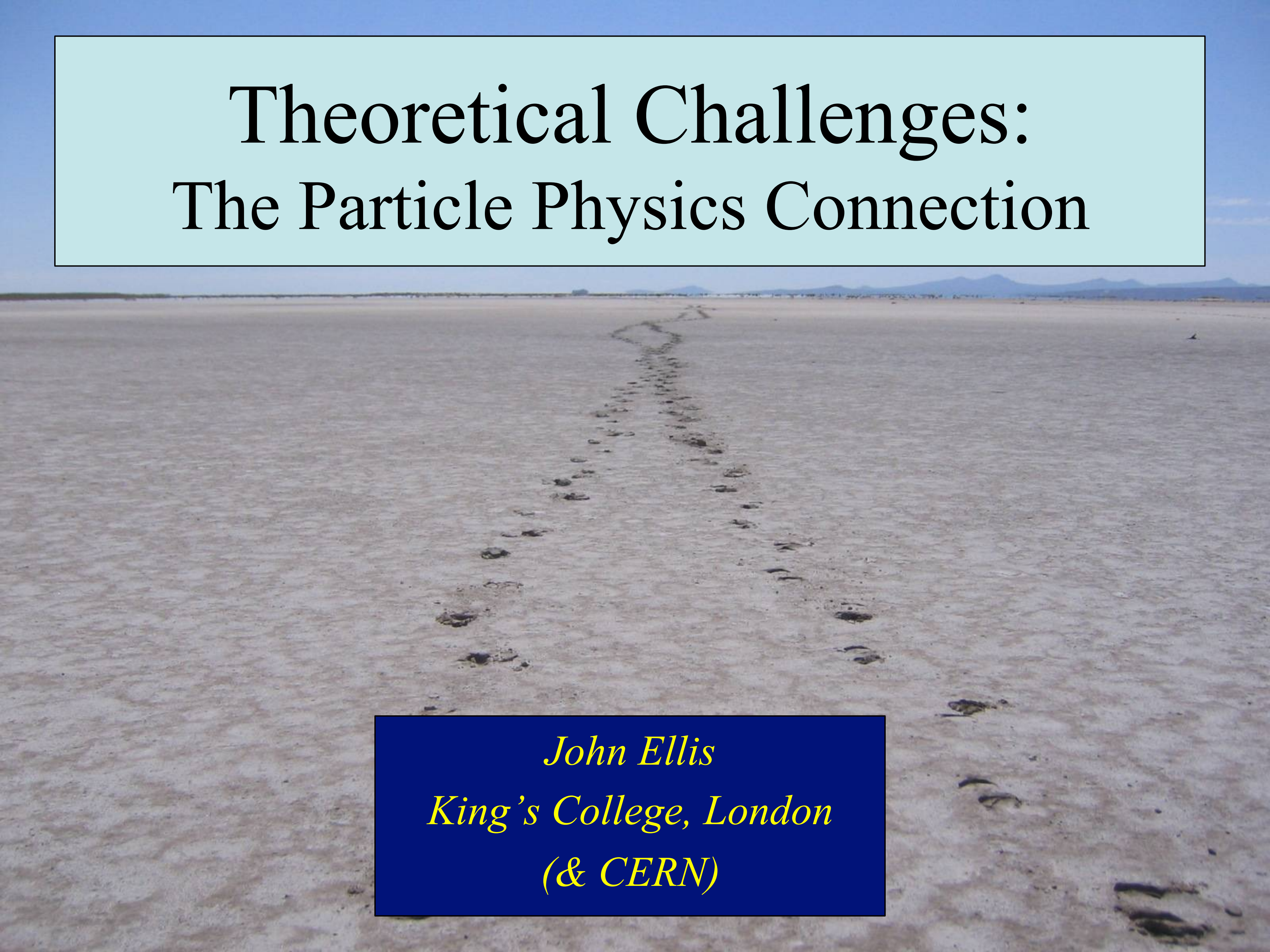
Theoretical Challenges:
The Particle Physics Connection



John Ellis
King's College, London
(& CERN)

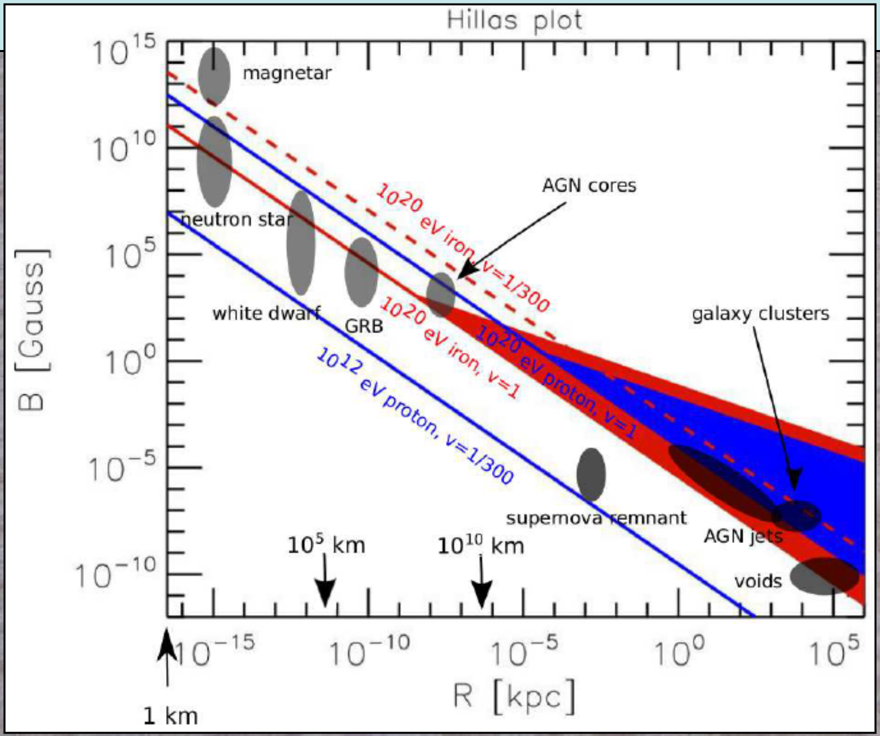
Outline

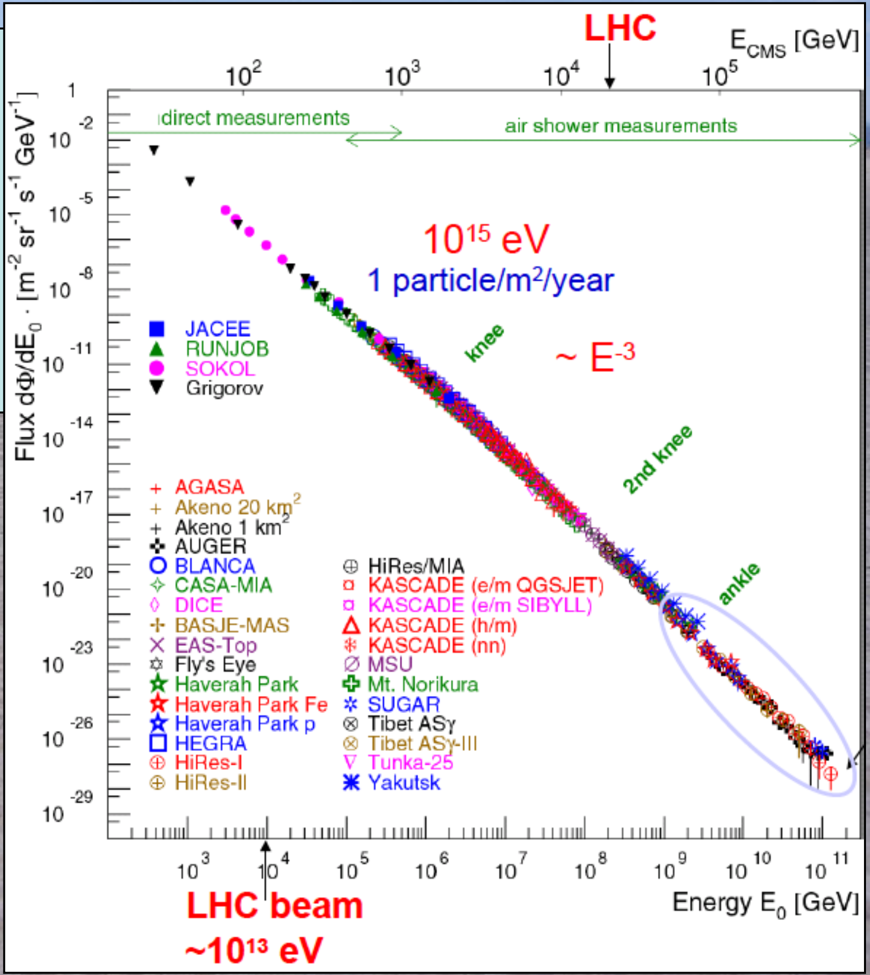
- RIP Top-down models?
  - Composition
  - Photon fraction
  - Angular distribution
- Strangelets and black holes?
- Lorentz violation?
  - In UHECR?
  - In neutrinos: OPERA, GZK?

Increasing Speculation

Origin of the UHECR?

