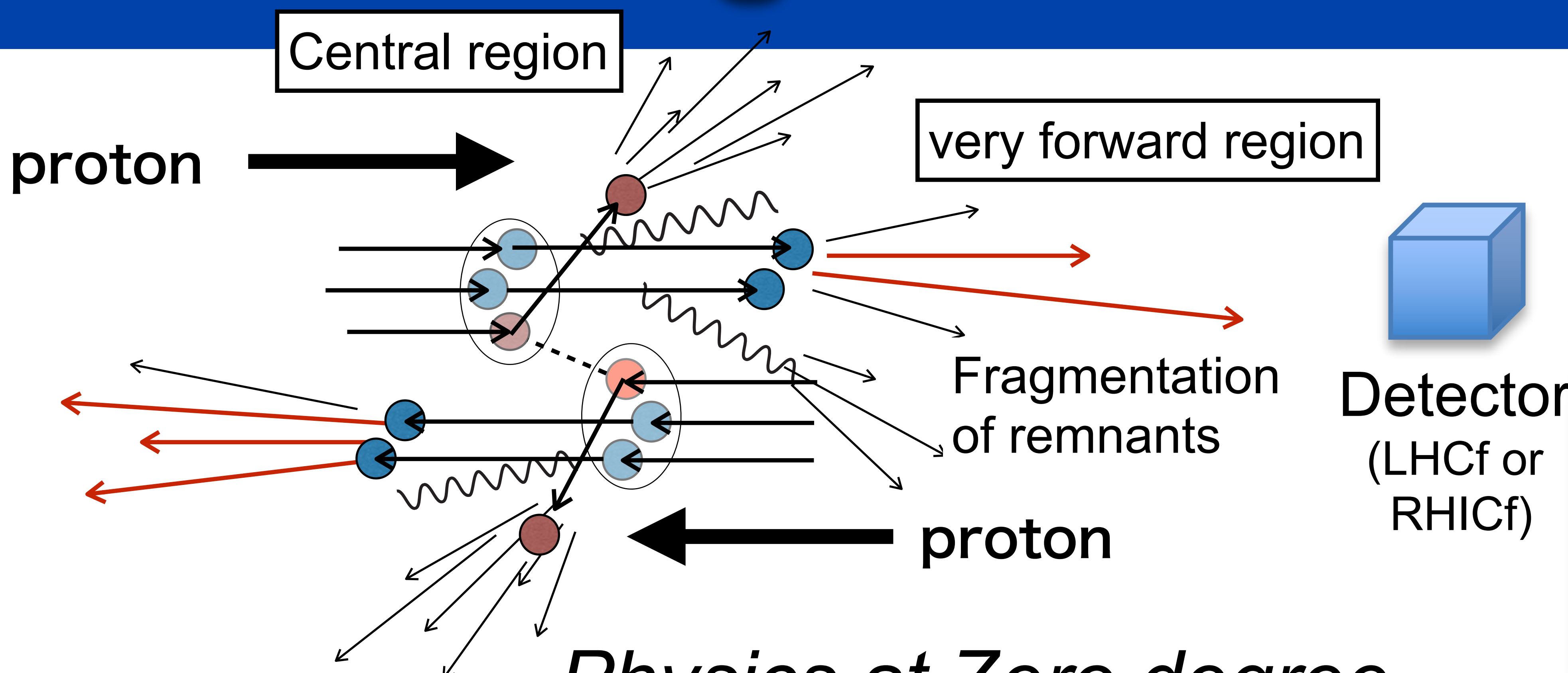
RHICf I detector and Cosmic-ray physics

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

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

Japan-Korea collaboration meeting, 15-16 July 2021

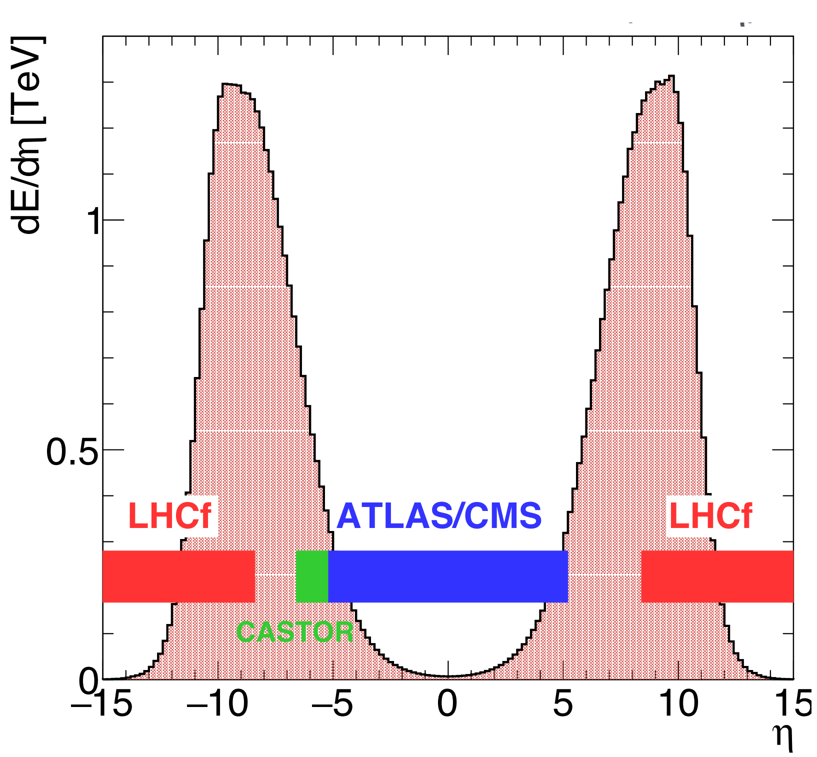
Zero-degree of collisions



Physics at Zero degree

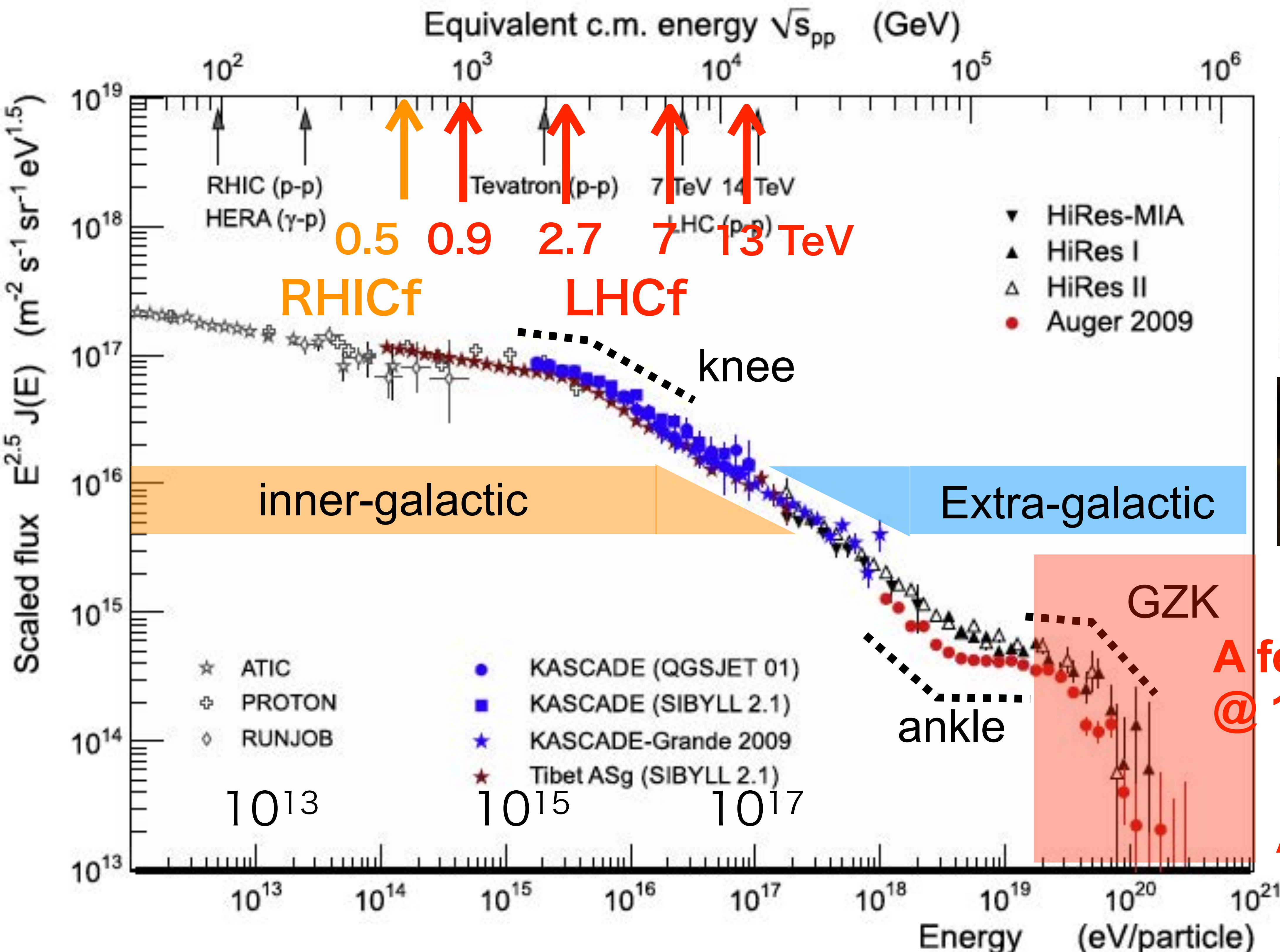
✓Soft collisions, low-pT < 1GeV
→ pQCD does not work.
→ Phenomenological model is needed

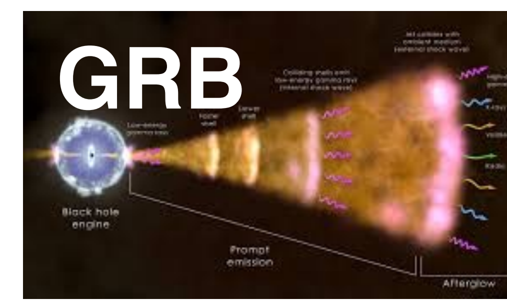
✓High energy flux
→ Most of longitudinal momentum is carried by remnants of collisions.



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

Cosmic-rays





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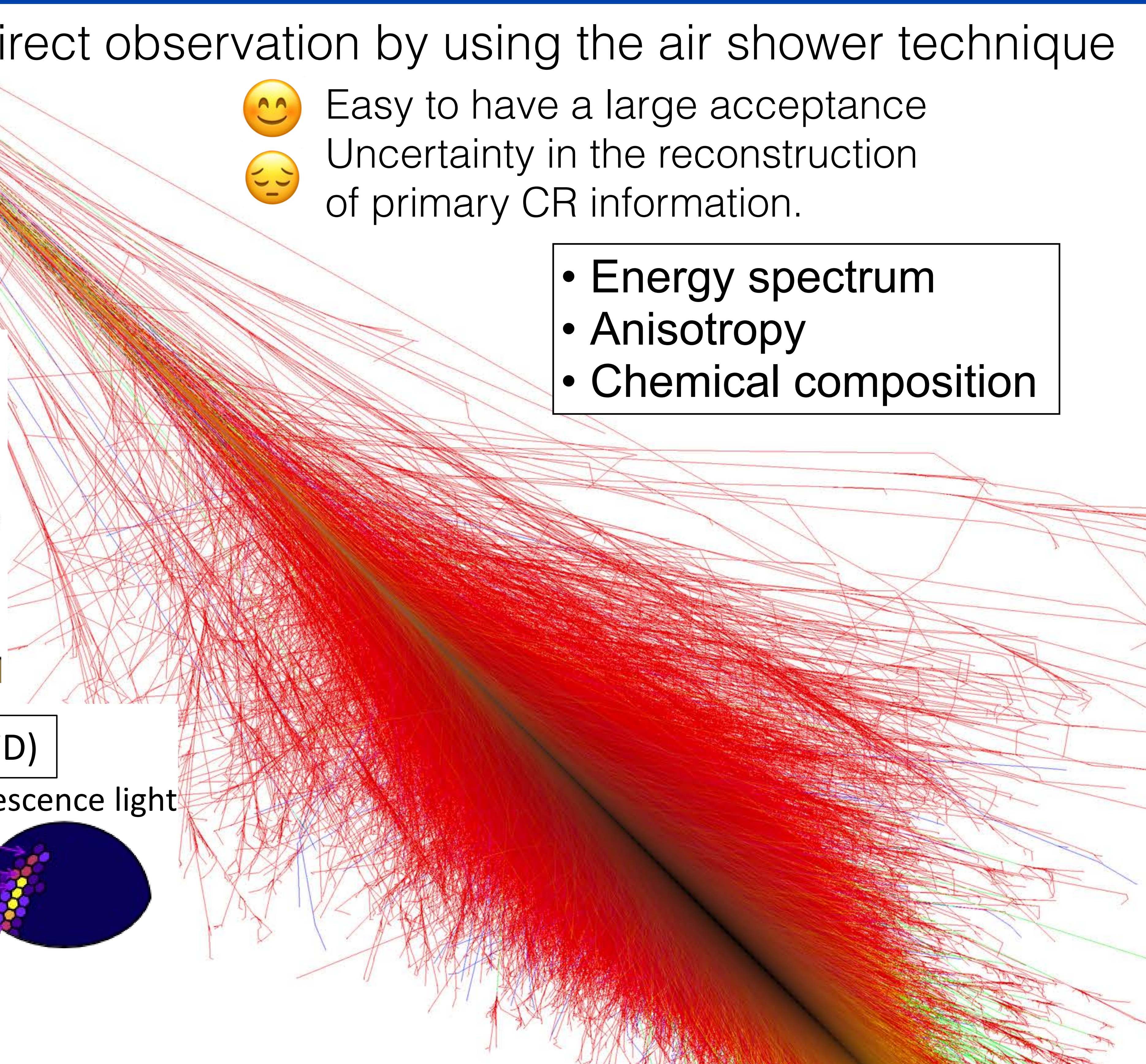
A few degrees @ 10^{19}eV proton

UHECR Astronomy

D'Enterria et al., 2011

UHECR observations

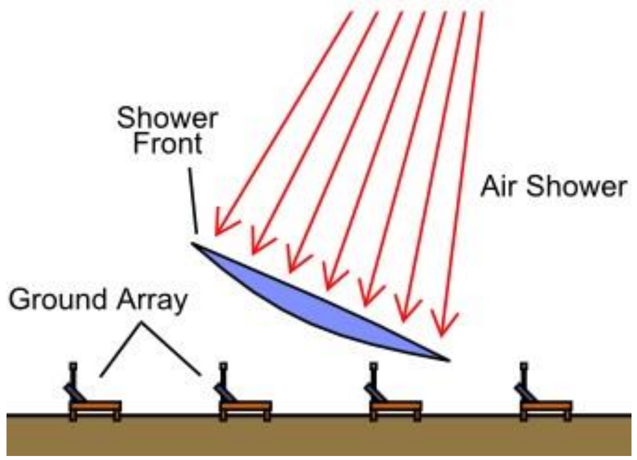


Indirect observation by using the air shower technique

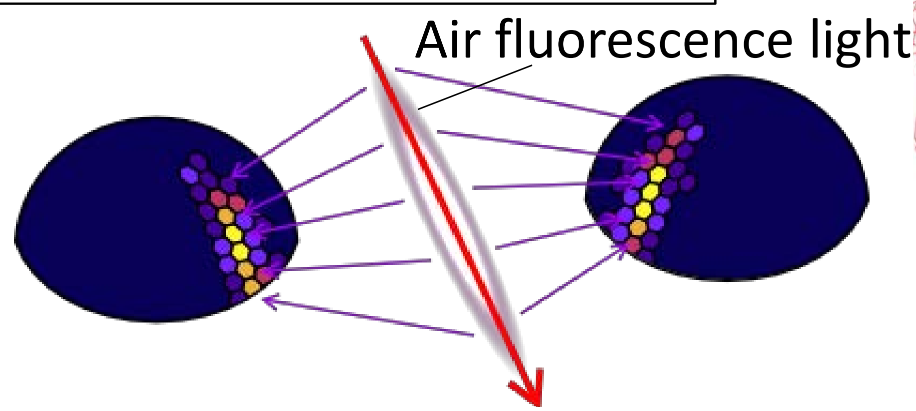
- Easy to have a large acceptance
- Uncertainty in the reconstruction of primary CR information.

- Energy spectrum
- Anisotropy
- Chemical composition

Surface detector (SD)

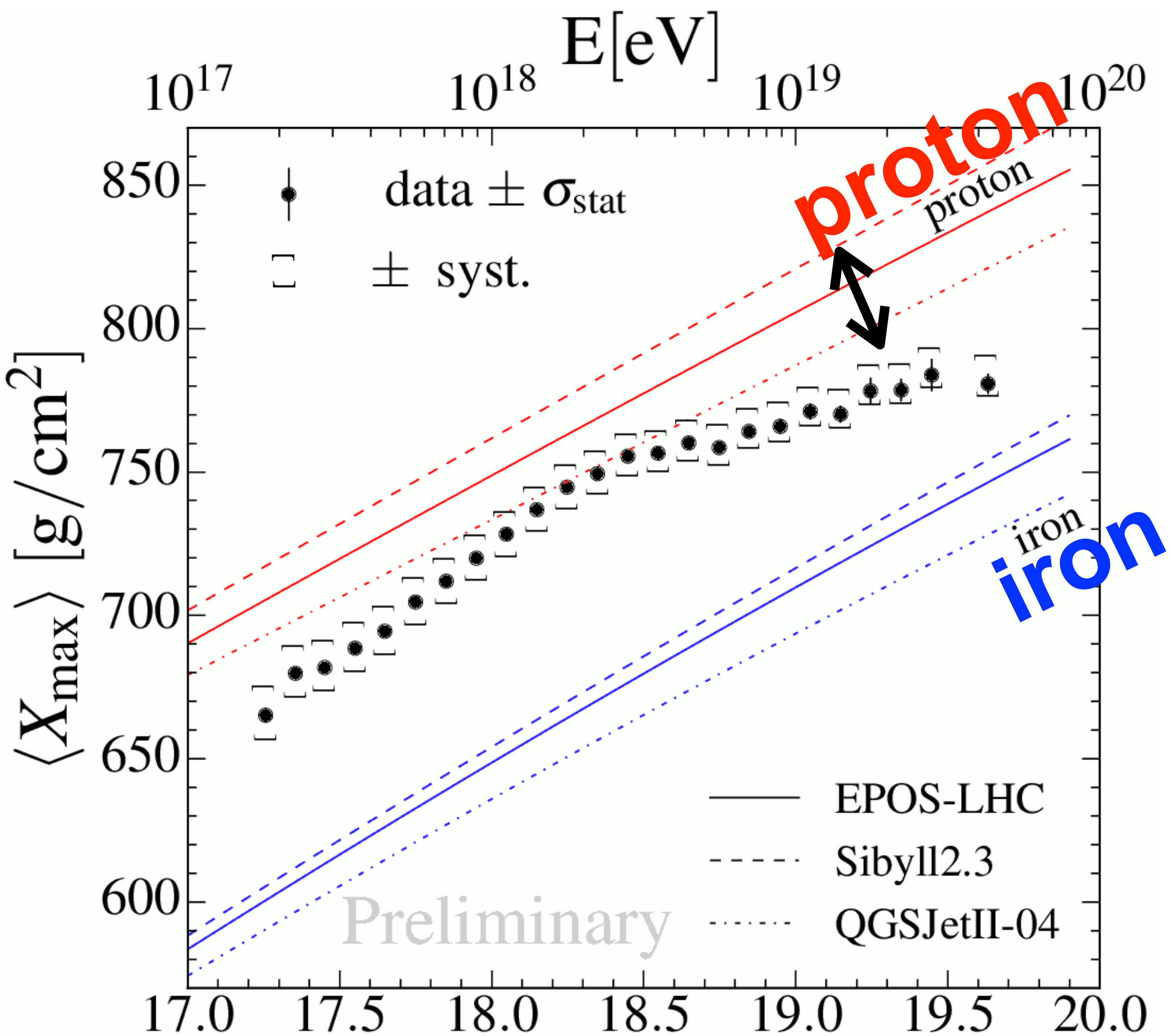


Fluorescence detector (FD)



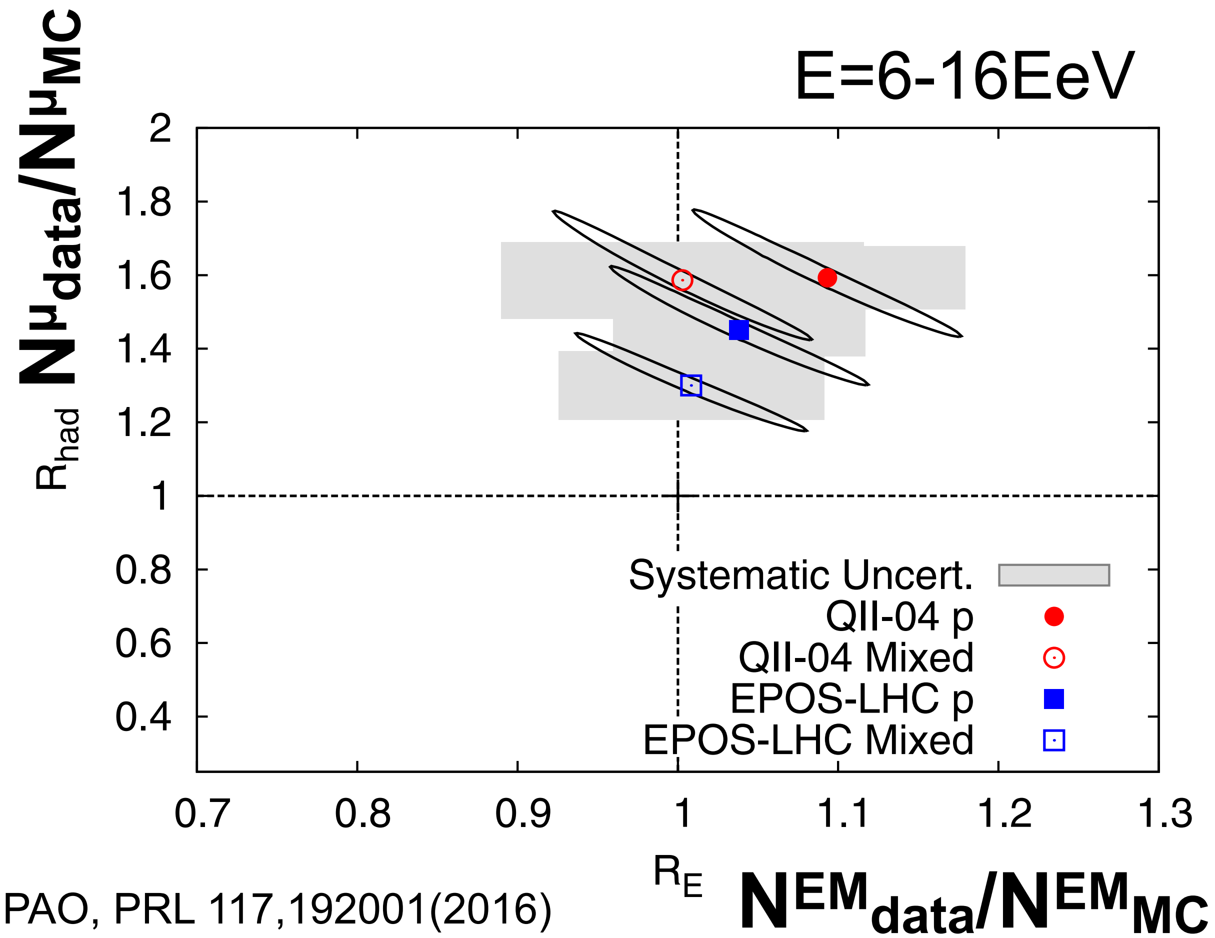
UHECR observation issues

Large model dependency of UHECR composition measurement



PAO collaboration (ICRC2017)

