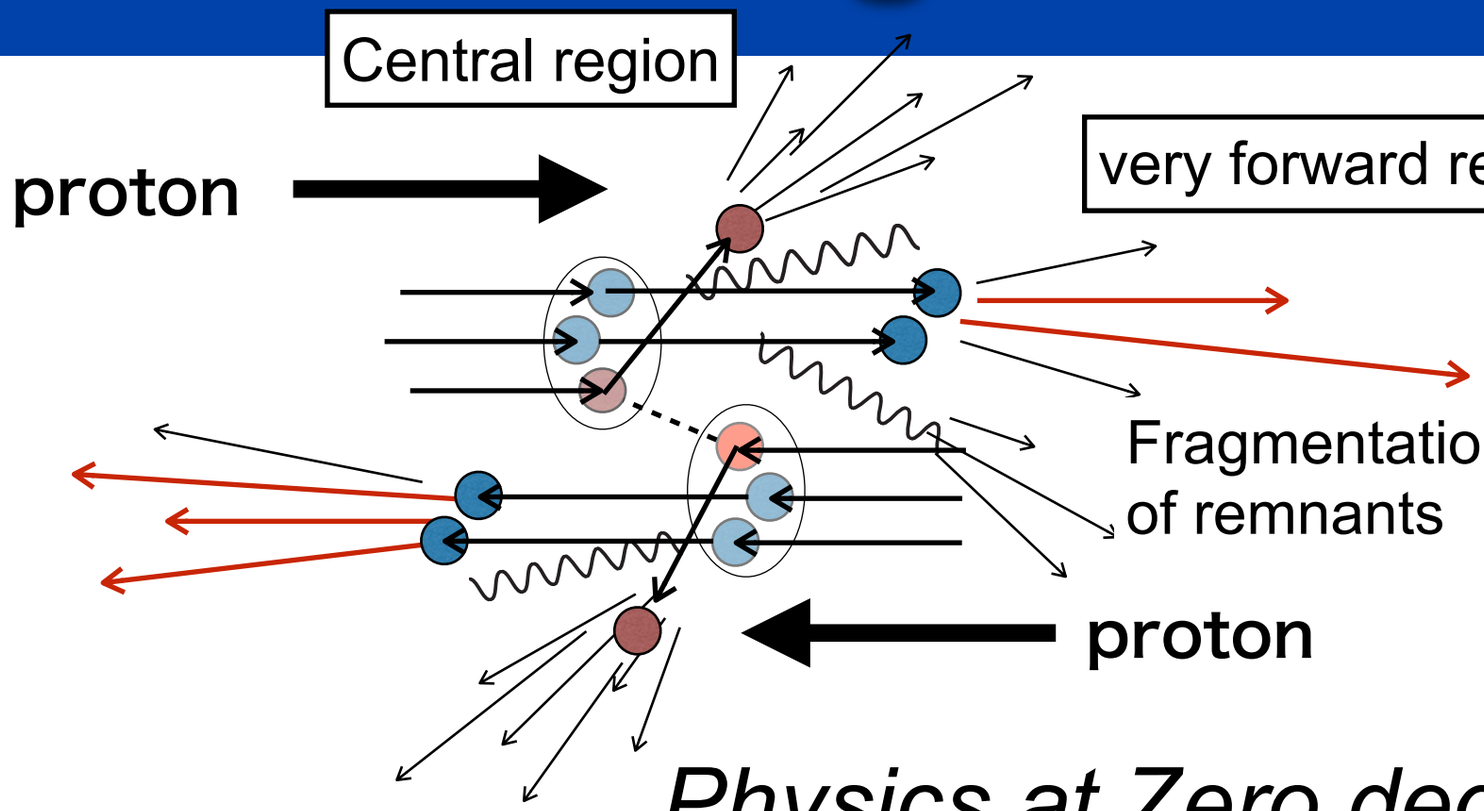
LHCf/RHICf: a zero degree calorimeter at LHC and RHIC

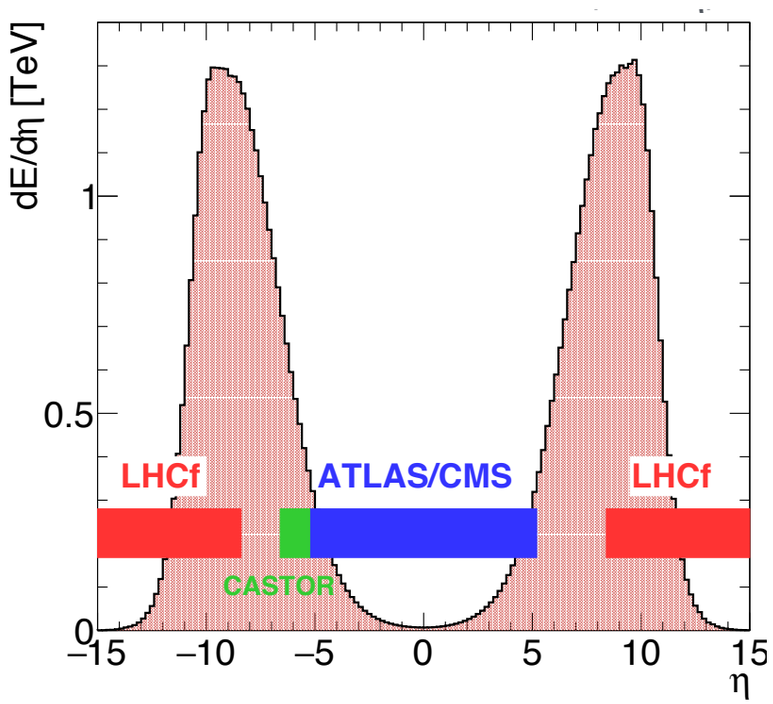
Hiroaki MENJO *Nagoya University*

Zero-degree of collisions



Detector
(LHCf or
RHICf)

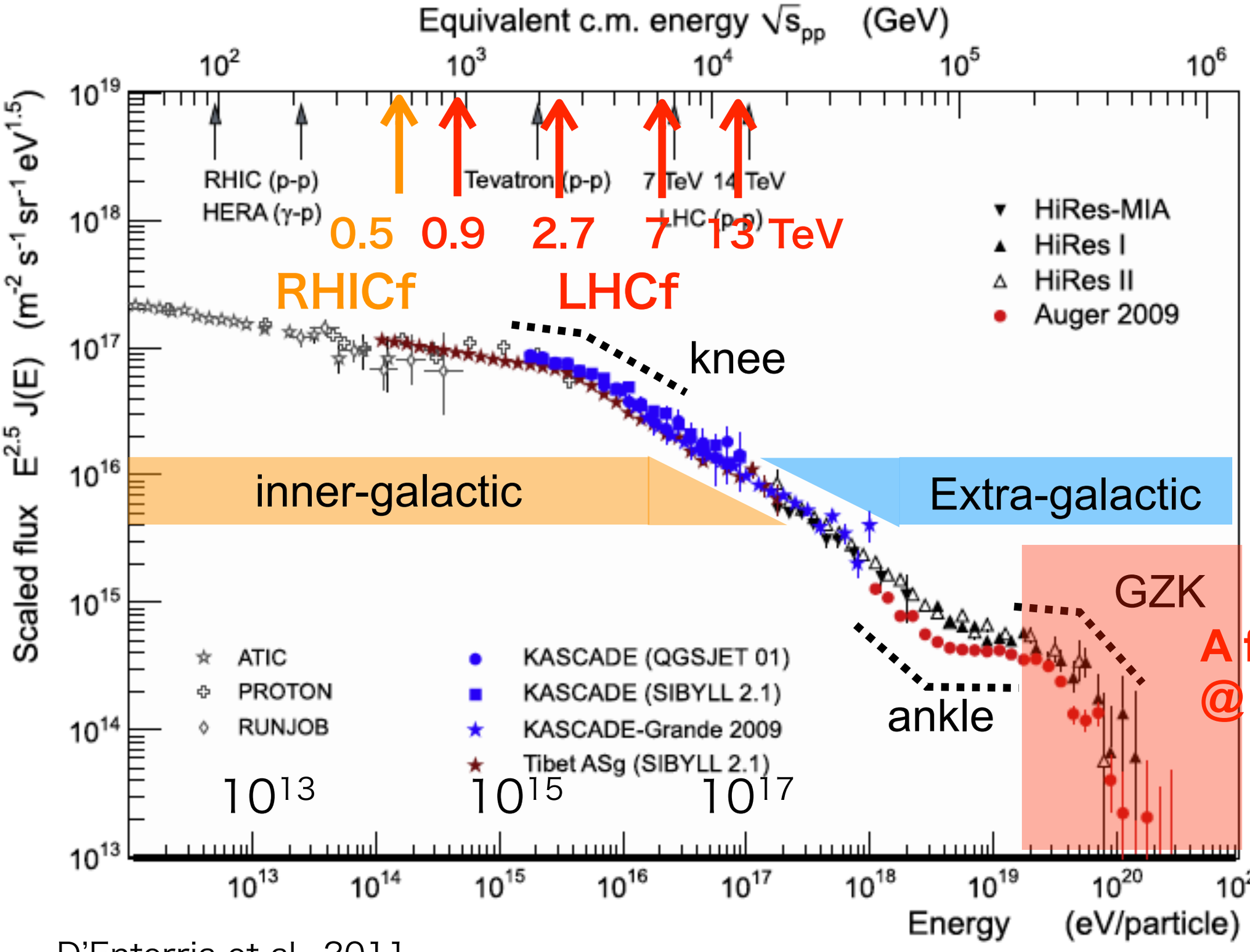
Physics at Zero degree

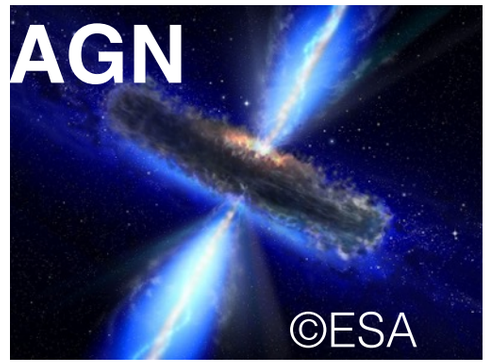


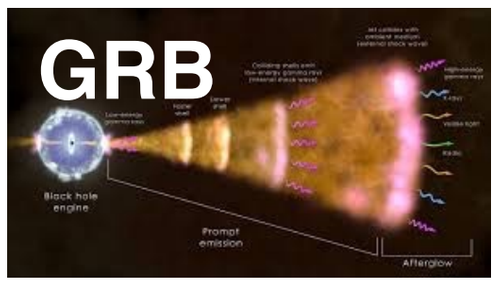
- ✓Soft collisions, low-pT < 1GeV
  - → pQCD does not work.
  - → Phenomenological model is needed
- ✓High energy flux
  - → Most of longitudinal momentum is carried by remnants of collisions.

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

Cosmic-rays







©NASA

A few degrees @ 10^{19}eV proton

UHECR Astronomy

D'Enterria et al., 2011

UHECR observations

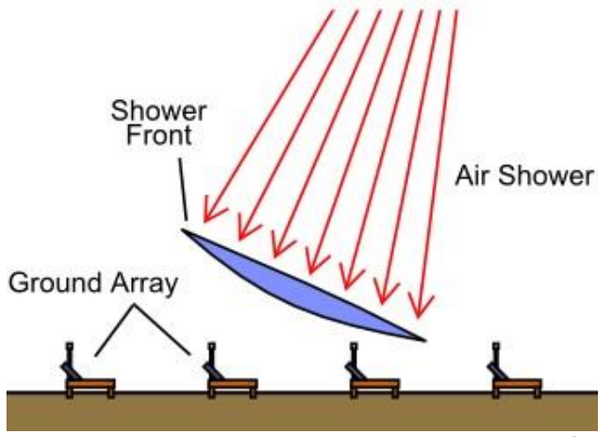
Indirect observation by using the air shower technique

😊 Easy to have a large acceptance

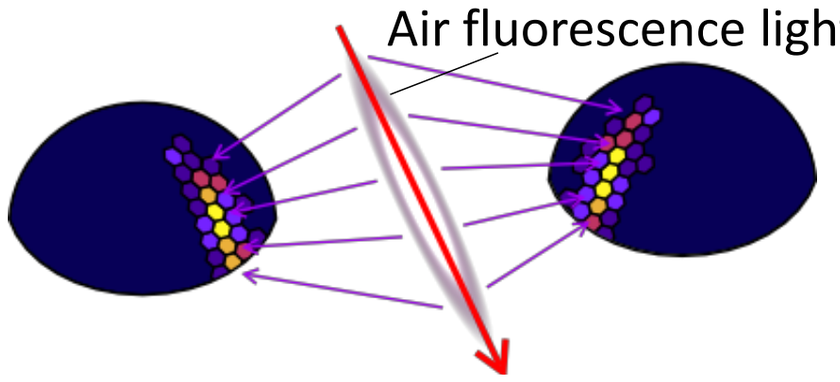
😔 Uncertainty in the reconstruction of primary CR information.

- Energy spectrum
- Anisotropy
- Chemical composition

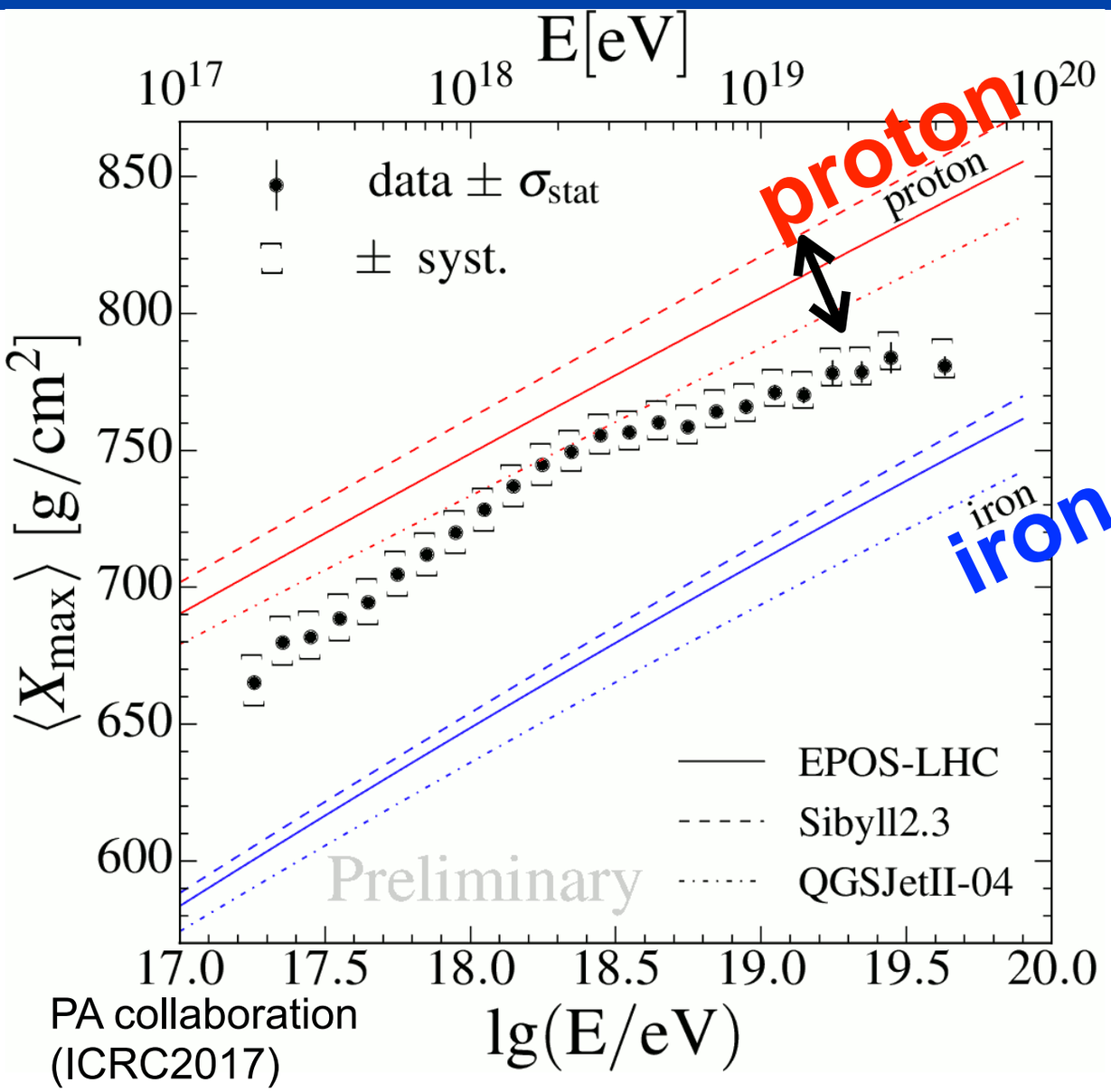
Surface detector (SD)



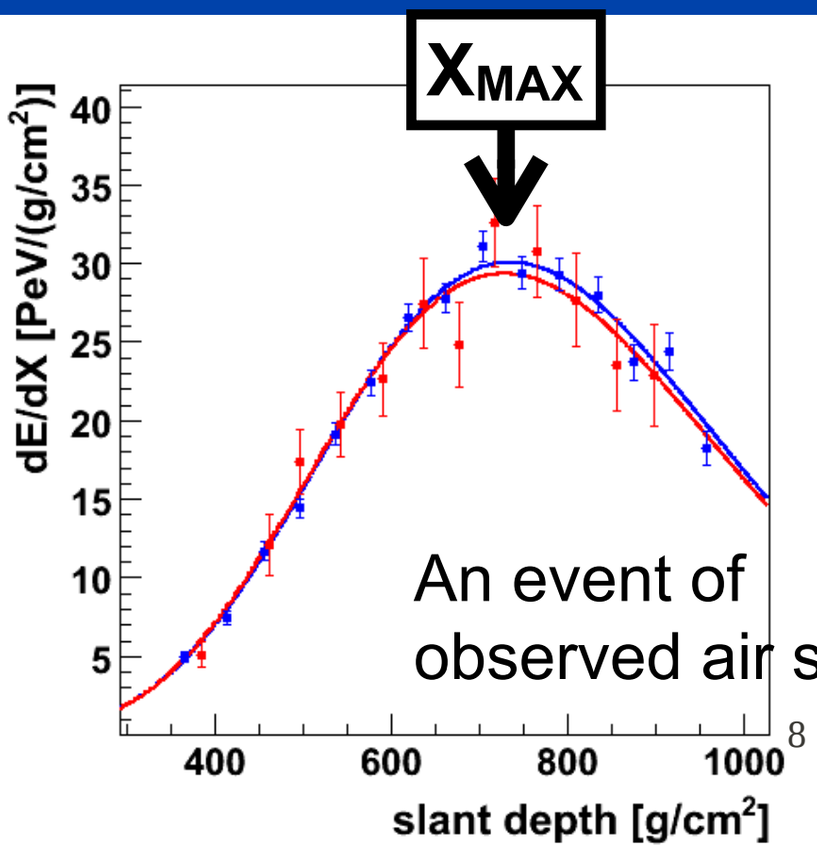
Fluorescence detector (FD)



Composition measurement



PA collaboration
(ICRC2017)



Uncertainty of hadron interaction models

V

Error of $\langle X_{max} \rangle$ measurement

- ✓ **Improvement of hadronic interaction models is one of the keys for UHECR studies.**
- ✓ **LHC provide unique opportunities to verify the models at $\sqrt{s}$=14TeV ($E_{CR}=10^{17}$eV)**

- **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** $k = \frac{E_{lead}}{E_{avail}}$

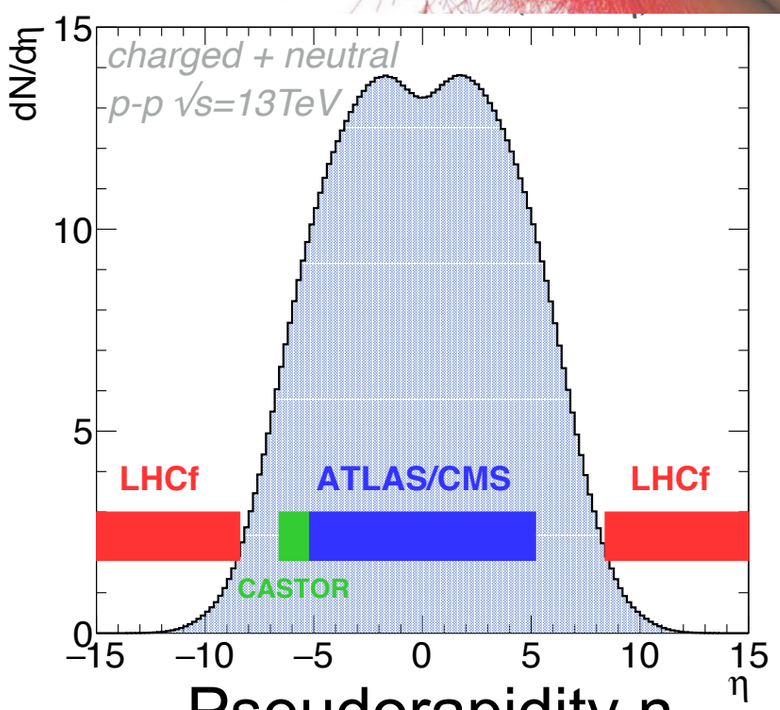
- If small k (π^0s carry more energy): rapid development
- If large k (baryons carry more energy): deep penetrating

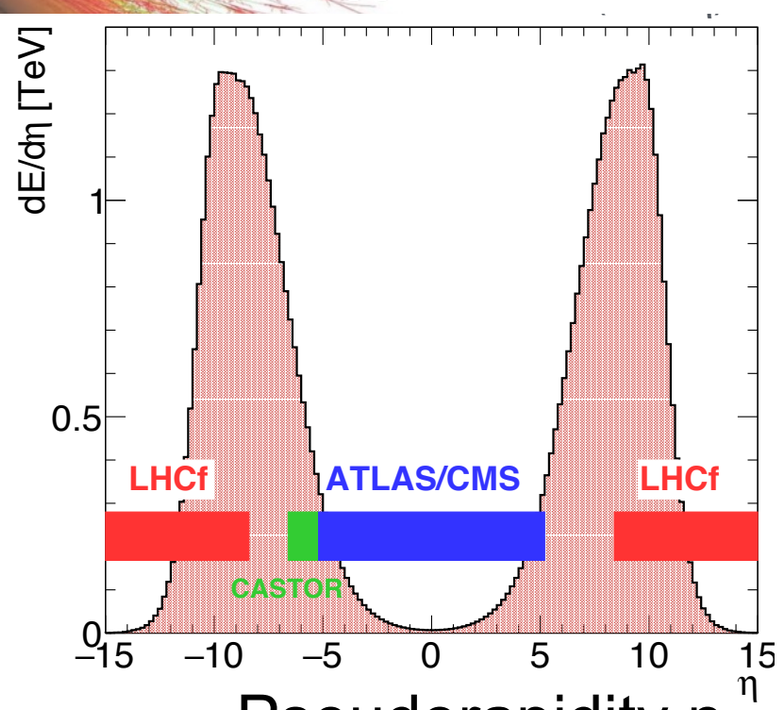
- **Secondary interactions** (n, p, π)

