CORSIKA Upgrade

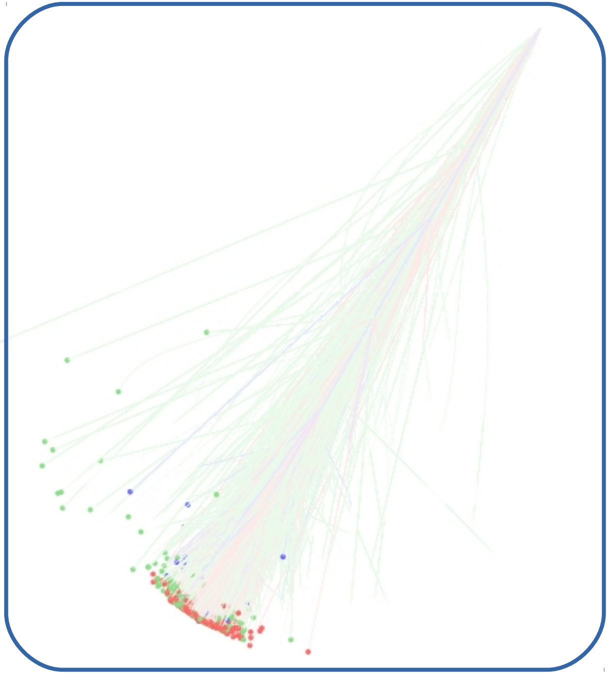
Simulating particle cascades for astroparticle physics

Ralf Ulrich, CERN, 7. November 2018
HERD Workshop

Air shower and cascade physics

- Tons of detailed **input data,** some relatively well know, others only poorly

- A lot of **theory**, microscopic modeling, phenomenology



the universe at the highest energies

and

the nature of cosmic rays

→ **What exactly is the relation between input data/models to final physics interpretation?**

Currently: world-leading tool for air shower modeling **CORSIKA**

Origin of CORSIKA

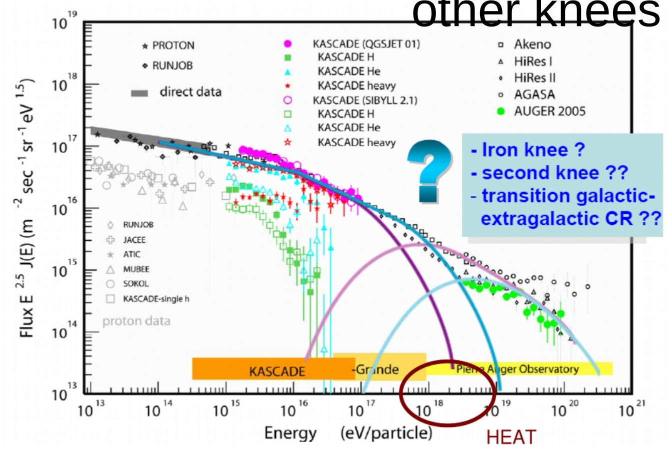
tool

Cosmic Ray SimulationS for KAscade

CORSIKA → CRES → KRETA

KASCADE → KRETA → Physics of the knee and other knees

Physics of the knee and other knees



The CORSIKA legacy: v1.0 from 1989

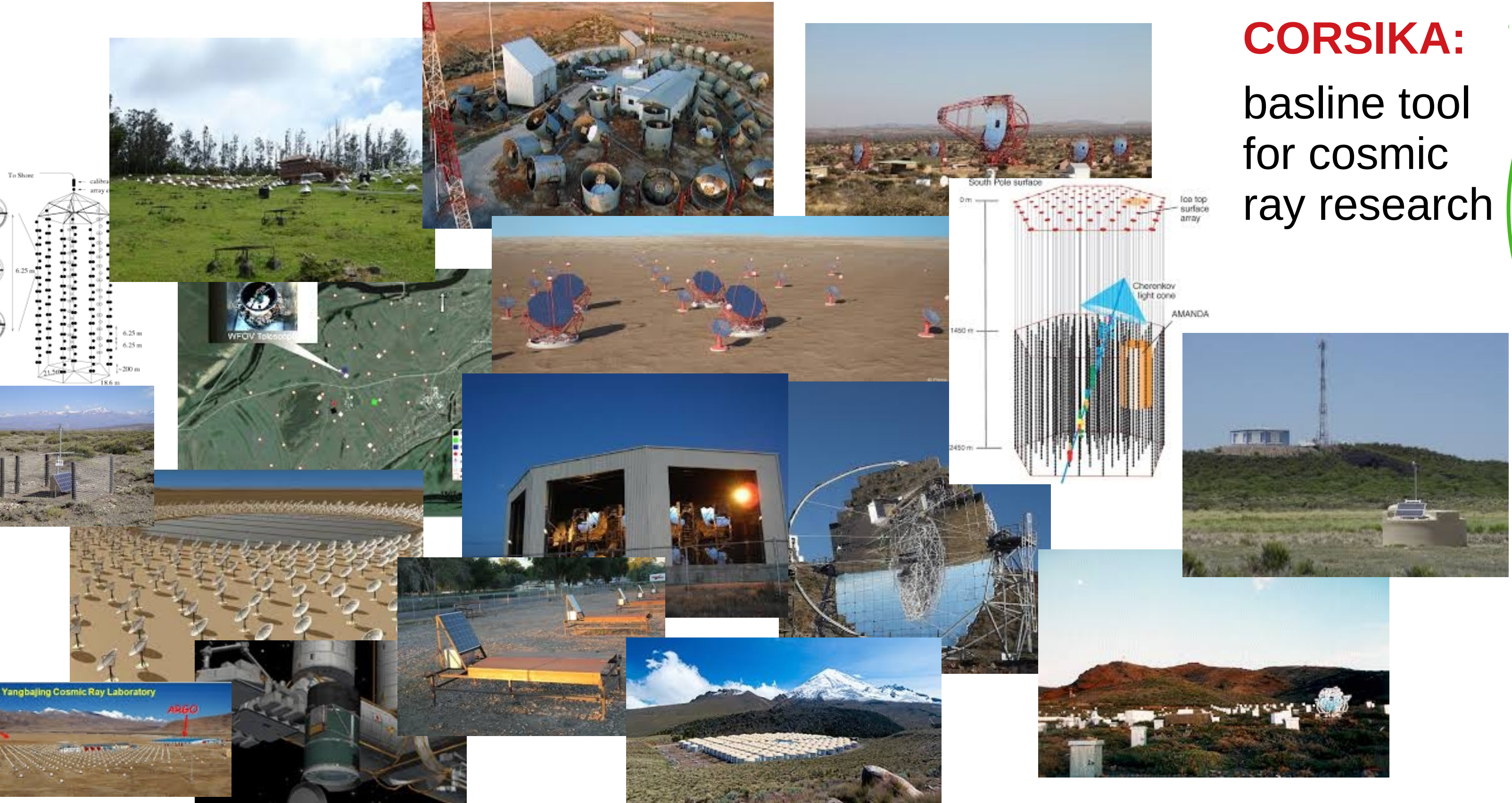
Status today:

- >1200 registered users, >50 Collaborations
  - Every single cosmic ray experiment uses it
  - Also applications in atmospheric physics, and radiation protection (aviation)
- Development statistics (rough estimates):
  - ≈ 700k lines of code
  - ≈ 200 man-year development
  - **≈ 20 MEUR**
- FZKA-6019, FZKA-6097 reports (1998)
  → combined 1583 citations (google scholar)

