

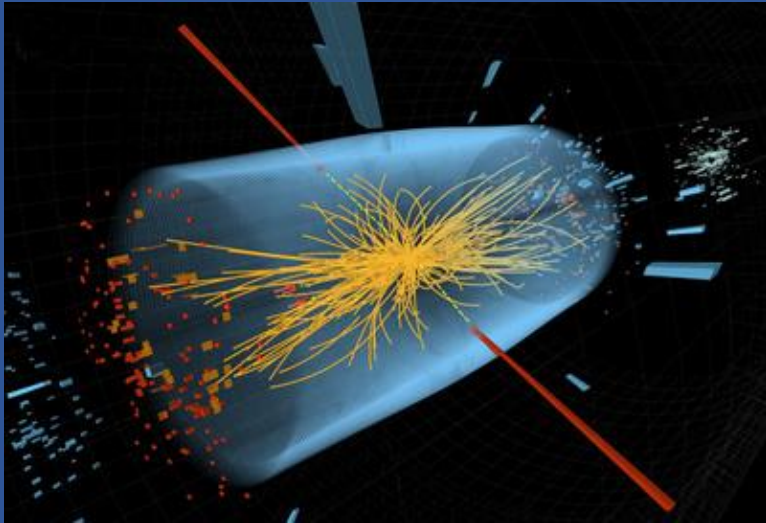
# Tuning Pythia for Forward Physics Experiments

FPF Theory Workshop

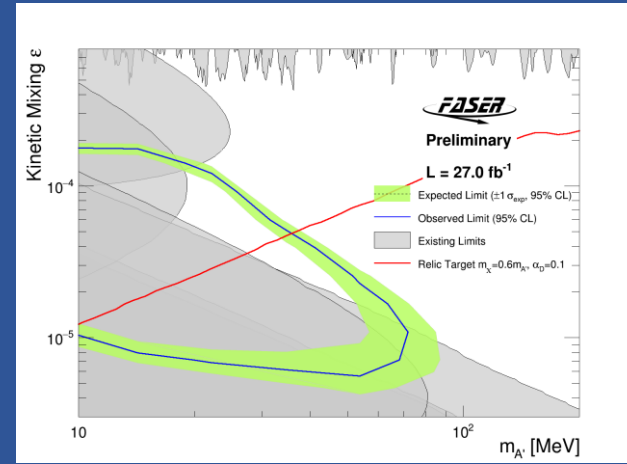
Max Fieg

In collaboration with Felix Kling, Holger Schulz, Torbjörn Sjöstrand

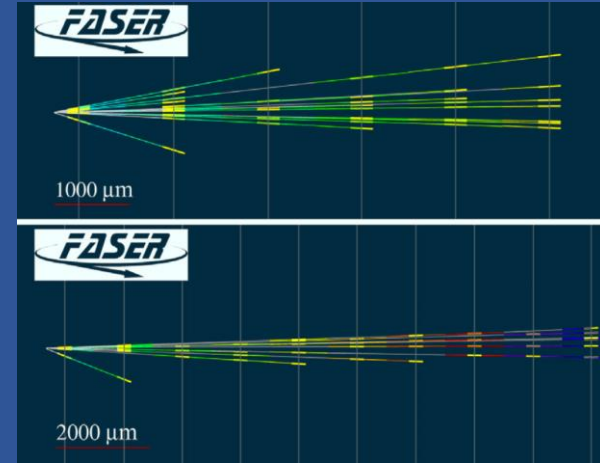




- Monte Carlo event generators used for LHC are tuned to central physics and have excellent agreement



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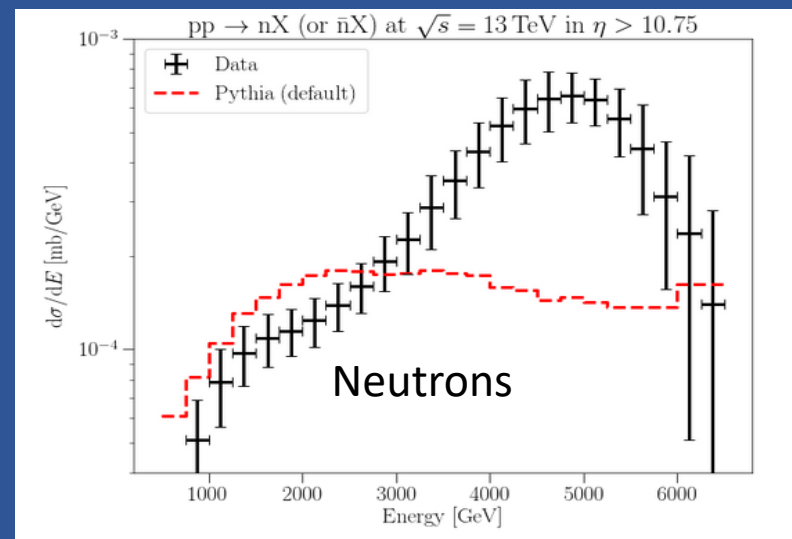
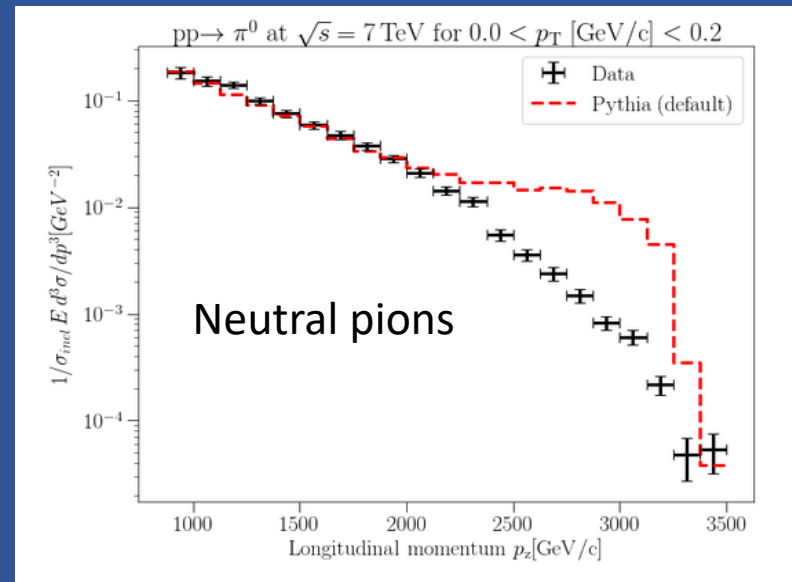
- Forward physics studies require an understanding of forward hadron production



Let's tune Pythia for forward physics without spoiling the success in the central region

# Main problem

- LHCf has measured neutral pions, neutrons, and photons (aka pions) at  $\sqrt{s} = 7, 13$  TeV.
  - Expect similar hadronization mechanisms at each energy
- Central Pythia tunes do not describe forward particle fluxes measured by LHCf
  - Other generators don't do well either
- Use forward measurements from LHCf as our target and tune hadronization parameters
  - bonus if we can minimize the impact on central predictions



