Proposal:
Precise measurements of very forward particle production at RHIC
-- RHICf experiment --

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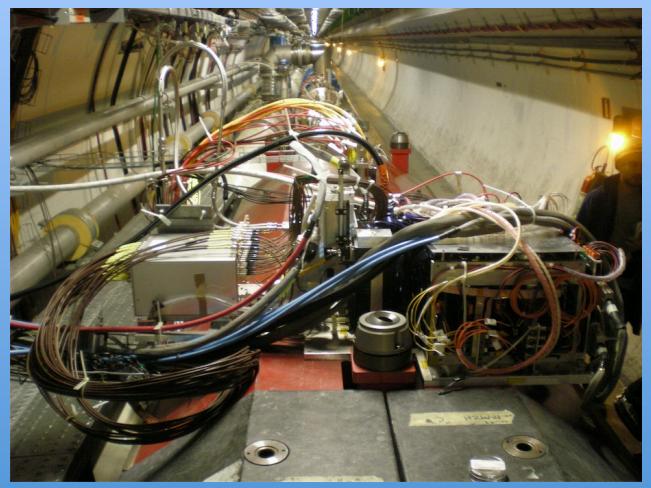
Outline of the proposal

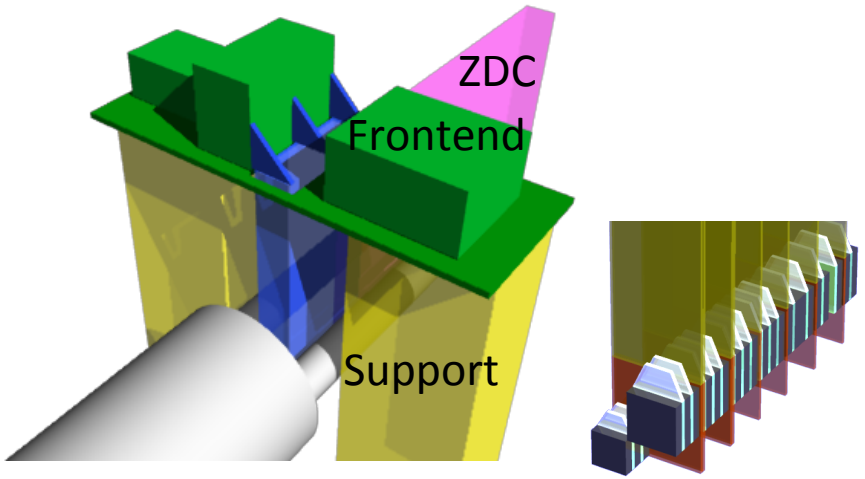
- Physics motivations:
  - Calibration of CR air shower interaction models in a wide range of √s, combining also the results at LHC
  - Precise measurements of spin asymmetry of forward particle production
- Technical idea:
  - To install position sensitive electromagnetic calorimeters in front of one of the PHENIX ZDCs using one of the existing LHCf detectors after the LHC 13TeV run (2015)
- Beam conditions:
  - 510 GeV polarized p+p collisions with β^*=10m
  - 1 day for physics and 1 day for contingency
  - 1-5 days for beam setup depending on the previous mode
  - Data taking in RUN16

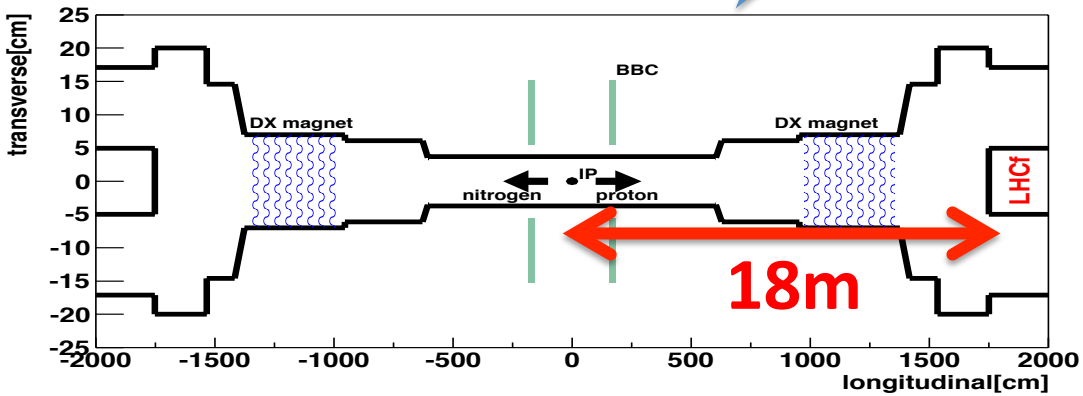
From the Large Hadron Collider to the Longisland Hadron Collider

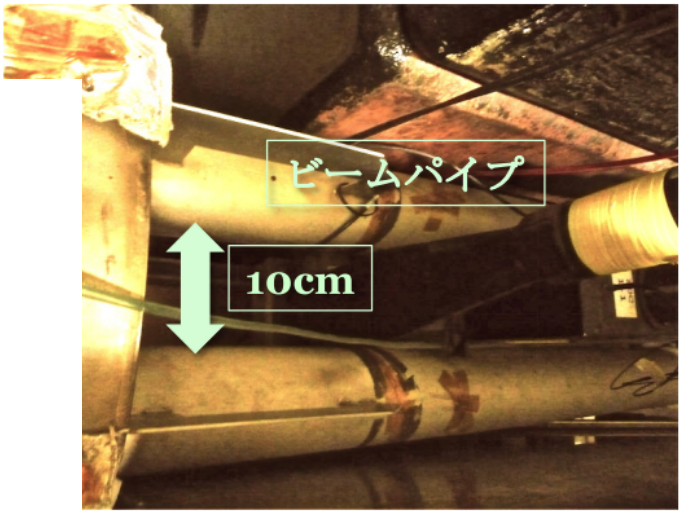
LHCf Arm2 detector in the LHC tunnel



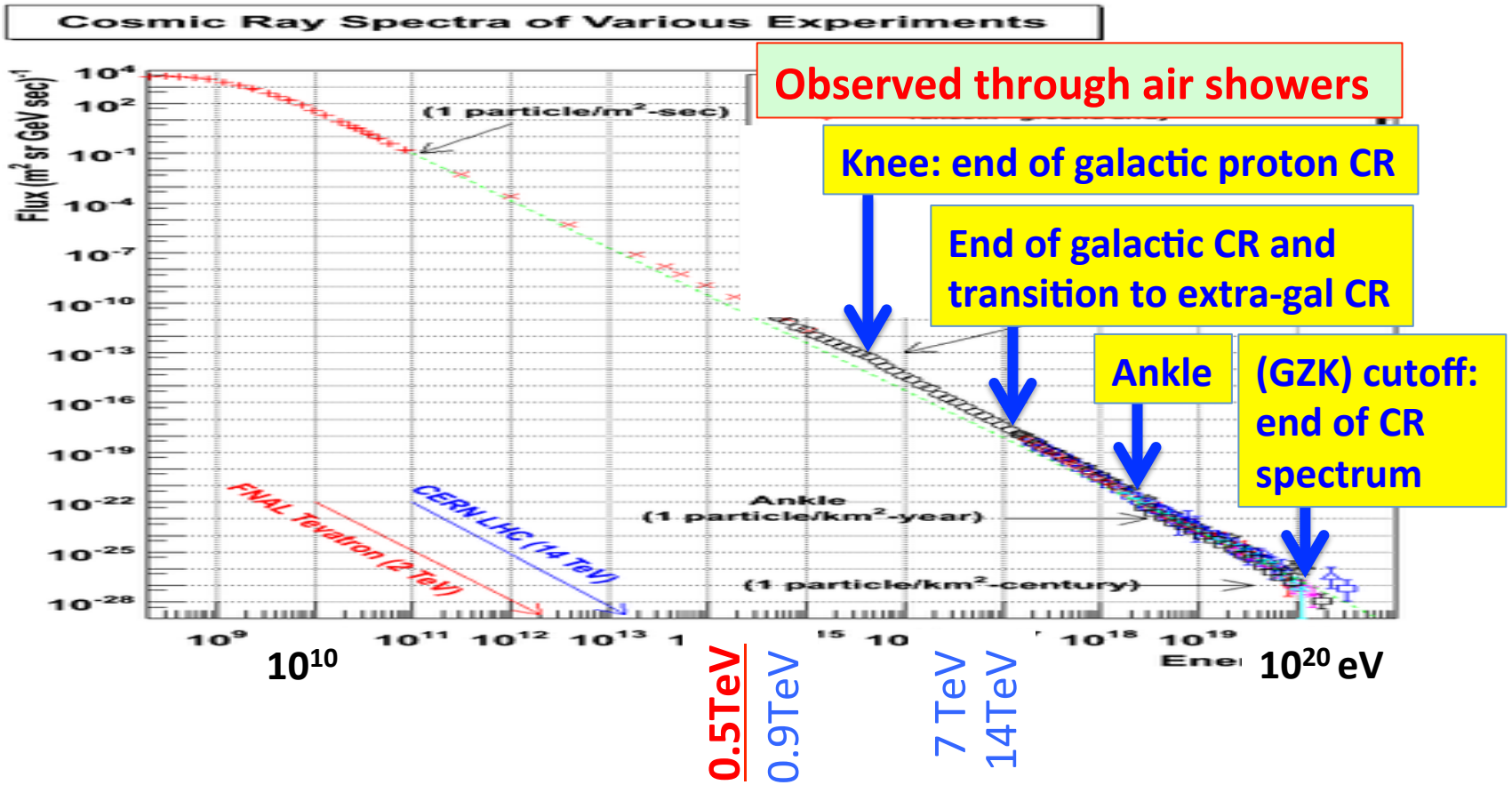
Schematic view of the RHICf installation



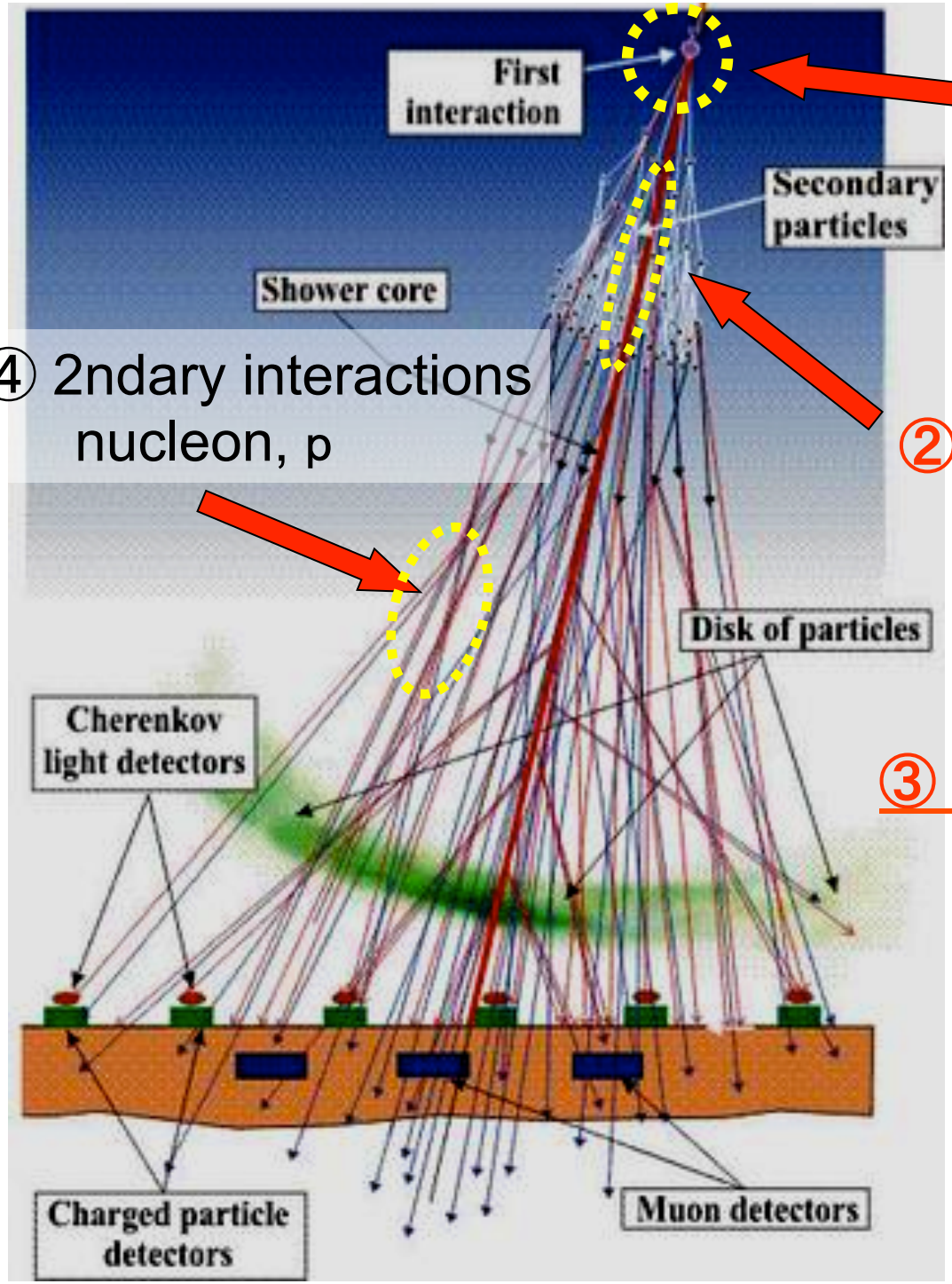




Cosmic-ray spectrum & Collider energy



- Interesting topics above knee (10^{15}eV)
- Observations are through air shower measurements
- Interpretation requires air shower simulations assuming hadronic interaction
- $\sqrt{s}$ dependence is important to extrapolate beyond the LHC energy



① Inelastic cross section

If large s
rapid development
If small s
deep penetrating

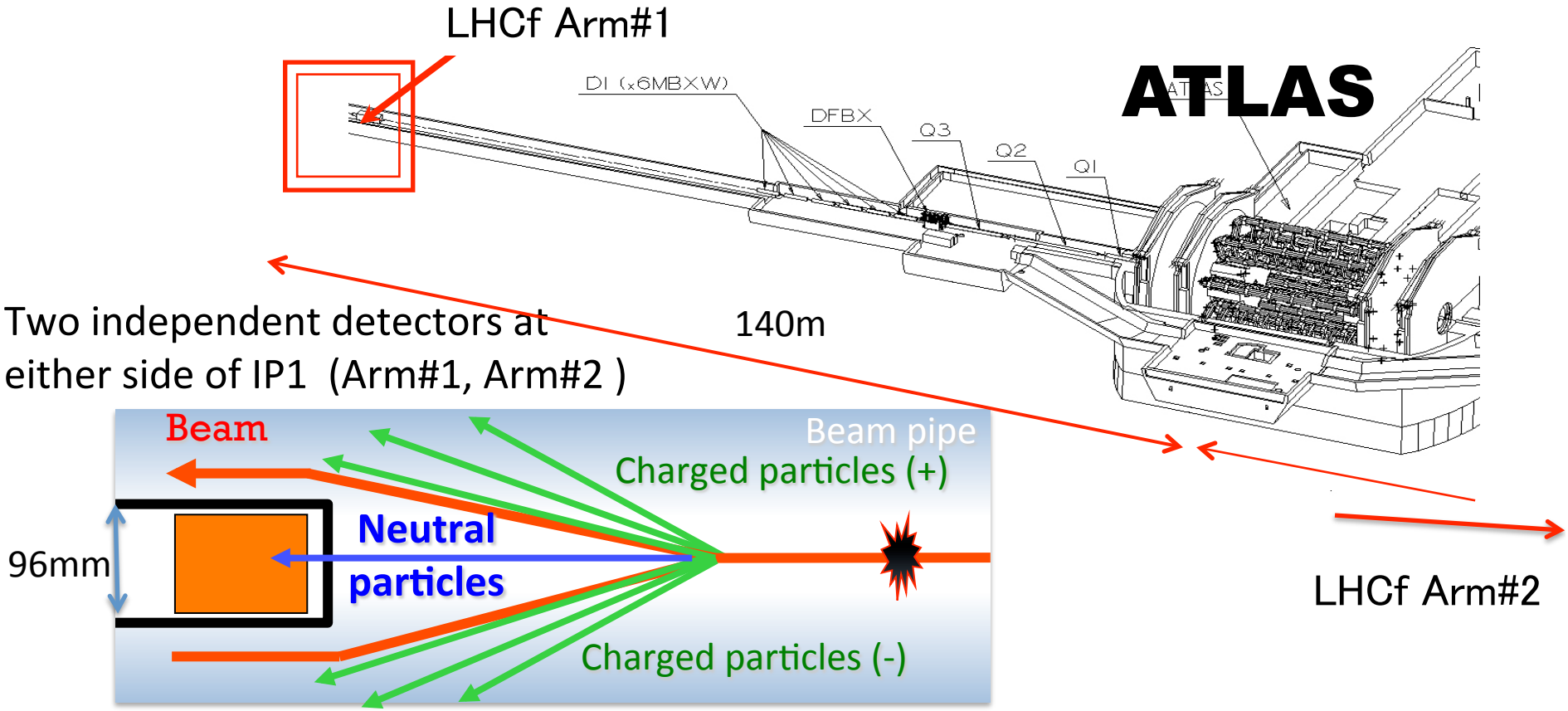
② **Forward energy spectrum**

If softer
shallow development
If harder
deep penetrating

③ **Inelasticity $k = 1 - p_{lead}/p_{beam}$**

If large k
(π^0s carry more energy)
rapid development
If small k
(baryons carry more energy)
deep penetrating

