FPF Implications and Opportunities for QCD and Astroparticle

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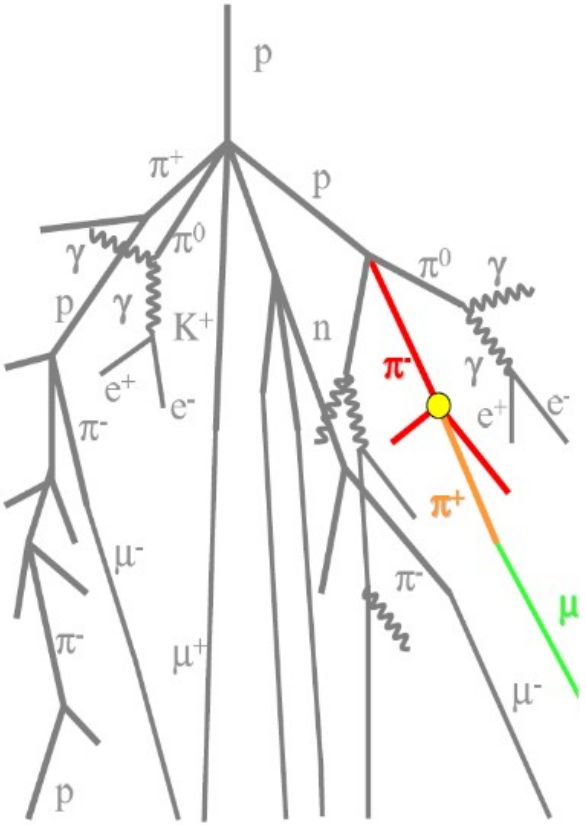
Air Showers and Hadronic Interactions



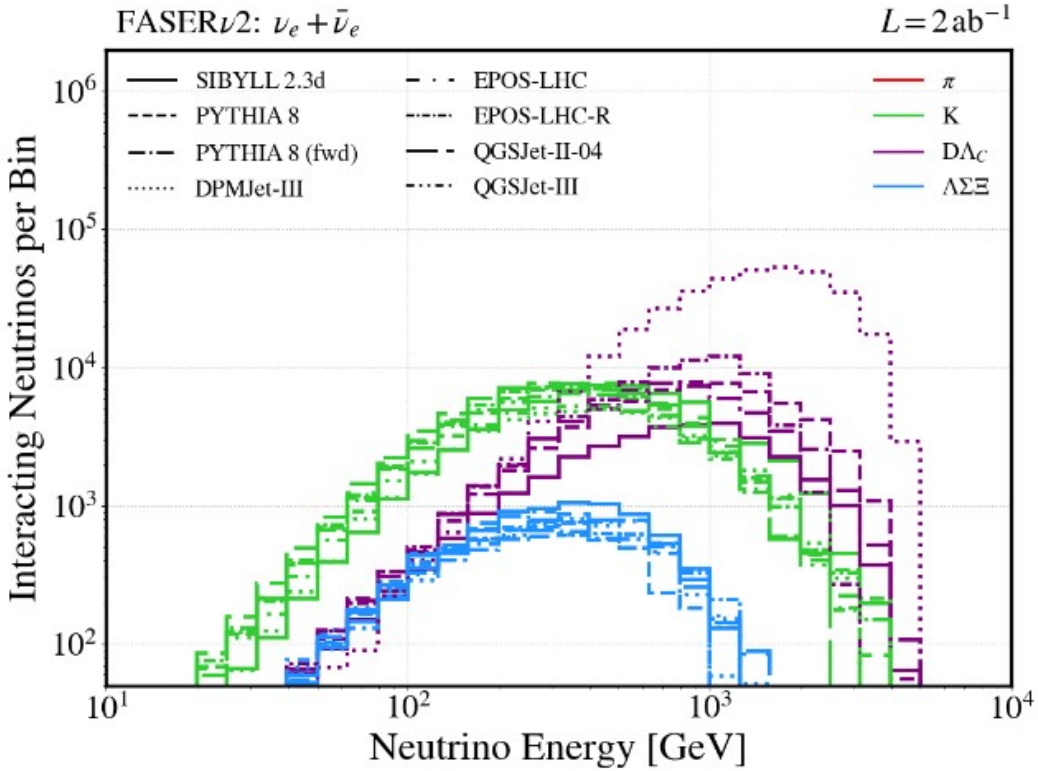
From R. Ulrich (KIT)

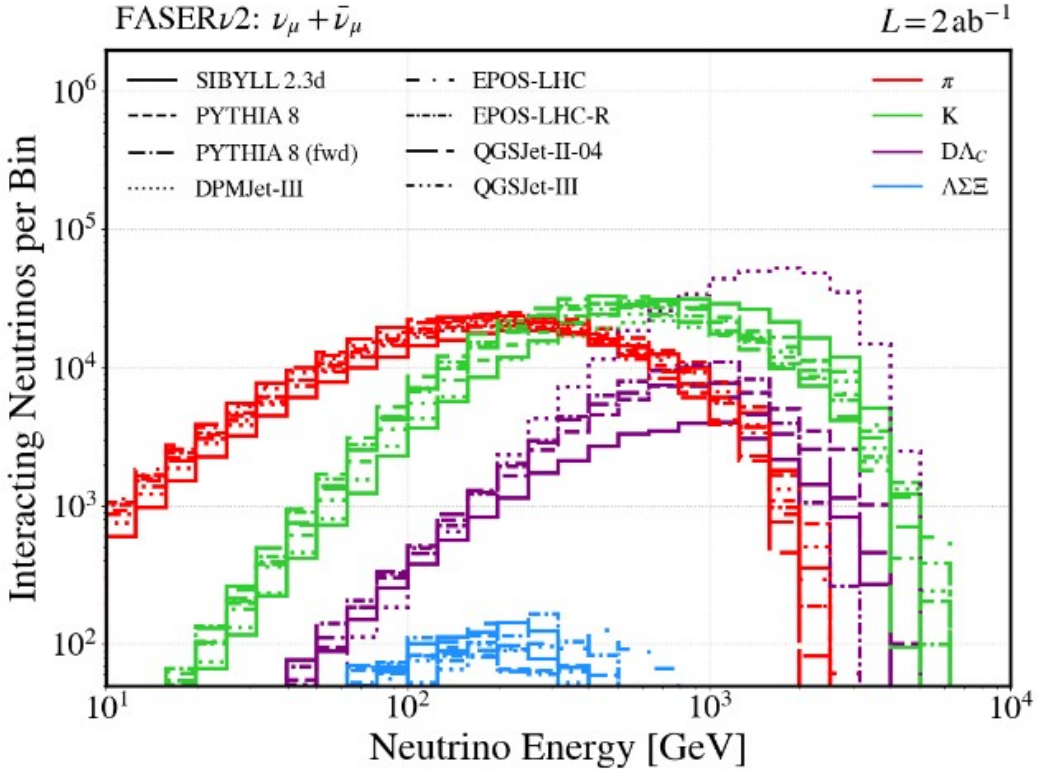
- **Air shower development dominated by few parameters**
  - cross-sections (p-Air and (π-K)-Air)
  - (in)elasticity
  - multiplicity
  - charge ratio and baryon production
- **Change of primary mass or energy = change of hadronic interaction parameters**
  - cross-section, elasticity, mult. …
- **Models constrained by theory**
- **Models tuned to reproduce accelerator data**

By measuring forward neutrinos, the FPF can constrain the hadronization (particle ratios) leading the muon production.

Test on Various Hadronic Interaction Models

- **FPF will be able to measure forward neutrino production with high sensitivity**
  - Phase space relevant for air showers ($x_{lab}>10^{-4}$)
  - Unique sensitivity to particle yields (strangeness and charm)
  - Large differences between models … but at mid-rapidity too !





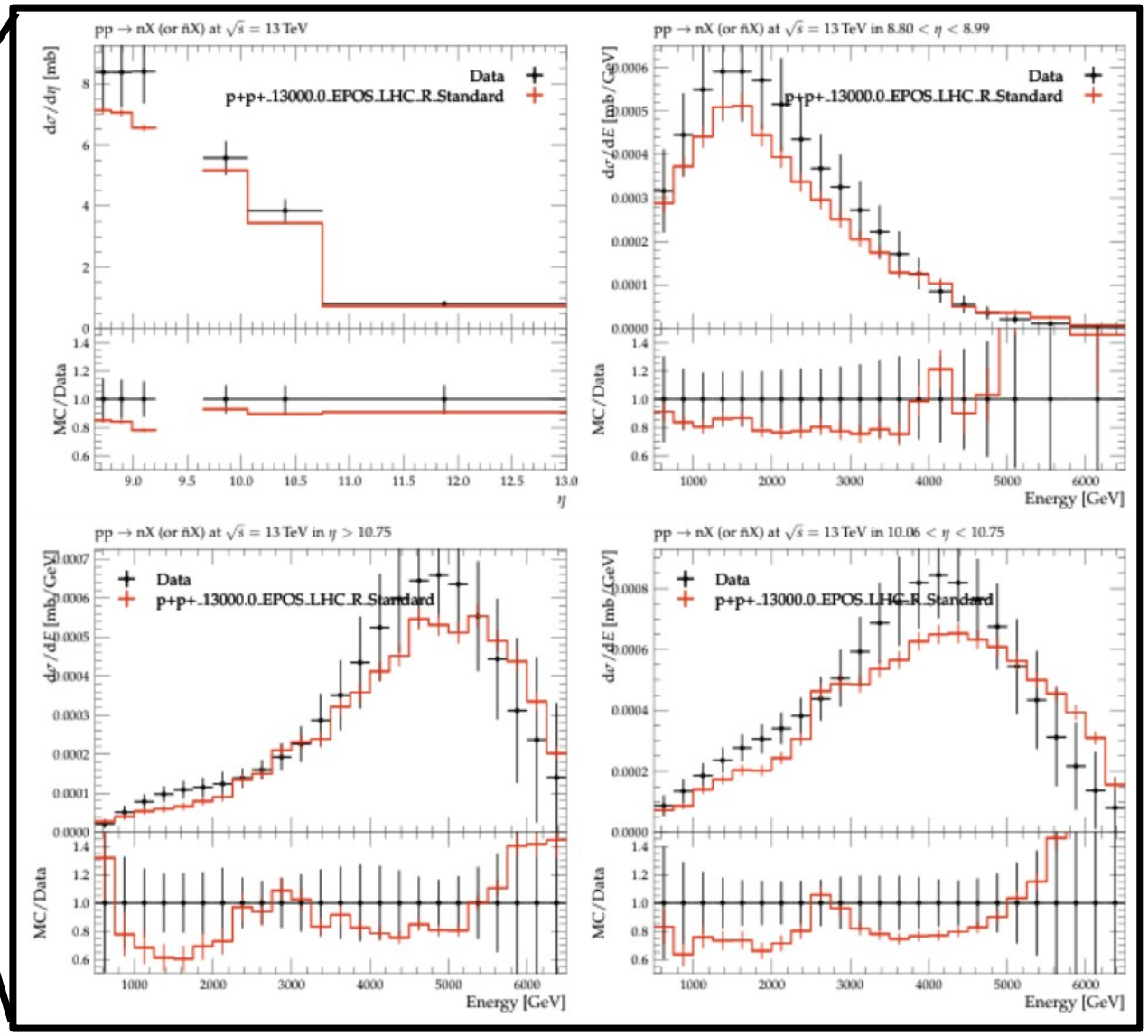
arxiv.org/abs/2510.26260

Model Quality

- Use all RIVET analysis (~800 plots) that EPOS, QGSJET and Sibyll can run

Inspire | HepData | Analysis reference | arXiv:2003.02192

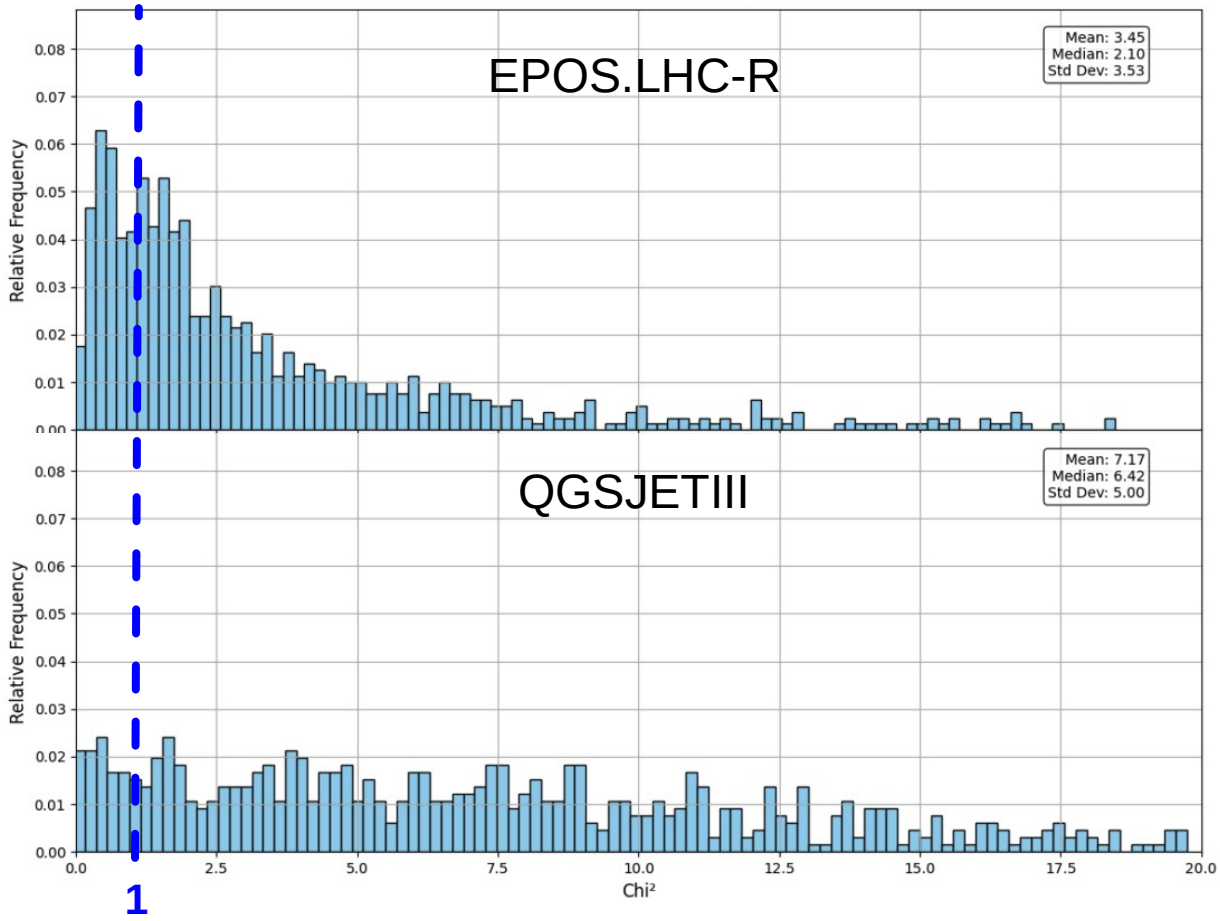
LHCf



Plots by Kamil Delassoud

Model Quality

- Use all RIVET analysis (~800 plots) that EPOS, QGSJET and Sibyll can run
- Plot the reduced Chi2 distributions of all the plots
  - EPOS (Pythia) reproduce existing data significantly better

