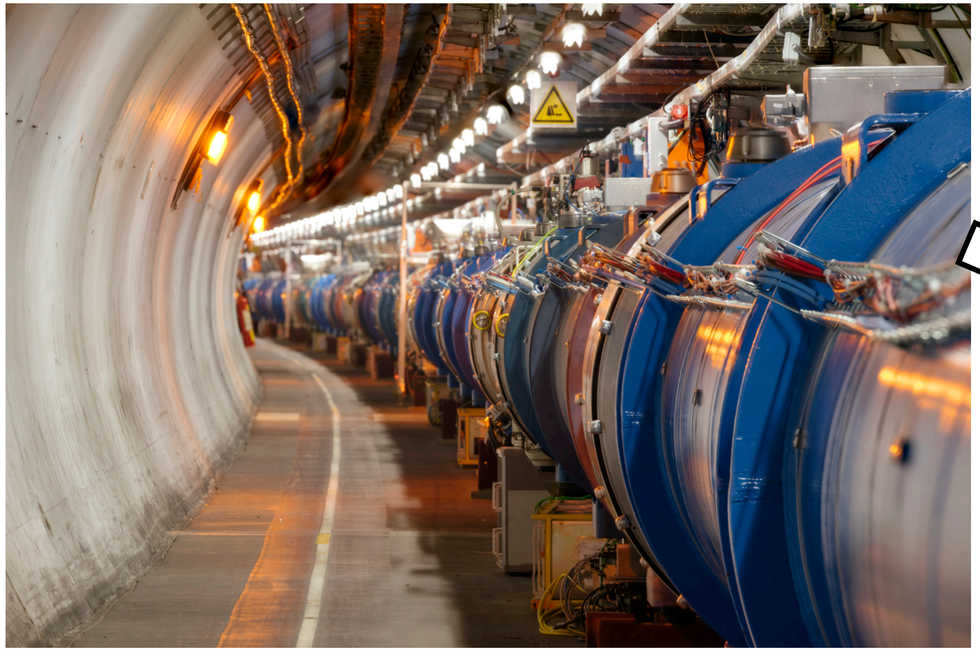
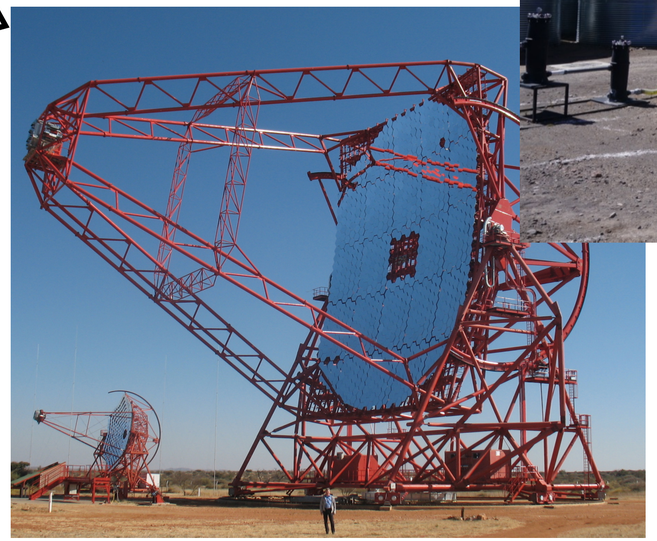




Systematics Uncertainties on Hadronic Models in the 100 GeV - 100 TeV Range

R D Parsons, H Schoorlemmer, A Pastor-Gutiérrez

Systematics in Post LHC Models

Simulations of **high energy hadronic interactions** are a key aspect in many areas of astroparticle physics

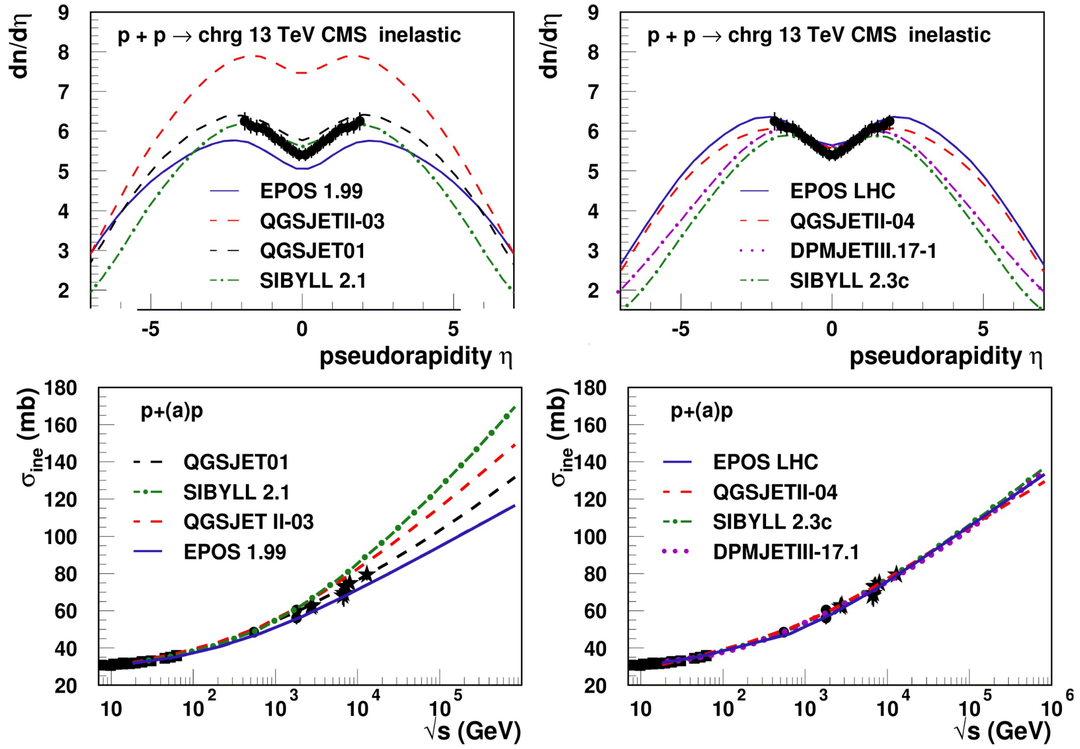
A new generation of models has been (relatively) recently created incorporating **data from the LHC**

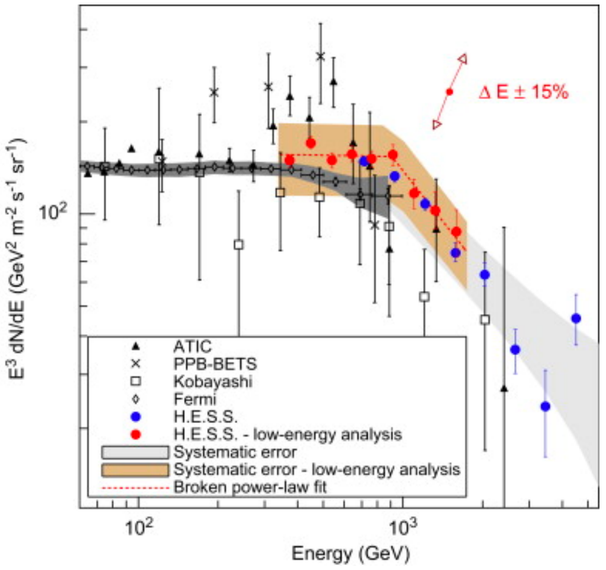
Much effort has been concentrated on understanding the models at **ultra high energies**

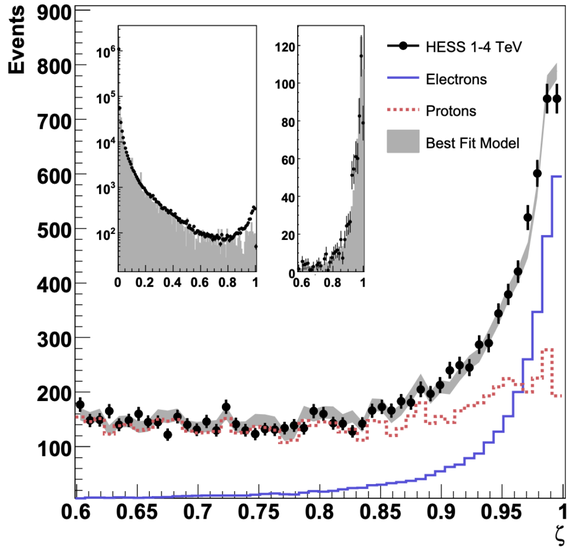
However models are used from **TeV to >EeV** we can't just assume that low energies are well described

