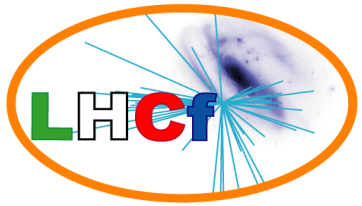


LHCf experiment : Current status and future prospect

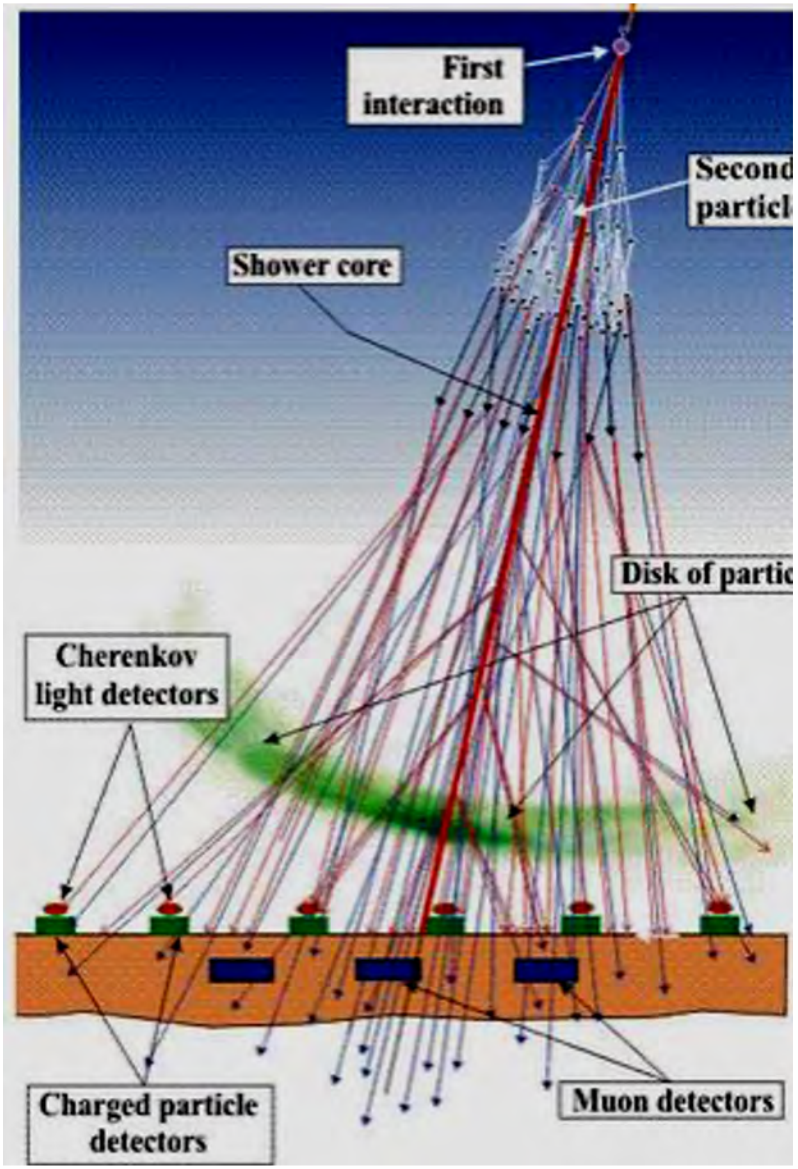
Yoshitaka Itow

Institute for Space-Earth Environmental Research / Kobayashi-Maskawa Institute for the Origin of Particles and the Universe,

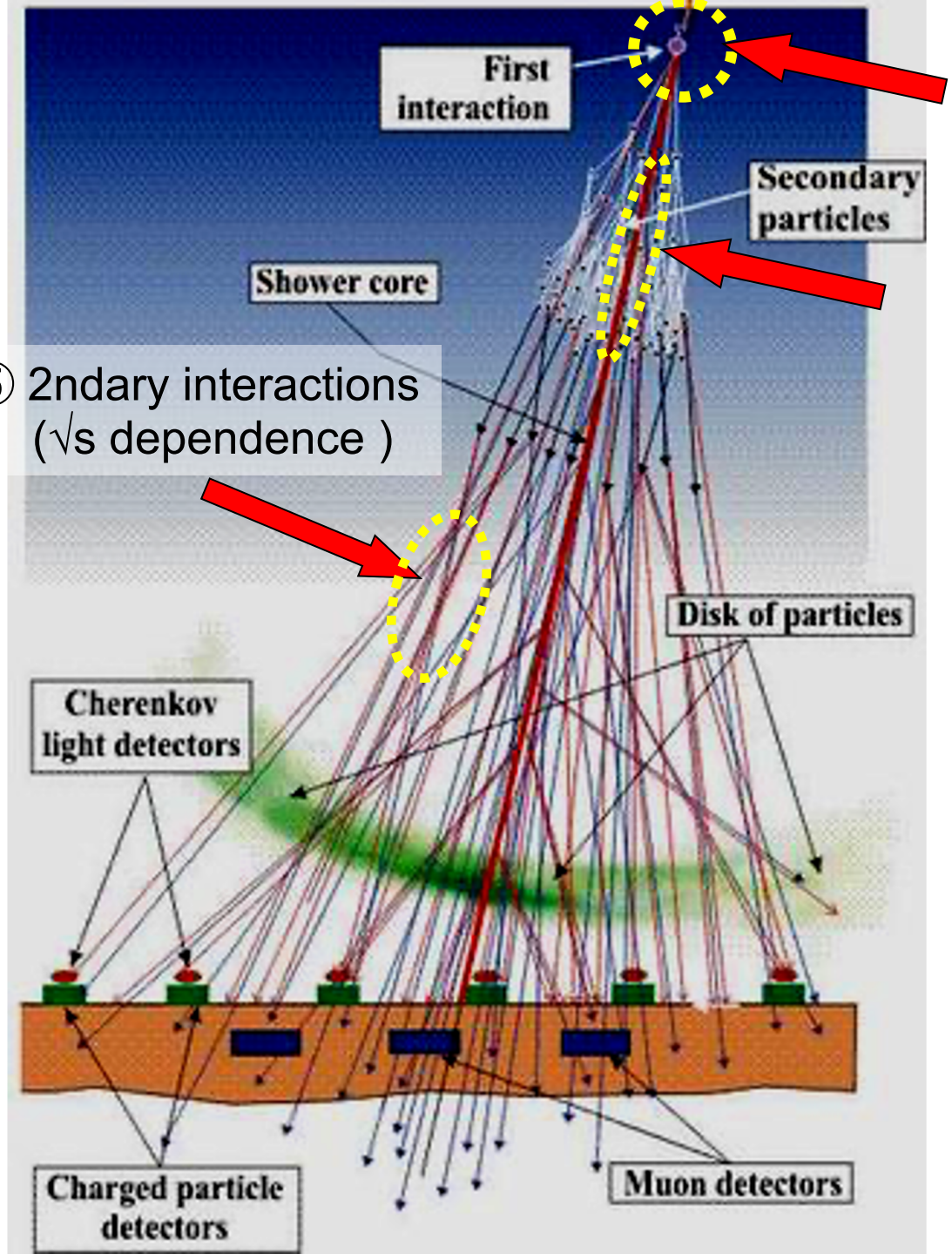
Nagoya University

Low-x 2021, 28 Sep 2021

Forward production and cosmic rays



- Air shower measurements of very high cosmic rays rely on hadronic interaction modeling.
- Need precise knowledge on minimum bias interactions, including forward productions
- They are high-energy and non-pQCD regime. Need collider data and a good phenomenological model.

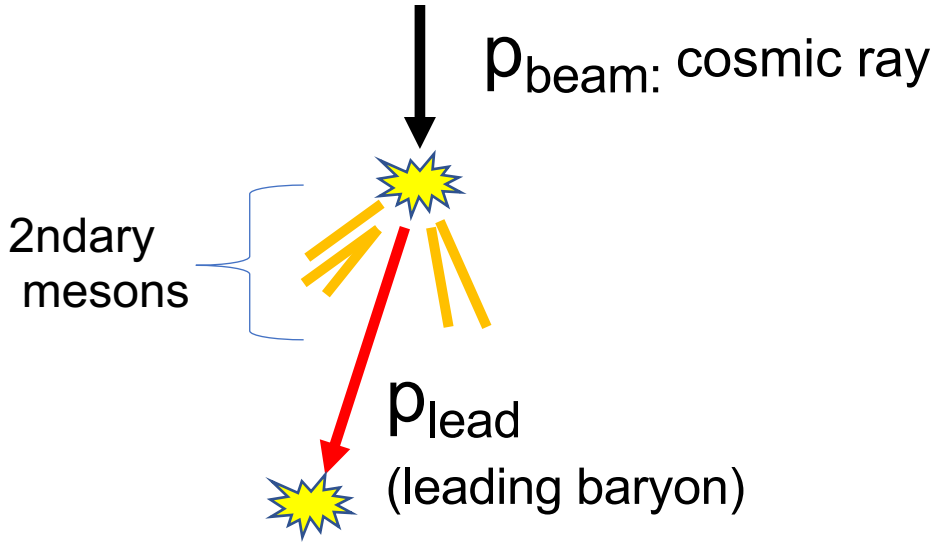


⑤ 2ndary interactions
(√s dependence)

① Inelastic cross section
(TOTEM and others)

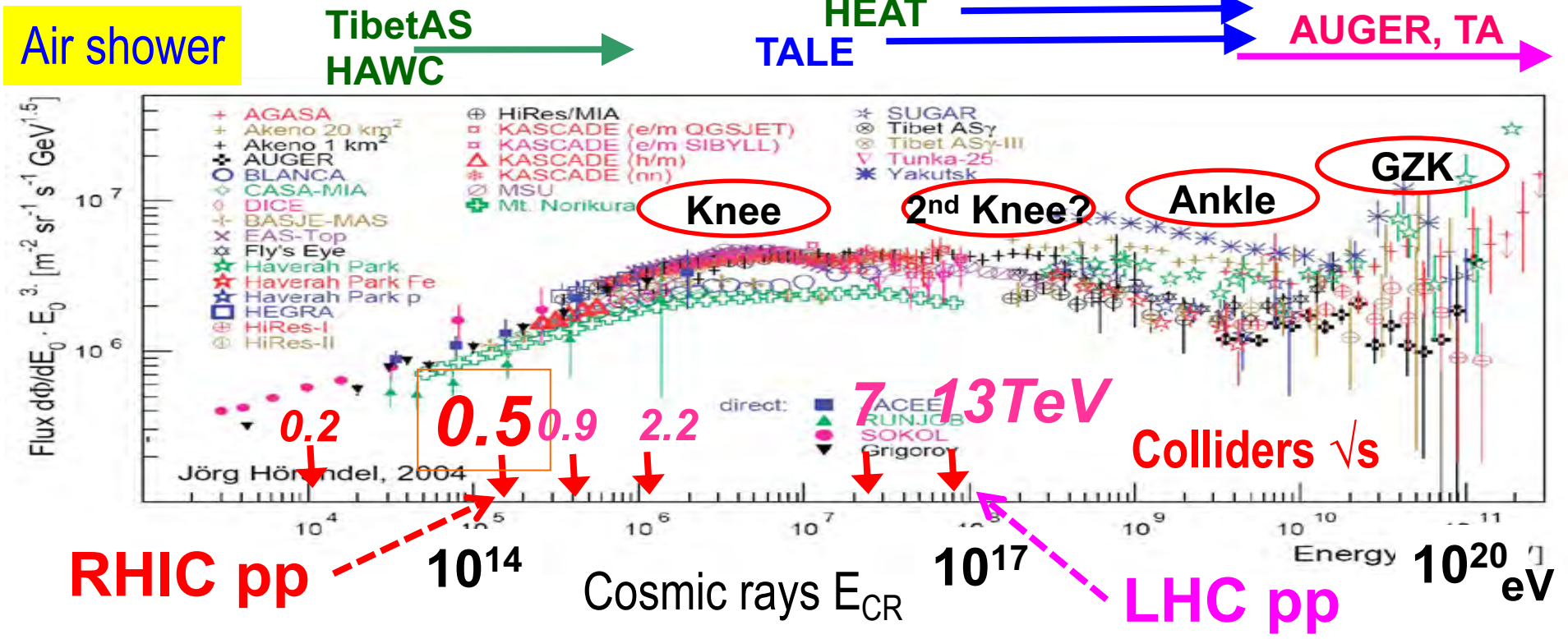
② Forward energy spectrum
(LHCf γ /π^0 spectrum)

③ Inelasticity k= 1-p_{lead}/p_{beam}
(LHCf forward neutron, n / γ ratio)



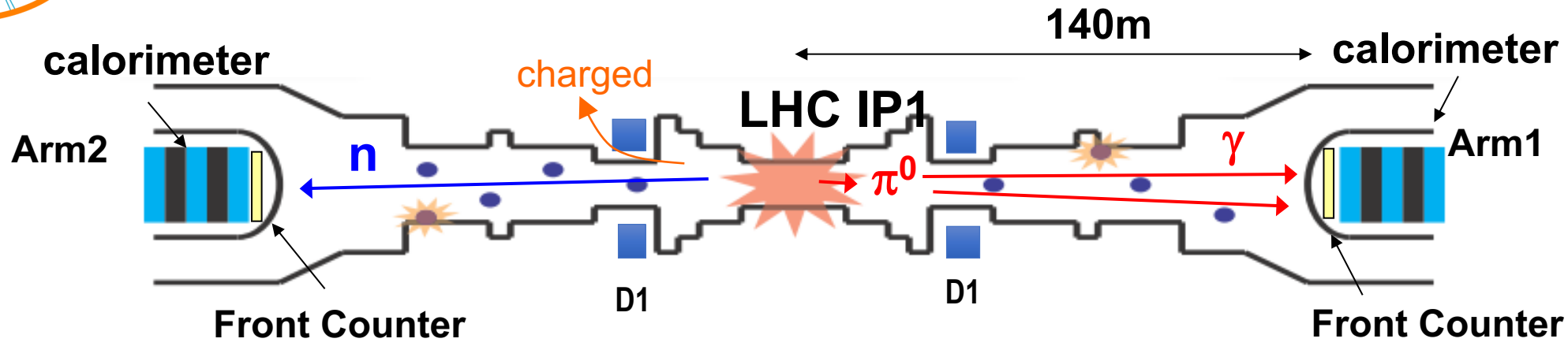
④ Nuclear effect
(shadowing, Cronin effect)

