CRIS2016 -10th Cosmic Ray International Seminar
Ischia, july 4-8 2016

LHCf Highlights

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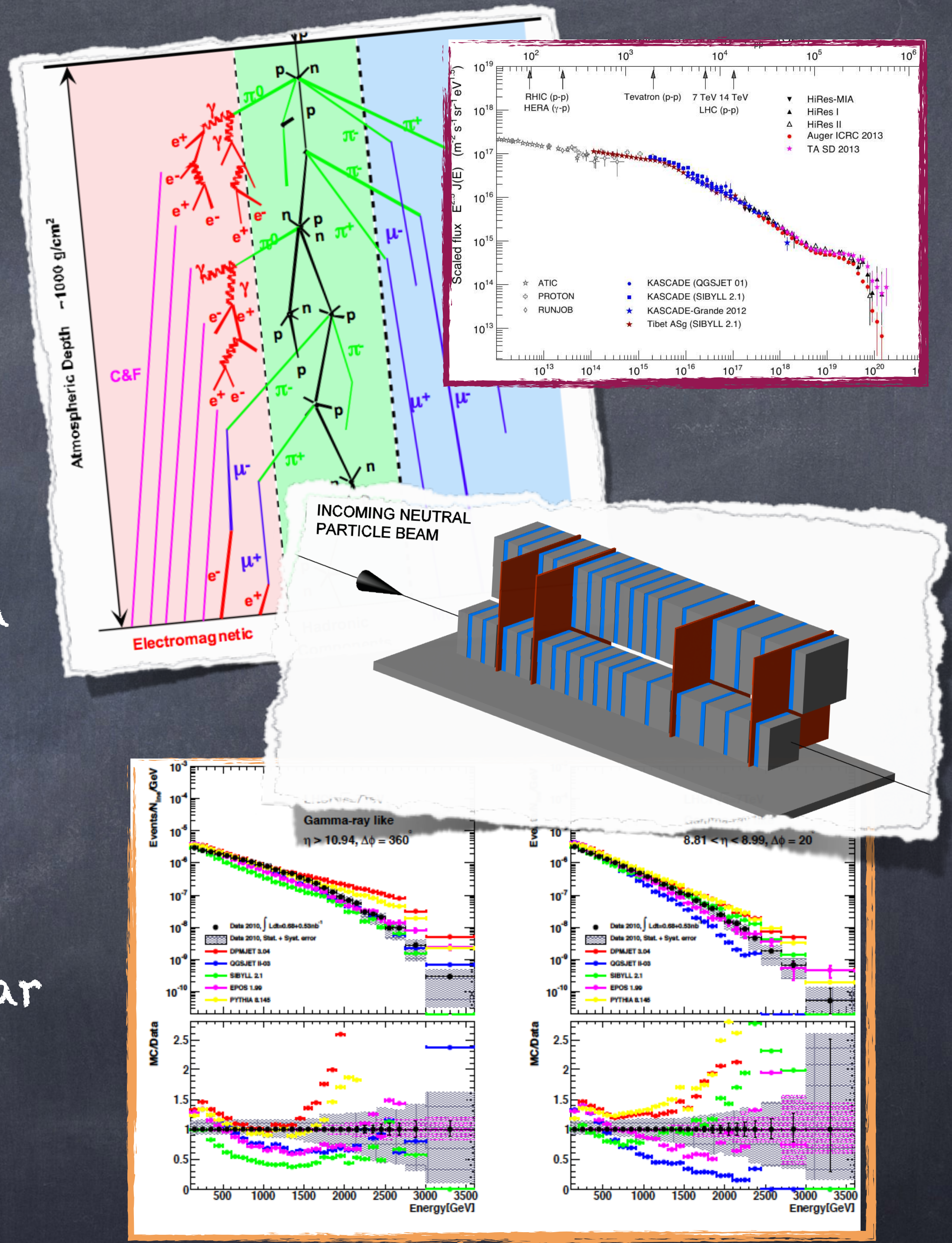
Outline

- 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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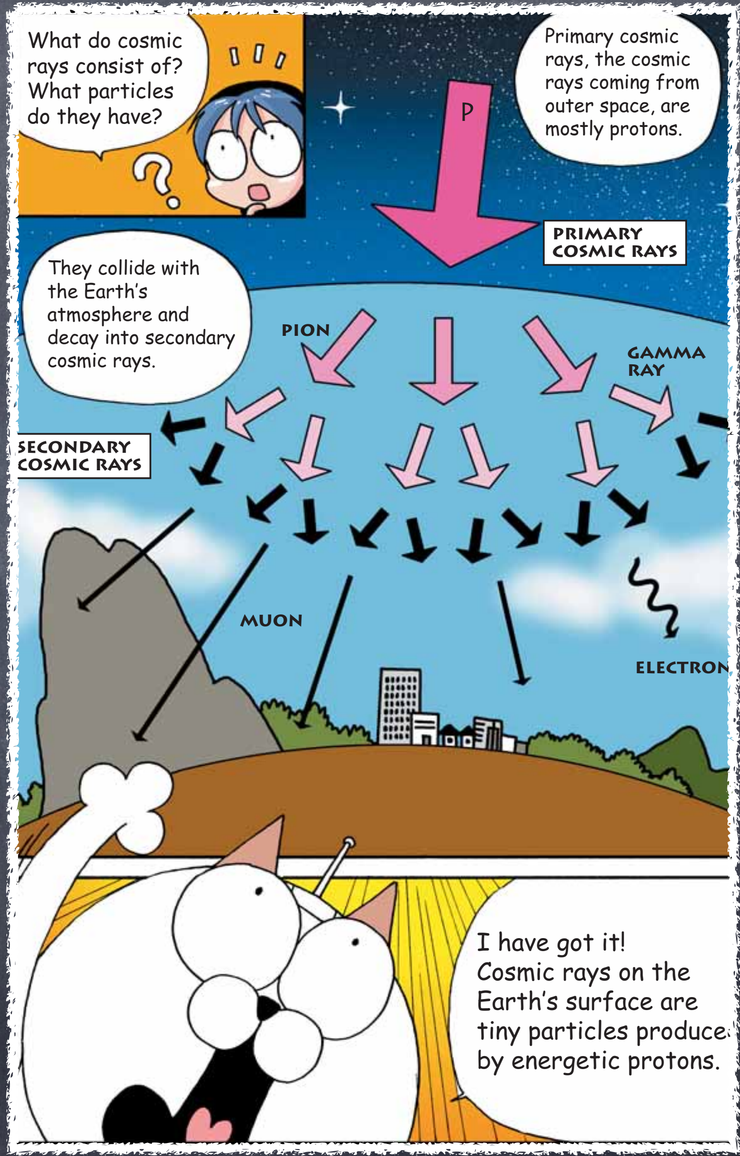
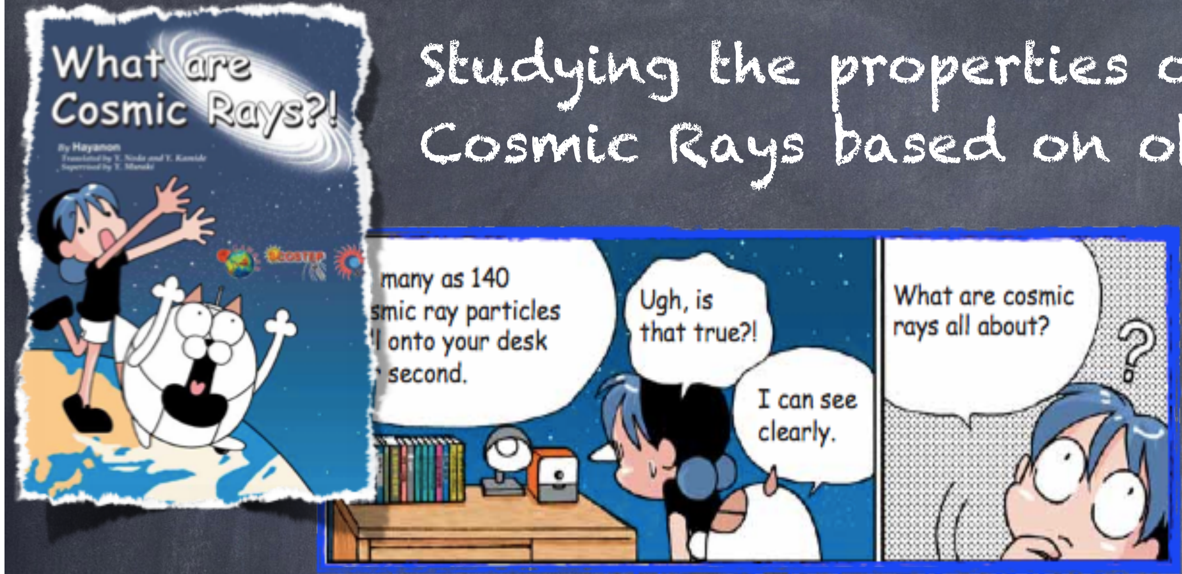
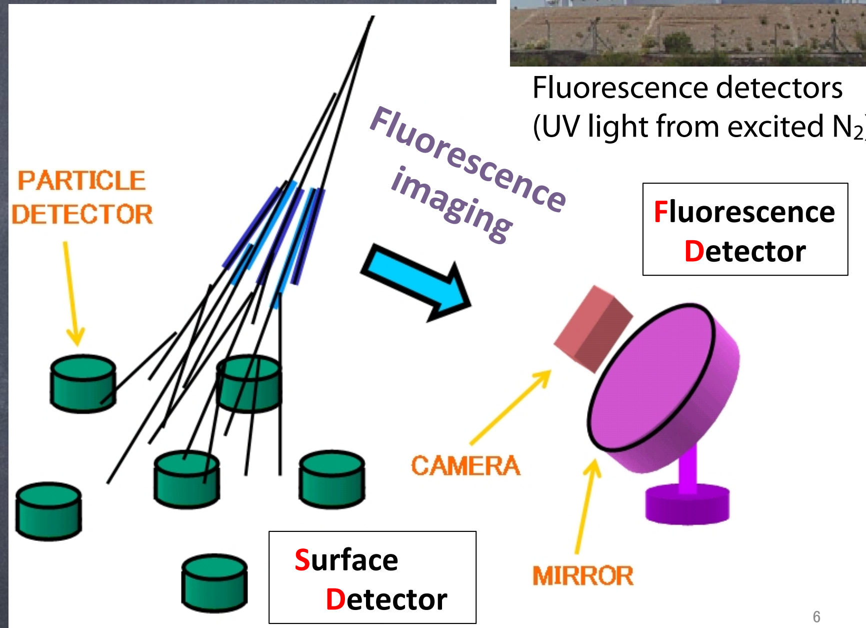


Ultra High Energy Cosmic Rays



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

Fluorescence detectors (UV light from excited N_2)



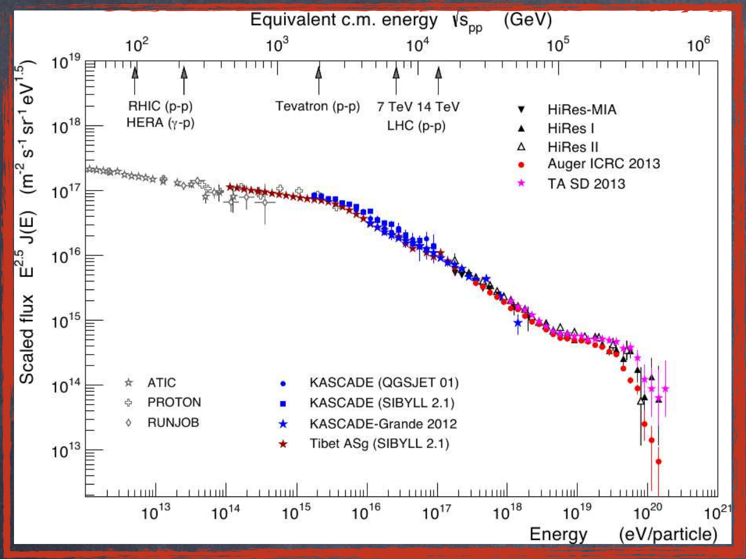
+

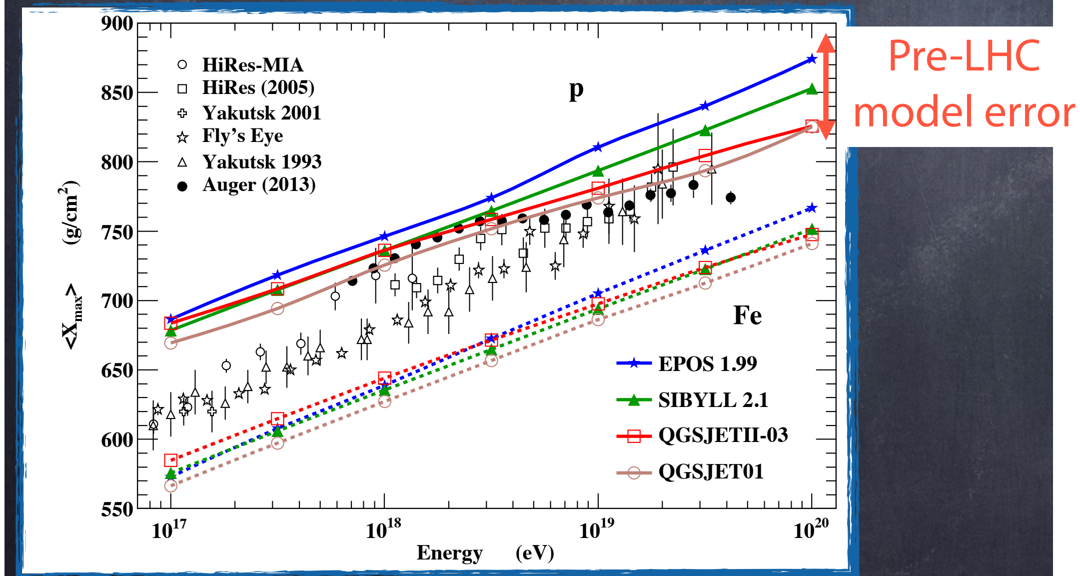
MC Simulation to describe hadronic interaction with atmosphere

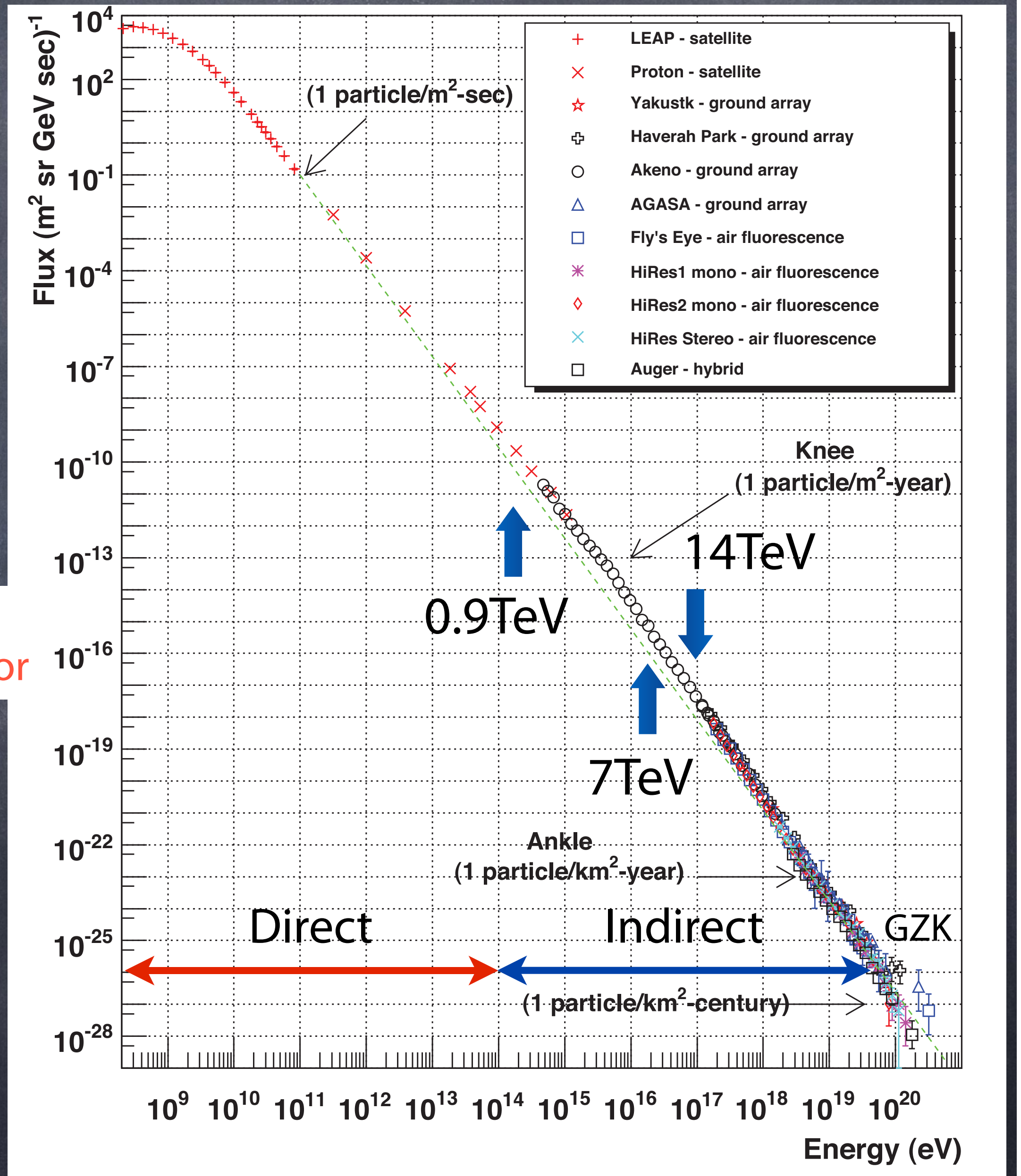
Surface detectors (charged+photon)

