Sub-TeV hadronic interaction models differences and their impact on air-shower development

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What's the point?

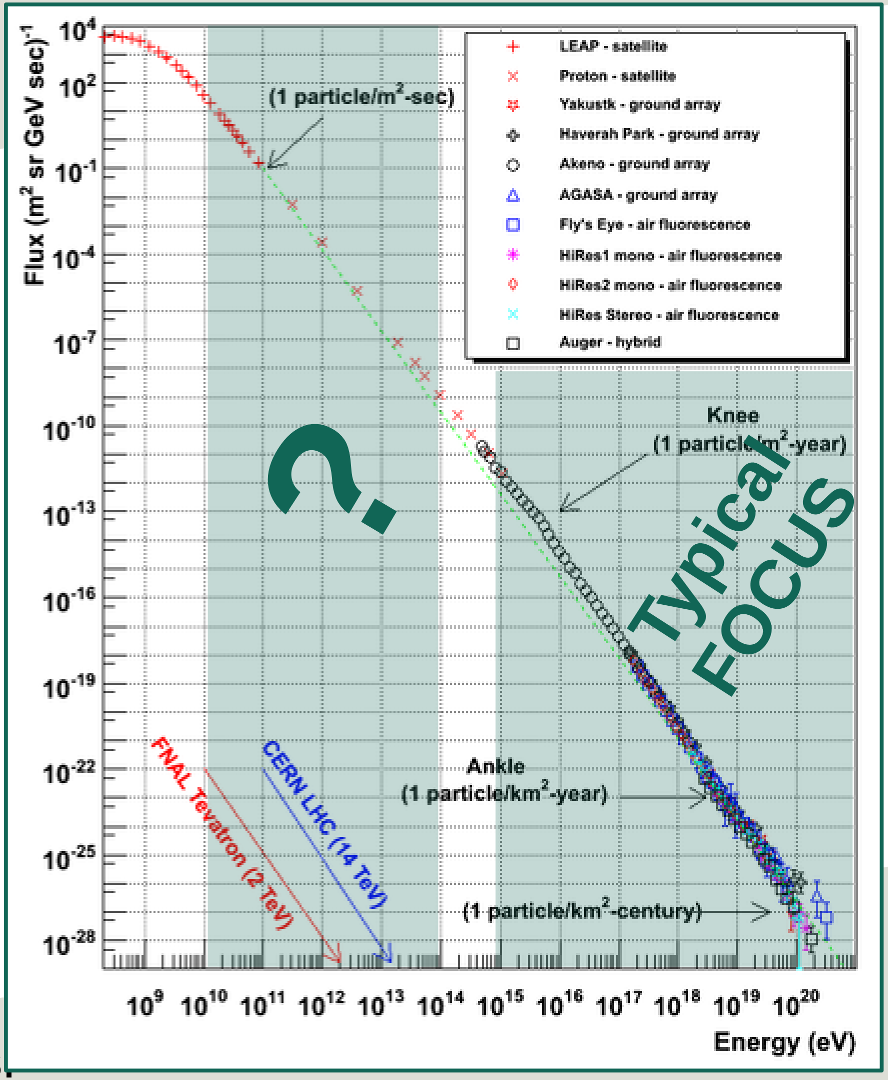
- Hadronic interaction models determine the shower profile.
  - ➔ Focus at high energies >10^{15} eV.

But, what about lower energies?

Do models agree?