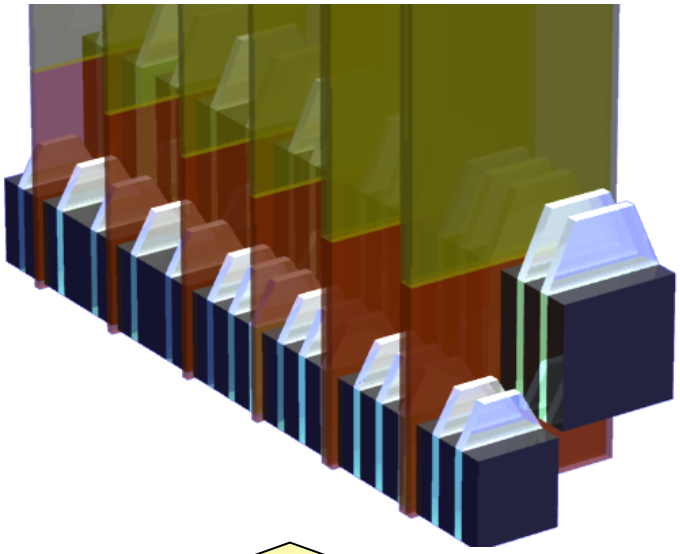
The LHC forward experiment



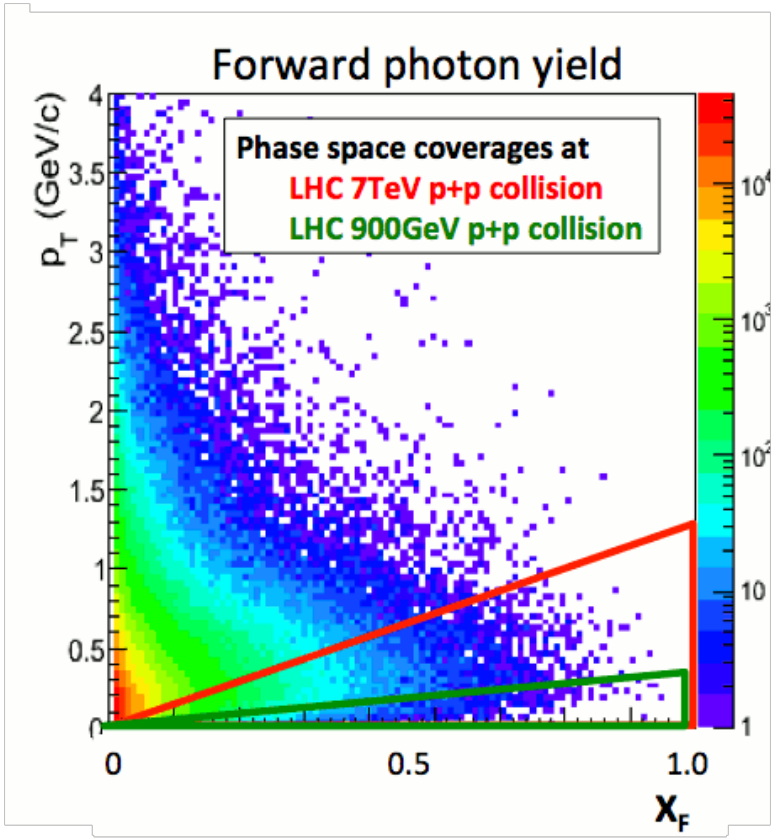
- All charged particles are swept by dipole magnet
- Neutral particles (photons and neutrons) arrive at LHCf
- 0 degree is covered
- Successfully operated at LHC 900GeV, 2.76TeV, 7TeV p+p collisions and 5TeV p+Pb collisions

LHCf Arm2 Detector => RHICf Detector

- Imaging sampling shower calorimeters
- Two calorimeter towers
- Each tower has 44 r.l. of Tungsten,16 sampling scintillators and 8 (4XY pairs) silicon strip sensors

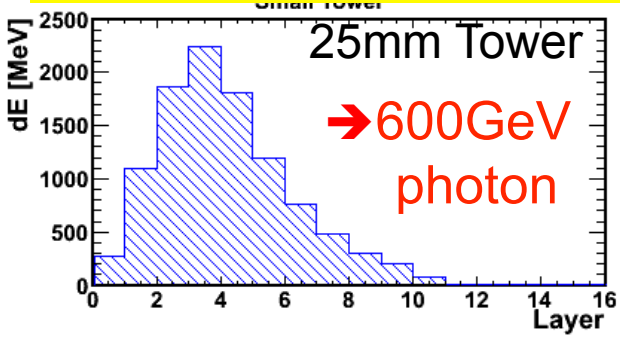


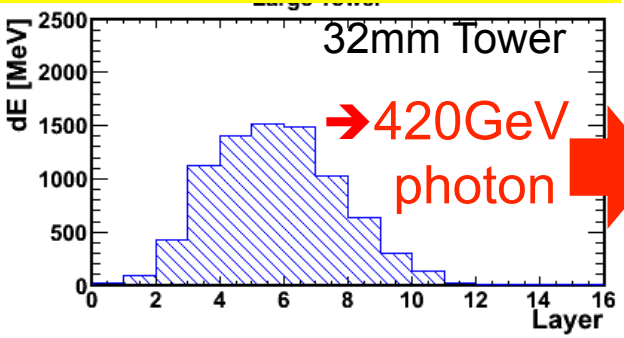
Arm#2 Detector
25mmx25mm+32mmx32mm
4 XY Silicon strip detectors



Event sample ($\pi^0 \rightarrow 2\gamma$) at LHC 7TeV p+p

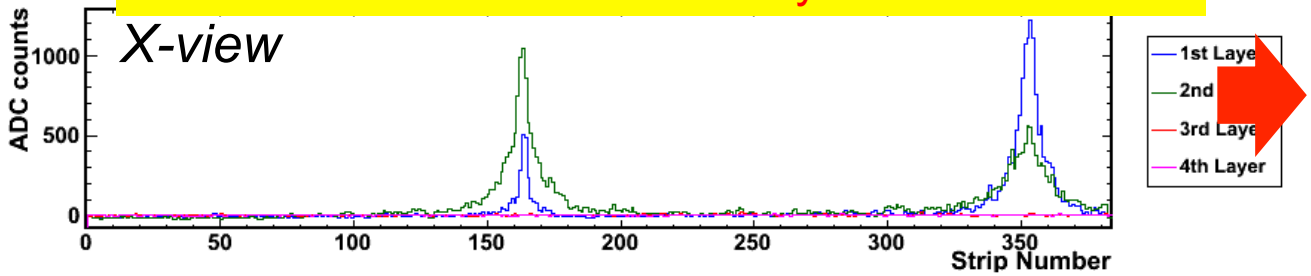
Longitudinal development measured by scintillator layers



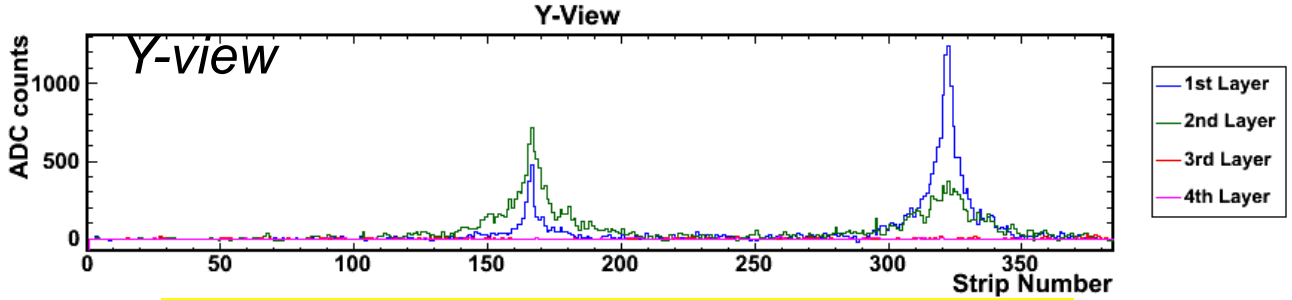


Total Energy deposit
➔Energy
Shape
➔PID

Lateral distribution measured by silicon detectors



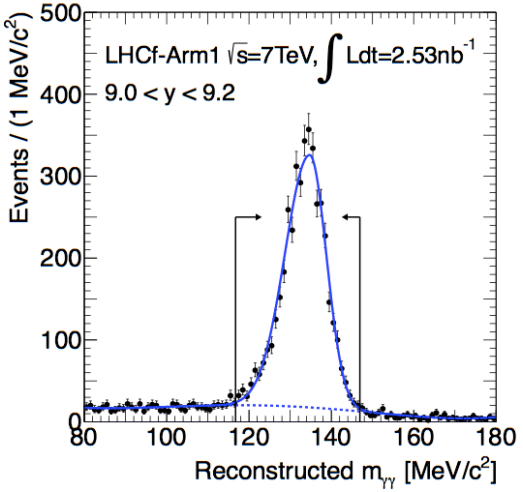
Hit position,
Multi-hit search.



π^0 mass reconstruction from two photon.

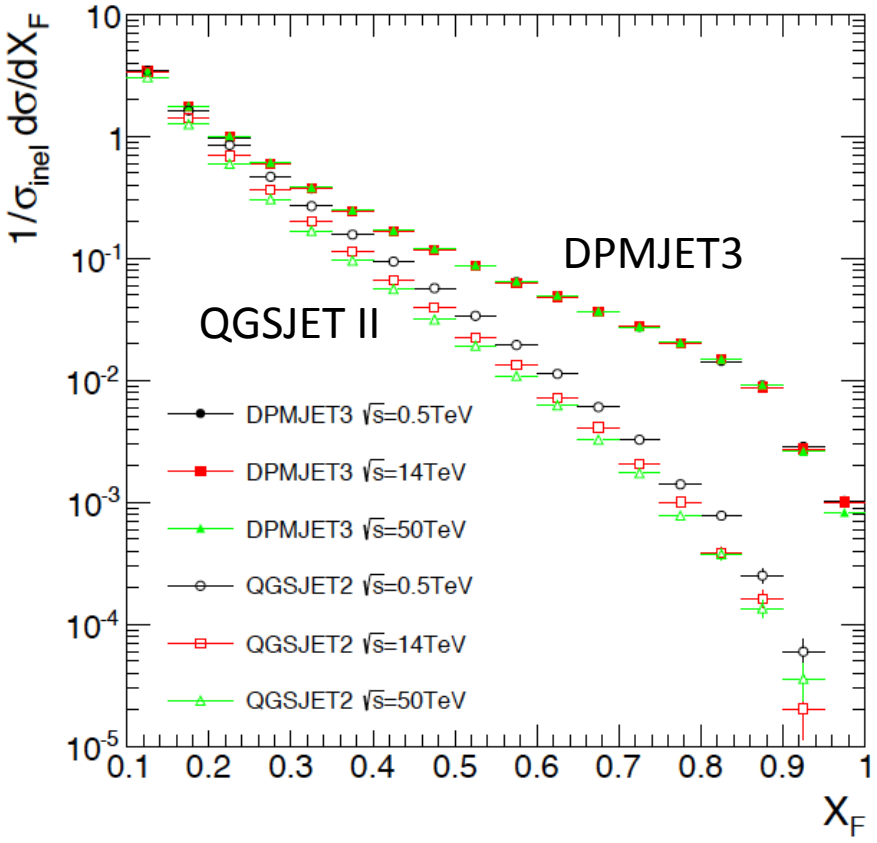
$$M_{\pi 0} = \sqrt{E_{\gamma 1} E_{\gamma 2}} \cdot \theta$$

Systematic studies

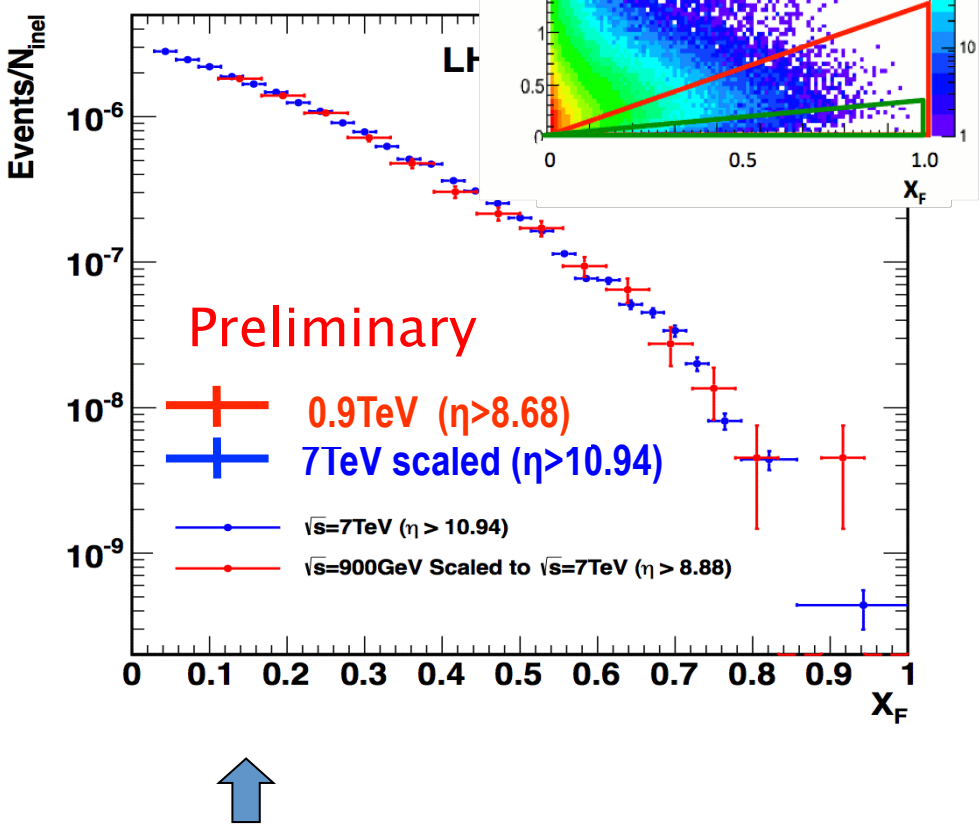


√s scaling : a key for extrapolation beyond the LHC

All π^0 expected from models (0.5TeV, 14TeV and 50TeV)



LHCf single photon data (900GeV pp , 7TeV pp)

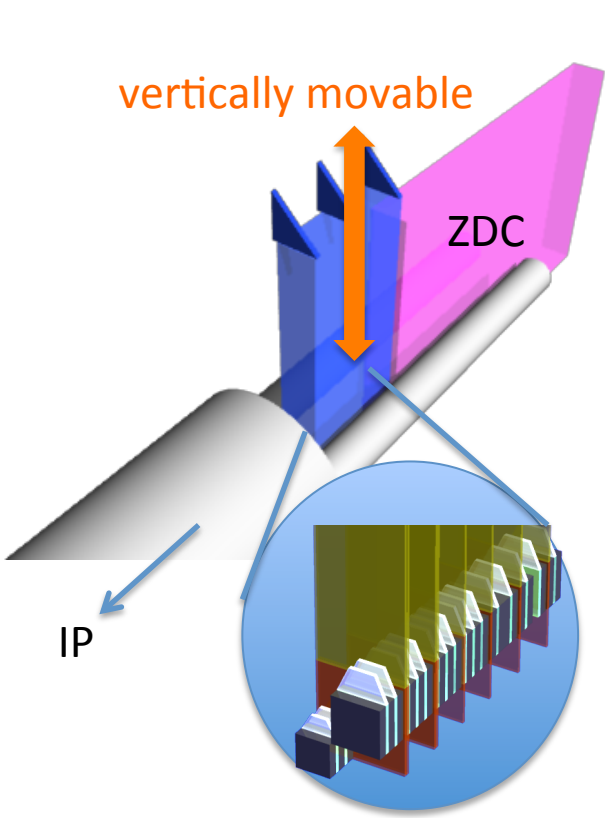


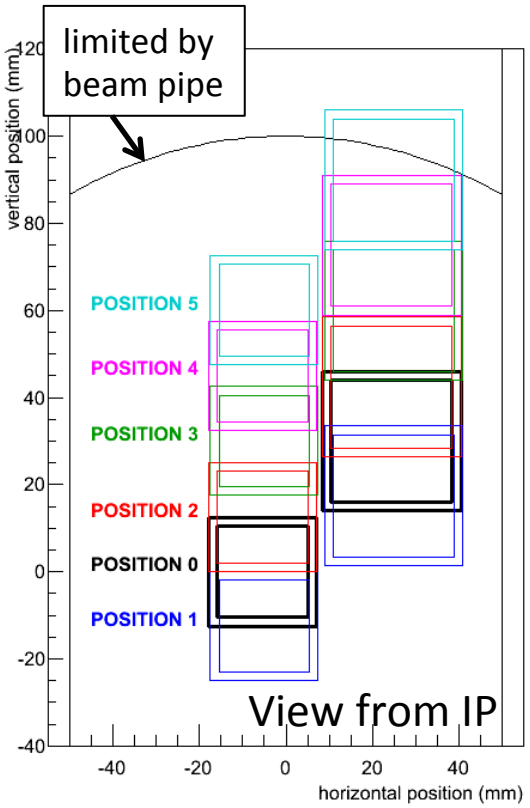
Comparison done in the very limited phase space of 900GeV collisions

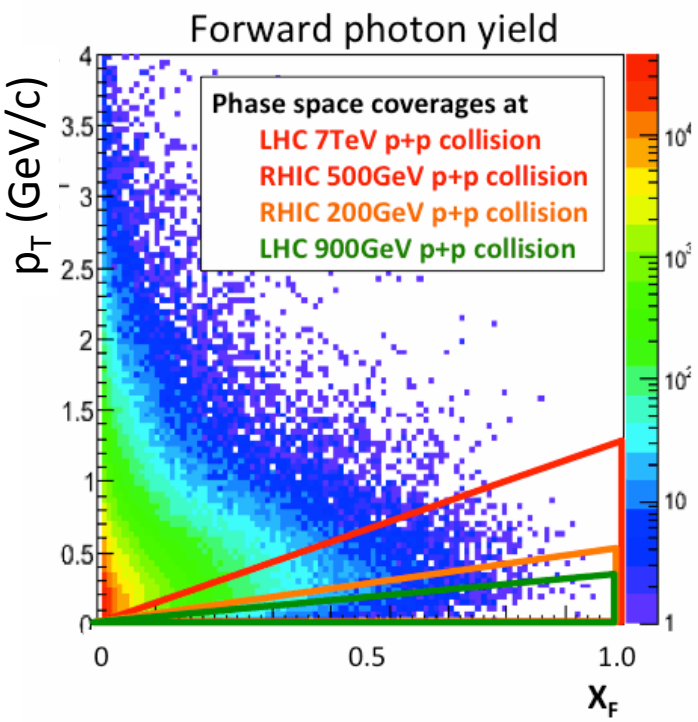
(green triangle in the phase space plot)

RHICf coverage

Installing the LHCf Arm2 detector at RHIC (PHENIX IP)

