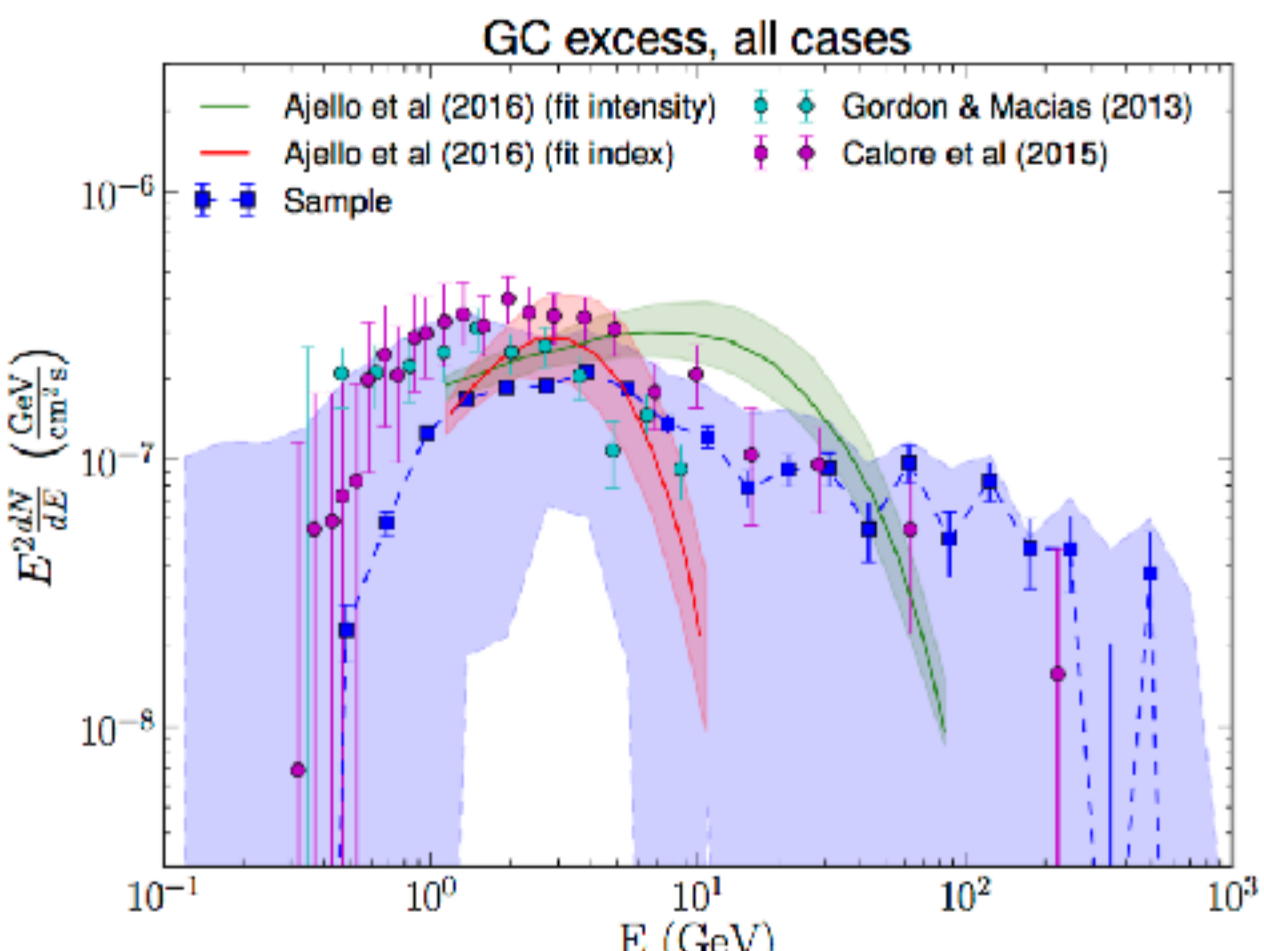
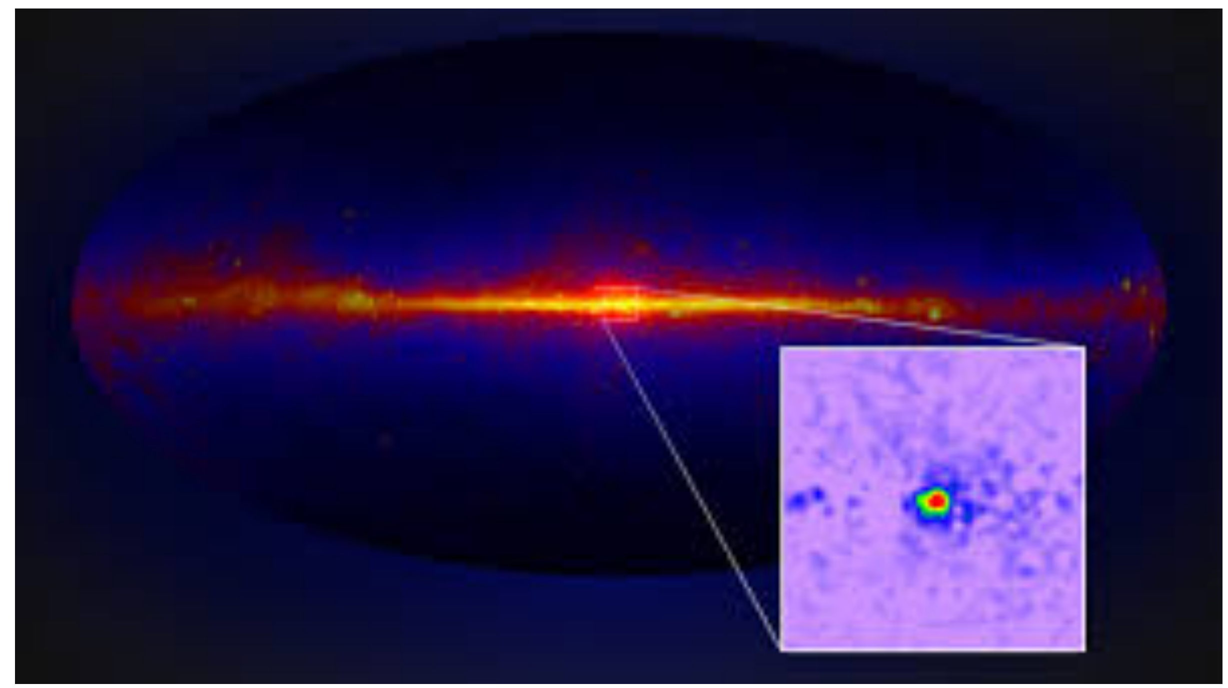
Attacking QCD uncertainties for gamma-ray Dark-matter searches

SUSY 2018 (Barcelona)