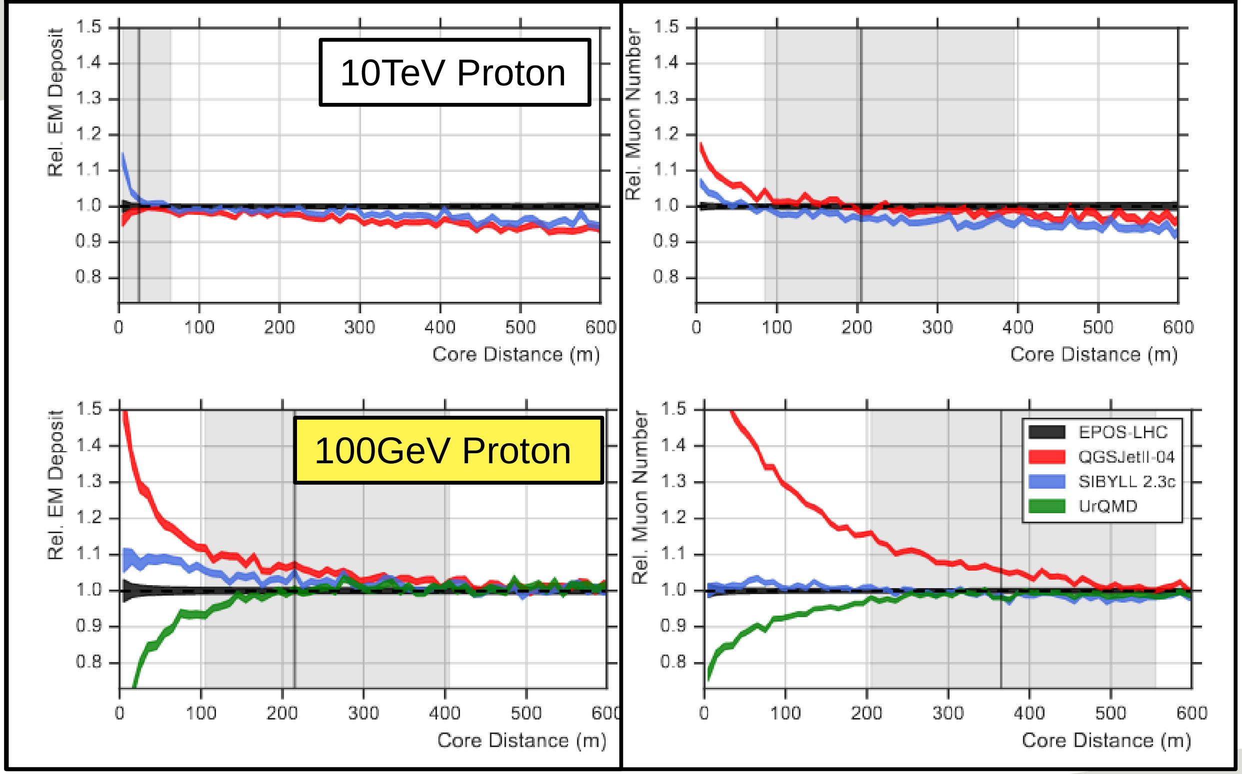
TeV and sub-TeV regime very important for experimental efforts:

- Instrument response.
- Energy range (**CTA**, **HAWC**, **HESS**, …) .
- Background characterization and cosmic ray studies.



Hadronic interaction models differences

EM LDF	Muon LDF

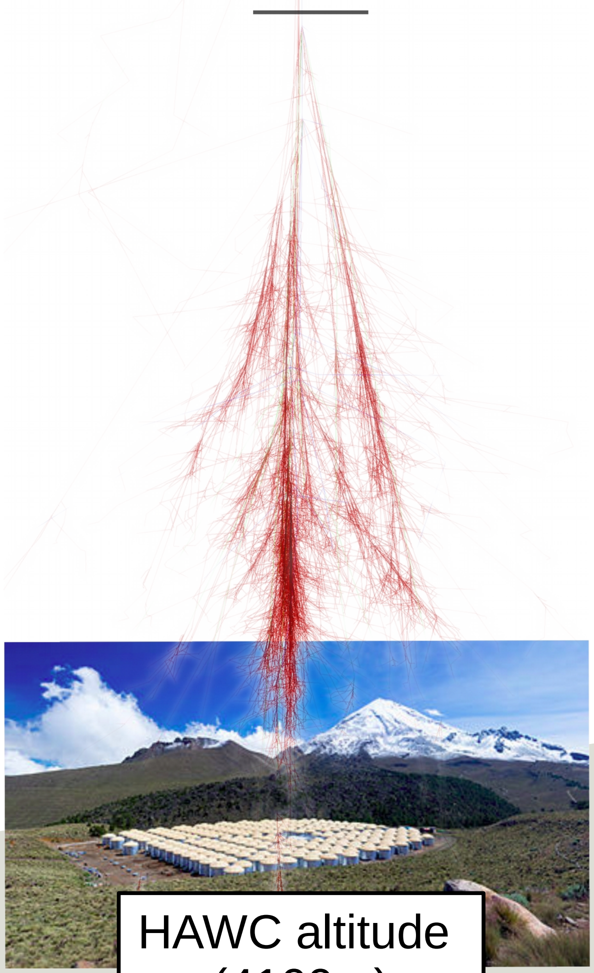


What causes these differences?

