Tuning Pythia for the FPF

Max Fieg - UC Irvine

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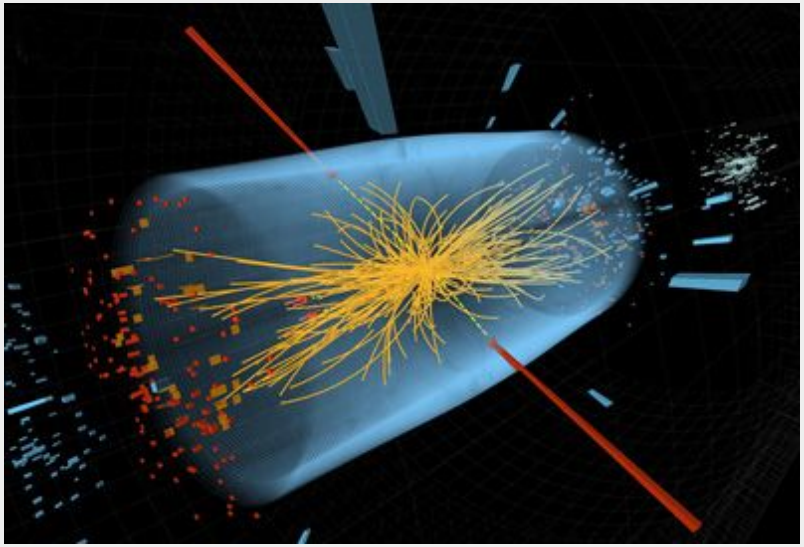
4th Forward Physics Facility Meeting
1-31-2022



LS2 Report: FASER is born

FASER, the Forward Search Experiment, has been installed in the LHC tunnel during Long Shutdown 2. It is currently being tested and will start taking data next year

24 MARCH, 2021 | By Anaïs Schaeffer

FORMOSA: Looking Forward to Millicharged Dark Sectors

Detecting Dark Matter with Far-Forward Emulsion and Liquid Argon Detectors at the LHC

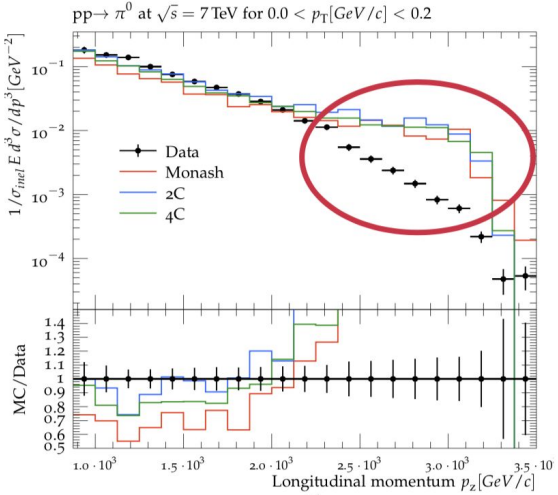
PYTHIA

Main Problem

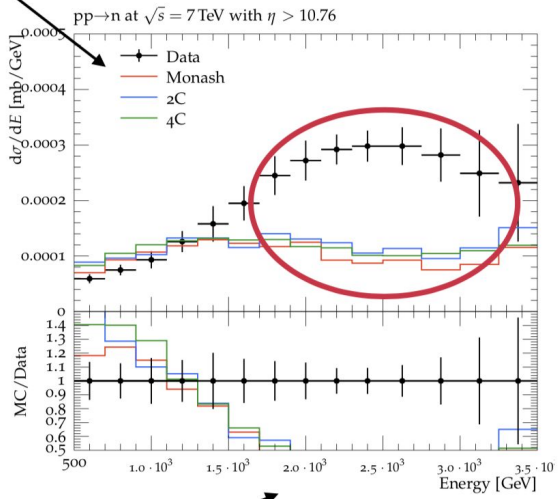
- Usual Pythia tunes don't describe LHCf data
  * other generators aren't that great either …

default tunes

LHCf pion spectrum

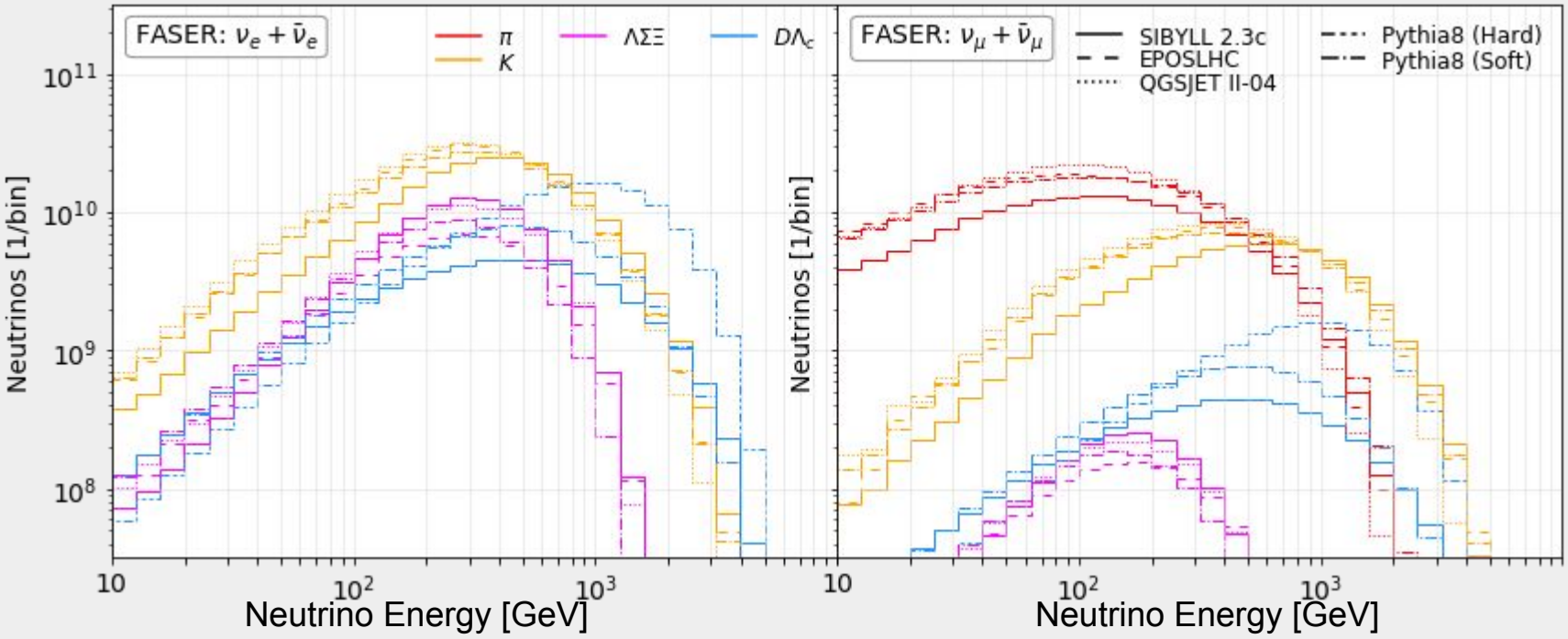


LHCf neutron spectrum



plots made with Rivet

Importance for Forward Neutrino Fluxes



Most neutrinos come from pion / kaons decays inside the LHC's beam pipe.
→ Neutrino spectrum sensitive to forward pion / kaon production.

Main Questions

1. Can we tune Pythia for forward experiments?

2. Which experiments can we hope to tune to?

3. How can we estimate the uncertainties in our tune?

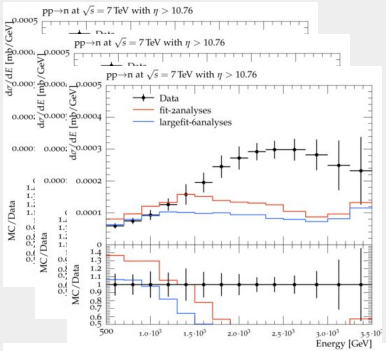
Tuning Pipeline

Generate Events with sets of tuning parameters

Tuning Pipeline

PYTHIA

Generate Events with sets of tuning parameters



Rivet — the particle-physics MC analysis toolkit

Combine experimental analyses with Pythia simulations

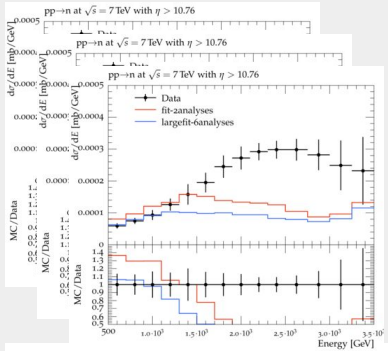
YODA — Yet more Objects for Data Analysis