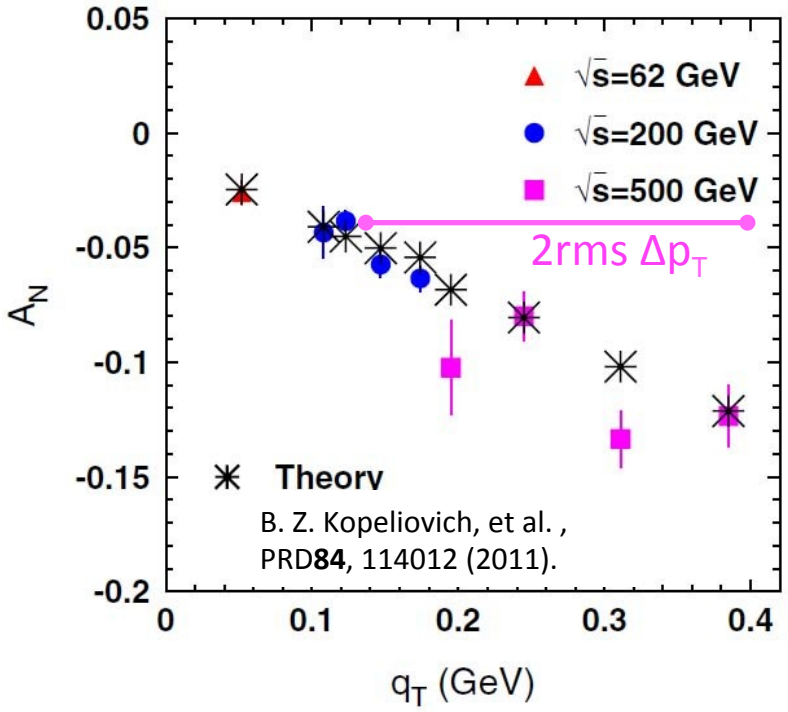






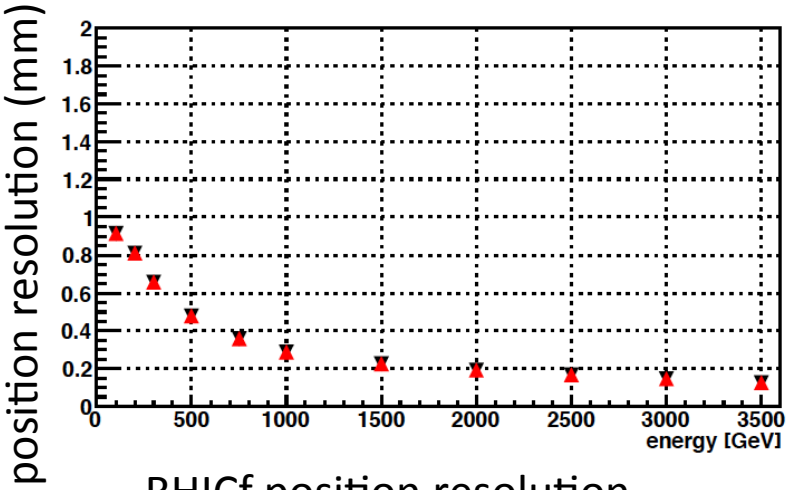
- Detector is moved up-down; wide p_T coverage and to avoid ZDC interference
- x_F-p_T coverage identical to LHC 7TeV collision
- Wider coverage and higher resolution in p_T than PHENIX ZDC+SMD measurements (joint analysis between ZDC and RHICf)

Spin asymmetry by PHENIX

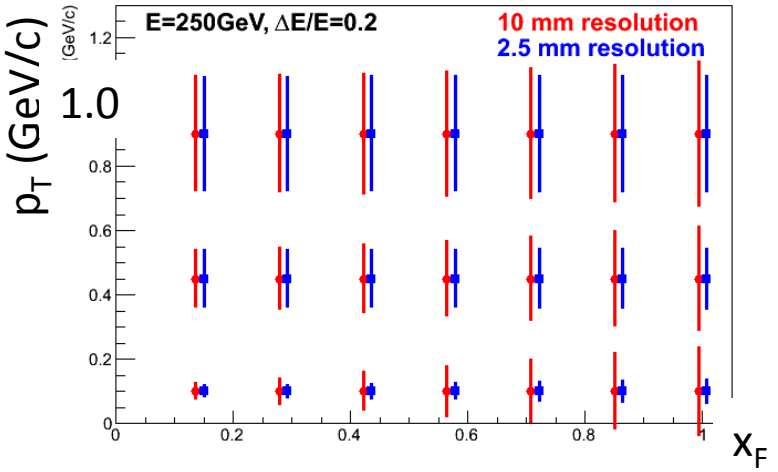


PHENIX result indicates p_T scaling in the neutron asymmetry

- Combination of RHICf and PHENIX ZDC can realize a wide p_T coverage with a higher resolution



RHICf position resolution for hadronic showers



p_T resolution of ZDC+SMD and ZDC+RHICf

RHICf beam condition proposal

- Constraints
  - RHICf DAQ speed is limited to 1kHz
  - Collision pile up cannot be resolved
  - Small angular dispersion is preferred
- Beam Proposal
  - 510GeV p+p collisions
  - $\beta^* = 10$m
  - Radial (horizontal) polarization; 0.4-0.5
  - $\varepsilon = 20$mm mrad, $I_b = 2\times10^{11}$, $n_{b\text{-colliding}} = 100$, $n_{b\text{-noncolliding}} = 20$ (nominal)
- Operation
  - 1 day for physics and another day for contingency
  - π^0 (double tower event) enhanced and single shower prescaled triggers are used simultaneously
  - Trigger exchange with PHENIX
  - Stay at the garage position not to interfere ZDC when RHICf does not take data

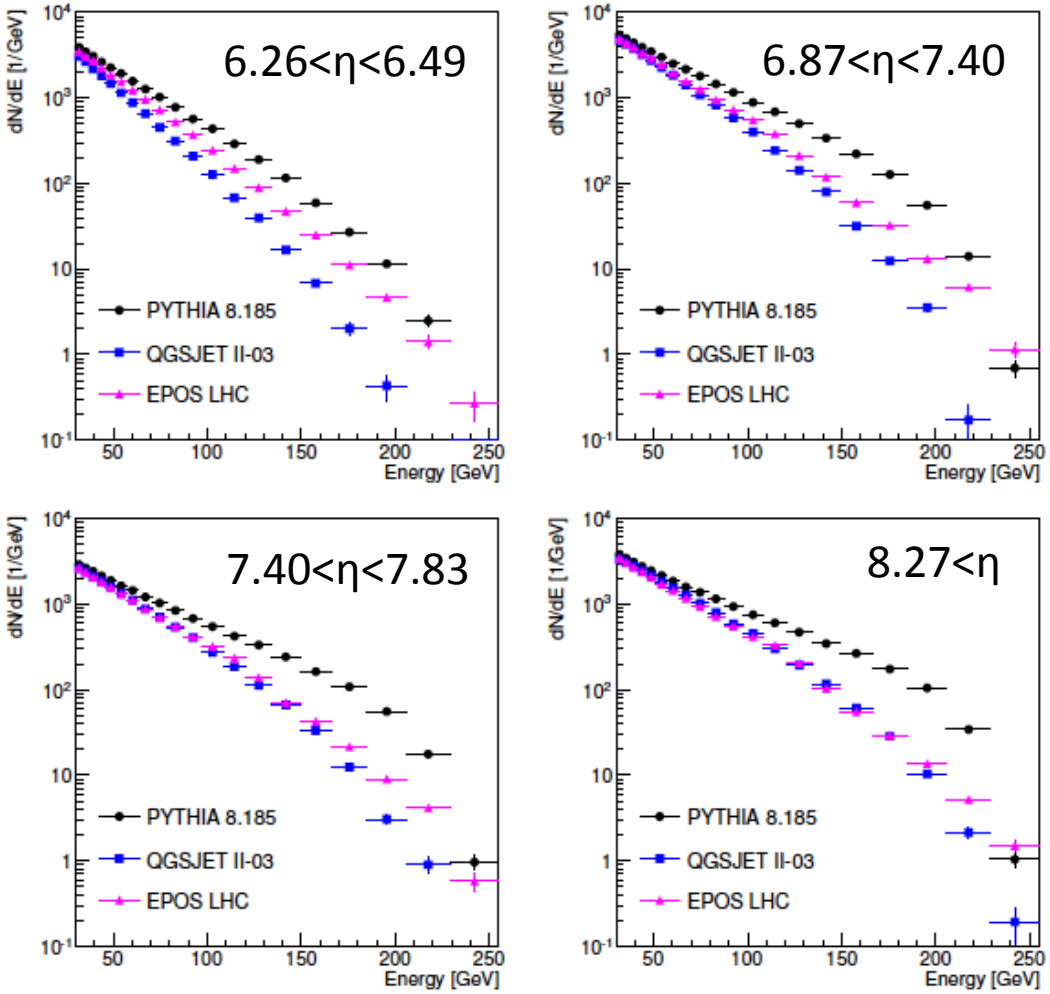
Beam setup time

"RHIC Collider Projection (FY2014–FY2018) version 6 April 2014"

- Previous mode: polarized protons at the same energy
  - 1 day of setup is needed
  - expected polarization is the same as in the previous running mode
- Previous mode: polarized protons at different energy
  - 2 days of setup are needed
  - some reduction in the proton intensity per bunch
  - expected polarization at 255 GeV is up to 55%
- Previous mode: heavy ions
  - 4-5 days of setup are needed
  - reduction in the proton intensity per bunch by up to 30%
  - expected polarization at 255 GeV is up to 50%
  - since the polarimeters also need commissioning time, the polarization measurements will have a large error

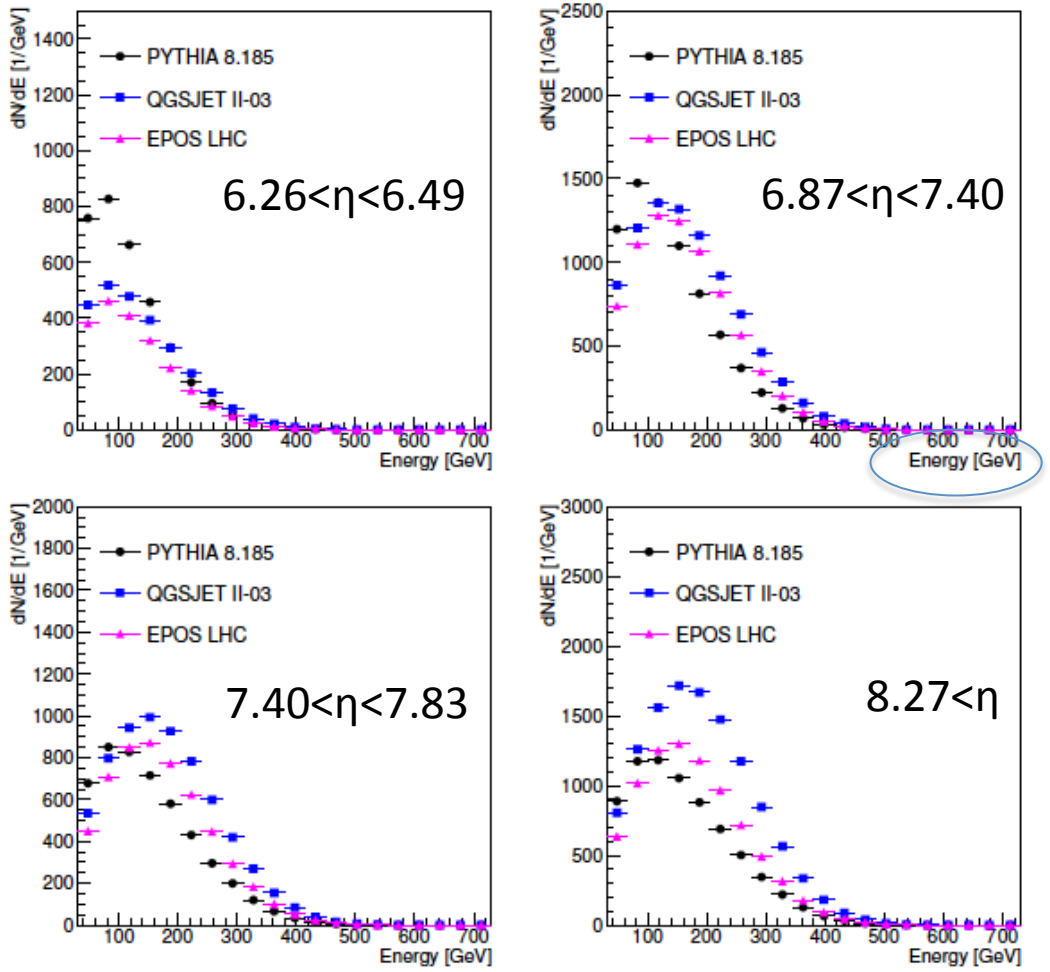
preferred case

Expected Results (single photons)



- Photon spectra at 4 rapidity samples
- 12 hours statistics (12 nb^{-1} effective luminosity; 360nb^{-1} delivered)
- Statistical error is almost negligible except at the highest energy bins

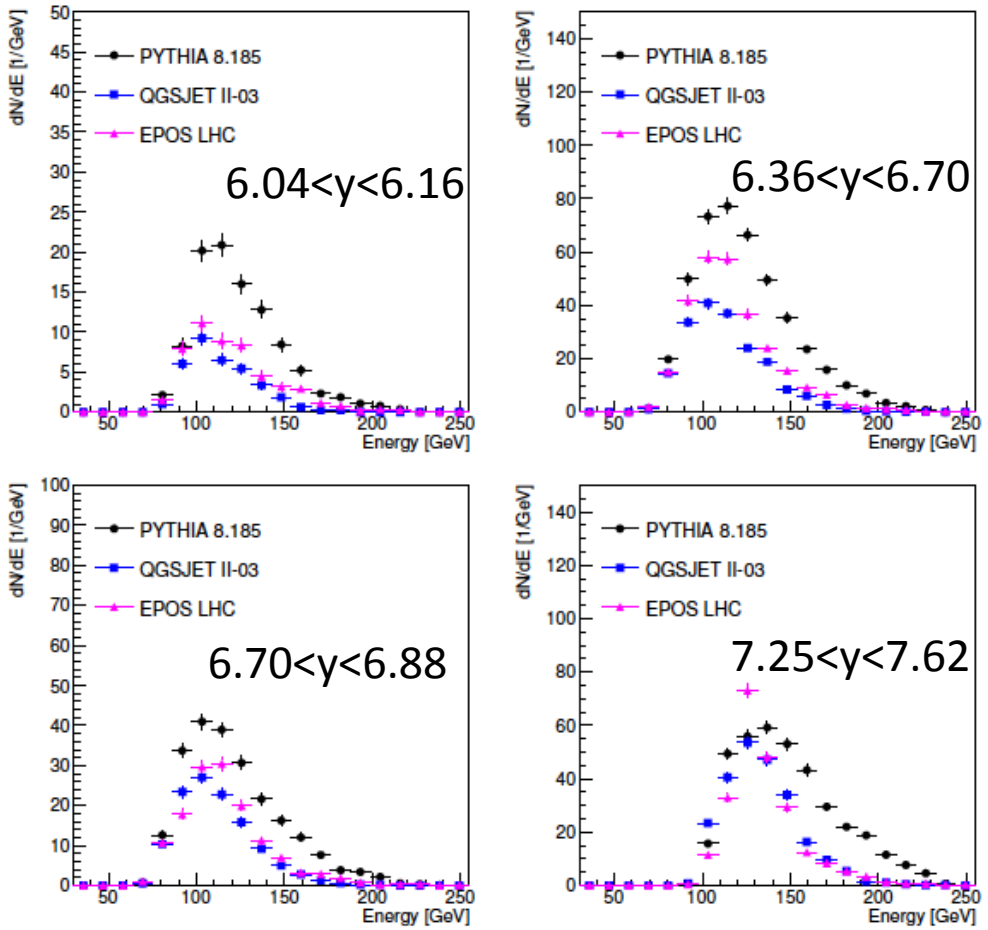
Expected Results (single neutrons)



measured energy
(resolution folded)

- Neutron spectra at 4 rapidity samples
- 12 hours statistics (12 nb^{-1} effective luminosity; 360nb^{-1} delivered)
- RHICf resolution taken into account, but ZDC joint analysis not considered
- Statistical error is almost negligible

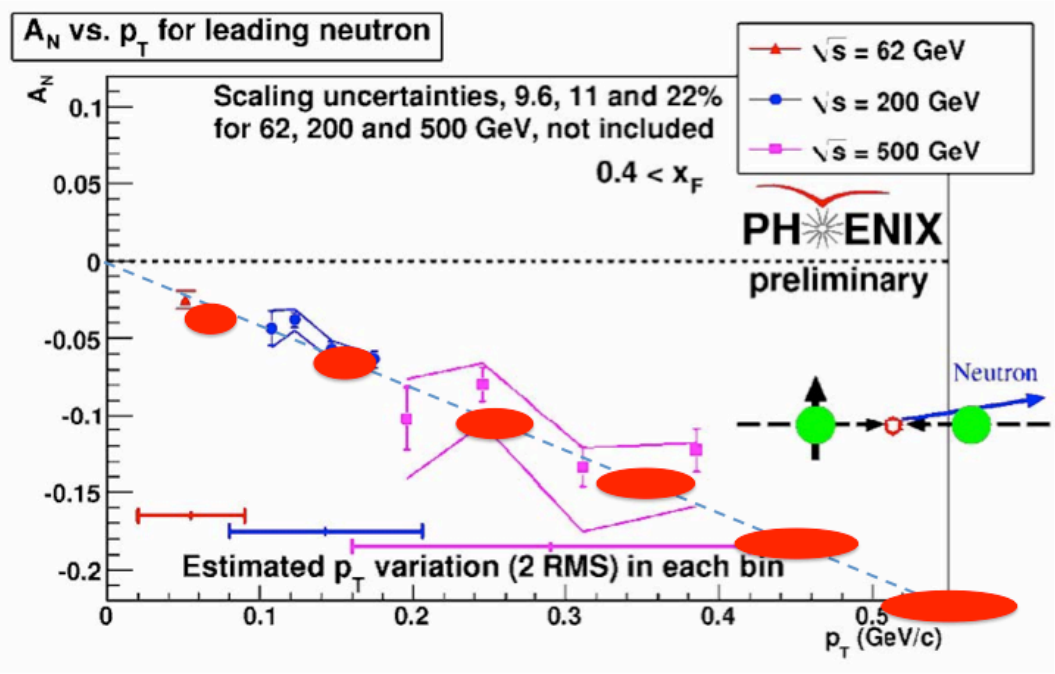
Expected Results (π^0)



- π^0 spectra at 4 rapidity samples
- <60GeV not detectable due to large opening angle of γγ
- 24 min statistics (12 nb^{-1} effective luminosity; 12 nb^{-1} delivered)
- Statistical error will be negligible with a reasonable run time