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

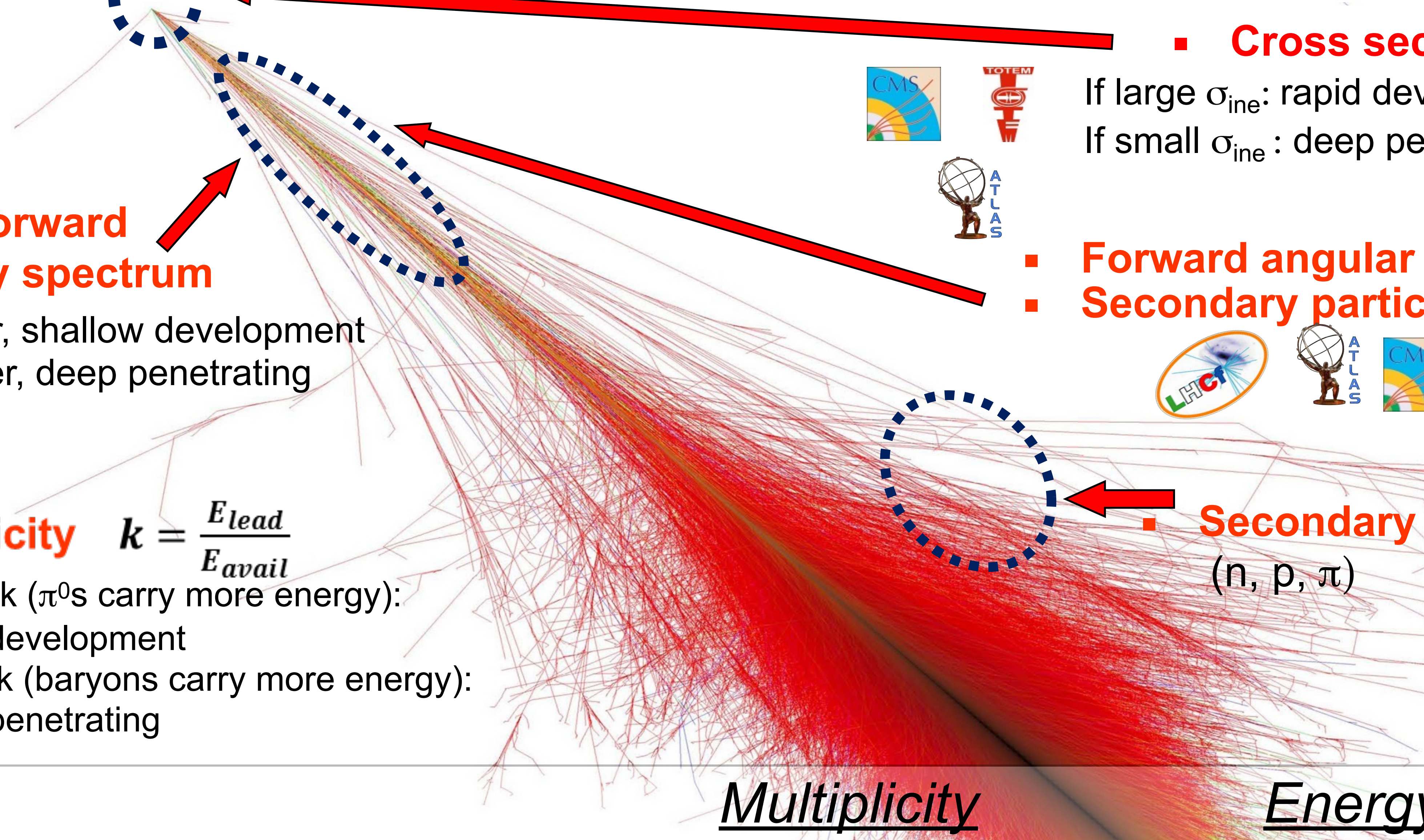


PAO, PRL 117,192001(2016)

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**

- **Secondary interactions**

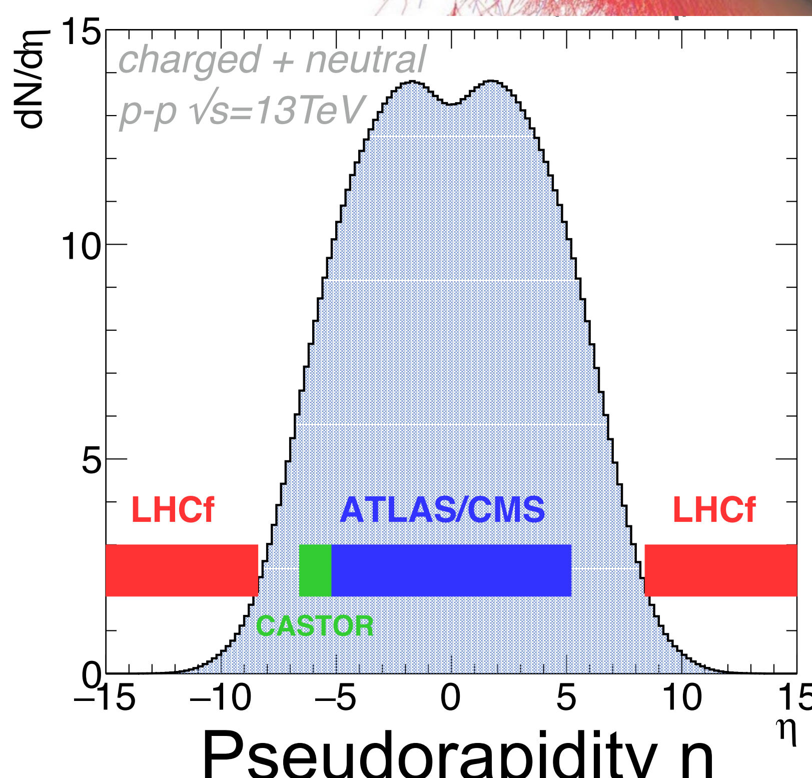
(n, p, π)

- **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

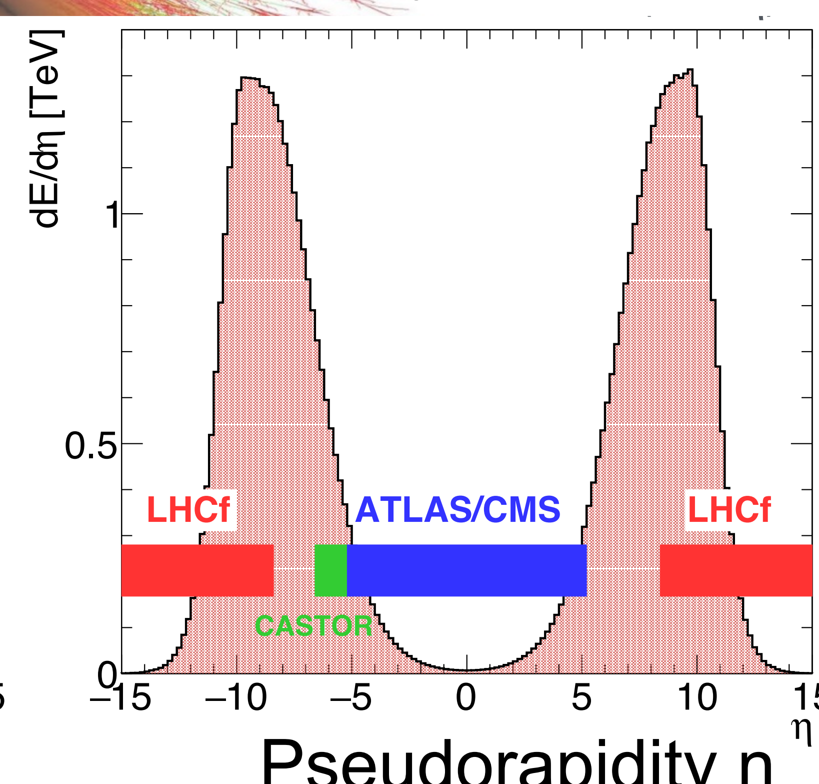
The coverage of the “wide” rapidity range by experiments is crucial

*Especially High Energy Flux in “**forward**” region*

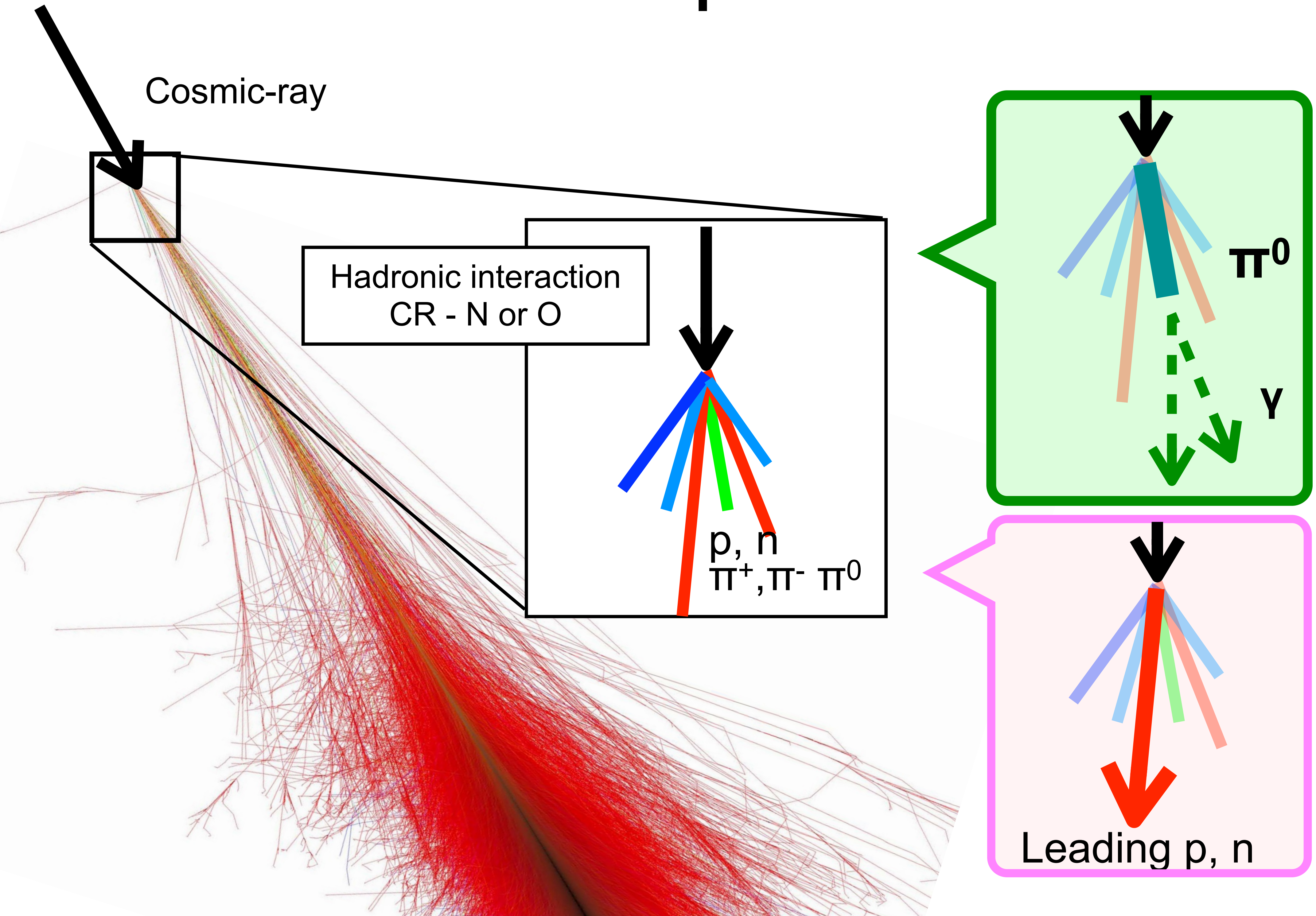
Multiplicity



Energy Flow



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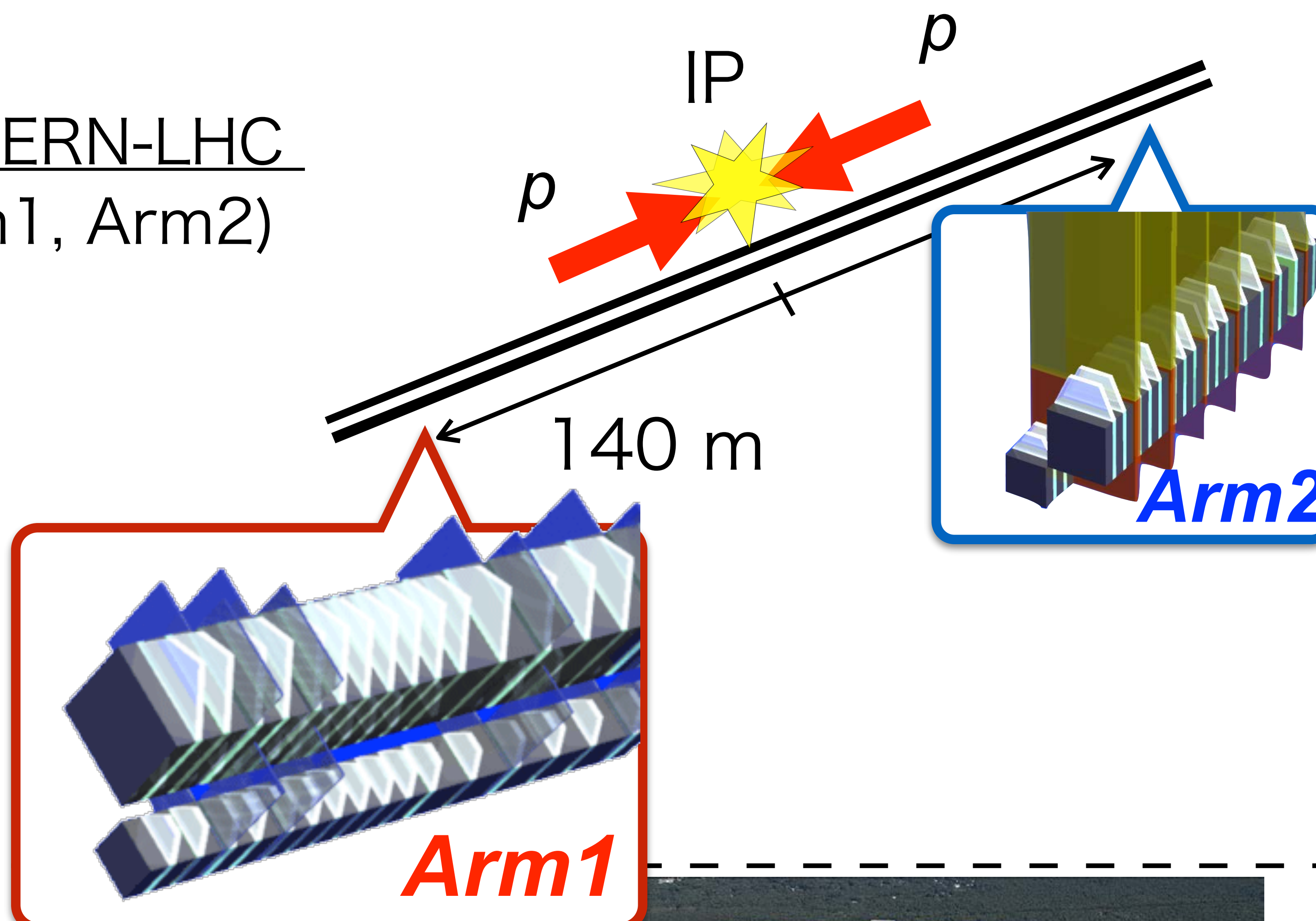
J. S. Park *(Seoul univ.)* B. Hong, M. H. Kim *(Korea univ.)*
O. Adriani, E. Berti, L. Bonechi, R.D'Alessandro *(INFN Florence)*
A. Trocomi *(INFN Catania)*

LHCf and RHICf experiments

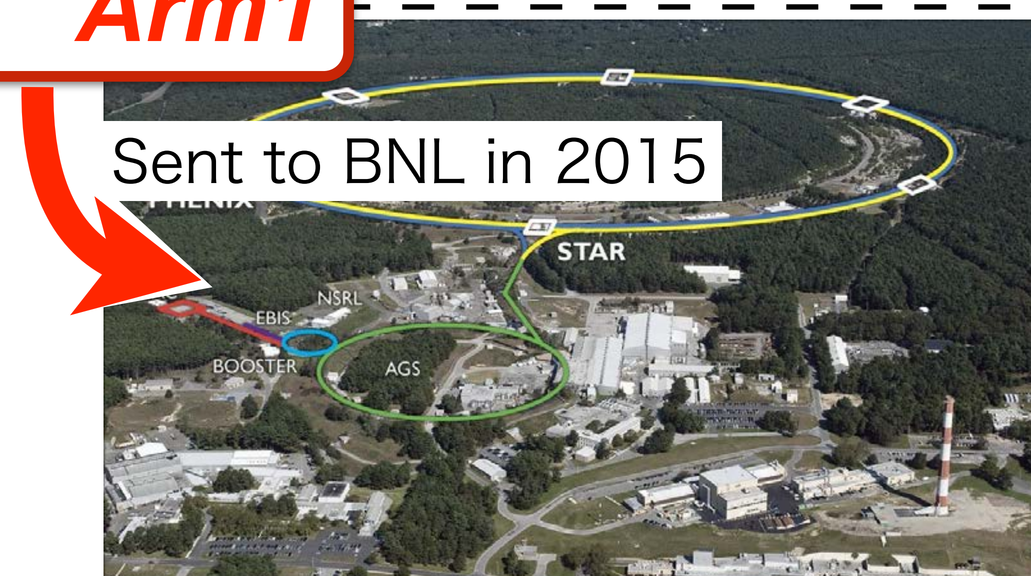
LHCf experiment

- 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

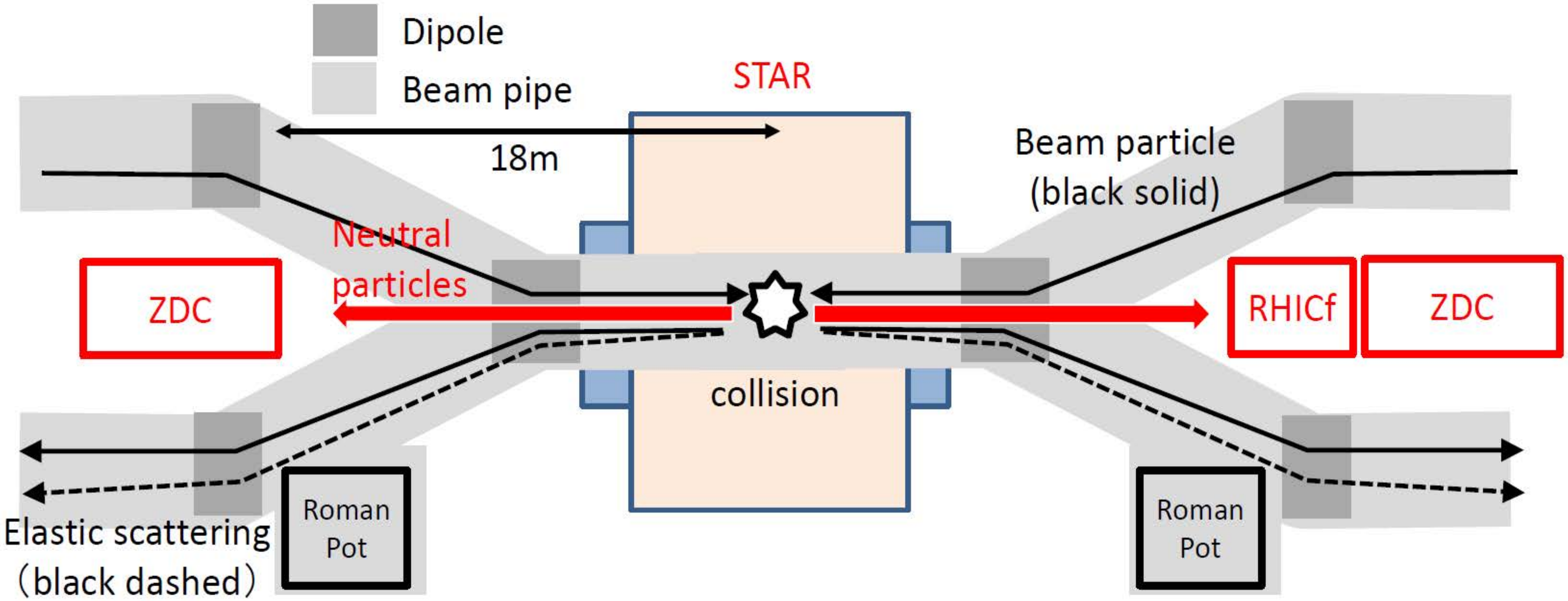
- Zero degree measurement at BNL-RHIC
- Only one detector at 18 m from STAR IP
- Spin asymmetry measurements with polarized proton beams
- Operation: pp $\sqrt{s}$ = 510 GeV (2017)



RHICf experiment

RHIC at BNL

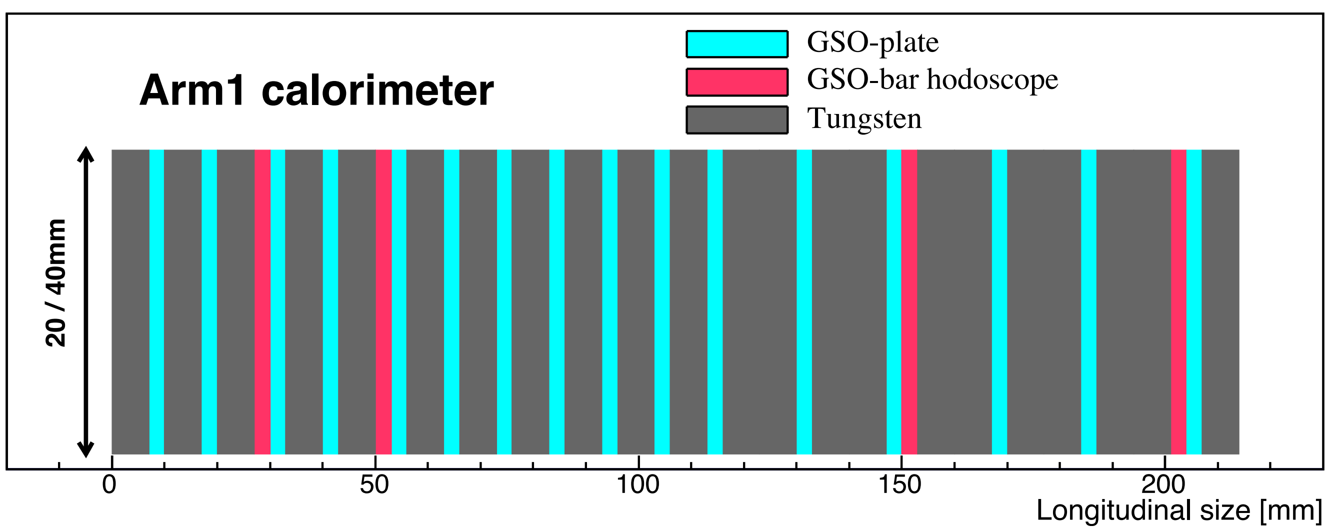
- p+p √s = 510 GeV
  (polarized beam)
- Test of energy scaling with the wide p_T range.
- The operation was successfully completed in June 2017
- RHICf covers η > 5.9
- Common operation with STAR