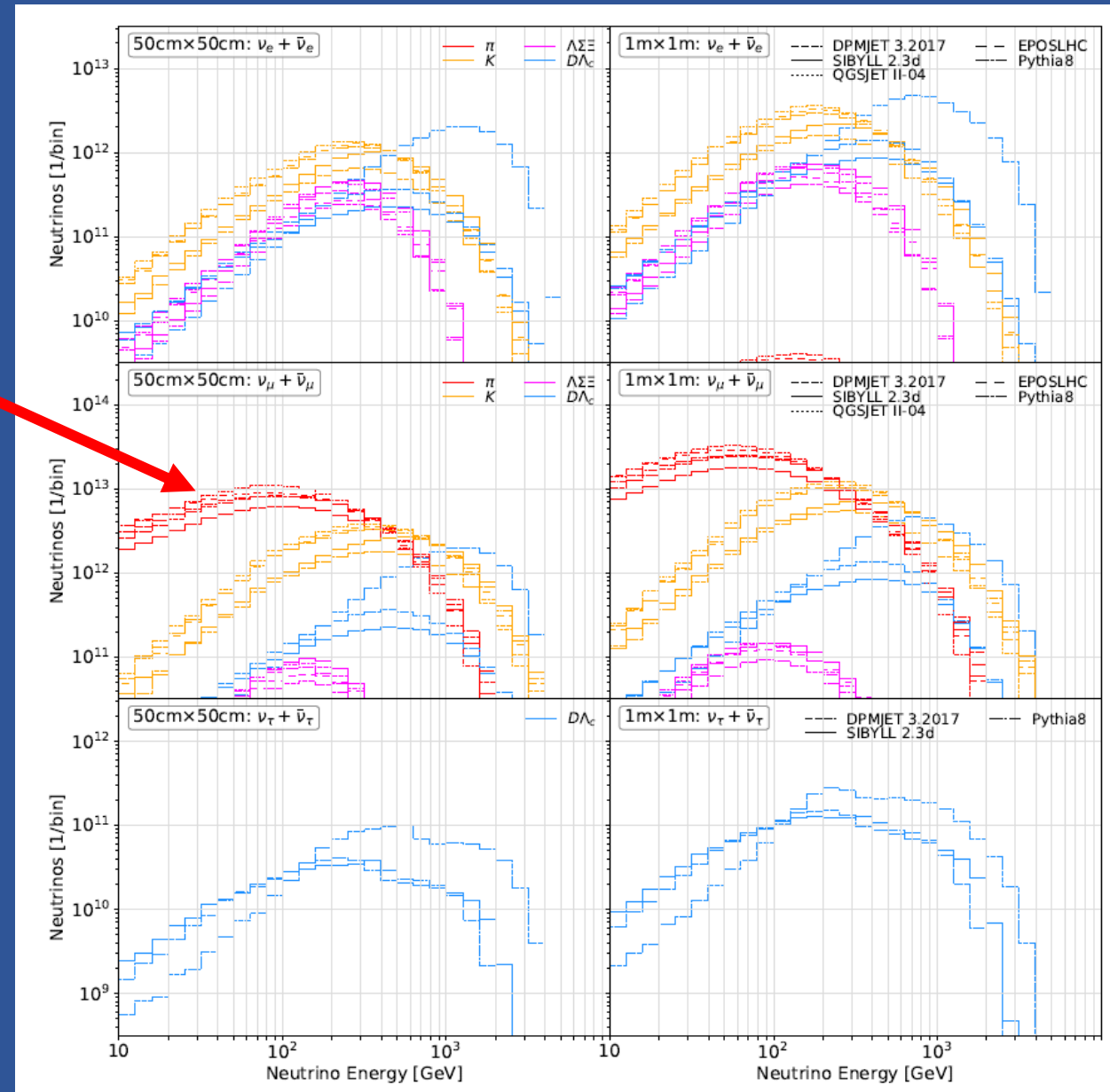
# Second problem

Different generators can give very different hadron / neutrino fluxes

How can we get a handle on flux uncertainties?

One method sometimes taken is to take the spread of generators' predictions

- But this is too dependent on the weakest generator... Need something more robust



# Outline

## 1. Pythia tuning methods

- Maximize success in fitting forward production while minimizing impact on central physics

## 2. Tuning uncertainties

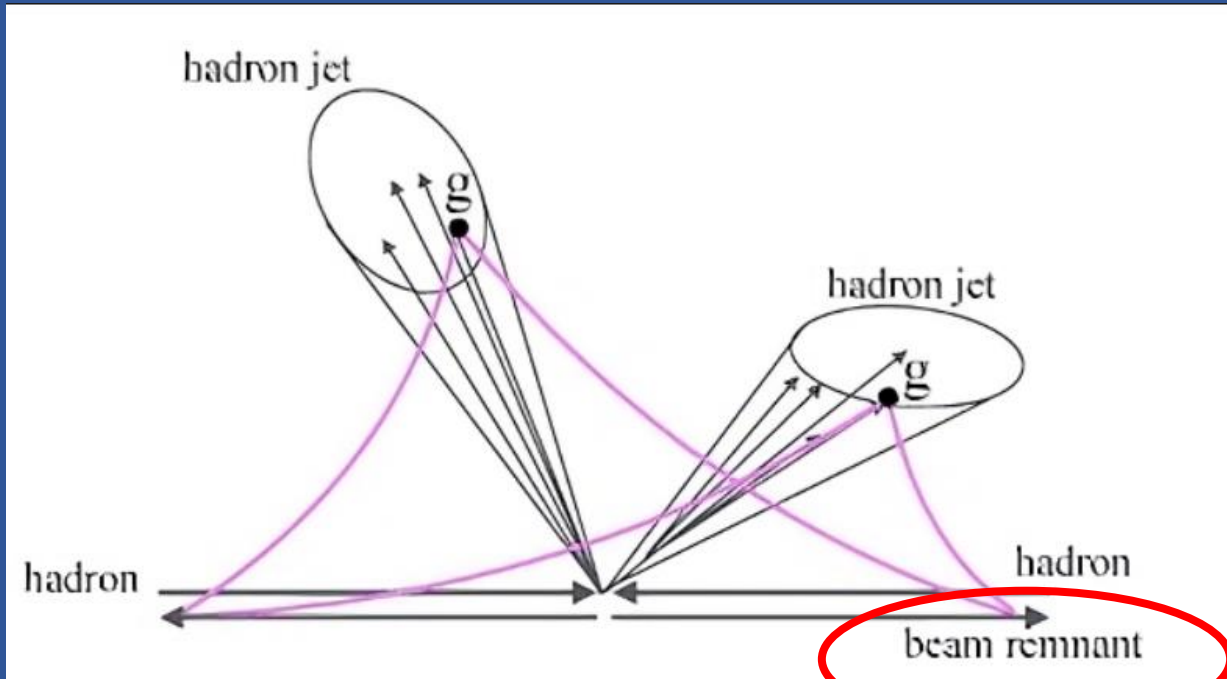
- Provide a tuning uncertainty which translates to a flux uncertainty

