

**Forward particle productions  
in UPC at  $\sqrt{s_{NN}}=5\text{TeV}$  p+Pb  
from first LHCf-ATLAS collaborated analysis**

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on behalf of the LHCf collaboration**



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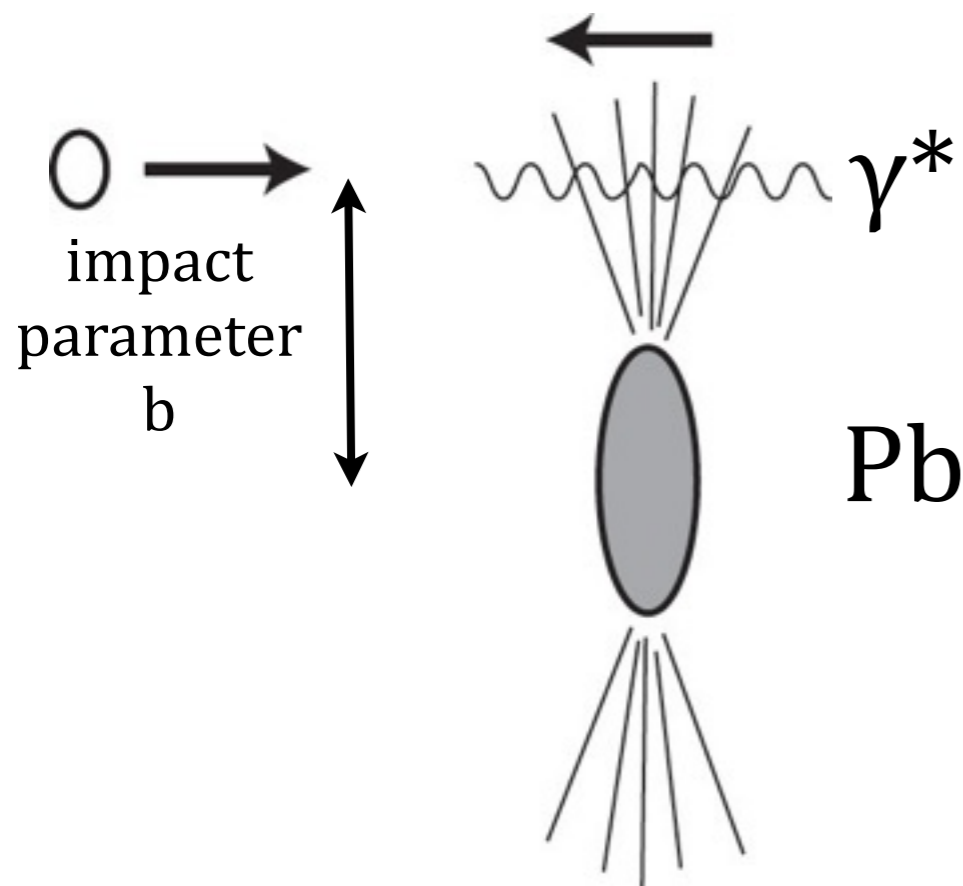
- UPC process
- LHCf operation at p+Pb collisions,
- Very forward particle production at UPC
- First ATLAS-LHCf collaborated analysis

ATLAS LHCf NOTE

*“Classification of Events in the Combined ATLAS-LHCf Data  
Recorded During the p+Pb Collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”*

ATL-PHYS-PUB-2015-038 <https://cds.cern.ch/record/2047832>

# UPC process at p-Pb



## Ultra Peripheral Collisions (UPCs)

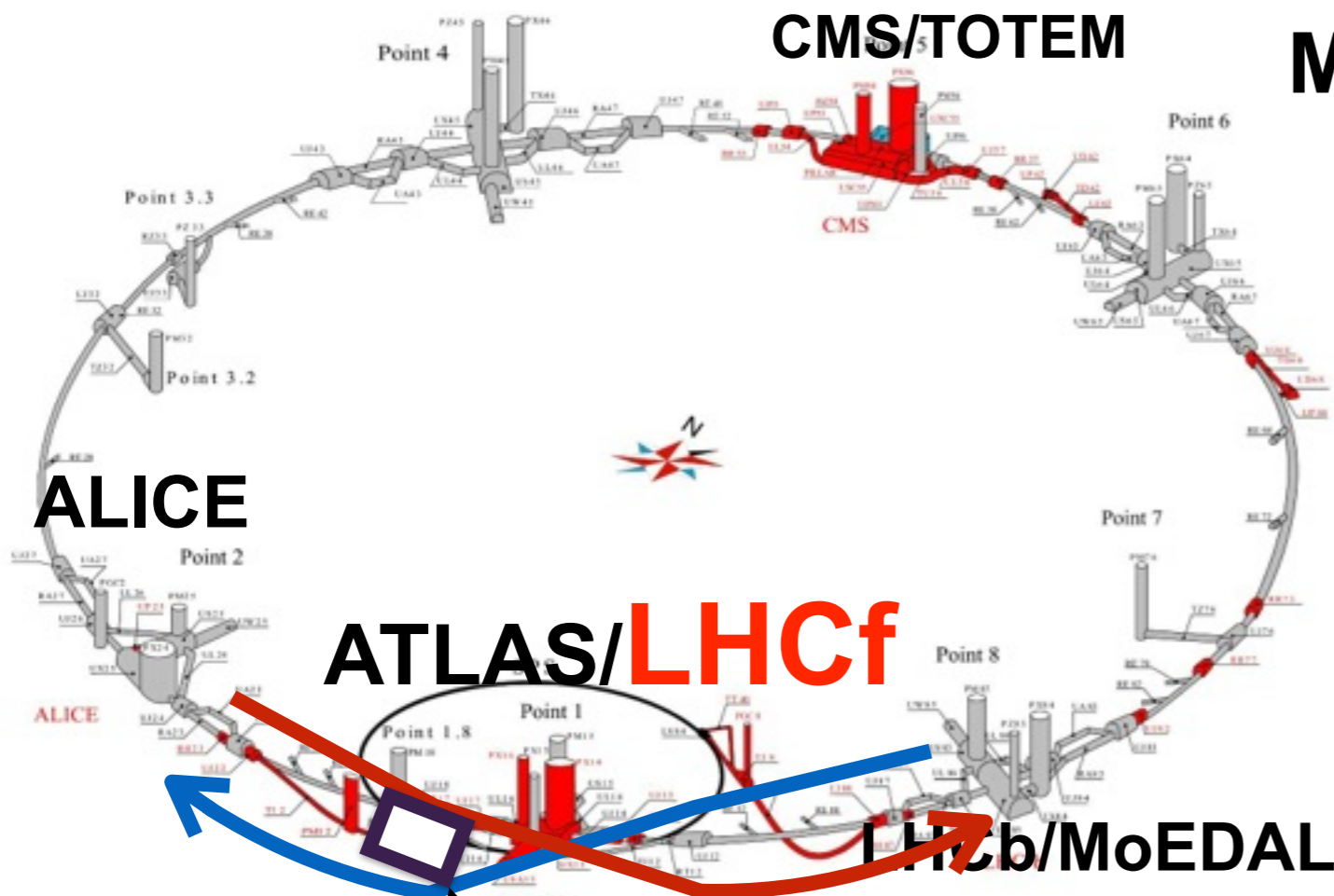
If  $b > R_p + R_{Pb}$ , hadron interaction is strongly suppressed and proton collides with electromagnetic field of Pb, of which strength is proportional to  $Z^2$ . The EM interaction can be described as a collision between proton and quasi-photon.

Exp.)  $p + Pb \rightarrow X + Pb \Leftrightarrow p + \gamma^* \rightarrow X$

***In UPCs, what can we see at zero degree of collision ?***  
***= in LHCf***

LHCf had operations with  $p+Pb$  collisions of  $\sqrt{s_{NN}} = 5.02$  TeV in 2013  
LHCf measured the energy spectra of  $\gamma$ ,  $\pi^0$ , neutron inclusively.

# The LHCf experiment



## Measurement of

- *Inclusive photons*
- *Inclusive  $\pi^0$*
- *Inclusive neutron*

at the zero degree of collisions for testing hadron interaction models used in CR air shower simulation.

TS-CE  
06.07.2004

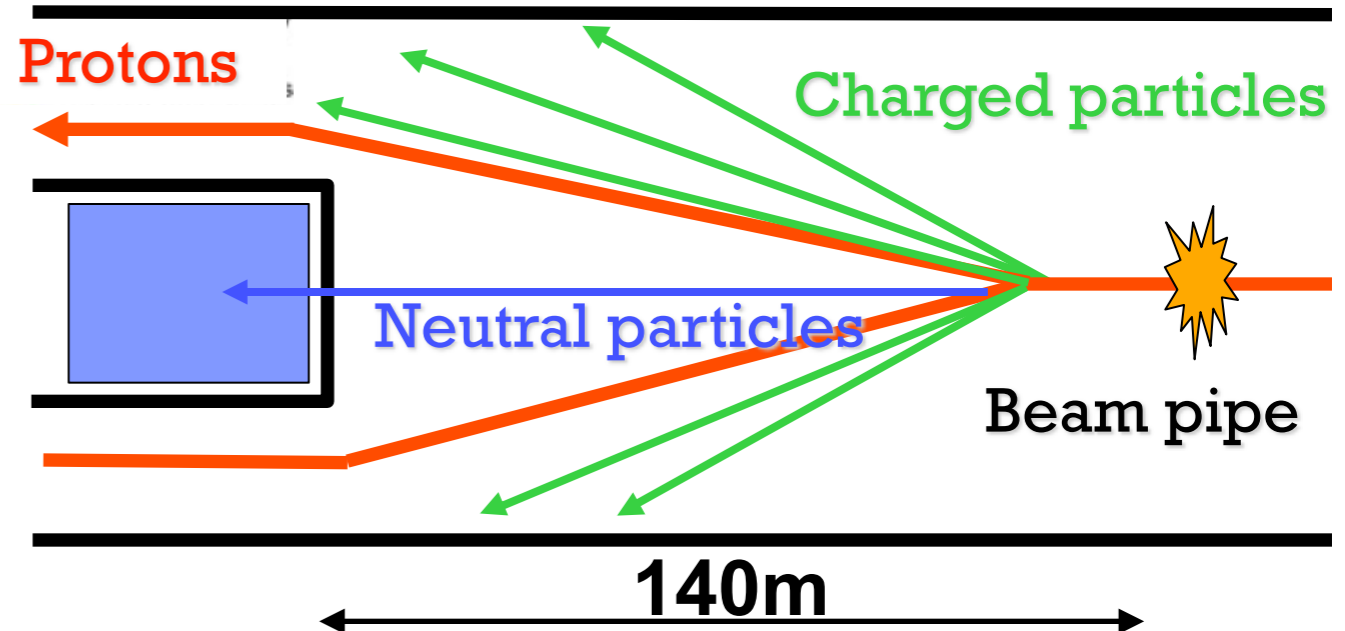
**p**

**Pb**

**Arm2**

32mm

25mm



# LHCf Detector



## Expected Performance

Energy resolution ( $> 100\text{GeV}$ )

