Cosmic Ray International Seminar 2015

Gallipoli, 15th Sep 2015

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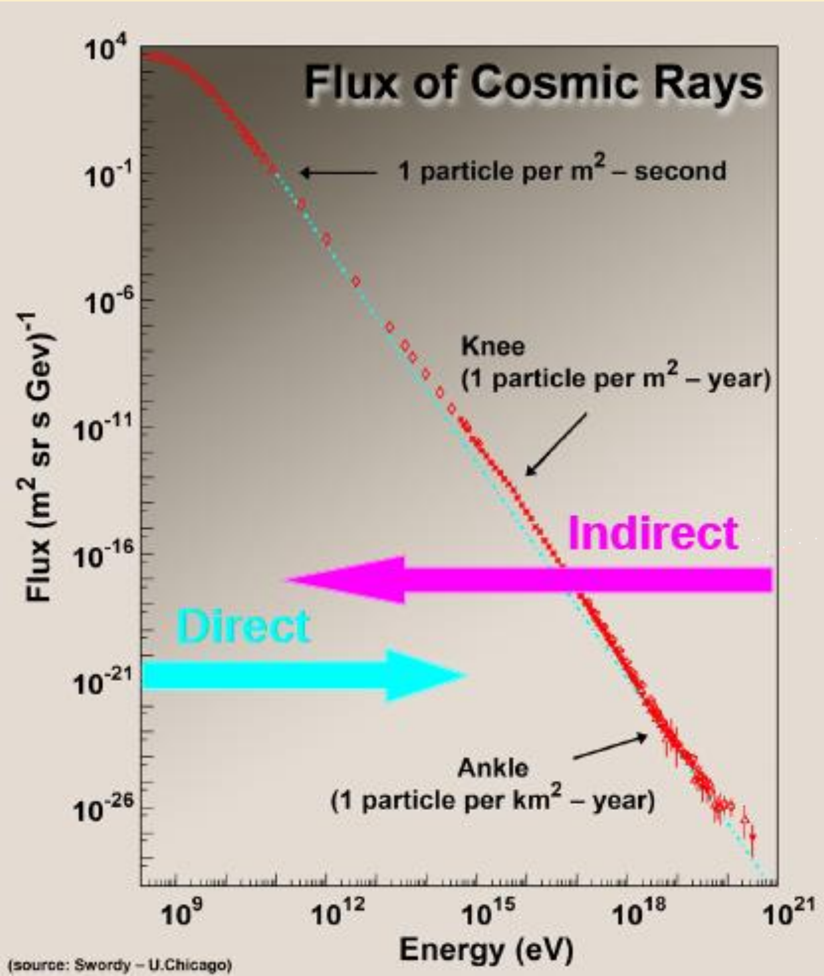
LHCf EXPERIMENT: PHYSICS RESULTS

PHYSICS MOTIVATIONS

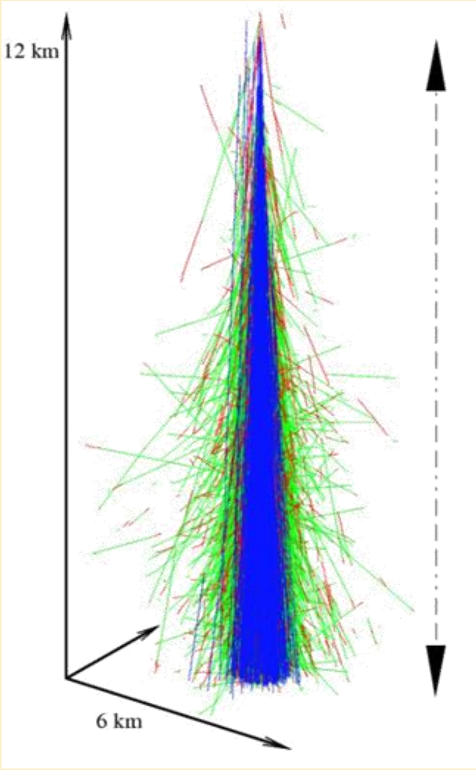
Impact on HECR Physics

THE HIGH ENERGY COSMIC RAY SPECTRUM

- The cosmic ray spectrum falls very rapidly with energy ($\sim E^{-2.7}$)
- At high energies direct measurements are limited by the very low flux of particles ($< 1/m^2/year$)
- We have to rely on atmospheric showers measurements



Detailed knowledge of high energy hadronic interactions is needed in order to reconstruct the primary CR type and energy



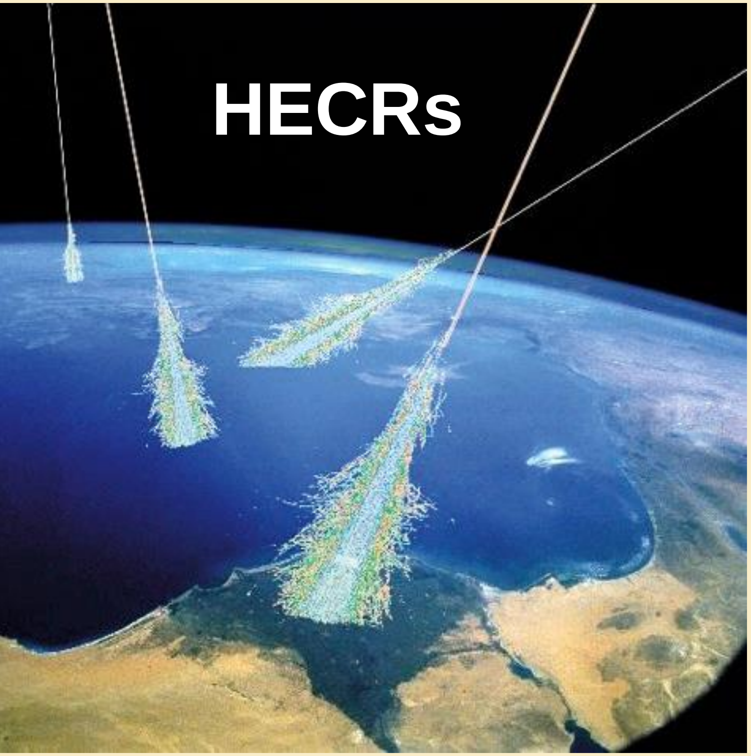
Calorimetric measurement using Earth's atmosphere

$\sim 27\ X_0$

$\sim 11\ \lambda_{int}$

10^{19} eV proton

HIGH ENERGY CR SHOWERS: MAIN OBSERVABLES



- **X_{max}** : depth of shower maximum in the atmosphere
- **rms(X_{max})** : fluctuations in the position of the shower maximum
- **N_{μ}** : number of muons in the shower at the detector level

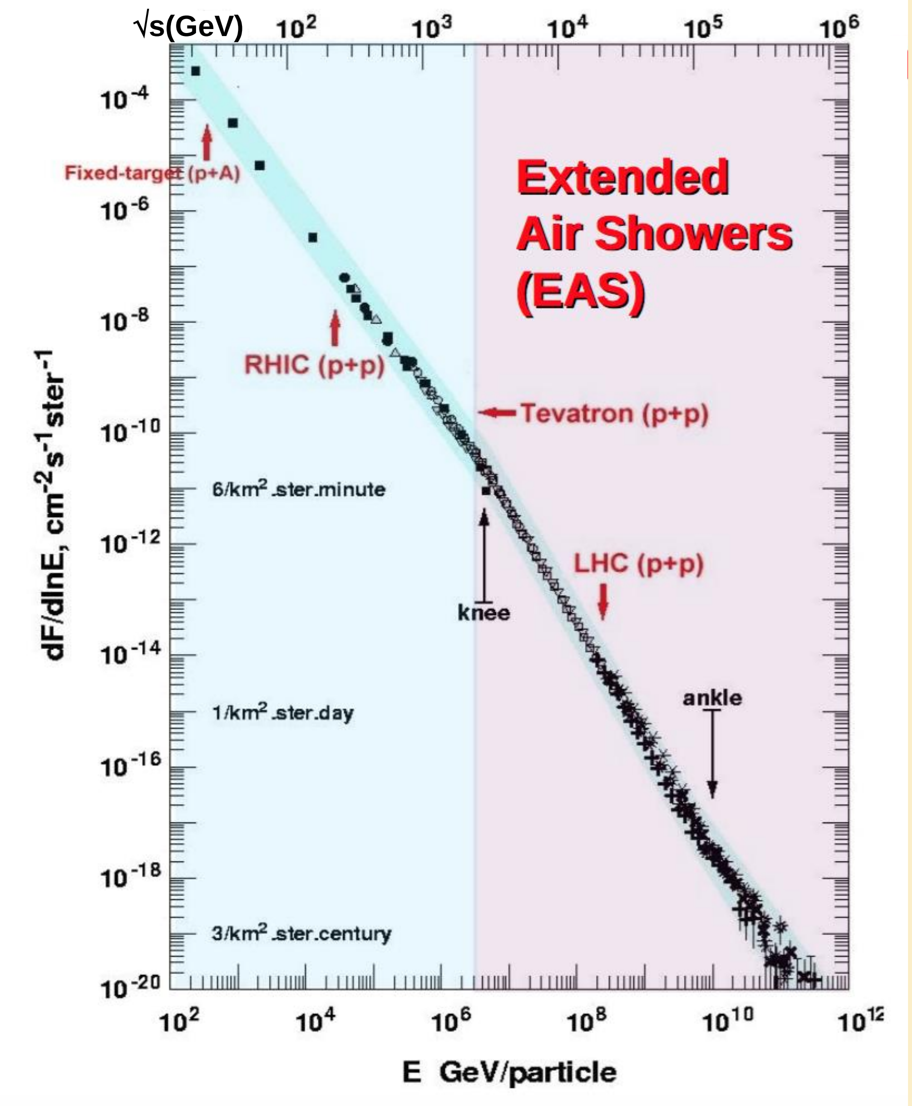
hadronic interaction models

CR composition and energy

Uncertainty in hadron interaction models

Uncertainty in the interpretation of the observables

THE ROLE OF ACCELERATOR BASED EXPERIMENTS



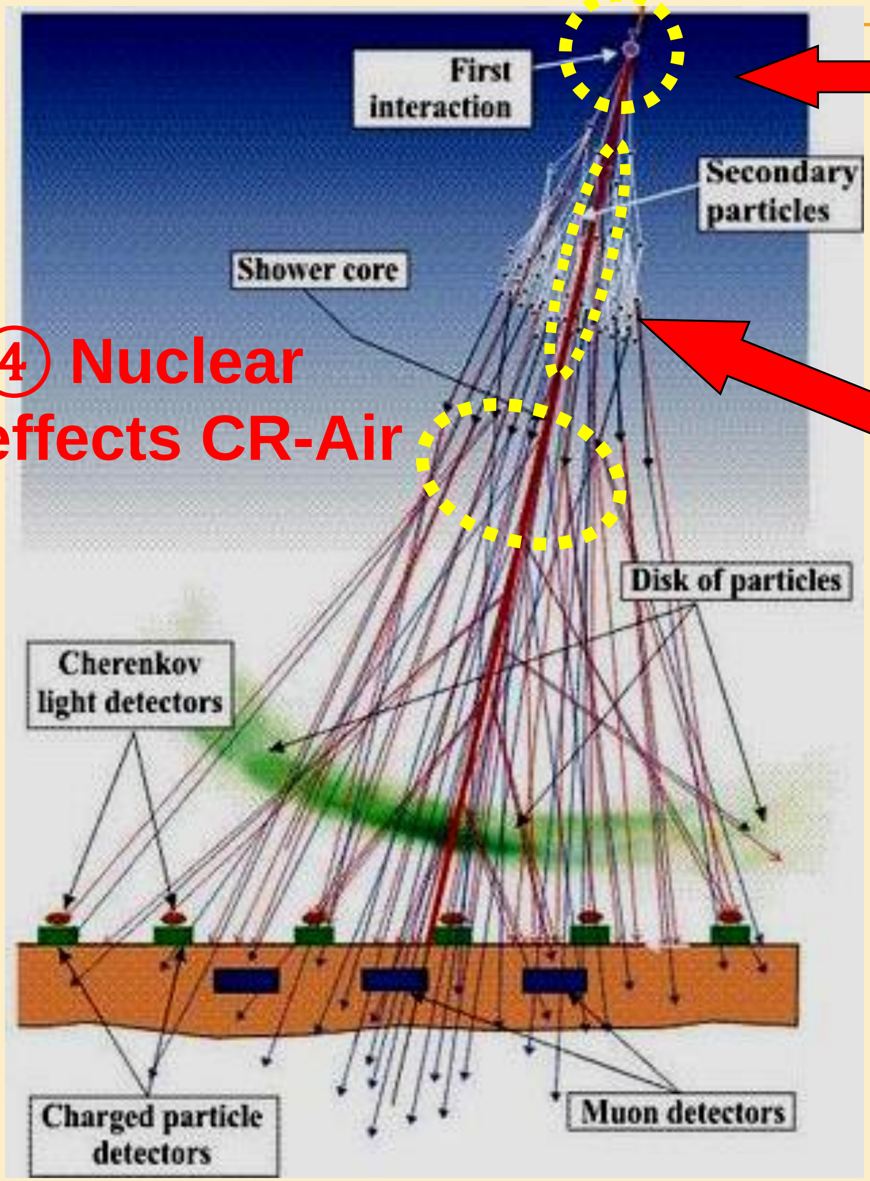
Accelerator based experiments are the most powerful available tools for:

