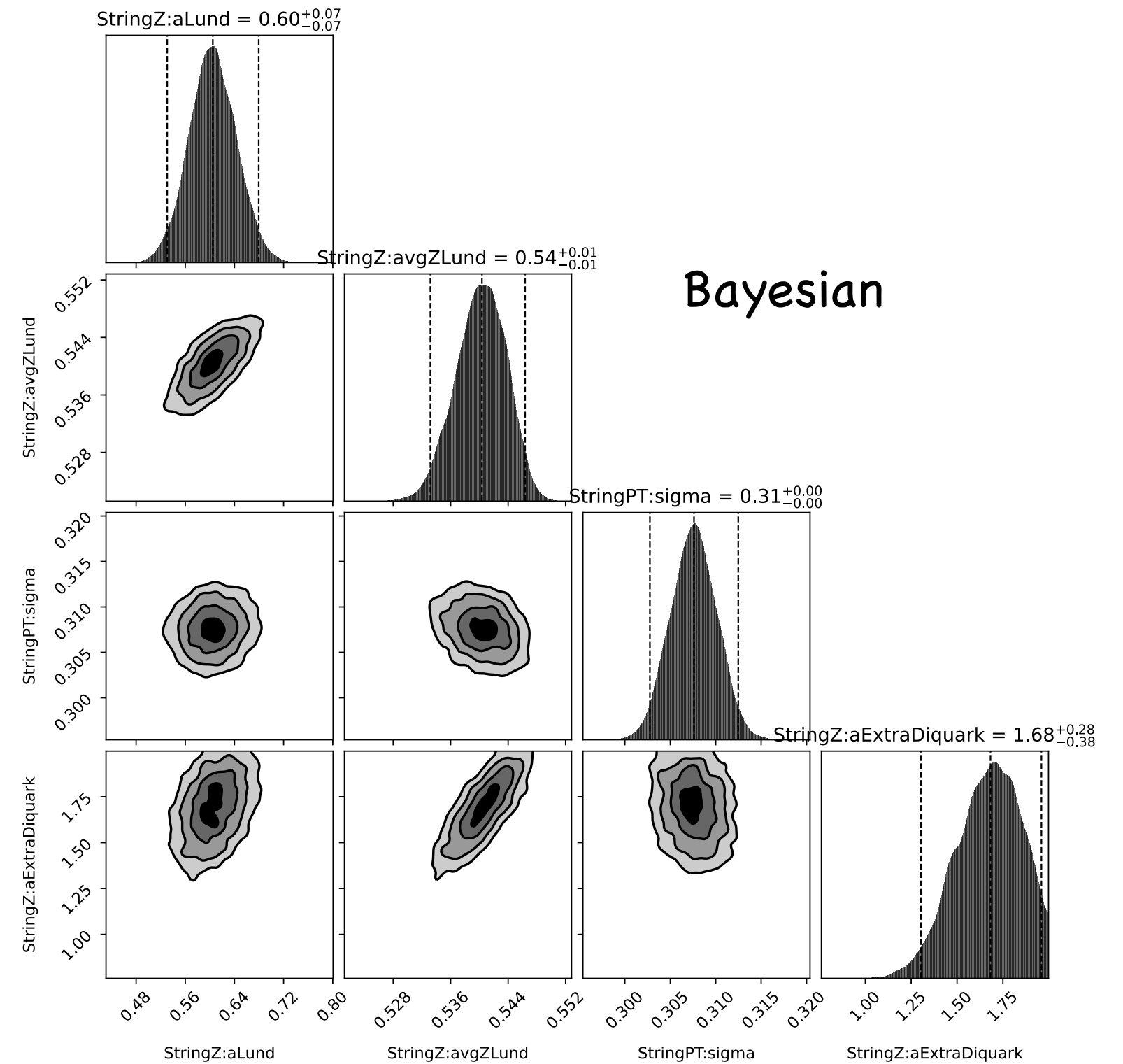
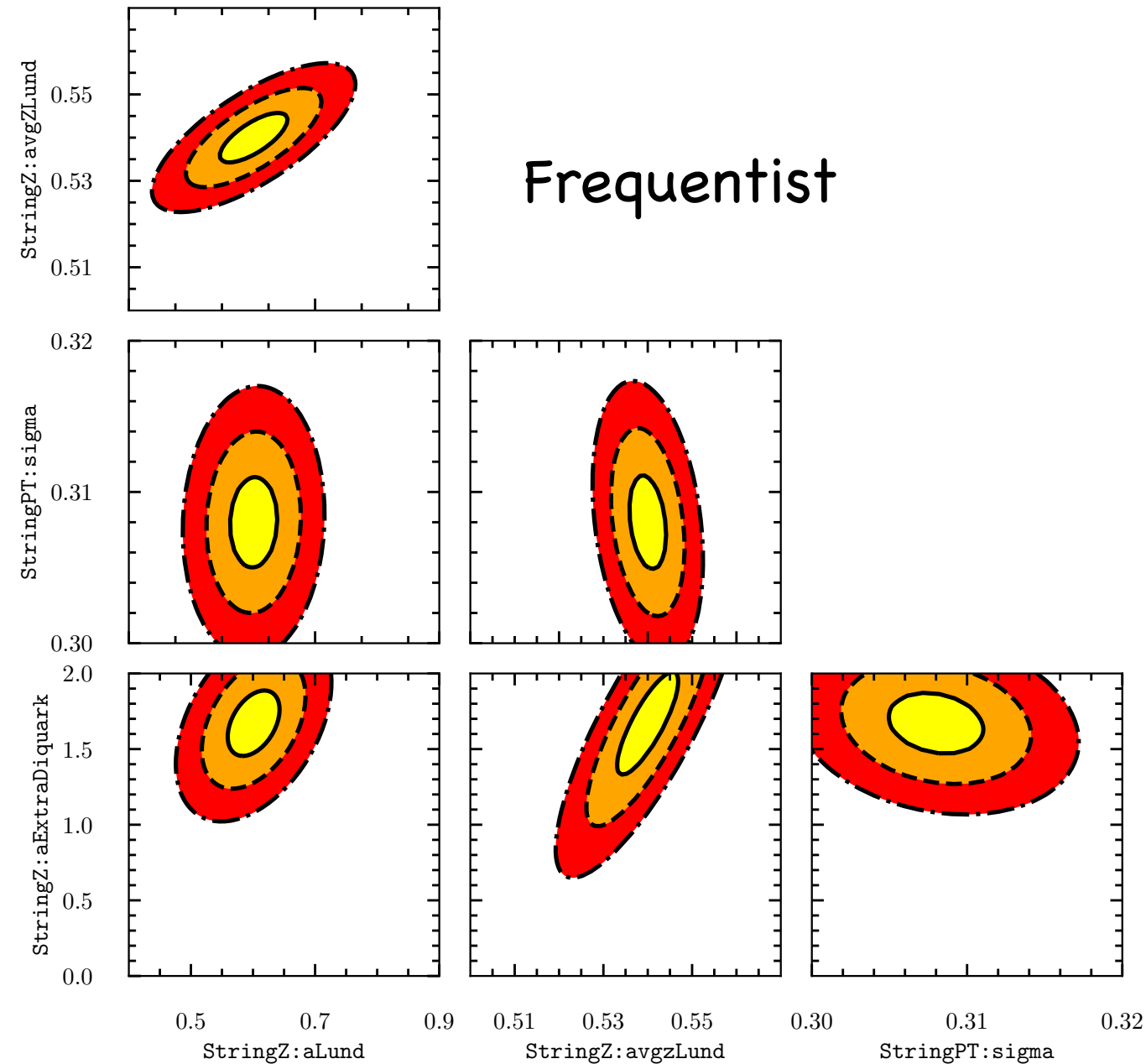
Tunes: Results