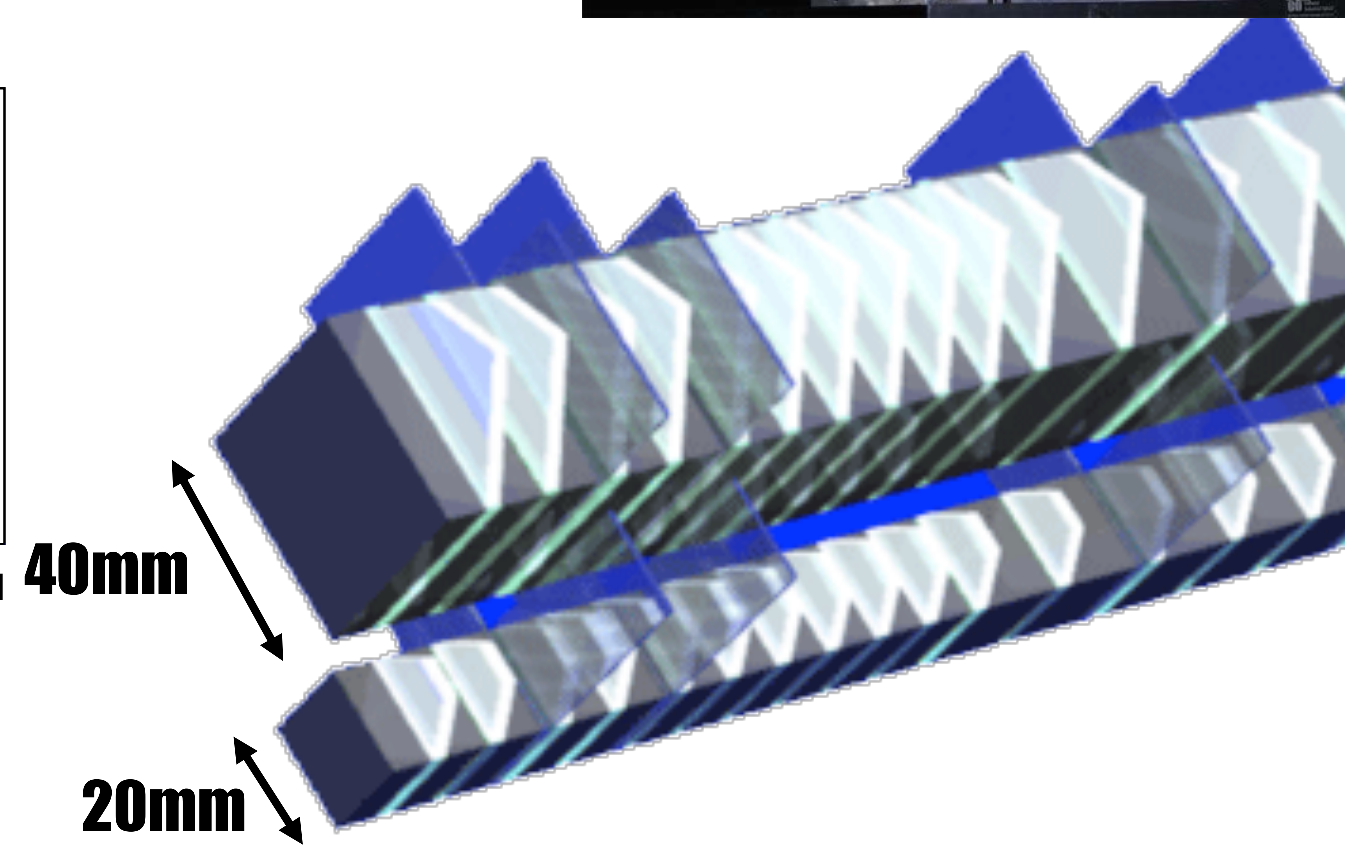


The RHICf detectors

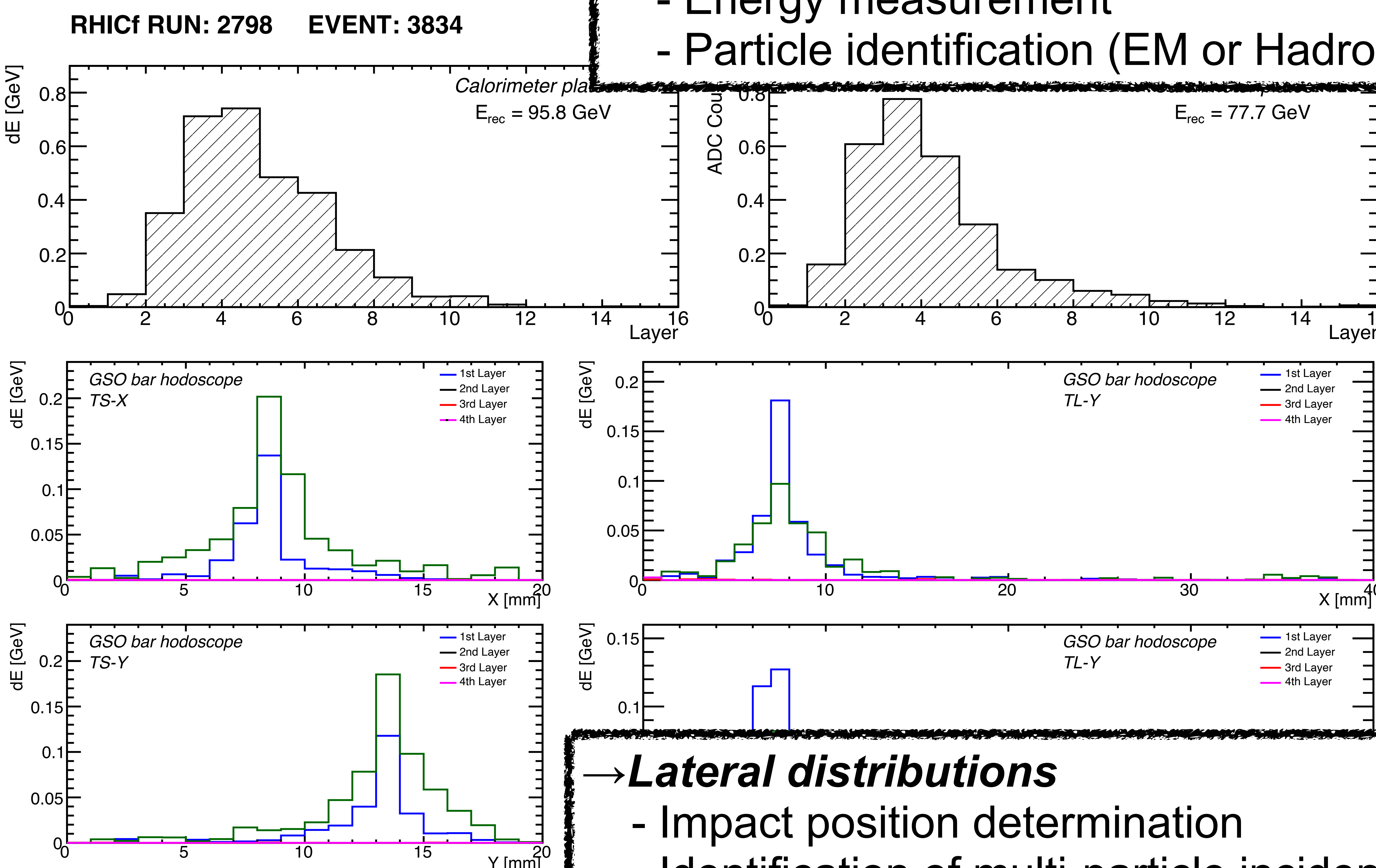
Sampling and Positioning Calorim

- 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



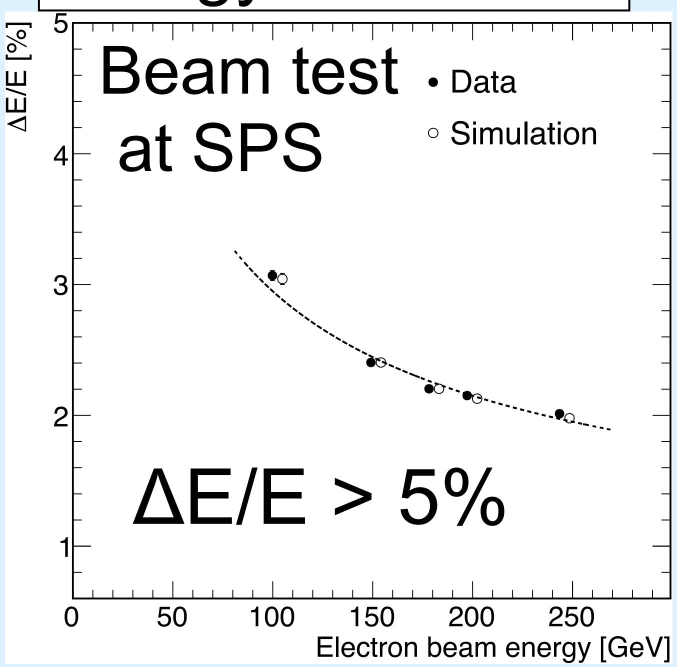
→***Longitudinal developments***
- Energy measurement
- Particle identification (EM or Hadronic)