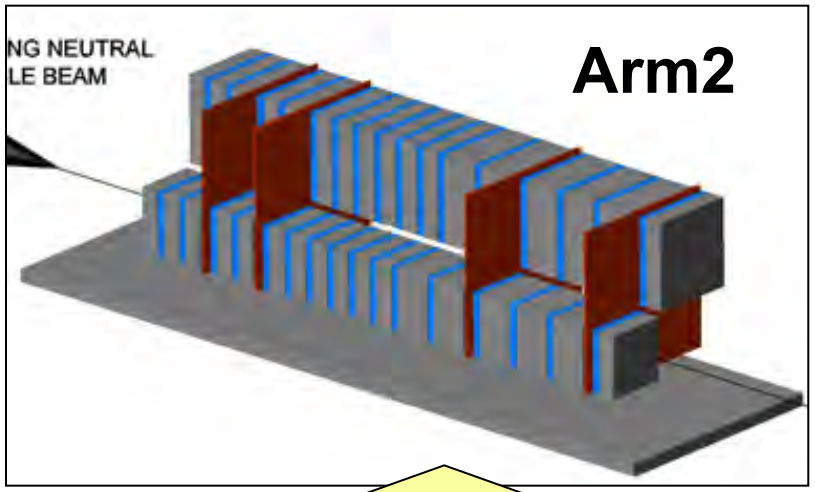
UHECR Interactions = Collider Energies



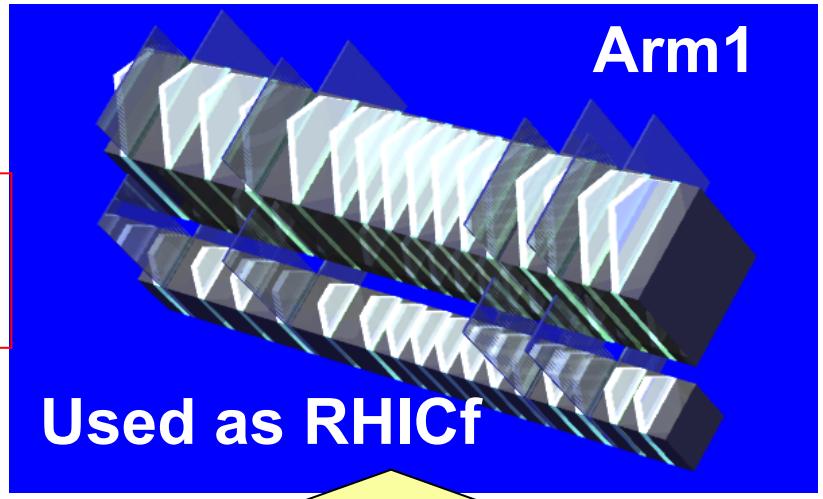
- Need dedicated very forward measurement at hadron colliders
- So far LHCf pp (13, 7, 2.76, 0.9 TeV) and p-Pb(5,8 TeV/n) available
- RHIC provies 0.5 TeV pol pp w/ same pT coverage as LHC
- RHIC also provides various p-A or A-A collisions

The LHCf experiment at LHC





$44X_0$,
$1.6\ \lambda_{int}$



16 tungsten + GSO scinti. layers
25x25mm(TS)+32x32mm (TL)
4 Silicon strip tracking layers

16 tungsten + GSO scinti. layers
20x20mm(TS)+40x40mm (TL)
4 GSO-bar tracking layers

The LHCf Collaboration

***,**Y.Itow, ***M.Kondo, *Y.Matsubara, *H.Menjo, *Y.Muraki, ***K.Ohashi,**

**Institute for Space-Earth Environmental Research, Nagoya University, Japan*
***Kobayashi-Maskawa Institute, Nagoya University, Japan*
****Graduate School of Science, Nagoya University, Japan*

T.Sako *ICRR, University of Tokyo, Japan*

K.Kasahara, K.Yoshida *Shibaura Institute of Technology, Japan*

S.Torii *Waseda University, Japan*

Y.Shimizu, T.Tamura, *Kanagawa University, Japan*

N.Sakurai *Tokushima University, Japan*

M.Haguenauer *Ecole Polytechnique, France*

W.C.Turner *LBNL, Berkeley, USA*

O.Adriani, E.Berti, L.Bonechi, M.Bongi, G.Castellini, R.D'Alessandro, P.Papini, S.Ricciarini, A.Tiberio

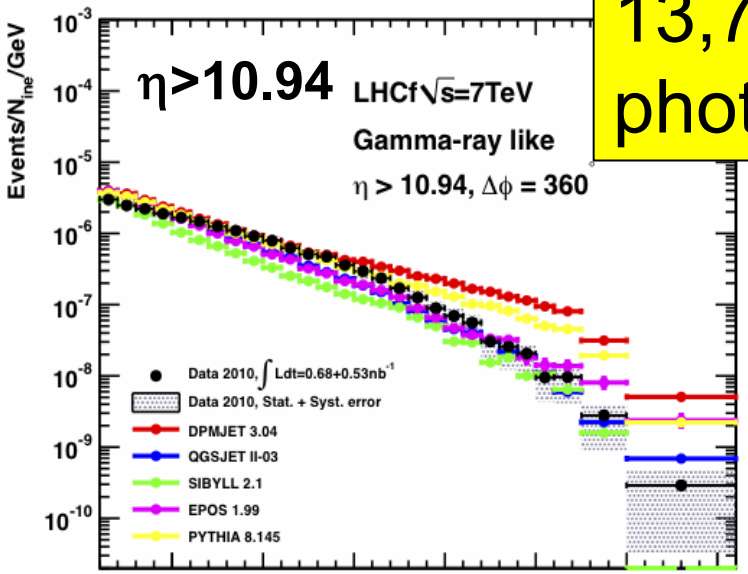
INFN, Univ. di Firenze, Italy

A.Tricomi *INFN, Univ. di Catania, Italy*

LHCf results and publication

Run	E_{lab} (eV)	Photon	Neutron	π^0		ATLAS-LHCf combined
p-p $\sqrt{s}$=0.9TeV (2009/2010)	4.3×10^{14}	PLB 715, 298 (2012)		-		
p-p $\sqrt{s}$=2.76TeV (2013)	4.1×10^{15}			PRC 86, 065209 (2014)	PRD 94 032007 (2016)	
p-p $\sqrt{s}$=7TeV (2010)	2.6×10^{16}	PLB 703, 128 (2011)	PLB 750, 360 (2015)	PRD 86, 092001 (2012)		
p-p $\sqrt{s}$=13TeV (2015)	9.0×10^{16}	PLB 780, 233 (2018)	JHEP 1811, 73 (2018) JHEP 07, 016 (2020)	preliminary		ATLAS-CONF-2017-075, paper in preparation
p-Pb $\sqrt{s_{NN}}$=5TeV (2013,2016)	1.4×10^{16}			PRC 86, 065209 (2014)		
p-Pb $\sqrt{s_{NN}}$=8TeV (2016)	3.6×10^{16}	Preliminary				
RHICf p↑ - p $\sqrt{s}$=510GeV (2017)	1.4×10^{14}	on-going		(Transverse asymmetry) PRL 124, 252501(2021)		

