Very forward particle production at colliders LHCf and RHICf

Takashi SAKO

(ISEE/KMI, Nagoya University)

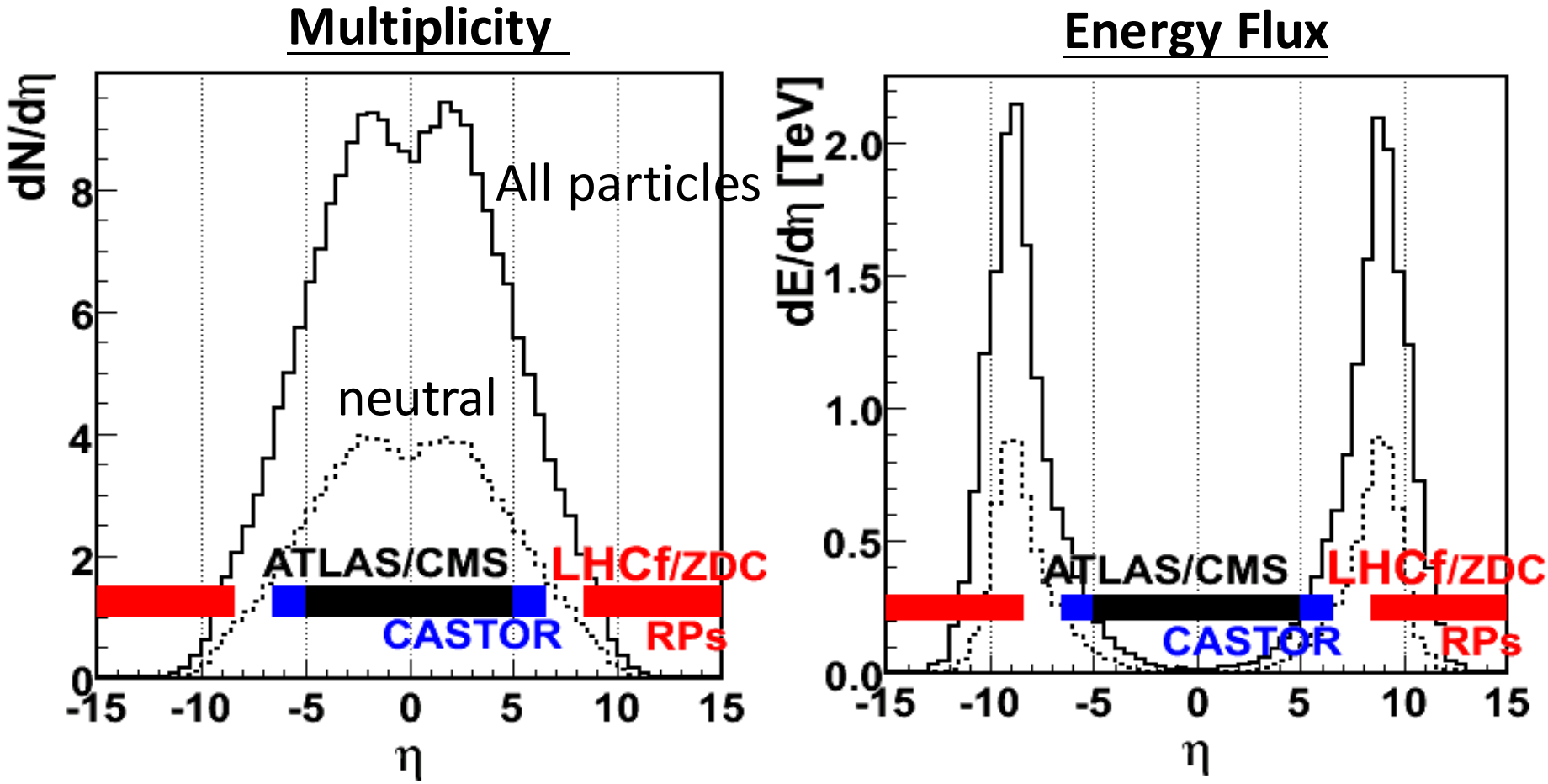
for the LHCf and RHICf collaborations

Outline

- Forward detectors and LHCf/RHICf
- LHCf results (mainly from 7TeV p-p collisions)
  - π^0
  - Neutron
  - (preliminary) photon result at 13 TeV
- Origin of LHCf measured particles in models, and prospect for LHCf-ATLAS joint analysis
- √s scaling
- Single-spin asymmetry at RHIC
- Future O-O collision at LHC

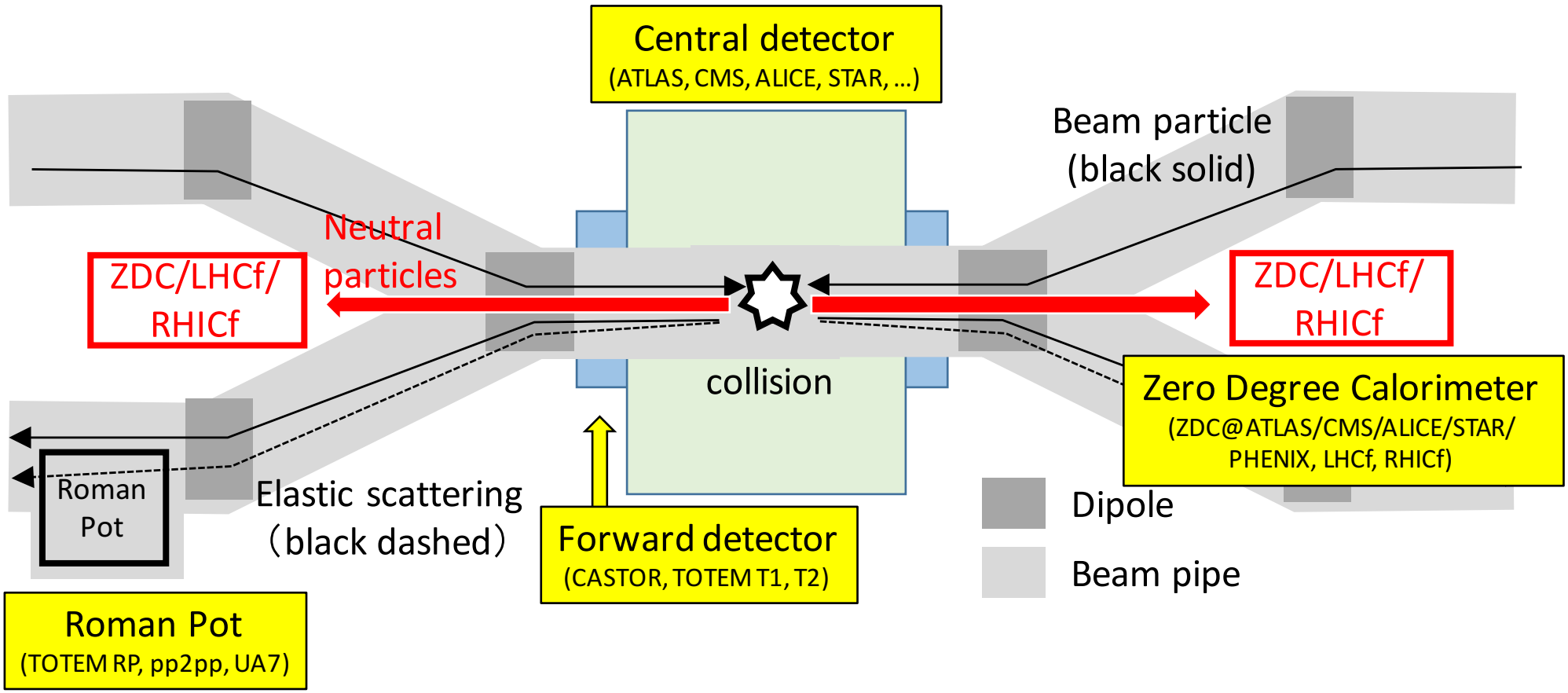
2ry particle flow at colliders

multiplicity and energy flux at LHC 14TeV p-p collisions



- LHCf covers the peak of energy flow
- √s=14 TeV pp collision corresponds to $E_{CR}=10^{17}$eV

Forward detectors @ Colliders

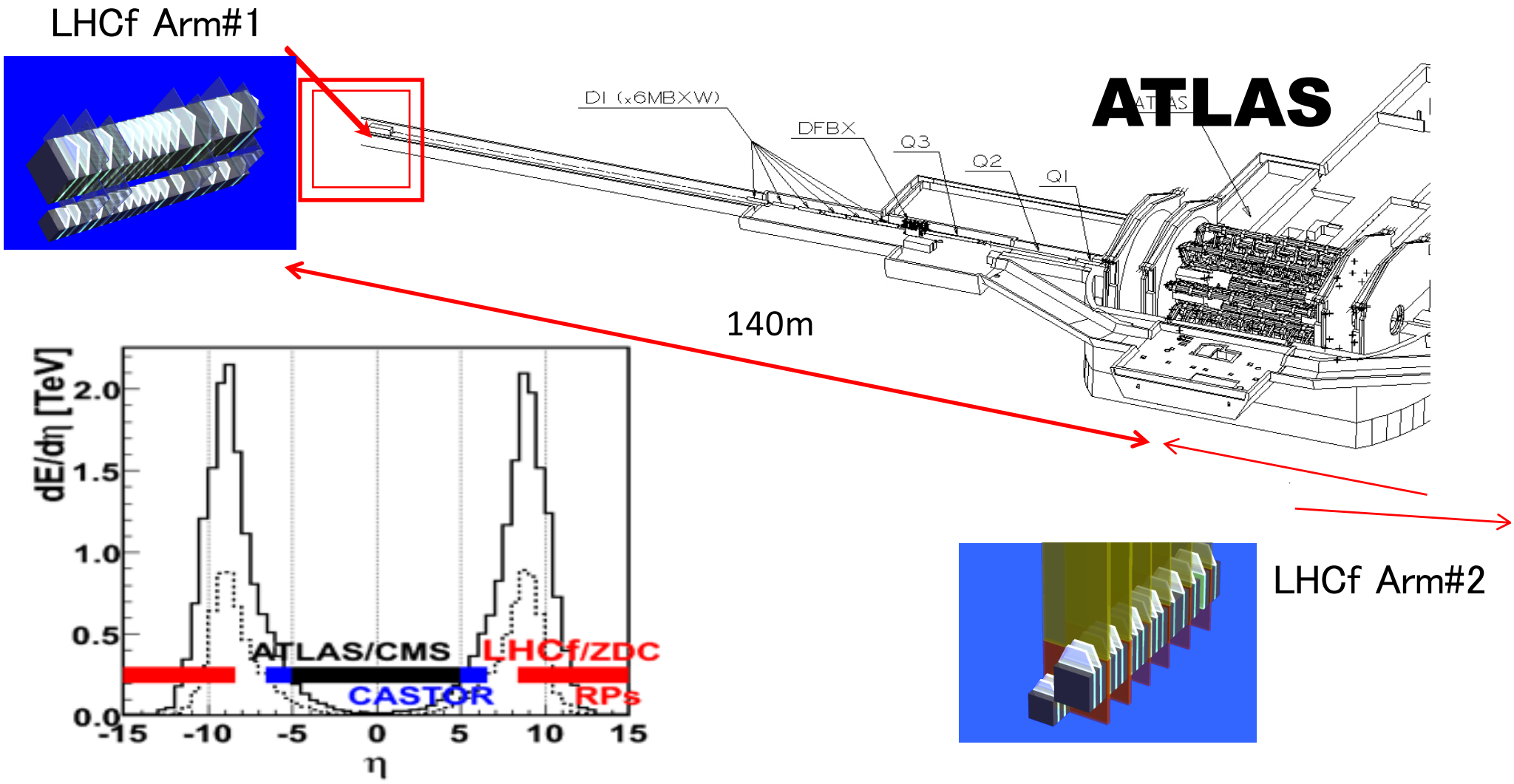


- ZDCs (including LHCf/RHICf) are sensitive to neutral particles including zero degree

ZDC and LHCf/RHICf

	ZDC	LHCf/RHICf
Original purpose	determination of centrality in A-A collisions => number of spectator neutrons	measurements of π^0 cross section => position sensitive EM calorimeter
Aperture	large	small
Thickness	thick	thin
Energy resolution	good	good in EM showers poor in hadronic showers
Position resolution	poor	good
Single particle identification	poor	good

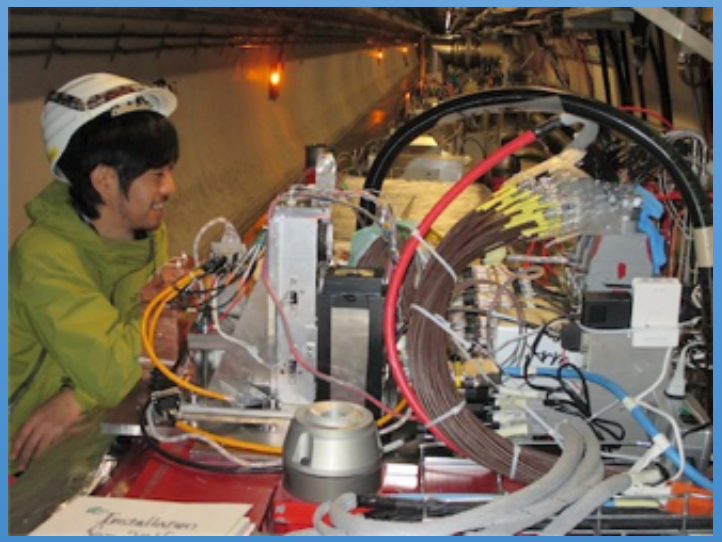
The LHC forward experiment



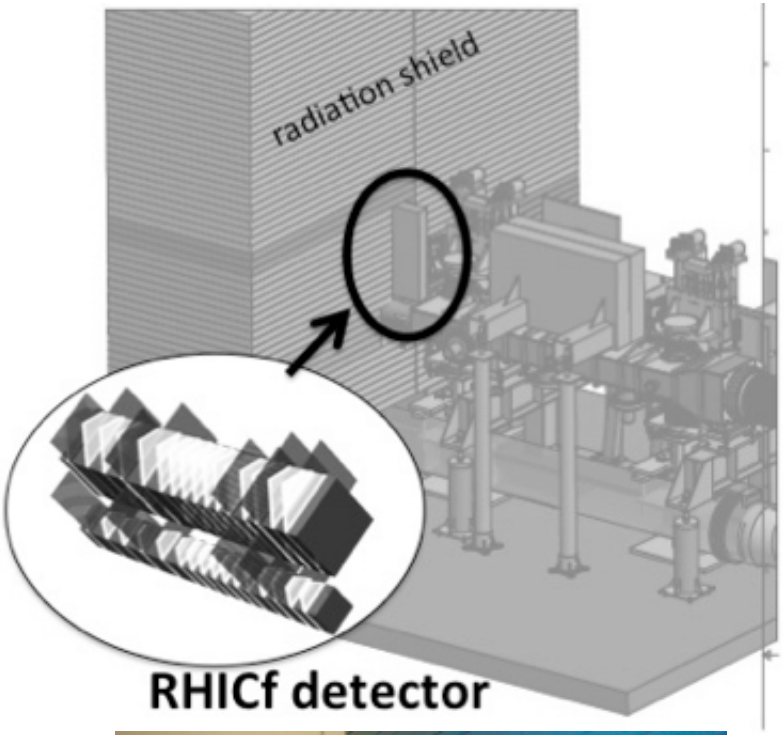
- Neutral particles (photons and neutrons) emitted around 0 degree arrive at LHCf

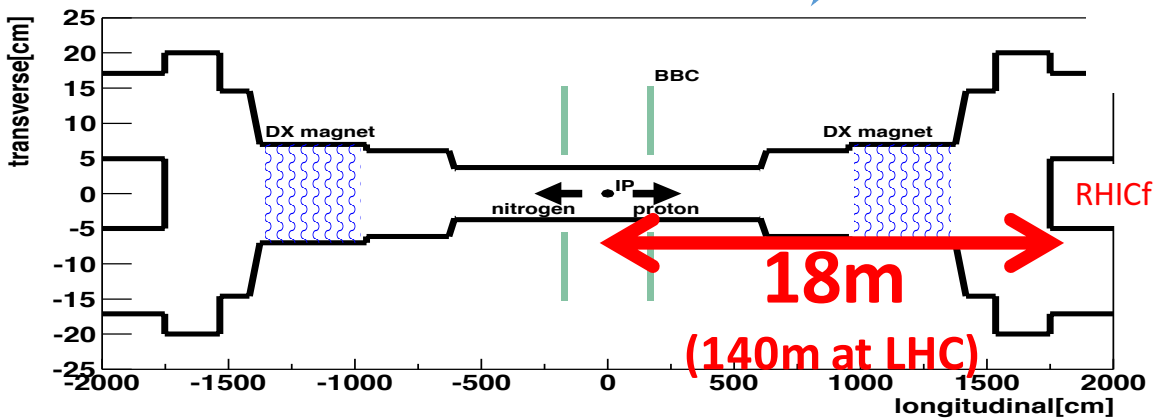
From the LHC forward (LHCf) to the RHIC forward (RHICf)

