LHC for VHEPA (LHCf)

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on behalf of the LHCf collaboration

- VHEPA2014, 19-20 Mar. 2014, ICRR University of Tokyo -

Contents

- Accelerator/Collider experiments for VHEPA
  - Hadronic Interaction for VHEPA
  - Large Hadron Collider (LHC) and LHC experiments

- LHCf Experiment
  - An Forward Experiment at LHC -
  - Resents results
  - Future Operations

Connection with Astronomy

Lots of connections

- Particle Physics

  → Fundamental Interaction

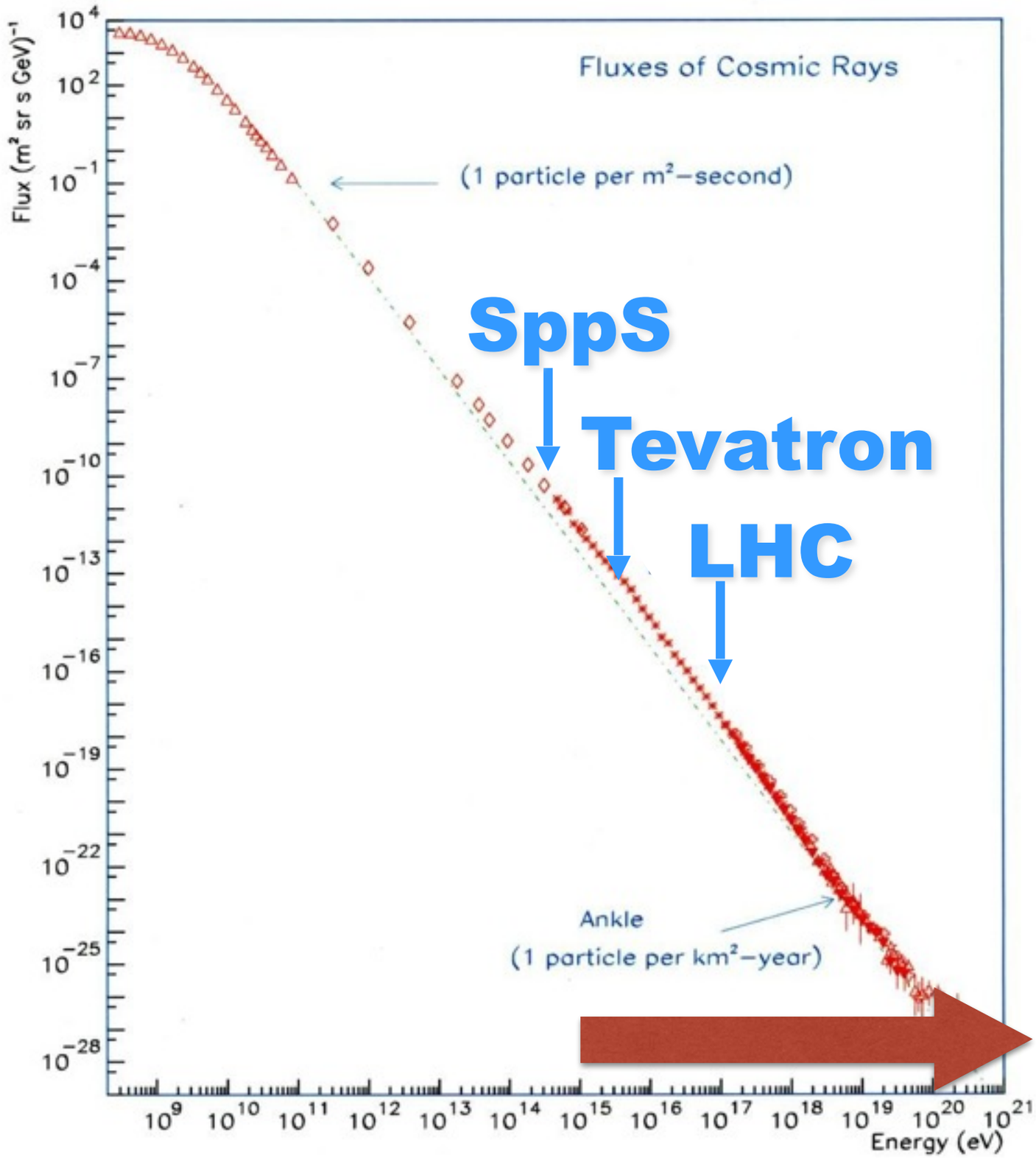
- Heavy Nuclear Physics

  → Dense matter in the early universe

- Hadronic interaction (QDC)

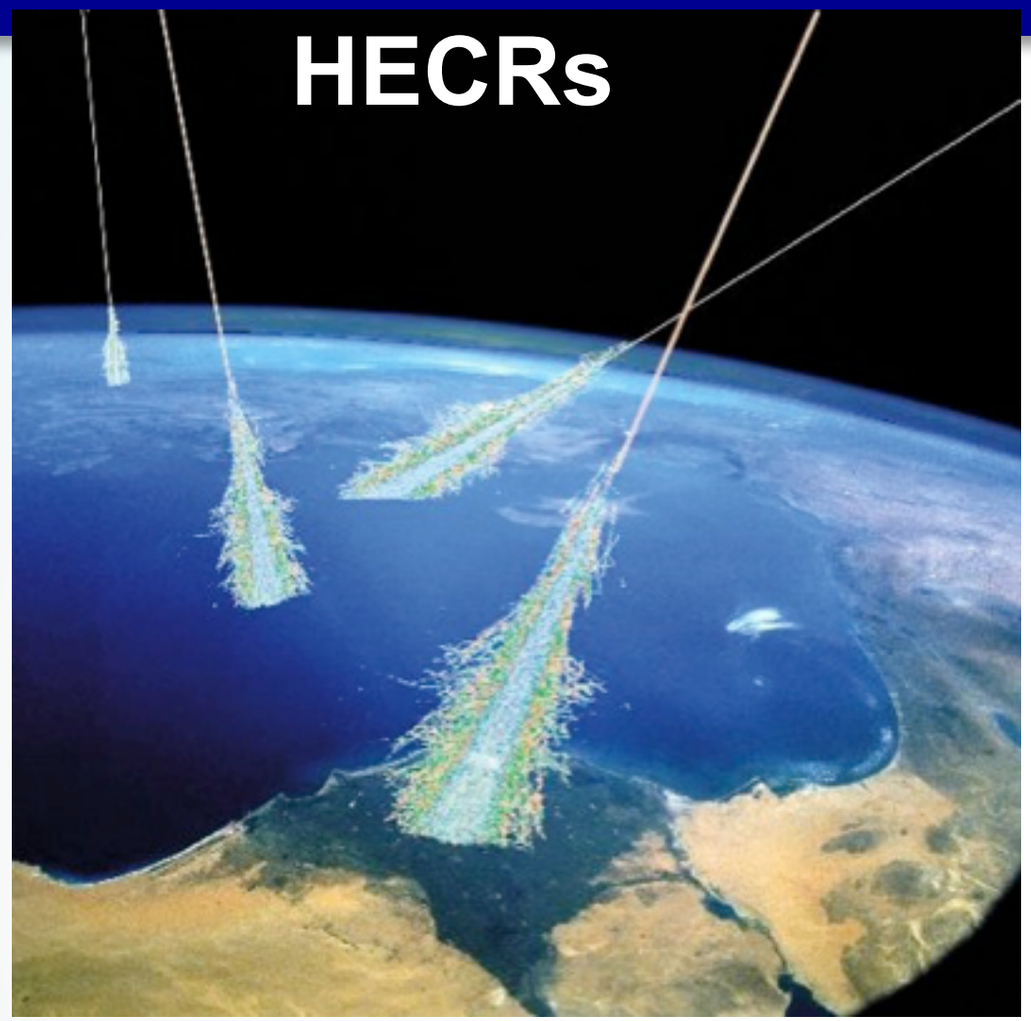
  → High Energy Cosmic-Ray

CR v.s. Collision Energy



AirShower Technique For Observation

Measurement of HECR



Extensive air shower observation

- longitudinal distribution
- lateral distribution
- Arrival direction

Air shower development

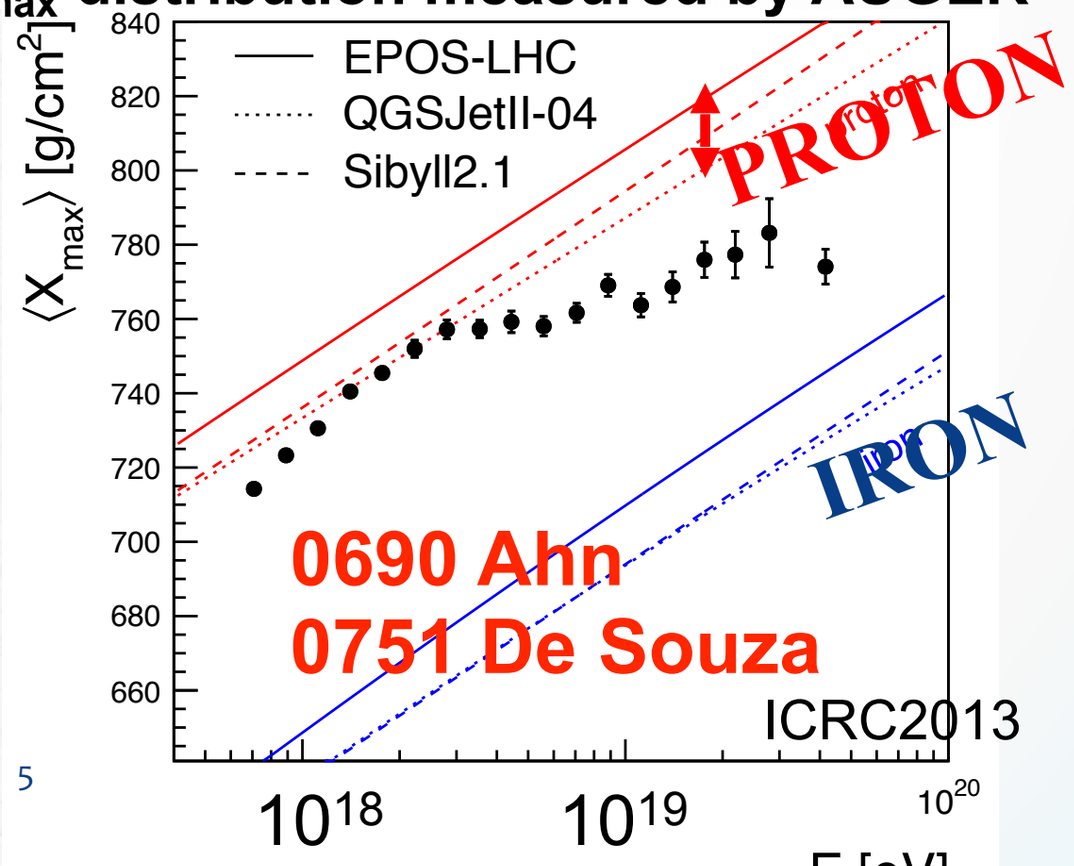
Astrophysical parameters

- Spectrum
- Composition
- Source distribution

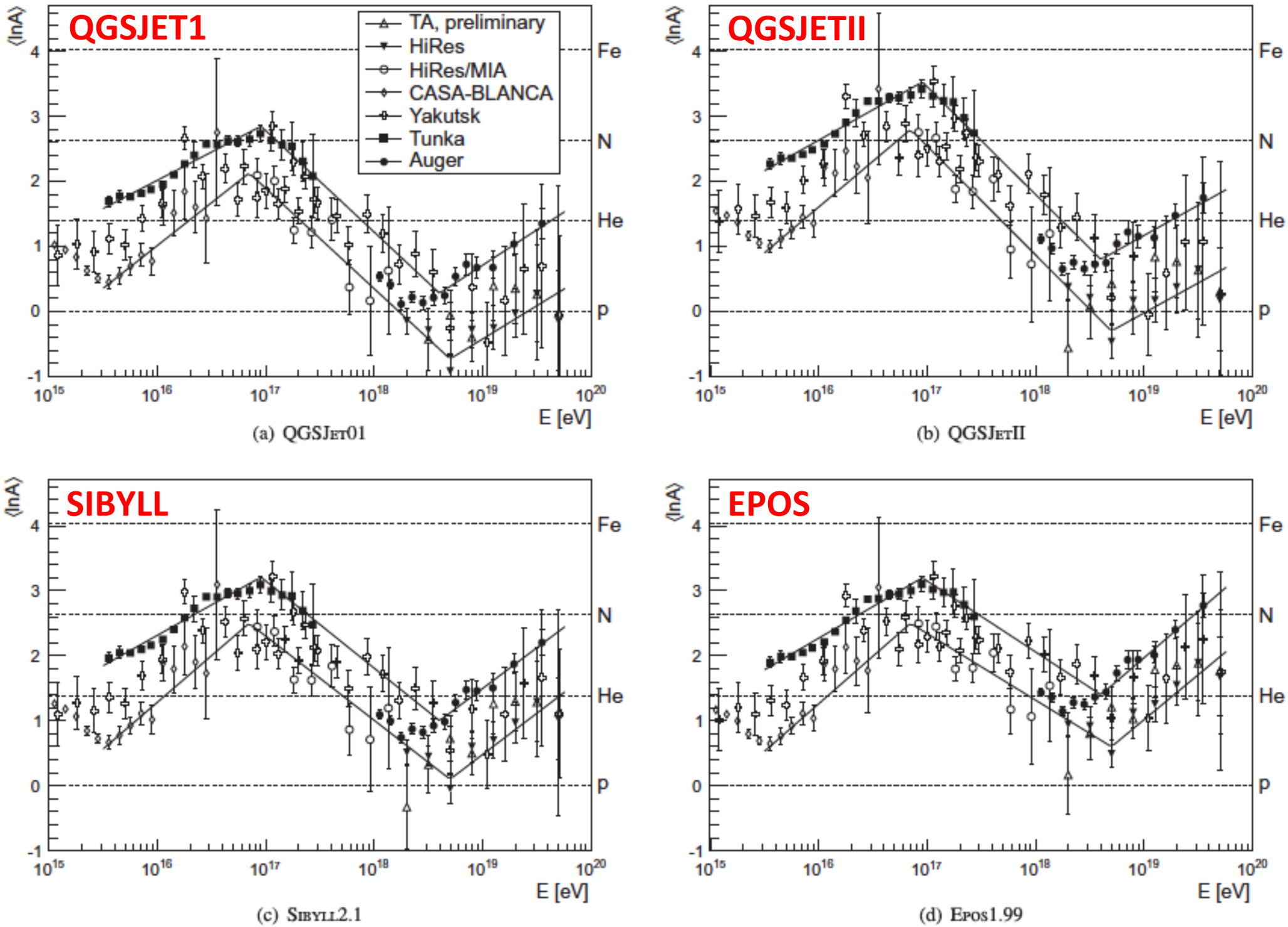
X_{max}
the depth of air shower maximum.
An indicator of CR composition

Uncertainty of hadron interaction models
V
Error of $<X_{max}>$ measurement

X_{max} distribution measured by AUGER



＜lnA＞ of CRs



(Kampert and Unger, Astropart. Phys., 2012)

Why so much different ?

No “perfect” hadronic interaction model in >10^{15}eV

- Hard Interaction (P_T > 1GeV/c)

  → pQCD “with input parameters like PDF”

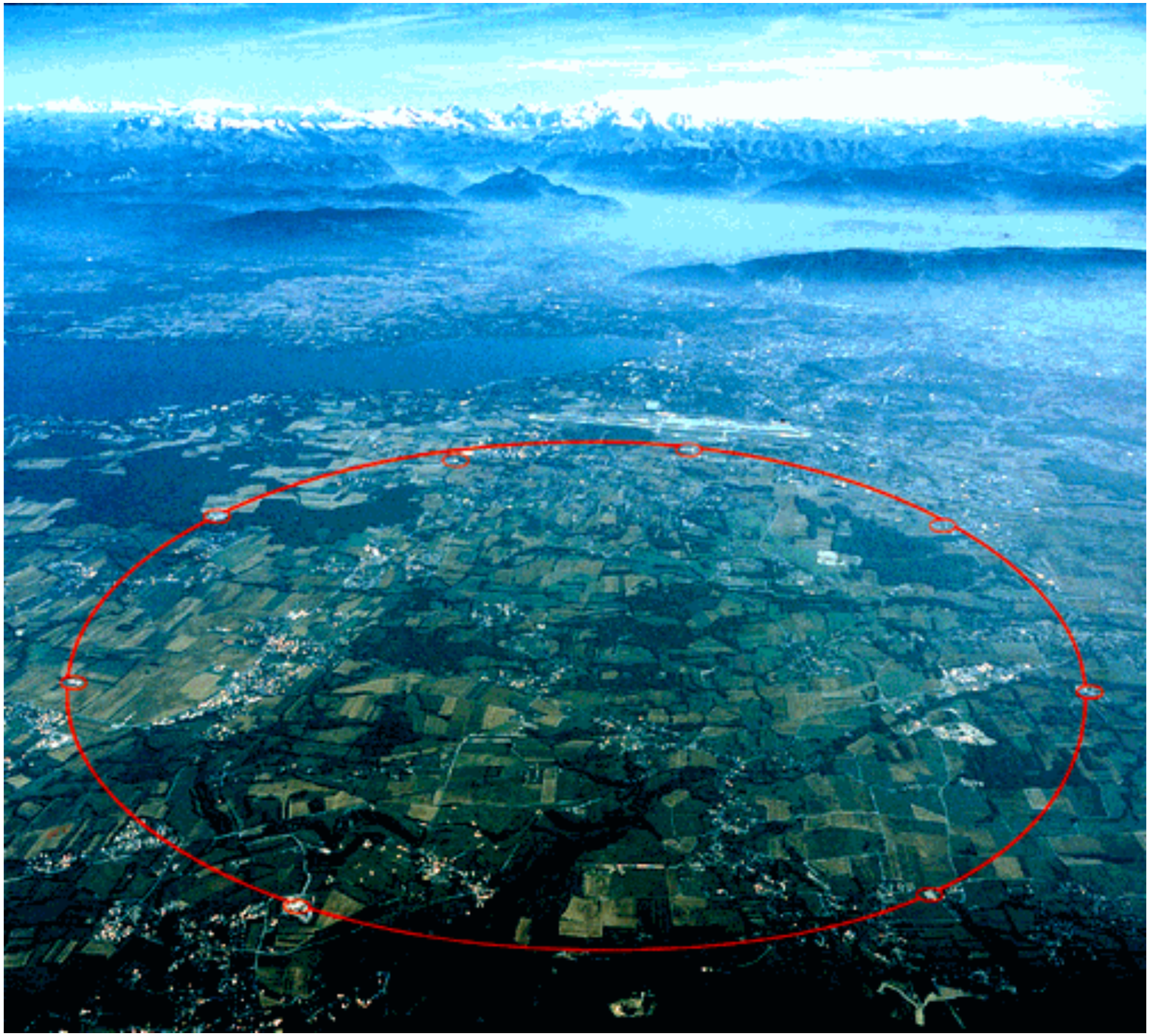
- Soft Interaction (P_T < 1GeV/c)

  → Not calculable by QCD

  Described by phonological model.

Measurements at colliders is mandatory for verifying/turning models

Large Hadron Collider (LHC)



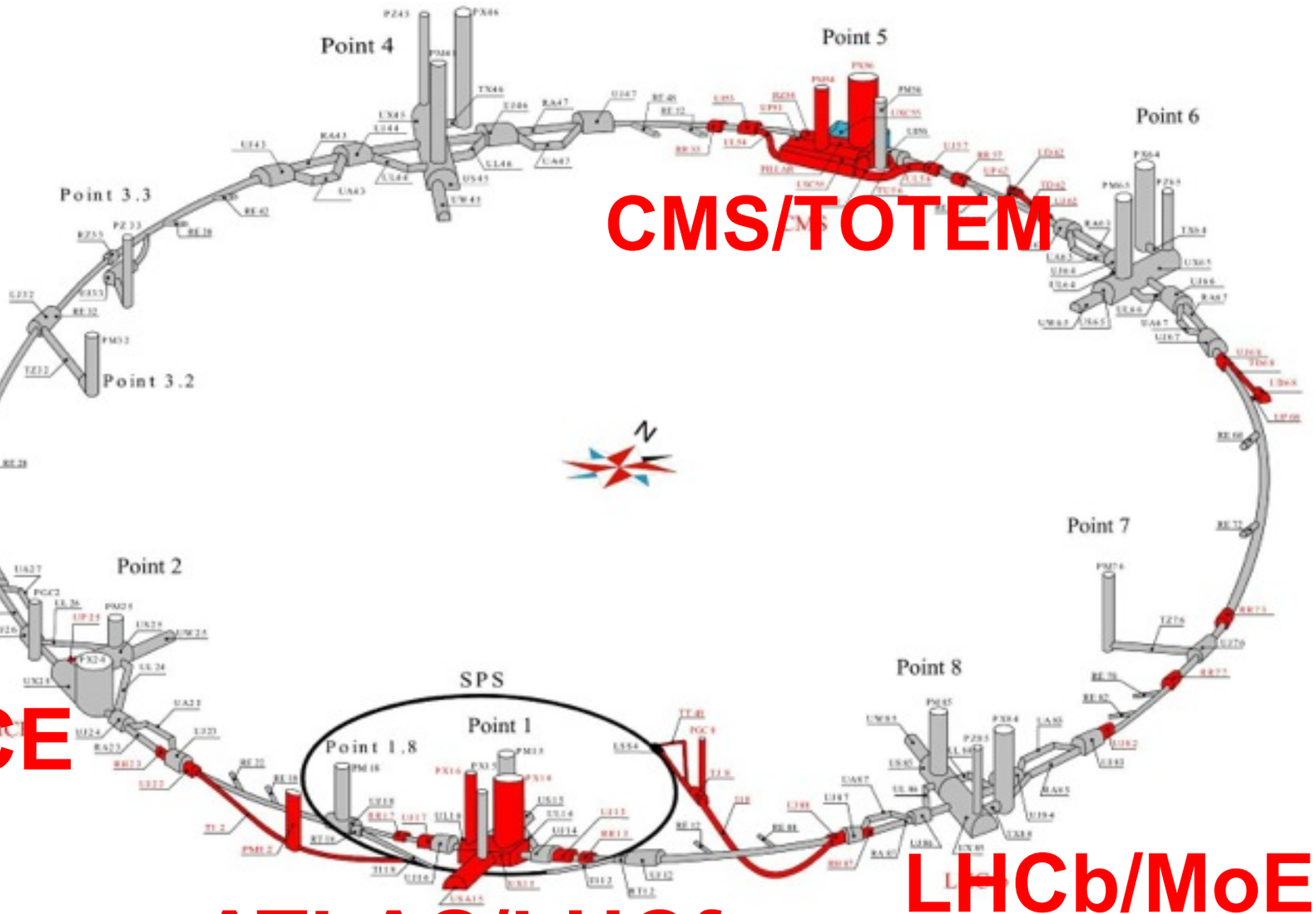
The Large Hadron Collider (LHC)

pp 7TeV+7TeV	**→ E_{lab} = 10^{17}eV**	**2015-**
pp 3.5TeV+3.5TeV	**→ E_{lab} = 2.6x10^{16}eV**	2010-2011
pp 450GeV+450GeV	**→ E_{lab} = 2x10^{14}eV**	2009,2010
pp $\sqrt{s}$=2.76TeV, 8TeV		
PbPb $\sqrt{s_{NN}}$=2.76TeV		2011-
p-Pb $\sqrt{s_{NN}}$=5TeV		2012-

CERN(2009)

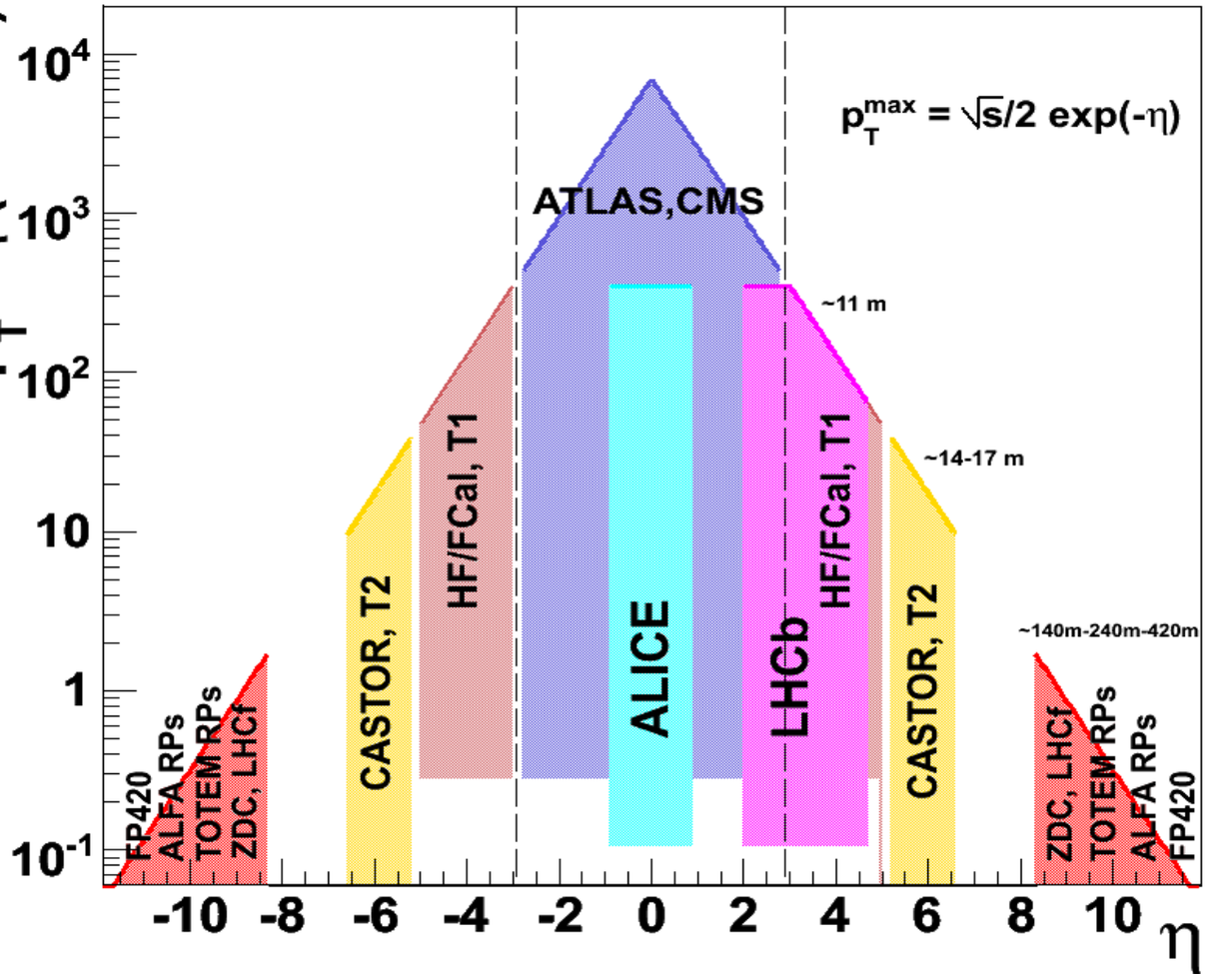
LHC Experiments

7 experiments are measuring hadronic interactions at 4 interaction points with several detectors.