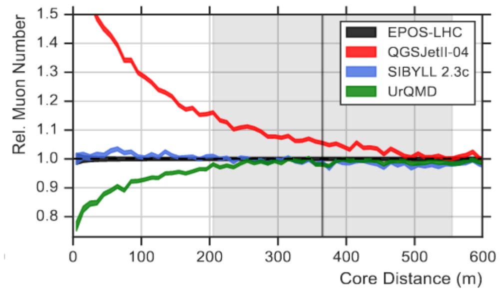
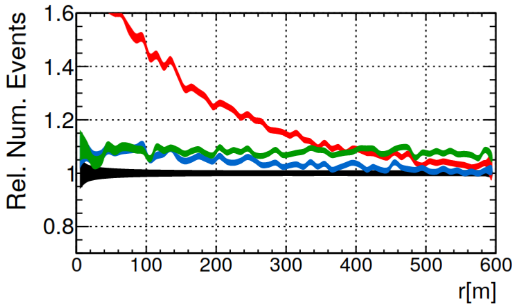
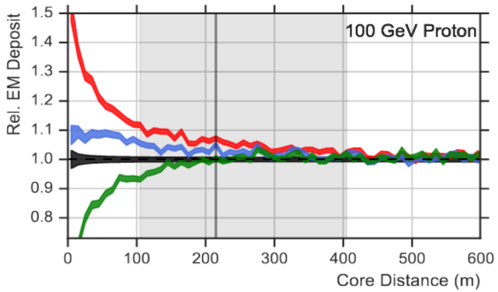
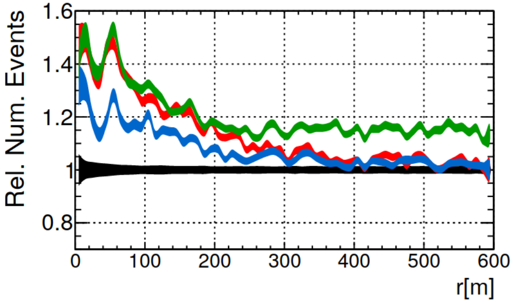
R.D.Parsons & H.Schoorlemmer. Phys. Rev. D, 100(2), 023010(2019)

Set-up

- $>10^6$ simulations on **CORSIKA v7.64**
- First interaction hadronic models:
  - EPOS-LHC
  - QGSJetII-04
  - SIBYLL 2.3c
  - UrQMD (low energy model)
- Always transition to low energy model (UrQMD) at 80 GeV (default **CORSIKA**).



100GeV Proton

	Free first interaction altitude	**Fixed** initial altitude
Muons		
EM energy		

EPOS-LHC
QGSJetII-04
SIBYLL 2.3c
UrQMD

Model	λ_{pAir} $[g \cdot cm^{-2}]$	σ $[mb]$	First interaction altitude $[km]$
EPOS-LHC	87.814 ± 0.086	275.12 ± 0.27	17.3405 ± 0.0060
QGSJetII-04	90.831 ± 0.089	265.99 ± 0.26	17.1324 ± 0.0060
SIBYLL 2.3c	85.952 ± 0.084	281.09 ± 0.27	17.4726 ± 0.0060
UrQMD	75.719 ± 0.074	319.07 ± 0.31	18.2545 ± 0.0060
Average	85.079 ± 0.083	285.32 ± 0.28	17.5500 ± 0.0060