Parameter	PYTHIA8 setting	MONASH	This work	a_q	$\langle z_\rho \rangle$	$\sigma_\perp$ [GeV]	a_{QQ}
a_q	StringZ:aLund	0.68	$0.601^{+0.038}_{-0.038}$	1.000			
$\langle z_\rho \rangle$	StringZ:avgZLund	(0.55)	$0.540^{+0.004}_{-0.004}$	0.718	1.000		
$\sigma_\perp$ [GeV]	StringPT:Sigma	0.335	$0.307^{+0.002}_{-0.002}$	0.057	-0.270	1.000	
a_{QQ}	StringZ:aExtraDiquark	0.97	$1.671^{+0.196}_{-0.196}$	0.415	0.816	-0.204	1.000
b	StringZ:bLund	0.98	(0.897)				

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.

Tunes: Results



Good agreement between the results of the Frequentist and Bayesian fits

Estimate of hadronisation Uncertainties

Eigentunes method (also Hessian)

- Diagonalisation 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 $\Delta\chi^2 \equiv \chi_{\text{var}}^2 - \chi_{\text{min}}^2 = N_{\text{df}}$; two sigma for $\Delta\chi^2 \equiv \chi_{\text{var}}^2 - \chi_{\text{min}}^2 = 4N_{\text{df}}$ 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.

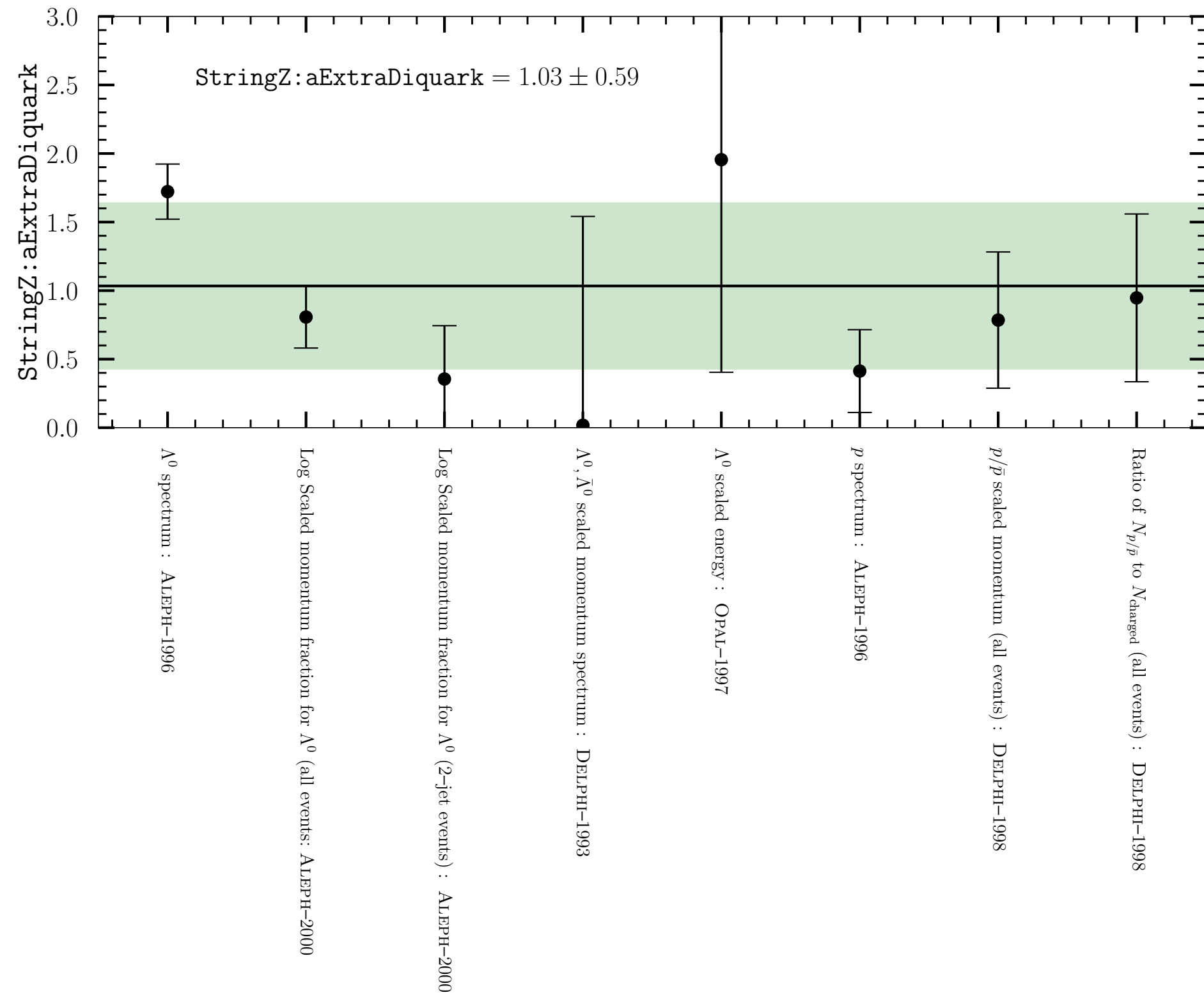
- Mrenna and Skands (1605.08352) developed an automatic method to estimate the shower uncertainties in PYTHIA.
- The method can be used as well to estimate the uncertainties on the non-singular parts of the DGLAP kernels.