- studying the characteristics of high energy hadronic interactions
- tuning hadronic interaction models

LHC: 13 TeV ⇨ 9.10^{16} eV

Unique opportunity to calibrate the models in the region beyond the "knee"

HOW ACCELERATOR EXPERIMENTS CAN CONTRIBUTE



④ **Nuclear effects CR-Air**

① **Inelastic cross section**

If large σ: rapid development
If small σ: deep penetrating

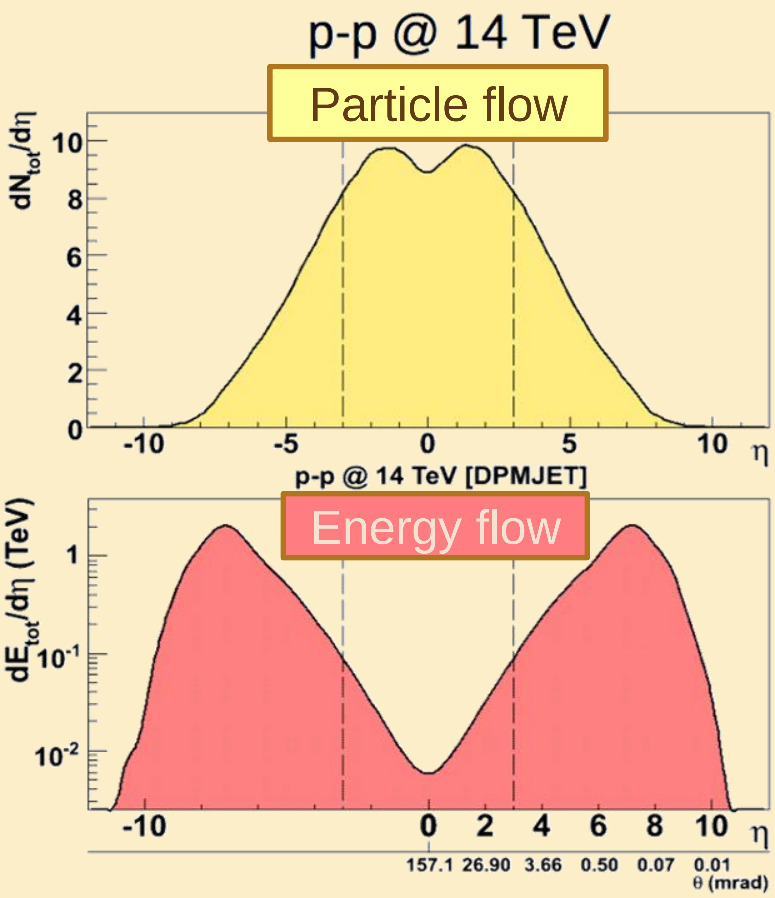
② **Forward energy spectrum**

If softer: shallow development
If harder: deep penetrating

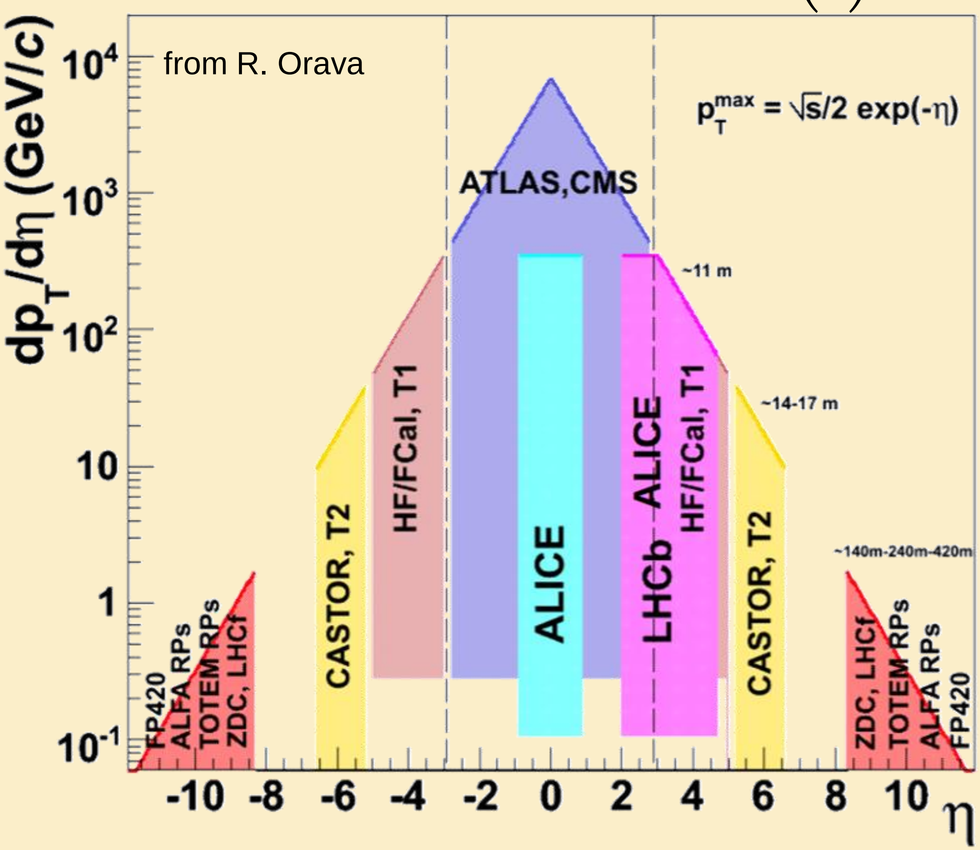
③ **Inelasticity** $k = 1 - \frac{E_{lead}}{E_{avail}}$

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

LHC PHASE SPACE COVERAGE



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



A very broad phase space coverage is available

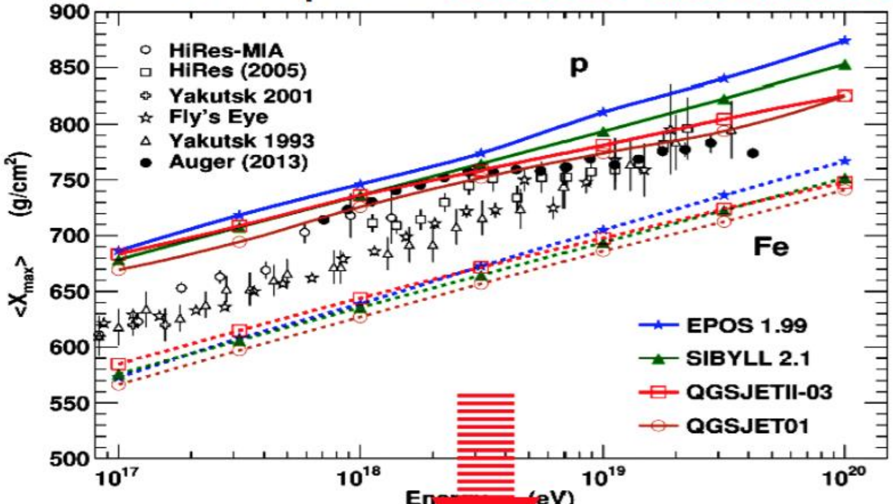
Dedicated forward detectors for a better measurement of the energy flow

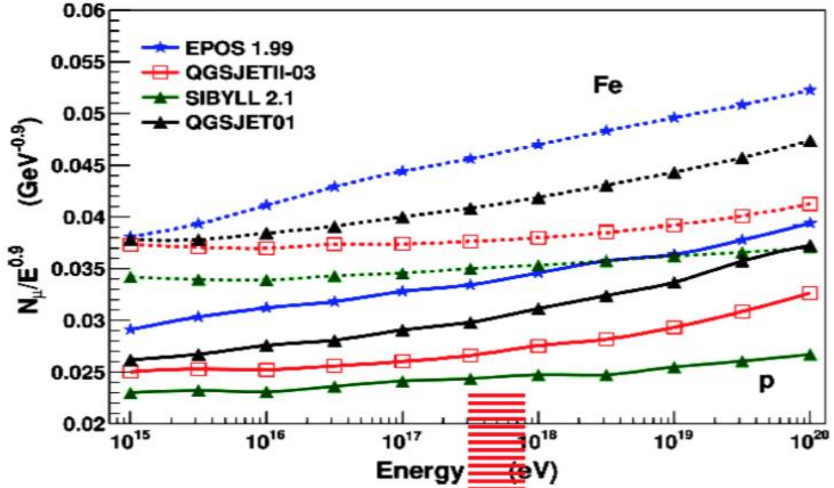
TUNING OF MODELS AFTER THE FIRST LHC DATA

Mean depth of shower maximum:

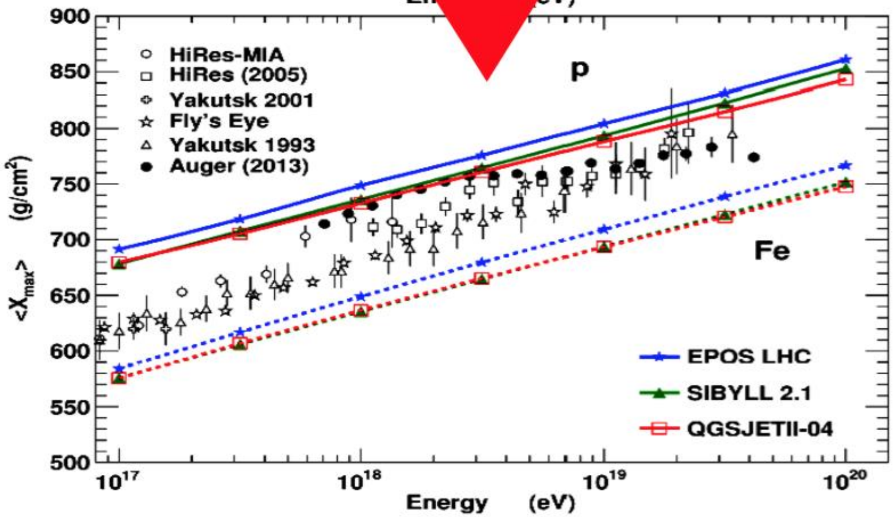
Number of muons on ground:

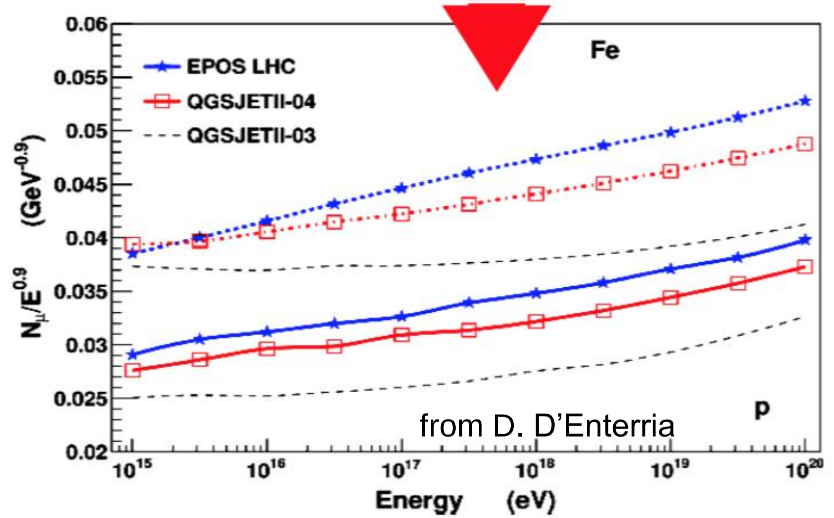
before LHC





after LHC



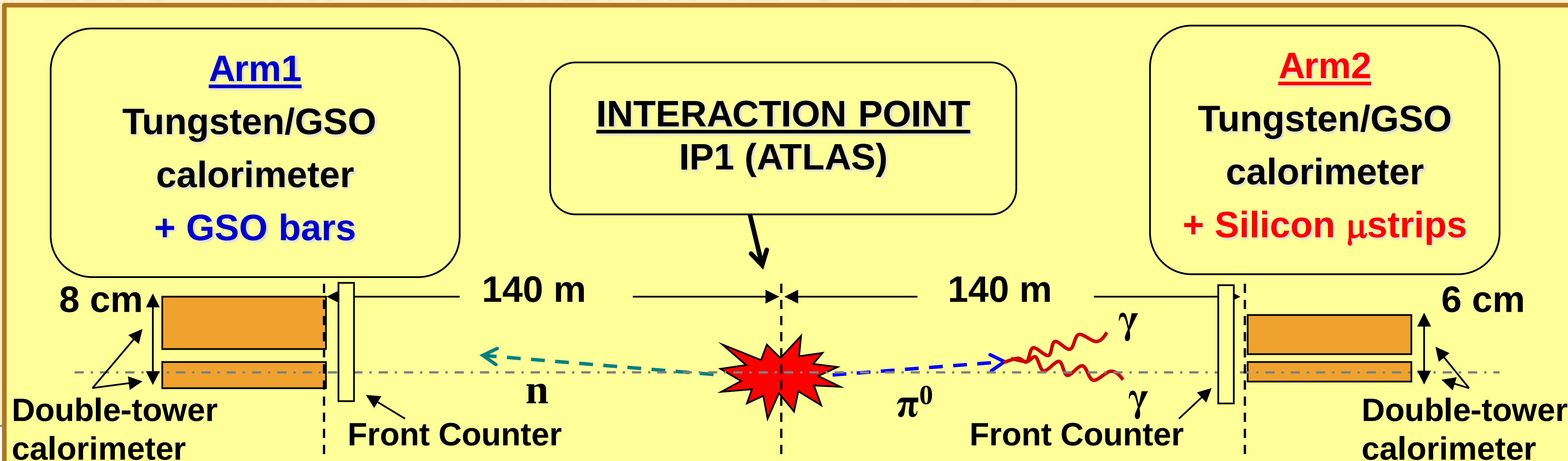


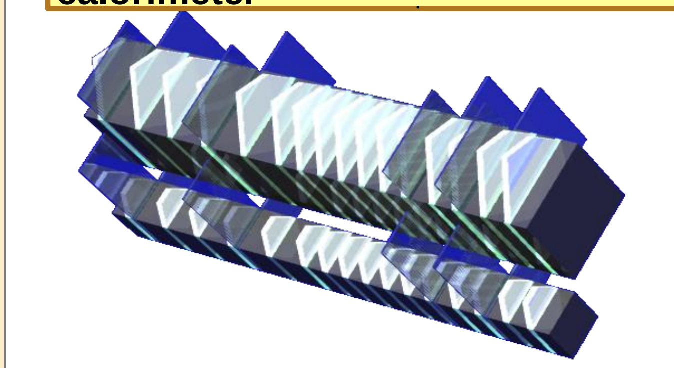
Significant reduction of differences among hadronic interaction models

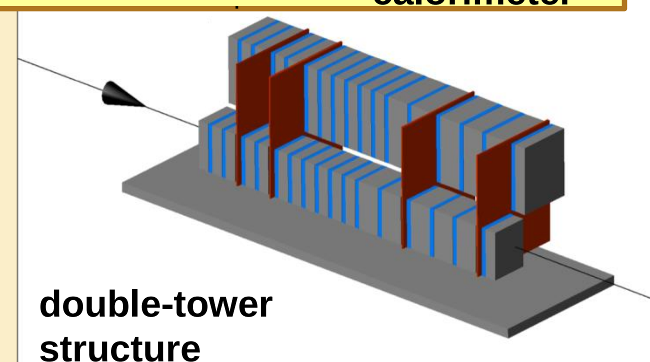
LHCf @ LHC

the experimental set-up

LHCf EXPERIMENTAL SET-UP







$44\ X_0$
$1.6\ \lambda_{int}$

Position resolution:
< 200 μm (Arm1)
40 μm (Arm2)

Energy resolution:
< 5% for photons
30% for neutrons

Pseudo-rapidity range:
η > 8.7 @ zero X-ing angle
η > 8.4 @ 140 μrad

Arm1 Detector
20mm x 20mm + 40mm x 40mm
4 X-Y GSO bars tracking layers

Arm2 Detector
25mm x 25mm + 32mm x 32mm
4 X-Y Silicon strip tracking layers

THE LHCf COLLABORATION

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e) *KMI, Nagoya University, Japan*
f) *STELAB, Nagoya University, Japan*
g) *RISE, Waseda University, Japan*
h) *School of Science, Nagoya University, Japan*
i) *CERN, Switzerland*
j) *Kanagawa University, Japan*
k) *University of Catania, Italy*
l) *INFN Section of Catania, Italy*
m) *LBNL, Berkeley, California, USA*

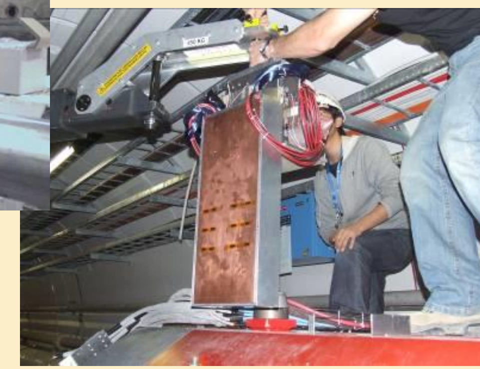
BRIEF HISTORY OF LHCf

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

Jul 2006 construction

Aug 2007 SPS beam test

Jan 2008 installation
Sep 2008 1st LHC beam



Dec 2009 - Jul 2010
0.9TeV & 7TeV pp,
detector removal

Dec 2012 - Feb 2013
5.02 TeV/n pPb & 2.76TeV pp
(Arm2 only),
detector removal

May - June 2015
13 TeV pp (dedicated run),
detector removal

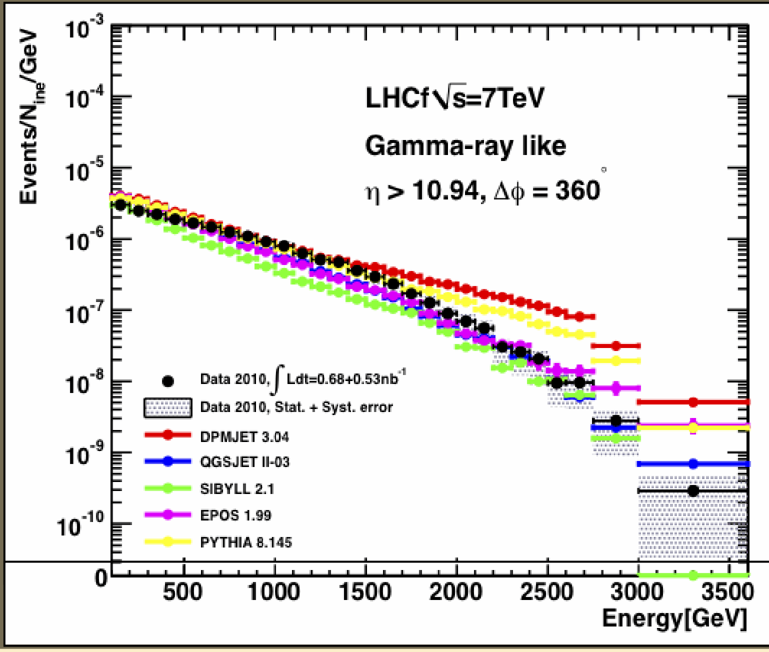
PHYSICS PROGRAM AND TABLE OF PUBLICATIONS

	Proton equivalent energy in the LAB (eV)	γ	n	π^0
SPS test beam		NIM A, 671, 129 (2012)	JINST 9 P03016 (2014)	
p-p 900 GeV	4.3×10^{14}	Phys. Lett. B 715, 298 (2012)		
p-p 7 TeV	2.6×10^{16}	Phys. Lett. B 703, 128 (2011)	Submitted to Phys. Lett. B	Phys. Rev. D 86, 092001 (2012) + Submitted to Phys. Rev. D (Type-II)
p-p 2.76 TeV	4.1×10^{15}			Phys. Rev. C 89, 065209 (2014) + Submitted to Phys. Rev. D (Type-II)
p-Pb 5.02 TeV	1.3×10^{16}			
p-p 13 TeV	9.0×10^{16}	Data taken in June 2015 after the restart of LHC		

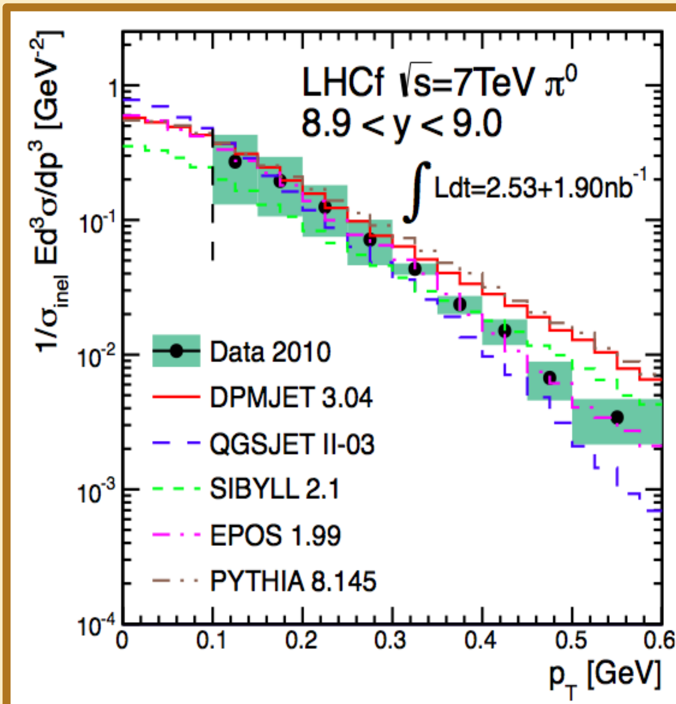
LATEST ANALYSES AND RESULTS

PREVIOUSLY PUBLISHED RESULTS

- comparison between data and expectation from different models
- inclusive energy spectra
- p_T spectra in different rapidity bins