Dedicated CORSIKA schools

2005 Freudenstadt
2008 Freudenstadt
2010 Ooty, India
2014 Freudenstadt
next: **2018 CERN**
→ indico.cern.ch/event/719824

Evolution of CORSIKA, 1989 – 2018



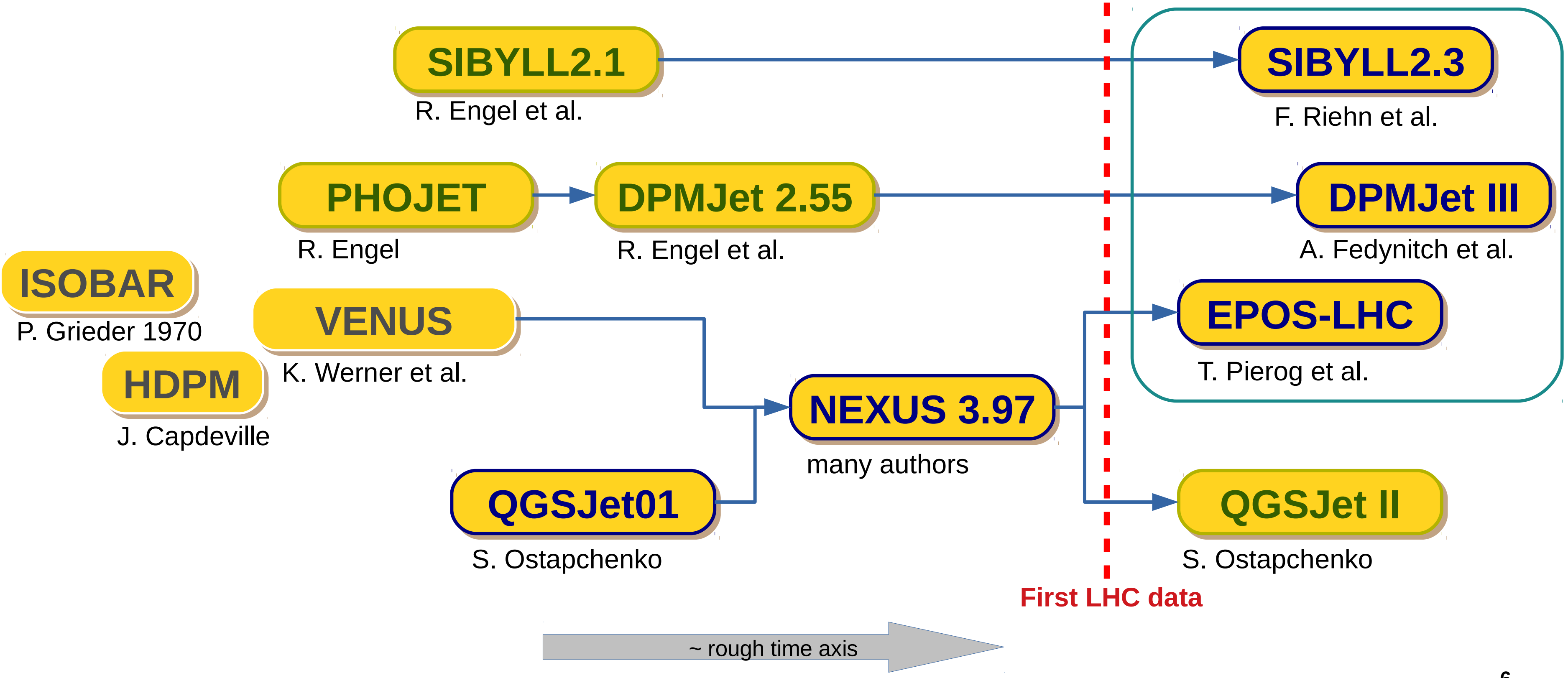
CORSIKA:

basline tool for cosmic ray research

Alternatives

- AIRES
- SENECA
- CONEX
- MOCCA
- COSMOS
- …

Hadron interaction models for air showers



Future of CORSIKA, challenges and targets

- Further improve quality of simulations, and hadronic event generators, reduce (and assess) modeling uncertainties
- Muon production in air showers
  - Not enough muons in simulations
  - Spectrum of muons too soft in simulations
  - Closely linked to hadronic shower core
- Improve computational efficiency for massive simulation libraries
- More flexibility for future experiments and new ideas: multi-media, deep/sophisticated cuts, etc.
- Better stability: debugging, testing facilities, automation

→ Laboratory to investigate the impact of detailed microscopic modeling on astroparticle physics

CORSIKA upgrade

- Cornerstone for the scientific work of many experimental collaborations
- Excellent understanding of particle cascades is important for almost all aspects in astroparticle physics
- There are existing limitations that must be overcome
- Need a new and modern framework that allows our field to tackle physics questions over the next ~3 decades
  - New large-scale detectors, new fundamental physics

Towards the next generation of CORSIKA: A framework for the simulation of particle cascades in astroparticle physics

Ralph Engel[1,2], Dieter Heck[1], Tim Huege[1,3], Tanguy Pierog[1], Maximilian Reininghaus[1,2], Felix Riehn[4], Ralf Ulrich*[1], Michael Unger[1], and Darko Veberič[1]

[1]Institut für Kernphysik, Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany
[2]Institut für Experimentelle Teilchenphysik, Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany
[3]Vrije Universiteit Brussel (VUB), Brussels, Belgium
[4]Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Lisboa, Portugal

August 2018

Abstract

A large scientific community depends on the precise modelling of complex processes in particle cascades in various types of matter. These models are used most prevalently in cosmic-ray physics, astrophysical-neutrino physics, and gamma-ray astronomy. In this white paper, we summarize the necessary steps to ensure the evolution and future availability of optimal simulation tools. The purpose of this document is not to act as a strict blueprint for next-generation software, but to provide guidance for the vital aspects of its design. The topics considered here are driven by physics and scientific applications. Furthermore, the main consequences of implementation decisions on performance are outlined. We highlight the computational performance as an important aspect guiding the design since future scientific applications will heavily depend on an efficient use of computational resources.

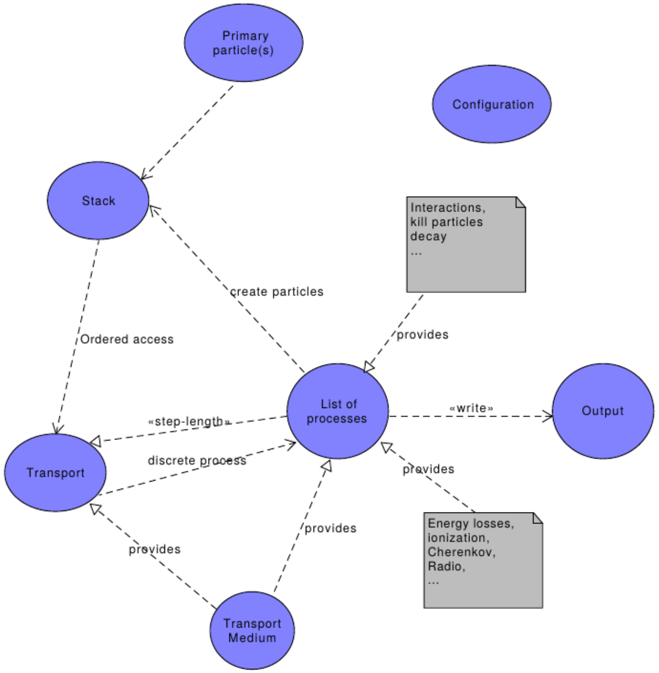
arxiv.org/abs/1808.08226

Next generation of CORSIKA

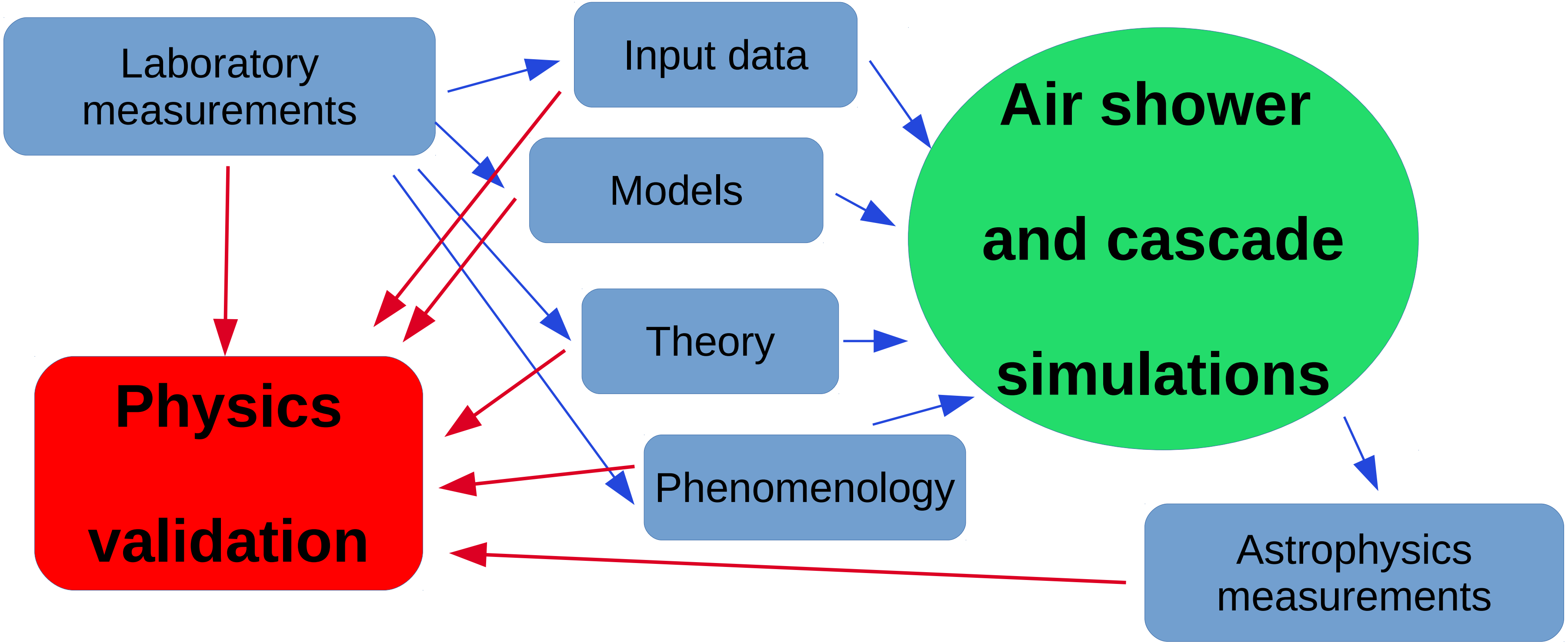
- Framework for simulating particle cascade processes
  - modular, flexibel
  - precise, fast