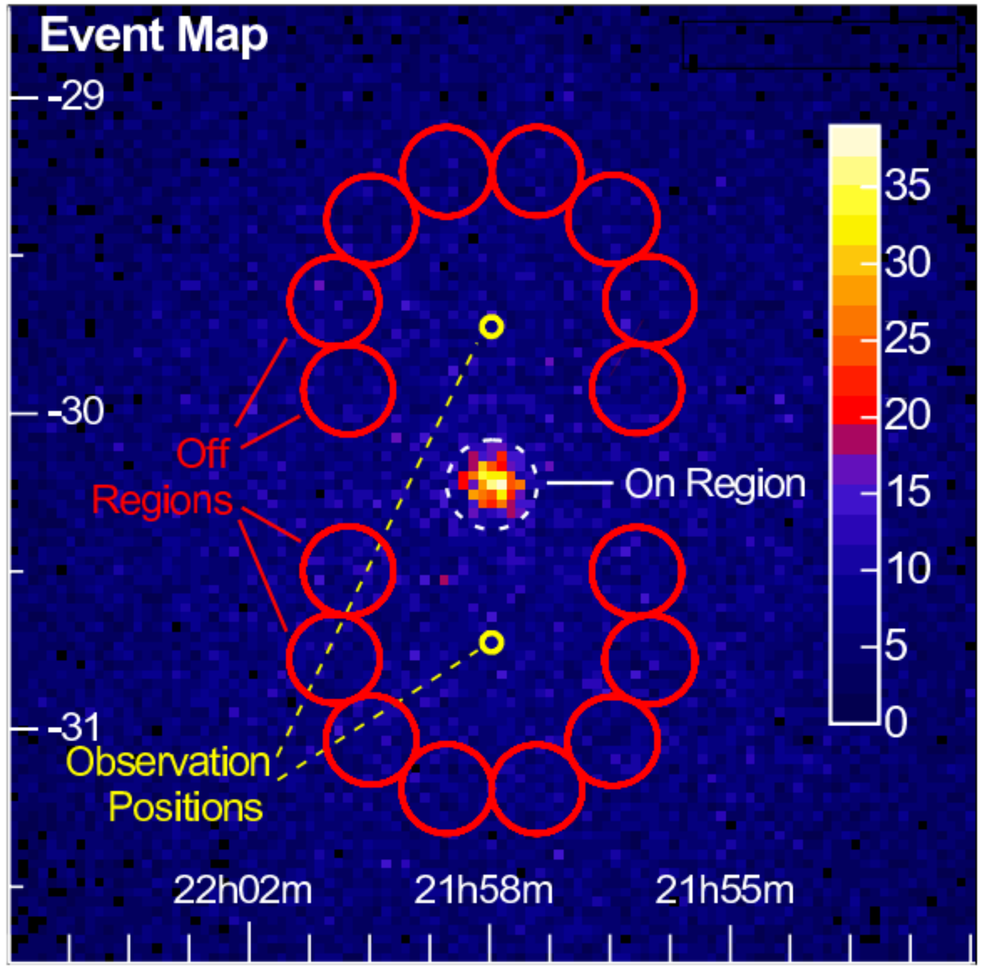
In some ground based gamma-ray observations (particle detectors and Cherenkov telescopes) we need to describe the hadronic background

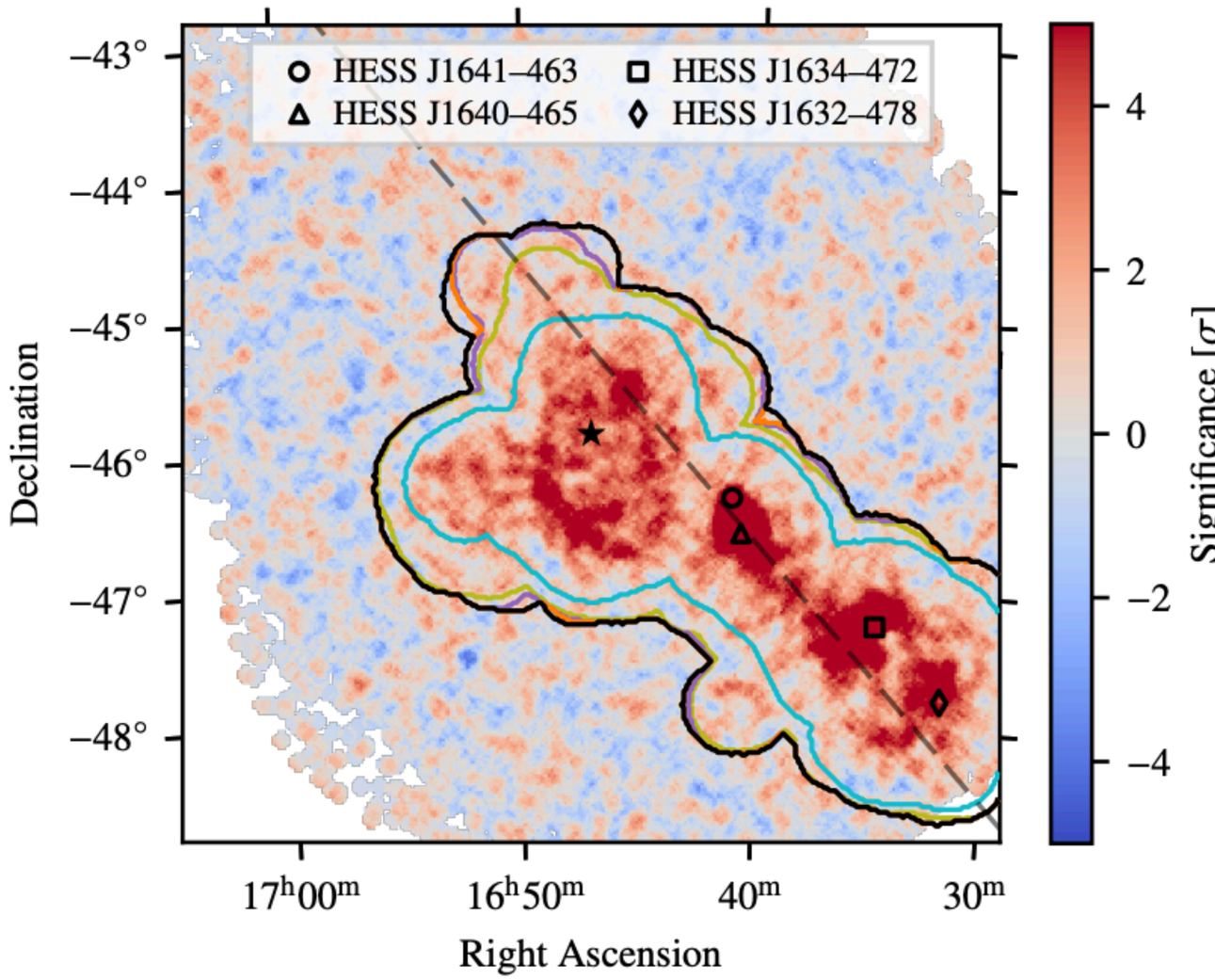
Sensitive from about **10 GeV to 100 TeV range**