small, mean and full of Jedi magic

Tuning Pipeline

PYTHIA

Generate Events with sets of tuning parameters



Rivet — the particle-physics MC analysis toolkit

YODA — Yet more Objects for Data Analysis

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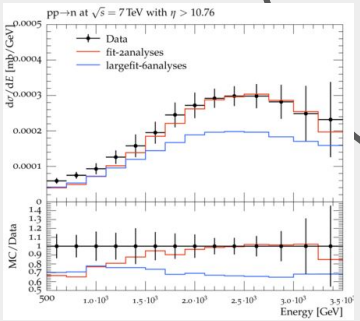
Combine experimental analyses with Pythia simulations



pyapprentice 1.0.6

Predict Pythia response to tuning parameters and fit to experimental data

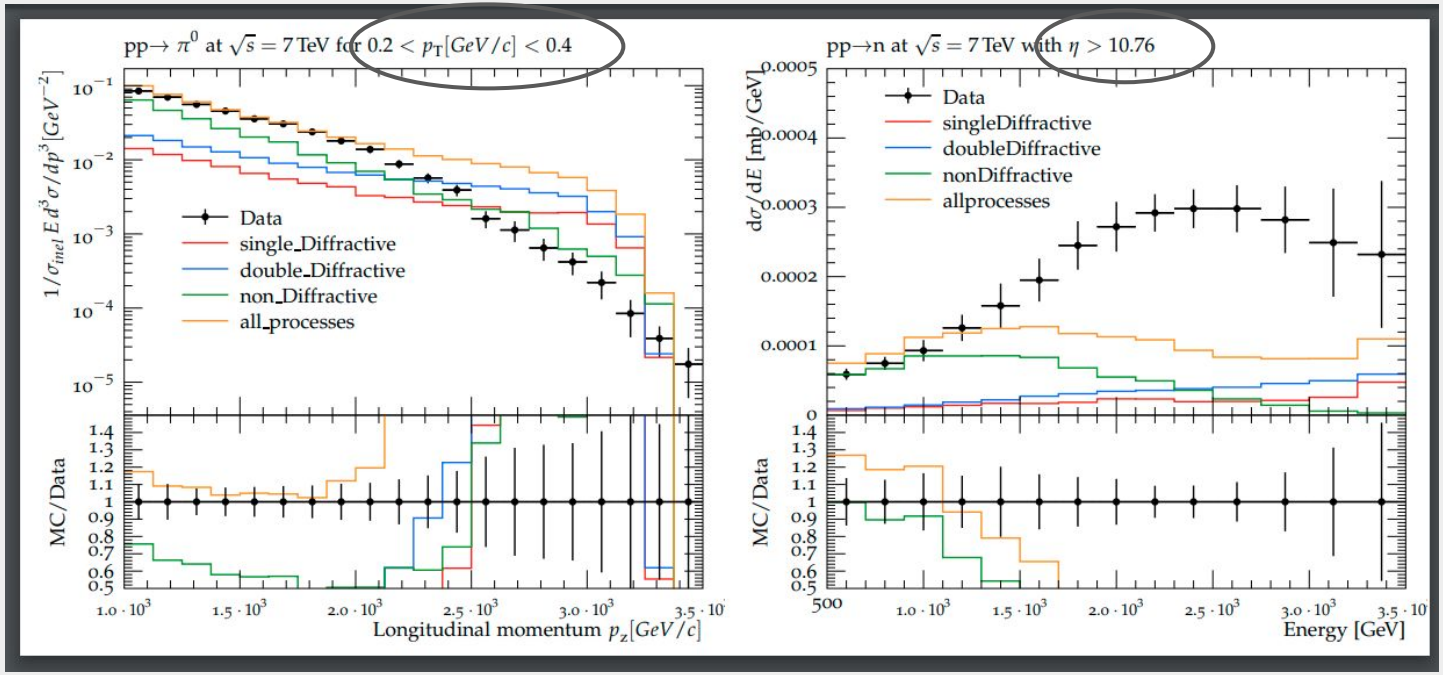
Main Questions

1. Can we tune Pythia for forward experiments?

2. Which experiments can we hope to tune to?

3. How can we estimate the uncertainties in our tune?

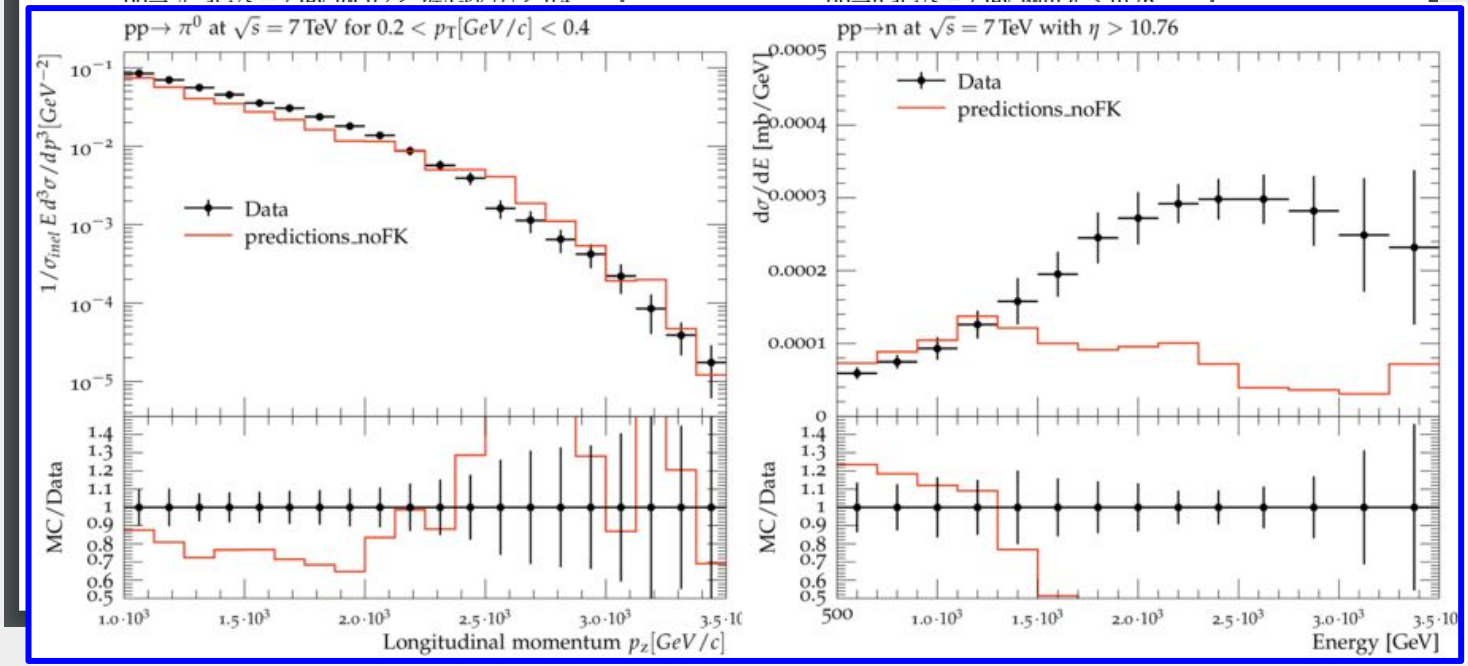
Before Tuning



Poor predictions in the forward region.

Too many pions and too few far neutrons

After Tuning



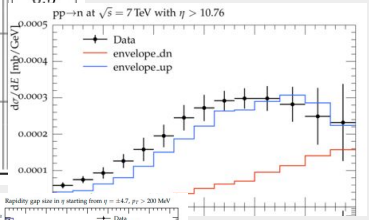
Poor predictions in the forward region.

