Tuning Pythia for Forward Physics

Felix Kling -
SLAC

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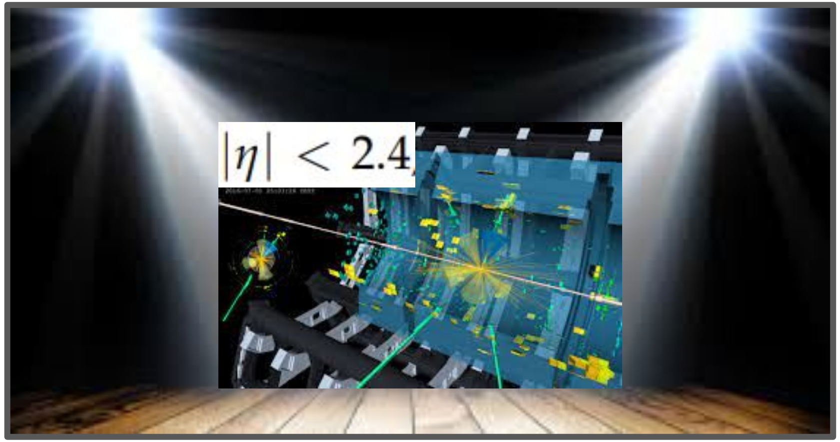
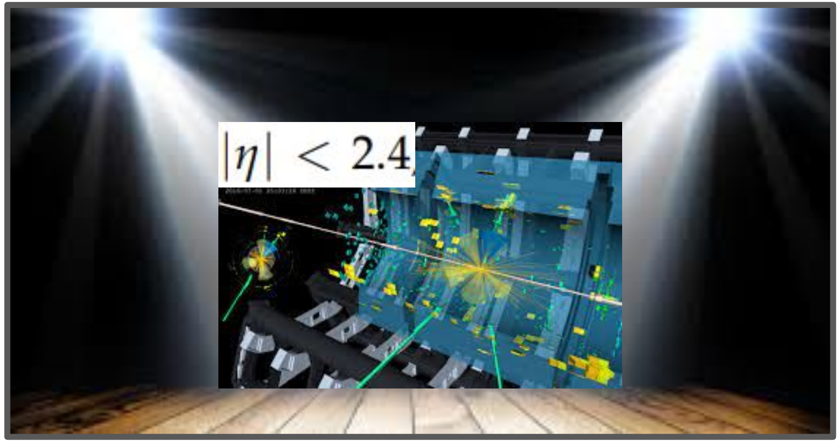
BSM IX
Tomorrow 4:30 PM EDT
Forward Physics Facility

mfieg at uci dot edu

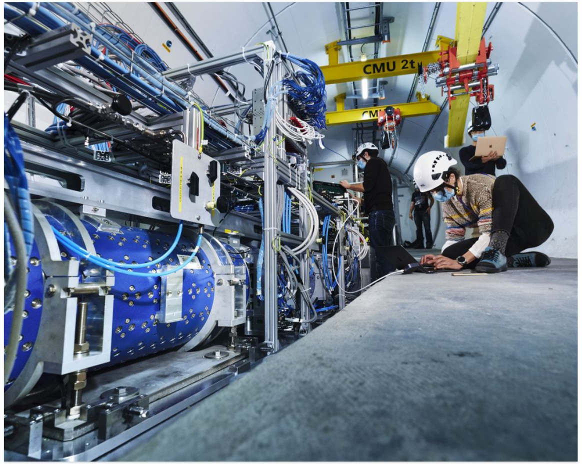

$|\eta| < 2.4$



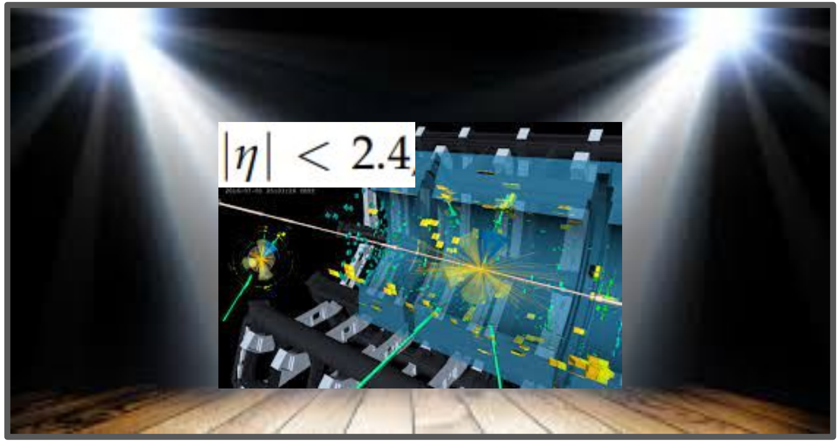
LS2 Report: FASER is born

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



The final elements of FASER were put into place this month. (Image: CERN)



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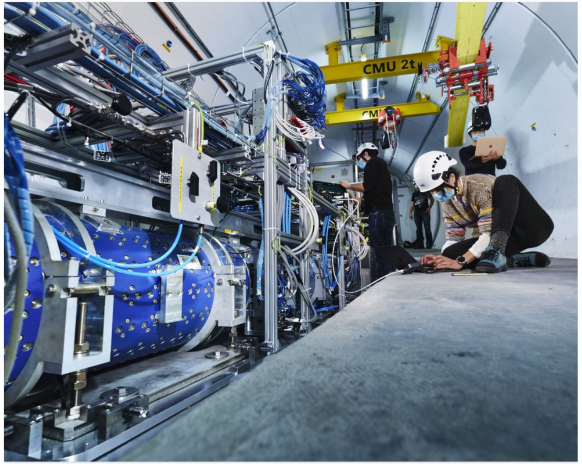

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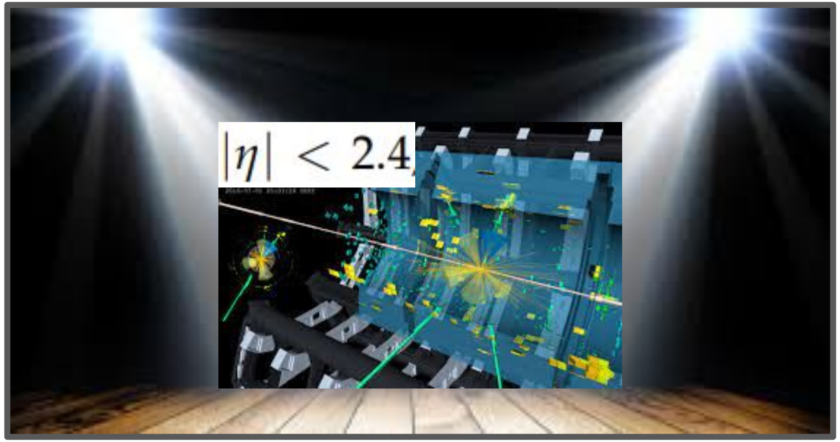
PYTHIA



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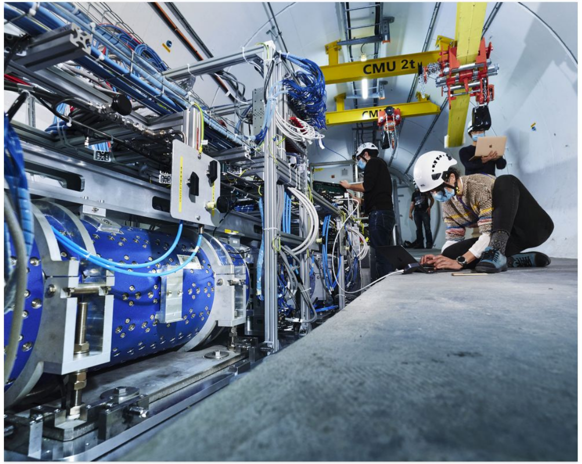


The final elements of FASER were put into place this month. (Image: CERN)

PYTHIA

"If you are the 100th person to look under a rock, you are unlikely to find anything…

...but if you are using a new tool, or find a rock that's been left unturned, you don't have to be smart to find something"

