Tuning Pythia for Forward Physics Experiments

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2309.08604 + PRD

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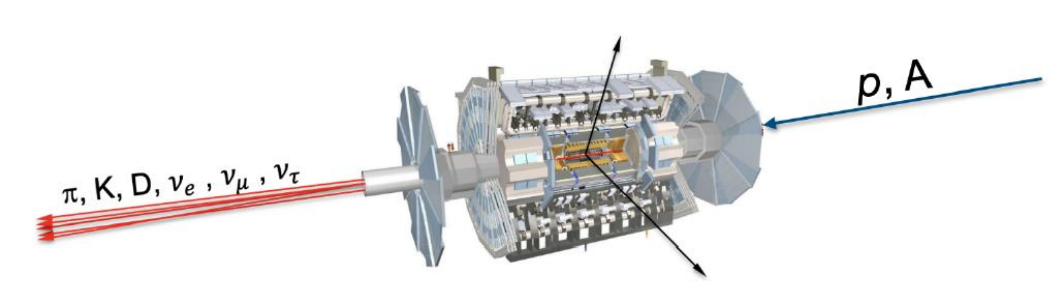
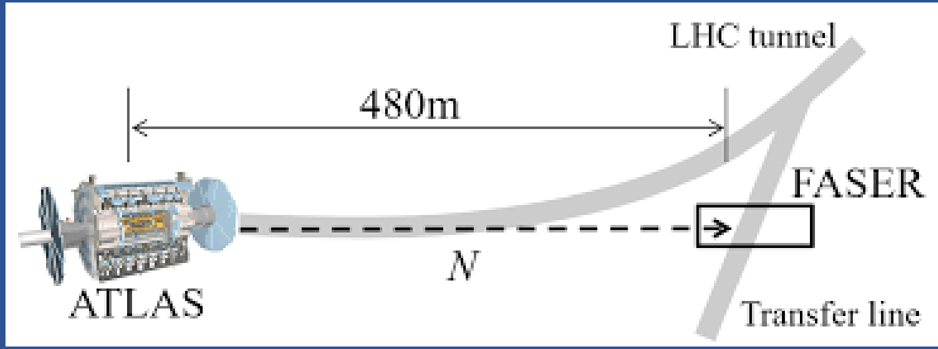
FASER and the Forward Physics Facility (FPF)

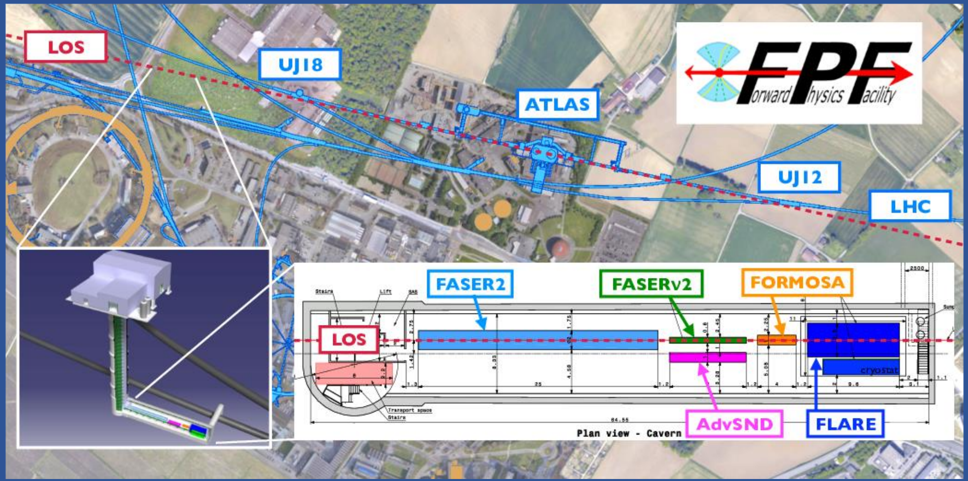
In the forward, large η, region at the LHC there is an intense flux of hadrons which can decay to, e.g., neutrinos or BSM states



The Forward Search Experiment (FASER) sits 480m downstream from the ATLAS IP and is looking for the decays of long-lived particles



The proposed Forward Physics Facility program, would carve out a cavern along the beamline to host a suite of experiments with different technologies



FASER and the Forward Physics Facility (FPF)

First FASER results already in!
Dark photon bounds and collider neutrino discovery

CERN-FASER-CONF-2023-001
29 March 2023

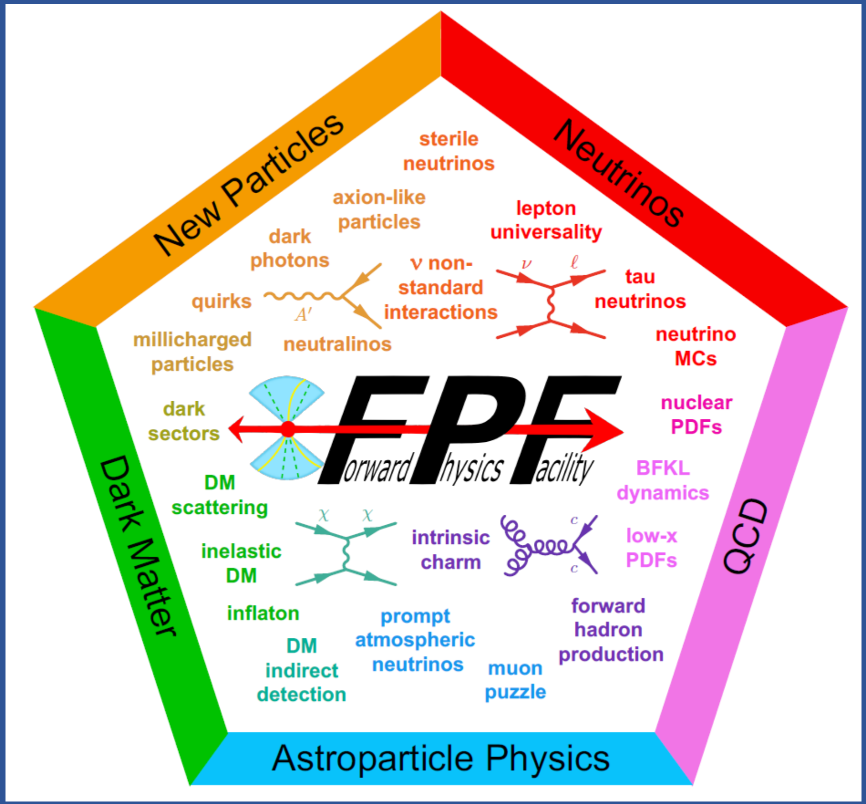
First Results from the Search for Dark Photons with the FASER Detector at the LHC

FASER Collaboration

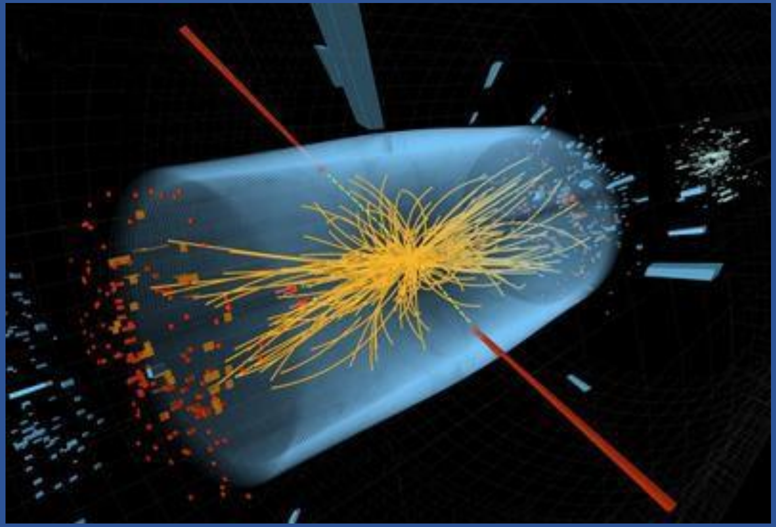
First Direct Observation of Collider Neutrinos with FASER at the LHC

