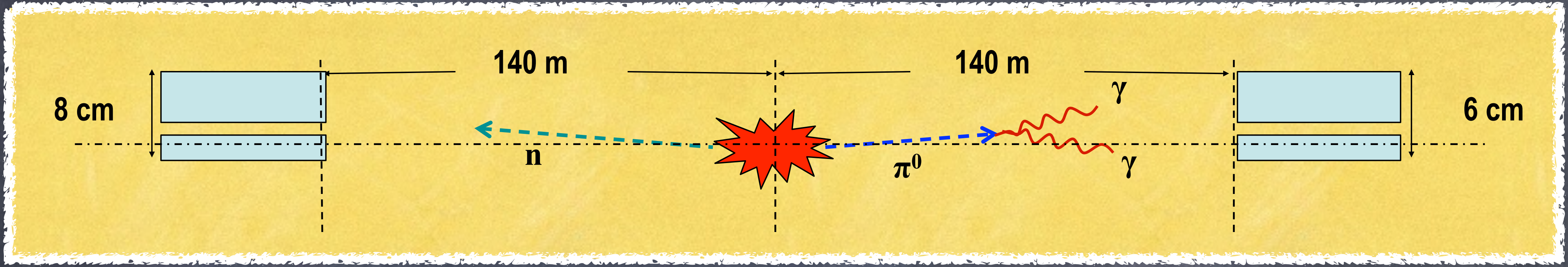
SAS@LHC

CERN, 1 - 2 October 2015



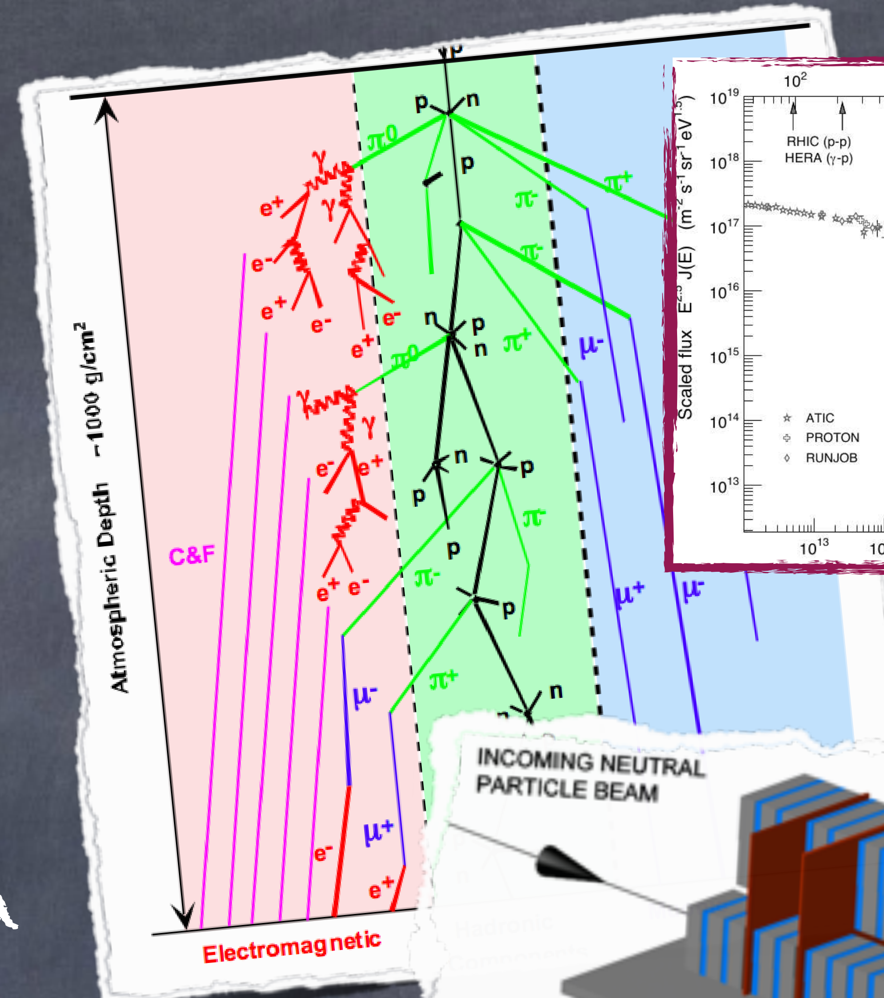
Zero-degree neutral measurements with LHCf at LHC

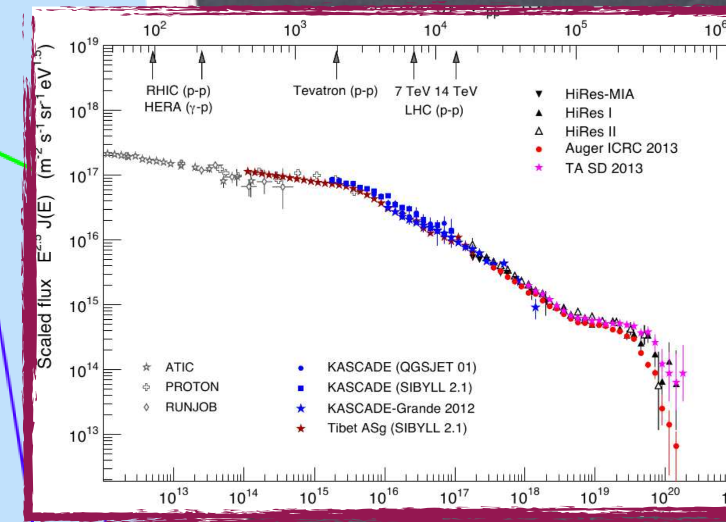
Alessia Tricomi

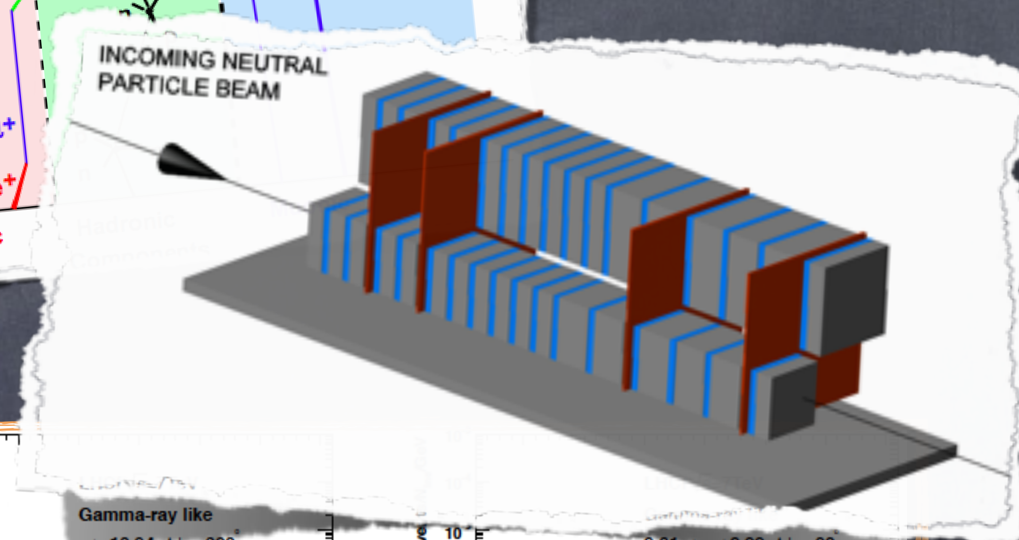
University and INFN Catania, Italy

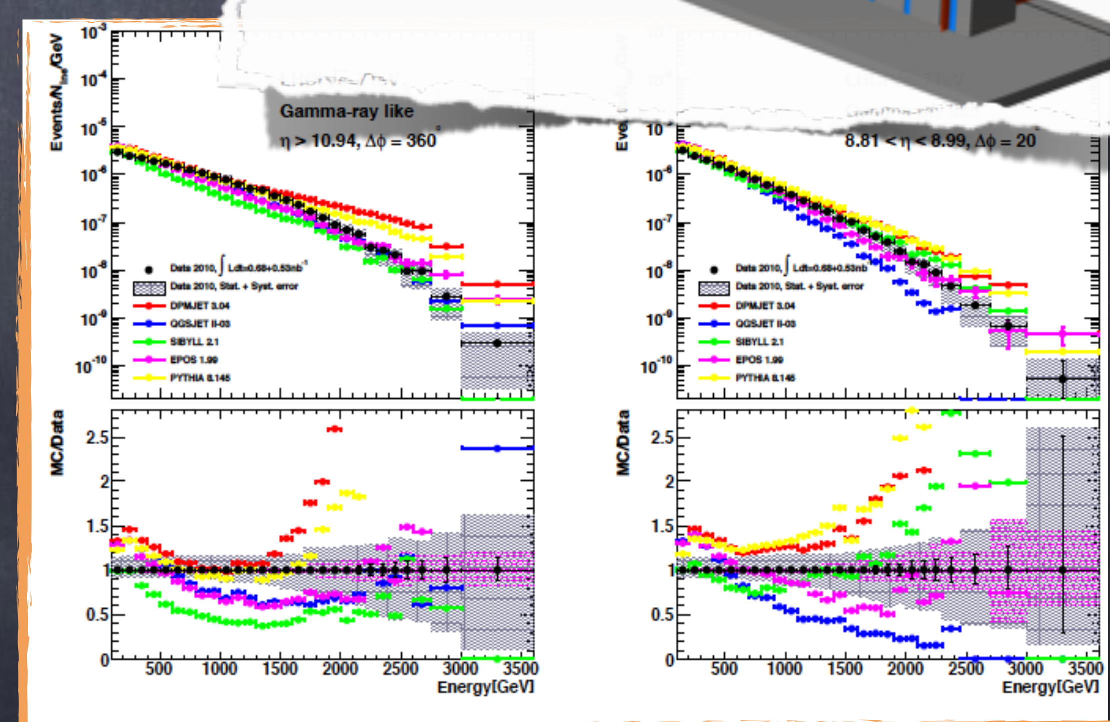
Outline

- Physics Motivations
  - The link between HECR Physics and LHC
- The LHCf detectors
  - "Il vino buono sta nella botte piccola" or "good things comes in small packages"
- Physics Results
  - what we have done so far
- Future Plans
  - what's next...









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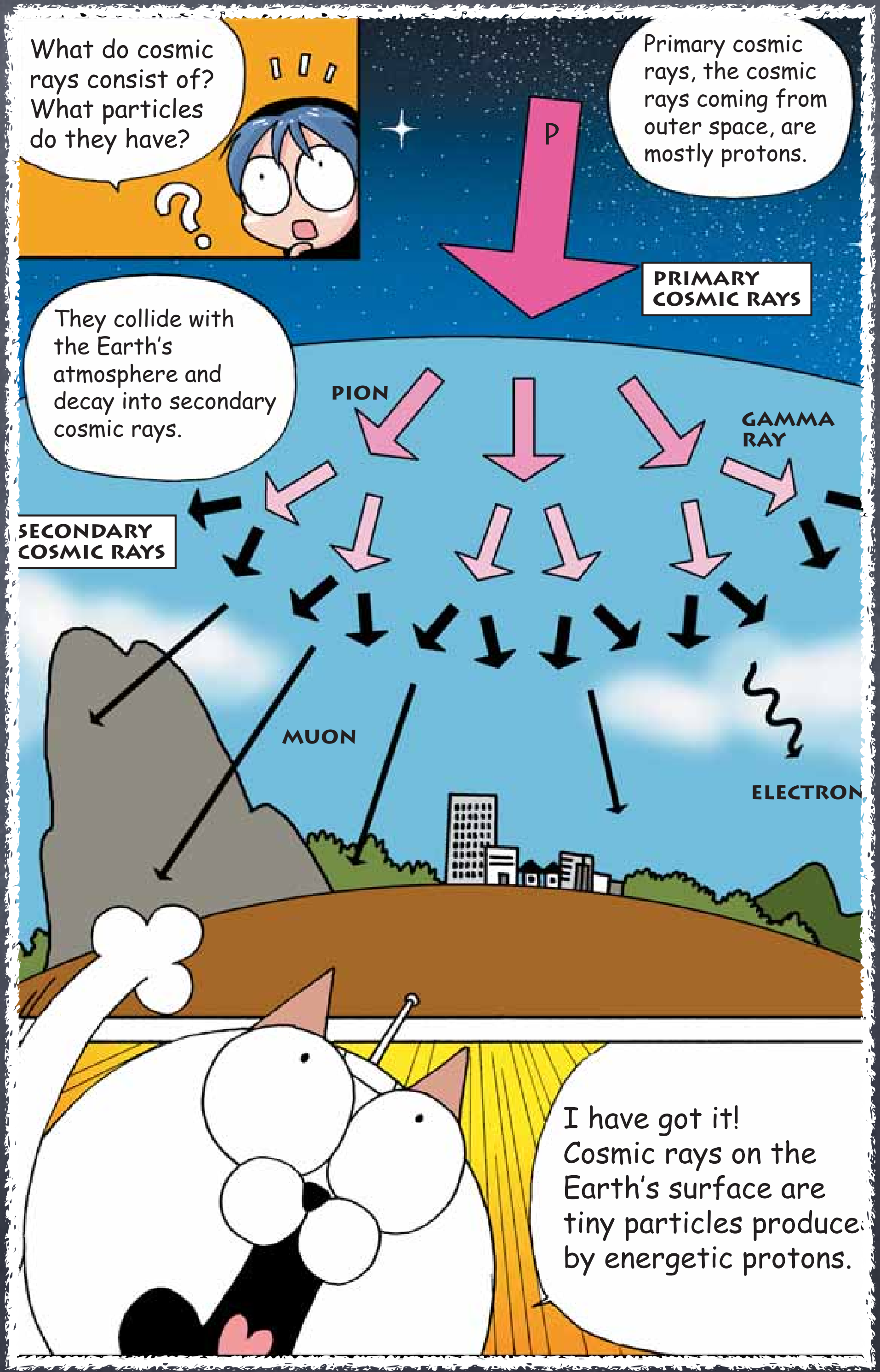
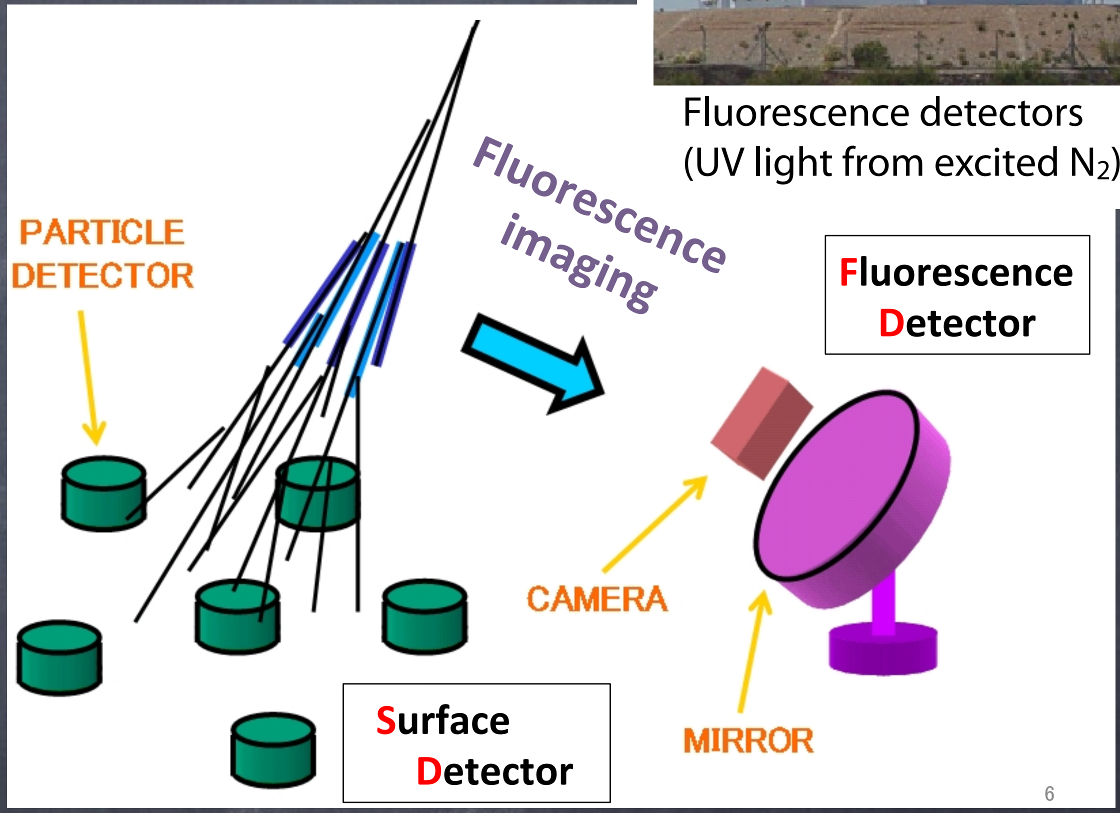


Ultra High Energy Cosmic Rays

Studying the properties of primary High Energy Cosmic Rays based on observation of EAS

Fluorescence detectors (UV light from excited N_2)



+

MC Simulation to describe hadronic interaction with atmosphere

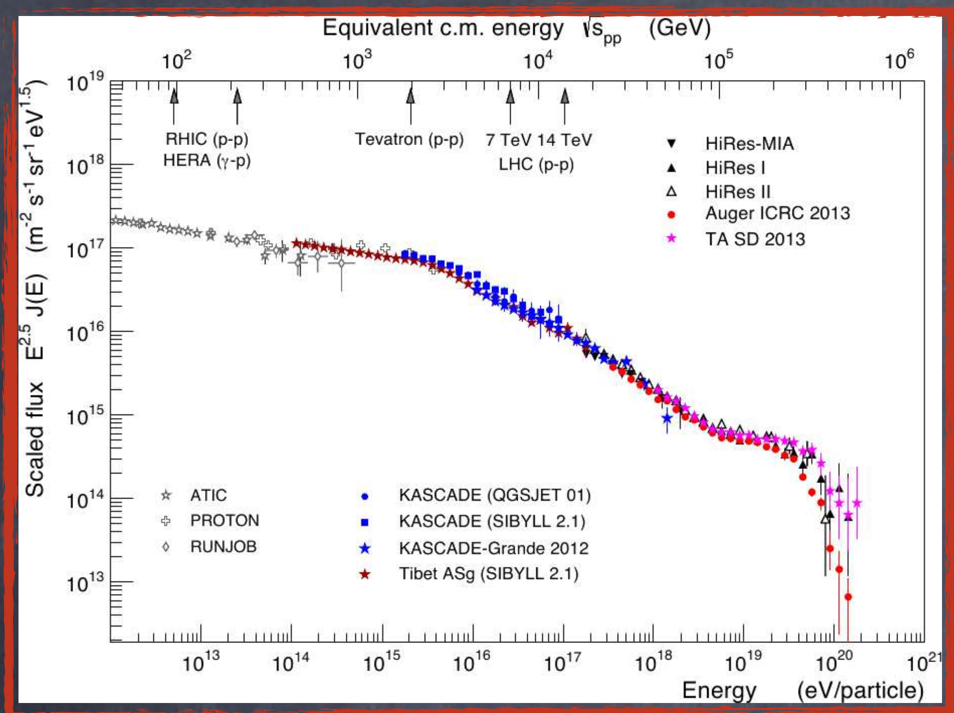
Surface detectors (charged+photon)

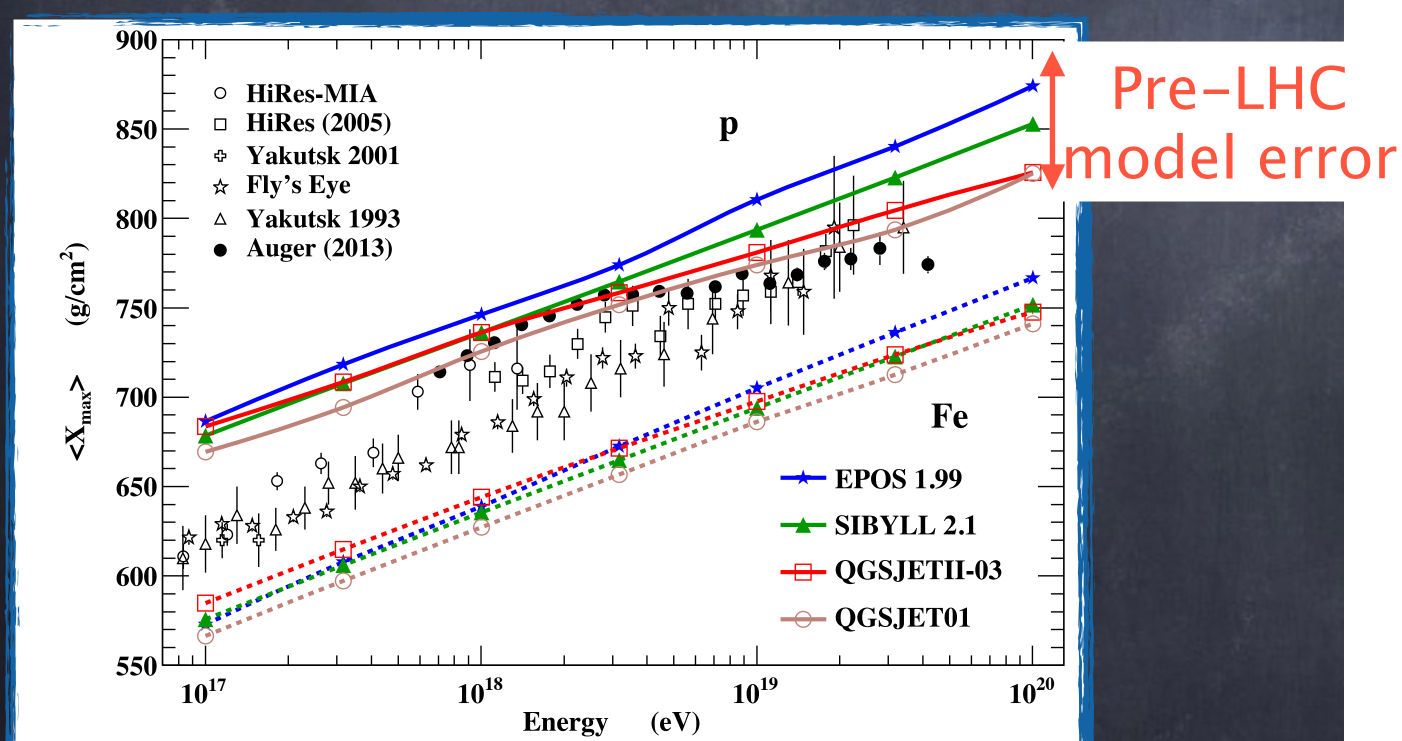
Energy, mass composition, direction

-> source of primary cosmic rays

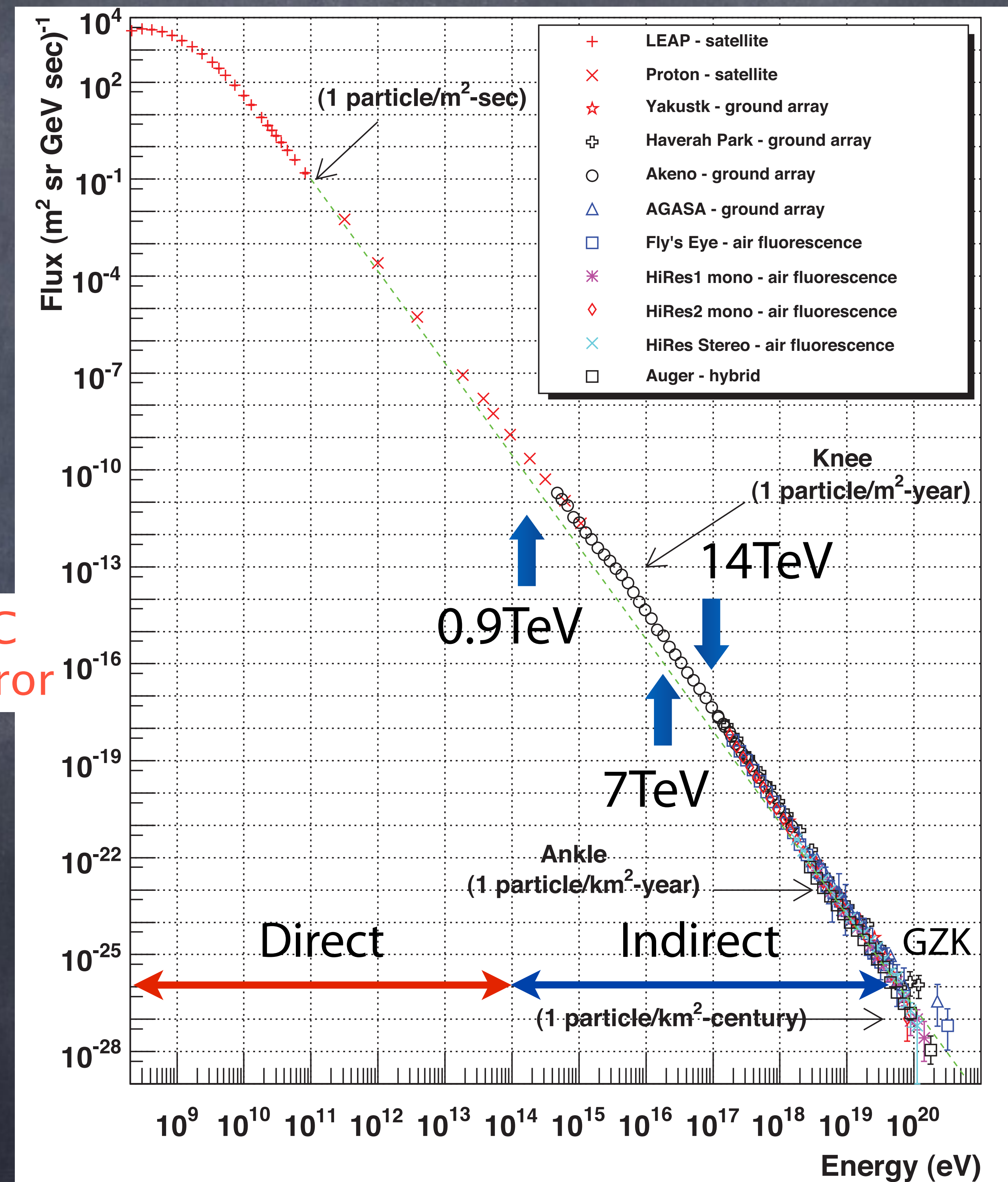
-> origin of the universe (final goal)

Observation of UHECR





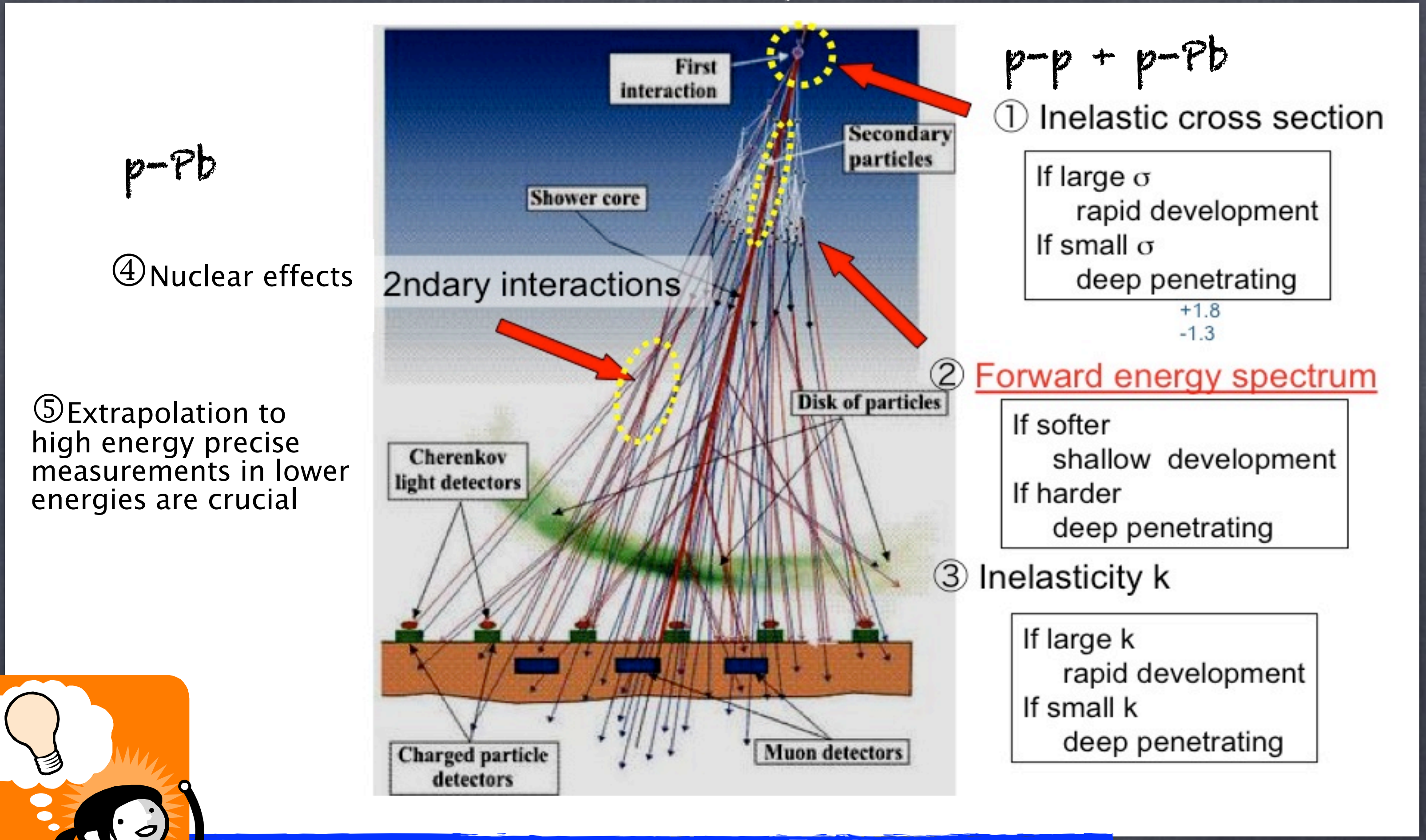
(Pierog 2013, 2014)



HECR Physics at LHC: LHCf Physics

Model-originated uncertainties or even discrepancies

- Energy
  - $E_{SD} > E_{FD}$: discrepancy
  - missing energy (μ,ν) in FD : uncertainty
- Mass
  - Mass vs. X_{max} in FD: uncertainty
  - Mass vs. e/μ or μ excess in SD : discrepancy



LHCf ->use LHC

6.5 TeV+6.5 TeV ⇒ $E_{lab}=9*10^{16}$ eV

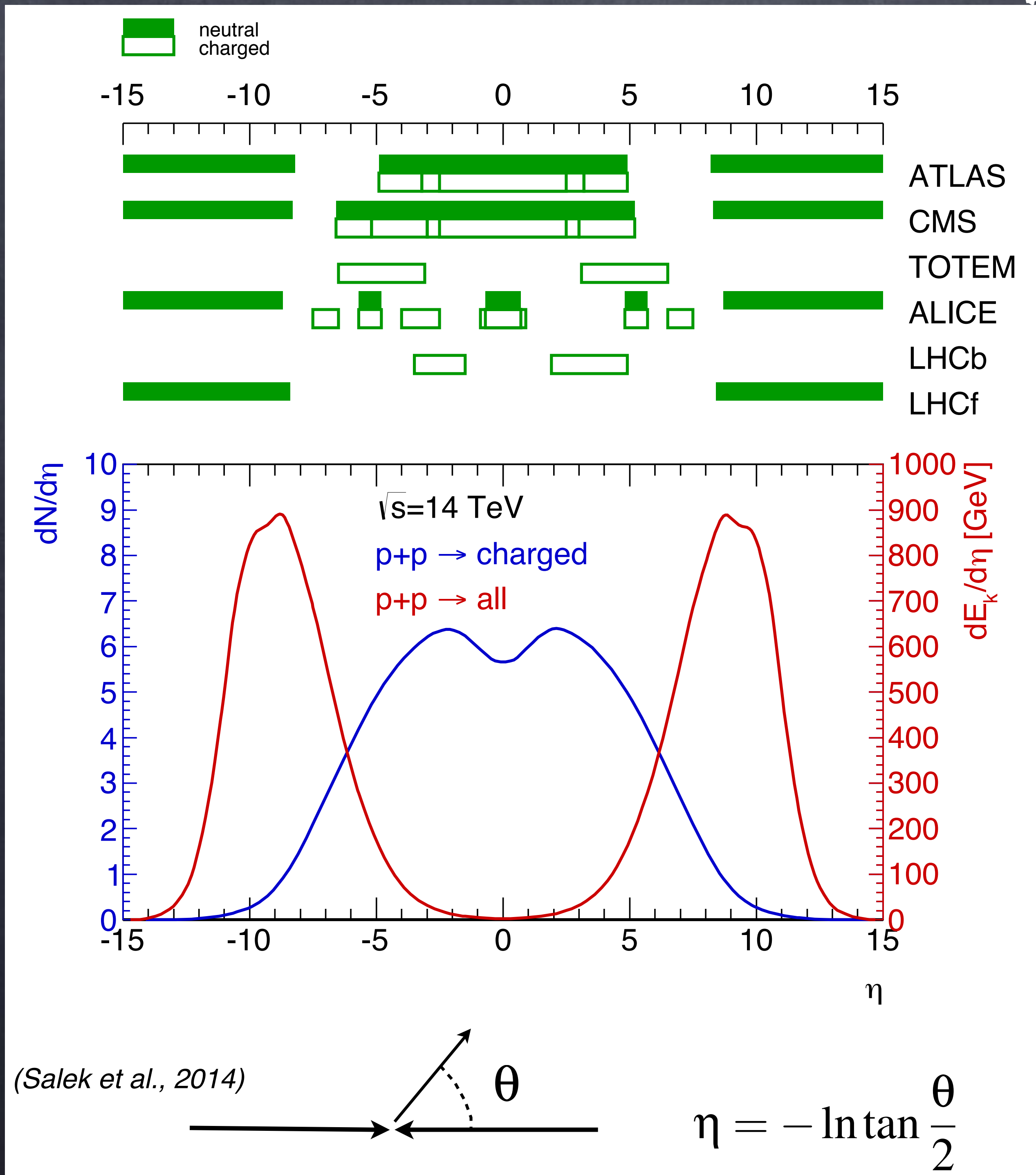
3.5 TeV+3.5 TeV ⇒ $E_{lab}=2.6*10^{16}$ eV