LHCf Arm1 detector in the LHC tunnel



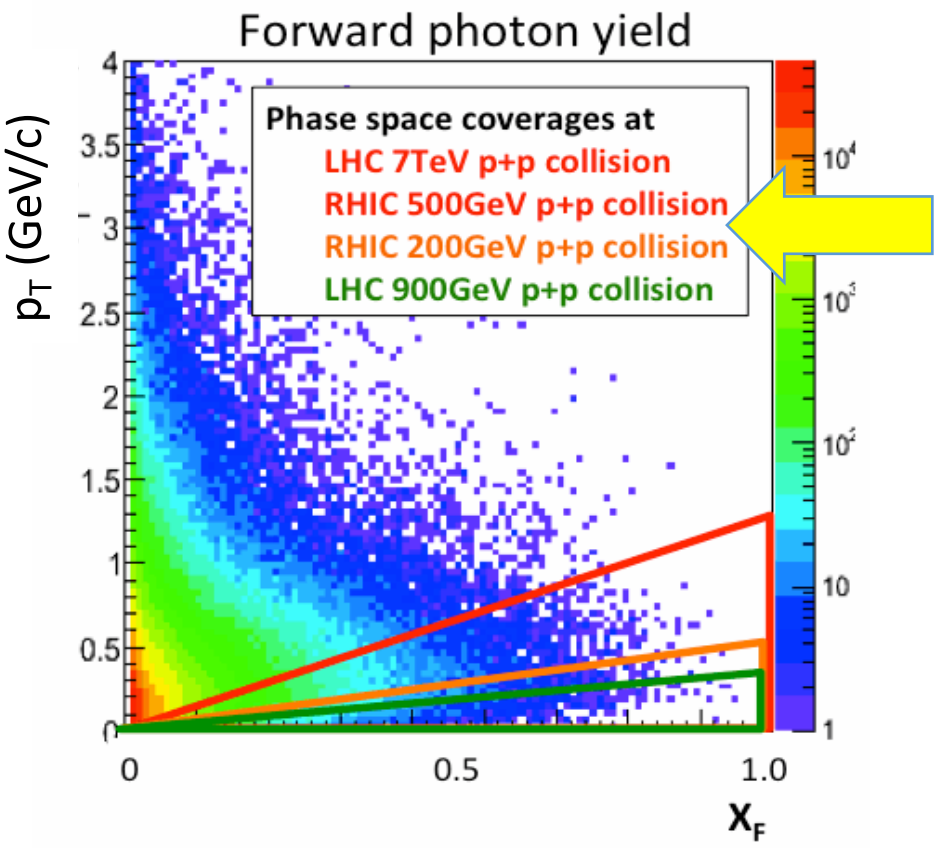
Schematic view of the RHICf installation@STAR





Data taking in RUN17 is approved

Zero degree detector and acceptance



$$p_T = p\sin\theta \le \tfrac{1}{2}\sqrt{s}\sin\theta$$

$$x_F = 2p_z/\sqrt{s}$$

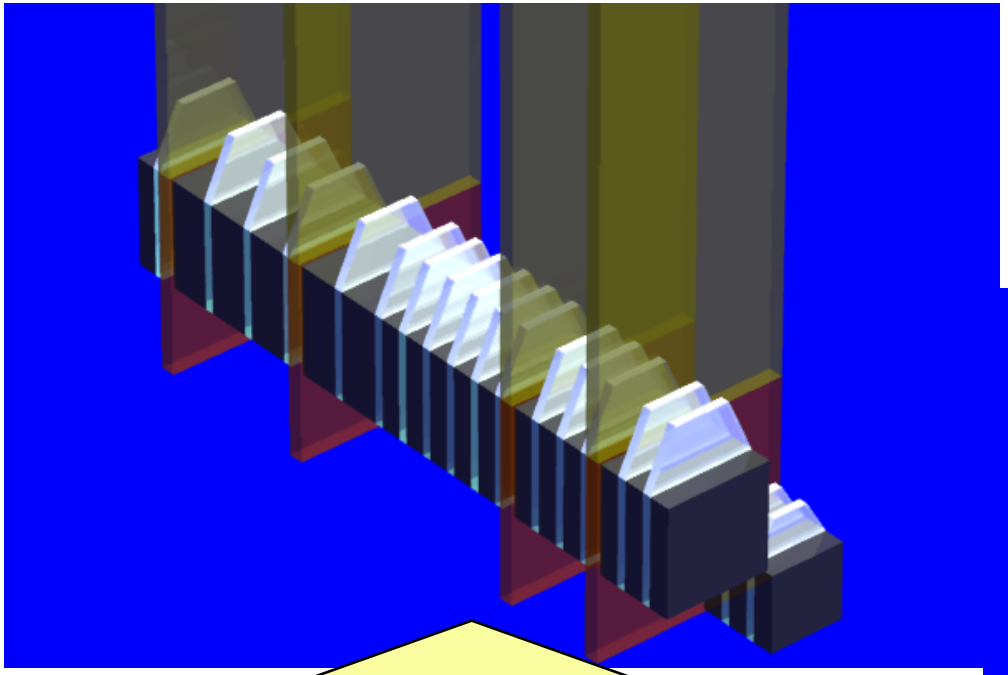
θ

RHIC

LHC

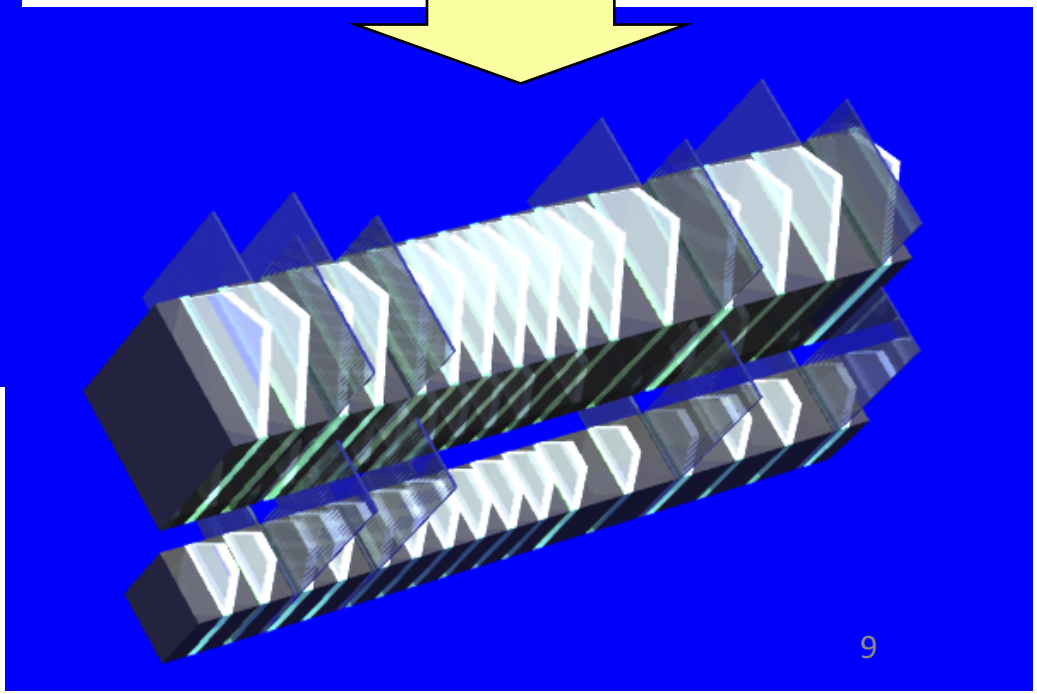
LHCf/RHICf Detectors

- Imaging sampling shower calorimeters
- Two calorimeter towers in each of Arm1 (RHICf) and Arm2
- Each tower has 44 r.l. of Tungsten,16 sampling scintillator and 4 position sensitive layers

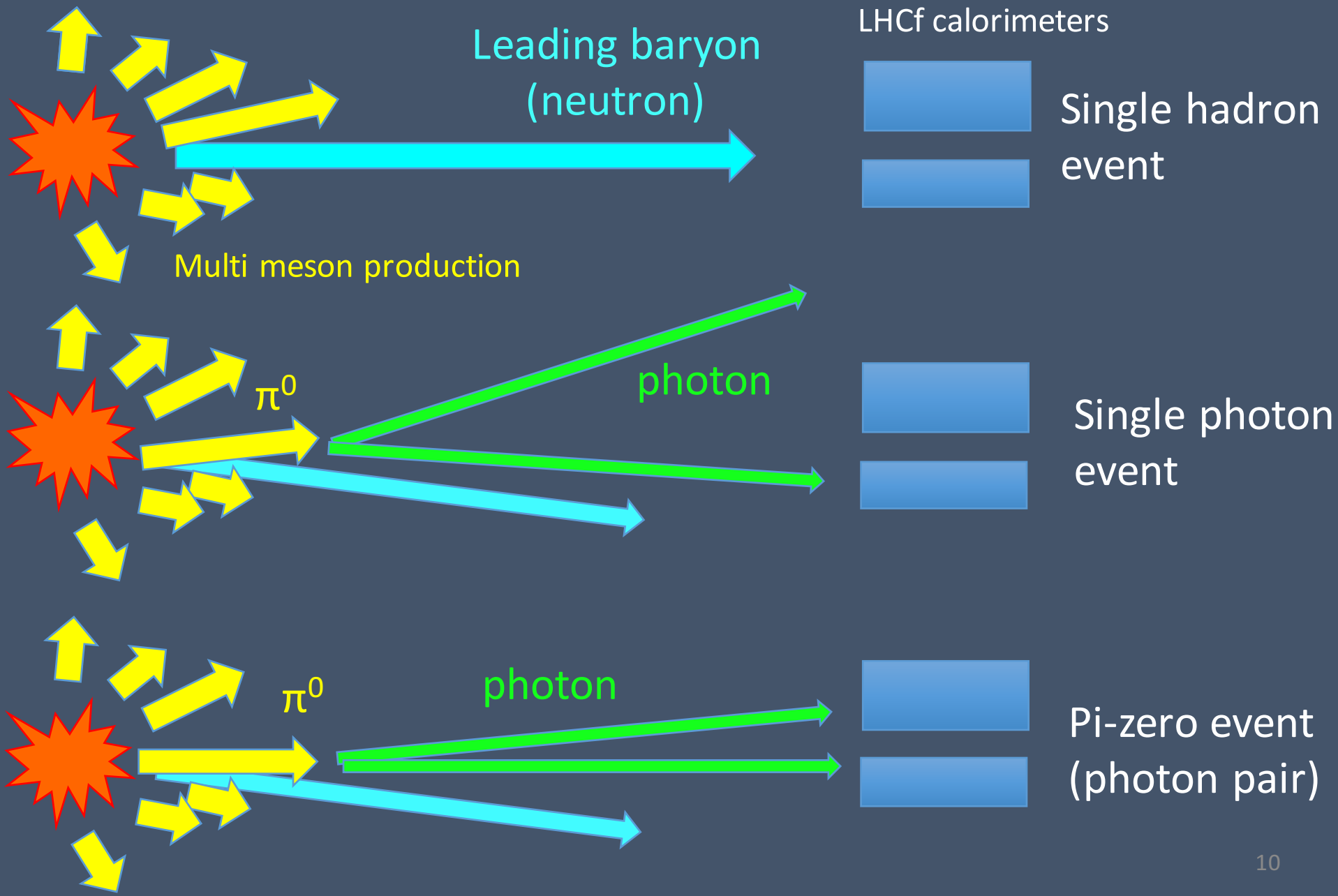


LHCf Arm#2 Detector
25mmx25mm+32mmx32mm
4 XY Silicon strip detectors

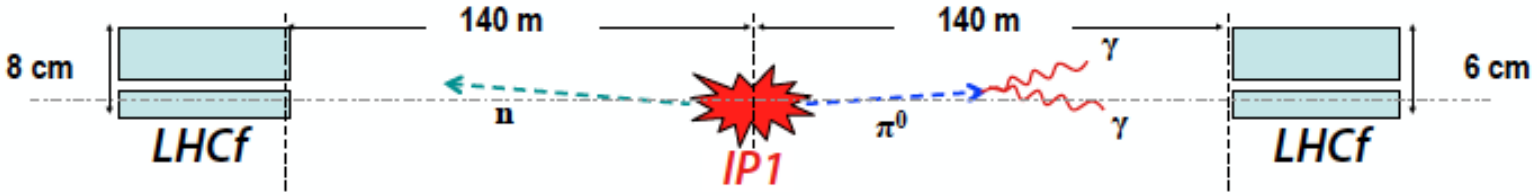
LHCf Arm#1 / RHICf Detector
20mmx20mm+40mmx40mm
4 XY SciFi+MAPMT



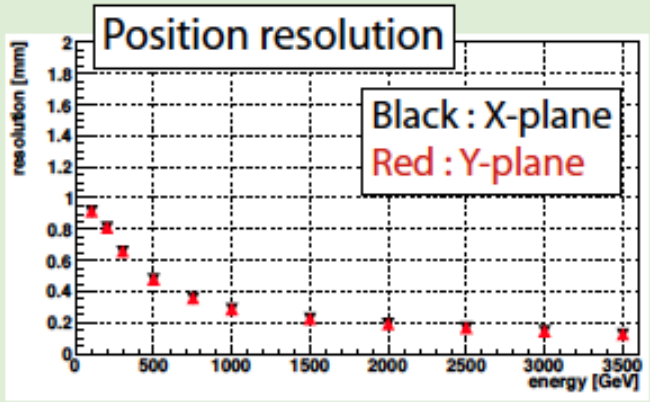
Event category of LHCf

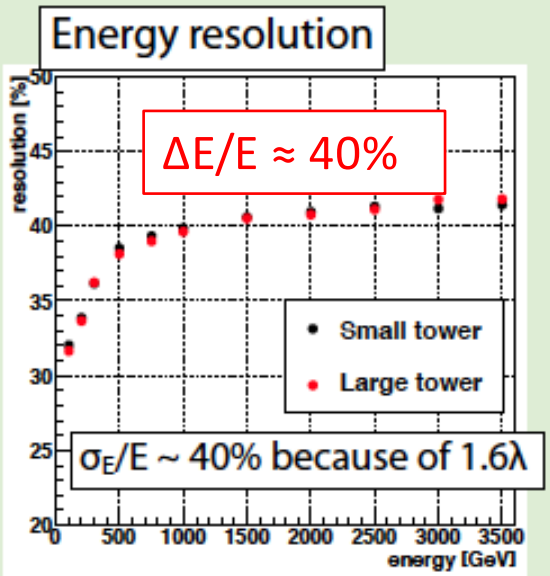


Detector performance

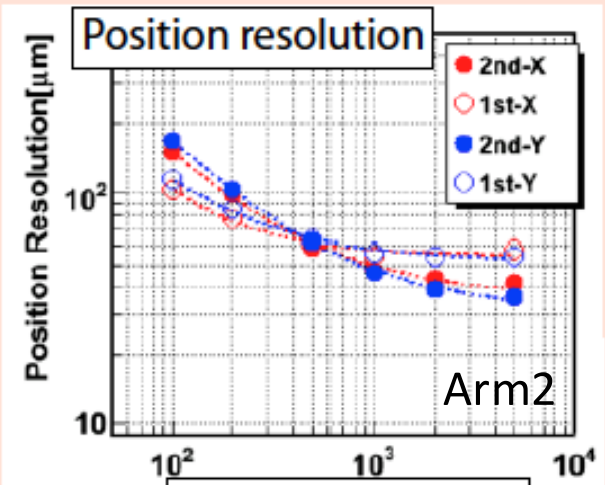


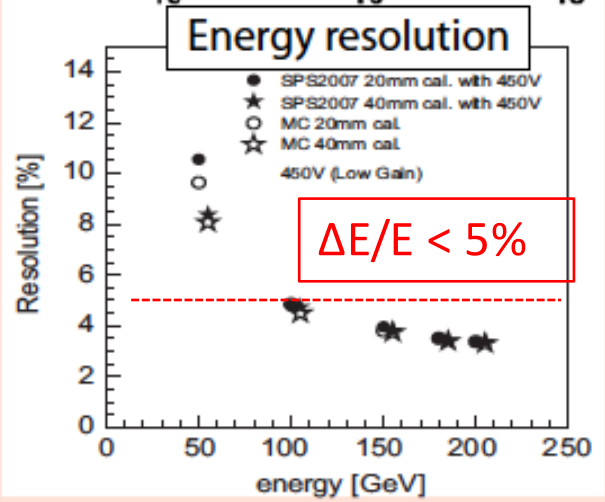
Hadronic shower (MC)





EM shower (MC)