FASER Collaboration

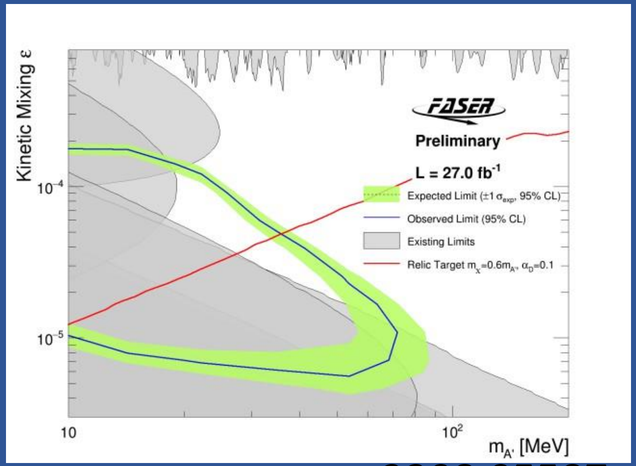
- If the FPF is approved, we are in for a broad physics program that requires careful study of forward physics



FPF Whitepaper 2203.05090



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



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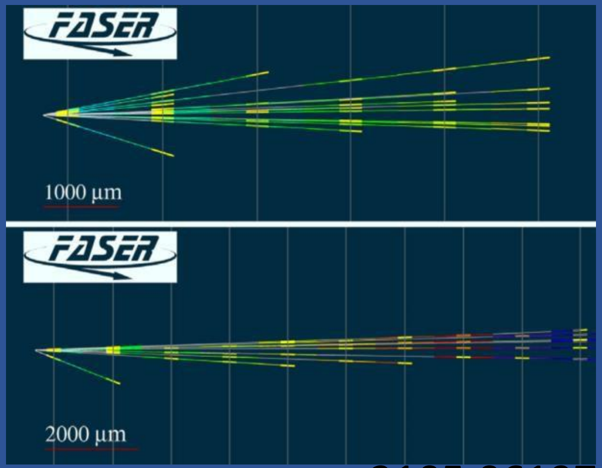


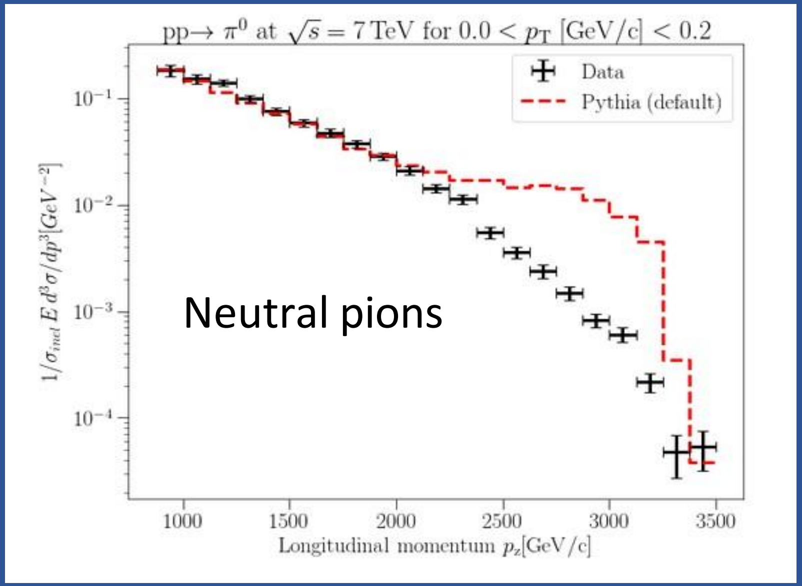
2105.06197

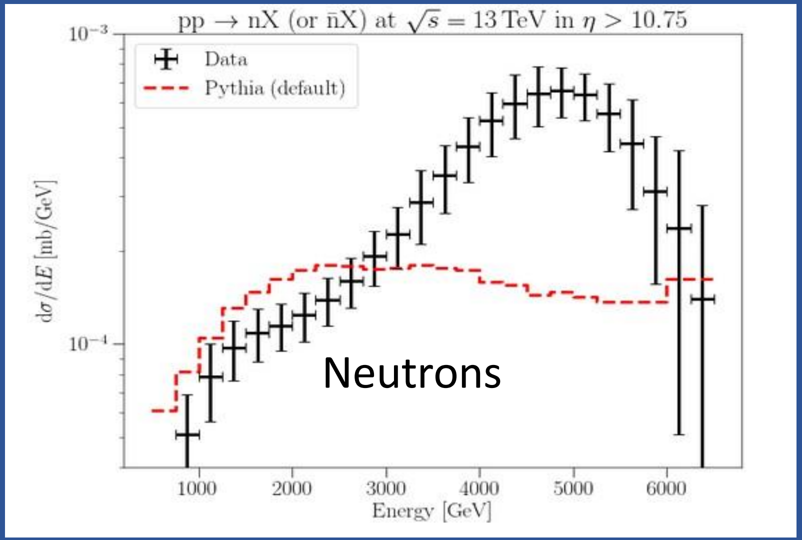
- Forward physics studies require an understanding of forward (light) hadron production

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 mechanism at each energy
  - $\pi^{\pm}$ important for ν_{μ} production
  - Charm decay important for all flavors at high energies – see 2309.12793
- Central Pythia tunes do not describe forward particle fluxes measured by LHCf
  - Other generators don't do very well either
- Use forward measurements from LHCf as our target and tune hadronization parameters
  - bonus if we can minimize the impact on central predictions