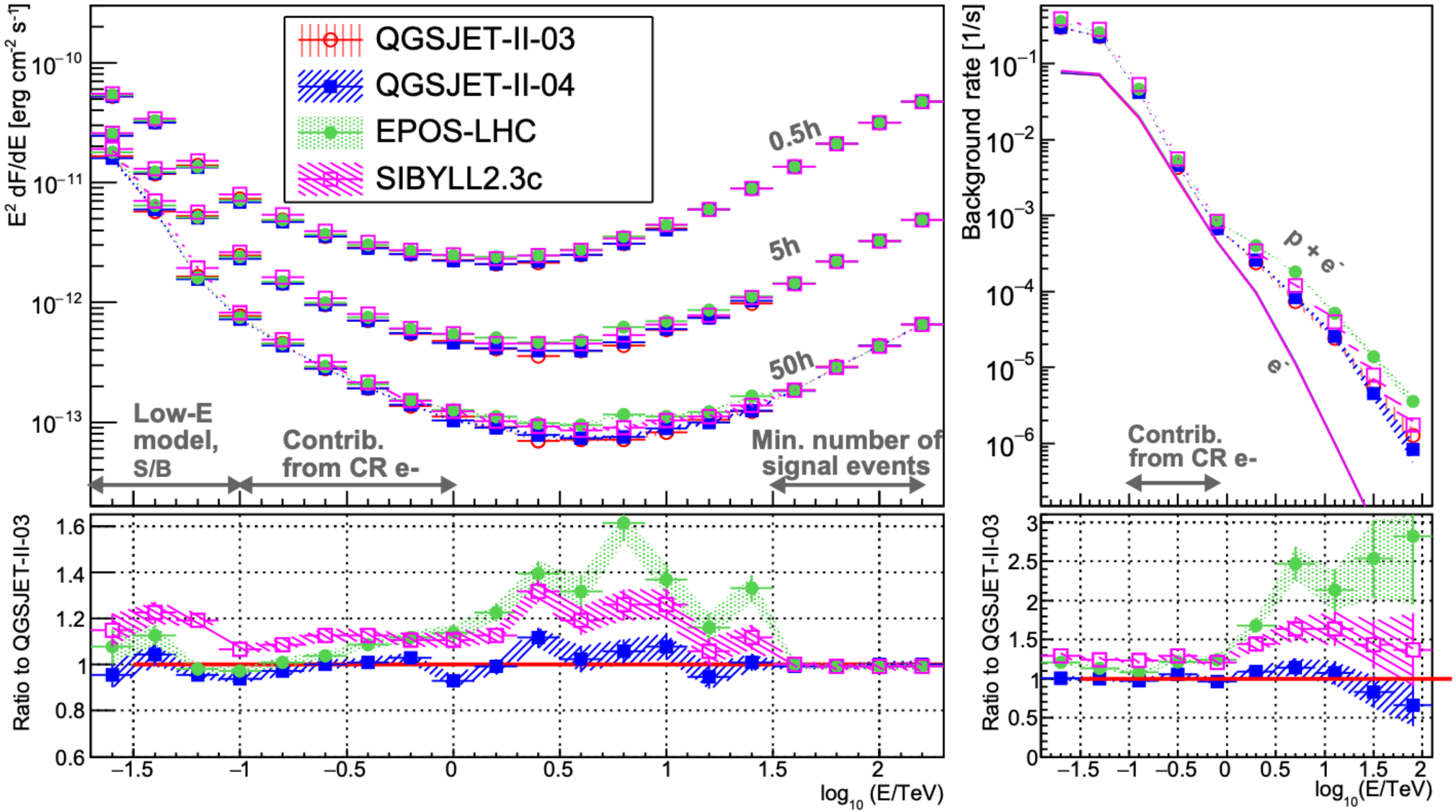




In some cases BG estimation from FoV difficult or impossible (see L Mohrmann W1 talk)

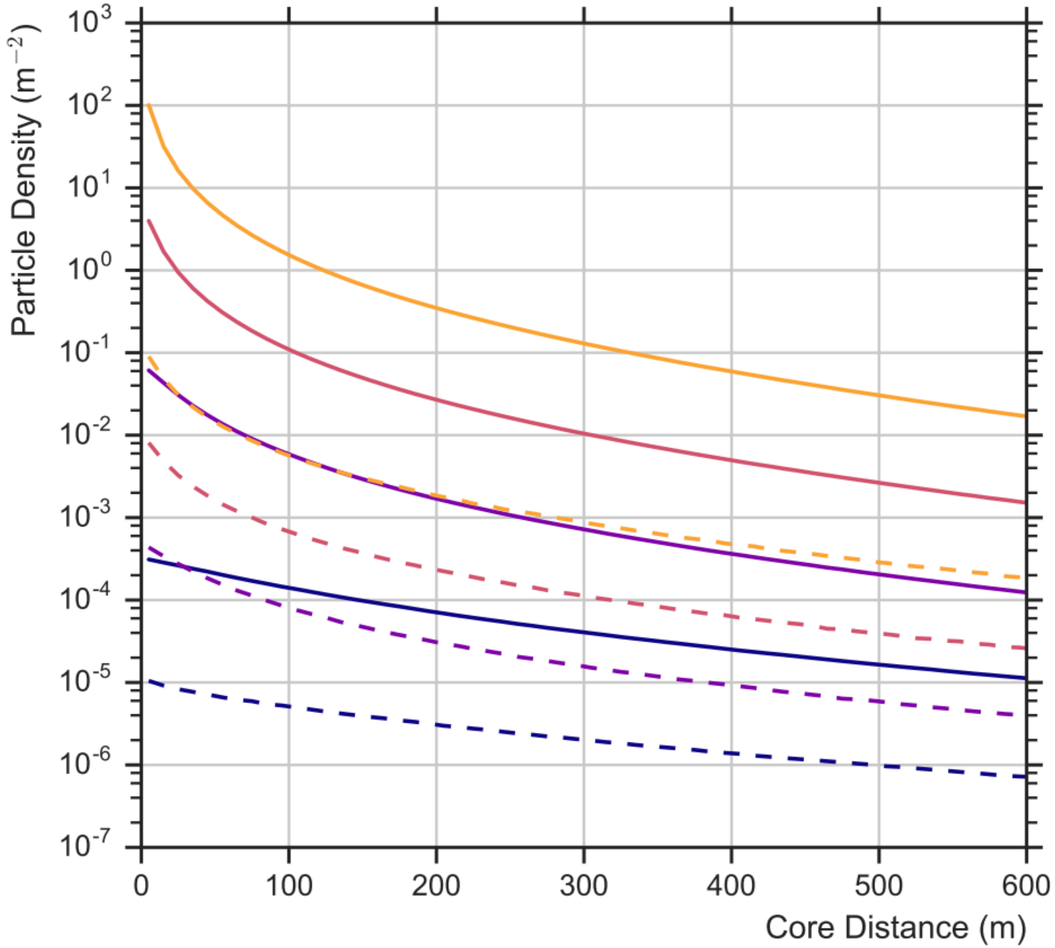
Ran full simulations of CTA array of IACTs using different model

Predicted sensitivity differs by up to 40%

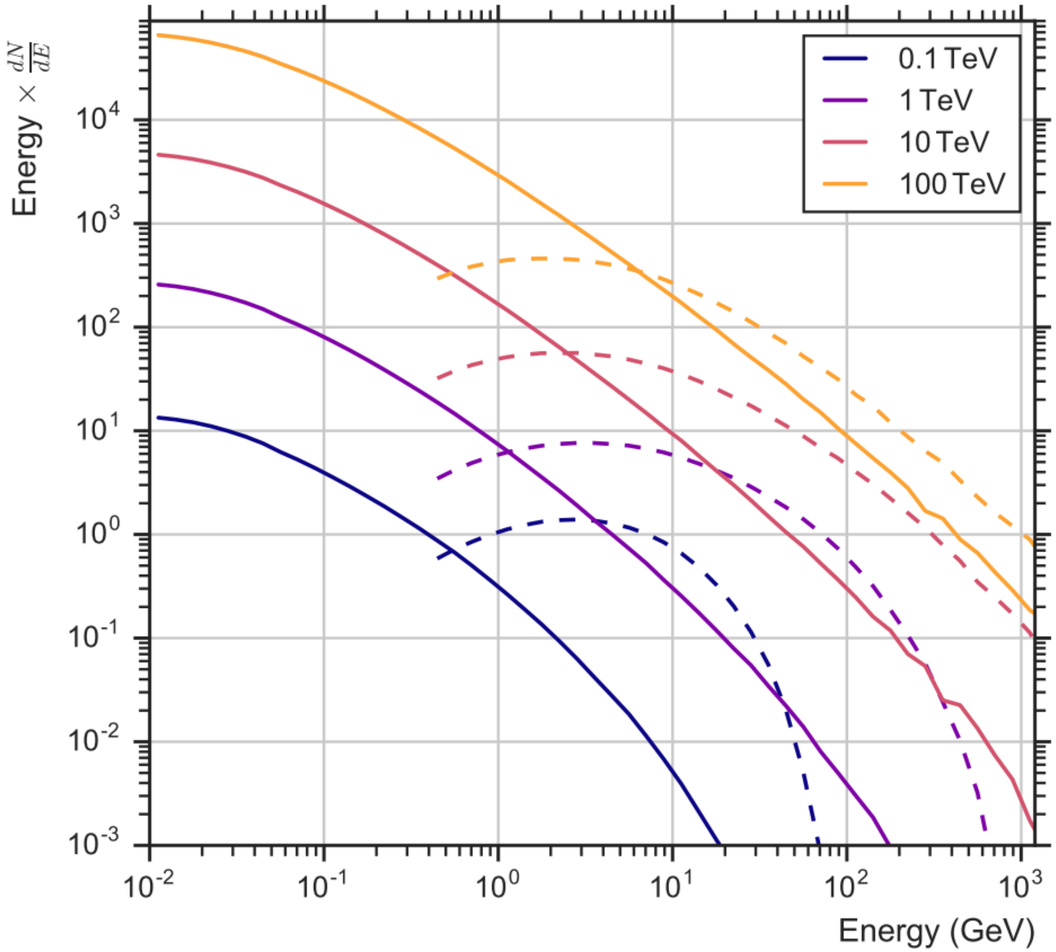


Ohishi et al, 2021 https://arxiv.org/abs/2105.05822

LDF



Spectrum



We ran a large number of vertical showers using **EPOS LHC**, **SIBYLL 2.3c**, **QGSJetII-04** and **UrQMD**
UrQMD as low energy model (80 GeV crossover)
Simulate at **100 GeV, 1 TeV, 10 TeV** and **100 TeV**

