(Future of)Shower Physics

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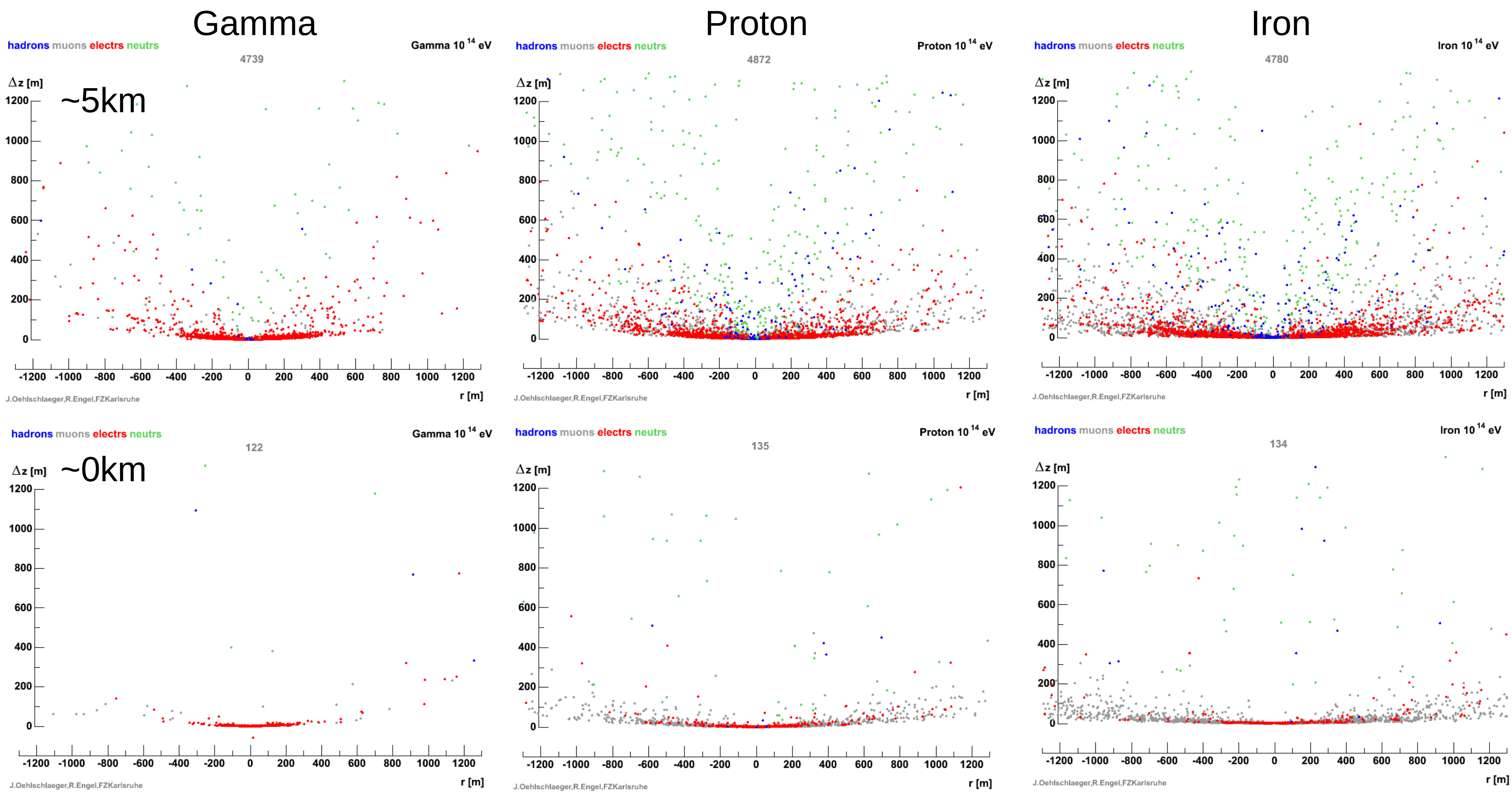
Air Showers at High Altitude

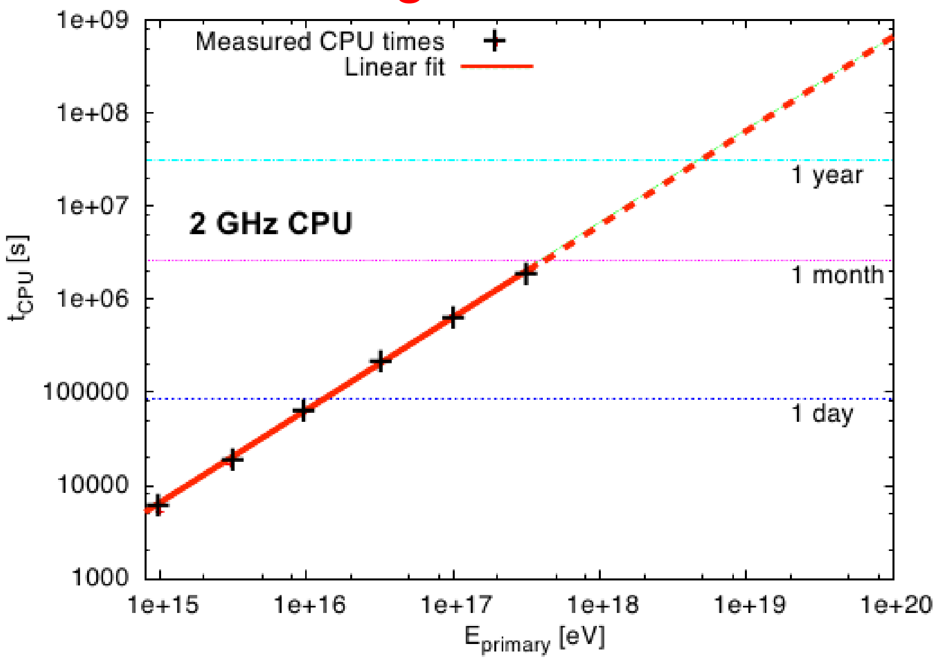
- **Thick shower front (close to maximum) :** ➜ more particles and less fluctuations
  ➜ shell structure detection ?



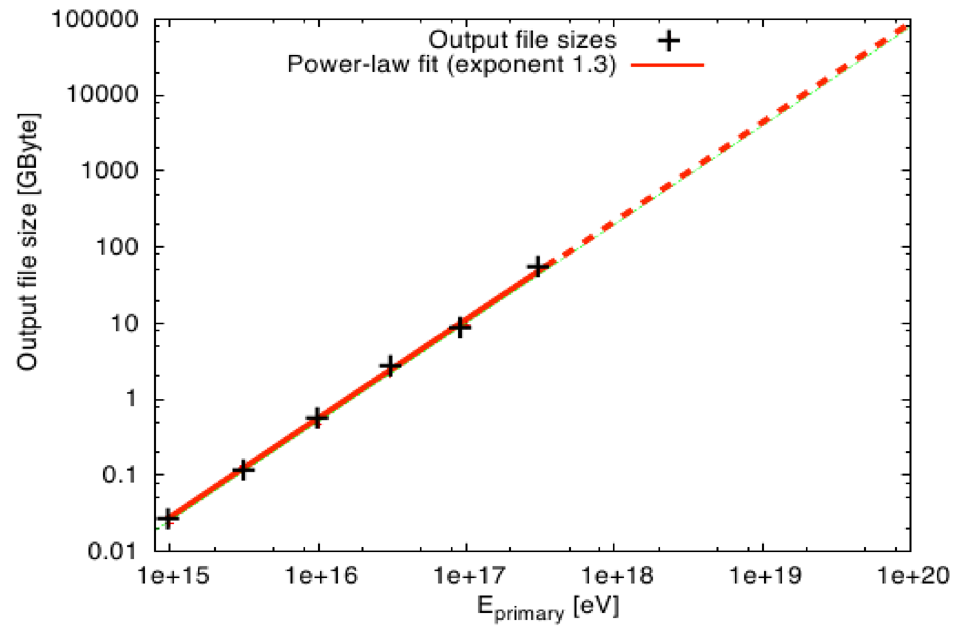
Limitations of Air Shower Simulations

- **Analysis based on air shower simulations affected by 2 main problems :**
  - ➡ limited statistic due to :

Large CPU time



Large disk space



  - ➡ <u>problems with fluctuations created by thinning</u>
  - ➡ uncertainties due to hadronic interactions

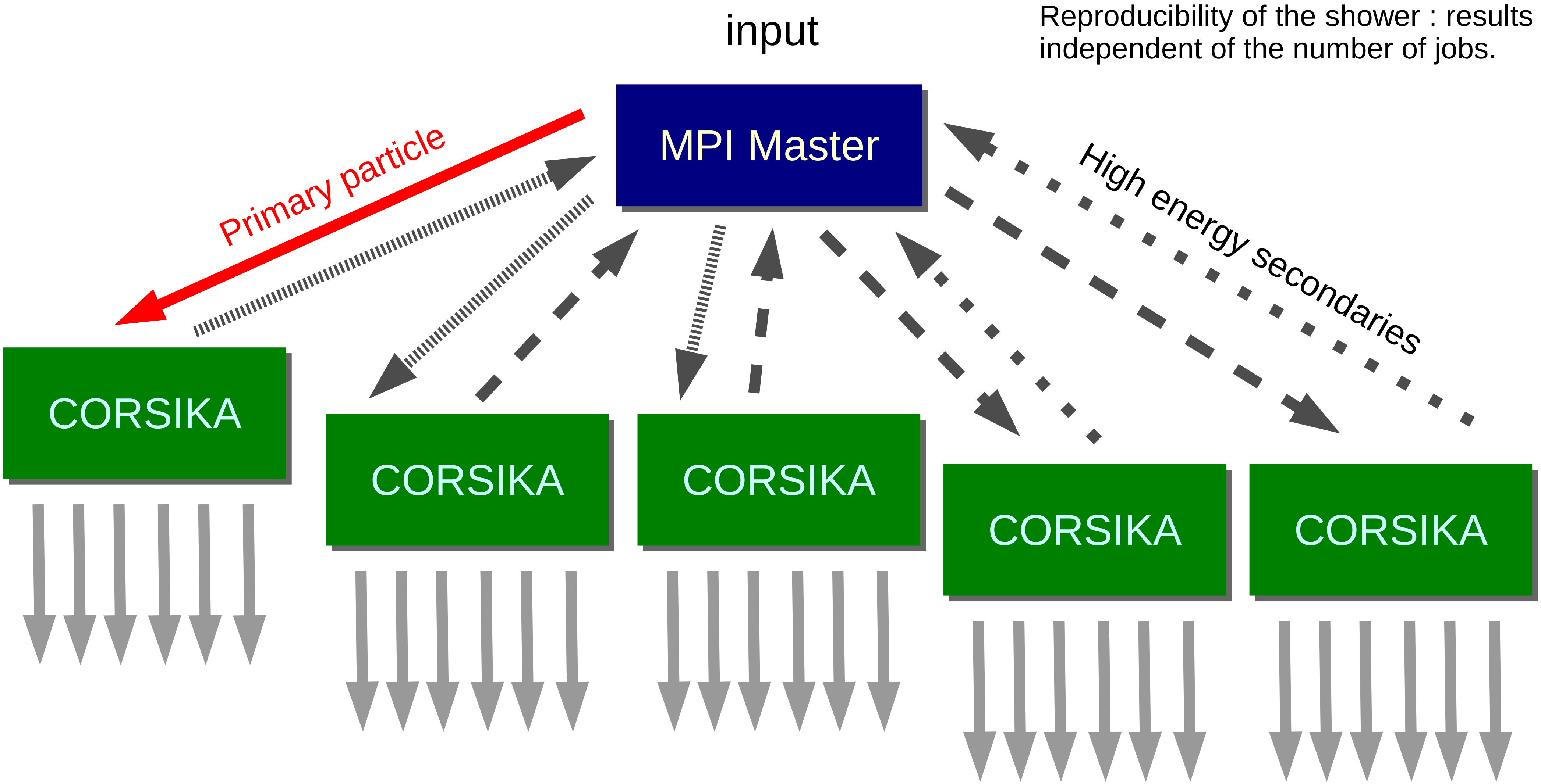
Outline

- **Fast air shower simulations**
  - ➔ Parallelization
  - ➔ Cascade equations
- **Consequences of current and future LHC data**
  - ➔ Hadronic models
- **Summary**

New possibilities for fast simulations and reduced uncertainties.

Parallelization of CORSIKA with MPI

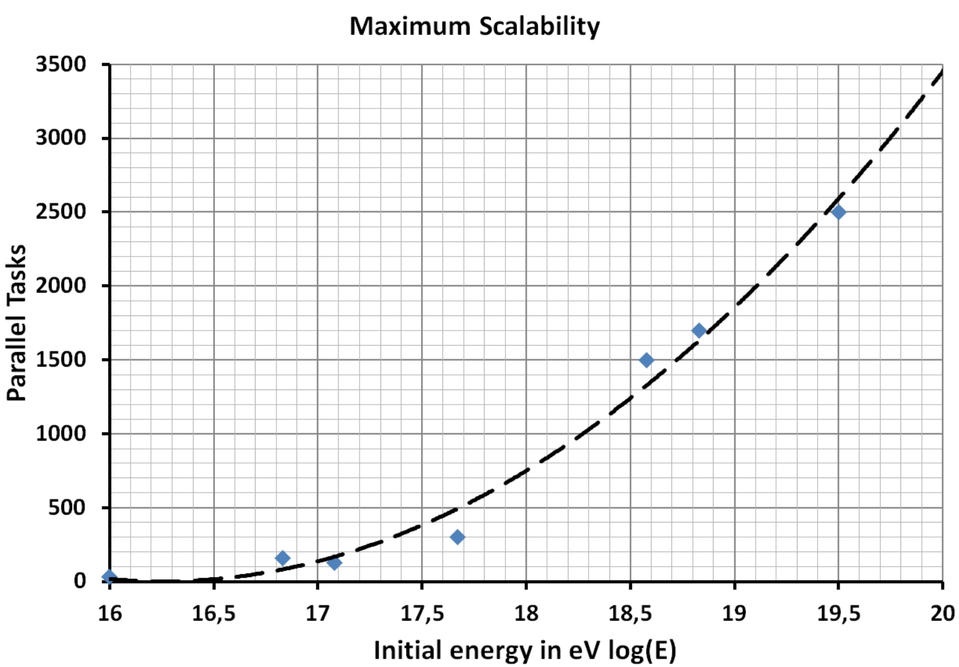
Reproducibility of the shower : results independent of the number of jobs.

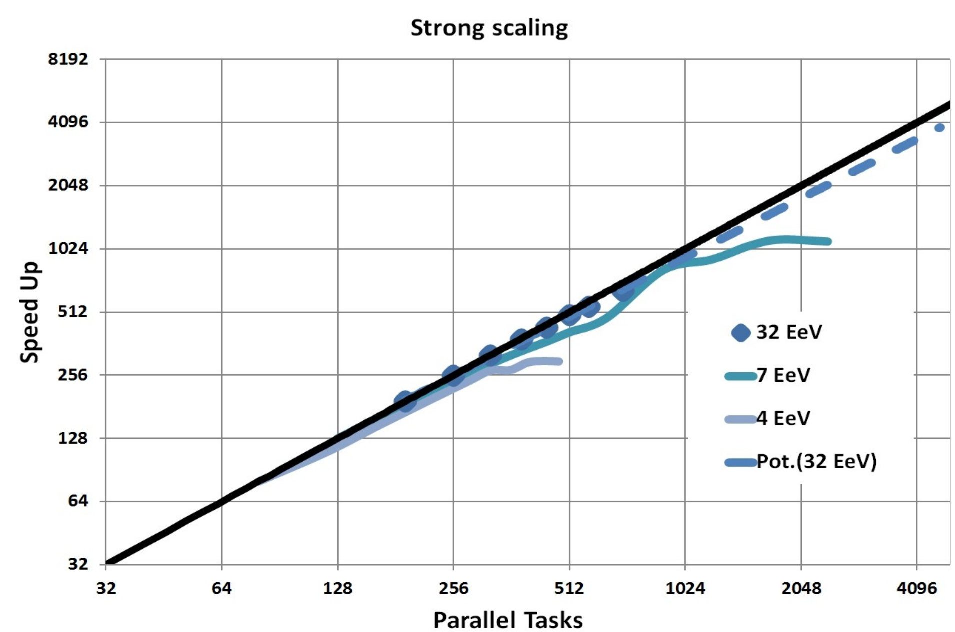


Low energy secondaries down to observation level

Parallelization of CORSIKA

- **Each shower is simulated on a large number of CPU**
  - ➜ Simulation time reduction limited by the number of machines
  - ➜ Disk space problem solved by saving particles in detectors only
    - ➜ possible only if simulation time is short
- **solution at high energy : unthinned simulations for each real events**





Parallel version tested on HP XC3000 (2.53 GHz CPUs, InfiniBand 4X QDR)

New Developments

- **Parallel option already available**
  - ➔ simulation shower-by-shower (high energy)
  - ➔ system dependent, please contact us in case of problem
- **On-going developments**
  - ➔ data merging to limit the number of final files
  - ➔ automatic multi-shower management
    - mix low/high energy by user : master job decide if a shower should be treated on a single node or many
    - high statistic of low and high energy unthinned showers from a single job on giant CPU clusters (billions of CPU hours available)
- **Project**
  - ➔ Use of GPU for Cerenkov photon calculation

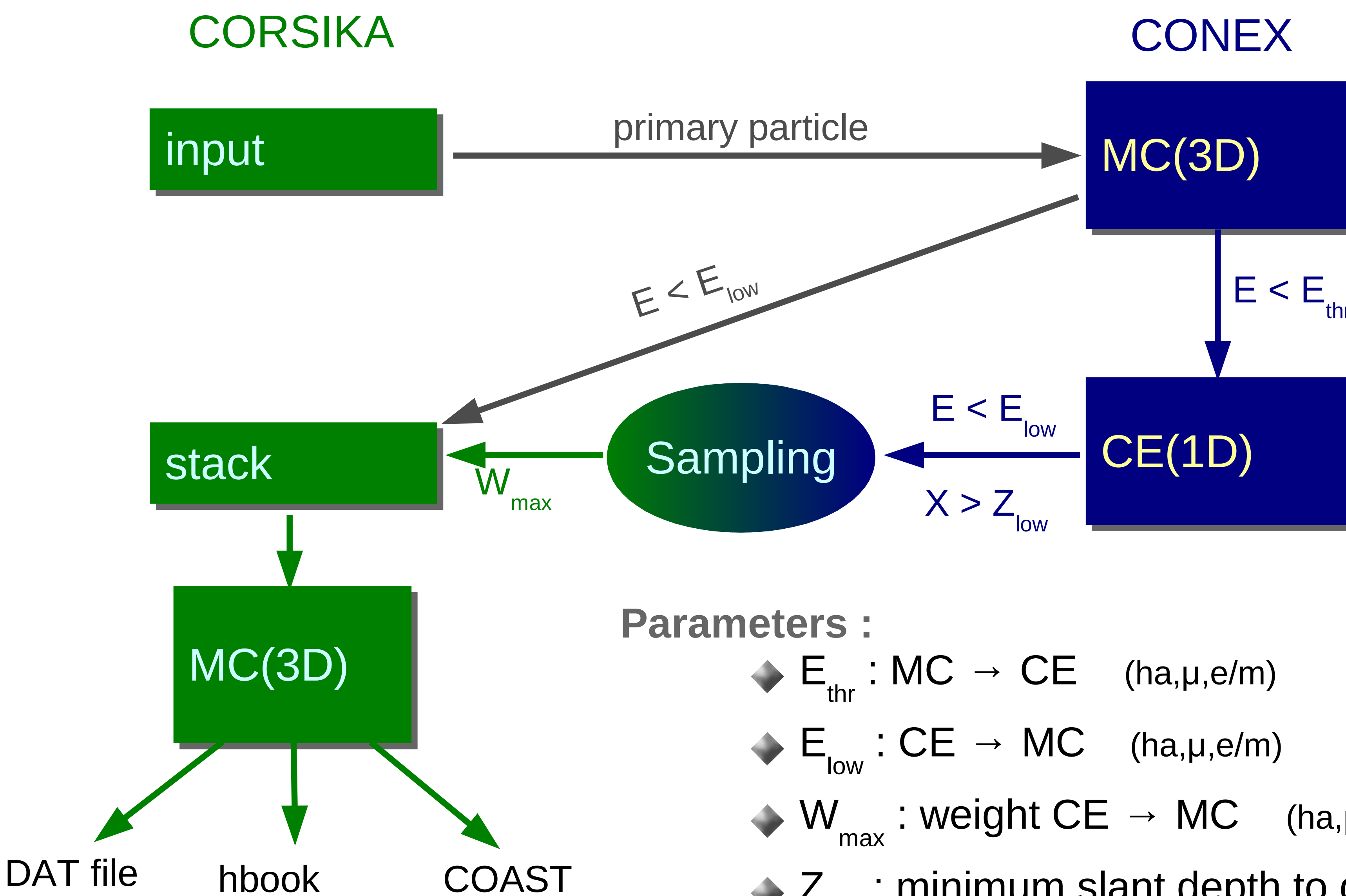
CONEX v4.37 in CORSIKA v7.4

CONEX as an option in CORSIKA

- Hybrid 3D simulation (other model: SENECA by H.J. Drescher)
  - same seed = same shower (1D (fast) or 3D (slow))
- CORSIKA running script and installation
- CORSIKA input
  - one more line in steering file for CONEX parameters
- CORSIKA output
  - no new interface (MC compatible with COAST)
- CORSIKA low energy hadronic interactions models
- CONEX high energy hadronic interaction models
  - EPOS LHC, QGSJET01, QGSJETII-04, SIBYLL 2.1

CONEX (cascade equations (CE)) used as a new type of thinning in CORSIKA : transparent for users !