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

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

Multiplicity ***Energy Flow***





The LHCf Collaboration

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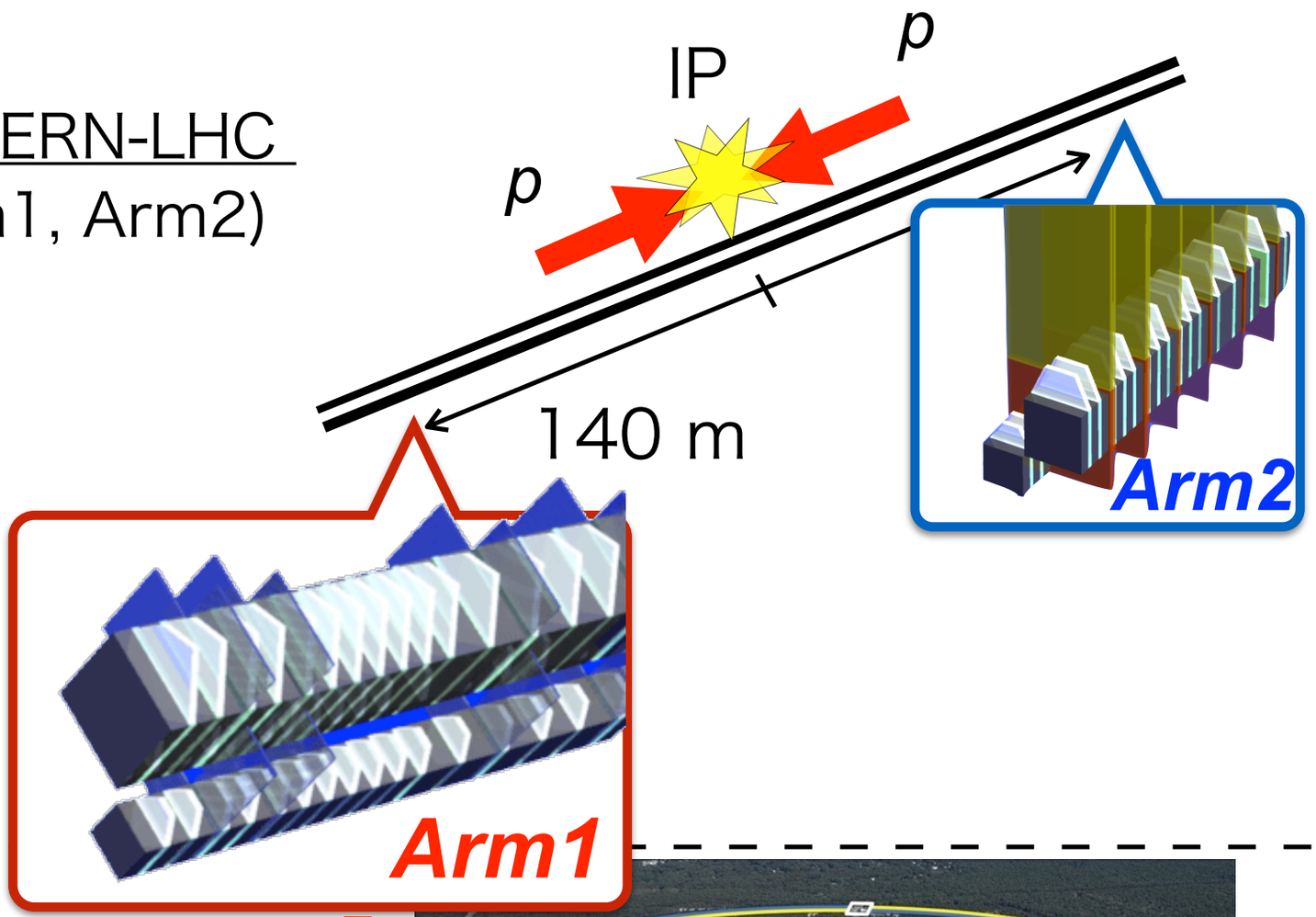
A. Trocomi *(INFN Catania)*

LHCf and RHICf experiments

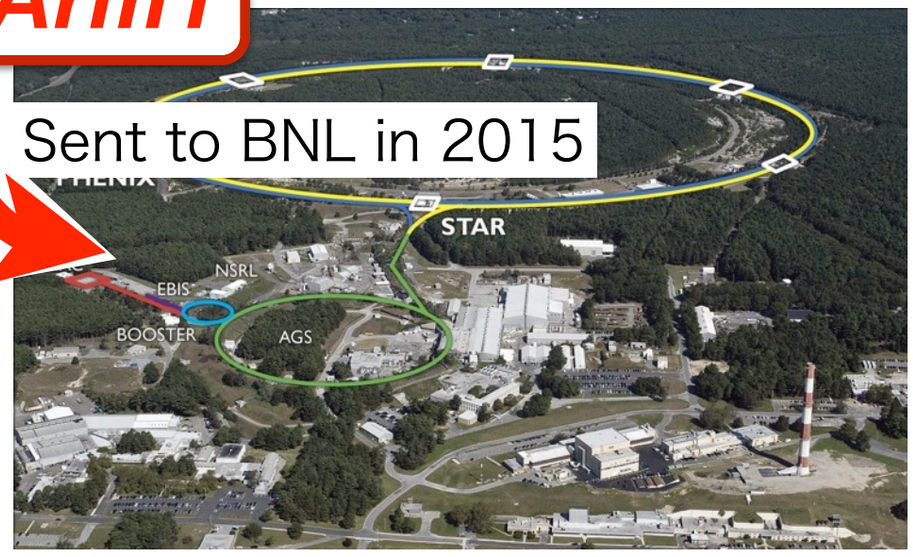
LHCf experiment

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



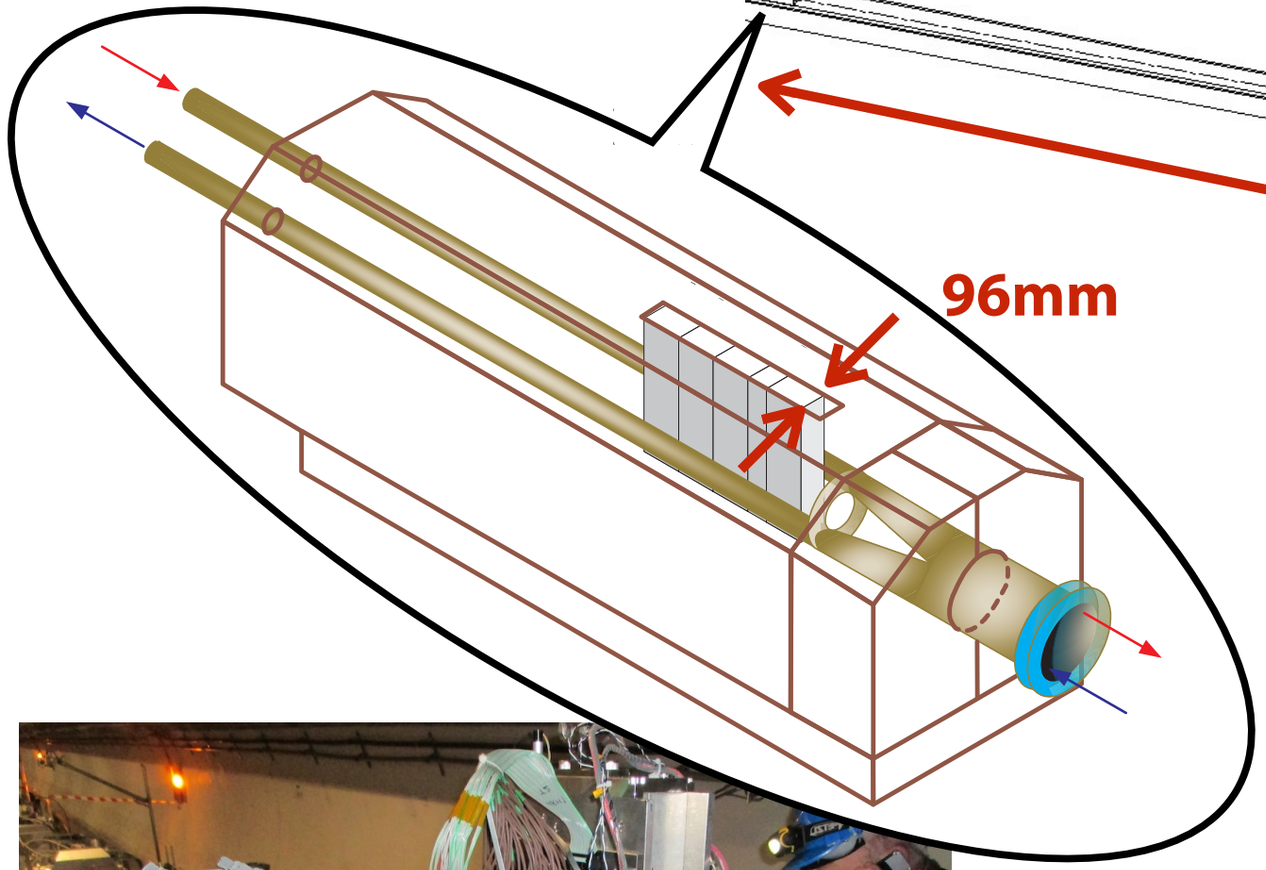
RHICf experiment

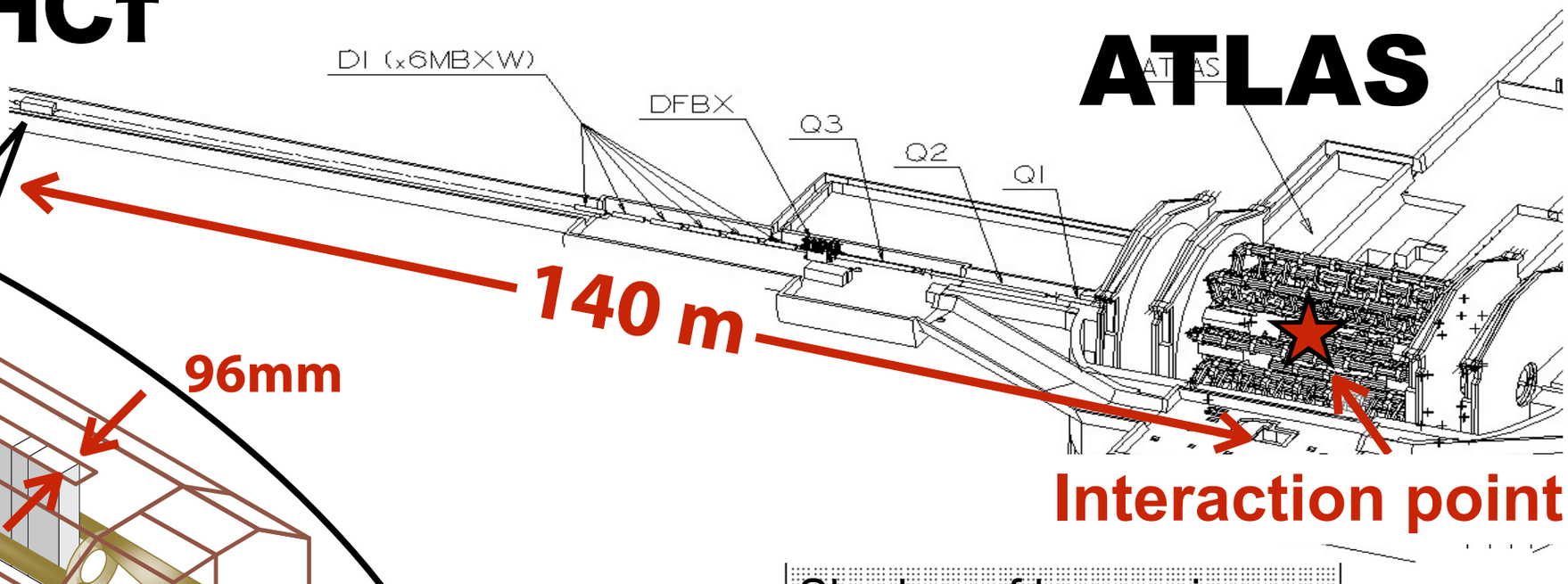
- Zero degree measurement at BNL-RHIC
- Only one detector at 18 m from STAR IP
- Spin asymmetry measurements with polarized proton beams
- Operation: pp √s = 510 GeV (2017)