LDF and Spectrum at 4100 m for **EPOS** model

Electrons - Solid line
Muons - Dashed line

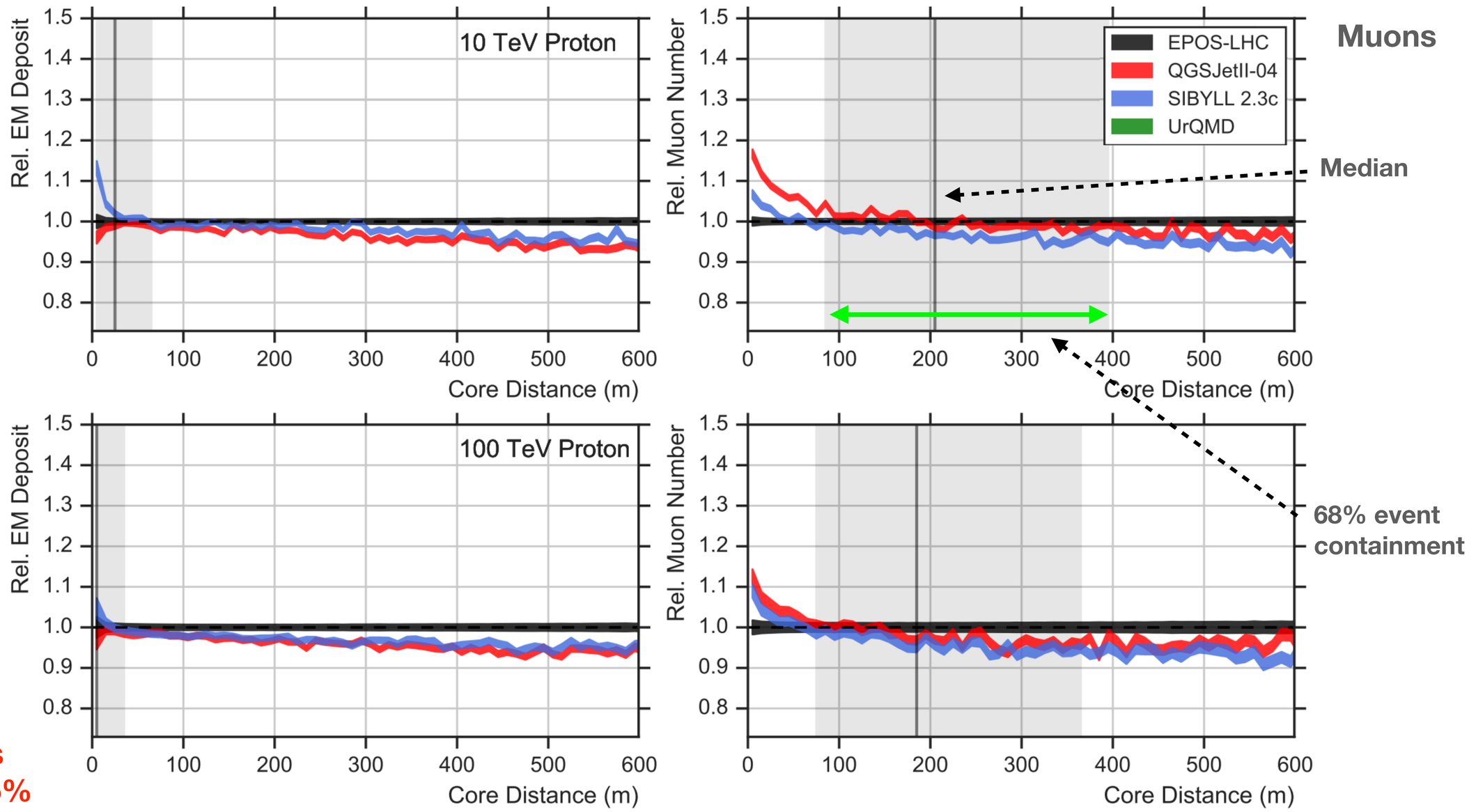
LDF

Energy Deposit / m²
Roughly analogous to EM deposit in WC detector

Particles / m²
Roughly analogous to minimum ionising muon detection

EM Particles

Muons

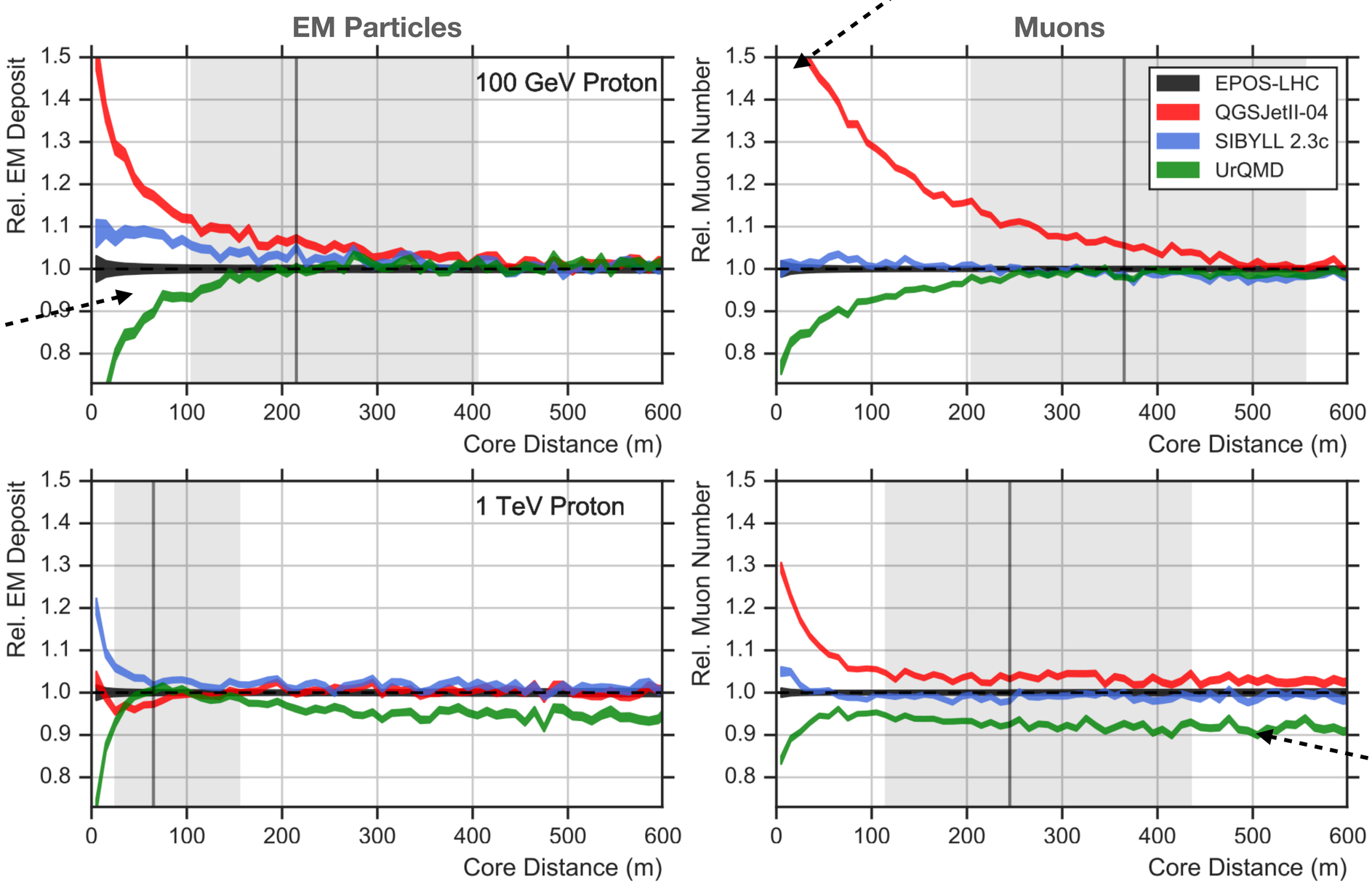


Differences between models is small **below 5%**

LDF

Differences up to 60% in muon number!