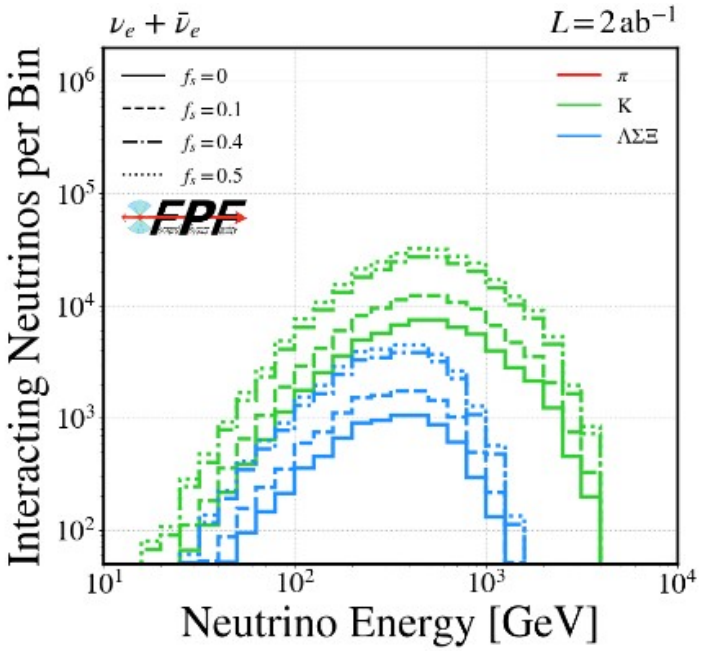


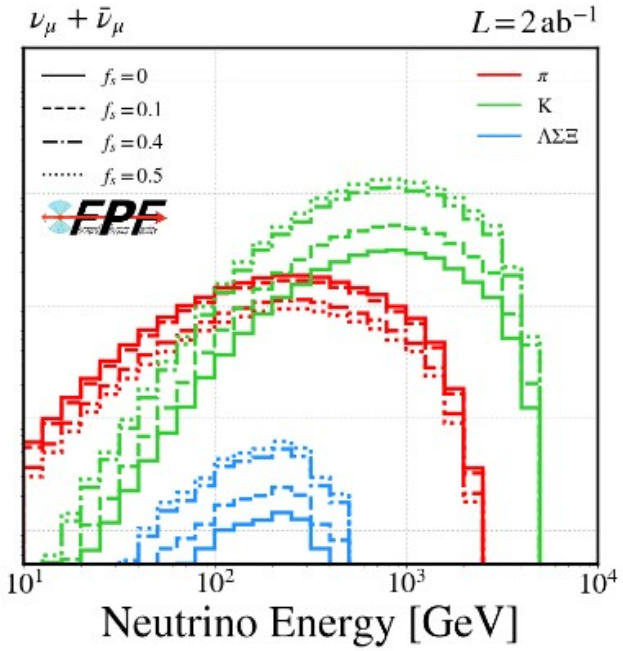
Plots by Kamil Delassoud

- Once properly tuned at midrapidity, can something be seen @ FPF ?

Test Scenario for the Muon Puzzle

- **FPF will be able to measure forward neutrino production with high sensitivity**
  - Phase space relevant for air showers ($x_{lab}>10^{-4}$)
  - Unique sensitivity to particle yields (strangeness and charm)
  - Sensitive to a model like piKswap or Sibyll* but …
    - Simplistic ad-hoc models with effect phase-space independent ! Overestimation ?





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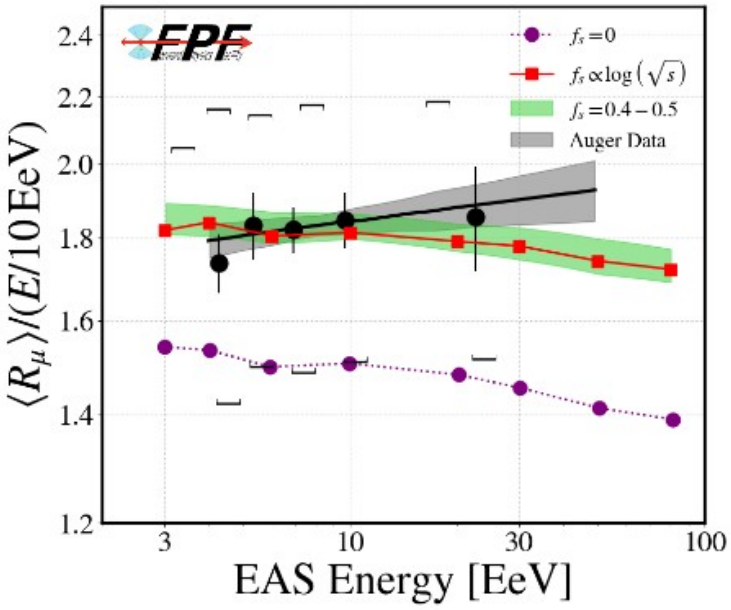
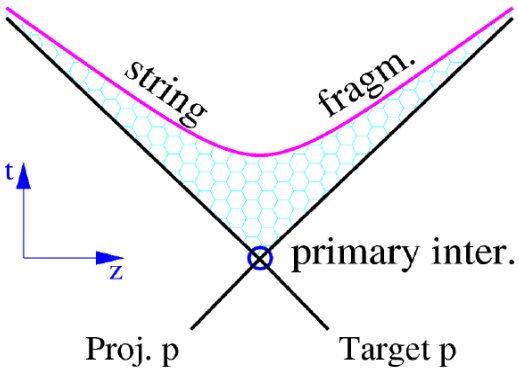


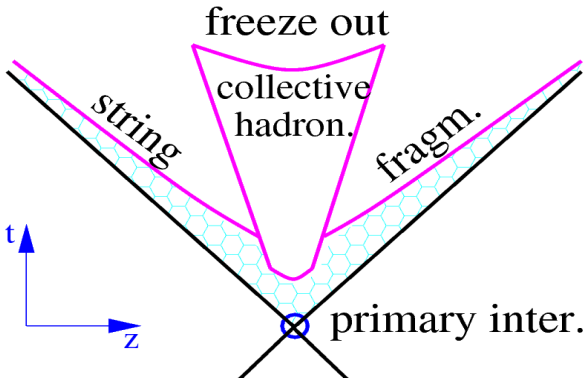
What means global approach ?

Global approach is the key !

- Tuning models neglecting some physics process lead to wrong parameters !
- Proper tune possible to do, only if everything is taken into account
  - All collective effects considered for the first time in EPOS.LHC-R !
- Either with a direct impact on the shower development (new elasticity)
- Or no direct impact on the shower development but change model parameters… leading to different shower properties.

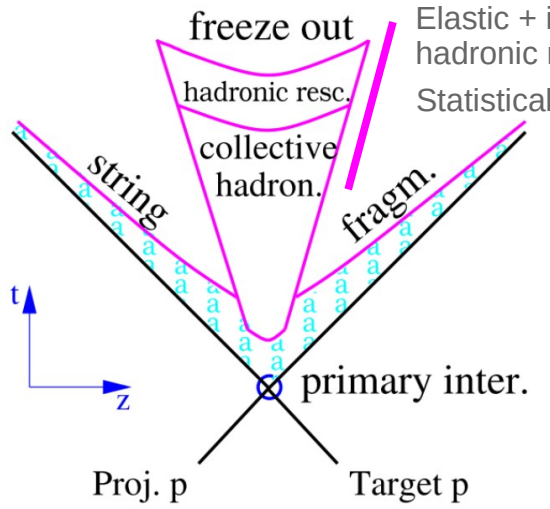


Sibyll, QGSJET



EPOS LHC
(no rescattering)

All collective effects
Elastic + inelastic hadronic rescattering
Statistical hadron.

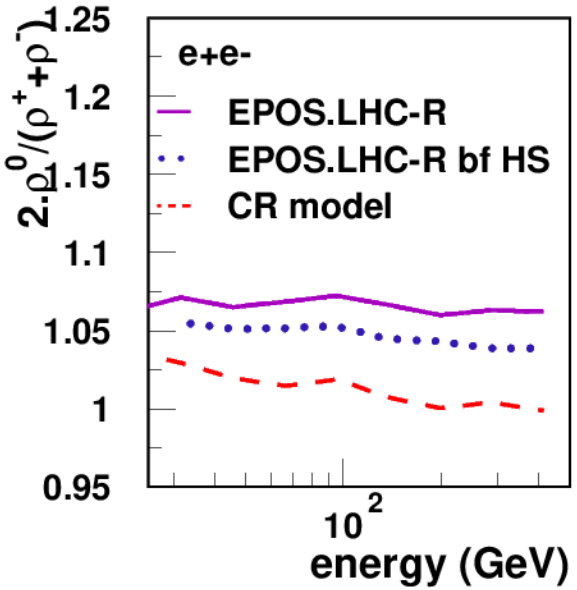


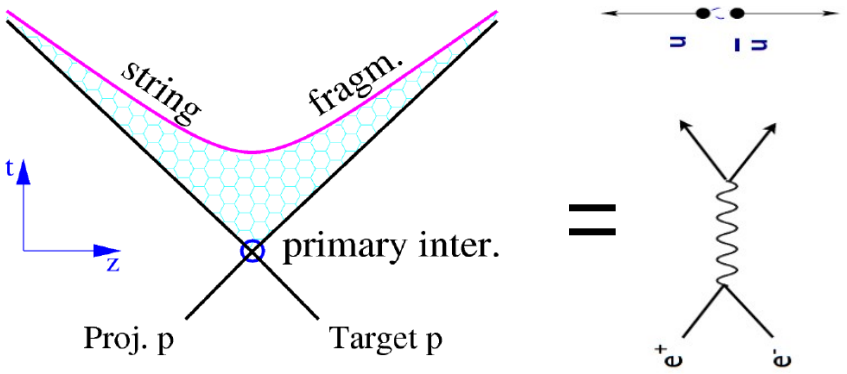
EPOS.LHC-R
(with hadronic rescattering)

String Fragmentation

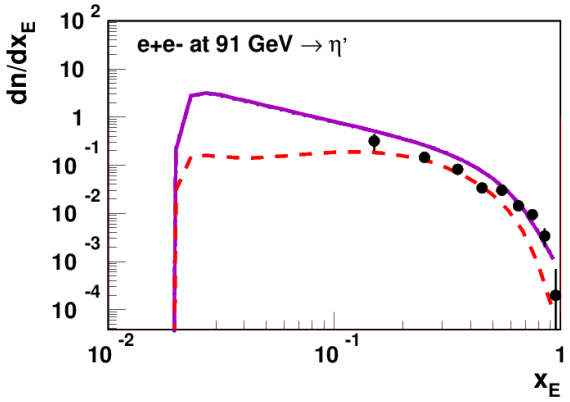
Universal scheme for particle production

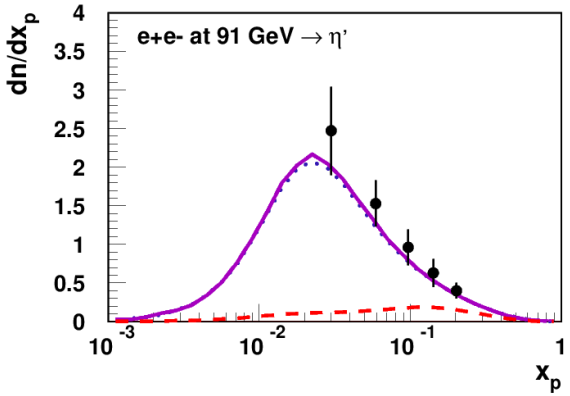
- Common hadronization in all the models
- Parameters fixed on e+-e- only in EPOS
  - Other CR models tuned on p-p data
    - Possible biases (remnant, density)
    - Less data on high mass resonances (isospin symmetry at production ➡ isospin asymmetry after decay)
- Very important for forward particle production (EAS)
  - Used for beam remnant hadronization





Used in dilute systems = CORONA

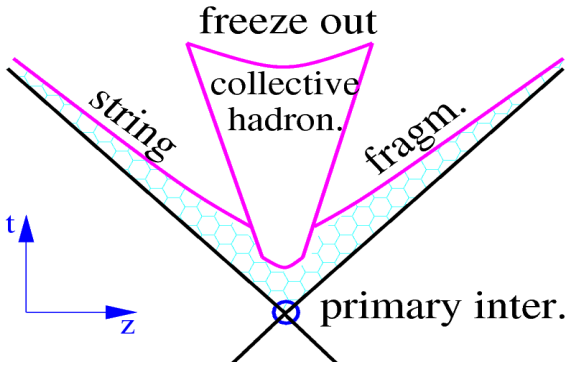




Produce η' and f_0 in addition to η (to conserve isospin) ➡ introduce asymmetry for ρ (and π)

Core-Corona (co-co)

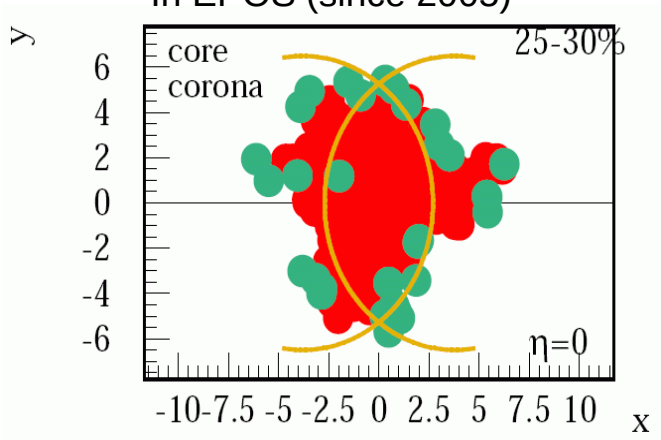
- **Core hadronization** = thermal hadronization of Quark Gluon Plasma
- **Mixing of core and corona hadronization needed to achieve detailed description of p-p data (ref K.Werner)**
  - Evolution of particle ratios from pp to PbPb
  - Particle correlations (ridge, Bose Einstein correlations)
  - Pt evolution, …
- **Both hadronizations are universal but the fraction of each change with particle density**



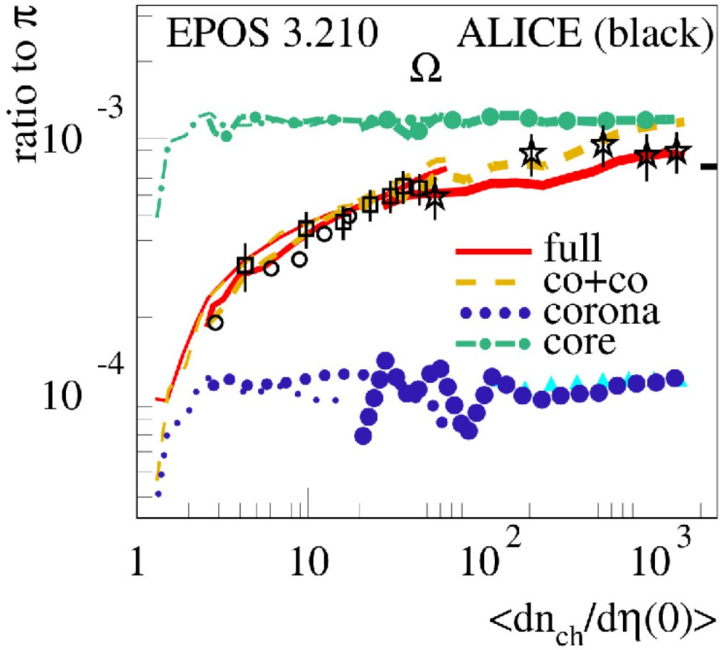
Difference high/low multiplicity

- **2 simultaneous source of particles**

In EPOS (since 2005)