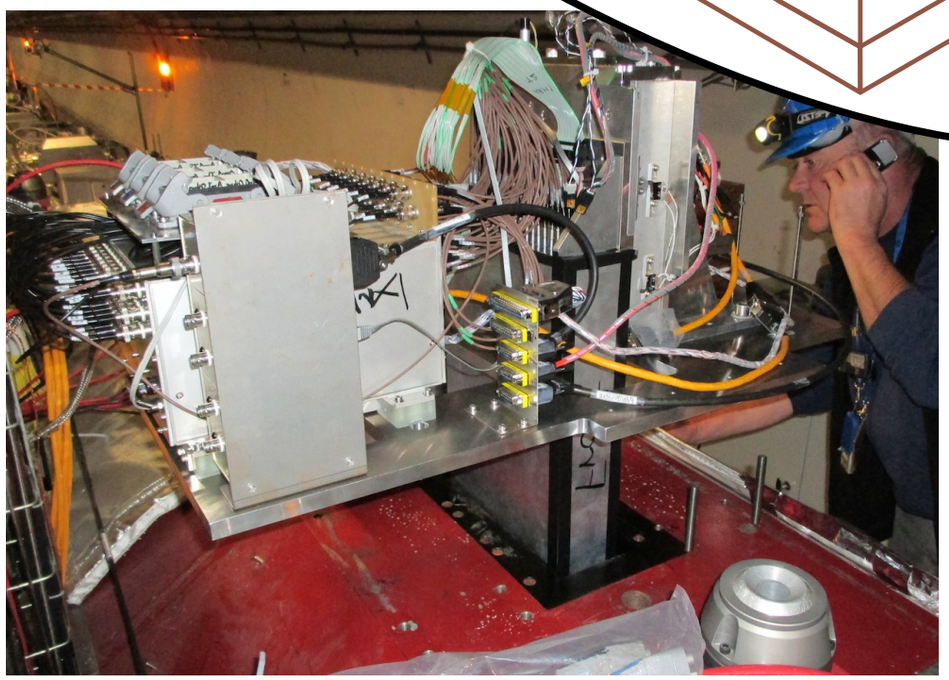


LHCf experimental setup

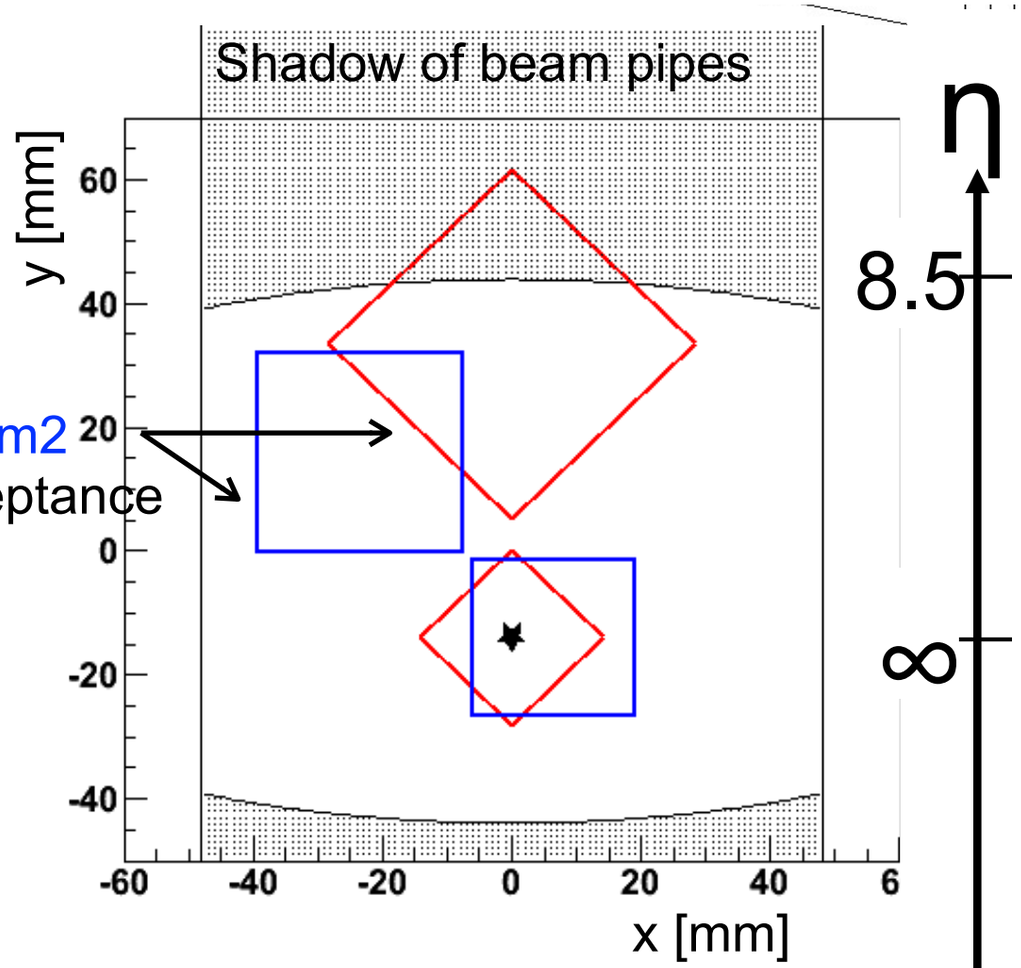
LHCf







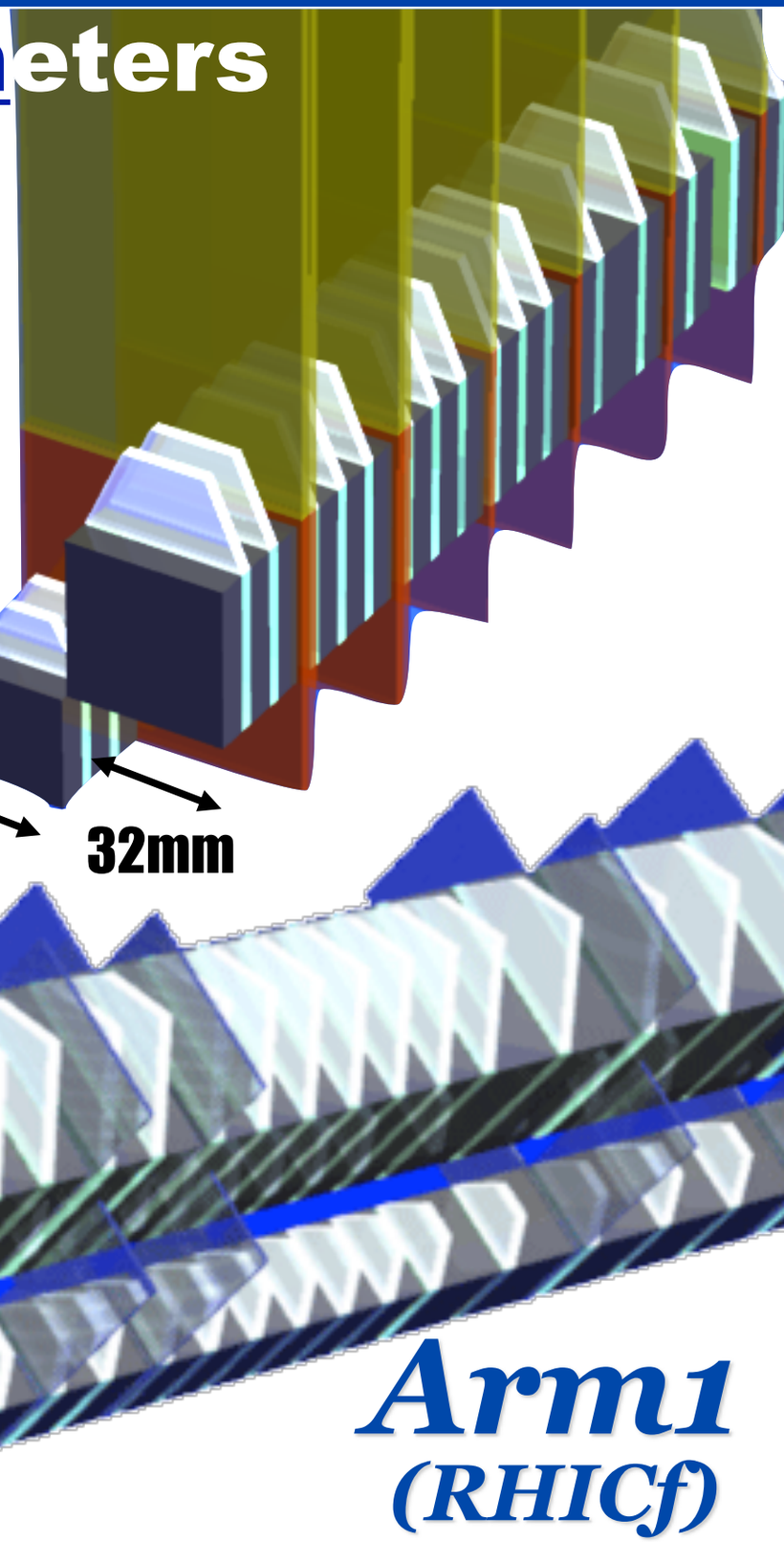
Arm1 and Arm2
Calorimeter acceptance

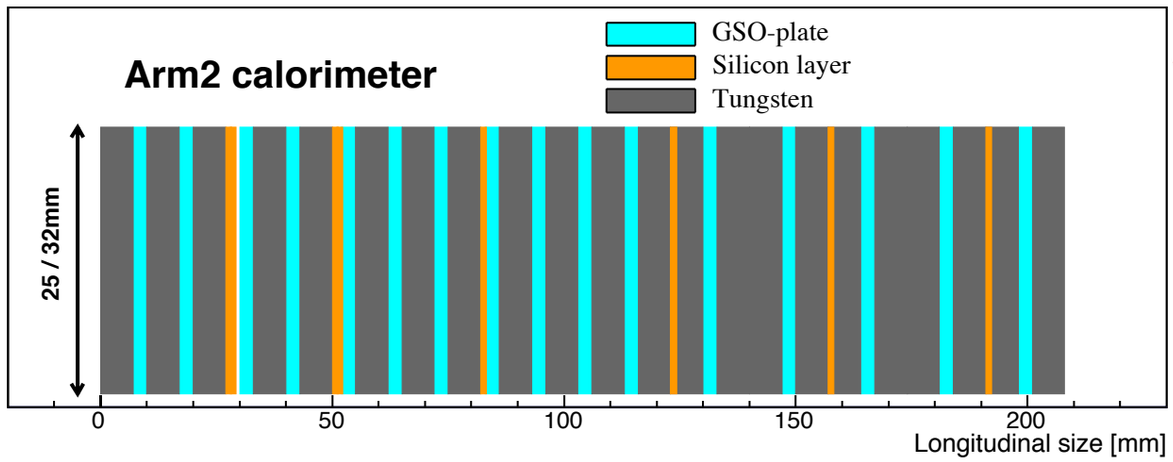


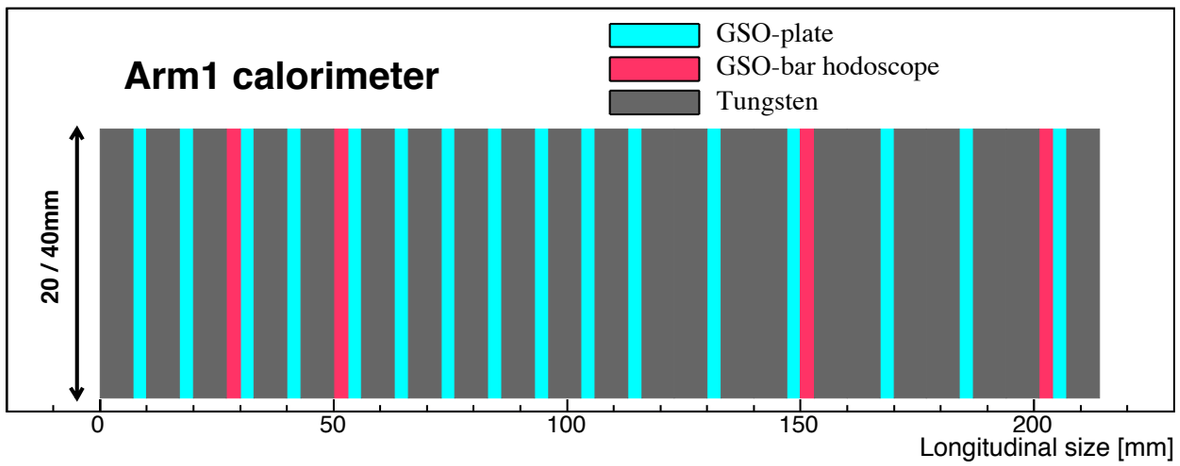
The LHCf/RHICf detectors

Sampling and Positioning Calorimeters

- 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**

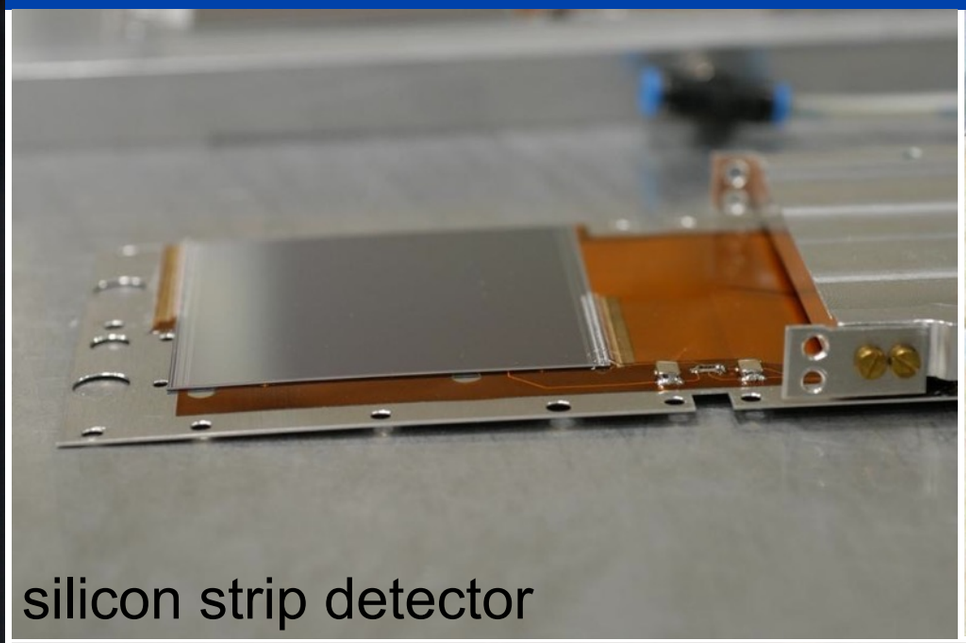




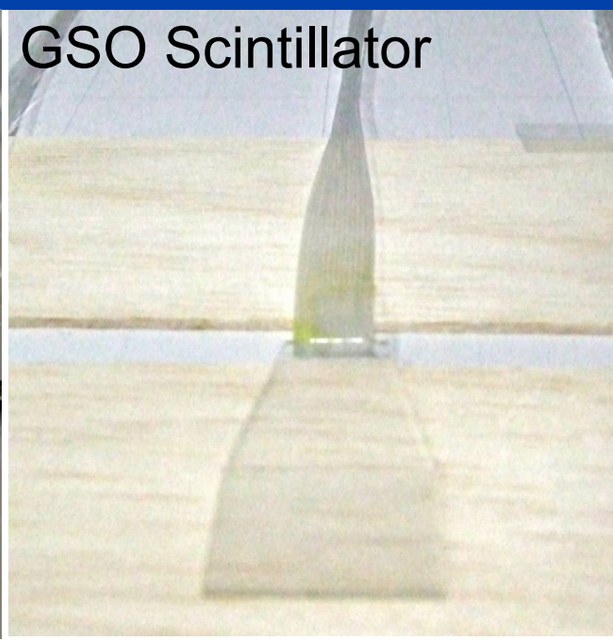


The LHCf detectors

Arm1 Detector

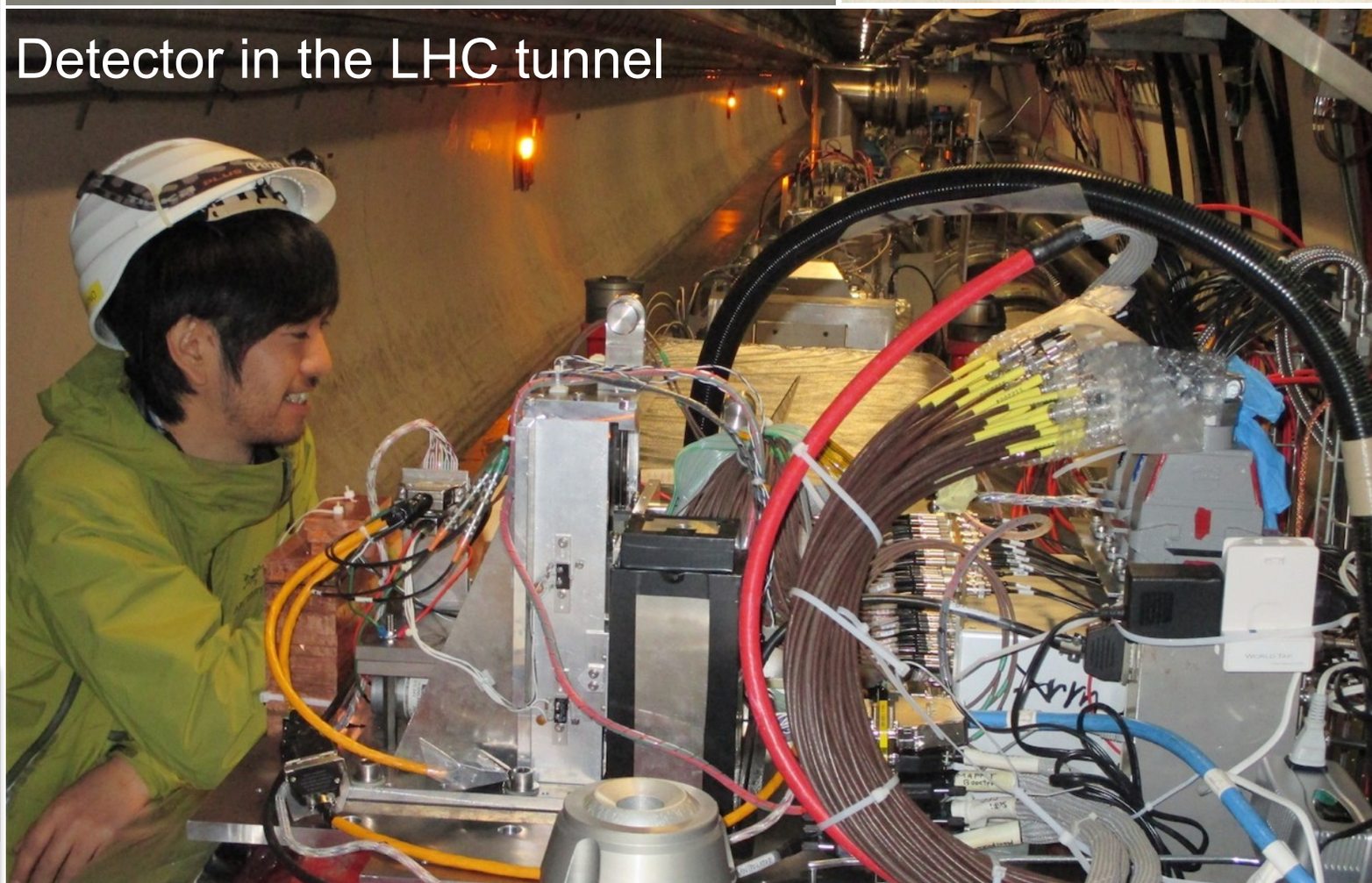


silicon strip detector



GSO Scintillator

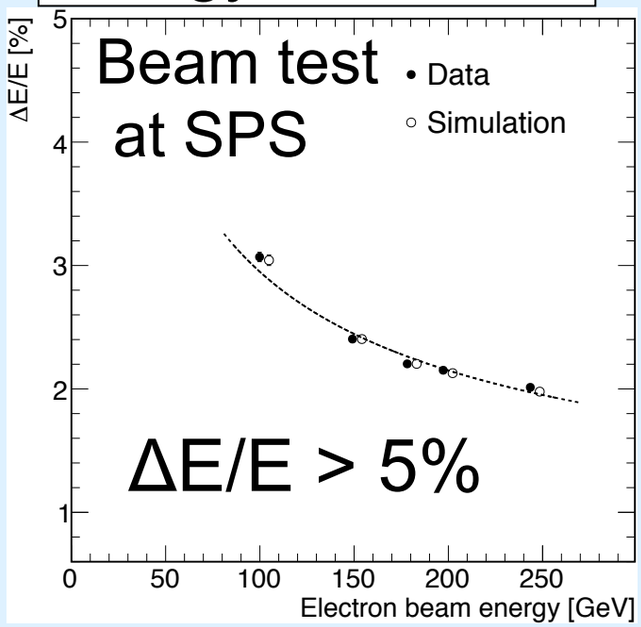
Detector in the LHC tunnel



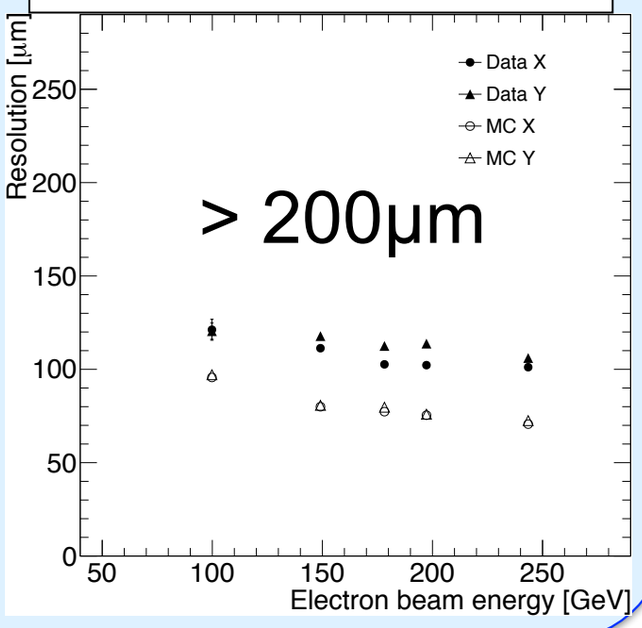
Calorimeter performances

EM showers

Energy resolution

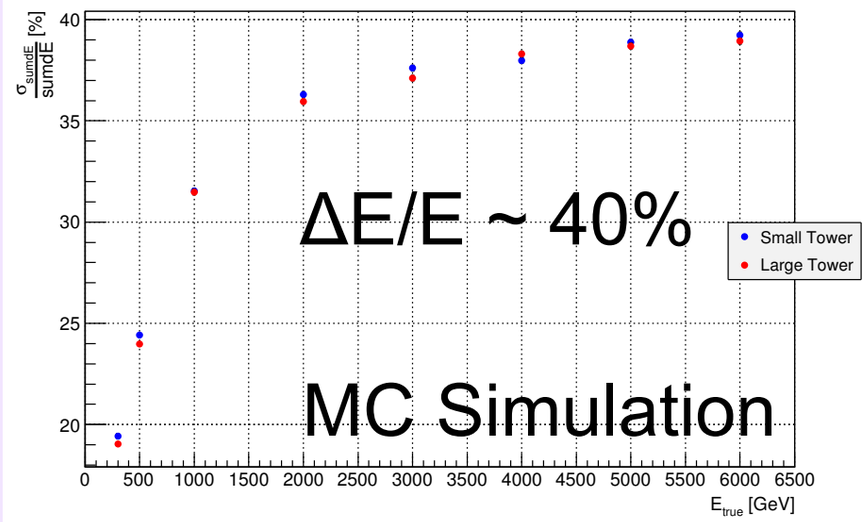


Position resolution

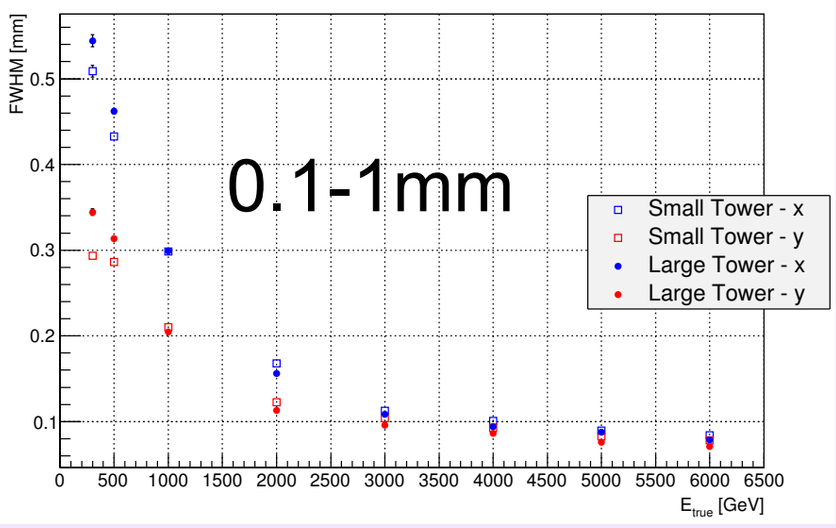


Had. showers

Energy resolution



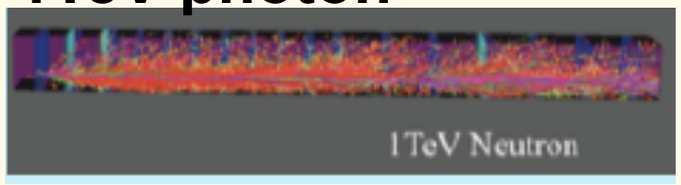
Position resolution



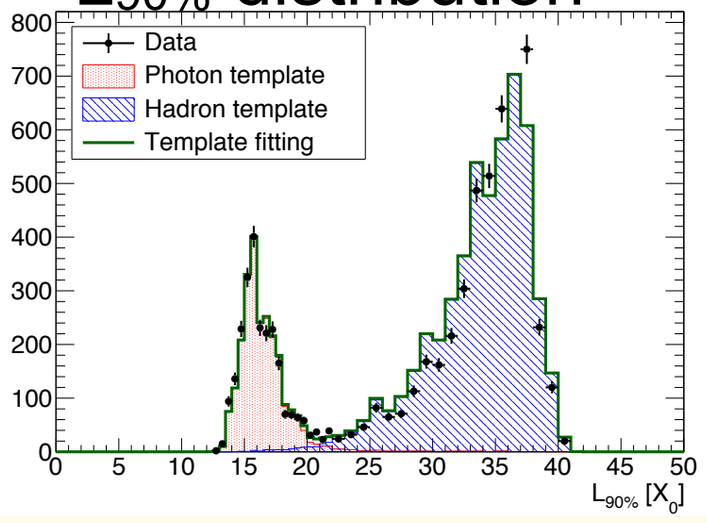
PID

400 GeV photon

1TeV photon



$L_{90\%}$ distribution

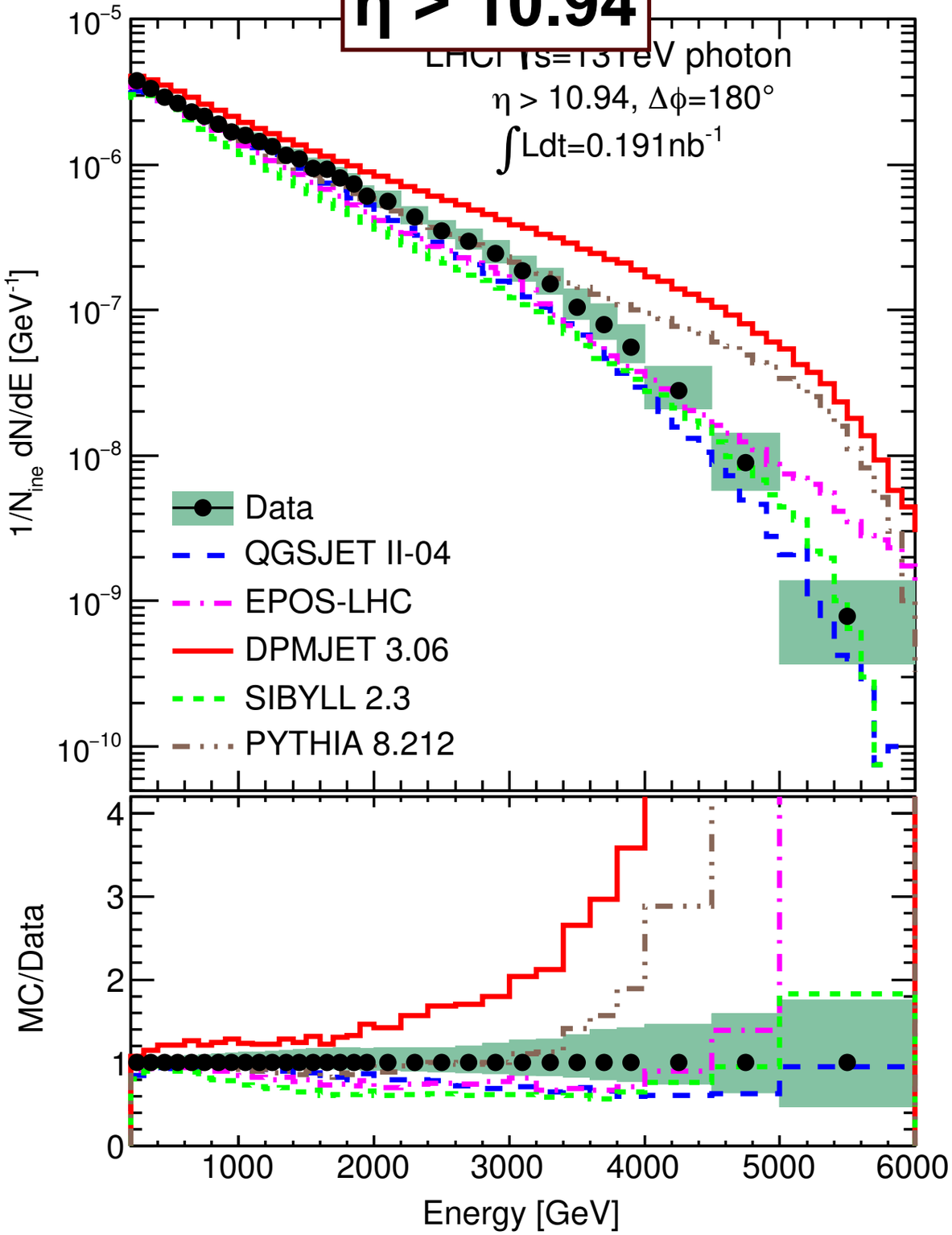


LHCf operations and results

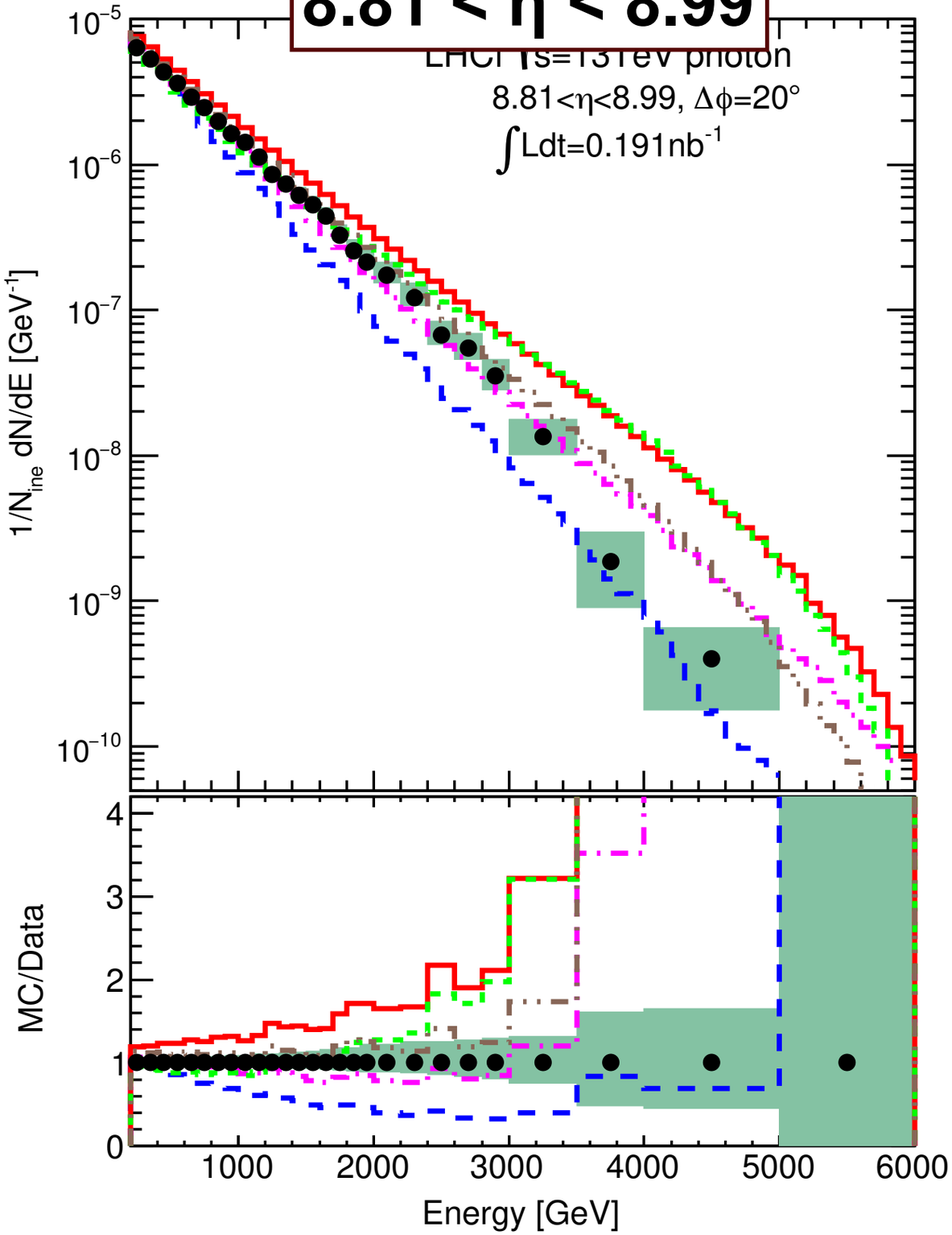