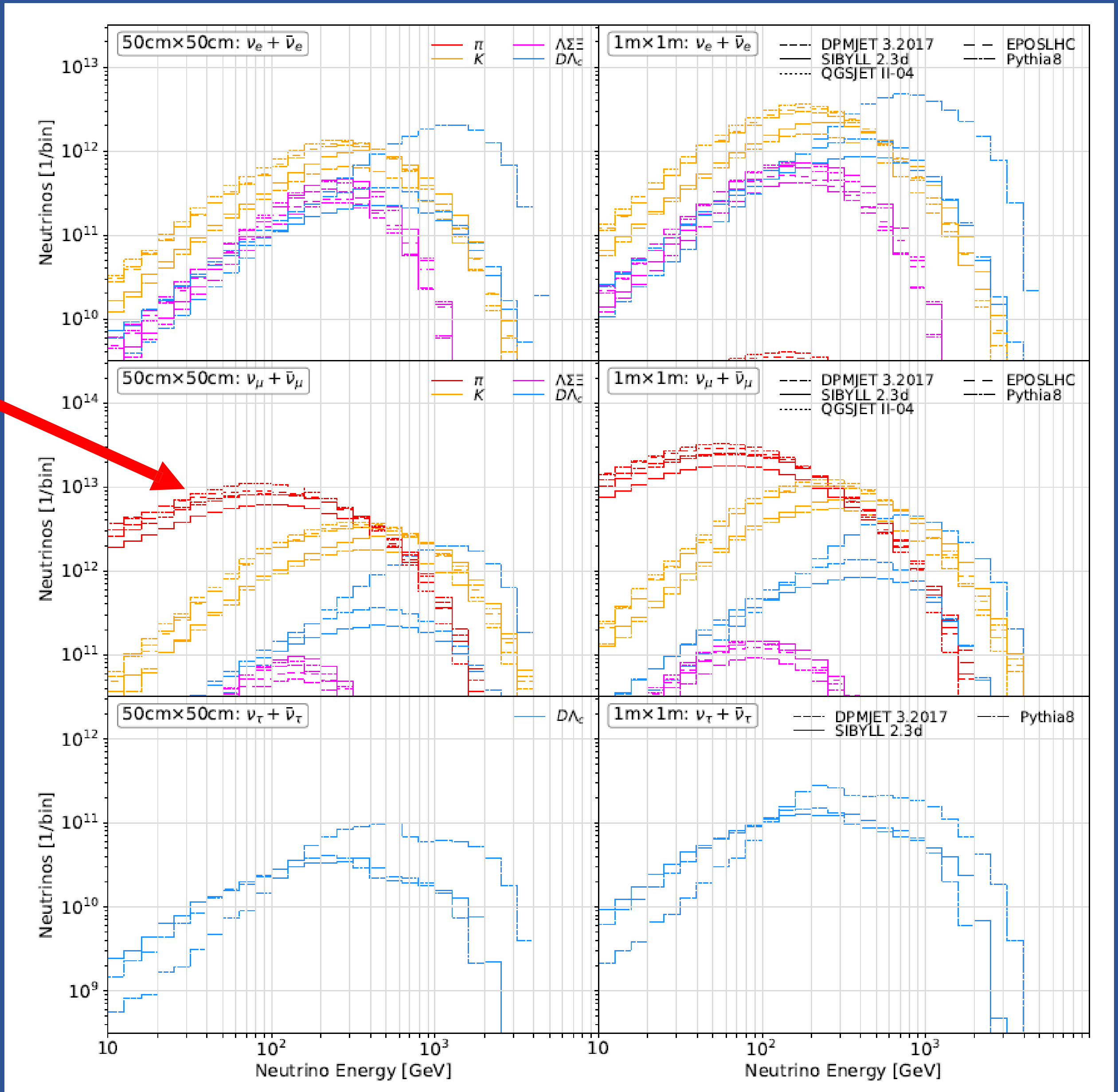




Second problem

Different generators can give very different hadron / neutrino fluxes

How can we get a handle on flux uncertainties?



2203.05090

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

1. Pythia tuning methods

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

2. Tuning uncertainties

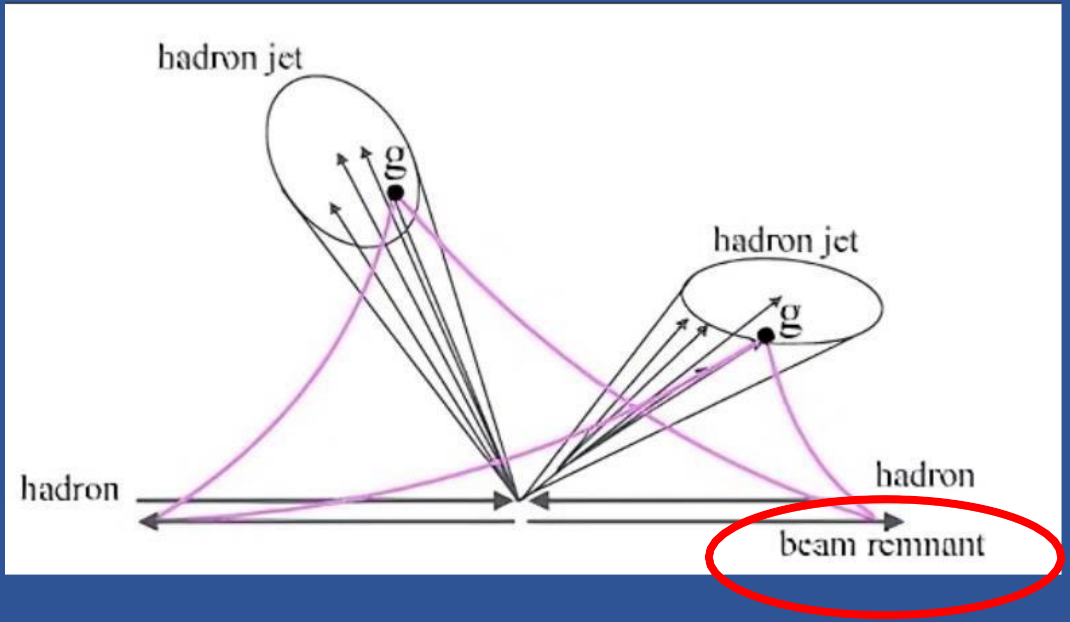
- Provide a tuning uncertainty which translates to a flux uncertainty

3. Applications at FASER

- Demonstrate tune for applications

Tuning methods: beam remnant

After a coarse scan through many parameters 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

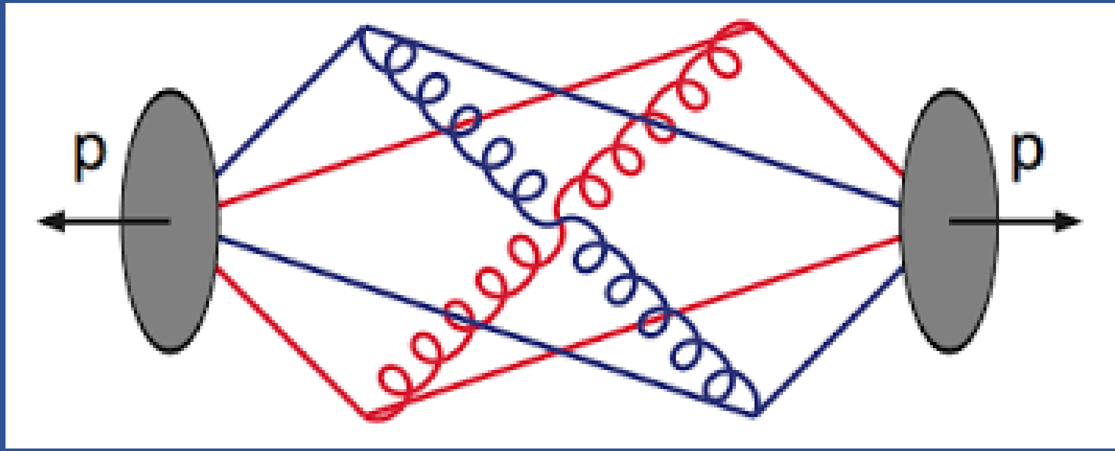
BeamRemnants:dampPopcorn

Tuning Methods: Color Reconnection (CR)

As baseline tunes, we compare the Monash tune vs. a central tune based on QCD Color Reconnection (1505.01681)

Here, explicit colors are assigned to partons in an MPI and string reconnections can occur if they reduce the total string length

We find that that using the QCD CR tune as our baseline is some improvement over our Monash based tune

