Chapter 6 : cosmic ray physics, multiplicities, correlations and spectra

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Chapter 6

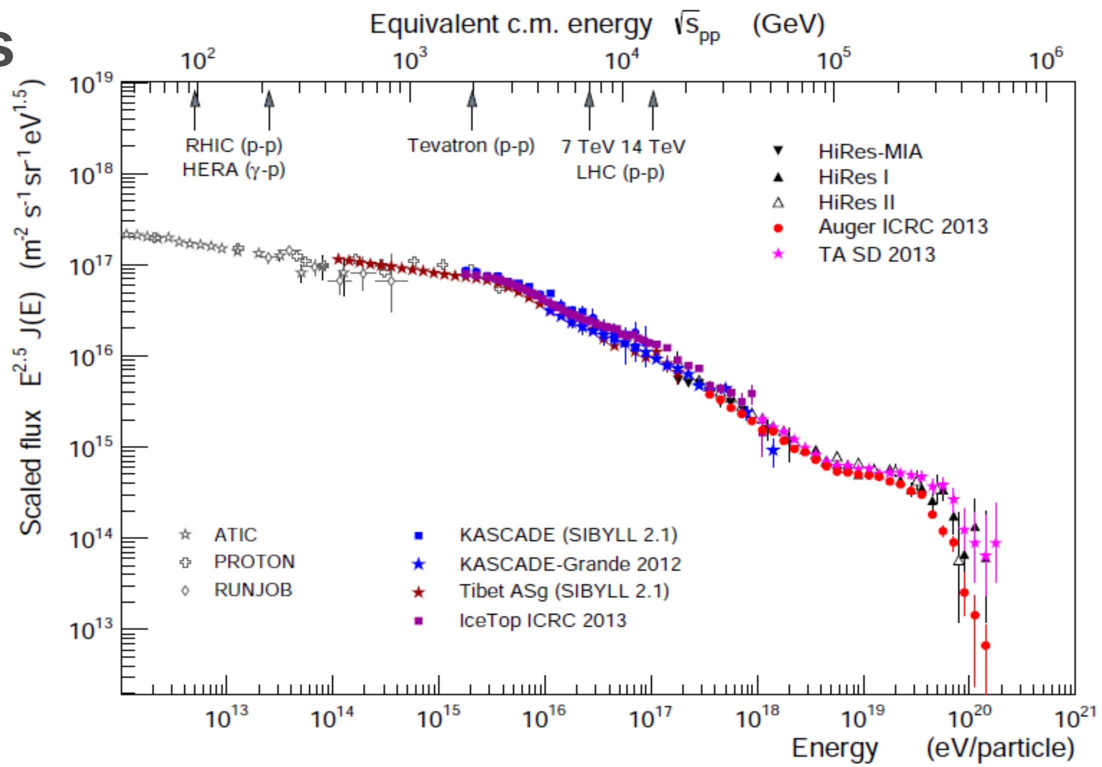
- **Measurements of particular interest to improve hadronic models used for air shower simulations**
  - ➔ no real direct test of cosmic ray property
  - ➔ but fundamental to reduce uncertainty in air shower measurements (mass composition analysis)
- **Min bias type of analysis**
  - ➔ high cross section processes (~mb)
  - ➔ need low luminosity and low pile-up (each event is relevant)
- **Contributions from all experiments**
  - ➔ ATLAS, LHCf, CMS, TOTEM, LHCb and ALICE

Sections

- 1.Introduction
- 2.LHC and Air Showers
- 3.Energy Flow
- 4.Particle Multiplicities
- 5.Spectra
- 6.Beam

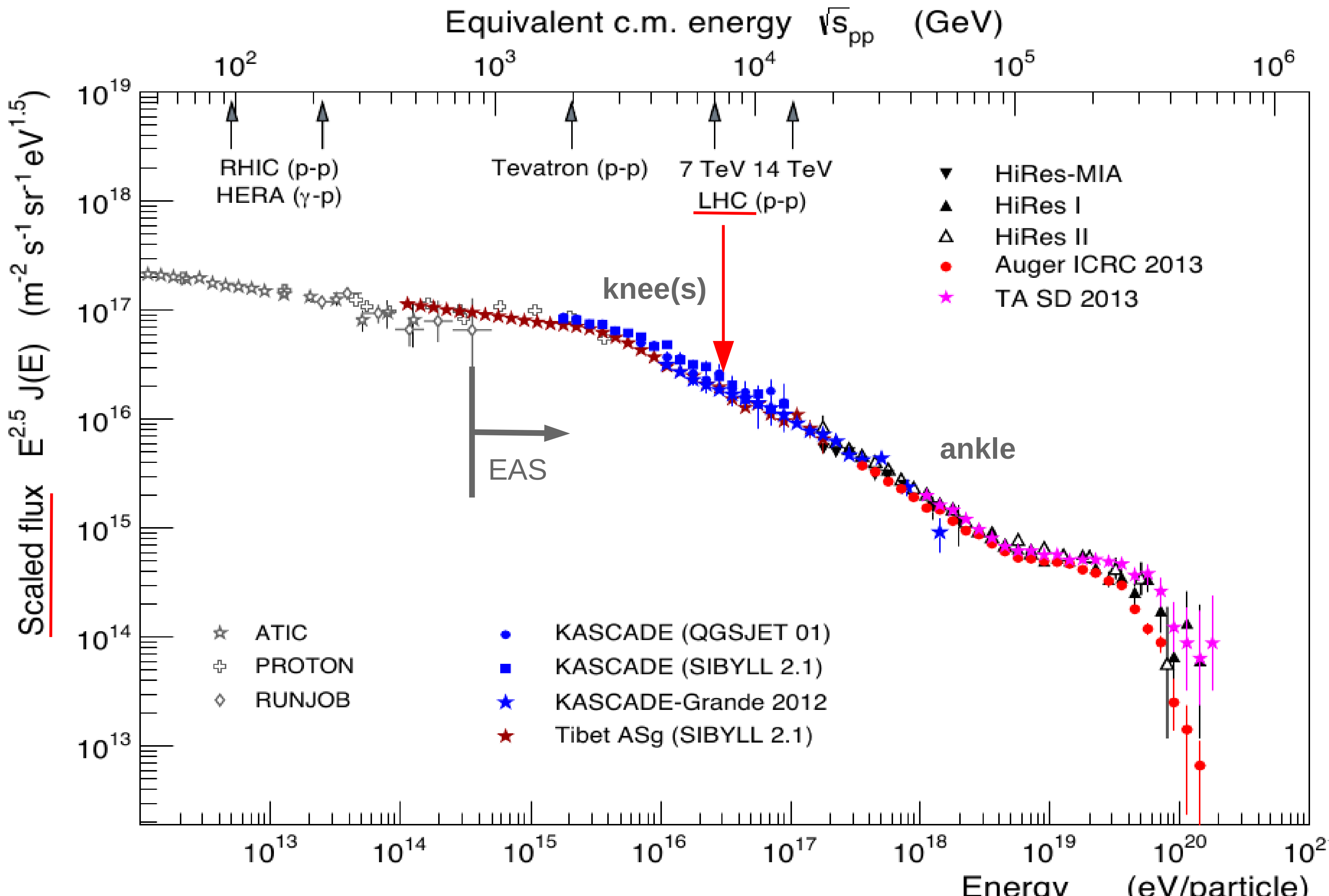
Section 6.1: Introduction

- **motivations from CR physics**
  - spectral feature
  - mass composition
  - test of particle physics at ultra-high energy
    - modified hadronic inter.
    - lorentz invariance or extra-dimensions



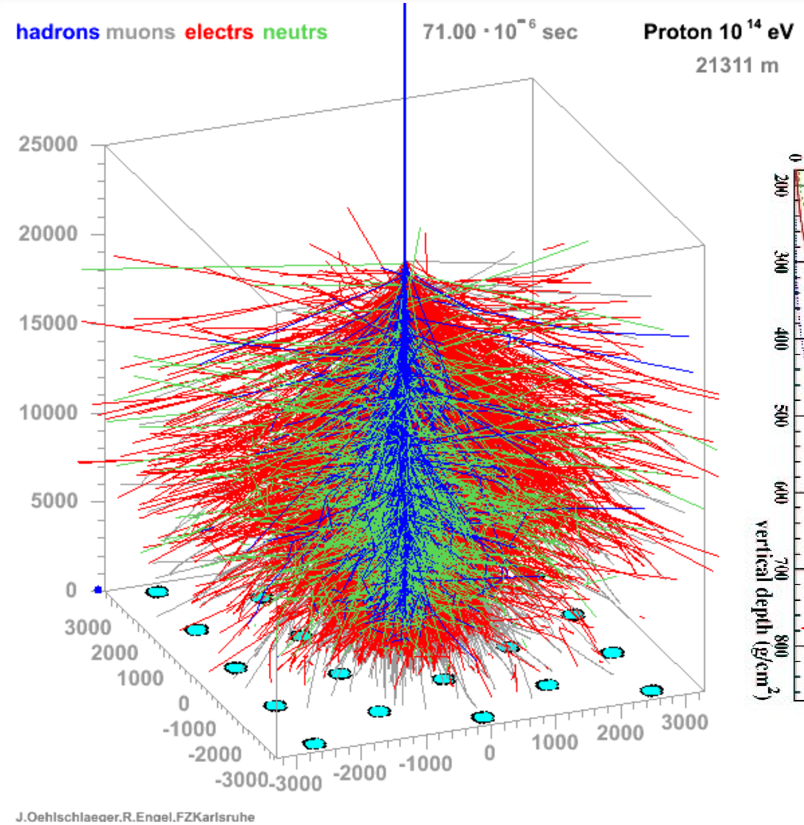
- **Hadronic interaction (models)**
  - main source of uncertainty in CR (air shower (EAS)) analysis
  - LHC data: highest energy to test and tune models before extrapolation
  - forward measurements most important for EAS development

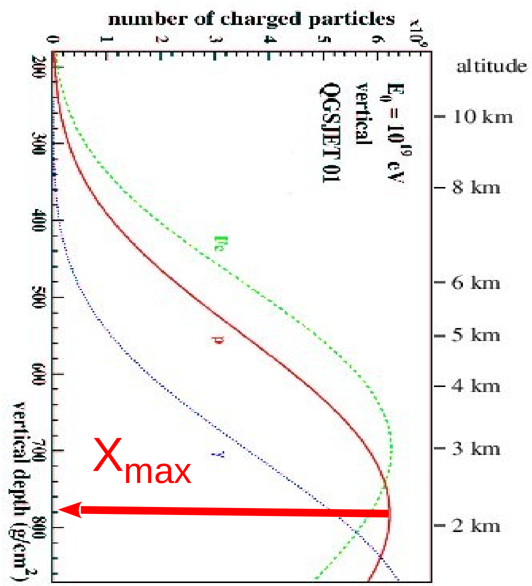
Cosmic Ray Spectrum

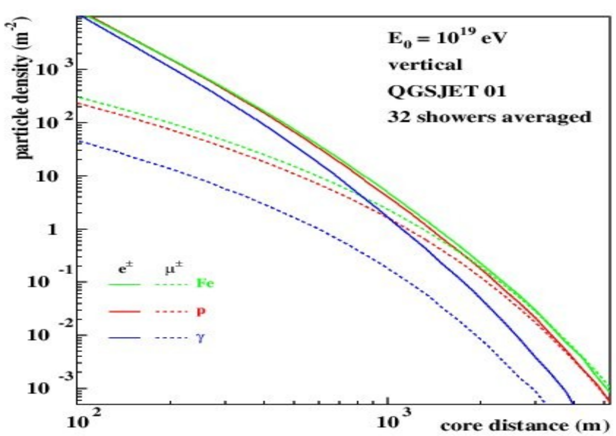


R. Engel (KIT)

Extensive Air Shower Observables







- **Longitudinal Development**
  - number of particles vs depth

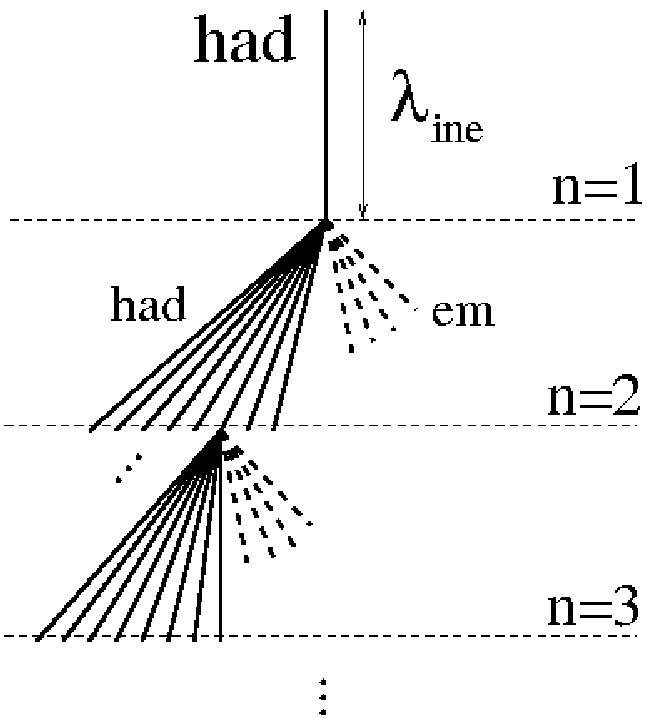
    $$X = \int_h^\infty dz\, \rho(z)$$

  - Larger number of particles at X_{max}

    For many showers
    - mean : $\langle X_{max} \rangle$
    - fluctuations : RMS X_{max}

- **Lateral distribution function (LDF)**
  - particle density at ground vs distance to the impact point (core)
  - can be muons or electrons/gammas or a mixture of all.