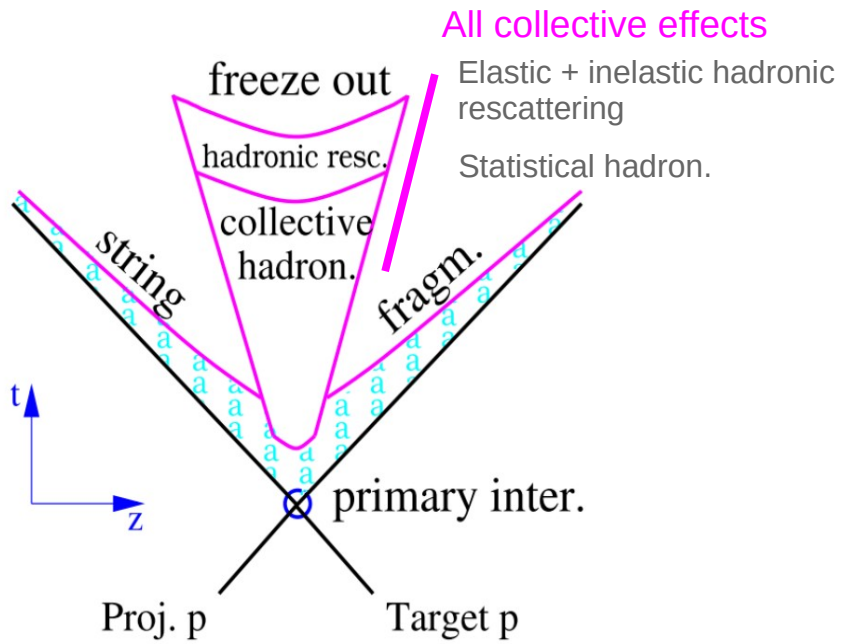
p-p ,Pb-p, Pb-Pb data

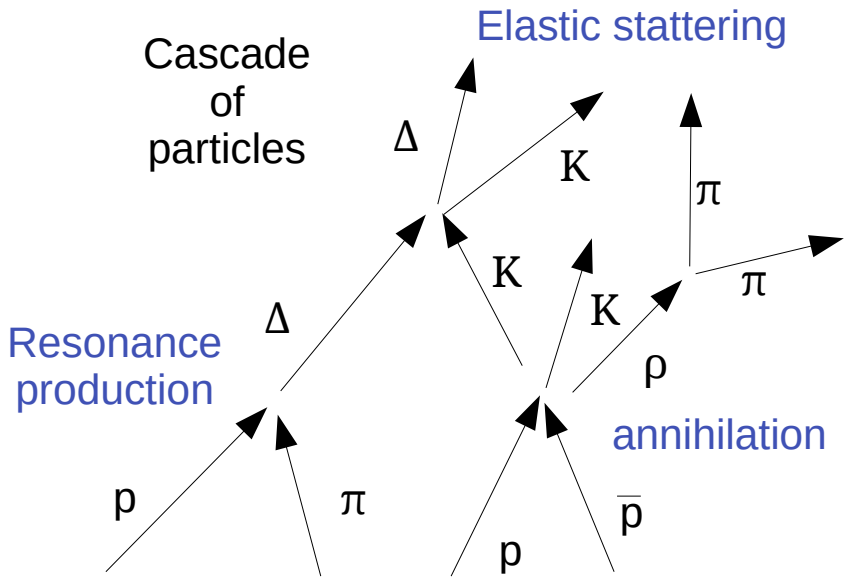


Hadronic reScattering (HS)

Missing effect in all CR models until now !

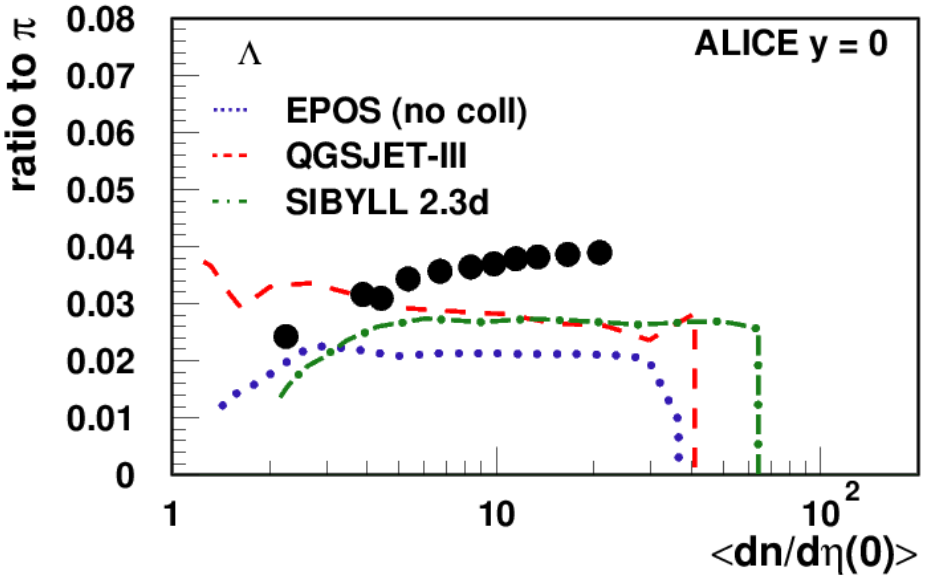
- Re-interaction of hadrons after parton hadronization (space-time evolution)
- “traditionally” used only for heavy ion collisions (until recently NOT in p-p)
- No direct impact on EAS development since forward particles escape
- But significant to large impact at midrapidity in heavy ion collisions !
  - Applied to all system (from e+-e- to PbPb) !

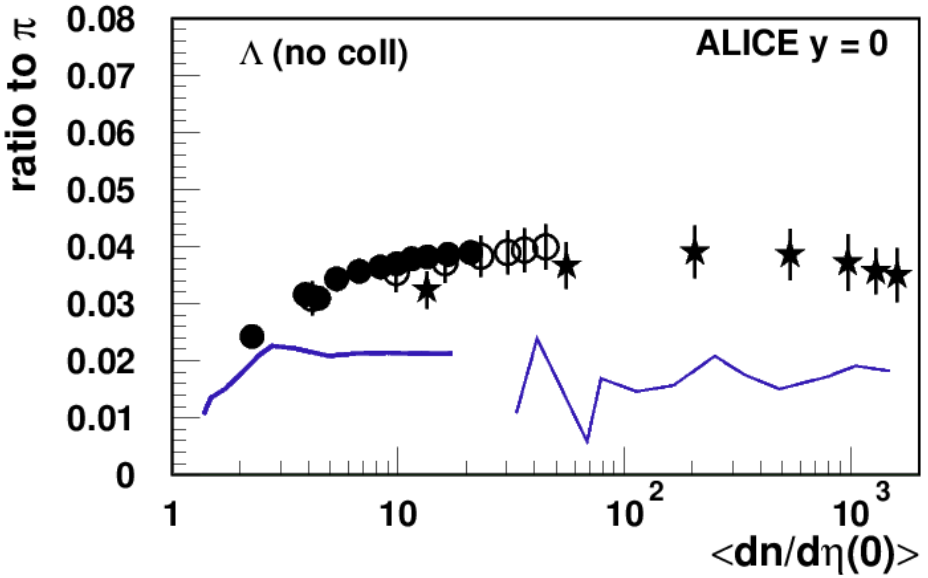


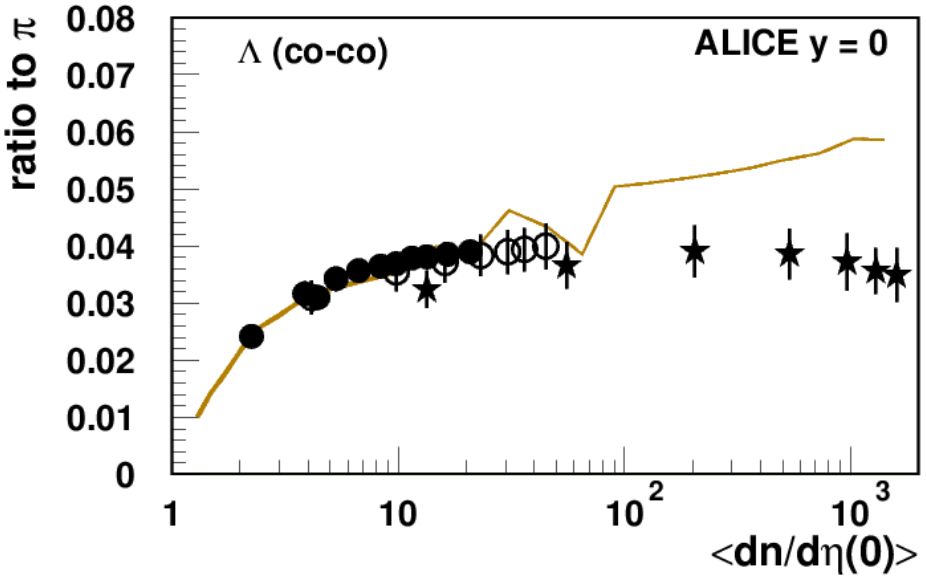


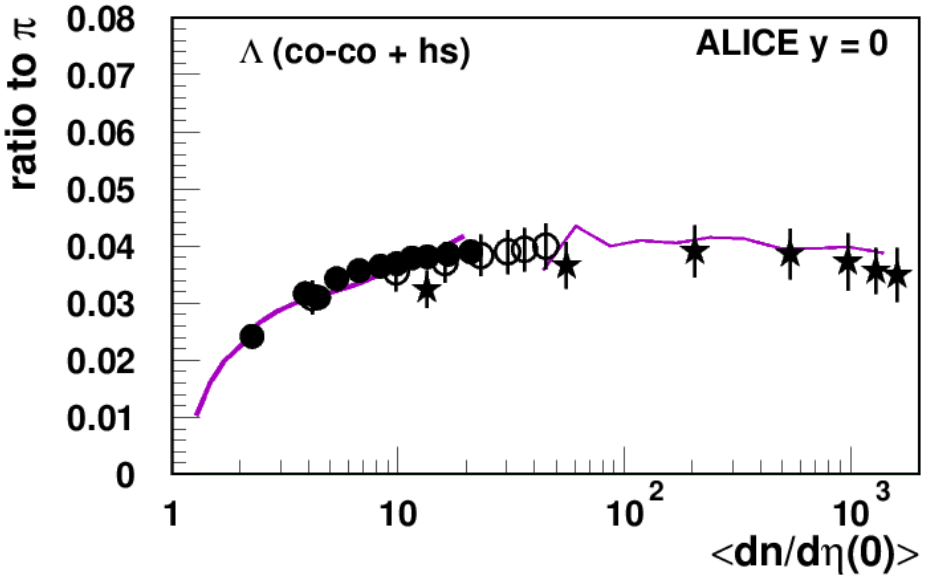
Difference small/large rapidity (emission angle)