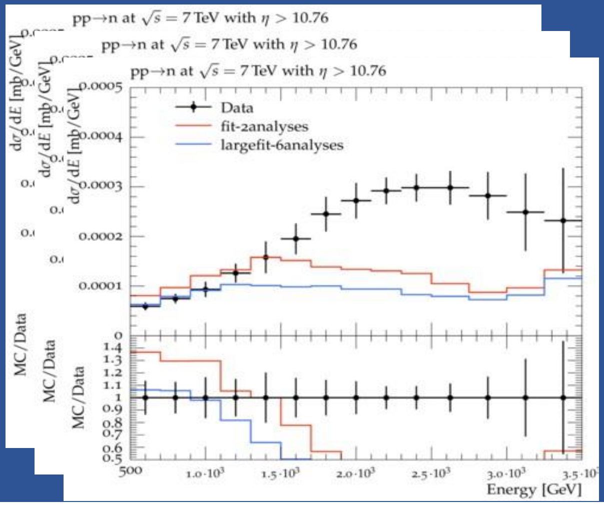


Tuning methods

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

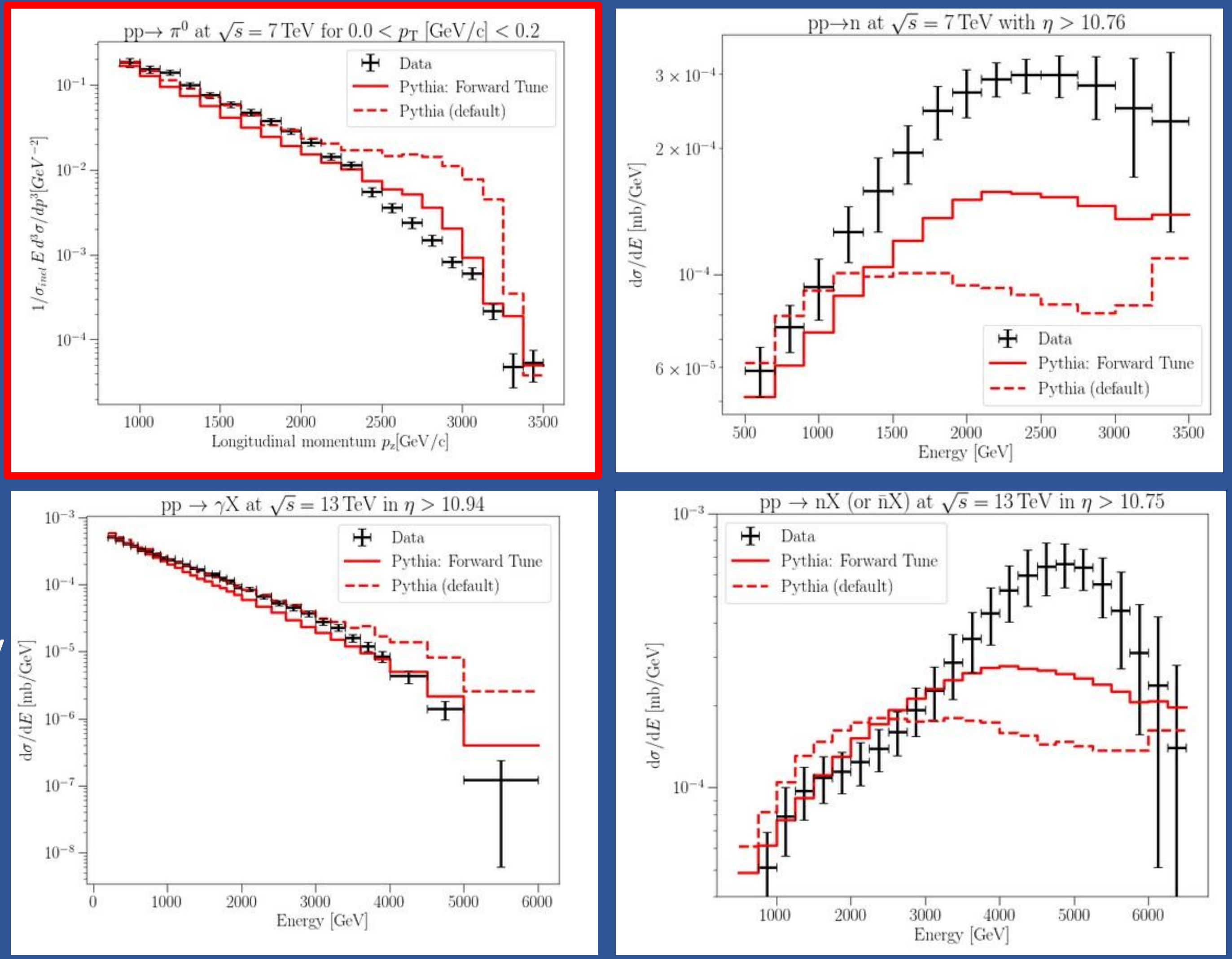
Flux normalization controlled by fitting primordial parton p_T: “kT_{remn}”

Pions*

neutrons

7 TeV

13 TeV

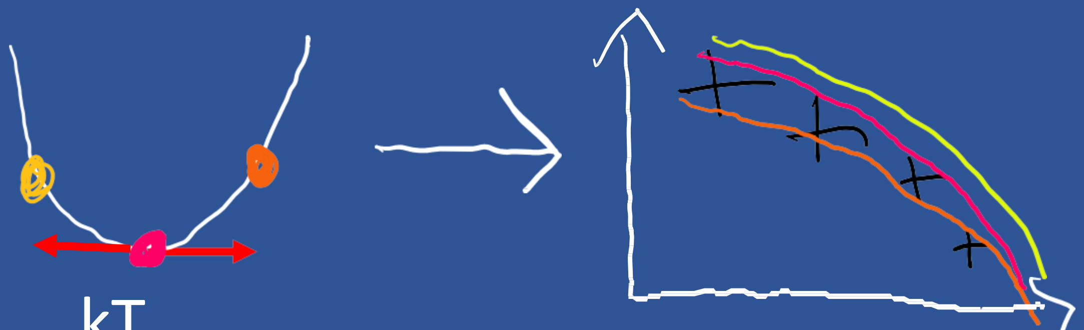


Can we define an uncertainty that captures imperfections in our tune? a naïve $\Delta\chi^2$ returns an unreasonable underestimate of uncertainties

Tuning uncertainties

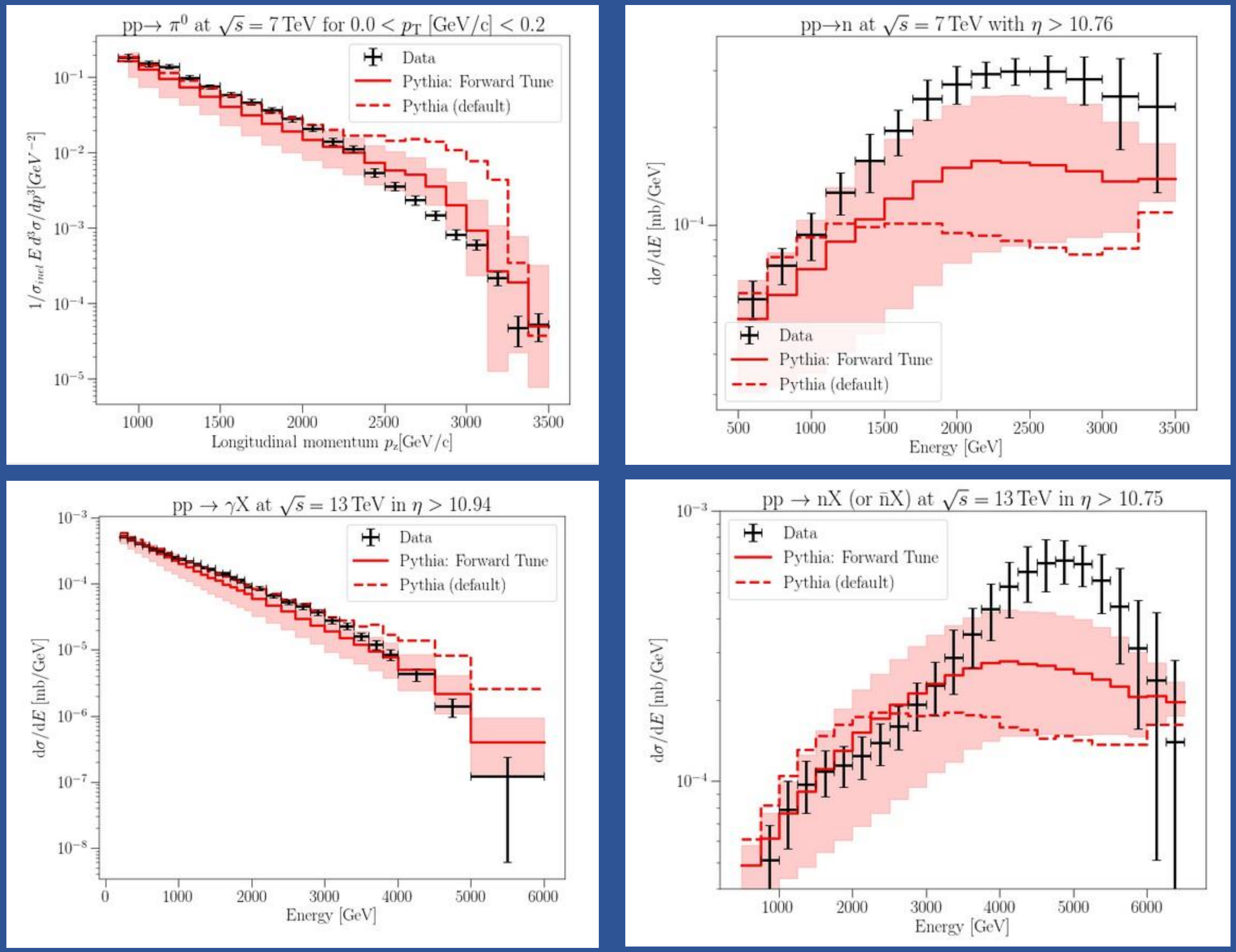
We reduce to the most sensitive tuning parameter (kT_{remn}) and take a pragmatic data-driven approach

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



kT_{remn}

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



How does Monash Compare?