We will use this method to estimate parton-shower uncertainties

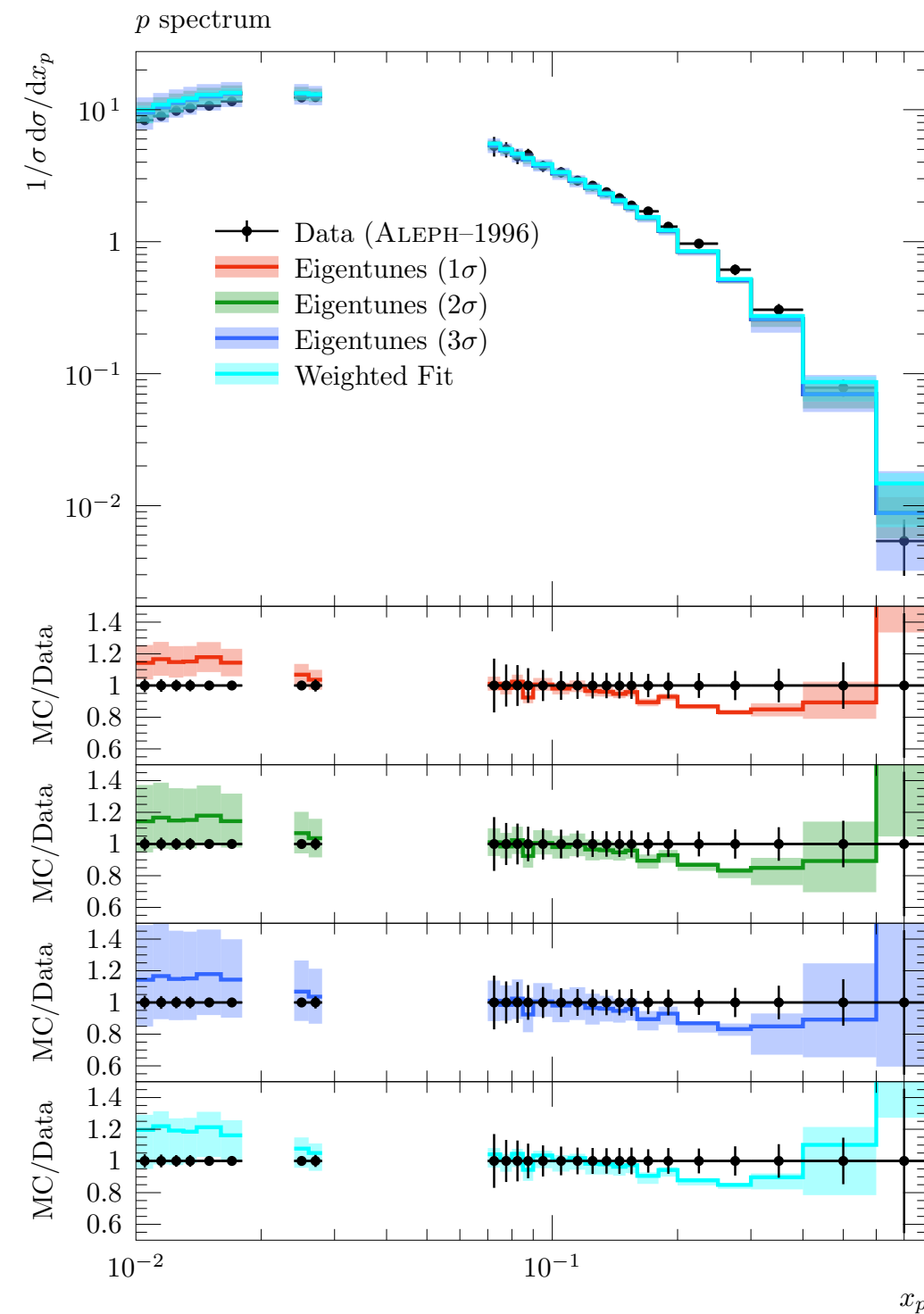
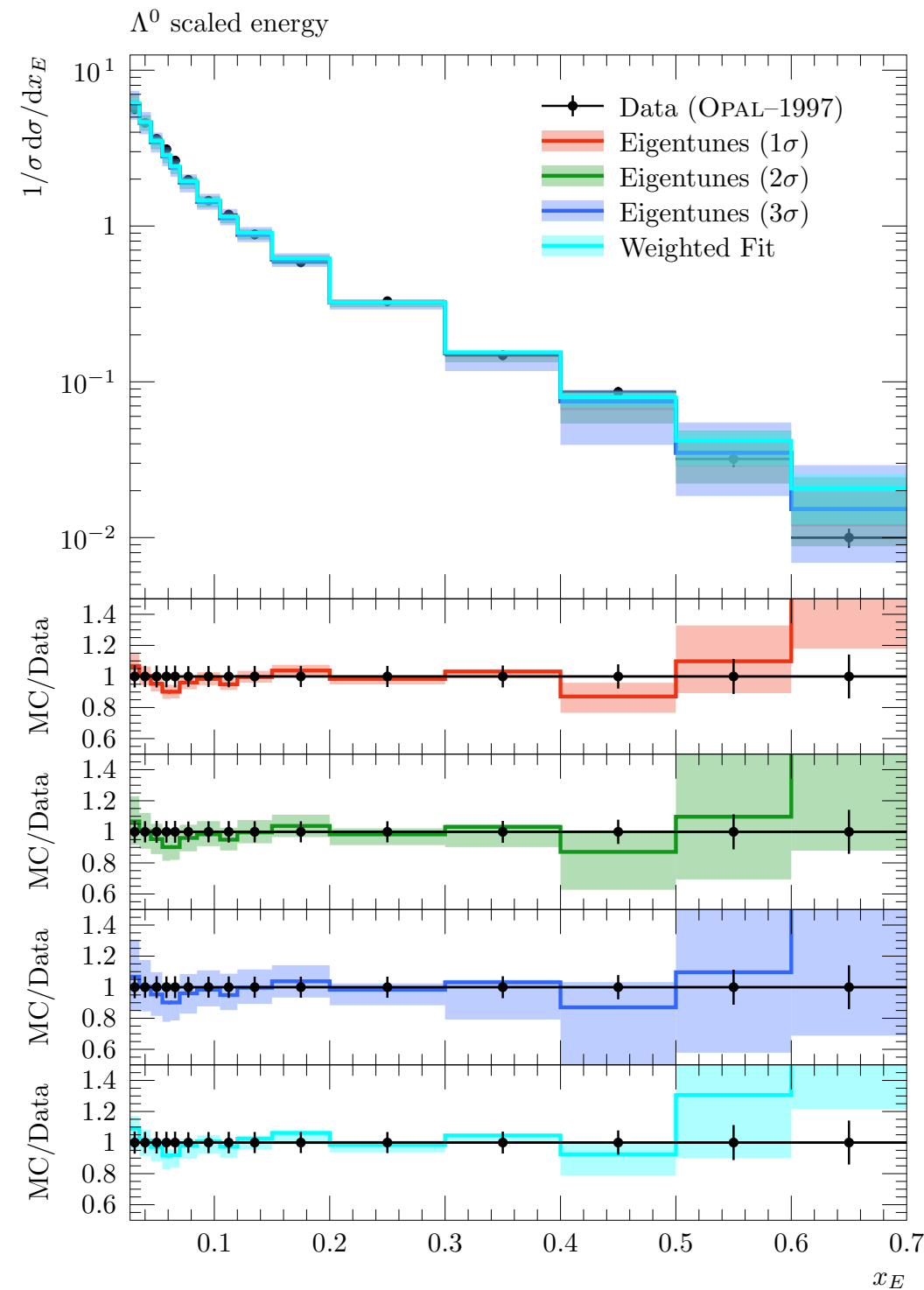
Hadronisation uncertainties: eigentunes