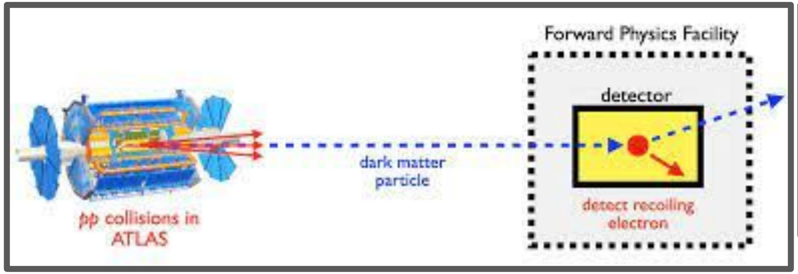
Dr. Steven Chu

Main Questions

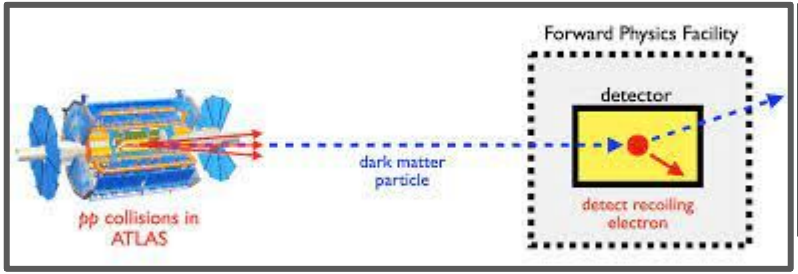
1. Can we tune Pythia for forward experiments?

2. Which experiments can we hope to tune to?

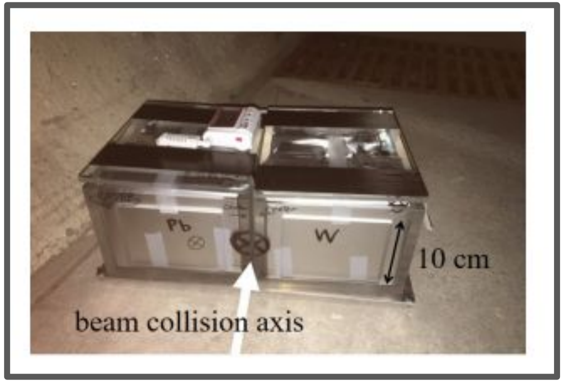
3. How can we estimate the uncertainties in our tune?


Forward Physics Facility
detector
dark matter
particle
pp collisions in
ATLAS
detect recoiling
electron

FASER



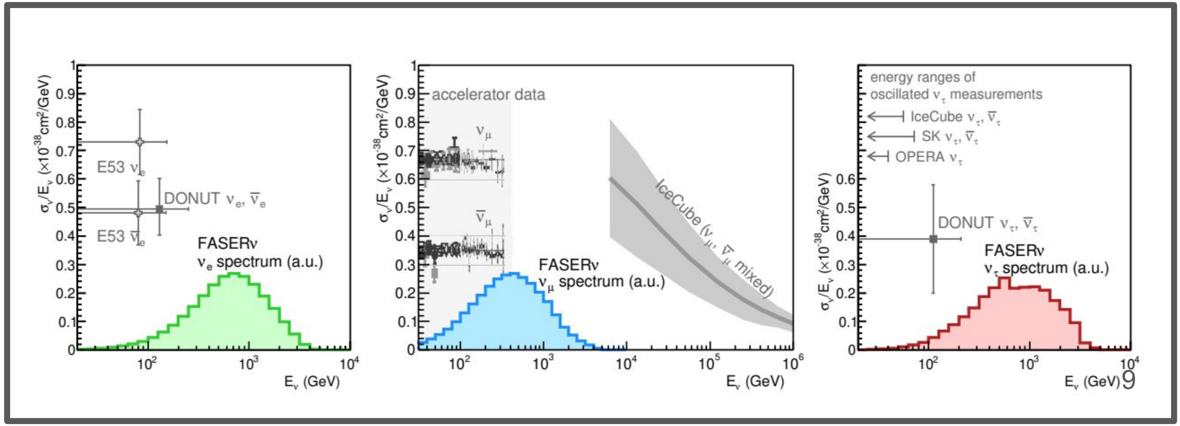
FASER

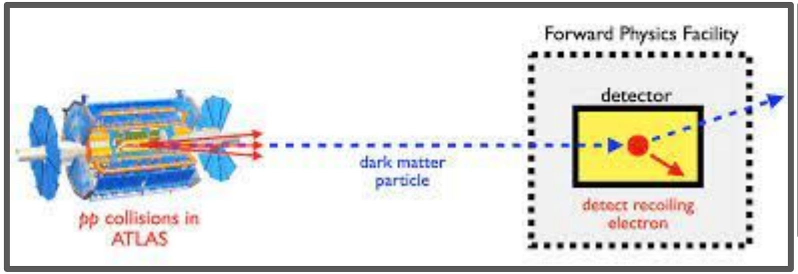


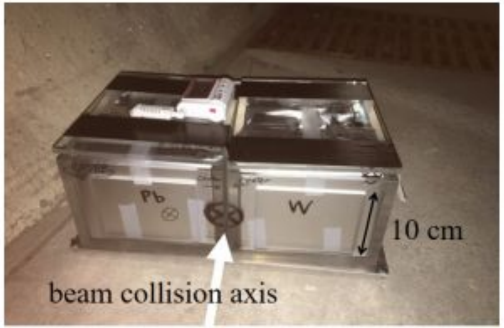
High Energy Physics - Experiment

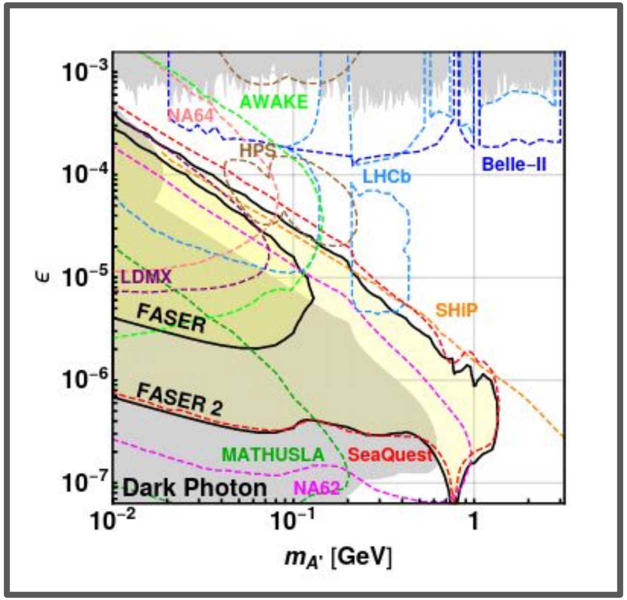
[Submitted on 13 May 2021]

First neutrino interaction candidates at the LHC









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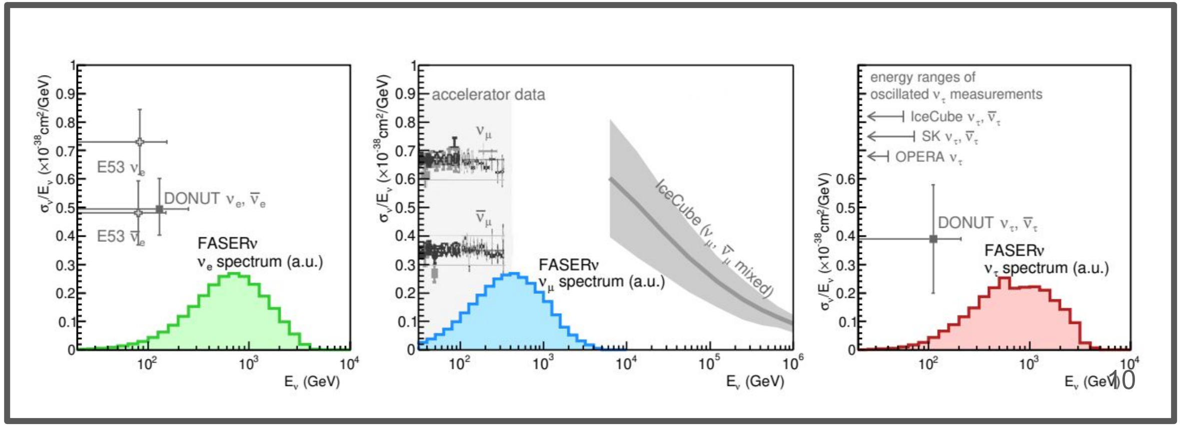


https://arxiv.org/pdf/1811.12522.pdf

Probing PDFs via Neutrino Scattering with FASERν

https://indico.fnal.gov/event/48868/contributions/213502/attachments/142718/180250/Strange_PDFs_Snowmass_21.pdf