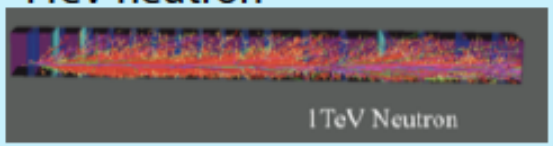




PID technique

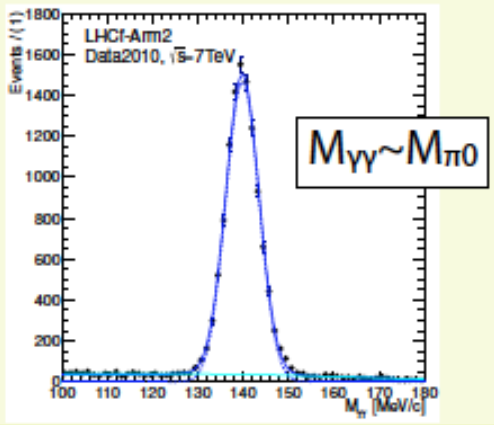
400GeV photon

1TeV neutron



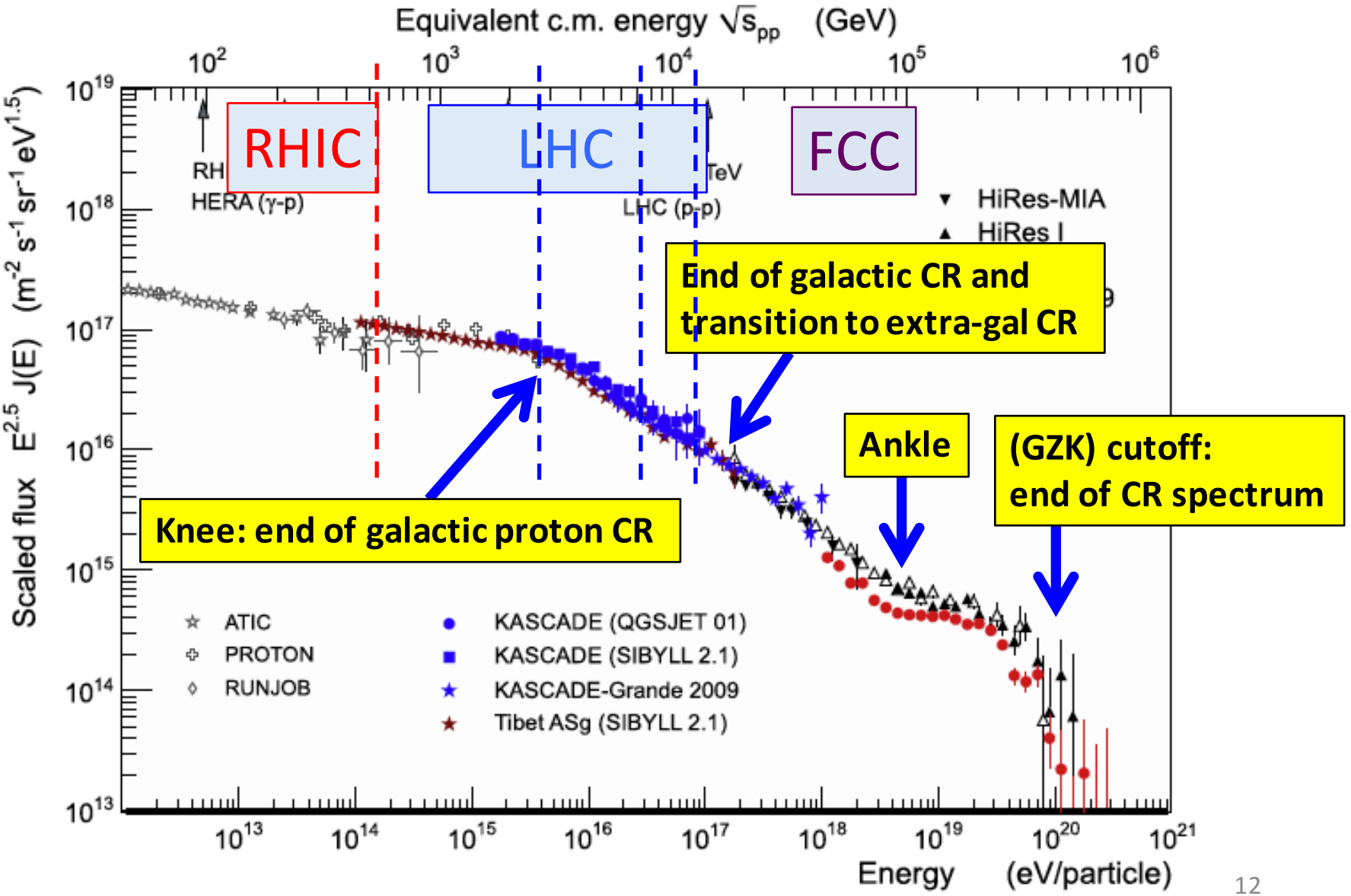
Identification of incoming particle by shower shape

π0 reconstruction



Cosmic-ray spectrum and collider energy

（D’Enterria et al., APP, 35,98-113, 2011）



Publications

	Photon (EM shower)	Neutron (hadron shower)	π^0 (limited acceptance)	π^0 (full acceptance)	Performance
Beam test	**NIM, A671 (2012) 129-136**	**JINST, 9 (2014) P03016**			
0.9TeV p-p	**PLB, 715 (2012) 298-303**				**IJMPA, 28 (2013) 1330036**
7TeV p-p	**PLB, 703 (2011) 128-134**	**PLB, 750 (2015) 360-366**	**PRD, 86, (2012) 092001**	**PRD submitted (arXiv:1507.08764)**	
2.76TeV p-p			**PRC, 89 (2014) 065209**		
5.02TeV p-Pb					
13TeV p-p	**Analysis in progress**				

physics results

performance results

Publications

	Photon (EM shower)	Neutron (hadron shower)	π^0 (limited acceptance)	π^0 (full acceptance)	Performance
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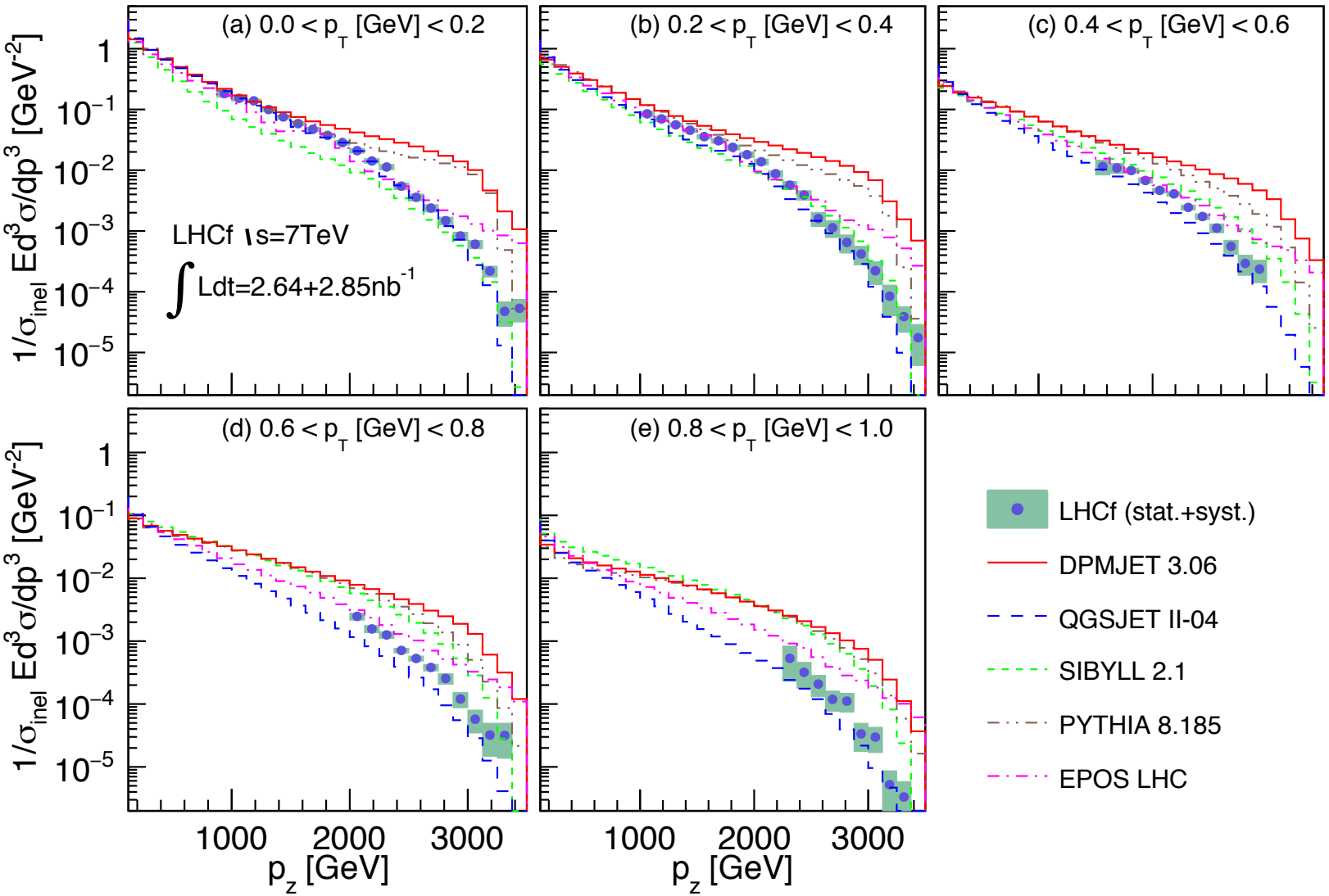
2.76TeV p-p			**PRC, 89 (2014) 065209**		
5.02TeV p-Pb					
13TeV p-p	**preliminary**	**Analysis in progress**			

physics results

performance results

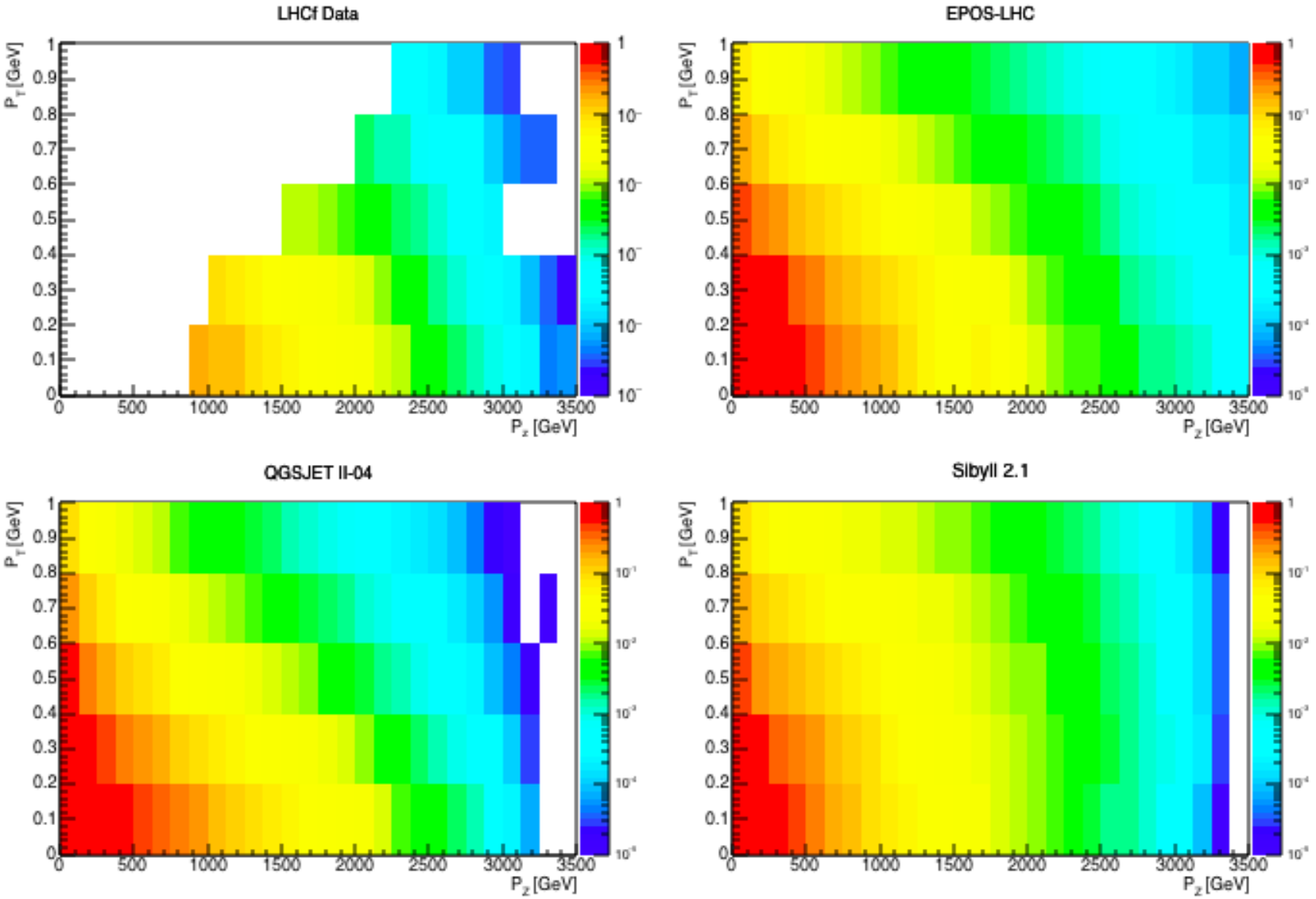
π^0 p_z spectra in 7TeV p-p collisions

(PRD submitted,arXiv:1507.08764 [hep-ex])

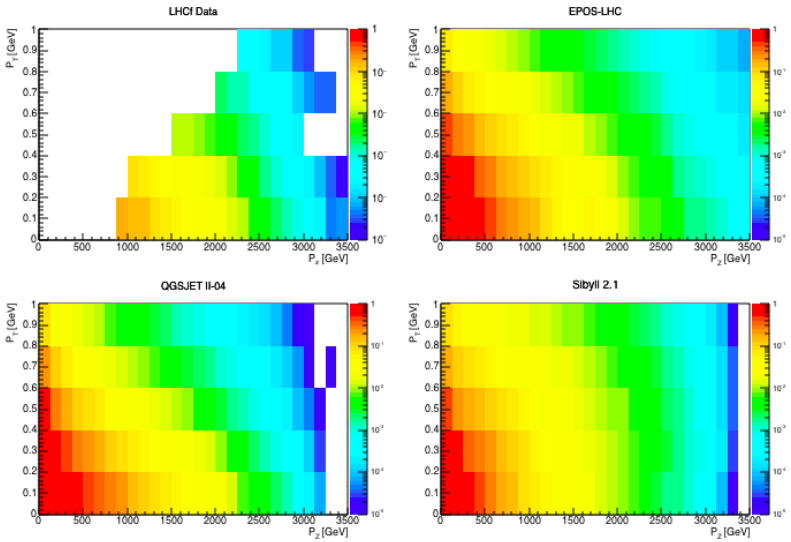


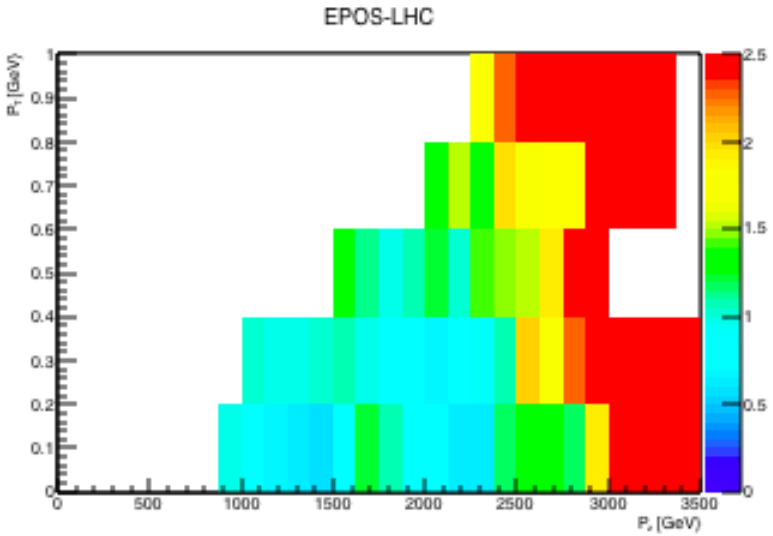
- DPMJET3 and PYTHIA8 overestimate over all E-p_T range

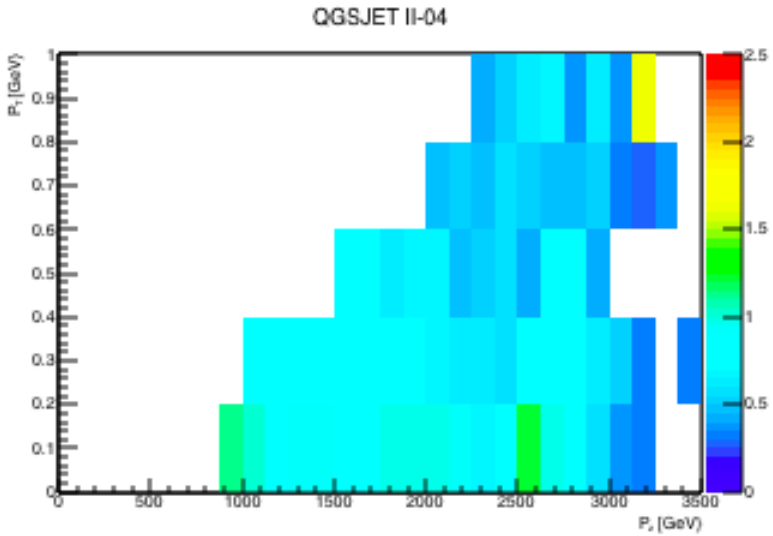
π^0 in 7TeV p-p collision
LHCf and models

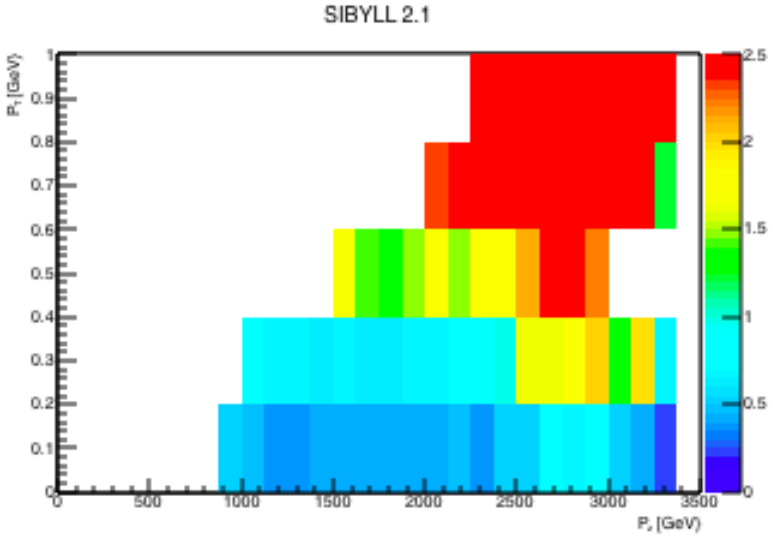


π^0 in 7TeV p-p collision
LHCf and models (ratio to data)