- Fundamental integration of
  - Parallelization
  - GPUs
  - Modularity and flexibility

- Highest quality air shower simulations and complex data analyses

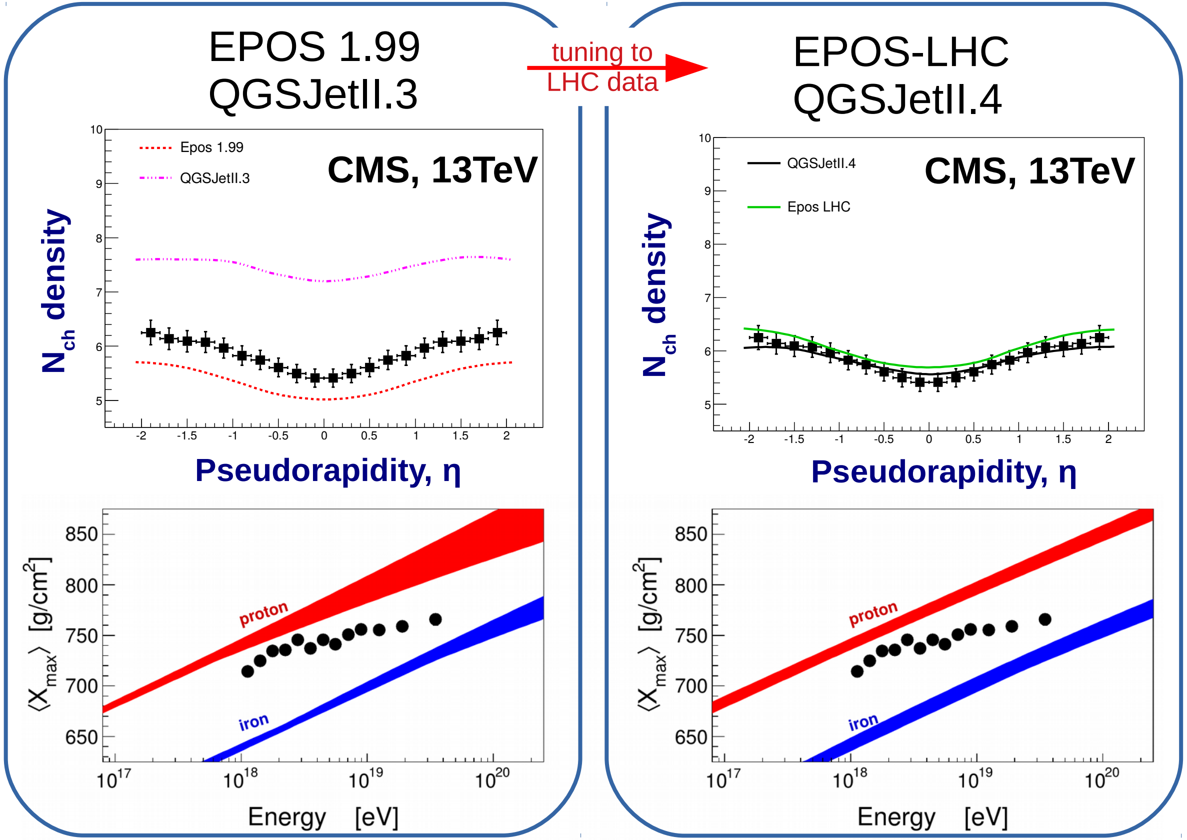


Importance of validation for CORSIKA upgrade



Fully quantified validation (→ likelihood) with all constraints and parameters.

Some consequences and implications

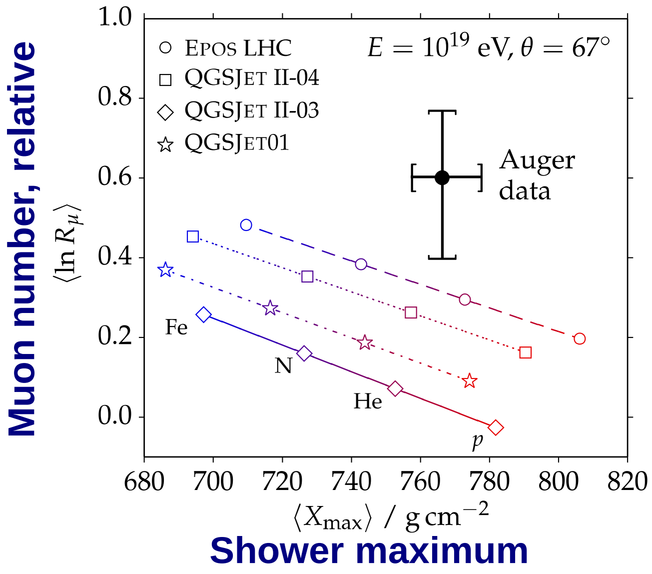


- Extrapolation is a fundamental problem
- New measurements lead to improved models and better air shower predictions

Phys. Rev. D 83 (2011) 054026
Phys. Lett. B 751 (2015) 143

Muon production in air showers

Experimental situation

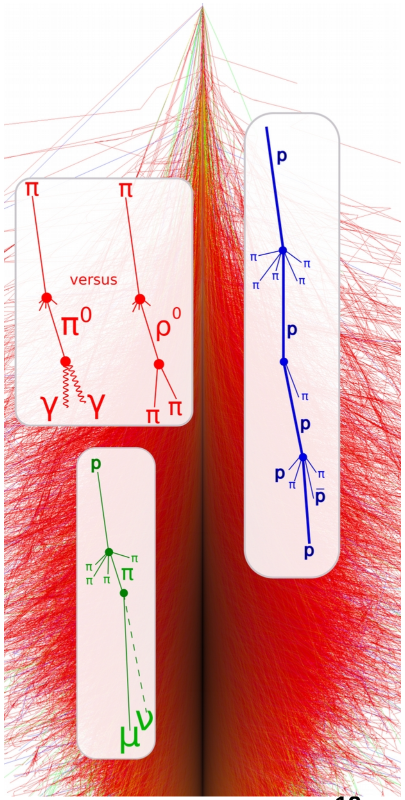


Phys. Rev. D 91 (2015) 032003

New ideas/ investigations

Size of the pion/kaon cascade at ≈GeV level:

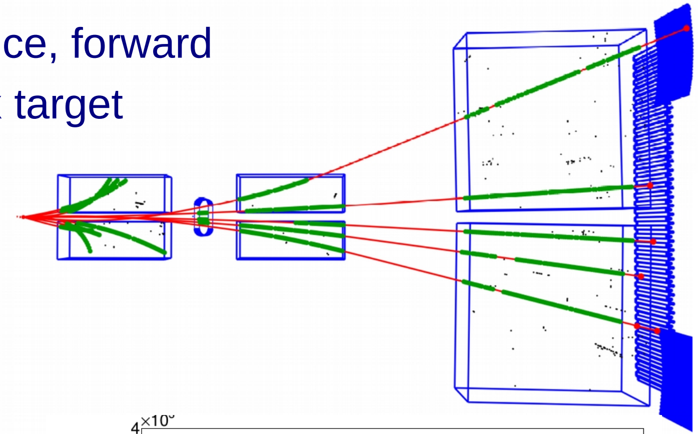
- Baryon production
- Forward ρ^0 vs. π^0, charge-exchange
- Elementary vs. nuclear effects
- New physics



