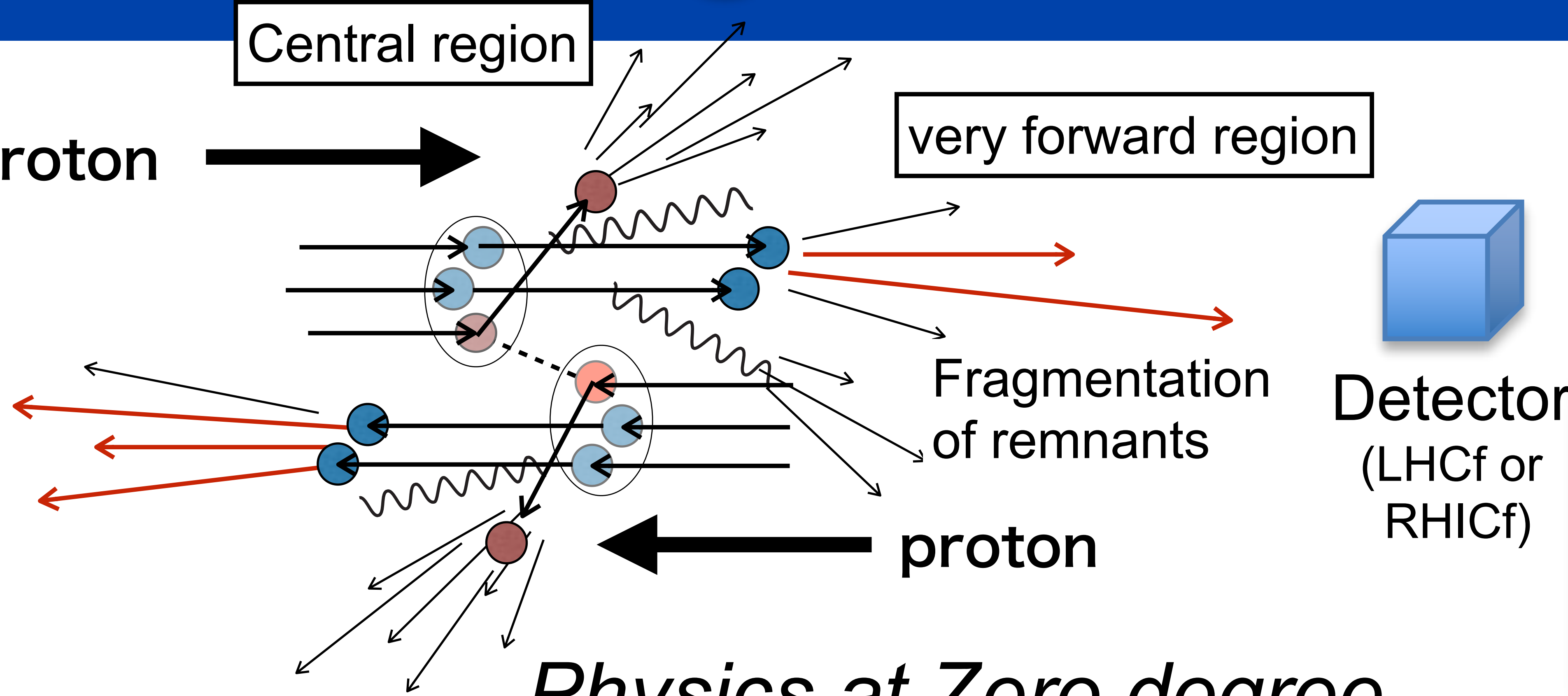
RHICf (+LHCf) for cosmic-ray physics

Hiroaki MENJO ***Nagoya University***
for RHICf collaboration

- Cosmic-ray physics
- RHICf I setup and detector
- Run 17 operation
- Physics results (of LHCf)
- Expect

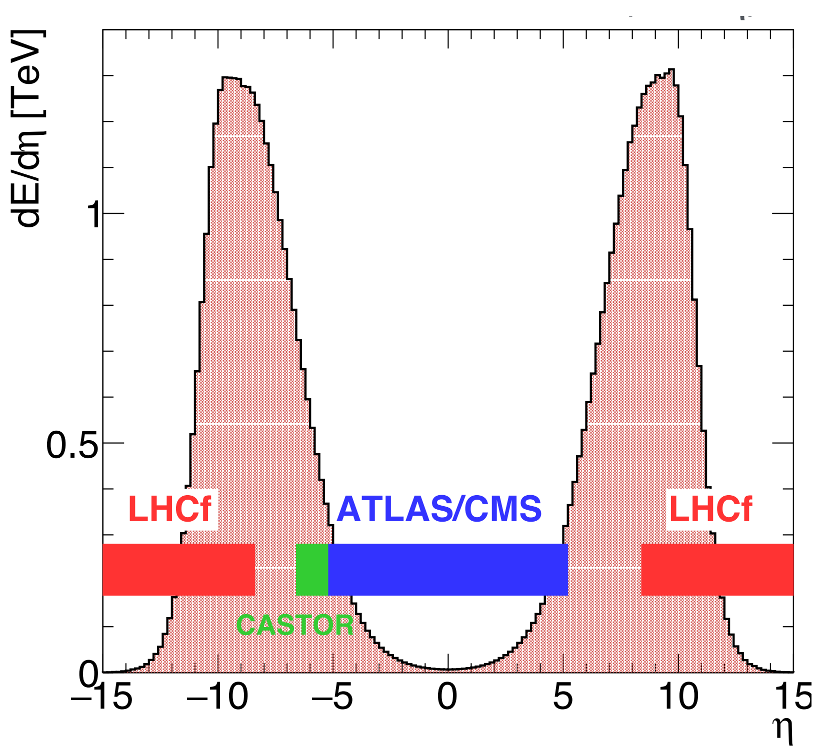
QCD Workshop, RIKEN, 15 July 2022

Zero-degree of collisions



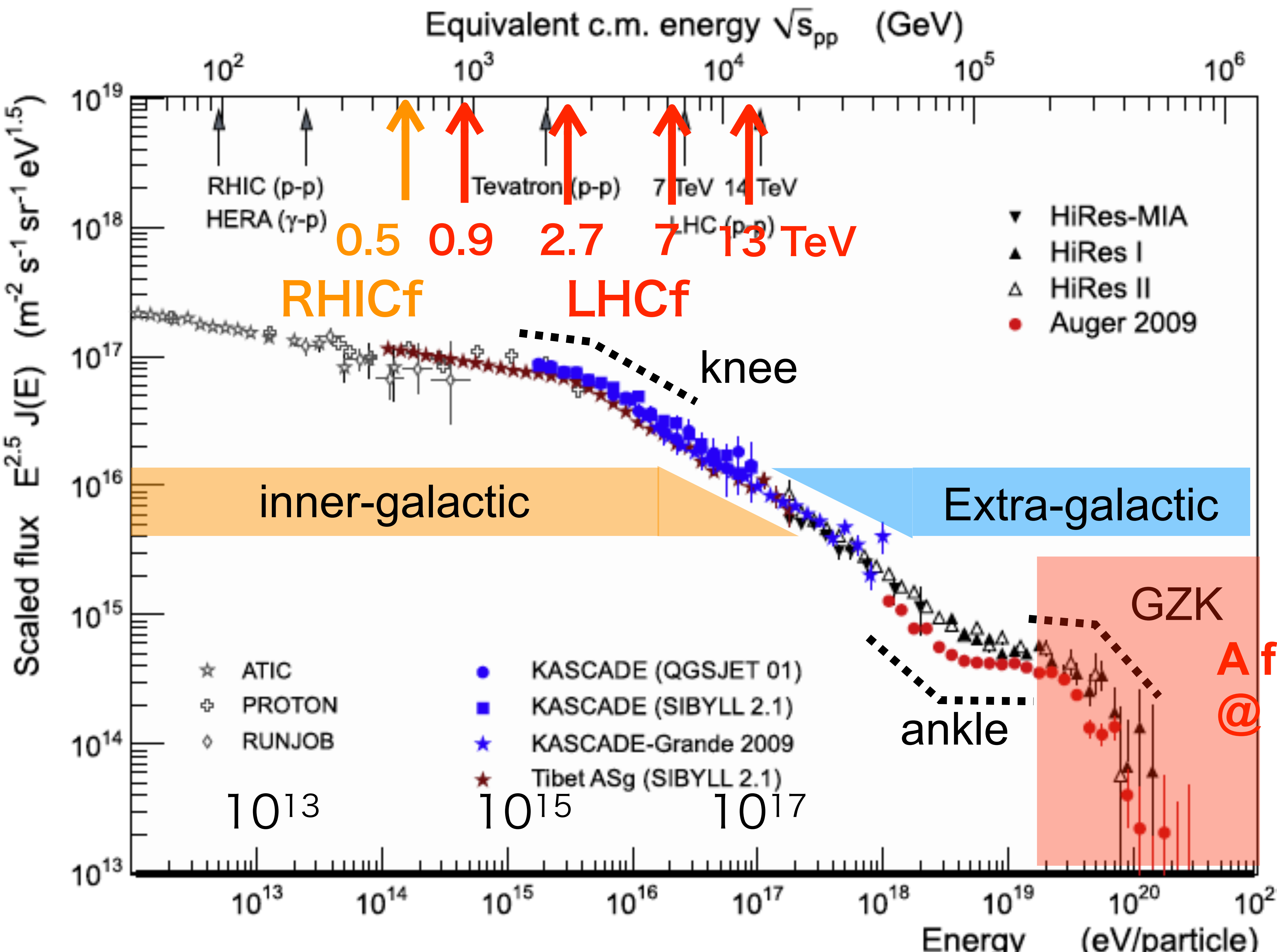
Physics at Zero degree

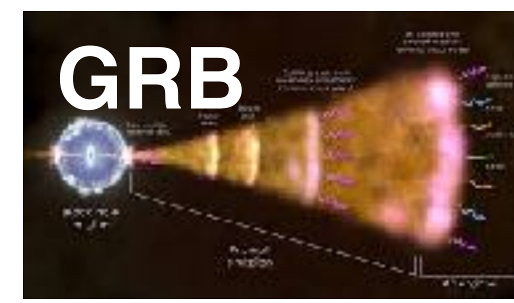
✓Soft collisions, low-pT < 1GeV
→ pQCD does not work.
→ Phenomenological model is needed
✓High energy flux
→ Most of longitudinal momentum is carried by remnants of collisions.



These are important for cosmic-ray physics, especially observation of ultra-high energy cosmic-rays

Cosmic-rays





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A few degrees @ 10^{19}eV proton

UHECR Astronomy

D'Enterria et al., 2011

Cosmic-ray studies

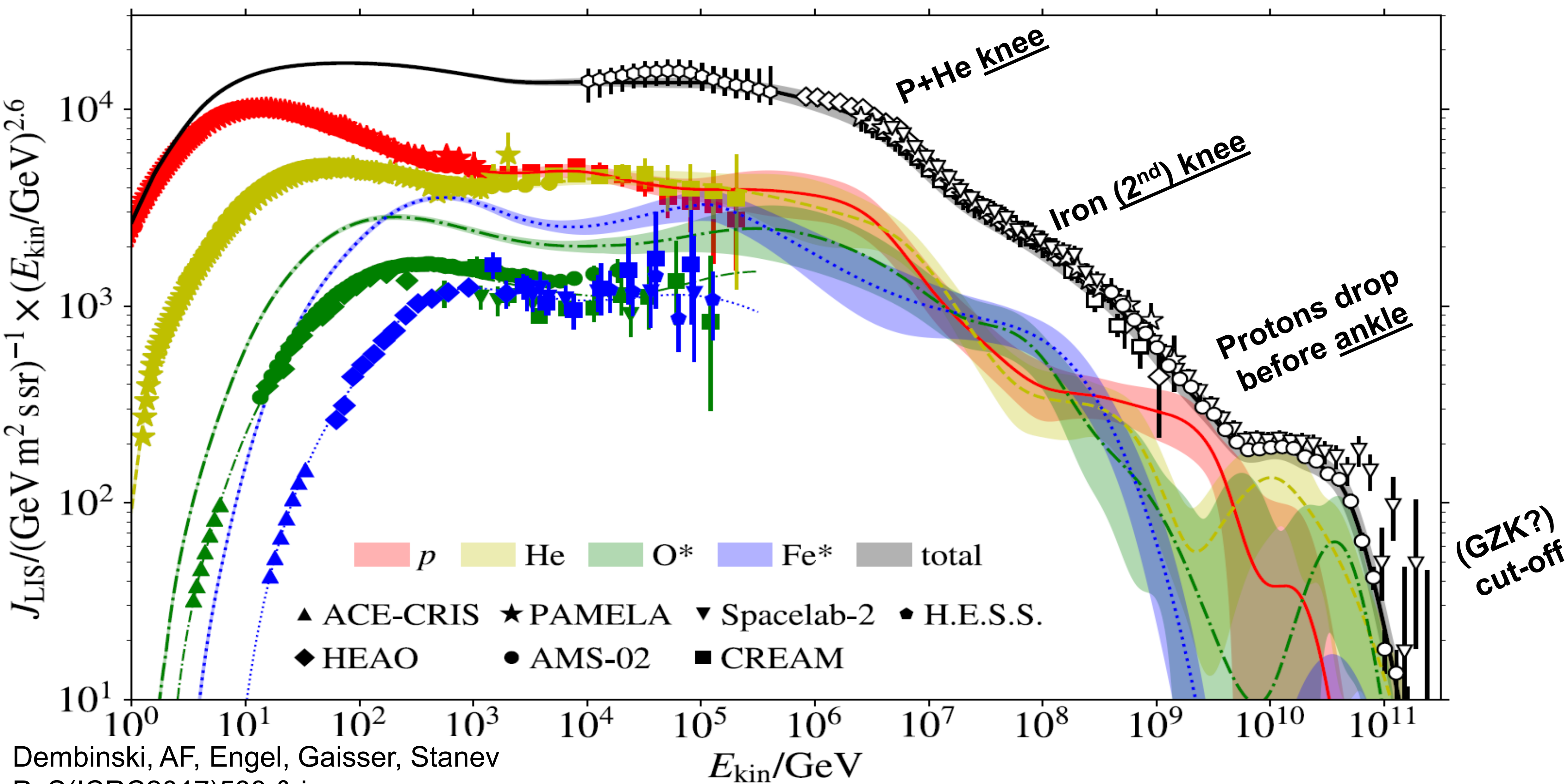
Charged particles (p,He,CNO,Fe)

- Spectrum
- Mass Composition

Neutral Particles

→ Pointing the sources

- Gamma-rays
- Neutrinos



Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533 & in prep.

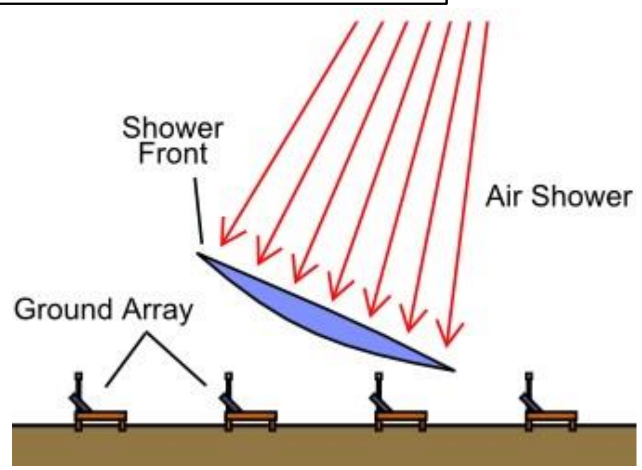
UHECR observations

Indirect observation by using the air shower technique

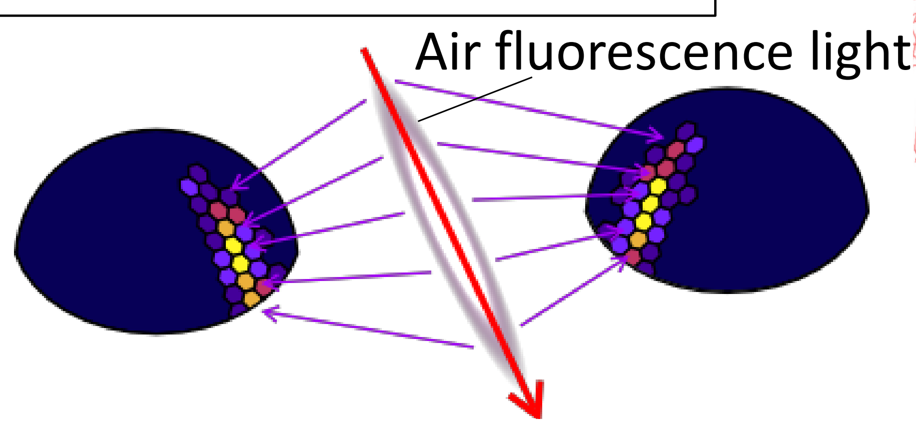
😊 Easy to have a large acceptance
😔 Uncertainty in the reconstruction of primary CR information.

- Energy spectrum
- Anisotropy
- Chemical composition

Surface detector (SD)



Fluorescence detector (FD)



timation of Composition

Shower Maximum (X_{Max})

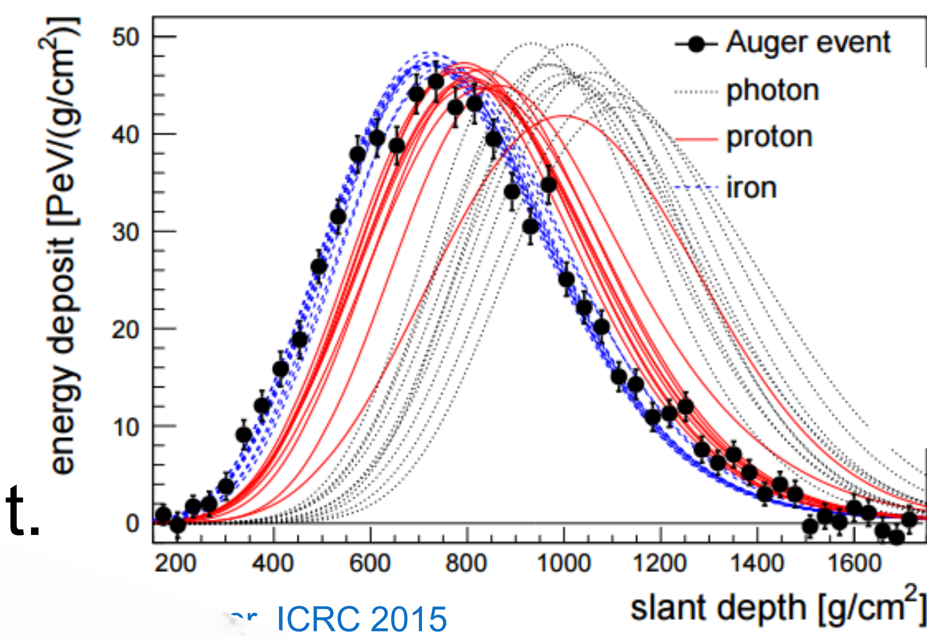
CR primary energy: 10^9-10^{20} eV

High energy interaction

secondaries' interactions

...

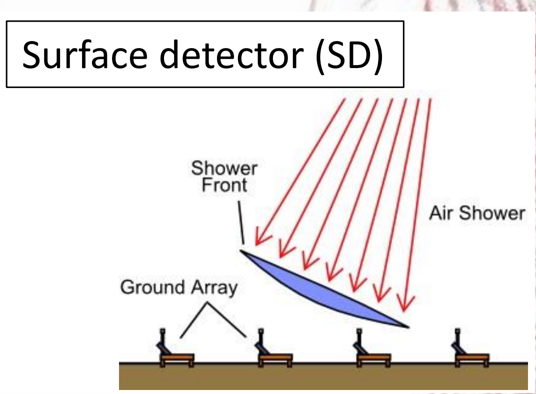
- A-dependency is mainly from difference of σ_{inela}
- High energy interactions are more important.

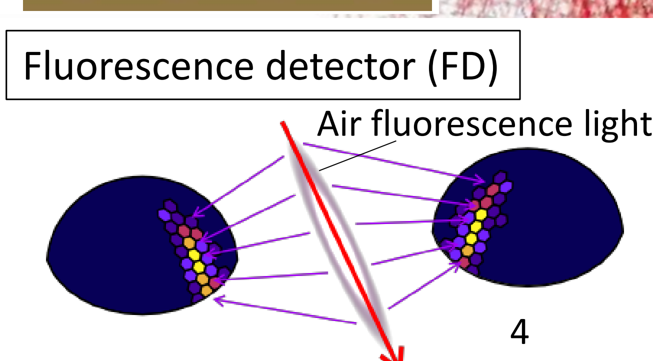


Muon (X^{μ}_{Max}, N_{μ})

Low energy interactions

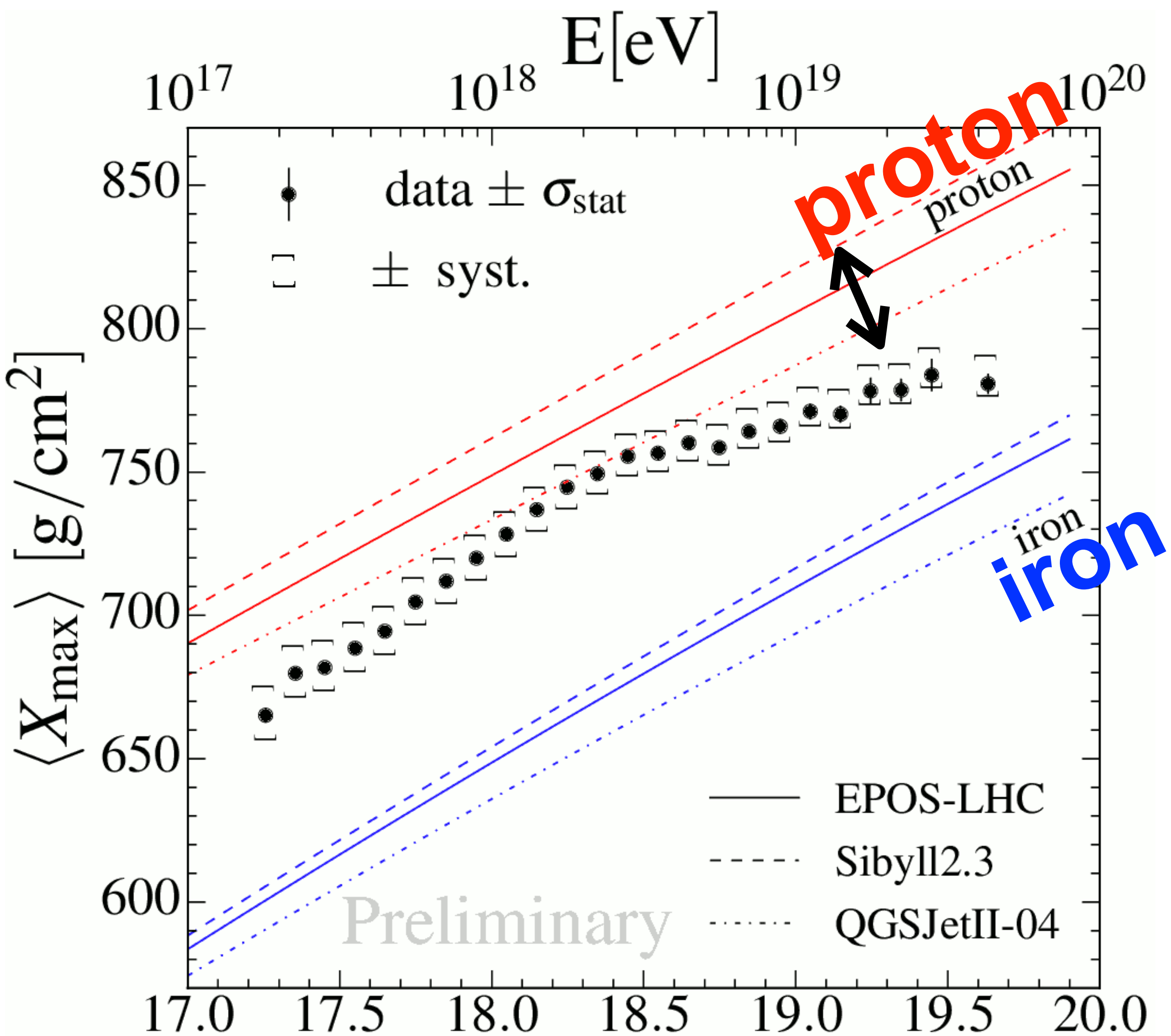
- X^{μ}_{Max}: σ_{inela} + particle production
- $N\mu$: particle production contribution of wide energy ranges





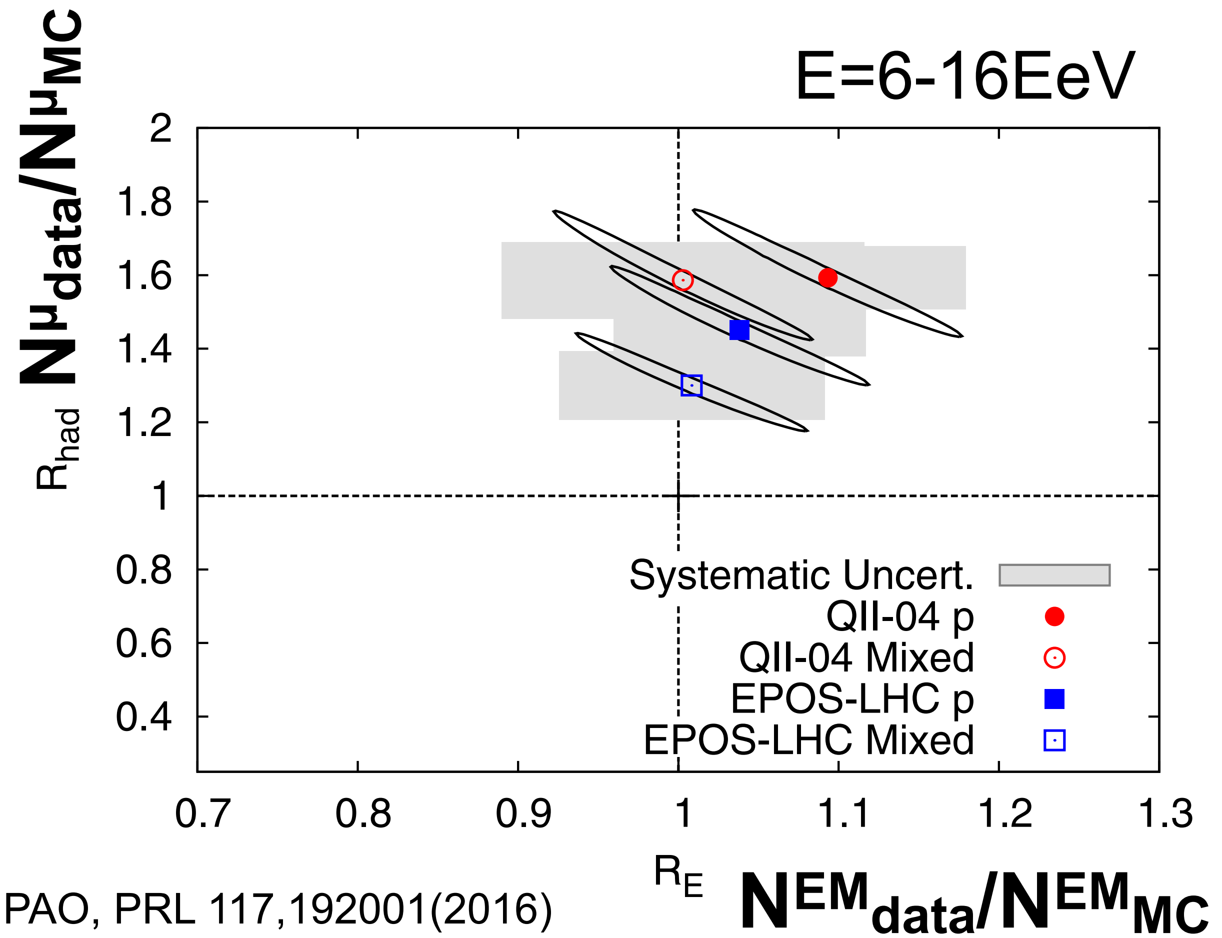
UHECR observation issues

Large model dependency of UHECR composition measurement



PAO collaboration (ICRC2017)