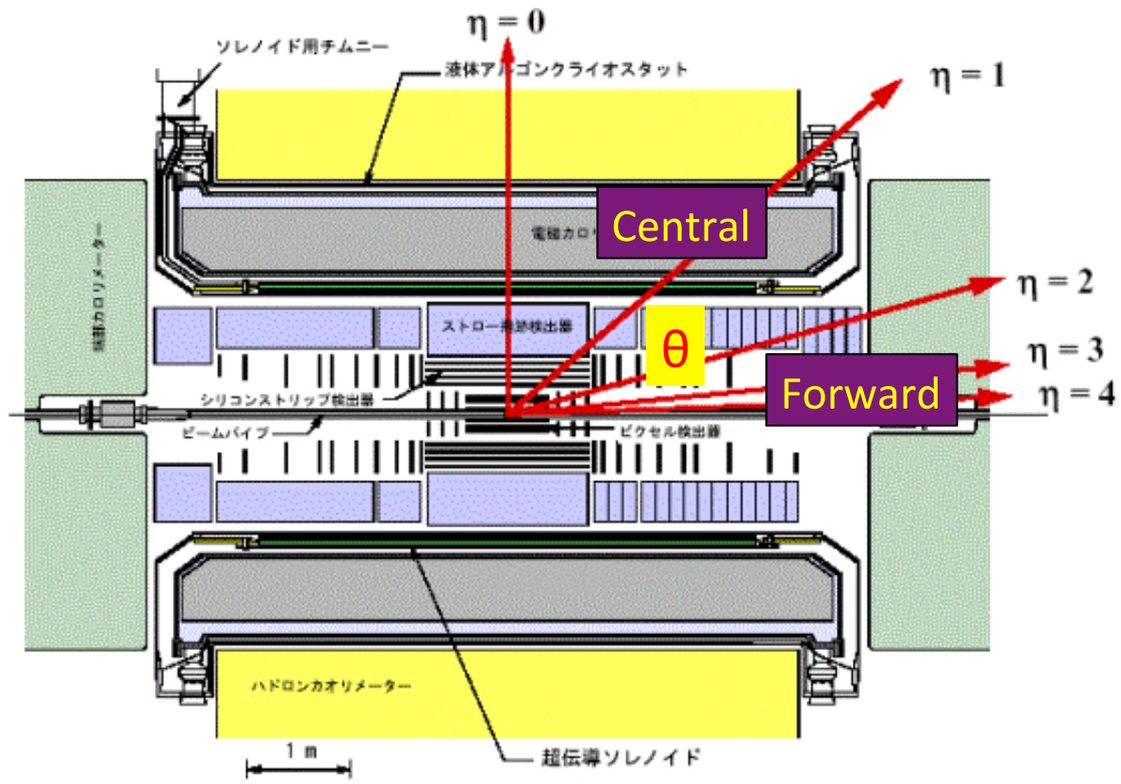
Experimental coverage at LHC

DdE, arXiv:0708.0551



pseudorapidity

$$\eta = -\ln(\tan\frac{\theta}{2})$$

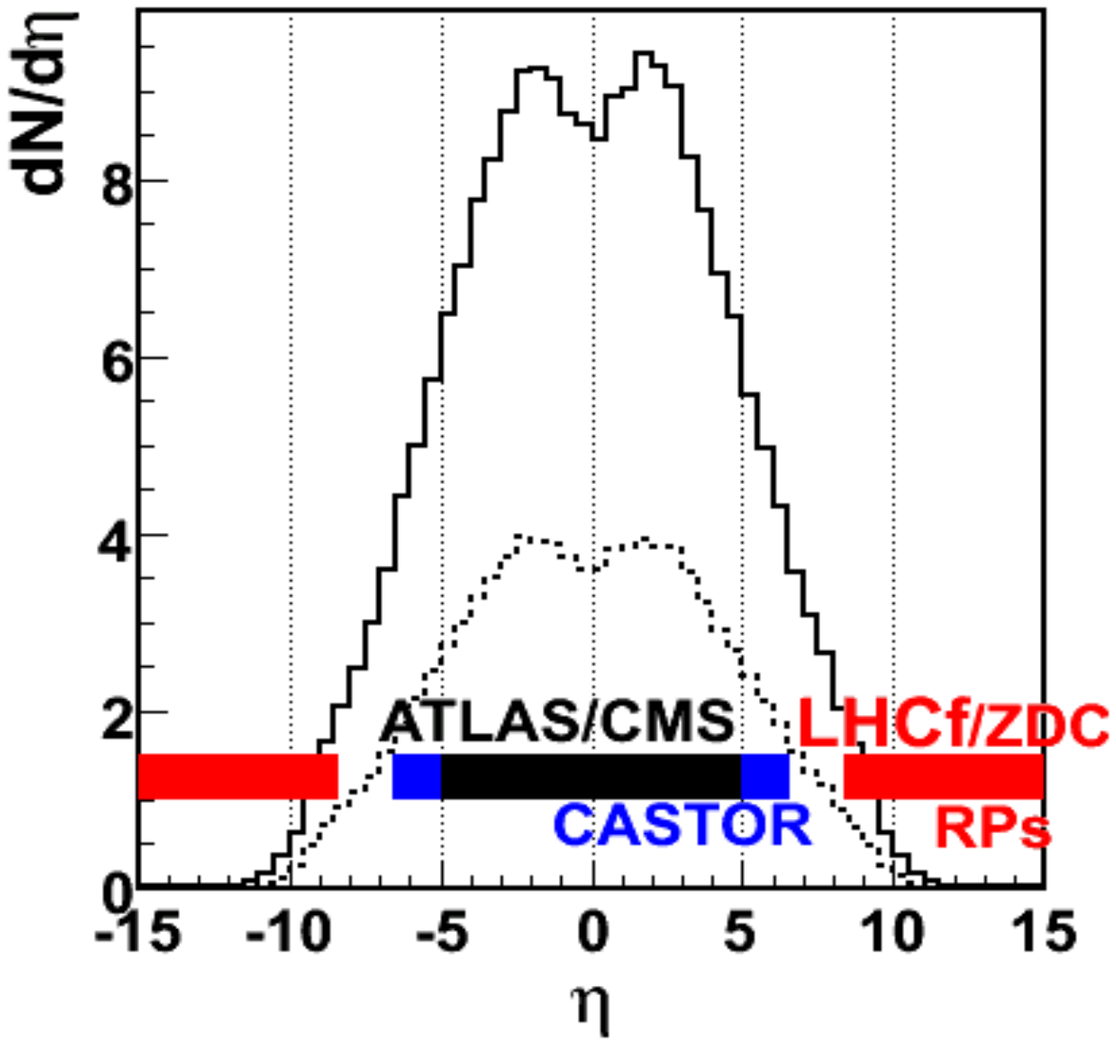


The detectors mostly cover the full range of rapidity even at zero degree of collisions.

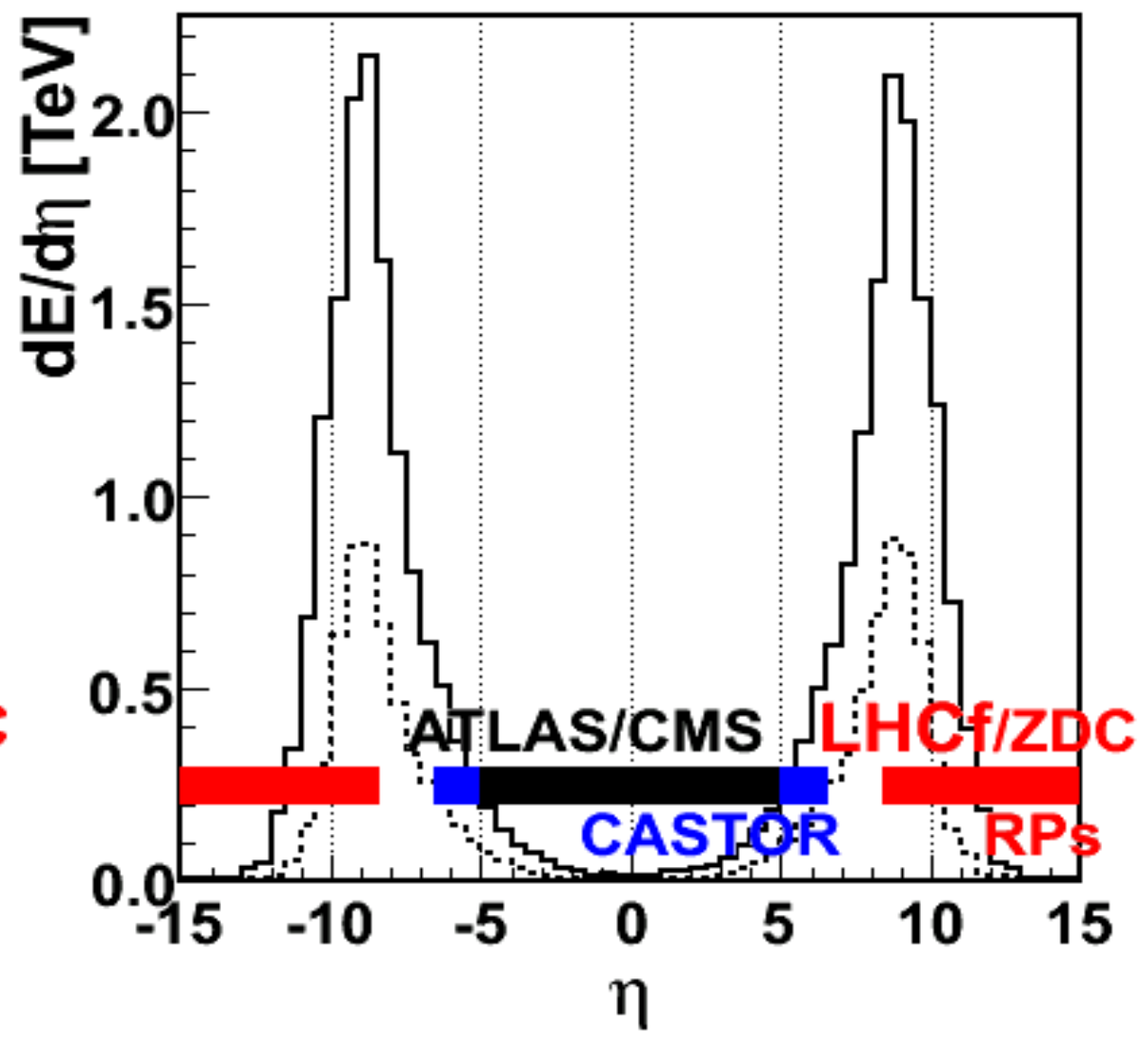
Particle production at LHC collisions

p-p @ √s=14TeV (DPMJET3)

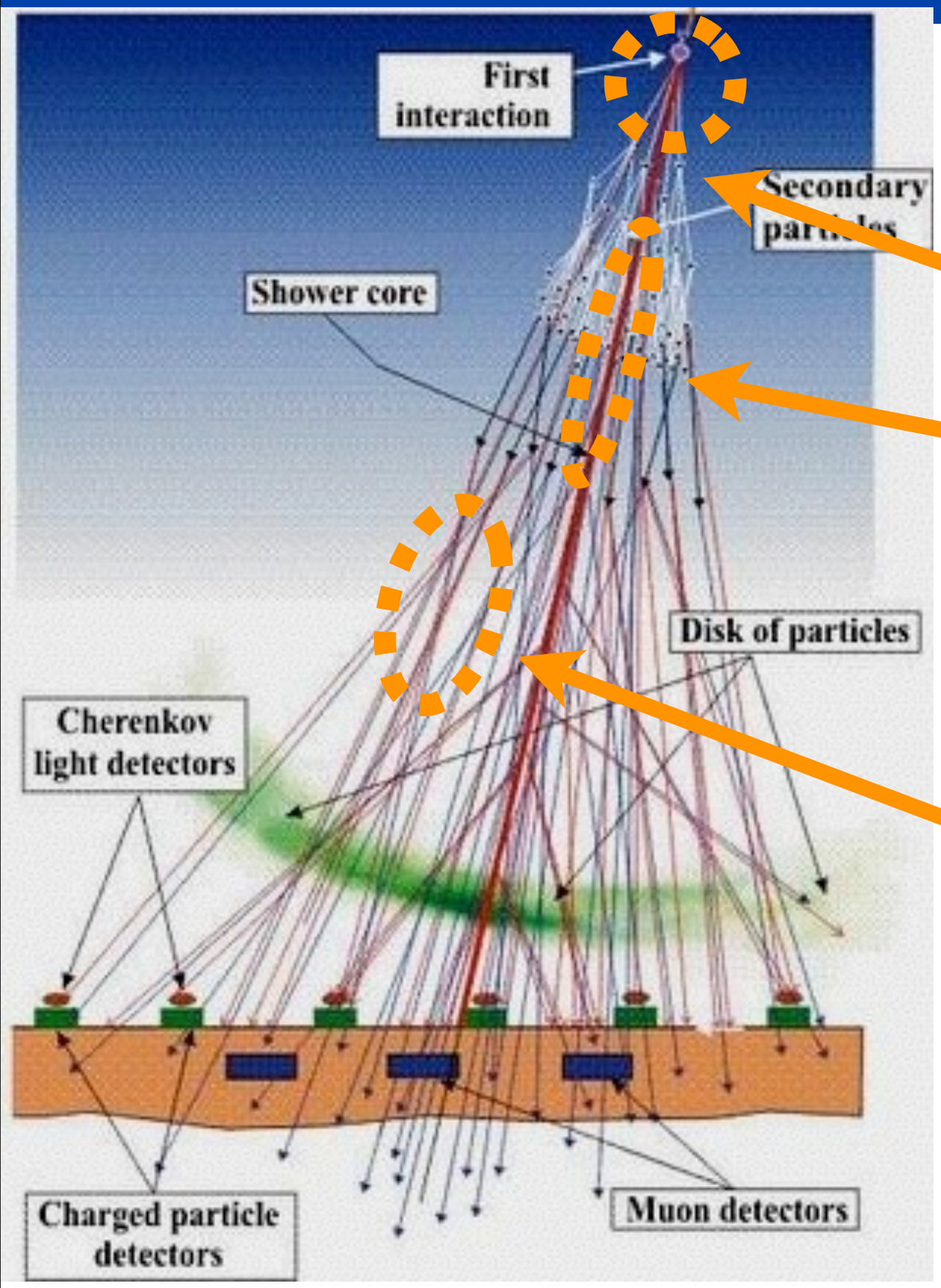
Multiplicity



Energy Flux



Key parameters for Air Showers



Key Parameters

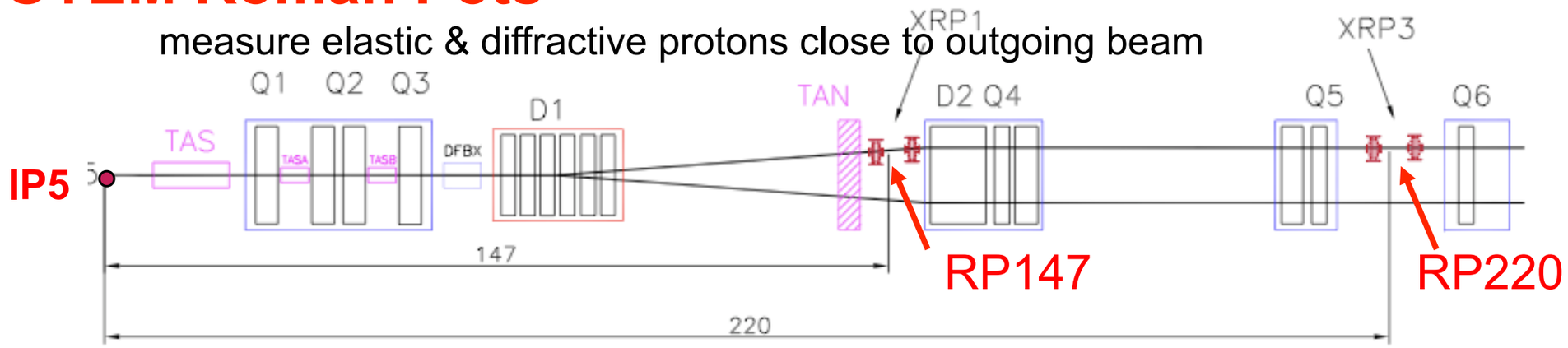
- Inelastic Cross Section
  →TOTEM, ATLAS, CMS,ALICE
- Forward Energy Spectrum
  →LHCf, ZDC and etc.
- Inelasticity k= 1-p_{lead}/p_{beam}
  →LHCf, ZDC and etc.
- Secondary interactions

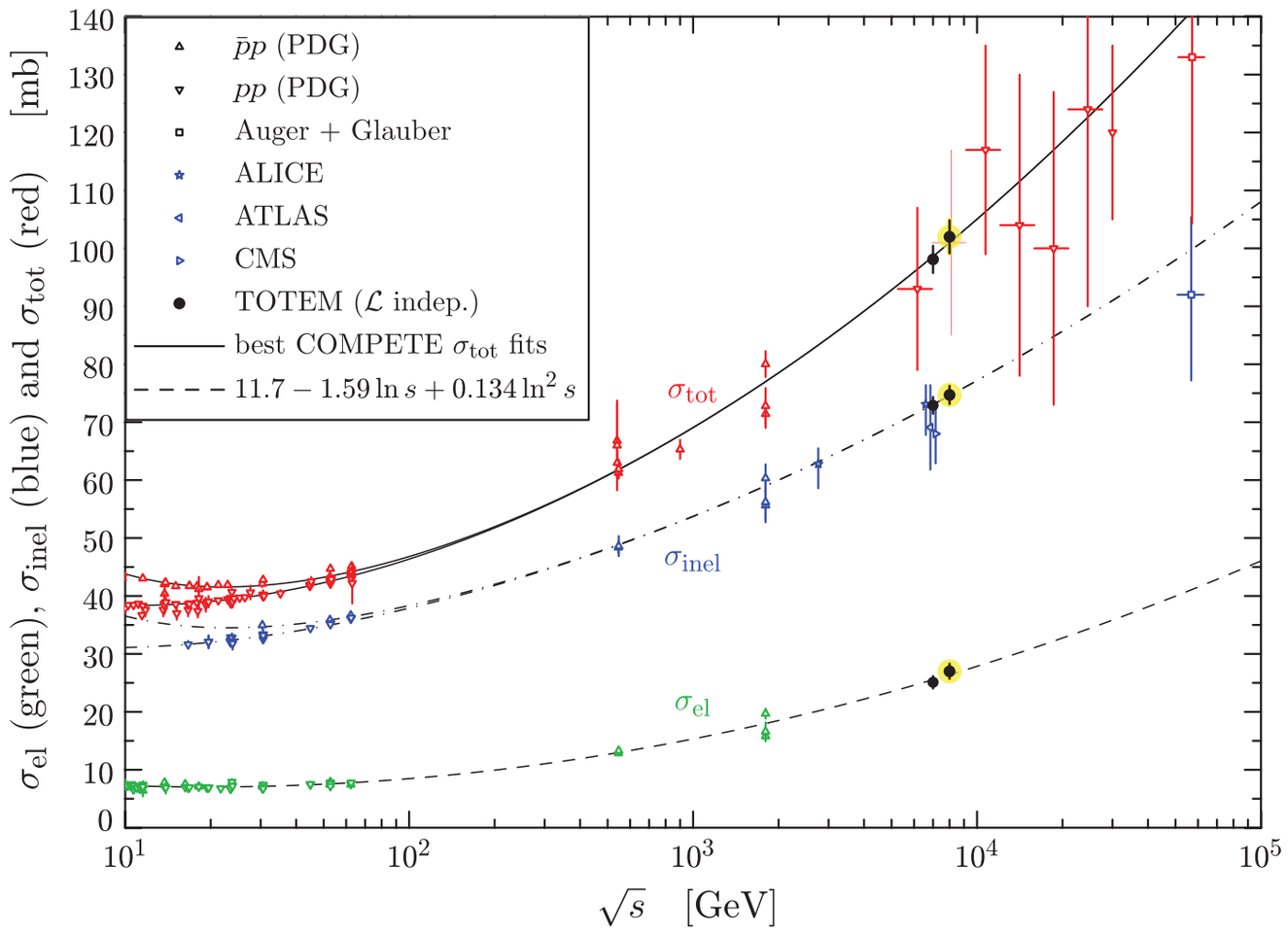
+Nuclear Effect @ CR-Air

Total/Inelastic Cross-section

TOTEM Roman Pots

measure elastic & diffractive protons close to outgoing beam

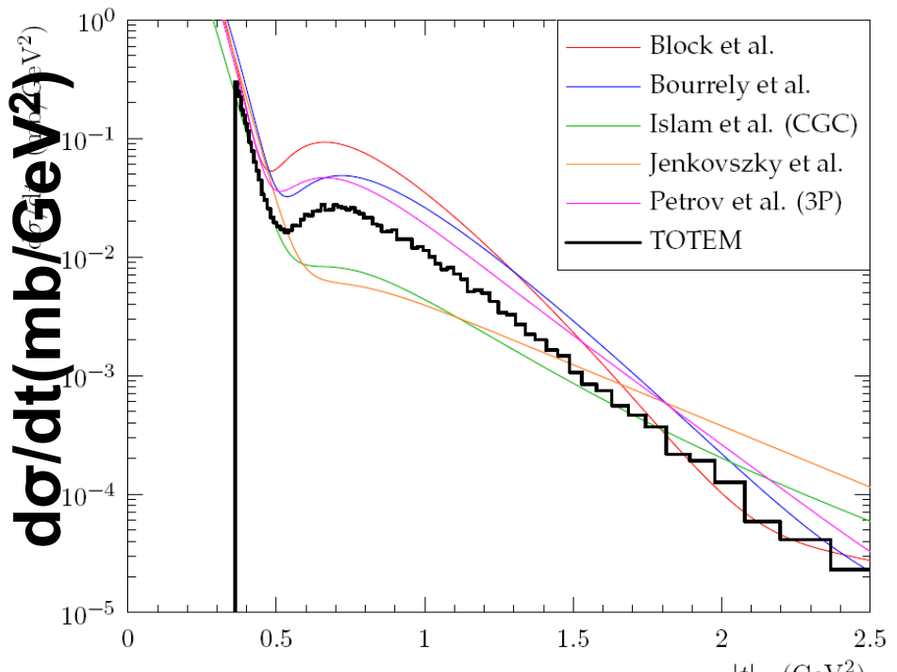




σ_{tot}=101.7±2.9mb

σ_{inel}=74.7±1.7mb

@ pp,$\sqrt{s}$=8TeV

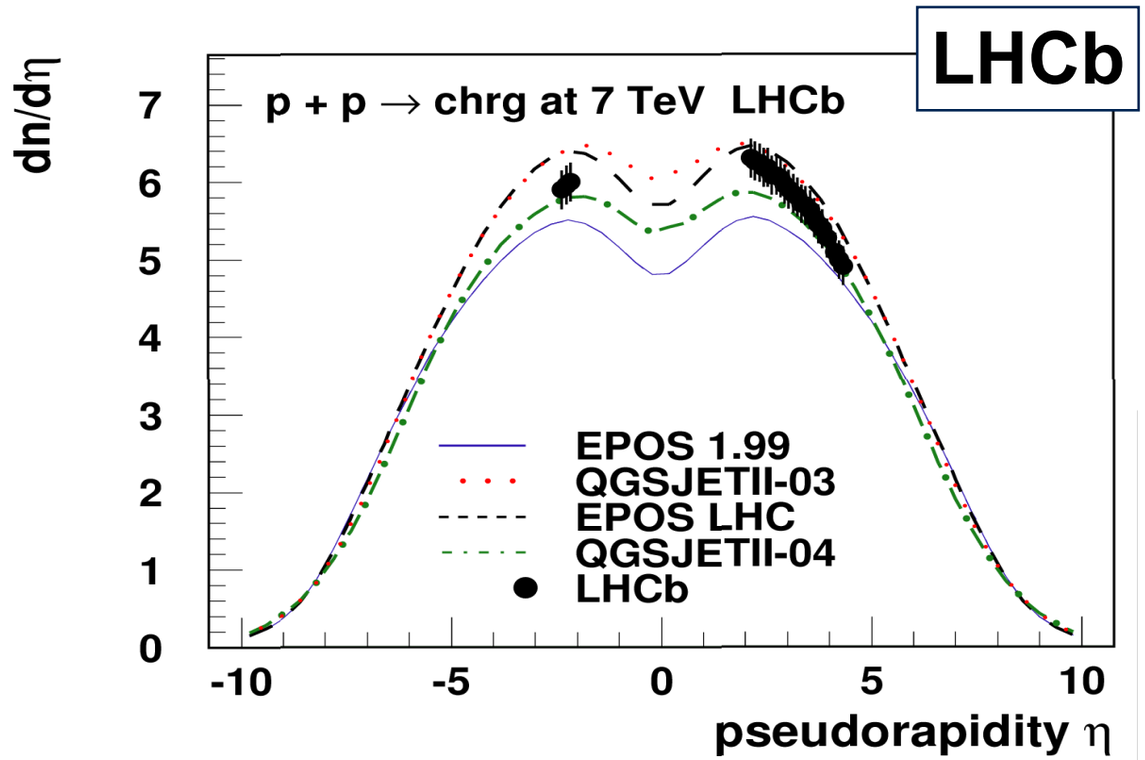


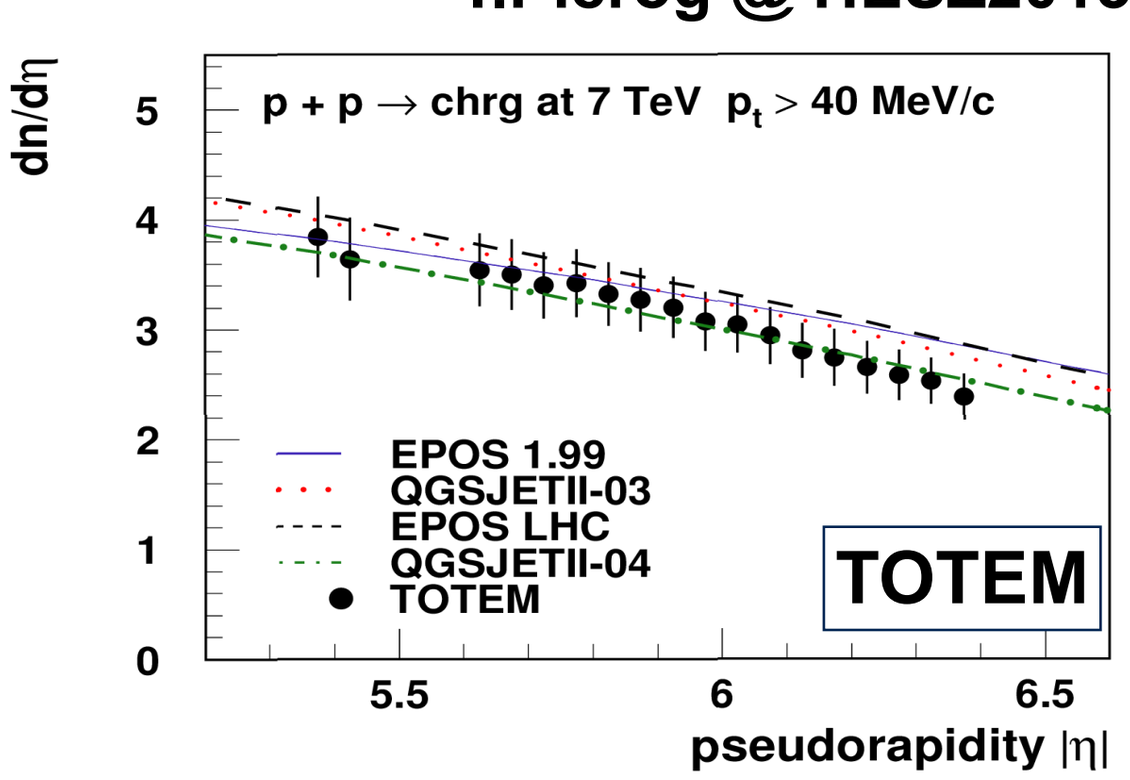
|t|(GeV^2)