Run	E_{lab} (eV)	Photon	Neutron	π^0	
p-p $\sqrt{s}$=0.9TeV (2009/2010)	4.3×10^{14}	PLB 715, 298 (2012)		-	
p-p $\sqrt{s}$=2.76TeV (2013)	4.1×10^{15}			PRC 86, 065209 (2014)	PRD 94 032007 (2016)
p-p $\sqrt{s}$=7TeV (2010)	2.6×10^{16}	PLB 703, 128 (2011)	PLB 750 360 (2015)	PRD 86, 092001 (2012)	
p-p $\sqrt{s}$=13TeV (2015)	9.0×10^{16}	PLB 780, 233 (2018)	JHEP, 2018, 73 (2018)	on-going	
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			

Photon at p-p, 13TeV

η > 10.94

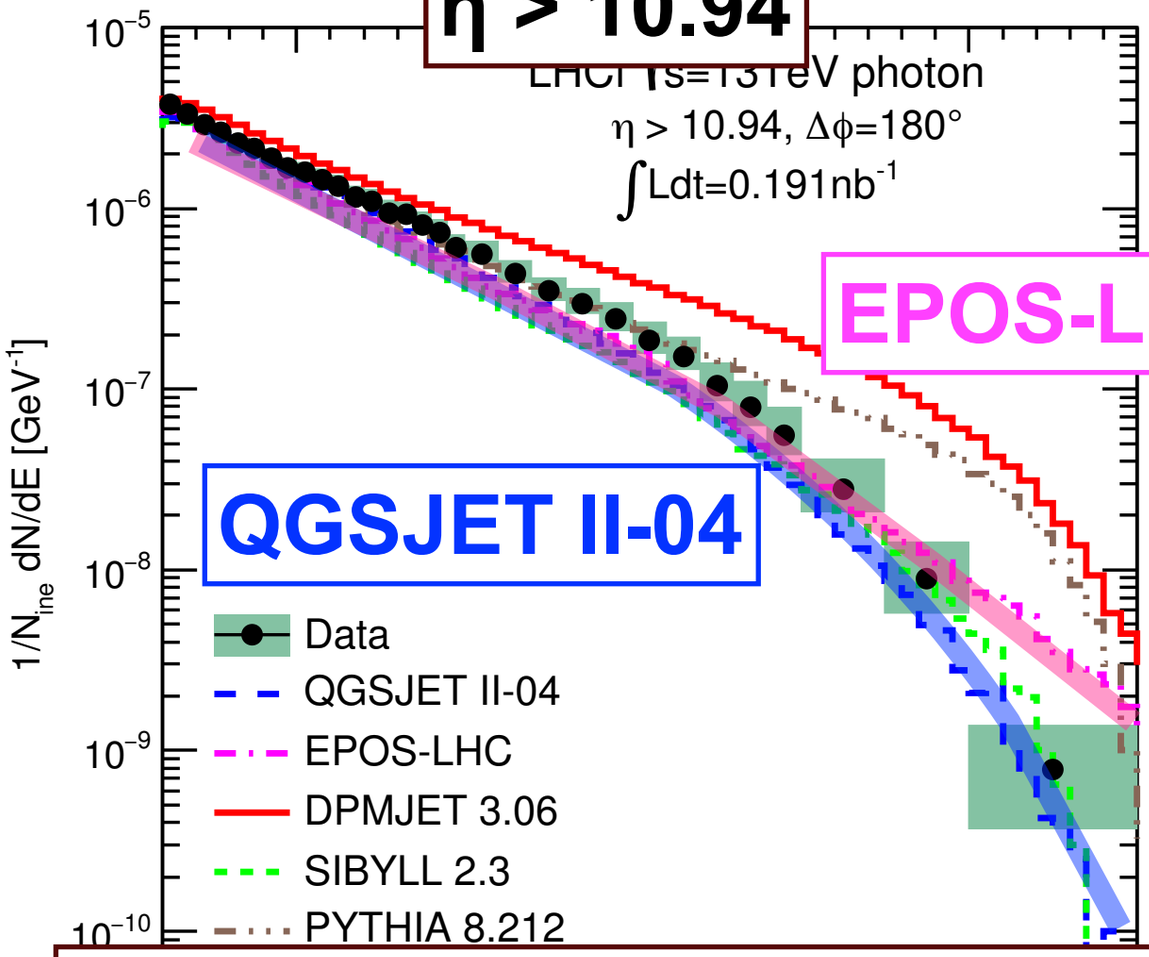


8.81 < η < 8.99

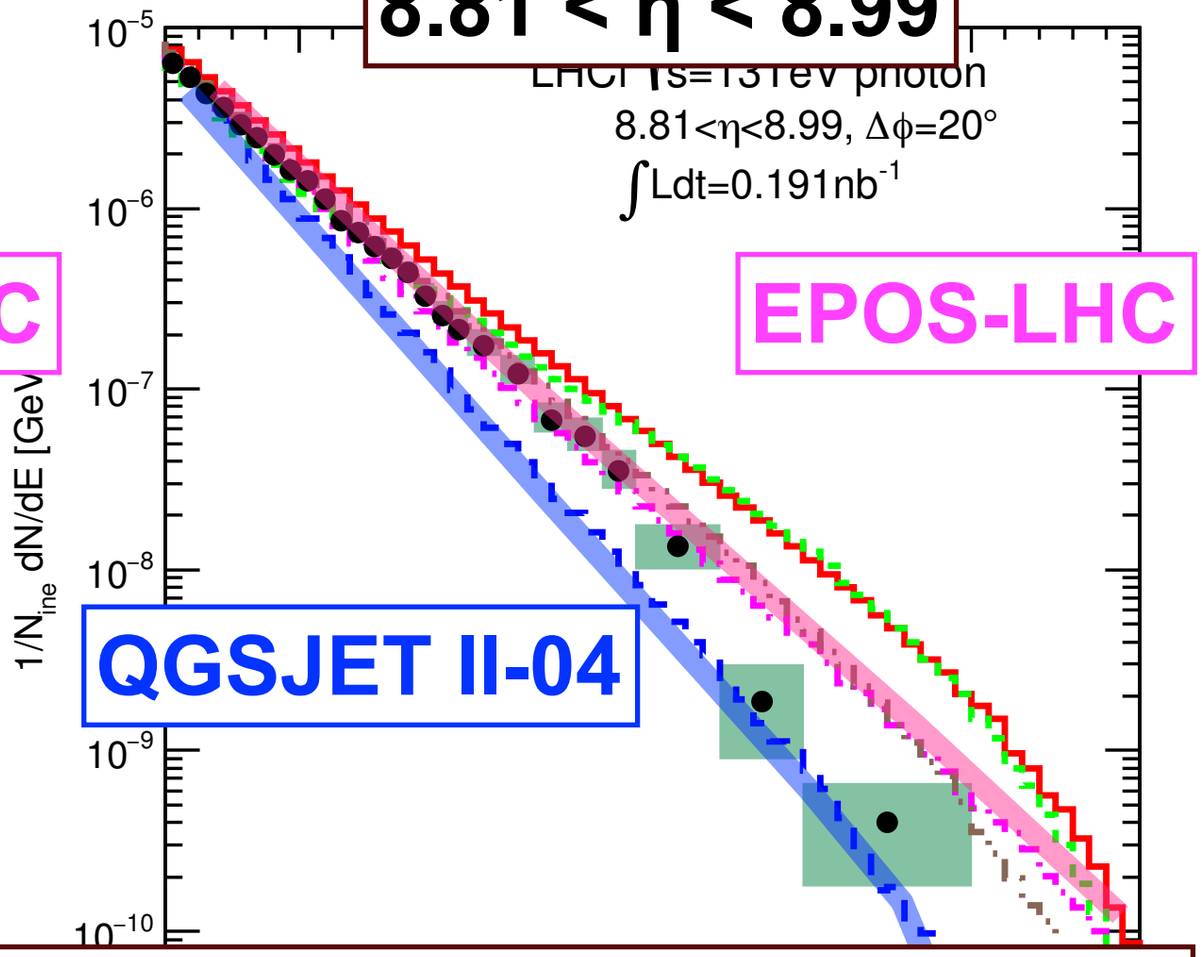


Photon at p-p, 13TeV

η > 10.94



8.81 < η < 8.99



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

Photon Energy Flow

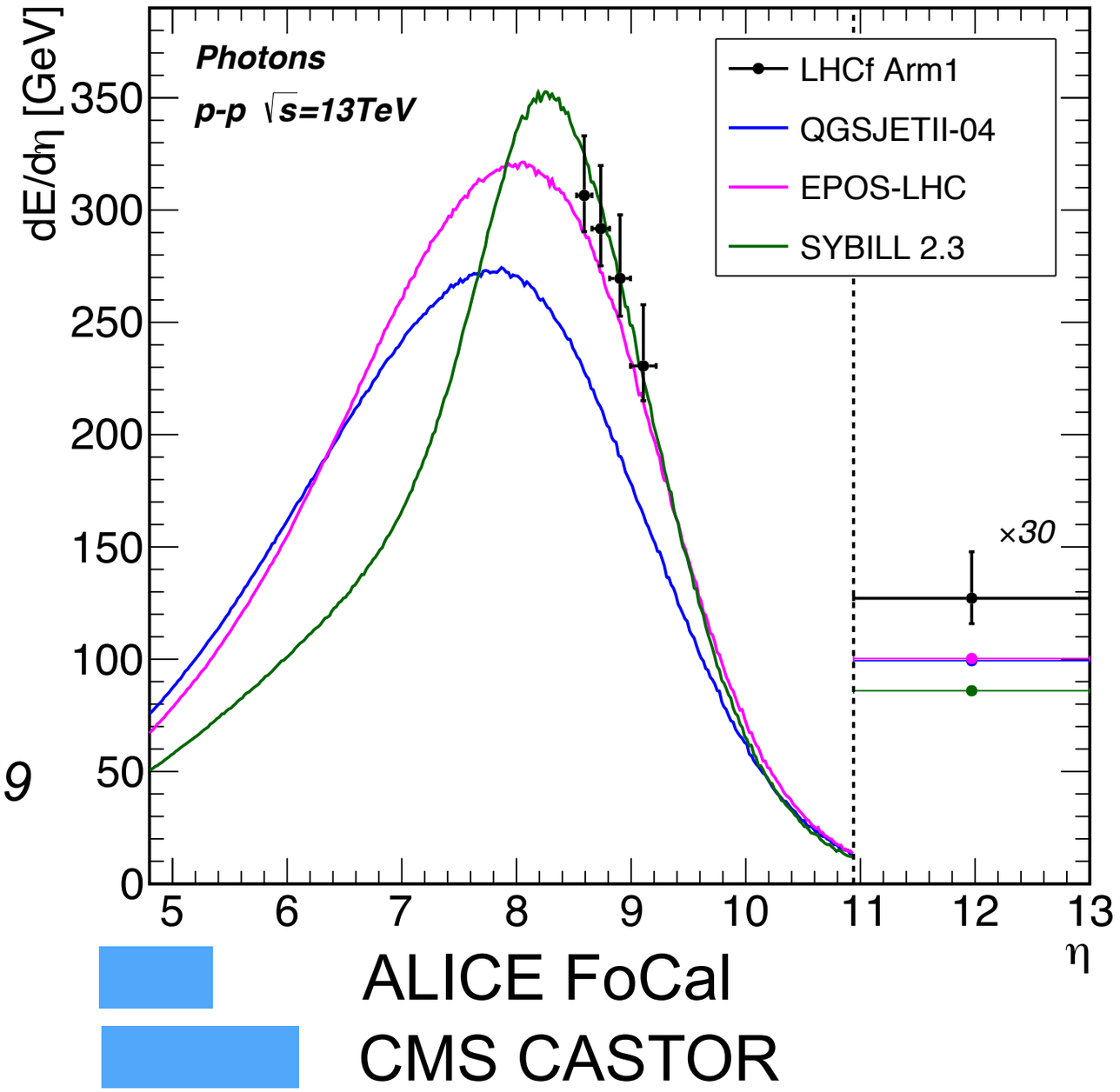
Energy Flow Calculation:

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

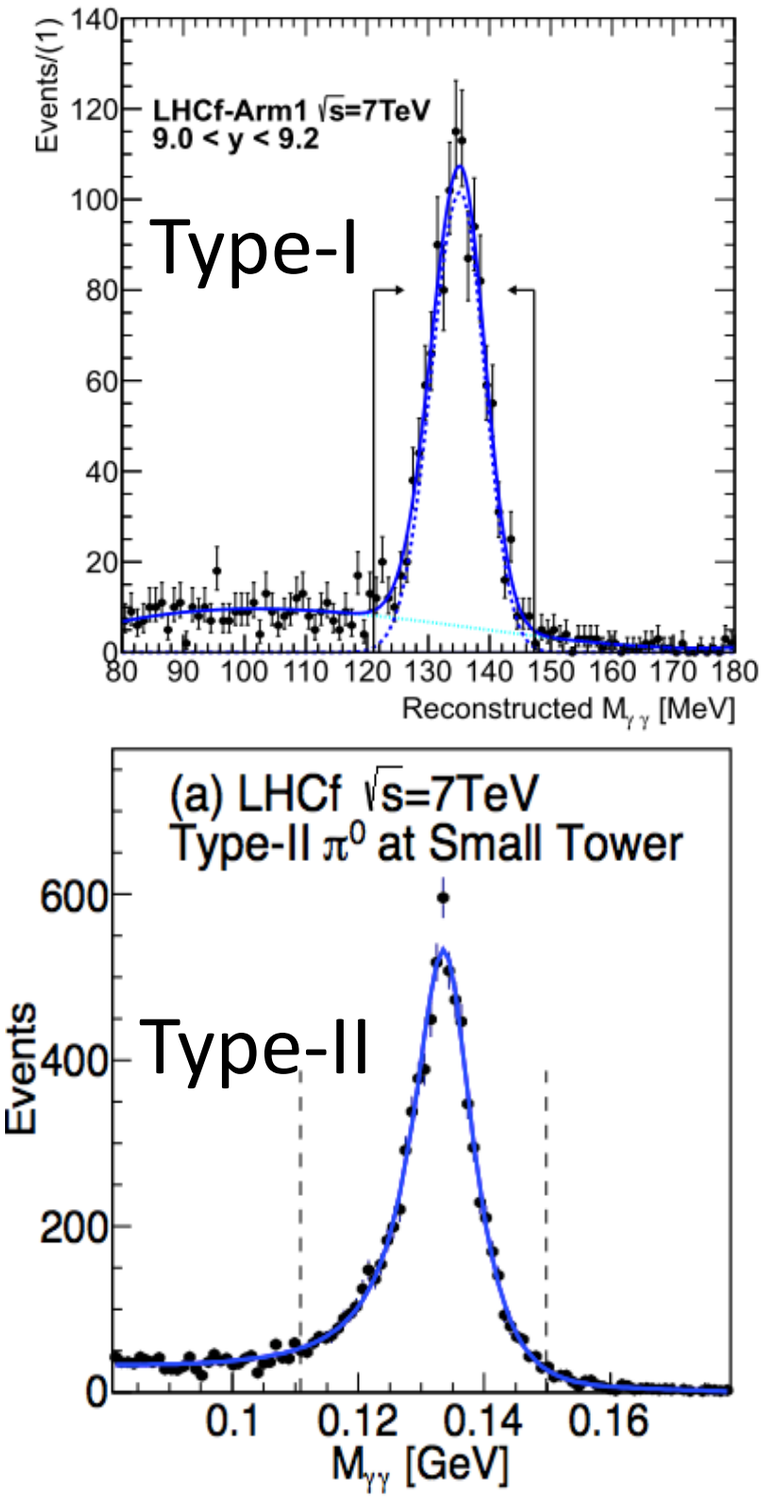
F(Ej) : Measured differential cross-section
Δη : The pseudo-rapidity range
C_{thr} : Correction factor for the threshold
200 GeV→ 0 GeV.

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

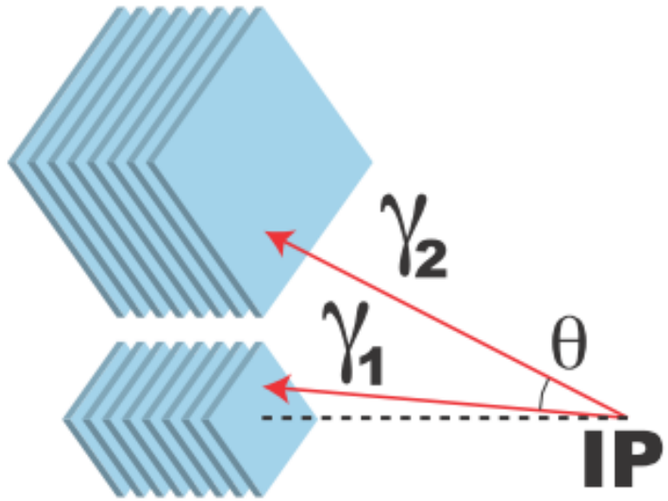
EPOS-LHC, SIBYLL2.3
Good agreement
QGSJET II-04
~ 30% lower than data