Energy, mass composition, direction
-> source of primary cosmic rays
-> origin of the universe (final goal)

Observation of UHECR





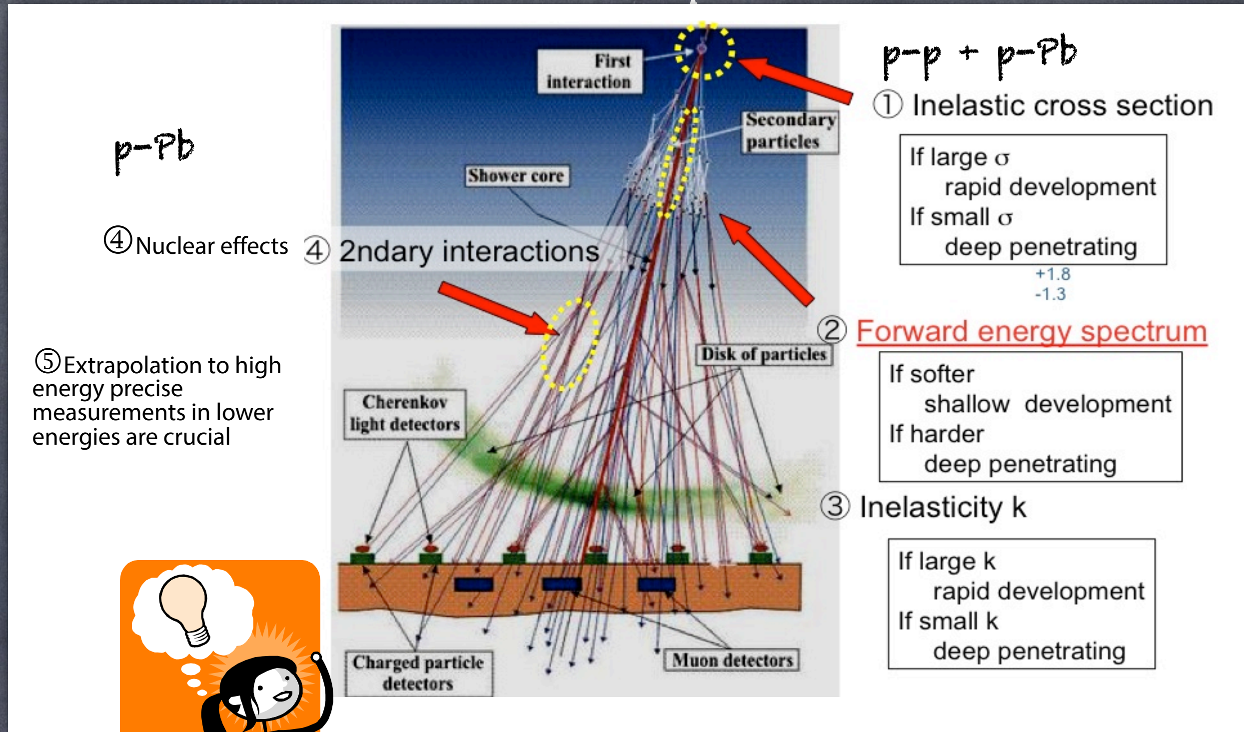


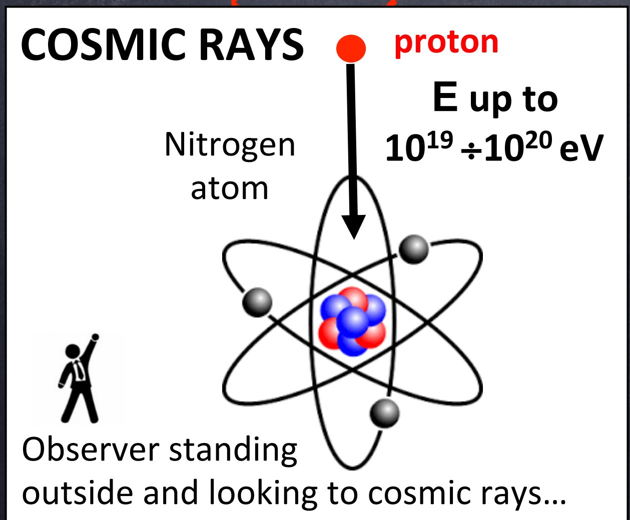
(Pierog 2013, 2014)

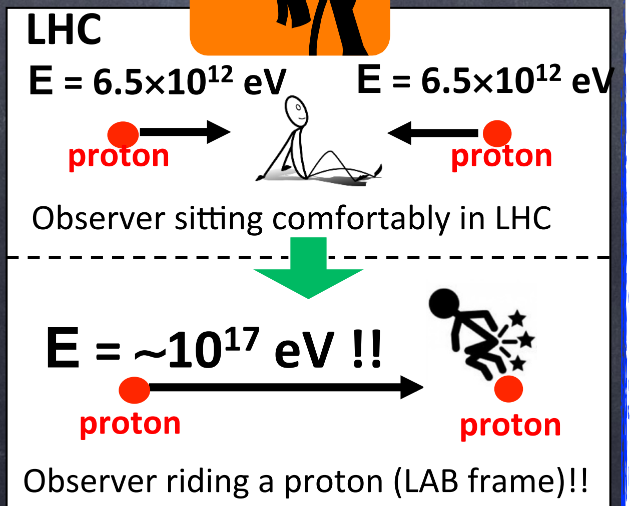
HECR Physics at LHC: LHCf Physics

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





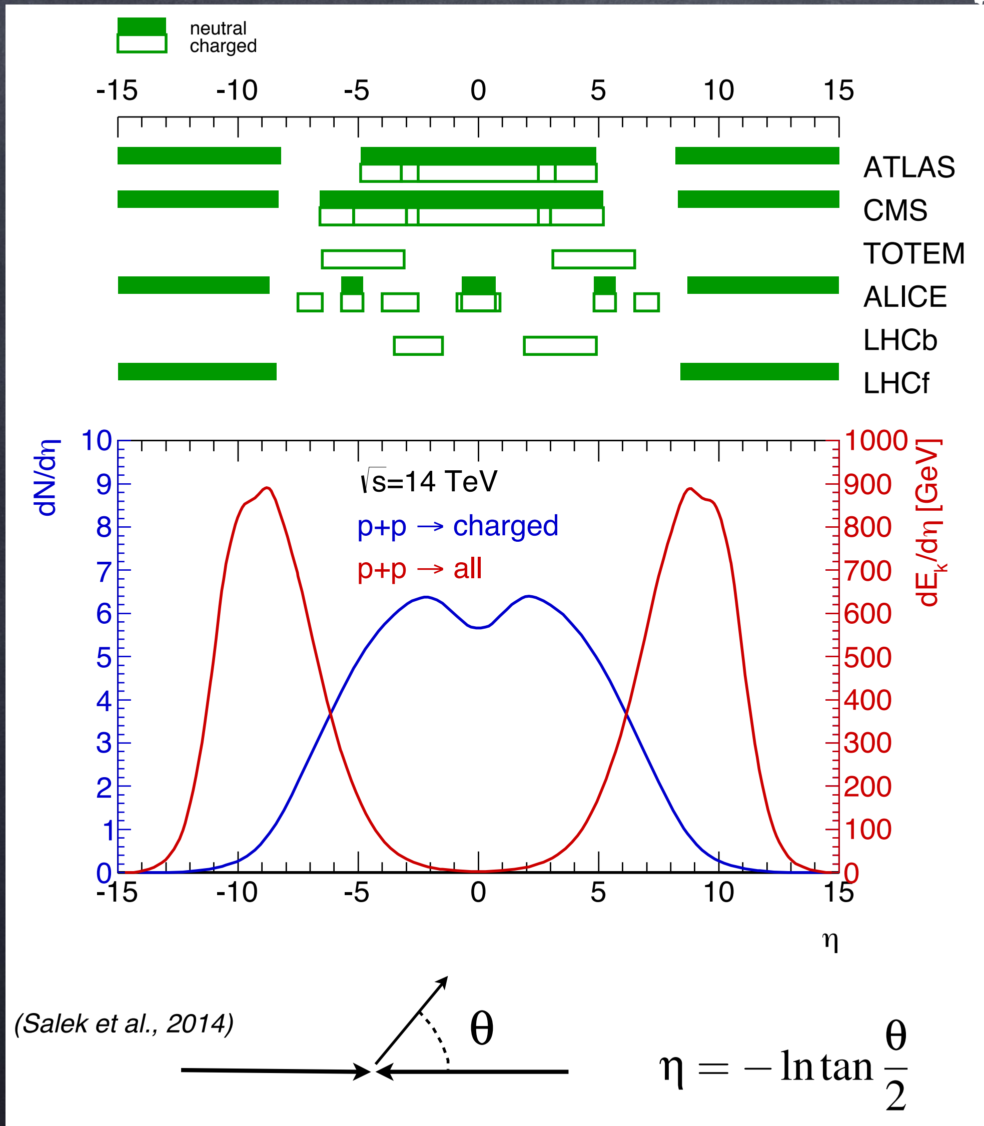


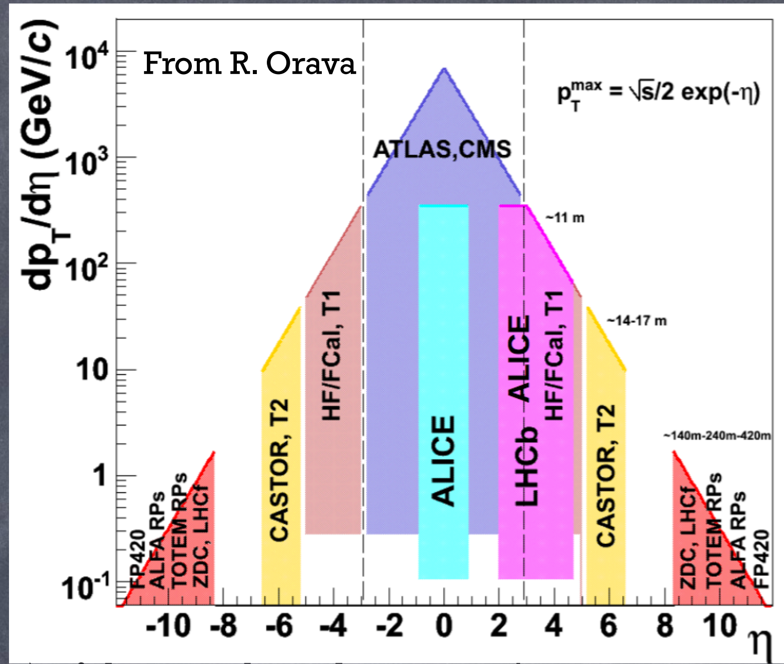
LHCf ->use LHC

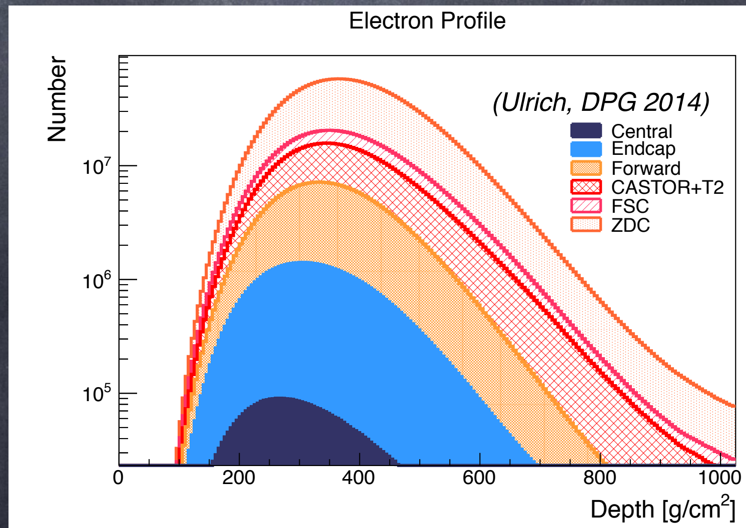
6.5 TeV+6.5 TeV⇒E_{lab}=9*10^{16} eV
3.5 TeV+3.5 TeV⇒E_{lab}=2.6*10^{16} eV
450 GeV+450 GeV⇒E_{lab}=2*10^{14} eV
to calibrate MCs

In addition: p-Pb collision at 5.02&8TeV to study nuclear effect

LHC Phase space coverage







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

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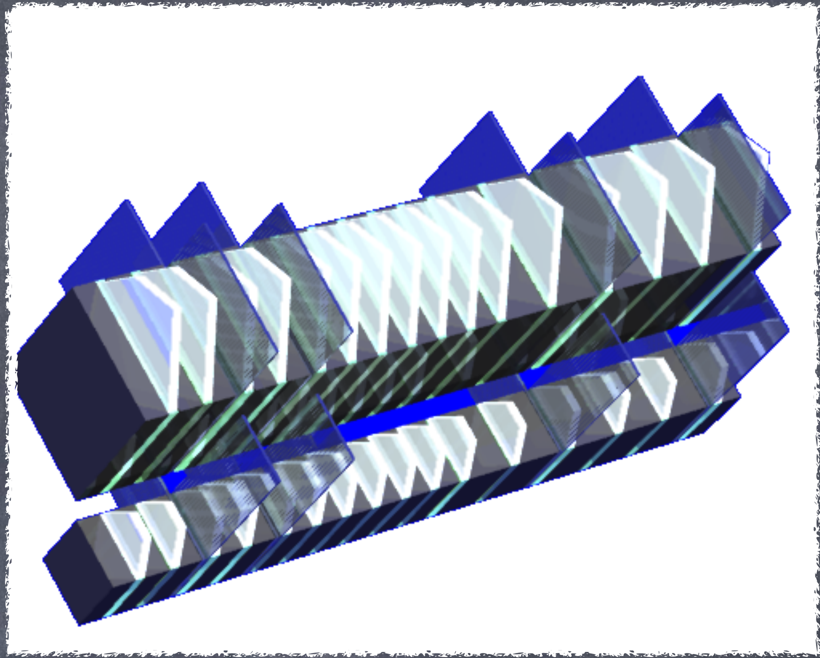
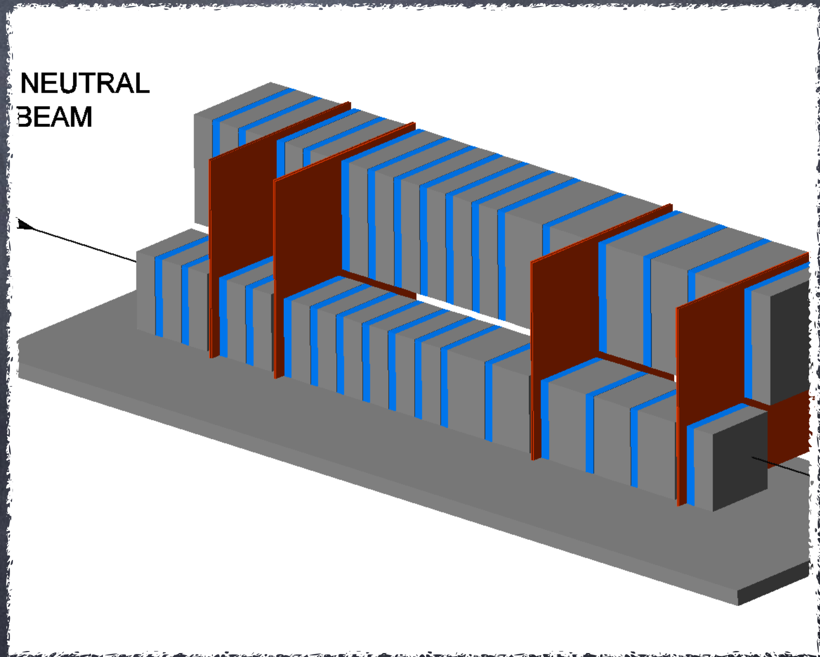
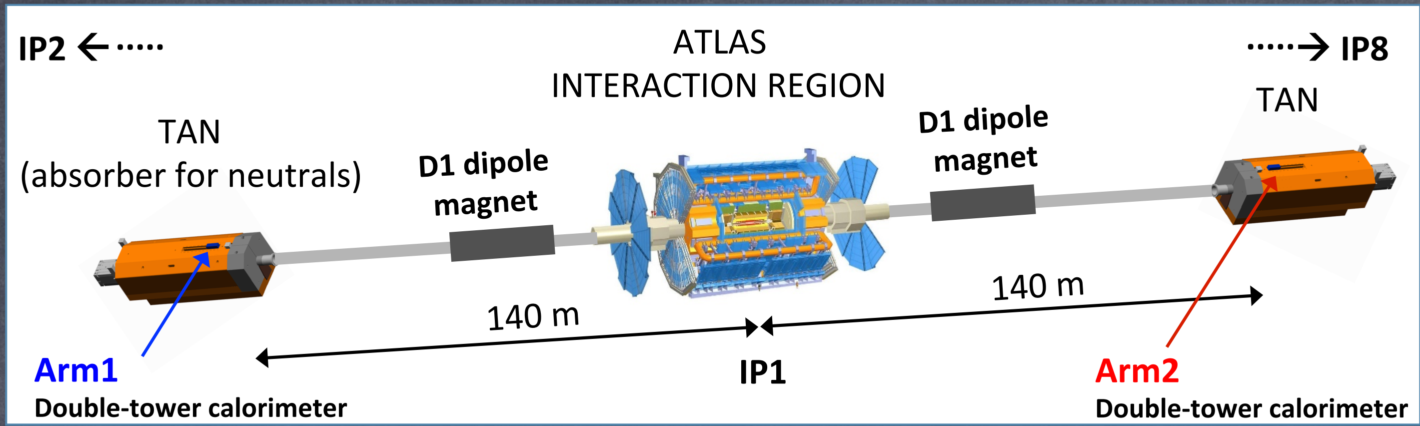
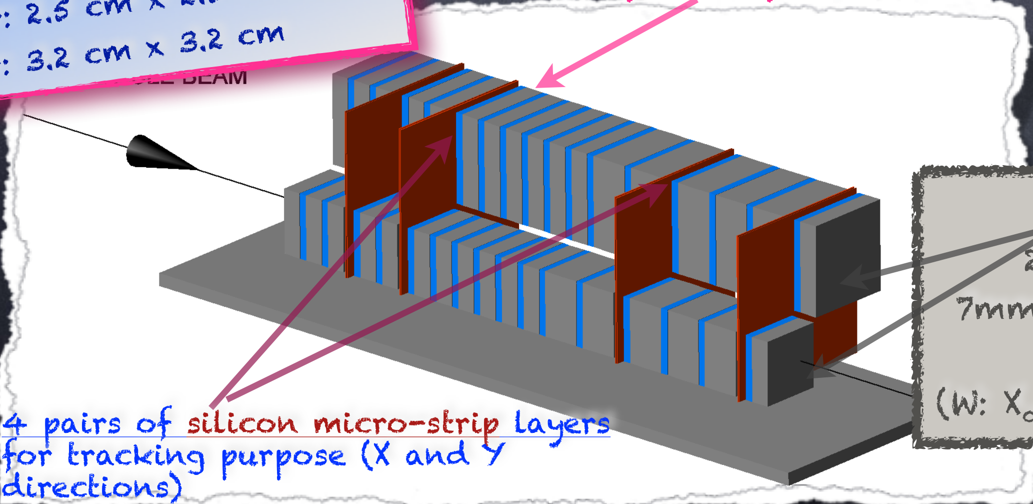
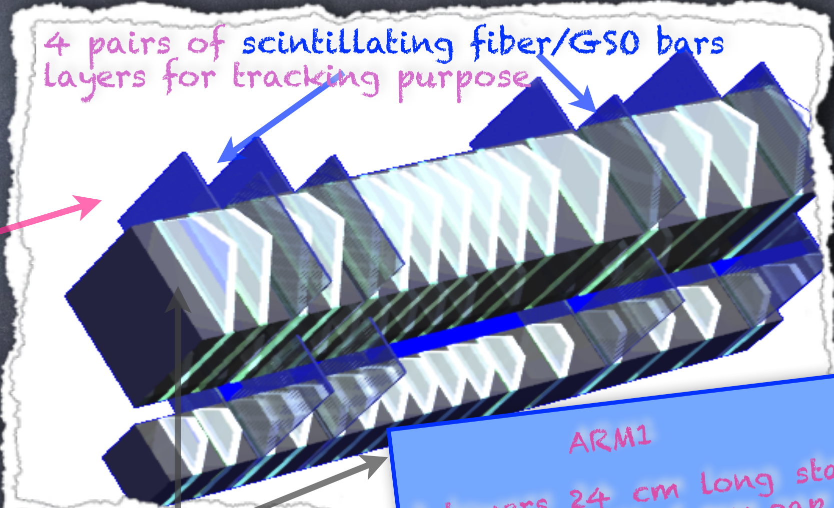