Example with Lambda particle in p-p and Pb-Pb @ LHC

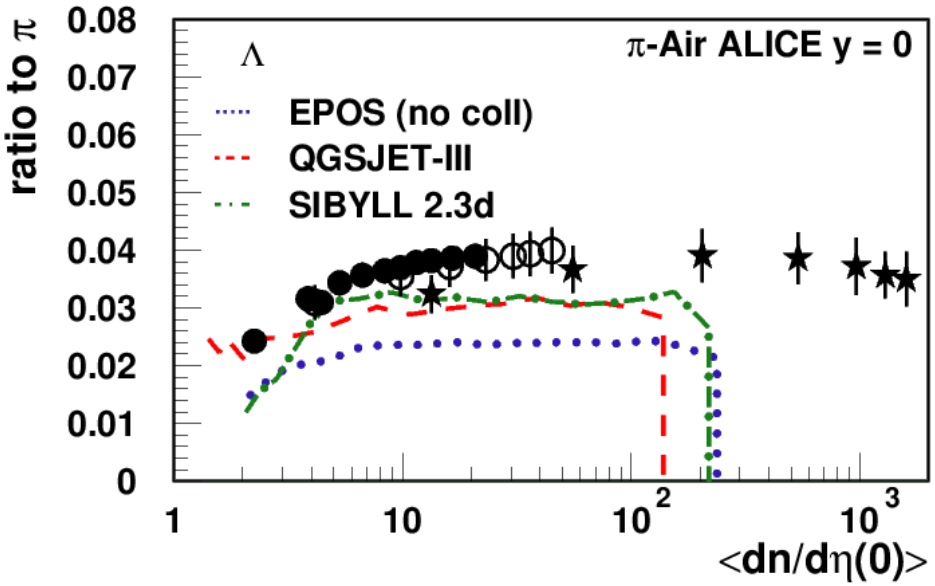


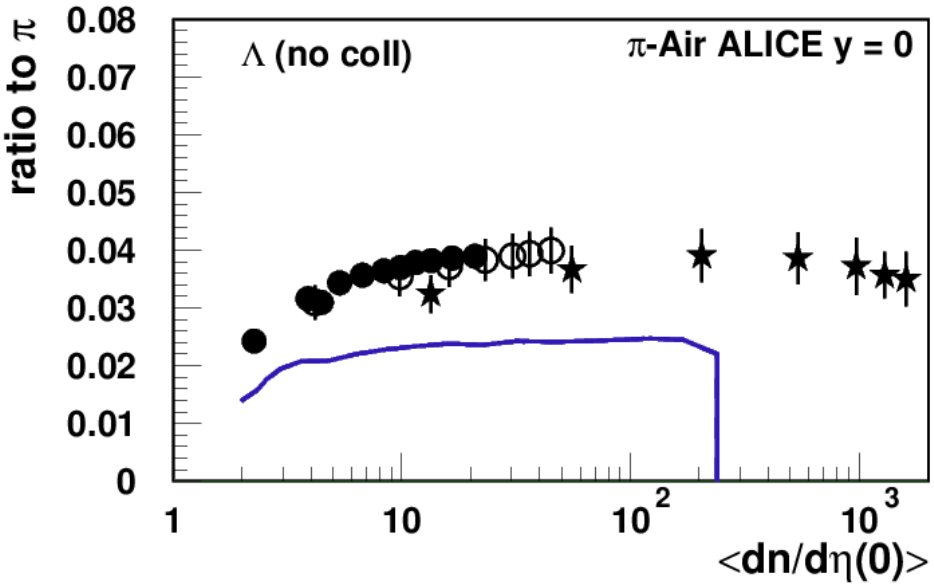


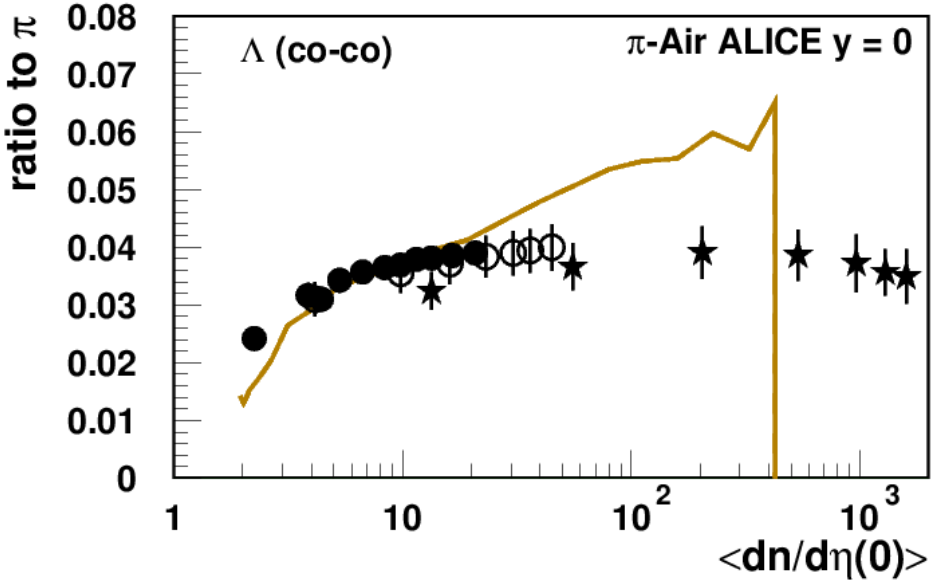


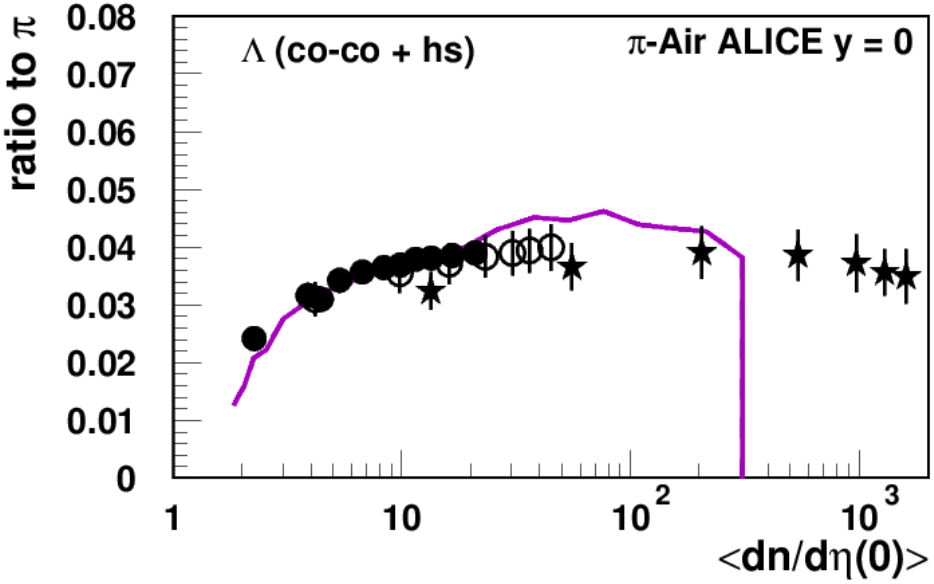


Example with Lambda particle in π-Air @ all energies





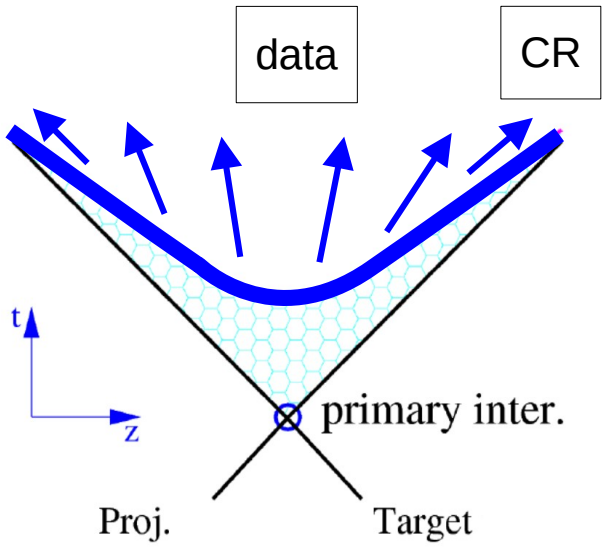




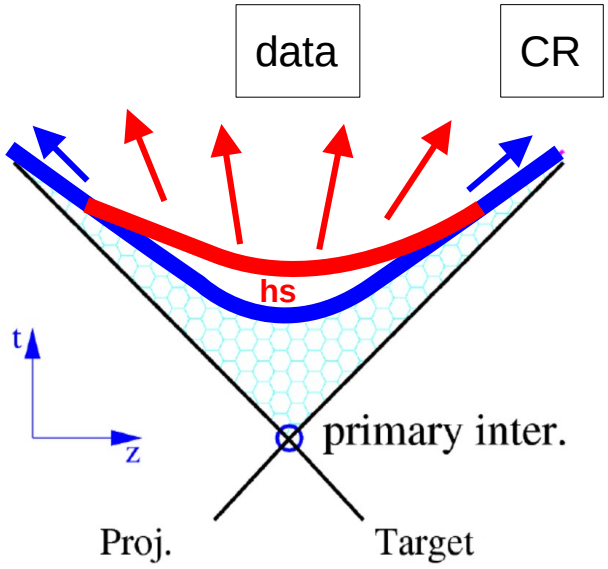
What is really new ?

Collective effects are important to tune properly the models !

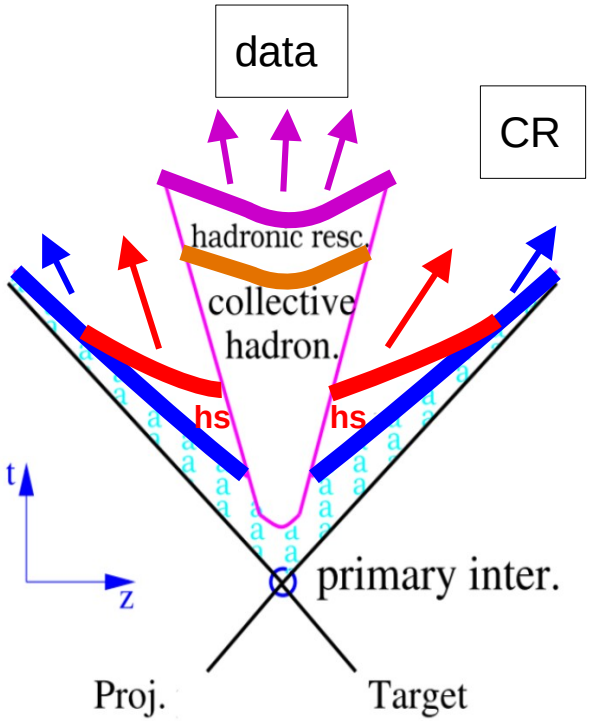
- Change multiplicity/elasticity and hadronization depending on particle density
  - Introduce energy + centrality dependence in accelerator data comparisons
  - Modify model parameters
    - Multiples mid-rapidity particle production mechanisms
- Change ratio between π and ρ in string fragmentation depending on phase-space
    - Forward particle production not the same than at mid-rapidity



No collective effects



Hadronic reScattering (hs)

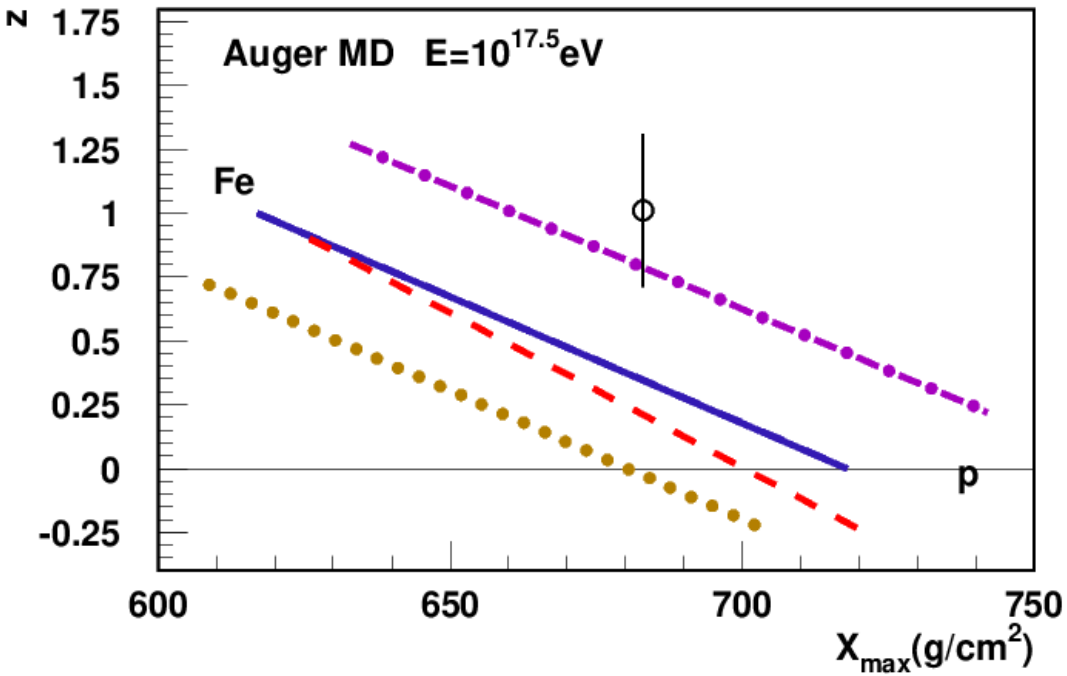


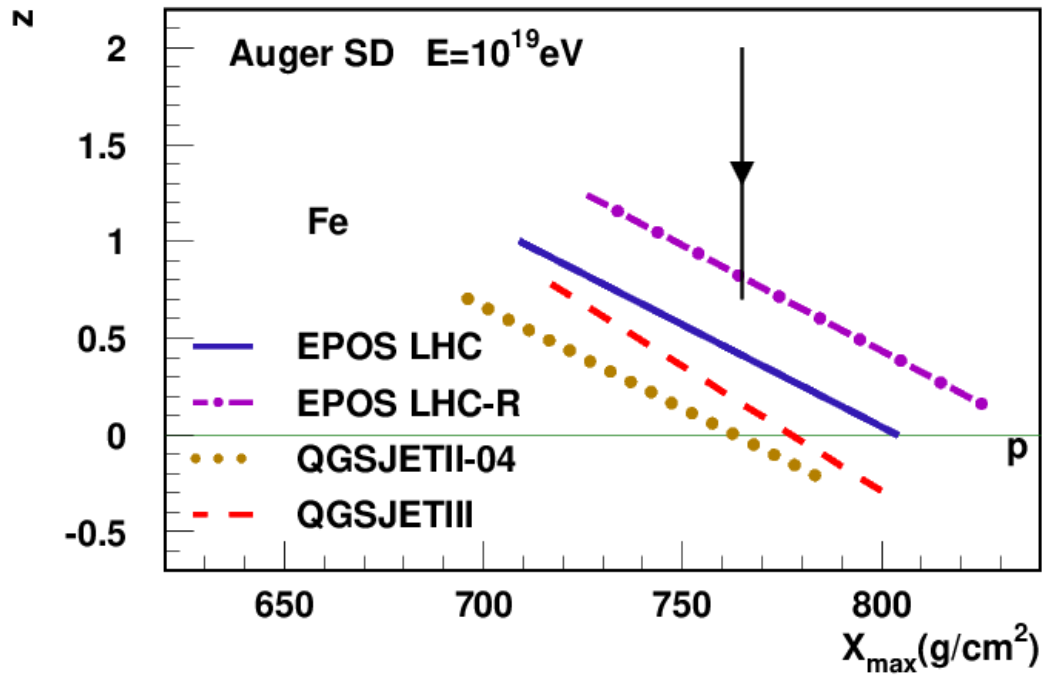
Muon Puzzle Solved ?

EPOS.LHC-R, first model producing a deeper X_{max} and more muons and being compatible with all measured accelerator data :

- Deeper X_{max} give larger <lnA> reducing the gap with measured muon content
- Increase of muons further decrease the gap to reach Auger systematics
- Change not large enough for QGSJET
- Still problem seen in the zenith angle dependence
  - Still not enough muons for vertical showers ! Need more...

$$z = \frac{\ln N_{\mu}^{\rm det} - \ln N_{\mu,p}^{\rm det}}{\ln N_{\mu,{\rm Fe}}^{\rm det} - \ln N_{\mu,p}^{\rm det}}$$

