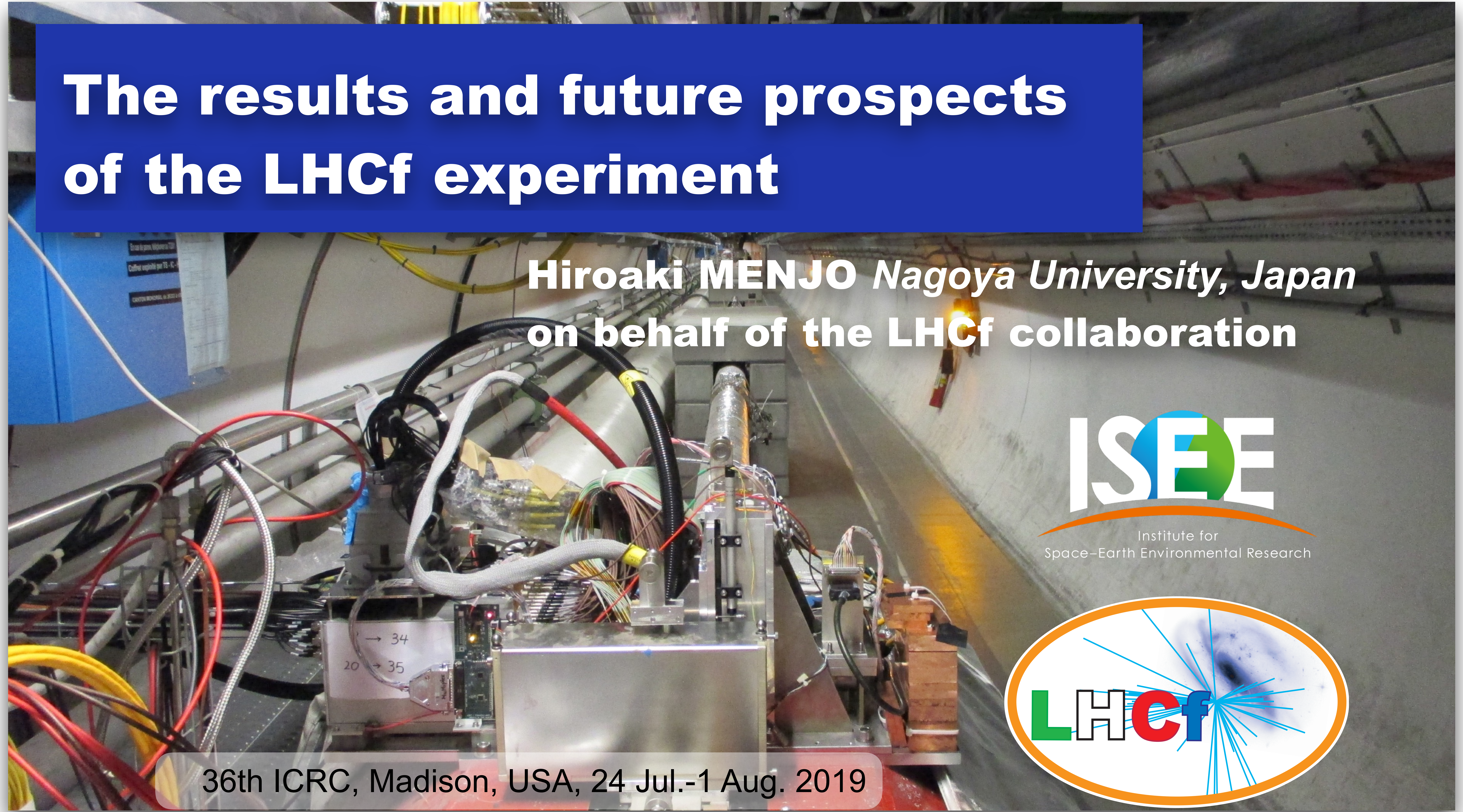
The results and future prospects of the LHCf experiment

Hiroaki MENJO ***Nagoya University, Japan***
on behalf of the LHCf collaboration

Institute for Space–Earth Environmental Research



36th ICRC, Madison, USA, 24 Jul.-1 Aug. 2019

The LHCf collaboration

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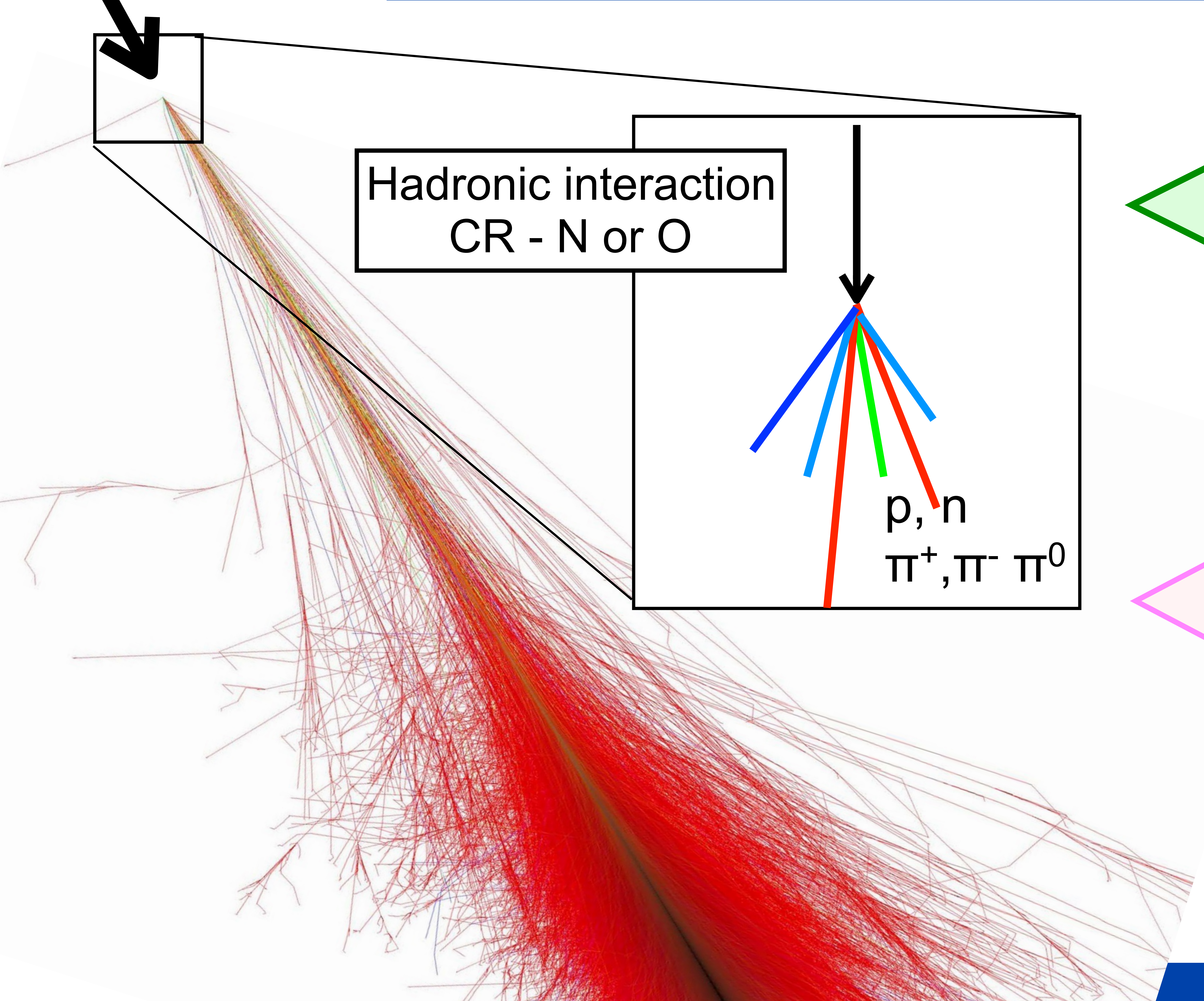
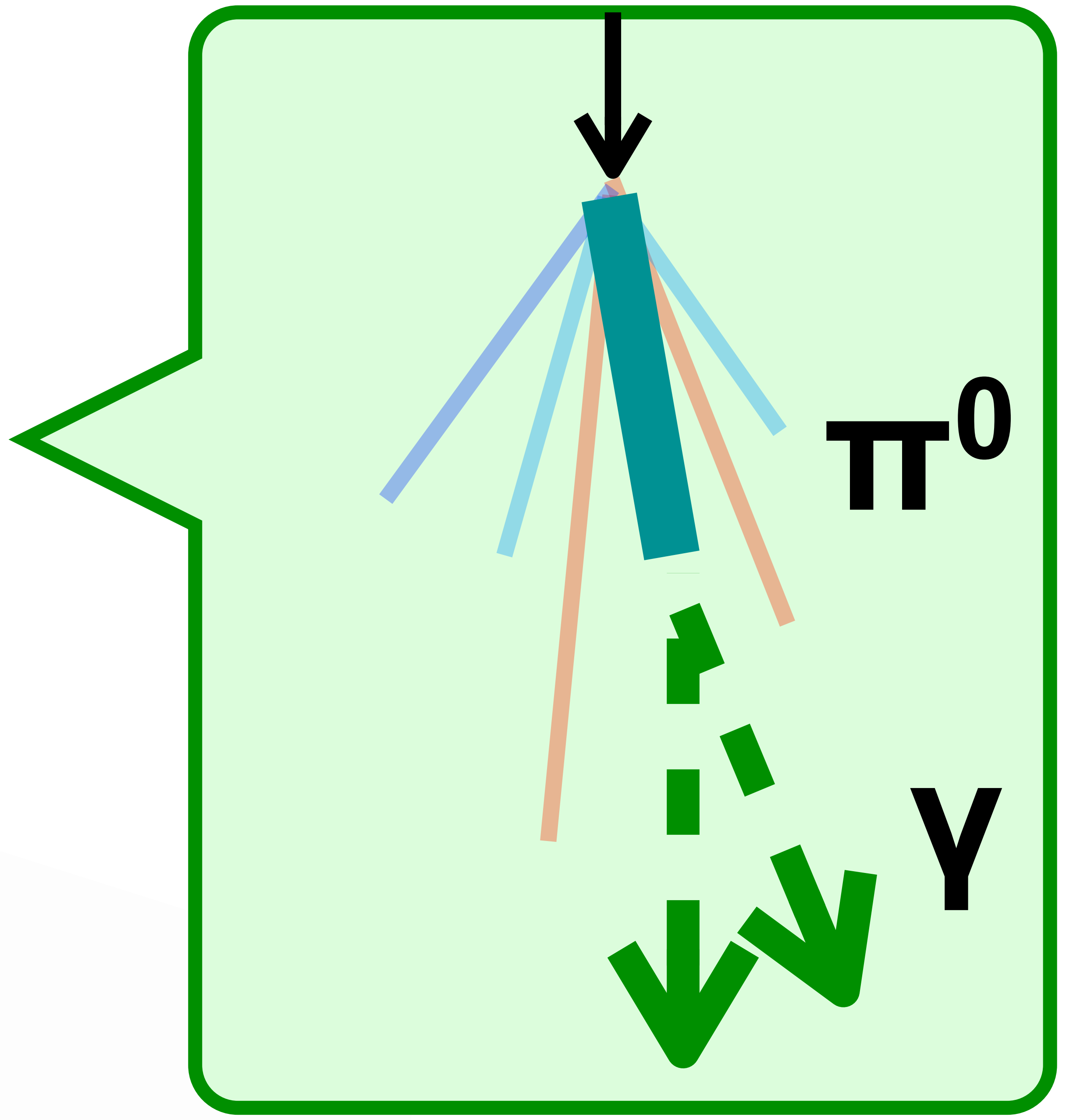
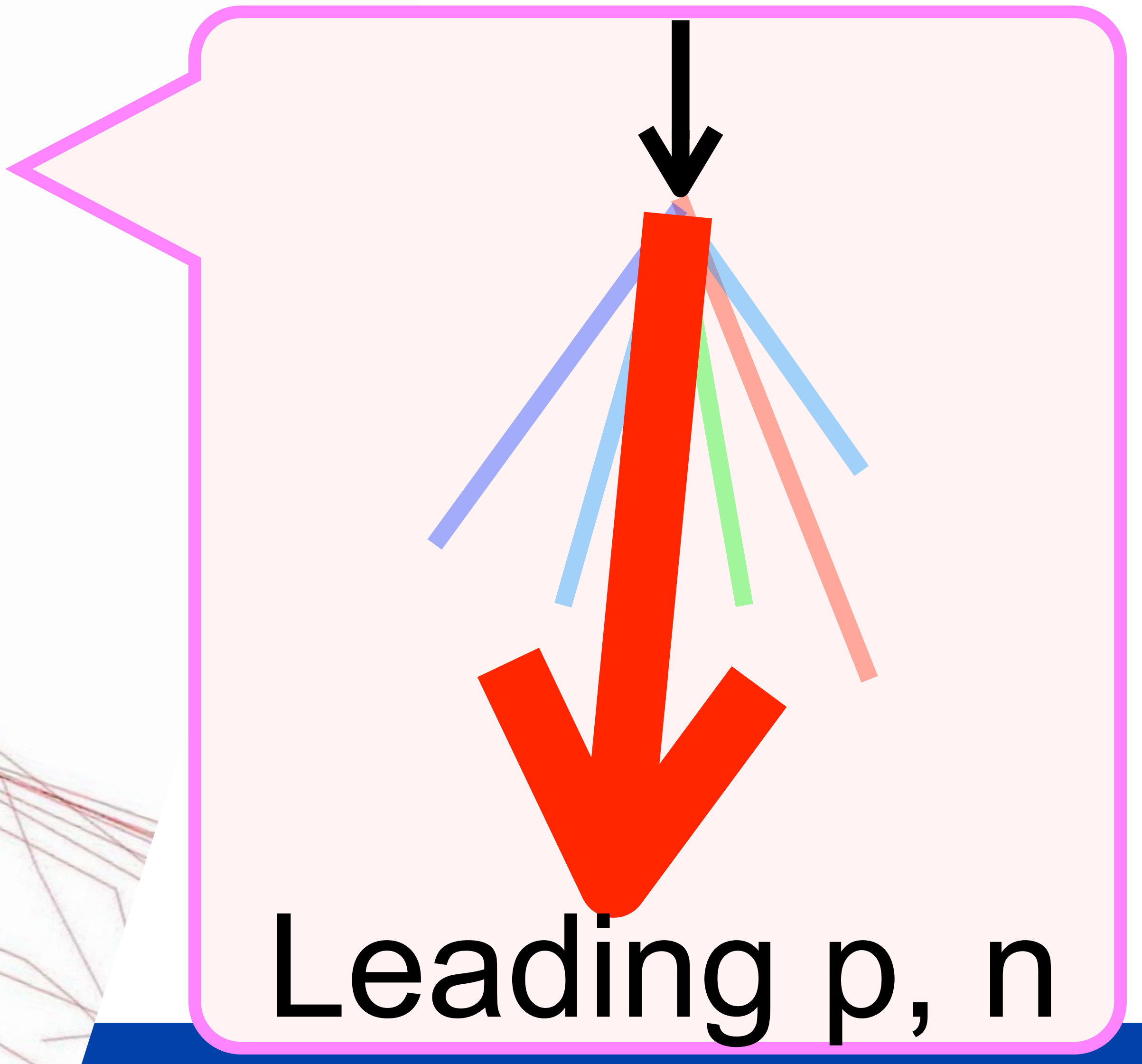
Air shower and hadronic interaction





Neutral pions

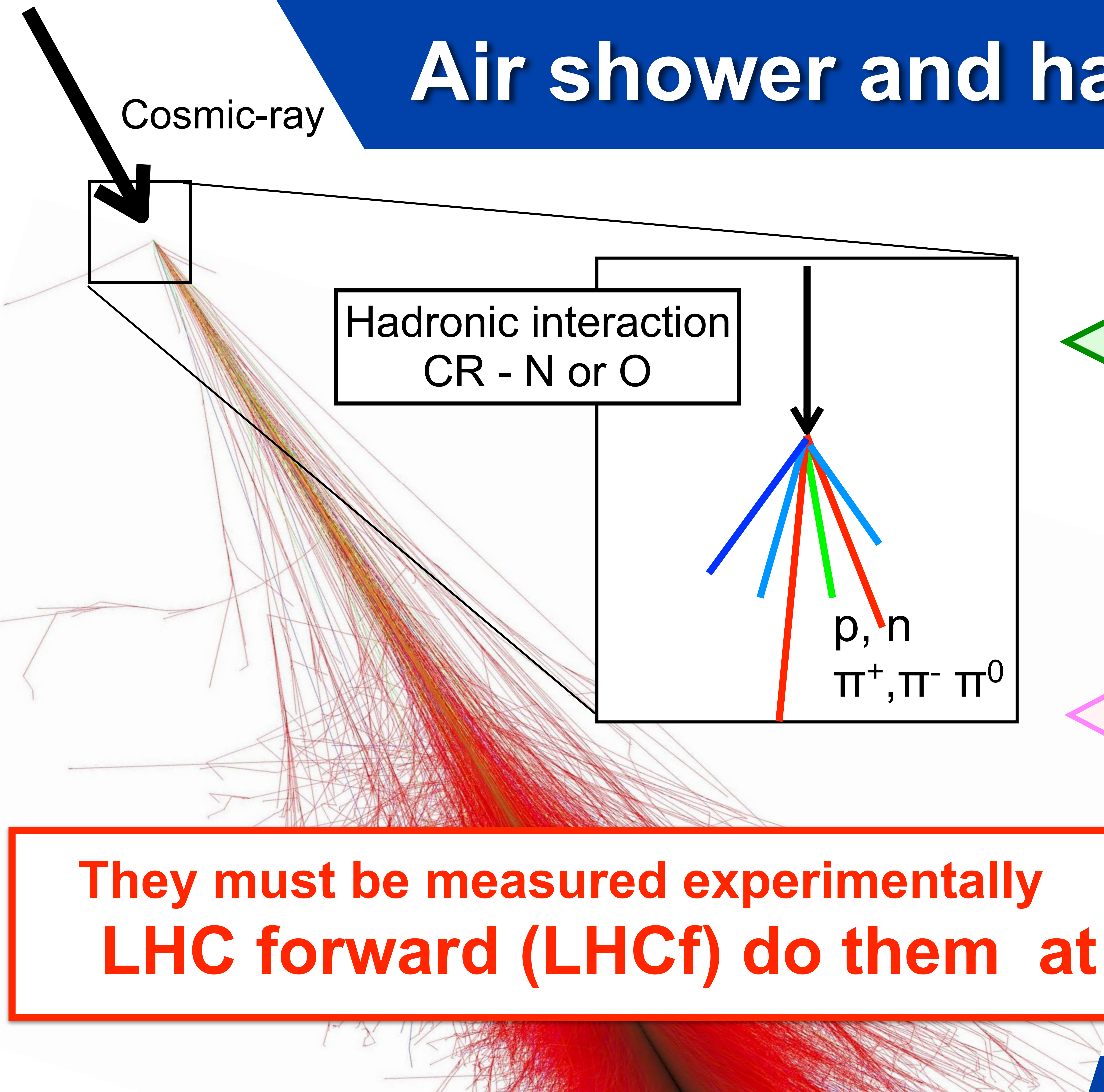
- $\pi^0 \rightarrow 2\gamma$
- Induce electromagnetic showers