Expected Results (asymmetry)

	neutron		photon		π^0	
p_T (GeV/c)	$N(\times 10^3)$	δA	$N(\times 10^3)$	δA	$N(\times 10^3)$	δA
0.0 – 0.1	660	0.0025	110	0.0060	100	0.0063
0.1 – 0.2	920	0.0021	120	0.0058	130	0.0055
0.2 – 0.3	820	0.0022	110	0.0060	89	0.0067
0.3 – 0.4	670	0.0024	79	0.0071	58	0.0083
0.4 – 0.5	450	0.0030	43	0.0096	37	0.010
0.5 – 0.6	250	0.0040	18	0.015	14	0.017
0.6 – 0.8	170	0.0049	8	0.022	8	0.022
0.8 – 1.0	29	0.012	1	0.063	1	0.063

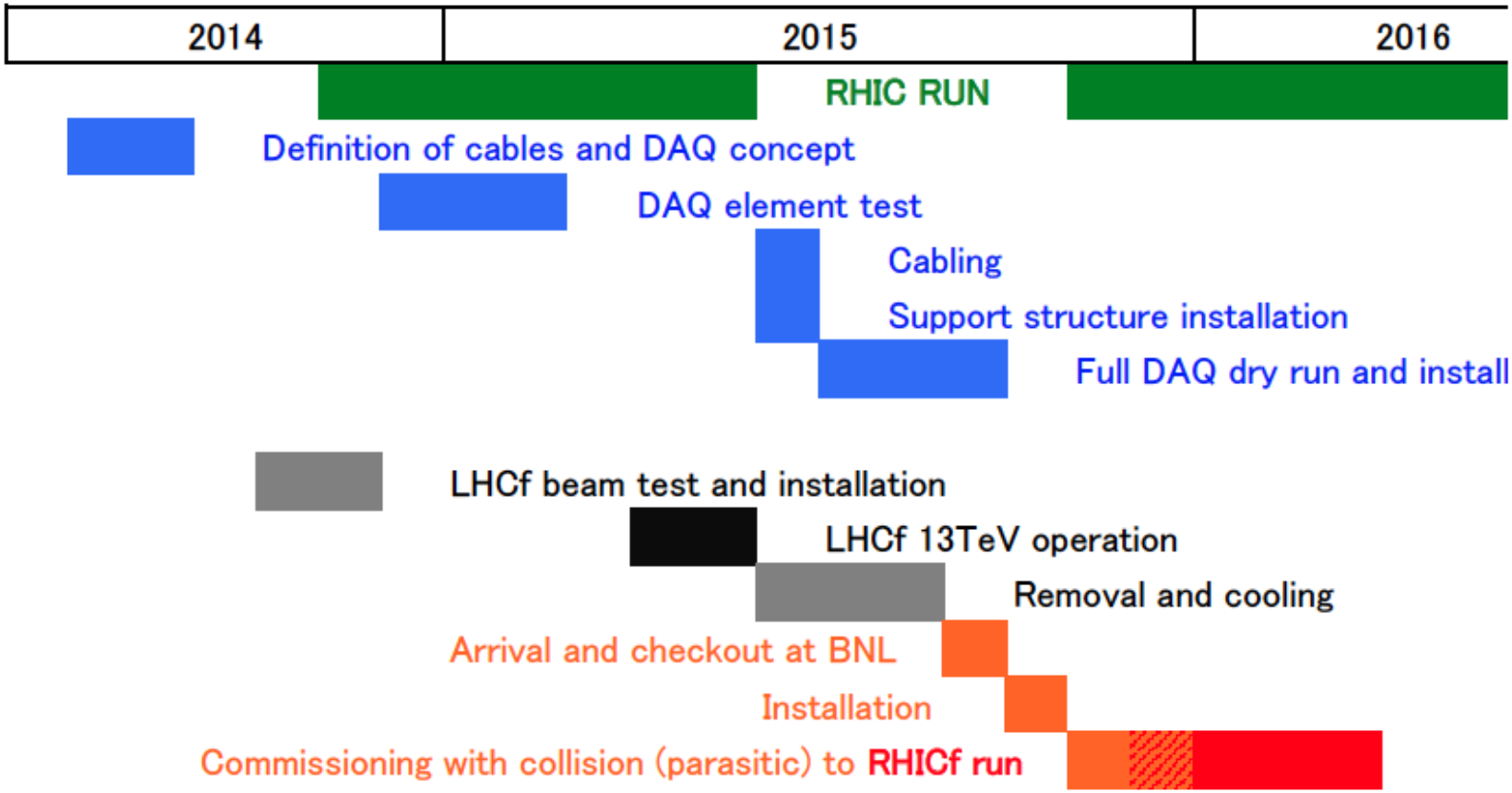


- single-spin asymmetry; statistics expected by PYTHIA 8
- 12 hours for single particles (10^8 collisions at each position)
- 4 hours for π^0 (10^9 collisions at each position)
- Same dataset as the spectral analysis

- RHICf+ZDC p_T resolution and ±1% errors are plotted over PHENIX result

Schedule

- LHCf Arm2 detector will be removed from LHC in June 2015 (weak radio activation is expected)
- Detector will arrive at BNL in 2015 autumn
- RHICf run in RUN16



Technical discussions on going

(Discussions at BNL in 19-20 May)

- Cabling
  - Normal and shortcut routes from ZDC to PHENIX rack room are in consideration
  - Some power supplies will be installed near ZDC
- Detector support
  - Available space for installation will be surveyed in this summer
- Clock and timing signal
  - Will be provided from PHENIX
- Trigger exchange with PHENIX
  - RHICf -> PHENIX is the base idea
  - Sharing the PHENIX clock counter to identify the common events

Expected supports from BNL/PHENIX

- Manpower for cabling
- Construction and installation of the support structure
- Transportation, installation and geometrical survey of the detector (and mockup for test this procedure)
- Support for the custom process from CERN/ Italy/Japan to BNL

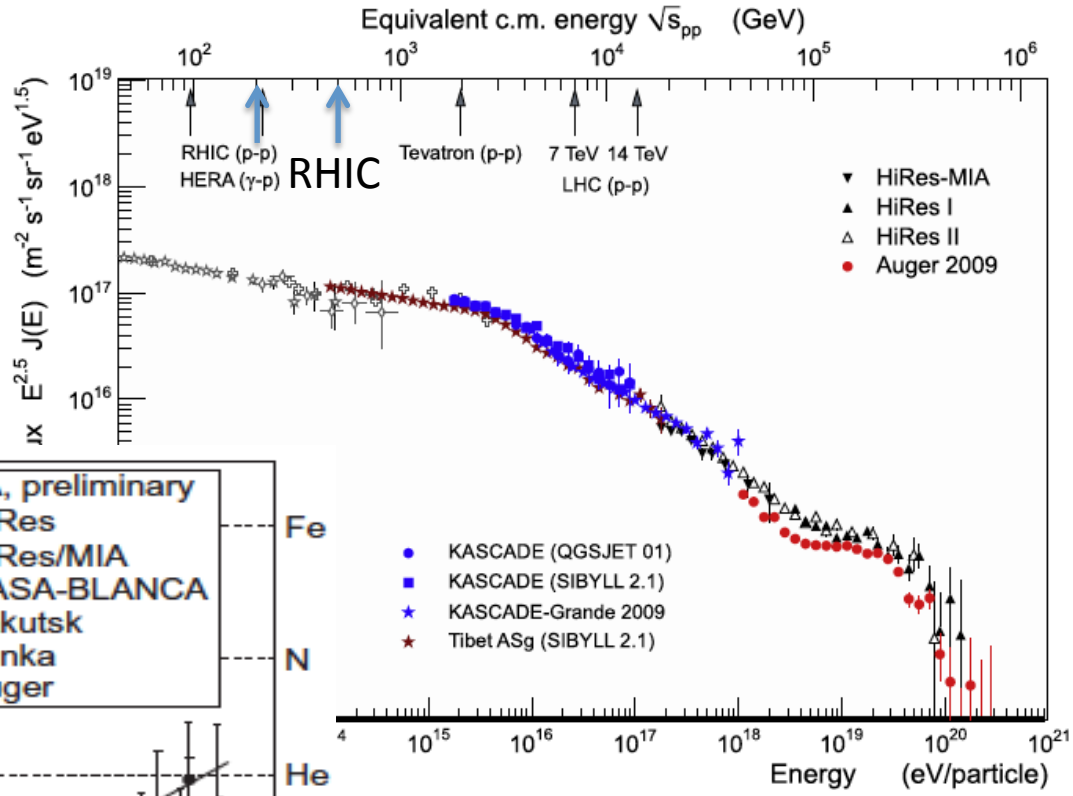
Summary

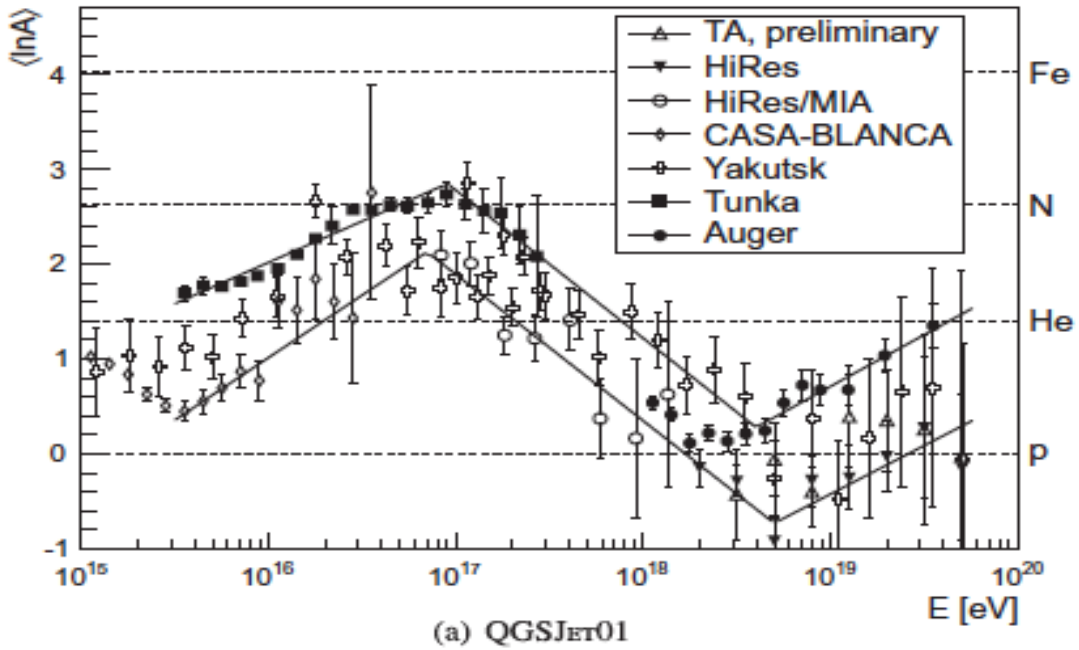
- RHICf is motivated
  - to calibrate cosmic-ray air shower interaction models in wide √s combined with LHC data
  - to measure the spin asymmetry of forward particle production in more detail
- Using the LHCf Arm2 detector, the experiment will be operational in RUN16
- 510GeV p+p collisions, radial polarization and β^*=10m (other parameters nominal) provide sufficient statistics in 1 day of operation
- Another day for contingency and 1-5 days of beam setup time are requested
- Technical details such as cabling, mechanical structure, clock and timing signals and trigger exchange with PHENIX are already in discussion

Backup

Recent progress on UHECR observation

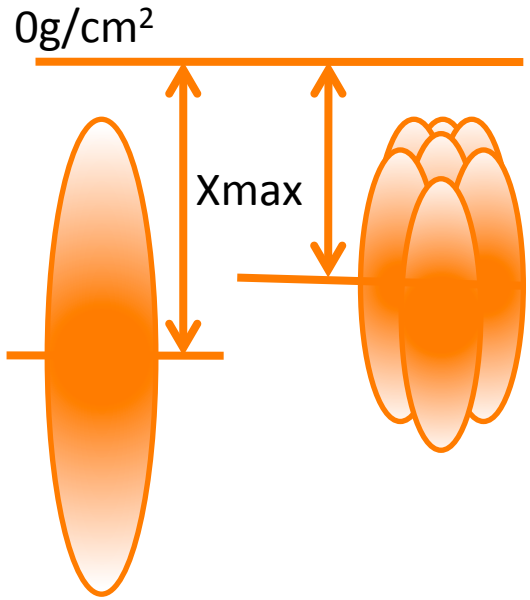
D'Enterria et al., APP, 35,98-113, 2011



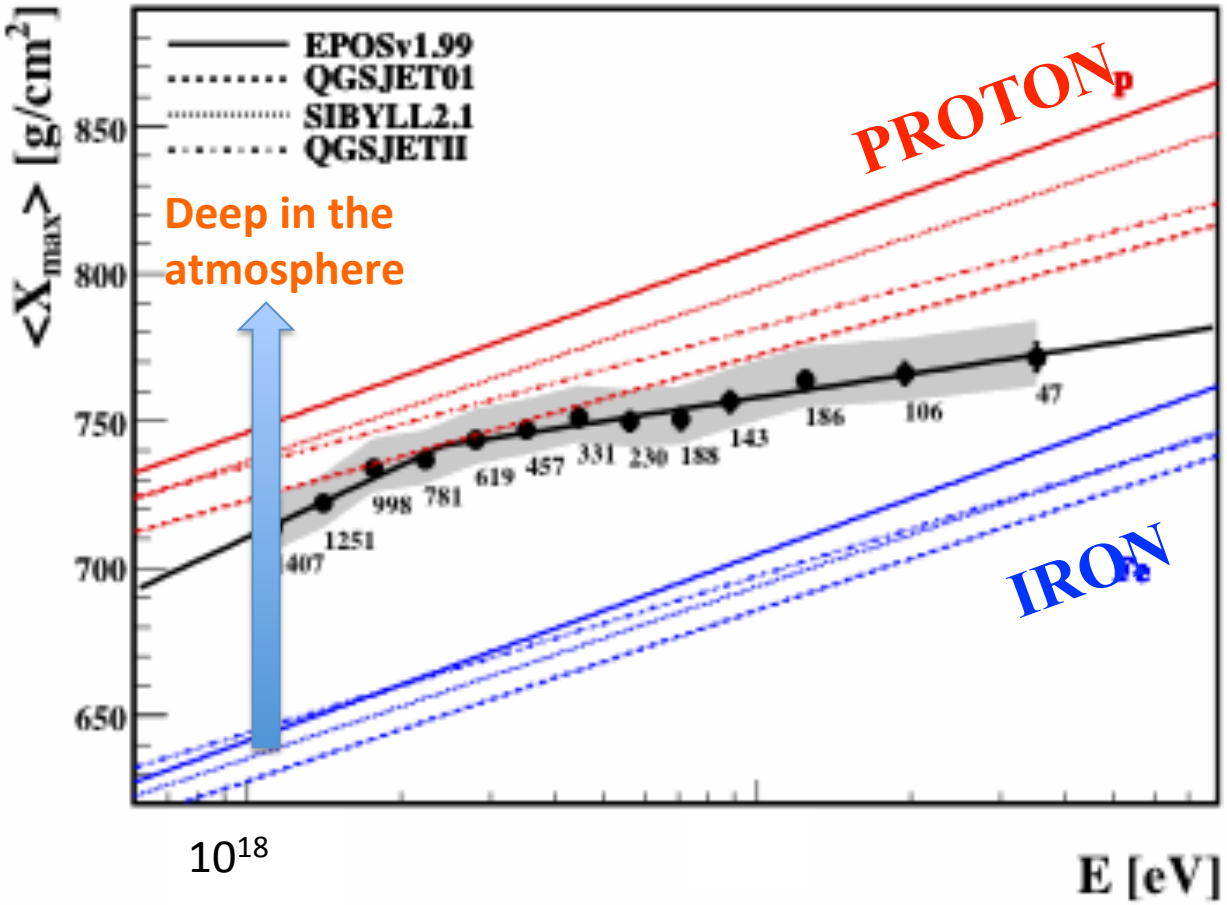


Kampert and Unger, APP., 2012

Uncertainty in hadronic interaction

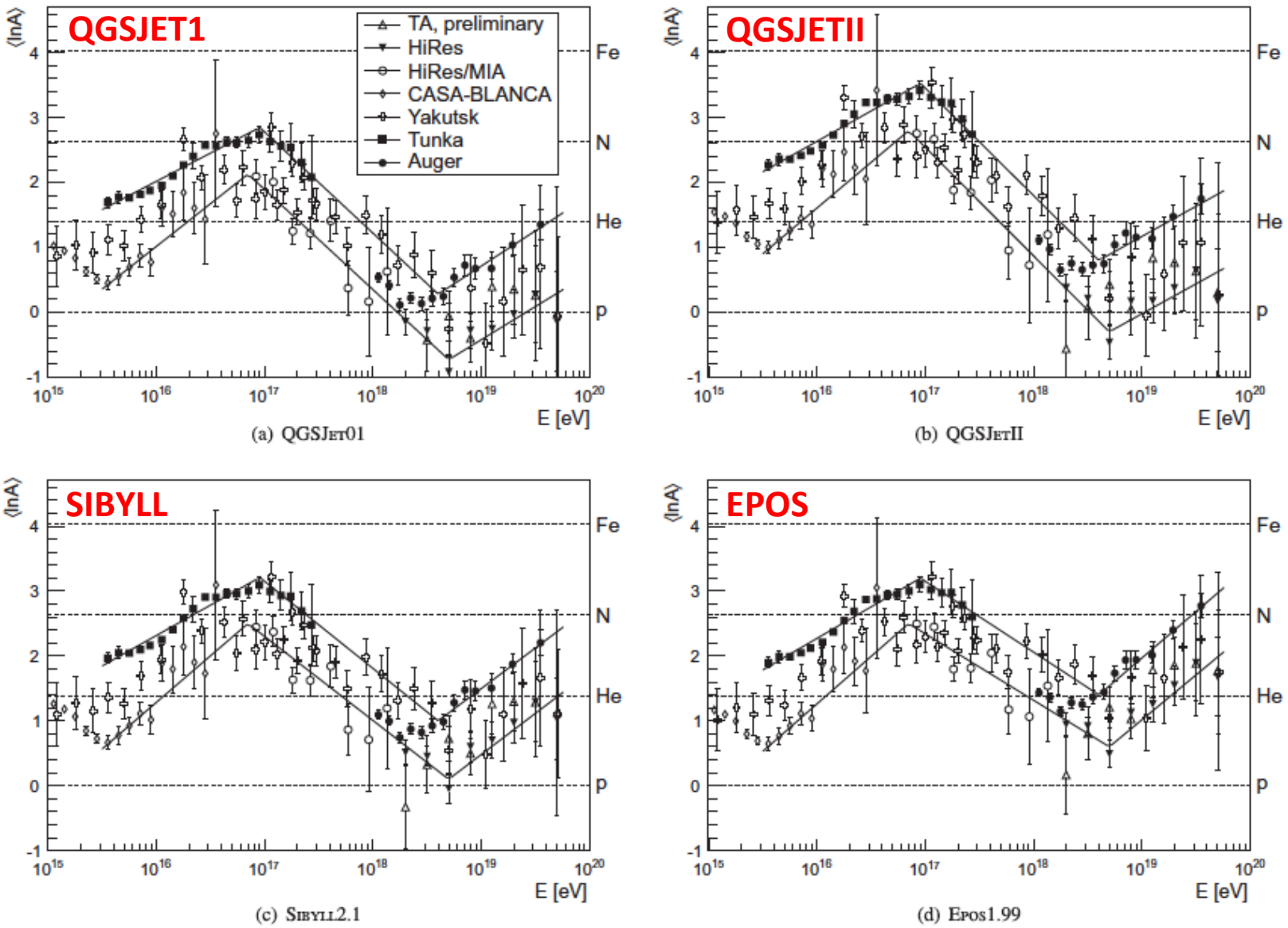


Proton shower and nuclear shower of same total energy



Pierre Auger Observatory (PAO)