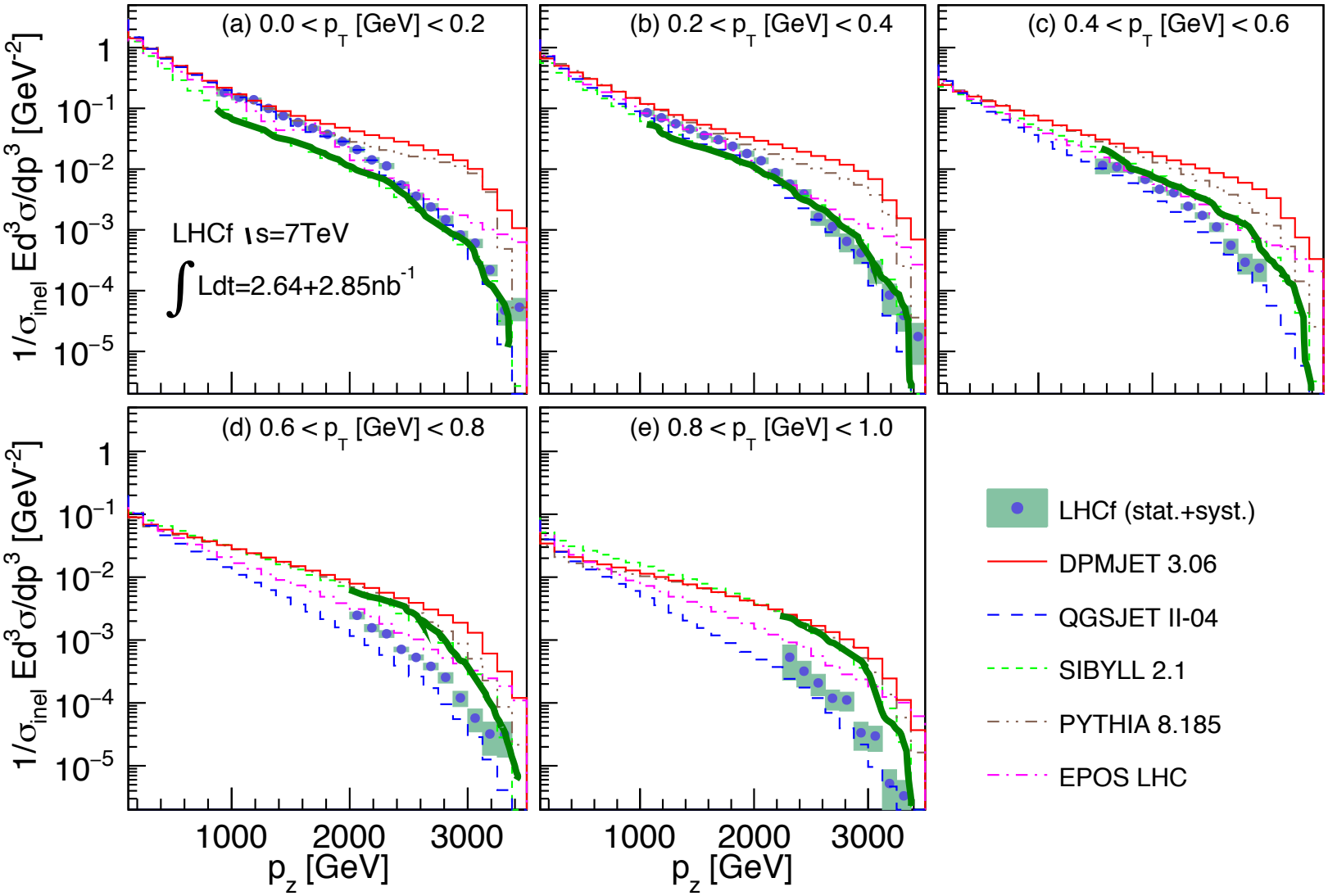






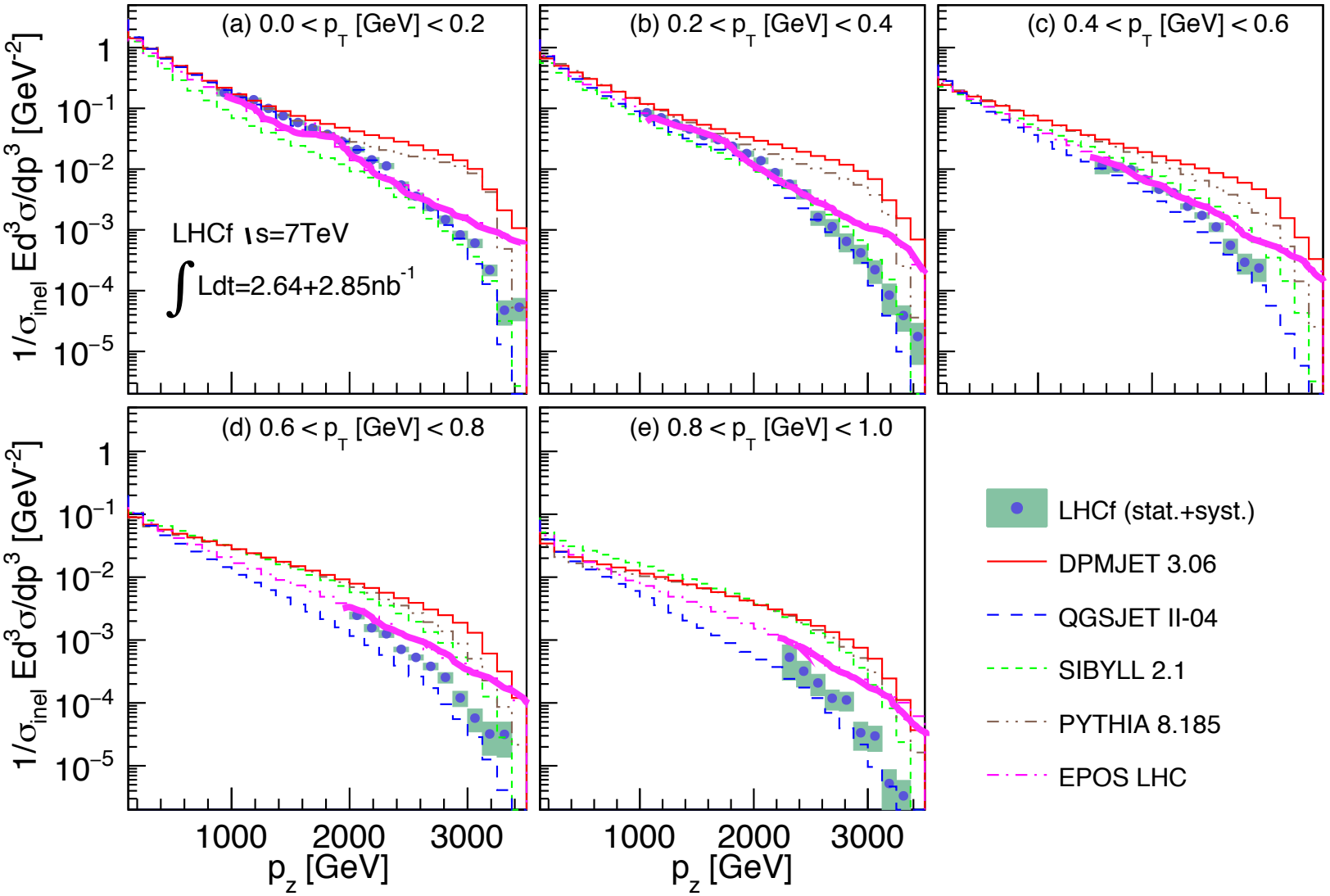


π^0 SIBYLL 2.1



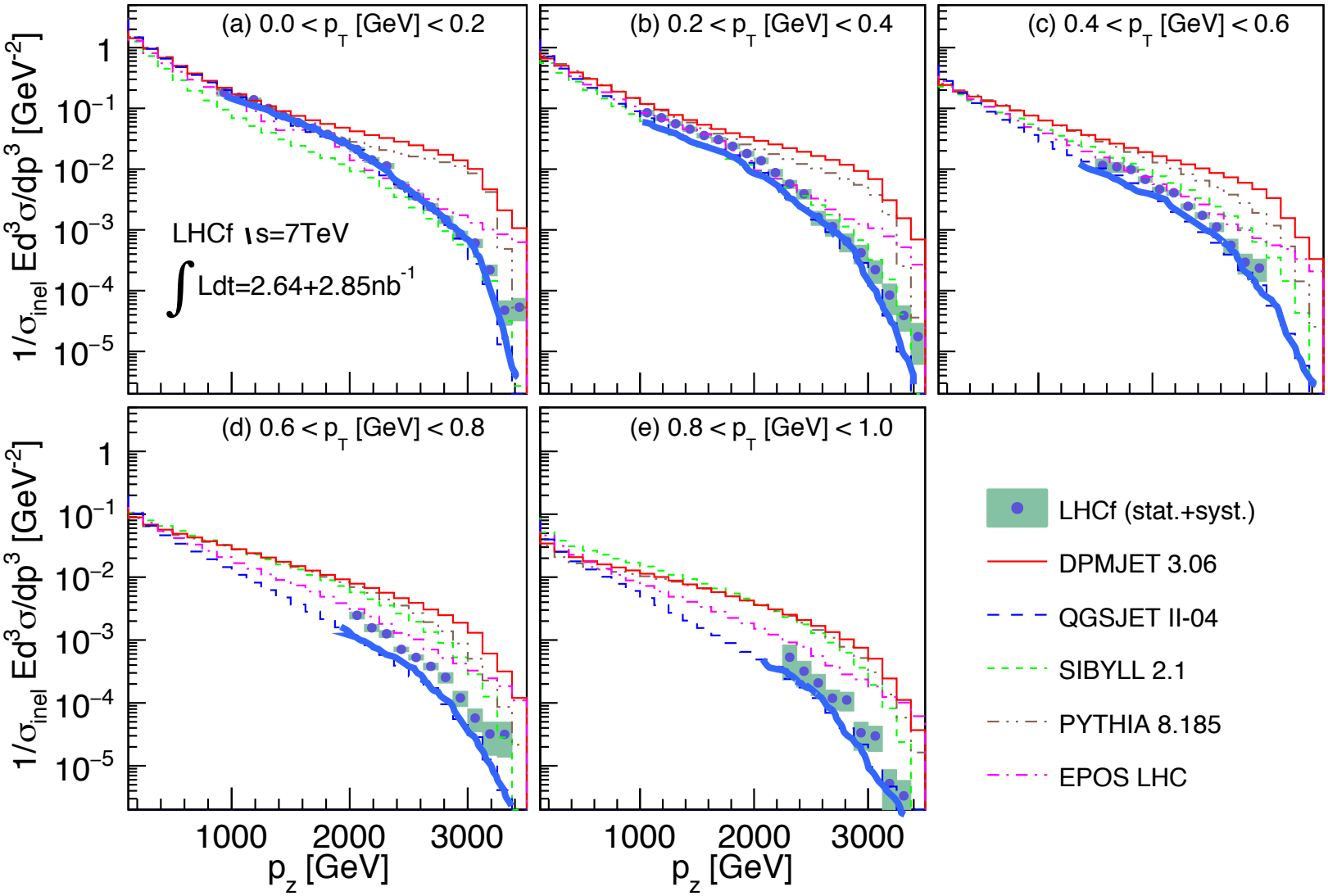
- Underestimate in low p_T, overestimate in high p_T
- Totally overestimate because of larger phase space in high p_T

π^0 EPOS-LHC



- Not bad, slightly overestimate in high energy

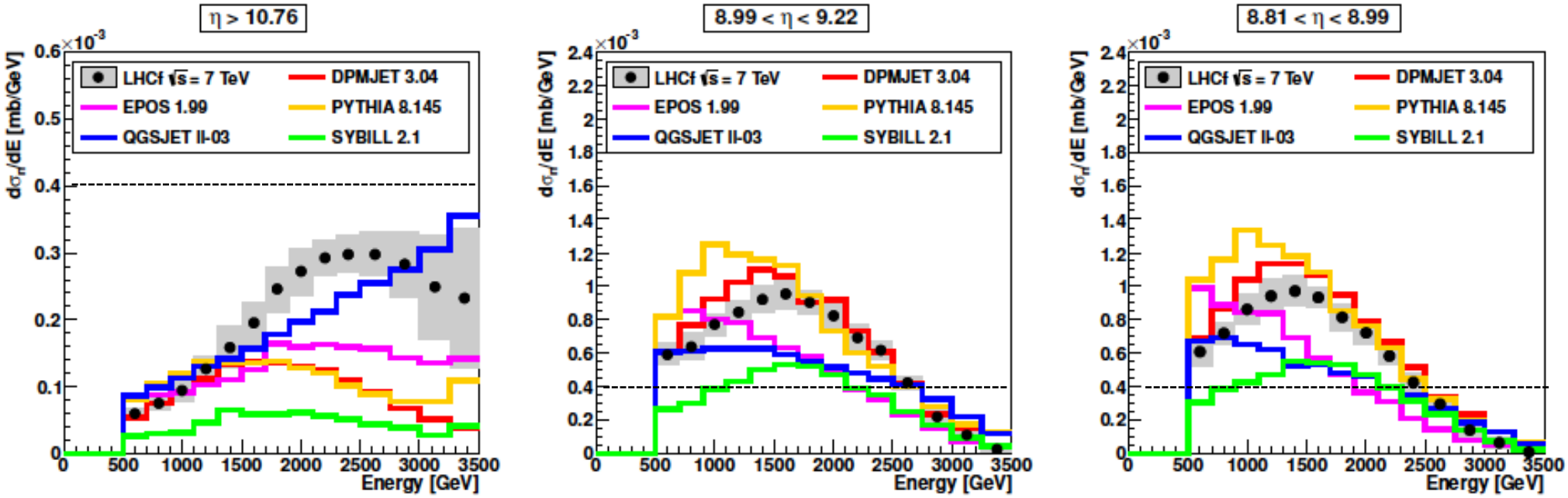
π^0 QGSJET II-04



- Perfect in shape, slightly underestimate in higher p_T
- Totally slightly underestimate

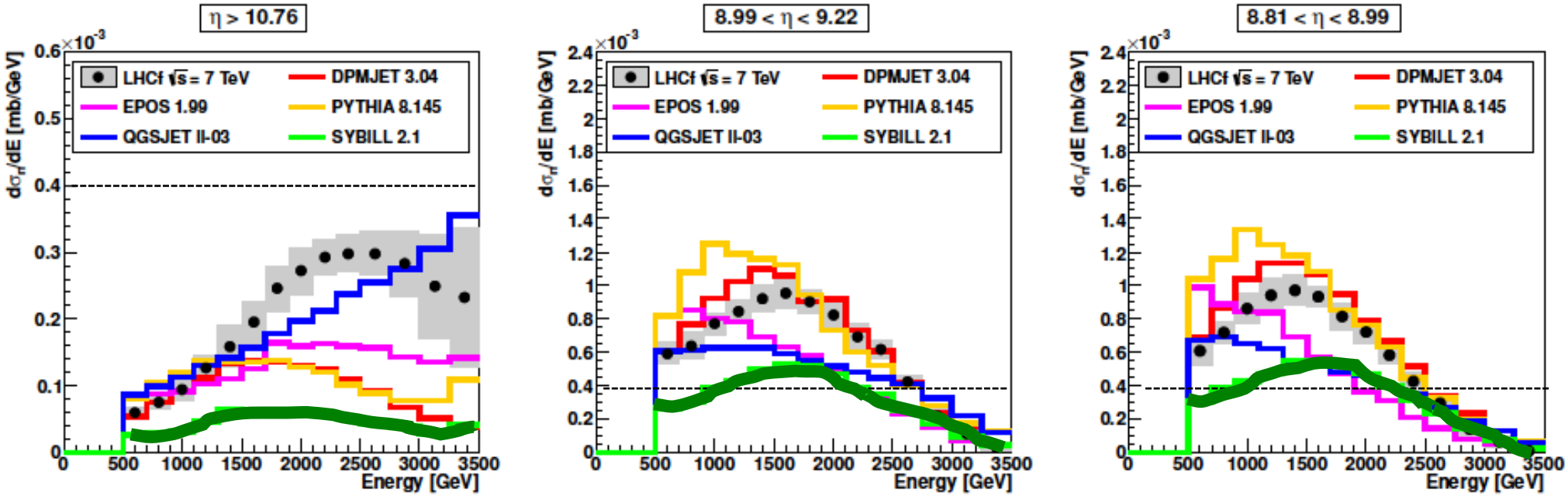
Neutron

(√s=7TeV p-p ; PLB 750 (2015) 360-366)



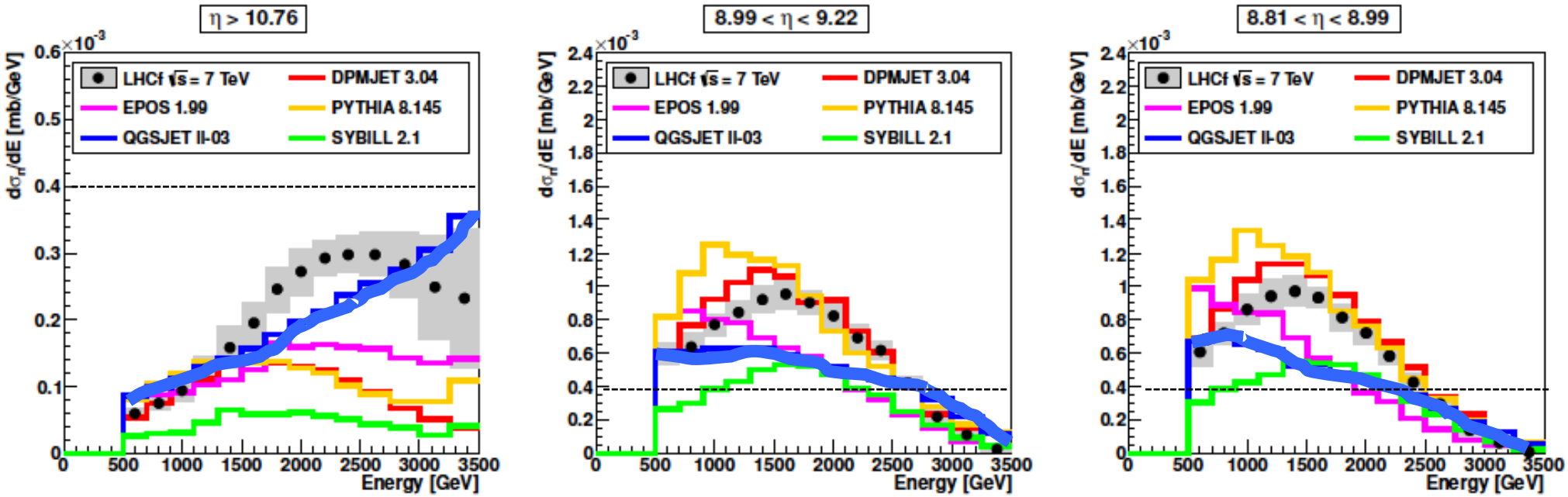
- DPM and PYTHIA under production at zero degree
- DPM and PYTHIA not bad at off-zero degree. DPM is best.