## 3. Applications at FASER

- Demonstrate tune for applications

# Tuning methods: beam remnant

We find a subset of tuning parameters which are important for forward physics. Those that are associated with the beam remnant



We tune parameters relating to:

- Primordial kT of incoming partons to tune overall normalization

`BeamRemnants:primordialKTremnant`

`BeamRemnants:primordialKTsoft`

- Remnant  $\rightarrow$  baryon fragmentation function to produce more hard neutrons

`BeamRemnants:hardRemnantBaryon`

`BeamRemnants:bRemnantBaryon`

- Reduce "Popcorn production" to produce fewer hard mesons from remnant diquarks

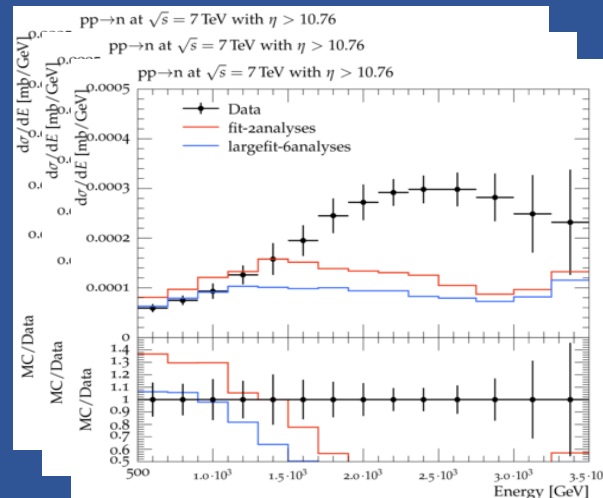
`BeamRemnants:dampPopcorn`

# Tuning methods

With parameters identified, we generate and fit the parameters to data



Generate events in Pythia across tuning space



**Rivet — the particle-physics MC analysis toolkit**

Fill out LHCf histograms for pion, neutron and photon analyses at 7 and 13 TeV

**pyapprentice 1.1.0**

Using the *Apprentice* toolkit, fit parameters to LHCf data

- Neutrons
- Pions
- photons

\*democratic weighting across analyses



# Tuning results

Excess hard pions reduced by disabling the “popcorn mechanism”: forces a remnant diquark to form a baryon

Independent handle on baryons by modifying diquark → baryon fragmentation function

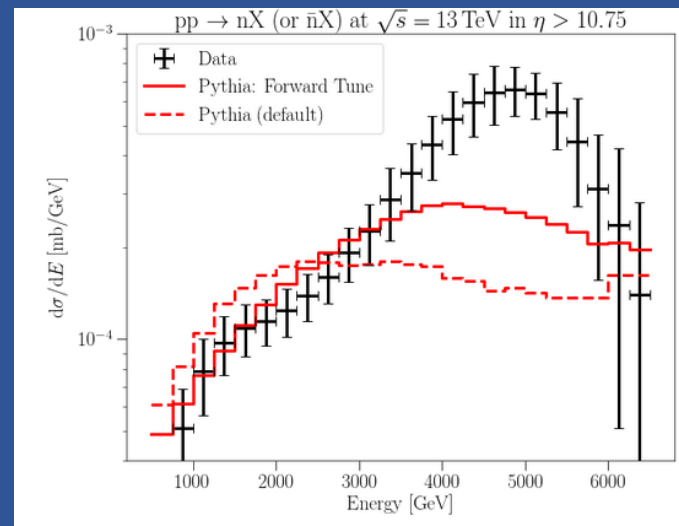
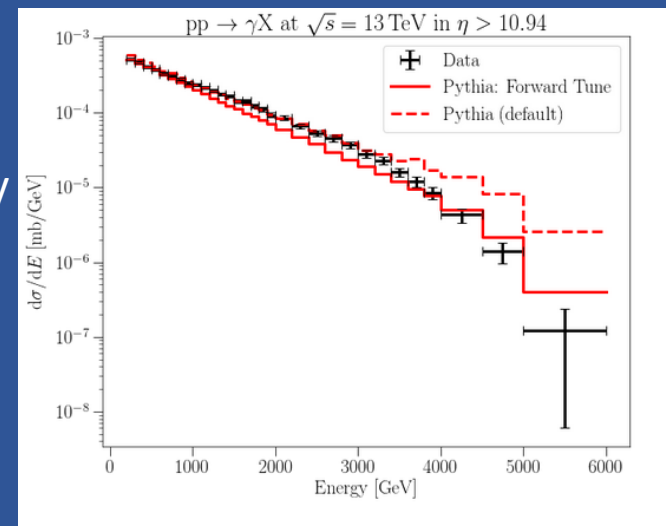
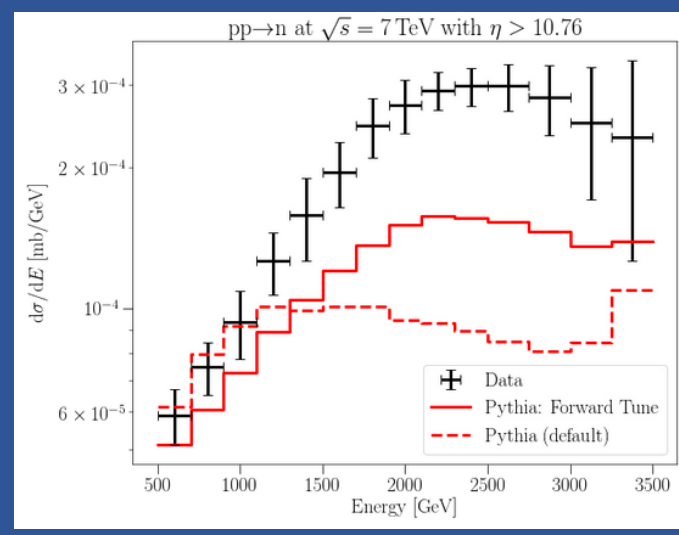
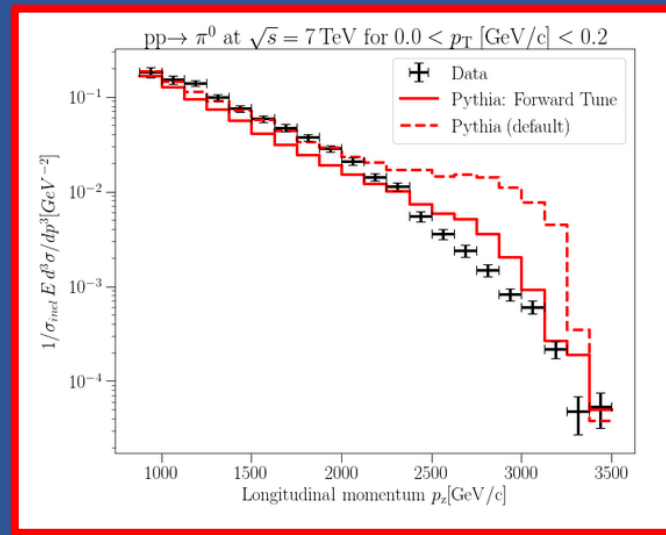
Flux normalization controlled by fitting primordial parton  $p_T$ : “ $kT_{remn}$ ”