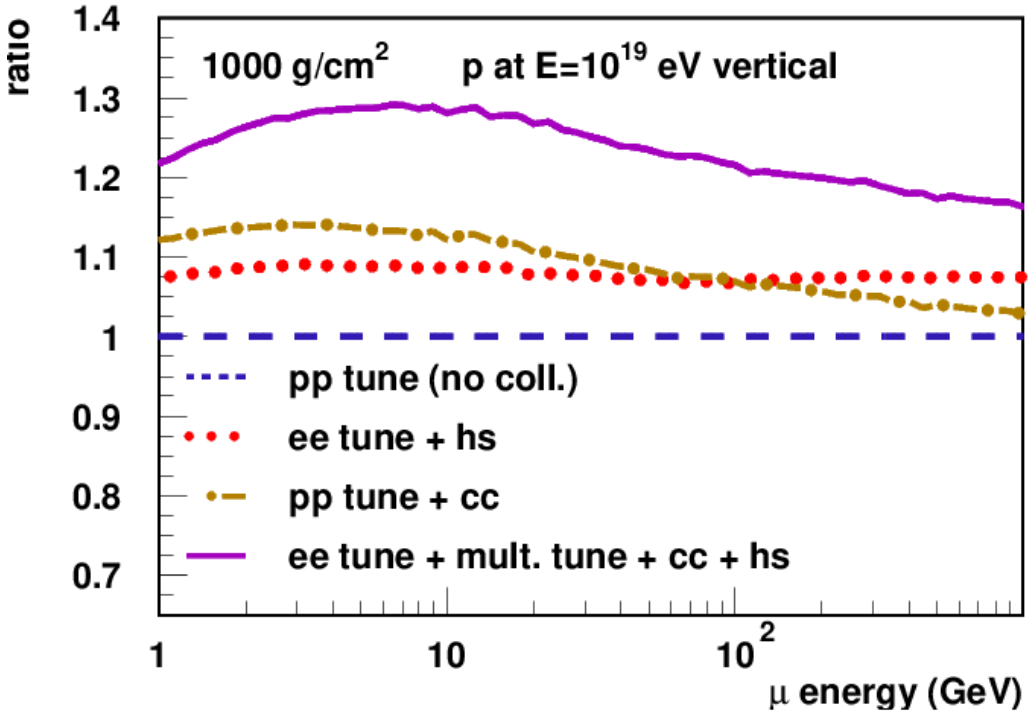


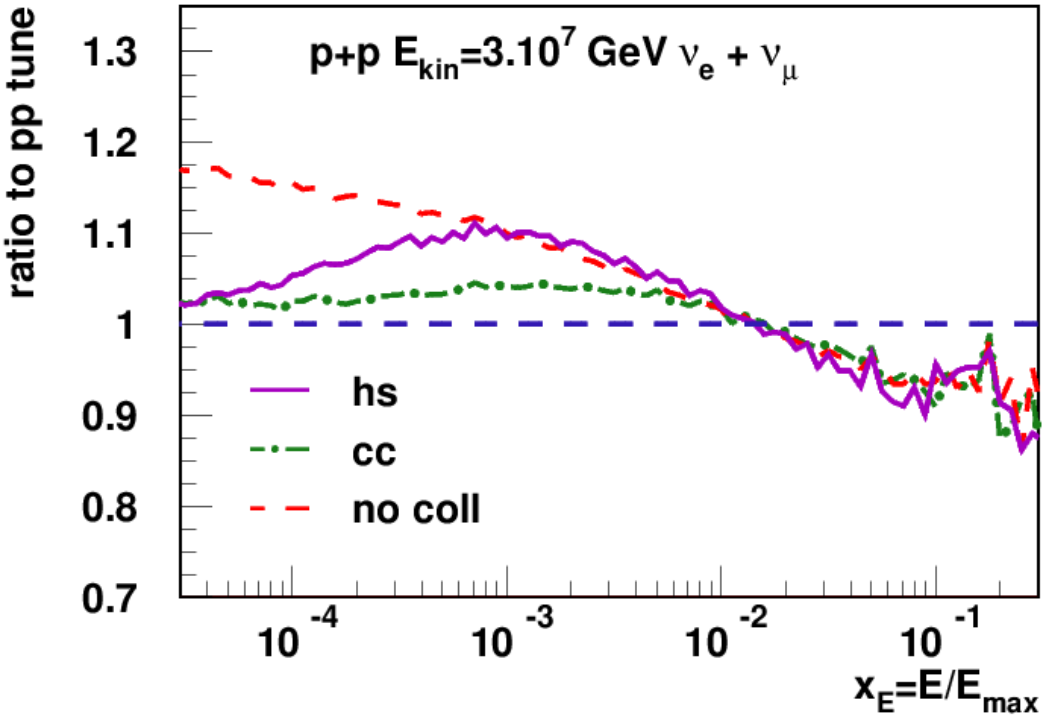


Impact of differences

Changes with new tune taking into account collective effects (LHC)

- Increase the number of muons by ... 10 to 20% (different slope) !
  - Impact of core-corona on baryon/strangeness prod. AND change in multiplicity/elasticity to accommodate hydrodynamical evolution (flow)
  - Impact of tune based on full e+-e- data with hs instead of just p-p/p-A
- Differences visible in the neutrino production
  - FPF sensitive to collective effects

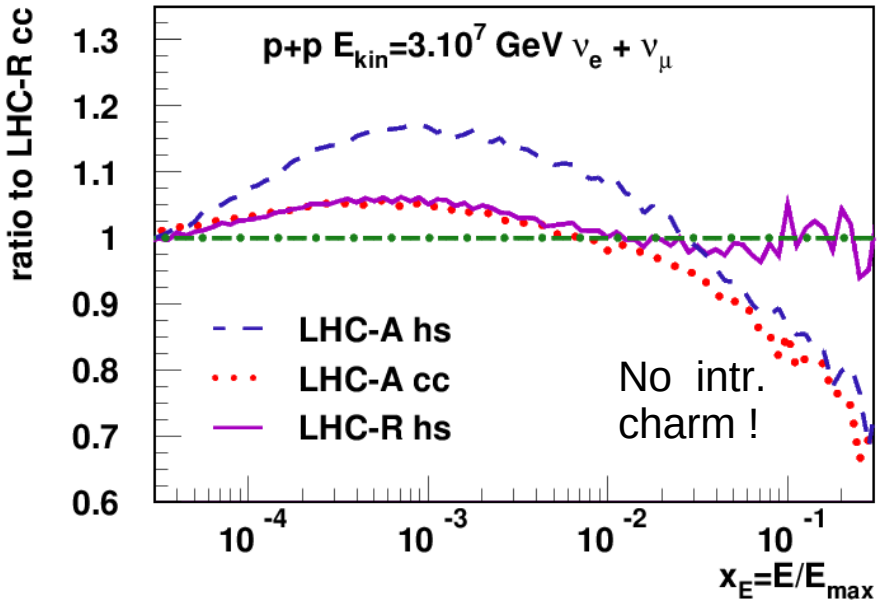


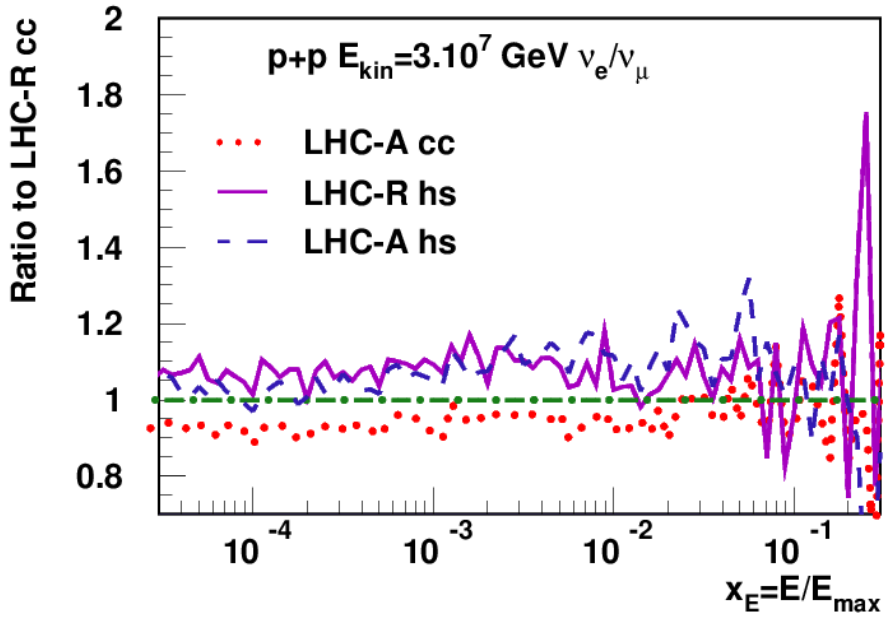


Change of String Fragmentation

ATROPOS*, new model to do string fragmentation by Roman Nikolaenko

- Complete new model (first time since decades) taking into account angular momentum conservation (new !) introduced in EPOS: EPOS.LHC-A
  - Tuned on same data (e+e-)
  - Isospin symmetry broken by new constraint on angular momentum: $\rho^0/\rho^{+/-} > 0.6$!
    - Muon production enhanced
- Differences visible in the neutrino production
    - FPF sensitive to details of hadronization and hadronic rescattering





Outlook

- **Current tests of FPF for forward particle production based on optimistic scenarios**
  - Models used for air showers but not all describing properly mid-rapidity data
  - Models to solve the muon puzzle too simple and artificial
- **Details of hadronization matters for muon production in air showers**
  - Important role of resonances
    - $\rho^0/\rho^{+/-}$ impacted by hadronic rescattering and decay of higher mass res.
  - Evolution of strangeness with multiplicity
    - Different type of hadronization in core = more muons
  - Phase space dependent effects appear when a proper global approach is used
- **Is FPF still sensitive enough when realistic simulations are used ?**
  - Forward neutrino production impacted by nuclear collective effects
  - Hadronic rescattering introduce some phase space dependence in the FPF range
  - Change of fragmentation model visible in the neutrino spectra

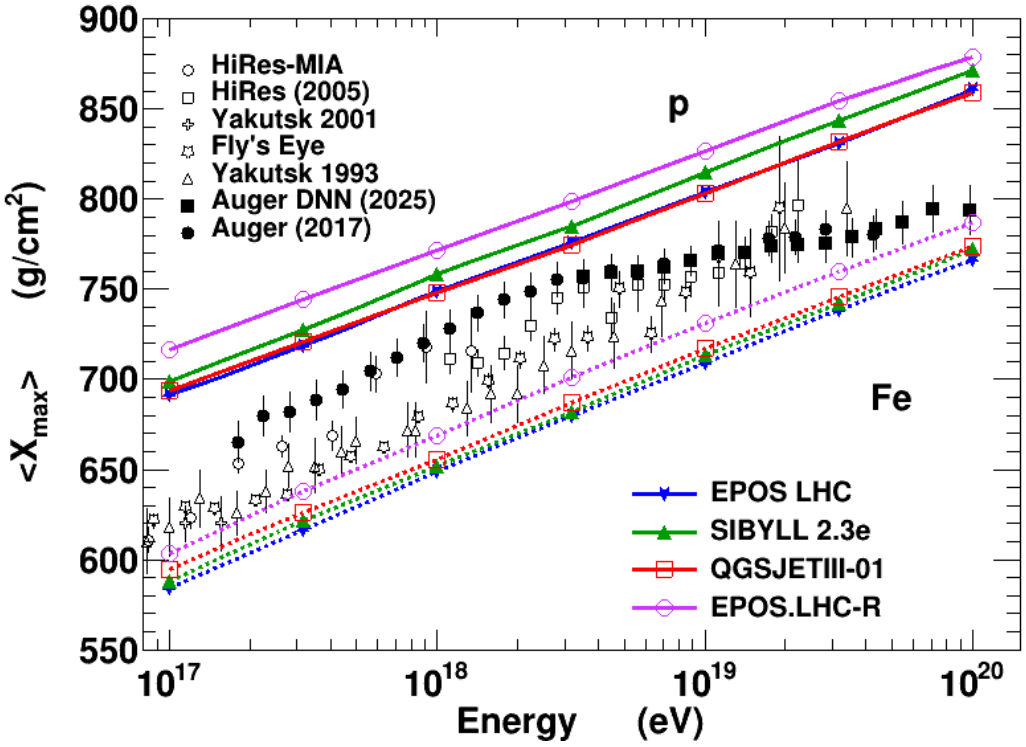
By measuring forward neutrinos, the FPF can constrain the hadronization (particle ratios) leading the muon production.

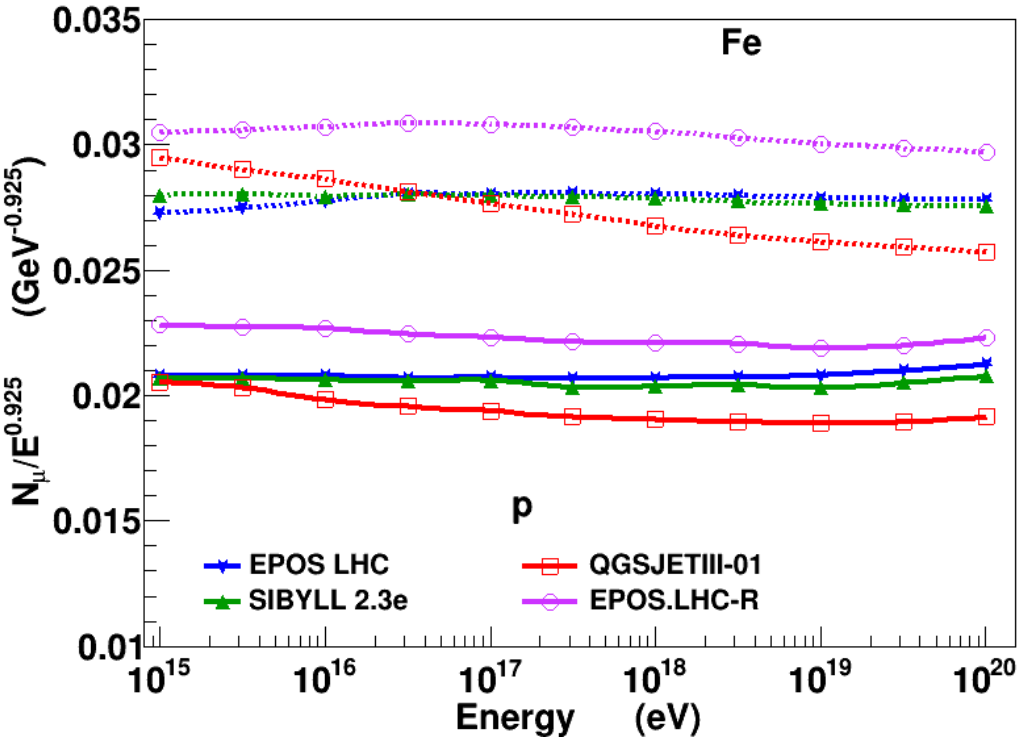
The sensitivity will be large enough even using a realistic model !

Thank you !

X_{max}

- Using a global approach and latest LHC data:
  - EPOS.LHC-R shifted by +20g/cm^2 (+/- 5g/cm^2)
  - Increase of the total number of muons by about 10% (+/- 5%) vs EPOS LHC
- Using latest LHC data and tradional approach:
  - QGSJETIII-01 shifted by +15g/cm^2 (=EPOS LHC)
  - ~ same number of muons compared to QGSJETII-04

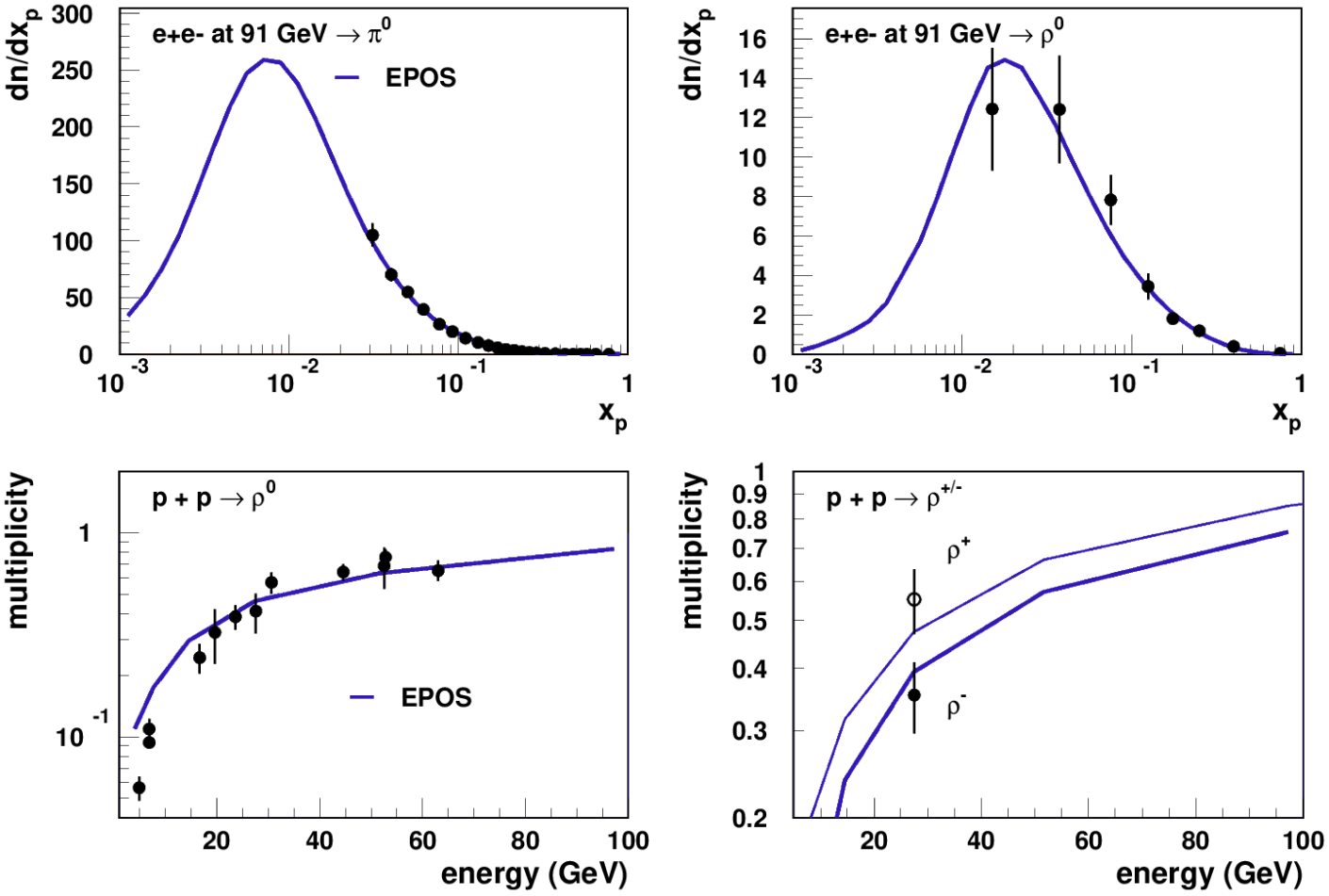




Generic "EPOS"

