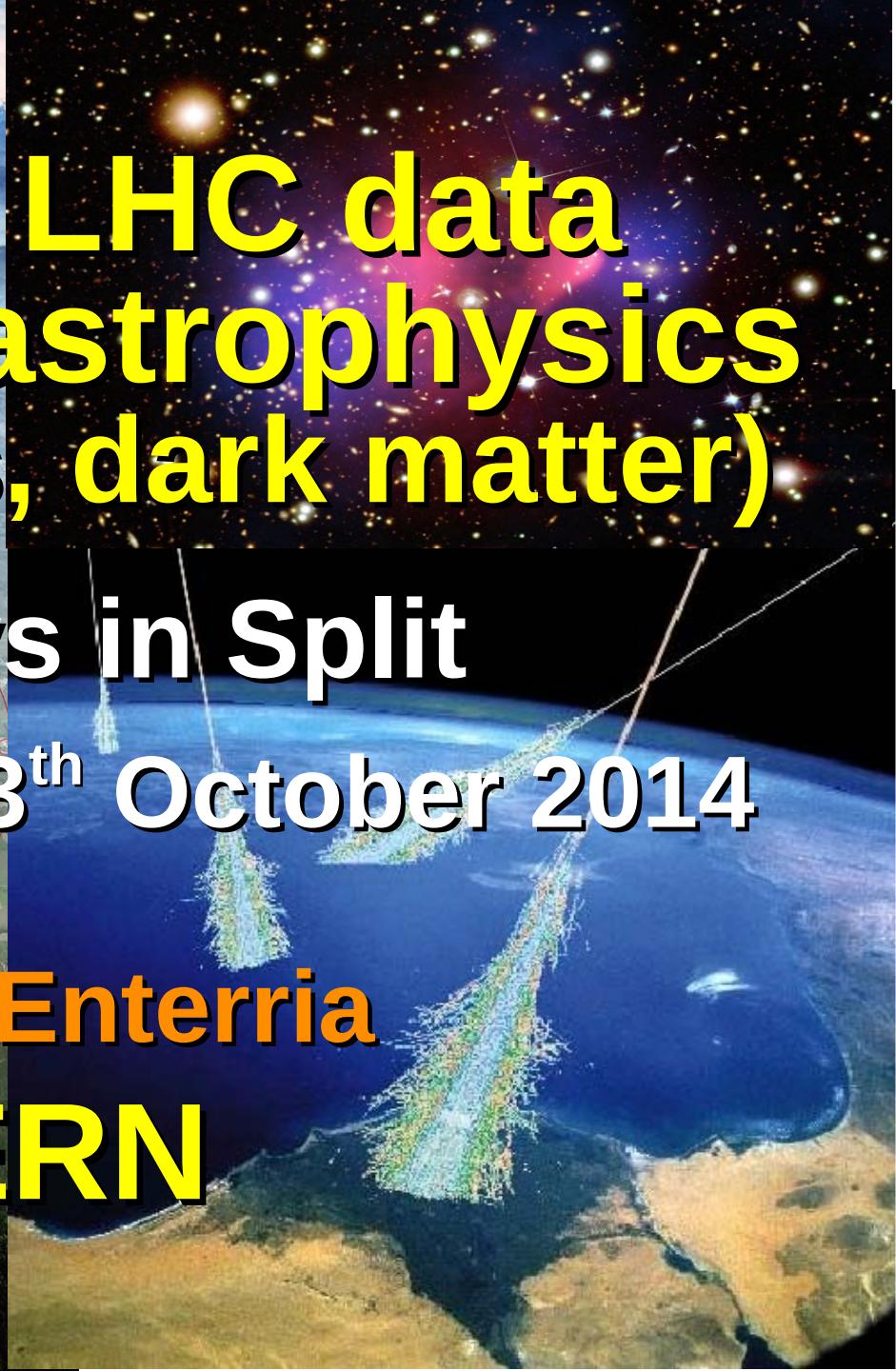




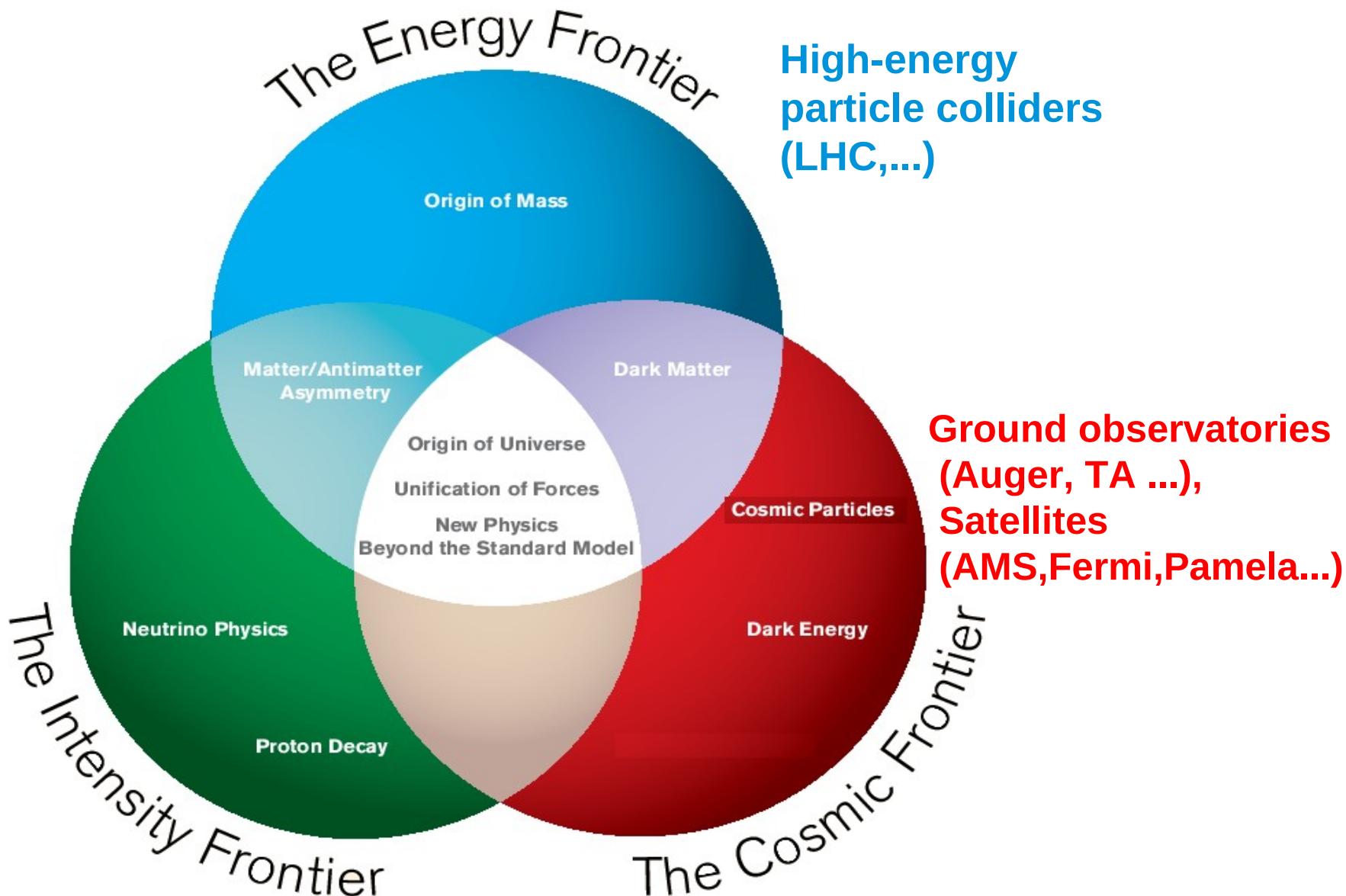
Impact of LHC data on particle astrophysics (cosmic rays, dark matter)



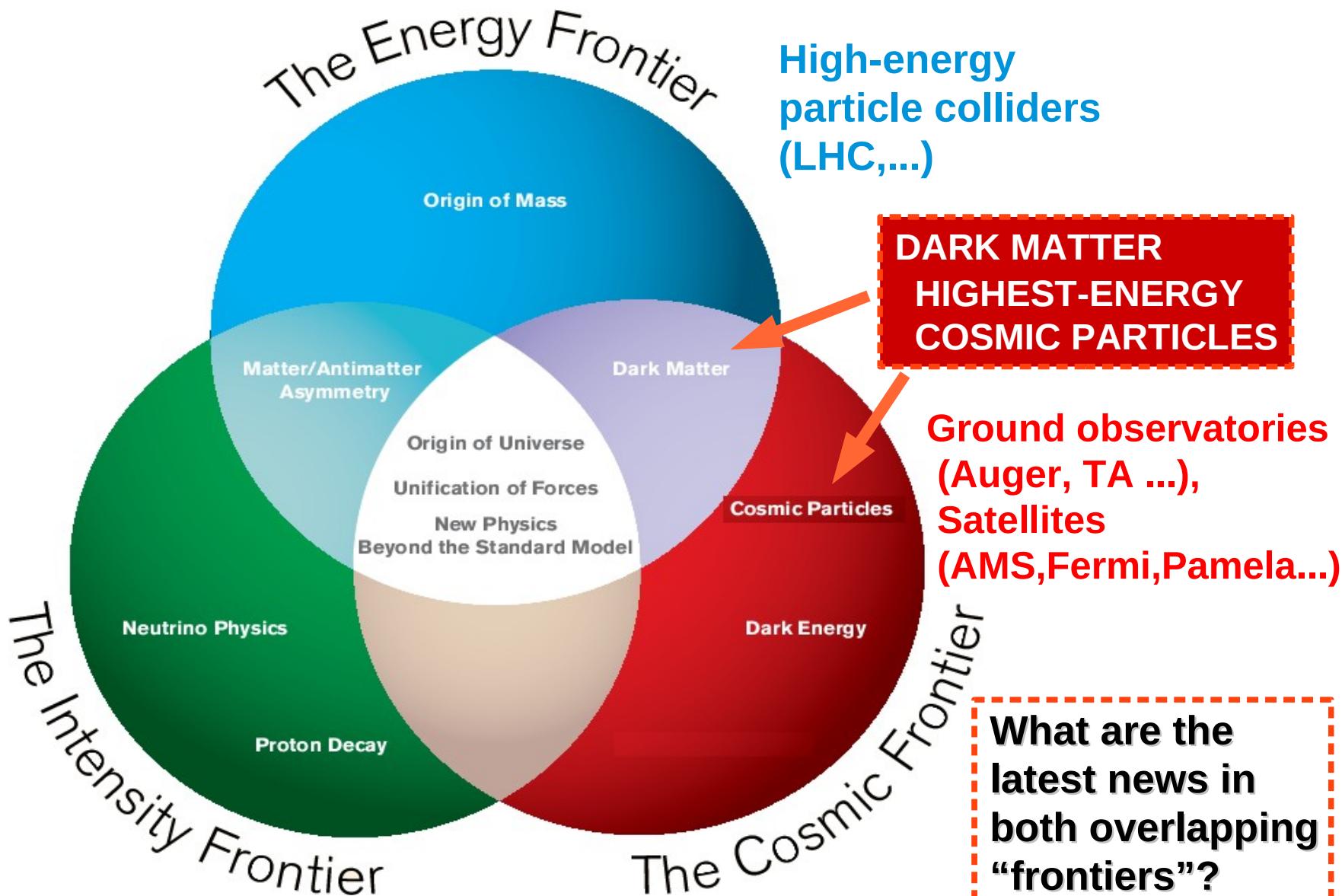
LHC Days in Split
Split (Croatia), 3rd October 2014

David d'Enterria
CERN

Open questions & tools in particle physics



Open questions & tools in particle physics

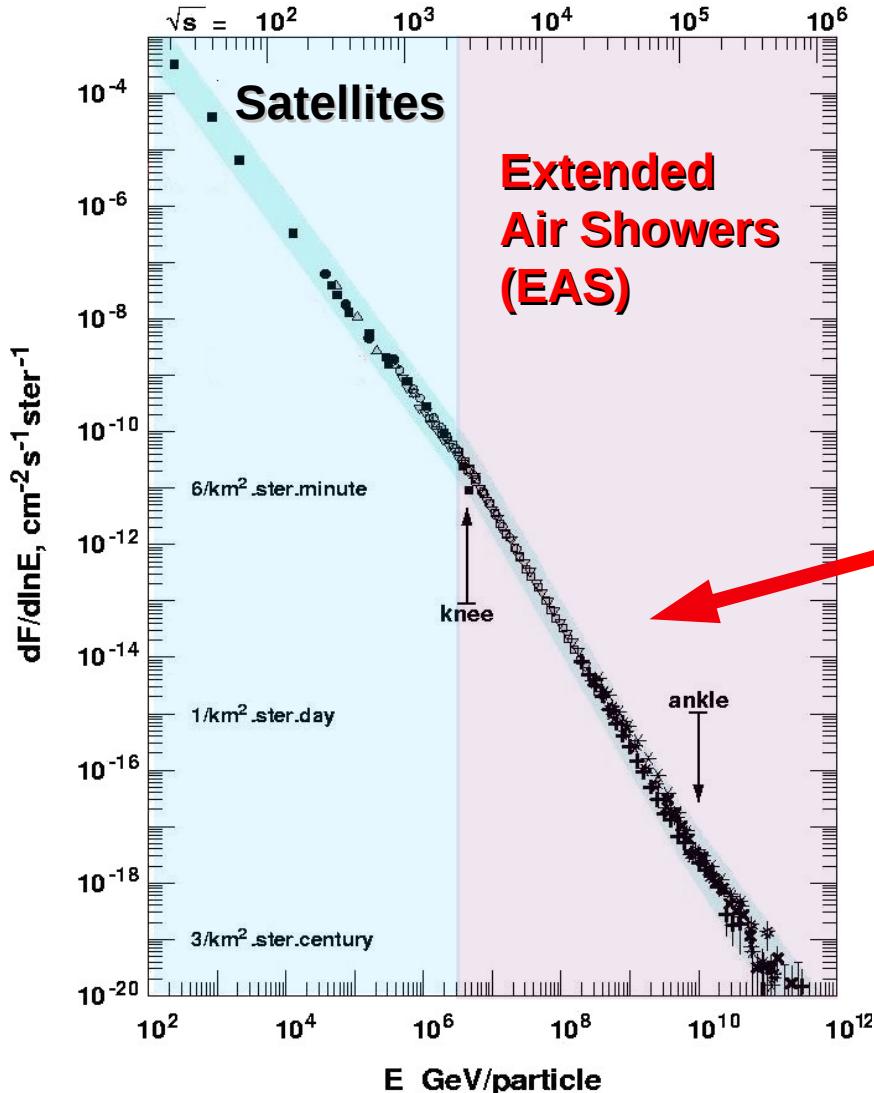




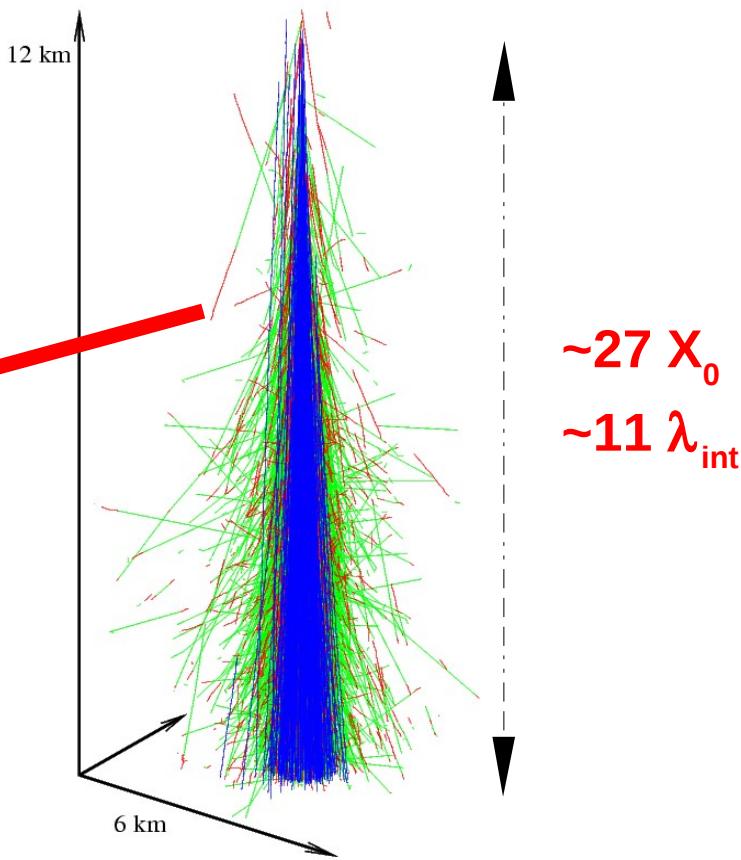
Ultra High Energy Cosmic-Rays: Where do we stand today? What have we learned from the LHC?

Ultra High Energy Cosmic-Rays (UHECRs)

- Cosmic-ray flux falls very rapidly with energy (power-law: E^{-n}).
For $E_{\text{lab}} > 10^{15}$ eV flux too low for satellites/balloons (1 CR per $\text{m}^2\text{-year}$):

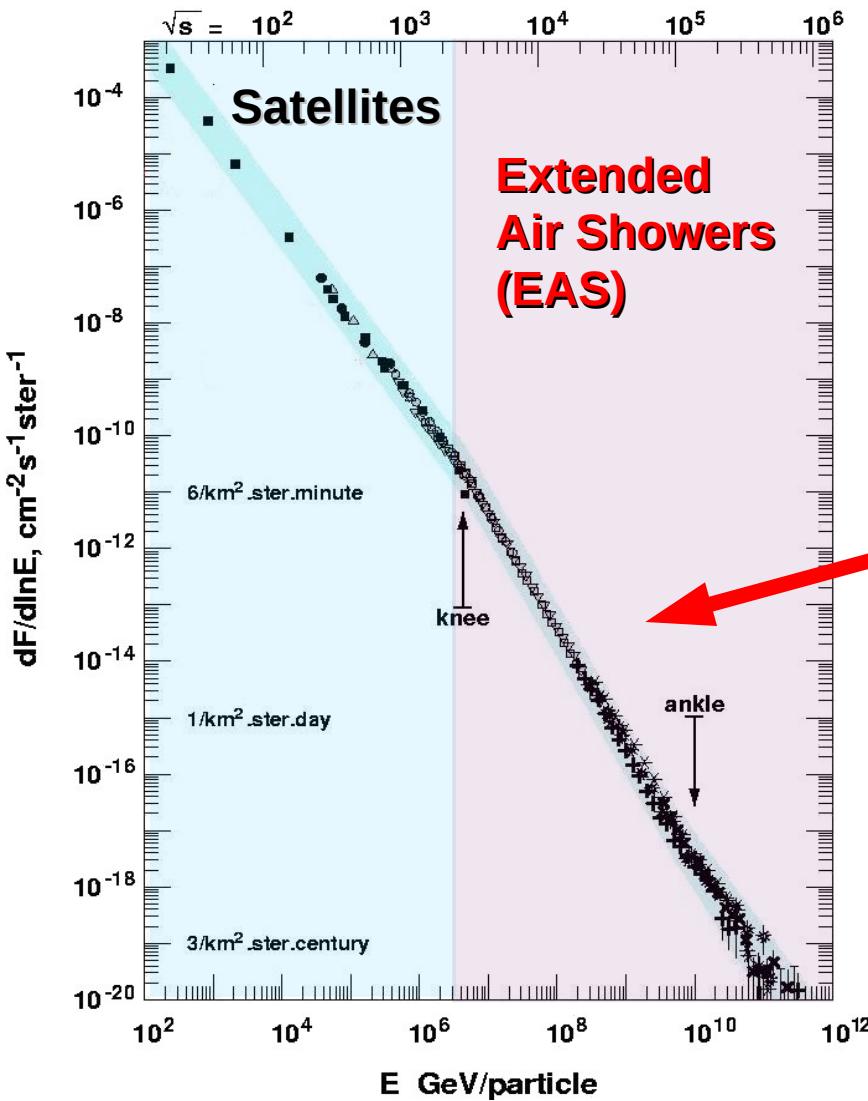


- Indirect measurements using the atmosphere as a “calorimeter”:

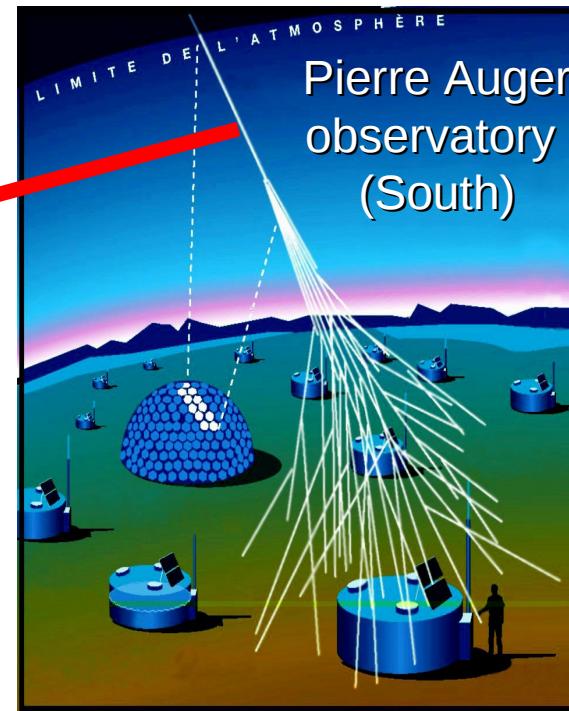


Ultra High Energy Cosmic-Rays (UHECRs)

- For $E_{\text{lab}} > 10^{15}$ eV flux too low for satellites/balloons (1 CR per m²-year):



- Indirect measurements using the atmosphere as a “calorimeter”:
 - UV fluorescence light in air (N^*)
 - Cherenkov-light from e^\pm, μ^\pm at ground

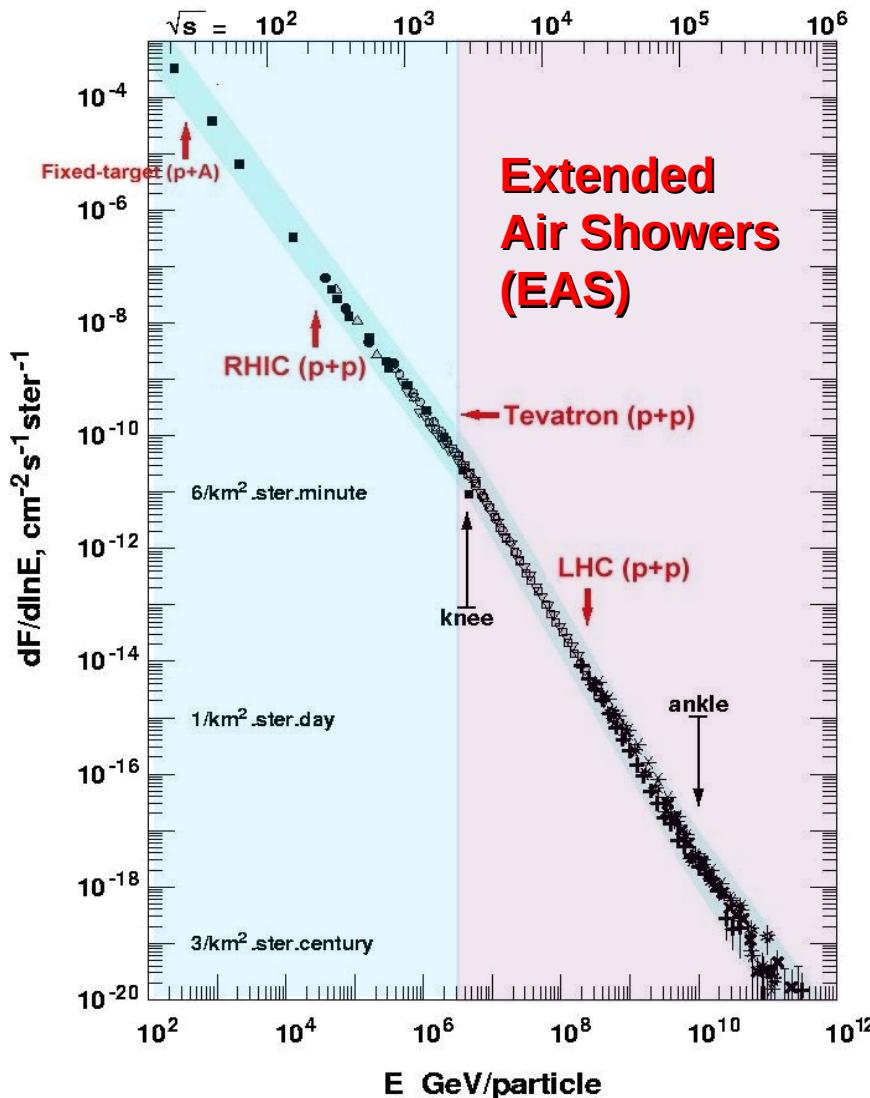


HiRes/TA observatory (North)

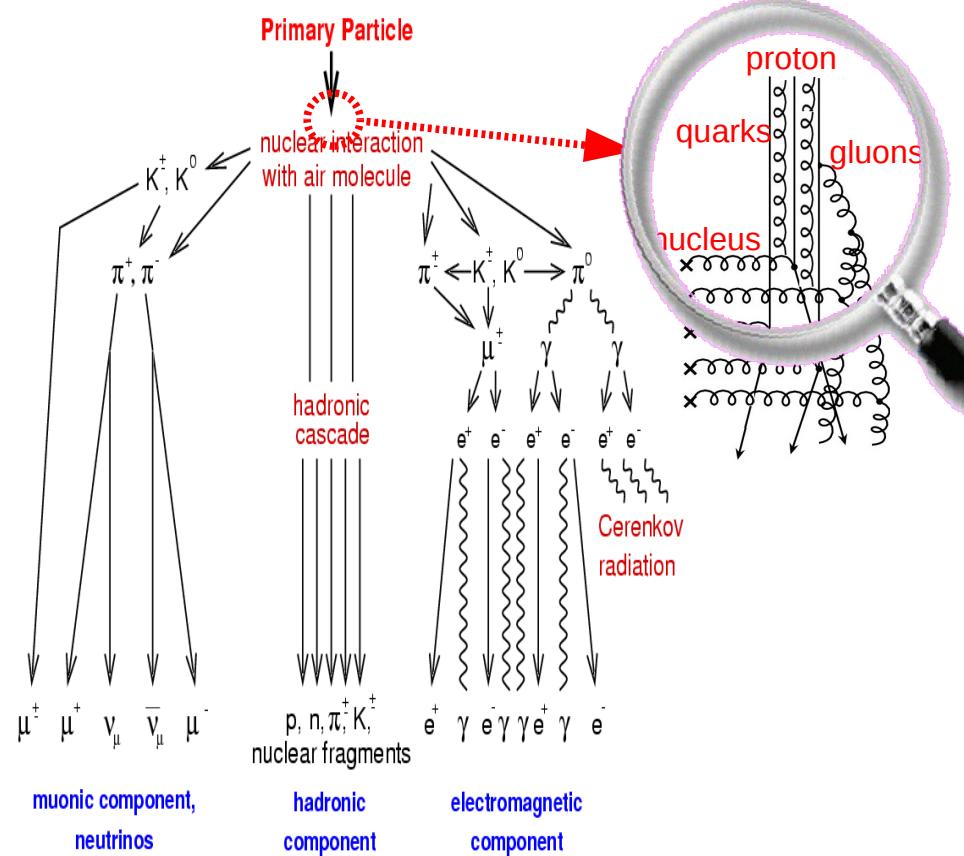


Ultrahigh-energy cosmic rays & QCD

- Above 10^{15} eV CR energy & id determined via hadronic Monte Carlos:

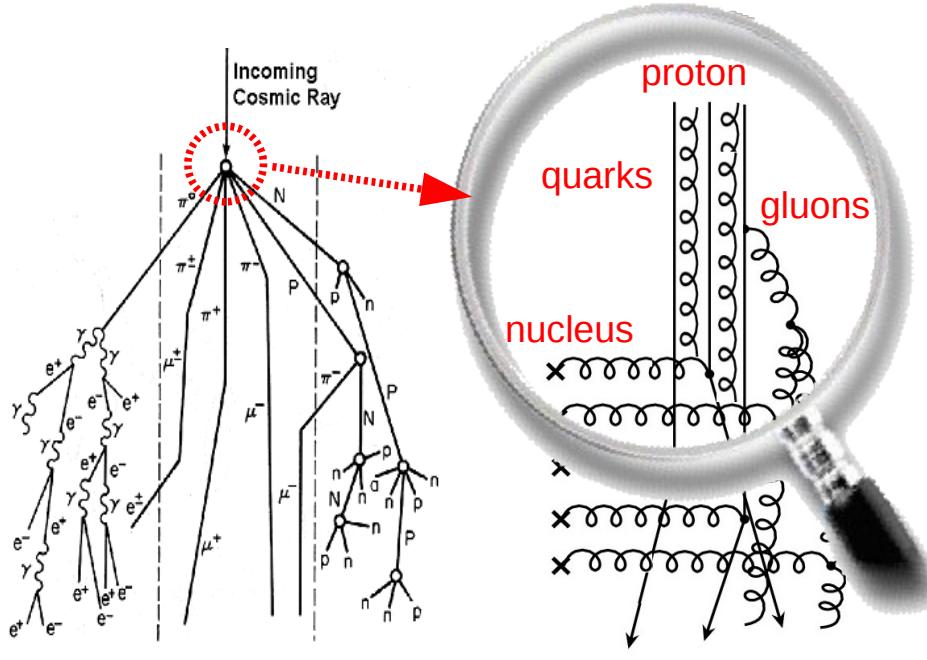


- Comparison of X_{\max} , N_{μ} ... to predictions for p,Fe+Air collisions up to $\sqrt{s}_{\text{GZK}} \sim 300 \text{ TeV}$



Hadronic Monte Carlos for UHECR

■ Primary hadronic collisions ($p-p$, $p-A$) = Complex QCD interactions:



P Proton
n Neutron
 π Pion
 e Electron
 μ Muon
 γ Photon

■ Theoretical basis :

- Gribov-Regge: soft, diffraction, multi-scattering.
- pQCD hard scatterings.
- Parton saturation in PDFs.