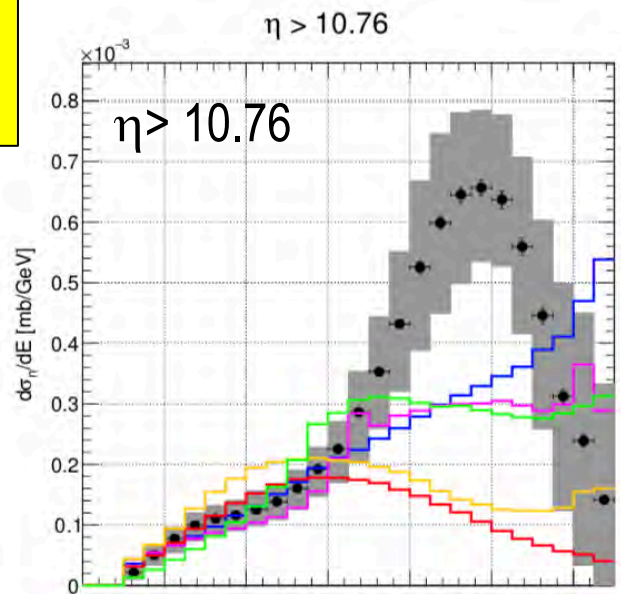
13,7 & 0.9 TeV pp photon

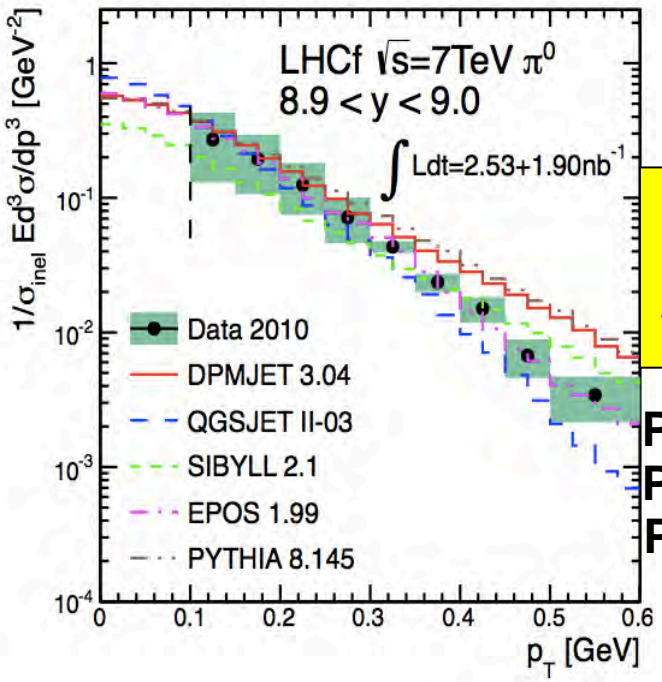


PLB 703 (2011) 128
PLB 715 (2012) 298
PLB 780 (2018) 233

13&7TeV pp neutron

PLB 750 (2015) 360
JHEP 11 (2018) 073
JHEP 07 (2020) 016



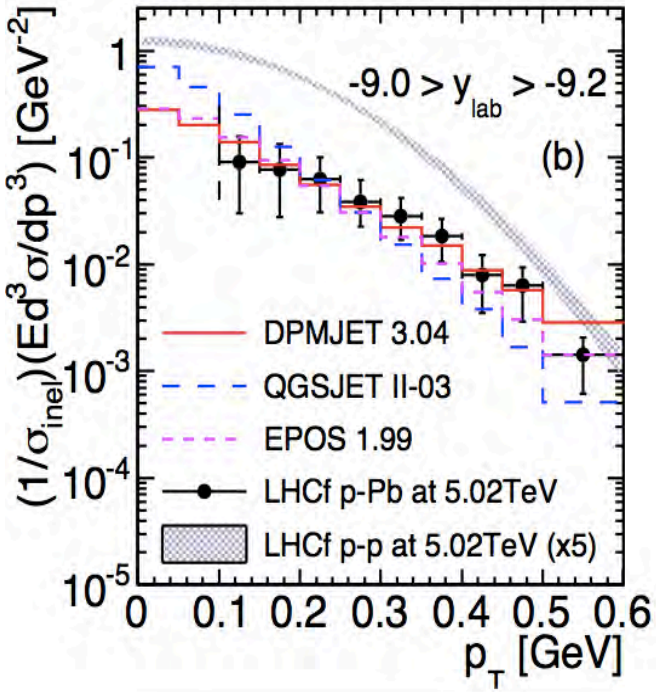


7&2.76 TeV pp π^0

PRD 86 (2012) 092001
PRC 86 (2014) 065209
PRD 94 (2016) 032007

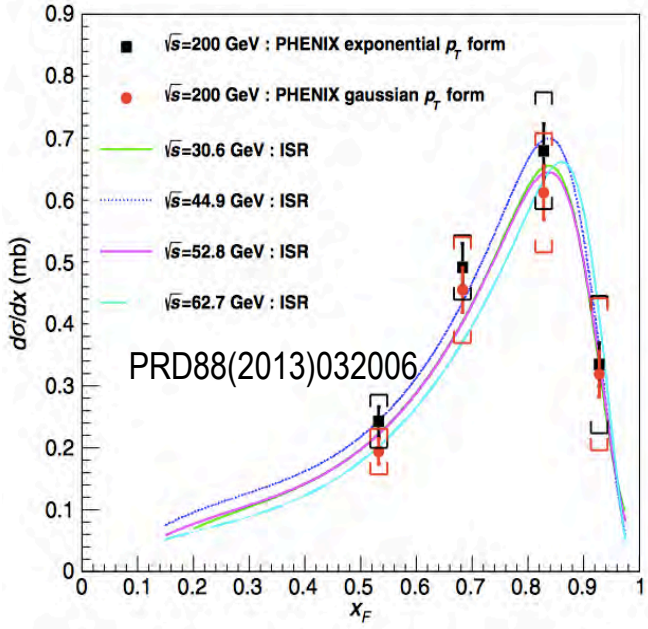
5TeV pPb π^0

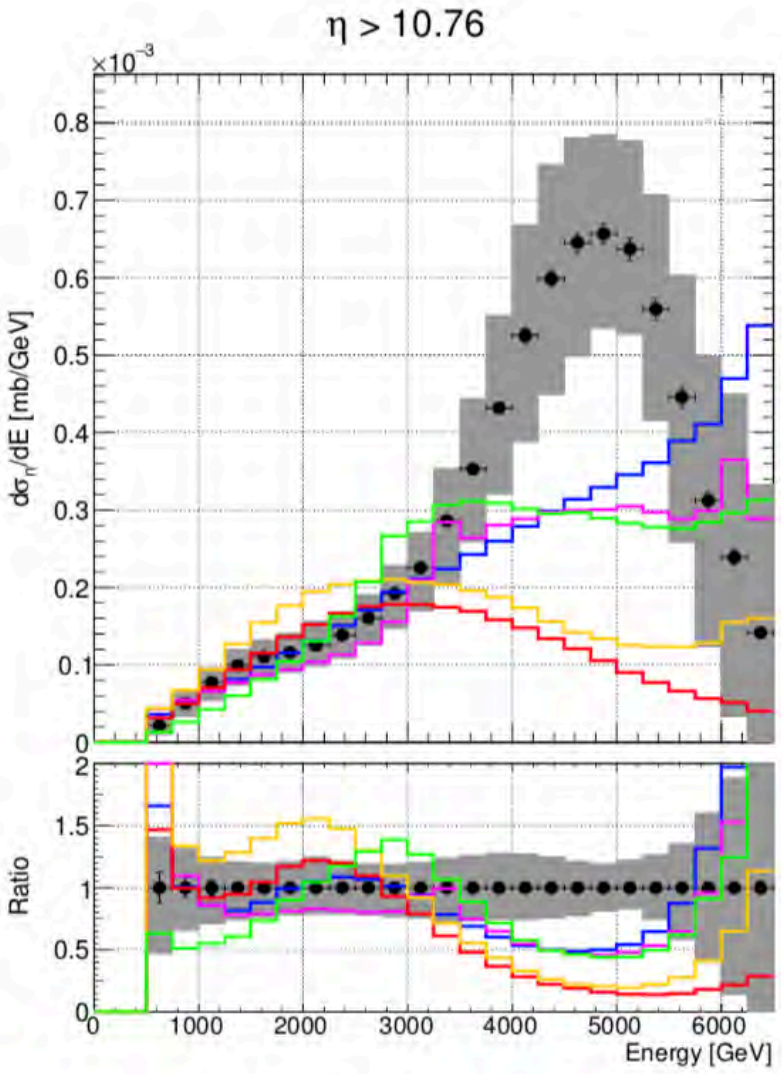
PRC 89 (2014) 065209

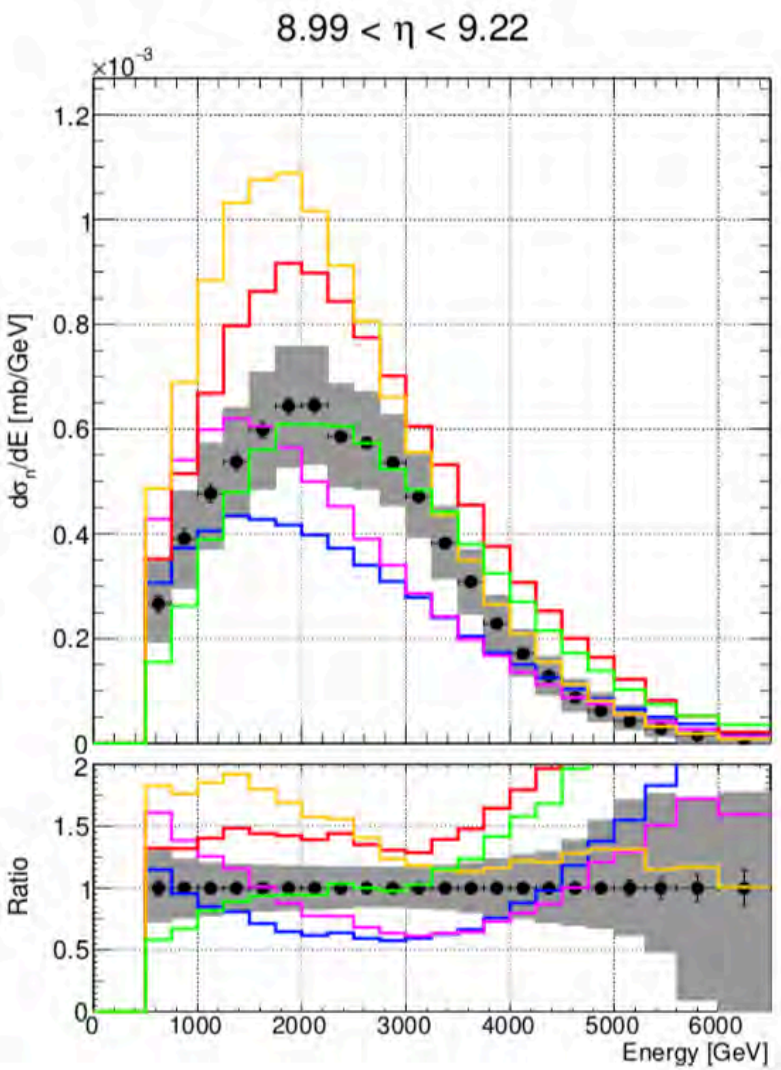


Very forward neutron production at 13 TeV

JHEP 11 (2018) 073



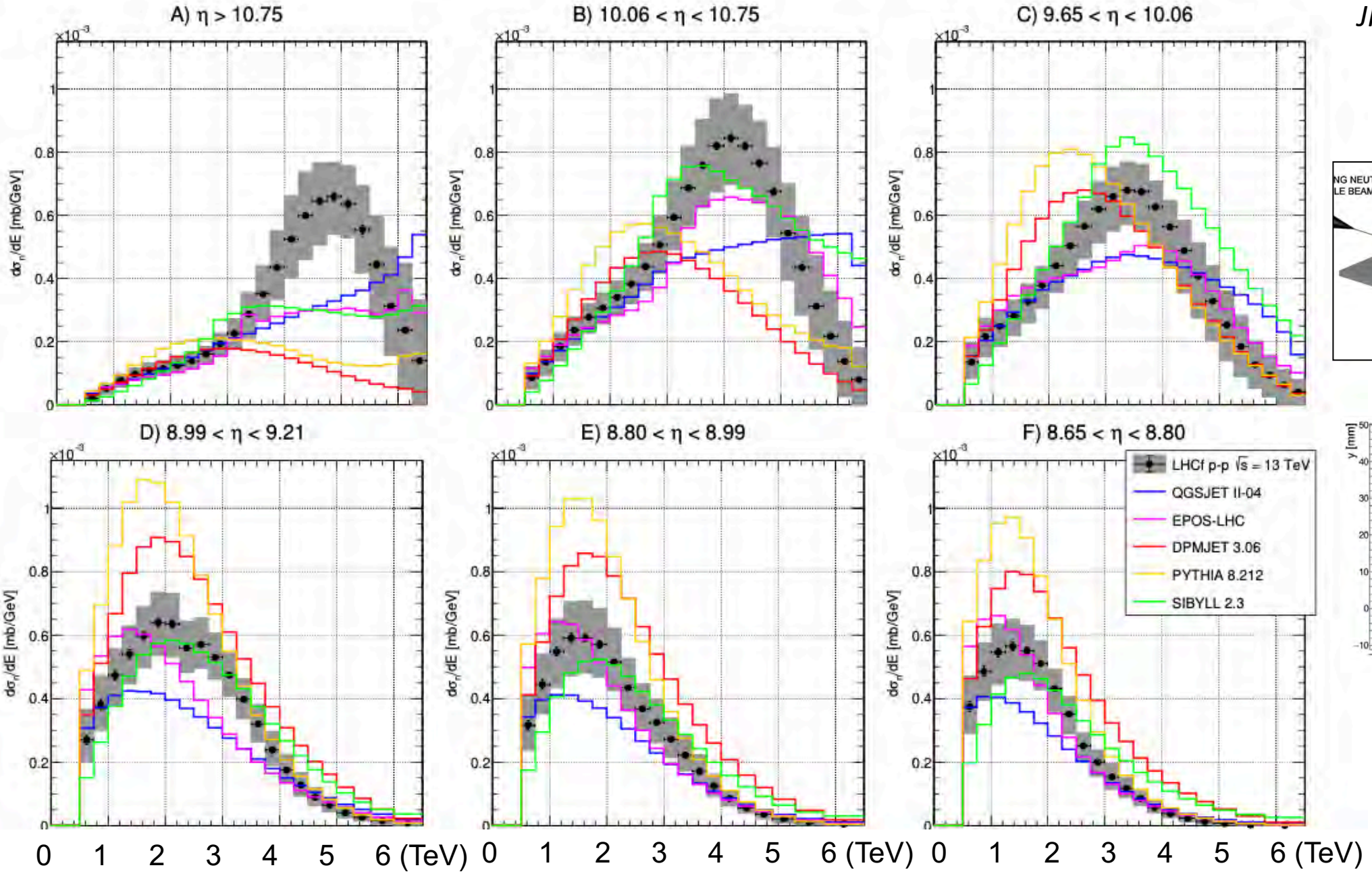


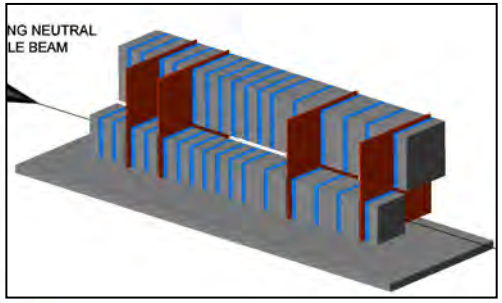


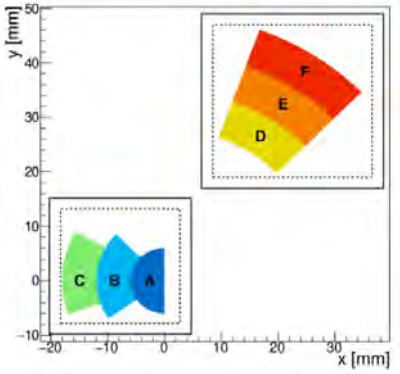
- Large excess in data than any other models at 0-degree (η >10.76)
- XF scaling ? comparison with ISR, PHENIX