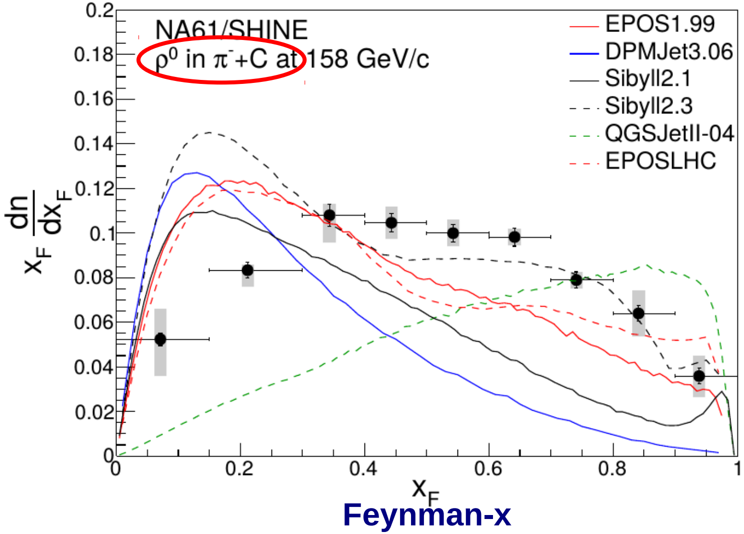
Constraining muon production with NA61

Large-acceptance, forward TPC at SPS, fix target

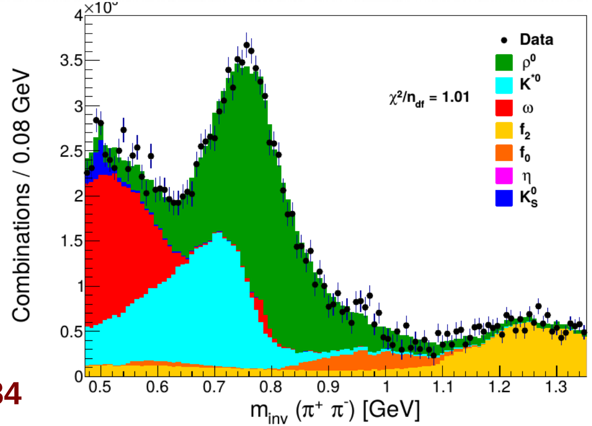
$\pi + C$



- Nuclear effects, carbon target
- Dedicated pion beams (etc.)

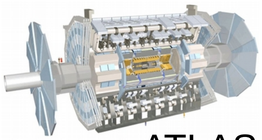


Invariant mass template fitting, $\pi^+\pi^-$ final state



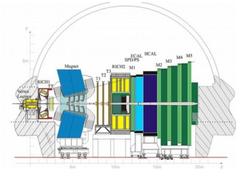
Eur. Phys. J. C 76 (2016) 84

Acceptance of LHC experiments



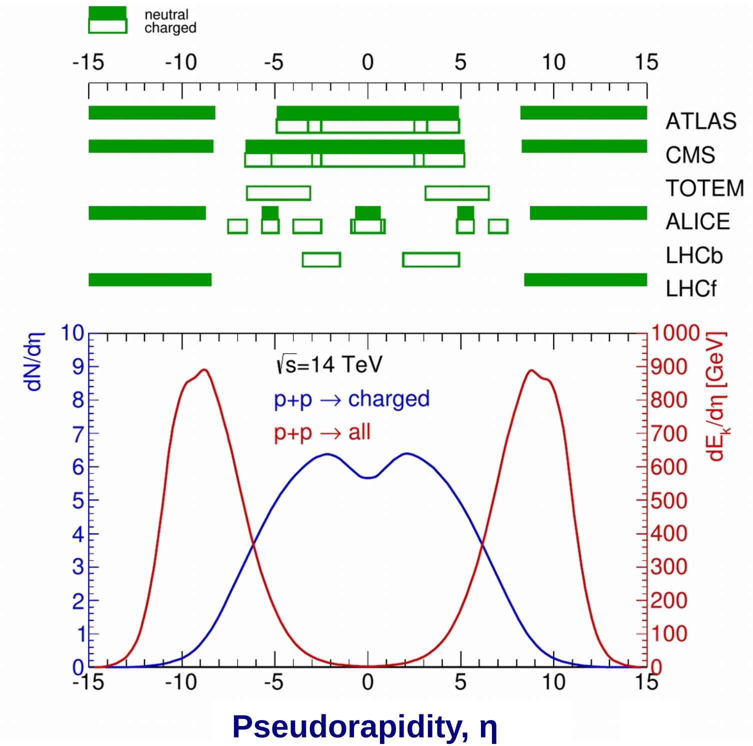
ATLAS

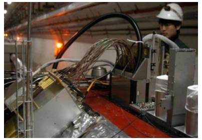
CMS



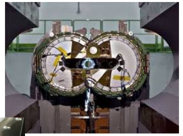
LHCb

ALICE

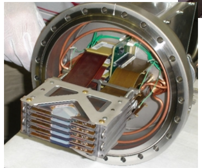




LHCf

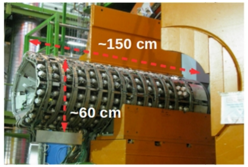


T2



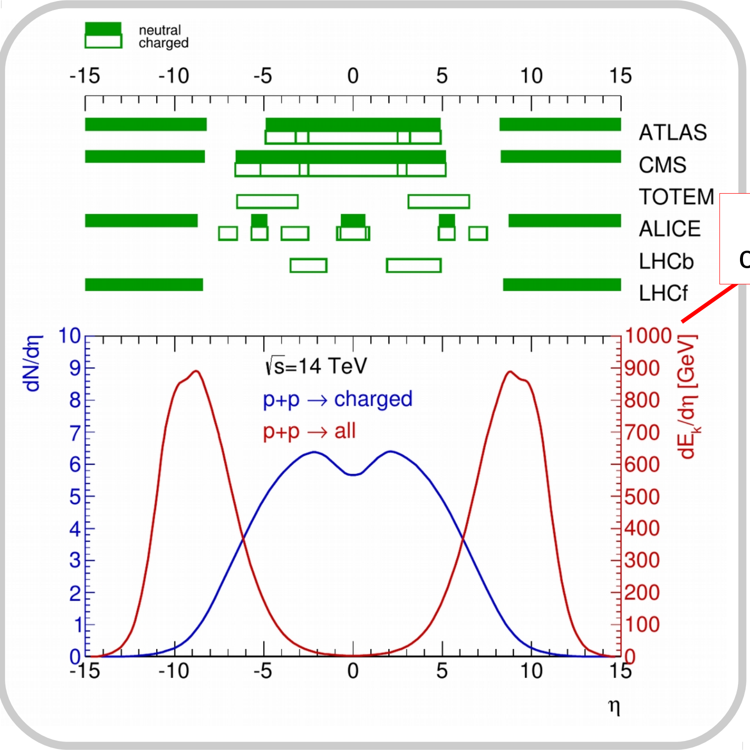
TOTEM

Roman Pots

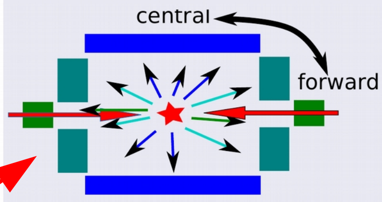


CASTOR

Acceptance of LHC experiments, and relevance for air showers

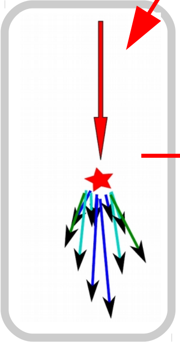


LHC collisions

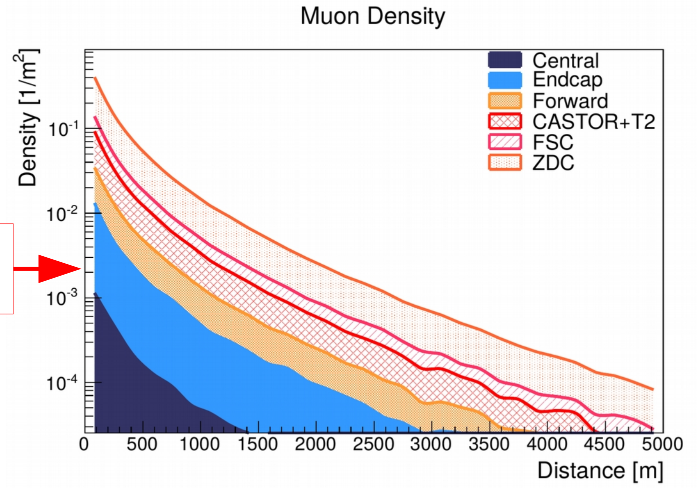


- Central ($|\eta| < 1$)
- Endcap ($1 < |\eta| < 3.5$)
- Forward ($3 < |\eta| < 5$), HF
- CASTOR+T2 ($5 < |\eta| < 6.6$)
- FSC ($6.6 < |\eta| < 8$)
- ZDC ($|\eta| > 8$), LHCf