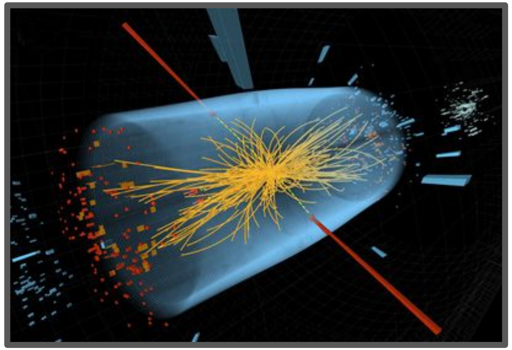
Detecting Dark Matter with Far-Forward Emulsion and Liquid Argon Detectors at the LHC

Brian Batell,[1,*] Jonathan L. Feng,[2,†] and Sebastian Trojanowski[3,4,5,‡]

https://arxiv.org/pdf/2101.10338.pdf

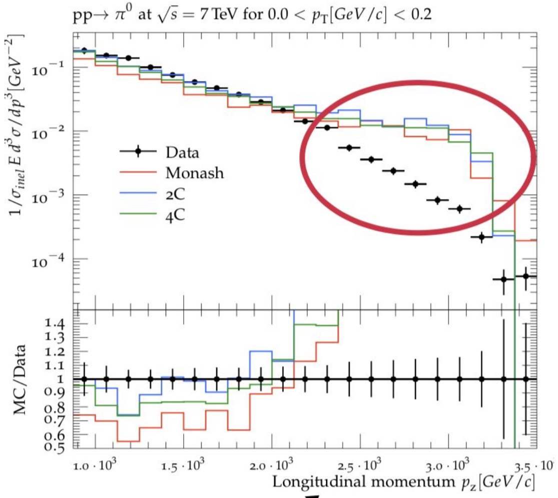
Main Problem

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

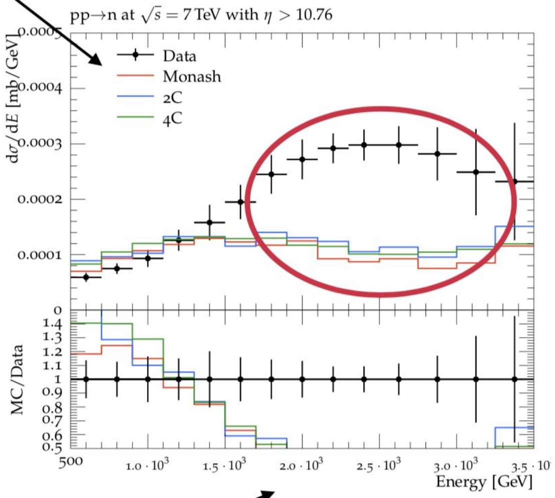


default tunes

LHCf pion spectrum



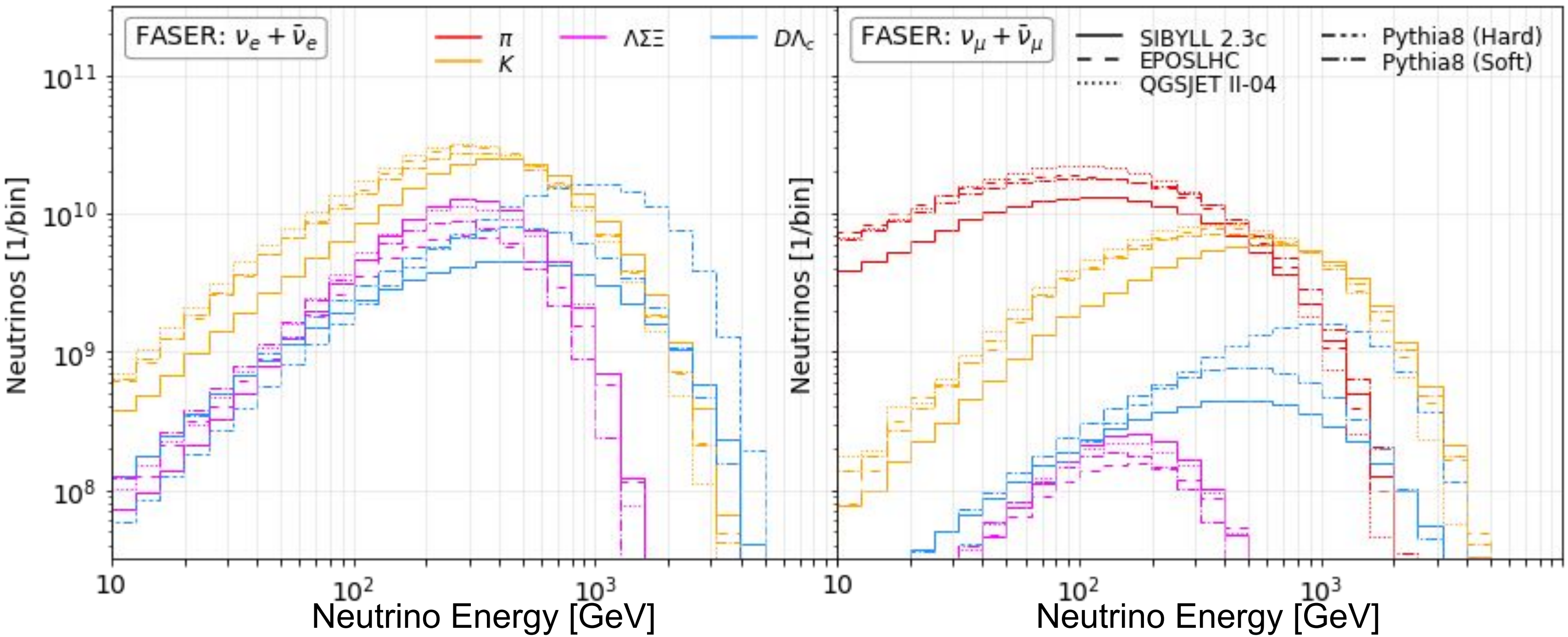
LHCf neutron spectrum



plots made with Rivet

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	4.0
Diffraction:sigmaRefPomP	10.
Diffraction:mRefPomP	100
Diffraction:mPowPomP	0.0
SigmaDiffractive:PomFlux	1.0
SigmaDiffractive:PomFluxEpsilon	0.085
SigmaDiffractive:PomFluxAlphaPrime	0.25

Importance for Forward Neutrino Fluxes



Most neutrinos come from pion / kaon 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

PYTHIA

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

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Rivet — the particle-physics MC analysis toolkit