First attempt using theoretical constraints

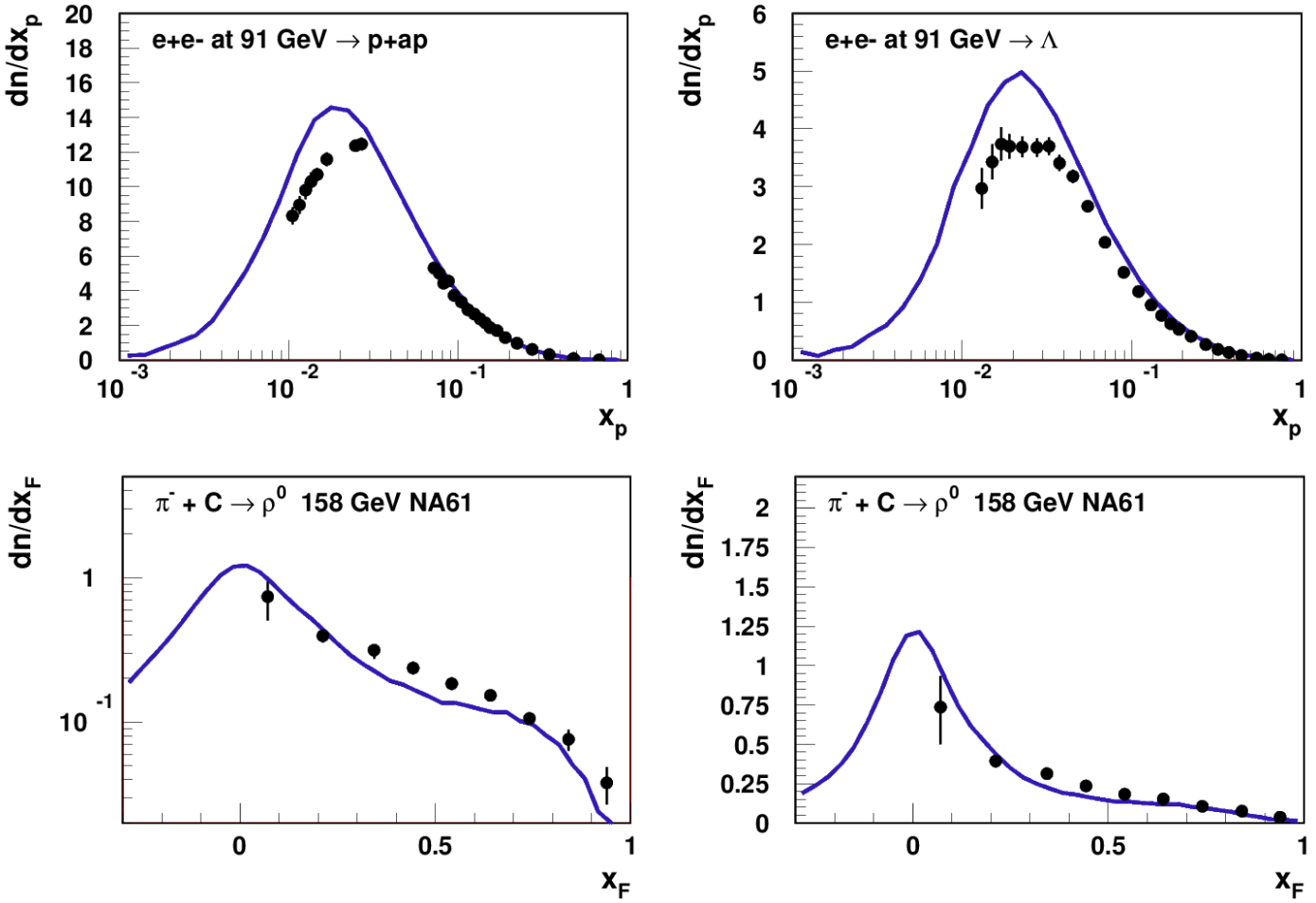
- Impose isospin symmetry (u=d) for pions, ρs and nucleons BEFORE decay
- Fix ρ^0 and multiplicity



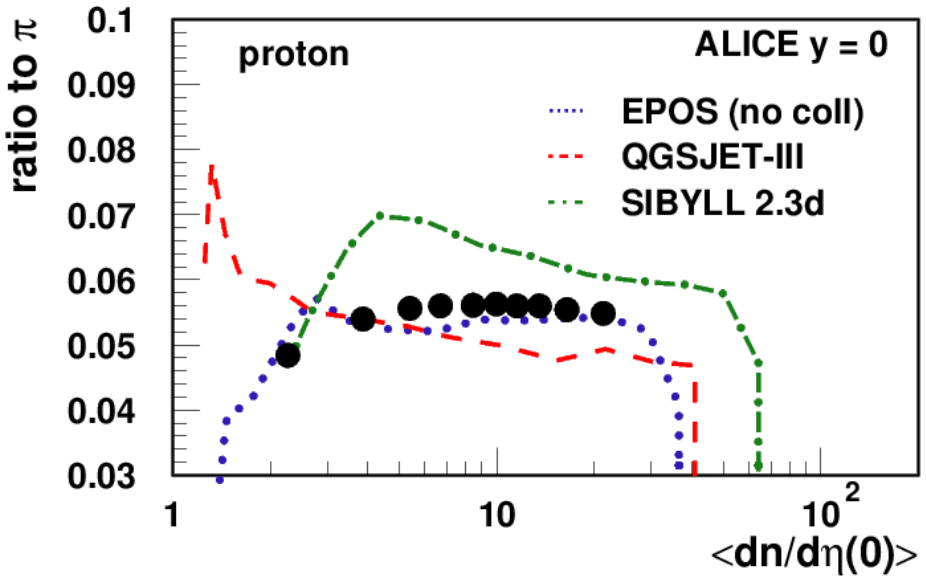
Generic CR tuning

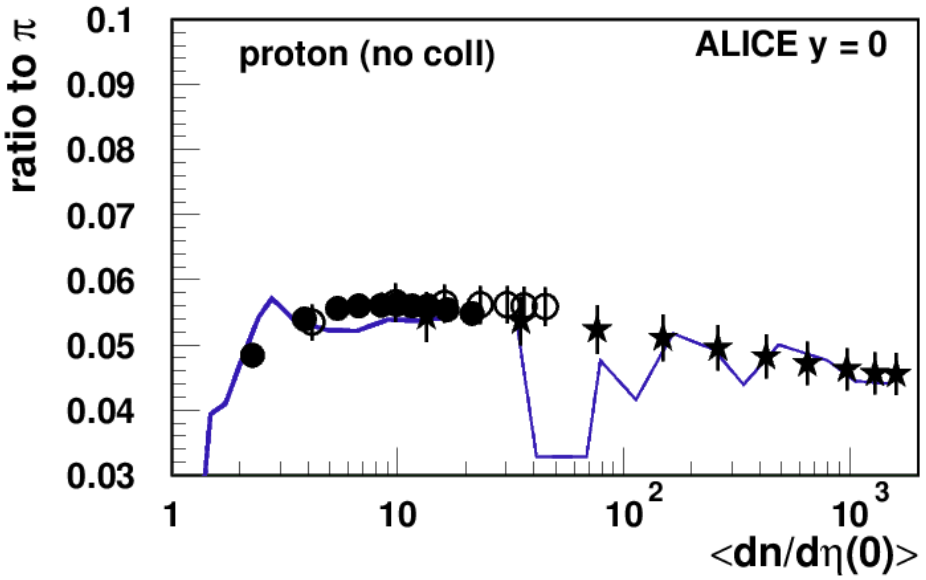
CR models usually tuned on hadronic interactions (not LEP)

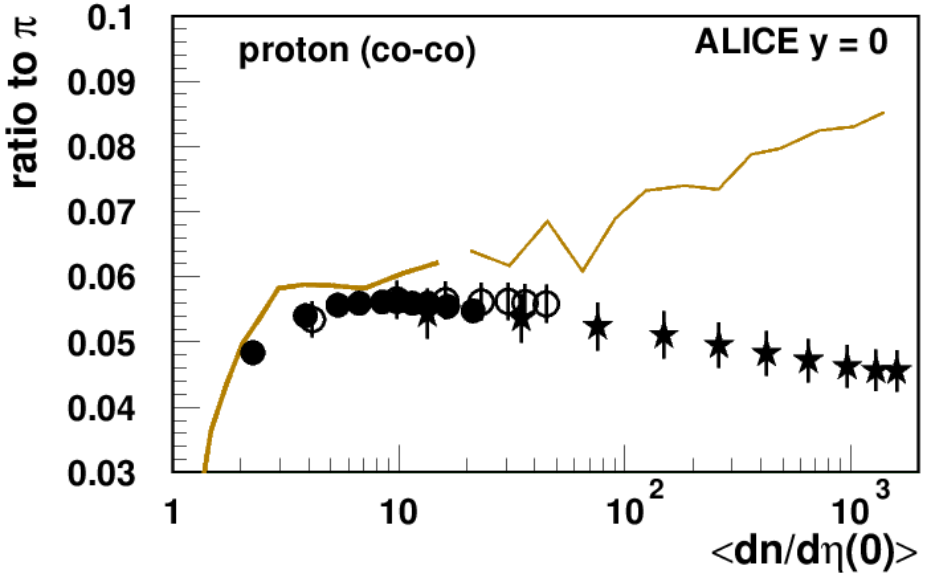
- Impose isospin symmetry (u=d) for pions, ρs and nucleons BEFORE decay
- Produce only most common particles π, ρ and η and tuned to pp data
  - LEP ~ OK but overestimate baryons and tension in h-A for ρ