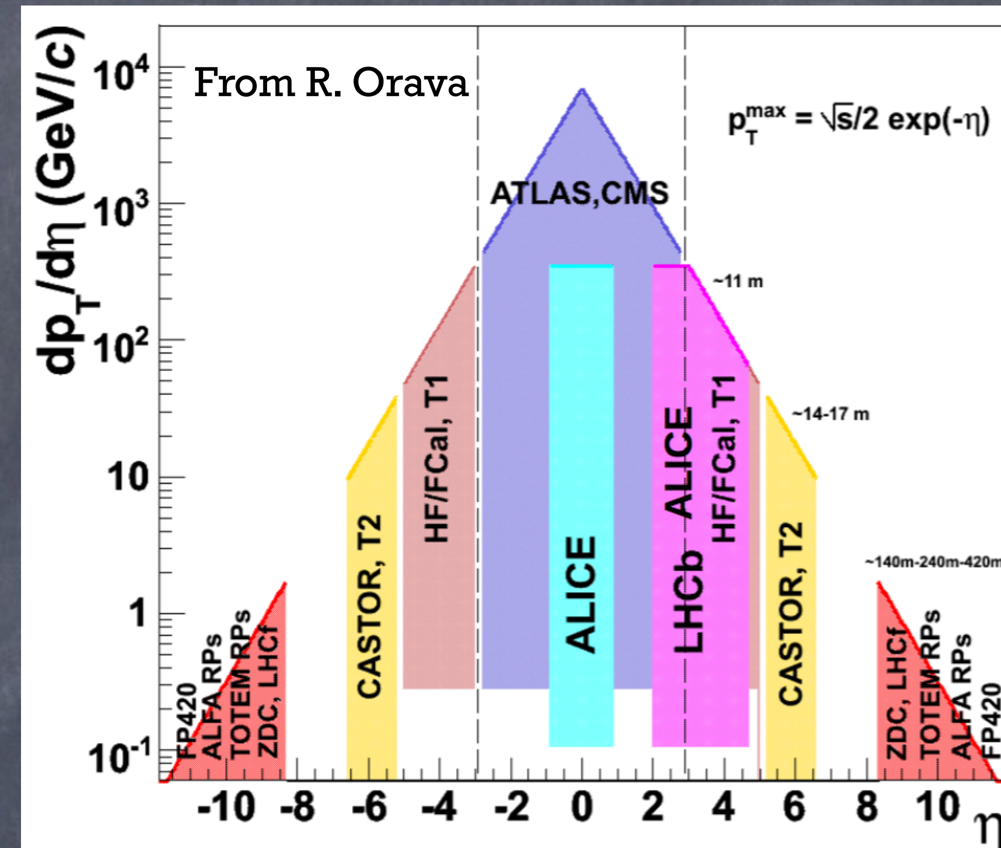
450 GeV+450 GeV ⇒ $E_{lab}=2*10^{14}$ eV

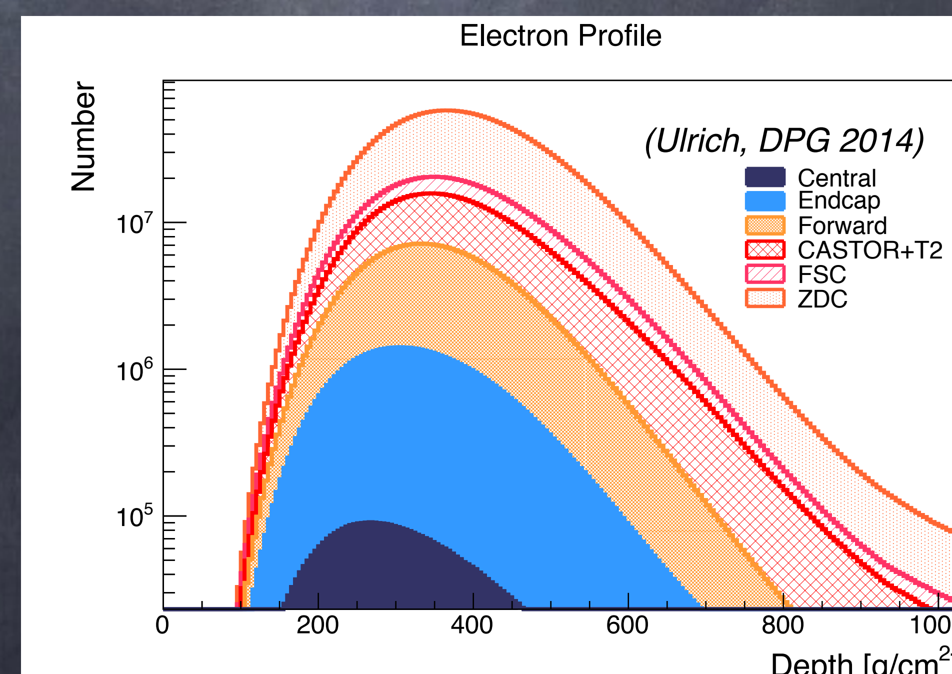
to calibrate MCs

In addition: p-Pb collision at 5.02 TeV to study nuclear effect

LHC Phase space coverage







We are profiting of the broad coverage
but more than 50% of the shower from $\eta>8$
Dedicated fwd experiments crucial!

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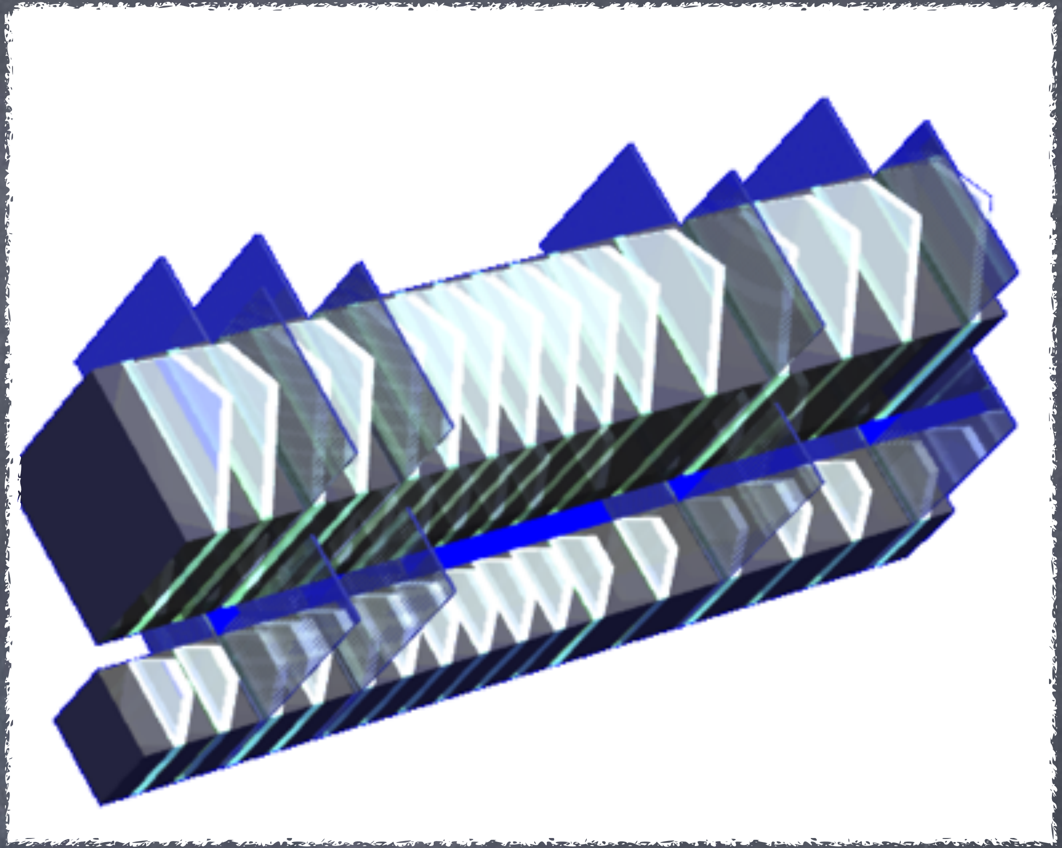
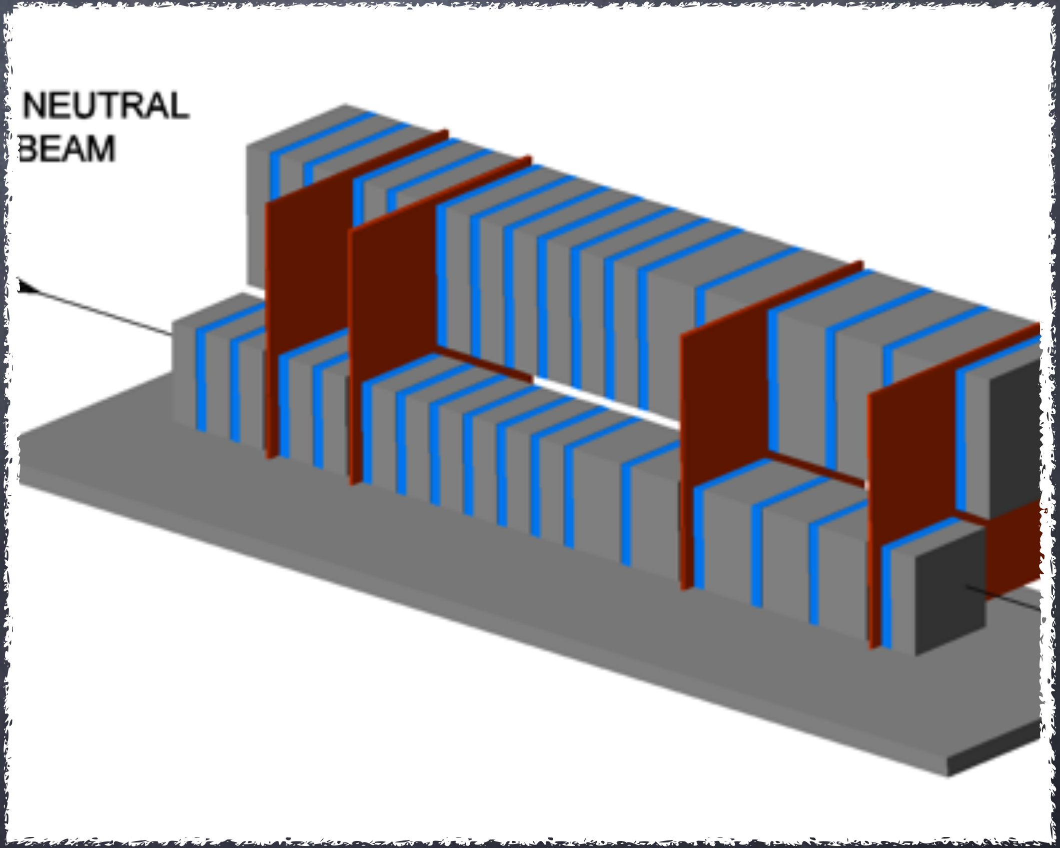
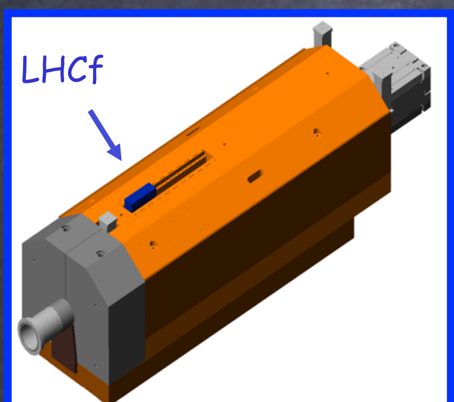
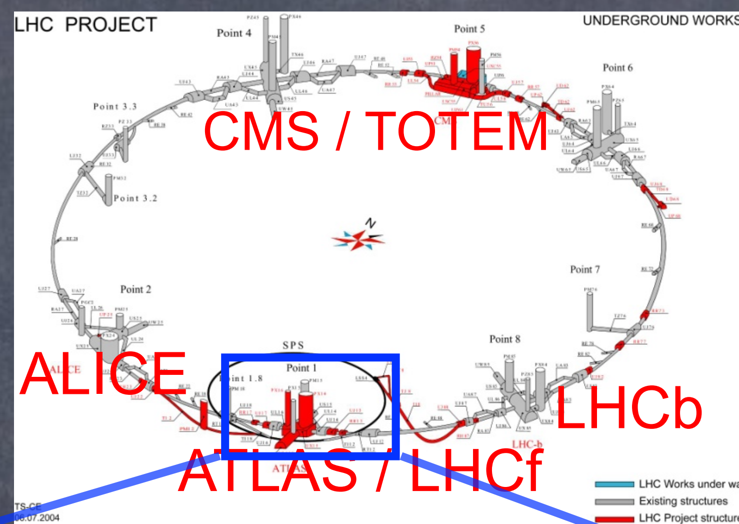


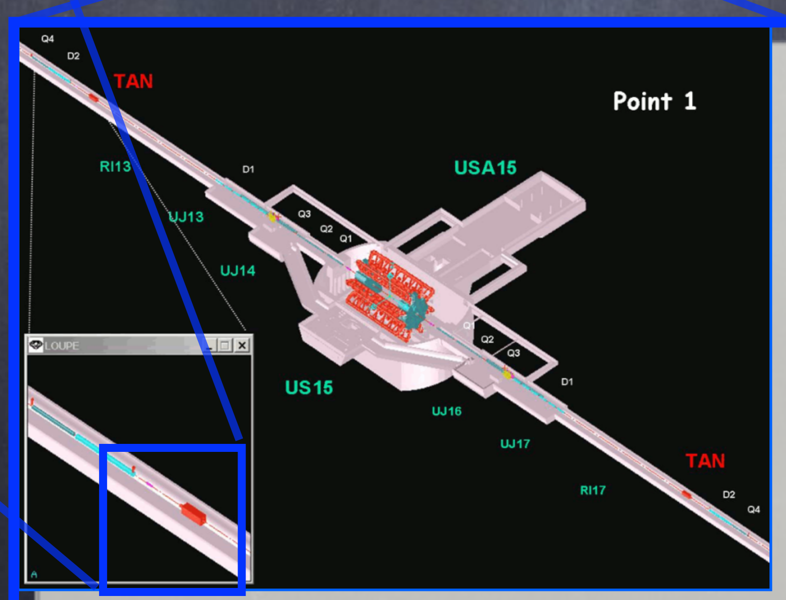


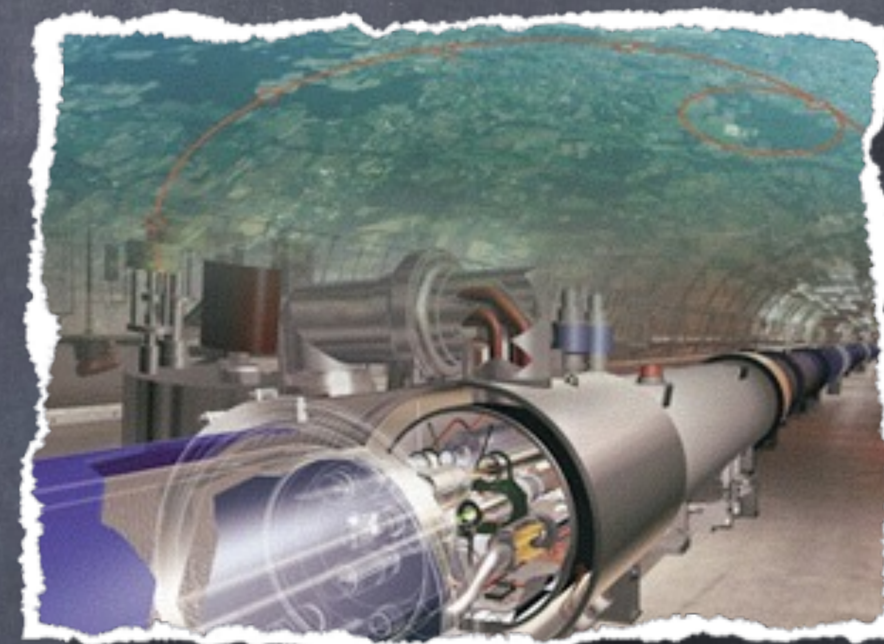
The LHC-forward experiment

- Two independent electromagnetic calorimeters equipped with position sensitive layers, on both sides of IP1





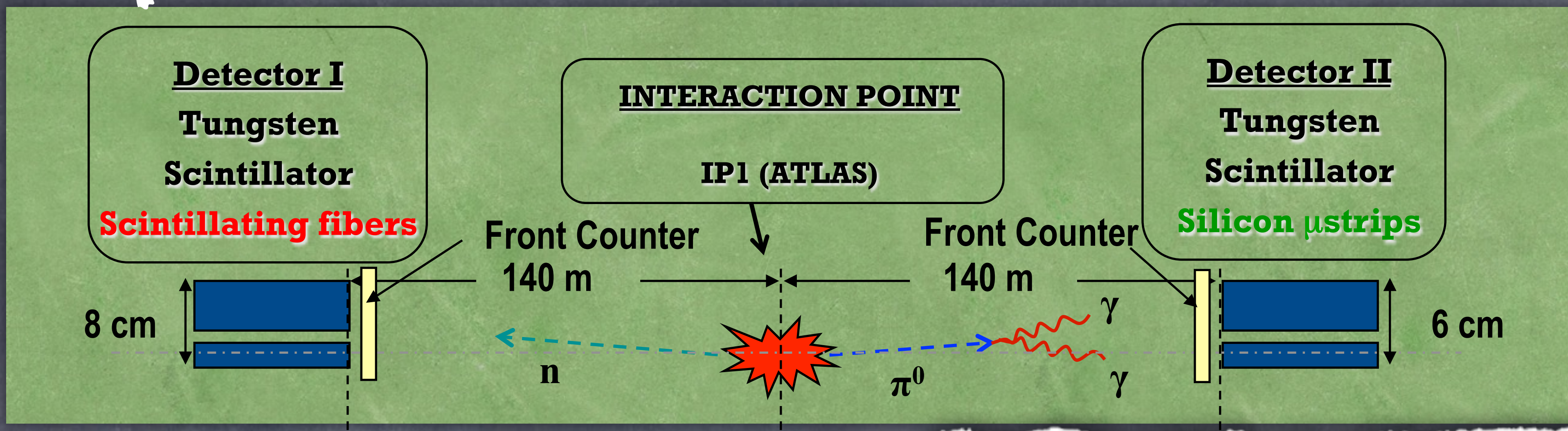


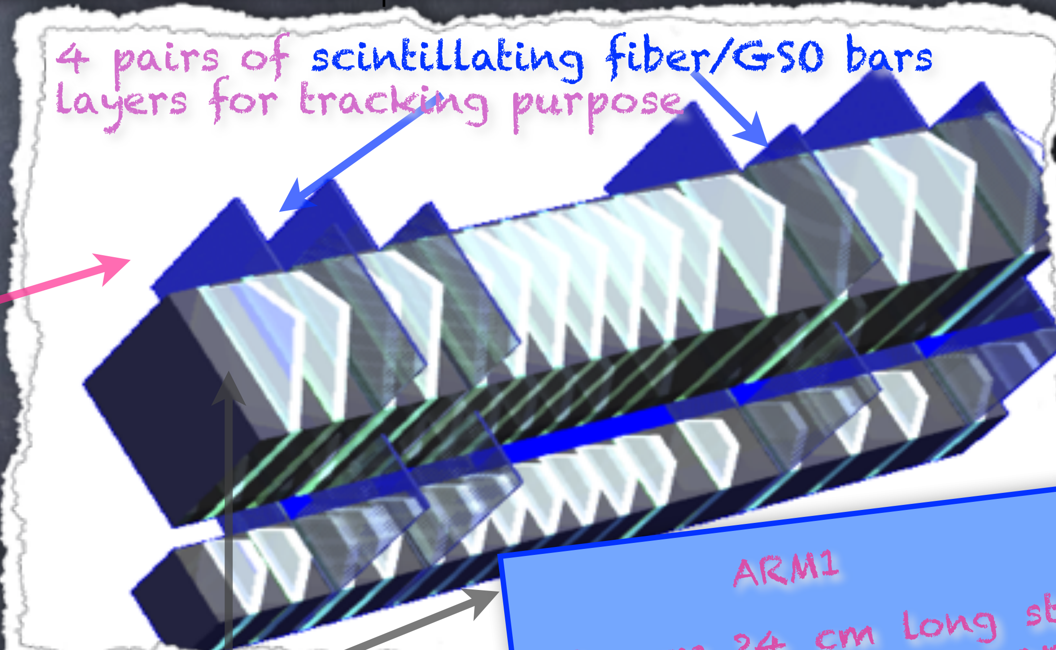


7 TeV + 7 TeV proton collisions at LHC correspond to $E_{LAB} = 10^{17}$ eV

- Measure energy and position for $|\eta|>8$ of γ from π^0 decays and neutrons produced in pp interaction at LHC
- International Collaboration mainly Japan-Italy (about 30 members)

Experimental Set-up





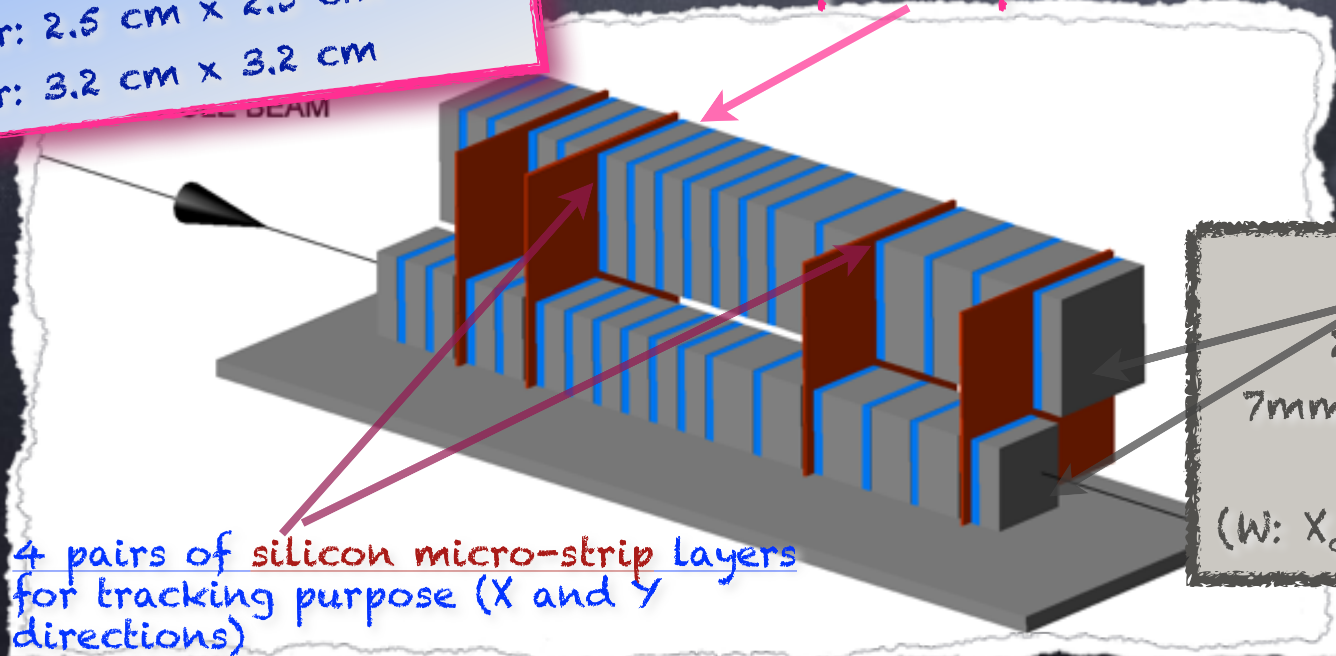
ARM2

2 towers 24 cm long stacked on their edges and offset from one another

Lower: 2.5 cm x 2.5 cm

Upper: 3.2 cm x 3.2 cm

Impact point (η)



ARM1

2 towers 24 cm long stacked vertically with 5 mm gap

Lower: 2 cm x 2 cm area

Upper: 4 cm x 4 cm area

Absorber

22 tungsten layers

7mm – 14 mm thick (2-4 r.l.)

(W: X_0 = 3.5mm, R_M = 9mm)

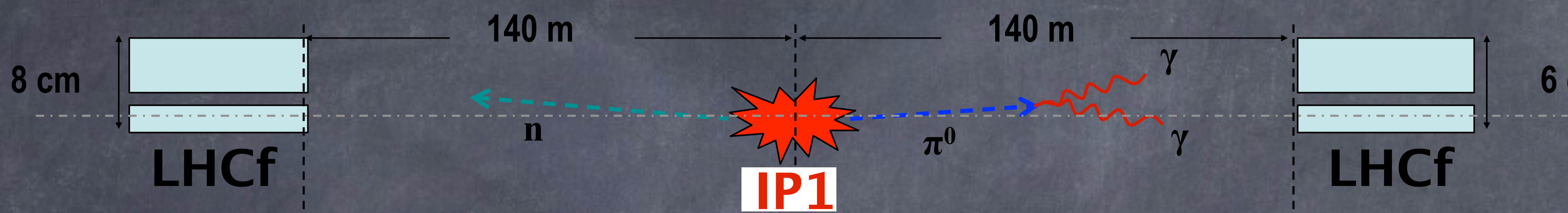
Energy

16 scintillator layers

(Plastic or GSO)

Trigger and energy profile measurements

Detector Performance



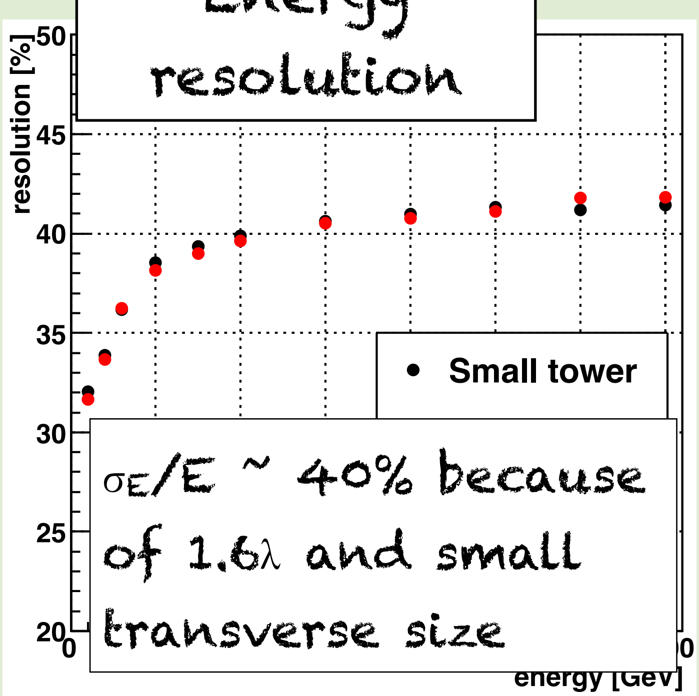
Hadronic shower (MC)

Position resolution

Black : X-plane

Red : Y-plane

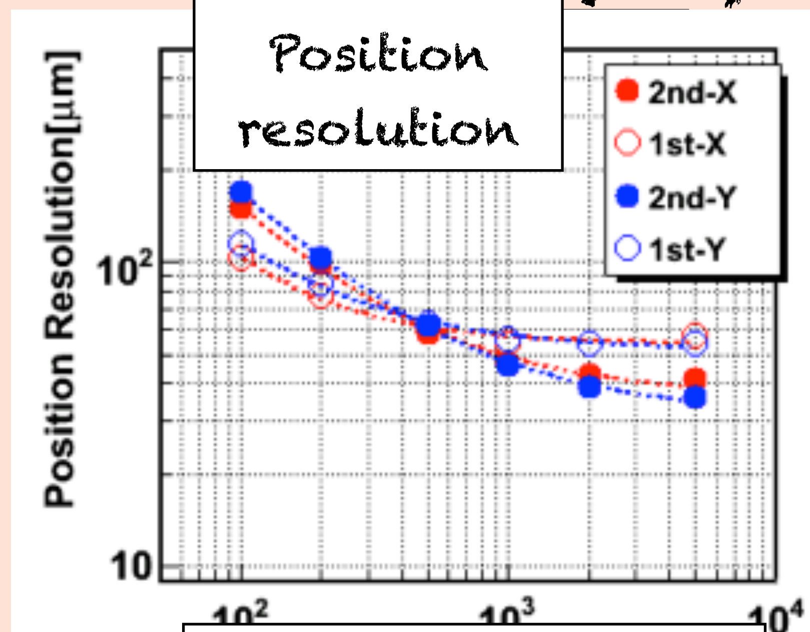
Energy resolution



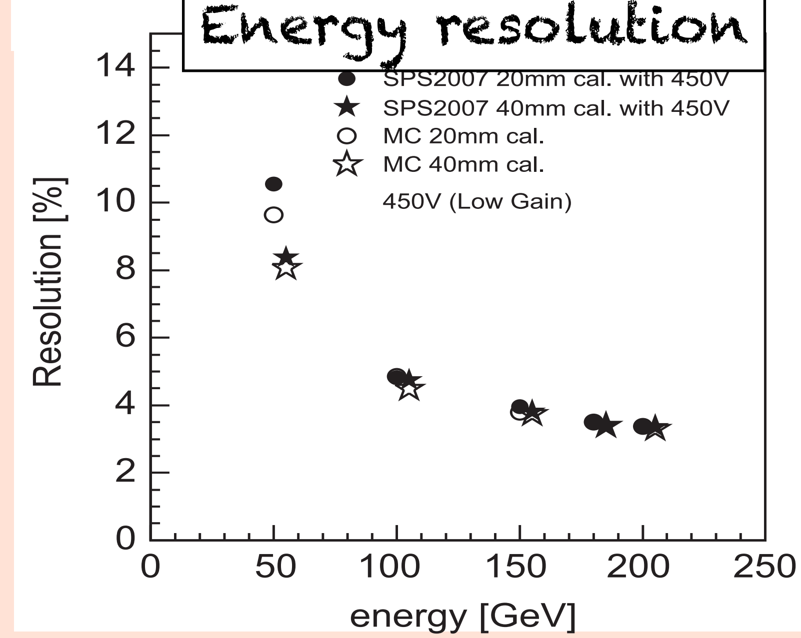
σ_E/E ~ 40% because of 1.6λ and small transverse size

EM shower (MC)

