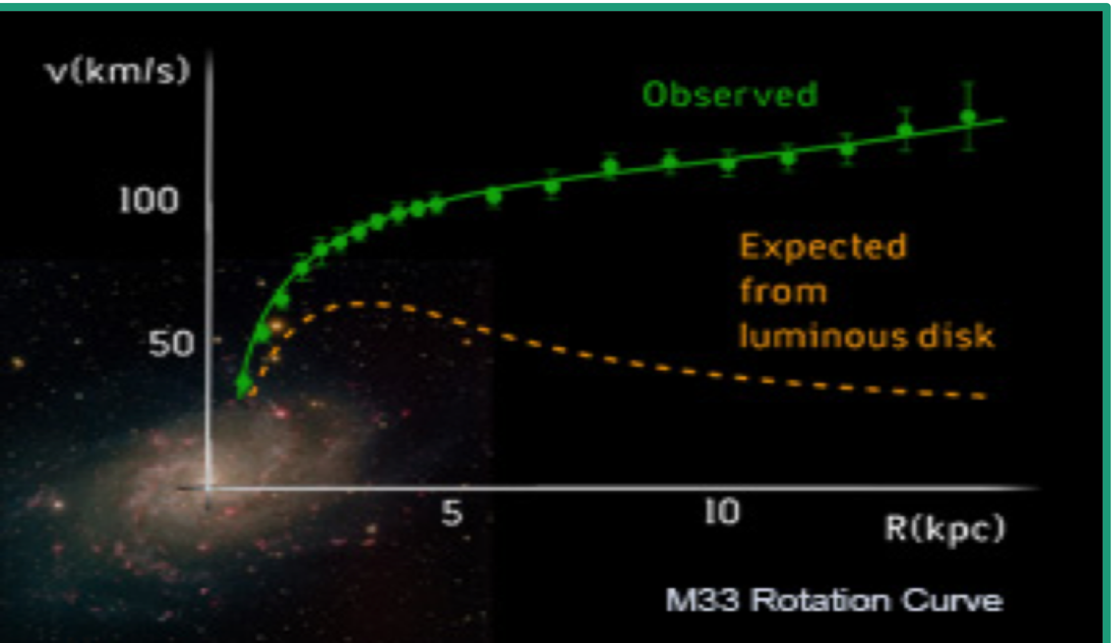
Studying QCD modeling of uncertainties in photon spectra from dark matter annihilation

上海交通大學
Shanghai Jiao Tong University

APEC Seminar, Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo

15 February 2019



ADIL JUEID

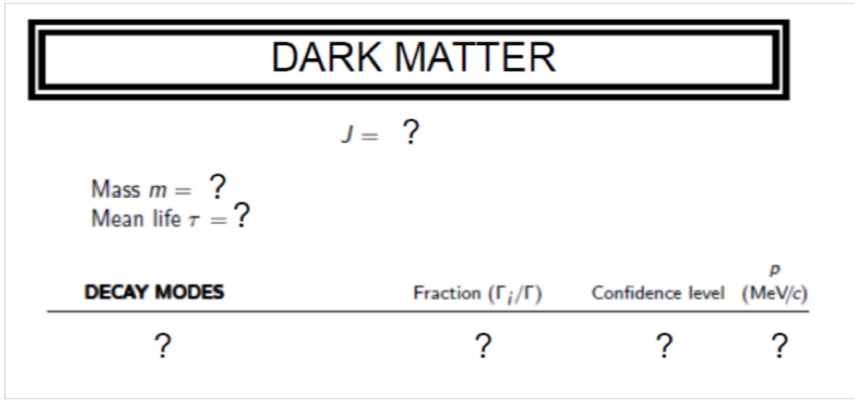
In Collaboration with

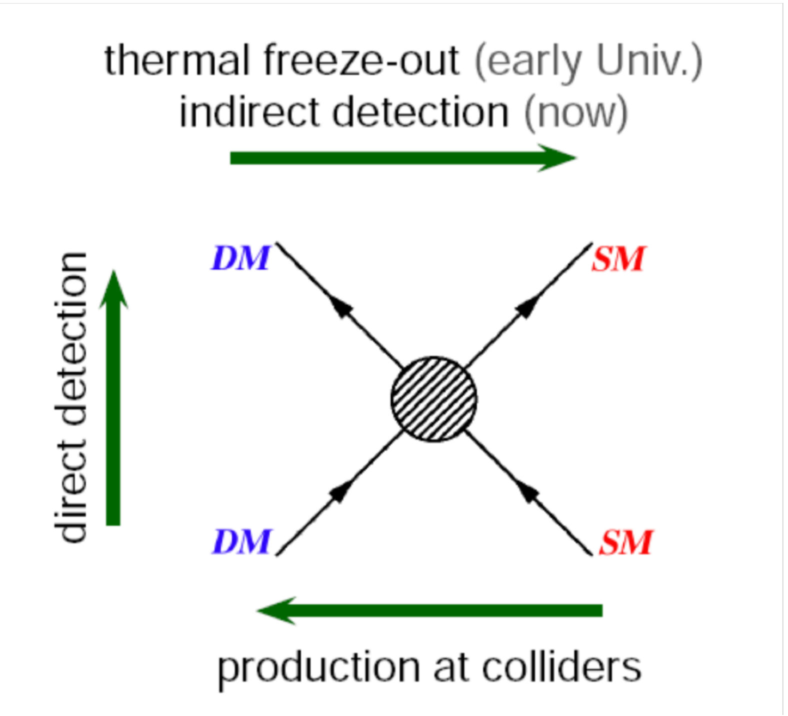
Simone Amoroso (DESY), Sascha Caron (NIKHEF), Roberto Ruiz de Austri (Valencia) and Peter Skands (Monash)

Based on 1812.07424 (Under review)

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 life time larger than the age of the universe.
- No SM particle can be a dark matter candidate. Dark Matter implies a Physics Beyond the Standard Model.
- There are different types of DM (WIMPs, axions, …).