Tuning Results: Monash vs. QCD CR

Monash tune is comparable but with some notable deficiencies

QCD CR better predicts the shape of the forward neutron spectra, Monash predicts more soft neutrons

Monash also underpredicts the photon spectra

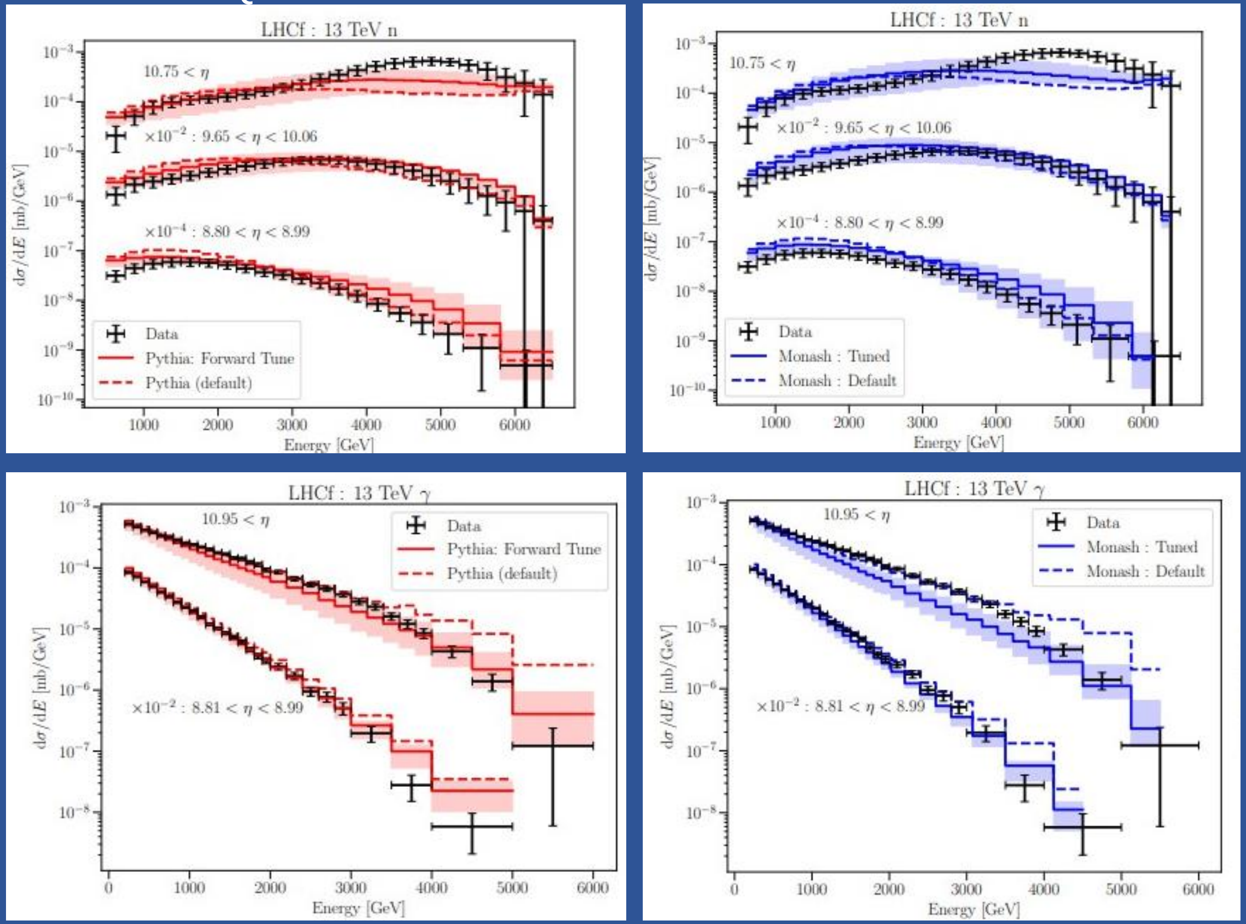
$\sim$ 20% overall improvement of QCD CR over Monash

QCD CR

Monash

neutrons

photons



Tuning Results

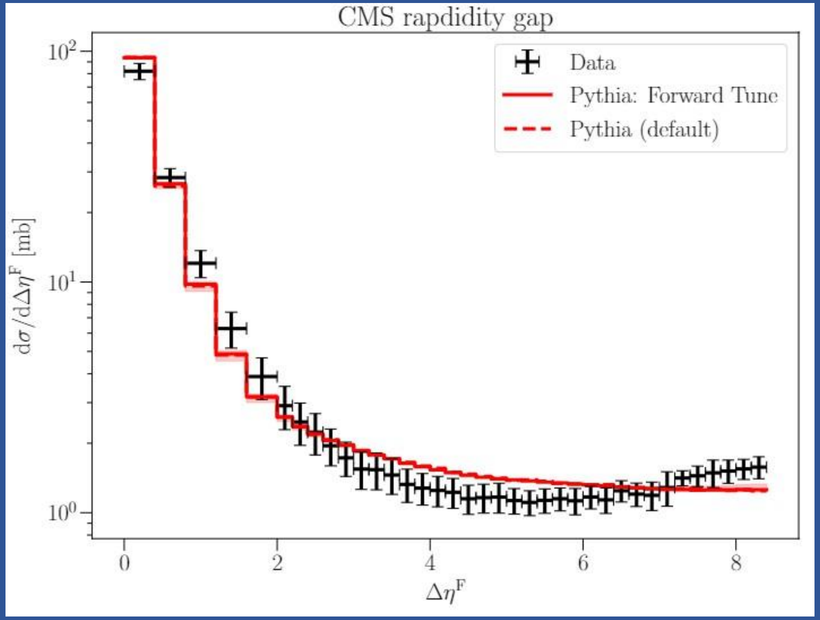
Full name	Shorthand	Baseline (QCDCR)	Forward Tune	Uncertainty
BeamRemnants:dampPopcorn	$d_{\rm pop}$	1	0	
BeamRemnants:hardRemnantBaryon	$f_{\rm remn}$	off	on	
BeamRemnants:aRemnantBaryon	$a_{\rm remn}$	-	0.36	
BeamRemnants:bRemnantBaryon	$b_{\rm remn}$	-	1.69	
BeamRemnants:primordialKTsoft	$\sigma_{\rm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