Lorentz boost

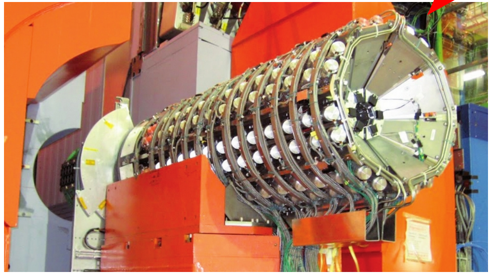


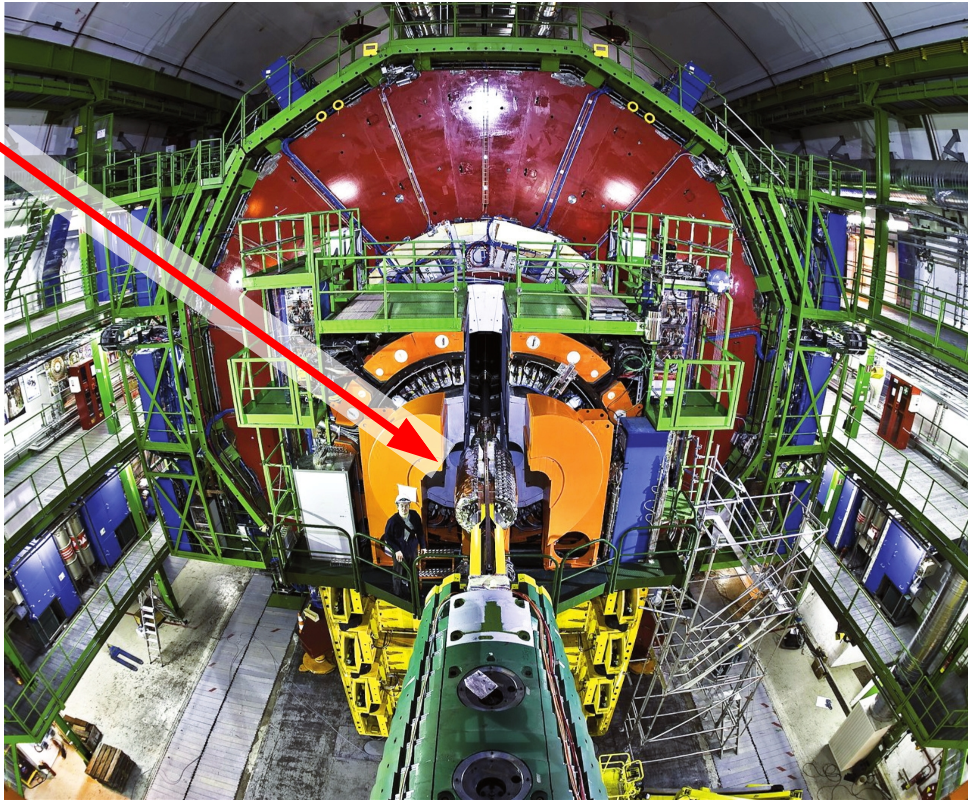
Air shower



Constraining the high energy part of air shower cascades, CMS-CASTOR

CASTOR



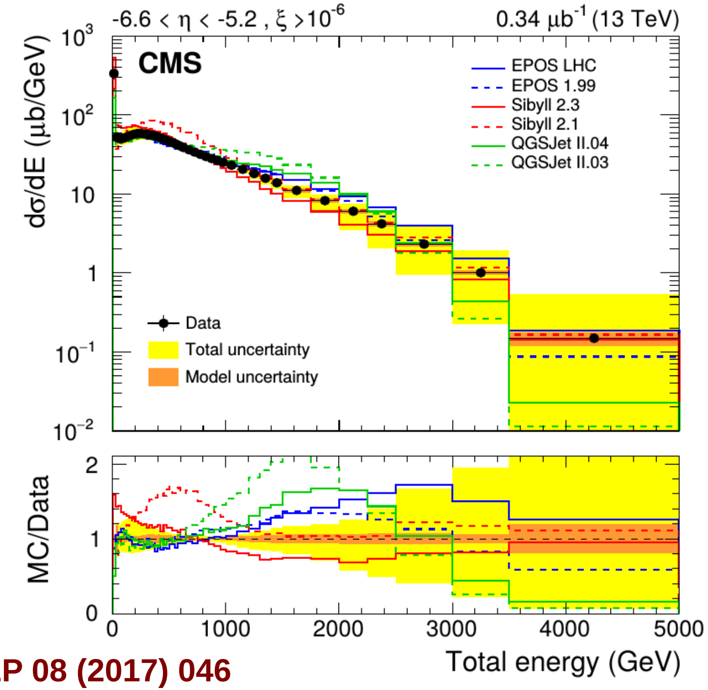


- Highest possible center-of-mass energy at colliders
- Most forward charged-particle LHC calorimeter

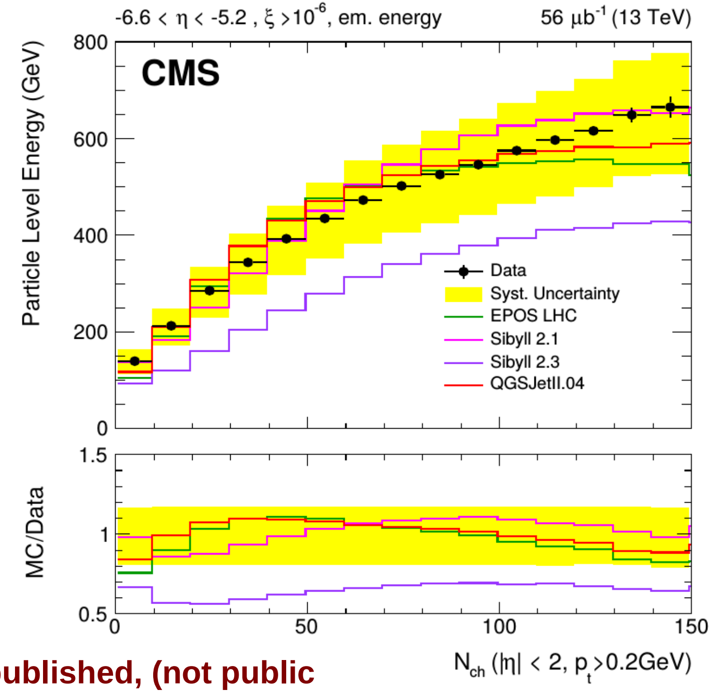
Dedicated CASTOR measurements

Karlsruhe Institute of Technology

Very forward energy distributions → Differential in N_{ch} ($|\eta|<2$)



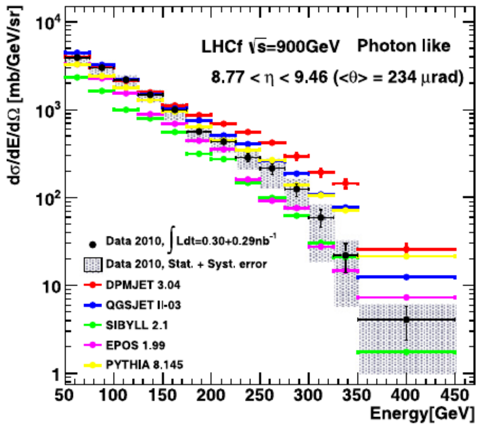
JHEP 08 (2017) 046

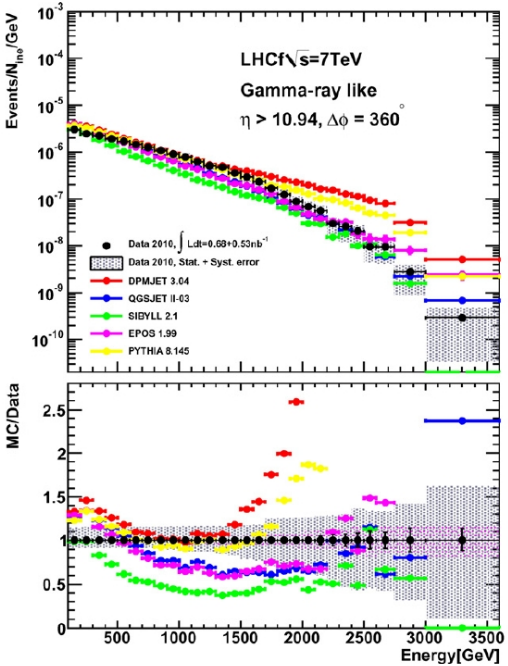


to be published, (not public yet...)