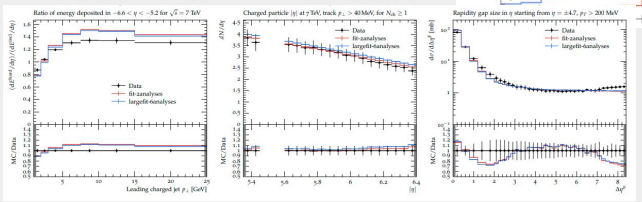
An improvement, but some analyses are problematic

Tuning Parameters

Many parameters

Parameter	Def.
SigmaDiffractive:maxXB	65
SigmaDiffractive:maxAX	65
SigmaDiffractive:maxXX	65
SigmaDiffractive:maxAXB	3.0
SigmaDiffractive:mMin	0.28
SigmaDiffractive:lowMEnhance	2.0
SigmaDiffractive:mResMax	1.062
SigmaDiffractive:SaSepsilon	0.0
StringPT:sigma	0.335
Diffraction:mMinPert	10.
Diffraction:mWidthPert	10.
Diffraction:probMaxPert	1.0
Diffraction:pickQuarkNorm	5.0
Diffraction:pickQuarkPower	1.0
Diffraction:primKTwidth	0.5
Diffraction:largeMassSuppress	
Diffraction:sigmaRefPomP	
Diffraction:mRefPomP	
Diffraction:mPowPomP	
SigmaDiffractive:PomFlux	
SigmaDiffractive:PomFluxEpsilon	
SigmaDiffractive:PomFluxAlphaPrime	





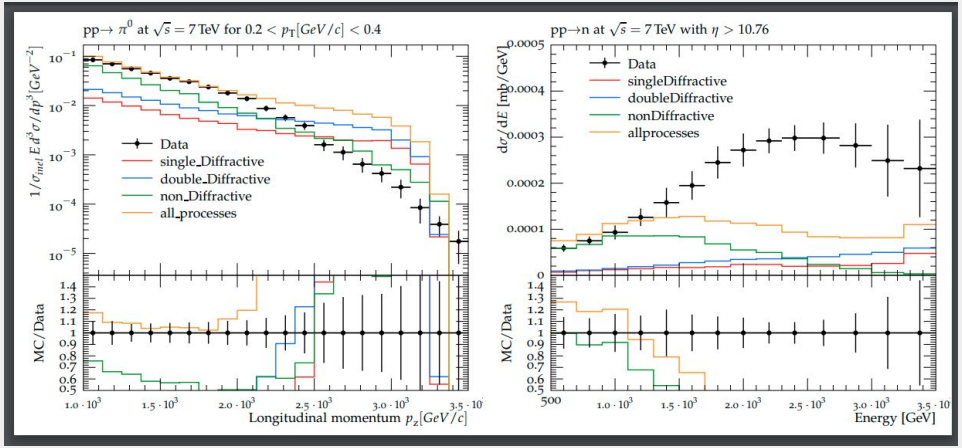
A few parameters

`parm` **StringFlav:popcornRate** (`default = 0.5; minimum = 0.; maximum = 2.0`)
gives the relative rates of *B Bbar* and *B M Bbar* production, roughly as
Prob(B M Bbar) / (Prob(B Bbar) + Prob(B M Bbar)) = popcornRate / (0.5 + popcornRate)

`flag` **BeamRemnants:primordialKT** (`default = on`)

+ a few more

Tuning Method



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Forbid popcorn production

- Forbids a beam remnant diquark from hadronizing into a meson → Less mesons (π^0), more baryons (*n*)

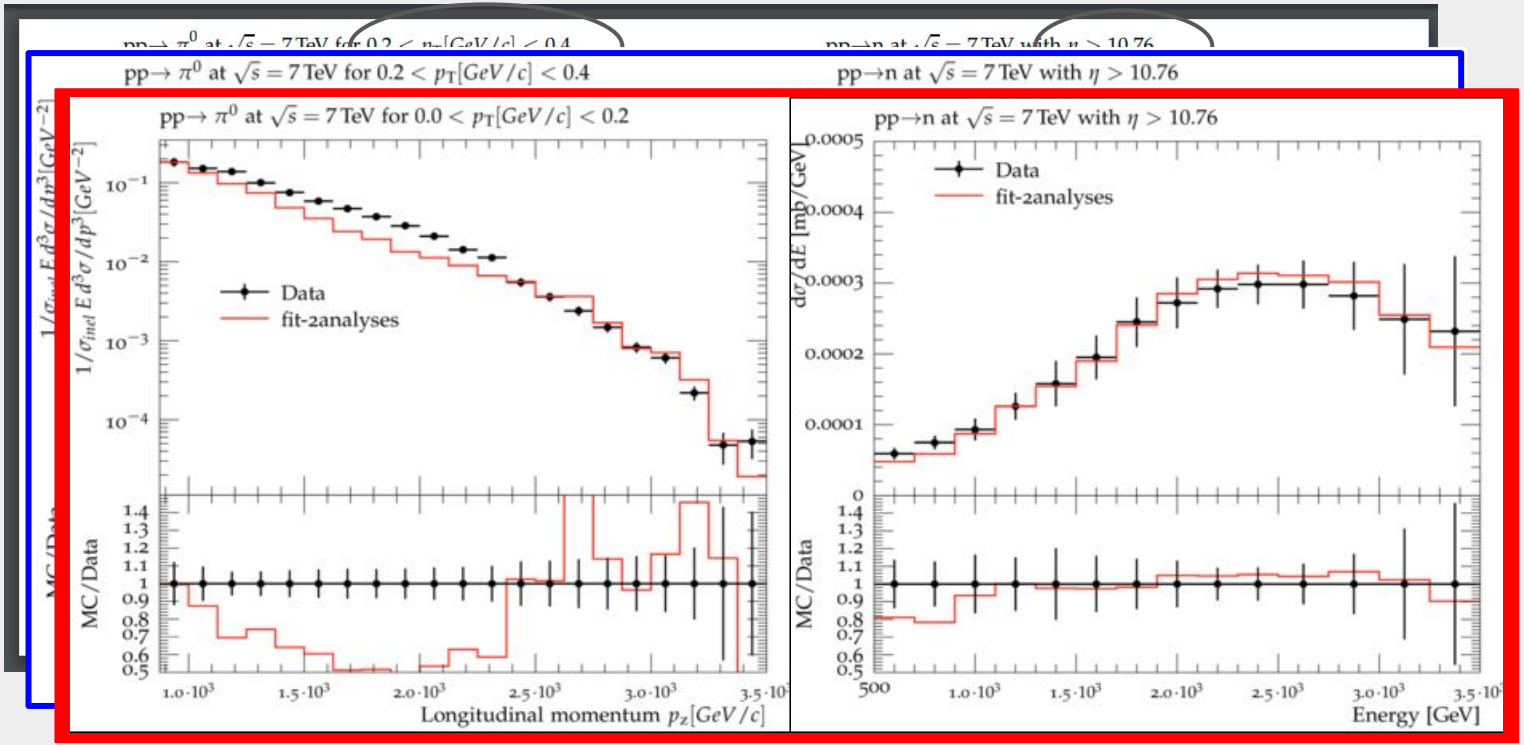
`flag` **BeamRemnants:primordialKT** (`default = on`)

- Tune the primordial transverse momentum of partons within a colliding hadron:
  - A main source of p_T. Tuning conservatively gives a strong handle on forward predictions with modest impact on central predictions

+ a few more

Tuning the fragmentation function on the beam remnant to provide harder or softer hadrons

How much forward physics data can we fit at once?



Poor predictions in the forward region.

An improvement, but some analyses are problematic

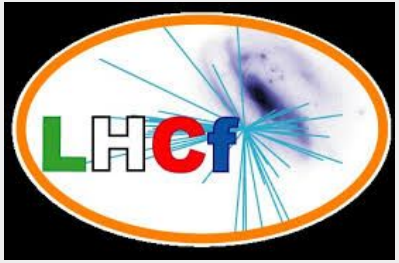
Simultaneous tunes can be achieved

Main Questions

1. Can we tune Pythia for forward experiments?
2. Which experiments can we hope to tune to?
3. How can we estimate the uncertainties in our tune?

Forward Experiments

LHCf ($\eta > 8.81$)				
Analysis	$\sqrt{s}$ [TeV]	HD	**Refs.**	**RIVET**
forward π^0 or γ	7	$\surd$	[1]	LHCF_2012_I1115479
	2.76, 7	$\surd$	[2]	LHCF_2016_I1385877
	13	$\surd$	[3]	LHCF_2018_I1518782
forward γ (diffractive)	13	—	[4]	—
forward neutrons	7	$\surd$	[5]	LHCF_2015_I1351909
	13	$\surd$	[6]	LHCF_2018_I1692008
	13	—	[7]	



Forward Experiments

LHCf ($\eta > 8.81$)				
Analysis	$\sqrt{s}$ [TeV]	HD	**Refs.**	**RIVET**
forward π^0 or γ	7	√	[1]	LHCF_2012_I1115479
	2.76, 7	√	[2]	LHCF_2016_I1385877
	13	√	[3]	LHCF_2018_I1518782
forward γ (diffractive)	13	—	[4]	—
forward neutrons	7	√	[5]	LHCF_2015_I1351909
	13	√	[6]	LHCF_2018_I1692008
	13	—	[7]	

