Karlsruhe Institute of Technology

ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

Combined analysis of accelerator and ultra-high energy cosmic ray data

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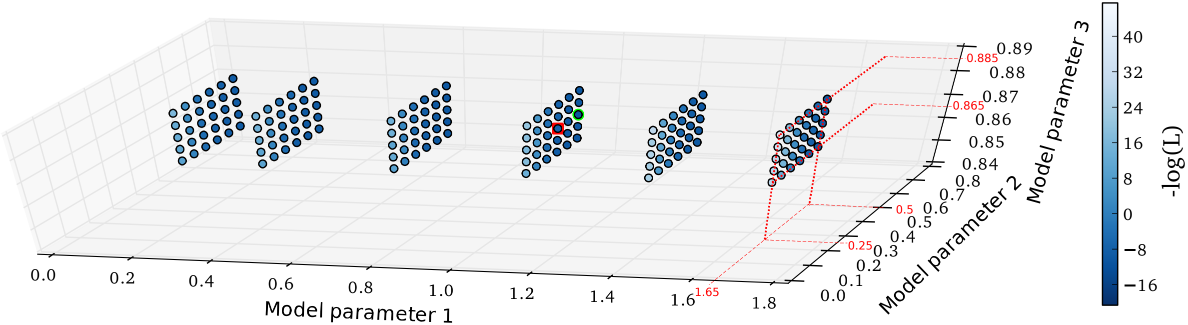


2015-08-03

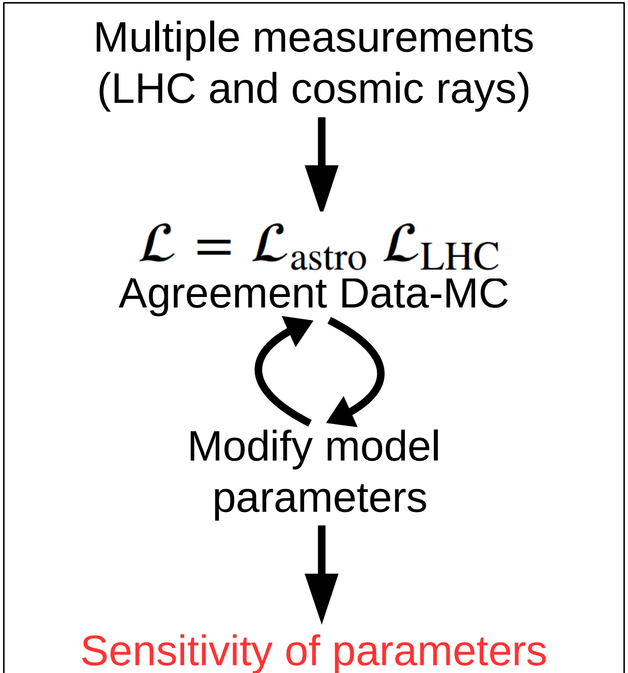
Motivation

- Hadronic interaction models introduce large systematic uncertainties for air shower measurements
  - Phenomenological
  - Over 100 parameters

- Tuning of parameters
  - To low-energy fixed target measurements and
  - New data forward phase-space by the LHC
  - Air shower measurements contain information about hadronic interactions
  - Tedious parameter tuning process → optimisation

- How to use air shower data?
  - Interpretation always depends on the composition
    - Either rely on weak constraints or
    - Reduce dependencies by dedicated selections

Method and benefit



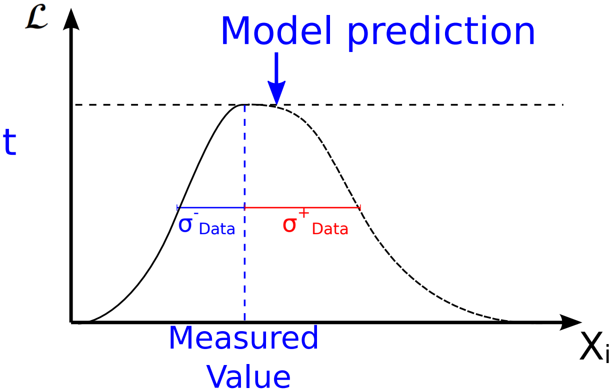
- Likelihood-based method
  - More flexible than X²-approach
  - Include asymmetric uncertainties and complex functions for CR data
  - treat many measurements in a consistent way
- Allows to decide which parameters are important
- Connection between changes in LHC prediction and CR prediction
- Later: optimisation of parameters