AS Interpretation depends on the hadronic interaction model

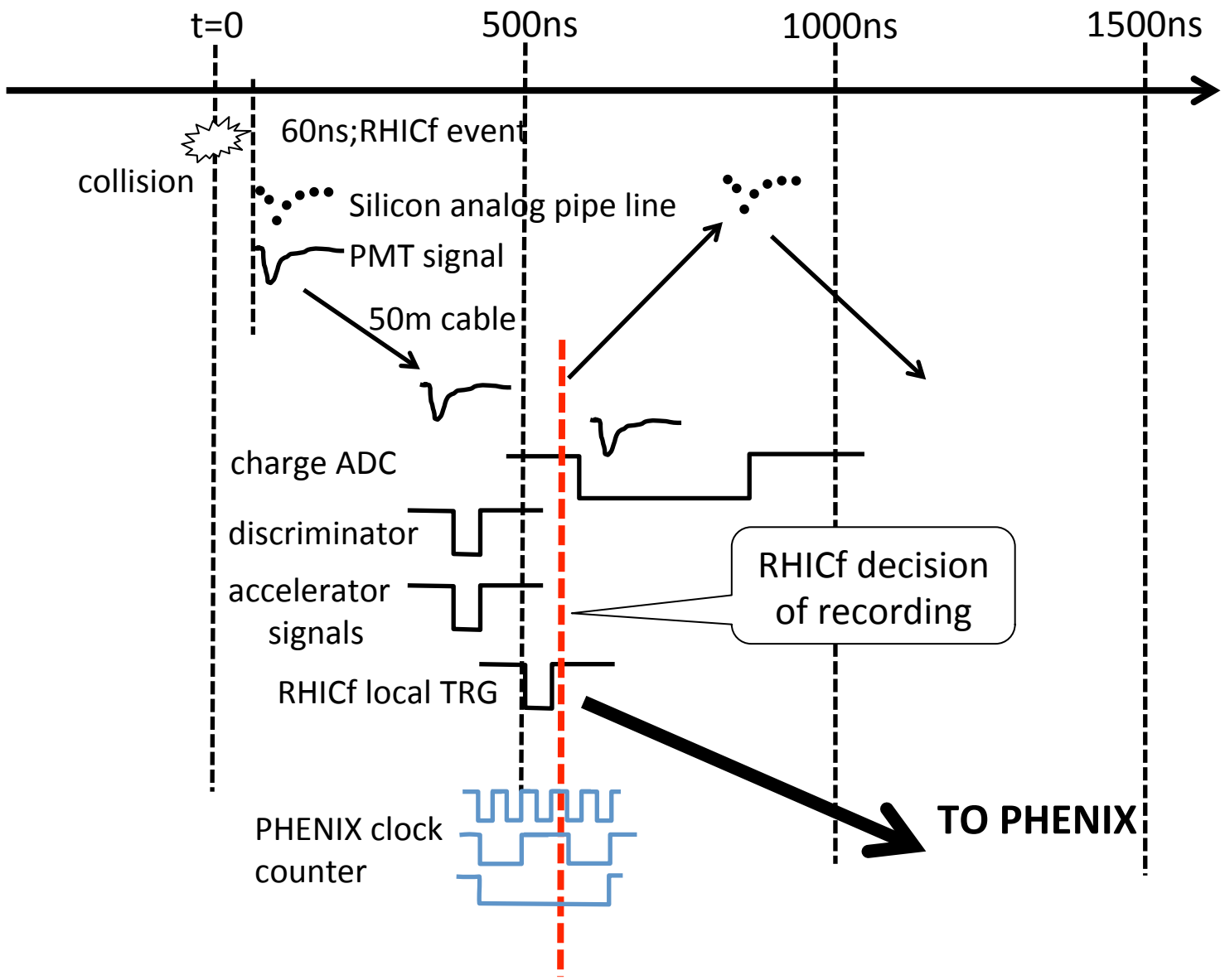


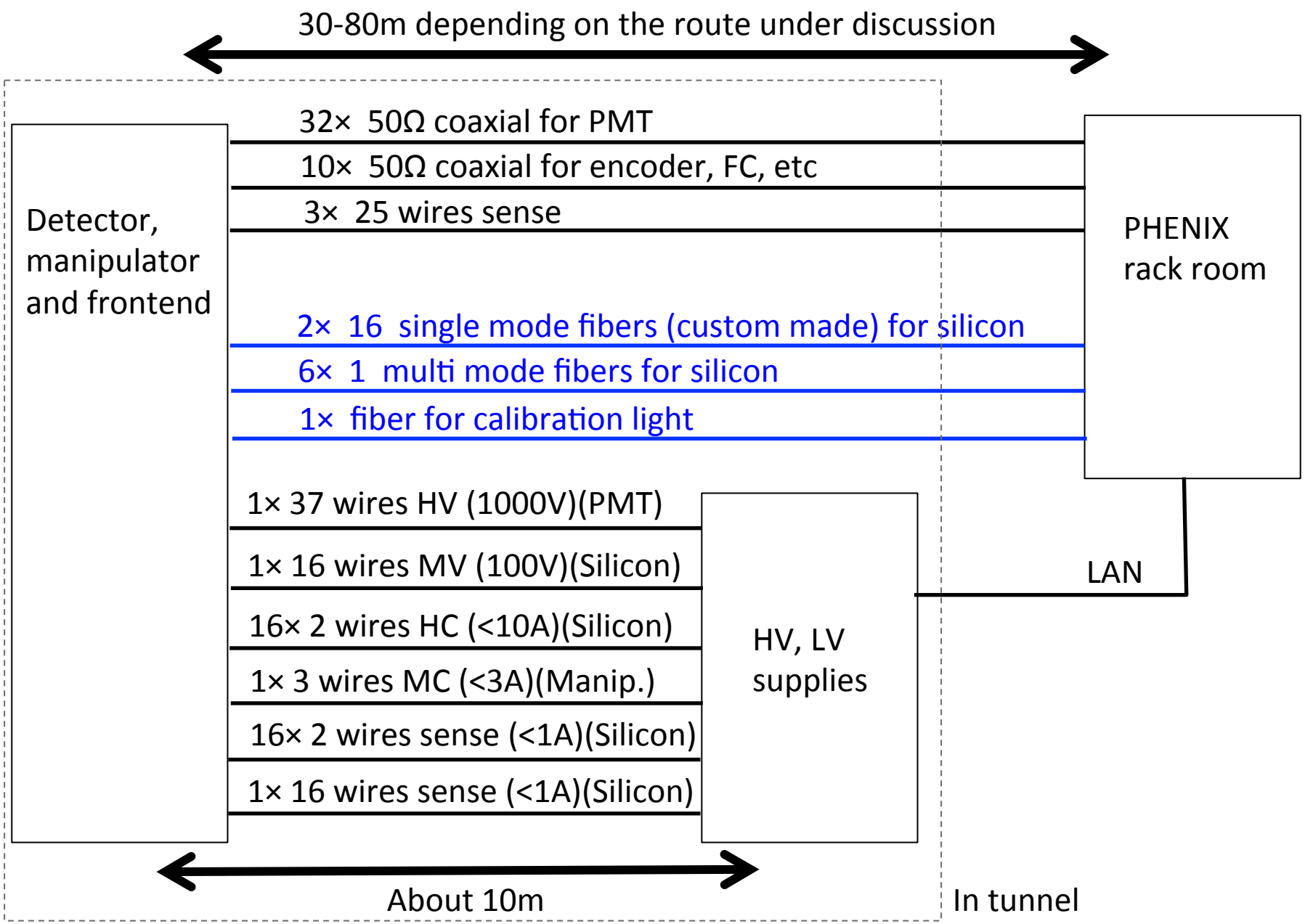
(Kampert and Unger, Astropart. Phys., 2012)

AS Interpretation depends on the hadronic interaction model

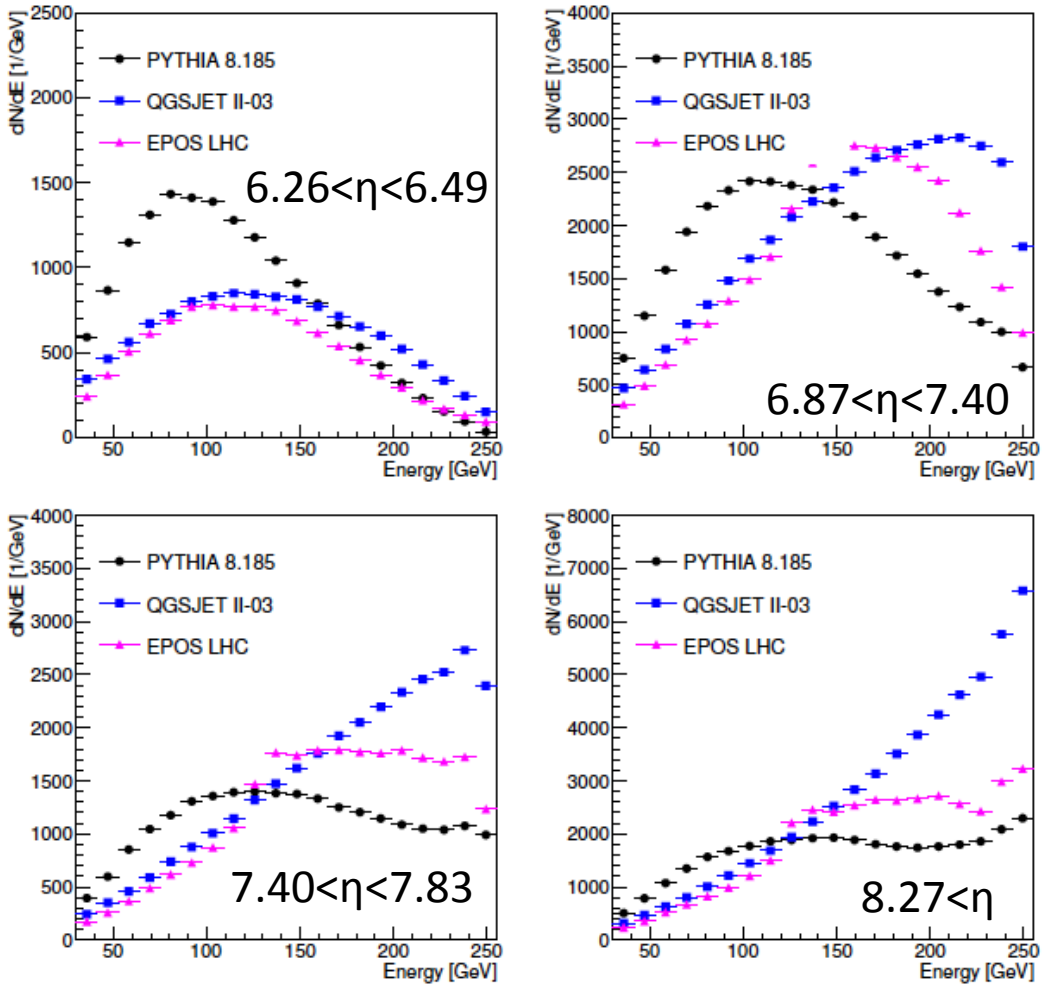
Requested Beam Condition

Parameter	Value
Beam energy (GeV)	255
Beam intensity (protons per bunch)	2×10^{11}
Number of colliding bunch	100
Number of non-colliding bunch	20
Beam emittance (mm mrad)	20
β^* (m)	10
Luminosity ($cm^{-2}s^{-1}$)	1.1×10^{31}
Polarization direction	radial
Polarization amplitude	0.4–0.5
Operation time	1 day


t=0
500ns
1000ns
1500ns
collision
60ns;RHICf event
Silicon analog pipe line
PMT signal
50m cable
charge ADC
discriminator
accelerator
signals
RHICf decision
of recording
RHICf local TRG
PHENIX clock
counter
TO PHENIX


30-80m depending on the route under discussion
Detector, manipulator and frontend
32× 50Ω coaxial for PMT
10× 50Ω coaxial for encoder, FC, etc
3× 25 wires sense
PHENIX rack room
2× 16 single mode fibers (custom made) for silicon
6× 1 multi mode fibers for silicon
1× fiber for calibration light
1× 37 wires HV (1000V)(PMT)
1× 16 wires MV (100V)(Silicon)
16× 2 wires HC (<10A)(Silicon)
1× 3 wires MC (<3A)(Manip.)
16× 2 wires sense (<1A)(Silicon)
1× 16 wires sense (<1A)(Silicon)
HV, LV supplies
LAN
About 10m
In tunnel

Expected Results (single neutrons)

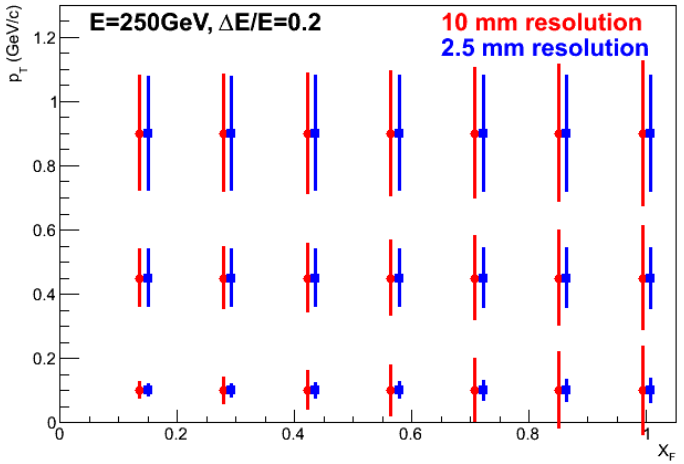


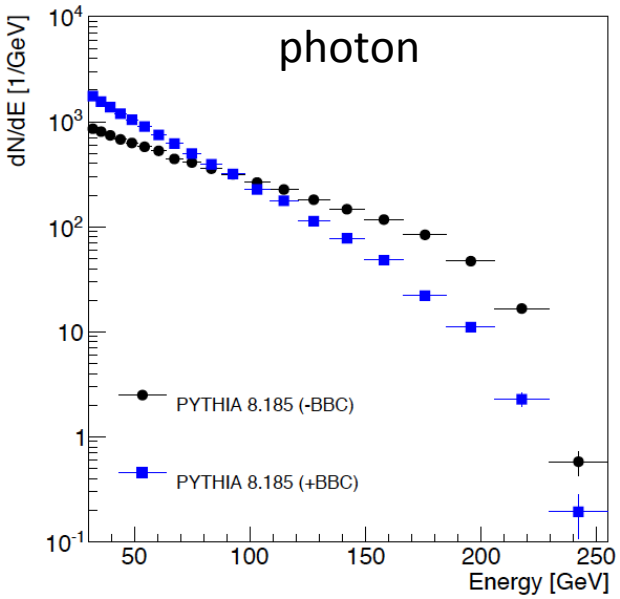
- Neutron spectra at 4 rapidity samples
- 12 hours statistics (12 nb^{-1} effective luminosity; 360nb^{-1} delivered)
- RHICf resolution not considered; true spectra
- Statistical error is almost negligible

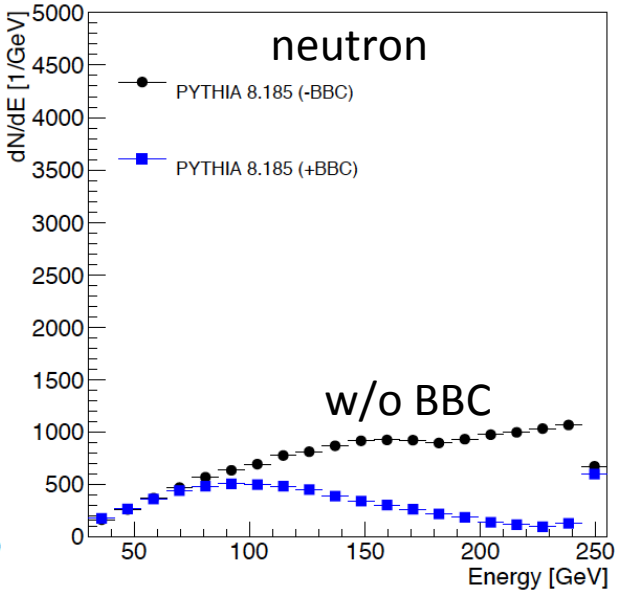
RHICf+PHENIX

Higher p_T resolution

p_T resolution of ZDC+SMD and ZDC+RHICf





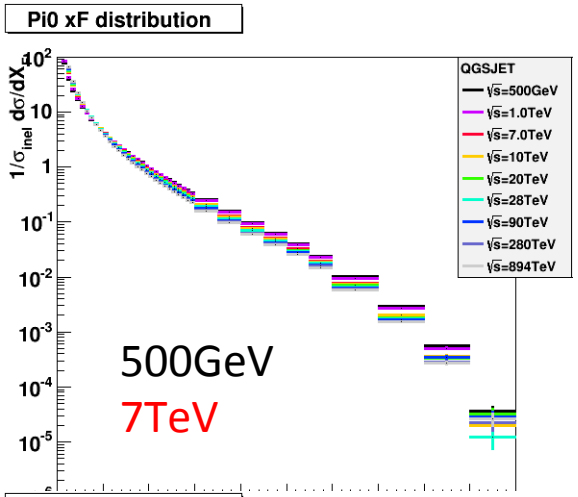


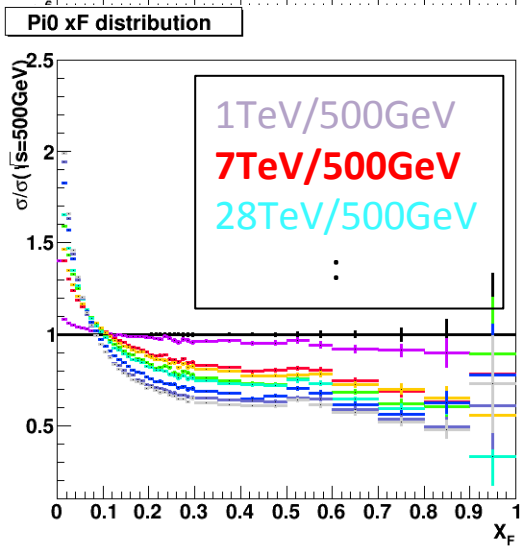
BBC Correlation (diffraction ID)

photon and neutron spectra with/without BBC tagging (PYTHIA8)

w/ BBC (Minimum Bias)