7 TeV

13 TeV

Pions\*

neutrons



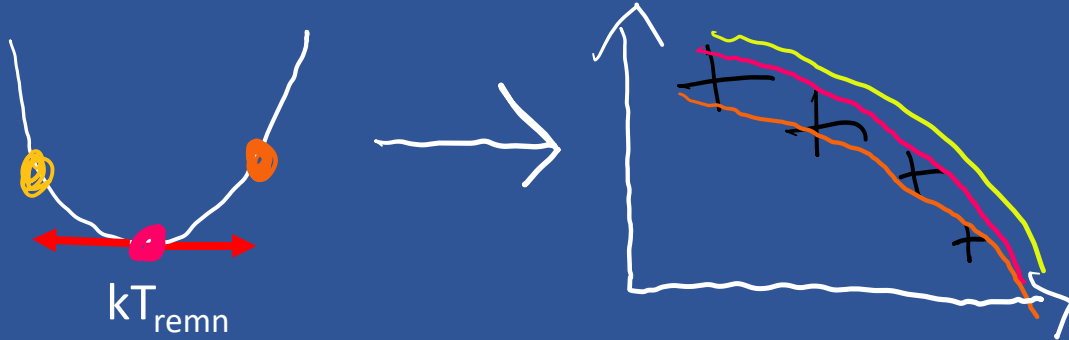
Can we define an uncertainty that captures imperfections in our tune? a naïve  $\Delta\chi^2$  returns an unreasonable underestimate of uncertainties <sup>8</sup>



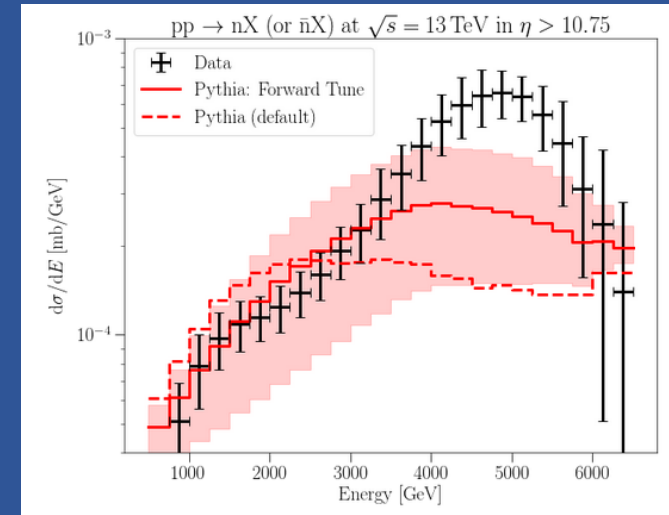
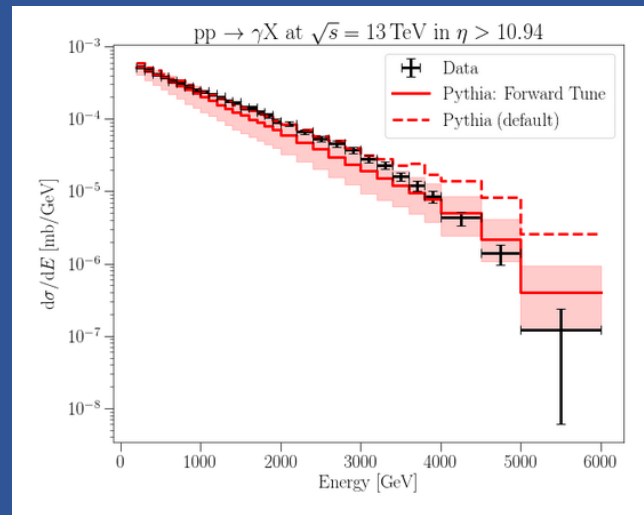
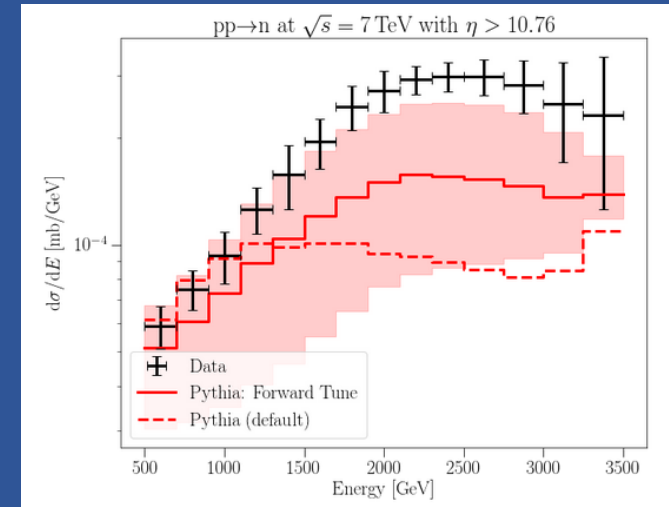
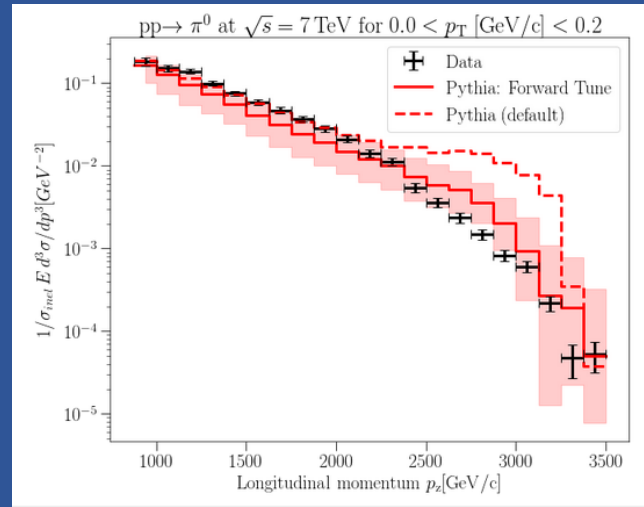
# Tuning uncertainties

We reduce to the most sensitive tuning parameter ( $kT_{\text{remn}}$ ) and take a pragmatic data-driven approach

- Define a band specified by  $kT_{\text{remn}} \pm \Delta$
- Increase  $\Delta$  from best fit until 68% of the datapoints are contained in the band



By construction, result is a band enveloping 68% of data, resembling  $1\sigma$



# Tuning Results

Full name	Shorthand	Baseline (QCDCR)	Forward Tune	Uncertainty
BeamRemnants:dampPopcorn	$d_{pop}$	1	0	
BeamRemnants:hardRemnantBaryon	$f_{remn}$	off	on	
BeamRemnants:aRemnantBaryon	$a_{remn}$	-	0.36	
BeamRemnants:bRemnantBaryon	$b_{remn}$	-	1.69	
BeamRemnants:primordialKTsoft	$\sigma_{soft}$	0.9	0.58	0.26 ... 1.27
BeamRemnants:primordialKTthard	$\sigma_{hard}$	1.8	1.8	
BeamRemnants:halfScaleForKT	$Q_{half}$	1.5	10	
BeamRemnants:halfMassForKT	$m_{half}$	1	1	
BeamRemnants:primordialKTremnant	$\sigma_{remn}$	0.4	0.58	0.26 ... 1.27