CORSIKA with CONEX



Parameters :

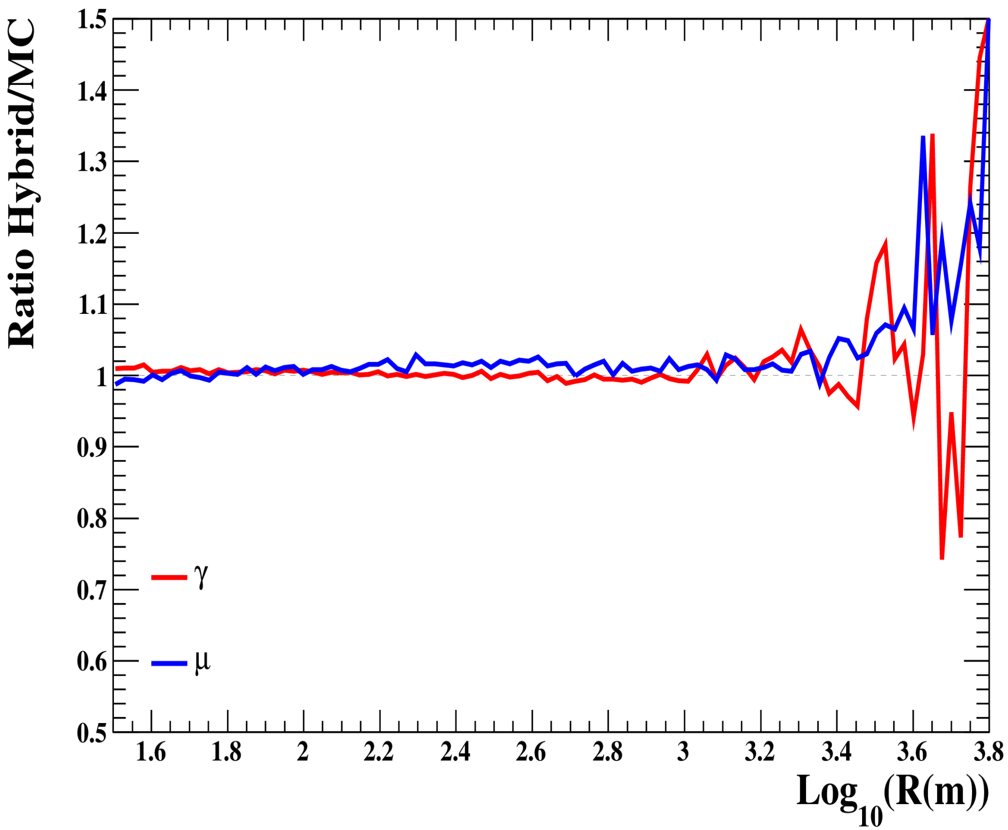
- E_{thr} : MC → CE (ha,μ,e/m)
- E_{low} : CE → MC (ha,μ,e/m)
- W_{max} : weight CE → MC (ha,μ,e/m)
- Z_{low} : minimum slant depth to ground for CE → MC (only e/m)

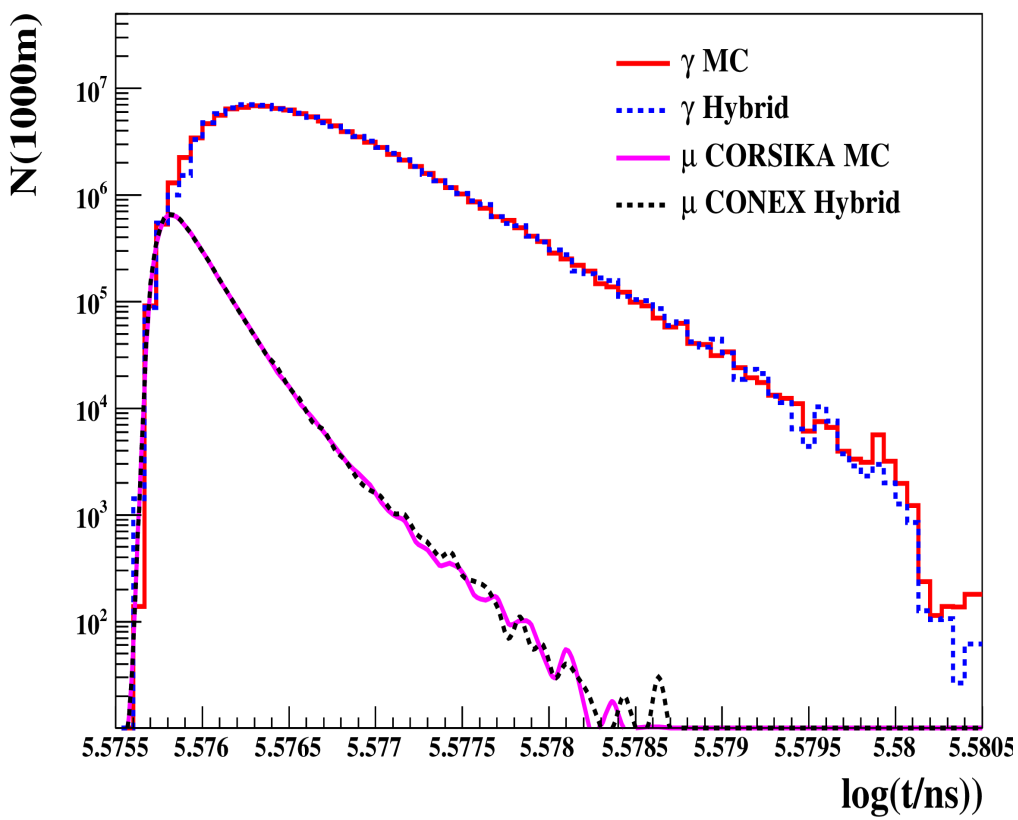
Properties

- **CORSIKA replace part of the CE**
  - ➔ First interactions in CONEX independent from E_{low}
    - Event-by-event simulations using first 1D only and then 3D with exactly the same shower (top-down reconstruction :Golden Hybrid, radio)
- **CE replace part of the thinning in CORSIKA**
  - ➔ No thinned high energy gammas (stay in CE)
    - No muons from EM particles with very large weight
  - ➔ Very narrow weight distributions : less artificial fluctuations
  - ➔ No thinning for very inclined shower
    - Only muons and corresponding EM sub-showers in MC
- **CONEX and CORSIKA are independent**
  - ➔ Different media might be used
- **Mean showers can be simulated directly** **(no high energy MC)**
- **Not tested for Cherenkov photons yet ...**

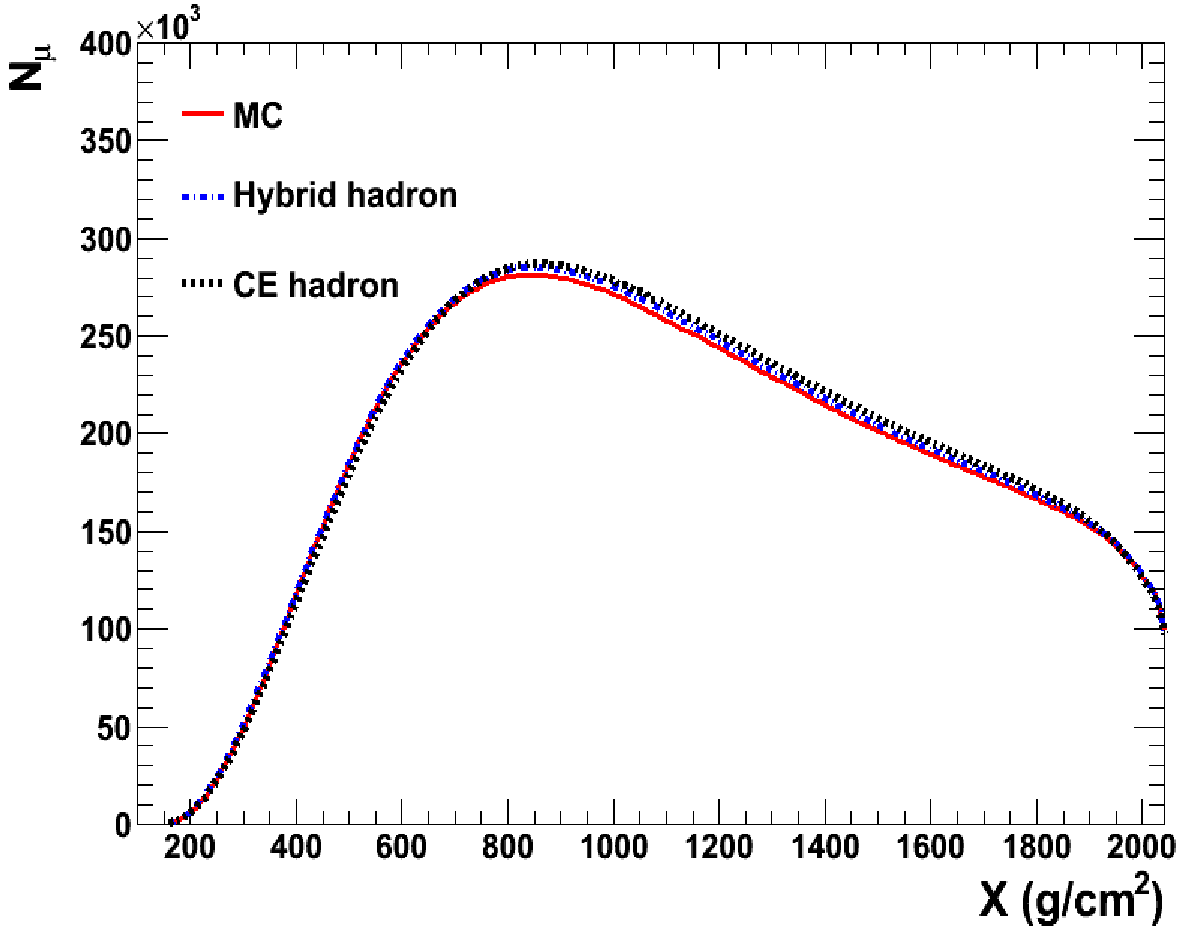
Example

- QGSJET01/GHEISHA Iron shower 10^{19} eV
  - MC : 49h (max weight = 1000(em)/100(had))
  - Hyb : 10h (max weight = 1000(em)/100(had))
- 1 shower (same seed) : X_{max}=670(MC) / 673(Hyb) g/cm^2





Example :
1 shower with different thresholds



Same profile within 3%

Proton @ 0.1 EeV EGS4 off

QGSJET + GHEISHA

- MC : CONEX MC FOR E > 1 TeV

  CORSIKA FOR E < 1 TeV

- Hybrid hadron : CONEX MC < 1 TeV

  100 GeV < hadronic CE < 1TeV

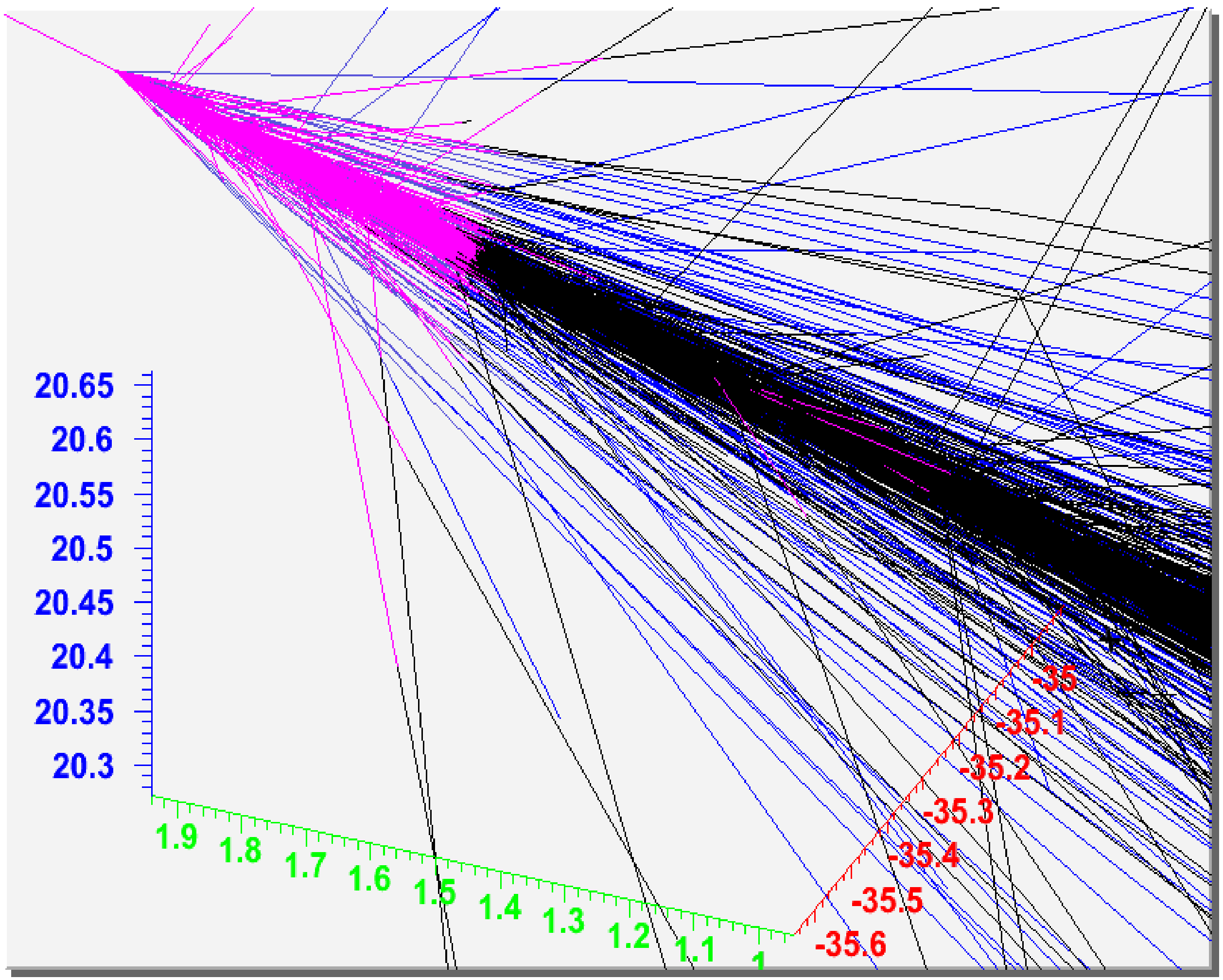
  CORSIKA < 100 GeV

- CE hadron : CONEX MC < 1 TeV

  CORSIKA only for muons (all E)

One shower, same random numbers

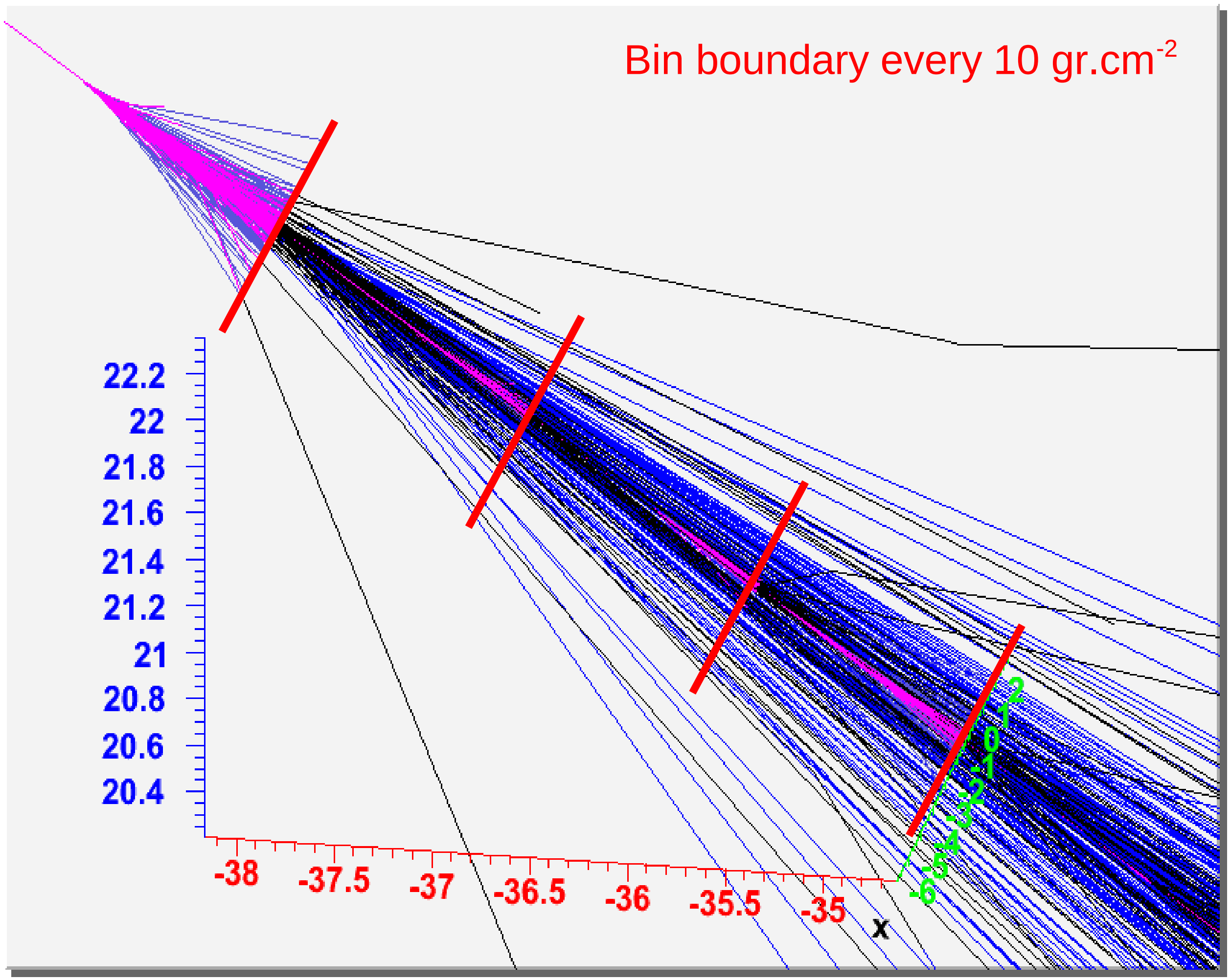
Example : 3D View with COAST



- **MC 3D : no cascade equation**
  - CONEX MC at high energy
  - CORSIKA at low energy
  - Track connection at bin boundary

Purple : CONEX hadrons
Dark blue : CONEX muons
Dark : CORSIKA hadrons
Blue : CORSIKA muons

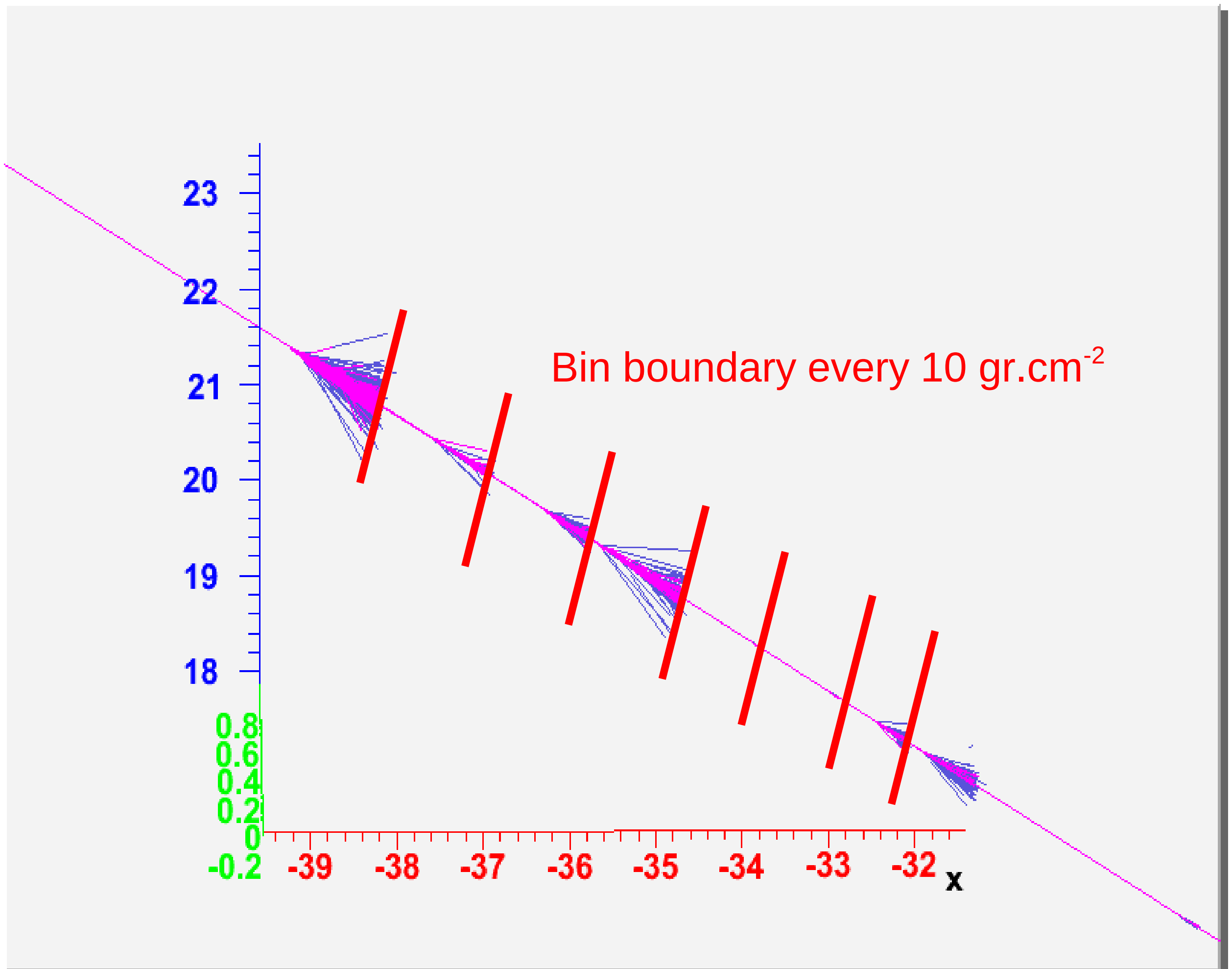
Example :
3D View with COAST



- **Hybrid 3D : Cascade equation only at intermediate energy**
  - High energy particle tracks until bin boundaries
  - Low energy particle tracks from bin boundaries

Purple : CONEX hadrons
Dark blue : CONEX muons
Dark : CORSIKA hadrons
Blue : CORSIKA muons

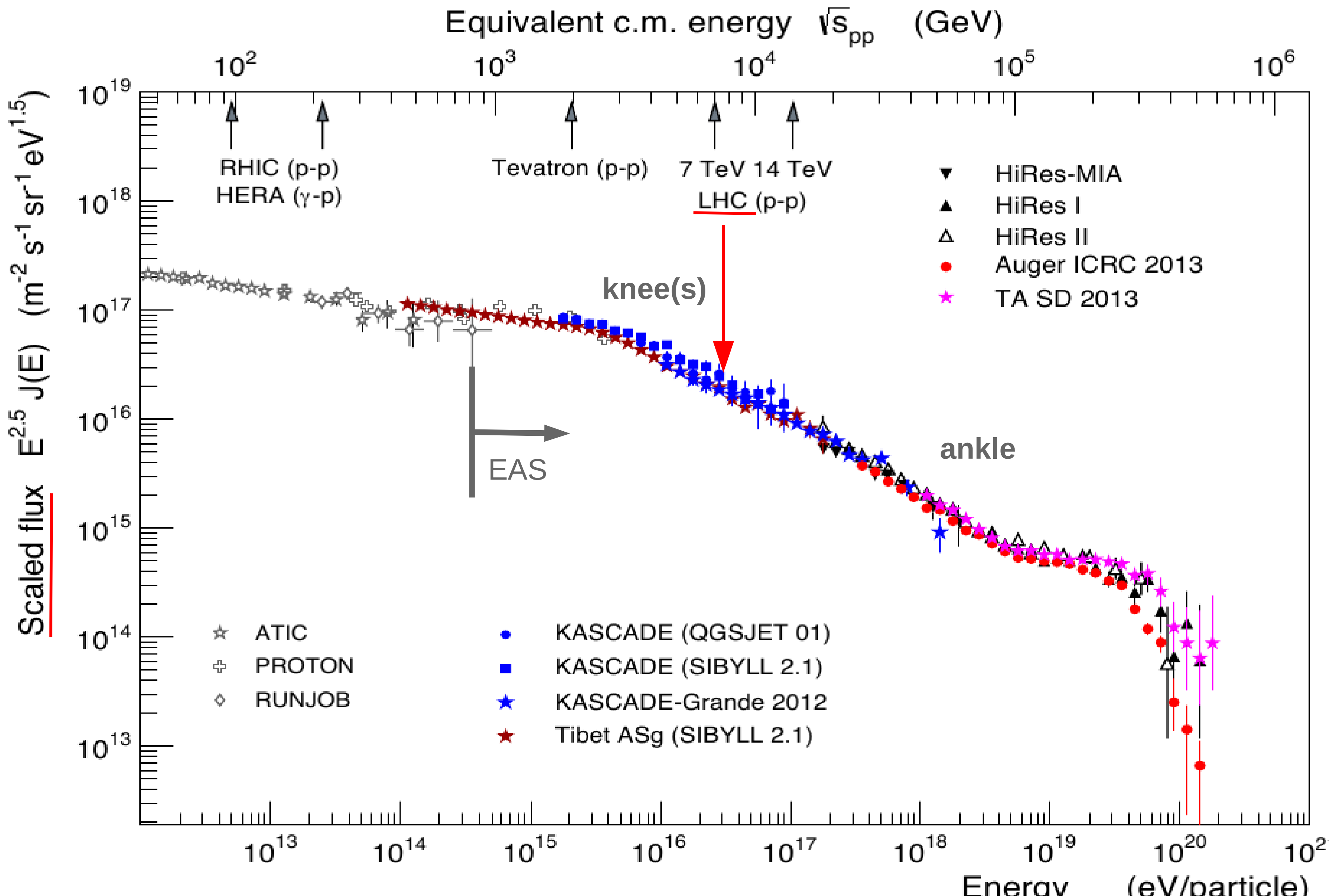
Example :
3D View with COAST



- **Hybrid 1D : Cascade equation only at low energy**
  - Particle track only until bin boundaries
  - Interaction off leading particles

Purple : CONEX hadrons
Dark blue : CONEX muons

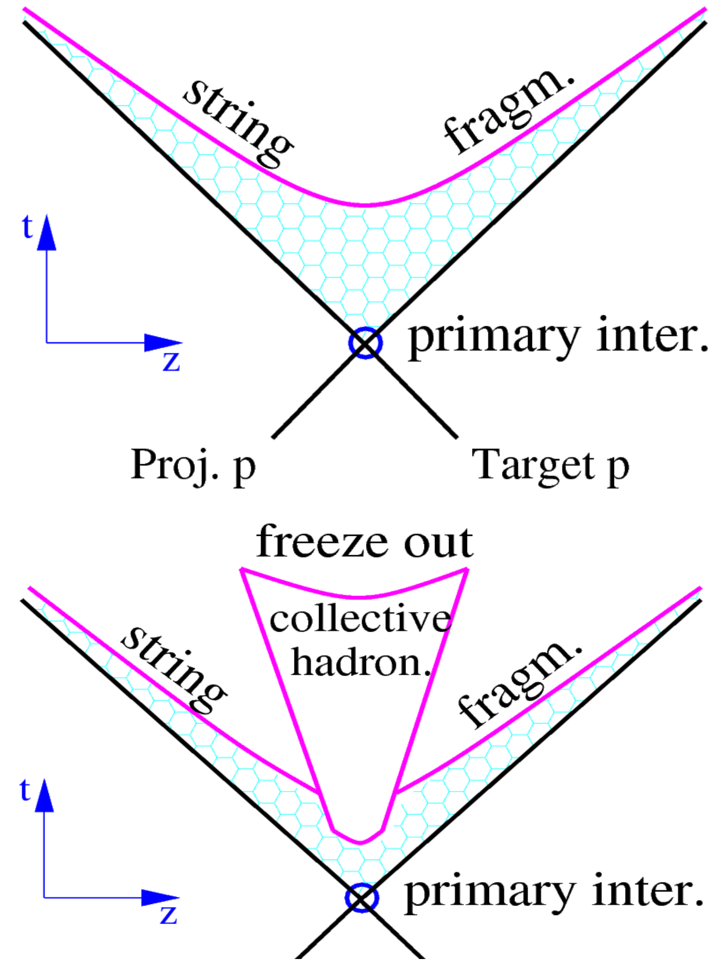
Cosmic Ray and Hadronic Interactions



R. Engel (KIT)

New Models

- **QGSJETII-03 to QGSJETII-04 :**
  - loop diagrams
  - rho0 forward production in pion interaction
  - re-tuning some parameters for LHC and lower energies



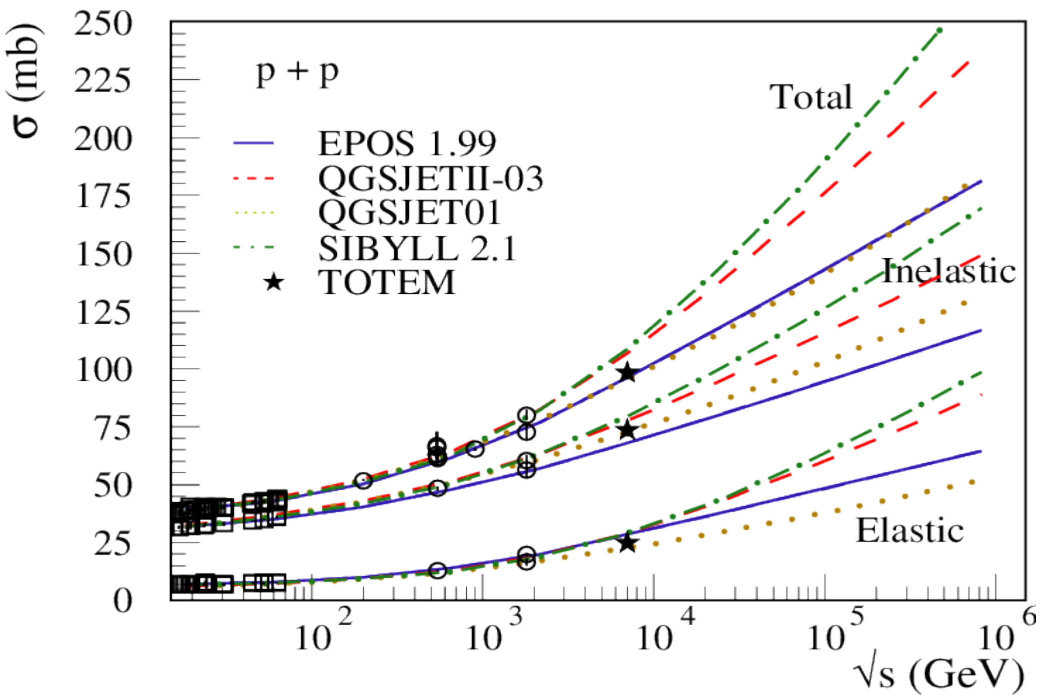
- **EPOS 1.99 to EPOS LHC**
  - tune cross section to TOTEM value
  - change old flow calculation to a more realistic one
  - introduce central diffraction
  - keep compatibility with lower energies

Direct influence of collective effects on EAS simulations has to be shown but important to compare to LHC and set parameters properly (<pt>, ...).