Different cross-section in the low energy model UrQMD

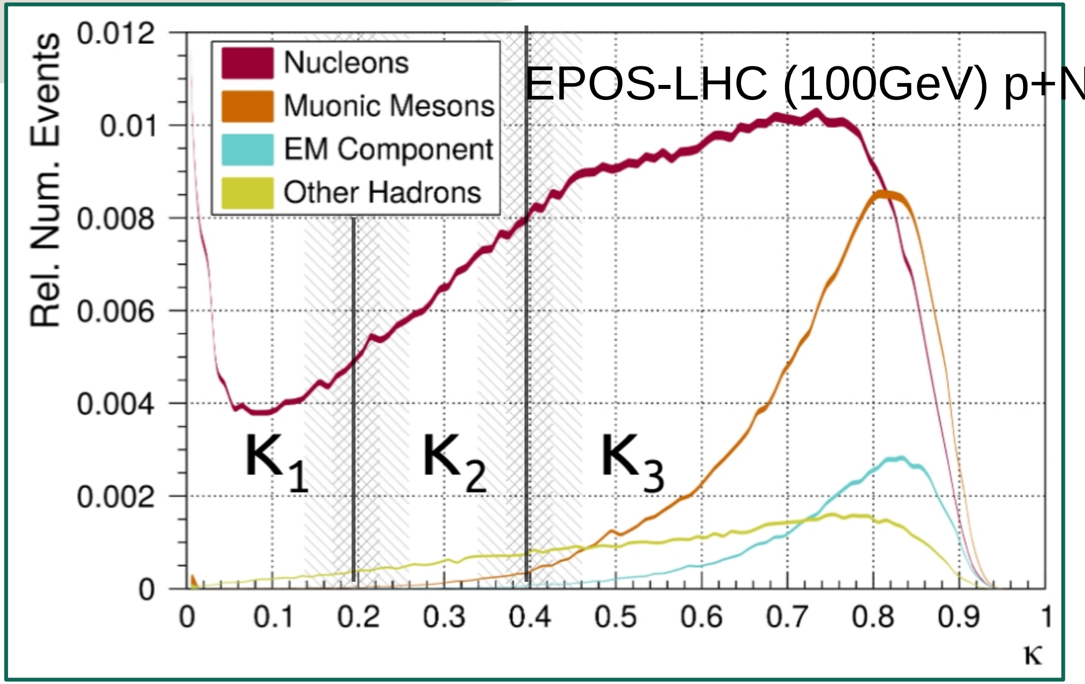
Event characterization

Nucleons	$p, \bar{p}, n, \bar{n}$
Muonic mesons	$\mu^+, \mu^-, \pi^+, \pi^-, \rho^0, K_L^0, K^+, K^-, K_S^0$
EM component	γ, e^-, e^+, π^0
Other hadrons	$\Lambda, \Sigma^+, \Sigma^-, \bar{\Sigma}^-, \bar{\Sigma}^+, \Xi^0, \Xi^-, \Omega^-, \bar{\Lambda}, \ldots$

$$\kappa = 1 - \frac{E_{LP}}{E_{pFI}}$$

E_{pFI}: Total shower energy after the first interaction.
E_{LP}: Leading particle energy.

- Most common leading particles:
  1. Nucleons ~66%
  2. Muonic mesons ~20%
  3. Other hadrons ~ 6%
  4. EM component ~ 6%

