Tuning Pythia for Forward Physics Experiments

FPF Theory Workshop

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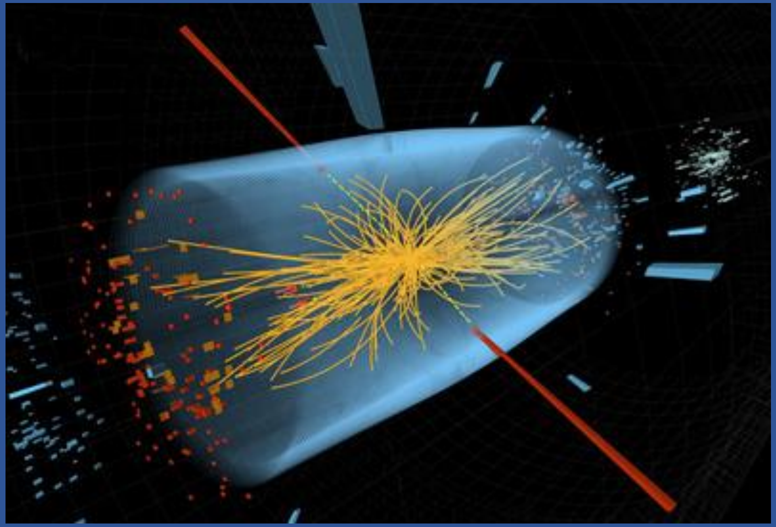
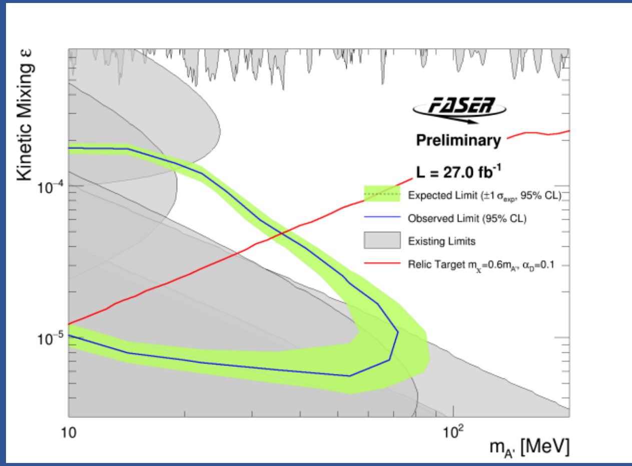
In collaboration with Felix Kling, Holger Schulz, Torbjörn Sjöstrand



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



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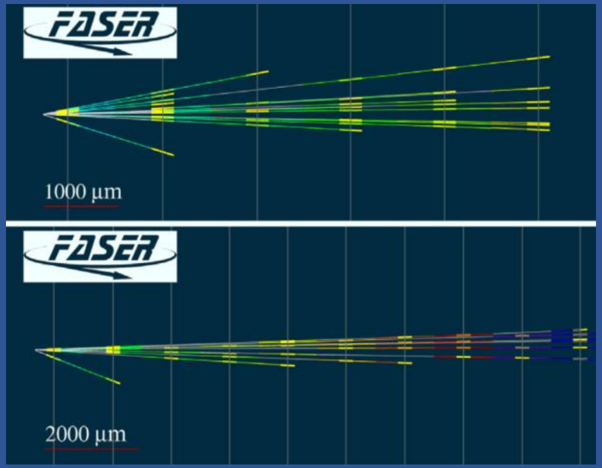

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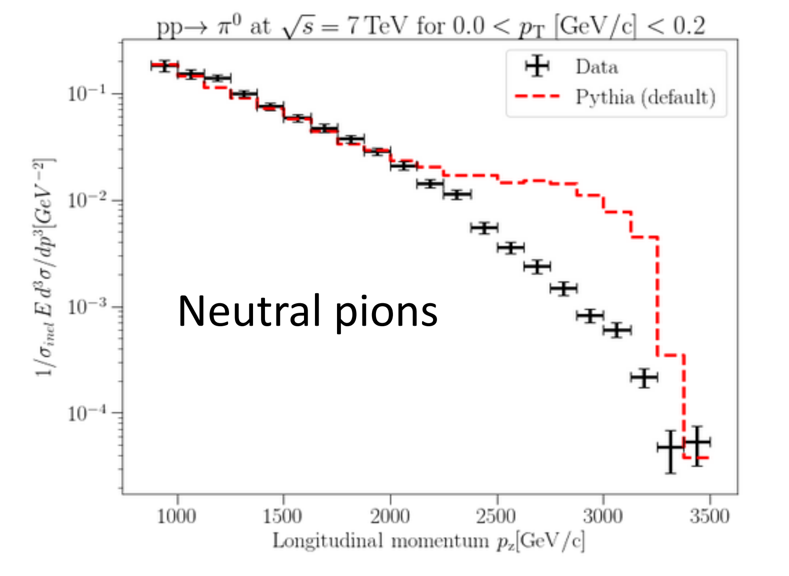
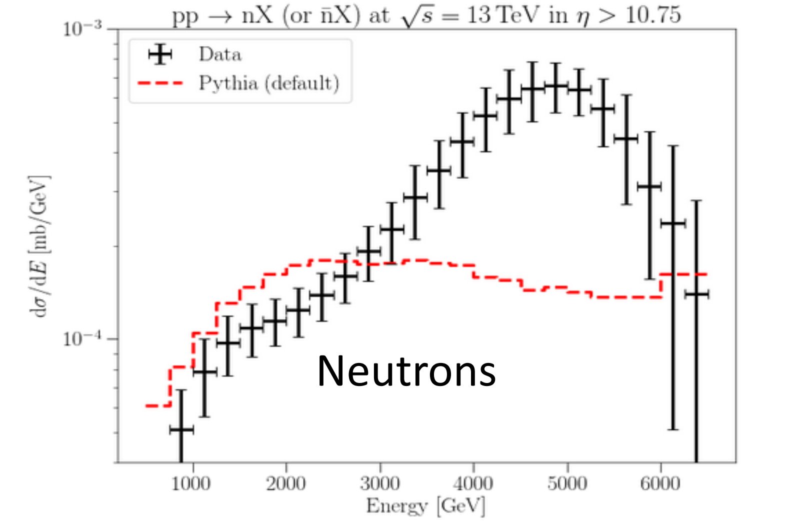
- Forward physics studies require an understanding of forward hadron production

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 √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





