

Tuning Pythia for Forward Physics Experiments

MPI@LHC 2023

Max Fieg

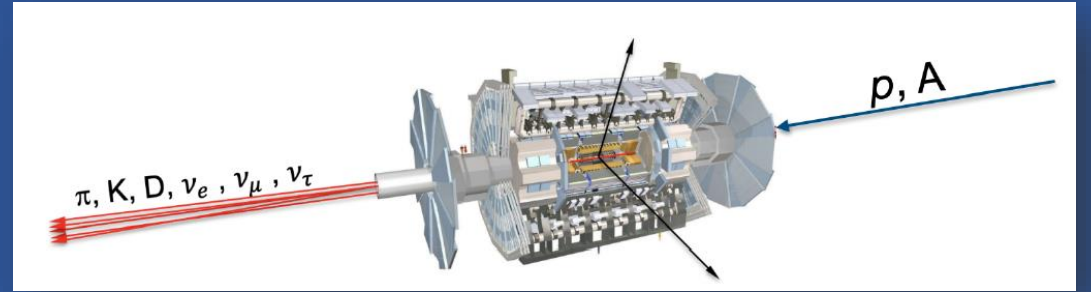
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In collaboration with Felix Kling, Holger Schulz, Torbjörn Sjöstrand

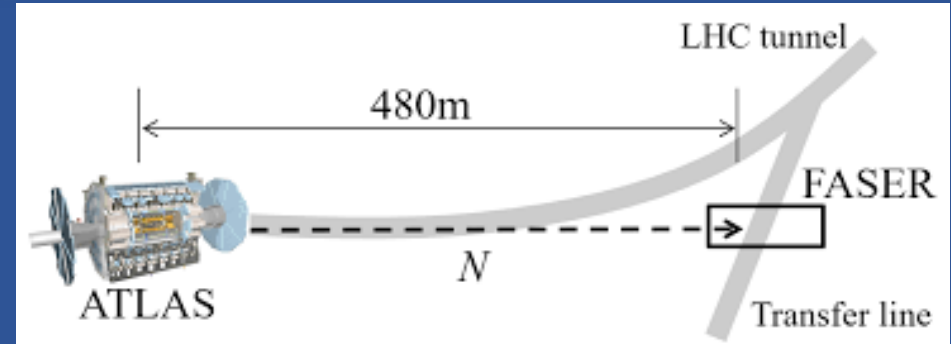


FASER and the Forward Physics Facility (FPF)

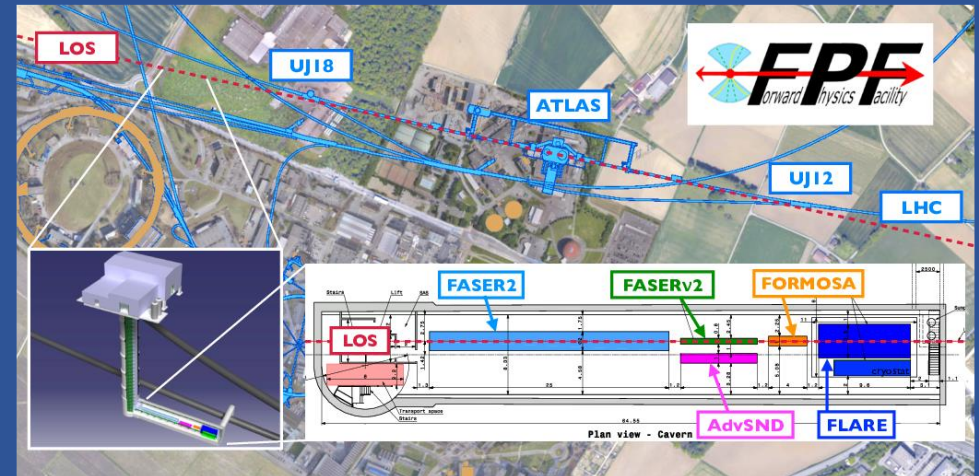
In the forward, large η , region at the LHC there is an intense flux of hadrons which can decay to, e.g., neutrinos or BSM states



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



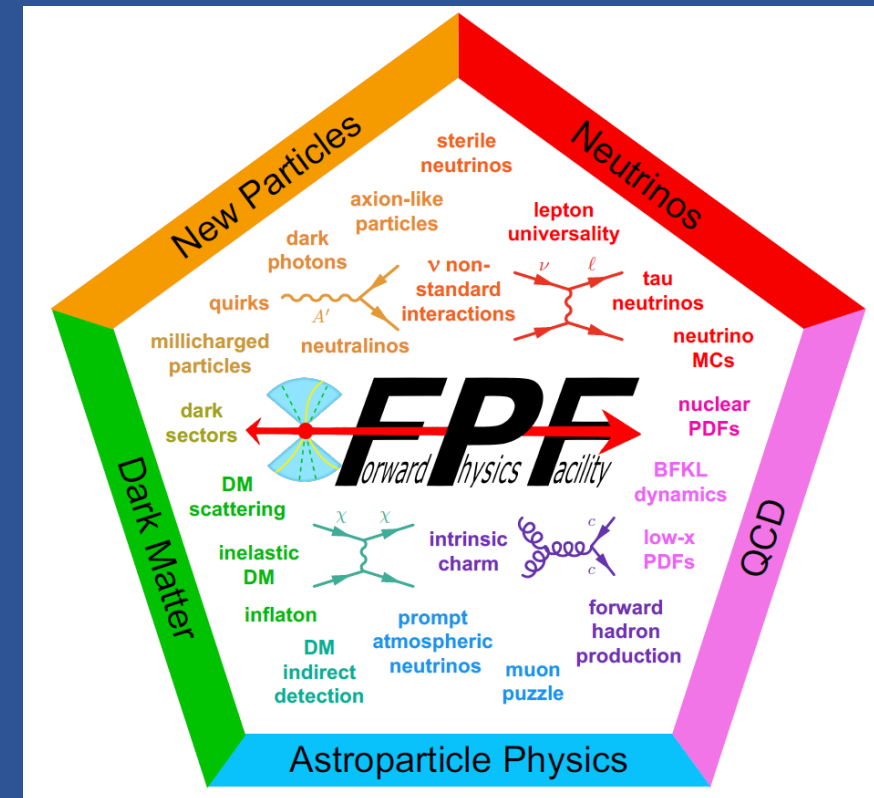
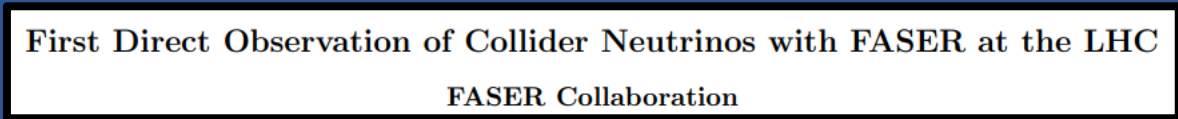
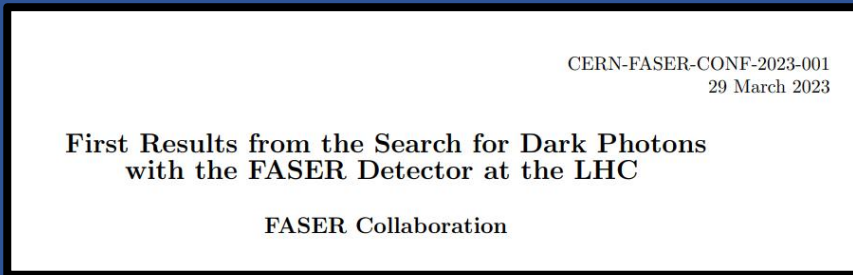
The proposed Forward Physics Facility program, would carve out a cavern along the beamline to host a suite of experiments with different technologies