At low energies **huge** differences lie at low impact distance

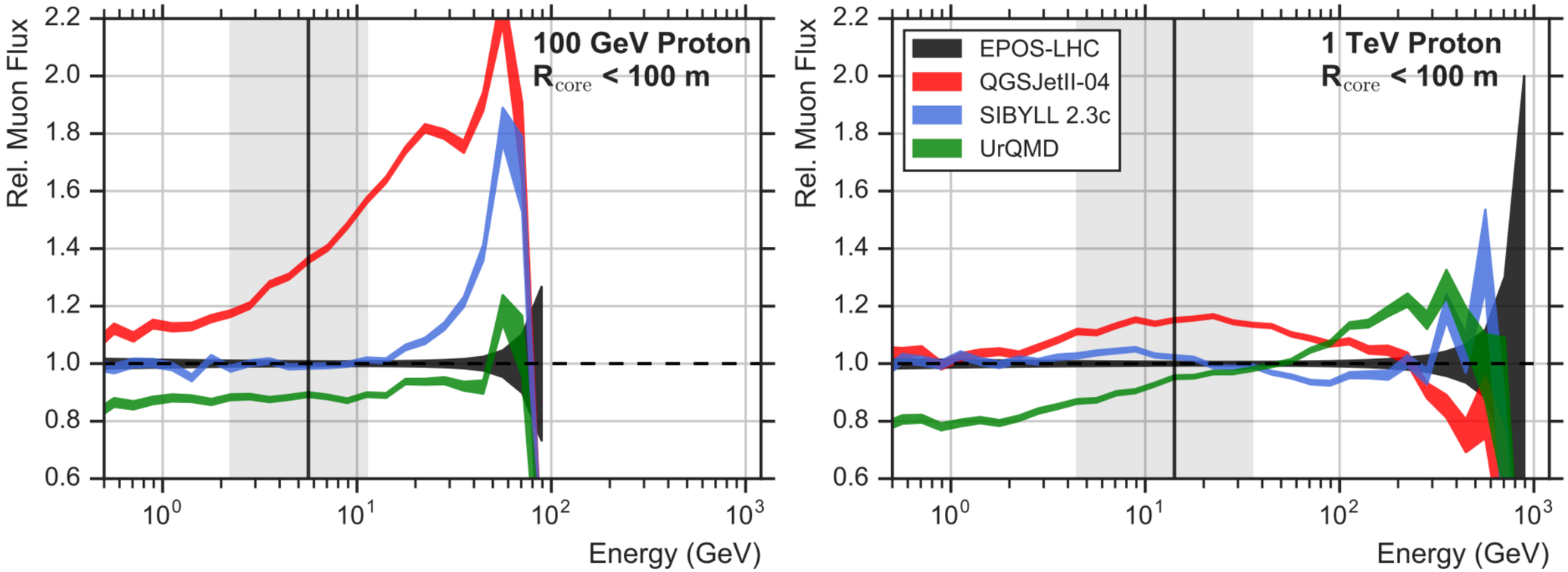


UrQMD shows offset in total muon number **Right at edge of it's applicability**

Muon Spectrum at Ground Level

Let's take a look at the muons that we see close to the shower core

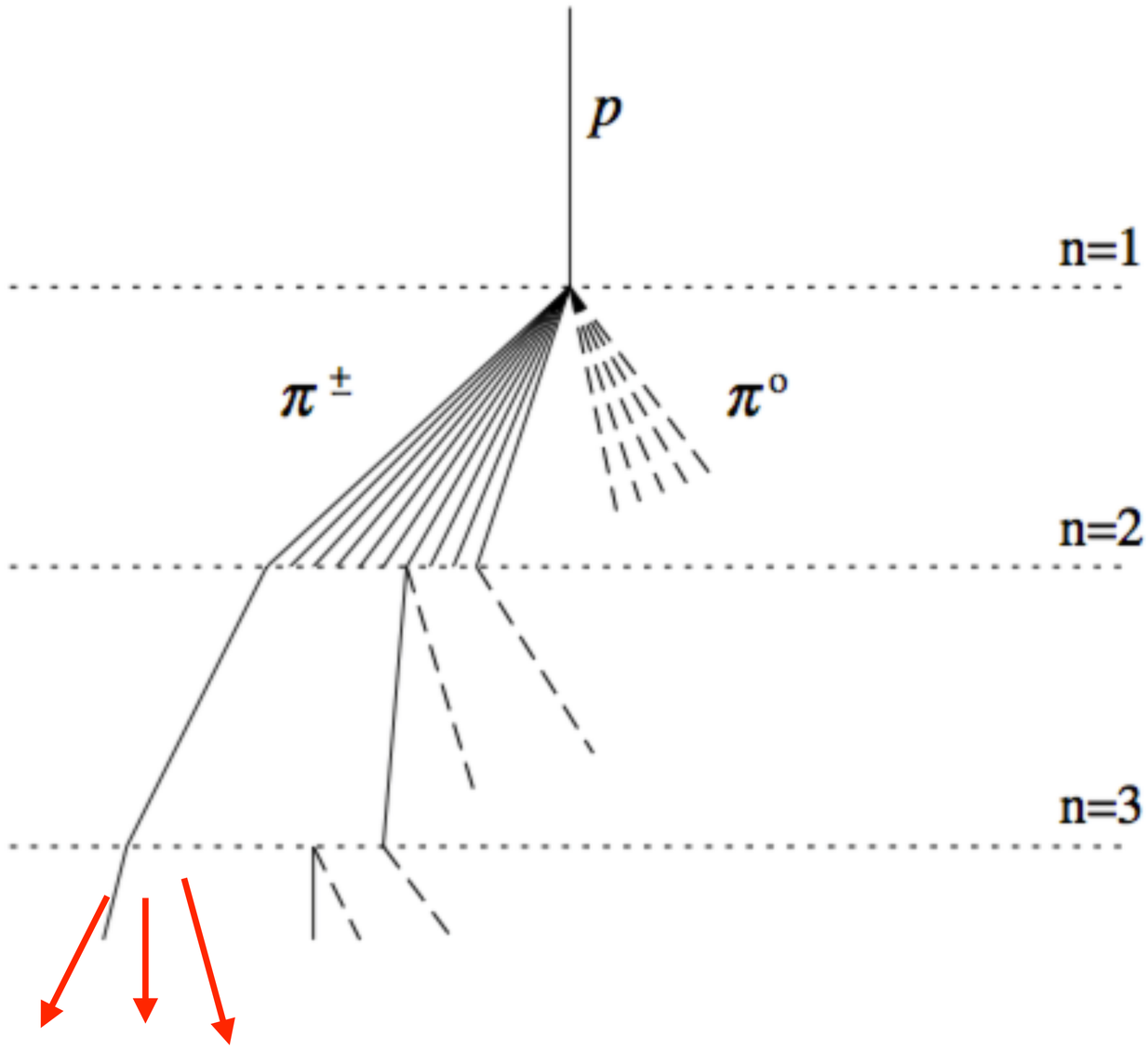
Take the muons from the **central 100m and make a spectrum**



The differences we see in both **QGSJet and and SIBYLL** clearly come from a **high energy muons** at ground level

UrQMD deficit comes from **lower energy muons**

Why is the huge difference? (100 TeV)