Neutron SIBYLL 2.1



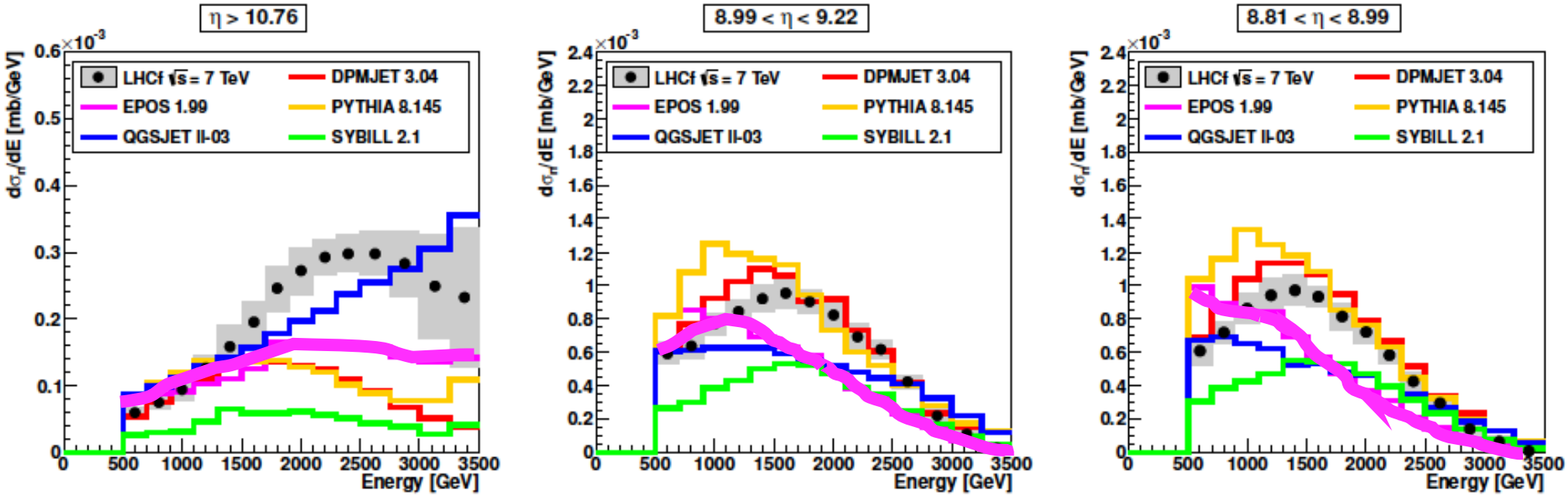
- Lowest neutron yield, especially at zero degree

Neutron QGSJET II-03



- Qualitatively nice agreement, only model, at zero degree
- Lower yield at non-zero angle

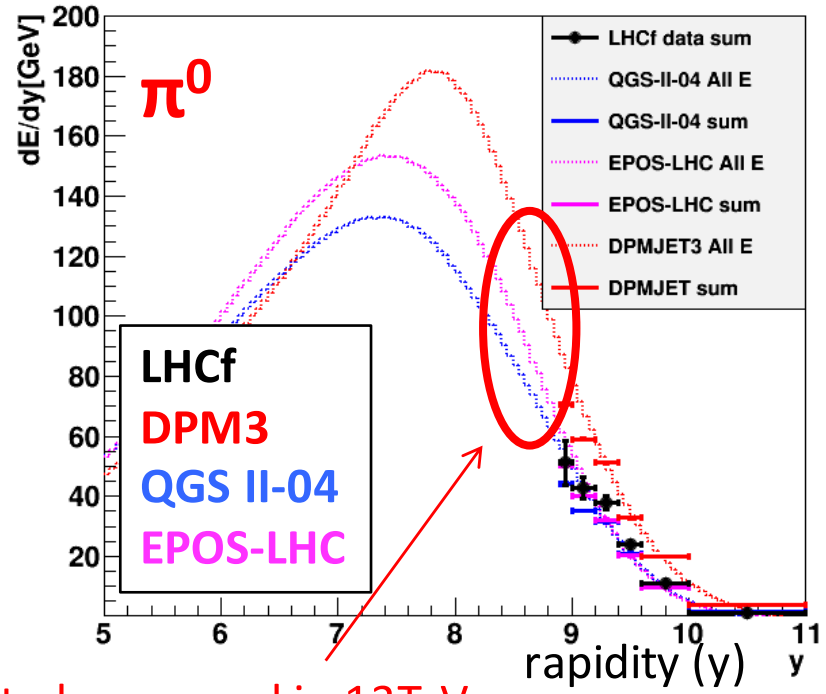
Neutron EPOS 1.99



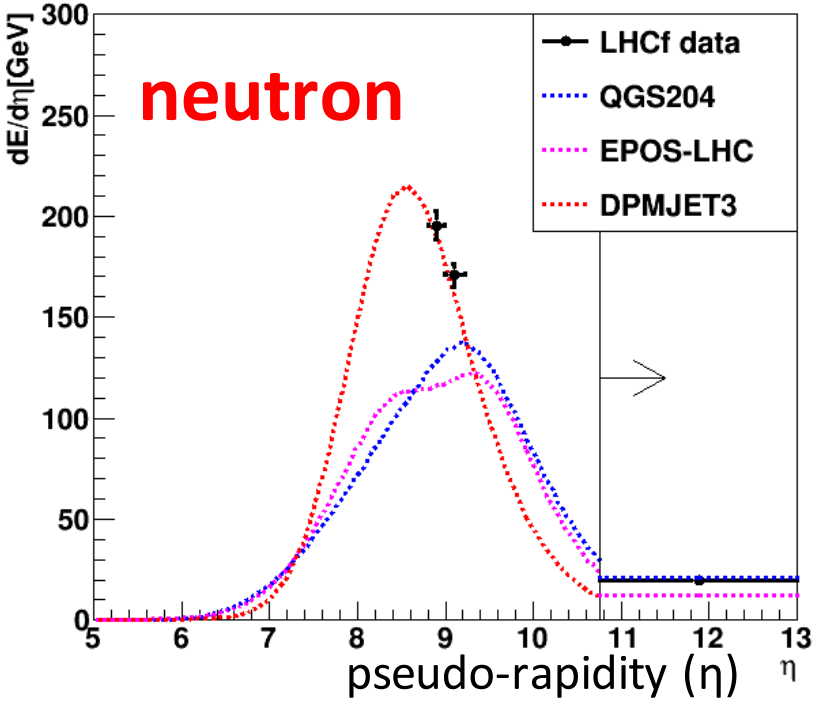
- Generally low yield

Energy flow

- Post-LHC models (EPOS-LHC and QGSJET II-04) well explain the π^0 results, but not for neutrons
- DPMJET3 explains the neutron results, but it is not recently used for CR simulations



to be covered in 13TeV



Black solid circle : LHCf data (π^0 , LHCf 2012)
Dotted lines : π^0 energy flow distribution of each model
Thick horizontal line : Energy flow calculation after p_T cut

Energy share between π^0 (photon) and neutron

	π^0	neutron	neutron/π^0
LHCf	1	1	1
DPMJET 3.04 (PYTHIA)	>>1	~1	<<1
SIBYLL 2.1	>1	<<1	<<1
QGSJET II-03, 04	~1	<1	<1
EPOS 1.99, LHC	~1	<1	<1

"pseudo"-elasticity

Elasticity:

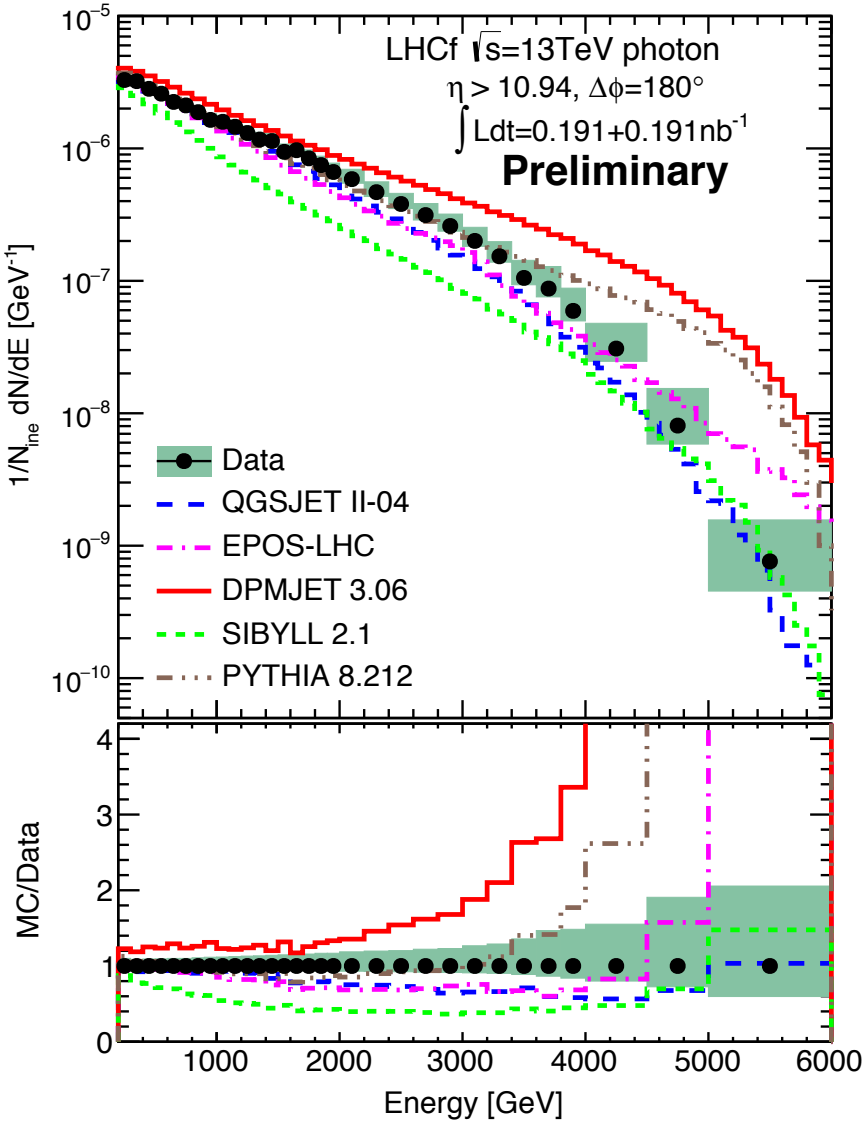
$$K_{ela} = \frac{E_{lead}}{E_{lead} + \sum E_{\pi}}$$

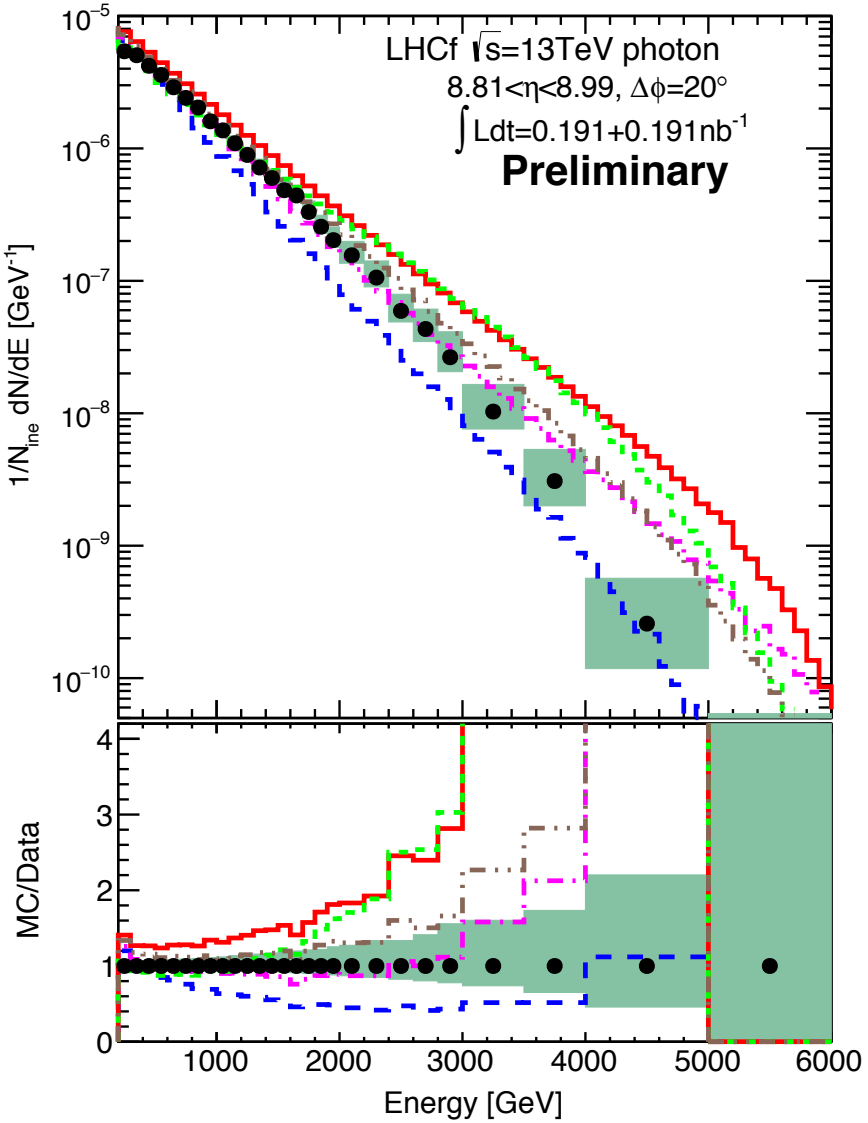
is important for air showers

Neutron/photon "number" ratio in the same angular ranges

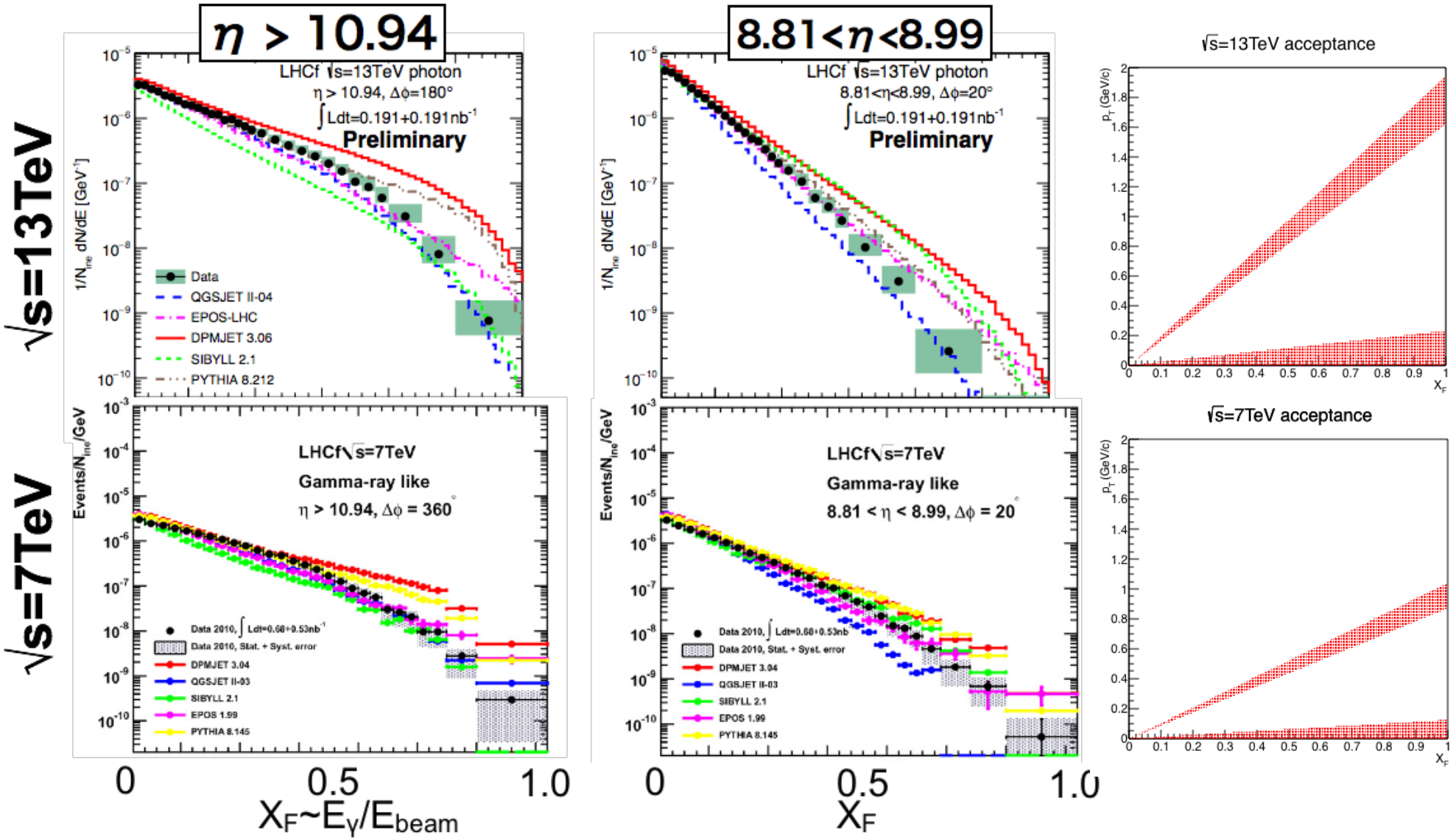
N_n/N_γ	Small (η>10.76)	Large A (9.22>η>8.99)	Large B (8.99>η>8.81)
Data	3.05 ± 0.19	1.26 ± 0.08	1.10 ± 0.07
DPMJET 3.04	1.05	0.76	0.74
EPOS 1.99	1.80	0.69	0.63
PYTHIA 8.145	1.27	0.82	0.79
QGSJET II-03	2.34	0.65	0.56
SYBILL 2.1	0.88	0.57	0.53