\*Some details skipped over here, see paper or ask me for details

# Tuning Results

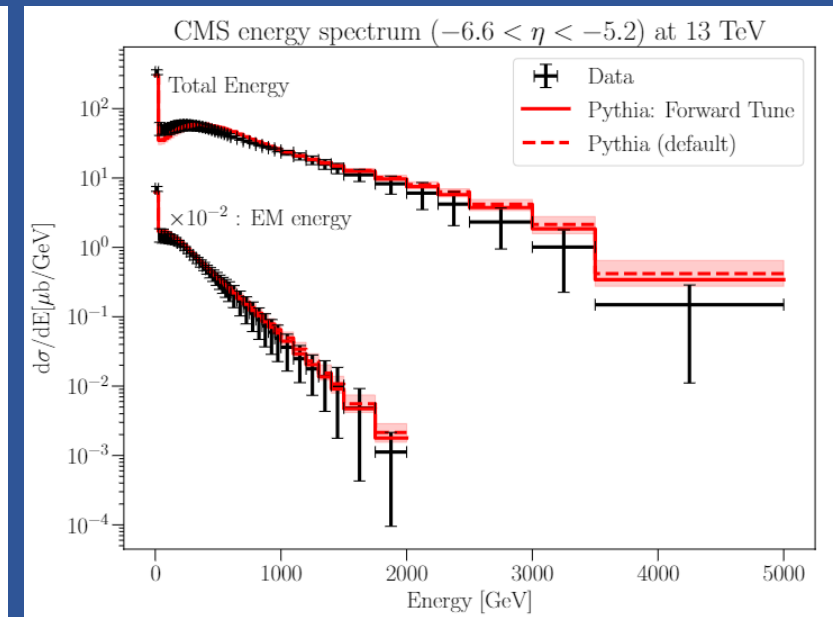
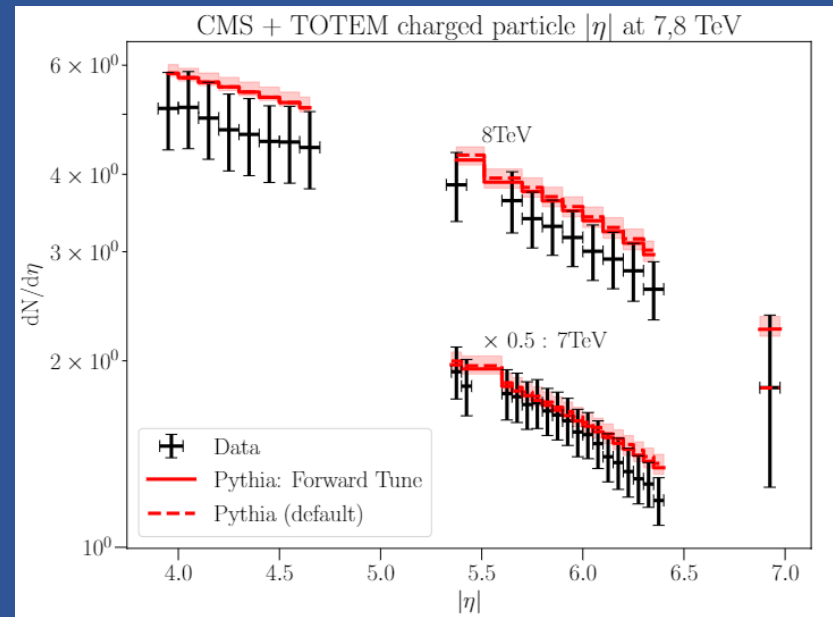
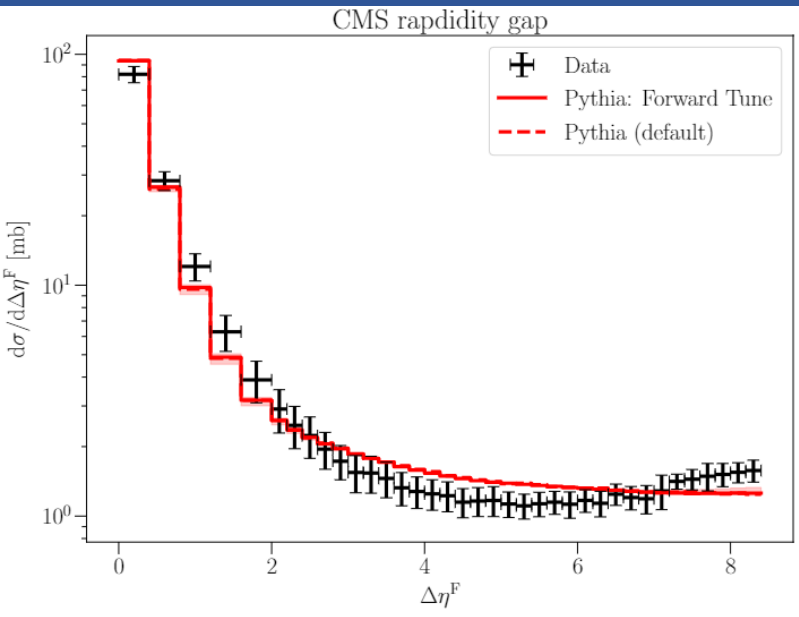
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\*Some details skipped over here, see paper or ask me for details

Did we spoil success in the central region , at CMS, ATLAS or even TOTEM?