Simplified Shower Development



$$N_{tot} = N_{had} + N_{em}$$

J. Matthews, Astropart.Phys. 22 (2005) 387-397

- **Using generalized Heitler model and superposition model :**

$$X_{max} \sim \lambda_e \ln\left((1-k).E_0/(2.N_{tot}.A)\right) + \lambda_{ine}$$

Model independent parameters :

- E_0 = primary energy
- A = primary mass
- λ_e = electromagnetic mean free path

➡ Model dependent parameters :

- k = elasticity
- N_{tot} = total multiplicity
- λ_{ine} = hadronic mean free path (cross section)

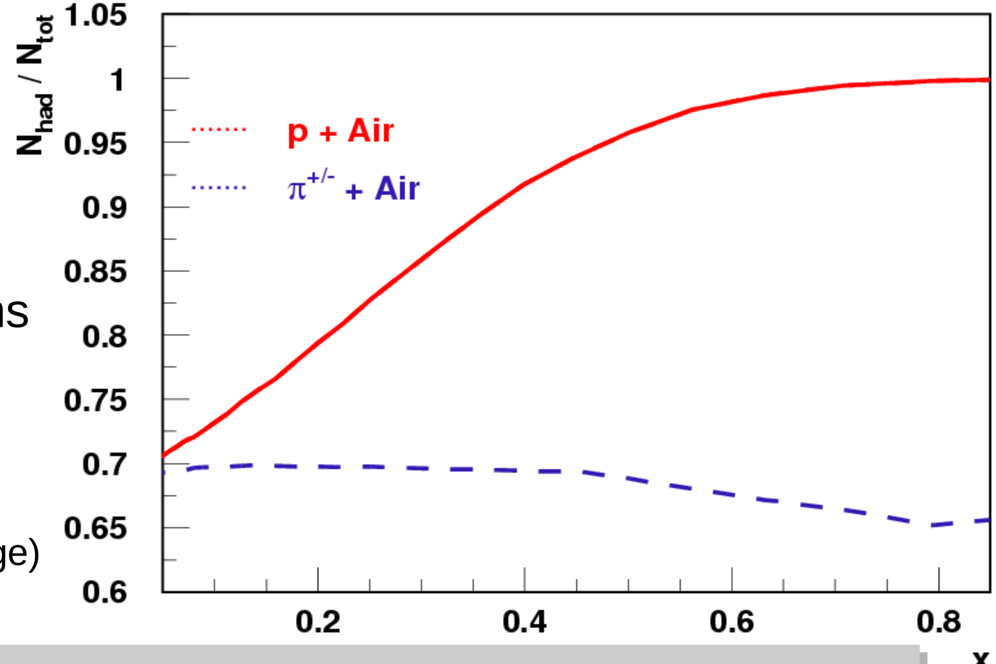
Muon Number

- **From Heitler**

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln N_{\pi^{ch}}}{\ln(N_{\pi^{ch}} + N_{\pi^0})}$$

→ after n generations

- In real shower, not only pions : Kaons and (anti)Baryons (but 10 times less …)
- Baryons do not produce leading π^0
- With leading baryon, energy kept in hadronic channel = muon production
- Cumulative effect for low energy muons
- High energy muons
  - important effect of first interactions and baryon spectrum (LHC energy range)

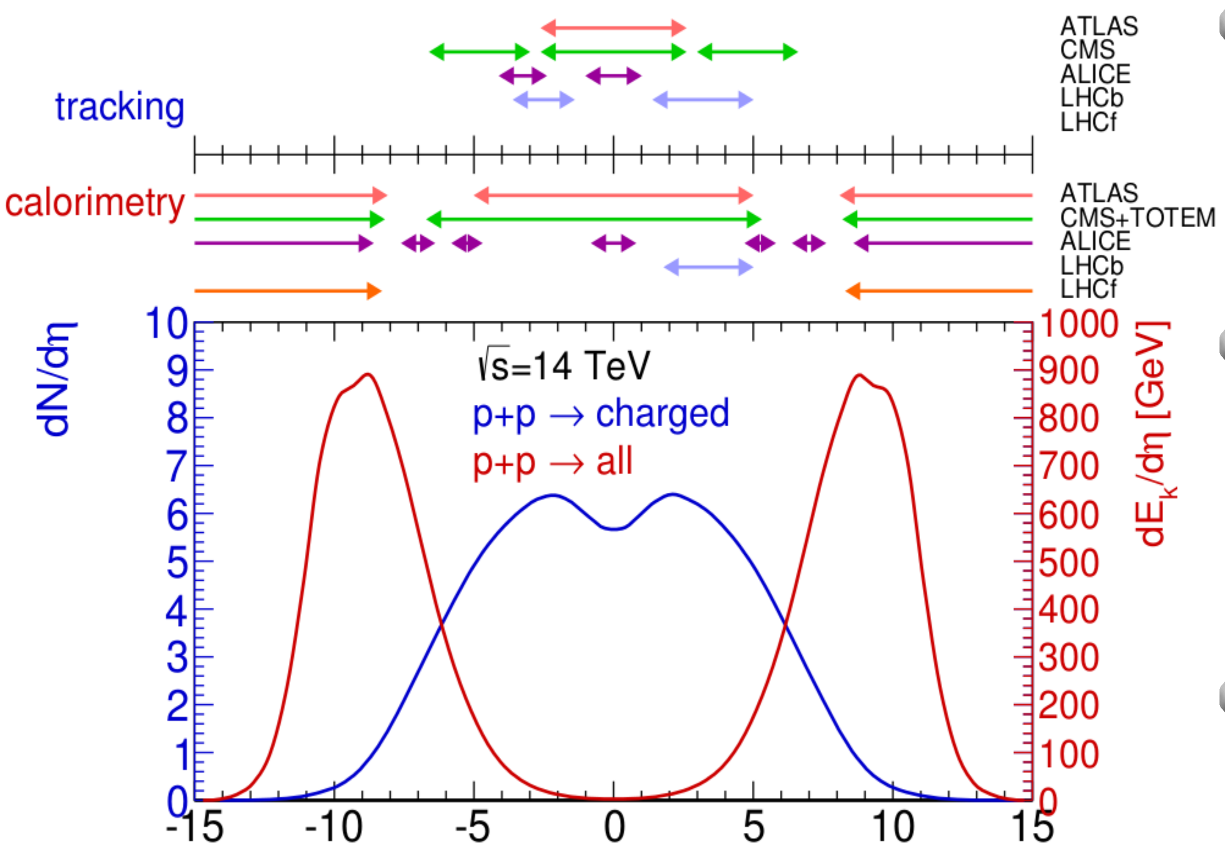


Muon number depends on the number of (anti)B in p- or π-Air interactions at all energies

More fast (anti)baryons = more muons

T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

Ideal Measurements for CR

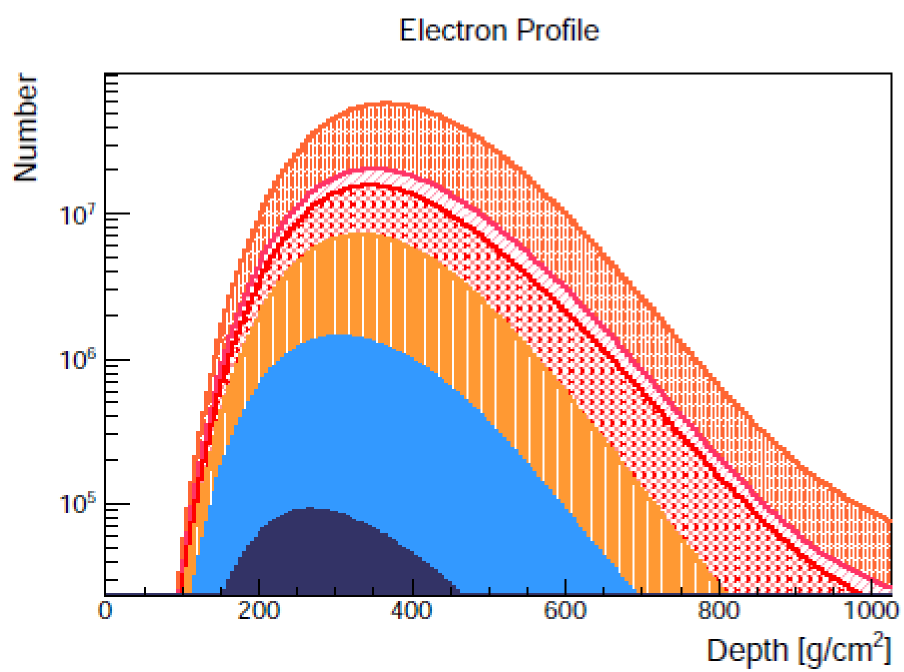


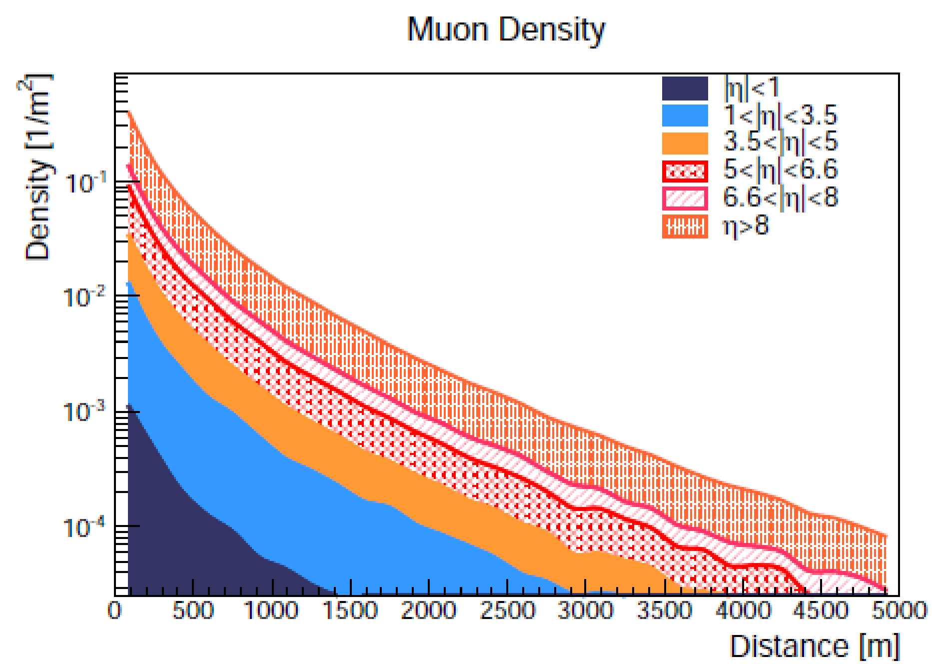
More direct measurement of particles important for air shower development not really possible at LHC !
(excluded by kin. and techn. limits)

- **Inelastic cross-section (and all other obs.) for p-Air and pion-Air**
  - LHC: p-p or p-Pb … pO ?
- **Average elasticity/inelasticity** (energy fraction of the leading particle)
  - LHC: SD with proton tagging only
- **Multiplicity of id. particles in forward region (x_F~0.1)**
  - LHC: tracking for eta<7 (id<5)
- **EM/Had Forward Energy flow (x_F>0.1)**
  - LHC: ZDCs for neutral particles
    - add tracking in ZDC ?

Chapter 6.2: LHC and Air Showers

- **2.1.LHC data and hadronic interaction models**
  - 2 type of measurements
    - direct connection with air shower development
    - necessary to fix physics of the models





  - comparison old-new models for pseudorapidity
  - first discussion on experiment (proton tagging, direct measurement, etc ...)