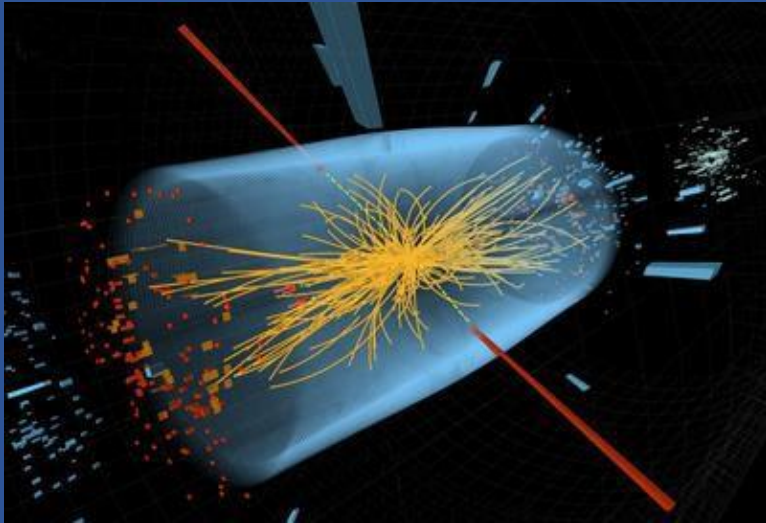


FASER and the Forward Physics Facility (FPF)

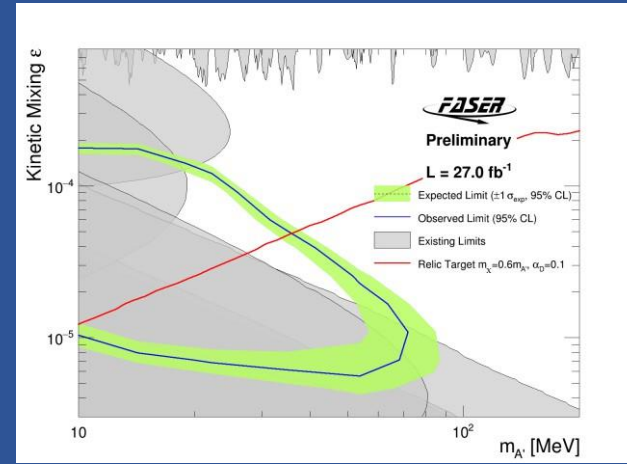
First FASER results already in!
Dark photon bounds and collider neutrino discovery

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

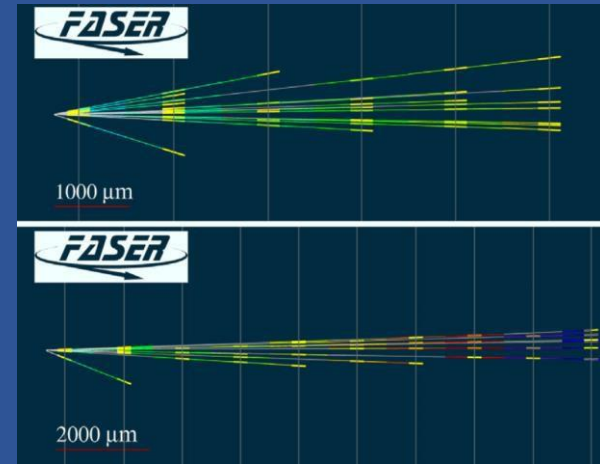




- Monte Carlo event generators used for LHC are tuned to central physics and have excellent agreement



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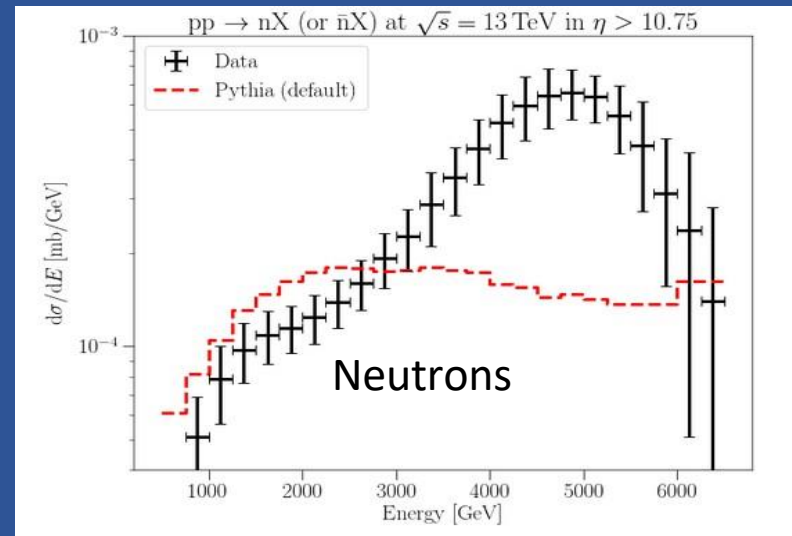
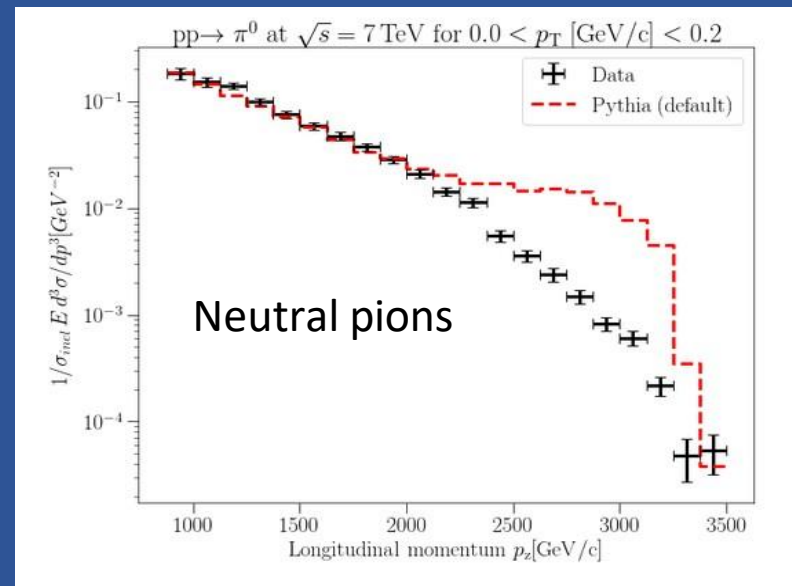
- Forward physics studies require an understanding of forward hadron production



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 mechanism 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