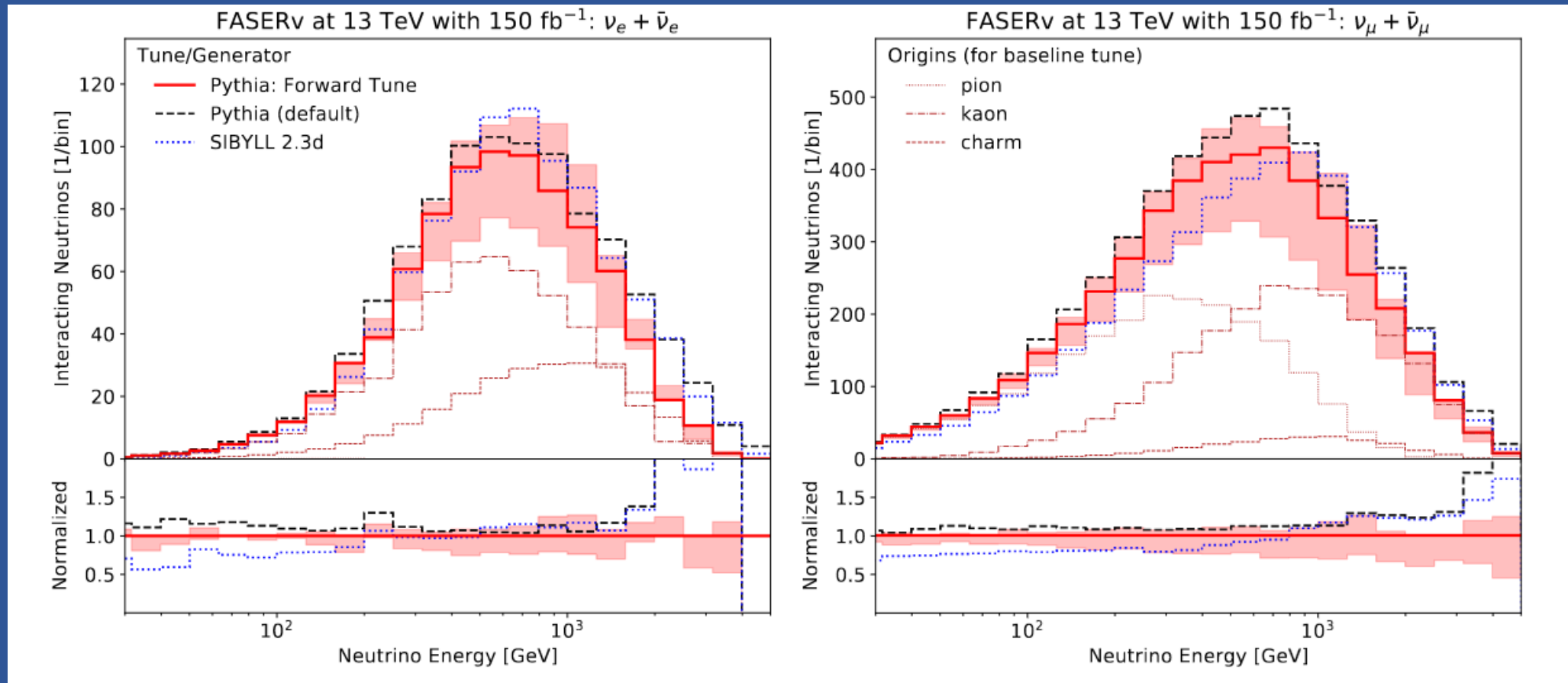
# Impact on central physics

Some “central” analyses where we would most likely see effect of tuning



# Applications for forward physics - Neutrinos

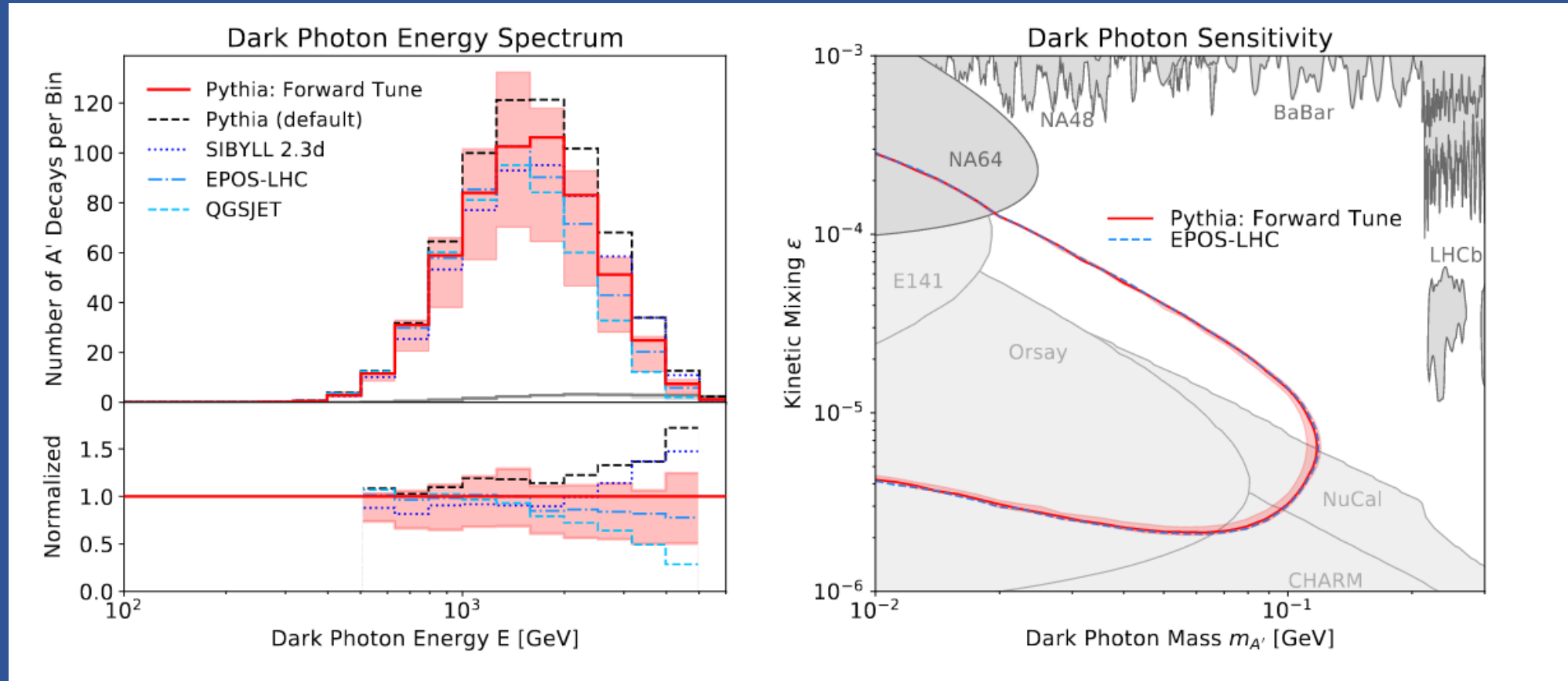
- Interacting electron and muon neutrino spectrum at FASER. Our improved tune predicts  $\sim 10\%$  fewer neutrinos as compared to the default Pythia configuration and we find a 20% uncertainty band



# Applications for forward physics – Dark Photons

Dark photon spectra for fixed  $m_{A'}$ ,  $\epsilon$  and dark photon reach plot