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

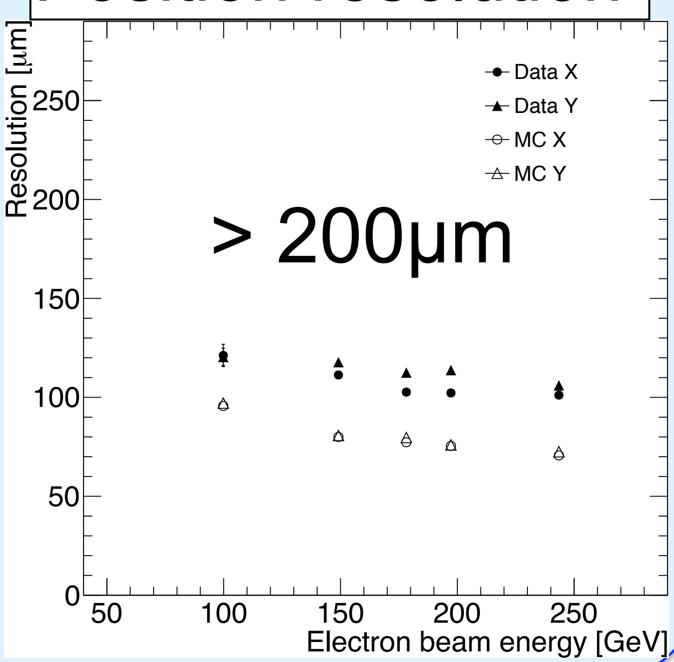
Calorimeter performances

EM showers

Energy resolution

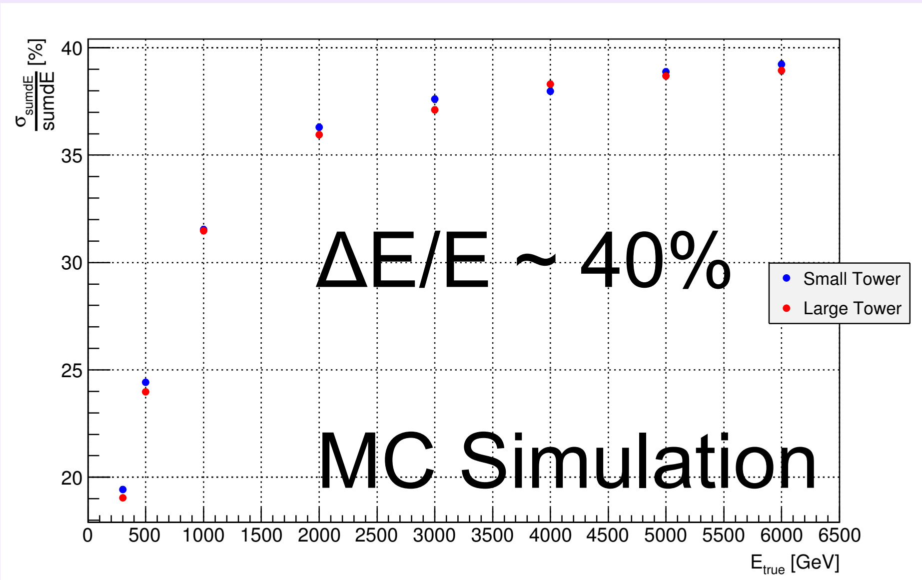


Position resolution

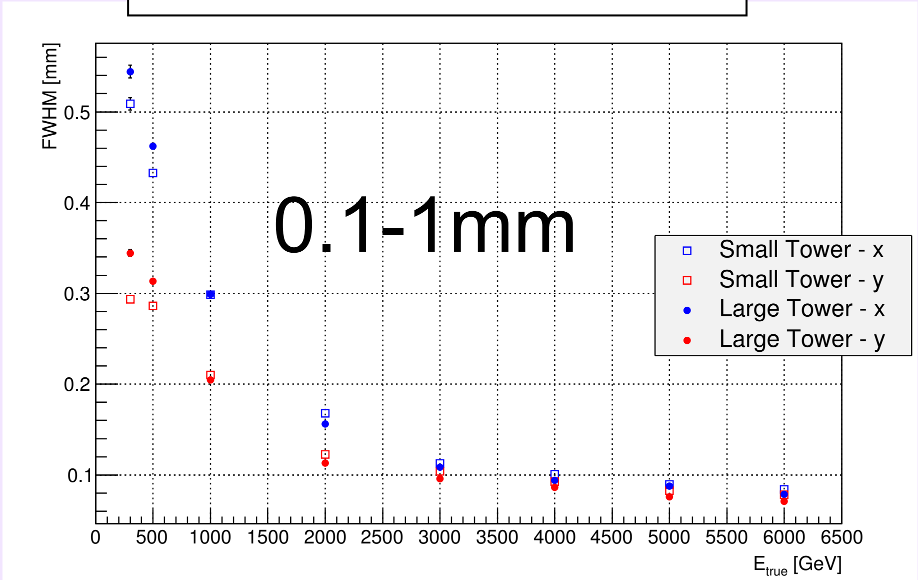


Had. showers

Energy resolution



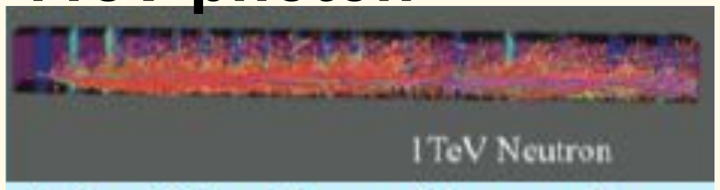
Position resolution



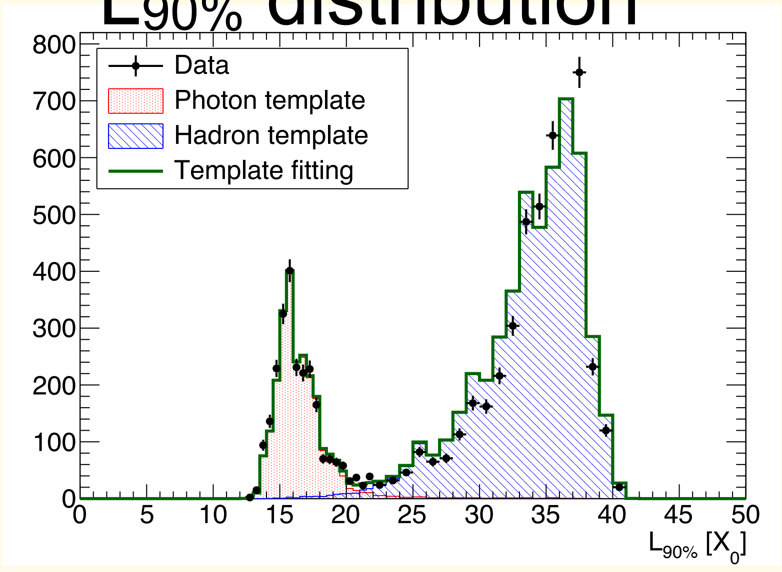
PID

400 GeV photon

1TeV photon

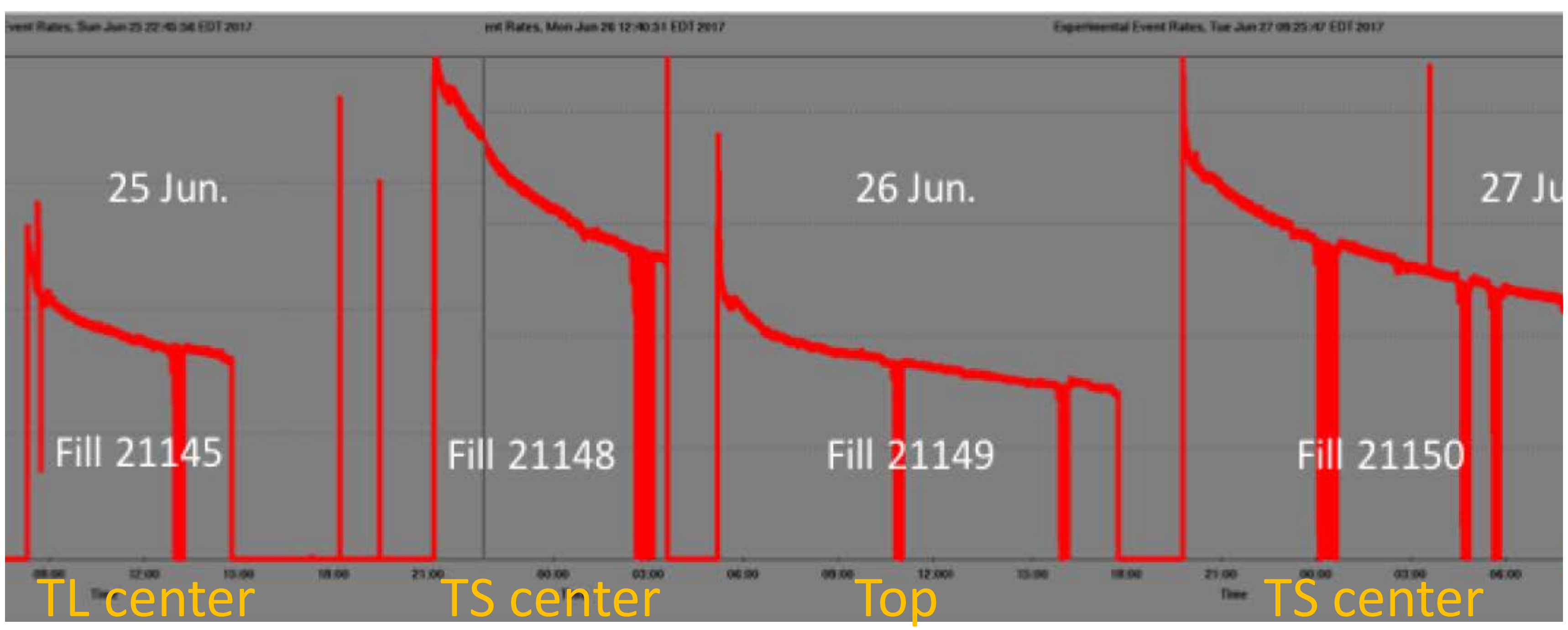


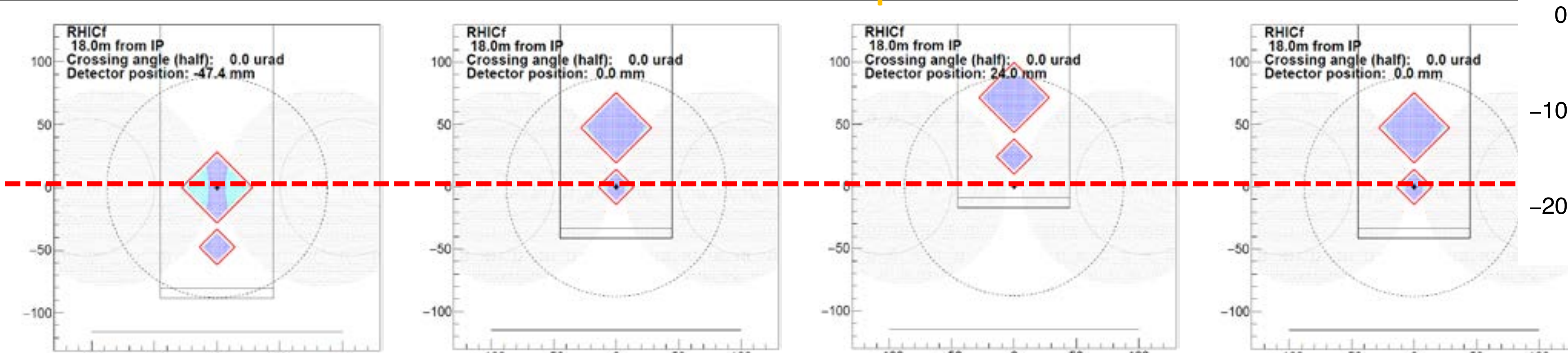
$L_{90\%}$ distribution

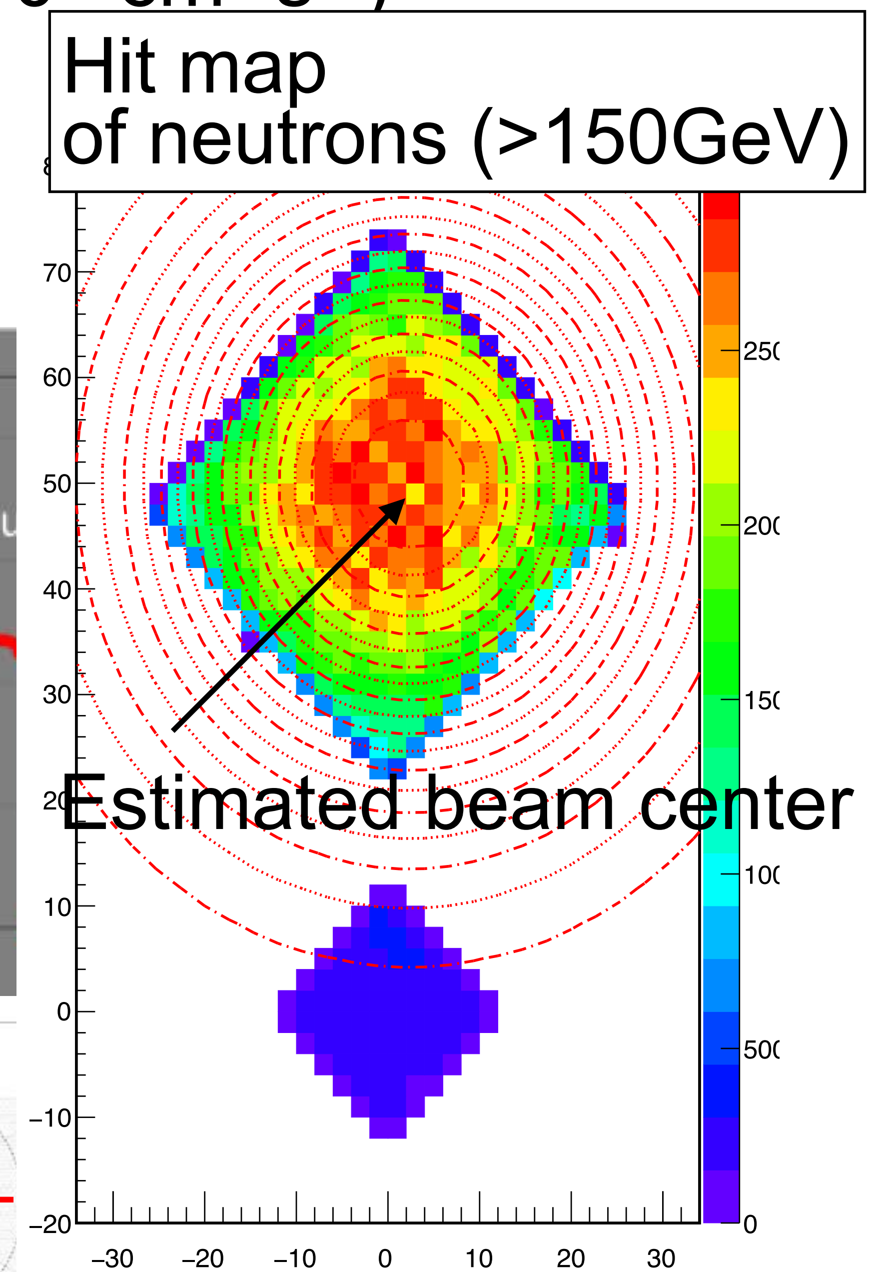


RHICf operation

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



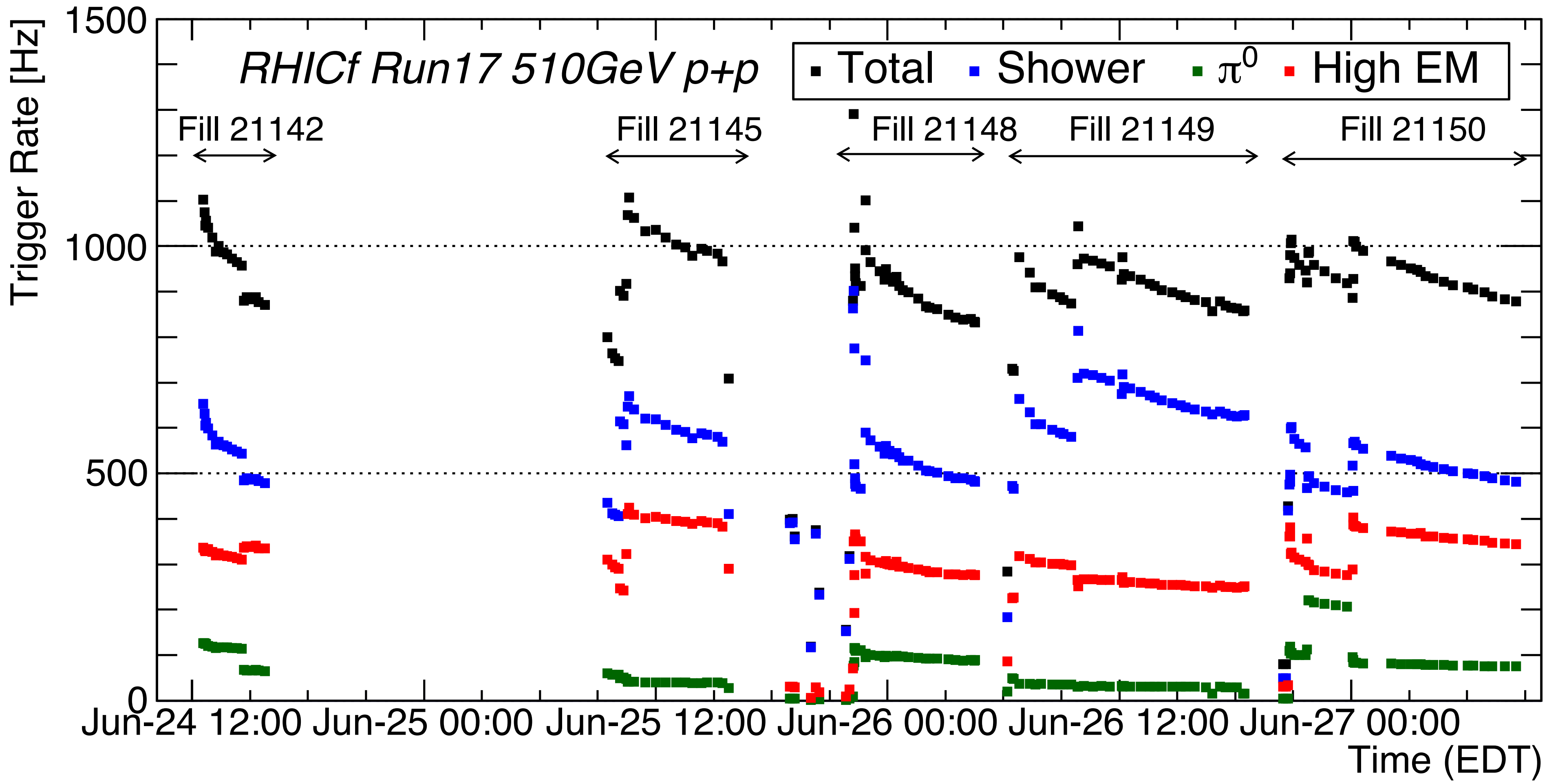




RHICf Trigger

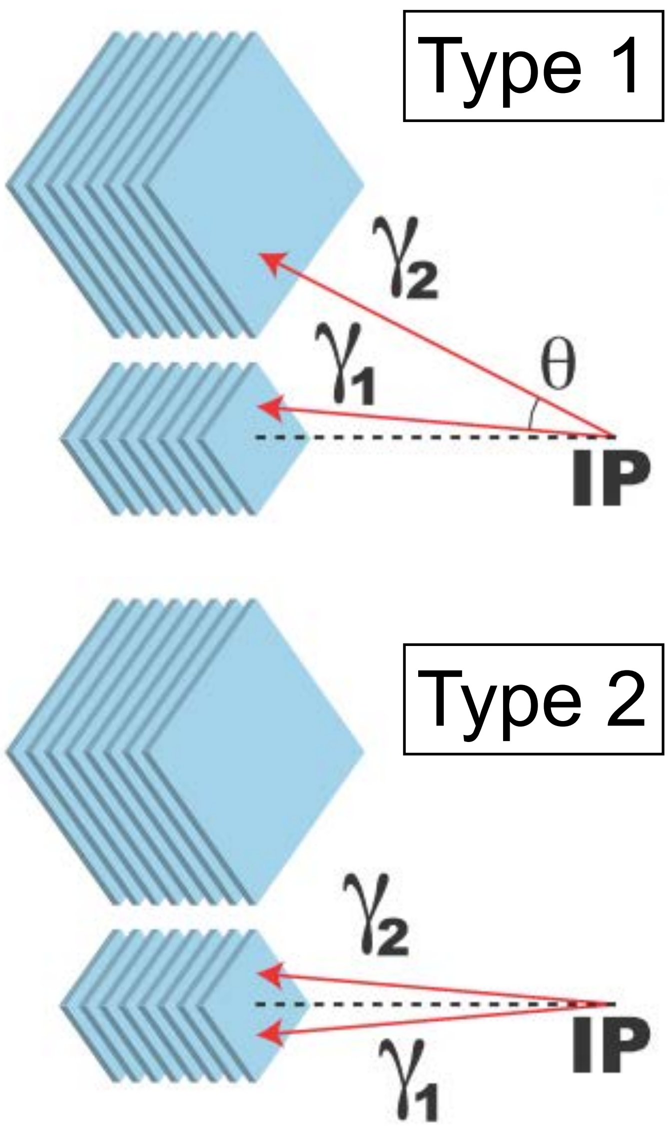
- 3 trigger modes
  - Shower trigger (γ,n) 6-30 kHz
  - High EM trigger (γ > 100 GeV) ~ 1 kHz
  - π^0 trigger (π^0) ~ 200 Hz

⇒ 1 kHz readout, 100 M events in Run17

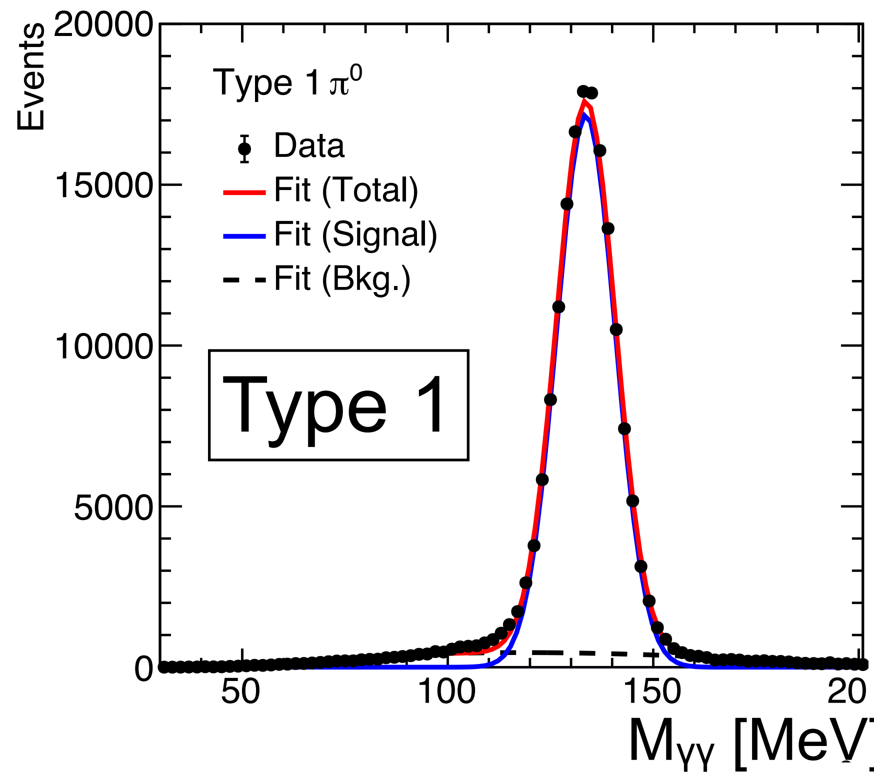


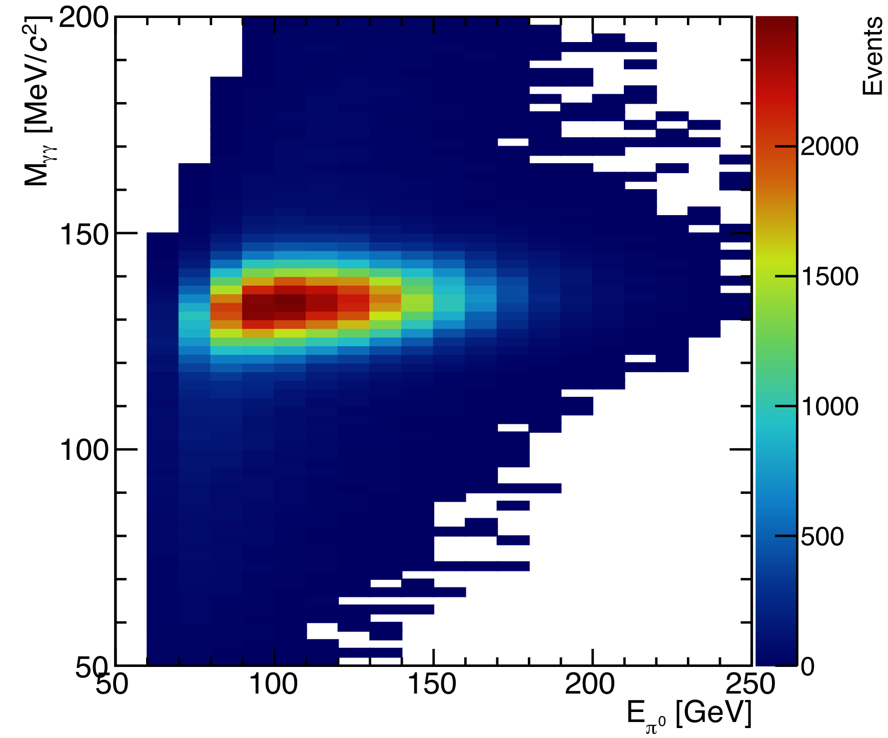
π^0 measurement

- 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



<u>Reconstructed mass $M_{\gamma\gamma}$ distribution</u>





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

- Energy calibration
- Confirmation of linearity
- Stability check

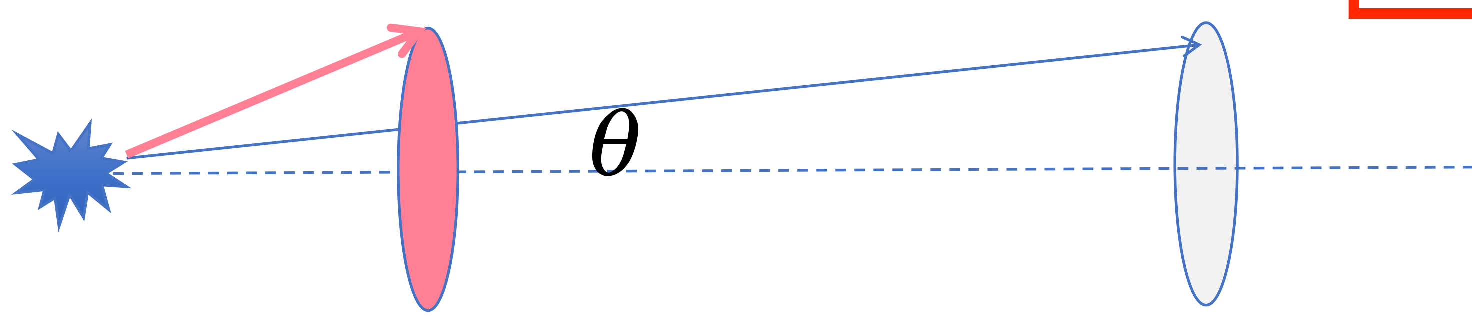
Physics results from RHICf (LHCf)

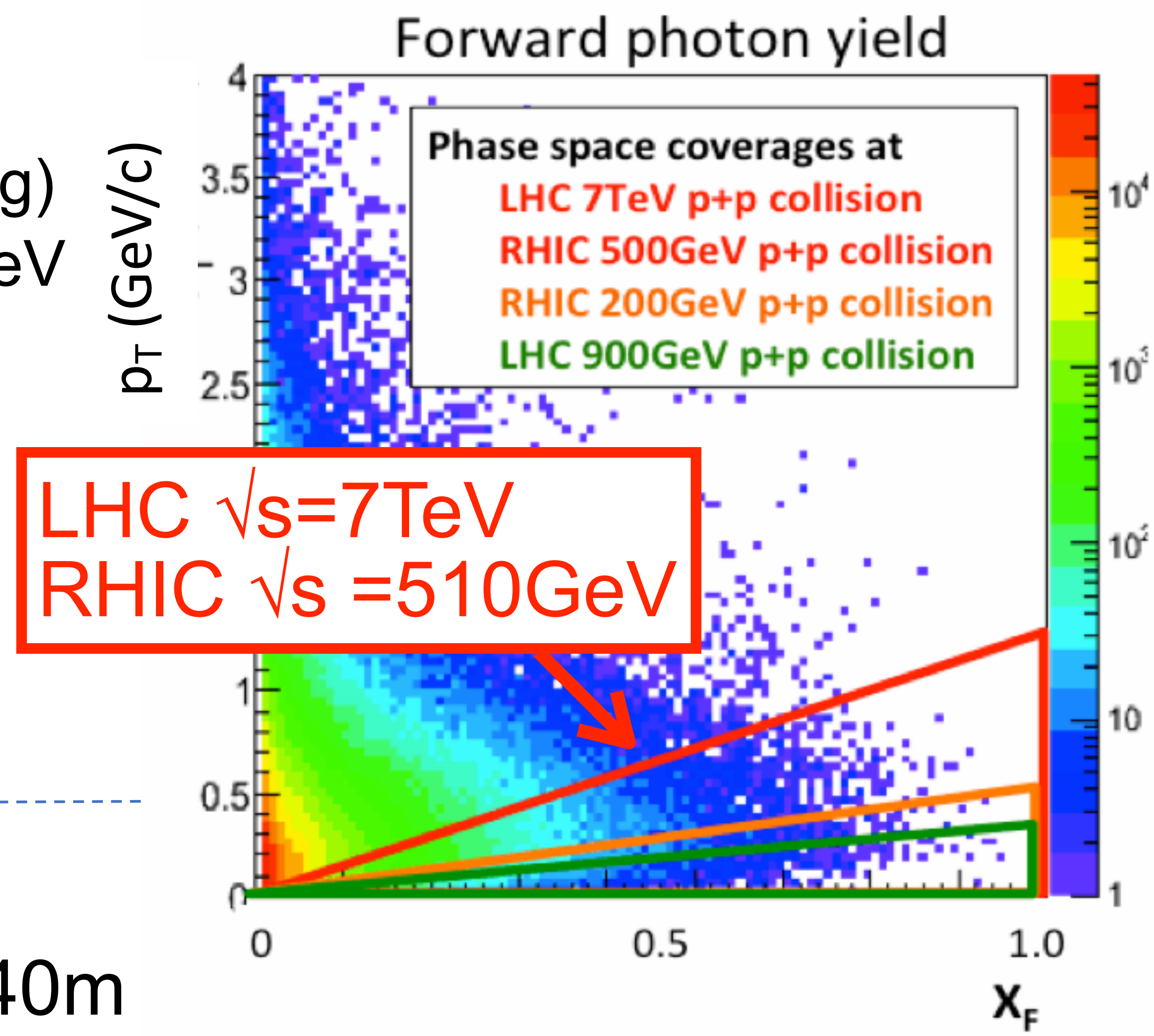
Physics in RHICf

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.

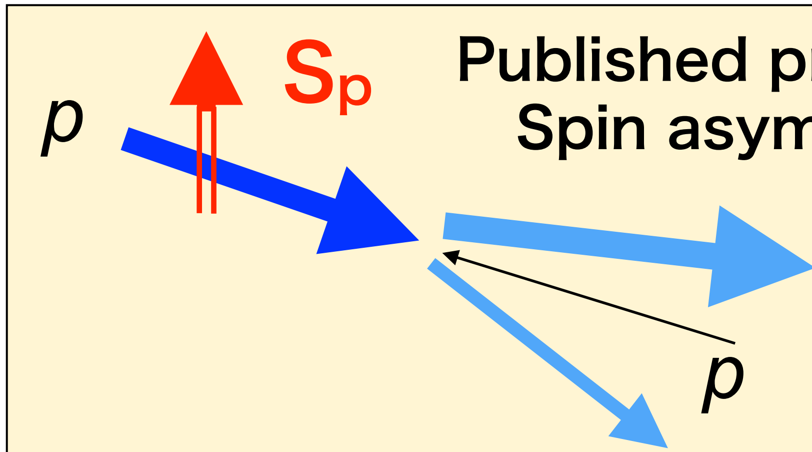
p_T coverage: < 1/2 √s sinθ





Spin asymmetry measurement

→ Goto-san's talk



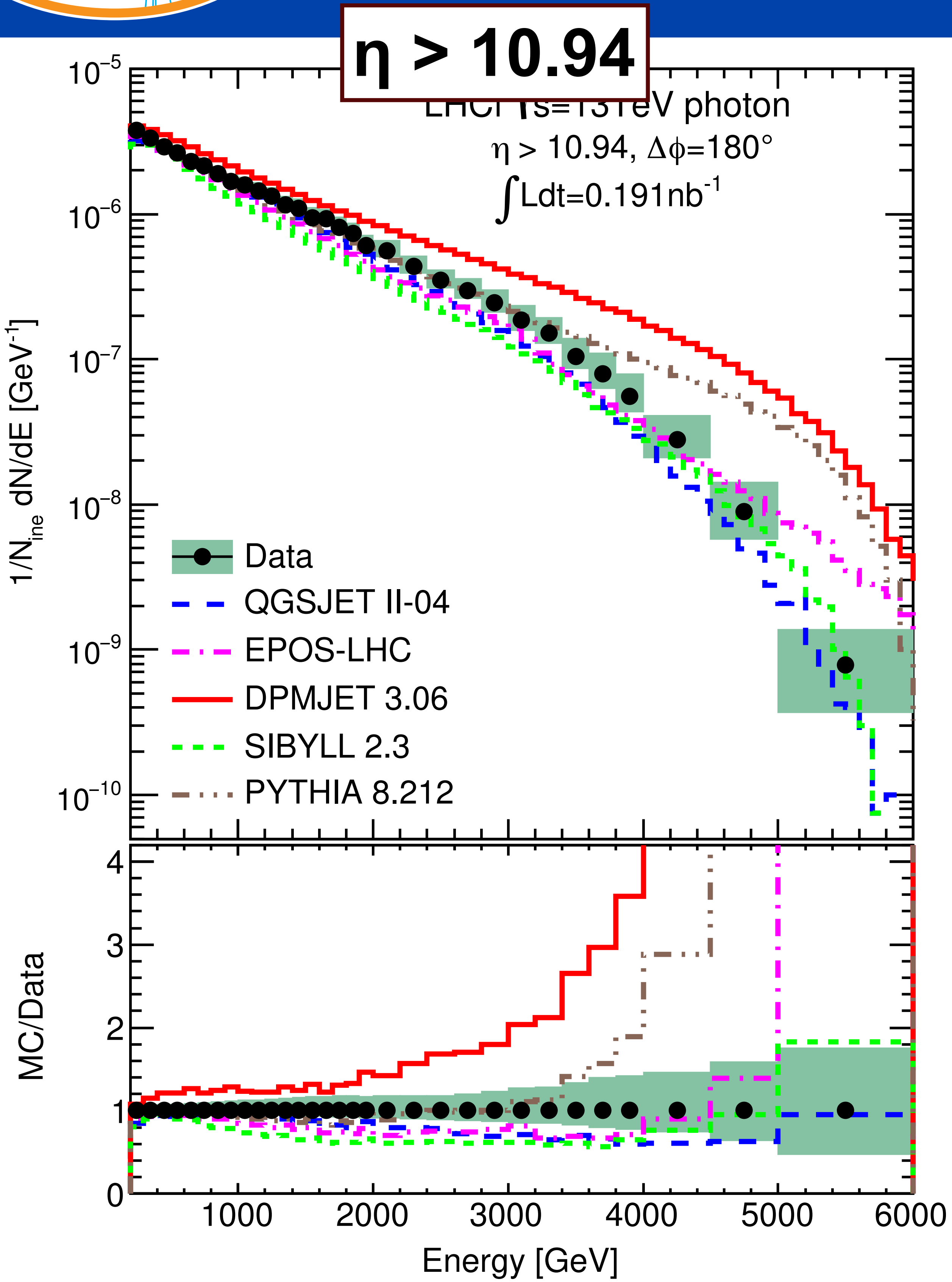
Published preliminary results of Spin asymmetry (A_N) for π^0