In this energy range the air shower proceeds as one would normally picture

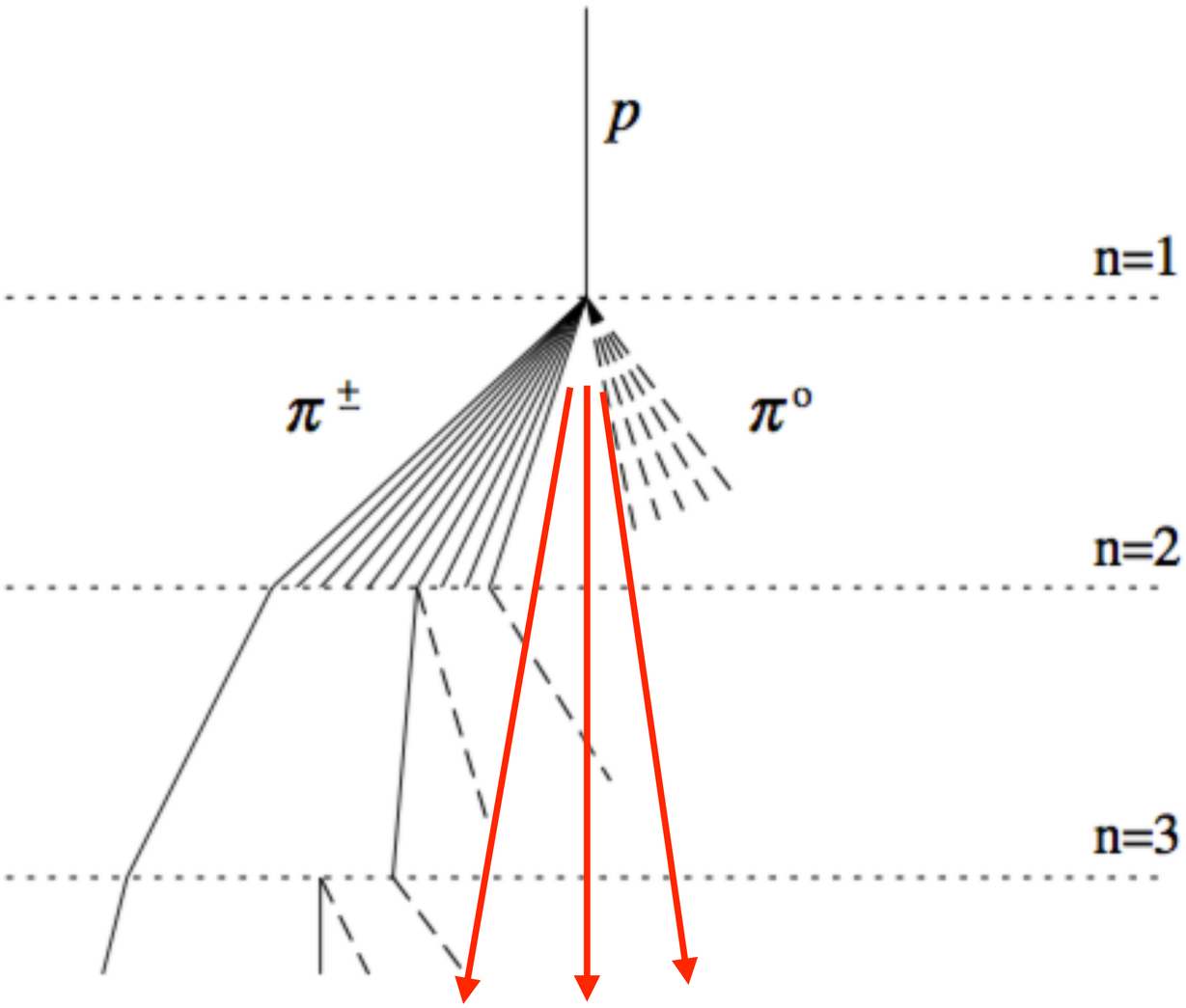
There **many** generations of hadron production

Most electrons at ground originate **EM cascades** within the shower

Muons originate from the decay of pions **close to Xmax**

Excess in low energy pions @ 100 GeV lead to **more muons for EPOS**

Why is the huge difference? (100 GeV)



At **100 GeV** the shower looks rather different

There are only a **few generations** of pion production

Most muons on ground come from the **first or second generation** of pions

Only muons above a few GeV reach the ground without decaying

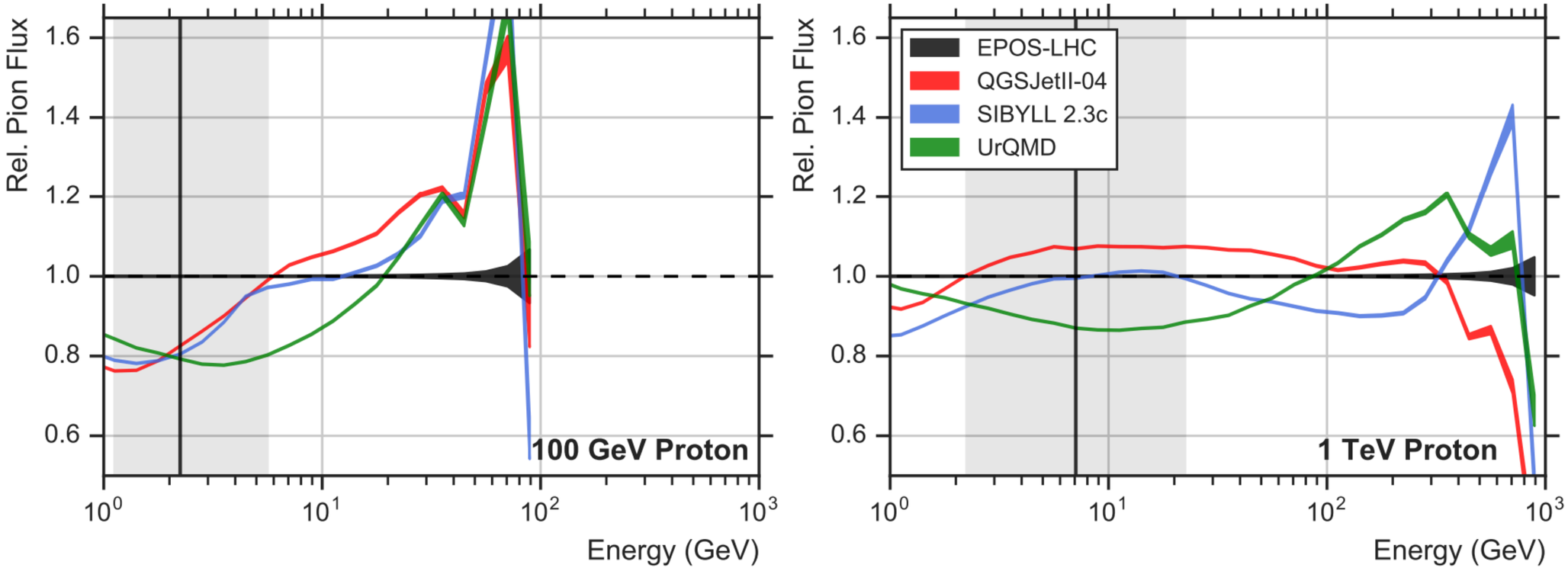
Many electrons come from **muon decay close to ground level**

Leads to an equivalent increase in EM energy deposit

First interaction is clearly very important here, so lets take a closer look…

Investigating First Interactions (Spectrum)

Pion spectrum at first interaction point

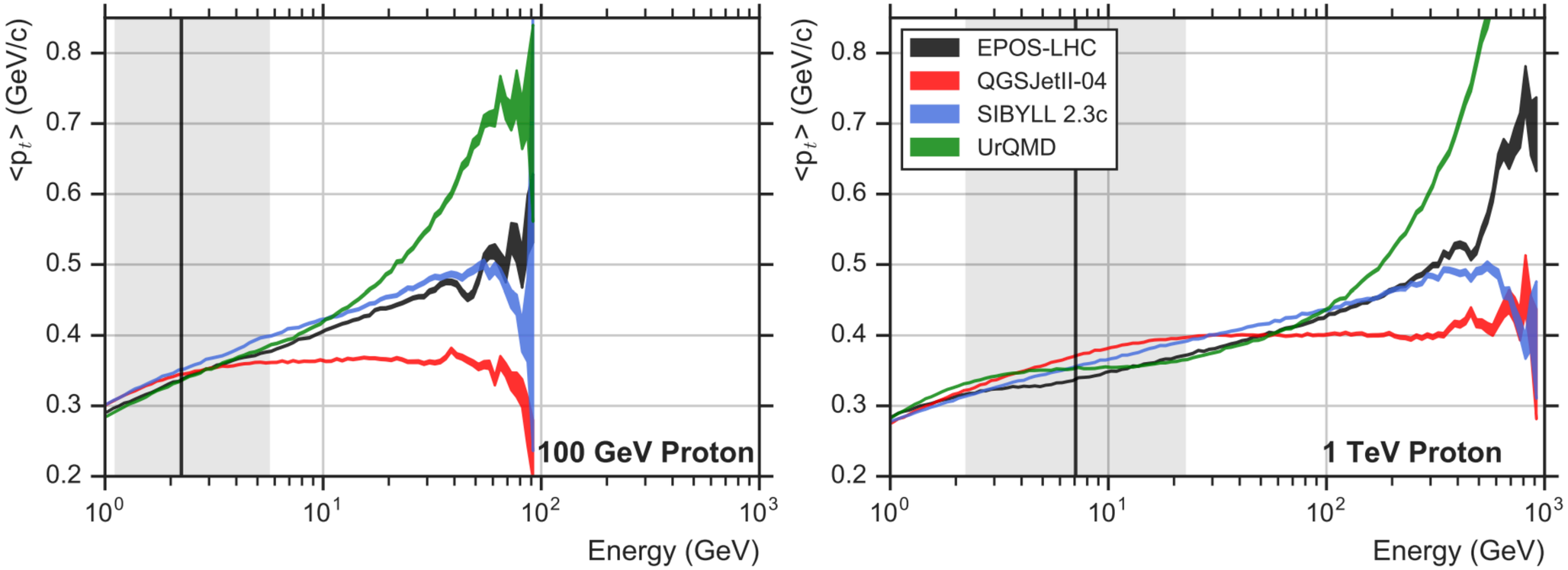


At **100 GeV** clearly EPOS has a steeper pion production spectrum that the other models