The LHCf Detector







4 pairs of scintillating fiber/GSO bars layers for tracking purpose

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)

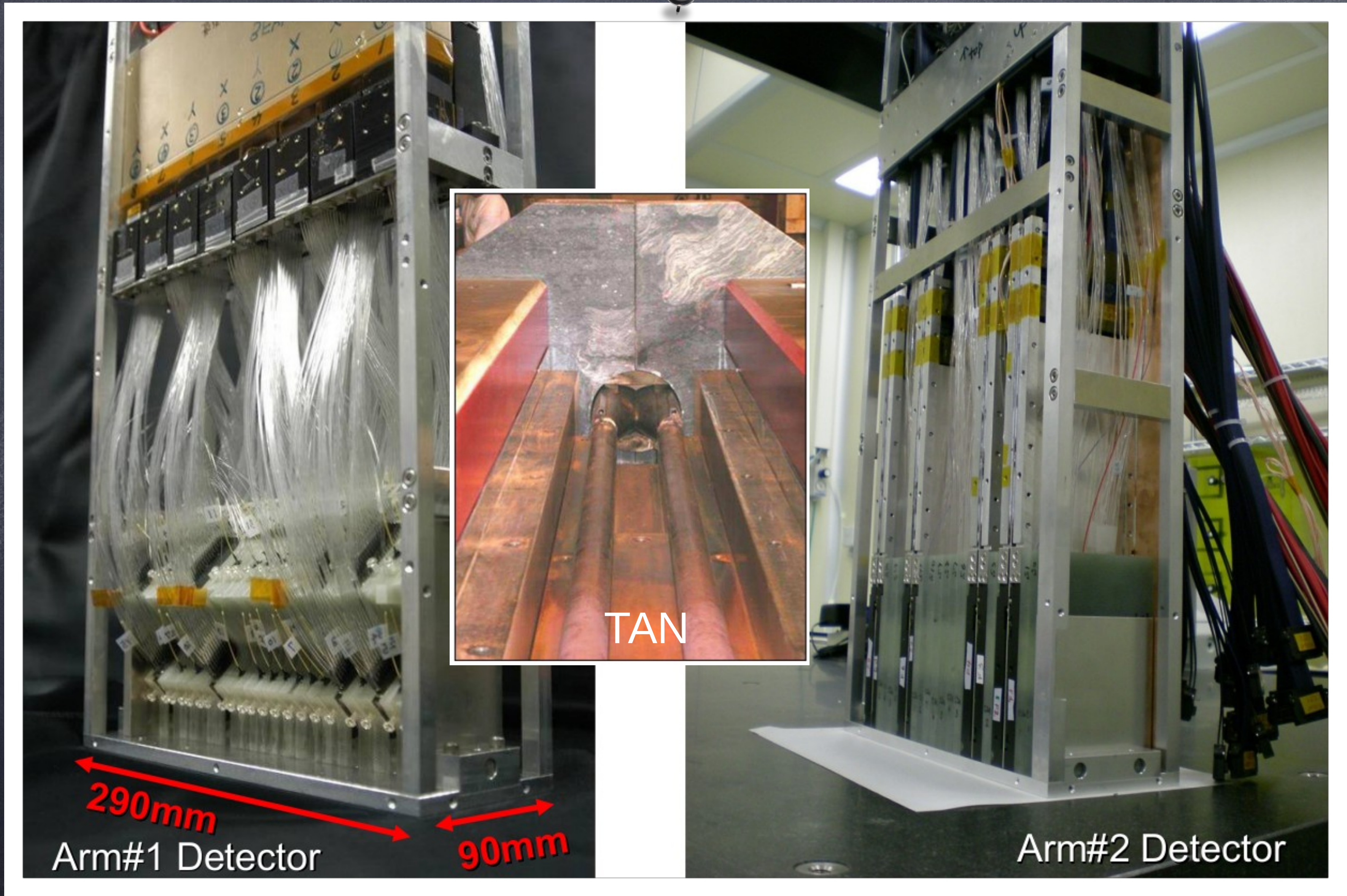
16 scintillator layers (Plastic or GSO)

Trigger and energy profile measurements

Energy

4 pairs of silicon micro-strip layers for tracking purpose (X and Y directions)

From our photo album...



A brief LHCf photo-history

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

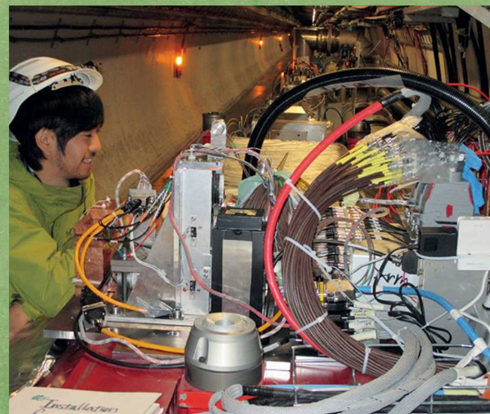
Jul 2006
construction

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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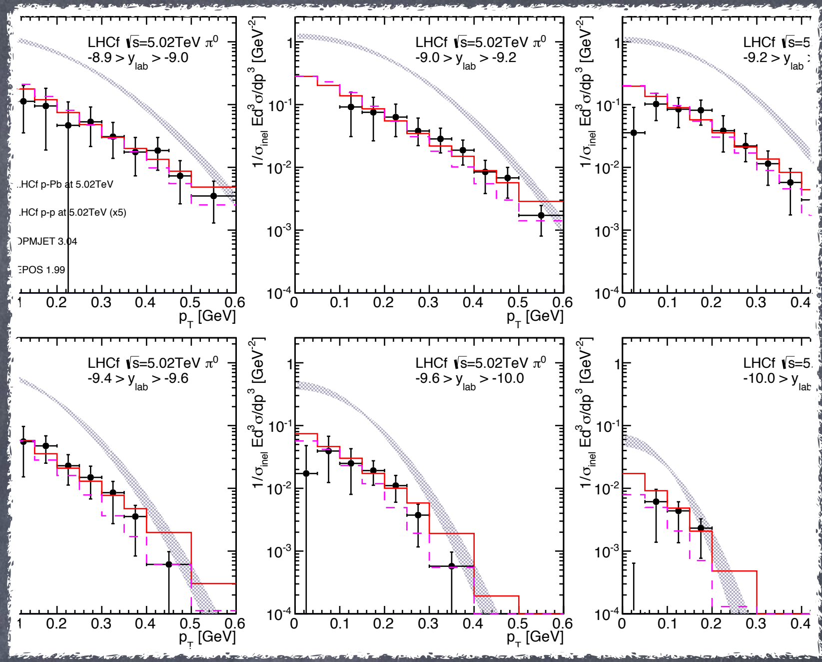
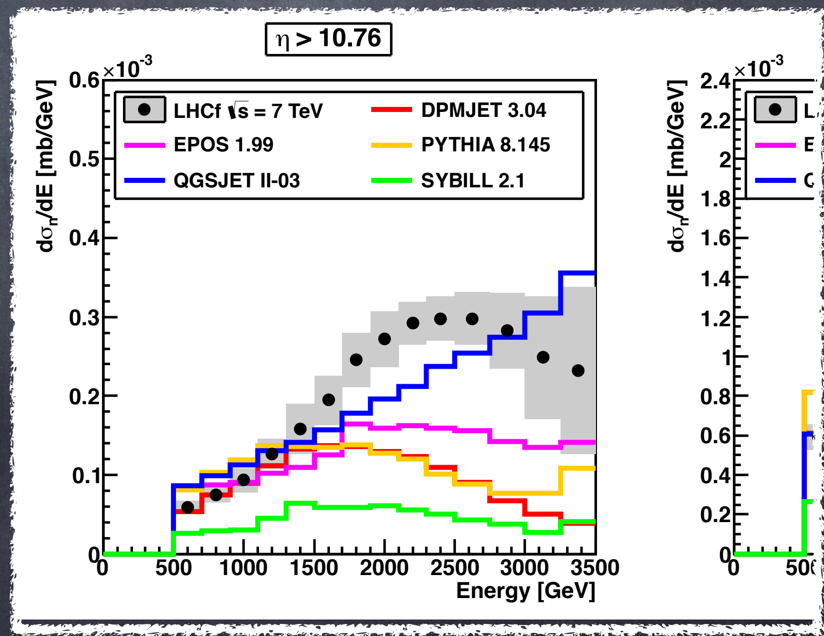


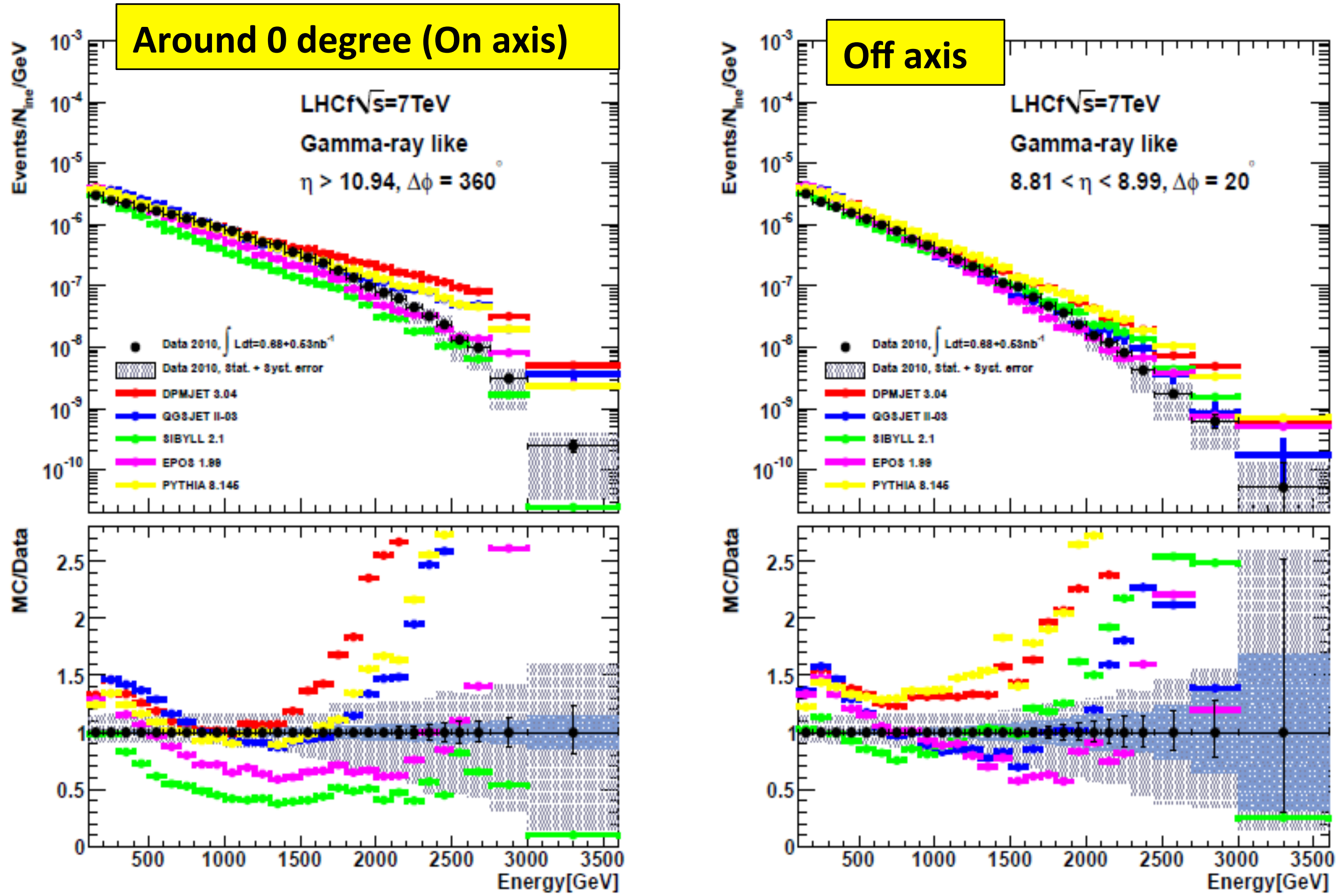


LHCf Data Taking and Analysis matrix

	Proton E	Photon (EM shower)	Neutron (hadron	π (EM shower)	
Test beam at SPS		NIM. A 671, 129-136 (2012)	JINST 9 (2014)P03016		Run1
p-p at 900GeV	4.3x10	Phys. Lett. B 715, 298-303 (2012)			Run1
p-p at 7TeV	2.6x10	Phys. Lett. B 703, 128-134 (2011)	Phys. Lett. B 750, 360-366 (2015)	Phys. Rev. D 86, 092001 (2012)+ Submit. Type II	Run1
p-p at 2.76TeV	4.1x10			Phys. Rev. C 89, 065209 (2014)+ Submit. Type II	Run2
p-Pb at 5.02TeV	1.3x10				Run2
p-p at 13TeV	9.0x10	Data taken in June 2015 dedicated run! Analysis activity ongoing...			Run3
p-Pb at 8.1 TeV	3.6x10	Letter of Intent submitted at [illegible] March 2016 Approved!!!			Run4

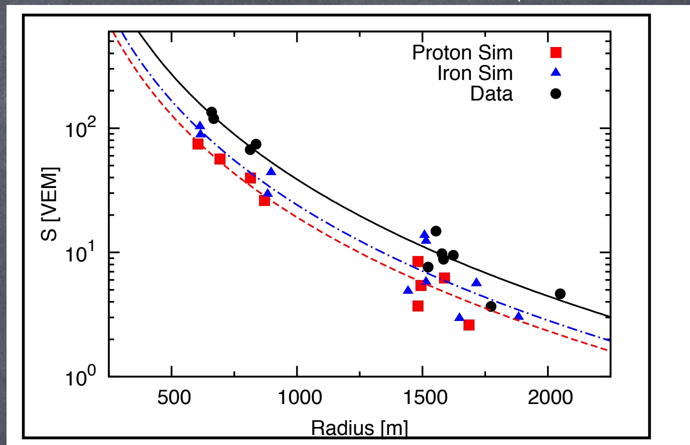
LHCf @ pp 7TeV: Single photon spectra MC vs Data