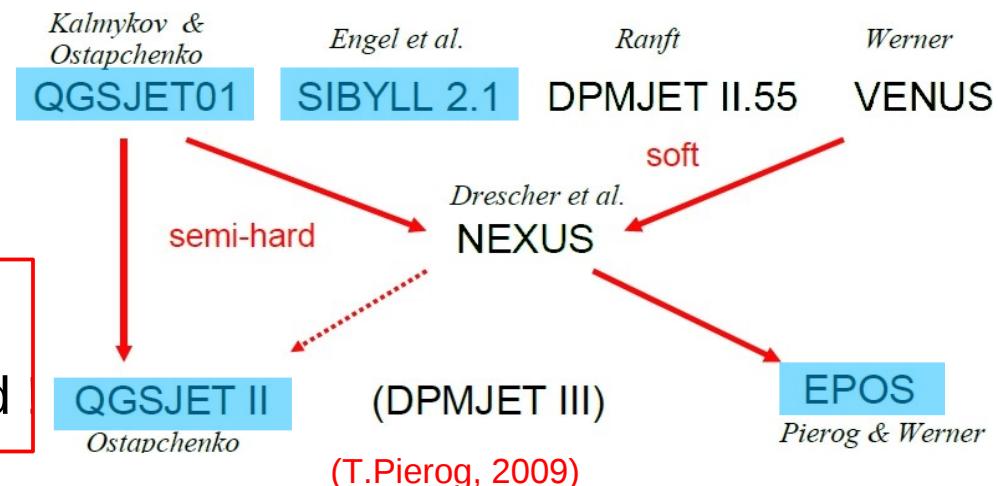
■ Extra modeling:

- Parton fragmentation (Lund)
- Beam-remnants
- ...

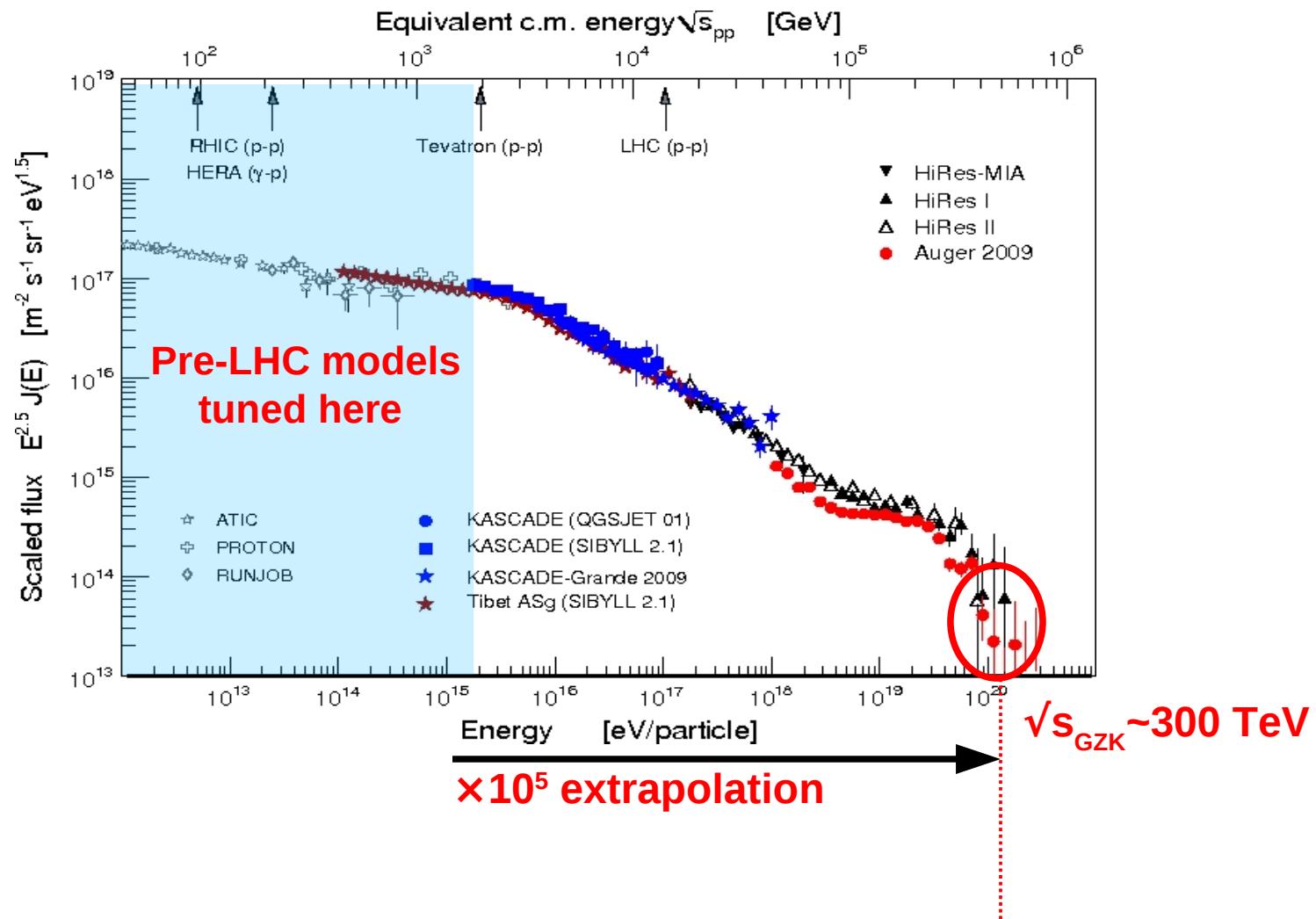
■ Hadronic Monte Carlos:

Tuned with accelerator data.

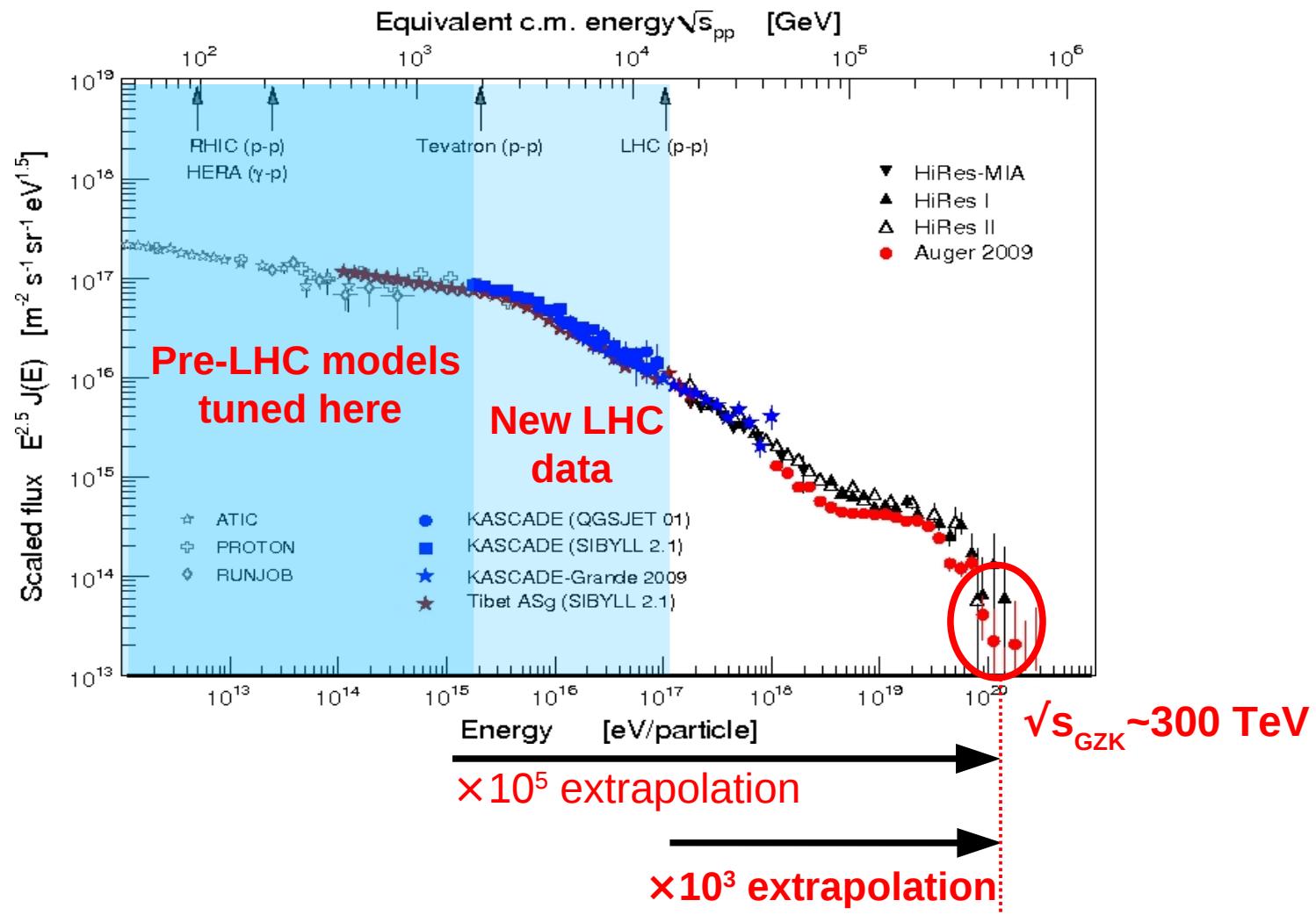
Large \sqrt{s} extrapolations involved



Hadronic MCs tuning with collider data



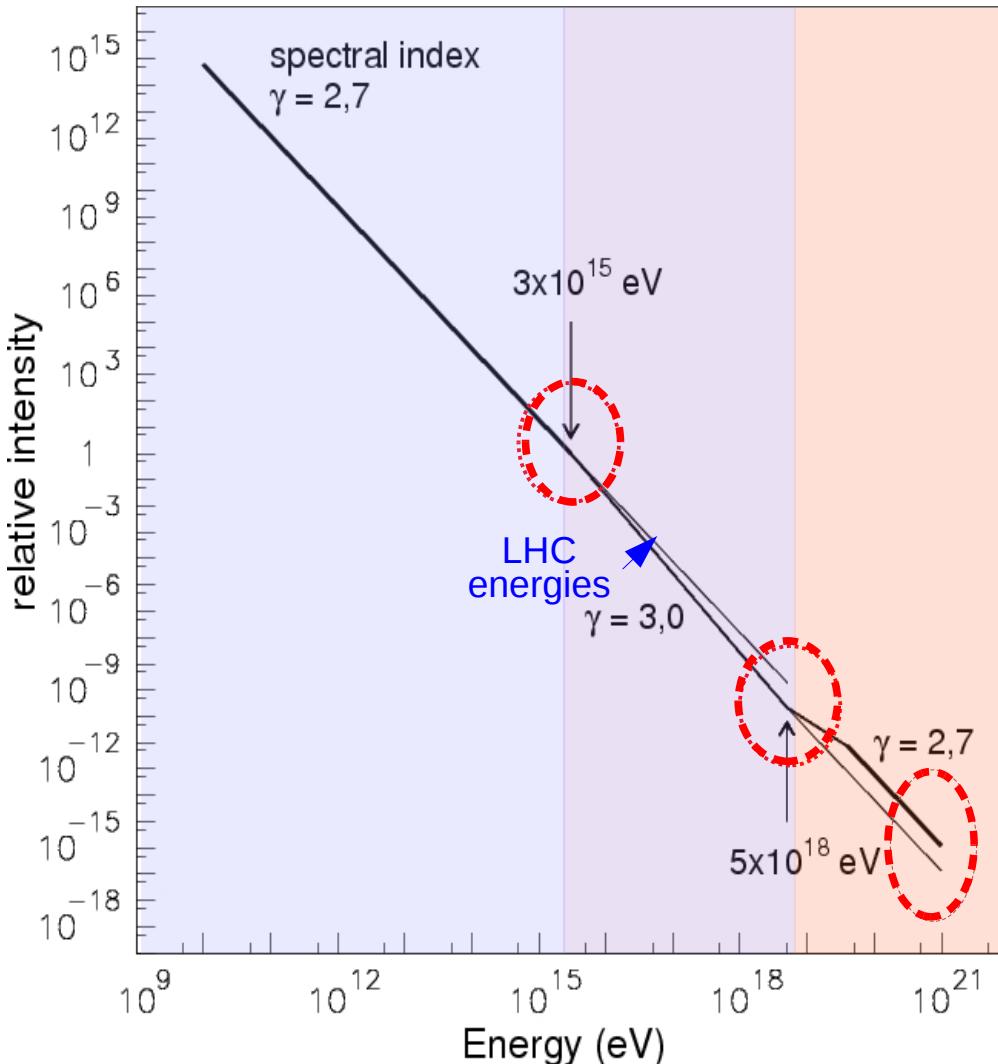
Hadronic MCs tuning with collider data



- The LHC provides a significant lever-arm in providing constraints for hadronic Monte Carlos for UHECR

Open issues in UHECR physics

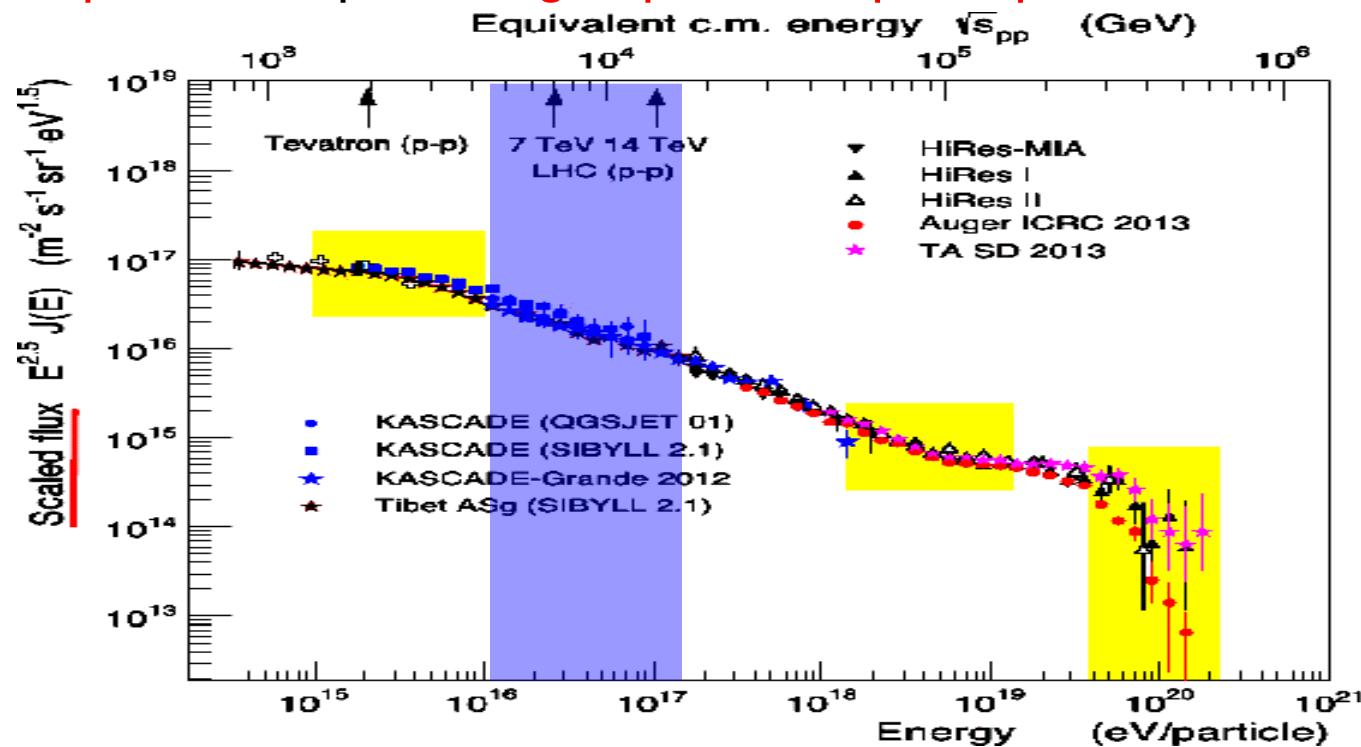
- Two spectral slope changes plus abrupt drop in cosmic-ray flux:



- Flux has 2 slope changes:
 - "knee" at $E_{\text{lab}} \sim 10^{15} \text{ eV}$: $E^{-2.7} \rightarrow E^{-3.1}$
 - "ankle" at $E_{\text{lab}} \sim 10^{18} \text{ eV}$: $E^{-3.1} \rightarrow E^{-2.6}$
- Cosmic-rays break at maximum energies $E_{\text{lab}} \sim 10^{20} \text{ eV}$

Open issues in UHECR physics

- Two spectral slope changes plus abrupt drop in cosmic-ray flux:



- Two slope changes:

"knee" at $E_{\text{lab}} \sim 10^{15}$ eV: $E^{-2.7} \rightarrow E^{-3.1}$

"ankle" at $E_{\text{lab}} \sim 10^{18}$ eV: $E^{-3.1} \rightarrow E^{-2.6}$

☞ Origin of these structures ?

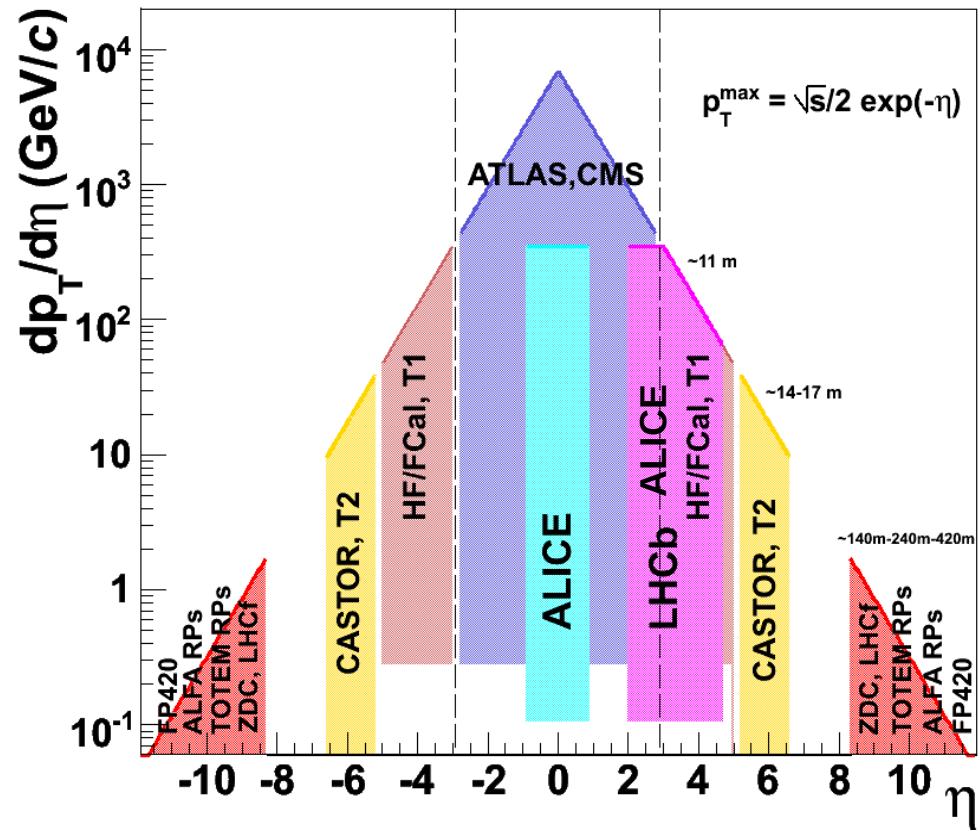
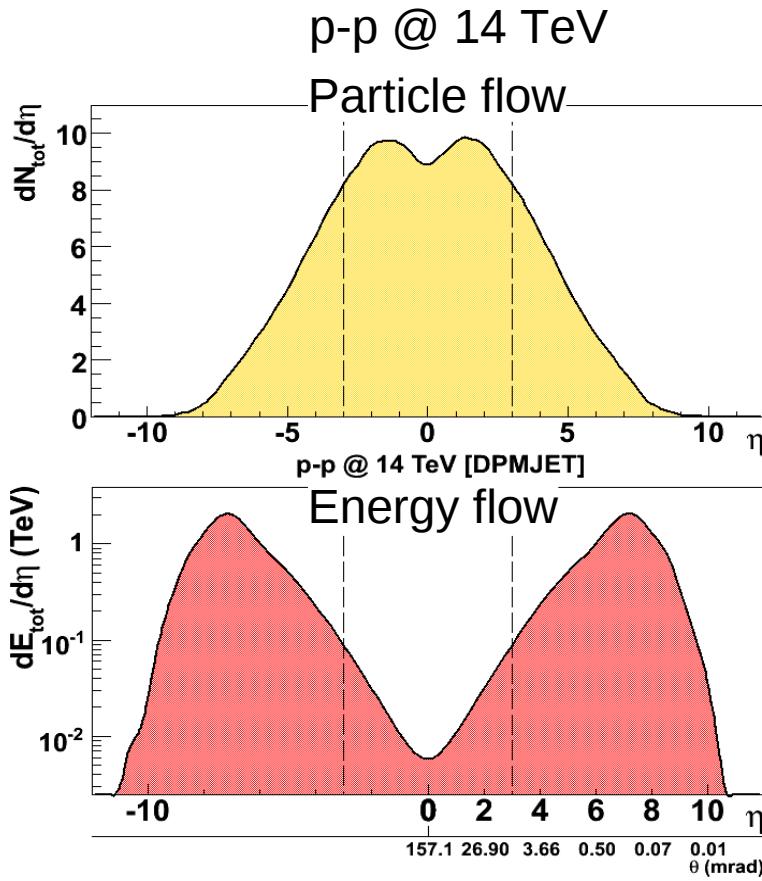
- Break at energies $E_{\text{lab}} \sim 10^{20}$ eV:

☞ Astrophysical acceleration limit ($E_{\text{max}} = Z \cdot \beta_{\text{shock}} \cdot B \cdot L$) ?

☞ CMB- γ induced disintegration of protons/ions (GZK-cutoff) ?

What can the LHC do to solve those open questions ?

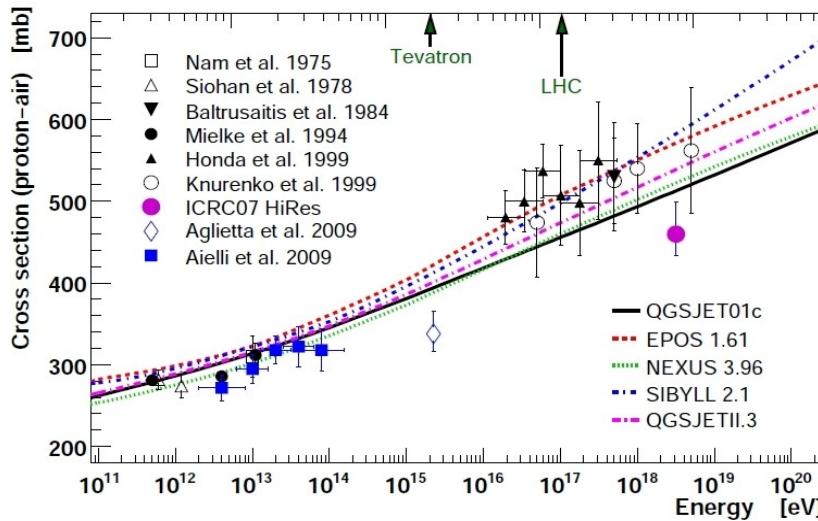
LHC experiments: (p_T, η) acceptance



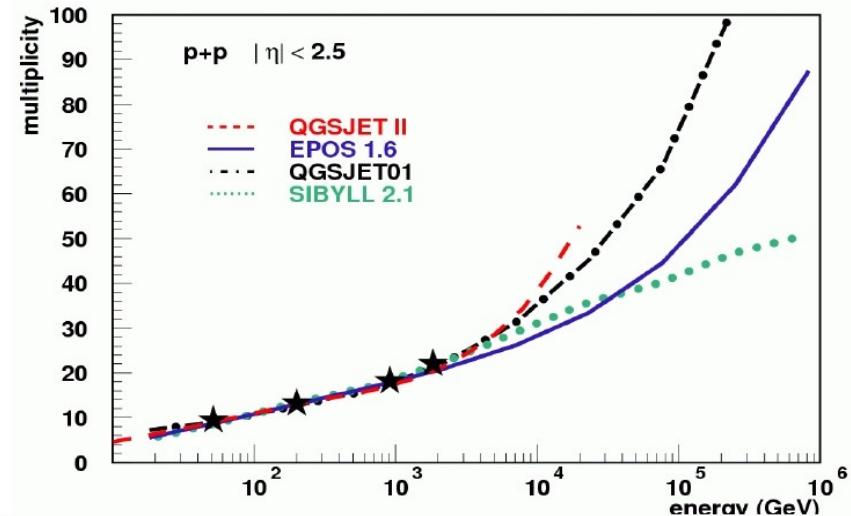
- Particle production at the LHC over $\Delta\eta \sim 2 \times \ln(\sqrt{s})/m_p \sim 20$
- Dedicated detectors at **forward** rapidities: TOTEM,LHCf,Alfa,CASTOR...
- All phase-space virtually covered: **1st time in a collider !**

Cosmic-ray MCs (pre-LHC) vs. LHC data

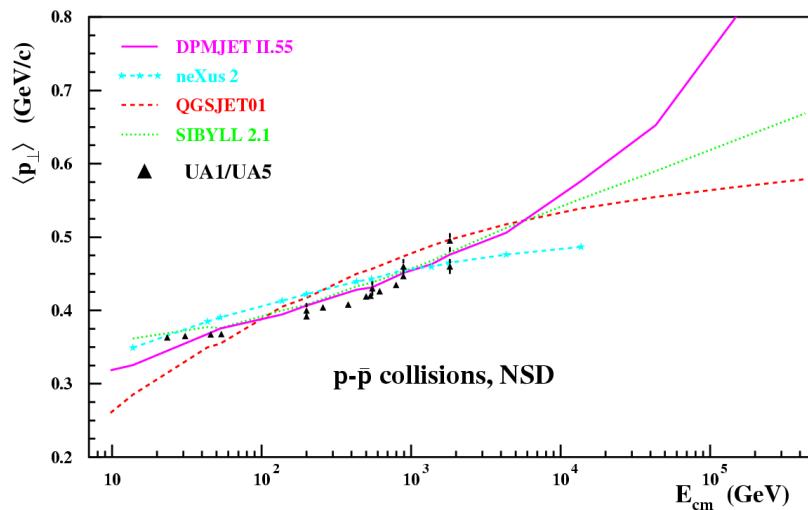
Hadronic cross-sections



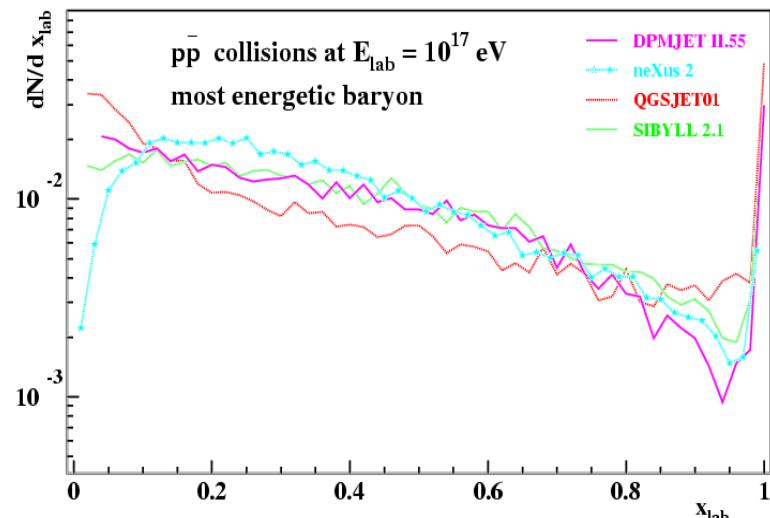
Hadron multiplicity



Average transverse momentum

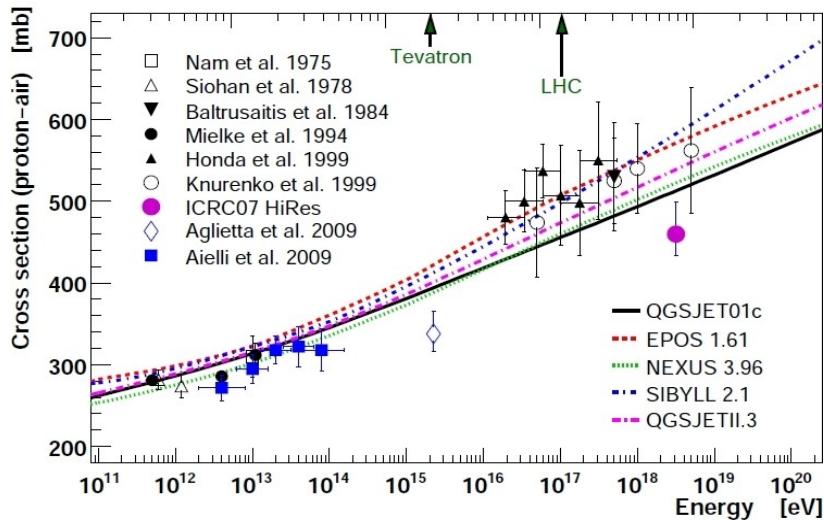


Forward beam remnants

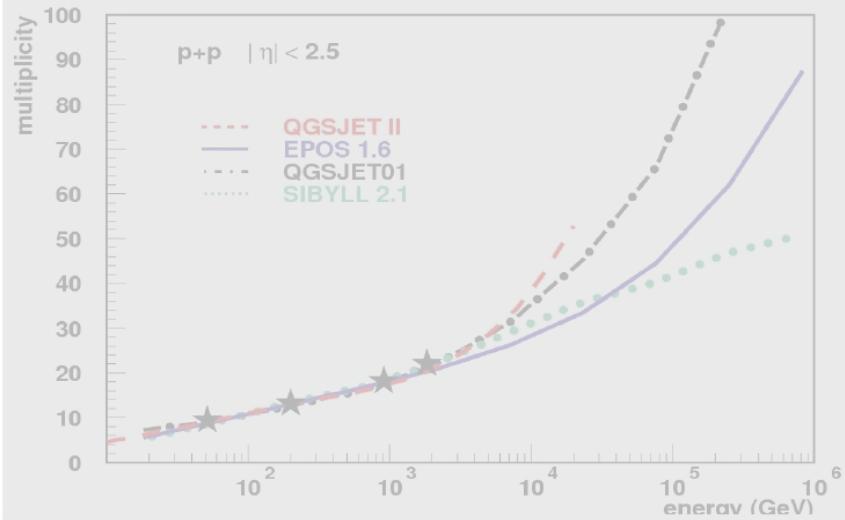


Cosmic-ray MCs vs. LHC data (I)