- Top-down or bottom-up?
  - Heavy metastable particles?
  - Astrophysical sources?





Heavy Metastable Particles

- Topological defects, WIMPzillas, …
- "Cryptons"
  - Hidden sector of string model
  - Weakly coupled to Standard Model particles
  - Decay slowly through higher-order operators
- Specific examples in flipped SU(5) from string
  - Estimate lifetime: $\tau \approx \frac{\alpha_{string}^{2-N}}{m_X}\left(\frac{M_s}{m_X}\right)^{2(N-3)}$
  - Calculate decay spectra: $\Phi^{halo}(E) = \frac{n_X}{\tau_X}\frac{1}{\Gamma_X}\frac{d\Gamma(X \to g_1 + \cdots)}{dE}$

$$\frac{1}{\Gamma_X}\frac{d\Gamma(X \to g_1 + \cdots)}{dE} = \sum_a \int_0^x \frac{1}{\Gamma_a}\frac{d\Gamma_a(y, \mu^2, M_X^2)}{dy}\bigg|_{y=x/z} D_a^g(z, \mu^2)$$

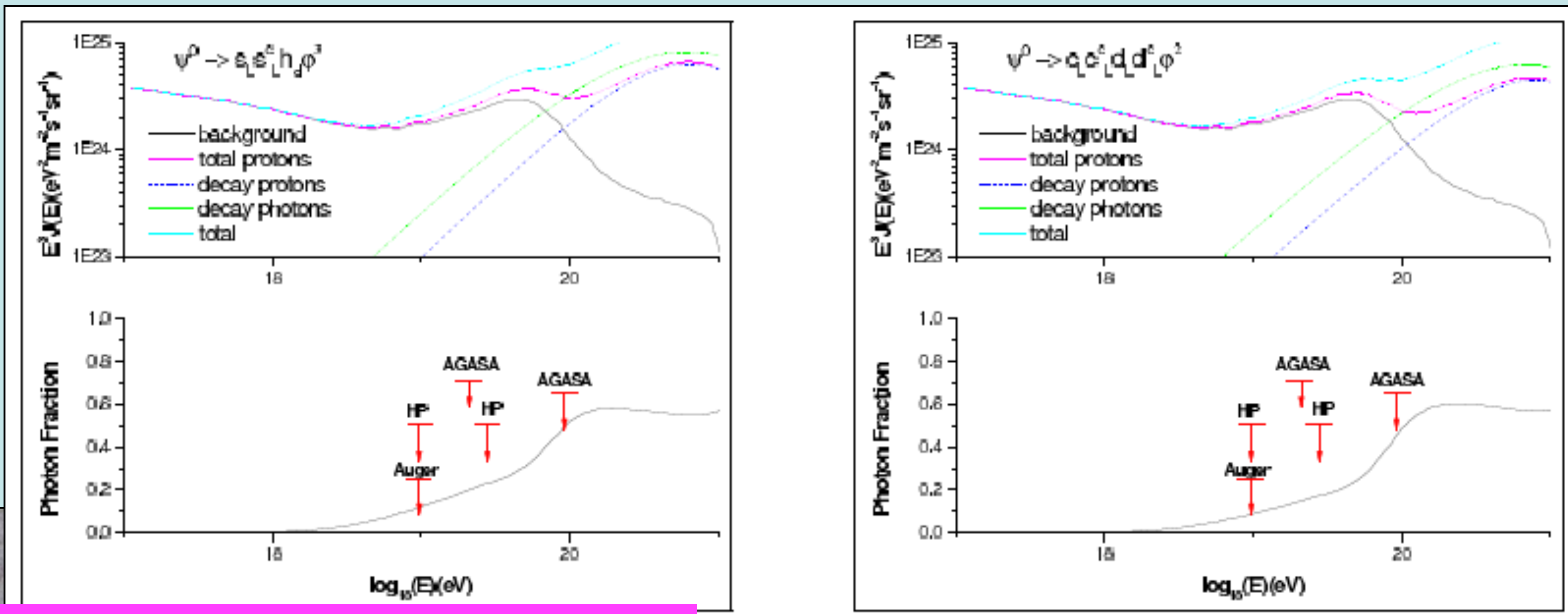
JE, Mayes & Nanopoulos: hep-ph/0403144, 0512303

Sample Crypton Decay Models

- Known decay modes, e.g.

$$\Psi^0 \to \tau\ \tau^c\ h_d\ \phi^3, \Psi^0 \to e/\mu\ e^c/\mu^c\ h_d\ \phi^3, \Psi^0 \to b\ b^c\ h_d\ \phi^3,$$
$$\Psi^0 \to b\ b^c\ h_d\ h_d\ h_u \phi, \Psi^0 \to t\ t^c\ h_u\ \phi^3, \Psi^0 \to t\ t^c\ h_u\ h_u\ h_d\ \phi,$$
$$\Psi^0 \to c\ c^c\ d\ d^c\ \phi^2, \Psi^0 \to s\ s^c\ h_d\ \phi^3$$

- Calculable decay spectra



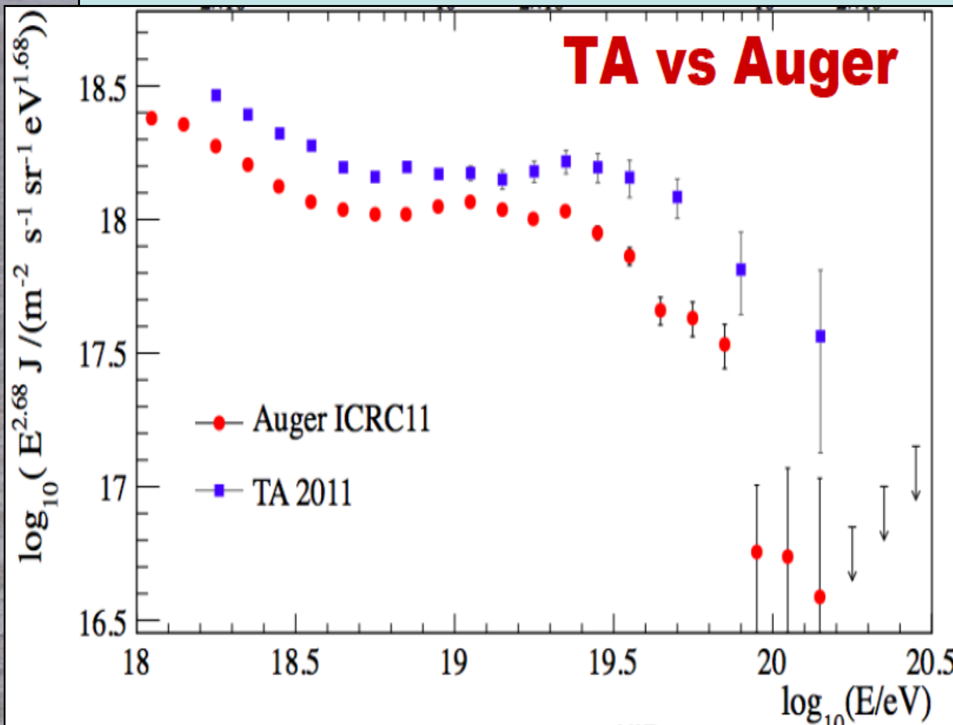
JE, Mayes & Nanopoulos: hep-ph/0403144, 0512303

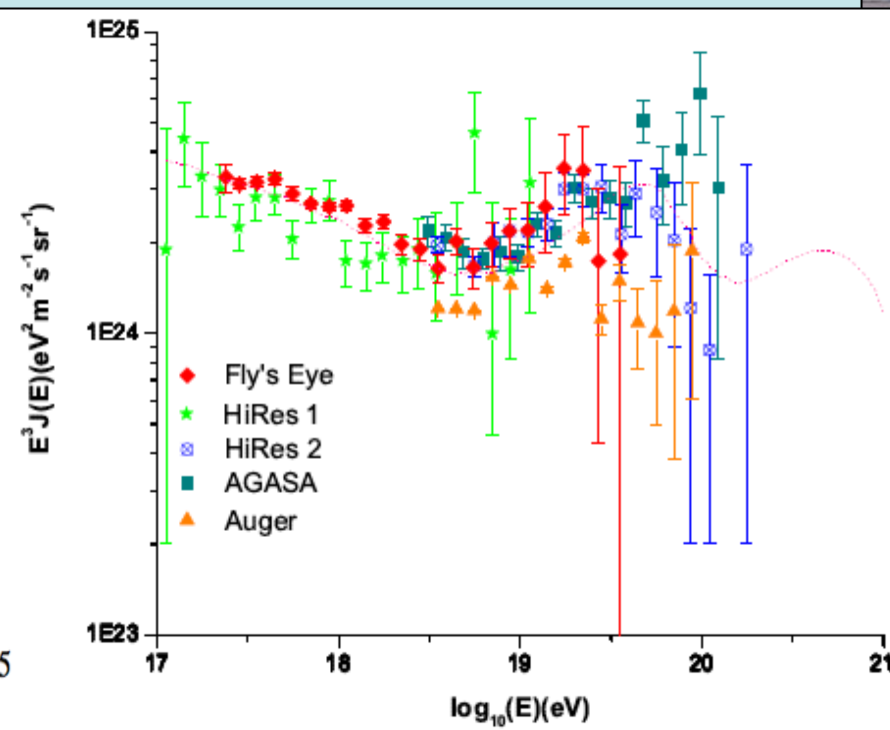
Four Strikes and You are Out

- Evidence for GZK cutoff
  - But feature possible in crypton models
- Composition
  - More heavy nuclei at higher energies
- Photon fraction
  - Strong upper limits from Auger
- Angular distribution
  - No indication of galactic anisotropy