Combine experimental analyses with Pythia simulations

pyapprentice 1.0.6

Predict Pythia response to tuning parameters and fit to experimental data

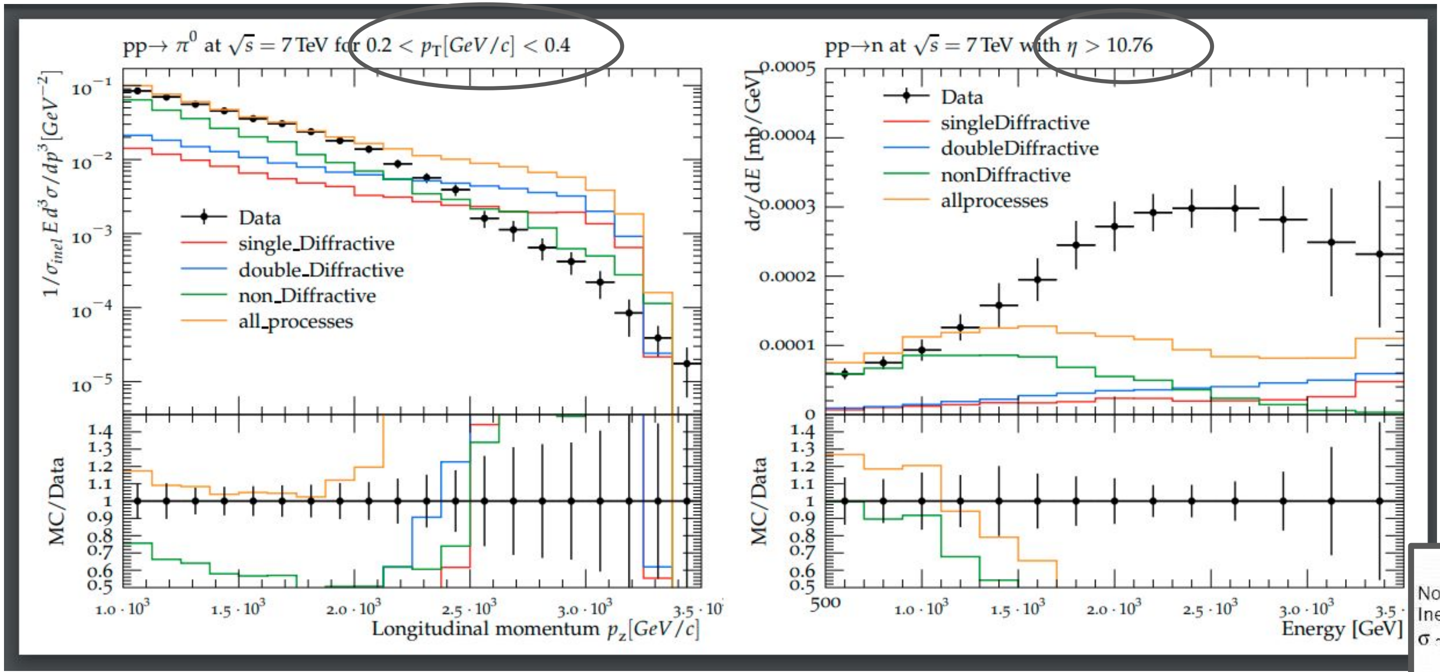
Main Questions

1. Can we tune Pythia for forward experiments?

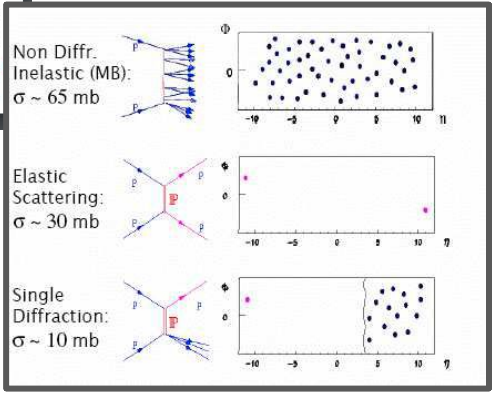
2. Which experiments can we hope to tune to?

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

How much forward physics data can we fit at once?



Poor predictions in the forward region.



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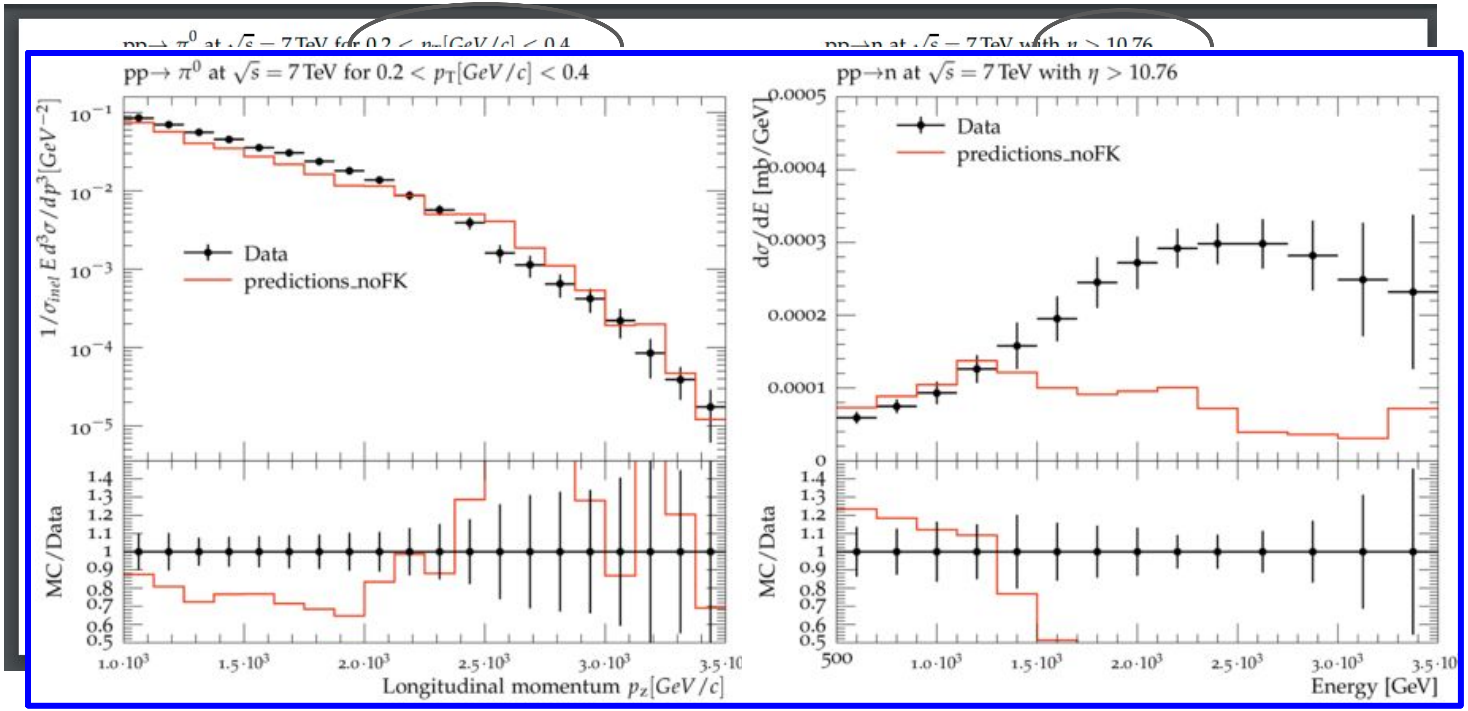
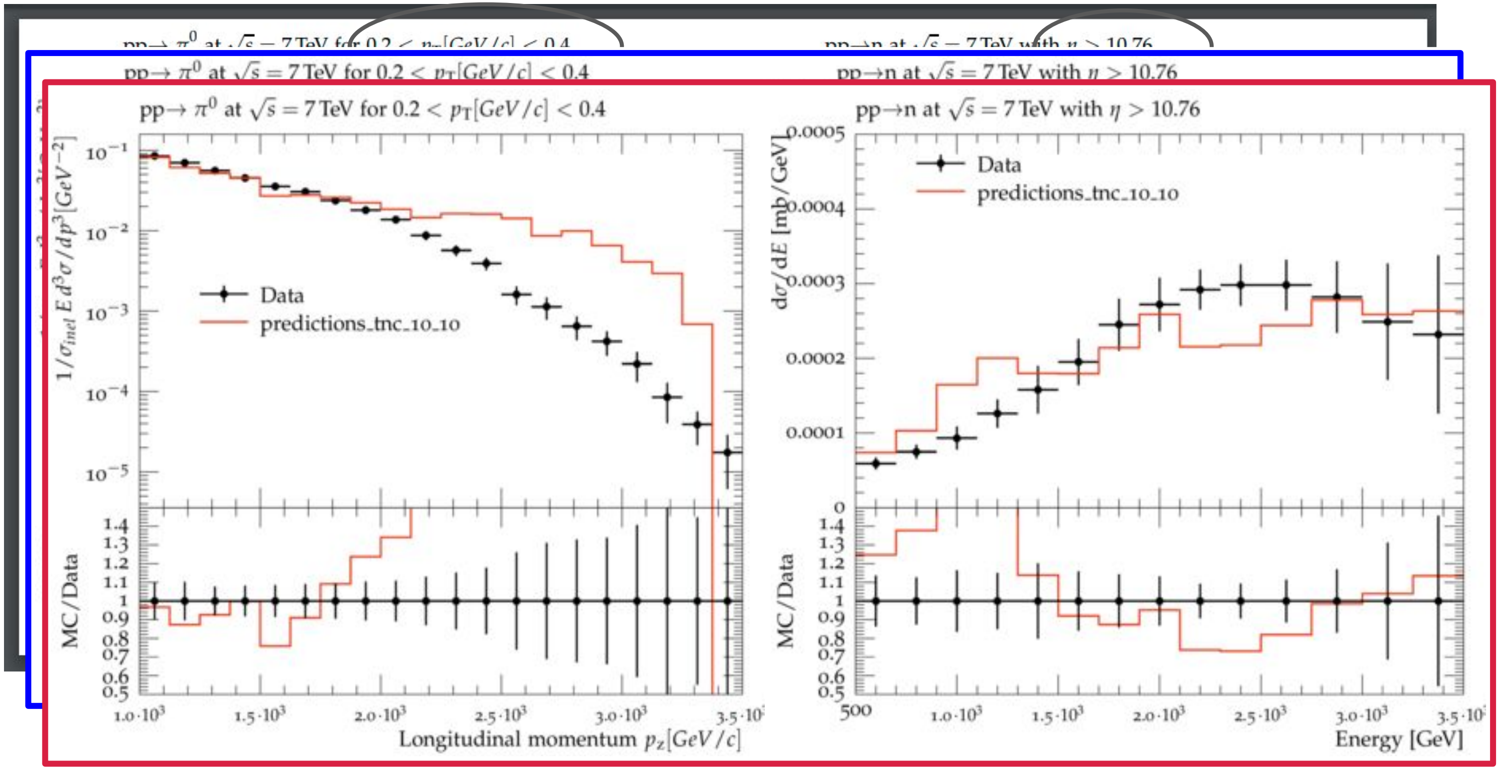