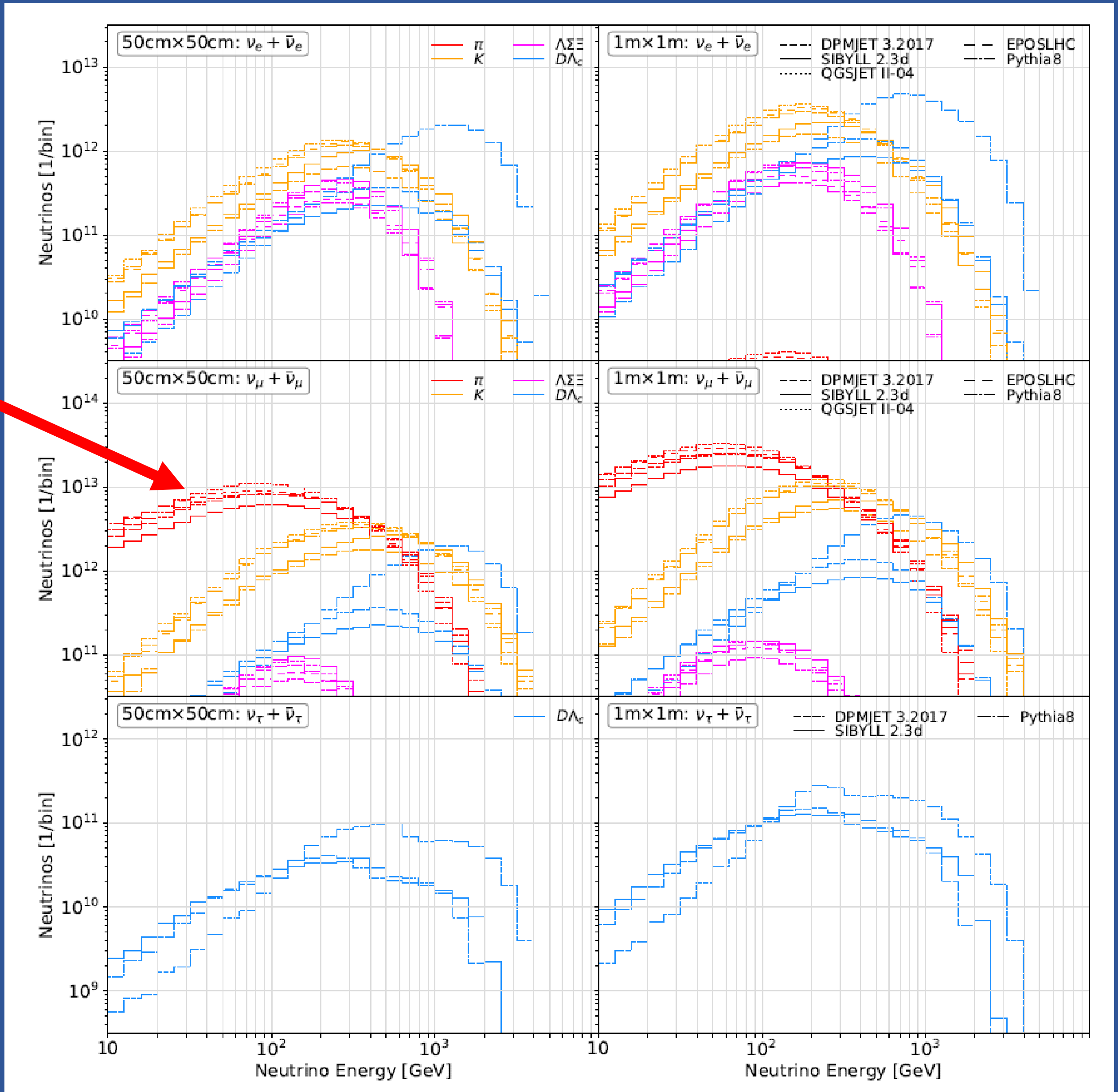
Second problem

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



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Outline

1. Pythia tuning methods

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

2. Tuning uncertainties

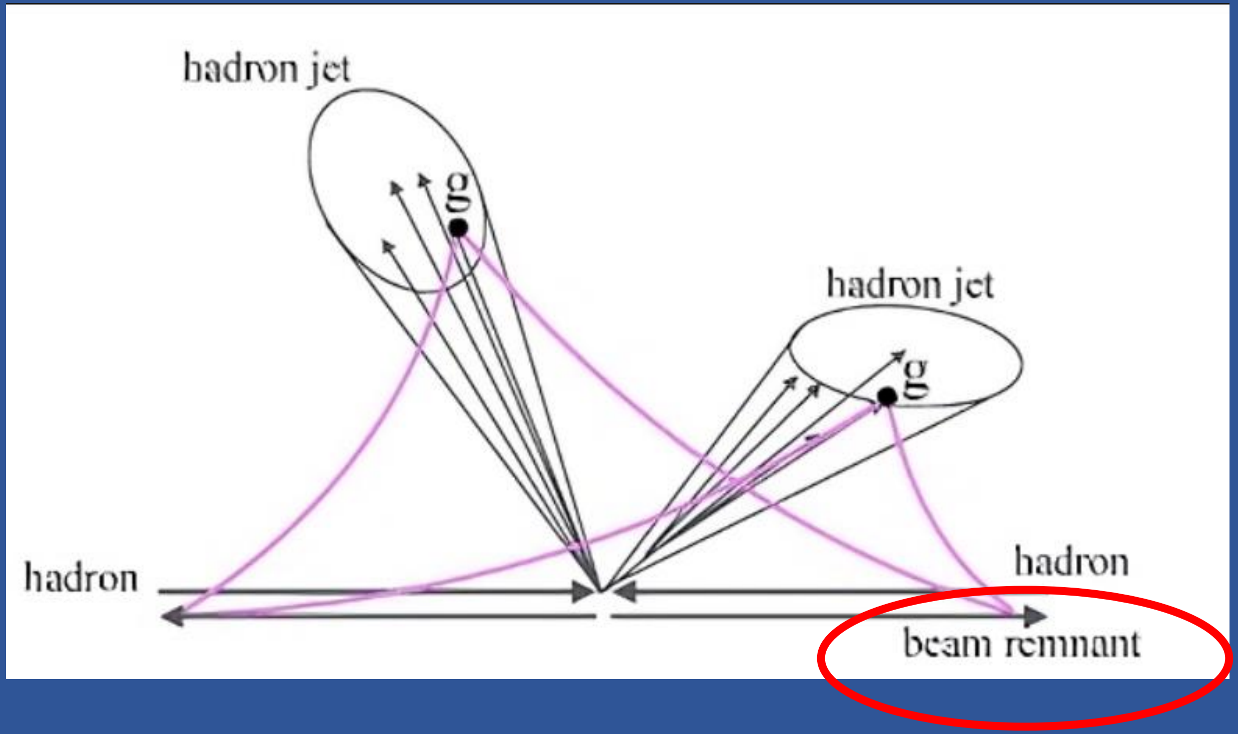
- Provide a tuning uncertainty which translates to a flux uncertainty