Tune	StringZ:aLund	StringZ:avgZLund	StringPT:sigma	StringZ:aExtraDiquark
Central	0.601	0.540	0.307	1.671
<i>1σ eigentunes</i>				
Variation 1 ⁺	0.608	0.542	0.307	1.771
Variation 1 ⁻	0.592	0.538	0.307	1.568
Variation 2 ⁺	0.498	0.535	0.306	1.679
Variation 2 ⁻	0.701	0.544	0.309	1.662
Variation 3 ⁺	0.599	0.575	0.321	1.671
Variation 3 ⁻	0.602	0.506	0.295	1.671
Variation 4 ⁺	0.601	0.511	0.384	1.671
Variation 4 ⁻	0.600	0.563	0.245	1.671
<i>2σ eigentunes</i>				
Variation 1 ⁺	0.609	0.542	0.307	1.775
Variation 1 ⁻	0.591	0.538	0.307	1.558
Variation 2 ⁺	0.501	0.535	0.306	1.679
Variation 2 ⁻	0.700	0.544	0.308	1.662
Variation 3 ⁺	0.597	0.609	0.333	1.670
Variation 3 ⁻	0.603	0.474	0.283	1.671
Variation 4 ⁺	0.601	0.478	0.475	1.672
Variation 4 ⁻	0.600	0.581	0.197	1.669

