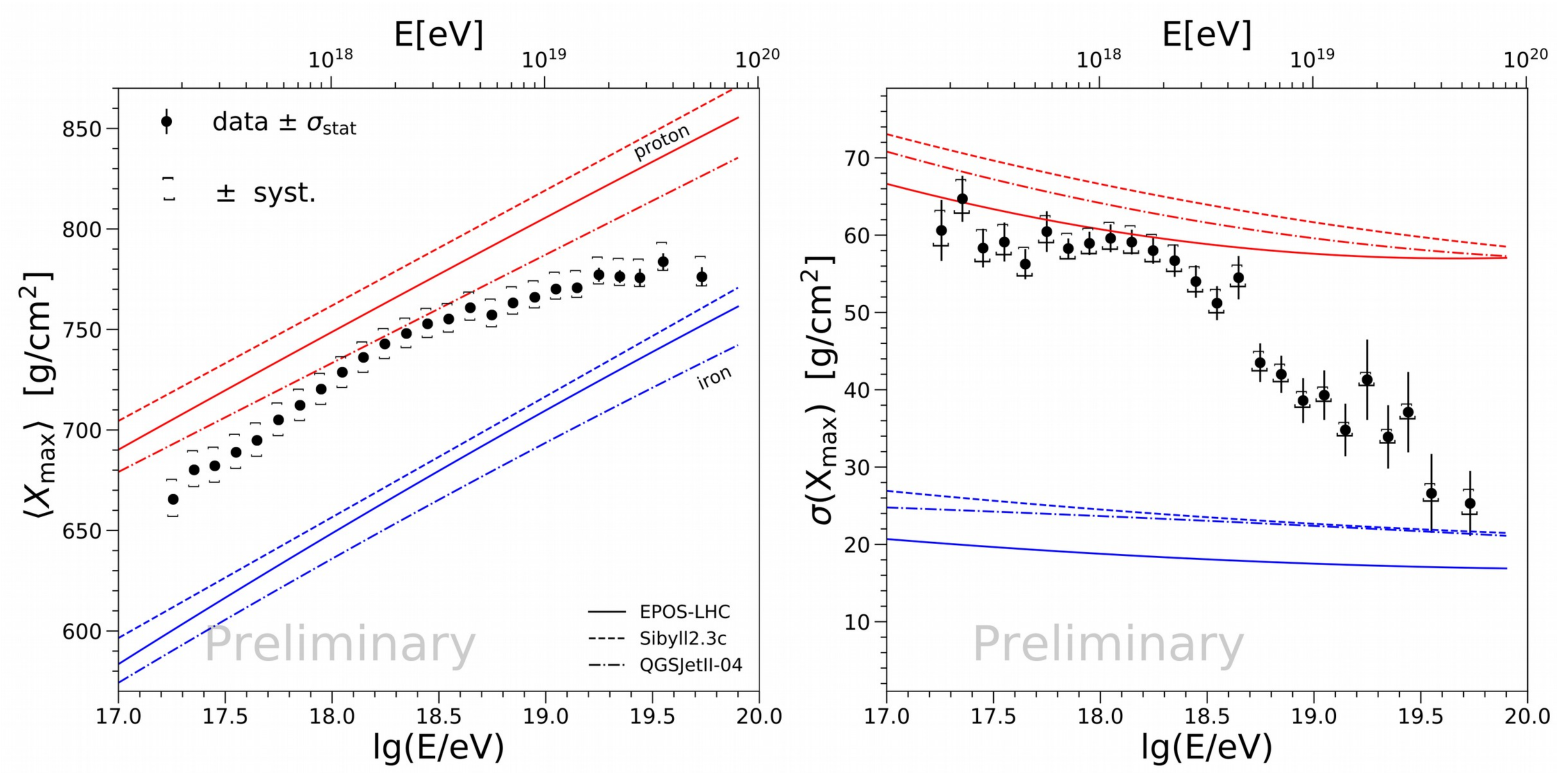
Recent results from LHC (and SPS) and their implication for cosmic ray physics

Sebastian Baur

10th COSPA meeting, Bussels, 04/10/2019

UHECR composition and interaction models

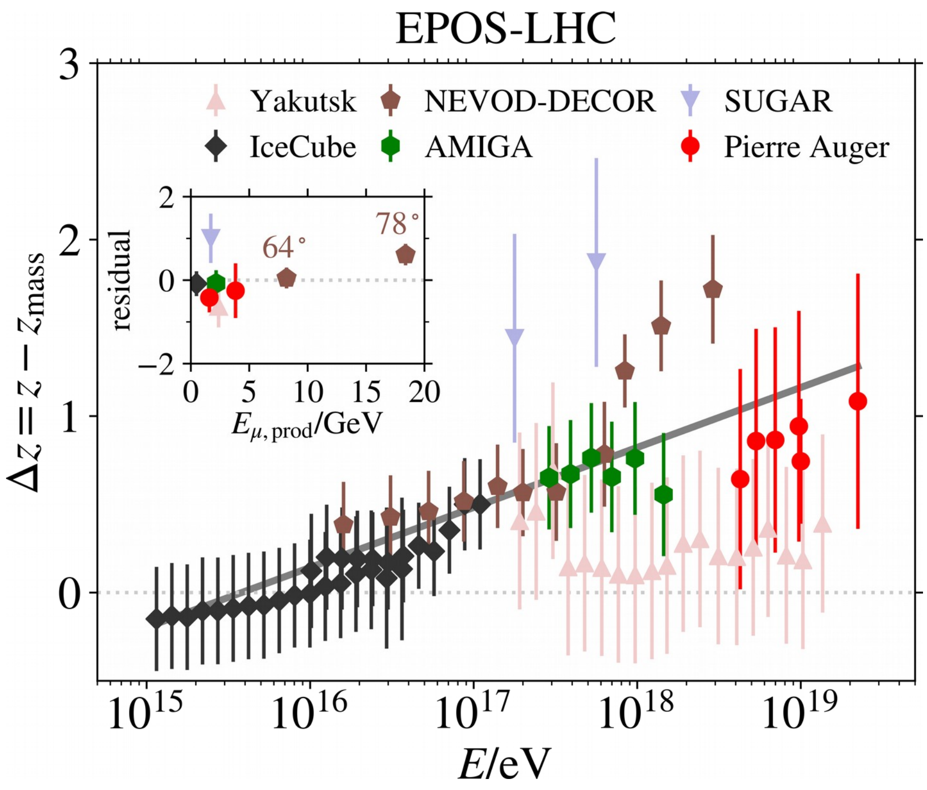


[A. Yushkov (AUGER), ICRC 2019]

Hadronic interaction models have large differences and uncertainties!

Hadronic interaction models are vital to interpret air shower data!

UHECR composition and interaction models



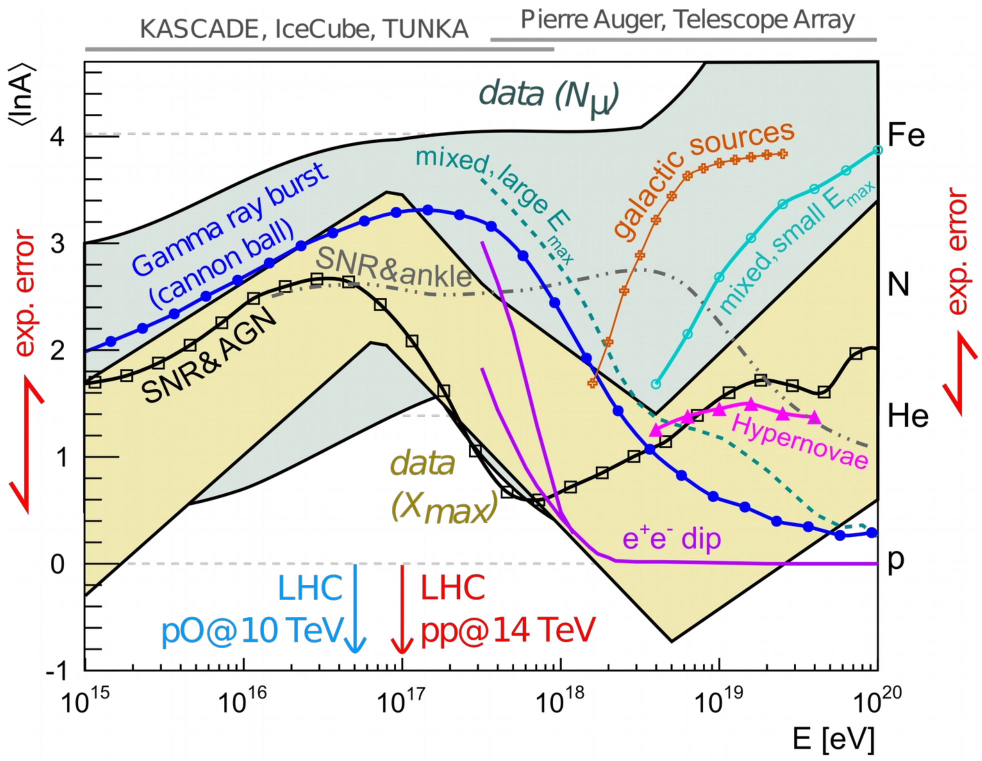
[L. Cazon (WHISP), ICRC 2019]

Combining muon data from 6 experiments:

$$z = \frac{\ln N_\mu^{\mathrm{det}} - \ln N_\mu^{\mathrm{det}}{}_{\mathrm{p}}}{\ln N_\mu^{\mathrm{det}}{}_{\mathrm{Fe}} - \ln N_\mu^{\mathrm{det}}{}_{\mathrm{p}}}$$

Relative to energy-dependent mass
→ increasing muon deficit (8σ significance)

UHECR composition and interaction models



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

[H. Dembinski, ICRC 2019]

Inconsistent interpretation of composition measurements!

Largely due to uncertainties in hadronic interaction models.

→ dedicated tests at accelerators needed

How to connect LHC and air showers

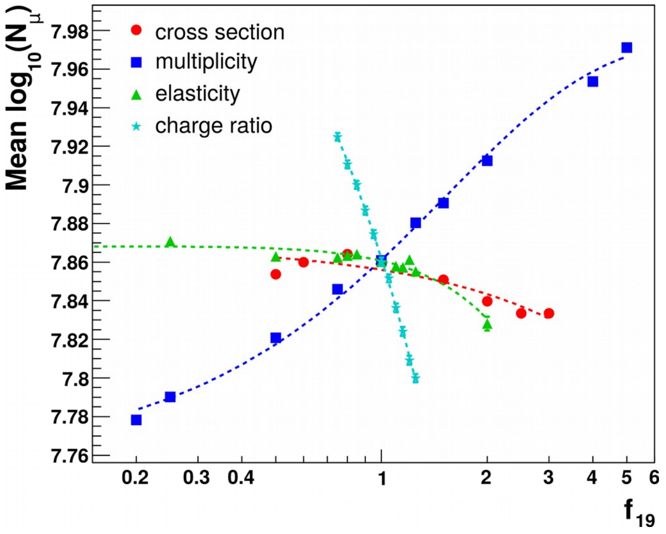
R. Ulrich et al. PRD 83 (2011) 054026:

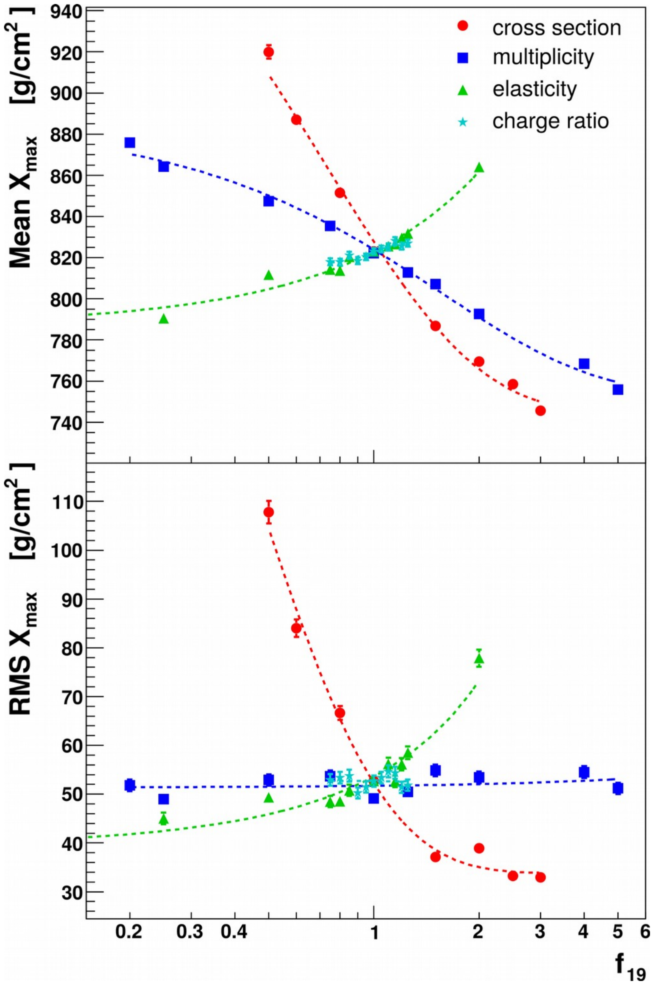
Ad-hoc modify model features by energy-dependent factor