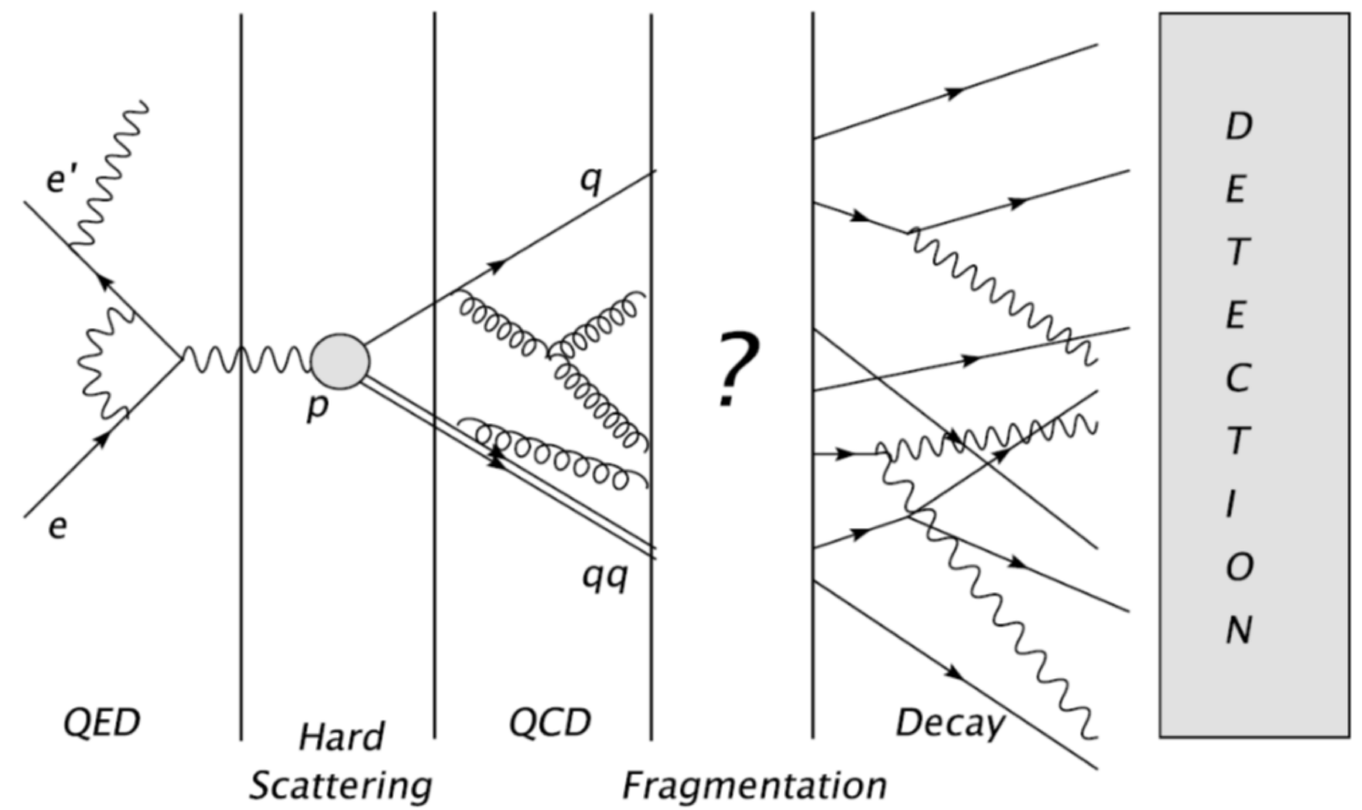
Introduction

- In many beyond the SM scenarios, WIMPs DM can be annihilated into a number final state particles $W^+W^-, q\bar{q}$ … etc.
- Those final state particles will undergo cascade of QED/QCD showers, hadronization and hadron decays to produce stable particles; photons, positrons, anti-protons, and neutrinos which can be detected in experiments such as FERMI-LAT or AMS.

Impossible to predict the spectra from first principles.

- There are two ways to model the spectra; either using parametric fits called fragmentation functions or dynamical models. The latter are implemented in multi-purpose MC event generators.
- The important point is that hadronization occurs at longer distances compared to the scale of the hard process ⟹ The parameters of the hadronization model can be constrained from fits to data (e.g. $e^+ e^- \longrightarrow$ hadrons) and then used to make predictions for other processes (e.g. dark matter annihilation).

Introduction



Introduction

- Gamma-rays are one of the most important channels for DM indirect detection.
- There are hints for possible excess over the SM astrophysical backgrounds (could be a sign of DM?)
- There are claims for it in the Fermi-LAT data (1511.02938) which triggered lots of theoretical papers to explain the excess in different theoretical models.
- The precision in the determination of the photon spectra from DM annihilation is important in the fitting procedure.

- The best-fit point is very sensitive to whether you choose a flat $X\%$ (like what many people do) uncertainty or non uncertainty at all (like what the others do).
- But we need to understand the modeling of the spectra, how to tune the hadronization model in way that we don't mess with the other observables and then try to estimate the uncertainty (that we claim to be conservative?)

Modeling of the Photon Spectra: QED part

- We consider the process

  $\chi\chi \longrightarrow X_1 X_2 X_3 \ldots X_n$ followed by $X_i \rightarrow Y_{i1}\, Y_{i2} Y_{i3}\, \ldots Y_{in}$

- The underlying physics depends on the nature of the produced resonance X_i and the particles produced in its decay.
- If X_i contains photons and/or electrically charged particles, then there are further QED emissions producing additional photons and charged fermions through $X_i^{\pm} \rightarrow A_i^{\pm}\gamma$ and $\gamma \rightarrow F\bar{F}$.
- The former is enhanced in both the soft $(E_\gamma \rightarrow 0)$ and the collinear $\theta_{A\gamma} \rightarrow 0$ regions. Therefore, the produced photon may take the whole energy of the parent provided that $\theta_{A\gamma} \rightarrow 0$.

These processes depend on the value of $\boldsymbol{\alpha_{EM}}$.

Modeling of the Photon Spectra: QCD part

- If X_i contains colored particles (such as gluons or top 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 showering is treated a la Sudakov with a shower evolution variable (which is different in different MC event generators); Herwig uses an angular ordered variable, Pythia uses a dipole p_T-ordered shower. Don't worry! the singular part (which dominates the emission) is universal and does not depend on the variable. Only some features are different (shower cut-off, treatment of mass effects, non-singular parts…).