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:

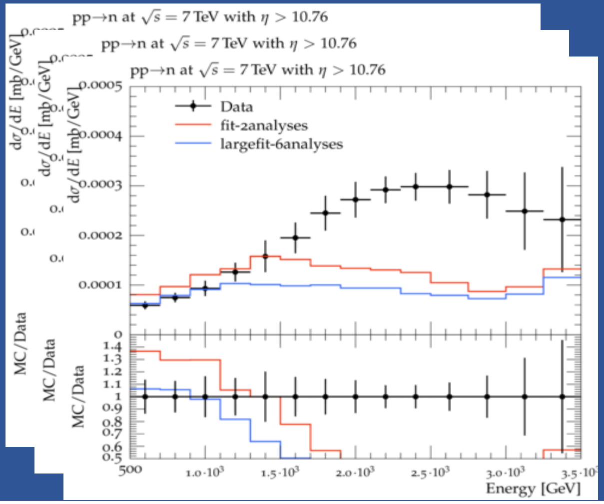
- Primordial kT of incoming partons to tune overall normalization
  - BeamRemnants:primordialKTremnant
  - BeamRemnants:primordialKTsoft
- Remnant → baryon fragmentation function to produce more hard neutrons
  - BeamRemnants:hardRemnantBaryon
  - BeamRemnants:bRemnantBaryon
- Reduce "Popcorn production" to produce fewer hard mesons from remnant diquarks
  - BeamRemnants:dampPopcorn

Tuning methods

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

PYTHIA

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

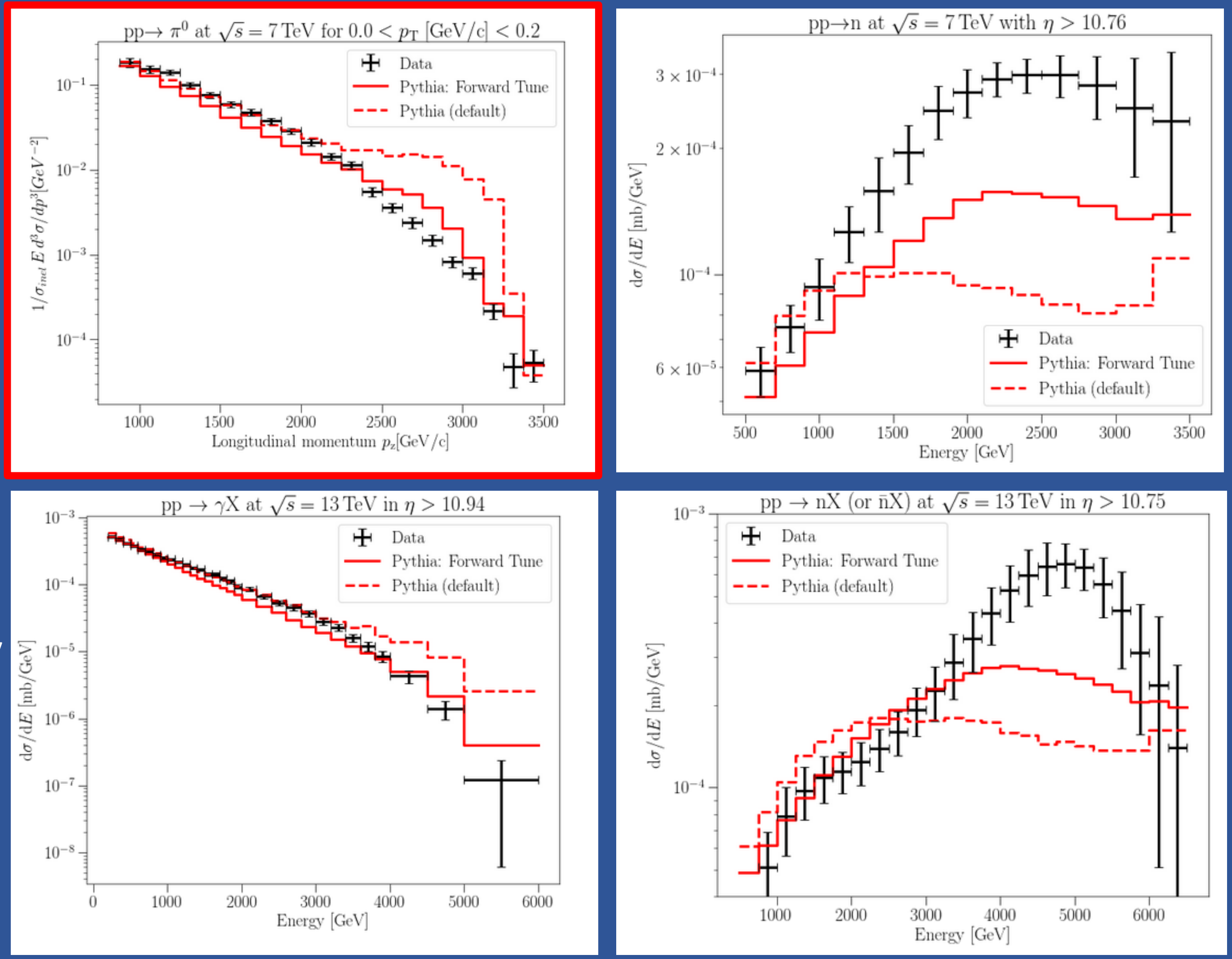
Flux normalization controlled by fitting primordial parton p_T: “kT_{remn}”

