New Physics at UHE

- No combination of conventional physics & composition can explain UHE showers (both Xmax distribution AND ground signal)

- Most New Physics models don't help

- Existence proof: a model inspired by Chiral Symmetry Restoration does explain data

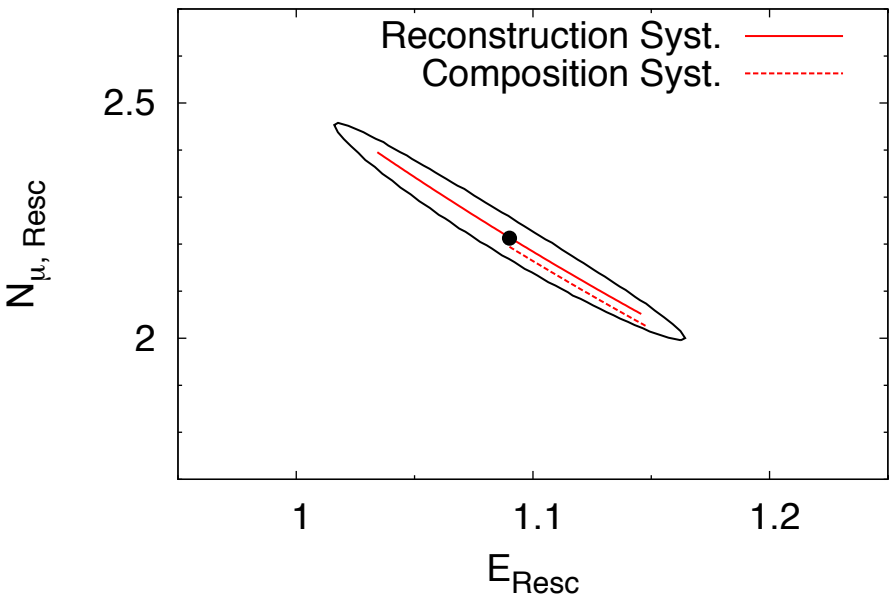
Jeff Allen &Glennys Farrar

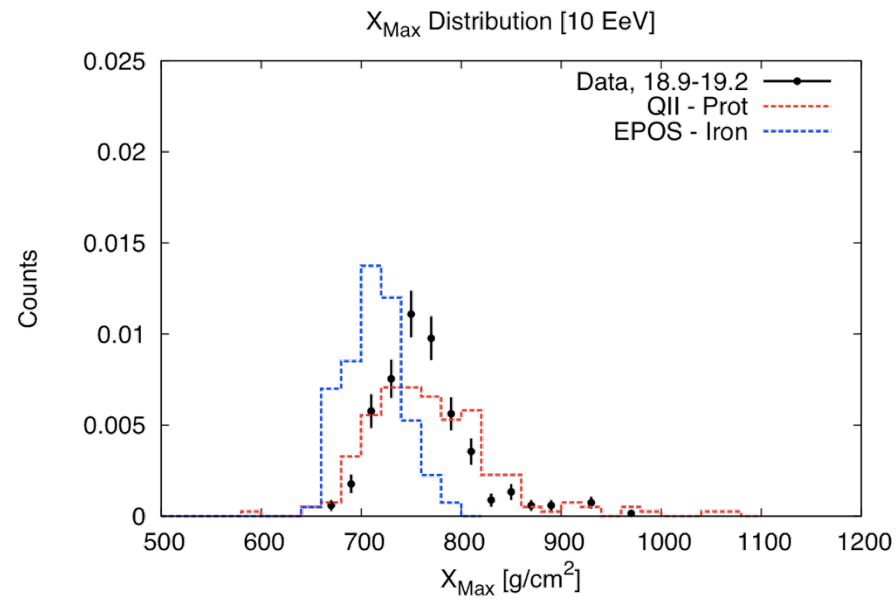
New York University

Best fits with conventional physics

QGSJetII-p: factor-2 deficit in muons at ground, but good Xmax distribution

EPOS-Fe: factor-1.3 muon deficit, and wrong Xmax distribution





Auger distribution: arxiv:1107.4804

For latest from experiments,see A. Yuskov and R. Engel talks

Keep in mind…

- 10 EeV = 10^{19}eV ⇔ Sqrt[s_{NN}] = 140 TeV

- Average 10^{19} eV shower (QGSJetII) has

  2 20 200 secondary interactions

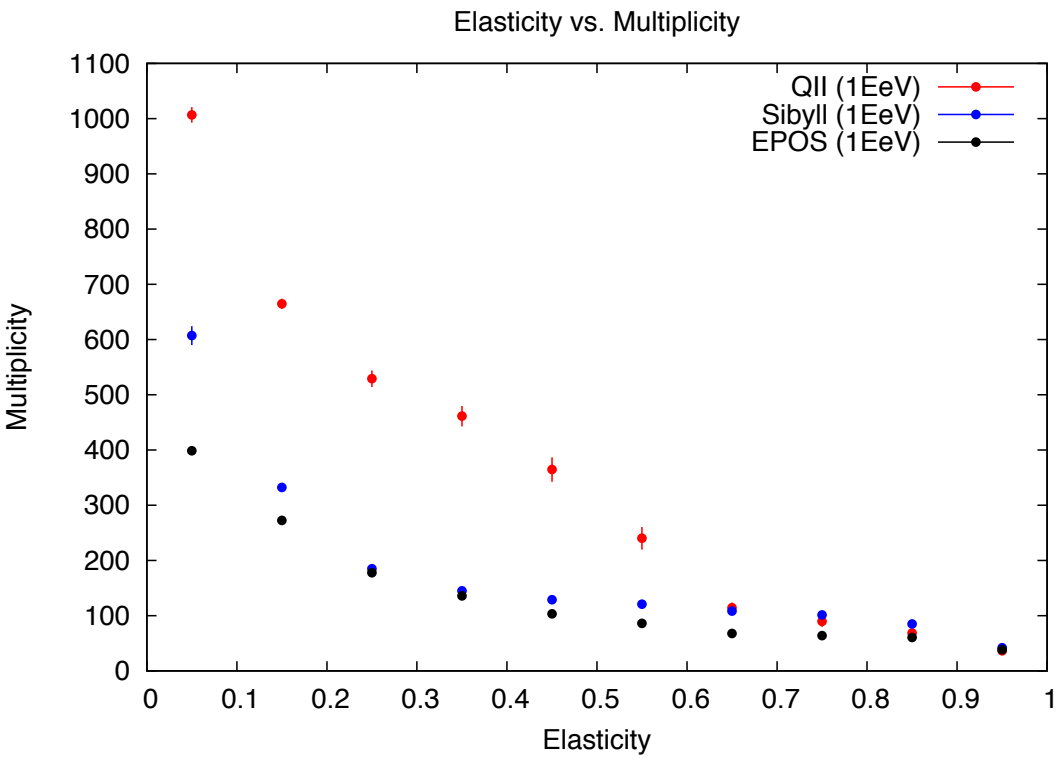
  above 10^{18} 10^{17} 10^{16}eV

- A substantial extrapolation beyond constrained physics…

What knobs can be turned?

- Primary Composition
- Cross section (direct measurement only below 10^{17}eV)