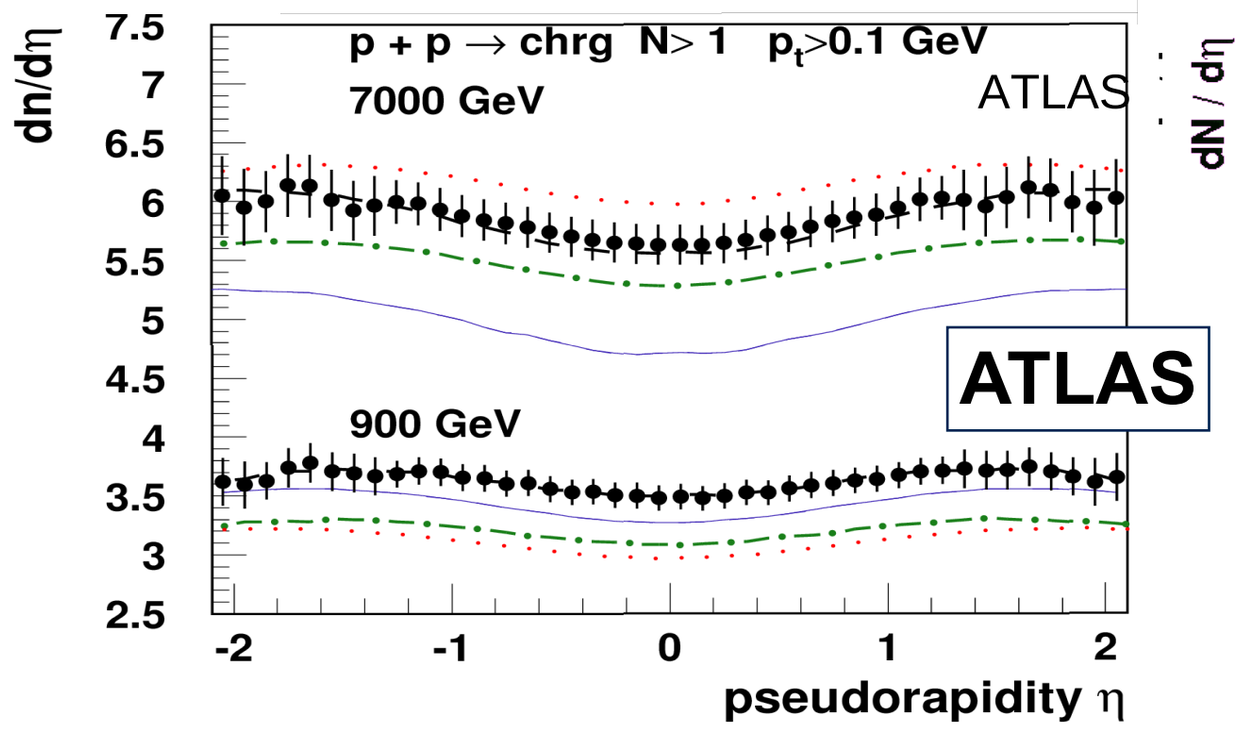
Charged Multiplicity Distribution

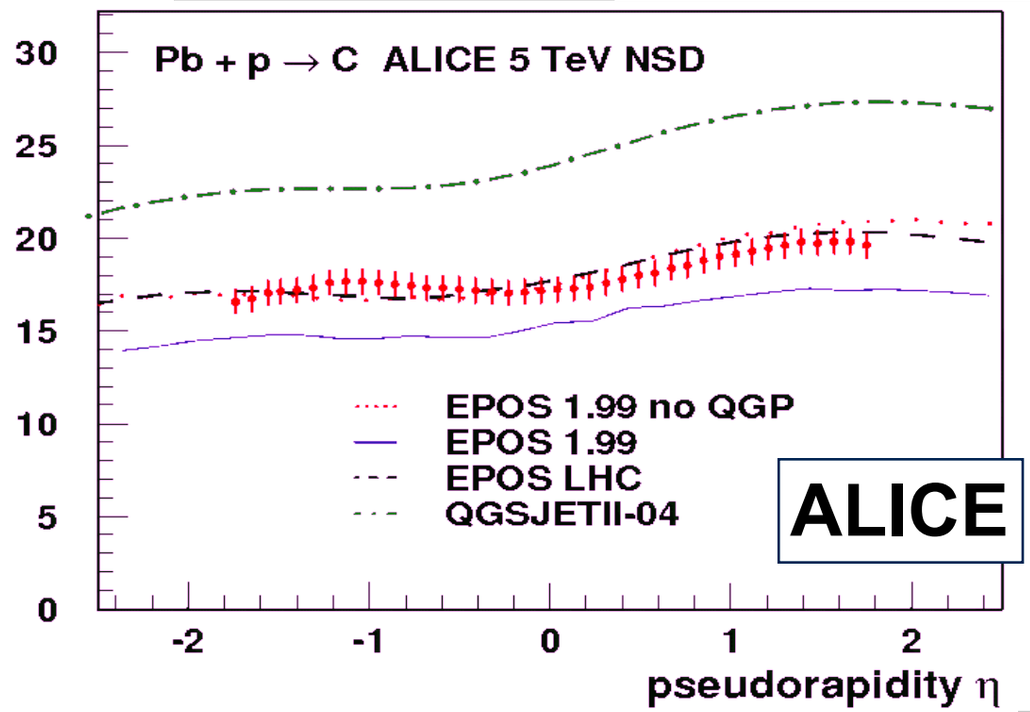
Measured by several experiments

T.Pierog @ HESZ2013

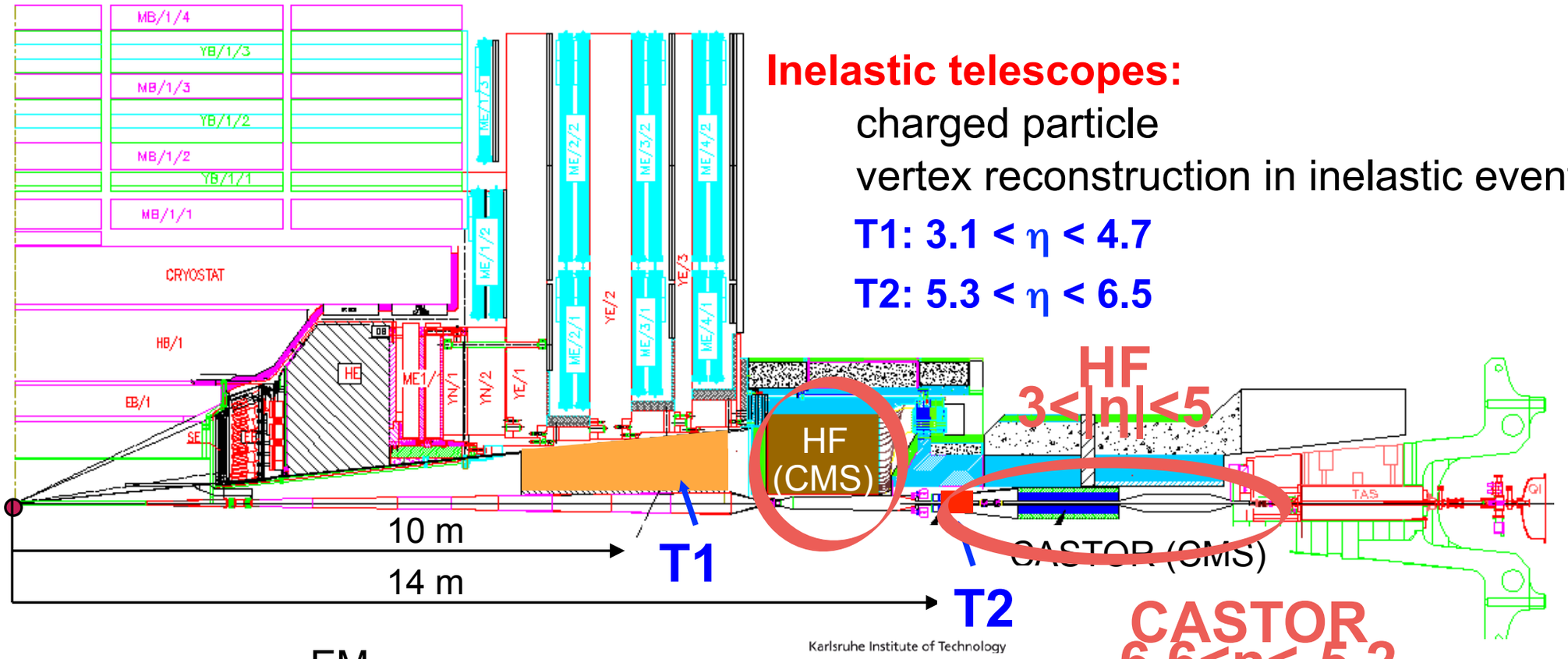








Energy Flow : CMS Forward



Karlsruhe Institute of Technology

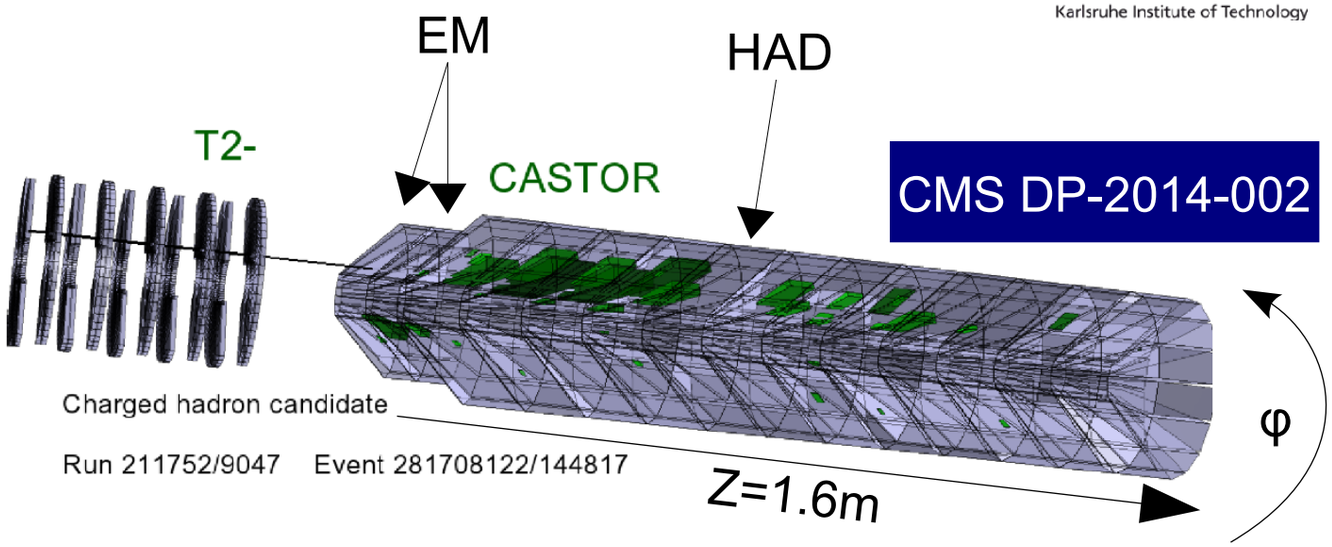
Inelastic telescopes:

charged particle

vertex reconstruction in inelastic events

T1: 3.1 < η < 4.7

T2: 5.3 < η < 6.5



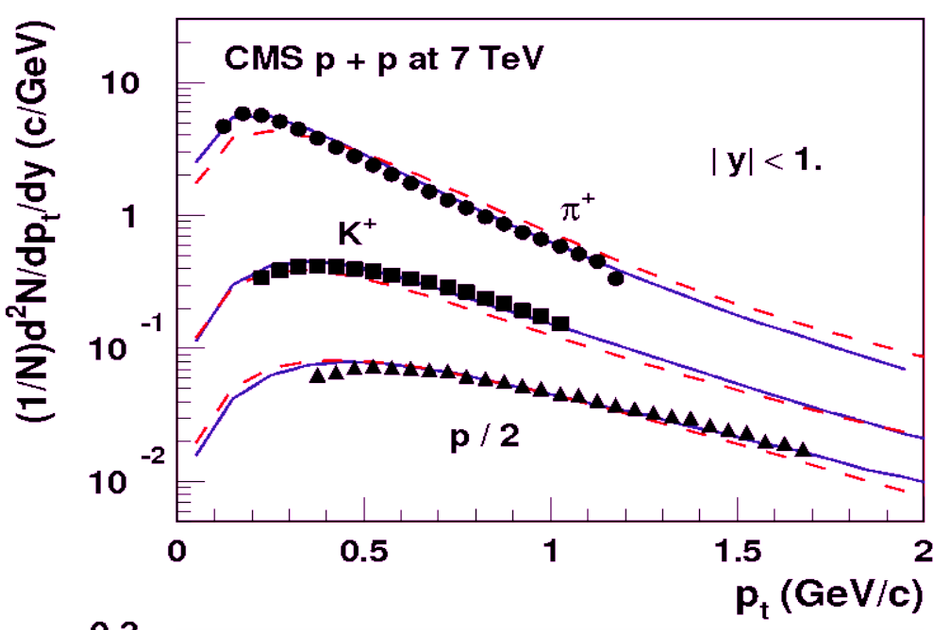
- **Tungsten+silica quartz**
- **10λ$_i$**

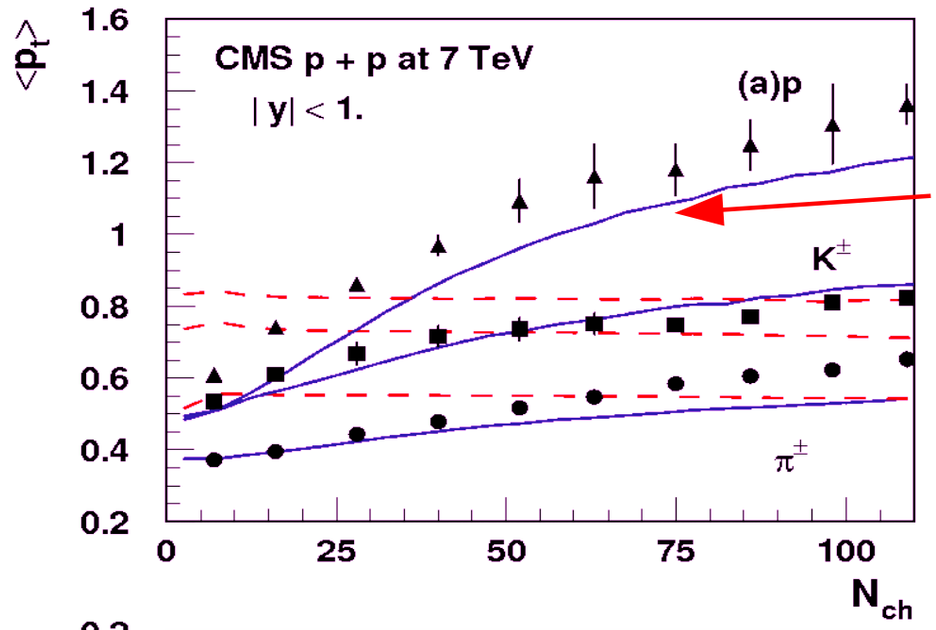
```
Castor:   central (most energetic) sector 9
          E=205 GeV (sectors 8,9,10)
T2:       phi=-2.935; eta=-5.69
```

Spectra of independent particles

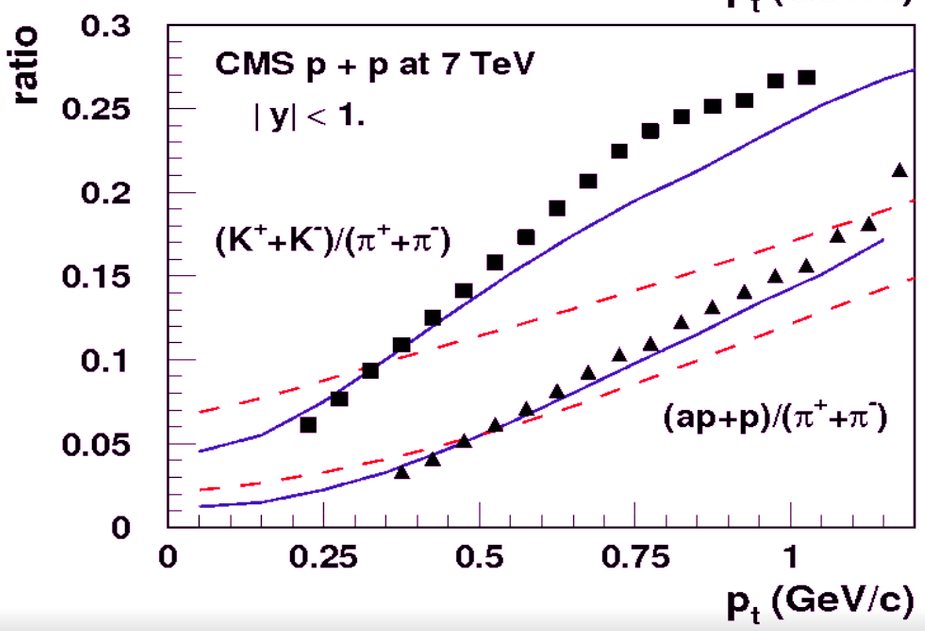
- **Detailed description can be achieved**
  - identified spectra
  - p_t behavior driven by collective effects (in EPOS statistical hadronization + flow)

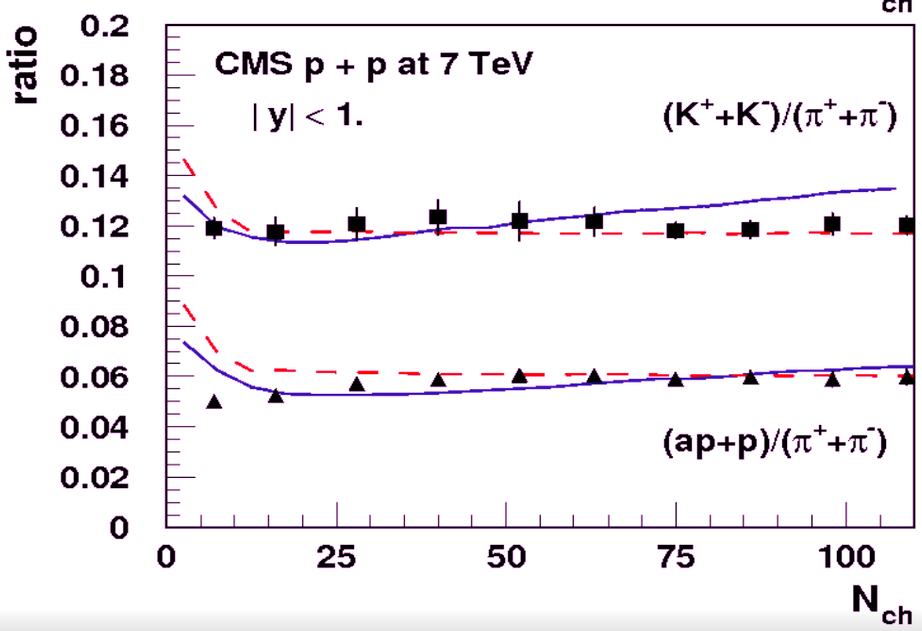
T.Pierog @ HESZ2013





Collective flow effect only in EPOS

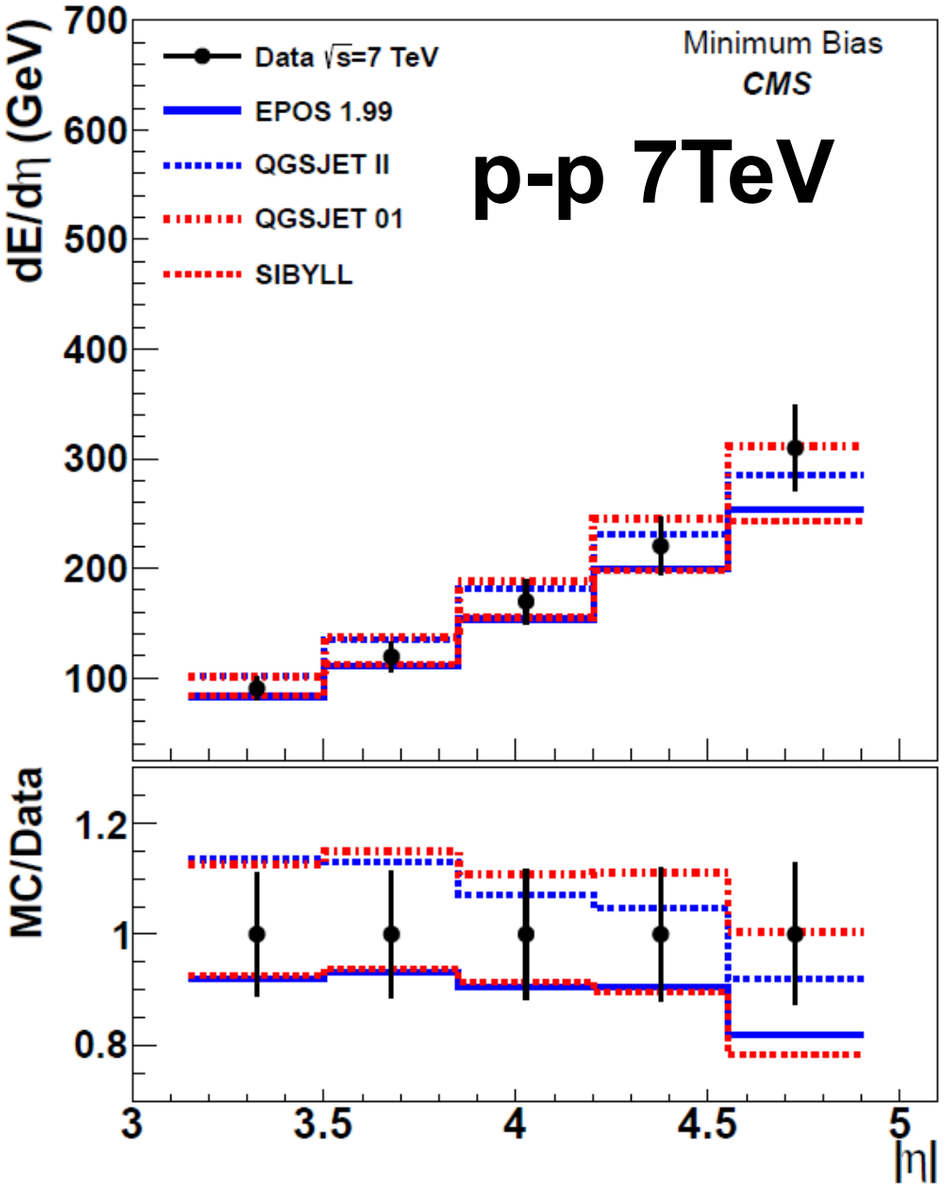




Baryon number now fixed at mid-rapidity.

EPOS LHC
QGSJETII-04

CMS Forward



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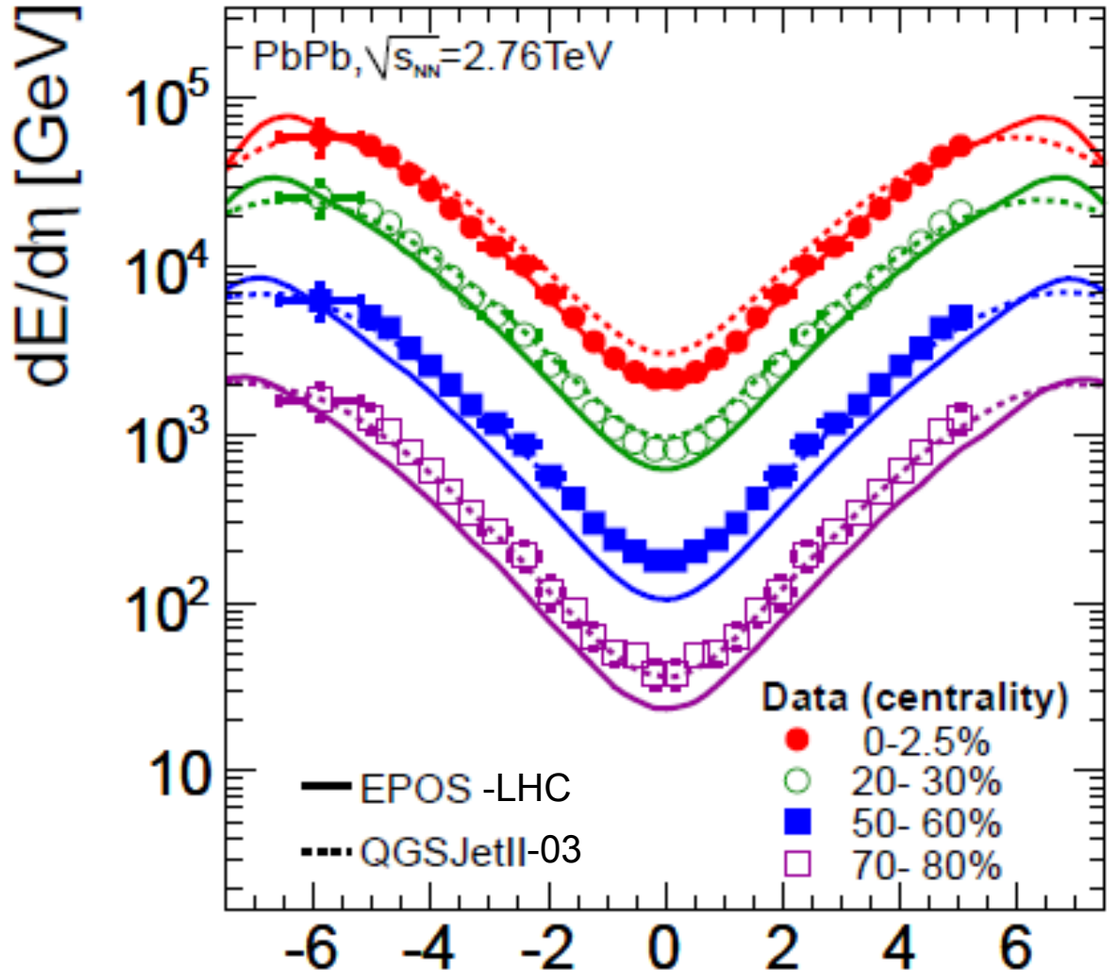
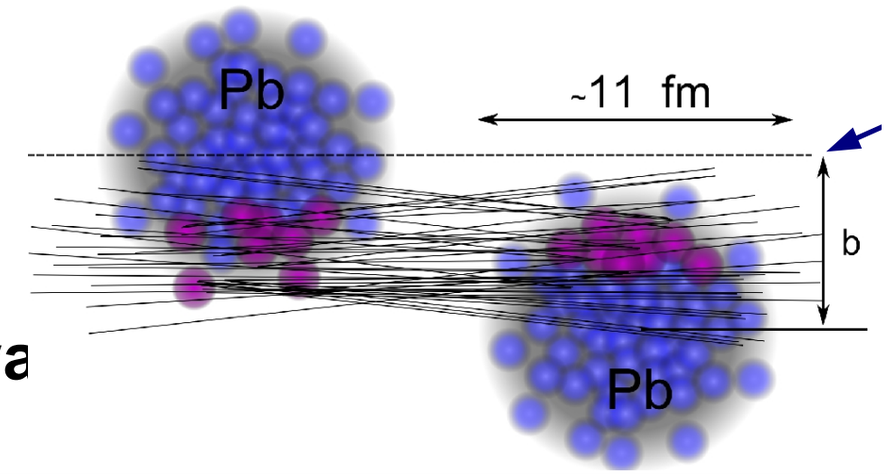
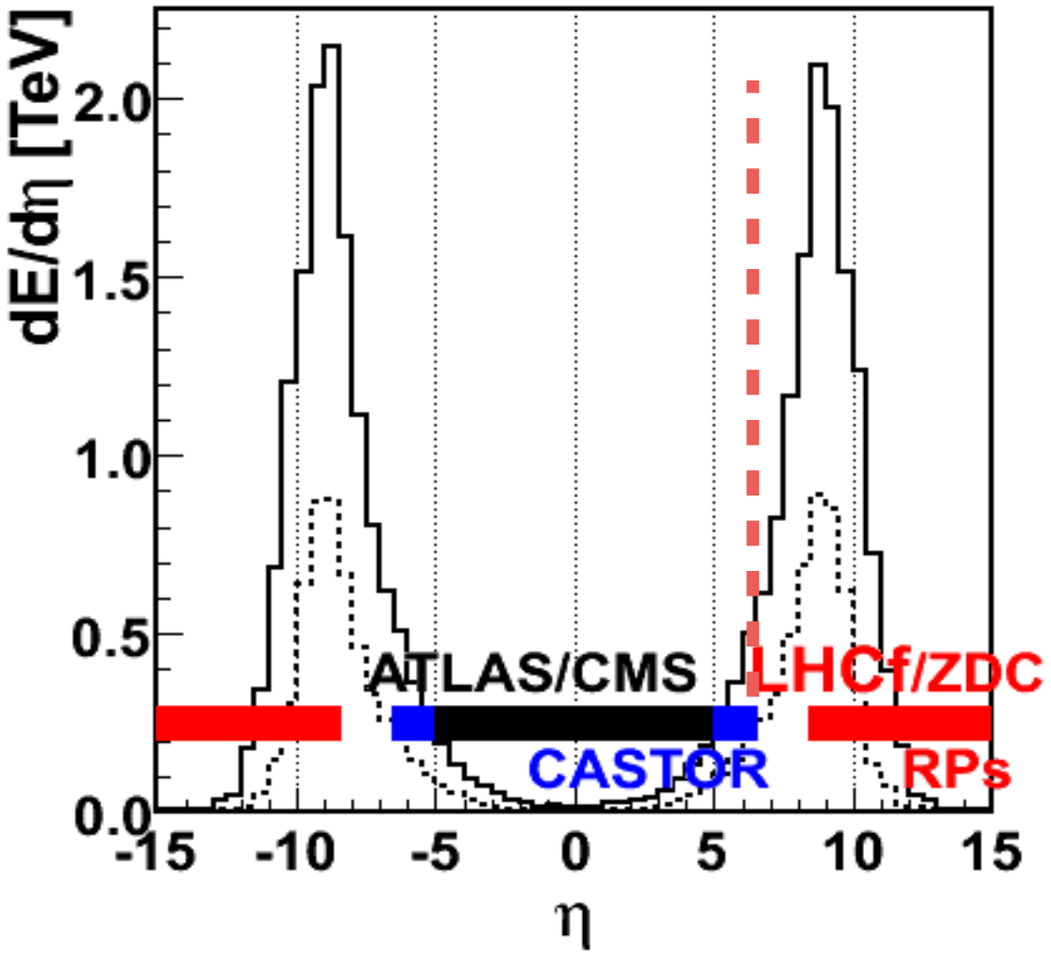
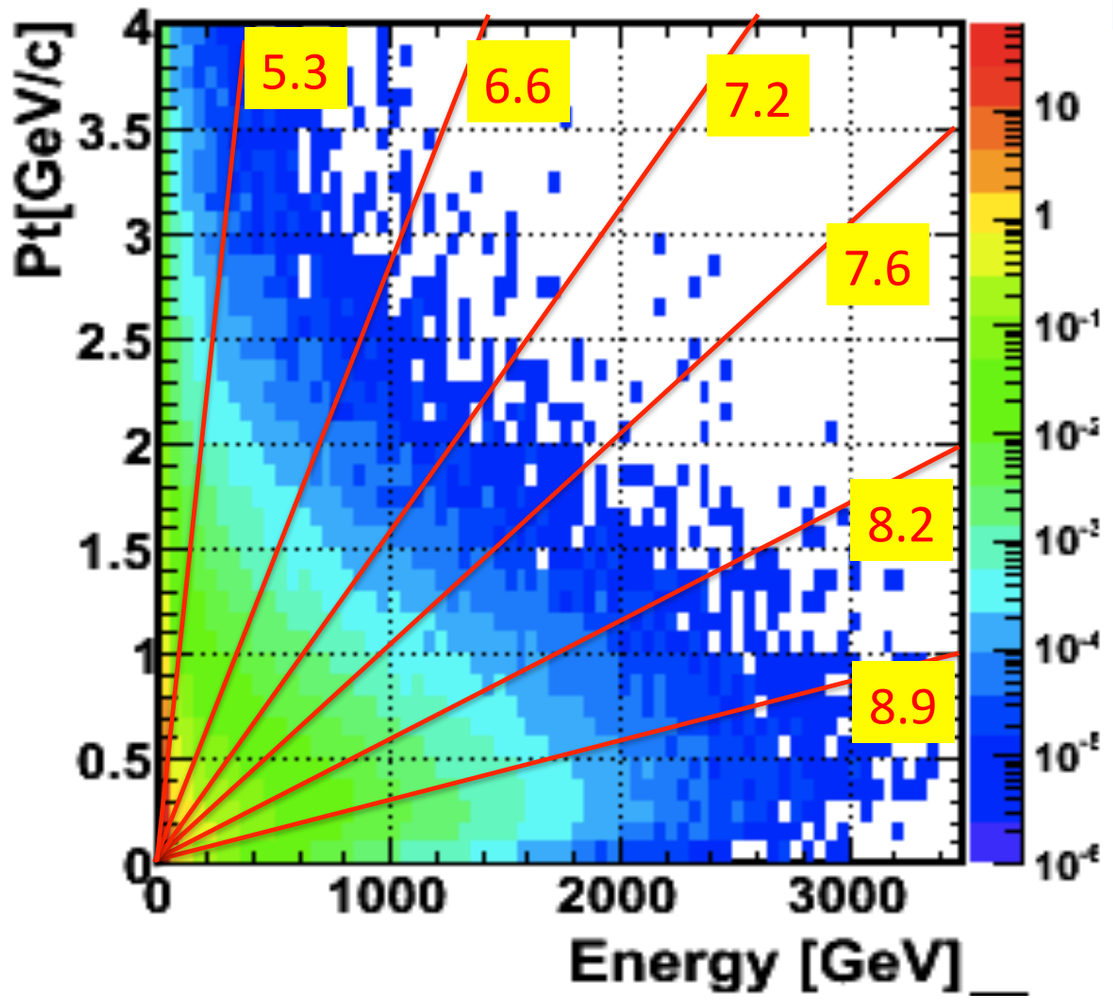
CMS PRELIMINARY