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



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

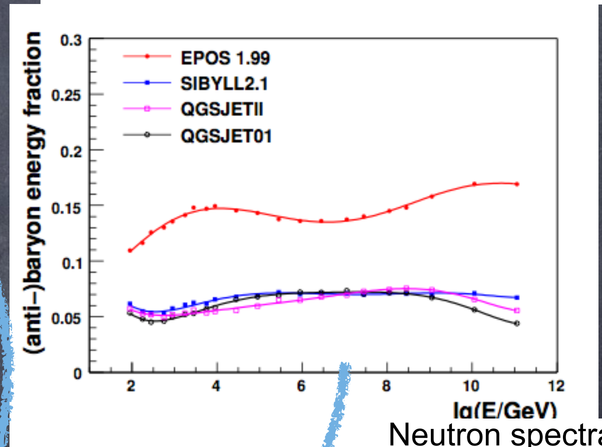
LHCf @ pp 7 TeV: neutron analysis

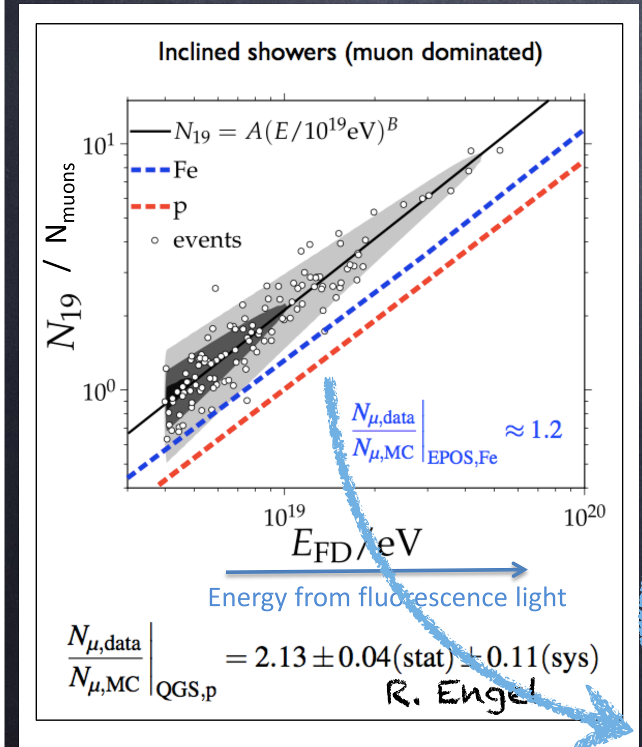


[J.Allen, et al. ICRC2011 Proceedings]

Motivations:

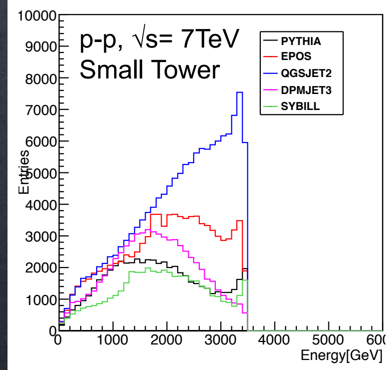
- Inelasticity measurement $k=1-p_{leading}/p_{beam}$
- Muon excess at Pierre Auger Observatory
  - cosmic rays experiment measure PCR energy from muon number at ground and florescence light
  - 20-100% more muons than expected have been observed





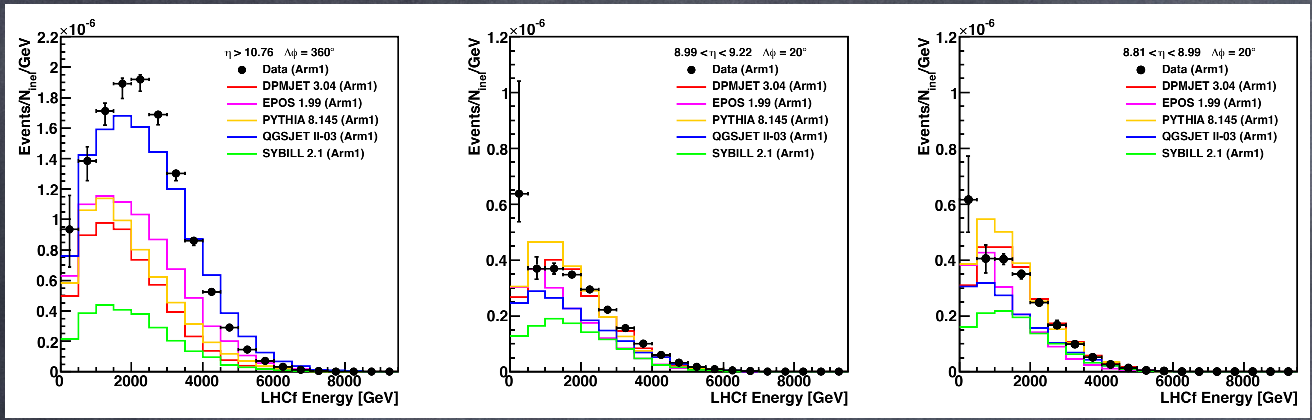
- Number of muons depends on the energy fraction of produced hadron
- Muon excess in data even for Fe primary MC
- EPOS predicts more muon due to larger baryon production

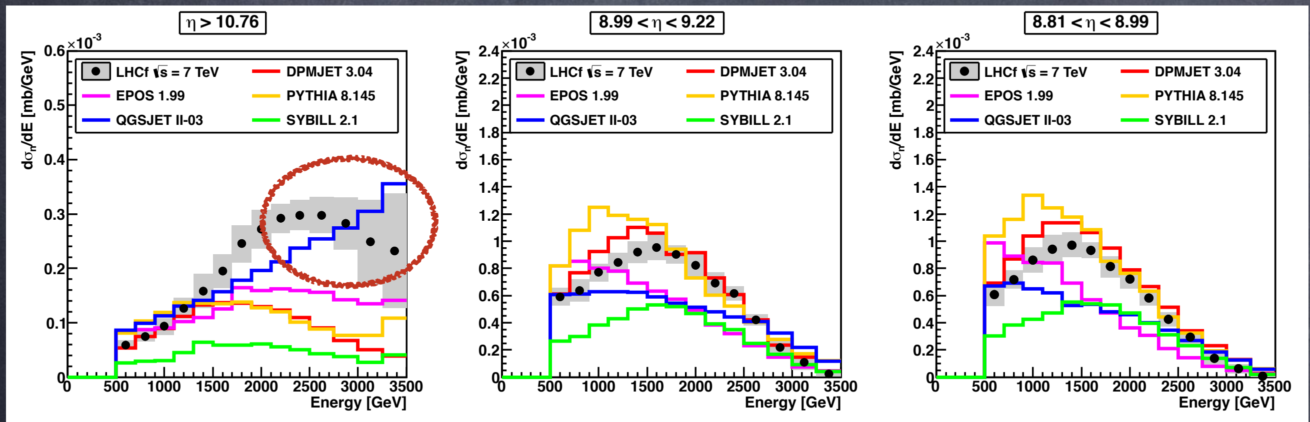
Neutron spectra predicted by interaction models



importance of baryon measurement

LHCf @ pp 7 TeV: neutron spectra





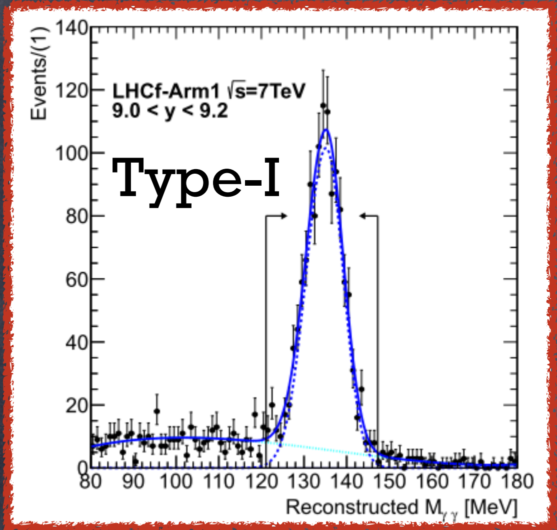
n/γ ratio

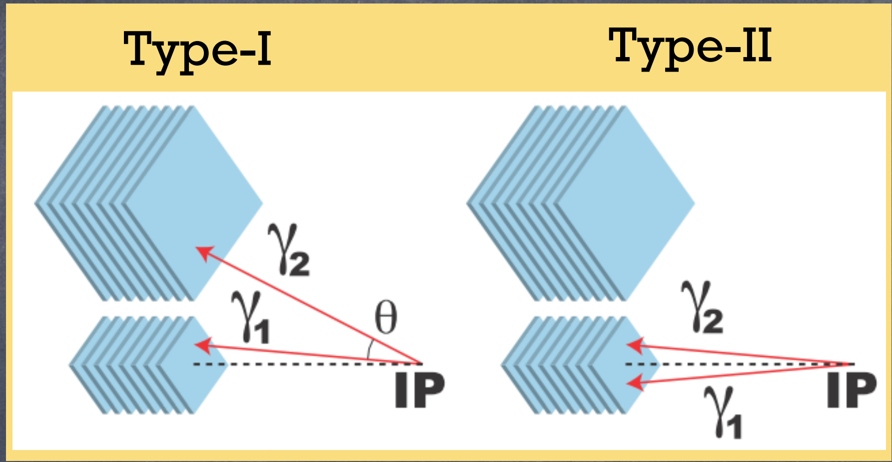
Data (	3.05±0.19
DPMJET3.04	1.05
EPOS 1.99	1.80
PYTHIA 8.145	1.27
QGSJET II-03	2.34
SYBILL 2.1	0.88

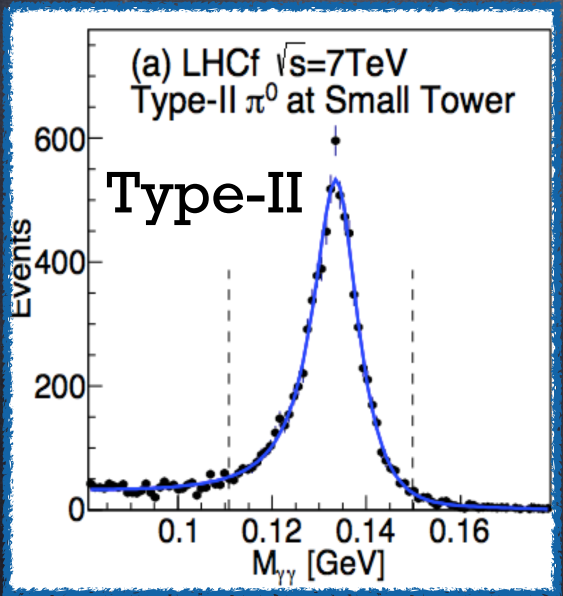
Data (8.99<	1.26±0.08
DPMJET3.04	0.76
EPOS 1.99	0.69
PYTHIA 8.145	0.82
QGSJET II-03	0.65
SYBILL 2.1	0.57

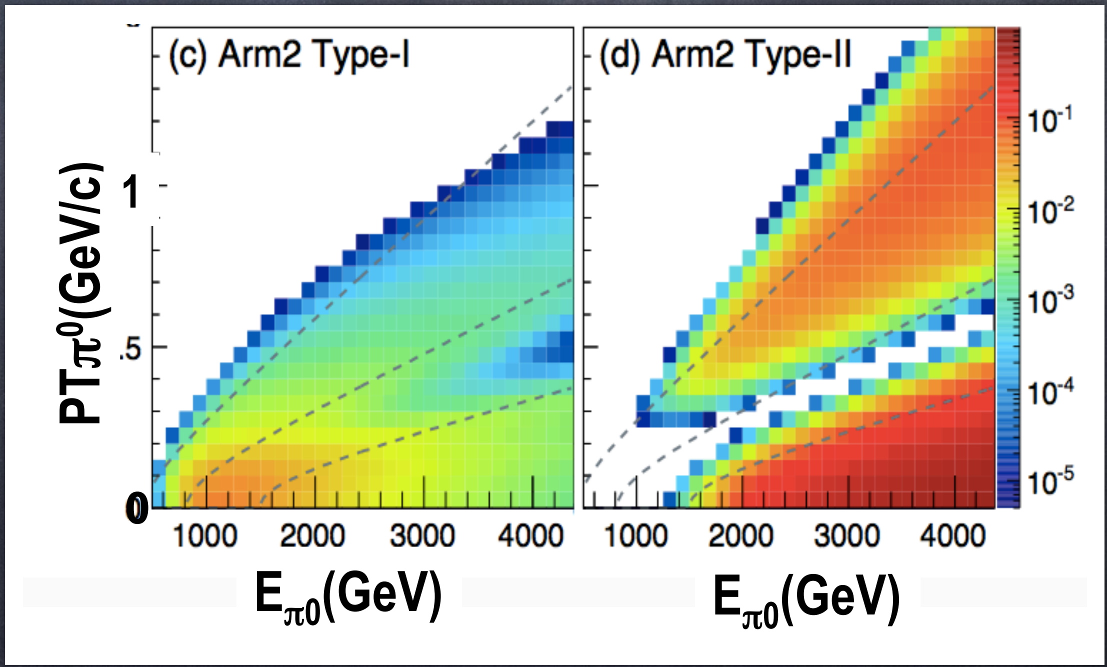
- LHCf Arm1 and Arm2 agree with each other within systematic error, in which the energy scale uncertainty dominates.
- In η>10.76 huge amount of neutron exists. Only QGSJET2 reproduces the LHCf result.
- In other rapidity regions, the LHCf results are enclosed by the variation of models.