Muon excess $N^{\mu}_{data} > N^{\mu}_{MC}$

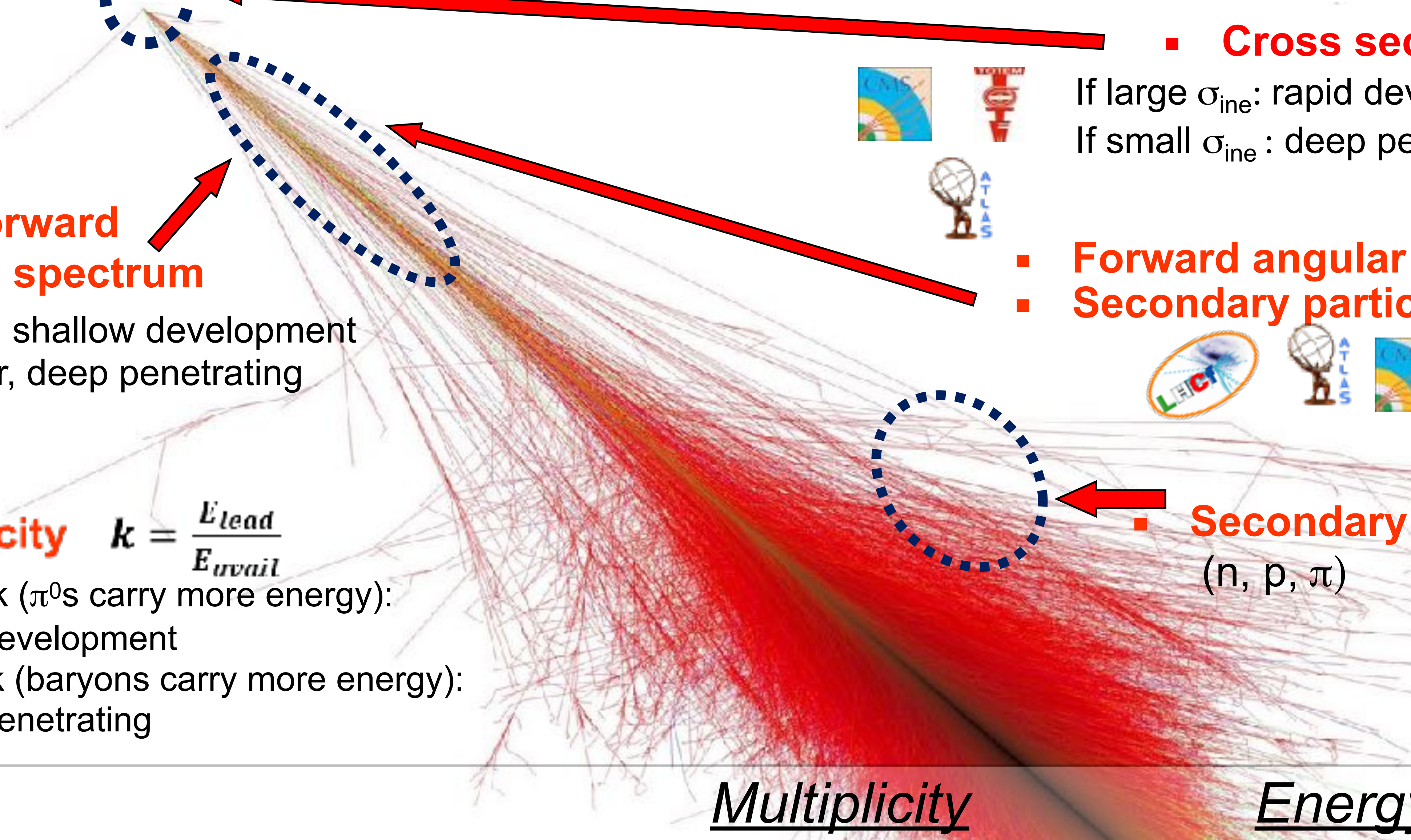


PAO, PRL 117,192001(2016)

Sensitive $E^{\pi 0}/E^{had}$ for a collision

Several ideas to solve it

- Strange particles
- Vector meson productions
- QGP



- **Cross section**

If large σ_{ine}: rapid development

If small σ_{ine} : deep penetrating

- **Very forward energy spectrum**
  - If softer, shallow development
  - If harder, deep penetrating

- **Forward angular emission**
- **Secondary particle multiplicity**

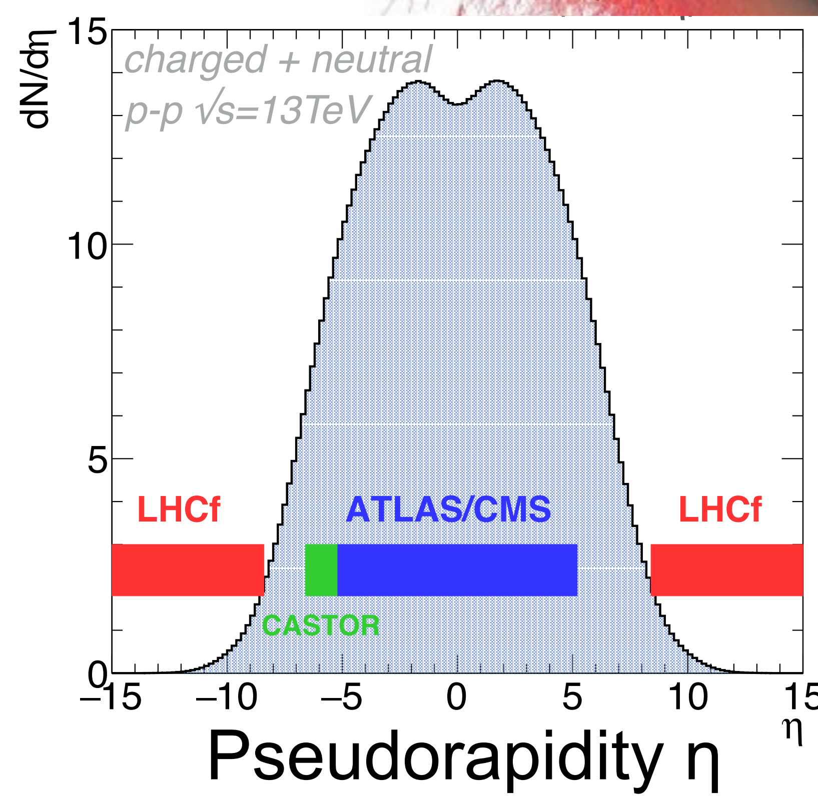
- **Elasticity** $k = \frac{E_{lead}}{E_{avail}}$
  - If small k (π^0s carry more energy): rapid development
  - If large k (baryons carry more energy): deep penetrating

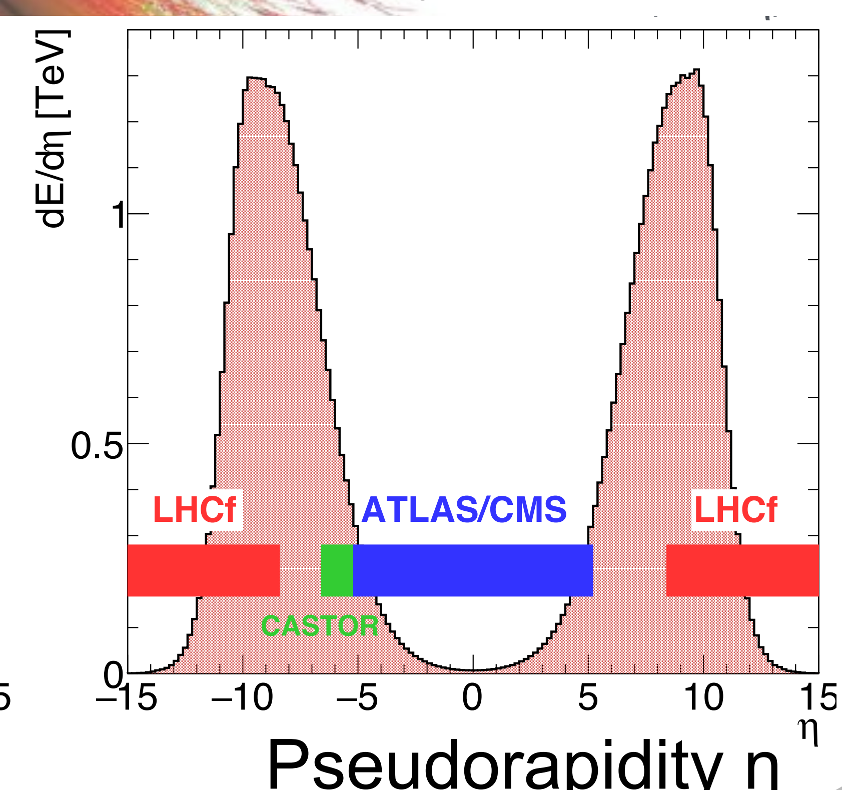
- **Secondary interactions**

(n, p, π)

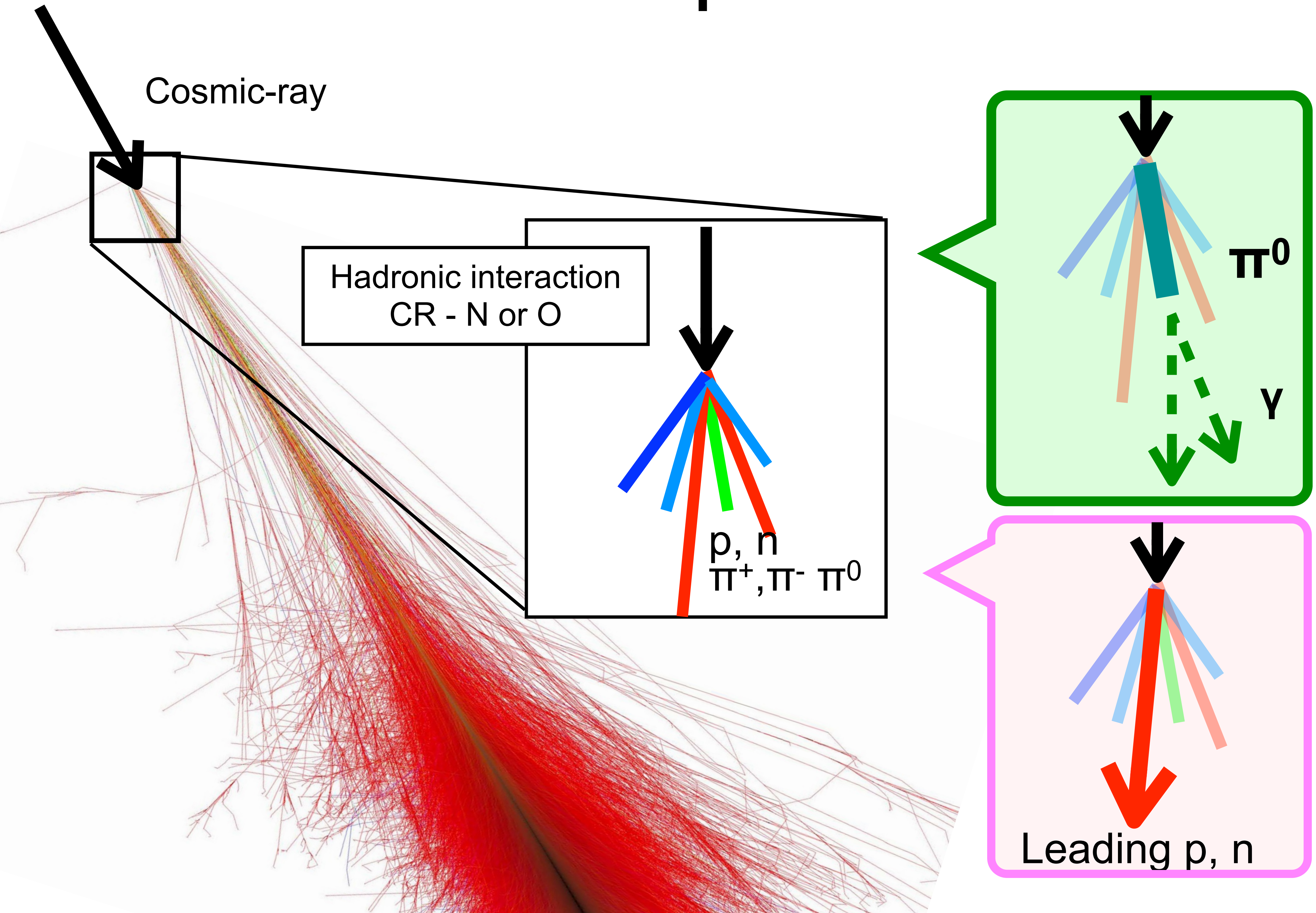
The coverage of the "wide" rapidity range by experiments is crucial

*Especially High Energy Flux in "**forward**" region*





Air shower developments and hadronic interaction



Neutral pions

- $\pi^0 \rightarrow 2\gamma$
- Induce electromagnetic showers which is dominant components of the shower.

Leading baryons

- bring the energy to next collisions
- Inelasticity: fraction of energy used for particle productions
  $k = 1 - E_{leading}/E_{CR}$

They must be measured experimentally

We do them at LHC and RHIC

These energetic π^0 and n are always emitted into the very forward region.

The LHCf Collaboration

Y. Itow, Y. Matsubara, H. Menjo, Y. Muraki,
K. Sato, K. Ohashi, M. Ueno *(Nagoya Univ.)*
T. Sako *(Univ. Tokyo)* K. Yoshida *(Shibaura Tech.)* N. Sakurai *(Tokushima Univ.)*
K. Kasahara, S. Torii *(Waseda Univ.)* K. Shimizu, T. Tamura *(Kanagawa univ.)*
M. Haguenauer *(PolyTech)* W.C. Turner *(Bereley)*
O. Adriani, E. Berti, L. Bonechi, M. Bongi, G. Castellini,
R.D'Alessandro, P. Papini, S. Ricciarini, A. Tiberio *(INFN Florence)*

The RHICf Collaboration

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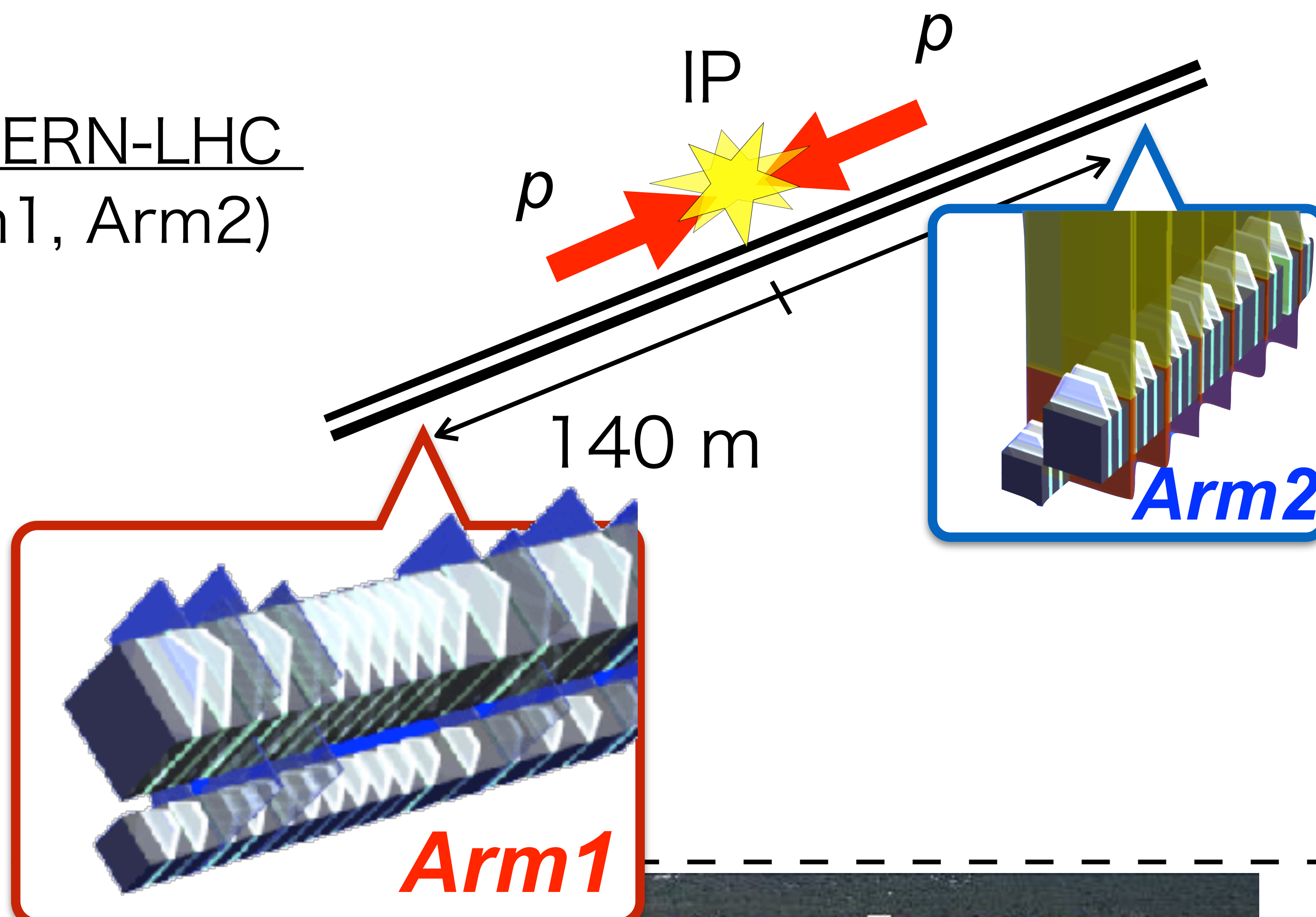
J. S. Park *(Seoul univ.)* B. Hong, M. H. Kim *(Korea univ.)*
O. Adriani, E. Berti, L. Bonechi, R.D'Alessandro *(INFN Florence)*
A. Trocomi *(INFN Catania)*

LHCf and RHICf experiments

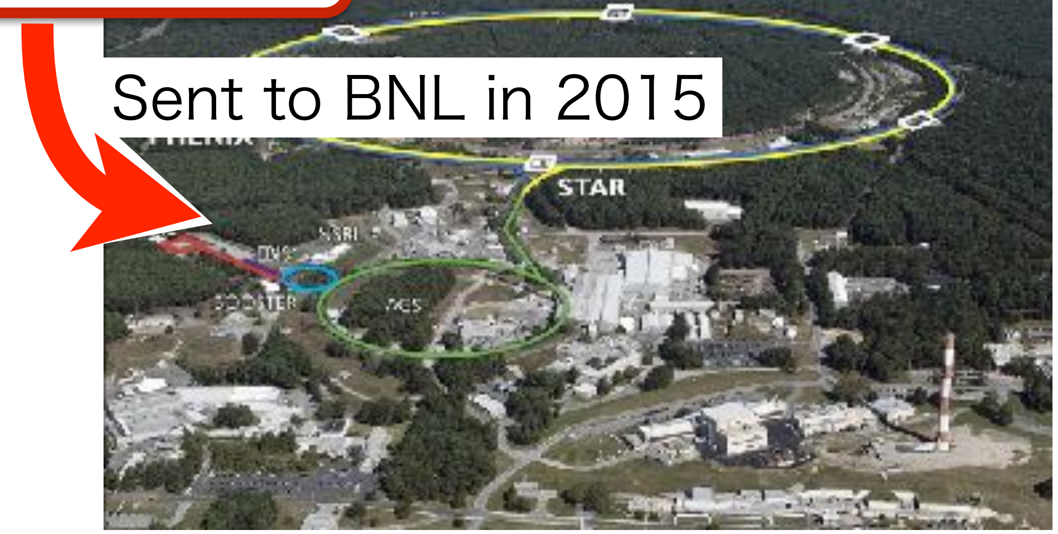
LHCf experiment

- Zero degree measurement at CERN-LHC
- Two calorimeter detectors (Arm1, Arm2) at ± 140 m from ATLAS IP
- Operations
  - pp: $\sqrt{s}$ = 0.9 TeV (2010),
    $\sqrt{s}$ = 2.76 TeV (2013),
    $\sqrt{s}$ = 7 TeV (2010),
    $\sqrt{s}$ = 13 TeV (2015)
  - pPb: $\sqrt{s_{NN}}$ = 5 TeV (2013,2016)
    $\sqrt{s_{NN}}$ = 5 TeV (2016)



RHICf experiment

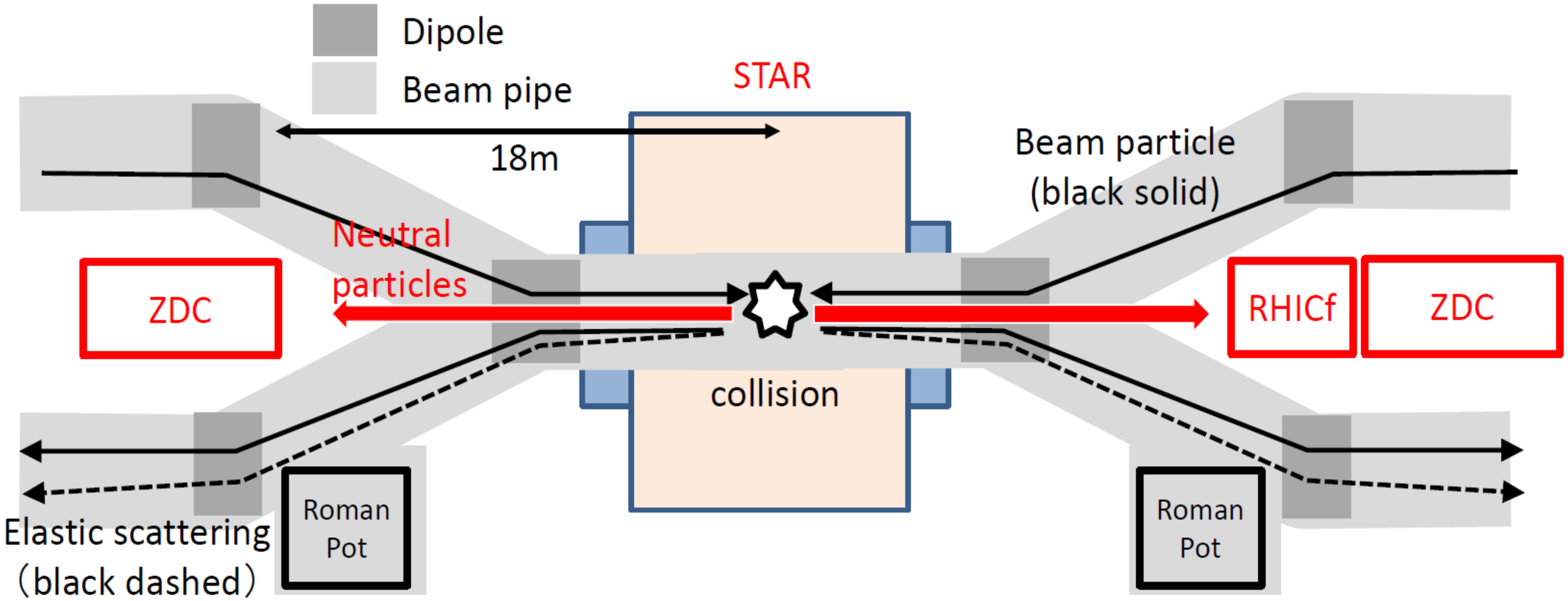
- Zero degree measurement at BNL-RHIC
- Only one detector at 18 m from STAR IP
- Spin asymmetry measurements with polarized proton beams
- Operation: pp $\sqrt{s}$ = 510 GeV (2017)



RHICf experiment

RHIC at BNL

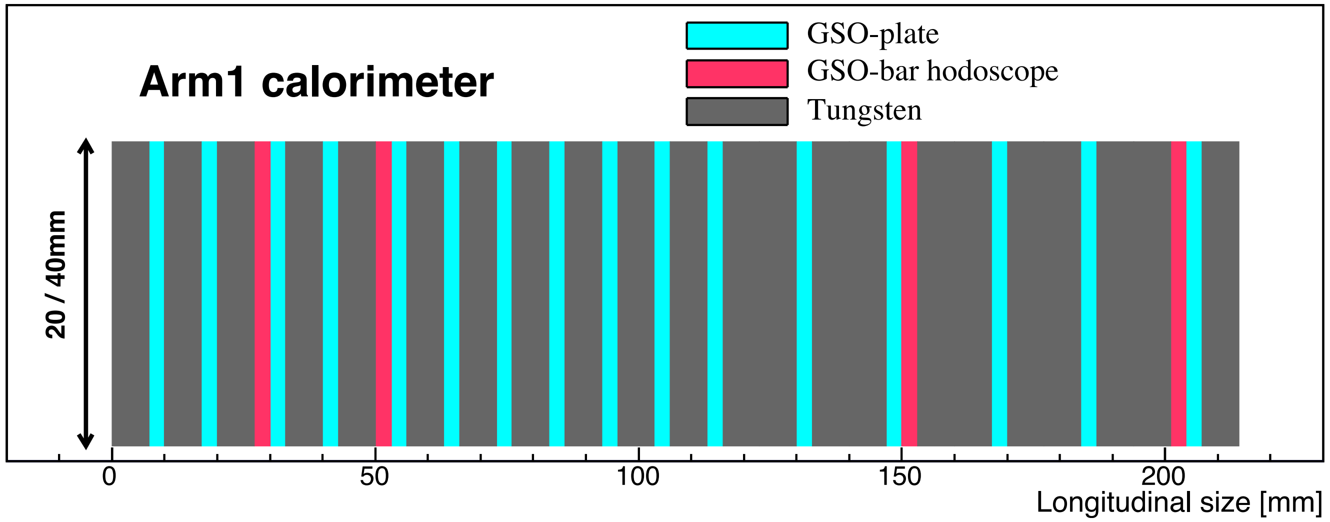
- **p+p √s = 510 GeV**
  (polarized beam)
- Test of energy scaling with the wide p_T range.
- The operation was successfully completed in June 2017
- RHICf covers η > 5.9
- Common operation with STAR

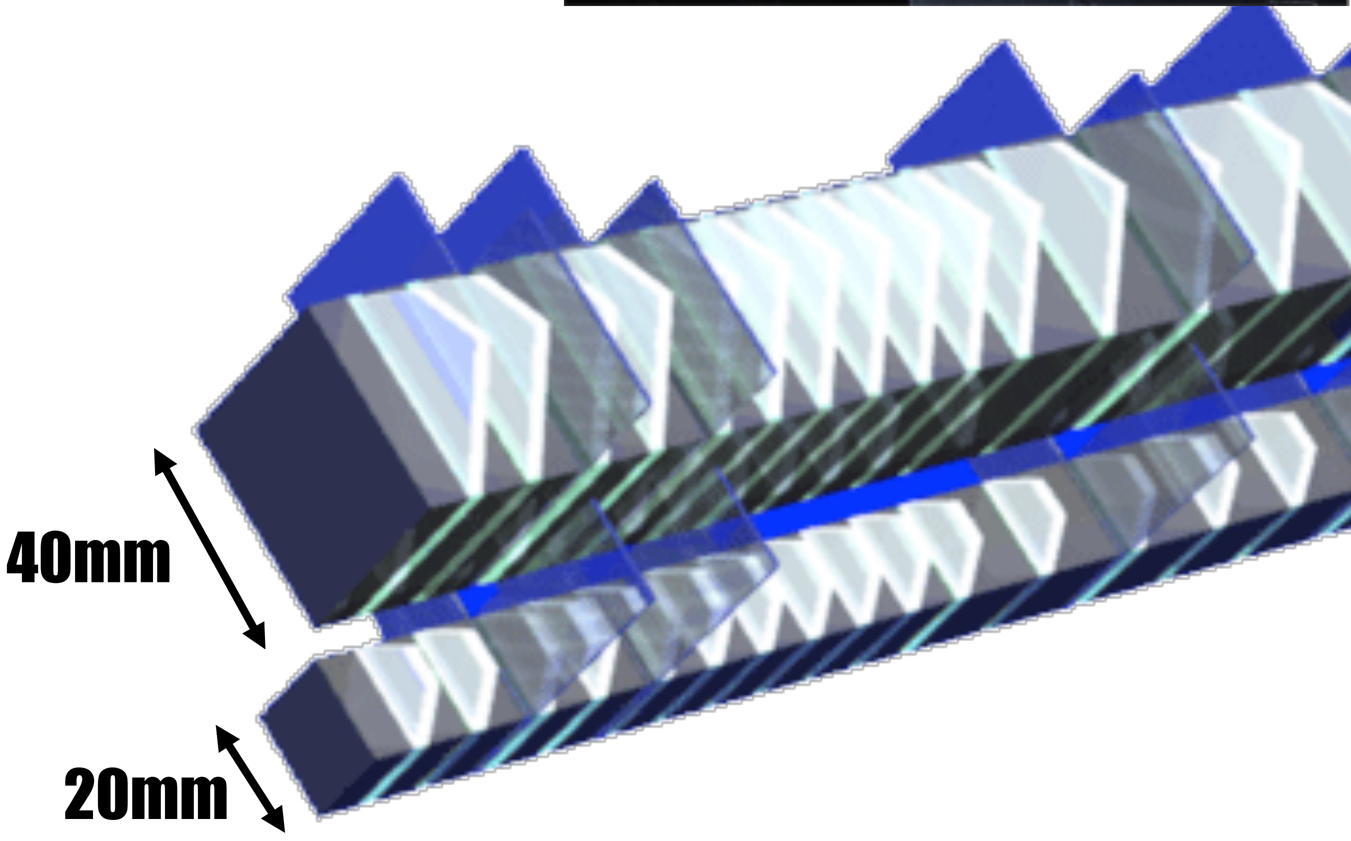


The RHICf detectors

Sampling and Positioning Calorim

- W (44 r.l , 1.7λ_I) and 16 GSO scintillator layers
- Four positioning sensitive layers;
  Arm1: XY-hodoscope of GSO bars (1mm step)
  Arm2: XY-Silicon strip (160 μm step)
- **Each detector has two calorimeter towers, which allow to reconstruct** π^0