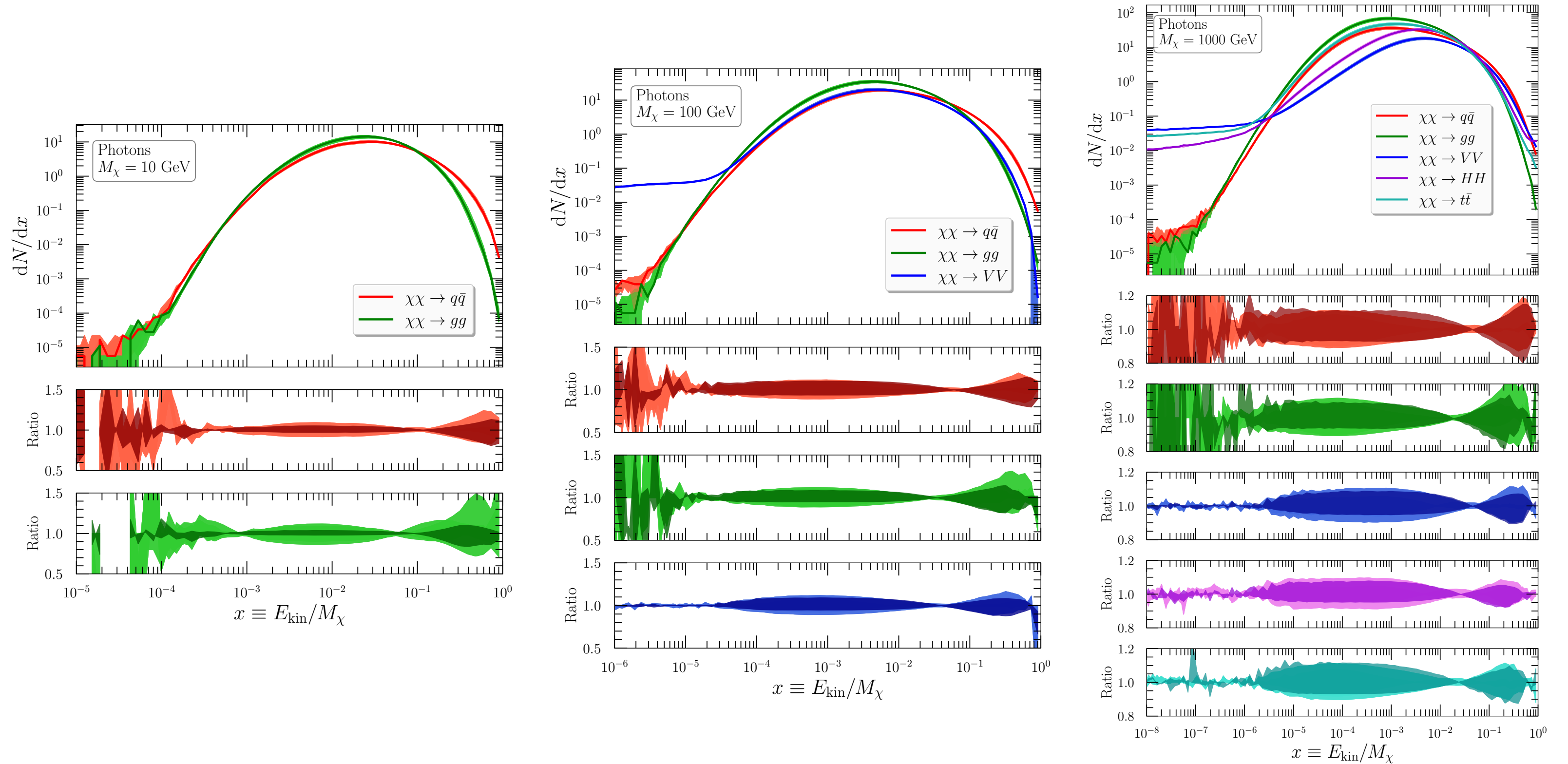
Hadronisation uncertainties: weighted fit