LHCf: measurements for cosmic ray community

Photon production spectra

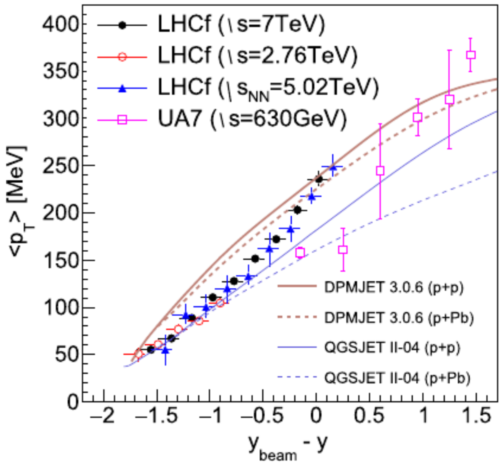




Phys. Lett. B 715 (2012) 298

Phys. Lett. B 703 (2011) 128

Pion production spectra

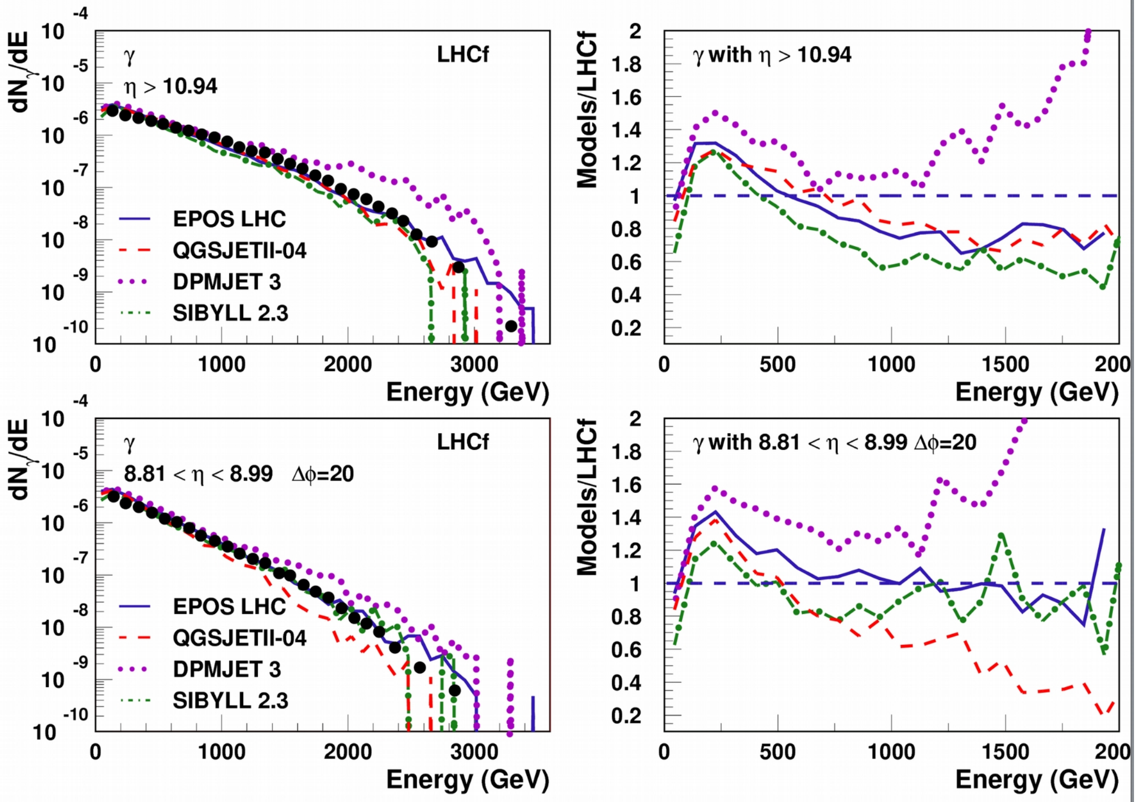


Phys. Rev. D 86 (2012) 092001

Phys. Rev. D 94 (2016) 032007

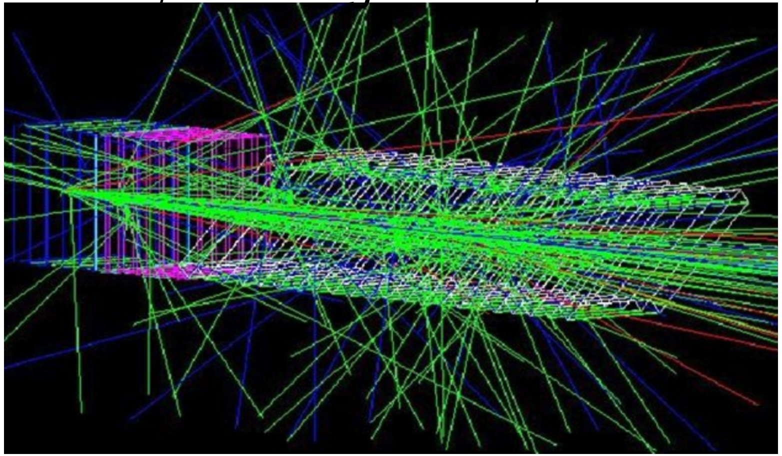
and: **Neutron production spectra**, see charge-exchange

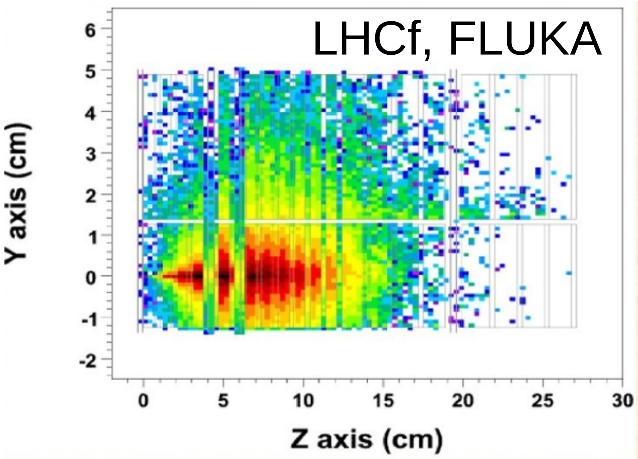
LHCf data and model tuning



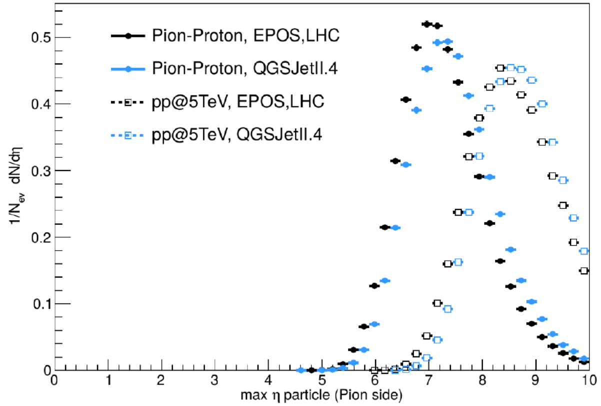
Shower in calorimeters

CMS, Zero degree cal., GEANT4





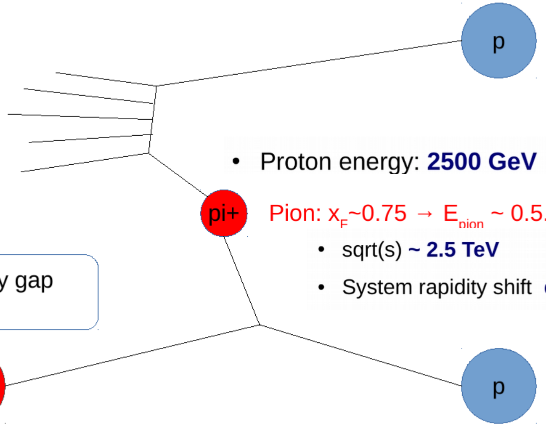
Charge-exchange reaction at LHC



Pion-proton collision, central detector

Small forward rapidity gap in particle production

Neutron at zero-angle



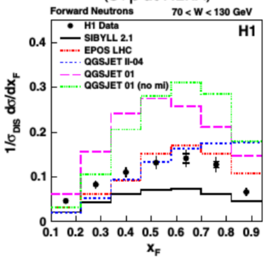
- Proton energy: **2500 GeV**

Pion: x_F~0.75 → E_{pion} ~ 0.5...1 TeV

- sqrt(s) **~ 2.5 TeV**
- System rapidity shift **dy ~ 0.97**

HERA

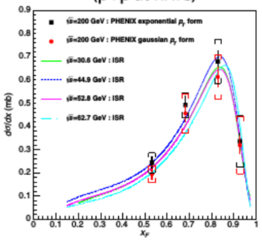
(e+p at HERA)