- Fraction of quasi-diffractive (high elasticity) events: f_{el}
- Multiplicity of non-diffractive events
- Particle content: strangeness fraction, meson-baryon ratio, [π^0 fraction]

Example differences between Event Generators



- Pi-0 energy fraction:

	QII	EPOS	Sybill
$f_{\pi 0}$	0.21	0.15	0.14

- Difference stems mainlyfrom larger baryon/meson ratio in EPOS and Sybill.

- Replacing QGSJet II with EPOS below 10^{16}eV increases S_{mu} by 10-15%, for 10 EeV proton showers.

J. D. Allen & GRF, in preparation

Key Physics of Showers

- Ground signal ≥ 800 m from core:
  - $S_{mu} \Leftrightarrow \pi^{\pm}$ at O(100 GeV) ; $S_{EM} \Leftrightarrow$ last generation π^0 's
  - Quick energy degradation =>fewer generations before $\pi^{\pm}$'s reach O(100 GeV) =>bigger S_{mu}[$S_{mu}(Fe) \approx 1.4\ S_{mu}(p)$]
  - Every generation: π^0 's siphon energy from hadronic shower
- Longitudinal shower development
  - EM shower recharged byπ^0 's produced in hadronic shower.
  - Quick energy degradation => shallower X_{max}

  [$X_{max}(p) - X_{max}(Fe) \approx 100$ g/cm^2]