GZK are alive and well

- Dixit HiRes, Auger, TA



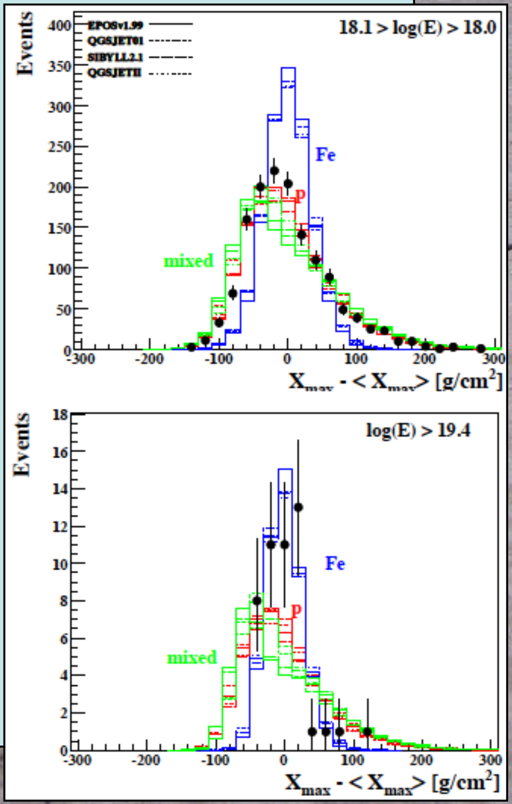


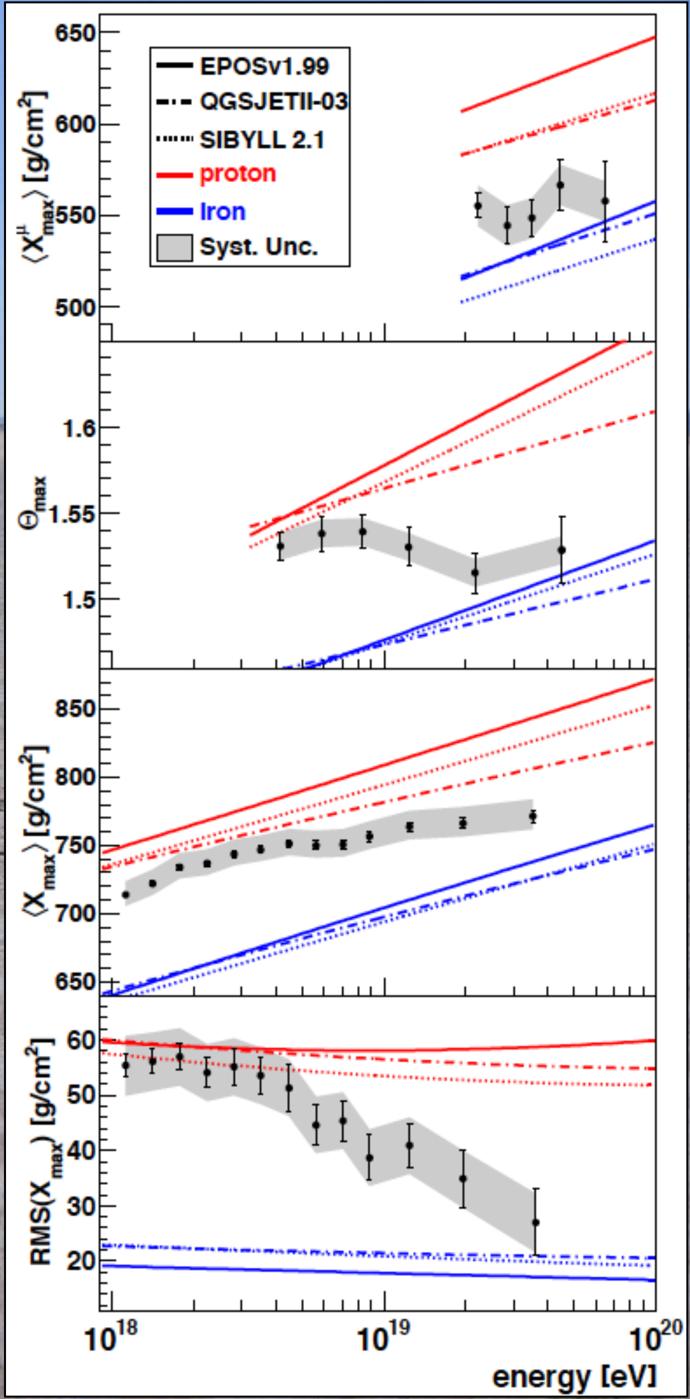
- But features possible in crypton decay models

JE, Mayes & Nanopoulos: hep-ph/0403144, 0512303

Cosmic-Ray Composition

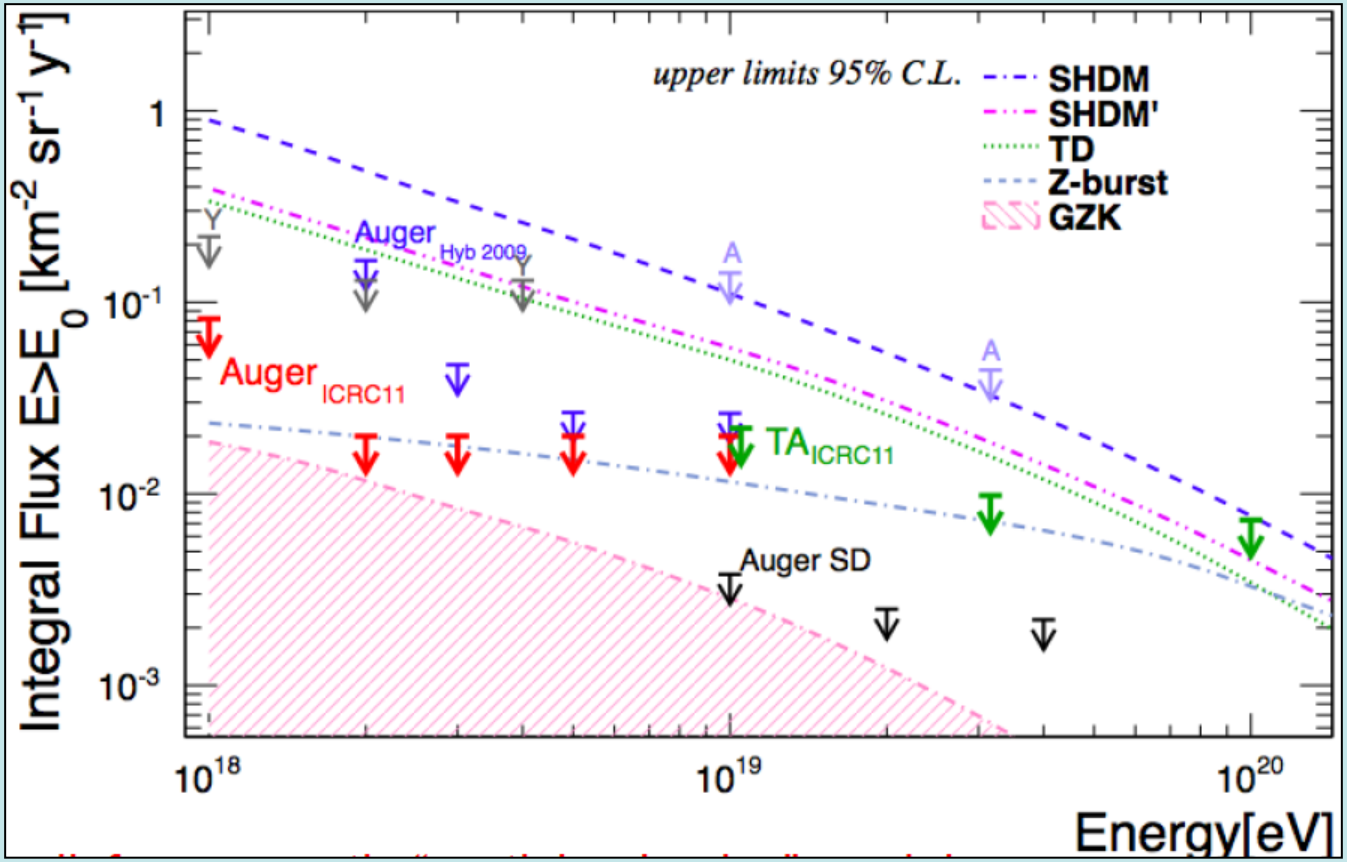
- Auger suggests increasing fraction of heavy nuclei in UHECR
- Impossible in top-down model
- But may be some protons even at UHE