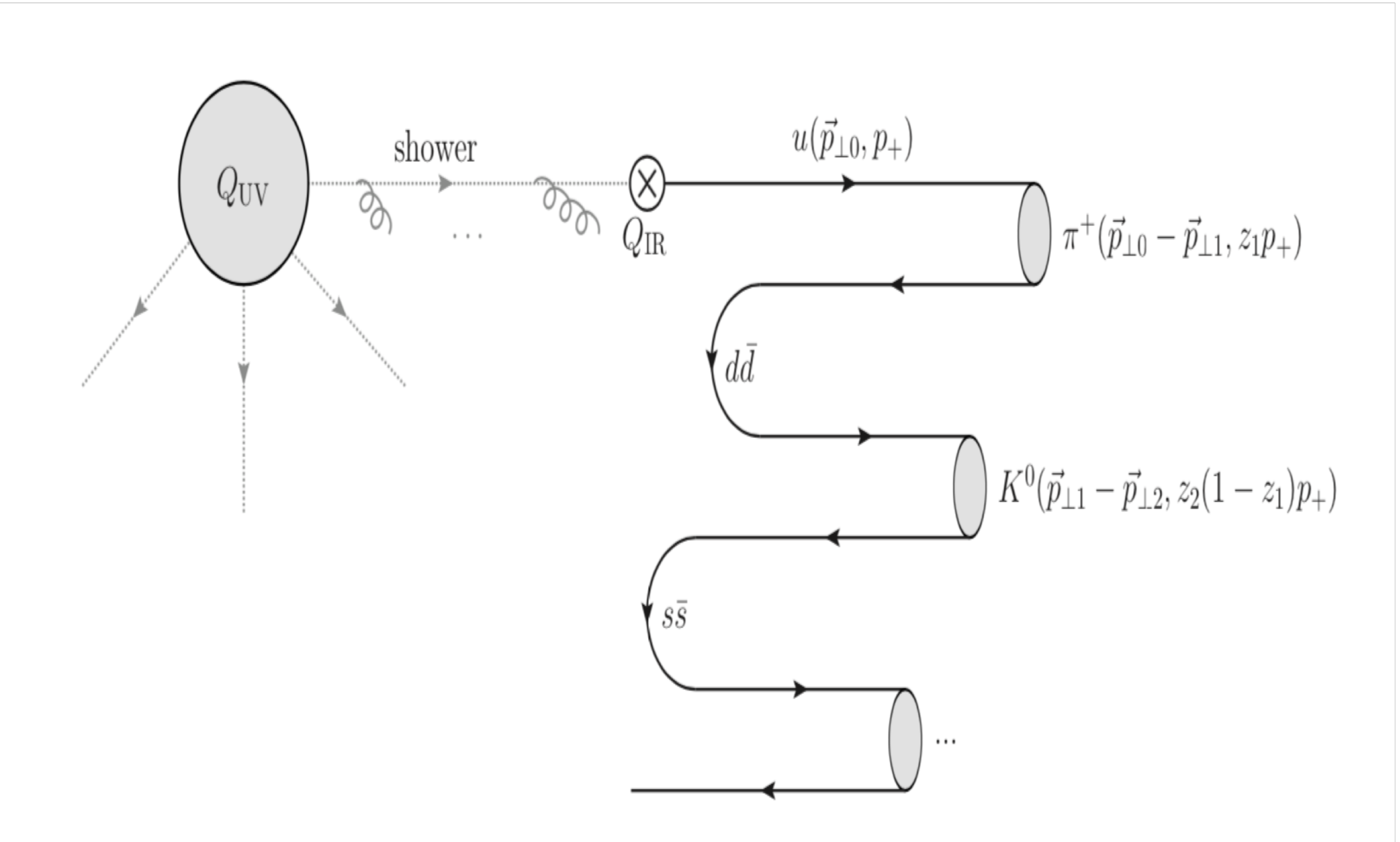
These processes depend on the value of α_S.

$t\bar{t}$ final state as an example

- It's an interesting example where all the phenomena (QED and QCD showers, resonance decays and hadronization) happen.
- First, the $t\bar{t}$ system will radiate gluons, and photons – depending on how far the system is from threshold –.
- If photons are produced in the radiation, then they will carry the highest composition of the initial top quark energy (although it happens with low probability).
- Second, resonant $t \rightarrow b\,W$ decays occur followed by showering of the b quark and W. Then the W-boson will decay and its decay products will shower before hadronization occurs.

Review: Hadronization in PYTHIA8

- Hadronization is a process where color triplets and octets (i.e. quarks and gluons) will fragment to form *color singlet hadrons*.
- The process happens at low scales (at the shower cut-off).
- There are two famous models used in MC event generators; Cluster and String models.



Taken from Skands' Lecture notes (1207.2389)

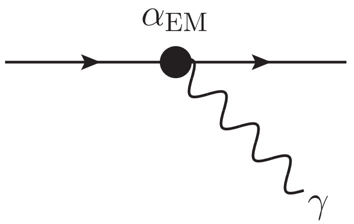
Review: Hadronization in PYTHIA8

The Lund string model is based on the following symmetric function

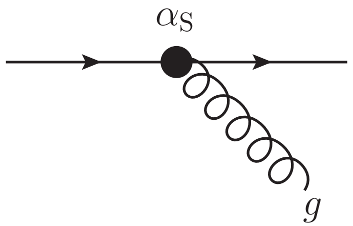
$$f(z, m_{\perp h}) = N\frac{(1-z)^a}{z}\exp\left(\frac{-bm_{\perp h}^2}{z}\right)$$

- It gives the probability to produce a hadron with energy fraction z and transverse mass $\mathrm{m}_{\perp \mathrm{h}}$.
- 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.
- If $f(z)$ is peaked around 1, then the QCD jet consists of few hadrons each carrying a high fraction of the parent energy.
- If $f(z)$ is peaked around 0, then the QCD jet consists of many hadrons each carrying a very low fraction of the parent energy.

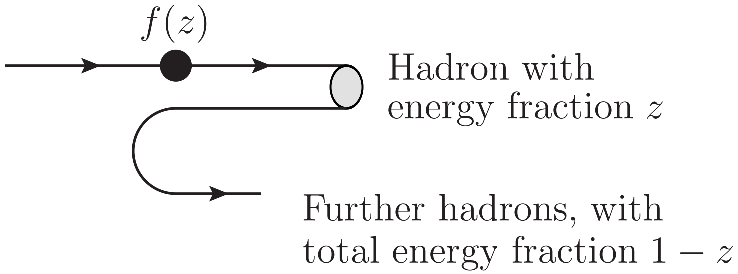
Modeling of the Photon Spectra: Resume



- 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.
- Should we ignore the variations on this parameters?