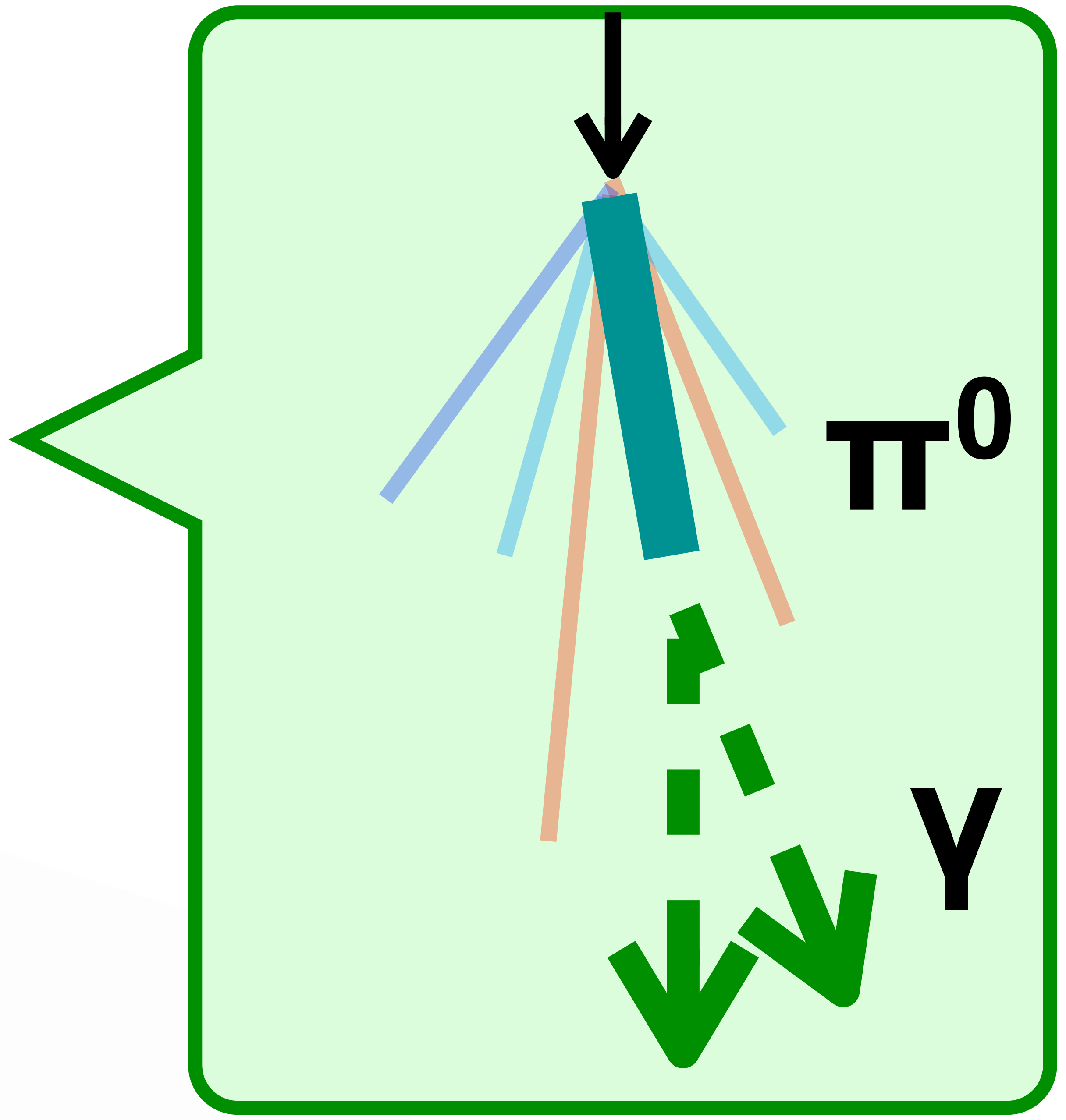


Leading baryons

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

Air shower and hadronic interaction





Neutral pions

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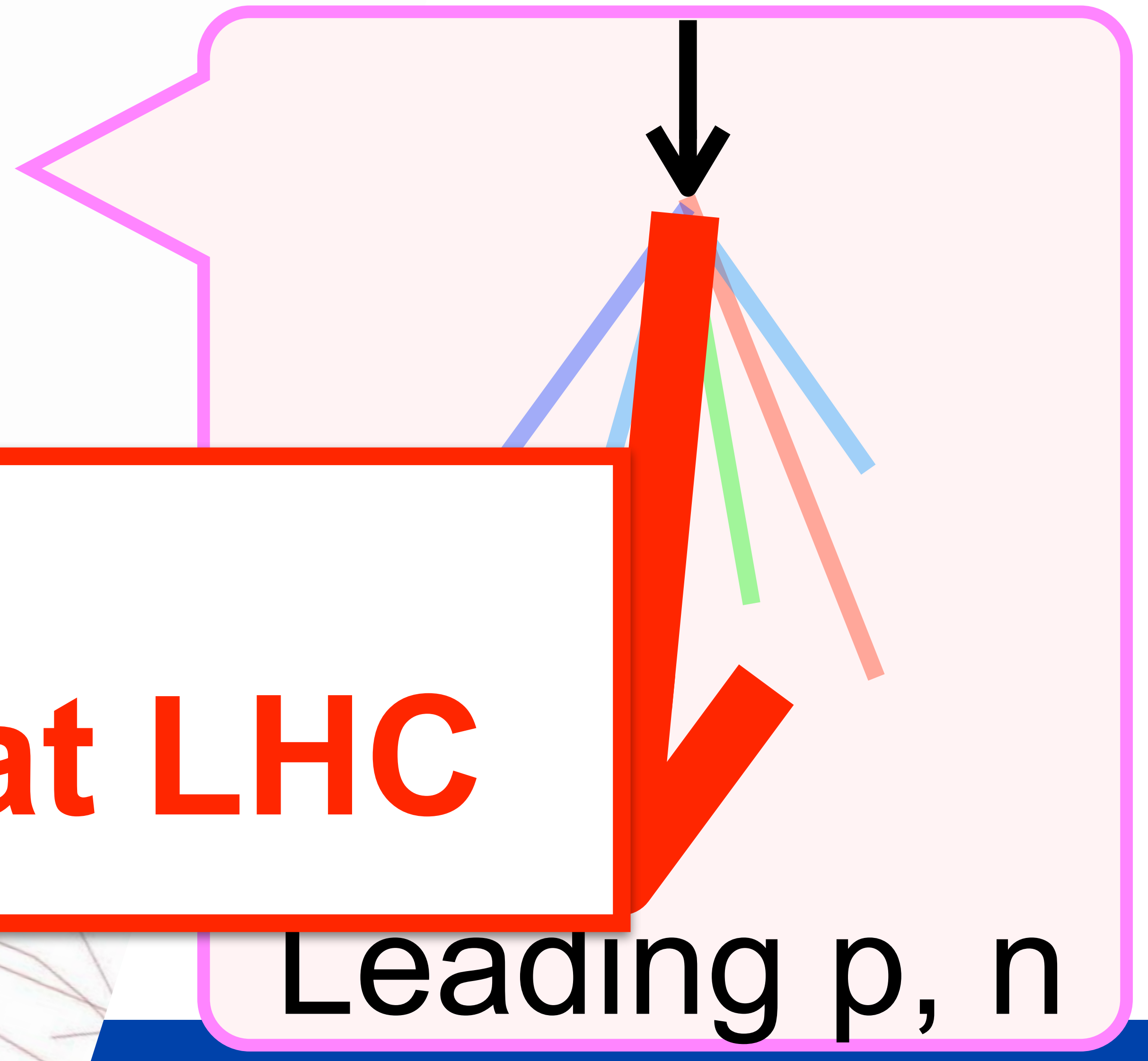


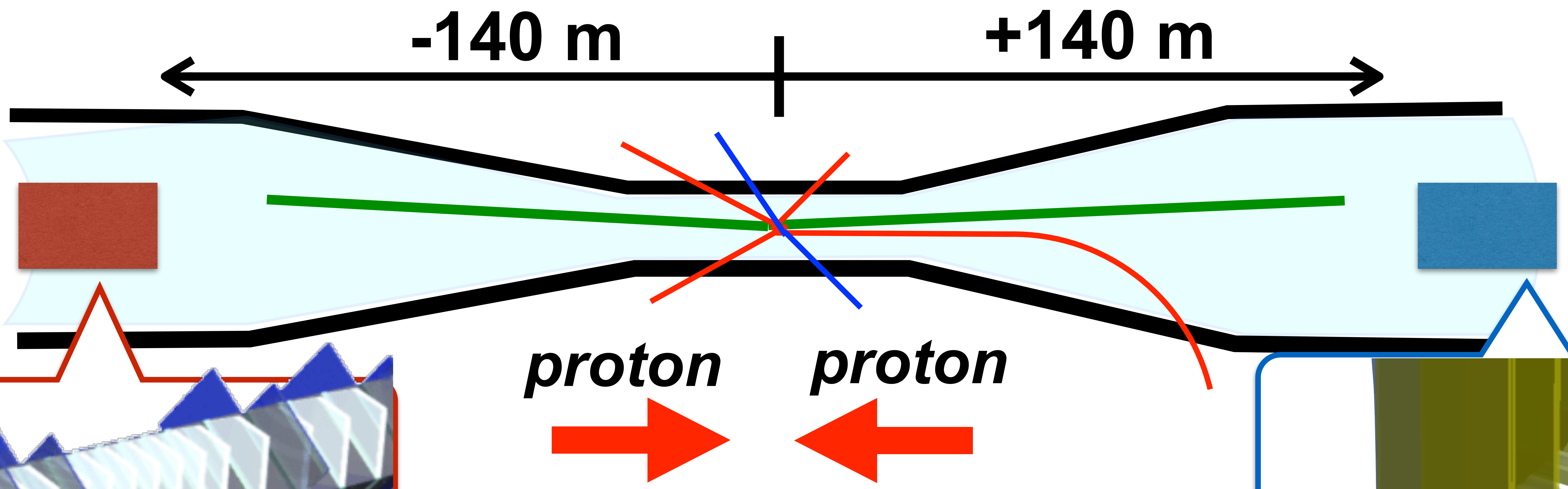
Leading baryons

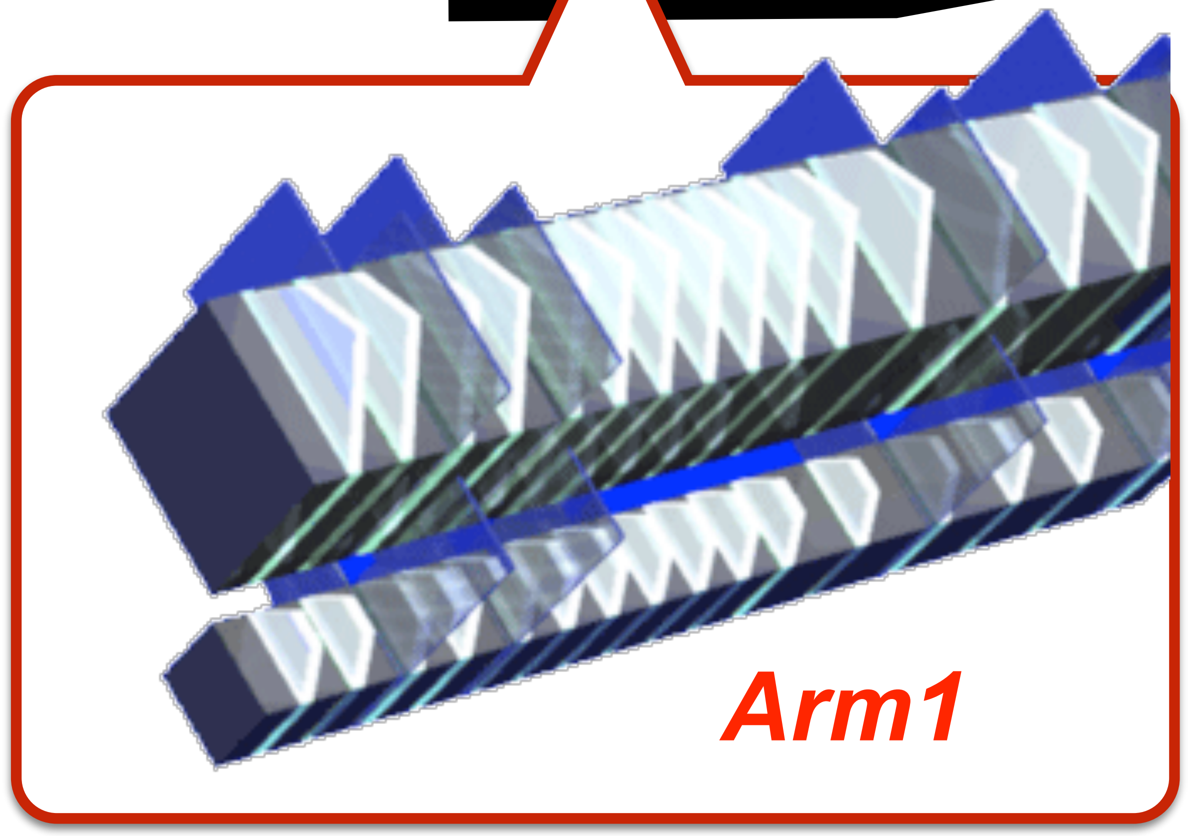
- bring the energy to next collisions
- Inelasticity: fraction of energy used for particle productions
  $k = 1 - E_{leading}/E_{CR}$

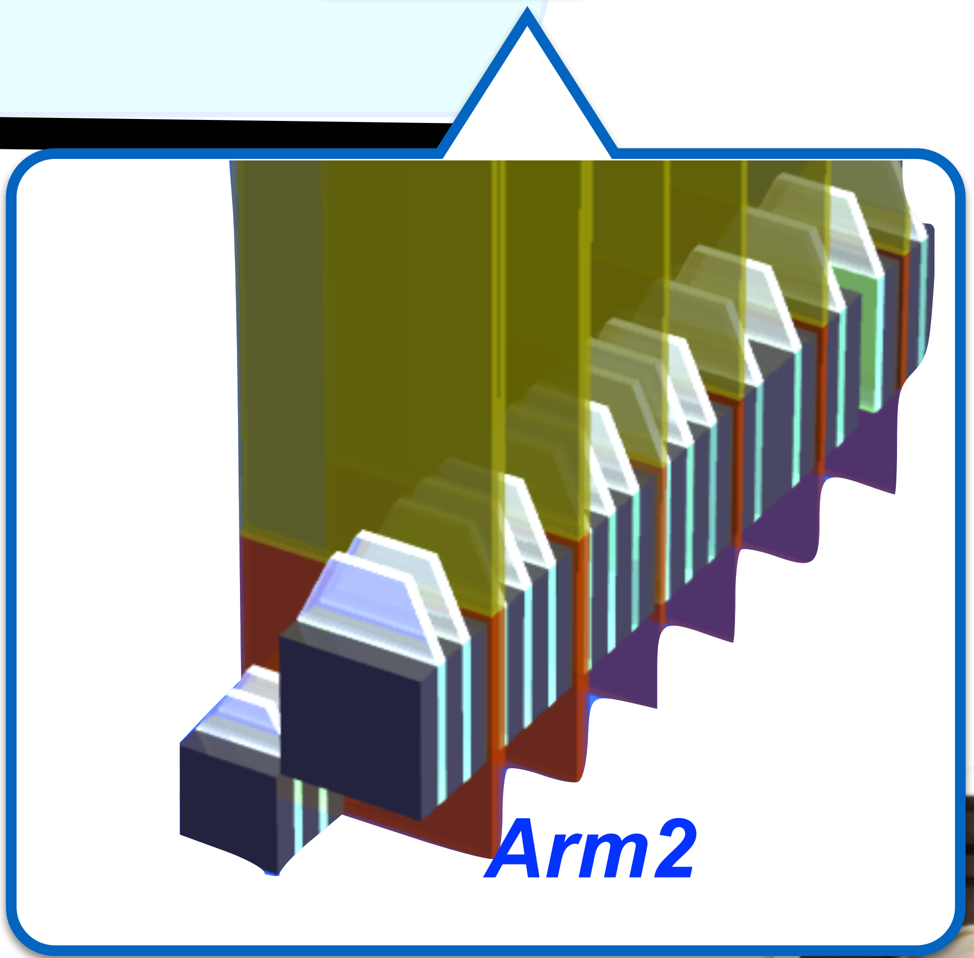
They must be measured experimentally

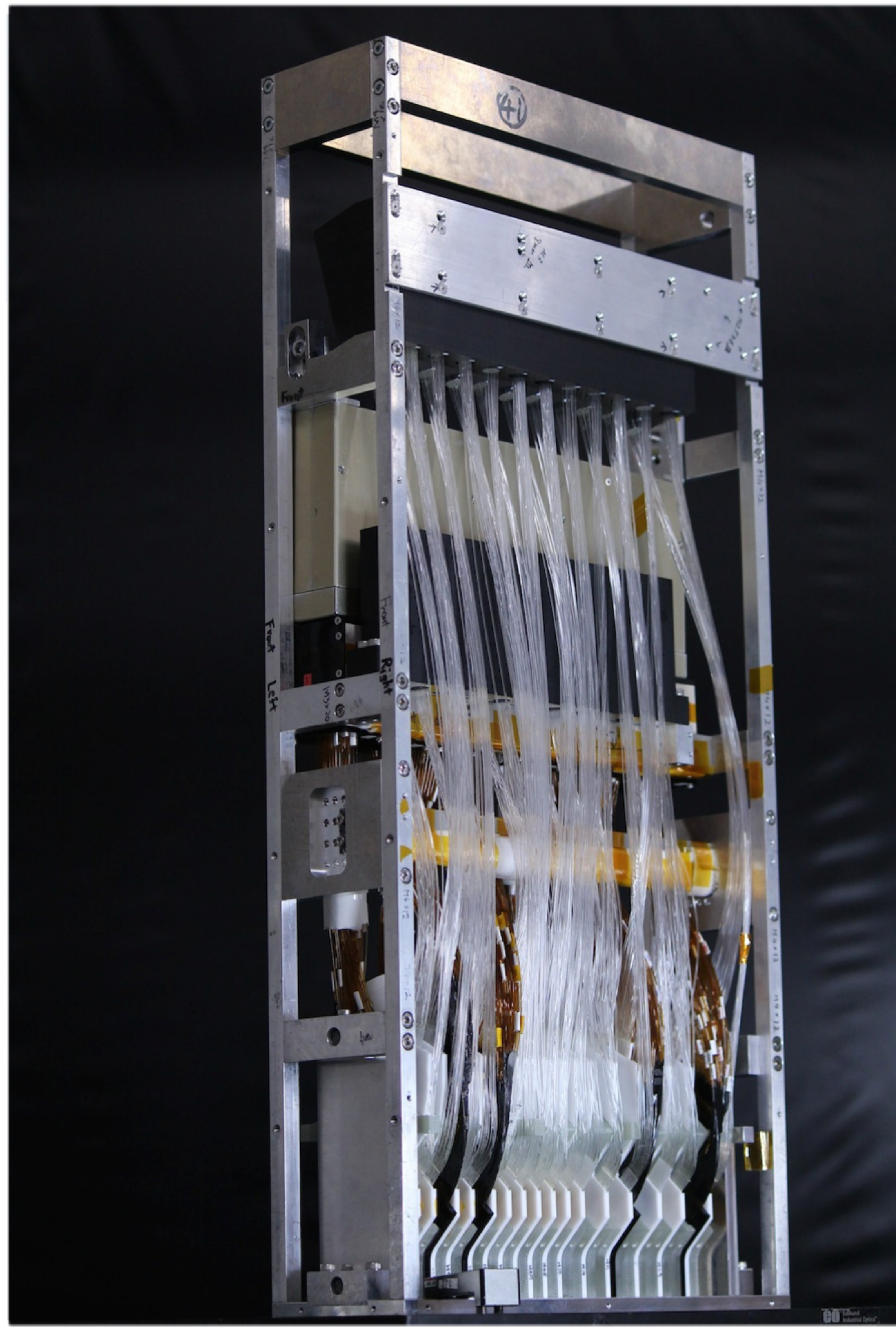
LHC forward (LHCf) do them at LHC

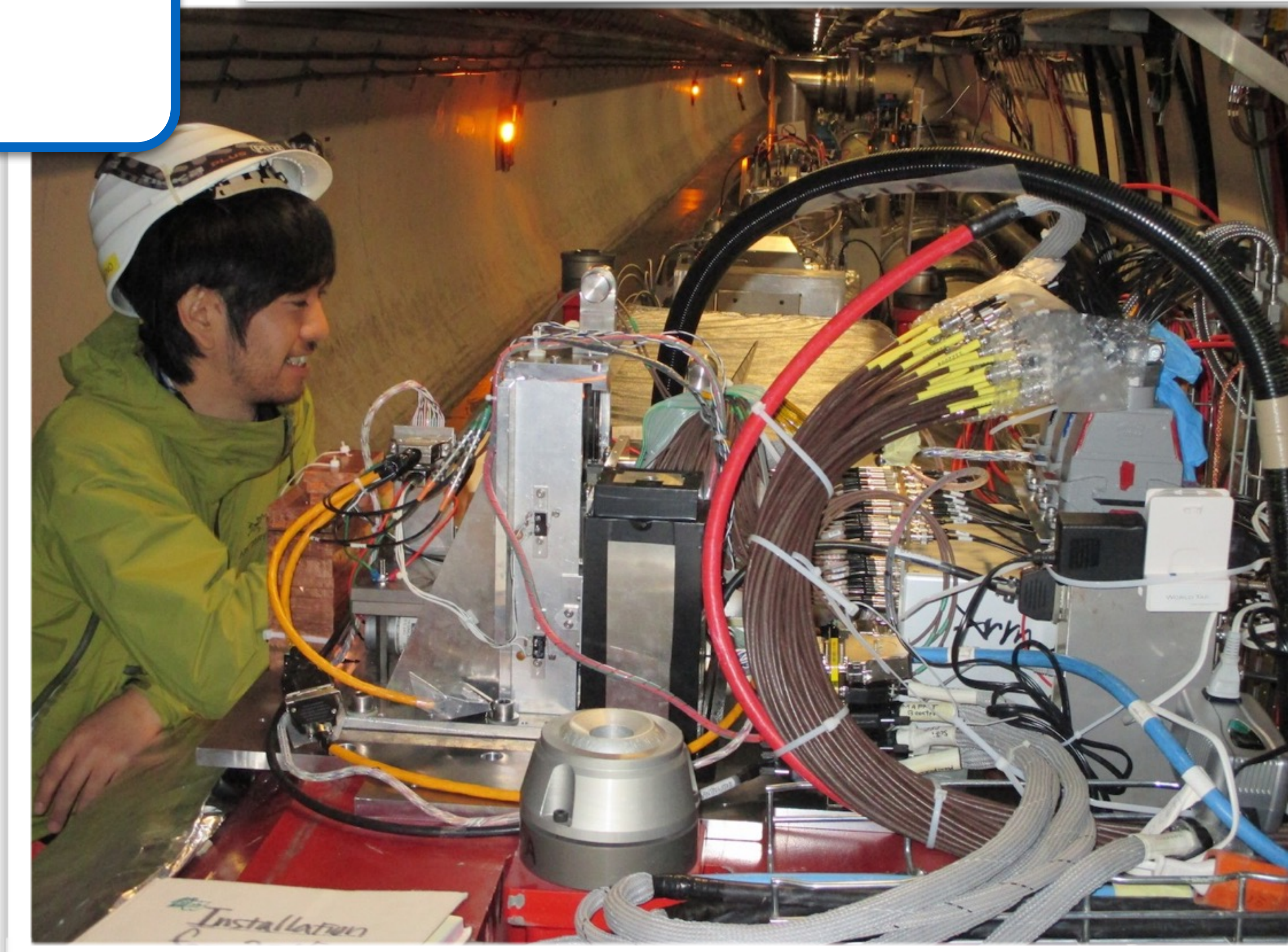
Experimental setup











Location

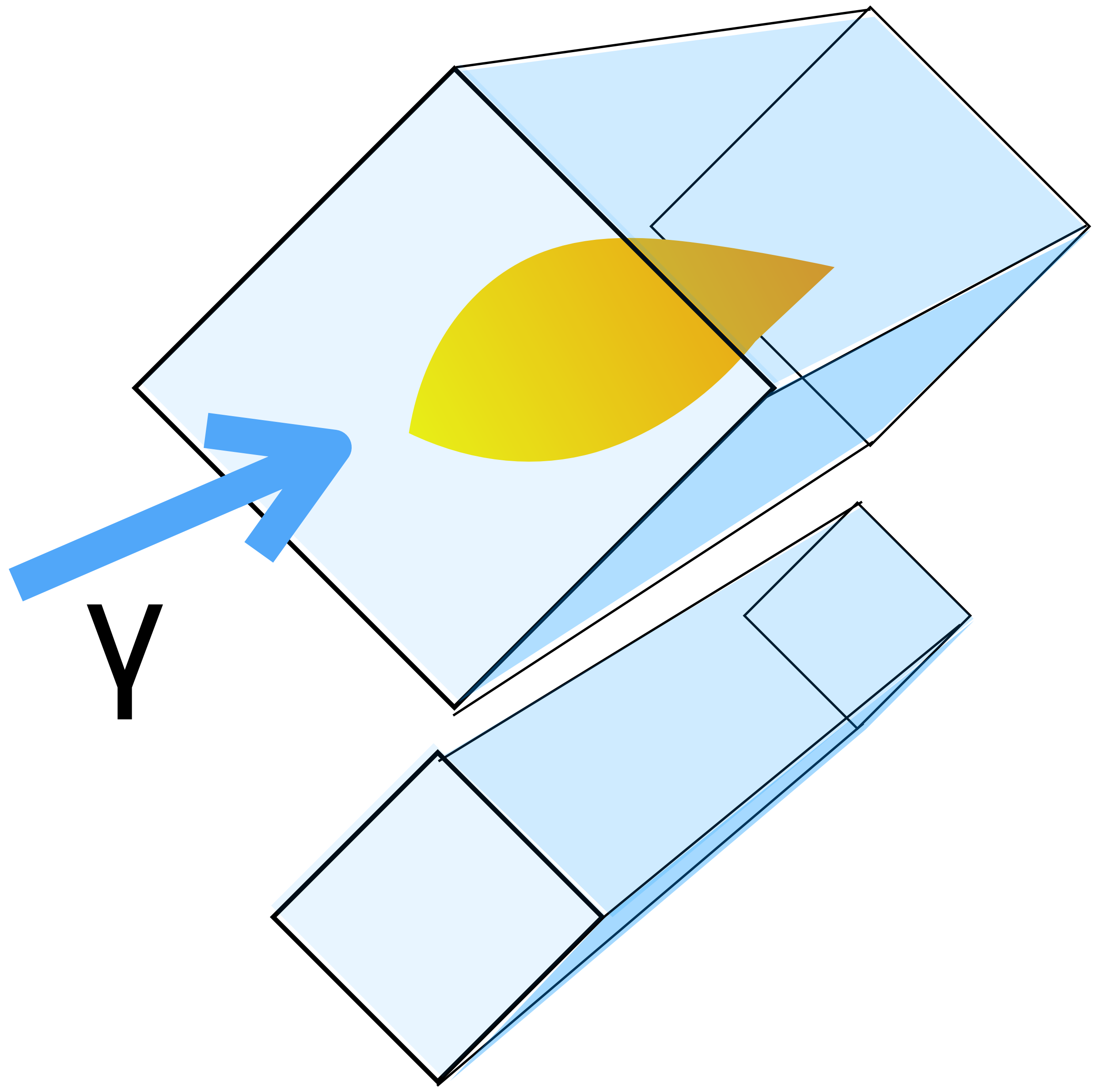
- ATLAS interaction point
- +/- 140m from the IP
- Cover Zero degree of collisions pseudo rapidity $\eta > 8.4$