Upper Limits on Photons

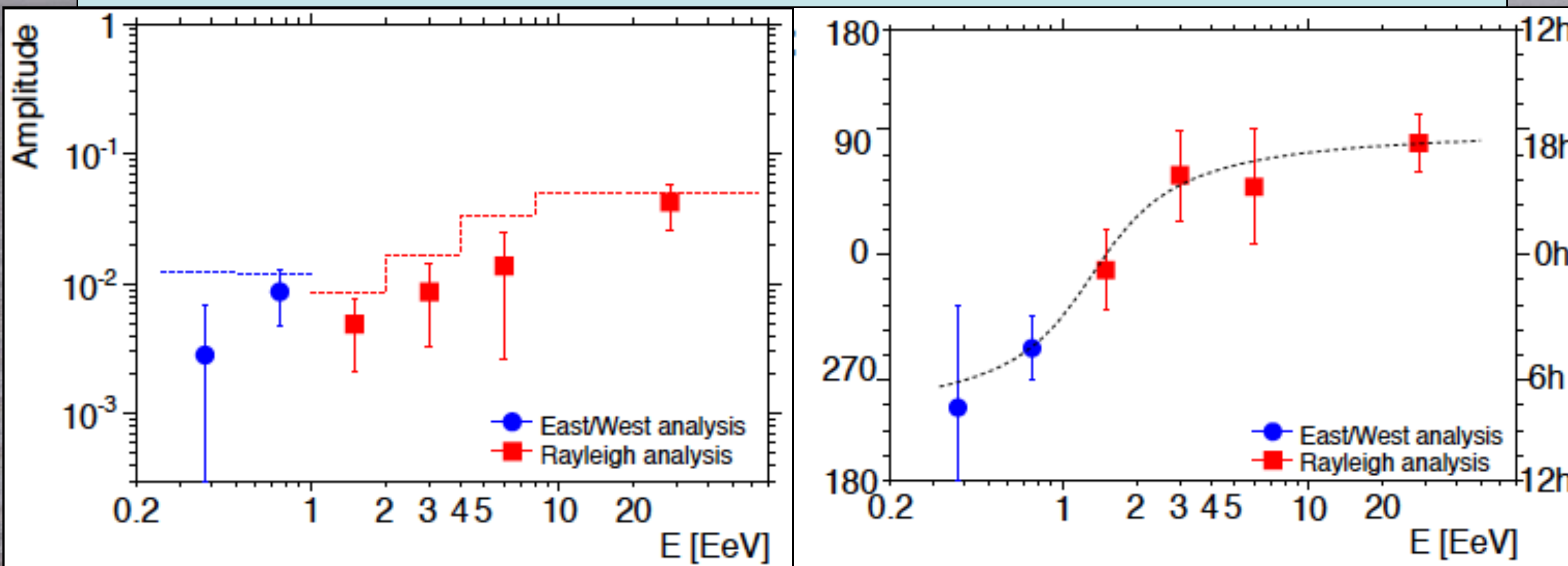
- Upper limits below (many) top-down models



- BUT: possibility of absorption by γ background?

UHECR Anisotropy?

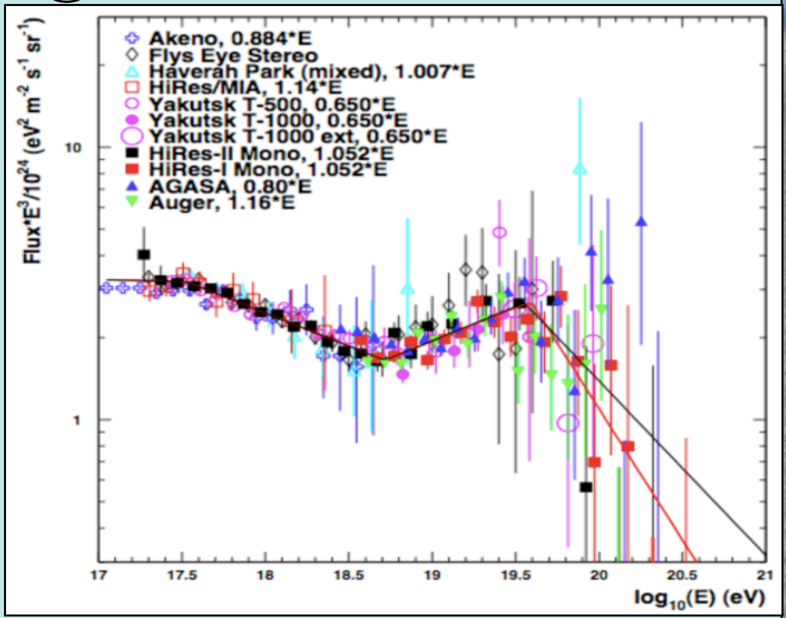
- Compatible with statistical fluctuations



- But non-trivial energy dependence of phase

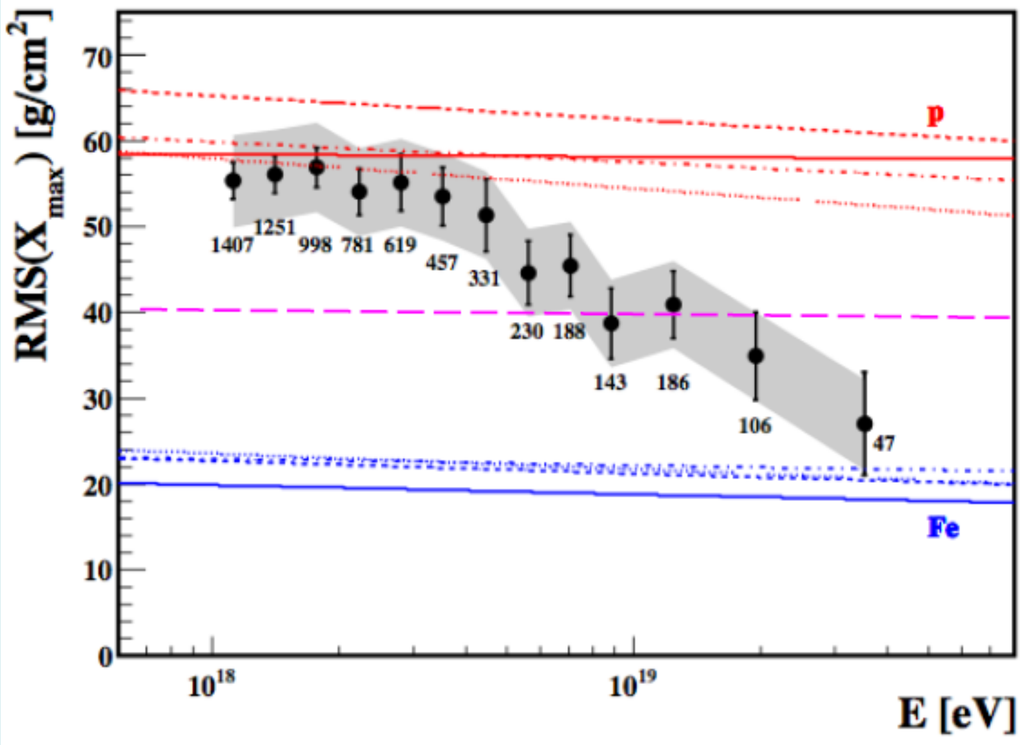
Nasties at the LHC?

- LHC @ 14 TeV = cosmic rays @ 10^{17} eV
- Cosmic rays seen to 10^{20} eV
- Protons and/or Iron?
- ~ 3.10^{22} cosmic rays above 10^{17} eV have struck Earth
- Equivalent to 10^{5} LHCs
- Area of Sun 10^{4} larger
- 10^{11} stars in Galaxy, 10^{11} galaxies in Universe
- Nature has performed 10^{31} LHC programmes
- Nature carries out 3.10^{13} LHC programmes per second



Cosmic-Ray Composition

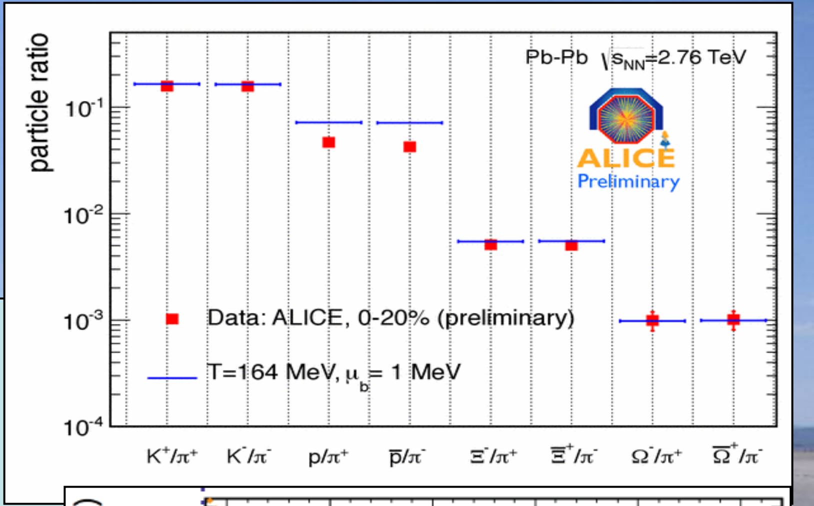
- Rates reduced by 1/A if all heavy nuclei
  - But Auger consistent with not all Fe