And propagate to full $10^{19.5}$ eV proton shower

Investigated features:

- inelastic cross section
- hadron multiplicity
- elasticity: $E_{leading}$ / E_{total}
- charge ratio (π^0 fraction)





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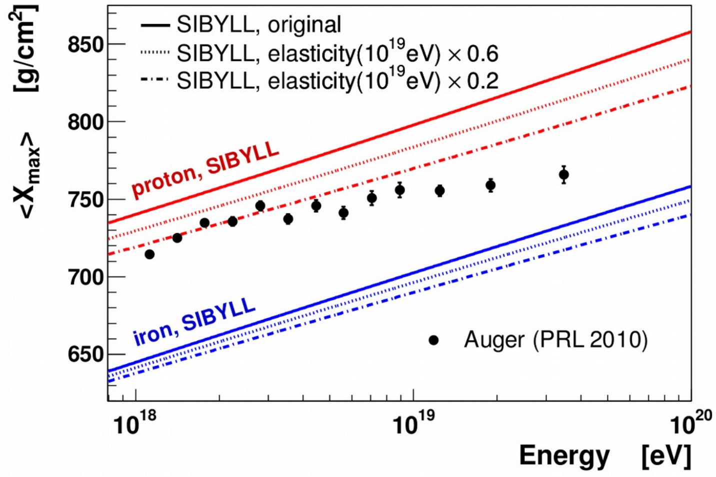

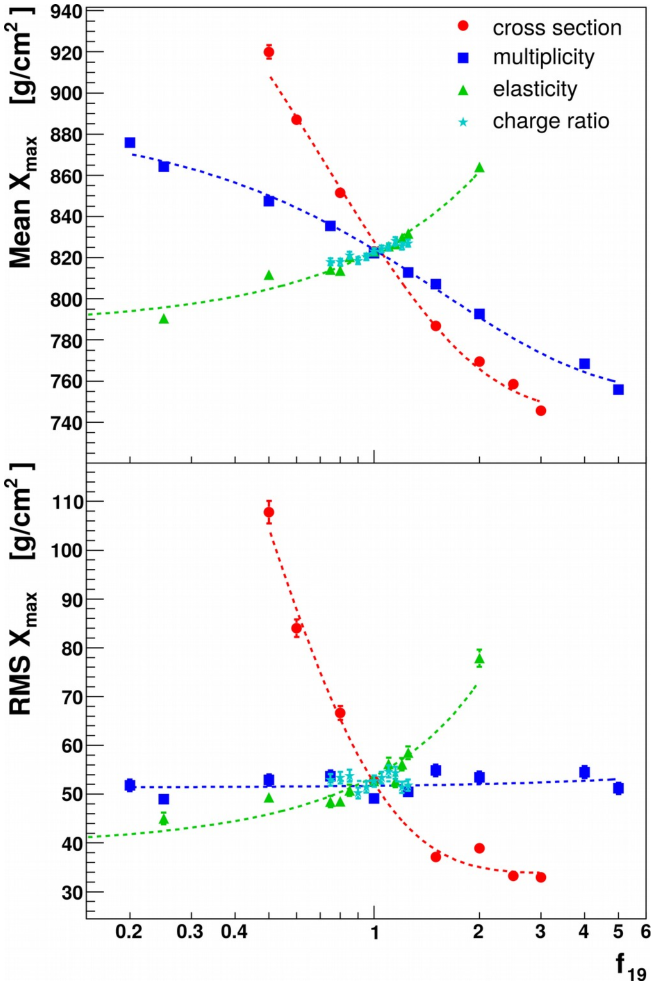

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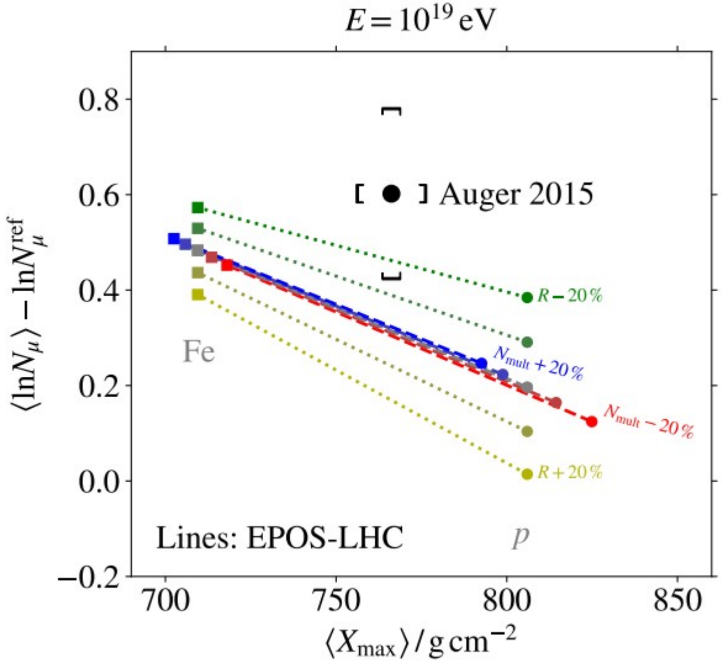
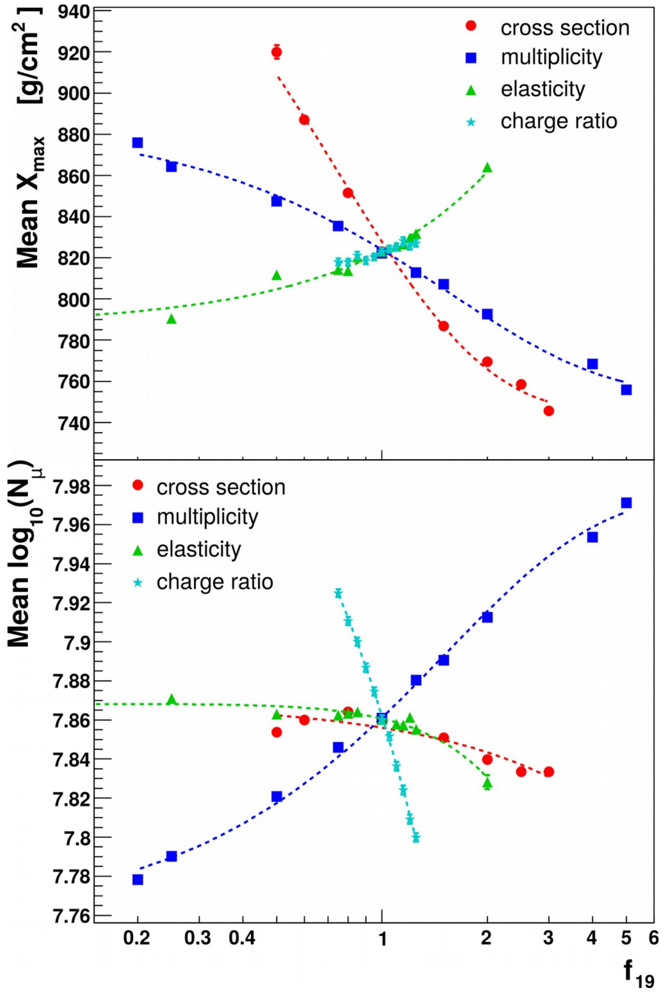


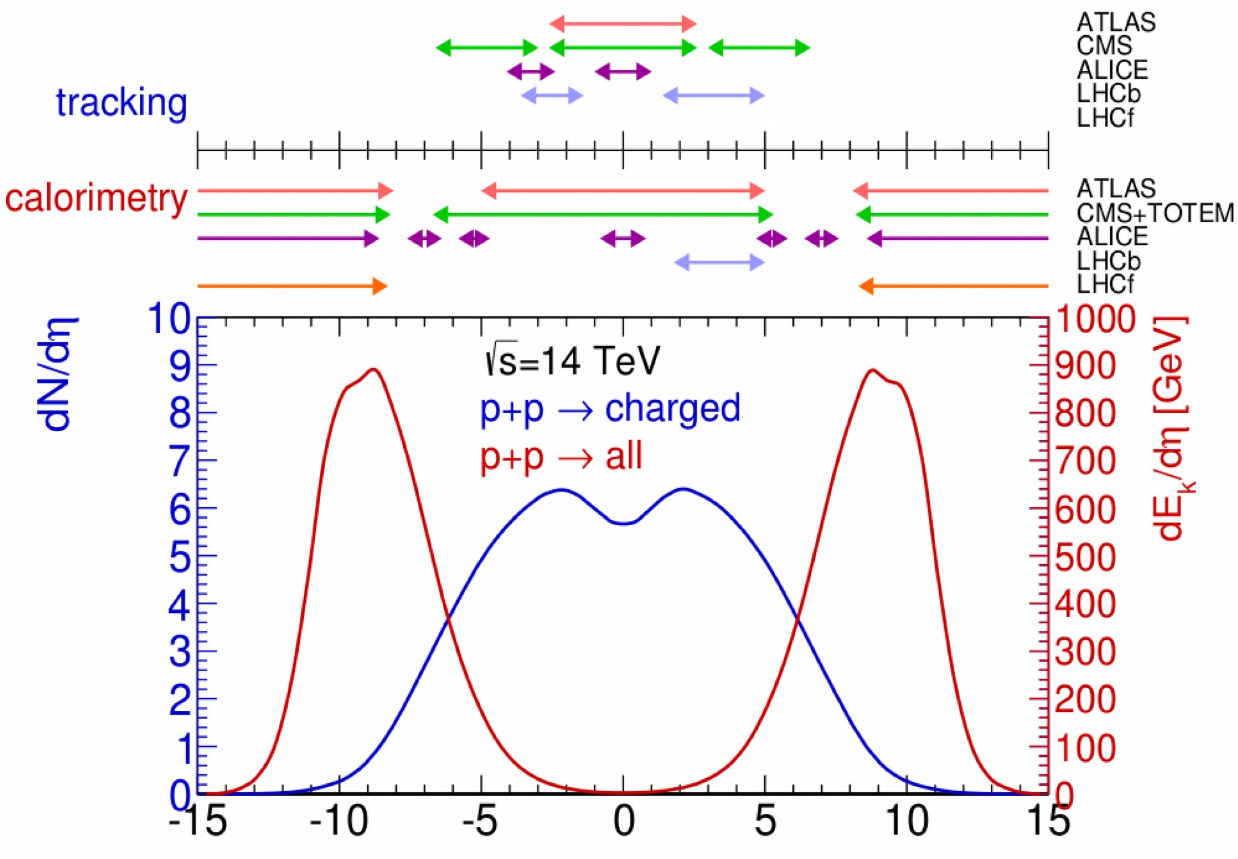


Investigated features:

- inelastic cross section
- hadron multiplicity
- elasticity: $E_{leading} / E_{total}$
- charge ratio (π^0 fraction)

$$R = E_{\pi^0} / E_{had}$$

What and where to measure

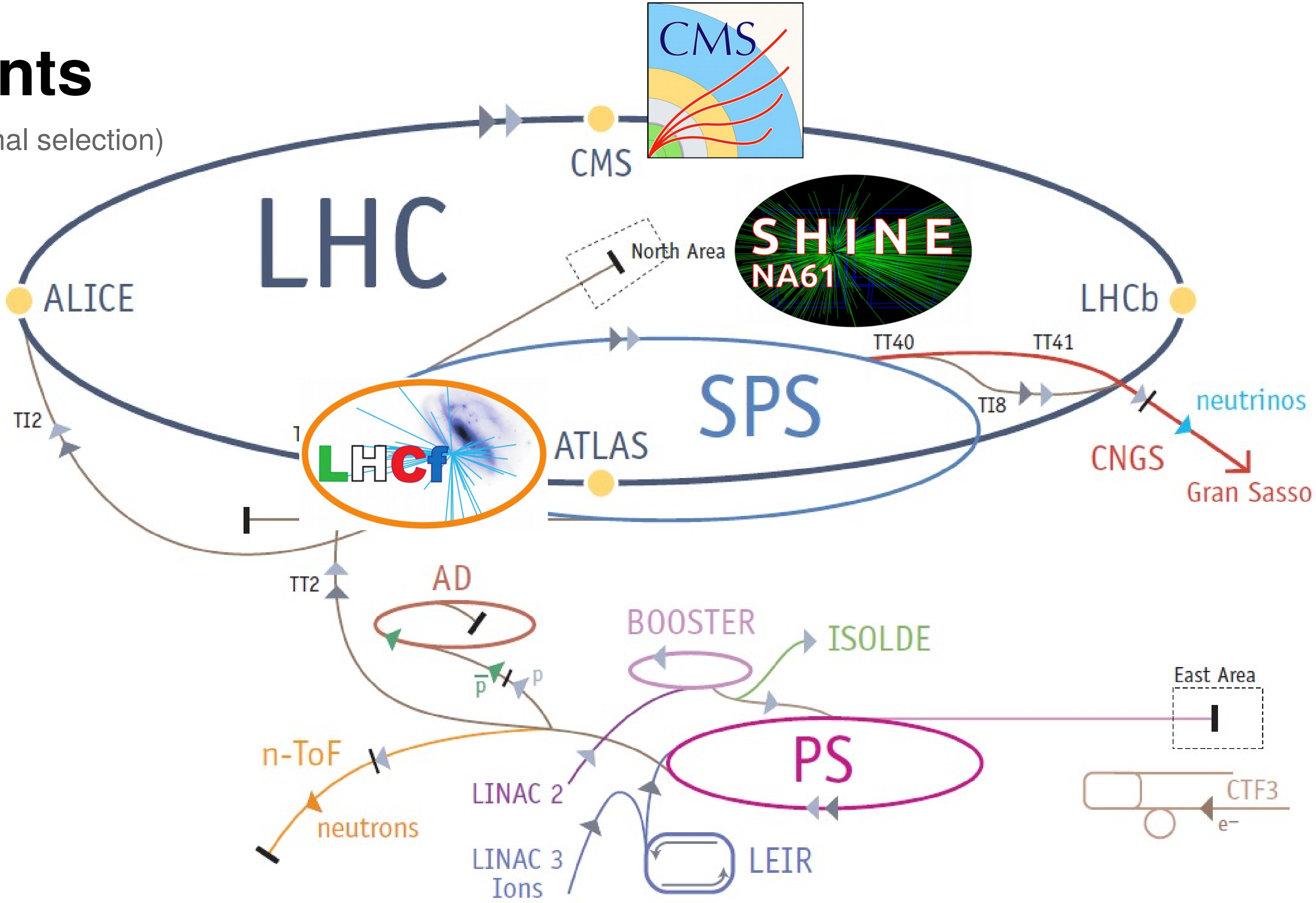


$$\eta = -\ln\left(\tan\theta/2\right)$$

- Most particles are produced at central rapidity
  → focus for LHC experiments
- Most energy is carried by forward particles
  → most relevant for air showers

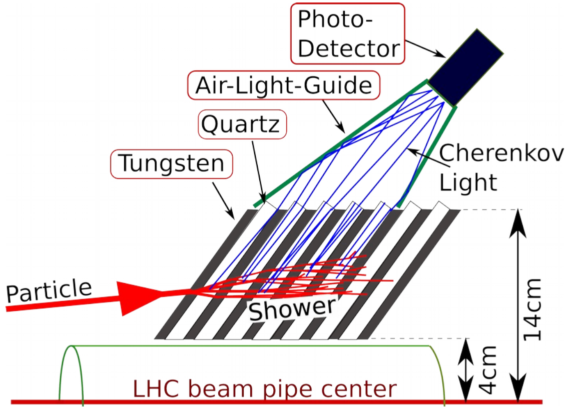
Experiments

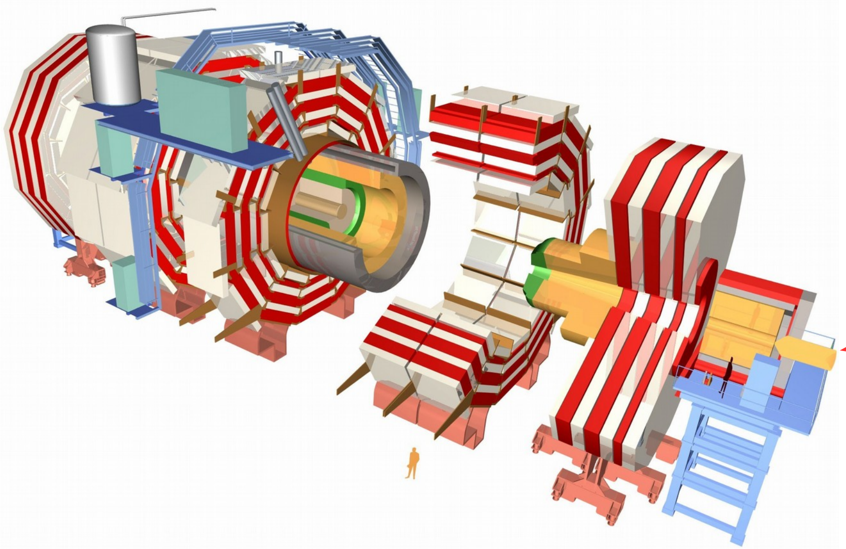
(slightly biased personal selection)

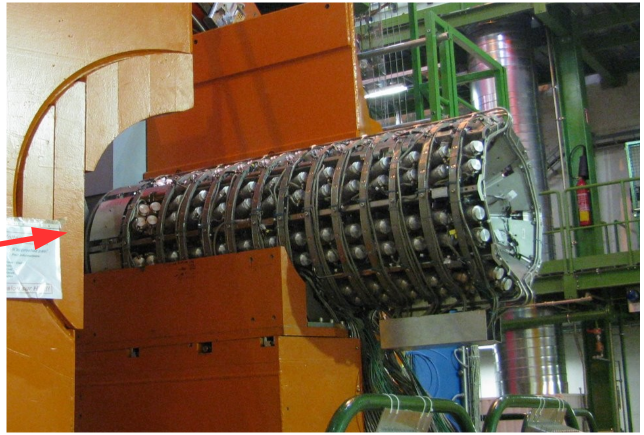


CASTOR in CMS

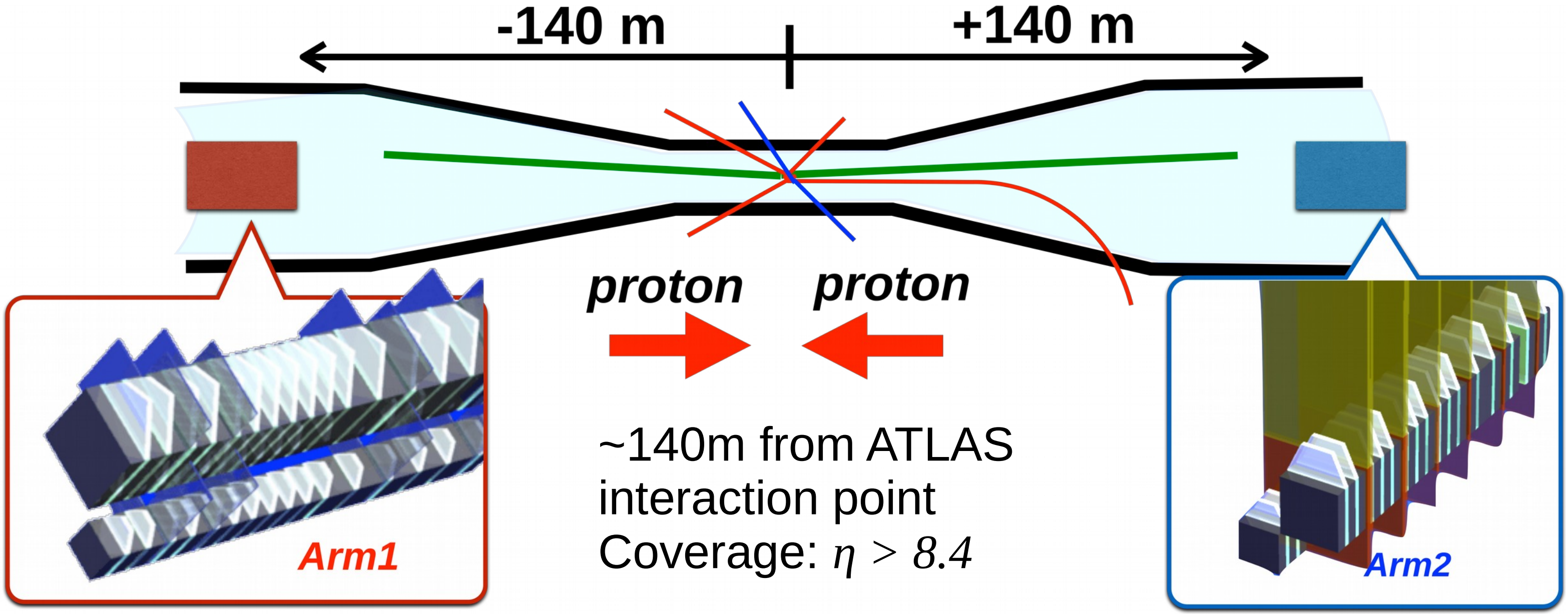
- Tungsten-Quartz sampling calorimeter
- Coverage $-6.6 < \eta < -5.2$
- Segmentation in φ and z
- Separated electromagnetic and hadronic sections with depth of $20\ X_0\ /\ 10\ \lambda_{int}$







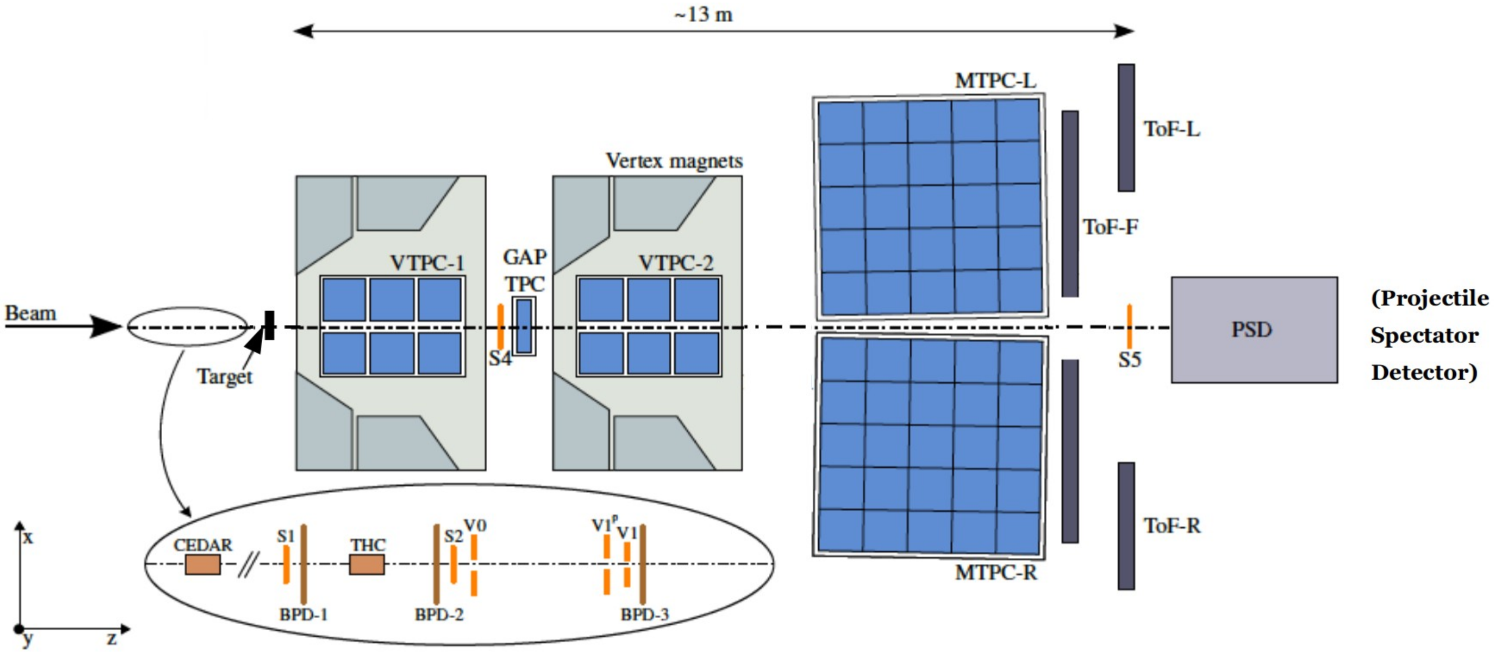
LHCf



~140m from ATLAS interaction point
Coverage: $\eta > 8.4$

- Two towers per Arm
- Sampling and positioning calorimeters: Tungsten layers and plastic scintillators + 4 position sensitive layers
- Neutral particles only