Photon spectra, √s=13TeV





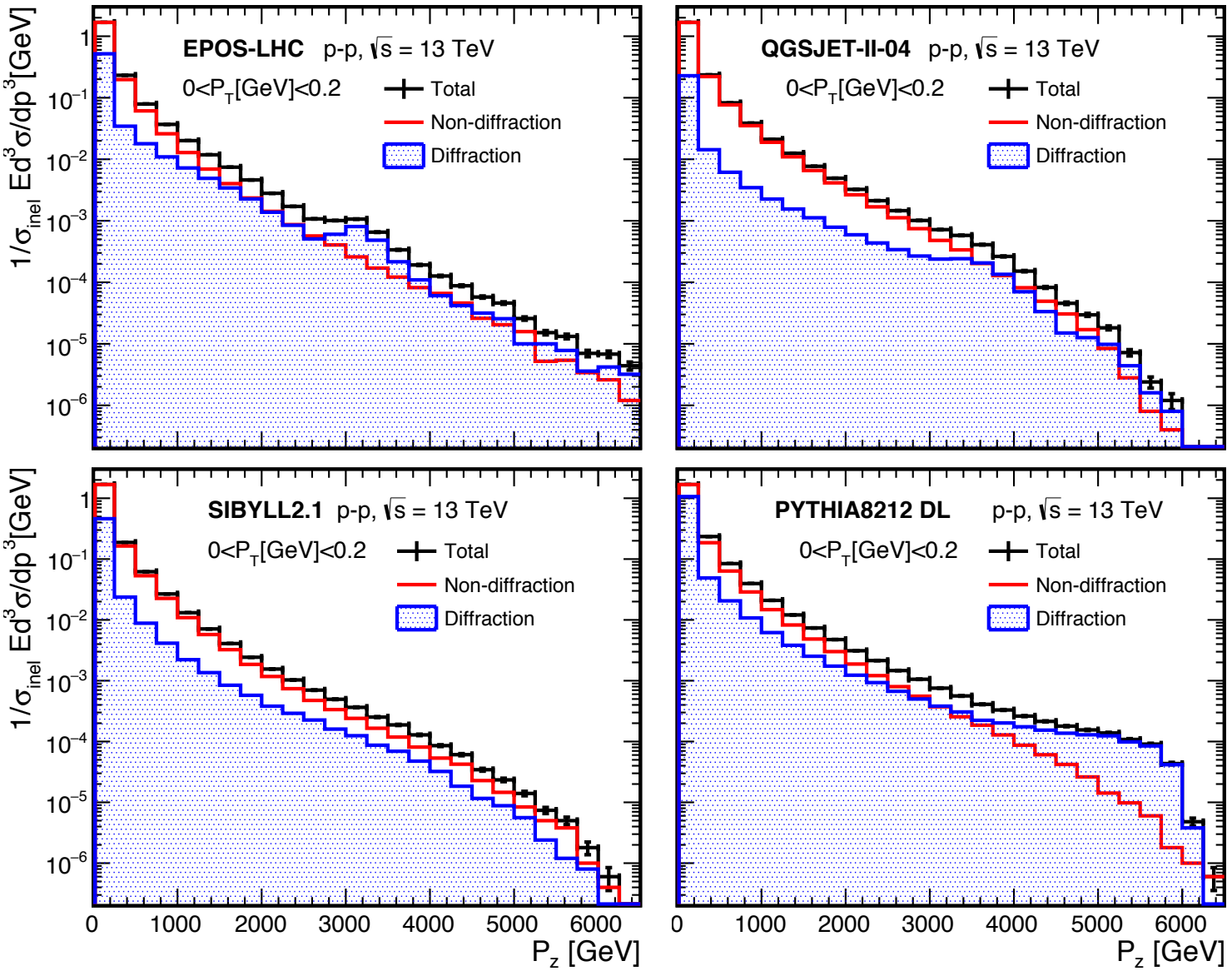
Photon 7TeV vs. 13TeV



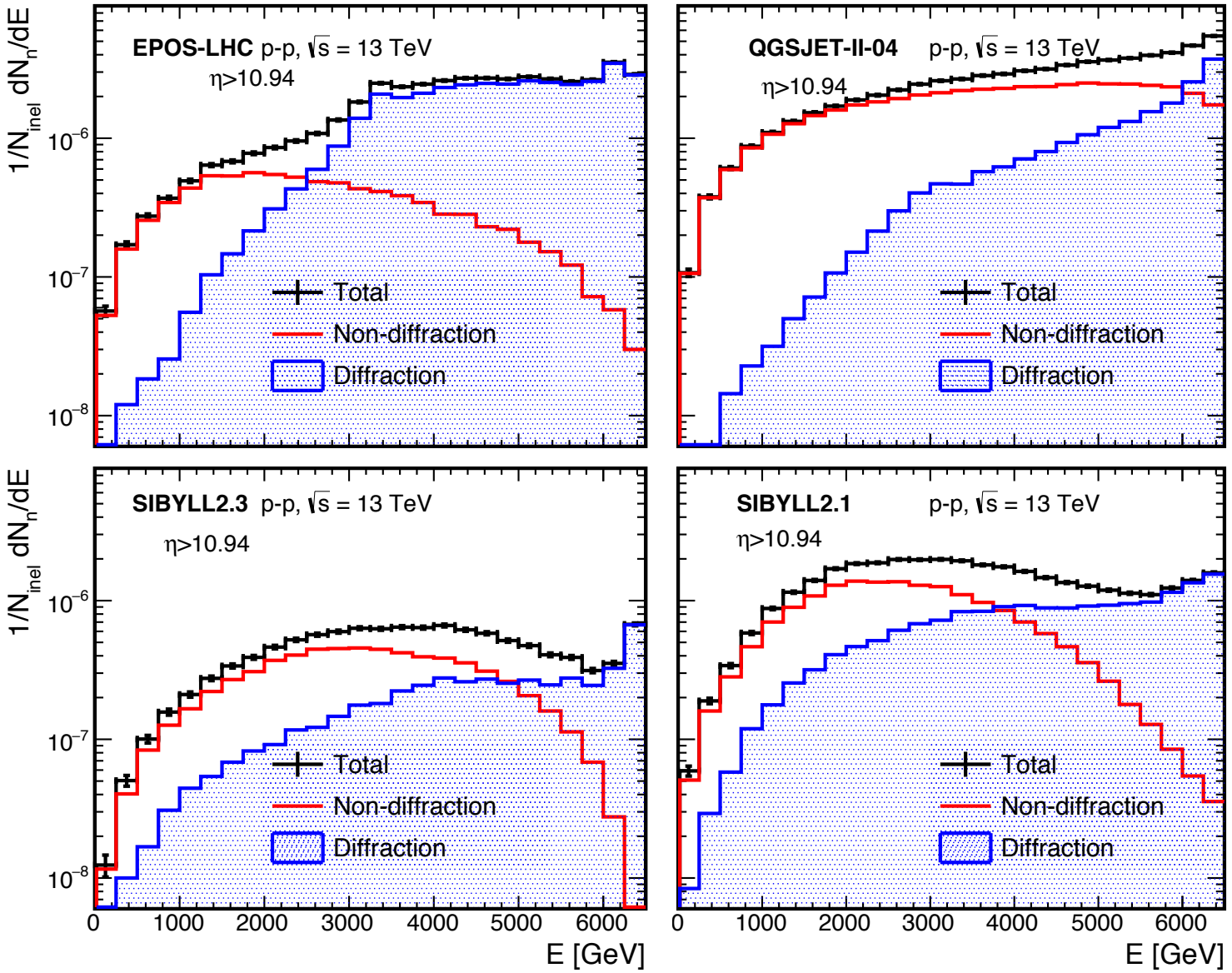
Diffraction/non diffraction tagging by ATLAS (prospect for 13TeV analysis)

Diffraction or Non-diffraction ?

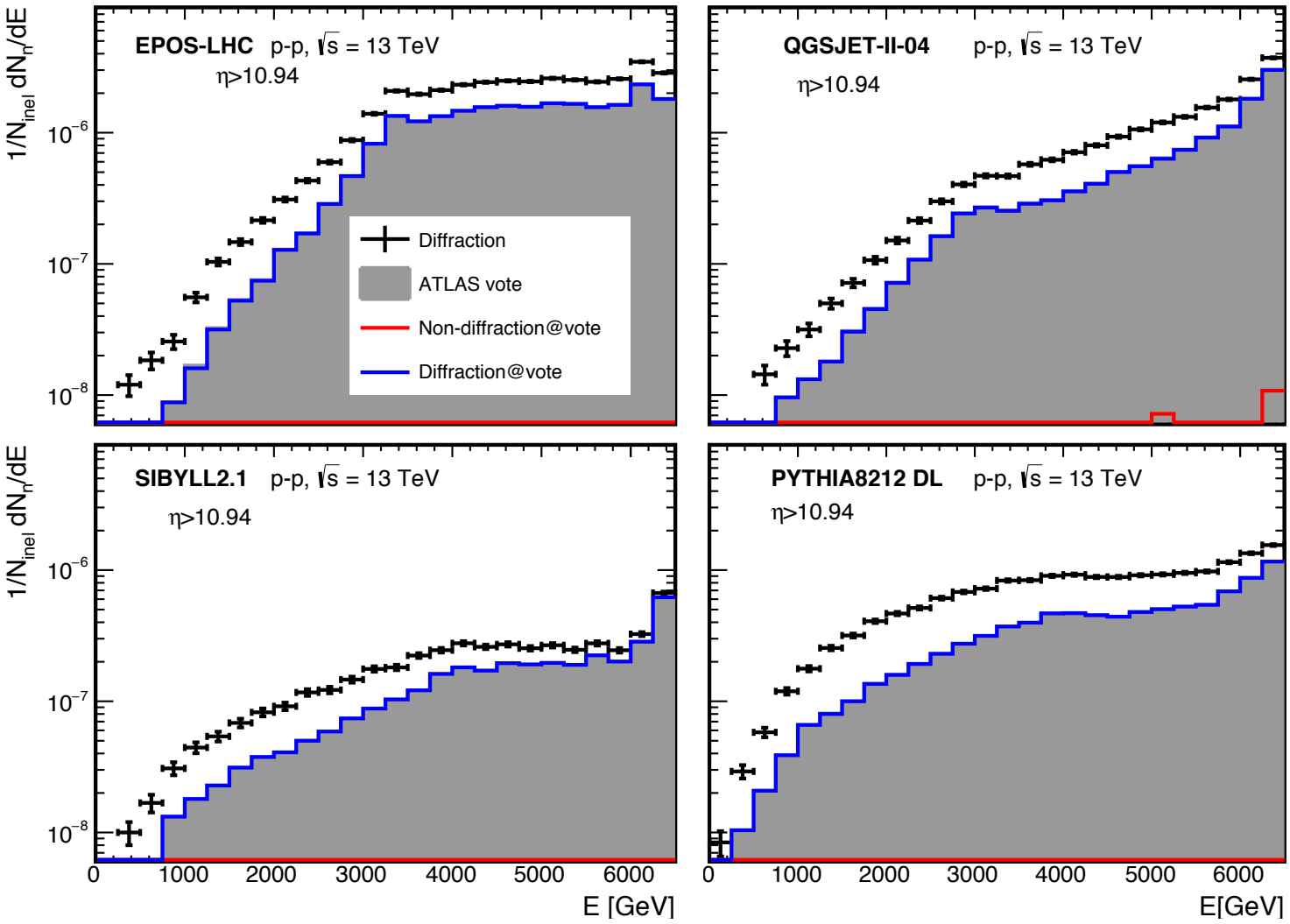
π^0



Diffraction or Non-diffraction ? neutron



Tagging by ATLAS (no track=diffraction-like)



Technical feasibility

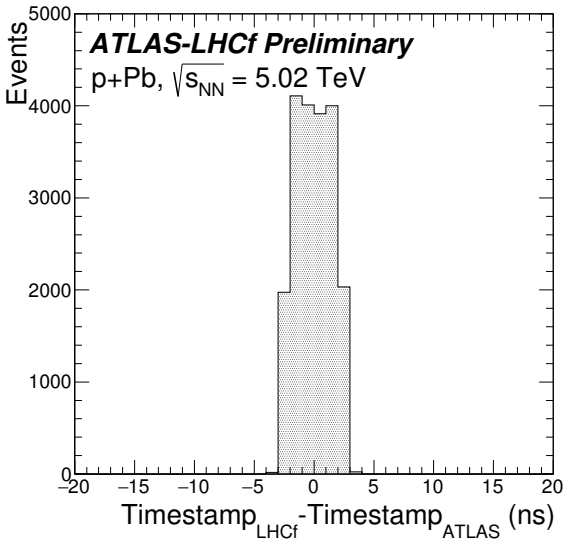
ATLAS LHCf NOTE
August 26, 2015

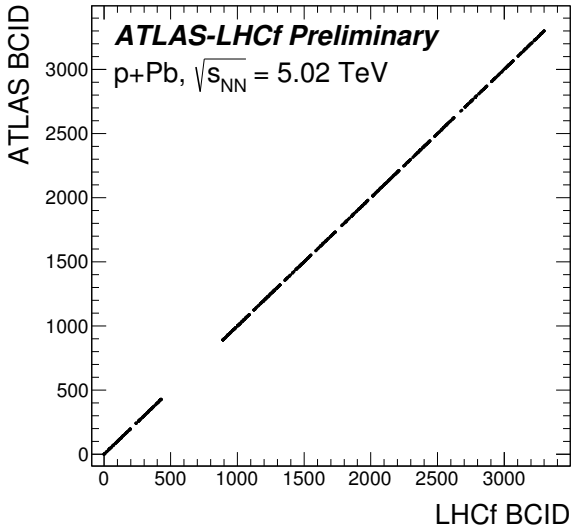
ATL-PHYS-PUB-2015-038
30 August 2015

Classification of Events in the Combined ATLAS-LHCf Data Recorded During the p+Pb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