Position resolution



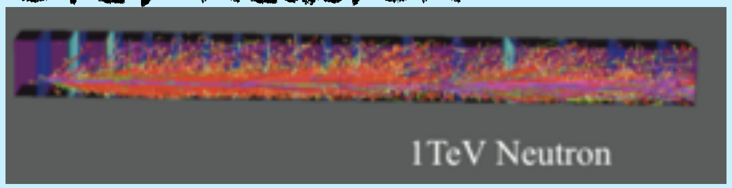
Energy resolution



PID technique

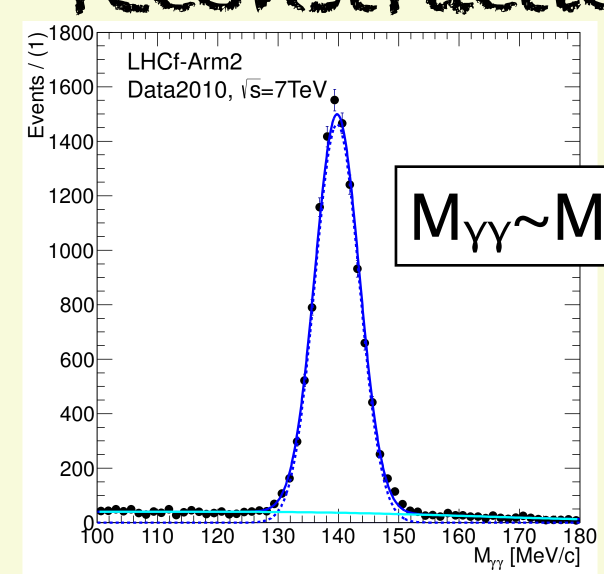
400GeV photon

1TeV neutron



Identification of incoming particle by shower shape

π⁰ reconstruction



$M_{\gamma\gamma} \sim M_{\pi 0}$

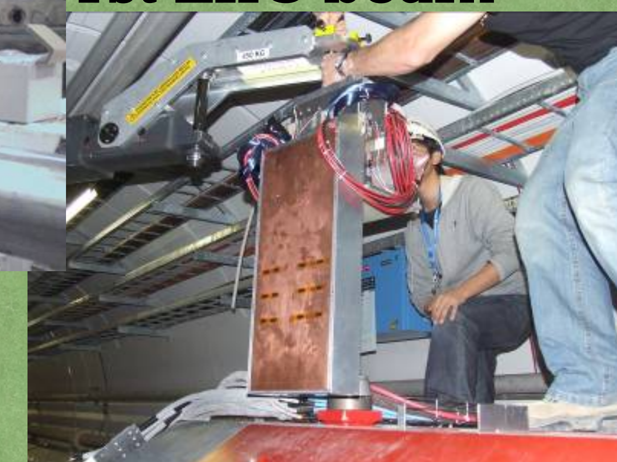
A brief LHCf photo-history

- May 2004 LOI
- Feb 2006 TDR
- June 2006 LHCC approved

Jul 2006
construction

Aug 2007
SPS beam test

Jan 2008
Installation
Sept
1st LHC beam



Dec- Jul 2010
0.9TeV& 7TeV pp
Detector removal

Dec 2012- Feb 2013
5TeV/n pPb, 2.76TeVpp
(Arm2 only)
Detector removal

May-June 2015
13 TeV dedicated pp
Detector removal

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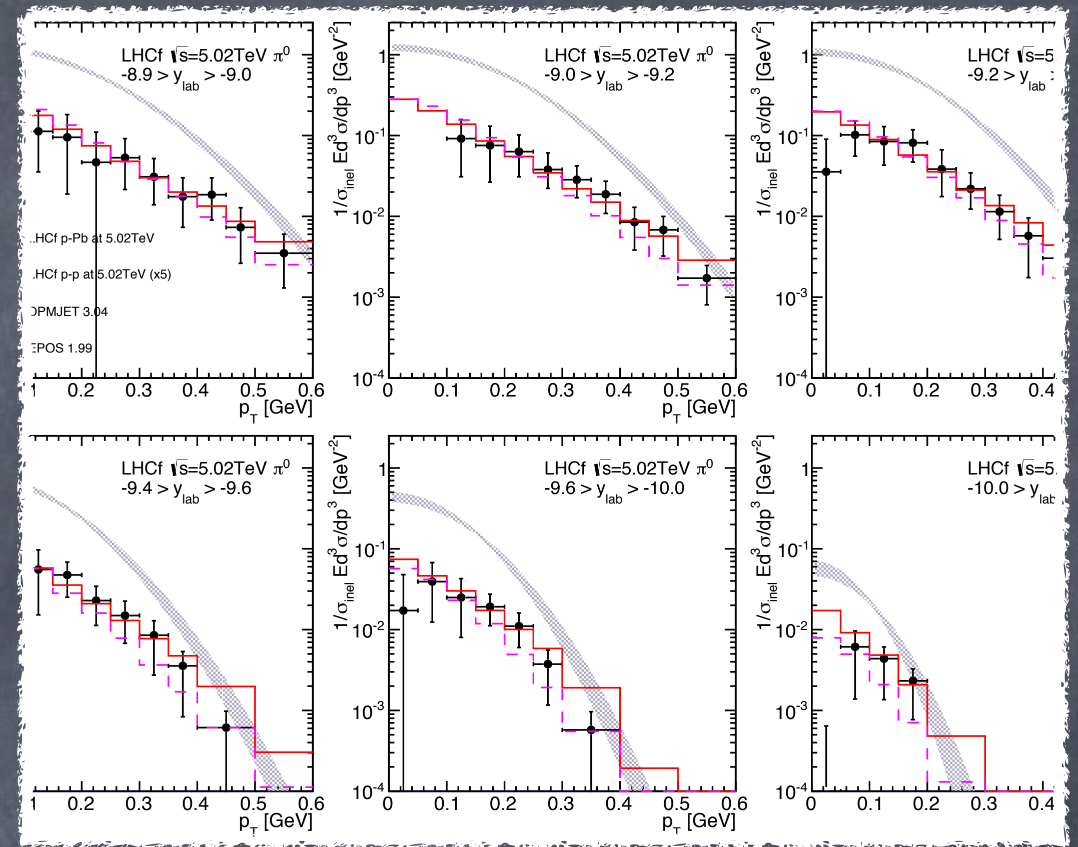
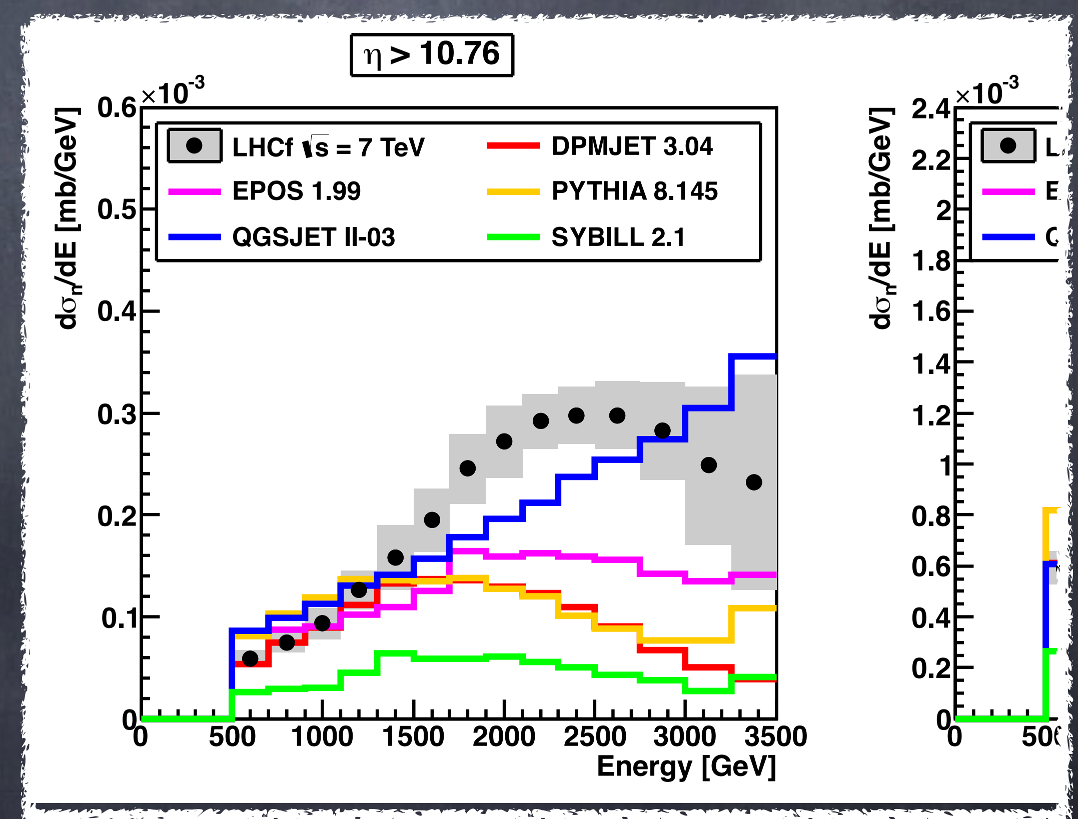




LHCf Data Taking and Analysis matrix

	Proton E	Photon (EM shower)	Neutron (hadron	π (EM shower)
Test beam at SPS		NIM. A 671, 129-136	JINST 9 (2014)P03016	
p-p at 900GeV	4.3x10	Phys. Lett. B 715, 298-303		
p-p at 7TeV	2.6x10	Phys. Lett. B 703, 128-134 (2011)	New Accept PLB	Phys. Rev. D 86, 092001 (2012)+ Submit. Type II
p-p at 2.76TeV	4.1x10			Phys. Rev. C 89, 065209 (2014)+ Submit. Type II
p-Pb at 5.02TeV	1.3x10			
p-p at 13TeV	9.0x10	Data taken in June 2015 dedicated run! Analysis activity just started...		

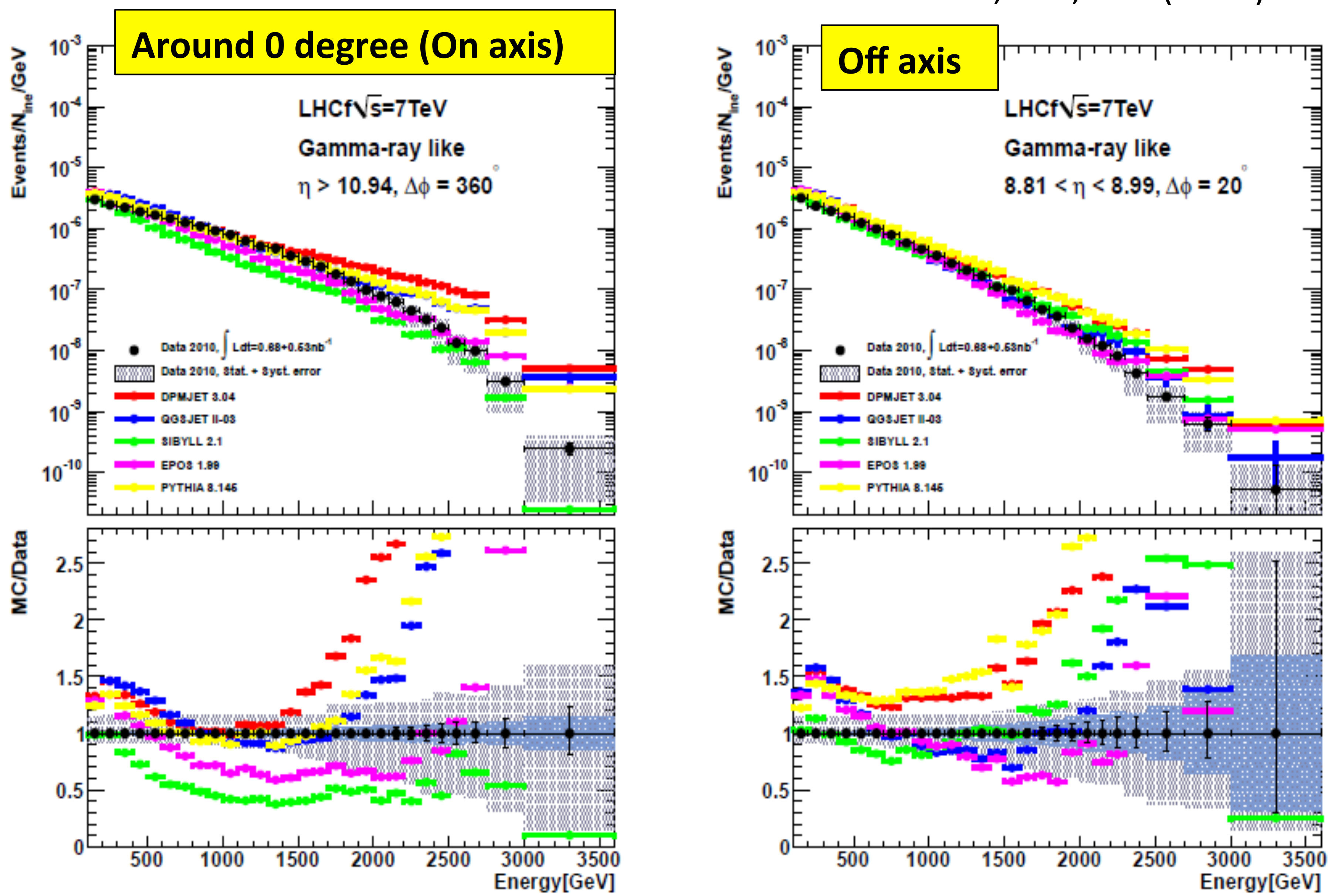
Run1

Run2

Run3

LHCf @ pp 7TeV: Single photon spectra MC vs Data

Adriani et al., PLB, 703 (2011) 128-134

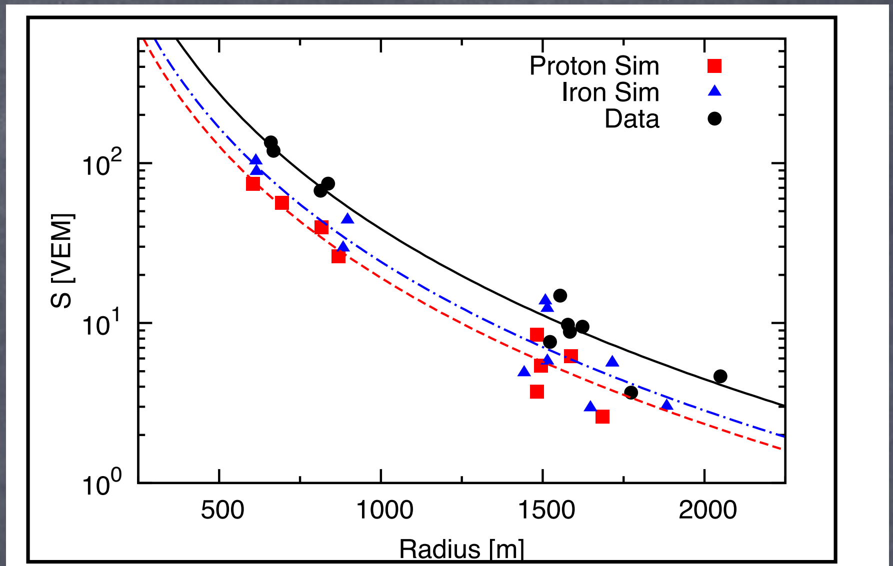


DPMJET 3.04 QGSJET II-03 SIBYLL 2.1 EPOS 1.99 PYTHIA 8.145

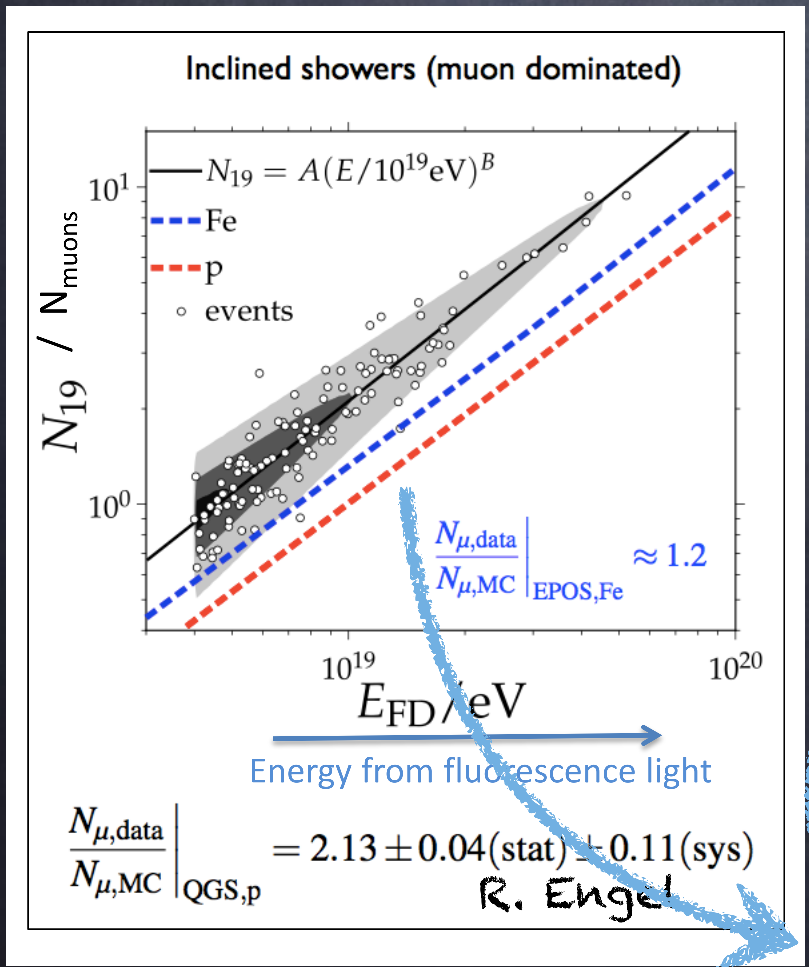
LHCf @ pp 7 TeV: neutron analysis

Motivations:

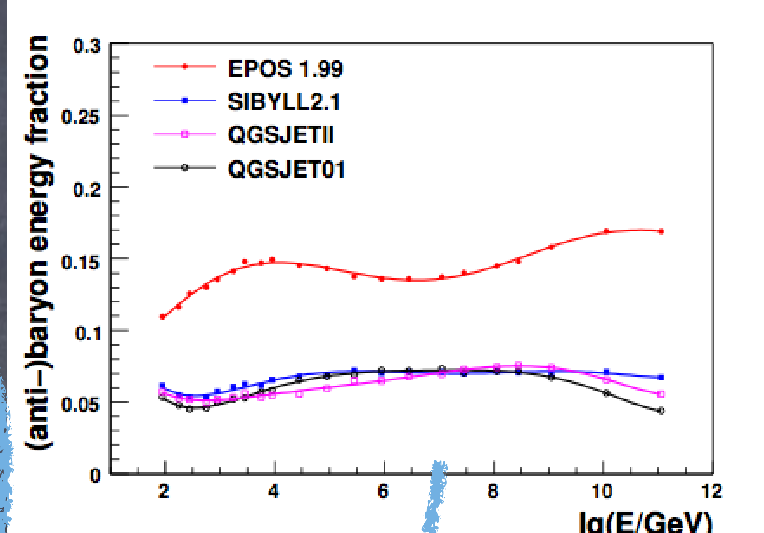
- Inelasticity measurement $k=1-p_{leading}/p_{beam}$
- Muon excess at Pierre Auger Observatory
  - cosmic rays experiment measure PCR energy from muon number at ground and florescence light
  - 20-100% more muons than expected have been observed



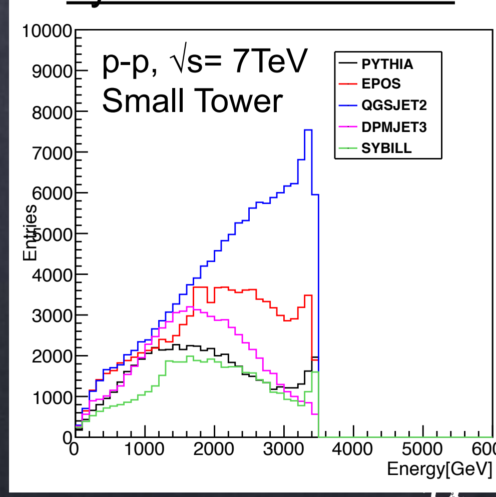
[J.Allen, et al. ICRC2011 Proceedings]



- Number of muons depends on the energy fraction of produced hadron
- Muon excess in data even for Fe primary MC
- EPOS predicts more muon due to larger baryon production

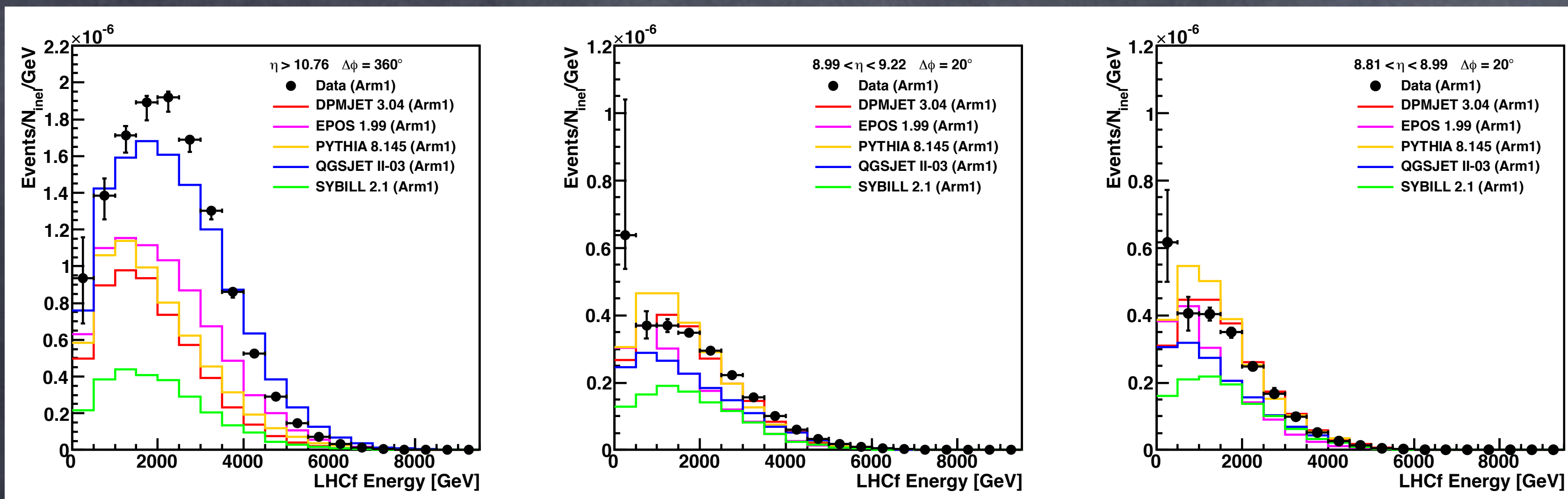


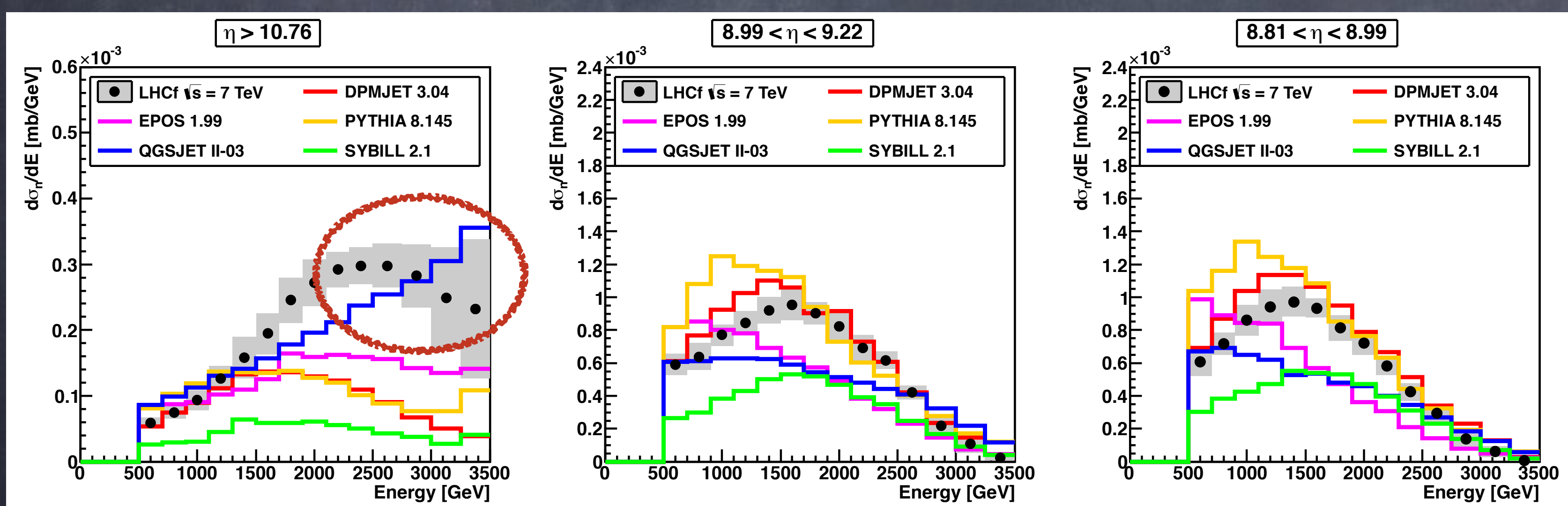
Neutron spectra predicted by interaction models



importance of baryon measurement

LHCf @ pp 7 TeV: neutron spectra



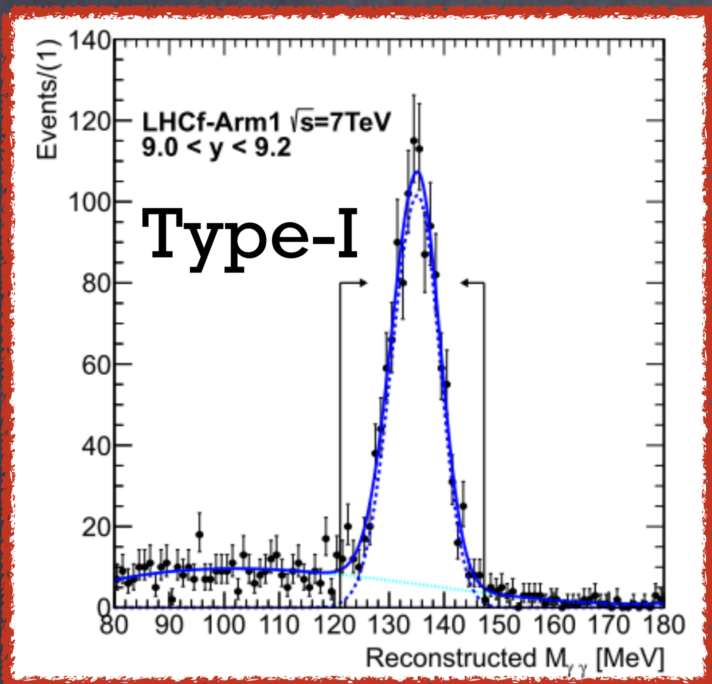


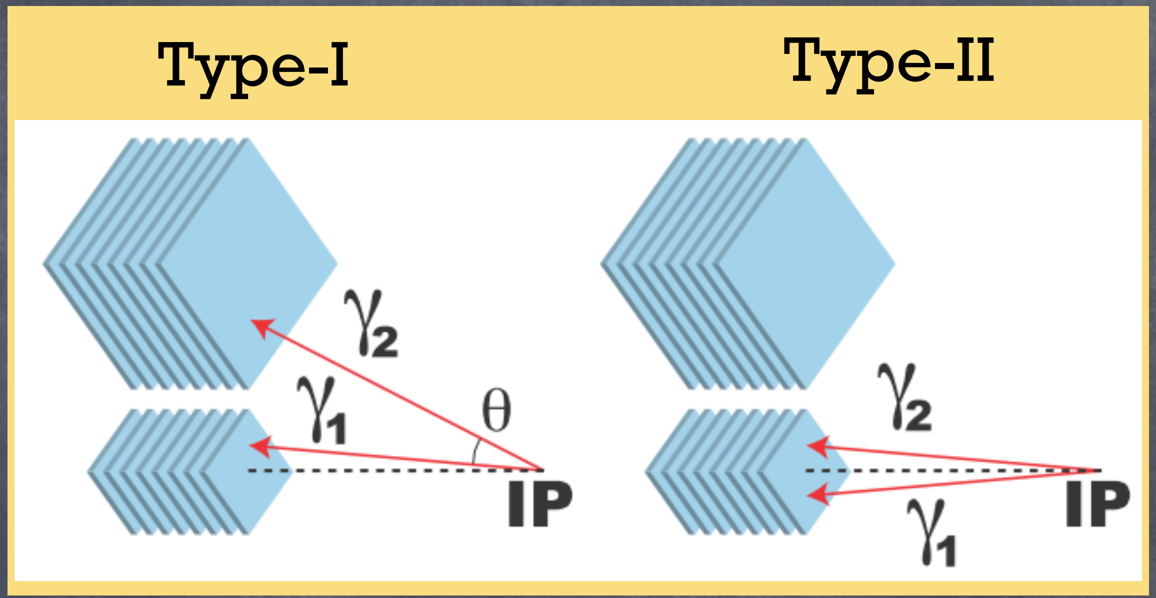
Data (	3.05±0.19
DPMJET3.04	1.05
EPOS 1.99	1.80
PYTHIA 8.145	1.27
QGSJET II-03	2.34
SYBILL 2.1	0.88

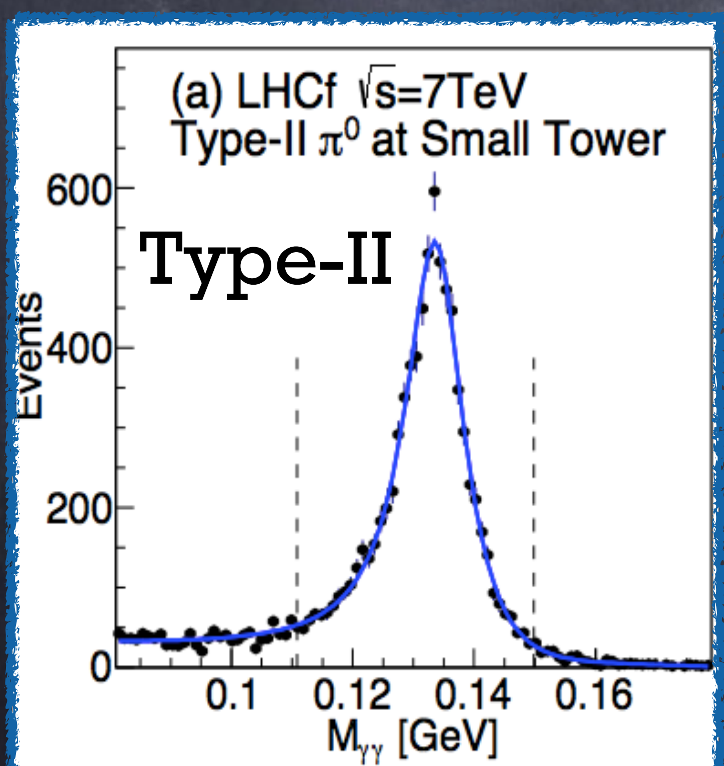
Data (8.99<	1.26±0.08
DPMJET3.04	0.76
EPOS 1.99	0.69
PYTHIA 8.145	0.82
QGSJET II-03	0.65
SYBILL 2.1	0.57

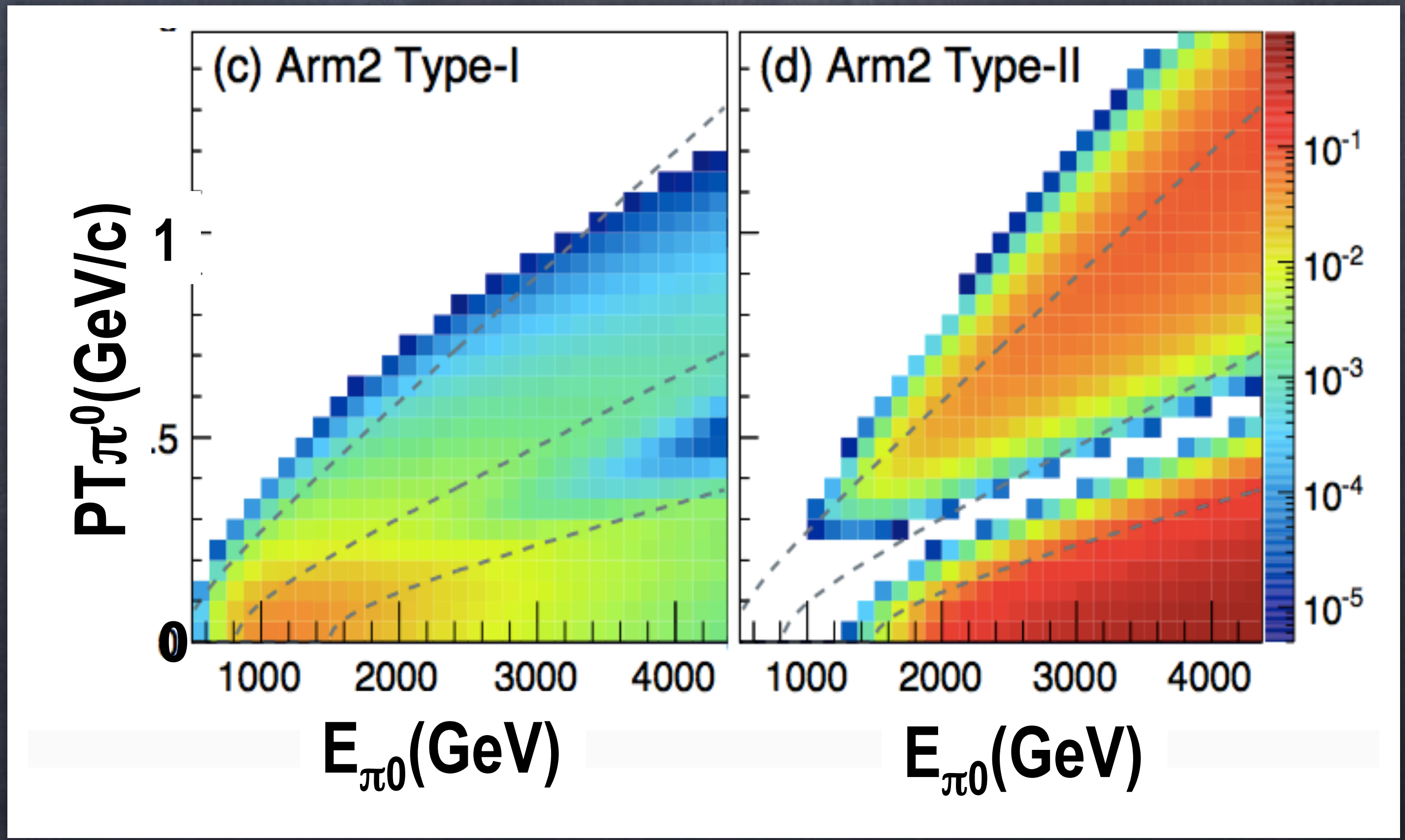
- LHCf Arm1 and Arm2 agree with each other within systematic error, in which the energy scale uncertainty dominates.
- In η>10.76 huge amount of neutron exists. Only QGSJET2 reproduces the LHCf result.
- In other rapidity regions, the LHCf results are enclosed by the variation of models.