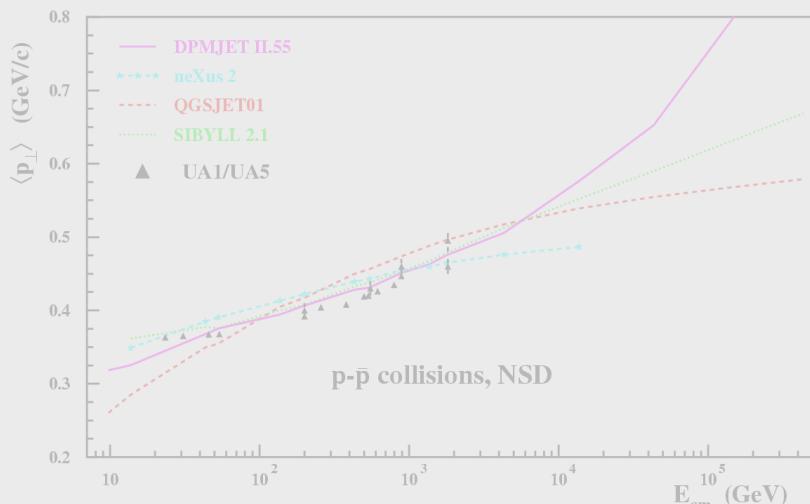
Hadronic cross-sections



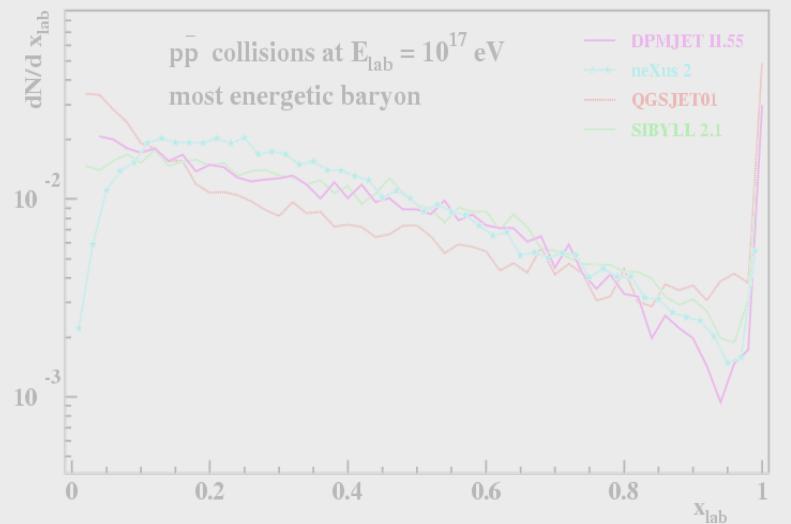
Hadron multiplicity



Average transverse momentum



Forward particle spectra

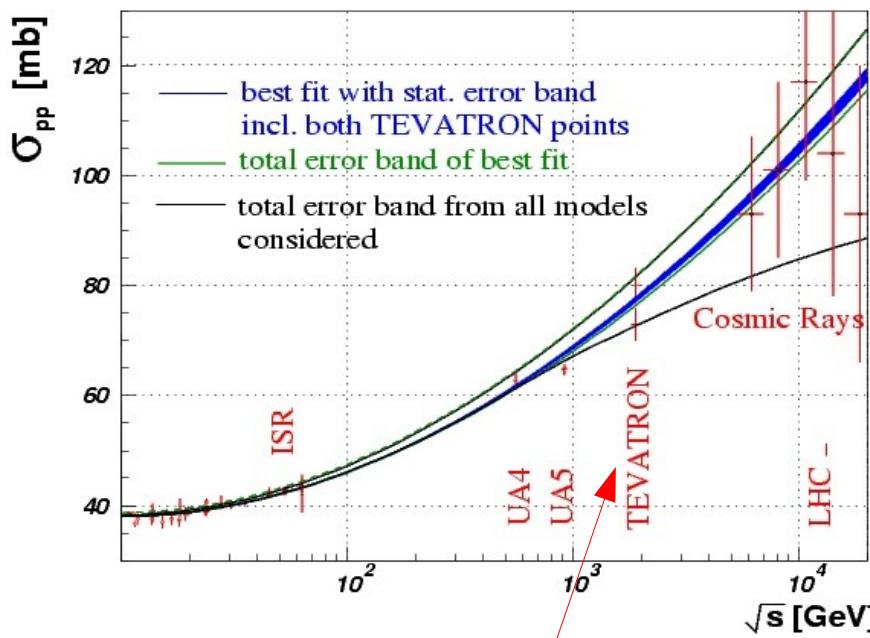


Total & (in)elastic p-p cross sections (pre-LHC)

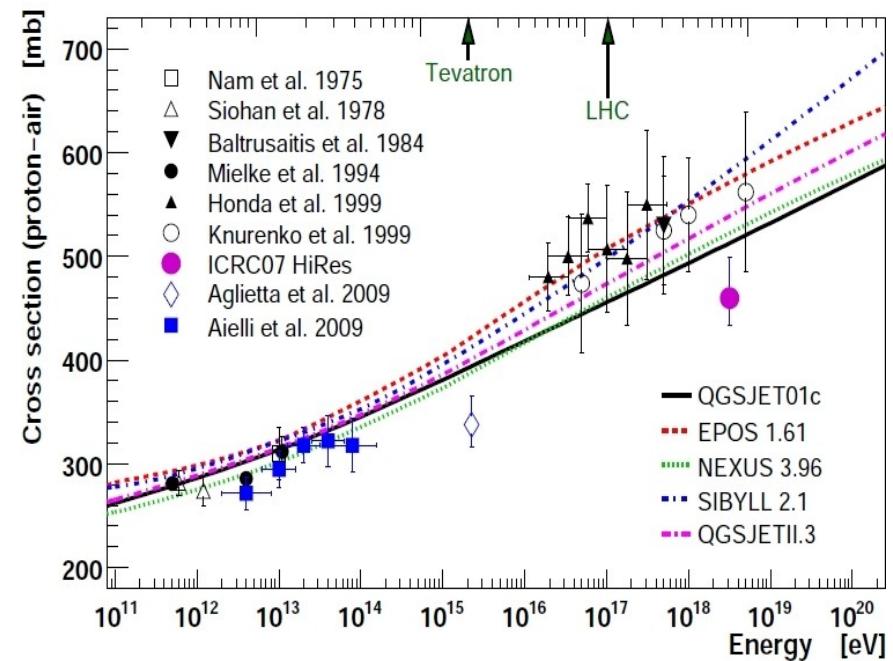
- Non-computable from QCD Lagrangian (maybe lattice?), but constrained by fundamental QM relations: **Froisart bound**, optical theorem, dispersion relations.

- LHC p-p x-section predictions:

$$\sigma_{\text{tot}}(\text{LHC}) = 90-120 \text{ mb} \quad {}^{+10}_{-20} \%$$



- p-Air x-sections even more uncertain (Glauber model):

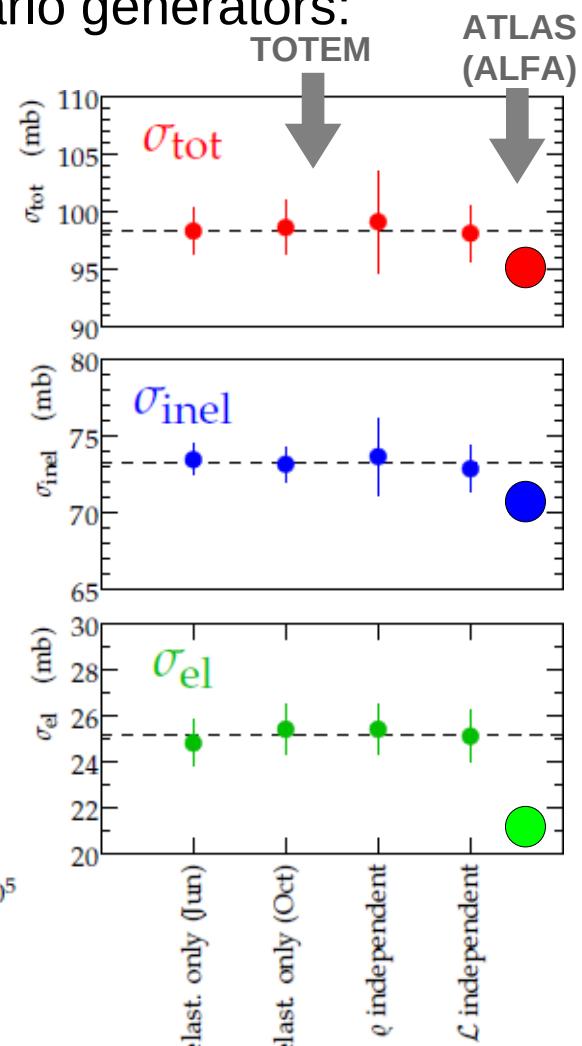
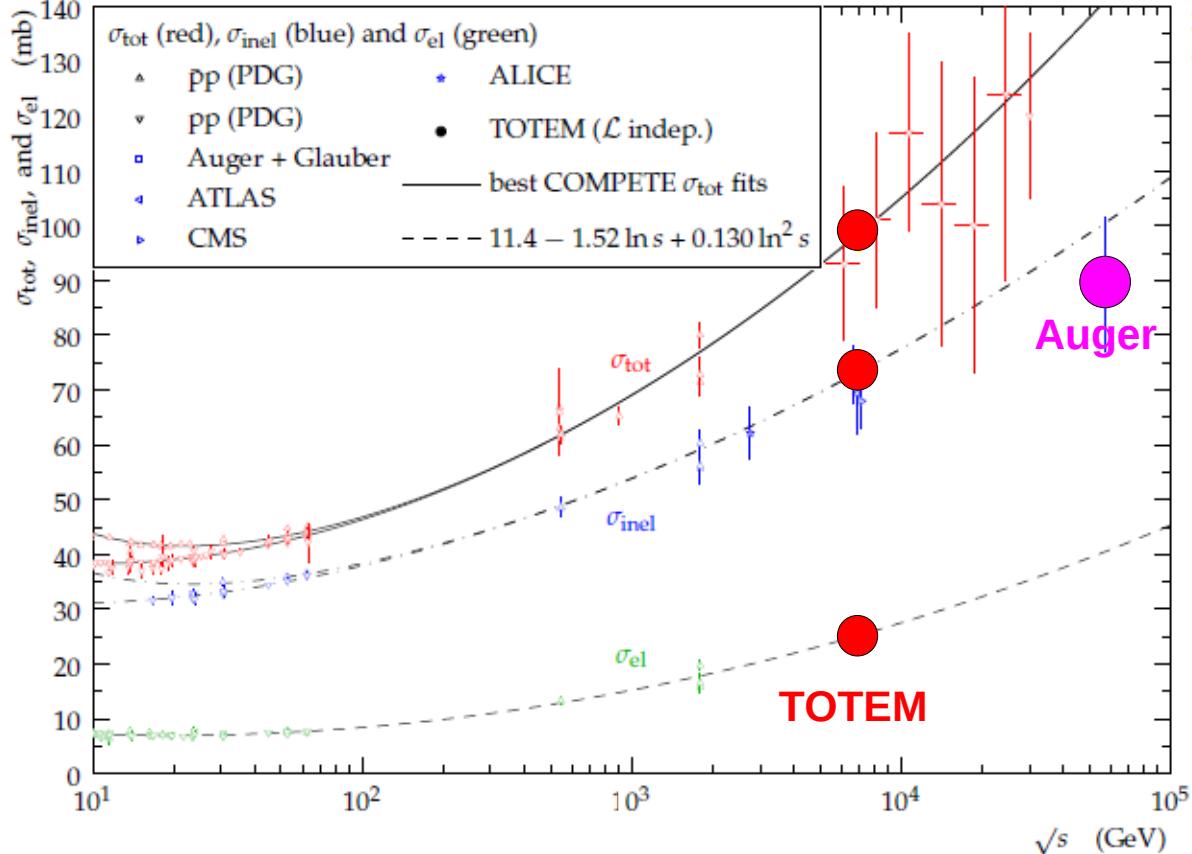


- Pre-LHC model uncertainties driven by E710–CDF 2.6 σ disagreement

R.Ulrich, eConf C0906083 (2009)

Total & (in)elastic p-p cross sections (LHC)

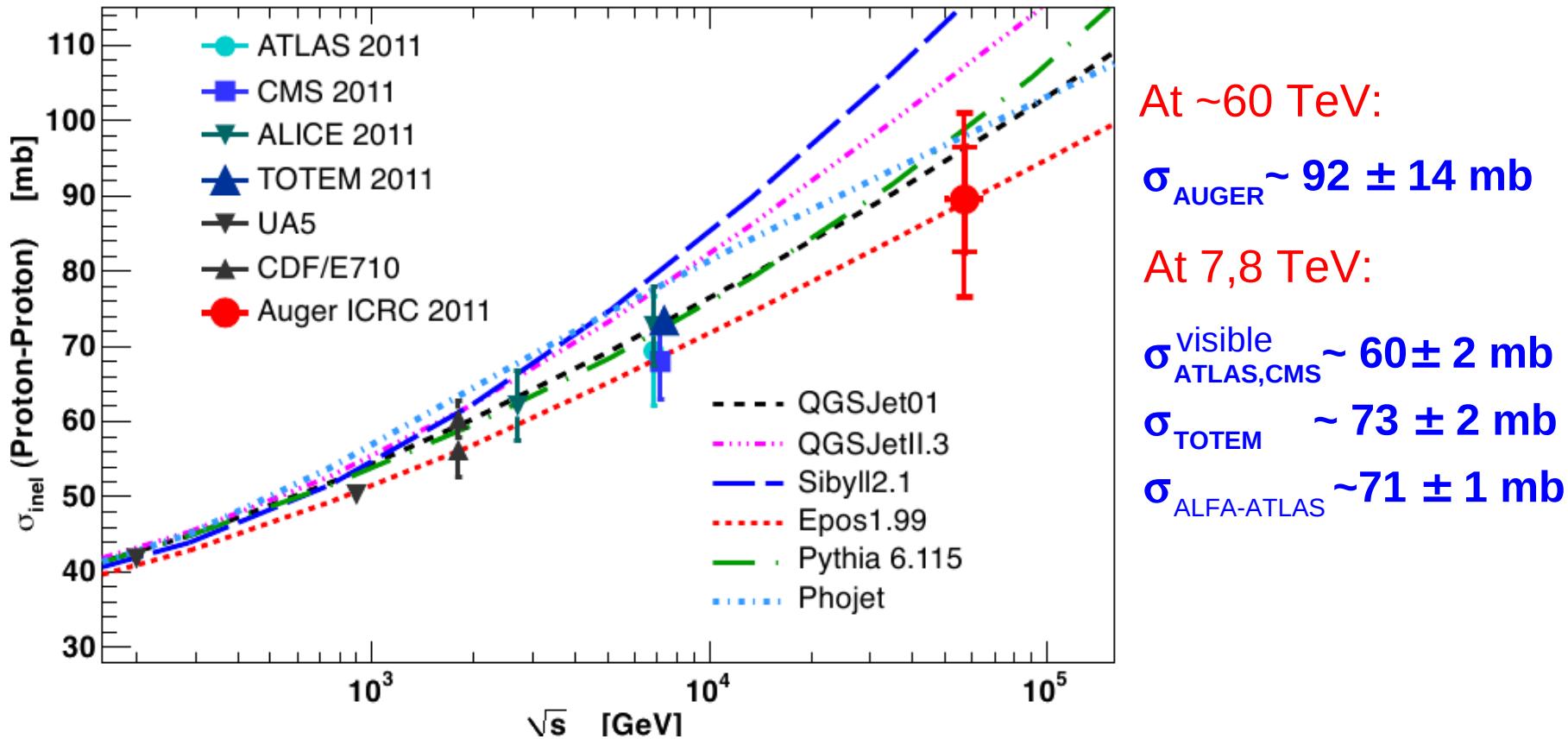
- TOTEM,ALFA $\sigma_{\text{TOT}} \sim 98,95 \pm 2.5,1.5 \text{ mb}$, $\sigma_{\text{elastic}} \sim 25.1,24 \pm 1.1,0.6 \text{ mb}$
provide extra constraints on hadronic Monte Carlo generators:



- Measured $\sigma(p-p)$ LHC leads to reduced $\sigma(p-Air)$
i.e. deeper shower X_{max} position.

Inelastic p-p cross sections (LHC+Auger)

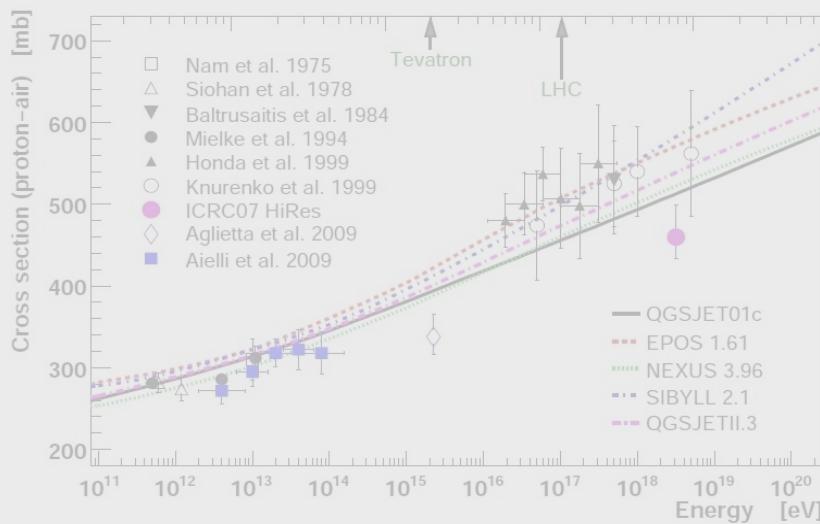
- Inelastic cross section mostly overestimated by MCs.
- Most models over-(under-)estimate high-(low-)mass diffraction.



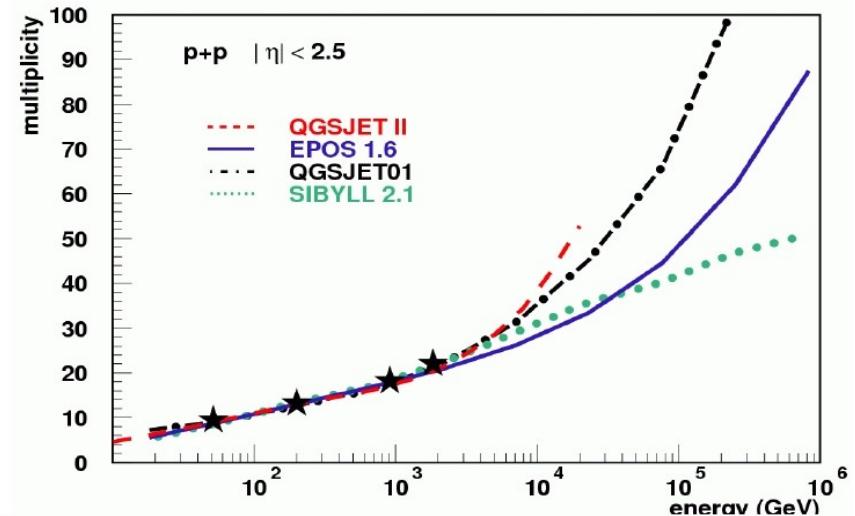
- Measured $\sigma(p-p)$ LHC leads to reduced $\sigma(p-Air)$: Deeper shower X_{max} position

Cosmic-ray MCs vs. LHC data (II)

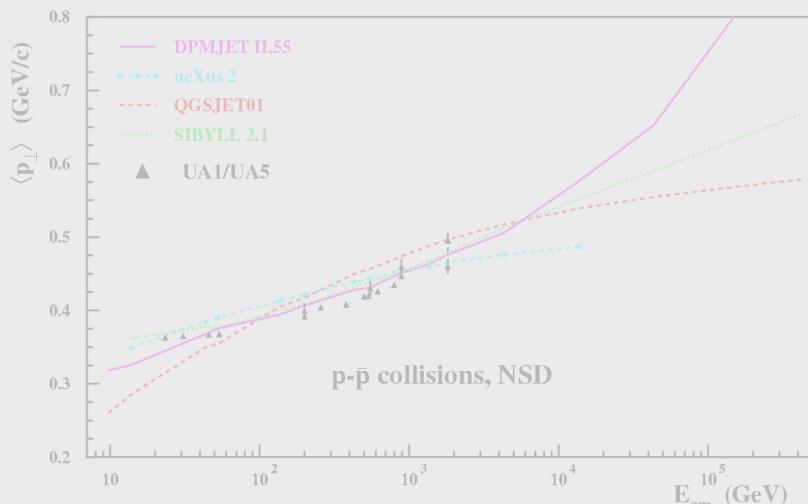
Hadronic cross-sections



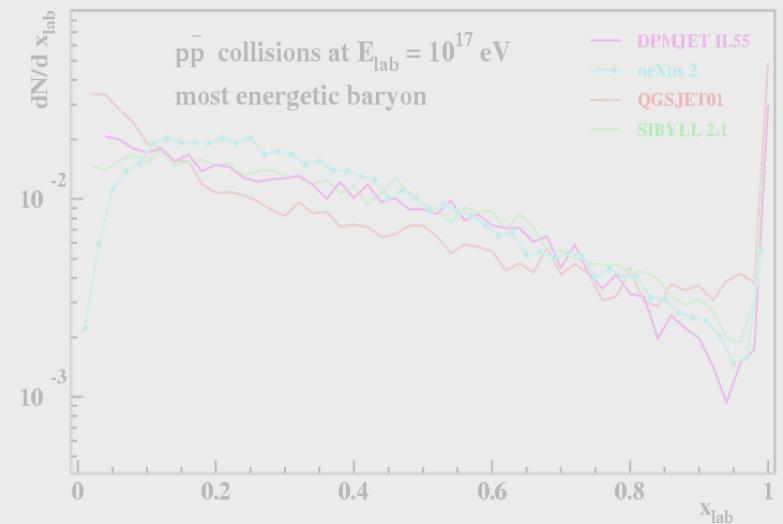
Hadron multiplicity



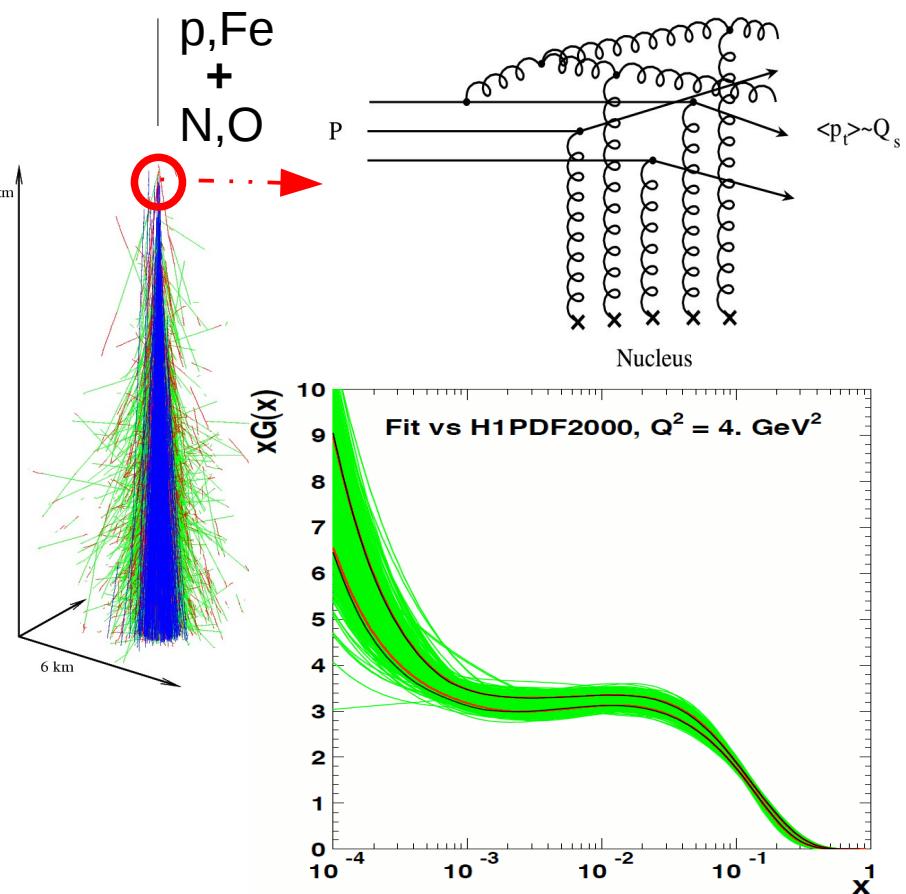
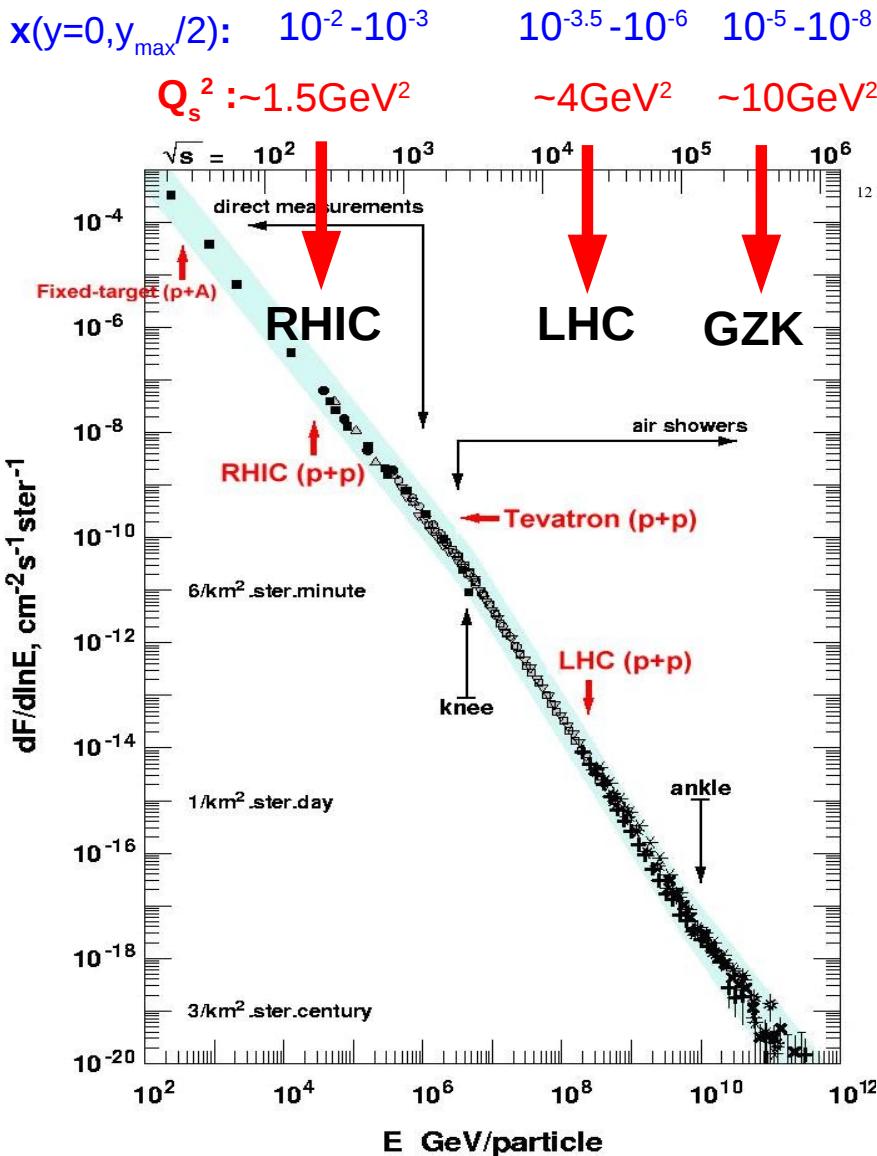
Average transverse momentum