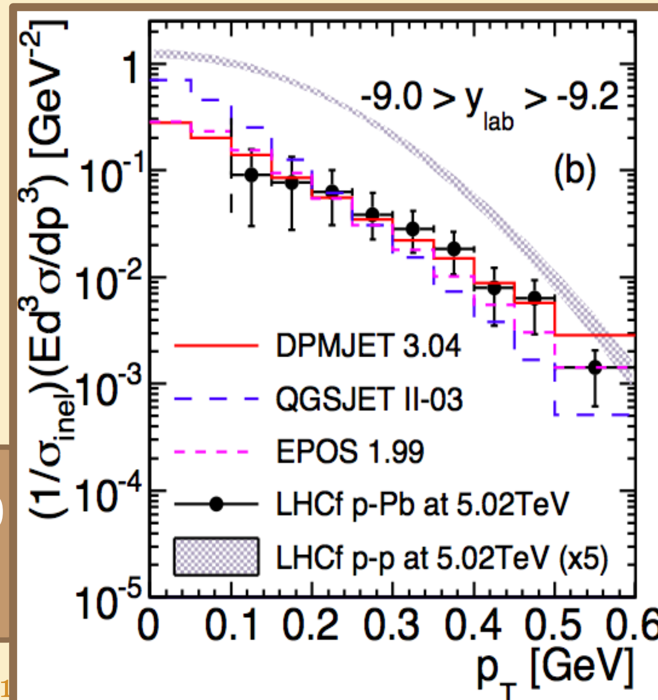


7 & 0.9 TeV pp photon



7 TeV pp π^0

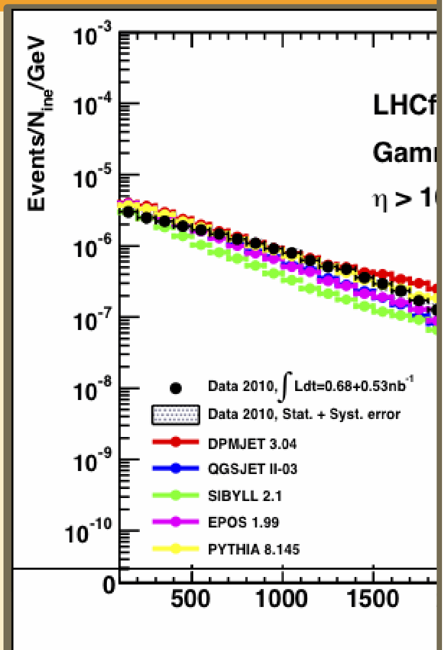
5.02 TeV/n pPb π^0

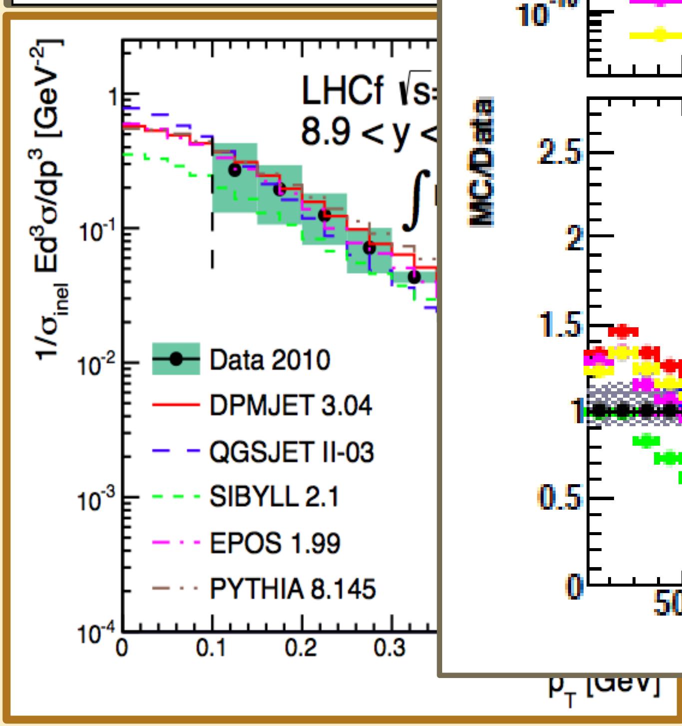


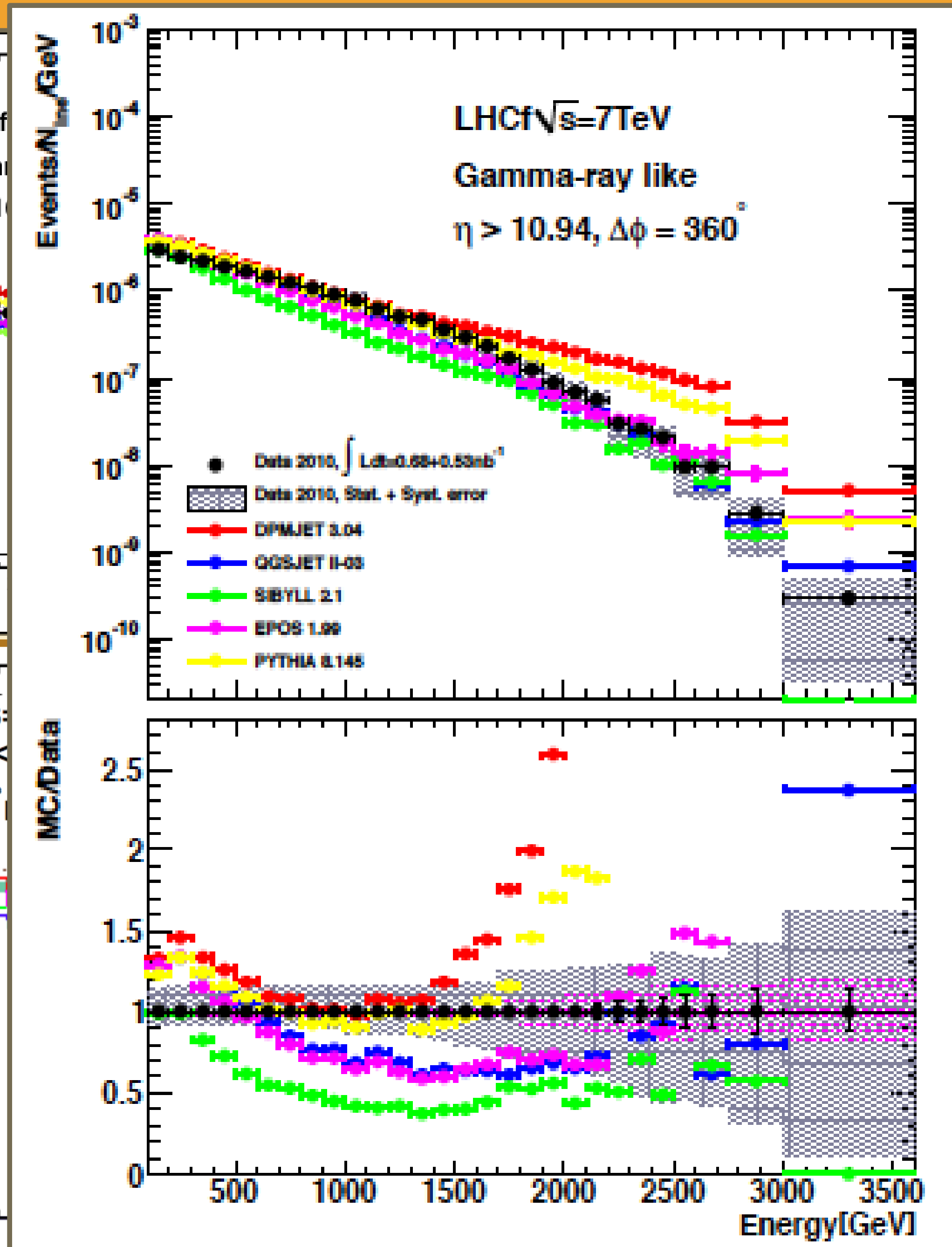
...HED RESULTS

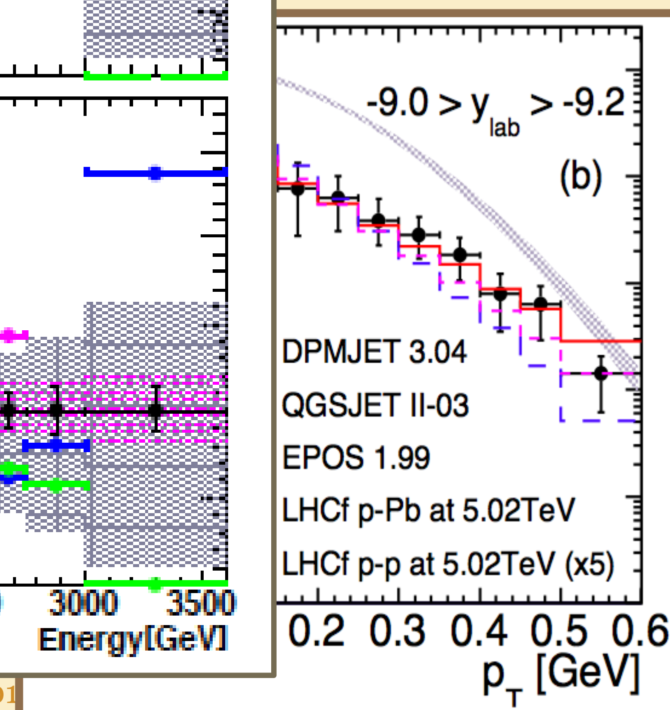
...a and expectation

...idity bins

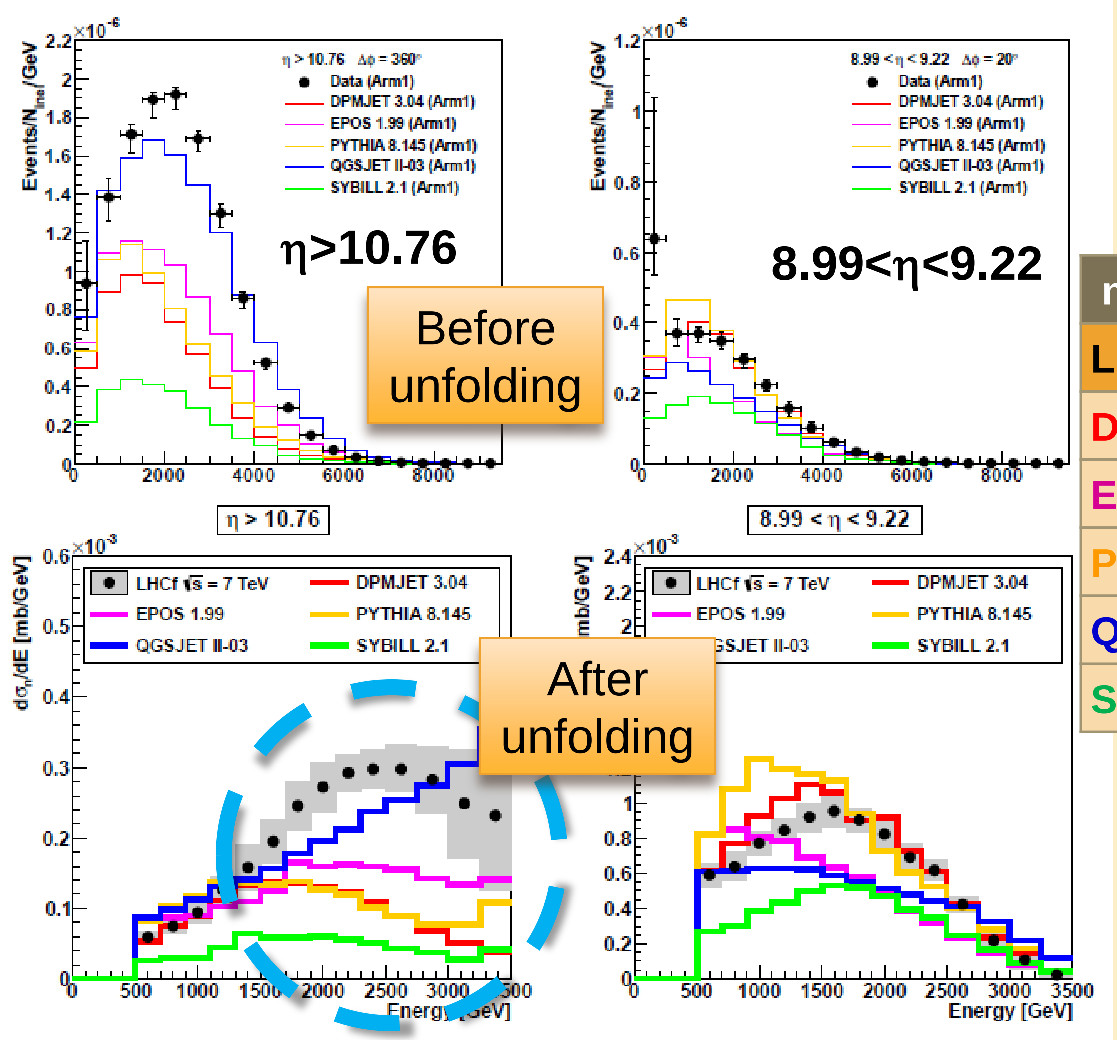








INCLUSIVE NEUTRON SPECTRA (7 TeV pp)