NA61/SHINE



Fixed target at CERN North Area: very versatile beam conditions

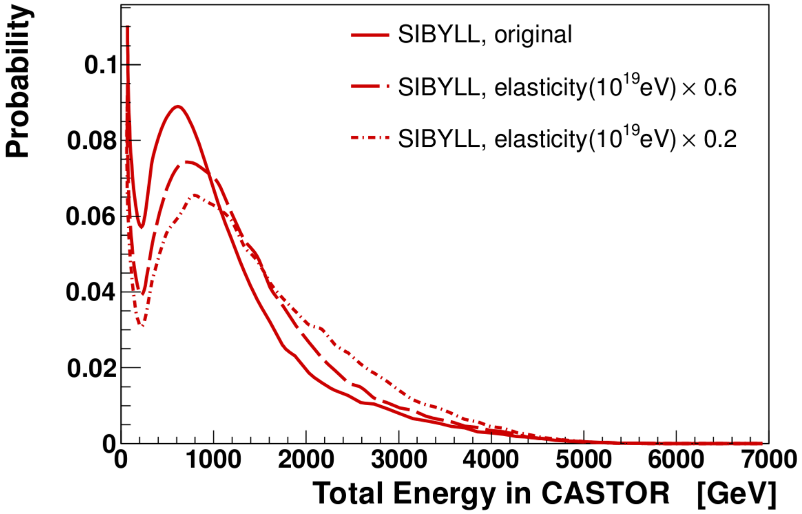
2 superconducting magnets and 4 time projection chambers

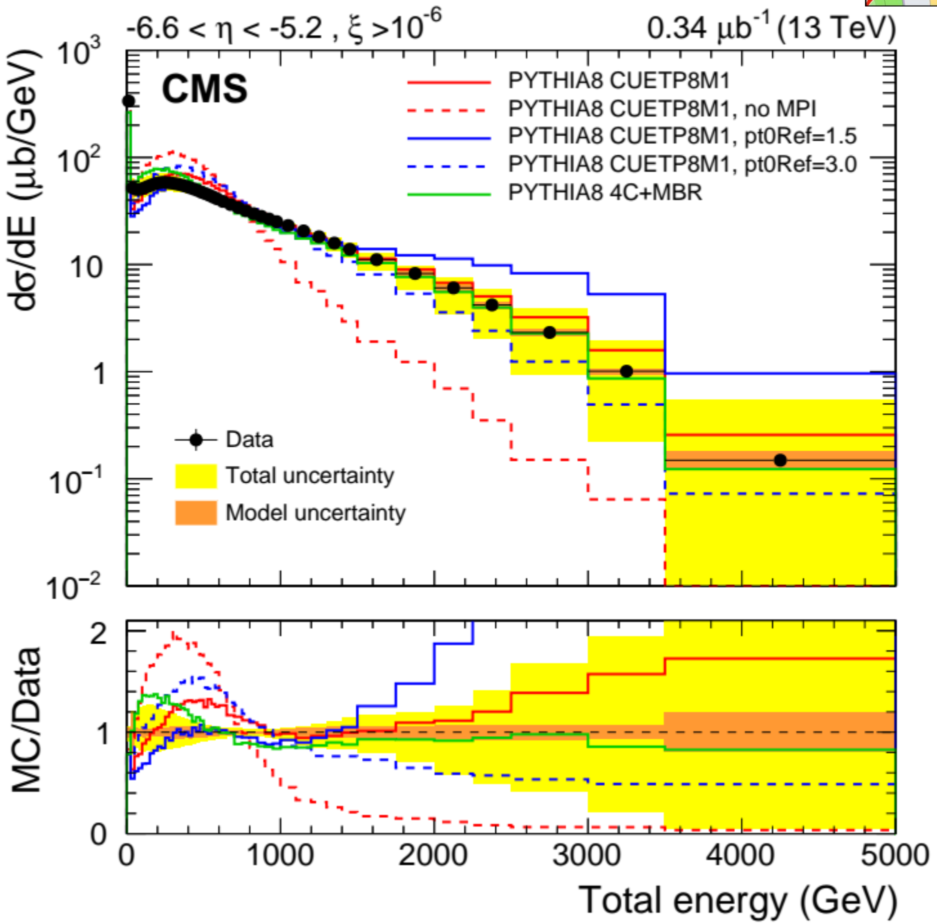
→ large acceptance, momentum resolution and tracking efficiency

→ PID and reconstruction with dE/dx and ToF

CMS: Forward energy spectra [JHEP 08 (2017) 046]

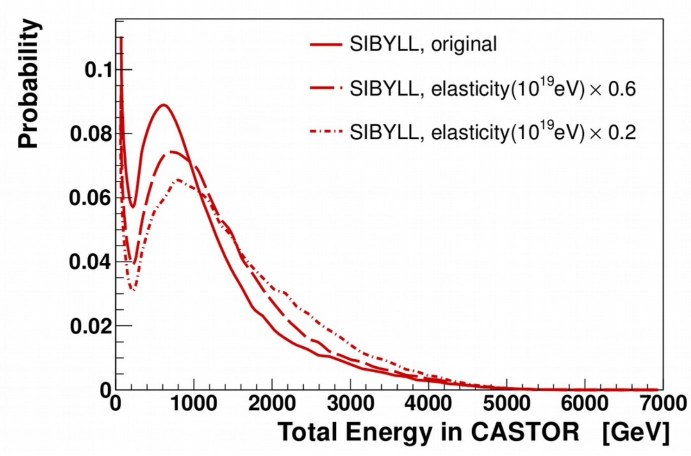
- Detailed energy distribution in CASTOR acceptance
- Differential cross-section as function of total energy
- Sensitive to the model elasticity

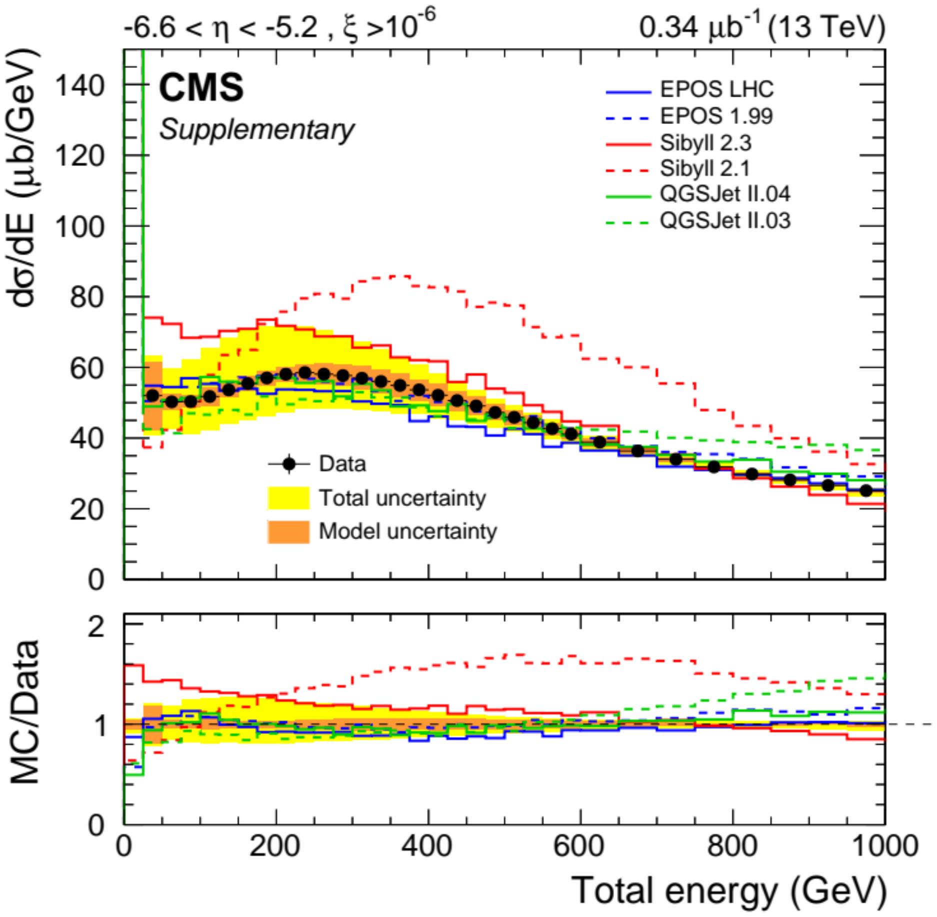




CMS: Forward energy spectra [JHEP 08 (2017) 046]

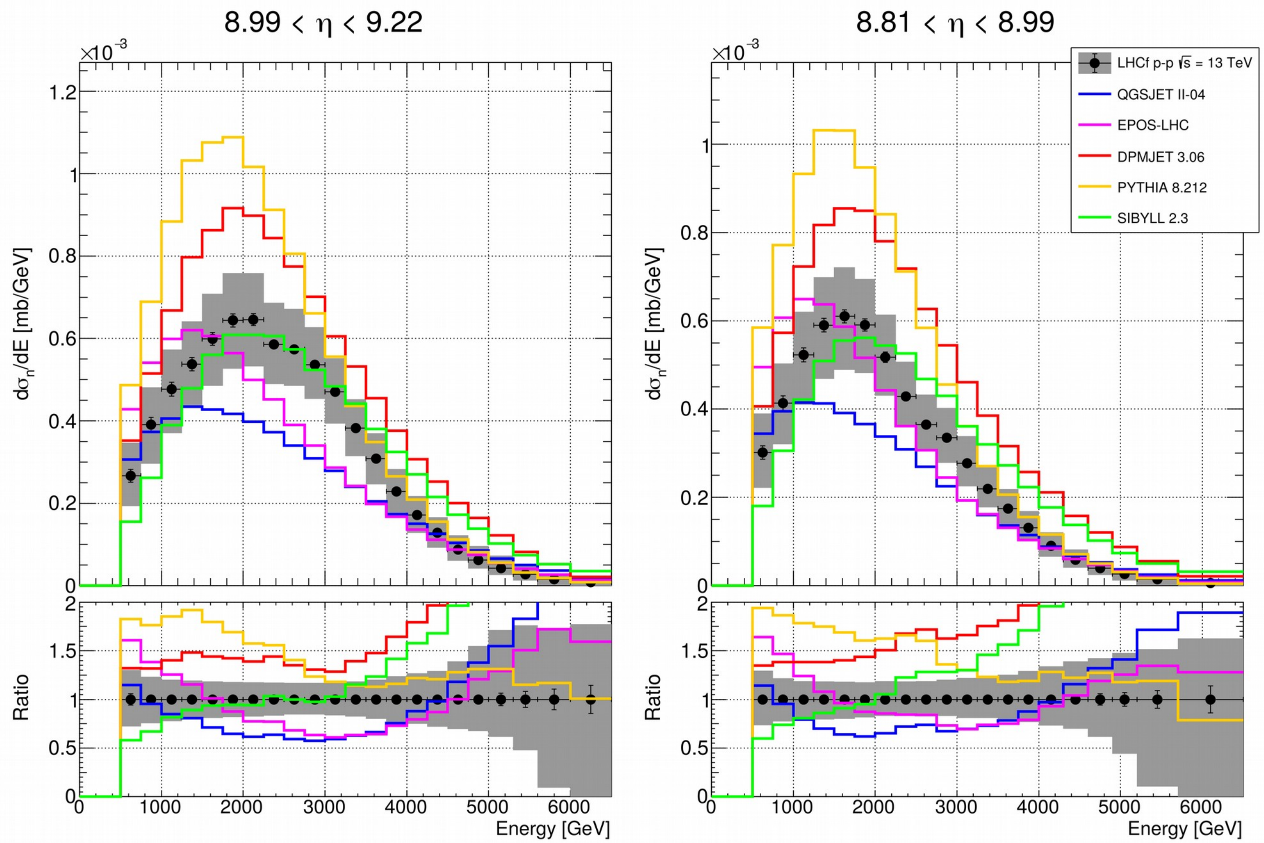
- Bulk of events at low energies: contribution from diffraction (1st bin)
- Sensitive to model elasticity
- Most models perform well
- Sibyll 2.3 overestimates this region
  → hint of too large elasticity