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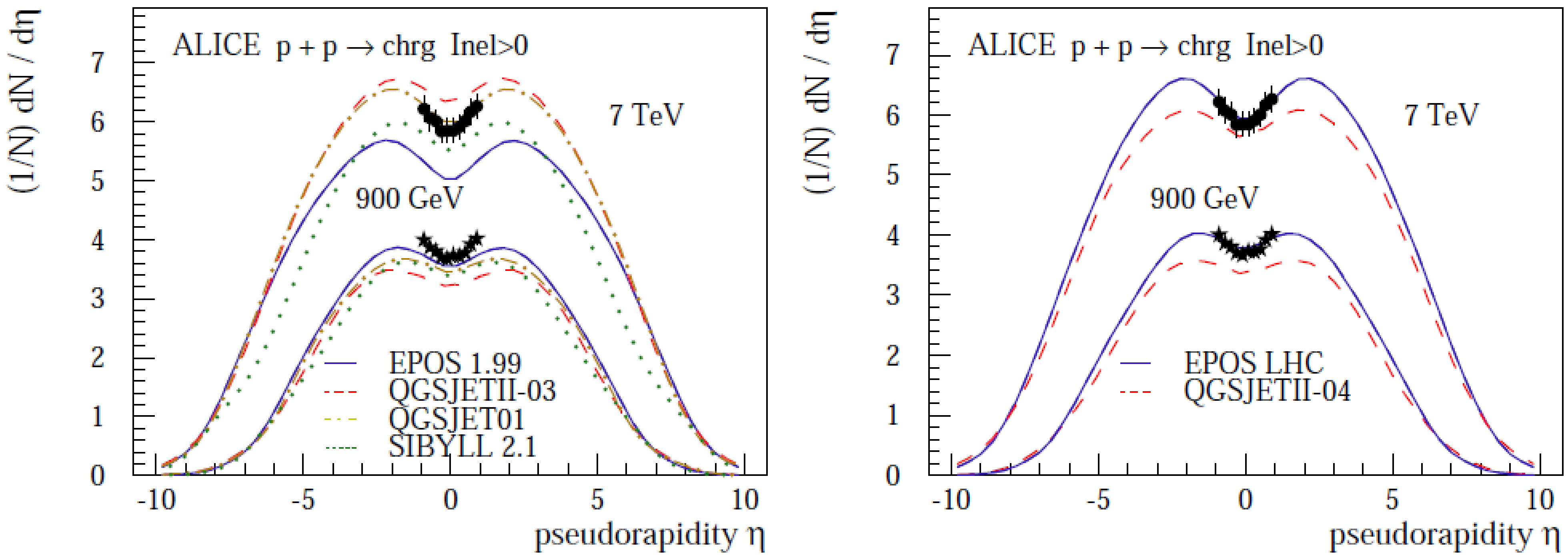

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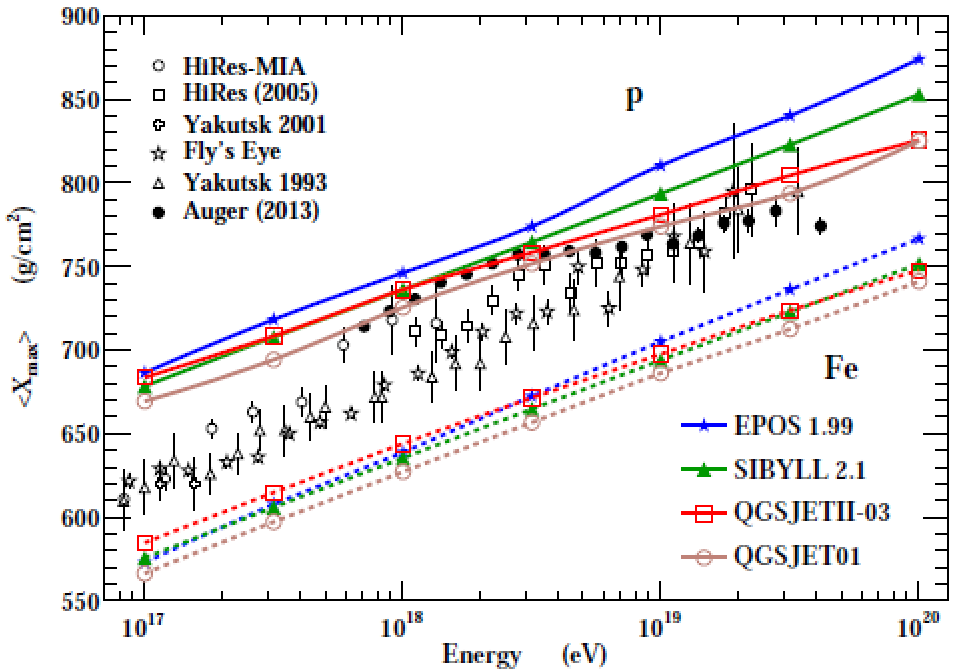
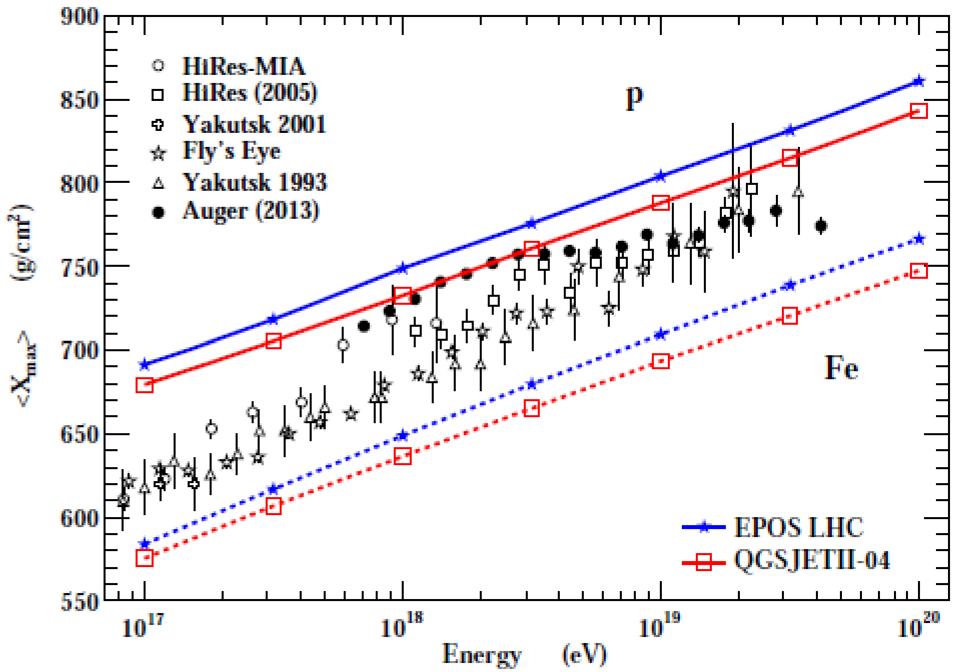
Chapter 6.2: LHC and Air Showers

2.2.Hadronic interaction models and air showers

- X_{max} : difference between models reduced by a factor of 2





- N_{mu}

Chapter 6.2: LHC and Air Showers

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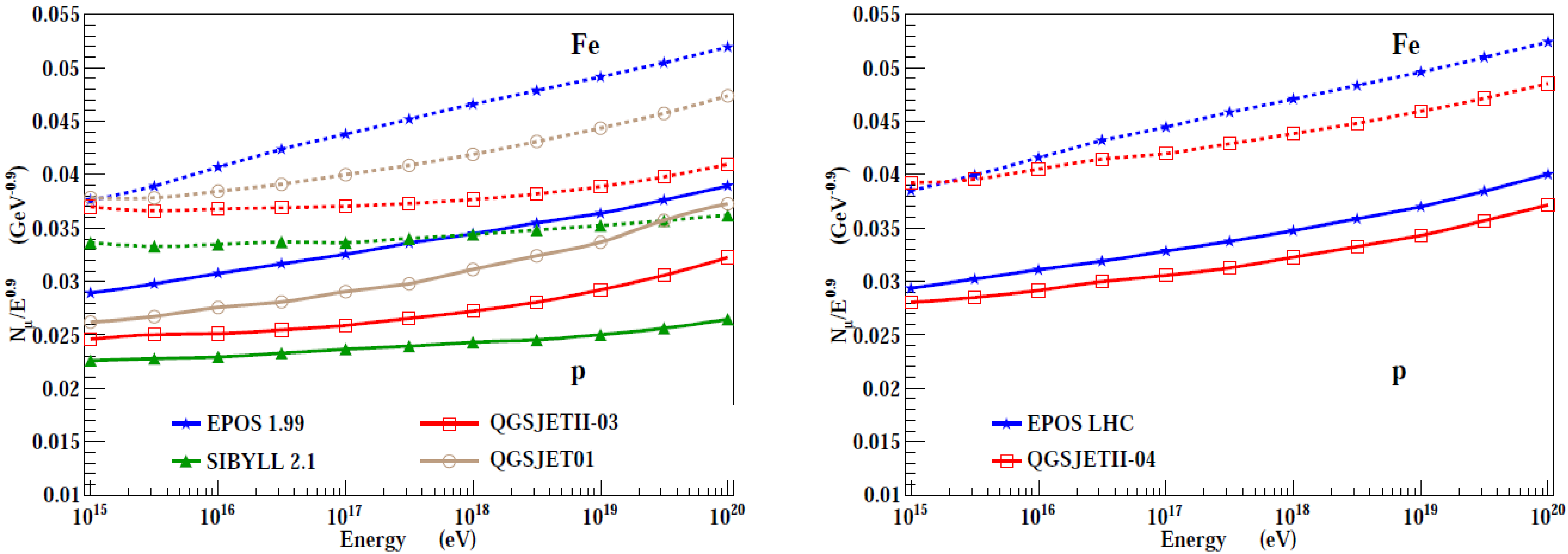
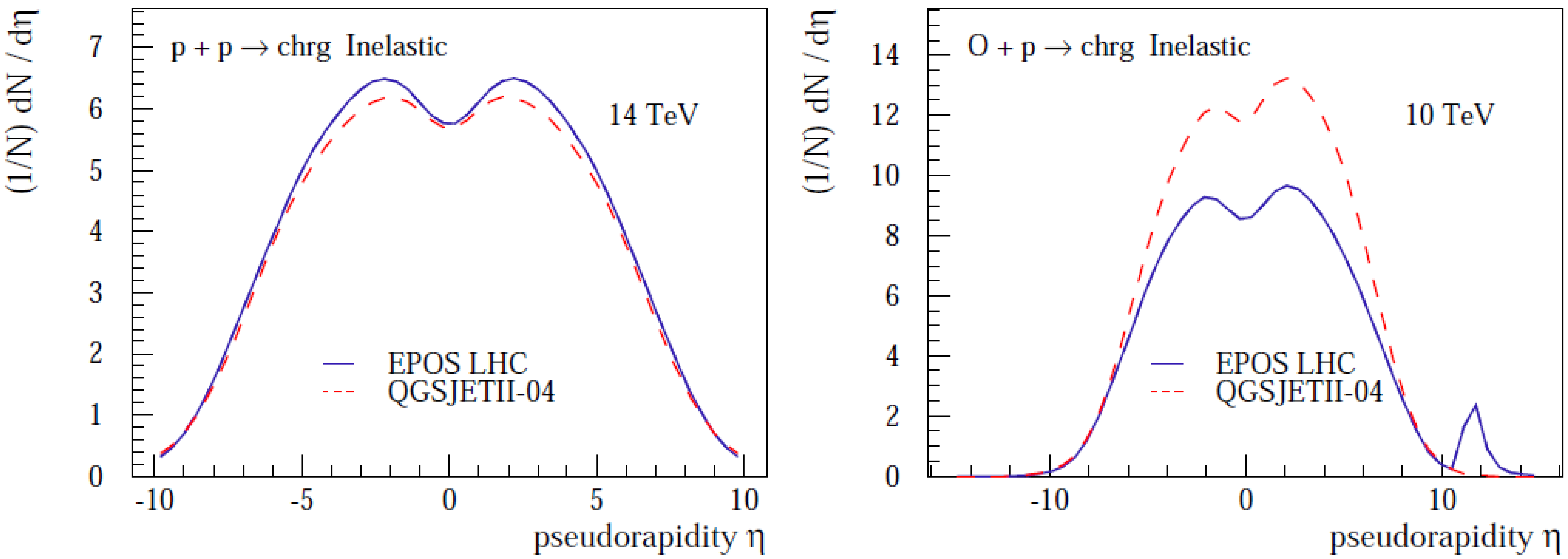
- N_{mu} : difference between models reduced by a factor of 3



Chapter 6.2: LHC and Air Showers

2.3.Need for measuring p-O interactions

- comparison p-p and p-O
  - p-Pb not good enough because of difficulty of selecting peripheral collisions and having proper fluctuations (and no cross-section measurement)