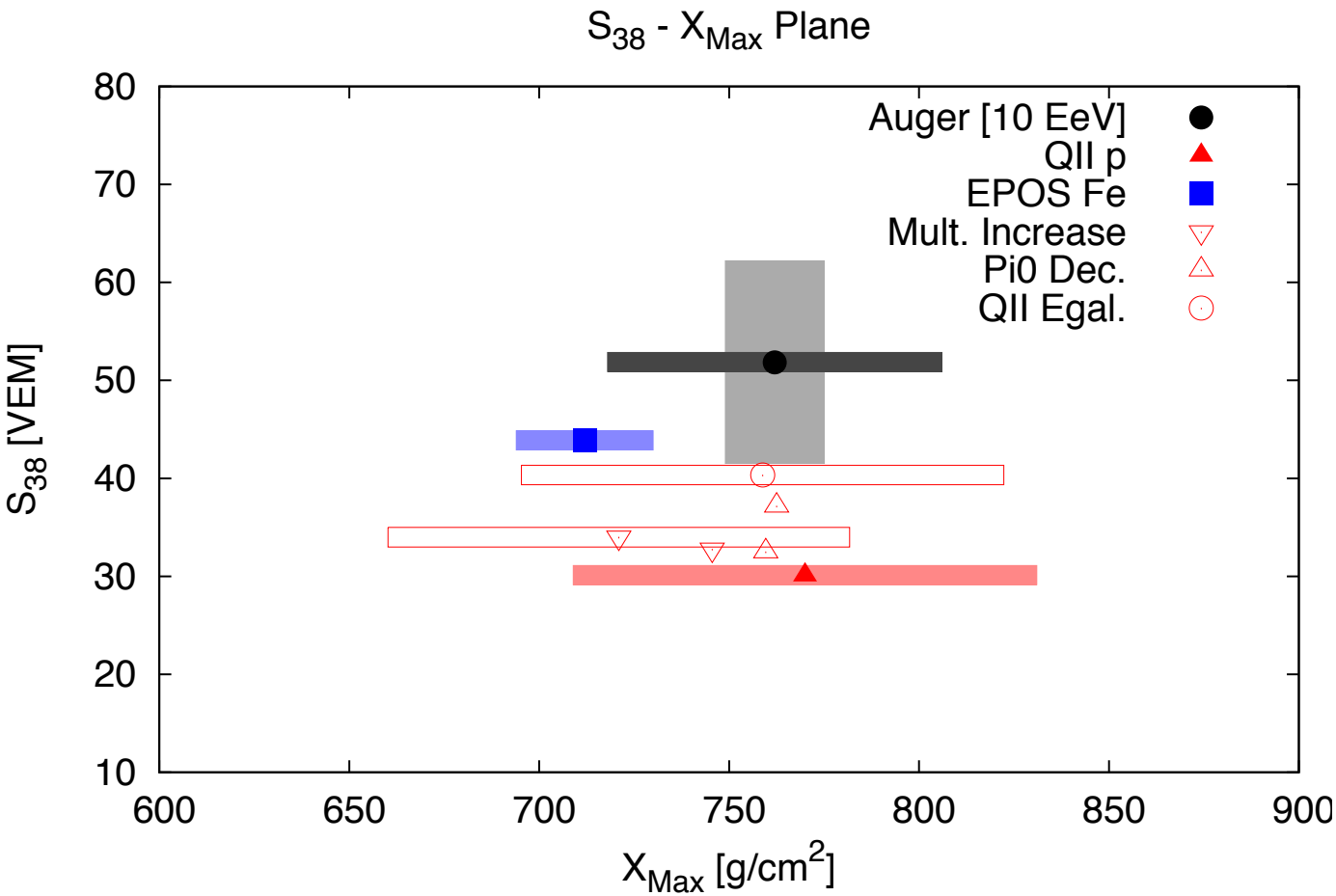
Effect of turning knobs

Knob	S_{mu}	$\langle X_{max} \rangle$	RMS_{Xmax}
Compositionheavier	↑	↓ (shallower)	↓ (narrower)
Mixed composition	↑ (mean of mix)	↓ (mean of mix)	↑ (broader -- lots)
Cross section ↑	---	↓ (shallower)	↓ (narrower)
Diffractive $fracf_{el}$ ↓	↑	↓ (shallower)	↓ (narrower)
Multiplicity ↑	↑	↓ (shallower)	↓ (narrower)
π^0 fraction ↓	↑	---	---
Strangeness, B-Bbar	---	---	---

- The Table shows the direct effect of the change listed. Most knobs affect X_{max}, but X_{max} is observationally fixed so secondary effects following from an X_{max} change are excluded.
- **All the knobs that increase S_{mu} make the X_{max} distribution shallower and narrower, except the π^0 fraction.**

Combining shower profile and ground signal

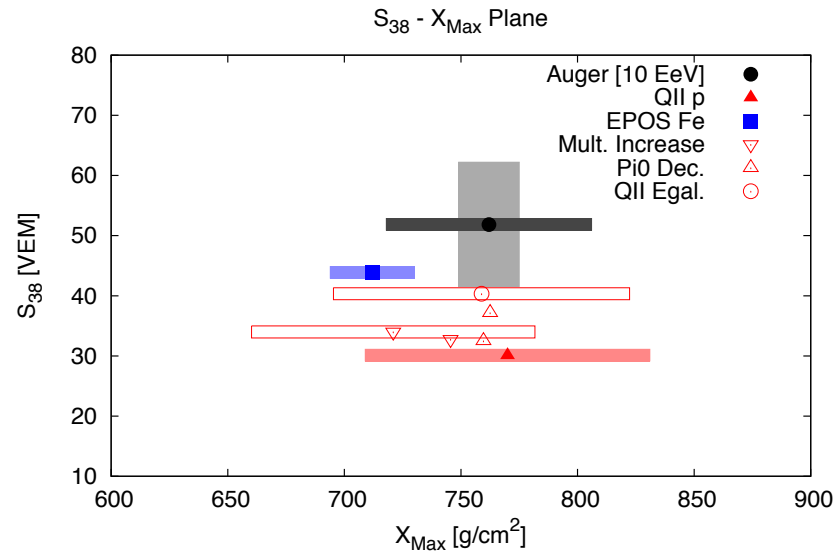
$\langle X_{max} \rangle$, RMS_{Xmax}, S_{38} @10 EeV



Data fromFacal San Luis for Auger, ICRC2011 arXiv: 1107.4804

- S_{38} is ground signal, S_{1000},rescaled to standard zenith angle 38°
- Data in black:
  - shaded region shows systematic uncertainty on S_{38} and $\langle X_{max} \rangle$
  - horizontal bars show RMS_{Xmax}(width of X_{max}; systematics negligible)

Knob-turning



- Heavy composition does not solve the problem:

S_{mu} is insufficient even for Fe, and Fe gives too-low X_{max} and RMS_{Xmax}. To solve S_{mu} would need Fe + heavier, but that necessarily has too-low X_{max} .

- Conventional physics changes cannot solve problem:
  - X_{max} distribution of QGSJet II is good, and all conventional physics modifications that increase S_{mu} go in the same direction: shallower and narrower X_{max}
  - No conventional physics knob can offset problems in X_{max} distribution needed to get needed increase in S_{mu} !