Forward particle spectra



Gluon-gluon collisions in UHECRs

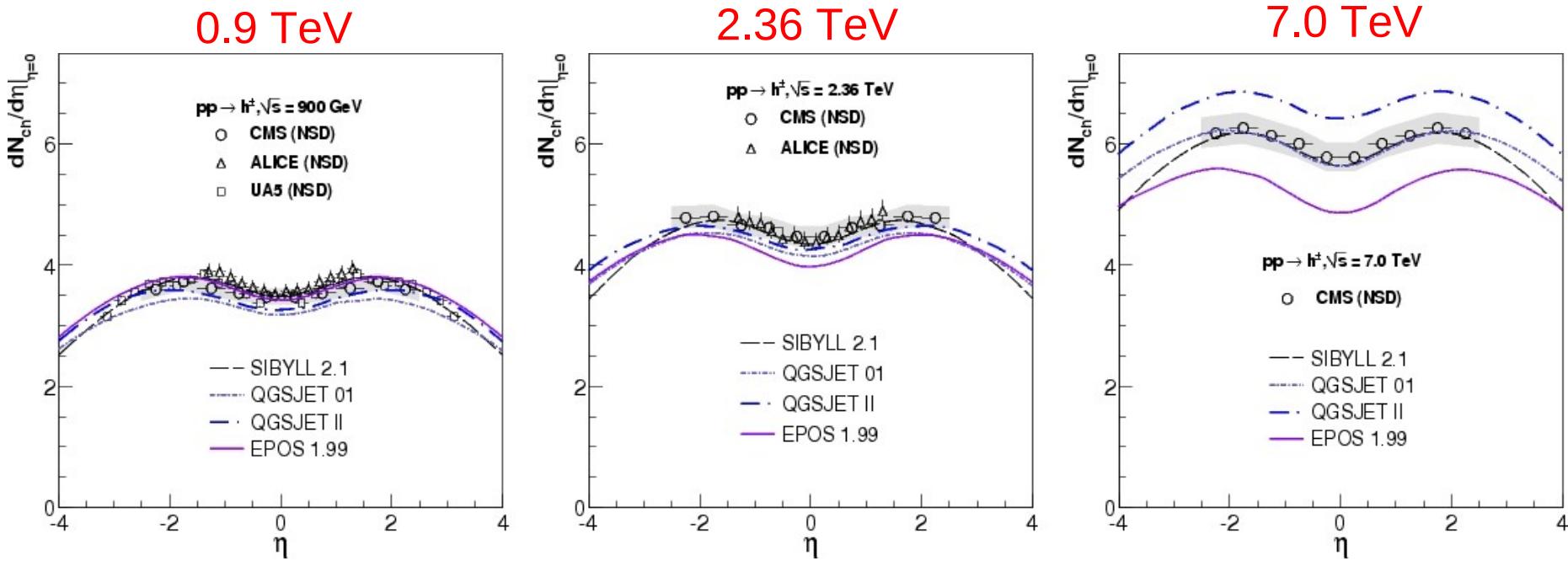


■ p-nucleus at GZK cut-off energies:
multiple gluon-gluon interactions
at $x \sim 10^{-5}-10^{-8}$! (saturation regime)

Particle pseudorapidity density

[DdE et al., Astr.Phys. 35 (2011) 98]

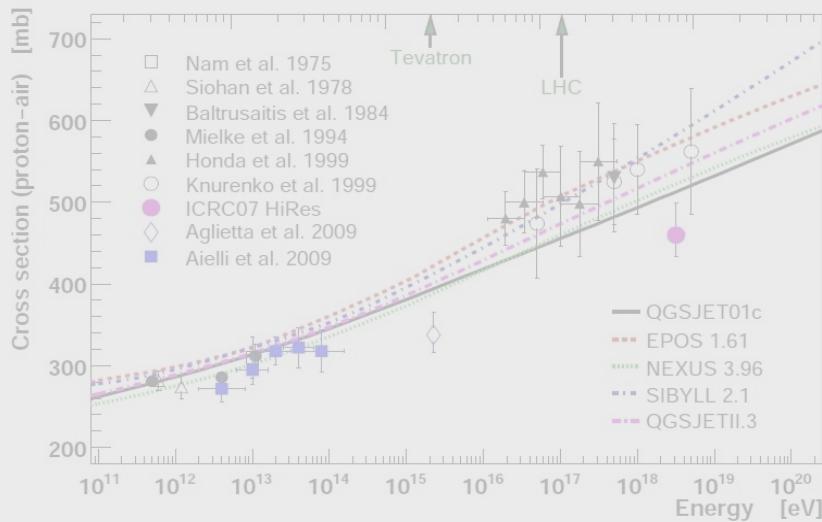
- Most (~70%) of charged-hadrons come from semi-hard gluon fragmentation.
- Pseudorapidity distribution data vs CR models:



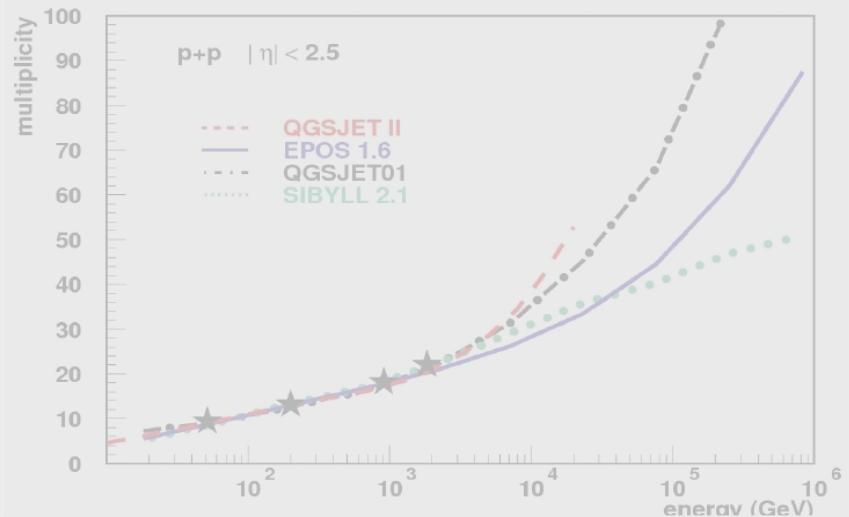
- 900-GeV data well reproduced (MCs tuned to SppS, Tevatron)
- Particle multiplicity less well predicted at 7.0 TeV but all CR models “bracket” the experimental distributions.

Cosmic-ray MCs vs. LHC data (III)

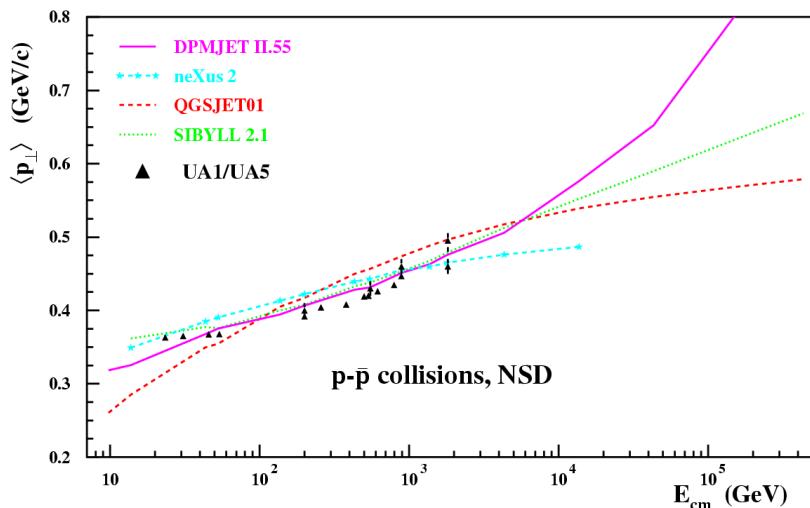
Hadronic cross-sections



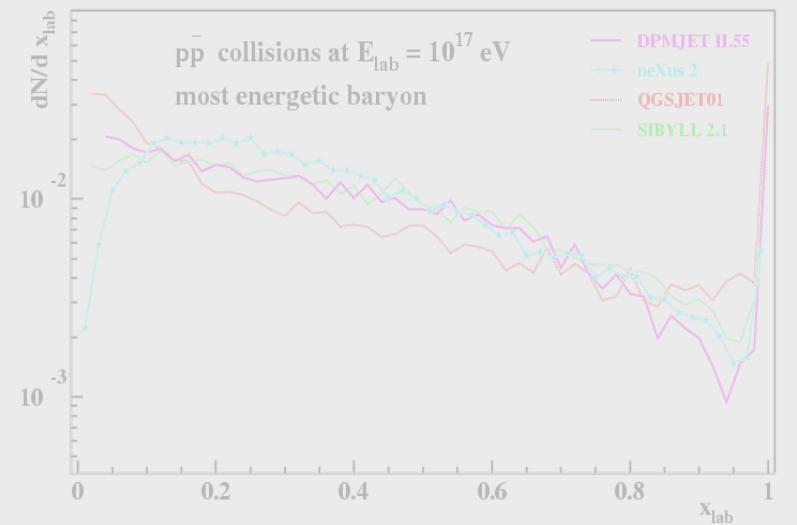
Hadron multiplicity



Average transverse momentum

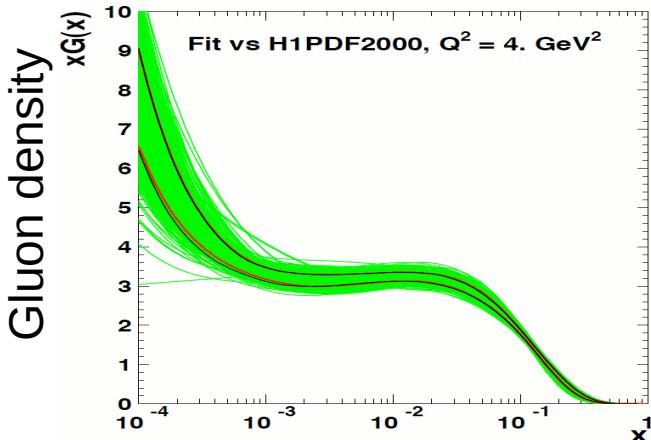


Forward particle spectra



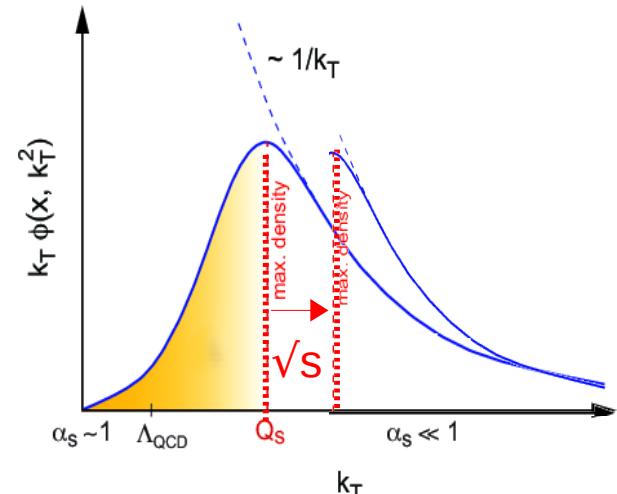
Average p_T driven by gluon saturation dynamics

- Gluons start to overlap at “saturation scale”

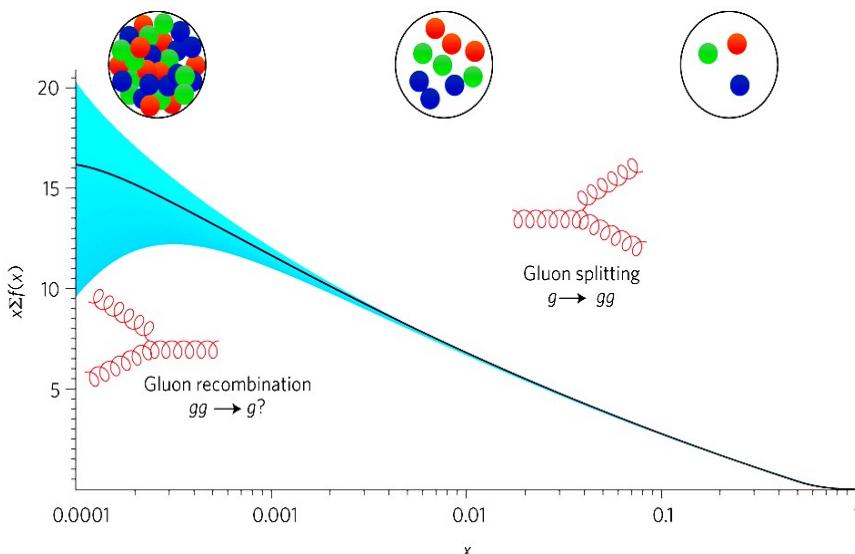


$$Q_s^2 \sim \alpha_s \frac{x G_A(x, Q_s^2)}{\pi R_A^2}$$

- pQCD g-g x-section peaks at $p_T \sim Q_s(\sqrt{s}) \sim 1-4$ GeV



$$Q_{\text{sat}}^2 \propto \log(1/x) \propto \log(\sqrt{s})$$



- Saturation effects enhanced in ultra-relativistic nuclei (“squashed gluon pancakes”):

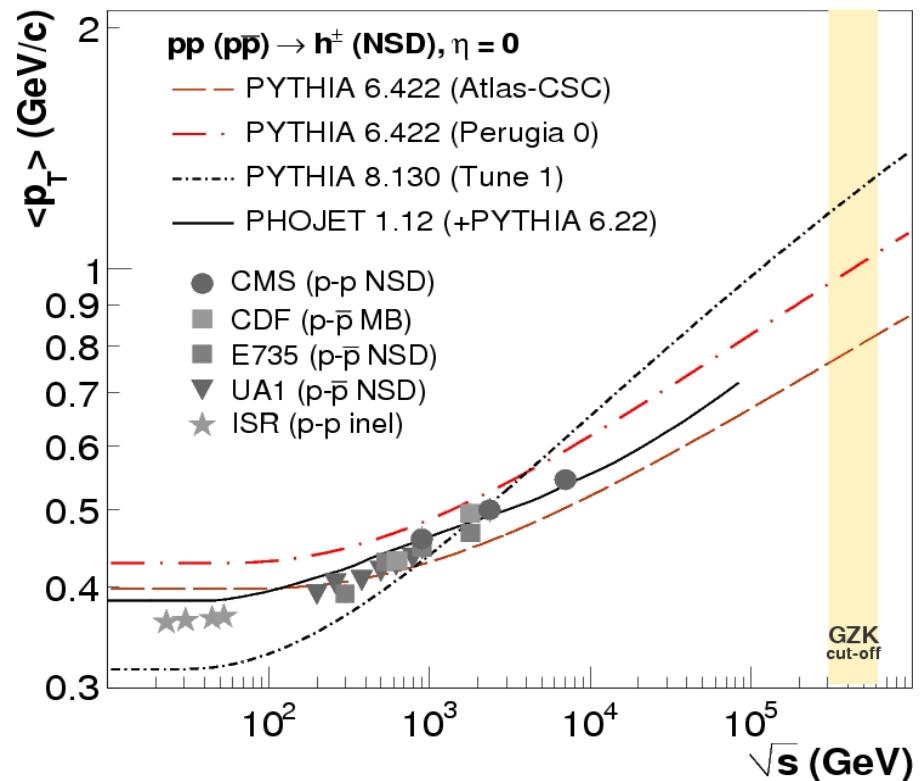
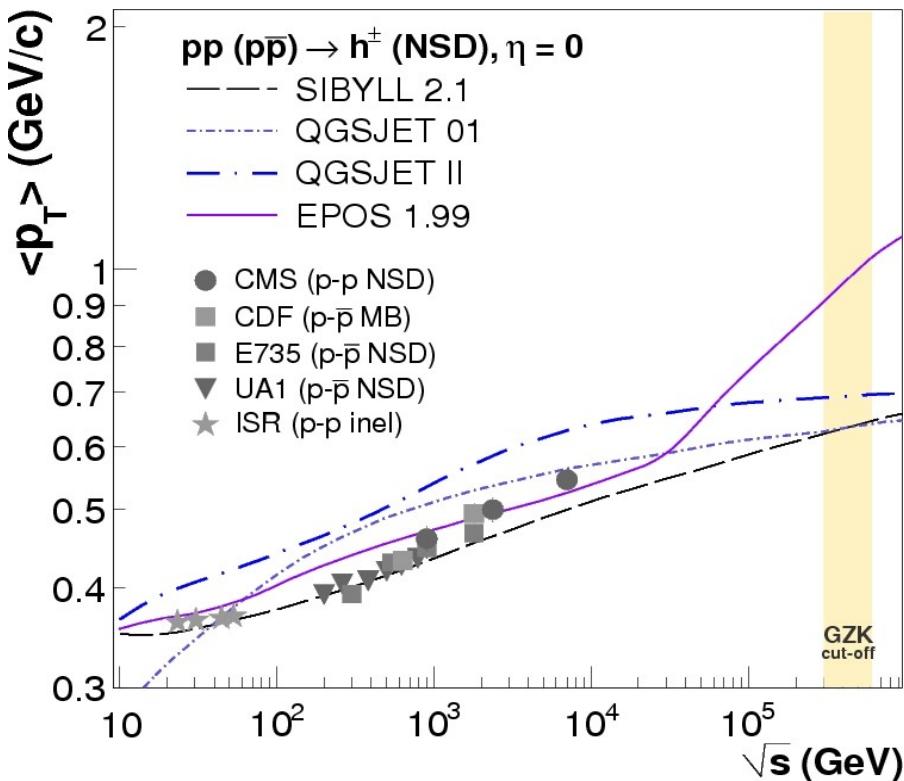
Larger # of partons per transverse area

$$Q_s^2 \sim A^{1/3} \sim 6$$

Average p_T vs. \sqrt{s}

[DdE et al., Astr.Phys. 35 (2011) 98]

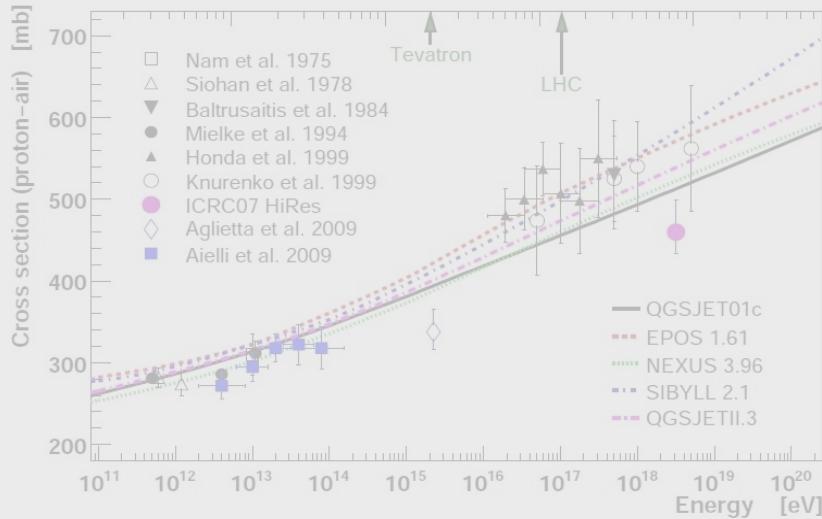
- $\langle p_T \rangle$ is sensitive to pQCD x-sections & gluon-saturation
- $\langle p_T \rangle$ should approach asymptotically the saturation scale: $\langle p_T \rangle \sim Q_{\text{sat}}$



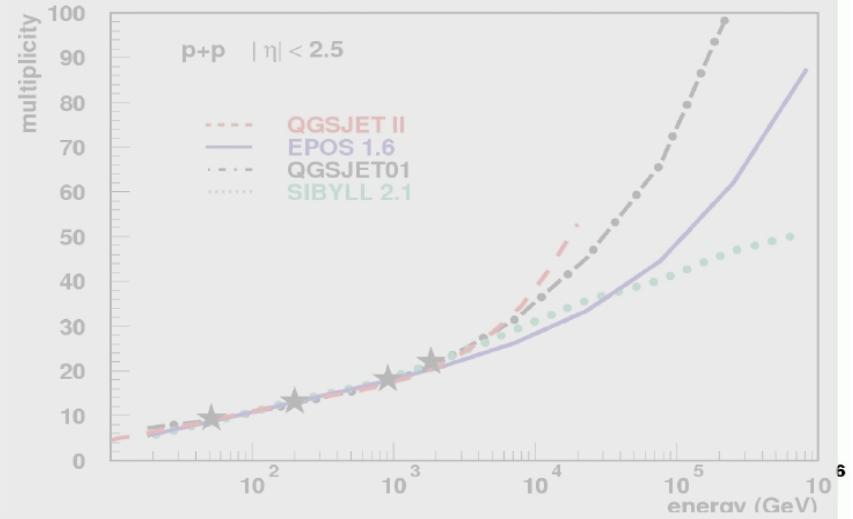
- CRs MCs predict very slow $\langle p_T \rangle$ increase (but EPOS, due to collective flow)
- At GZK: $\langle p_T \rangle \sim 0.6 - 1.0$ GeV/c (PYTHIA: $\langle p_T \rangle \sim 0.7 - 1.5$ GeV/c)

Cosmic-ray MCs vs. LHC data (IV)

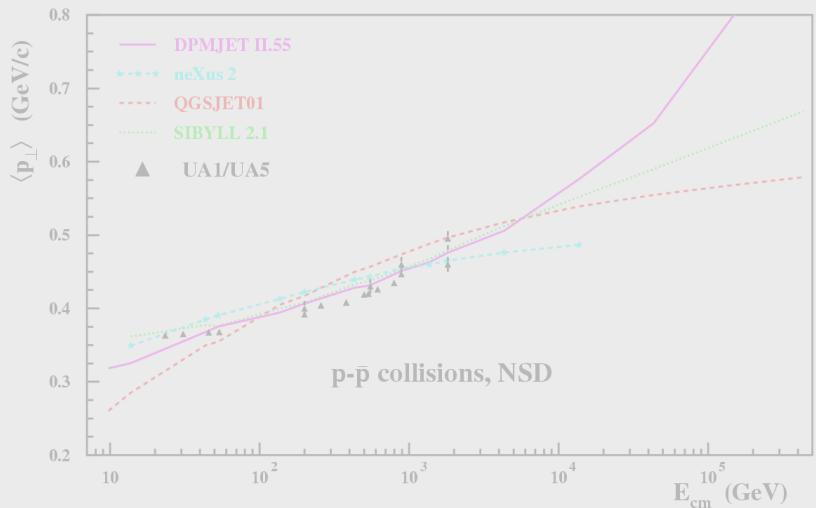
Hadronic cross-sections



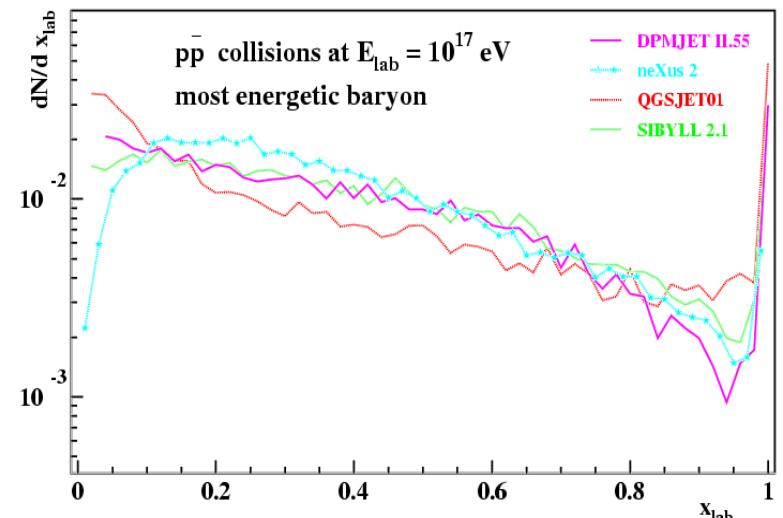
Hadron multiplicity



Average transverse momentum

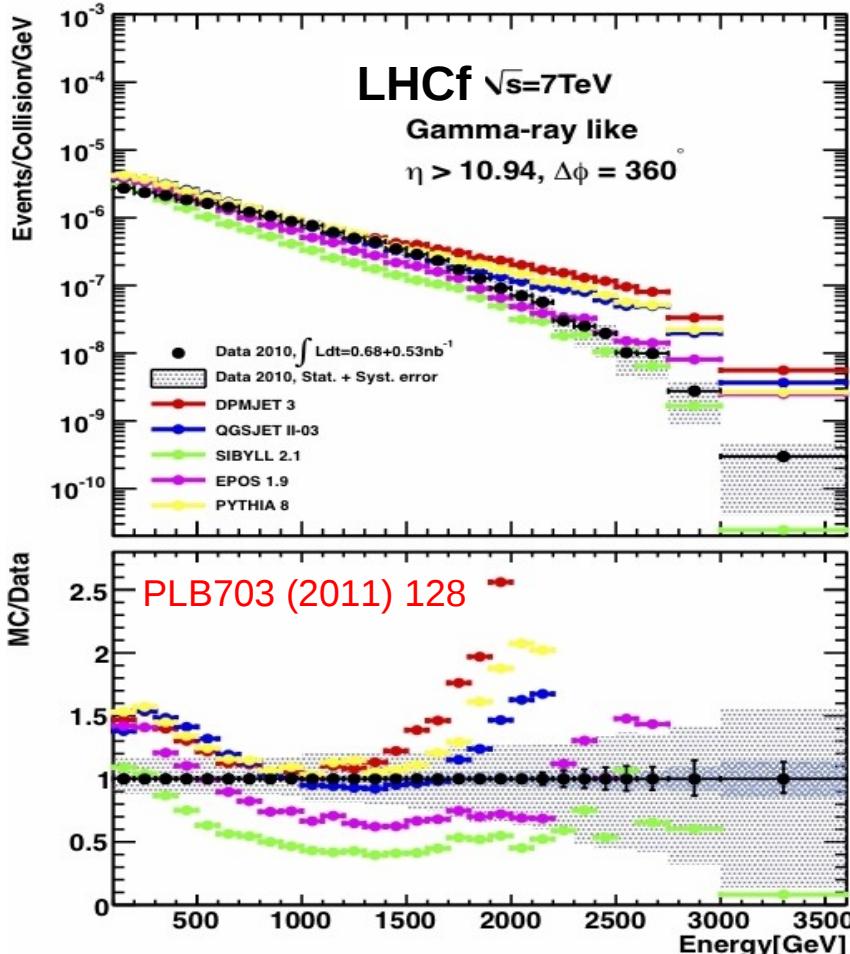


Forward beam remnants

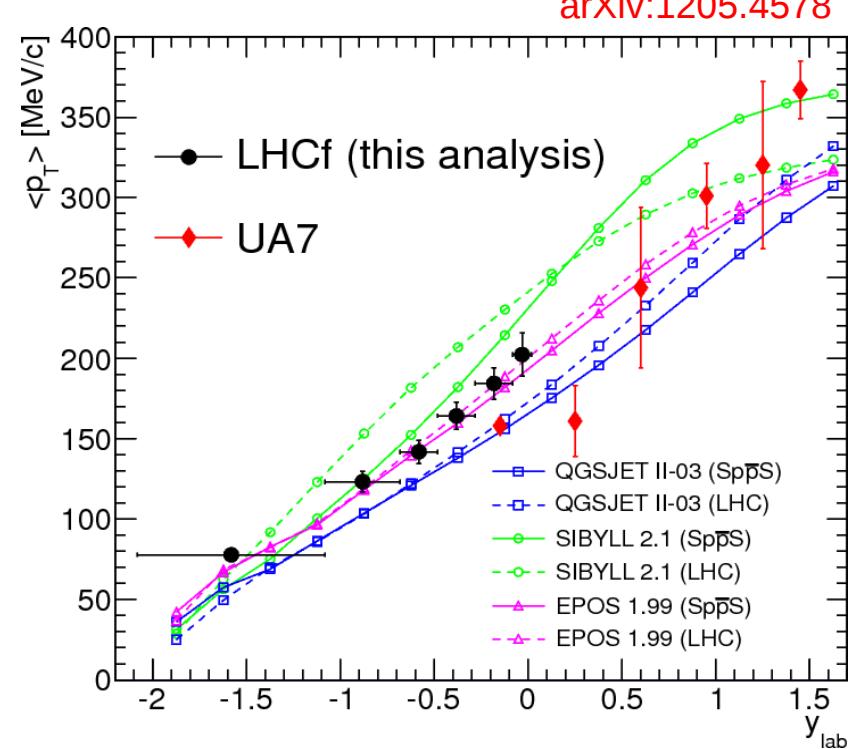


Forward beam remnants (LHCf): $|\eta| \sim 8. - 11.$

- Important influence on cosmic-ray EAS development:
Leading baryon (inelasticity) & had-to-e.m. energy transfer ($\pi^0 \rightarrow \gamma\gamma$)



- $> \pm 50\%$ data-model differences for zero degree photon showers.