EPOS model: parameters for diffraction and cross section

- EPOS-LHC model
  - widely used for cosmic ray physics
  - tuned to LHC data (up to 7 TeV)
- Current parameters under investigation
  - Name: "wdiff(2)": w_{diff} = {0.865, 0.870, **0.875**, 0.880, 0.885}
    - Probability of diffraction for protons
  - Name "epscrx": ε_{crx} = {0.25, 0.3, 0.35, **0.4**, 0.45, 0.5}
    - Scale parameter for saturation scale in scattering amplitude. Influences high-energy cross section
  - Name "alpdi": α_{diff} = {0.2, 0.4, 0.725, **1.05**, 1.35, 1.65}
    - Modifies the mass distribution of diffractive events $\sim 1/M^{(2\,\alpha_{diff})}$
    - Larger values of α_{diff} → more low-mass states (influences forward multiplicity)

⟹ Grid of 180 parameter sets

Analysing collider measurements



- Asymmetric gaussian distribution for probability function for each data point
- Included LHC measurements
  - Cross sections:
    - p-p at 7 and 8 TeV (TOTEM)
    - p-Pb at 5 TeV/nn (CMS)
  - Multiplicity: forward and central charged particles at 8 TeV (CMS+TOTEM)
  - Soft diffractive cross section at 7 TeV (CMS)
  - Very forward neutrons at 7 TeV (LHCf)
- Started to include pion charge ratio (NA49) for low-energy data

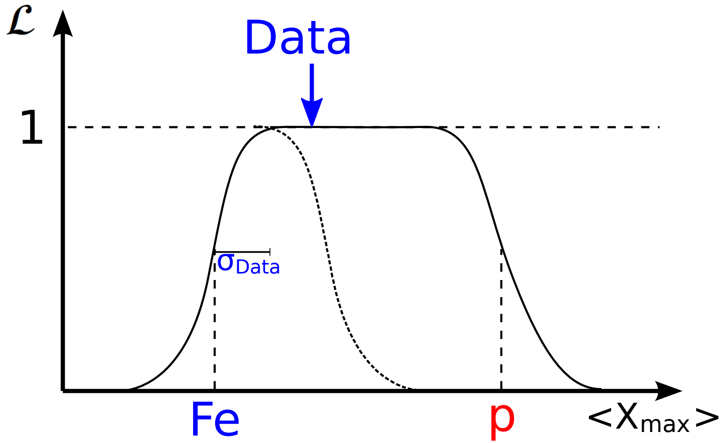
Integrating ultra-high energy cosmic ray measurements

- Mass composition unknown at highest energies
- Use measurements of longitudinal shower profile
- Constrain data without any assumptions
  - Physically allowed regions
    → Predictions of proton and iron must bracket data
  - Fit tail of distribution (only light particles, even He less important)
- Constrain with weak assumption on mass
  - ln(A) and V[ln(A)] cannot be below 0
  - Fit distributions with templates for multiple components
- Later: Muon measurements

Cross section
Elasticity/Diffraction
Multiplicity

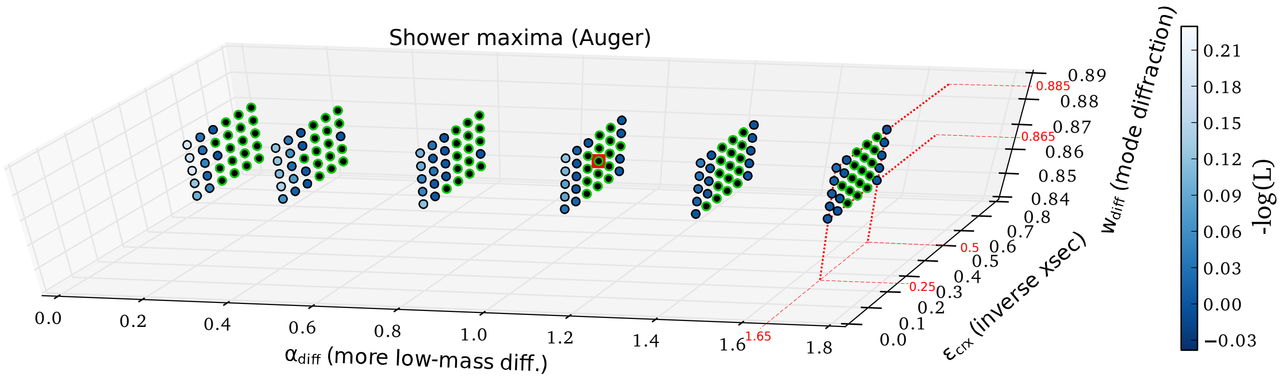
Diff. mass distribution
Meson/Baryon production