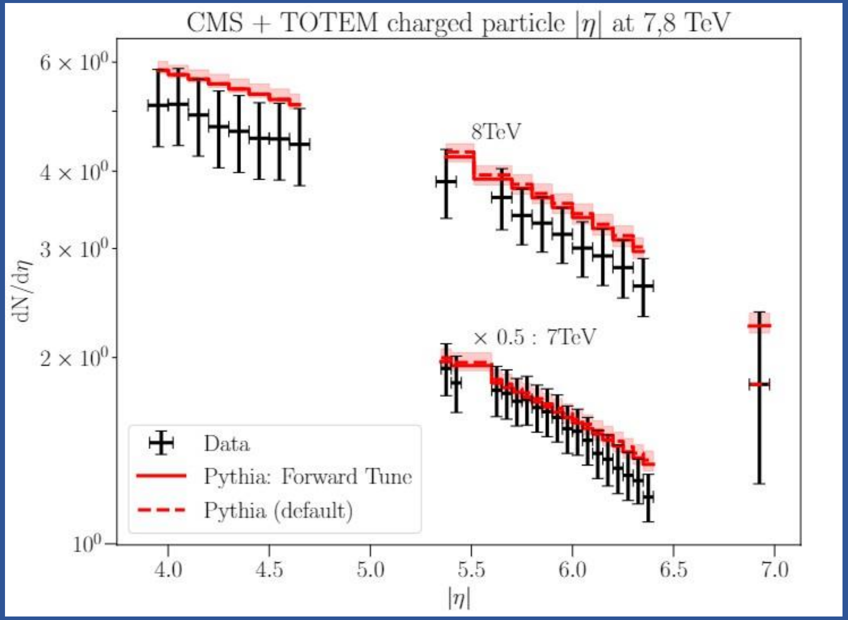
*Some details skipped over here, see paper or ask me for details

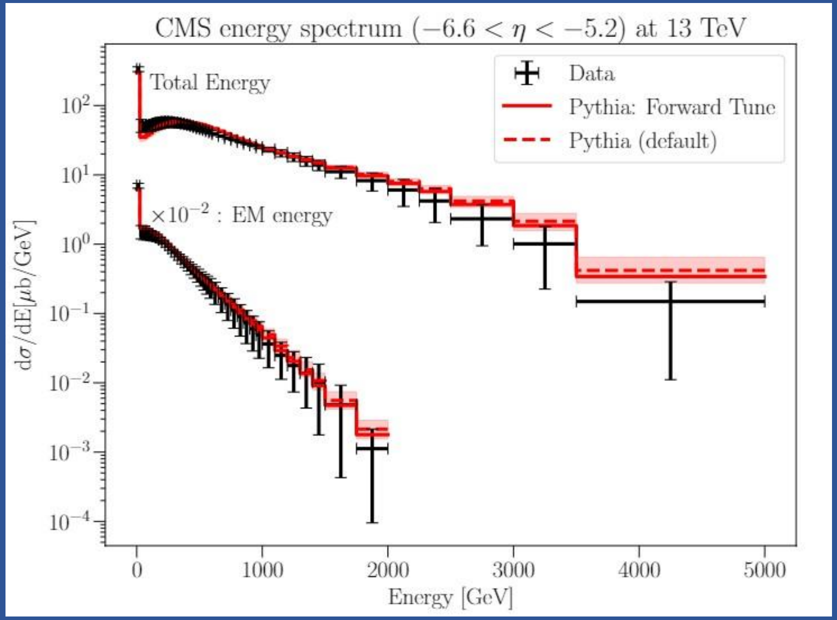
Did we spoil success in the central region , at CMS, ATLAS or even TOTEM?