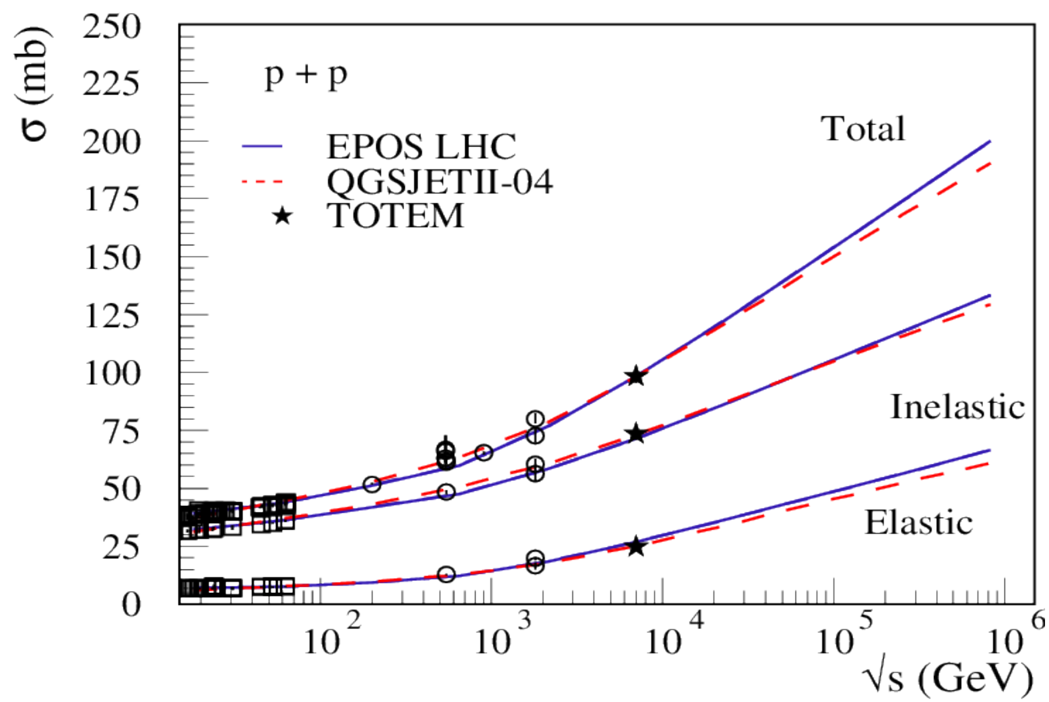
Cross Sections

- Same cross sections at pp level up to LHC
  - weak energy dependence : no room for large change beyond LHC
- other LHC measurements of inelastic cross-section (ALICE, ATLAS, CMS) test the difference between models (diffraction)

Pre - LHC



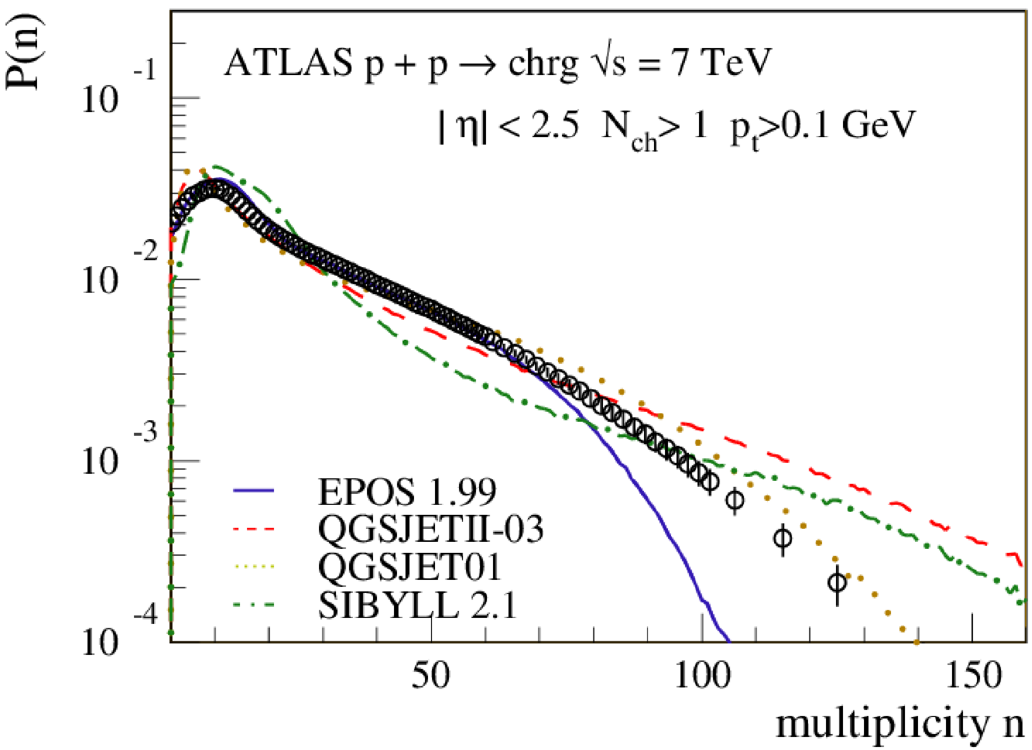
Post - LHC



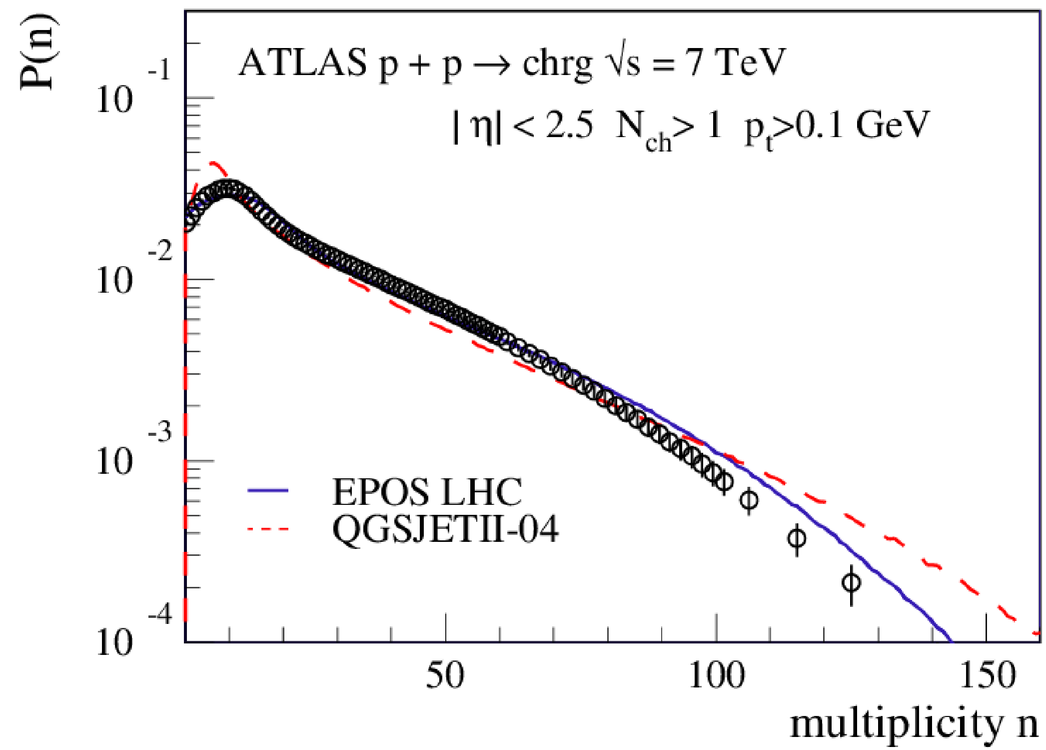
Multiplicity

- **Consistent results**
  - ➜ Better mean after corrections
    - difference remains in shape
  - ➜ Better tail of multiplicity distributions
    - corrections in EPOS LHC (flow) and QGSJETII-04 (minimum string size)

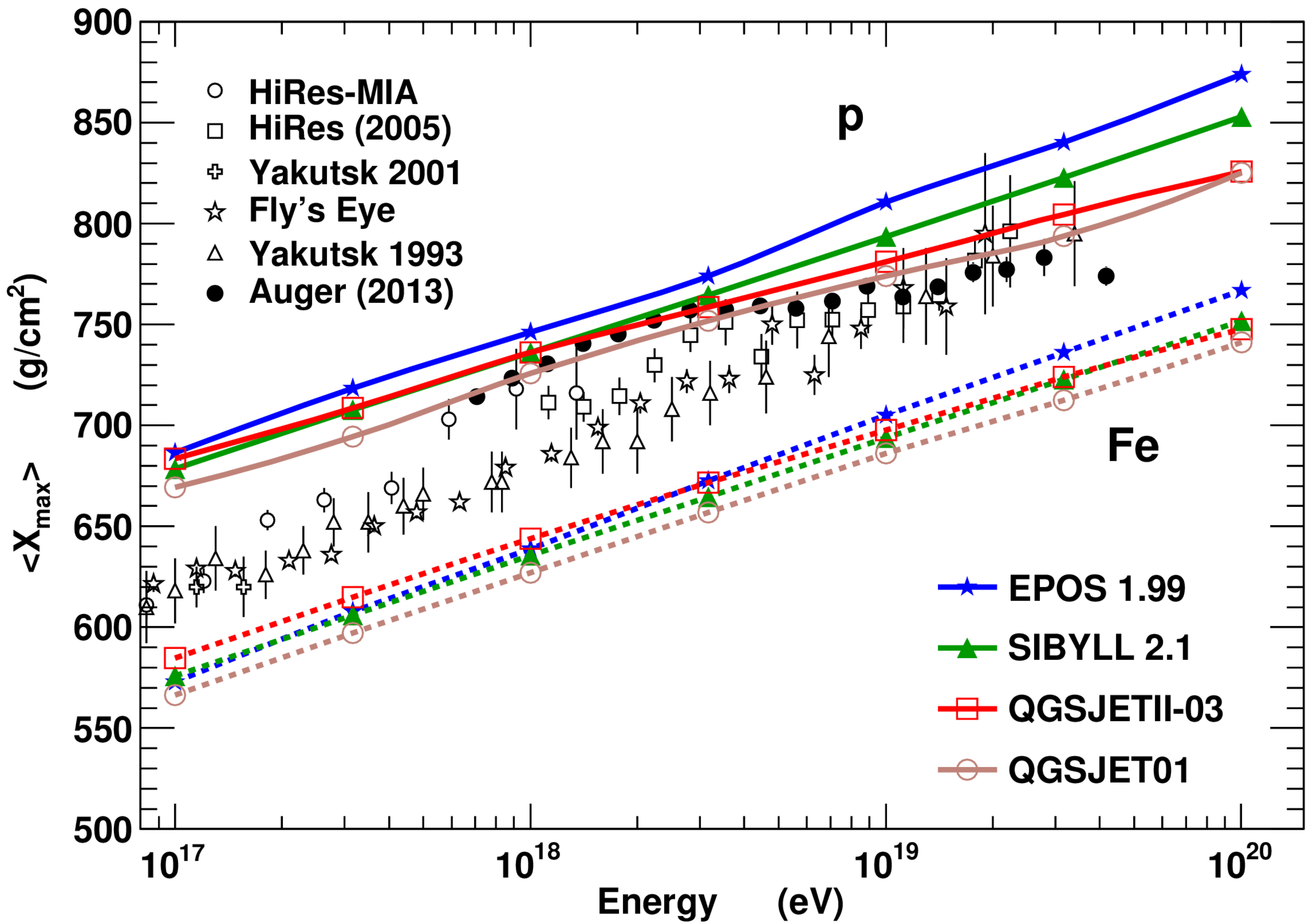
Pre - LHC



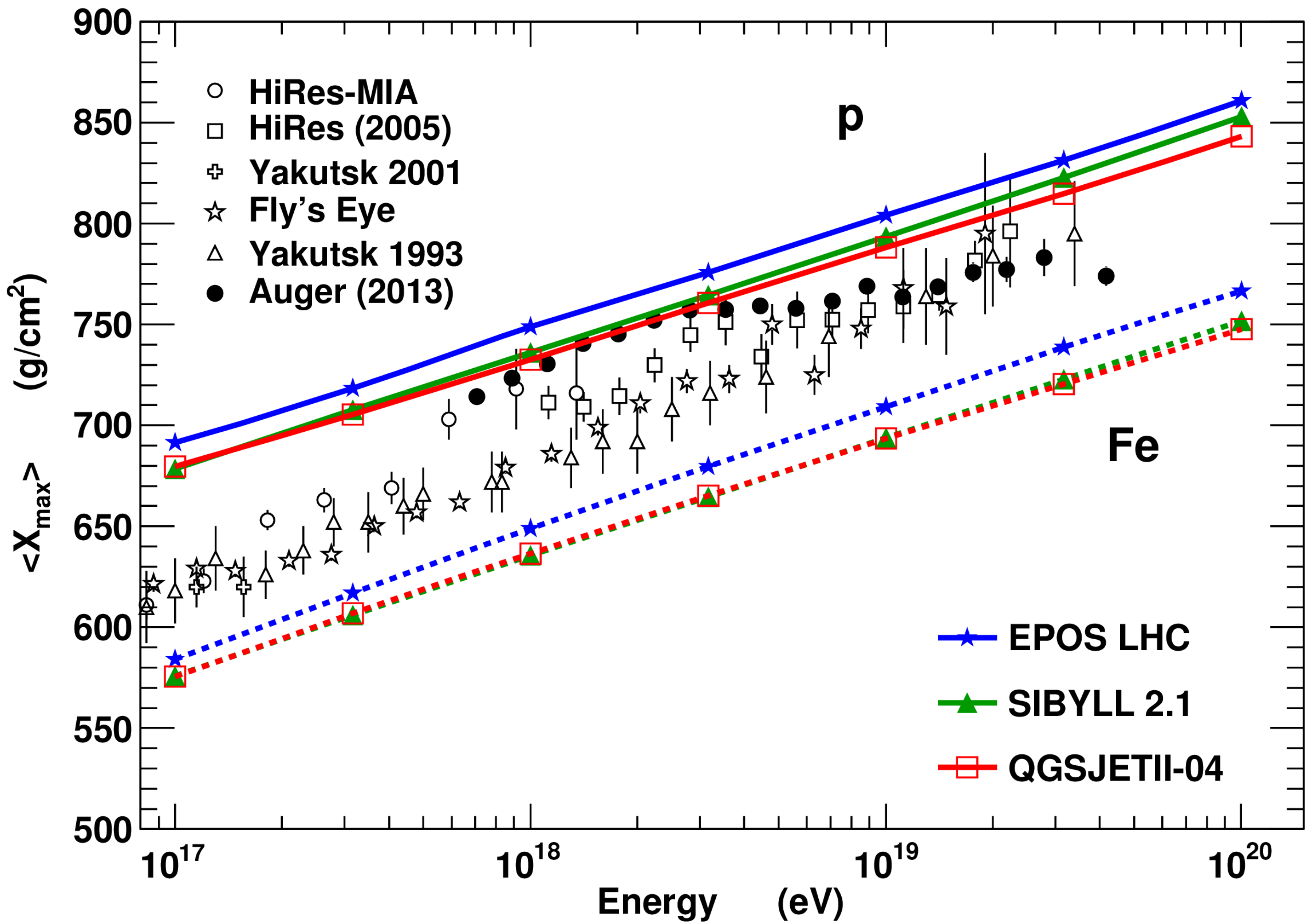
Post - LHC



EAS with Old CR Models : X_{max}

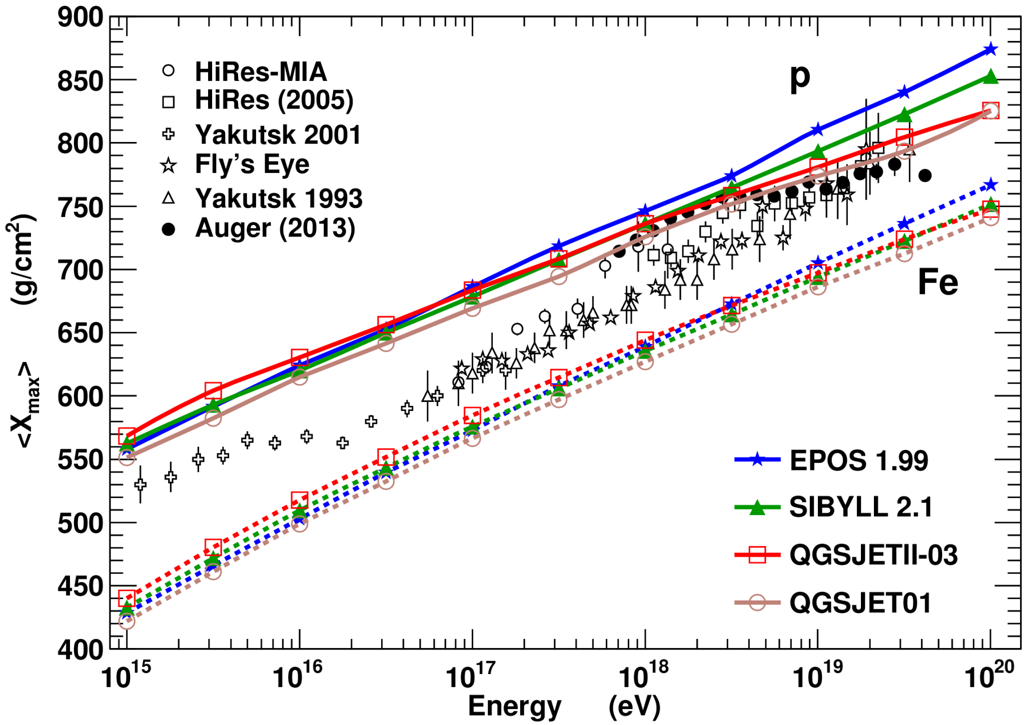


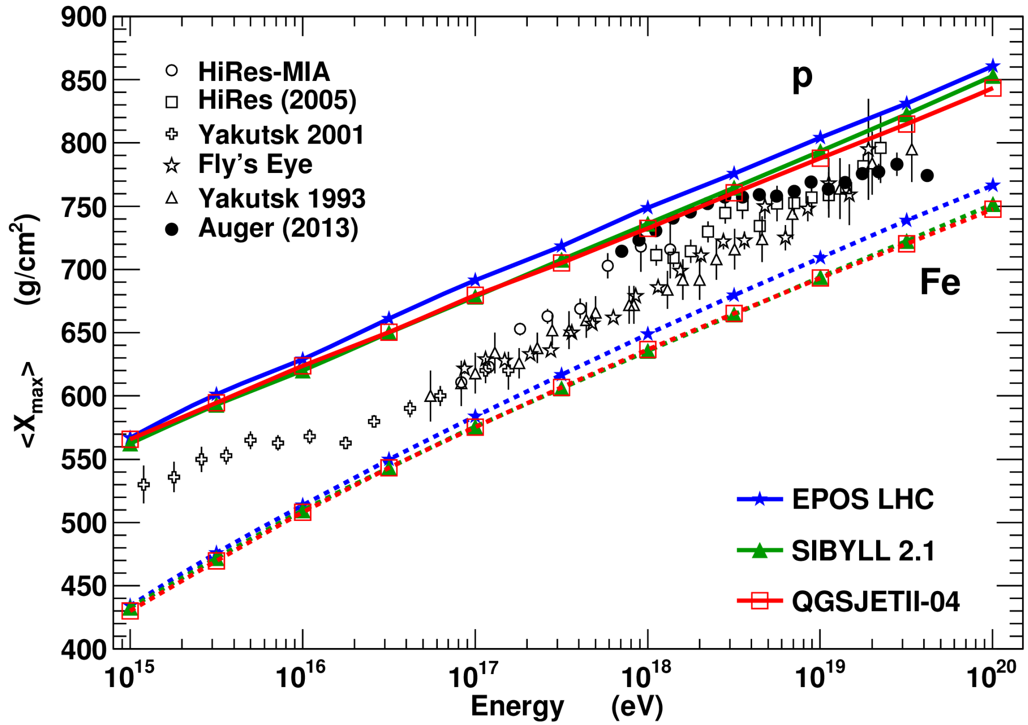
EAS with Re-tuned CR Models : X_{max}



EAS with Re-tuned CR Models : X_{max}

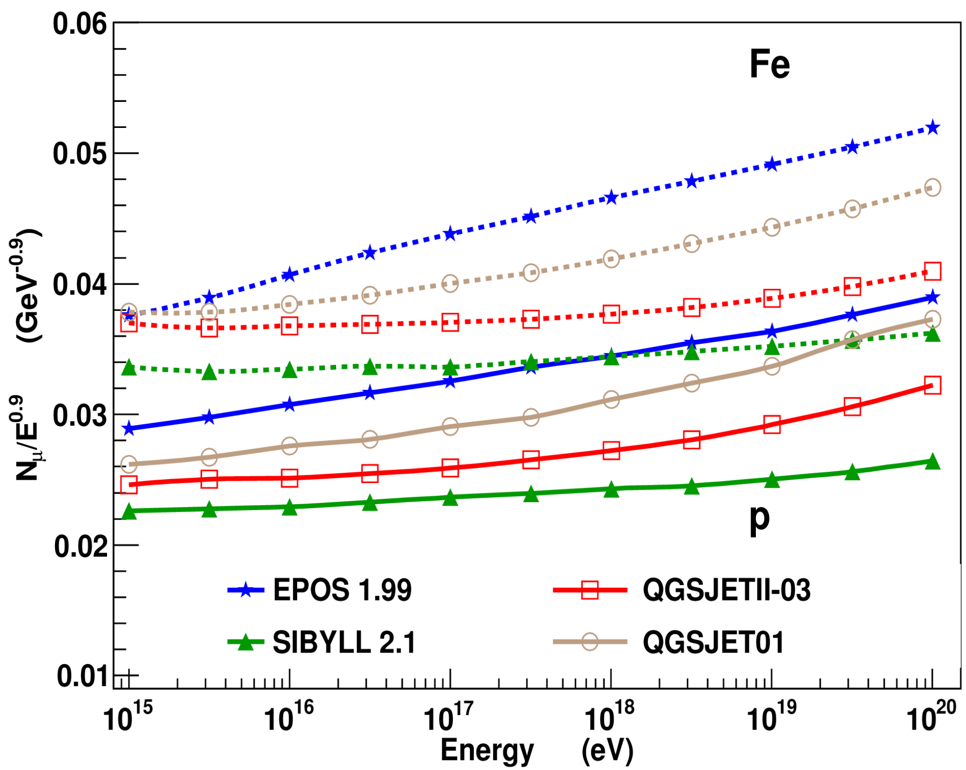
- **Cross section and multiplicity fixed at 7 TeV**
  - ➡ smaller slope for EPOS and larger for QGSJETII
  - ➡ re-tuned model converge to old Sibyll 2.1 predictions
    - ◆ reduced uncertainty from ~50 g/cm^2 to ~20 g/cm^2 (difference proton/iron is about 100 g/cm^2)