Jul. 23rd, 2018





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In collaboration with
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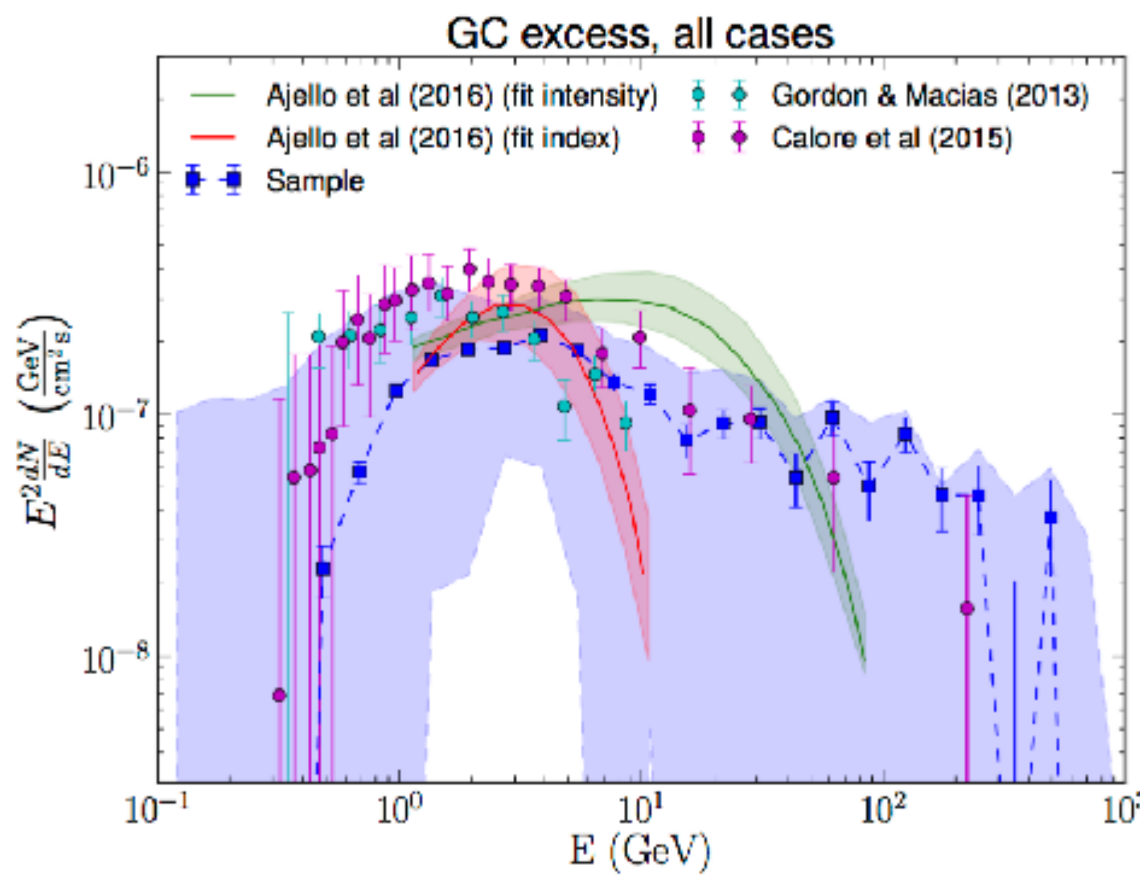
- Gamma-rays are one of the primary channels for DM indirect detection
- And we do have hints for possible excesses over astrophysical backgrounds (e.g. GC excess)
  - Claims for it to be present in the Fermi-LAT data [1704.03910]
  - Tons of phenomenological papers interpreting the excess in different models (e.g. MSSM)
- Precision in the determination of the gamma-ray spectrum from DM annihilation plays a fundamental role in fits to data



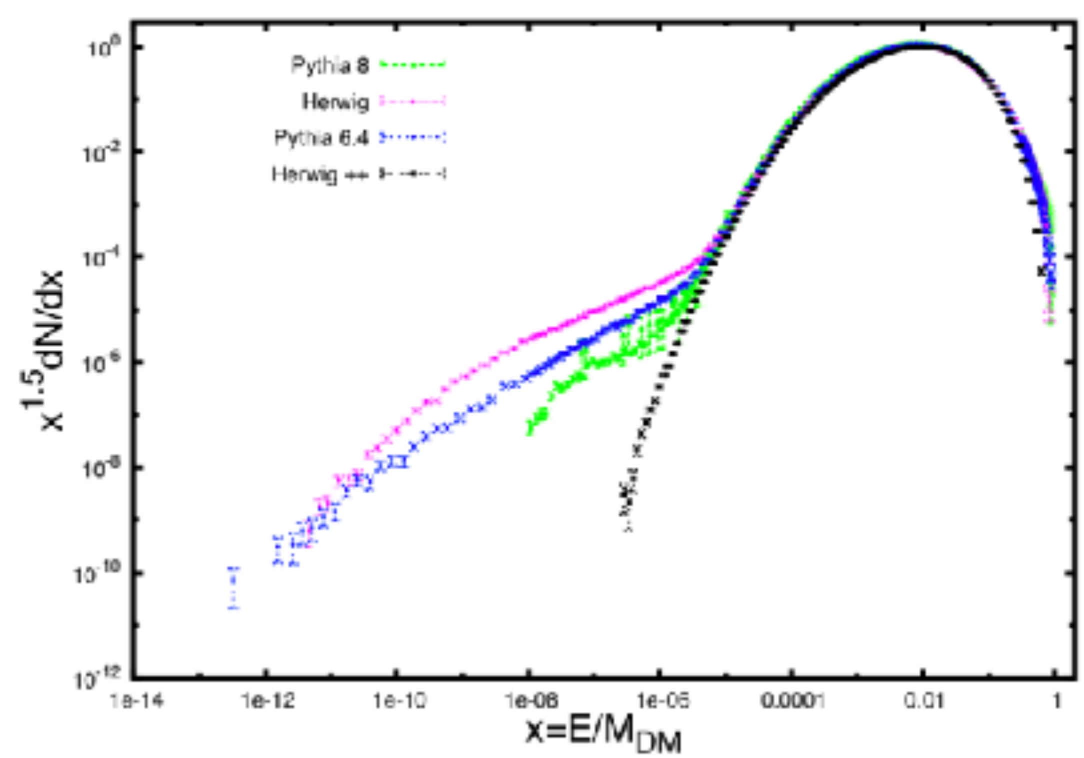
*Purpose of our study is a **precise** determination of the **QCD uncertainties** associated with the production of high energy gamma-rays from DM annihilation*

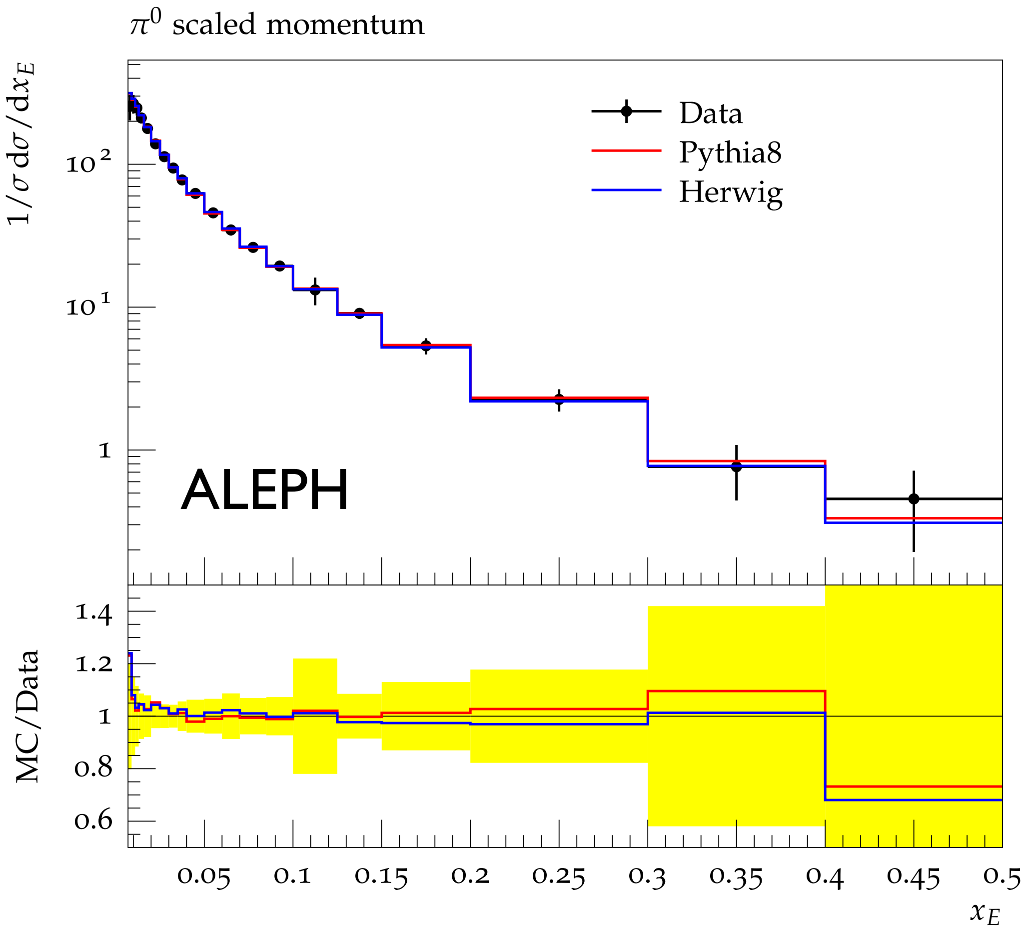
Fluxes at production

- The photon fluxes from DM annihilation are typically computed using Monte Carlo simulations
  - They provide the final-state particles produced in the DM annihilation including effects of *parton showering* and *hadronisation*