- **Decreasing the π^0 energy fraction is the only solution.**

Comments on knob-turning

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- **Decreasing the π^0 energy fraction is the only solution!**

Conventional physics does not allow the π^0 fraction to be changed much

- Isospin invariance => $\pi^0 = \pi^+ = \pi^-$
- Isospinbreaking (e.g., from resonance production and decay) is small
- Pion fraction is nearly universal
  - Z^0-decay:
  - Final states of hadron collisions (central region)
  - Even QGP
- If accounting for UHECR showers requires significantly lower π^0 fraction, that means it requires New Physics!

ChiralSymmetryRestoration

- Long-standing prediction of QCD:
  - Chiral symmetry is restored at $T_{CSR} \geq T_{conf}$
  - Lattice & hi-T field theory predict $T_{CSR} \approx T_{conf}$
- Chiral-symmetric phase:
  - <q –qbar> = 0
  - Baryons in parity doublets
  - No requirement for pions to exist; if they exist, pions are not light
  - Mesons may be very wide resonances
- Low-T chiral symmetry broken phase:
  - <q –qbar> ≠ 0
  - Pions are (pseudo-)Goldstone bosons of Chiral Symmetry Breaking
  - Pion mass ≈140 MeV is much lower than in naïve quark model
  - High observed abundance of pions is primarily due to their low masses

Chiral Symmetry Restoration(-inspired) Model

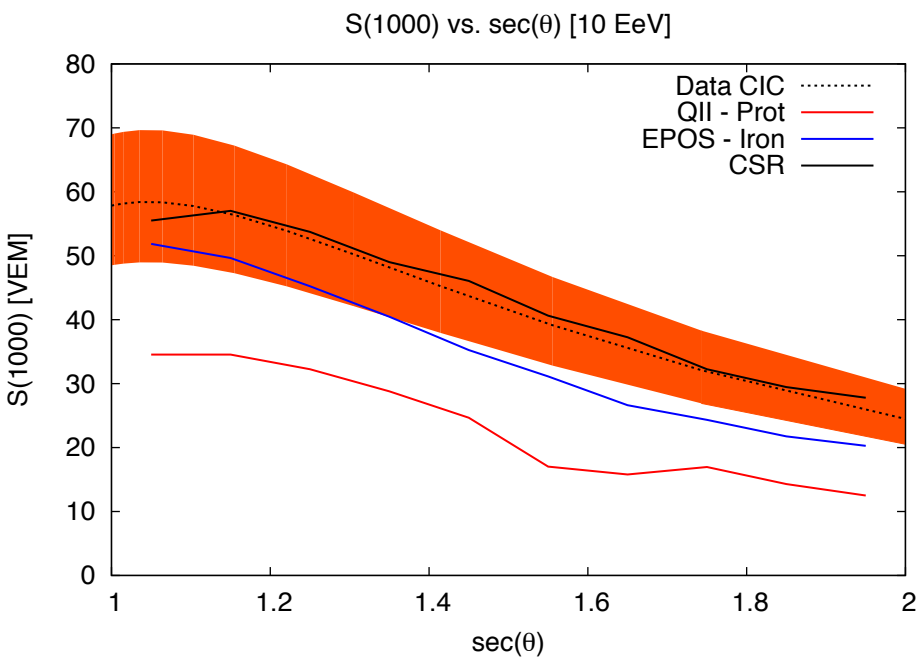
an existence proof that observations can be fit

- CSR phase:
  - Only baryons and anti-baryons (no mesons) in final state
  - Fraction of events in CSR phase increases with E
- Central p-Air collisions produce CSR phase if E >10^{17}eV
  - Use f_{el} from event generator to infer centrality
  - Events with $f_{el}>f_{el,thesh}$ are "normal"
- Reasonable parameter choices $f_{el,thesh}$, CSR-phase multiplicity, σ =>
  - ✓ X_{max} distribution (mean and shape at 10 EeV)
  - ✓ $<X_{max}>$ and RMS_{Xmax} as function of energy
  - ✓ Magnitude and shape of CIC curve (S_{1000} vs zenith angle)

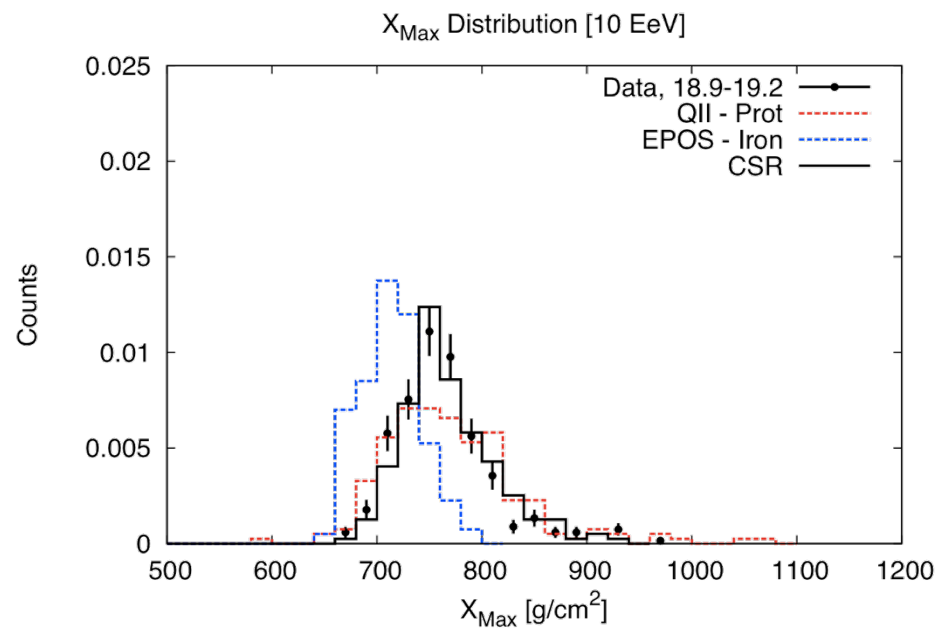
* MUON DEFICIT SOLVED, behavior of X_{max} explained with pure proton composition