More detail neutron spectra vs η in 13 TeV pp

JHEP 07 (2020) 016





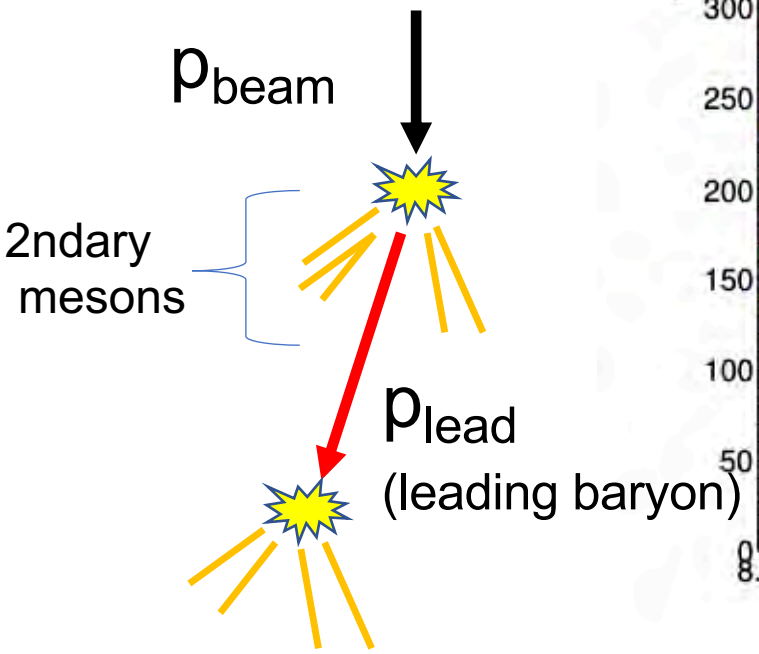


Inelasticity measurement by leading-neutrons

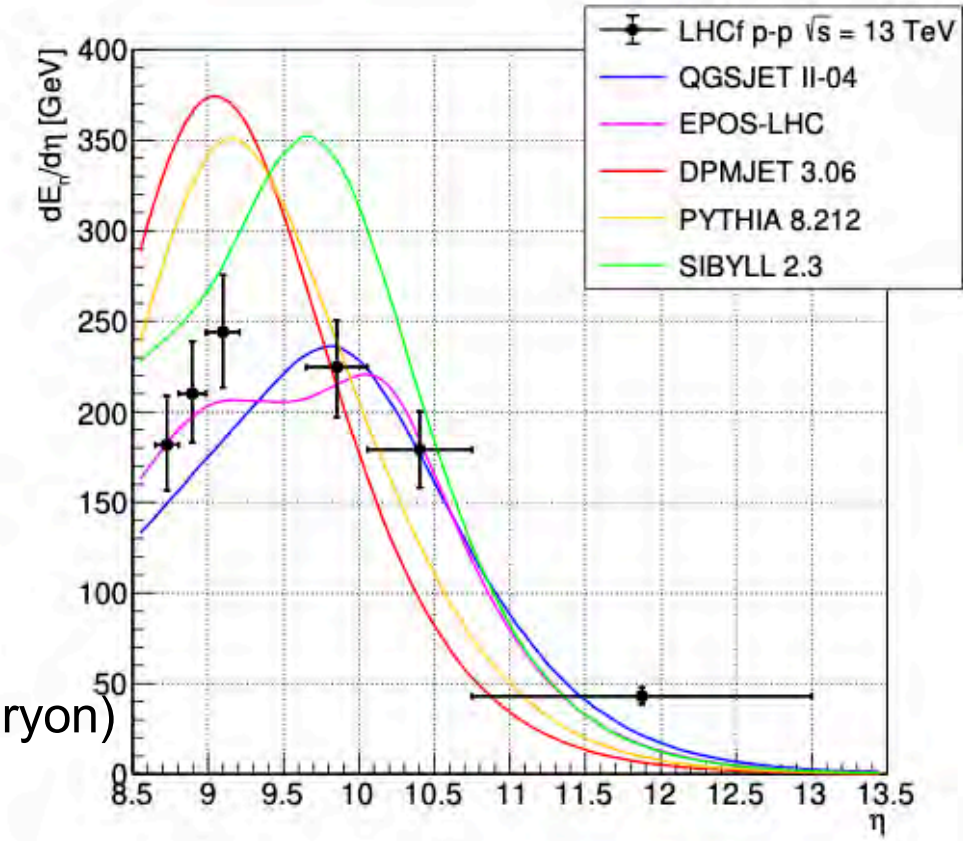
JHEP 07 (2020) 016

Inelasticity

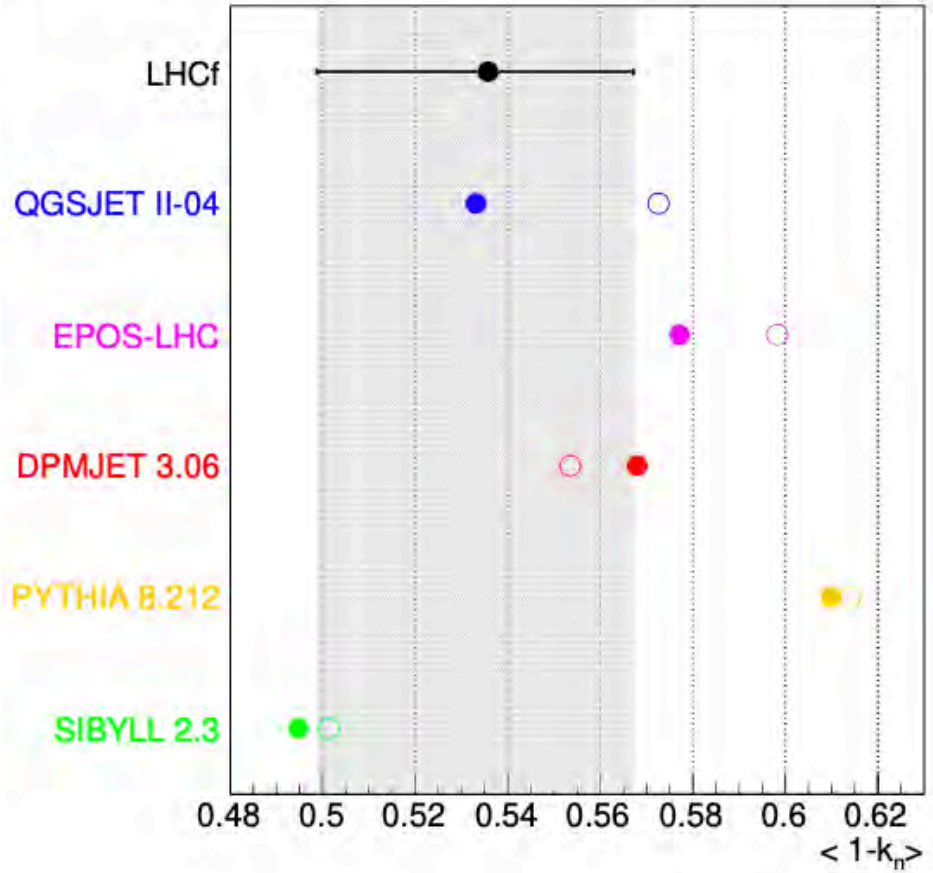
$k = 1 - p_{lead}/p_{beam}$



Neutron energy flow vs η



Inelasticity k

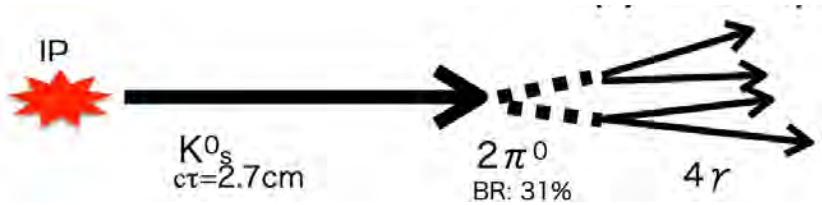


closed circles show the events where a neutron is leading

Prospects at LHC Run3

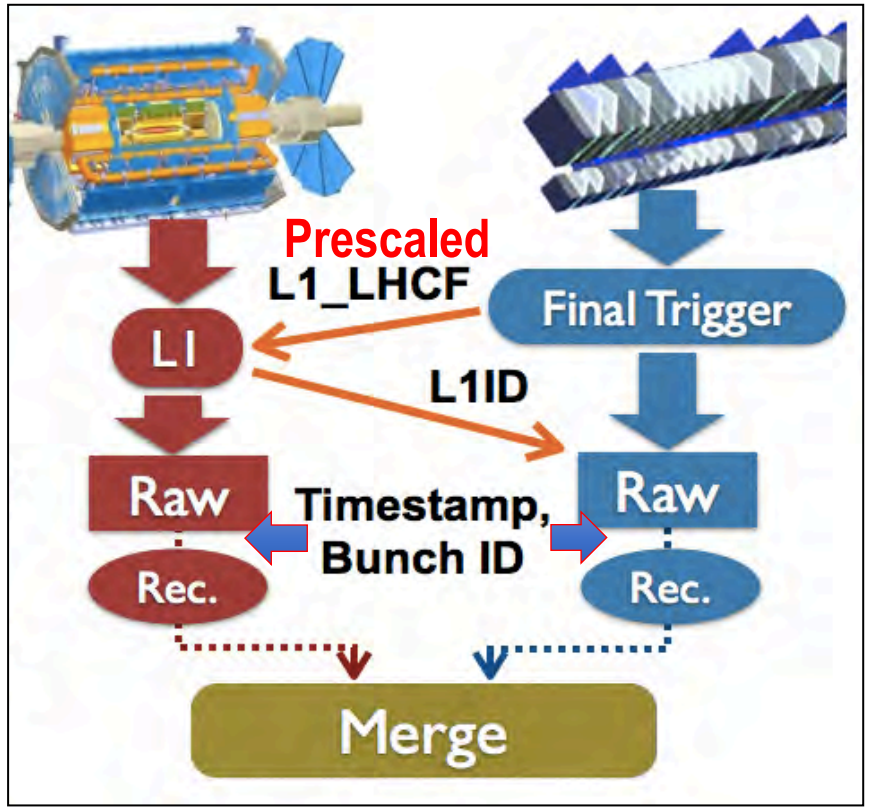
LHCf ~14 TeV pp run at Run3

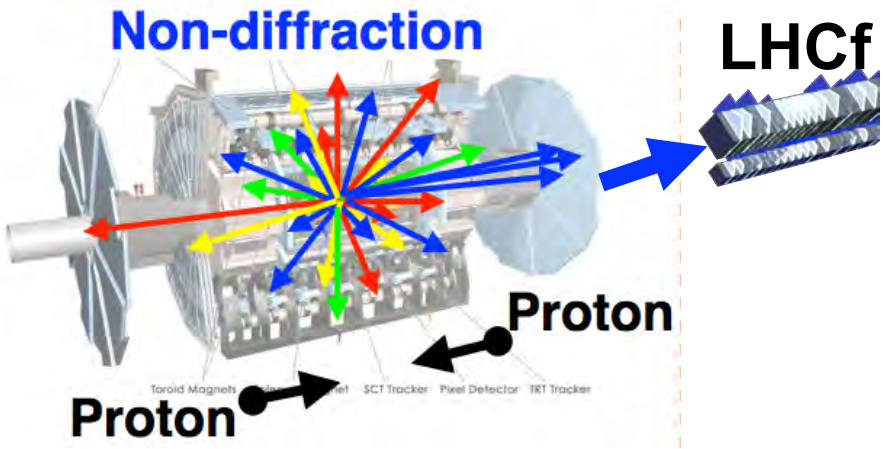
- High statistics with improved trigger and new Si electronics
  - 2 days dedicated run after TS1 w/ ~10^{30}cm^{2}s^{-1} (x10), giving 40nb^{-1}
  - Precise π^0 / η spectra, very forward strangeness (K^0_s, Λ…)

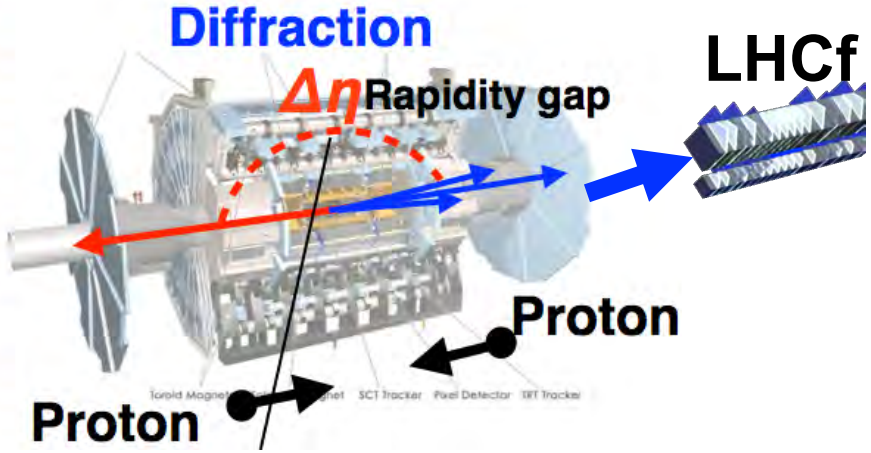


- Trigger exchange with ATLAS
  - Correlation analysis with central rapidity data
  - Possible joint data-taking w/ ATLAS-ZDC and Roman Pot
  - Measurement of p-πcoupling at very high energy