LHCf detectors

- Sampling and positioning calorimeters
- Two towers, 20x20, 40x40mm^2 (Arm1) , 25x25, 32x32mm^2(Arm2)
- Tungsten layers, 16 GSO scintillators, 4 position sensitive layers (Arm1: GSO bar hodoscopes, Arm2: Silicon strip detectors)
- Thickness: 44 r.l. and 1.7 λ

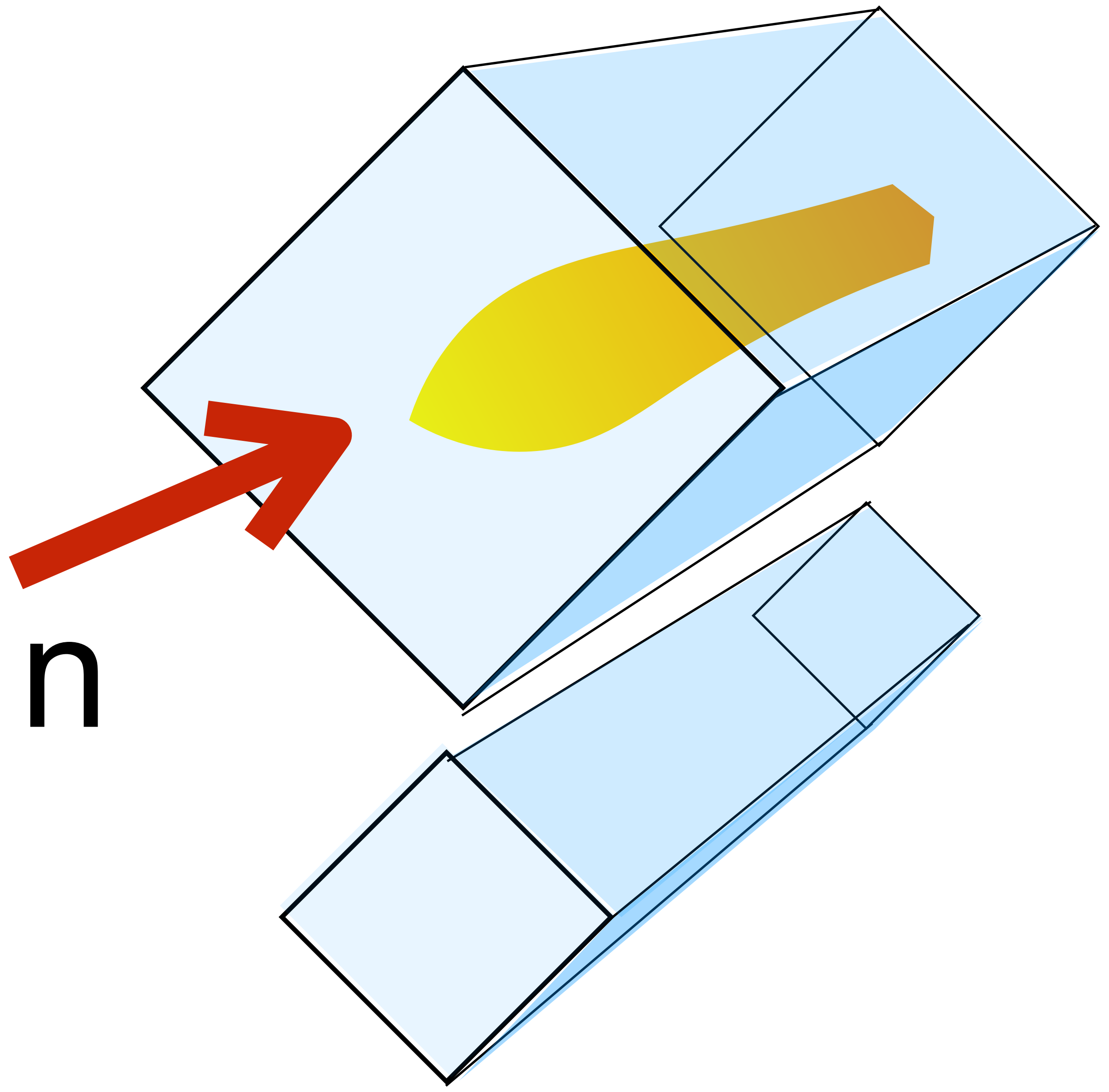
γ, n, π^0 detections

Photons



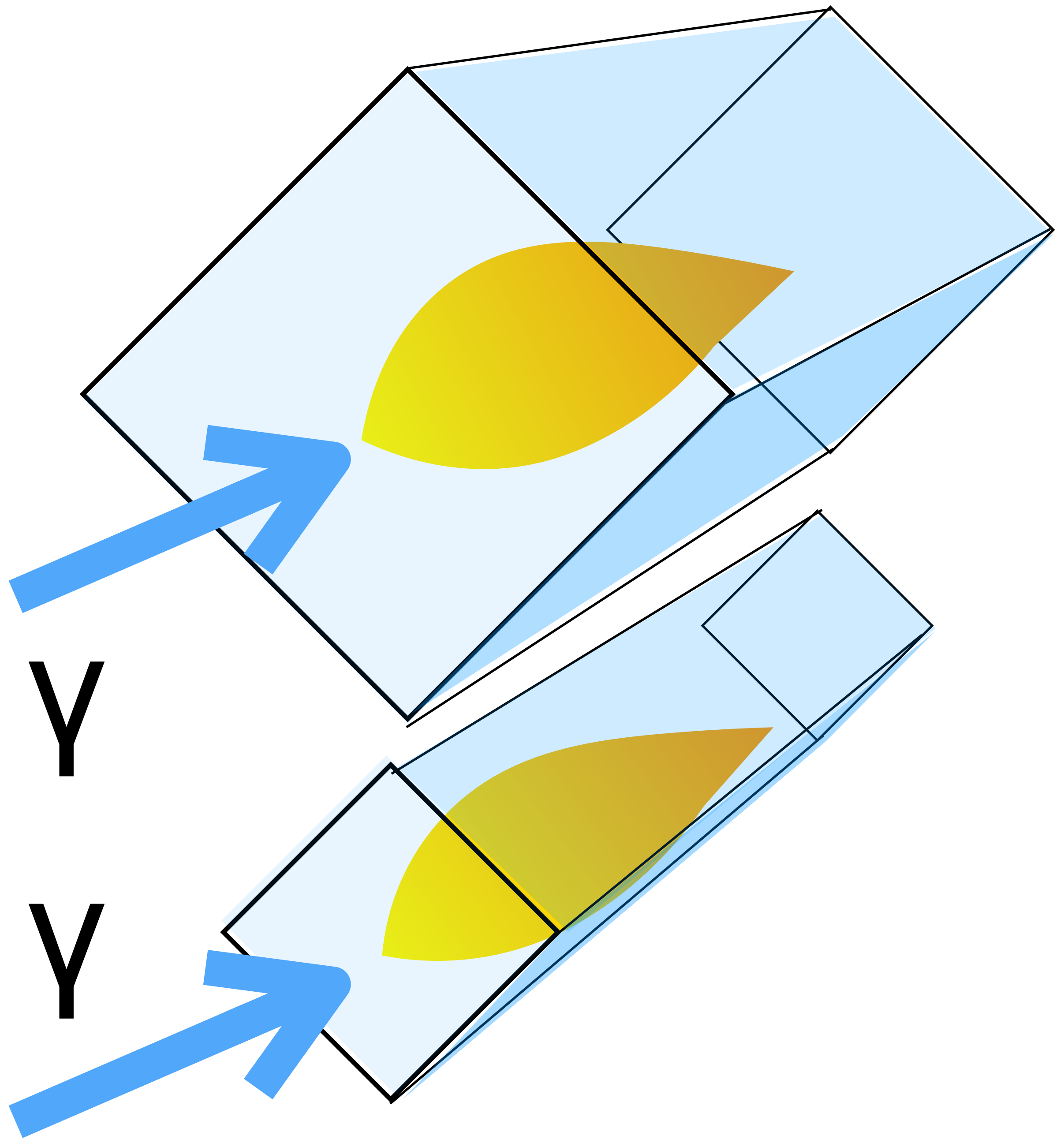
- EM showers
- $\Delta E/E < 5\%$
- $\Delta pos < 0.2$ mm

Neutrons



- Hadronic showers
- $\Delta E/E \sim 40\%$
- $\Delta pos \sim 1.0$ mm
- deeper and longer than EM showers

π^0



- "Pairs" of EM showers
- $\pi^0 \rightarrow 2\gamma$ (BR:98.8%)
- $E_\pi = E_{\gamma 1} + E_{\gamma 2}$

LHCf Operations and Analyses

<table>
<tr><th>Run</th><th>E_{lab} (eV)</th><th>Photon</th><th>Neutron</th><th colspan="2">π^0</th><th>LHCf-ATLAS joint analysis</th></tr>
<tr><td>p-p $\sqrt{s}$=0.9TeV (2009/2010)</td><td>4.3×10^{14}</td><td>PLB 715, 298 (2012)</td><td></td><td colspan="2">-</td><td></td></tr>
<tr><td>p-p $\sqrt{s}$=2.76TeV (2013)</td><td>4.1×10^{15}</td><td></td><td></td><td>PRC 86, 065209 (2014)</td><td rowspan="2">PRD 94 032007 (2016)</td><td></td></tr>
<tr><td>p-p $\sqrt{s}$=7TeV (2010)</td><td>2.6×10^{16}</td><td>PLB 703, 128 (2011)</td><td>PLB 750 360 (2015)</td><td>PRD 86, 092001 (2012)</td><td></td></tr>
<tr><td>p-p $\sqrt{s}$=13TeV (2015)</td><td>9.0×10^{16}</td><td>PLB 780, 233 (2018)</td><td>JHEP, 2018, 73 (2018)</td><td colspan="2">preliminary</td><td>Photon in diffractive coll. ATLAS-CONF-2017-075</td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=5TeV (2013,2016)</td><td>1.4×10^{16}</td><td></td><td></td><td>PRC 86, 0[illegible] (2014)</td><td></td><td></td></tr>
<tr><td>p-Pb $\sqrt{s_{NN}}$=8TeV (2016)</td><td>3.6×10^{16}</td><td>Preliminary</td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>RHICf p-p $\sqrt{s}$=510GeV (2017)</td><td>1.4×10^{14}</td><td colspan="4">on-going</td><td>with STAR</td></tr>
</table>

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

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

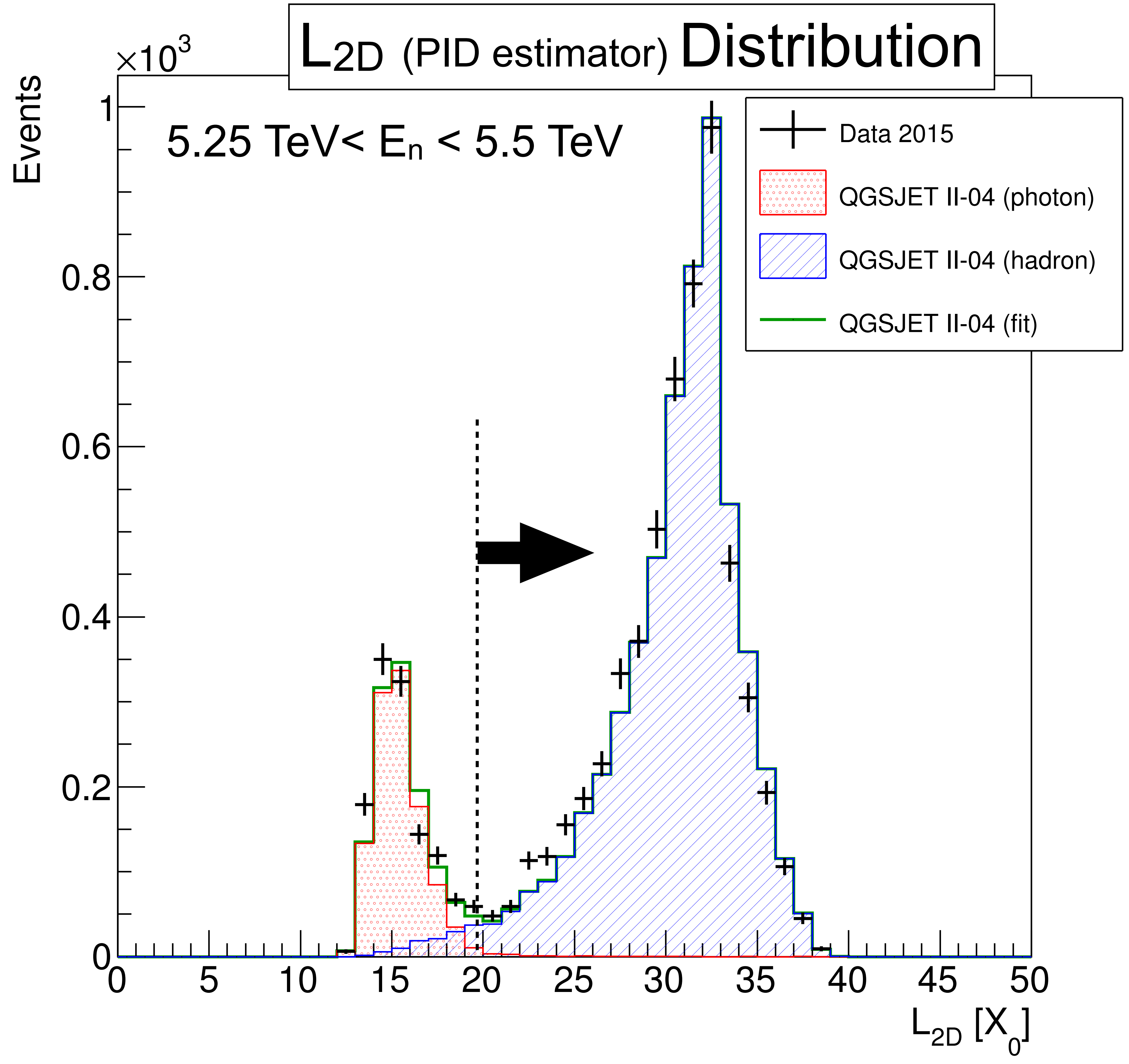
- 3 hour operation in June 2015
- Low pile-up, μ~0.01

Analysis

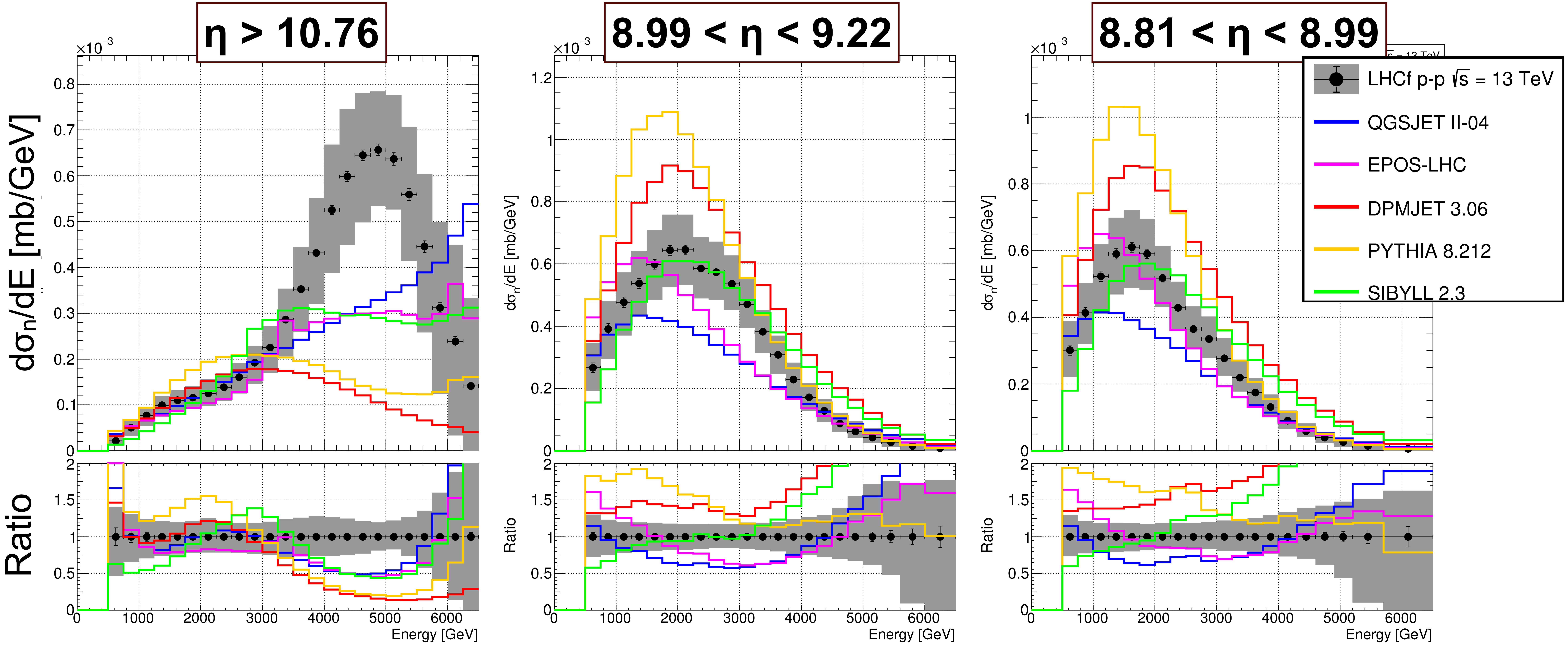
- Particle Identification

  EM shower → develop in shallow layers

  Hadronic showers → develop in deep layers
- Energy resolution of 40%
- Contamination of Δ^0, K^0