- Mean p_T of zero-degree pions is \sqrt{s} -independent.
EPOS shows the best overall agreement

Summary: Cosmic-ray MCs vs. LHC data

[DdE et al., Astr.Phys. 35 (2011) 98]

- Reasonable agreement (all MCs bracket data),
though no model reproduces consistently all results:

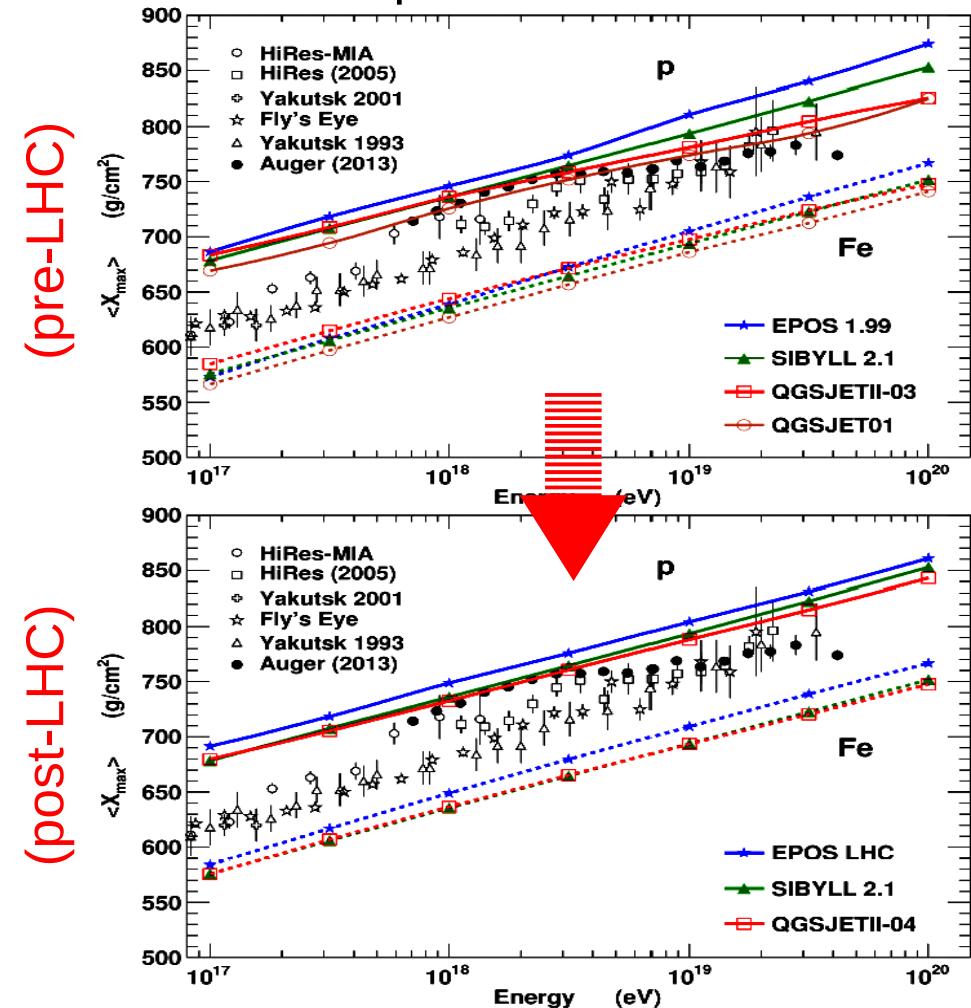
Model \sqrt{s} (TeV)	SIBYLL 2.1			QGSJET01			QGSJETII			EPOS 1.99		
	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7	0.9	2.36	7
σ_{inel}	✓	↑↑	↑↑	✓	✓	✓	✓	↑↑	↑↑	✓	✓	✓
$dN_{ch}/d\eta _{\eta=0}$	✓	✓	✓	✓	✓	✓	✓	✓	↑↑	✓	↓↓	↓↓
$P(N_{ch} < 5)$	↑↑	↑↑	↑↑	↑↑	↑↑	↓↓	↑↑	↑↑	↑↑	✓	✓	✓
$P(N_{ch} > 30)$	↑↑	✓	↑↑	✓	↓↓	↓↓	✓	✓	↑↑	↓↓	↓↓	↓↓
$\langle p_\perp \rangle$	✓	↓↓	↓↓	↑↑	↑↑	✓	↑↑	↑↑	↑↑	✓	✓	✓

- Energy evolution of semi-hard QCD dynamics is crucial for predictions (N_{ch} , $\langle p_T \rangle$) at GZK-cutoff energies ($\sim 10^{20}$ eV).
- EPOS-LHC, QGSJET-II-4 updates: Diffraction, MPI, saturation retuned. Extra MCs constraints coming from recent p-Pb @ 5 TeV (2013).
- No significant change of multiparticle production at the LHC ($\sim 10^{16}$ eV): "CR knee" at $\sim 10^{15.5}$ eV not due to new (unobserved) particles.

Impact of LHC data on UHECR MCs

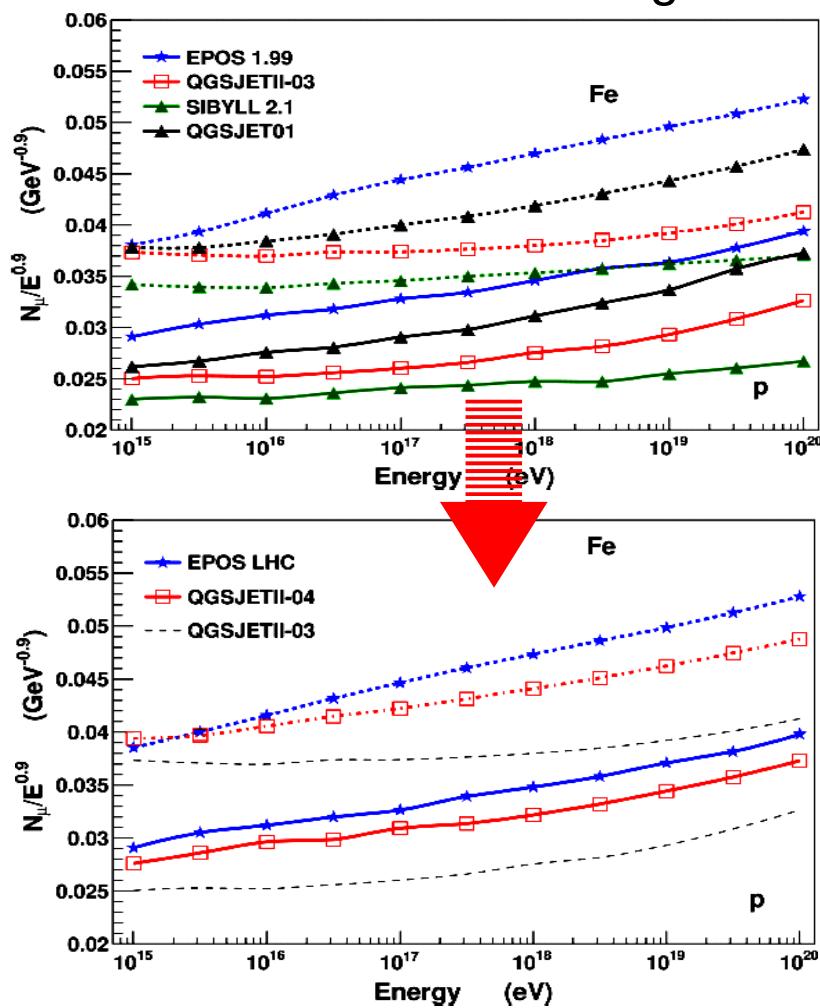
(T. Pierog, 2014)

Mean depth of shower maximum:



- X_{\max} predictions increase
(converge with Sybill 2.1)

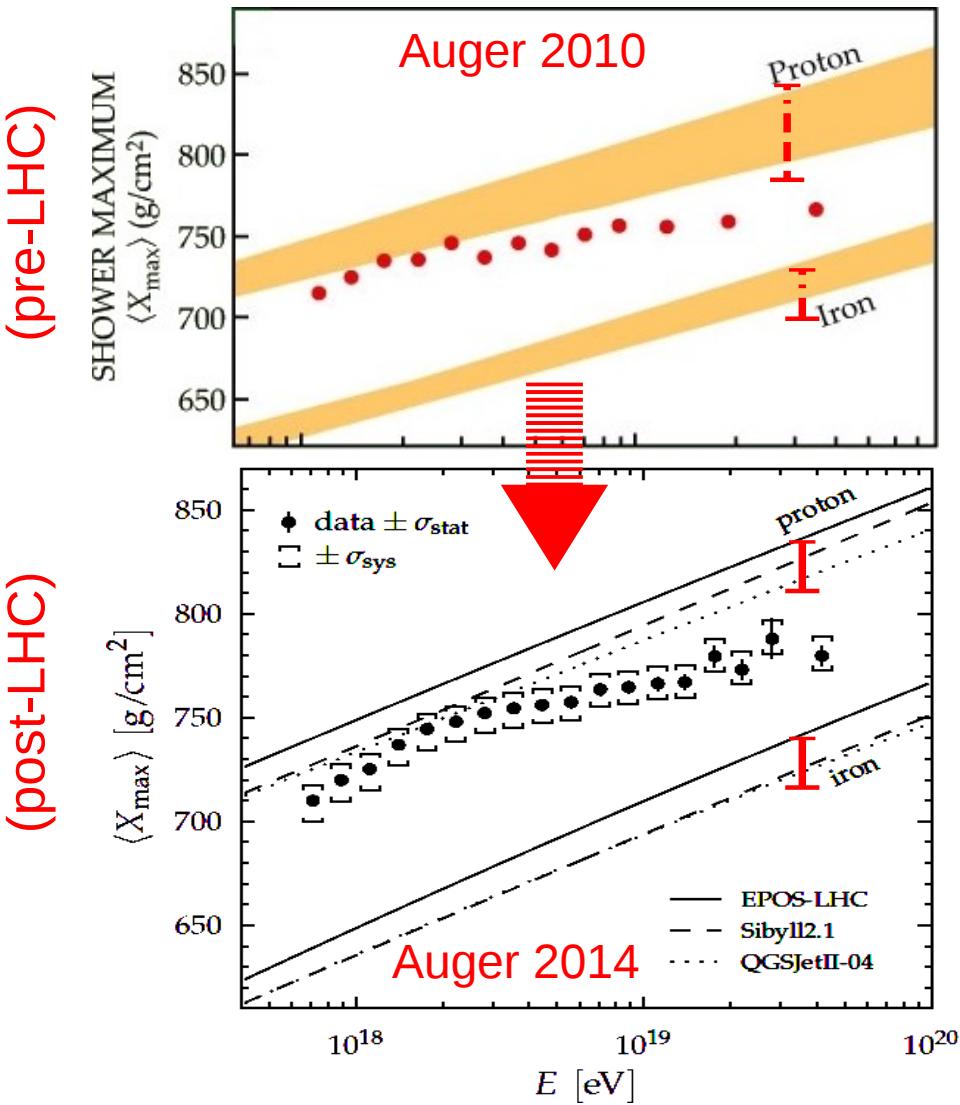
Number of muons on ground:



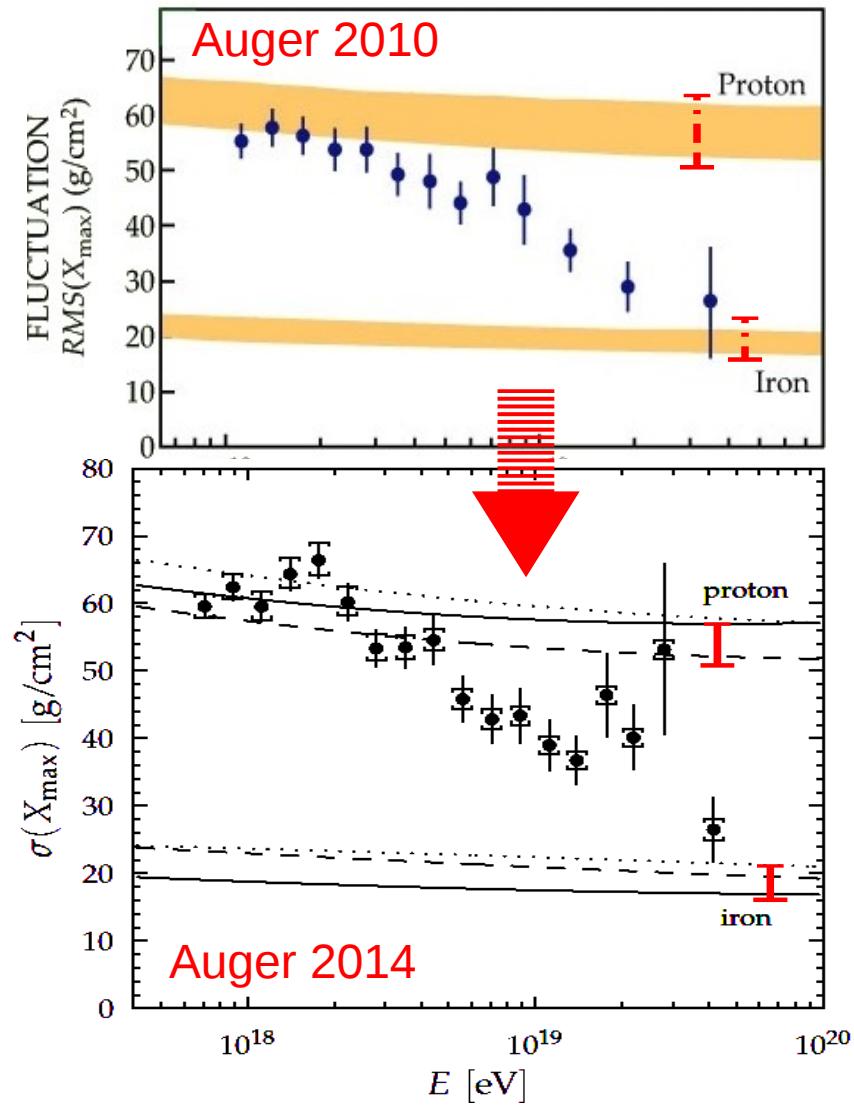
- N_{μ} increase but still ~30% deficit compared to data (heavy-quarks?)

Impact of LHC data on UHE CRs (Auger)

Mean depth of shower maximum:



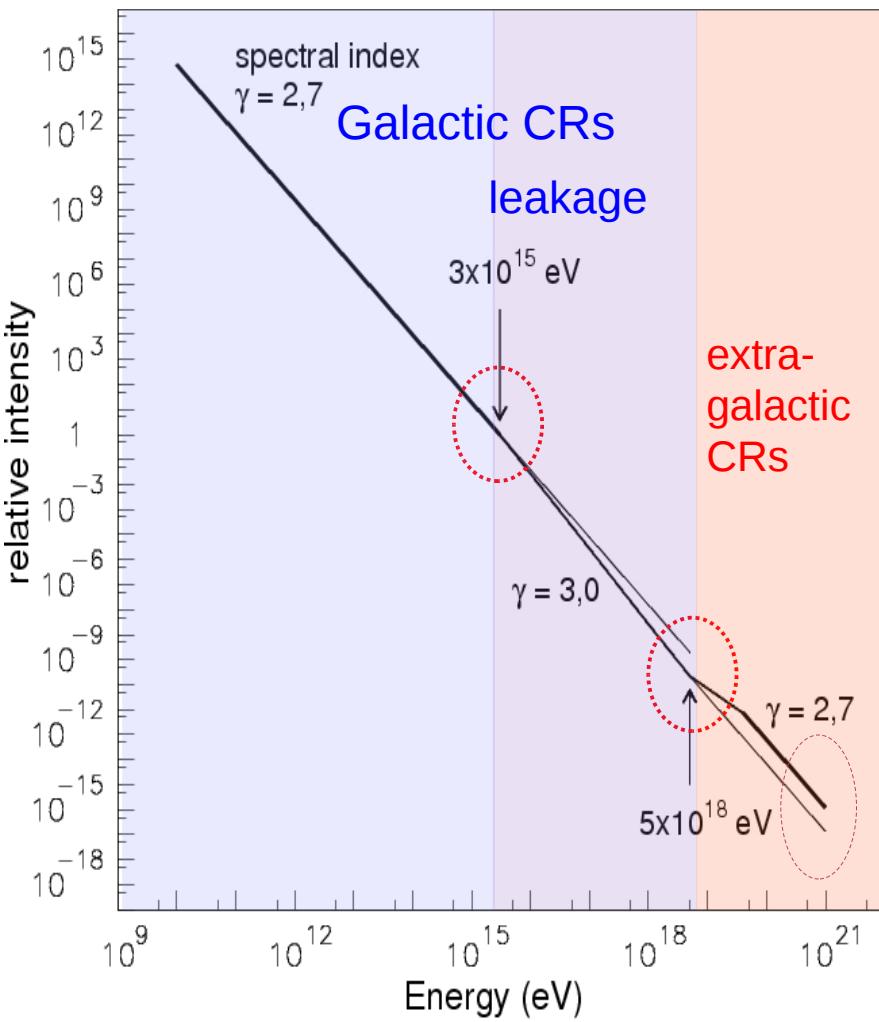
Fluctuations of shower max:



■ Data prefer average p-Fe composition, w/ reduced model uncertainties.

Summary: UHE cosmic-rays

- What are the origin of the 3 structures in the spectral flux slope ?



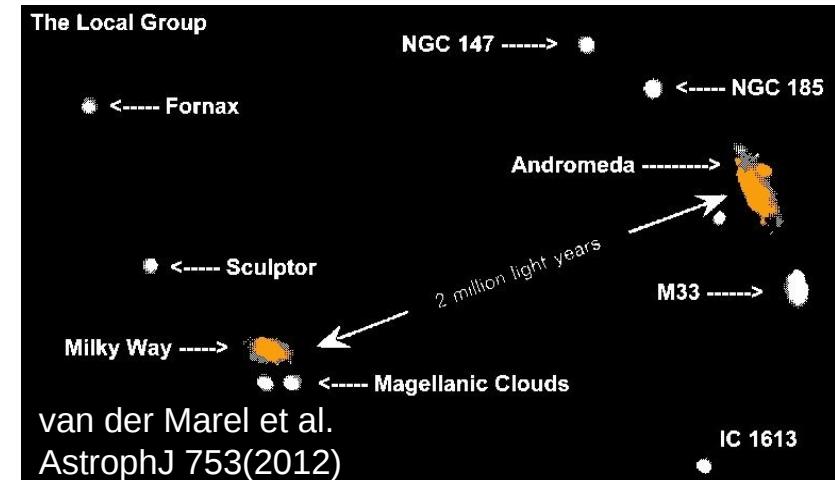
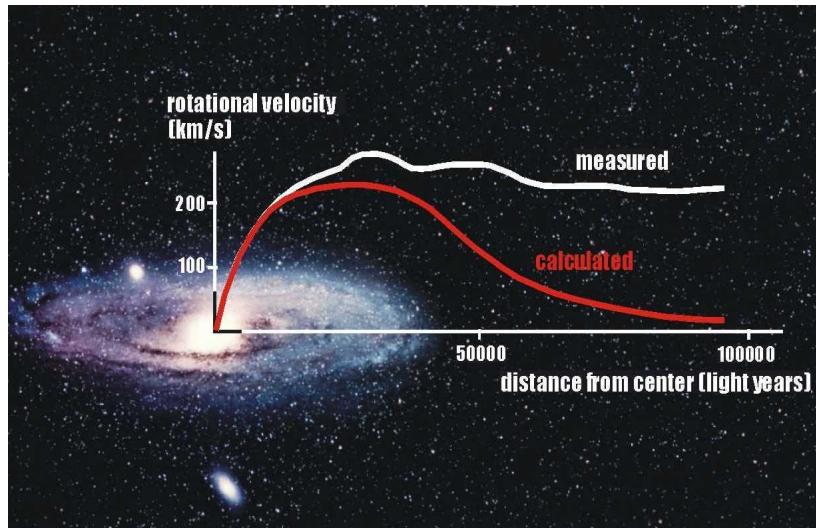
- "Knee" at $E_{\text{lab}} \sim 10^{15}$ eV:
 - ✓ LHC: Changes in **EAS** due to production of **new (unobserved) particles** excluded
 - Consistent with **increasing leakage** outside galaxy of CRs with **smaller Z** (r_{Larmor}).
 - $E_{\text{max}} \sim 10^{15}$ eV in Galactic SNRs
- "Ankle" at $E_{\text{lab}} \sim 10^{18}$ eV:
 - p-dominated? Dip due to e+e- pair prod.
 - Fe-dominated? Extragalactic CRs kick-in
- Cut-off at $E_{\text{lab}} \sim 10^{19-20}$ eV:
 - GZK dissociation or limit of acceleration?
 - ✓ LHC: **Reduced composition uncertainties**. Data seem to point to **p-Fe mixture**. Improvements still needed (e.g. N_{μ})



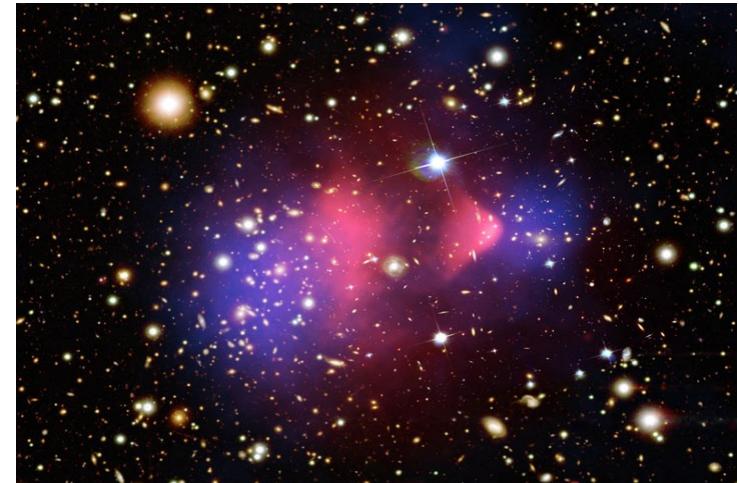
Dark matter: Where do we stand today? What have we learned from the LHC?

Dark matter: Galactic evidences

- Non-Kleperian rotation curves in spiral galaxies (1980):
- Relative motion MilkyWay-Andromeda: $M_{\text{virial}} \sim 3.2 \cdot 10^{12} \times M_{\text{sun}}$ (stars&gas~10%)

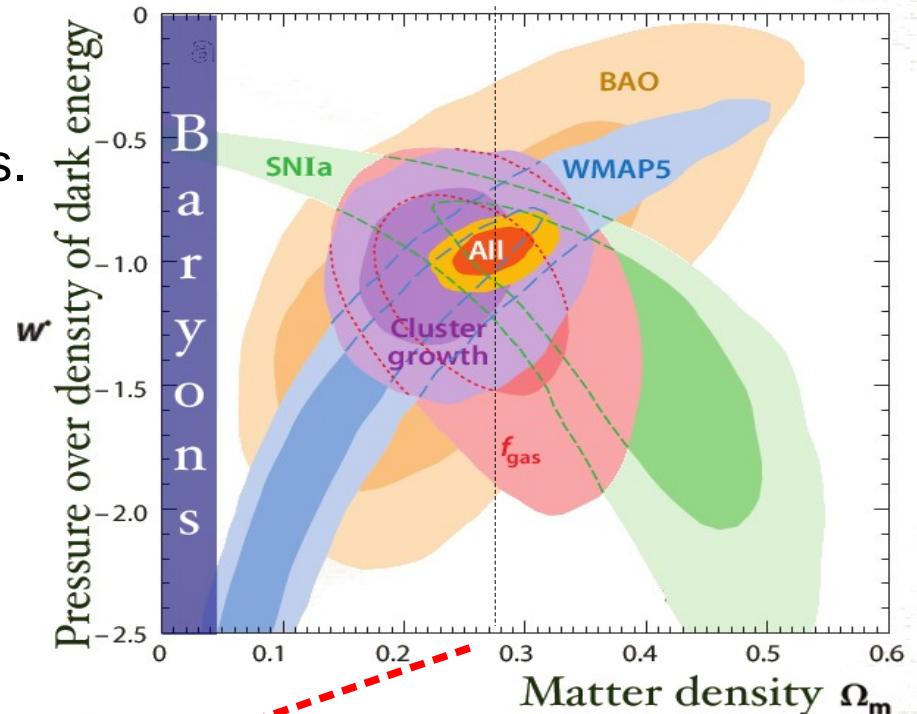
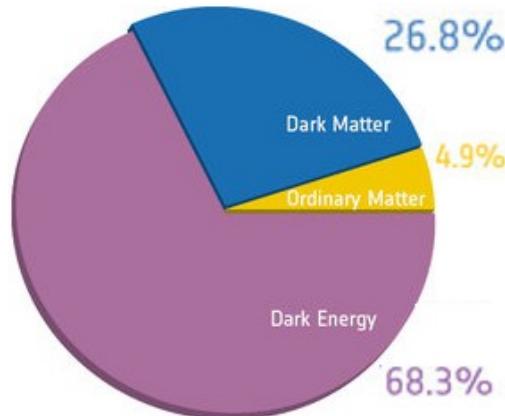


- Collision of Bullet Cluster (2004):
Gravitational-lensing reveals DM,
coincident with collision-less galaxies,
lying ahead of visible collisional gas.
- Others: hot-gas in clusters, growth
of clusters, ...



Dark matter: Cosmological evidences

- Large-scale structure universe:
SDSS/2dfGRS vs. Millenium
stat. galaxy distribution simulations.
- Cosmic microwave background:
Peak heights (WMAP, Planck)
lower than in absence of DM.
- Other measures of matter density:
BAO, BBN, supernova distances,
...
- Global post-Planck fit (2013)
DM~27% of energy budget
in universe:



DM density: $\rho_{\text{halo}} \sim 0.3 \text{ GeV/cm}^3$
DM average speed: $\langle v \rangle \sim 220 \text{ km/s}$
100-GeV WIMP flux on Earth: $10^5 \text{ cm}^{-2}\text{s}^{-1}$

Dark matter: Properties, candidates, searches

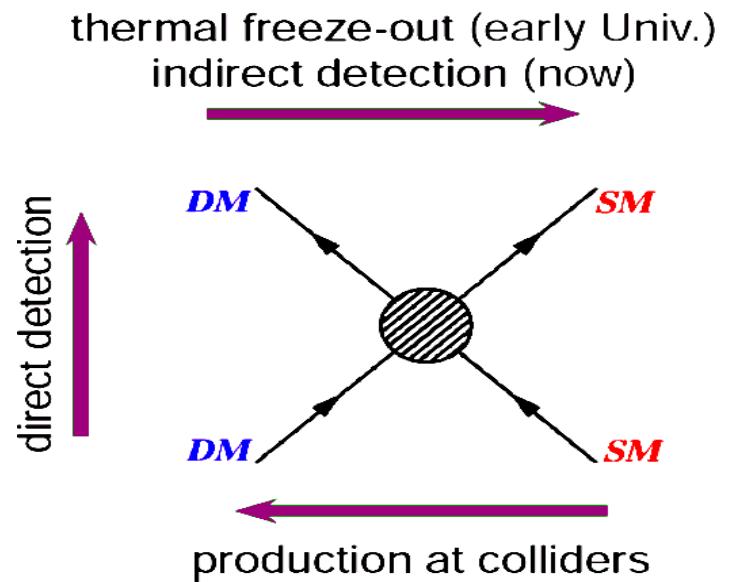
■ Properties favour Weakly Interacting Massive Particle (WIMP)

- Sensitive to gravitation, stable, massive, early Universe relic
- “WIMP paradigm”: $m_{\text{DM}} \sim 10 \text{ GeV} - 1 \text{ TeV}$, $\sigma_{\text{DM-SM}} \sim \sigma_{\text{weak}}$, $\Omega_{\text{DM}} \sim O(10\%)$
(alternative models exist that yield lower or higher m_{DM} , $\sigma_{\text{DM-SM}}$...)

■ Possible beyond-SM candidate particles:

- Lightest SUSY Particle (LSP): neutralino, ...
- Extra-Dims: lightest Kaluza-Klein tower, ...
- Heavy R-handed or sterile neutrinos. Axions.
- Unknown hidden sector.