LHCf Type I and Type II π^0 analysis

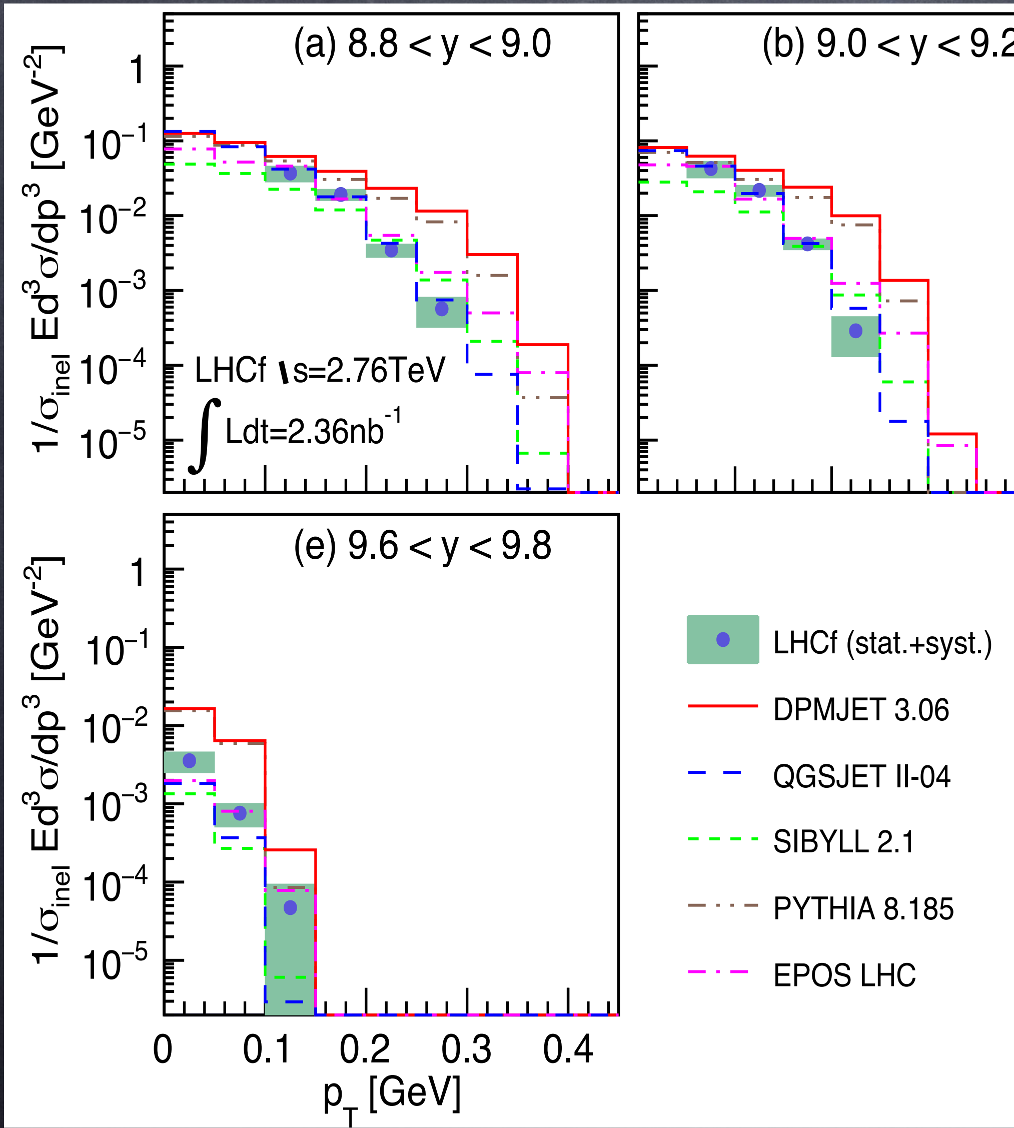






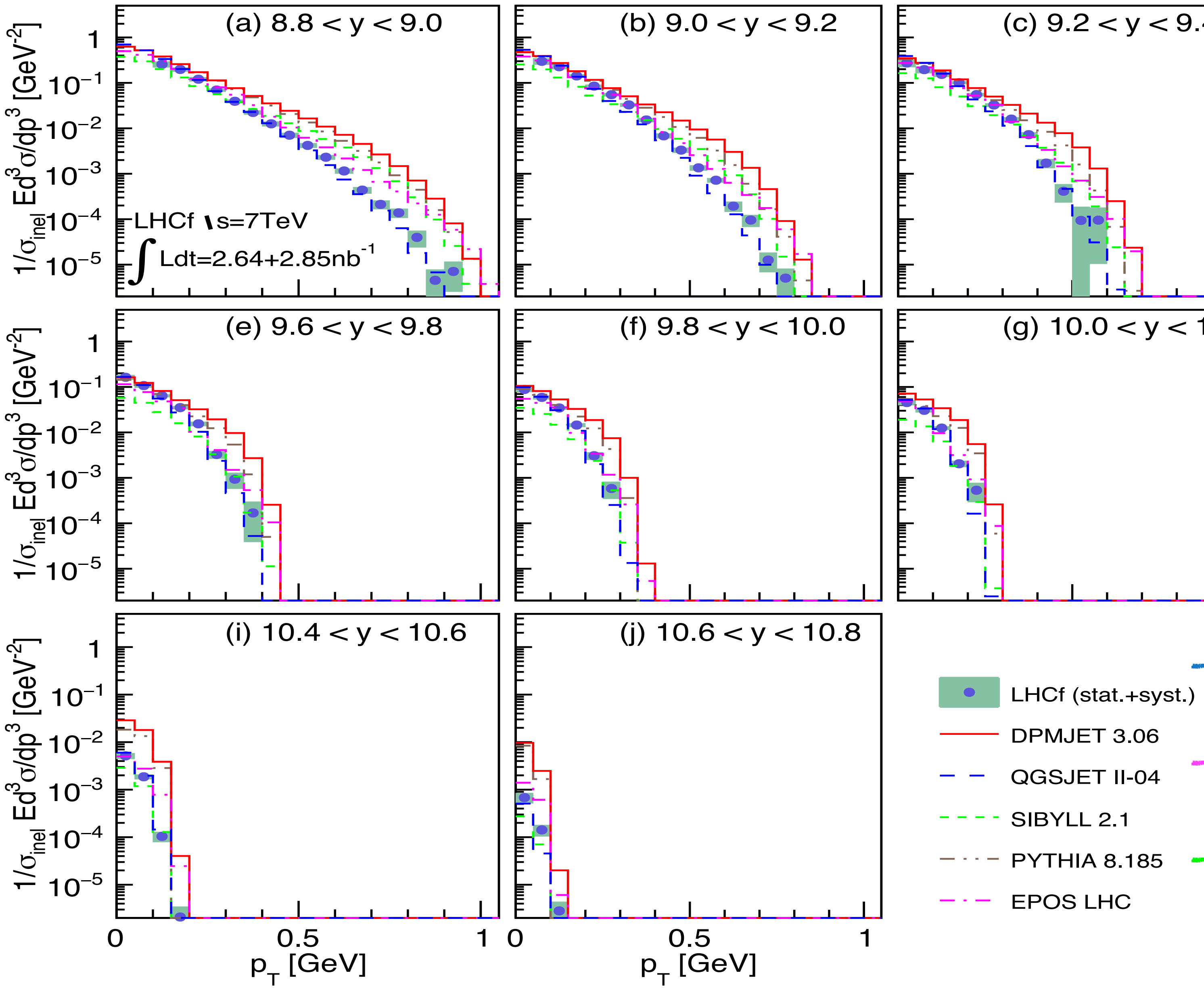


LHCf @ pp 2.76 TeV: π^0 p_T spectra



- 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

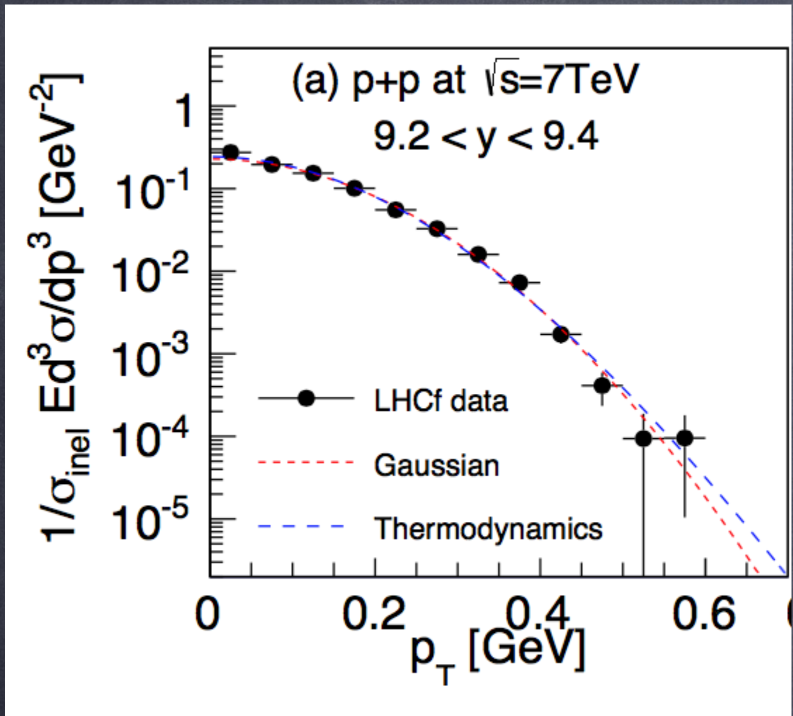
LHCf @ pp 7 TeV: π^0 p_T spectra



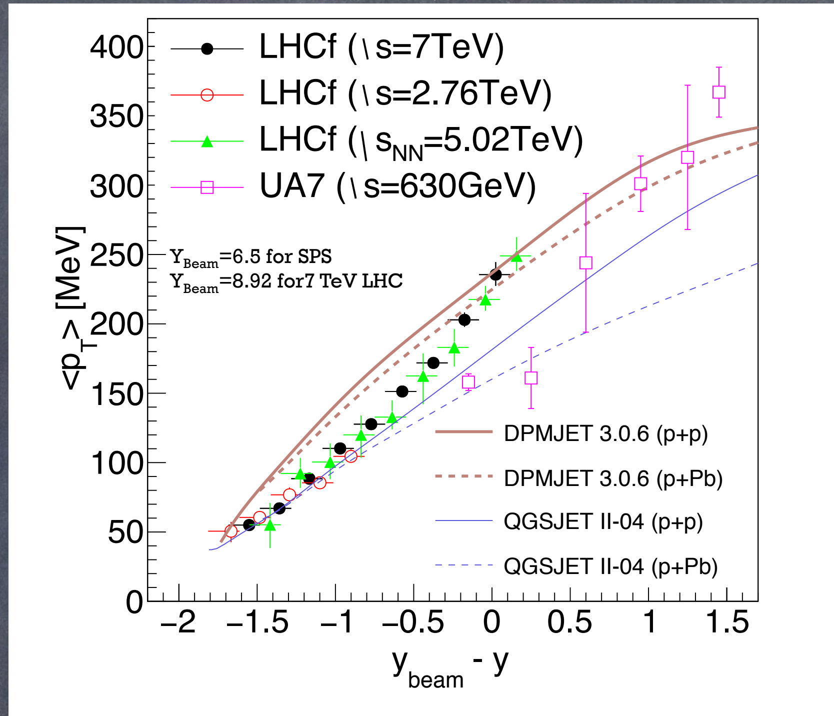
- QGSJETII-04: best agreement
- EPOS-LHC: harder than data for large p_T
- SYBILL: good agreement only for small y

π° average p_T for different cm energies

p_T spectra vs best-fit function



Average p_T vs y_{lab}



$\langle p_T \rangle$ is inferred in 3 ways:

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

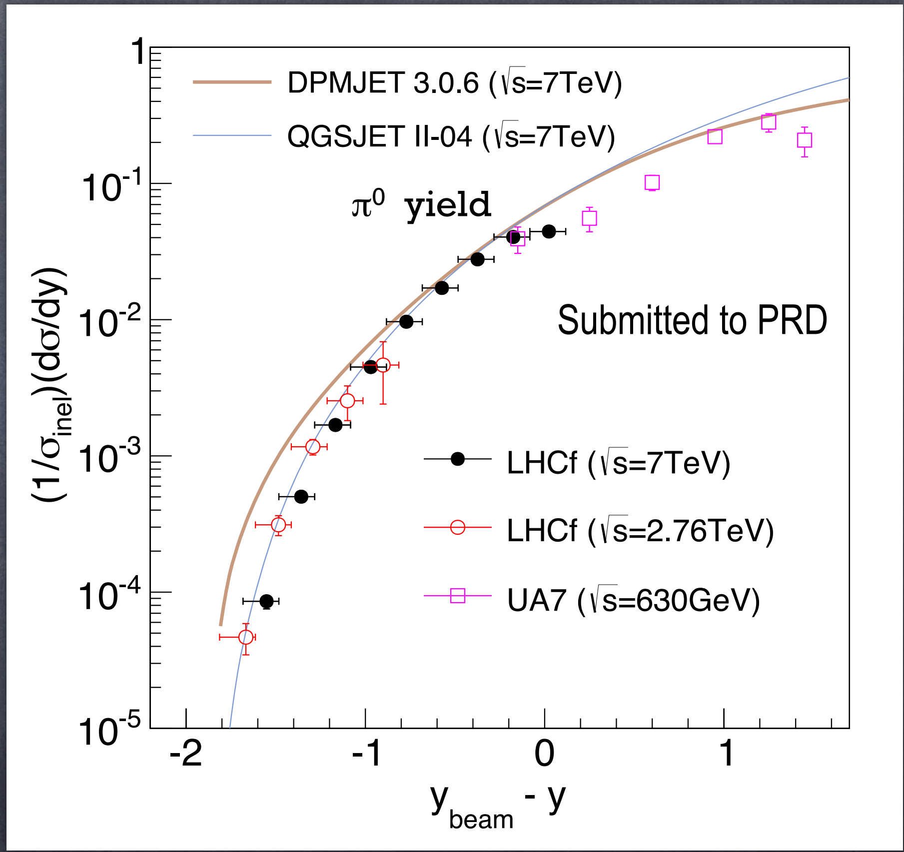
From scaling considerations (projectile fragmentation region) we can expect that $\langle p_T \rangle$ vs rapidity loss should be independent from the c.m. energy

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.

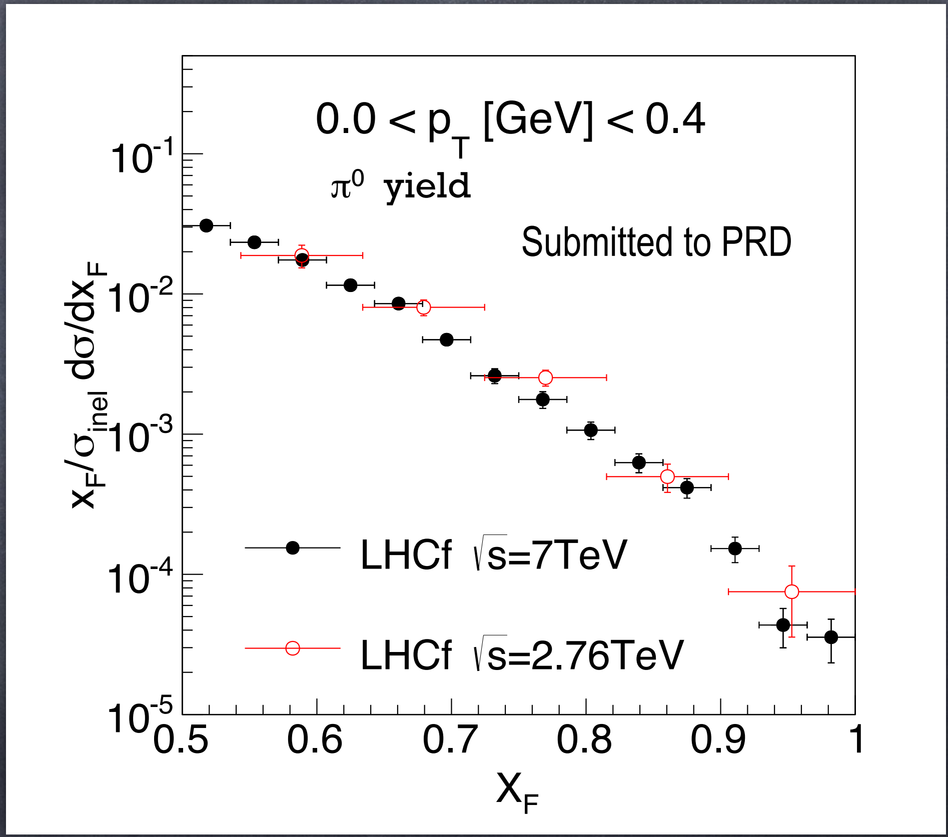
This hypothesis for π^0 is true at the level of ±15%



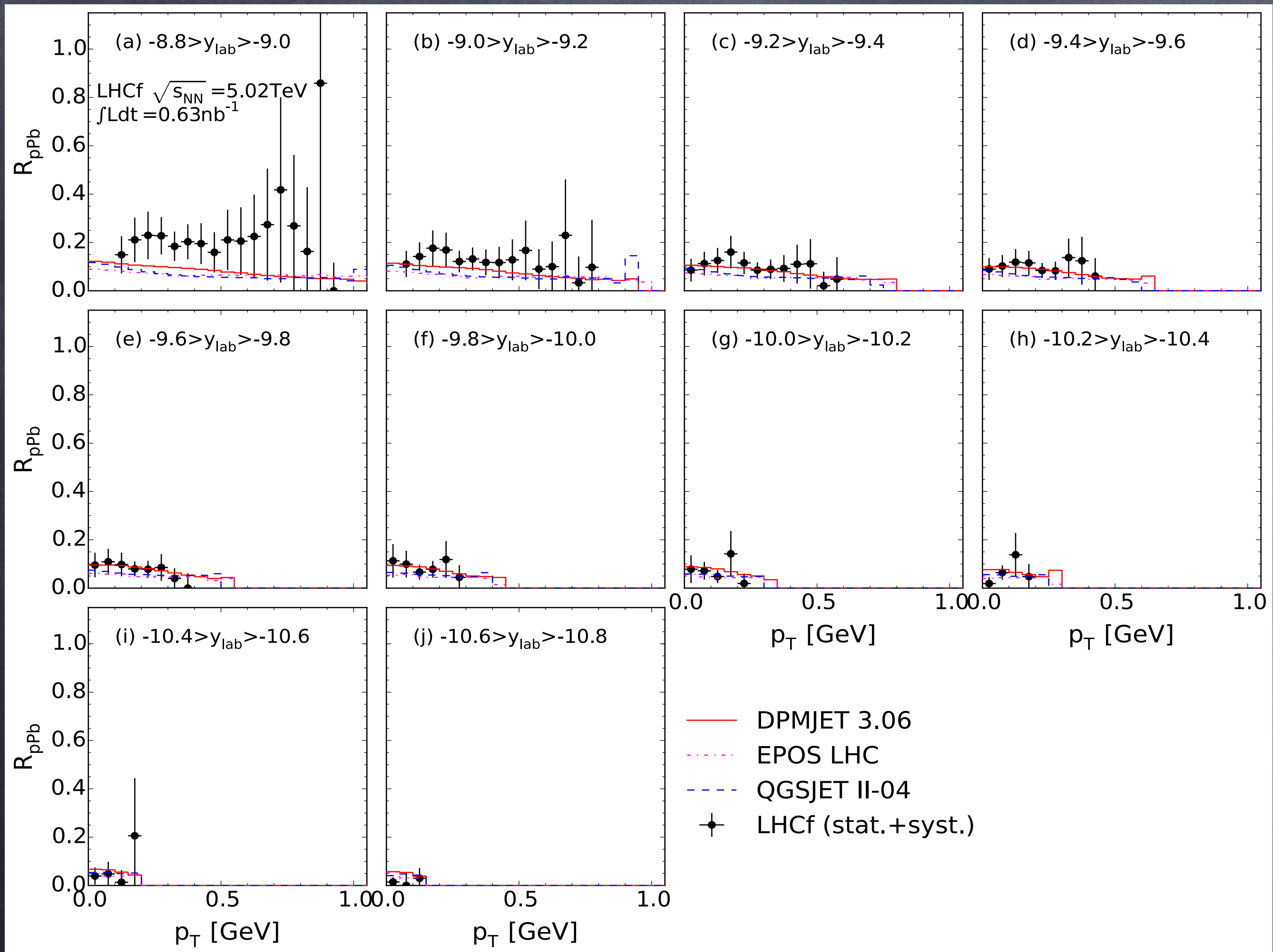
Feynman scaling in forward π^0 production

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 ($x_F > 0.2$).