π^0 measurement



Type-I



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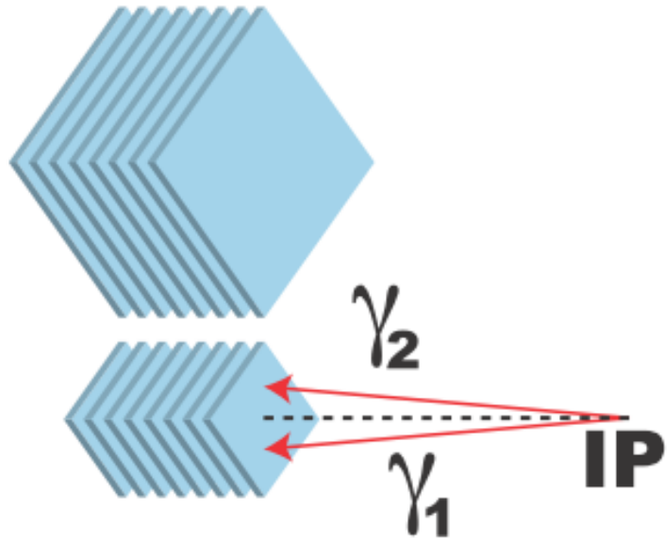
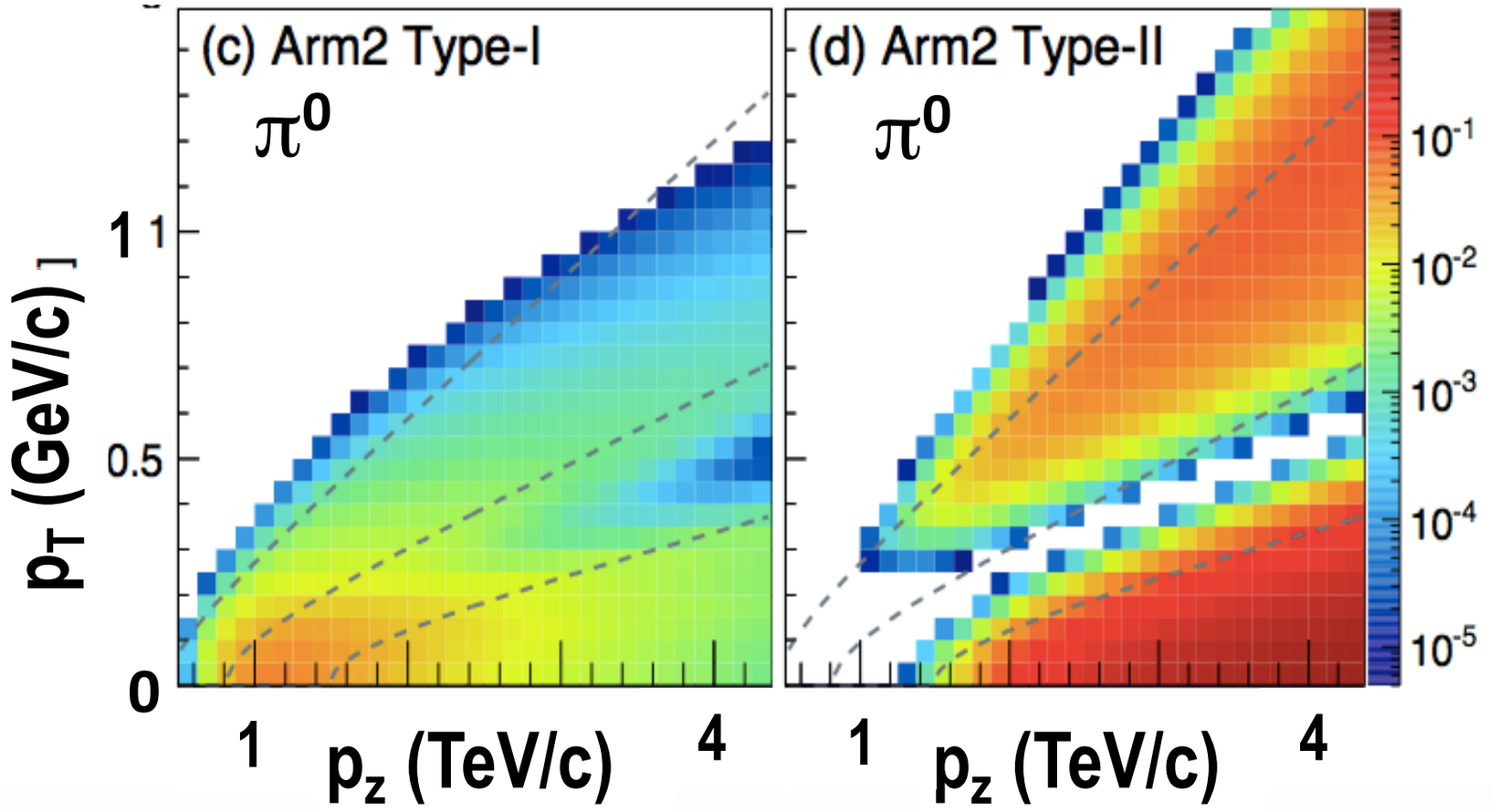
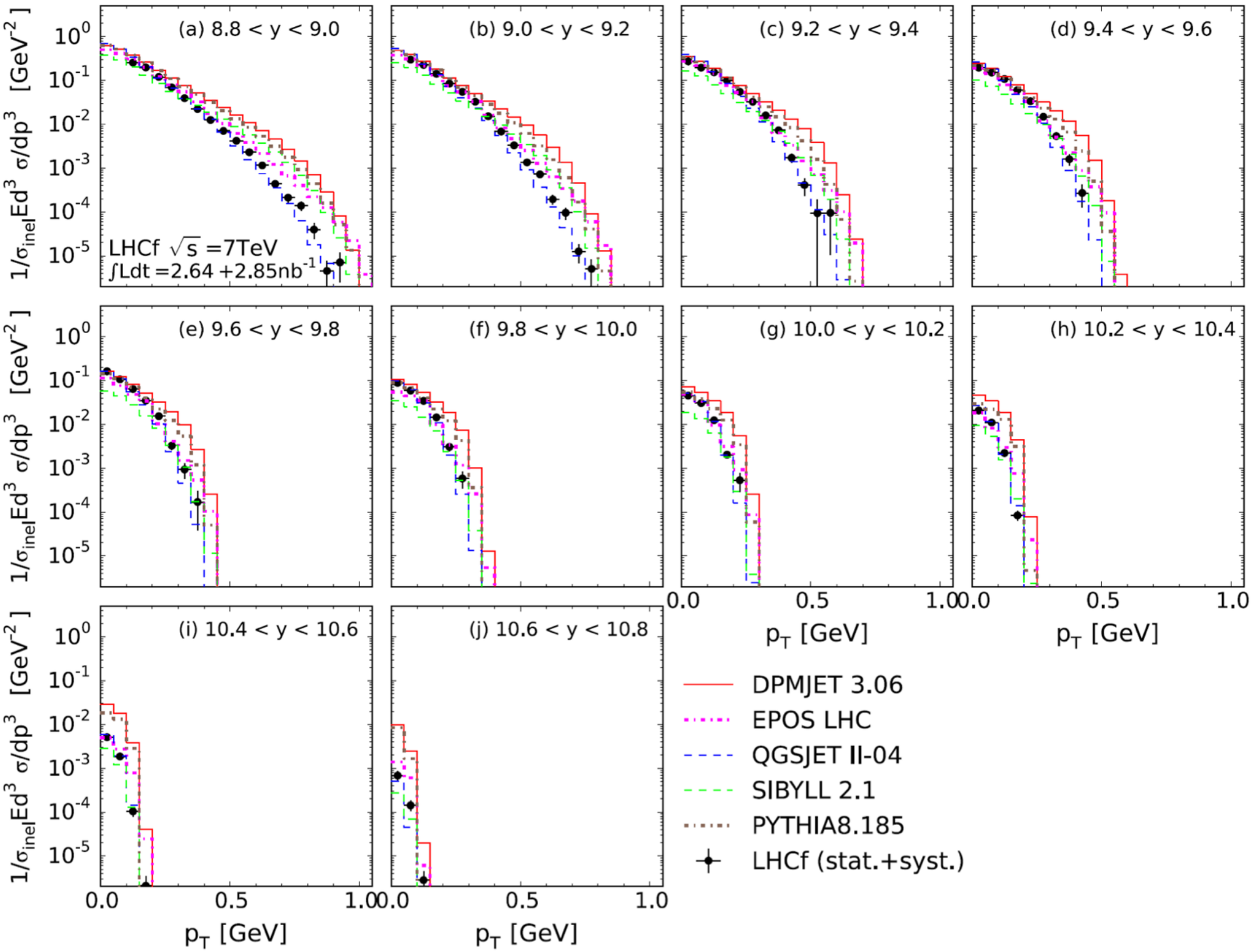




π^0 p_T spectra at pp,7TeV



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

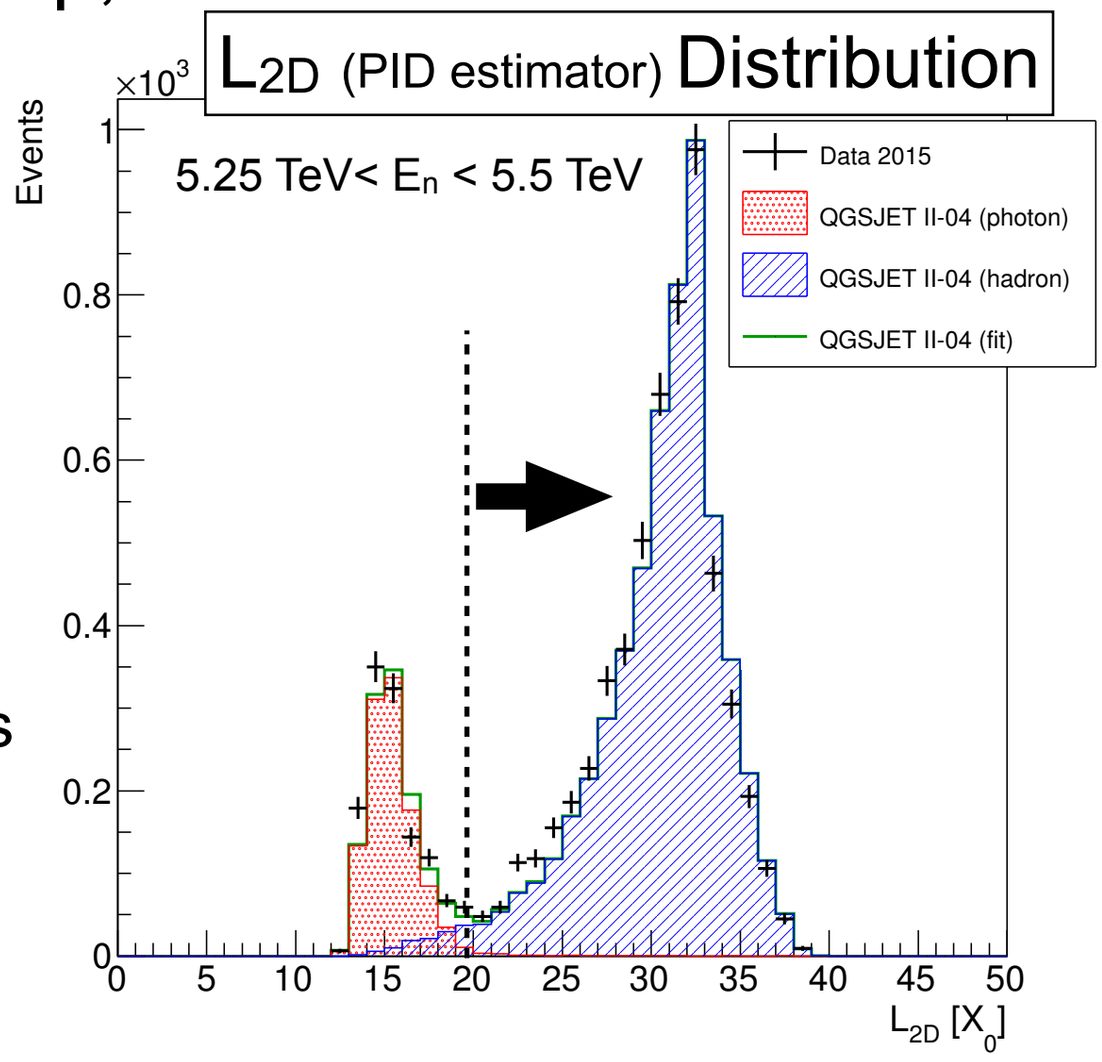
- 3 hour operation in June 2015
- Low pile-up, μ~0.01

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

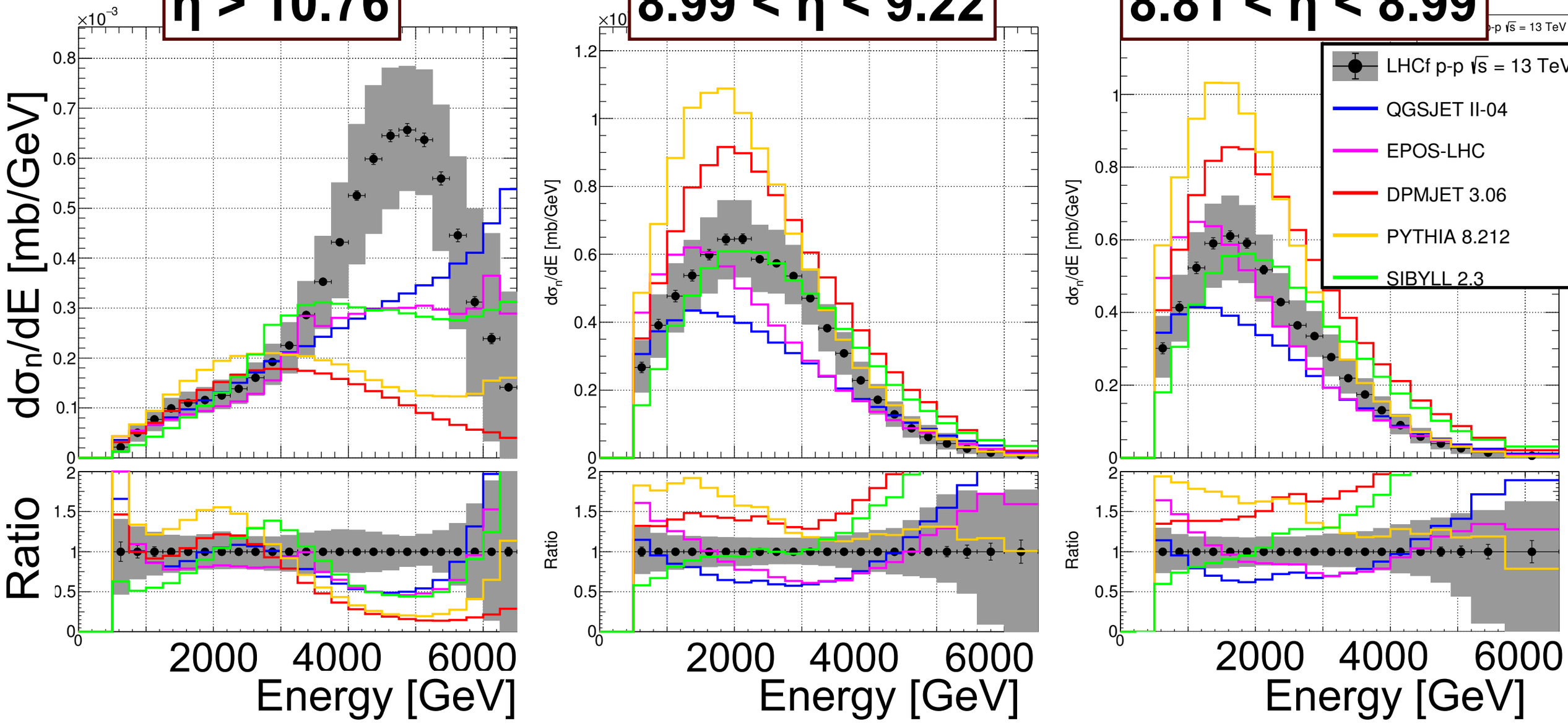


Neutron, p-p $\sqrt{s}$=13TeV Unfolded Spectra

$\eta > 10.76$

$8.99 < \eta < 9.22$

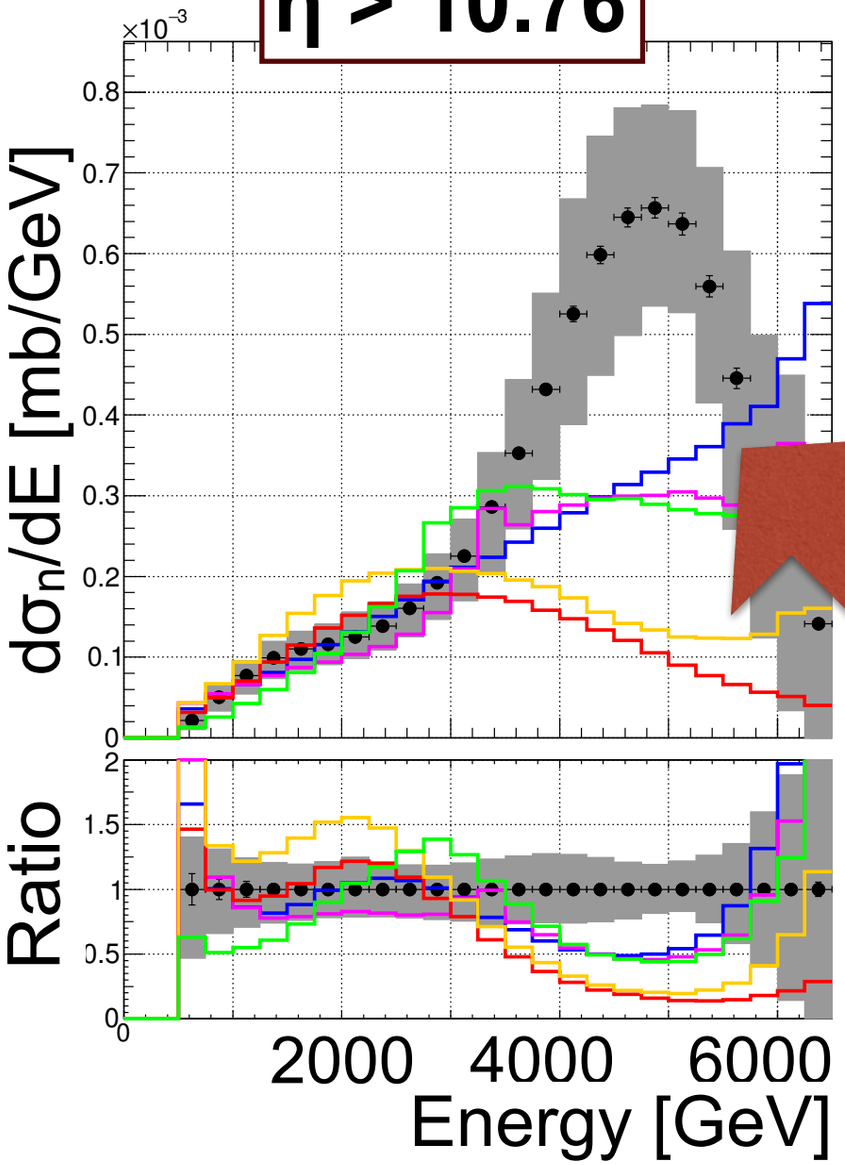
$8.81 < \eta < 8.99$



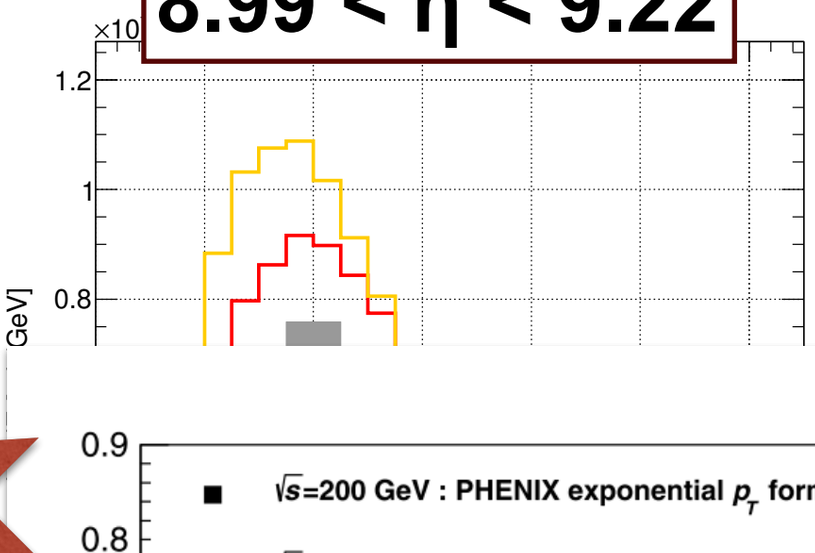
- In $\eta > 10.76$, data shows a strong increasing of neutron production in the high energy region. This behavior is not predicted by all models.
- EPOS-LHC and SIBYLL 2.3 have the best agreement in $8.99 < \eta < 9.22$, $8.81 < \eta < 8.99$, respectively.

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

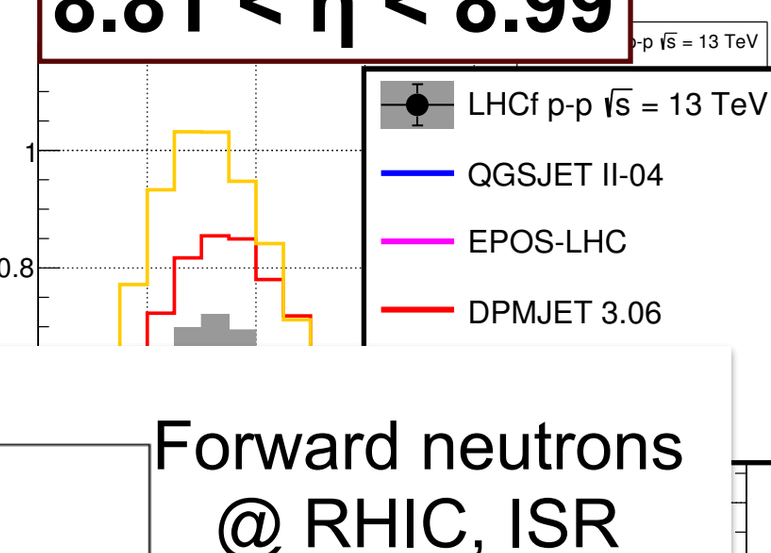
η > 10.76



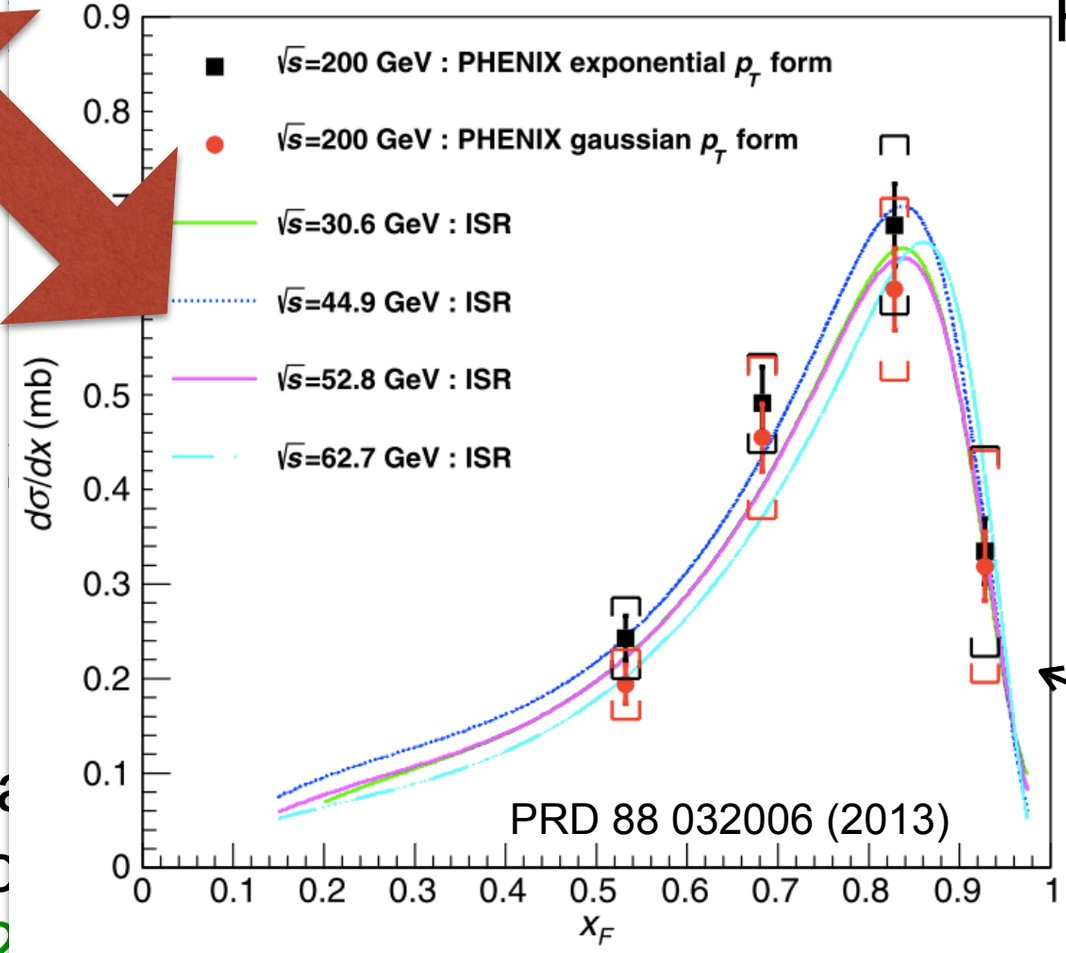
8.99 < η < 9.22



8.81 < η < 8.99



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



Forward neutrons @ RHIC, ISR

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

Detailed comparison is needed

$p_T < 0.11\ X_F$

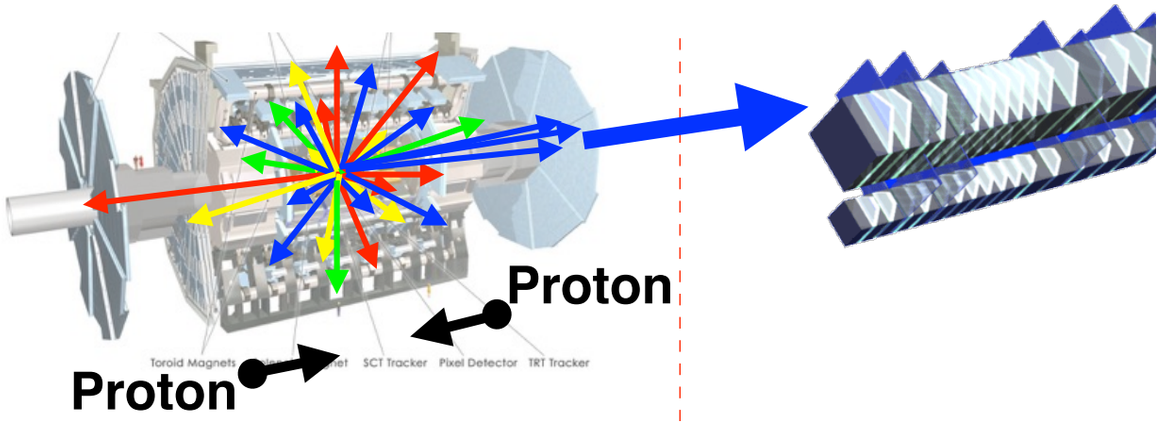
⇕

$p_T < 0.28\ X_F$

@ η>10.76, 13TeV

What's next ?