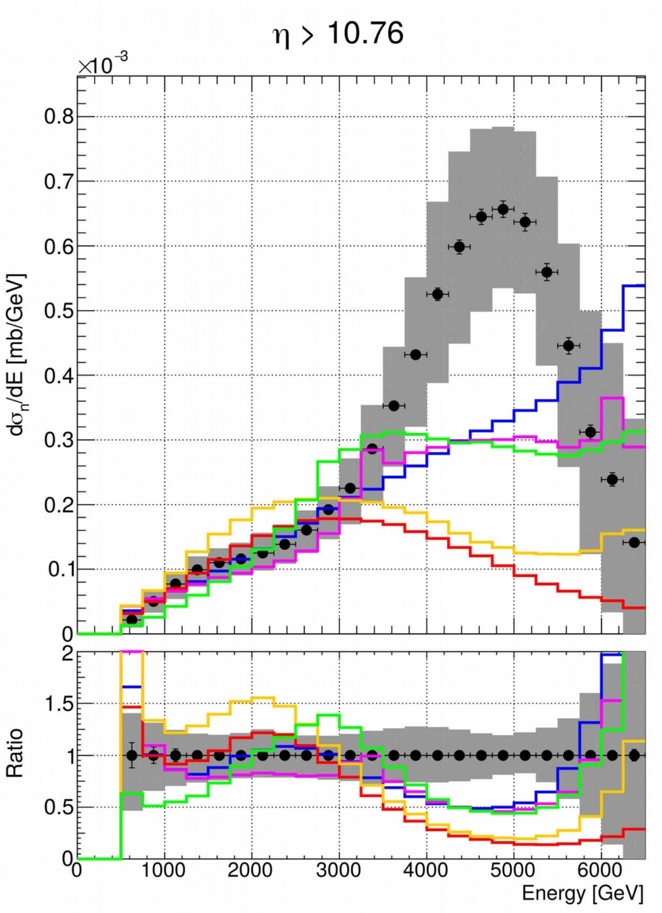


LHCf: Forward neutron spectra [JHEP 11 (2018) 073]

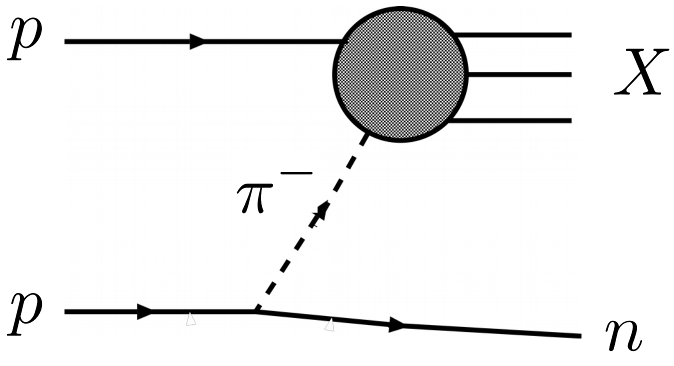
- Sensitive to elasticity
- Most models perform well
- QGSJet II-04 has too little forward neutrons
  → hint of too small elasticity



LHCf: Forward neutron spectra [JHEP 11 (2018) 073]



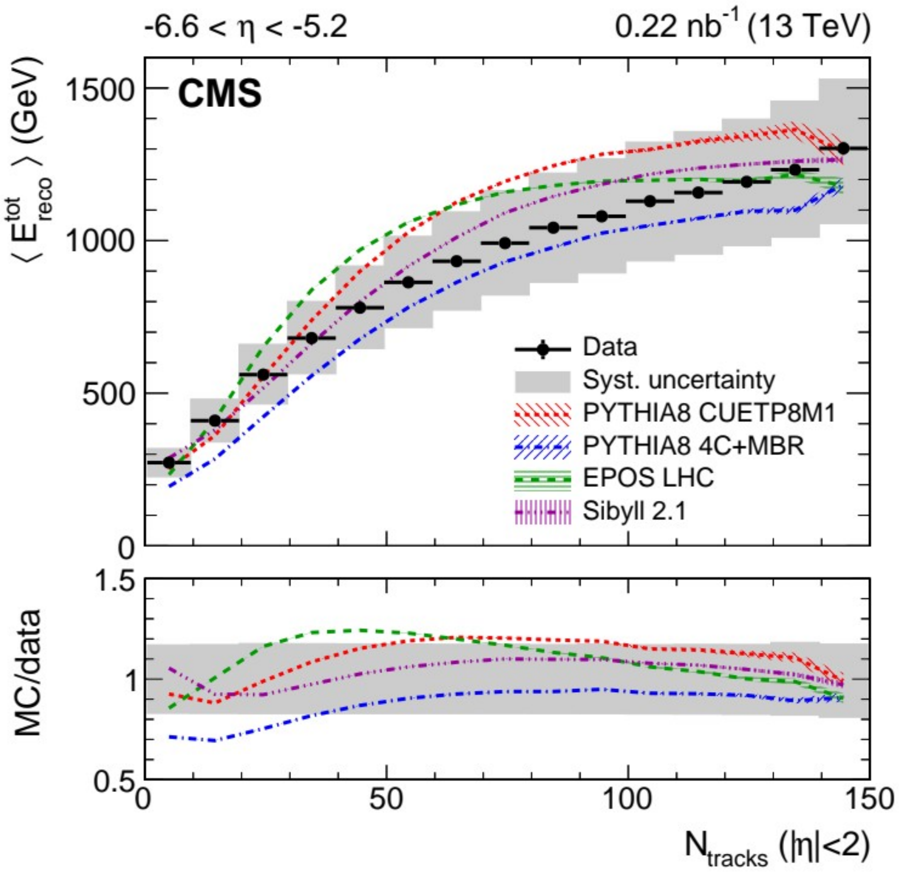
- Significant excess of high energy zero-degree neutrons
- Could be explained by diffractive single pion exchange
- Potential impact on air showers (π–nucleus interactions)



CMS: Forward-central correlation [arXiv:1908.01750]

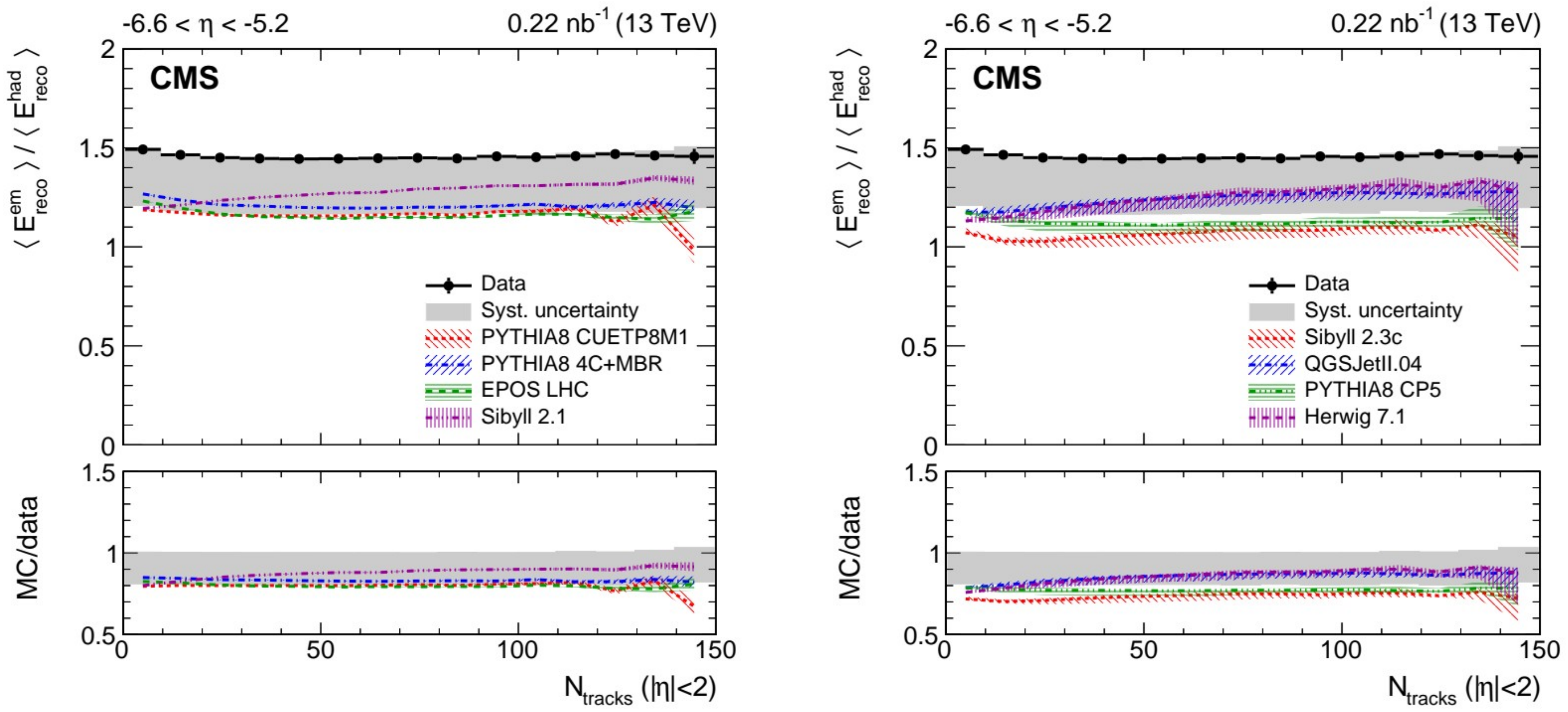
- Correlate forward energy to central particle multiplicity

$$\langle E_{reco} \rangle (N_{tracks,|\eta|<2})$$



CMS: Forward-central correlation [arXiv:1908.01750]

Ratio of electromagnetic to hadronic energy → charge ratio R



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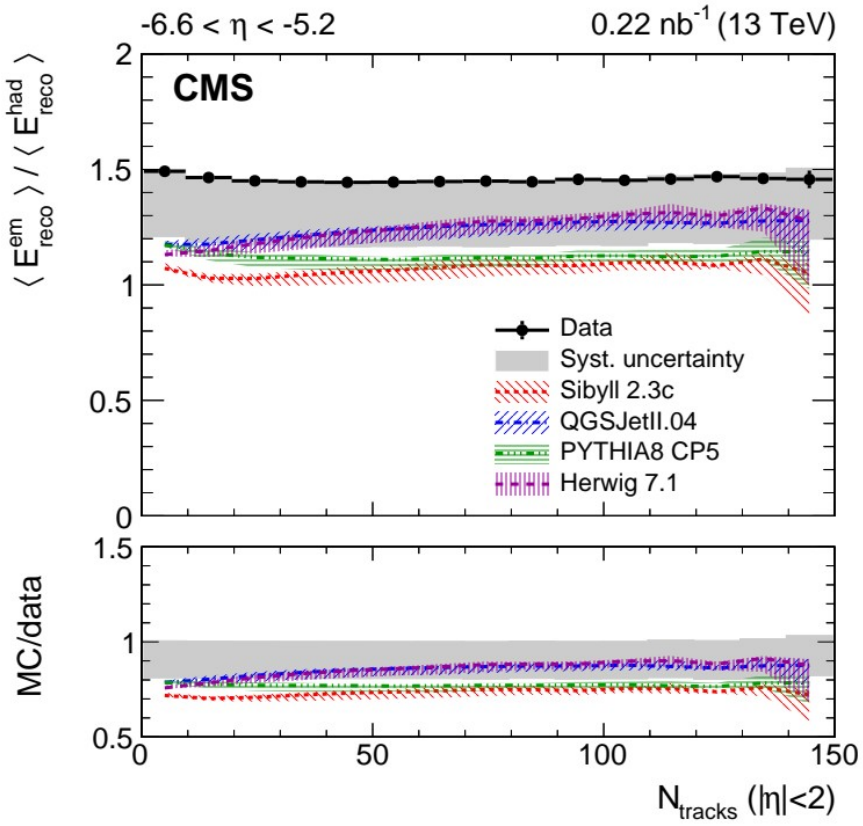
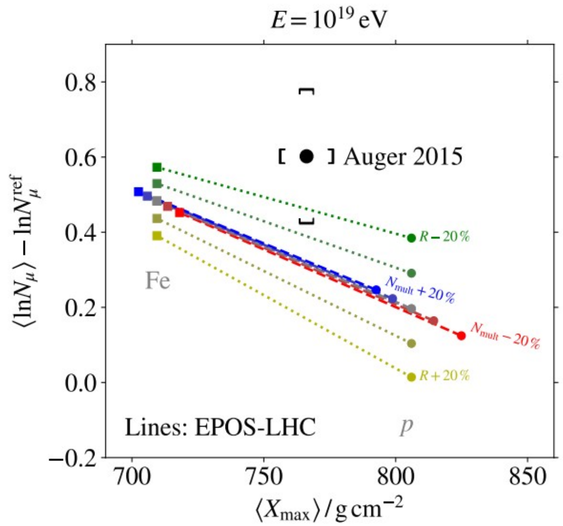