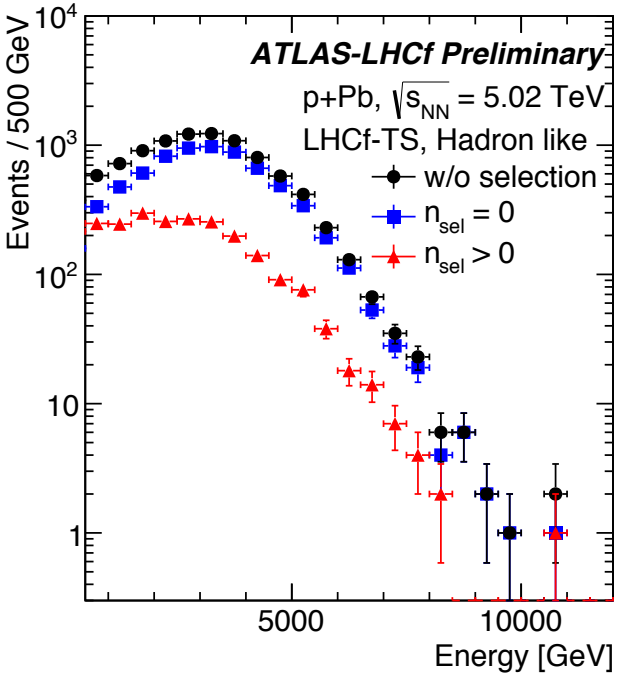
The ATLAS and the LHCf Collaborations

- Common Event ID was already tested using 5TeV p-Pb collision data in 2013





Timing and bunch ID matching

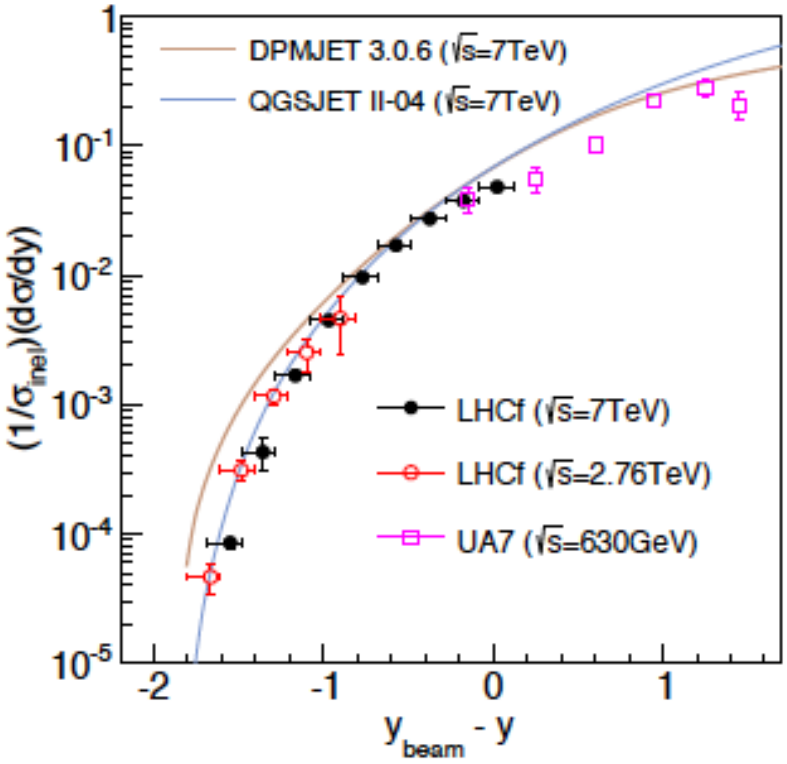


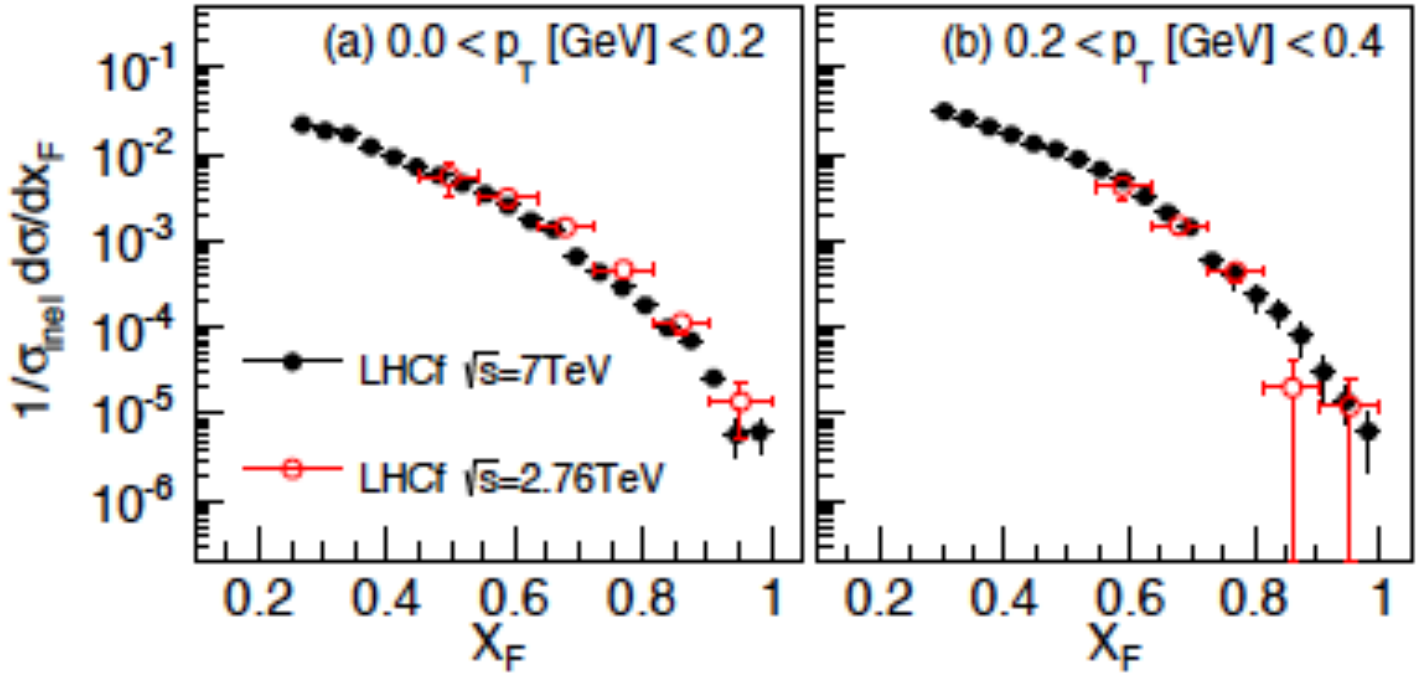
hadron spectrum@ 0 degree
(folded energy)

√s scaling

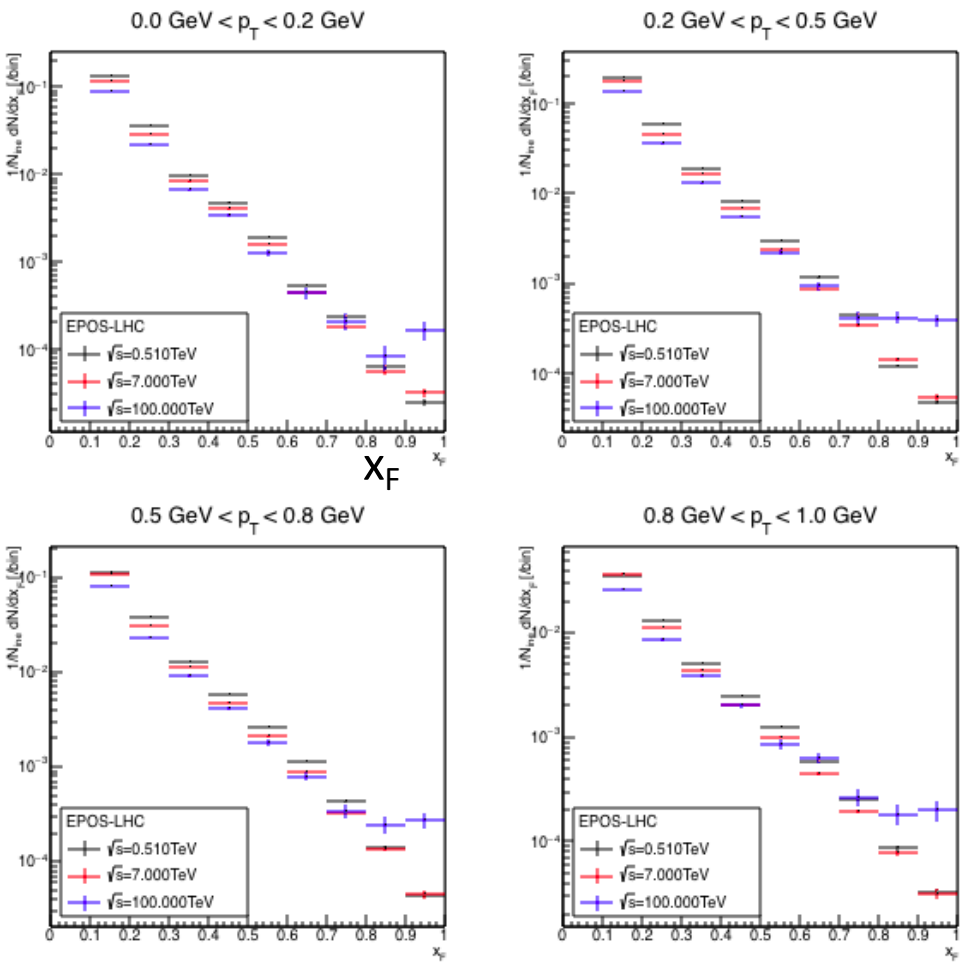
√s scaling ; π^0

- (630GeV –) 2.76TeV – 7TeV
  good scaling within uncertainties
- Wider coverage in y and p_T with 13TeV data
- Wider √s coverage with RHICf experiment in 2017 at √s=510GeV

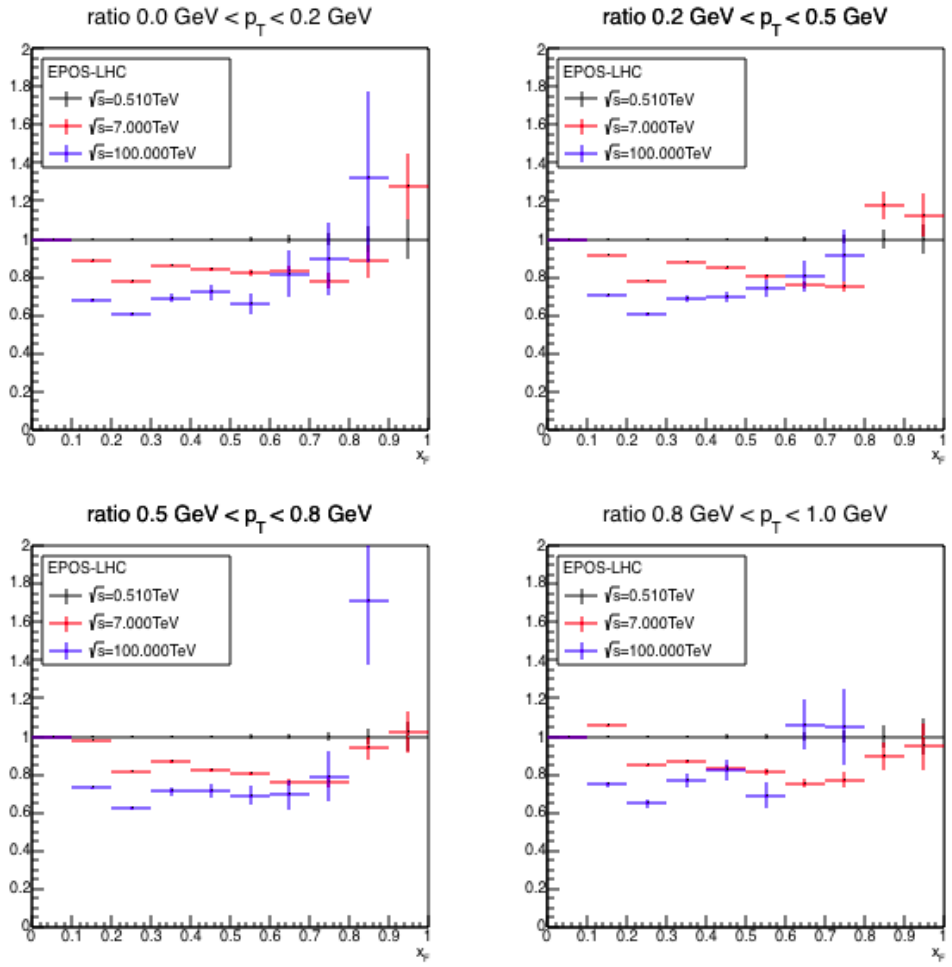




√s scaling in EPOS-LHC, π^0



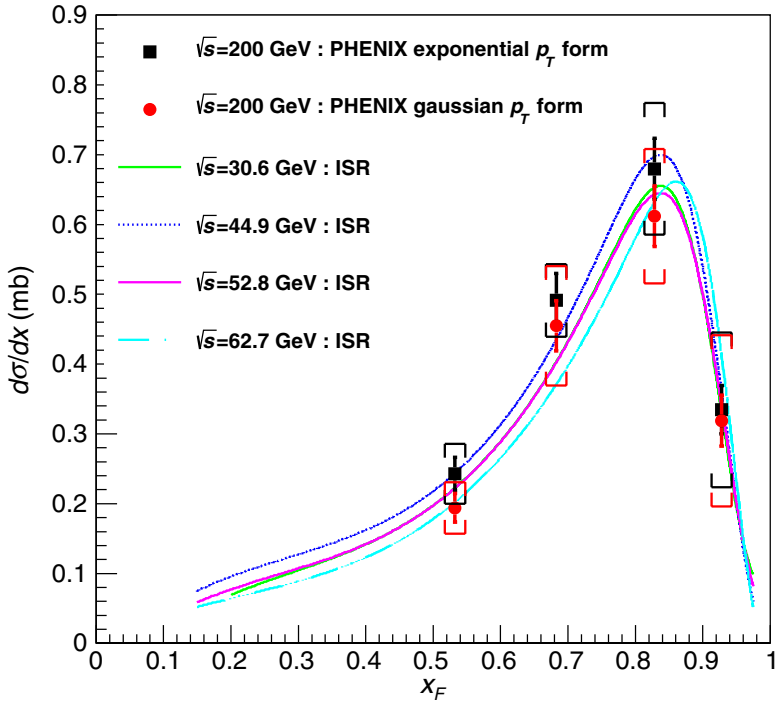
7TeV / 510GeV
100TeV / 510GeV



510GeV (RHIC)
7TeV (LHC)
100TeV (FCC)

(x14 each step)

√s scaling; Neutron

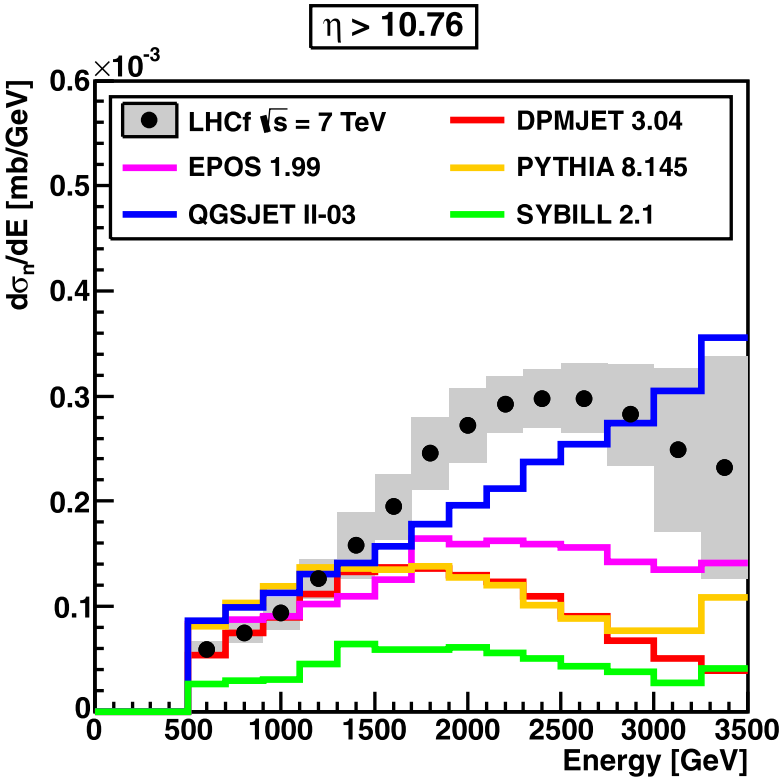


PHENIX, PRD, 88, 032006 (2013)

$p_T < 0.11\ x_F$ GeV/c

√s = 30-60 GeV @ISR

√s = 200 GeV @RHIC



LHCf

$p_T < 0.15\ x_F$ GeV/c

√s = 7000 GeV @LHC

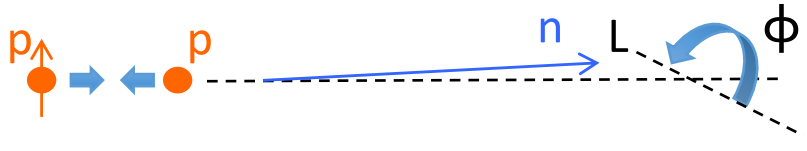
- PHENIX explains the result by 1 pion exchange
- More complicated exchanges at >TeV?

RHICf takes data at 510GeV p+p in RUN17

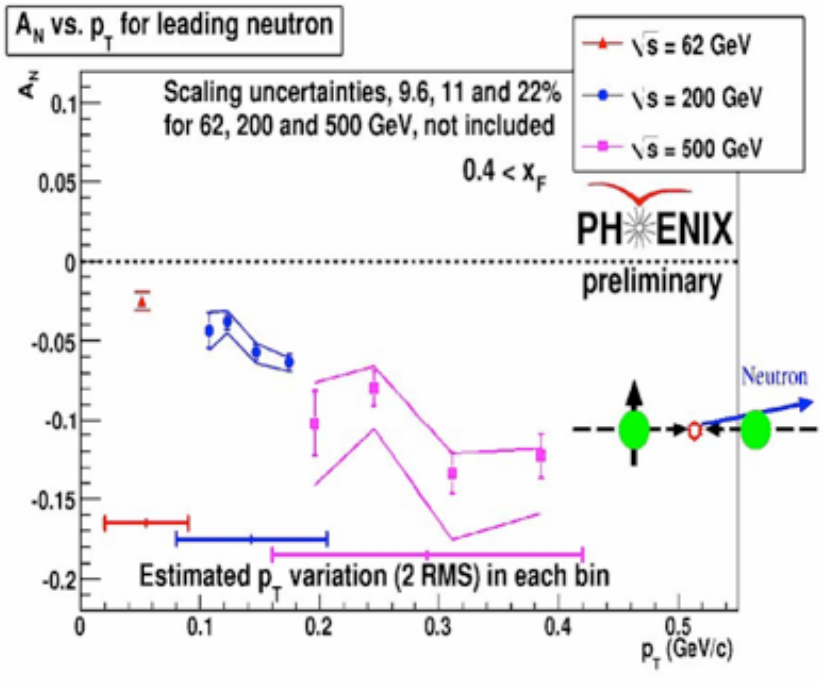
Single-Spin Asymmetry at RHIC

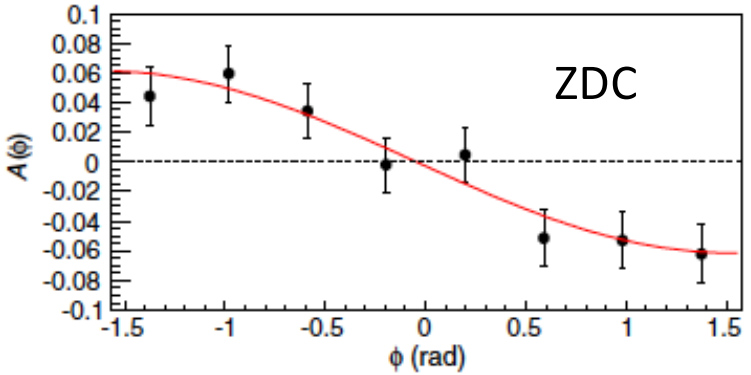
Single spin asymmetry by PHENIX

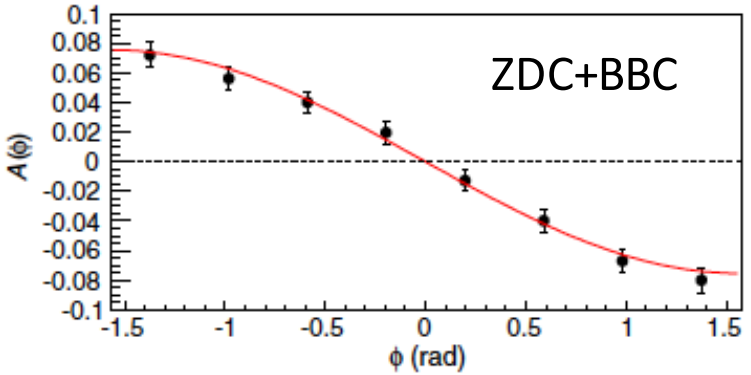
(PRD, 88, 032006, 2013)