Impact on central physics

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

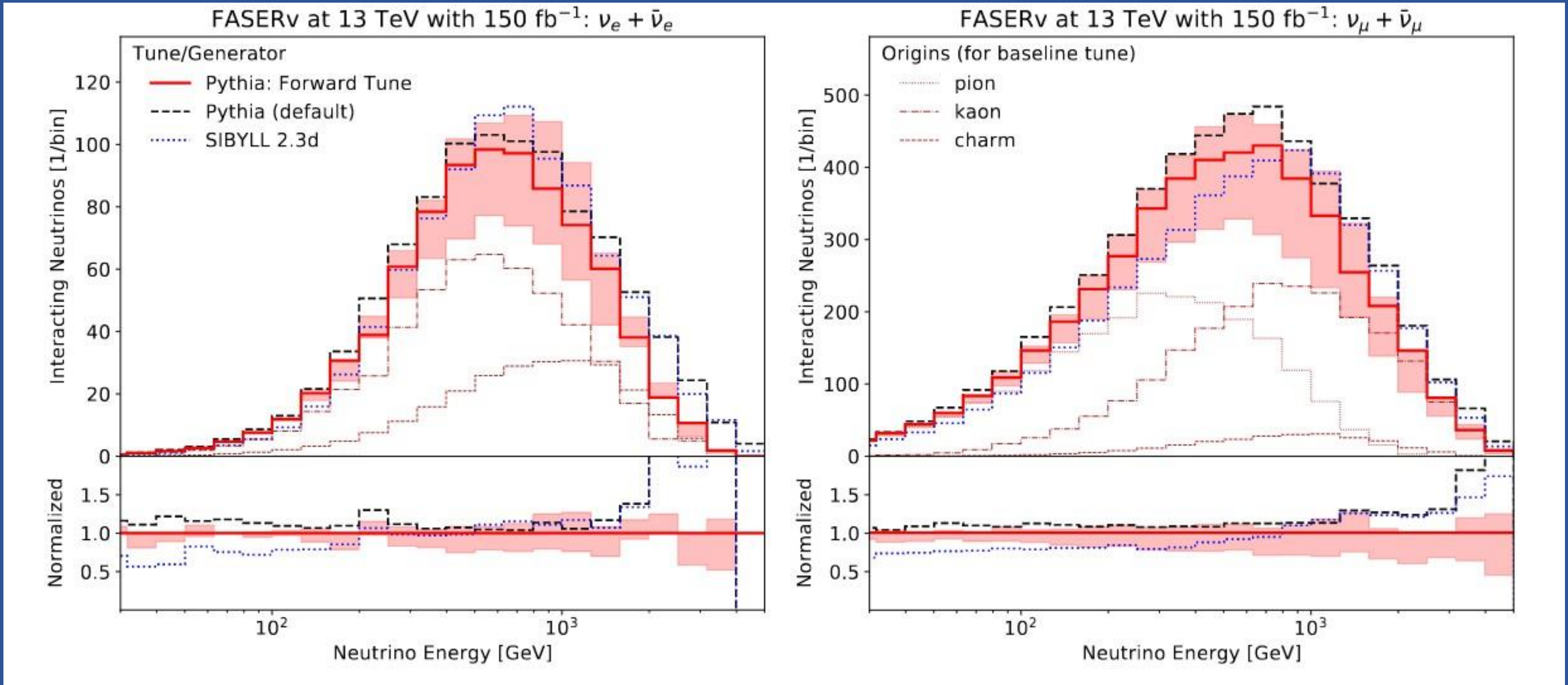






Applications for forward physics - Neutrinos

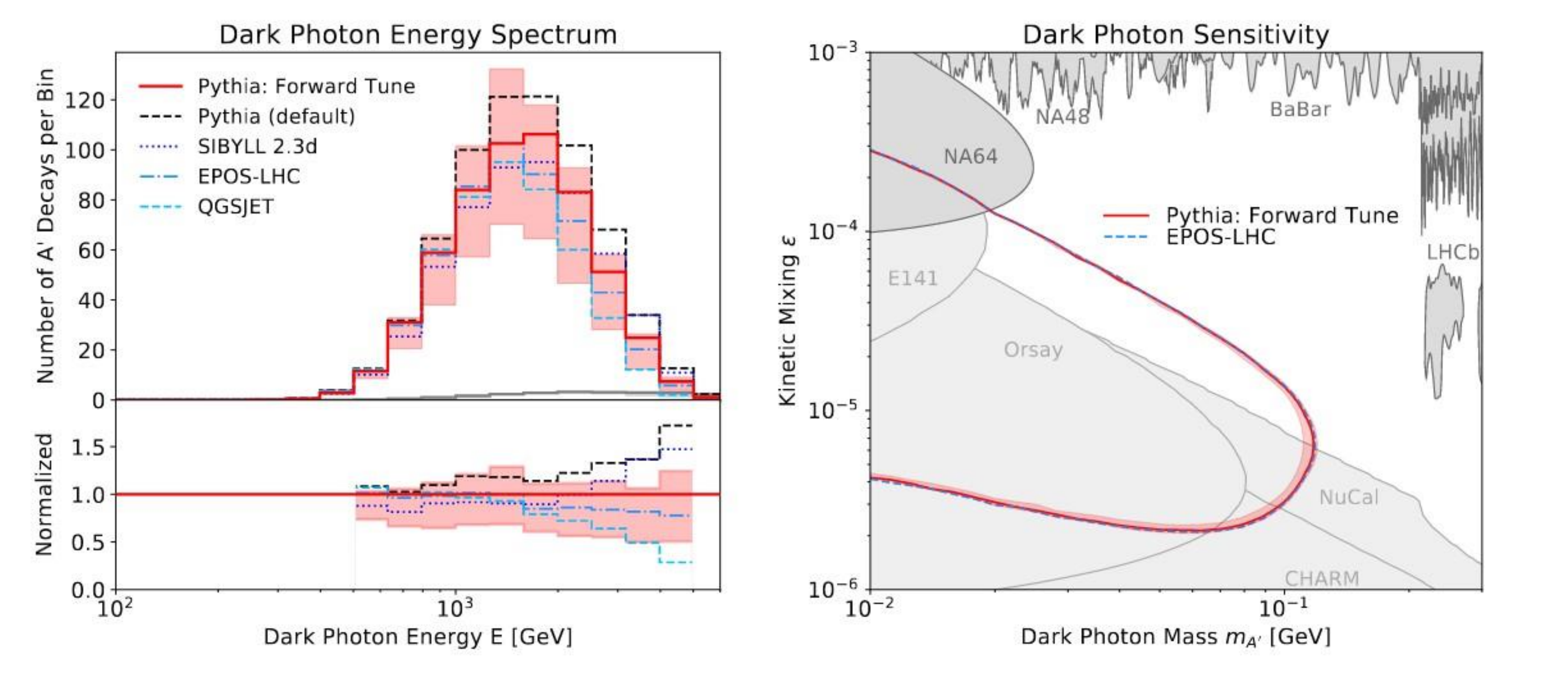
- Interacting electron and muon neutrino spectrum at FASER. Our improved tune predicts ~10% fewer neutrinos as compared to the default Pythia configuration, and we find a ~20% uncertainty band



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 estimate
- We demonstrate an application of our tune by showing its impact on neutrino and dark photon measurements at FASER

Thank you for listening!

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	
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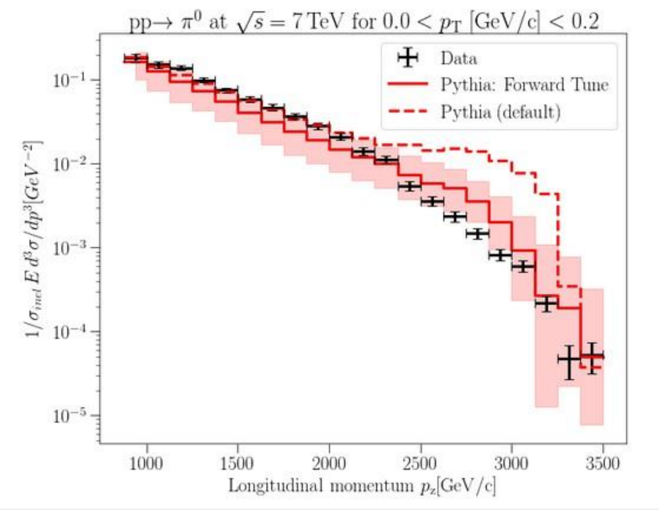
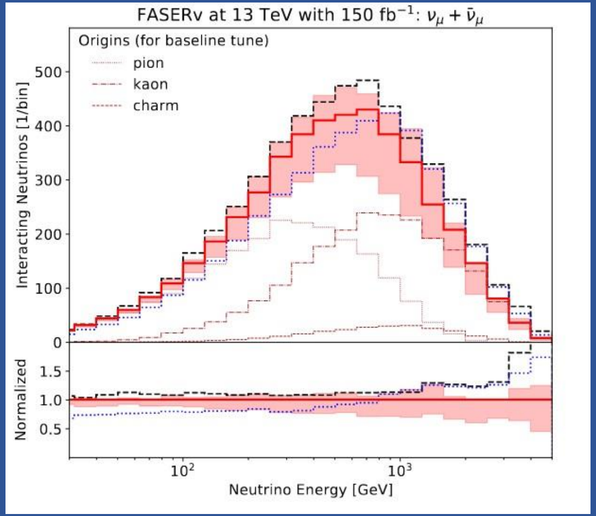
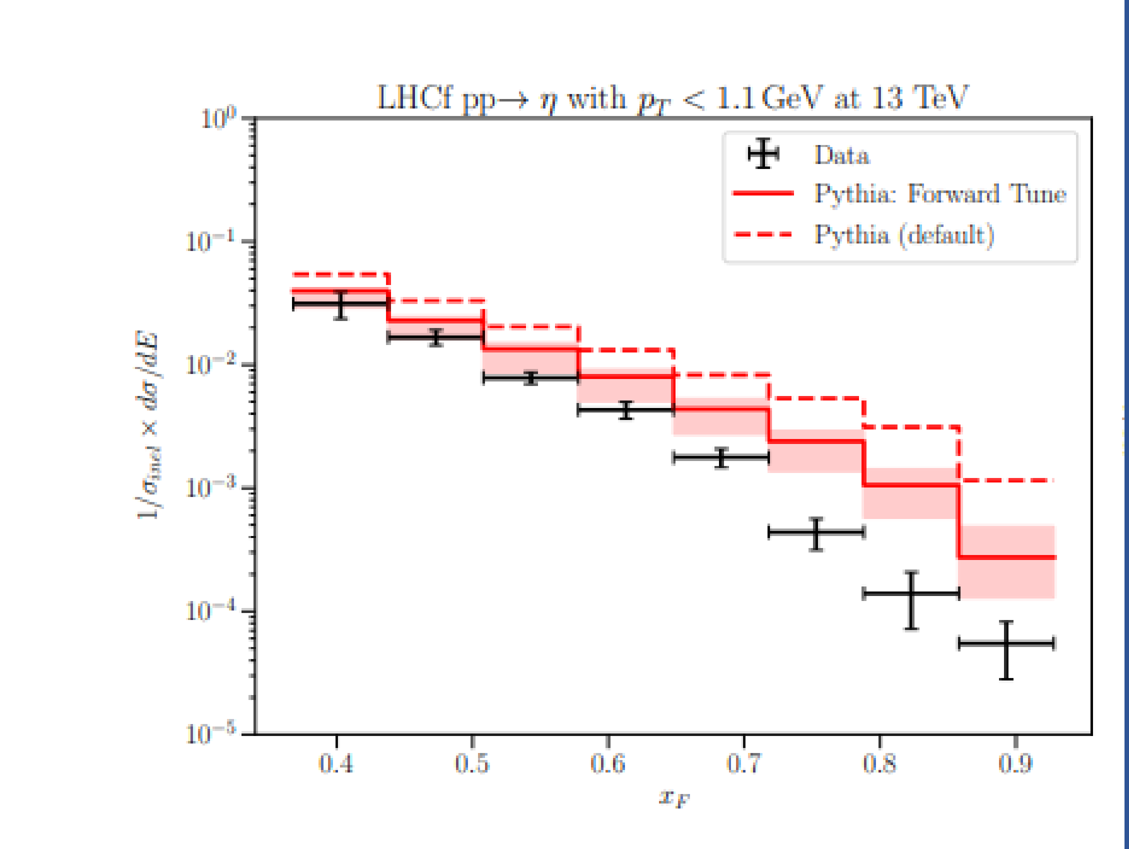
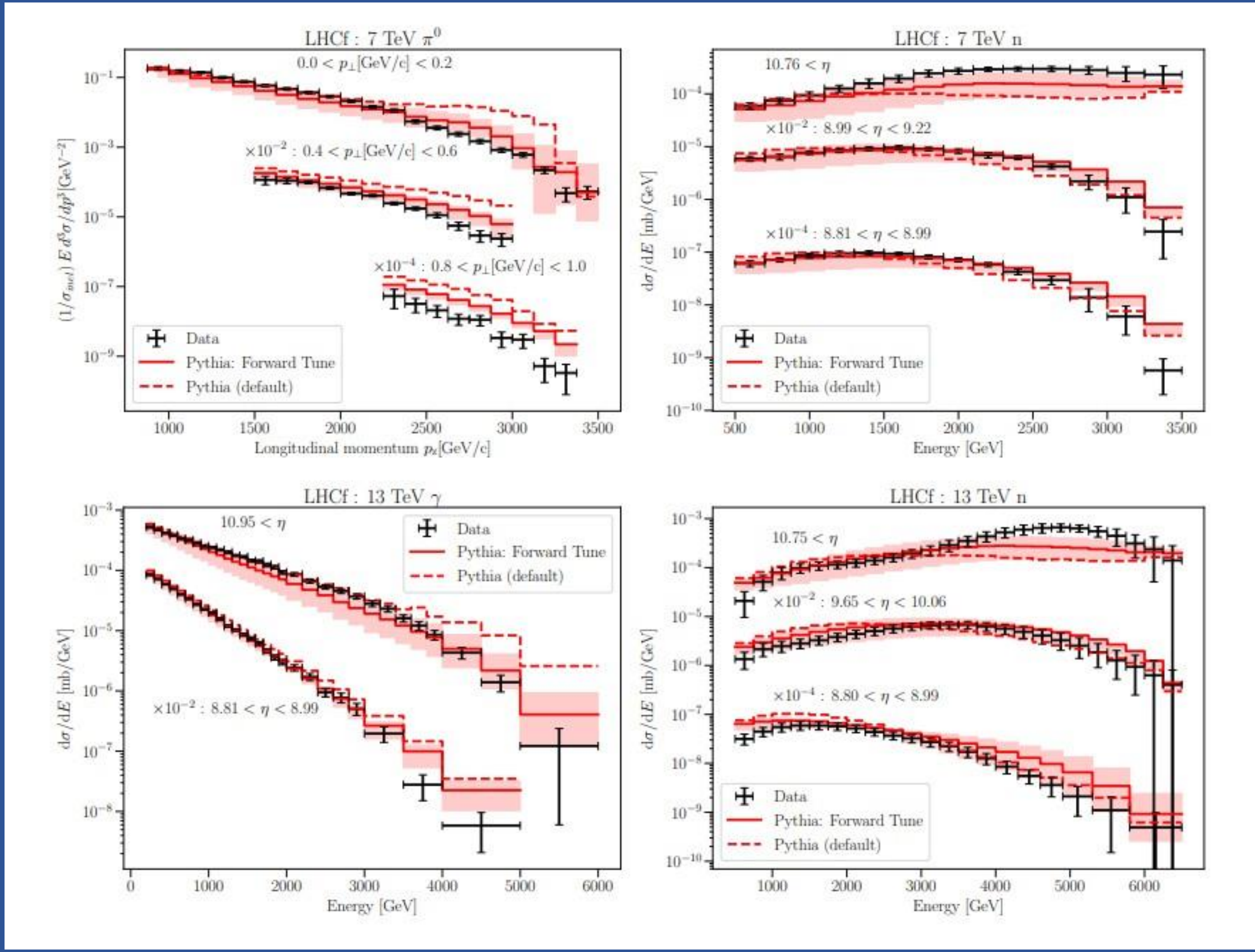