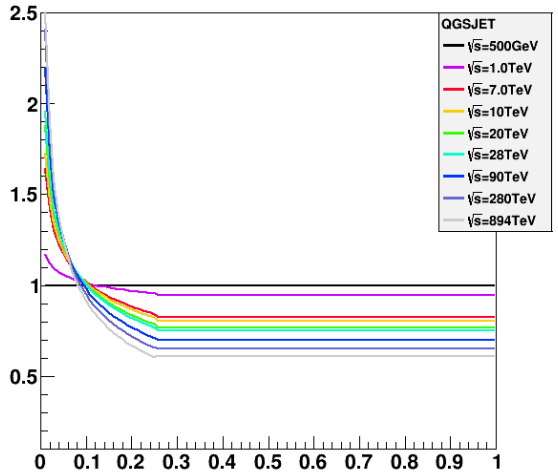
Scaling violation and Air shower
(on going study)

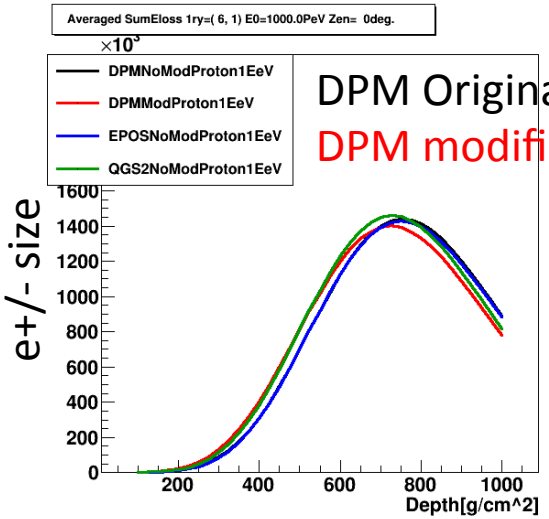


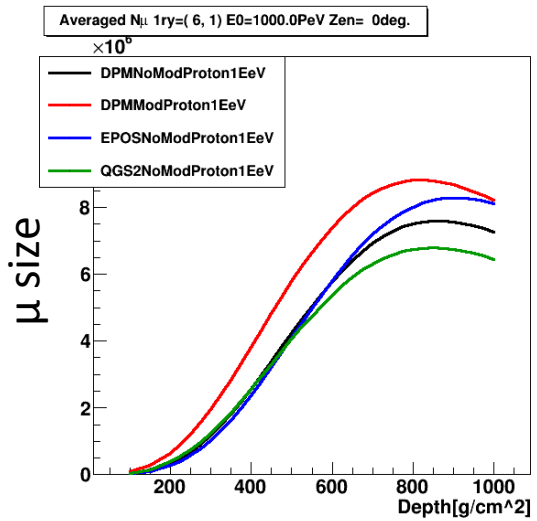


QGSJET II-04 π^0

Artificial scaling-violation function applied to DPMJET3 (perfect scaling model)

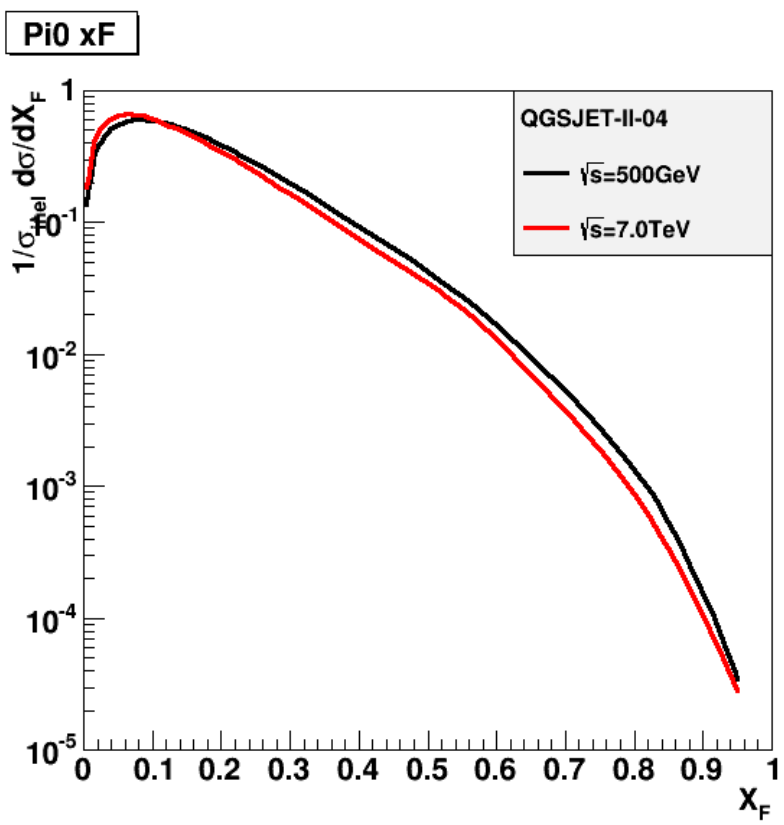




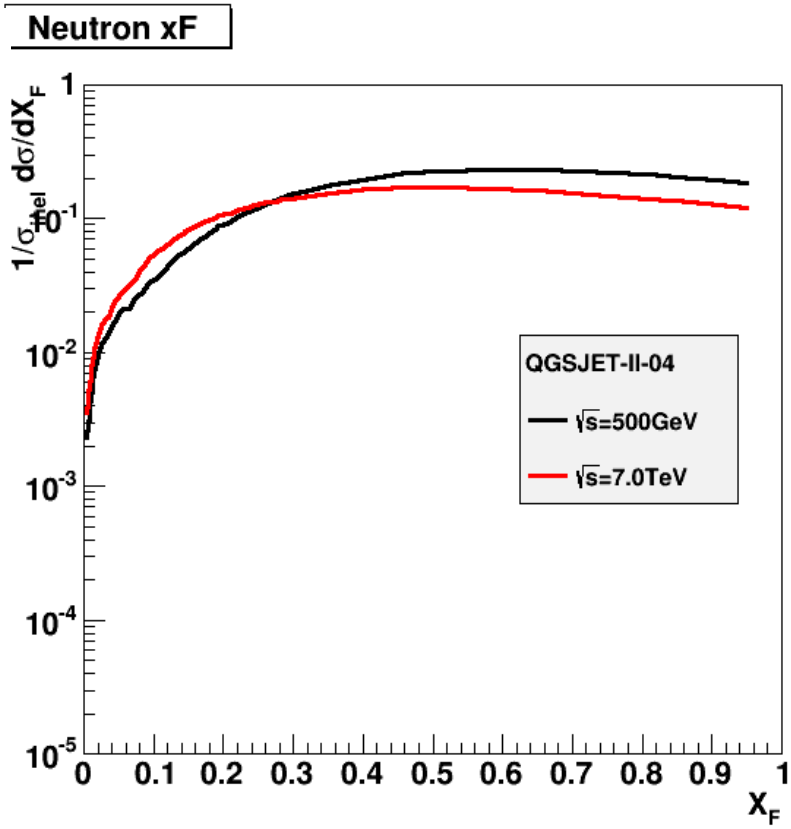


proton shower 10^{18}eV

Scaling and Forward spectra



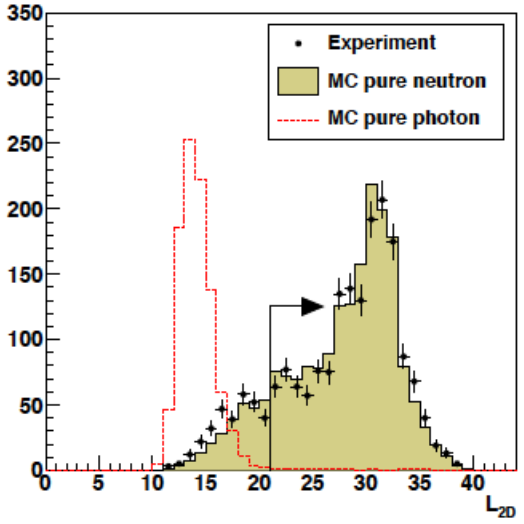
QGSJET II-04 π^0 in the RHICf, LHCf acceptances



QGSJET II-04 neutron in the RHICf, LHCf acceptances

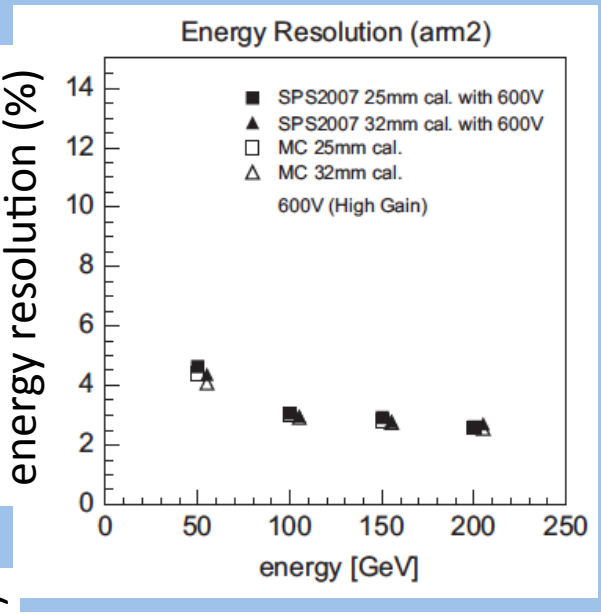
LHCf Arm2 (RHICf) detector performance

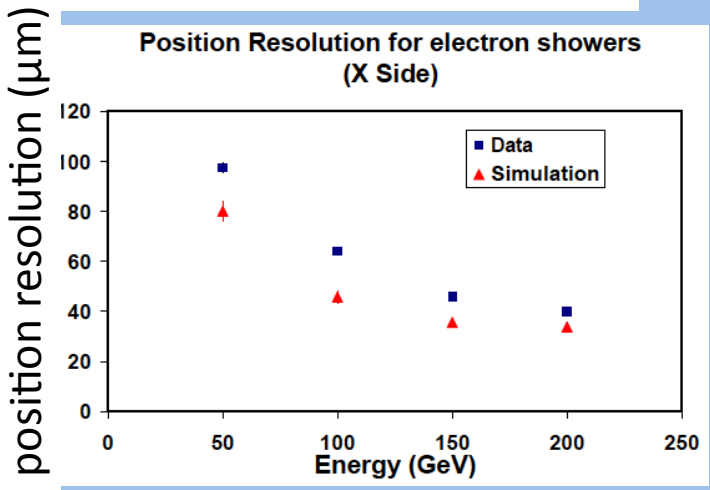
PID (SPS energy)



EM shower (SPS)

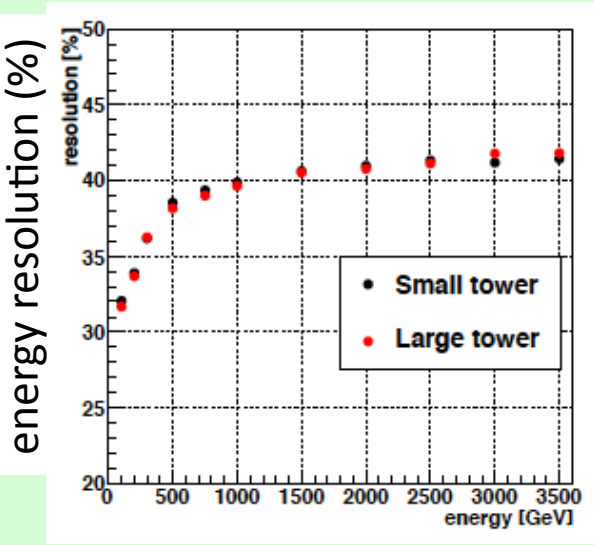
NIM, A671 (2012) 129-136
JINST, 5, P01012, 2010

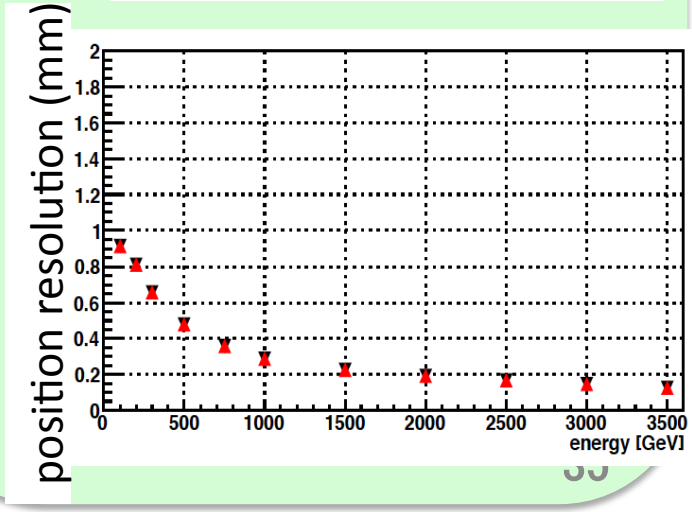




Hadronic shower (LHC MC)

JINST, 9, P03016 (2014)





LHCf Results

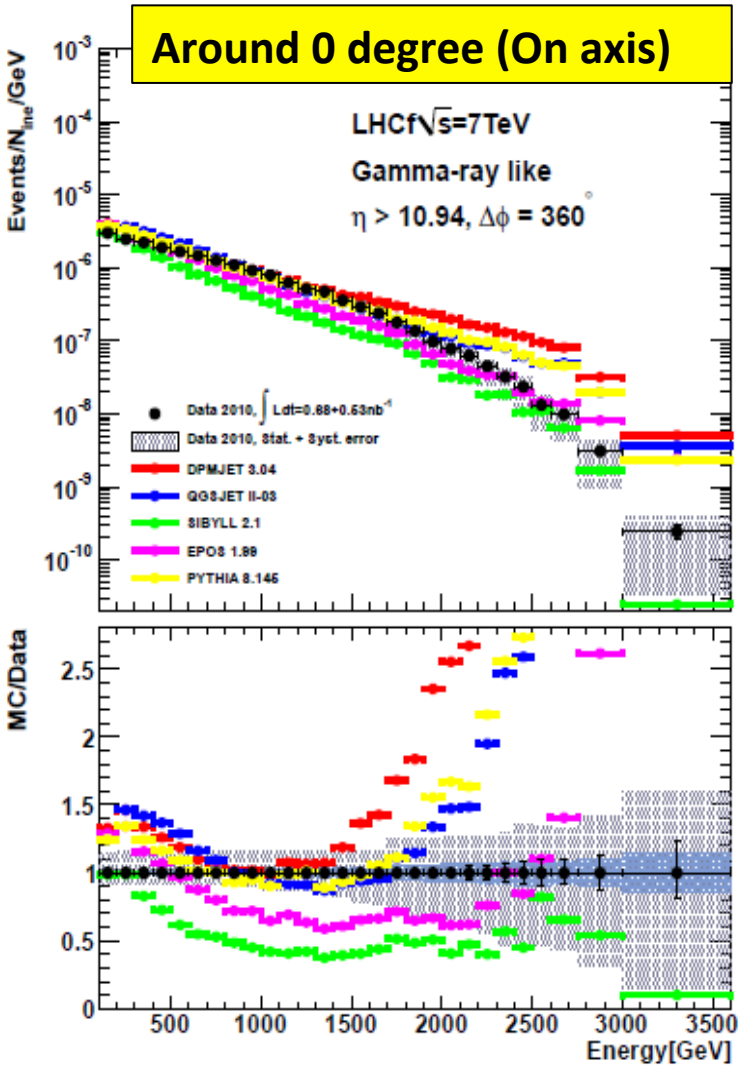
Publication Summary

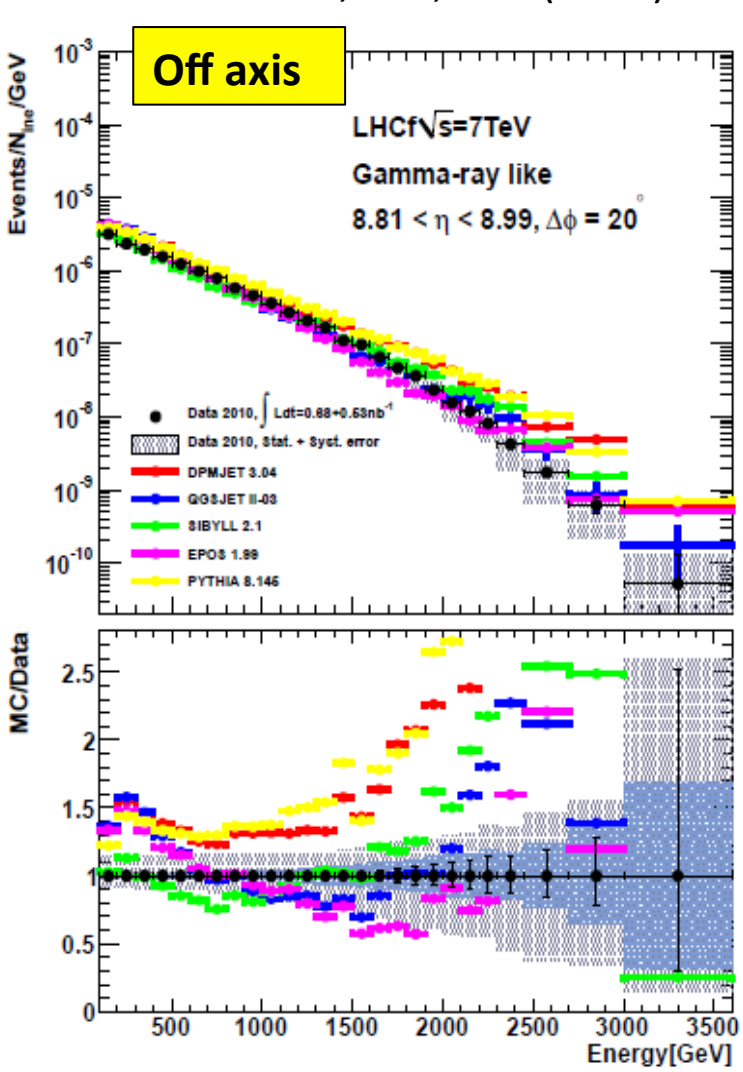
	Photon (EM shower)	Neutron (hadron shower)	π (EM shower)
Test beam at SPS	NIM. A 671, 129–136 (2012)	**JINST, 9, P03016 (2014)**	
p-p at 900GeV	Phys. Lett. B 715, 298-303 (2012)		
p-p at 7TeV	Phys. Lett. B 703, 128–134 (2011)	**to be submitted soon**	Phys. Rev. D 86, 092001 (2012)
p-p at 2.76TeV			**PRC in press arXiv:1403.7845 [nucl-ex](2014)**
p-Pb at 5.02TeV			