"Chiral Symmetry Restoration" model gives an excellent fit at 10 EeV

Ground signal at 10 EeV



X_{max} distribution at 10 EeV



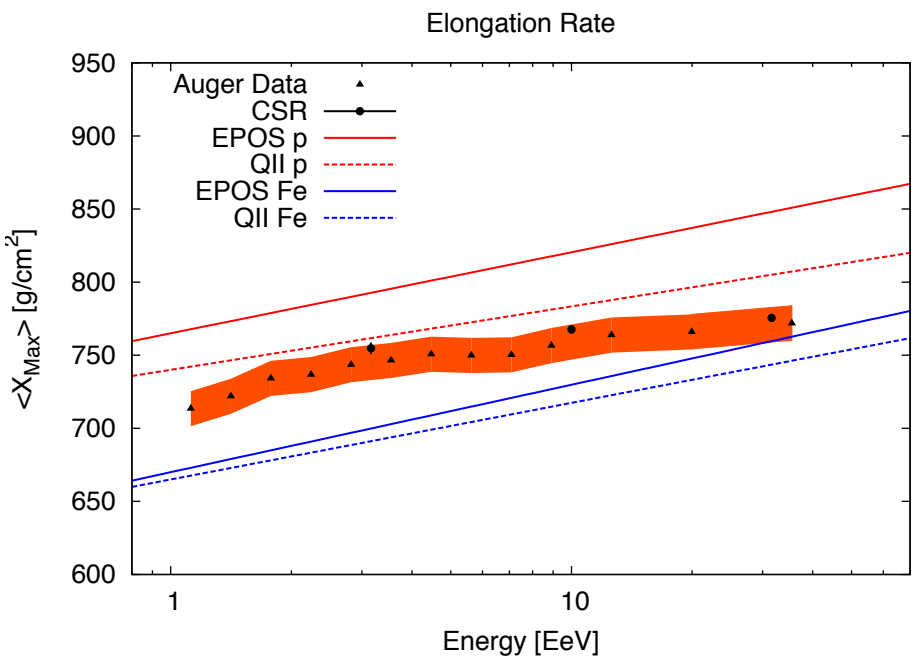
Auger distribution: arxiv:1107.4804

S1000 and $\langle X_{max} \rangle$ agree with data within systematics (20 g/cm^2 for X_{max}). Tweaking parameters brings into perfect agreement.

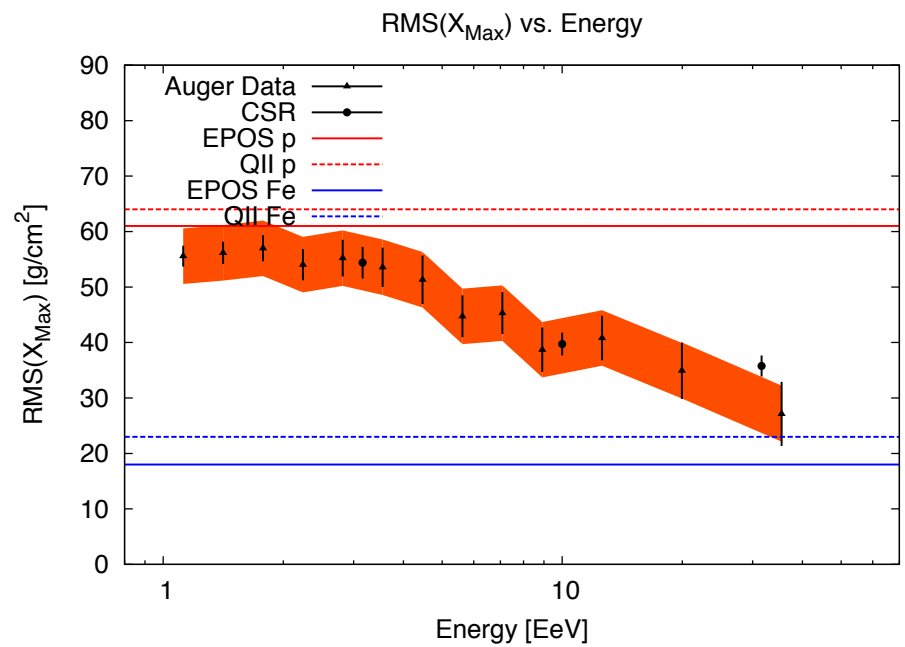
CSR also fitsenergy evolution

$<X_{max}>$, RMS_{Xmax} (and it's pure proton!)