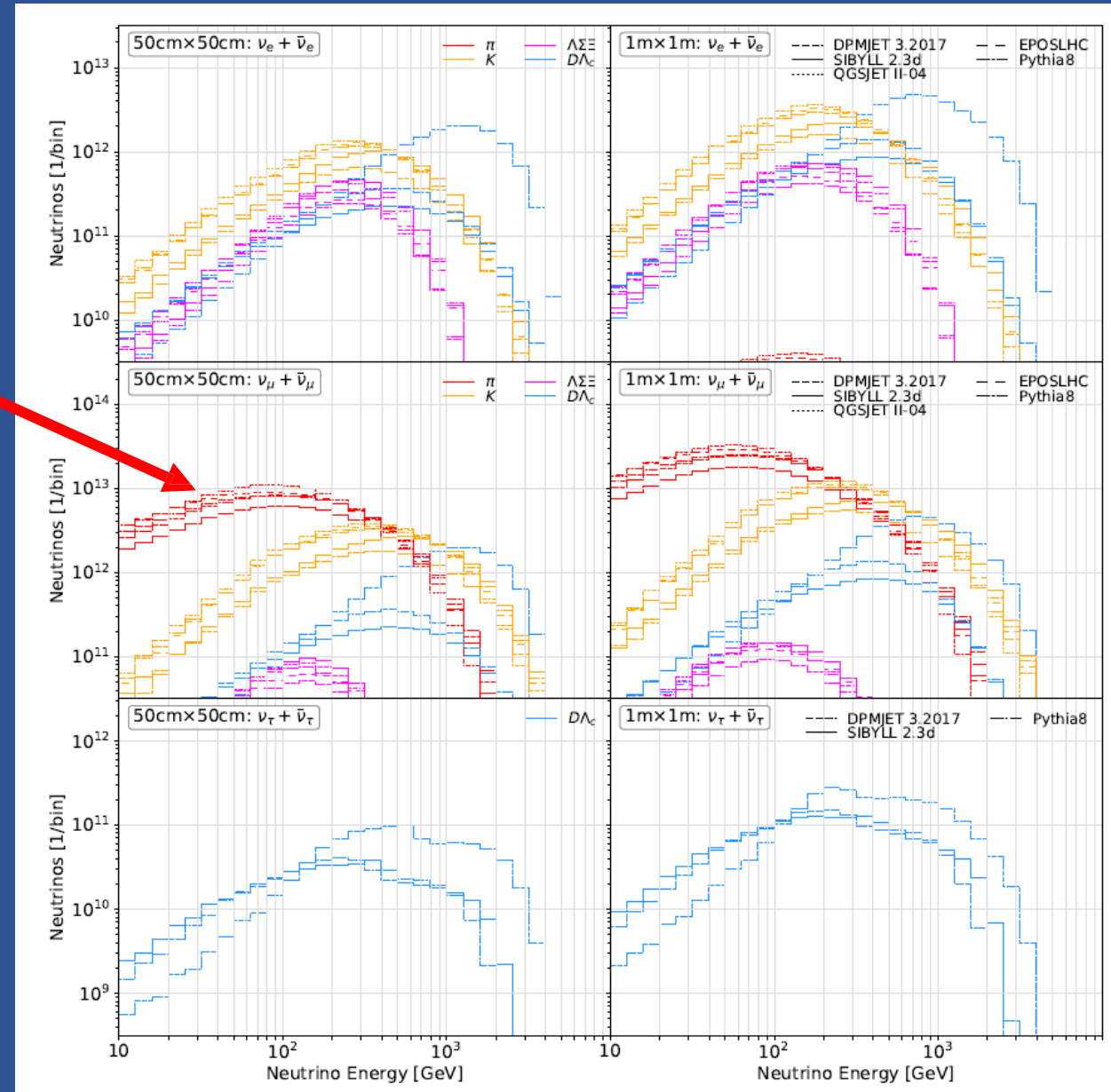
Second problem

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

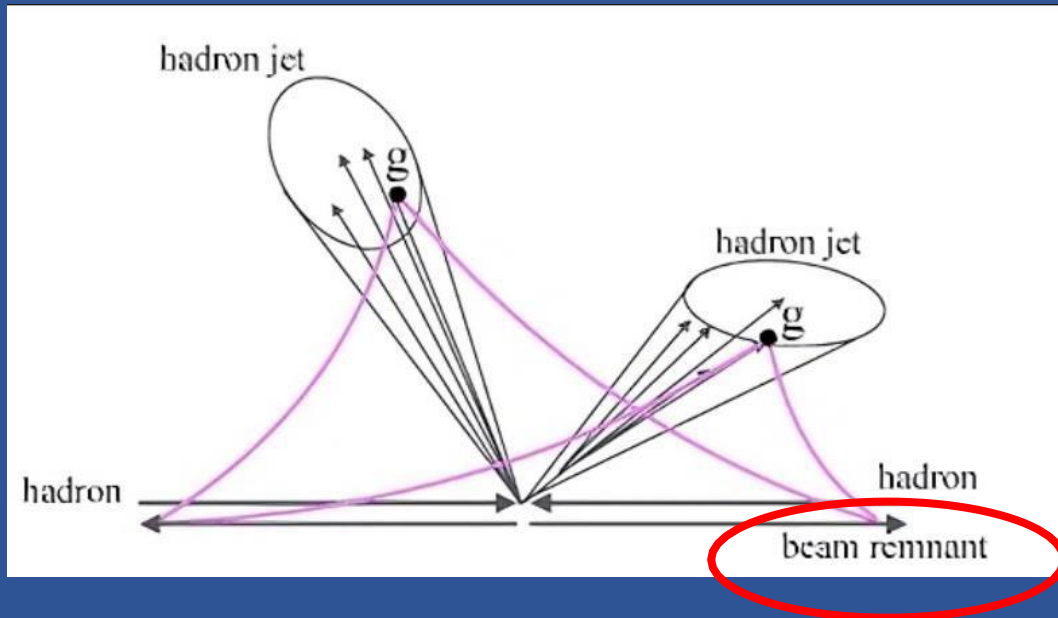
- Provide a tuning uncertainty which translates to a flux uncertainty

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 → baryon fragmentation function to produce more hard neutrons

`BeamRemnants:hardRemnantBaryon`

`BeamRemnants:bRemnantBaryon`

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

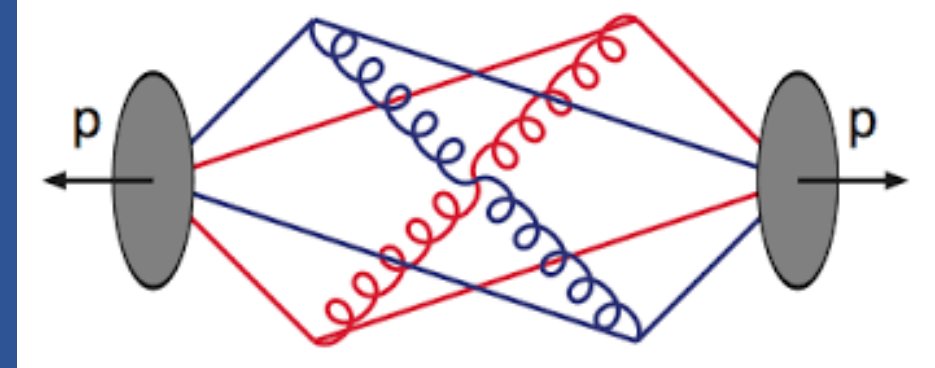
`BeamRemnants:dampPopcorn`

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 an improvement over our Monash based tune



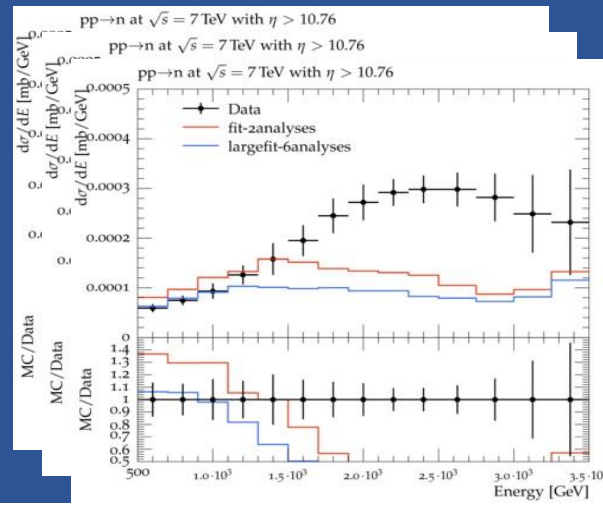
See Anna Statso's talk (next) for more on CR's affect on J/ψ production