Poor predictions in the forward region.

An improvement, but some analyses are problematic

How much forward physics data can we fit at once?



Poor predictions in the forward region.

An improvement, but some analyses are problematic

Problematic analyses *can* be generated by Pythia

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?

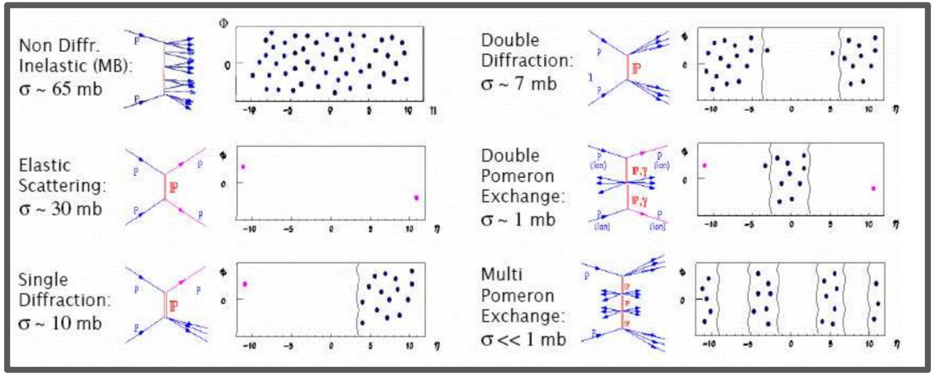
Forward Experiments

LHCf ($\eta > 8.81$)				
Analysis	$\sqrt{s}$ [TeV]	HD	**Refs.**	**RIVET**
forward π^0 or γ	7	√	[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 ($\lvert\eta\rvert < 5$)				
Analysis	$\sqrt{s}$ [TeV]	HD	**Refs.**	**RIVET**
$\sigma_{SD}, \sigma_{DD}, \sigma_{inel}$	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 ($\lvert\eta\rvert < 5$)				
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 (unpublished)	8	√	[30]	ATLAS_2019_I1762584(1)
	13		[31]	

CMS ($\lvert\eta\rvert < 5$)				
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]	

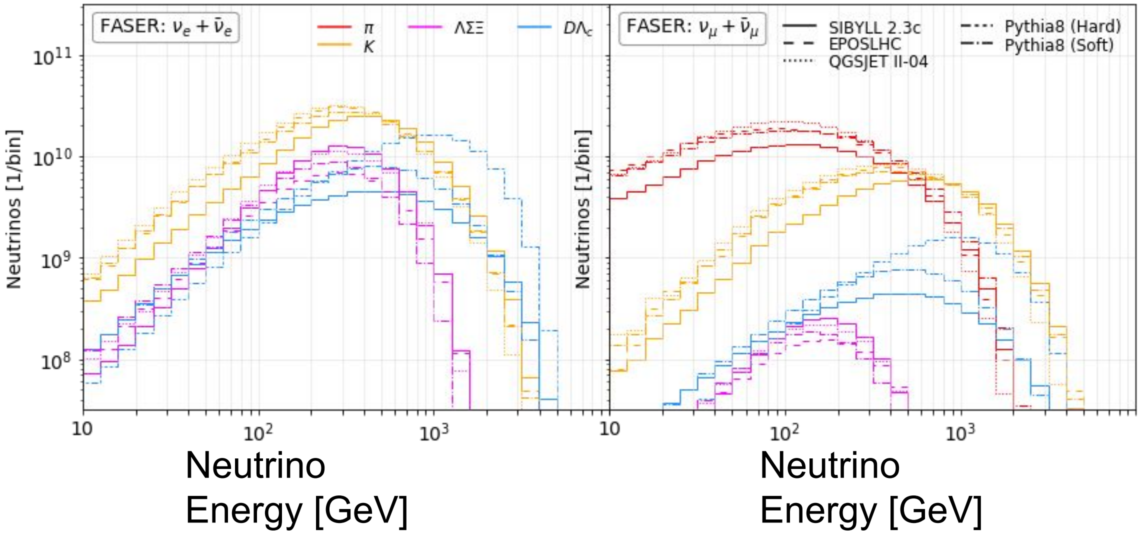
Main Questions

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

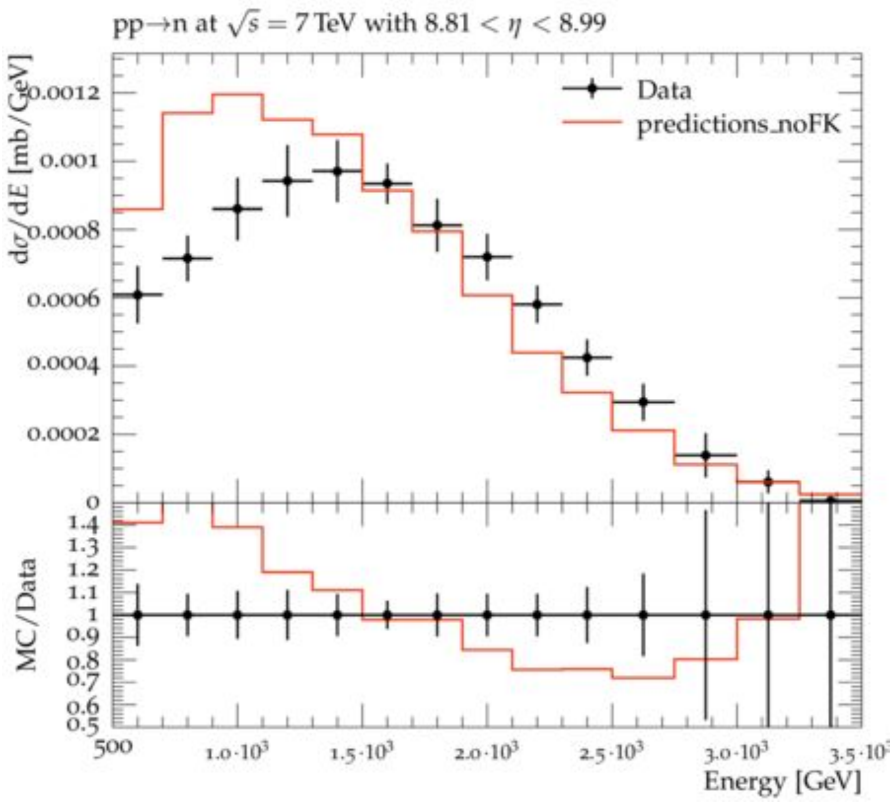


- Naively, one could take the error band defined by multiple generators' predictions