(H1, Eur. Phys. J. C 74 2915 (2014))

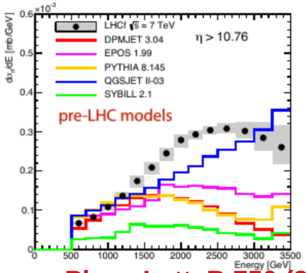
RHIC

(p+p at RHIC)



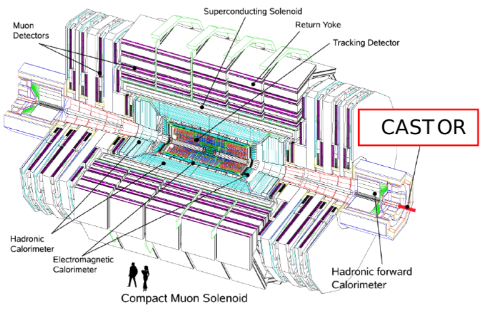
(PHENIX, Phys. Rev. D 88 032006 (2013))

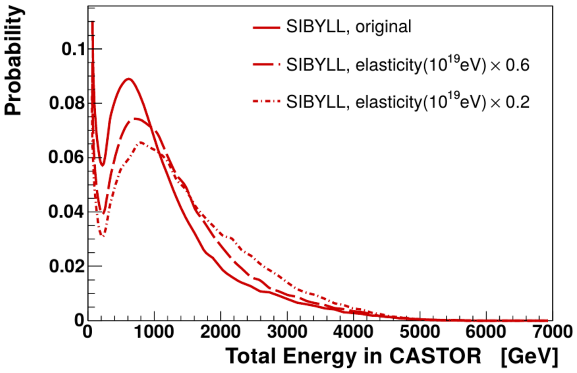
LHC, LHCf

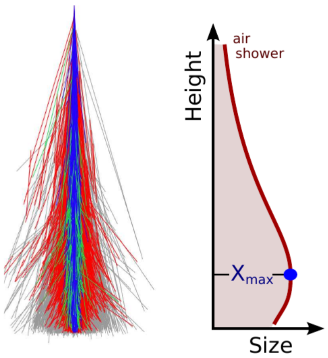


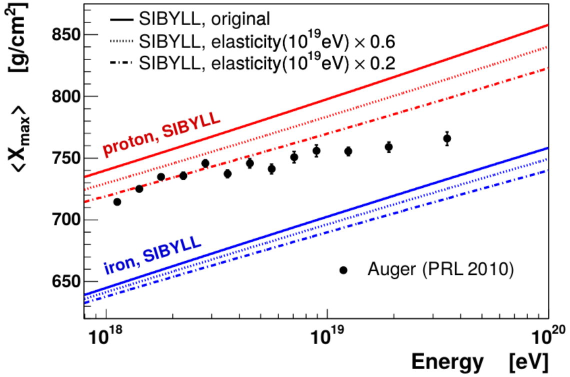
Phys. Lett. B 750 (2015) 360

Connection between laboratory measurements and air showers









General modeling questions to CORSIKA

- There is an artificial break between low- and high-energy interaction models. What is the signifcance of that?
- What exactly is the impact of „thinning“ on air shower predictions?
- How well do we really know all aspects of electromagnetic showers?
- What is the eventual room for new physics in cascades?
- Why is there a deficiency of muons in air shower simulations?
- What is the precise „charm“, „strange“ and also „bottom/top“ content of hadrons?
- ...

Milestones, planning

Requirement for CORSIKA-upgrade: better physics performance than CORSIKA

- Milestone 0: July 2018, Workshop at KIT, and white paper
- Milestone 1: CORISKA 8.0.0, September 2018
  Framework definition, working environment/infrastructure, first documentation
- Milestone 2: CORSIKA 8.0.1, end of 2018
  First cascade calculations, w/ simple atmosphere
- Milestone 3: CORSIKA 8.0.2, February 2019
  SIBYLL2.3 and UrQMD included and a useful atmosphere model
- Milestone 4: CORSIKA 8.0.3, ~Summer 2019
  Include E.M. interactions
- Milestone 5: CORSIKA 8.1.0, ~2020
  First full physics (demonstrator) release

Impact on community

- **There is opportunity to actively contribute**
  - Shape parts of the project for the future, and for specific applications
  - Get in contact:
    - Write to me, connect to corsika-devel@lists.kit.edu, and to gitlab.ikp.kit.edu

- **Some goals and standards**
  - Make it really hard/impossible to produce wrong physics and results
  - Make complete use of available optimization and high-performance concepts
  - High standards on code, combined with excellent documentation
  - Extensive use of testing, automation and unit testing
  - Direct access to high-level validation
  - Very low-level enforcement of physical concepts on the level of code compilation

Brief introduction to some concepts

- In physics we often think+work within well defined reference frames. We want to map this fact into code and enforce it!
- Help physicist to produce correct algorithms.
- Code as close as possible to natural physics representation.

OK	not OK
567_GeV + 1_TeV	constants::c + 1_m
point1.GetX(showerFrame)	point1.GetX()
particle::GetMass(Sib2Cors(PID::Electron))	particle::GetMass(5)

→ **does simply not compile**

Example, main cascade loop

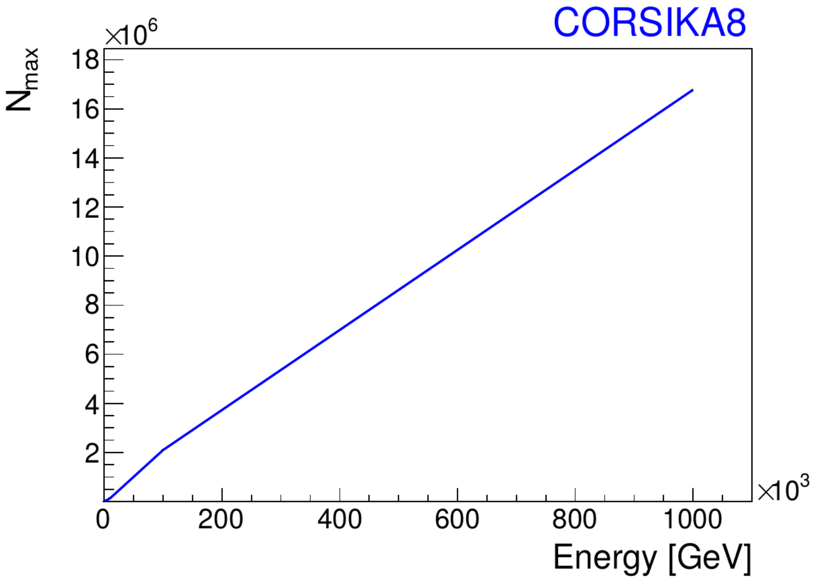
```
void Run() {
  while (!fStack.IsEmpty()) {
    Particle& p = *fStack.GetNextParticle();
    Step(p);
  }
}

void Step(Particle& particle) {
  double nextStep = fProcesseList.MinStepLength(particle);
  fProcesseList.DoContinuous(particle, fStack);
  fProcesseList.DoDiscrete(particle, fStack);
}
```

```
ProcessReport p0(false);
HeitleModel p1;
const auto sequence = p0 + p1;
corsika::stack::super_stupid::SuperStupidStack stack;
corsika::cascade::Cascade EAS(sequence, stack);
stack.NewParticle().SetEnergy(10_TeV);
EAS.Run();
```

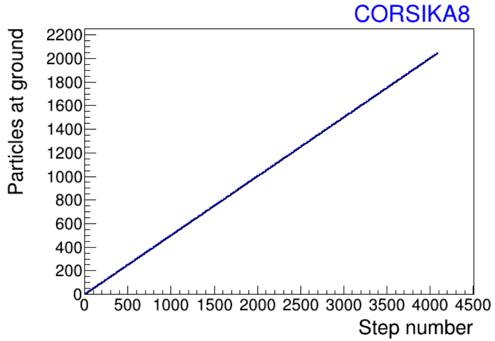
Heitler model (equal energy splitting)

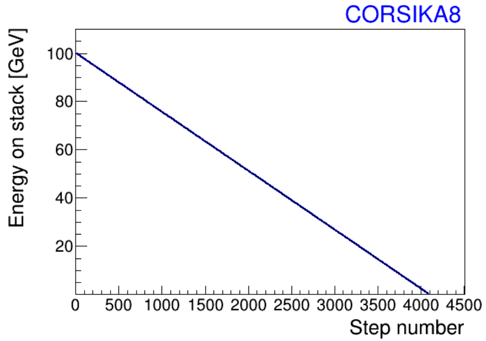
```
class ProcessSplit : public corsika::process::BaseProcess<ProcessSplit> {
public:
  template <typename Particle, typename Stack>
  void DoDiscrete(Particle& p, Stack& s) const {
    EnergyType E = p.GetEnergy();
    if (E < 1_GeV) {
      p.Delete();
      fCount++;
    } else {
      p.SetEnergy(E / 2);
      s.NewParticle().SetEnergy(E / 2);
    }
  }
```