Elongation Rate



Width of X_{max} Distribution

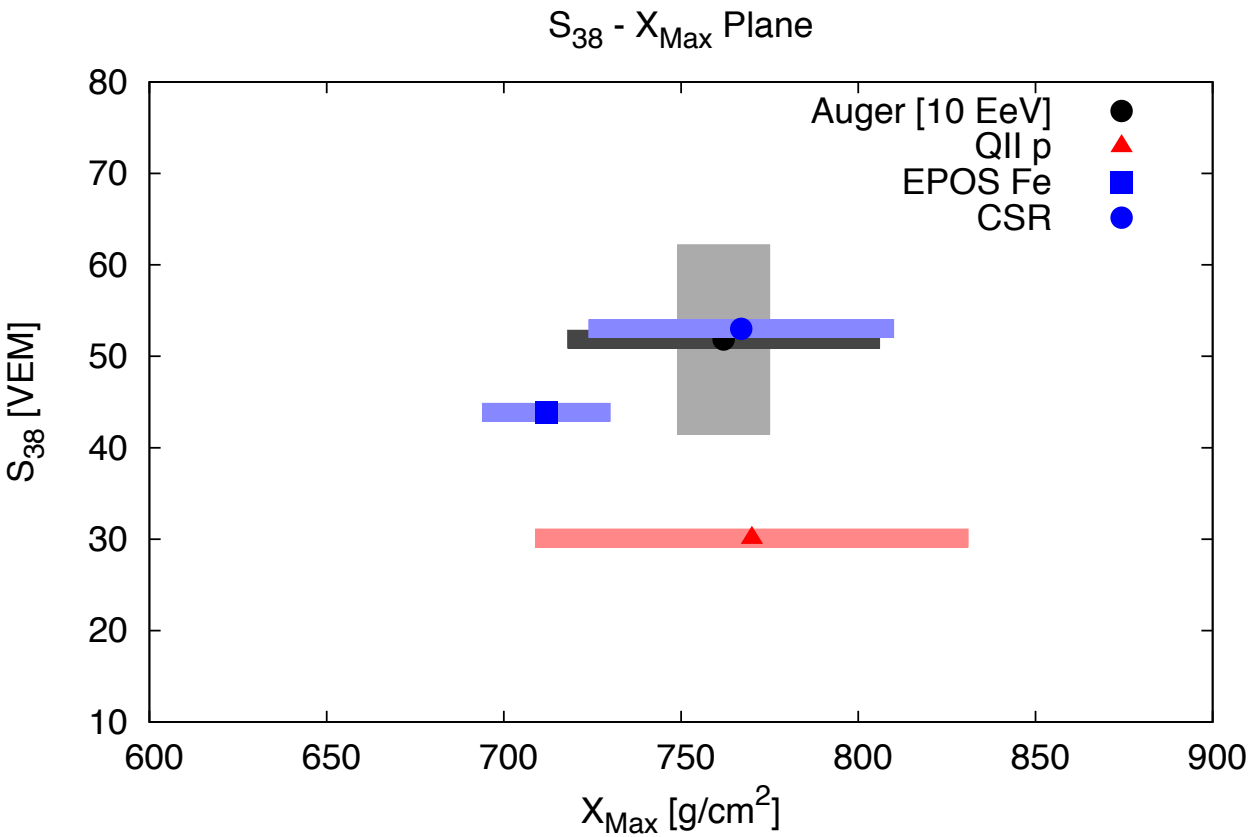


Very small increase in cross-section will bring $<X_{max}>$ into perfect agreement.

Tweaking evolution of CSR fraction with energy should improve fit to $RMS(X_{max})$ evolution.

CSR:near-perfect agreement

$\langle X_{max} \rangle$, RMS_{Xmax}, S_{38} @10 EeV and E-dependence



- S_{38} is ground signal -- S_{1000} -- rescaled to standard zenith angle 38°
- Shaded region shows systematic uncertainty on S_{38} and $\langle X_{max} \rangle$
- Horizontal bars show width of X_{max} RMS_{Xmax} (negligible systematics)

Can differentNew Physics work?

- New physics must
  - impact almost all events
  - affect almost all the final state energy
- QGP a la LHC: Multiplicity increase, no significant reduction in pions => too-narrow and shallow $X_{max}$and insufficient increase in S_{mu} .
- SUSY or other exotic particle production:
  - [Predicted rates too low (only produced in tiny fraction of events)]
  - Missing energy not helpful!
  - Decays to SM quanta => standard π^0 fraction => no significant increase in S_{mu}
- Black Hole production:
  - [Predicted rates too low]
  - Generally leads to too-high multiplicity final states (bad for X_{max} distribution)
  - Decays to SM quanta => standard π^0 fraction => no significant increase in S_{mu}

Summary

- Combined constraints of X_{max} distribution and ground signal **cannot be explained** by standard physics.
- Only known solution is suppressed pionproduction

  THISISNEW PHYSICS!