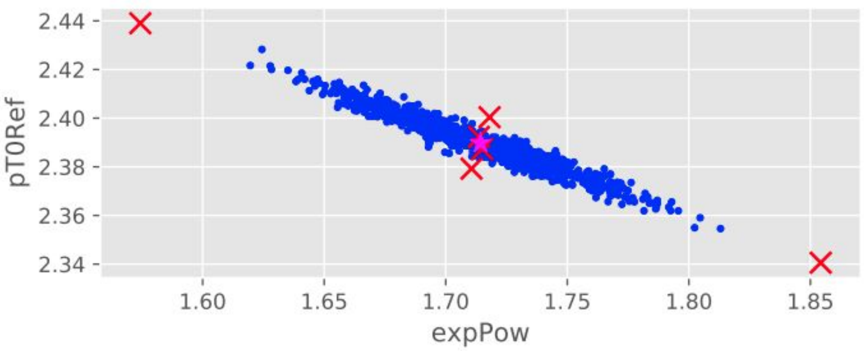
This is problematic: uncertainty strongly depends on the weakest generator

Want something more robust

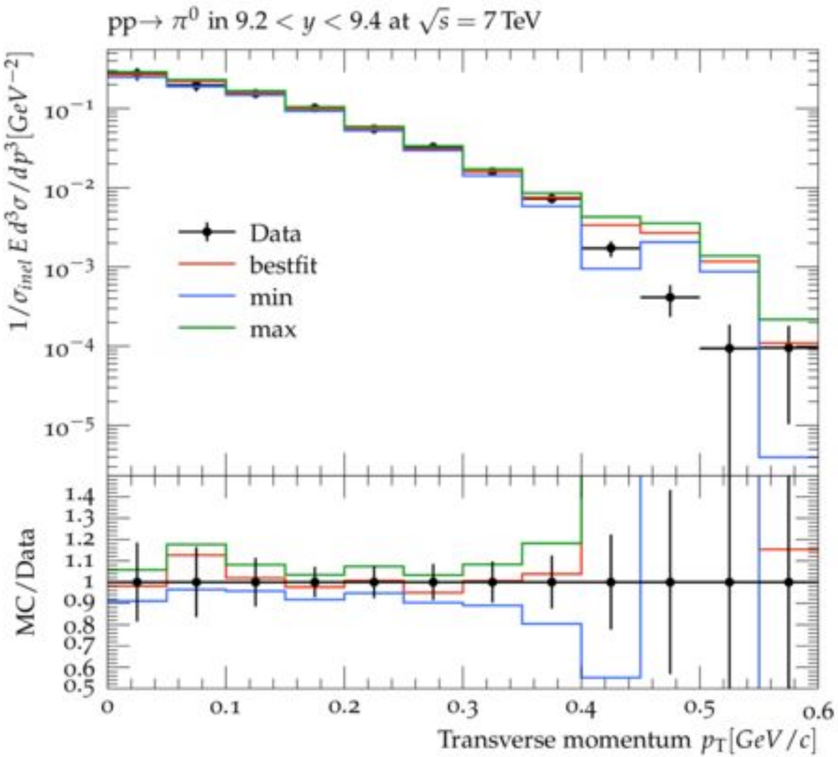
Estimating Uncertainty - Replica Tunes



1. Create replica datasets
2. Create replica *tunes* from these
3. Use these replica tunes to explore parameter space effectively



Estimating Uncertainty - Replica Tunes



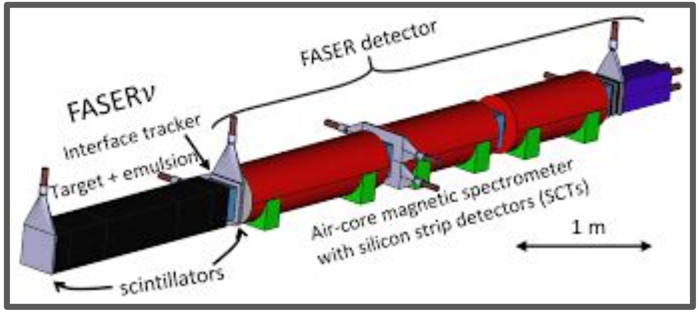
- Preliminary error bars

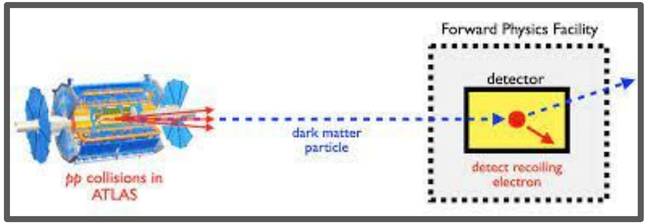
Main Questions

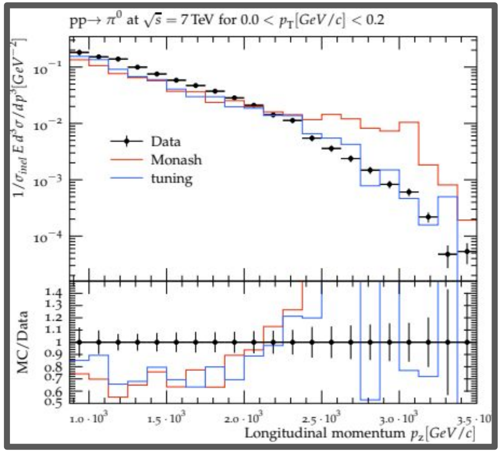
1. Can we tune Pythia for forward experiments? ✅

2. Which experiments can (or should) we tune to?
   Are there other experiments we should focus on?
   Are there other experiments we are ignoring?

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







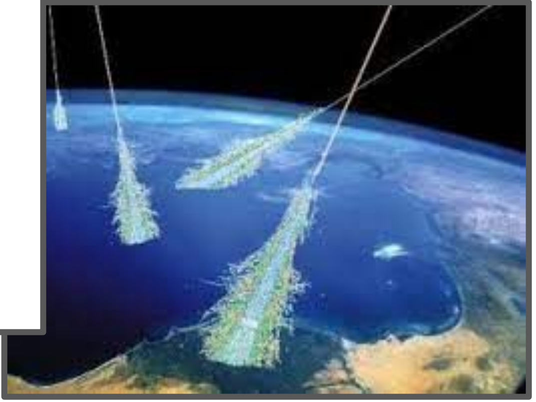
IV. FASER Reach for Dark Vectors
A. Benchmark V1: Dark Photons
B. Benchmark V2: $B - L$ Gauge Bosons
C. Benchmark V3: $L_i - L_j$ Gauge Bosons

V. FASER Reach for Dark Scalars
A. Benchmark S1: Dark Higgs Bosons
B. Benchmark S2: Dark Higgs Bosons with Large Trilinear Couplings

VI. FASER Reach for Heavy Neutral Leptons
A. Benchmarks F1, F2, F3: HNLs Coupled to e, μ, τ

VII. FASER Reach for Axion-Like Particles
A. Benchmark A1: Photon Dominance
B. Benchmark A2: Fermion Dominance
C. Benchmark A3: Gluon Dominance

VIII. FASER Reach for Dark Pseudoscalars
A. Benchmark P1: Pseudoscalar with Yukawa-like Couplings



Forward Physics
(w/ tuned Pythia)

Dr. Steven Chu

Thank You!