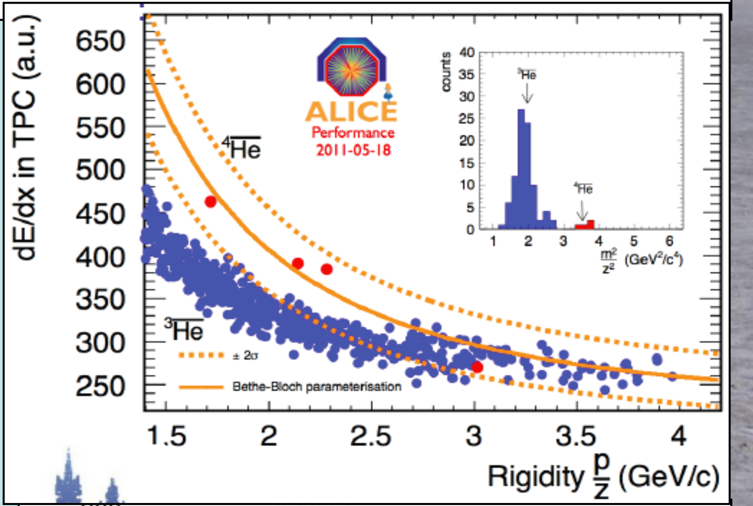


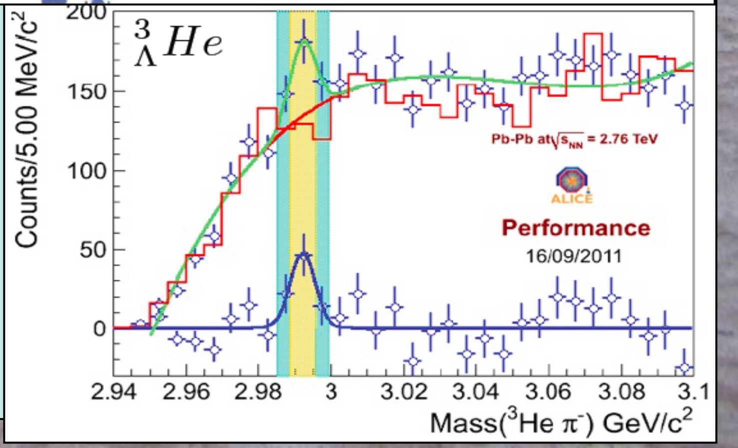
- Even if all Fe at source, ≥ 10% protons on arrival

Strangelets?

- LHC heavy-ion collisions: strange particle production agrees with thermal models
- Production of (anti-)nuclei agrees with coalescence models
- Also strange nuclei
- **Negligible strangelet production predicted: $< 10^{-24}$ for A = 10**

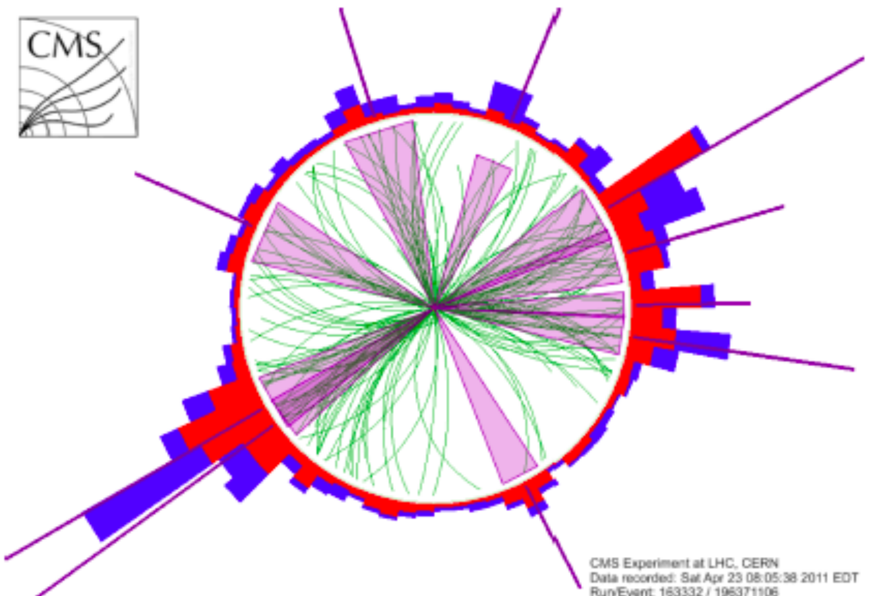






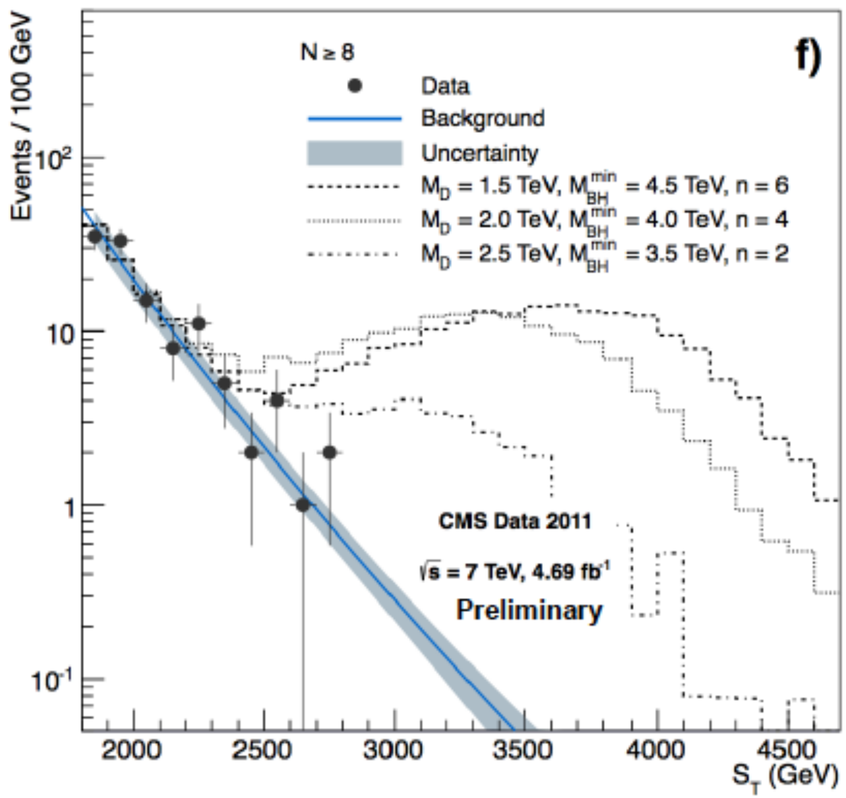
No Black Holes at LHC

- Democratic and isotropic decay
- High S_T events (total transverse energy)
- High total multiplicity (e.g. ≥4)



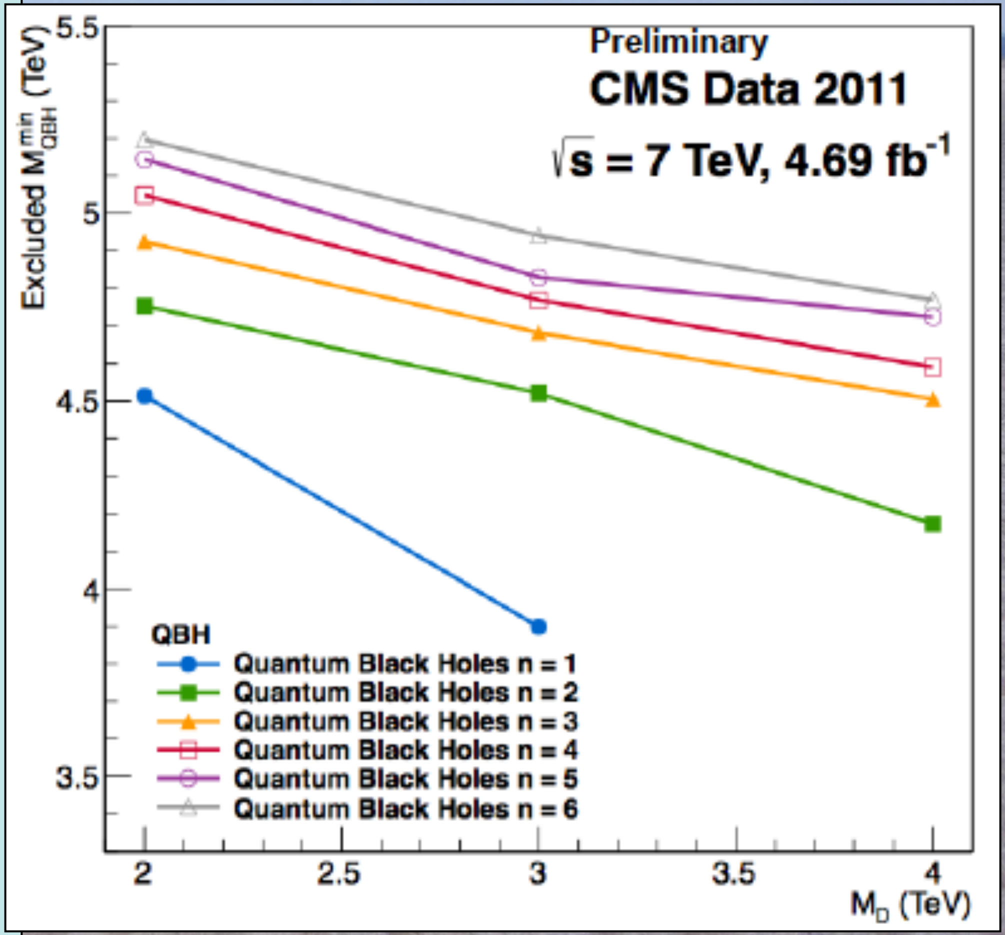
N=10 S_T = 1.1 TeV

Use N=2, 3 for background model.