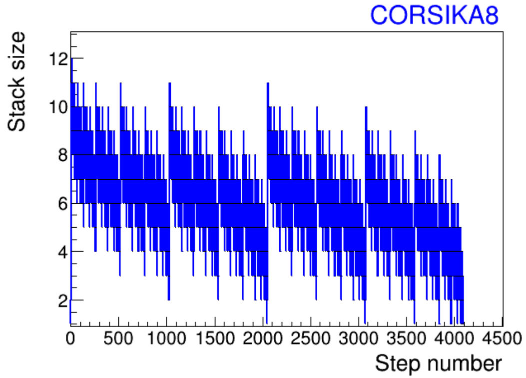


Diagnostics of the cascade process, E_0=100GeV

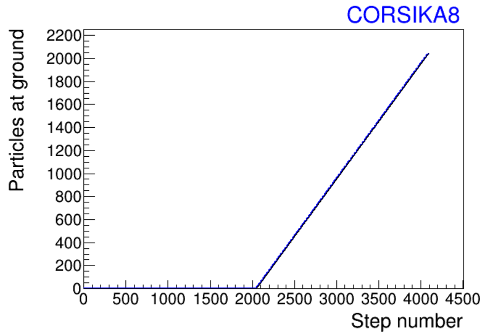
Use lowest energy particle for next step in cascade:

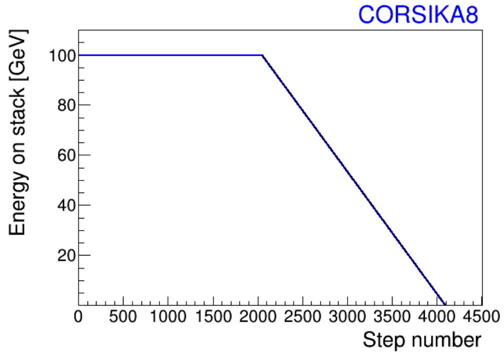


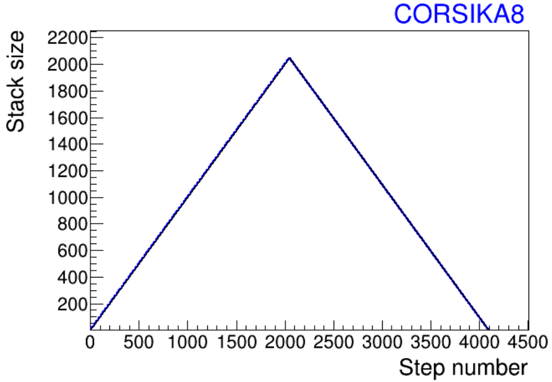




Use highest energy particle for next step in cascade:







Summary

CORSIKA was started 20 years ago for a very specific task, has evolved to a critical piece of infrastructure for astroparticle physics

Modernize for optimal support of astroparticle physics for the next ~3 decades!

More flexibility, more modularity, fundamentally enforce physical concepts, much better access to modeling uncertainties, fast, efficient and precise

Set new benchmark for physics software frameworks.

Open to community effort!

Additional material

Cascade equations

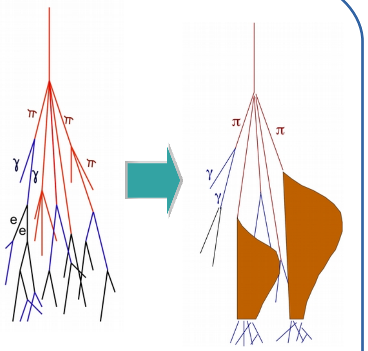
Numeric solution of systems of partial differential equations (via transport-matrix in energy-, PID-, ...-space)

- Ultra-fast, and -efficient
- High accuracy, realistic fluctuations

CONEX

Ultra-high energy air showers

→ **Pierre Auger**

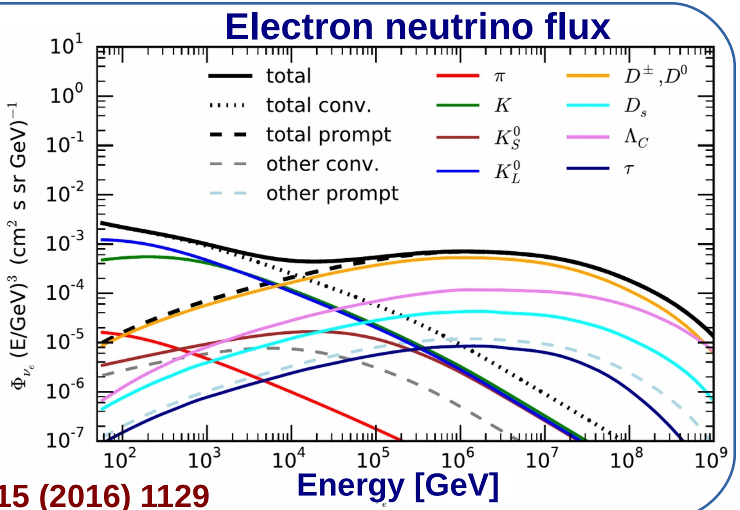


Astropart. Phys. 26 (2007) 420

MCEq

Inclusive lepton fluxes

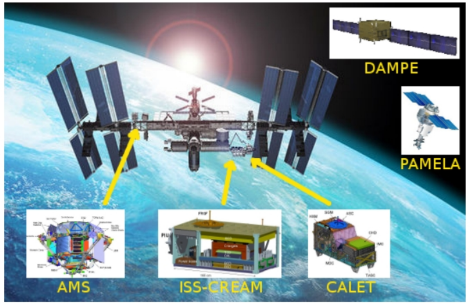
→ **IceCube**

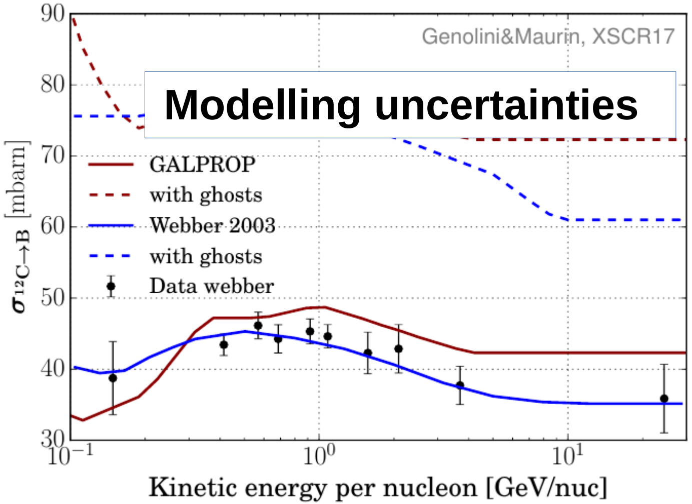


PoS ICRC2015 (2016) 1129

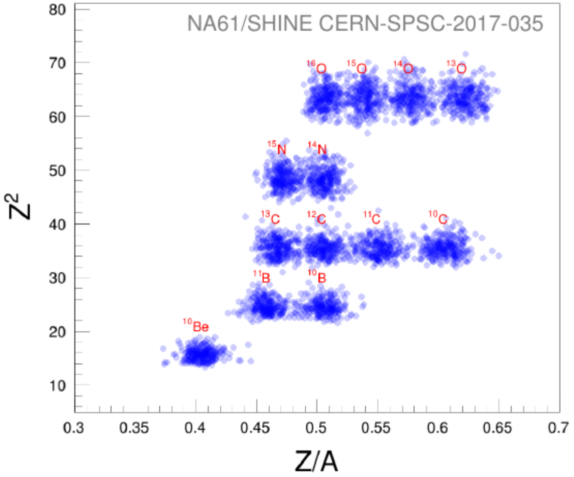
Plans at SPS – NA61

- Nuclear spallation for precision cosmic ray transport calculations, **A + p/He → fragments**
- NA61 fixed-target at SPS
- Start: 2018





Reconstruction, TPC



Data taking plan:

reaction	number of interactions
^{12}C+p	200k
^{16}O+p	100k
^{11}B+p	4k
^{15}N+p	2k
^{14}N+p	2k
^{13}C+p	2k
^{12}C+He	50k
^{16}O+He	50k

(more under study)