7 TeV

13 TeV

Pions*

neutrons

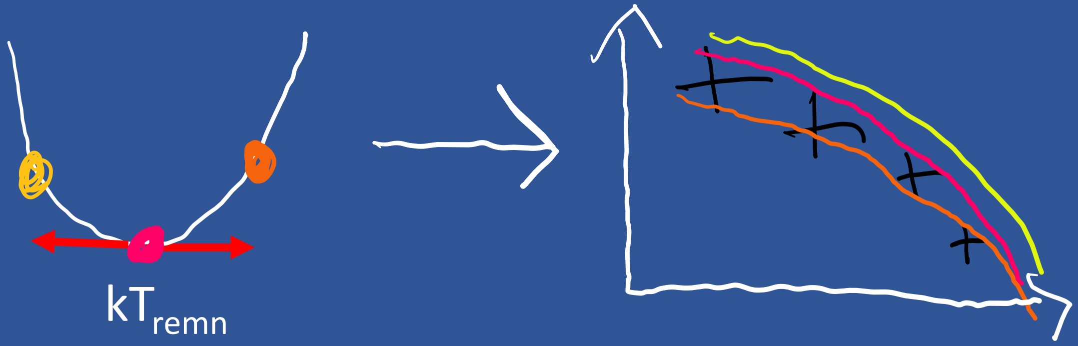


Can we define an uncertainty that captures imperfections in our tune? a naïve $\Delta\chi^2$ returns an unreasonable underestimate of uncertainties

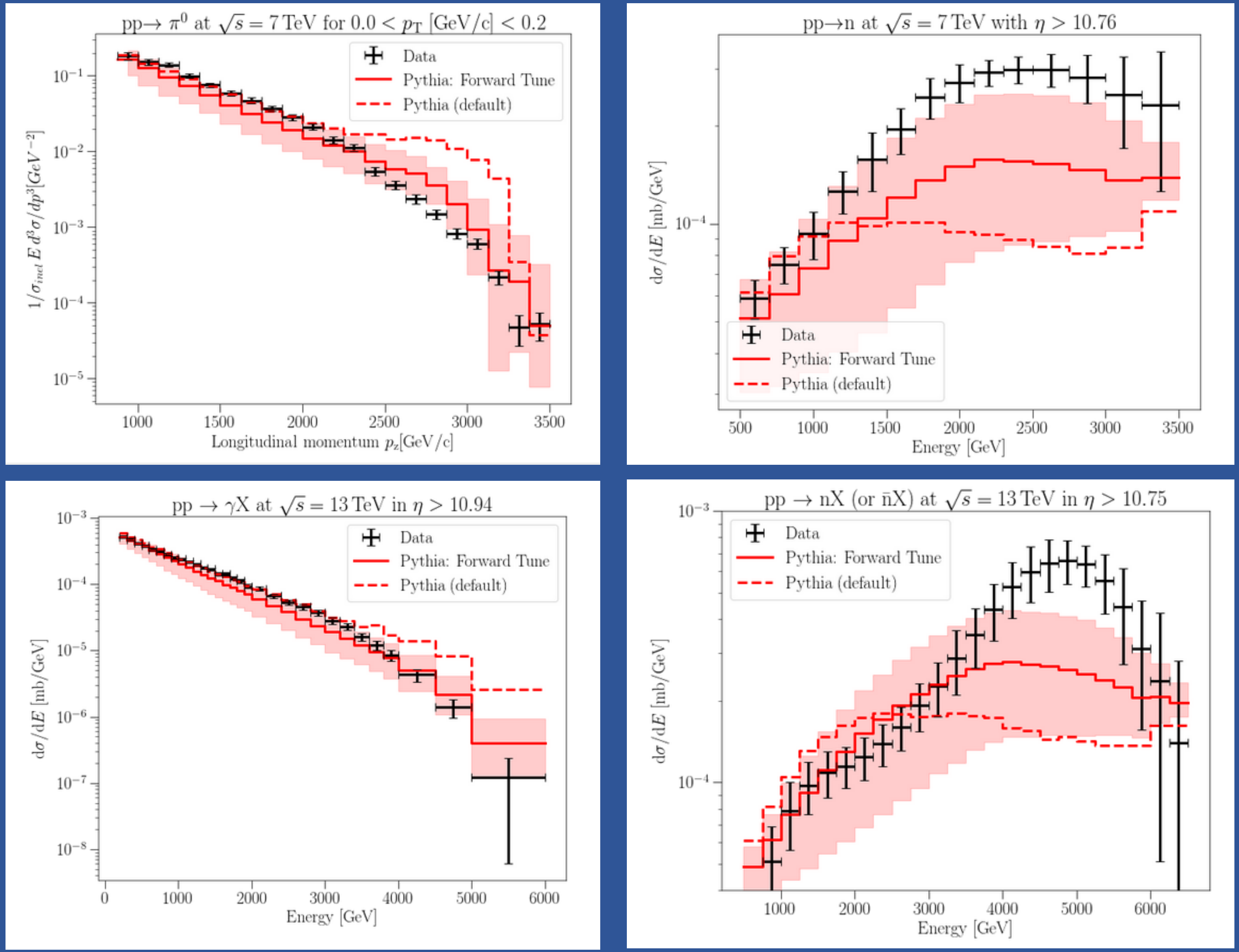
Tuning uncertainties

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

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



By construction, result is a band enveloping 68% of data, resembling 1σ



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	σ_{soft}	0.9	0.58	$0.26 \ldots 1.27$
BeamRemnants:primordialKThard	σ_{hard}	1.8	1.8	
BeamRemnants:halfScaleForKT	Q_{half}	1.5	10	
BeamRemnants:halfMassForKT	m_{half}	1	1	
BeamRemnants:primordialKTremnant	σ_{remn}	0.4	0.58	$0.26 \ldots 1.27$