LHCf Type I and Type II π°analysis

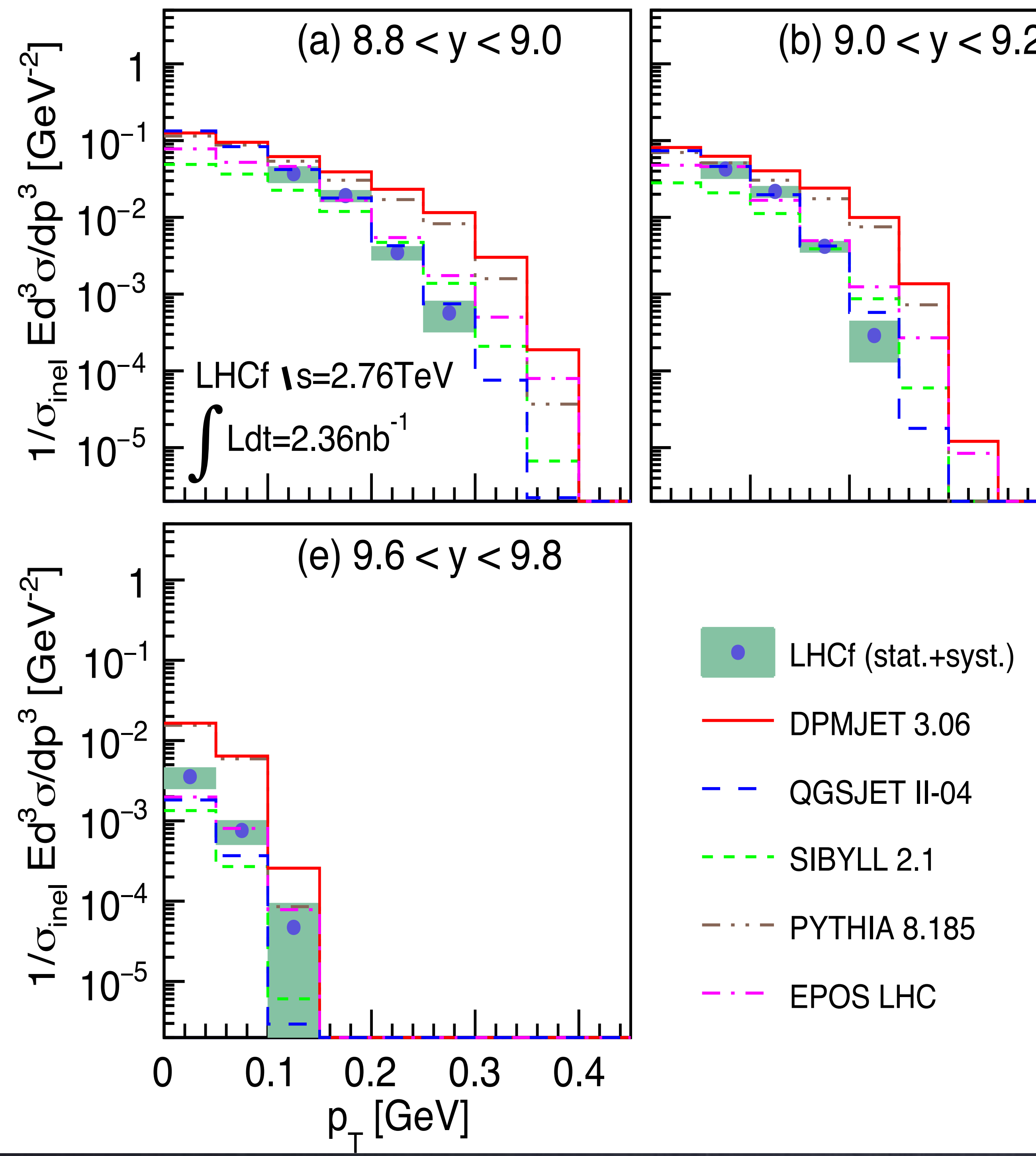






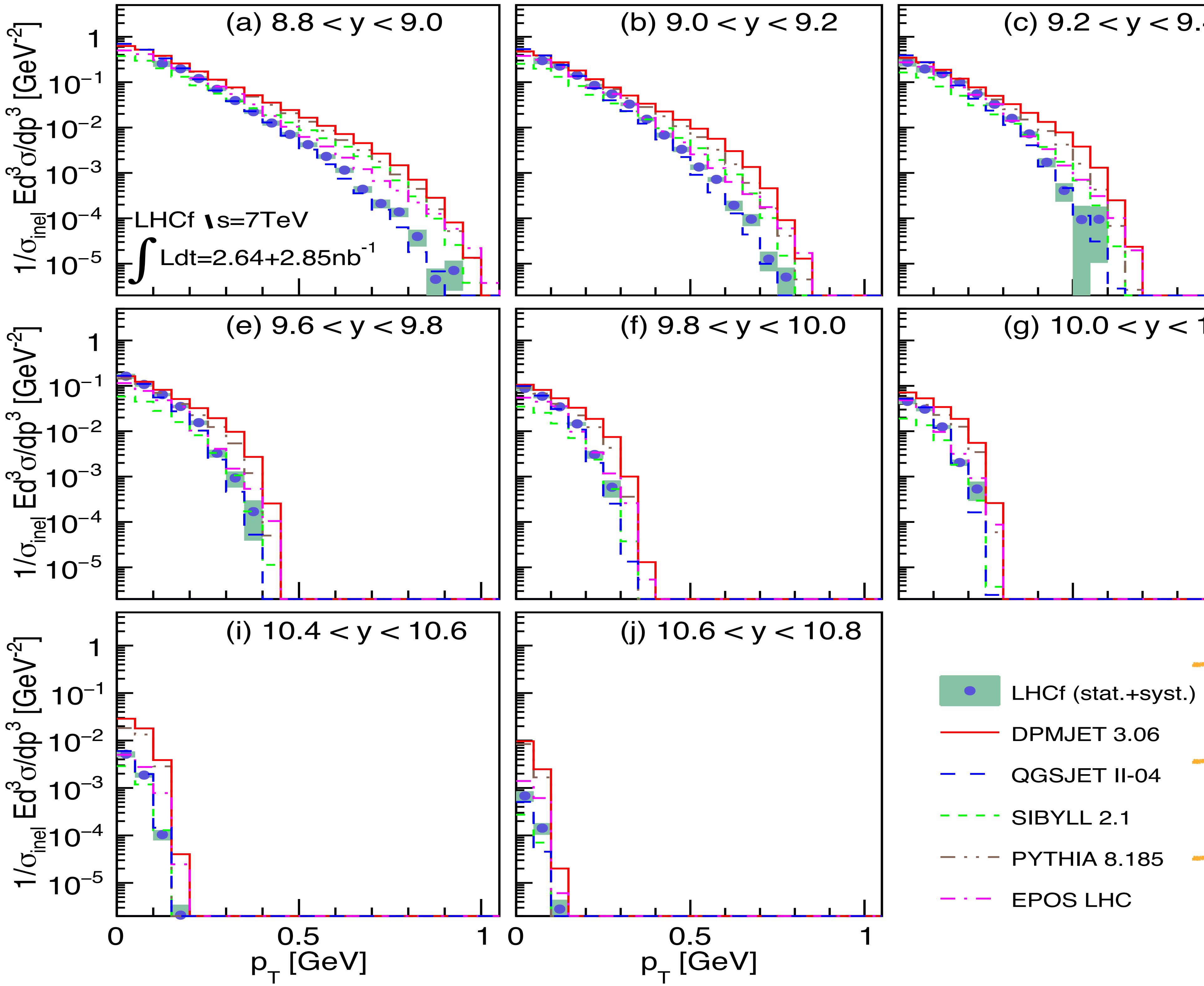


LHCf @ pp 2.76 TeV: π^0 p_T spectra



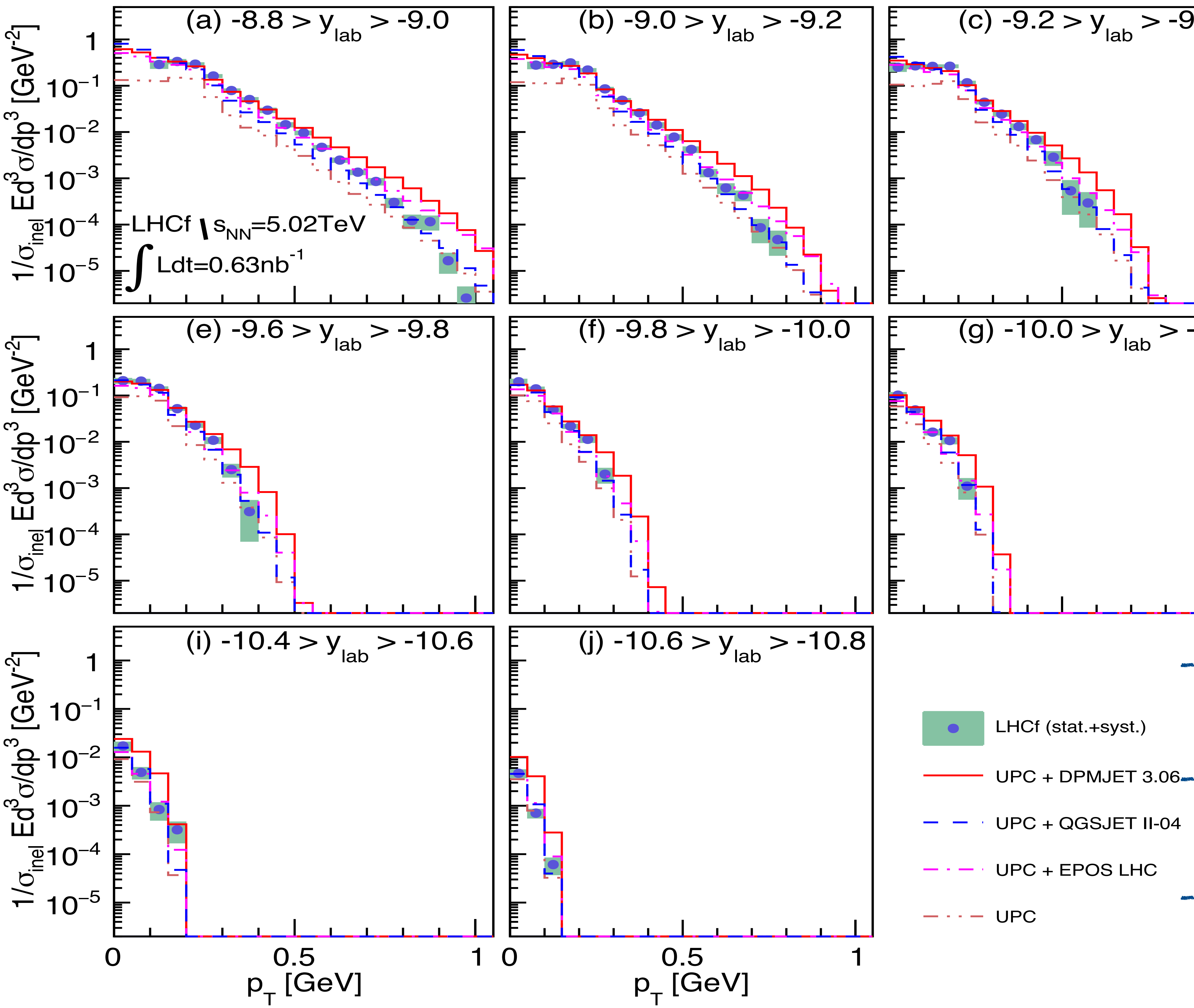
- QGSJETII-04: best agreement
- EPOS-LHC: harder than data
- SYBILL: small π^0 yield, harder spectrum
- DPMJET and Pythia larger π^0 yield in the whole rapidity range

LHCf @ pp 7 TeV: π^0 p_T spectra



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

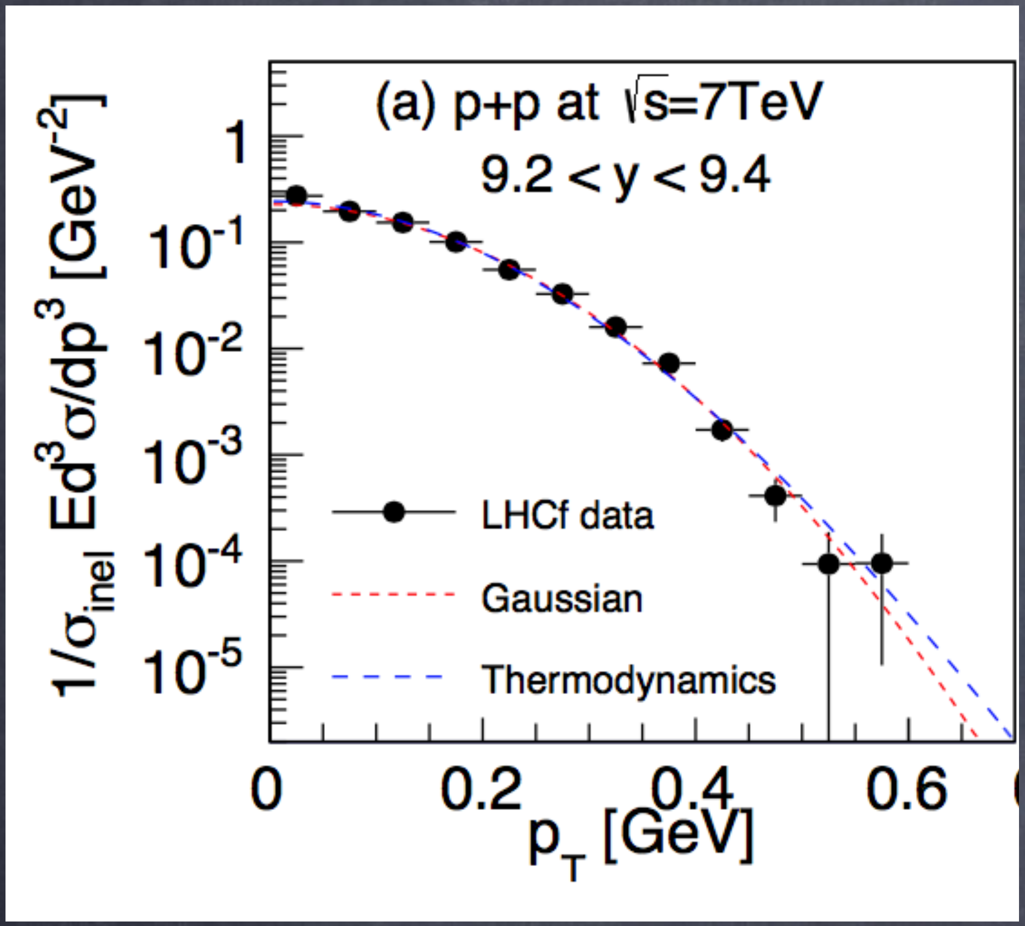
LHCf @ pPb 5.02 TeV: π^0 p_T spectra



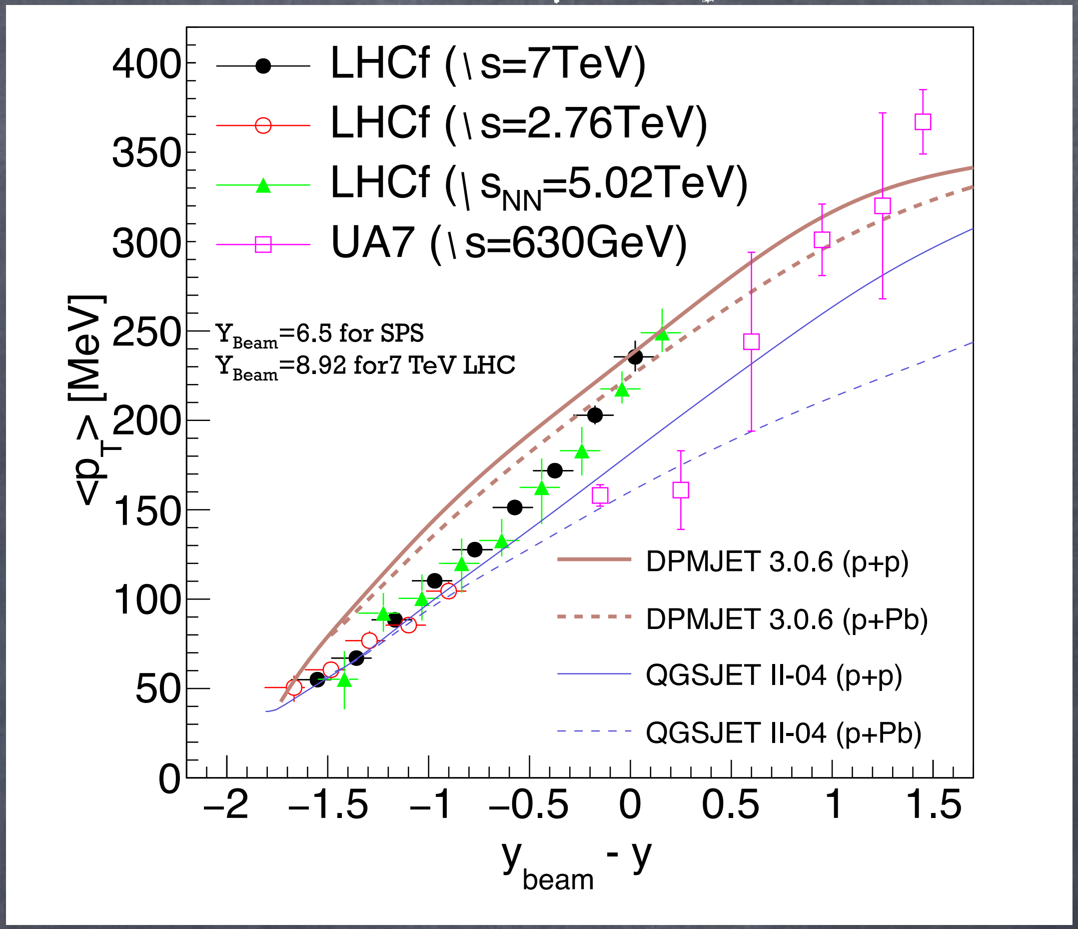
- QGSJETII-04 and EPOS-LHC: similar, good agremeent for pT>0.4 GeV
- DPMJET: good agreement for -8.8 > ylab > -10.0 and p_T < 0.3 GeV
- Characteristic bump at y > -9.6 and p_T ~ 0.2GeV: Ultra Peripheral Collisions

π^0 average p_T for different cm energies

p_T spectra vs best-fit function



Average p_T vs y_{lab}



<p_T> is inferred in 3 ways:

1. Thermodynamical approach
2. Gaussian distribution fit
3. Numerical integration up to the histogram upper bound

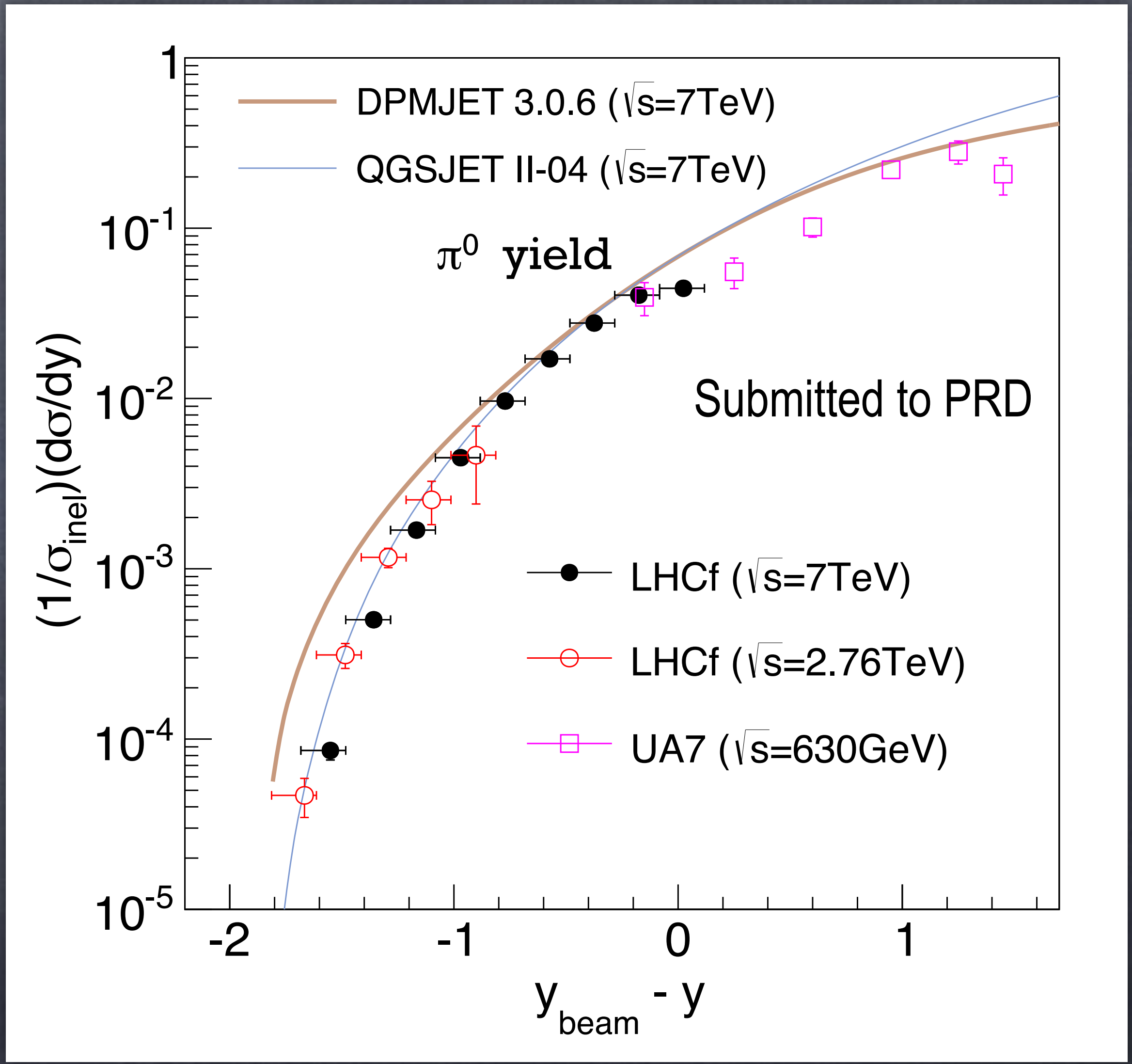
From scaling considerations (projectile fragmentation region) we can expect that <p_T> vs rapidity loss should be independent from the c.m. energy

Reasonable scaling can be inferred from the data

Limiting fragmentation in forward π^0 production

Limiting fragmentation hypothesis:
rapidity distribution of the secondary particles in the forward rapidity region (target's fragment) should be independent of the center-of-mass energy.

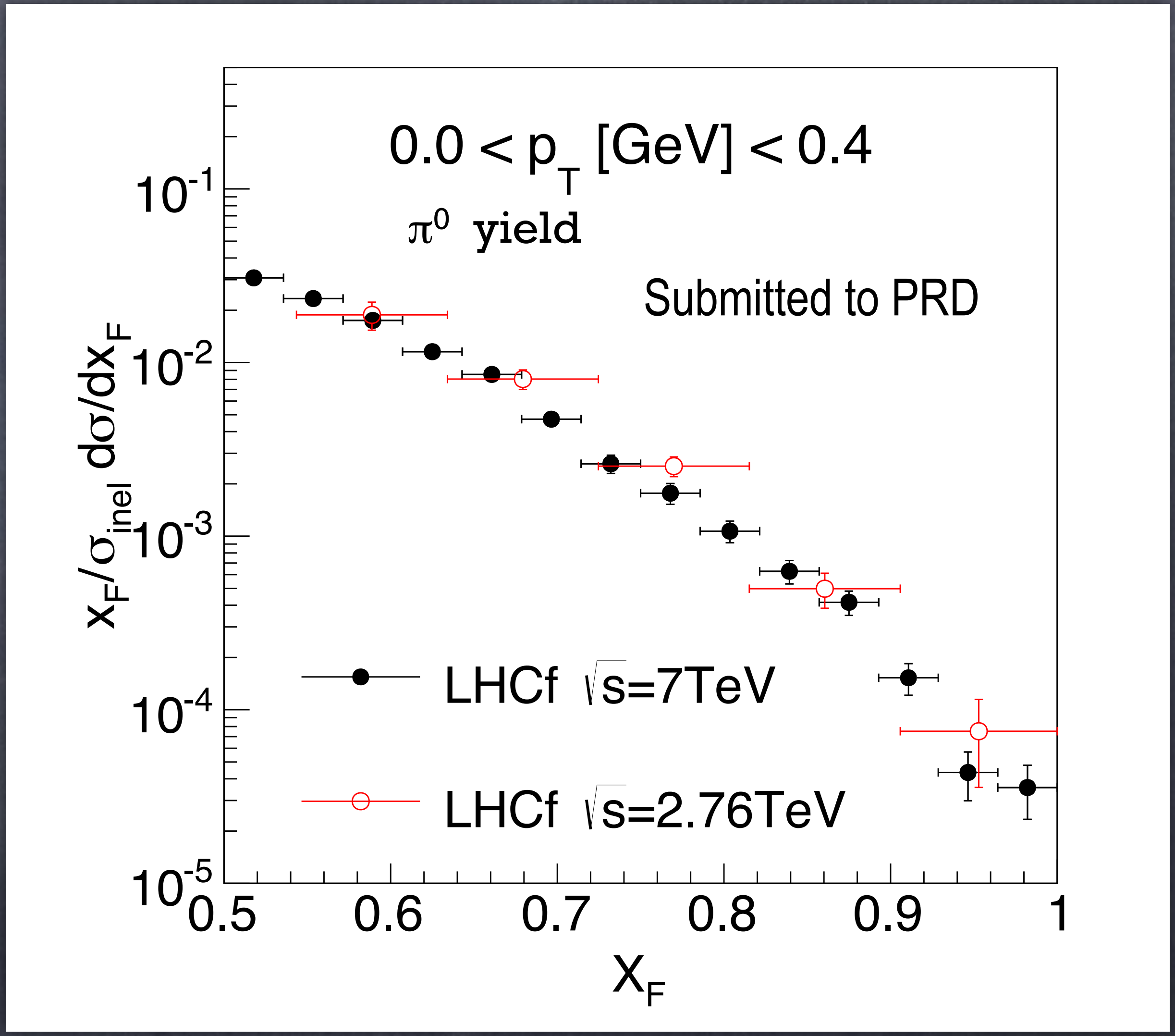
This hypothesis for π^0 is true at the level of ±15%



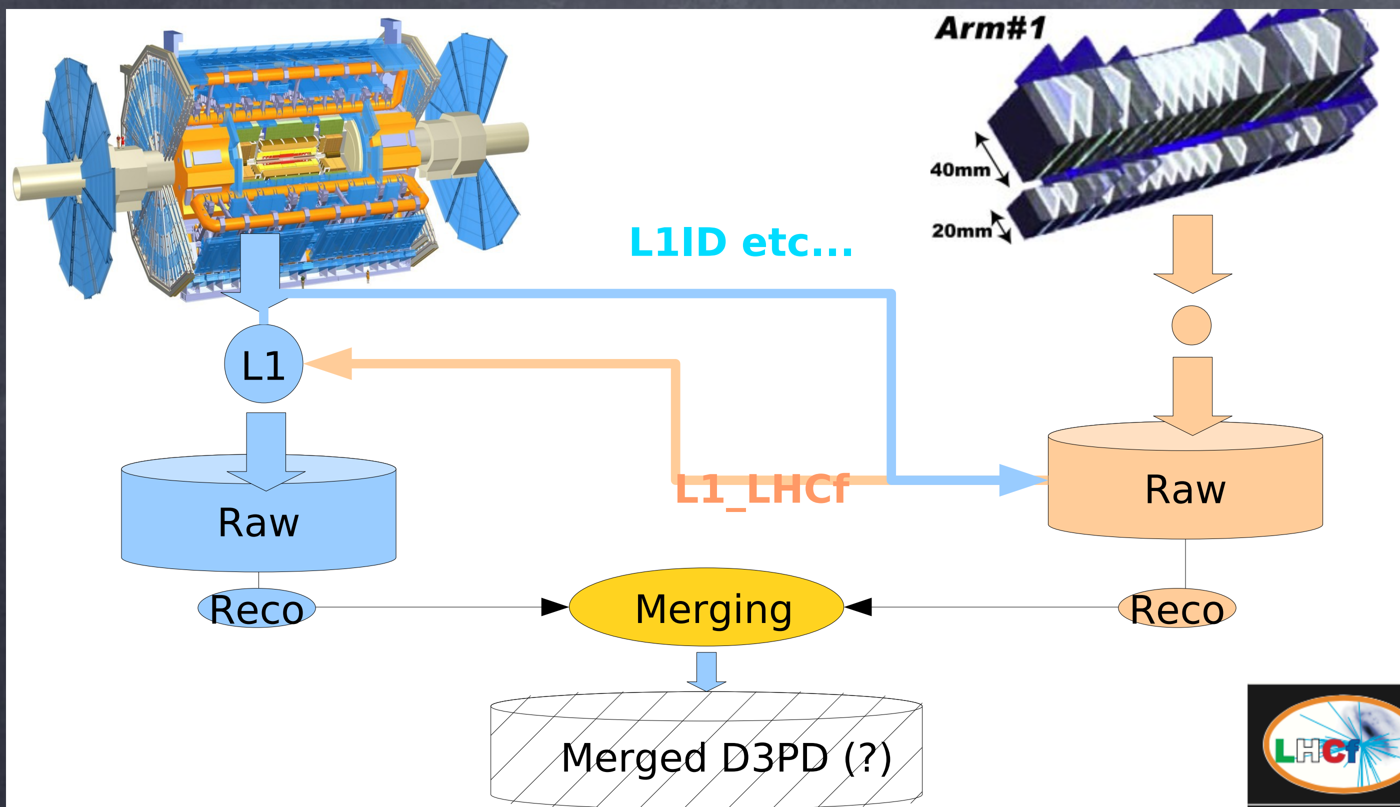
Feynman scaling in forward π^0 production

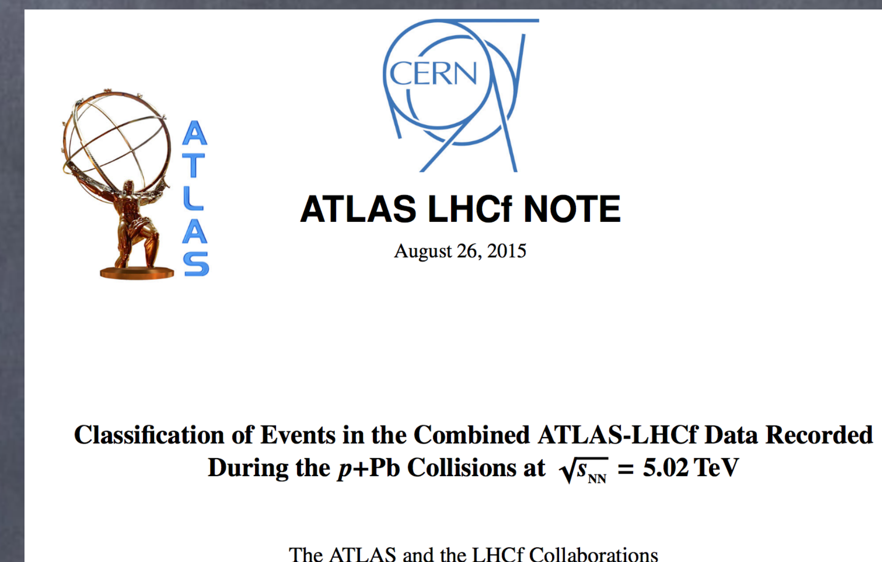
Feynman scaling hypothesis:
cross sections of secondary particles as a function of $x_F \equiv 2p_z/\sqrt{s}$ are independent from the incident energy in the forward region ($x_F > 0.2$).