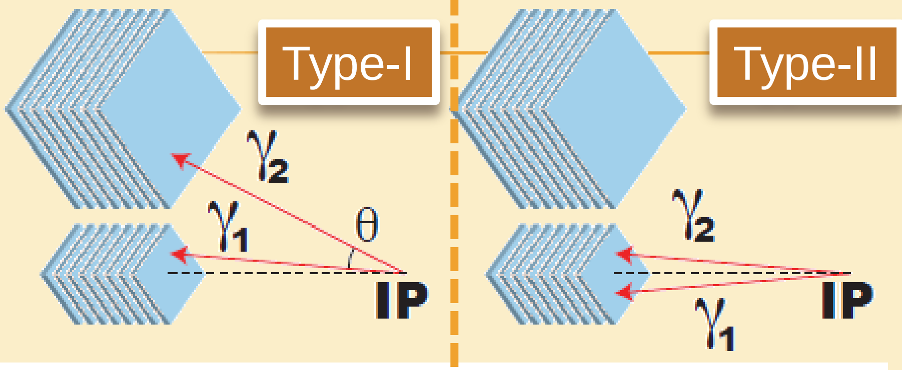
Submitted to Phys. Lett. B

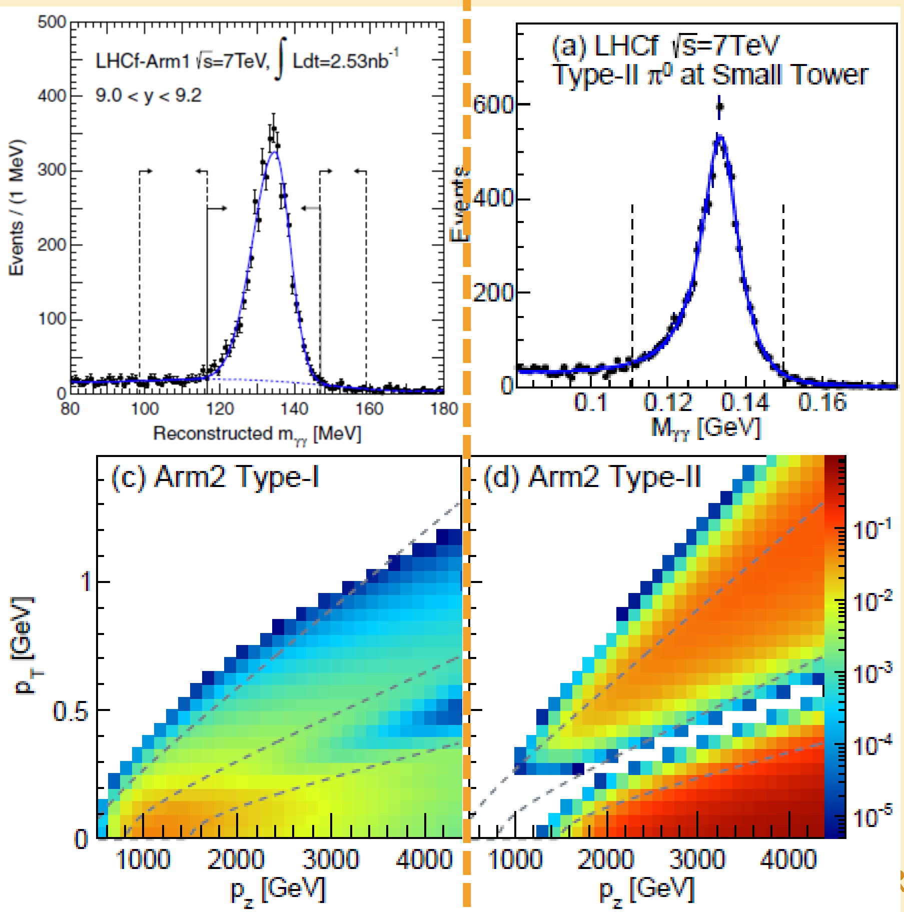
n / γ ratio	η>10.76	8.99<η<9.22
LHCf data	3.05±0.19	1.26±0.08
DPMJET3.04	1.05	0.76
EPOS 1.99	1.80	0.69
PYTHIA 8.145	1.27	0.82
QGSJET II-03	2.34	0.65
SYBILL 2.1	0.88	0.57

More abundant neutron yield wrt photons, not expected from MC

Large high-energy peak in the η>10.76 region (predicted only by QGSJET)
→ small inelasticity in the very forward region

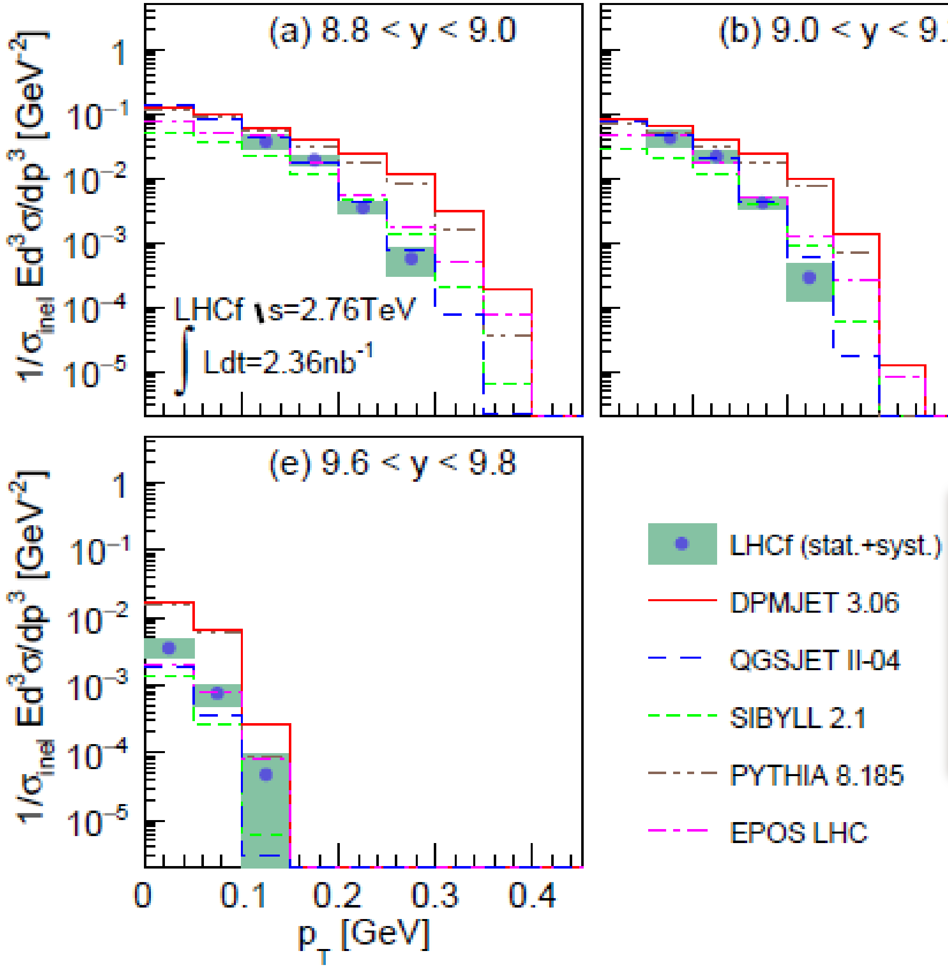
π^0 ANALYSIS: TYPE-I AND TYPE-II EVENTS





- pair of photons each detected in one of the towers (Type-I) or both in the same tower (Type-II)
- multi-hit events excluded
- p_T and p_Z of π^0 reconstructed from energy and incident position of photon pair
- invariant mass distribution to select π^0 candidates
- data are corrected for experimental effects:
  - background contamination
  - detector response and reconstruction efficiency (unfolding)
  - detector acceptance
  - multi-hit rejection efficiency

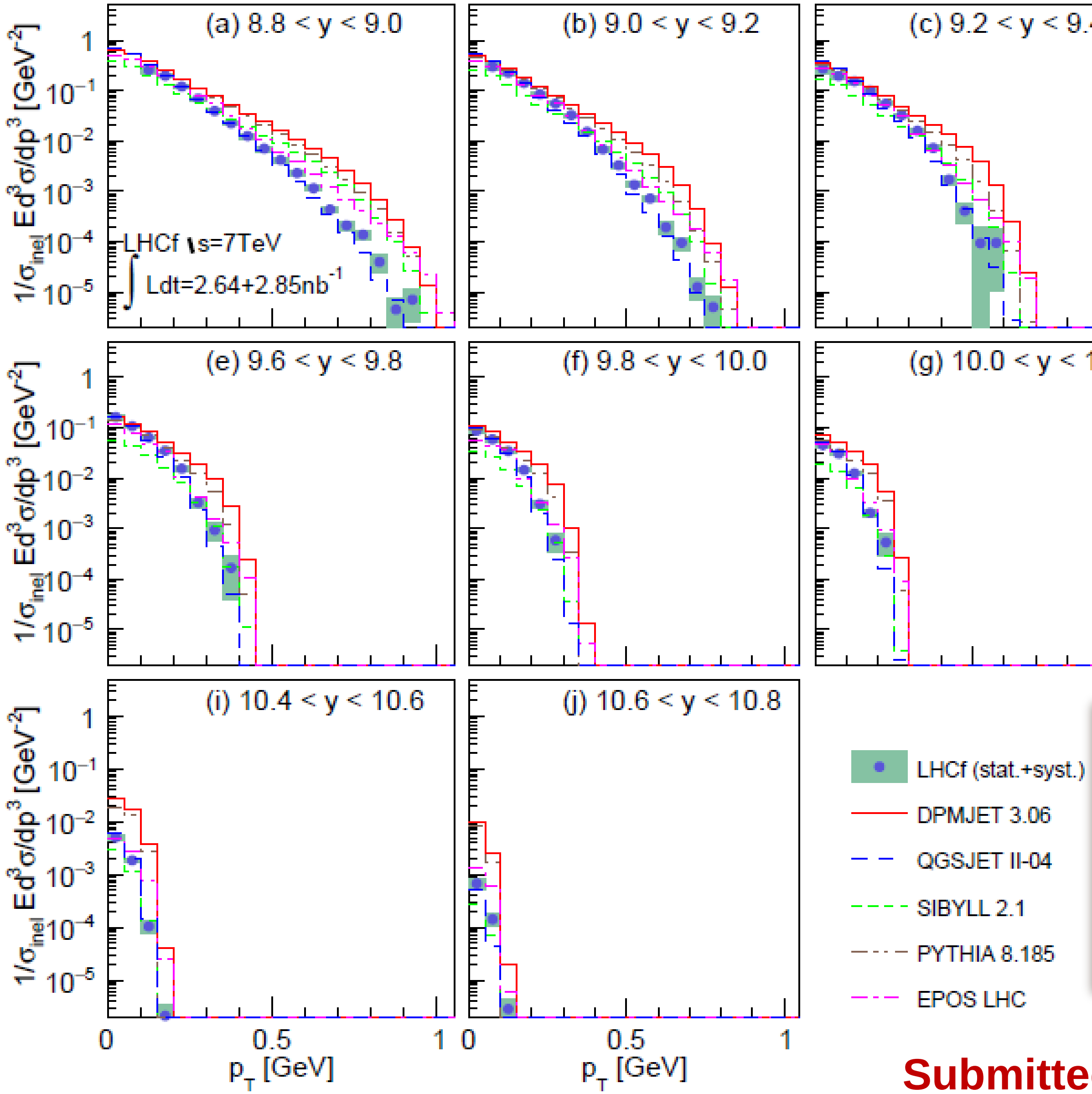
π^0 p_T SPECTRA (TYPE-I + TYPE-II): 2.76 TeV pp



- QGSJETII-04: best agreement
- EPOS-LHC: harder than data
- SIBYLL: smaller yield
- DPMJET and PYTHIA: larger yield