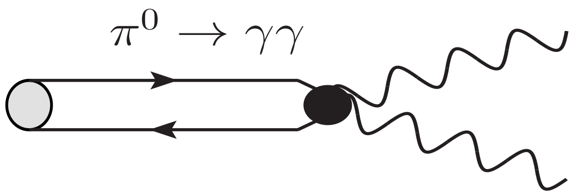
- Dominates at the bulk and the peak of the photon energy.
- The main parameter controlling the QCD showers is α_S.
- Very different value from the Msbar scheme; $\alpha_S(M_Z) \sim 0.139$
- Can be subjected to uncertainty estimates.

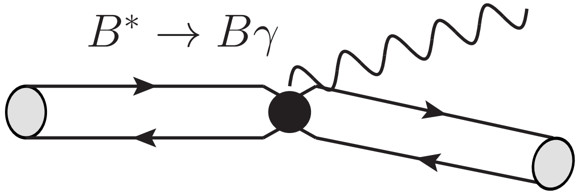


- Dominate at the bulk and the peak of the photon energy.
- Three parameters are relevant for this process (flavor-independent part).
- Can be subjected to uncertainty estimates.

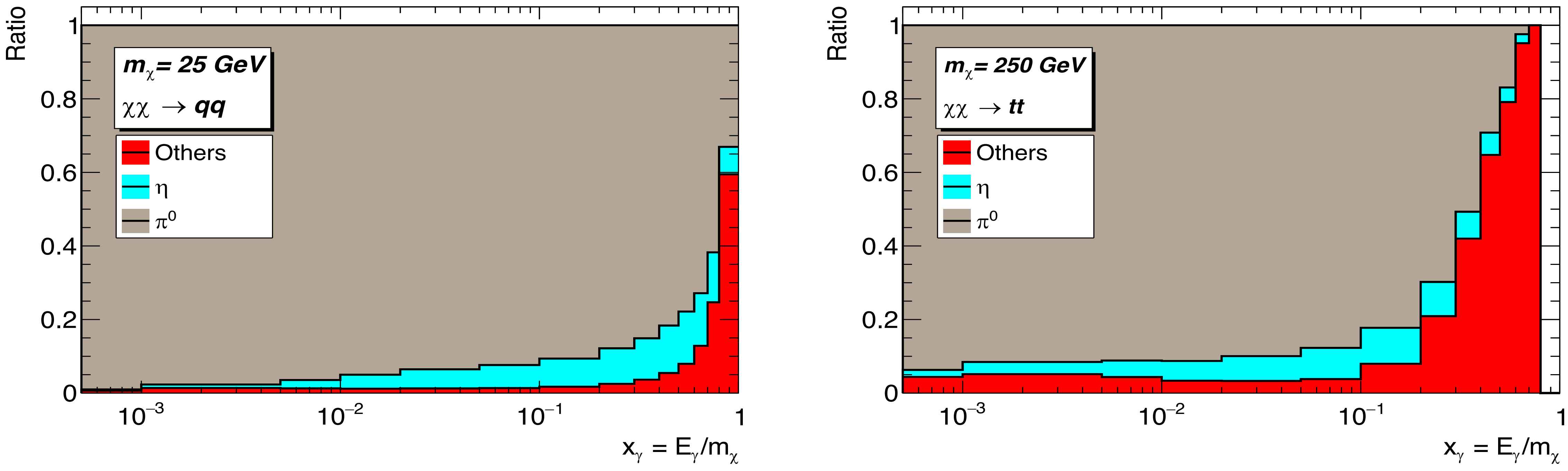
Origin of Photons

- In most of the cases, photons in QCD jets are produced from the decays of the neutral pions since $BR(\pi^0 \to \gamma\gamma) \approx 100\%$.
- In some cases, e.g. production of b-quarks near the threshold, the photons are produced from radiative decays of vector mesons.
- Second most important source of photons is the decay of η mesons; either through $\eta \to \gamma + X$ or $\eta \to \pi^0 + X$.
- Photons from bremsstrahlung dominate the extreme of the energy distribution





Origin of Photons



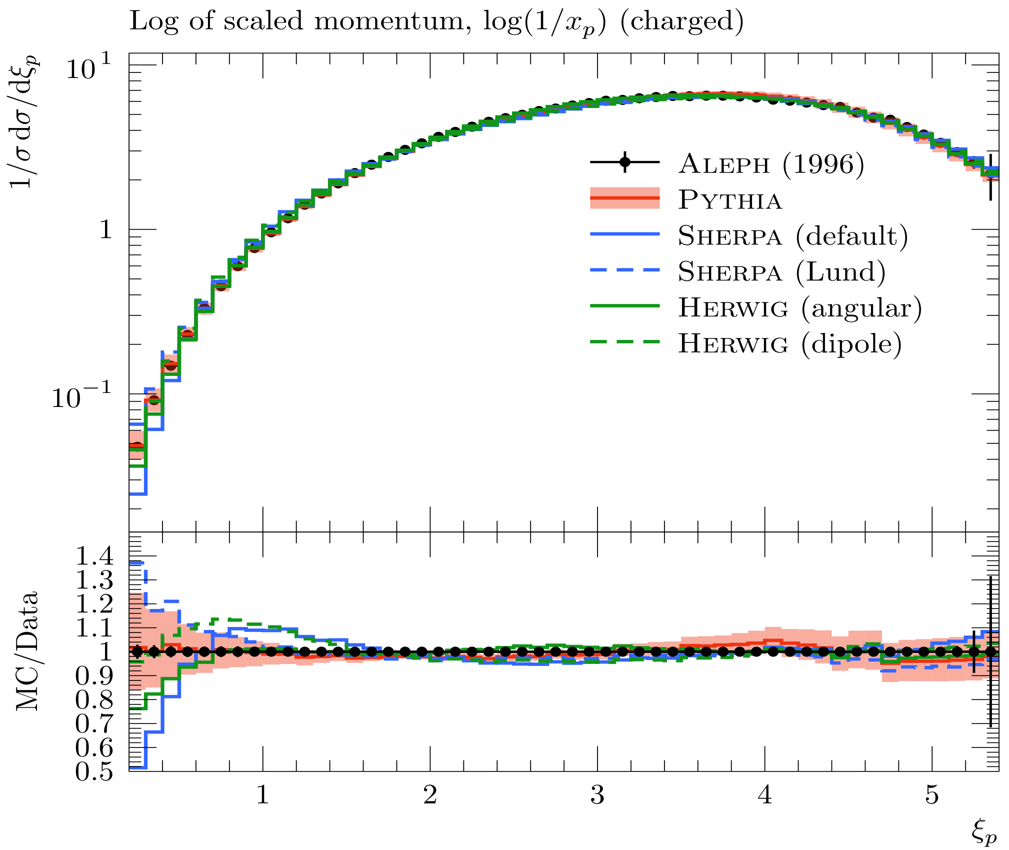
Important Question: what is the uncertainty on the derived spectra?