This hypothesis for π^0 is true at the level of ±20%



Common trigger with ATLAS in p-Pb operation





ATLAS

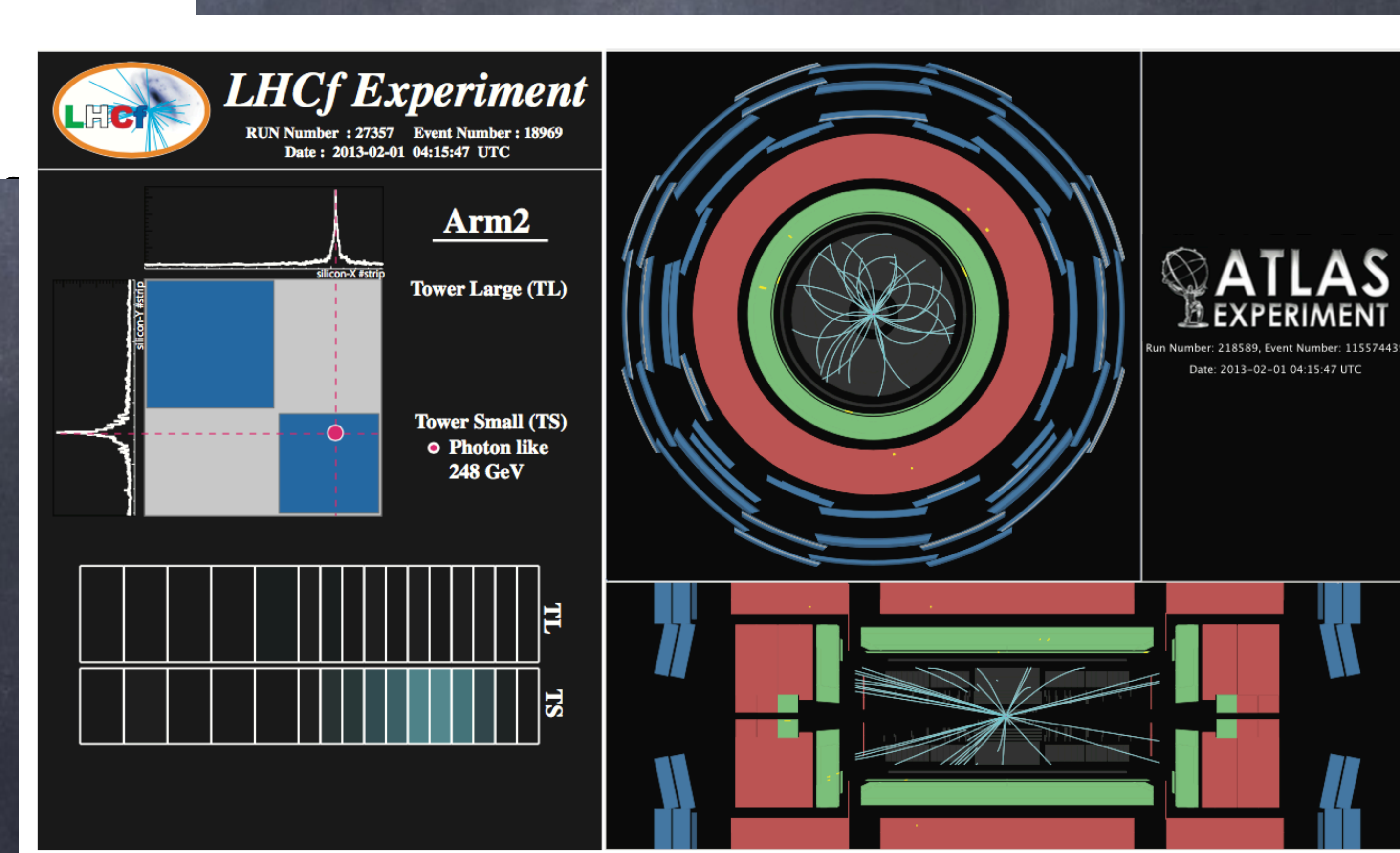
CERN

ATLAS LHCf NOTE

August 26, 2015

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

The ATLAS and the LHCf Collaborations

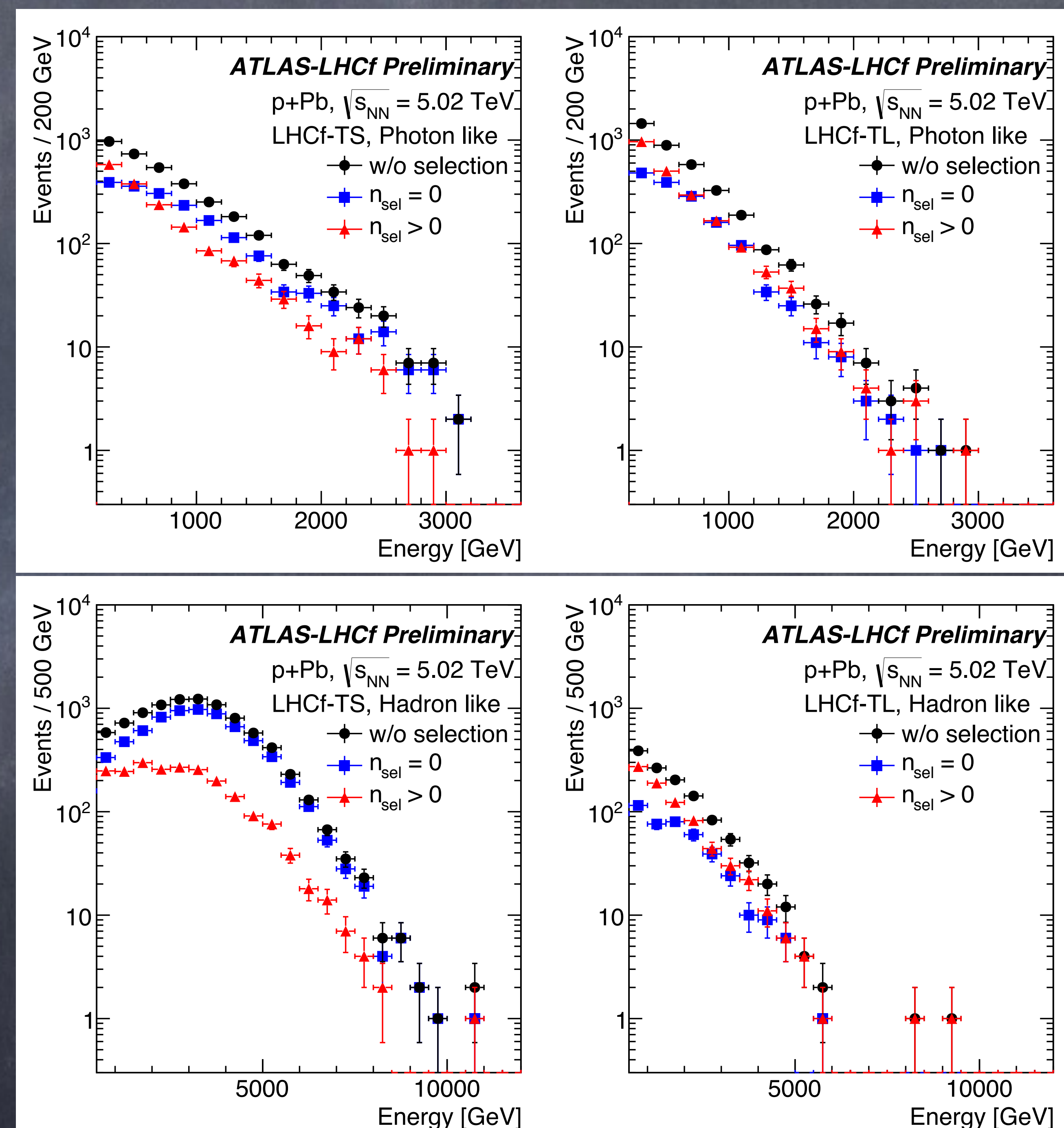


LHCf spectra in p-Pb collisions with Atlas tagging on tracks

Nsel:

number of good charged ATLAS tracks

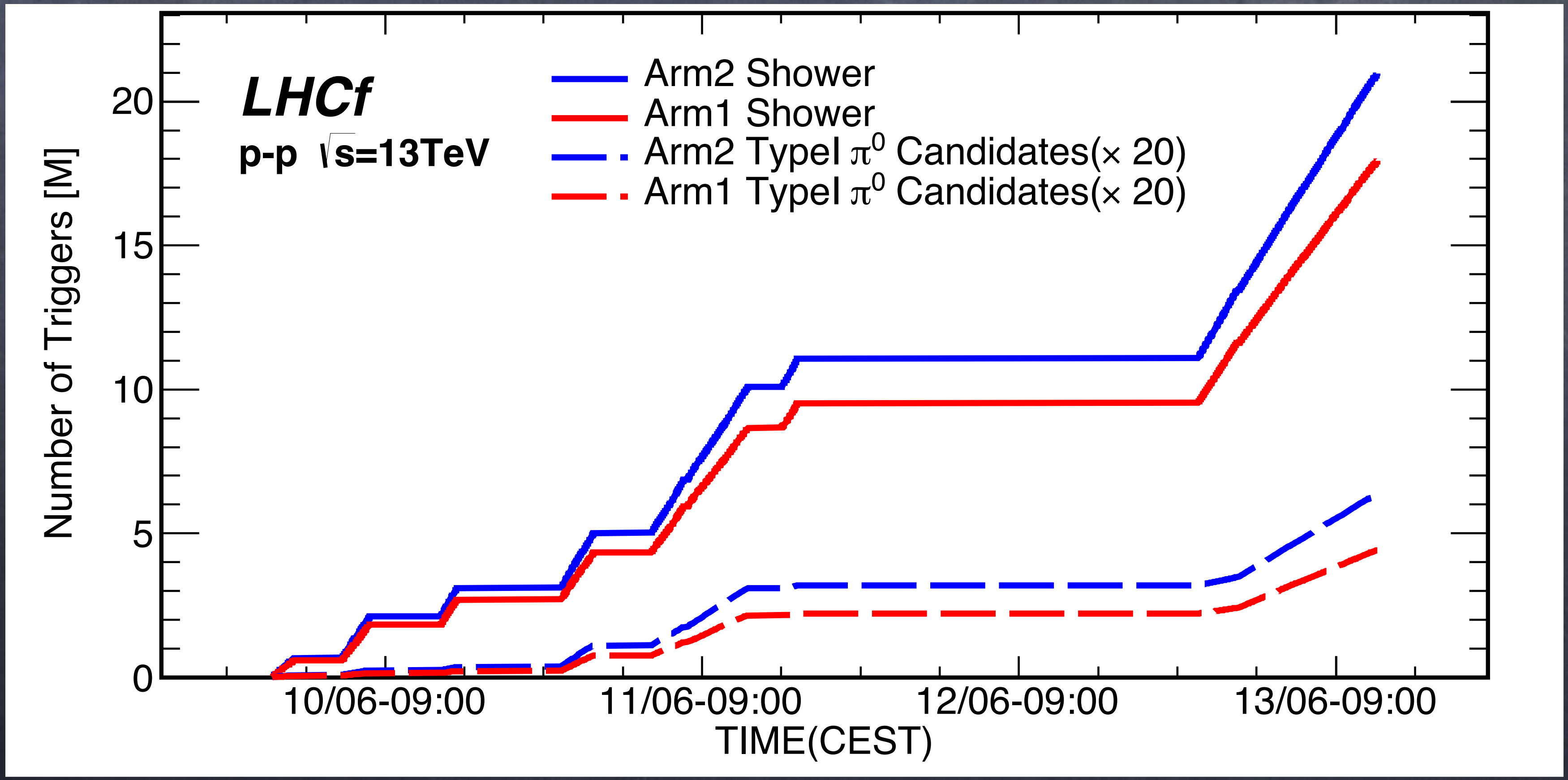
- $p_T > 100$ MeV
- vertex matching
- $|\eta| < 2.5$.



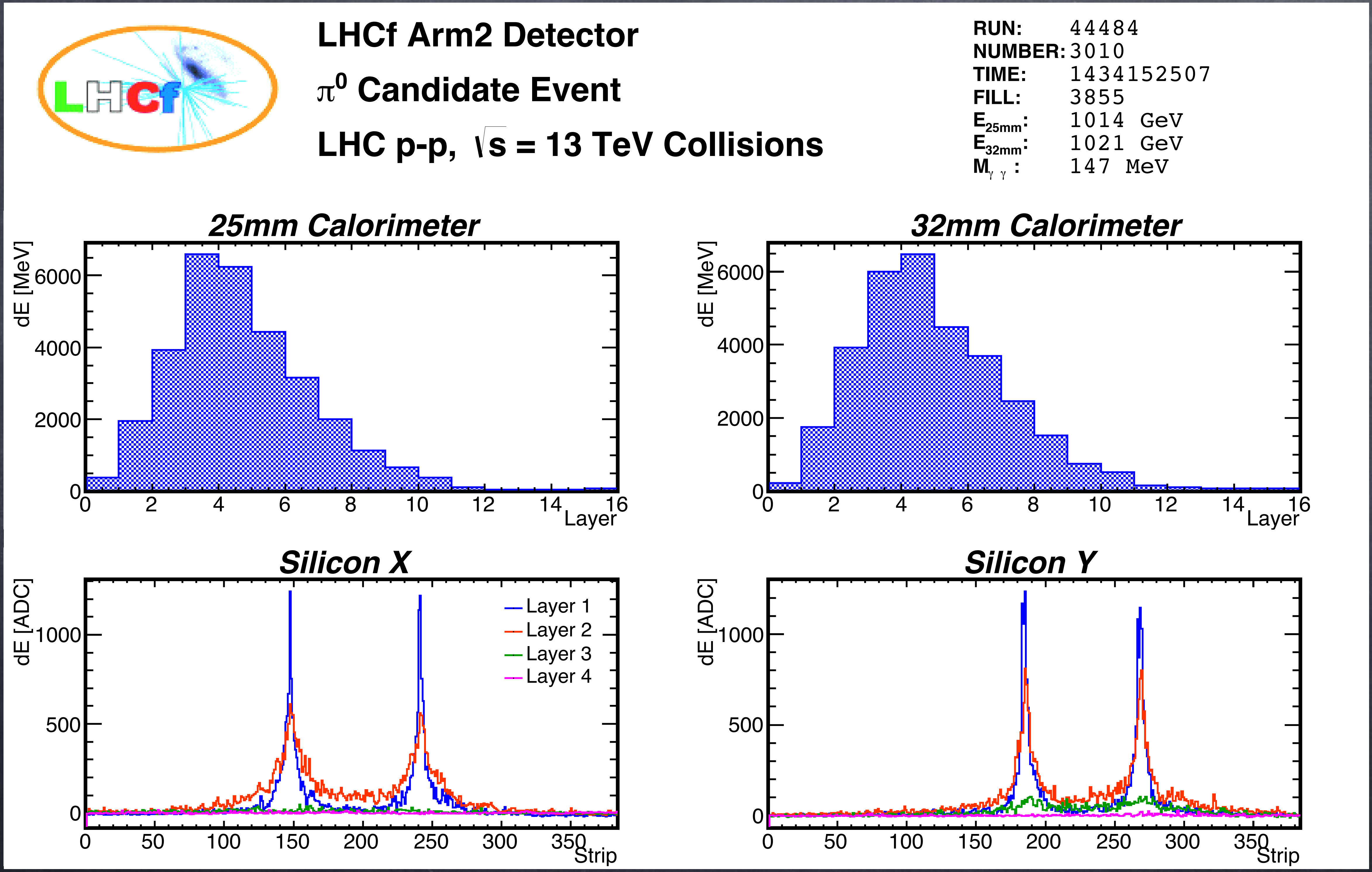
Significant UPC contribution in the very forward region with $N_{sel}=0$

LHC 13 TeV Run

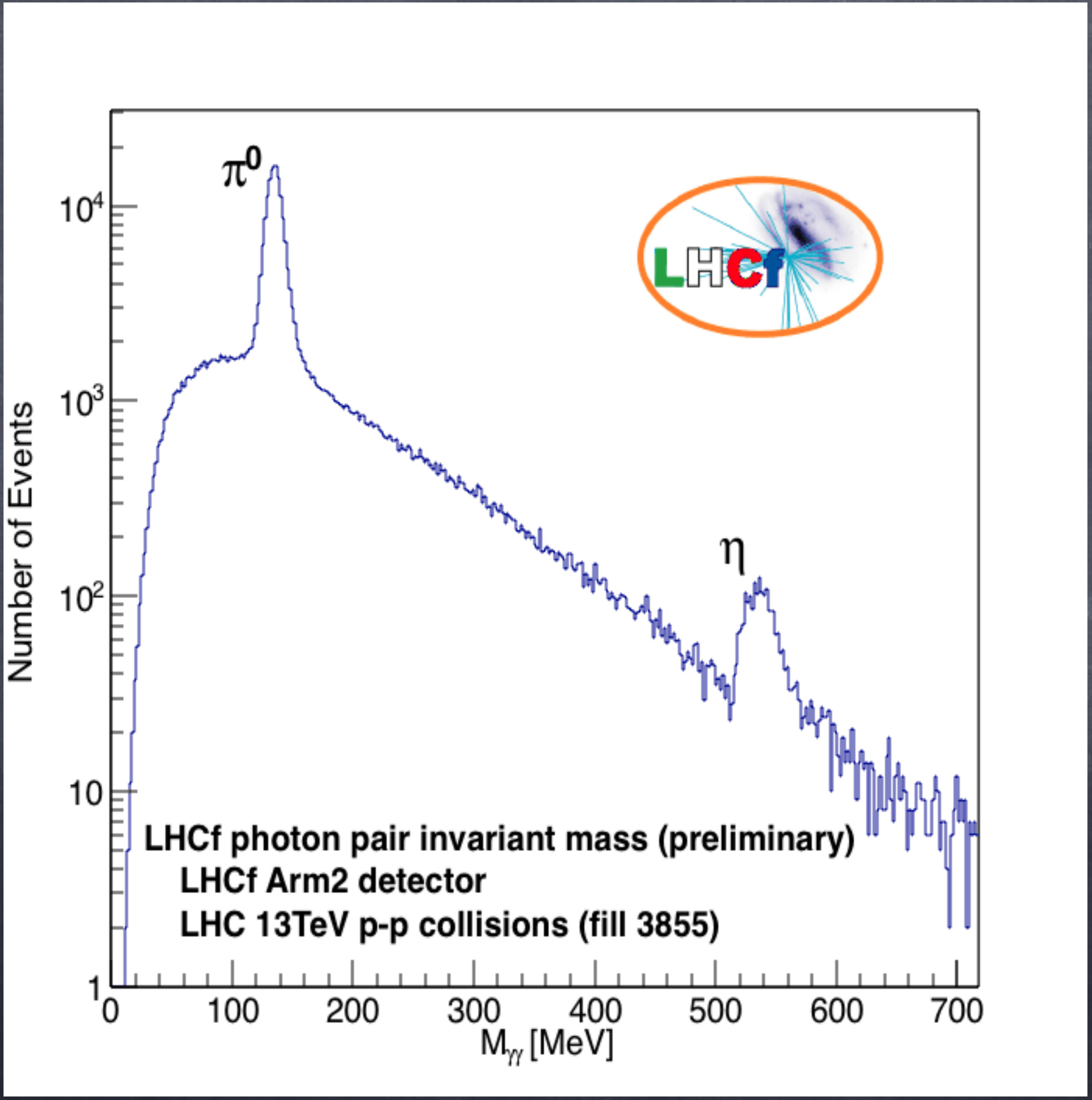
- During Week 24, June 9-13, LHCf dedicated low-lumi run
- Total 26.6 hrs with $L=0.5\sim1.6.10^{29}$ $cm^{-2}s^{-1}$ (16 nb^{-1})
- ~39 M showers, 0.5 M π^0 obtained
- Trigger exchange with ATLAS
- Detector removal on June 15th during TS1
- Run was very successful!!!!



An impressive high energy π^0

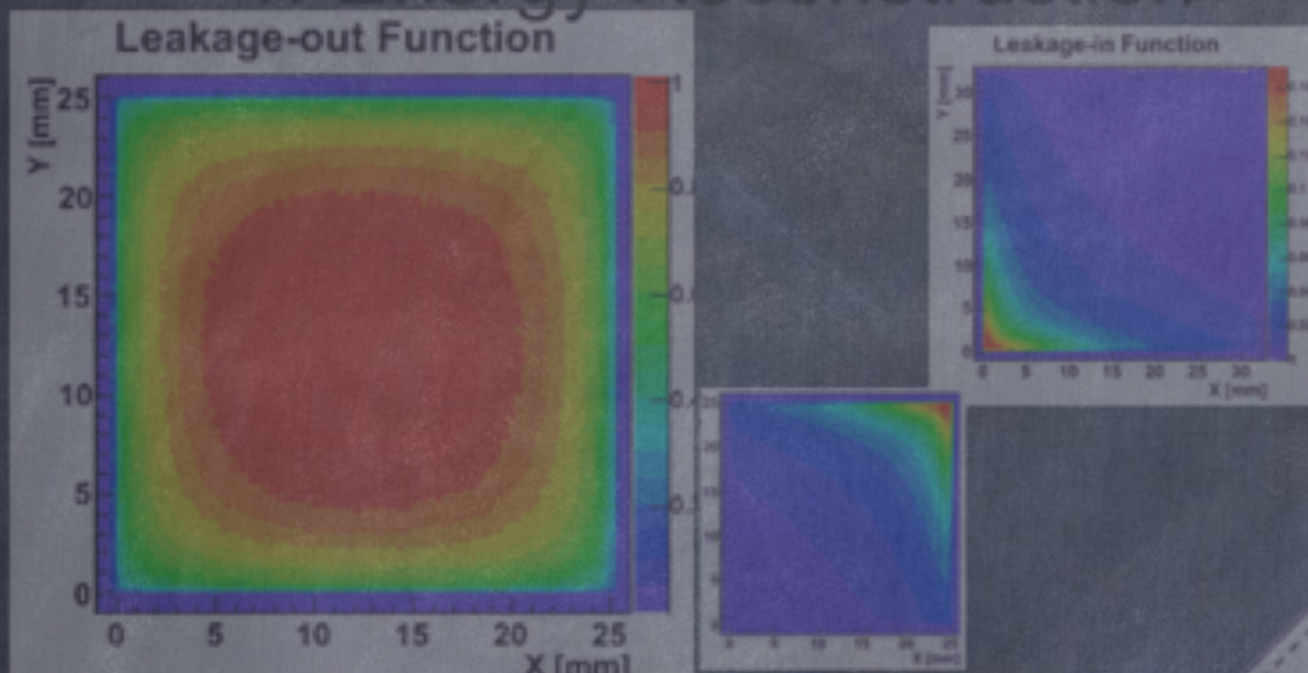


First look at 13 TeV data

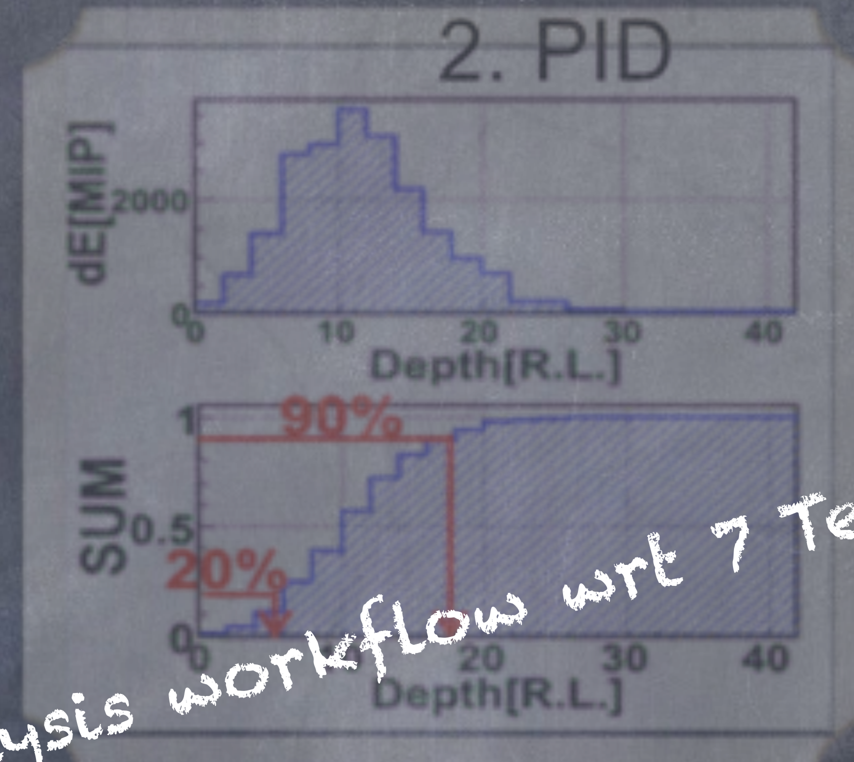


Analysis workflow

1. Energy Reconstruction

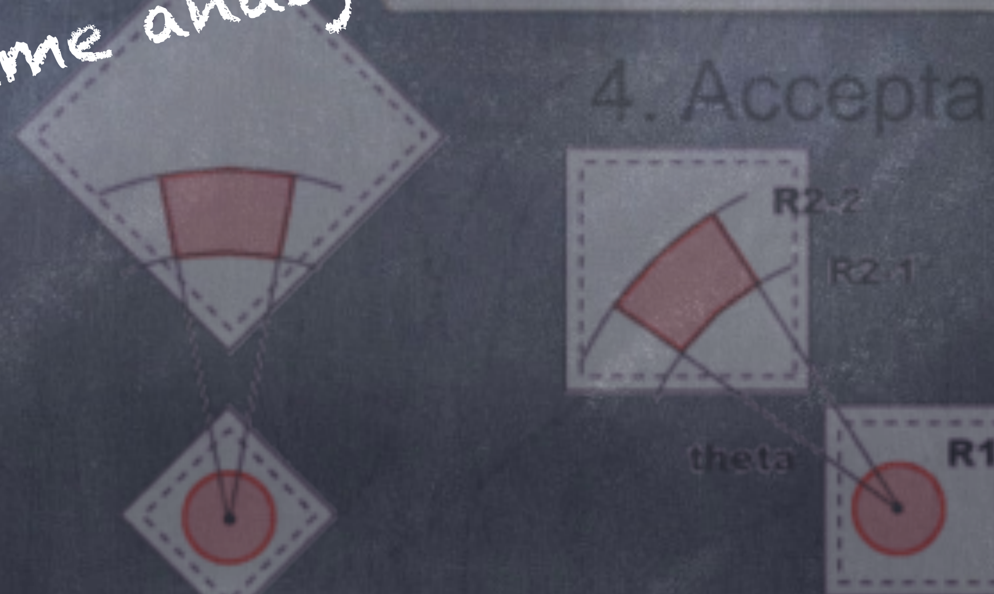


2. PID



3. Multi-Hit rejection

4. Acceptance cut

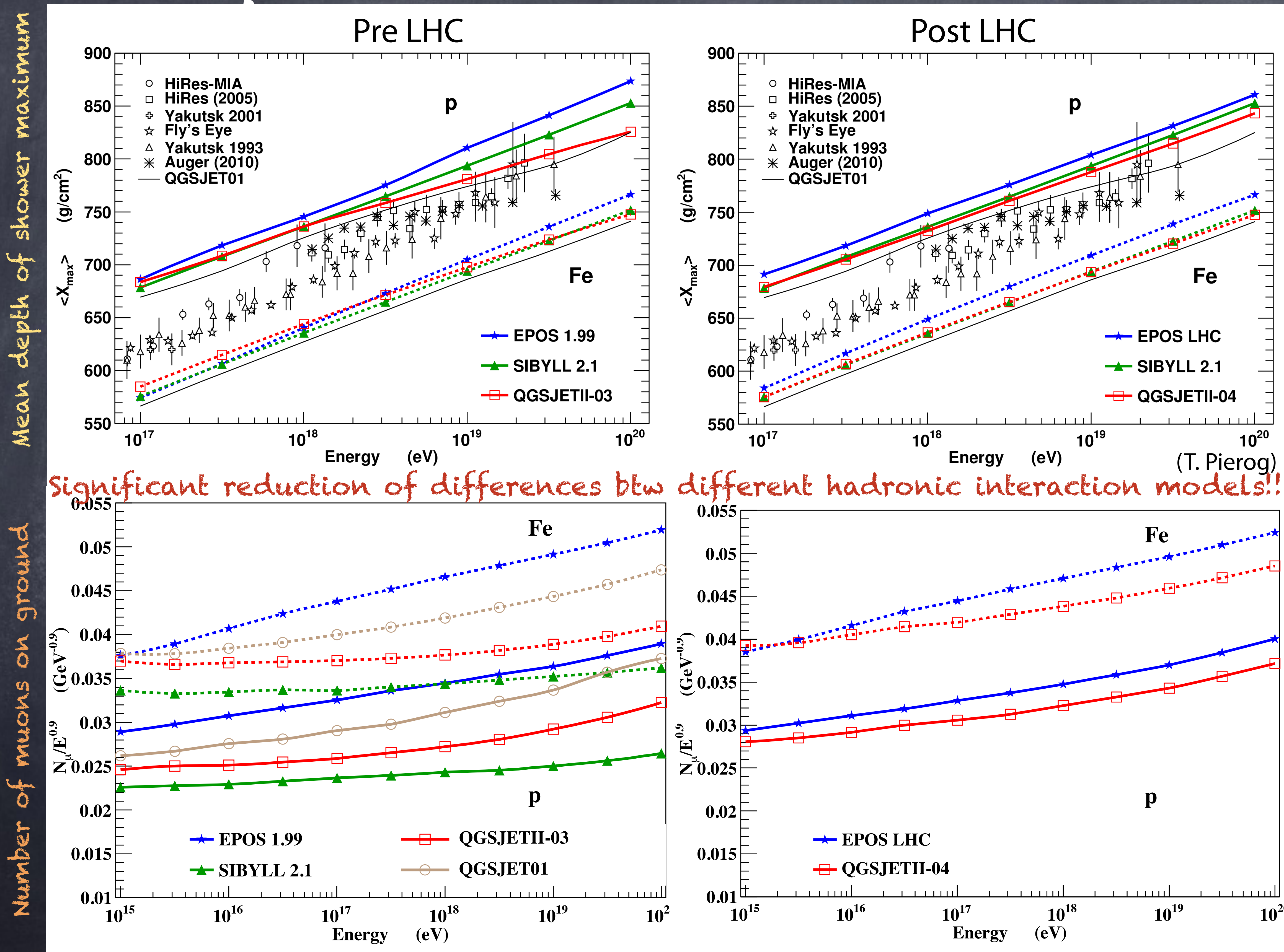


Small Tower
$\eta > 10.94$
Large Tower
$8.81 < \eta < 8.99$

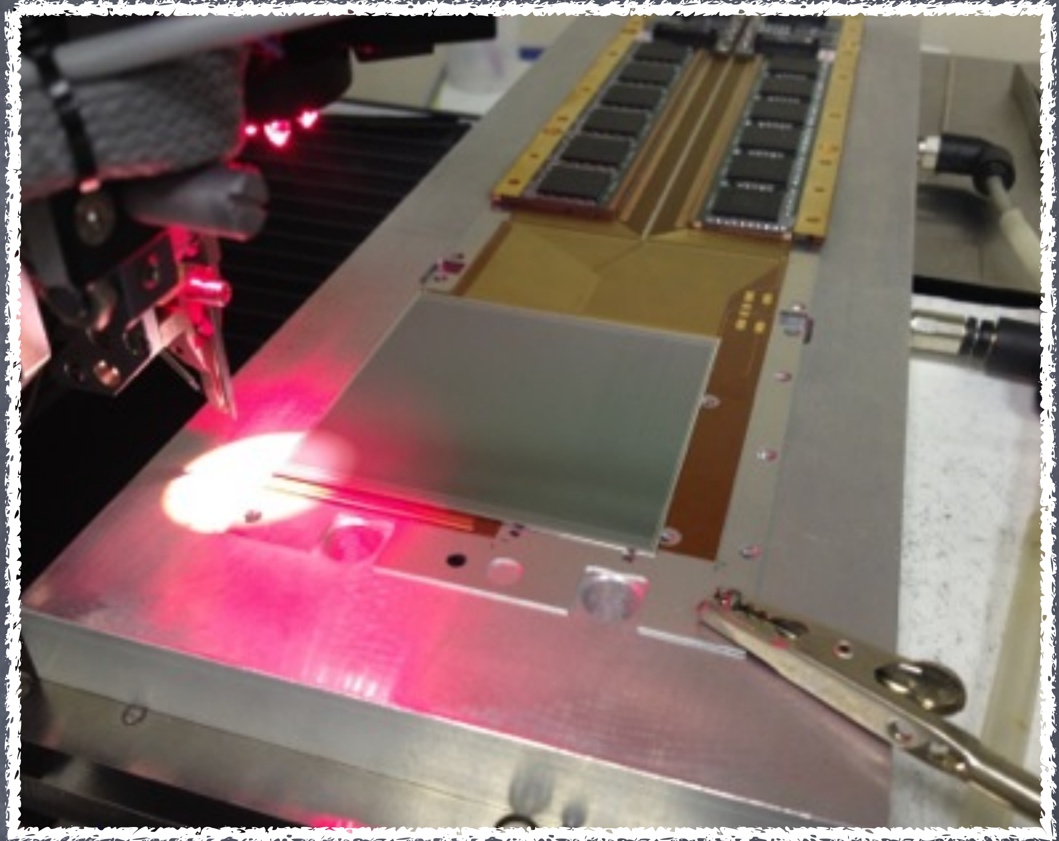
5. Systematic uncertainties

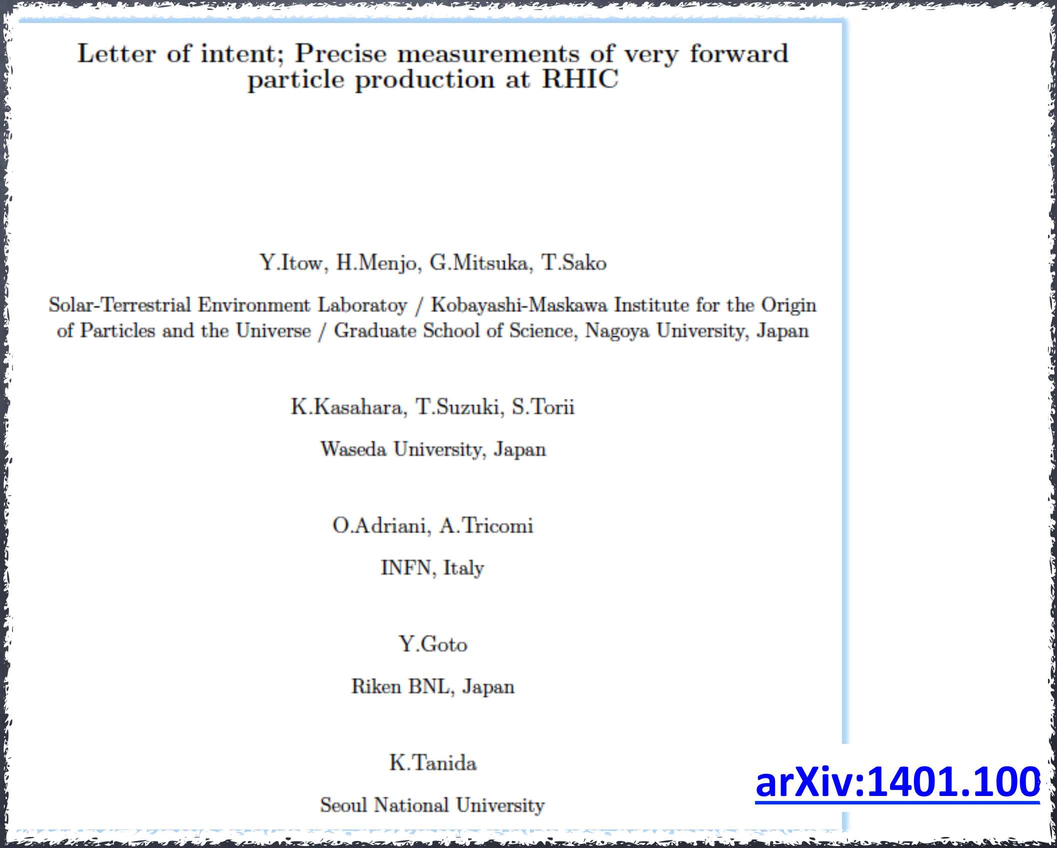
We are now repeating the same analysis workflow wrt 7 TeV data

The impact of LHC measurements



- Physics Motivations
  - The link between HECR Physics and LHC
- The LHCf detectors
  - "Il vino buono sta nella botte piccola" or "good things comes in small packages"
- Physics Results
  - what we have done so far
- **Future Plans**
  - **what's next...**





Letter of intent; Precise measurements of very forward particle production at RHIC

Y.Itow, H.Menjo, G.Mitsuka, T.Sako

Solar-Terrestrial Environment Laboratoy / Kobayashi-Maskawa Institute for the Origin of Particles and the Universe / Graduate School of Science, Nagoya University, Japan