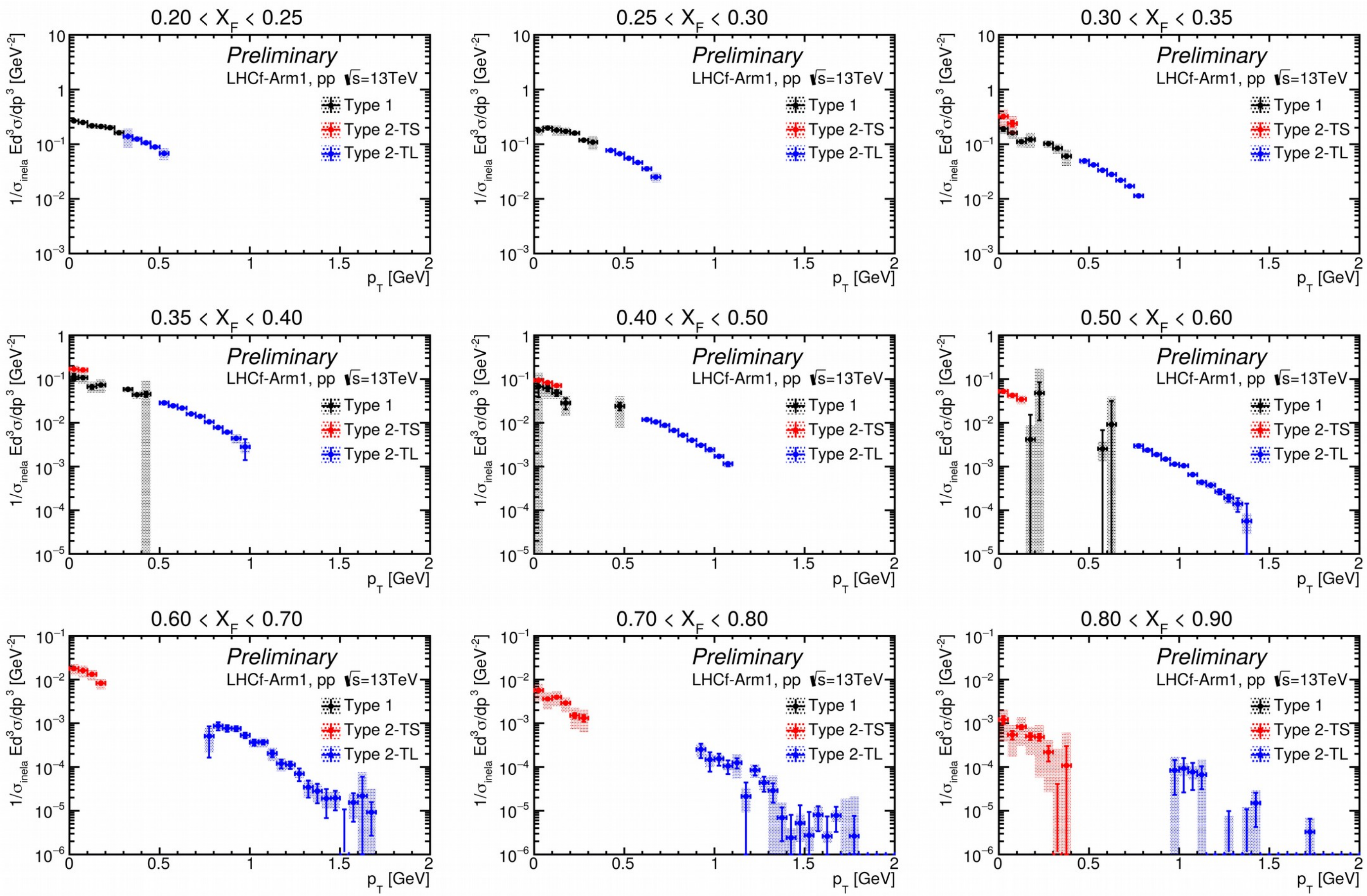


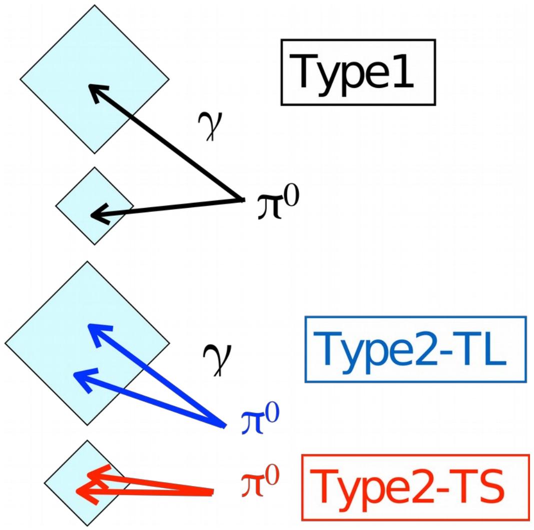
Models are at the lower bound:

→ no room for a significant reduction of R

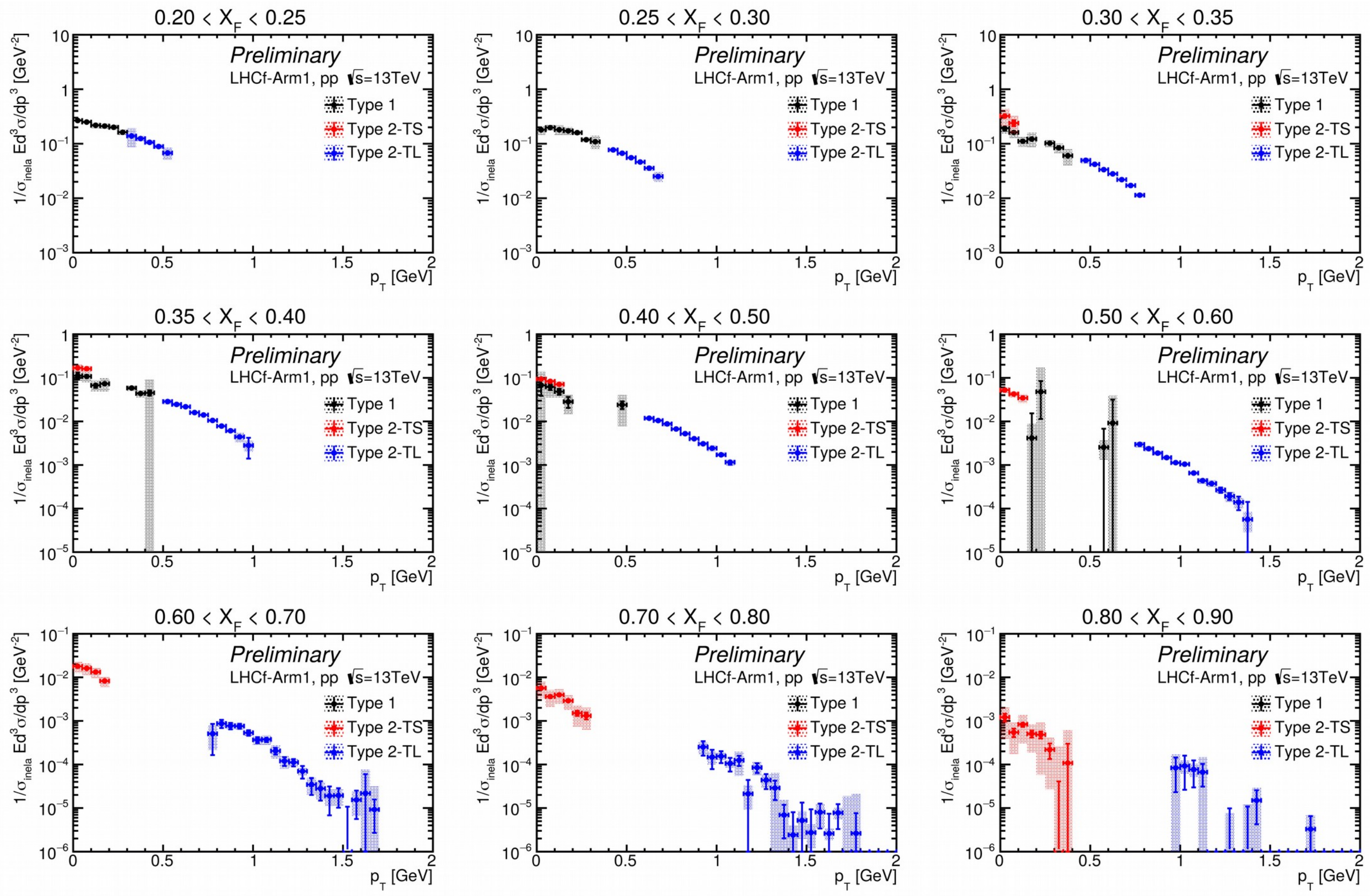
→ little hope to solve the muon deficit by QCD tuning

LHCf: Forward pion spectra [Preliminary: PoS(ICRC2019)349]





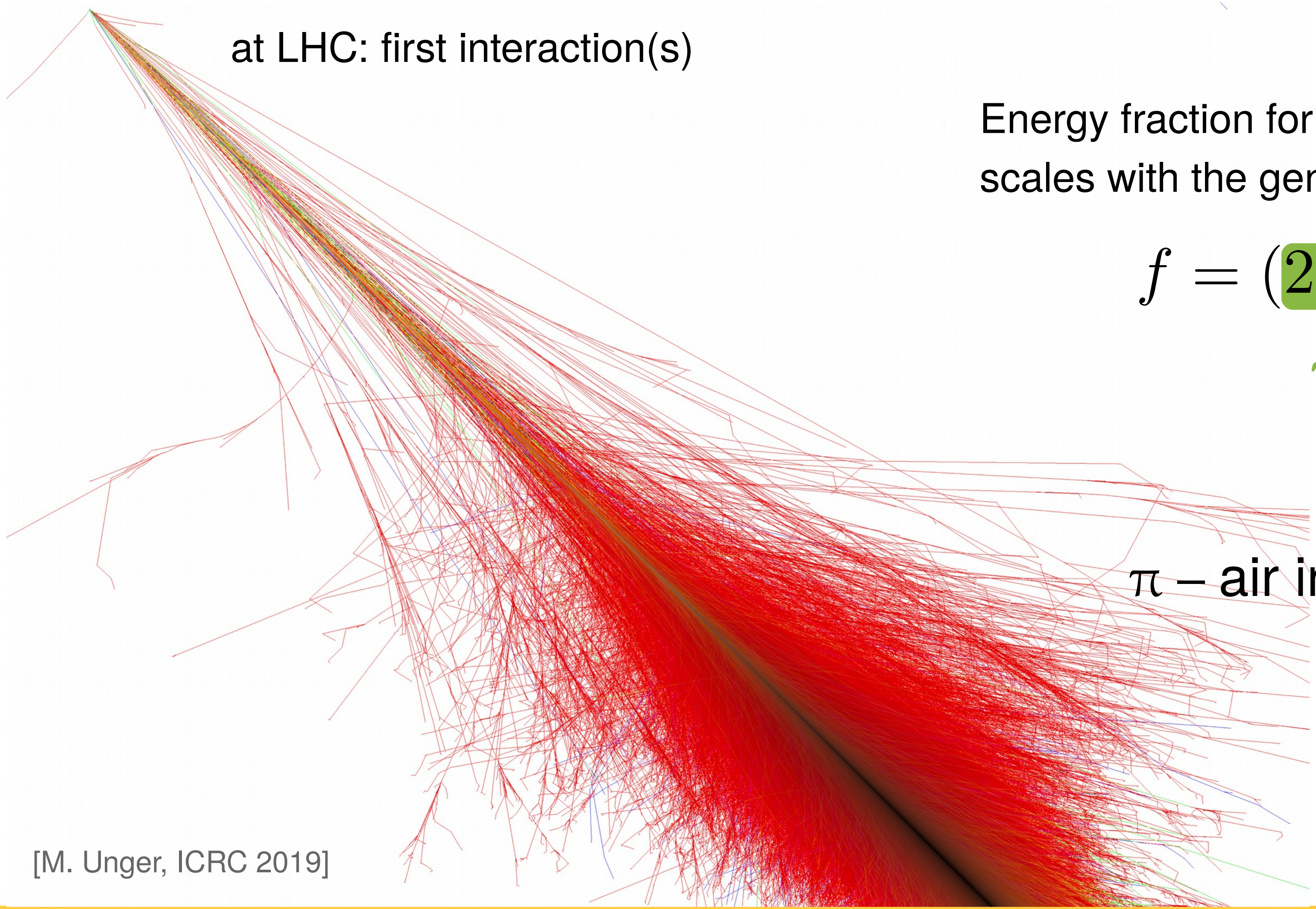
LHCf: Forward pion spectra [Preliminary: PoS(ICRC2019)349]