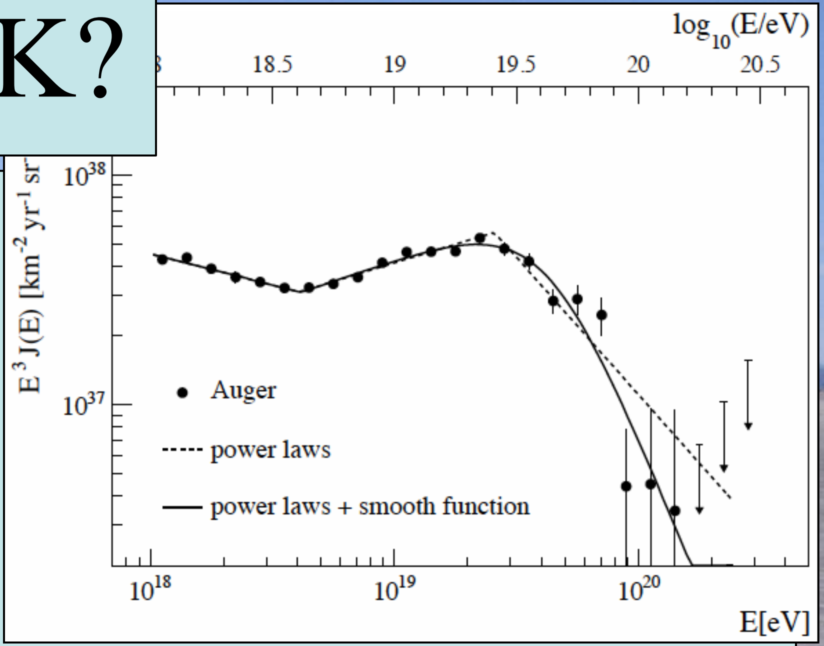


No Black Holes at LHC

- Many variant models studied
  - Stable remnants
  - Unstable remnants
  - Different numbers of dimensions
- ☹ : would have been wonderful quantum gravity laboratory



To GZK or not to GZK?



- Not GZK mechanism?
- Cutoff at production?
  - Limited acceleration?
  - Mass in top-down model?
- Avoid GZK by Lorentz violation?
  - Could affect kinematics of $p + \gamma \Rightarrow \Delta \Rightarrow N + \pi$

Gonzalez-Mestres; Cohen & Glashow

- Why use exotic mechanism to explain absence of standard effect that is probably present?
- GZK protons would have γ-factor $E/m \sim 10^{11}$

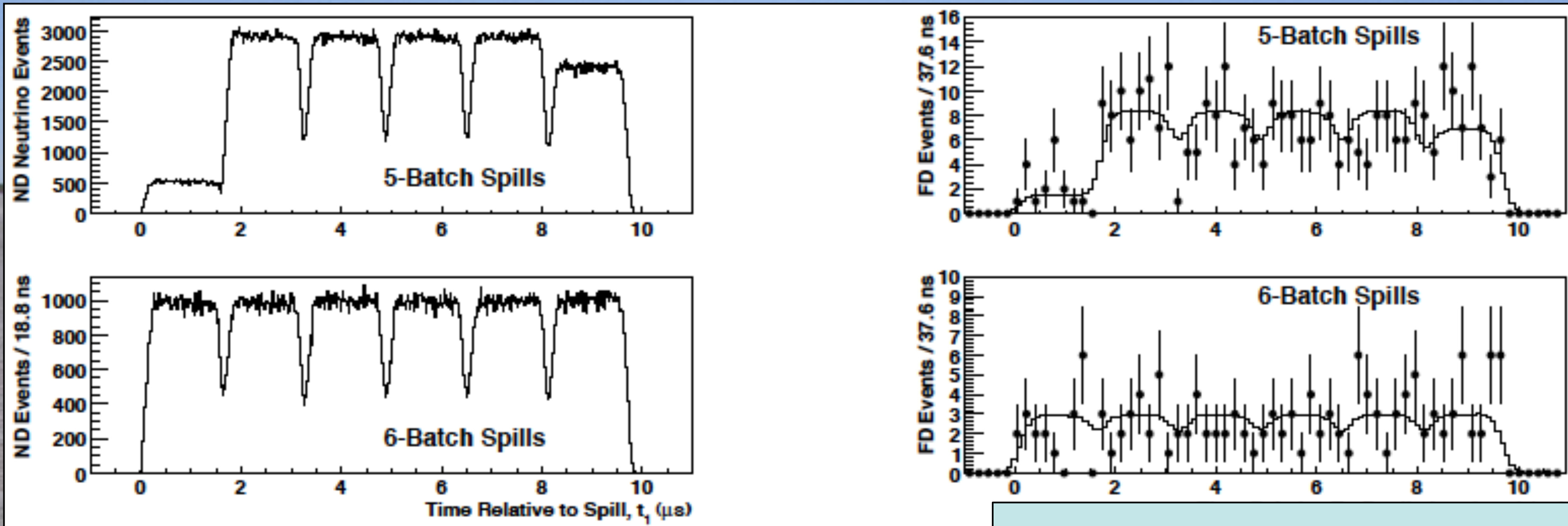
Just like OPERA neutrinos!

The End of Relativity is Nigh?

- 1862: Maxwell found that there should be electromagnetic waves travelling at approximately the (known) speed of light
- 1905: Einstein used universal speed of light as foundation of geometric description of physics
- 2011: OPERA finds 6-σ discrepancy between neutrino speed and that of light

"Life in the fast lane"

MINOS Measurement of ν Speed



Near & far detectors

	Description	Uncertainty (68% C.L.)
A	Distance between detectors	2 ns
B	ND Antenna fiber length	27 ns
C	ND electronics latencies	32 ns
D	FD Antenna fiber length	46 ns
E	FD electronics latencies	3 ns
F	GPS and transceivers	12 ns
G	Detector readout differences	9 ns
	Total (Sum in quadrature)	64 ns

Uncertainties

Published result

$$(v - c)/c = 5.1 \pm 2.9 \times 10^{-5}$$

almost 2 σ > 0

CERN-PH-TH/2008-088

Probes of Lorentz Violation in Neutrino Propagation

John Ellis[1], **Nicholas Harries**[1,2], **Anselmo Meregaglia**[3], **André Rubbia**[4] and **Alexander S. Sakharov**[1,4]

[1] *TH Division, PH Department, CERN, CH-1211 Geneva 23, Switzerland*

[2] *Theoretical Physics, University of Oxford, 1Keble Road, Oxford, UK*

[3] *IPHC, Universit, Louis Pasteur, CNRS/IN2P3, Strasbourg, France*

[4] *Swiss Institute of Technology ETH-Zürich, CH-8093 Zürich, Switzerland*

Abstract

It has been suggested that the interactions of energetic particles with the foamy structure of space-time thought to be generated by quantum-gravitational (QG) effects might violate Lorentz invariance, so that they do not propagate at a universal speed of light. We consider the limits that may be set on a linear or quadratic violation of Lorentz invariance in the propagation of energetic neutrinos, $v/c = [1 \pm (E/M_{\nu QG1})]$ or $[1 \pm (E/M_{\nu QG2})^2]$, using data from supernova explosions and the OPERA long-baseline neutrino experiment. Using the SN1987a neutrino data from the Kamioka II, IMB and Baksan experiments, we set the limits $M_{\nu QG1} > 2.7(2.5) \times 10^{10}$ GeV for subluminal (superluminal) propagation, respectively, and $M_{\nu QG2} > 4.6(4.1) \times 10^4$ GeV at the 95 % confidence level. A future galactic supernova at a distance of 10 kpc would have sensitivity to $M_{\nu QG1} > 2(4) \times 10^{11}$ GeV for subluminal (superluminal) propagation, respectively, and $M_{\nu QG2} > 2(4) \times 10^5$ GeV. With the current CNGS extraction spill length of 10.5 μs and with standard clock synchronization techniques, the sensitivity of the OPERA experiment would reach $M_{\nu QG1} \sim 7 \times 10^5$ GeV ($M_{\nu QG2} \sim 8 \times 10^3$ GeV) after 5 years of nominal running. If the time structure of the SPS RF bunches within the extracted CNGS spills could be exploited, these figures would be significantly improved to $M_{\nu QG1} \sim 5 \times 10^7$ GeV ($M_{\nu QG2} \sim 4 \times 10^4$ GeV). These results can be improved further if similar time resolution can be achieved with neutrino events occurring in the rock upstream of the OPERA detector: we find potential sensitivities to $M_{\nu QG1} \sim 4 \times 10^8$ GeV and $M_{\nu QG2} \sim 7 \times 10^5$ GeV.