■ 3 complementary search methods:



Dark matter: Direct searches (underground)

■ Direct detection via WIMP-nucleus scattering:

Look for anomalous **recoils** in ultralow-background

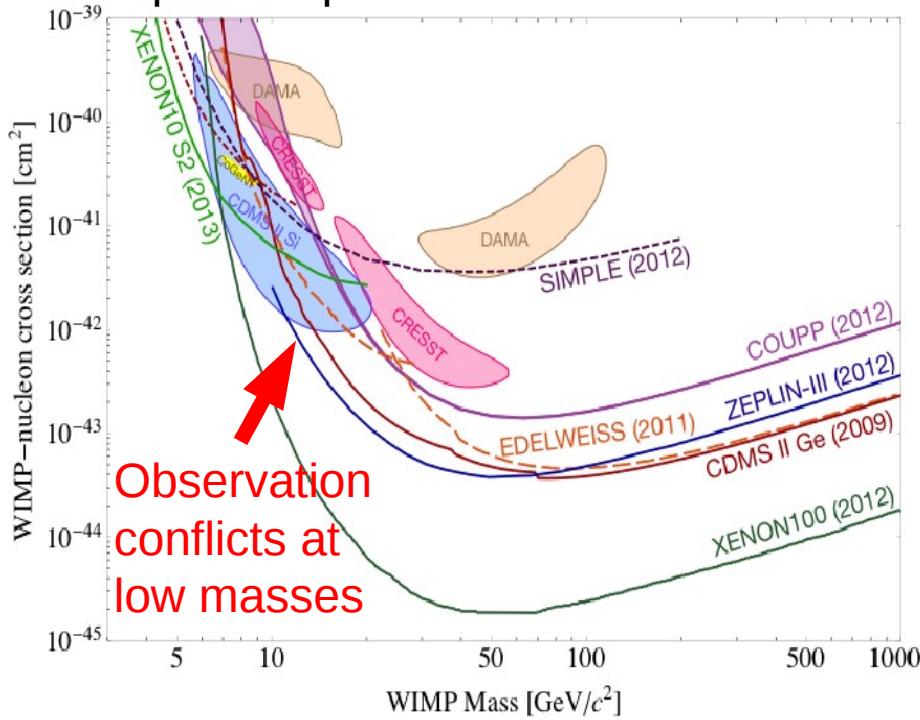
detector: $R = N \cdot \rho \cdot \sigma \cdot \langle v \rangle \sim 10 \text{ keV}$

Scintillation/ionization/phonon sensitivity $> 1 \text{ evt}/100\text{kg}/\text{year}$

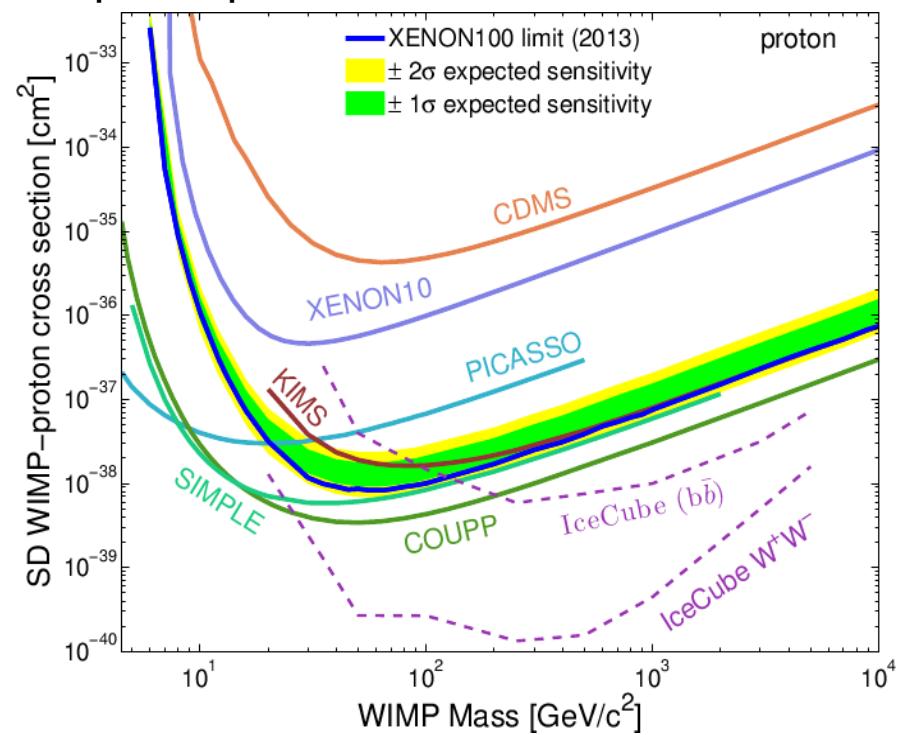


■ Current limits:

Spin-independent interactions:



Spin-dependent interactions:



Dark matter: Direct searches (underground)

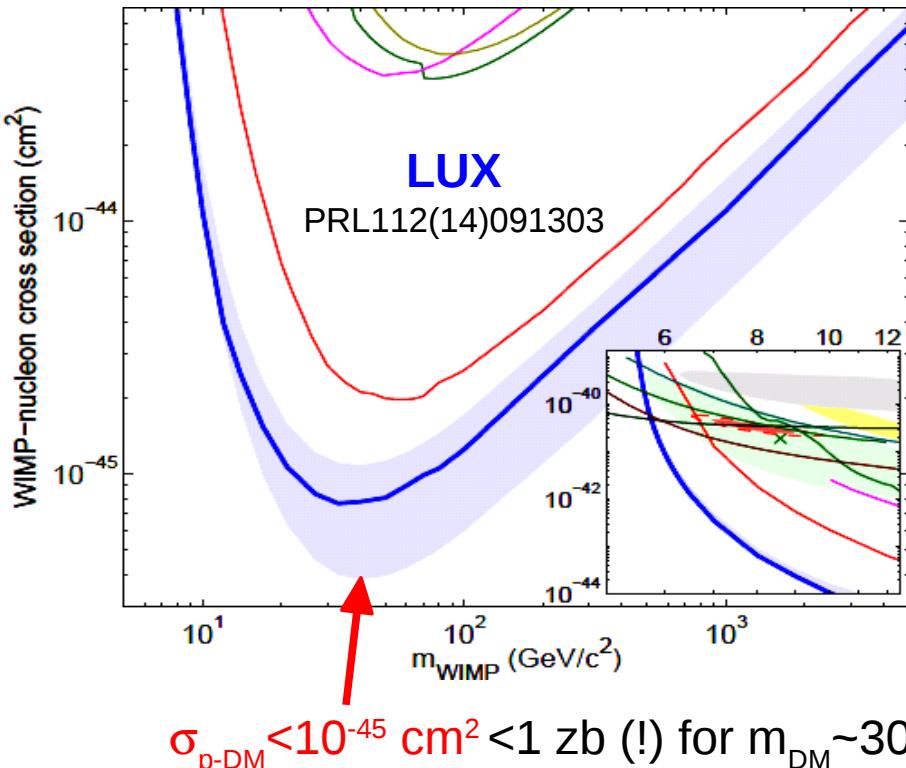
■ Direct detection via WIMP-nucleus scattering:

Look for anomalous **recoils** in ultralow-background detector: $R = N \cdot \rho \cdot \sigma \cdot \langle v \rangle \sim 10 \text{ keV}$

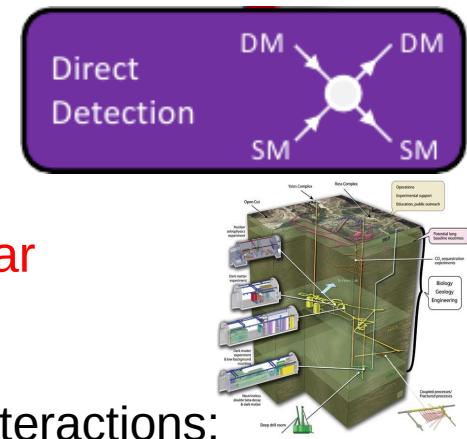
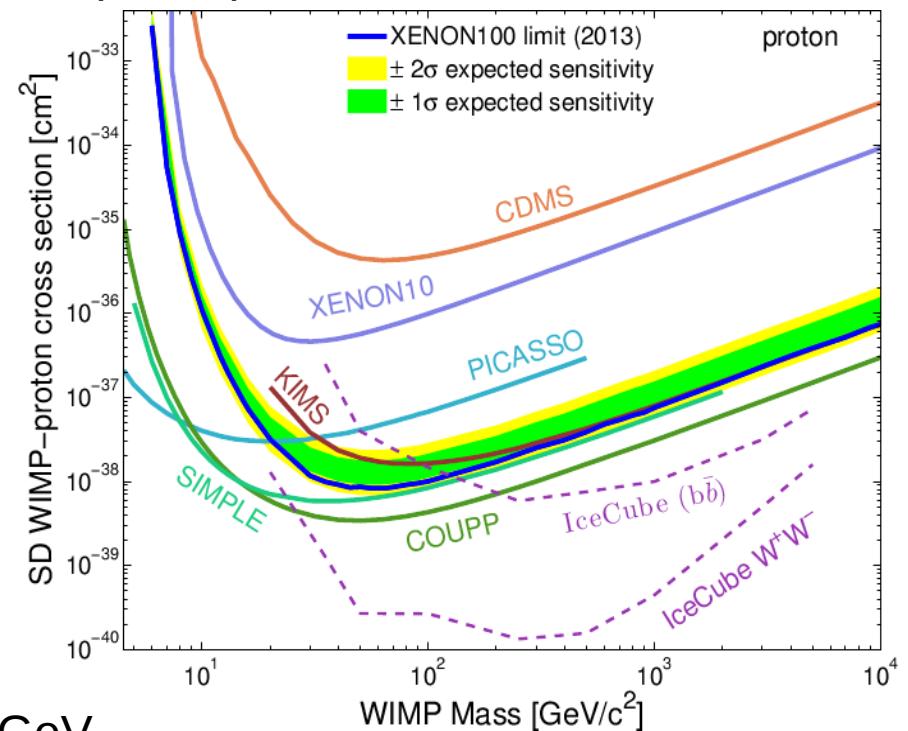
Scintillation/ionization/phonon sensitivity $> 1 \text{ evt}/100\text{kg}/\text{year}$

■ Current limits:

Spin-independent interactions:



Spin-dependent interactions:



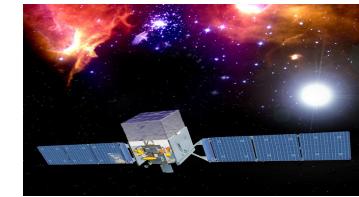
Dark matter: Indirect searches (space)

■ Indirect detection via DM-DM annihilation, DM decay:

Look for SM-pairs from DM annihilation/decays:

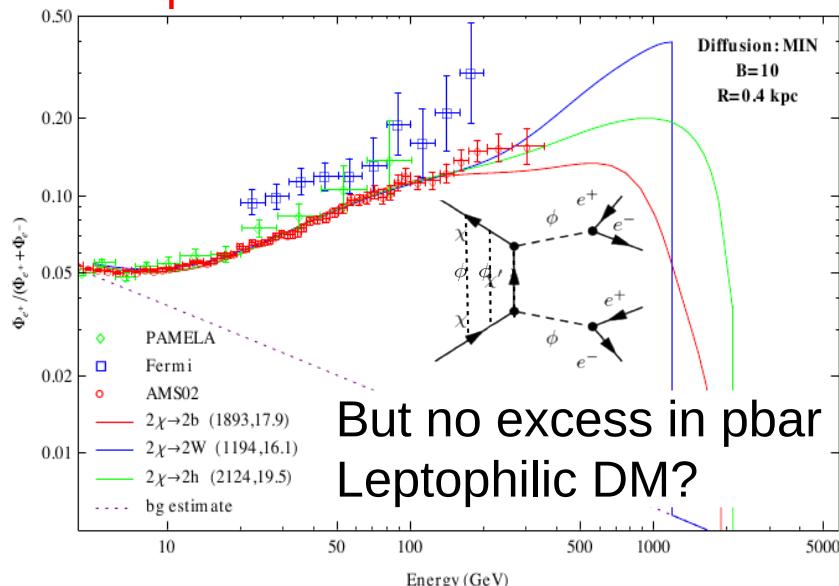
γ (FERMI,Veritas), ν (IceCube), cosmic-rays (Pamela,AMS)

Annihilation x-sections: $\langle\sigma \cdot v\rangle \sim 3 \cdot 10^{-26} \text{ cm}^3/\text{s}$ (thermal relic)

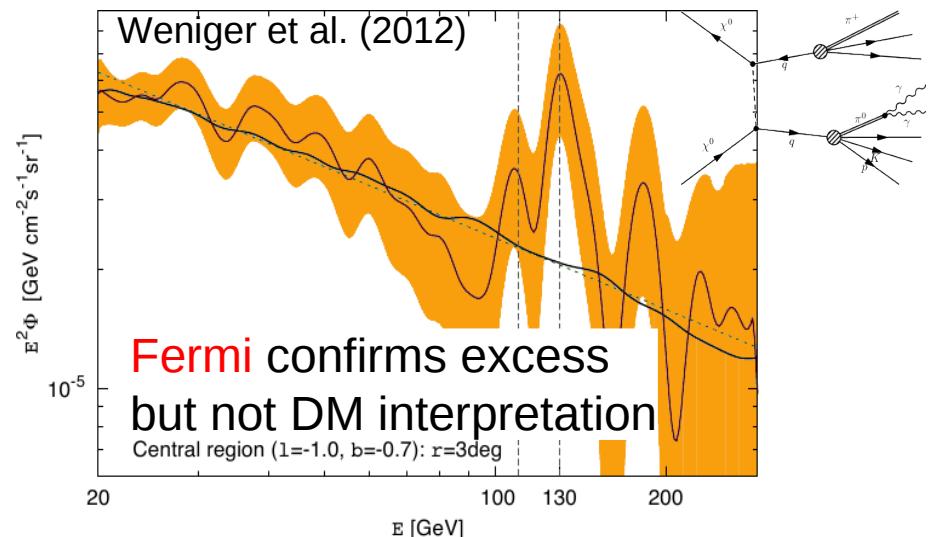


■ Excesses seen...

CR positron fluxes above ~ 30 GeV



Galaxy center γ -ray line at 130 GeV:



■ Uncertainties: CR propagation, extra sources (pulsars? SM contributions?):

$$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \underbrace{\left(E_{\gamma, \text{TeV}} \frac{dN}{dE_{\gamma, \text{TeV}}} \right)}_{\text{Particle Physics Input}} \left(\frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^{-3} \text{s}^{-1}} \right) \left(\frac{100 \text{GeV}}{M_\chi} \right)^2 \underbrace{\frac{1}{8.5 \text{kpc}} \left(\frac{1}{0.3 \text{GeV/cm}^3} \right)^2}_{\text{Astrophysics/Cosmology Input}} \int_{\text{line of sight}} \rho^2(l) dl(\theta)$$

Dark matter: Collider searches

■ Collider detection – DM produced in p-p final-state:

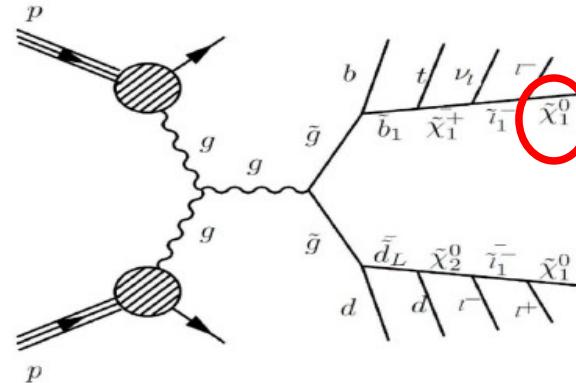
Signature: large missing transverse energy (MET)
in SUSY-type, generic WIMPs, and invisible Higgs decay



(1) Lightest Particle (χ^0) in RP-conserving SUSY:

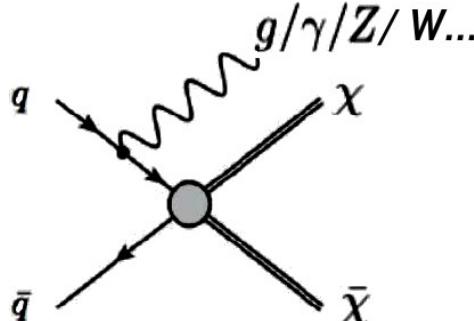
Prominent WIMP candidate.

Decay cascade with
large MET, many jets & leptons

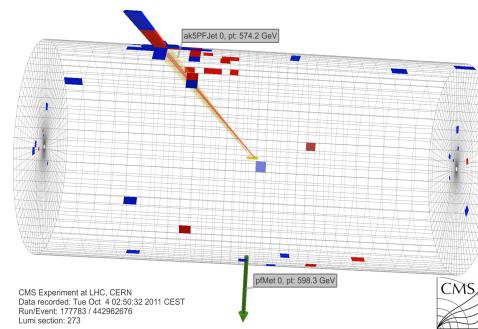


(2) Generic DM-pair:

Large MET plus initial-state
QCD/EWK radiation:

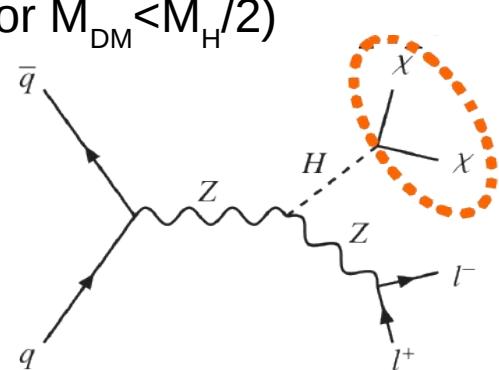


Mono-jet, γ , W or $t\bar{t}$...



(3) Higgs decay to DM-pair:

(for $M_{DM} < M_H/2$)

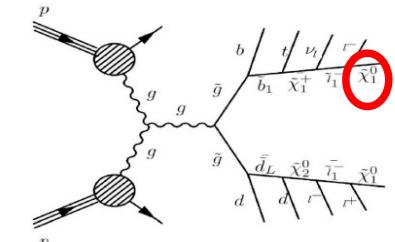


Dark matter: LHC searches (SUSY)

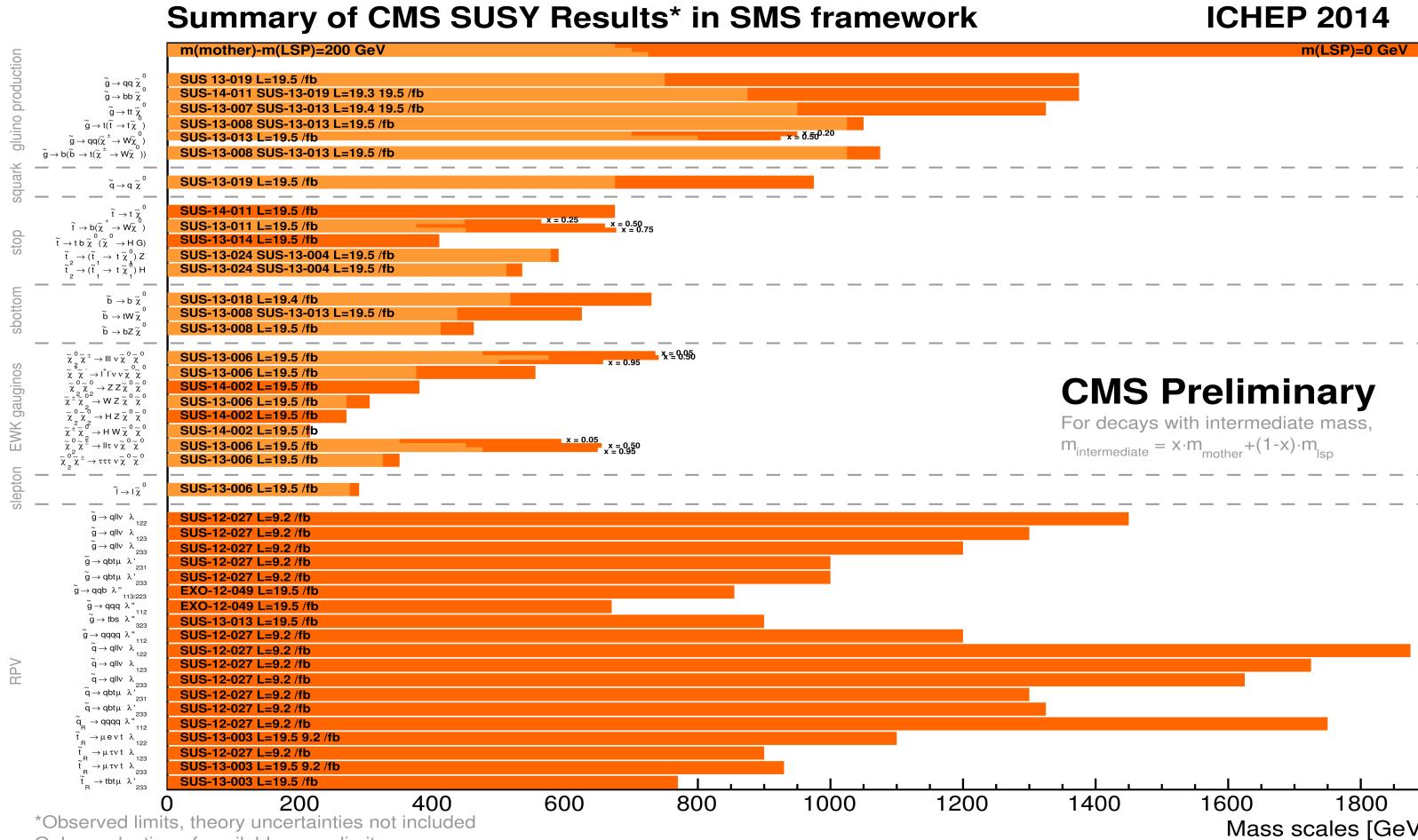
■ Collider detection – DM produced in p-p final-state:

Look for missing transverse energy (MET) from WIMPs.

No indirect χ^0 signal in simplified SUSY models so far...

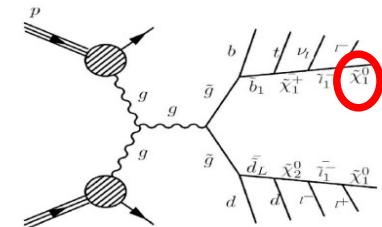


ICHEP 2014



Dark matter: LHC searches (SUSY)

- Collider detection – DM produced in p-p final-state:
- Look for missing transverse energy (MET) from WIMPs.
- No indirect χ^0 signal in simplified SUSY models so far...



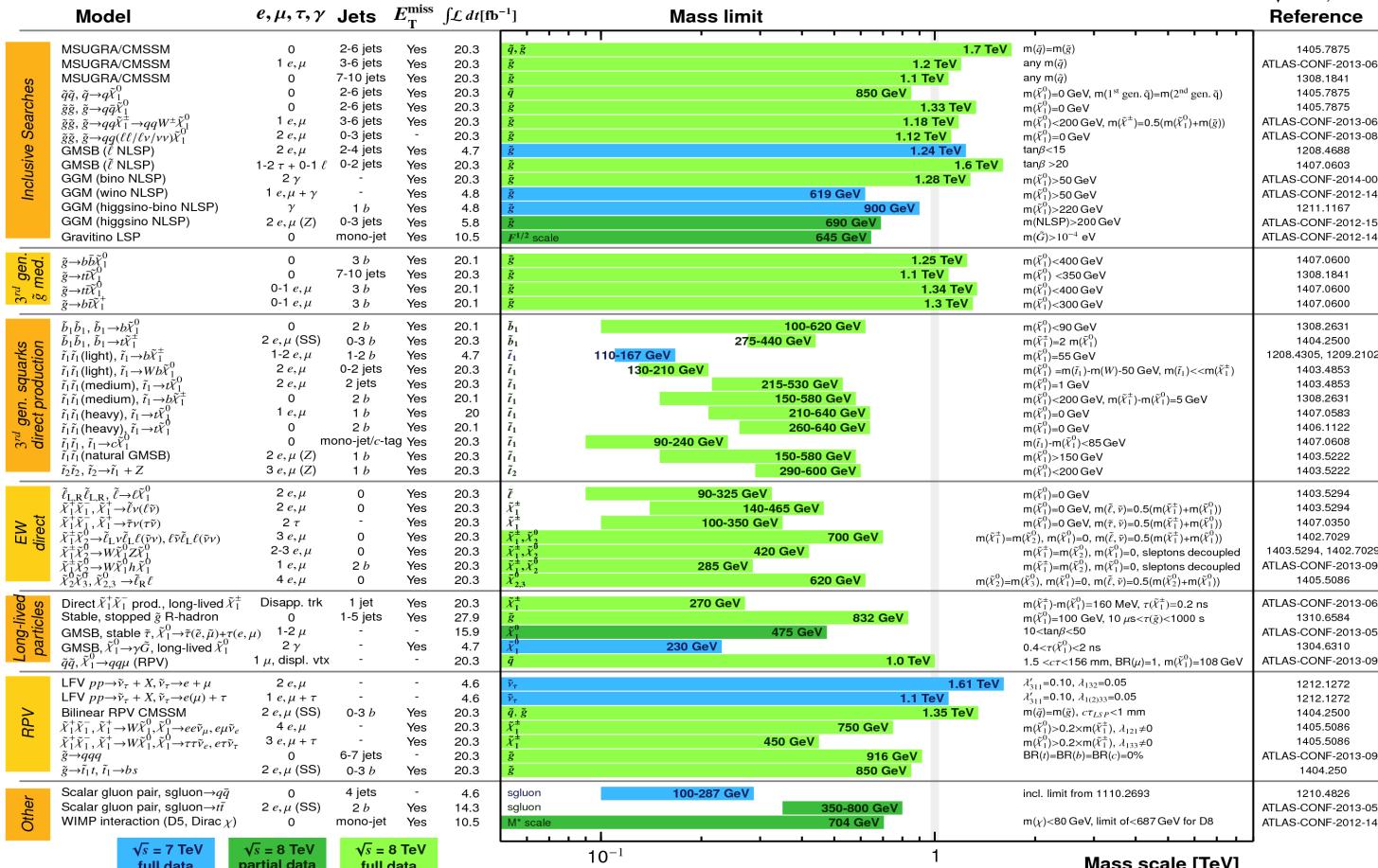
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

Reference



$\sqrt{s} = 7 \text{ TeV}$
full data

$\sqrt{s} = 8 \text{ TeV}$
partial data

$\sqrt{s} = 8 \text{ TeV}$
full data

Mass scale [TeV]

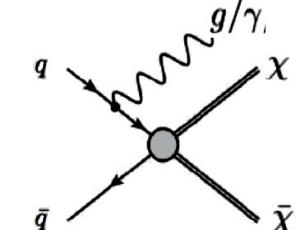
David d'Enterria (CERN)

LHC Days

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

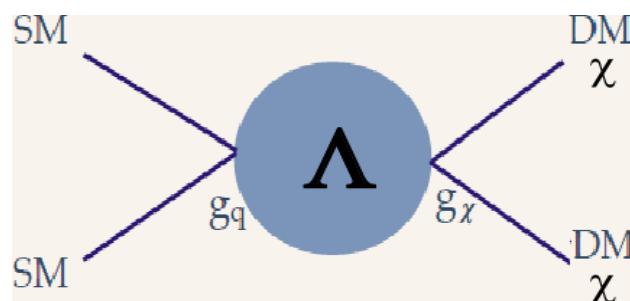
Dark matter: Collider searches (generic DM)

- (1) Search mono-jet,mono-photon excess above SM background: $Z(vv)+j,\gamma$ (~70%), $W(vl_{\text{escape}})+j,\gamma$ (~30%).