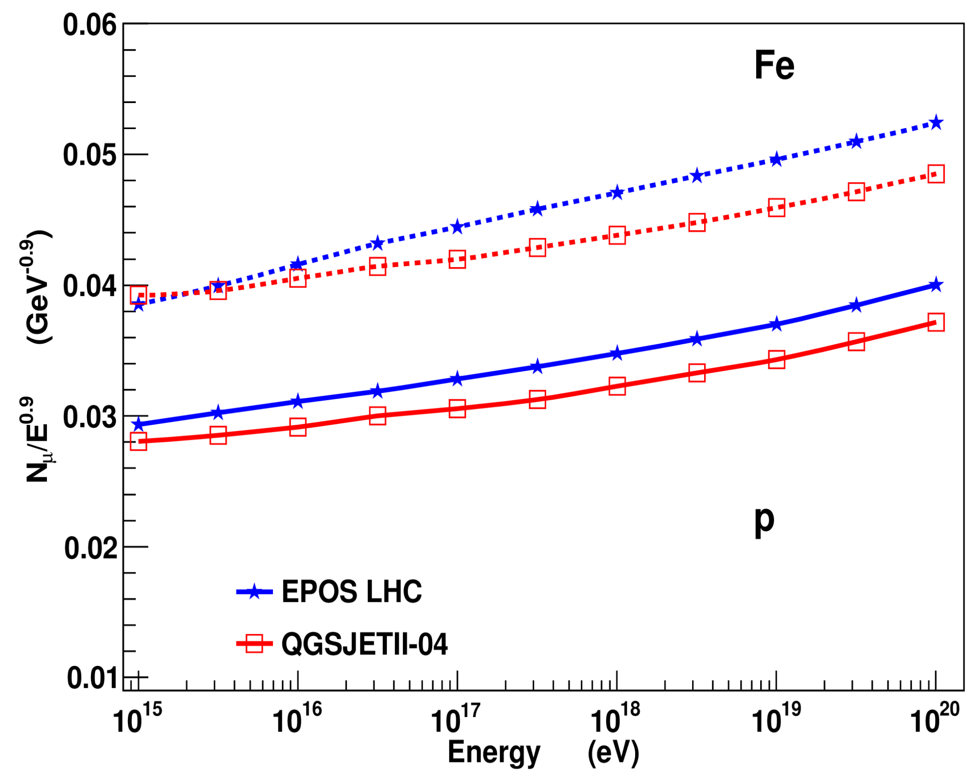




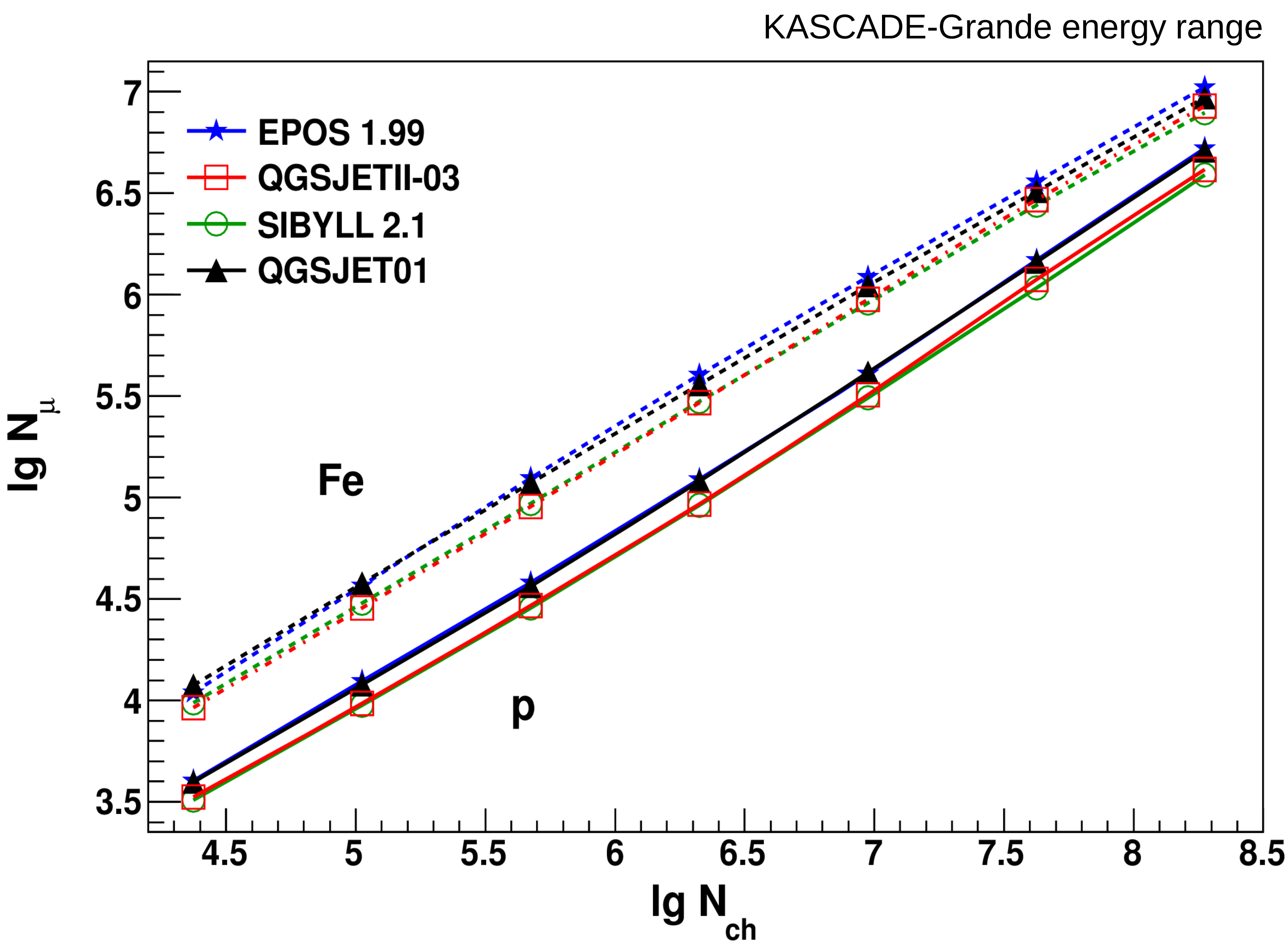
EAS with Re-tuned CR Models : Muons

- **Effect of LHC hidden by other changes**
  - Corrections at mid-rapidity only for EPOS
  - Changes in QGSJETII motivated by pion induced data
  - EPOS LHC ~ EPOS 1.99 and only -7% for QGSJETII-04





EAS with Re-tuned CR Models : Correlations



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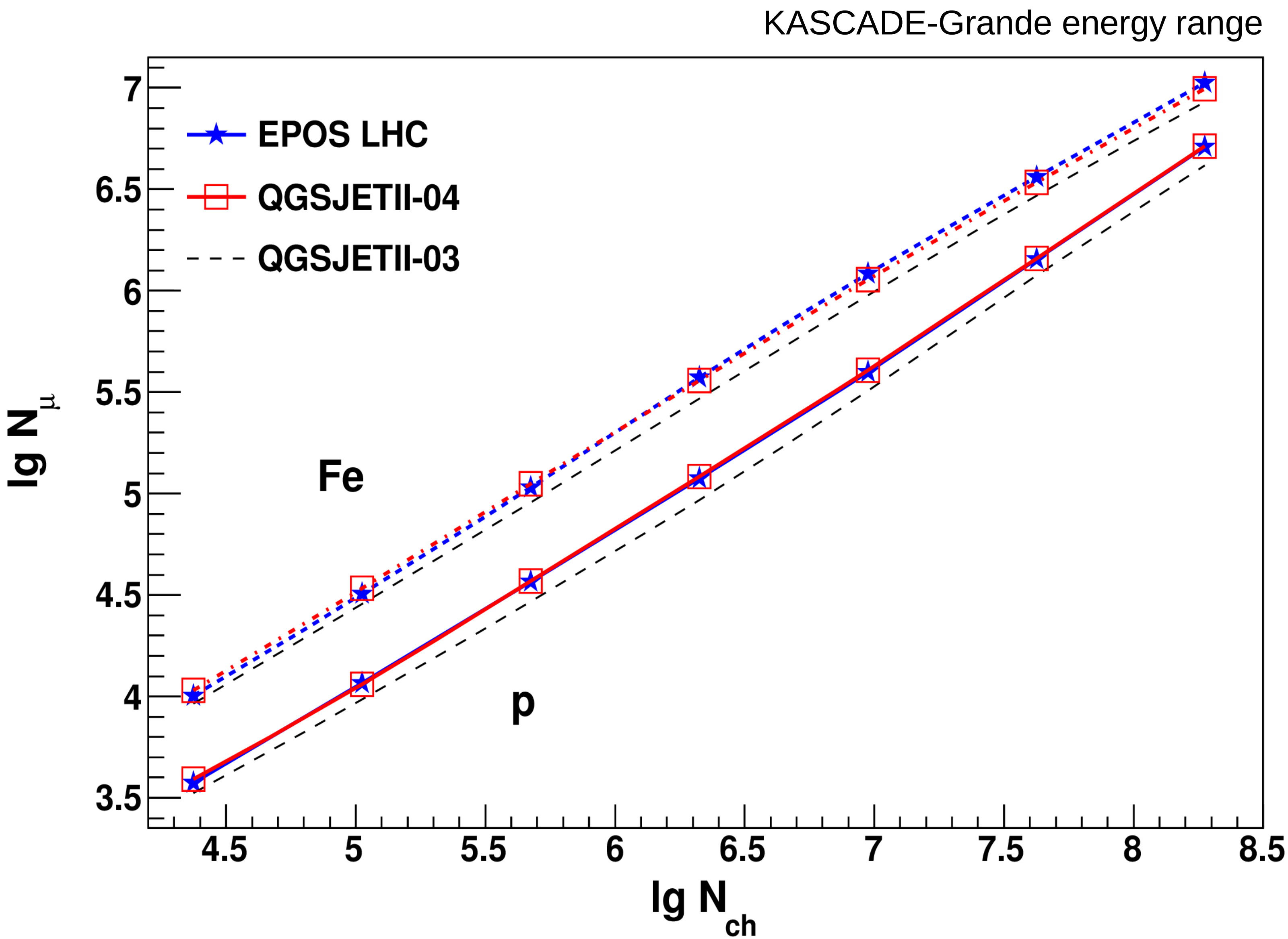
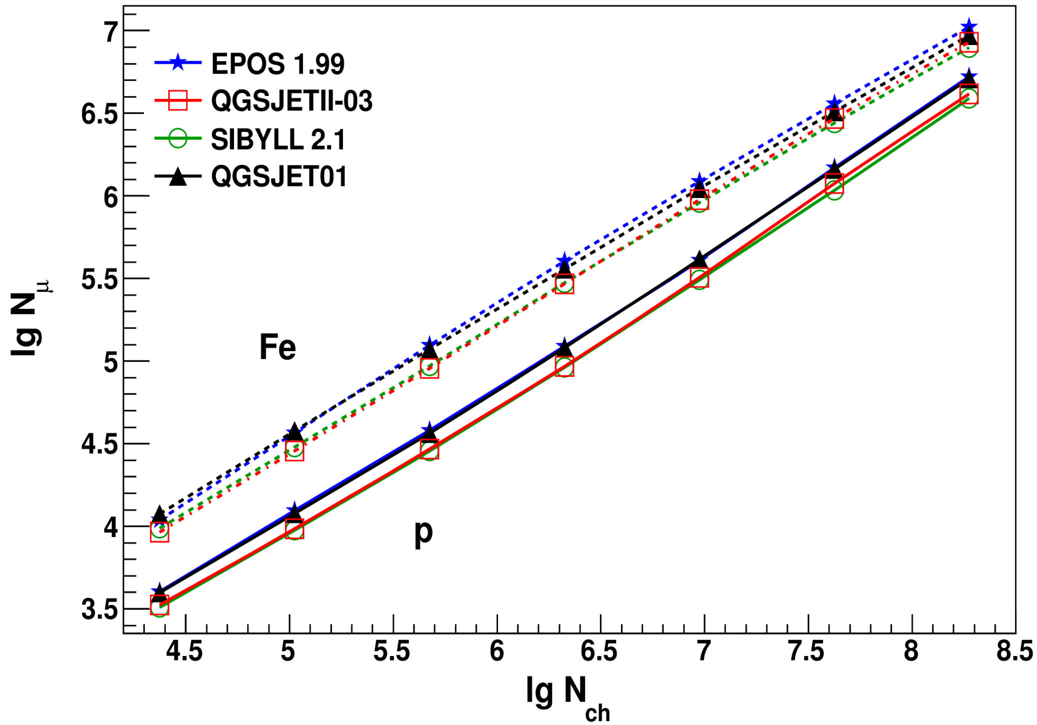
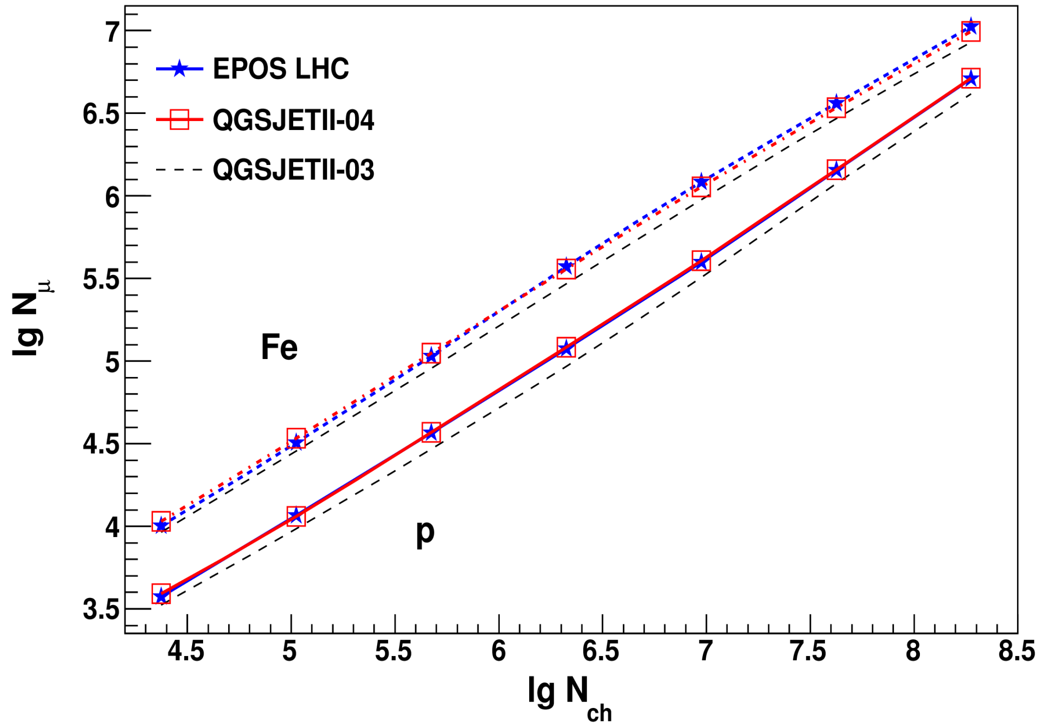


EAS with Re-tuned CR Models : Correlations

- **QGSJETII-04 and EPOS LHC similar to EPOS 1.99**
  - ➡ More muons AND more electrons with EPOS LHC compared to QGSJETII-04
  - ➡ More muons and less electrons with QGSJETII-04 compared to QGSJETII-03
  - ➡ Same correlations with EPOS LHC and QGSJETII-04
  - ➡ Lighter composition compared to QGSJETII-03

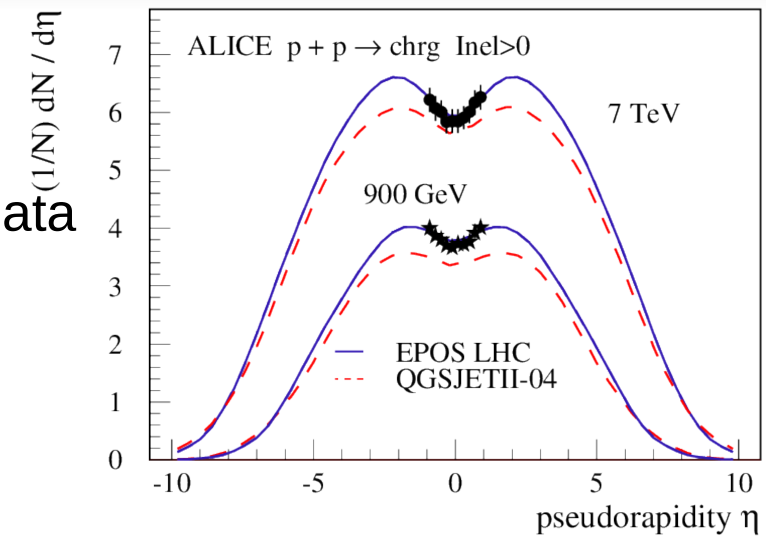
KASCADE-Grande energy range

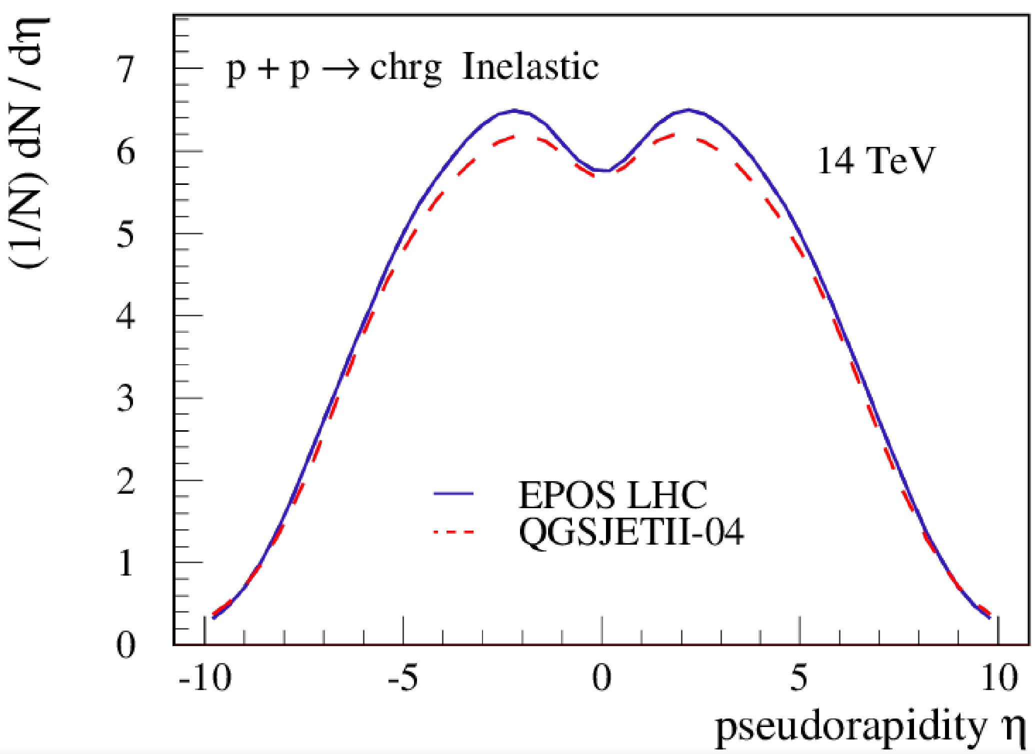


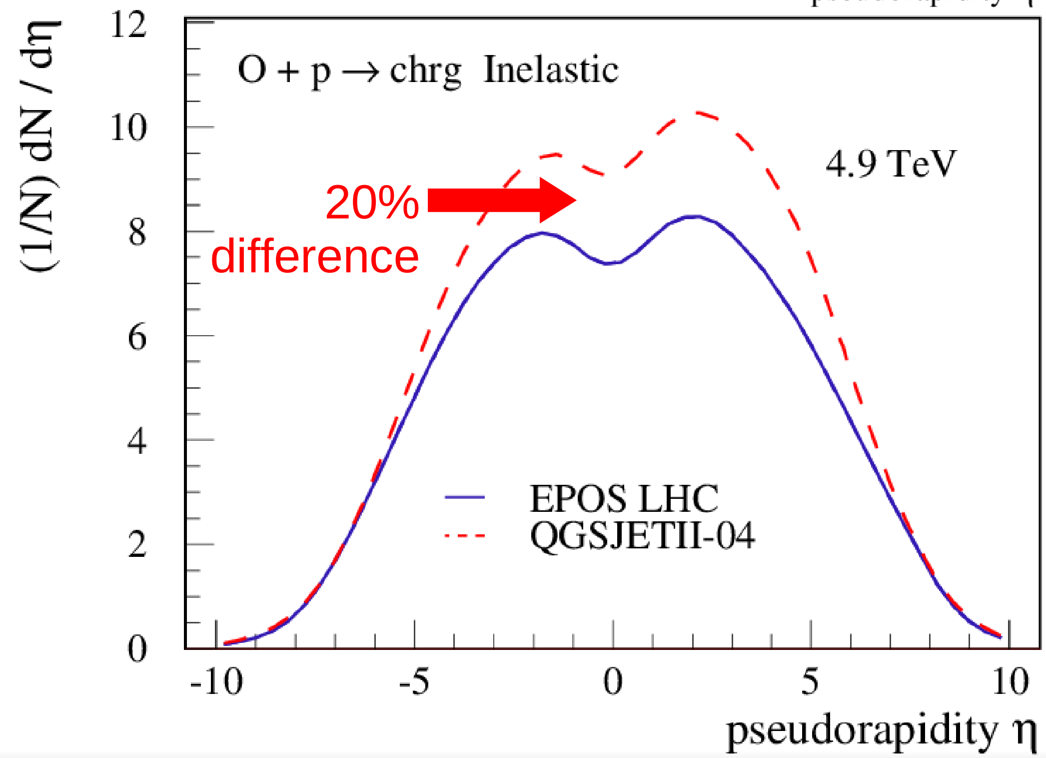


Interactions in Air Shower : p-Air

- **Source of uncertainties : extrapolation**
  - to higher energies
    - strong constraints by current and future LHC data
  - from p-p to p-Air
    - current main source of uncertainty
- **Request new LHC data : p-O**