Average shower maximum

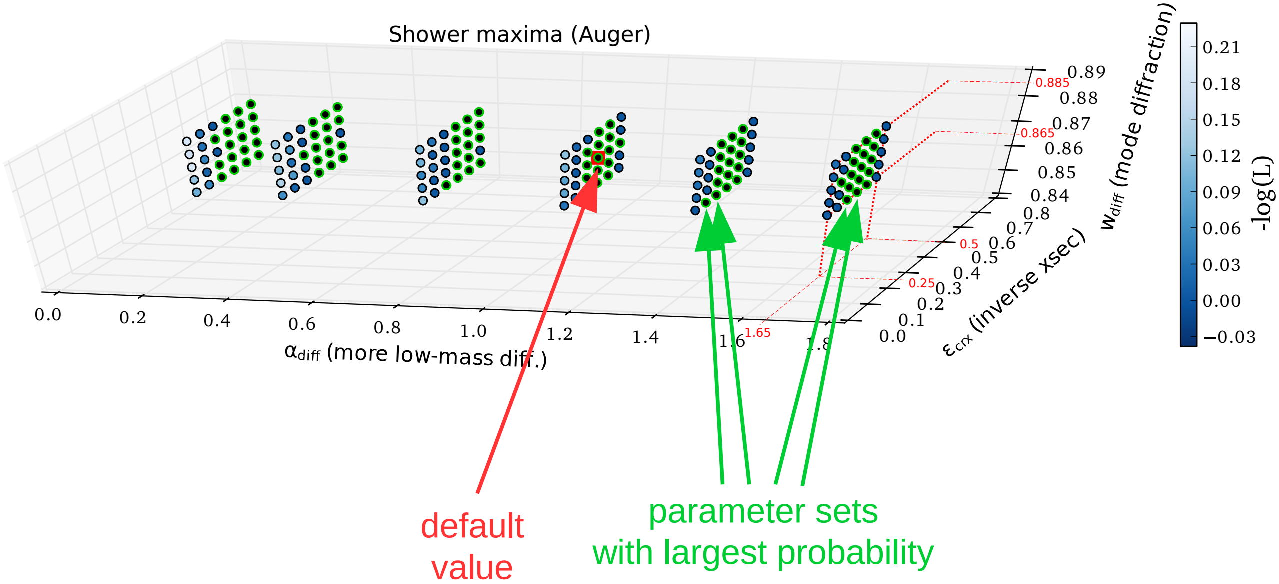


$$P(X_{\max}^{\mathrm{Fe/p}}|X_{\max},\sigma) = \begin{cases} c_1\,\mathrm{Gaus}(X_{\max}+\sigma-X_{\max}^{\mathrm{p}},\,\sigma) & \text{for } X_{\max} \geqslant X_{\max}^{\mathrm{p}}-\sigma \\ c_2 & \text{for } X_{\max}^{\mathrm{Fe}}+\sigma < X_{\max} < X_{\max}^{\mathrm{p}}-\sigma \\ c_1\,\mathrm{Gaus}(X_{\max}-\sigma-X_{\max}^{\mathrm{Fe}},\,\sigma) & \text{for } X_{\max} \leqslant X_{\max}^{\mathrm{Fe}}+\sigma\,. \end{cases}$$