ATLAS-LHCf trigger exchange





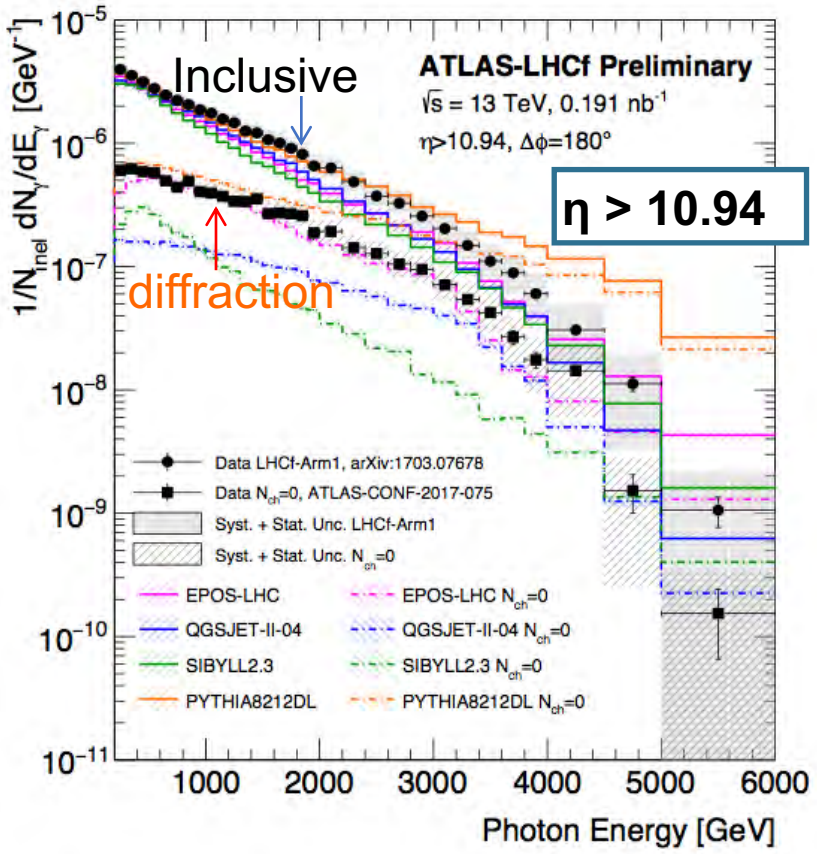


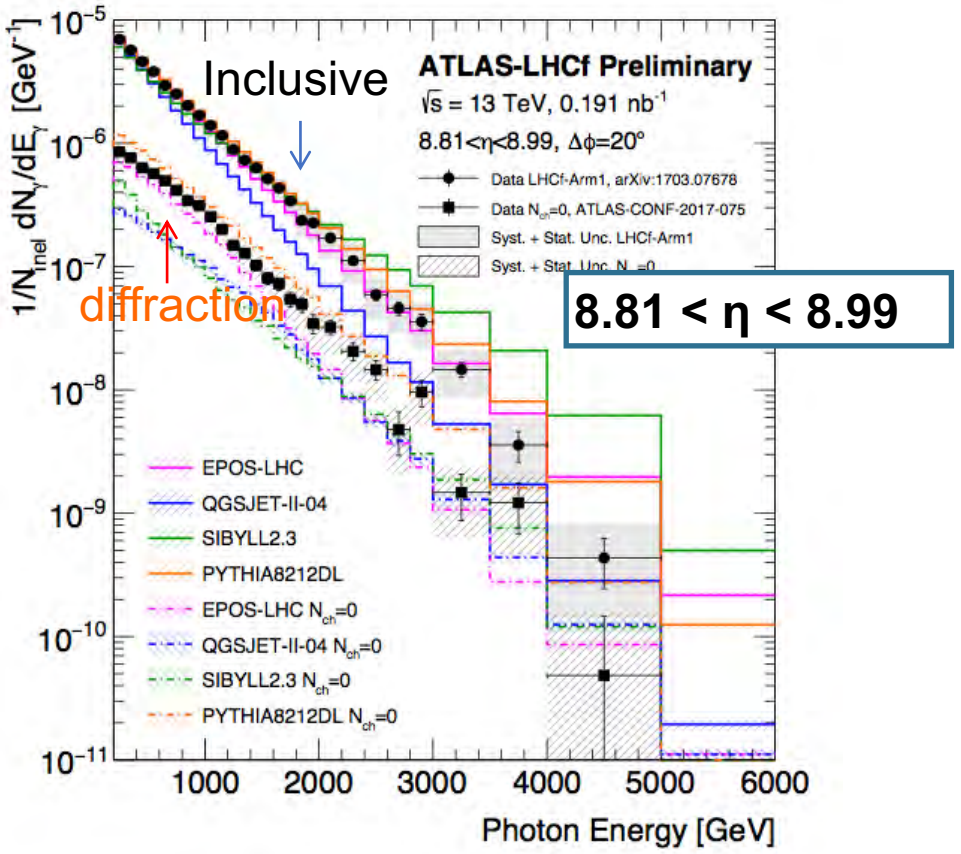
Powerful tool to study diffraction/non-diffraction separately

Very forward photon from diffraction at 13TeV

ATLAS-CONF-2017-075

- ATLAS-LHCf common data at 13TeV pp
- Rapidity gap events selected as diffraction

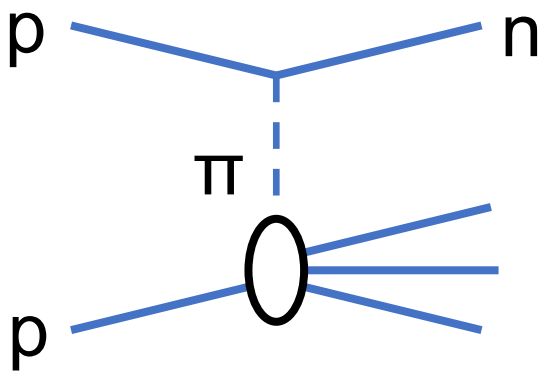


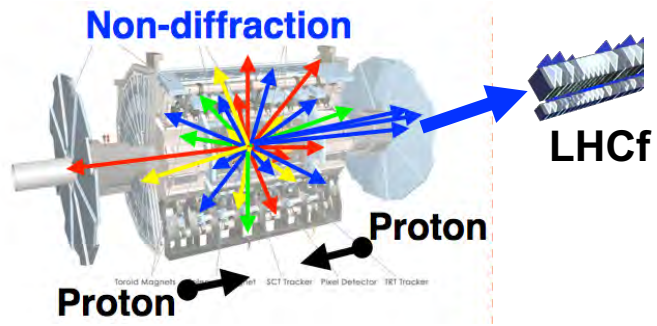


Some of cosmic ray interaction models need large modification
(Both diffraction and non-diffraction)

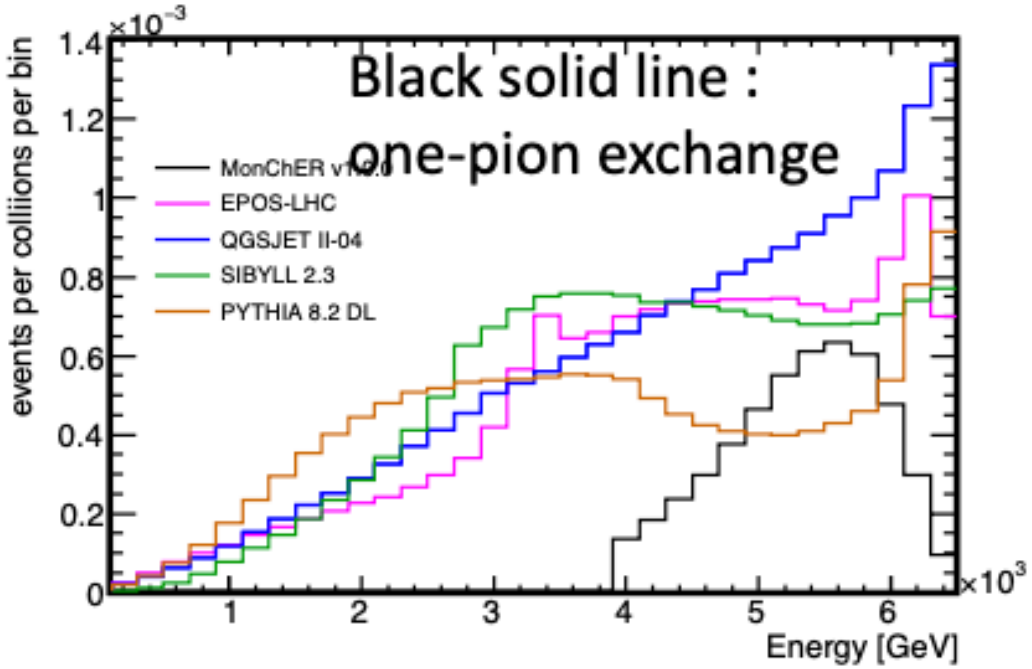
Tagging one-π-exchange in very forward neutrons

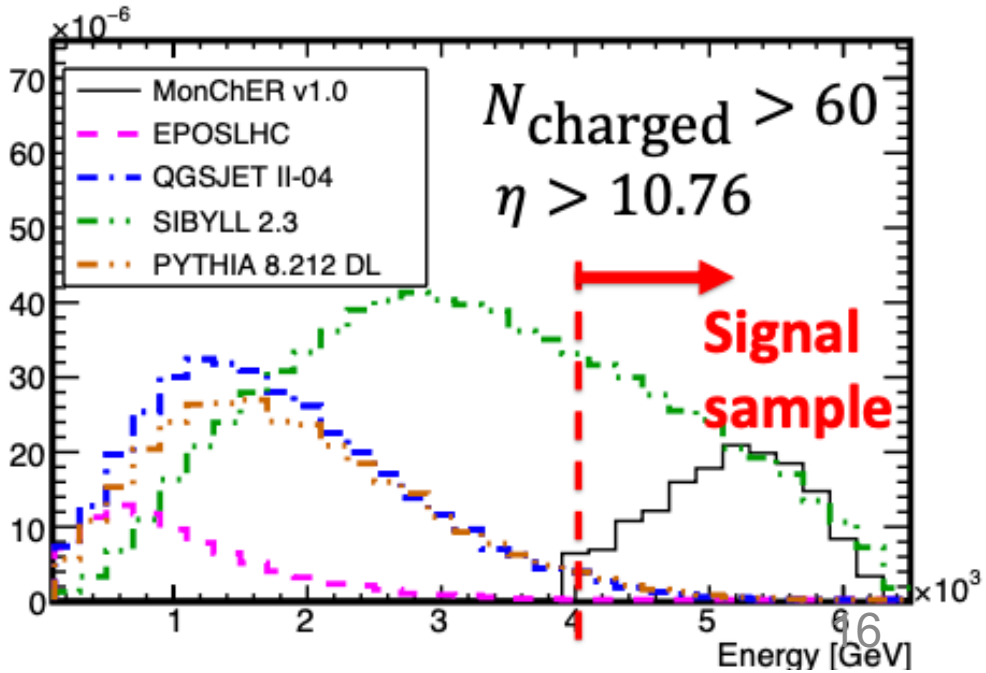
K.Ohashi et al.,
POS(ICRC2021)190





- Using pp→ npX, πp coupling can be measured at LHC
- Signals in high X_F neutrons in very forward
- To differentiate from diffraction, high N_{ch} in central rapidity is selected



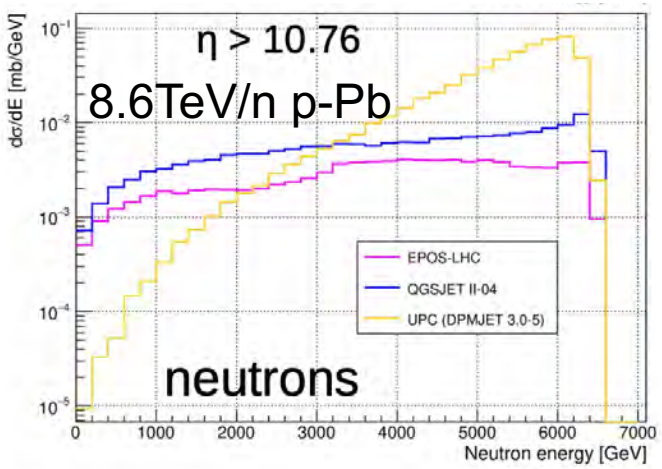


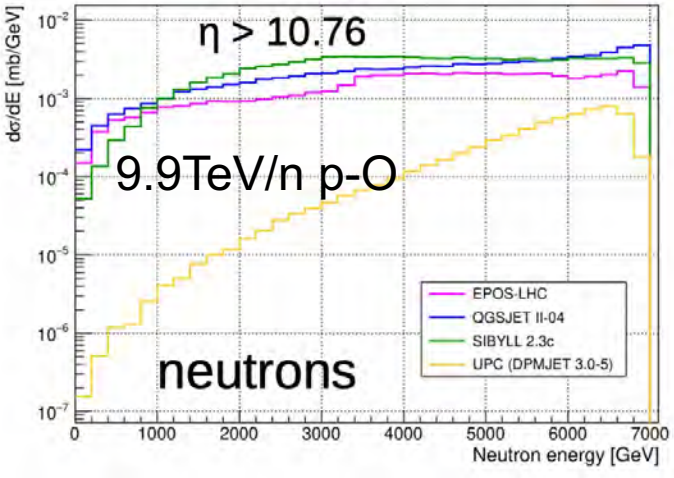
"LHC as πp (ππ) collider" Petrov, Ryutin, Sobol, Eur.Phys.J. C (2010) 65:637

Future p-O (and O-O) runs at LHC

Now p-O (O-O) runs are officially considered for 2022 or 2023.

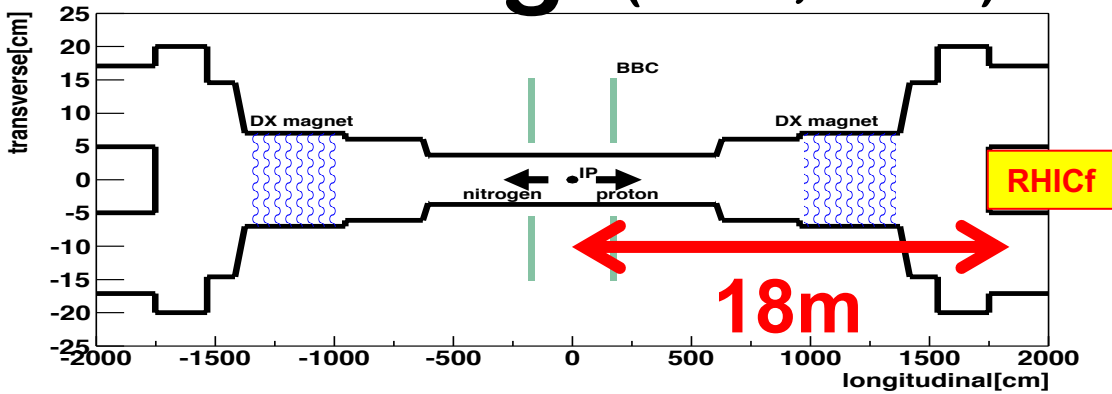
- p-O (N) run at LHC gives ideal check of air shower physics
  - LHCf p-Pb data available but w/ large UPC BG (air atoms are ionized !)
  - After Run-4, LHCf will be no longer available (due to new beam-pipes)
- Intensive discussions in “OppOrtunities” workshop (4-10Feb2021)
  - https://indico.cern.ch/event/975877/overview
- Detail run plan is under discussion
  - Desirable for LHCf, L=10^{28}cm^{2}s^{-1}, 43-bunches





RHICf: LHCf-Arm1 @RHIC-STAR 0deg (June, 2017)