K.Kasahara, T.Suzuki, S.Torii

Waseda University, Japan

O.Adriani, A.Tricomi

INFN, Italy

Y.Goto

Riken BNL, Japan

K.Tanida

Seoul National University

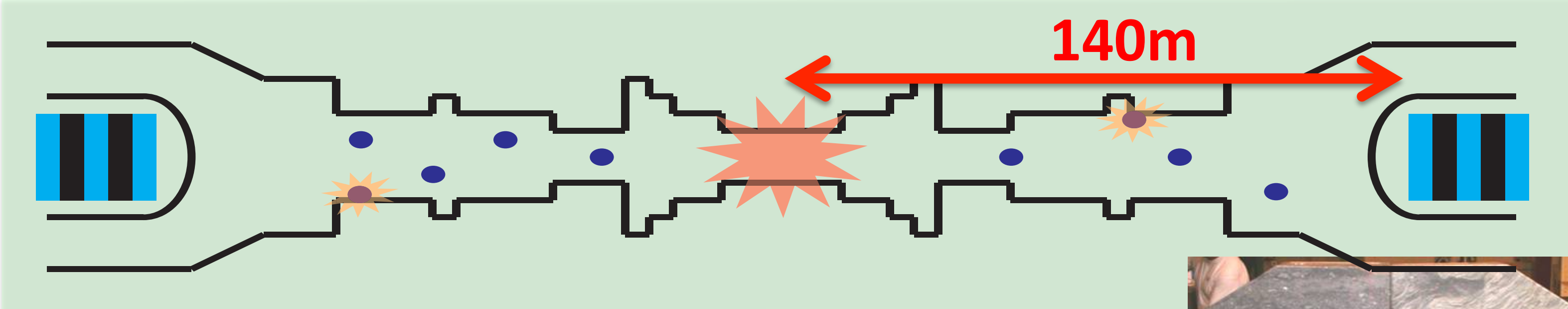
arXiv:1401.100

What's next? Let's start from p-Pb

- LHCf is certainly very interested in a possible high energy p-Pb run (2016-2017?)
  - Physics simulations are ongoing
  - We plan to present soon a LoI
  - Nuclear Modification factor can be measured at the highest energies

- Installation issues should be very carefully investigated
  - – TAN activation at the end of the long high luminosity pp run
  - + Remote handling system works very efficiently
  - + Past experience from the 2012 re-installation helped us and the RP team to better understand the modeling of the radioactive activation

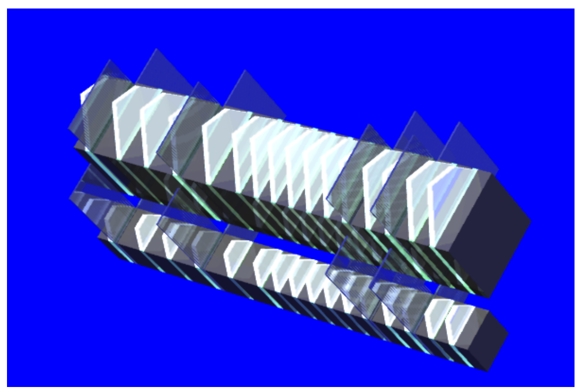
From LHCf to RHICf

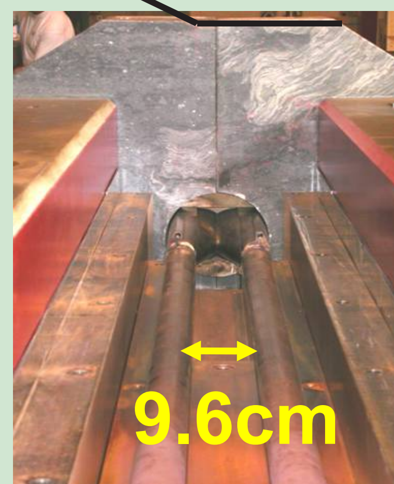


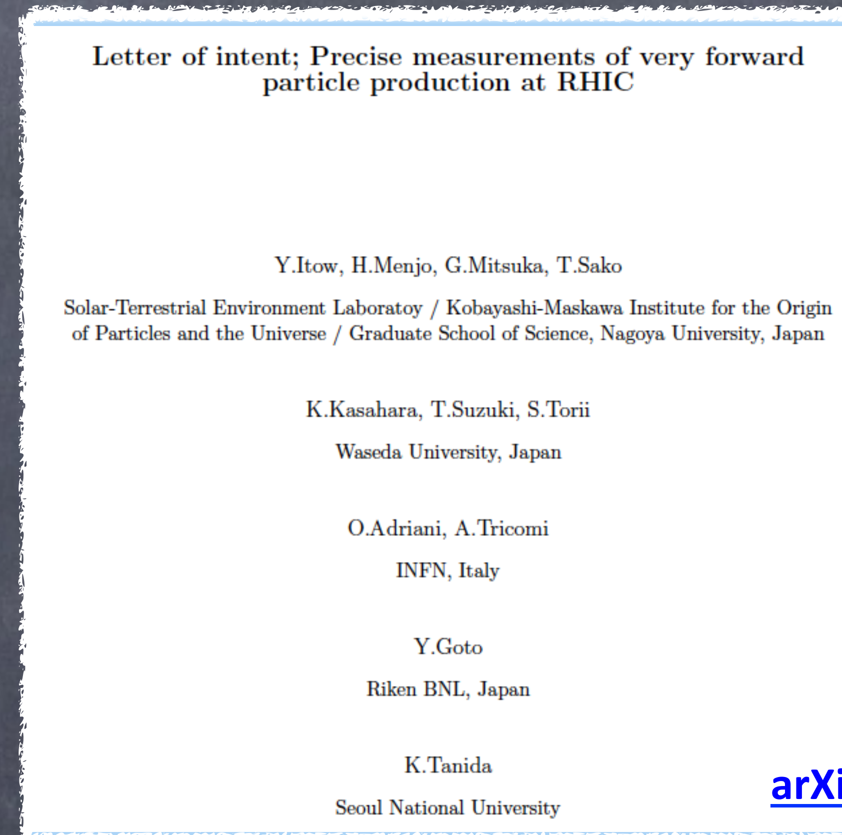
LHC

Why RHIC?

RHIC



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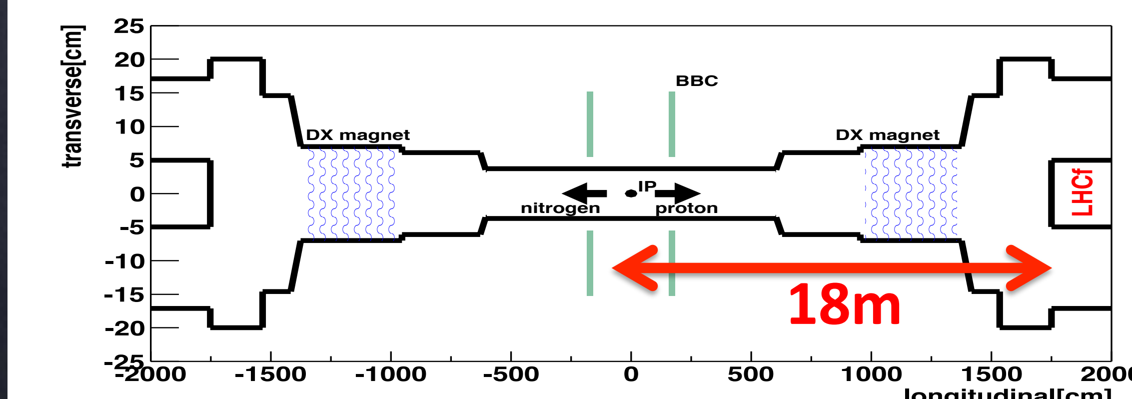
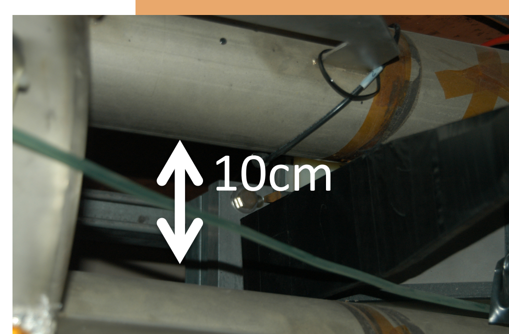
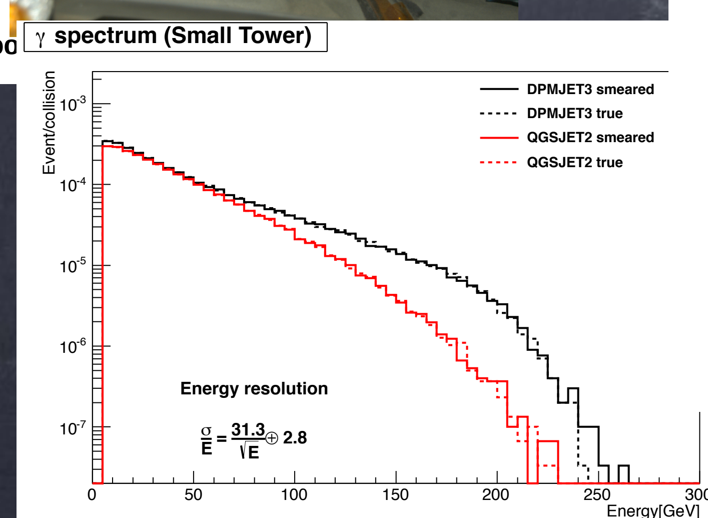
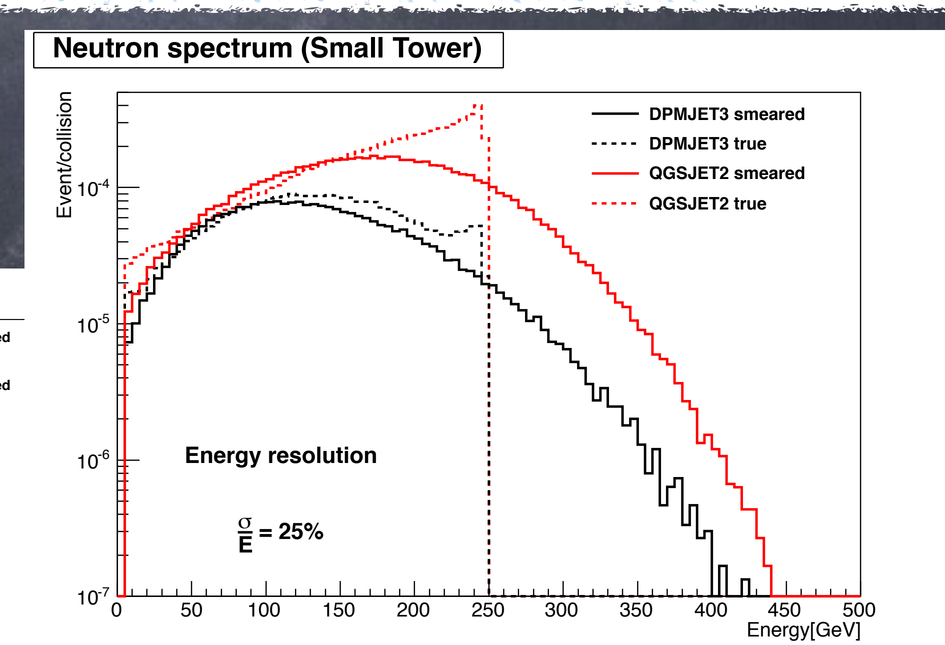








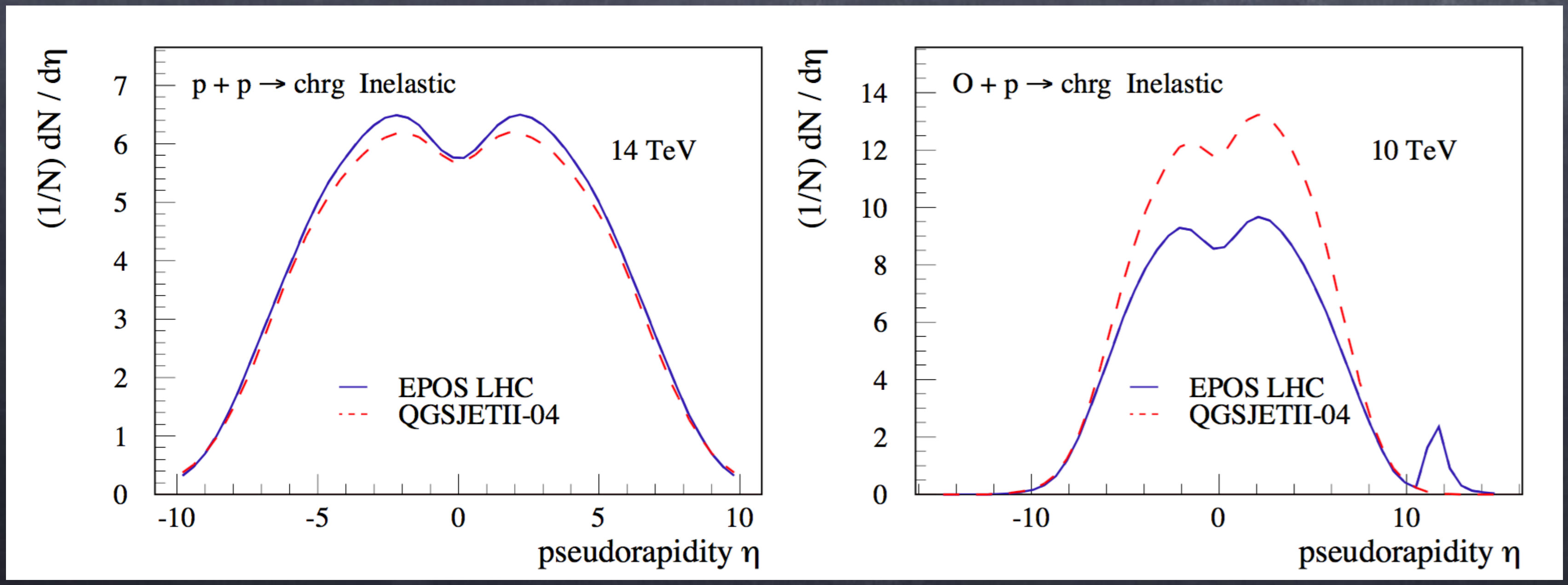
The Far Future at LHC

- The most promising future at LHC for LHCf involve the proton-light ion collisions

- To go from p-p to p-Air is not so simple....

  - Comparison of p-p, Pb-Pb and p-Pb is useful, but model dependent extrapolations are anyway necessary

- Direct measurements of p-O or p-N could significantly reduce some systematic effects



Summary

- Very forward γ, n and $\pi 0$ production in p-p and p-Pb collision have been precisely measured by LHCf at $E_{CM} \leq 7$ TeV
  - LHCf zero degree results are significantly contributing to improve our knowledge of hadronic interaction model fro HECR Physics
  - New results with hadrons are particularly interesting to understand the muon excess
  - p-Pb results give important hints to understand nuclear medium effect
- Very successful 13 TeV pp run has been done in June 2015
  - Analysis is on going
- For the future at LHC we are certainly interested in:
  - Higher energy p-Pb collisions in 2016-2017
  - p-Light ions at LHC in the far future
- We are also approved to take data at RHIC in 2017
- Still a lot of results will come in the next years so... stay tuned!

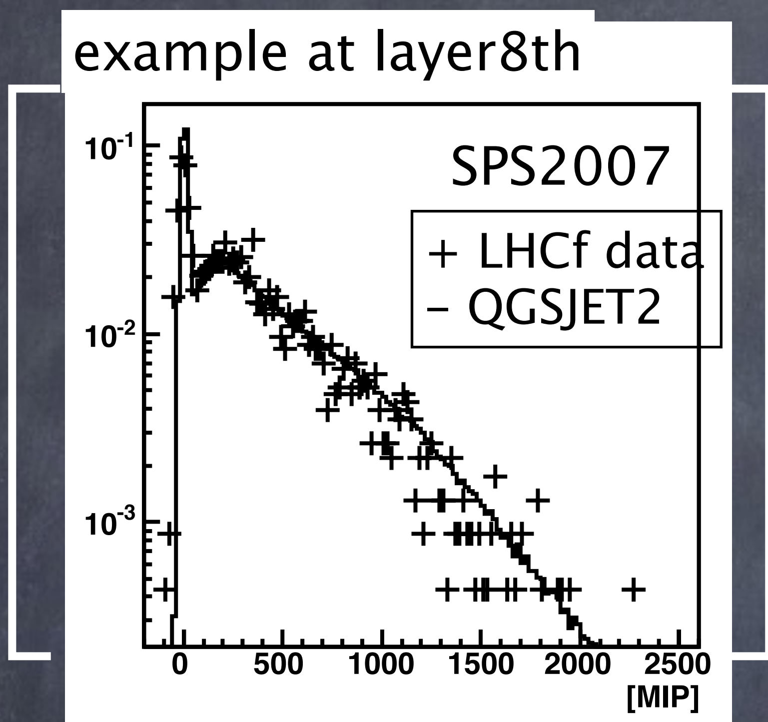
Back up slides

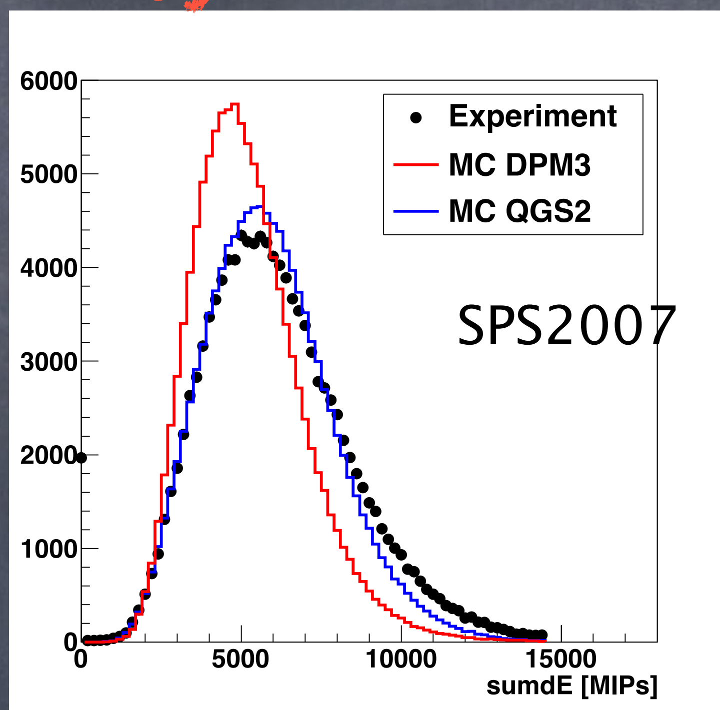
LHCf @ pp 7 TeV: neutron analysis

Neutron energy reconstruction

JINST 9 (2014)P03016

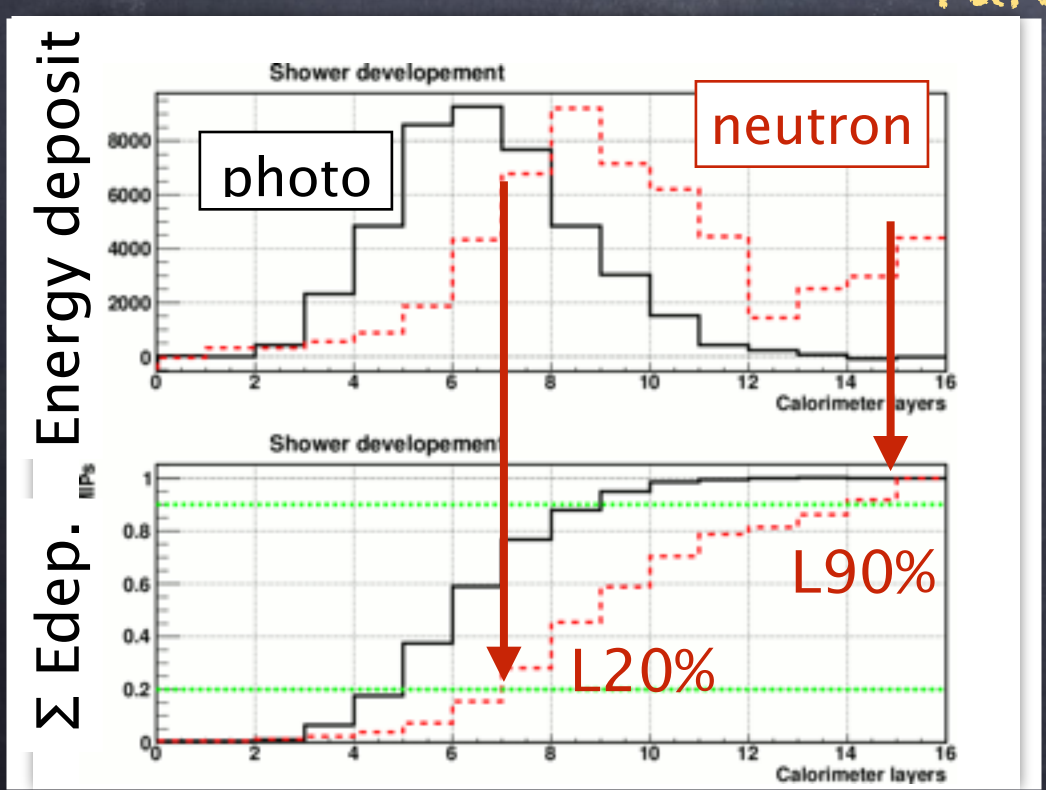
$$\sum_{l=2}^{15} \left[\quad \right] =$$

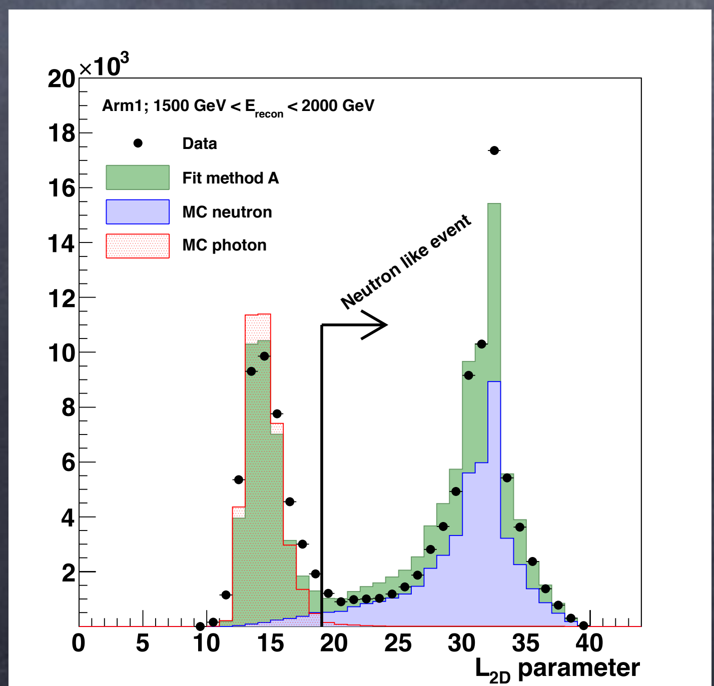




- Neutron energy is reconstructed by a sum of energy deposits.
- Detector simulation based on QGSJET2 for hadronic shower reproduces the test beam data better than that on DPMJET3.
- Difference between QGSJET2 and the test beam data is taken into account as a systematic error in the latter analysis.

Particle identification

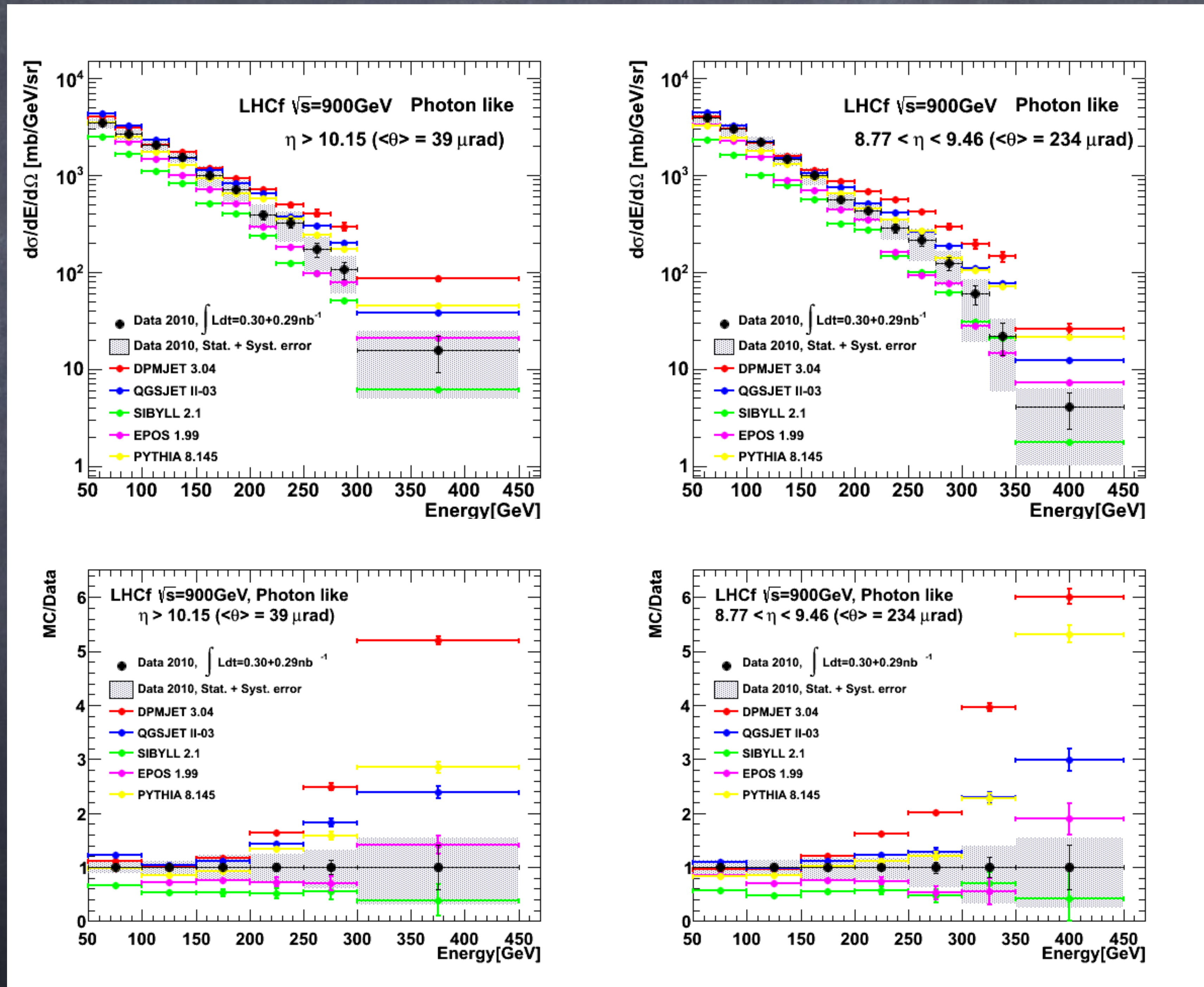




$L_{2D} = L90\% - 0.25 * L20\%$

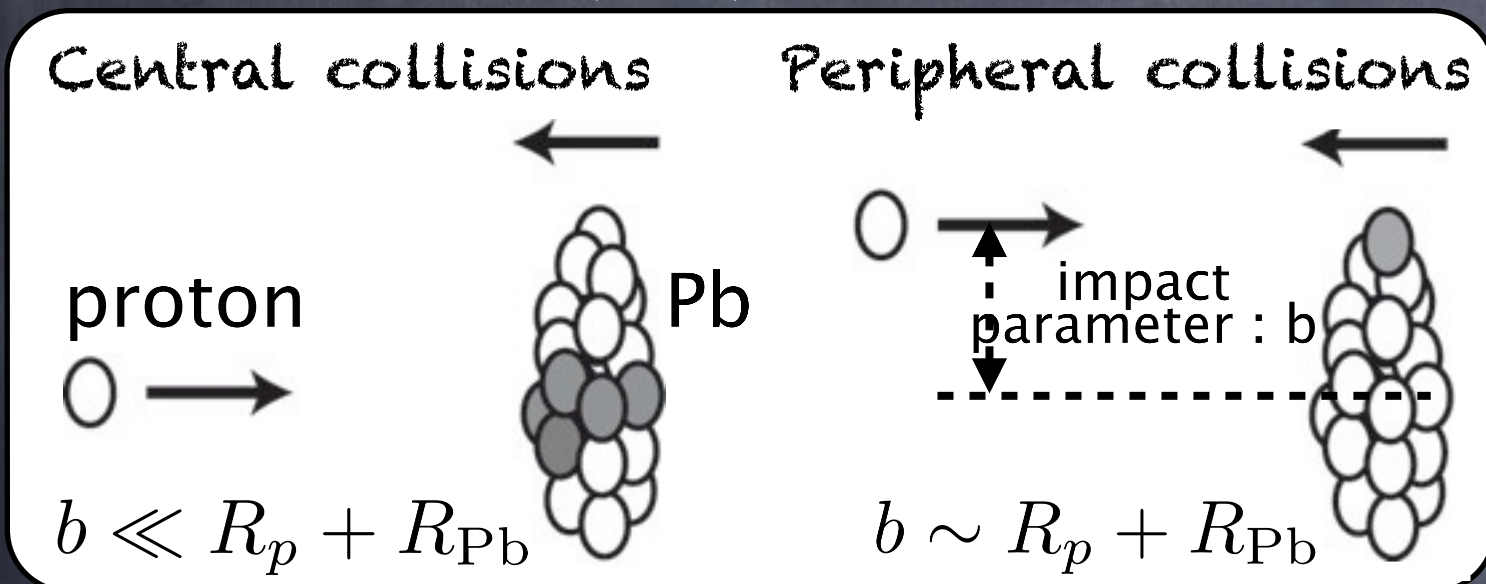
- With two variables, L90% and L20%, PID performance is improved to reduce the photon contamination in neutron events.
- PID efficiency and purity are >90%.
- Energy spectra are corrected for PID inefficiency and BG contamination.