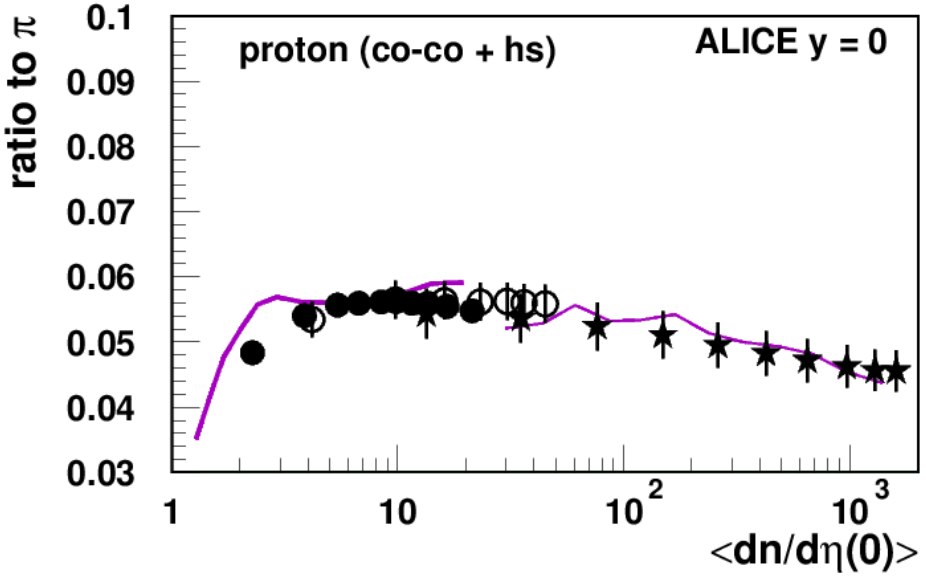


Example with protons in p-p and Pb-Pb @ LHC

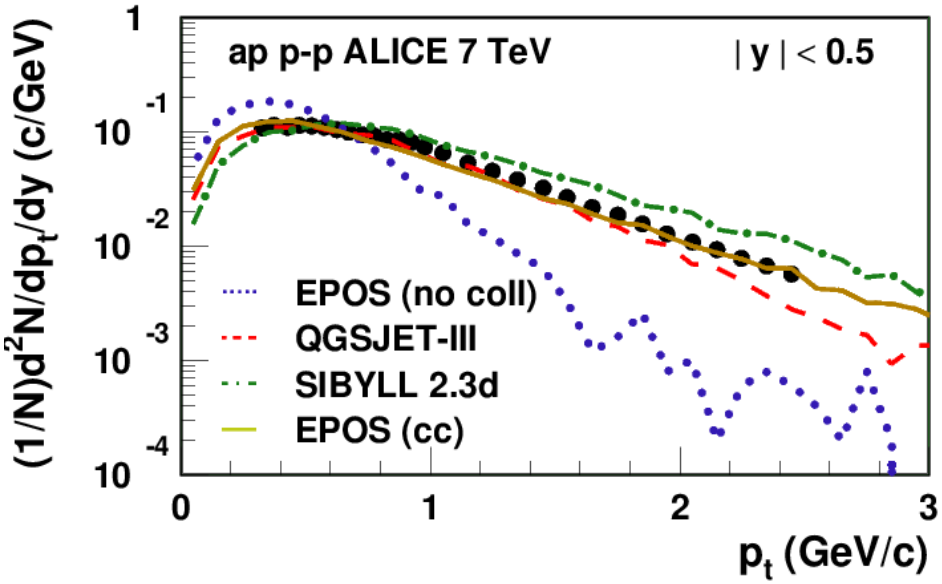


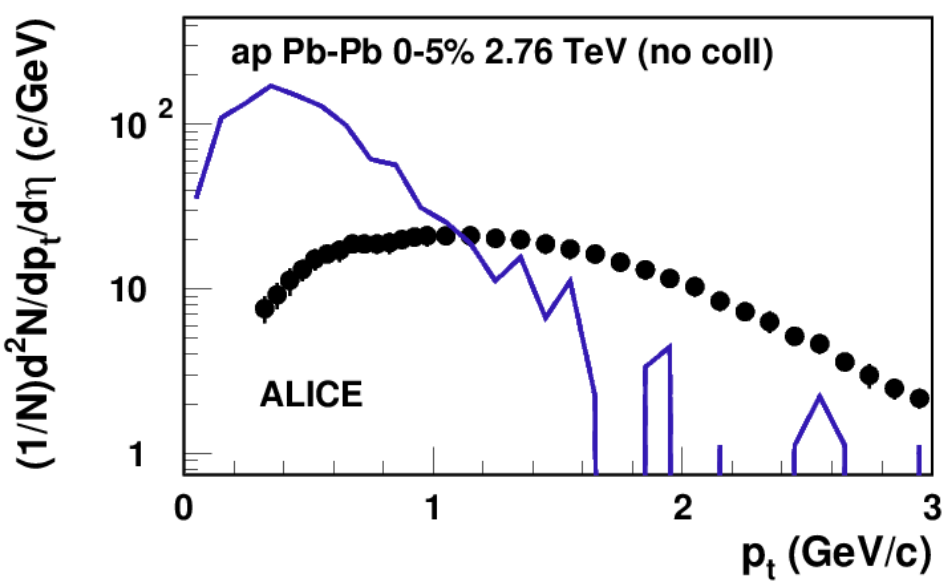


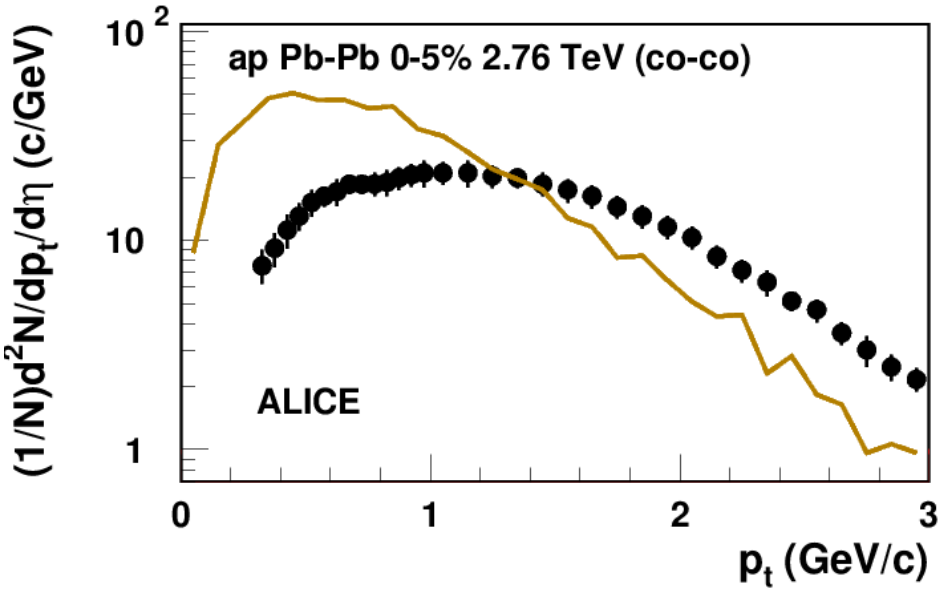


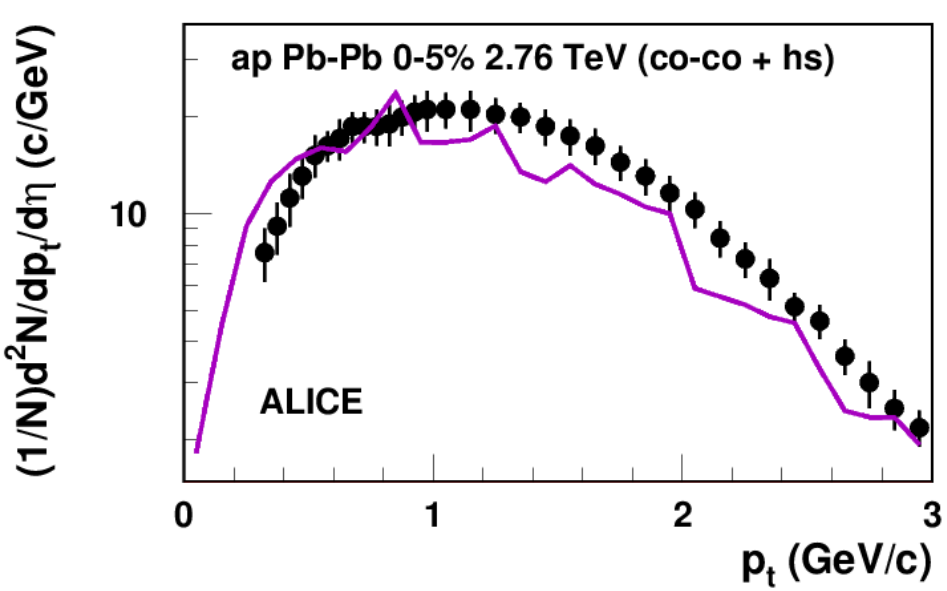


Example with protons in p-p and Pb-Pb @ LHC





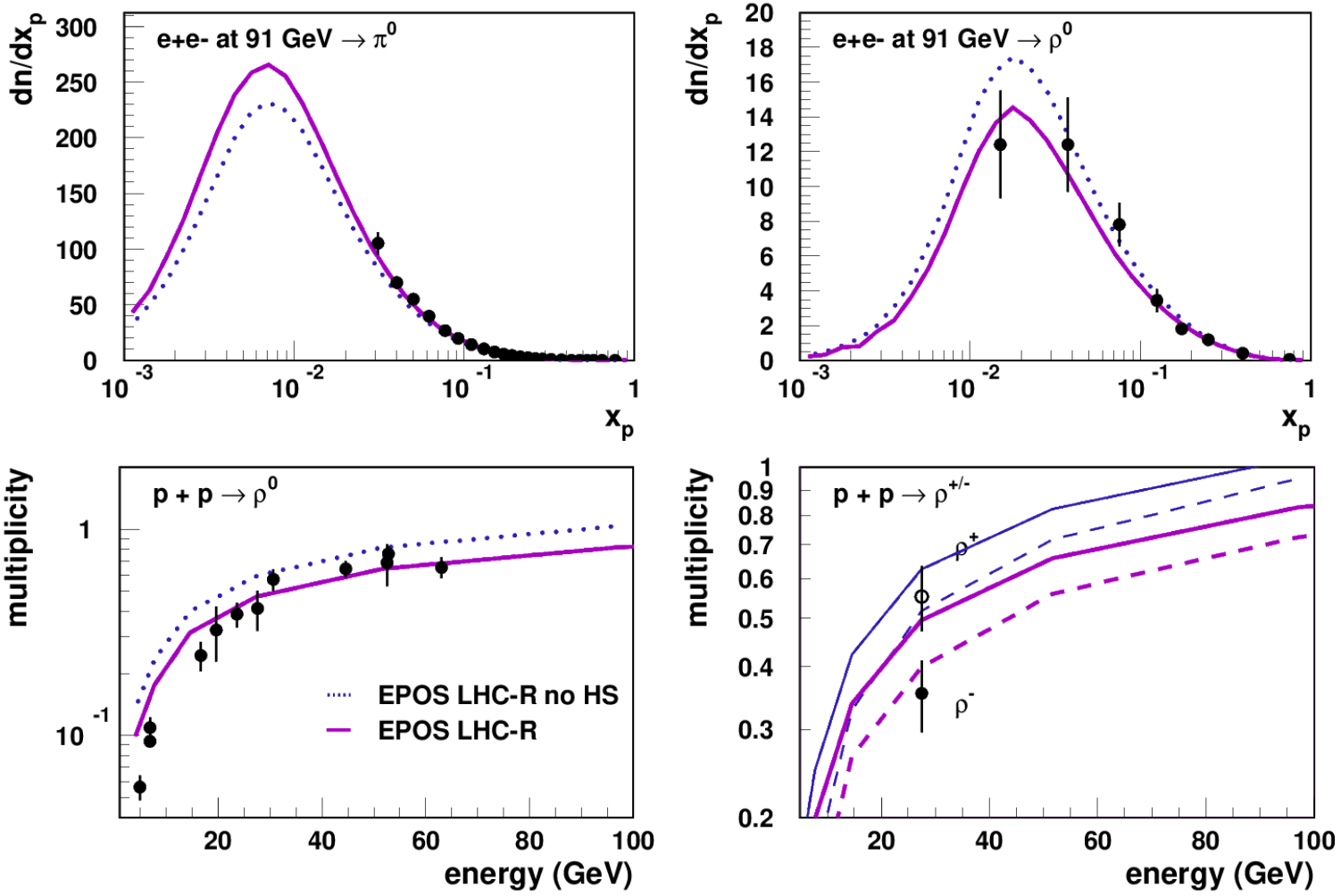




Retune basic parameters with HS and LEP

EPOS.LHC-R uses experimental constraints from LEP

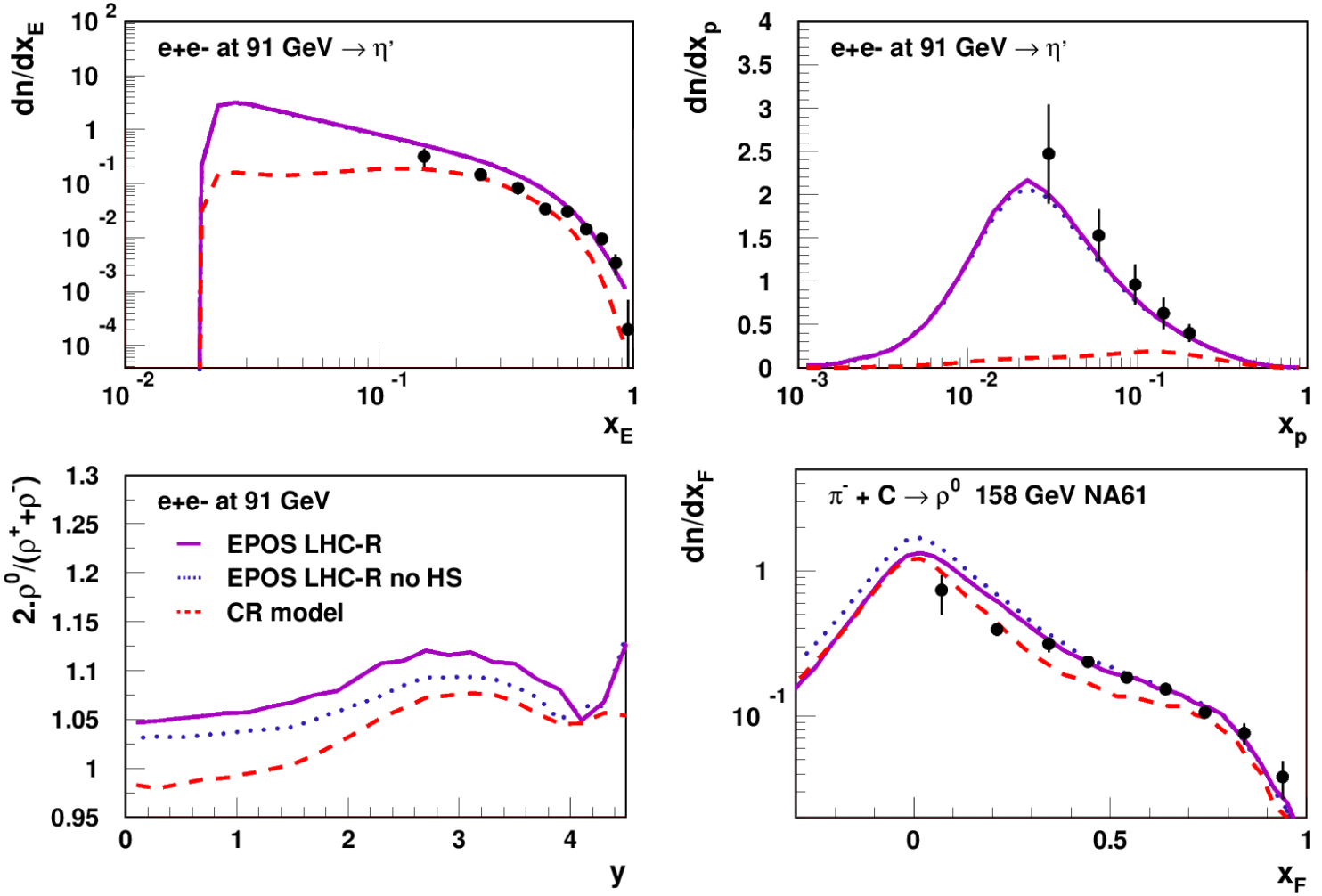
- Increase contribution of ρs to compensate the effect of HS



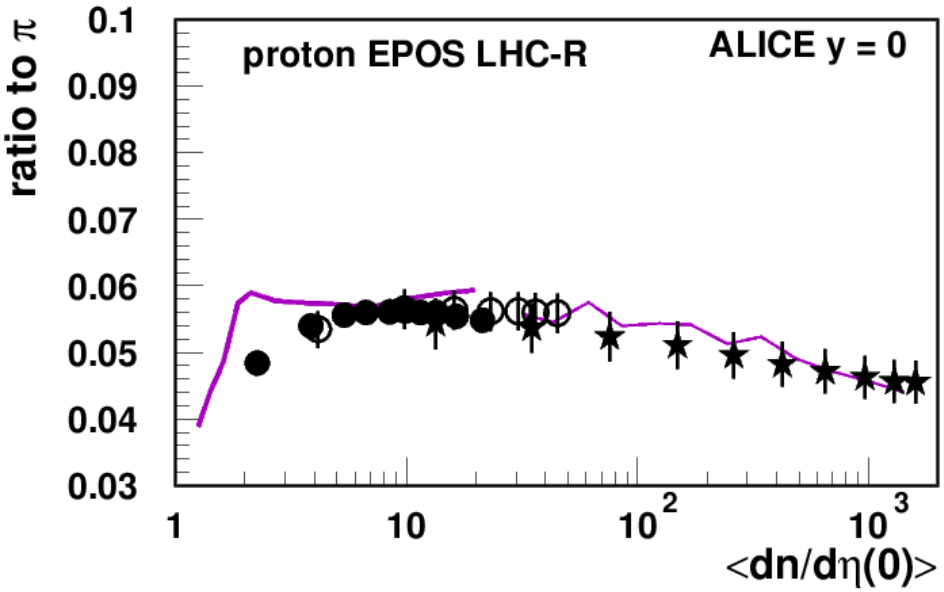
Retune basic parameters with HS and LEP

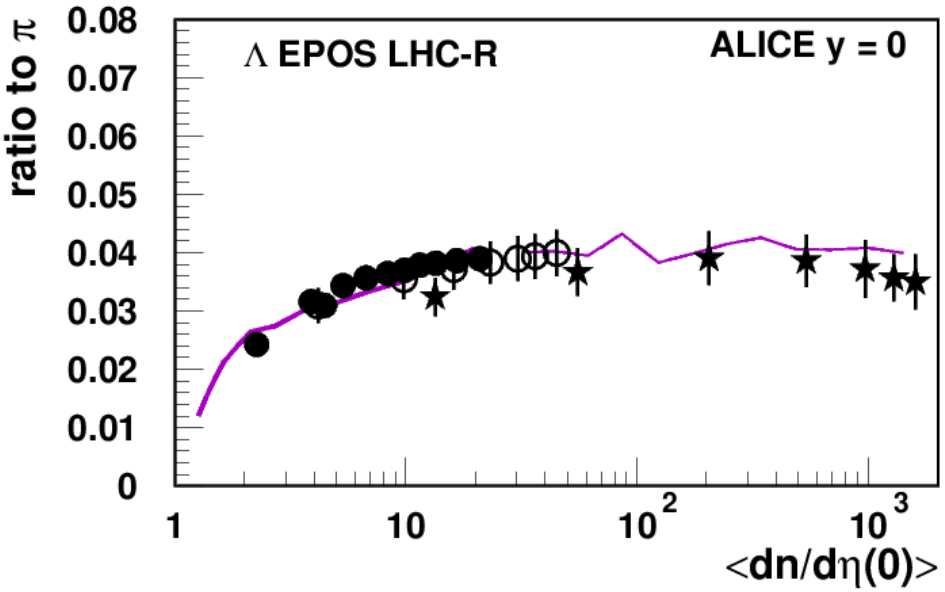
EPOS.LHC-R uses experimental constraints from LEP