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

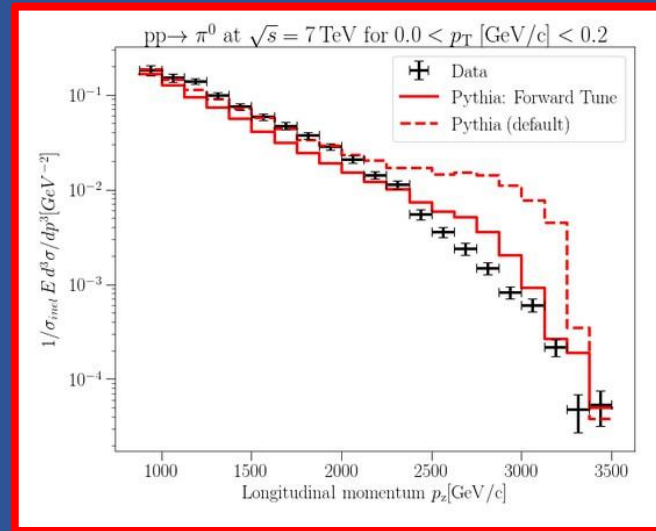
Tuning results

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

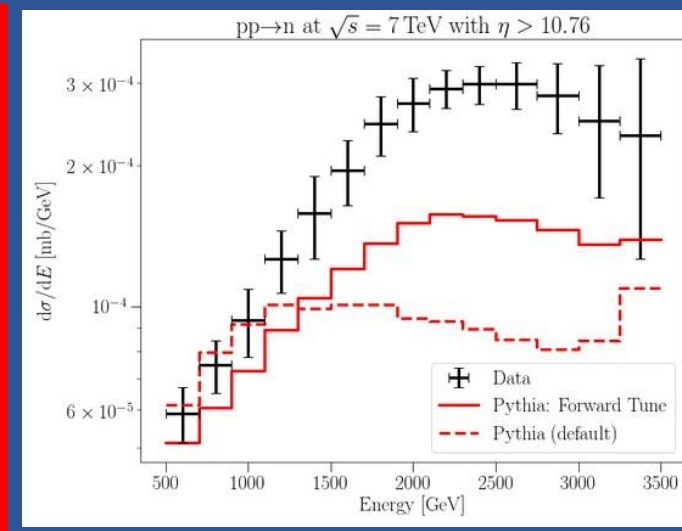
Independent handle on baryons by modifying diquark \rightarrow baryon fragmentation function

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

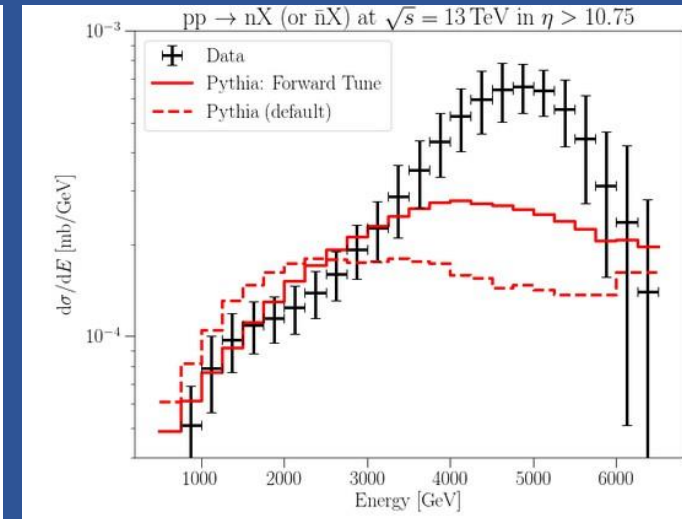
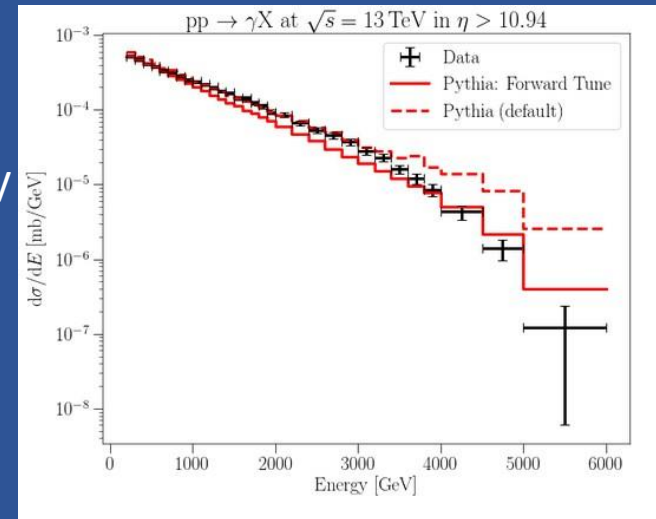
7 TeV



neutrons



13 TeV

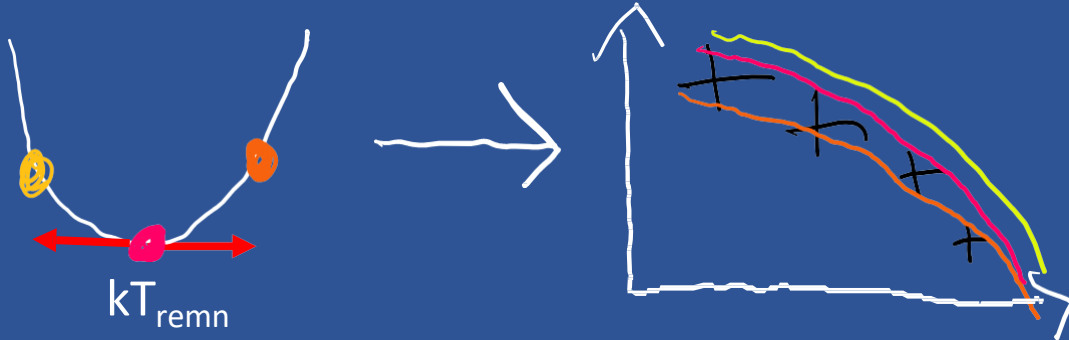


Can we define an uncertainty that captures imperfections in our tune? a naïve $\Delta\chi^2$ returns an unreasonable underestimate of uncertainties 11