Submitted to Phys. Rev. D

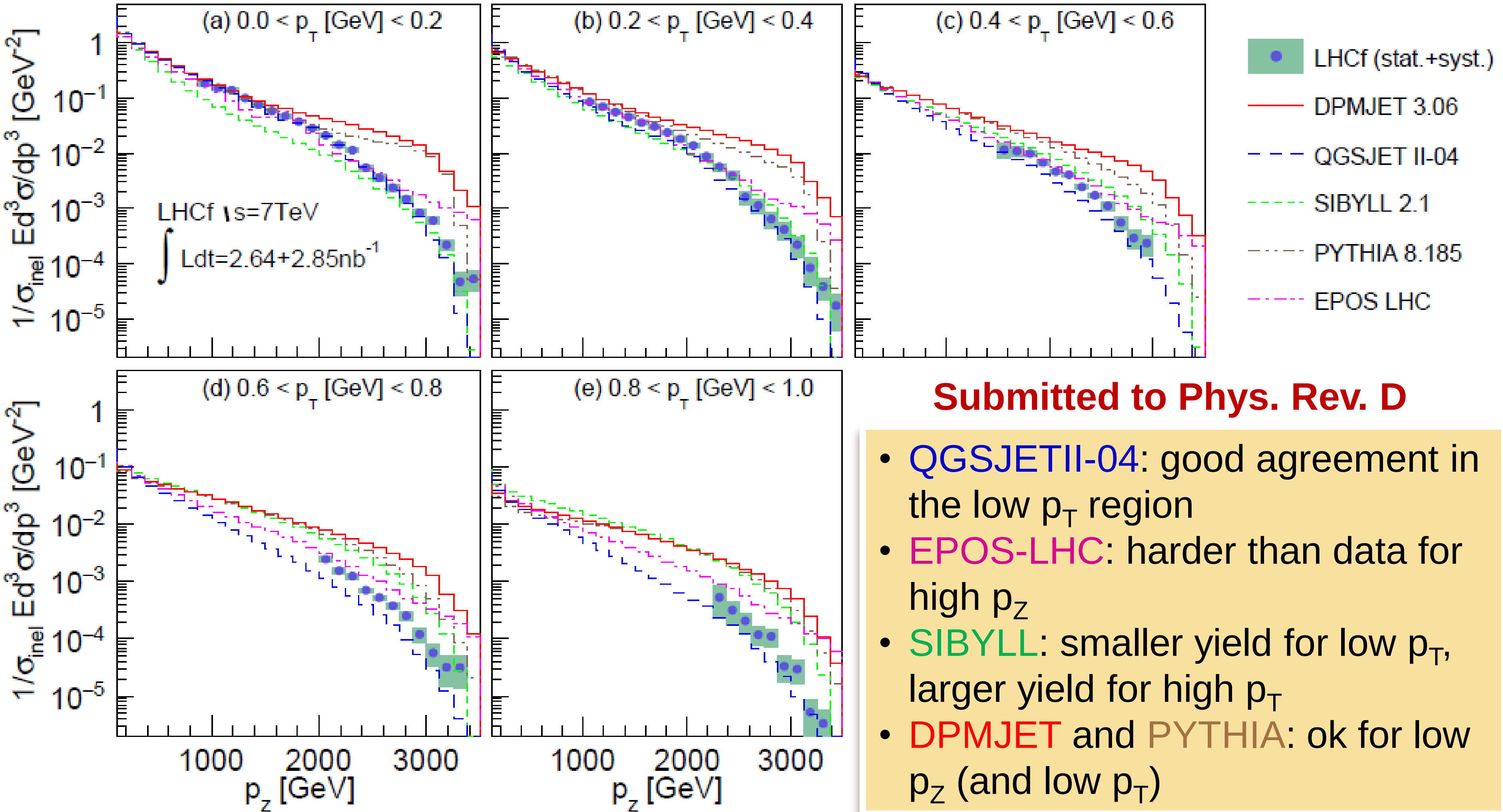
π^0 p_T SPECTRA (TYPE-I + TYPE-II): 7 TeV pp



- QGSJETII-04: best agreement
- EPOS-LHC: larger yield for high p_T
- SIBYLL: harder than data

Submitted to Phys. Rev. D

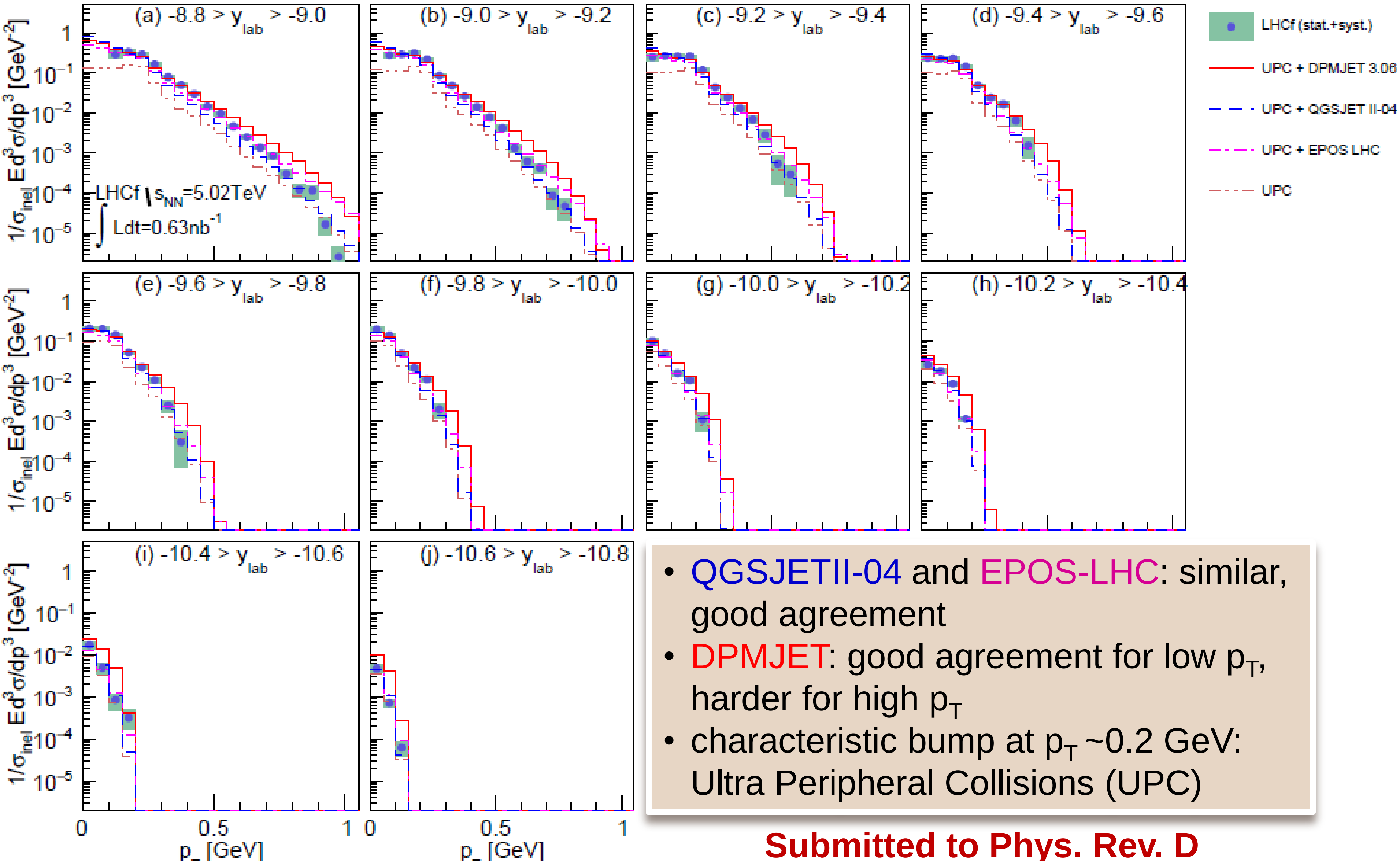
π^0 p_Z SPECTRA (TYPE-I + TYPE-II): 7 TeV pp



Submitted to Phys. Rev. D

- QGSJETII-04: good agreement in the low p_T region
- EPOS-LHC: harder than data for high p_Z
- SIBYLL: smaller yield for low p_T, larger yield for high p_T
- DPMJET and PYTHIA: ok for low p_Z (and low p_T)

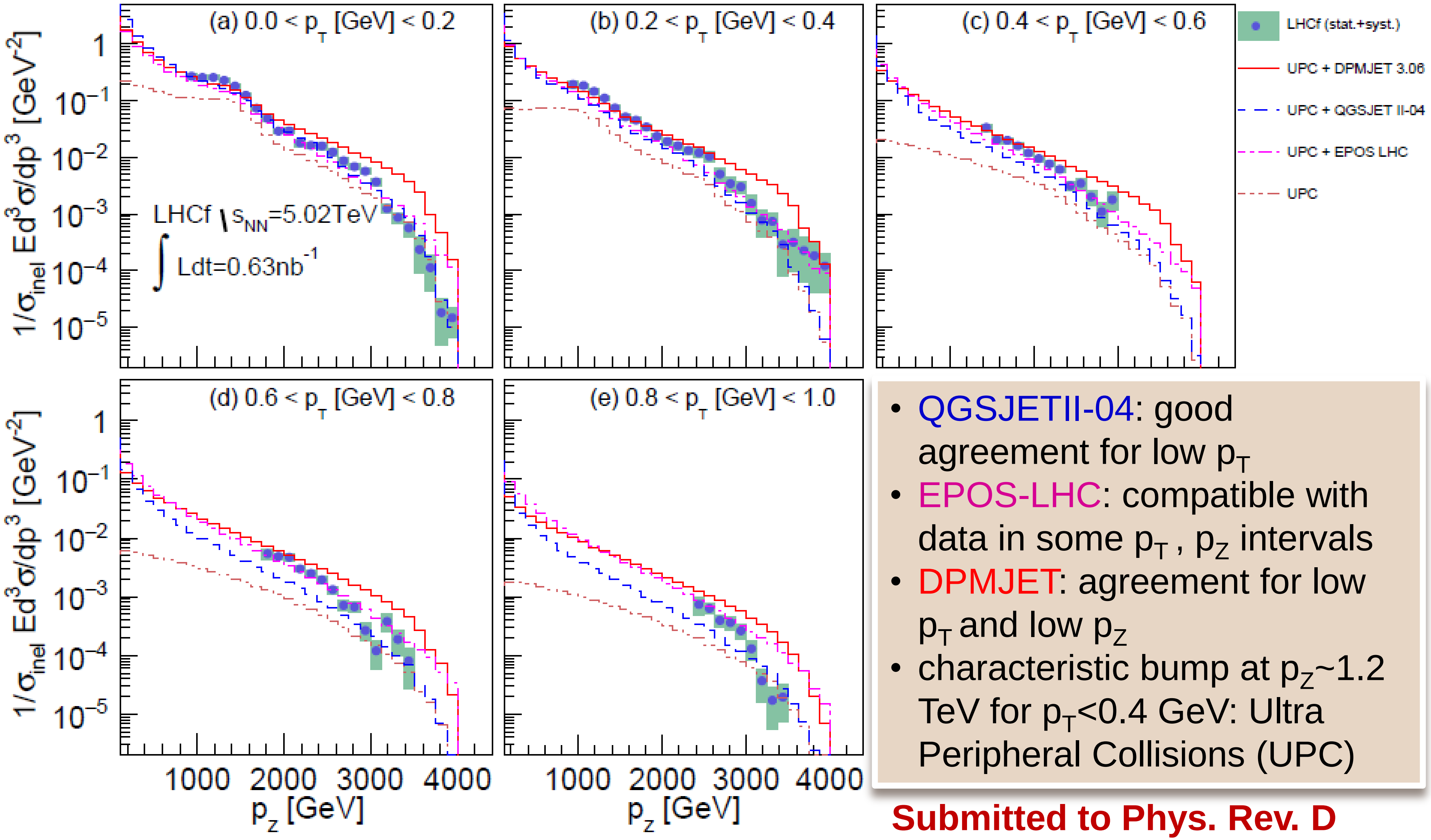
π^0 p_T SPECTRA (TYPE-I + TYPE-II): 5.02 TeV pPb



- QGSJETII-04 and EPOS-LHC: similar, good agreement
- DPMJET: good agreement for low p_T, harder for high p_T
- characteristic bump at p_T ~0.2 GeV: Ultra Peripheral Collisions (UPC)