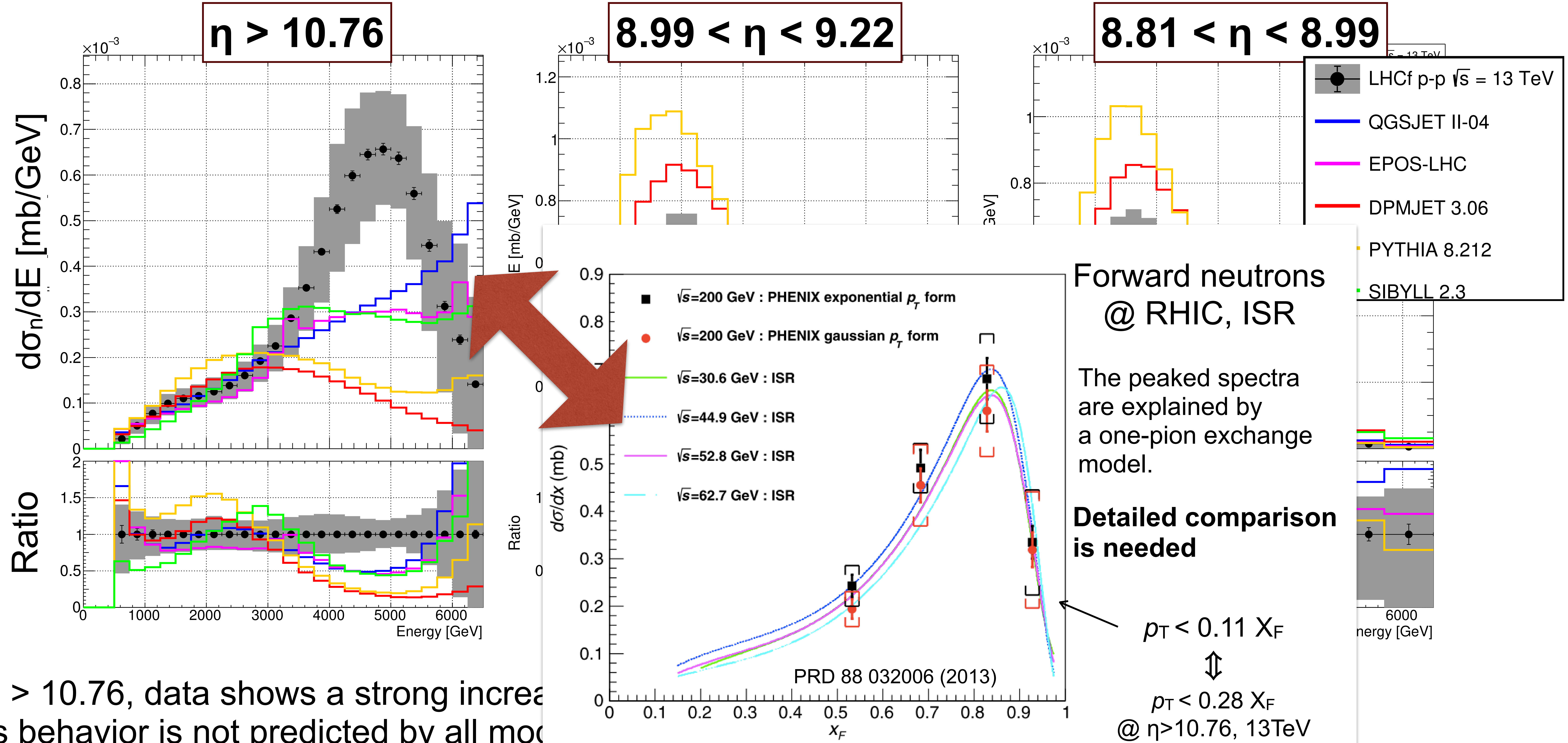


Neutron measurement at p-p, $\sqrt{s}$ = 13 TeV



- 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 measurement at p-p, √s = 13 TeV



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 strong increa
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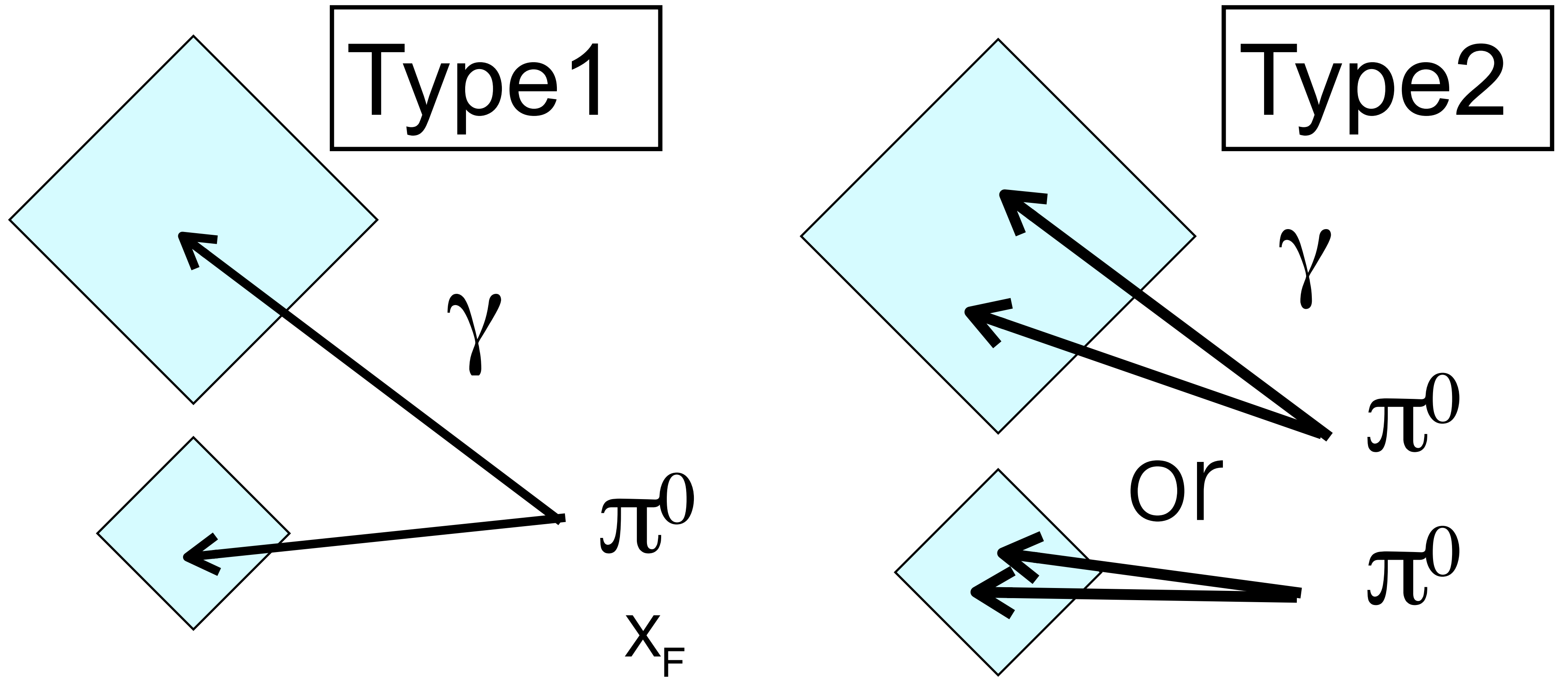
- EPOS-LHC and SIBYLL 2.3 have the best agreement in 8.99 < η < 9.22, 8.81 < η < 8.99, respectively.

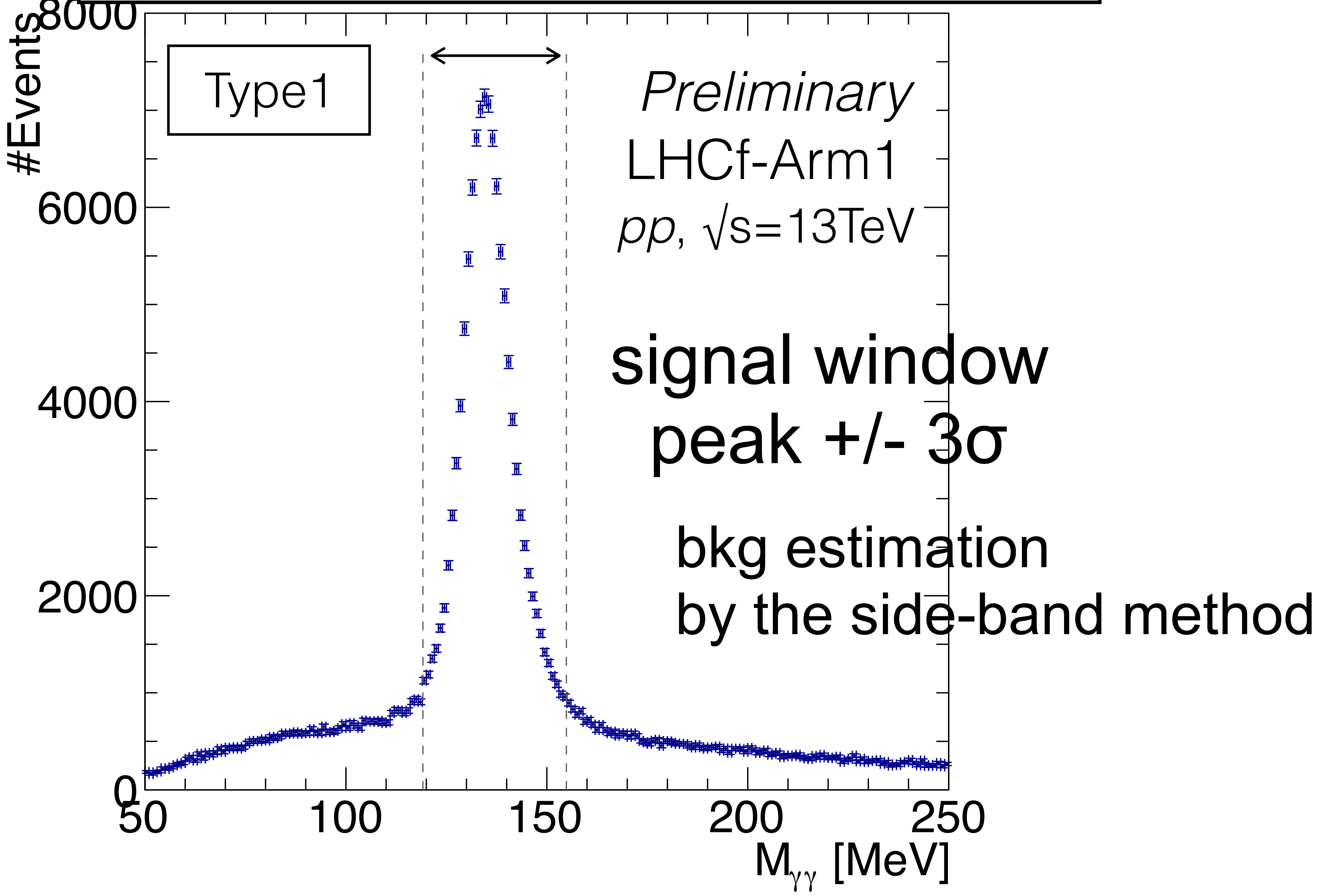
π^0 measurement at p-p, $\sqrt{s}$ = 13 TeV

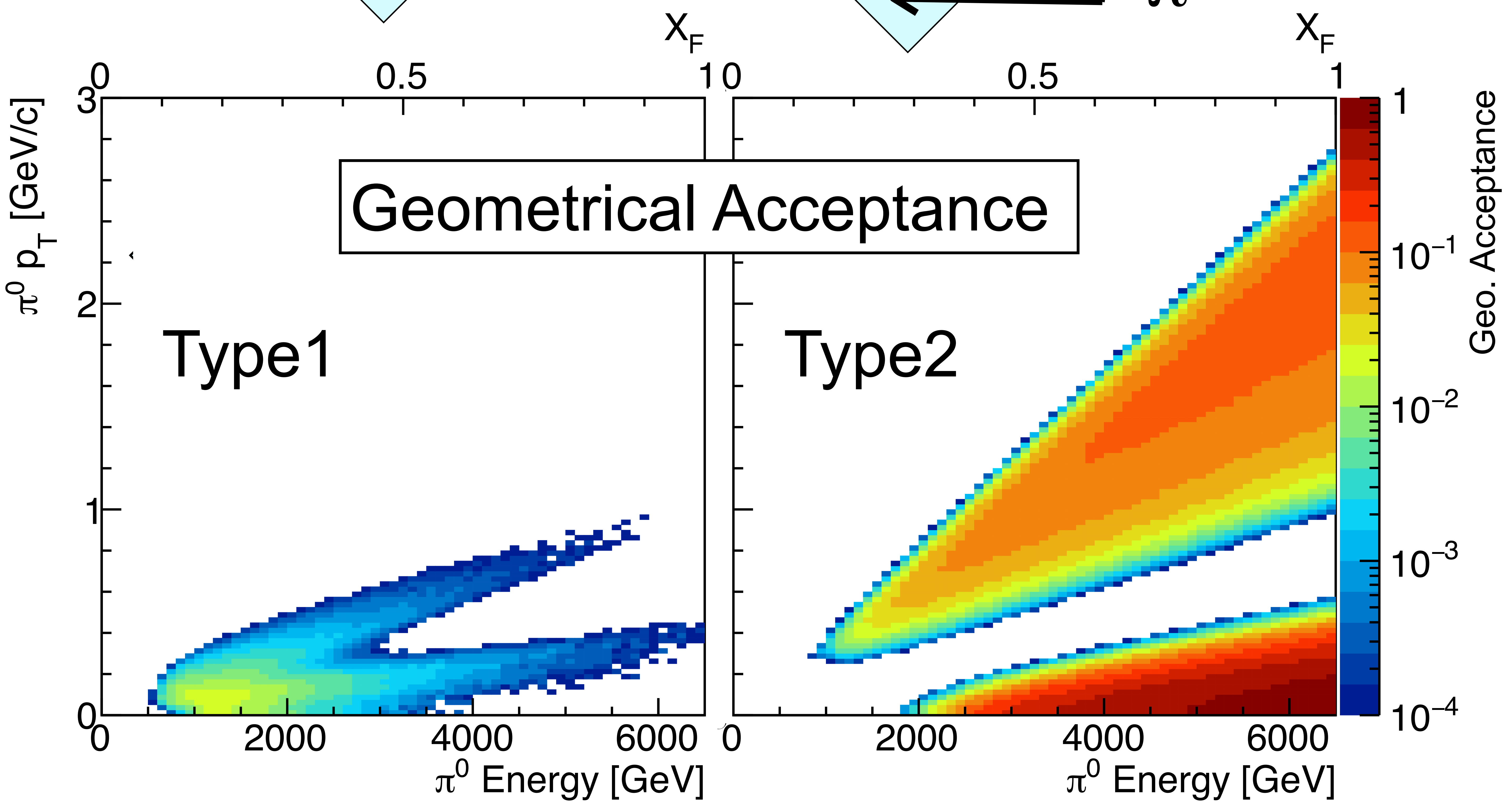
Data
- 3 + 5 hour operations in June 2015
- Arm1, one detector position
- Dedicated trigger for Type1 events

Analysis
- 2 types of events: Type 1, 2
- Event selection by π^0 mass

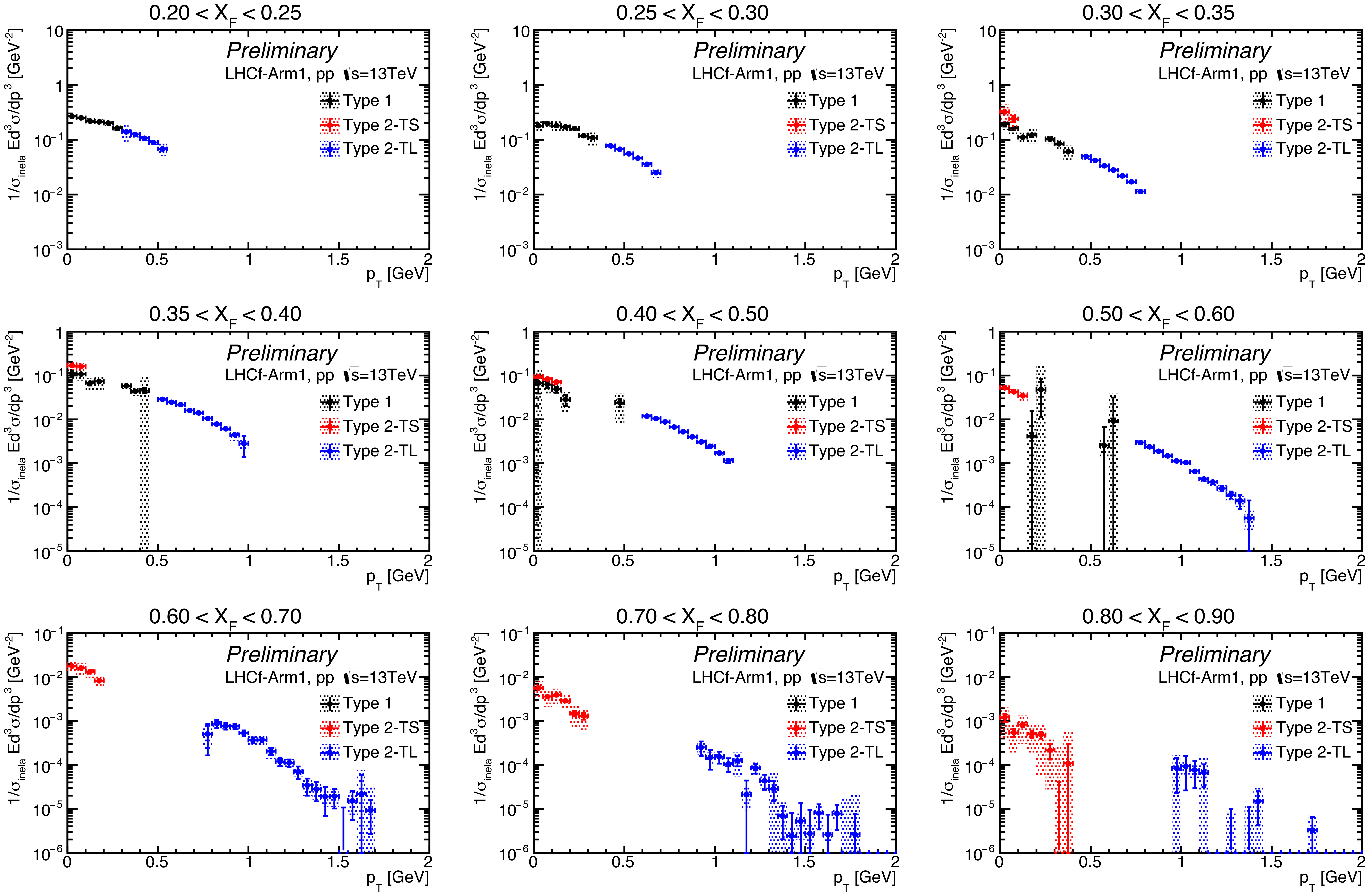


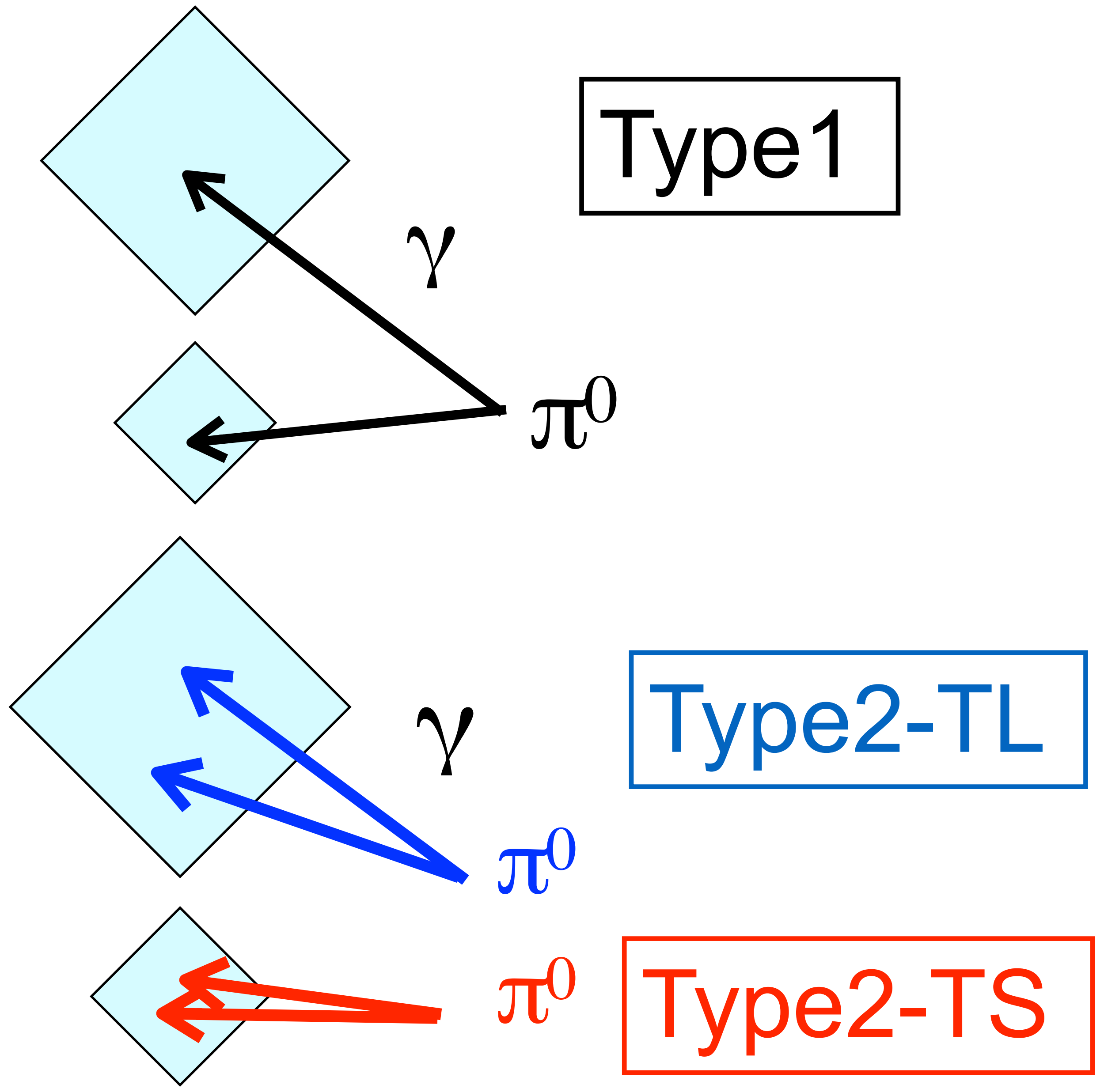
reconstructed mass distribution





π^0 measurement at p-p, $\sqrt{s}$ = 13 TeV





- Smooth connection of 3 spectra
- Wide transverse momentum coverage
- The gaps will be covered by Arm2 and other detector position data.