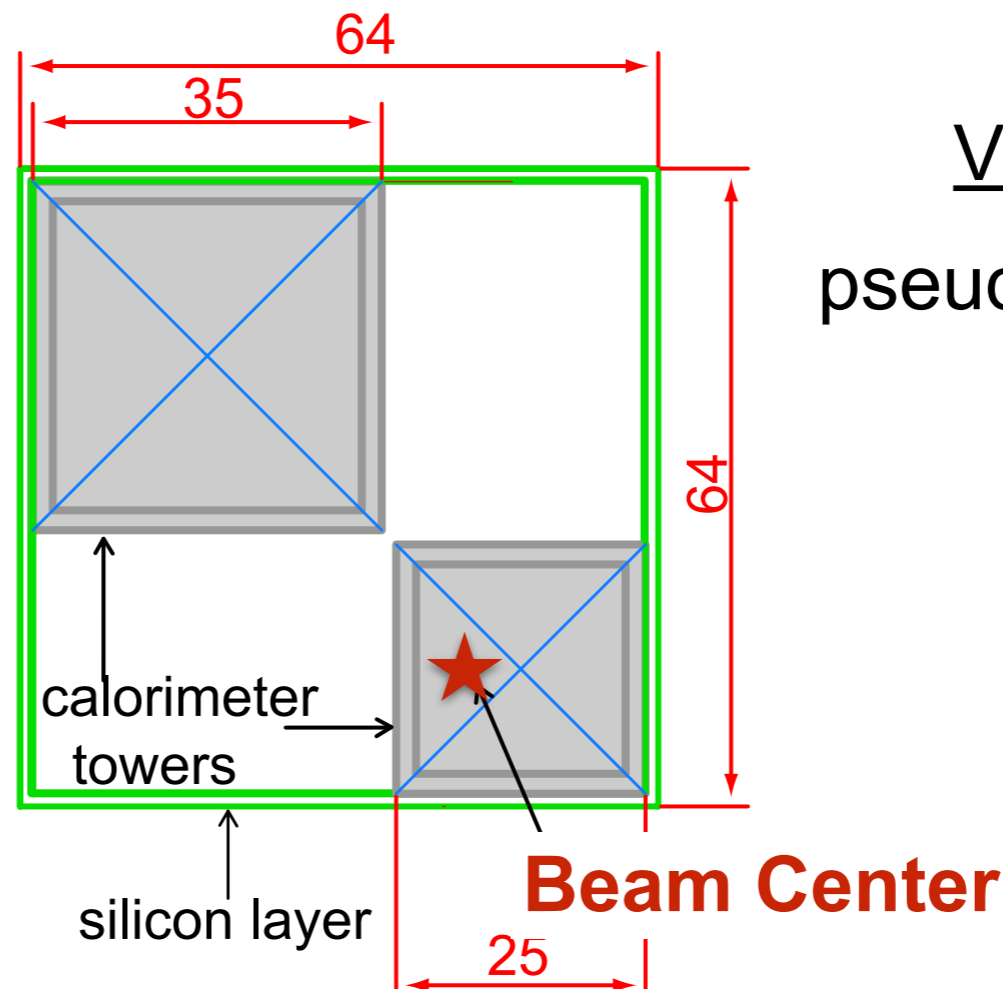
$< 5\%$  for Photons

$40\%$  for Neutrons

Position resolution

$< 200\mu\text{m}$  for Photons

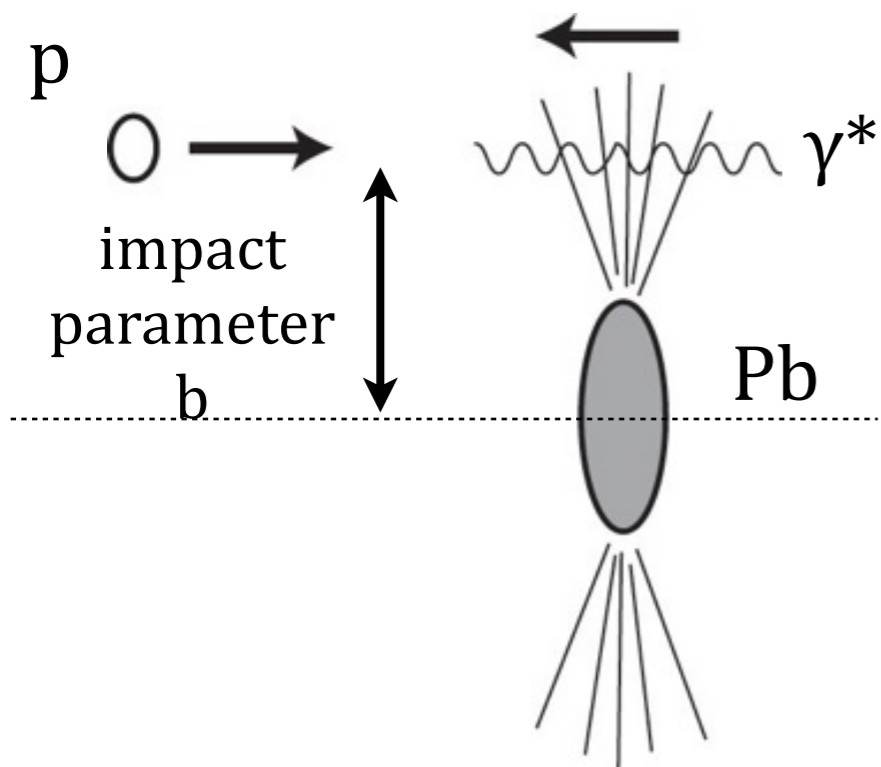
a few mm for Neutrons



## View of IP

pseudorapidity range  
 $\eta > 8.4$

# Event Generation of UPCs



## Event Generation of UPCs

Flux of quasi photons

Cross section of p- $\gamma$

Event Generation of p- $\gamma$

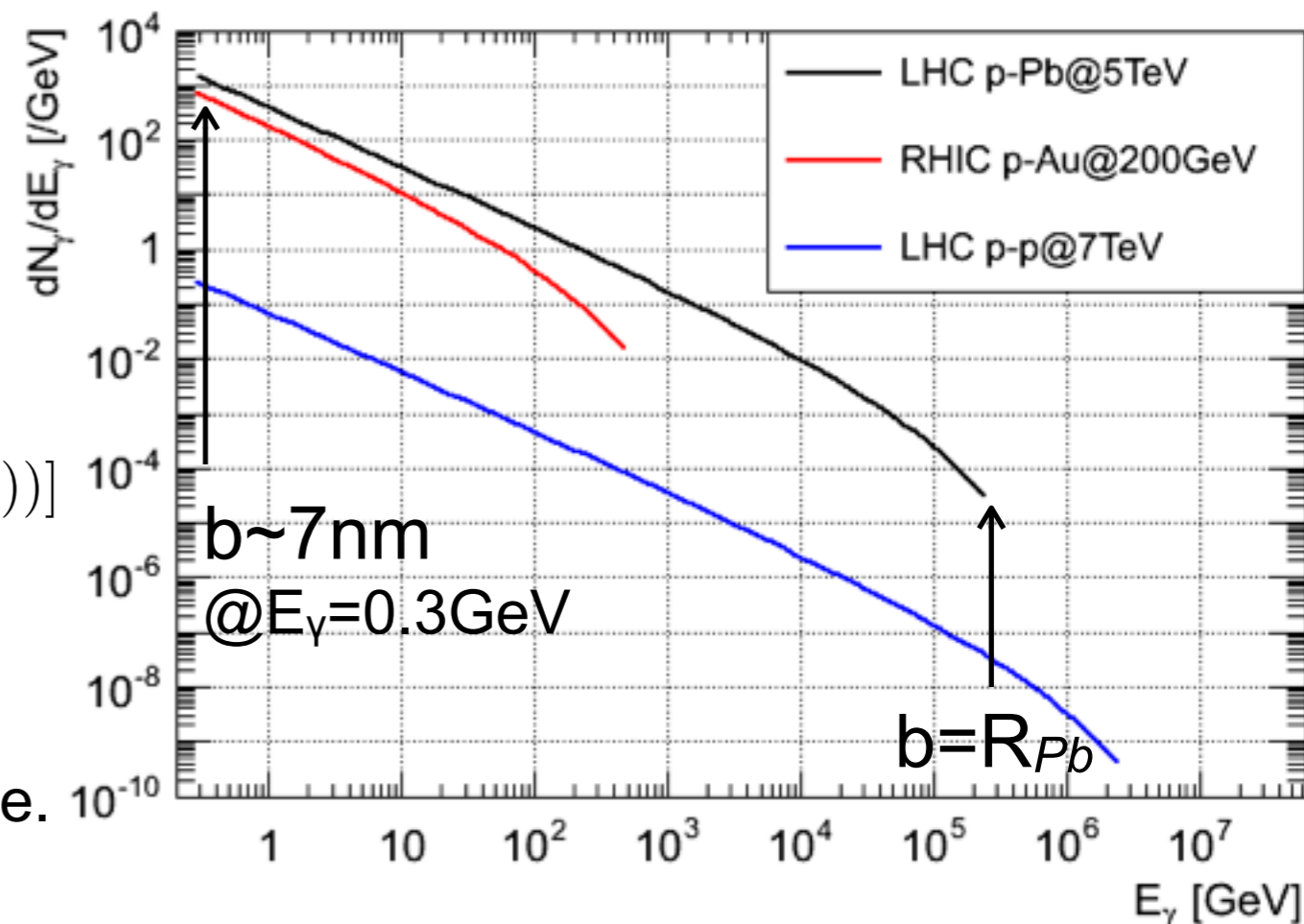
## Flux of quasi photons

### Weizsacker-Williams method

$$\frac{dN_{\gamma^*}}{dE_{\gamma^*}} = \frac{2Z^2\alpha}{\pi E_{\gamma^*}} \left[ xK_0(x)K_1(x) + \frac{x^2}{2} (K_0^2(x) - K_1^2(x)) \right]$$

$$\simeq \frac{2Z^2\alpha}{\pi E_{\gamma^*}} \left( \log \frac{1.123}{x} - 1 \right) \quad (\text{if } E_{\gamma^*} \ll E_{max})$$

$E_{\gamma^*}$ : energy of photons at the proton rest frame.

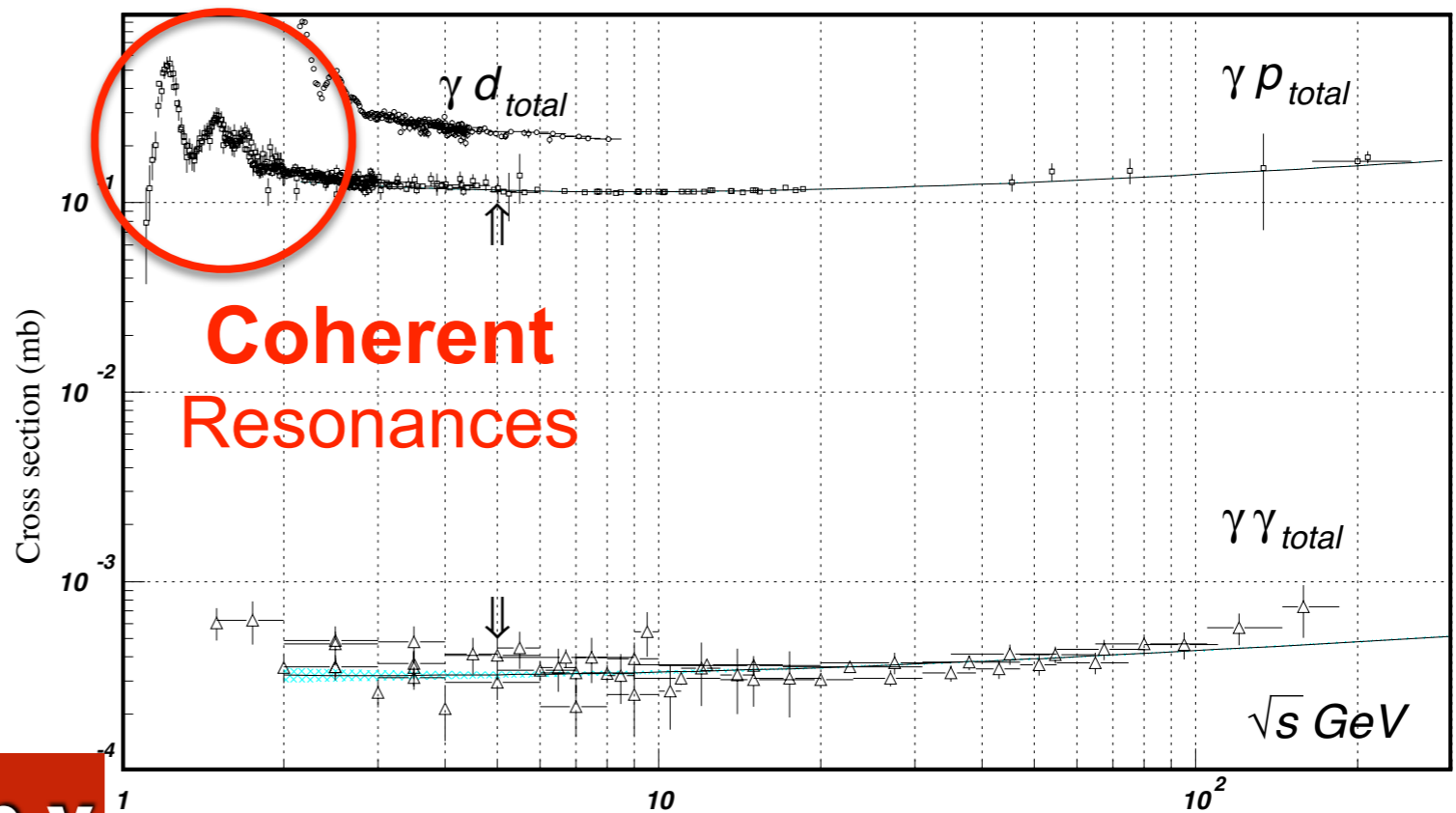


# Cross section of p- $\gamma$

ref. PDG

Estimate the cross-section of the  $\Delta(1232)$  production

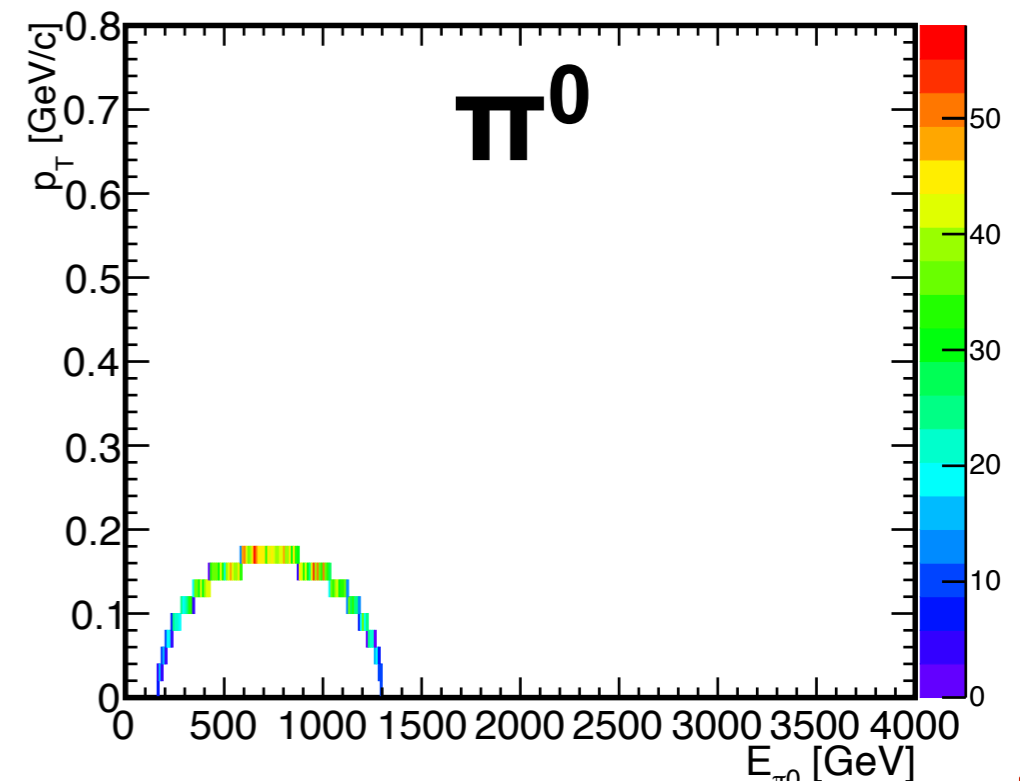
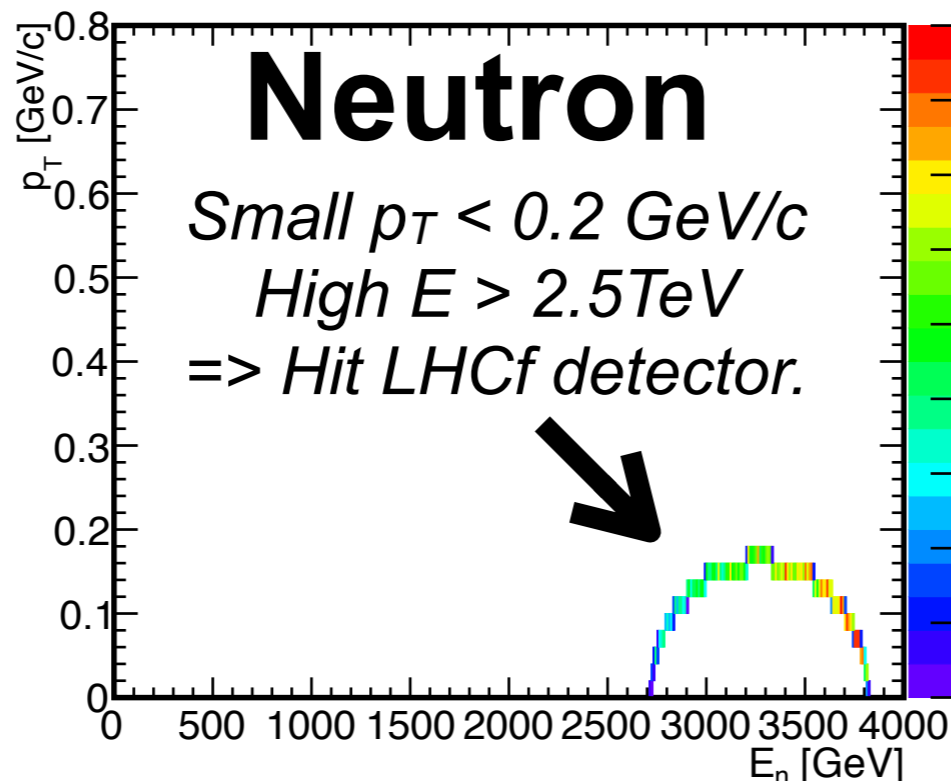
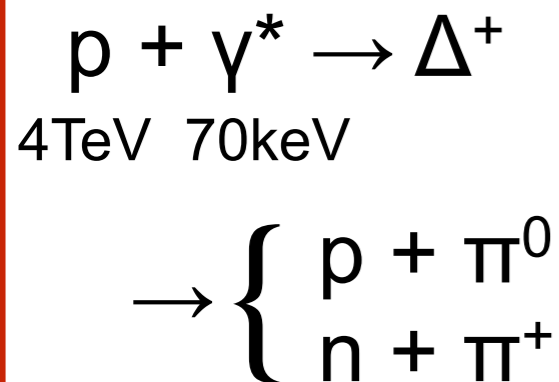
$$\begin{aligned} \sigma_{p+\gamma \rightarrow \Delta+Pb} & \\ & \sim 1.5 \times 10^3 / \text{GeV} \\ & \times 0.6 \text{mb} \times 0.2 \text{GeV} \\ & = 180 \text{mb} \end{aligned}$$