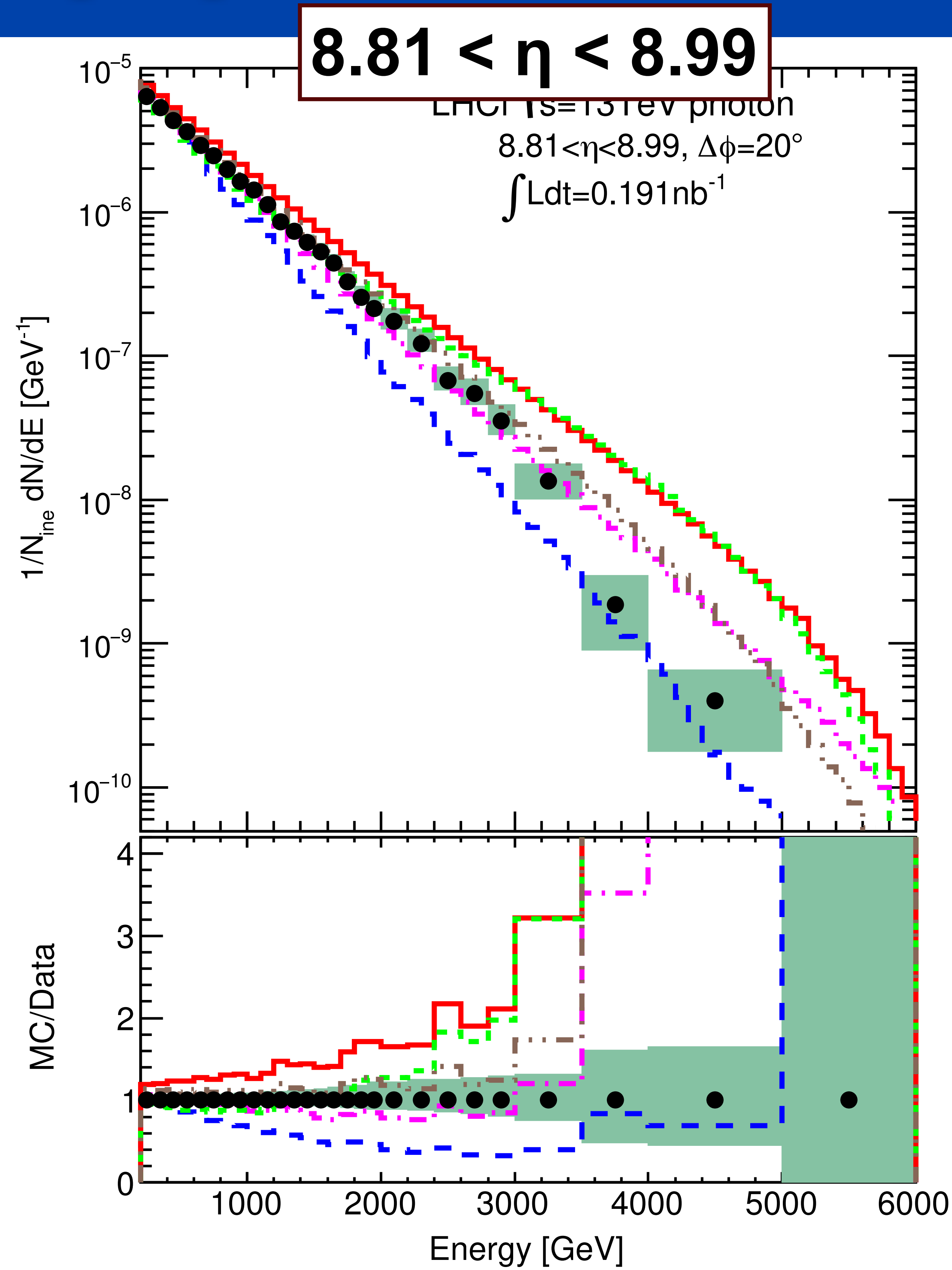
$$A_N = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

Operations and Results

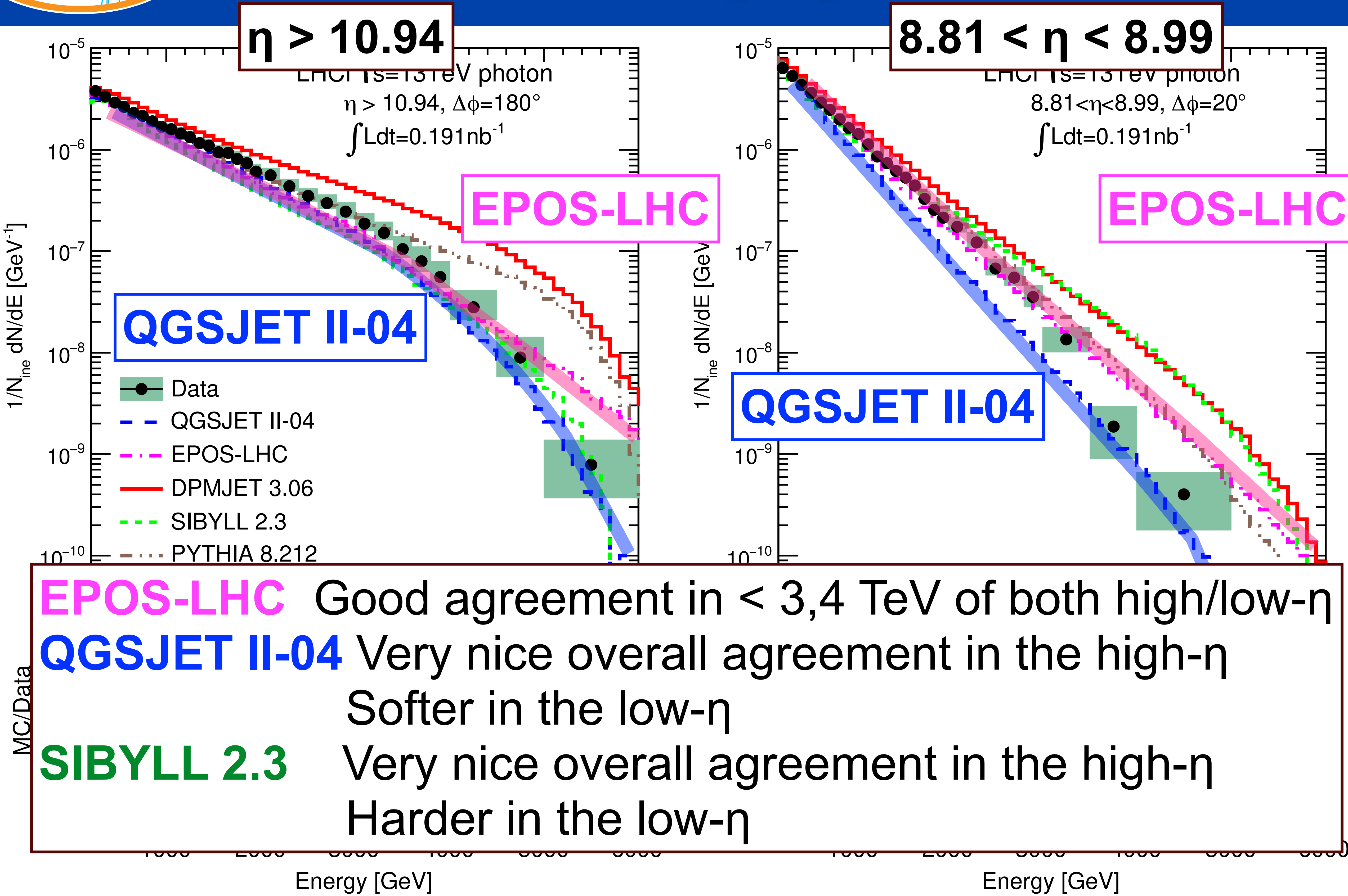
Run	E_{lab} (eV)	Photon	Neutron	π^0	
p-p $\sqrt{s}$=0.9TeV (2009/2010)	4.3×10^{14}	PLB 715, 298 (2012)		-	
p-p $\sqrt{s}$=2.76TeV (2013)	4.1×10^{15}			PRC 86, 065209 (2014)	PRD 94 032007 (2016)
p-p $\sqrt{s}$=7TeV (2010)	2.6×10^{16}	PLB 703, 128 (2011)	PLB 750 360 (2015)	PRD 86, 092001 (2012)	
p-p $\sqrt{s}$=13TeV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

Photon at p-p, 13TeV





Photon at p-p, 13TeV

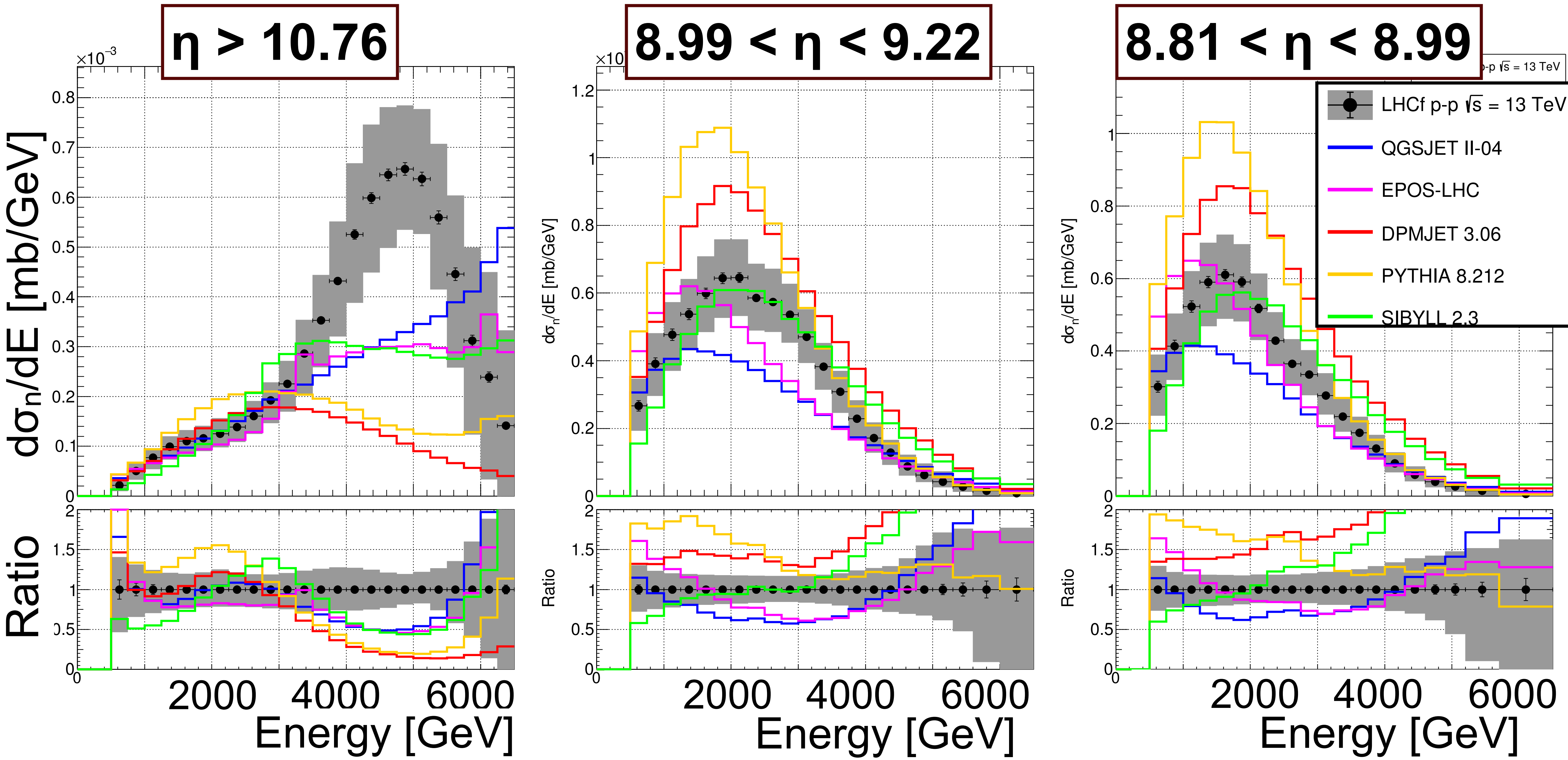


EPOS-LHC Good agreement in < 3,4 TeV of both high/low-η

QGSJET II-04 Very nice overall agreement in the high-η
Softer in the low-η

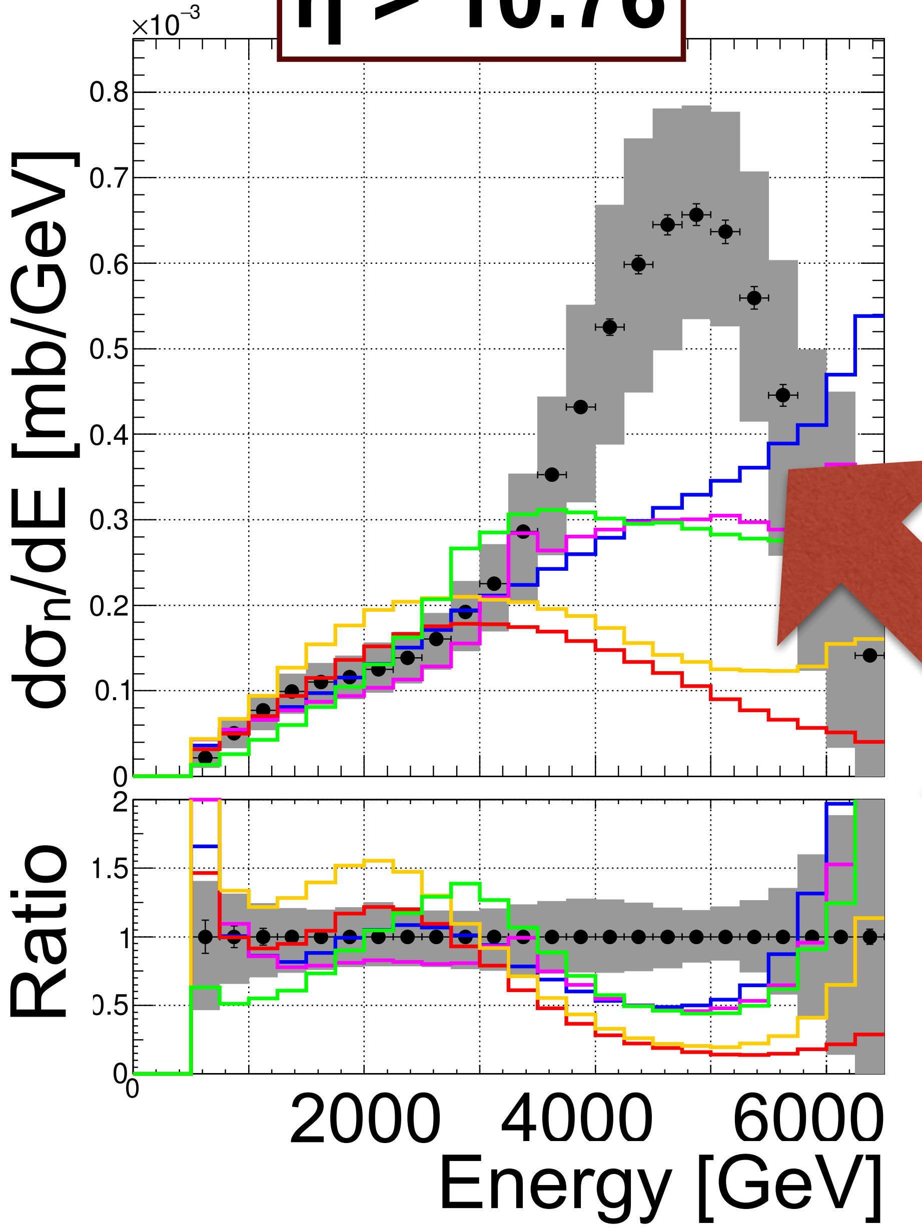
SIBYLL 2.3 Very nice overall agreement in the high-η
Harder in the low-η

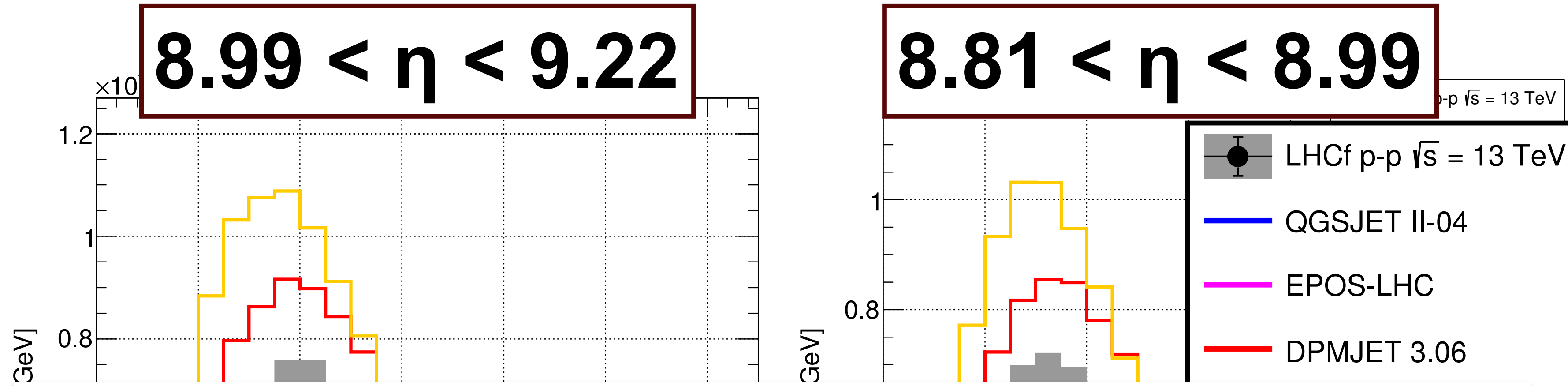
Neutron, p-p √s=13TeV

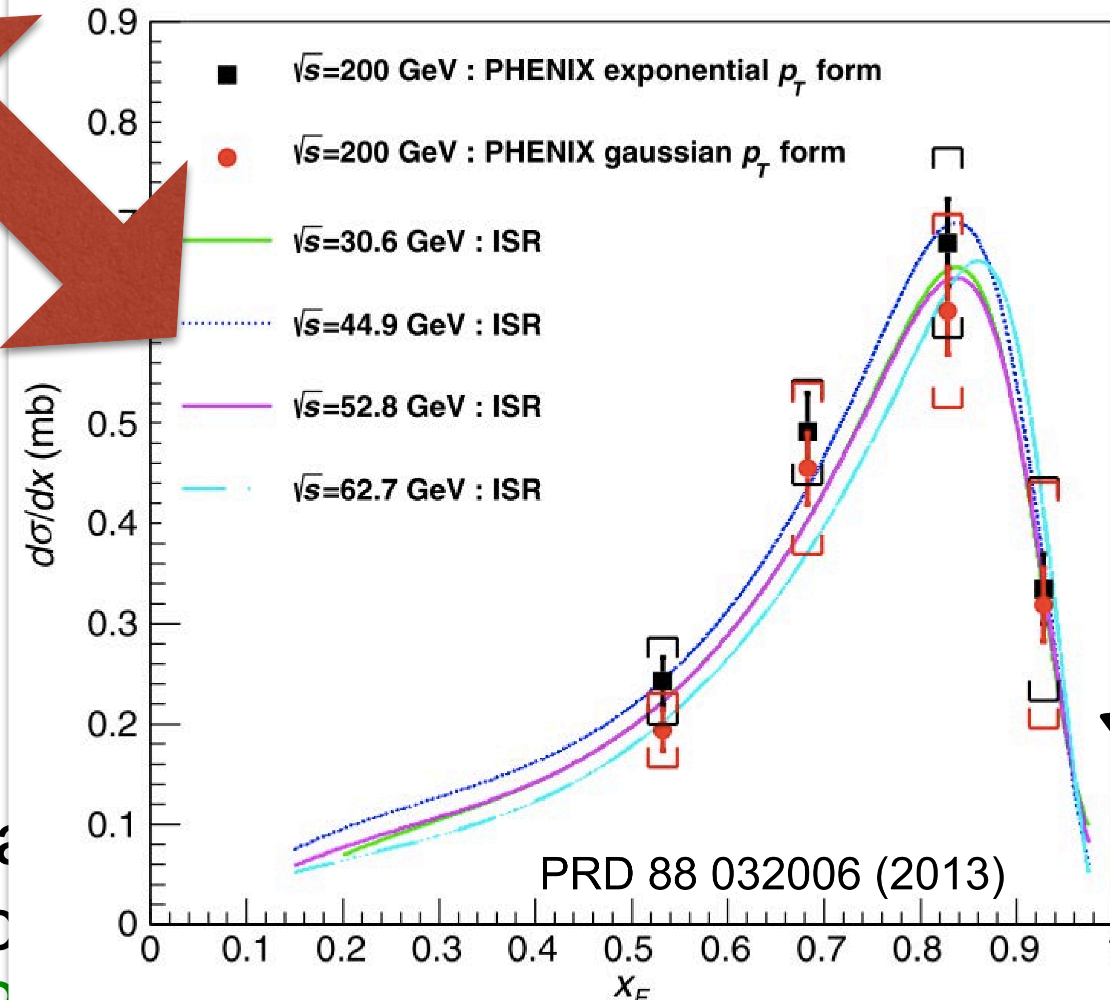


- In η > 10.76, data shows a strong increasing of neutron production in the high energy region. This behavior is not predicted by all models.
- EPOS-LHC and SIBYLL 2.3 have the best agreement in 8.99 < η < 9.22, 8.81 < η < 8.99, respectively.

Neutron, p-p $\sqrt{s}$=13TeV







Forward neutrons @ RHIC, ISR

The peaked spectra are explained by a one-pion exchange model.

Detailed comparison is needed

$p_T < 0.11\ X_F$ ⇕ $p_T < 0.28\ X_F$ @ η>10.76, 13TeV

- In η > 10.76, data shows a
high energy region. This b
- EPOS-LHC and SIBYLL 2
8.81 < η < 8.99, respectively.