Very Forward :Most Energetic part





Very nice results from Forward Detectors

But the most energetic part is not covered.
Very Forward Experiments like LHCf and ZDC are important

The LHCf collaboration

The LHCf collaboration involves
~30 members at 10 institutions.

Feb. 2009

Jul. 2011

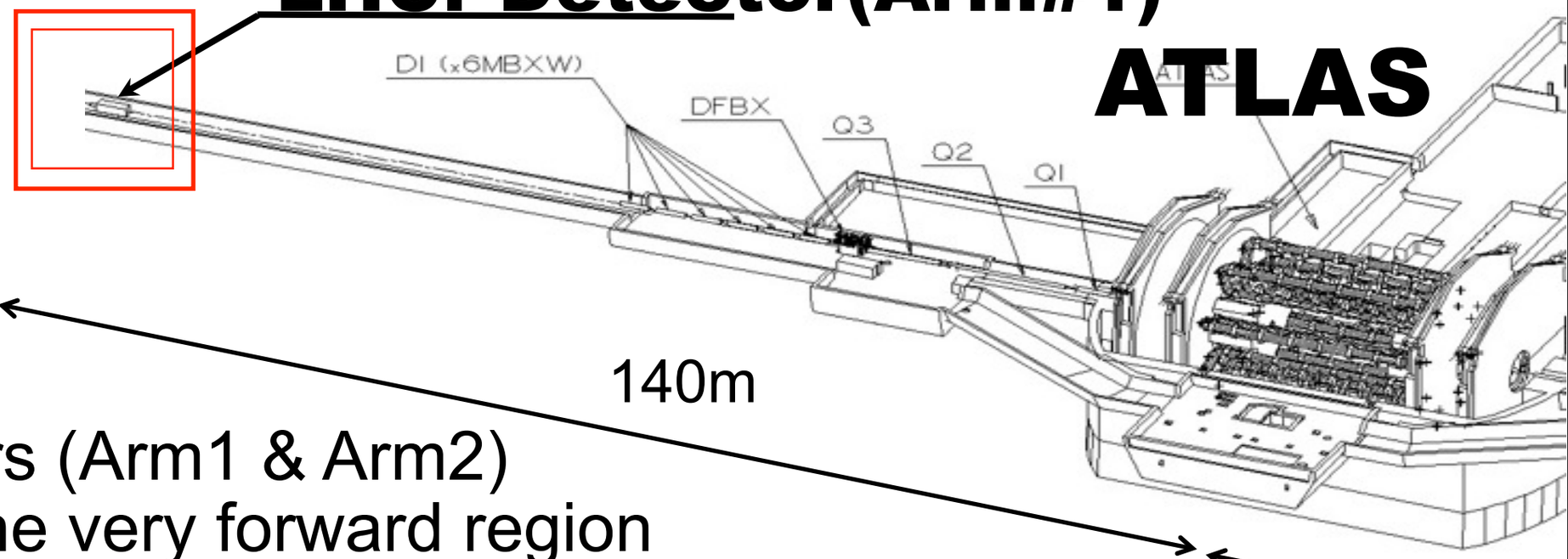
LHCf

Jul. 2013

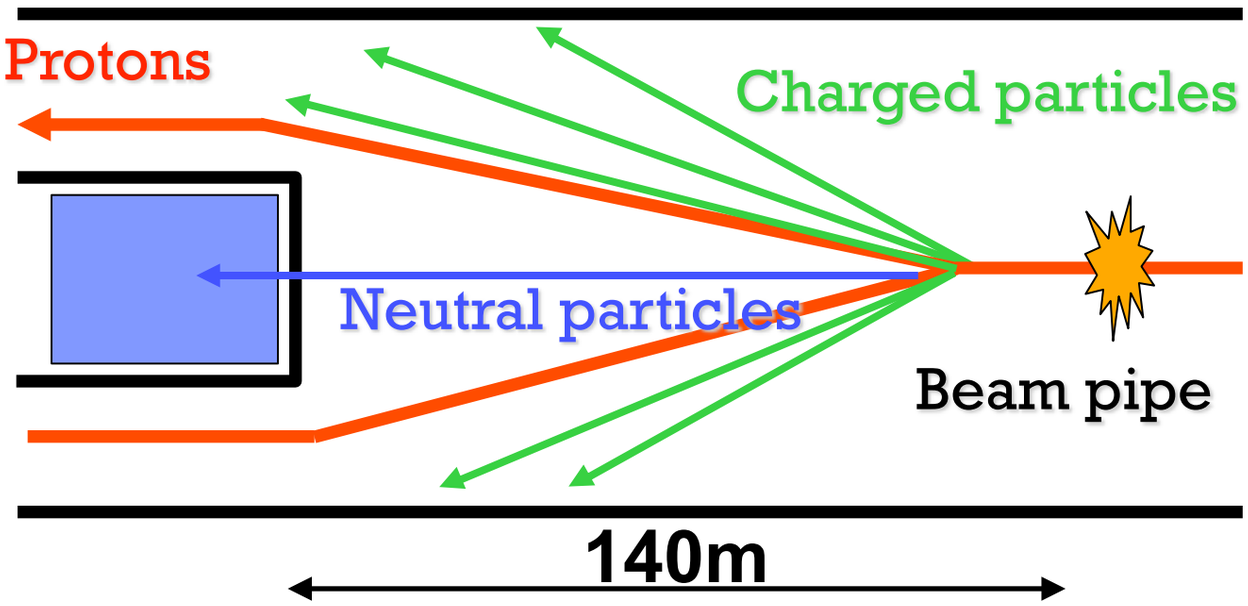
Apr. 2013

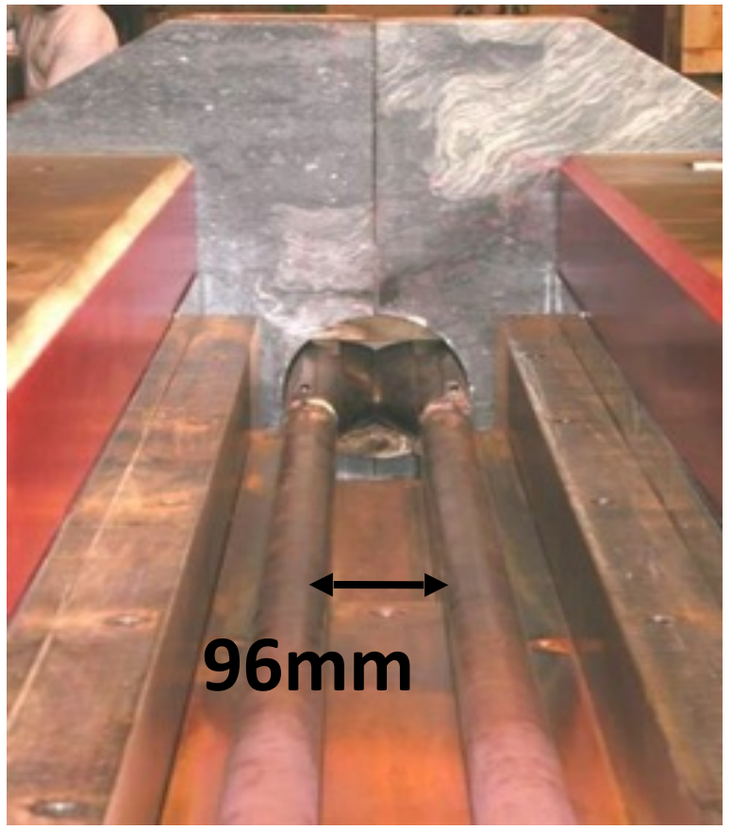
LHCf Experiment

LHCf Detector(Arm#1)



Two LHCf detectors (Arm1 & Arm2) are installed into the very forward region of the LHC interaction point (IP1). LHCf can measure neutral particles (γ, n) at the rapidity range η > 8.4.

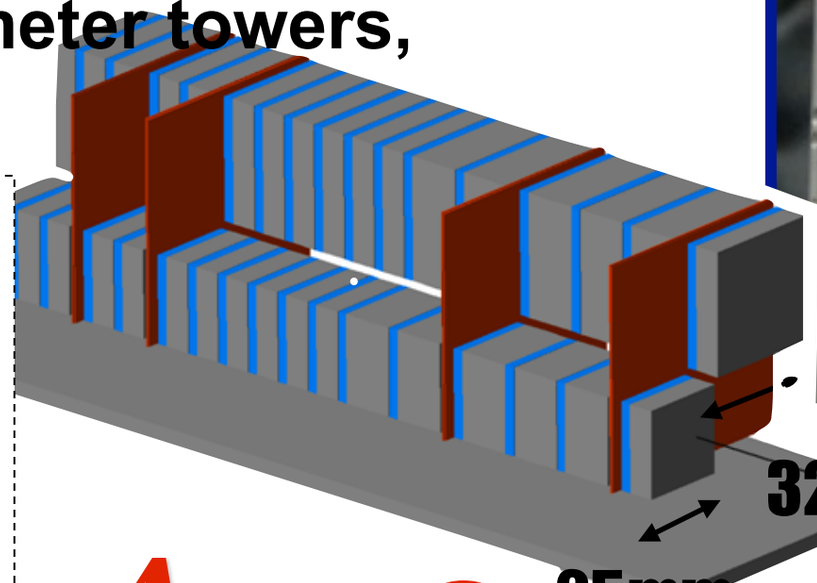




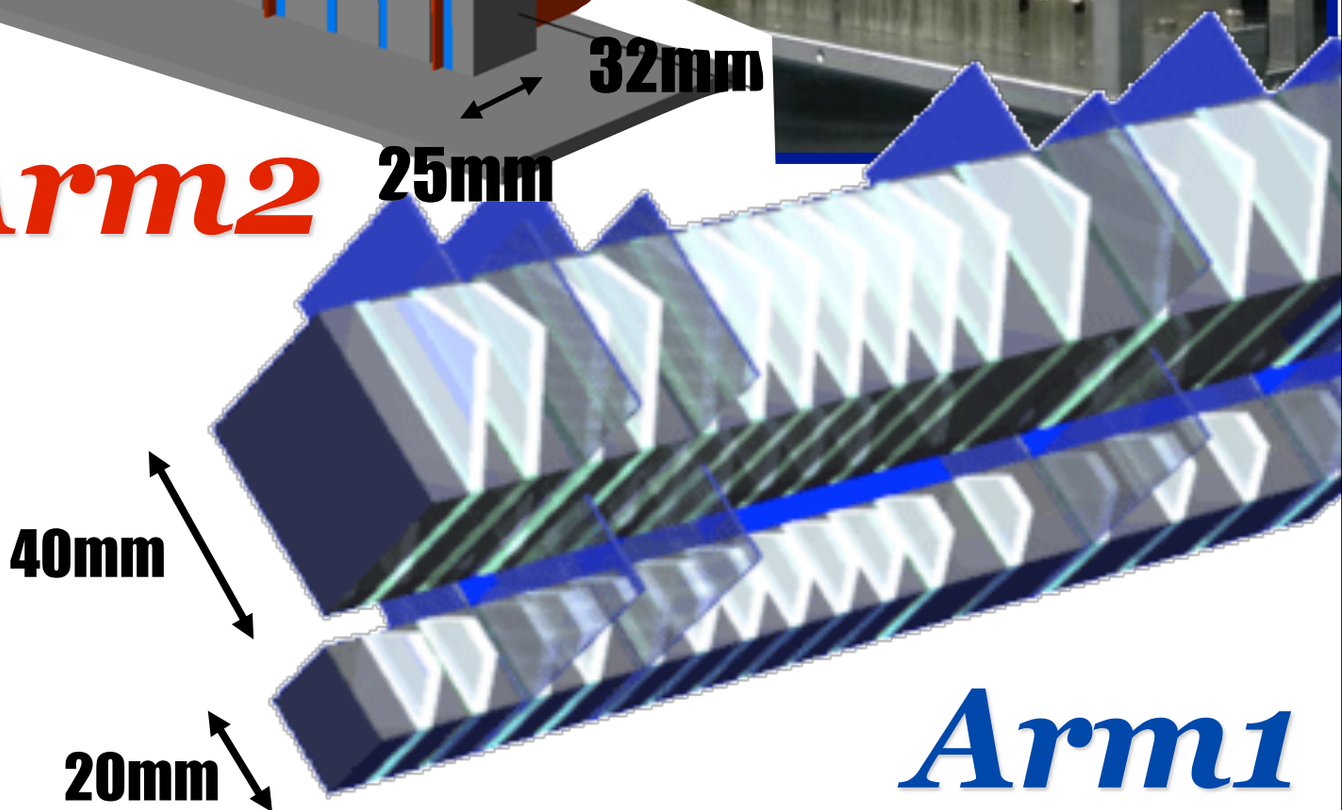
The LHCf detectors

Sampling and Positioning Calorimeters

- W (44 r.l , 1.7λ_I) and Plastic Scintillator x 16 Layers
- 4 positioning layers
  XY-SciFi (Arm1) and XY-Silicon strip(Arm#2)
- **Each detector has two calorimeter towers, which allow to reconstruct π^0**



Arm2



Arm1

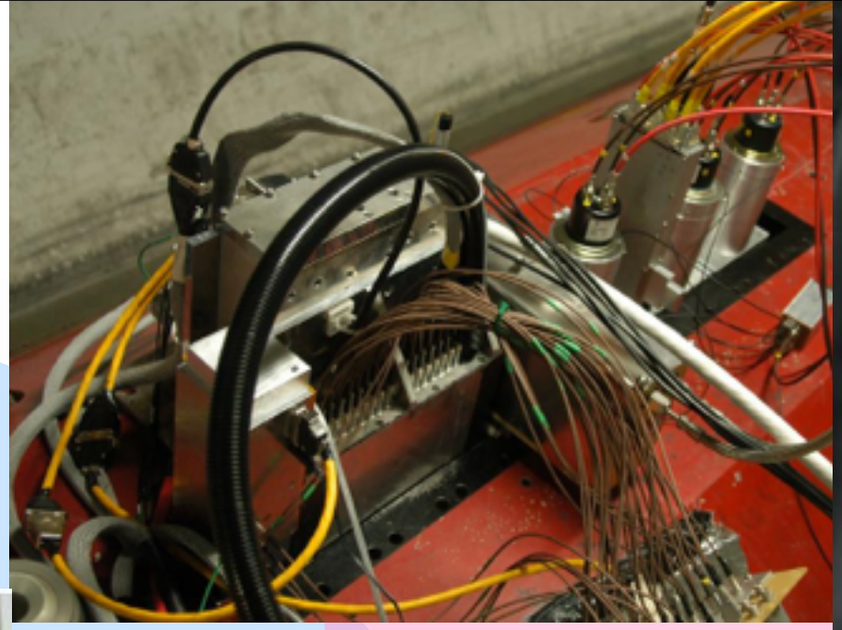
Expected Performance

Energy resolution (> 100GeV)
- < 5% for Photons
- 30-40% for Neutrons

Position resolution
- < 200μm for Photons
- a few mm for Neutrons

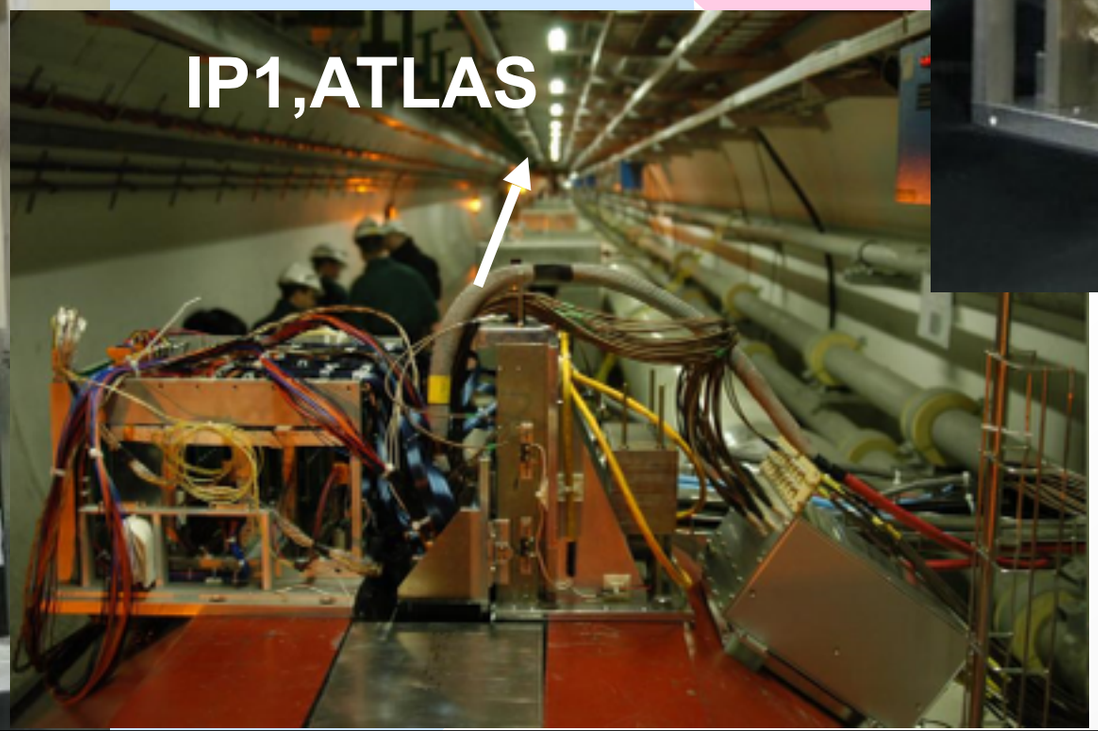
Front Counter

- thin scintillators with 80x80mm^2
- **To monitor beam condition.**
- **For background rejection of beam-residual gas collisions by coincidence analysis**



Arm1

Arm2



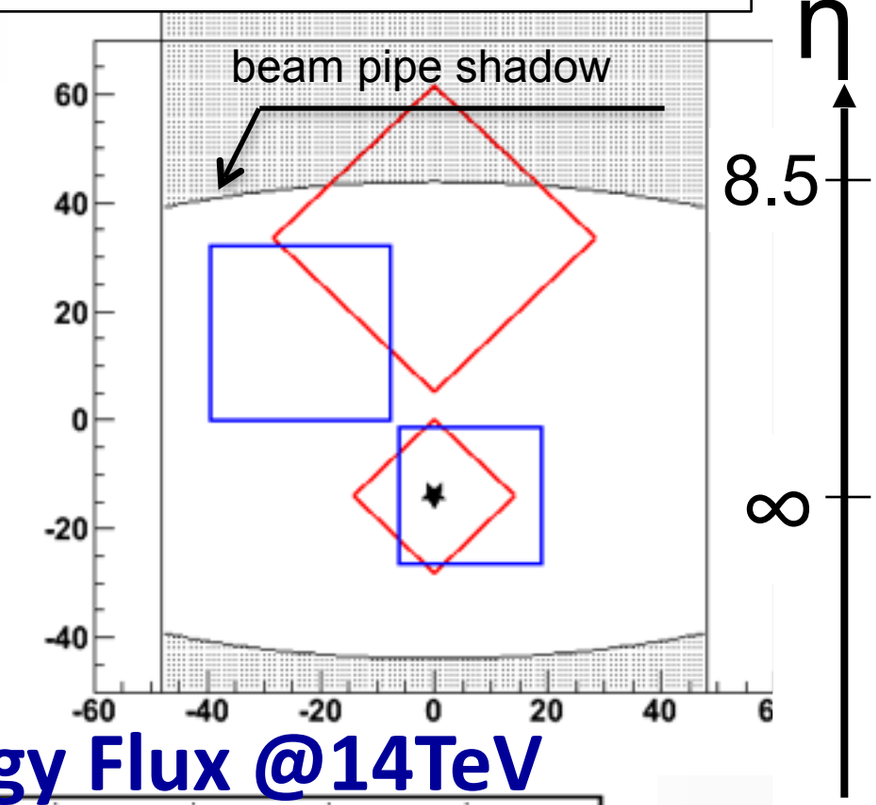
LHCf can measure

Energy spectra and
Transverse momentum distbution of

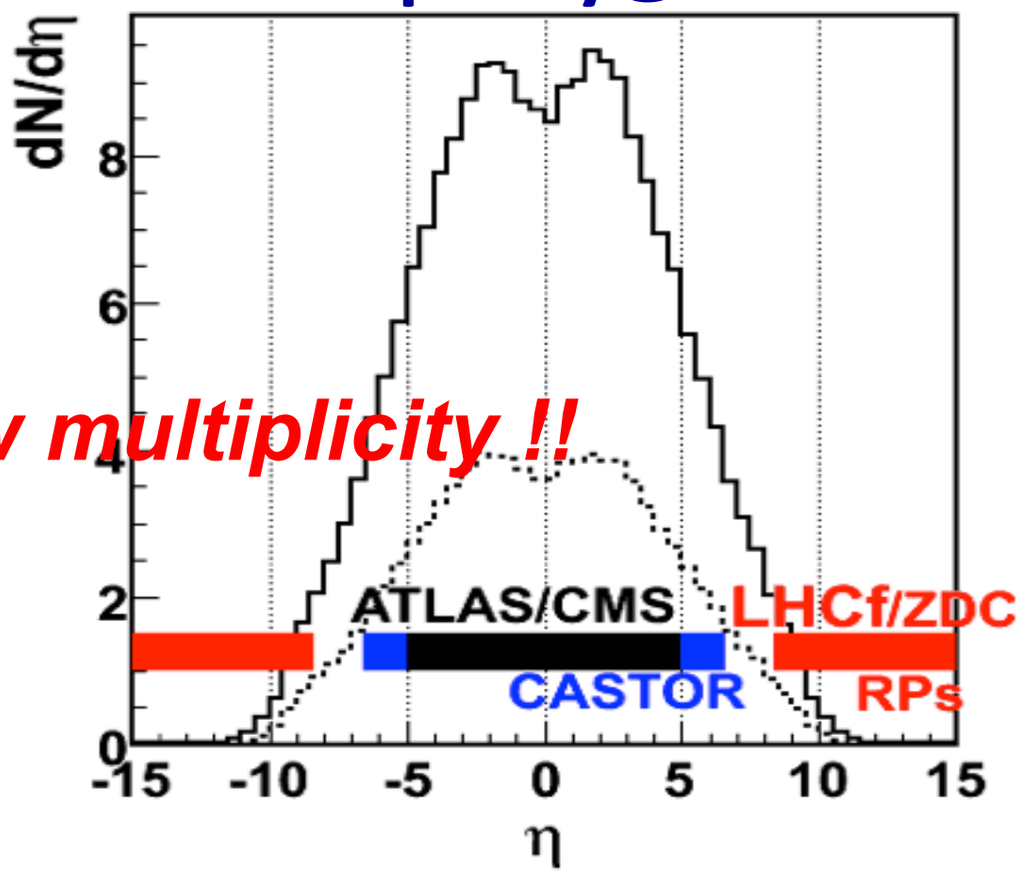
- **Gamma-rays (E>100GeV,dE/E<5%)**
- **Neutral Hadrons (E>a few 100 GeV, dE/E~30%)**
- **π^0 (E>600GeV, dE/E<3%)**

at pseudo-rapidity range >8.4

Front view of calorimeters
@ 100μrad crossing angle

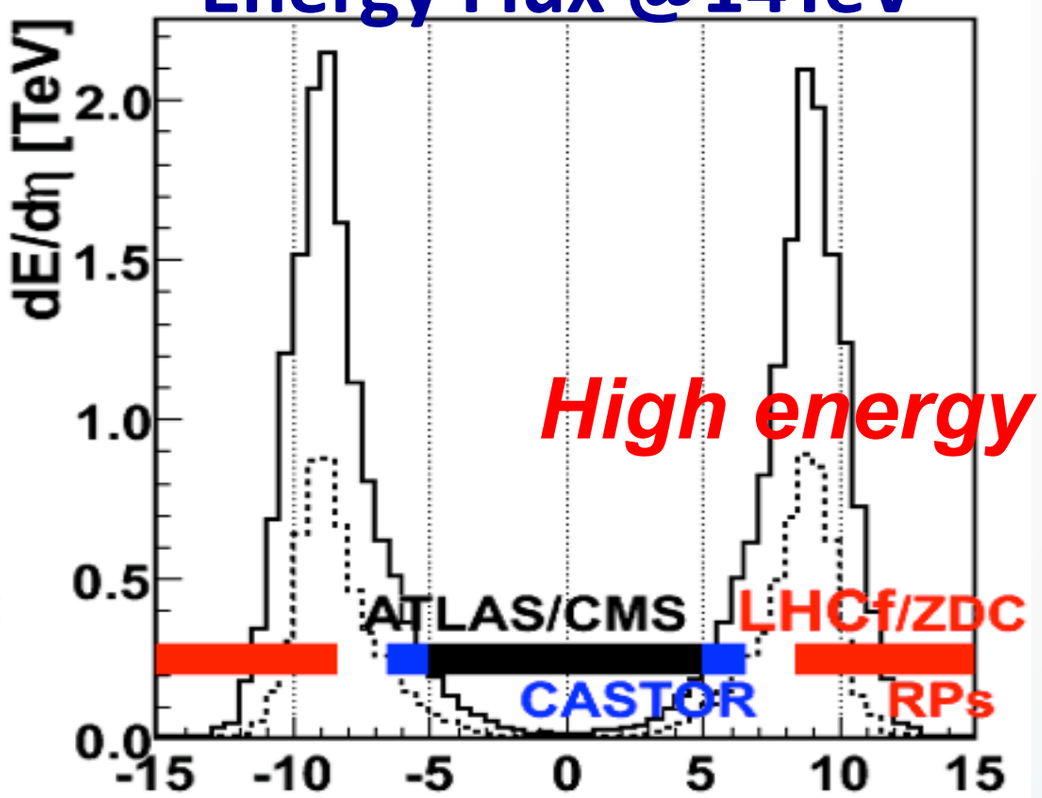


Multiplicity@14TeV



Low multiplicity !!