- Complete the analysis for inclusive γ,π^0,n.
- Additionally,
  - Process-based measurement
    For understanding the sources of discrepancy between data and models
    ⇒ **LHCf+ATLAS joint analysis**



First target:

Measurement of contribution of diffractive processes to the forward particle production

  - Collision-energy dependence (Feynman Scaling)
    For improving the predictive power in > E_{LHC}
    ⇒ **RHIC forward (RHICf) at pp,$\sqrt{s}$=0.5TeV**

RHIC 10^{14}eV ⟷ (x10^3) LHC 10^{17}eV ⇢ (x10^3) UHECR ~10^{20}eV

Diffractive processes

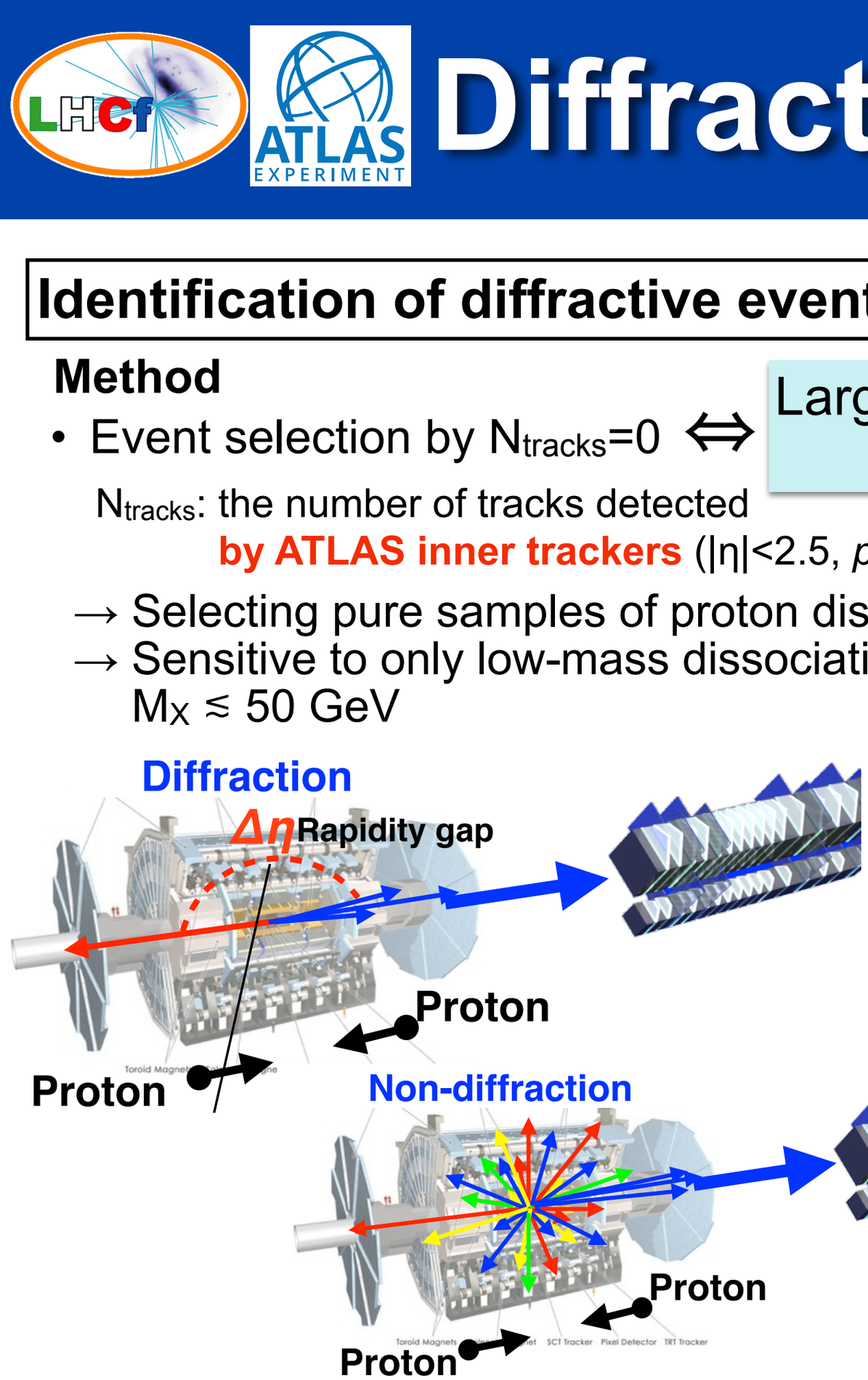
Identification of diffractive events by ATLAS

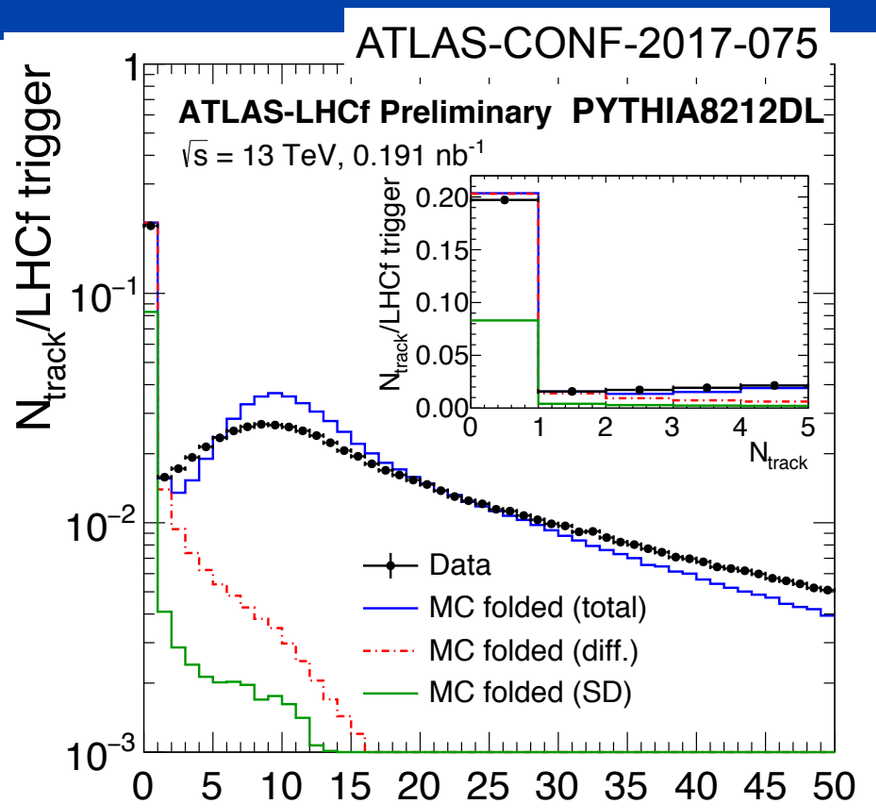
Method

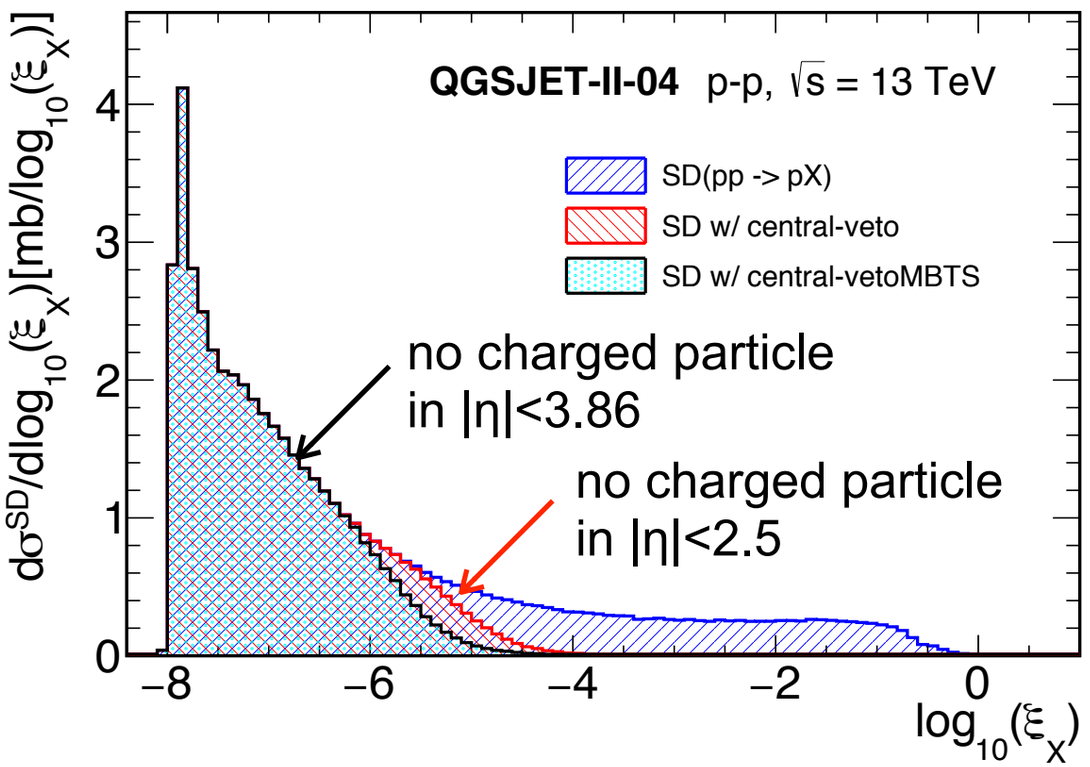
- Event selection by N_{tracks}=0 ⇔ Large rapidity gap $\Delta\eta > 5$

  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





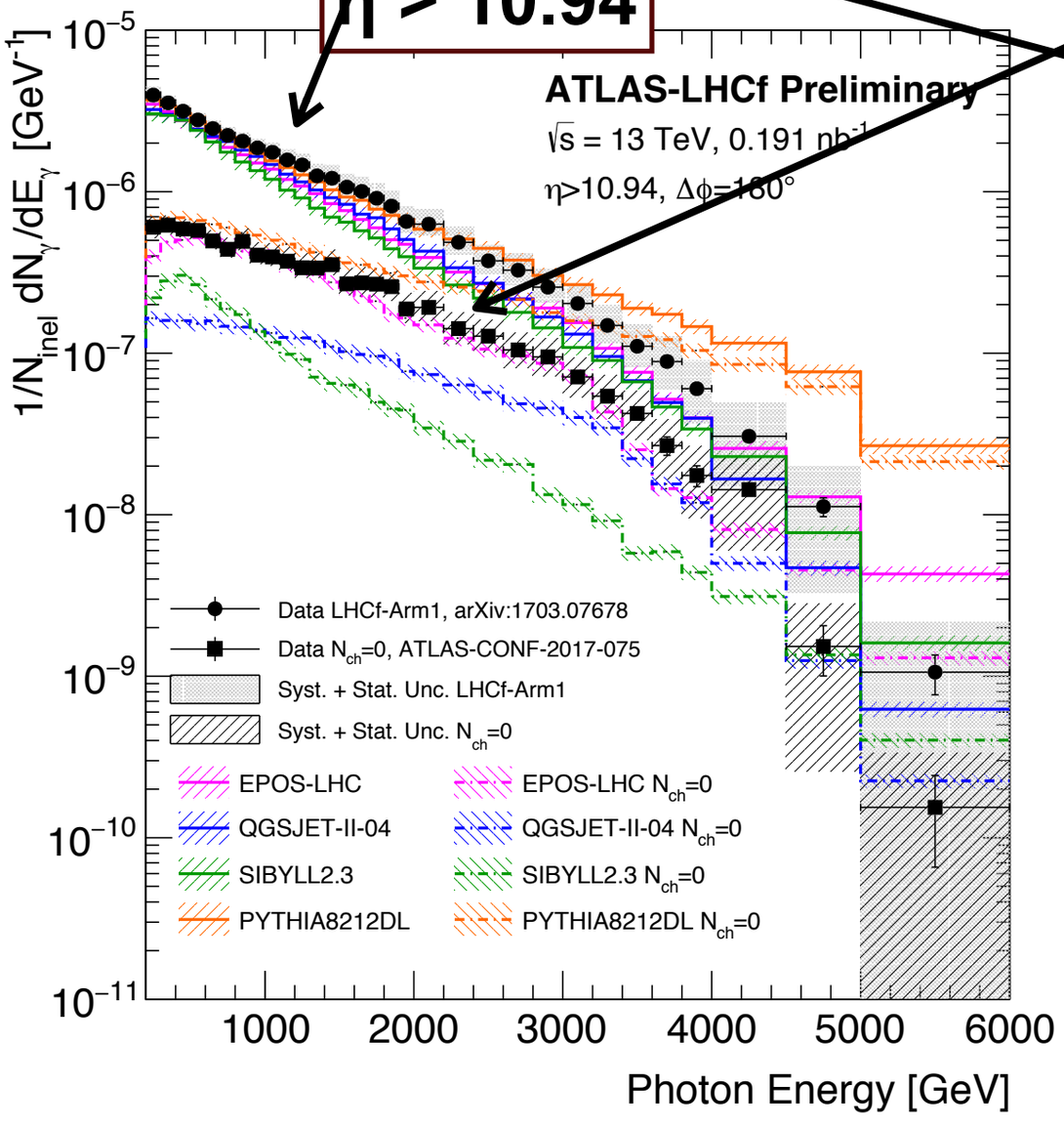


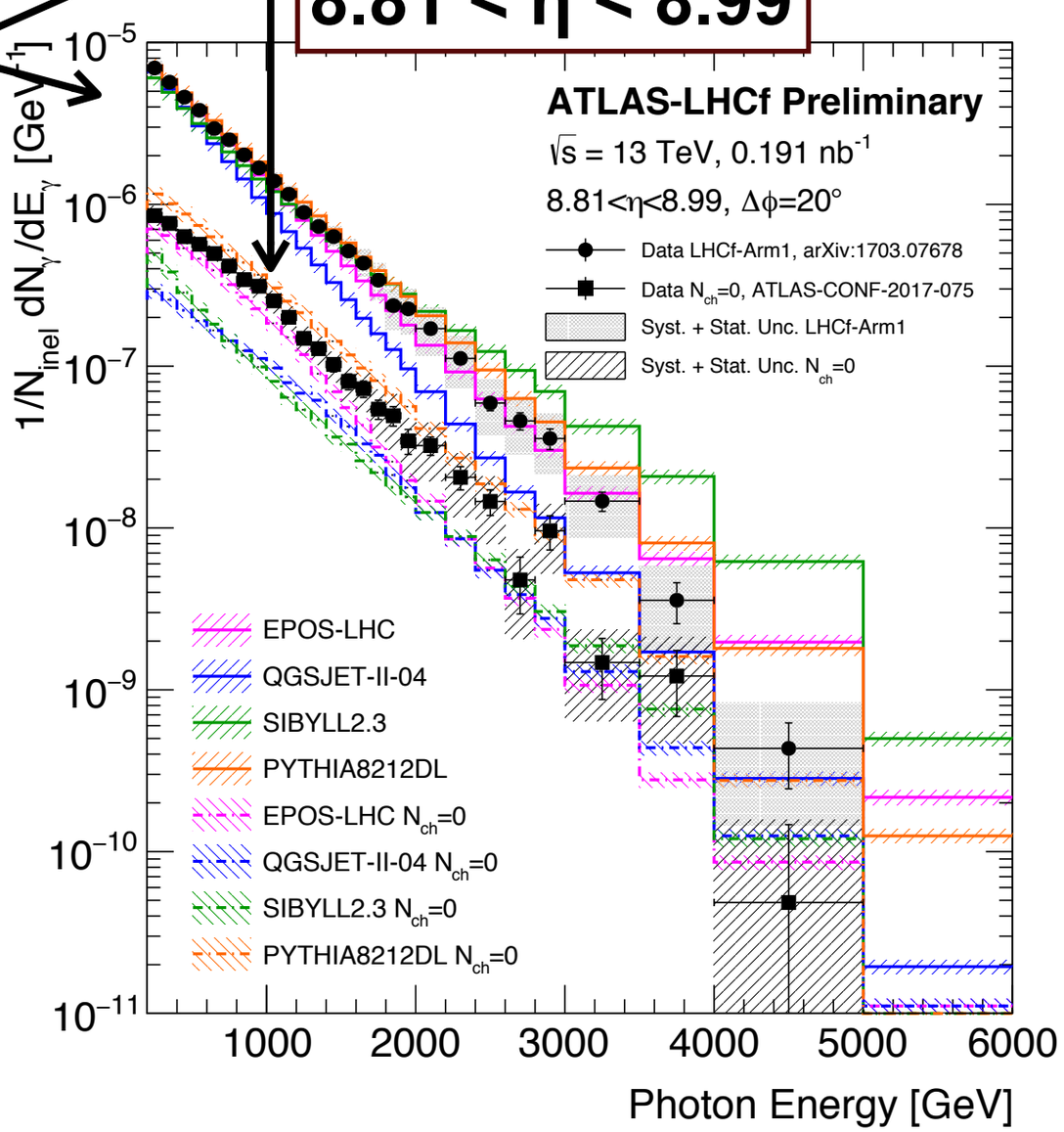
Measurement of contributions of diffractive processes to forward photon spectra in *pp* collisions at $\sqrt{s}$ = 13 TeV

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

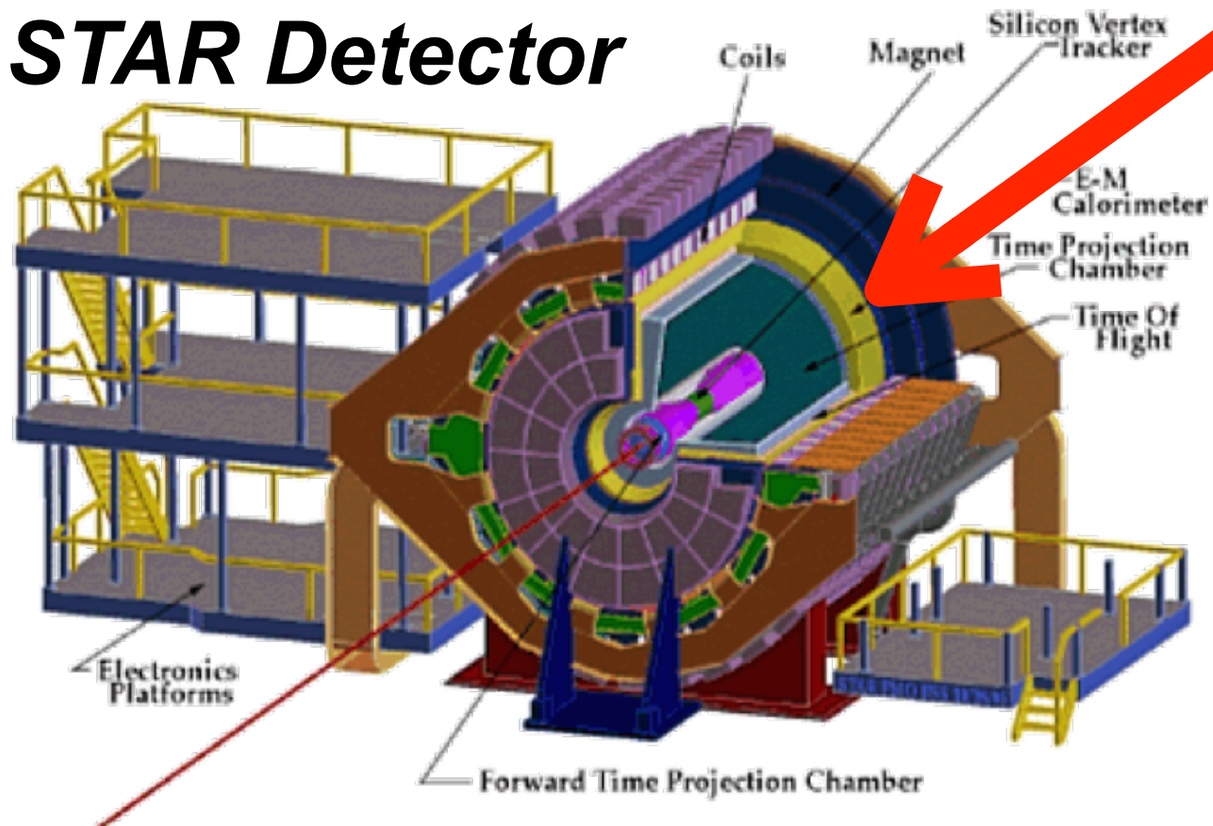




RHICf experiment

RHIC at BNL

- **p+p $\sqrt{s}$ = 510 GeV**
  (polarized beam)
- Test of energy scaling with the wide p_T range.
- The operation was successfully completed in June 2017
- Common operation with STAR