LHCf @ pp 900 GeV:
Single photon spectra MC vs Data

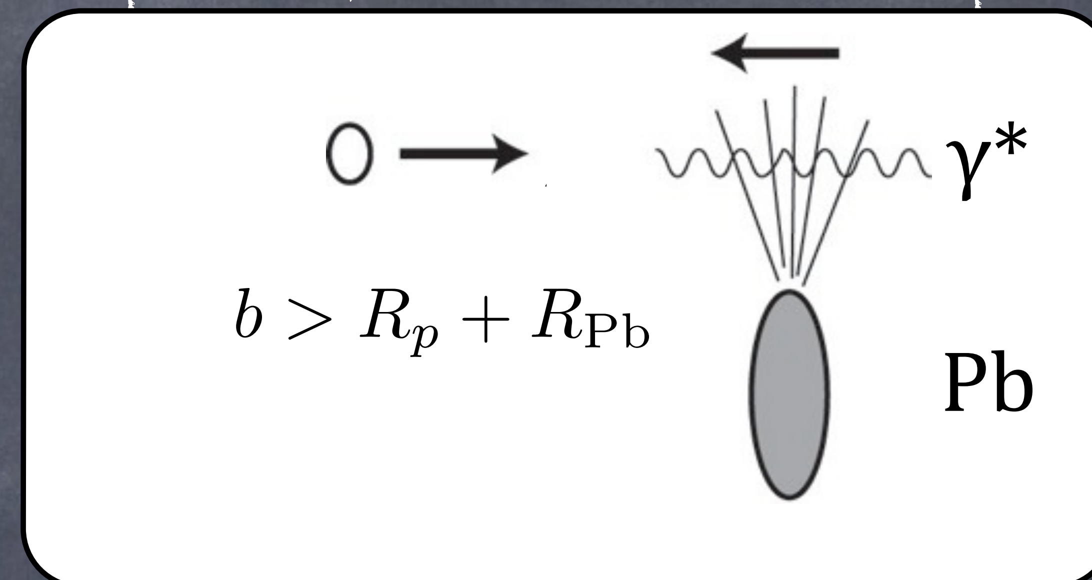


LHCf @ pPb 5.02 TeV: π^0 analysis

(Soft) QCD :
central and peripheral collisions



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



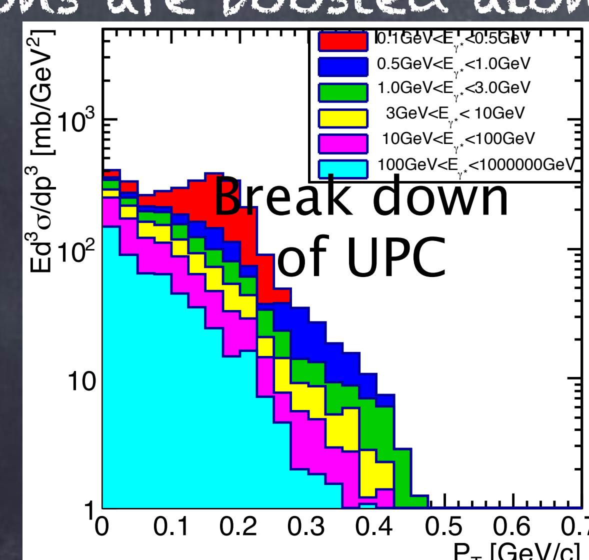
Momentum distribution of the UPC induced secondary particles is estimated as
1. energy distribution of virtual photons is estimated by the Weizsacker Williams approximation.
2. photon-proton collisions are simulated by the SOHIA model (E_γ > pion threshold).
3. produced mesons and baryons by γ-p collisions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

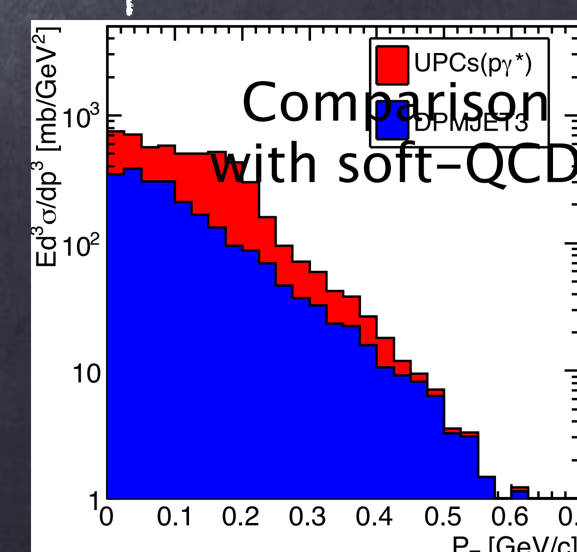
(proton rest frame)

Dominant channel to forward π^0 is

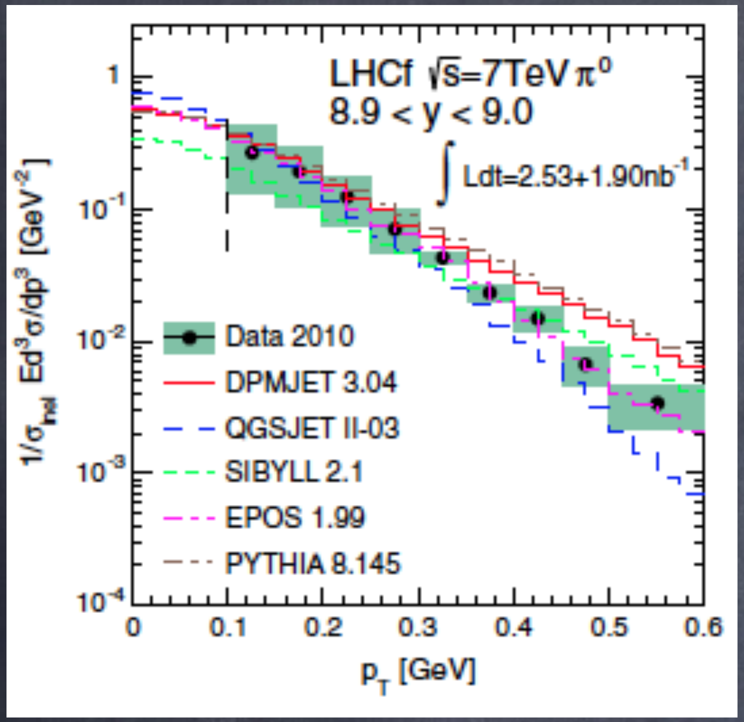
$$\gamma + p \rightarrow \Delta(1232) \rightarrow p + \pi^0$$

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

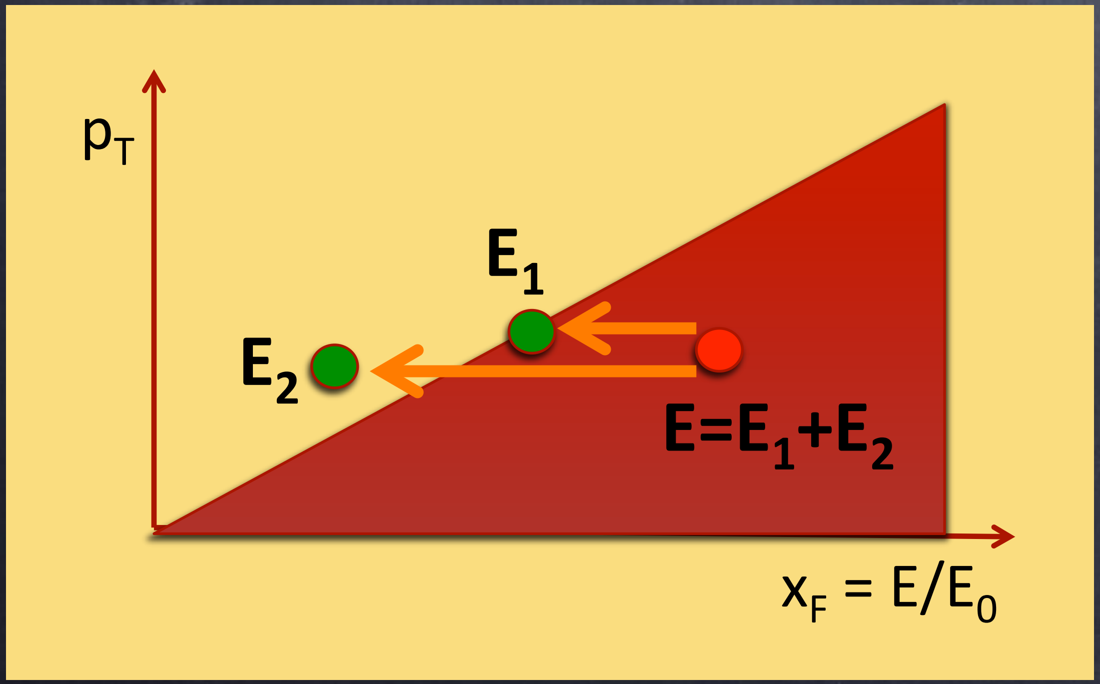


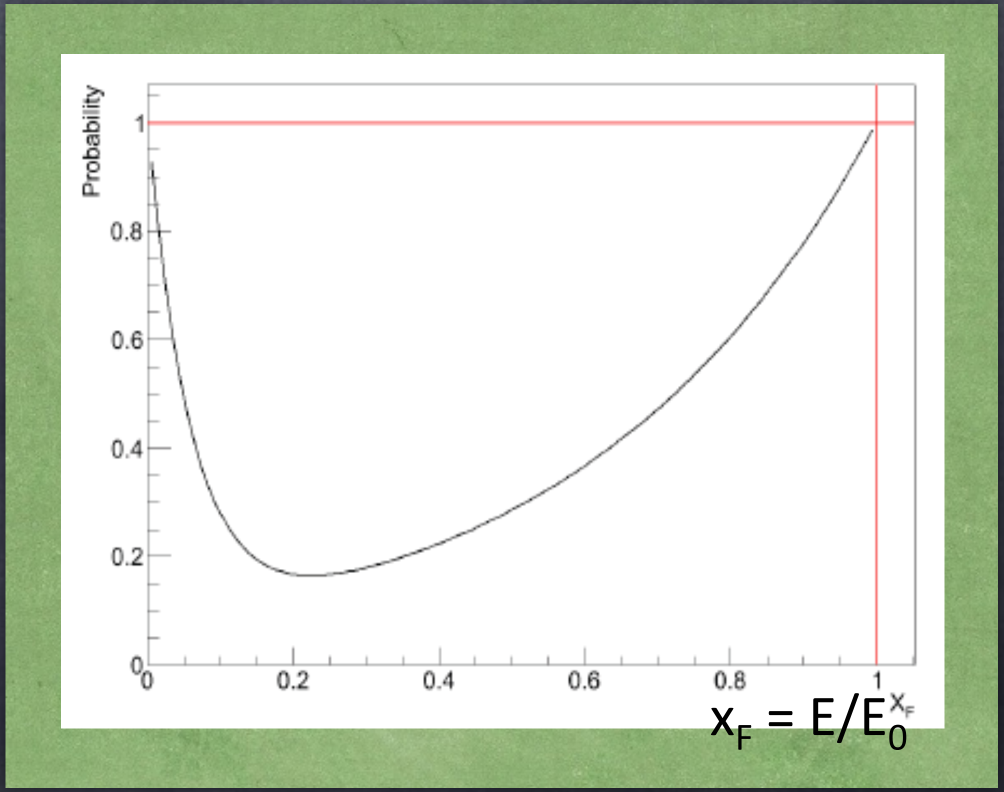


Playing a game with air shower – effect of forward meson spectra

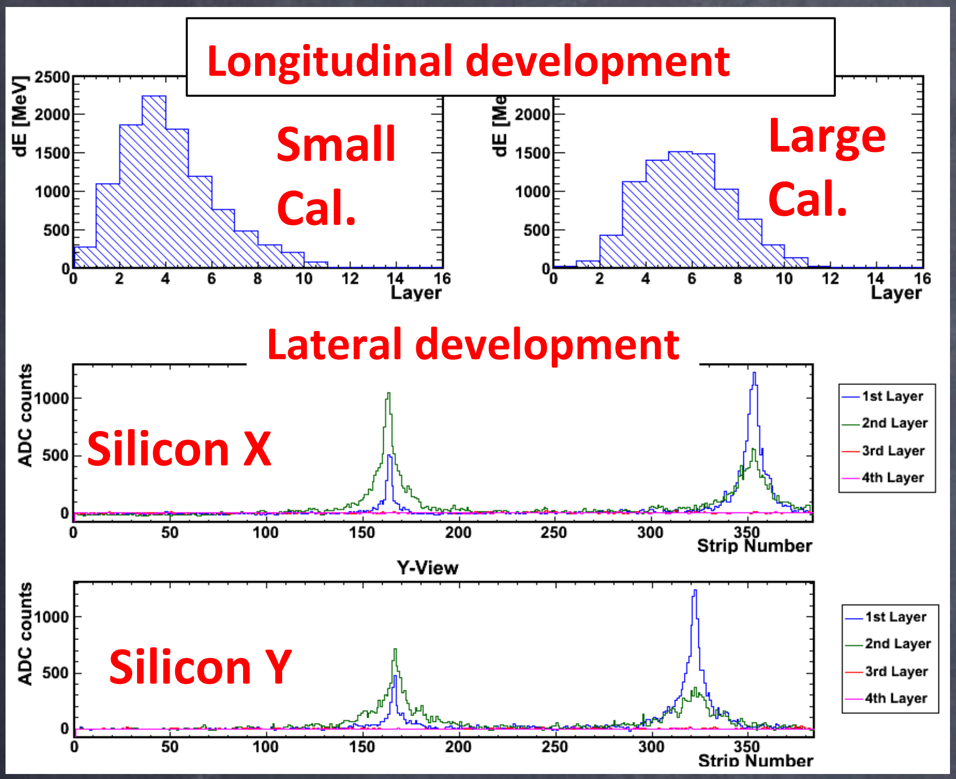


- DPMJET3 always over-predicts production
- Filtering DPMJET3 mesons
  - according to an empirical probability function, divide mesons into two with keeping p_T
  - Fraction of mesons escape out of LHCf acceptance
- This process
  - Holds cross section
  - Holds elasticity/inelasticity
  - Holds energy conservation
  - Changes multiplicity
  - Does not conserve charge event-by-event

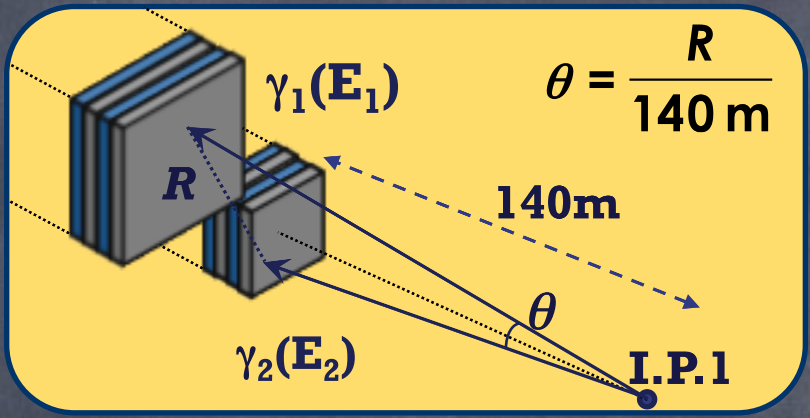




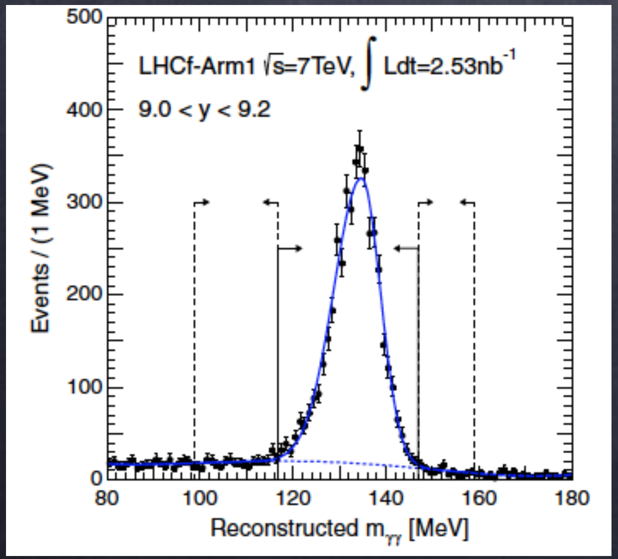
LHCf @ pp 7 TeV & p-Pb 5 TeV: π^0 analysis



Mass, energy and transverse momentum are reconstructed from the energies and impact positions of photon pairs measured by each calorimeter



$$M_{\pi^0} = \sqrt{E_{\gamma 1} E_{\gamma 2} \theta^2},$$
$$E_{\pi^0} = E_{\gamma 1} + E_{\gamma 2},$$
$$P_{T\pi^0} = P_{T\gamma 1} + P_{T\gamma 2}$$



Analysis Procedure

Standard photon reconstruction

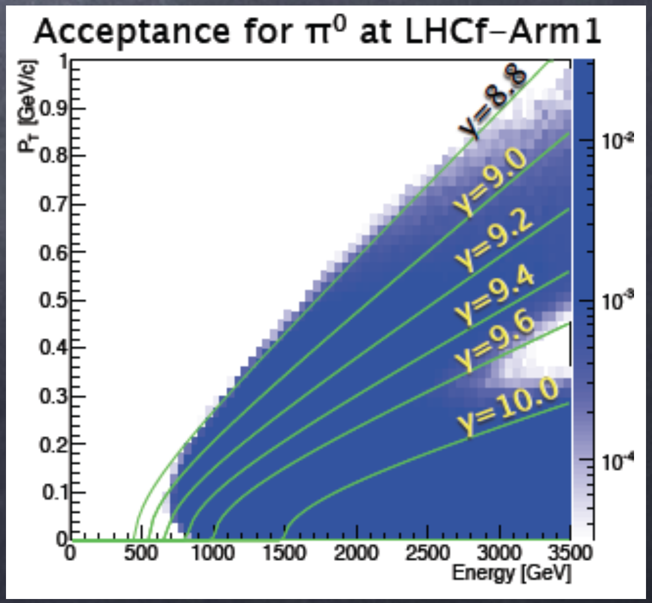
Event selection
- one photon in each calorimeter
- reconstructed invariant mass

Background subtraction
by using outer region of mass peak

Unfolding for detector response.

Acceptance correction.

Dedicated part for π^0 analysis



LHCf @ pp 7 TeV: π^0 p_T spectra

dpmjet 3.04 & pythia 8.145

- overall agreement with LHCf data for 9.2<y<9.6 and p_T <0.25 GeV/c
- the expected π^0 production rates by both models exceed the LHCf data as p_T becomes large

sibyll 2.1

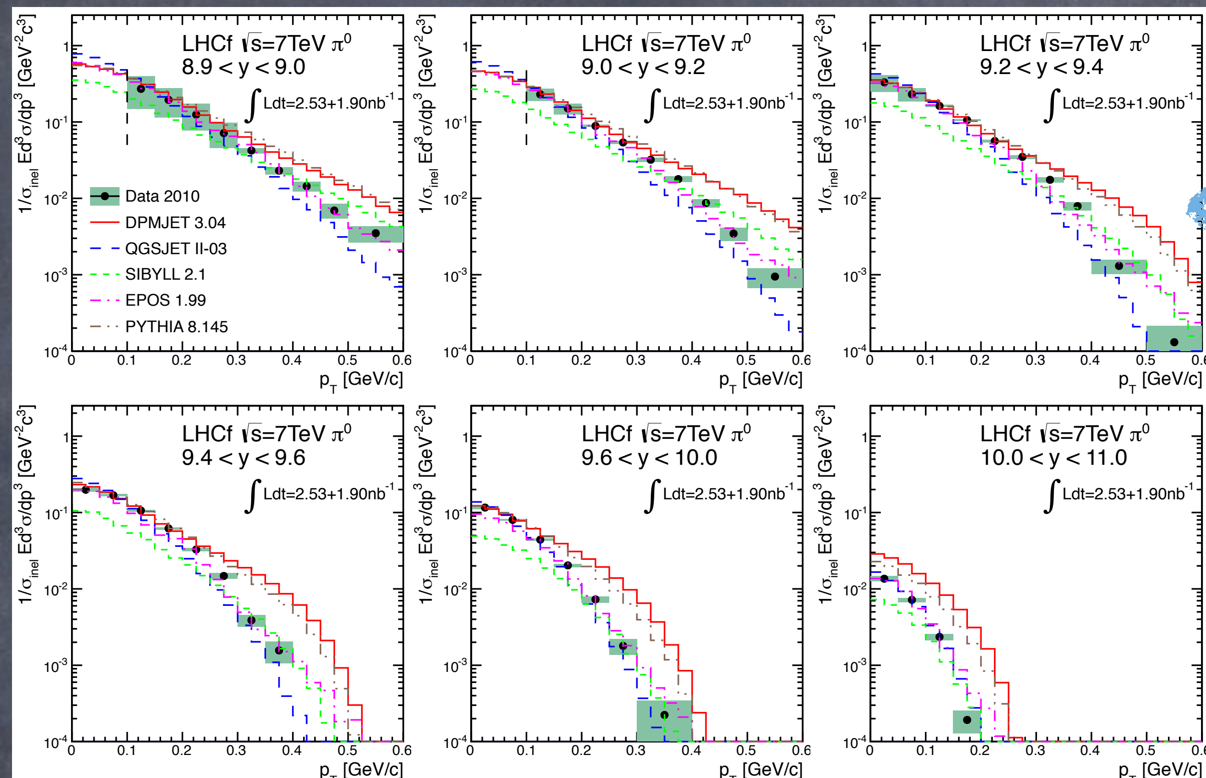
- predicts harder pion spectra than data
- the expected π^0 yield is generally small

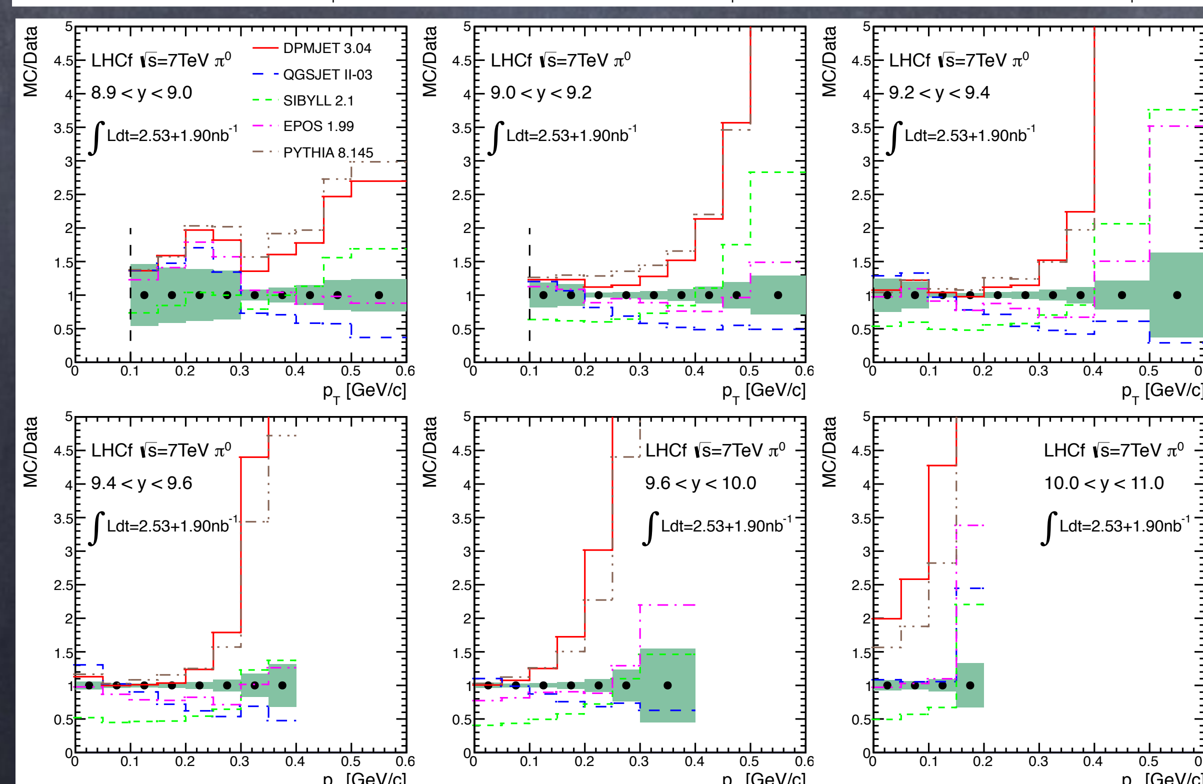
qgsjet II-03

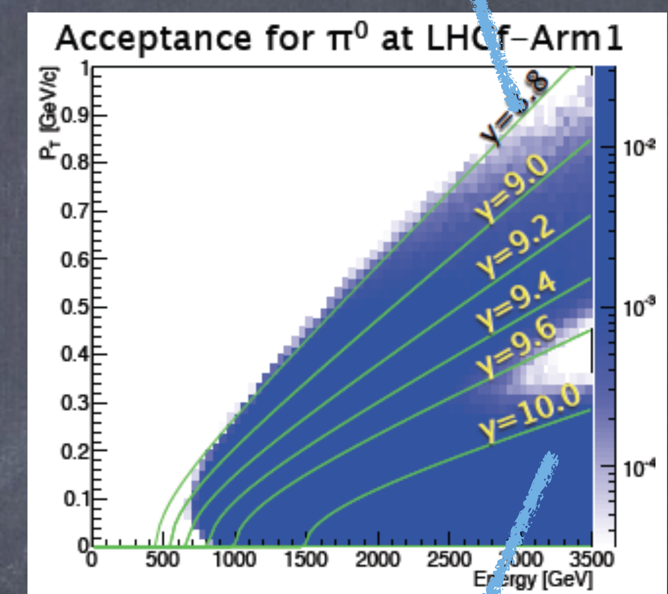
- predicts π^0 spectra softer than LHCf data

epos 1.99

- shows the best overall agreement with the LHCf data:
- behaves softer in the low p_T region, p_T < 0.4GeV/c in 9.0<y<9.4 and p_T <0.3GeV/c in 9.4<y<9.6
- behaves harder in the large p_T region.



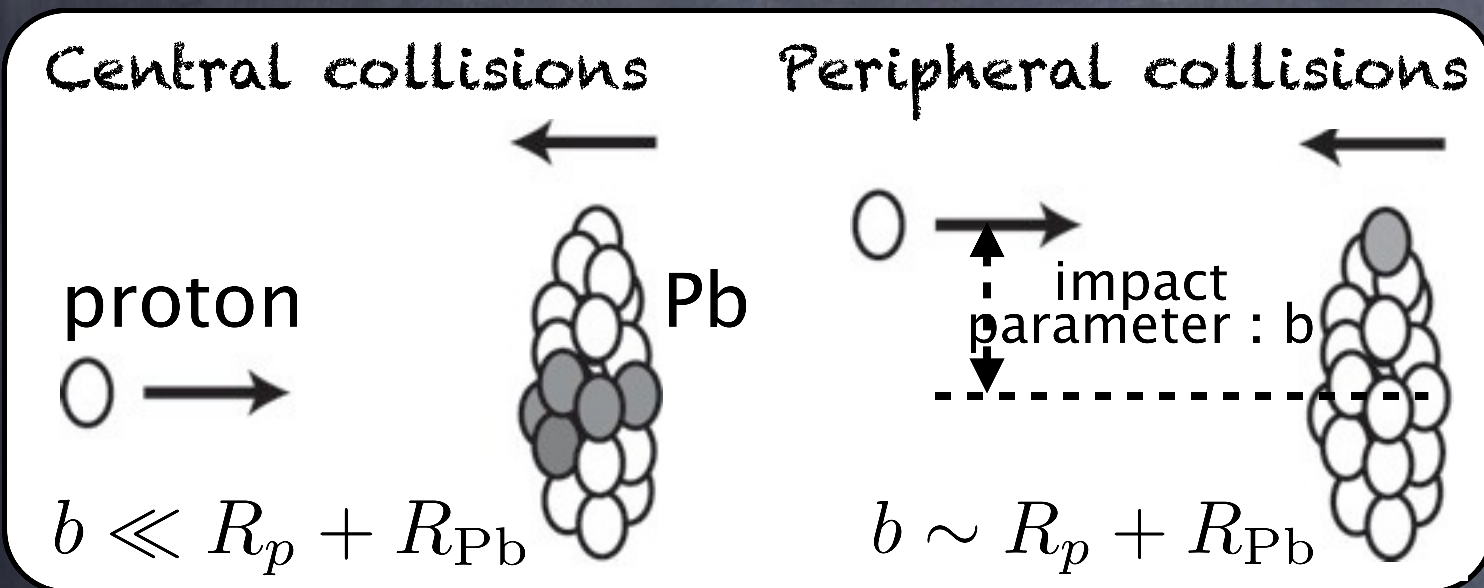


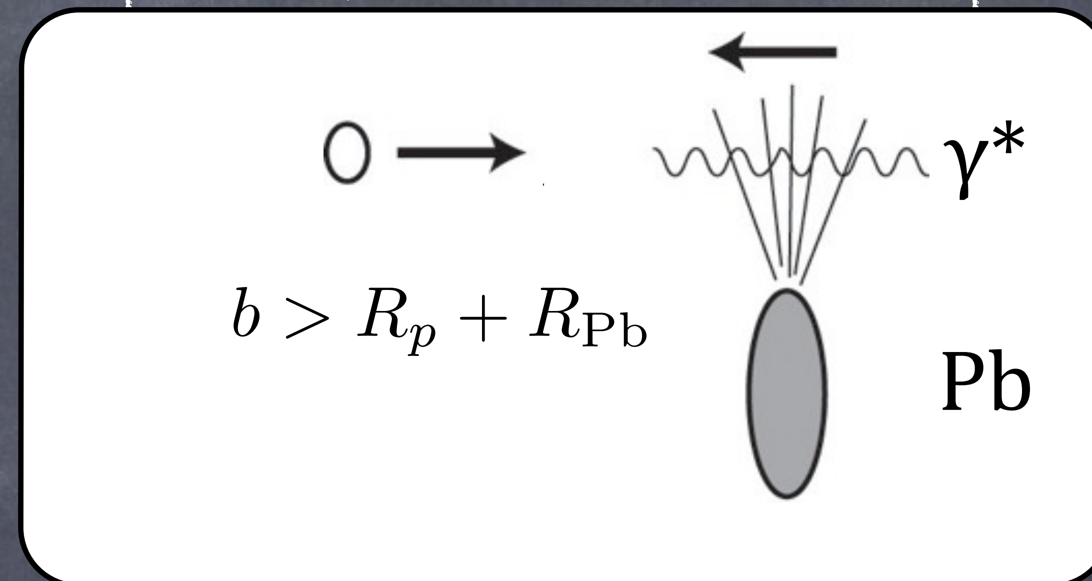


LHCf @ pPb 5.02 TeV: π^0 analysis

(Soft) QCD :
central and peripheral collisions

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



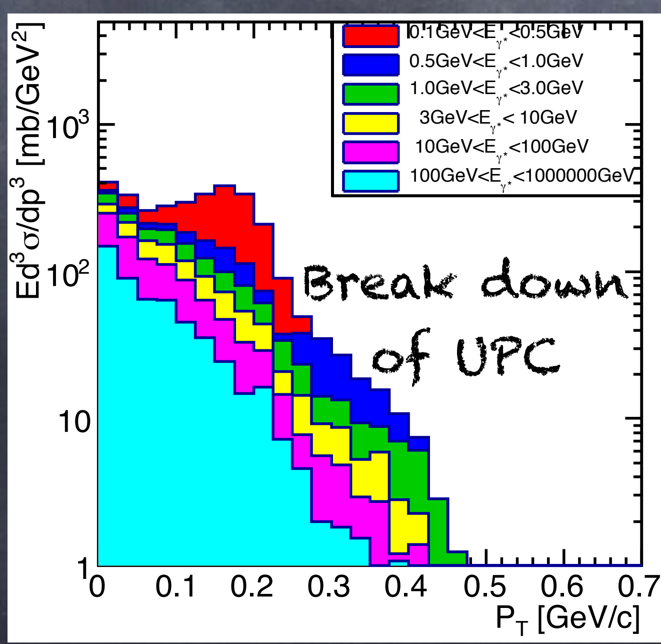


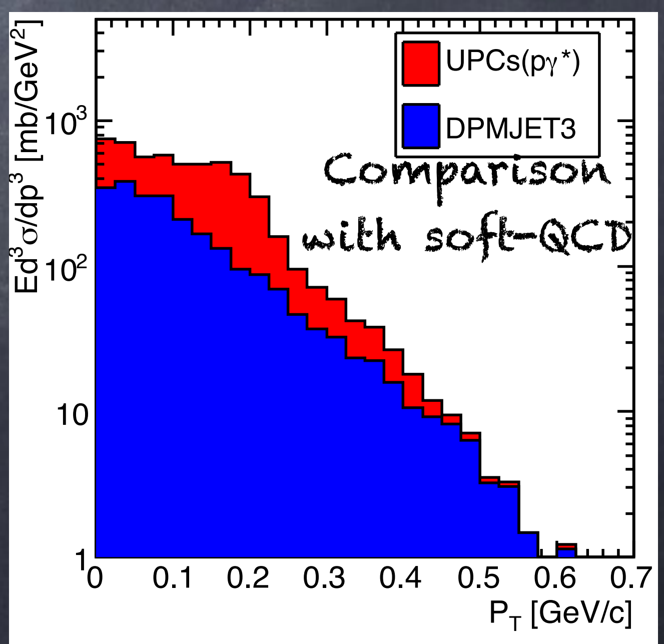
Dominant channel to forward π^0 is

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

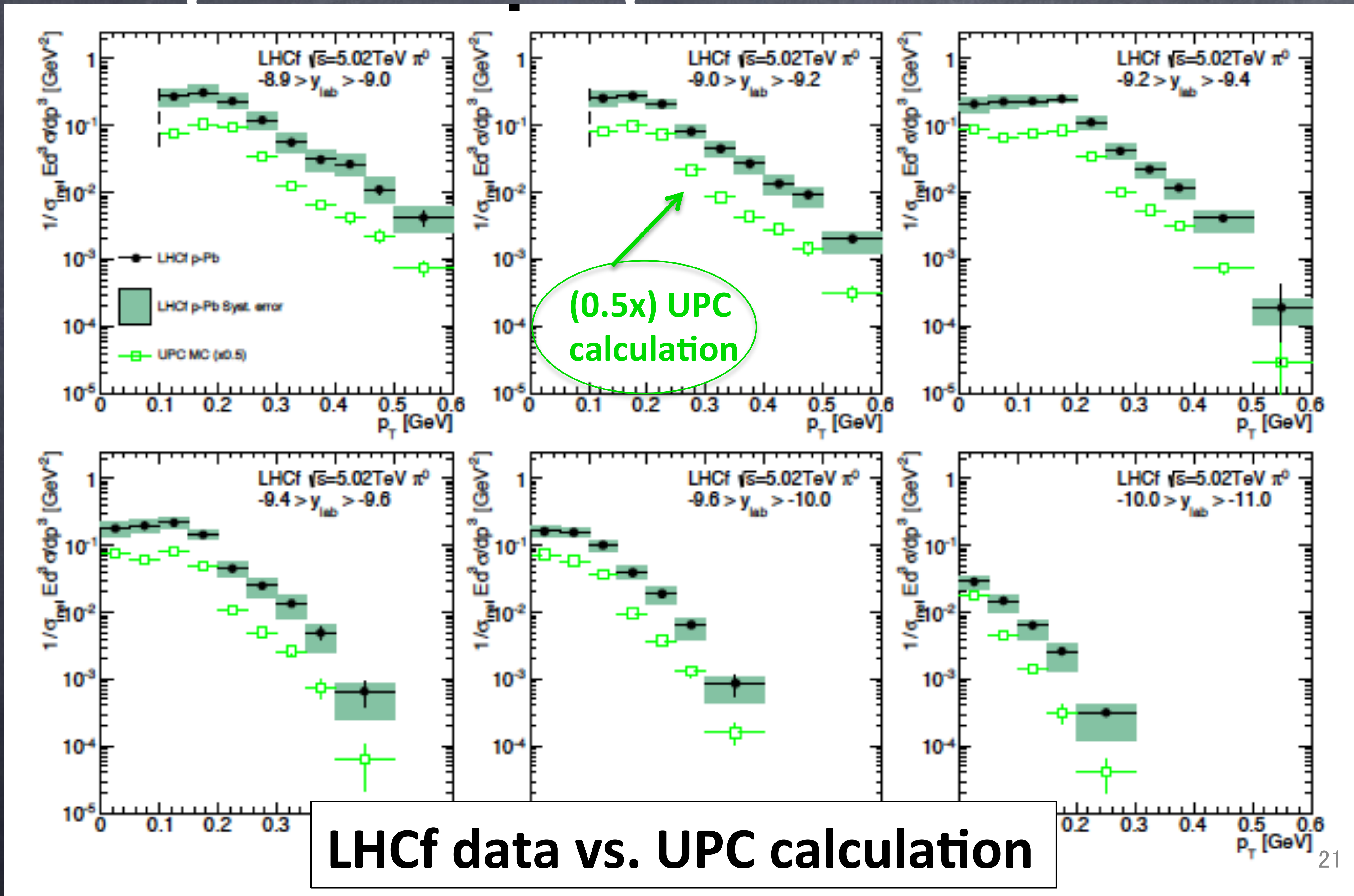
About half of the observed π^0 may originate in UPC, another half is from soft-QCD