- effect of extrapolation

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- comparison p-p and p-O
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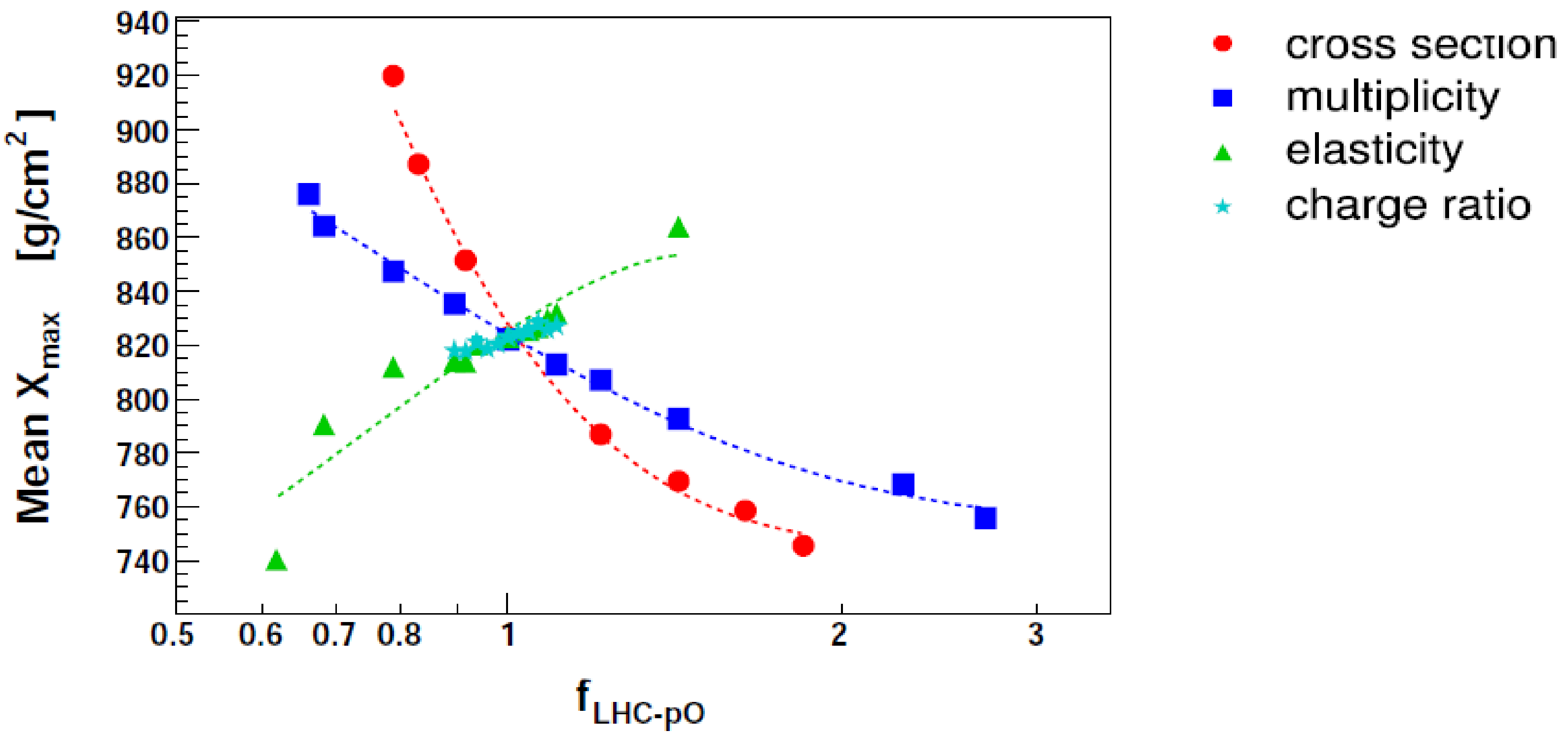
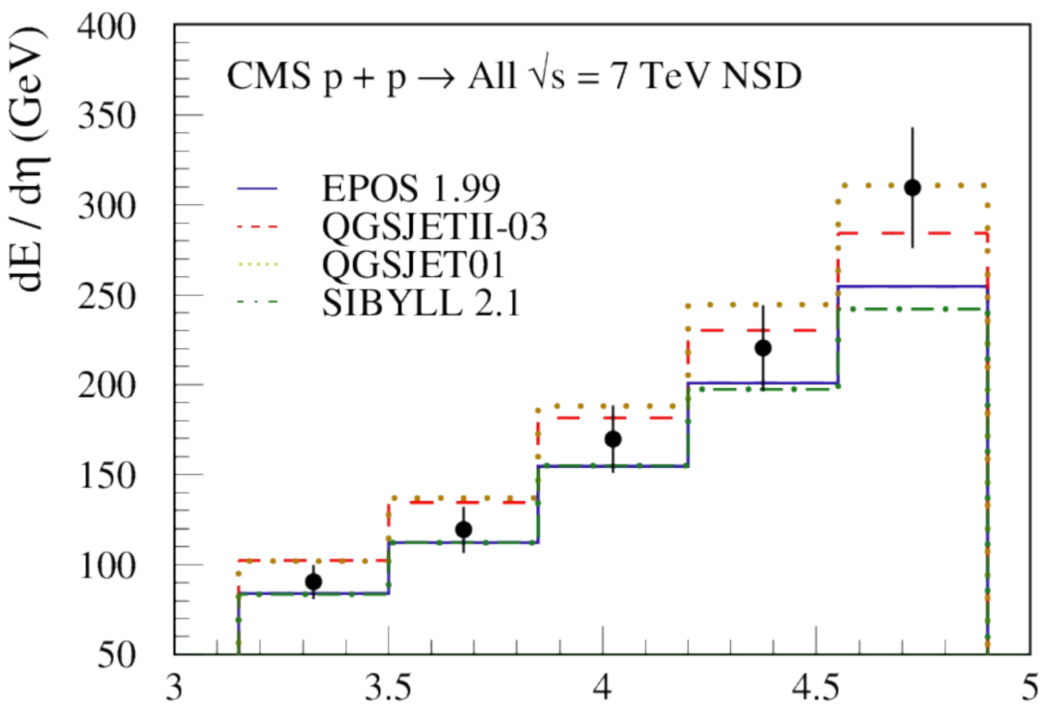
- effect of extrapolation
  - 10% difference in cross-section ~ proton/helium difference in Xmax

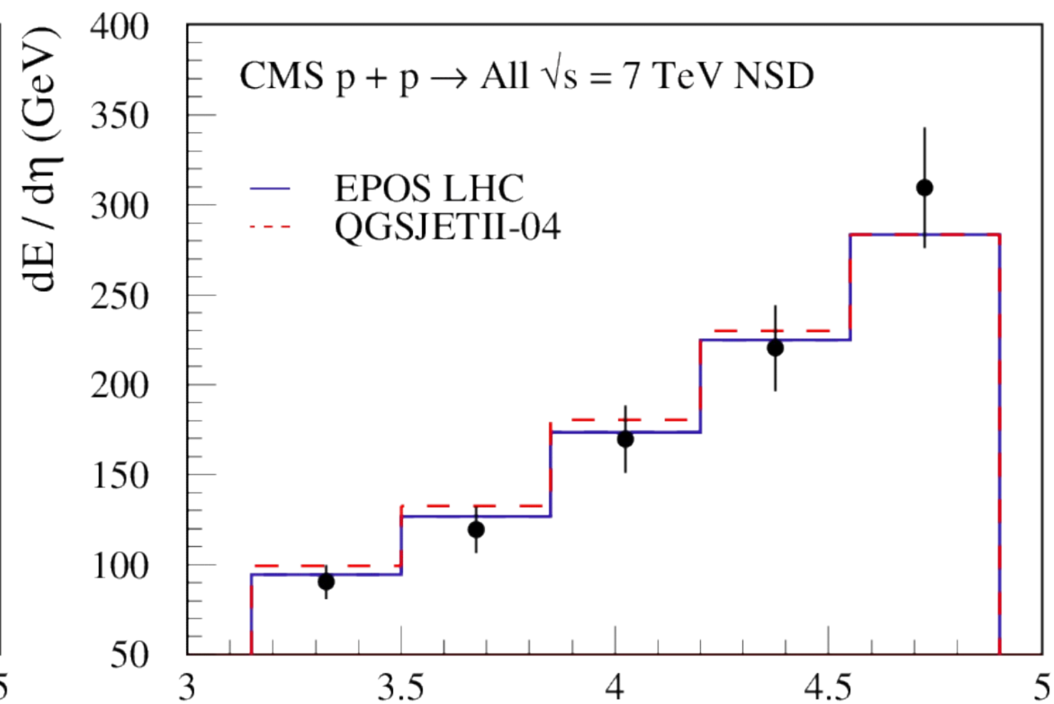


Chapter 6.3: Energy Flow

- **3.1.Past measurements of energy flow**
  - ATLAS, CMS, LHCb



Pre - LHC



Post - LHC

- **3.2.Future measurements of energy flow**
  - better model discrimination using ALPHA or AFP
  - ATLAS, CMS, LHCb common fiducial definition for energy flow

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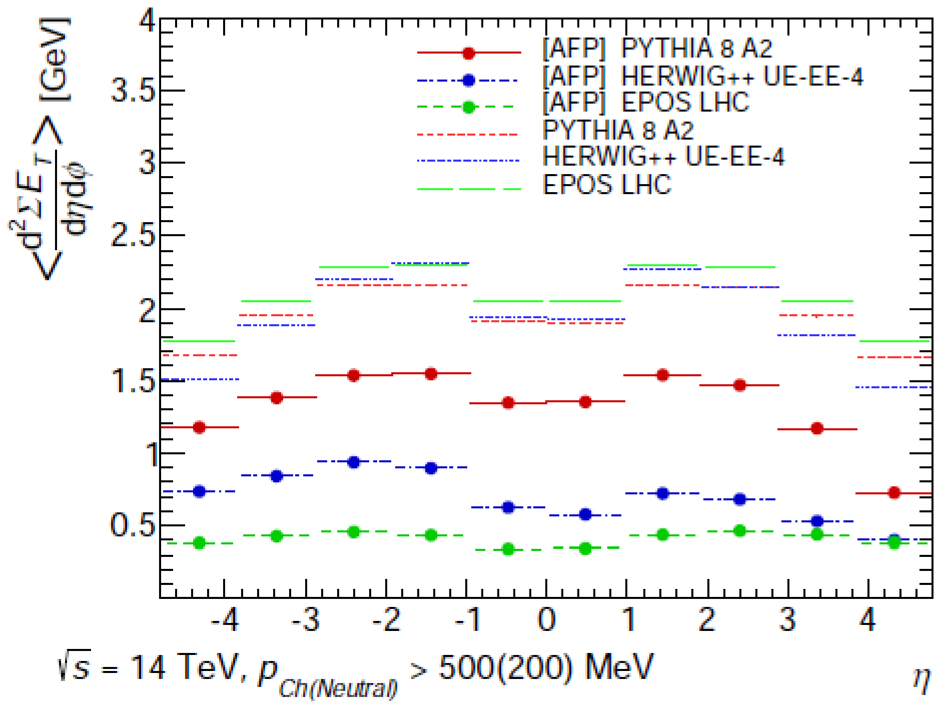

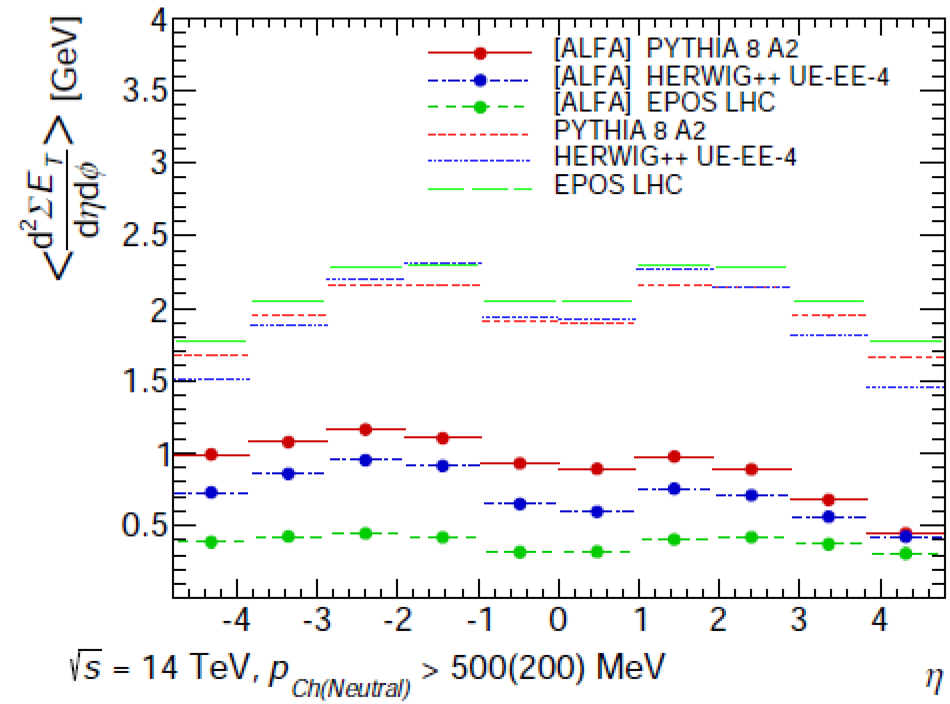

- ATLAS, CMS, LHCb common fiducial definition for energy flow

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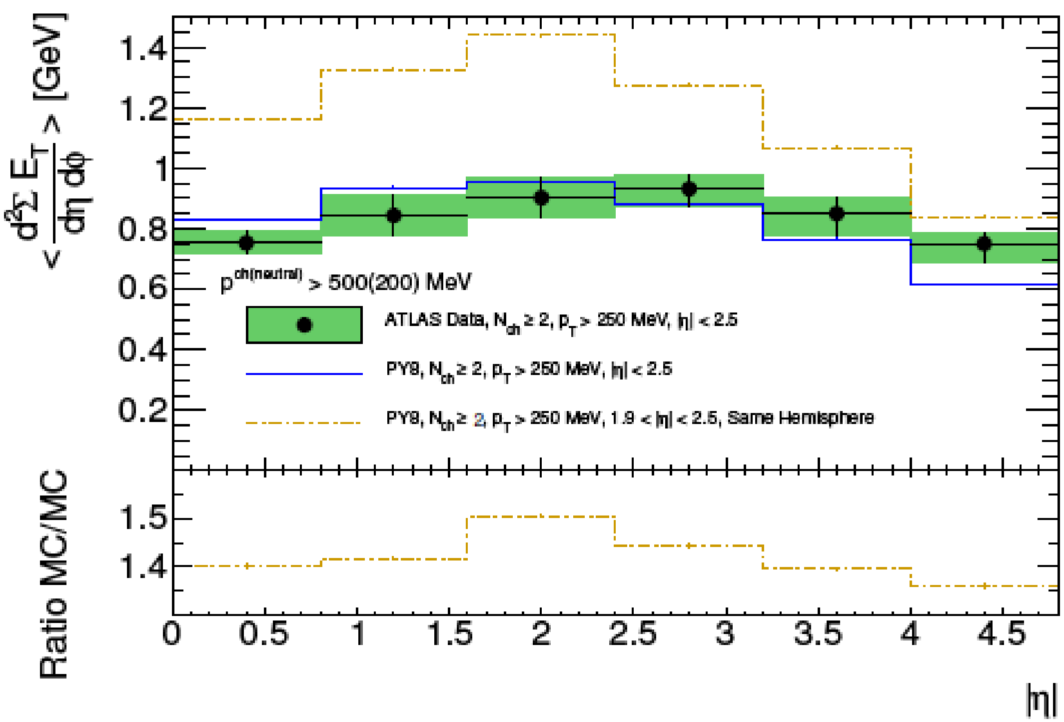