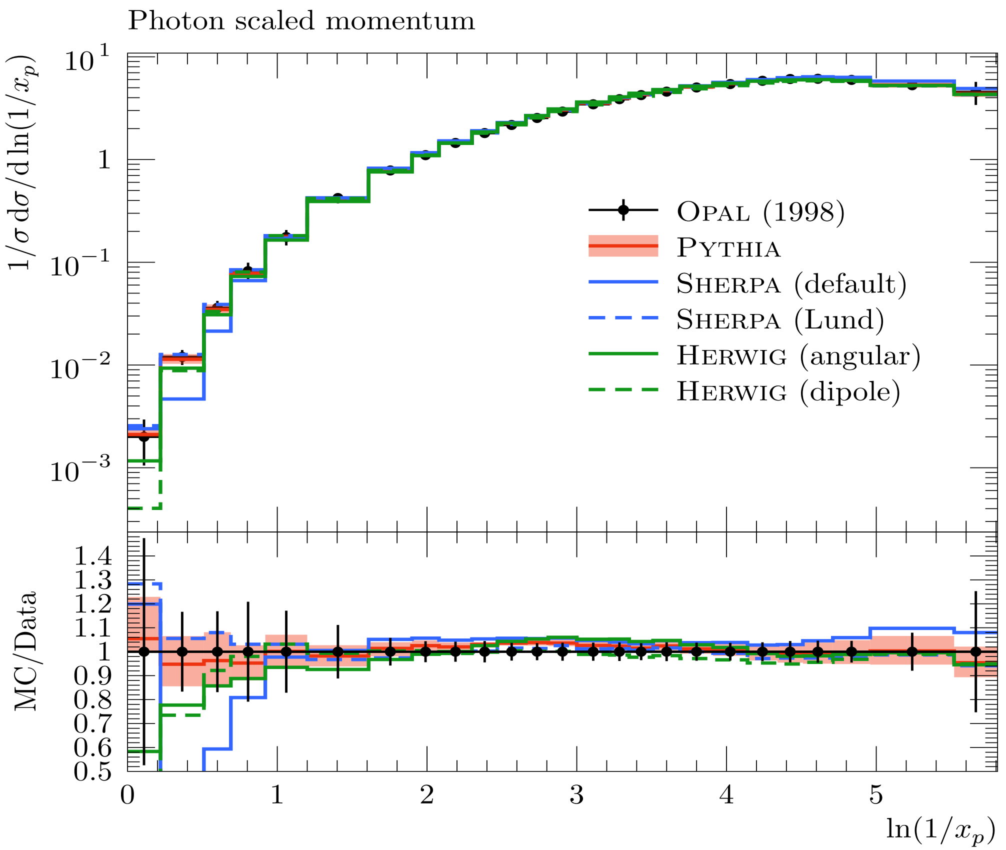
The modeling of the uncertainties: The old method

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 as 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).

The modeling of the uncertainties: The old method





What to include in the Tuning?

- From the study of photons sources; it seems natural to include the spectra of π^0 and η mesons in addition to the photon spectra itself.
- Due to isospin symmetry, the spectra of $\pi^\pm$ need to be included. The good thing about charged pions is that they provide complementary constraints as they are more precisely measured down to very low energies.
- We should also make sure that the tuning don’t imply significant variations to the event shapes (more sensitive to the transverse components of the fragmentation function).

Tuning procedure

- Different tunings of the parameters of the Lund fragmentation function are performed.
- Three parameters are tuned (a, b and σ) or equivalently ($a, < z_\rho >$ and σ).
- They are tuned to a set of measurements available at LEP-I energy (ALEPH, DELPHI, L3, OPAL and SLD).
- We include the most sensitive measurements; mean multiplicities, identified particle momenta ($\pi^0, \pi^\pm, \gamma$ and η), event shapes, jet rates and charged particle momenta.

Tuning procedure

- We use Professor (0907.2973) for optimization of the parameters of the fragmentation function in Pythia.
- We modify slightly the definition of the Goodness-of-Fit in Professor to account for a flat 5% uncertainty in the MC predictions.
    - Necessary to account for the incomplete knowledge of the modeling e.g. missing higher order corrections.
    - Necessary to avoid over-fitting effects in the tuning.
    - Necessary to get a Goodness-of-Fit/ndf of order unity.
- We include different weights for different measurements (highest weight given to photon and pion spectra, and so on).

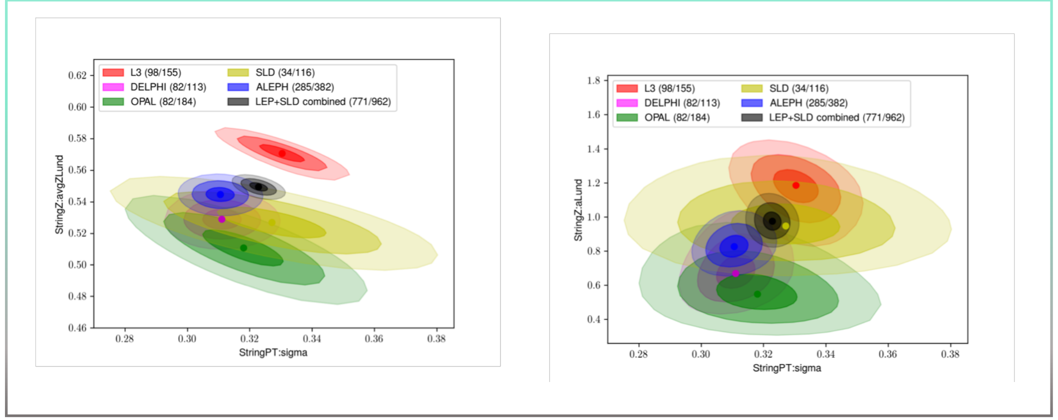
Tuning results: with or without 5% theory uncertainty?