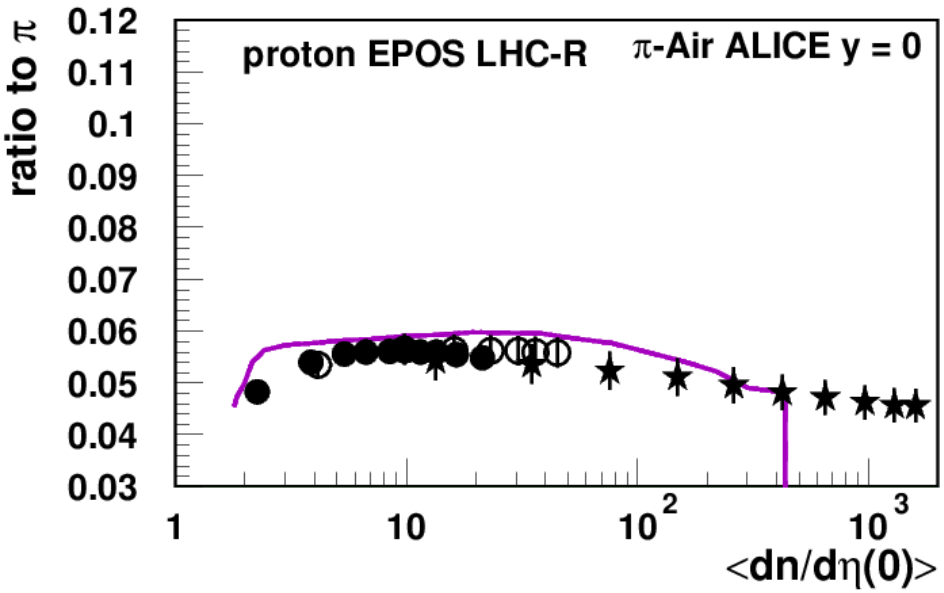
- Produce η' and f_0 in addition to η : change asymmetry for ρ (and π)
  - Effect on muon production in air showers !

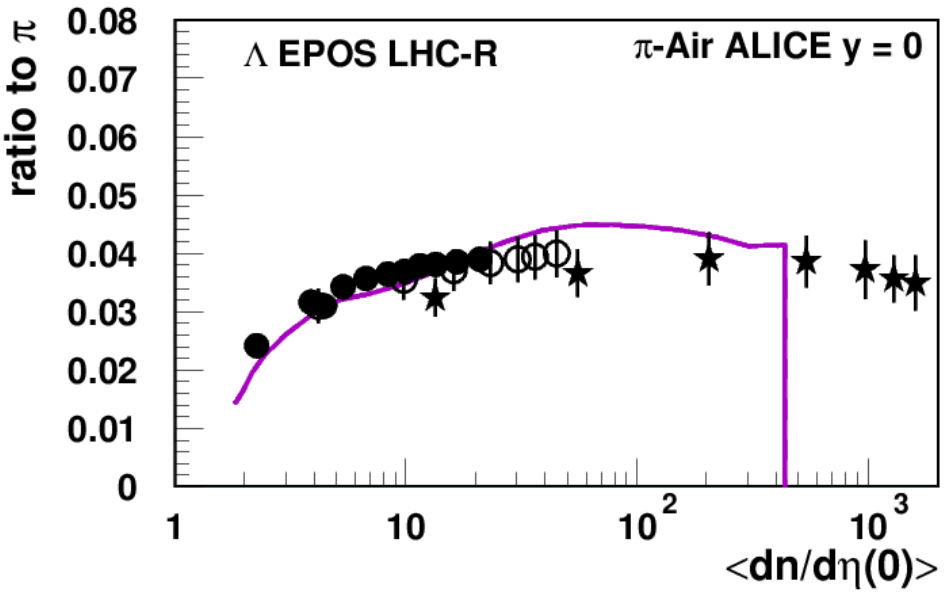


Check ALICE data





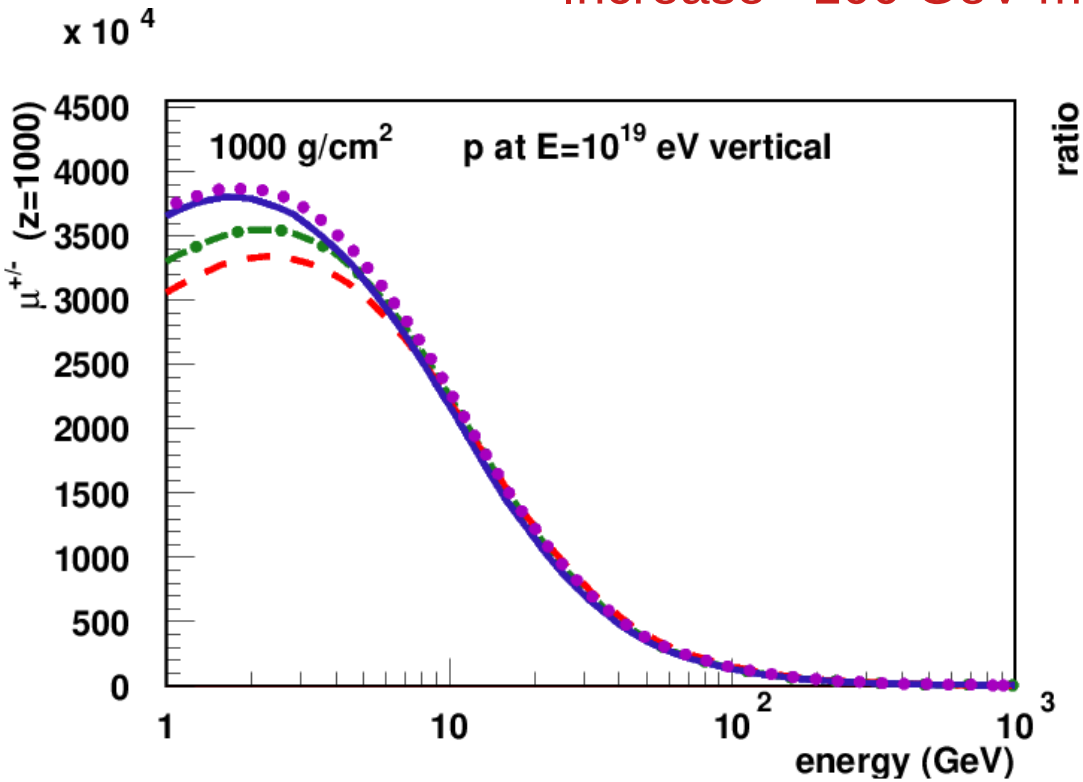


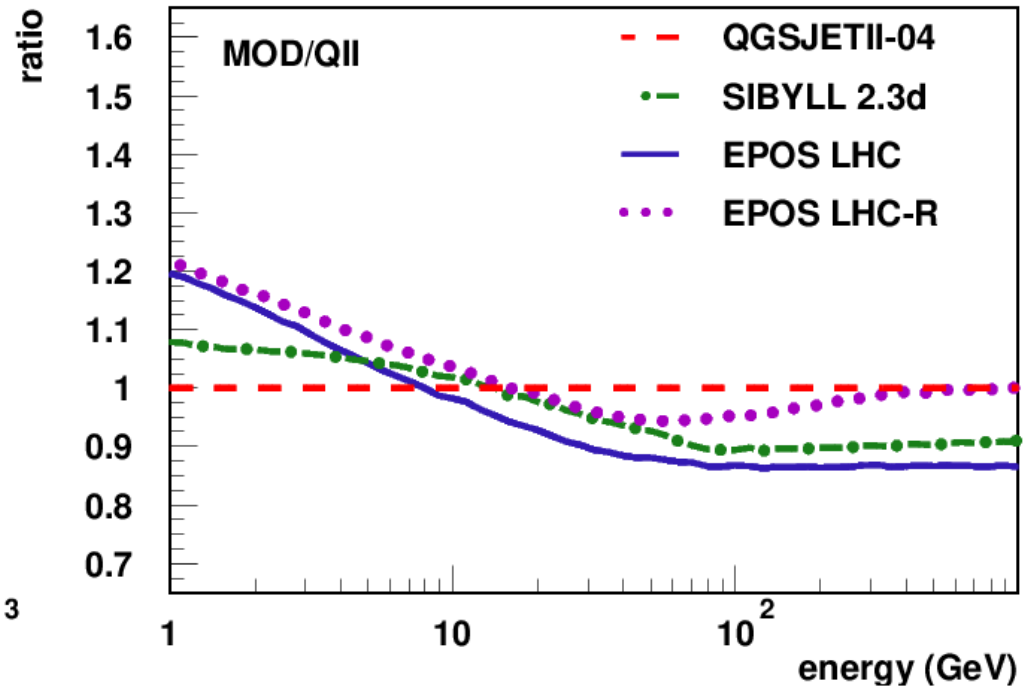


E_μ

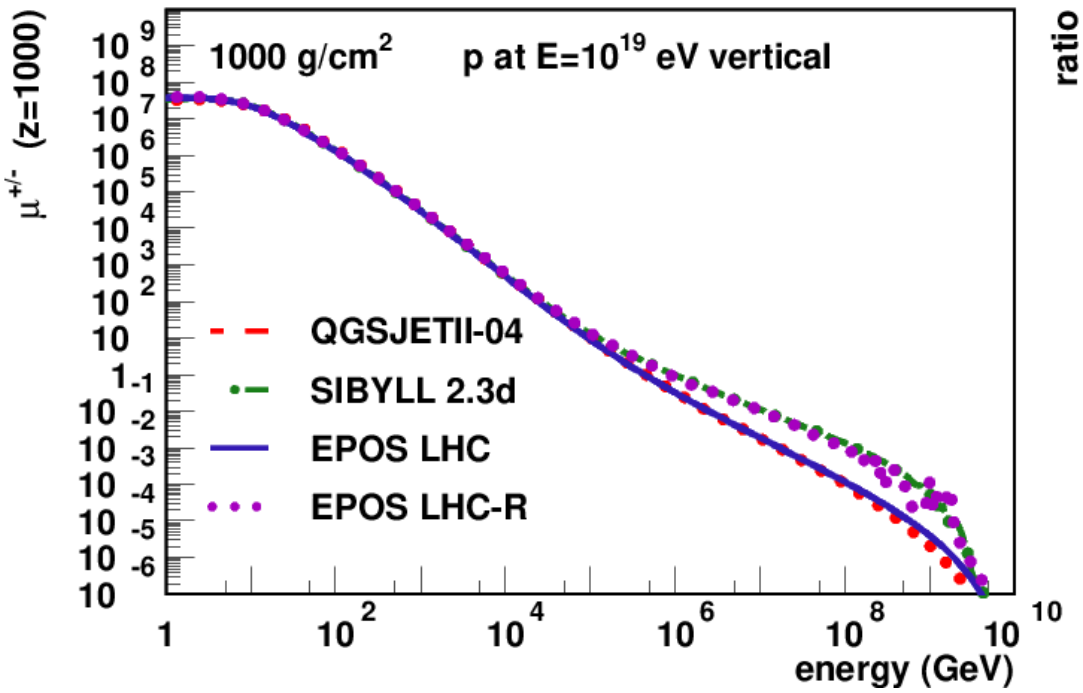
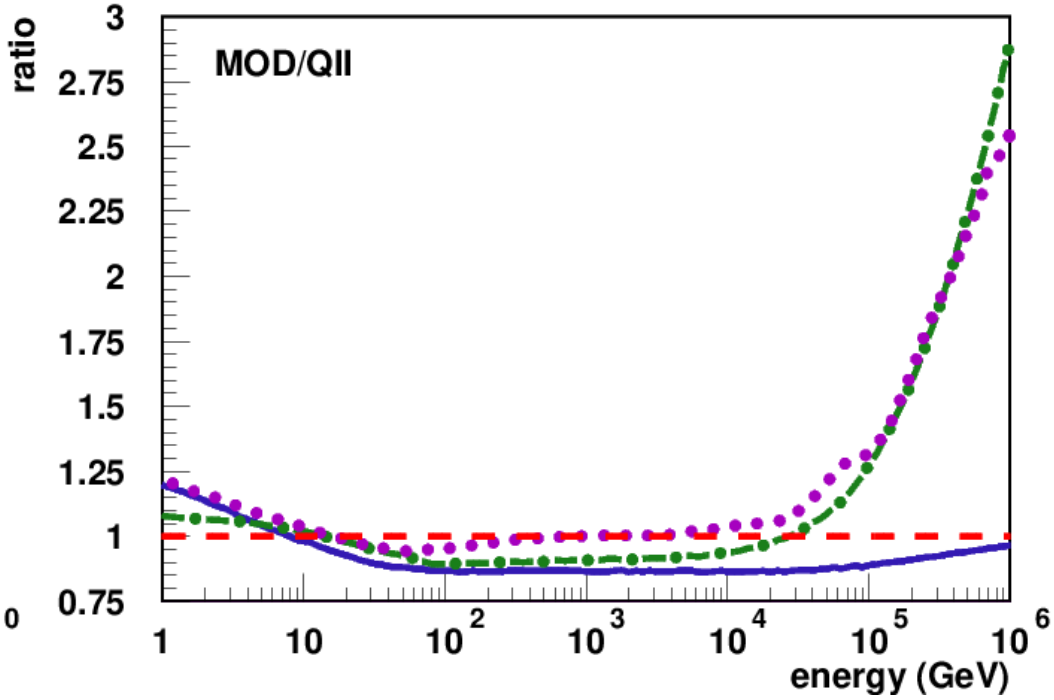
First simulations with full collective effect implementation:

- Simulations without core-corona but ρ asymmetry already have more muons
  - Parallel shift changing all muon energies
- Pion-Air multiplicity impact muon energy between 10 and 100 GeV
- Better tune of kaons (indirect impact of core-corona)
  - Increase >100 GeV muons (Ice-Top/Ice-Cube)





E_μ

First simulations with full collective effect implementation:

- Simulations without core-corona but ρ asymmetry already have more muons
  - Parallel shift changing all muon energies
- Pion-Air multiplicity impact muon energy between 10 and 100 GeV
- Better tune of kaons (indirect impact of core-corona)
- Very high energy muons from charm ! (background for neutrino analysis)