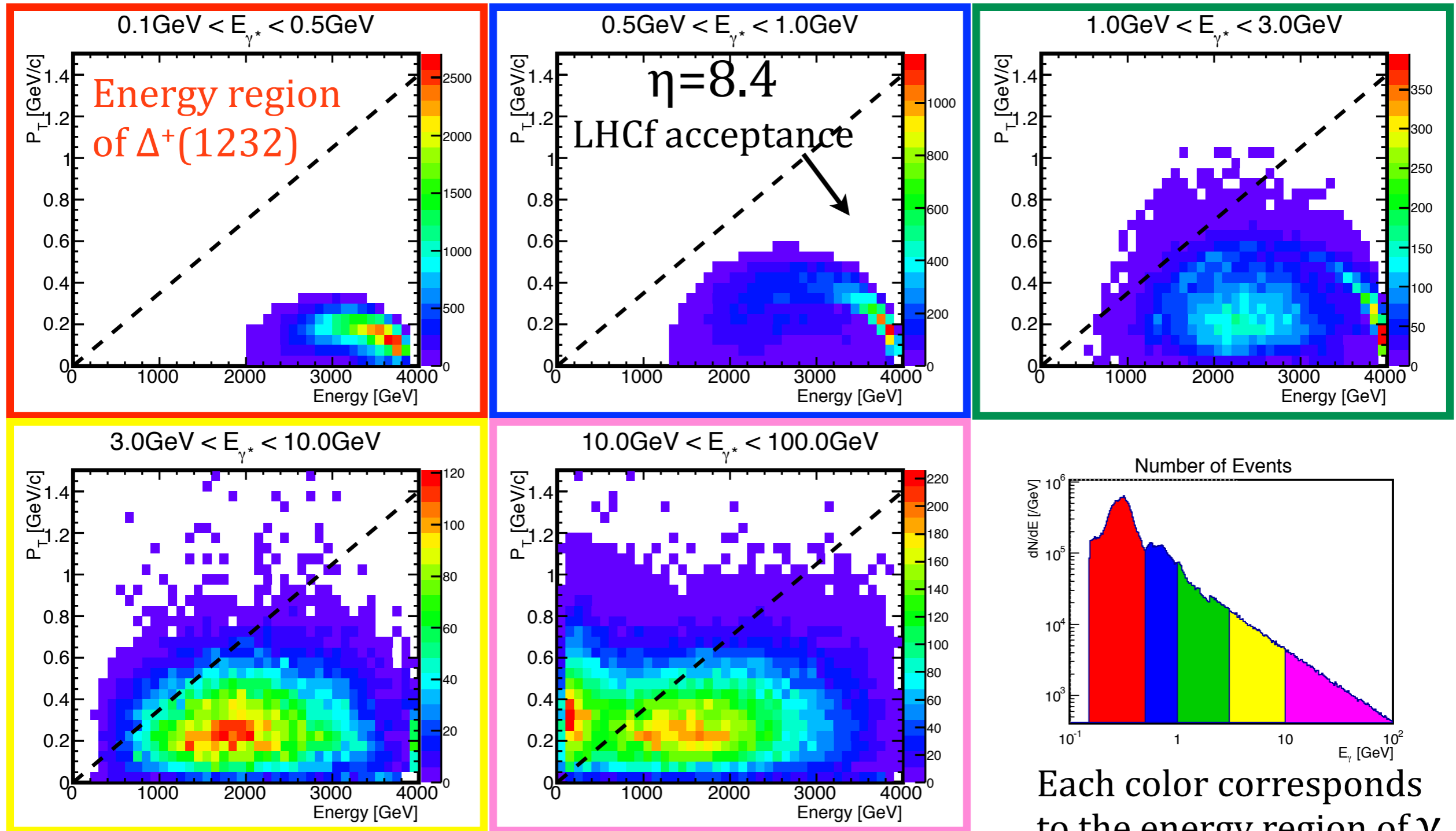
## Event Generation of p- $\gamma$

Event Generation by the Sophia model

Example:



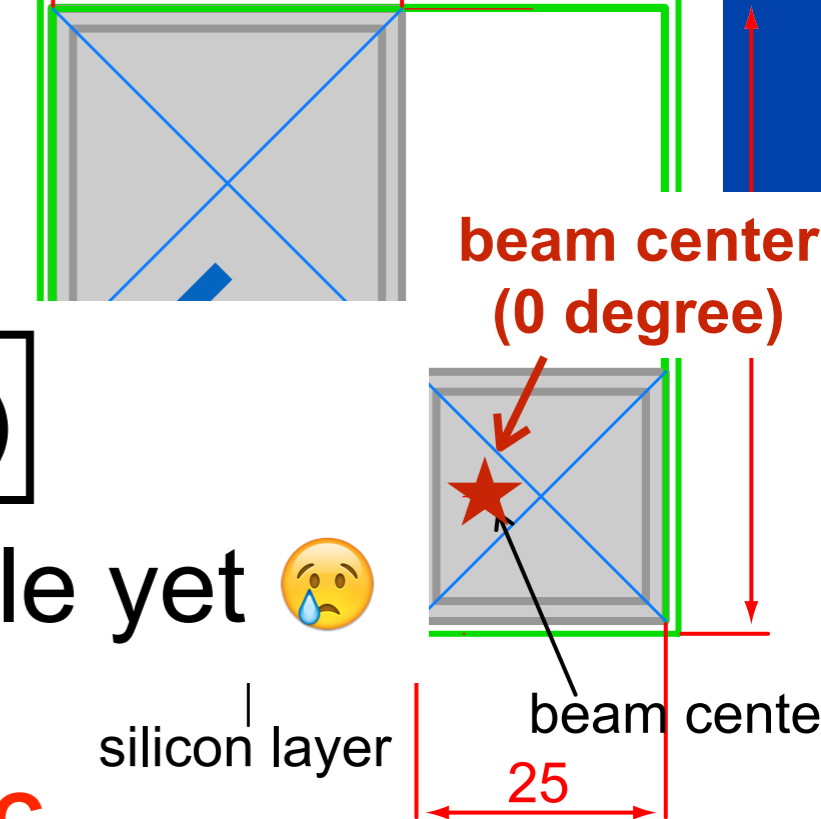
# Energy vs. $p_T : p + \gamma^* \rightarrow n + X$



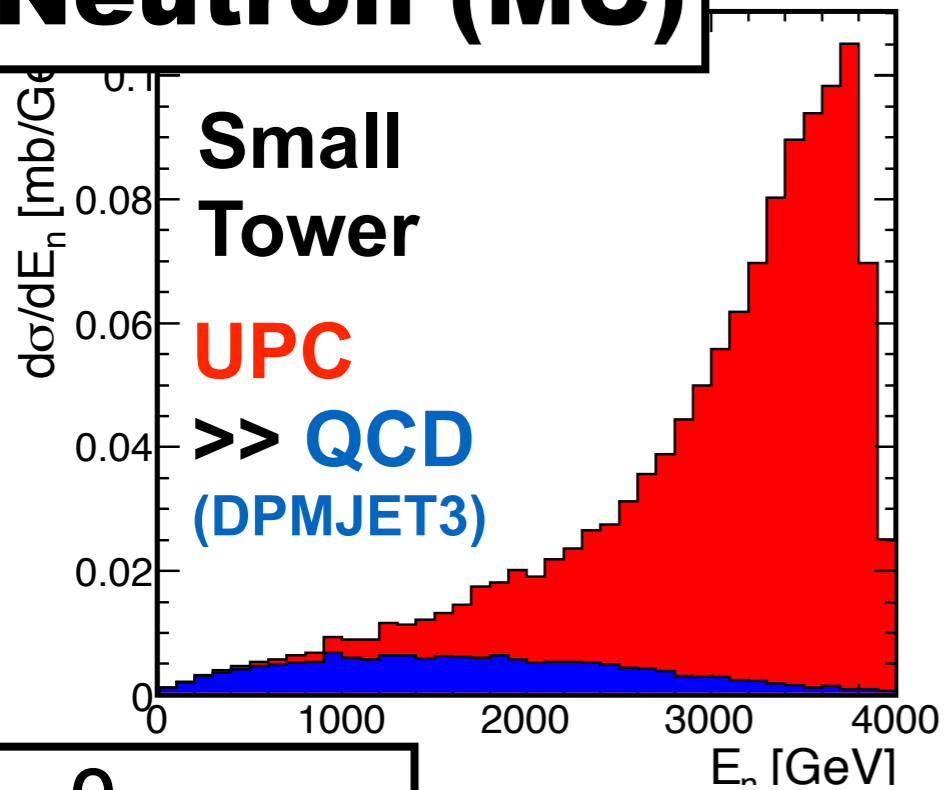
Each color corresponds to the energy region of  $\gamma$  in the p rest frame



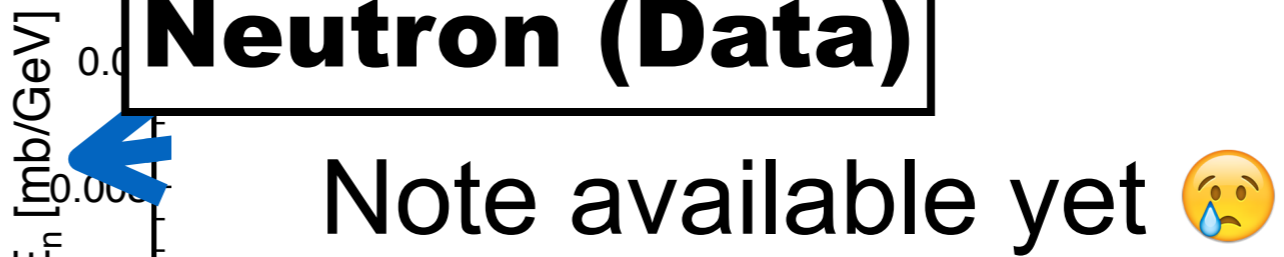
# UPC vs QCD in LHCf



## Neutron (MC)



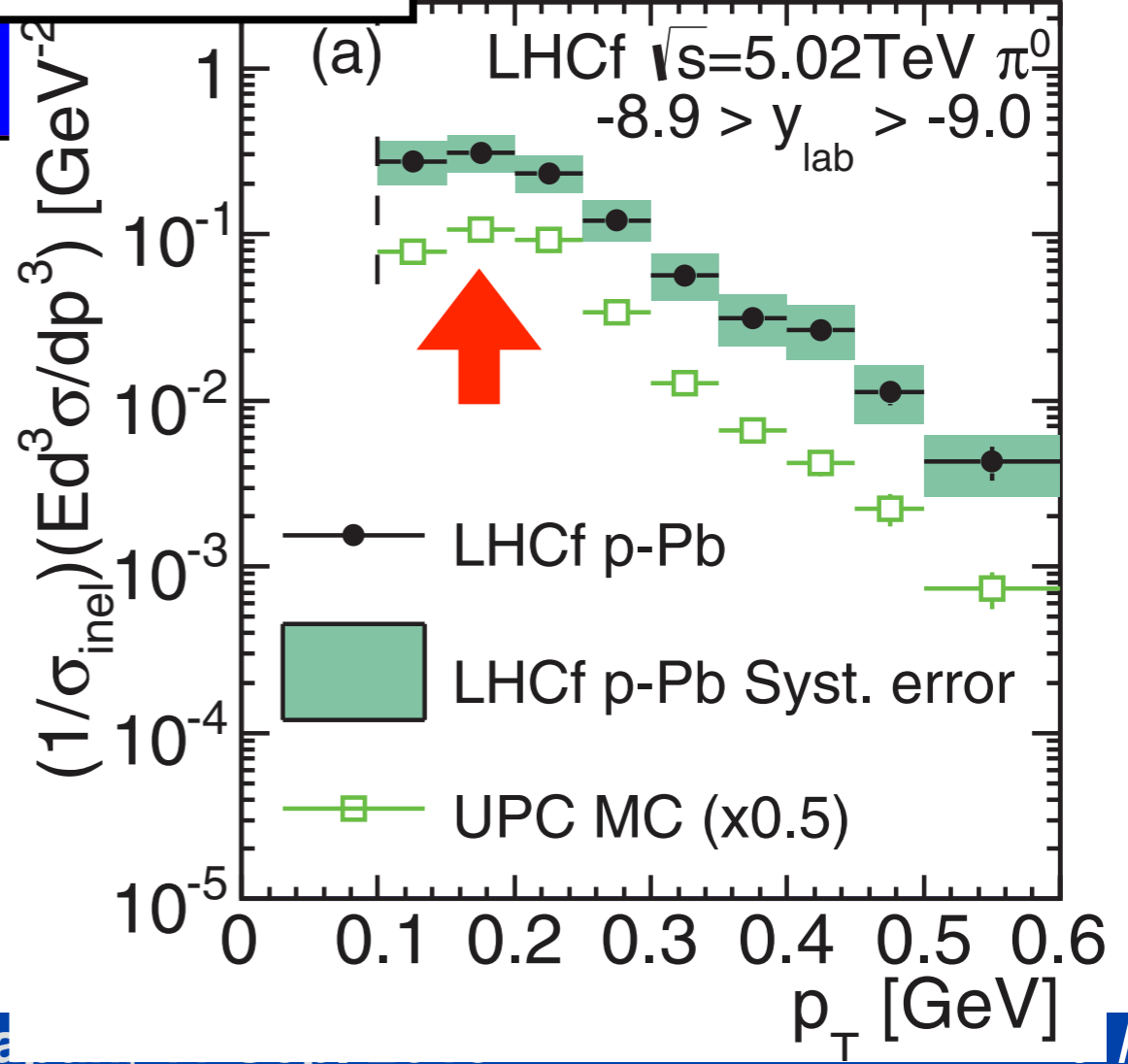
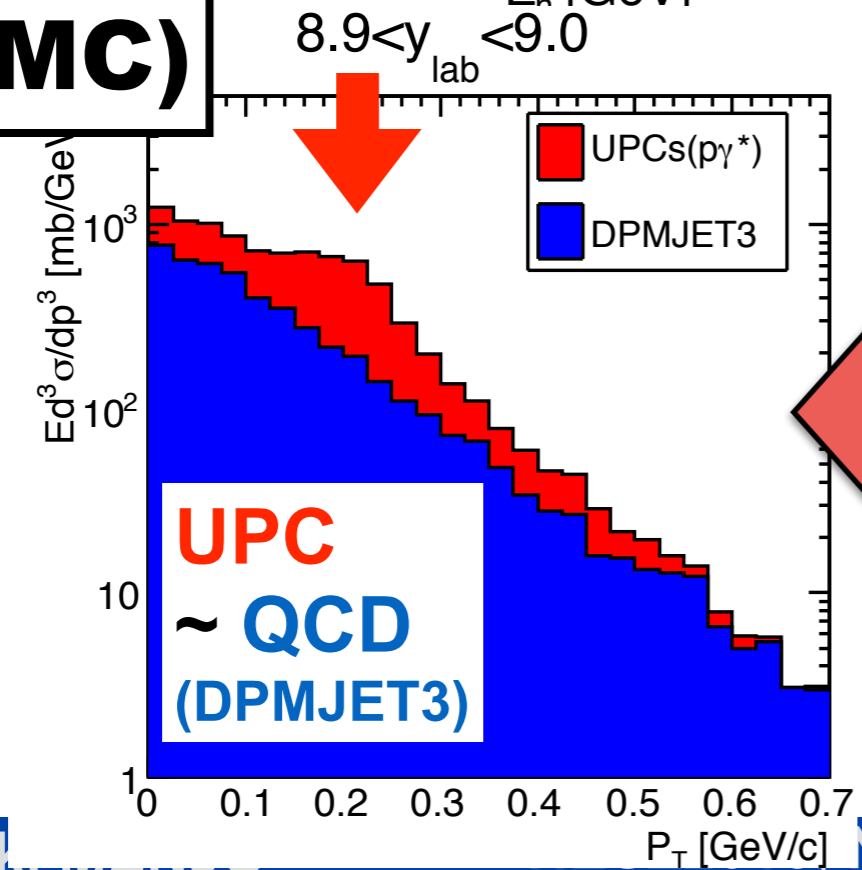
## Neutron (Data)