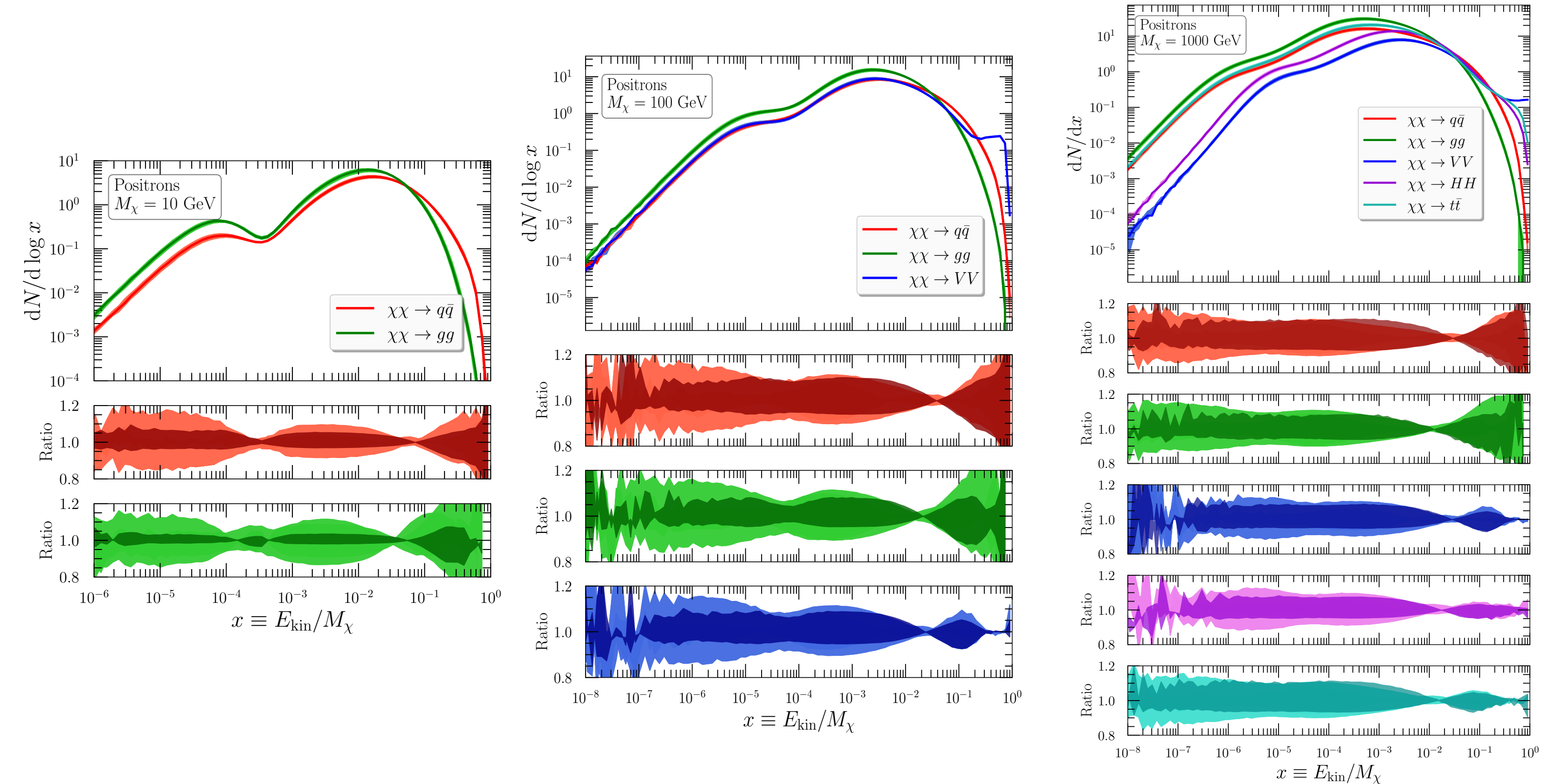
Hadronisation uncertainties: results



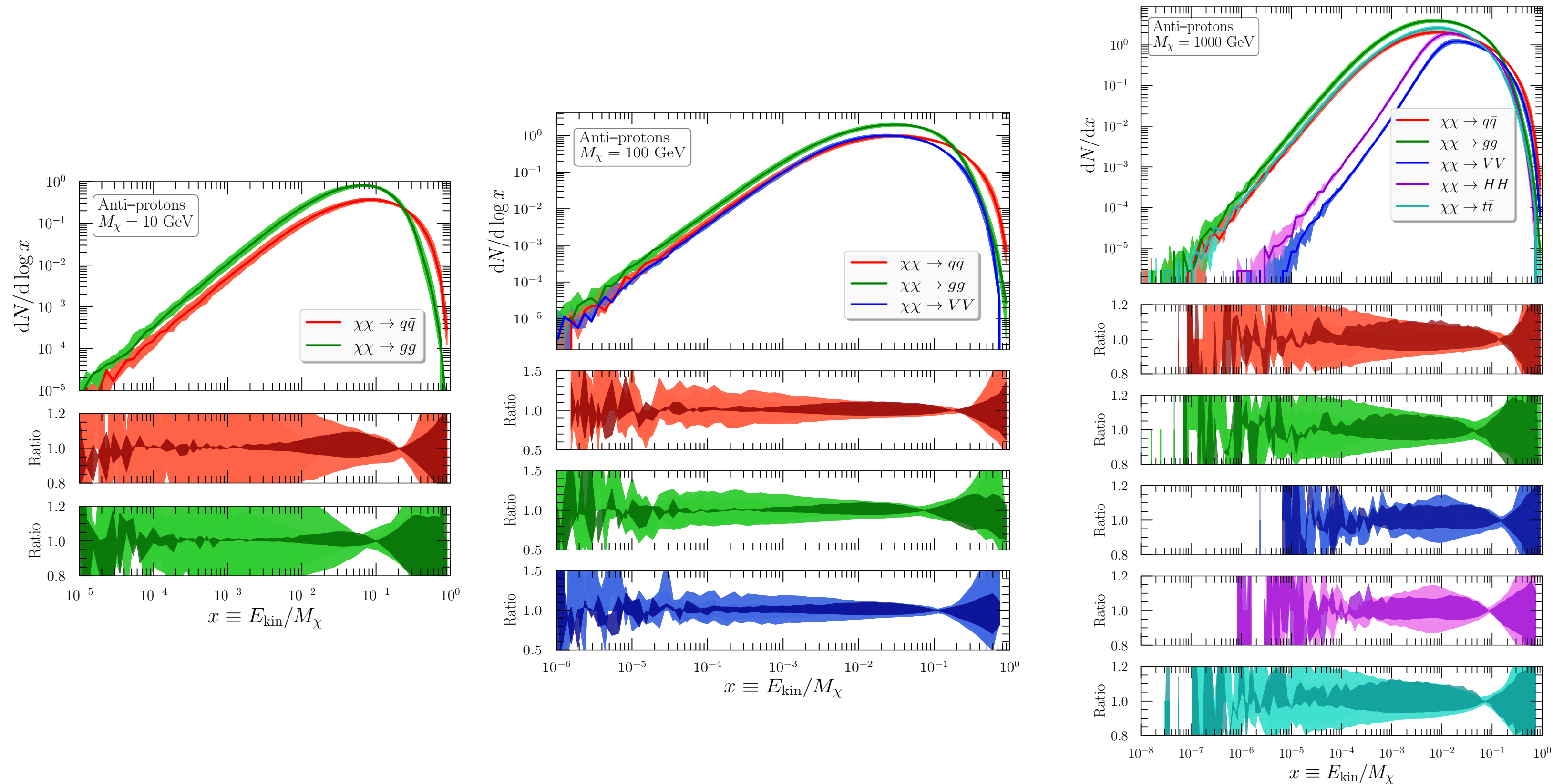
Particle spectra: Photons



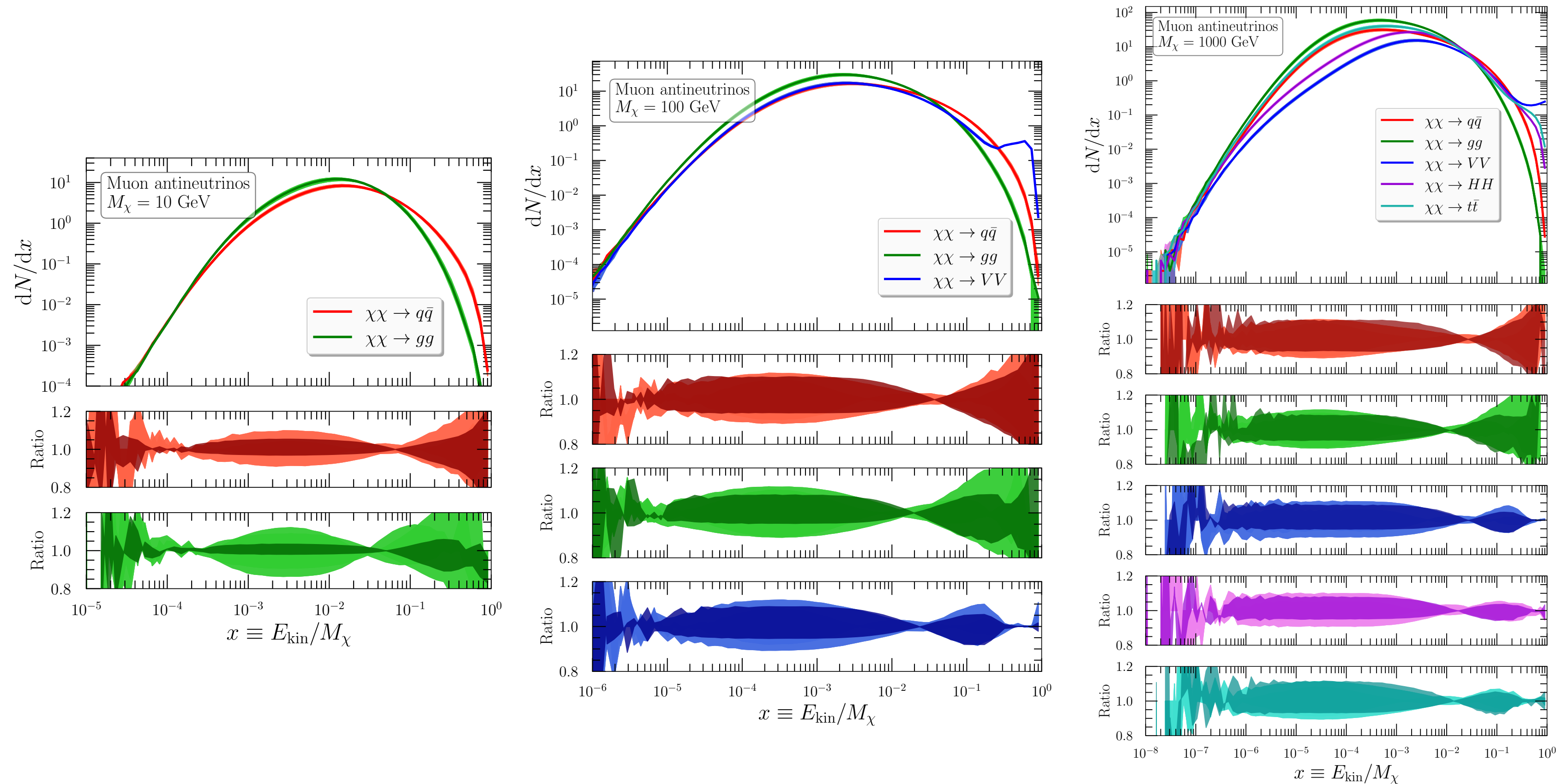
Particle spectra: Positrons



Particle spectra: Anti-protons

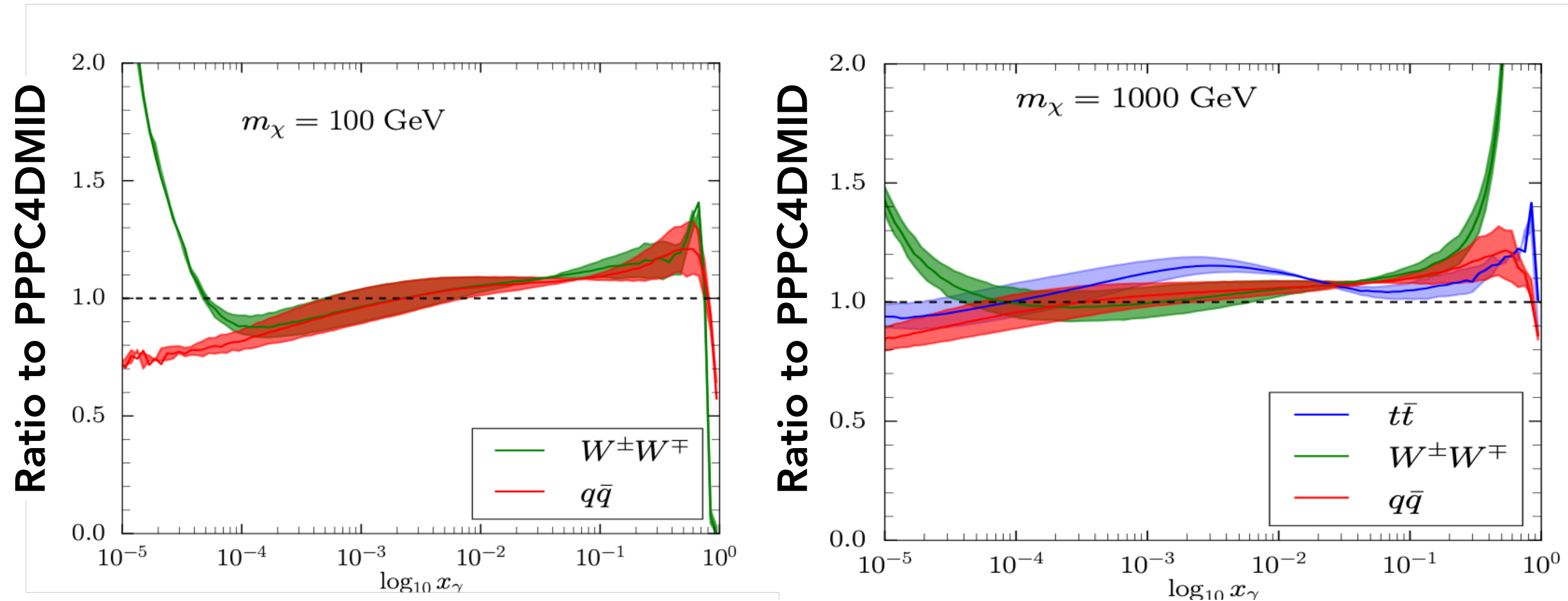


Particle spectra: Anti-neutrinos



Our results compared to the PPPC4DMID

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

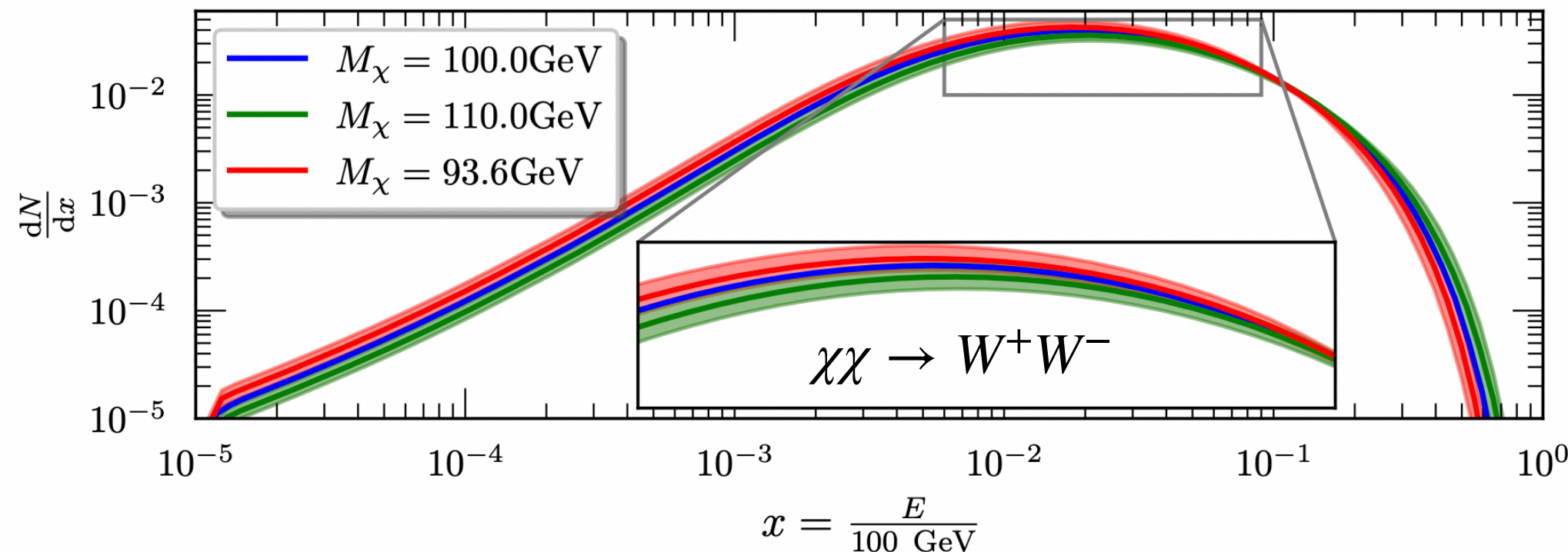


Disagreement of order 10 – 20 % in the peak region.

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

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

The screenshot shows the GitHub repository page for 'ajueid / qcd-dm.github.io'. The repository is public and has 13 commits. The file list includes:

File	Description	Last Commit
data	Tables for particle fluxes without uncertainties	last year