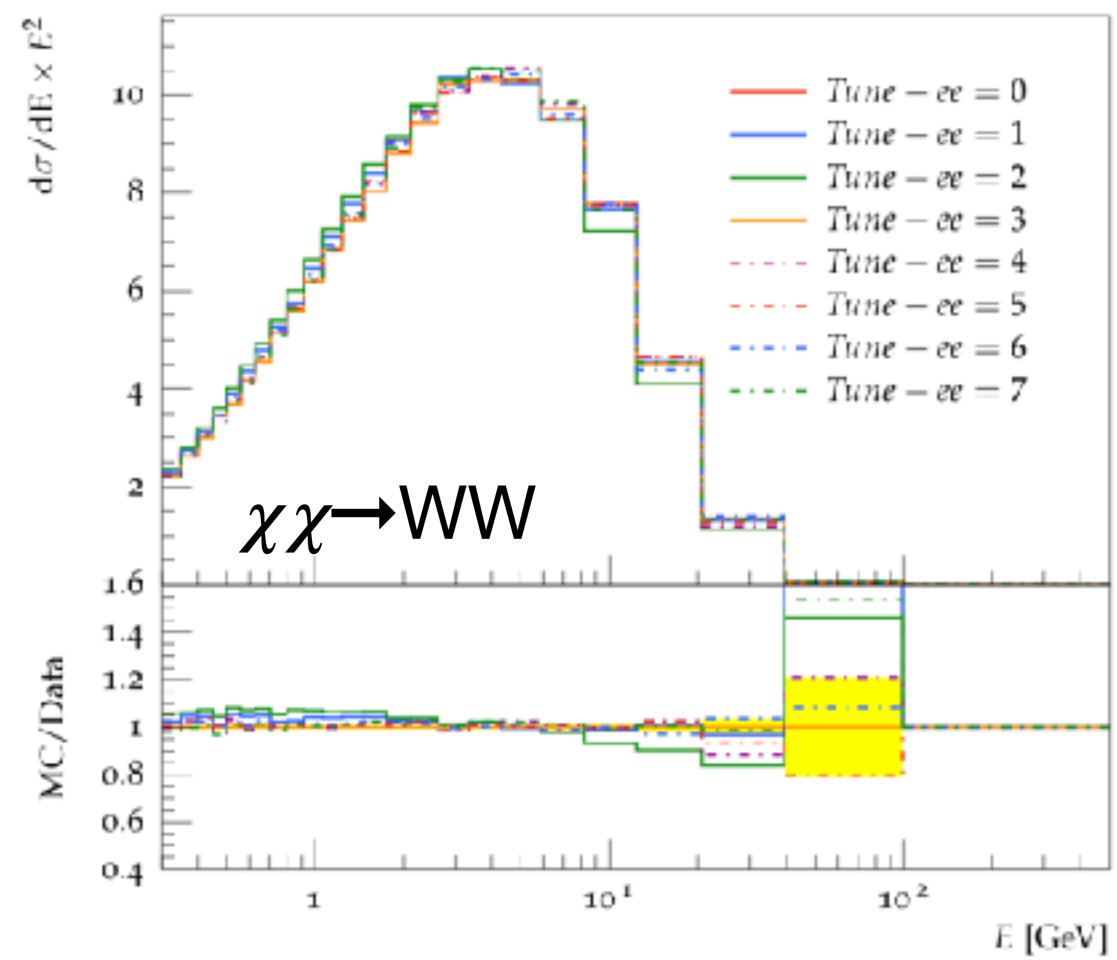
- Most of the available tools (e.g. *DarkSUSY, Micromegas*) take these fluxes from tabulated values using the Pythia8 program
- But no uncertainty on the spectra themselves are provided

- A couple of studies in the literature attempted to compare predictions using different MC generators [1012.4515, 1305.2124]
  - Different programs in agreement with each other (~10-30%) for the peak
  - Larger differences in the tails
  - All models fitted to data in similar ways, their difference might not represent the true uncertainty in the predictions





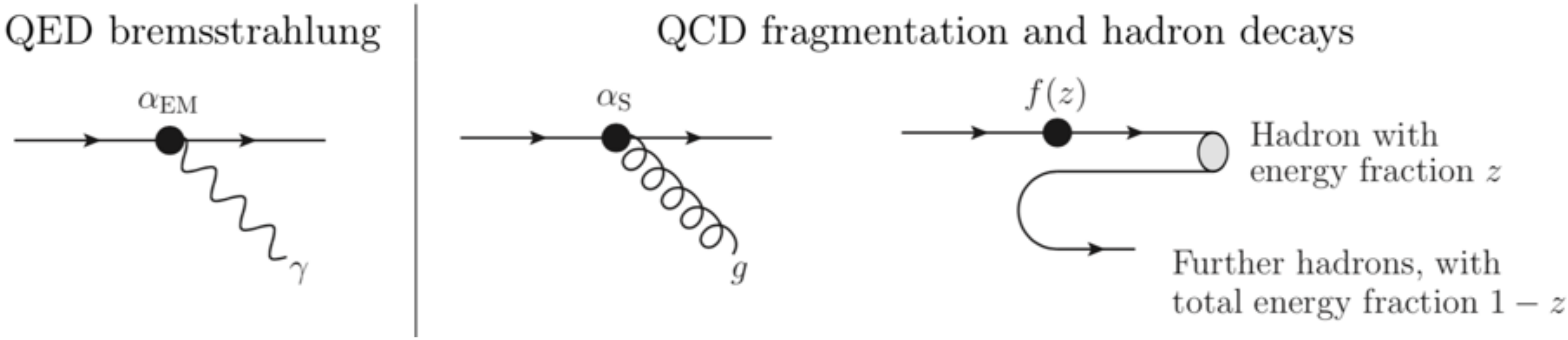
- The same generators show only small differences in their description of e^+e^- data
  - But they are in fact both fitted to the same measurements
  - Yet no uncertainty on those fits is given



- The effect of different tunes of the same generator on a DM annihilation spectra [1502.05703] is similarly small
  - Differences mostly arising from different choice of data, author's prejudice
- It is not currently possible to estimate fragmentation uncertainties in a consistent way

Modelling of QED and QCD effect

- Consider a generic DM annihilation process $\chi\chi \rightarrow X$



- QED bremmstrahlung $X \rightarrow X\gamma$ and $\gamma \rightarrow ff$ production are very well known and their uncertainty typically very small, we don't consider them further in this study

- If X (or its decay products) includes coloured particles, they will undergo QCD showering
  - Resums the enhancement of soft and collinear QCD emissions
  - The main parameter governing the rate of QCD branchings is the effective value assumed for α_S at each vertex,
  - And an uncertainty on the perturbative emissions can be estimated by variations of a factor 2