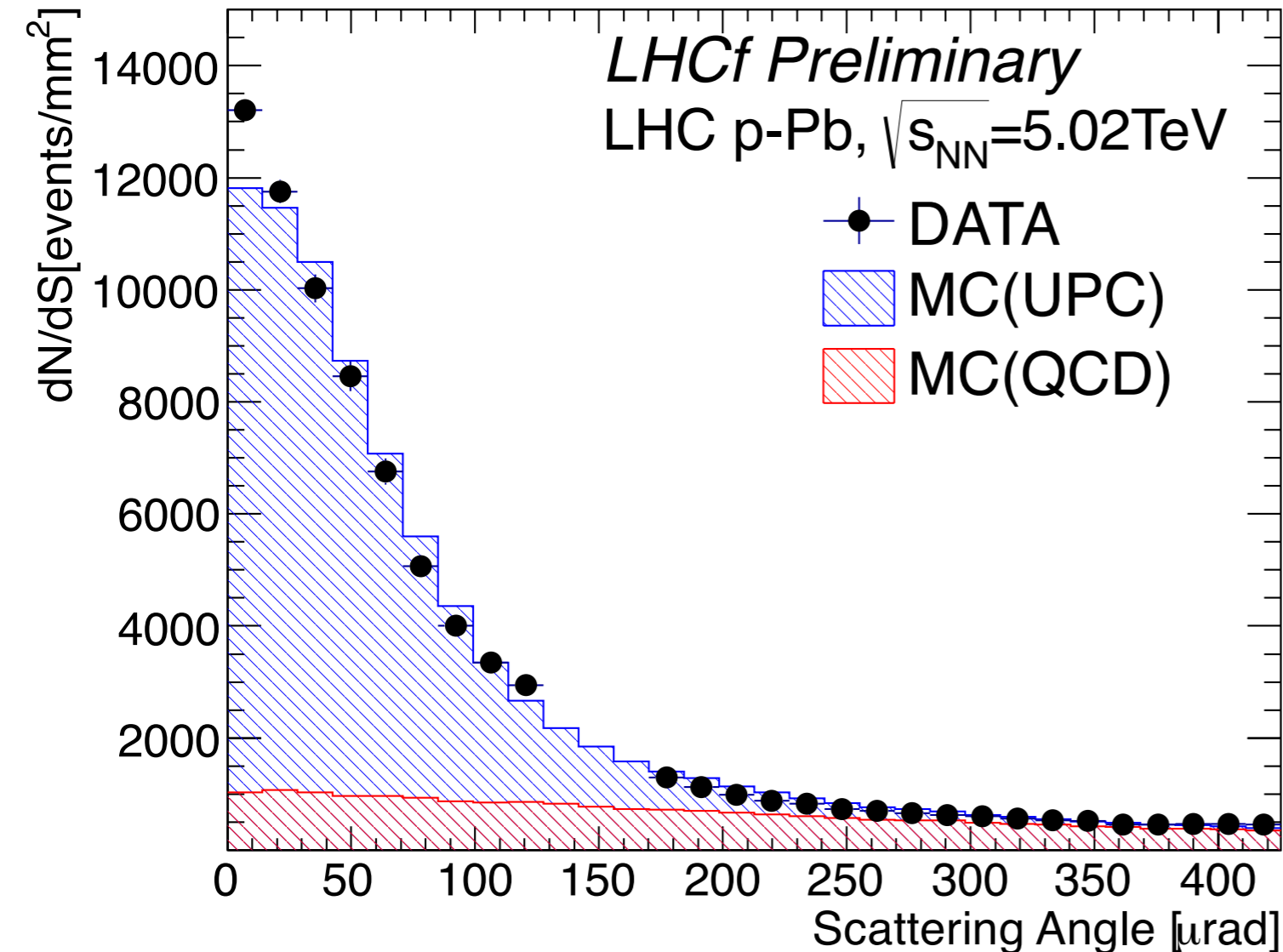
## π<sup>0</sup> (Data)



## π<sup>0</sup> (MC)



# Scattering Angle Distribution of Neutrons



High concentration of neutrons, seen in LHCf data is well reproduced by MC of UPCs, especially  $p+\text{Pb} \rightarrow \Delta+\text{Pb} \rightarrow n+\pi^+ + \text{Pb}$

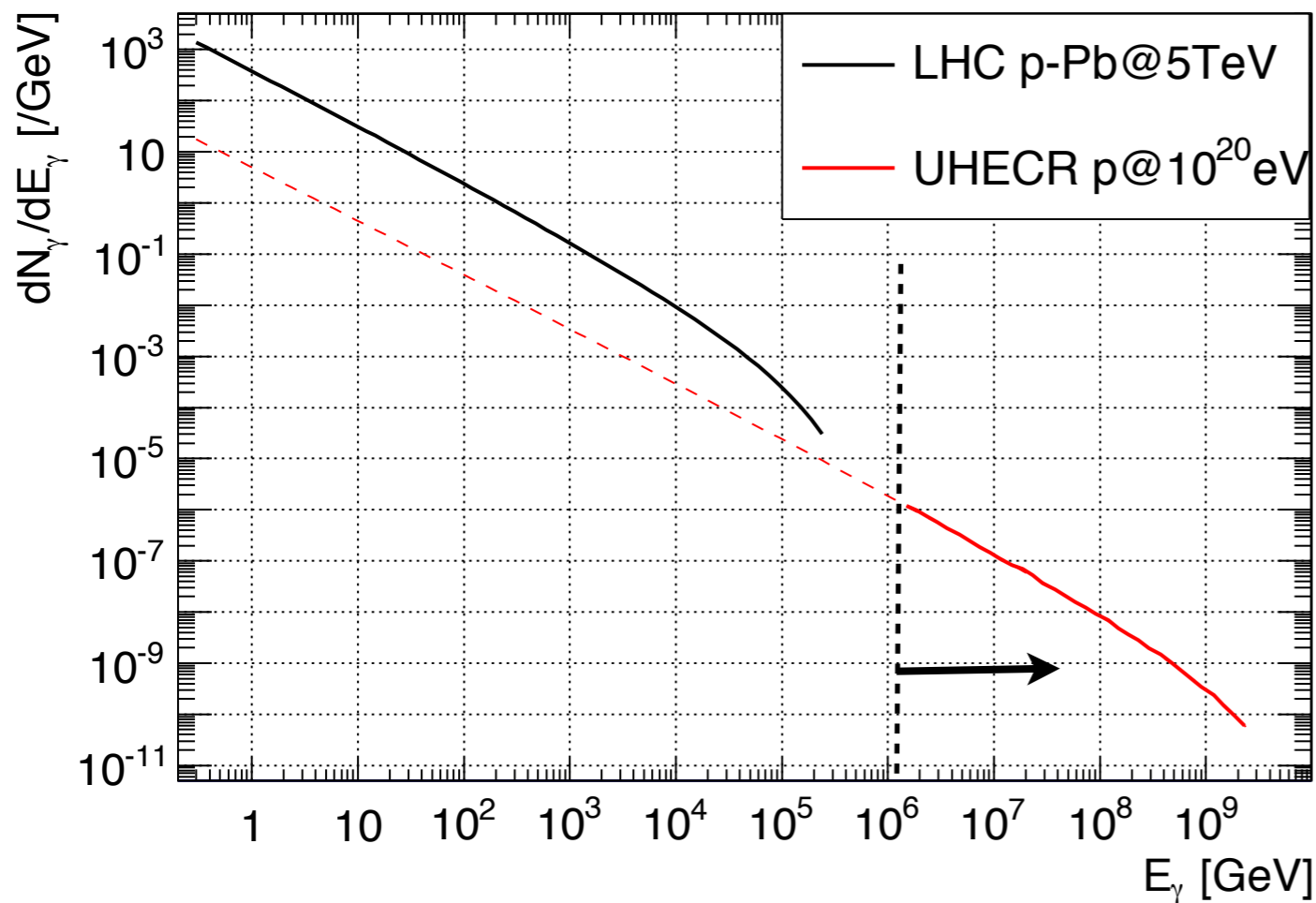
**For testing interaction models,**

**QDC contribution must be extracted from the measured results.**

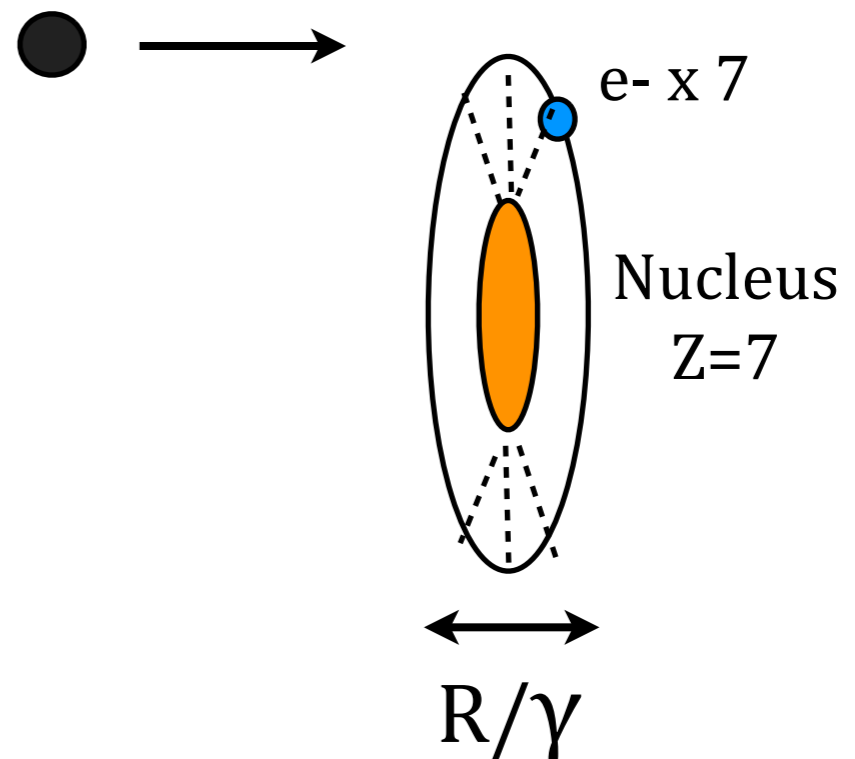
**UPC  $\leq$  Background, factor 10 higher than signal at 0 degree.**

**How it can be rejected (reduced) experimentally ?**

# Impact of UPC on UHECRs



UHECRs, 10<sup>20</sup>eV



- Quasi-photon flux in UPC is proportion to  $Z^2$ , Flux at Nitrogen is  $\sim 1/100$  of Pb
- Nitrogen nuclei are shadowed by electrons.  
 Assuming the radius of atom,  $R$ , is 1 Å, the minimum energy of quasi-photon,  $E_{\min}$ , is estimated as  $E_{\min} = hc\gamma/R \sim 10^6 \text{ GeV} @ \text{UHECR } 10^{20} \text{ eV}$
- The total cross section of  $(p, \gamma^*)$  is estimated as  

$$d\sigma^{p\gamma^*} = \int_{>10^6 \text{ GeV}} dN_{\gamma^*}/dE_{\gamma^*} d\sigma^{p\gamma} dE \sim 30 \times 0.14 \text{ mb} \sim 4 \text{ mb. } (= 0.8 \% \text{ of } \sigma_{\text{ine}}).$$

# **First ATLAS-LHCf collaborated analysis**

ATLAS LHCf NOTE

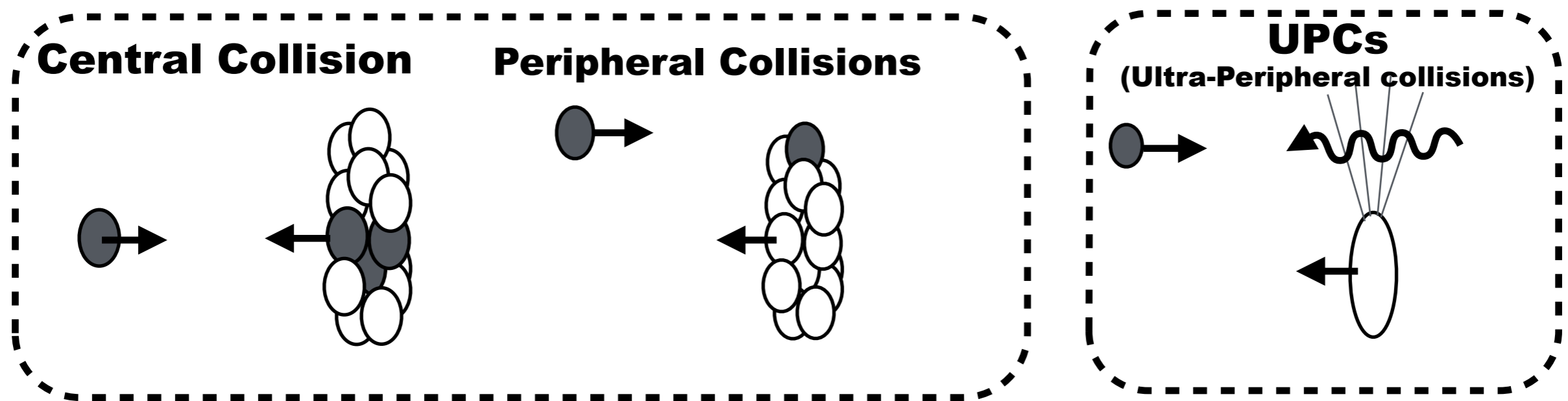
*“Classification of Events in the Combined ATLAS-LHCf Data  
Recorded During the  $p+Pb$  Collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”*

ATL-PHYS-PUB-2015-038 <https://cds.cern.ch/record/2047832>

# Purposes of first joint analysis

- Verify the correct behavior of common operation (trigger exchange) with data
- Have preliminary results to demonstrate the worth of ATLAS-LHCf common operation.