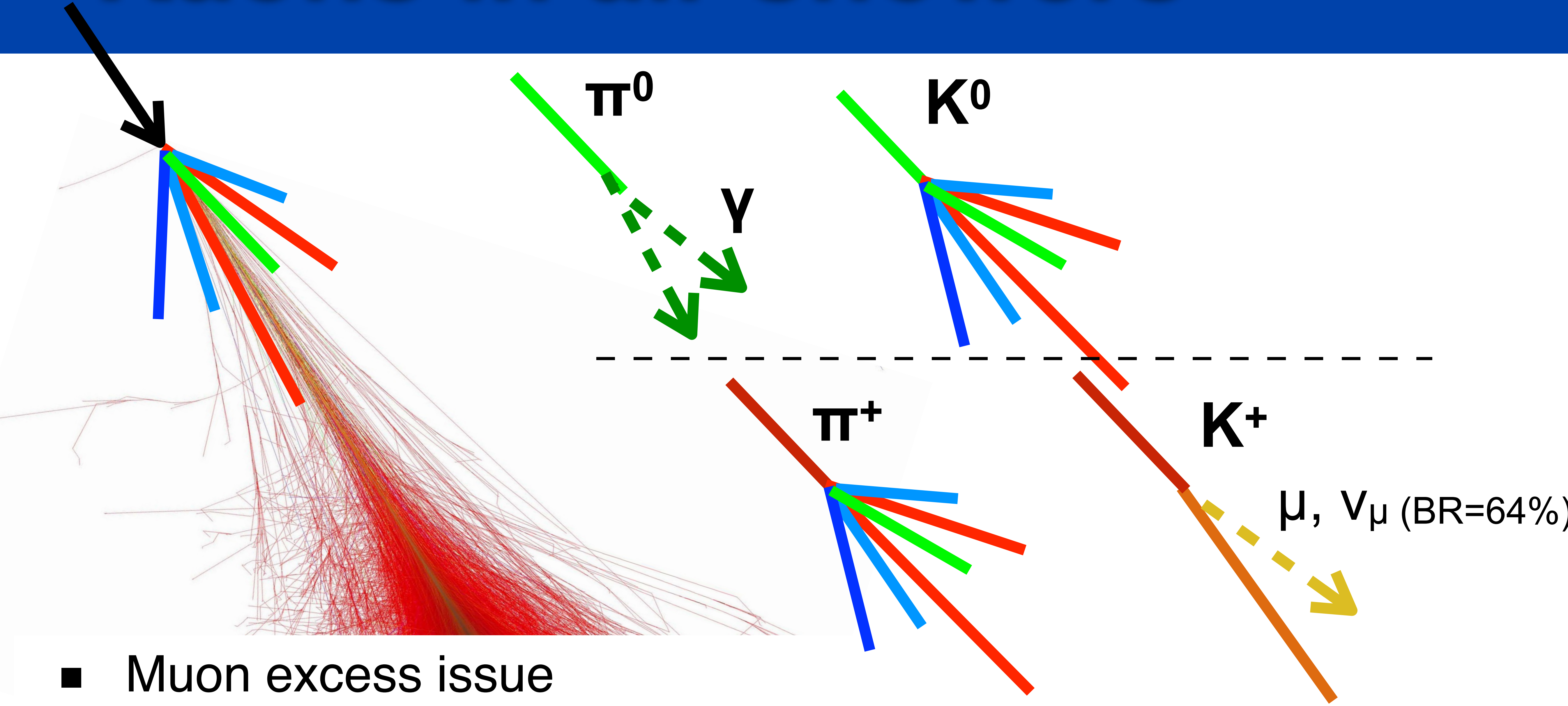
Physics of RHICf II

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

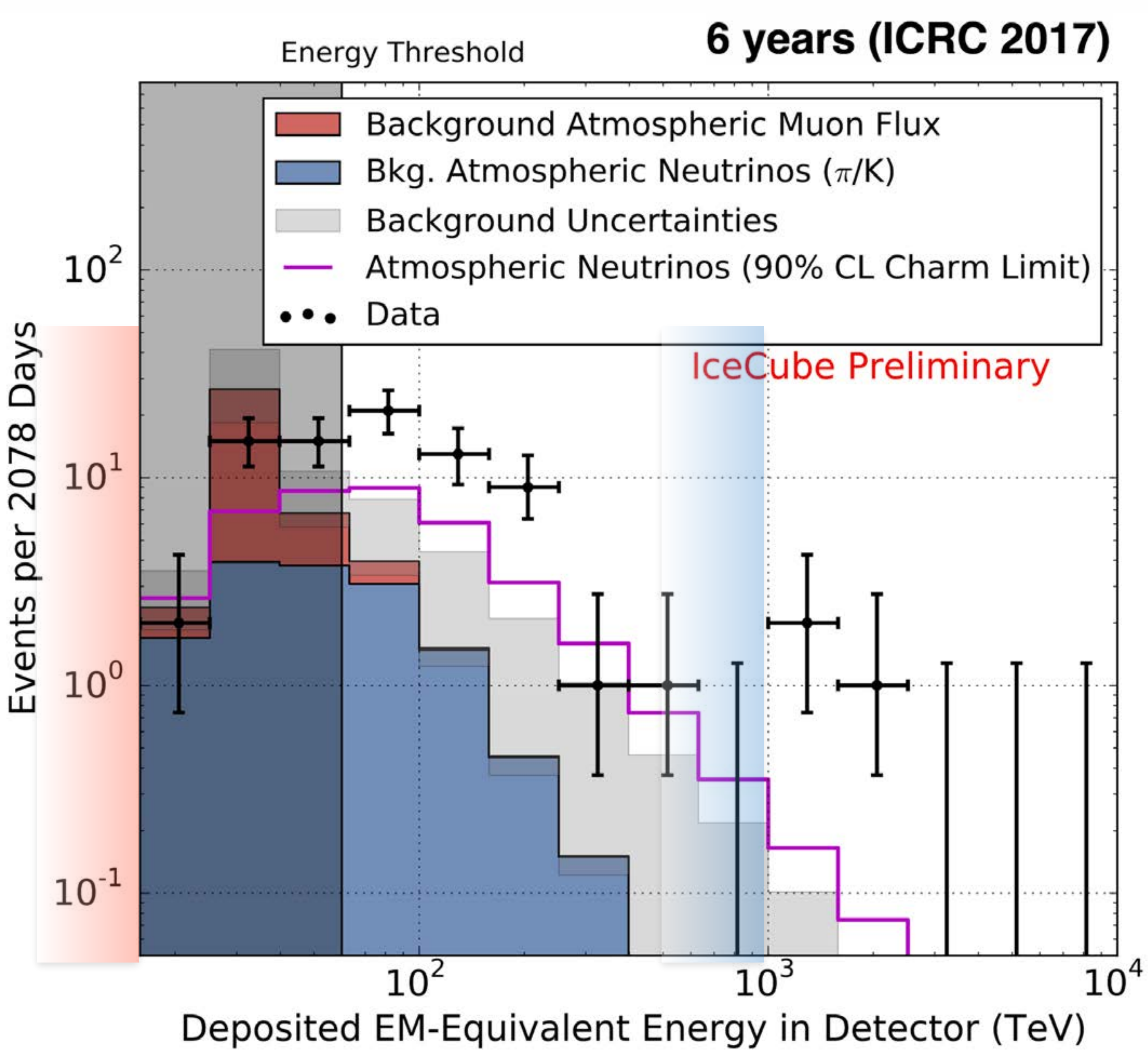
Kaons in air showers

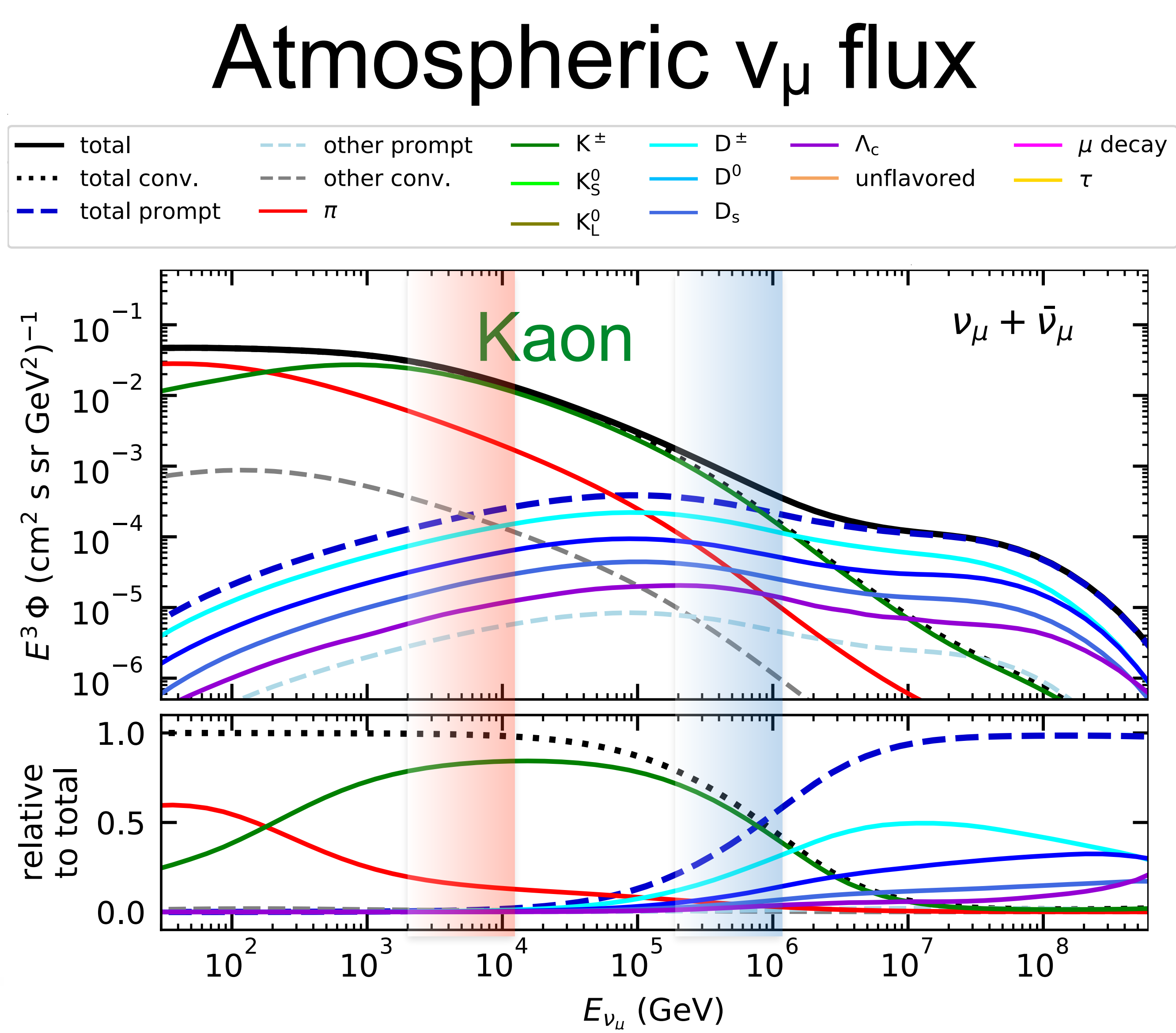


- Muon excess issue
  - If higher Kaon production in high energy
    → increase the muon number on the ground.
    A high energy π^0 decays immediately →EM component,
    A high energy K^0 collides air before its decay→ Hadronic component
  - Large K/π ratio in QGP
- Impact on atmospheric ν flux (next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

Atm. neutrinos from Kaon decays

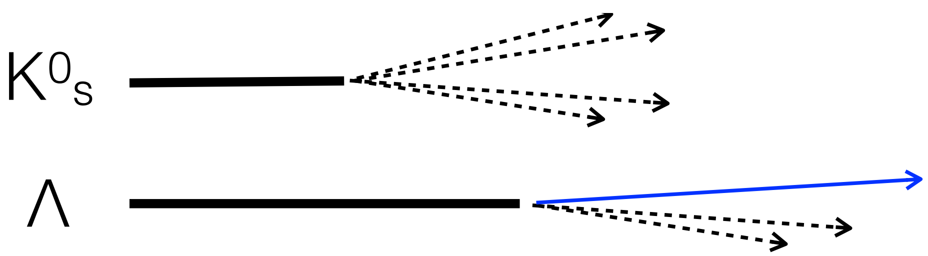
- Hot topics: Astro-neutrino detection by IceCube
- large uncertainty on background estimation of Atm. ν
- Kaons are dominant source of ν_μ in E_ν <~ 10^{15}eV





K^0_s and Λ measurement by RHICf II

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



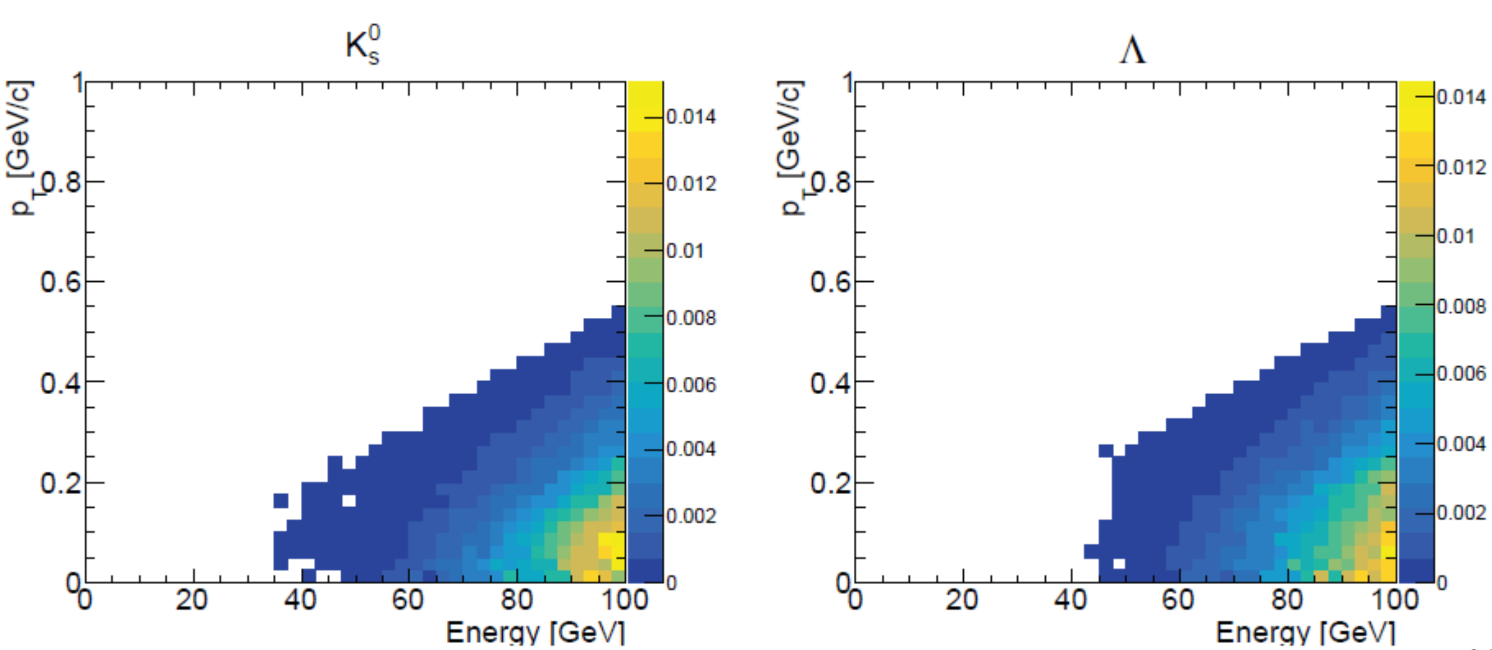
$$K^0_s \to 2\,\pi^0 \to 4\,\gamma$$

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

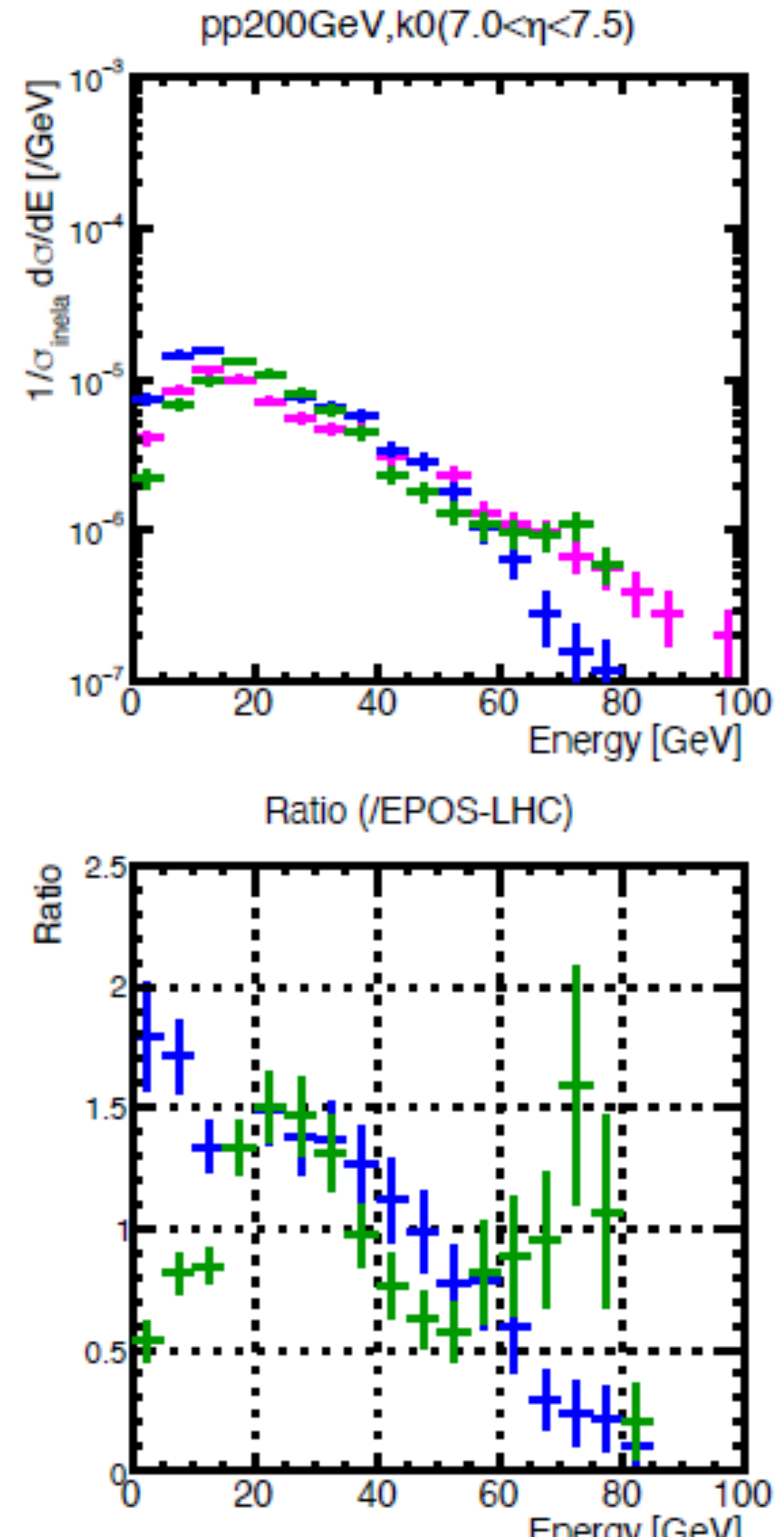
- Wide acceptance
- Fine segmentation

RHICf 👍

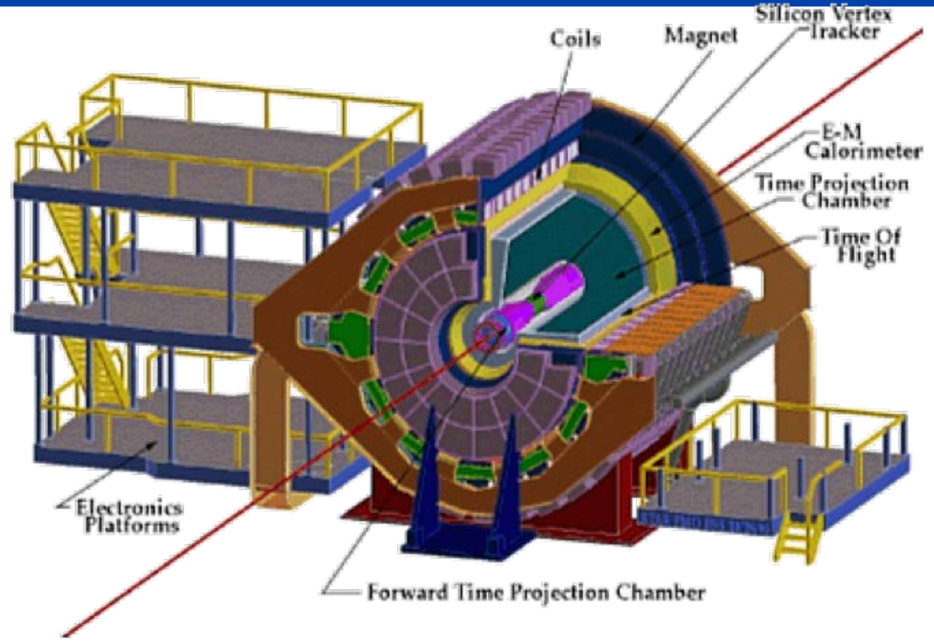
- Geometrical accettante



Model predictions

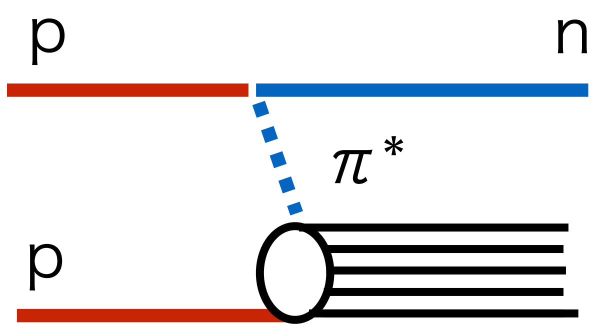


Joint analyses with STAR



+

- Various physics cases with STAR detectors
  - Diffractive collisions measurement
    - Pure diffractive sample obtained with a selection of N_{ch}=0 in the central region.
  - Probing Multi-parton interactions (MIPs)
    - Correlation analysis between forward spectra (remnant) and N_{ch} in the central region (#MPIs)
  - p-π collision measurement via one-pion-exchange process



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
  - Analyses are on-going
  - Extend physics by joint analyses with STAR
- Future RHICf II operation can address the forward particle productions of strange hadrons, K^0_s and Λ.