Remove other EWK&QCD backgds: veto iso-leptons & $\Delta\phi$ cut

- (2) Interpret (no) excess within generic **effective field theory (EFT)** for **contact SM-DM interaction**, characterized by **2 parameters**:



(less-simplified models proposed more recently)

$\Lambda = M_*/\sqrt{g_\chi g_q}$: **Scale** of effective interaction

M_χ : **mass of DM particle** (Dirac Fermion)

for various **types of DM-SM couplings**, e.g.:

Name	Initial state	Type	Operator
D5	qq	vector	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$ (spin-independent: SI)
D8	qq	axial-vector	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$ (spin-dependent: SD)

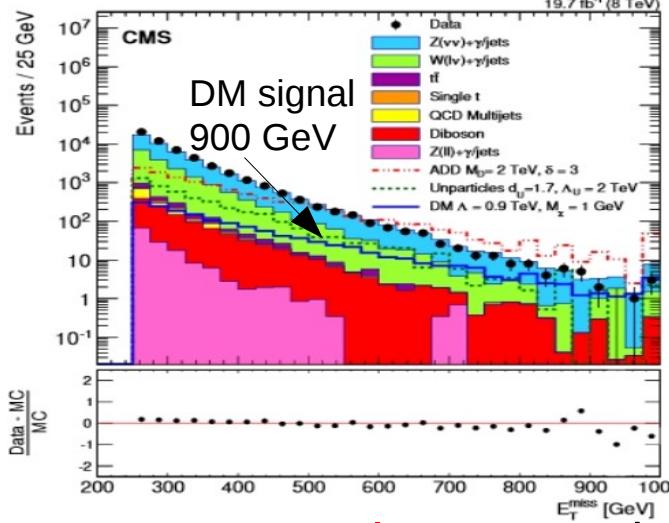
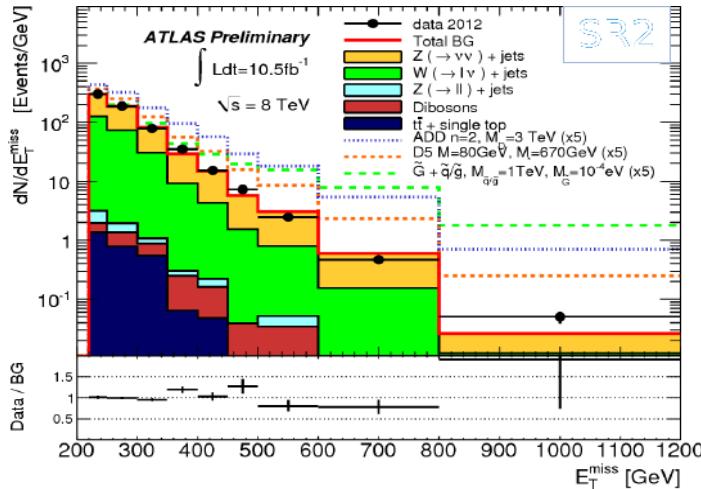
- (3) Set limits in **DM mass vs. interaction-strength** for SI & SD couplings:

$$\sigma(\chi N \rightarrow \chi N) \sim \frac{g_q^2 g_\chi^2}{M_*^4} \mu_{\chi N}^2$$

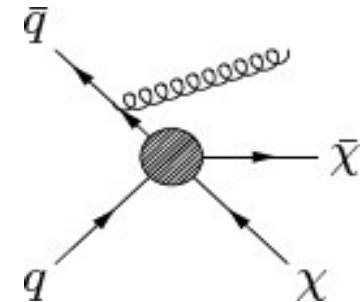
$M_{\chi N}$ = reduced mass of DM-nucleon system

Dark matter: LHC searches (monojets)

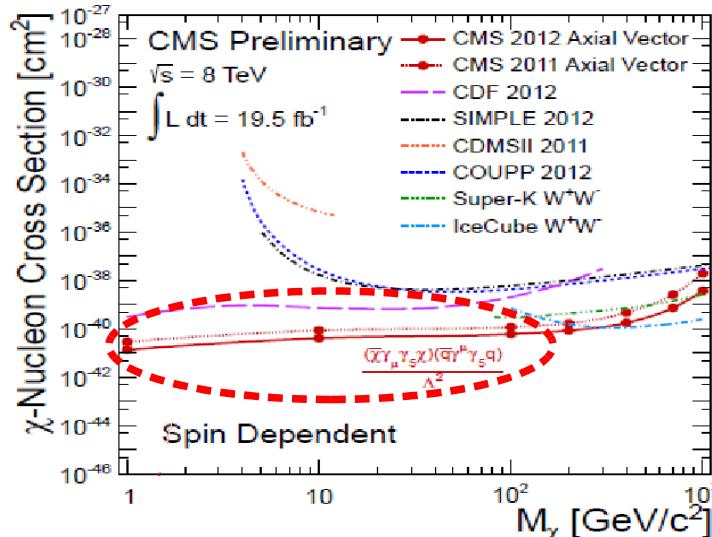
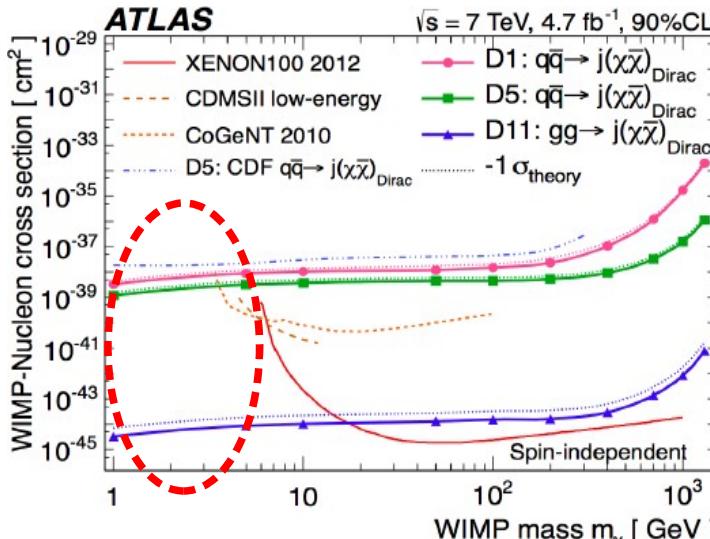
MET distribution after cuts for SM backgds & DM signal:



ATLAS-CONF-2013-073
 CMS-PAS-EXO-12-048



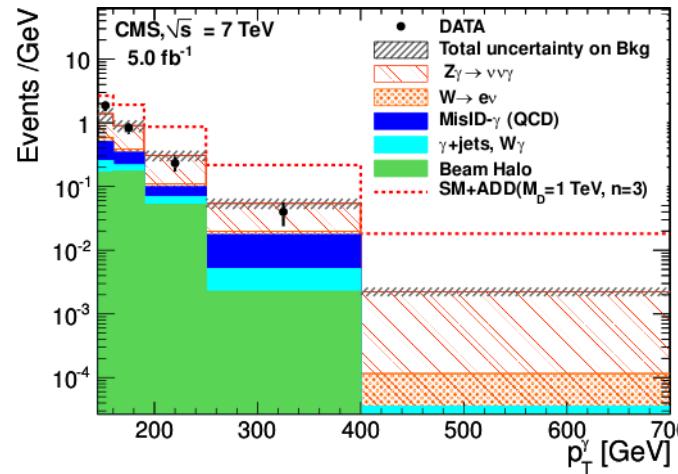
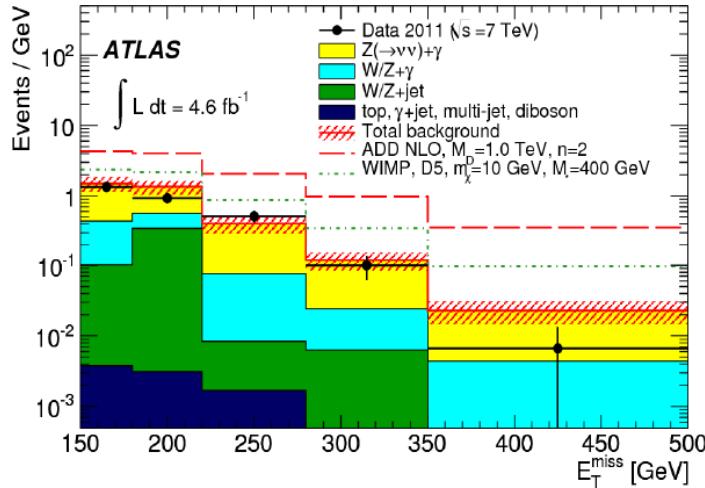
No excess: Limits on DM mass & WIMP-nucleon x-sections:



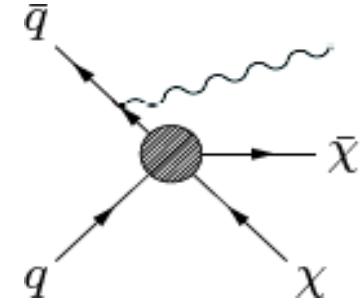
Best limits for light DM:
 $M_\chi \sim 1 - 10 \text{ GeV}$
 $\sigma_{\chi N} \sim 10^{-39} \text{ (SI)}$
 $\sigma_{\chi N} \sim 10^{-41} \text{ (SD)}$

Dark matter: LHC searches (monophotons)

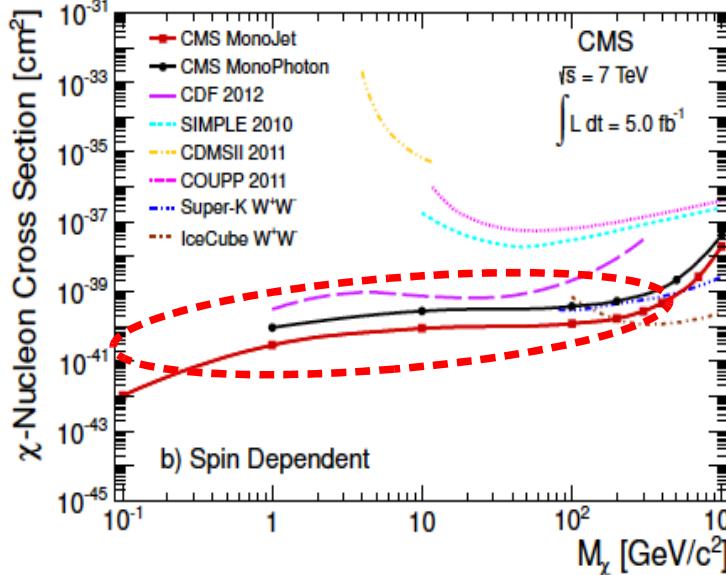
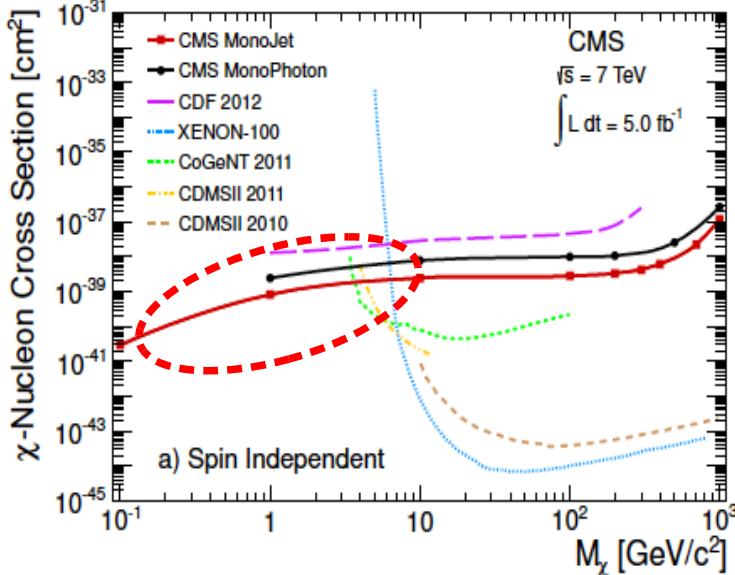
■ MET distribution after cuts for SM backgds & DM signal:



ATLAS:
PRL 110 (2013) 011802
CMS:
JHEP09(2012)094
PRL 108 (2012)261803



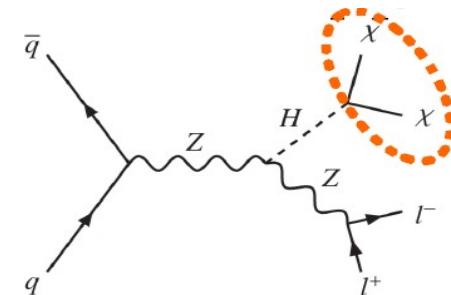
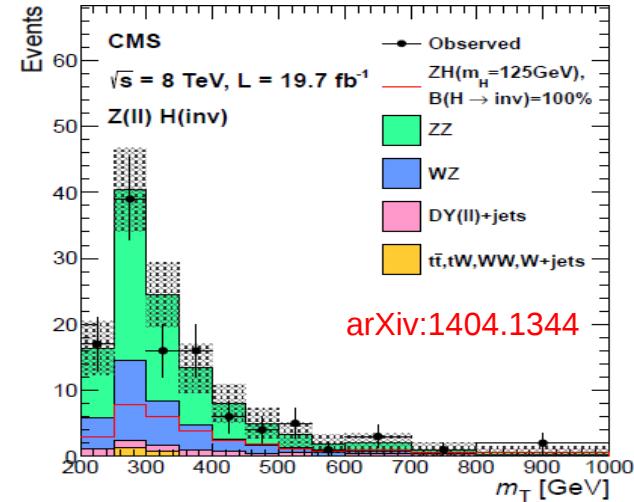
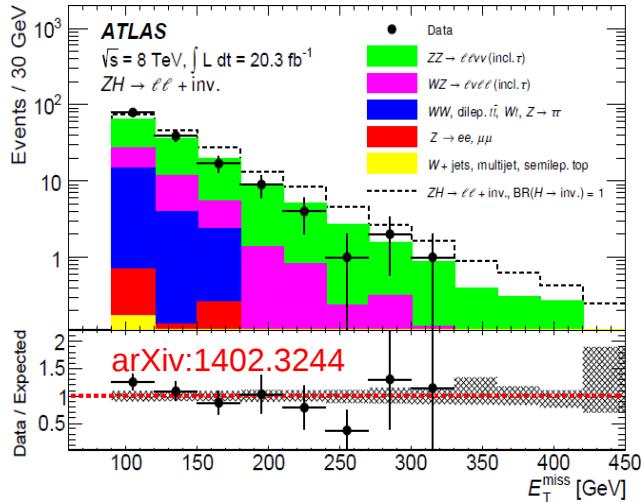
■ No excess: Limits on DM mass & WIMP-nucleon x-sections:



Best limits for light DM:
 $M_\chi \sim 1 - 10$ GeV
 $\sigma_{\chi N} \sim 10^{-39}$ (SI)
 $\sigma_{\chi N} \sim 10^{-40}$ (SD)

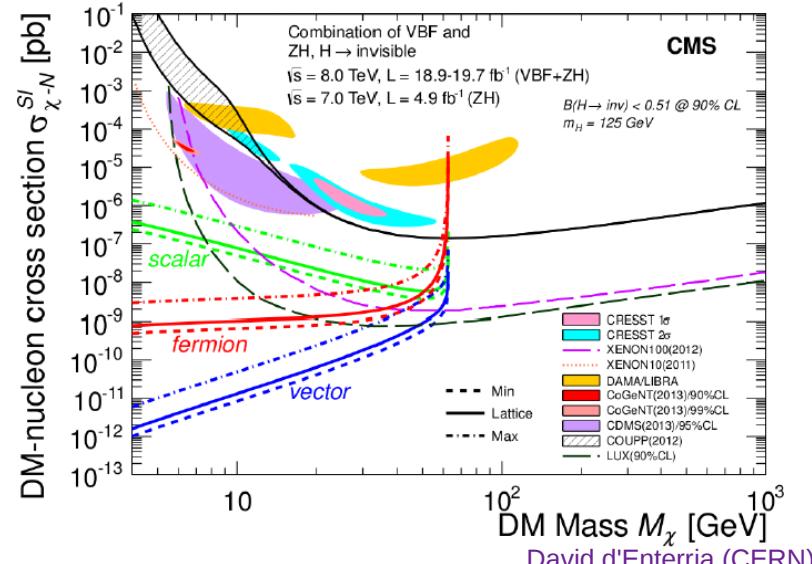
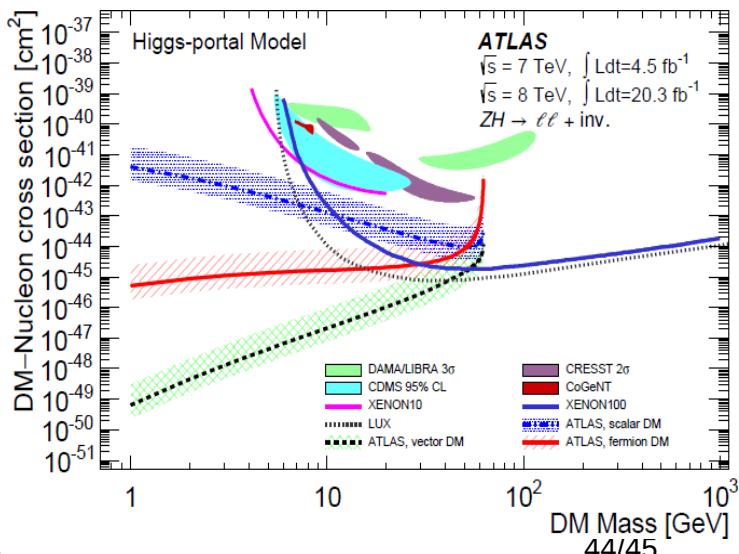
Dark matter: LHC searches (invisible H decay)

MET distributions after cuts (2 leptons with $m_{\ell\ell} \sim m_H$):



No excess wrt. SM interpreted as: $\text{BR}(H \rightarrow \chi\chi) < 75\% (\text{Atlas}), 58\% (\text{CMS})$

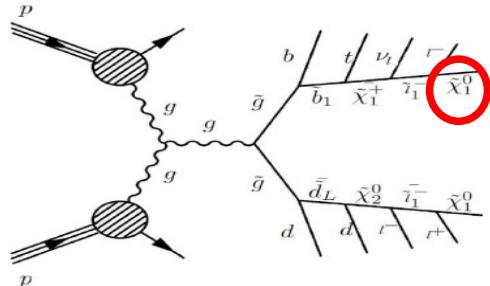
+ also
limits for
light DM:



Summary: Dark matter searches at the LHC

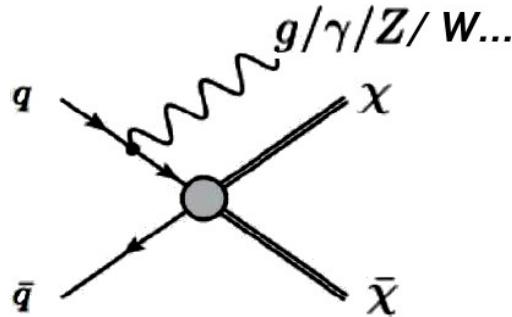
■ p-p collisions at 7,8 TeV with large missing transverse energy (MET):

(1) SUSY-type final-states (hard multi-lepton,jet, ... activity):



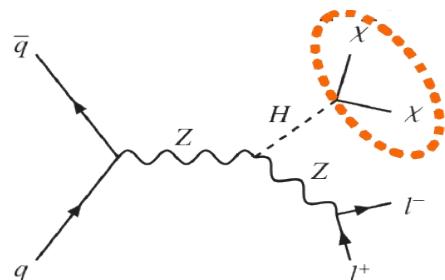
No signal of LSP (nor any other spartner) in simplified SUSY searches.

(2) Generic DM-pair in mono-jet,photon,W,ttbar,... events:



Best limits for low-mass DM :
 $M_\chi \sim 1 - 10$ GeV, in particular for
spin-dependent DM-SM couplings

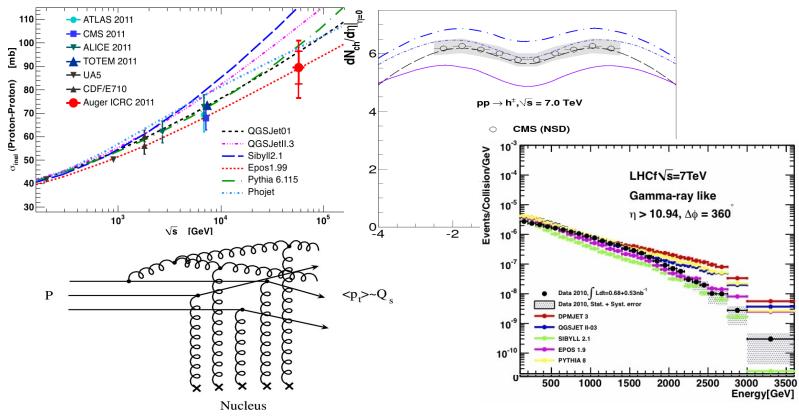
(3) Higgs invisible decay to DM-pair in VBF & HZ production:



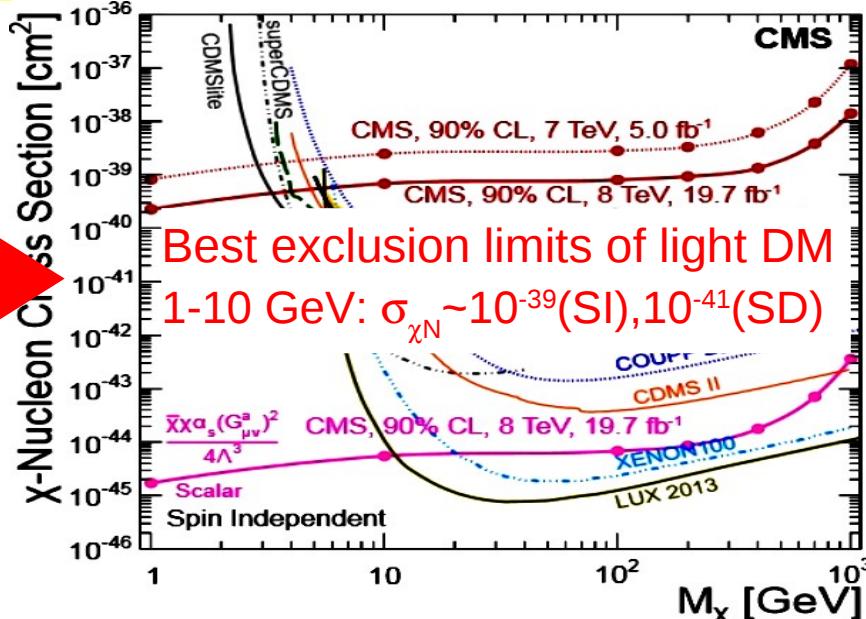
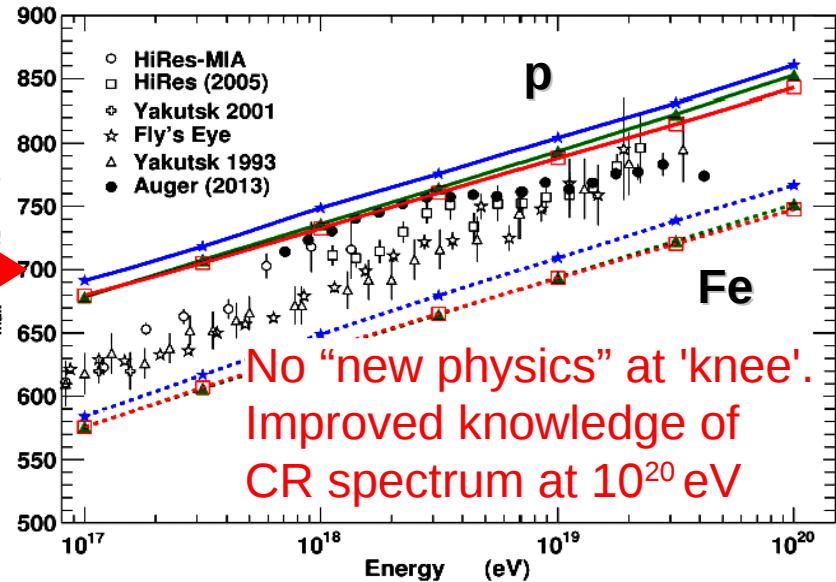
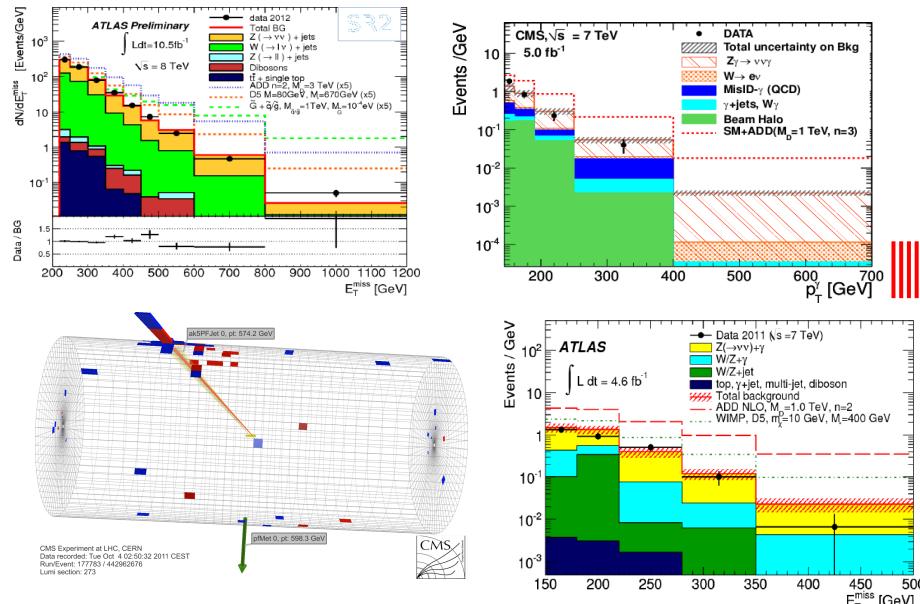
No excess wrt SM sets decay limits:
 $BR(H \rightarrow \chi\bar{\chi}) < 75\%$ (Atlas), 58% (CMS)
for $M_{DM} < M_H/2$

Summary: Impact of LHC to CR & DM physics

Soft & semihard QCD in p-p collisions:



p-p events with unbalanced jet, gamma, W, ttbar:



Backup slides

Limits of cosmic accelerators ?

- Astrophysical objects with large B-field or large acceleration length:

$$E_{\max} \sim Z_{\text{CR}} \cdot (\beta_{\text{shock}} \cdot B \cdot L)$$

Difficult to reach 10^{20} eV !

(required shock-front speeds $\beta \sim 1$)

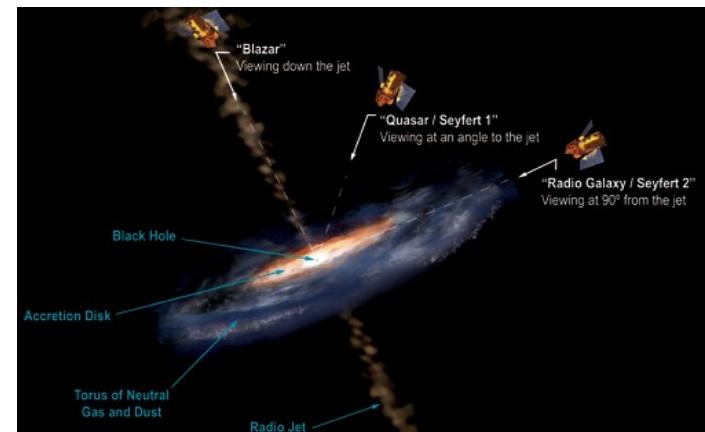
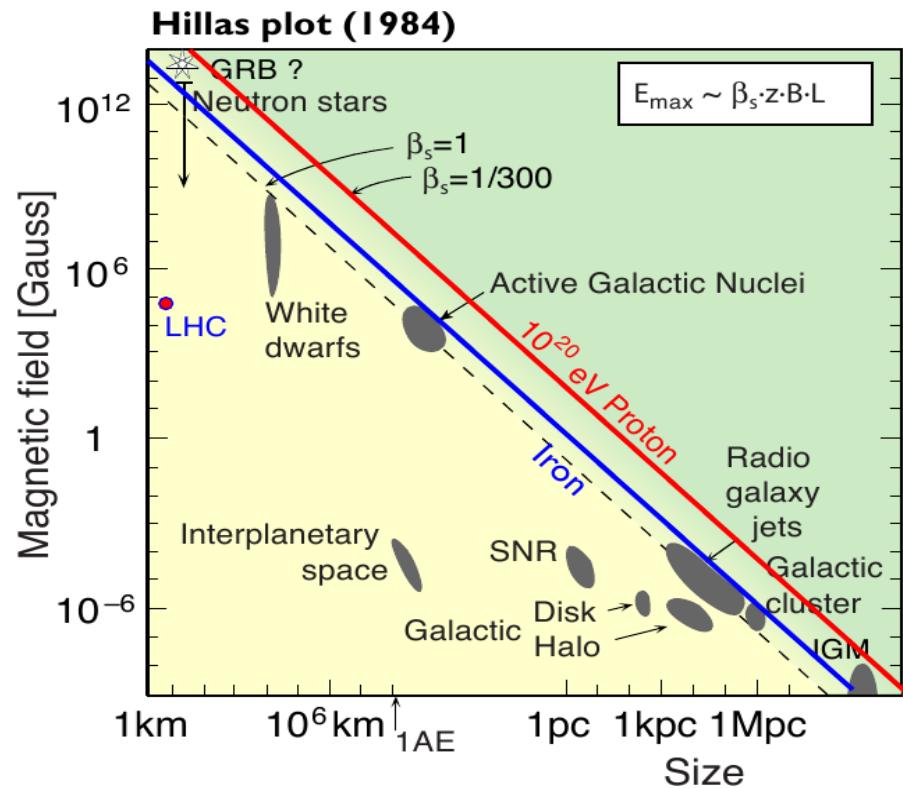
easier for ions, $Z(\text{Fe})=26$.

(Extra constraints: acceleration efficiency, synchrotron losses, interactions in source)

- Best candidates:

- Neutron-star: Highly magnetized & spinning
- AGN/GRB: Rapidly spinning giant black-holes

Supernova: Shockfronts “only” $E_{\max} = Z \cdot 10^{14-17}$ eV
(range: single explosion – multiple remnants)



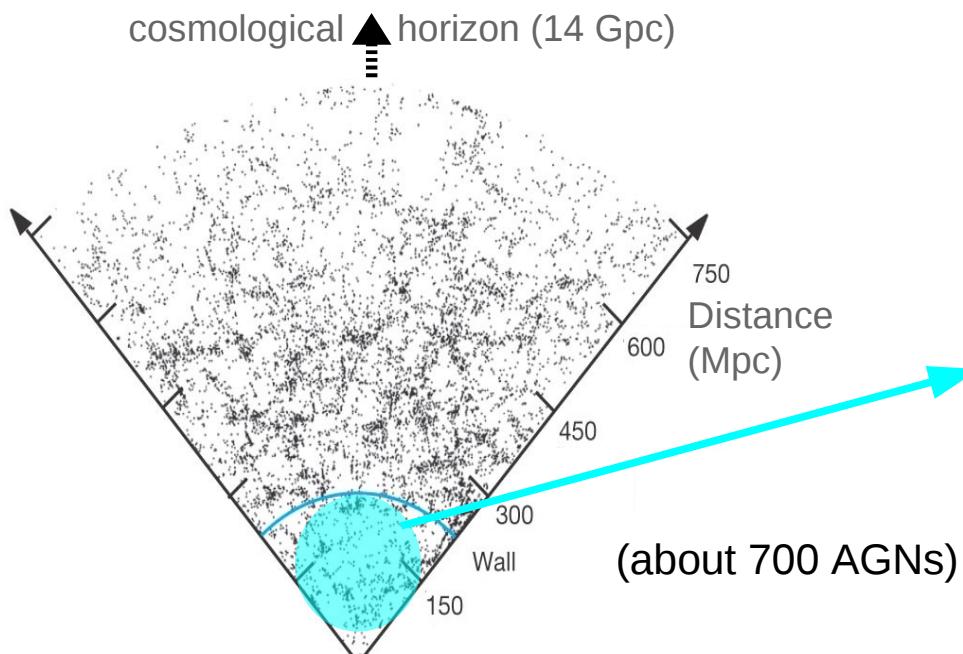
GZK γ -induced dissociation cut-off ?