CASTOR ($5.2 < \eta < 6.6$)				
Analysis	$\sqrt{s}$ [TeV]	HD	**Refs.**	**RIVET**
forward E	13	√	[14]	CMS_2017_I1511284
forward E vs central N_{ch}	0.9, 2.76, 7	√	[15]	CMS_2013_I1218372
	13	—	[16]	CMS_2019_I1747892(1)
$dE/d\eta$	13	—	[17]	CMS_2018_I1708620

TOTEM (L2) ($5.3 < \eta < 6.5$)				
Analysis	$\sqrt{s}$ [TeV]	HD	**Refs.**	**RIVET**
$dN_{\mathrm{ch}}/d\eta$	7	√	[10]	TOTEM_2012_I1115294
	8	√	[11]	TOTEM_2014_I1328627
	8	√	[12]	CMSTOTEM_2014_I1294140
σ_{DD}	7	√	[13]	

Analyses Targeting Diffractive Processes

ALICE ($|\eta| < 5$)

Analysis	$\sqrt{s}$ [TeV]	HD	Refs.	RIVET
σ_{SD}, σ_{DD}, σ_{inel}	7	√	[18]	ALICE_2012_I1181770
incl. photons	0.9, 2.76, 7	√	[19]	—
N_{ch}	0.9, 7, 8 TeV	√	[20]	—
ϕ	2.76 TeV	√	[21]	—

ATLAS ($|\eta| < 5$)

Analysis	$\sqrt{s}$ [TeV]	HD	Refs.	RIVET
MB: dN_{ch}, η and pT	0.9, 2.36, 7	√	[22]	ATLAS_2010_S8918562
	8	√	[23]	ATLAS_2016_I1426695
	13	√	[24]	ATLAS_2016_I1419652
MB: $\sum E_T$	7	√	[25]	ATLAS_2012_I1183818
σ_{inel}	7	√	[26]	ATLAS_2011_I894867
	13	√	[27]	ATLAS_2016_I1468167
η gap	7	√	[28]	ATLAS_2012_I1084540
	7	√	[29]	
ALFA: tagged p SD	8	√	[30]	ATLAS_2019_I1762584(1)
(unpublished)	13		[31]	

CMS ($|\eta| < 5$)

Analysis	$\sqrt{s}$ [TeV]	HD	Refs.	RIVET
η gap	7	—	[32]	CMS_2015_I1356998
TOTEM SD σ_{2j} w. tagged p	8	√	[33]	
Strange Production	0.9, 7	√	[34]	CMS_2011_S8978280
	13	√	[35]	CMS_2017_I1608166(1)
σ_{inel} (incl. SD enhanced)	13	√	[36]	CMS_2018_I1653948
diffractive (unpublished)	7	—	[37]	
	8	—	[38]	
	13	—	[39]	

LHCb ($2 < \eta < 5$)

Analysis	$\sqrt{s}$ [TeV]	HD	Refs.	RIVET
N_{ch}, η	0.9, 7	√	[40]	LHCB_2012_I1119400
	7	√	[41]	—
	7	√	[42]	LHCB_2014_I1281685
energy flow	7	√	[43]	LHCB_2013_I1208105
strange hadrons	0.9	√	[44]	LHCB_2010_S8758301
	0.9, 7	√	[45]	LHCB_2011_I917009
	7 TeV	√	[46]	LHCB_2011_I919315

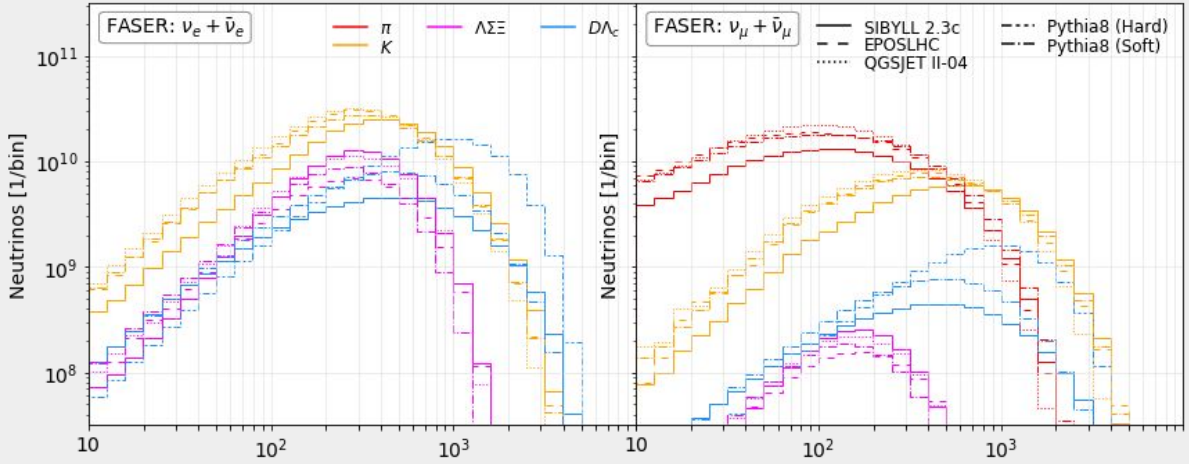
Main Questions

1. Can we tune Pythia for forward experiments?

2. Which experiments can we hope to tune to?

3. How can we estimate the uncertainties in our tune?

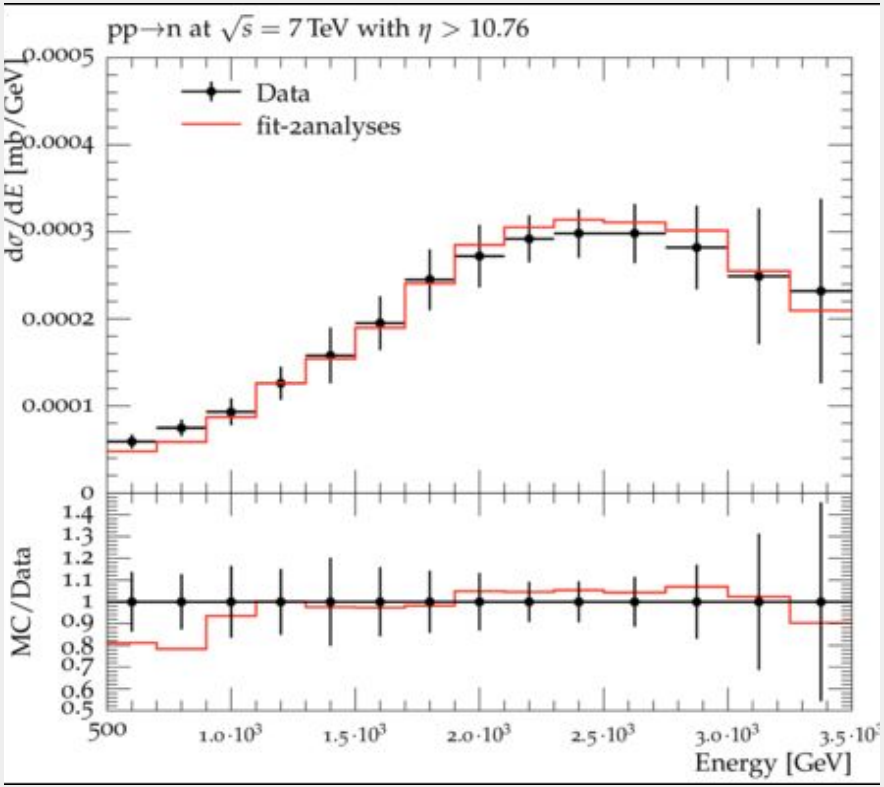
Estimating Uncertainty



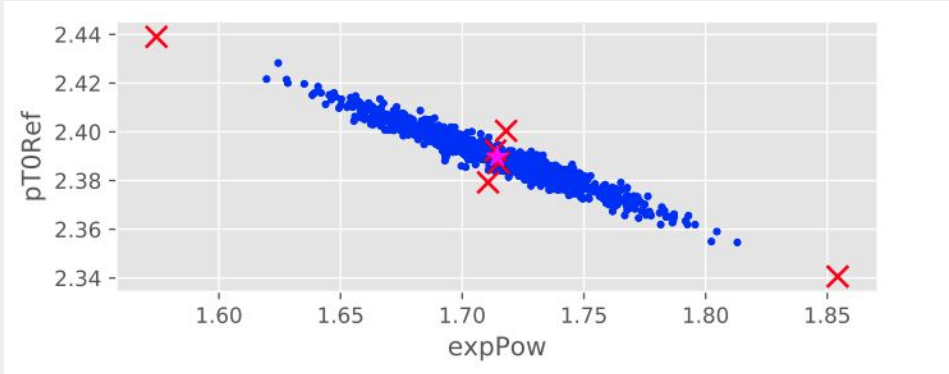
Naively, one could take the error band defined by multiple generators' predictions