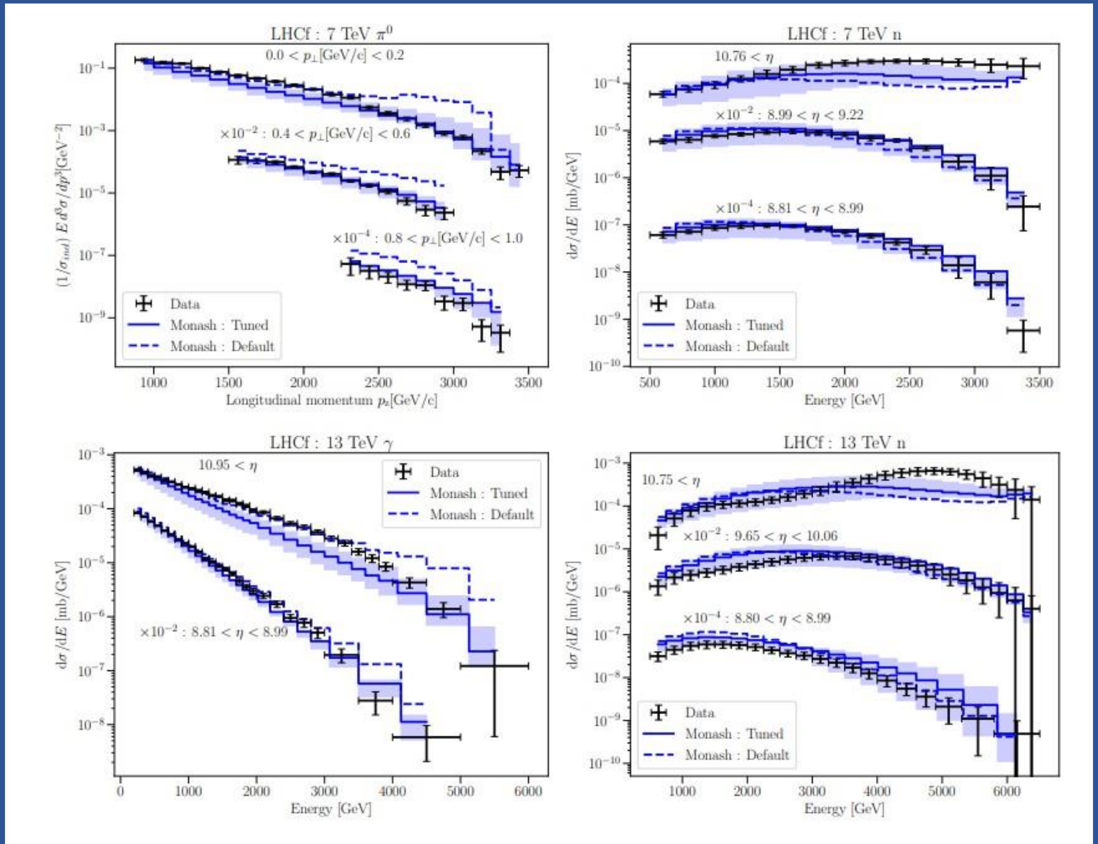
Back up

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
Longitudinal momentum p_z[GeV/c]
LHCf : 7 TeV n
$10.76 < \eta$
$\times 10^{-2}$: $8.99 < \eta < 9.22$
$\times 10^{-4}$: $8.81 < \eta < 8.99$
Energy [GeV]
LHCf : 13 TeV γ
$10.95 < \eta$
$\times 10^{-2}$: $8.81 < \eta < 8.99$
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]
Data
Pythia: Forward Tune
Pythia (default)

Monash



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$\times 10^{-4}$: $8.80 < \eta < 8.99$
Data
Monash : Tuned
Monash : Default
$d\sigma/dE$ [mb/GeV]