Energy Flux @14TeV



High energy flux !!

η simulated by DPMJET3

LHCf Operations

At √s=900GeV p-p

- 06 Dec. –15 Dec. in 2009
  27.7 hours for physics, 2.6 hours for commissioning
  ~2,800 and ~3,700 shower events in Arm1 and Arm2
- 02 May – 27 May in 2010
  ~15 hours for physics
  ~44,000 and ~63,000 shower events in Arm1 and Arm2

At √s=7TeV p-p

- 30 Mar. – 19 July in 2010
  ~ 150 hours for physics with several setup
  With zero-crossing angle and with 100μrad crossing angle.
  ~$2x10^8$ and ~$2x10^8$ shower events in Arm1 and Arm2

2009-2010

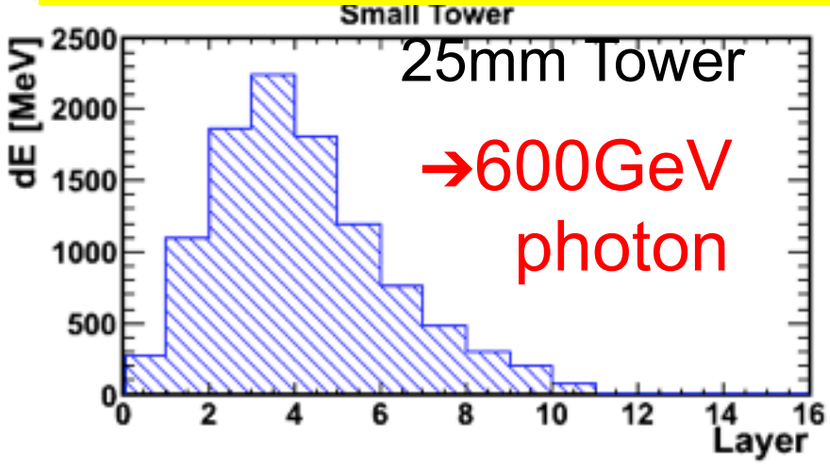
2013

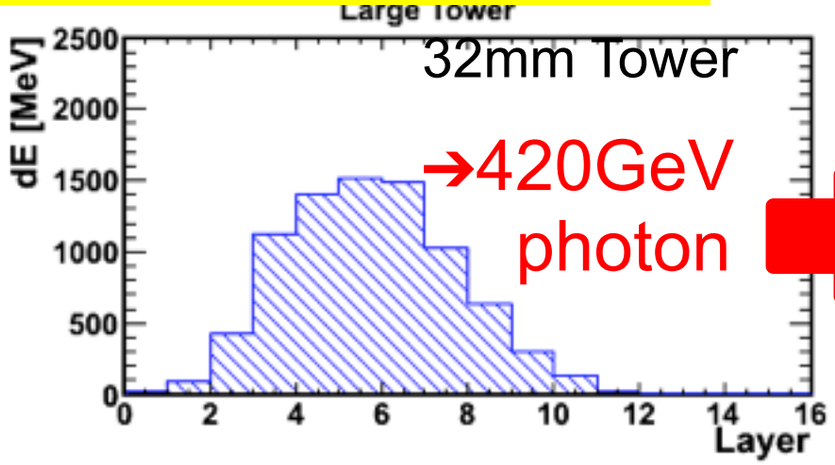
At $\sqrt{s_{NN}}$=5TeV p-Pb

- 20 Jan. – 4 Feb. in 2013
  Only Arm2 had been operated.
  ~$2x10^8$ shower events were taken.

Event sample

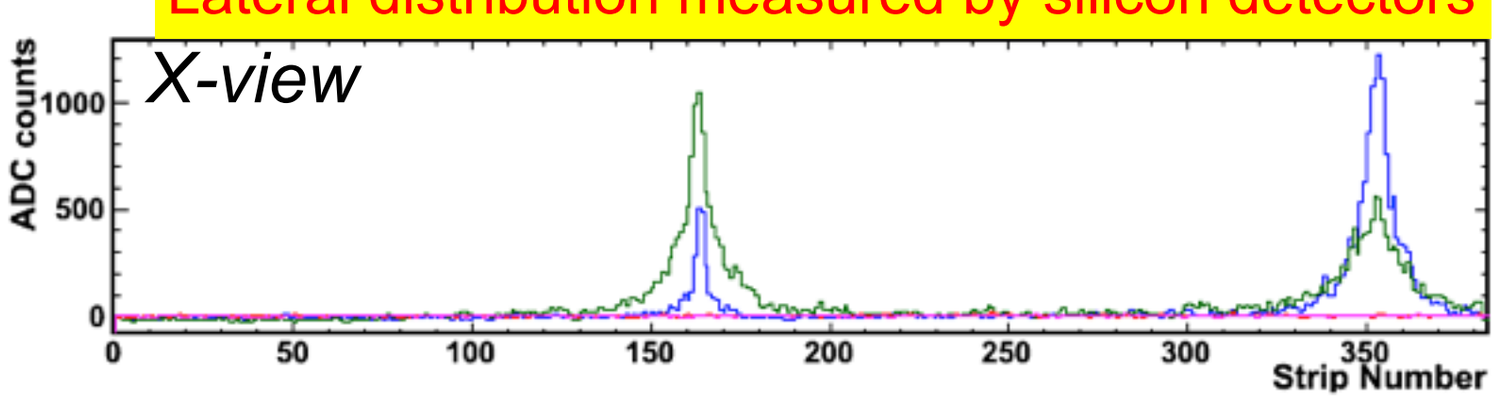
Longitudinal development measured by scintillator layers





Total Energy deposit
→Energy
Shape
→PID

Lateral distribution measured by silicon detectors



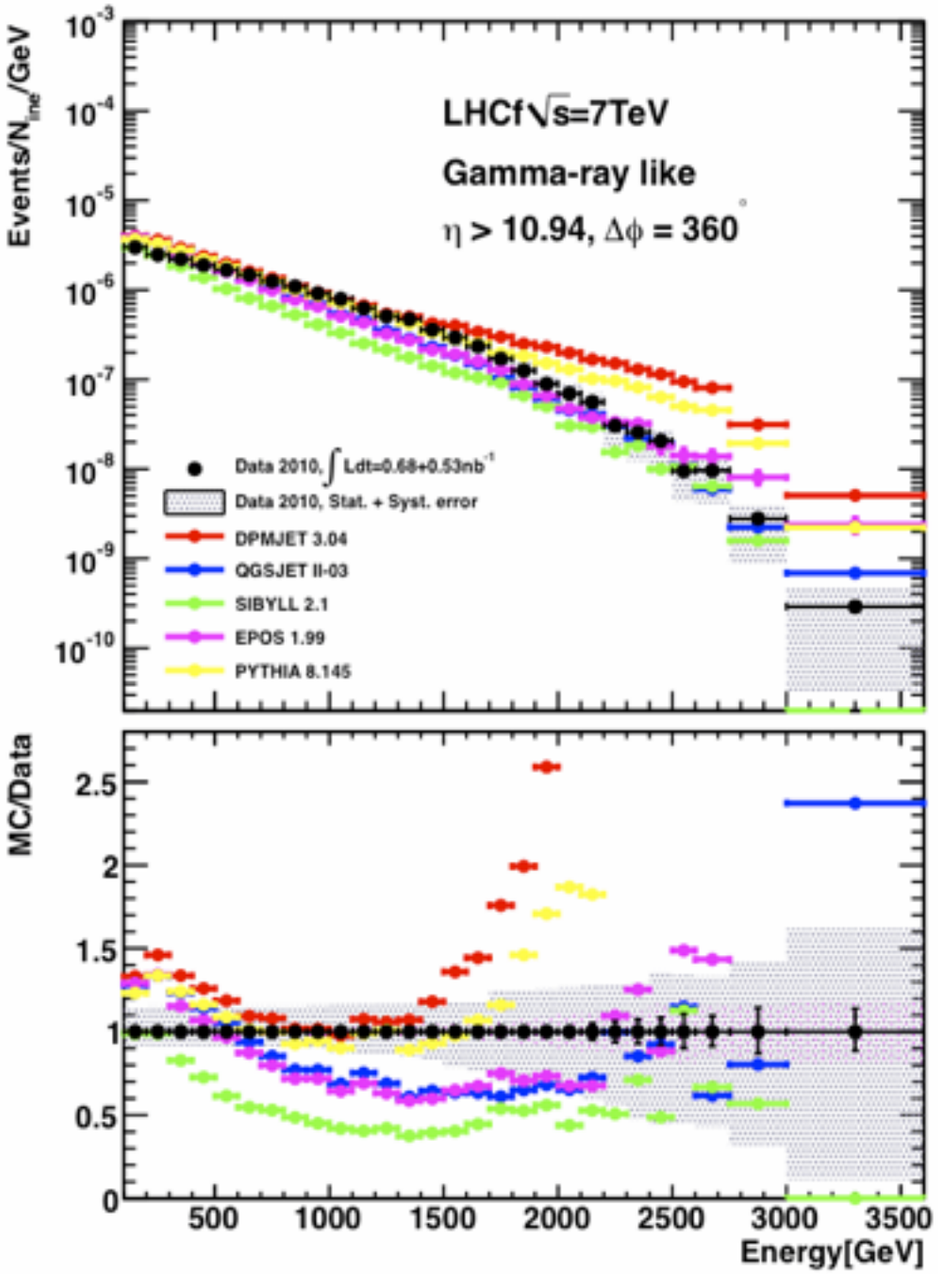
Hit position,
Multi-hit search.

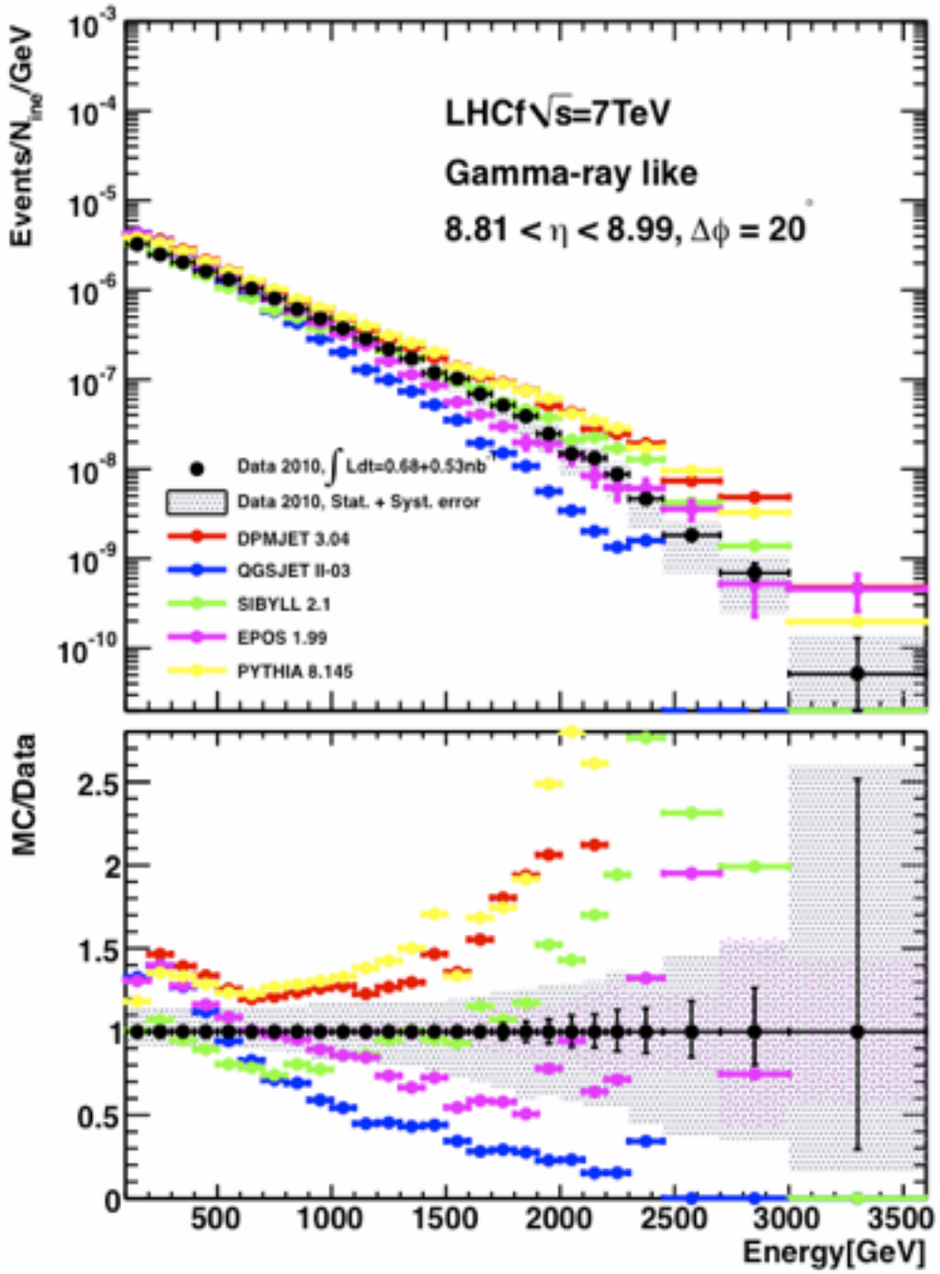
π^0 mass reconstruction from two photon.

$$M_{\pi 0} = \sqrt{E_{\gamma 1} E_{\gamma 2}} \cdot \theta$$

Systematic studies

Photons at 7TeV p-p





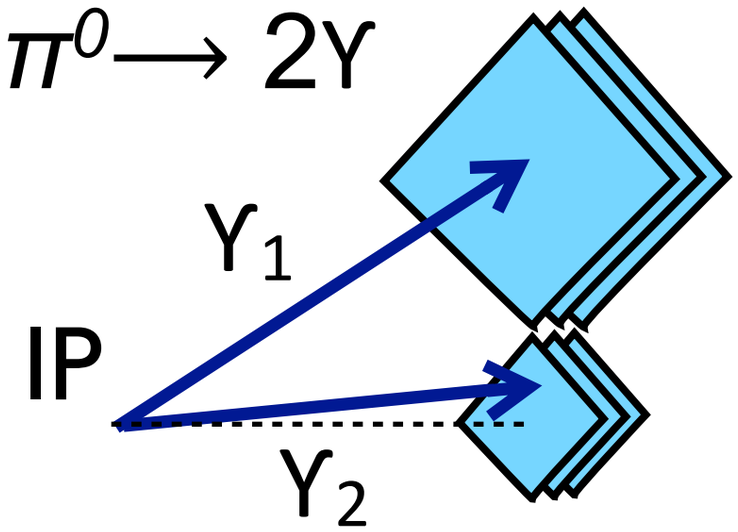
Data

Sys.+Stat.

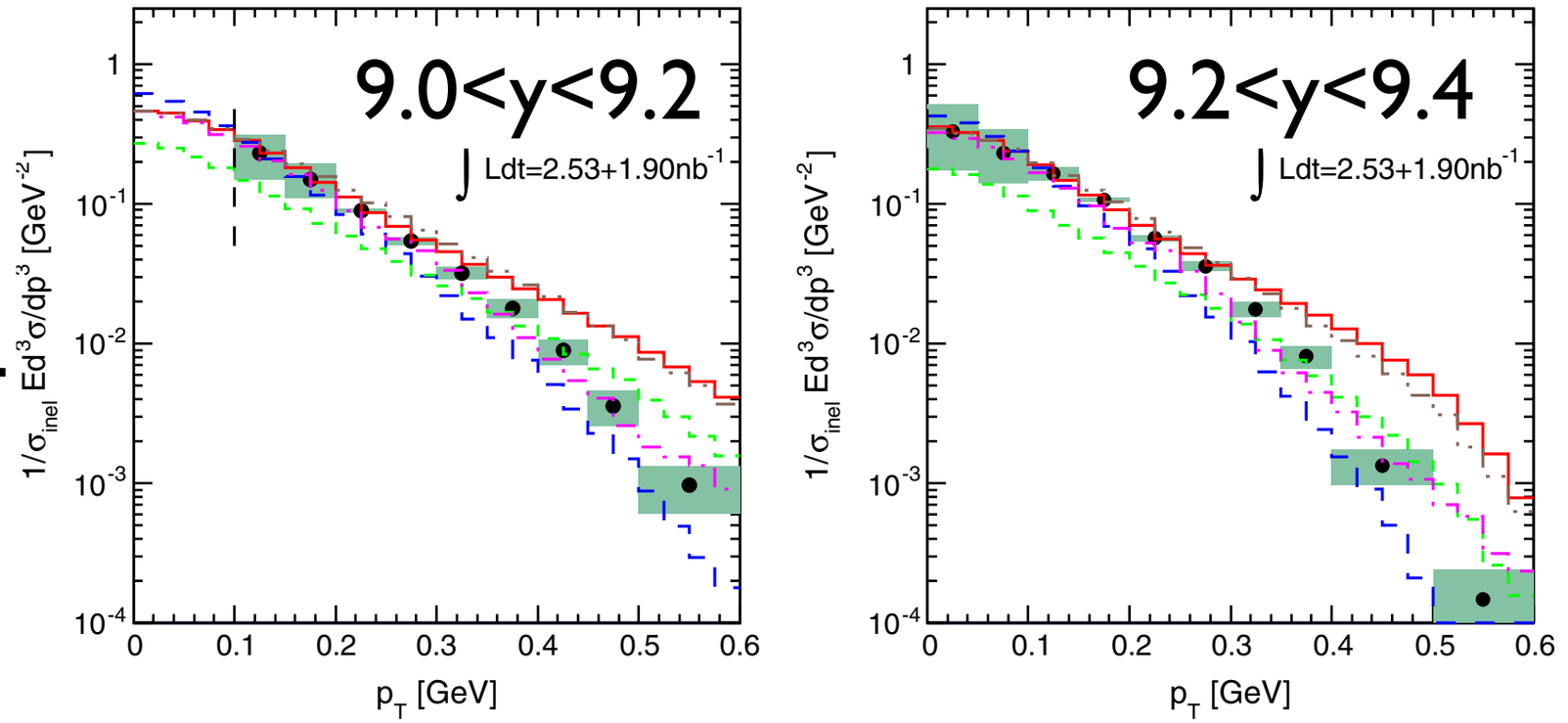
DPMJET 3.04
QGSJETII-03
SIBYLL 2.1
EPOS 1.99
PYTHIA 8.145

- No model can reproduce the LHCf data perfectly.
- Data points are on the middle of MC predictions except E < 500GeV.

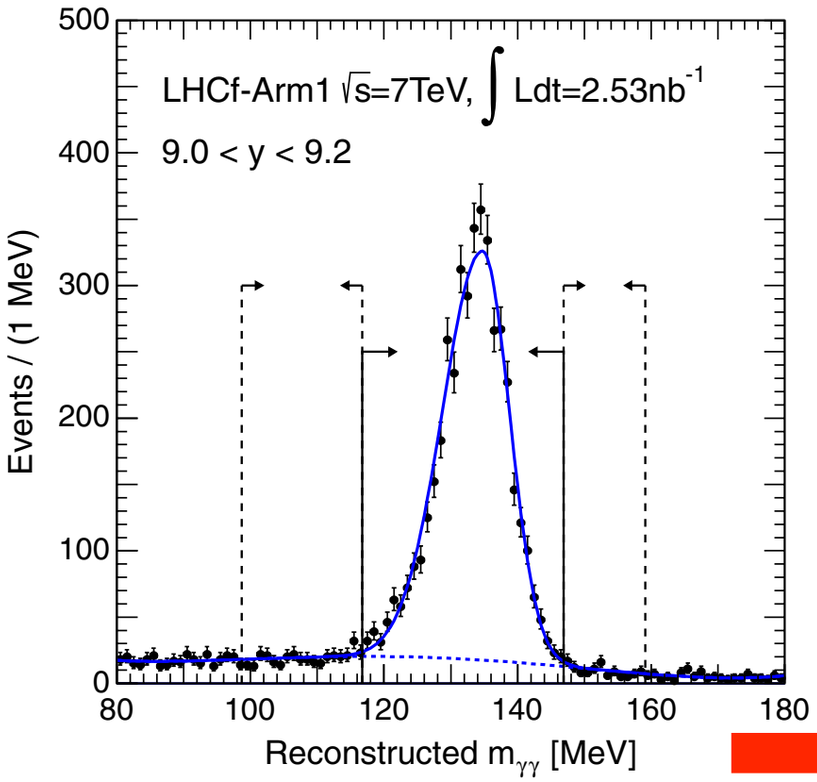
Neutral Pions at 7TeV p-p



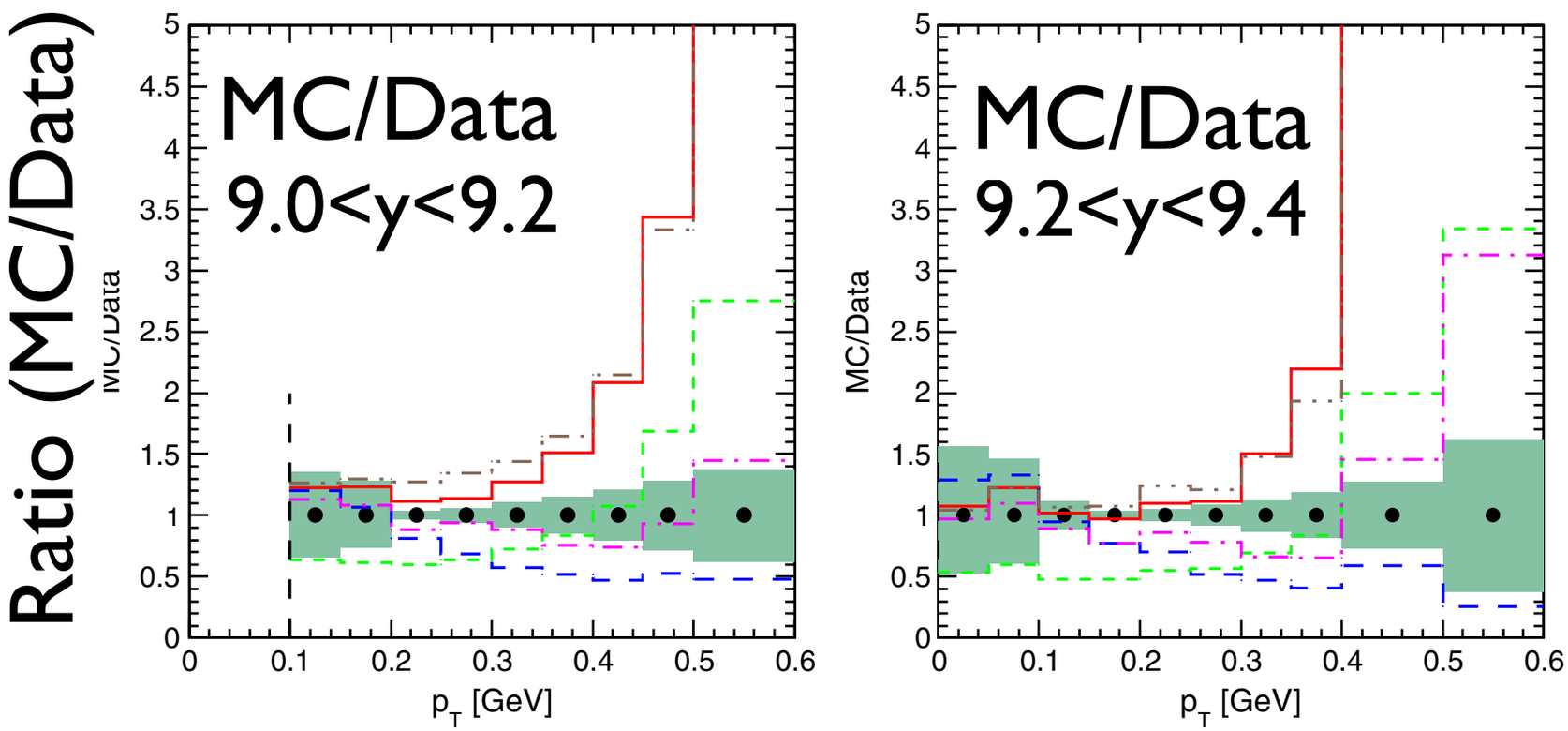
P_T spectra



Reconstructed Mass



Ratio (MC/Data)



Consistent with Photon results P. 28

Results in 2009~2012

- Operation
  - 2009-2010 : pp,√s=900GeV and 7TeV
  - 2013 : pPb, √s=5TeV and pp, √s=2.76TeV
- Published Results
  - Forward photon spectra @ pp√s=0.9, 7TeV
  - Forward neutral pion spectra @ pp, √s=7TeV

☑ **Electromagnetic Components in the products**
⇒Data favors EPOS1.99

☐ **How about baryons ?**
⇒ Inelasticity measurement

☐ **How about p-A collisions ?**
⇒ Nuclear effect

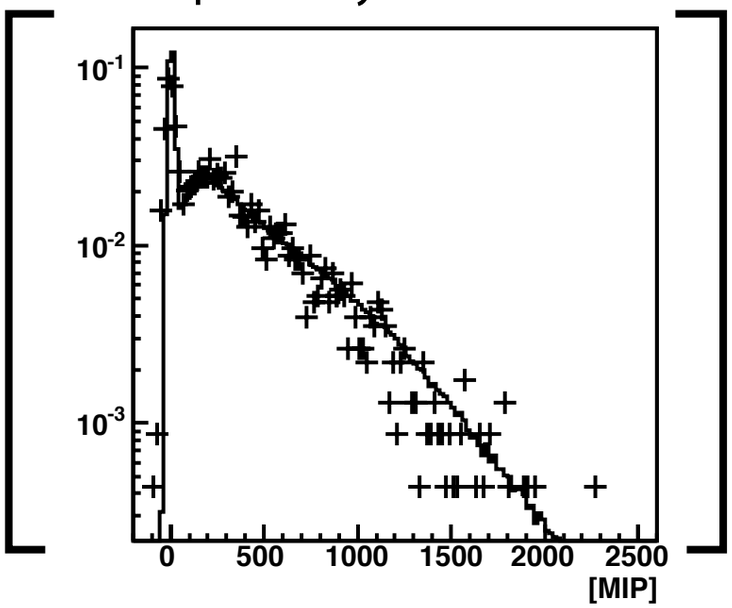
Neutron event reconstruction

Preliminary
(arXiv:1312.5950)