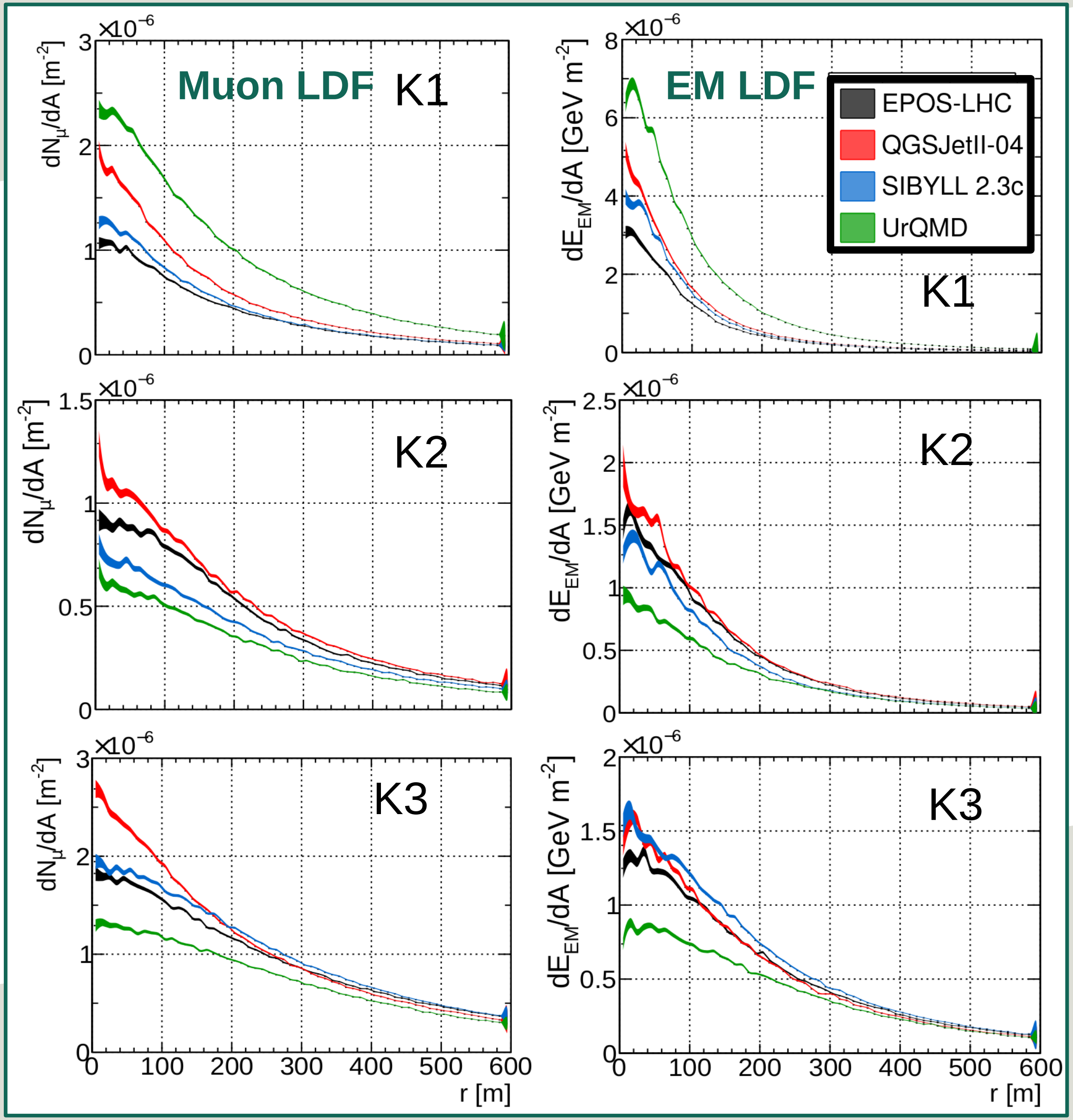


K_1 ~> Elastic events
K_3 ~> Inelastic events

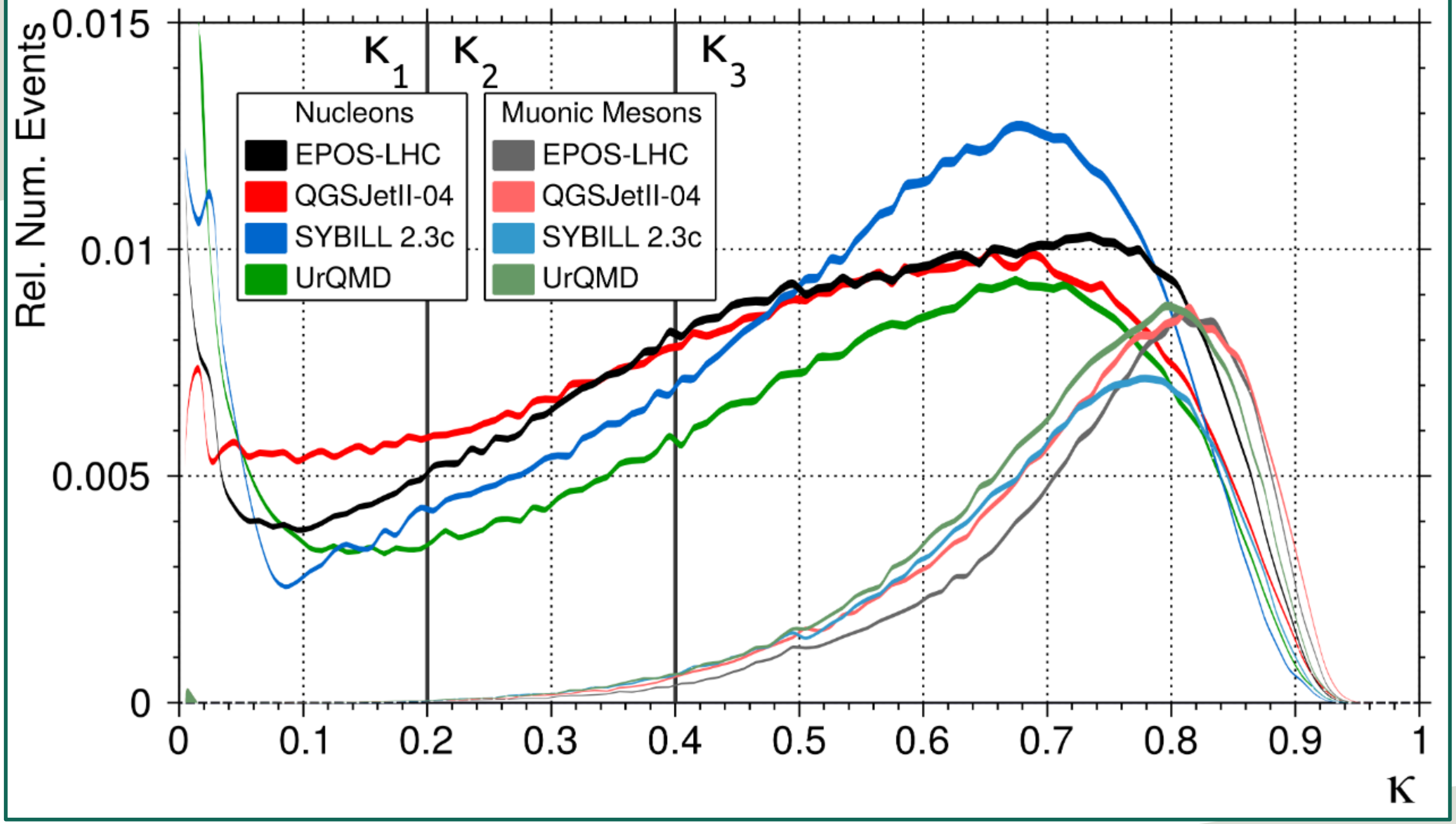
Deconstructing nucleon led events

- **UrQMD** really different. Largest component from elastic events.
- **EM component** grows with elasticity.
- **QGSJetII-04** creates more muons at short distances.

We would expect similar contributions in “same” physical nature showers.