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

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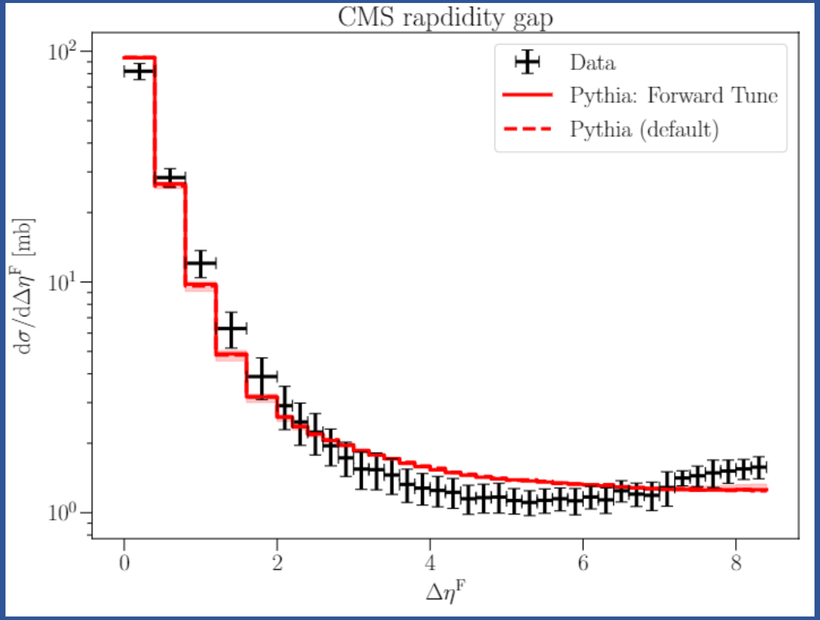
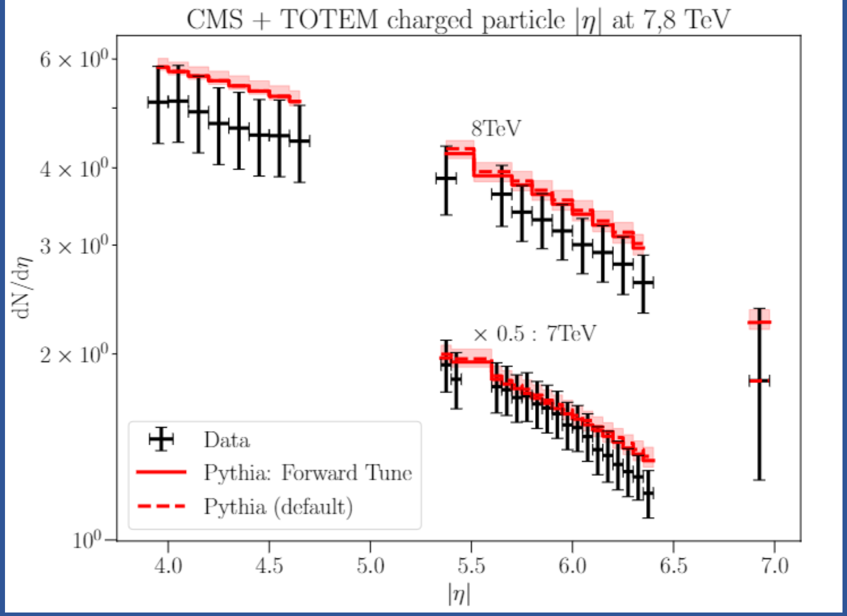
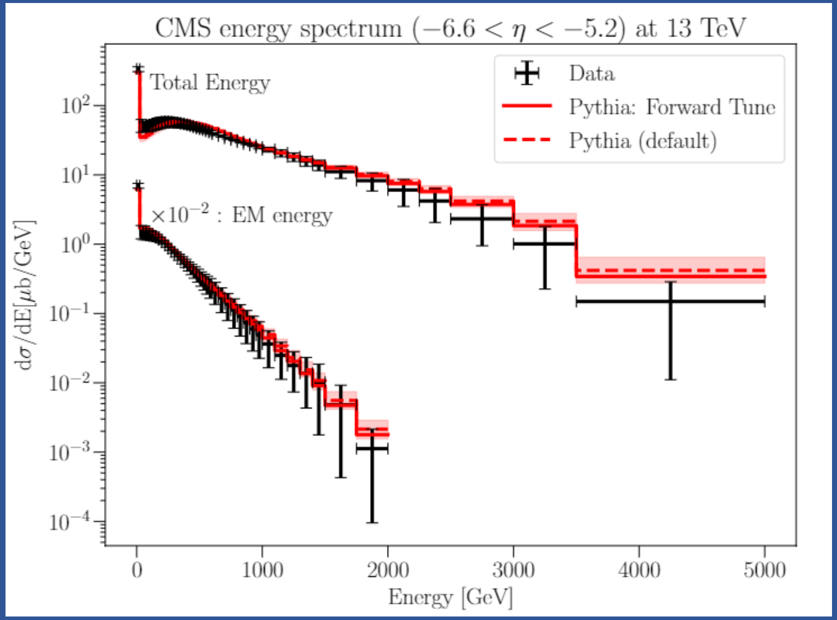
Did we spoil success in the central region , at CMS, ATLAS or even TOTEM?