Average shower maximum



Average shower maximum



Average shower maximum

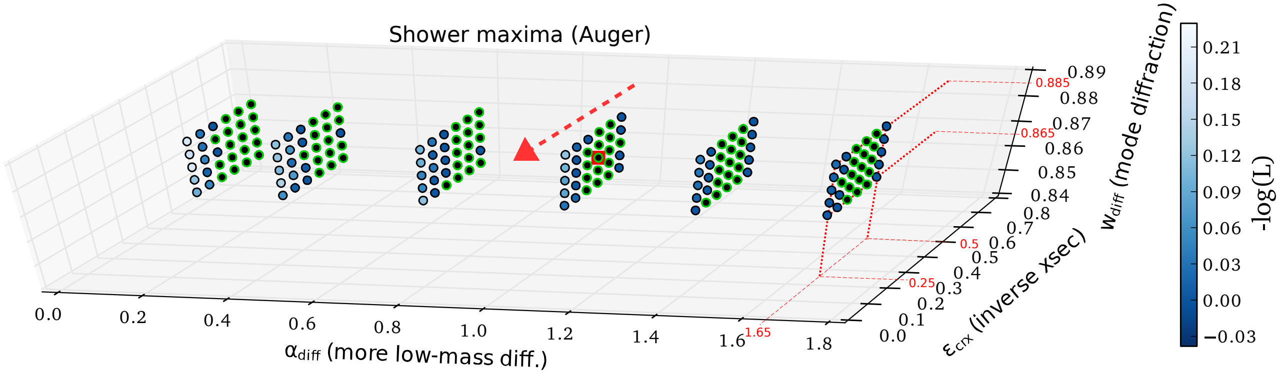
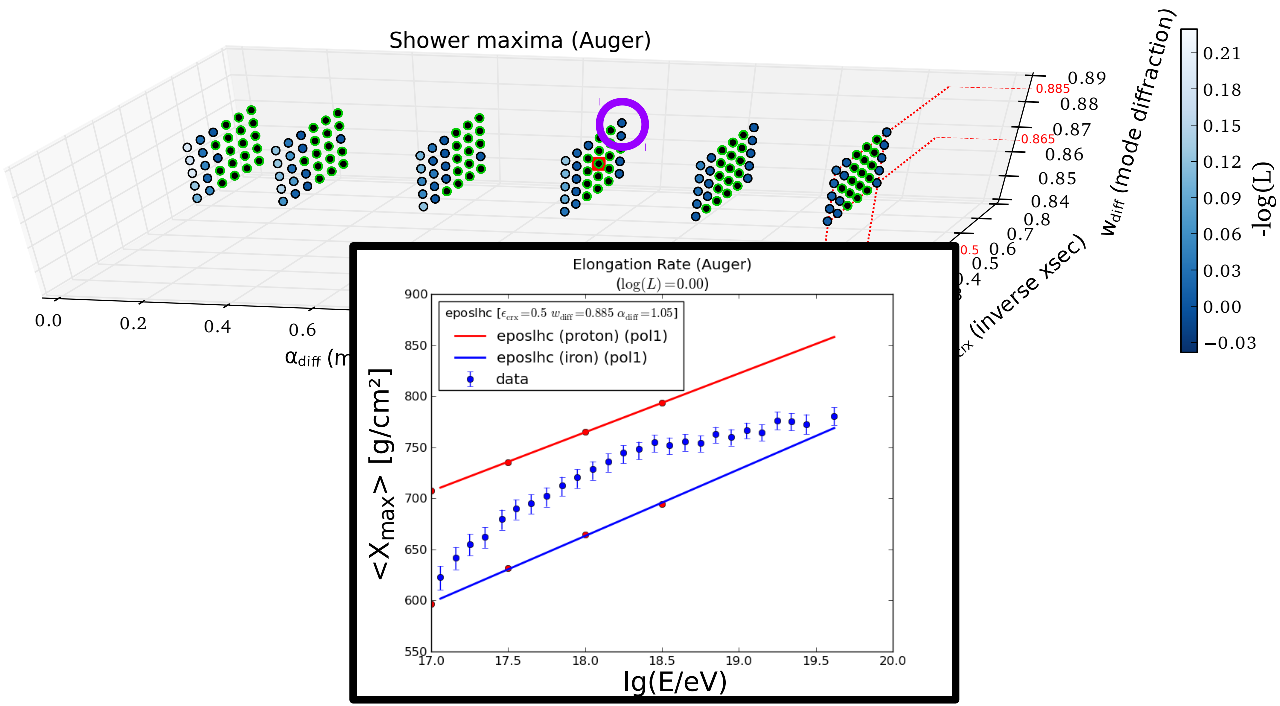
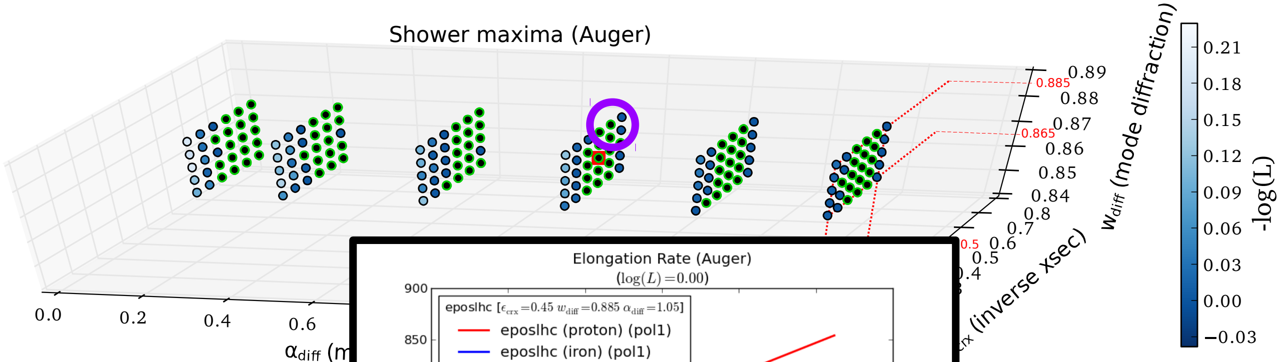