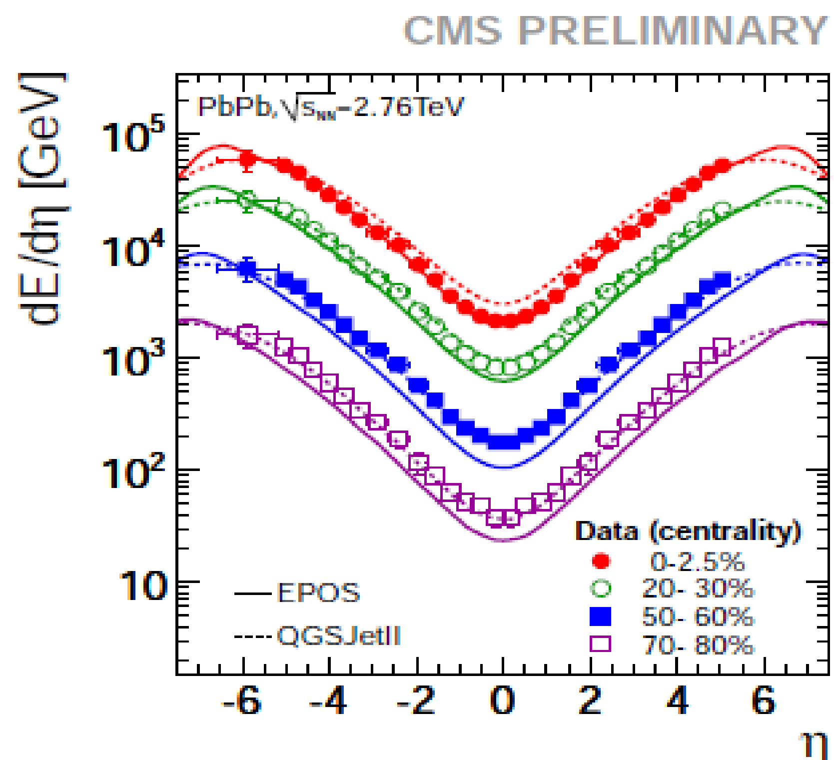

Chapter 6.4: Particle Multiplicities

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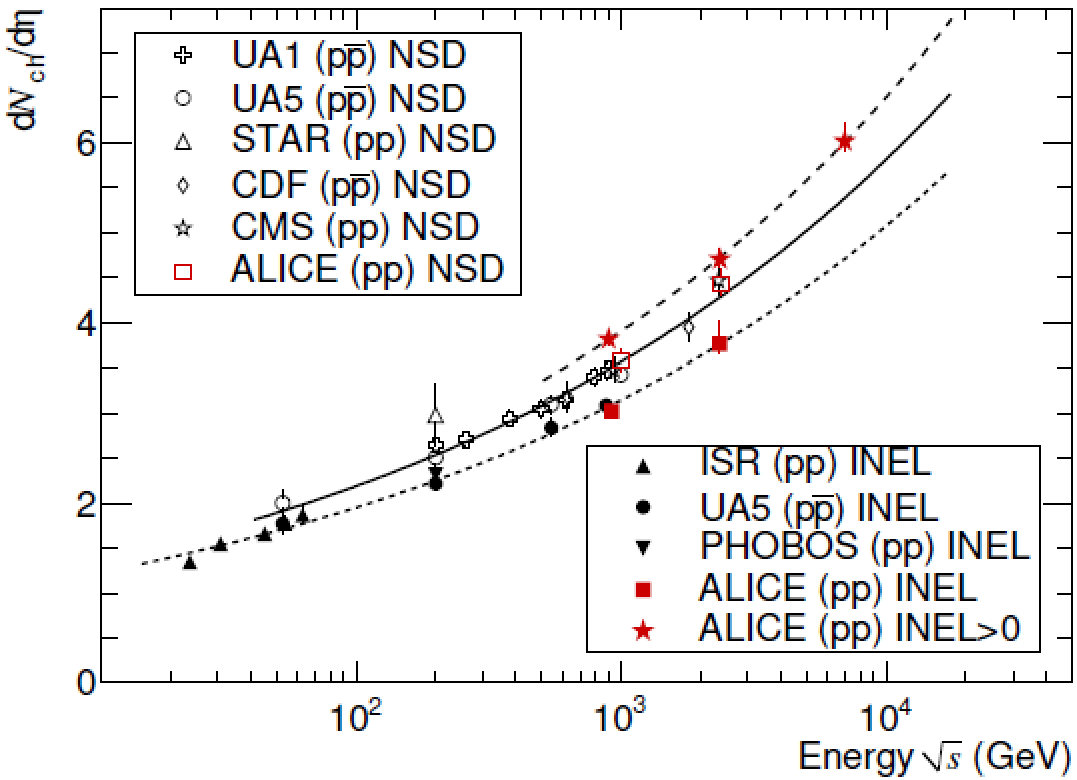

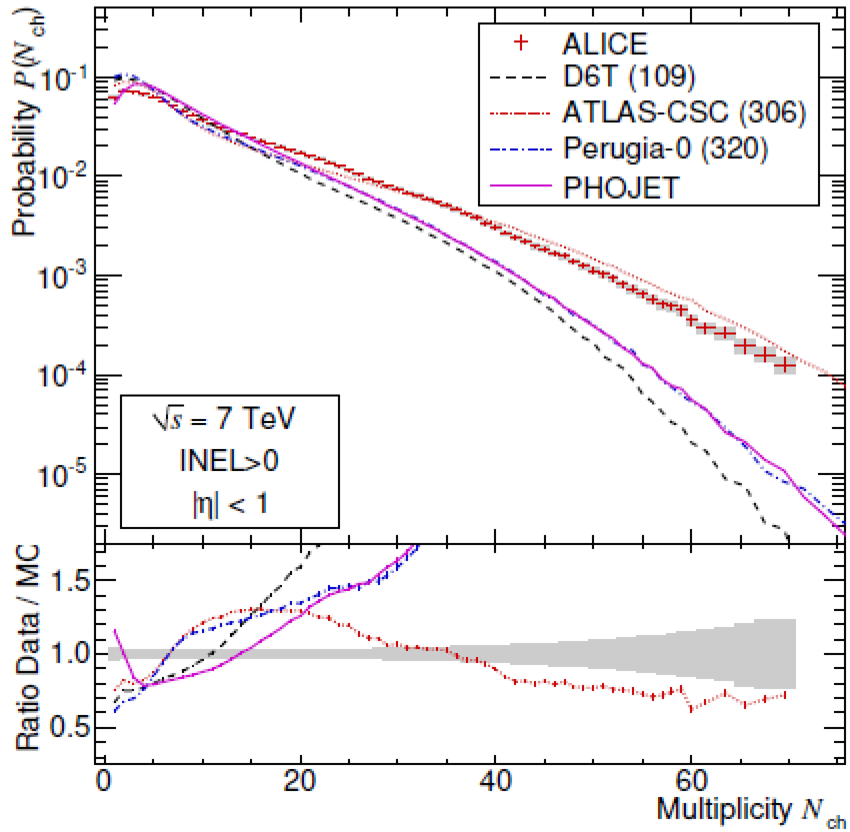

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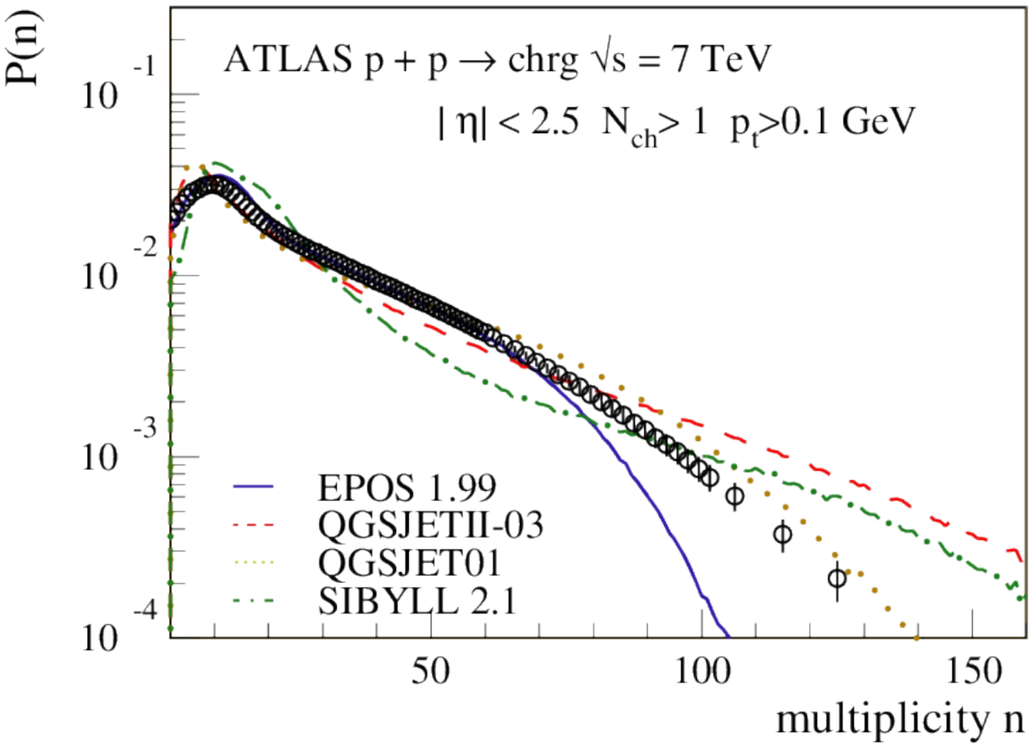
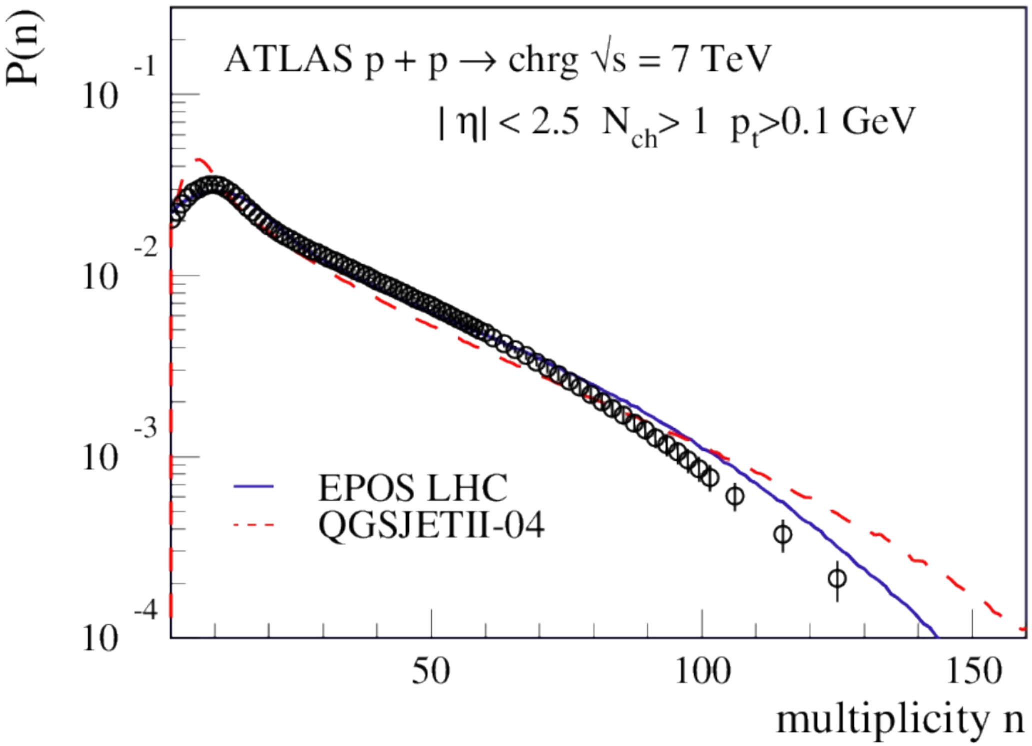


Post - LHC



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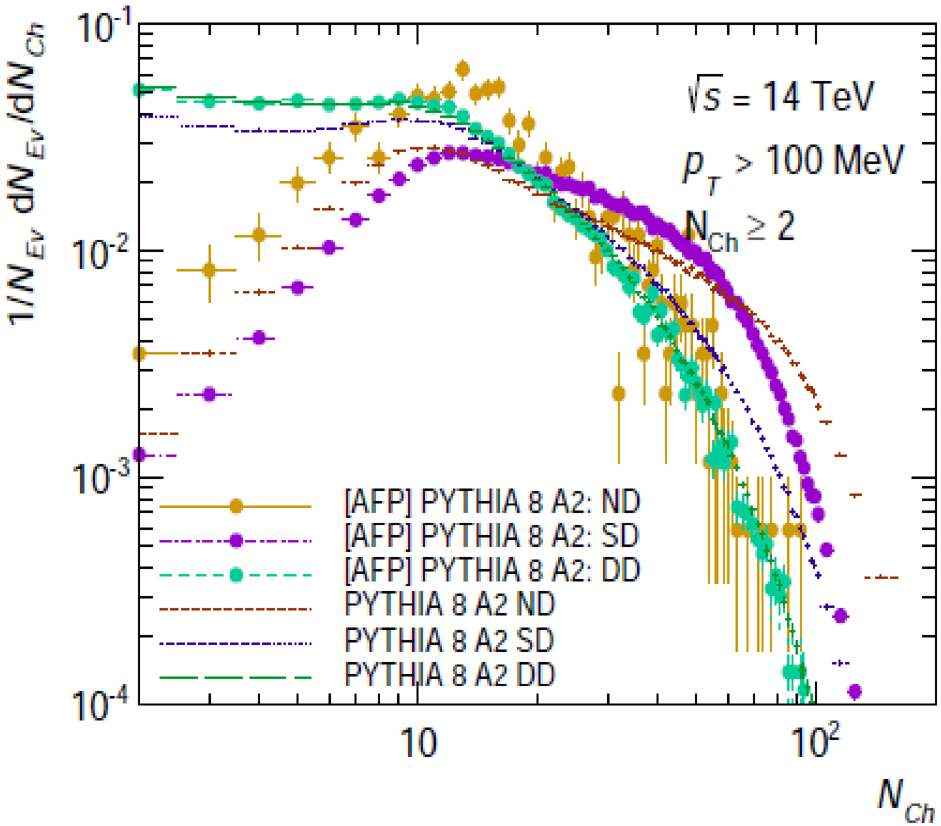