Future prospects

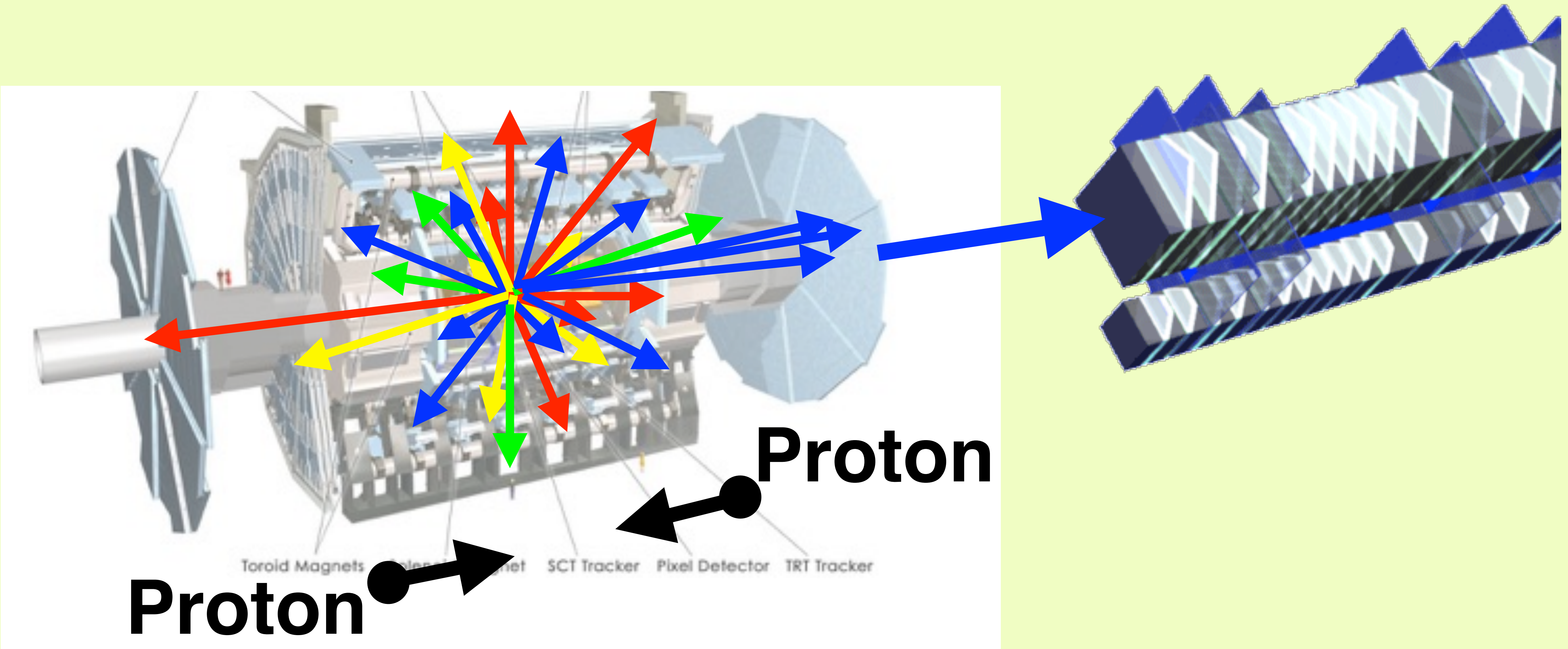
- ✓ On going analyses
- ✓ Operation plan in 202X

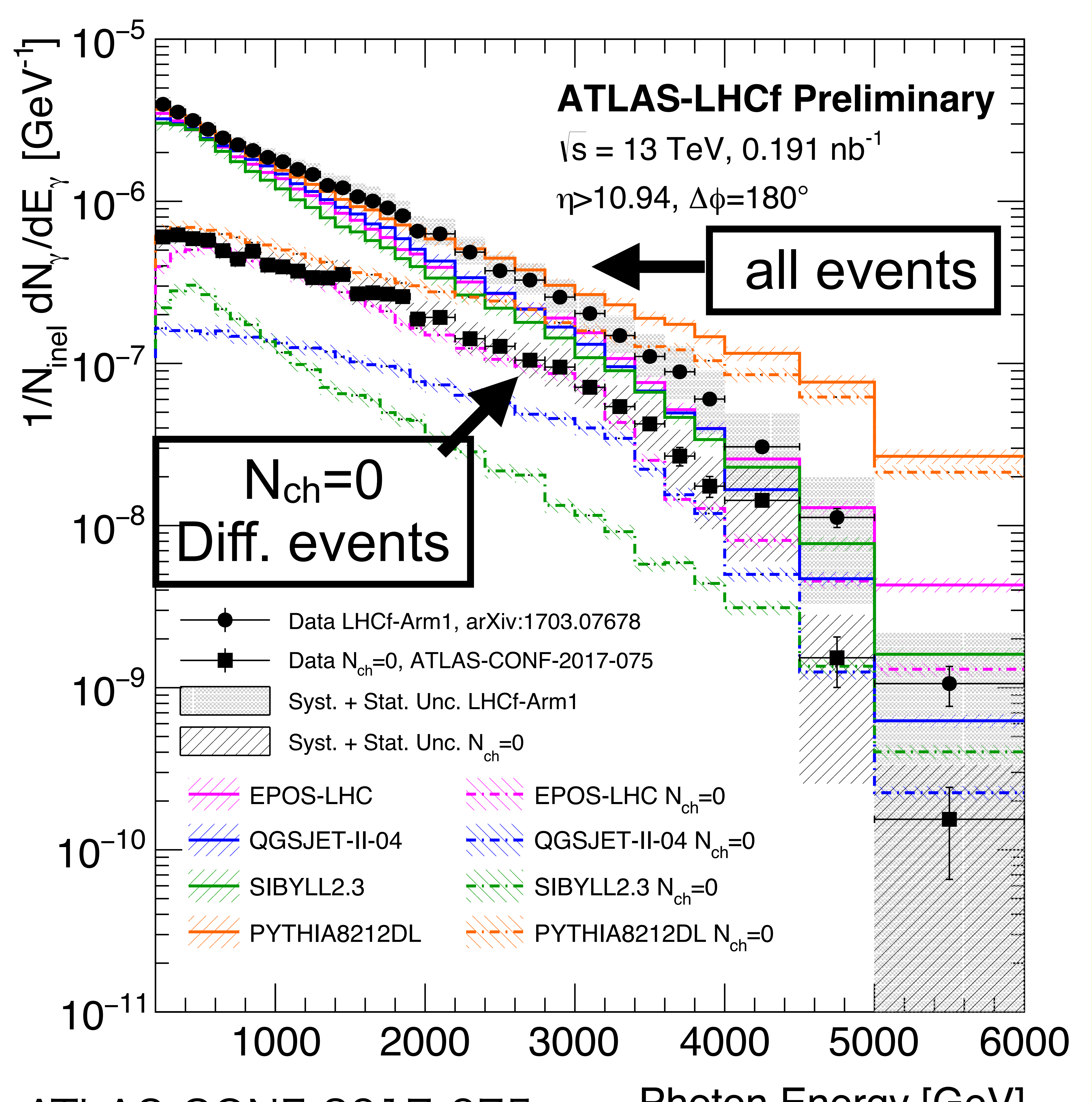
LHCf-ATLAS joint analysis

- **Central (ATLAS) + Forward (LHCf)**

➡ Detailed studies of hadronic interaction by using central and forward correlation.

- Common operations has been performed in the operation since 2013.
- Studying the diffractive collisions by requiring no track in ATLAS,





ATLAS-CONF-2017-075

On-going analyses

LHCf-ATLAS joint analysis

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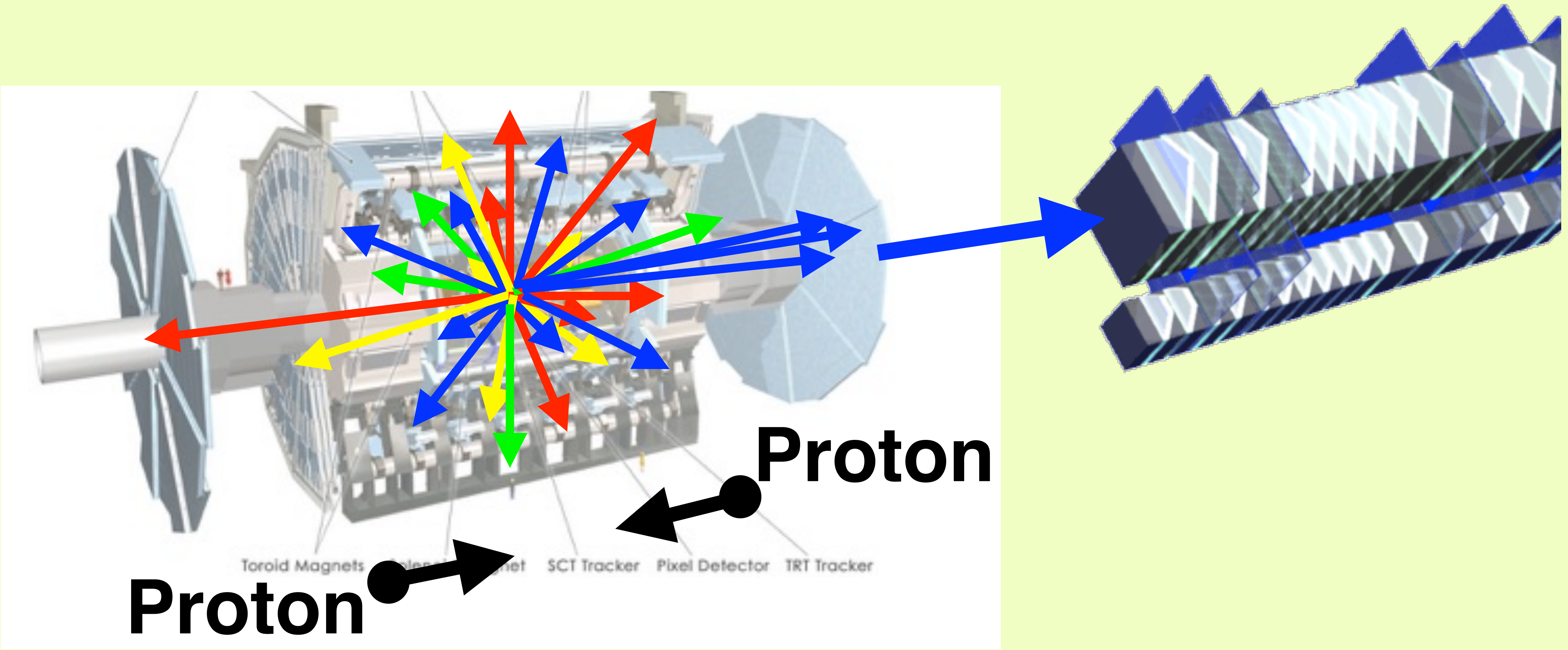


The RHICf data analysis

- **p+p $\sqrt{s}$ = 510 GeV at RHIC, BNL** (polarized beam)

➡Test of energy scaling with the wide p_T range.

(The X_F-pT coverage is almost same as LHCf @ p+p $\sqrt{s}$=7TeV)

- Operation completed in June 2017.
- Common operation with STAR

RHIC 10^{14}eV

x10^3

LHC 10^{17}eV

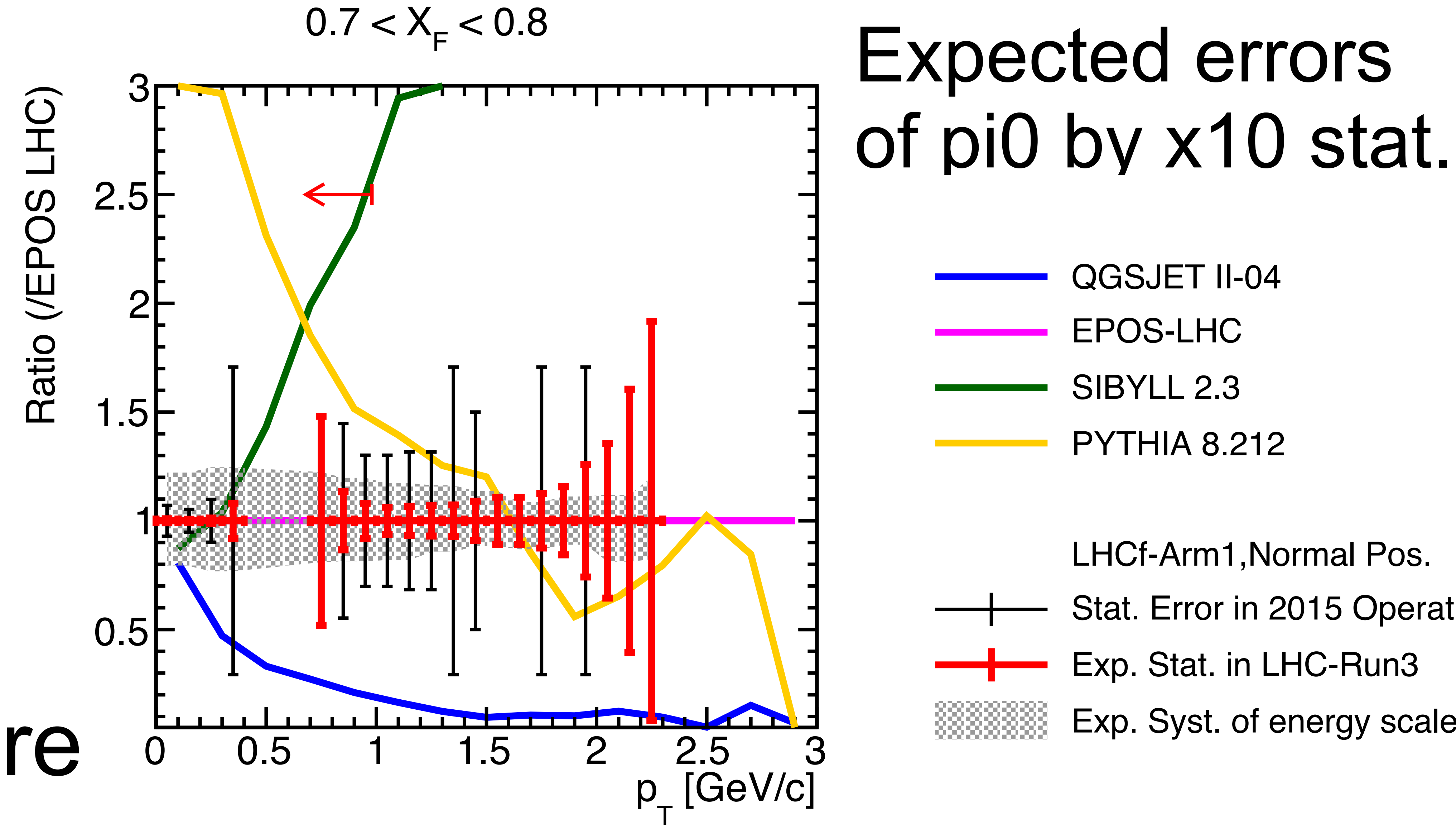
x10^3

UHECR ~10^{20}eV

poster by K. Sato

Two operations in LHC-Run3 (2021-2023)

- **proton - proton collisions at $\sqrt{s}$ = 14 TeV (or 13 TeV)** **2021**
  - Increase the statistics of high energy π^0 events and common events with ATLAS
  - Operation with 10 times higher luminosity
  - Measurement of rare particles
    - η ($\eta \rightarrow 2\gamma$: BR 39.4%)
    - K^0_s ($K^0_s \rightarrow 2\pi^0 \rightarrow 4\gamma$: BR 30.7%)



Expected errors of pi0 by x10 stat.

- **proton - Oxygen collisions** **2023 (?)**
  - Ideal for study of CR interaction in the atmosphere
  - First light A collision in a collider
  - Negligible background from UPC collisions ($\sigma_{UPC} \sim Z^2$)
    $\leftrightarrow$ Huge background at p-Pb (50%,90% for γ,n)

→ Physics cases and related upgrade of the DAQ system are summarized in a Tech. Report (CERN-LHCC-2019-008)

Summary

- LHCf provided the experimental results of forward particle production
  - We found a peak around 5TeV on neutron energy spectrum, which is not reproduced by the models
  - Preliminary π^0 spectrum by LHCf-Arm1 was presented.
- Hadronic interaction is studied in more details
  - Detail studies of particle production mechanism by LHCf-ATLAS joint analysis are performed. For example, study of diffractive collisions.
  - Collision energy dependency is studied by comparing between LHCf and RHICf.
  - Operations in 2021-2023 will provide crucial data at high stat. pp, and proton-Oxygen collisions

Backup

Diffractive processes

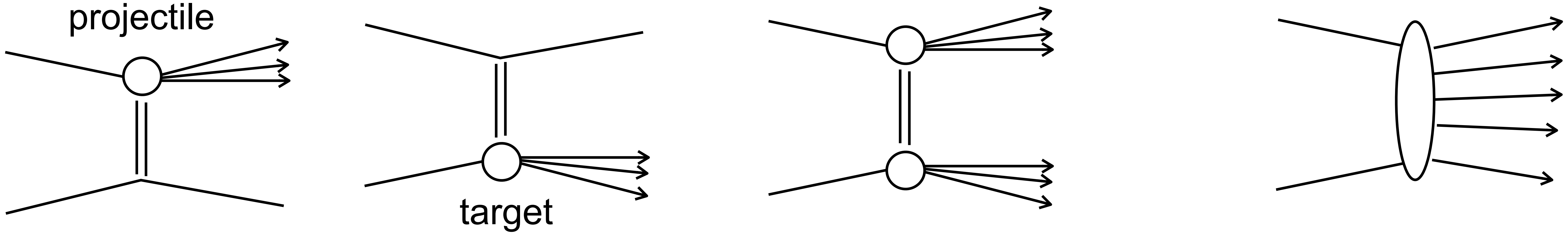
Inelastic processes

Diffractive (20%)

Non-diffractive (80%)

Single diffractive

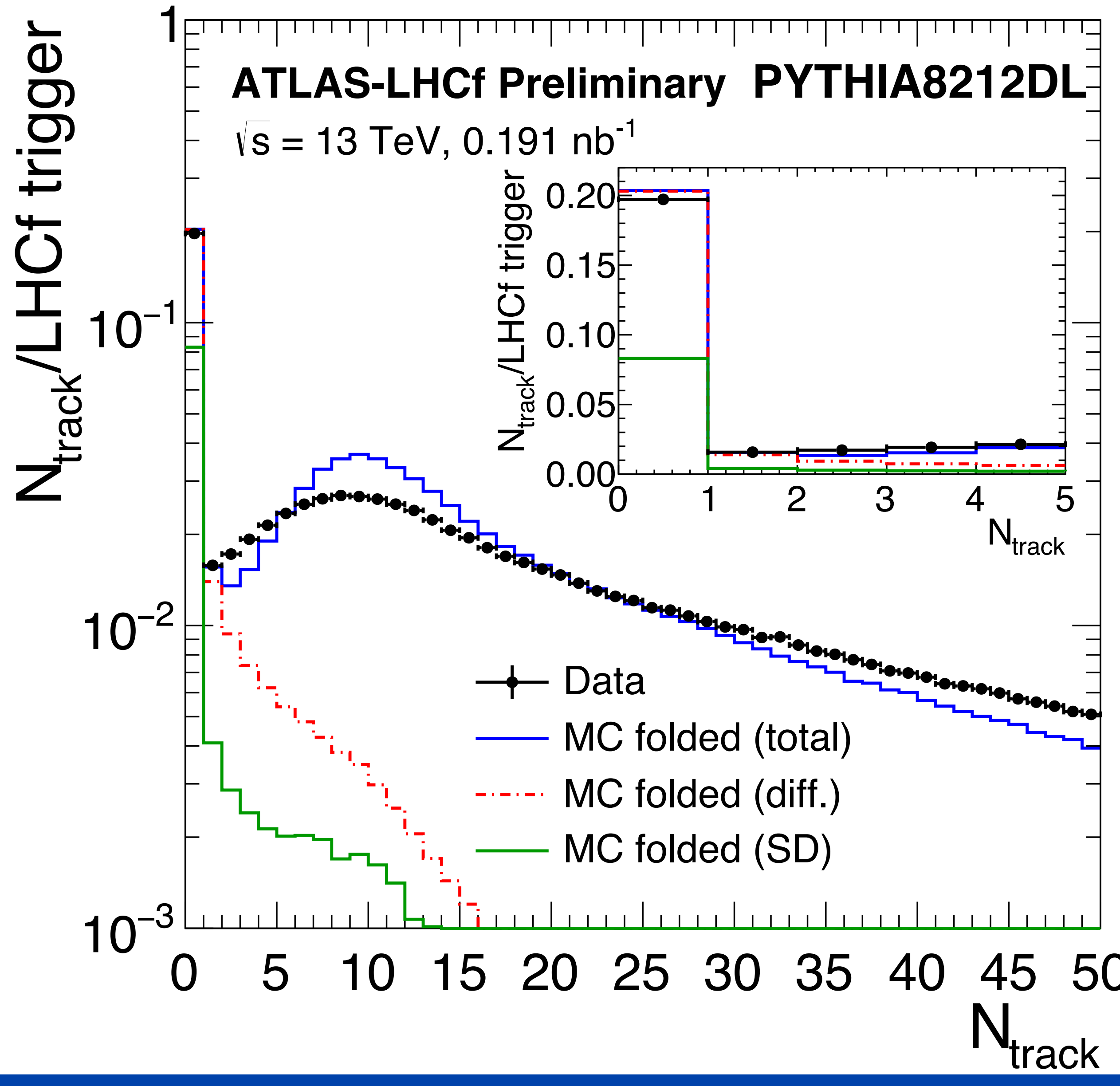
Double diffractive



K_{el}=0.55 K_{el}=0.99 K_{el}=0.54 K_{el}=0.45

K_{el} : Elasticity @ pp,$\sqrt{s}$=13TeV

ATLAS-CONF-2017-075



Identification of diffractive events by ATLAS

Method

- Event selection by N_{tracks}=0 ⇔ Large rapidity gap $\Delta\eta > 5$

N_{tracks}: the number of tracks detected **by ATLAS inner trackers** ($|\eta|$<2.5, p_T > 100 MeV)