Submitted to Phys. Rev. D

π^0 p_Z SPECTRA (TYPE-I + TYPE-II): 5.02 TeV pPb



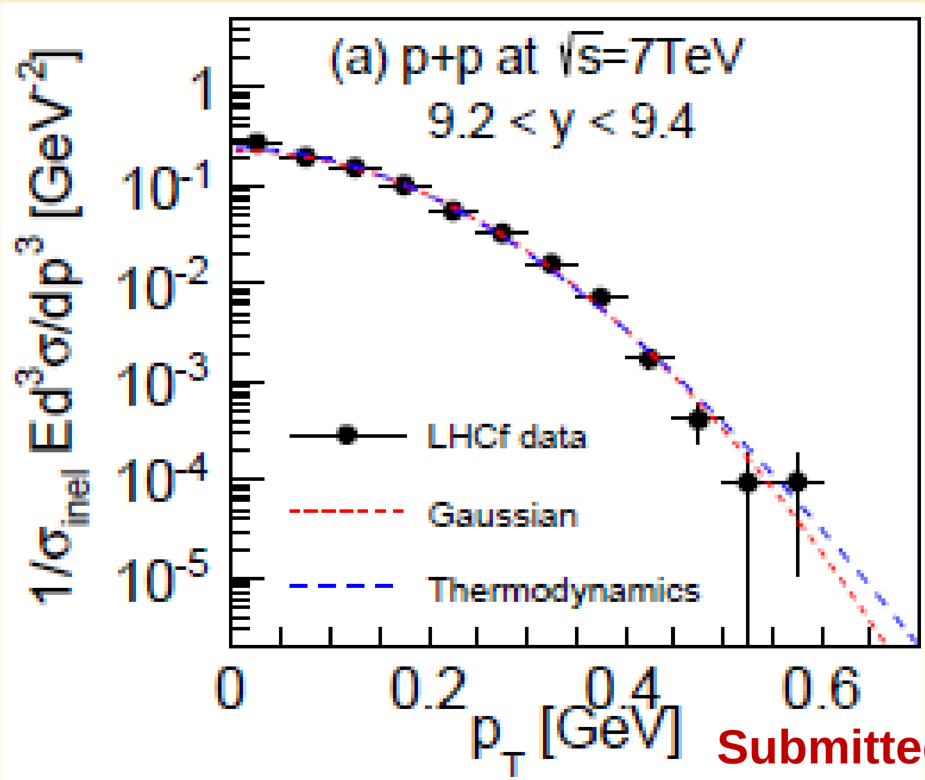
- QGSJETII-04: good agreement for low p_T
- EPOS-LHC: compatible with data in some p_T , p_Z intervals
- DPMJET: agreement for low p_T and low p_Z
- characteristic bump at p_Z~1.2 TeV for p_T<0.4 GeV: Ultra Peripheral Collisions (UPC)

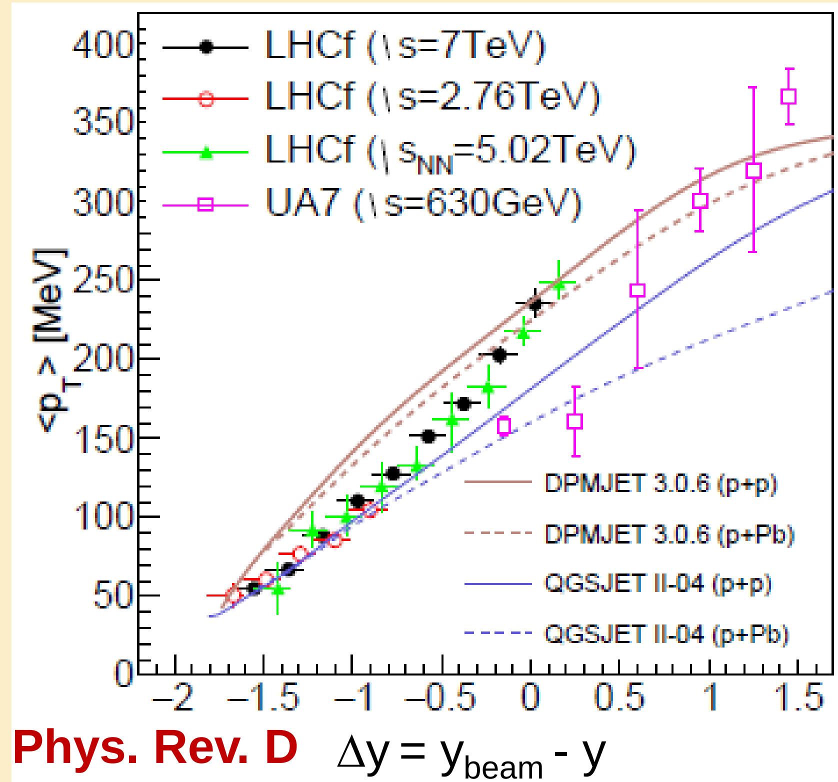
Submitted to Phys. Rev. D

SOME TESTS OF SCALING HYPOTHESES

(for the first time in the forward region at E~TeV)

π^0 AVERAGE p_T FOR DIFFERENT C.M. ENERGIES





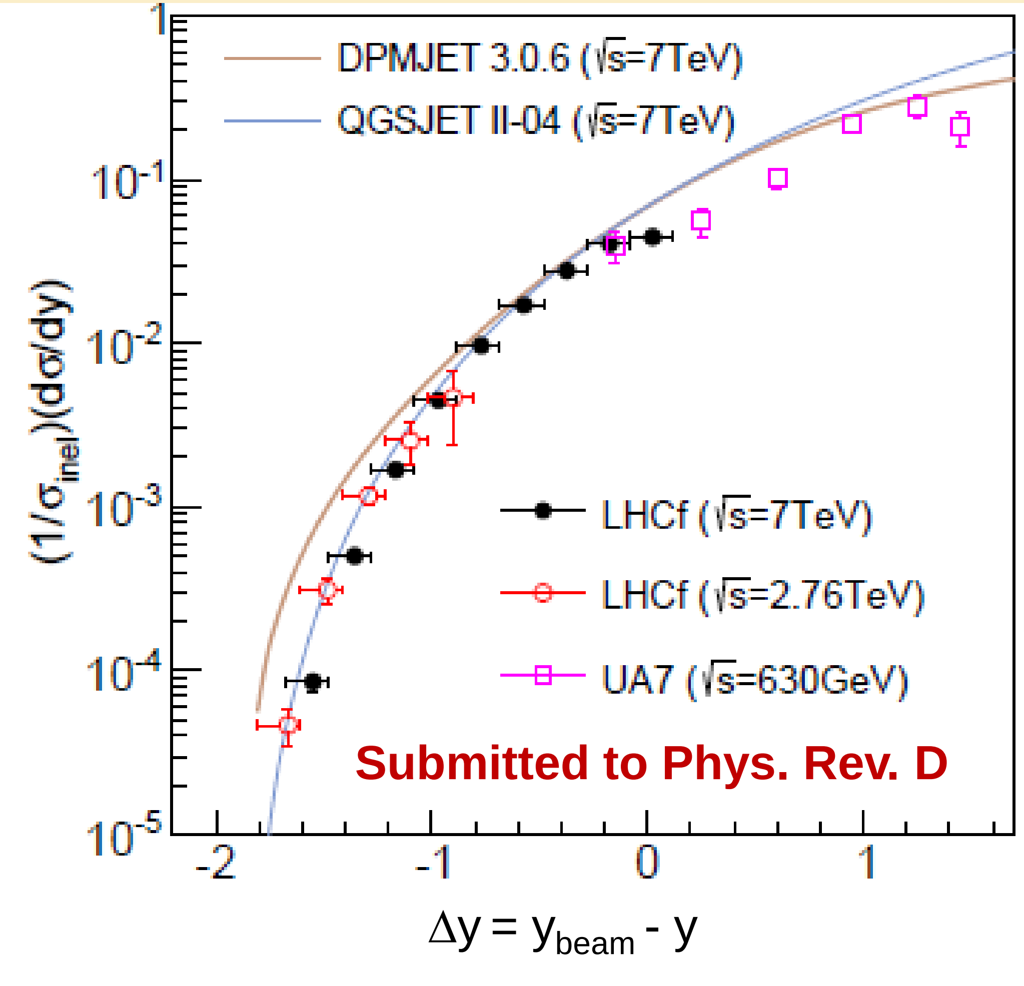
Submitted to Phys. Rev. D

Average p_T is inferred with 3 different methods:

- Gaussian distribution fit
- Thermodynamical approach
- Numerical integration of the histogram

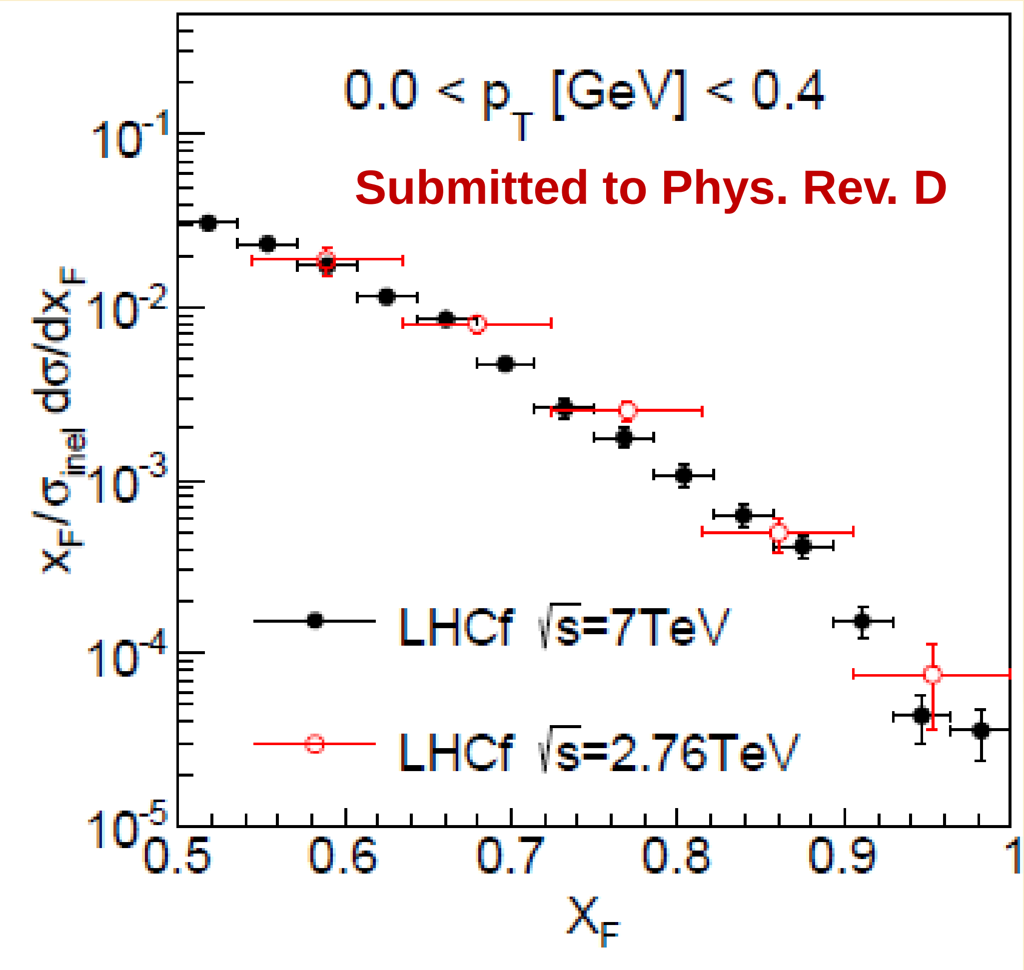
- Test of independence of average p_T (as a function of the rapidity loss Δy) in the very forward rapidity region wrt the c.m. energy $\sqrt{s}$
- **Scaling hypothesis holds at ±10% level**

LIMITING FRAGMENTATION IN FORWARD π^0 PRODUCTION



- Test of independence of rapidity distribution in the very forward rapidity region wrt the c.m. energy √s
- **limiting fragmentation hypothesis holds at ±15% level**