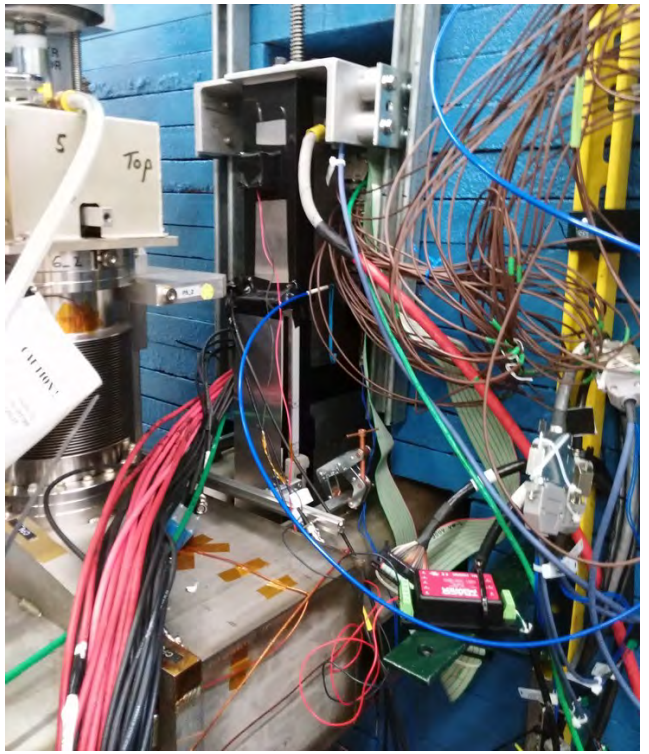
- $\sqrt{s}$=510 GeV p+p (= E_{lab} ~10^{14} eV)
- Similar p_T coverage of LHCf 7 TeV pp
- Radial polarization to maximize the single-spin asymmetry in vertical
- Luminosity~10^{31} $cm^{-2}s^{-1}$, w/ 10GeV threshold



The RHICf collaboration

Y.Itow[ab], H.Menjo[a], K.Sato[a], M.Ueno[a], Q.D.Zhou[a], T.Sako[c], Y.Goto[d], I.Nakagawa[d], R.Saidl[d], K.Tanida[e], K.Kasahara[f], T.Suzuki[f], S.Torii[f], N.Sakurai[g], J.S.Park[h], M.H.Kim[i], B.Hong[i], O.Adriani[j], E.Berti[j], L.Bonechi[j], R.D'Alessandro[j], A.Tricomi[k]

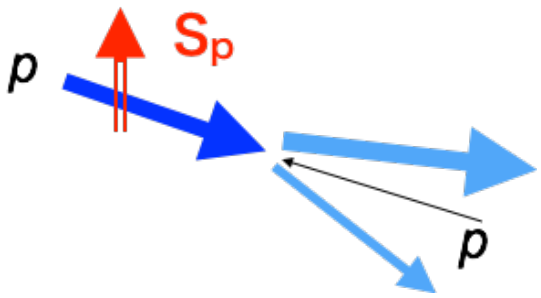
a) Institute for Space-Earth Environmental Research, Nagoya University,
b) Kobayashi-Maskawa Institute, Nagoya University,
c) ICRR, University of Tokyo,
d) Riken/Riken BNL Research Center,
e) JAEA,
f) Waseda University,
g) Tokushima University,
h) Seoul National University,
i) Korea University,
j) INFN, University of Florence,
k) INFN, University of Catania



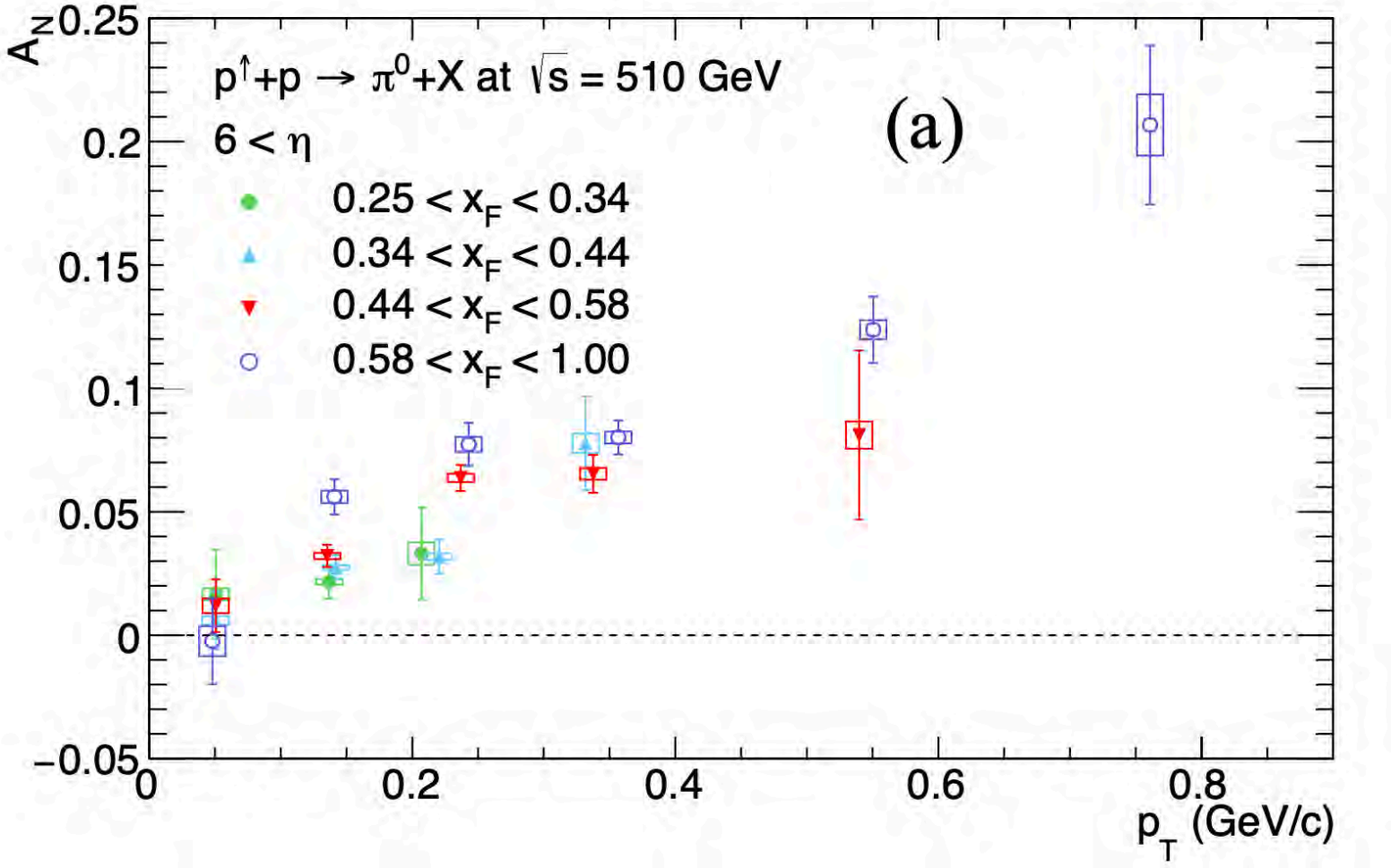
RHICf-II : A new W+Si pad&pixel calorimeter with ALICE FoCAL technology is being discussed

RHICf observed large A_N in very forward π^0

PRL 124, 252501(2021)



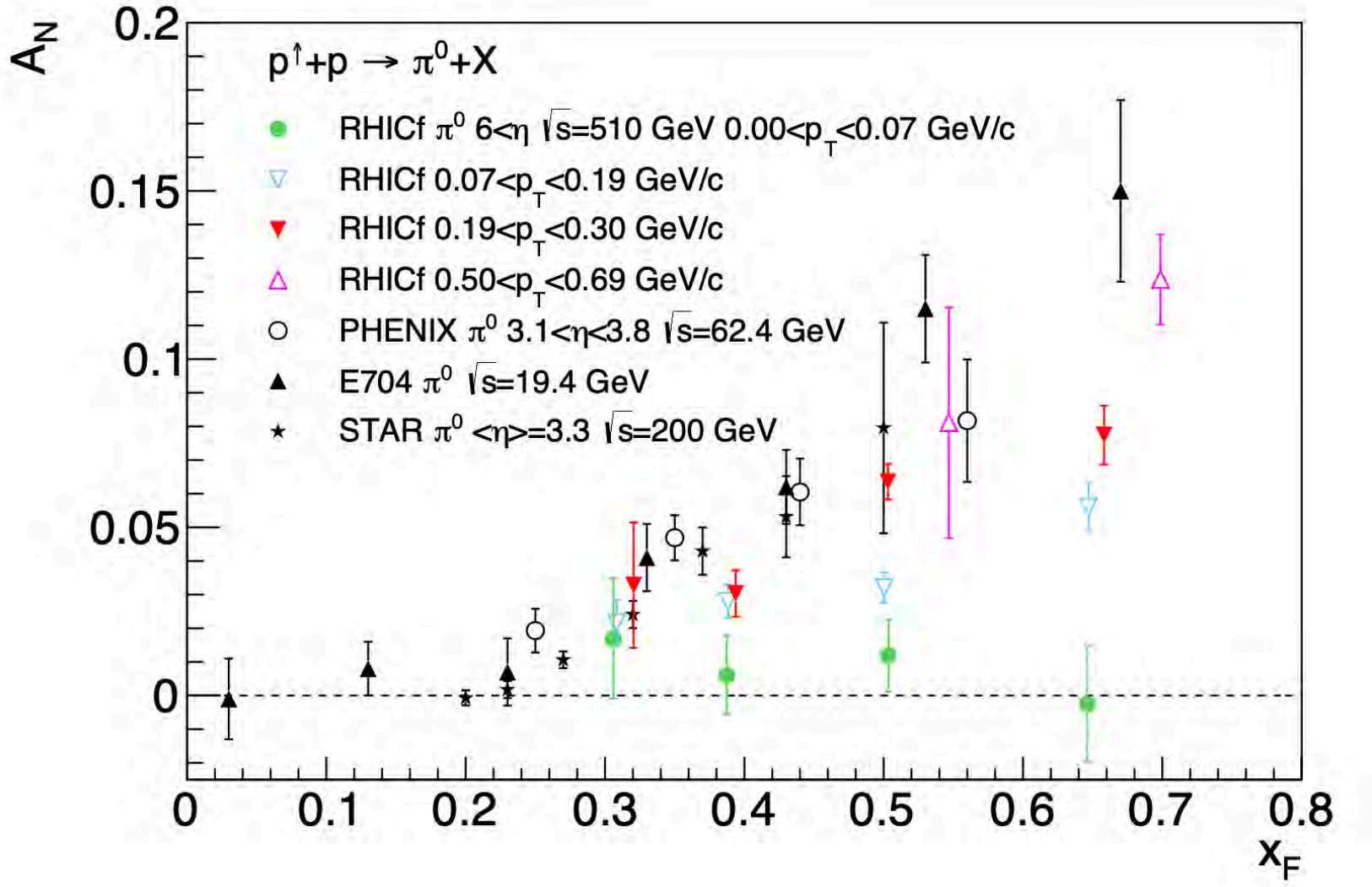
$$A_N = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



A_N observed at very forward (η>6) in low (<1GeV/c) first time

Perhaps Reggeon exchange origin ?

Comparison of A_N in different $\sqrt{s}$ and η



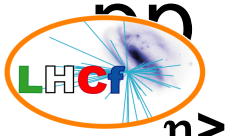
Maybe previously reported A_N vs X_F show similar tendency with RHICf data ?

Summary

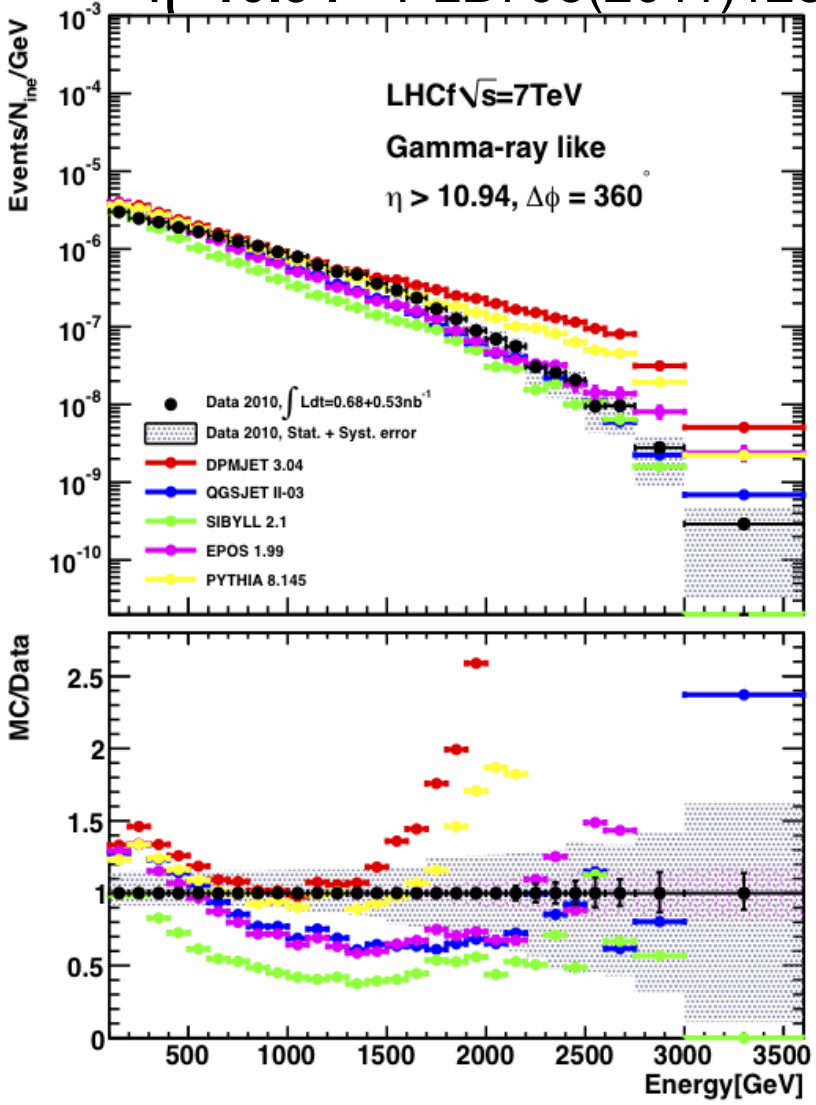
- LHCf measures neutral particles produced in 0-deg. of LHC, dedicated to study VHE cosmic ray interactions.
- Analysis on-going for 13 TeV pp data. Detail very forward neutron spectra and inelasticity measured.
- A new LHCf run scheduled in LHC Run-3 2022. High statistics pp run for π^0 ,η, K^0, Λ measurements.
- ATLAS-LHCf joint operation useful to tag diffraction / 1π-exchange. Combing ZDC will improve E_{had} resolution.
- LHC p-O (O-O) run under discussion, foreseen in 2022 or 2023.
- RHICf found unexpectedly large π^0 AN in very forward.