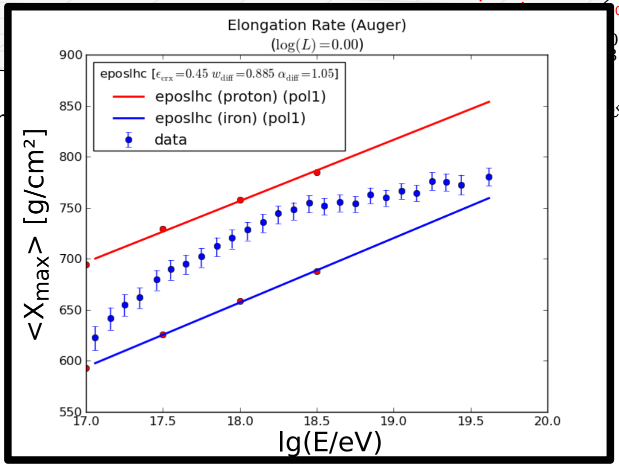
Illustration for increasing extrapolated cross section
⇒ lower X_{max} values

Average shower maximum

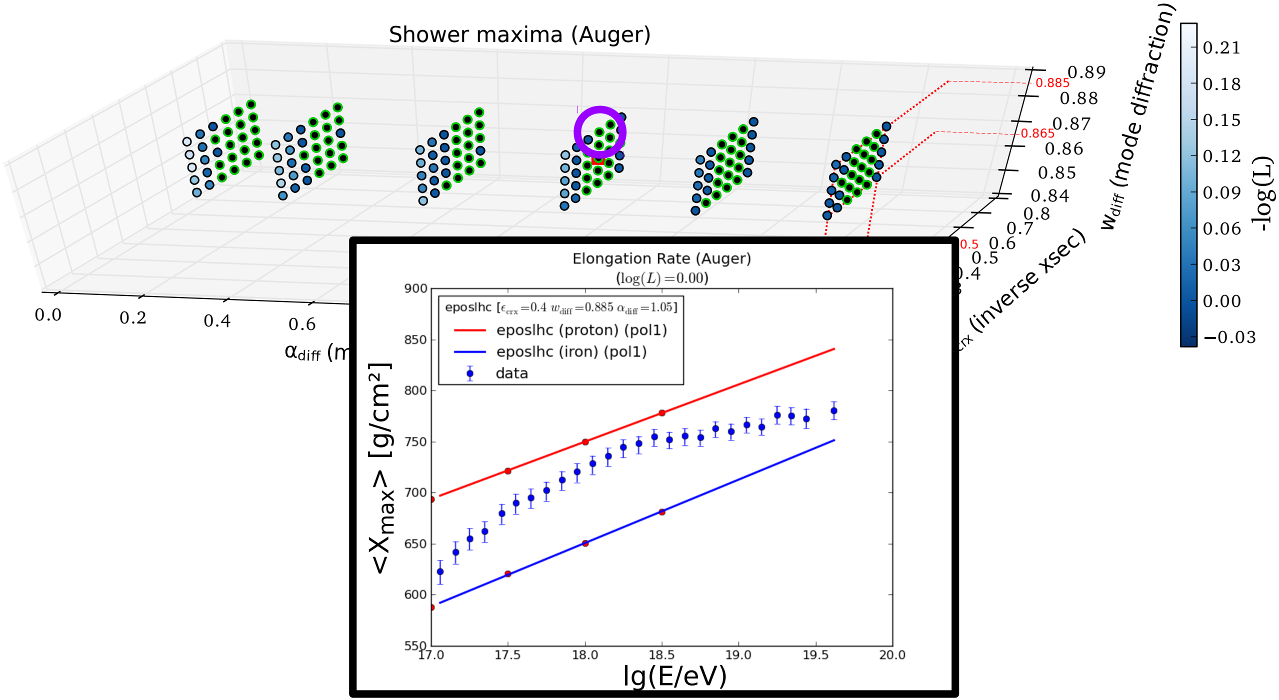


Average shower maximum

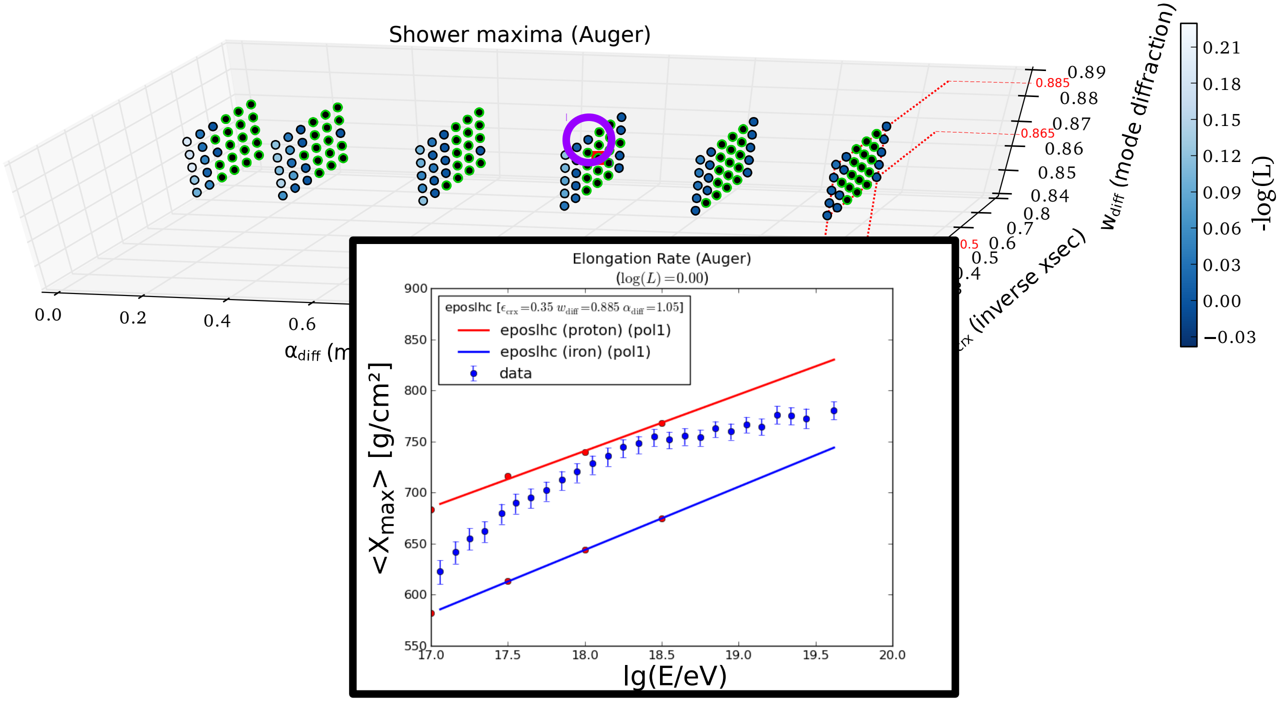




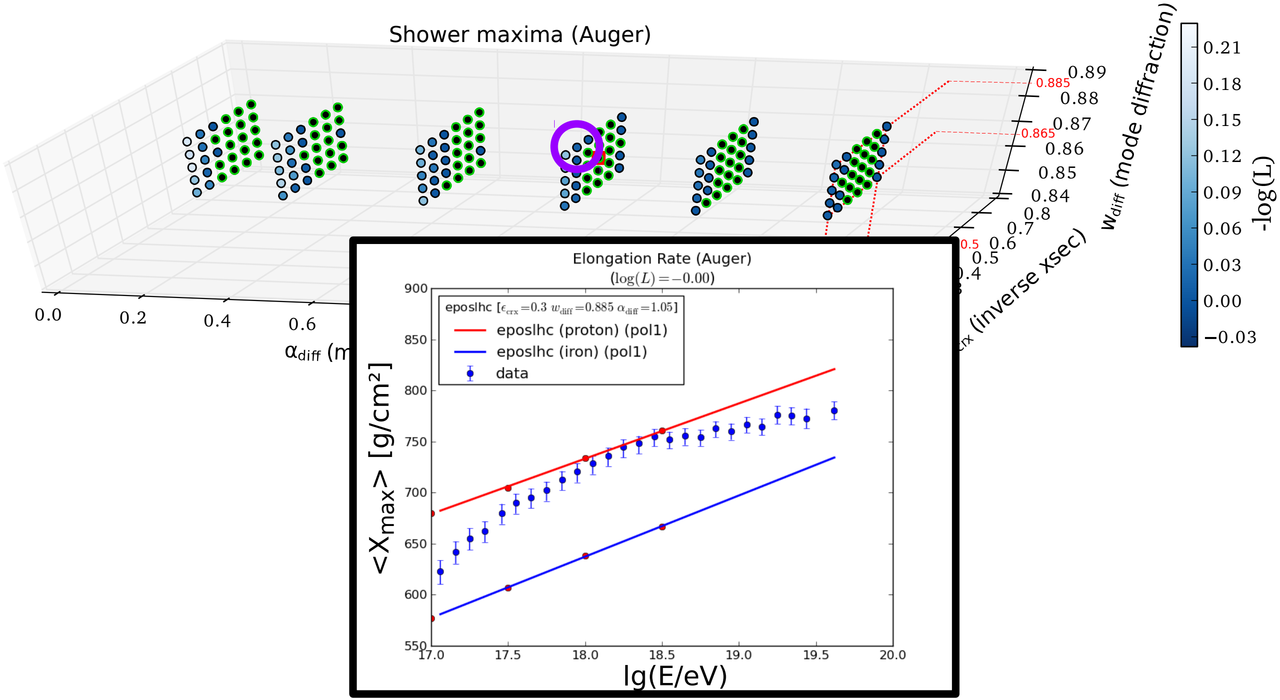