Impact on central physics

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

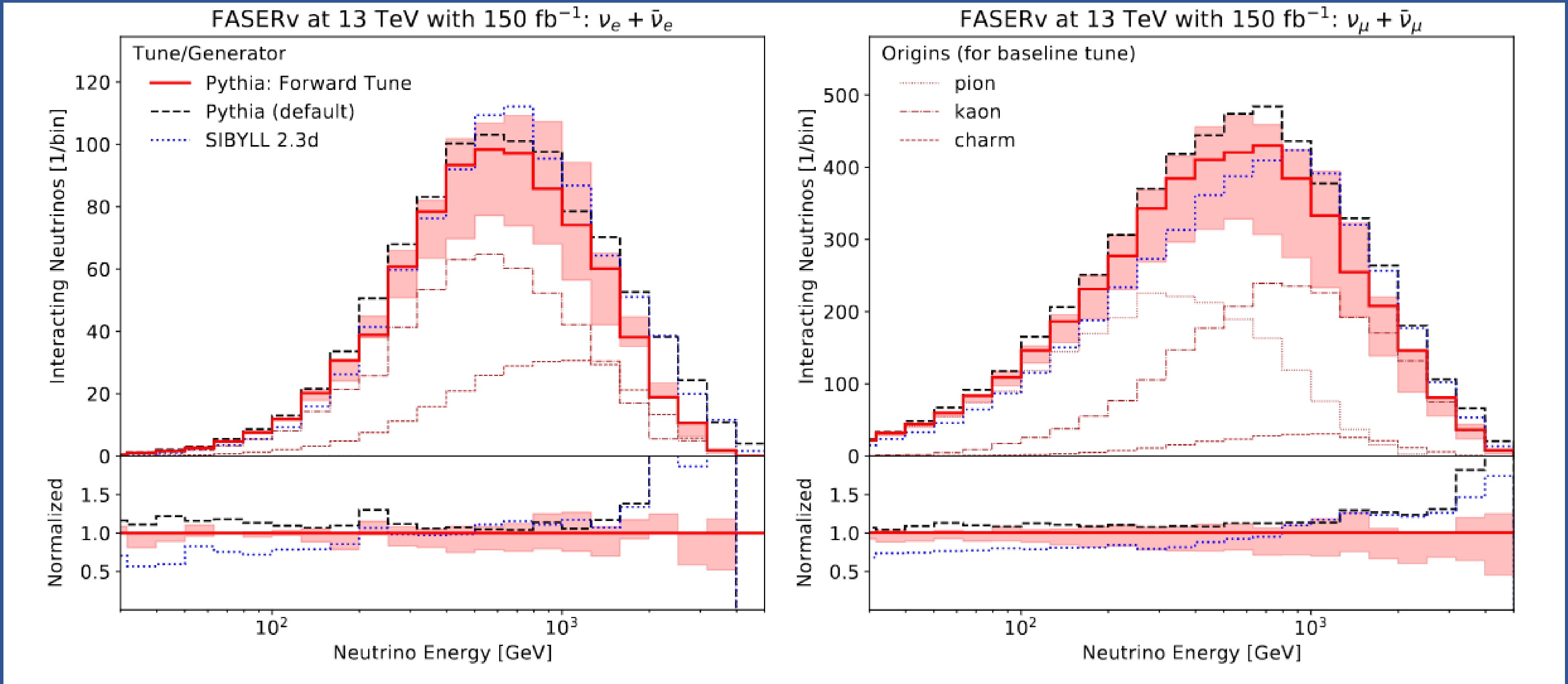






Applications for forward physics - Neutrinos

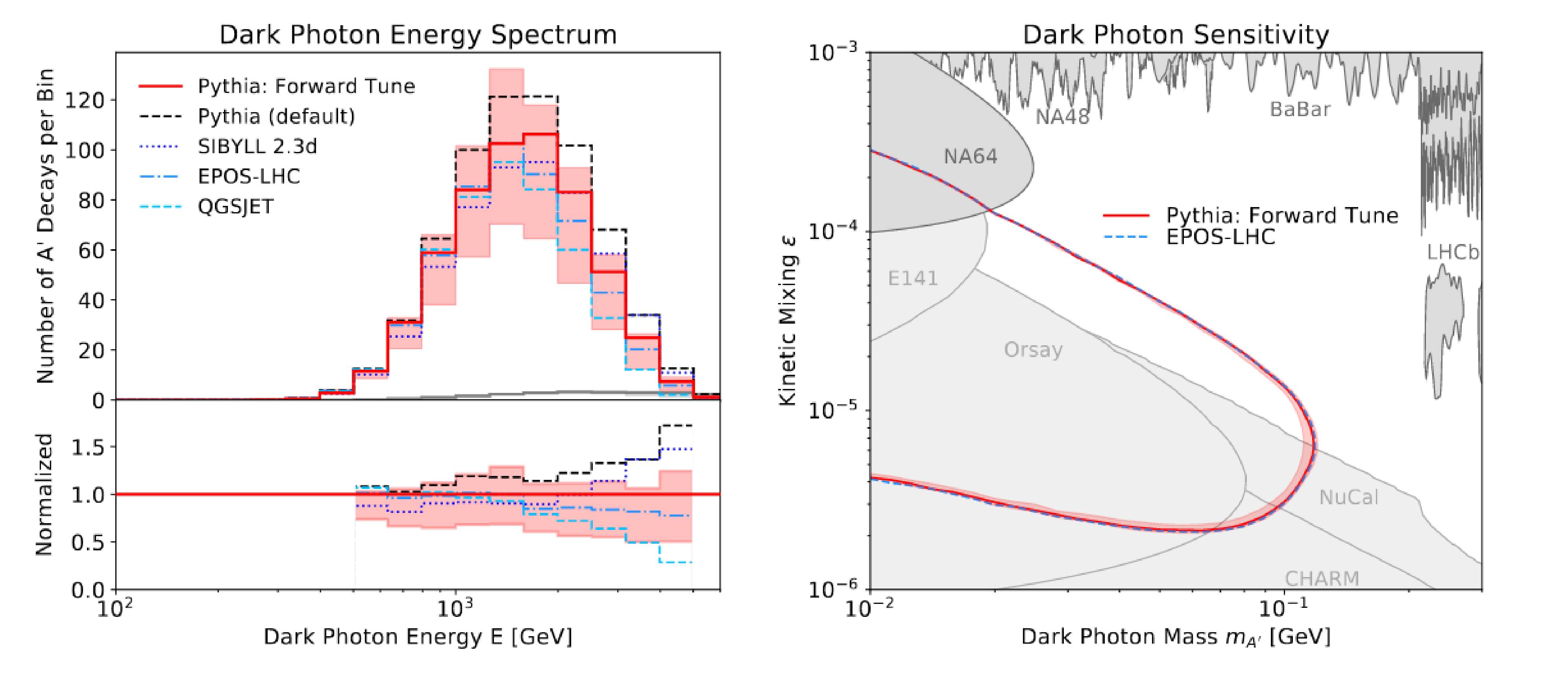
- Interacting electron and muon neutrino spectrum at FASER. Our improved tune predicts ~10% fewer neutrinos as compared to the default Pythia configuration and we find a 20% uncertainty band



Applications for forward physics – Dark Photons

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

-About 50% uncertainty in number of dark photon decays. Reach is largely unaffected due to large ε 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