→ Selecting pure samples of proton dissociations.
→ Sensitive to only low-mass dissociations $M_X \lesssim 50$ GeV

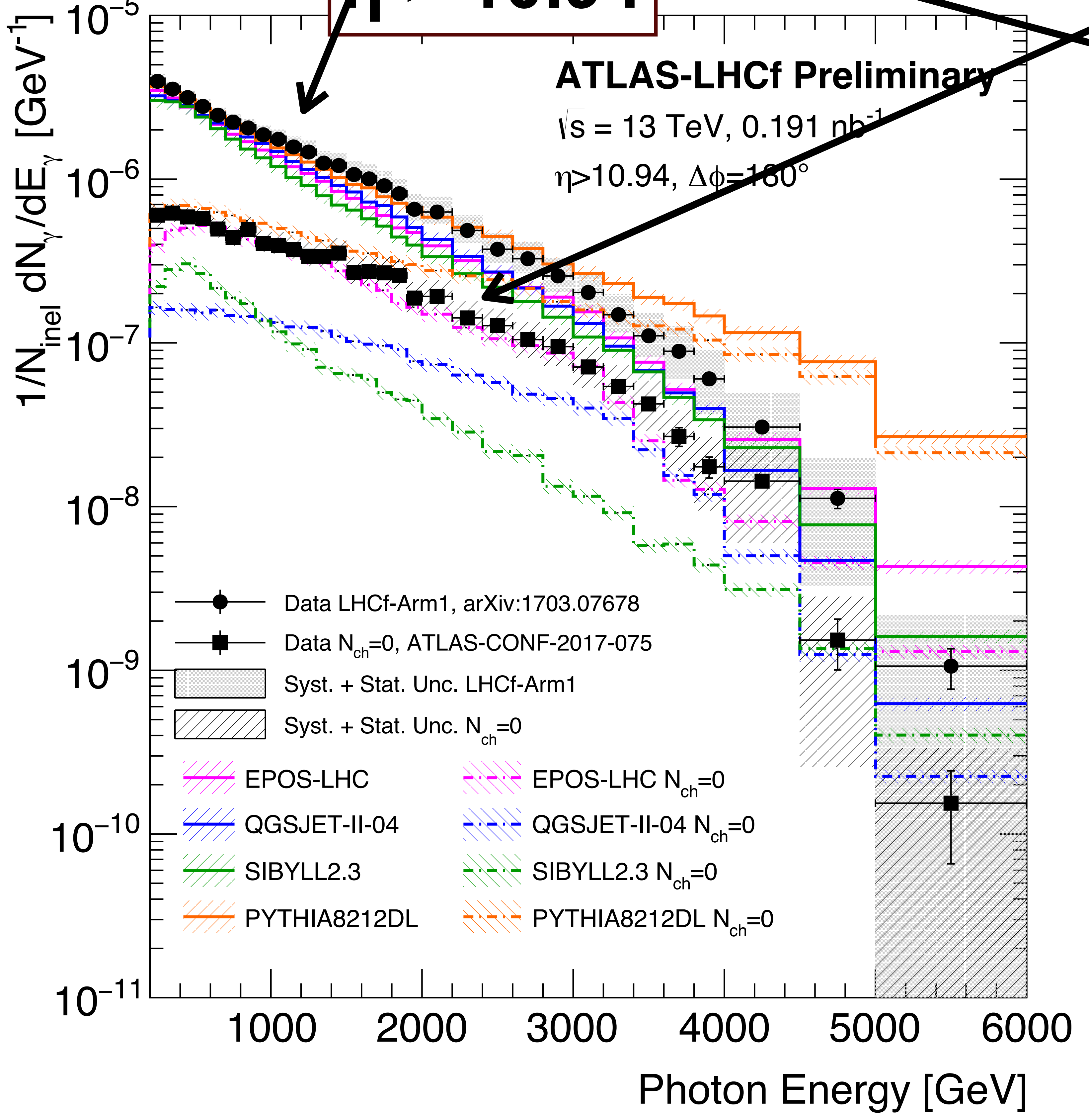
Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at √s = 13 TeV

Preliminary result of the measurement for forward photons is published in a conference-note; ATLAS-CONF-2017-075

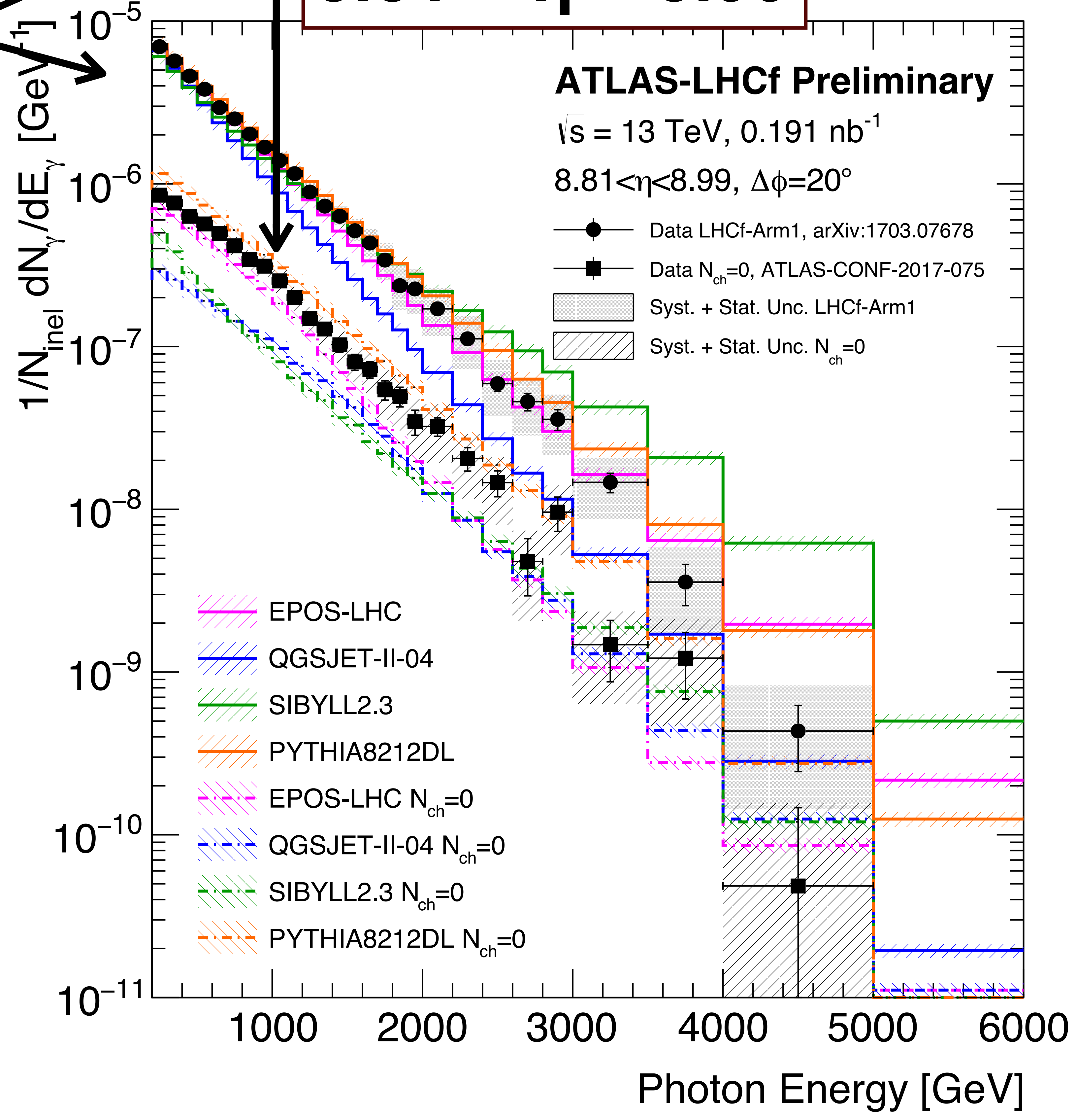
Inclusive photon spectra

Photon spectra w/ N_{ch} = 0 selection

η > 10.94



8.81 < η < 8.99



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

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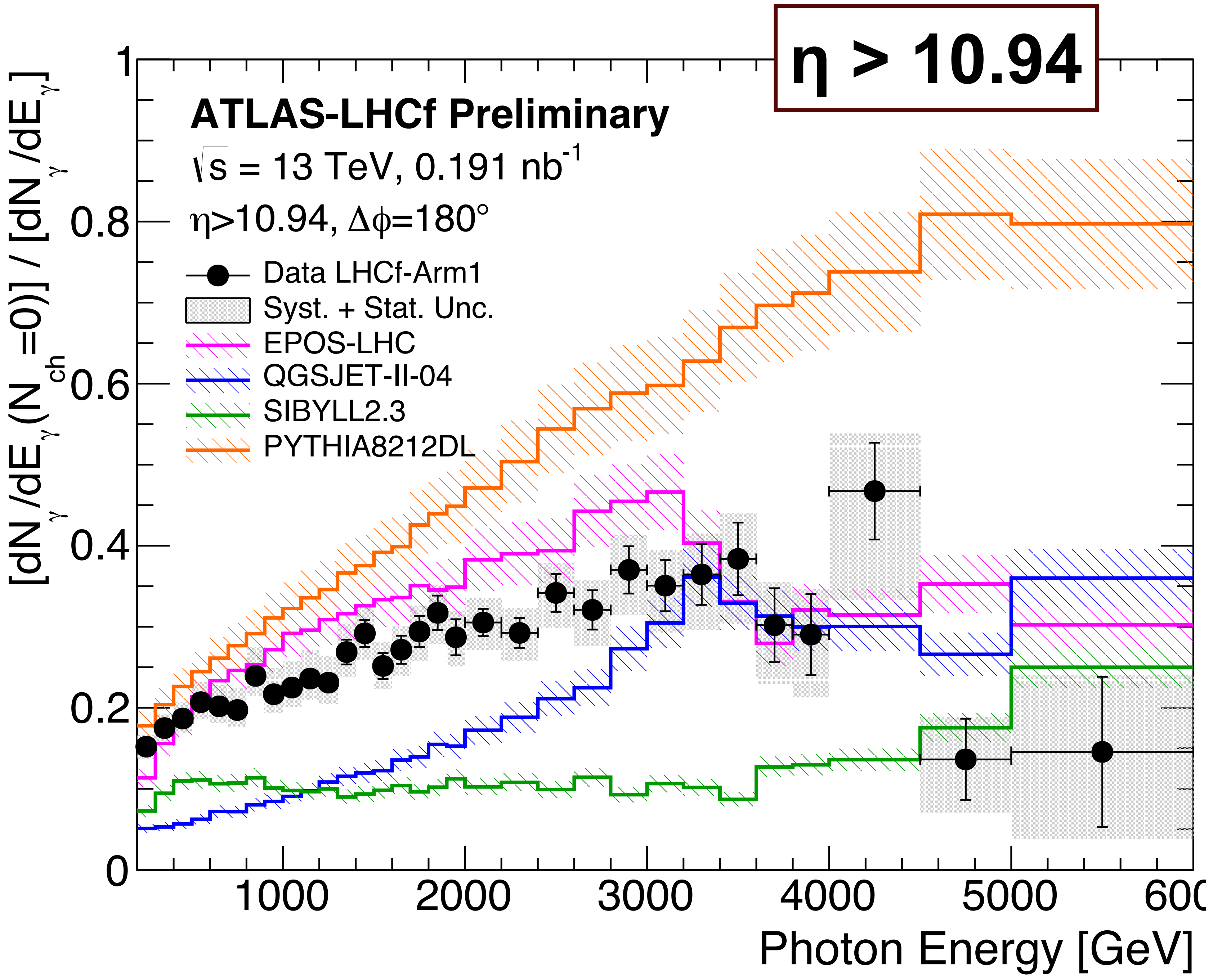
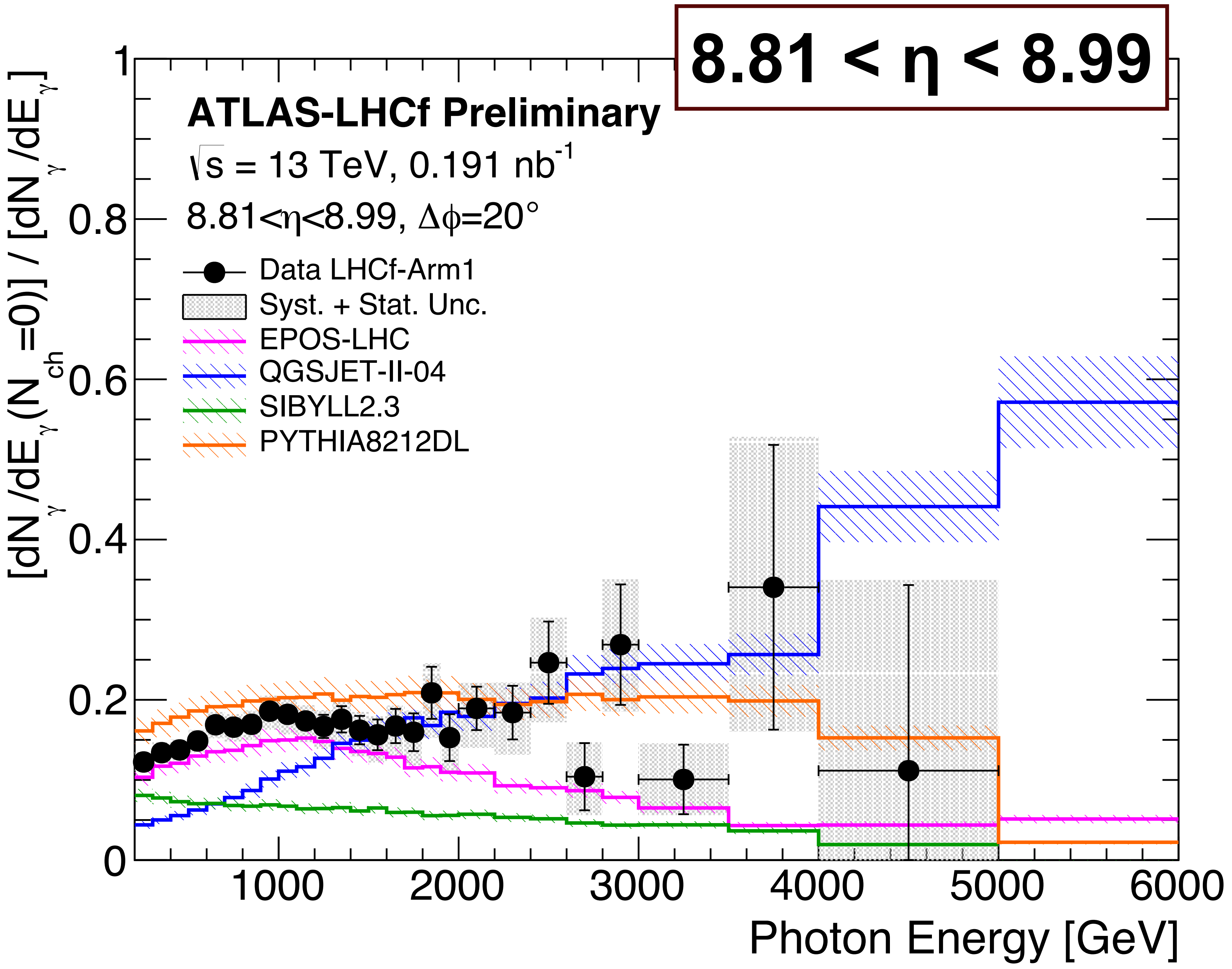


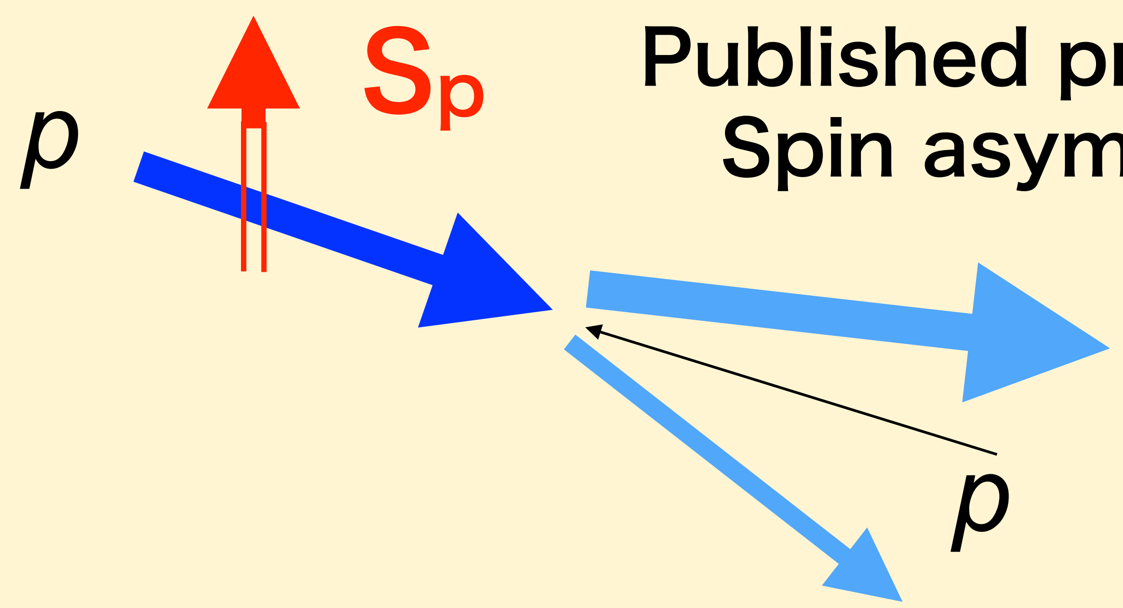


- At η>10.94, the ratio of data increased from 0.15 to 0.4. with increasing of the photon energy up to 4TeV.
- PYTHIA8212DL predicts higher fraction at higher energies.
- SIBYLL2.3 show small fraction compare with data at η>10.94.
- At 8.81 < η < 8.99, the ratio of data keep almost constant as 0.17.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

RHICf experiment

RHIC at BNL

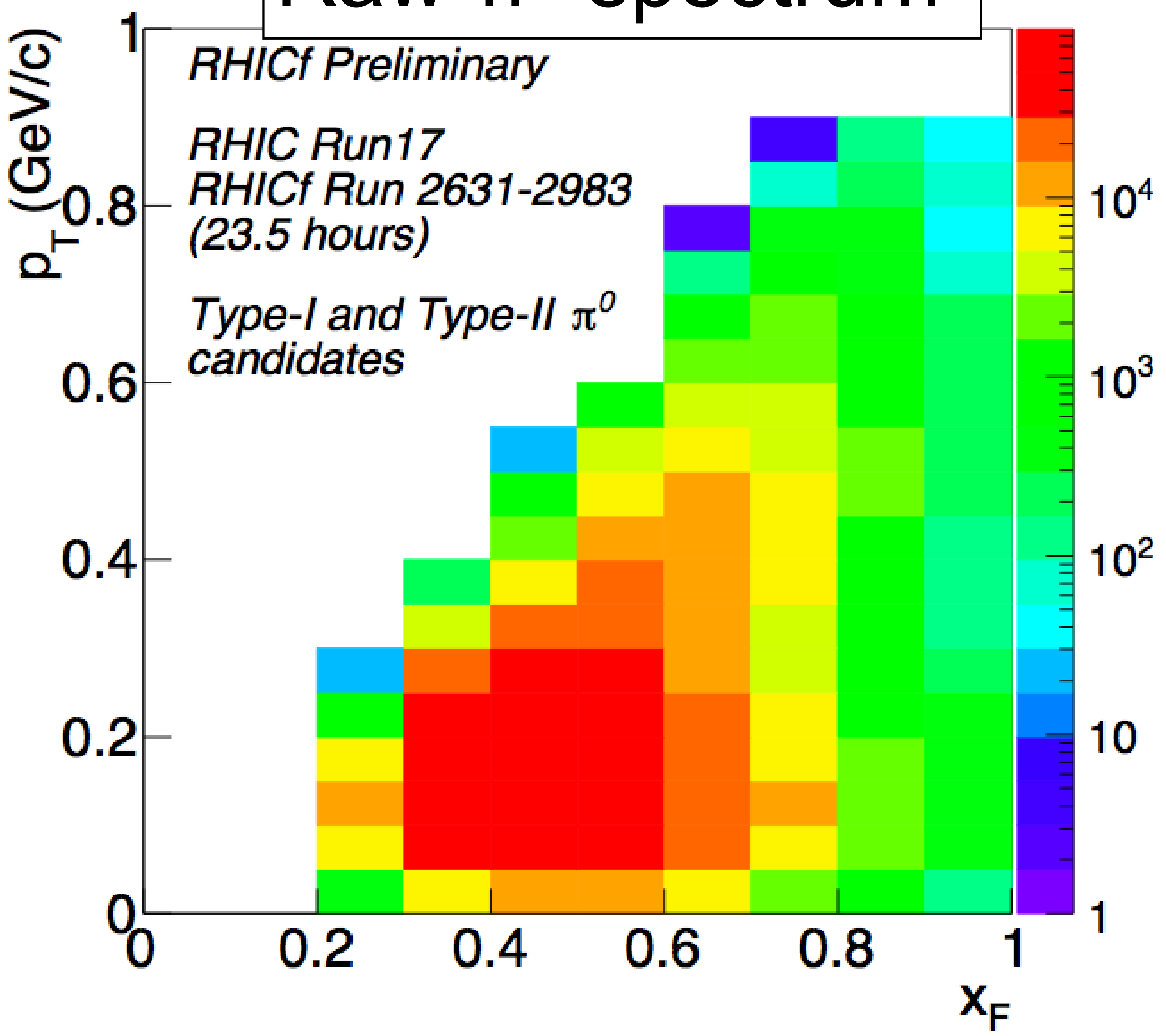
- p+p $\sqrt{s}$ = 510 GeV
  (polarized beam)
- Operation in June 2017.
- Test of energy scaling with the wide p_T range.
  (The X_F-pT coverage is almost same as LHCf @ p+p $\sqrt{s}$=7TeV)
- Common operation with STAR