18 m

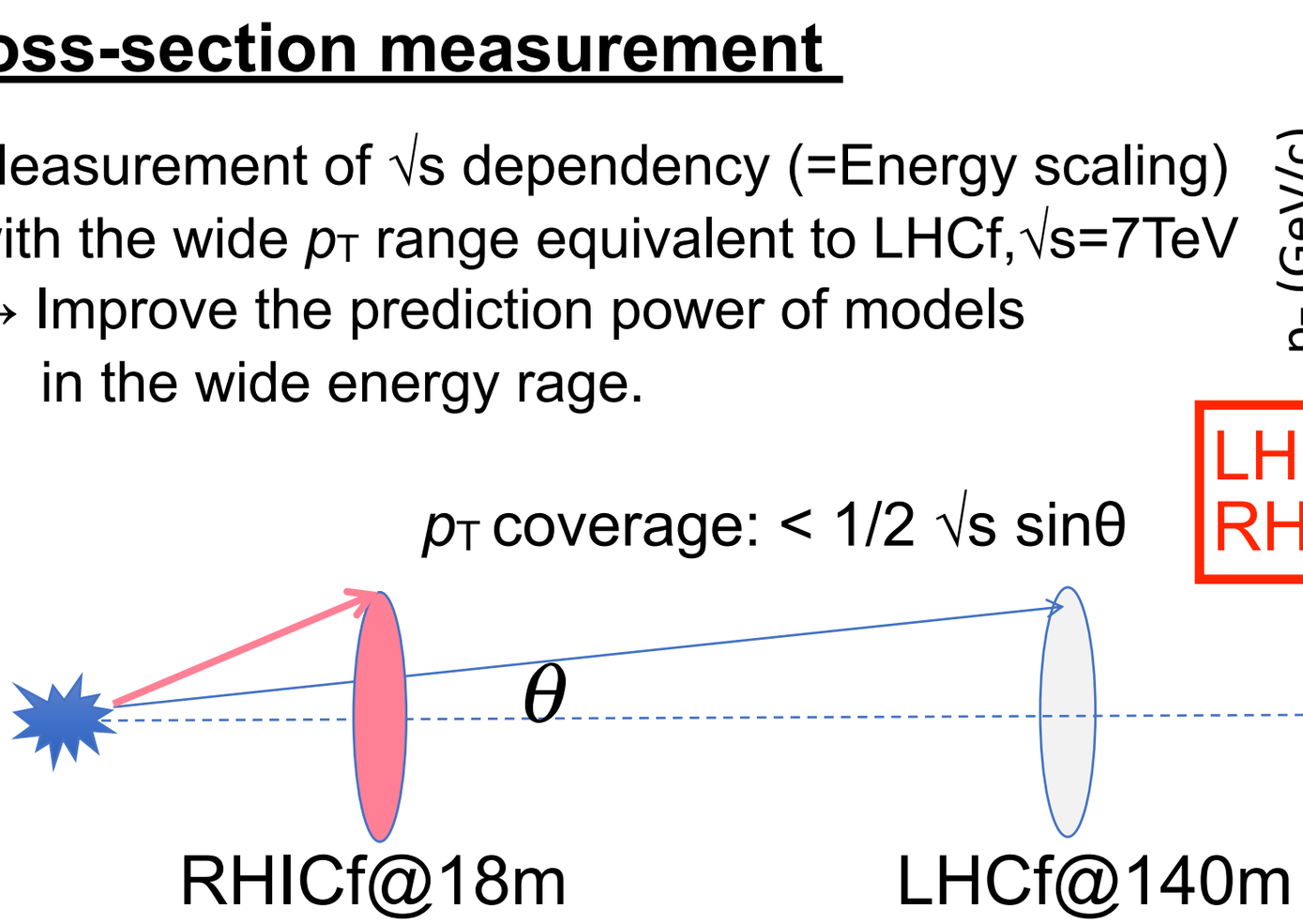
RHICf coverage:
$\eta > 5.9$

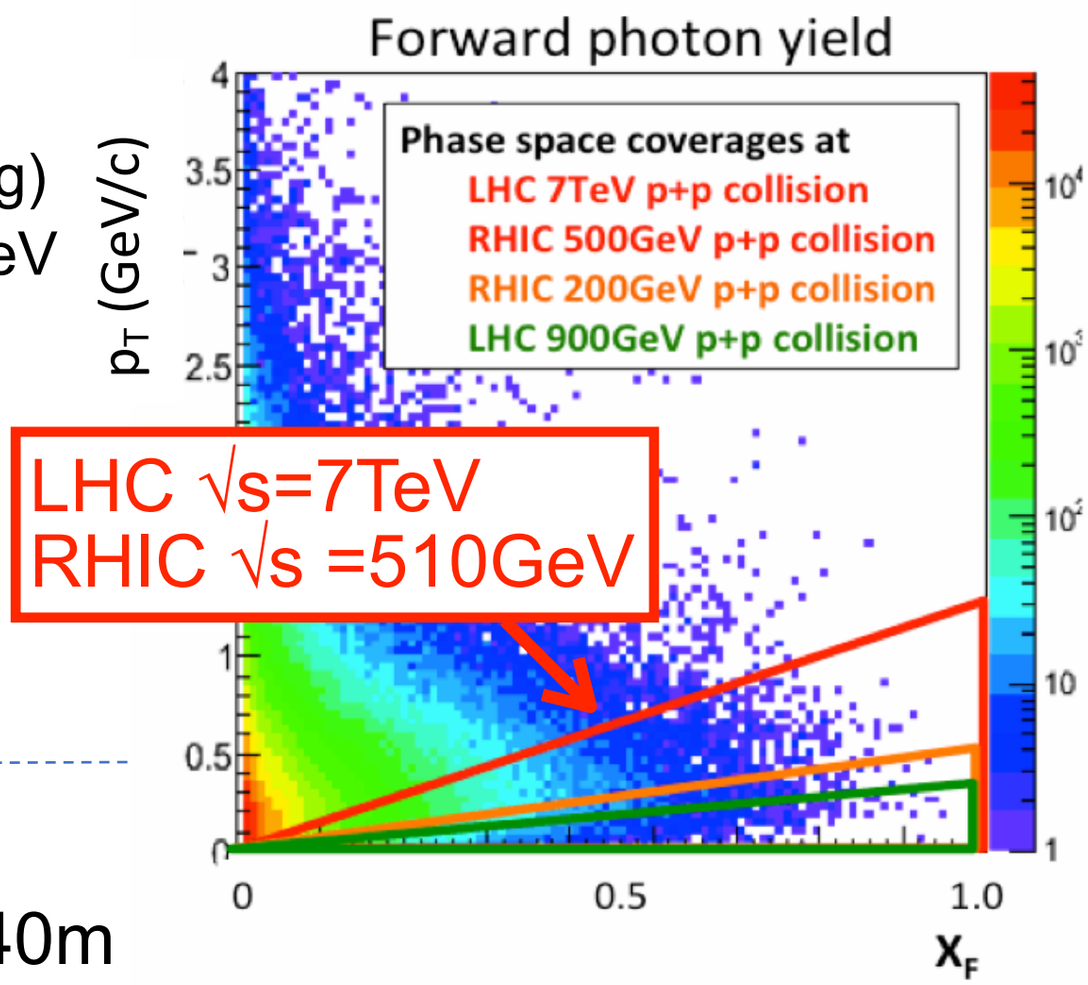
Physics in RHICf

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.

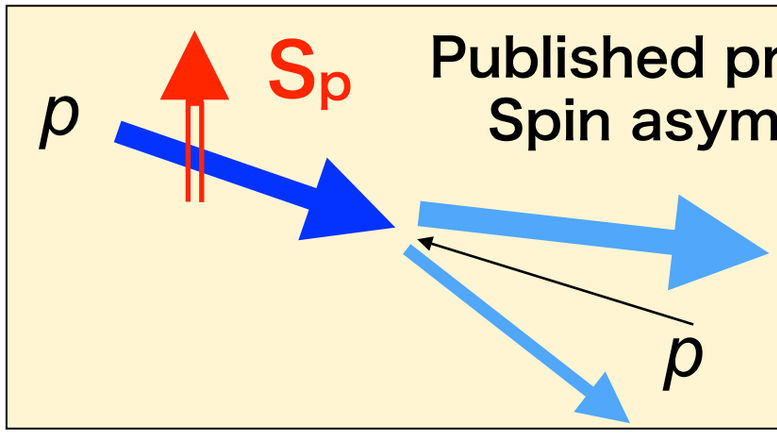
p_T coverage: < 1/2 √s sinθ





Spin asymmetry measurement

→ Nakagawa-san's talk

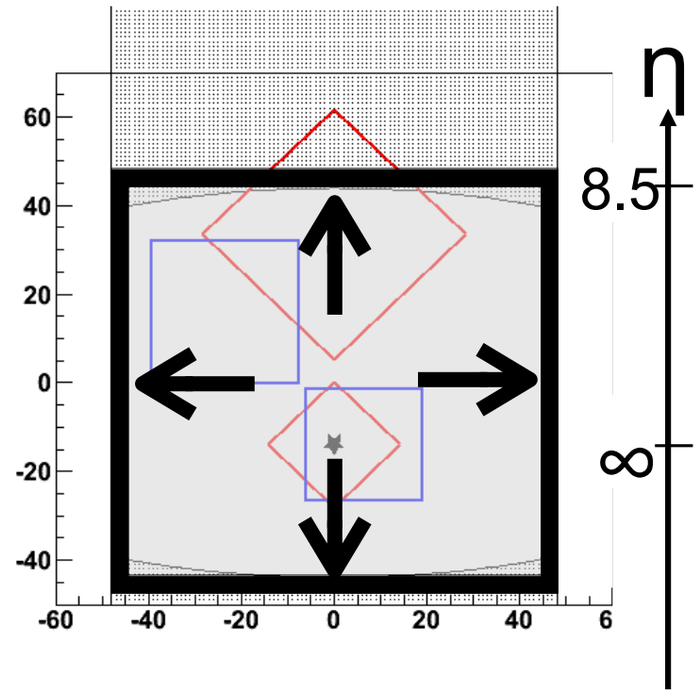


Future plans of LHCf/RHICf

- Operations at LHC, LHC-Run3
  - *pp*, √s=13 or 14TeV again
    - Increasing the statistics, measurement of η
    - common-operation with ATLAS RP and ZDC
  - *p*O (OO) collisions
    - Ideal for studying the cosmic-ray interactions of CR-Air
    - Measurement of nuclear effect at light ion collisions
- Operation at RHIC
  - *pp* √s=510GeV again
  - Zero degree measurement at EIC?

Upgrade plan(idea) of the detectors

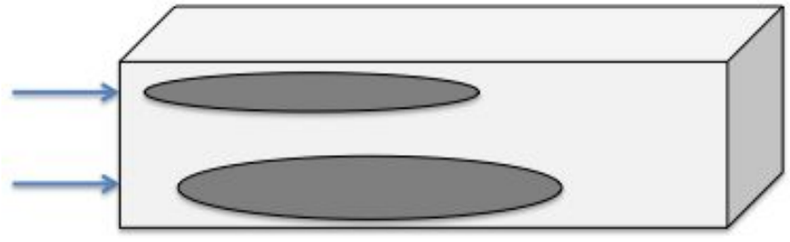
- Upgrade of the read-out system
  - The DAQ rate of 0.8 kHz is limited by the readout speed via the VME bus.
  - Replacing it to Ethernet, it improves to 2kHz, at least.



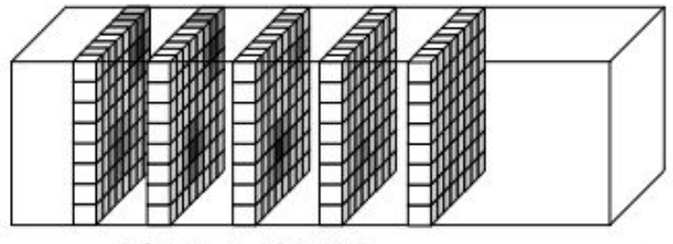
- Future idea of the detector upgrade
  - Maximize the acceptance
    with keeping the performances, good energy
    and position resolution for individual particles
  - Physics
    - Measurement of fluctuation of energy flows
    - Measurement at O-remnant side in pO or OO
    - Measurement of strange particles, K^0, Λ

      $K^0_s \rightarrow 2\pi^0 \rightarrow 4\gamma$

      $\Lambda \rightarrow n+\pi^0 \rightarrow n+2\gamma$
    - Full ϕ coverage for spin asymmetry measurement



→ Si Pad + W calorimeter



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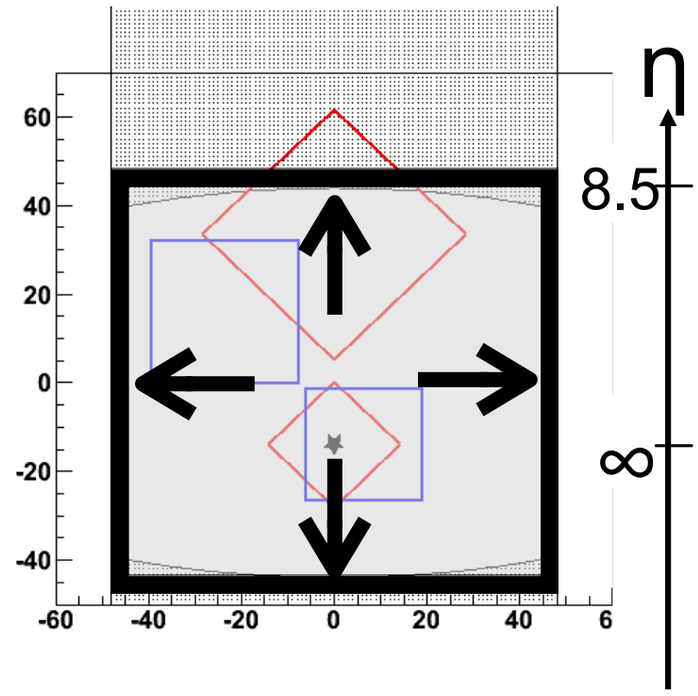

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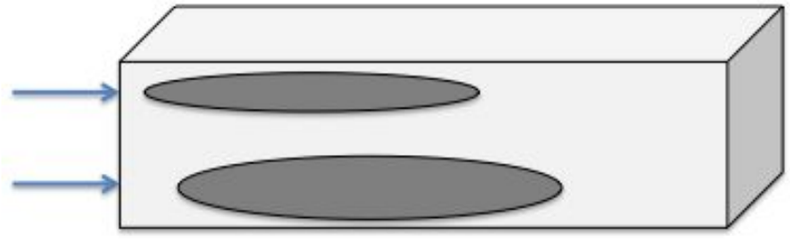
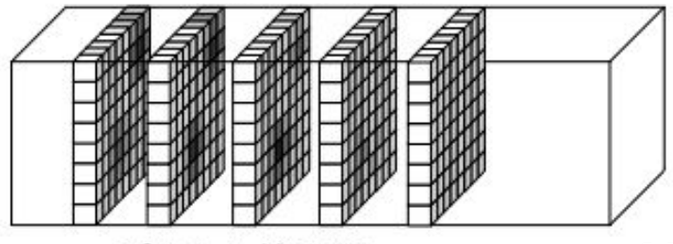


Si Pad + W calorimeter

= ALICE FoCal

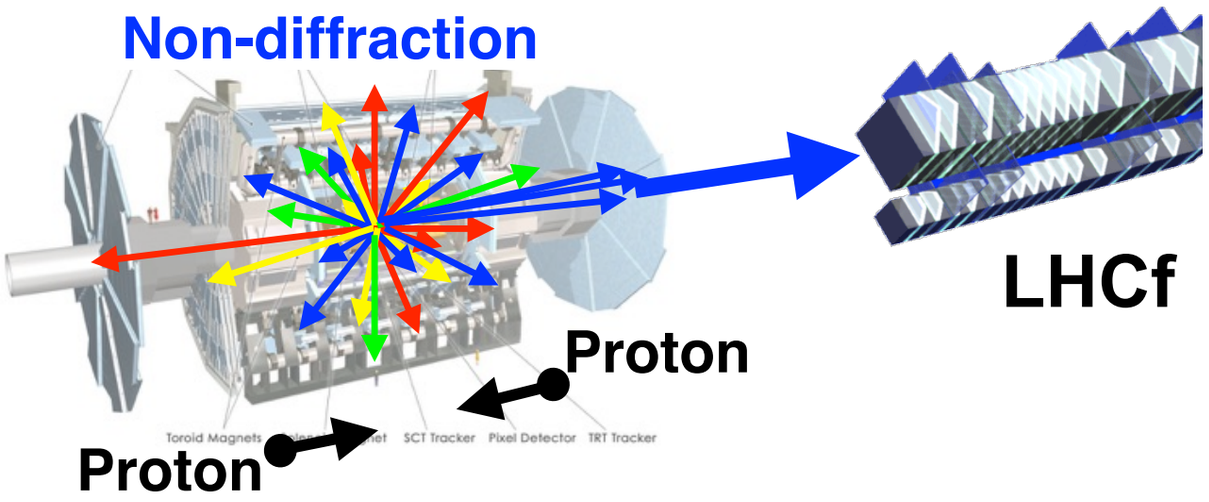


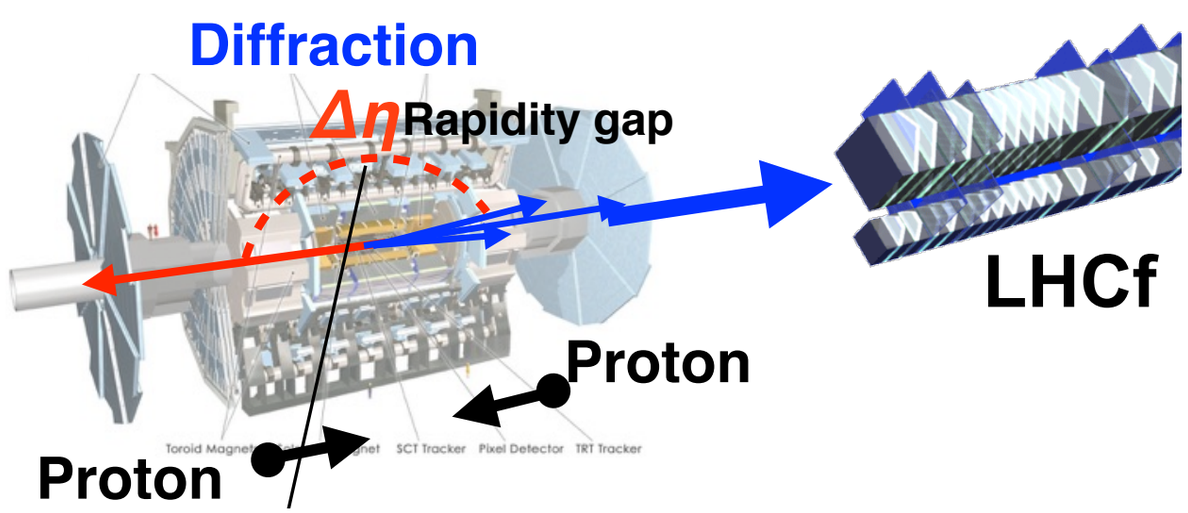
Summary

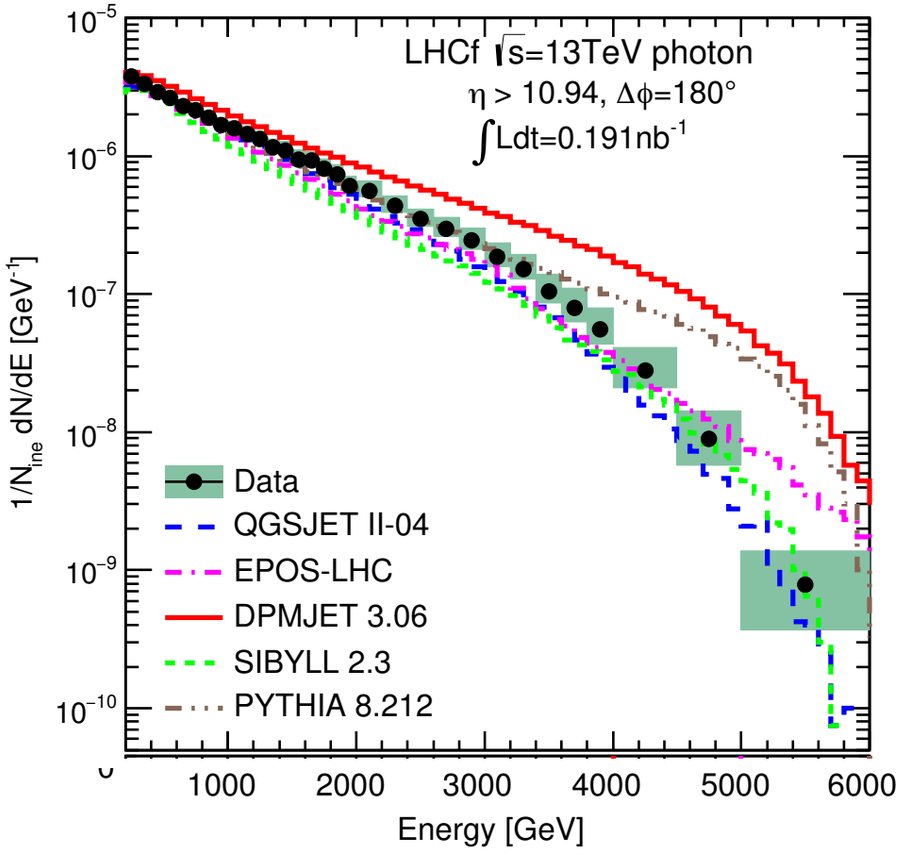
- LHCf/RHICf measures the energy spectra of neutral particles, γ, π^0, and n in the very forward regions of collisions, which is important for understanding air-shower developments.
- Operations have successfully completed for
  LHCf pp: $\sqrt{s}$ = 0.9, 2.76, 7, 13 TeV and
  pPb: $\sqrt{s_{NN}}$ = 5, 8 TeV.
  RHICf pp: $\sqrt{s}$ = 510GeV (polarized beam)
- Many results were already published and many analyses are still on-going including the combined analyses with ATLAS or STAR.
- Future plan
  - Operations at LHC with pp and pO (or OO) and operation at RHIC with pp
  - Upgrade the detector to Si Pad+W calorimeter ***(collaborating with ALICE FoCal hopefully)***