- Any coloured particle produced will finally undergo hadronisation
- In Pythia modelled with the Lund string fragmentation
- Crucial component in this model is the fragmentation-function:
  - Parametrises the probability for a hadron to take a fraction z of the parton momentum

a, *b* tunable parameters

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

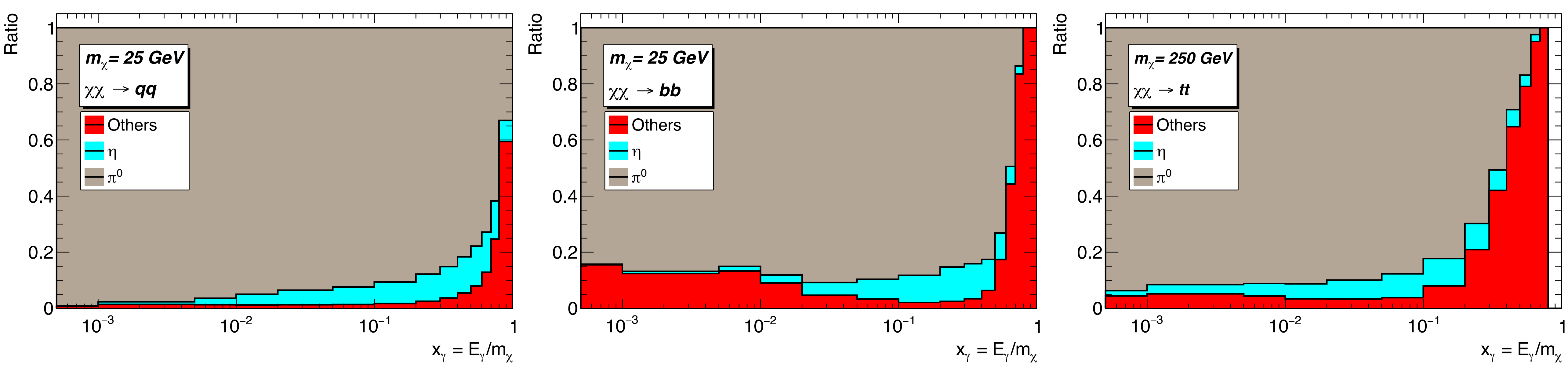
  - If f(z) is peaked at one, QCD jets will consist of only few hadrons
  - If instead it peaks near zero, very many hadrons are produced, each taking only a small fraction of the available energy

- An additional important parameter is the size of the p_T kicks involved in the string breaking process
  - This is governed by $\sigma_\perp$, half of the mean value of the p_T of the hadron
  - Typically tuned to event shapes data in e^+e^- collisions

The origin of photons

- We then looked at the origin of the photons in DM annihilation

- Evaluated using Pythia8 implementing the production of a fictitious generic resonance which undergoes 2-body decays
  - Since the $\pi^0 \rightarrow \gamma\gamma$ branching-ratio is ~99% the number and hardness of photons in DM annihilation processes will be strongly correlate with the pion spectra
  - In all cases the contribution from secondary pions (from other particle decays) amounts to 70-90% of the total pions
  - Subleading contributions from eta decays (~4%) or quark bremmstrahlung
  - For higher DM masses (well above particle thresholds) the distributions for all annihilation channels are very similar



Strategy of the tune

- Aim to derive a *new tune of the Pythia8 fragmentation* parameters to precisely constrain the photon spectra and to determine a set of *conservative uncertainties*
  - Using precise measurements from e^+e^- colliders (LEP+SLD) at the Z-pole
  - Including measurements of photon spectra, but also of pion and eta spectra
- Important to ensure our non-perturbative tuning does not introduce "too-large" corrections to infrared and collinear safe observables
  - For that we include event shape observables as well, focusing on the Thrust and C-parameter distributions
  - These observables are mostly sensitive to the transverse component of the fragmentation, complementary to particle spectra in constraining $\sigma_\perp$
- A total of 26 observables are included (963 data bins)

parameter	PYTHIA8 setting	Variation range	Monash
$\sigma_\perp$ [GeV]	`StringPT:Sigma`	$0.0 - 1.0$	0.335
a	`StringZ:aLund`	$0.0 - 2.0$	0.68
b	`StringZ:bLund`	$0.2 - 2.0$	0.98
$\langle z_\rho \rangle$	`StringZ:avgZLund`	$0.3 - 0.7$	(0.55)

Default tune of Pythia8 (← Monash)

Alternative parametrisation of the Lund string (← (0.55))

And methodology

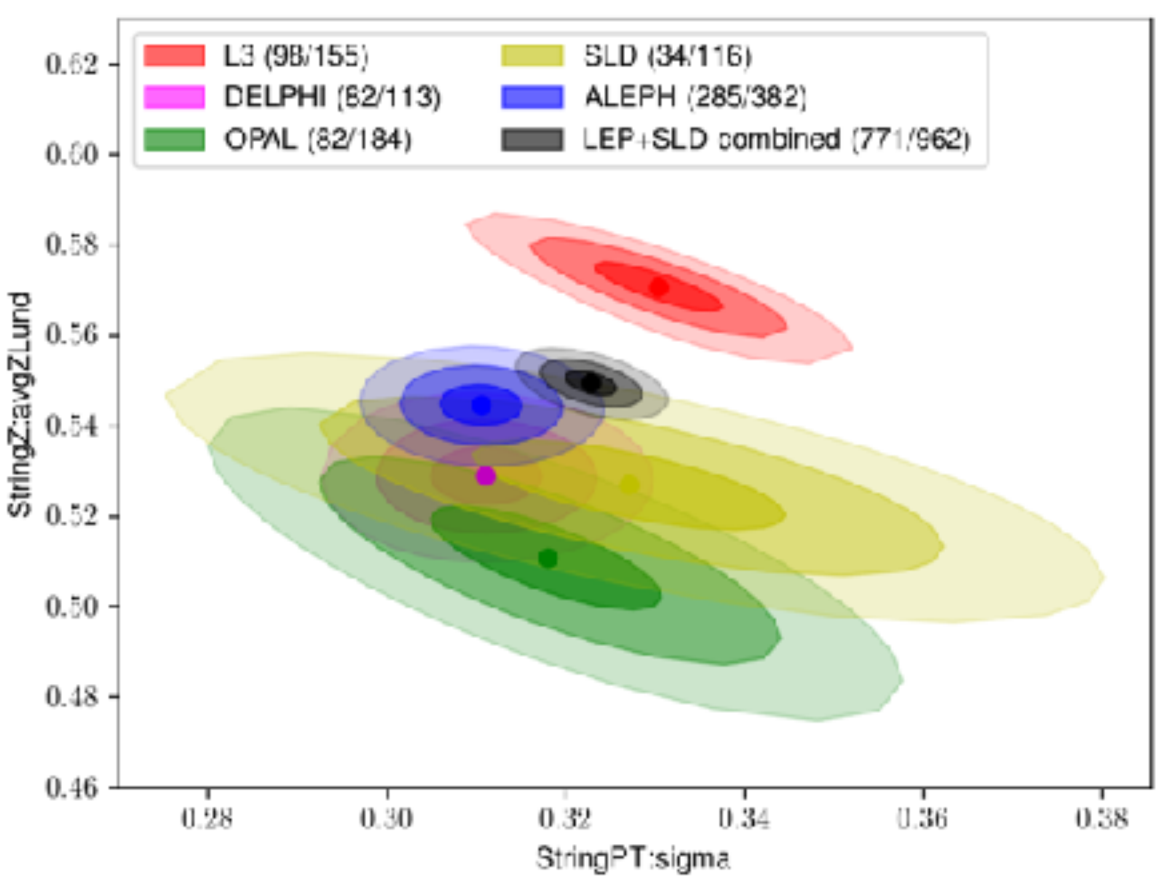
- The tune is performed using the *Professor* code and using RIVET to implement the data measurements
  - The 3-dimensional parameter (a, $\langle z \rangle$, $\sigma_\perp$) space is randomly sampled
  - From these points an analytical parametrisation of the MC response is obtained using polynomials of 4th order
  - A χ^2 measure between data and the parametrisation is minimised
- Naively performing a tune to all data results in a very bad χ^2
  - Partly as correlations among measurements bin are not included
  - But also since the model cannot describe all the data simultaneously
- An additional 5% uncertainty is added to data to avoid “over-fitting”