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

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

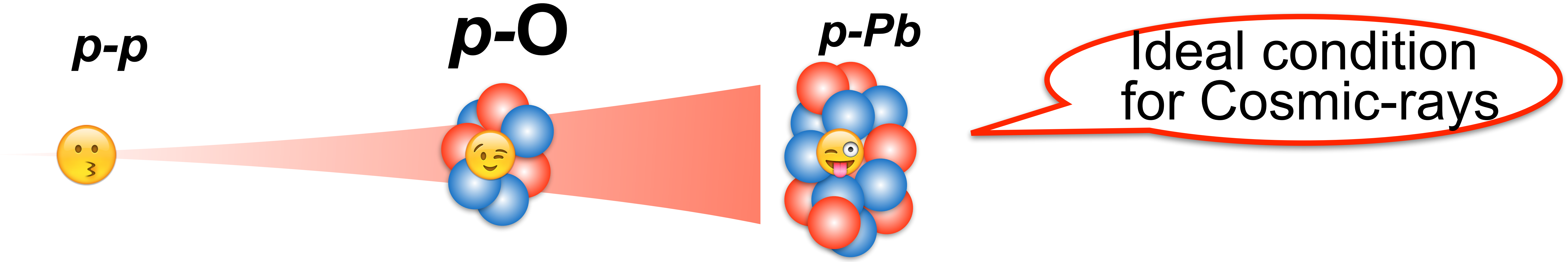
Raw π^0 spectrum



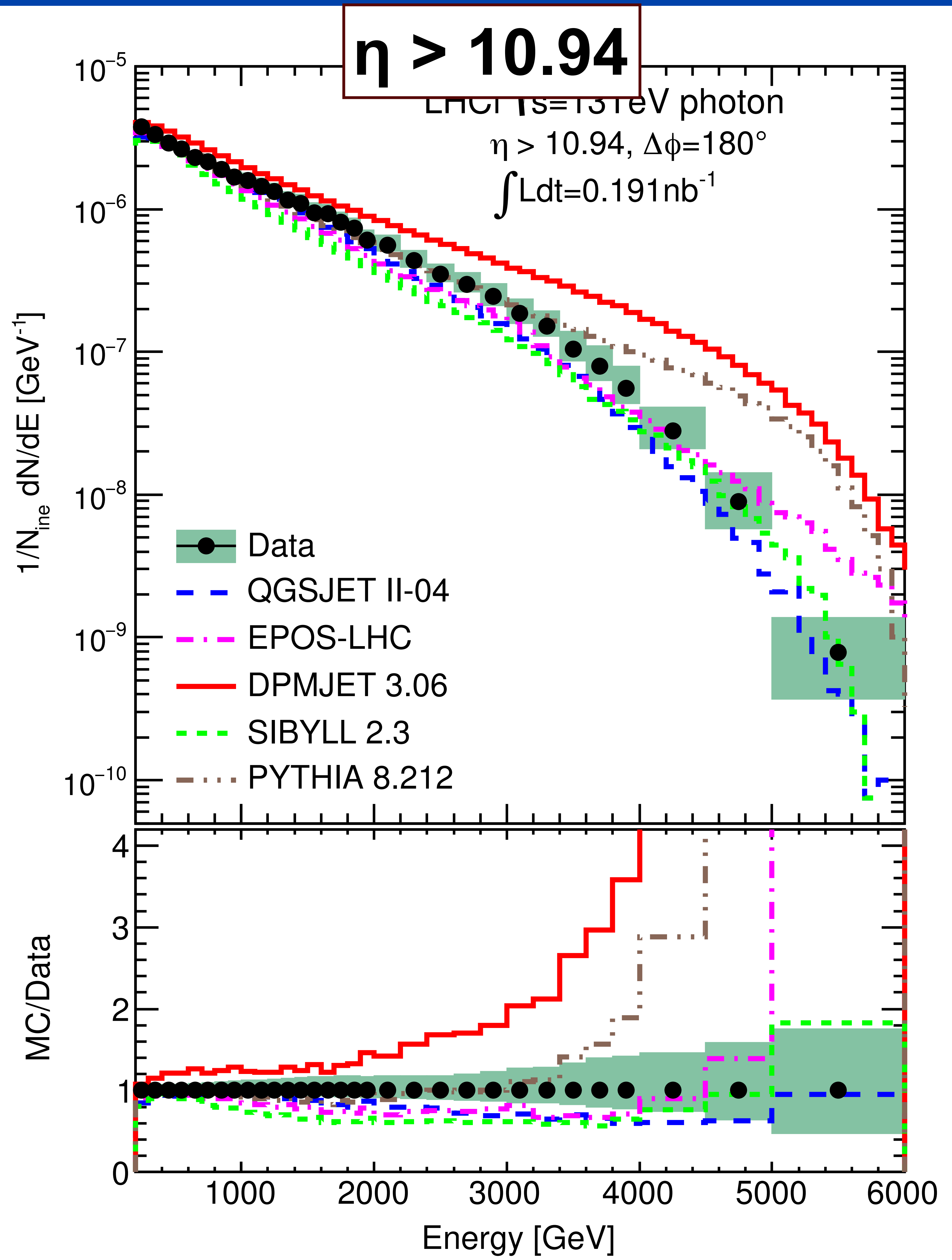
Analysis for π^0 production cross-section measurement is on-going.

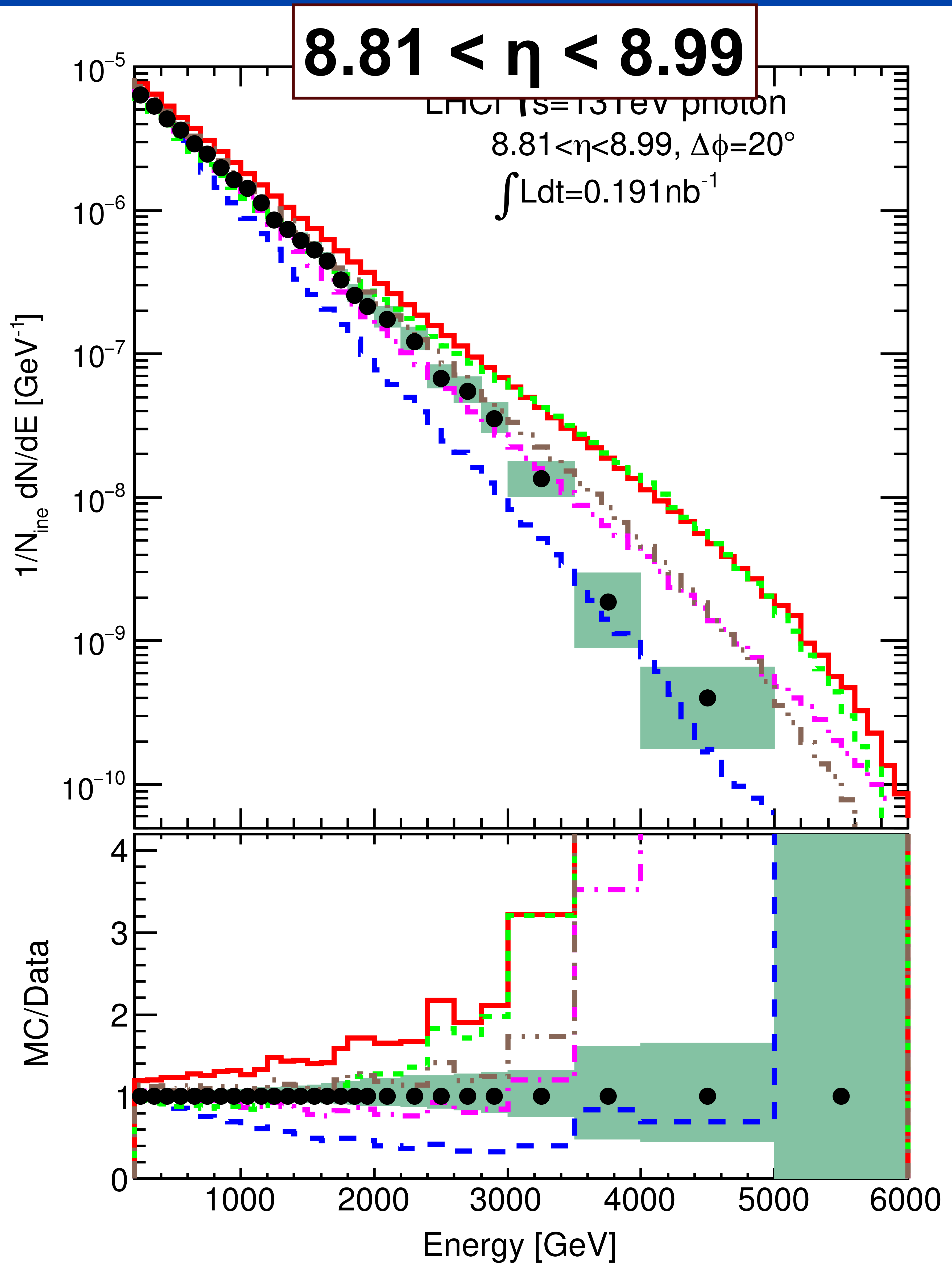
Summary

- Final/Preliminary results were shown.
  - Forward neutron cross-sections at p-p, $\sqrt{s}$ = 13 TeV
  - Forward photon energy spectra at p-Pb, $\sqrt{s}$ = 13 TeV
- On-going analyses
  - Diffractive contribution on forward photon production at p-p, $\sqrt{s}$ = 13 TeV from ATLAS-LHCf joint analysis.
  - Measurement of π^0 at p-p, $\sqrt{s}$ = 0.5TeV with RHICf
- Future plan
  - Operation with p-O collisions at LHC



Photon Energy Spectra





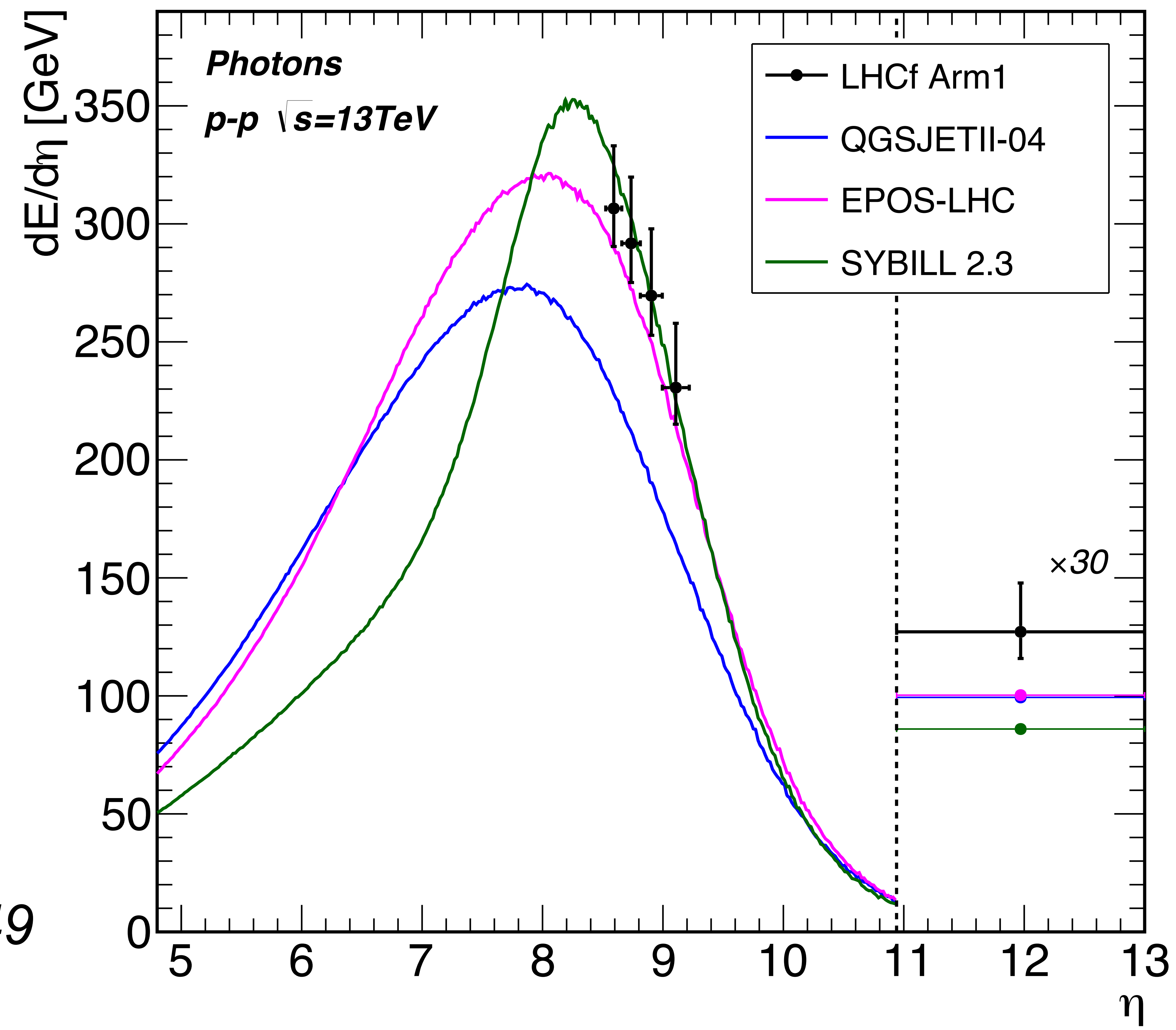
Photon Energy Flow

Energy Flow Calculation:

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

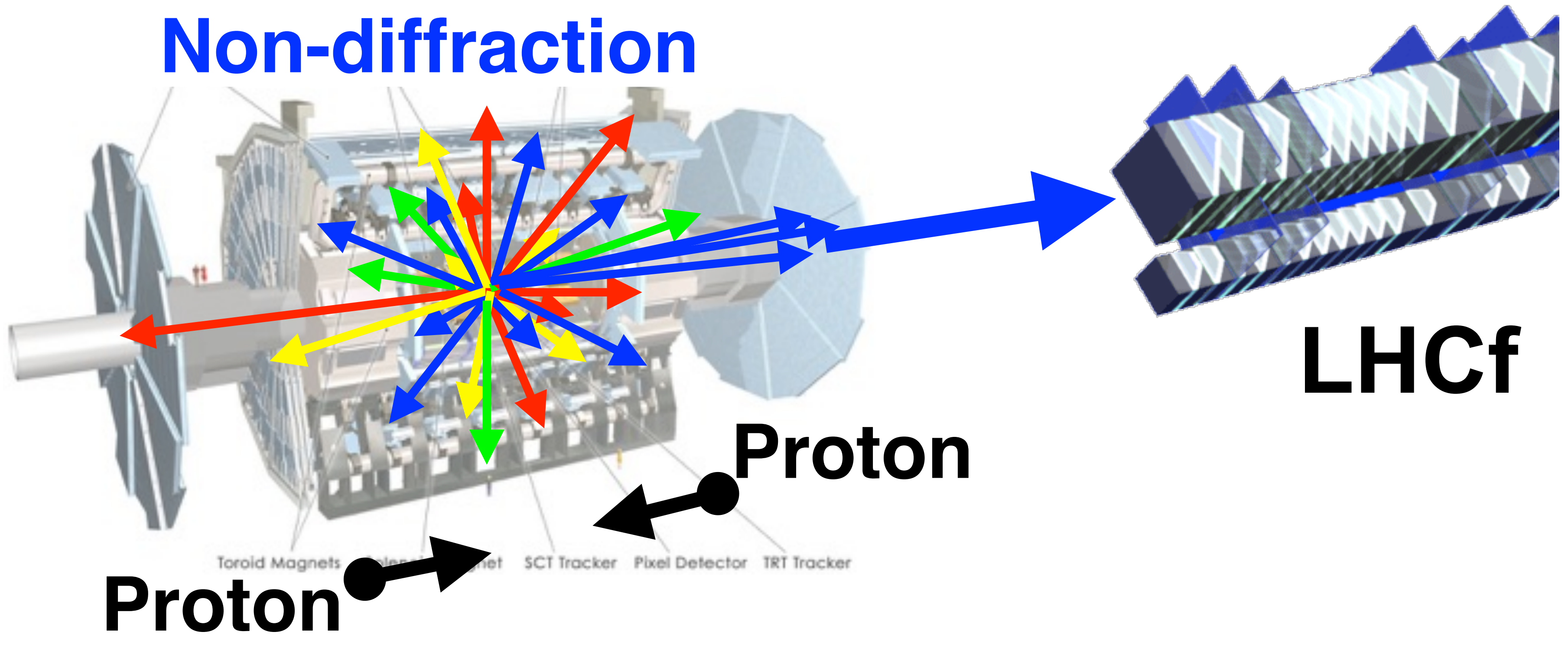
F(Ej) : Measured differential cross-section
Δη : The pseudo-rapidity range
C_{thr} : Correction factor for the threshold 200 GeV→ 0 GeV.