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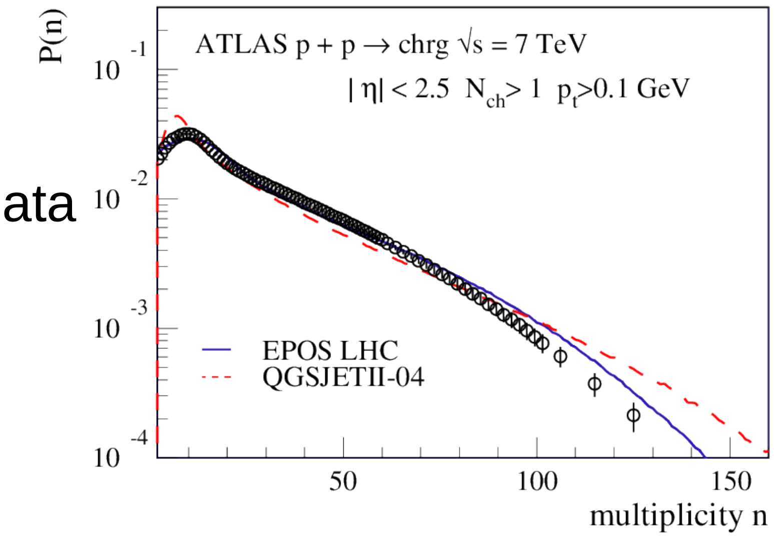
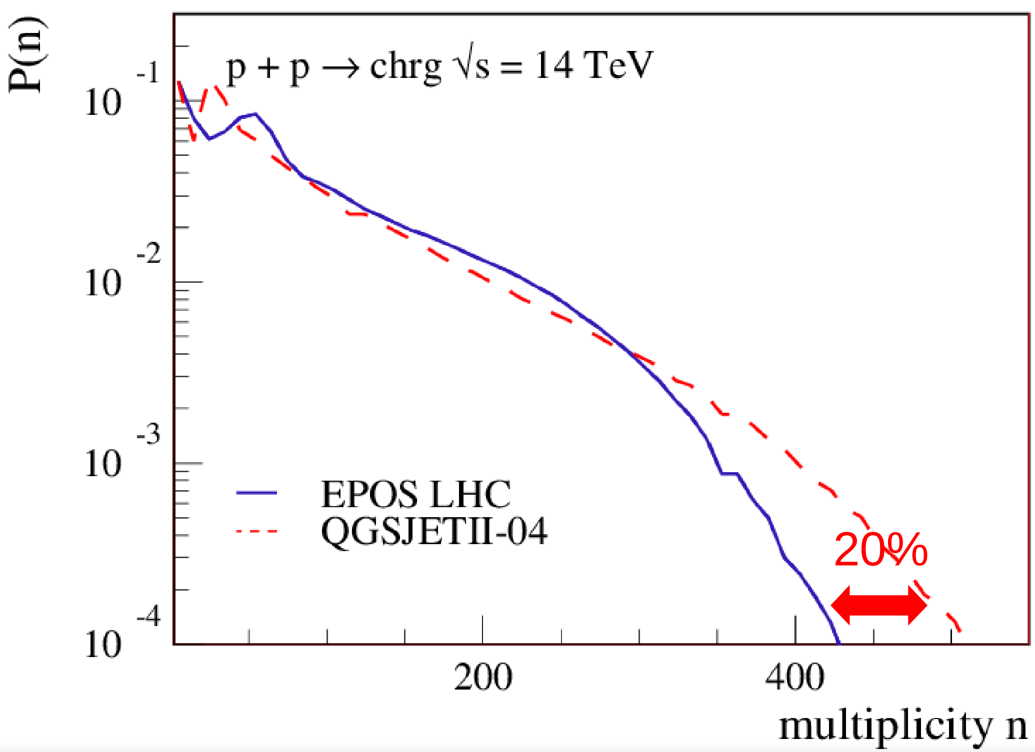
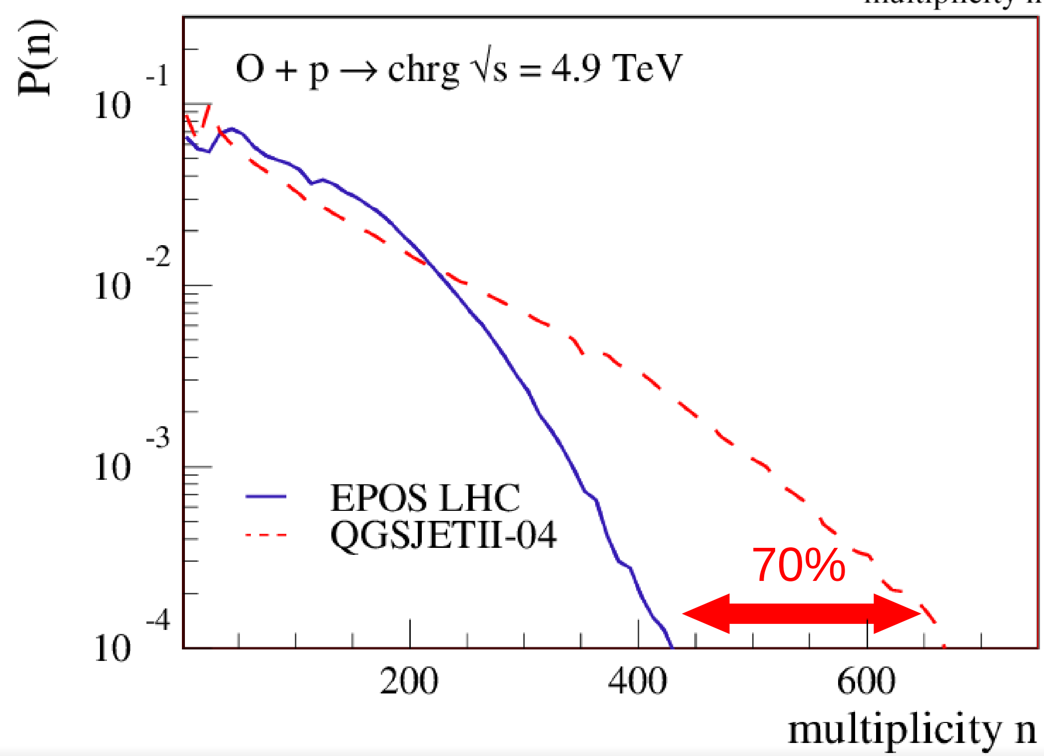
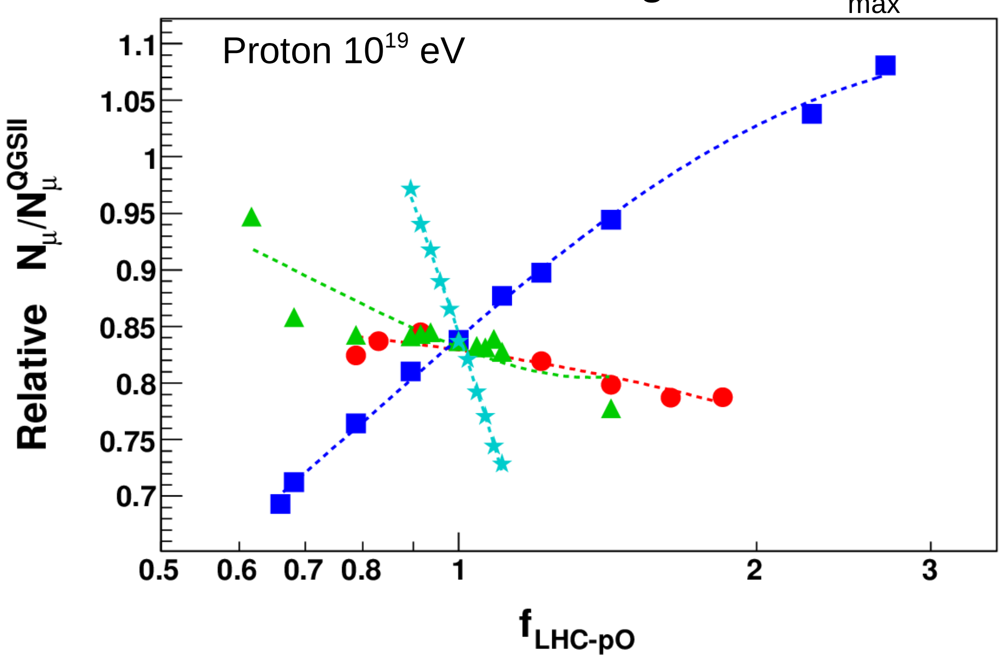


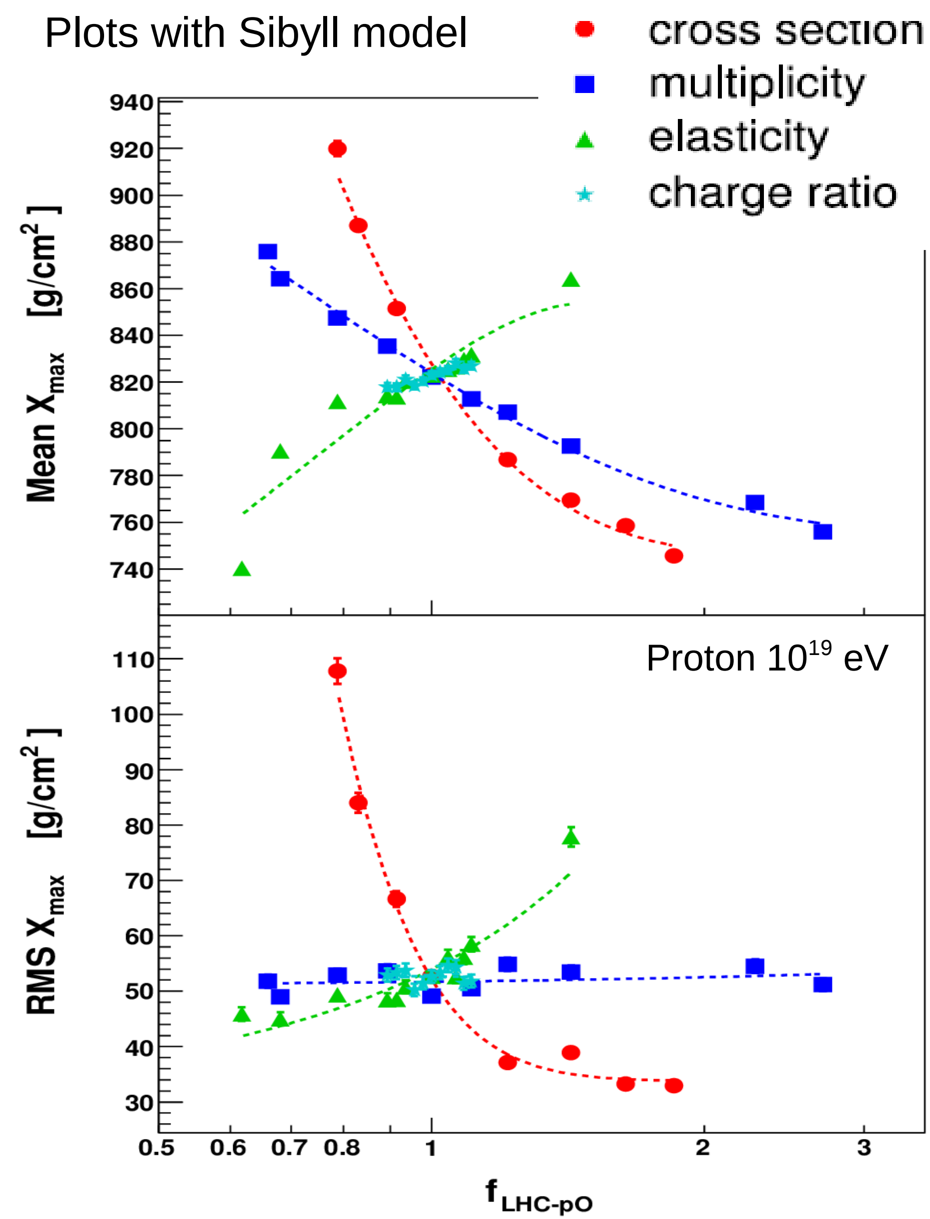




Effects of Parameters

- **Sensibility depends on observable and parameter :**
  - effect of uncertainties at LHC on air shower observables
    - $f_{LHC\text{-}pO}$ = modification factor@LHC
  - 20% difference in multiplicity is about
    - 10% muons
    - 20 gr/cm^2 <X_{max}>





Hadronic Interaction Models in CORSIKA

(HDPM)

Old generation : SIBYLL 2.1 (QGSJET01 DPMJET 2.55 VENUS) (<1999)

All Glauber based

But differences in hard, remnants, diffraction …

semi-hard

soft

NEXUS 3.97

Attempt to get everything described in a consistent way (energy sharing)

New generation : (QGSJET II-03)(DPMJET III) (EPOS 1.99) (2005-2012)

LHC tuned : QGSJET II-04 EPOS LHC (2013-)

LHC inspired : SIBYLL 3 QGSJET III EPOS 3 (2015-)

Motivation :

- update with latest LHC results in simple model

Motivation :

- Hard Pomeron-Pomeron connexion

Motivation :

- binary scaling in hard probes
- heavy flavors

Summary

- **Air Shower simulations**
  - ➔ new solutions for fast simulations
    - Parallel calculation : 1 event = 1 simulation no particle weight
    - CONEX calculation : faster and more stable than thinning : large statistic
    - Project to use GPU ...
  - ➔ New option to track Gamma ray sources

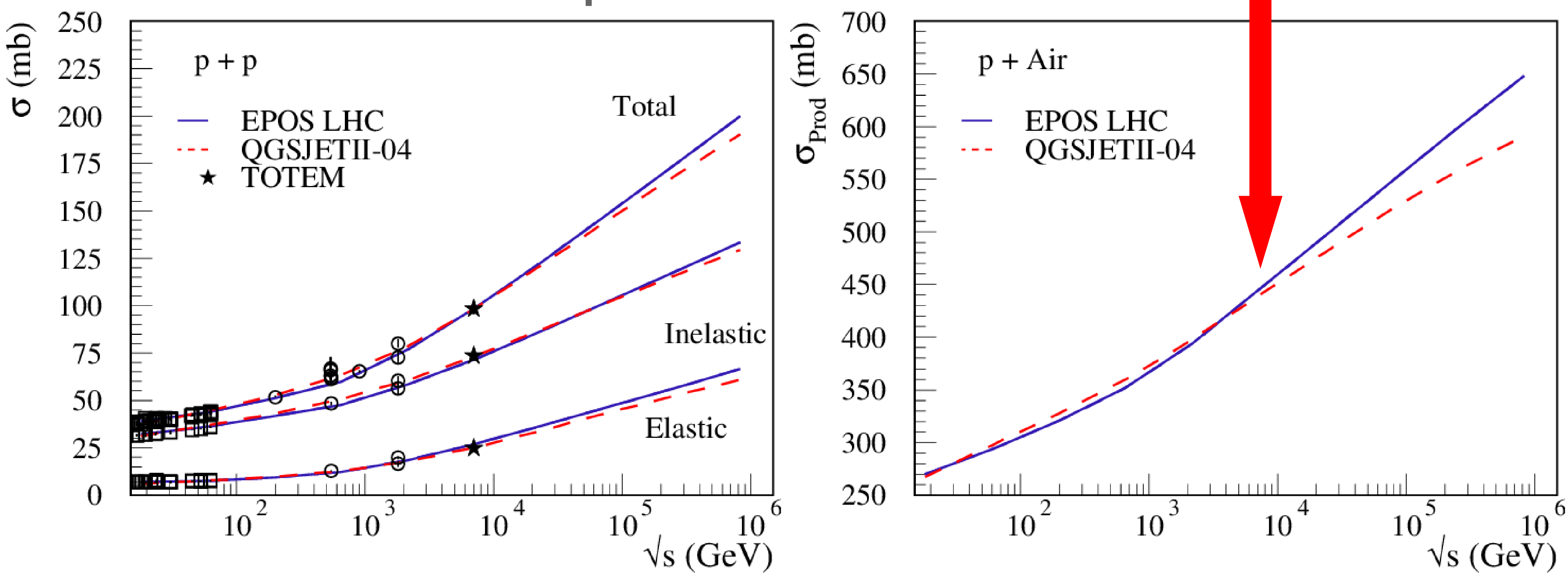
- **Hadronic interactions (LHC and NA61) :**
  - ➔ already strong constrains on energy evolution of particle production and cross-section
  - ➔ more constrain if new beam is used : proton-Oxygen would be a perfect test for hadronic interaction models
  - ➔ results converge between models both air shower observable like X_{max} and number of muons at ground (differences reduced by a factor of 2)
  - ➔ model under development (hard processes, heavy flavors)

Interactions in Air Shower : p-Air

- **Source of uncertainties : extrapolation**
  - ➡ to higher energies
    - strong constraints by current LHC data
  - ➡ from p-p to p-Air
    - current main source of uncertainty
- **Needs for new data : p-O**

Compare p-p@14TeV and p-O@4.9TeV
(same beam energy than p-p@7TeV)

No big difference @ LHC but larger uncertainty in extrapolation



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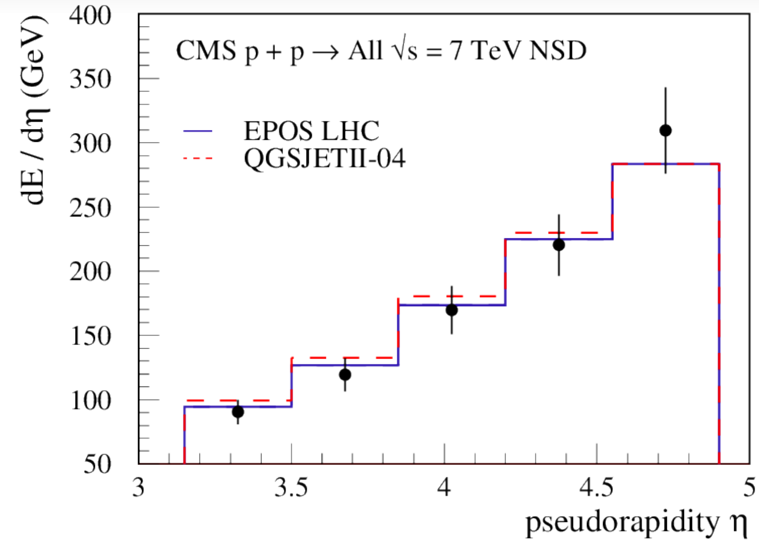

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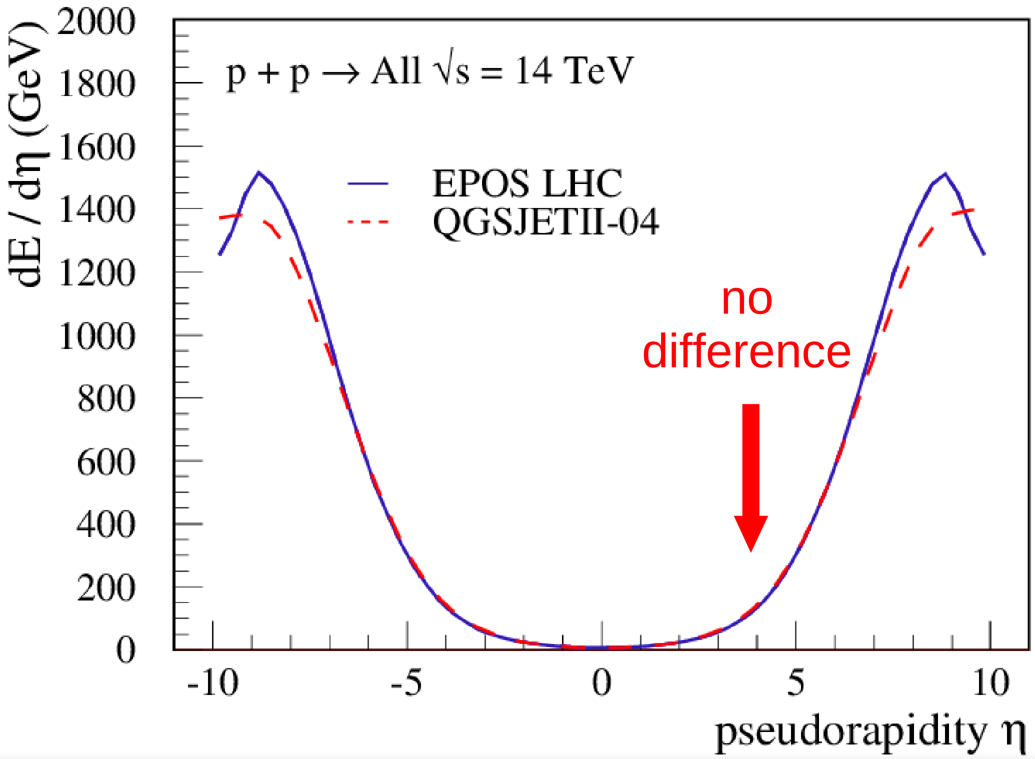
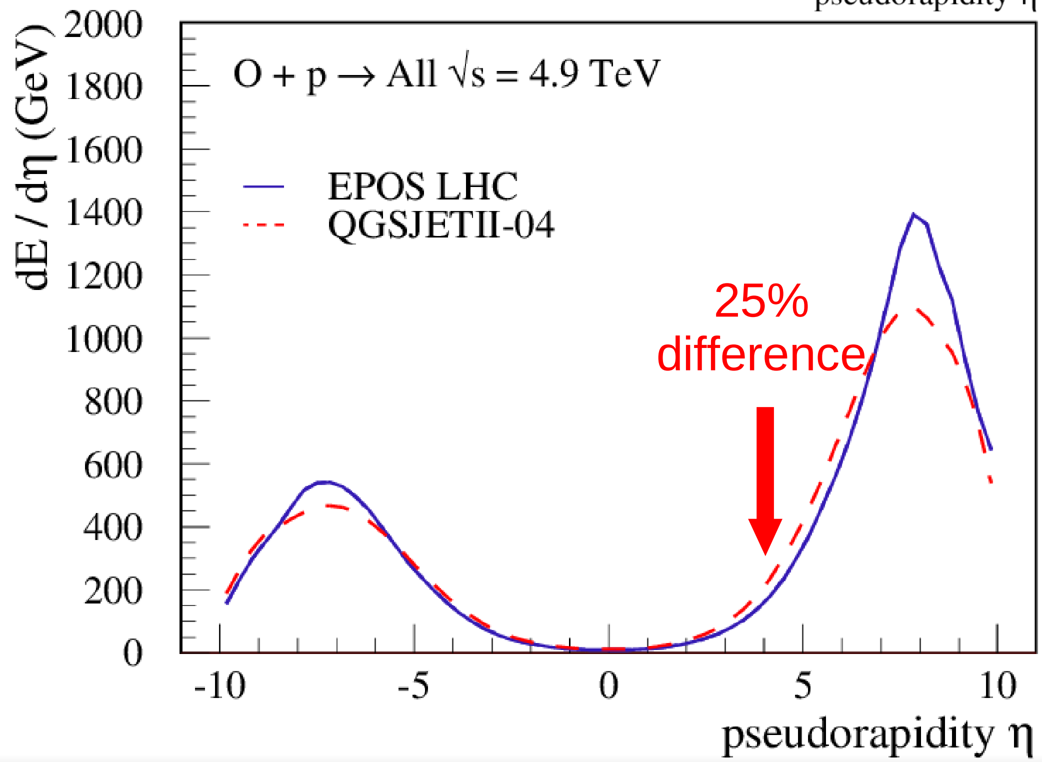
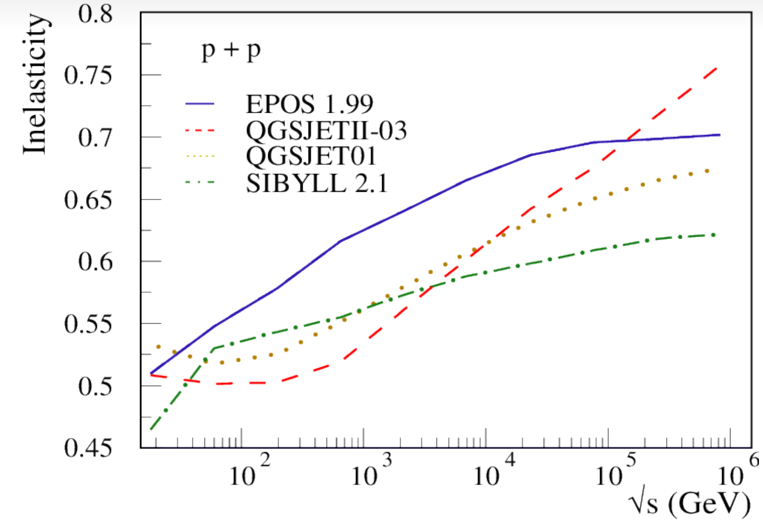
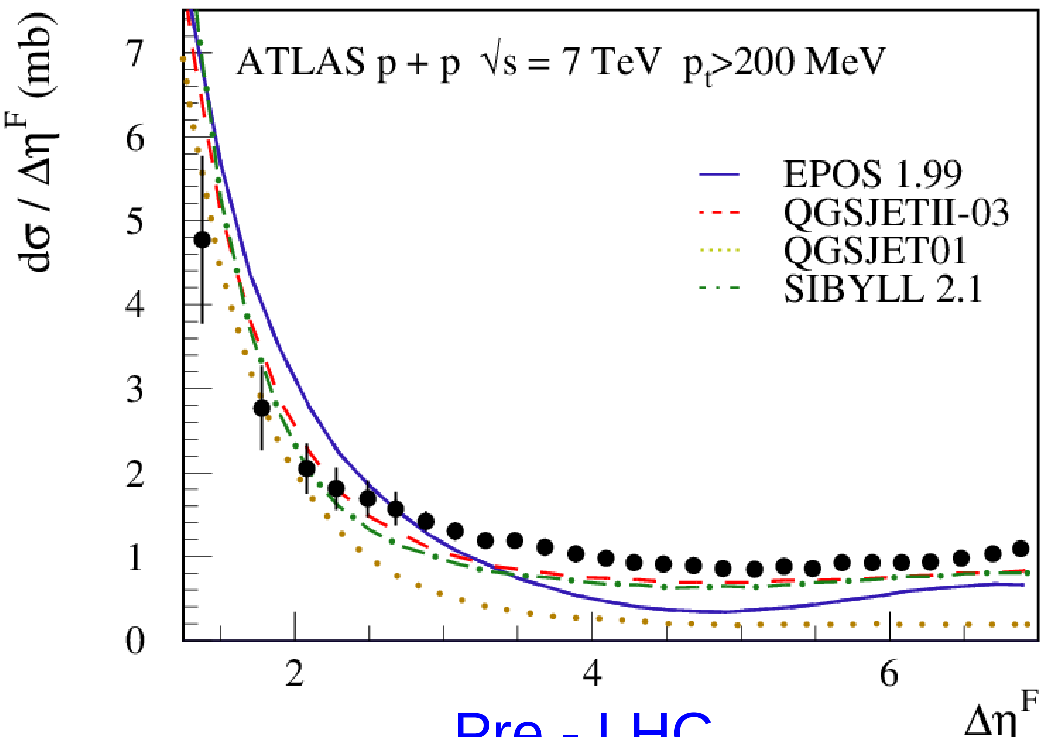