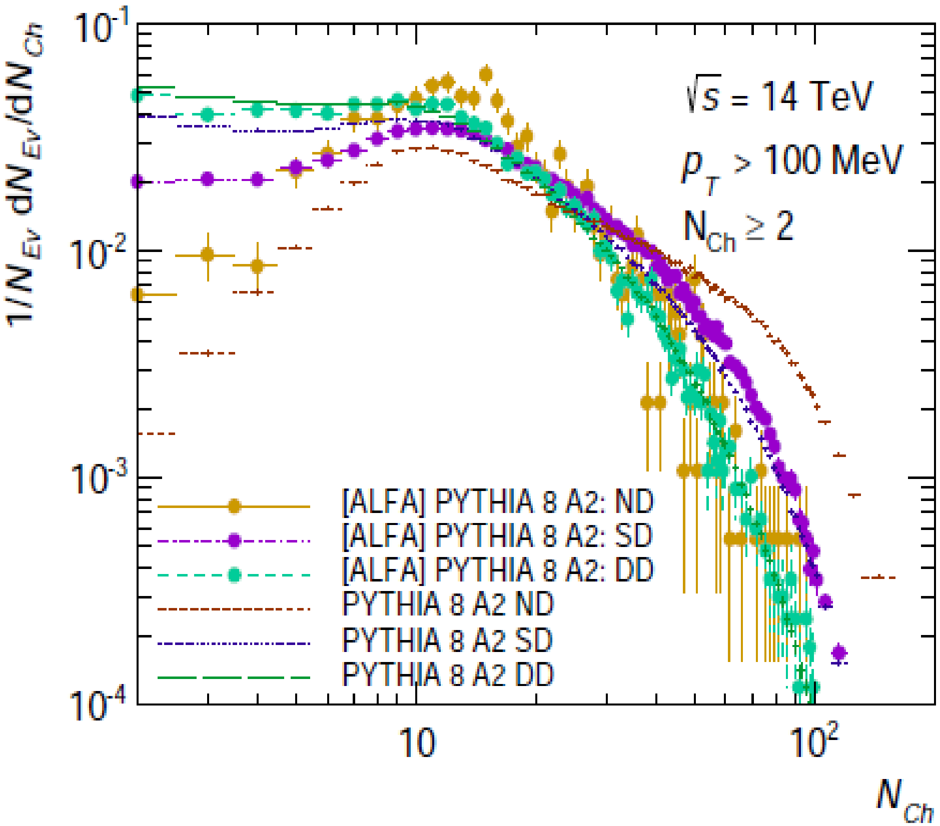

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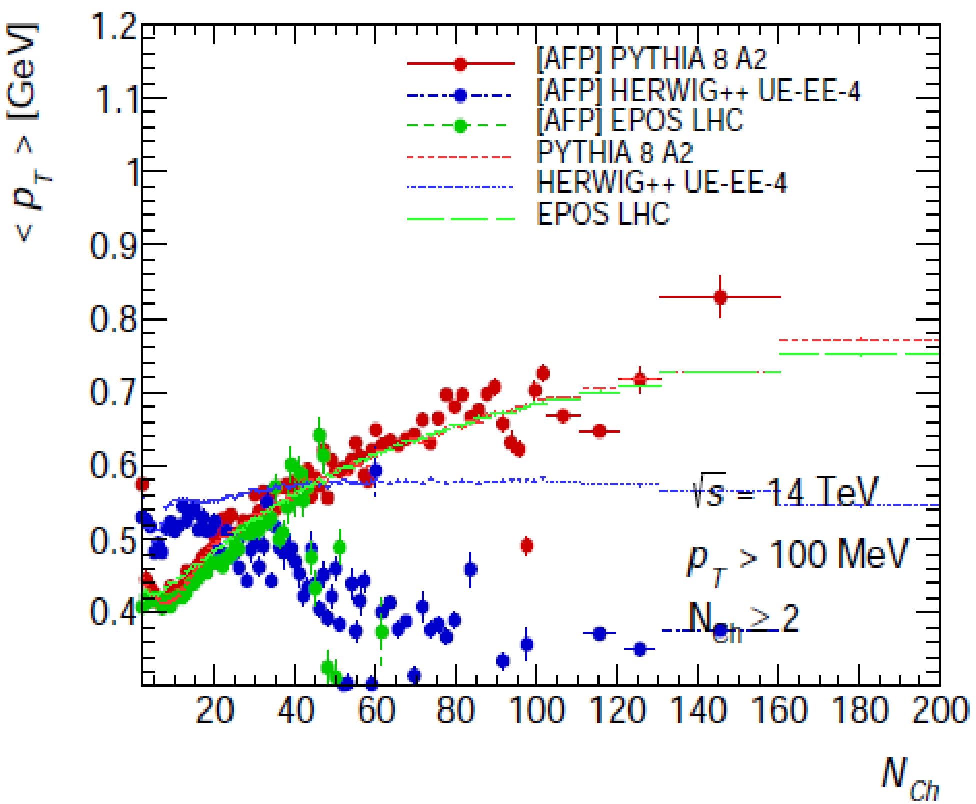
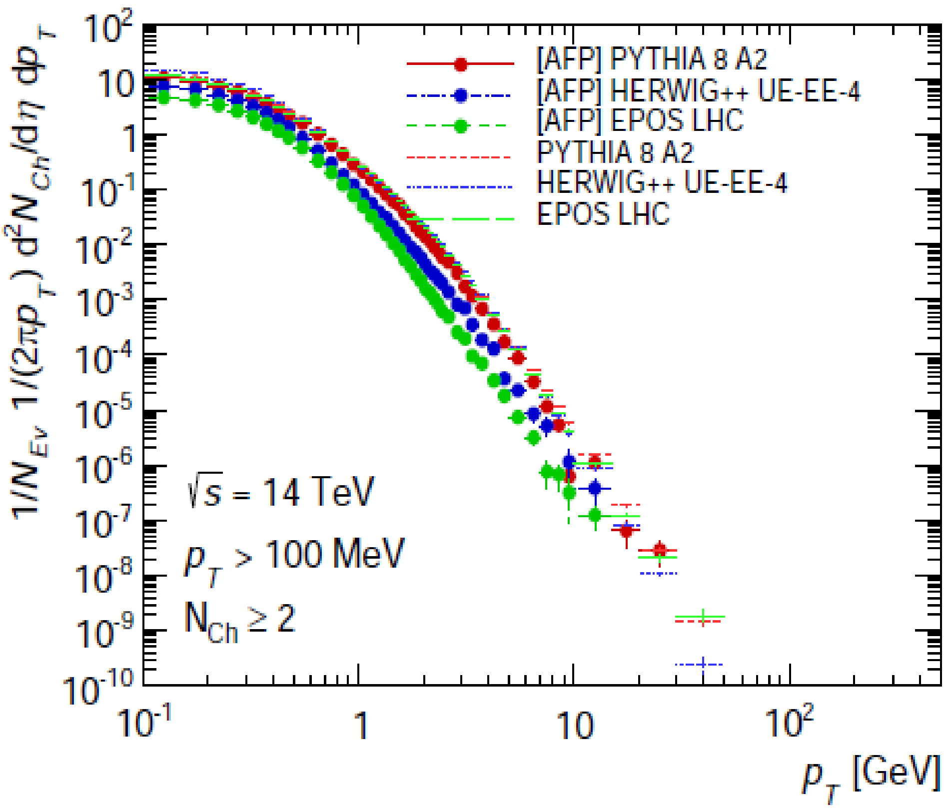
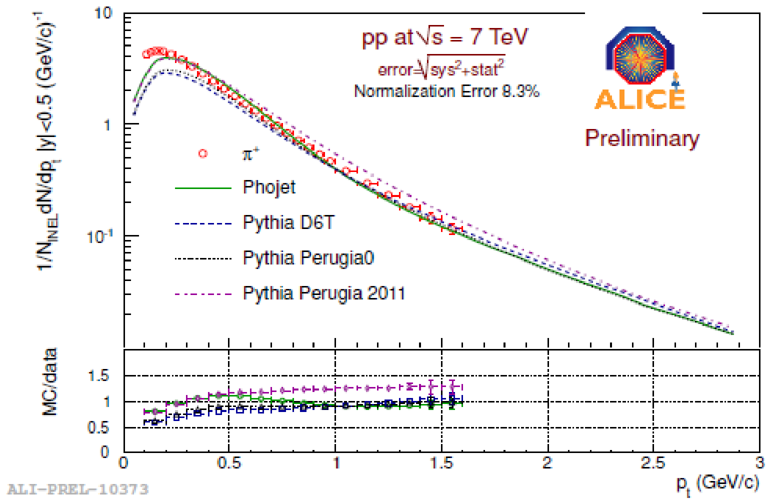


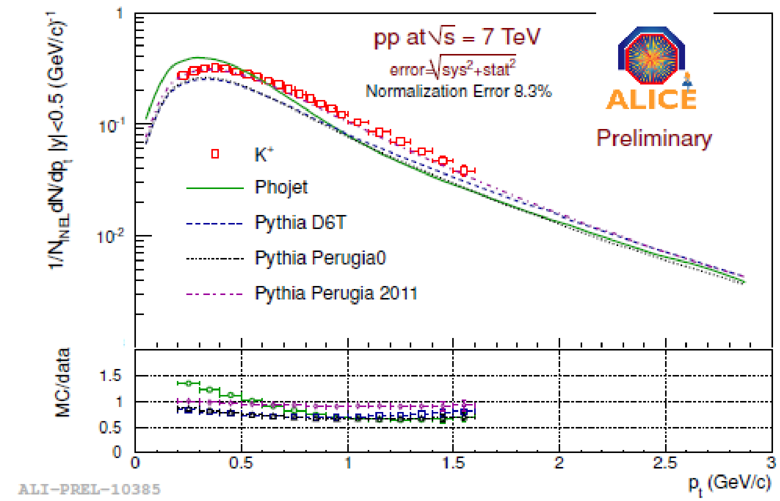


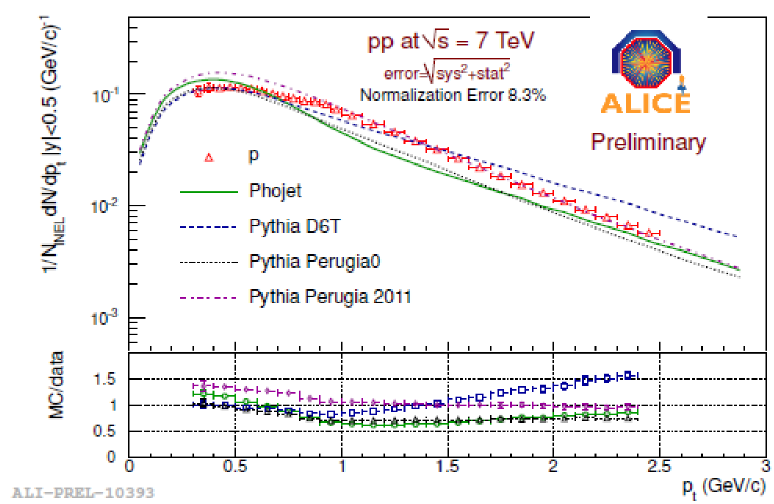
Chapter 6.5: Spectra

5.1.Identified charged particle spectra in p-p and p-Pb

- ALICE







Chapter 6.5: Spectra

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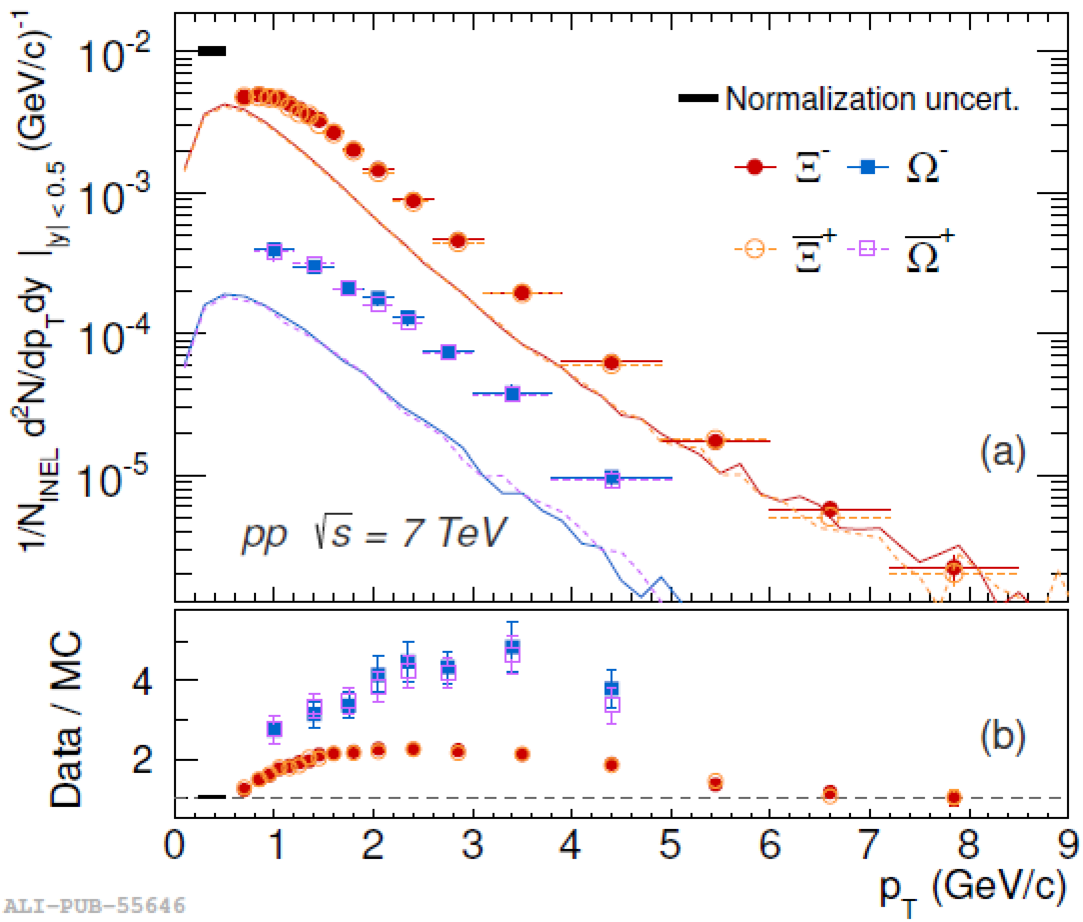
    - difficulties to reproduce all hadron production: important to understand for air shower development