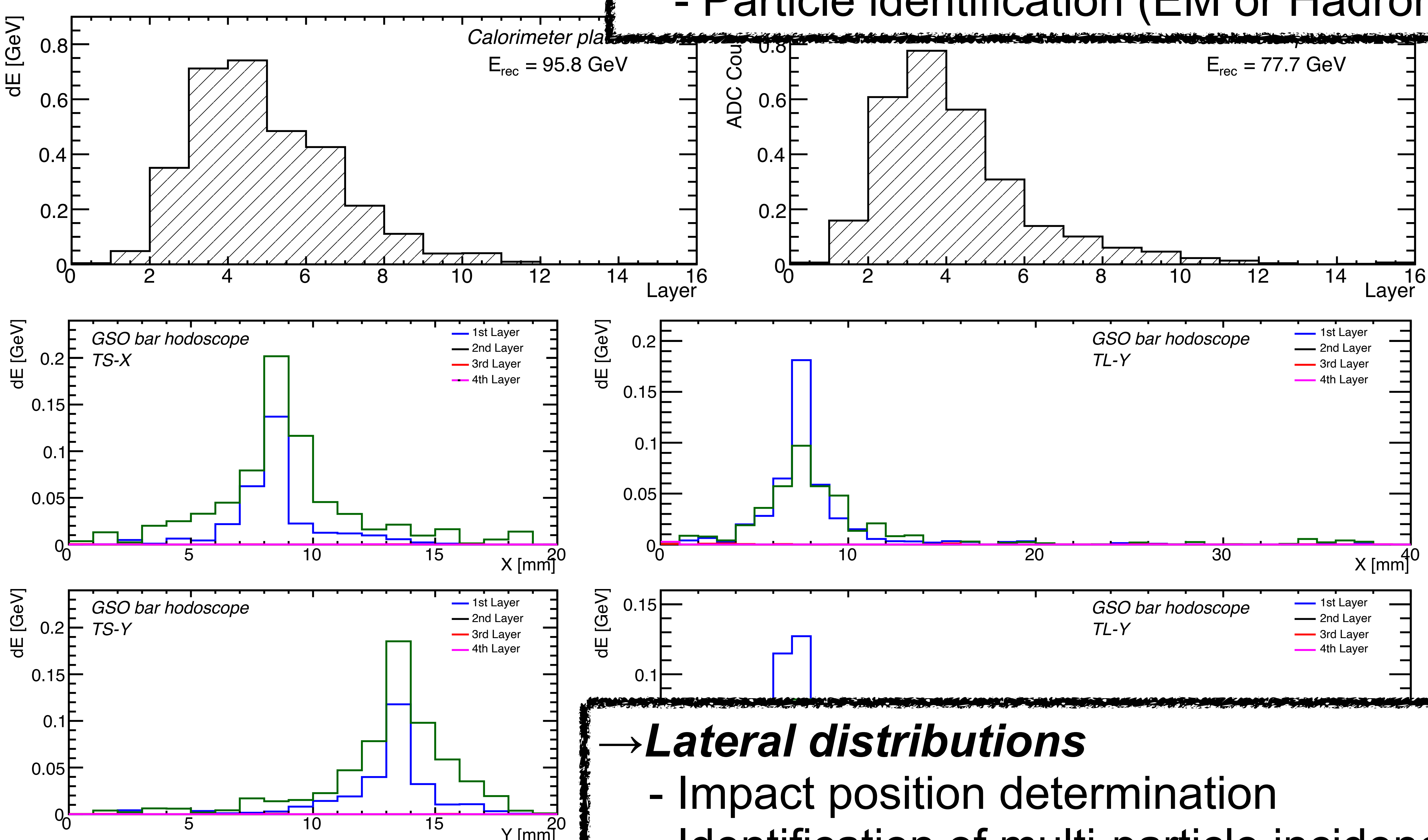




Event sample

→*Longitudinal developments*
- Energy measurement
- Particle identification (EM or Hadronic)

RHICf RUN: 2798 EVENT: 3834

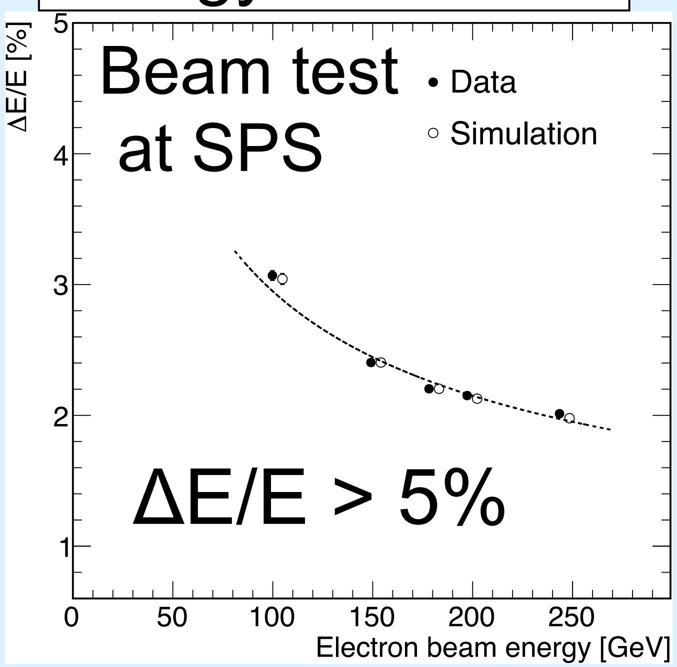


→*Lateral distributions*
- Impact position determination
- Identification of multi-particle incidence

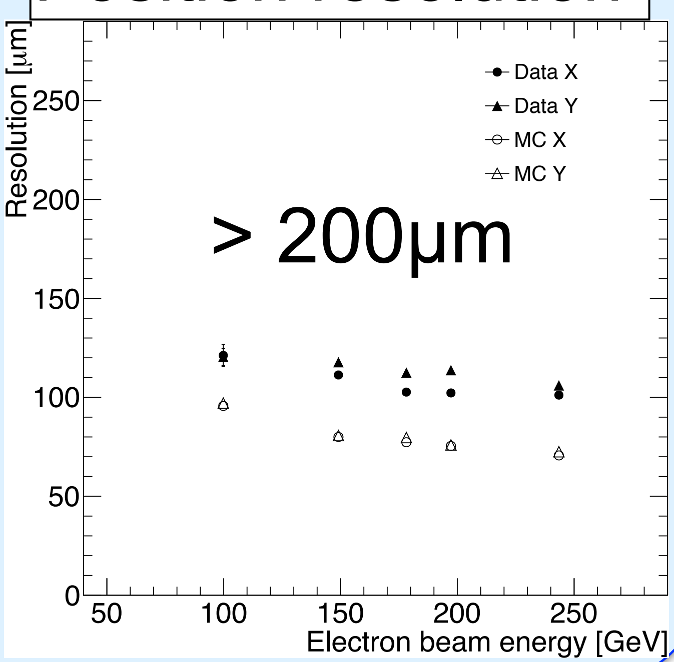
Calorimeter performances

EM showers

Energy resolution

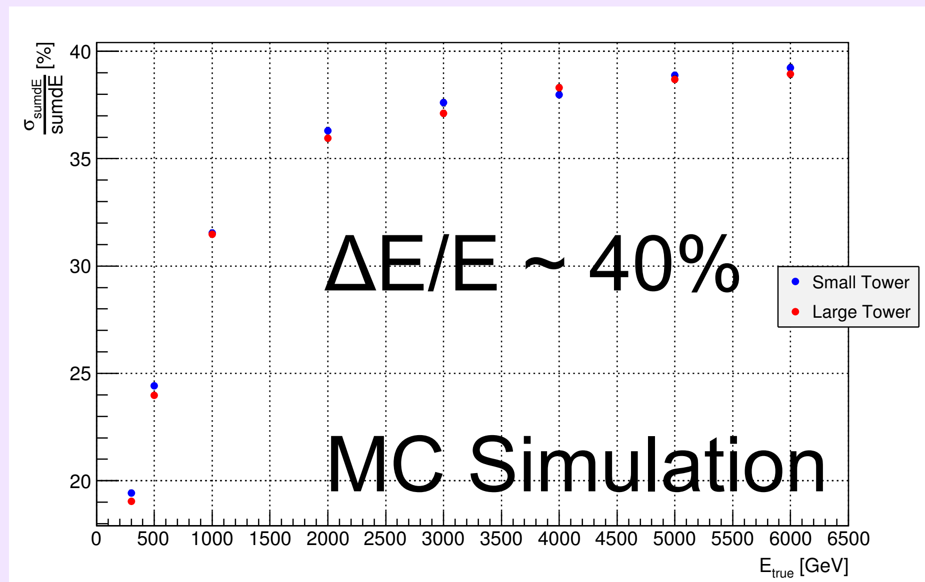


Position resolution

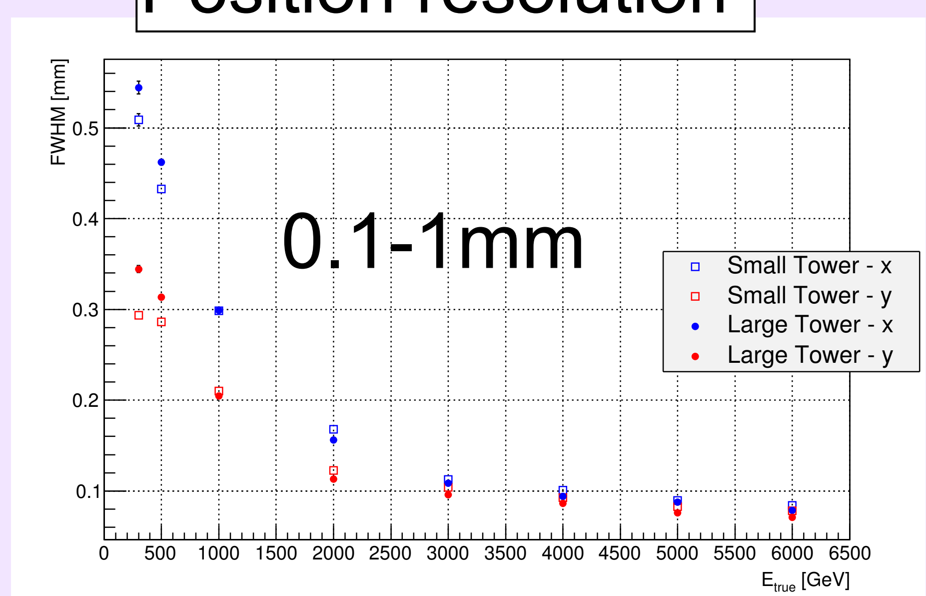


Had. showers

Energy resolution

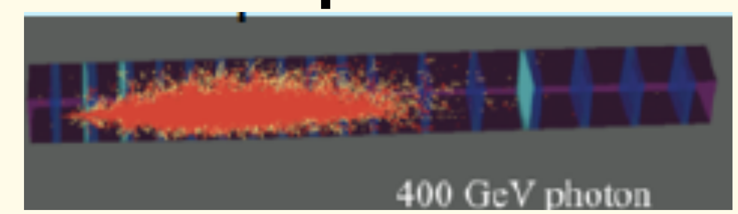


Position resolution

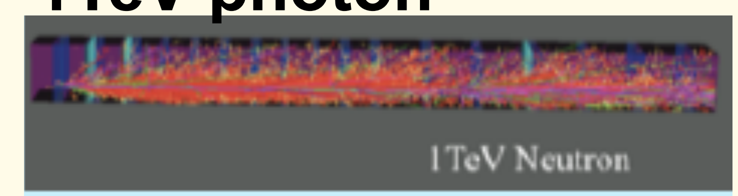


PID

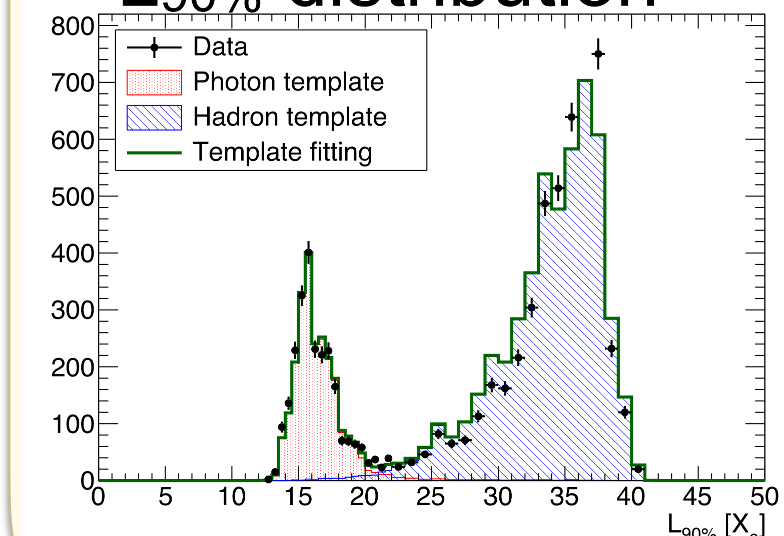
400 GeV photon



1TeV photon

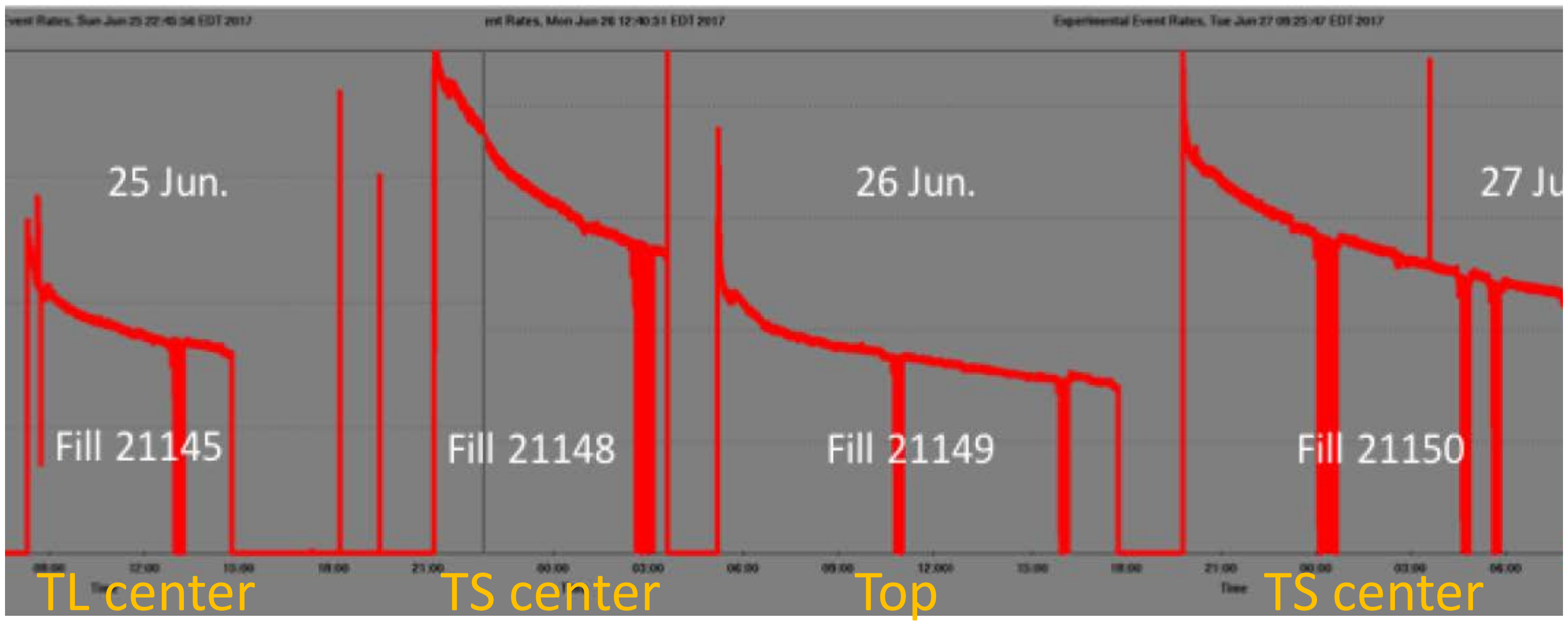


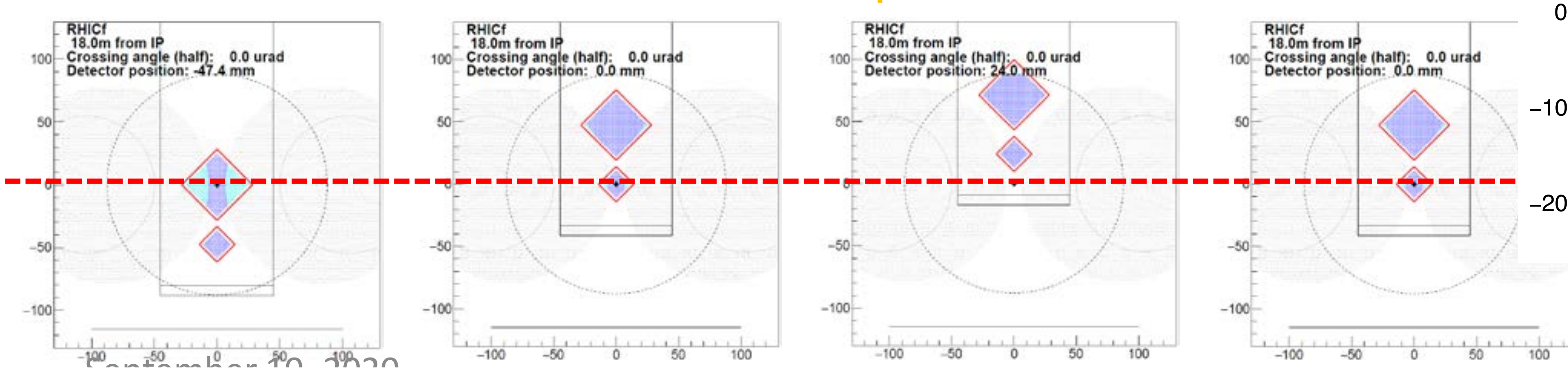
$L_{90\%}$ distribution

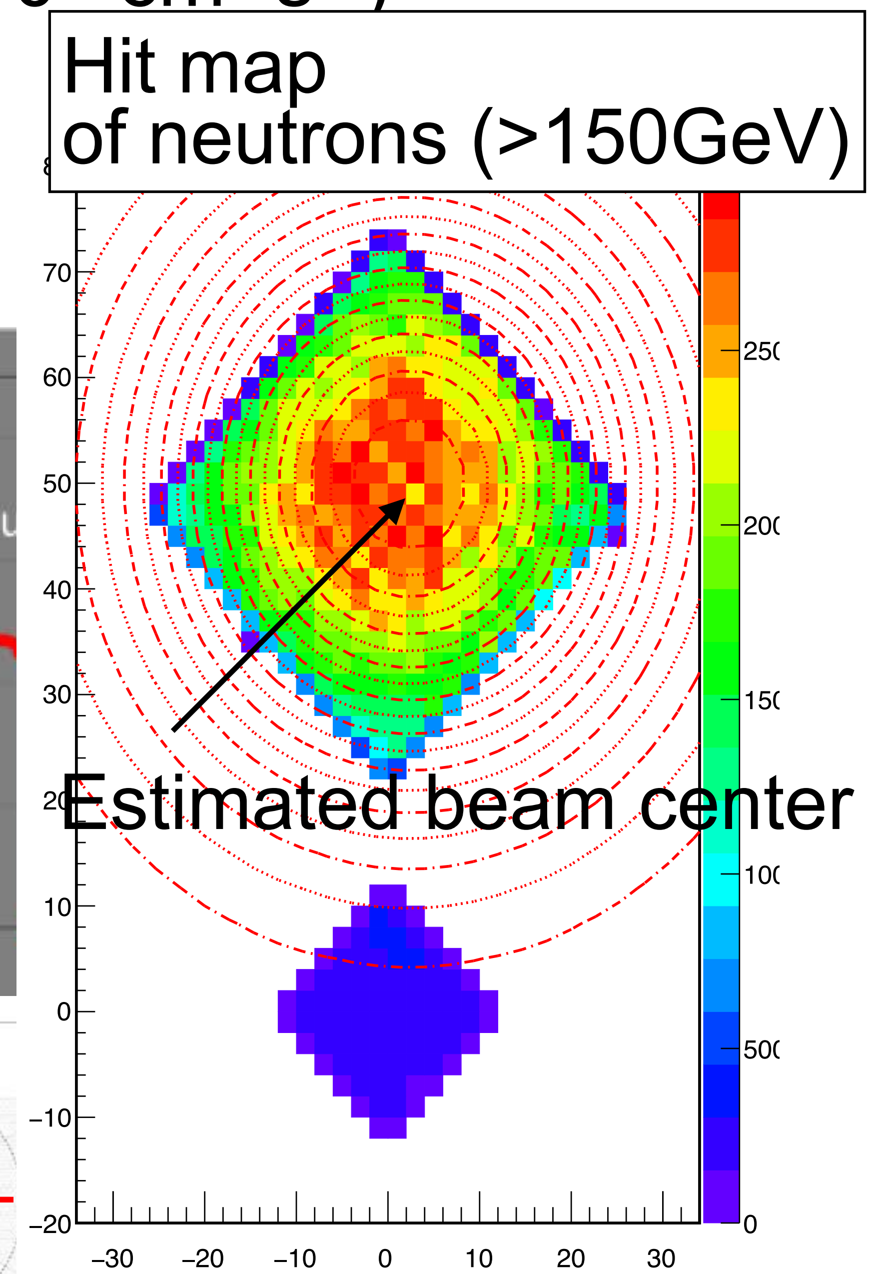


RHICf operation

- Successfully completed in June 2021
  - p+p, $\sqrt{s}$=510GeV, radial polarization.
  - 3 days operation with low luminosity ($L=10^{31} cm^{-2}s^{-1}$)
  - Joint operation with STAR
  - 3 detector positions



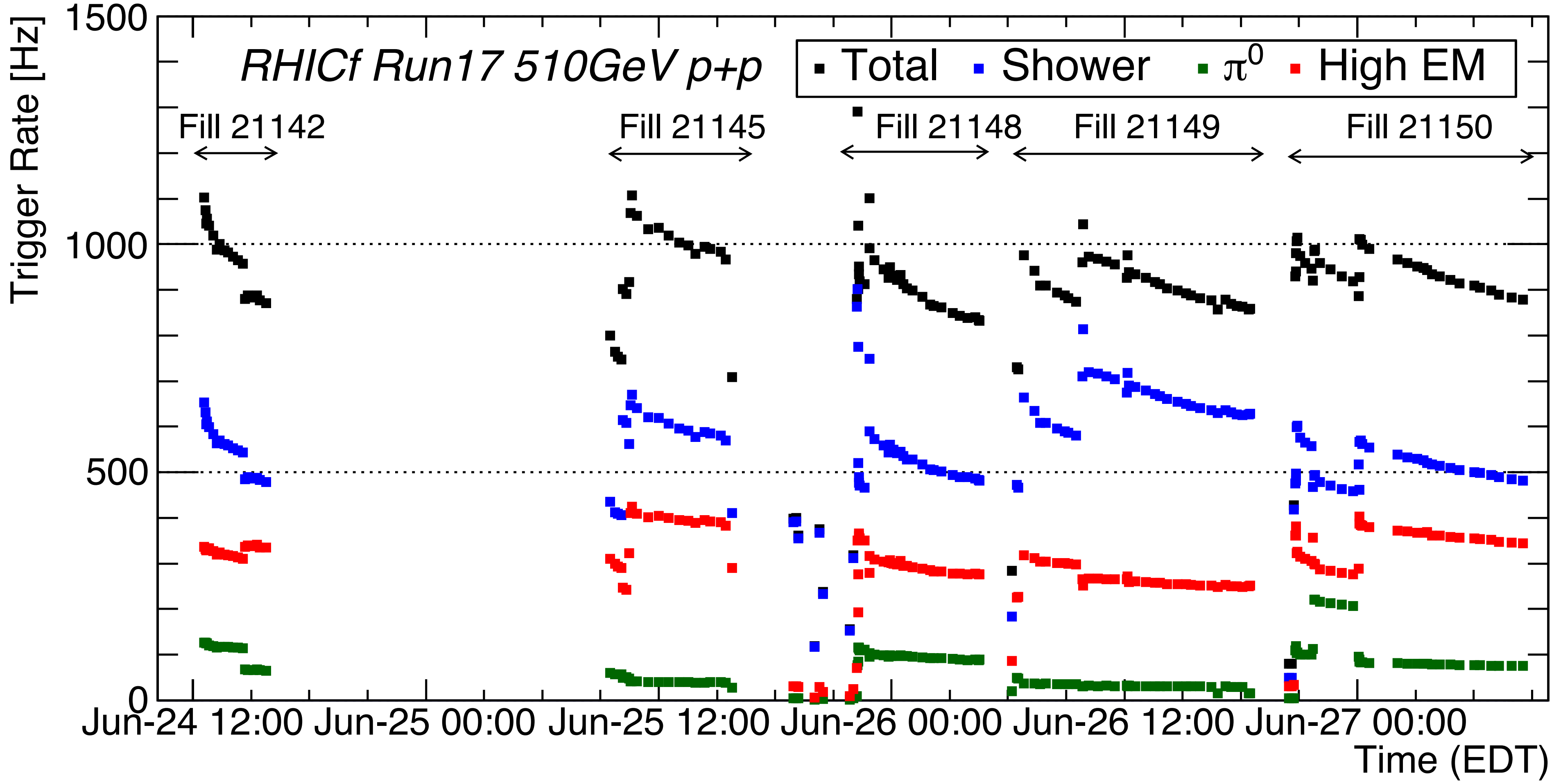




RHICf Trigger

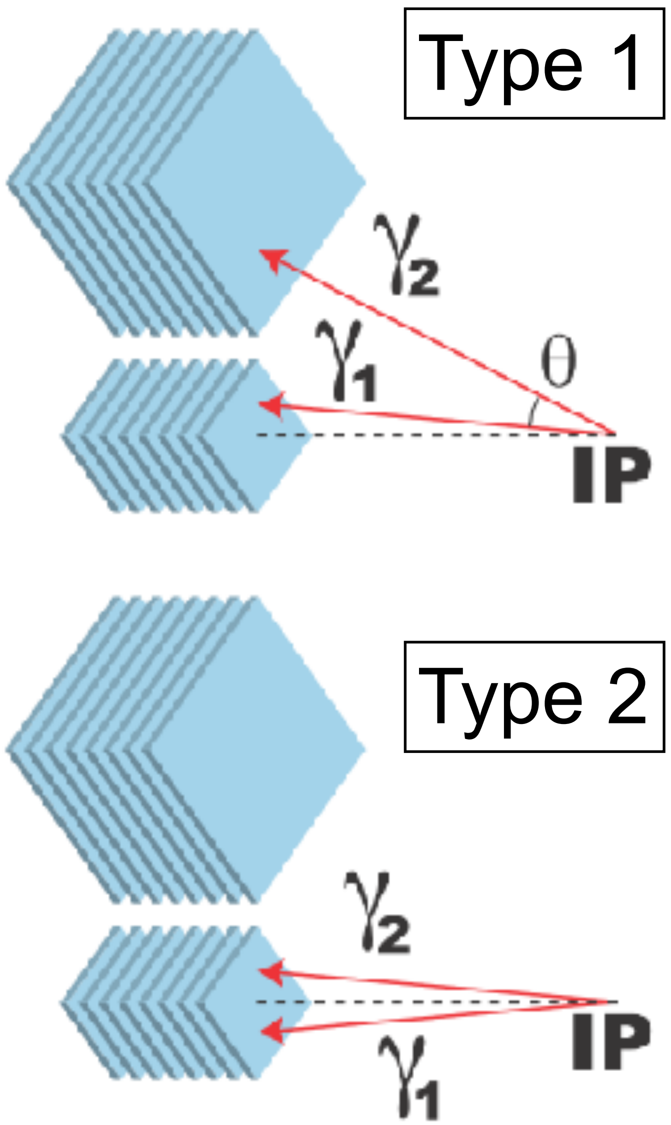
- 3 trigger modes
  - Shower trigger (γ,n) 6-30 kHz
  - High EM trigger (γ > 100 GeV) ~ 1 kHz
  - π^0 trigger (π^0) ~ 200 Hz