LHCf 7TeV pp photon

Photon spectra @ 7TeV (Data vs. Models)

Adriani et al., PLB, 703 (2011) 128-134

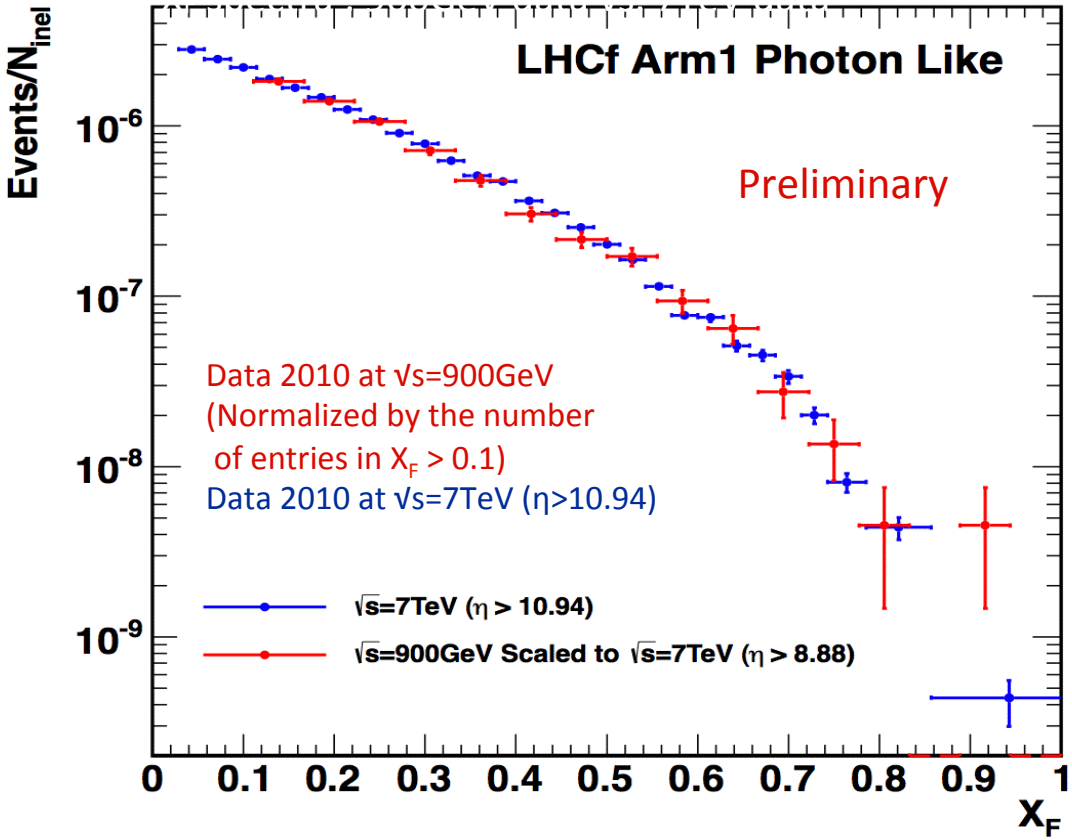




DPMJET 3.04 QGSJET II-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

LHCf 900GeV and 7TeV pp photon

900GeV vs. 7TeV

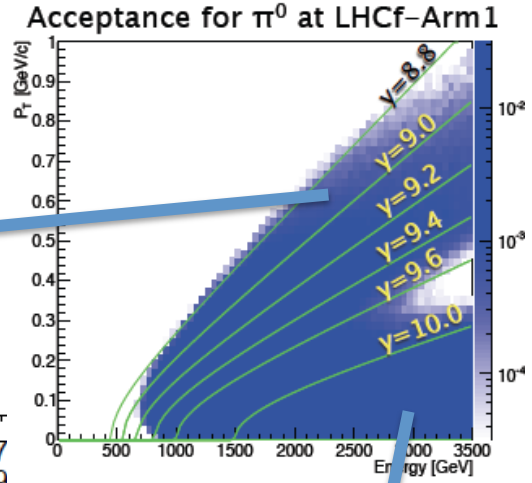


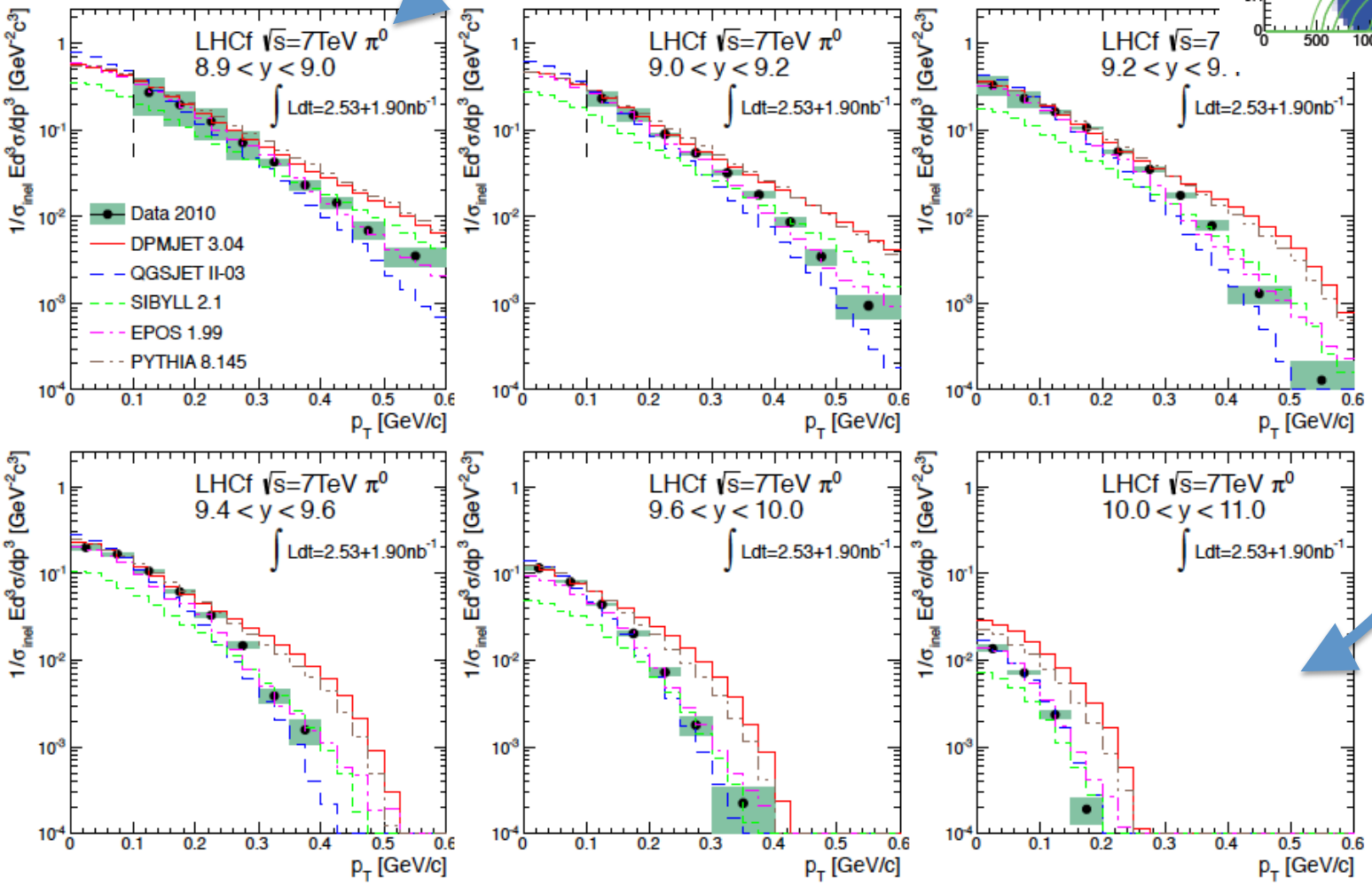
- ✓ Comparison in the same p_T range ($pT<0.13x_F$ GeV/c)
- ✓ Normalized by # of events $X_F > 0.1$
- ✓ Statistical error only
- ✓ Comparison with 2.76TeV, 13TeV (and RHIC 500GeV) are planned

LHCf 7TeV pp π^0

π^0 p_T distribution in different rapidity (y) ranges

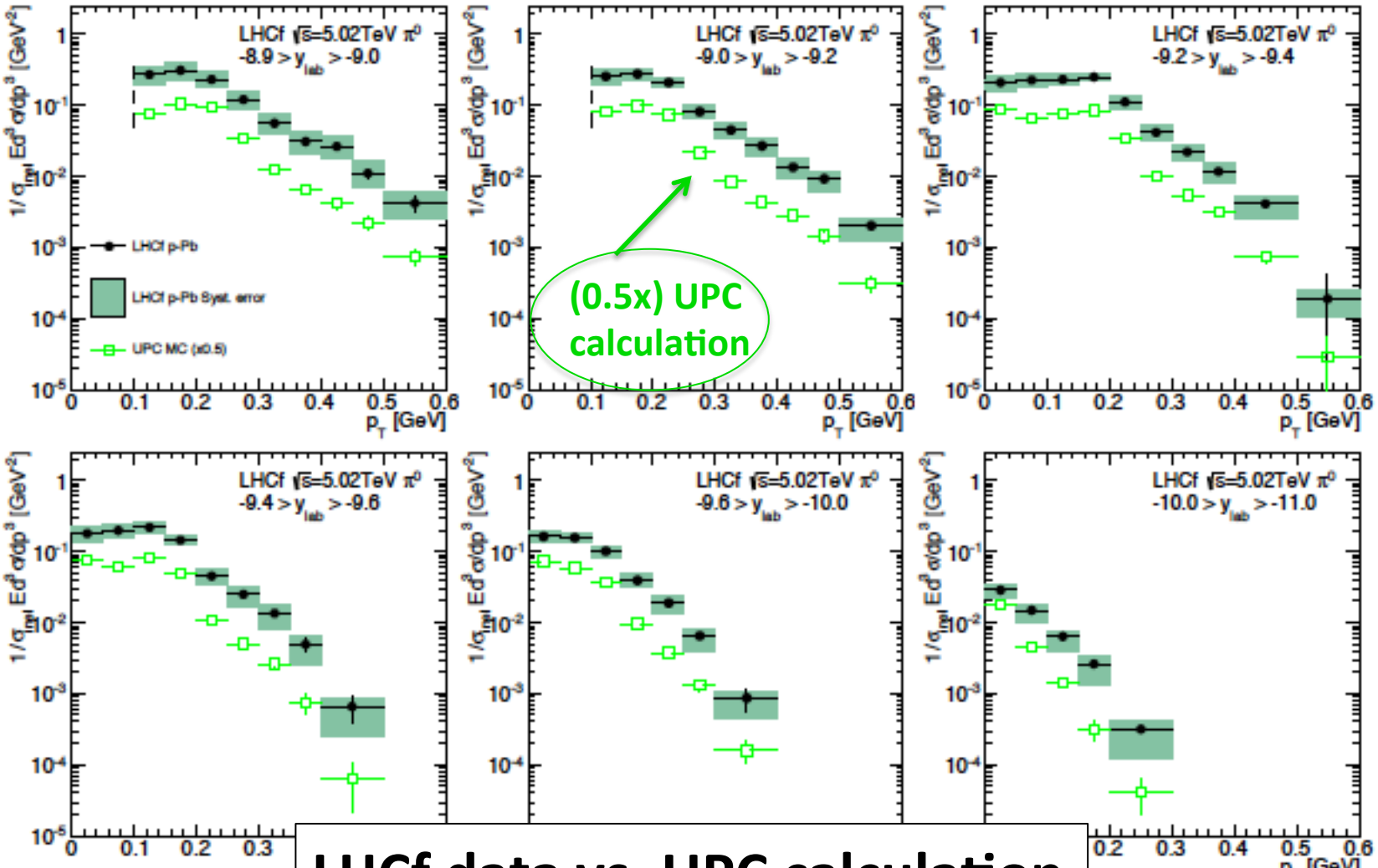
Adriani et al., PRD, 86, 092001 (2012)





LHCf 5TeV ppb π^0

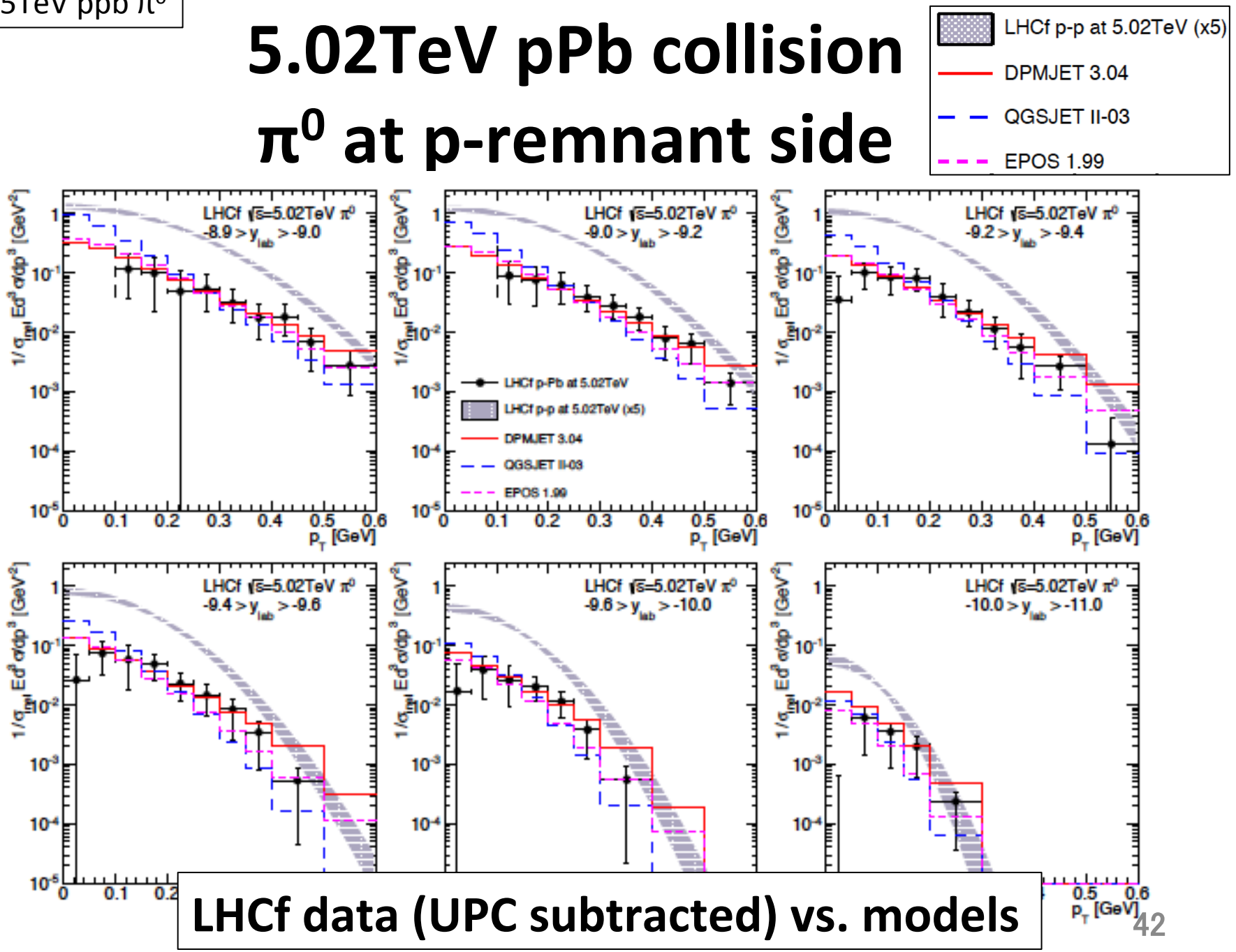
5.02TeV pPb collision
π^0 at p-remnant side