Average shower maximum



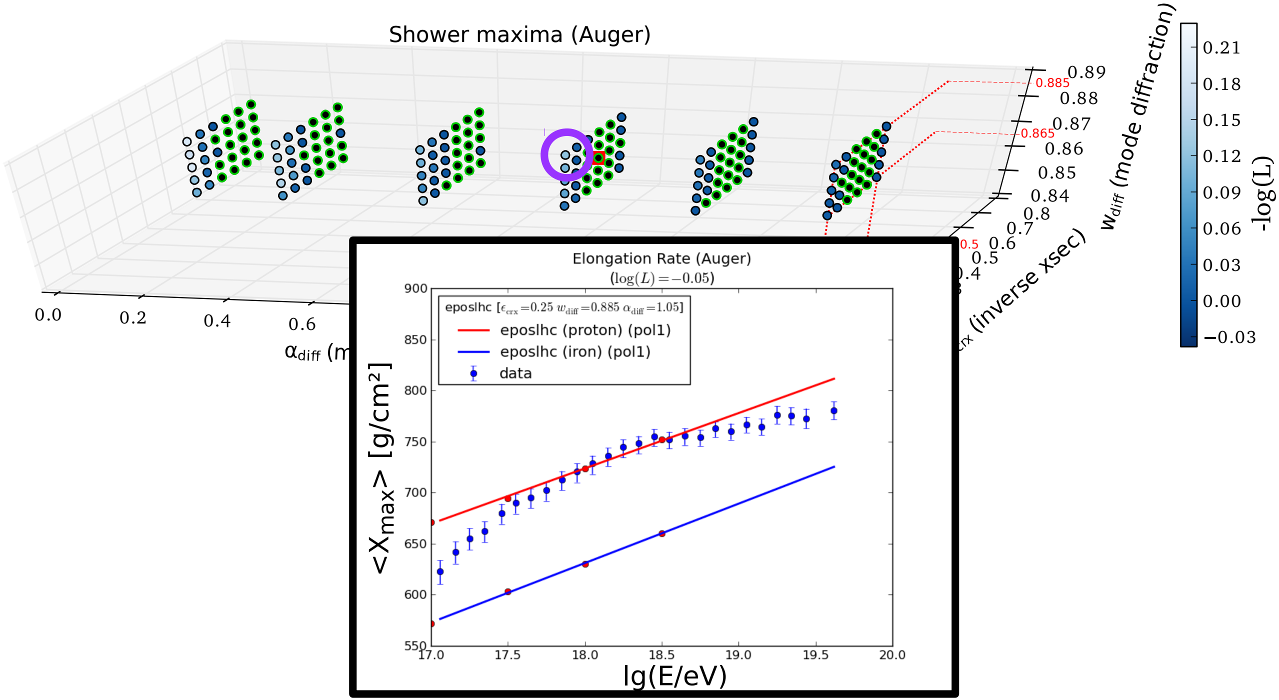
Average shower maximum



Average shower maximum



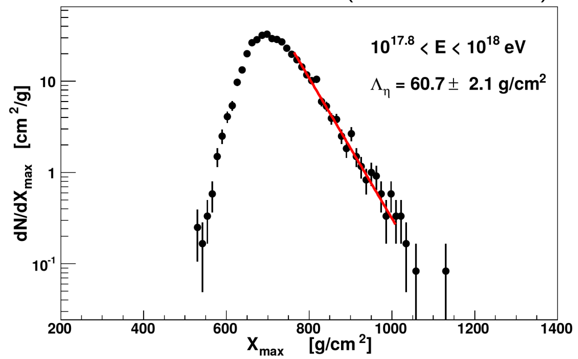
Average shower maximum

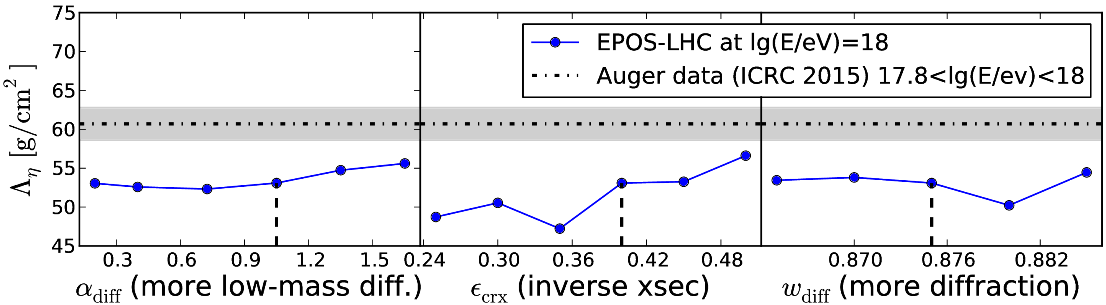


Tails of shower maxima

- Use additional information from distribution of shower maxima
- Tail of distribution at low Auger energies dominated by protons
- Unbinned $\mathcal{L}$-fit of 20% deepest penetrating showers (weights for p and He)
- Helium fraction always small (<10%) and no visible influence on Λ_η