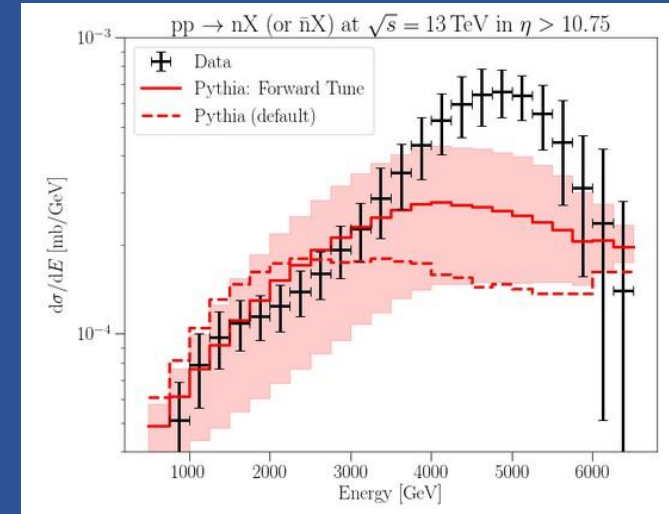
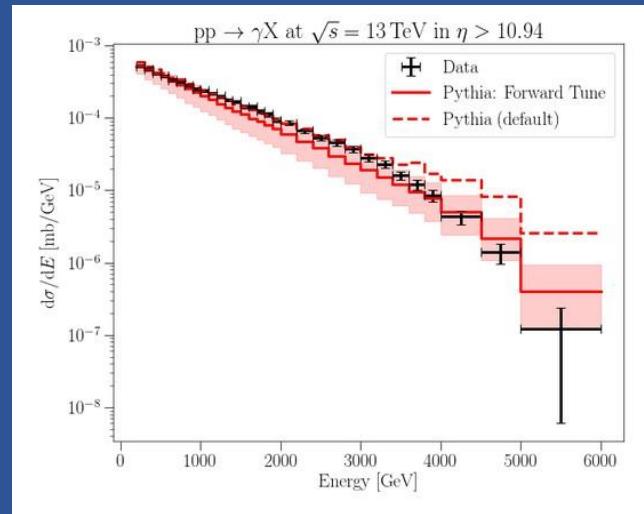
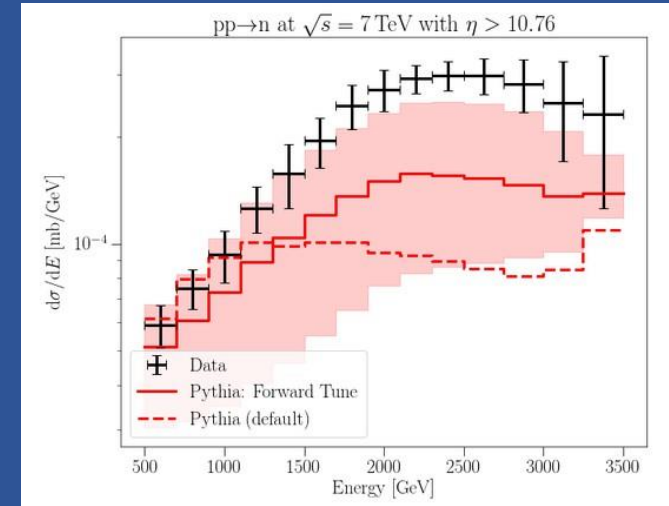
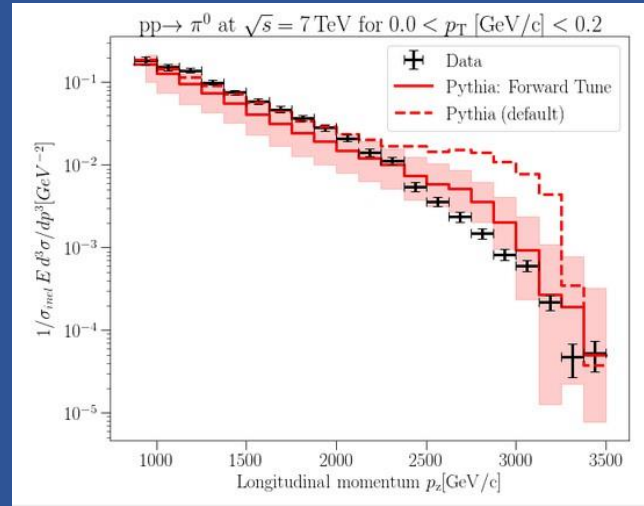
Tuning uncertainties

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



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

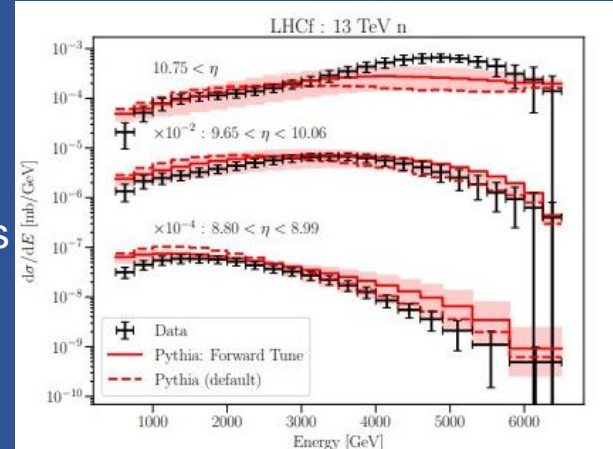
Monash also underpredicts the photon spectra

~ 20% overall improvement of QCD CR over Monash

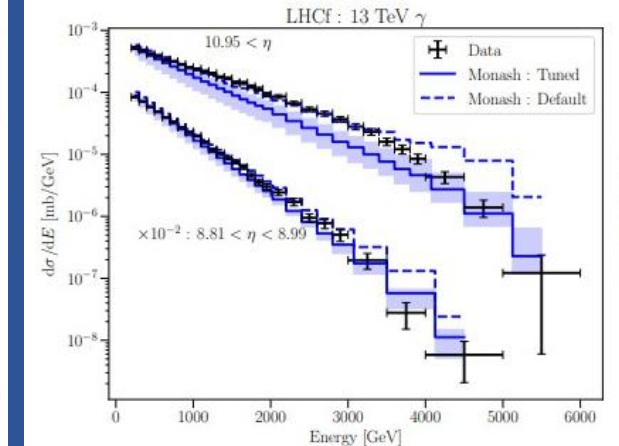
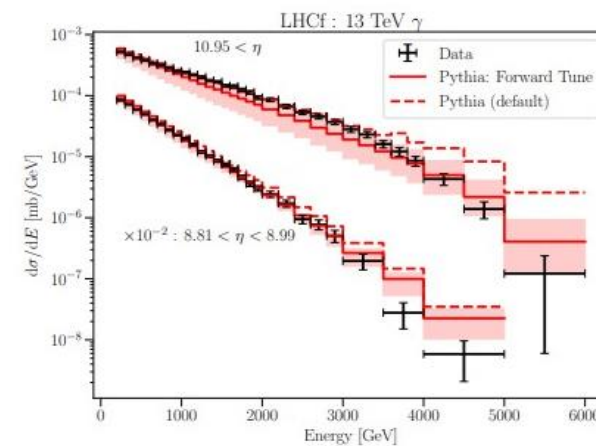
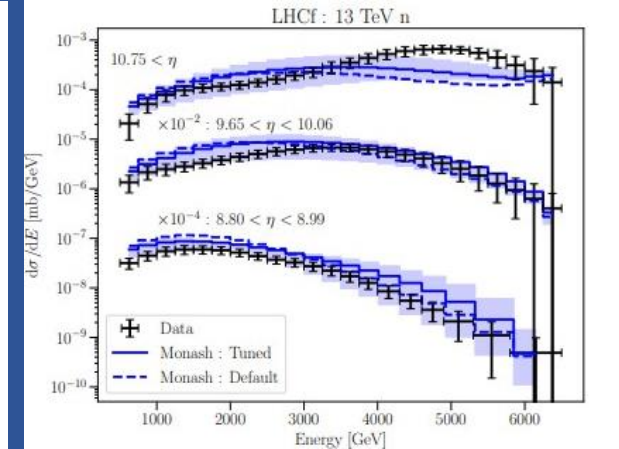
neutrons