⇒ **Specific feature of UPC events is perfect for this purpose.**



**Particle production in the central region**

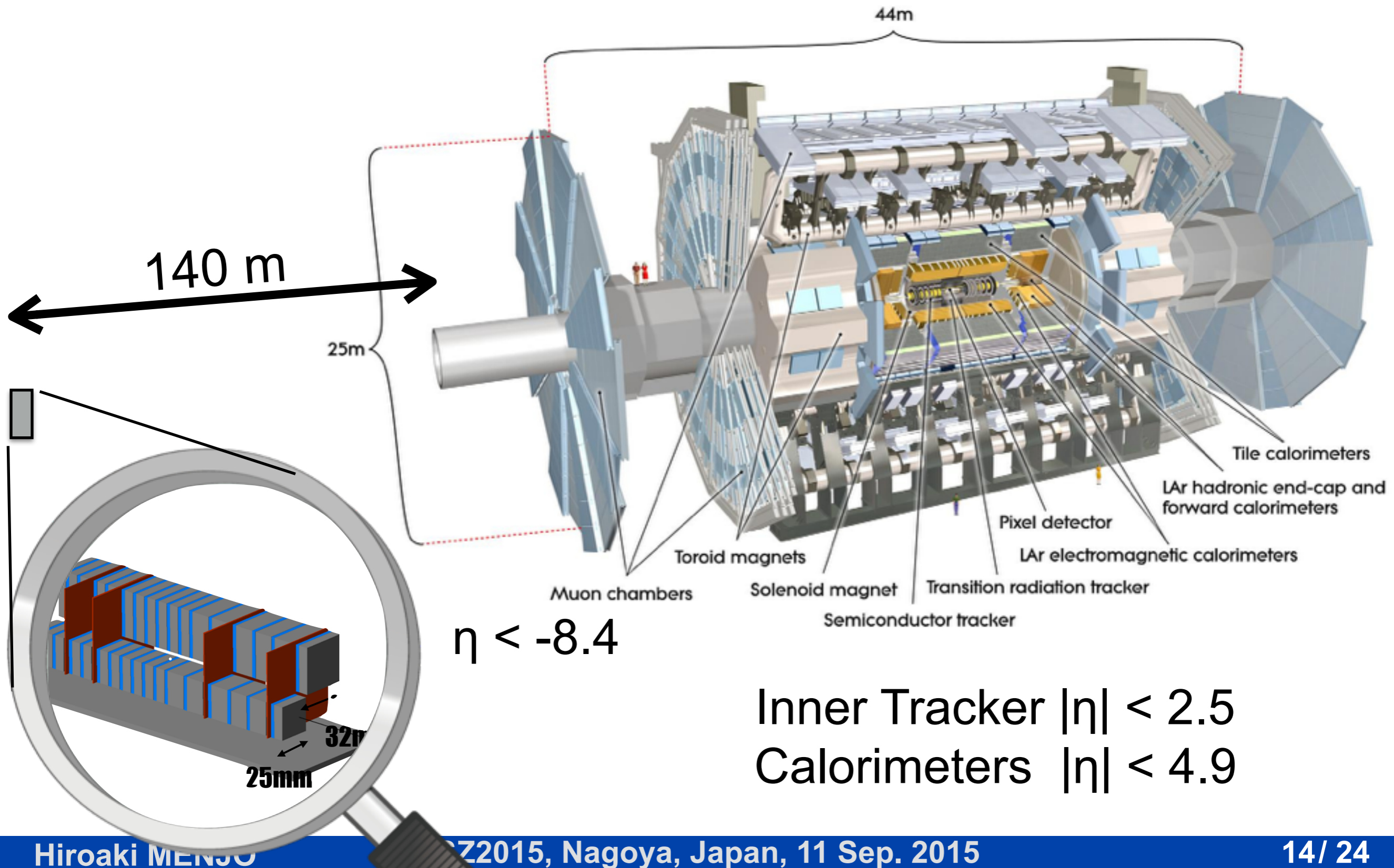
**Huge**

**Some**

**Few**

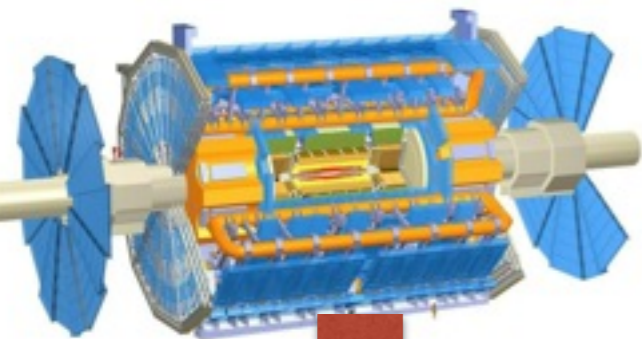
⇒ The events can be categorized by ATLAS information.

# Detectors at IP1

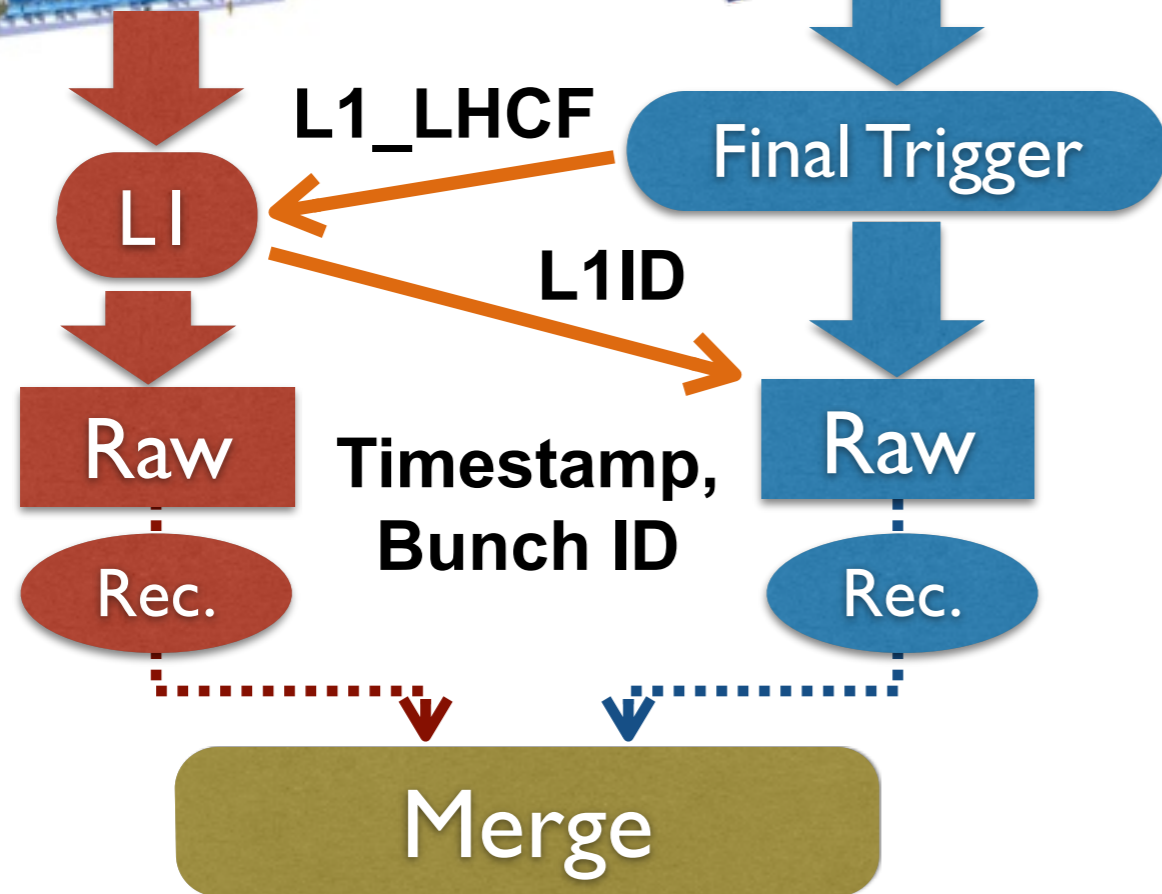
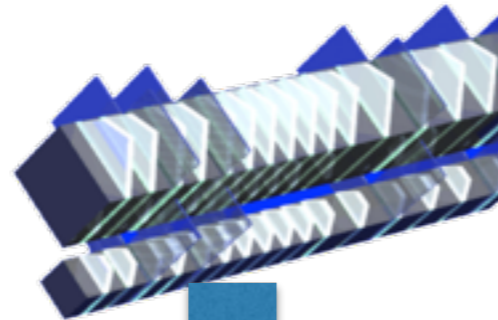


# Common operation in 2013

## ATLAS



## LHCf



## DAQ scheme

- LHCf sent the final trigger signals (~500Hz) to ATLAS DAQ
- ATLAS received the LHCf signals as one of inputs for Level 1 Trigger (L1\_LHCF).
- L1\_LHCF triggered ATLAS after the pre-scaling down to 20-40 Hz in the high level trigger.  
L1\_LHCF only => 10 Hz  
L1\_LHCF +  $\geq 1$  Tracks => 10-30 Hz
- Merge LHCf and ATLAS data after the event reconstruction in offline

# Analysis

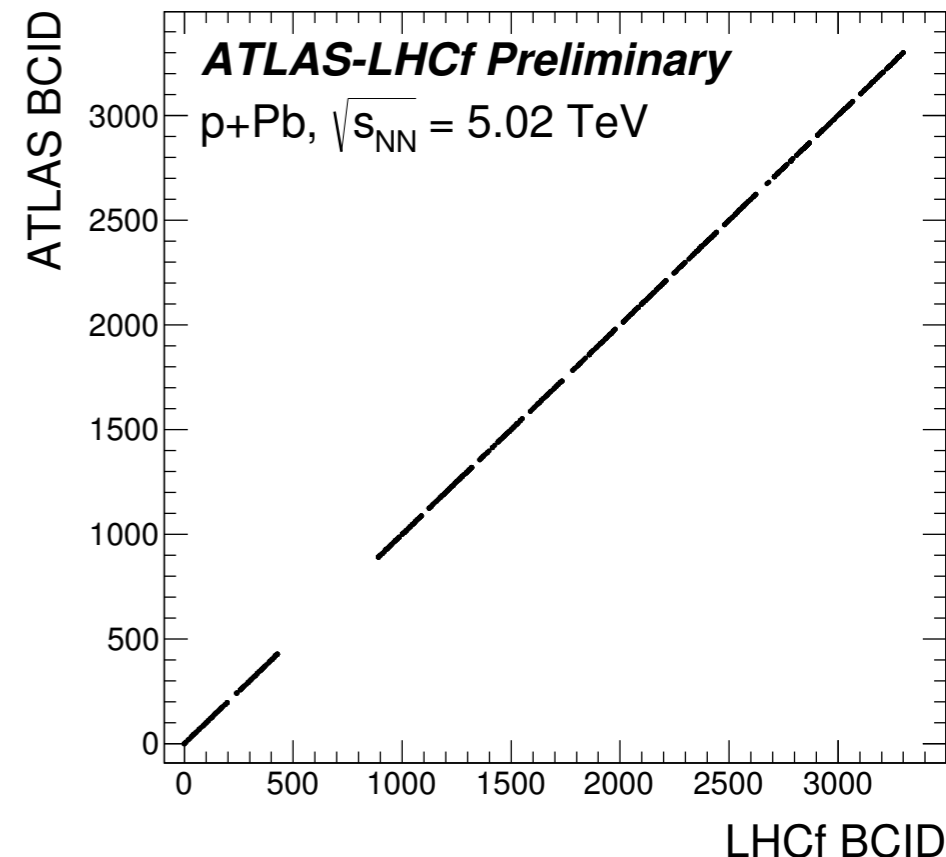
## ■ Data

1, Feb 2013 (Fill#3510) with  $p+Pb$   $\sqrt{s_{NN}}=5.02\text{TeV}$

## ■ Event matching

Event Matching btw LHCf and ATLAS by using event-by-event information recoded both in ATLAS and in LHCf.

- **L1ID**  $\Rightarrow$  Not correctly recoded in LHCf
- **TimeStamp**  $\Rightarrow$  **For Event-Matching**
- **Bunch ID**  $\Rightarrow$  **Verification**



## ■ Event categorization with a simple criteria

Number of tracks ( $N_{sel}$ ) in the ATLAS pixel detectors ( $p_T > 0.1 \text{ GeV}/c$ ,  $|\eta| < 2.5$ )

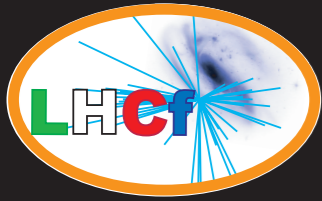
- { **Events w/  $N_{sel} = 0$**  - UPCs (+diffractive) rich sample
- { **Events w/  $N_{sel} > 0$**  - QCD rich sample

## ■ LHCf standard analysis for photons, neutrons

Energy resolution for photons and neutrons are  $< 5\%$  and  $40\%$  respectively.