- Proton with $E_{\text{GZK}} > 6 \cdot 10^{19} \text{ eV}$ breakup in collisions with CMB ($E_\gamma \sim 0.35 \text{ meV}$):



- GZK horizon $\sim 100\text{-}200 \text{ Mpc}$:

UHECR come within our Local-Supercluster:



Greisen-Zatsepin-Kuzmin (1966)

Photo-pion production

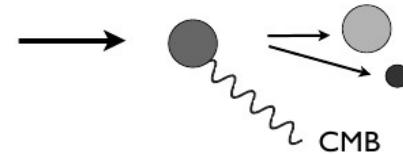
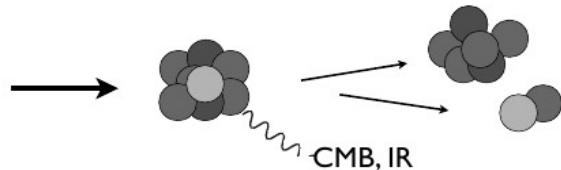
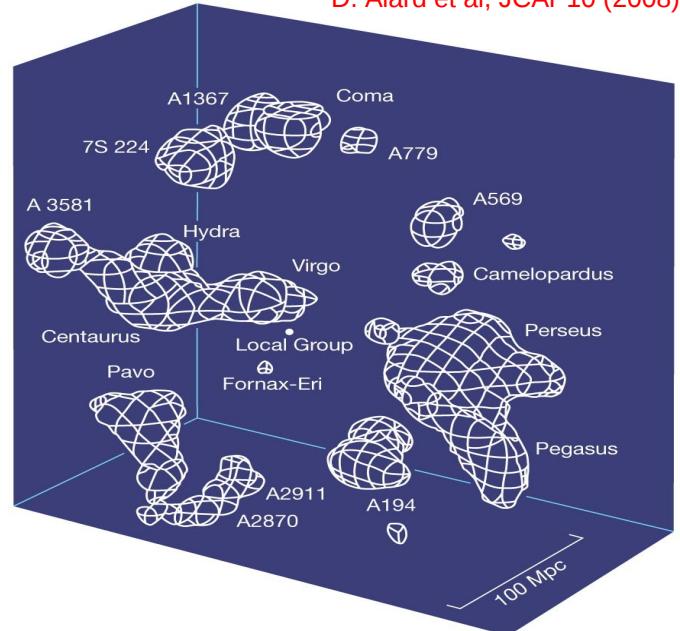


Photo-dissociation (giant dipole resonance)



D. Alard et al, JCAP10 (2008)033]



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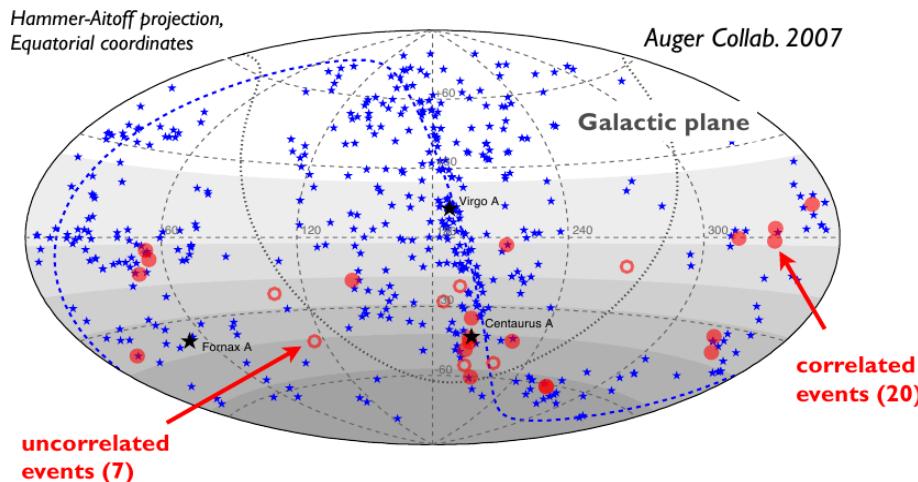
GZK γ -induced dissociation cut-off ?

- Proton with $E_{\text{GZK}} > 6 \cdot 10^{19} \text{ eV}$ breakup in collisions with CMB ($E_\gamma \sim 0.35 \text{ meV}$):



- GZK horizon ~ 100 - 200 Mpc:

UHE protons (heavier ions deflected by interstellar B-fields) should be correlated with closest AGN...



Strong correlation seen by Auger (2007) (protons favoured). It has washed out since ...

Greisen-Zatsepin-Kuzmin (1966)

Photo-pion production

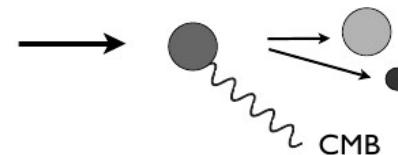
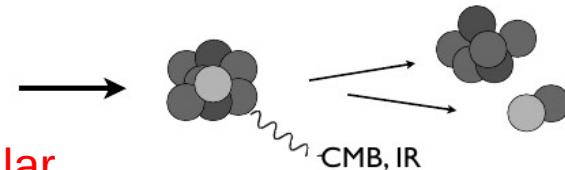
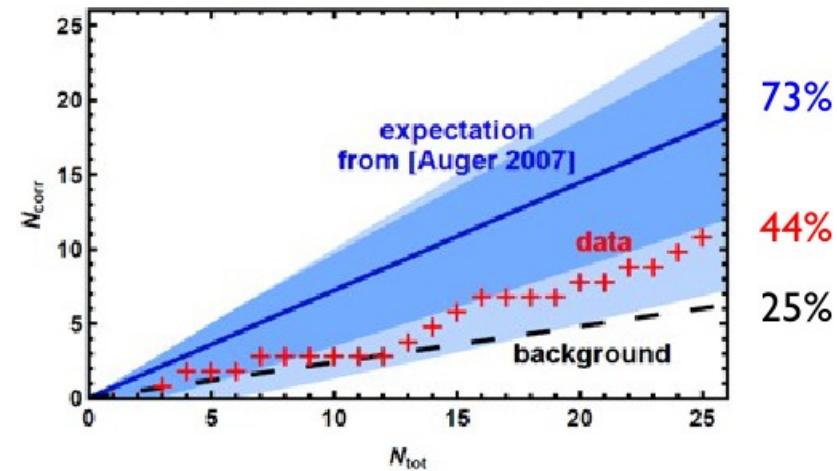


Photo-dissociation (giant dipole resonance)



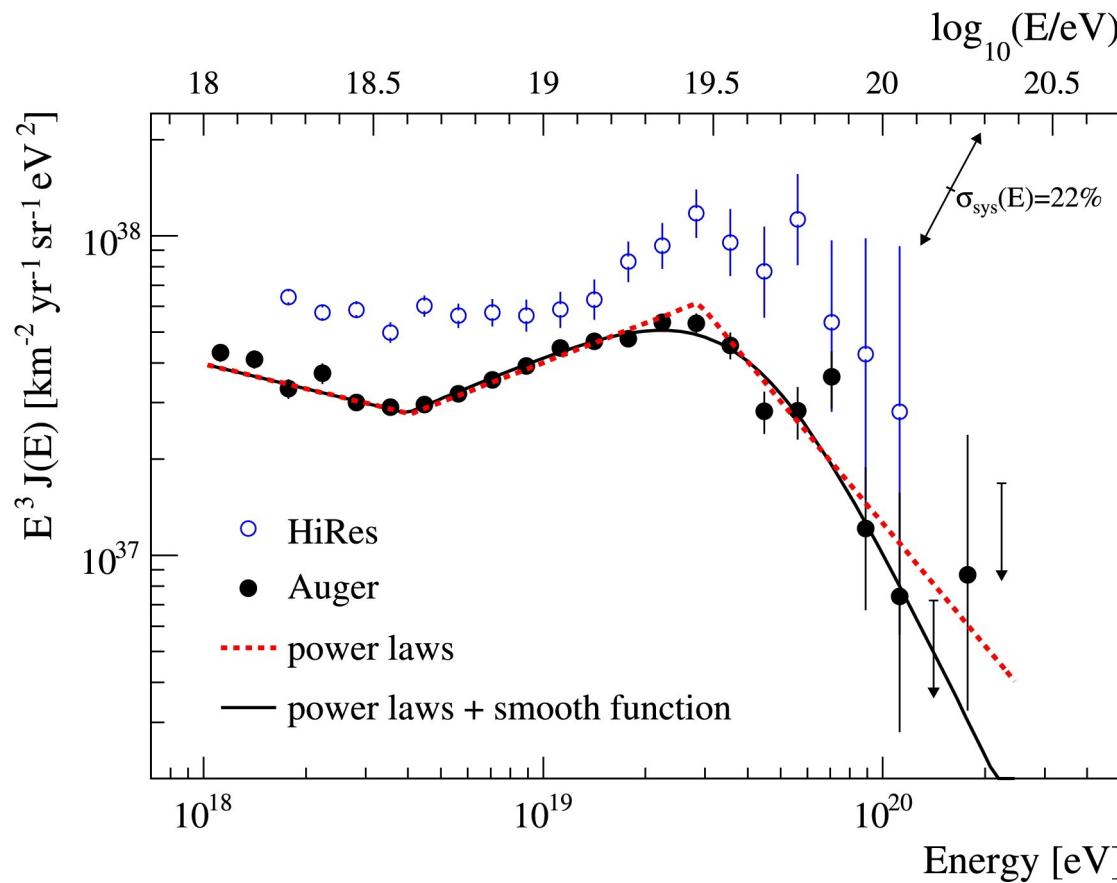
Telescope Array (2012)



Small correlation seen by TA (2012)
Still, isotropy disfavoured at 3σ

Origin of CR at highest energies O(10^{20} eV) ?

- Abrupt flux suppression at $E_{\text{CR}} \sim 3 \cdot 10^{19}$ eV:



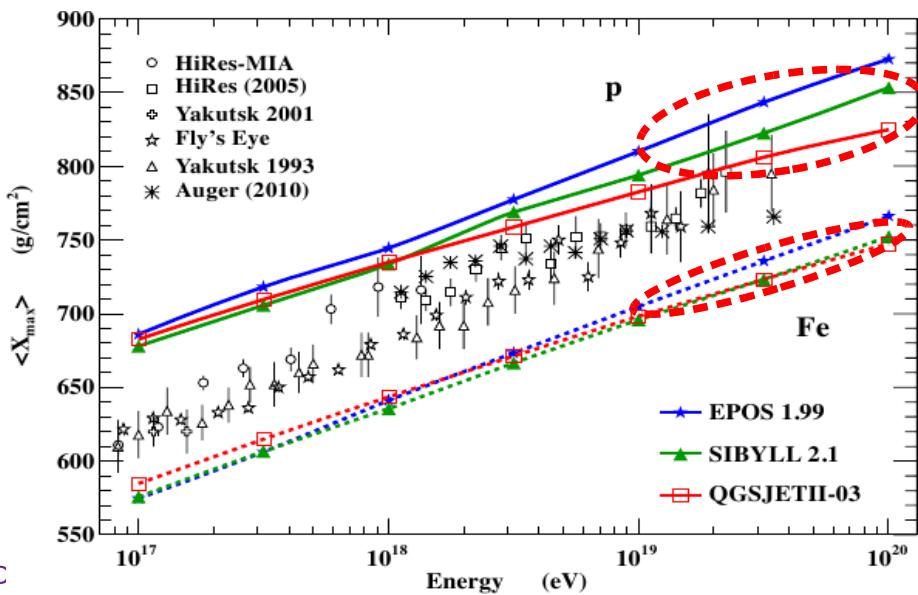
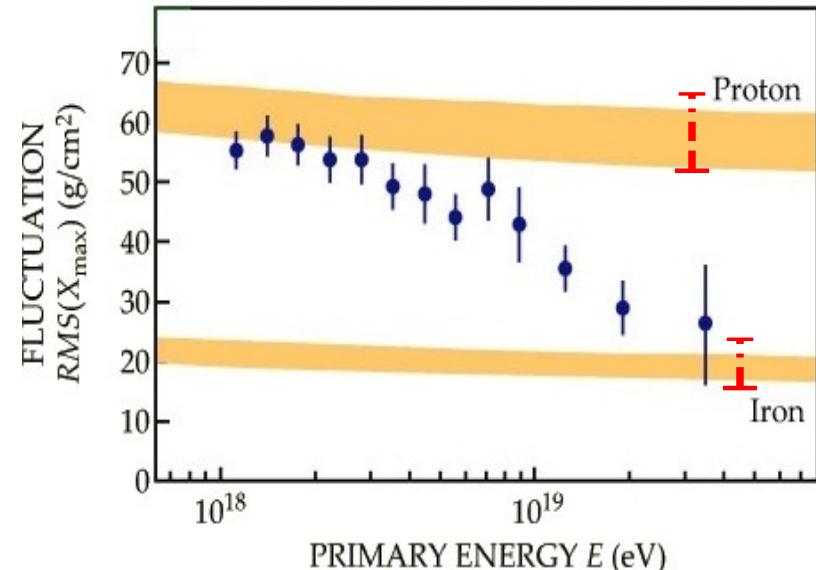
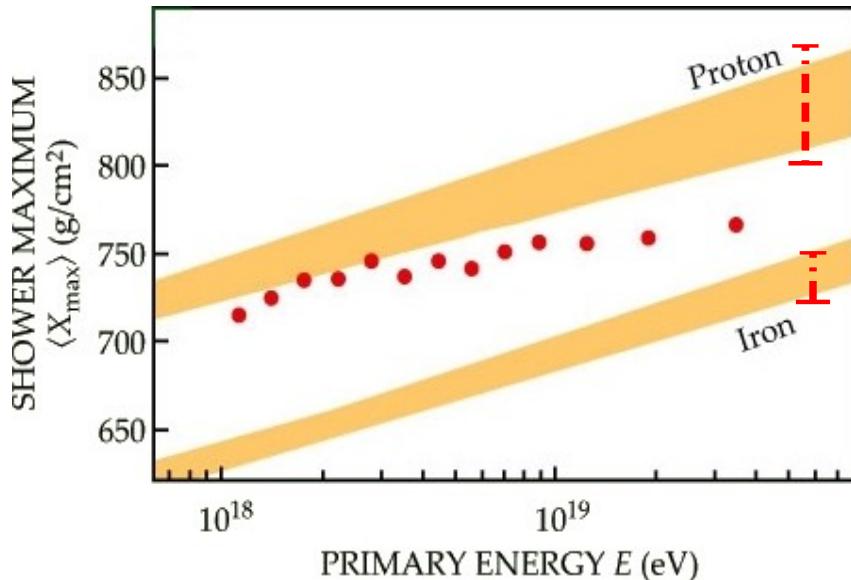
HiRes: PRL 100 (2008)101101
Auger: PLB 685 (2010)239

- Cutoff at source ? Astrophysical accelerators running out of steam ?
- Cutoff by CR photodissociation during propagation ?

UHECR at GZK-cutoff: p or Fe-ions ? (pre-LHC)

Auger: PRL 104 (2010) 091101

■ Auger shower-max position & fluctuations favour **heavy-ions** for $>10^{19}$ eV

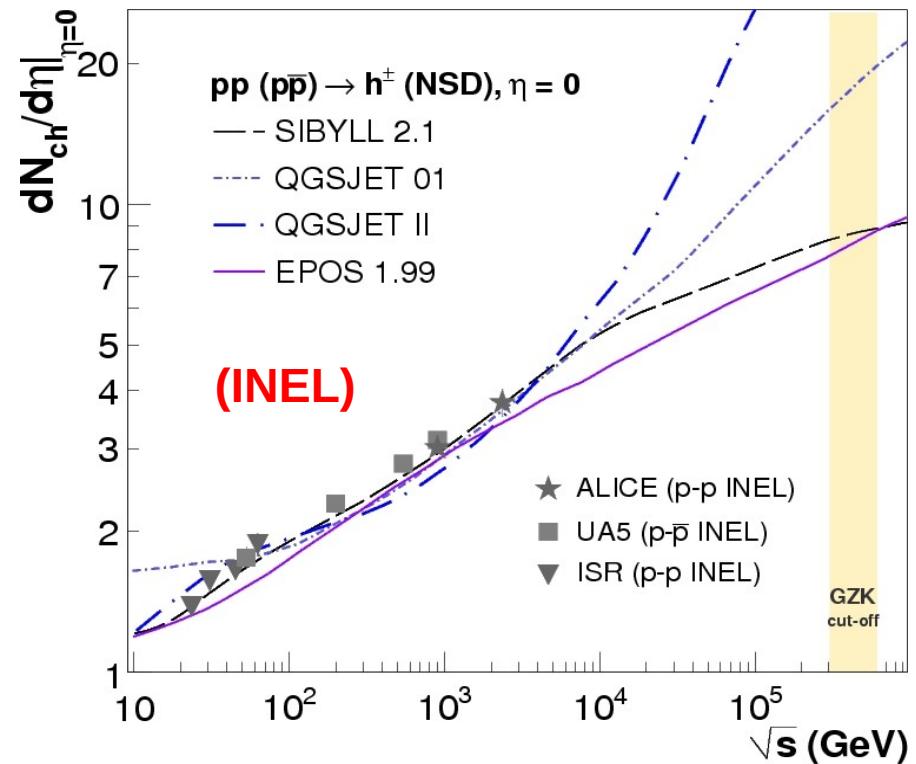
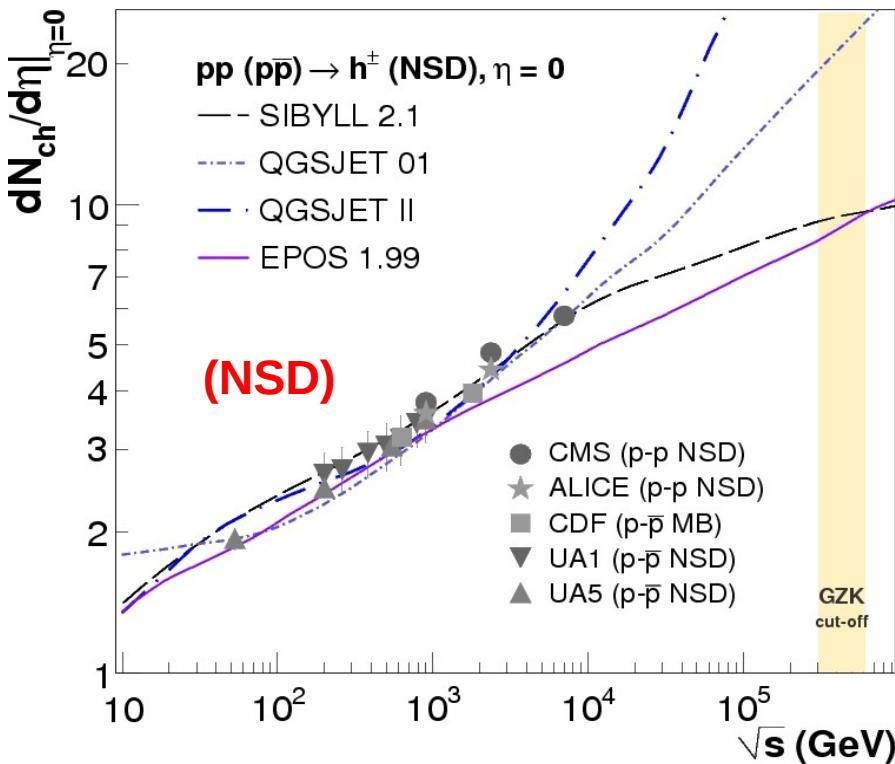


- Hadronic MC uncertainties propagate to CR mass.
- QGSJET-II,SIBYLL: favour **protons**
- EPOS: favours **mixture protons+Fe-ions**

Particle pseudorapidity density vs. \sqrt{s}

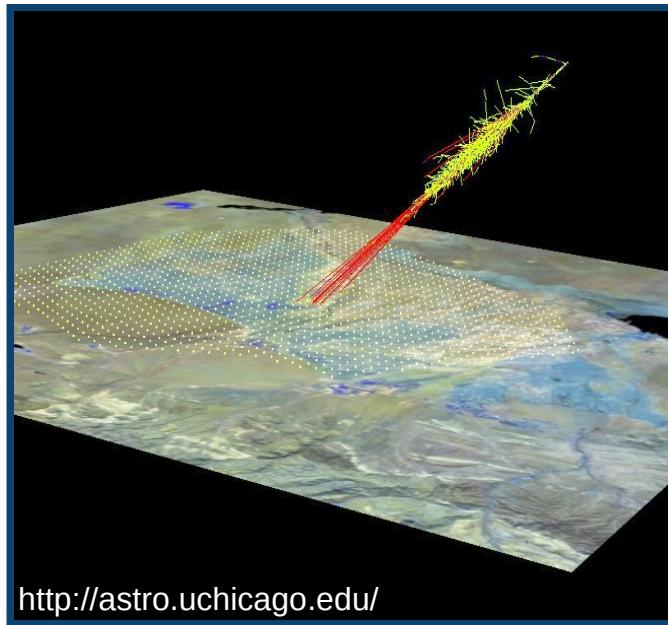
[DdE et al., Astr.Phys. 35 (2011) 98]

- Power-law s^ε , $\varepsilon \sim 0.1$ controlled by soft-hard p_T -cutoff (sat. scale) evolution
- Very large differences predicted at $\sqrt{s}_{GZK} \sim 300$ TeV !
 - QGSJET-II (~ 40) > QGSJET01 (~ 20) > SIBYLL 2.1, EPOS 1.99 (~ 8)



- GZK: models with $dN_{ch}/d\eta \sim 20$ favoured (p-p data at 14-TeV needed)

UHECRs detection in large ground-arrays



<http://astro.uchicago.edu/>

■ Detection techniques:

- Fluorescent light from N* de-excitation:
 - Near-UV telescope.
 - ~10% duty-cycle (moonless nights).
 - HiRes, TA, Auger.
- Charged particles on ground:
 - Cherenkov detectors.
 - ~100% duty-cycle.
 - AGASA, TA, Auger.

■ Measured shower parameters (event-by-event):

- Depth of **maximum of shower**: X_{\max} (g/cm²)
- Total **energy**: $E_{\text{CR}} = \text{Const} \times (\text{Signal}_{\text{alt}})^{1.02-1.08}$
- Number of electrons, muons at ground: N_e, N_μ
- Arrival **direction**: $\pm(0.5^\circ - 1.0^\circ)$

}

CR energy & identity

- statistical unfolding !
- MC-dependent !

UHECRs energy & identification

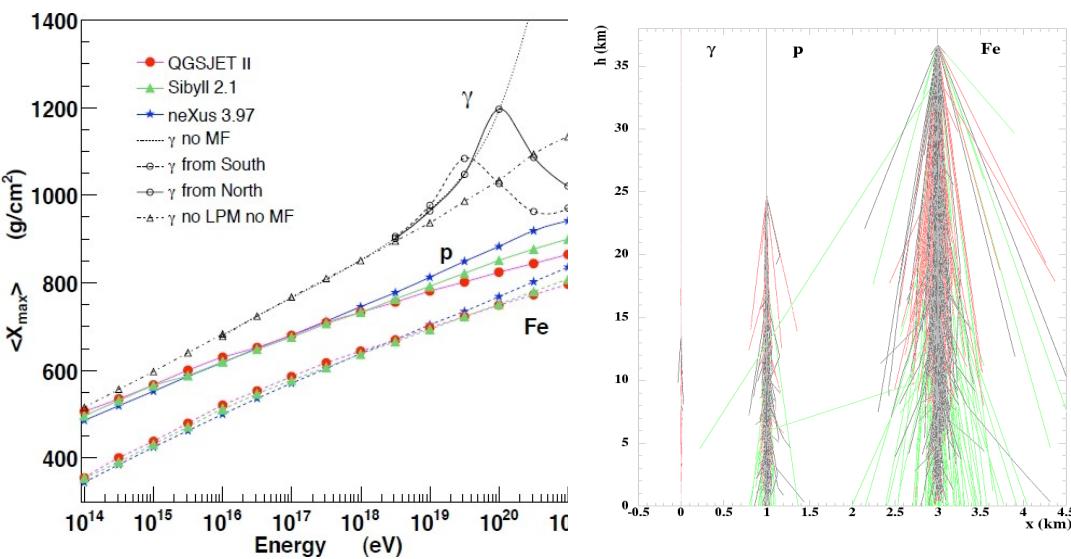
[Blumer-Engel-Horandel, PPNP 68(2009)293]

■ Position & fluctuations of shower maximum:

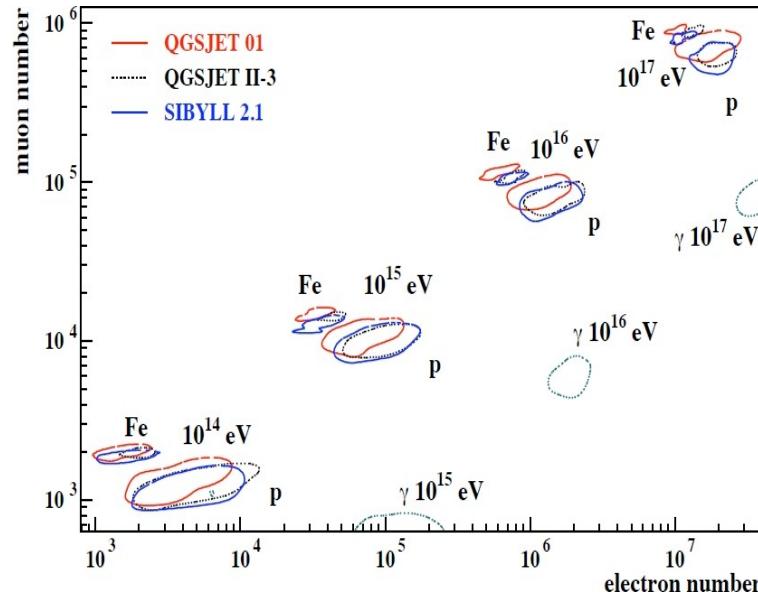
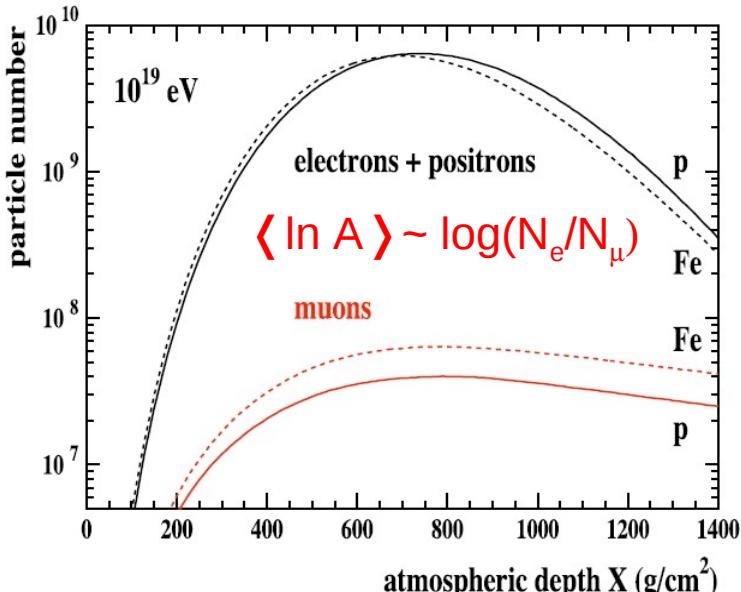
Depth: $\gamma > p > A$

$$X_{\max}(p) \sim X_{\max}(\text{Fe}) + 150 \text{ g/cm}^2$$

Shower-to-shower fluctuations:
smaller for ions than proton.



■ Number of e^\pm & muons:



Summary: UHE cosmic-rays

(1) “Knee” at $E \sim 10^{15}$ eV:

- LHC data confirms CR MCs validity (no “new physics”).
Probable cause: Z-dependent leakage of galactic Crs.

(2) “Ankle” at $E \sim 10^{18}$ eV:

(3) Cutoff at $E \sim 10^{20}$ eV:

- Small AGN-correlation, but anisotropy excluded at 3σ .
- X_{\max} position & fluctuations favour p-Fe (Auger) or p alone (TA).
- LHC data has reduced by ~50% identity uncertainties
Improvements still needed (e.g. +30% larger muon production on ground)

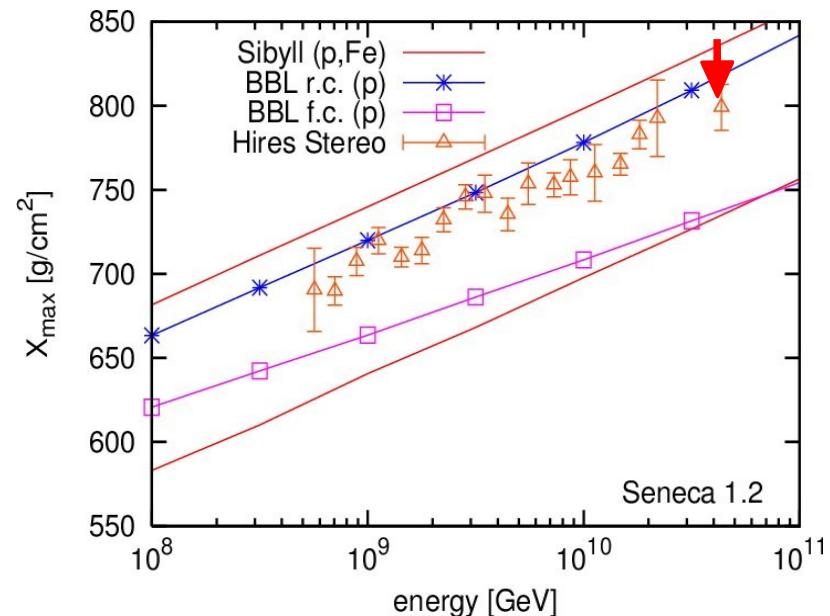
Examples of implications for EAS

- Reduced $dN/d\eta$ (esp. fwd):

Less penetration:

lower X_{\max} (~ -30 g/cm 2)

Drescher, Dumitru, Strikman
PRL 94 (2005) 231801



- Reduced charm cross sections:

Less muons

Machado&Goncalves
JHEP0704 (2007) 028