Problematic:
uncertainty strongly depends on the weakest generator

Estimating Uncertainty - Replica Tunes

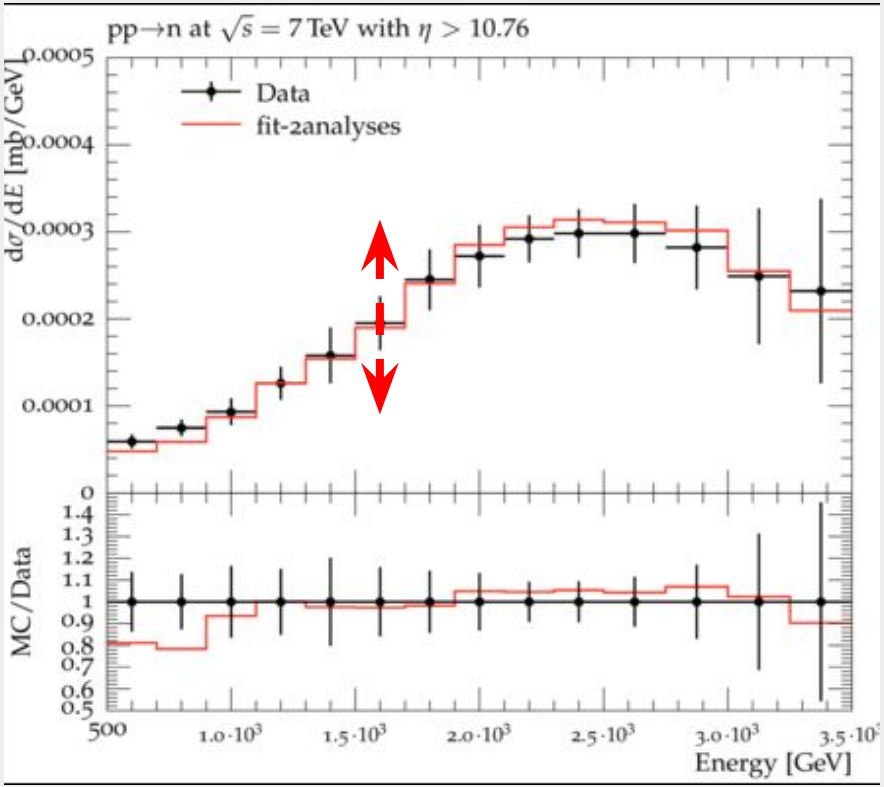


- Can diagonalize covariance matrix, find principal axes in parameter space, and obtain naive chi-squared confidence level
- But data do not follow a chi-squared distribution*, so how to define a meaningful confidence level?

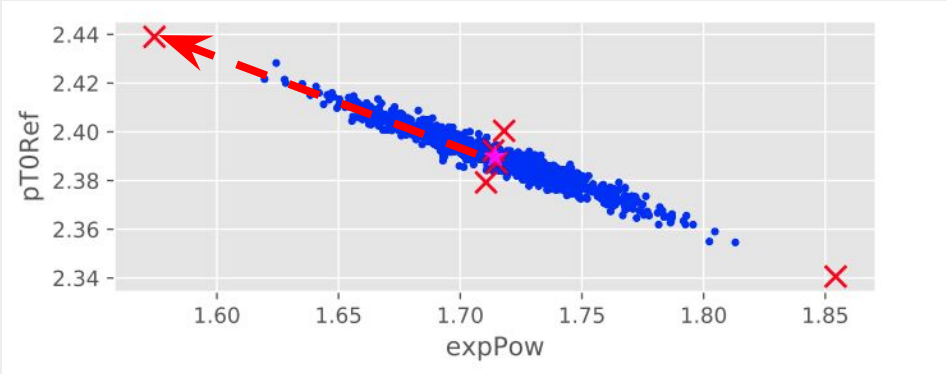


*See section 4A of FASERnu technical proposal for a more thourough discussion on this

Estimating Uncertainty - Replica Tunes



- Can diagonalize covariance matrix, find principal axes in parameter space, and obtain naive chi-squared confidence level
- But data do not follow a chi-squared distribution*, so how to define a meaningful confidence level?
  - Compare tuning with experimental error



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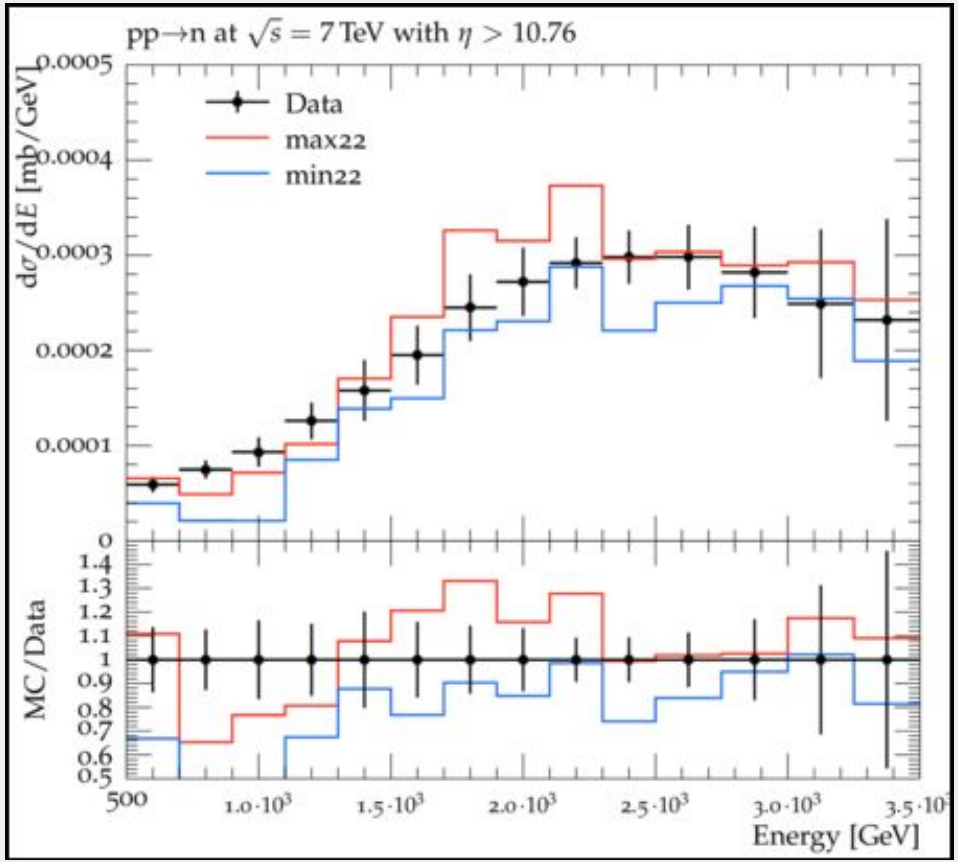
Estimating Uncertainty - Replica Tunes



- (very) Preliminary tuning uncertainties

Main Questions

1. Can we tune Pythia for forward experiments? ✅

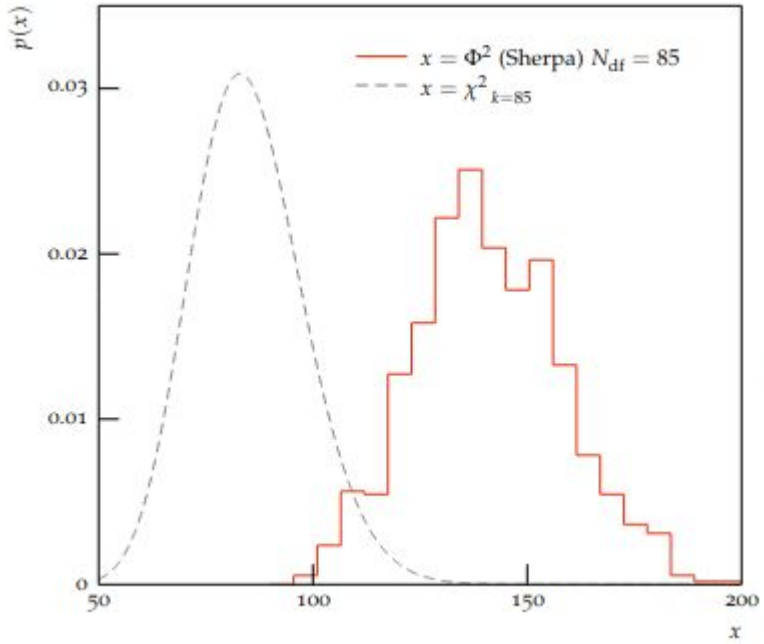
2. Which experiments can (or should) we tune to?
   LHCf has been the priority but we are looking at others

3. Can we estimate the uncertainties in our tune?
   Yes, but the uncertainty should be taken with a grain of salt

Thank You!