photons

QCD CR



Monash



Tuning Results

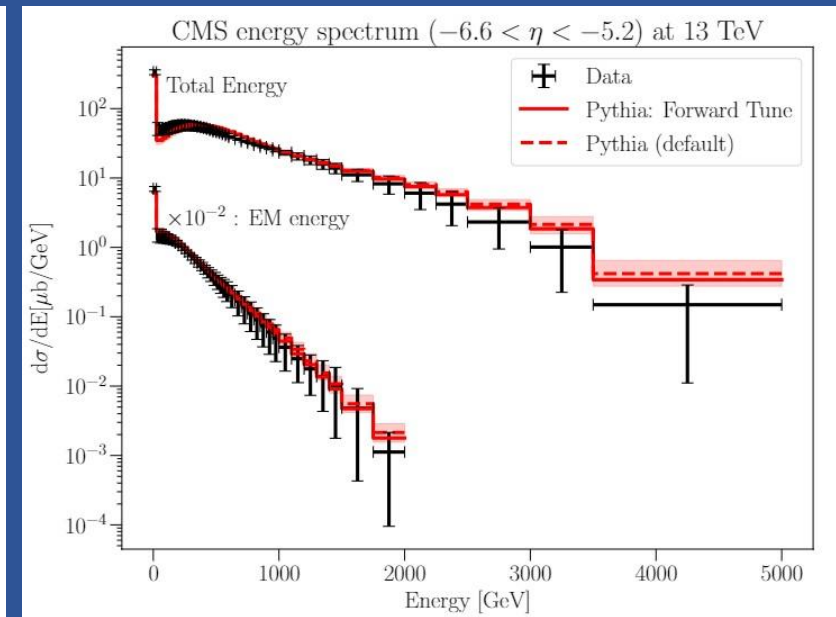
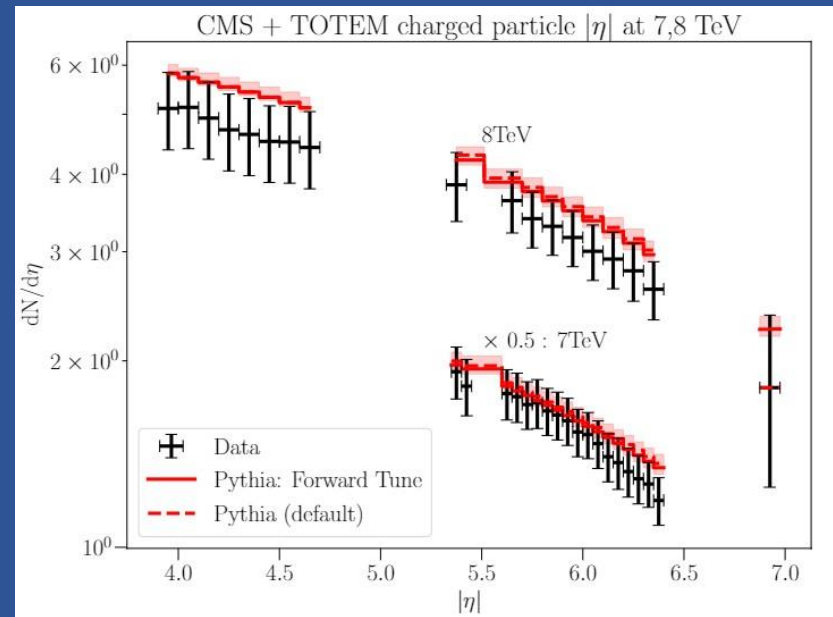
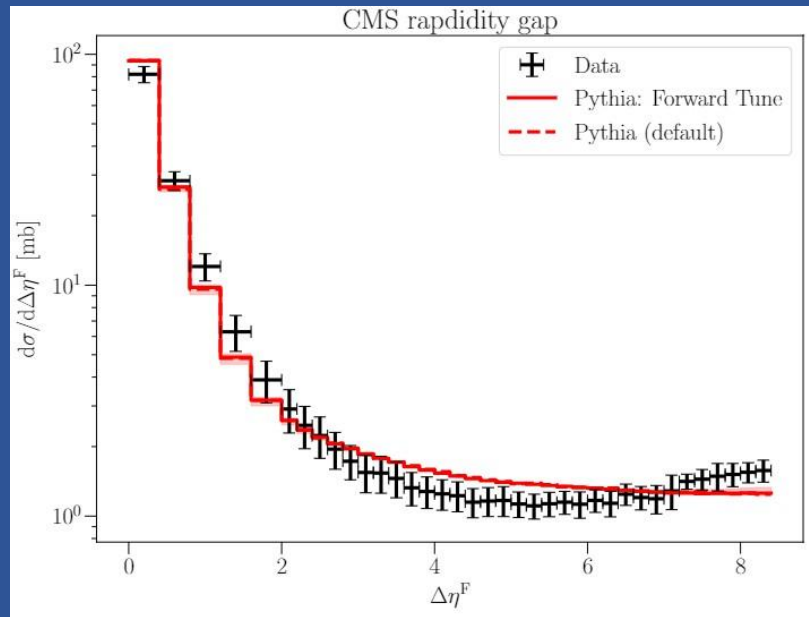
Full name	Shorthand	Baseline (QCDCR)	Forward Tune	Uncertainty
BeamRemnants:dampPopcorn	d_{pop}	1	0	
BeamRemnants:hardRemnantBaryon	f_{remn}	off	on	
BeamRemnants:aRemnantBaryon	a_{remn}	-	0.36	
BeamRemnants:bRemnantBaryon	b_{remn}	-	1.69	
BeamRemnants:primordialKTsoft	σ_{soft}	0.9	0.58	0.26 ... 1.27
BeamRemnants:primordialKTthard	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 ... 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?