Backup

Photon Energy Flow

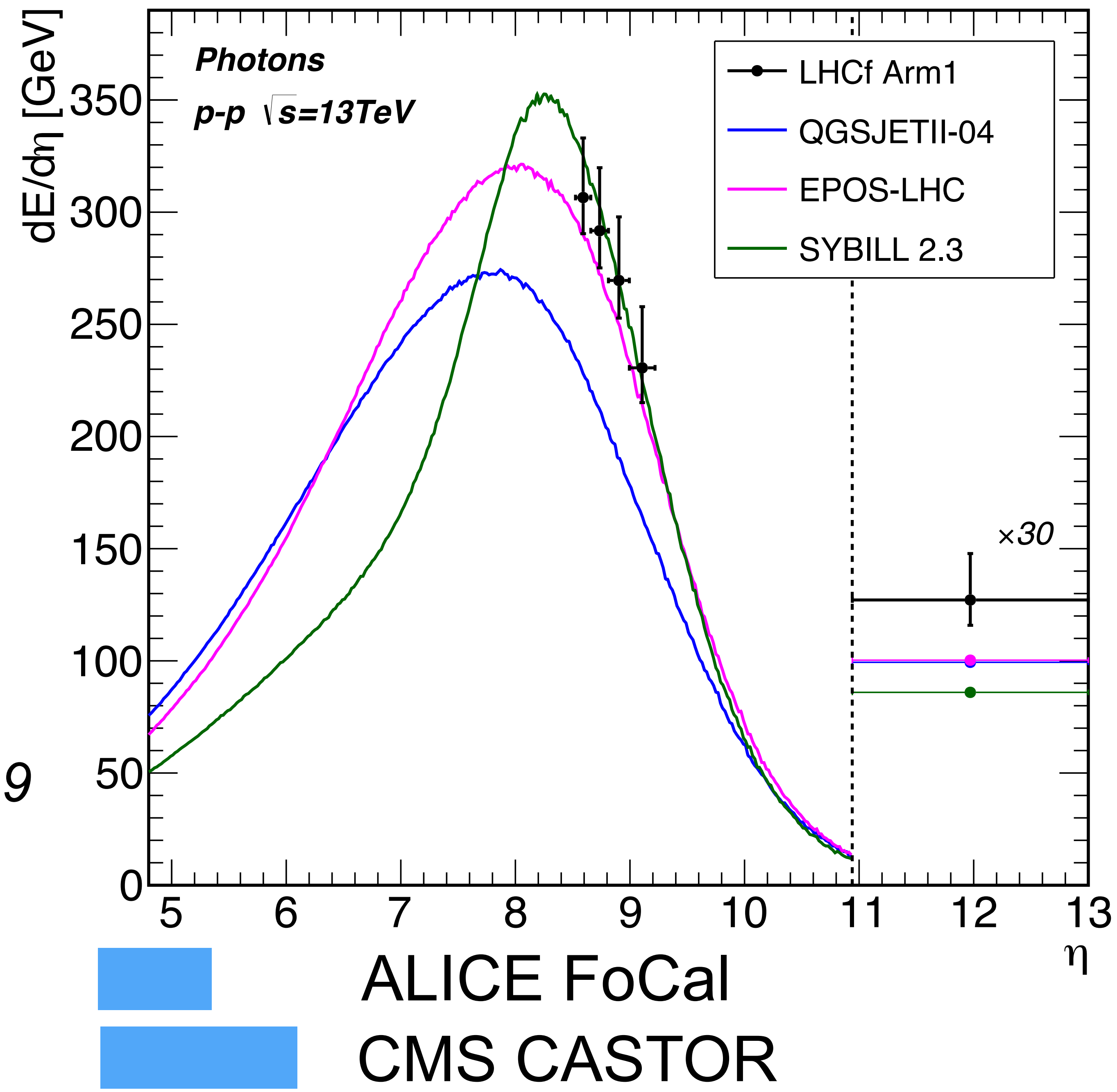
<u>*Energy Flow Calculation:*</u>

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

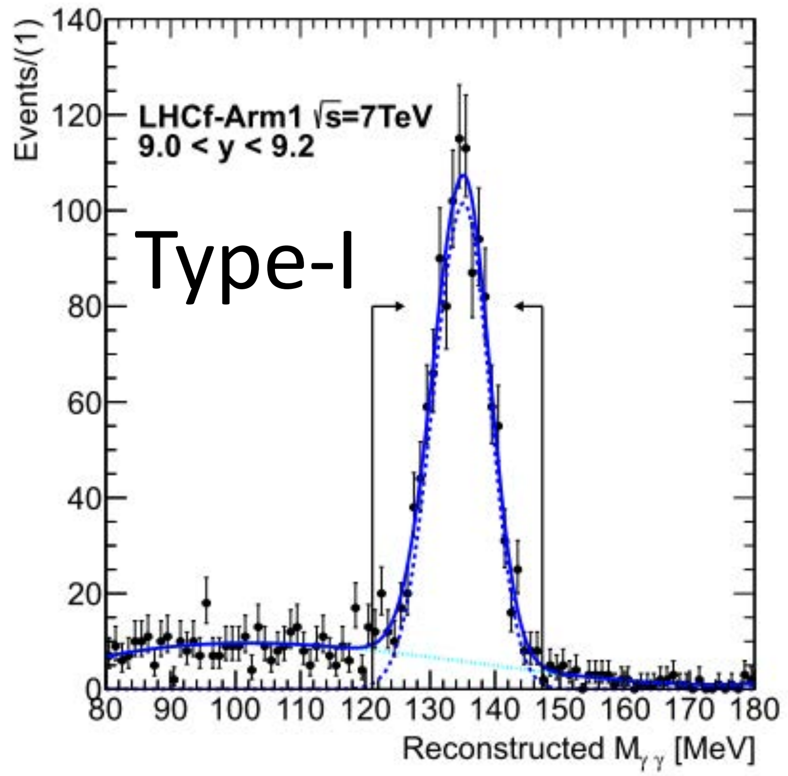
F(Ej) : Measured differential cross-section
Δη : The pseudo-rapidity range
C_{thr} : Correction factor for the threshold 200 GeV→ 0 GeV.

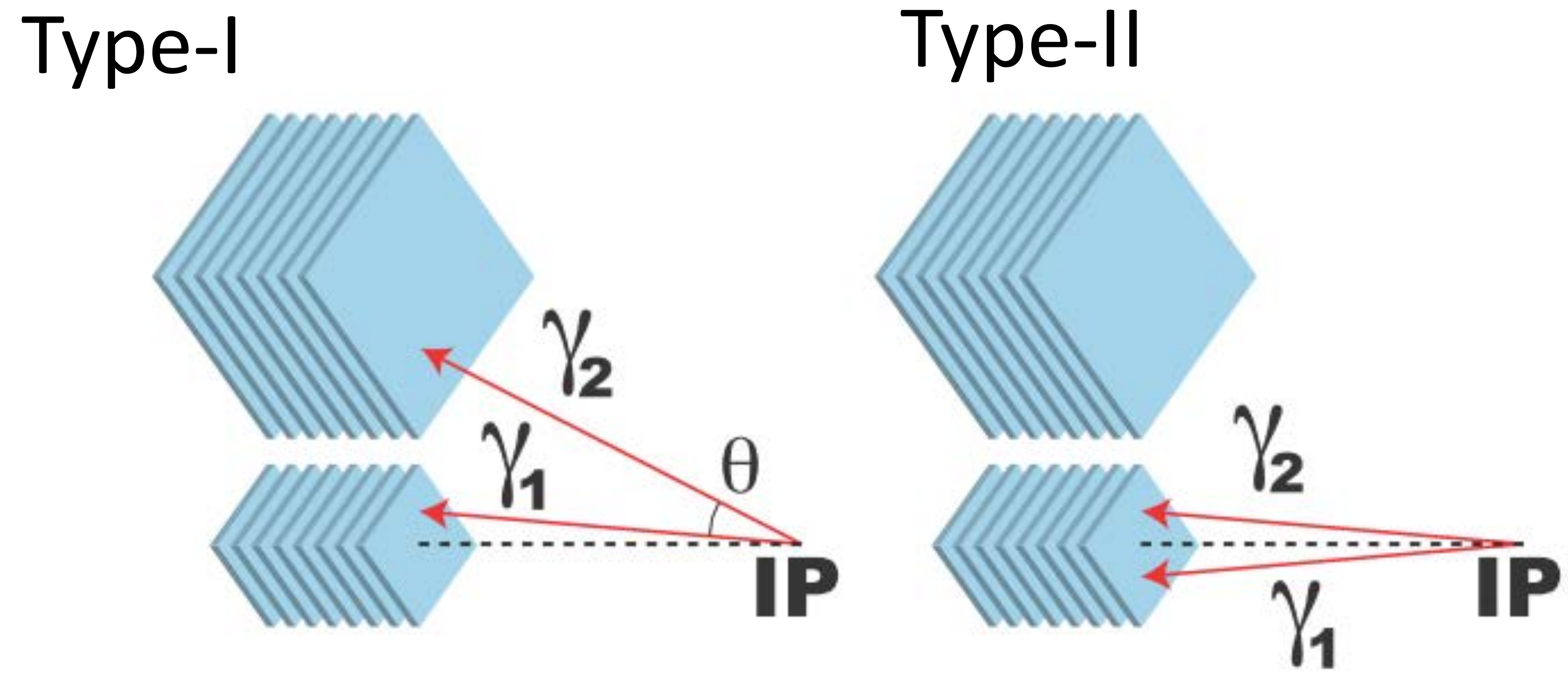
Ref: Y. Makino CERN-THESIS-2017-049

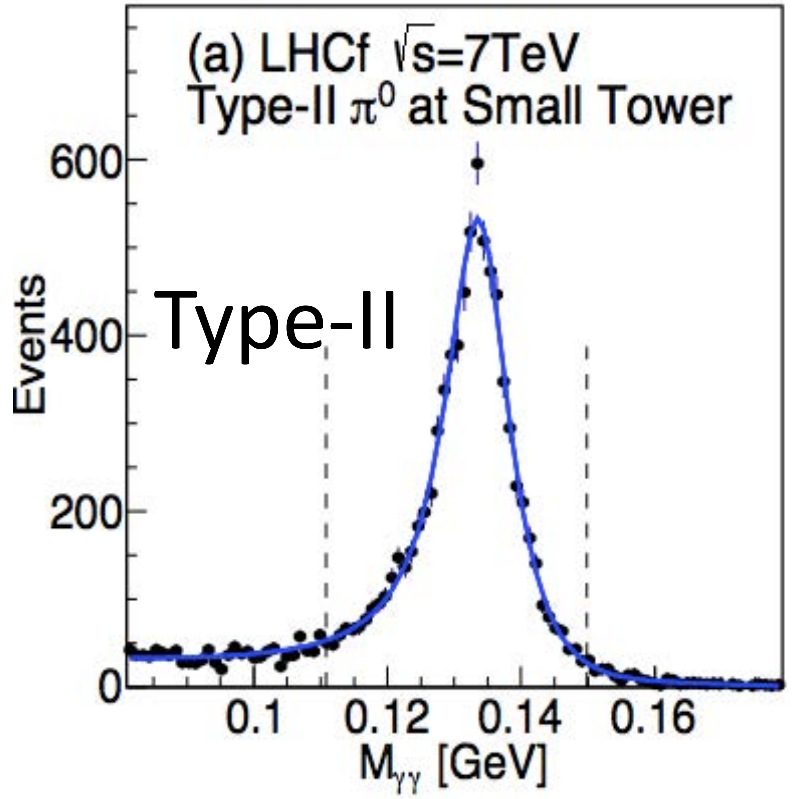
EPOS-LHC, SIBYLL2.3
Good agreement
QGSJET II-04
~ 30% lower than data

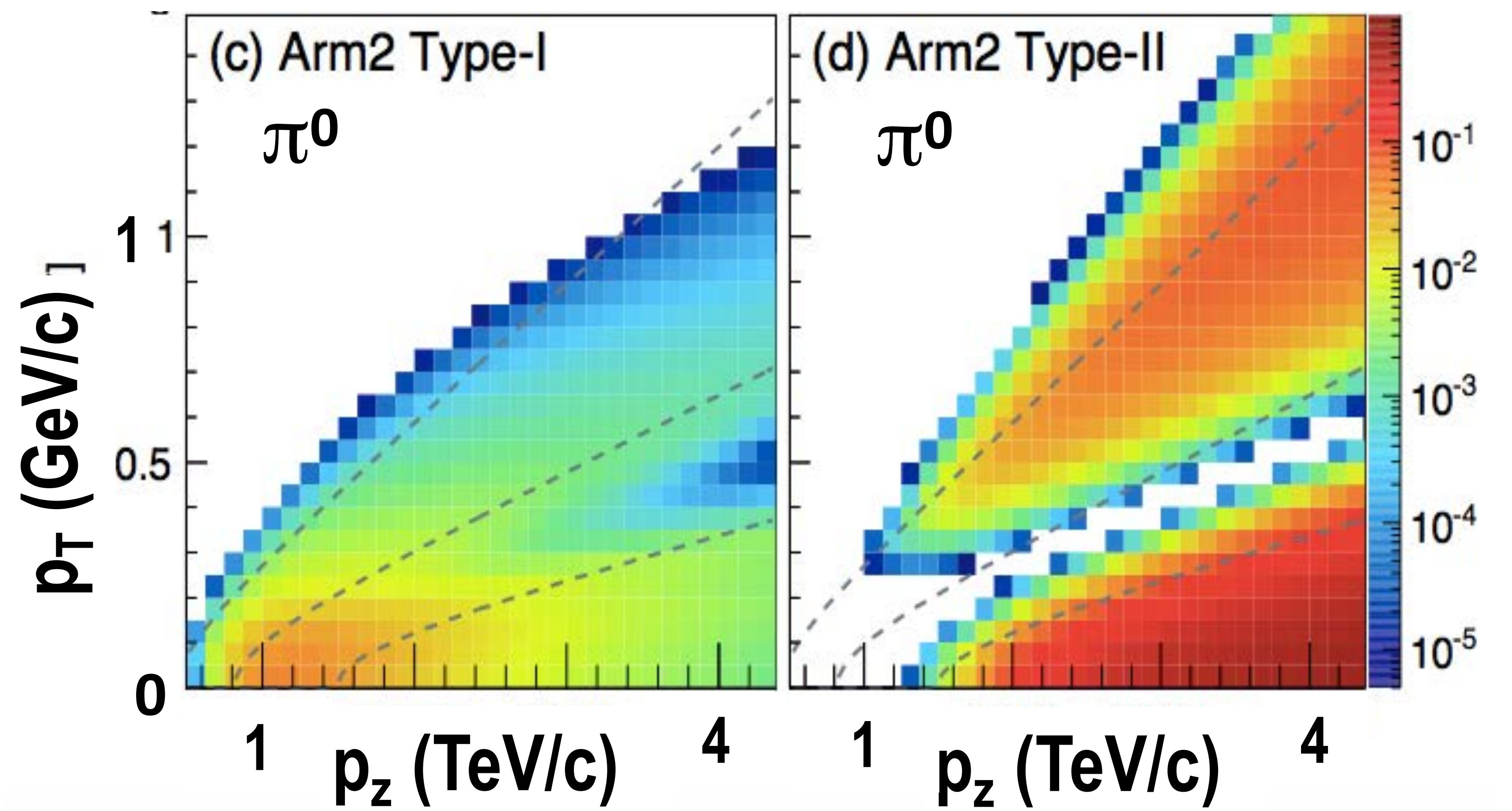


π^0 measurement









π^0 p_T spectra at pp,7TeV

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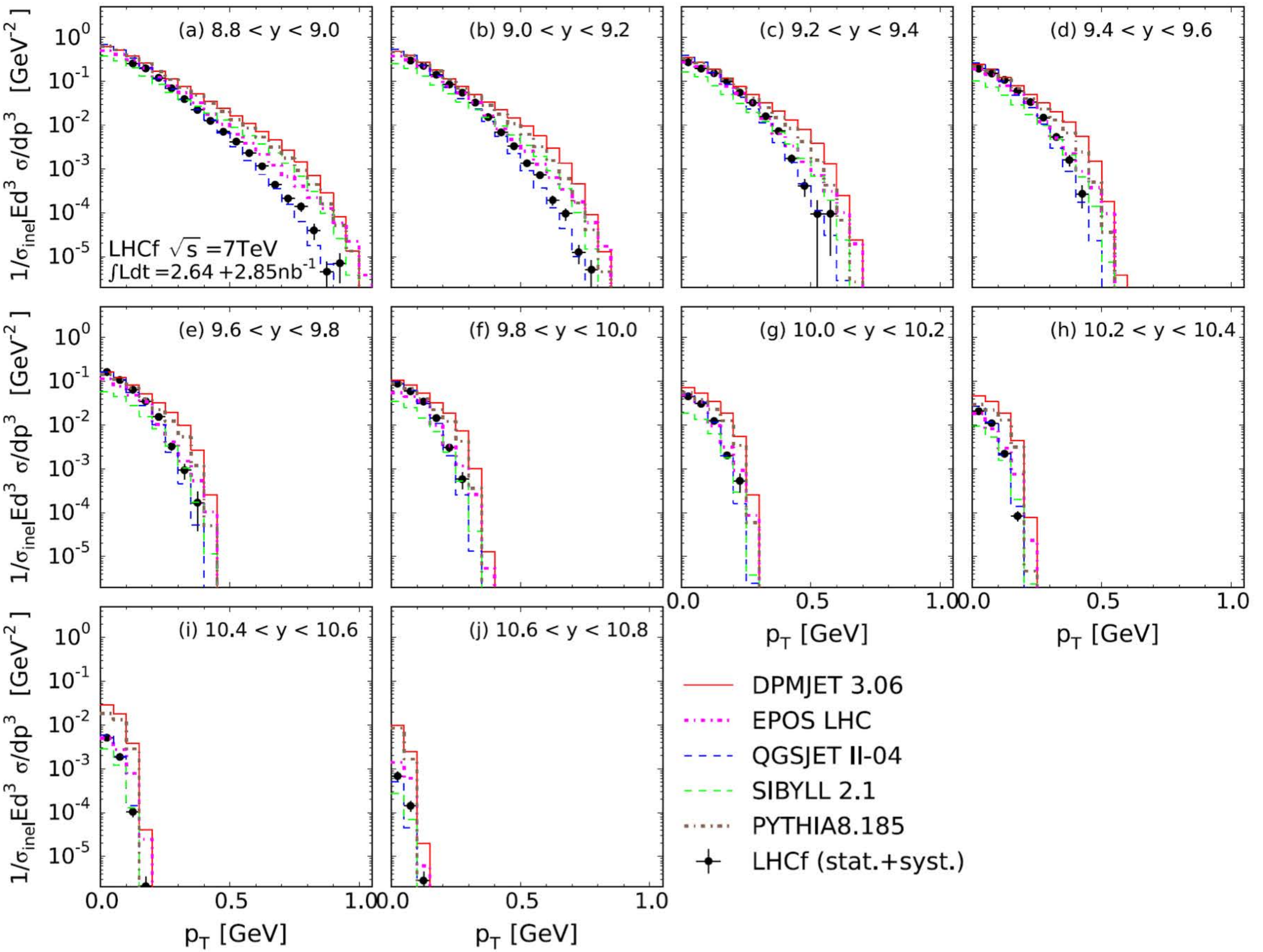