FPF
Forward Physics Facility
Give yourself something
to look forward to

Backup


$p(x)$
$x = \Phi^2$ (Sherpa) $N_{df} = 85$
$x = \chi^2_{k=85}$
0.03
0.02
0.01
0
50
100
150
200
x

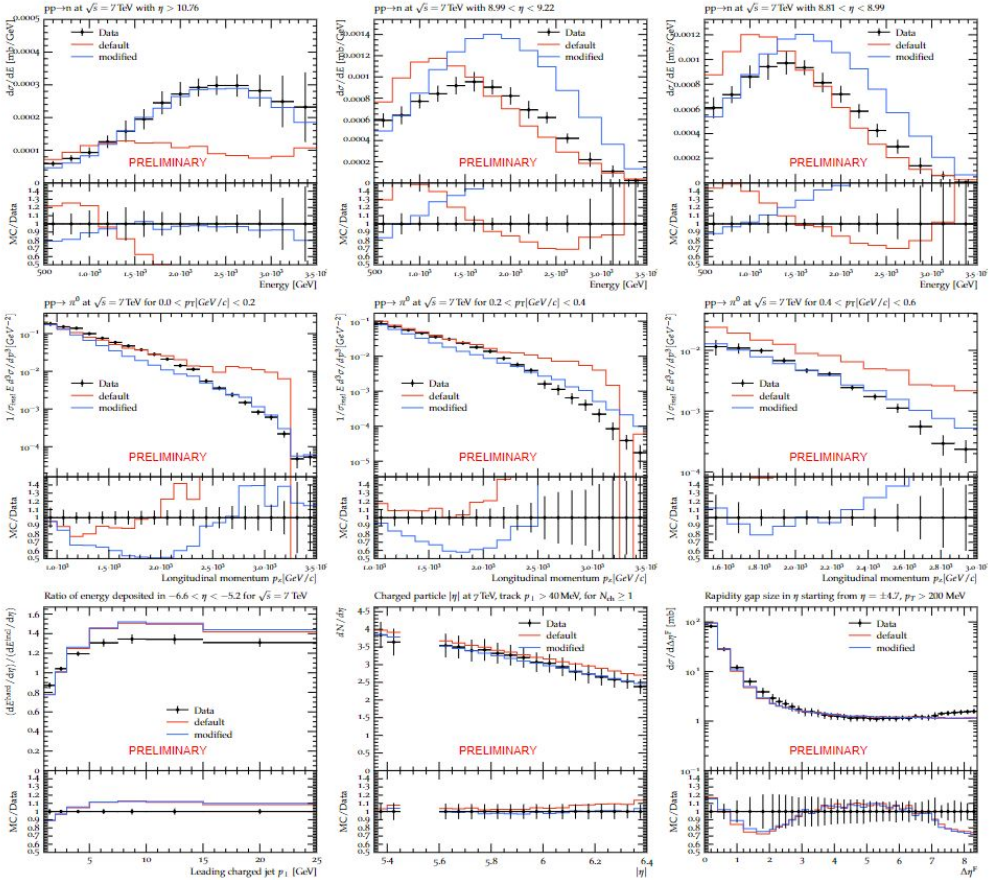
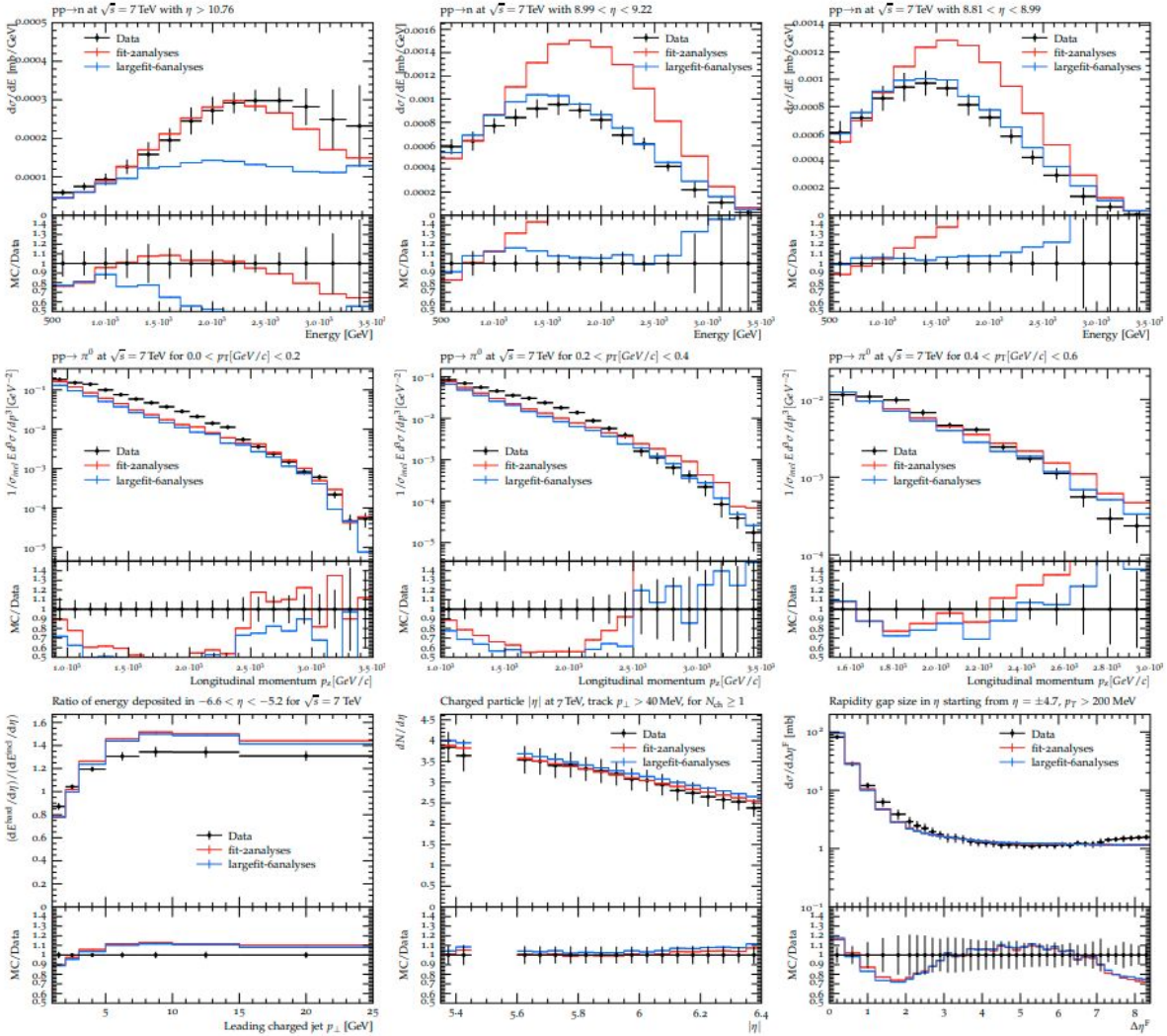


FIG. 14. Comparing the default Monash tune (red line) with our modified tune (blue line) against experimental data (black data points). The first 2 rows are measurements of the neutron and pion spectra respectively, with the left column being the most forward measurements. The third row from left to right is measurements from the CASTOR, TOTEM, and ATLAS collaborations. For each analysis, information on the process can be found at the top of each panel.