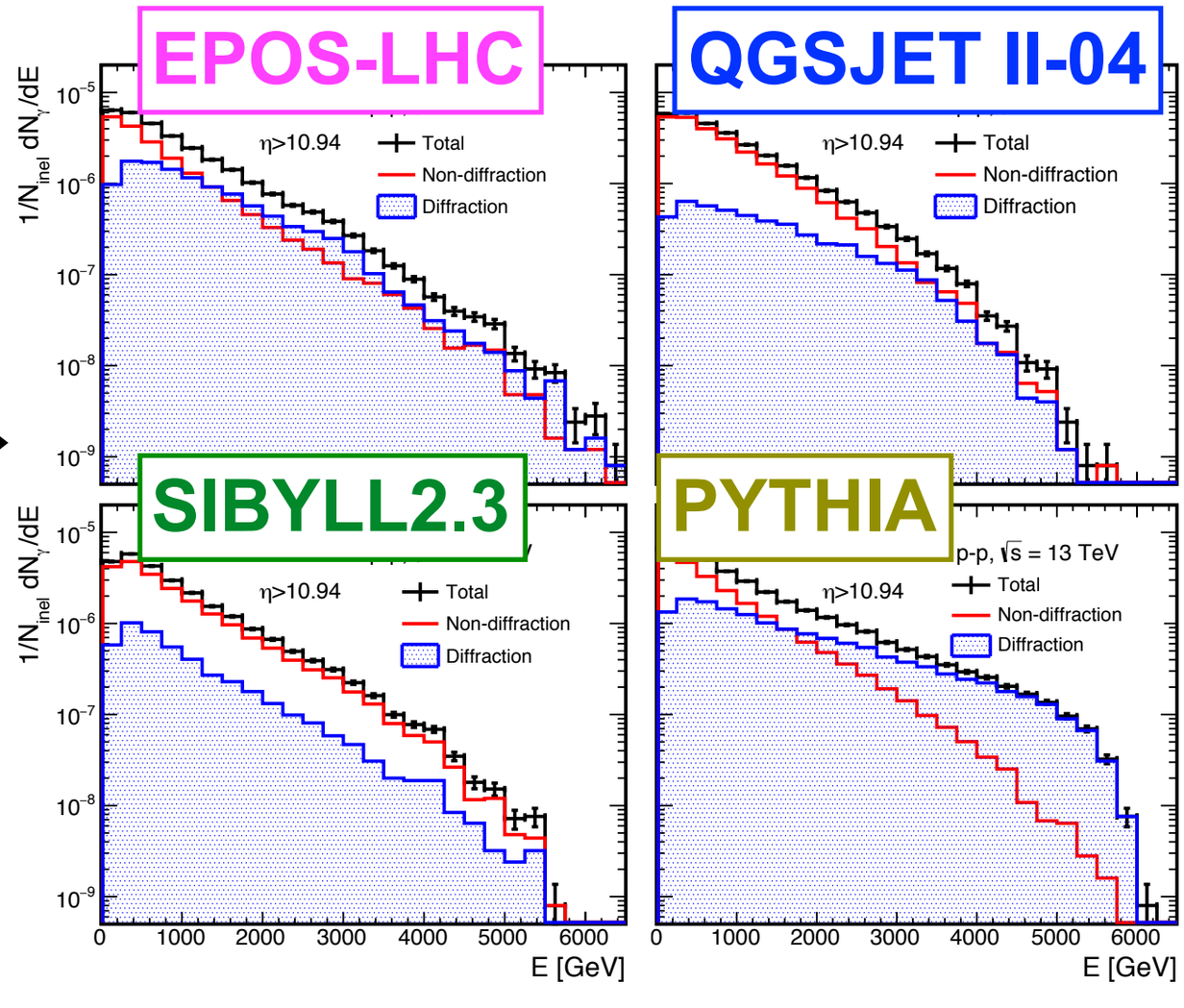
Backup

Joint Analysis with ATLAS
- Selection of Diffractive interactions -





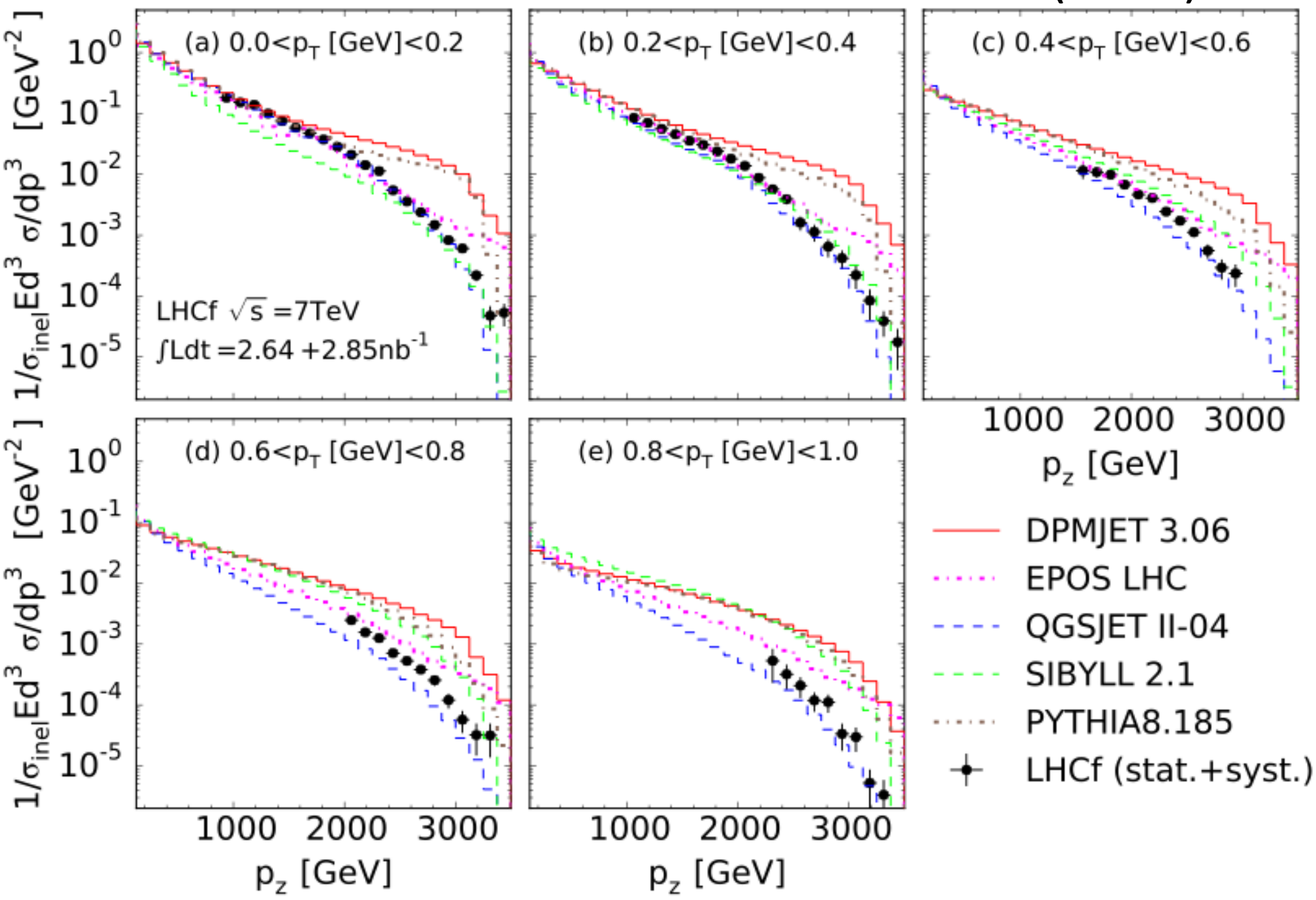




Poster by Q.Zhou; CRD131

π^0 p_z (~E) spectra at p+p,7TeV

PRD 94 (2016) 032007

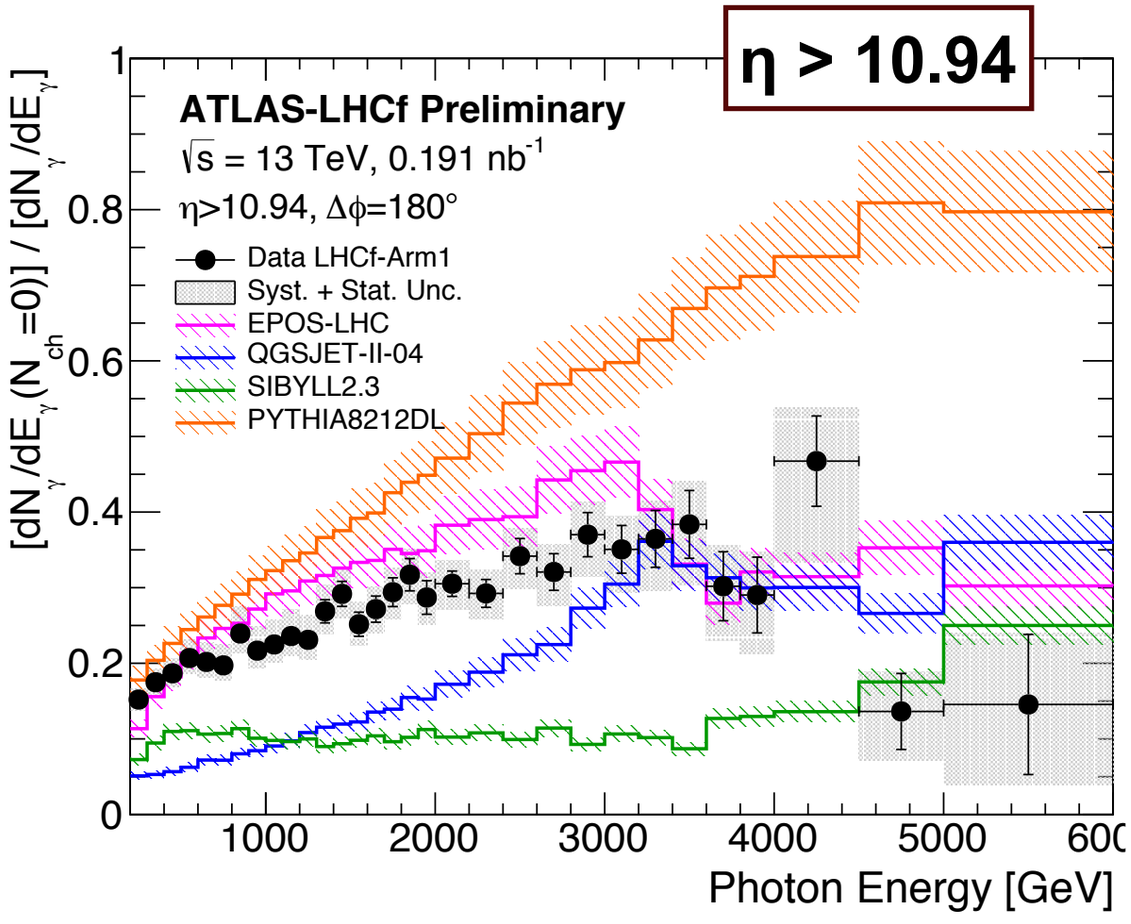


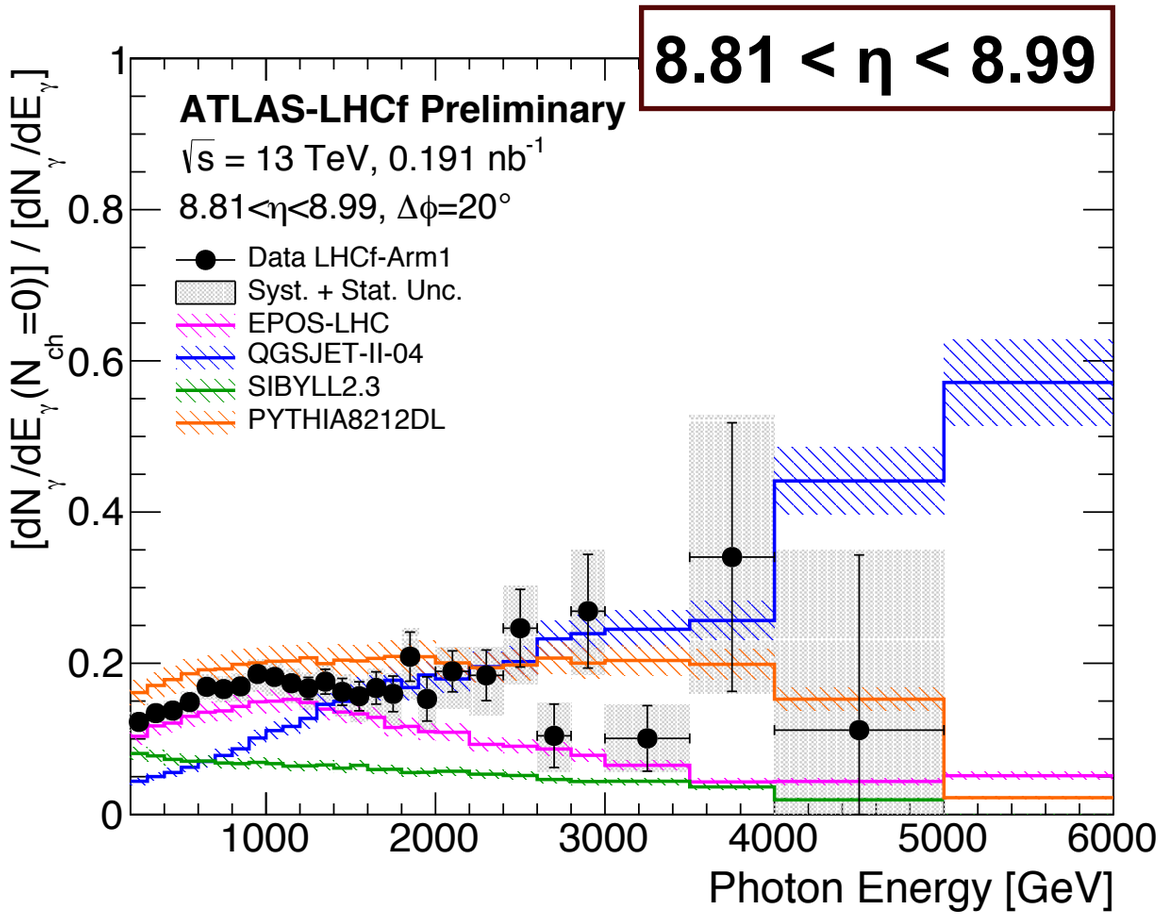
DPMJET and Pythia overestimate over all E-p_T range

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

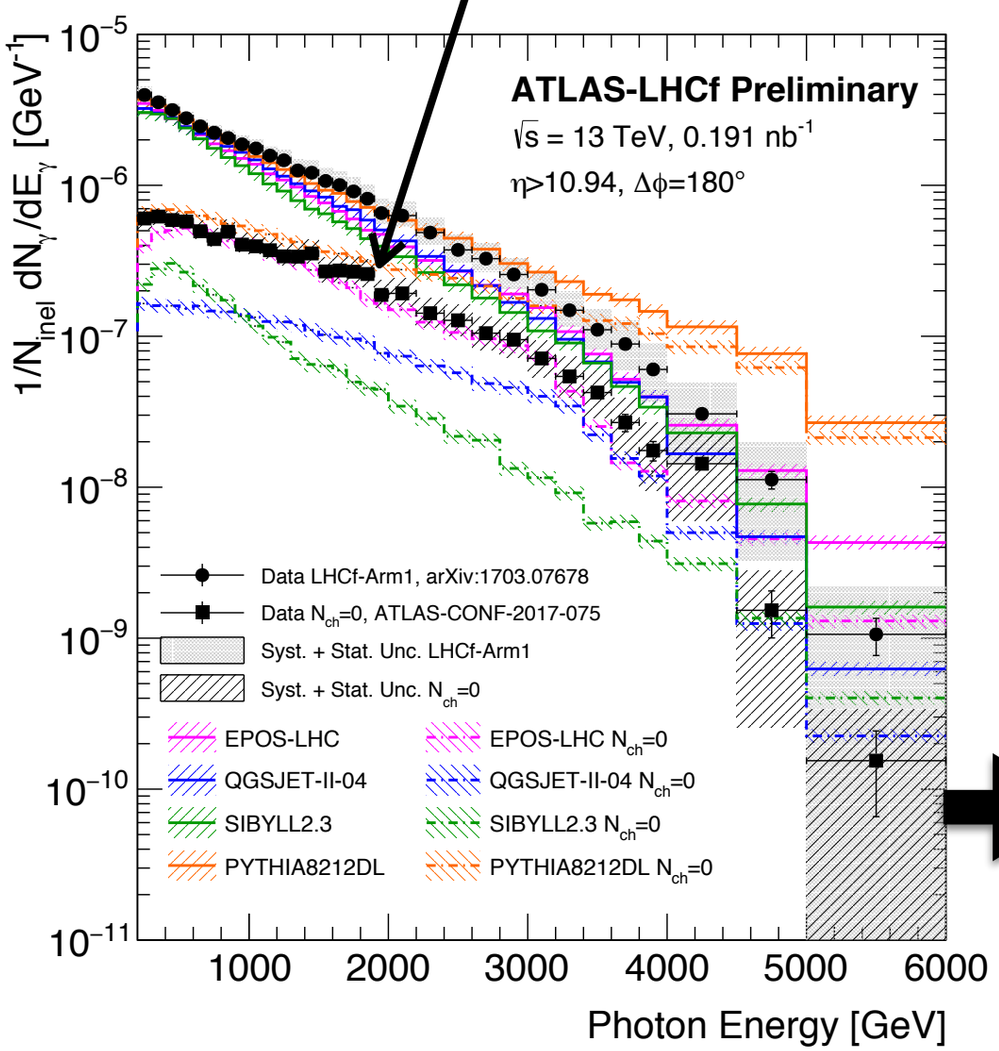




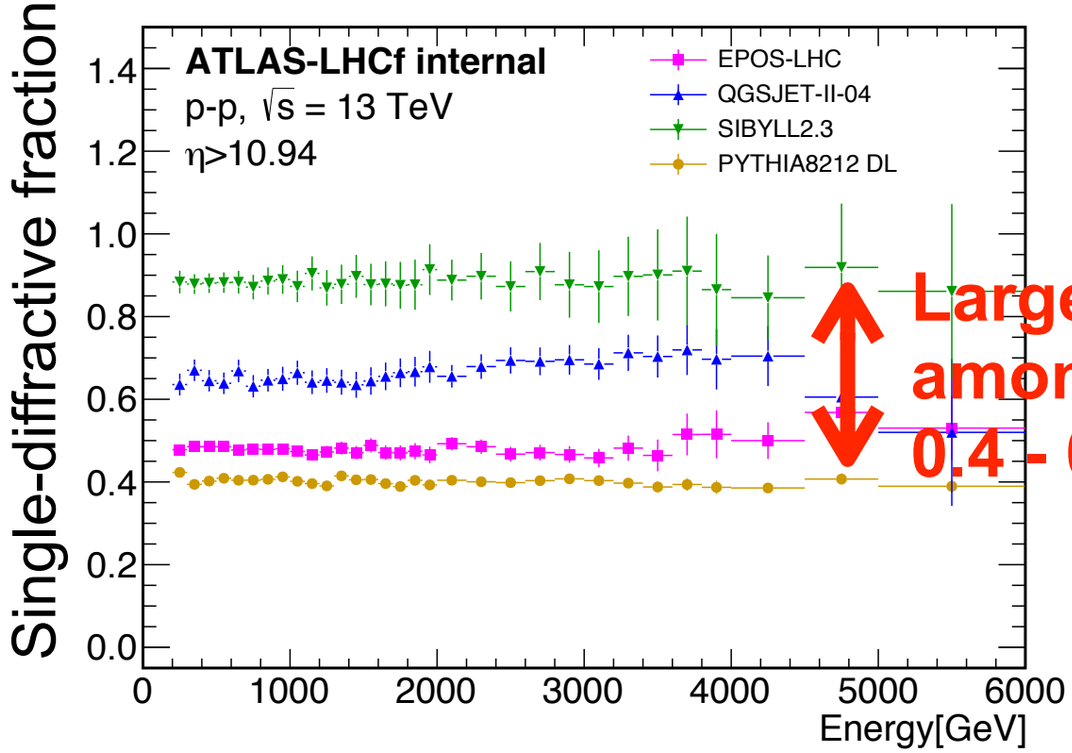
- At η>10.94, the ratio of data increased from 0.15 to 0.4. with increasing of the photon energy up to 4TeV.
- PYTHIA8212DL predicts higher fraction at higher energies.
- SIBYLL2.3 show small fraction compare with data at η>10.94.
- At 8.81 < η < 8.99, the ratio of data keep almost constant as 0.17.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