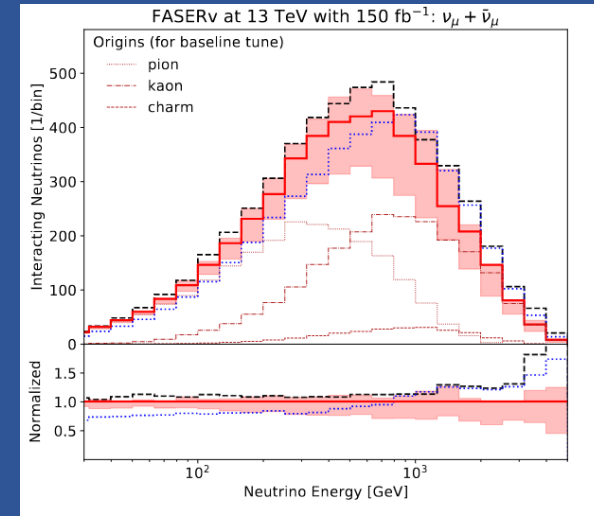
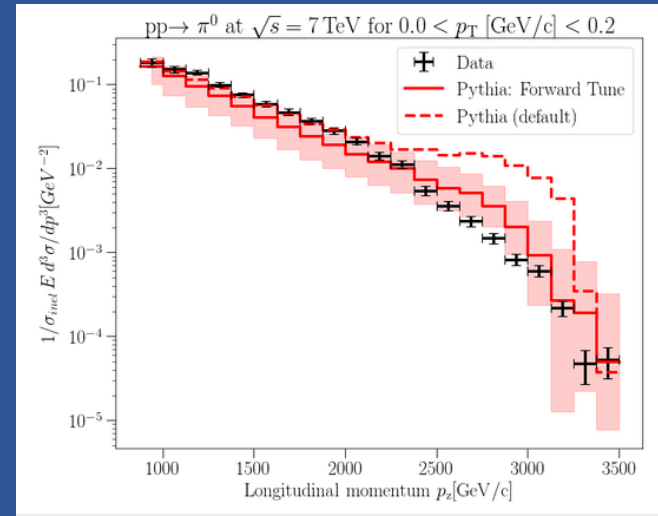
-About 50% uncertainty in number of dark photon decays. Reach is largely unaffected due to large  $\epsilon$  suppression



# Summary

- We tune Pythia for forward physics purposes at the LHC, by fitting beam remnant parameters which have negligible impact on central physics
- We provide a data-driven uncertainty which to a flux uncertainty
- We demonstrate an application of our tune by showing its impact on neutrino and dark photon measurements at FASER

Full name	Shorthand	Baseline (QCD CR)	Forward Tune	Uncertainty
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BeamRemnants:aRemnantBaryon	$a_{remn}$	-	0.36	
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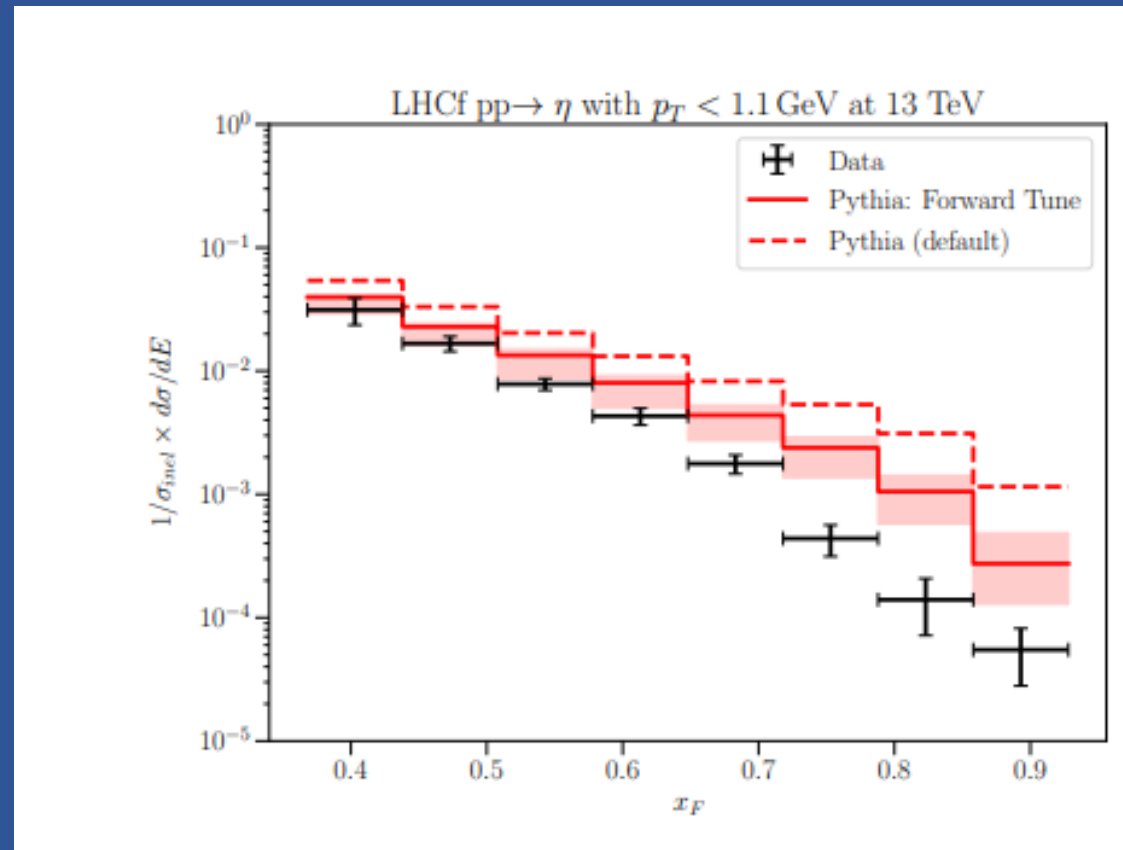
Thank you for listening!