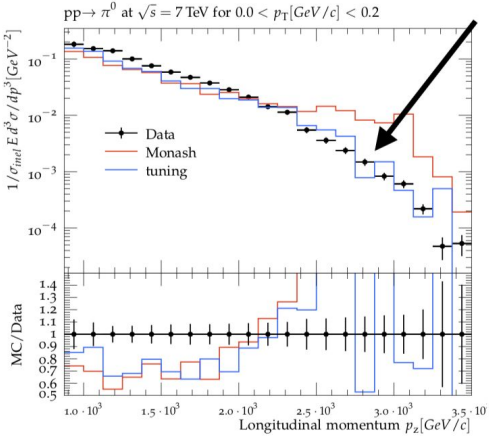

pp→n at $\sqrt{s} = 7$ TeV with $\eta > 10.76$
pp→n at $\sqrt{s} = 7$ TeV with $8.99 < \eta < 9.22$
pp→n at $\sqrt{s} = 7$ TeV with $8.81 < \eta < 8.99$
Data
fit-2analyses
largefit-6analyses
$d\sigma/dE$ [mb/GeV]
MC/Data
Energy [GeV]
pp→ π^0 at $\sqrt{s} = 7$ TeV for $0.0 < p_T[GeV/c] < 0.2$
pp→ π^0 at $\sqrt{s} = 7$ TeV for $0.2 < p_T[GeV/c] < 0.4$
pp→ π^0 at $\sqrt{s} = 7$ TeV for $0.4 < p_T[GeV/c] < 0.6$
$1/\sigma_{inel} E d^3\sigma/dp^3 [GeV^{-2}]$
Longitudinal momentum $p_z[GeV/c]$
Ratio of energy deposited in $-6.6 < \eta < -5.2$ for $\sqrt{s} = 7$ TeV
$(dE^{hcal}/d\eta)/(dE^{ecal}/d\eta)$
Leading charged jet $p_\perp$ [GeV]
Charged particle $|\eta|$ at 7 TeV, track $p_\perp > 40$ MeV, for $N_{ch} \geq 1$
$dN/d\eta$
$|\eta|$
Rapidity gap size in η starting from $\eta = \pm 4.7$, $p_T > 200$ MeV
$d\sigma/d\Delta\eta^F$ [mb]
$\Delta\eta^F$

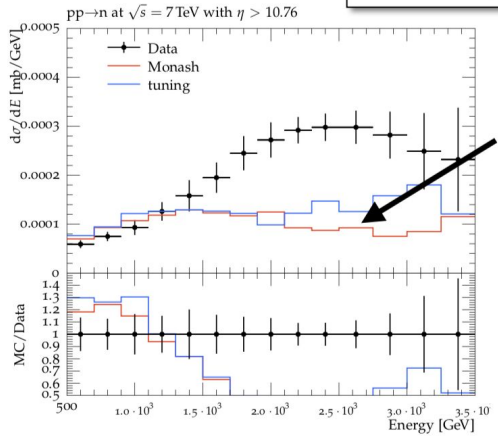
First Results

- we tested 76 Pythia8 parameters, plotted key distribution, and identified 9 relevant parameters
- We tuned them to the LHCf pion and neutron analyses
- First results look promising

Parameters:
SigmaDiffractive:mMin
SigmaDiffractive:lowMEnhance
SigmaDiffractive:maxAX
SigmaDiffractive:maxXX
SigmaDiffractive:mResMax
SigmaDiffractive:maxXB
SigmaDiffractive:maxAXB
SigmaDiffractive:SaSepsilon
StringPT:sigma
Analyses:
LHCF_2016_I1385877
LHCF_2015_I1351909