Forward (high energy) π^0:

- impact on early e.m. cascade
- take energy away from muon production
- No comparison to models yet

- Very important data, once fully analyzed and published at LHC: first interaction(s)



[M. Unger, ICRC 2019]

Energy fraction for muon production scales with the generations:

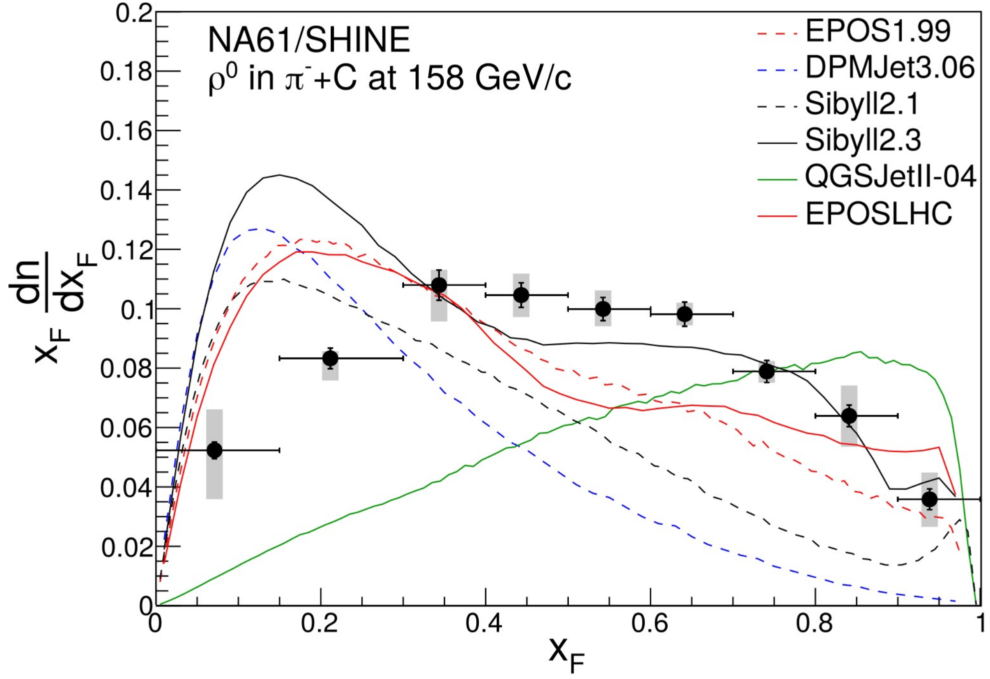
$$f = (2/3 + \Delta)^n$$

$\pi^{\pm}$ K, Λ, p, n, ...

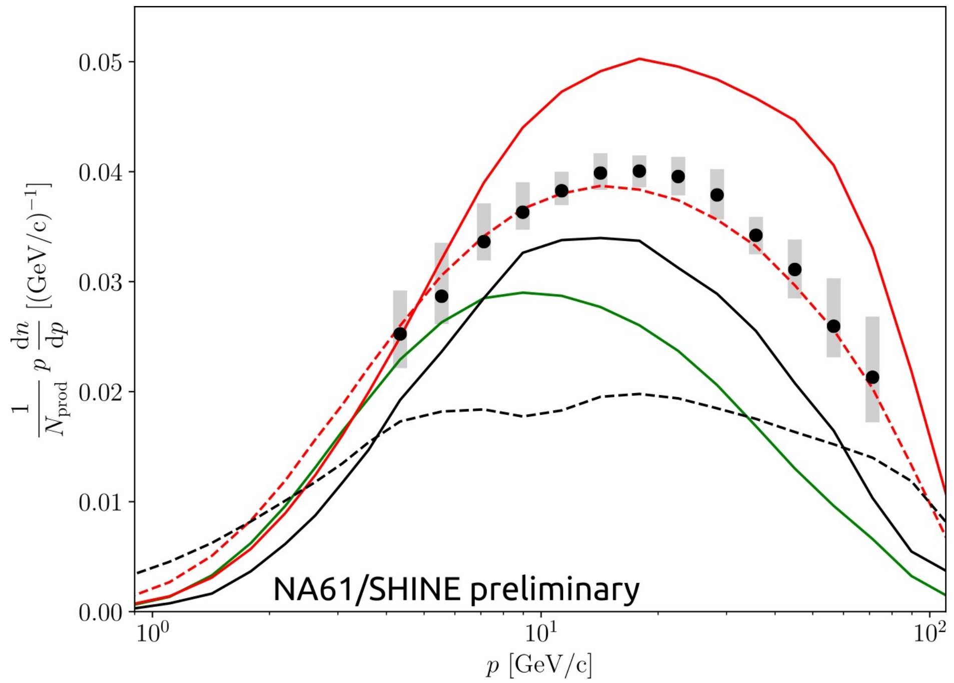
π – air interactions

NA61: Identified spectra in π-C (158 GeV/c)

[EPJC77 (2017) 626]



[PoS (ICRC2019) 446]

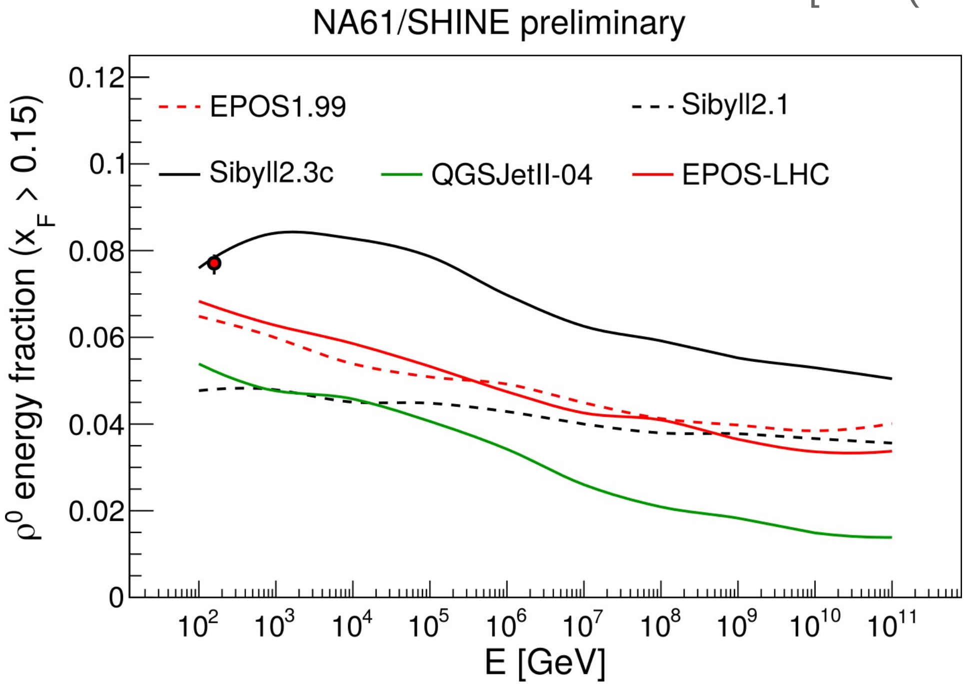


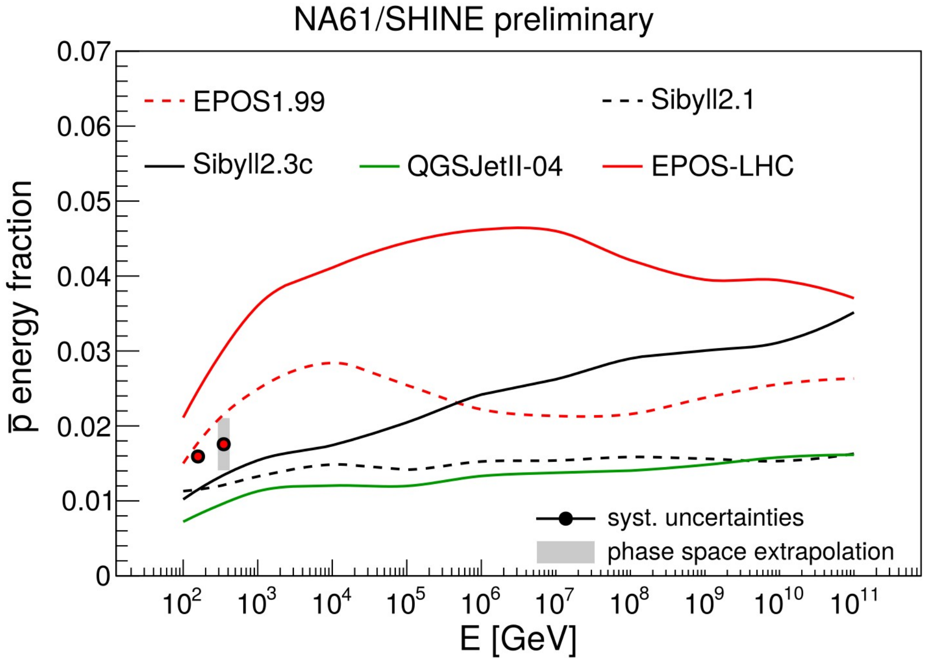
ρ^0 have a similar effect as π^0 → decay to $\gamma\gamma$ → feed the electromagnetic cascade

$\bar{p}$ is proxy for baryon production → feed the hadronic cascade

NA61: energy fractions in π-C (158 GeV)

[PoS (ICRC2019) 446]





Energy fraction carried by ρ^0 and $\bar{p}$ is poorly described

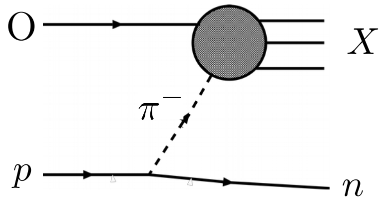
Overproduction of $\bar{p}$ and underproduction of ρ^0 both lead to an increased muon number

Summary

- Well founded interpretations of CR data require good hadronic interaction models
- Extensive and growing set of analyses
  → more complete and diverse picture of the forward particle production
- Benchmark tests for event generators:
  → model elasticity → constrains allowed shower maximum depth
  → fraction of hadronic energy → constrains allowed muon number
- A lot of work for model builders, no solution in sight yet
- Outlook: planned p-O collision for LHC Run3

  → better proxy for p-air

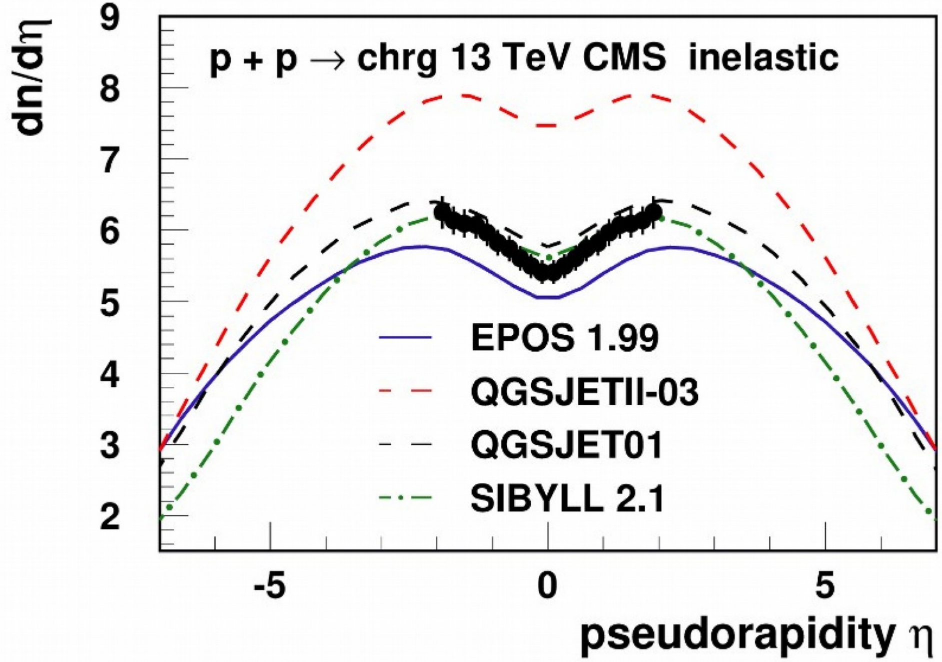
  → potential to measure π-O with LHCf+ATLAS