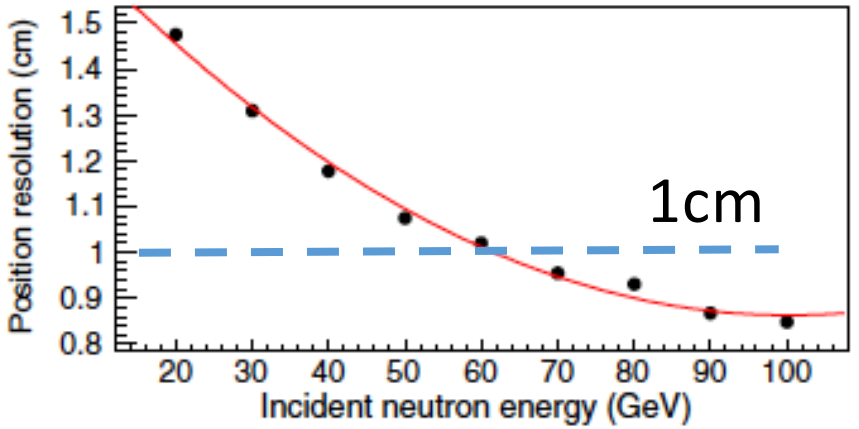
- ✓ strong asymmetry in forward neutrons was discovered at RHIC
- ✓ scaled with pT at √s = 62, 200, 500 GeV?
- ✓ position resolution ≈1cm





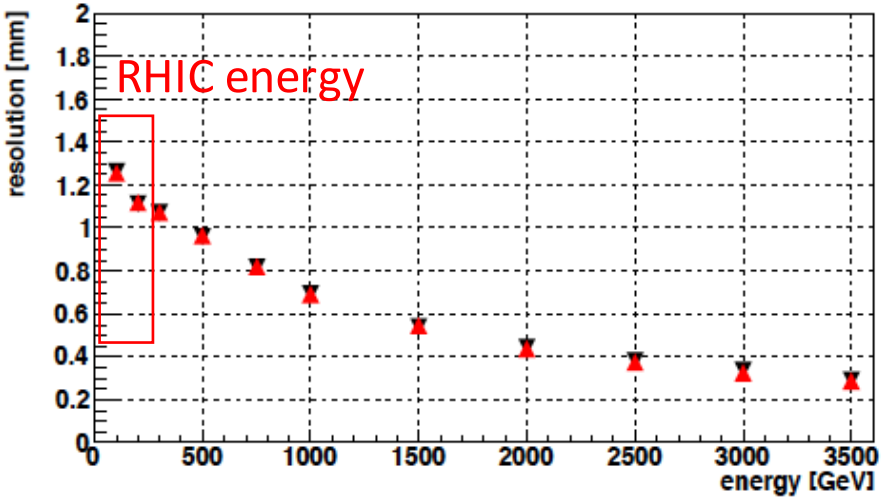


PHENIX results at 200GeV

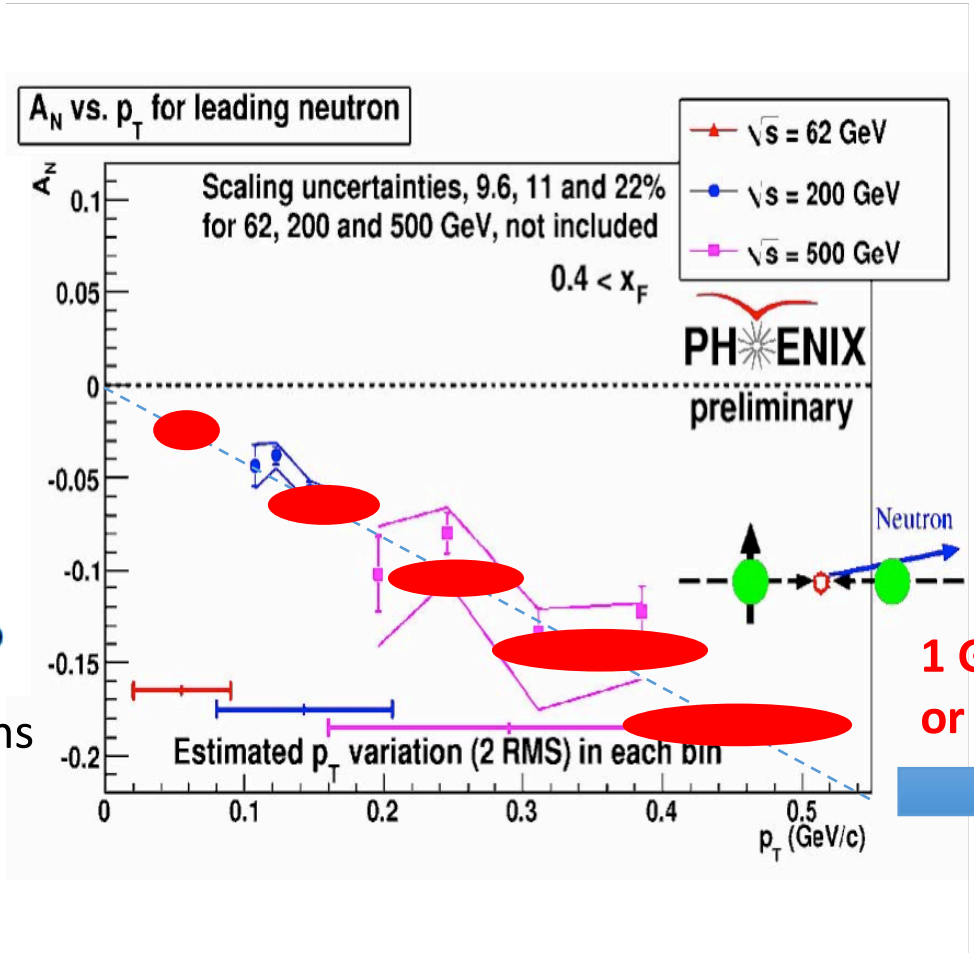


position resolution by SMD inserted in the PHENIX ZDC

Single spin asymmetry by RHICf



LHCf Arm1 position resolution for neutrons
(JINST, 9, P03016, 2014)



1 GeV/c or more

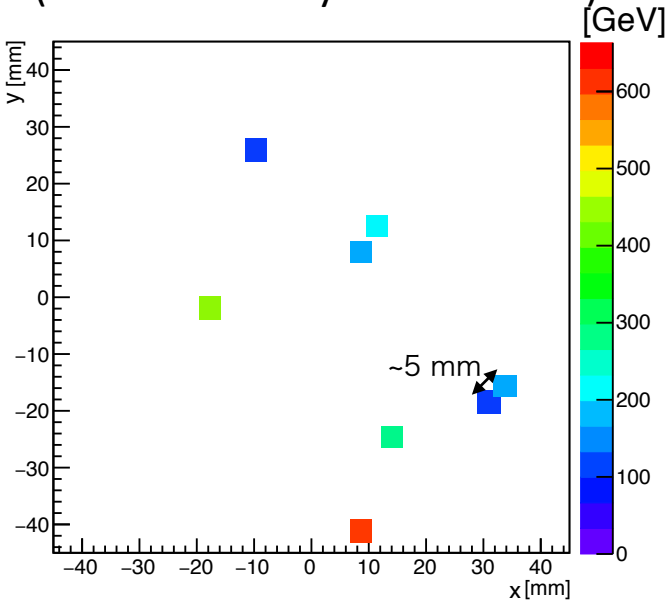
- Excellent position resolution allows to cover wide p_T in a single √s condition
- With horizontal polarization, covering p_T<1GeV/c

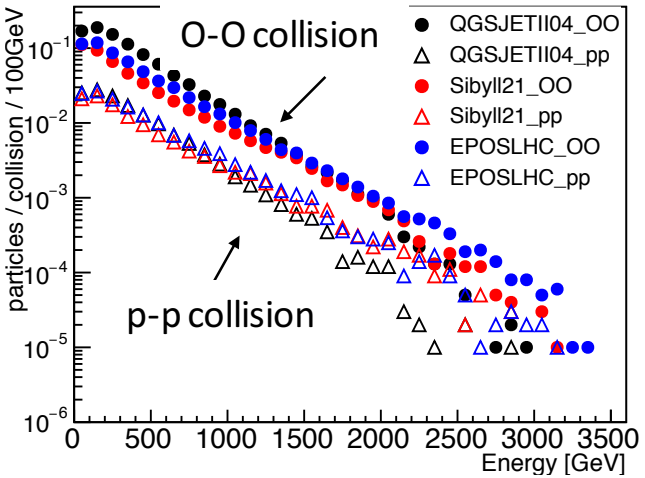
Very Future

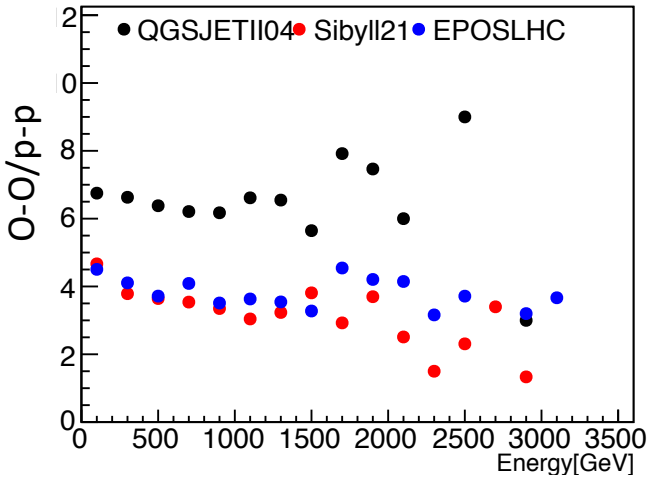
LHC O-O collisions ($\sqrt{s_{NN}}$=7TeV)

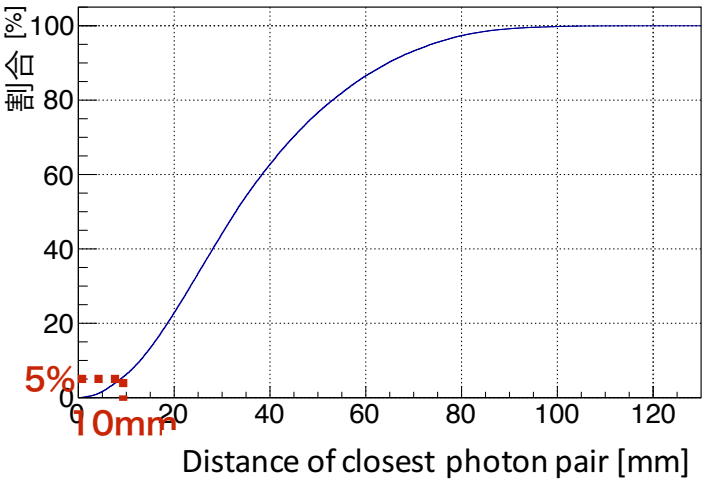
- LHC is TECHNICALLY able to accelerate and collide Oxygen beams
- Is nuclear effect in light ion collisions well understood?
- In A-A collisions, high multiplicity in the very forward region => new detector is required.

Event sample
Photon hit in 9cmx9cm
(neutron is not yet considered)

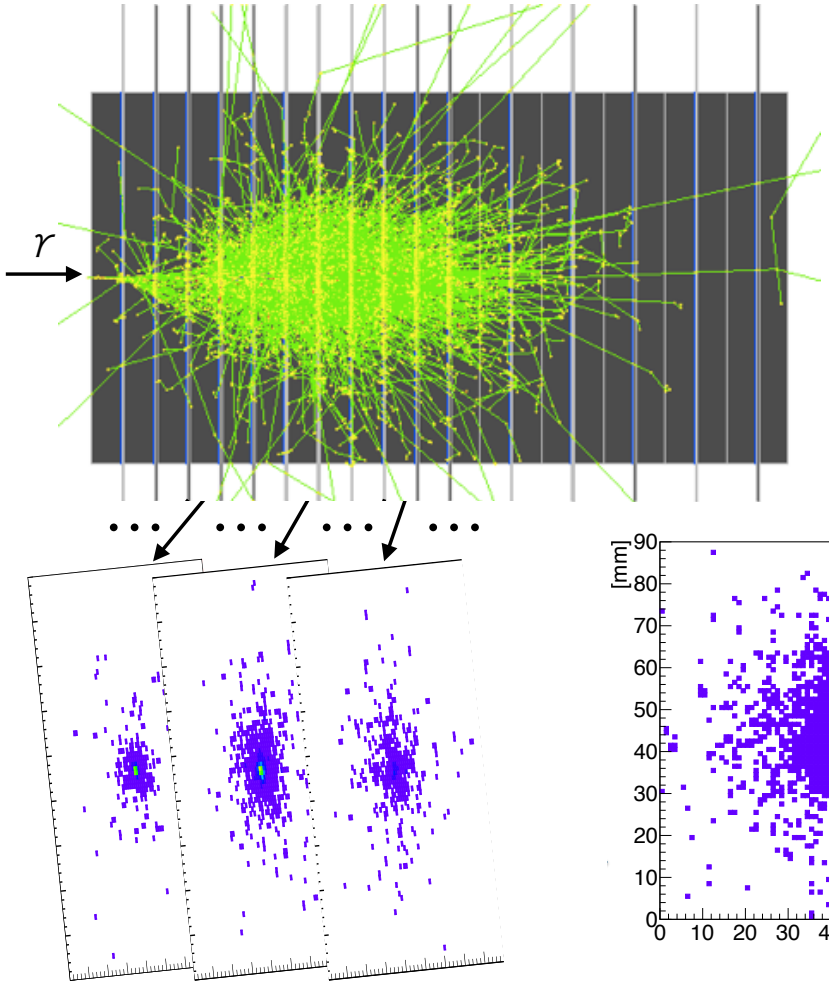




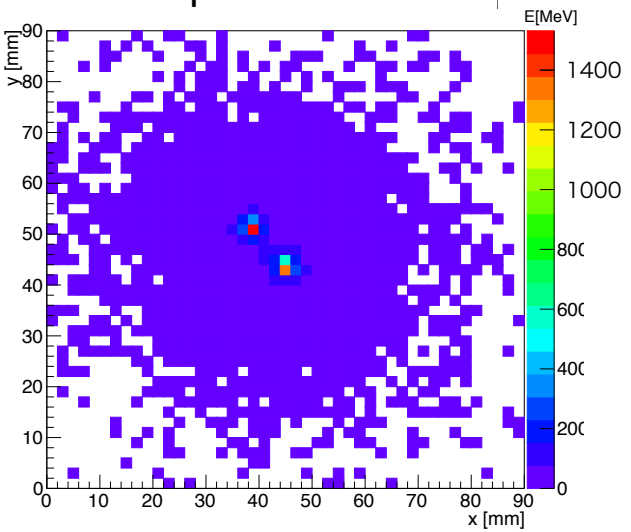




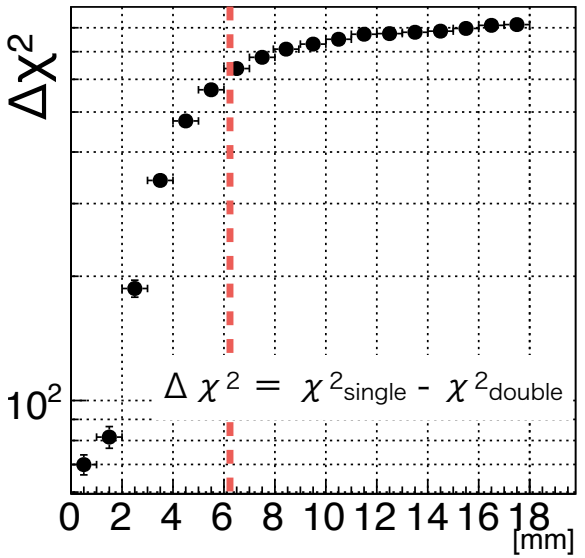
All pixelarized “Super ZDC”



2mm pixel size



2 photon separation power



Distance between photons

- Perfect electronics (no BG, perfect linearity, no saturation) are assumed

Summary

- LHCf/RHICf measure neutral particles at very characteristic phase space – zero degree – where a large fraction of collision energy is carried
- LHCf tests interaction models at LHC
  - EPOS-LHC and QGSJET II-04 are two best models to describe π^0 production
  - All models under produce neutrons
- √s scaling
  - Marginally scaling in π^0 between 2.76 and 7TeV is observed
  - Indication of scaling violation in neutron between 0.2 and 7TeV is observed
  - LHCf continues analysis of 0.9, 2.76, 7, and 13 TeV p-p collision data
  - RHICf will take data at 0.51TeV in 2017
- RCHIf is expected to test p_T scaling of single-spin asymmetry
- Detector design for future LHC O-O collision is on going

[not mentioned today: we have 5TeV p-Pb data and will have 8.2TeV p-Pb]