⇒ 1 kHz readout, 100 M events in Run17

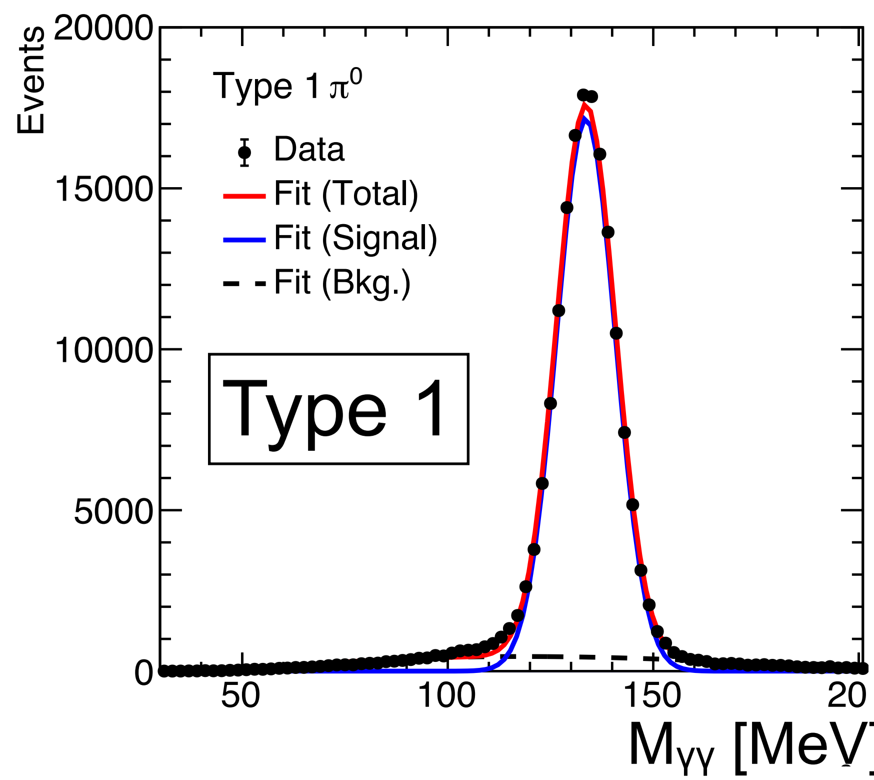


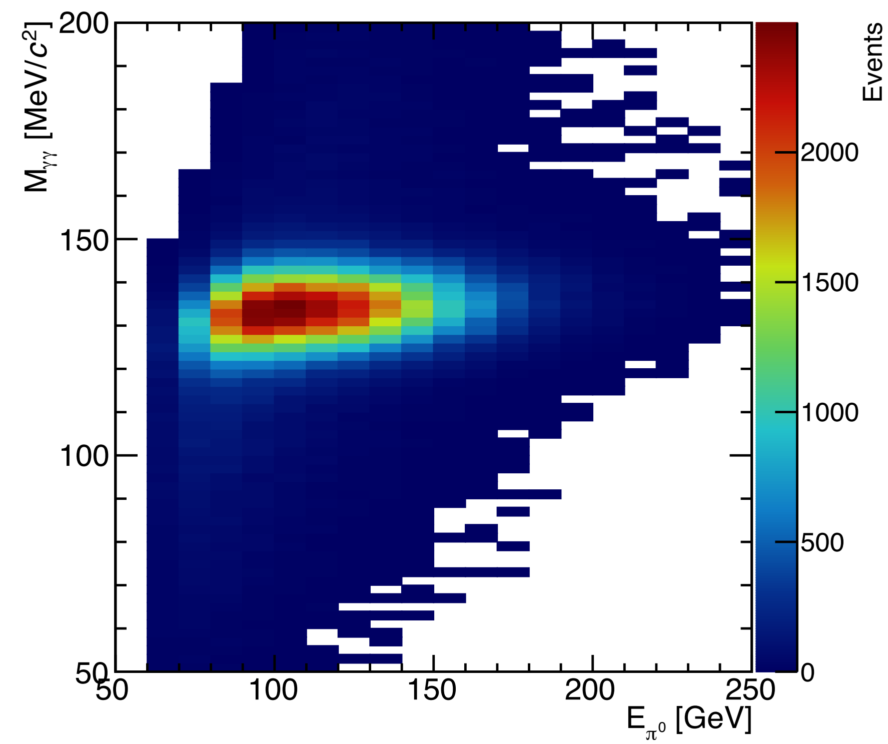
π^0 measurement

- Not only physics but also for calibration and performance studies.
- Reconstruct π^0 kinematics, energy, Pt, Mass, from a photon pair from a π^0 decay
- Two event types



Reconstructed mass $M_{\gamma\gamma}$ distribution





$$M_{\gamma\gamma} \sim \sqrt{E_{\gamma 1} E_{\gamma 2}}\,\theta$$

- Energy calibration
- Confirmation of linearity
- Stability check

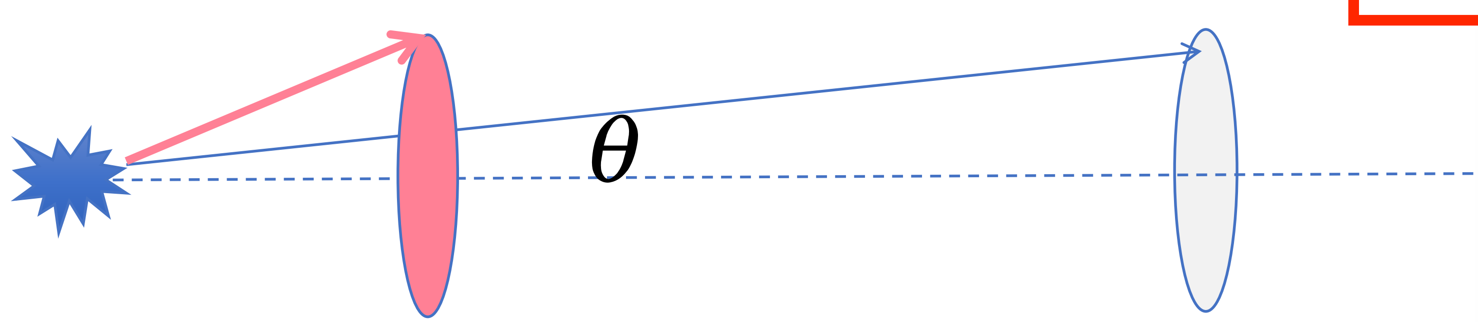
Physics results from RHICf (LHCf)

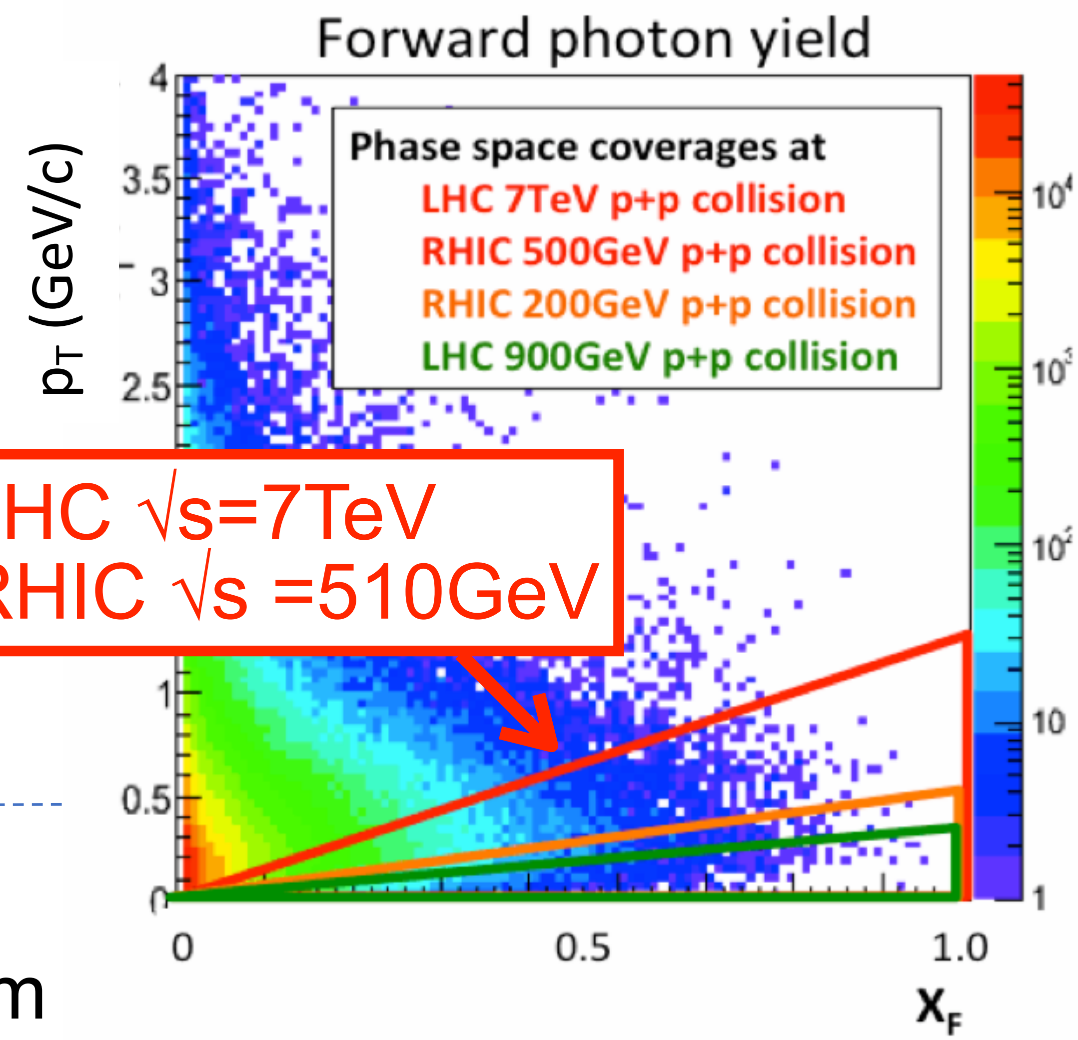
Physics in RHICf

Cross-section measurement

✓Measurement of √s dependency (=Energy scaling) with the wide p_T range equivalent to LHCf,√s=7TeV
→ Improve the prediction power of models in the wide energy rage.

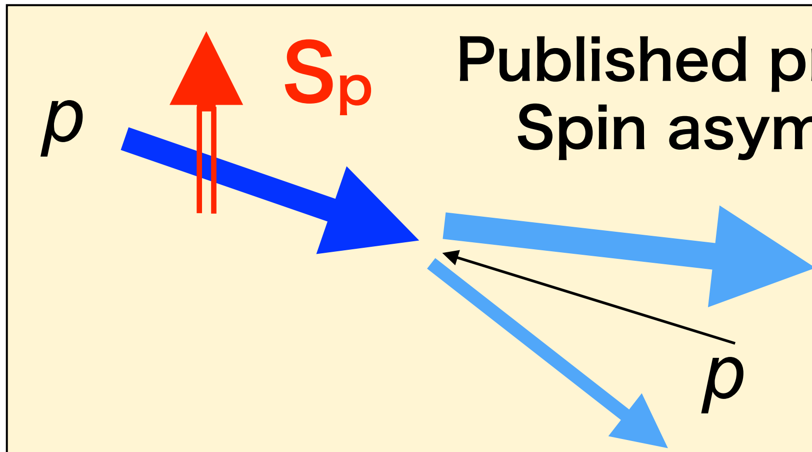
p_T coverage: < 1/2 √s sinθ





Spin asymmetry measurement

→ Minho's talk



Published preliminary results of Spin asymmetry (A_N) for π^0

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

Operations and Results

Run	E_{lab} (eV)	Photon	Neutron	π^0	
p-p √s=0.9TeV (2009/2010)	4.3×10^{14}	PLB 715, 298 (2012)		-	
p-p √s=2.76TeV (2013)	4.1×10^{15}			PRC 86, 065209 (2014)	PRD 94 032007 (2016)
p-p √s=7TeV (2010)	2.6×10^{16}	PLB 703, 128 (2011)	PLB 750 360 (2015)	PRD 86, 092001 (2012)	
p-p √s=13TeV (2015)	9.0×10^{16}	PLB 780, 233 (2018)	JHEP 2018, 73 (2018) JHEP 2020, 016 (2020)	preliminary	
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 √s=510GeV (2017)	1.4×10^{14}	Submitted to PLB		Spin Asymmetry PRL 124 252501 (2021)	

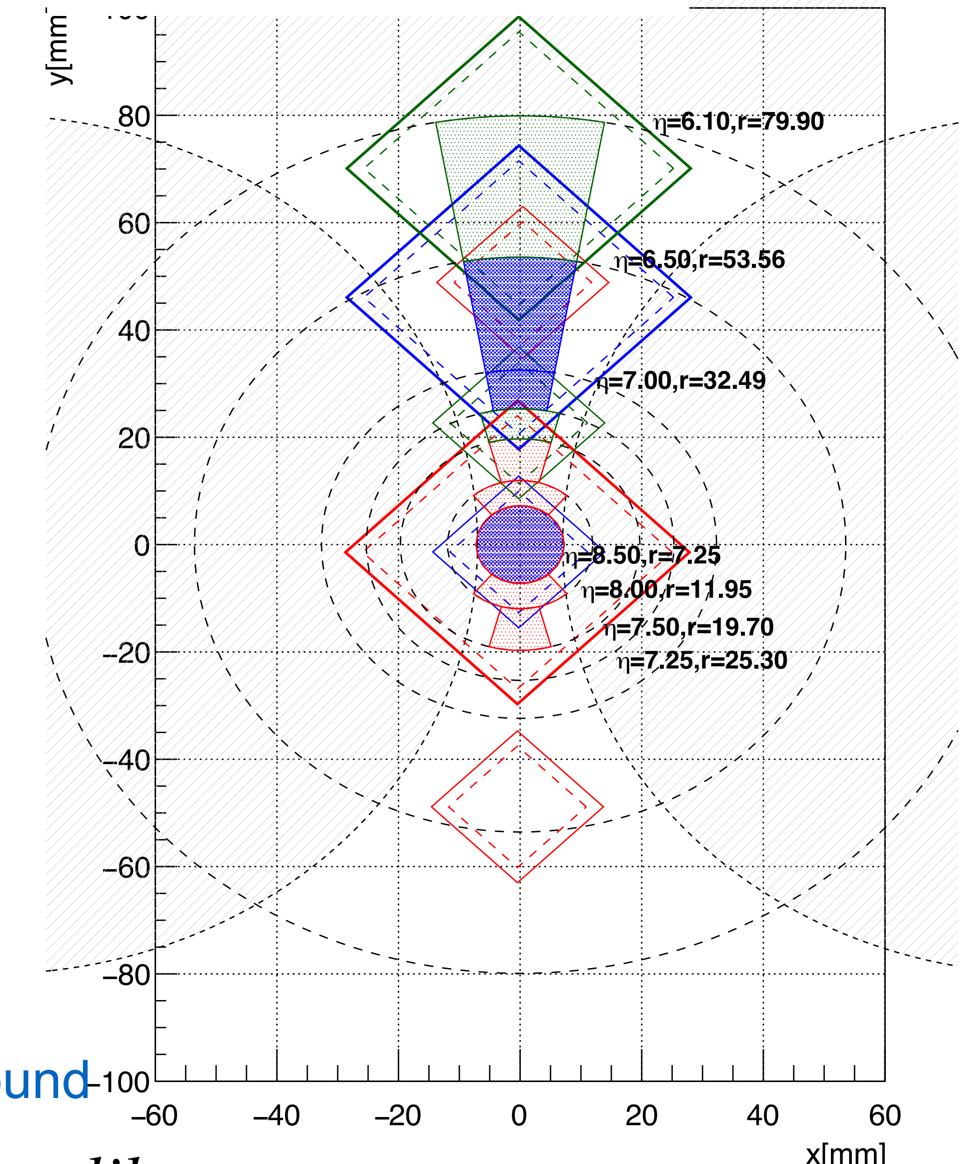
RHICf Photon measurement

- Data set
  - All data obtained in 2017
  - Three detector positions
  - Shower and HighEM trigger samples

- Event selection
  - PID selection (Photon like)
  - Singe hit selection
  - Fiducial area selection (right figures)

- Analysis method

Fiducial area for cross-section



Efficiency and Multi-hit contribution

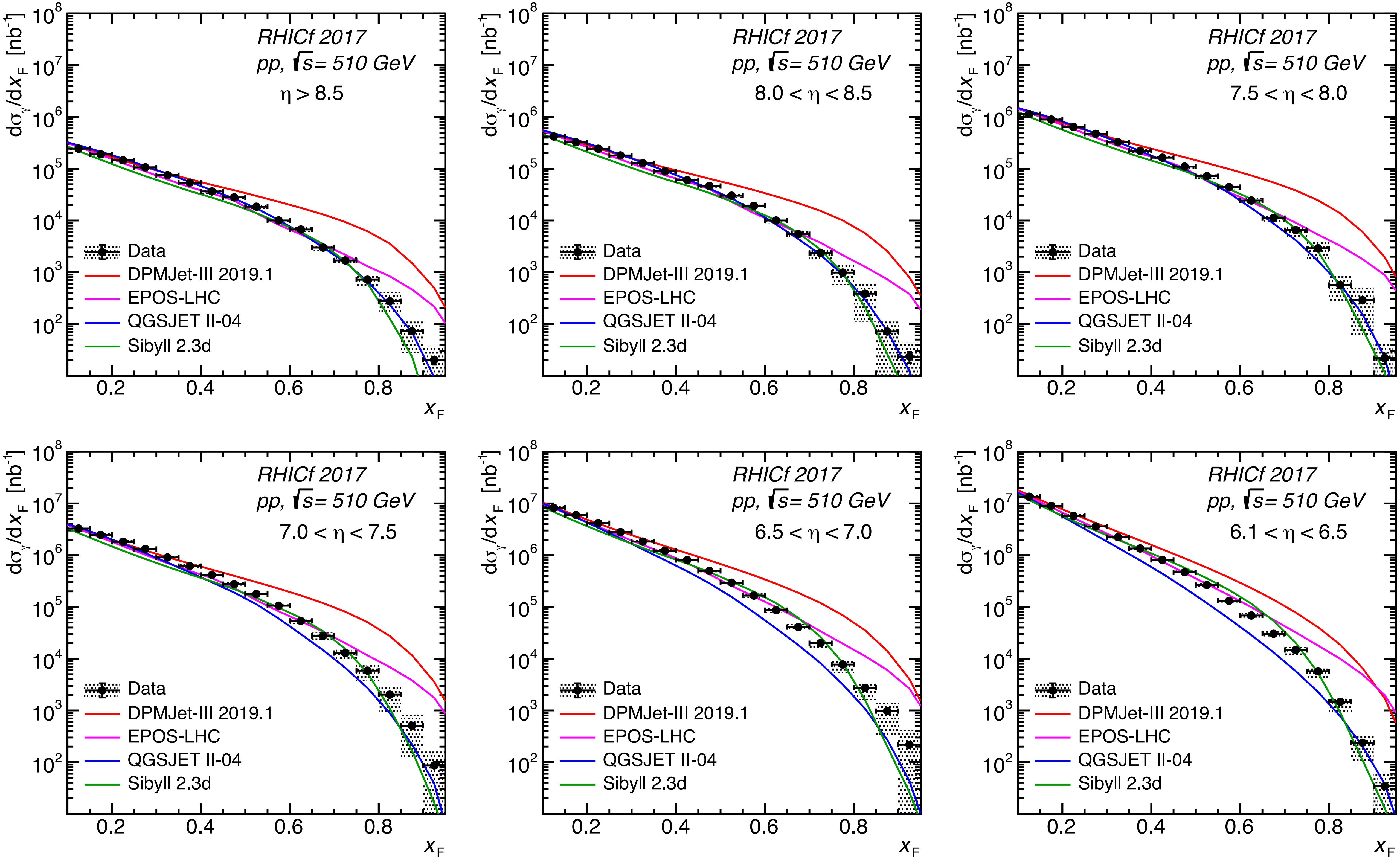
Hadron contamination

Beam-gas background

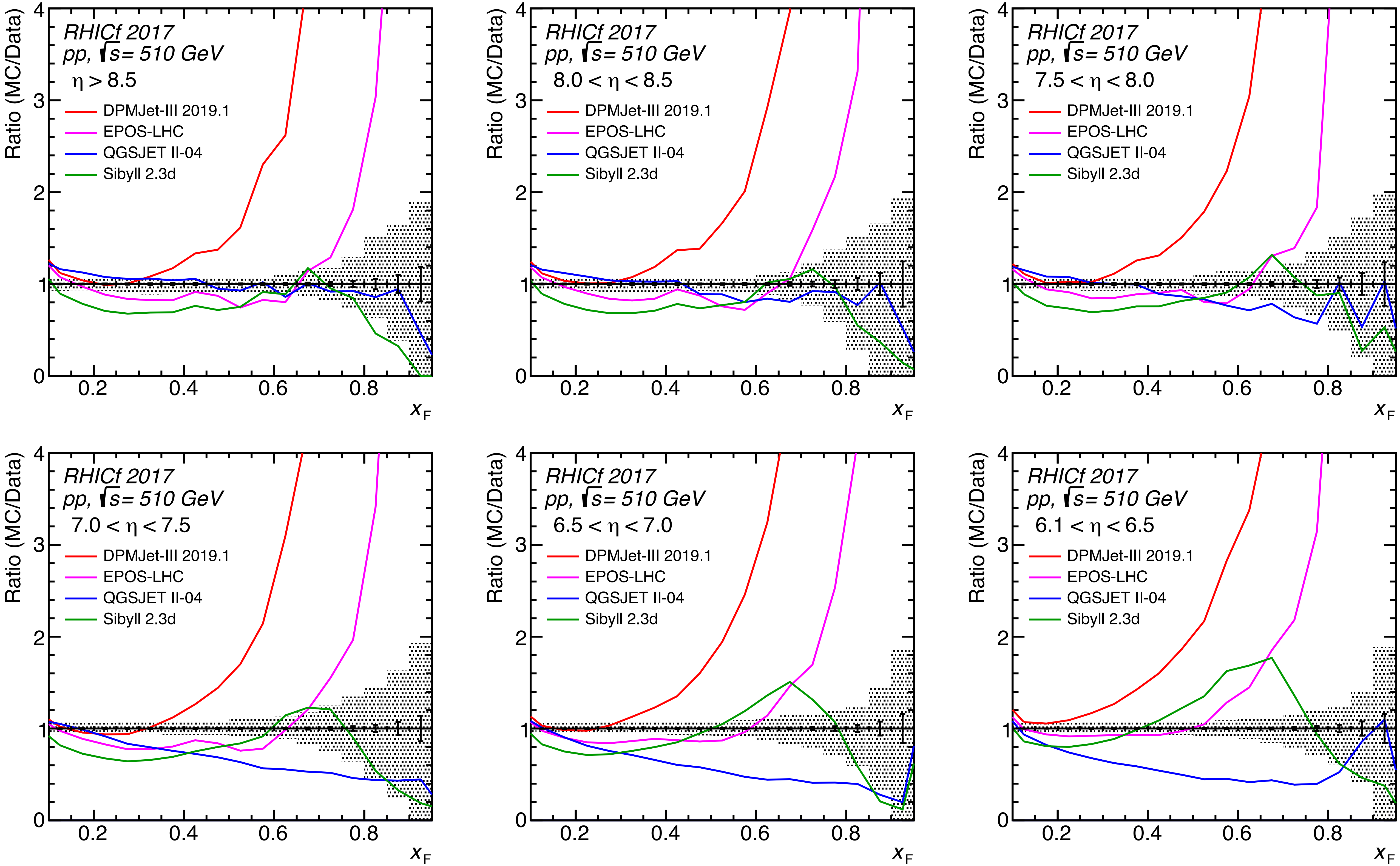
$$\frac{d\sigma}{dX_F} = \frac{C^{c\tau} C^{MC} C^{PID\,purity} (1 - R^{BKG})\, N^{single-\gamma\, like}_{i-trg,spin}}{L^{recode}_{i-trg,spin} \Delta X_F}$$

long life-particles' contribution

RHICf Photon result

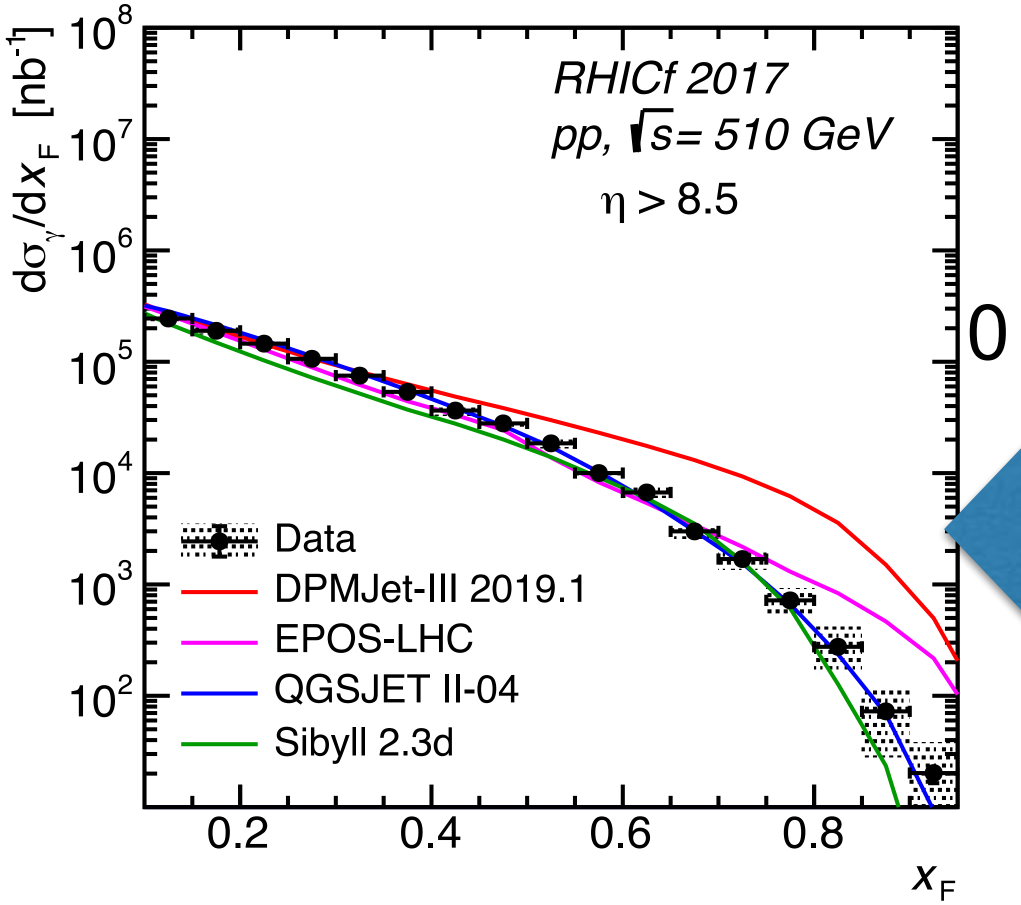


Ratio (MC/Data)