# - Event Display -



## LHCf Experiment

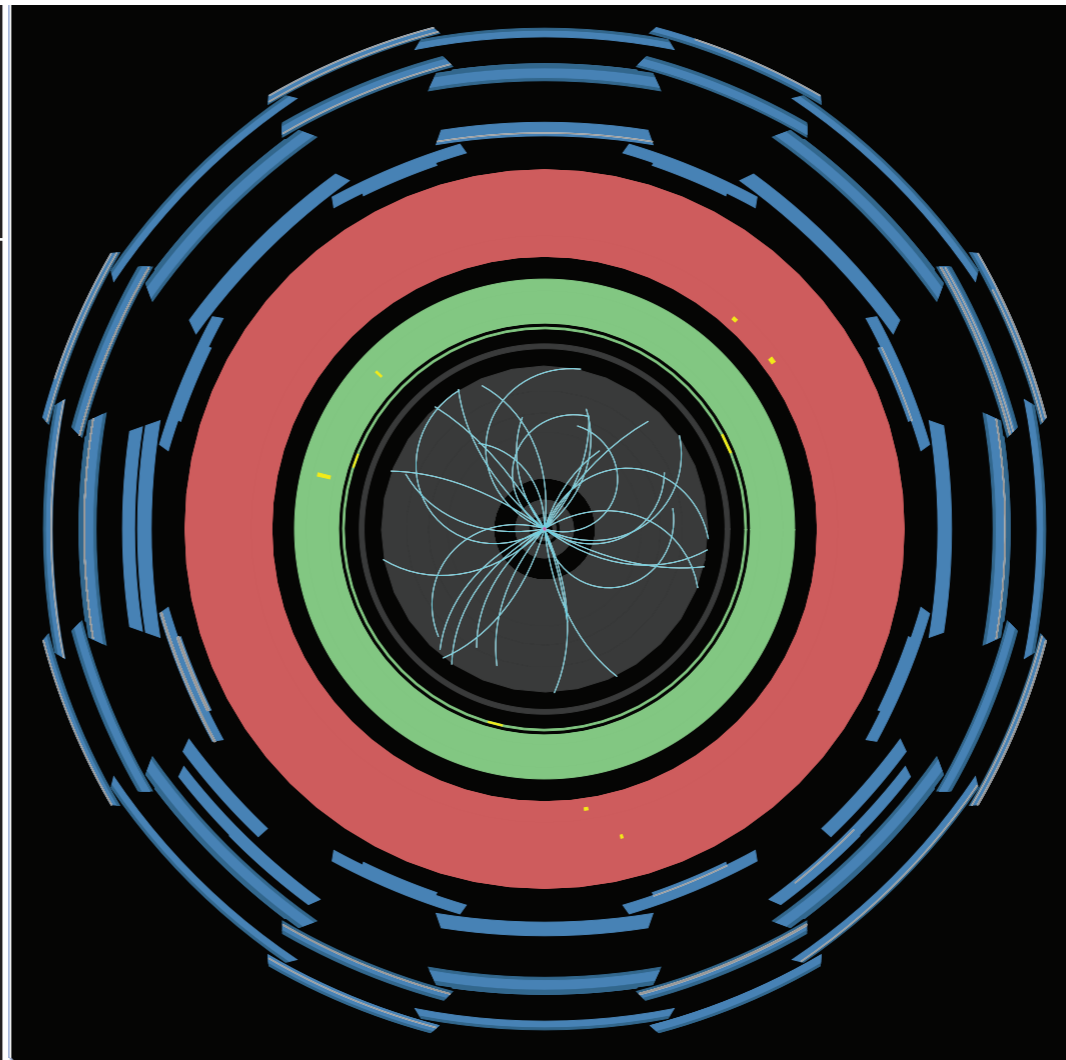
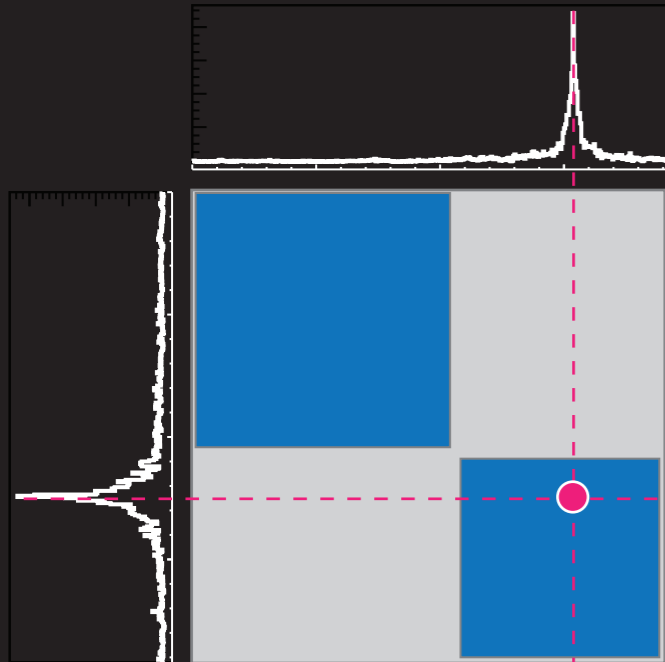
RUN Number : 27357    Event Number : 18969  
Date : 2013-02-01 04:15:47 UTC

### Arm2

Tower Large (TL)

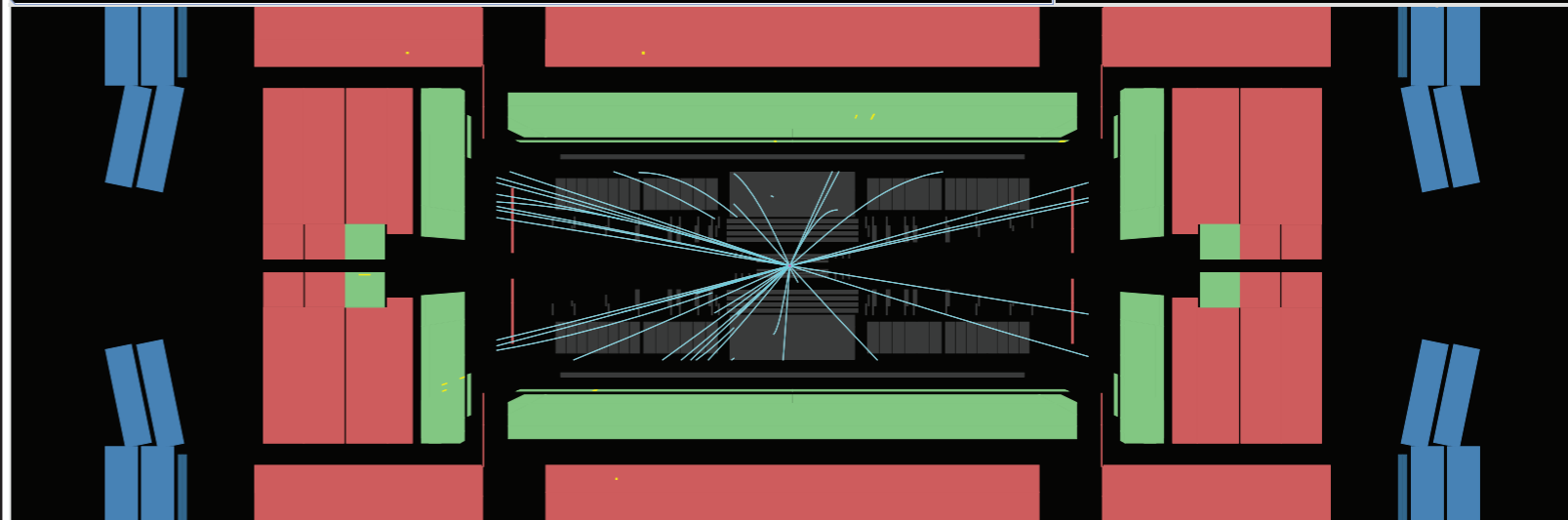
Tower Small (TS)

● Photon like  
248 GeV

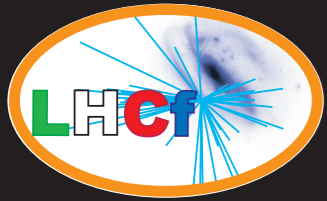


Run Number: 218589, Event Number: 115574439

Date: 2013-02-01 04:15:47 UTC



# - Event Display -



## LHCf Experiment

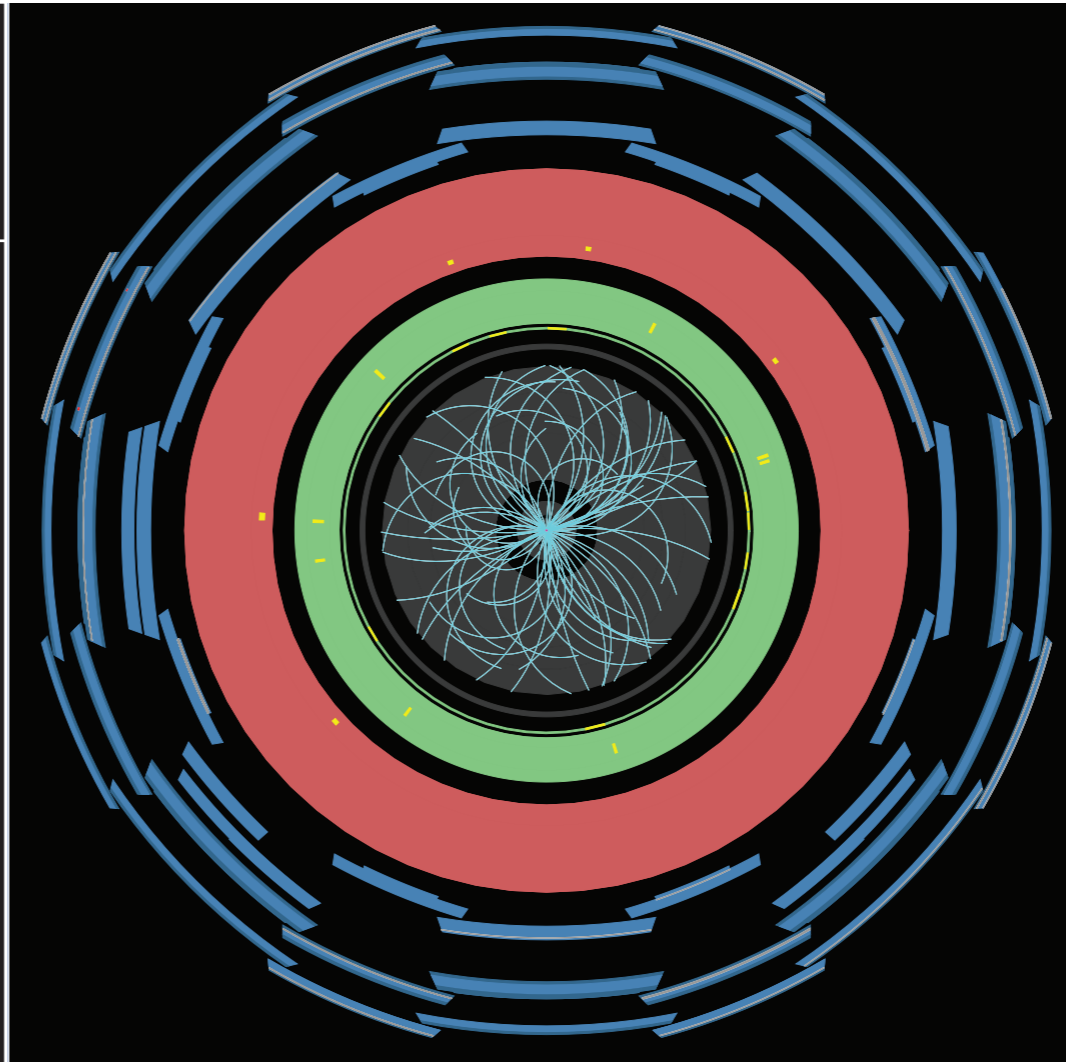
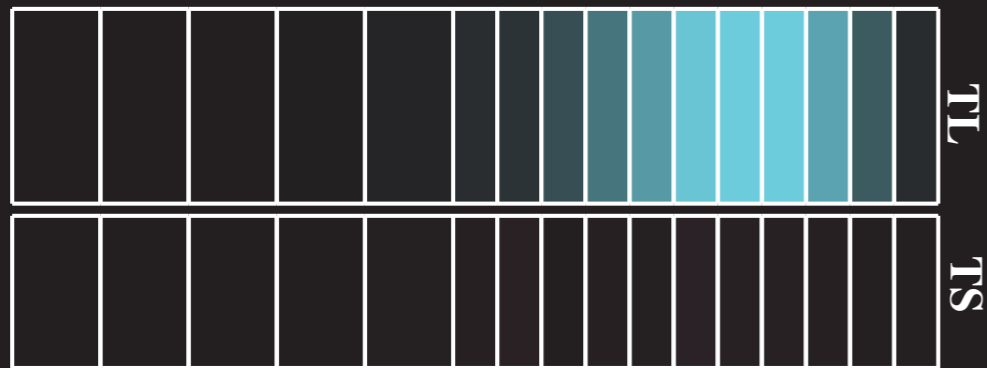
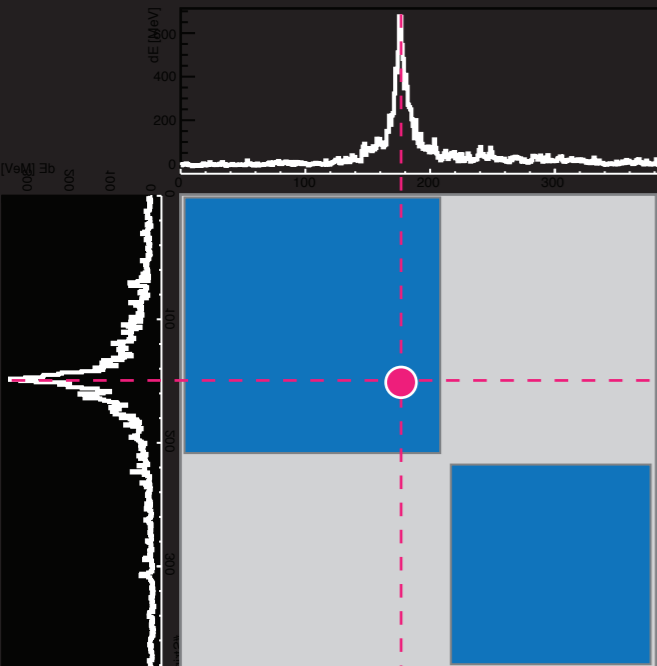
RUN Number : 27357    Event Number : 21926  
Date : 2013-02-01 04:15:51 UTC