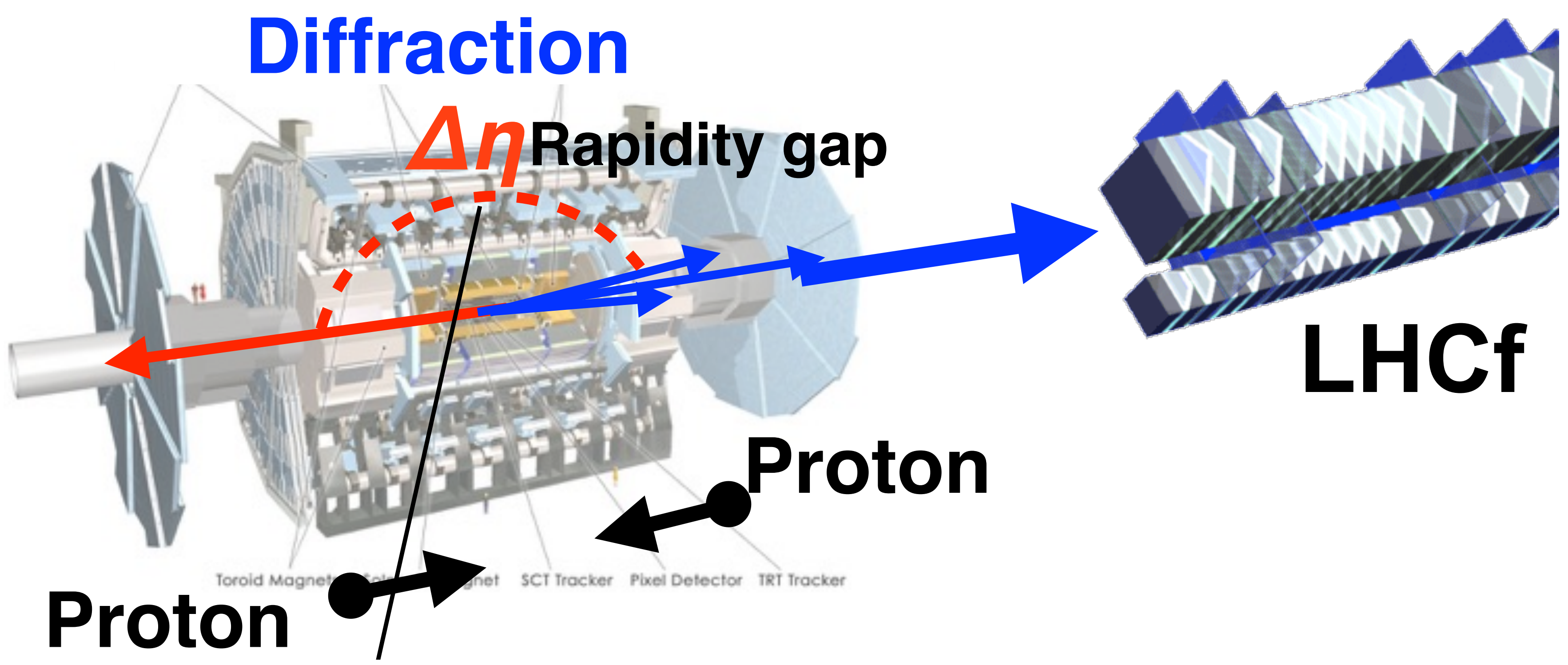
Ref: Y. Makino CERN-THESIS-2017-049

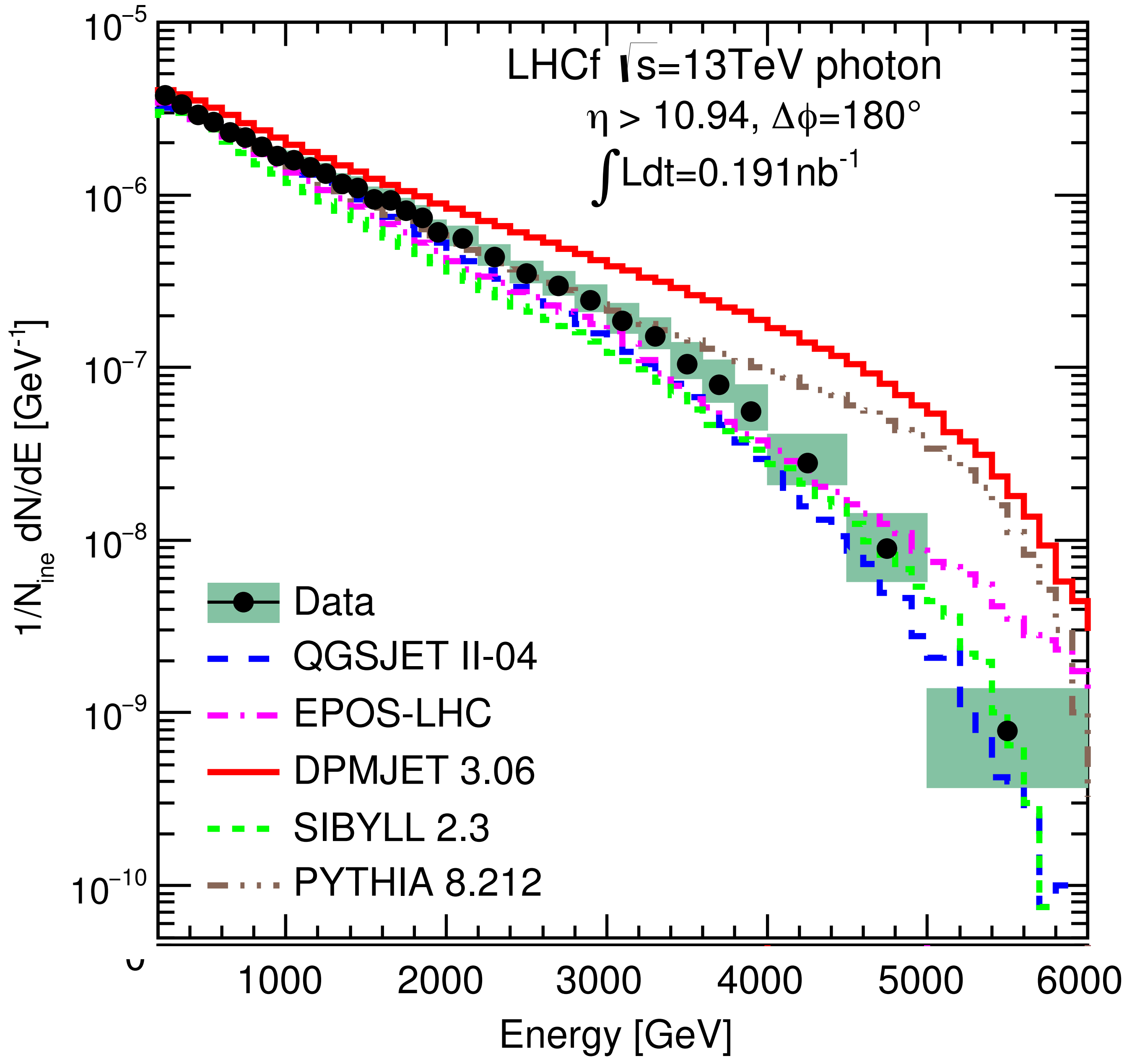


EPOS-LHC, SIBYLL2.3 Good agreement
QGSJET II-04 ~ 30% lower than data

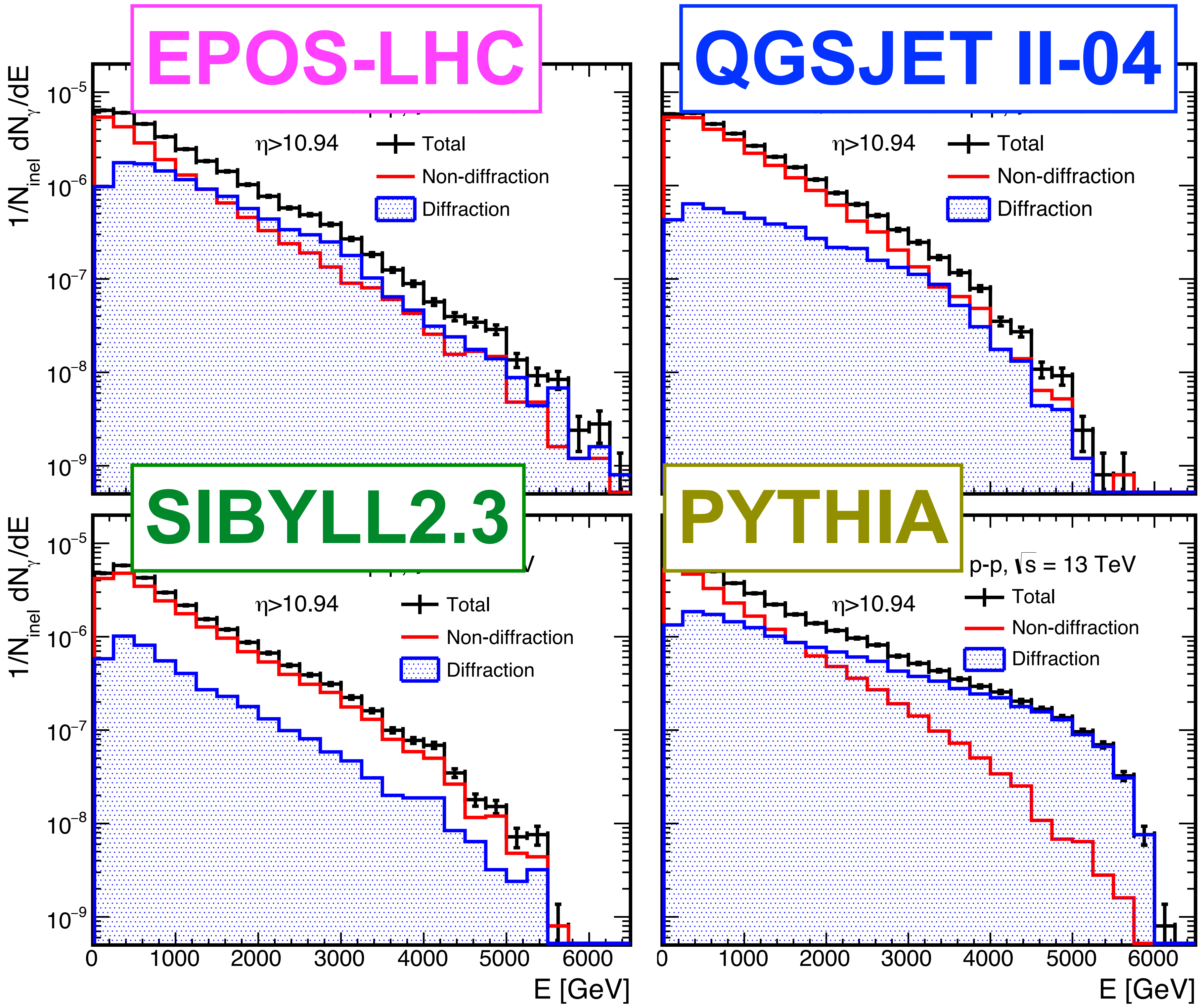
Joint Analysis with ATLAS
- Selection of Diffractive interactions -



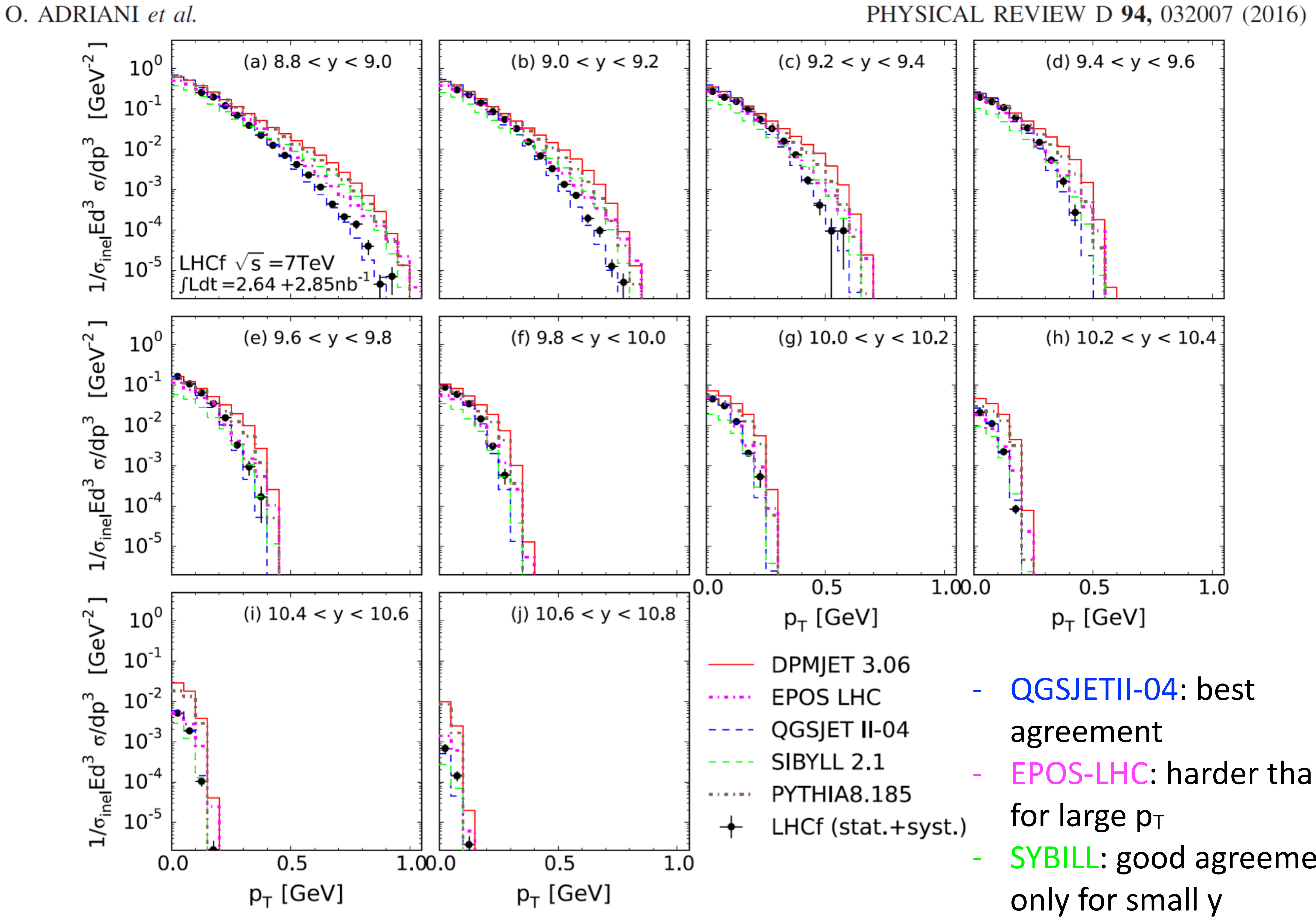




Poster by Q.Zhou; CRD131



π^0 p_T spectra at p+p,7TeV



- QGSJETII-04: best agreement
- EPOS-LHC: harder than data for large p_T
- SYBILL: good agreement only for small y

π^0 p_Z (~E) spectra at p+p,7TeV

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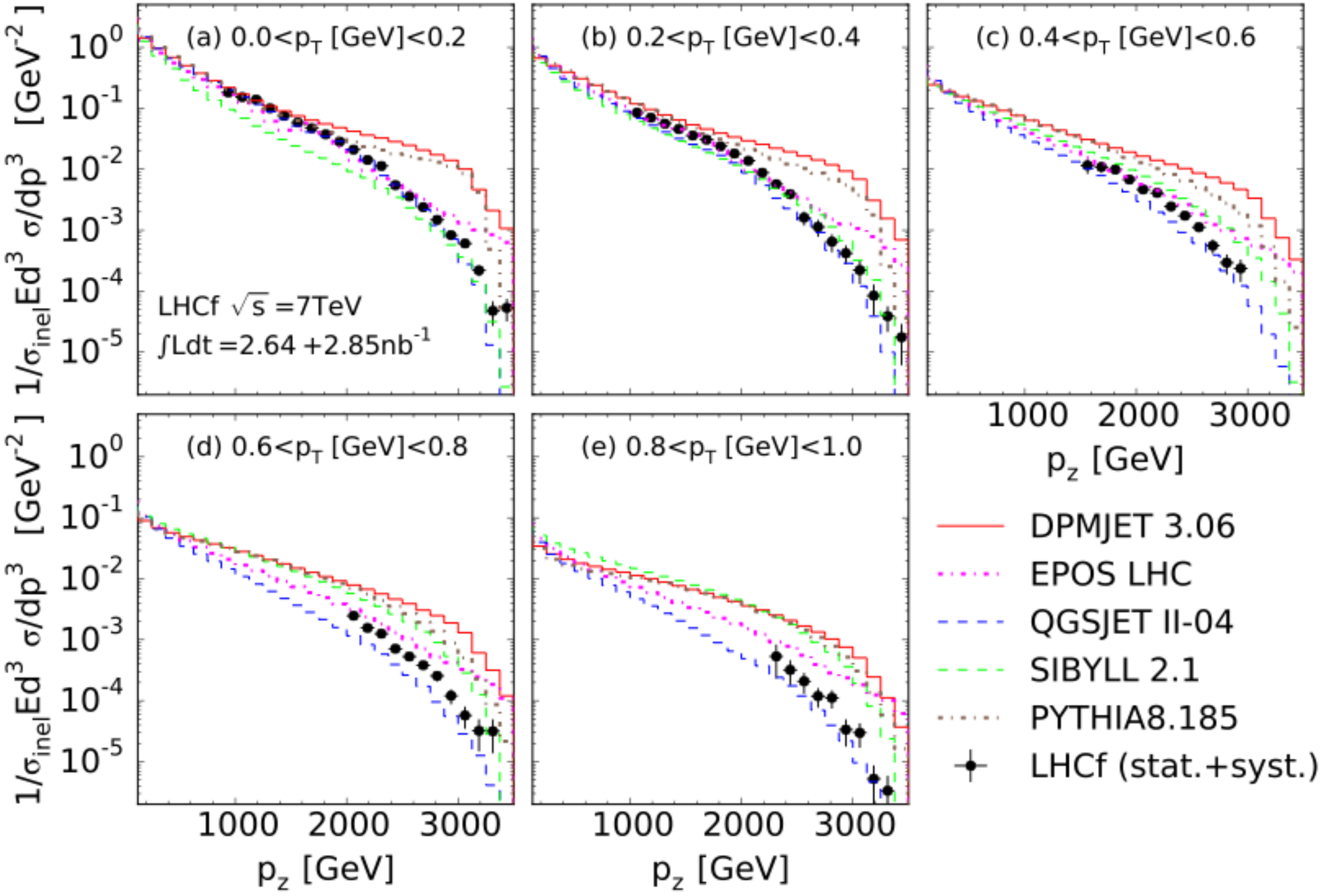
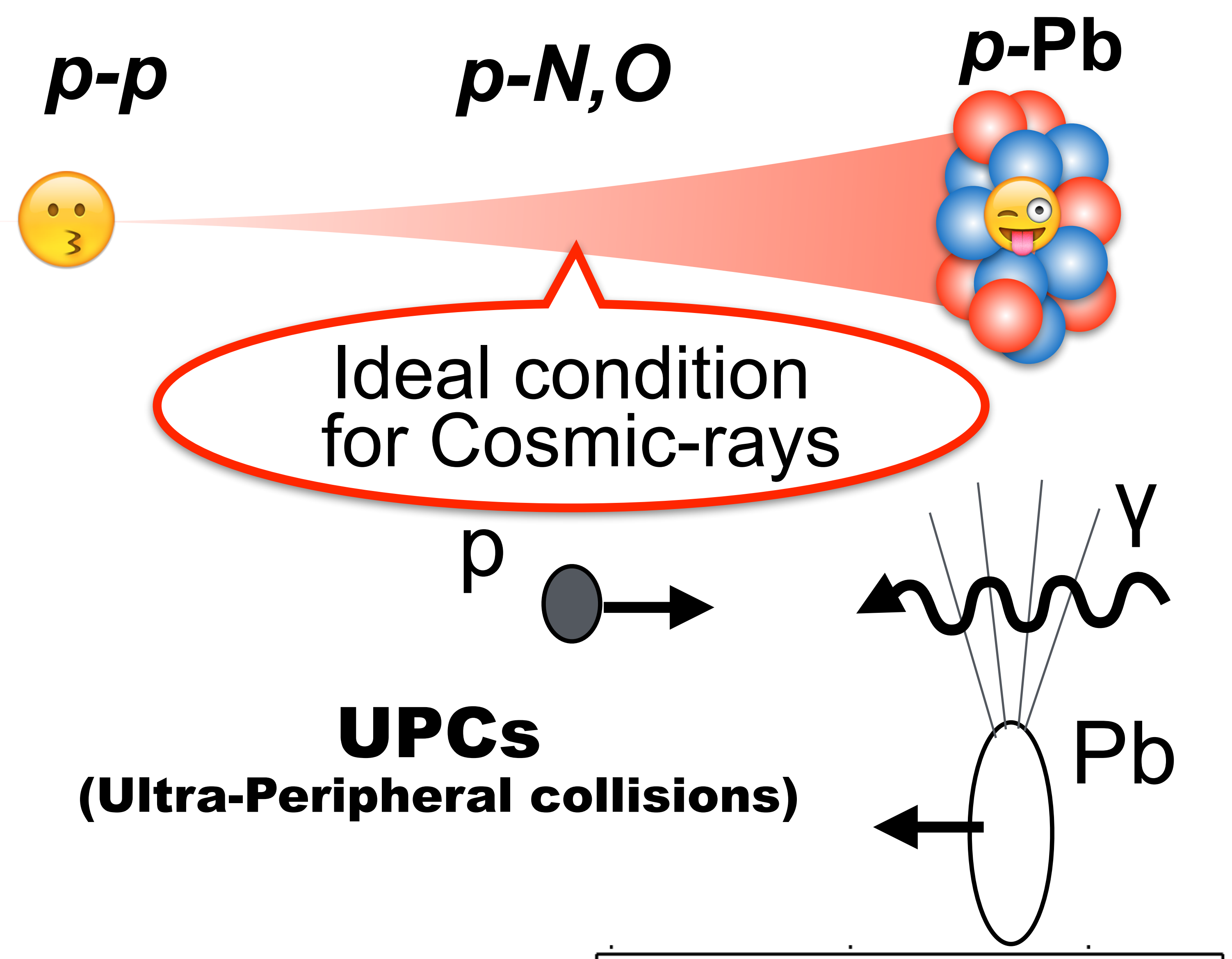


DPMJET and Pythia overestimate over all E-p_T range

Photon, p-Pb $\sqrt{s_{NN}}$=8TeV

Motivation

- Measurement of the nuclear effect
  CR interaction (p-N,O) ≠ p-p
- Large suppression of forward π^0 production was measured at p-Pb, $\sqrt{s_{NN}}$=5TeV

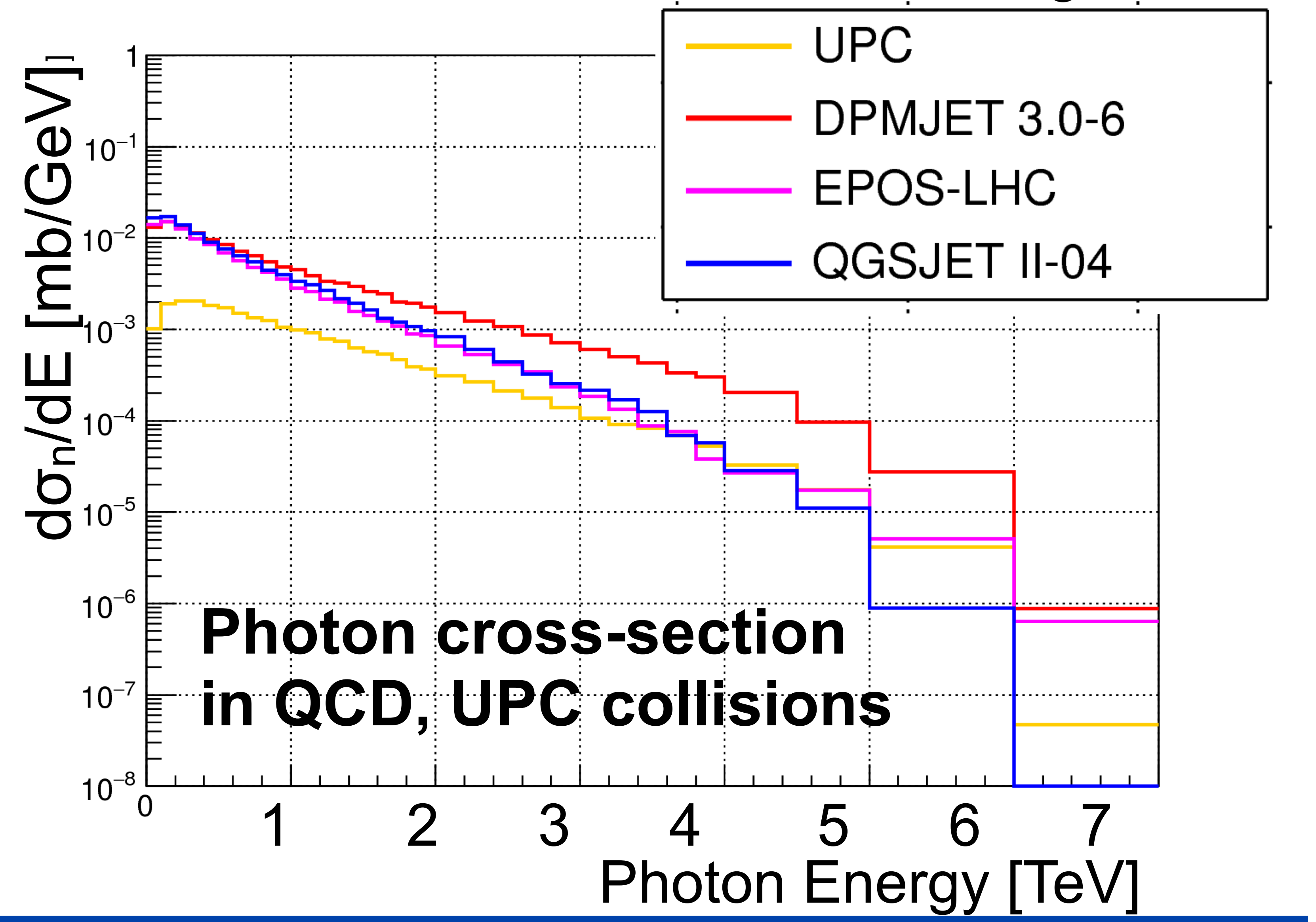


Data

- 2 hour operation in November 2016
- Low pile-up, μ~0.01

Analysis

- Use the well-developed method for photon analysis at p-p,13TeV
- Contribution of UPC collisions
  20 - 50 % of total photon events
  Estimated by the STARLIGHT simulator



Photon, p-Pb $\sqrt{s_{NN}}$=8TeV