More low energy pions, few high energy

At **1 TeV** pion spectrum is much more comparable

Investigating First Interactions (Transverse Momentum)



Transverse momentum transfer very different between models
about **10% of primary interaction energy**

Seems to scale with primary energy

Investigating First Interactions

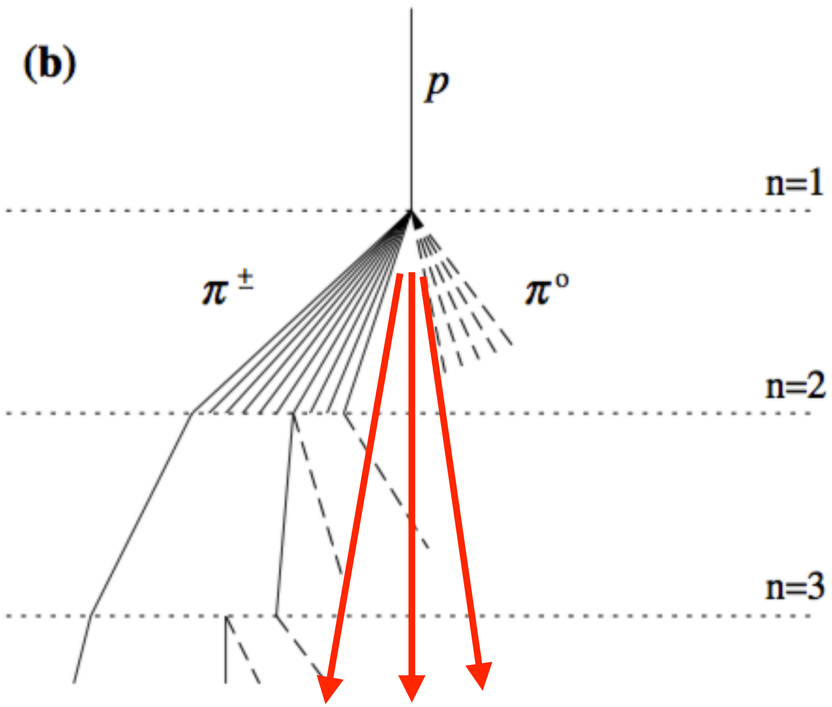
This difference in first interaction matches well with observed shower behaviour

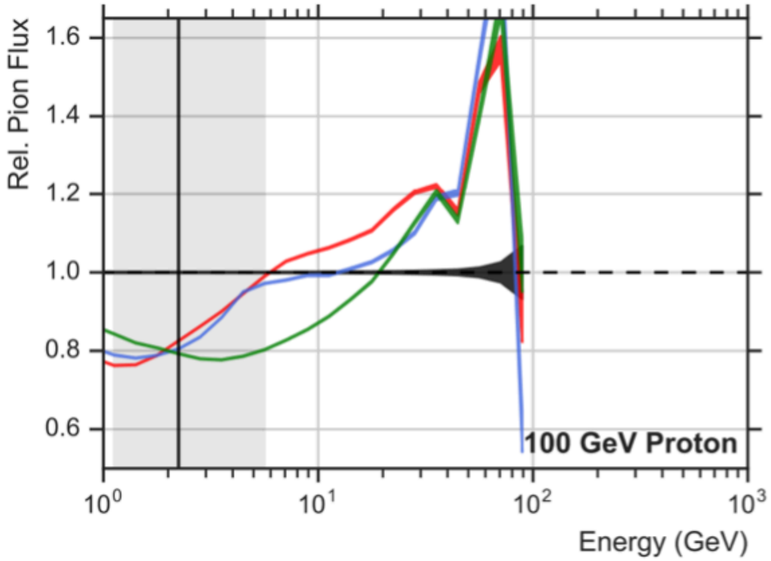
Any muons from our first interaction with an energy **below about 3 GeV will decay** before reaching the ground

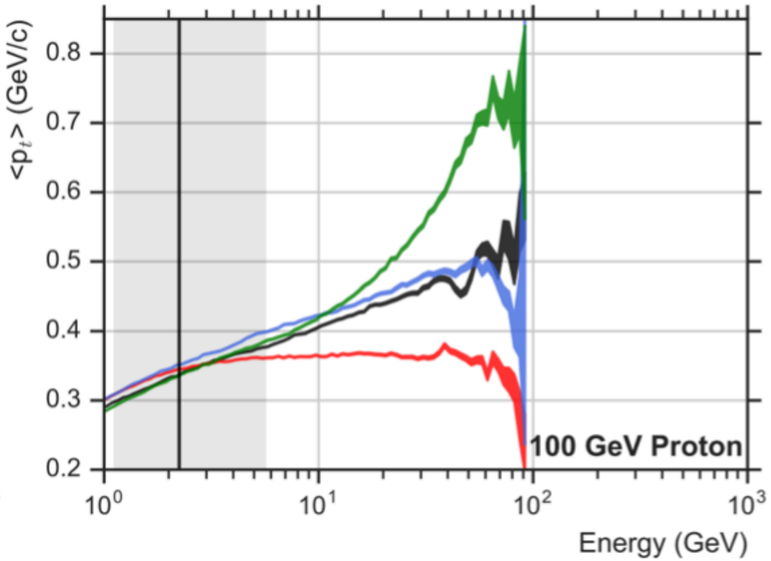
QGSJet and SIBYLL both produce an excess of energetic muons (UrQMD a deficit until 20 GeV)

QGSJet muons stay closer to the shower core due to **lower p_t**

Muon decays lead also to differences in EM signal

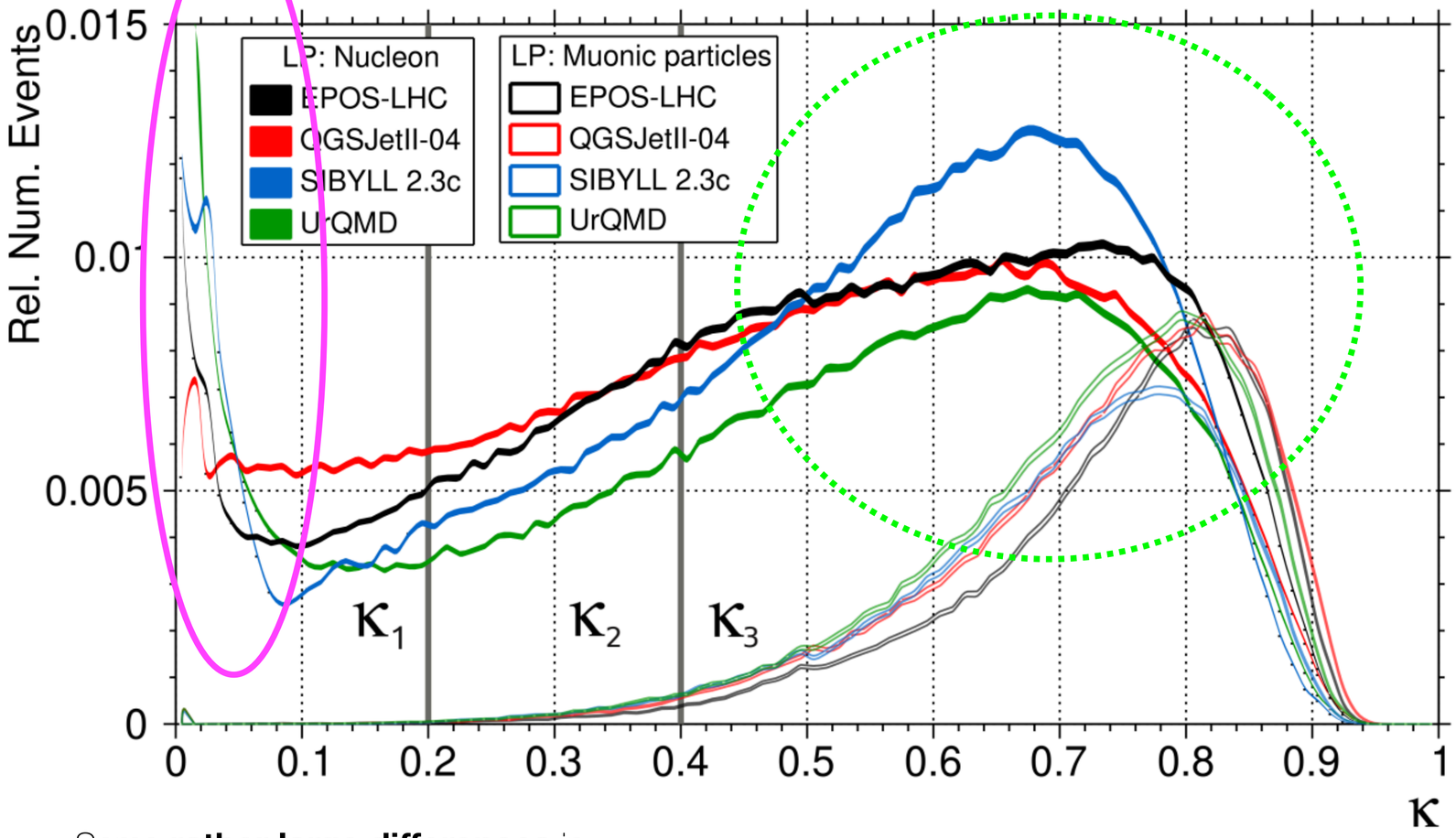






Investigating First Interactions (Inelasticity)