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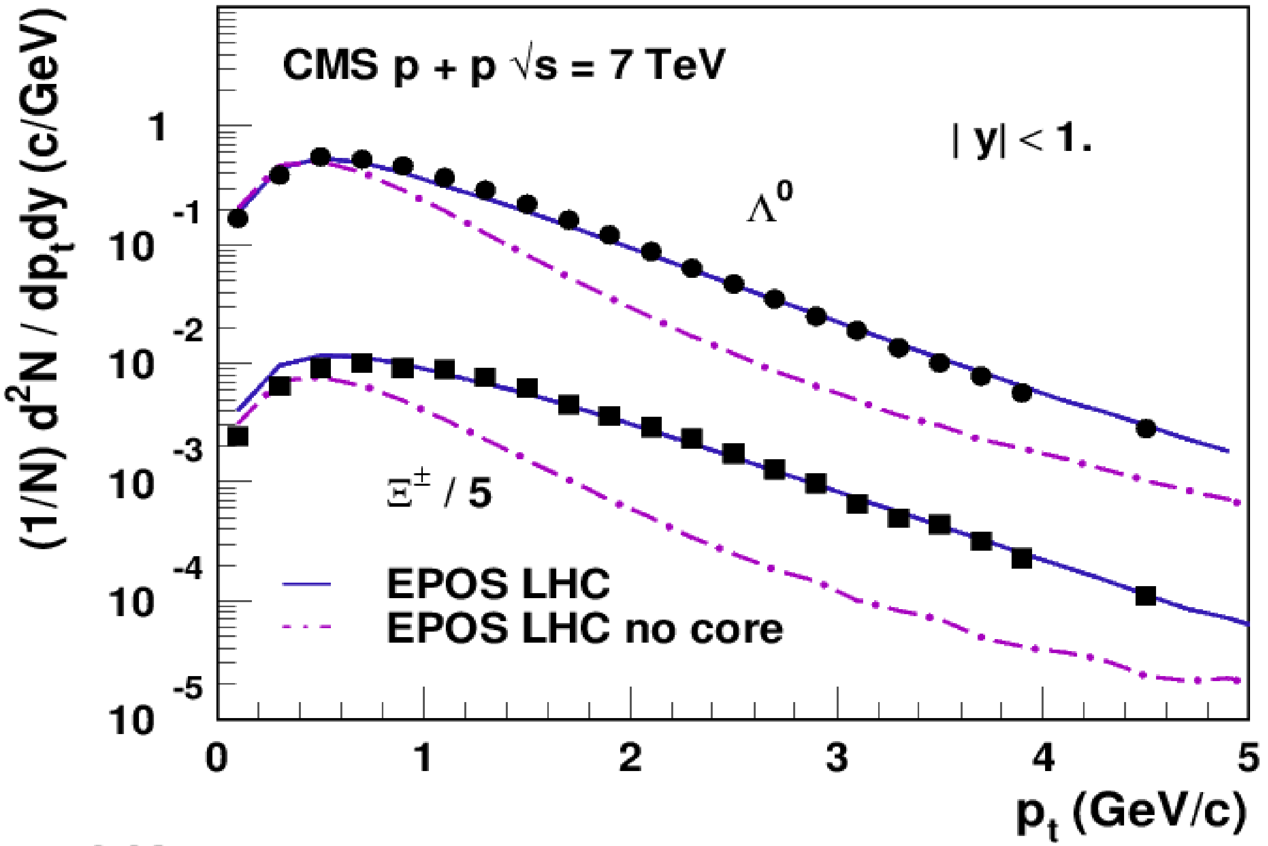
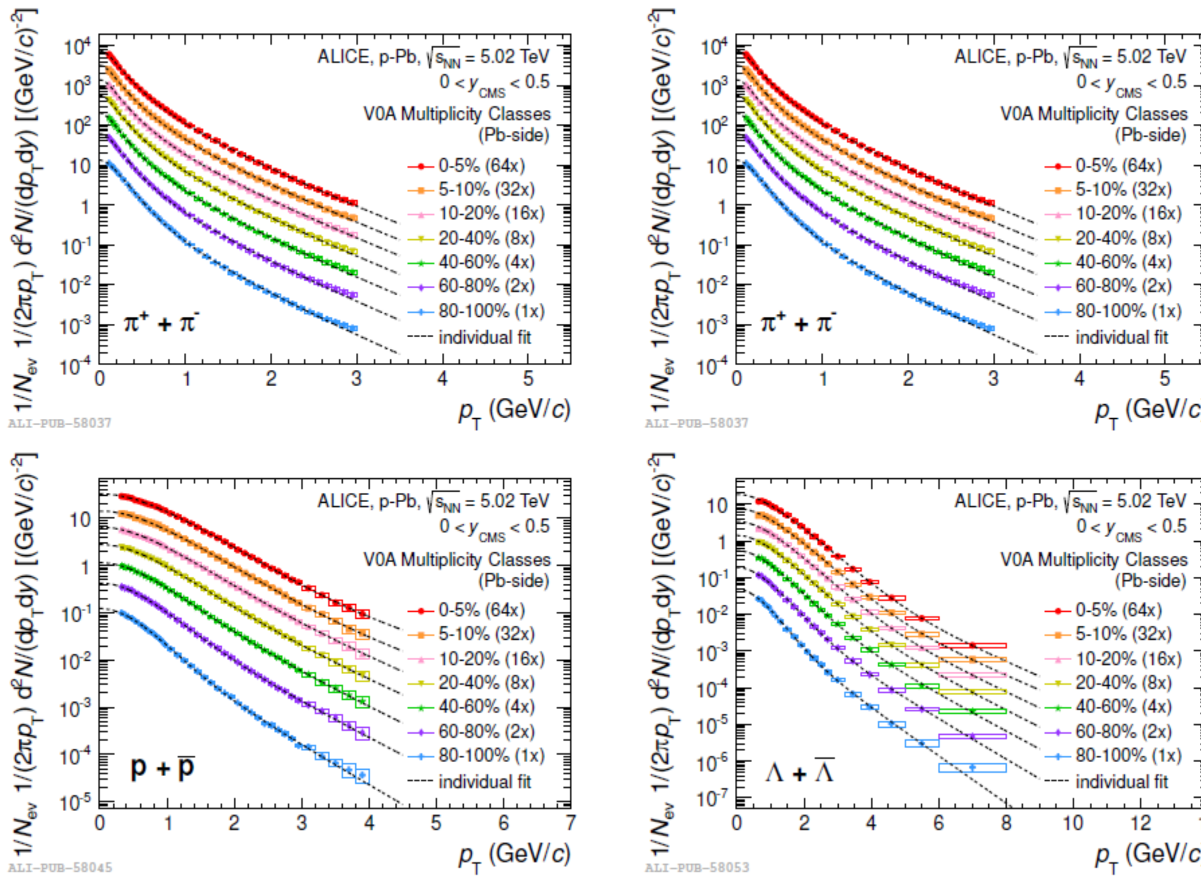


Chapter 6.5: Spectra

5.1.Identified charged particle spectra in p-p and p-Pb

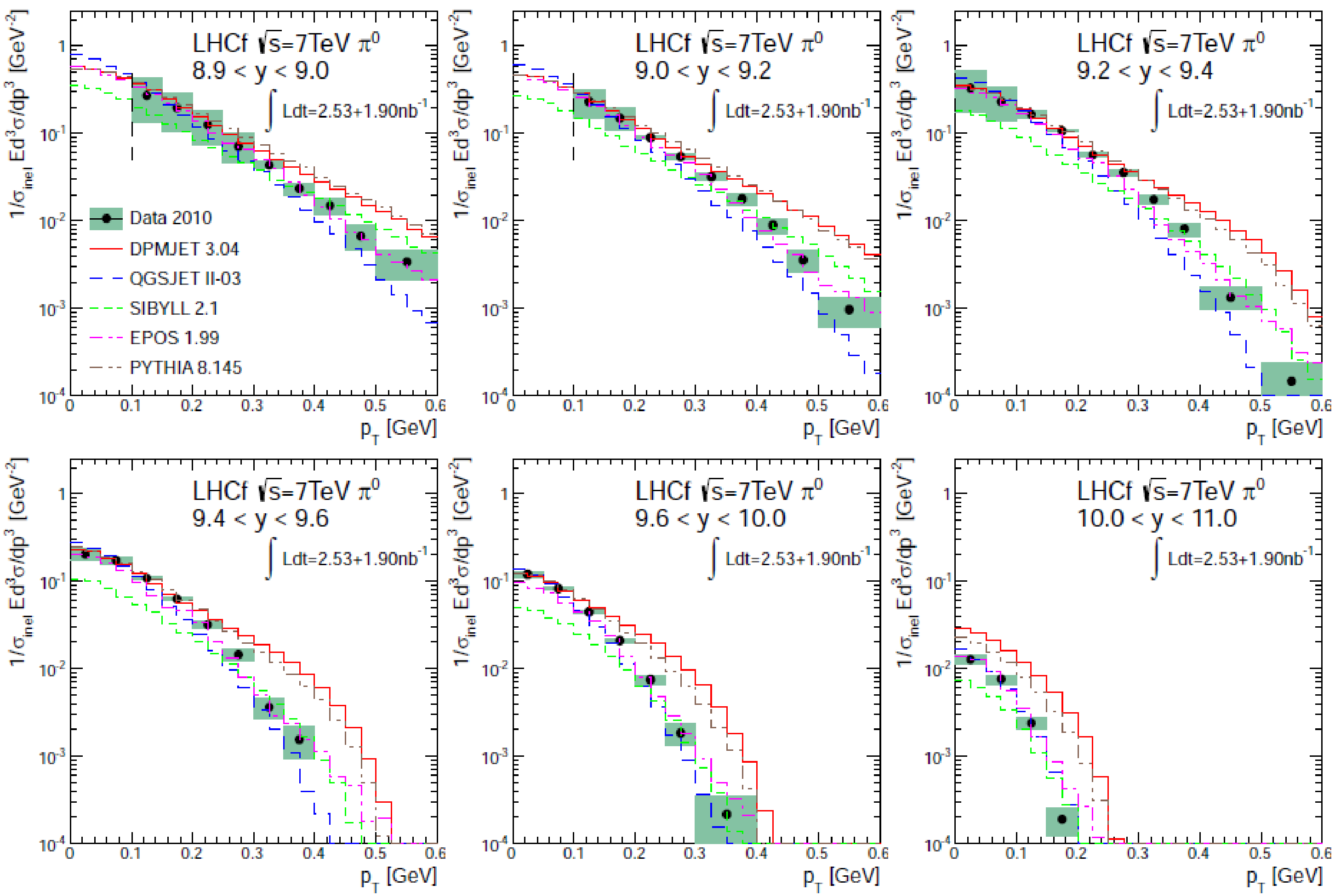
- ALICE
  - evolution as a function of event multiplicity: important to understand for air shower development