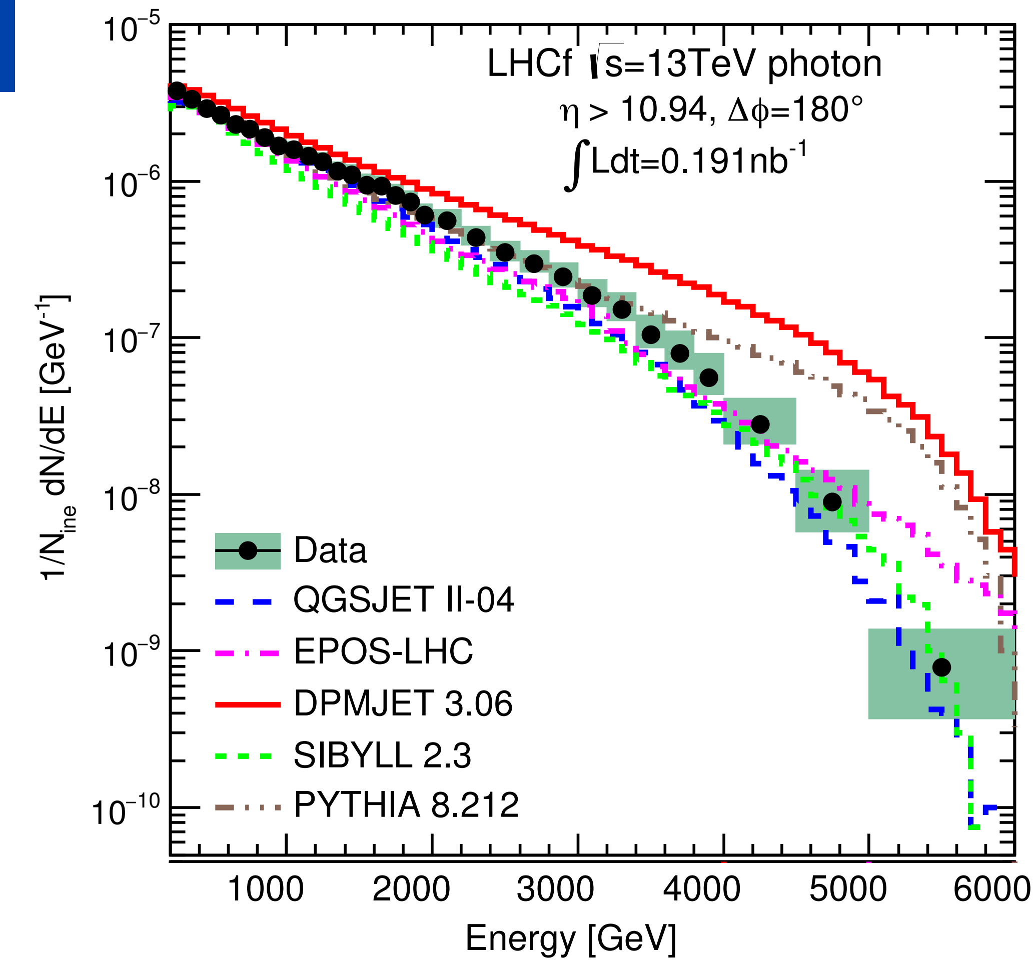


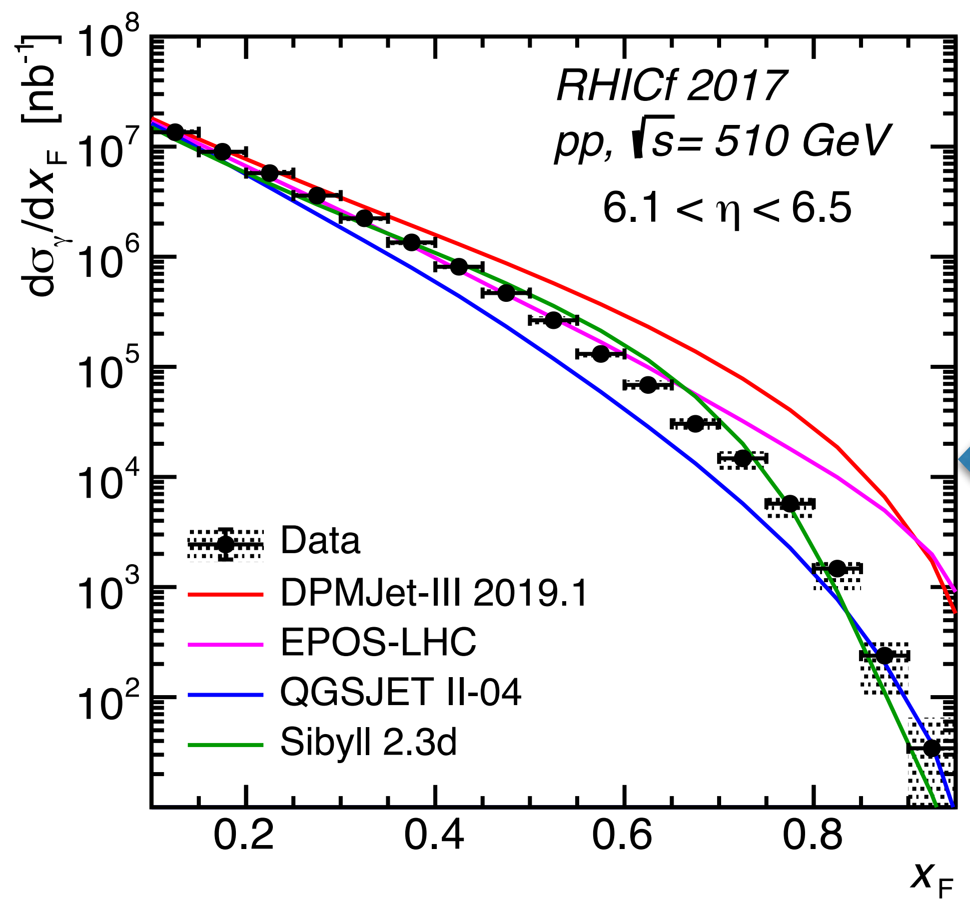
510GeV

13 TeV

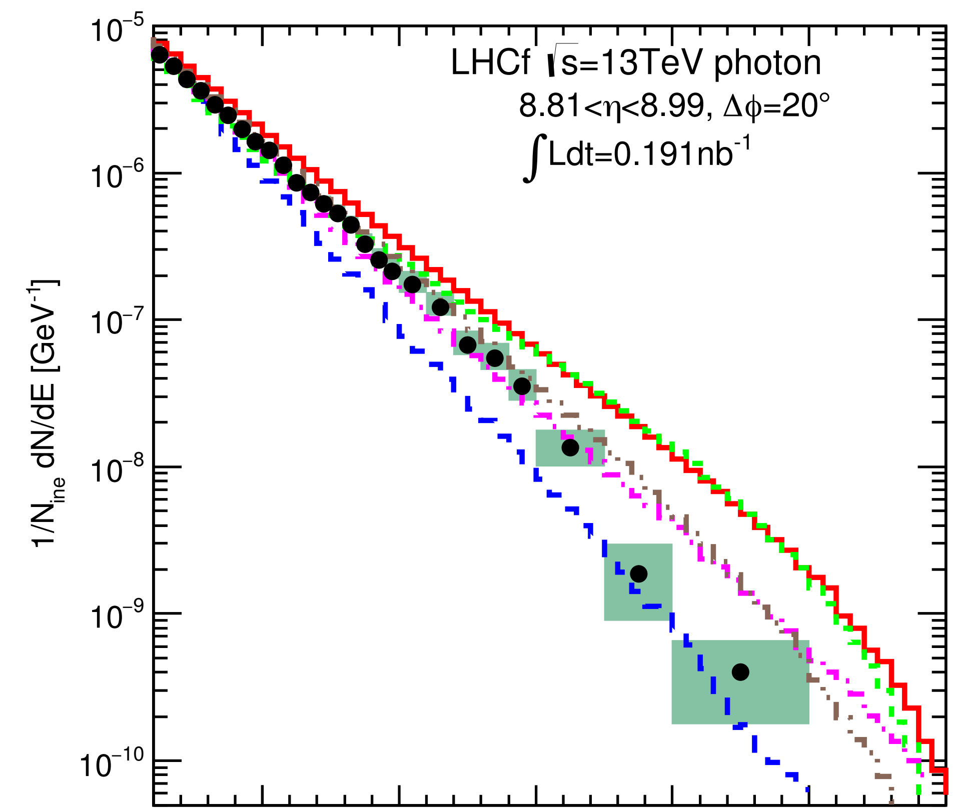


0 degree





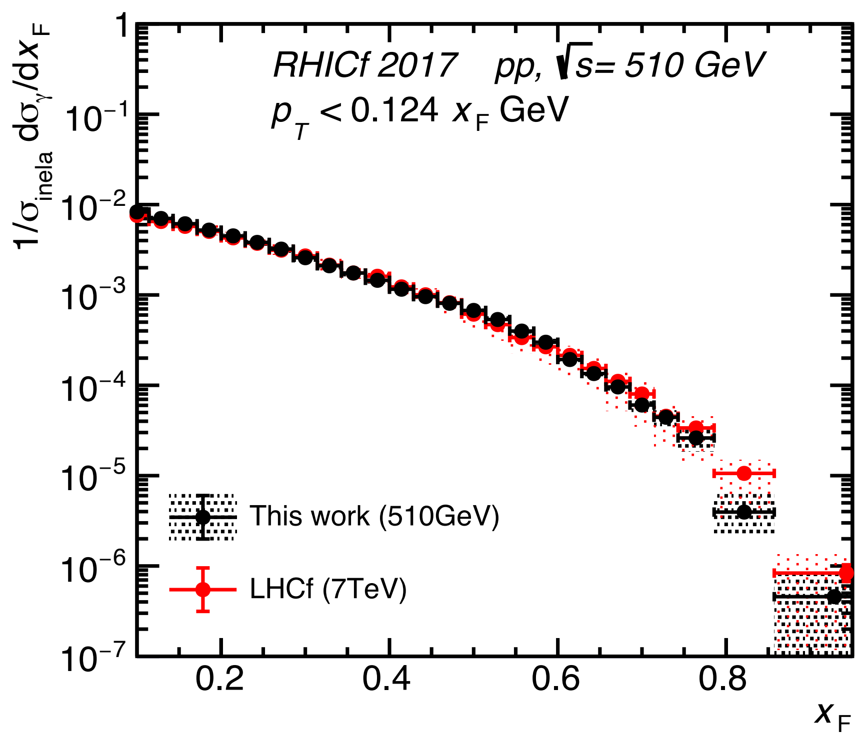
off region



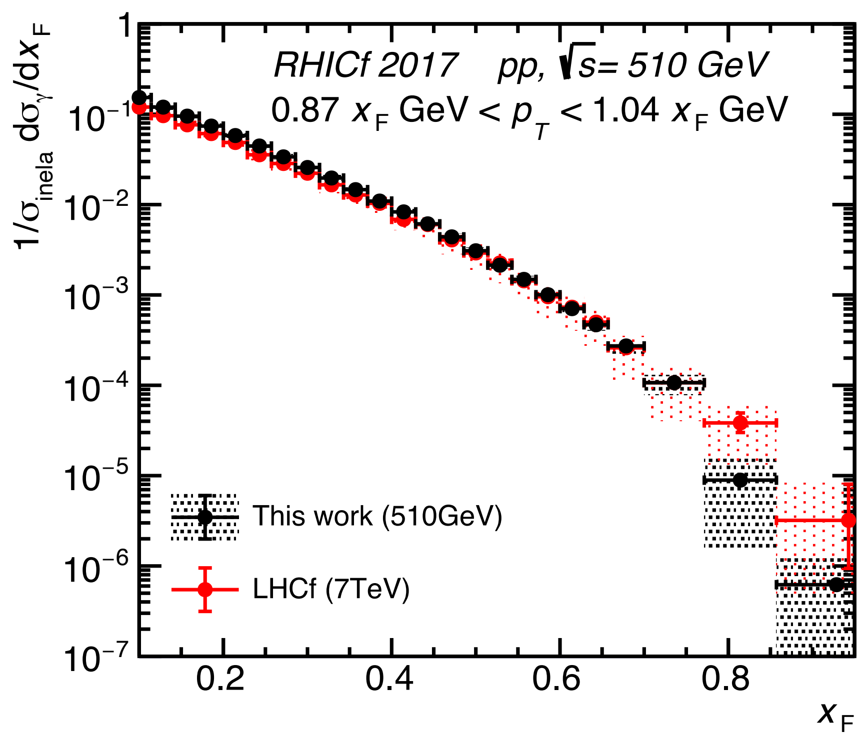
Test of collision energy scaling

- Comparison with LHCf ($\sqrt{s}$ = 7 and 13 TeV) photon results.
- Selected same X_F-p_T phase space coverage as those results
- Normalized by $\sigma_{inela.}$ (σ_{inela} = 48.3, 72.9, 79.5 mb for 0.5, 7, 13 TeV)

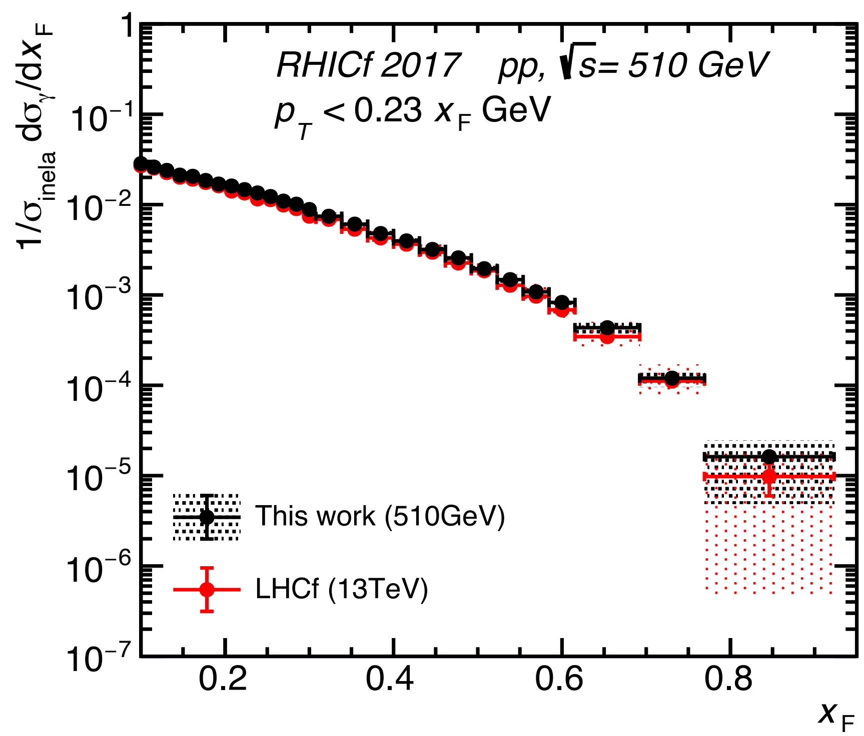
v.s. LHCf 7TeV η > 10.94



v.s. LHCf 7TeV 8.81 < η < 8.99

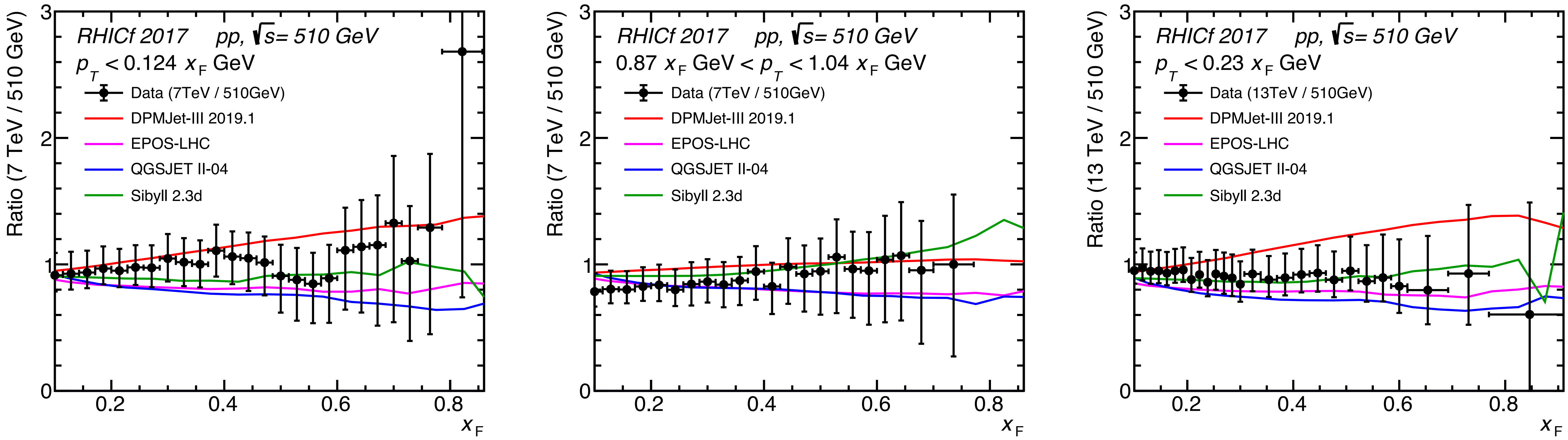


v.s. LHCf 13TeV η > 10.94



Confirmed the energy scaling within the error !!

Ratio (7TeV or 13TeV/ 510GeV)



- Consistent with the scaling within the errors
  Lower ratio at X_F<0.4 of the middle plot can be explained by the difference of method with the LHCf 7TeV paper.
- No sensitivity to test weak X_F dependency predicted by some models.
  → Need an effort to reduce the errors together with LHCf Collaboration

Future plan

- Neutron, π^0 cross-section measurements
- Combined analysis with STAR

Forward neutron measurement

- Inelasticity measurement

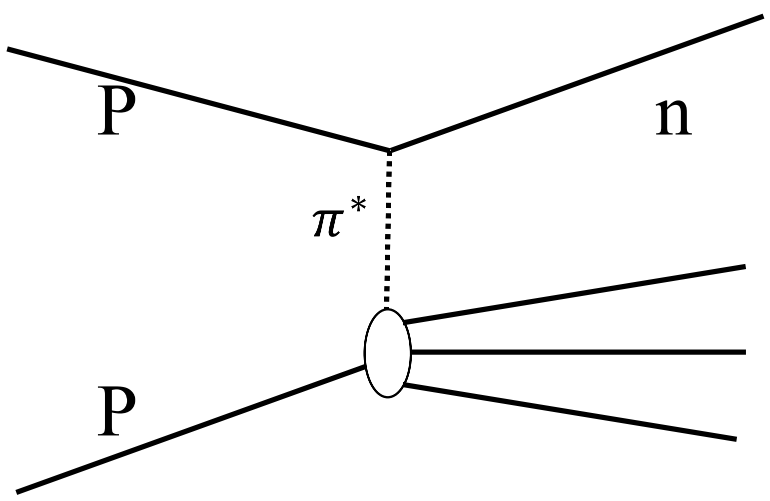
High energy neutron = primary particle in the collision.

→ Estimate the energy used for hadron productions

$E_{hadrons} = E_{beam} - E_{primary}$

→ Key parameter for CR air shower development

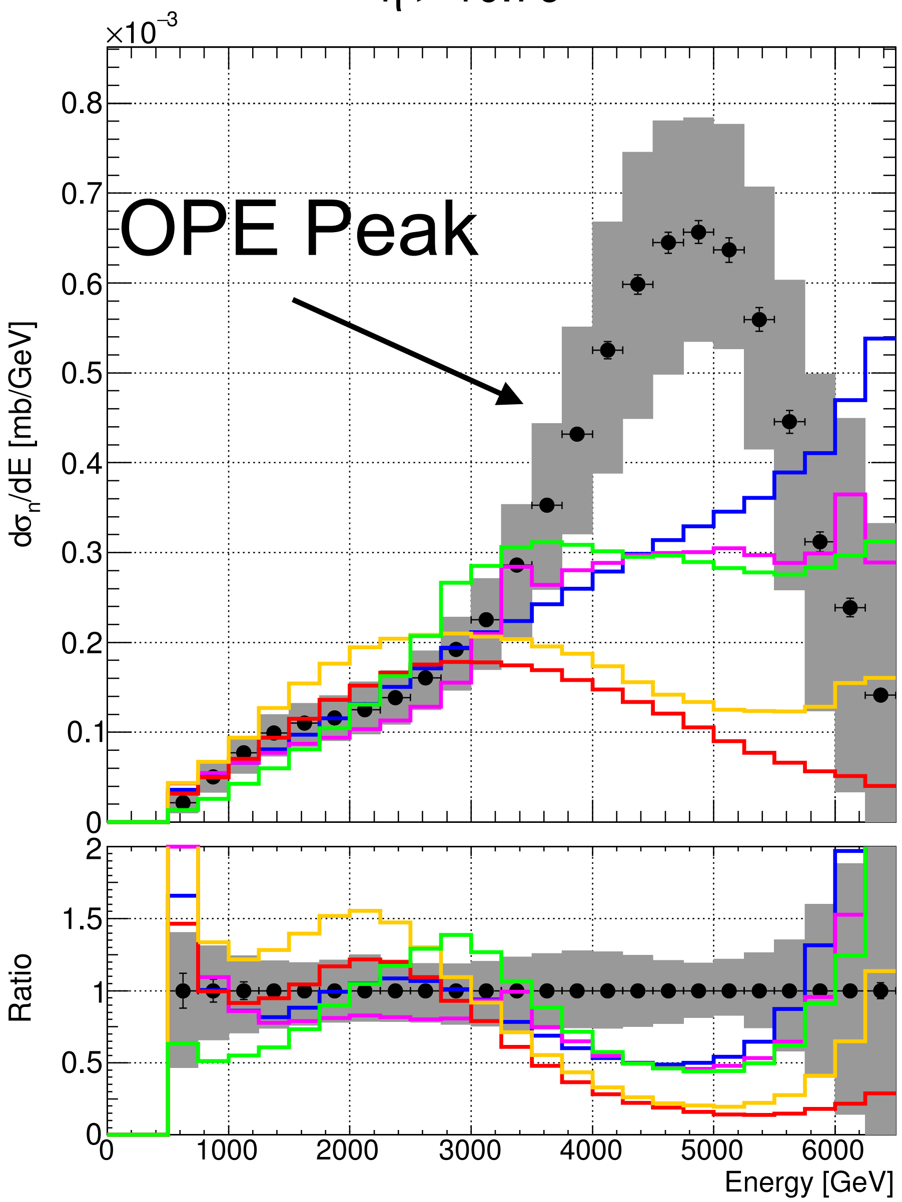
- One pion exchange (OPE)



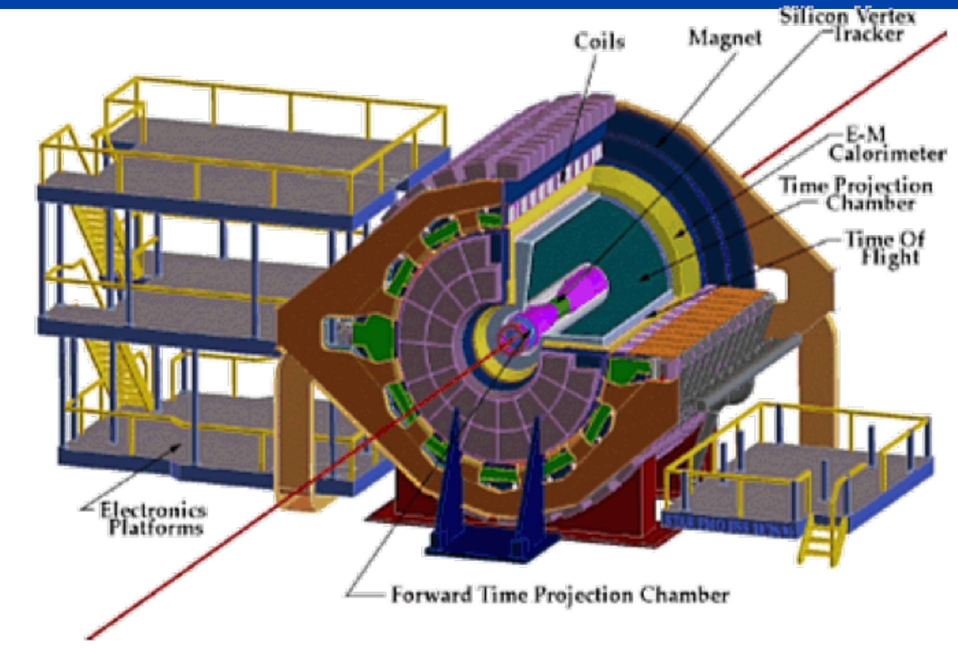
OPE makes a peak in neutron spectrum.

LHCf, √s=13TeV

η > 10.76



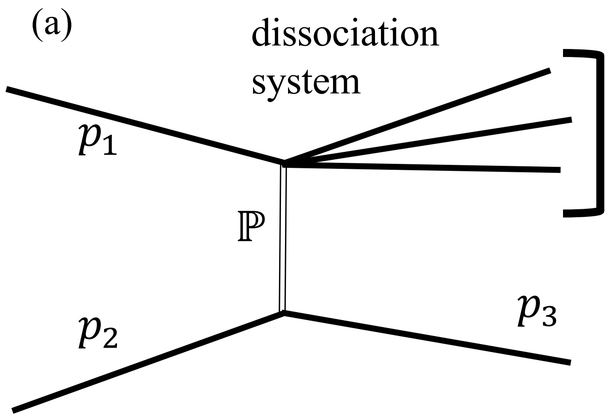
Combined analyses with STAR



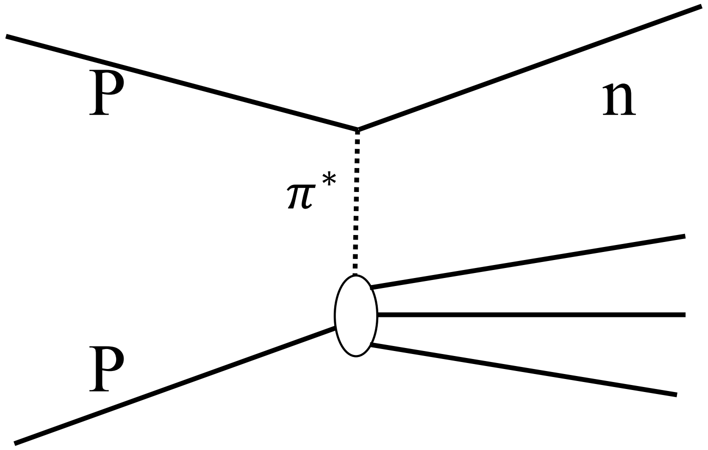
+

- Various physics cases with STAR detectors

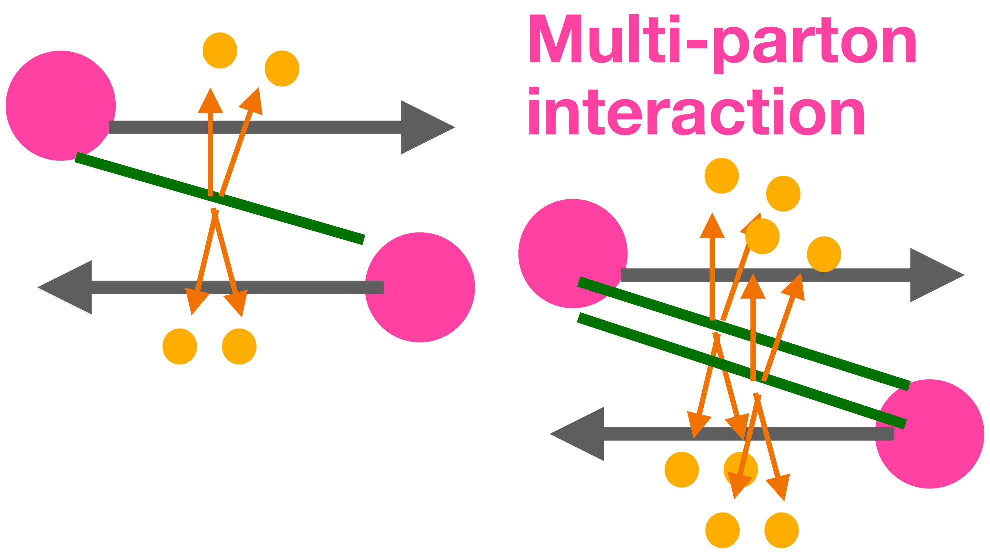
Diffractive dissociation



One pion exchange

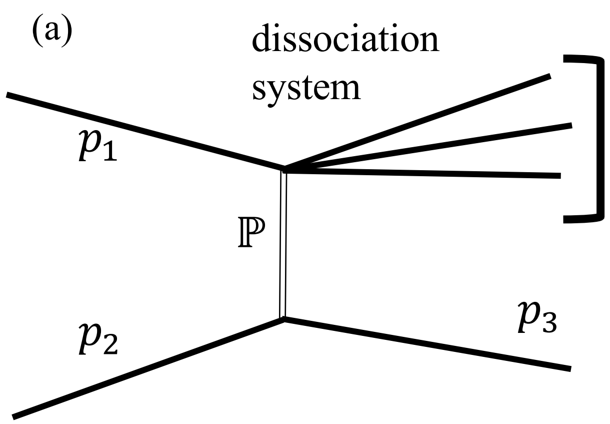


Others (Non-diffractive)

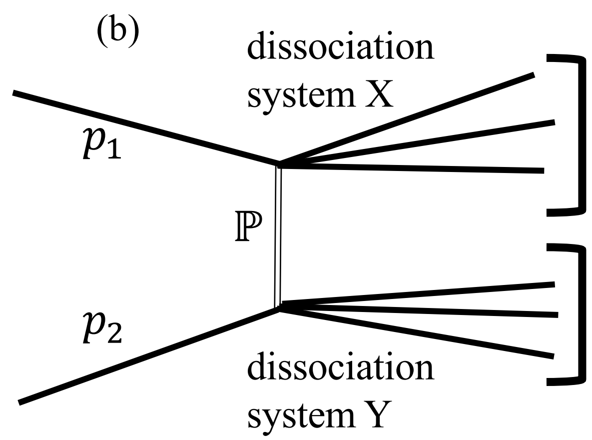


Diffractive dissociation

<u>Single diff.</u>



<u>Double diff.</u>



Forward particle production
= (Mass spectrum) x (hadronization)

Diffractive events can be identified using STAR detectors

- Veto by the central detector
  → Select pure and very low diffractive mass events
- Rapidity gap in the central detector
  → estimate the diff. mass.
- Tag of scattered protons in Roman Pot
  → Identification of single diffractive and
  measure the diff. mass directly

One-pion exchange

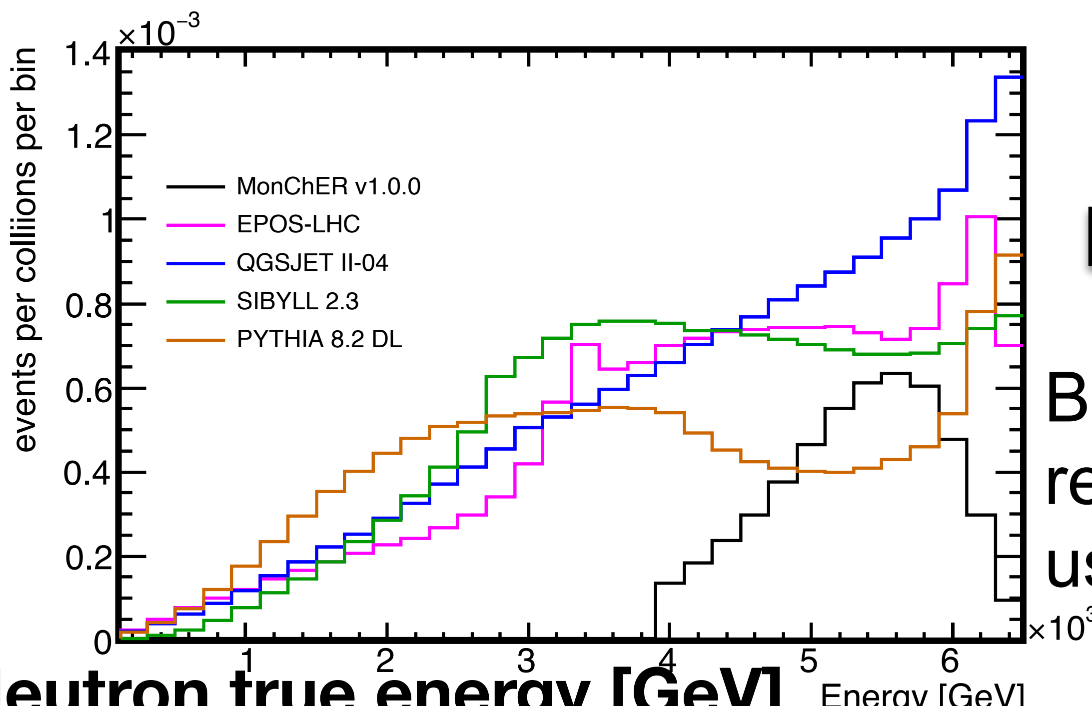
- Measurement of $\sigma_{p\pi}$ using OPE

$$\underbrace{\sigma_{OPE}(E_n)}_{\text{Neutron spectra}} = \boxed{\sigma_{p\pi}(E_{beam} - E_n)}\ \underbrace{F(E_{beam} - E_n)}_{\pi^*\ \text{flux}}$$

→ p−π cross section is very important for air shower development because of dominant collision in the shower.