FEYNMAN SCALING IN FORWARD π^0 PRODUCTION

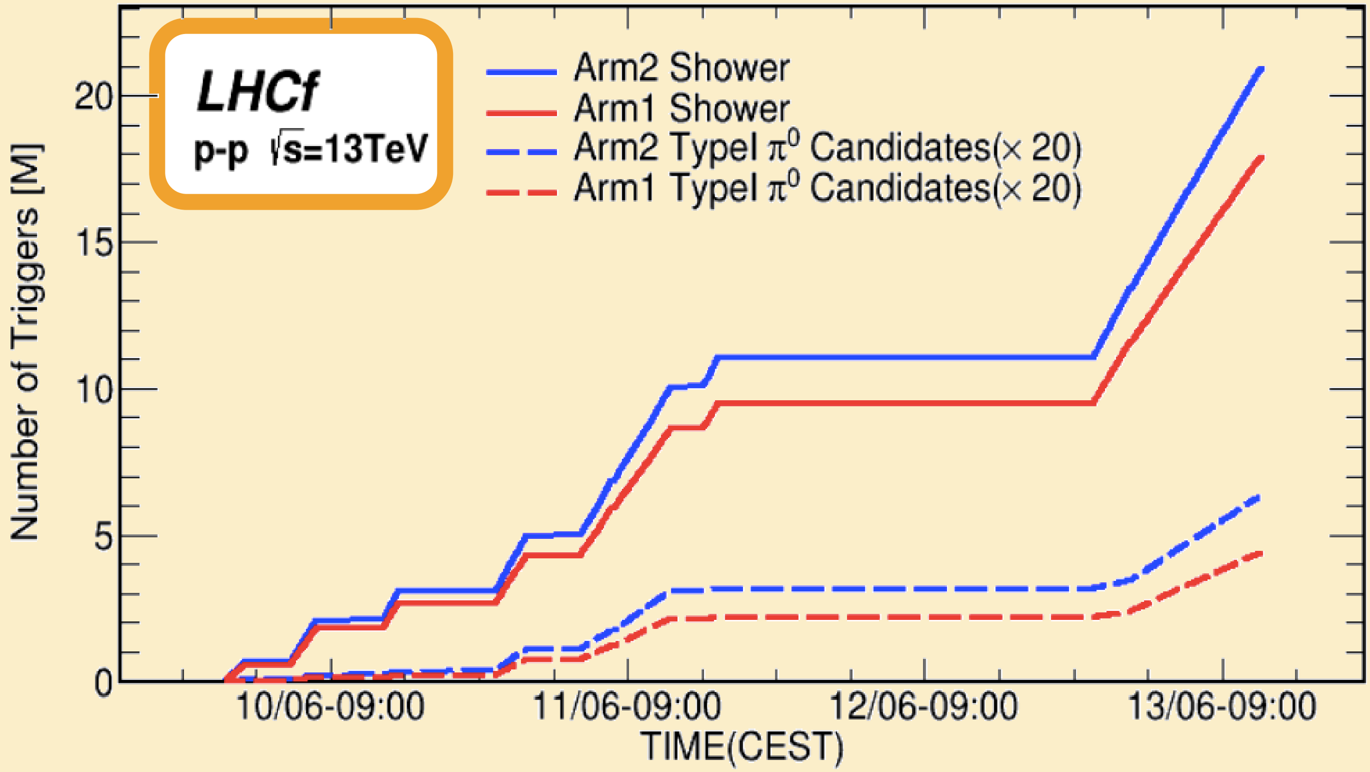


- Test of independence of cross section of secondary particles as a function of $x_F = 2p_Z/\sqrt{s}$ in the very forward rapidity region wrt the c.m. energy $\sqrt{s}$
- **Feynman scaling holds at ±20% level**

THE 13 TeV p-p RUN IN 2015

LHC 13 TeV p-p RUN IN 2015

- **Detector upgrade in 2014: plastic scintillators $\rightarrow$ GSO, new silicon detectors**
- During Week24, June 9th-13th, **LHCf dedicated low-luminosity run**
- Total of 26.6 hours with $L = 0.5 \div 1.6 \cdot 10^{29}$ $cm^{-2}s^{-1}$
- **~ 39 · 10^6 showers $\rightarrow$ 0.5 · 10^6 π^0 events**
- Trigger exchange with ATLAS
- Detector removal on June 15th during TS1
- Run was very successful!



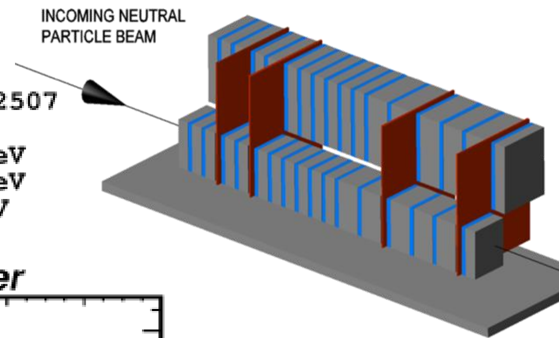
AN IMPRESSIVE HIGH ENERGY π^0

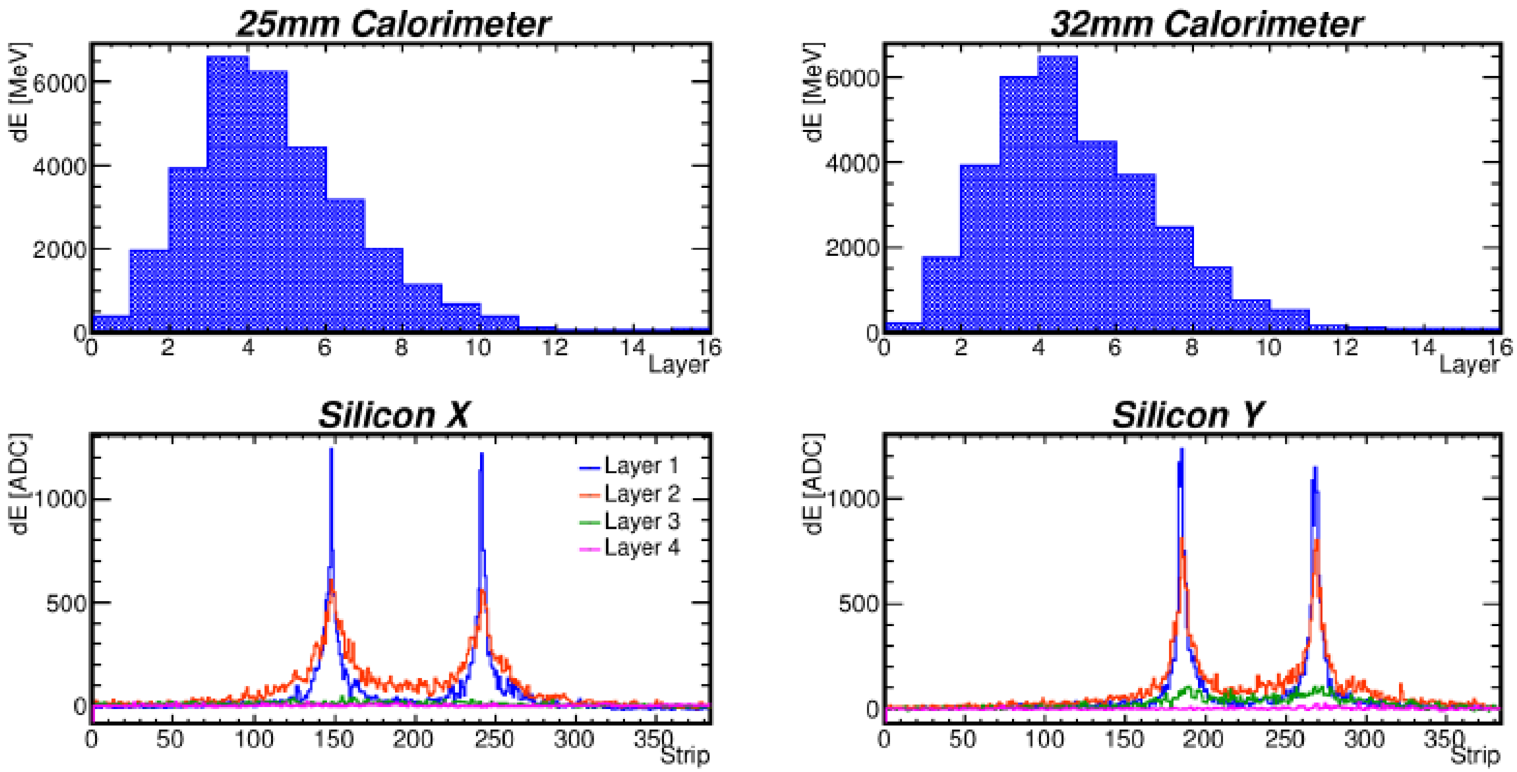
LHCf Arm2 Detector

π^0 Candidate Event

LHC p-p, $\sqrt{s}$ = 13 TeV Collisions

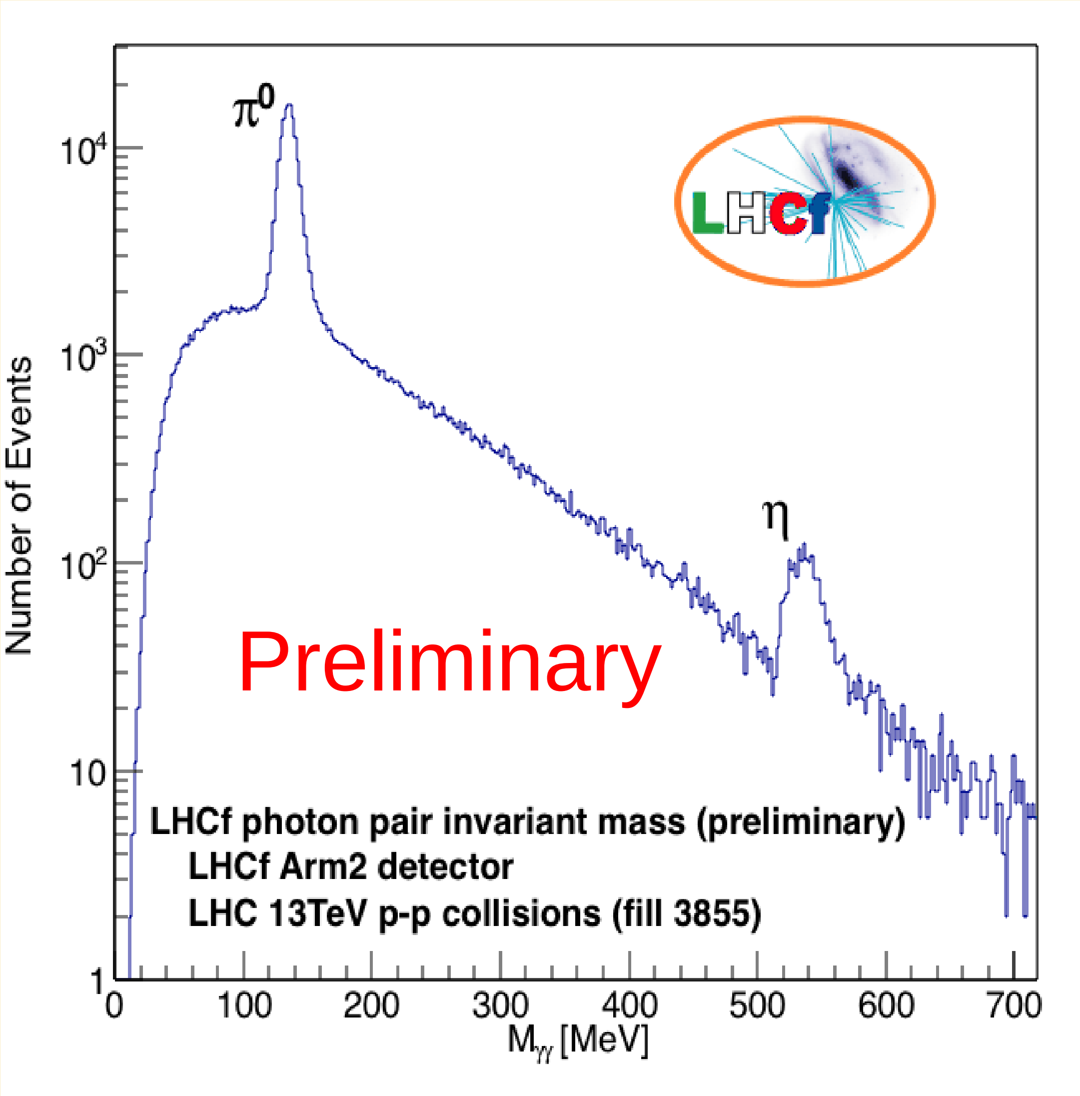
RUN: 44484
NUMBER: 3010
TIME: 1434152507
FILL: 3855
E_{25mm}: 1014 GeV
E_{32mm}: 1021 GeV
$M_{\gamma\gamma}$: 147 MeV





SMALL TOWER **LARGE TOWER**

FIRST LOOK AT 13 TeV DATA



CONCLUSIONS

- **Very forward production of γ, n and π^0 in p - p and p - Pb collision have been measured by LHCf at different c.m. energies**
- LHCf data provide a benchmark for hadronic interaction models and can contribute to improve their tuning
- Large amount of high-energy neutrons exists in very forward region of p-p collisions, leading to small inelasticity
- Detailed π^0 production studies in many different conditions
  - Reasonable agreement of LHCf π^0 data with QGSJET II-04 and EPOS-LHC
- **Very successful 13 TeV p - p run in June 2015 after detector upgrade**

- Stay tuned for future results at LHC:
  - p - Pb at 13 TeV in 2016-2017?
  - p - light-ions?
- 510 GeV polarized p-p RHIC run in 2017 has been accepted by RHIC PAC at BNL to increase the phase space coverage and for further checking the scaling laws