Chapter 6.5: Spectra

5.2.Neutral particle spectra

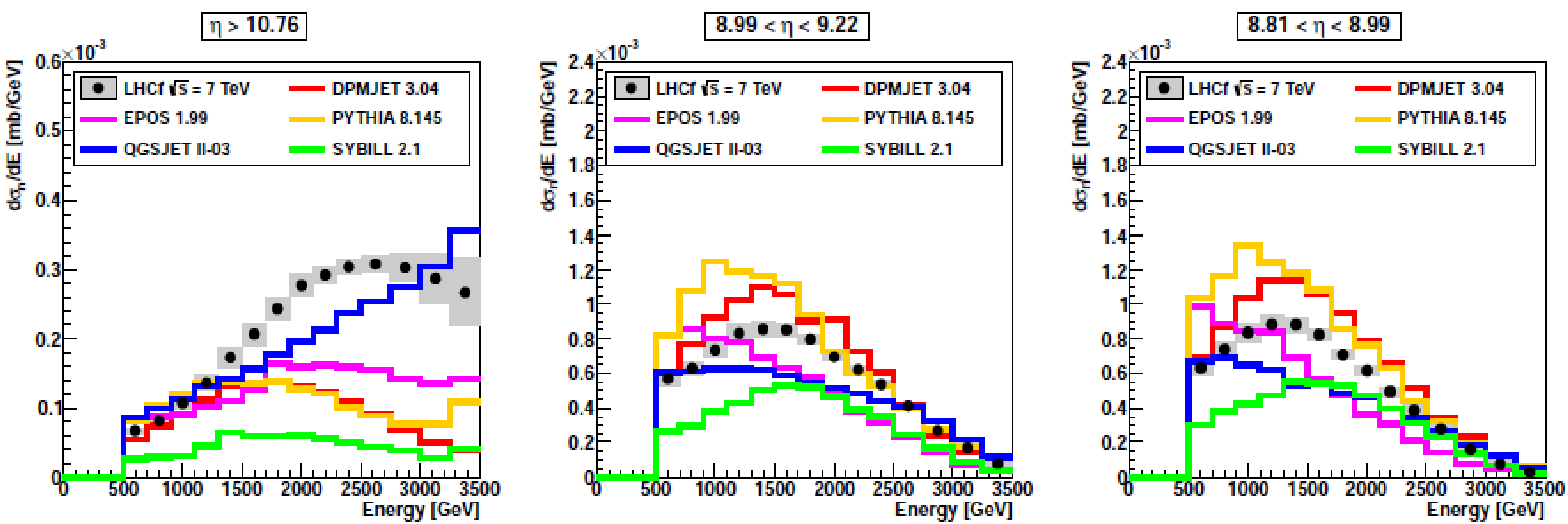
- ALICE and LHCf



Chapter 6.5: Spectra

5.2.Neutral particle spectra

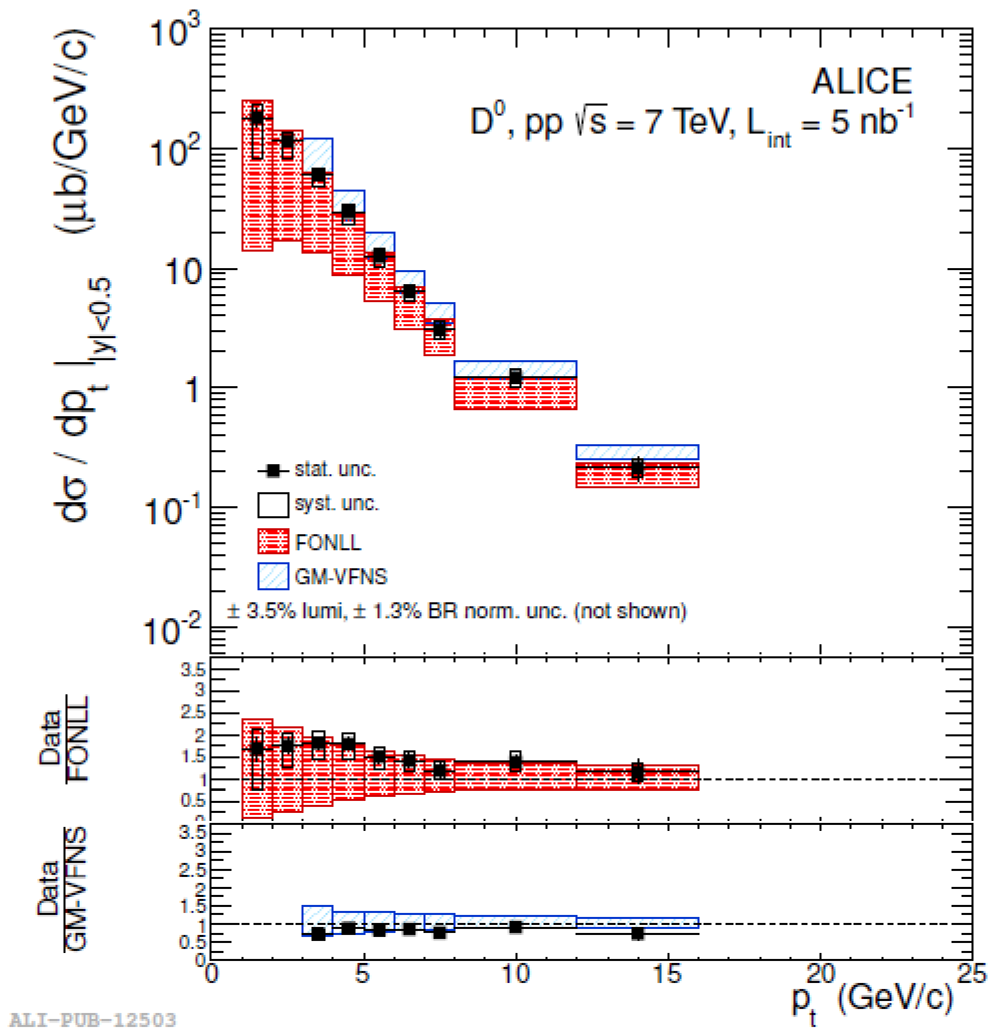
- ALICE and LHCf
  - direct measurements relevant for EAS development
  - both mesons and baryons
  - large model discrepancies

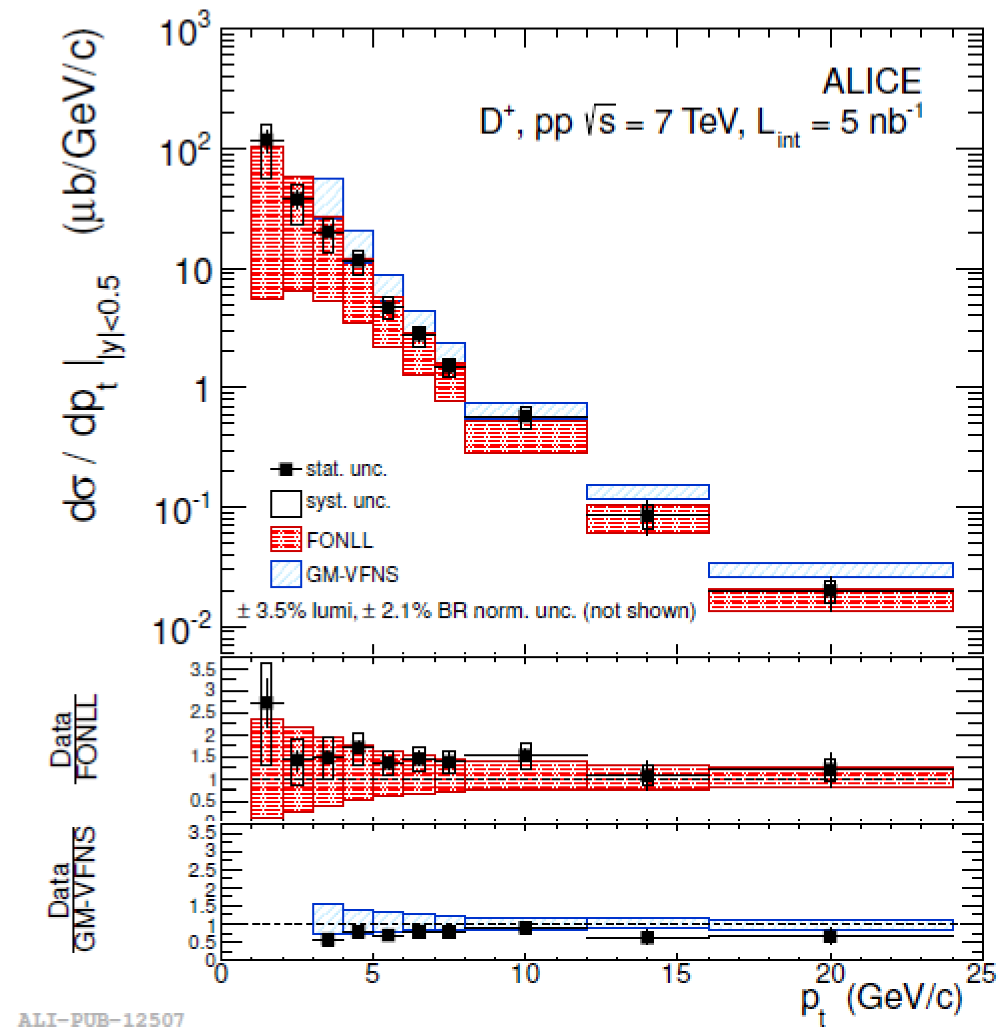


Chapter 6.5: Spectra

5.3.Heavy flavor particle spectra

➡ open charm: ALICE and CASTOR-CMS

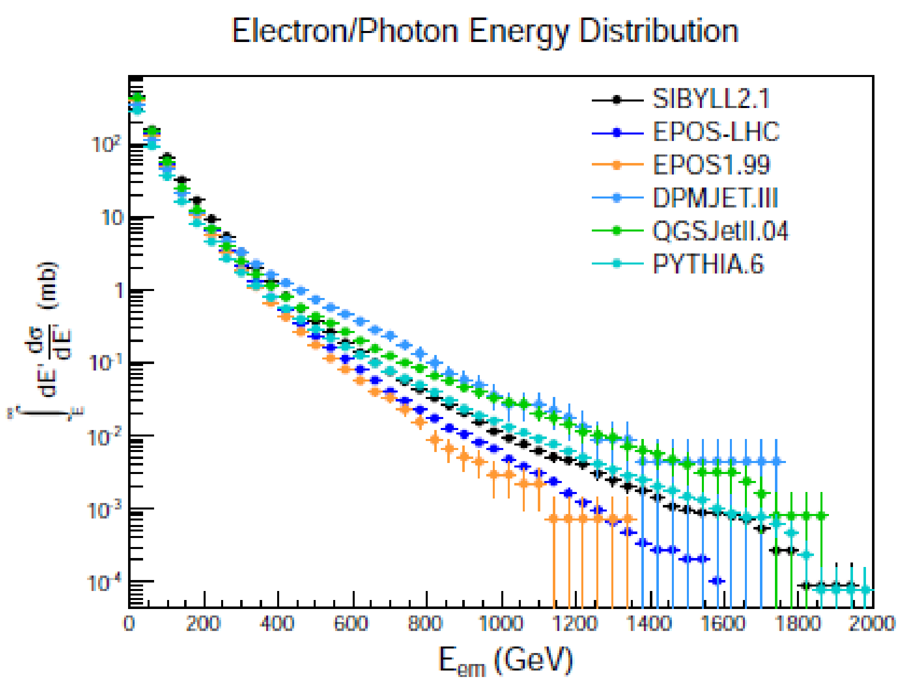


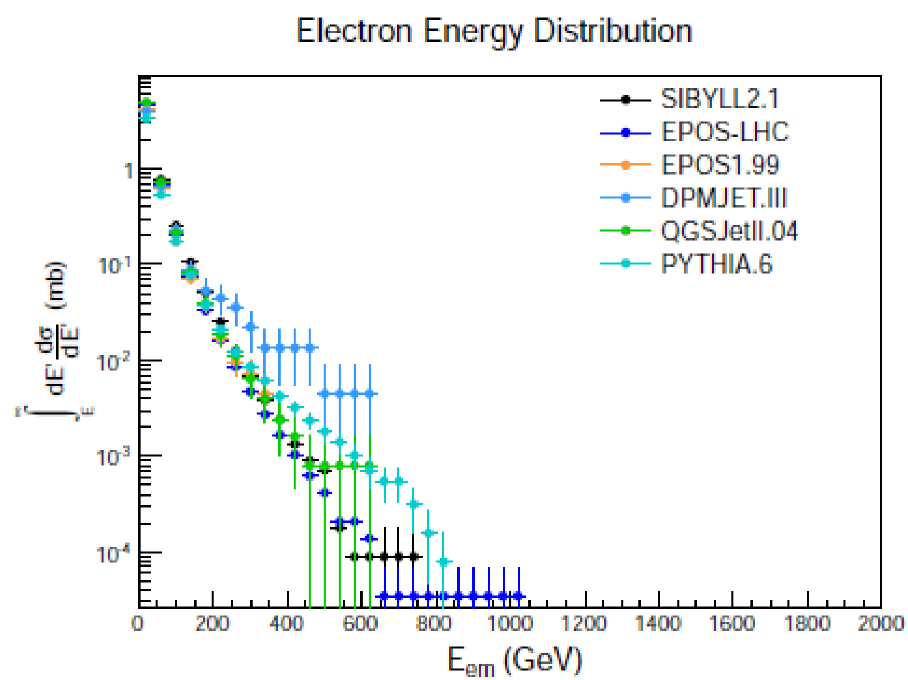


Chapter 6.5: Spectra

5.3.Heavy flavor particle spectra

- open charm: ALICE and CASTOR-CMS
  - important for high energy neutrino production
    - background for astrophysical PeV neutrinos measured by IceCube.





Chapter 6.6: Beam

6.1.Proton-proton collisions

	Exp	σ^{-1} (nb^{-1})	Pile-up	$\mathscr{L}$ ($cm^{-2}s^{-1}$)	β* (m)	N_b	N_p/b	bunch spacing (ns)
√	LHCf	5-20	<1	$6x10^{28}$	19	40	10^{10}	
	TOTEM	100	<1	10^{30}	90	<156	10^{11}	
	ATLAS	1	<1					200
	LHCb	10	<1					>50
	CR	1	<1					

6.2.Light ion Collisions

➔ fixed target (LHCb) and p-O beam

Summary

- **Measurements of particular interest to improve hadronic models used for air shower simulations**
  - ➔ fundamental to reduce uncertainty in air shower measurements (mass composition analysis)
- **Min bias type of analysis**
  - ➔ need low luminosity and low pile-up (each event is relevant)
- **Contributions from all experiments**
- **Final chapter**
  - ➔ 15 authors
  - ➔ 30 pages
  - ➔ 26 figures
  - ➔ 81 references
- **Thanks to the referees for the comments and to all contributors !**

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