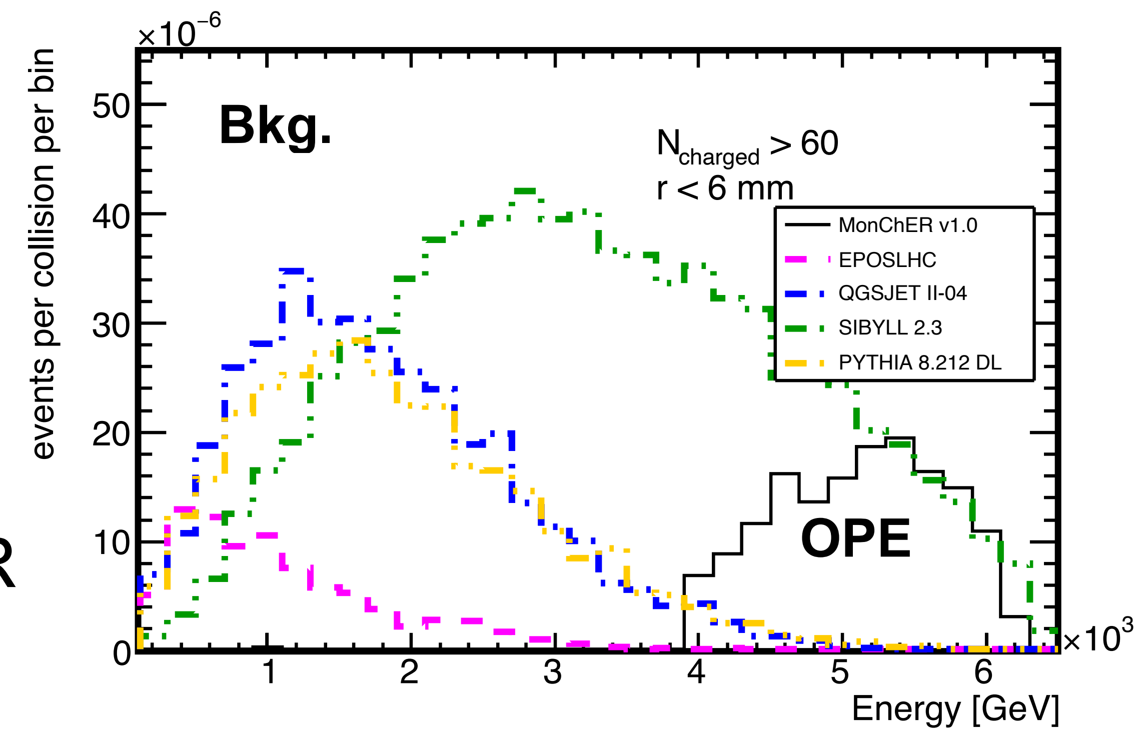
→ large uncertainty because of lack of data at high energy

Simulation (LHC, p-p $\sqrt{s} = 13$ TeV)



Neutron true energy [GeV]

Bkg. rejection using STAR



MPI modeling

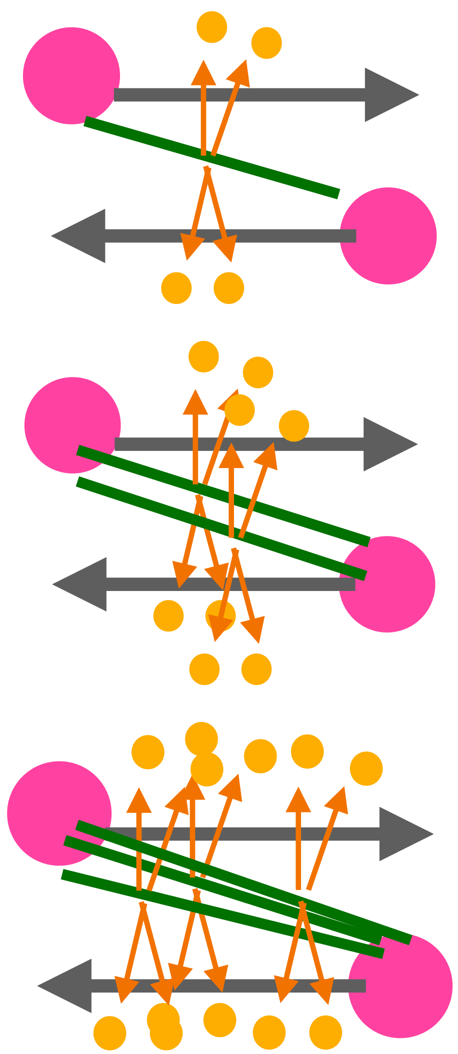
Multi-parton

The number of multi-parton interaction

$N_{MPI} = 1$

$N_{MPI} = 2$

$N_{MPI} = 3$

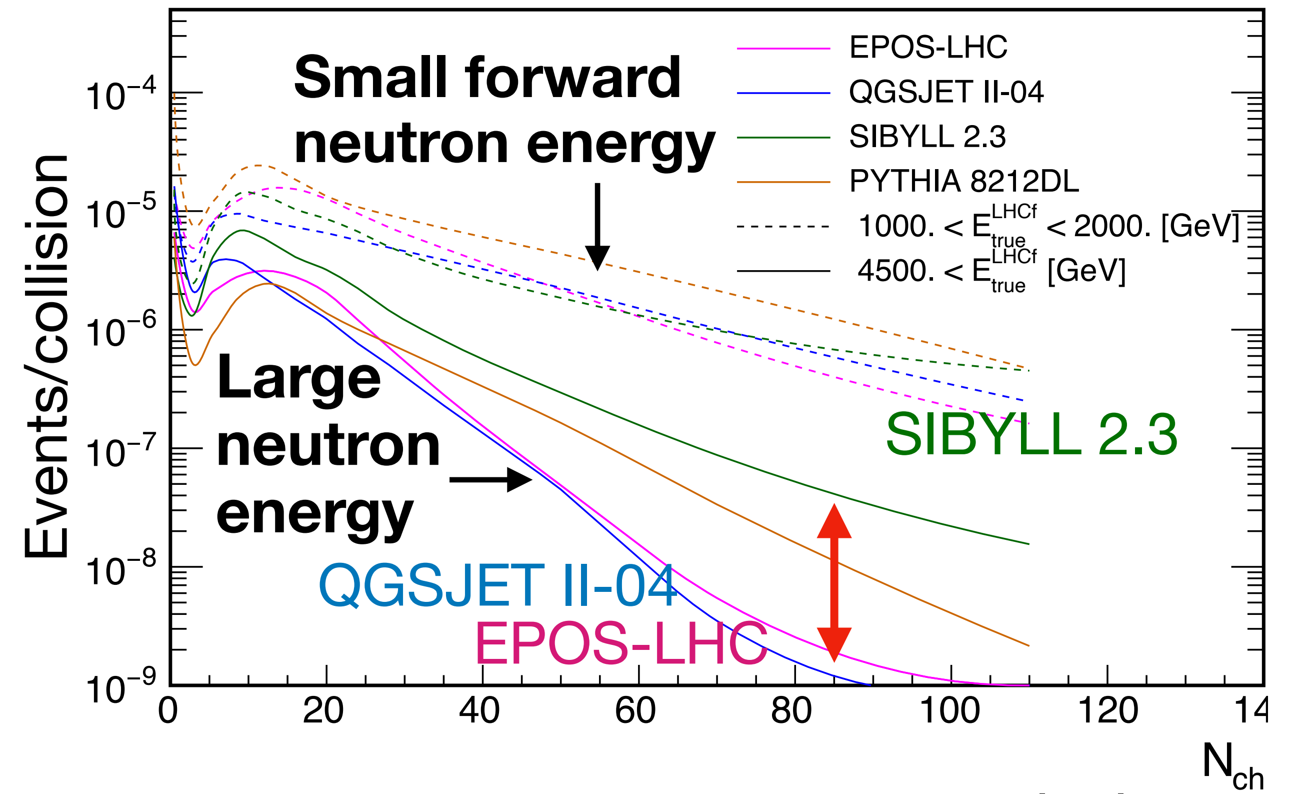


Energy of very forward neutron/ π^0

Large

Small

Simulation (LHC, p-p $\sqrt{s} = 13$ TeV)



The number of charged particles in $|\eta| < 2.5$

Large difference among models

Total MPI energy

1. SIBYLL, PYTHIA → Kinematic overlap
2. EPOS, QGSJET → Superposition of parton interactions with modified PDF.

Summary

- RHICf measurement is very important for cosmic-ray physics too.
  - Energy scaling of forward particle production by comparing with LHCf data.
- RHICf I operation was completed in June 2017
  - Energy scaling was confirmed in forward photon production within the errors.
  - Several physics cases by joint analyses with STAR

Backup

Photon Energy Flow

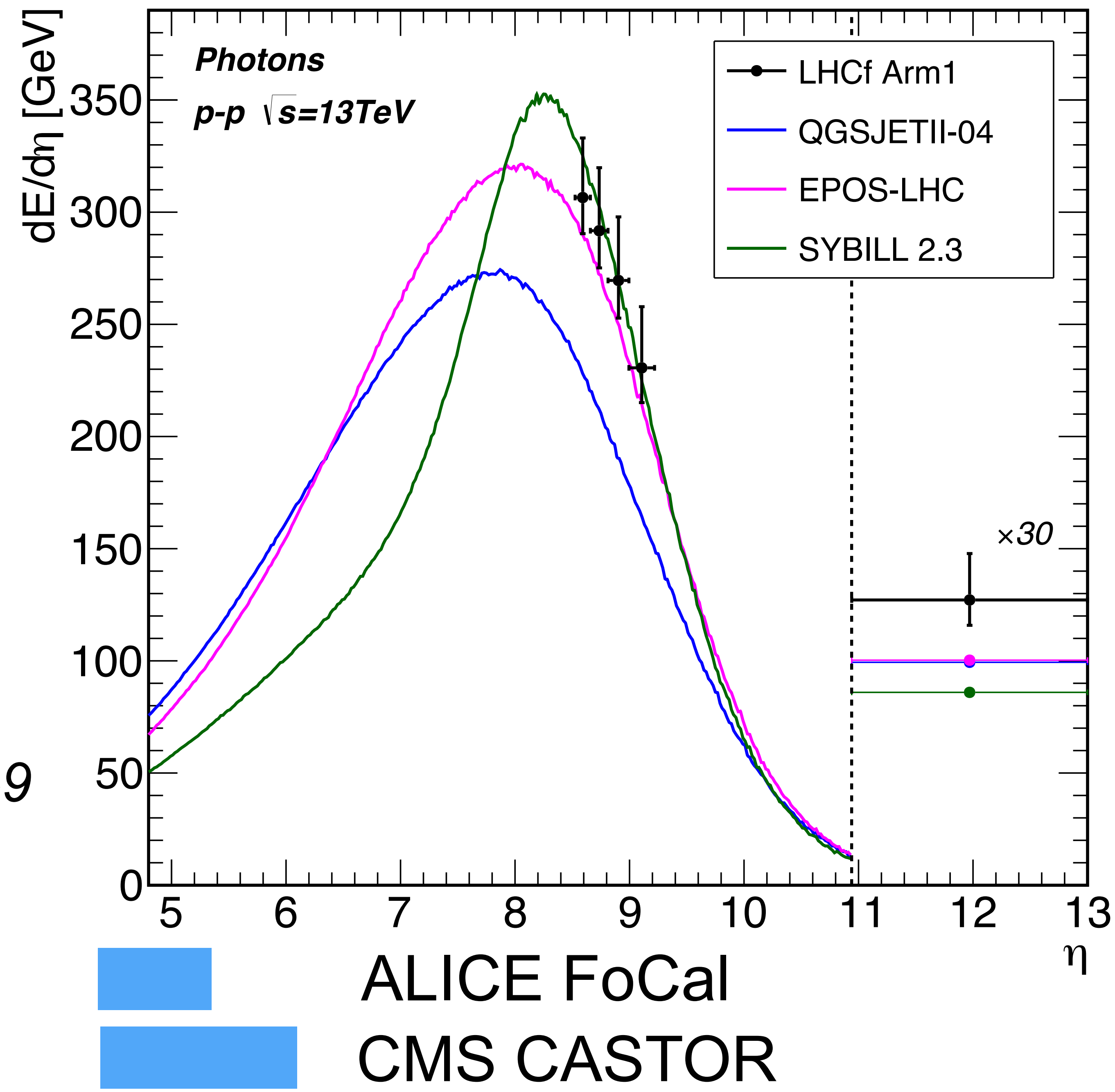
Energy Flow Calculation:

$$\frac{dE}{d\eta} = C_{thr} \frac{1}{\Delta\eta} \sum_{E_j > 200GeV} E_j F(E_j)$$

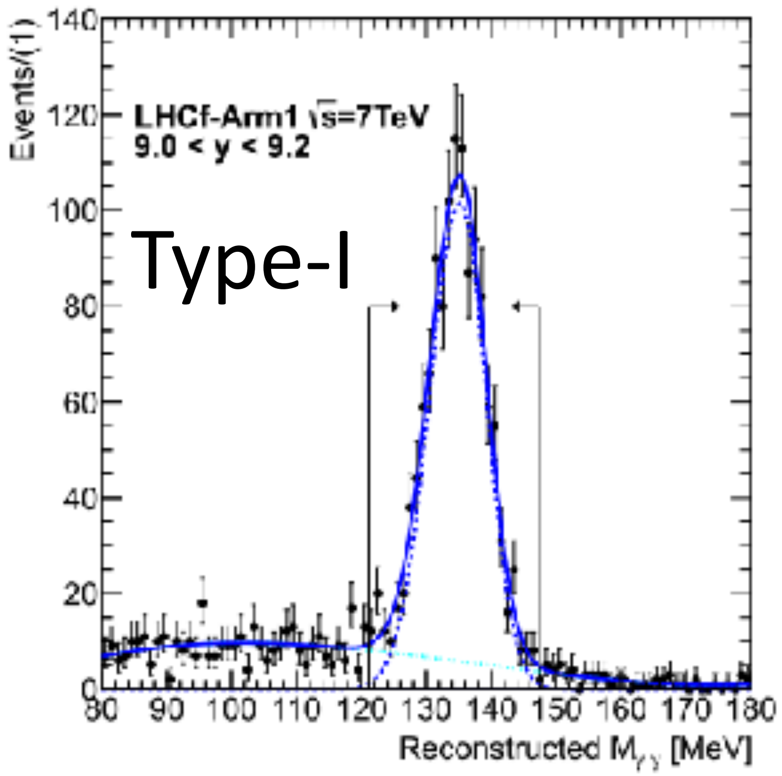
F(Ej) : Measured differential cross-section
$\Delta\eta$: The pseudo-rapidity range
C_{thr} : Correction factor for the threshold 200 GeV→ 0 GeV.

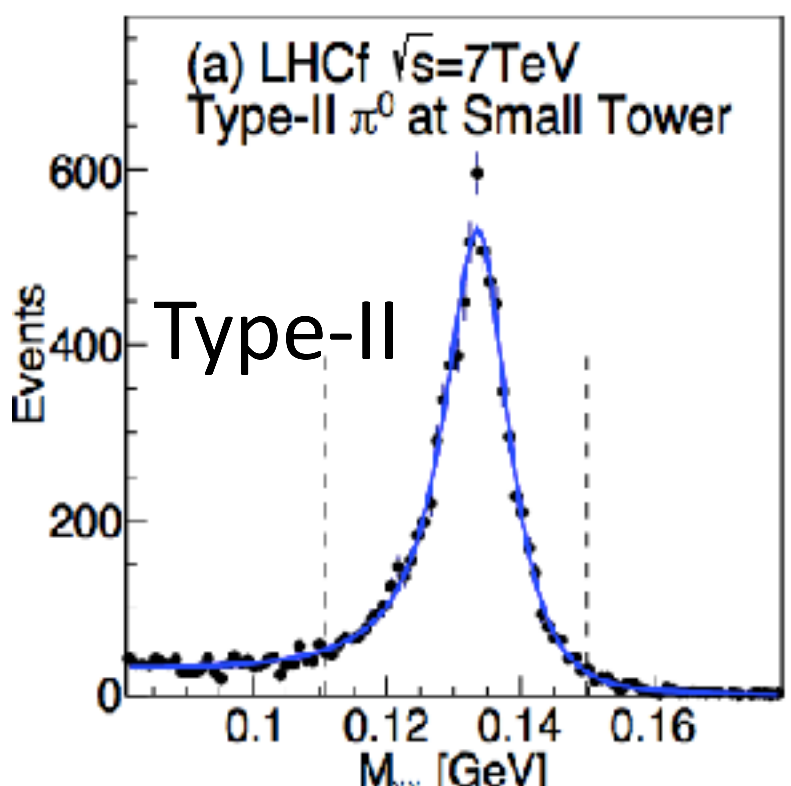
Ref: Y. Makino CERN-THESIS-2017-049

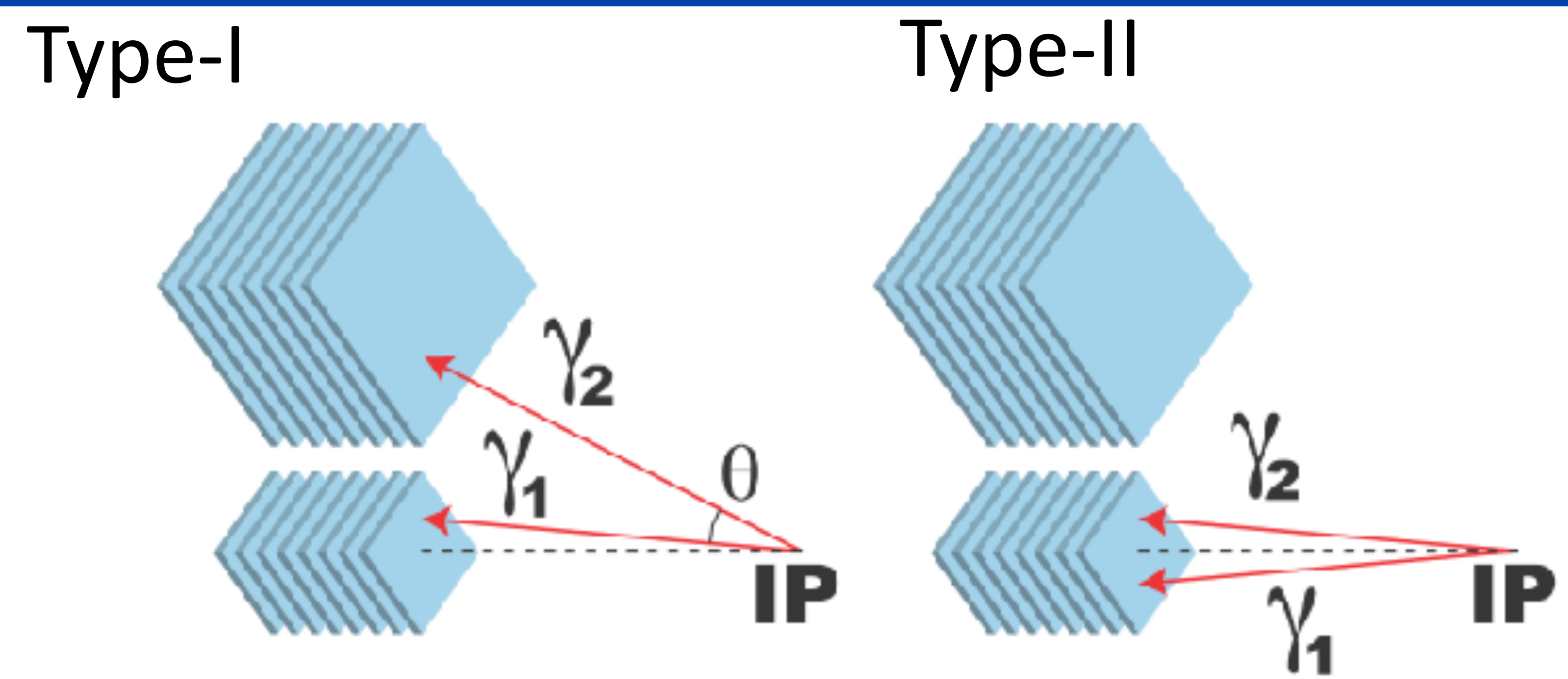
EPOS-LHC, SIBYLL2.3
Good agreement
QGSJET II-04
~ 30% lower than data

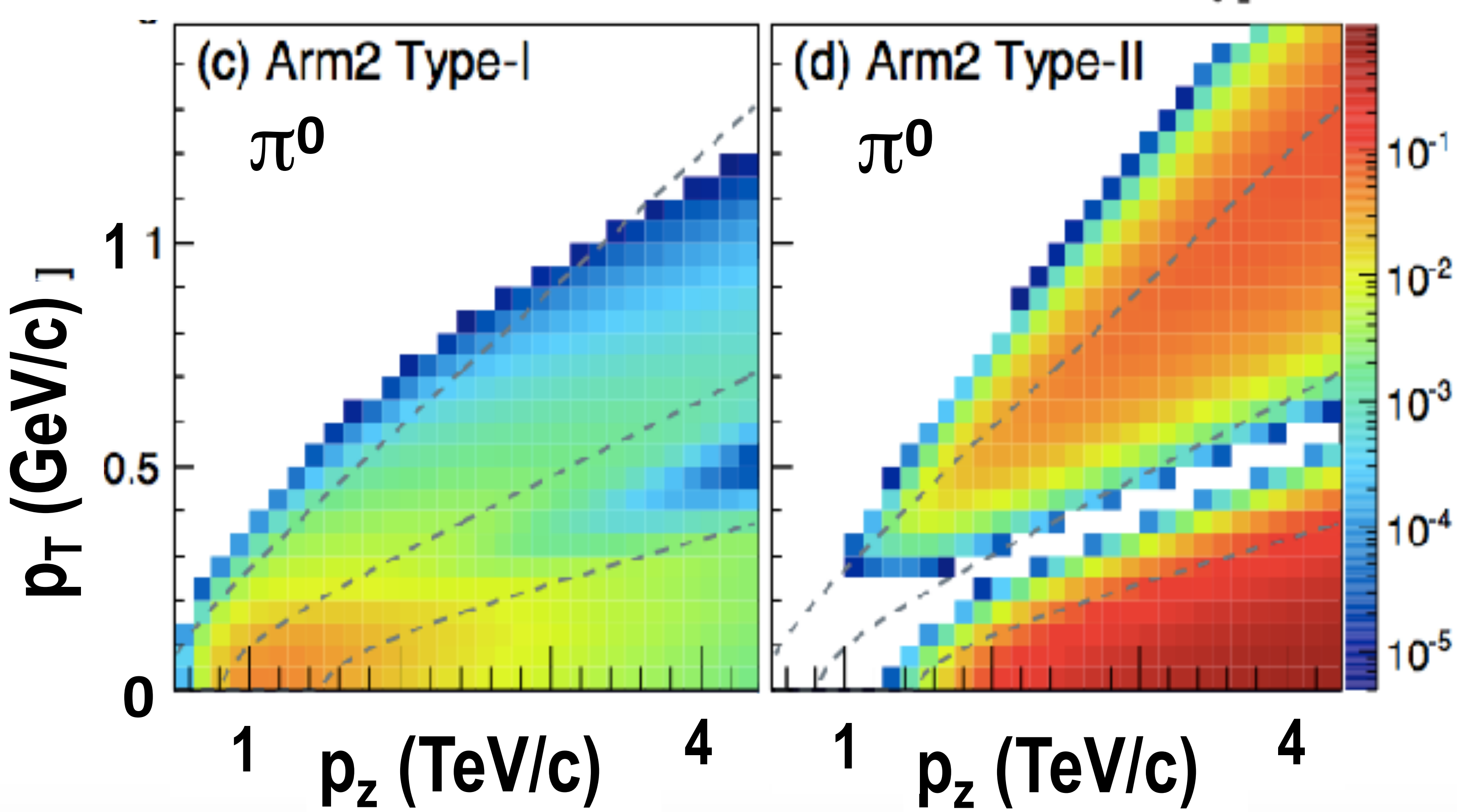


π^0 measurement

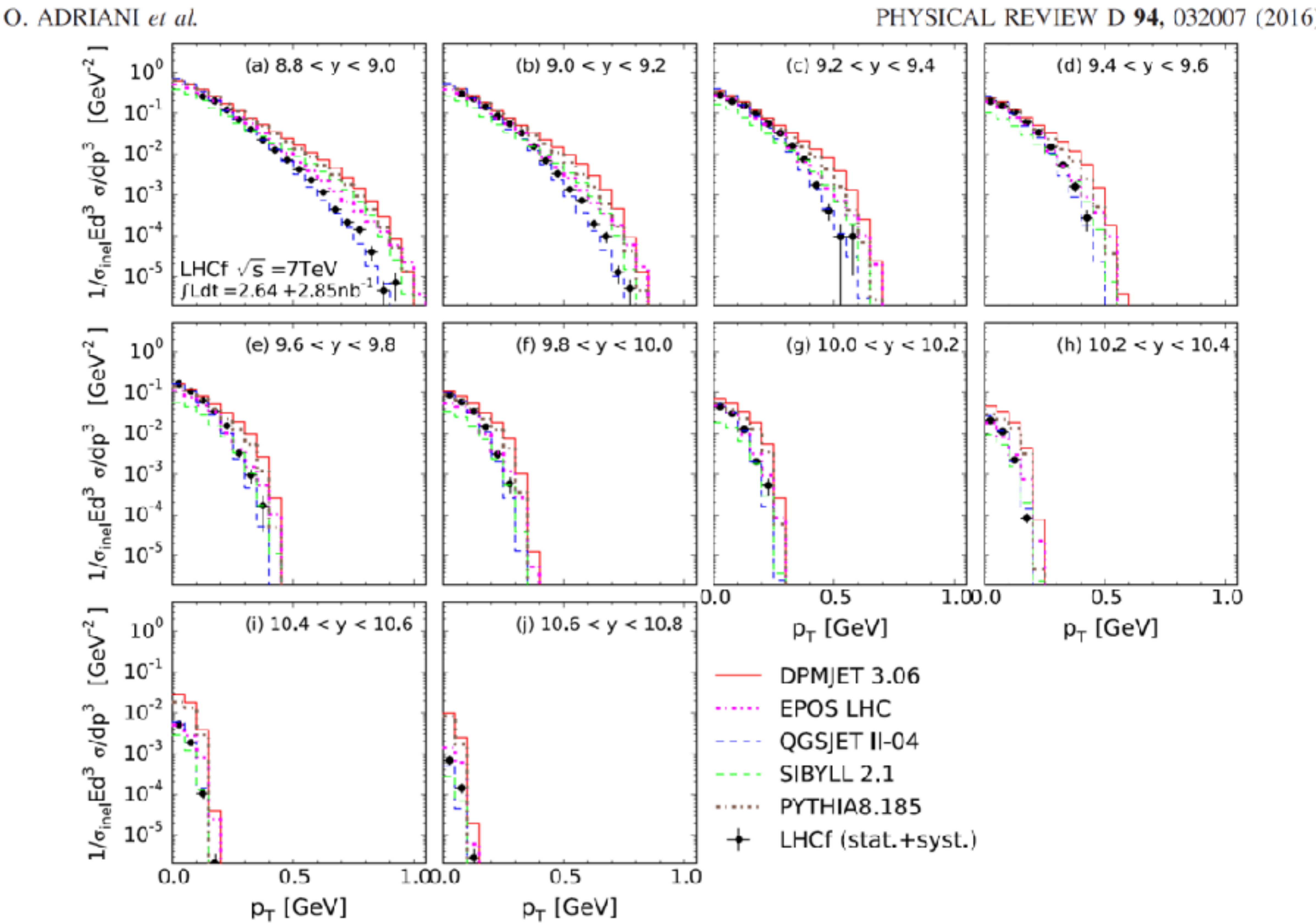








π^0 p_T spectra at pp,7TeV



Neutron, p-p √s=13TeV

Motivation

- Inelasticity measurement k_{inela}
  $k_{inela} = 1 - E_{leading}/E_{beam}$
- Large discrepancies between data and model prediction were found in the measurement at p-p, √s=7TeV