### Arm2

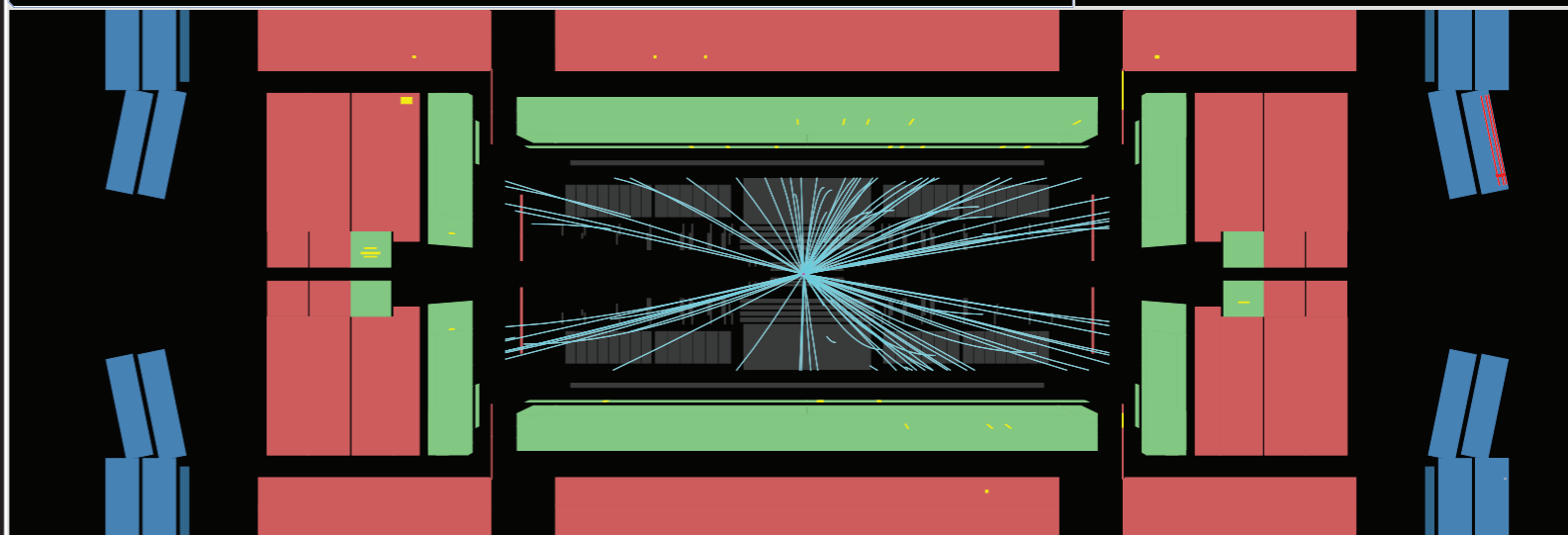
Tower Large (TL)

● Photon like  
485 GeV

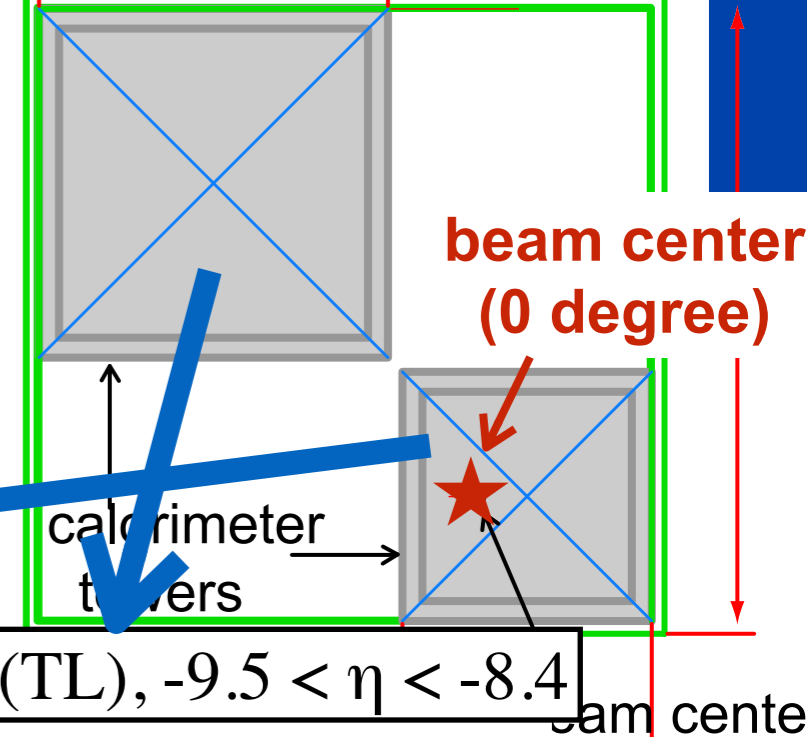
Tower Small (TS)



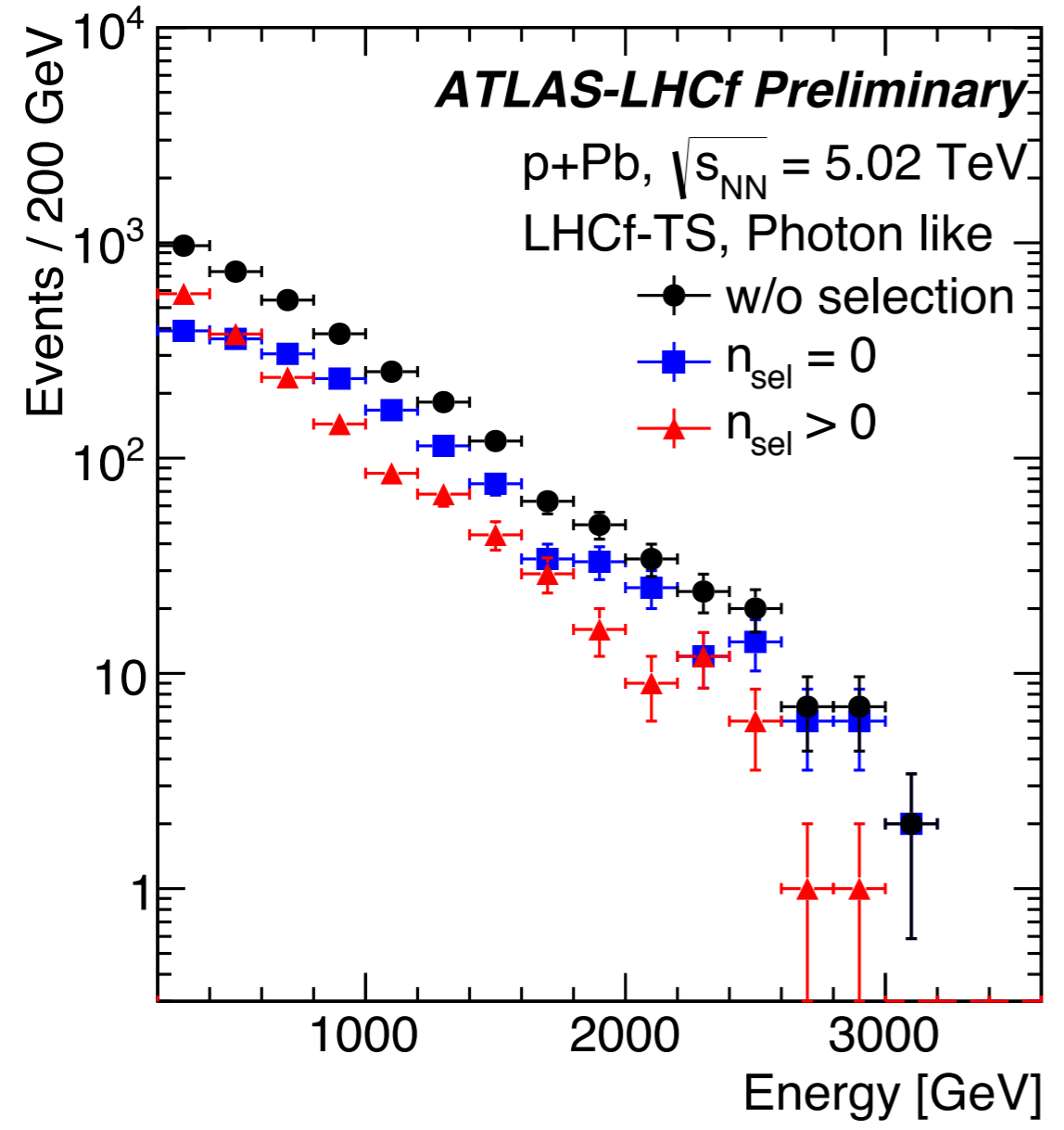
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Date: 2013-02-01 04:15:51 UTC