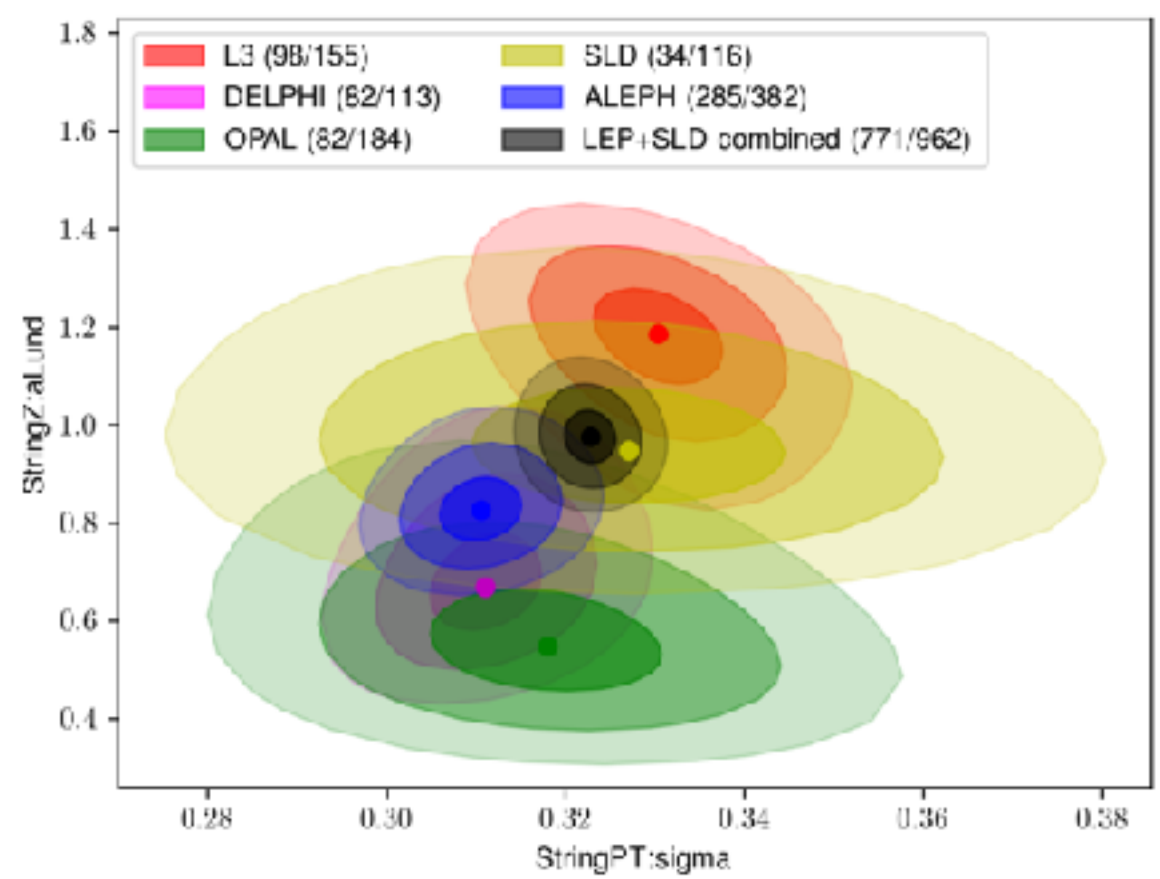
Parameter	Results
`StringPT:Sigma`	$0.3151^{+0.0010}_{-0.00010}$
`StringZ:aLund`	$1.028^{+0.031}_{-0.031}$
`StringZ:avgZLund`	$0.5534^{+0.0010}_{-0.0010}$
χ^2/ndf	5169/963

Additional 5% uncertainty →

New Z
$0.3227^{+0.0028}_{-0.0028}$
$0.976^{+0.054}_{-0.052}$
$0.5496^{+0.0026}_{-0.0026}$
778/963

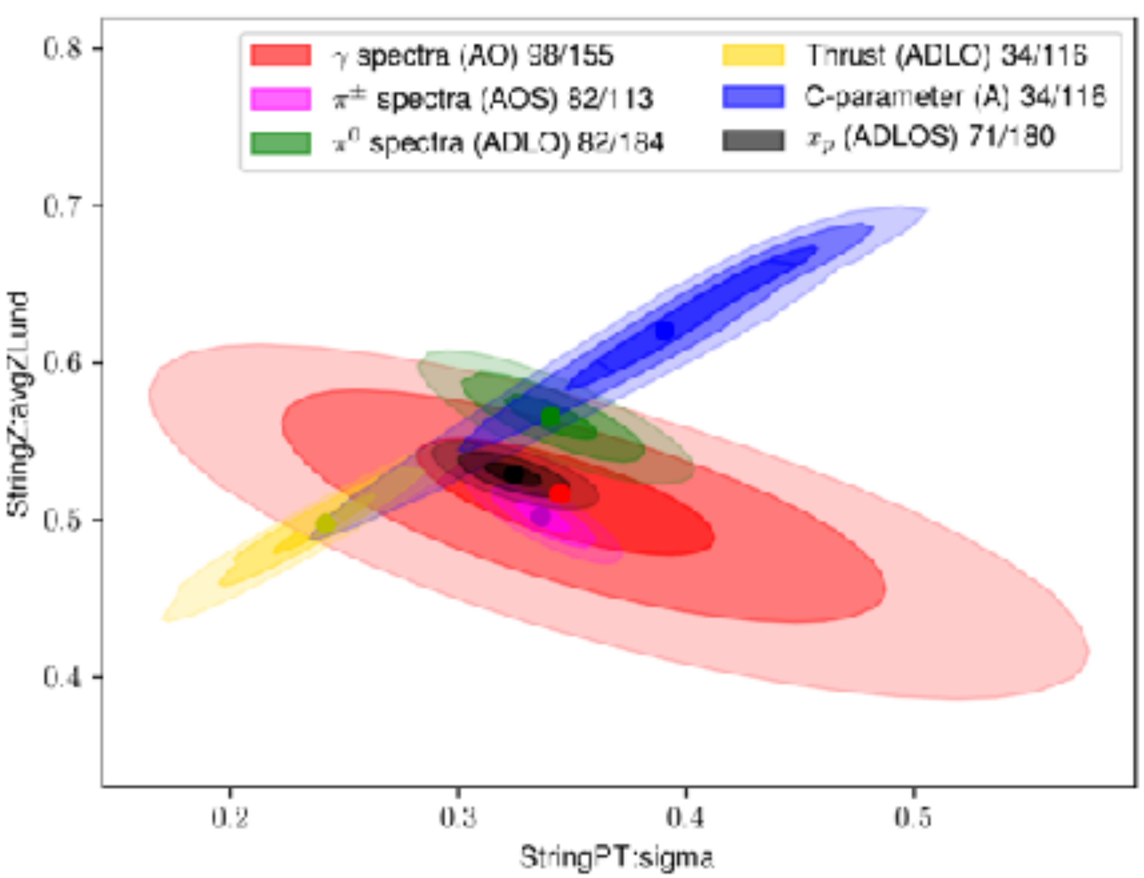
- We have looked at the consistency of the fitted parameters when fitting to data from each of the experiments separately
- OPAL and SLD have a smaller overall sensitivity due too fewer measurements included in our study
- All the experiments are compatible within three sigma, with the exception of L3