LHCf data vs. UPC calculation

LHCf 5TeV ppb π^0

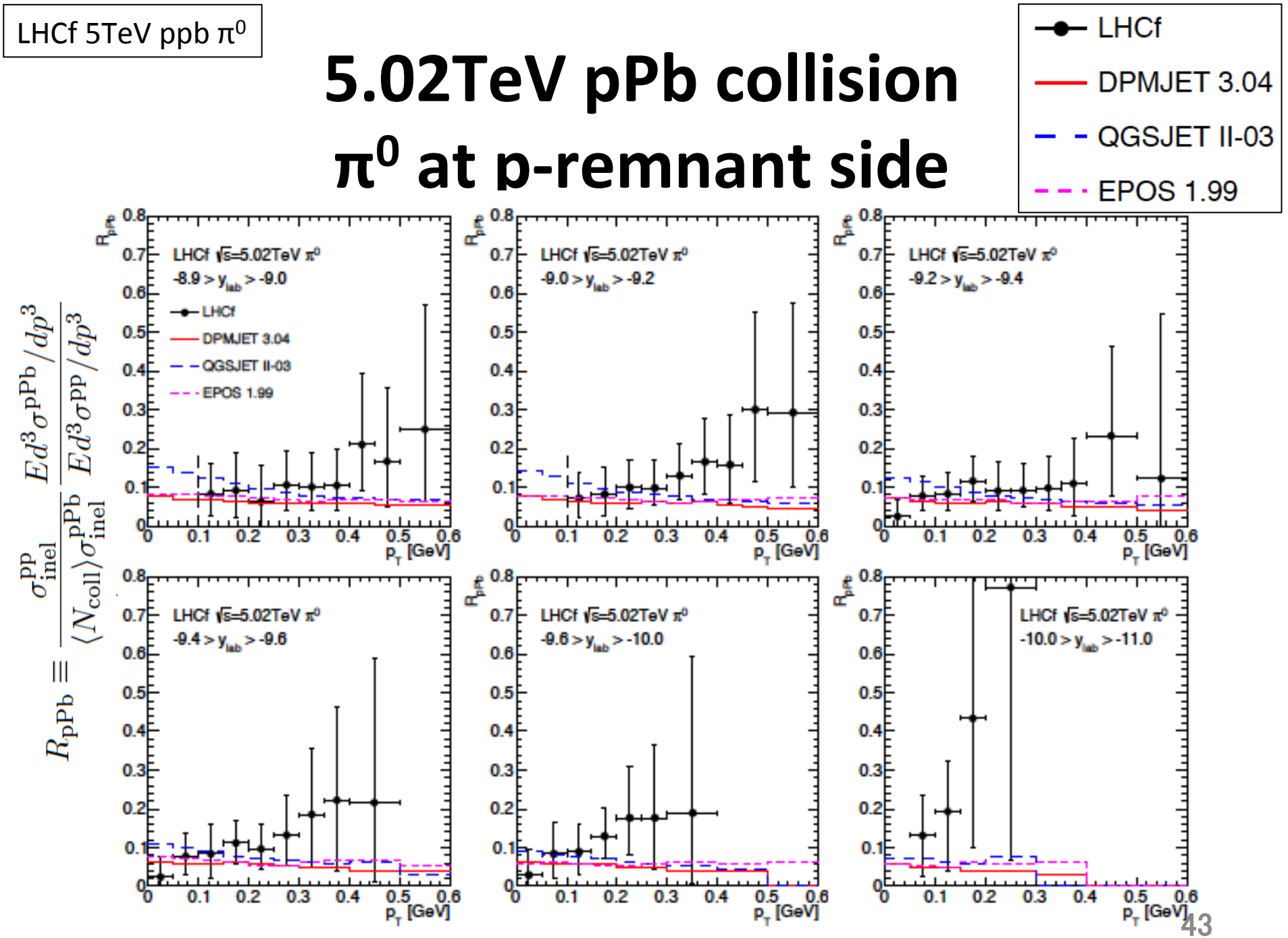
5.02TeV pPb collision
π^0 at p-remnant side



LHCf data (UPC subtracted) vs. models

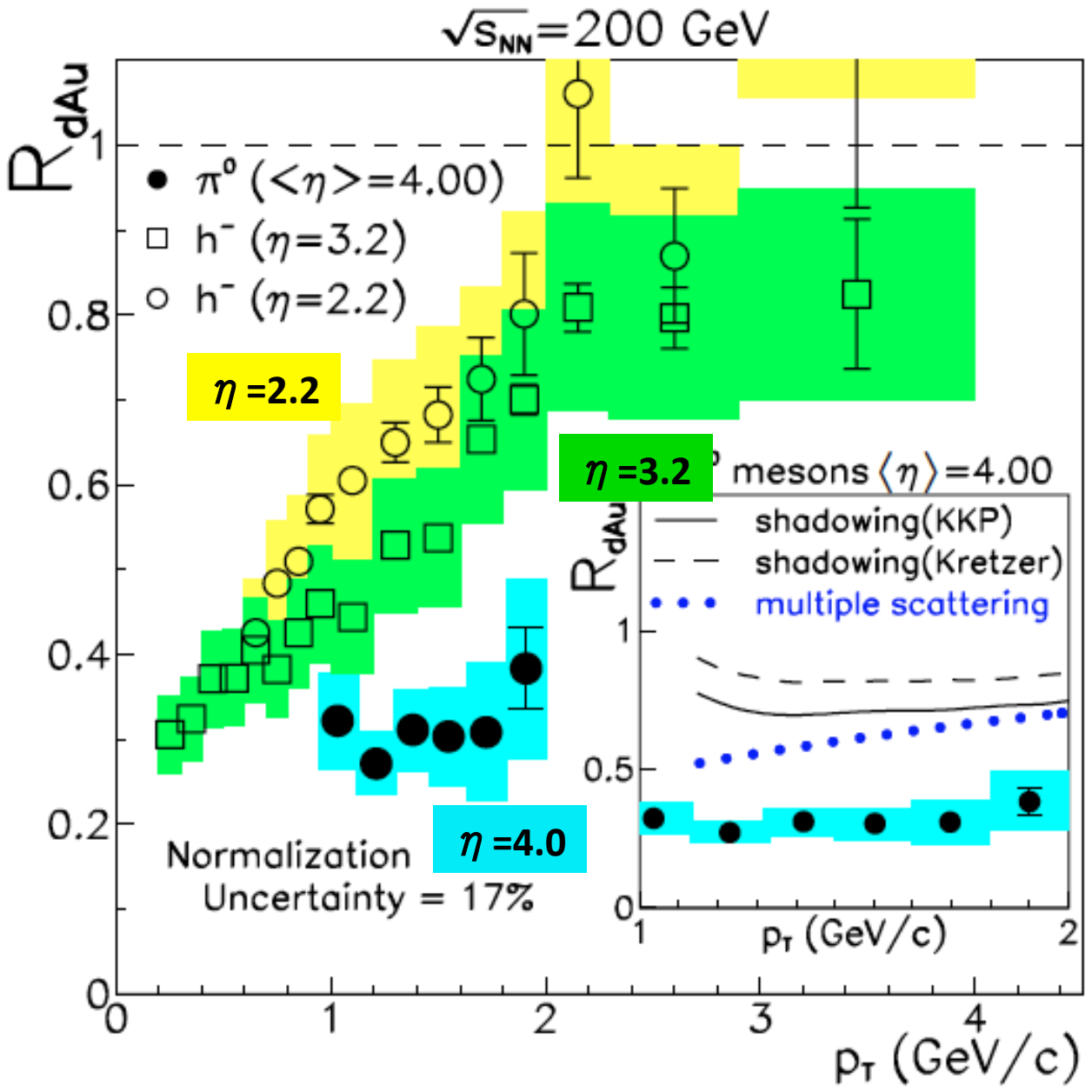
LHCf 5TeV ppb π^0

5.02TeV pPb collision
π^0 at p-remnant side



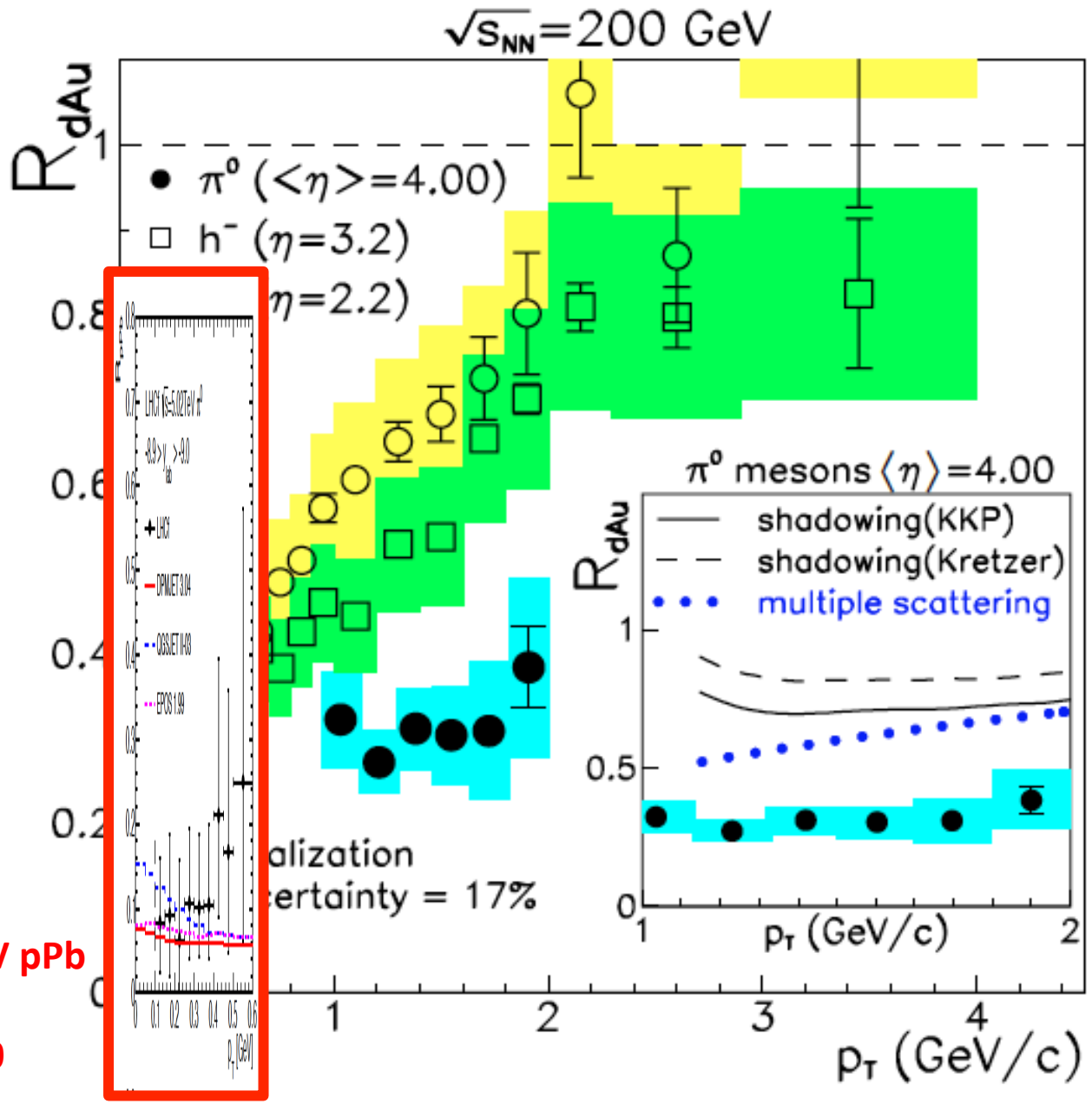
LHCf 5TeV ppb π^0

RHIC 200GeV d-Au, STAR Collaboration
Adams et al., PRL 97 (2006) 152302.



LHCf 5TeV ppb π^0

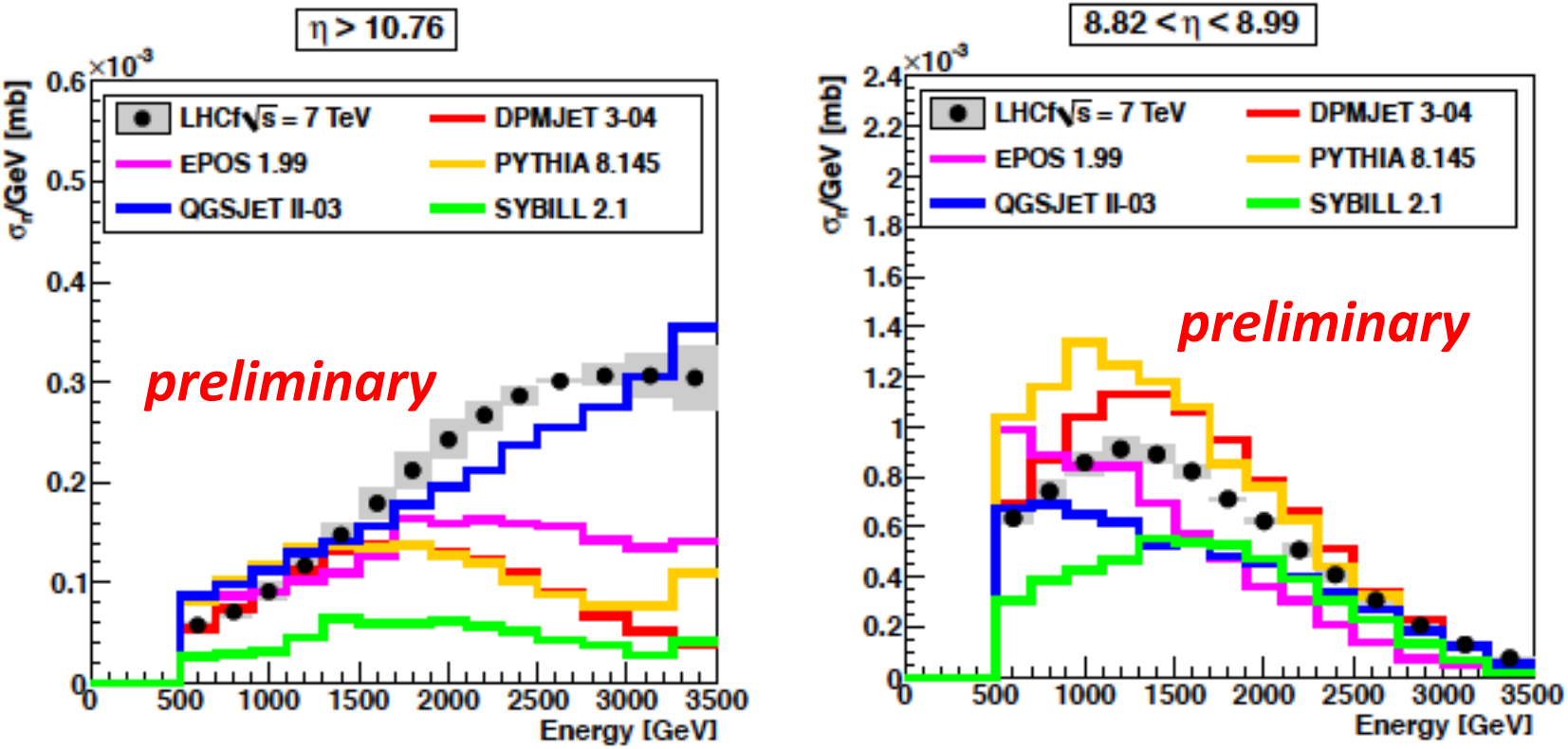
RHIC 200GeV d-Au, STAR Collaboration
Adams et al., PRL 97 (2006) 152302.



LHCf 5TeV pPb
π^0 R_{pPb}
8.9<η<9.0

LHCf 7TeV pp neutron

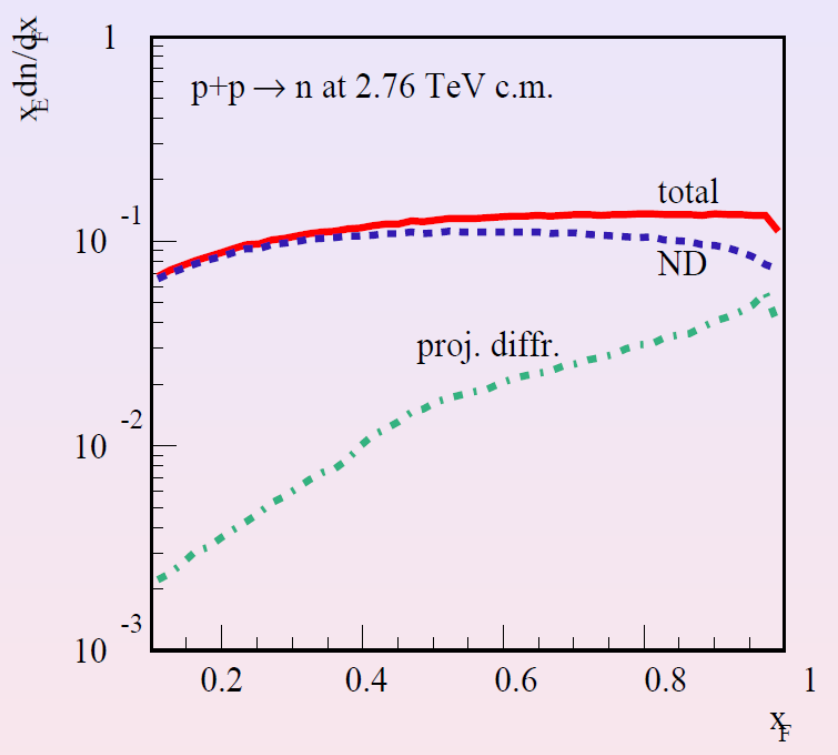
7TeV pp neutron

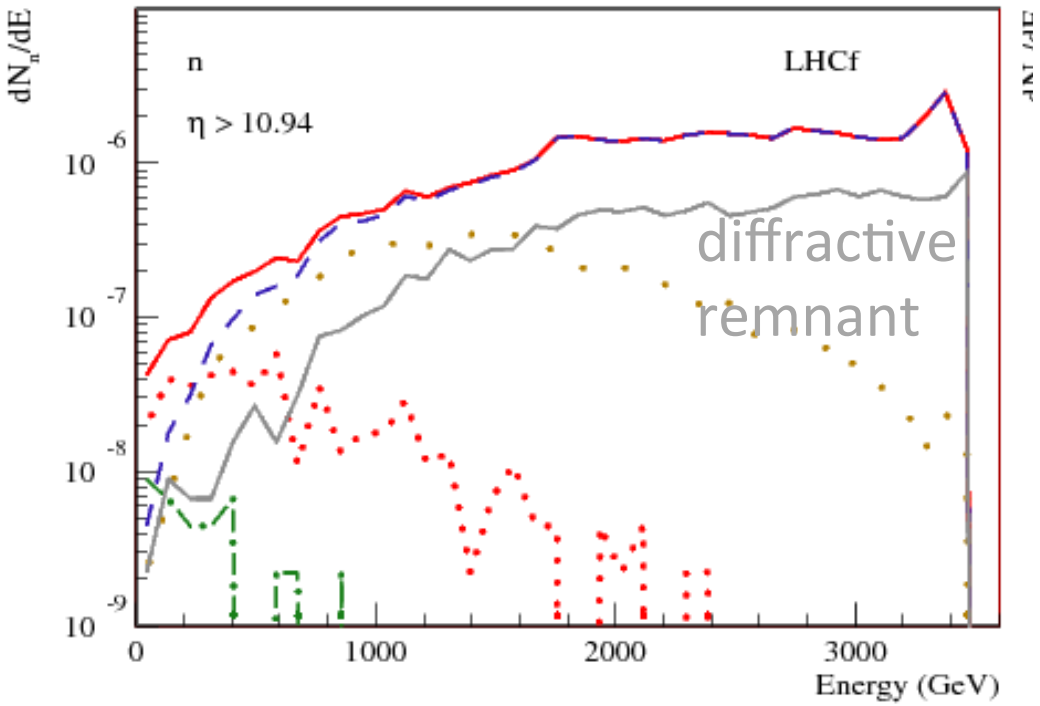


- ✓ Sys-error to be updated
- ✓ Energy resolution 40%, position resolution 0.1-1 mm are unfolded
- ✓ Detection efficiency, PID efficiency, purity are corrected

LHCf 7TeV pp neutron

Origin of 0 degree neutrons





Ostapchenko, QGSJET II

Pierog, EPOS