Parameter	Results	Additional 5% uncertainty → New Z
StringPT:Sigma	$0.3151^{+0.0010}_{-0.00010}$	$0.3227^{+0.0028}_{-0.0028}$
StringZ:aLund	$1.028^{+0.031}_{-0.031}$	$0.976^{+0.054}_{-0.052}$
StringZ:avgZLund	$0.5534^{+0.0010}_{-0.0010}$	$0.5496^{+0.0026}_{-0.0026}$
χ^2/ndf	5169/963	778/963

- Obvious that the Gof/ndf is improved after including the 5% uncertainty.
- Most importantly, the error on the determination of the parameters is getting larger by a factor of 2 (consequence of reducing overfitting).

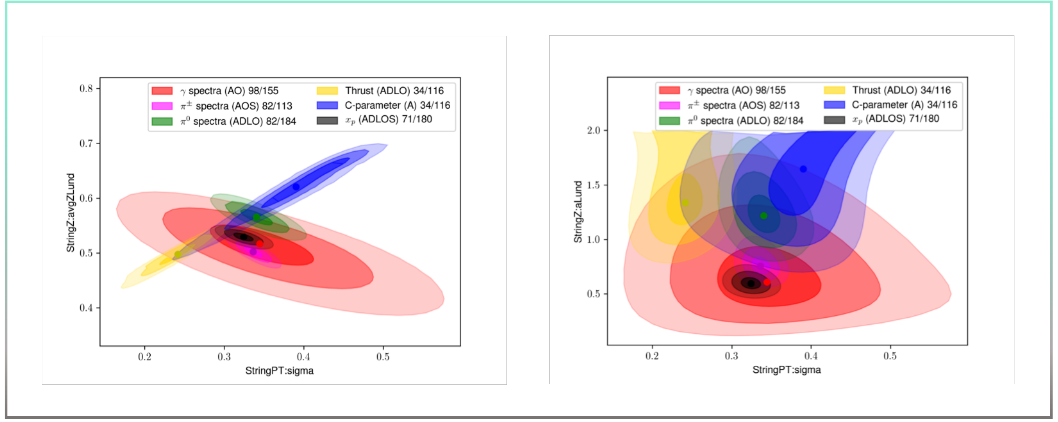
Tuning results: How data is consistent?

- Make different tunes including only measurements from one experiment at one time, i.e. one tune for ALEPH, one for DELPHI…
- Compare the central value of the parameters and their confidence intervals of different experiments.
- Only L3 is inconsistent with the others at more than the 3σ level.



Tuning results: How measurements are consistent?

- Make different tunes including only one observable at a time, i.e. one for the Thrust, ... etc (from all the experiments that contain measurement of the observable)
- Thrust prefers low values of σ compared to e.g. γ-spectrum (should be balanced by other parameters).
- This tune is only used to assess the effect of one observable at one time (won't be taken as a final result).



Uncertainty estimate: The eigentunes method

- Professor has a method of estimating the uncertainty by using the eigentunes method.
- The method consists of diagonalizing 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. If $\chi^2_{min} \leq 1$, then a one-sigma deviation corresponds to $\Delta\chi^2 = 1$, two-sigma deviation to $\Delta\chi^2 = 2$ and so on.
- Due to the correlation among the parameters, the eigentunes give tiny uncertainties which *cannot* interpreted as conservative.