- Naïve model motivated by chiralsymmetry restoration above 10^{17}eV accounts well for all published shower observables.
- PURE PROTON composition fits well; mixed composition may not be allowed.
- Missing energy correction is larger: $E_{true} \approx 1.1\ E_{Auger\text{-}FD}$

Conclusions

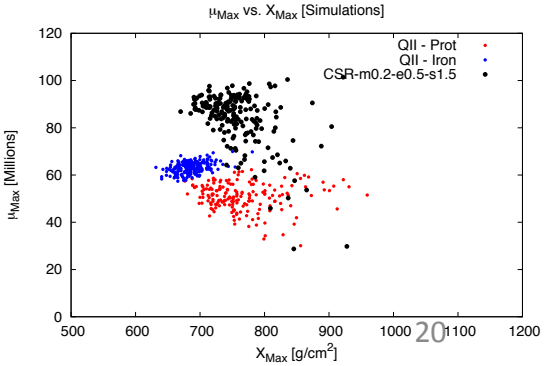
- Must have valid shower model before inferring composition.
- Model must simultaneously account for ground signal and longitudinal development.
- We argue that strong suppression of π^0 energy fraction is essential, so much that New Physics appears to be required.

Burden of proof now on "standard physics" event-generator-builders, to prove us wrong...

- Hi-Res/TA should reduce reliance on QGSJet for interpreting observations – it is manifestly wrong and may produce wrong conclusions. (N.b., CSR model also fixes their energy calibration mismatch.)

To-do List

- Theory / phenomenology needed!
  - Properties of CSR phase (multiplicity, meson fraction)
  - Onset of CSR phase (energy dependence, f_{el} as proxy for phase boundary?)
  - Alternate New Physics that works? Loop-hole in our claim that New Physics is required?
  - Relation to QGP? Evidence or implications at LHC?
- More detailed comparison to data
  - More sophisticated threshold model; optimizeCSRparameters; explore non-CSR events and CSR-non-CSR interface
  - Require detailed fit to shape of X_{max} distribution, at all energies, including < 1 EeV; possible to exclude mixed composition?
  - Hybrid events: Golden Hybrid analysis; S_{38}vsX_{max}distribution:
  - Test shape of LDF in detail
  - Does optimized Auger model give good fit to TA data? ....



Backup slides

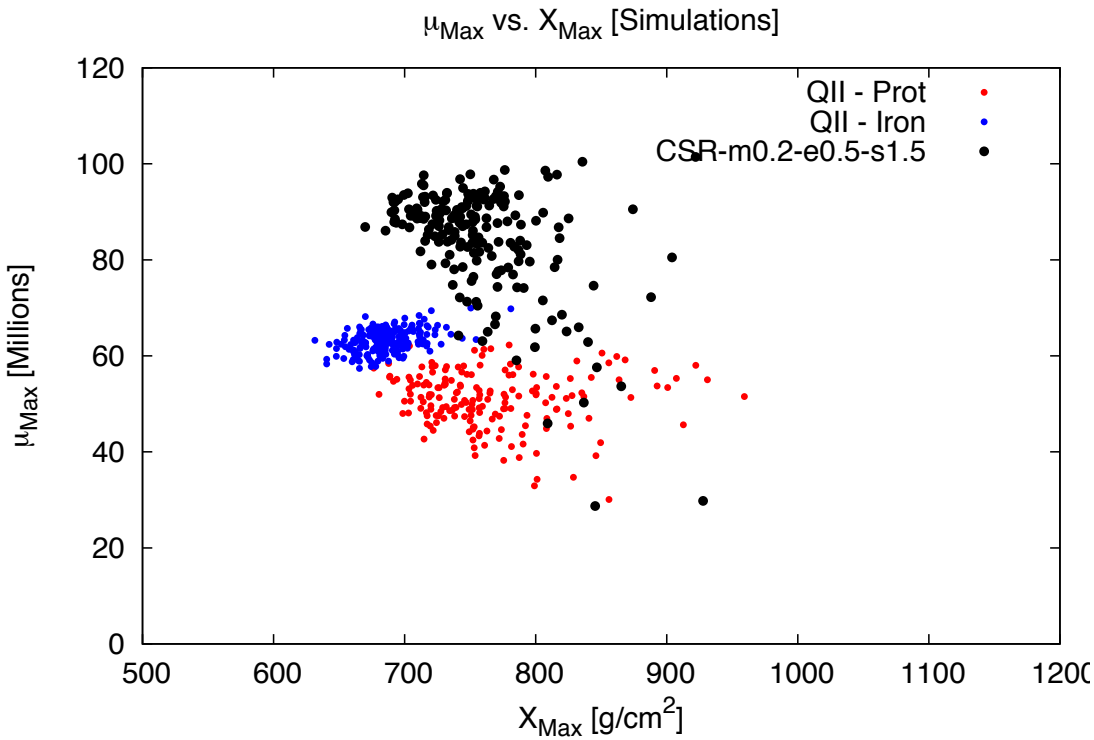
More on CSR model

- Above 10^{17}eV, central p-Air collisions produce CSR phase
  - Use f_{el} from event generator to infer centrality
  - Events more diffractive than $f_{el,thesh}$ are "normal"
  - Below $f_{el,thesh}$ events are in CSR phase

Modifying UHE events

- Only need to treat secondaries with large E/m, because low-energy secondaries in UHE collisions (hi altitude!) have negligible impact.
- Free to change flavor and swap baryon<->meson, without affecting E-p conservation or kinematics.
- Use accept-reject or particle splitting to adjust average multiplicity and fraction of events which are diffractive. (Hi E/m => co-linear decay).
- Method checked by starting with EPOS and reproducing gross features of QGSJet II or vice versa. [More extensive testing is planned.]