Interpolate.py	Example for mass interpolation	last year
README.md	Update README.md	10 months ago
Showcase.py	Example for mass interpolation	last year

The README.md file is open, showing the title 'Toolbox for QCD uncertainties on particle spectra from dark-matter annihilation' and an introduction section. The introduction text reads: '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:'. Below the text, there is a code snippet: 'DM DM -> e+e-, mu+ mu-, tau tau, uu, dd, ss, cc, bb, tt, WW, ZZ, gg, and hh (1)'.

We have released the spectra at production including QCD uncertainties in the form of tables along with some fast fitting and interpolation code snippets (<https://github.com/ajueid/qcd-dm.github.io>).

Conclusions

- We studied for the first time the QCD uncertainties relevant for DM searches through indirect detection experiments within the same modeling paradigm.
- We found that the envelope spanned by the predictions of the different multi-purpose event generators is not guaranteed to define a conservative uncertainty on the spectra.
- We found that uncertainties are not constant and can be small or large depending on many factors (DM mass, annihilation final state and energy bin of the particle specie) and the impact on DM fits can be dramatic.
- We released the datasets for 14 annihilation channels, and masses from 5 GeV to 100 TeV along with fast code snippets.
- The tables will be also included in the future releases of MicrOMEGAS, DarkSusy (already implemented) and MadDM.
- Work is ongoing on the high mass region ($M_\chi > 30$ TeV) where the electroweak corrections can be very important.

Thank you for your attention