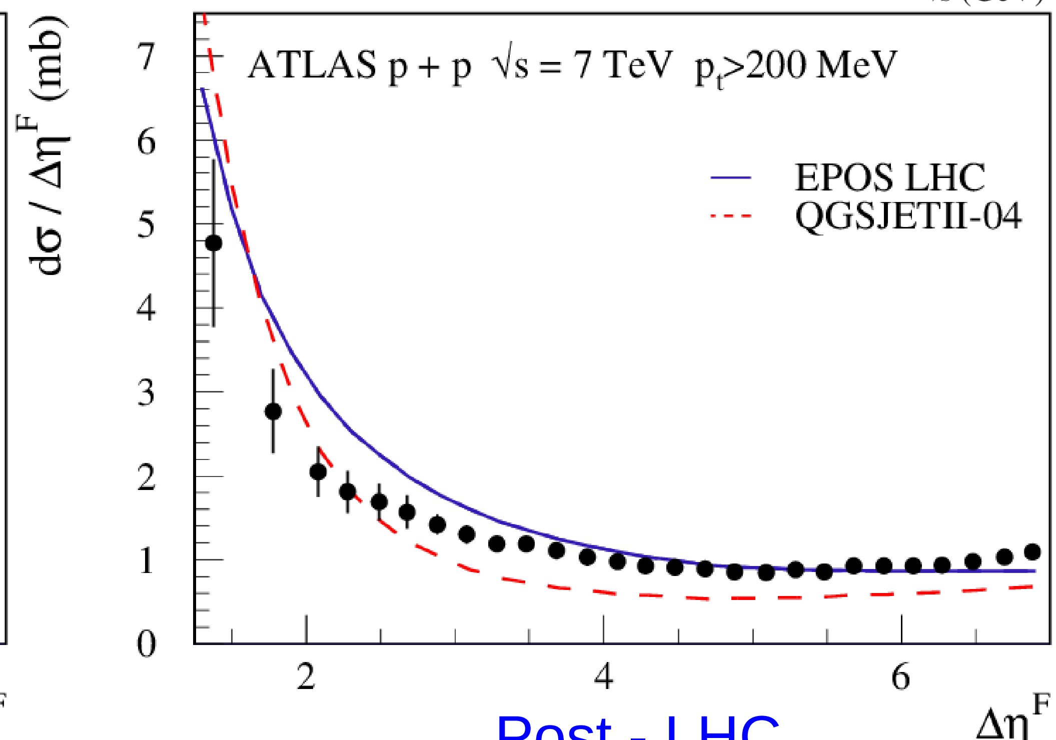
Inelasticity

- Difficult to measure : larger uncertainty
  - ➔ Difference in diffraction
    - low mass / high mass / central diffraction



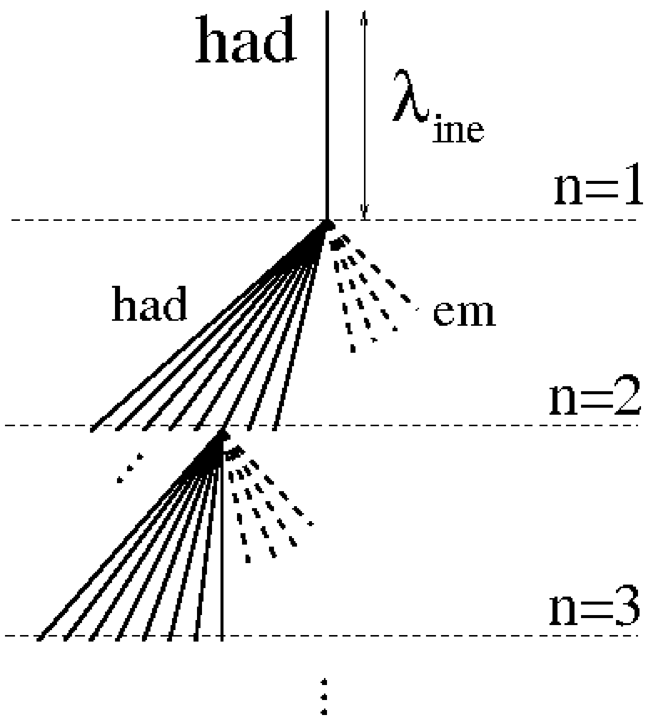


Pre - LHC



Post - LHC

Simplified Shower Development



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

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

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

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

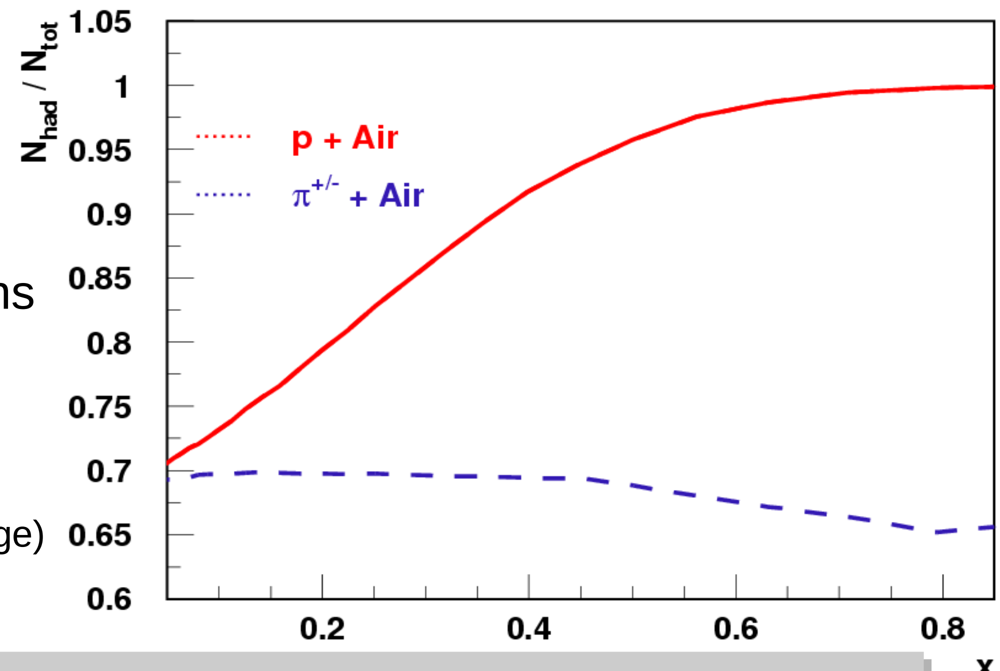
- Model independent parameters :
  - E_0 = primary energy
  - A = primary mass
  - λ_e = electromagnetic mean free path
- Model dependent parameters :
  - k = elasticity
  - N_{tot} = total multiplicity
  - λ_{ine} = hadronic mean free path (cross section)

Muon Number

- **From Heitler**

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

- 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

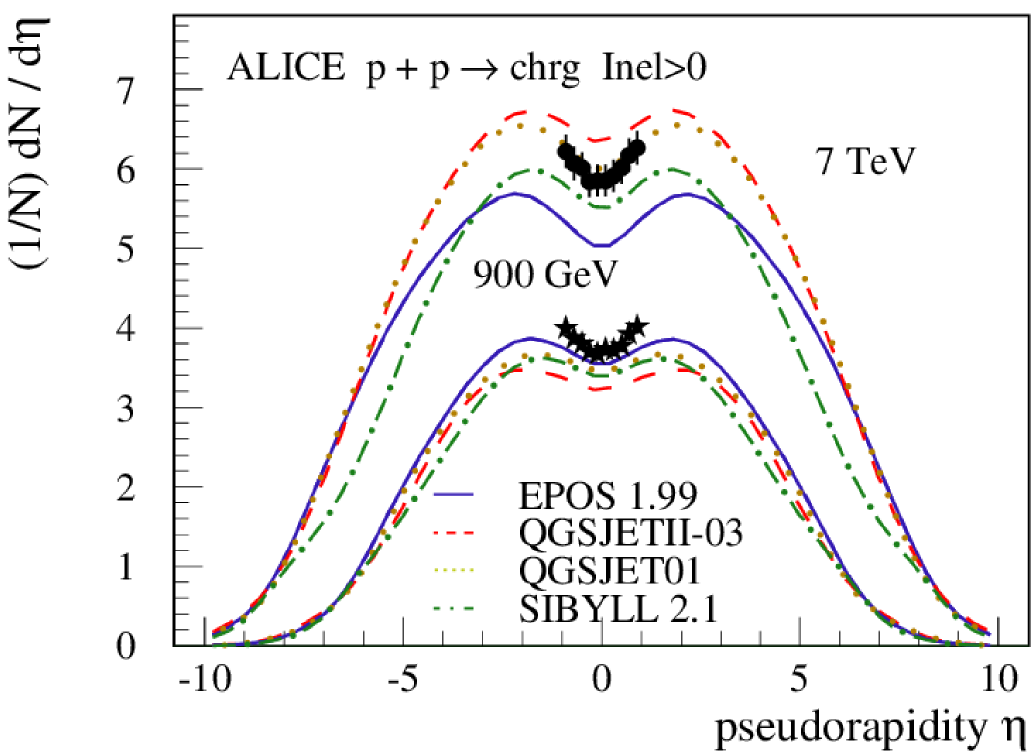
More fast (anti)baryons = more muons

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

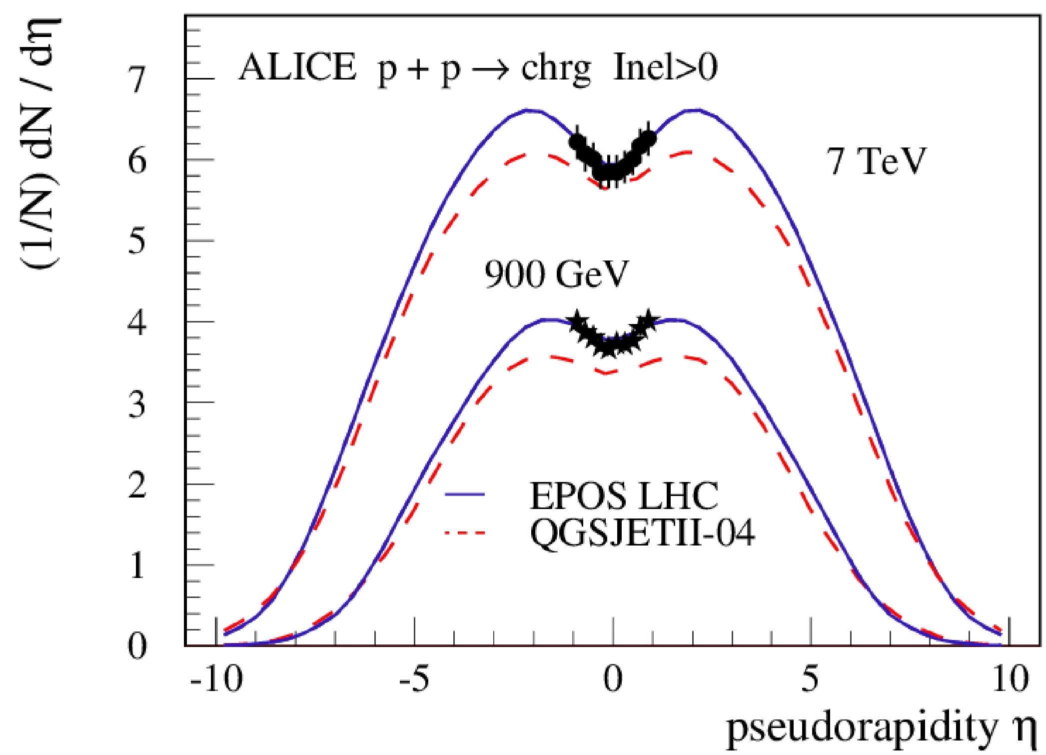
Multiplicity

- **Consistent results**
  - Better mean after corrections
    - difference remains in shape

Pre - LHC

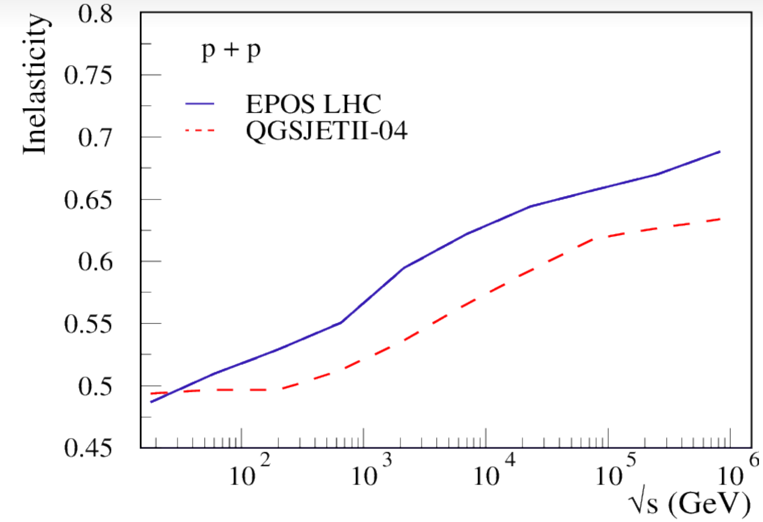


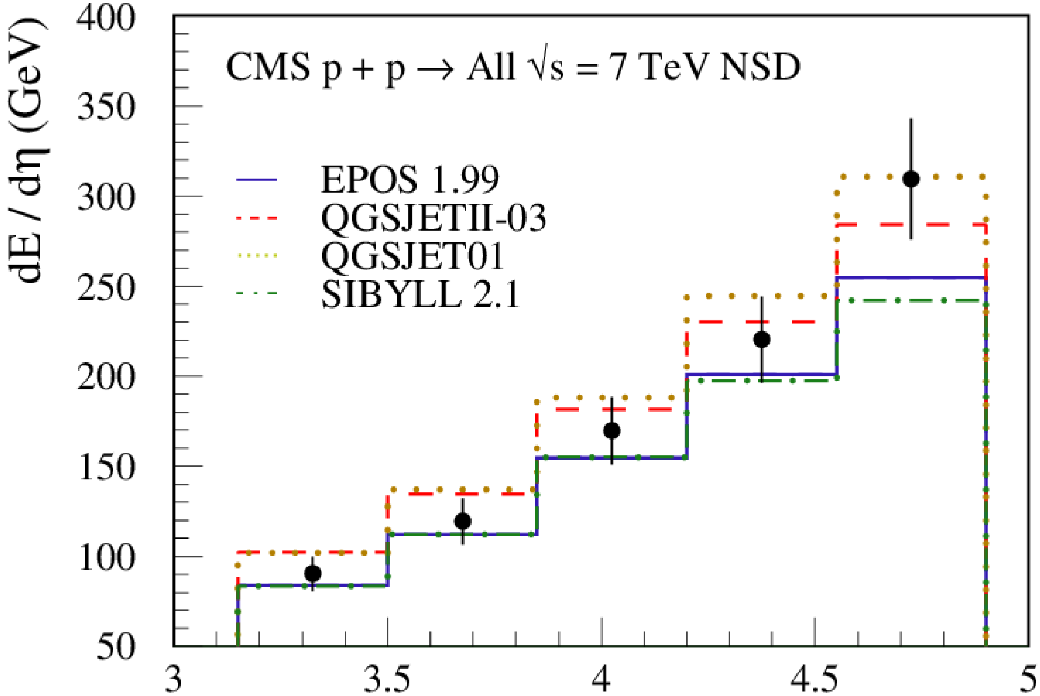
Post - LHC



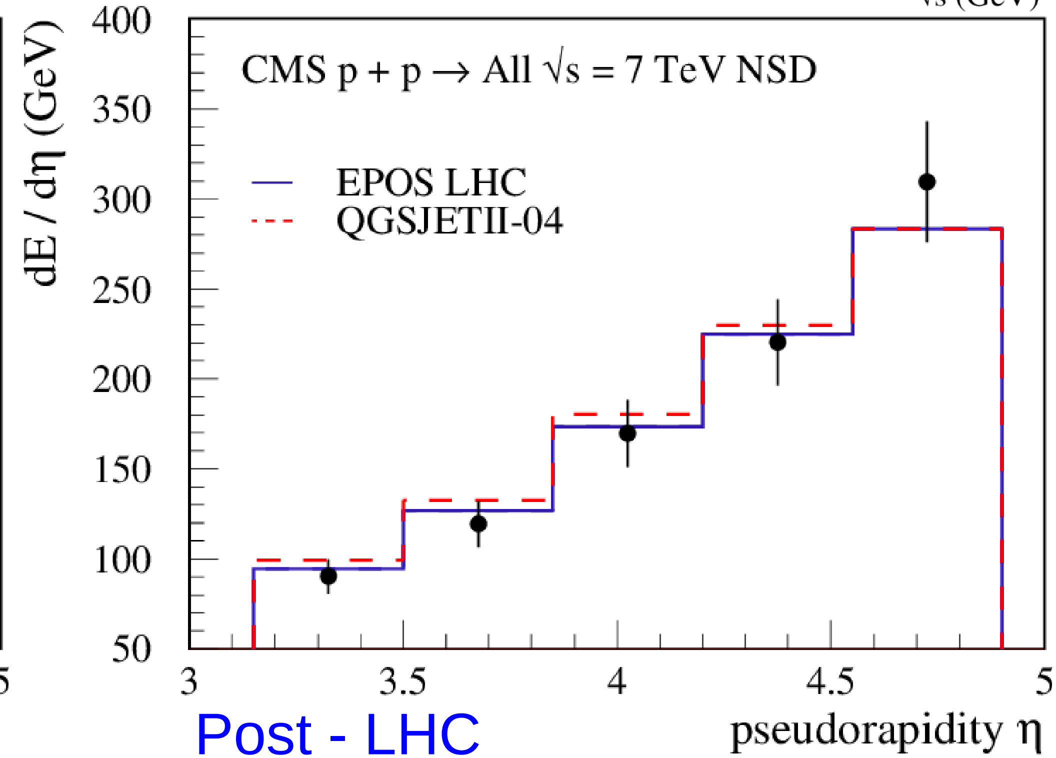
Inelasticity

- Difficult to measure : larger uncertainty
  - Difference in diffraction
    - low mass / high mass / central diffraction
  - very similar energy flow





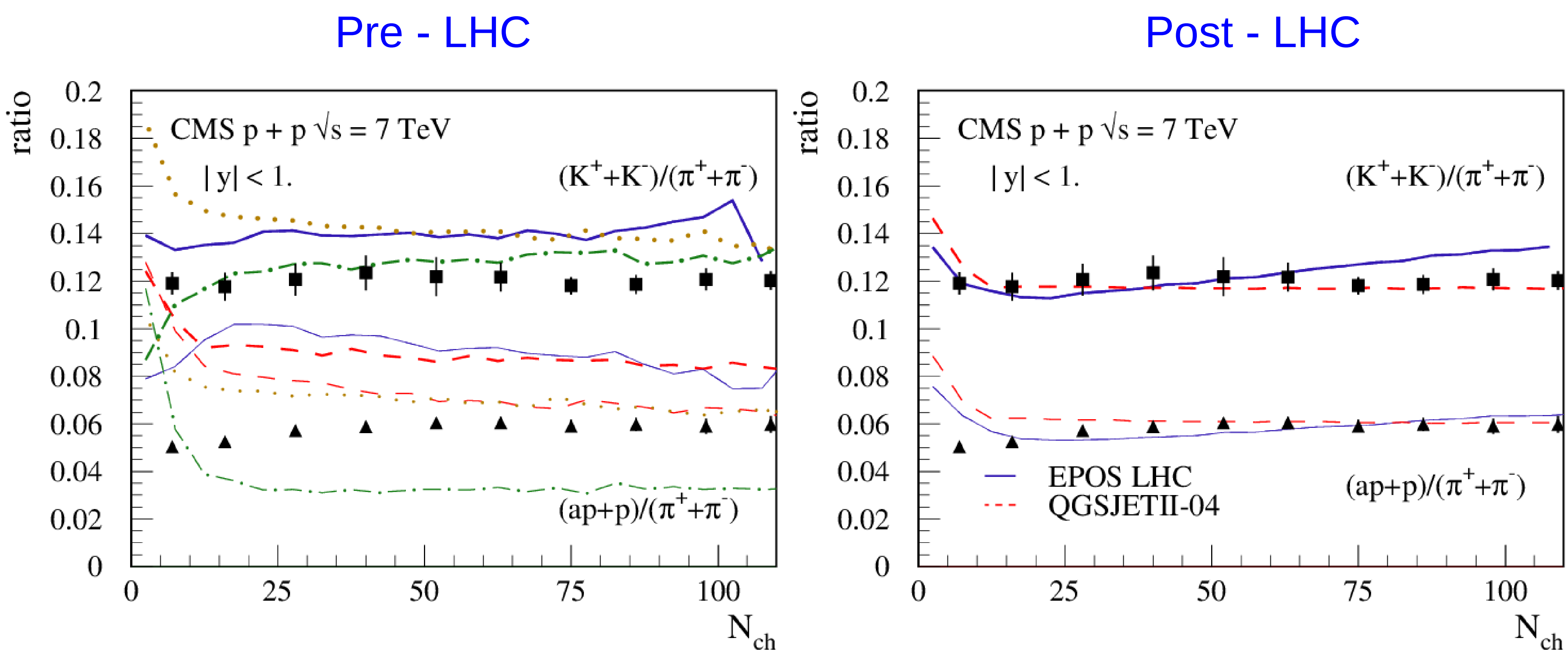
Pre - LHC



Post - LHC

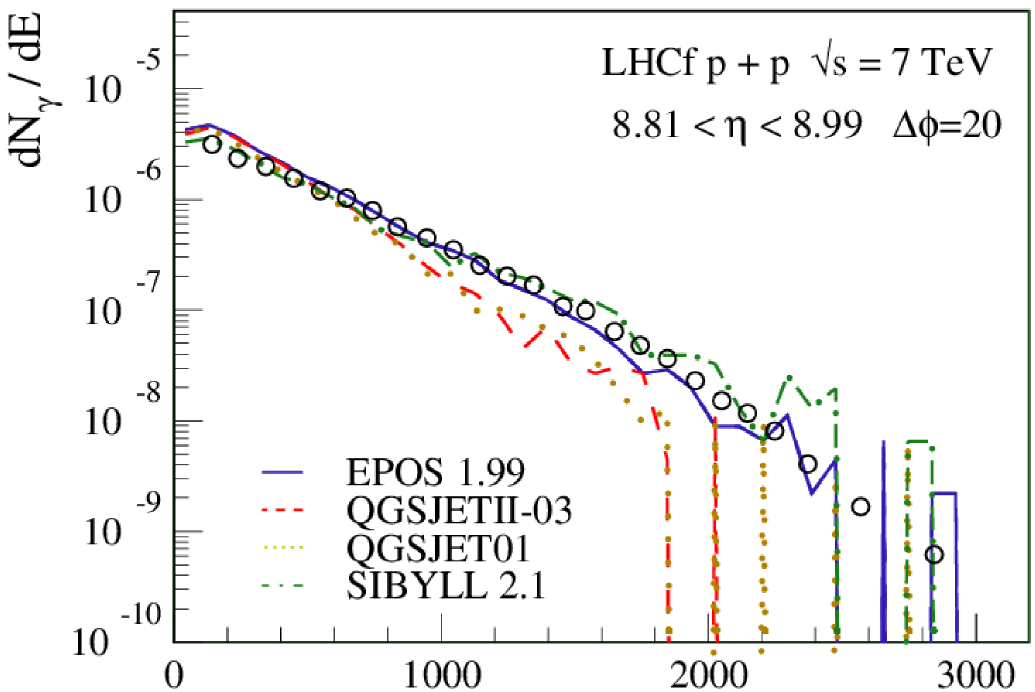
Identified particles

- **Large improvement at mid-rapidity**
  - very similar results for particle ratios
  - overestimation of baryon production before due to wrong interpretation of Tevatron data