(PoS 401 ICRC2015)





Technical Challenges

- Air shower
  - 1D-approach with CONEX
  - 10^{17} to 10^{19} eV (p,He,N,Fe)
  - each 1,000-10,000 showers

- LHC-type
  - CRMC (Cosmic Ray Monte Carlo) program
    - developed to simulate single collisions in
    - fixed or center-of-mass frames
    - keeping particle ancestry information
      in common output formats
  - 4 different energies for p-p and p-Pb collisions

CPU time

$\otimes$

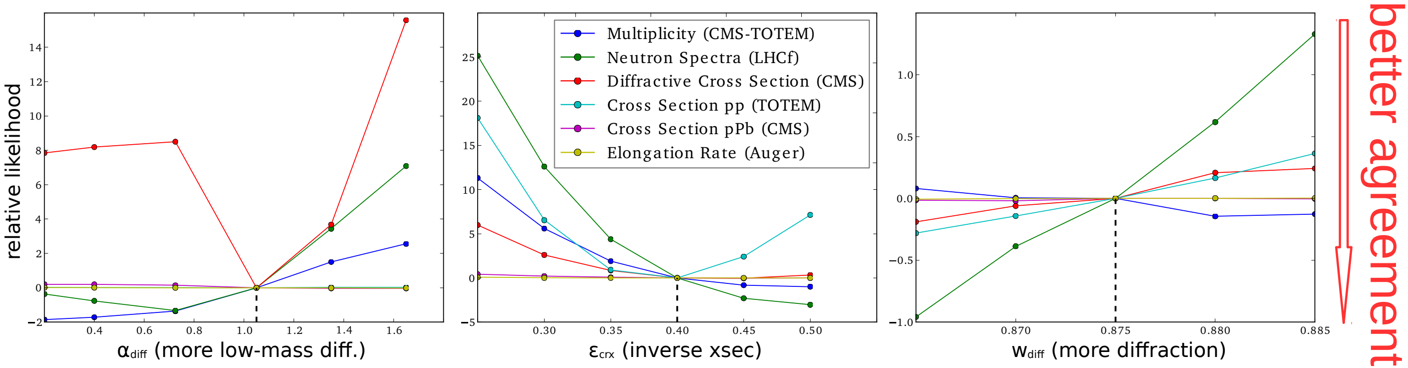
Storage

$\Downarrow$

CERN cluster

Comparison to data

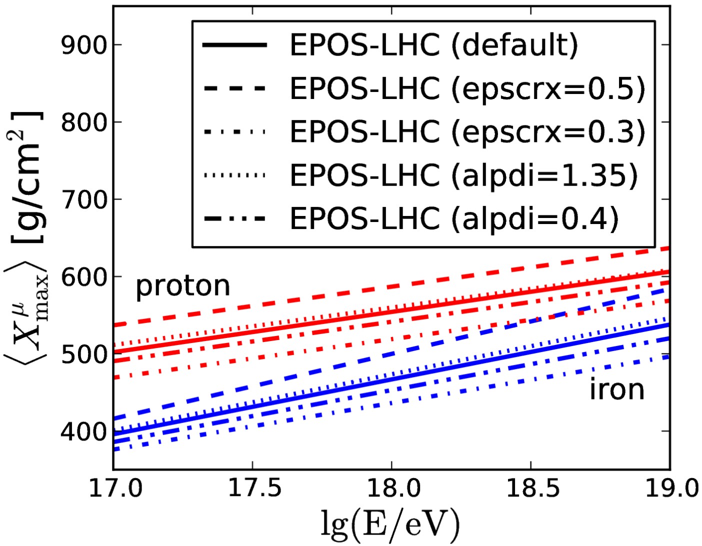
- Construct likelihood relative to default and "marginalised" (average over dimensions)
- Parameters well constrained except for diffractive probability in parameter range
- Default parameters reasonable
- Some tension between the data



Studying parameter influence on possible muon deficit

- One interesting aspect is the possible muon deficit with data from Auger, IceTop, Kascade

- Muon Production Depth (MPD):
  - For data comparison: 3D shower simulations necessary
  - Measurements for muons in certain lateral regions
  - Strong influence on hadronic physics and low prospective to use for mass composition



Conclusion

- We could show that hadronic interactions can be constrained by astrophysical data
- We propose and tested multiple methods with weak assumptions on the mass composition
- We developed a framework to combine these (air shower simulations) with collider measurements (p-p, p-Pb simulations)
- With this framework we derived constrains on three parameters on the recent tune of the EPOS model
- EPOS-LHC parameters in general reasonable

BACKUP

Helium fraction