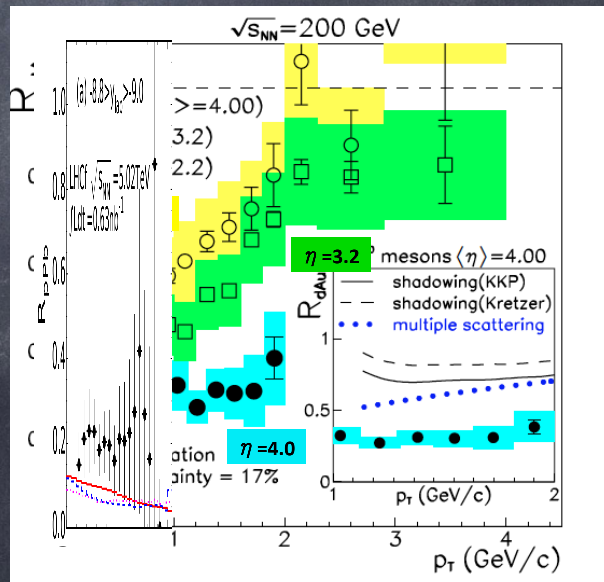
This hypothesis for π^0 is true at the level of ±20%



LHCf @ pPb 5.02 TeV: Nuclear modification factor



- LHCf show strong suppression in pPb wrt pp collisions
- Good agreement with the models

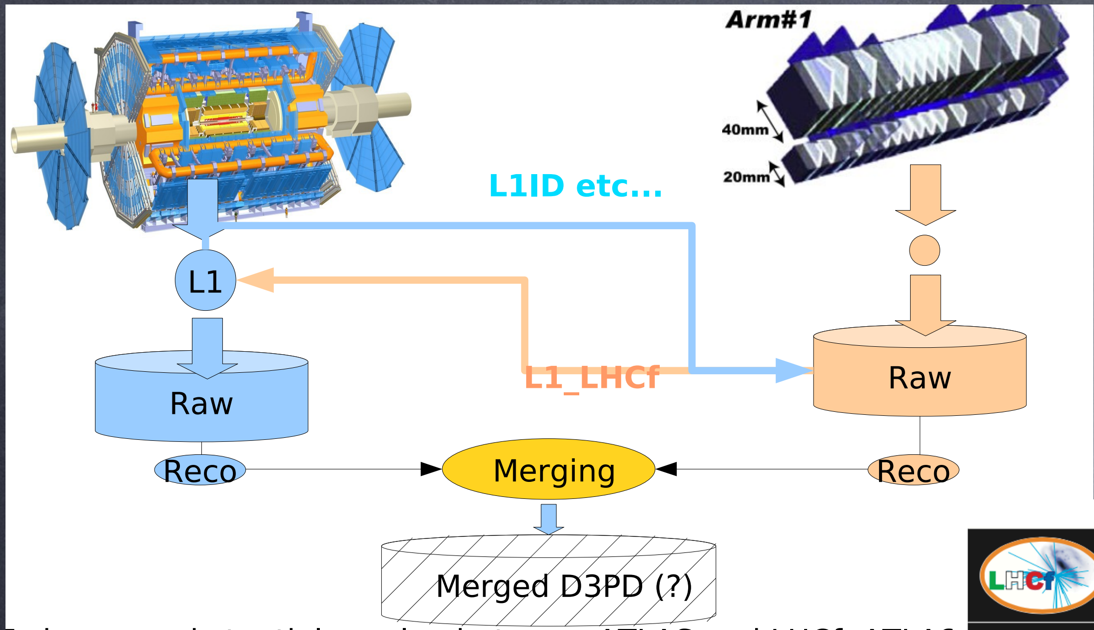


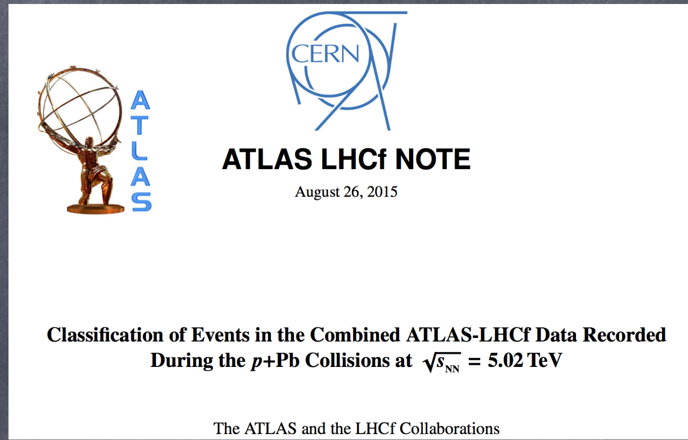
RHIC 200GeV d-Au, STAR Collaboration
Adams et al., PRL 97 (2006) 152302.

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

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

Common trigger with ATLAS

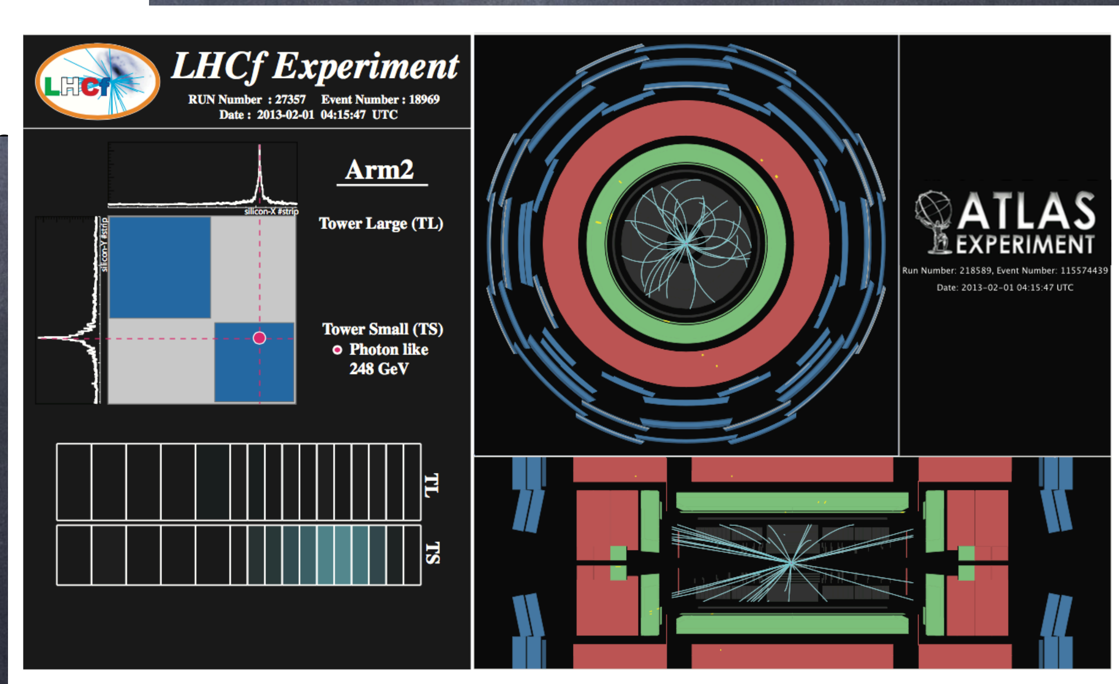



ATLAS LHCf NOTE

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



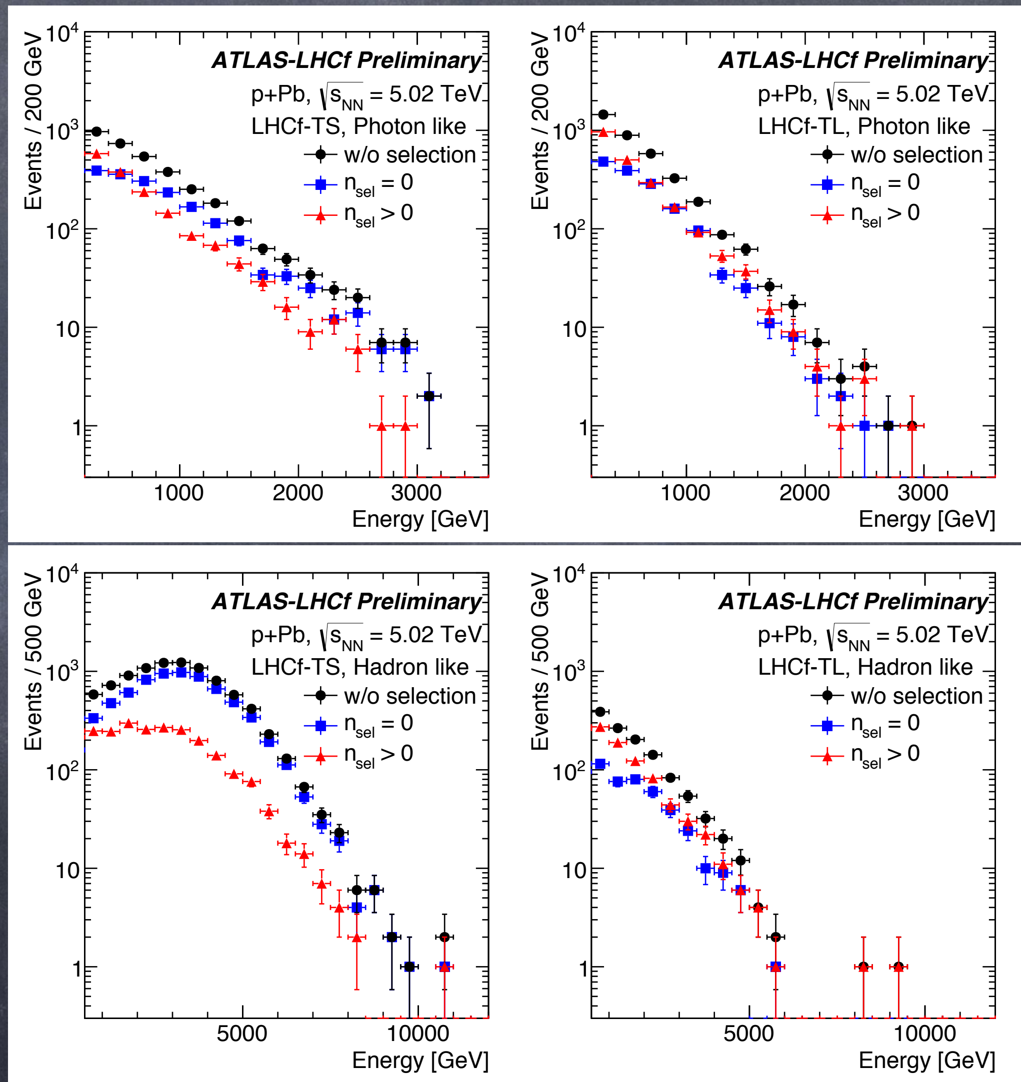
LHCf spectra in p-Pb collisions with Atlas tagging on tracks

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 $N_{sel}=0$



Impact of common ATLAS-LHCf trigger

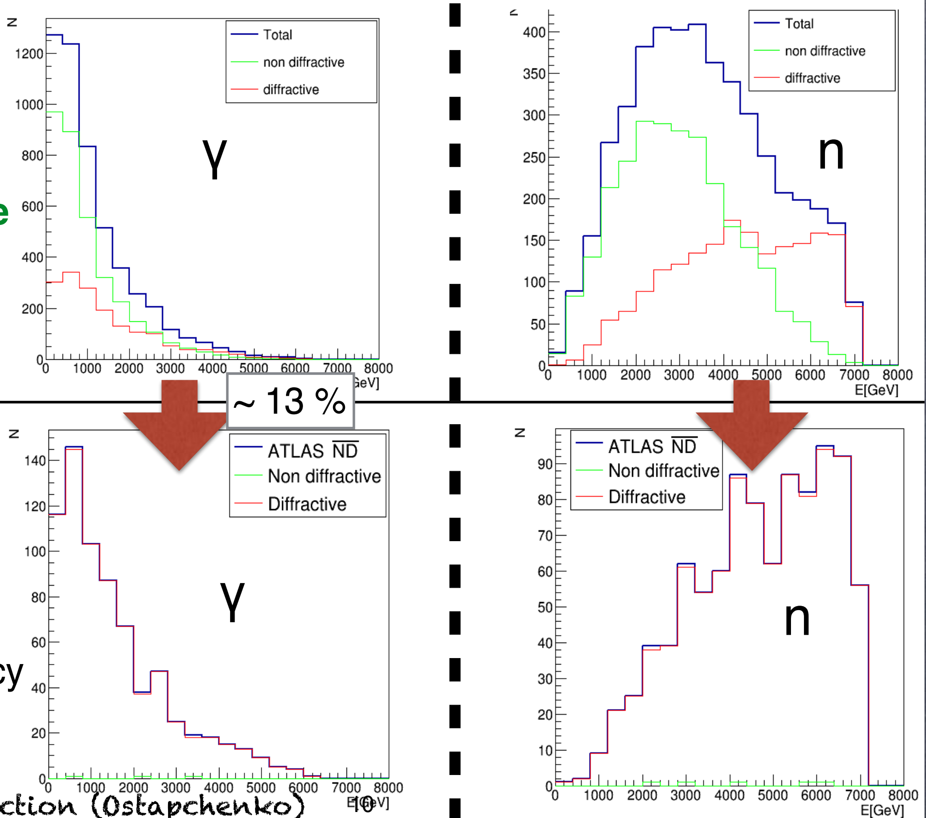
PYTHIA MC study @ 14 TeV. Diffractive event selection efficiency and purity:dropping events with (PT > 100 MeV/c & Nch>1 in |η|<2.5) @ATLAS

All events

in MC true,
Non-diffractive
Diffractive

w/ event selection (not ND)

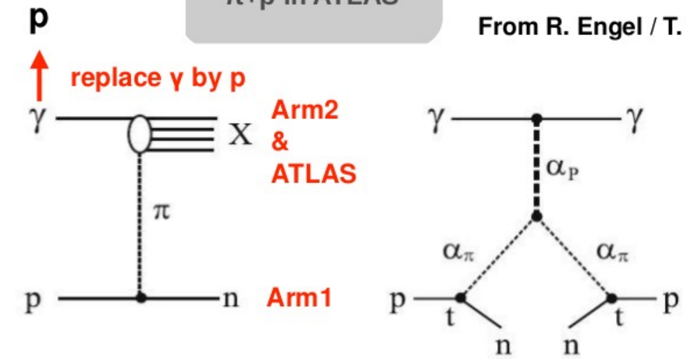
For diff. events,
35-40% efficiency
99 % purity



key: low mass diffraction (Ostapchenko)

Use neutron tag in LHCf to measure π+p in ATLAS

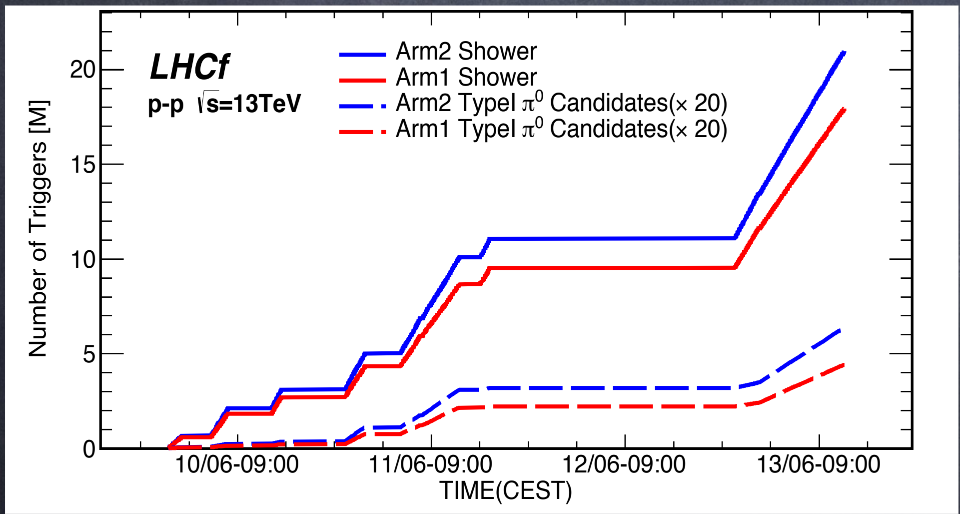
From R. Engel / T. Pierog

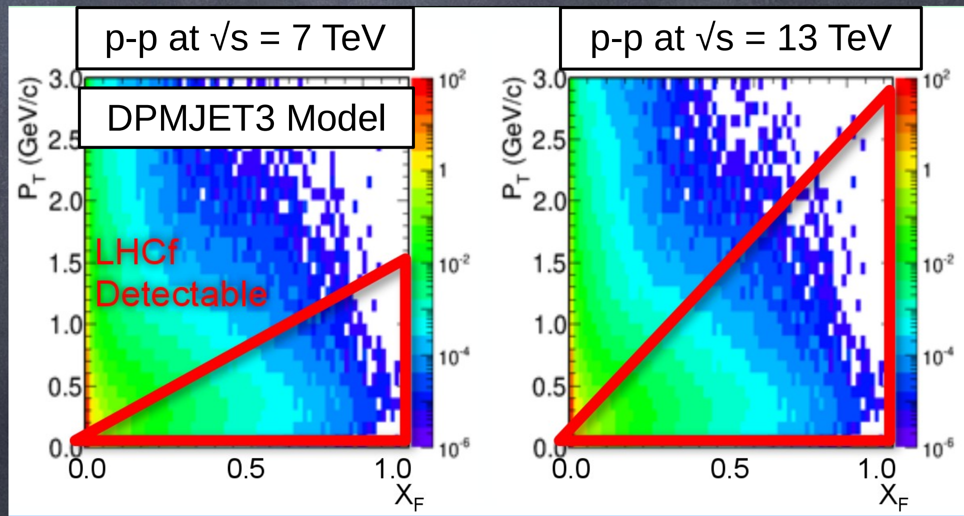


Physics discussed in detail for HERA (H1 and ZEUS) measurements
(see, for example, Khoze et al. Eur. Phys. J. C48 (2006), 797 and Refs. therein)

LHC 13 TeV Run

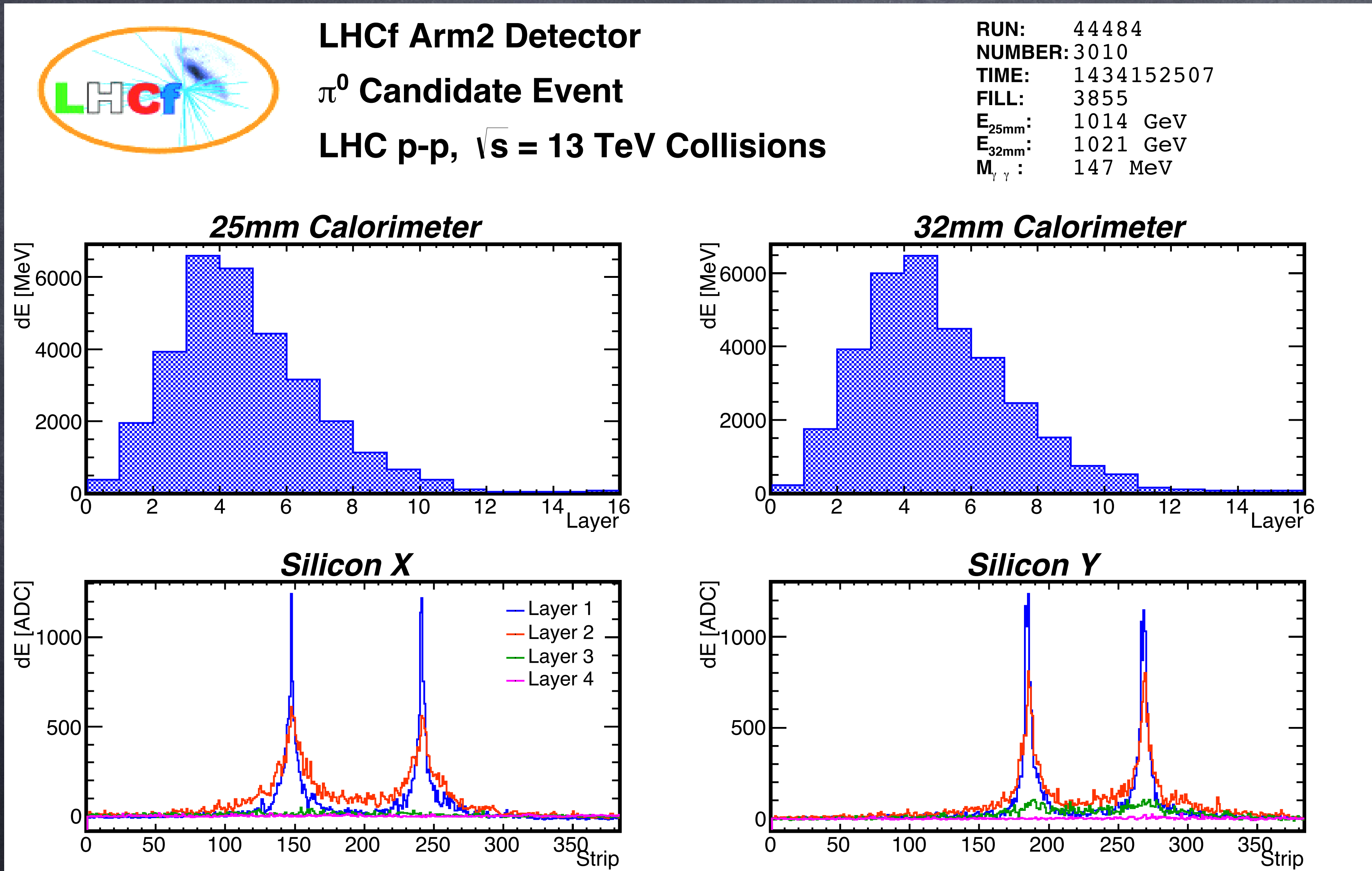
- During Week 24, June 9-13, LHCf dedicated low-lumi run
- Total 26.6 hrs with L=0.5~1.6.10^{29} cm^{-2}s^{-1} (16 nb^{-1})
- ~39 M showers, 0.5 M π^0 obtained
- Trigger exchange with ATLAS
- Detector removal on June 15th during TS1
- Run was very successful!!!!