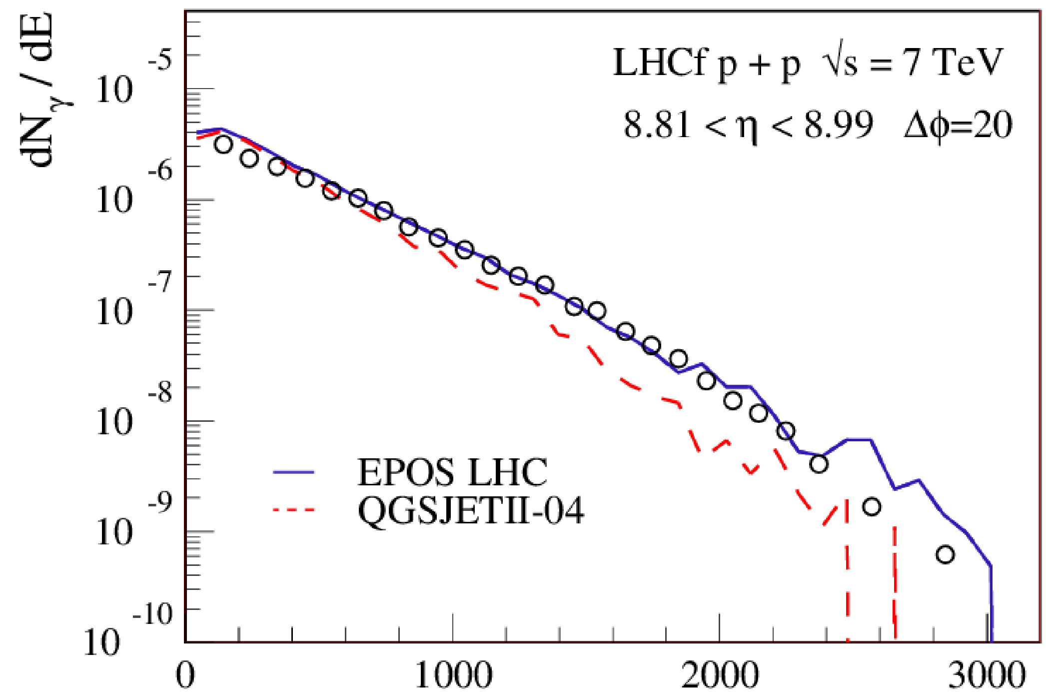


Identified particles

- **Large improvement at mid-rapidity**
  - very similar results for particle ratios
  - overestimation of baryon production before due to wrong interpretation of Tevatron data
- **Only small changes very forward**
  - no try to tune LHCf data yet (difficult)

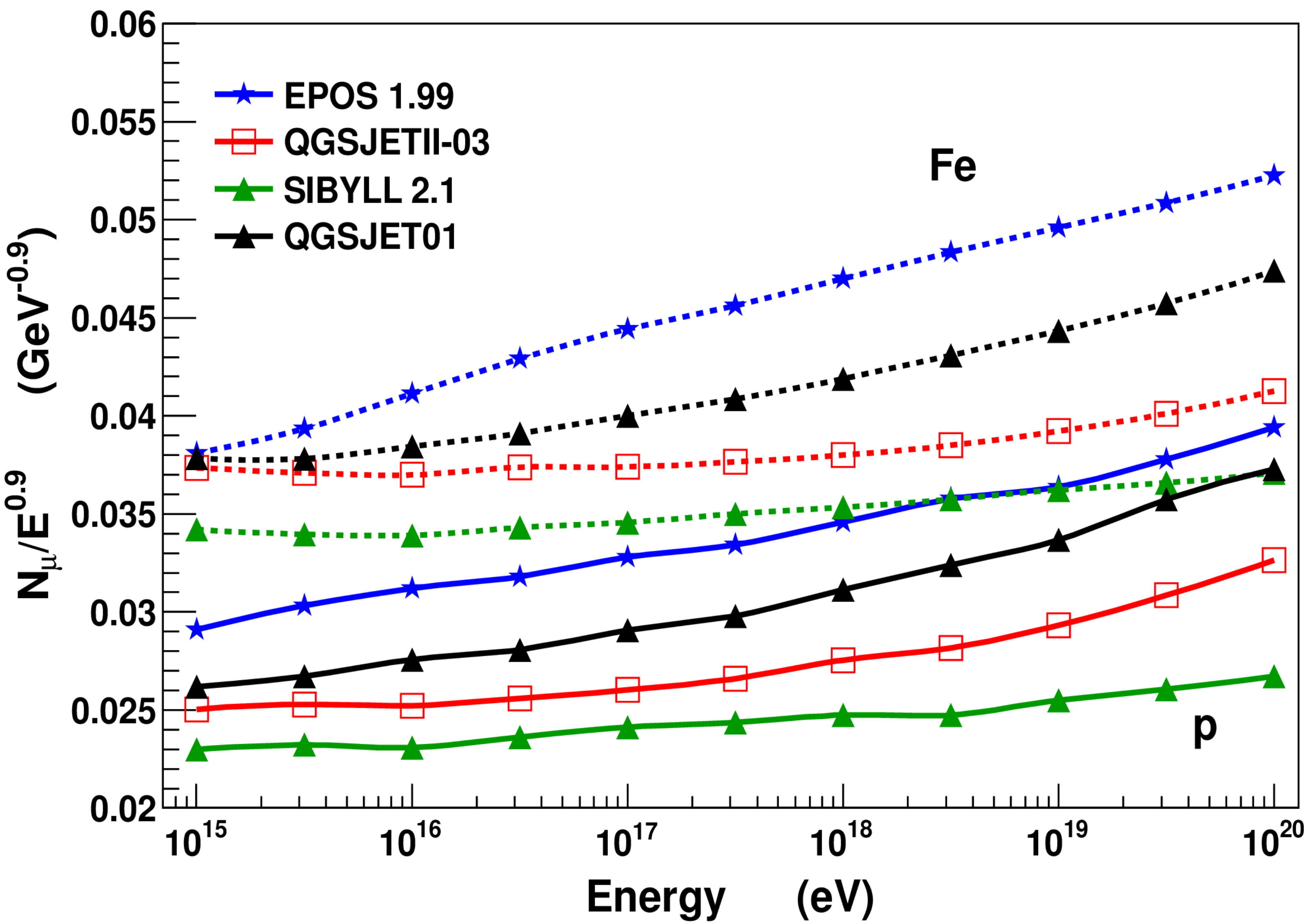


Pre - LHC

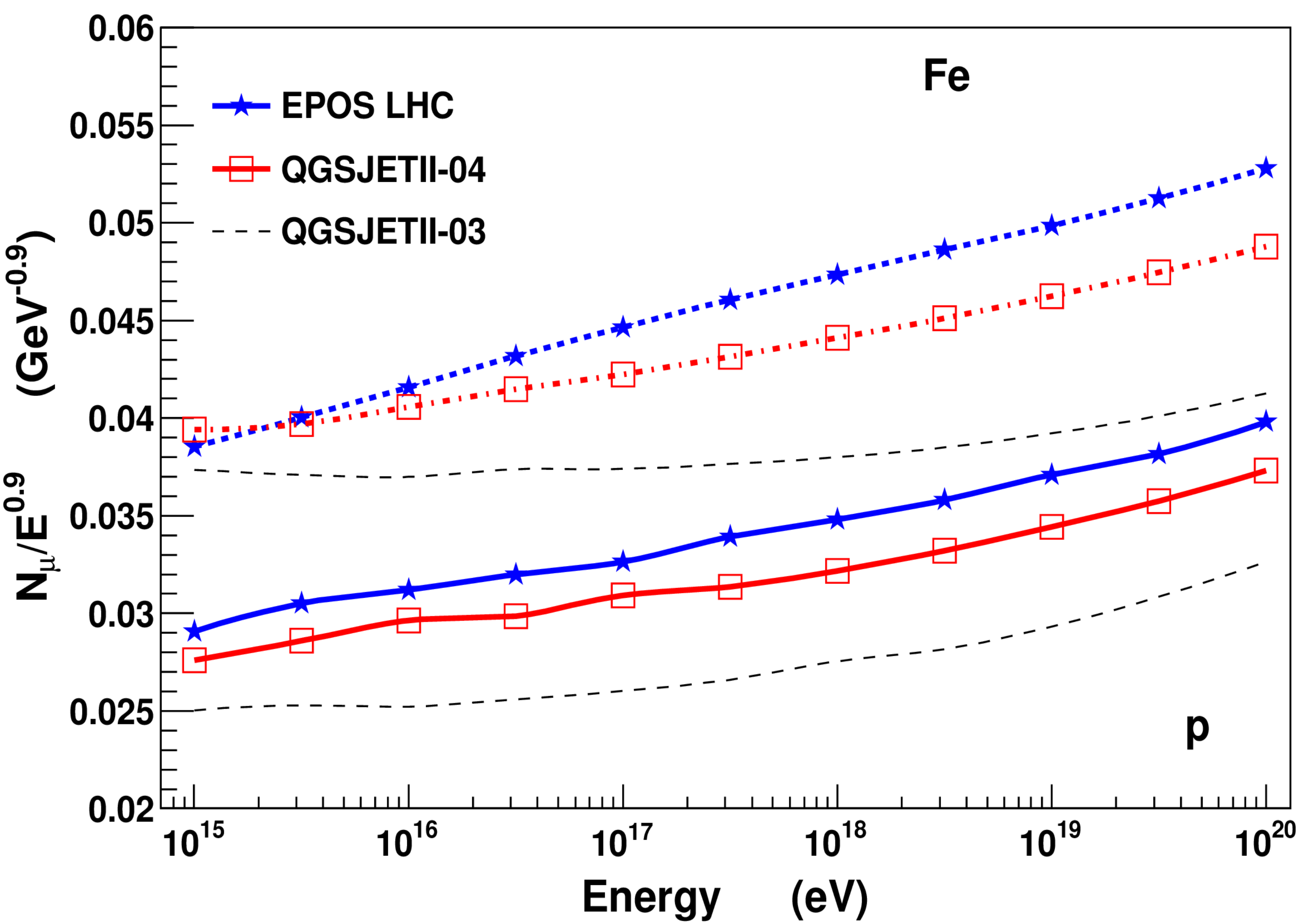


Post - LHC

EAS with Re-tuned CR Models : Muons



EAS with Re-tuned CR Models : Muons



Cosmic Ray Hadronic Interaction Models

- **Theoretical basis :**
  - pQCD (large p_t)
  - Gribov-Regge (cross section with multiple scattering)
  - energy conservation

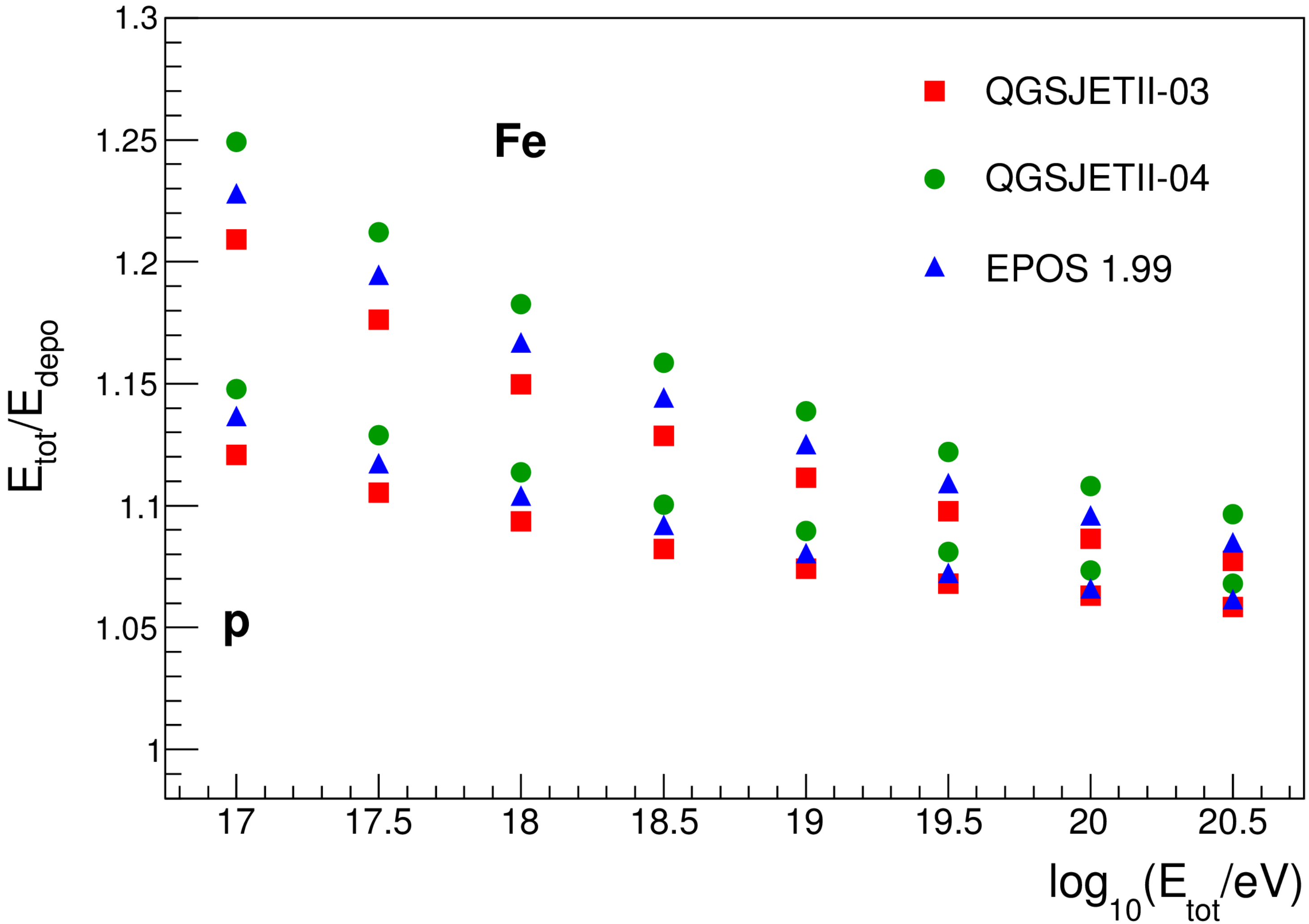
EPOS 1.99/LHC
QGSJet01/II-03/II-04
Sibyll 2.1

- **Phenomenology (models) :**
  - hadronization
    - string fragmentation — **EPOS modif. for LHC**
    - EPOS : high density effects (statistical hadronization and flow)
  - diffraction (Good-Walker, ...) — **QII and EPOS modif. for LHC**
  - higher order effects (multi-Pomeron interactions) — **QII modif. for LHC**
  - remnants
- **Comparison with data to fix parameters**

Better predictive power than HEP models thanks to link between total cross section and particle production (GRT) tested on a broad energy range (including EAS)

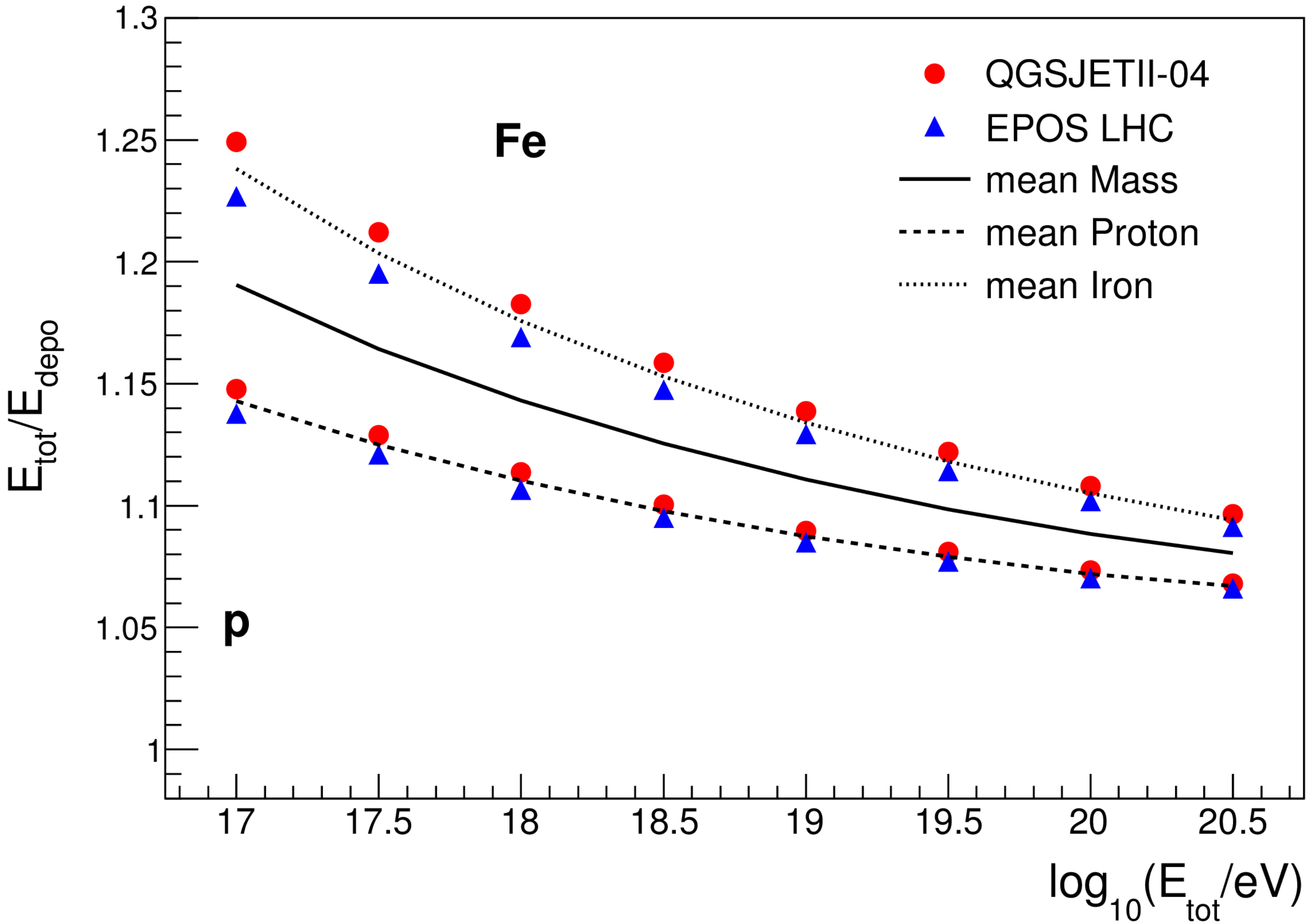
EAS Energy Deposit

- **Increase of muons in QII04**
  - ➔ larger correction factor from missing energy



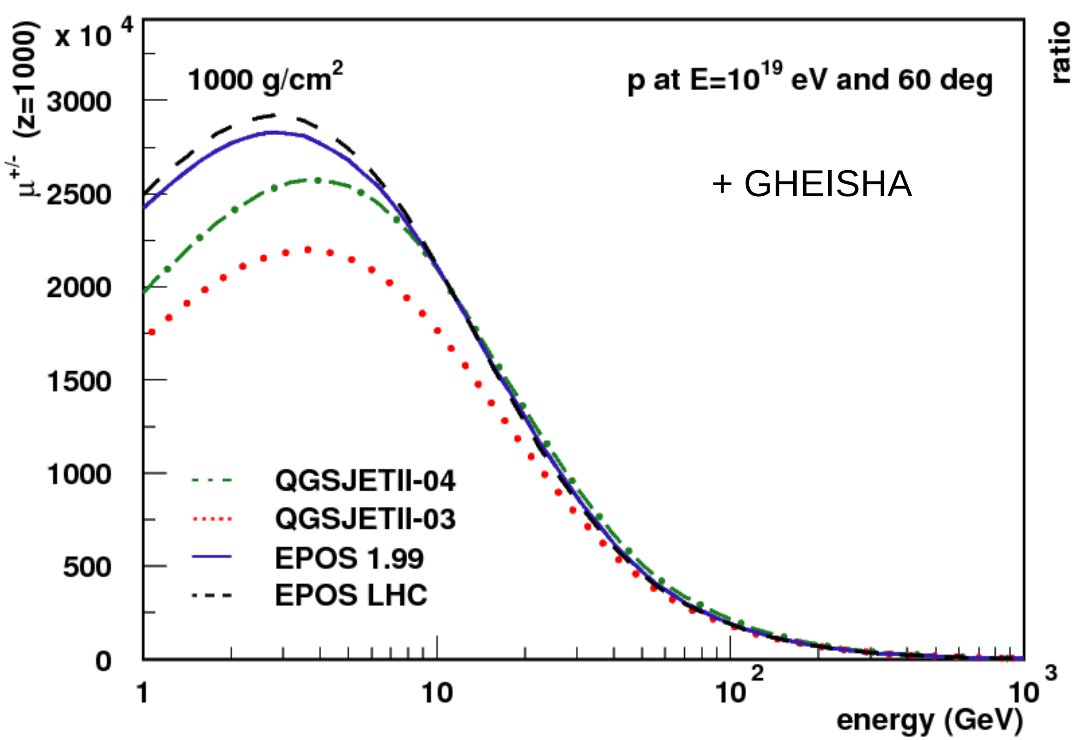
EAS Energy Deposit

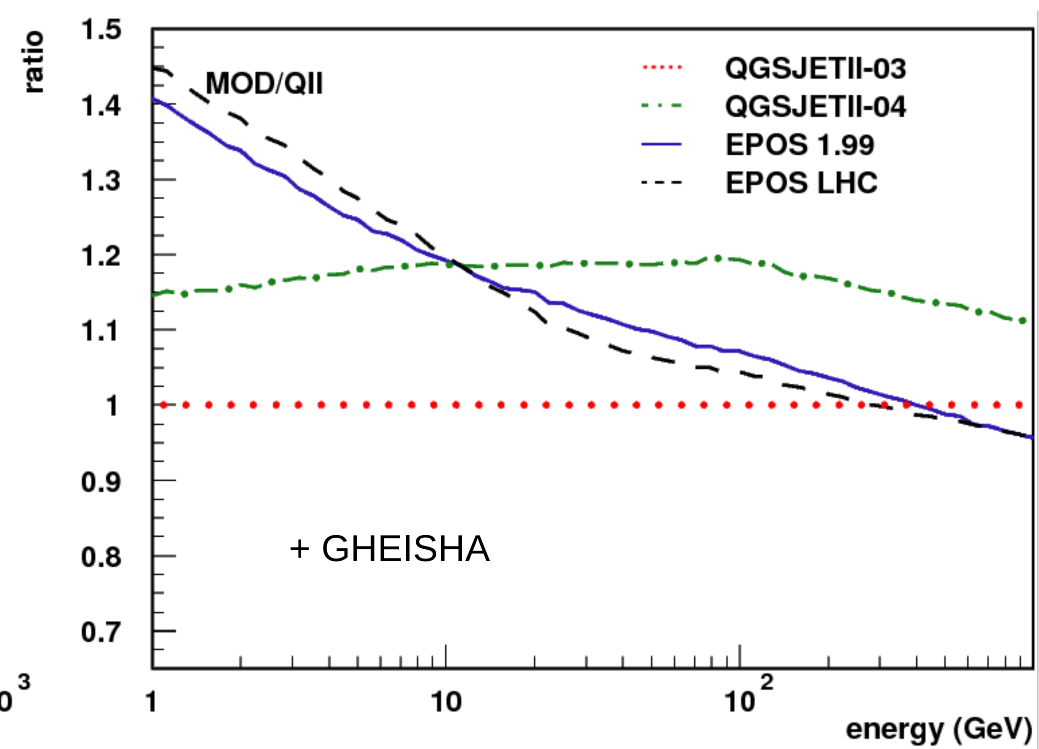
- **Increase of muons in QII04**
  - ➜ larger correction factor from missing energy



Muon Energy Spectra

- **Total number of muons in QGSJETII-04 (@60°) closer to EPOS BUT**
  - muons with different energy (hadronic energy stored in mesons or baryons ?)
  - different zenith angle dependence (attenuation length depends on muon energy spectrum)
  - effect of low energy hadronic interaction models (Gheisha, Fluka, UrQMD) ?
    - muon production dominated by last hadronic interaction(s) !