Neutron energy reconstruction

$$\sum_{l=2}^{15}$$

example at layer8th



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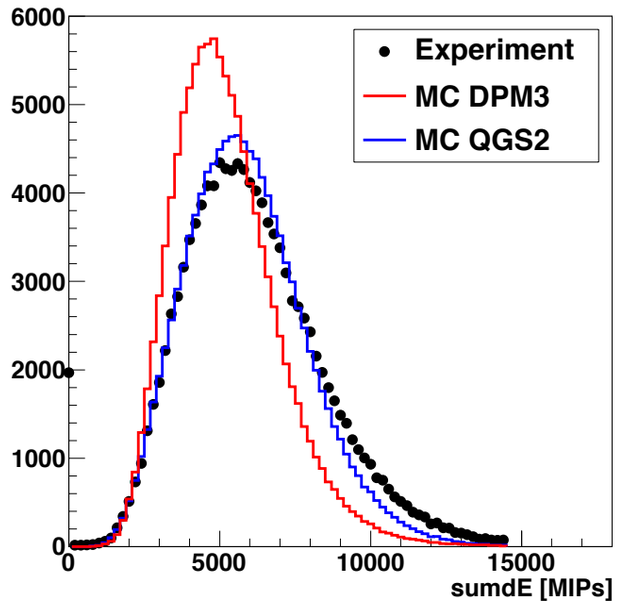
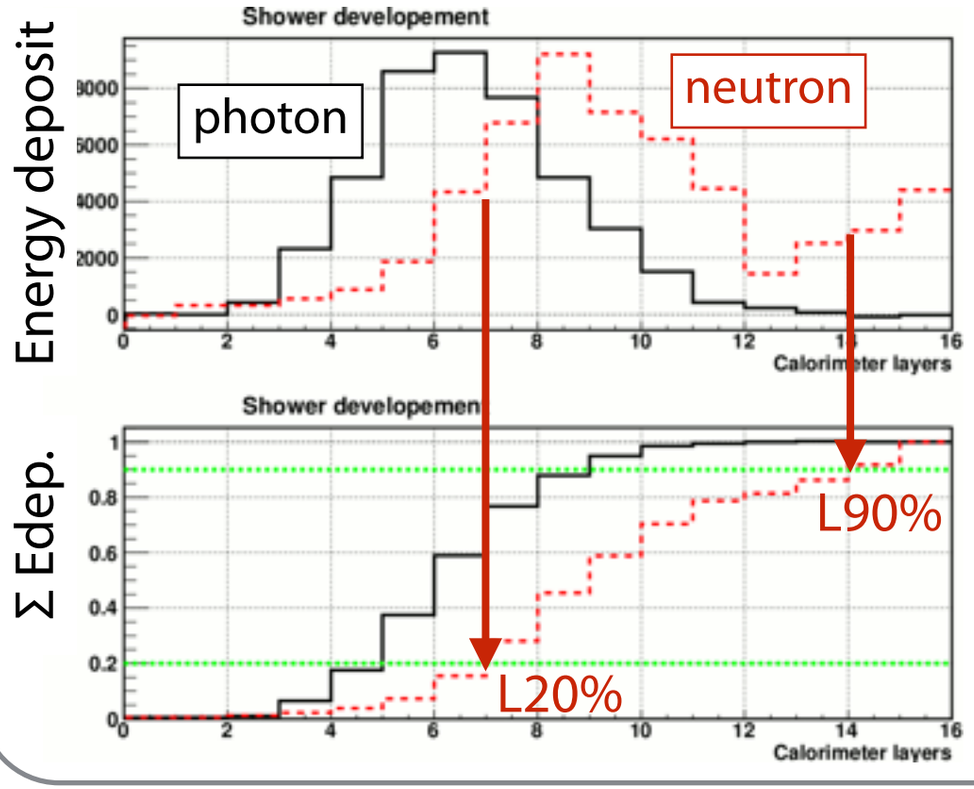
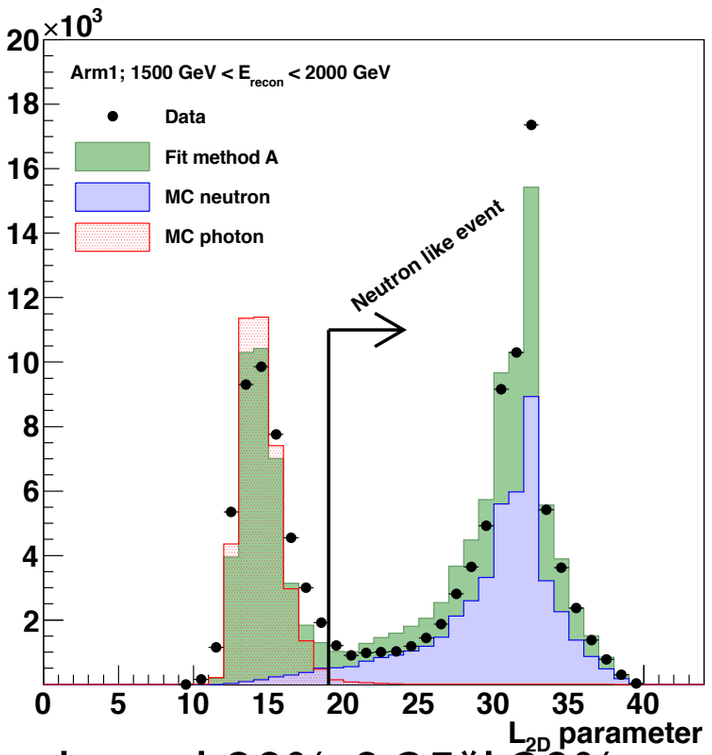


ΔE/E ~40%

- Neutron energy is reconstructed by a sum of energy deposits.
- Detector simulation based on QGSJET2 for hadronic shower reproduces the test beam data better than that on DPMJET3.
- Difference between QGSJET2 and the test beam data is taken into account as a systematic error in the latter analysis.

Particle identification

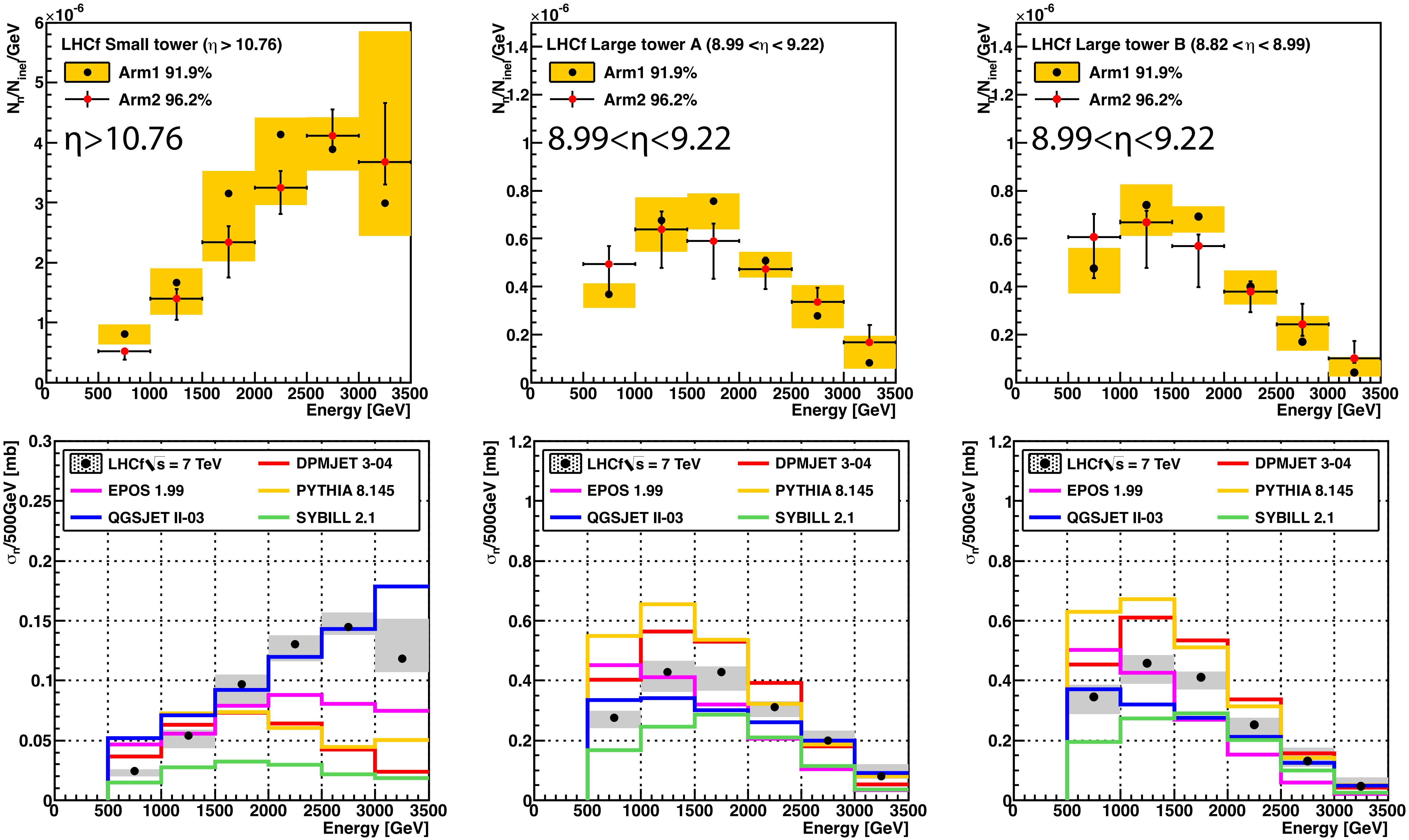




L_{2D} = L90%-0.25*L20%

- With two variables, L90% and L20%, PID performance is improved to reduce the photon contamination in neutron events.
- PID efficiency and purity are >90%.
- Energy spectra are corrected for PID inefficiency and BG contamination.

Neutron energy spectra in p-p collisions

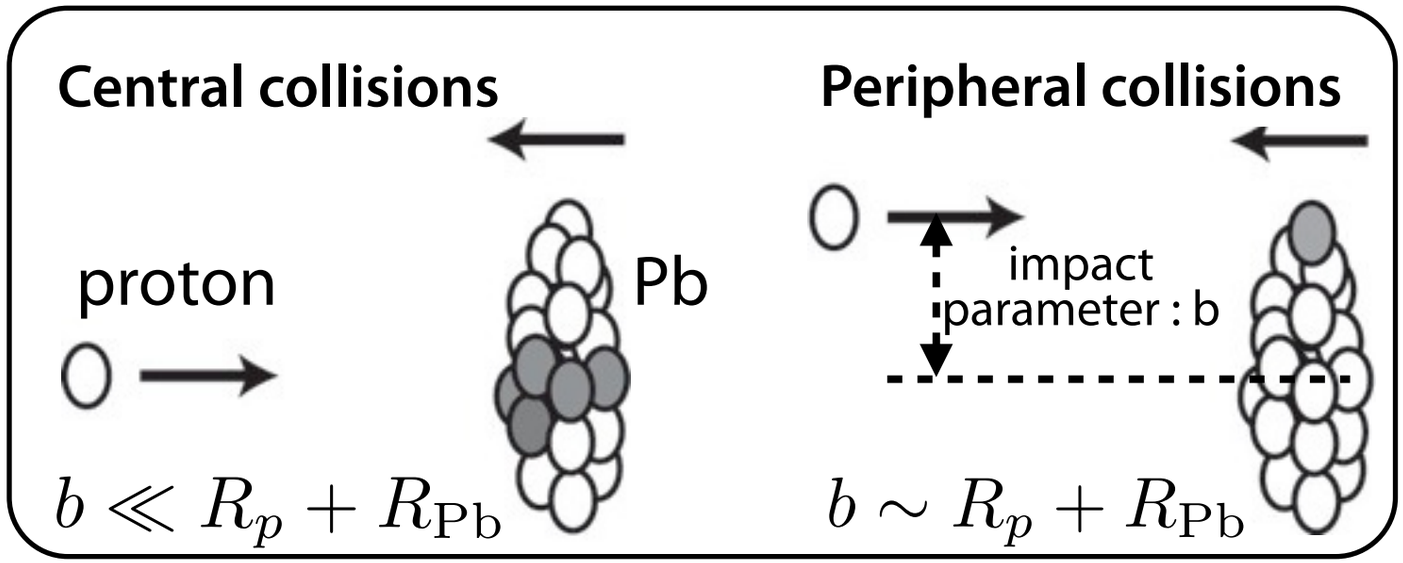


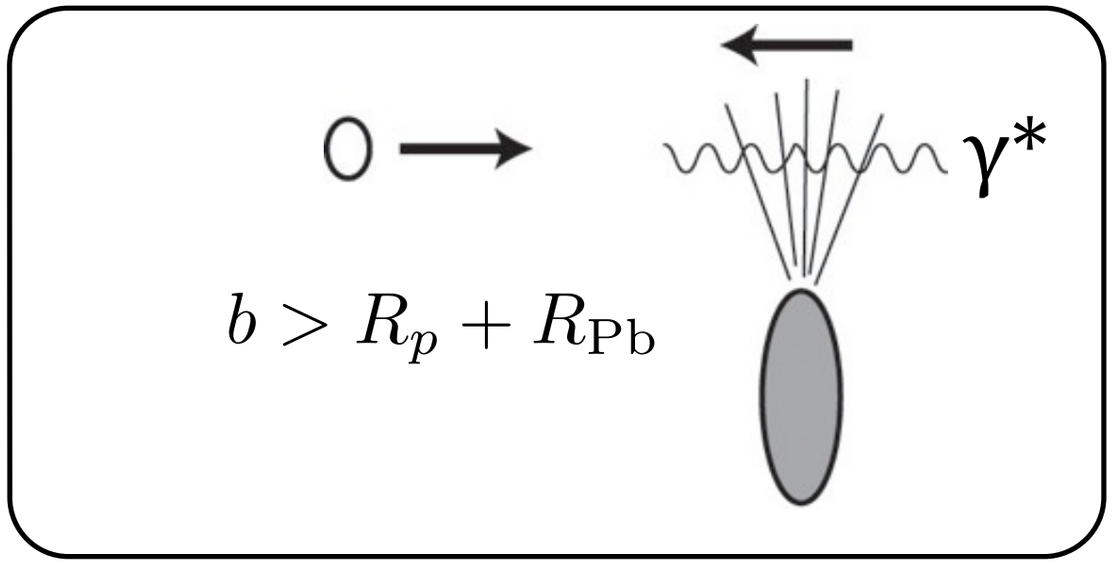
- LHCf Arm1 and Arm2 agree with each other within systematic error, in which the energy scale uncertainty dominates.
- In η>10.76 huge amount of neutron exists. Only QGSJET2 reproduces the LHCf result.
- In other rapidity regions, the LHCf results are enclosed by the variation of models.

π^0 event analysis in p-Pb collisions

(Soft) QCD :
central and peripheral collisions

Ultra peripheral collisions :
virtual photon from rel. Pb collides a proton.





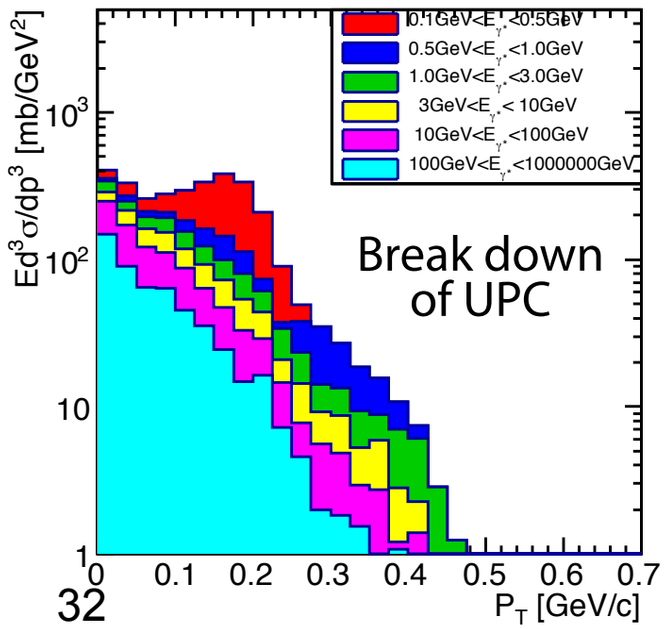
Momentum distribution of the UPC induced secondary particles is estimated as
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOHIA model (E > pion threshold).
3. produced mesons and baryons by γ-p collisions are boosted along the proton beam.

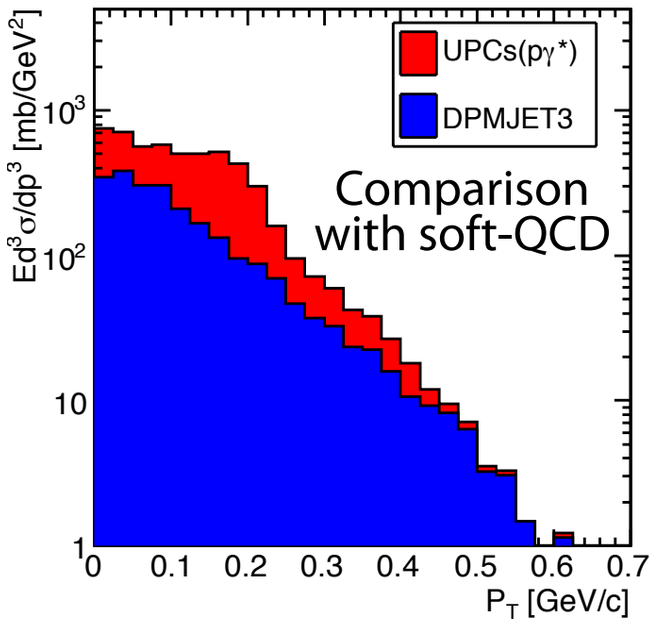
] proton rest frame

Dominant channel to forward π^0 is

$$\gamma + p \rightarrow \Delta(1232) \rightarrow p + \pi^0$$

About half of the observed π^0 may originate in UPC, another half is from soft-QCD.