Neutron, p-p $\sqrt{s}$=13TeV

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, $\sqrt{s}$=7TeV

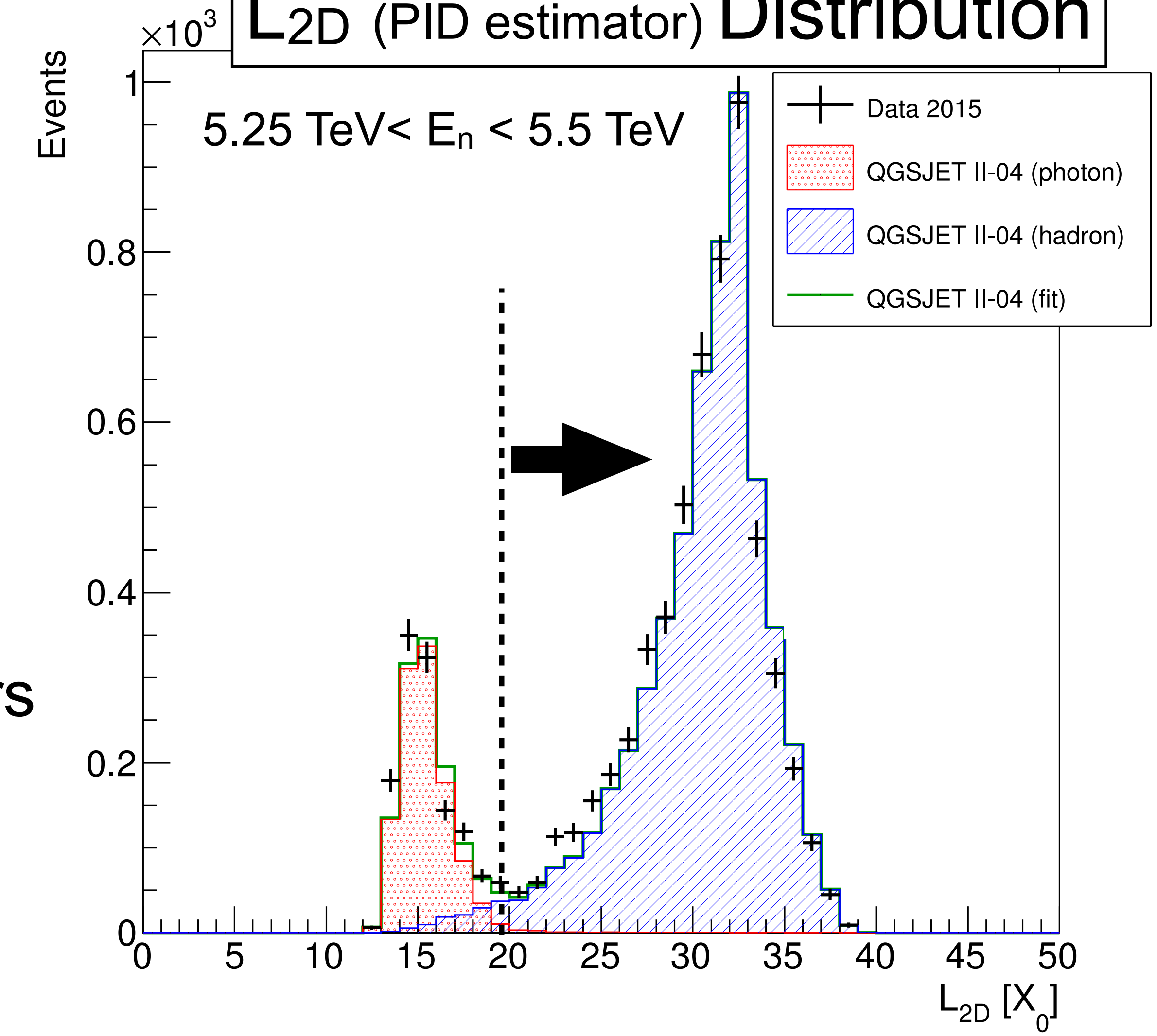
Data

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

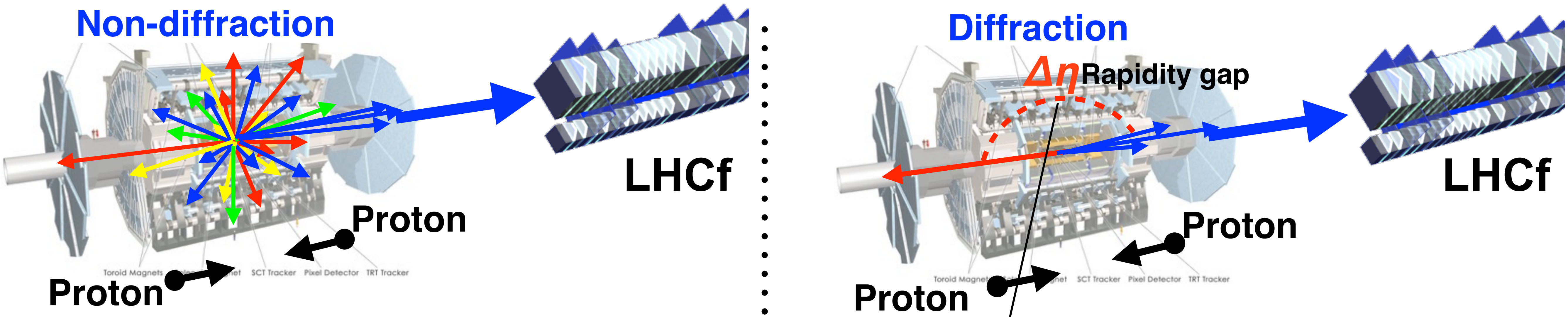
Analysis

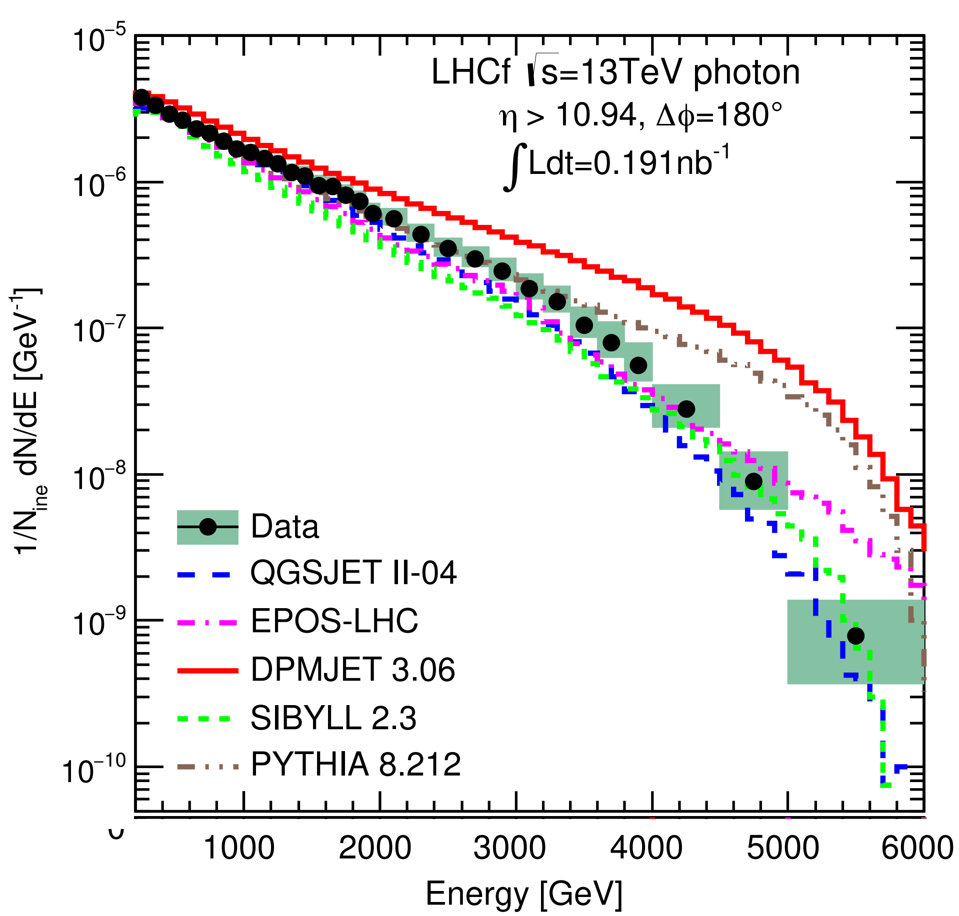
- Particle Identification
  EM shower → develop in shallow layers
  Hadronic showers → develop in deep layers
- Energy resolution of 40%
- Contamination of Δ^0, K^0

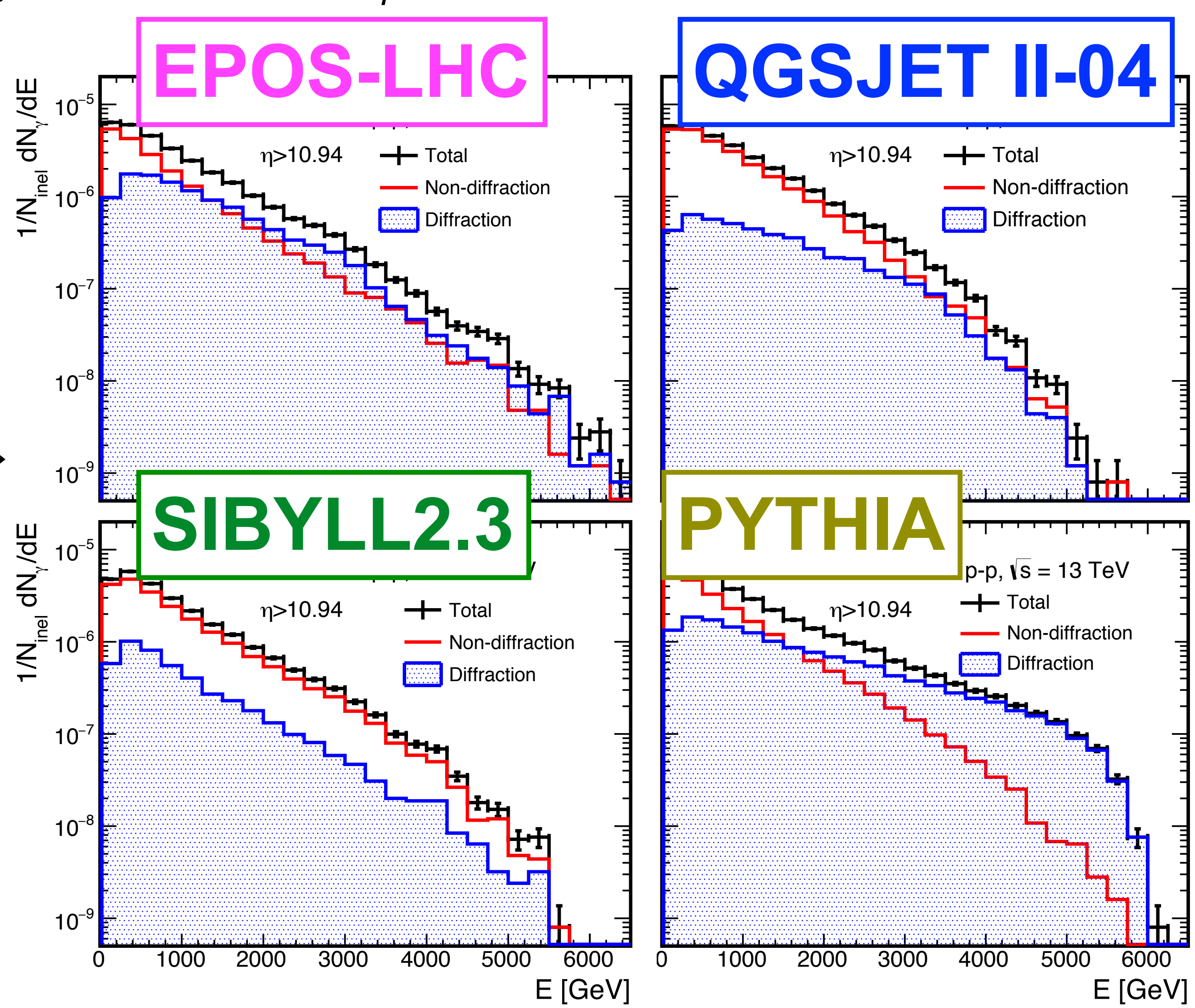
L_{2D} (PID estimator) Distribution



Joint Analysis with ATLAS
- Selection of Diffractive interactions -







Poster by Q.Zhou; CRD131

π^0 p_Z (~E) spectra at p+p,7TeV

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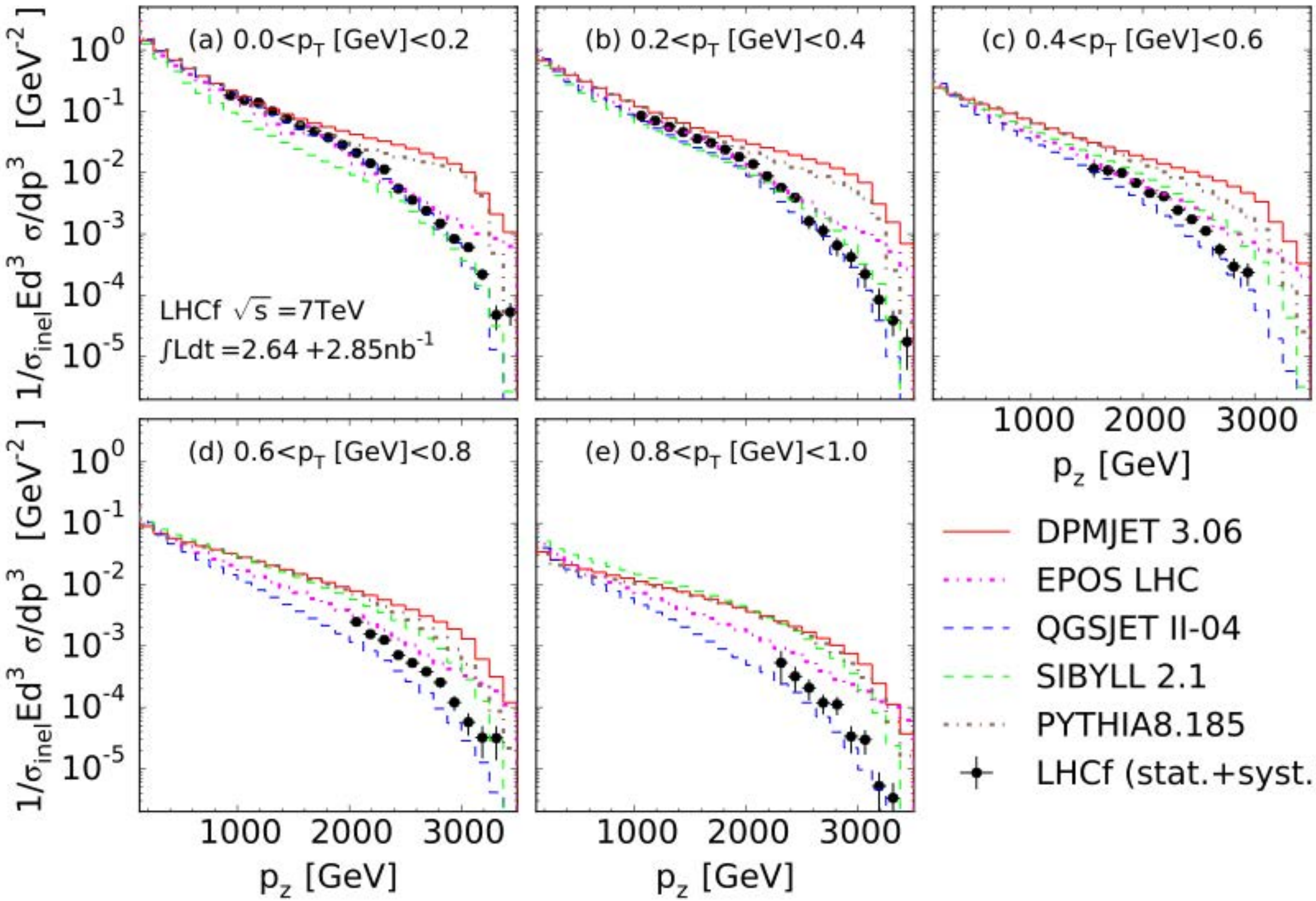
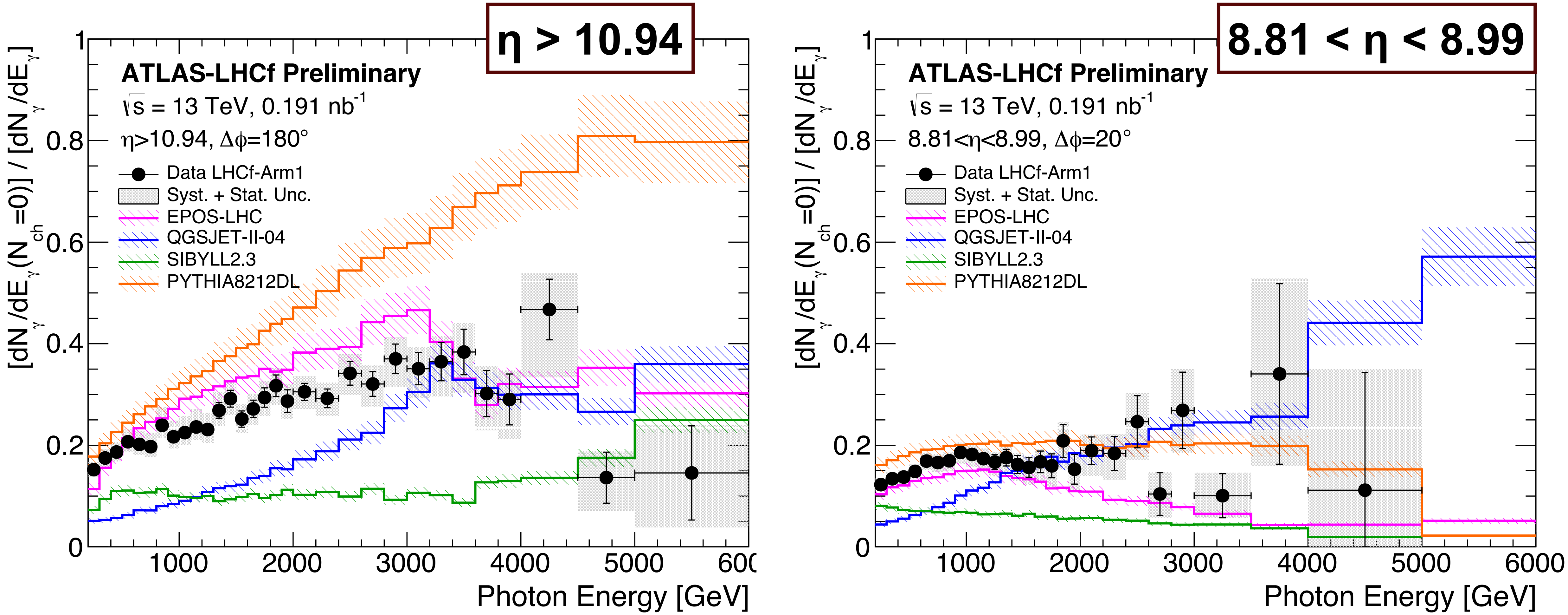


DPMJET and Pythia overestimate over all E-p_T range

Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at √s = 13 TeV

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

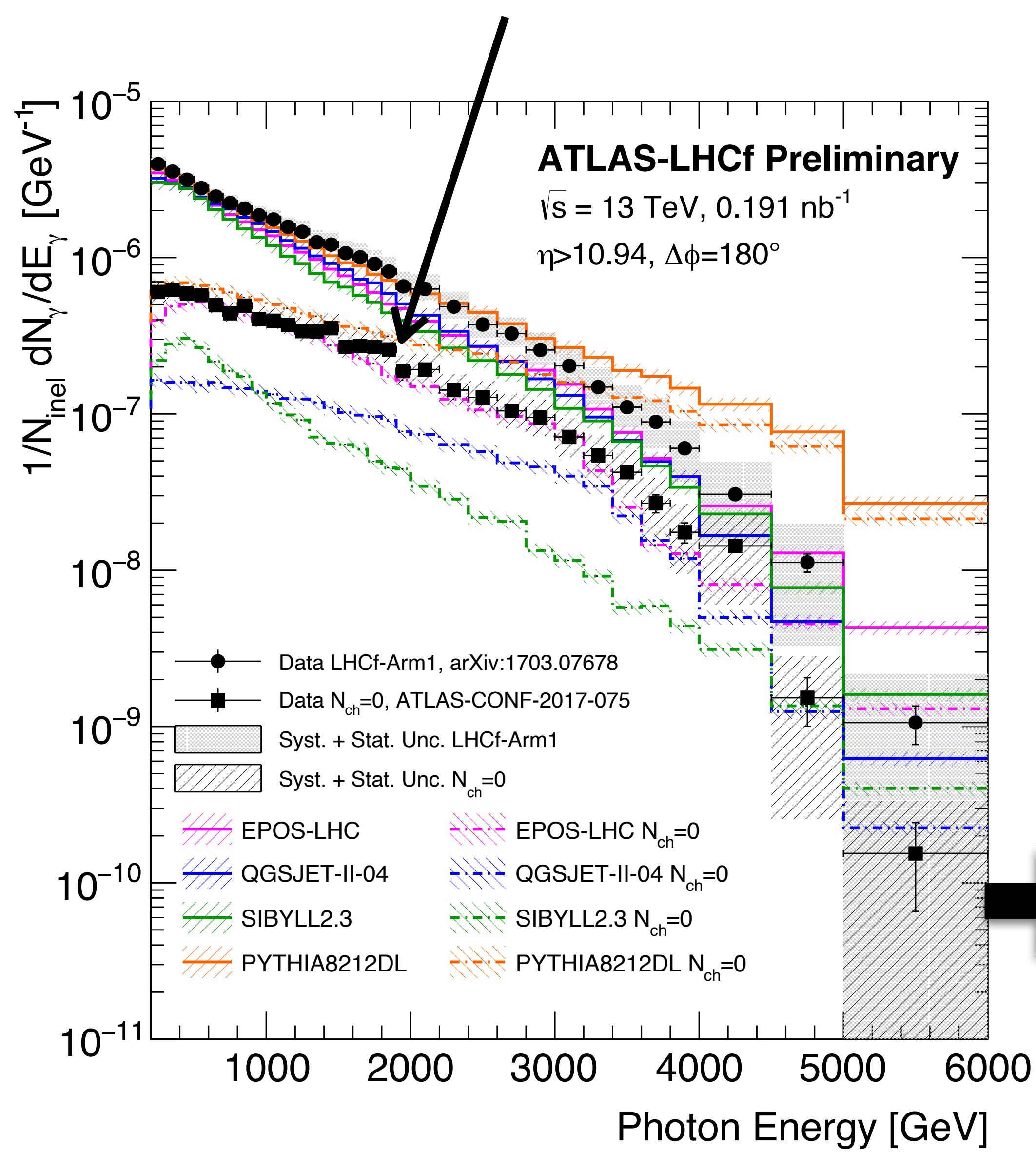
ATLAS-CONF-2017-075



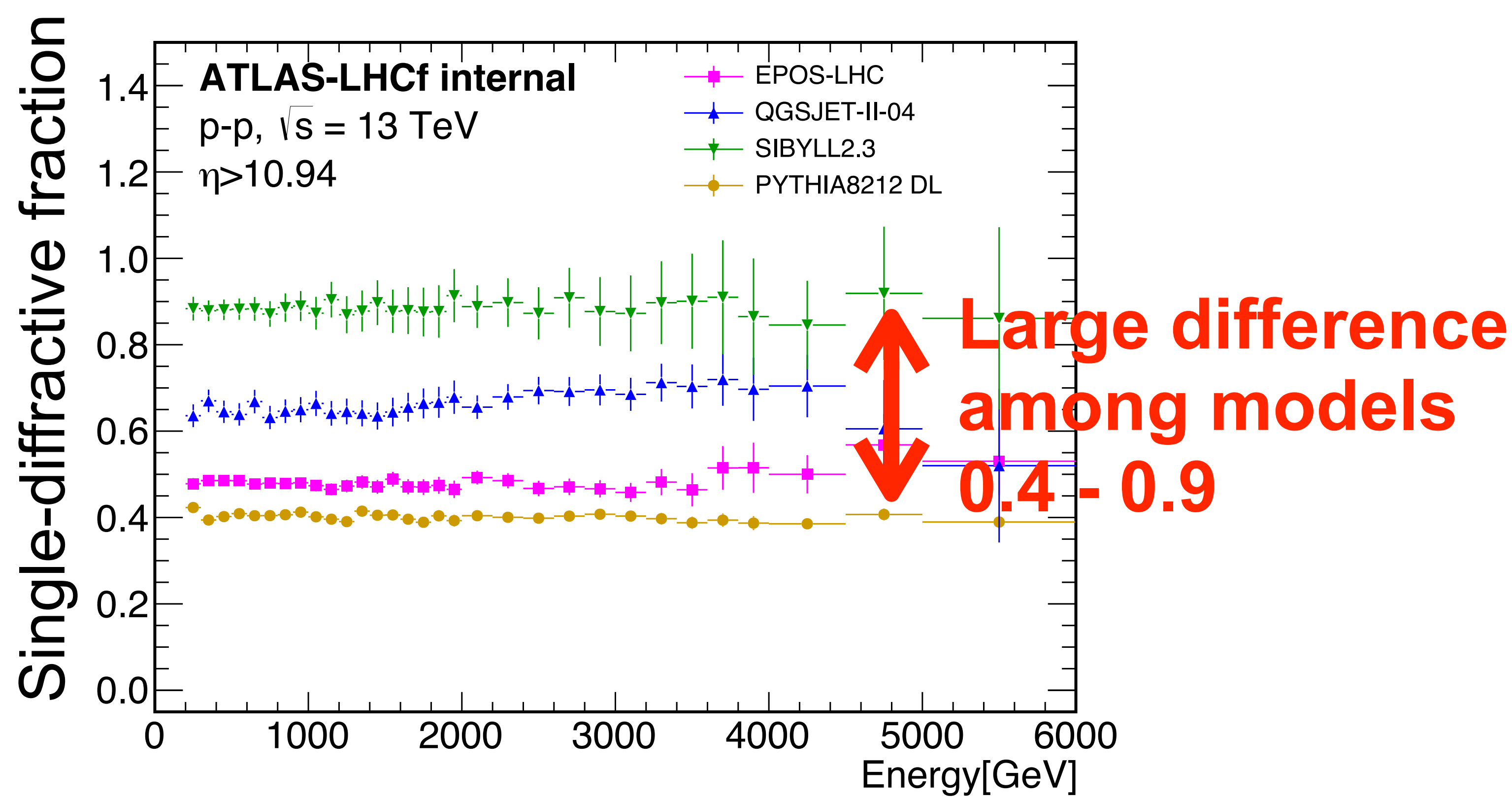
- At η>10.94, the ratio of data increased from 0.15 to 0.4. with increasing of the photon energy up to 4TeV.
- PYTHIA8212DL predicts higher fraction at higher energies.
- SIBYLL2.3 show small fraction compare with data at η>10.94.
- At 8.81 < η < 8.99, the ratio of data keep almost constant as 0.17.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



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