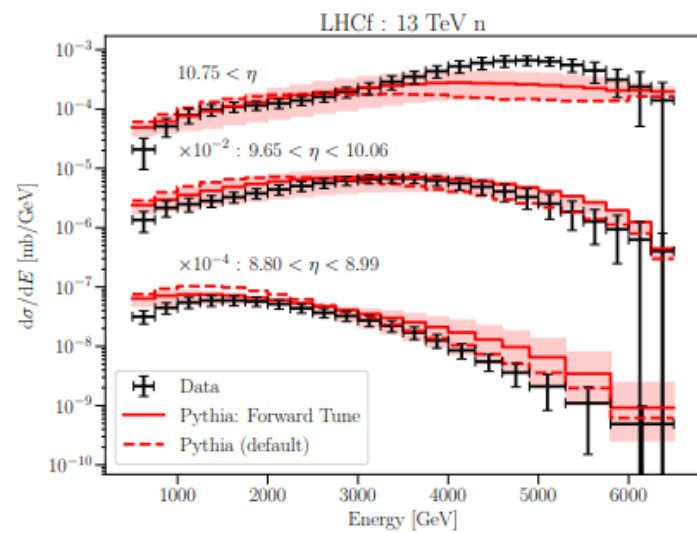
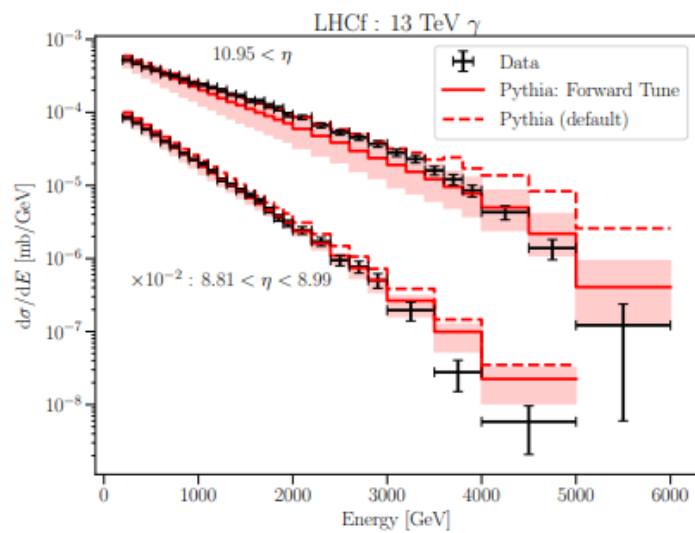
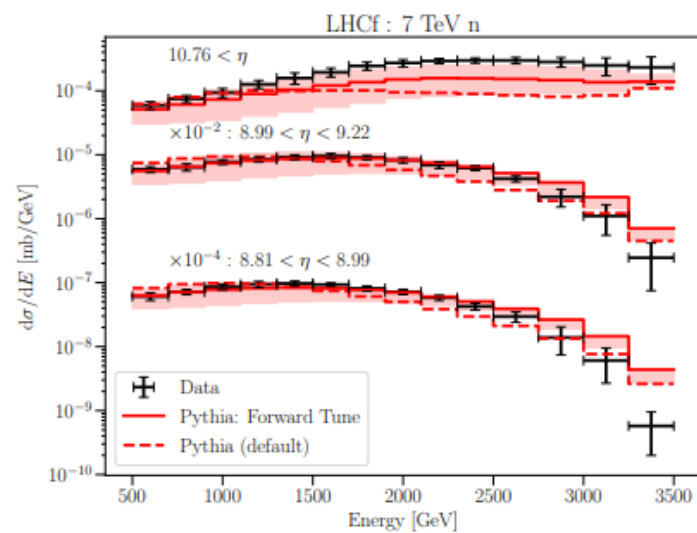
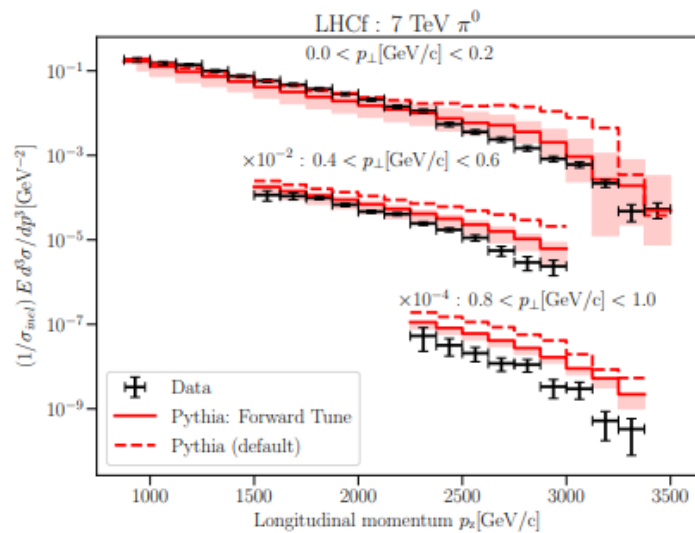




Back up

# Eta analysis





### Variation of MultipartonInteractions

3.1	MultipartonInteractions:alphaSvalue	.....
3.2	MultipartonInteractions:pT0Ref	.....
3.3	MultipartonInteractions:ecmRef	.....
3.4	MultipartonInteractions:ecmPow	.....
3.5	MultipartonInteractions:pTmin	.....
3.6	MultipartonInteractions:enhanceScreening	.....
3.7	MultipartonInteractions:bProfile	.....
3.8	MultipartonInteractions:expPow	.....

### Variation of ColourReconnection and BeamRemnants

4.1	ColourReconnection:range	.....
4.2	BeamRemnants:primordialKTsoft	.....
4.3	BeamRemnants:primordialKTthard	.....
4.4	BeamRemnants:halfScaleForKT	.....
4.5	BeamRemnants:halfMassForKT	.....
4.6	BeamRemnants:reducedKTatHighY	.....
4.7	BeamRemnants:primordialKTremnant	.....
4.8	BeamRemnants:companionPower	.....
4.9	BeamRemnants:valencePowerUinP	.....

### Variation of TimeShower and SpaceShower

5.1	TimeShower:alphaSvalue	.....
5.2	TimeShower:alphaSorder	.....
5.3	TimeShower:pTmin	.....
5.4	SpaceShower:alphaSvalue	.....
5.5	SpaceShower:alphaSorder	.....
5.6	SpaceShower:pT0Ref	.....
5.7	SpaceShower:ecmRef	.....
5.8	SpaceShower:ecmPow	.....
5.9	SpaceShower:pTmin	.....

### Variation of StringPT and StringZ

6.1	StringPT:sigma	.....
6.2	StringPT:enhancedFraction	.....
6.3	StringPT:enhancedWidth	.....
6.4	StringPT:telescopePeaking	.....

### 7 Variation of StringFlav

7.1	StringFlav:probStoUD	.....
7.2	StringFlav:probQQtoQ	.....
7.3	StringFlav:probSQtoQQ	.....
7.4	StringFlav:probQQ1toQQ0	.....
7.5	StringFlav:mesonUDvector	.....
7.6	StringFlav:mesonSvector	.....
7.7	StringFlav:mesonCvector	.....
7.8	StringFlav:mesonBvector	.....
7.9	StringFlav:etaSup	.....
7.10	StringFlav:etaPrimeSup	.....
7.11	StringFlav:decupletSup	.....
7.12	StringFlav:popcornRate	.....
7.13	StringFlav:popcornSpair	.....
7.14	StringFlav:popcornSmeson	.....
7.15	StringFlav:suppressLeadingB	.....

### 8 Variation of Diffraction

8.1	Diffraction:mMinPert	.....
8.2	Diffraction:mWidthPert	.....
8.3	Diffraction:probMaxPert	.....
8.4	Diffraction:pickQuarkNorm	.....
8.5	Diffraction:pickQuarkPower	.....
8.6	Diffraction:primKTwidth	.....
8.7	Diffraction:largeMassSuppress	.....
8.8	Diffraction:sigmaRefPomP	.....
8.9	Diffraction:mRefPomP	.....
8.10	Diffraction:mPowPomP	.....
8.11	Diffraction:bProfile	.....
8.12	Diffraction:doHard	.....

### 9 Variation of Diffraction (SaS Model)

9.1	PDF:PomSet	.....
9.2	SigmaDiffractive:mMin	.....
9.3	SigmaDiffractive:lowMEnhance	.....
9.4	SigmaDiffractive:mResMax	.....
9.5	SigmaDiffractive:dampen	.....
9.6	SigmaDiffractive:SaSepsilon	.....

### 10 Variation of Diffraction (ABMST Model)

10.1	SigmaDiffractive:ABMSTmodeSD	.....
10.2	SigmaDiffractive:ABMSTmultSD	.....
10.3	SigmaDiffractive:ABMSTpowSD	.....
10.4	SigmaDiffractive:ABMSTmultDD	.....
10.5	SigmaDiffractive:ABMSTpowDD	.....
10.6	SigmaDiffractive:ABMSTygap	.....
10.7	SigmaDiffractive:ABMSTypow	.....

# Monash