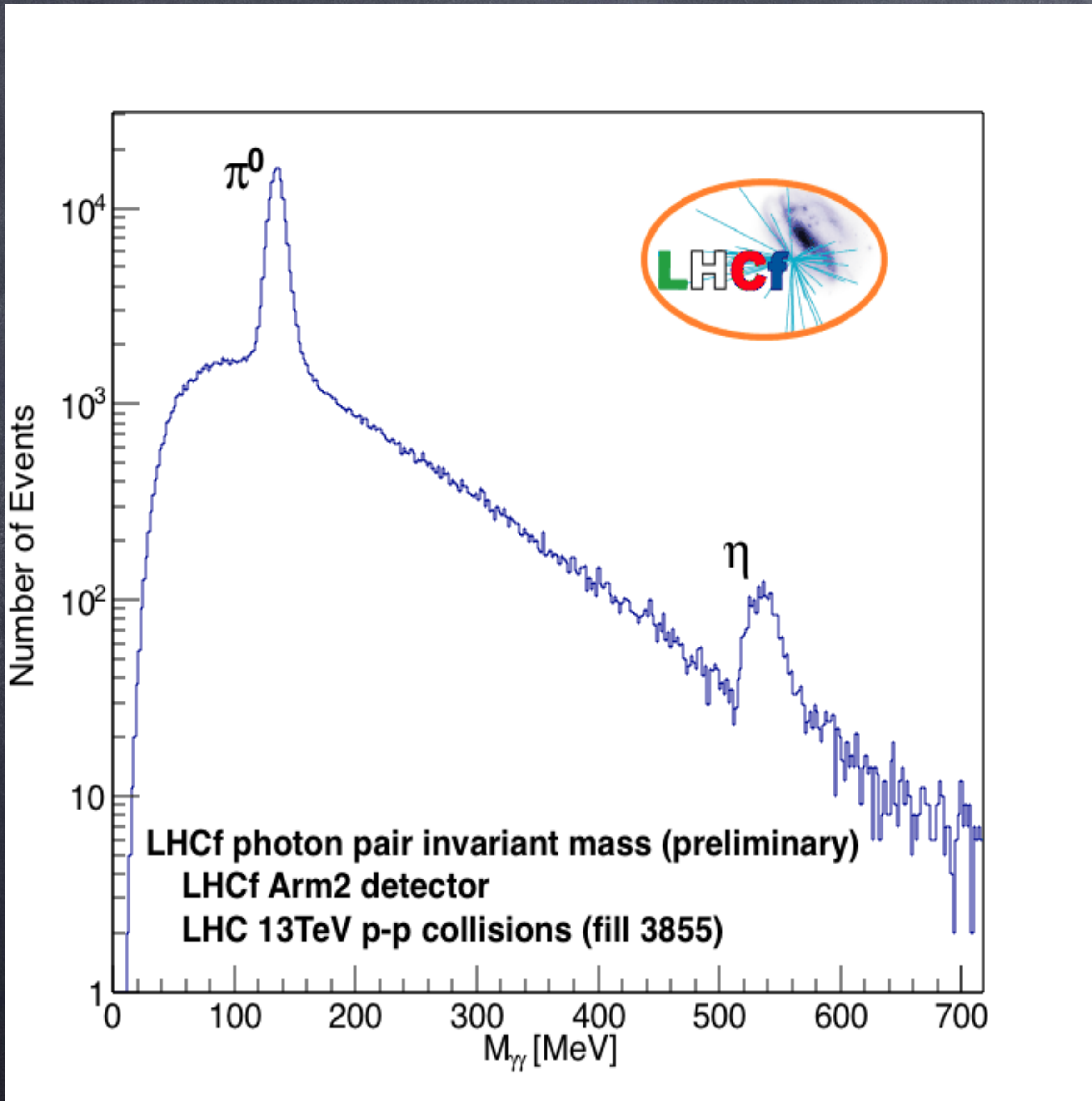


Significant improvement in phase-space acceptance

An impressive high energy π°

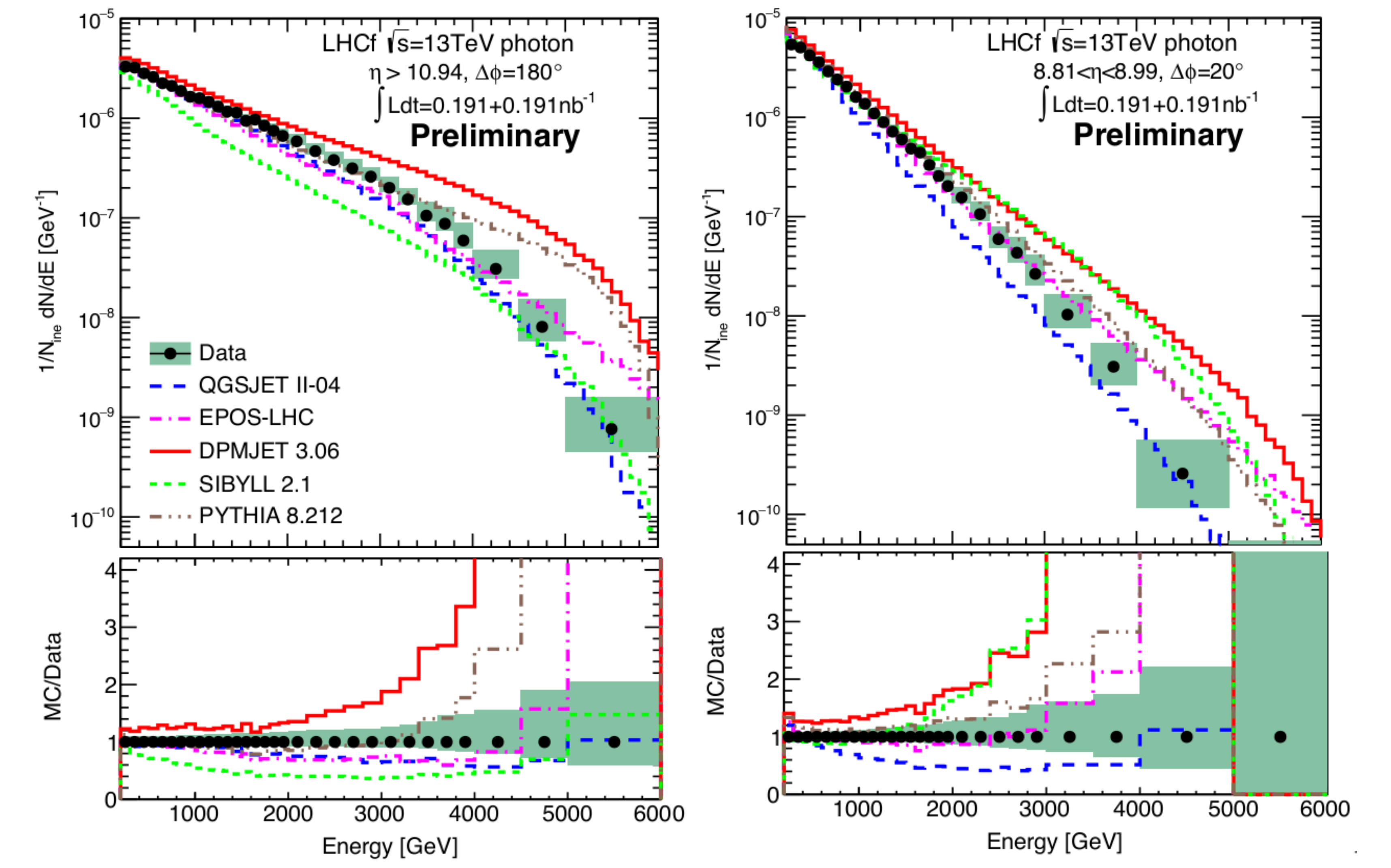


First look at 13 TeV data

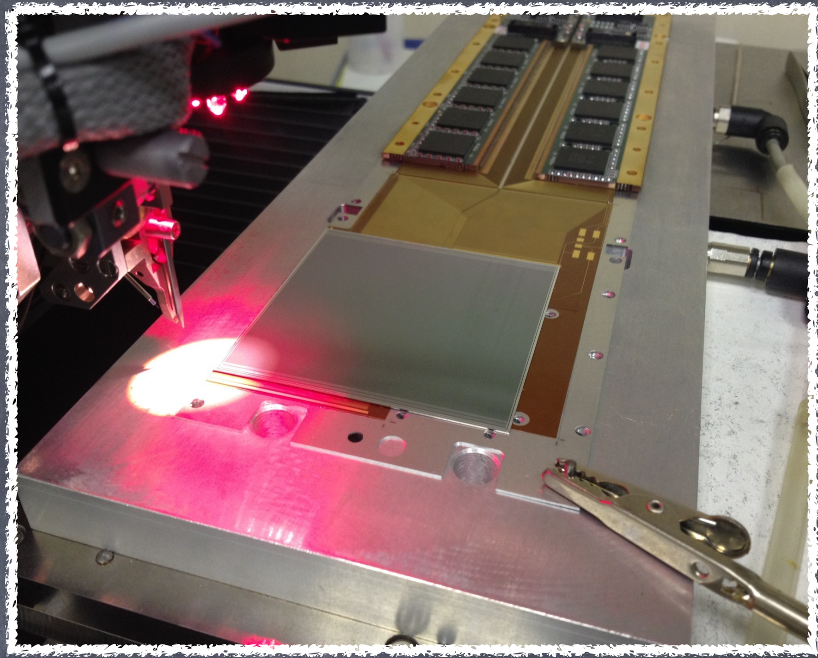


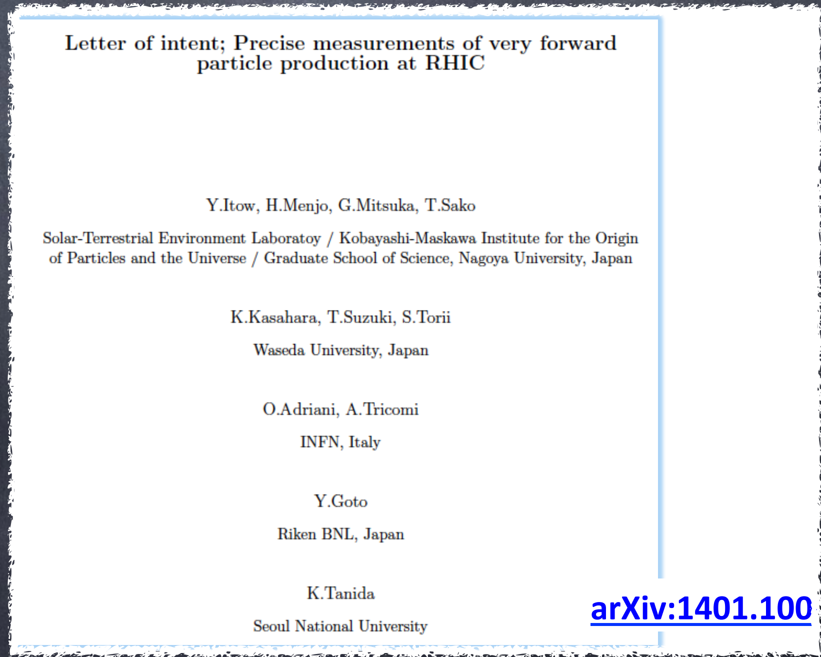
Mandatory tool for energy scale calibration

Preliminary γ energy spectra at 13 TeV



- 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

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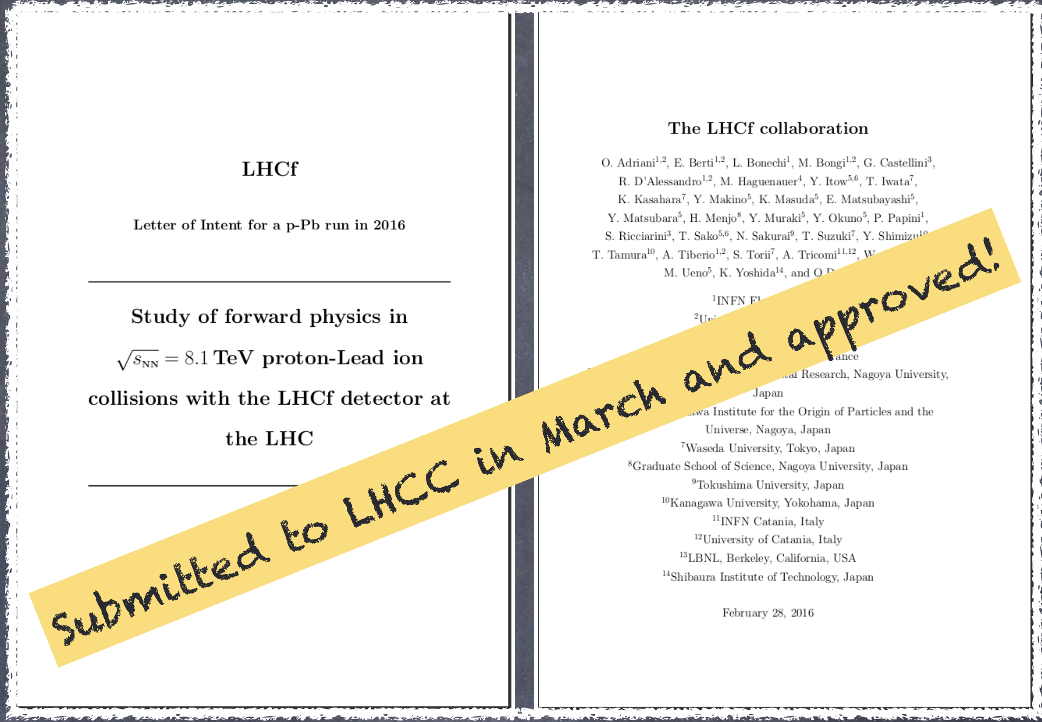
arXiv:1401.100

p-Pb at 8.1 TeV

Ony ARM2 Detector

Motivations:

- Statistics:
  - Measure π0 with increased statistics wrt 2013 run
  - Possibility to detect the η meson
  - Combined ATLAS-LHCf data take (very limited in 2013)
- Phase space
  - extend up to p_T>1 GeV/c
    - deviations from models suggested from 2013 data at high p_T
    - investigate pQCD phase-space region
- Scaling properties
  - Extrapolation at extreme CR energies
  - Feynman scaling: spectra in x_F



LHCf

Letter of Intent for a p-Pb run in 2016

Study of forward physics in $\sqrt{s_{NN}} = 8.1$ TeV proton-Lead ion collisions with the LHCf detector at the LHC

The LHCf collaboration

O. Adriani[1,2], E. Berti[1,2], L. Bonechi[1], M. Bongi[1,2], G. Castellini[3], R. D'Alessandro[1,2], M. Haguenauer[4], Y. Itow[5,6], T. Iwata[7], K. Kasahara[7], Y. Makino[5], K. Masuda[5], E. Matsubayashi[5], Y. Matsubara[5], H. Menjo[8], Y. Muraki[5], Y. Okuno[5], P. Papini[1], S. Ricciarini[3], T. Sako[5,6], N. Sakurai[9], T. Suzuki[7], Y. Shimizu[10], T. Tamura[10], A. Tiberio[1,2], S. Torii[7], A. Tricomi[11,12], M. Ueno[5], K. Yoshida[14], and