References

1. Faser_nu Technical Proposal: https://arxiv.org/abs/1812.09139
2. Faser Physics Reach for LLP's: https://arxiv.org/abs/1811.12522
3. FLARE - https://arxiv.org/pdf/2101.10338.pdf
4. Strange PDF's from FASER: https://indico.fnal.gov/event/48868/contributions/213502/attachments/142718/180250/Strange_PDFs_Snowmass_21.pdf
5. Rivet - https://rivet.hepforge.org/
6. Apprentice - https://iamholger.gitbook.io/apprentice/installation
7. Pythia - http://home.thep.lu.se/Pythia/

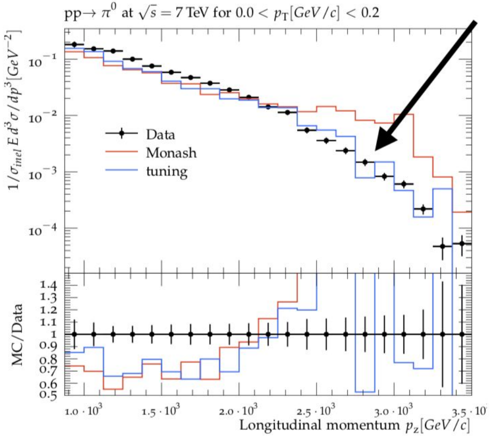
Backup

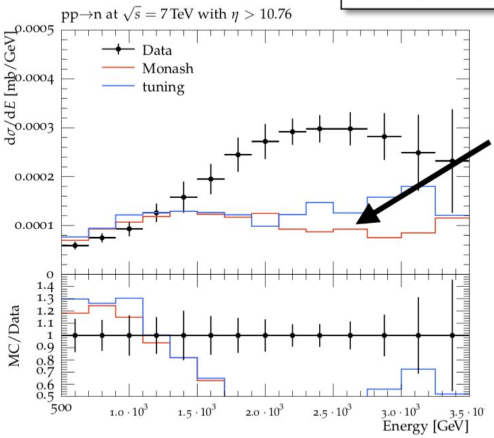
First Results

- 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



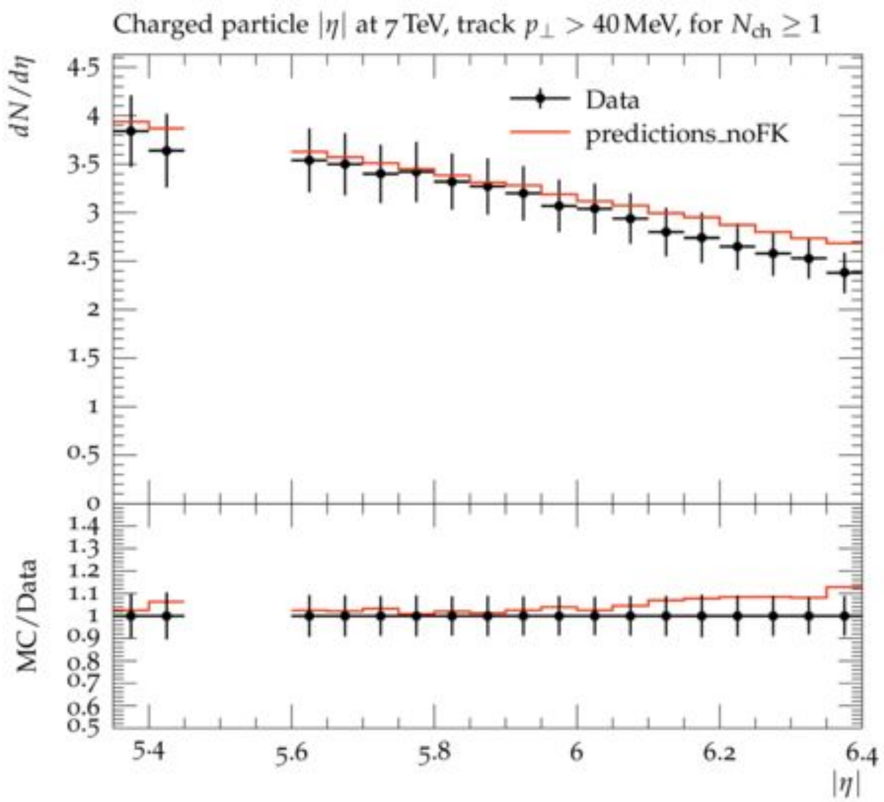


still bad

Tuning Parameters

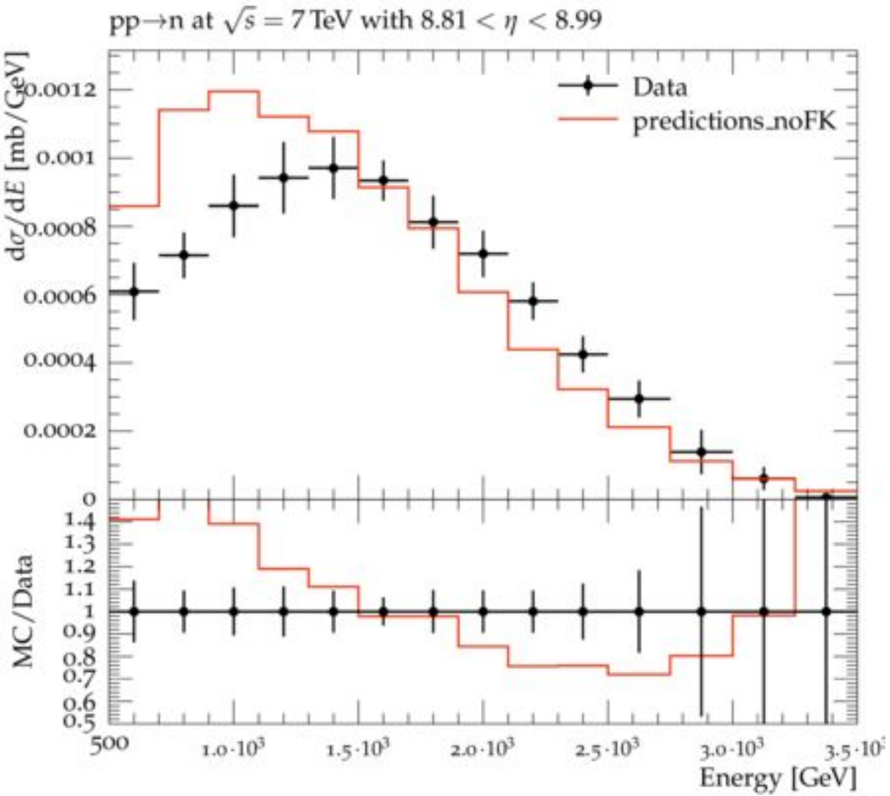
Parameter	Def.
SigmaDiffractive:maxXB	65
SigmaDiffractive:maxAX	65
SigmaDiffractive:maxXX	65
SigmaDiffractive:maxAXB	3.0
SigmaDiffractive:mMin	0.28
SigmaDiffractive:lowMEnhance	2.0
SigmaDiffractive:mResMax	1.062
SigmaDiffractive:SaSepsilon	0.0
StringPT:sigma	0.335
Diffraction:mMinPert	10.
Diffraction:mWidthPert	10.
Diffraction:probMaxPert	1.0
Diffraction:pickQuarkNorm	5.0
Diffraction:pickQuarkPower	1.0
Diffraction:primKTwidth	0.5
Diffraction:largeMassSuppress	4.0
Diffraction:sigmaRefPomP	10.
Diffraction:mRefPomP	100
Diffraction:mPowPomP	0.0
SigmaDiffractive:PomFlux	1.0
SigmaDiffractive:PomFluxEpsilon	0.085
SigmaDiffractive:PomFluxAlphaPrime	0.25