Need to subtract UPC component





LHCf @ pPb 5.02 TeV: π° spectra @ p-remnant side



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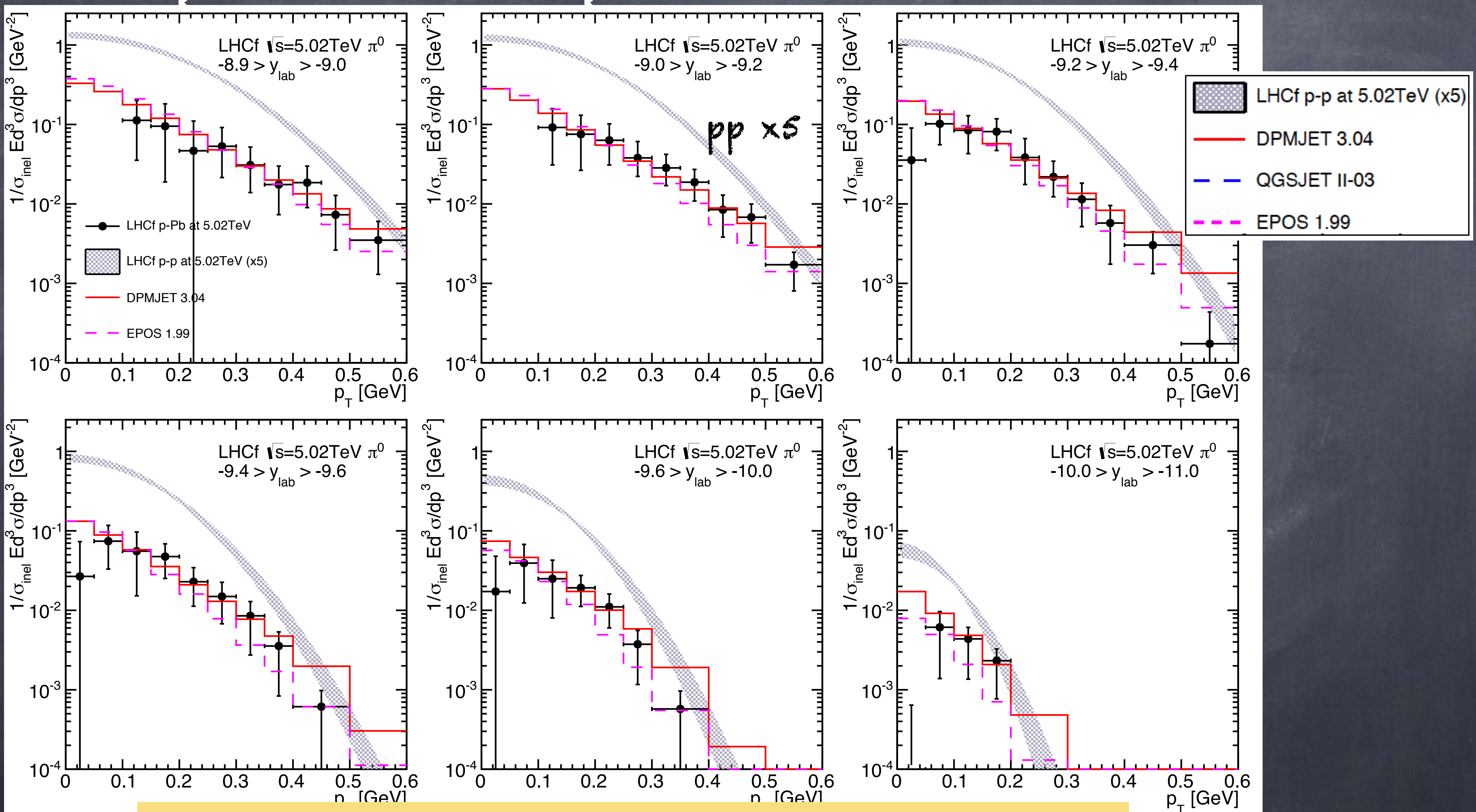
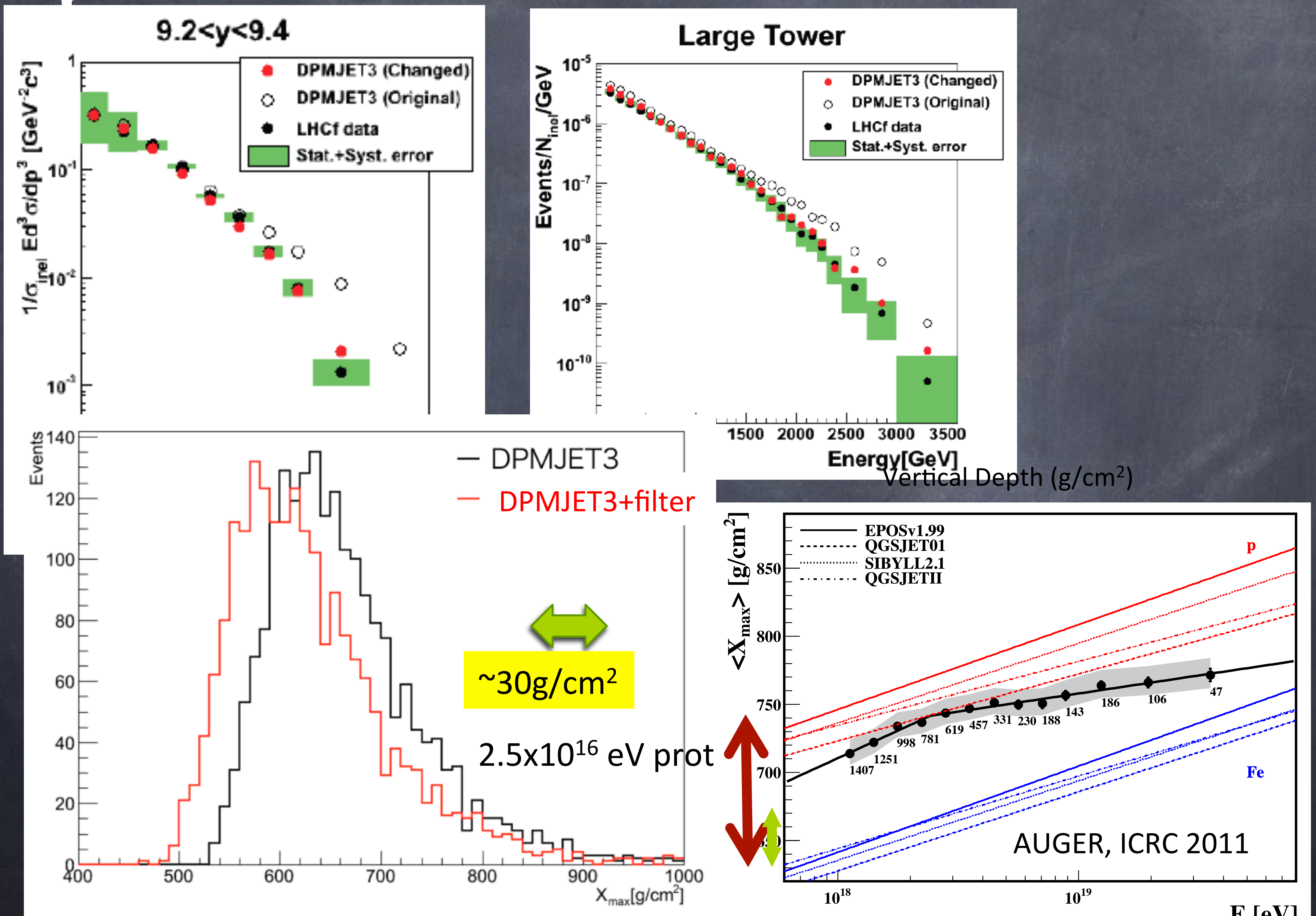


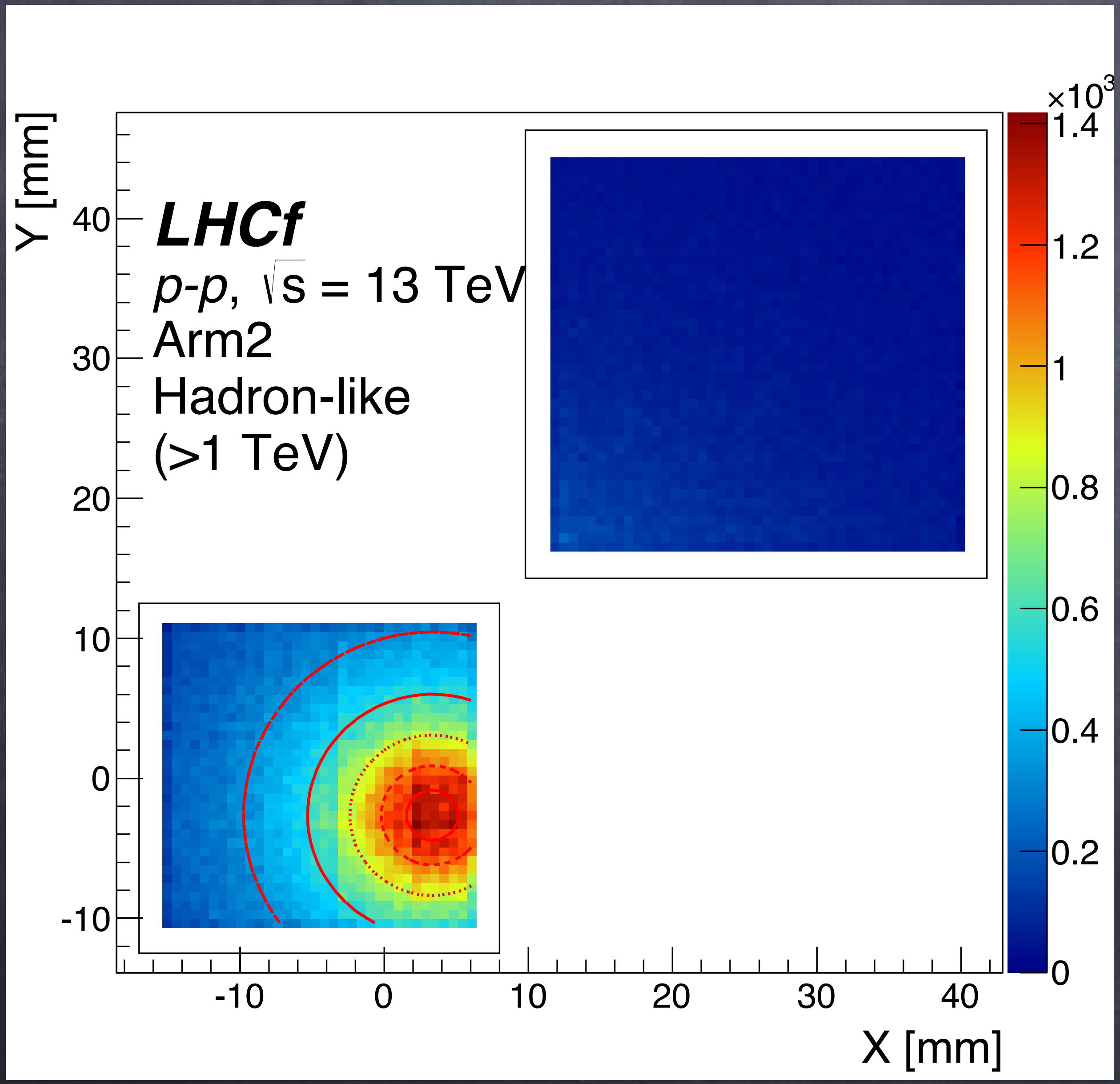
LHCf Data (UPC subtracted) vs Models

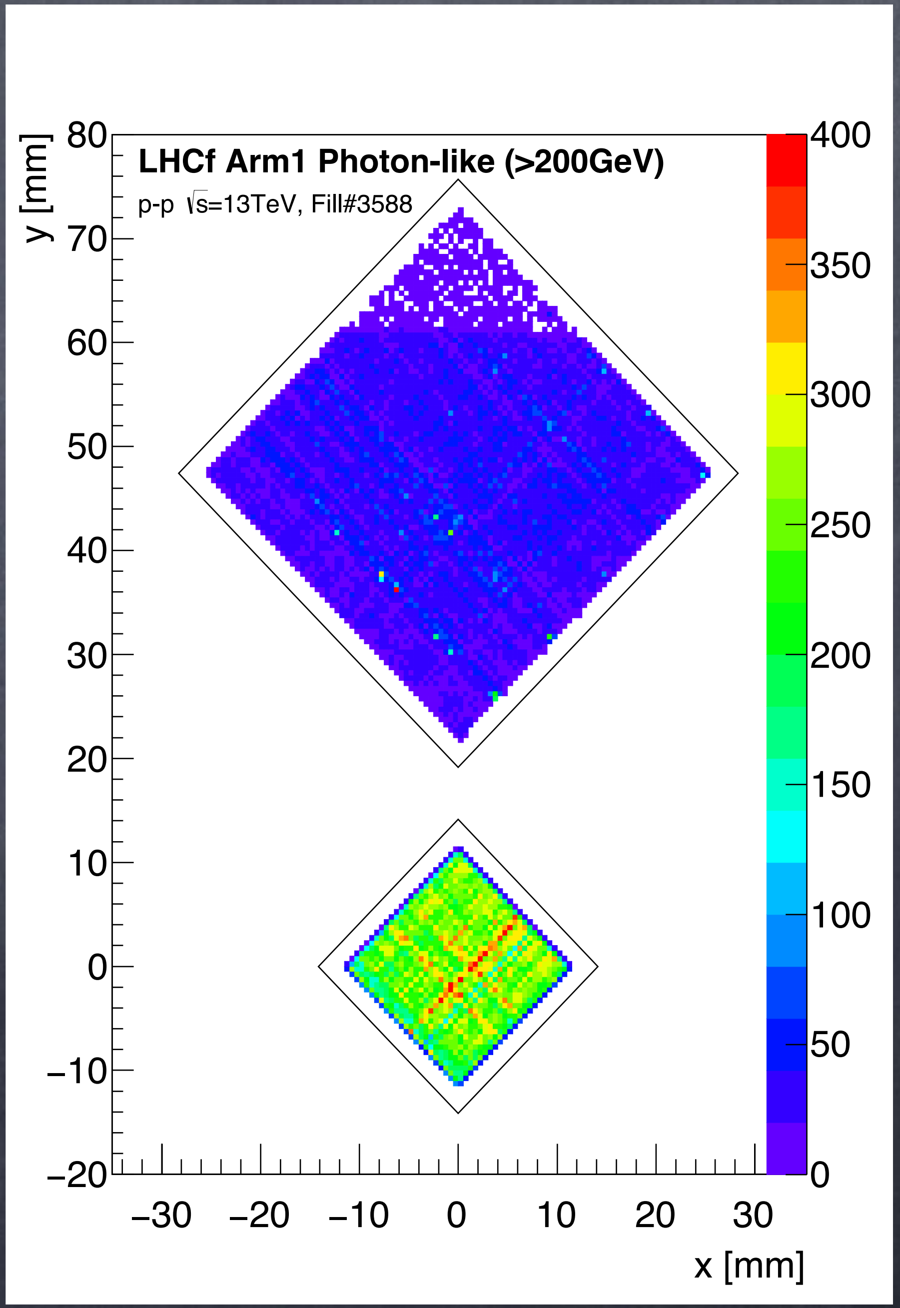
- The LHCf results in p-Pb (filled circles) show good agreement with DPMJET and EPOS.
- The LHCf results in p-Pb are clearly harder than the LHCf results in p-p at 5.02TeV (shaded area) which are interpolated from the results at 2.76TeV and 7TeV.

Impact of LHCf measurement

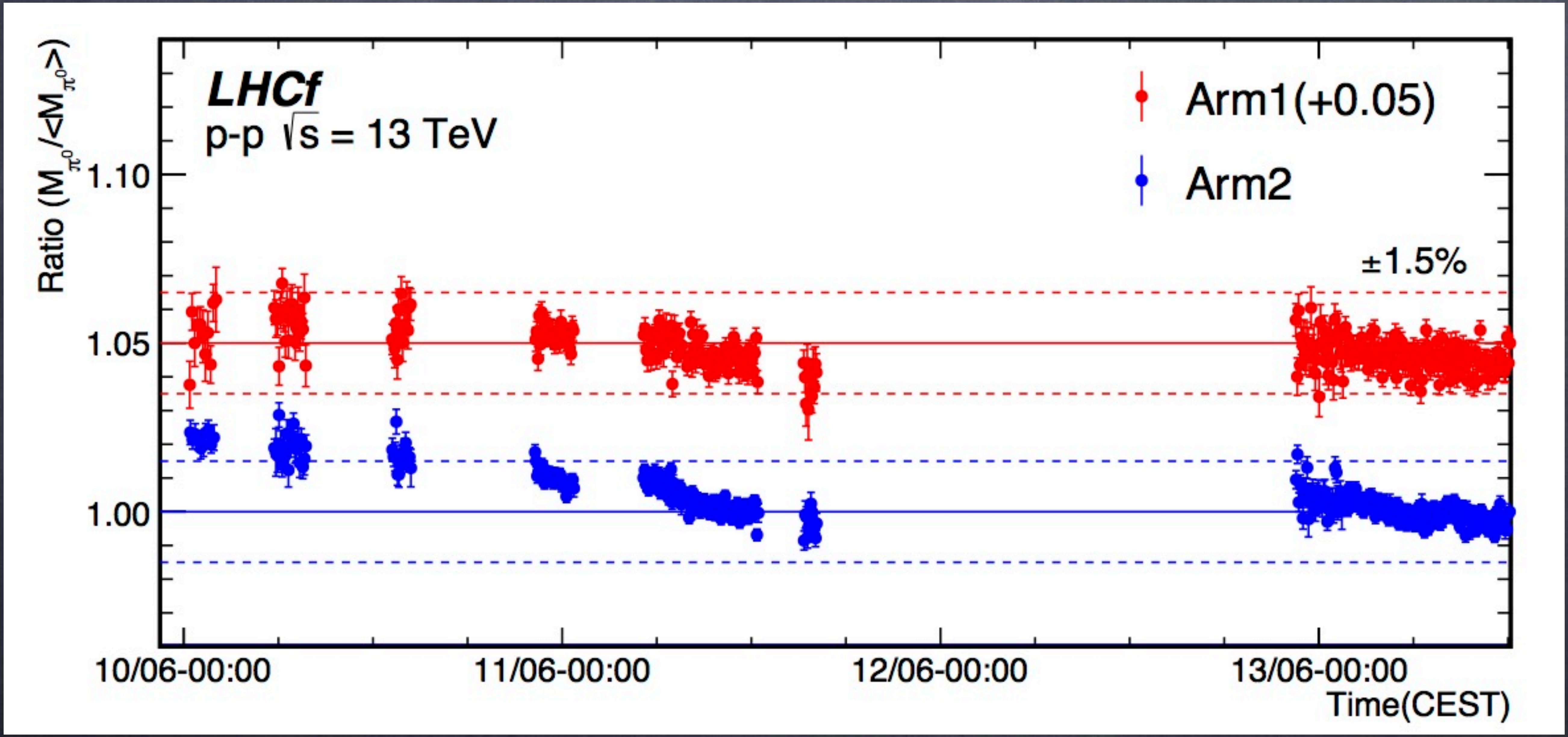


Analysis workflow: determination of the beam center

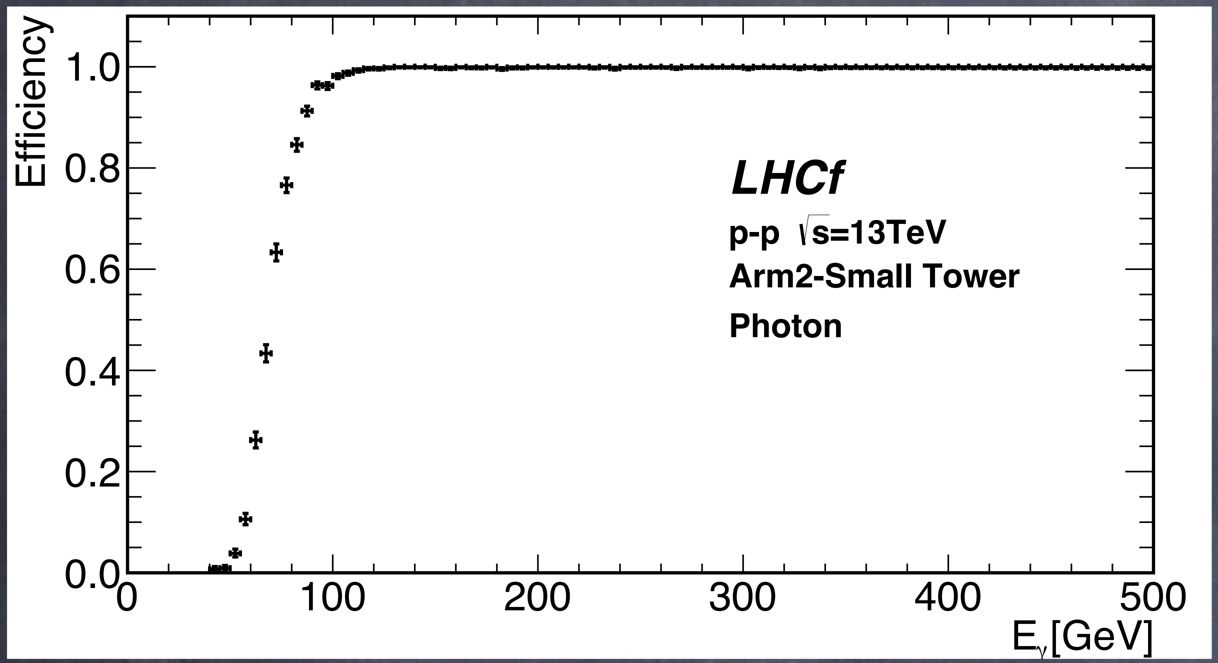




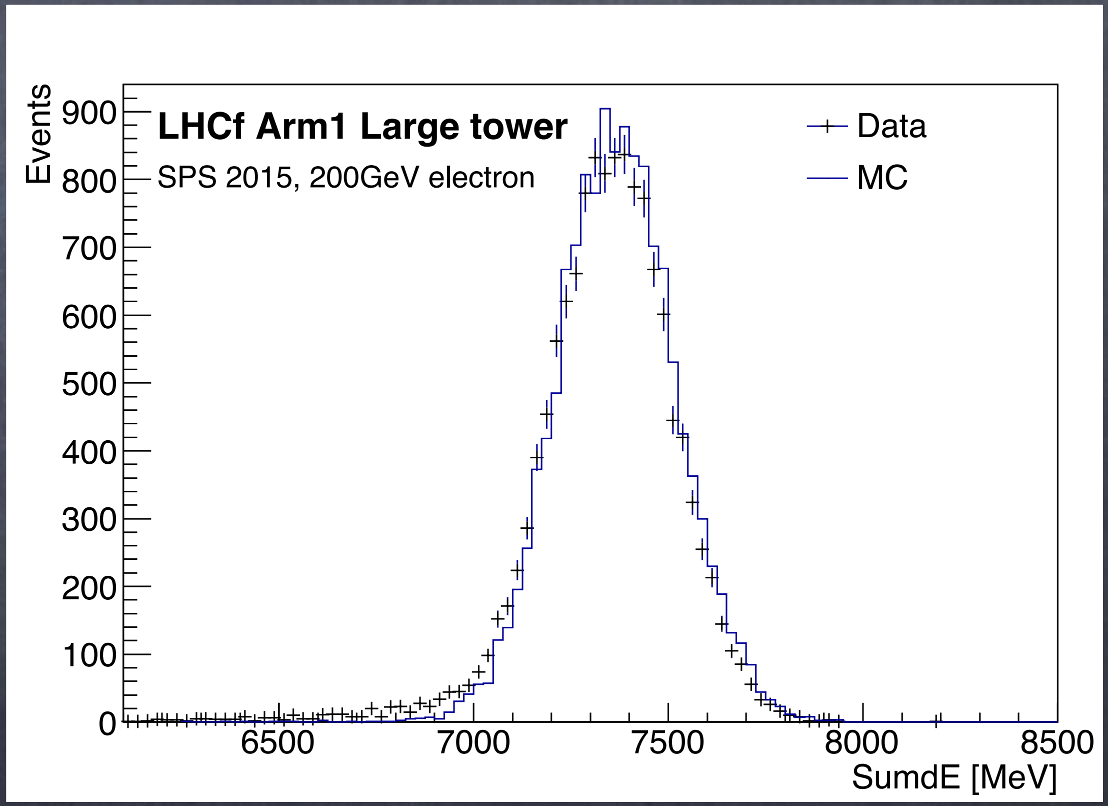
π^0 mass stability



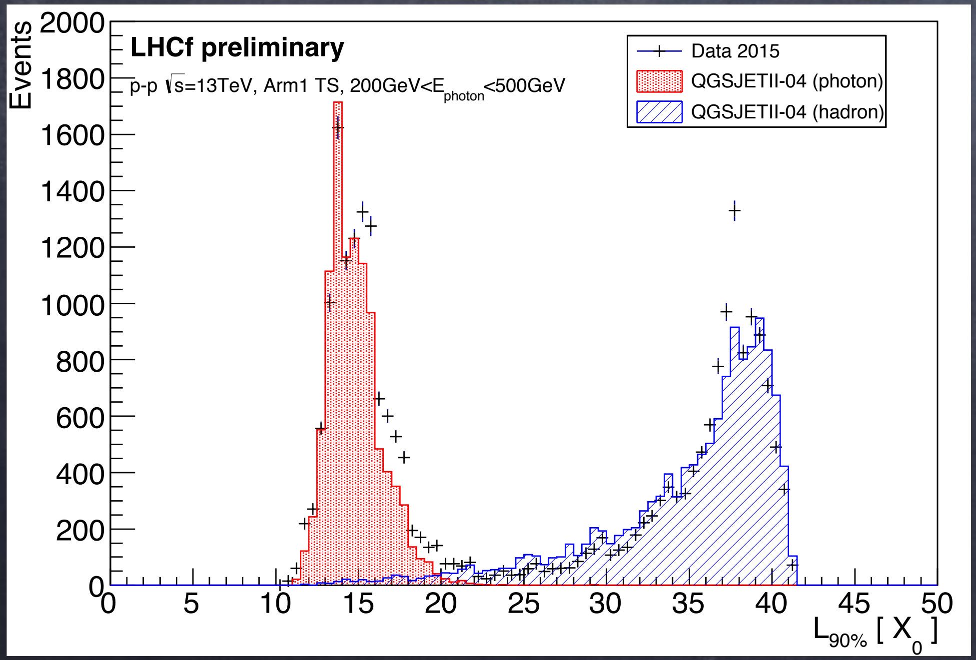
Analysis workflow: selections and reconstructions



Trigger efficiency:
Fully efficient for E>100 GeV

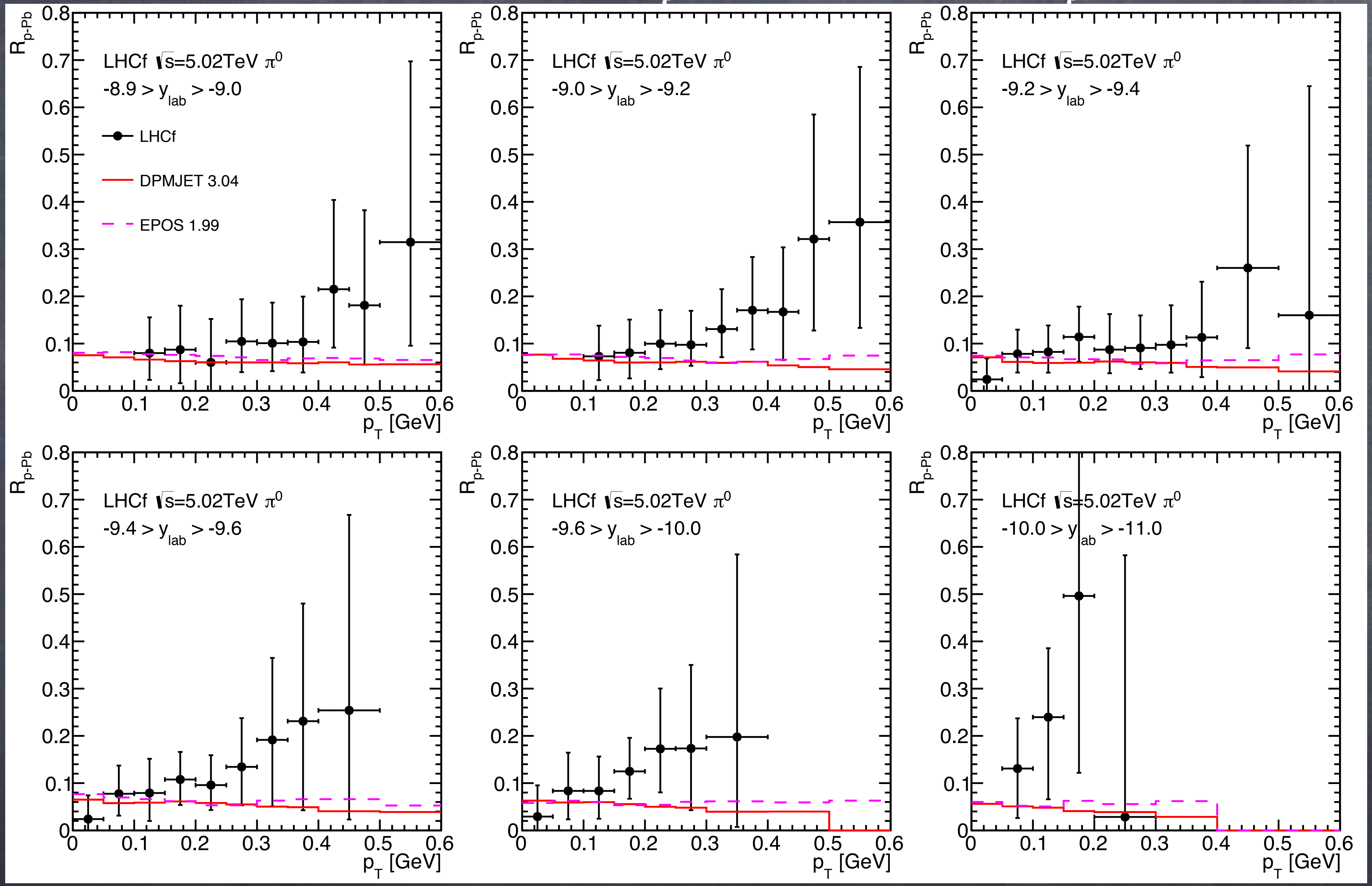


Energy calibration based on SPS beam test



PID based on longitudinal profile distribution ($L_{90\%}$)

LHCf @ pPb 5.02 TeV: Nuclear modification factor



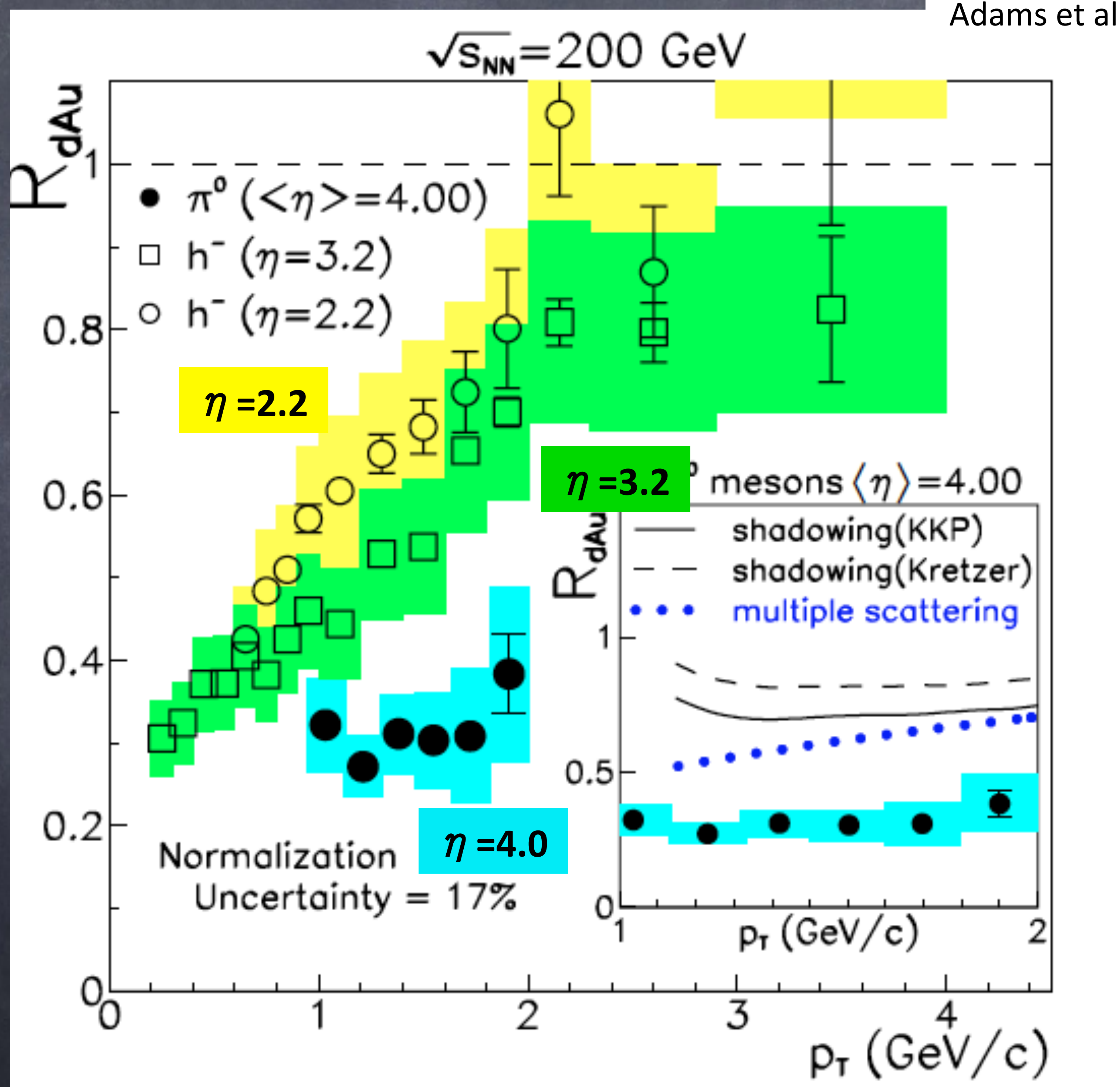
$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) \equiv \frac{d^2N_{\pi^0}^{\mathrm{pPb}}/dydp_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle d^2N_{\pi^0}^{\mathrm{pp}}/dydp_{\mathrm{T}}}$$

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

- 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.

Nuclear modification factor

RHIC 200GeV d-Au, STAR Collaboration
Adams et al., PRL 97 (2006) 152302.



LHCf @ pPb 5.02 TeV vs RHIC: Nuclear modification factor