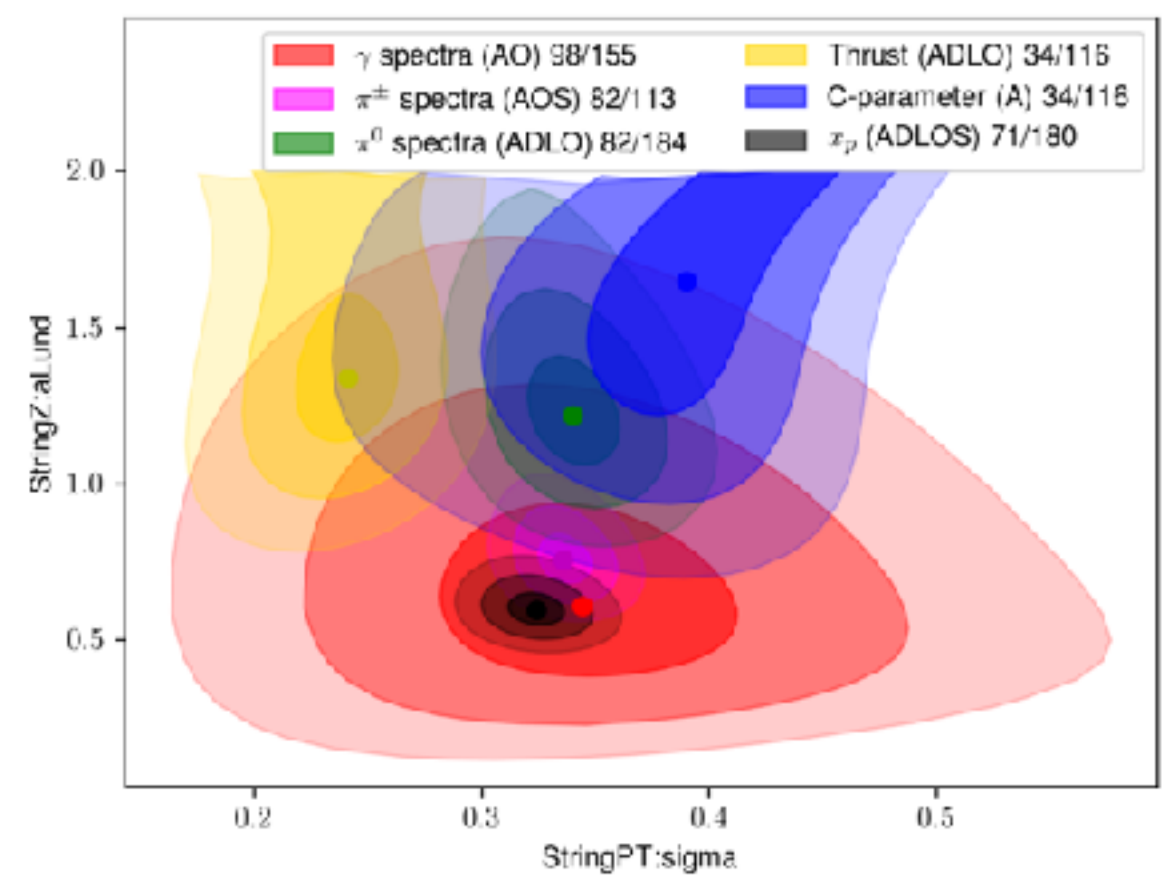




Compatibility among observables

- The gamma spectra gives only loose constraints on fragmentation parameters (measurements not very accurate)
- The $\pi^{\pm}$ and π^0 are extremely constraining, and in good agreement with each other (some tension in the <z>)
- The event shape observables do not add sensitivity for the *a* parameter, but gives information in the $\sigma_{\perp}$, <z> plane





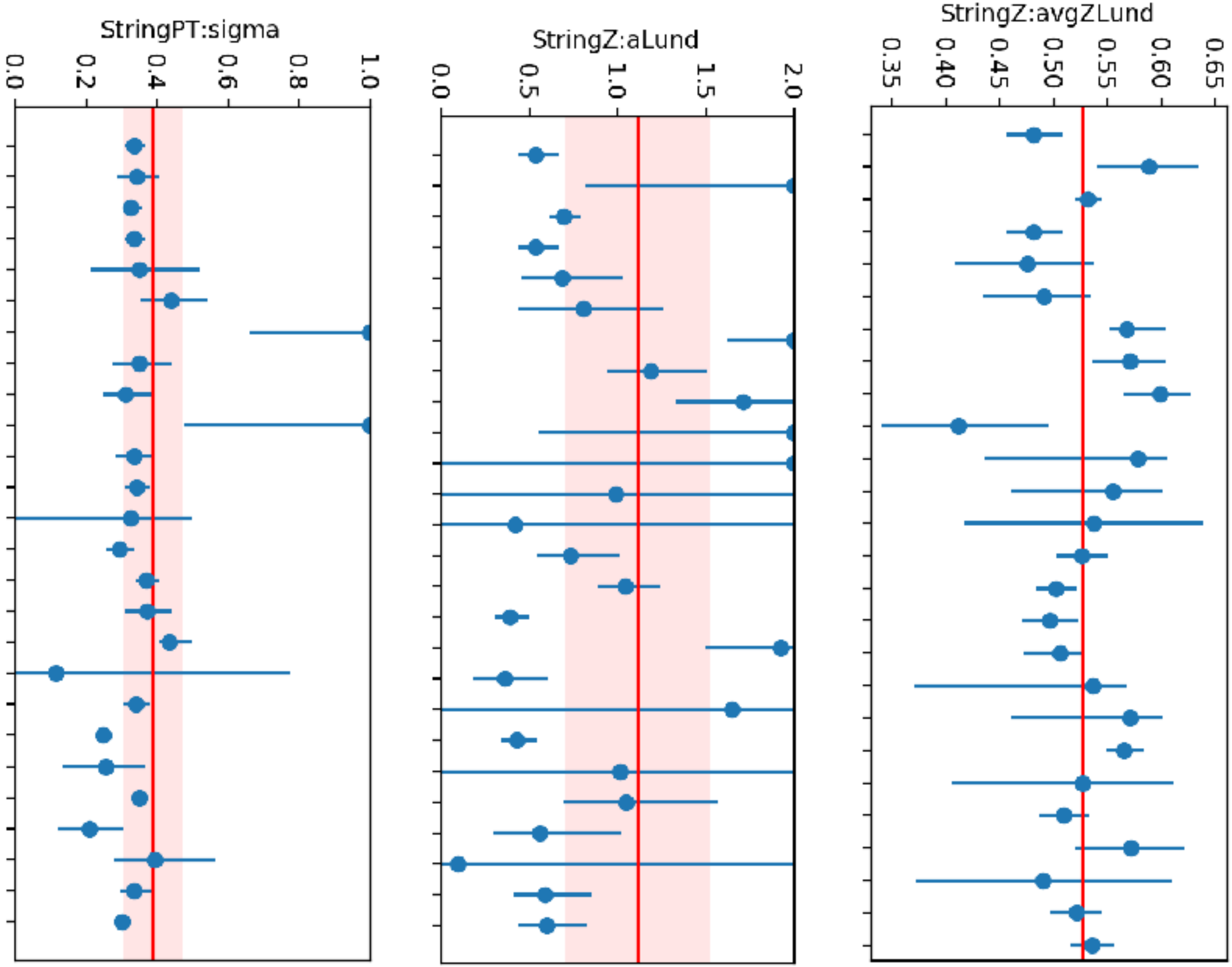
Estimating spectra uncertainties

* In our tunes we observed significant tensions:
  - When comparing different observables sensitive to the same physics effects
  - And when looking at measurements of the same quantity by different experimental collaborations
* Using a standard $\Delta\chi^2 = 1$ prescription would result in underestimated uncertainties