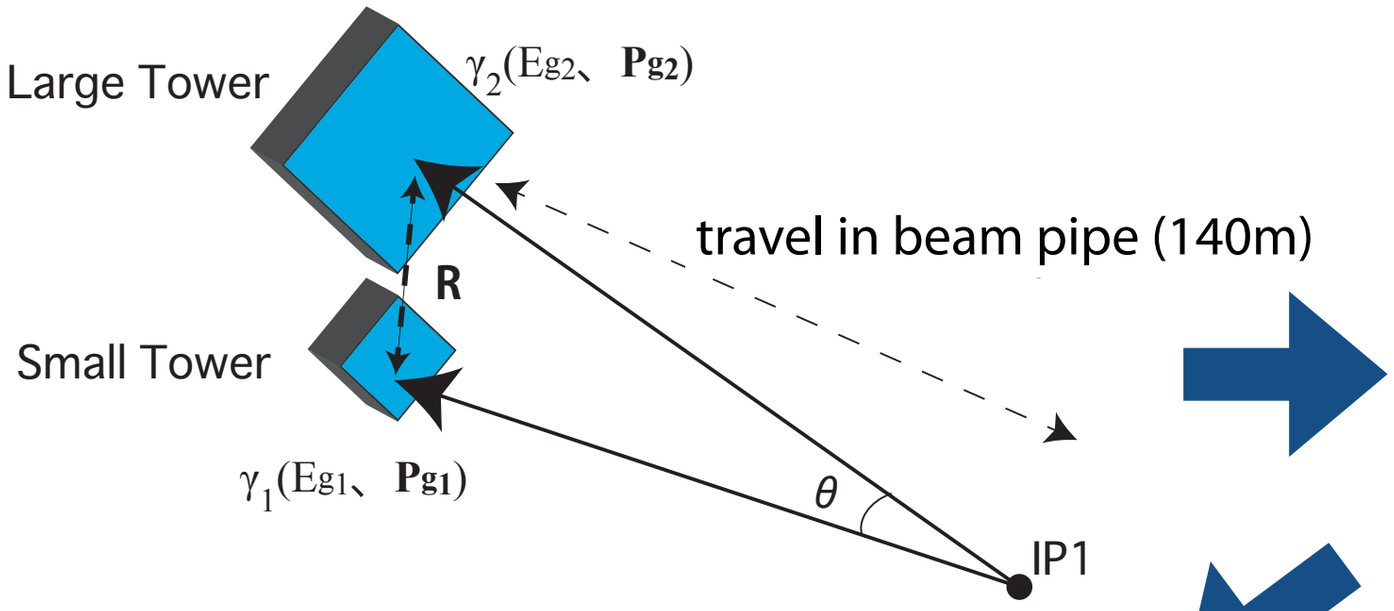




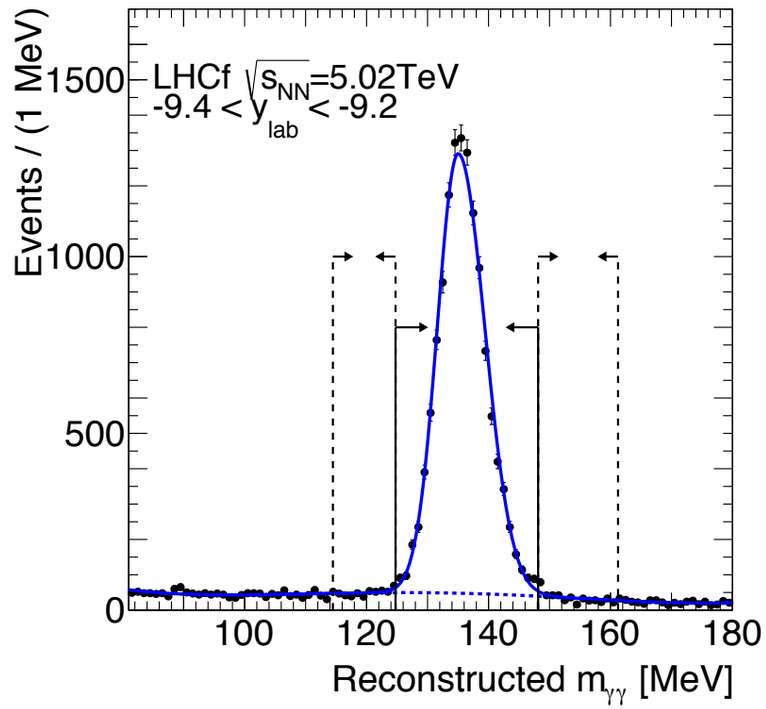
Preliminary

π^0 event reconstruction in p-Pb collisions

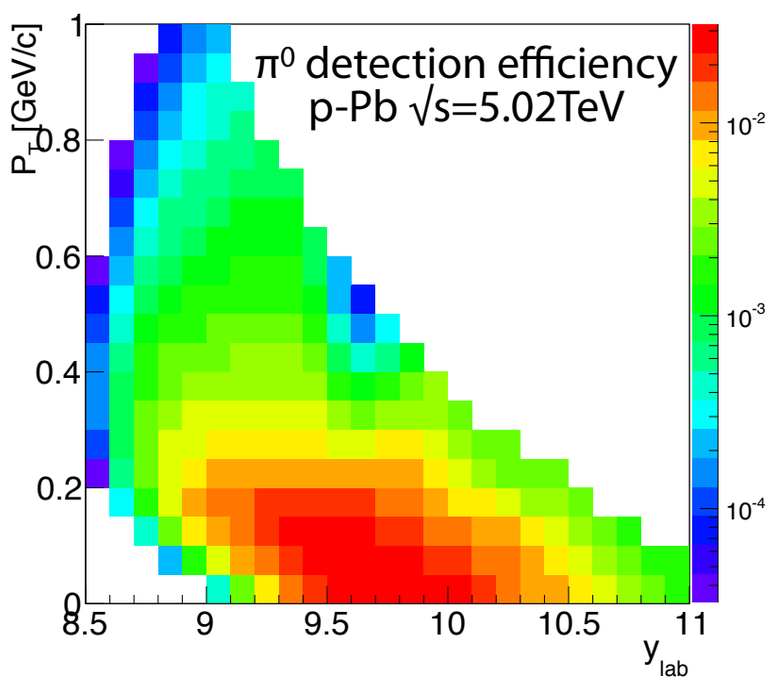
1. Search for two photons



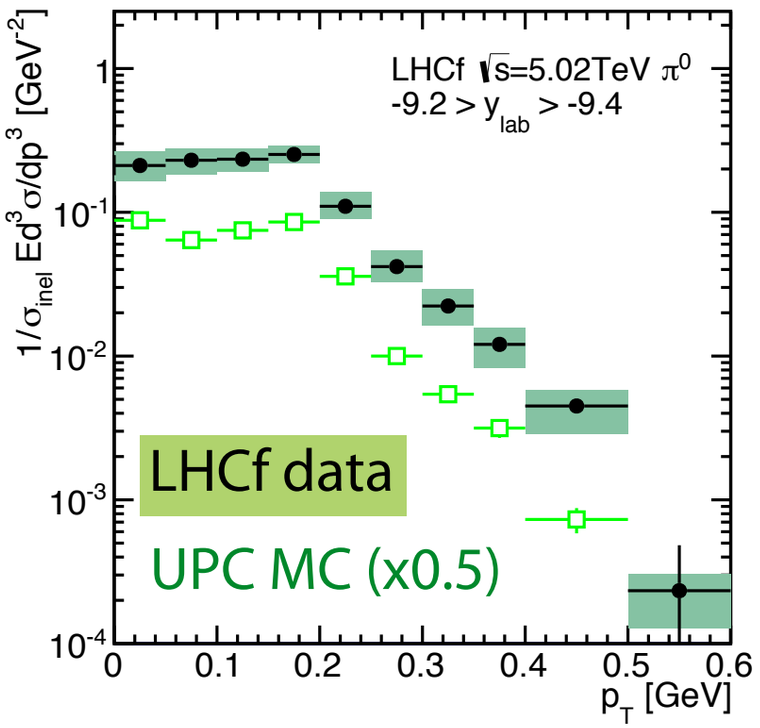
2. BG subtraction by sideband



3. Unfolding the smeared pT spectra and correction for geometrical inefficiency

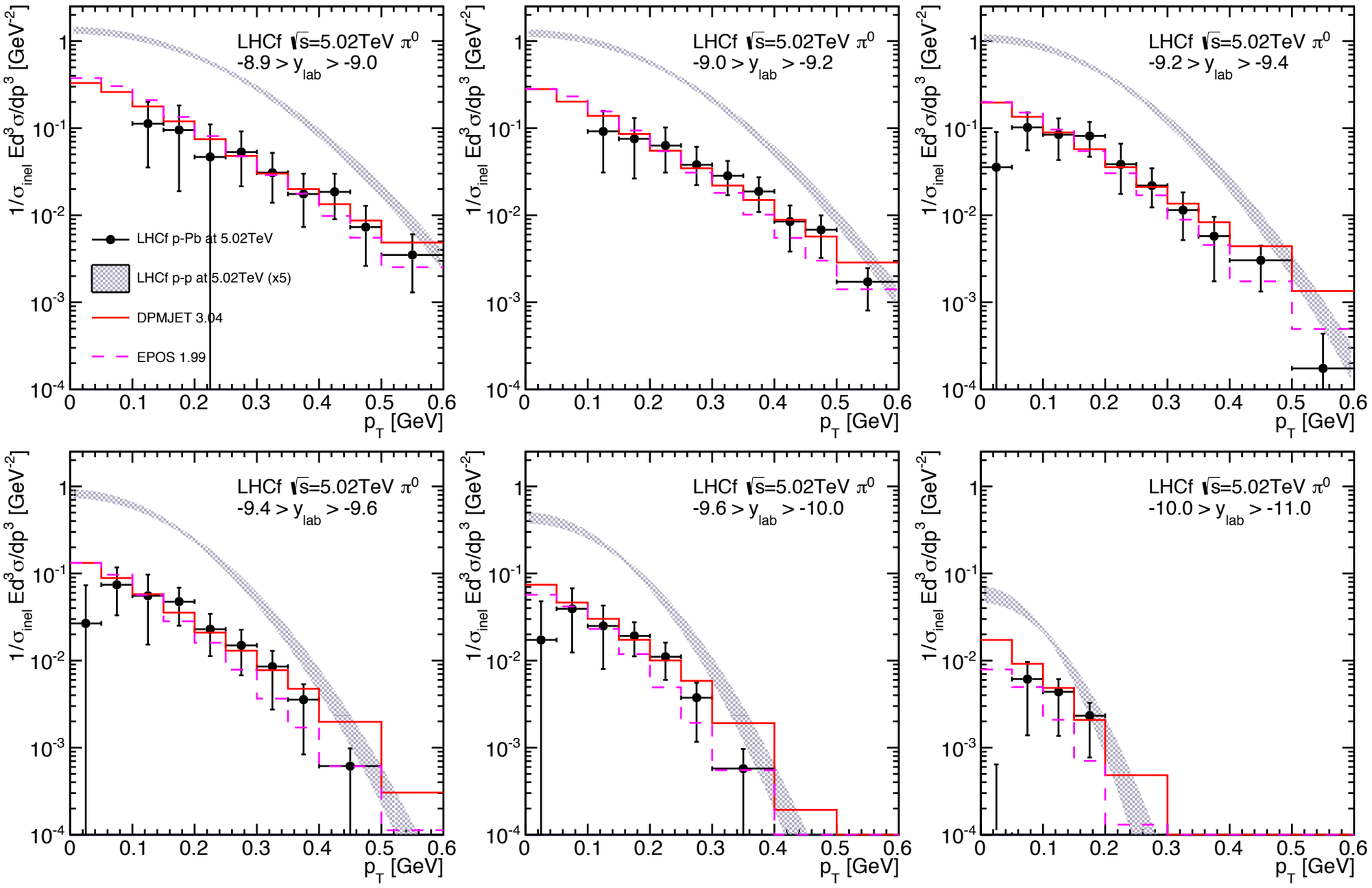


4. Subtraction of the UPC component



Preliminary

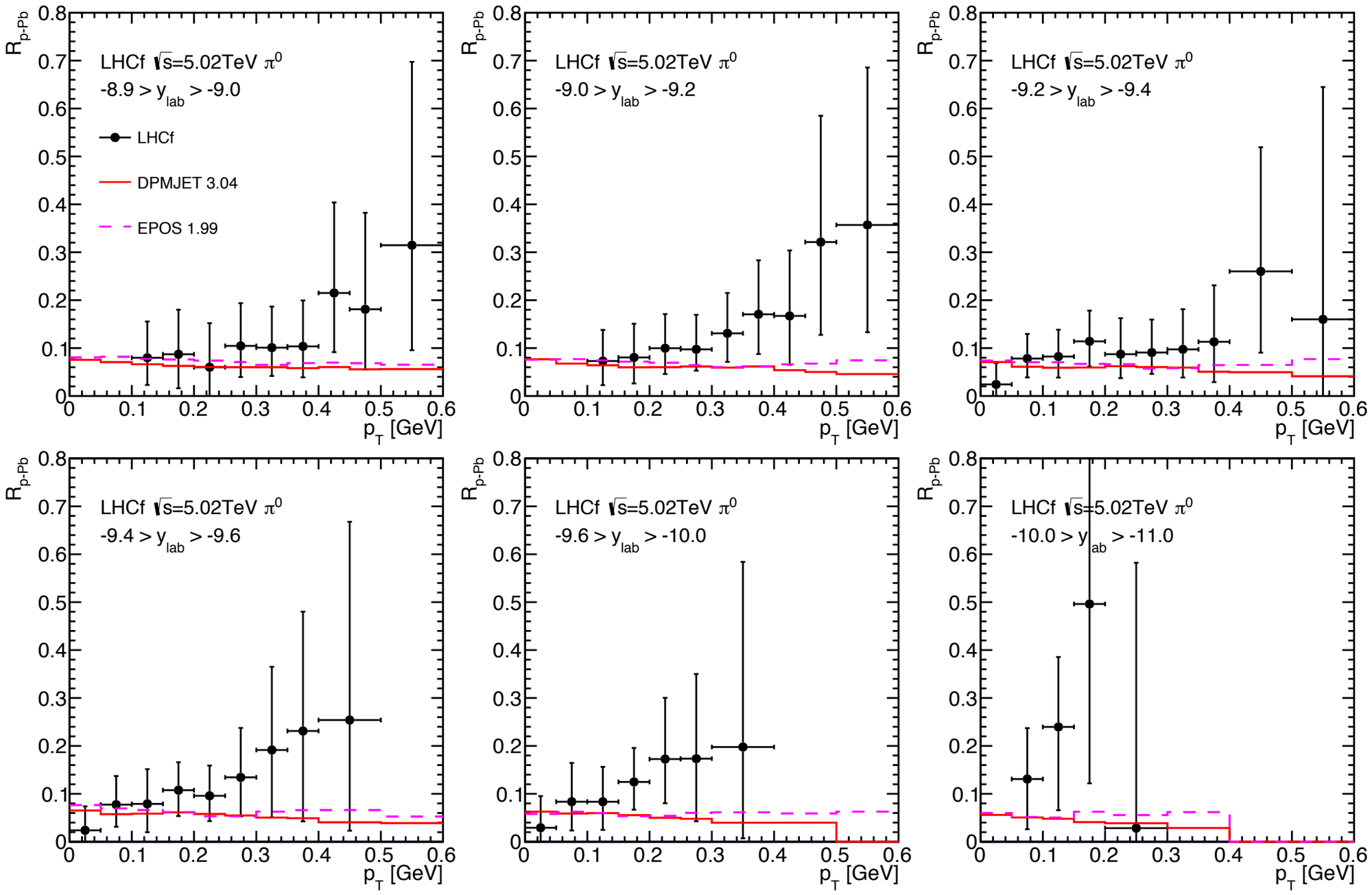
π^0 p_T spectra after the UPC subtraction



- The LHCf results in p-Pb (filled circles) show good agreement with DPMJET and EPOS. Note that UPC induced events are not involved in DPMJET and EPOS.
- The LHCf results in p-Pb are clearly harder than the LHCf results in p-p at 5.02TeV (shaded area) which are interpolated from the results at 2.76TeV and 7TeV.

Preliminary

Nuclear modification factor



$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) \equiv \frac{d^2 N_{\pi^0}^{\mathrm{pPb}}/dydp_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle d^2 N_{\pi^0}^{\mathrm{pp}}/dydp_{\mathrm{T}}}$$

$\langle N_{coll}\rangle = 6.9$

- Both LHCf and MCs show strong suppression.
- But LHCf grows as increasing p_T, understood by the softer p_T spectra in p-p at 5TeV than those in p-Pb.

Future Operations

- Future Operations
  - p-p collisions at $\sqrt{s}$ = 13TeV in 2015
    ⇒Energy Scaling
    ⇒Enlarge the P_T Acceptance

    Approved
  - p-light A (O) collisions in 2019 ?

    Starting discussion
  - Operation at RHIC,
    p-p at $\sqrt{s}$=500GeV, p-N at $\sqrt{s_{NN}}$=200GeV
    ⇒ Energy Scaling from the low energy region

    Proposing to RHIC
    Submitted LOI in May

→ Extend capability of verification of interaction models
Higher and Lower energy collisions, Nuclear effect

Summary

- LHCによって各種Dataが取得されており、
  CR-AS ハドロン相互作用モデルの検証が進んでいる
  - Total/Inelastic cross-section
  - Multiplicity
  - Forward Energy Flux
  - Spectra of each particle
- LHCfの最新結果
  - Neutron Measurement at pp, √s=7TeV
  - Nuclear Effect of neutral pions at p-Pb
- (個人的な感想)
  LHCから各種データが揃って来た。
  ⇒モデルとの違いを生み出しているソース（現象）を探るフェーズに進んで行く。
  また宇宙線観測でも空気シャワーを多角的に研究が進んでいる。
  相互作用モデルの特徴と空気シャワーの関係性を再度まとめる必要がある。

Summary

- LHC are providing excellent results and they are important for study of HECRs.
- LHCf measures spectra of neutral particles at zero degrees.
  - Photons, Neutral Pions published
  - Neutrons, Nuclear Effect at p-Pb : preliminary
- Discussing with UHECR experiments and model developer to understand the results of UHECRs.

Backup

pp Energy Flow with CASTOR

- First time energy flow at very high pseudorapidities 5.2 to 6.6 studied at LHC
- Combined with central CMS track jets
- {0.9, 2.76, 7} TeV
- Energy deposit in CASTOR as function of centre-of mass energy and track jet p_T

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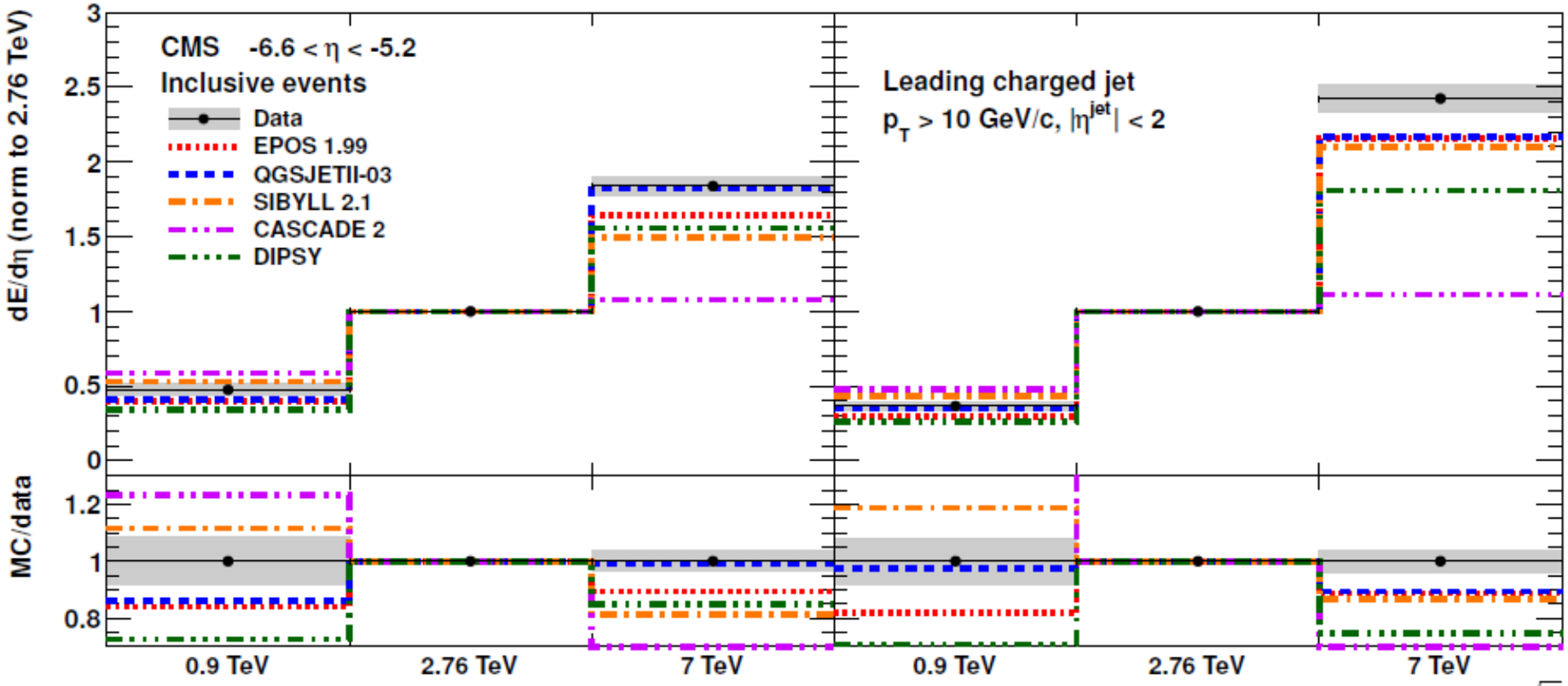
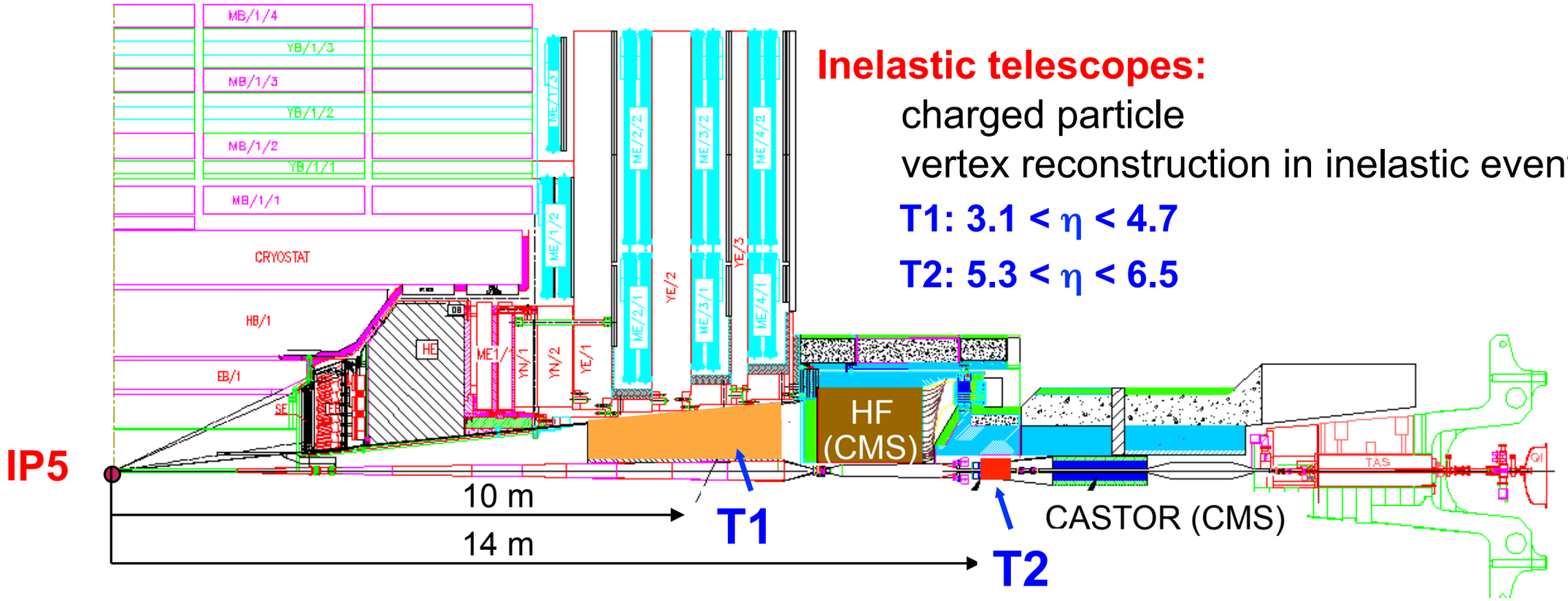


Inclusive (ND) **Hard scattering**

- Models have too small slope
- QGSJetII-03 describes data best
- *Cosmic ray models* do good job often better than *collider models*

TOTEM

For { Diffraction
Total/Inelastic Cross-section



Inelastic telescopes:

charged particle

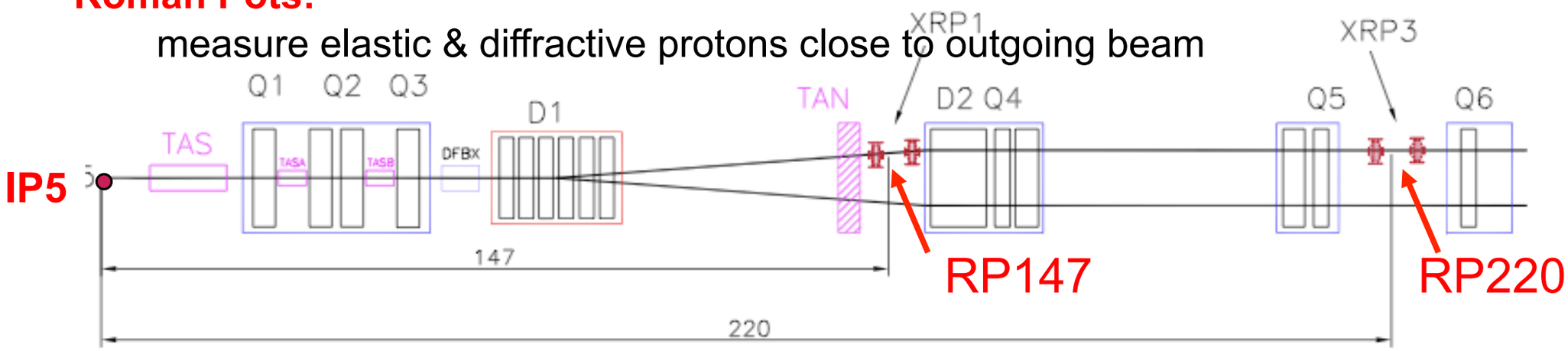
vertex reconstruction in inelastic events

T1: 3.1 < η < 4.7

T2: 5.3 < η < 6.5

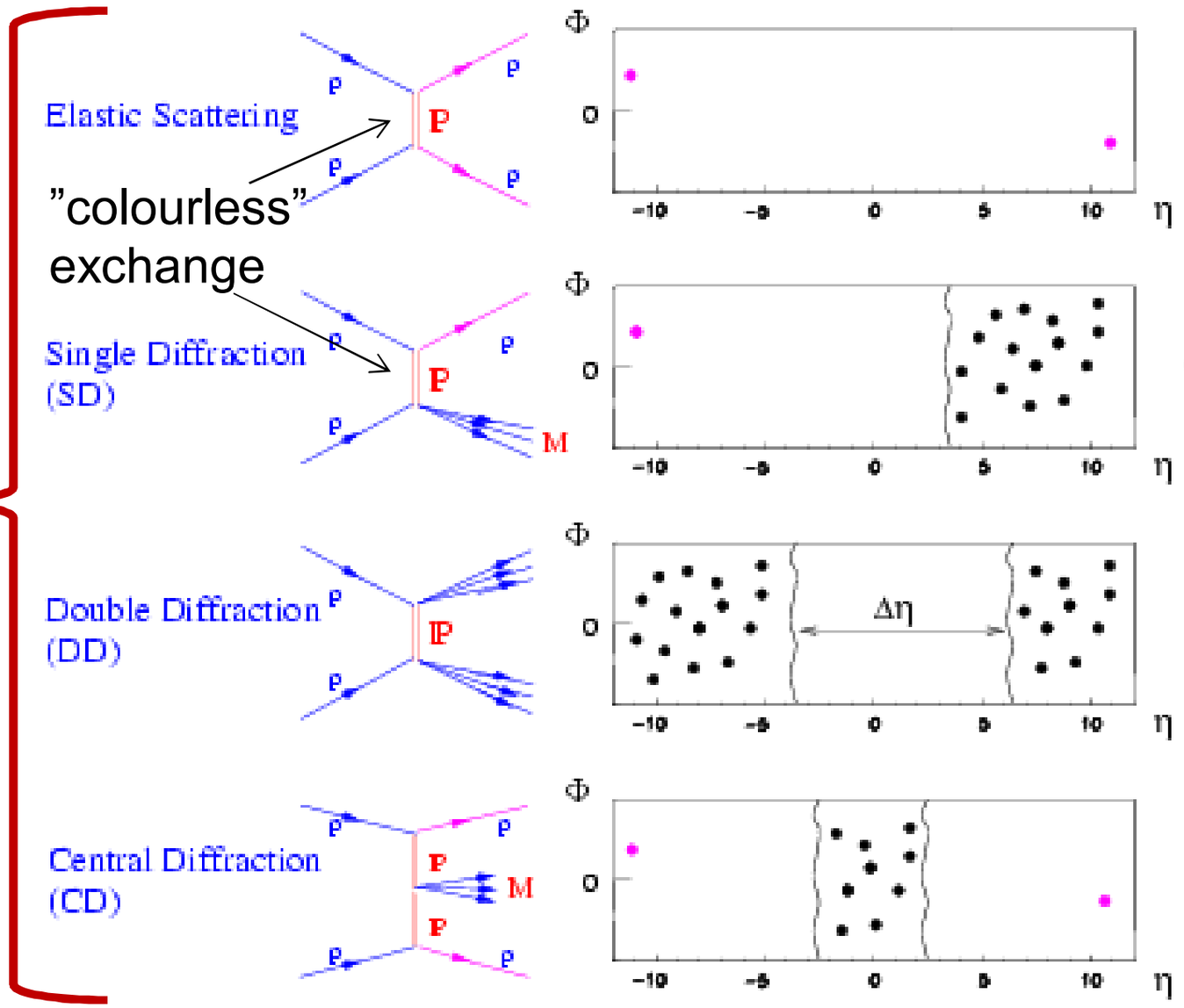
Roman Pots:

measure elastic & diffractive protons close to outgoing beam



Soft pp processes

Diffraction a large fraction of total pp cross-section !!



σ @ LHC

~25 mb

~10 mb

~5 mb

~1 mb

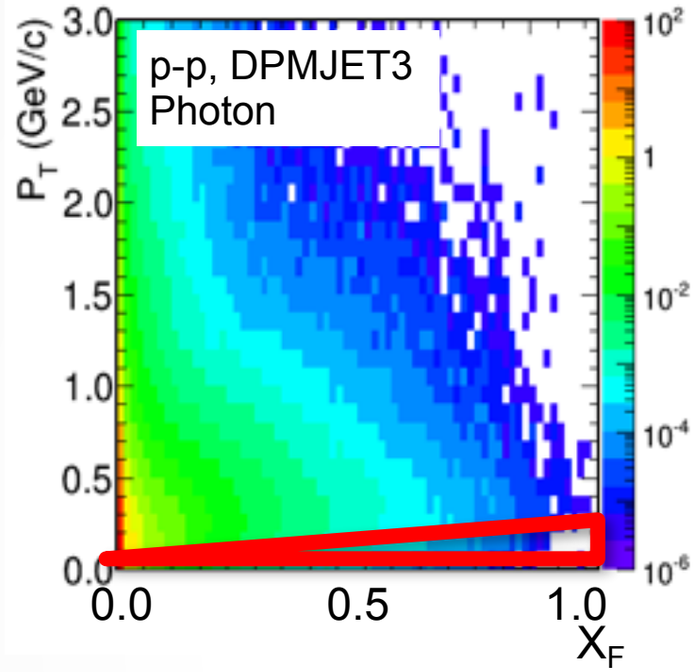
~60 mb

Measure σ (M,ξ,t)