Backup

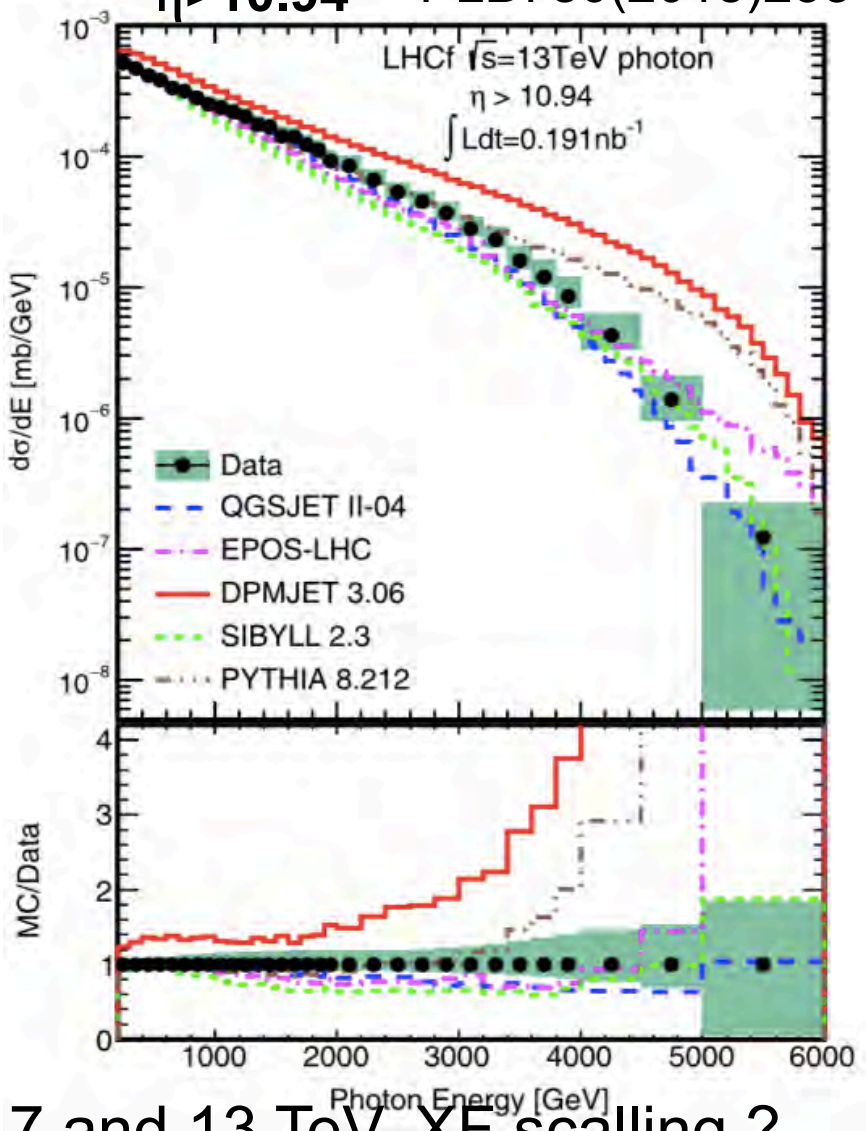
Very forward photon spectra at 7/13 TeV pp



η>10.94 PLB703(2011)128



η>10.94 PLB780(2018)233

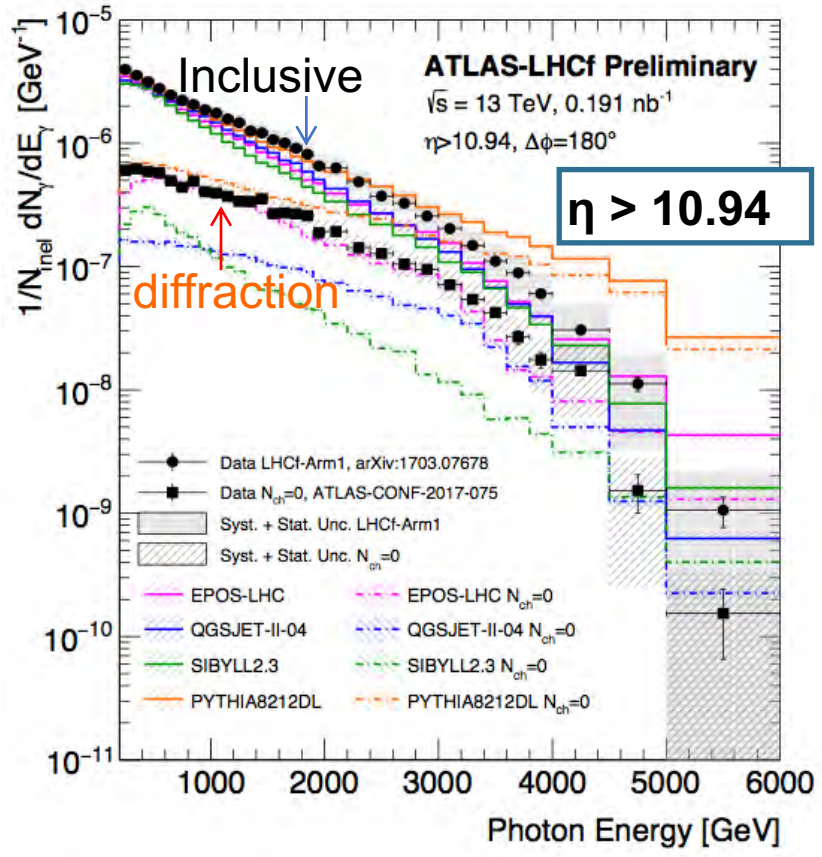


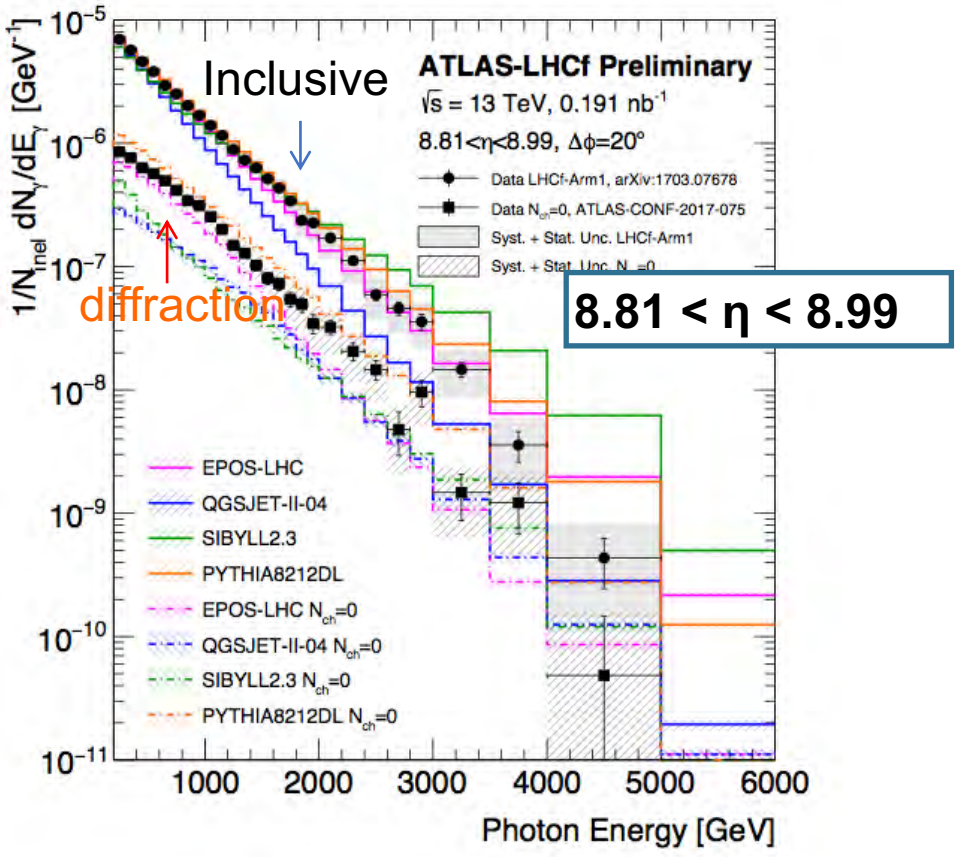
- Basically they look same btw 7 and 13 TeV. XF scalling ?

Very forward photon from diffraction at 13TeV

- ATLAS-LHCf common data at 13TeV pp
- Rapidity gap events selected as diffraction

ATLAS-CONF-2017-075





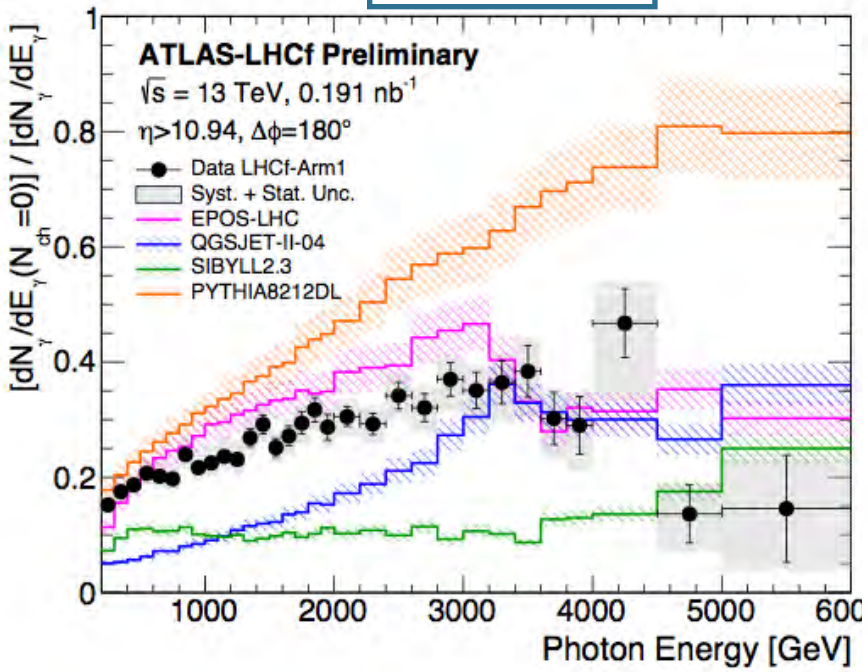
Some of cosmic ray interaction models need large modification
(Both diffraction and non-diffraction)

Very forward photon: diffraction/total

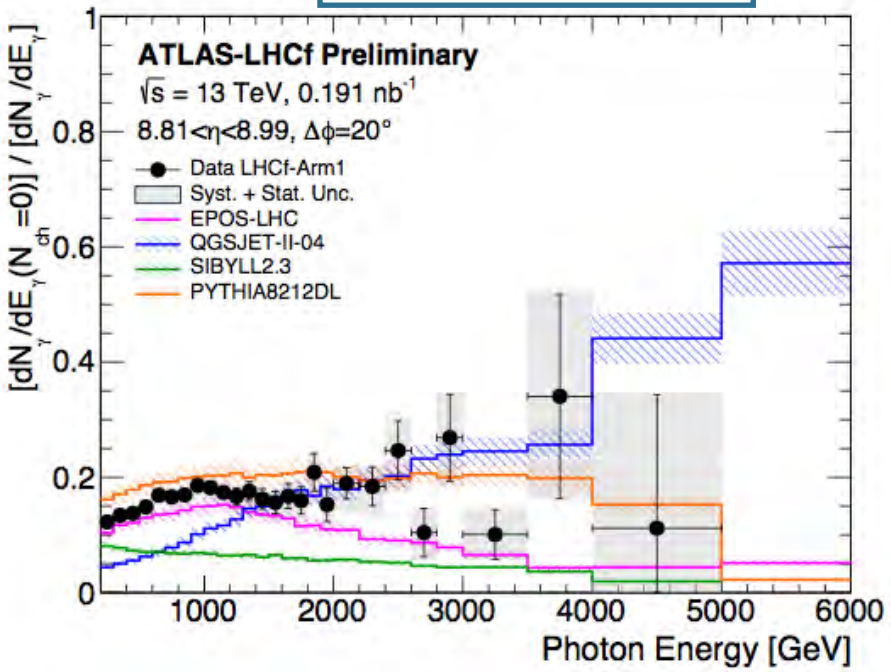
Ratio ($N_{ch=0}$/Inclusive)