First interaction inelasticity

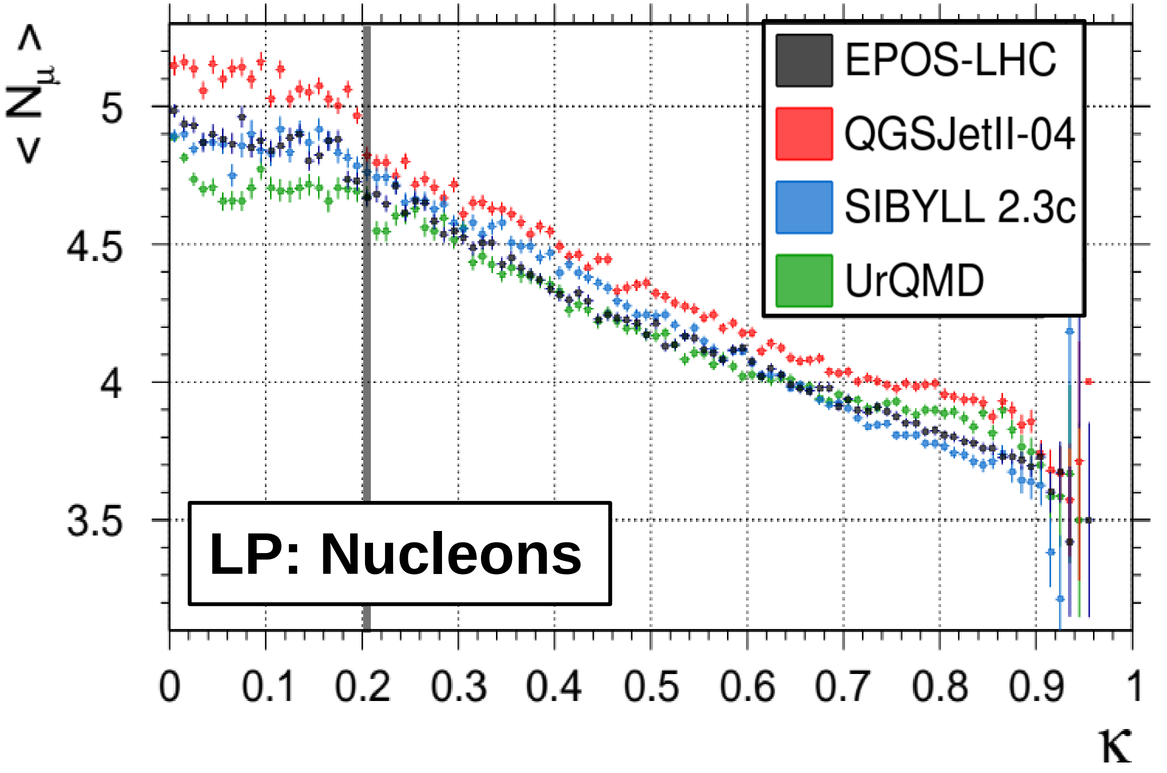


Significant differences between models:

- **UrQMD** enhances highly elastic intial events.
- **QGSJetII-04** enhances events as soon as energy is available for particle production.
- Disagreement in the transition regime K~0.1 .
- **SIBYLL2.3c** large number of inelastic proton led events.
- Dissimilarities in the muonic mesons led distributions.