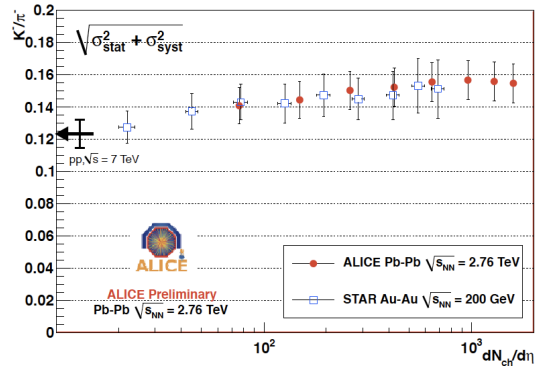
Hybrid events can discriminate models

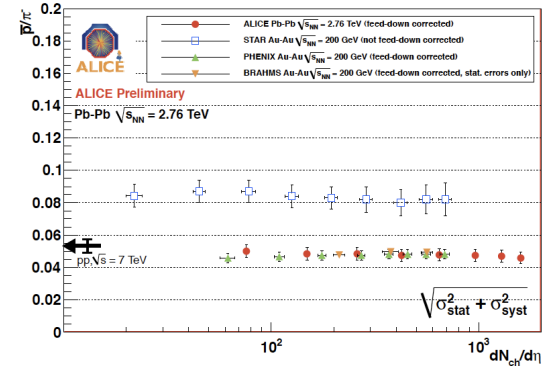


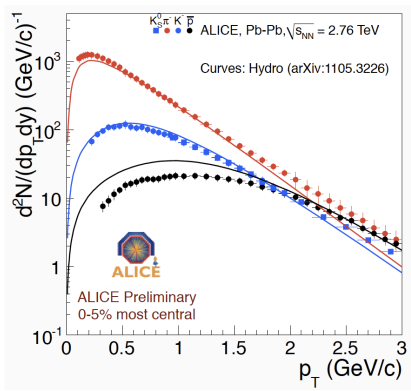
The vertical axis shows "mu_{max}", the maximum total number of muons in the shower. This is not an observable itself, but is correlated with observables that can be used.

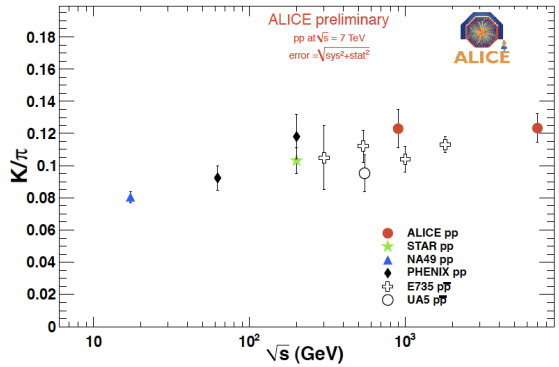
Quark Gluon Plasma (ALICE Pb-Pb)

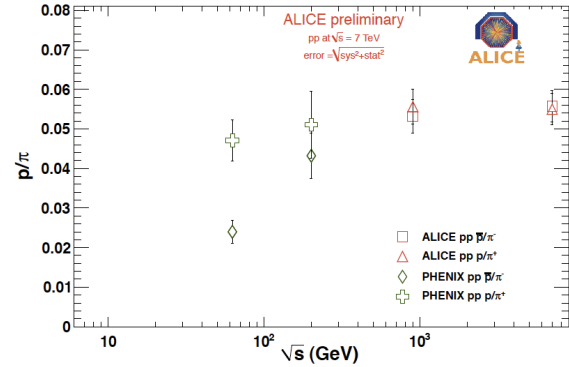
- At factor-2 level, important particle ratios are same as in pp
  K/π ~ 0.12-0.15
  p/π ~ 0.05- 0.08
- In central collisions, multiplicity much increased



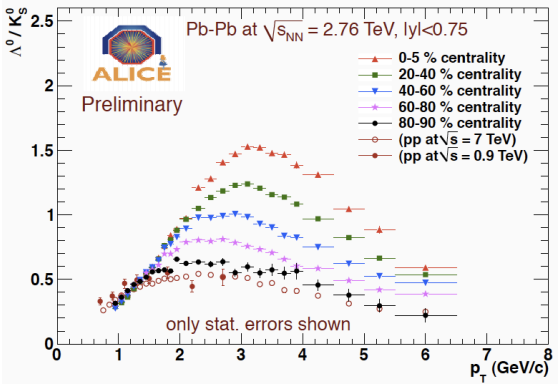








- Baryon enhancement at hi p_t
- Lots to be understood, interesting puzzles, etc.



c.f., Floris for ALICE, arXiv:1108.3257

Tests of CSR model

- Evolution from satisfactory description with standard physics below 10^{17}eV, to need for New Physics for events above ≈ 1 EeV. HEAT!
- Correlations between S_{mu} and X_{max} testable in hybrid data sample
- Predictions for TA (muons less relevant for ground signal)
- Detailed shape predictions for X_{max} distribution
  - The rising and falling edges and width of the central peak are sensitive to different f_{el}, multiplicity, ...
  - Break parameter degeneracies
- Need more theoretical input!