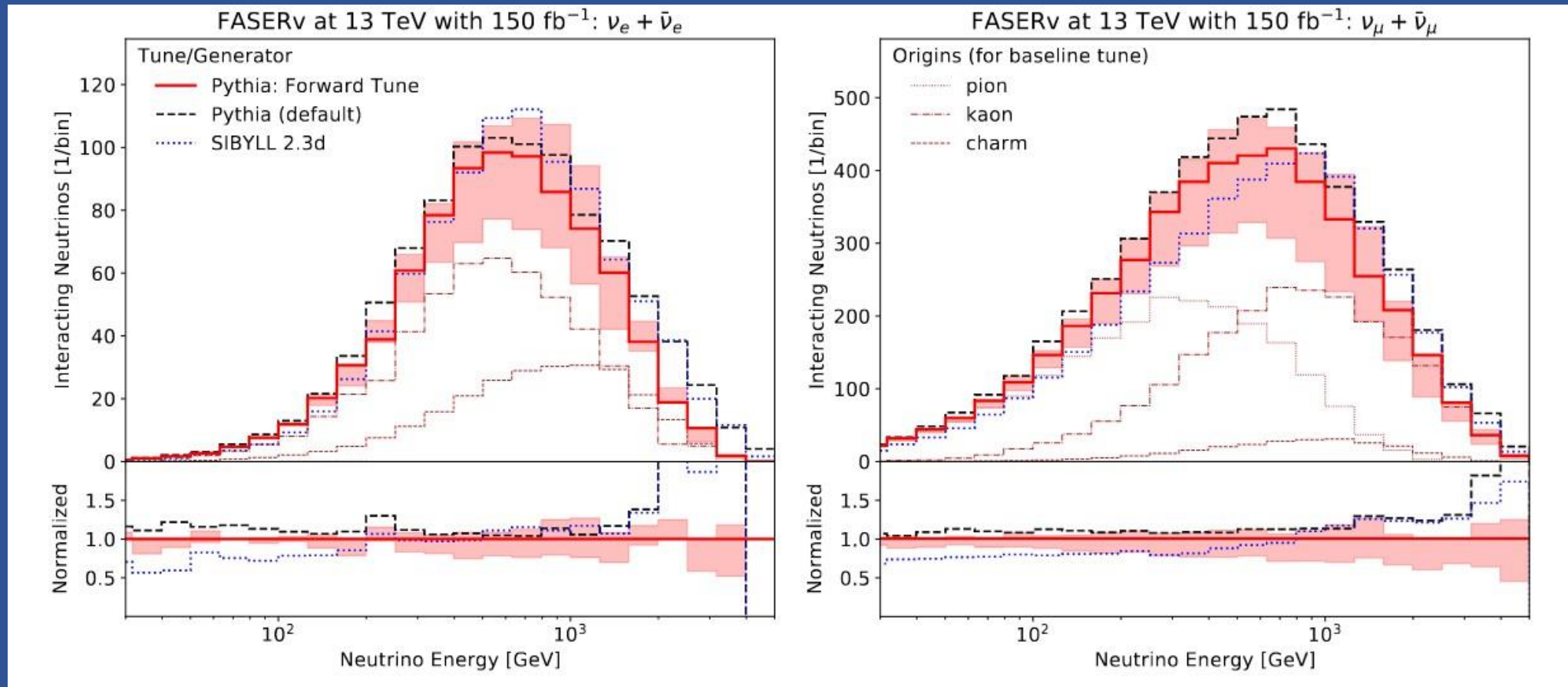
Impact on central physics

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



Applications for forward physics - Neutrinos

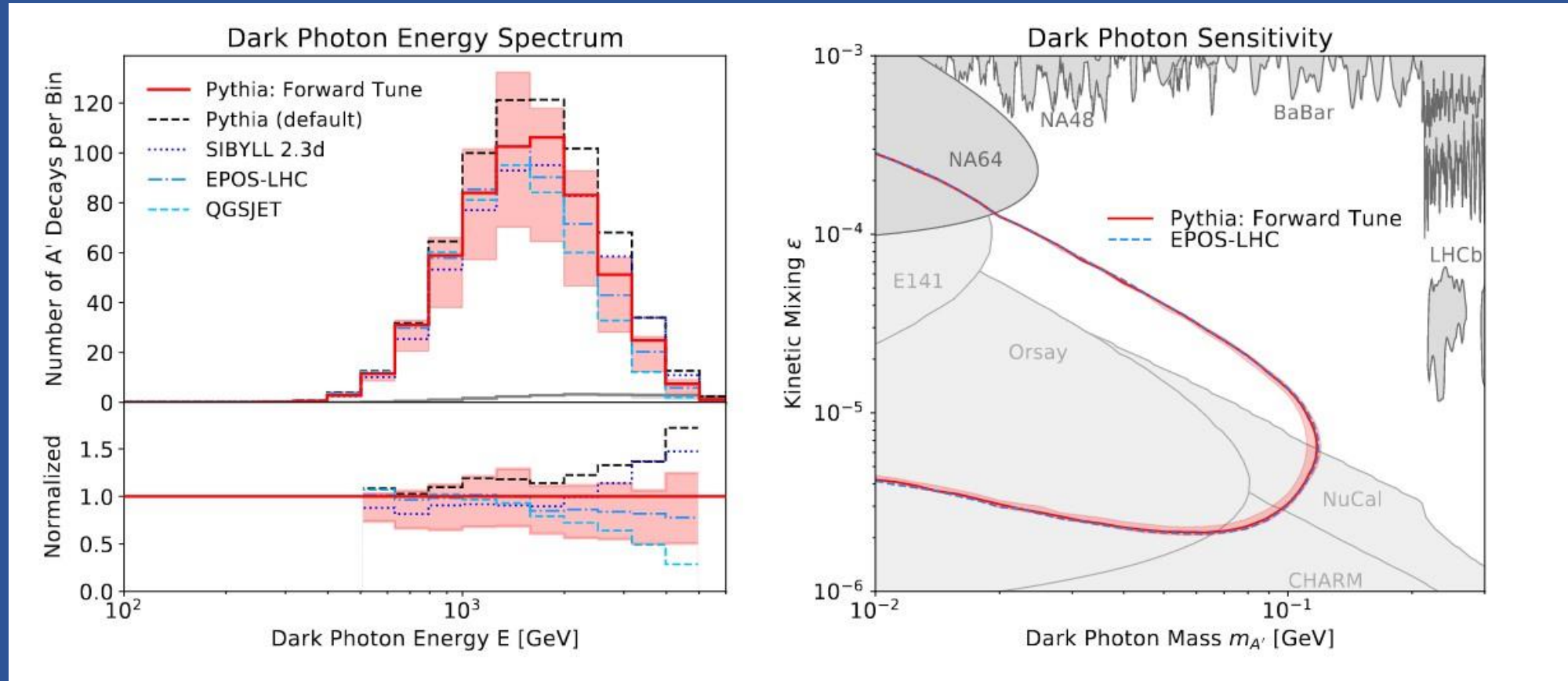
- Interacting electron and muon neutrino spectrum at FASER. Our improved tune predicts $\sim 10\%$ fewer neutrinos as compared to the default Pythia configuration and we find a 20% uncertainty band



Applications for forward physics – Dark Photons

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

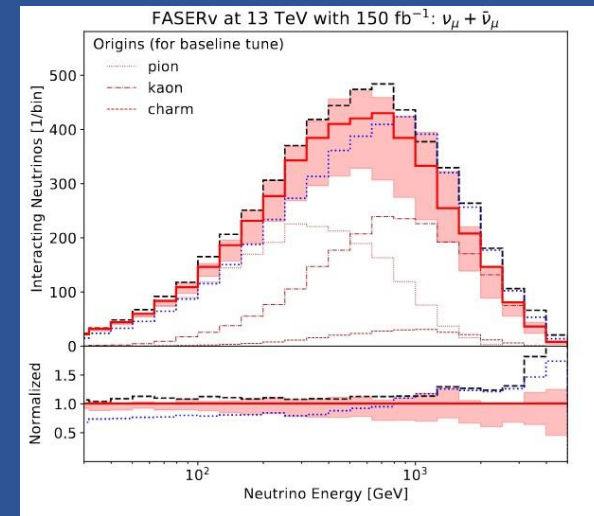
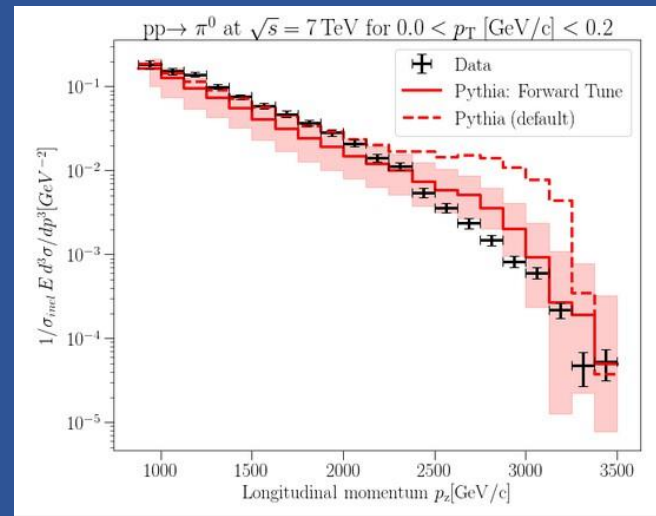
-About 50% uncertainty in number of dark photon decays. Reach is largely unaffected due to large ϵ suppression