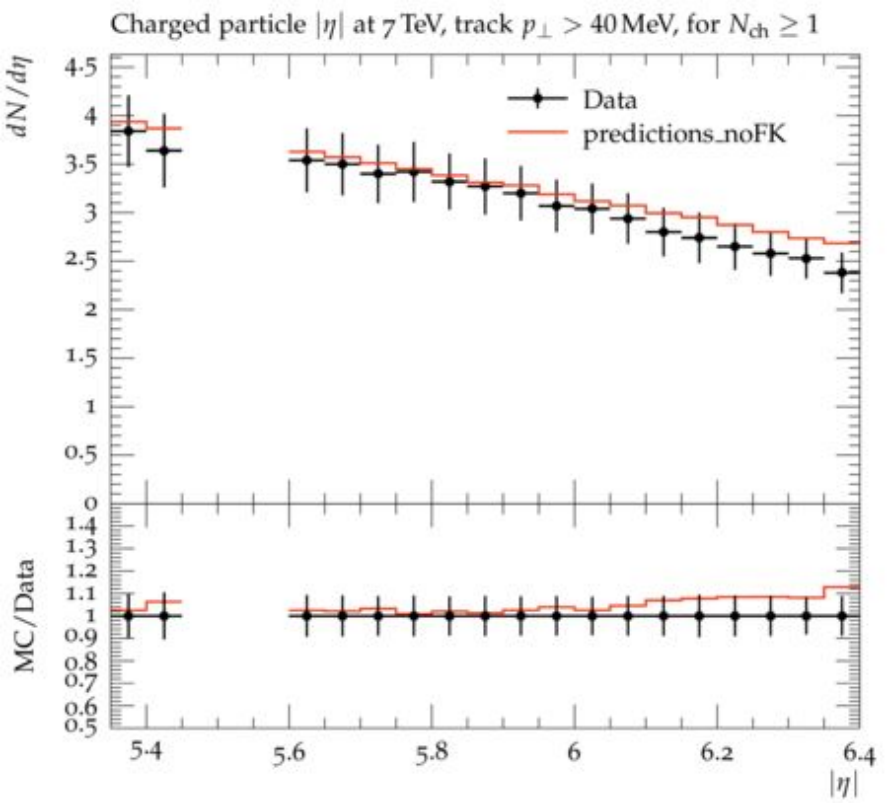
much better



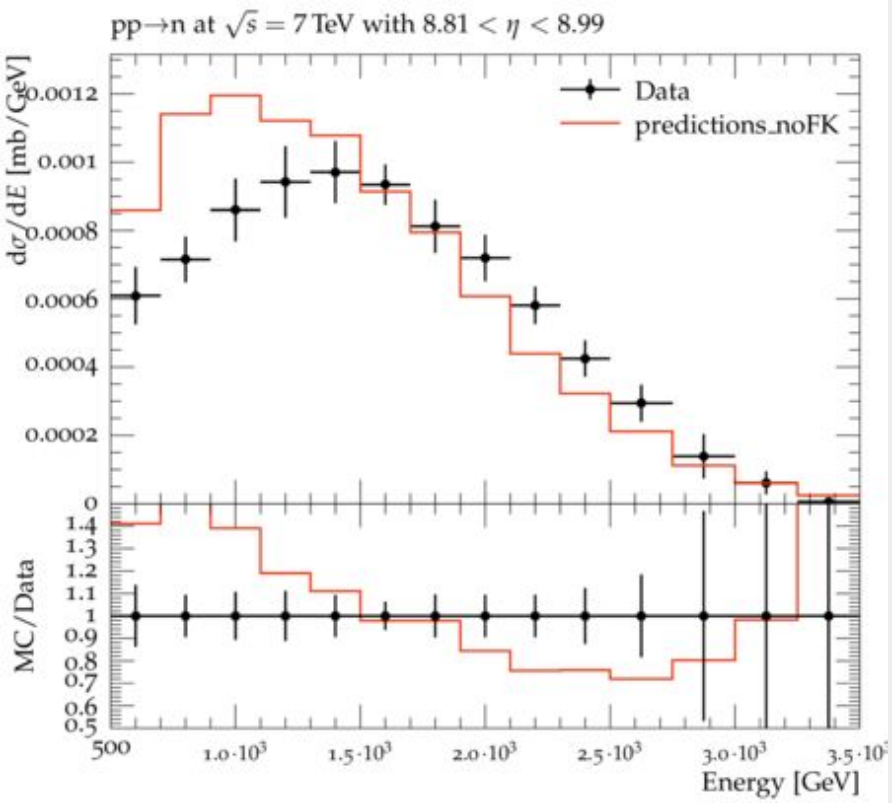


still bad

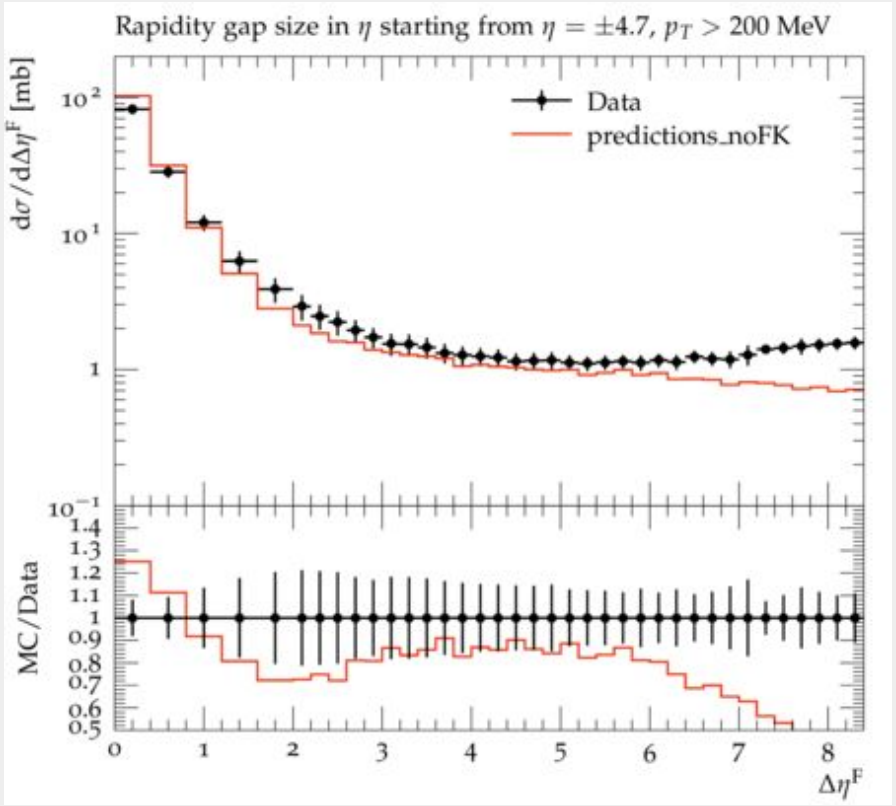
TOTEM

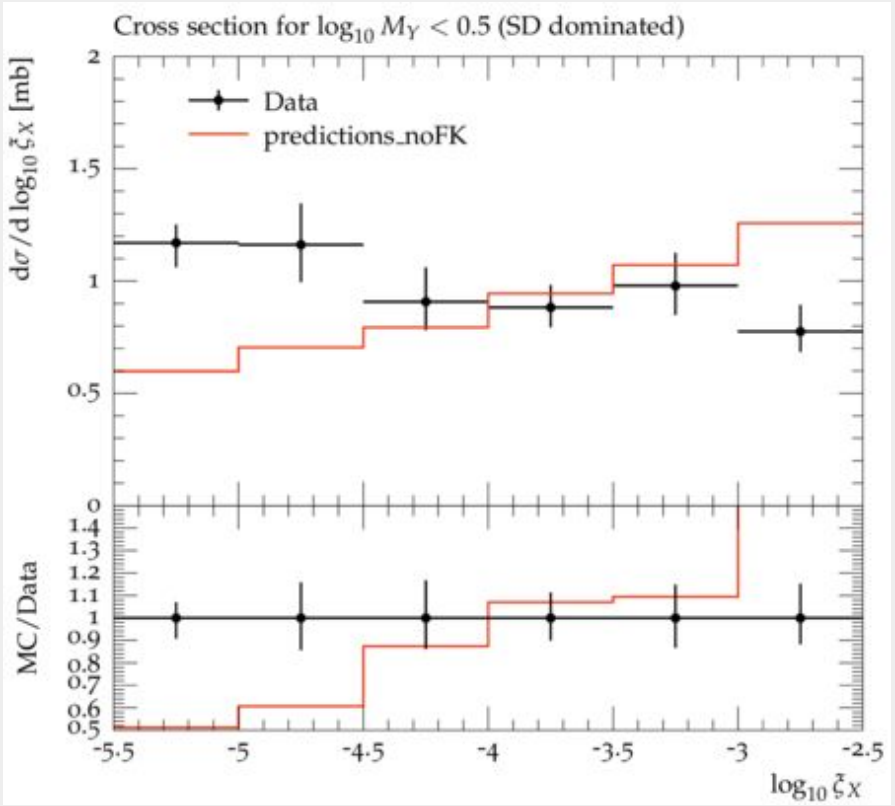

Charged particle $|\eta|$ at 7 TeV, track $p_\perp > 40$ MeV, for $N_{ch} \geq 1$
$dN/d\eta$
Data
predictions_noFK
MC/Data
$|\eta|$

LHCf Neutrons

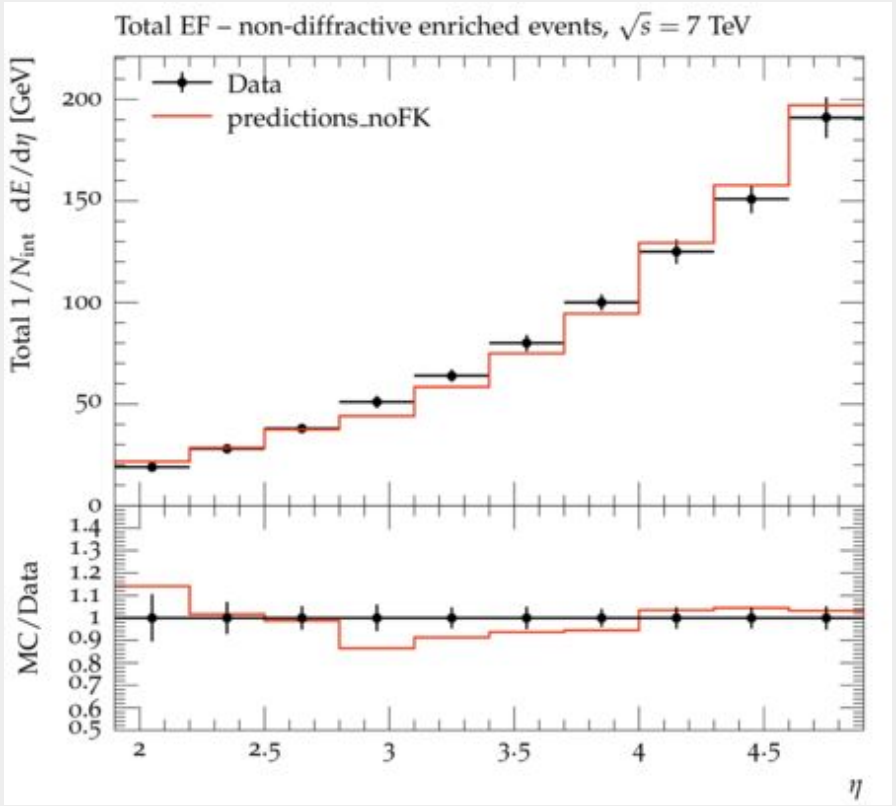


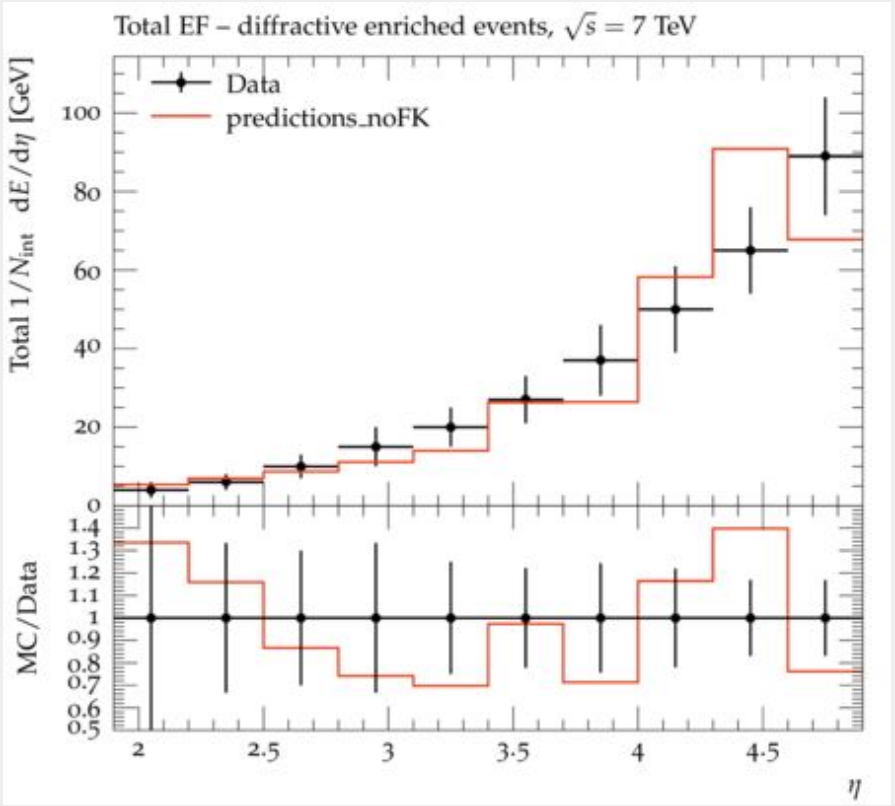
CMS


Rapidity gap size in η starting from $\eta = \pm 4.7$, $p_T > 200$ MeV
Data
predictions_noFK
$d\sigma/d\Delta\eta^F$ [mb]
MC/Data
$\Delta\eta^F$


Cross section for $\log_{10} M_Y < 0.5$ (SD dominated)
Data
predictions_noFK
$d\sigma/d\log_{10}\xi_X$ [mb]
MC/Data
$\log_{10}\xi_X$

LHCb


Total EF – non-diffractive enriched events, $\sqrt{s} = 7$ TeV
Data
predictions_noFK
Total $1/N_{\text{int}}$ $dE/d\eta$ [GeV]
MC/Data
η


Total EF – diffractive enriched events, $\sqrt{s} = 7$ TeV
Data
predictions_noFK
Total $1/N_{\text{int}}$ $dE/d\eta$ [GeV]
MC/Data
η