Counterexample : Muon Production Depth

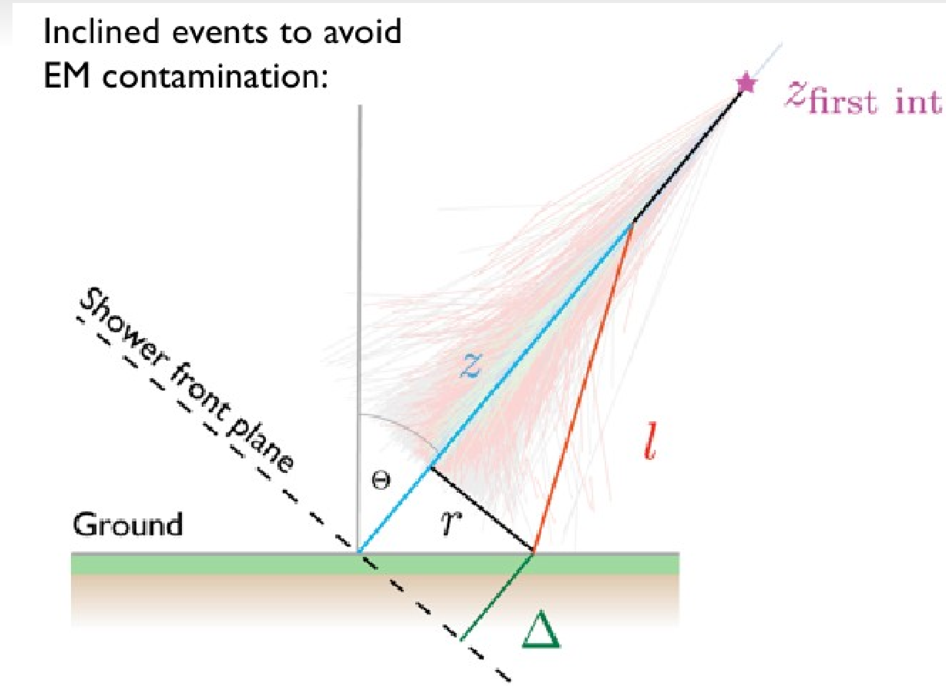
- **Independent SD mass composition measurement**
  - geometric delay of arriving muons

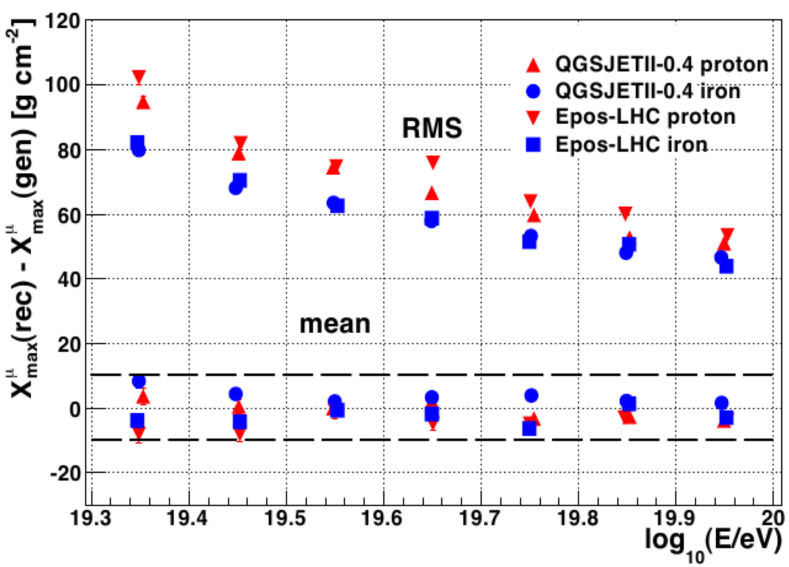
$$c \cdot t_{\mathrm{g}} = l - (z - \Delta) = \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

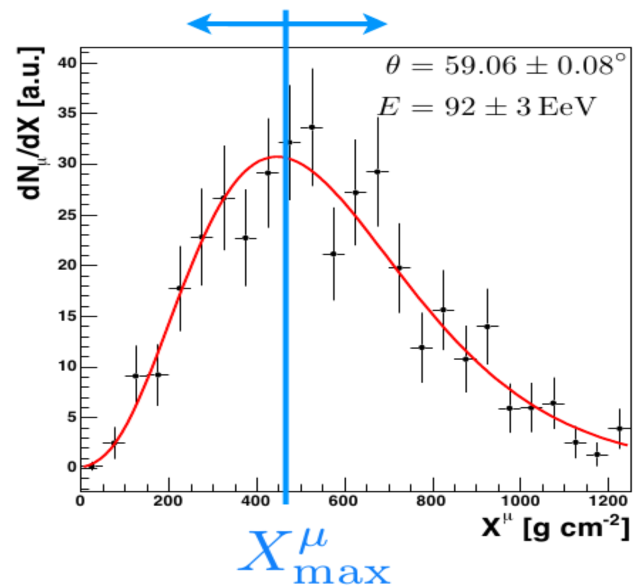
  - mapped to muon production distance

$$z = \frac{1}{2}\left(\frac{r^2}{ct_{\mathrm{g}}} - ct_{\mathrm{g}}\right) + \Delta$$

  - decent resolution and no bias

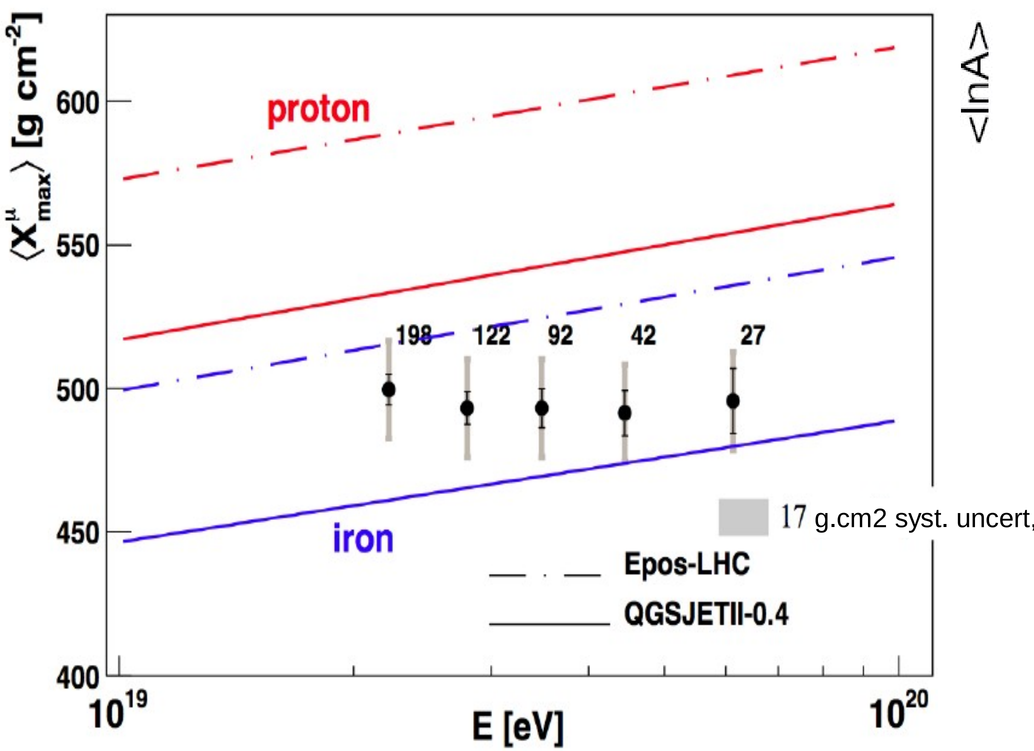


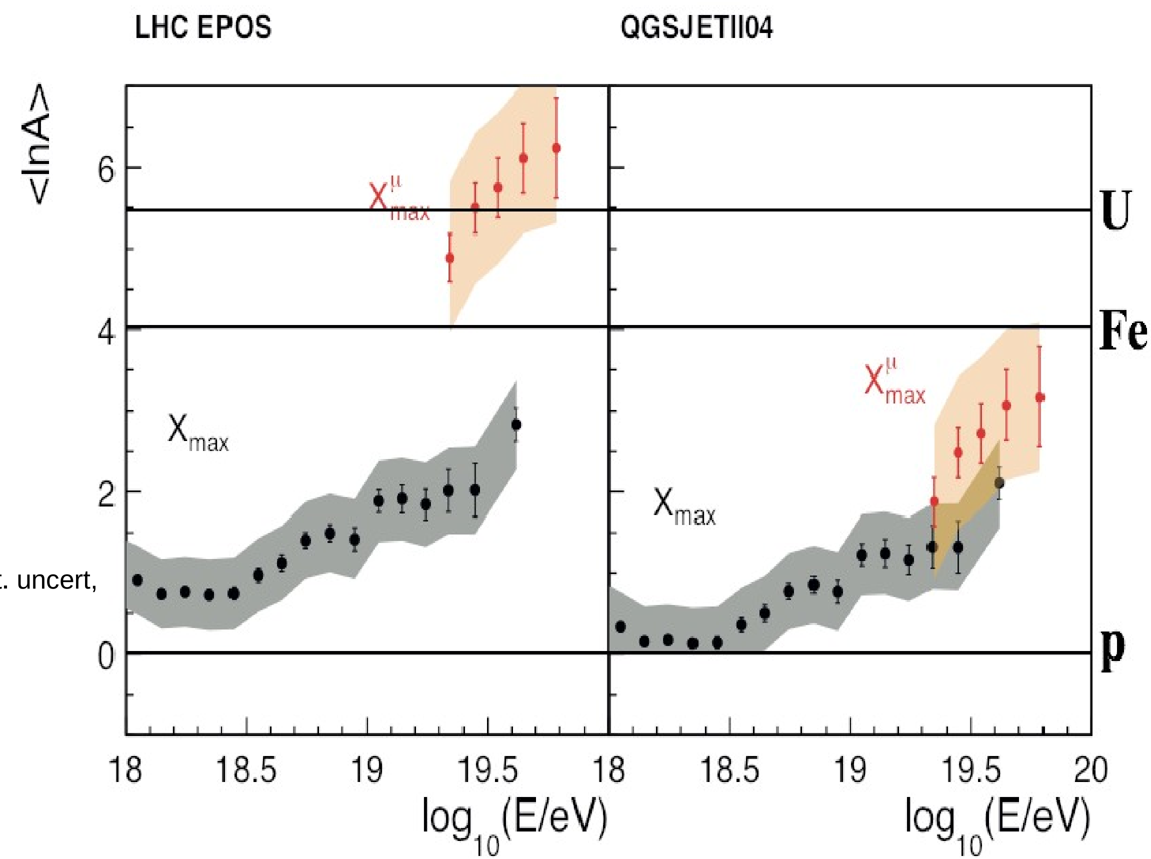




MPD and Models

- **2 independent mass composition measurements**
  - both results should be between p and Fe
  - both results should give the same mean logarithmic mass for the same model
  - problem with EPOS appears after corrections motivated by LHC data
    - lower diffractive mass motivated by rapidity gap cross-section !

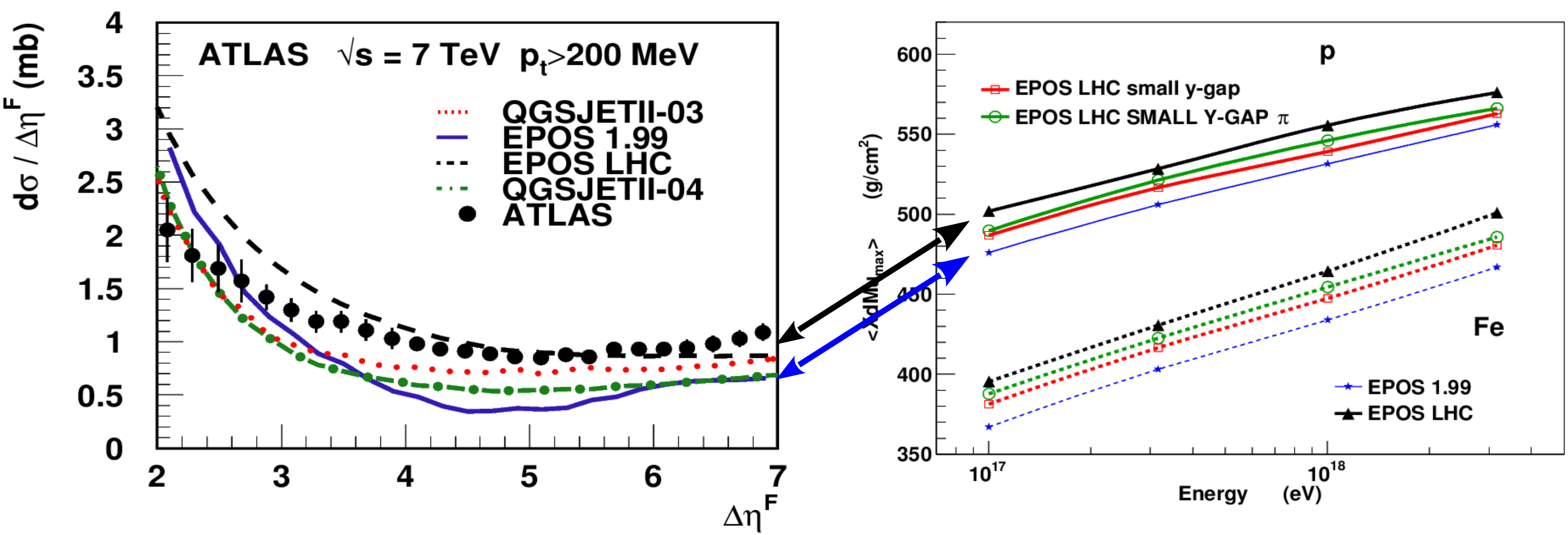




MPD and Diffraction

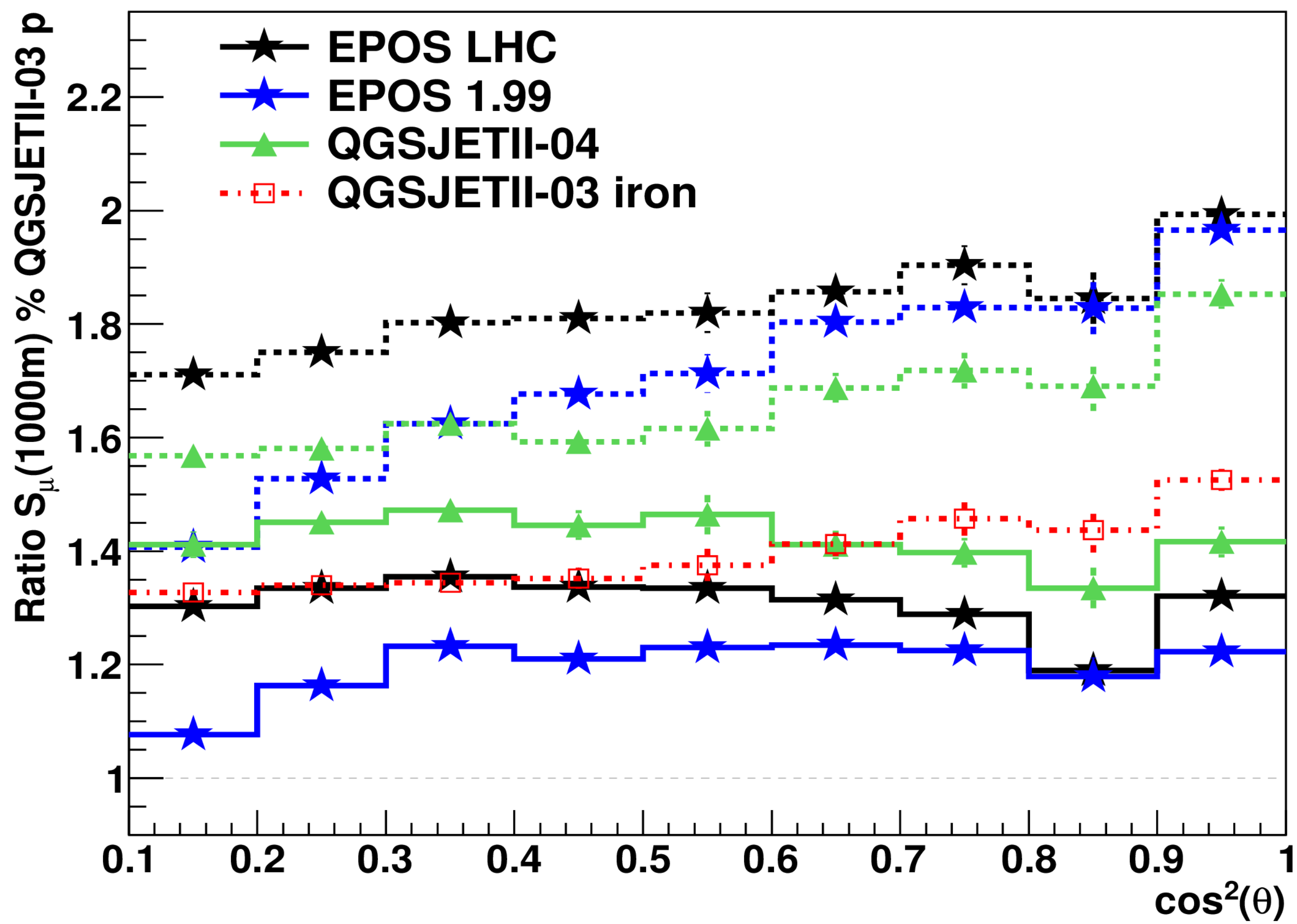
- **Inelasticity linked to diffraction (cross-section and mass distribution)**
  - weak influence on EM X_{max} since only 1st interaction really matters
  - cumulative effect for X^{μ}_{max} since muons produced at the end of hadr. subcasc.
  - rapidity-gap in p-p @ LHC not compatible with measured MPD
  - harder mass spectrum for pions reduce X^{μ}_{max} and increase muon number !

probably different diffractive mass distribution for mesons and baryons



Muon Signal at 1000m for PAO

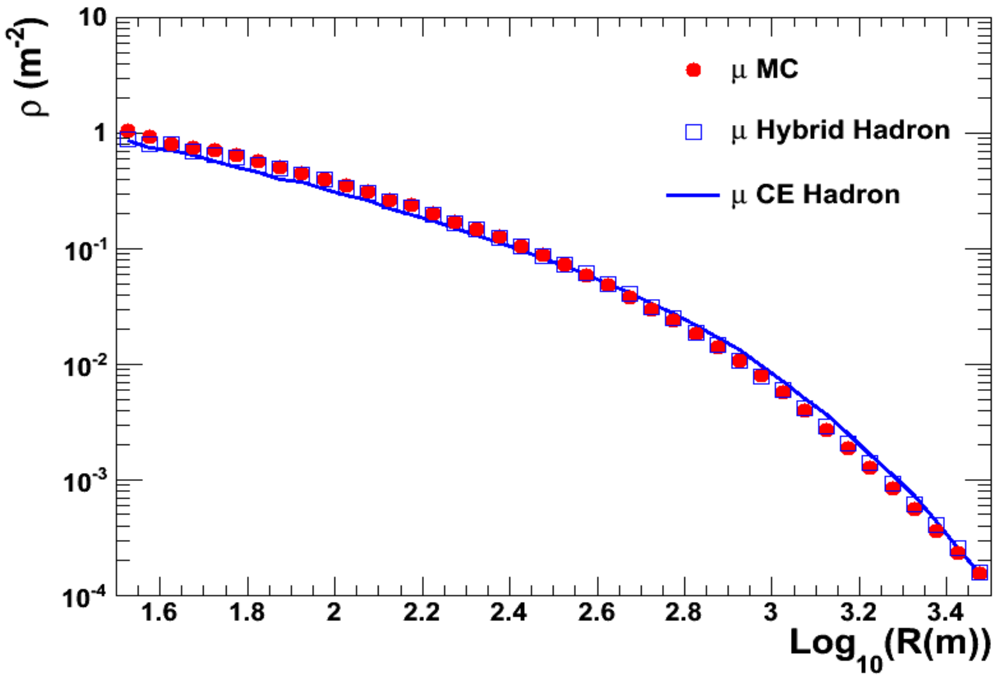
- **Different zenith angle dependence**
  - ➡ probably better description of muon number for PAO using heavy composition consistent with X_{max}

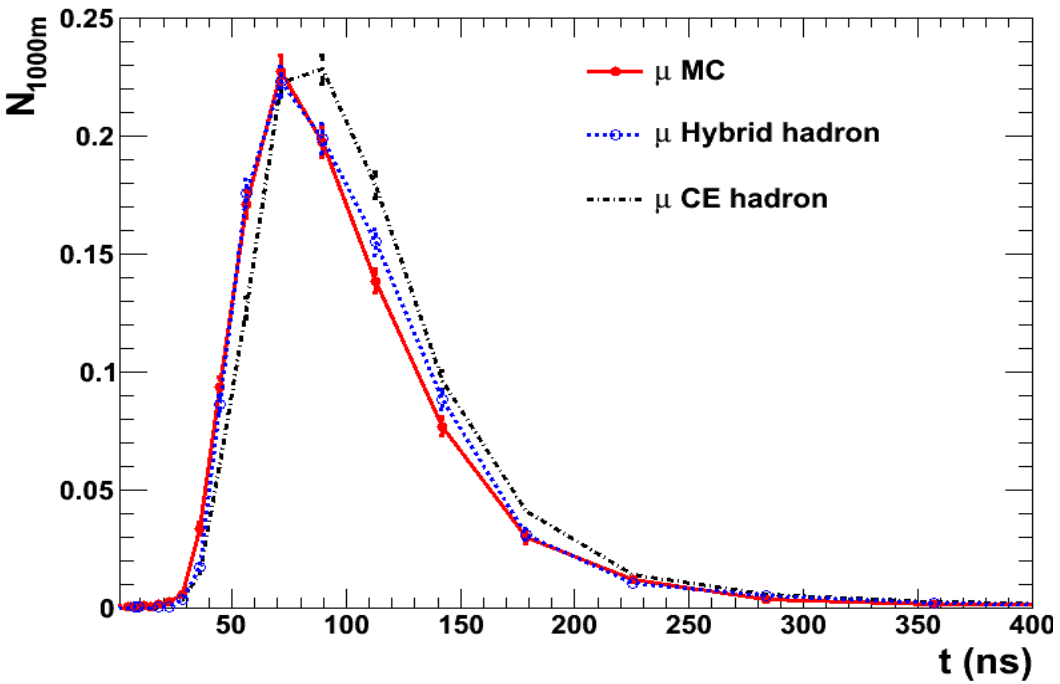


Example :
1 shower with different thresholds

Proton @ 0.1 EeV EGS4 off

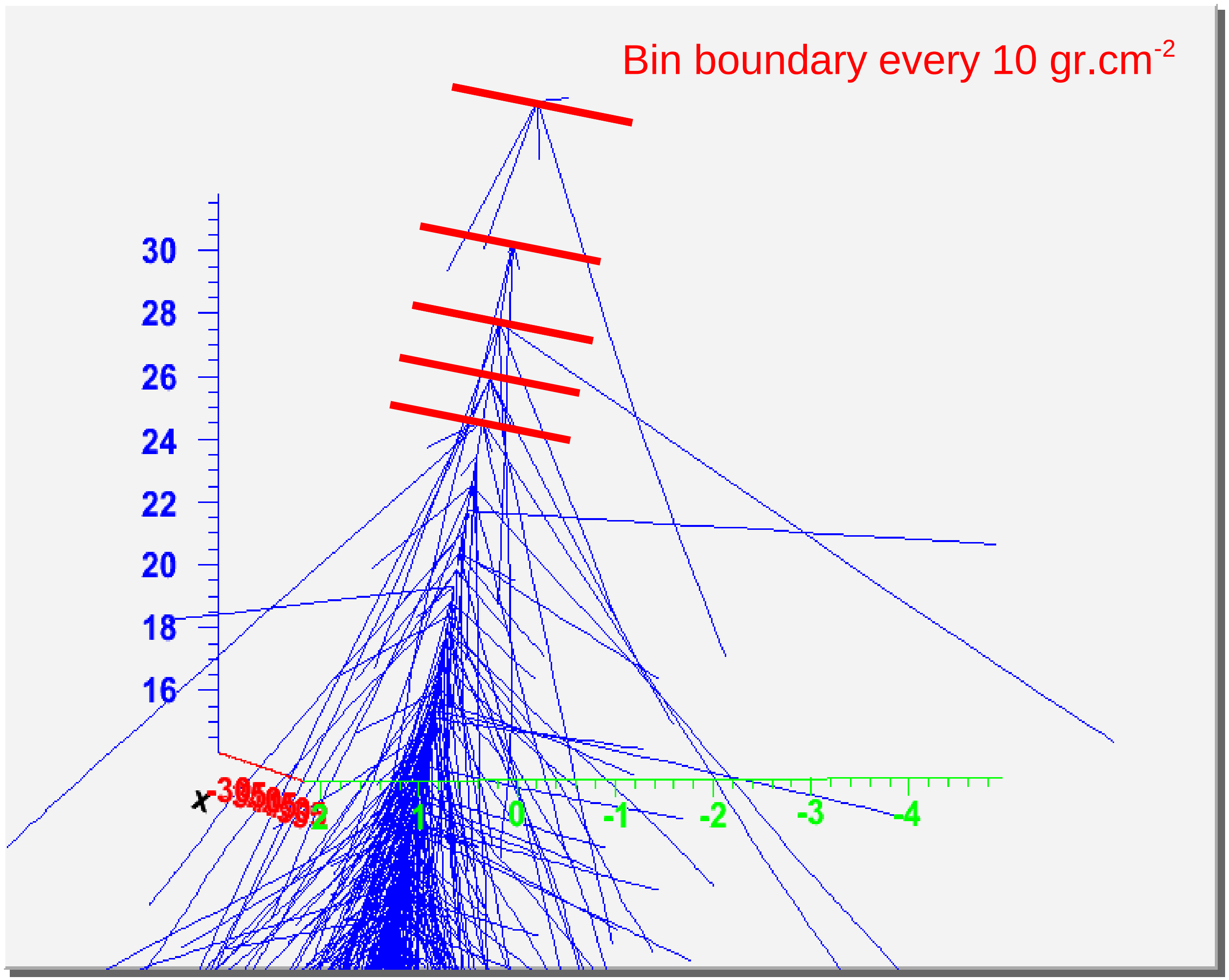
QGSJET + GHEISHA





Reasonable results for CE but hadronic MC needed for precise results

Example :
3D View with COAST



- **3D muons : Cascade equation only for hadrons**
  - Muon tracks start from bin boundaries
  - Muons generated with realistic angular distribution

Blue : CORSIKA muons