Research, Nagoya University, Japan

Institute for the Origin of Particles and the Universe, Nagoya, Japan

[7]Waseda University, Tokyo, Japan

[8]Graduate School of Science, Nagoya University, Japan

[9]Tokushima University, Japan

[10]Kanagawa University, Yokohama, Japan

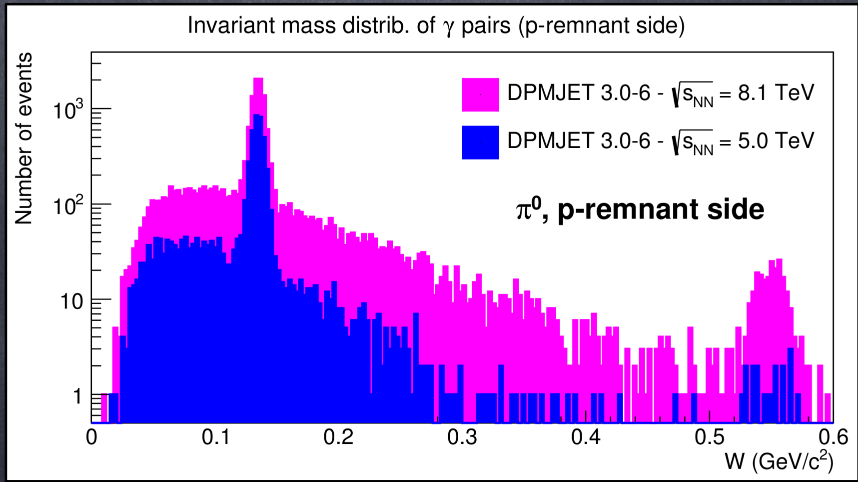
[11]INFN Catania, Italy

[12]University of Catania, Italy

[13]LBNL, Berkeley, California, USA

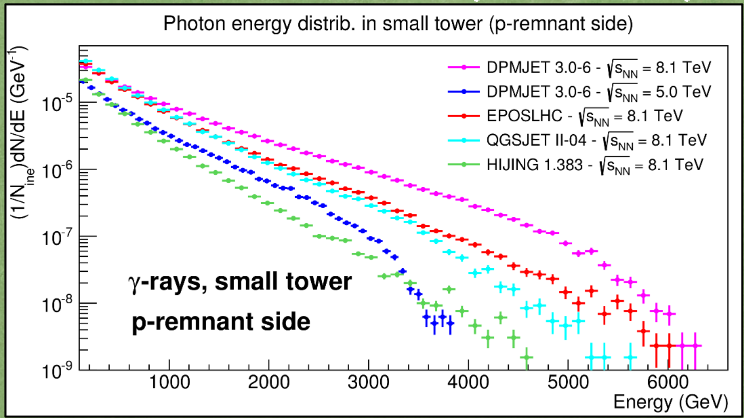
[14]Shibaura Institute of Technology, Japan

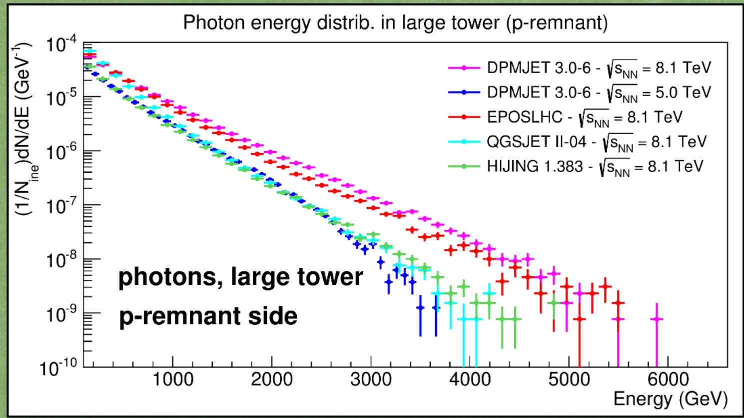
February 28, 2016



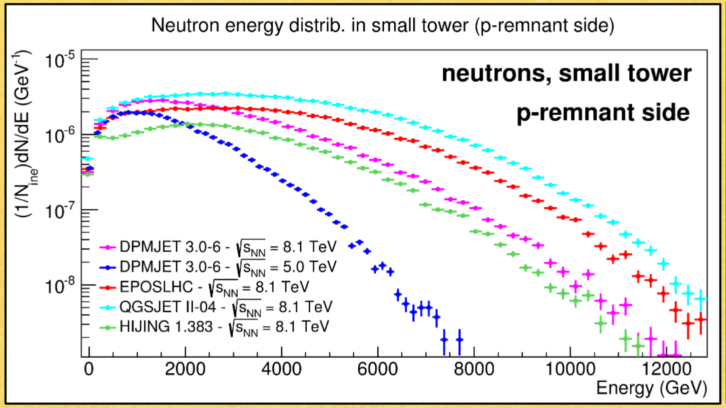
p-Pb at 8.1 TeV: γ & n spectra

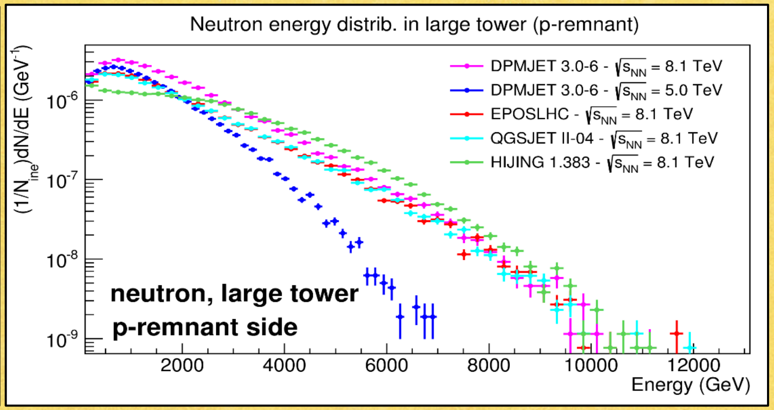
Expected photon distribution





Expected neutron distribution (35% energy resolution)





(CRMC)* framework has been used to simulate 10^7 collisions with 4 different hadronic interaction models:

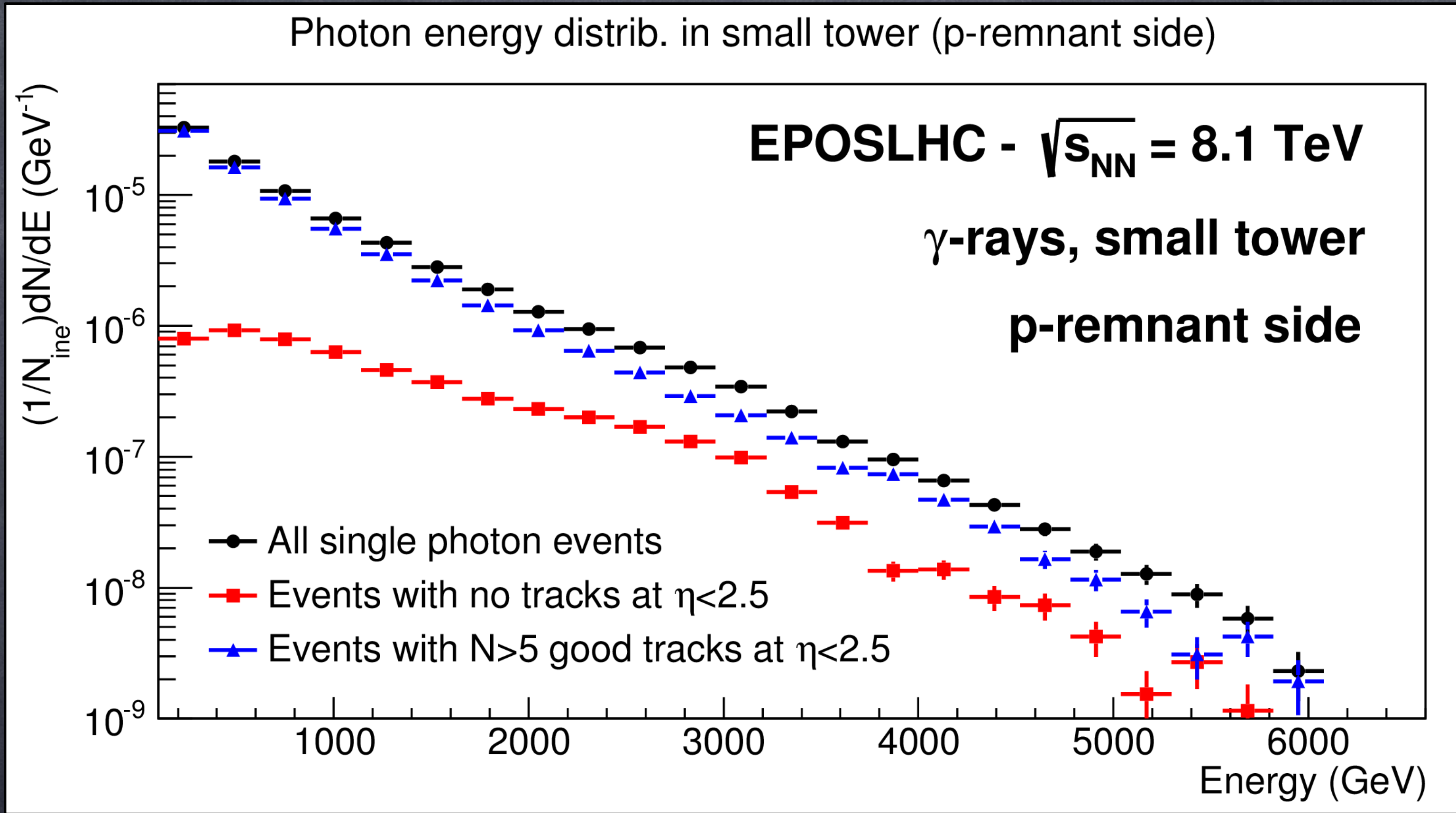
- DPMJET 3.0-6 p+Pb
- EPOSLHC p+Pb
- QGSJET II-04
- HIJING 1.383

Small calorimeter tower centered on the beam spot

Only p-remnant side considered

* We acknowledge T. Pierog, C. Baus and R. Ulrich for support

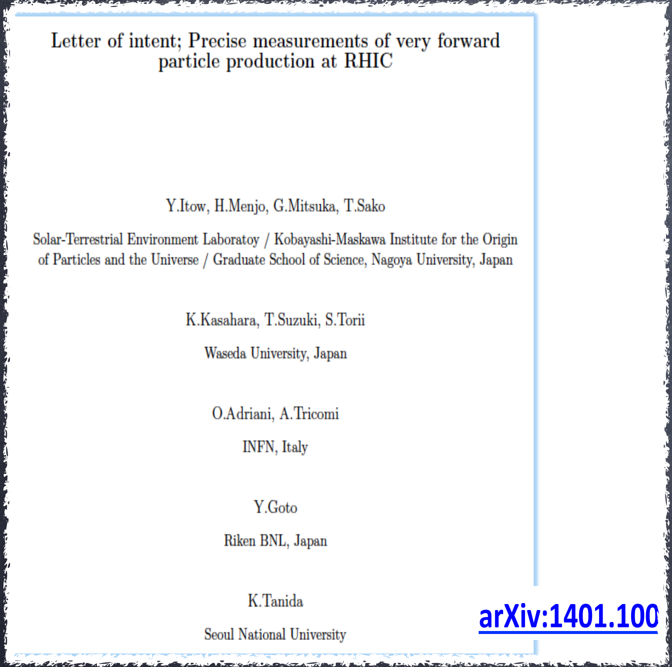
p-Pb at 8.1 TeV: perspective for ATLAS-LHCf combined analysis



Information from the ATLAS central region is essential to separate the contributions due to diffractive and non-diffractive collisions.

From LHCf to RHICf

p-p at $\sqrt{s}$=510 GeV with ARM1 in 2017
Extend $\sqrt{s}$ coverage for the test of Feynman scaling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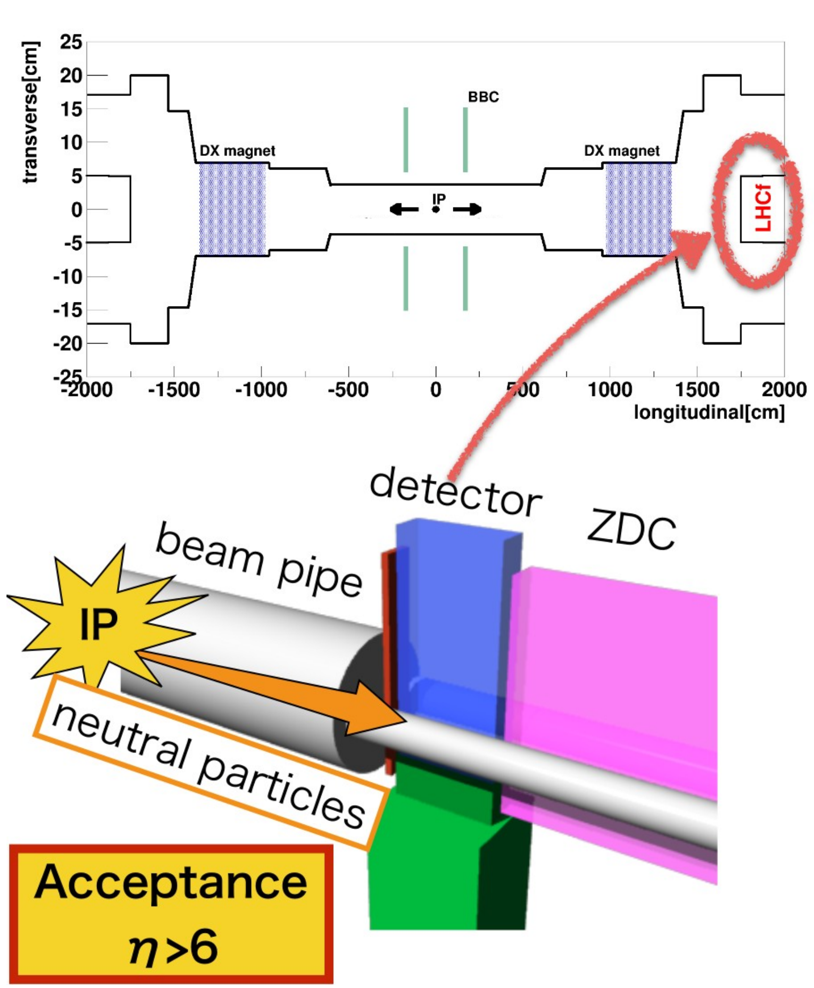
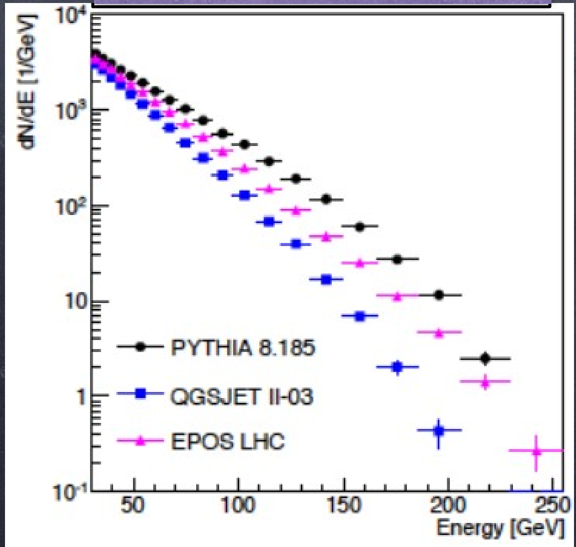
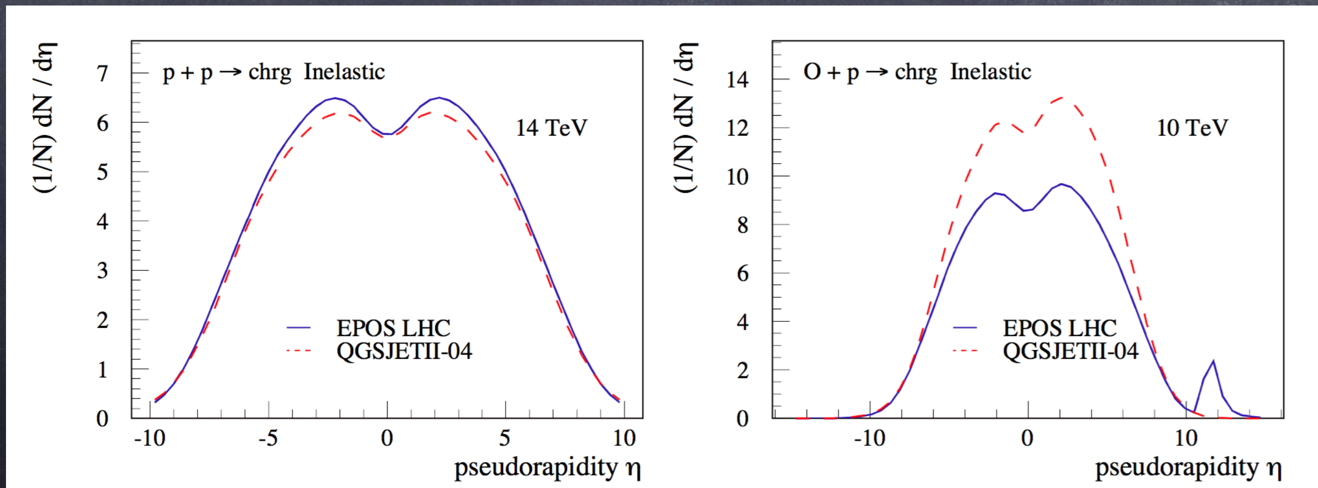


Photons



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 for 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
- An intensive 2016-2017 program is waiting for us
  - 8.1 TeV and 5 TeV p-Pb collisions at LHC in November 2016
  - 510 GeV p-p with polarized beam at RHIC in February 2017
- Still a lot of results will come in the next years... while waiting for p-Light Ion run at LHC
- So... stay tuned!