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

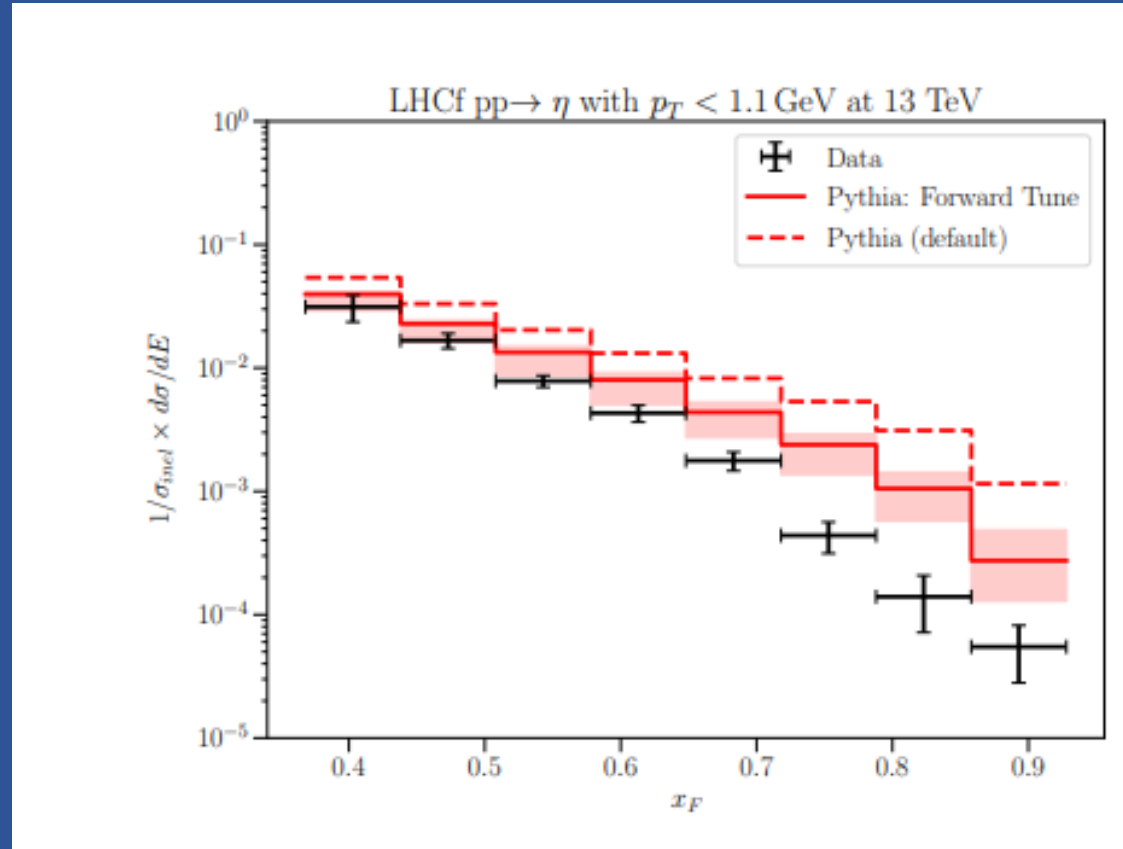
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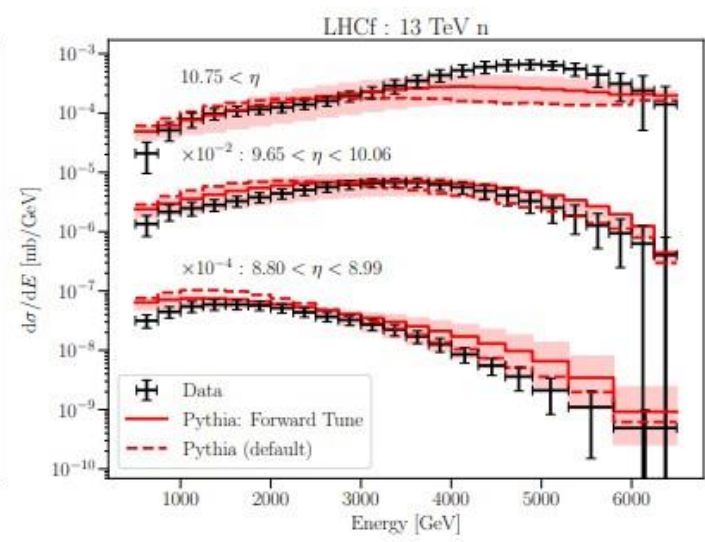
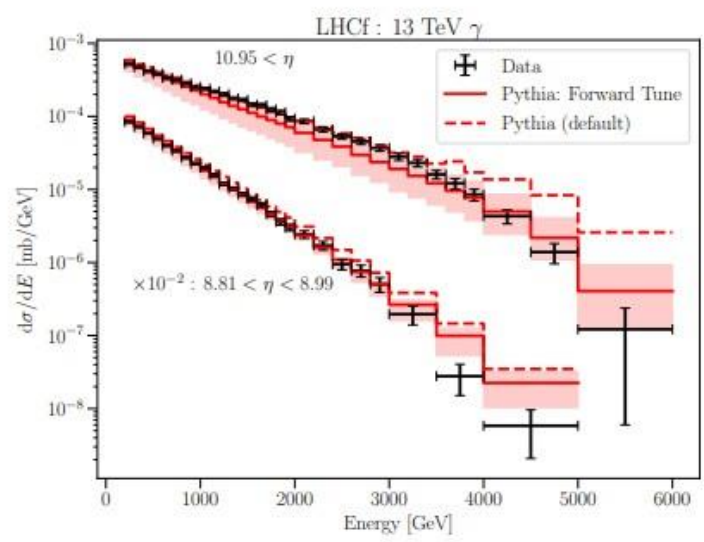
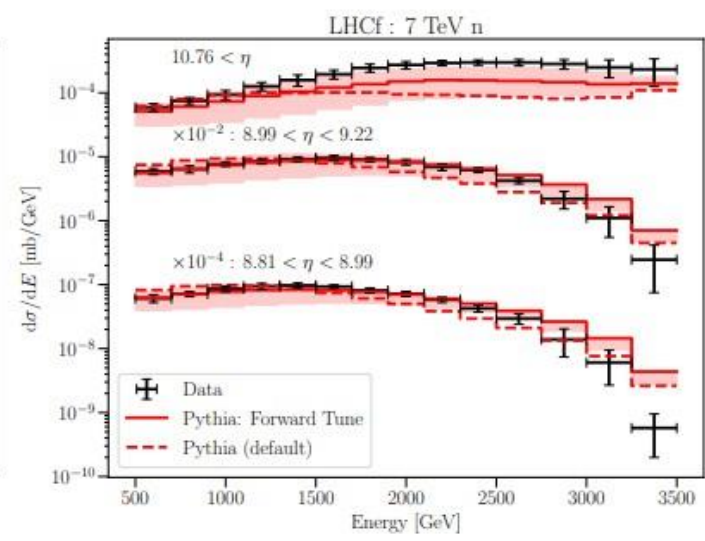
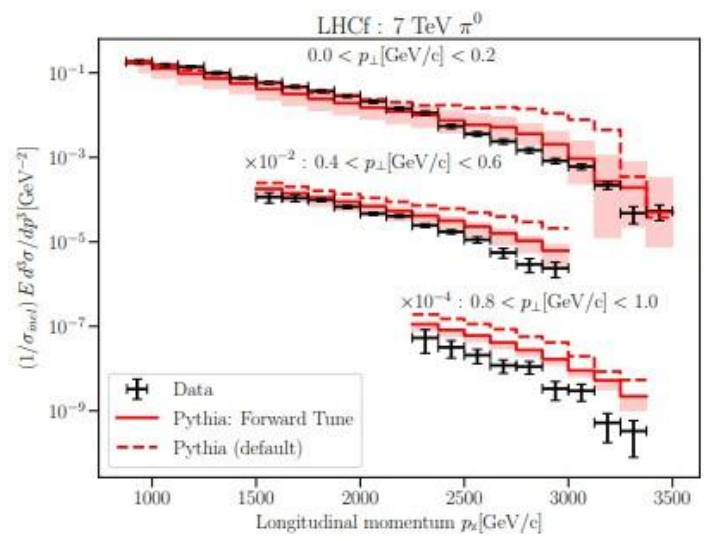


Thank you for listening!

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:alphaSOrder

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