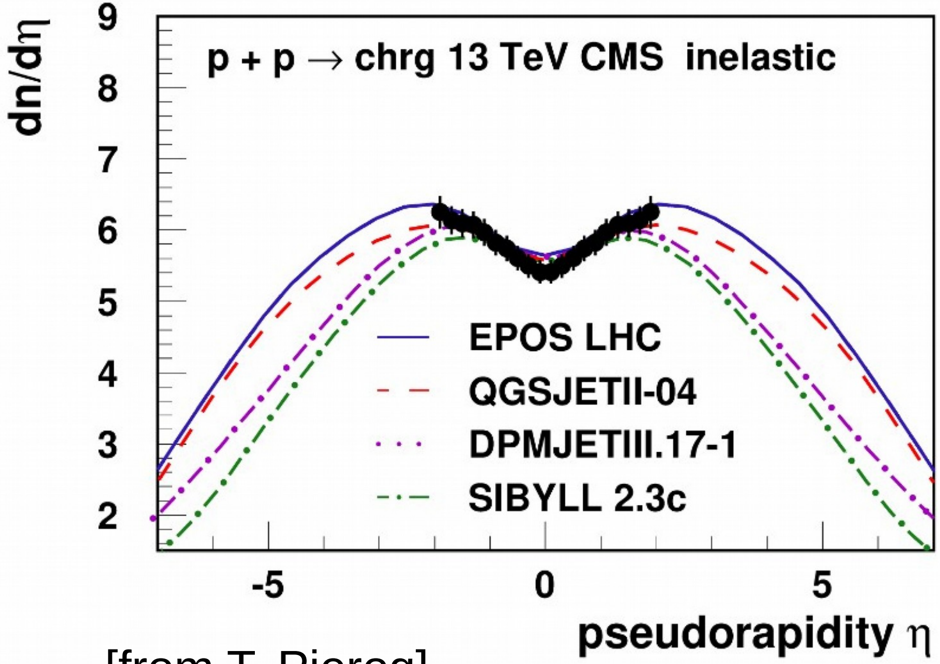
Backup

Big improvements after LHC Run 1

Pre - LHC



Post - LHC



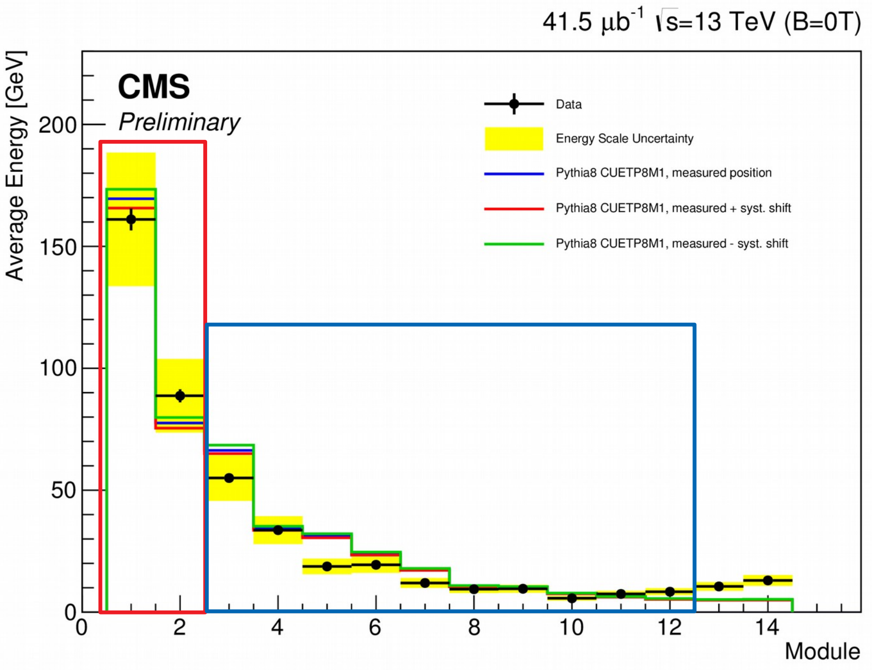
[from T. Pierog]

Energy measurements with CASTOR

- Total energy: Sum all calorimeter towers above noise threshold
- Signal in the first two modules of CASTOR is sensitive to the electromagnetic component
- Back part measures the hadronic contribution

Corresponding particle level energies:

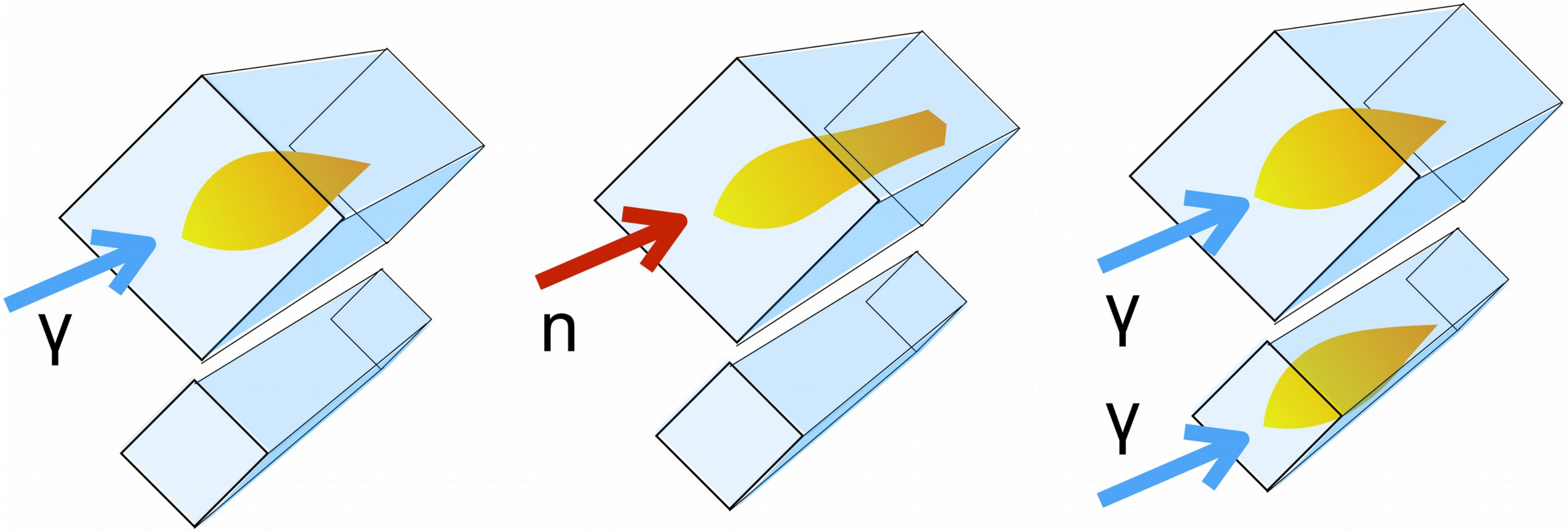
Energy sum of
- all stable particles except μ, ν
- e, γ (incl. π^0)
- all stable particles except μ, ν, e, γ



LHCf: PID

[From Hiroaki Menjo, ICRC 2019]

Photons | **Neutrons** | **π^0**



Photons

- EM showers
- $\Delta E/E < 5\%$
- $\Delta pos < 0.2$ mm

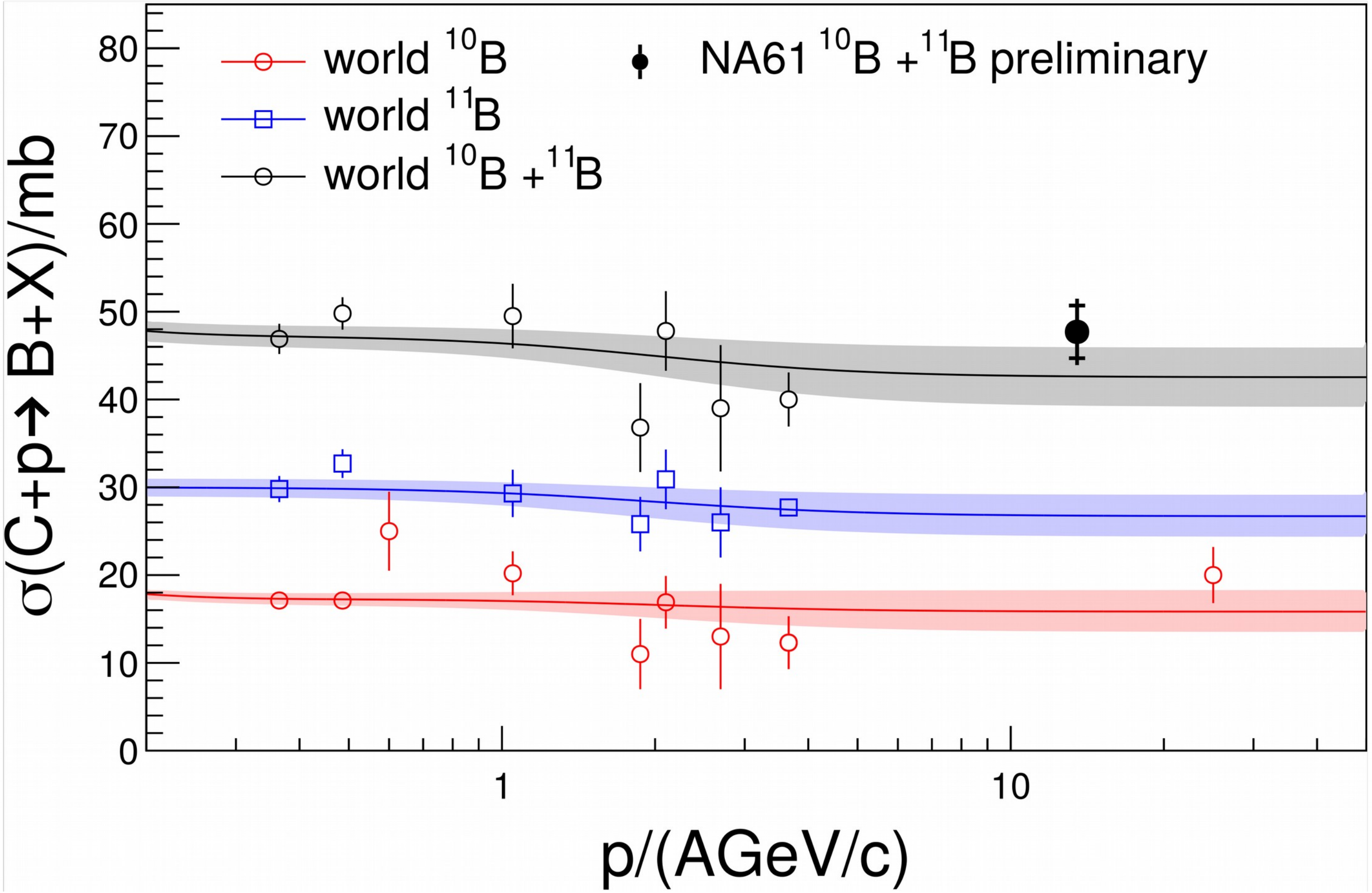
Neutrons

- Hadronic showers
- $\Delta E/E \sim 40\%$
- $\Delta pos \sim 1.0$ mm
- deeper and longer than EM showers

π^0

- "Pairs" of EM showers
- $\pi^0 \rightarrow 2\gamma$ (BR:98.8%)
- $E_\pi = E_{\gamma 1} + E_{\gamma 2}$

Preliminary Result on Direct $^{10}B + ^{11}B$ Production



[PoS (ICRC2019) 446]

QGP and muon numbers

- QGP-like states enhance baryon production
- QGP-like effects are observed in p-p at the LHC
  e.g. ‘Ridge’ (CMS: JHEP 09 (2010) 091), enhanced strangeness (ALICE: Nature Phys. 13 (2017) 535)
- Effects turn on earlier than predicted by EPOS-LHC
- Enhancement of the QGP phase space could lead to an increase of muon production