* We used a different method to derive fragmentation uncertainties:
  - Perform a tune to each individual observable (26)
  - Compute the 68% CL interval of the spread of the different tunes

* In addition variations of the strong coupling obtained through shower weight variation are added in quadrature to the fragmentation variations

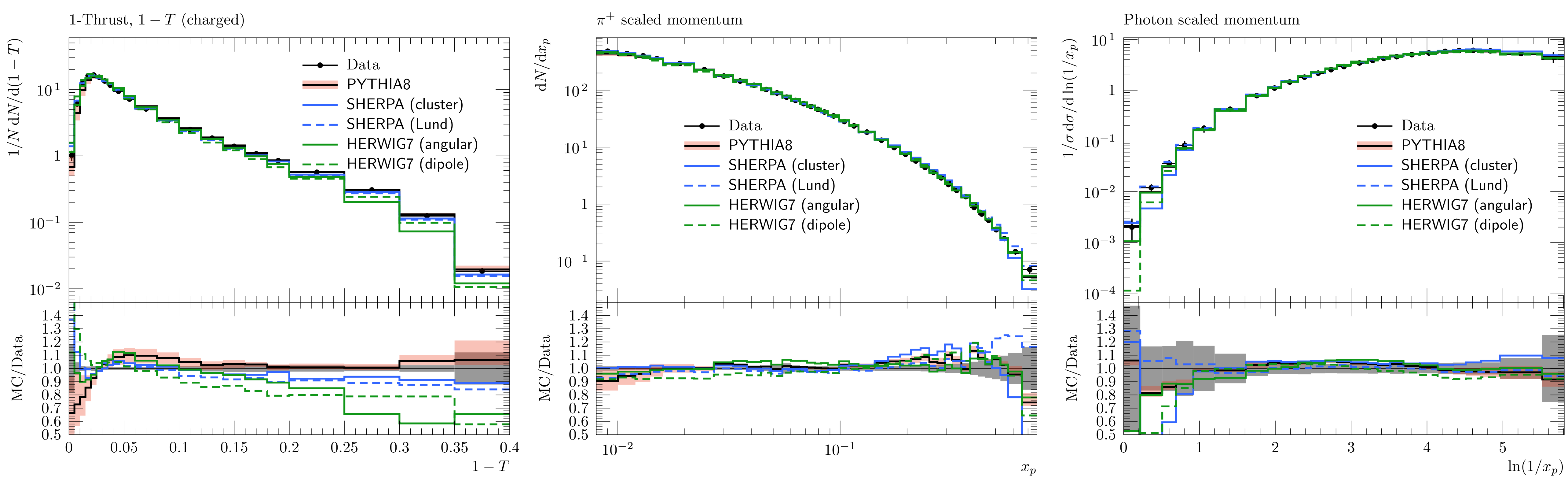
Fragmentation uncertainties



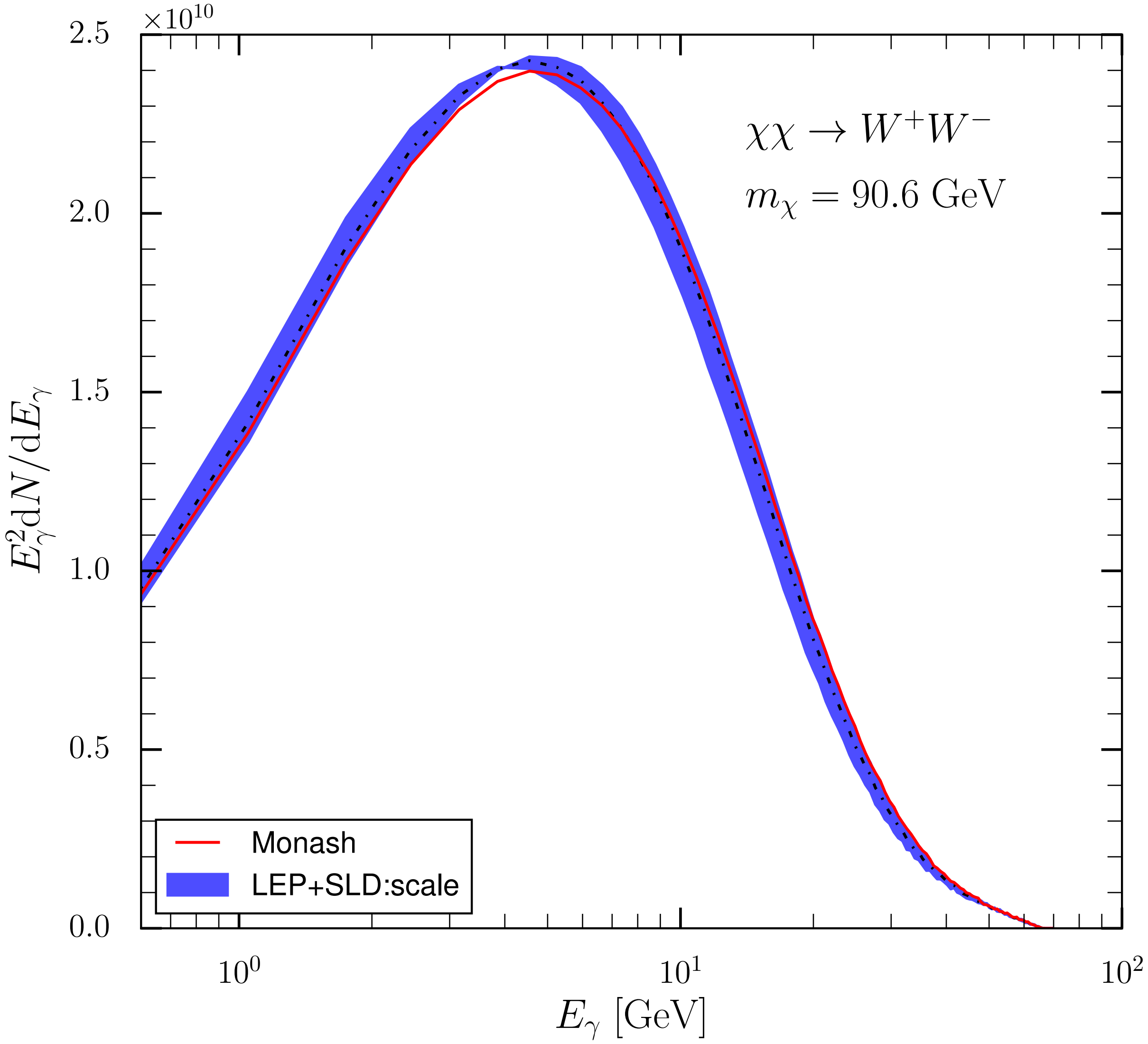
0.387±0.082 1.1±0.4 0.527±0.003

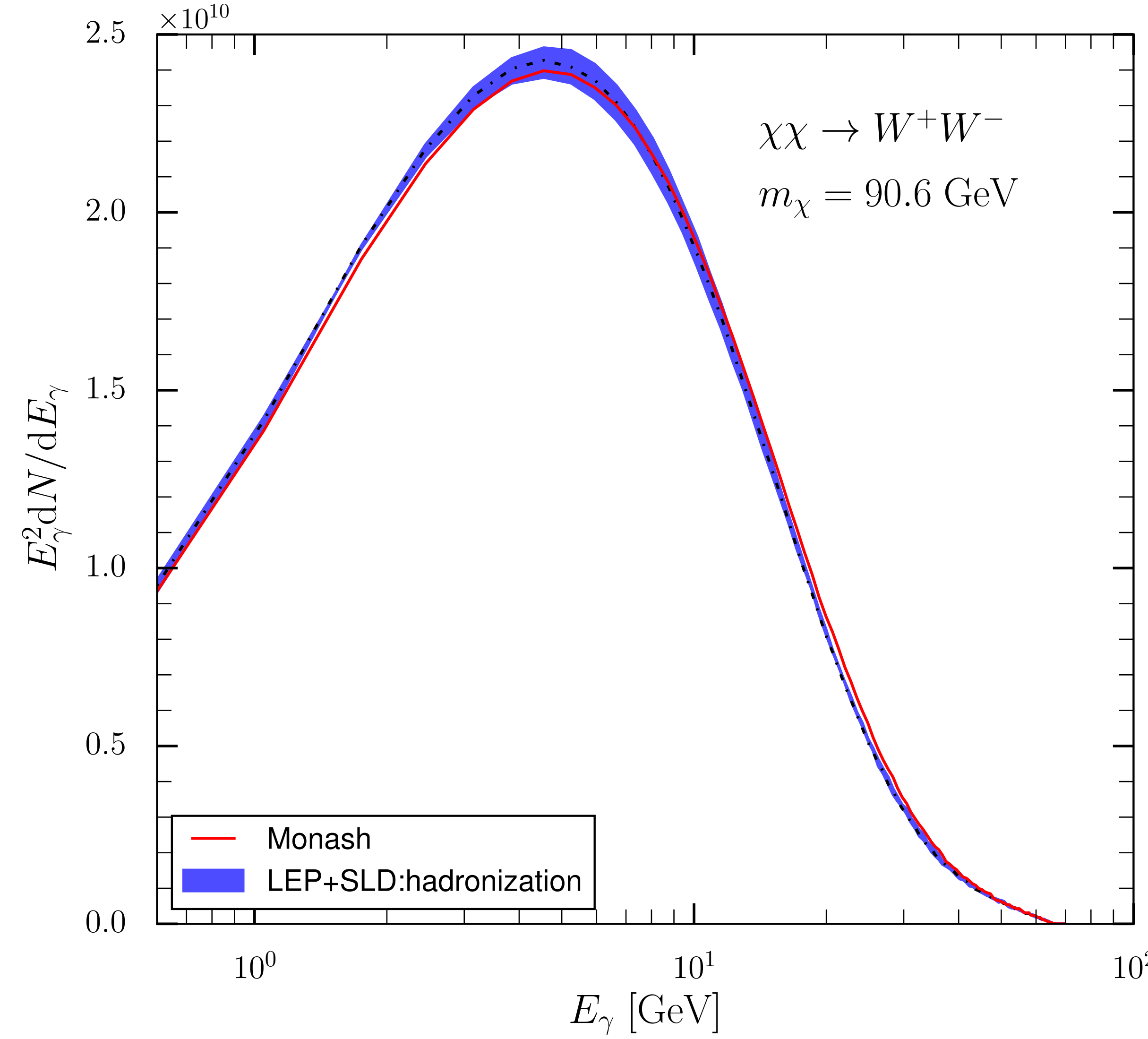
Results of the tune

- We can now compare the results of our tune (+fragmentation uncertainties) against the data used as input
  - Also including a comparison with other out-of-the box generators
- We are able to describe all of the distributions used as input
  - And a much better description than any of the other generators
- The uncertainties mostly cover differences wrt the data



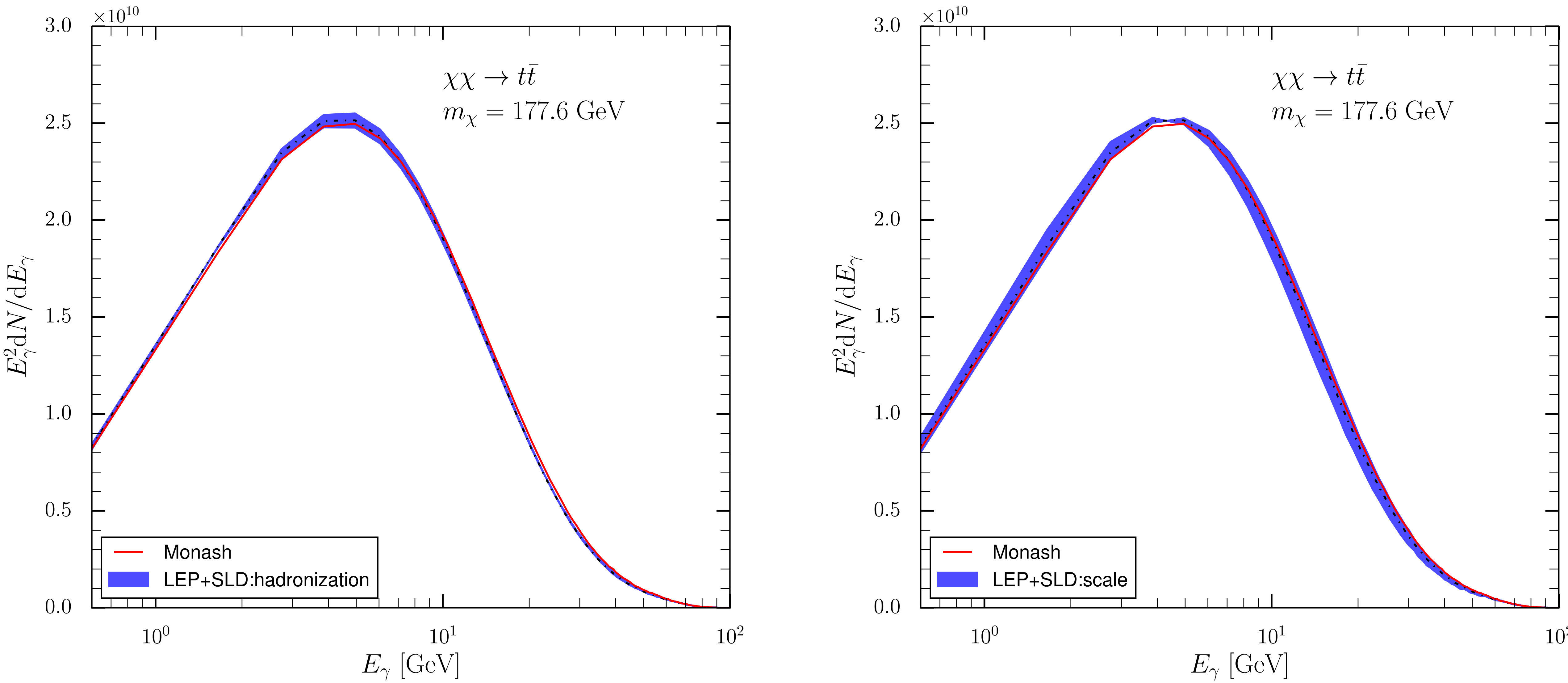
IMPACT ON GAMMA-RAY SPECTRA (WW)





- And now we can look at the effect of our uncertainties on the photon spectra for few DM masses and annihilation final states
  - Variations of the strong coupling shift the position of the peak
  - Fragmentation uncertainties affect the spectra at the 10-30% level

Impact on gamma-ray spectra (ttbar)



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Summary

* We have studied the shower and fragmentation uncertainties on the description gamma-ray spectra from DM annihilation
* A new tune of the Pythia8 MC generator was derived
    - Improving significantly on the description of γ and π spectra
    - Provides conservative uncertainties for both the perturbative (shower) and non-perturbative (fragmentation) component
    - Uncertainties covering both inconsistencies among different measurements and among different observables
* Currently evaluating their impact on actual fits of the galactic center excess
* Aim to provide both spectra and uncertainties tabulated for different masses and decay modes
    - In contact with M. Cirelli to include those in the *Cookbook website*
    - Would allow for a straightforward inclusion in standard DM tools
* This methodology could be extended to provide predictions and uncertainties for other particle fluxes (anti-p, e^+, …)

Backup