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BeamRemnants:dampPopcorn	d_{pop}	1	0	
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BeamRemnants:aRemnantBaryon	a_{remn}	-	0.36	
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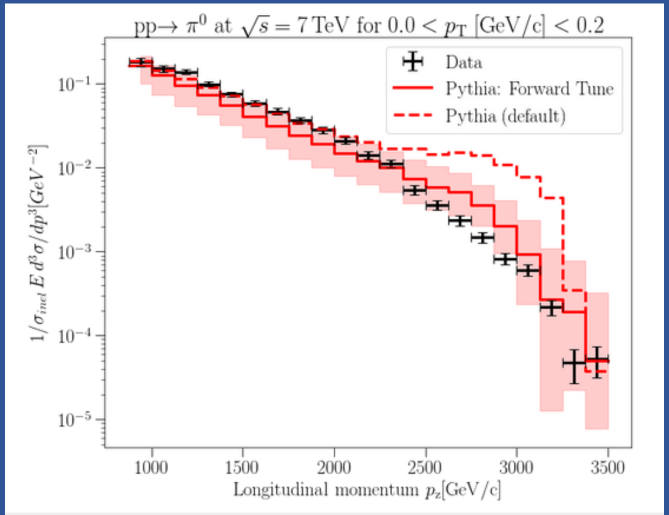
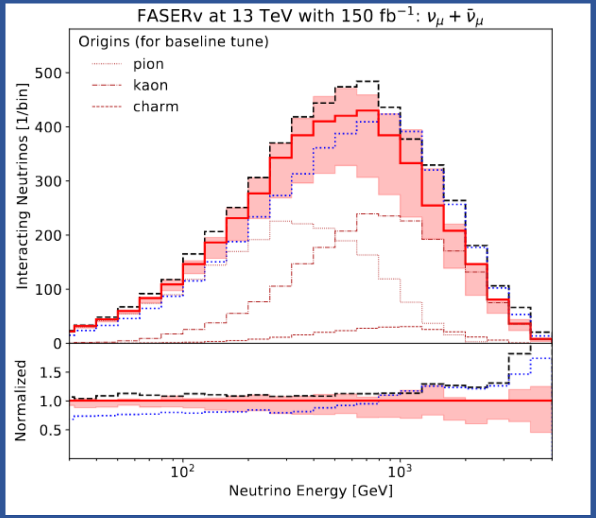
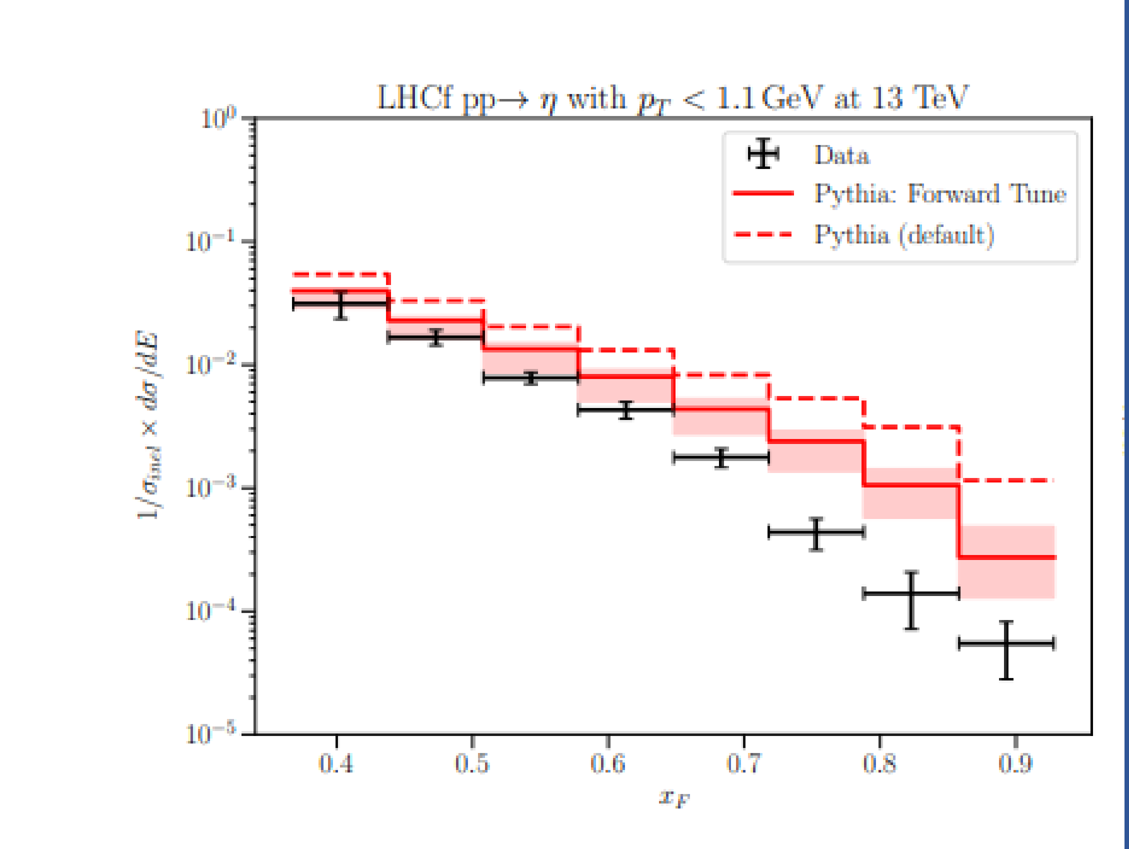