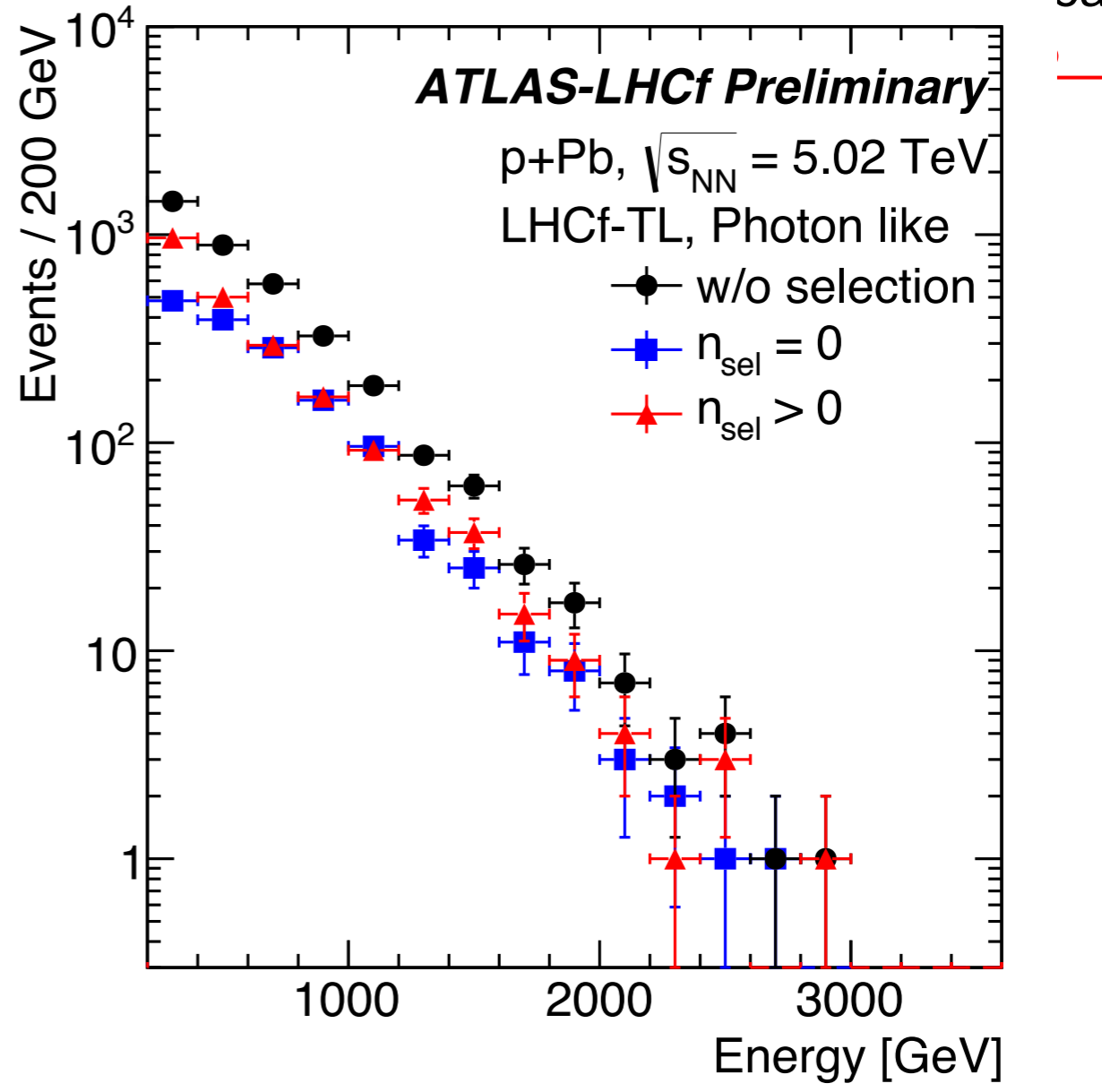
# Energy Spectra - Photon like -



LHCf-Tower Small(TS),  $\eta < -9.6$

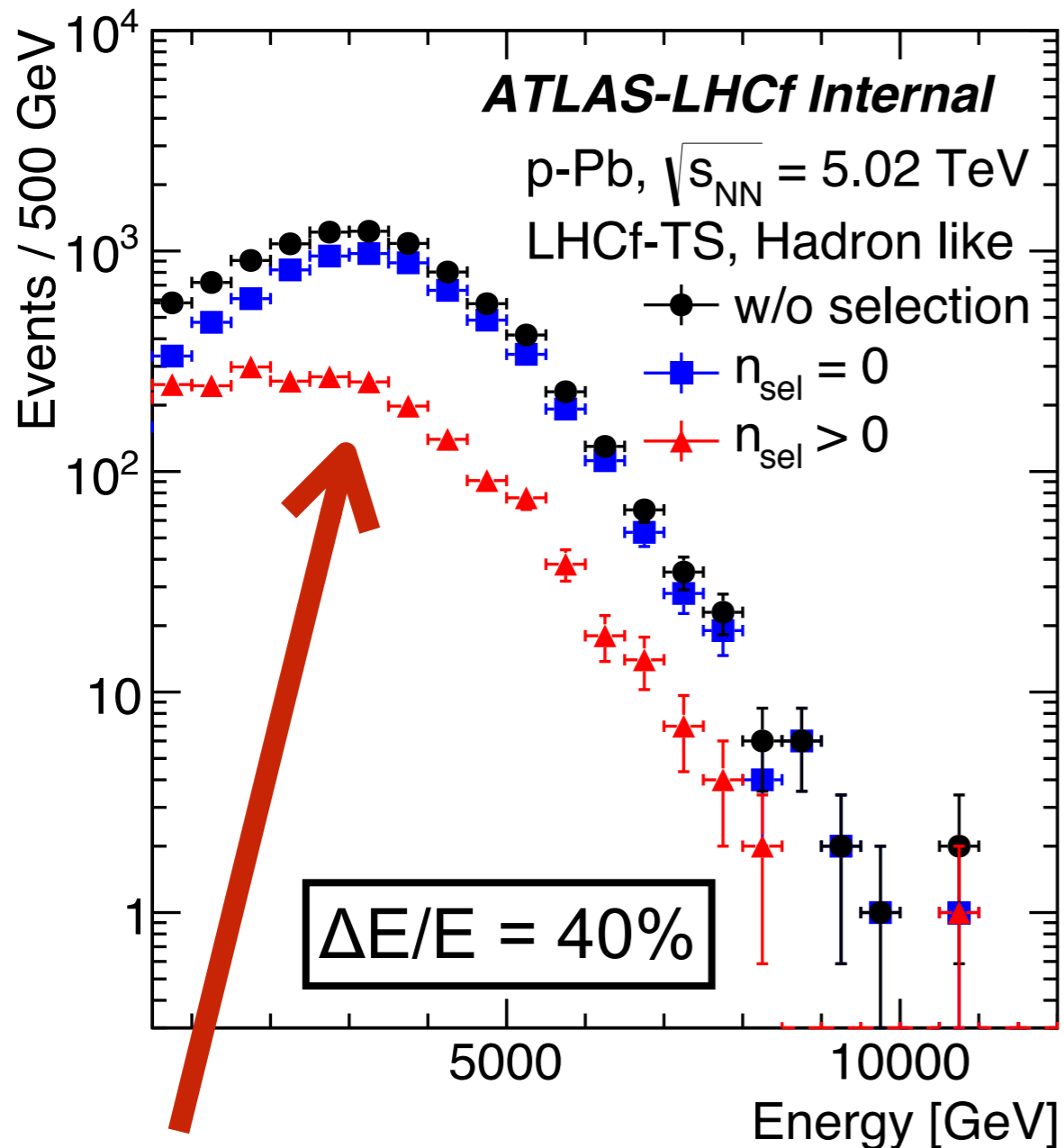


LHCf-Tower Large(TL),  $-9.5 < \eta < -8.4$

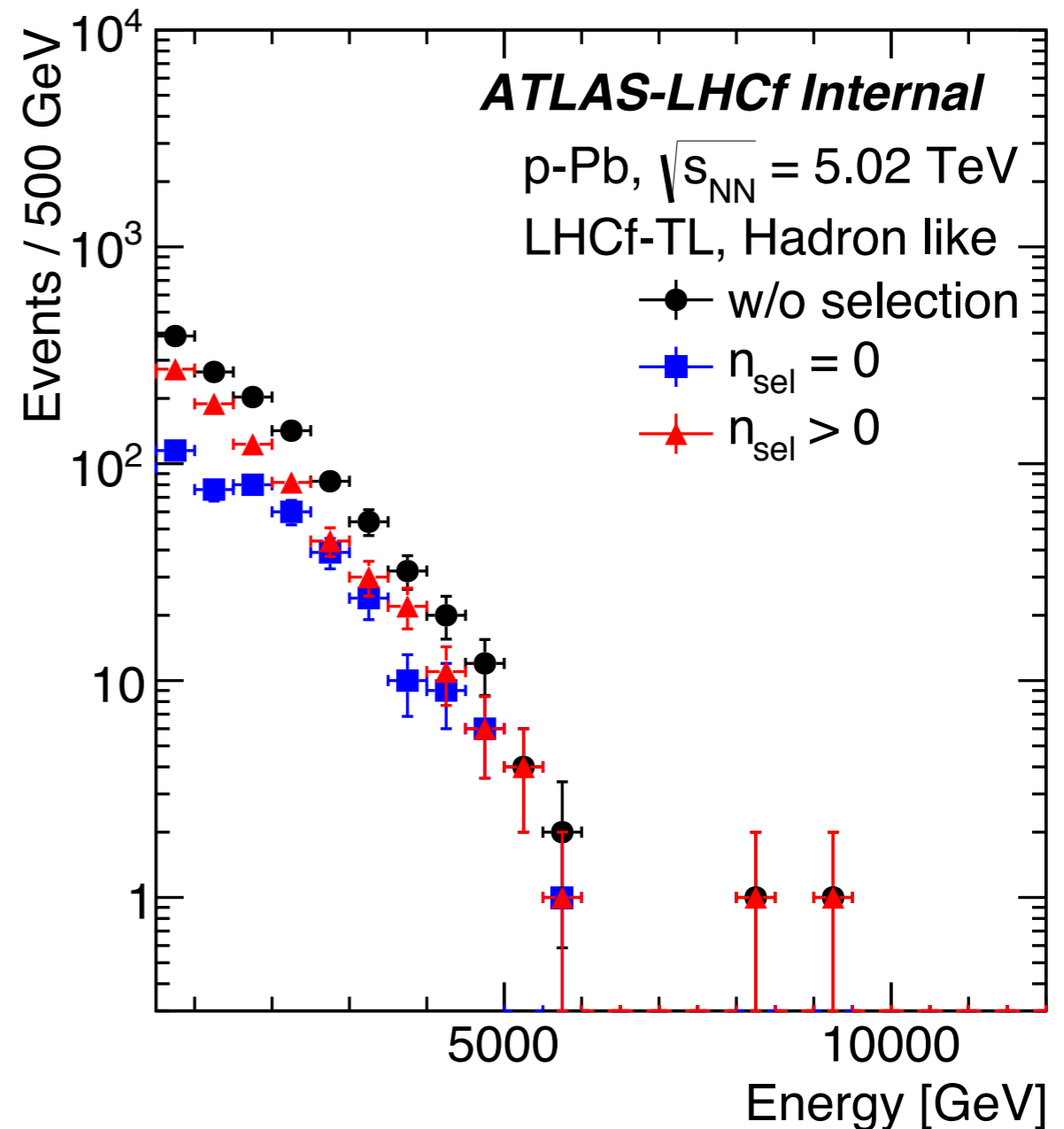


# Energy Spectra - Hadron like - (Neutron)

LHCf-Tower Small(TS),  $\eta < -9.6$

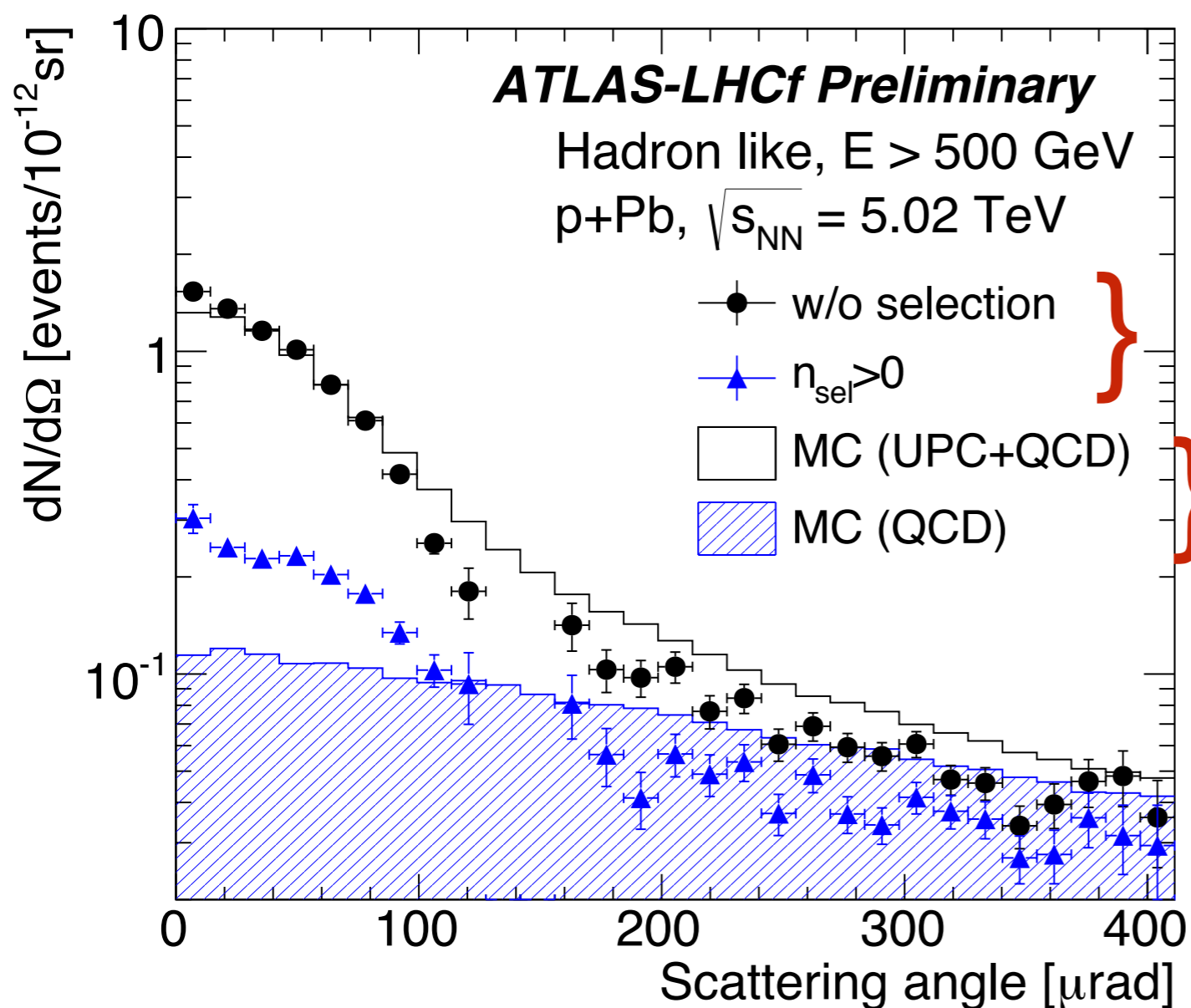


LHCf-Tower Large(TL),  $-9.5 < \eta < -8.4$



Clear difference between spectra of  $n_{sel}=0$  and of  $n_{sel}>0$ .  
 Harder spectrum of  $n_{sel}=0$  due to contribution of  $\Delta$  resonance at UPCs

# Hit Map of Hadron like events



Data with the event selection by number of tracks in ATLAS;  $n_{sel}$

MC with the selection by process

- ✓ Clear concentration at zero degree with events of  $n_{sel}=0$ .
- ✓ Similar distribution of  $n_{sel}>0$  as one of MC (QCD)

Note) The sum of UPC and QCD simulations was normalized to all data in the range from 0  $\mu$ rad to 120  $\mu$ rad.

- Confirmed that the trigger exchange in 2013 operation was correctly done.
- The joint analysis clearly helps to study the forward particle production with categorizing the type of interaction.

# Future prospects of ATLAS-LHCf joint analysis

- Analysis with p-Pb data precisely.
  - Inclusive forward neutron spectrum with background (UPC events) rejection by ATLAS information.
- Analysis with p-p  $\sqrt{s}=13\text{TeV}$  data taken in 2015

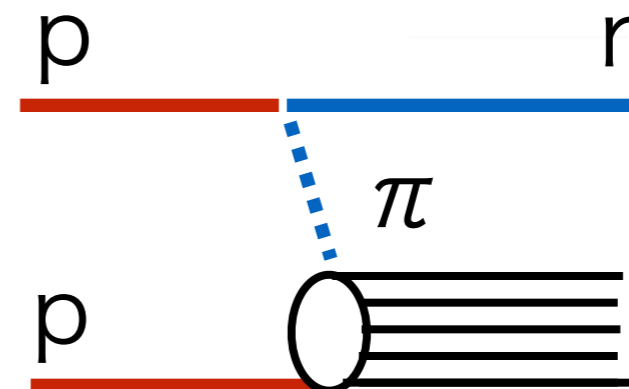
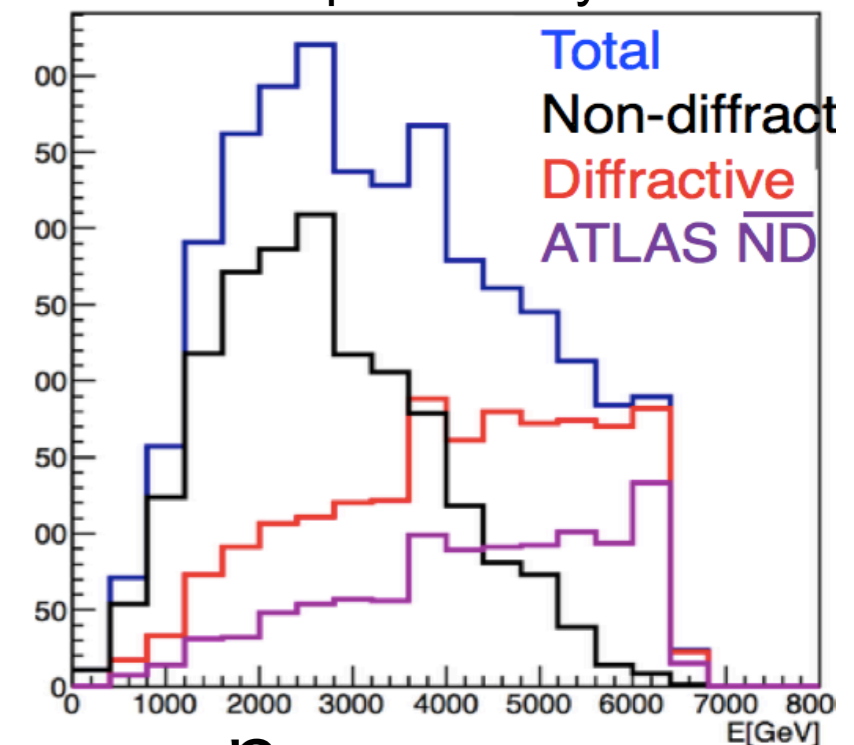
## - Forward particle production in diffractive/non-diffractive process

Forward particle production measurement with a event selection by ATLAS

## - Measurement of p- $\pi$ interaction

Study of p- $\pi$  interaction with tagging forward neutron by LHCf

Neutron Spectrum by PYTHIA



# Summary

- Very forward particle production at UPCs in  $p$ - $Pb$ ,  $\sqrt{s}=5\text{TeV}$  was estimated by Weizsacker-Williams method and  $p+\gamma$  event generation.
- Specific features in UPCs, a bump on  $\pi^0$   $p_T$  spectra and concentration of neutron on zero degree of collision has been measured by LHCf  $p$ - $Pb$  data.
- The results of ATLAS-LHCf first joint analysis were shown. By event selection with non-zero trackers on the ATLAS inter tracker, particles from UPCs were effectively suppressed.

**Thank you for your attention !!**



# $N_{\text{sel}}$ distribution on ATLAS tracker