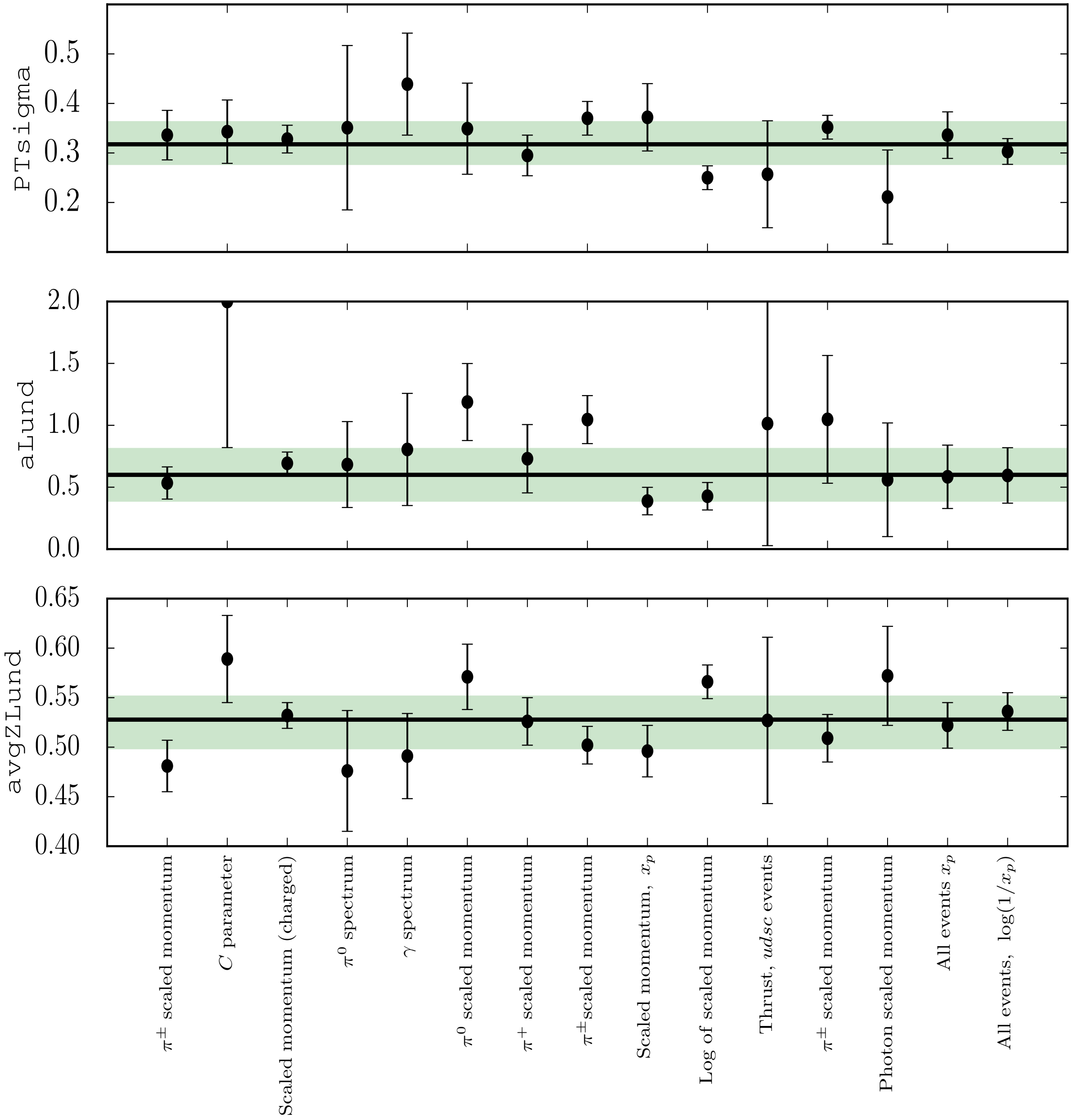
Uncertainty estimate: The manual method

- Due to the limitation of the eigentunes method, we use an alternative method to estimate the fragmentation uncertainties; we call it a manual method and you are allowed to call it a hybrid method (manual and automatic).
  - Choose a set of the most sensitive observables (remove the outliers). We choose 15 observables.
  - Perform a tune of the parameters to every observable separately.
  - The best fit point is the average of all the tunes.
  - The 68% CL interval of the spread of the different tunes can be defined as the uncertainty on the parameters' estimate.

Uncertainty estimate: The manual method

Parameter	Value
StringZ:aLund	0.5999 ± 0.2
StringZ:avgZLund	$0.5278^{+0.027}_{-0.023}$
StringPT:sigma	$0.3174^{+0.042}_{-0.037}$

- Values of the parameters are quite different from the other tunes. However, the predictions of this tune on different observables are in perfect agreement with those of the *weighted fit*.
- It is Unsurprising because in this manual fit, only the observables with largest impact and lowest experimental errors are included (i.e. no outliers such as e.g. η spectra are included).
- There are 26 possible variations of the parameters; the envelope spanned by the different variations defines a conservative estimate of the uncertainty (only 10 variations are relevant).



Uncertainty estimate: What about α_S?

- 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.

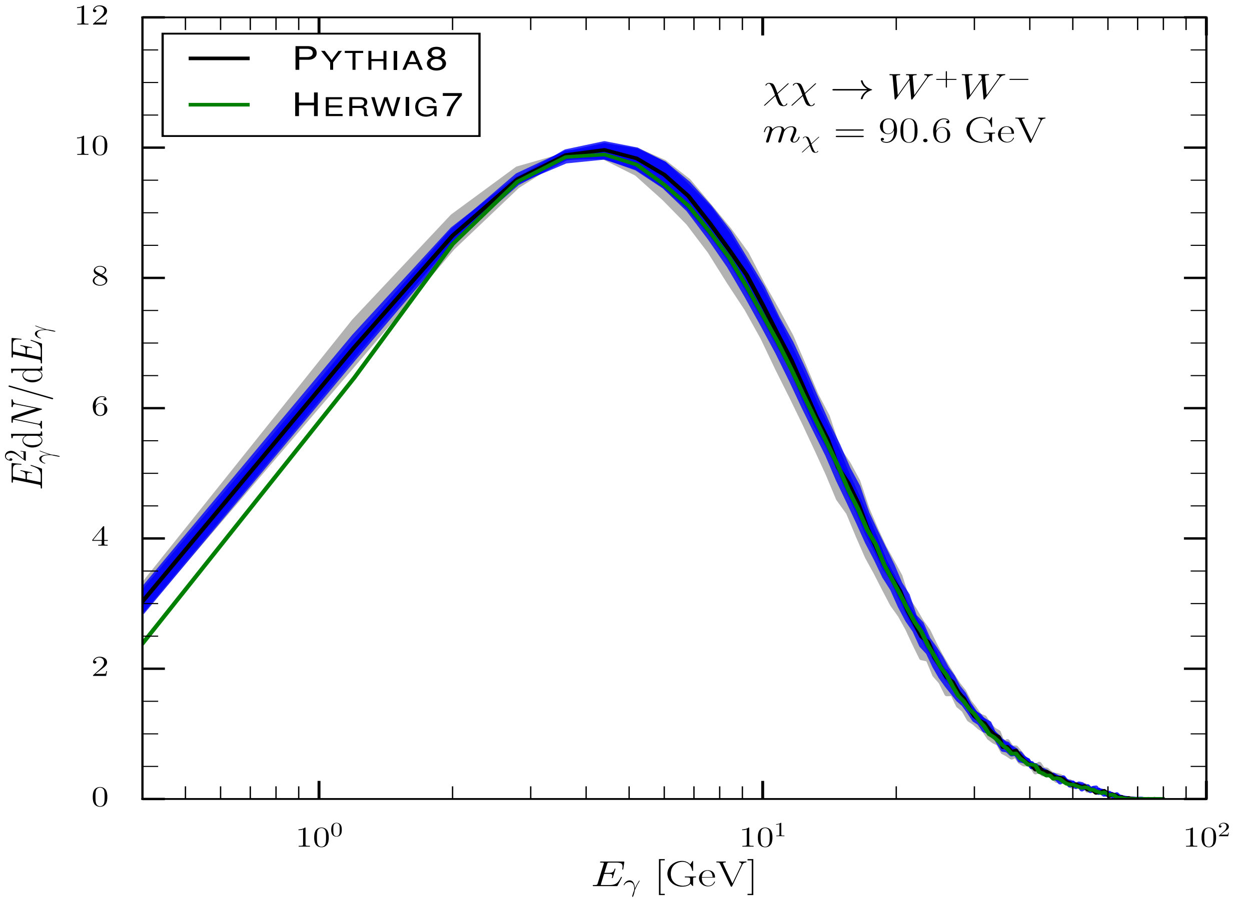
- Mrenna and Skands (1605.08352) developed an automatic method to estimate the shower uncertainties in PYTHIA.
- The method can be used as well to estimate the uncertainties on the non-singular parts of the DGLAP kernels.
- We use this method to estimate shower uncertainties as well.