Nucleons	p, $\bar{p}$, n, $\bar{n}$
Muonic family	μ^+, μ^-, π^+, π^-, K_L^0, K^+, K^-, K_S^0
EM component	γ, e^-, e^+
Other hadrons	Λ, Σ^+, Σ^-, $\overline{\Sigma}^-$, $\overline{\Sigma}^+$, Ξ^0, Ξ^-, Ω^-, $\bar{\Lambda}$, ...



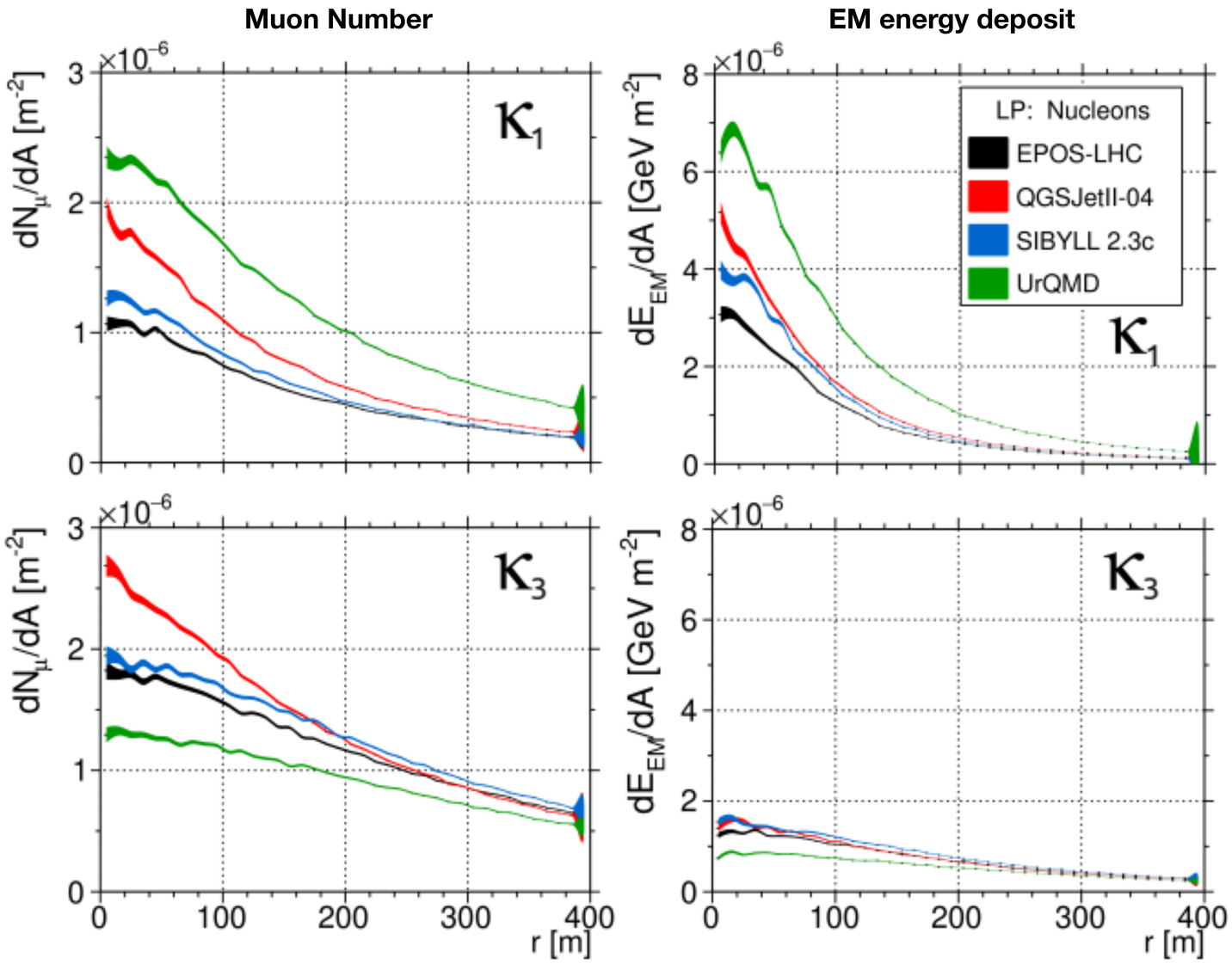
Some **rather large differences** in the interaction inelasticity

Simulate showers and compare first interaction properties to ground level behaviour

First interaction depth now fixed

Model	$\lambda_{\text{p-Air}}$ [g cm^{-2}]	σ [mb]	First interaction altitude [km]
EPOS-LHC	87.81	275.12	17.34
QGSJetII-04	90.83	265.99	17.13
SIBYLL 2.3c	85.95	281.09	17.47
UrQMD	75.72	319.07	18.26
Average	85.08	285.32	17.55

Investigating First Interactions (Inelasticity)

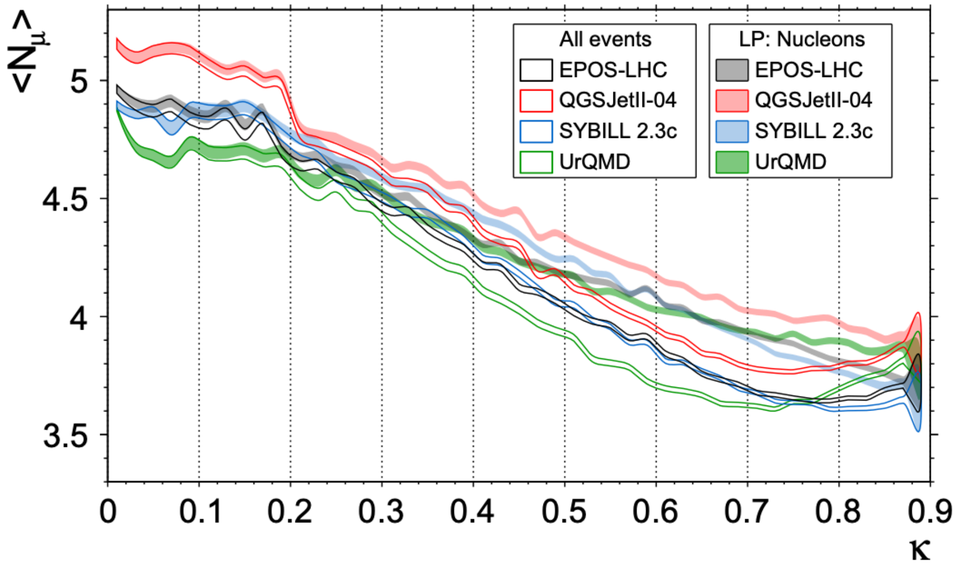


Huge differences seen in low inelasticity vs high, **especially in UrQMD**

Primarily due to the **much larger number of low inelasticity showers in UrQMD**

Air shower effectively starts deeper in the atmosphere

But no large difference in difference **muon number vs inelasticity**



Summary

As we push towards the next generation of ground-based gamma-ray telescopes (making precision measurements) **understanding the systematics of background simulations becomes very important**

It is already rather clear that the background predictions vary greatly from model to model

This extends even to rather basic ground level predictions, **most notably at the low energy boundary of 100 GeV**

The differences in ground level predictions at 100 GeV come **directly from differences in first interaction properties**

These differences **are concerning not only for 100 GeV** showers as we are almost on the boundary between HE & LE interaction models

Probably stem from **lack of tuning data** for the models, both from accelerators and ground-based detectors

p-O runs at LHC, specifically including analysis from LHCf and other forward detectors my help from one side

May need a concerted effort from the current generation of gamma-ray instruments to provide comparison of ground-level measurables (muon number, shower shape etc)