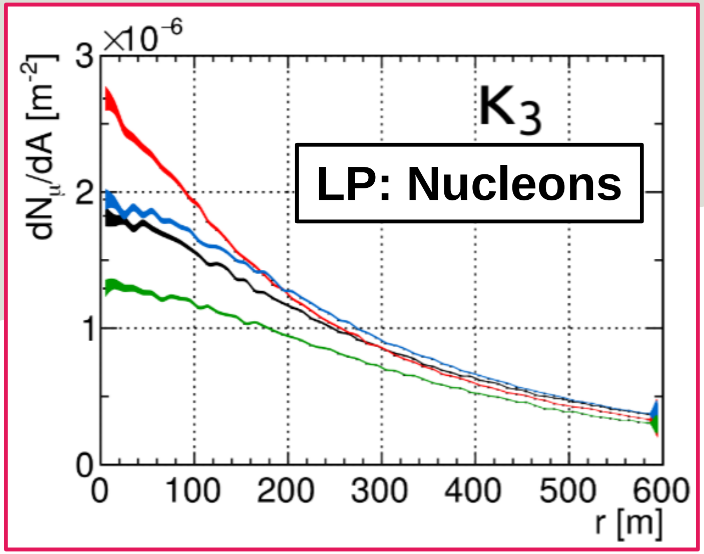
Differences in the regimes normalization account for most of the ground level dissimilarities.

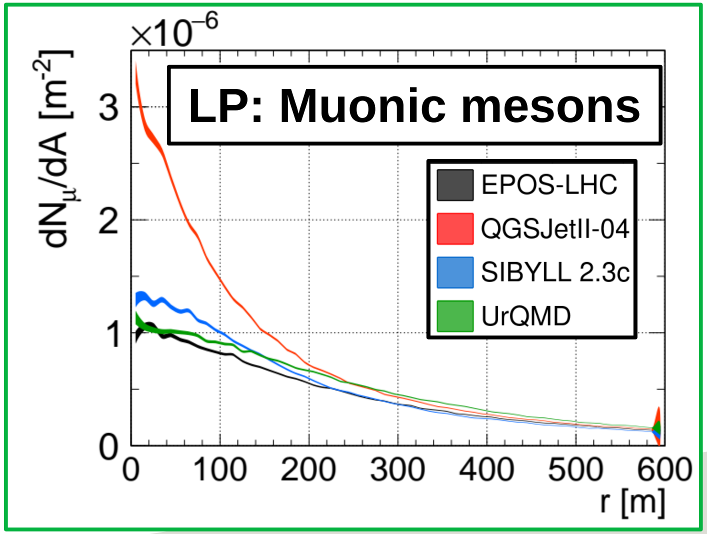
Average shower impact



- **QGSJetII-04** creates more muons at all inelasticities.
- **Secondary particles spectra** matter and **differ** between models.
- Abrupt change in the slope in the low energy model switch (K~0.2). (Difference between high and low energy model shown explicitly?)

Transverse momenta





Average number of GL muons from diff. First interaction scenarios

Leading Particle:	Nucleons				Muonic mesons				TOTAL
	κ_1	κ_2	κ_3	Total	κ_1	κ_2	κ_3	Total	
EPOS-LHC	0.463	0.585	1.794	2.842	0.001	0.008	0.711	0.719	4.006
QGSJetII-04	0.573	0.631	1.705	2.909	0.000	0.012	0.838	0.850	4.156
SIBYLL 2.3c	0.488	0.502	1.851	2.841	0.000	0.015	0.688	0.703	3.986
UrQMD	0.995	0.406	1.452	2.852	0.001	0.014	0.806	0.821	4.022