ATLAS-CONF-2017-075

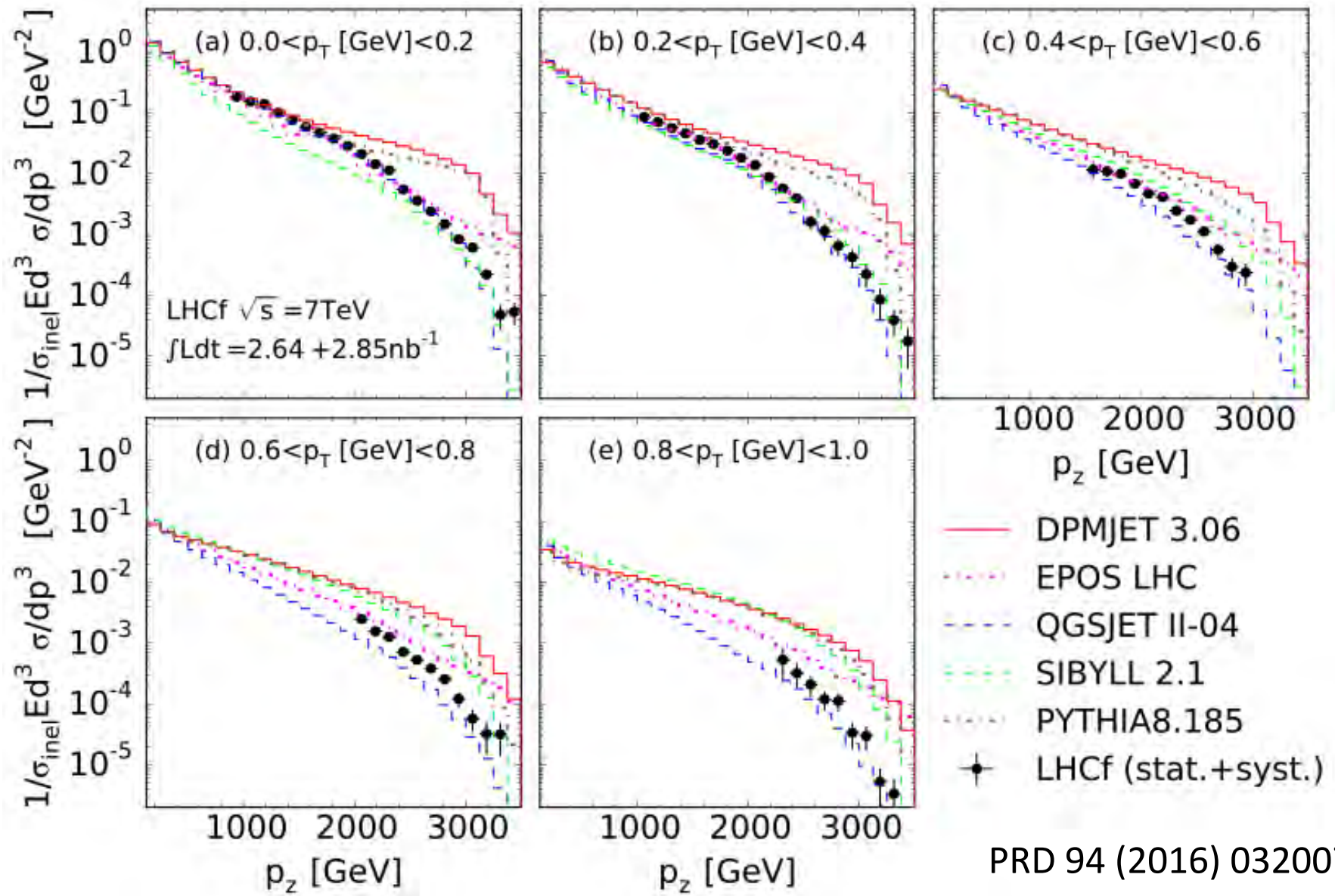
η > 10.94



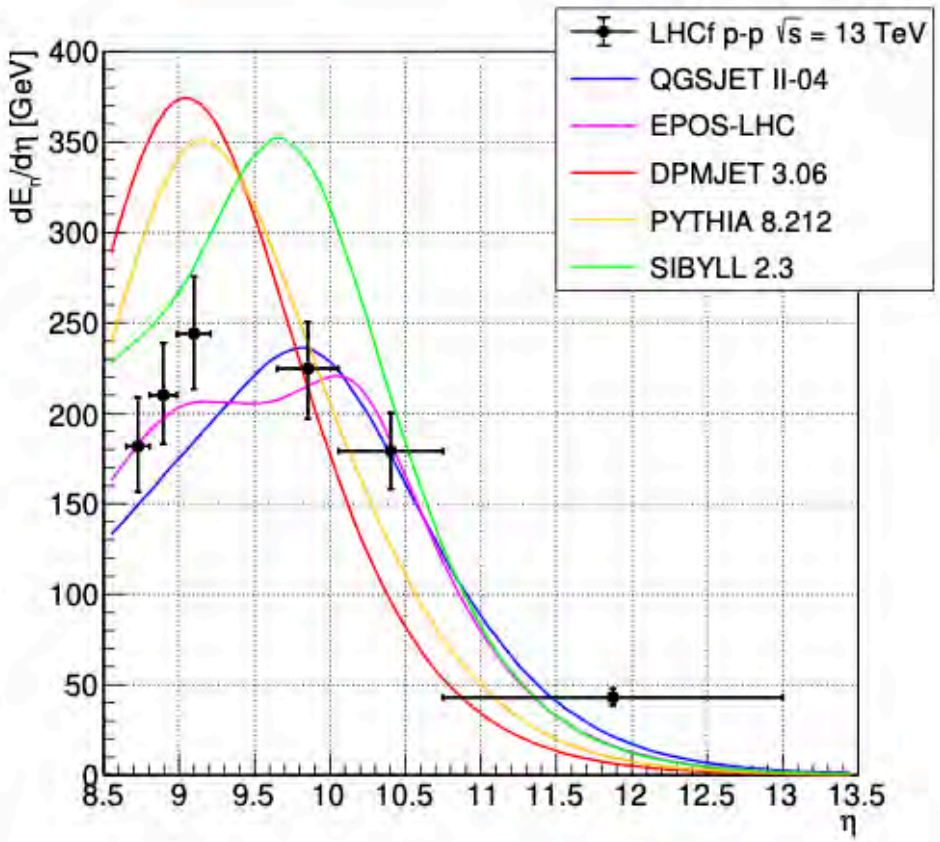
8.81 < η < 8.99

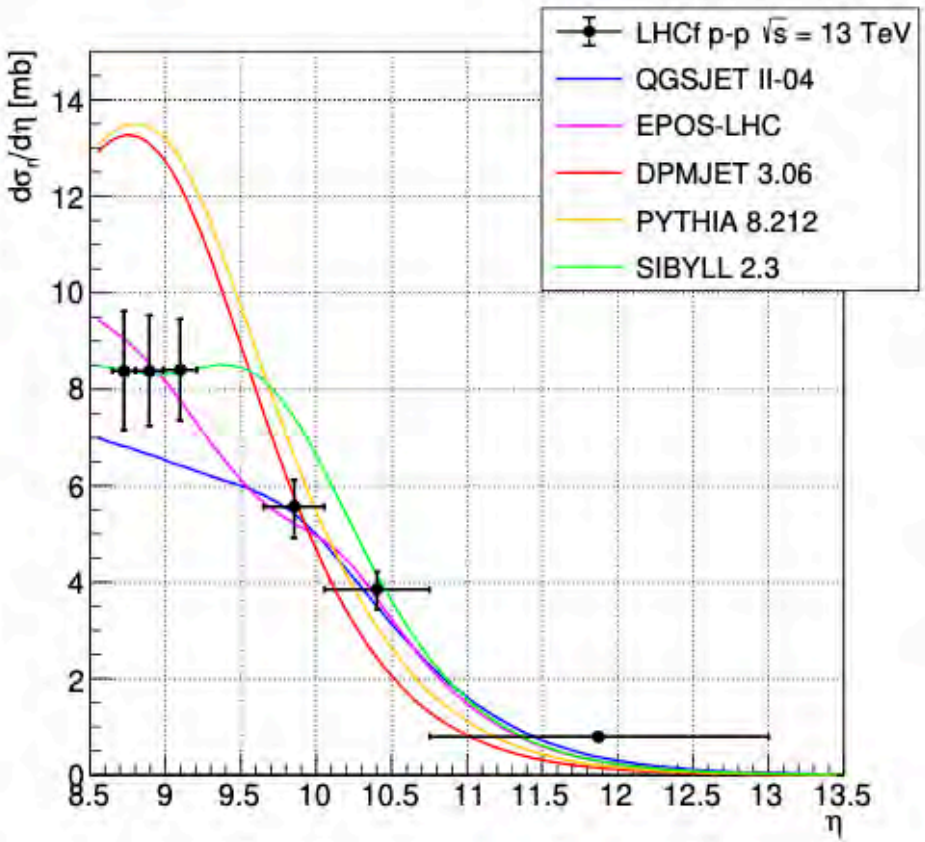


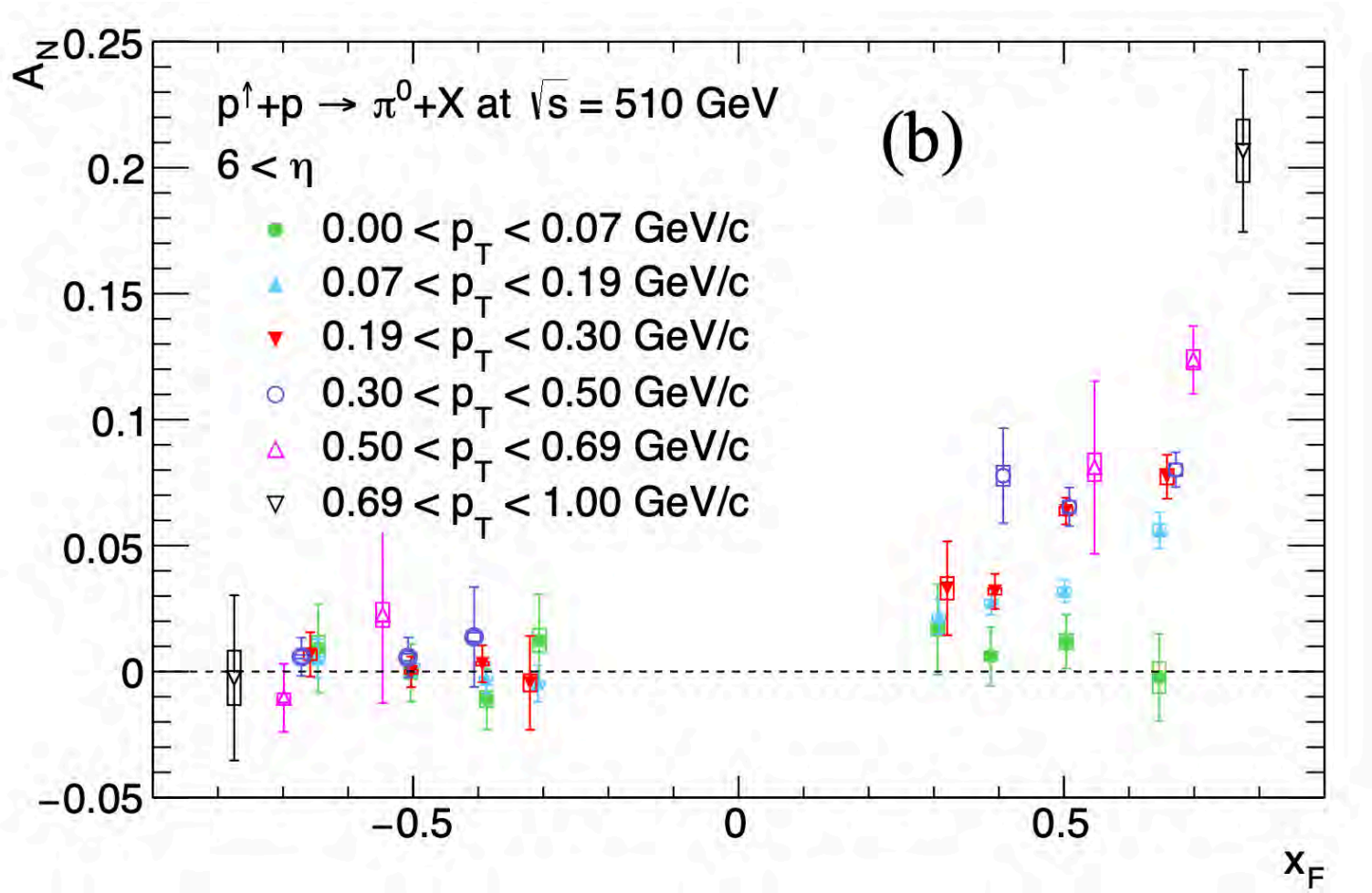
π^0 P_z (~ E) at 7 TeV pp



PRD 94 (2016) 032007


LHCf p-p √s = 13 TeV
QGSJET II-04
EPOS-LHC
DPMJET 3.06
PYTHIA 8.212
SIBYLL 2.3
dE_n/dη [GeV]
η


LHCf p-p √s = 13 TeV
QGSJET II-04
EPOS-LHC
DPMJET 3.06
PYTHIA 8.212
SIBYLL 2.3
dσ_n/dη [mb]
η


A_N
0.25
0.2
0.15
0.1
0.05
0
−0.05
−0.5
0
0.5
x_F
$p^{\uparrow}+p \rightarrow \pi^0+X$ at $\sqrt{s} = 510$ GeV
$6 < \eta$
(b)
$0.00 < p_T < 0.07$ GeV/c
$0.07 < p_T < 0.19$ GeV/c
$0.19 < p_T < 0.30$ GeV/c
$0.30 < p_T < 0.50$ GeV/c
$0.50 < p_T < 0.69$ GeV/c
$0.69 < p_T < 1.00$ GeV/c