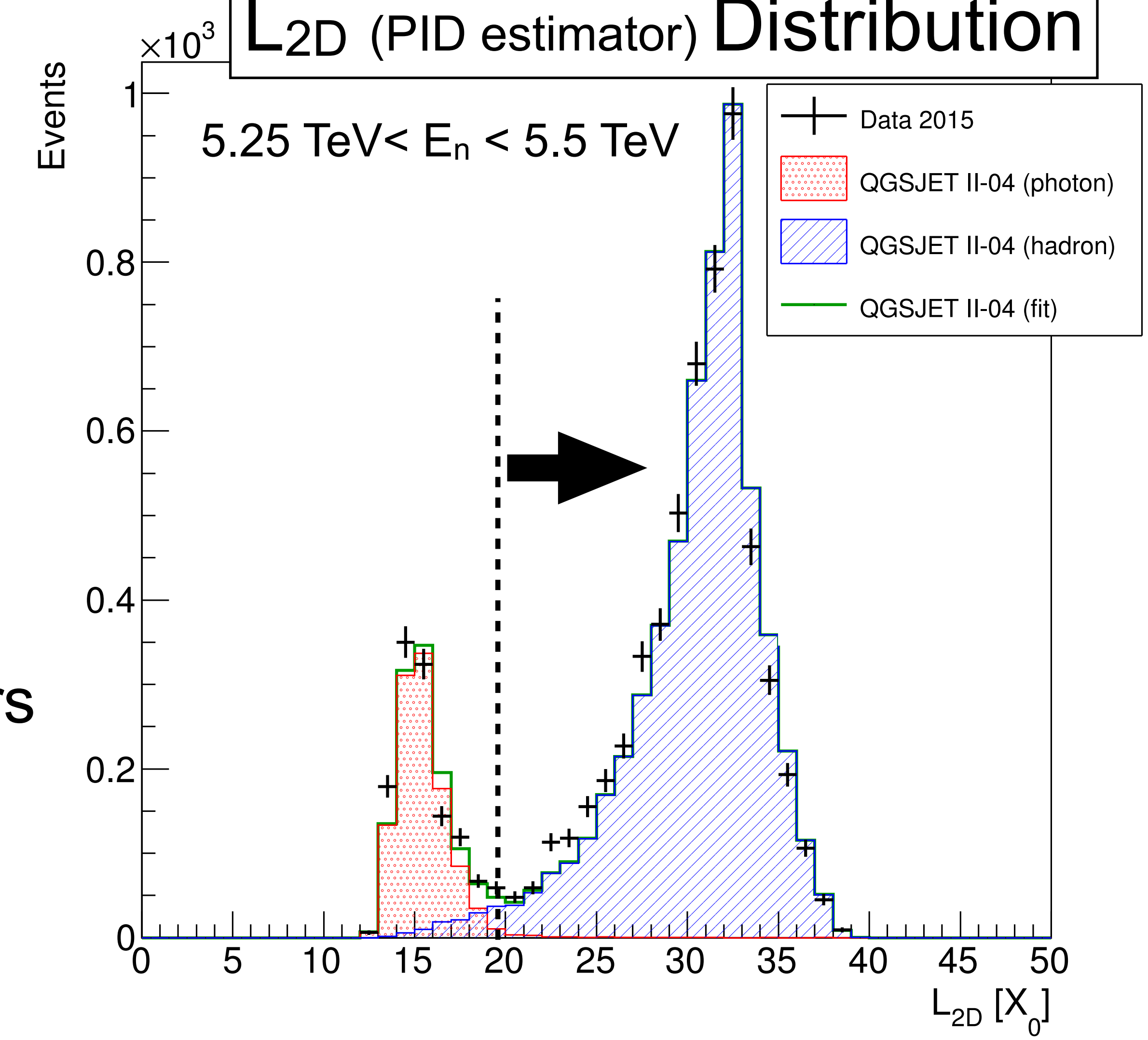
Data

- 3 hour operation in June 2015
- Low pile-up, μ~0.01

Analysis

- Particle Identification
  EM shower → develop in shallow layers
  Hadronic showers → develop in deep layers
- Energy resolution of 40%
- Contamination of Δ^0, K^0

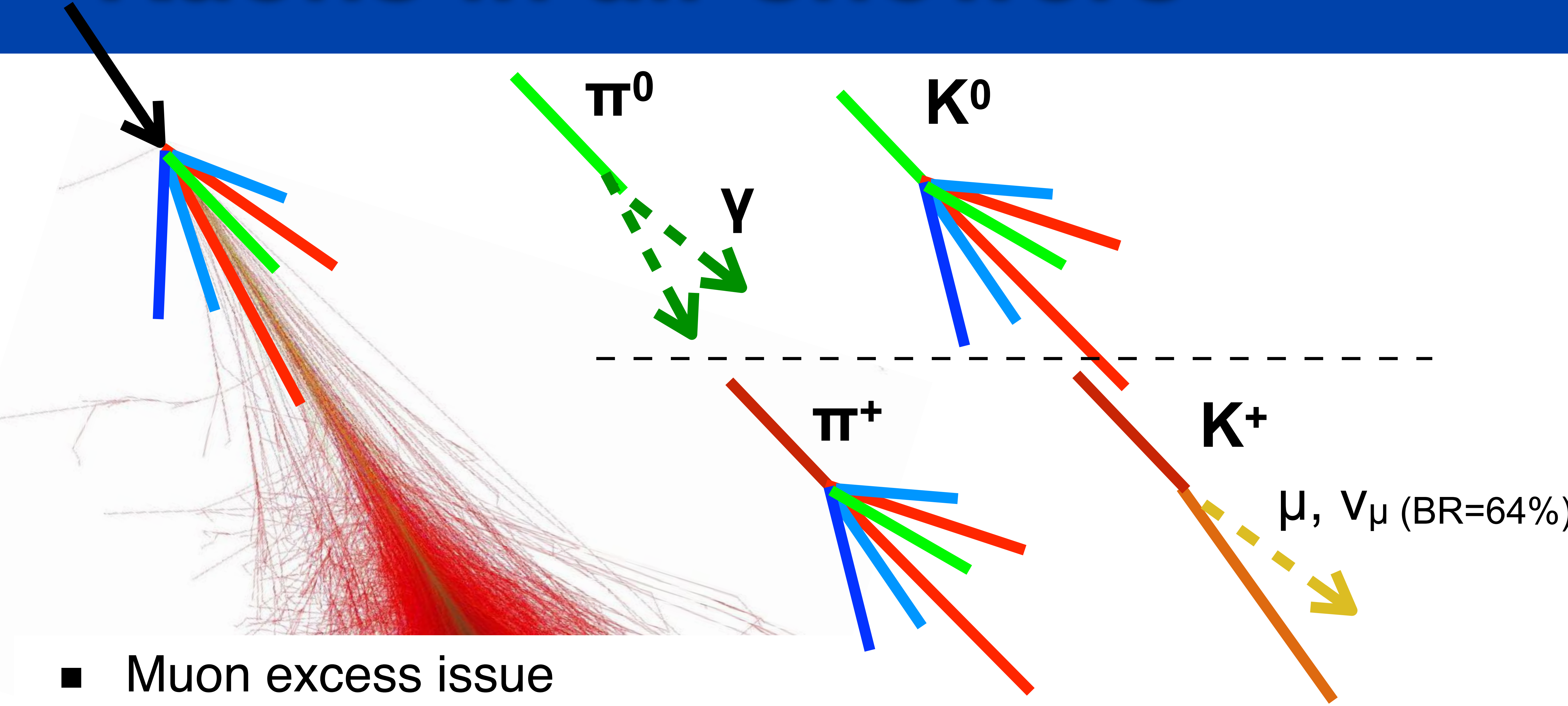
L_{2D} (PID estimator) Distribution



Motivations

- Increase statistics of high-X_F π^0
- Measurement of strange hadrons at 0 degree
  - $K^0_s \rightarrow 2\pi^0 \rightarrow 4\gamma$ (B.R. 30.7%)
  - $\Lambda \rightarrow n+\pi^0 \rightarrow n+2\gamma$ (B.R. 35.9%)
- p + A collisions
  - A-dependence of A
    - Strong A-dependence of Neutron by PHENIX (Pays. Rev. Lett 120, 022001 (2018))
    - A-depedence of very forward π^0
  - p + light ion collisions for Cosmic-rays
    - Ideal condition for CR-Air interaction studies

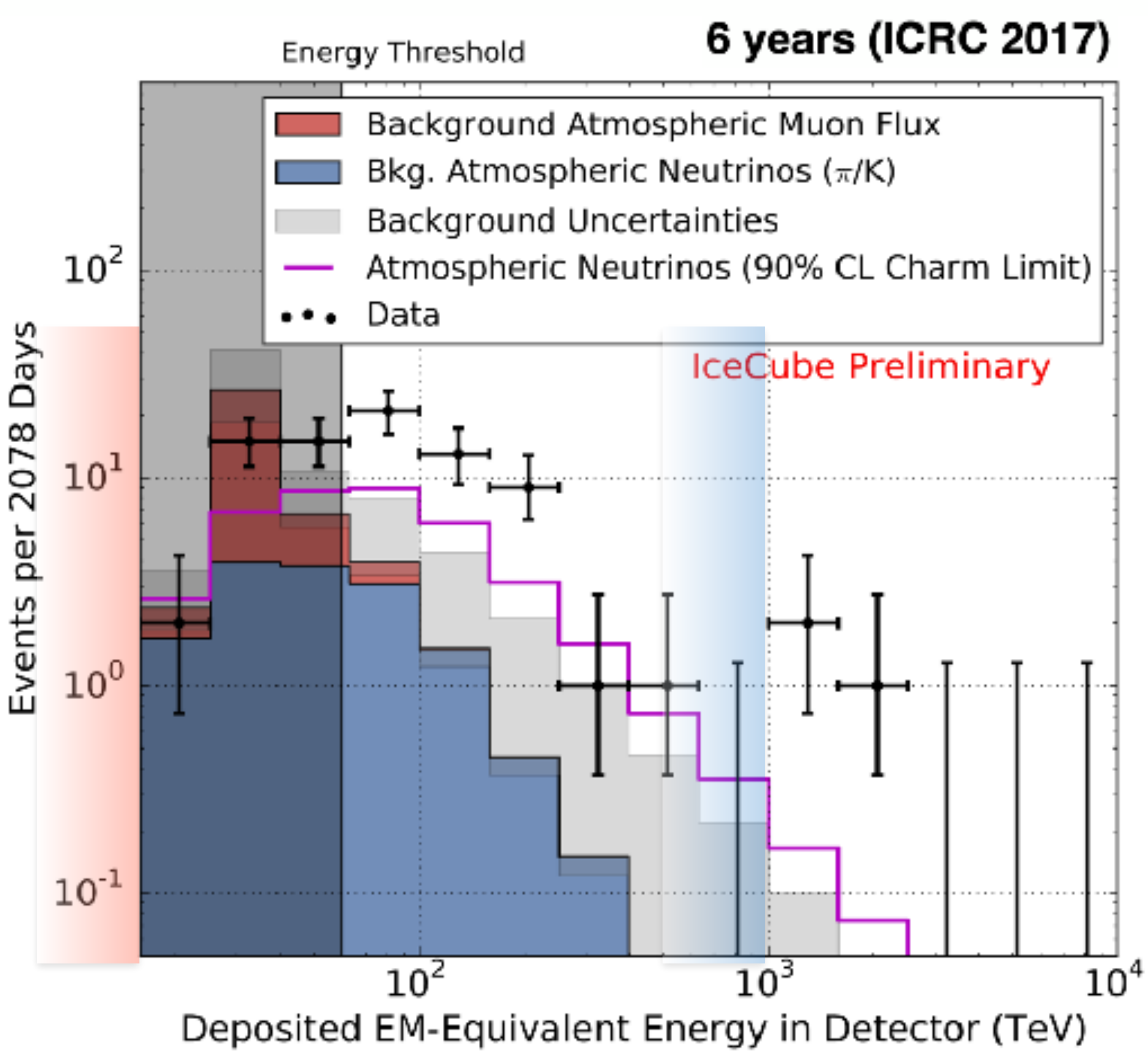
Kaons in air showers



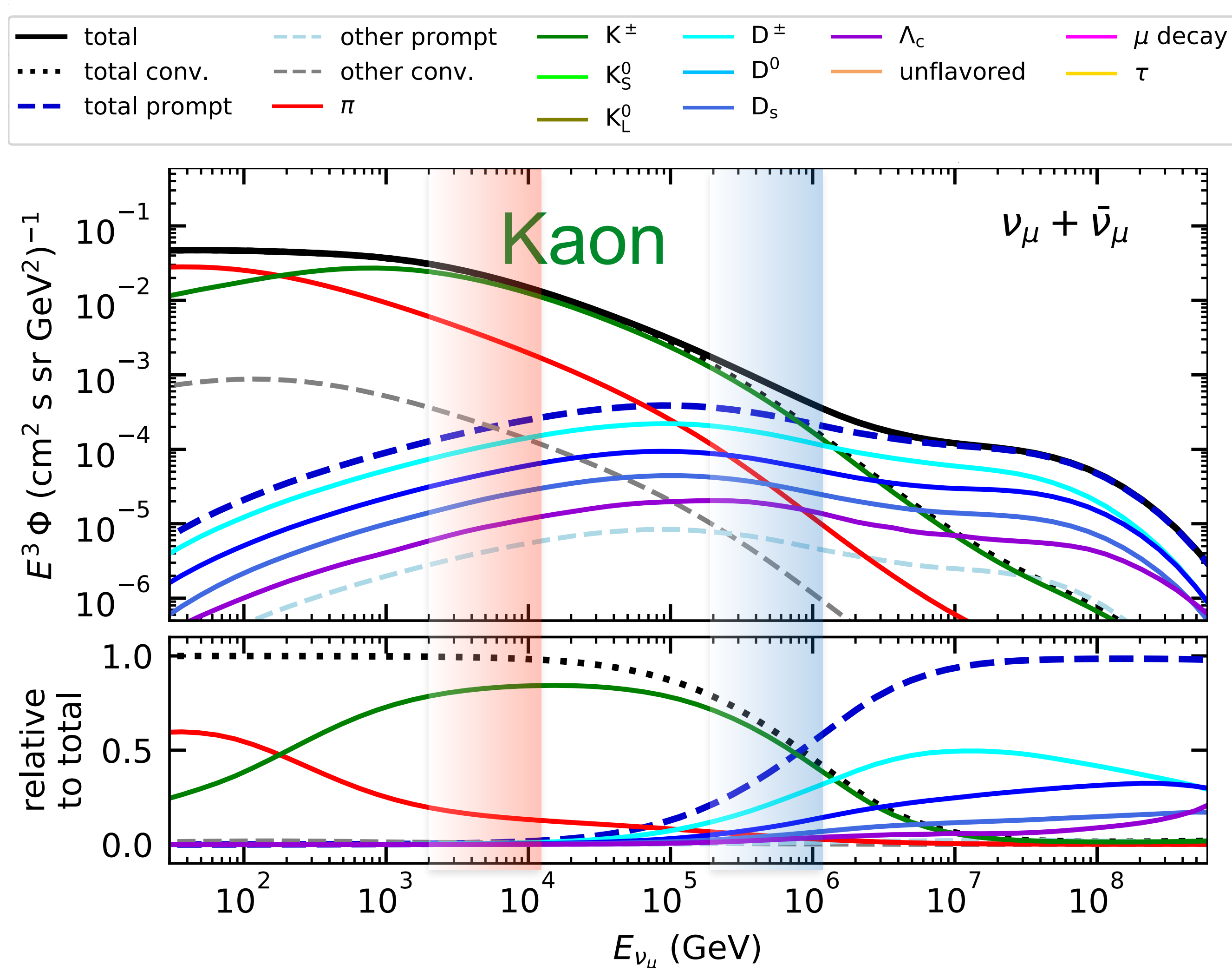
- Muon excess issue
  - If higher Kaon production in high energy
    → increase the muon number on the ground.
    A high energy π^0 decays immediately → EM component,
    A high energy K^0 collides air before its decay → Hadronic component
  - Large K/π ratio in QGP
- Impact on atmospheric ν flux (next page)

Atm. neutrinos from Kaon decays

- Hot topics: Astro-neutrino detection by IceCube
- large uncertainty on background estimation of Atm. ν
- Kaons are dominant source of ν_μ in E_ν <~ 10^{15}eV

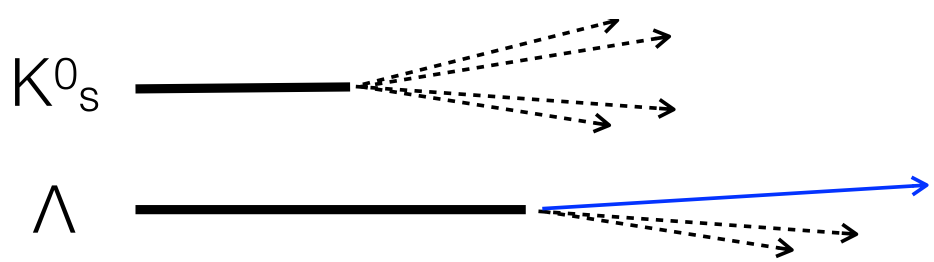


Atmospheric ν_μ flux



K^0_s and Λ measurement by RHICf II

- 4 γ for K^0_s and n+2γ for Λ detection simultaneously



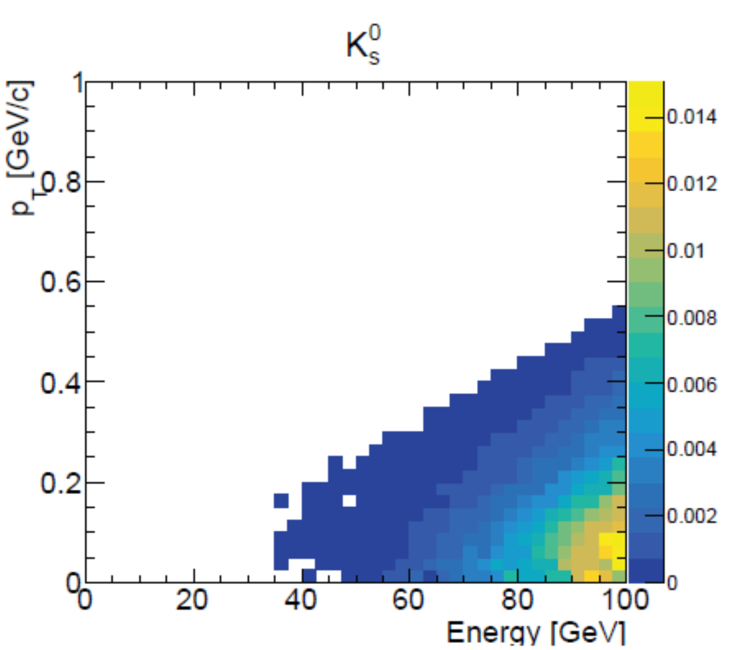
$$K_s^0 \rightarrow 2\,\pi^0 \rightarrow 4\,\gamma$$

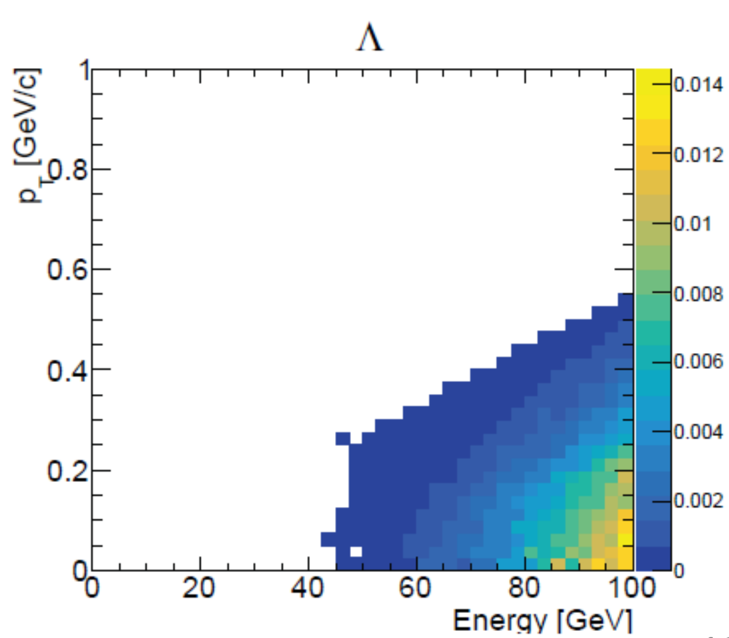
$$\Lambda \rightarrow n + \pi^0 \rightarrow n + 2\,\gamma$$