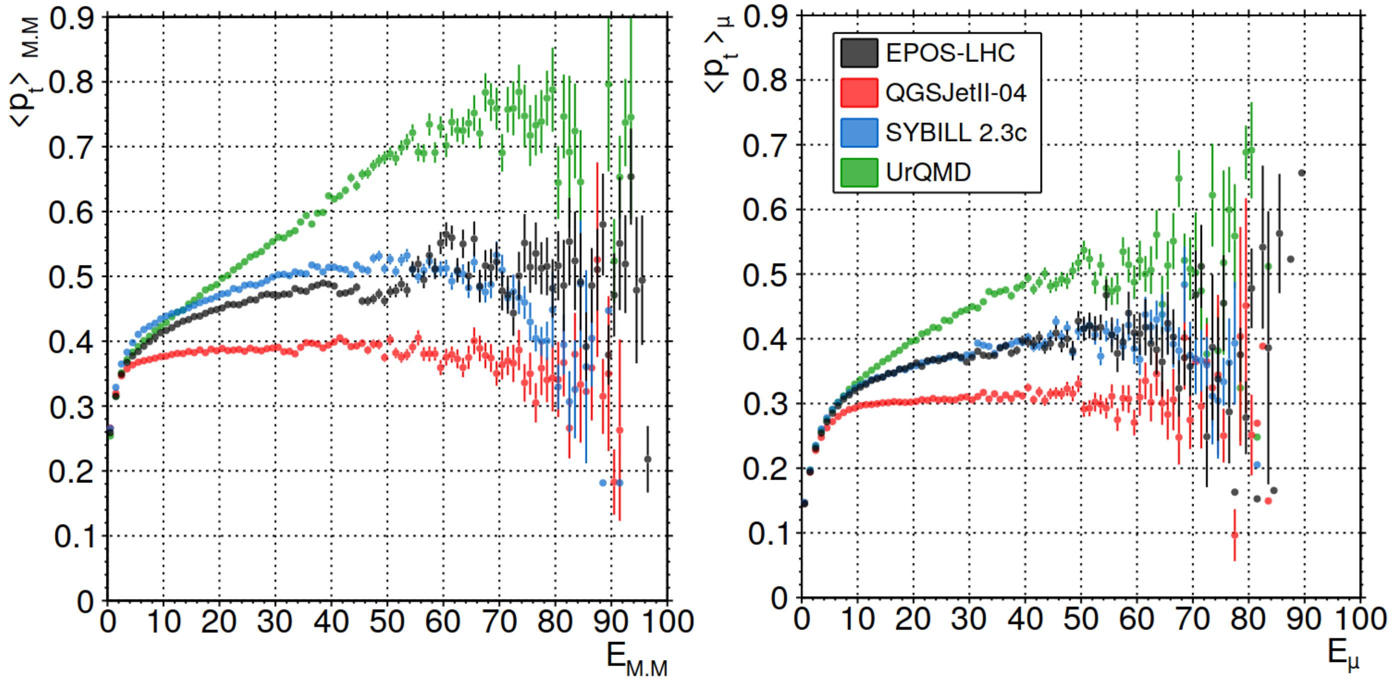
Muon number at short core distances (r <200m) does not represent the total.

- QGSJetII-04 concentrates muons at short core distances while UrQMD spreads them.

Transverse momenta

Relation between first interaction muonic mesons and GL muons. First interaction analyzable from the GL.

All events



- **QGSJetII-04** concentrates muons at short core distances while **UrQMD** spreads them.
- Disagreement between high and low energy models.
- Muonic mesons over 40GeV mostly leading particles.

Summary and discussion

No single argument for dissimilarities.

Some discussed points:

- **Inelasticity distributions** differences. (Account for absolute GL differences).
- Different rate of event types and secondary particle production.
- Muonic mesons p_t .

Energies well within the regime for collider **experiments**. (Post-LHC models).

Is there any validated hadronic interaction model at these energies?

- Difference between high and low energy models. Well defined transition regime?
- Differences scaling at higher initial energies?
  - Could this be causing a muon lack somewhere?
  - Do low energy dissimilarities affect secondary interactions in higher energies initiated showers? ...

?

EPOS-LHC:

- Similar GL outcome as SIBYLL 2.3c but different particle production.
- Effective secondary nucleons over muonic mesons.

QGSJetII-04:

- Better available energy distribution.
- Enhancement of events with particle production.
- Low pt muonic mesons and GL muons.

SIBYLL 2.3c:

- Enhancement of nucleon led inelastic events over muonic mesons (more energy into nucleons).
- Muonic mesons led events accompanied by high energy nucleons.

UrQMD:

- Larger proton-Air cross-section.
- Large enhancement of elastic events. Together with such high cross-section results in a different behavior
- Large pt muonic mesons and GL muons.