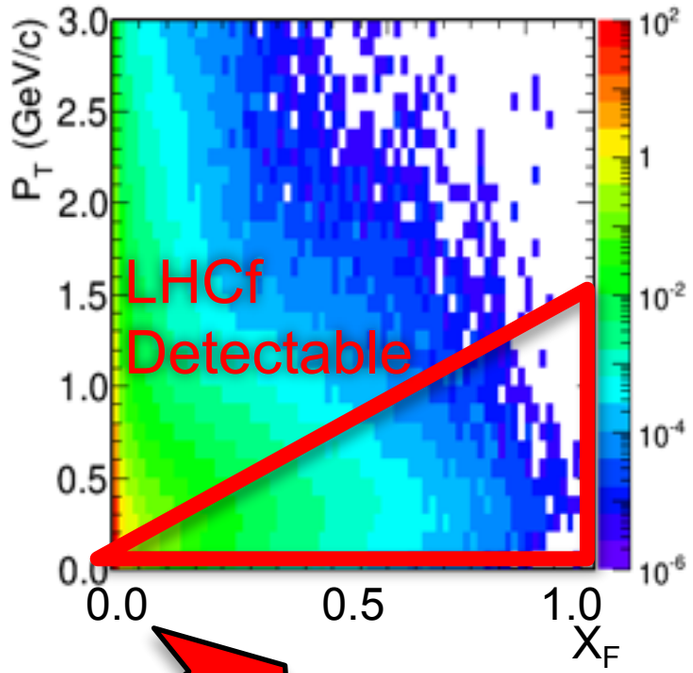
Energy Scan at LHC and RHIC

@LHC η>8.4

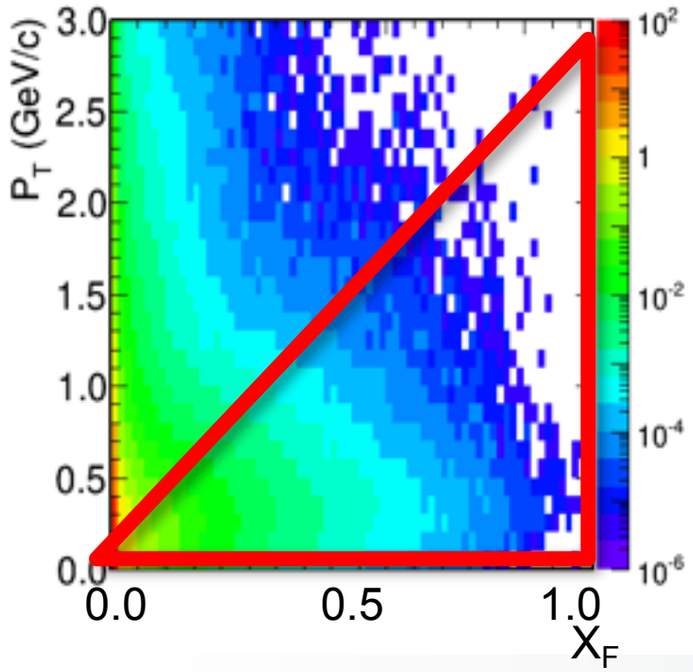
√s=900GeV



√s=7TeV

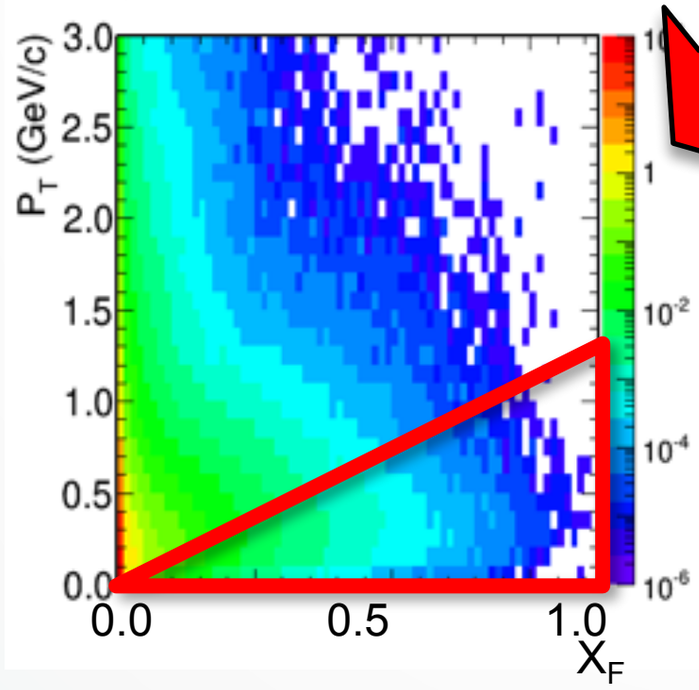


√s=13TeV

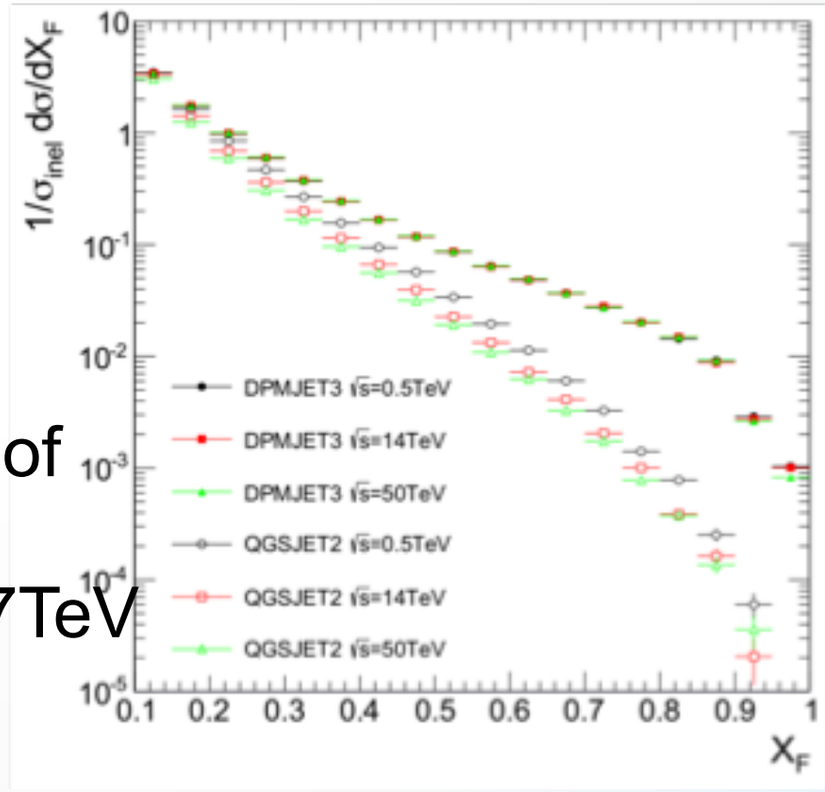


@RHIC η>6

√s=500GeV

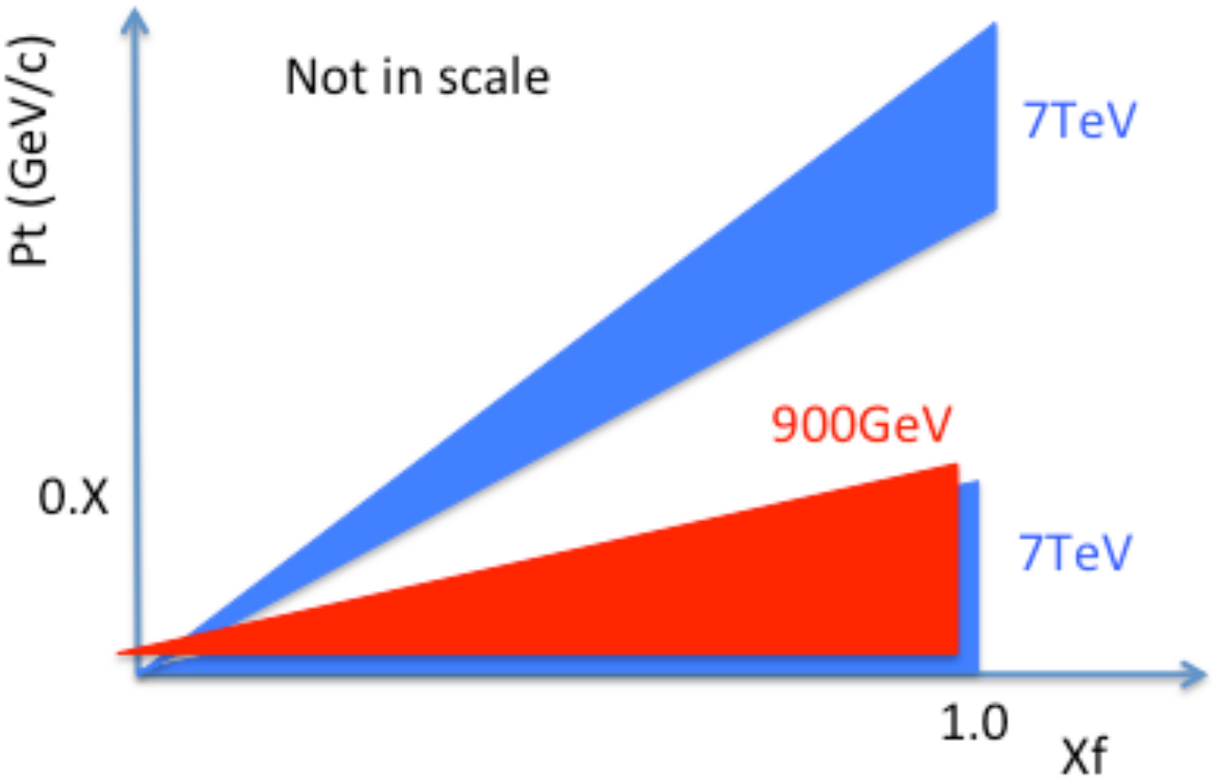


Comparison of
π^0 spectra
at 0.5TeV and 7TeV

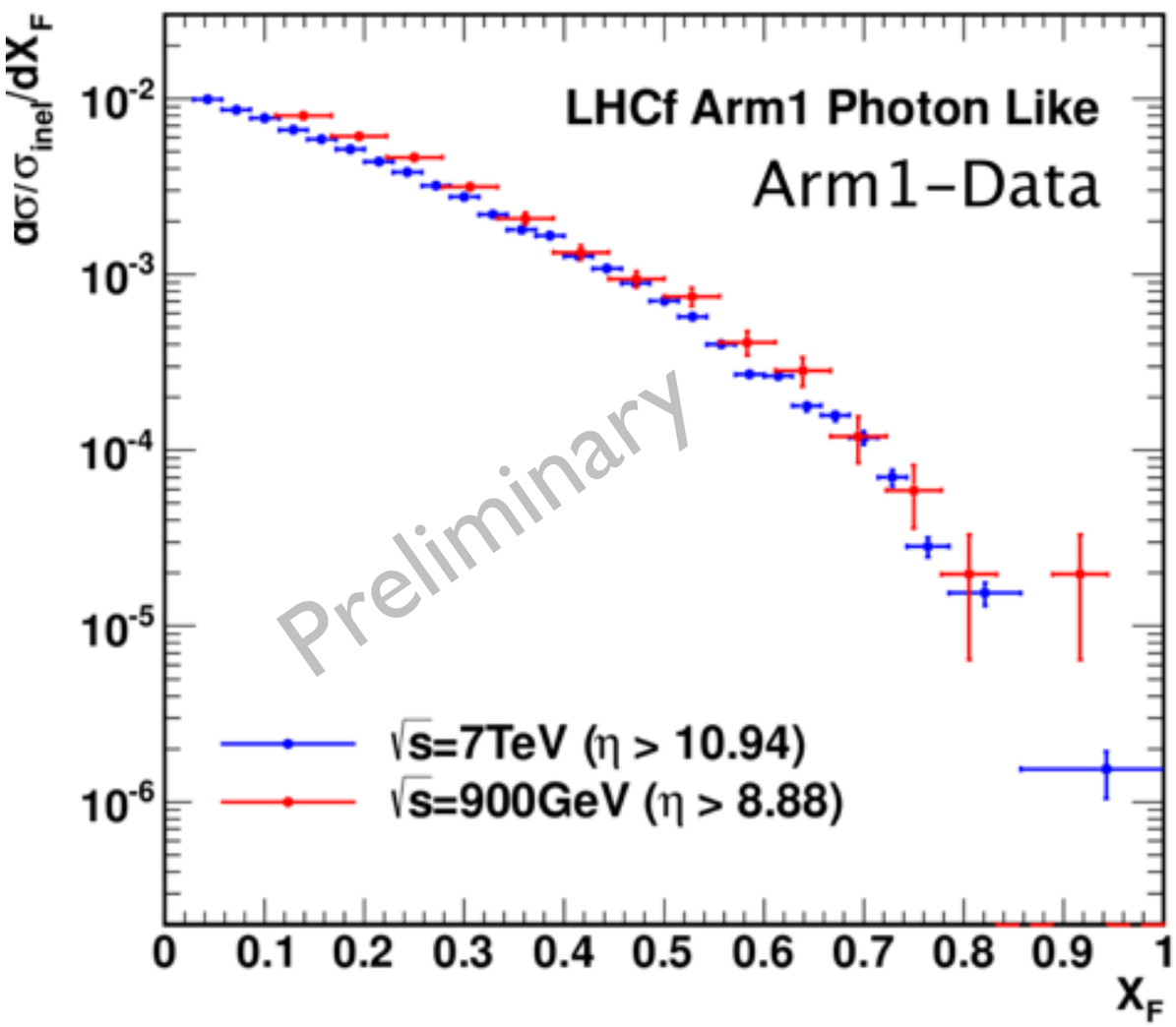


Photons at 900GeV p-p

Coverage of 900GeV and 7TeV results in Feynman-X and P_T



X_F spectra : 900 GeV data vs. 7 TeV data



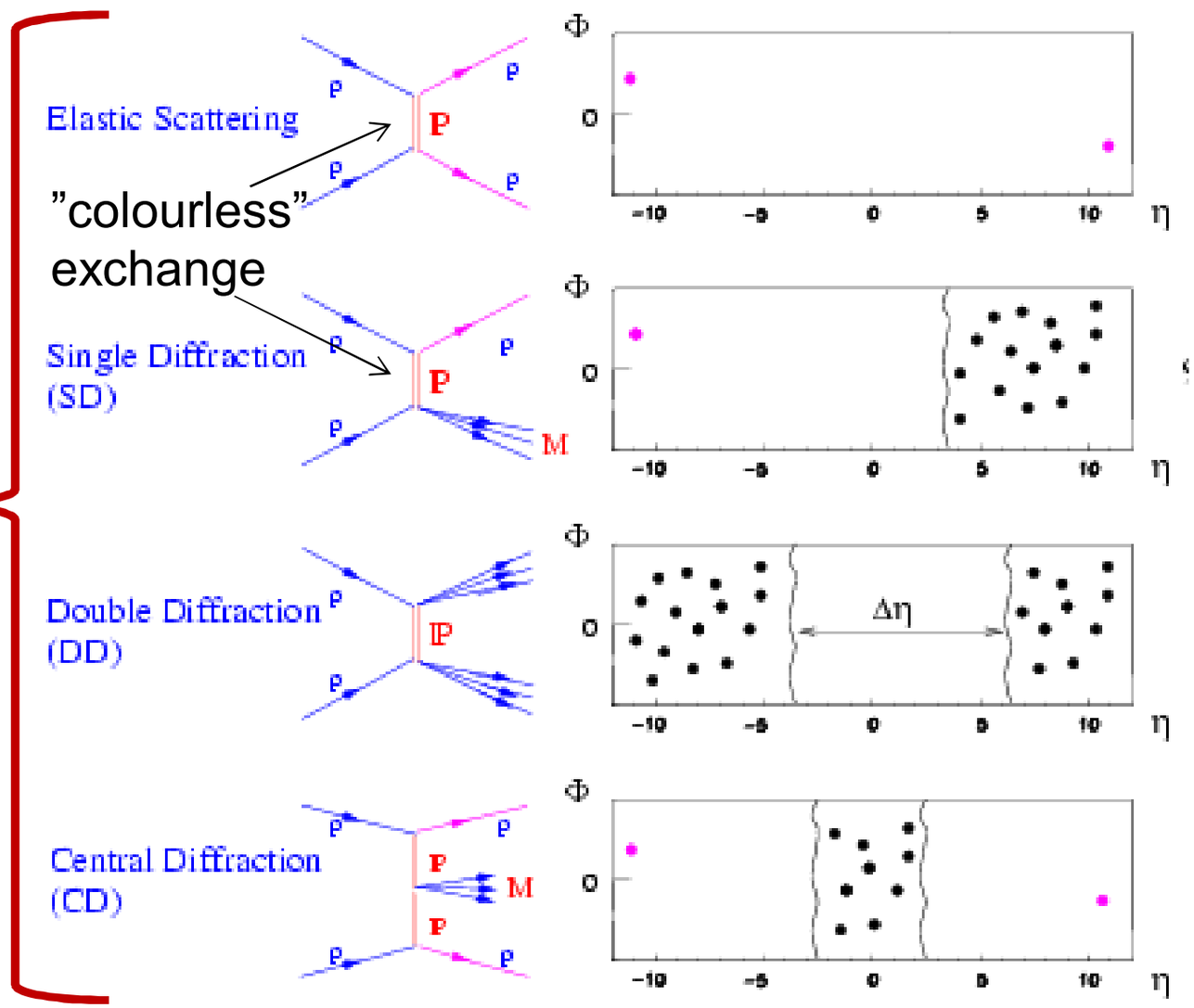
Good agreement of X_F spectrum shape between 900 GeV and 7TeV.
➔weak dependence of $<p_T>$ on E_{CMS}

Note : No systematic error is considered in both collision energies yet. 21% of the luminosity determination error allows vertical shift.

Soft pp processes

Diffraction a large fraction of total pp cross-section !!

σ @ LHC



~25 mb

~10 mb

~5 mb

~1 mb

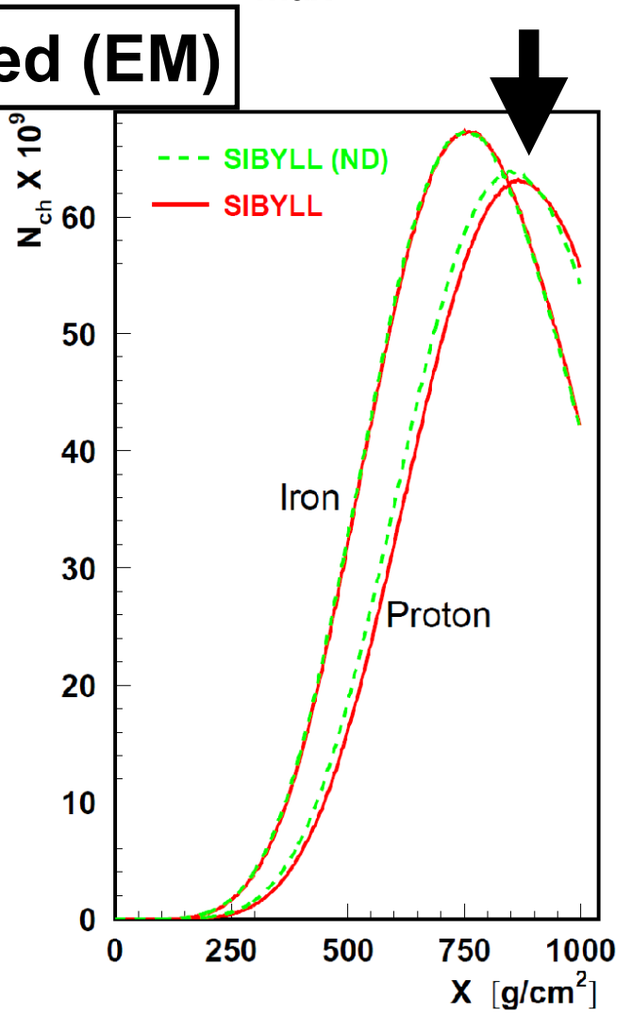
~60 mb

Measure σ (M,ξ,t)

Diffraction @ CR-AS

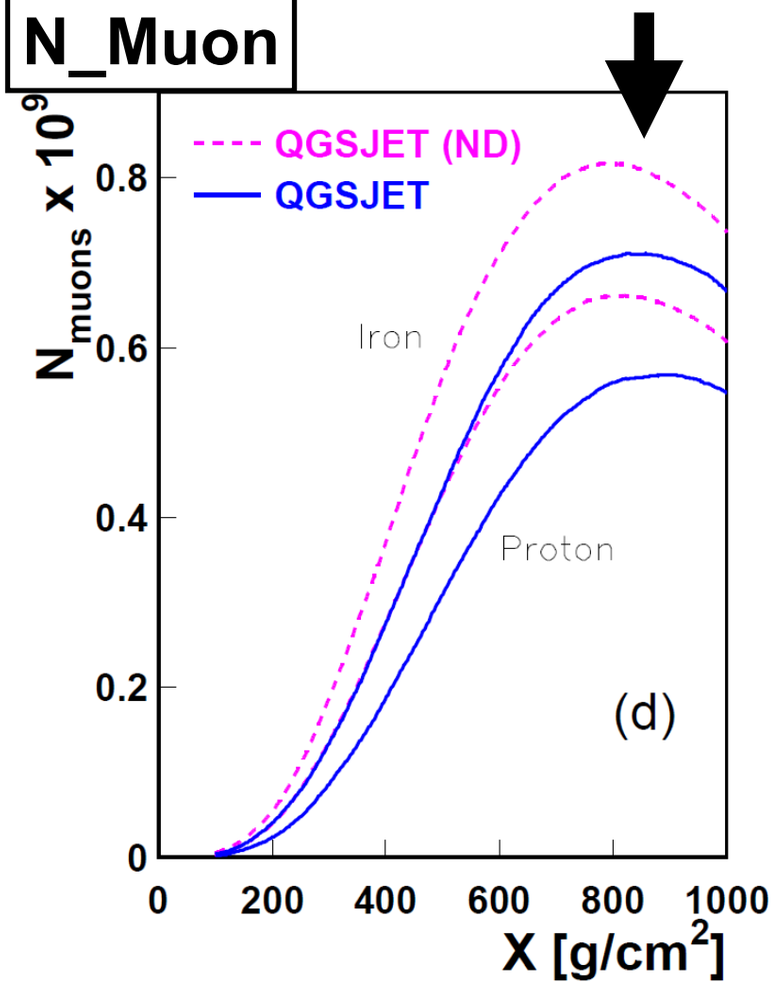
Small difference ΔX_{max}~ 2%

N_Charged (EM)



Large difference of flux ~15%

N_Muon



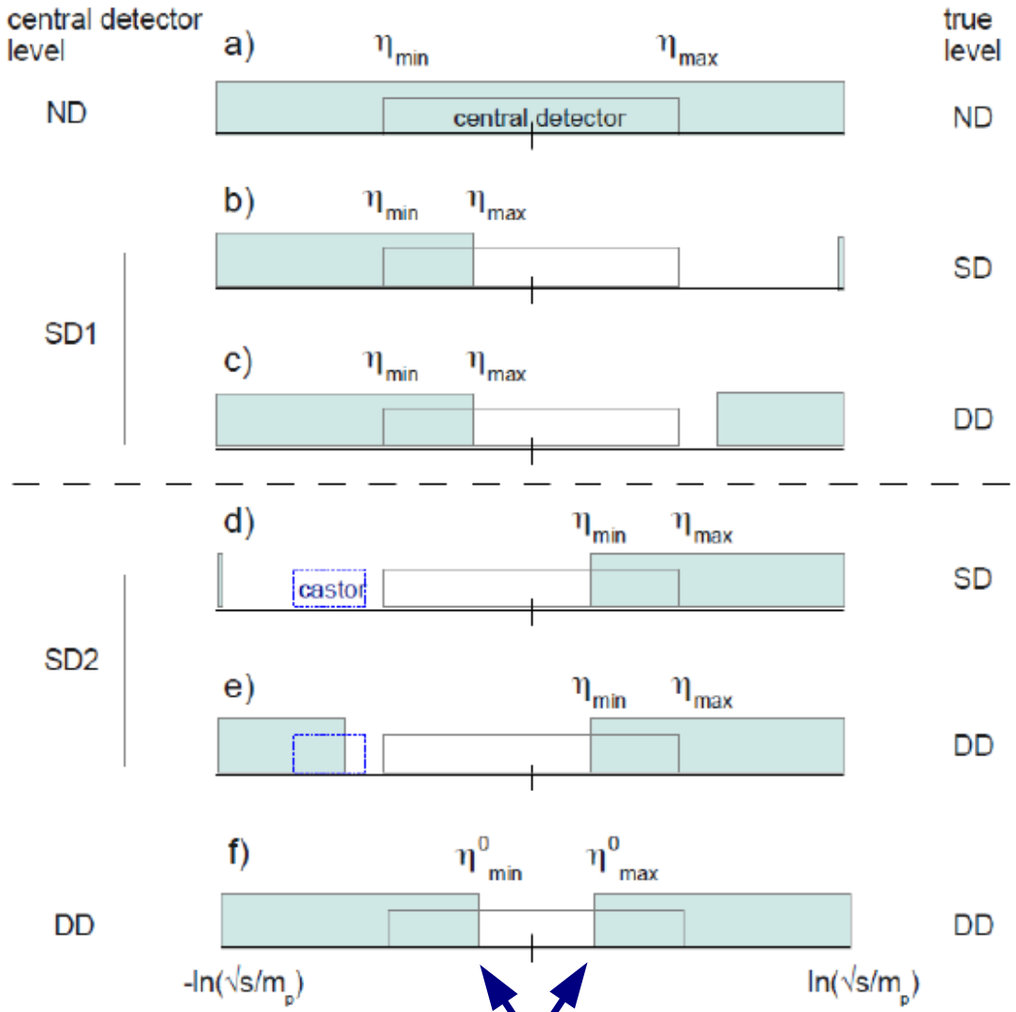
Phys.Rev. D70 (2004) 114034

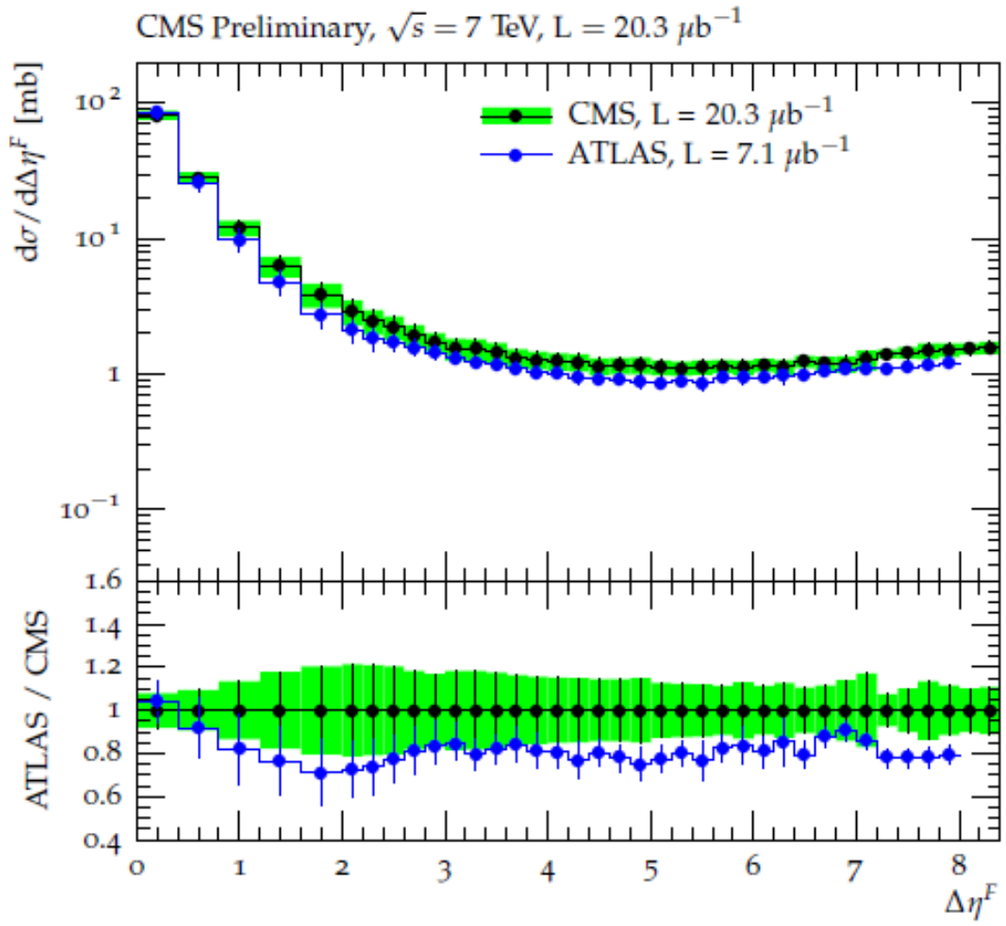
- Cross section fraction differs largely in models (~10^11eV → 10^20eV)
  - Sibyll: 12% → 1%
  - QGSJet 13% → 16%
  - DPMJet 1% → 5% (but rising at mid energies)

C.Baus @ Seminar in Nagoya

Diffraction with CASTOR

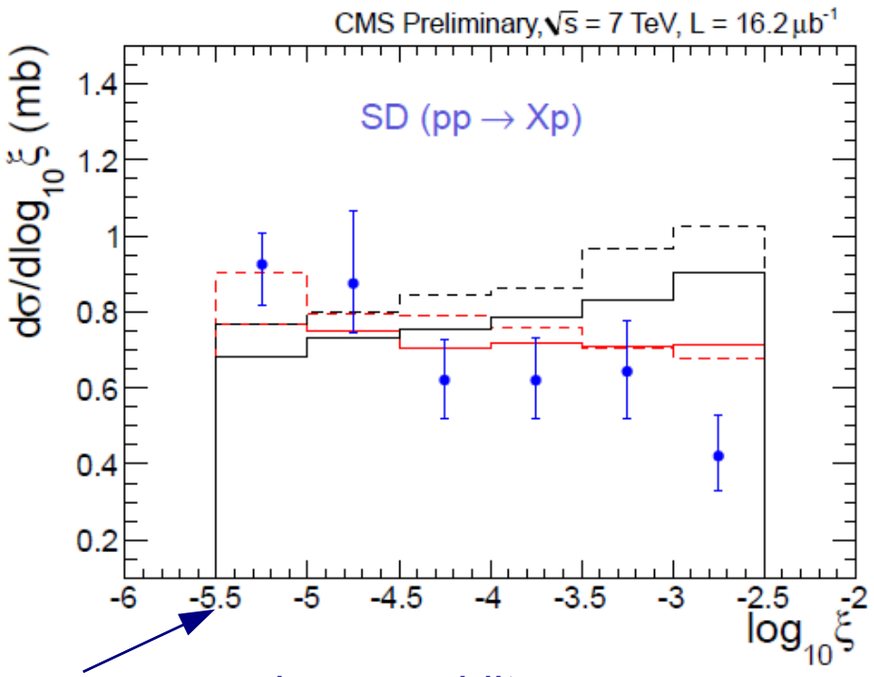
- Rapidity gap distribution measured at $|\eta| < 4.7$
- 0.4 units $\Delta\eta$ more than ATLAS

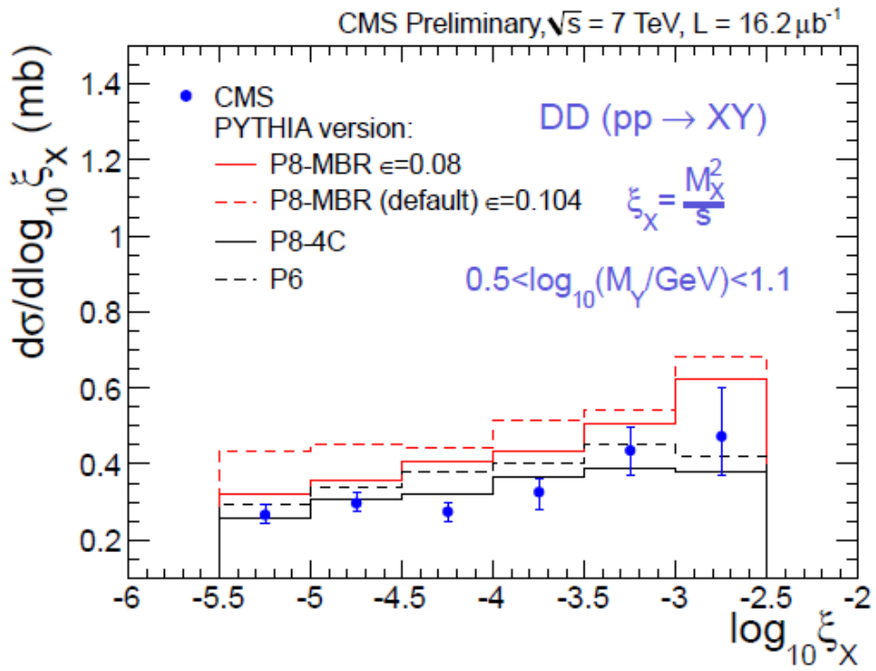




CMS-FSQ-12-005

Diffraction with CASTOR





low diffractive masses or large rapidity gap

- Differential single- and double-diffractive cross sections measured as function of longitudinal momentum loss ξ
- CASTOR used as tag for rapidity gap
- Phenomenological behaviour of diffractive cross section important for muon maximum in air showers