  - Wide acceptance
  - Fine segmentation

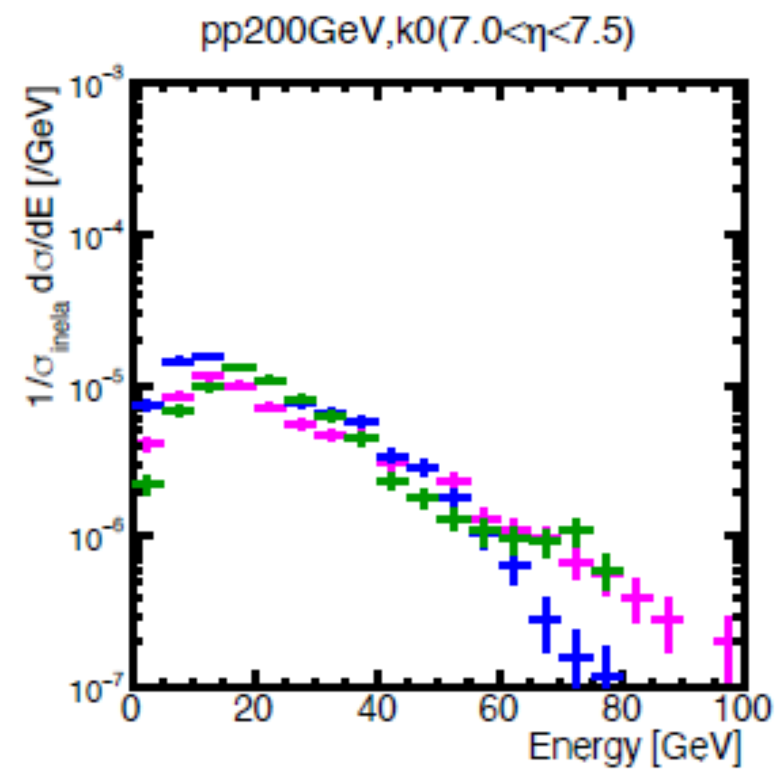
RHICf 👍

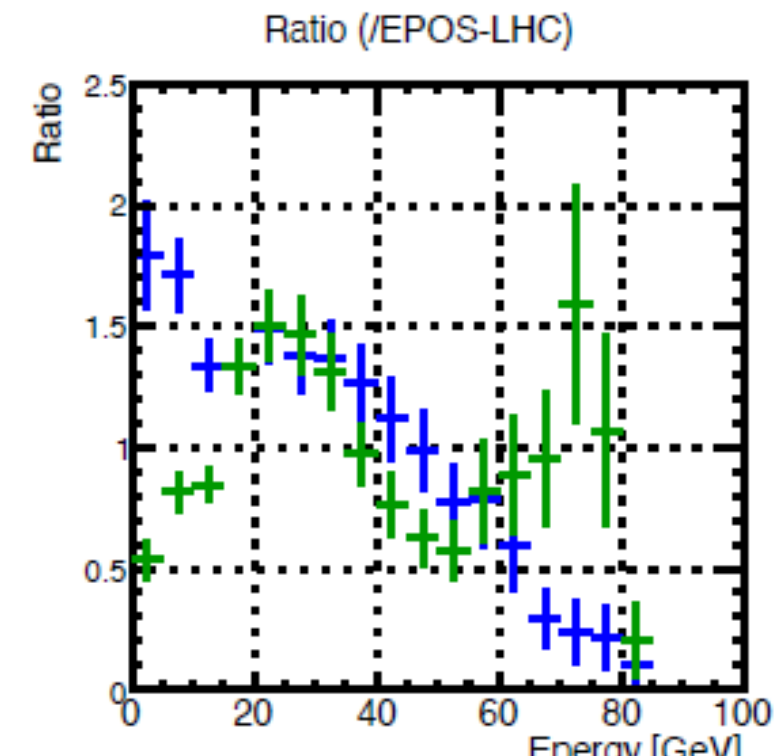
- Geometrical accettante



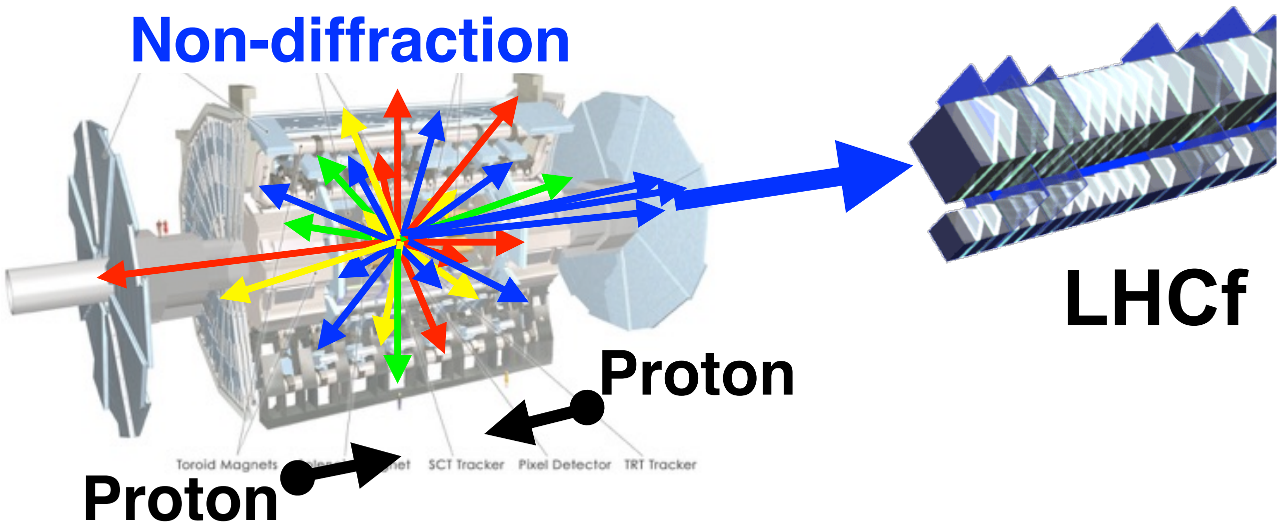


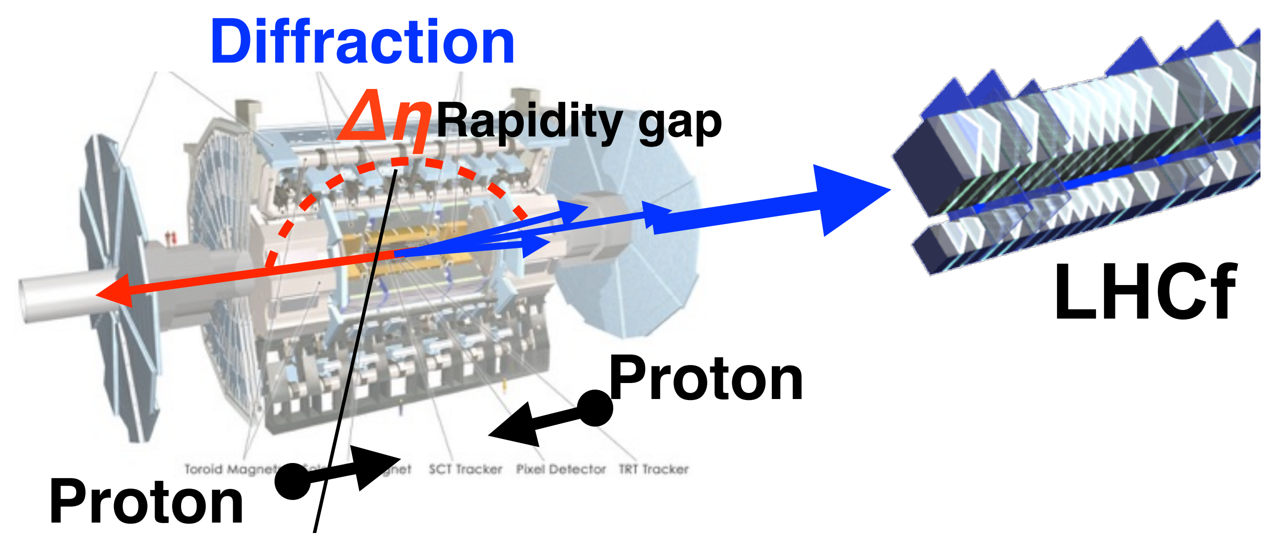
Model predictions

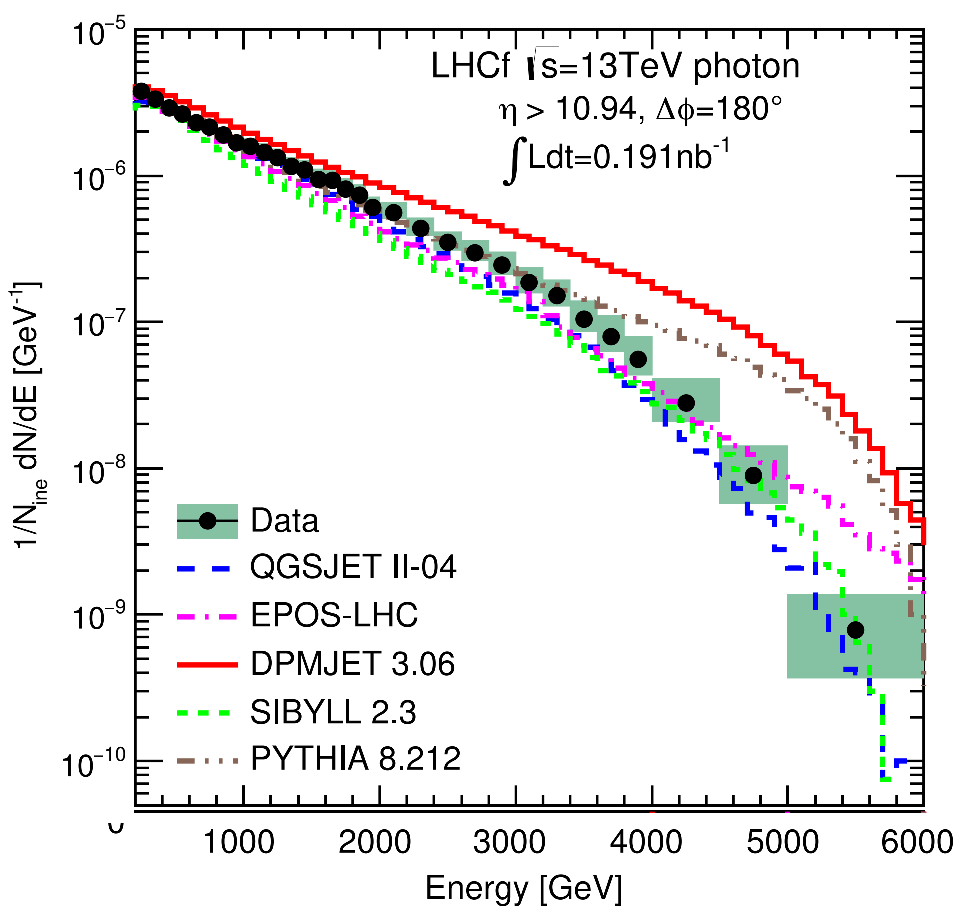


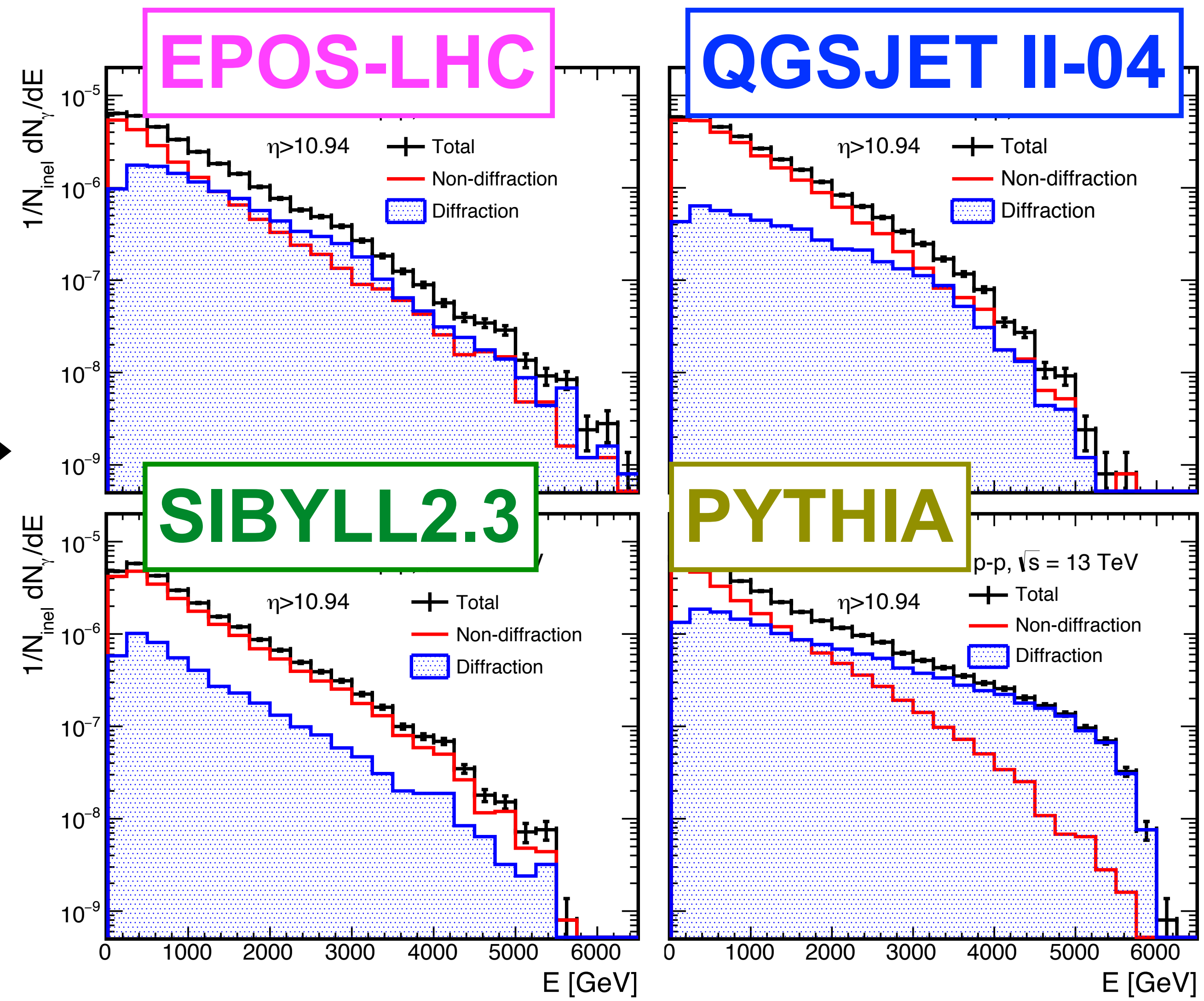


Joint Analysis with ATLAS - Selection of Diffractive interactions -





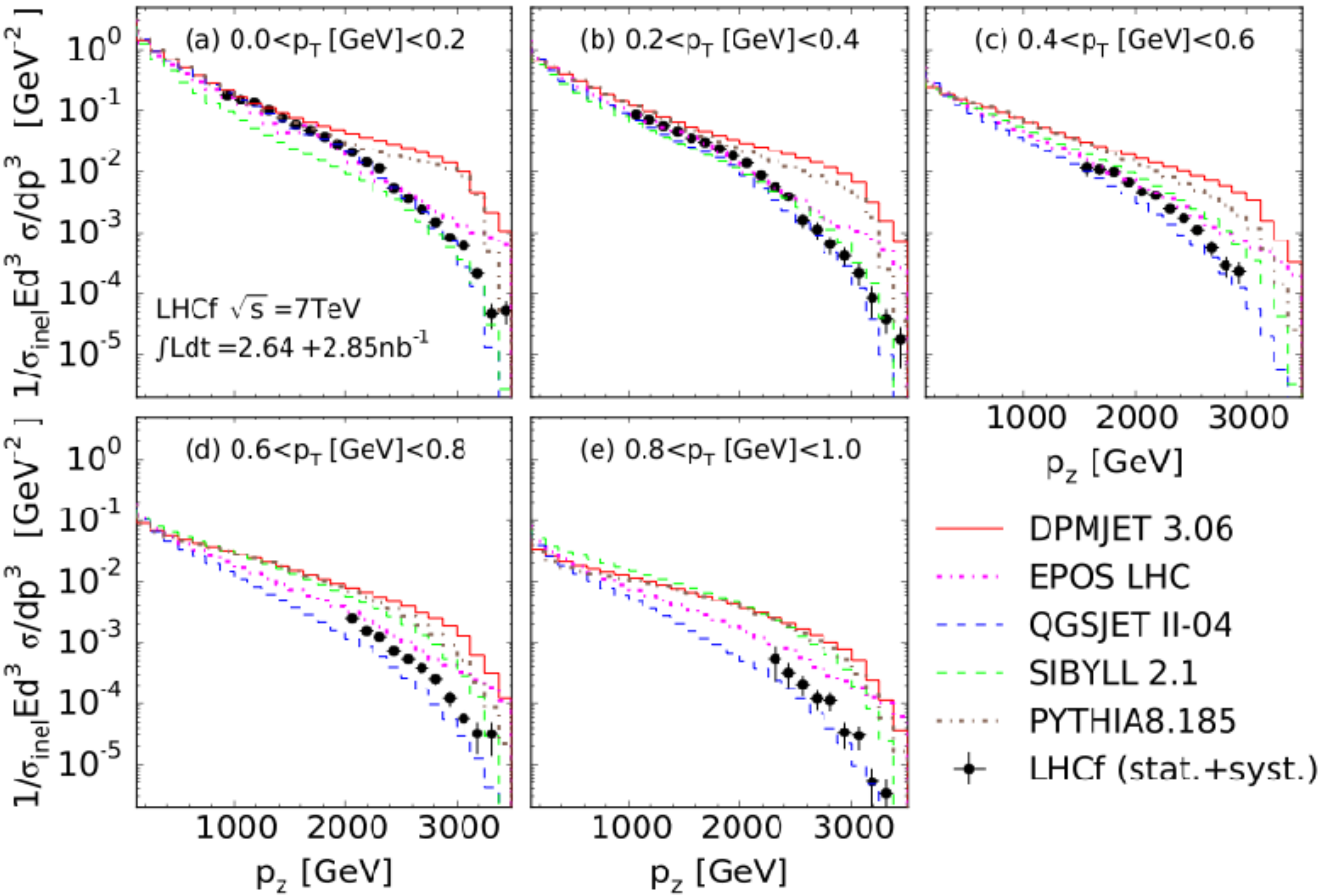




Poster by Q.Zhou; CRD131

π^0 p_Z (~E) spectra at p+p,7TeV

PRD 94 (2016) 032007

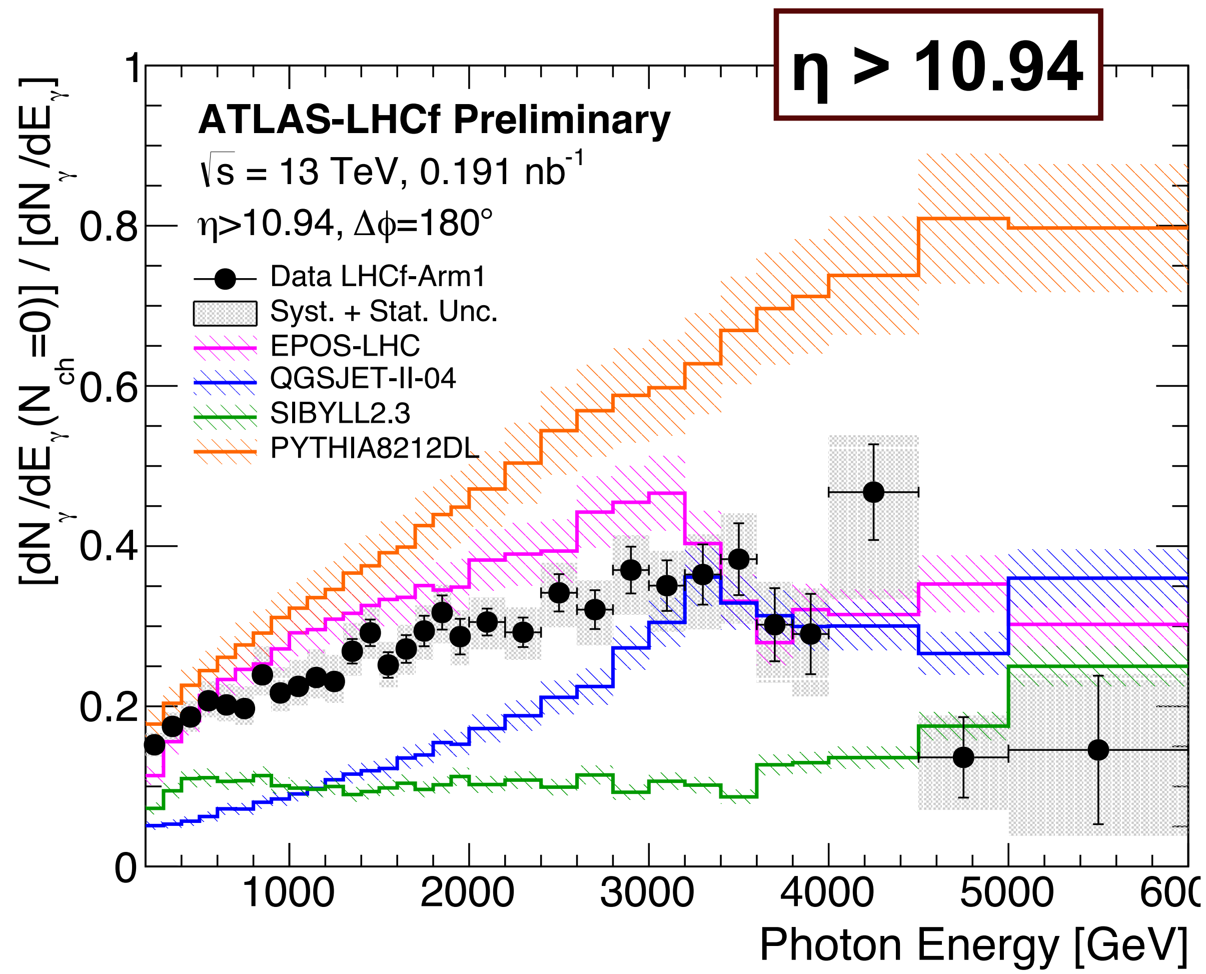


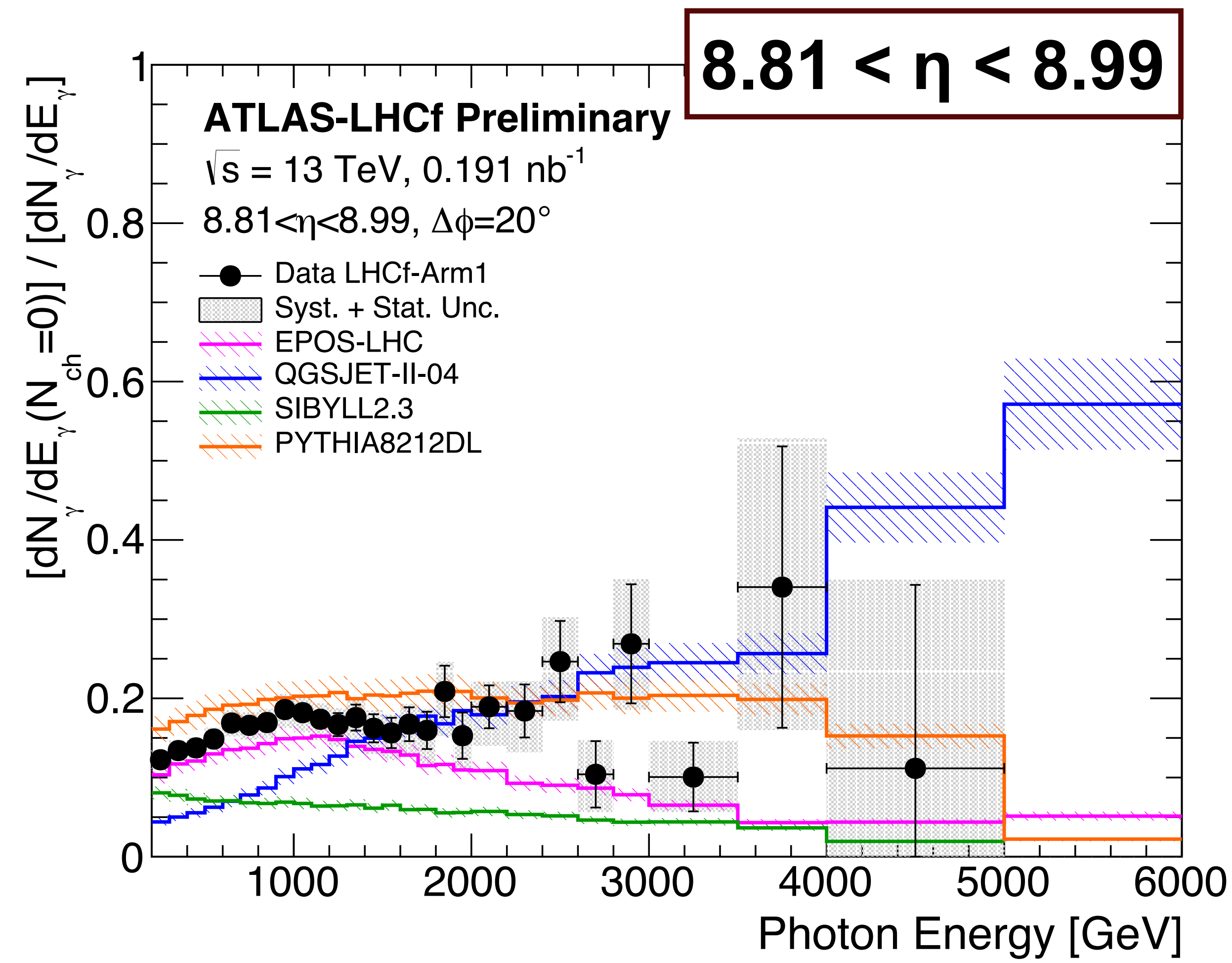
DPMJET and Pythia overestimate over all E-p_T range

Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at $\sqrt{s}$ = 13 TeV

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

ATLAS-CONF-2017-075

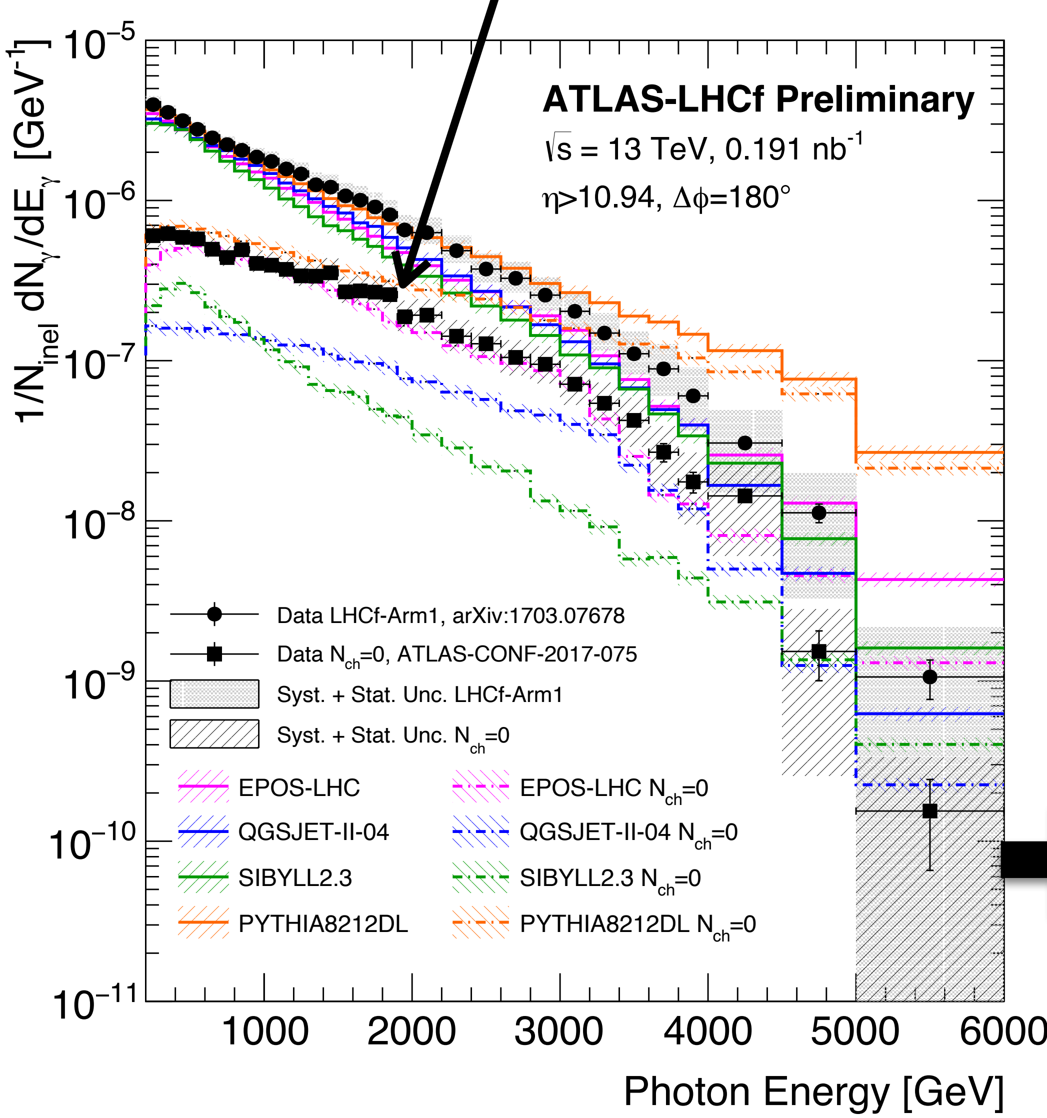




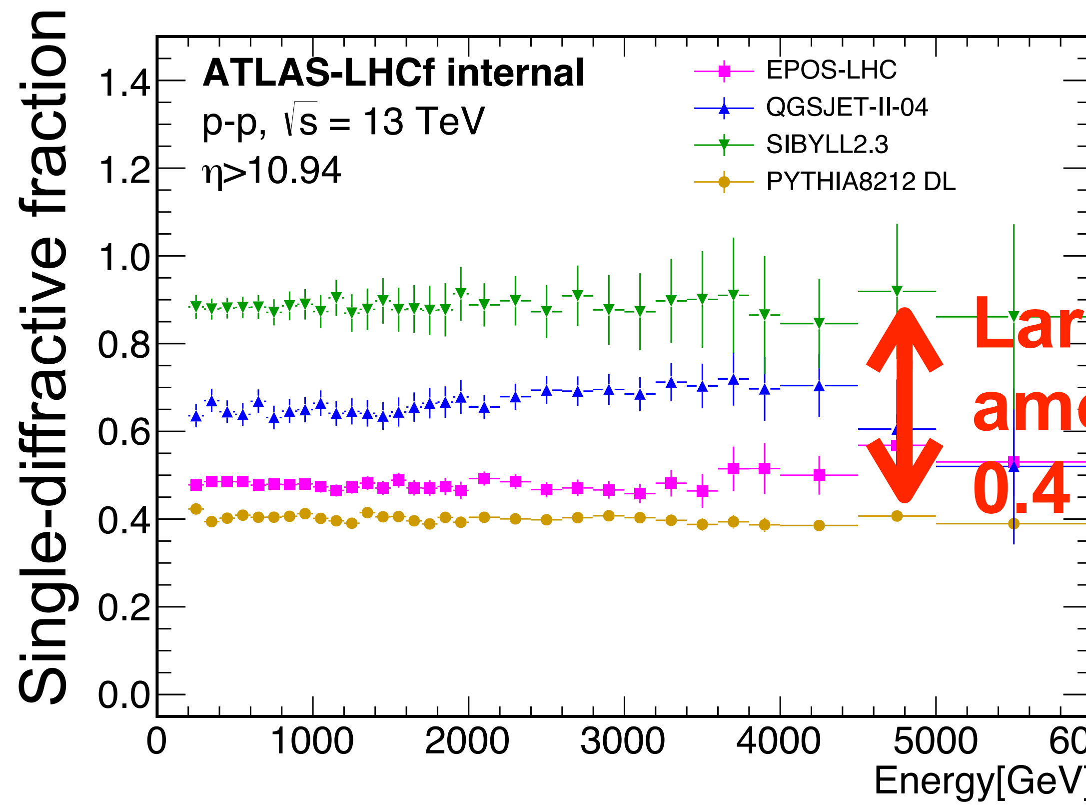
- At η>10.94, the ratio of data increased from 0.15 to 0.4. with increasing of the photon energy up to 4TeV.
- PYTHIA8212DL predicts higher fraction at higher energies.
- SIBYLL2.3 show small fraction compare with data at η>10.94.
- At 8.81 < η < 8.99, the ratio of data keep almost constant as 0.17.
- EPOS-LHC and PYTHIA8212DL show good agreement with data at 8.81 < η < 8.99.

Update plan of the joint analysis

Diffractive (=Single+Double)



How much fraction of single diffractive in the selected events ?



Large difference among models 0.4 - 0.9

Going to measure the fraction by using ATLAS-**MBTS** (2.08 < |η| < 3.86)