Impact on Photon Spectra in Dark Matter Annihilation

- In a previous work of some of us (1709.10429), a study of the implications of the Fermi-Lat excess on the phenomenological MSSM (pMSSM) was performed.
- They showed in their analysis that a neutralino DM with mass 85-220 GeV is consistent with the Data for DM annihilation to W-bosons and top quarks.
- We qualitatively study the impact on the photon spectra in DM annihilation in two pMSSM best-fit points (consistent with Fermi-Lat); i.e. $m_\chi = 90.6$ GeV annihilating to WW and $m_\chi = 177.6$ GeV annihilating to tt (I show here the case of WW).

Impact on Photon Spectra in Dark Matter Annihilation

- Parton shower variations imply a shift in the position of the peak (very interesting for fits to gamma-ray DM searches). Dominates in the regions just before and after the peak (can reach up to 10-15%).
- Hadronization uncertainties around 5-30%.
- Herwig deviates from Pythia in the very extremes of the photon spectra by 20-70% (Do not have a significant impact on the fits)



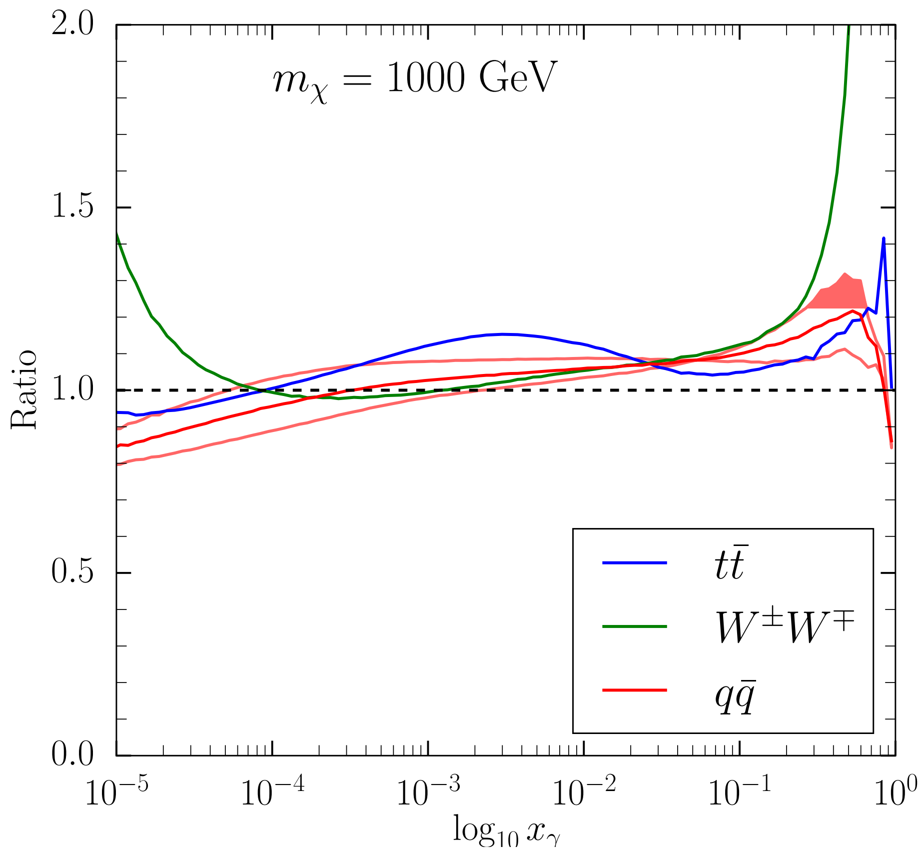
Blue band corresponds to hadronization uncertainties
Gray band corresponds to shower uncertainties.

Our results compared to the PPPC 4 DM ID ?

- M. Cirelli et al. studied particle spectra in DM indirect detection **(1012.4515)** producing a complete recipe (in the form of tables) of the spectra of photons, positrons, anti-protons and neutrinos for a wide range of DM masses (5 GeV-100 TeV). It's called Poor Particle Physics Cookbook for Dark Matter Indirection Detection (PPPC 4 DM ID).
- However, the study used Pythia8-135 which is based on an old tune that is replaced by the most recent Monash tune.
- Furthermore, the version used by the authors of the PPPC lacks several capabilities such as QED radiation off heavy-particles, EW showers, among others.

Our results compared to the PPPC 4 DM ID ?

- Disagreement of about 10-20% in the peak regions.
- More than 200% in the extreme region ($x_\gamma \to 1$) of the spectra for e.g. W^+W^-.
- Many salient changes on PYTHIA8 happened since PYTHIA8-135 (version used in the PPPC).
- The PPPC 4 DM ID should be updated (in progress).
- We are working on new Tables that will contain the spectra and the uncertainties for various final states and dark matter masses.



$x_\gamma = E_\gamma/m_\gamma$ and we display a Ratio defined as $\left(\frac{d\sigma}{dx_\gamma}\right)_{ACJRS} / \left(\frac{d\sigma}{dx_\gamma}\right)_{PPPC}$. The bands show hadronization uncertainties.

Conclusions

- We studied for the first time the QCD uncertainties relevant for gamma-ray DM searches 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 photon).
- We are in contact with the Cookbook authors to implement the spectra in their website and also in standard DM tools.
- The uncertainties we derived can be also applied to the flavor-independent part in collider studies as well.

Outlook

- This study will open new era for QCD uncertainties (especially the non-perturbative part); also because we are approaching a precision era in Collider and Non-Collider Particle Physics.
- The finding motivates new studies relevant for Collider Physics (especially in Top Quark and Higgs boson sectors); We believe that using this method is relevant for e.g. Top quark mass determination (especially in connection with global event-properties such as e.g. colour reconnections).
- The study itself can be extended (work in progress) to study the uncertainties on anti-matter spectra (relevant for e.g. AMS or IceCube).
- The spectra of secondary particles produced from cosmic-ray interactions are sensitive to QCD fragmentation (can be also used to test fragmentation function universality).

Thank you for your kind attention