TOTEM

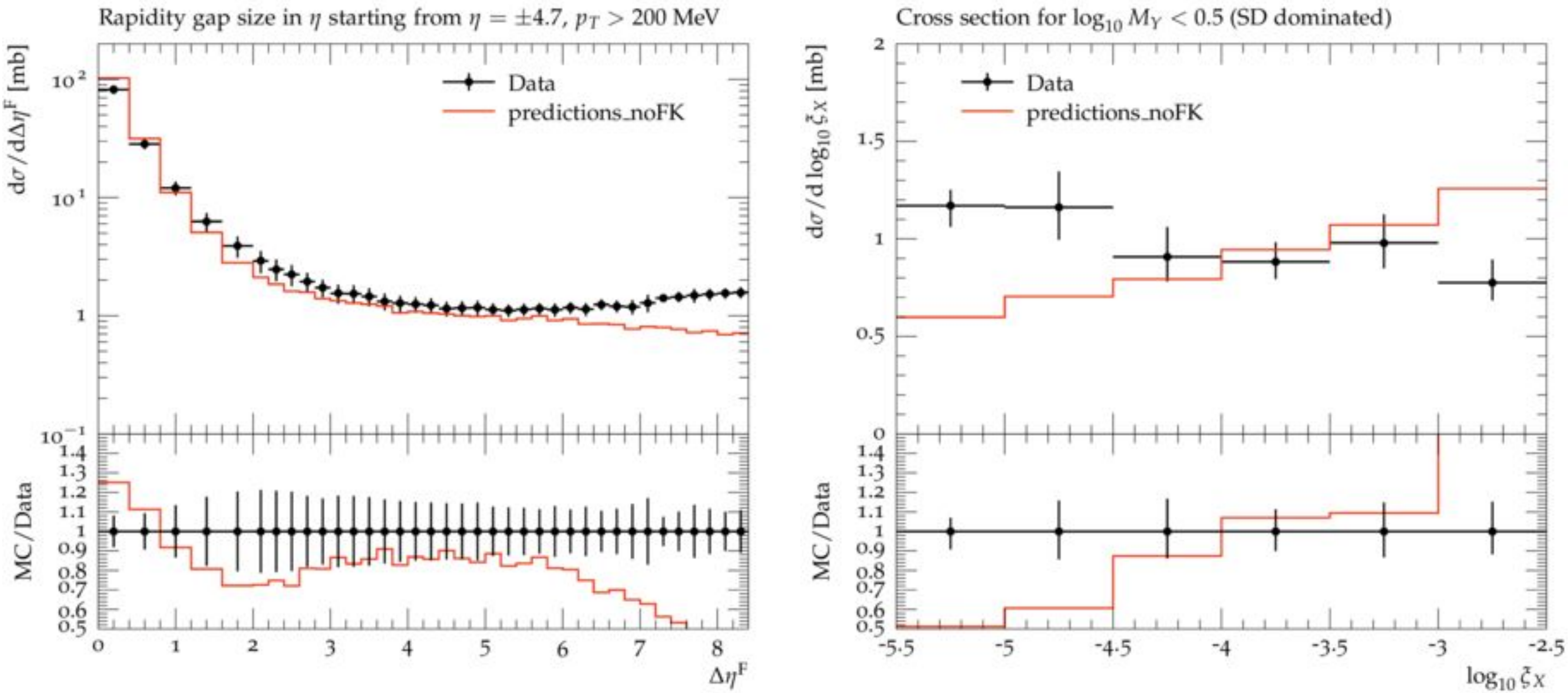


Charged particle $|\eta|$ at 7 TeV, track $p_\perp > 40$ MeV, for $N_{ch} \geq 1$
$dN/d\eta$
Data
predictions_noFK
MC/Data
$|\eta|$
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
5.4
5.6
5.8
6
6.2
6.4

LHCf Neutrons

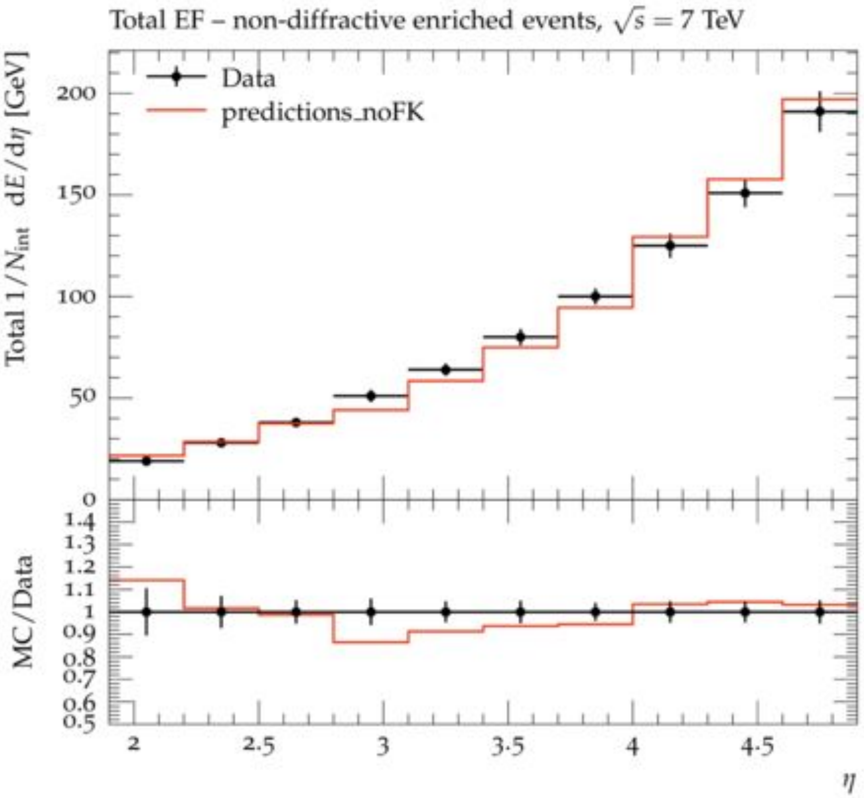


CMS

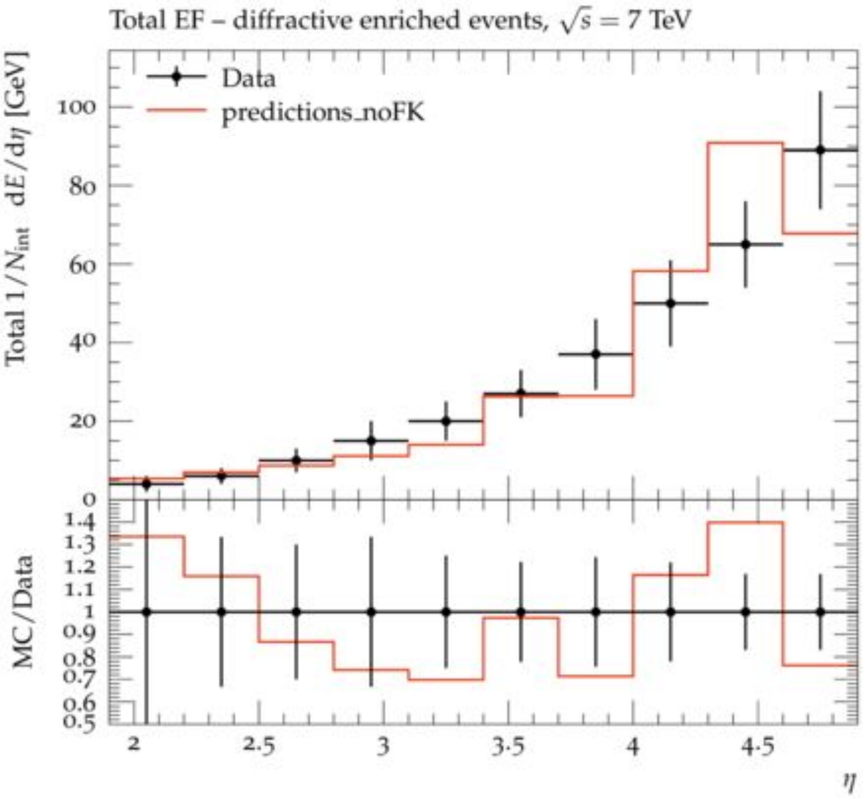


Rapidity gap size in η starting from $\eta = \pm 4.7$, $p_T > 200$ MeV
$d\sigma / d\Delta\eta^F$ [mb]
Data
predictions_noFK
MC/Data
$\Delta\eta^F$
Cross section for $\log_{10} M_Y < 0.5$ (SD dominated)
$d\sigma / d \log_{10} \xi_X$ [mb]
Data
predictions_noFK
MC/Data
$\log_{10} \xi_X$

LHCb



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



Total EF – diffractive enriched events, $\sqrt{s}$ = 7 TeV
Data
predictions_noFK
Total 1/N_int dE/dη [GeV]
MC/Data
η