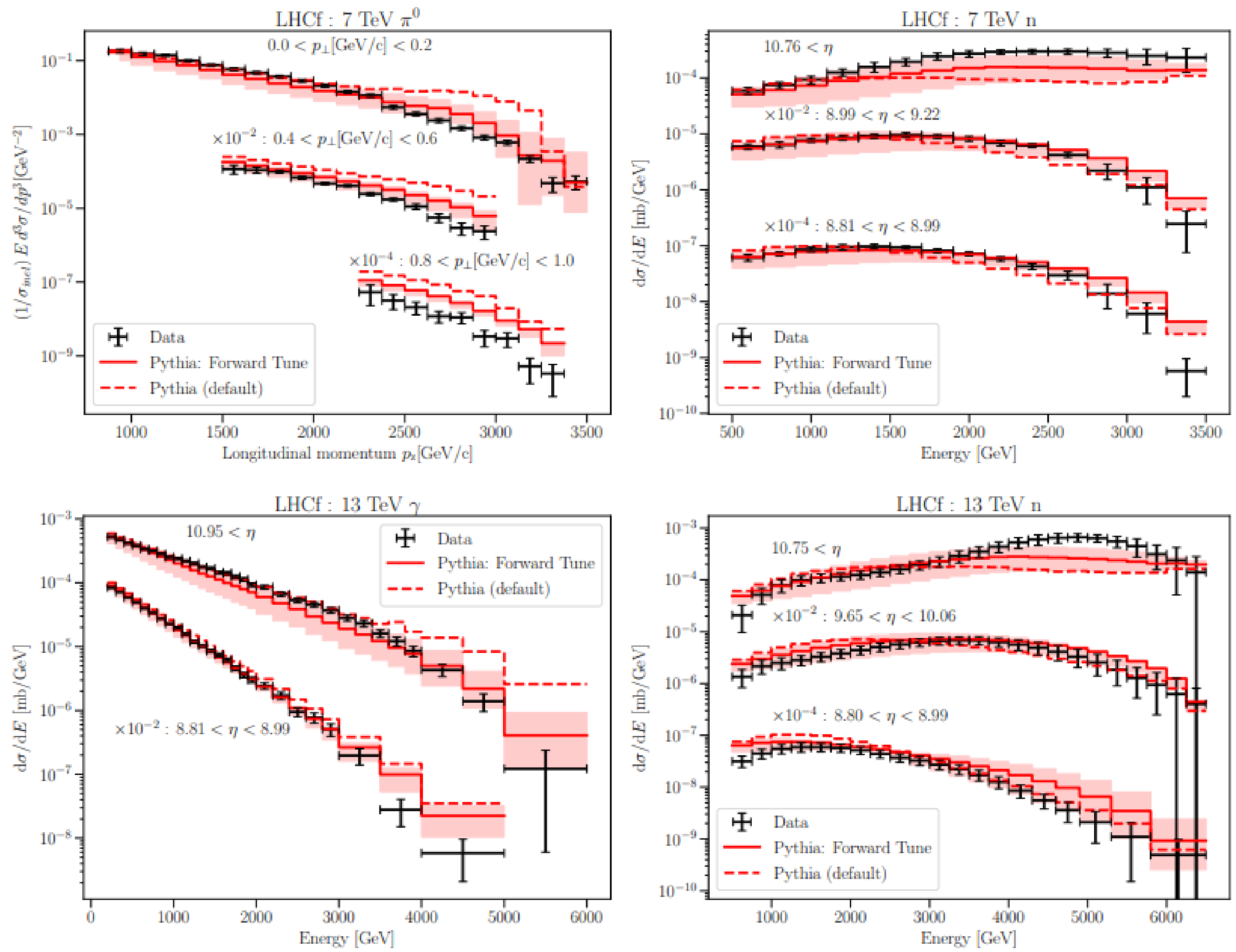


Thank you for listening!

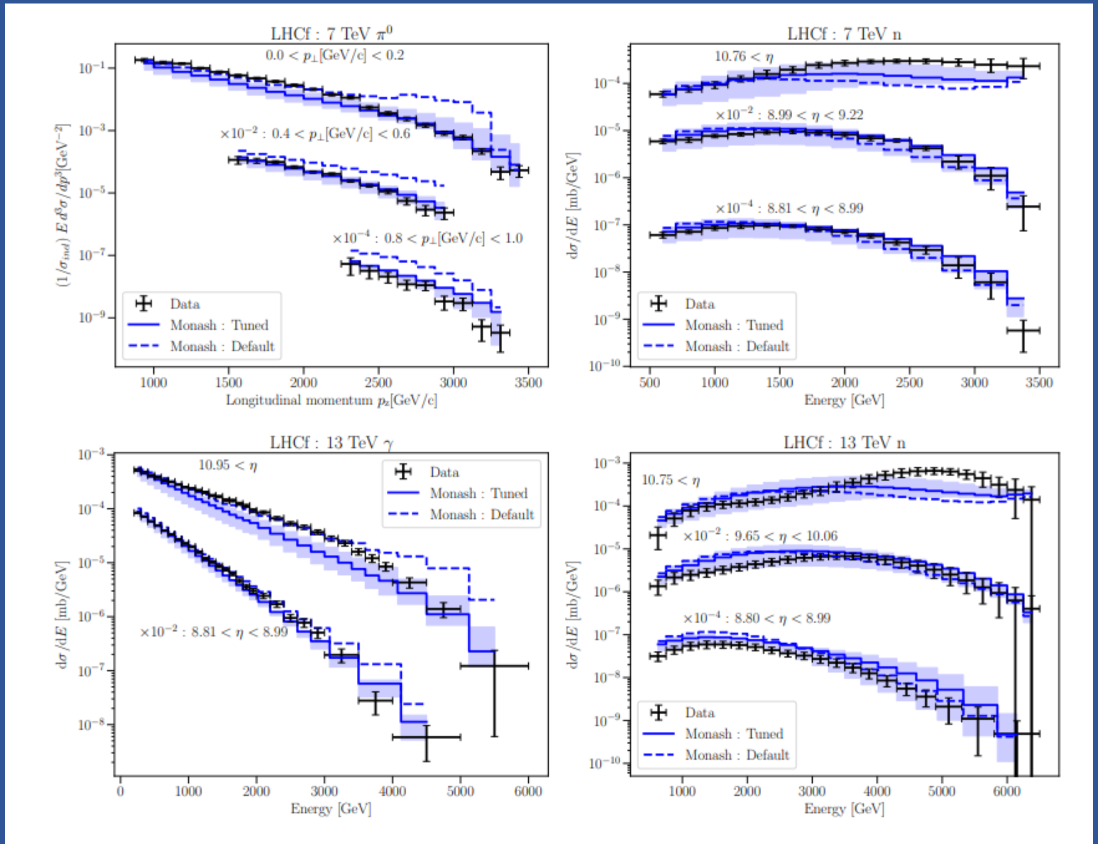
Back up

Eta analysis




LHCf : 7 TeV π^0
$0.0 < p_\perp$[GeV/c] < 0.2
$\times 10^{-2}$: $0.4 < p_\perp$[GeV/c] < 0.6
$\times 10^{-4}$: $0.8 < p_\perp$[GeV/c] < 1.0
$(1/\sigma_{inel})\, E\, d^3\sigma/dp^3$[GeV^{-2}]
Longitudinal momentum p_z[GeV/c]
LHCf : 7 TeV n
$10.76 < \eta$
$\times 10^{-2}$: $8.99 < \eta < 9.22$
$\times 10^{-4}$: $8.81 < \eta < 8.99$
dσ/dE [mb/GeV]
Energy [GeV]
LHCf : 13 TeV γ
$10.95 < \eta$
$\times 10^{-2}$: $8.81 < \eta < 8.99$
dσ/dE [mb/GeV]
Energy [GeV]
LHCf : 13 TeV n
$10.75 < \eta$
$\times 10^{-2}$: $9.65 < \eta < 10.06$
$\times 10^{-4}$: $8.80 < \eta < 8.99$
dσ/dE [mb/GeV]
Energy [GeV]
Data
Pythia: Forward Tune
Pythia (default)

Monash



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$10.75 < \eta$
$\times10^{-2}$: $9.65 < \eta < 10.06$
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Data
Monash : Tuned
Monash : Default