CERN-PH-TH/2008-088

April 2008

Constraints from Supernova 1987a

- Data from 3 experiments

IMB		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	38	7
0.412	37	7
0.650	28	6
1.141	39	7
1.562	36	9
2.684	36	6
5.010	19	5
5.582	22	5

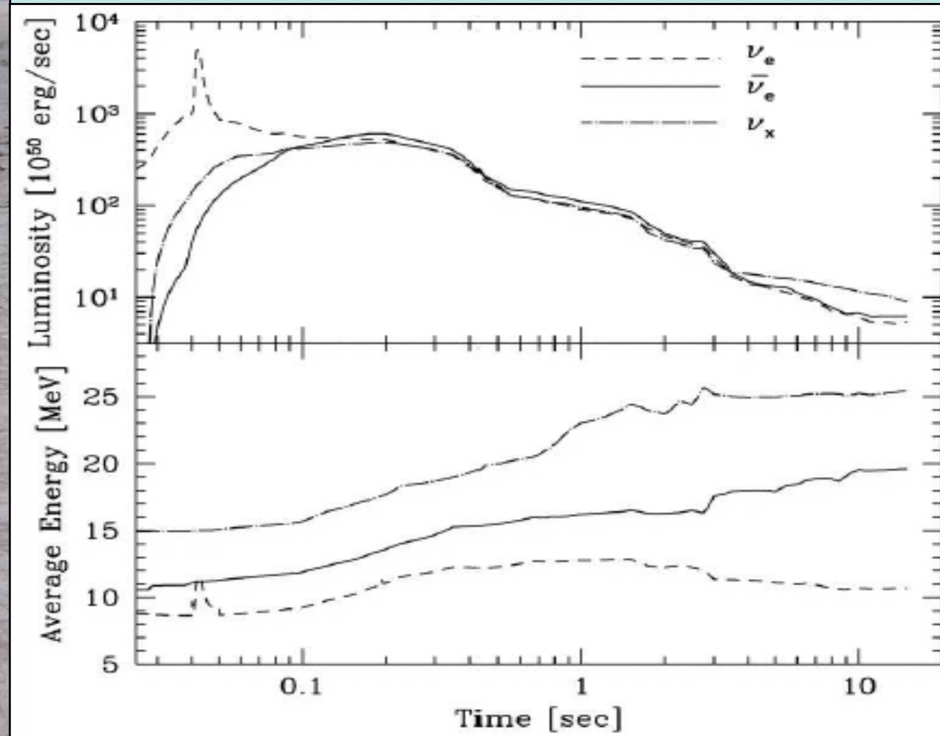
Baksan		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	12.0	2.4
0.435	17.9	3.6
1.710	23.5	4.7
7.687	17.6	3.5
9.099	10.3	4.1

Kamiokande II		
t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	20.0	2.9
0.107	13.5	3.2
0.303	7.5	2.0
0.324	9.2	2.7
0.507	12.8	2.9
1.541	35.4	8.0
1.728	21.0	4.2
1.915	19.8	3.2
9.219	8.6	2.7
10.433	13.0	2.6
12.439	8.9	1.9

- Arrived hours before γ's

➔ δv

- Supernova simulation

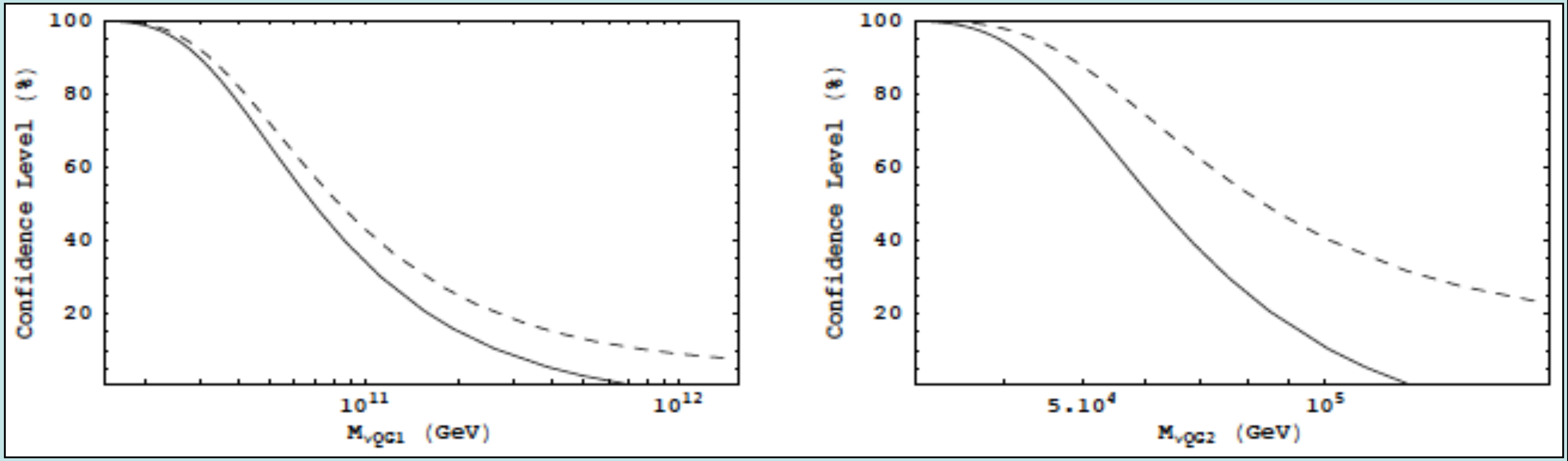


- Possible E dependence of δv constrained by bunching

JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

Constraints from SN1987a

- Fit to possible E-dependent time-lag



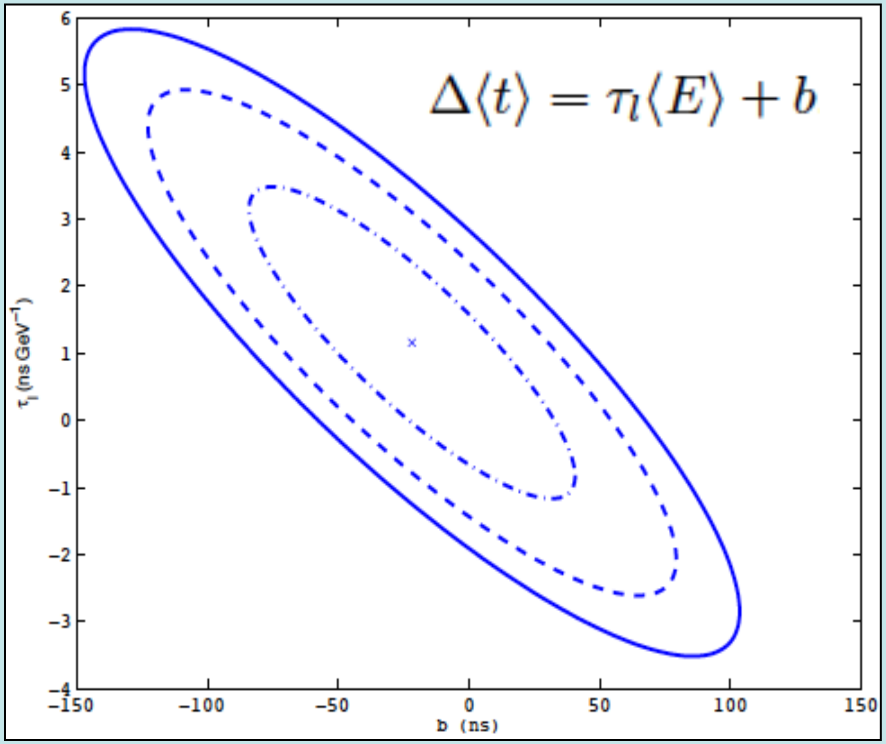
Subluminal and superluminal cases

- Linear: $M_{\nu QG1} > 2.7 \times 10^{10}$ GeV or $M_{\nu QG1} > 2.5 \times 10^{10}$ GeV
- Quadratic: $M_{\nu QG2} > 4.6 \times 10^{4}$ GeV or $M_{\nu QG2} > 4.1 \times 10^{4}$ GeV

JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

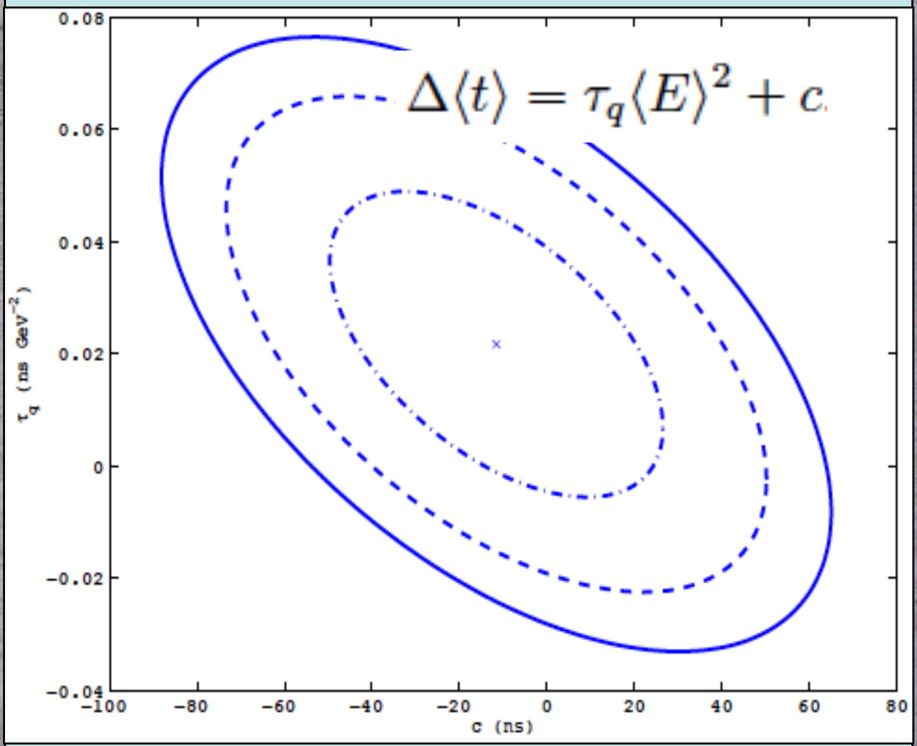
Fits to Simulated OPERA Data

- Linear case



- Sensitivity $M_{\nu QG1} \simeq 7 \times 10^5$ GeV

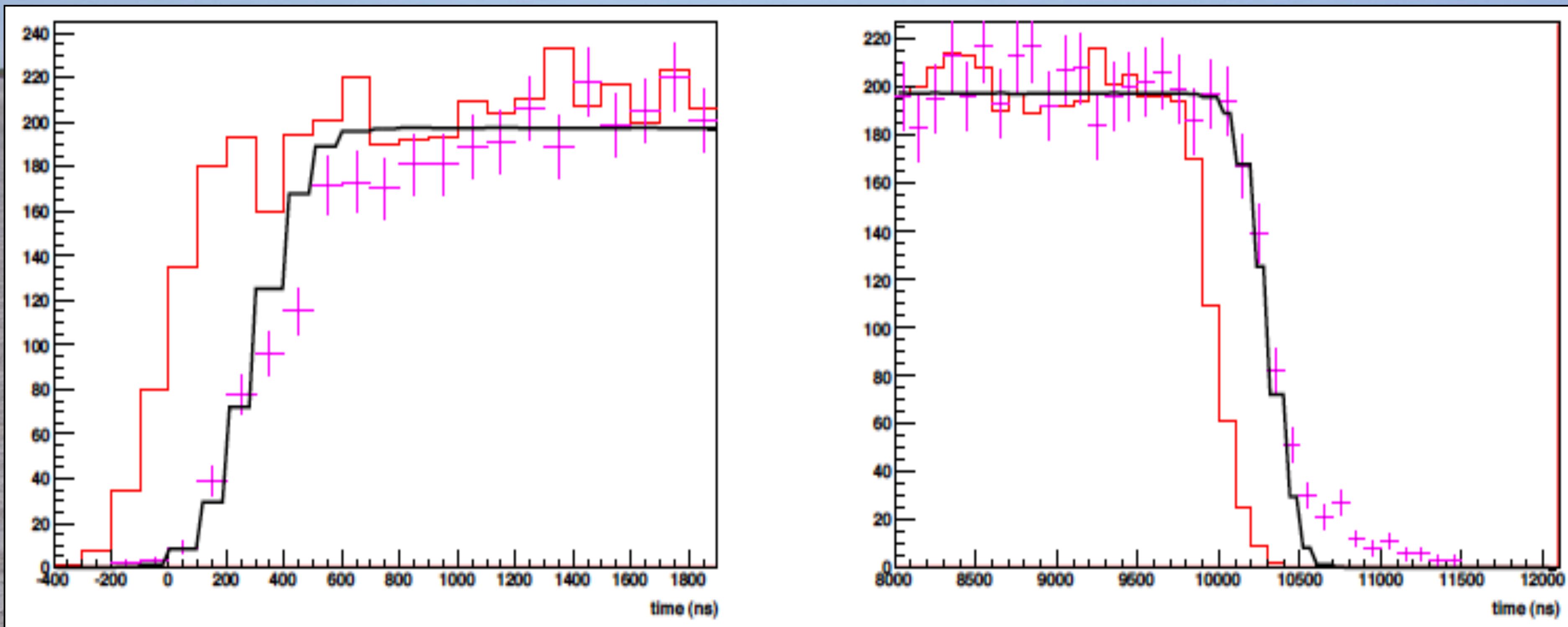
- Quadratic case



- Sensitivity $M_{\nu QG2} \simeq 8\times10^3$ GeV

JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

Fitting Edges of Spill



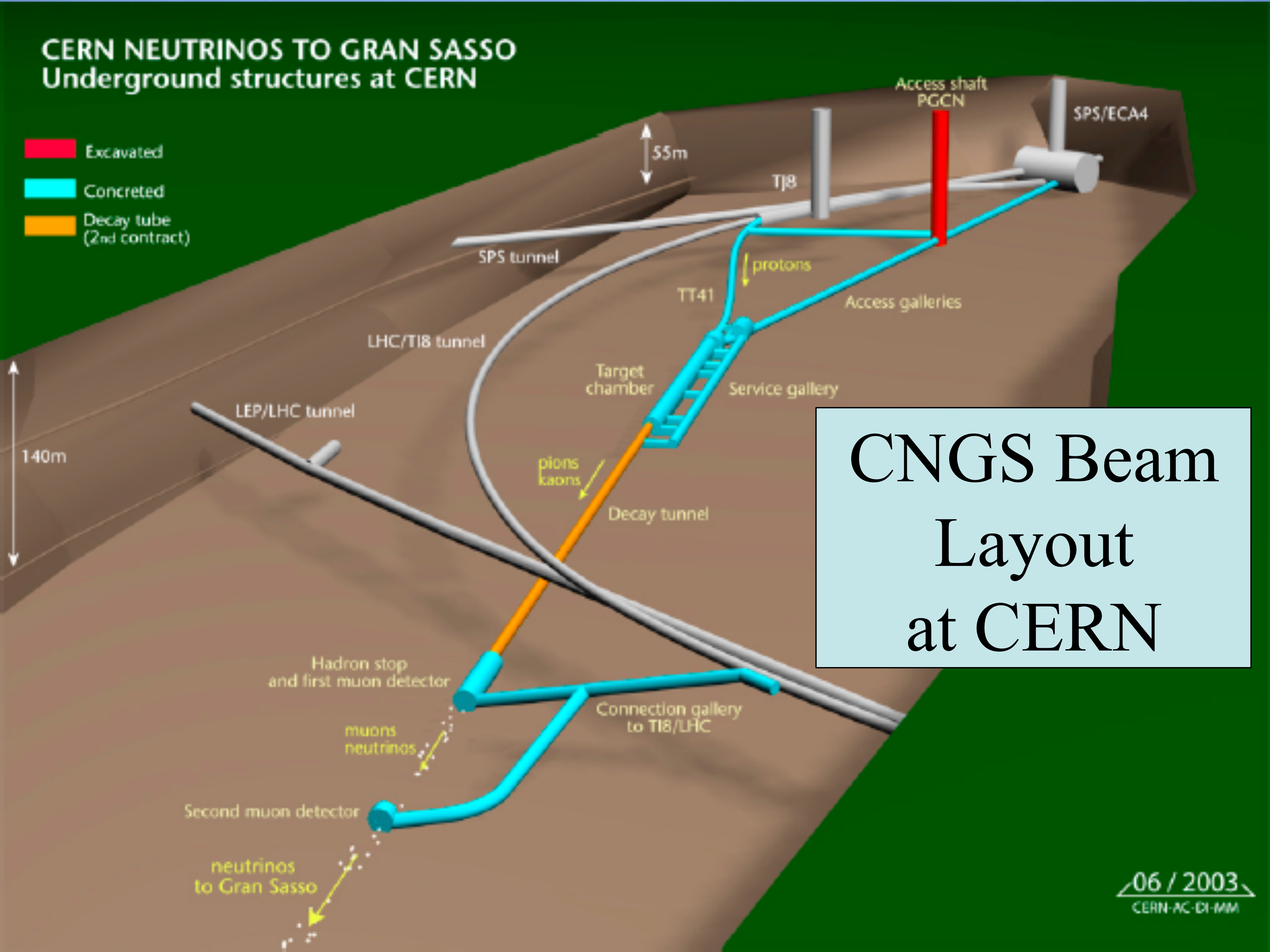
- Factor ~ 5 less sensitivity to energy dependence

JE, Harries, Mersegaglia, Rubbia & Sakharov: arXiv: 0805. 0253

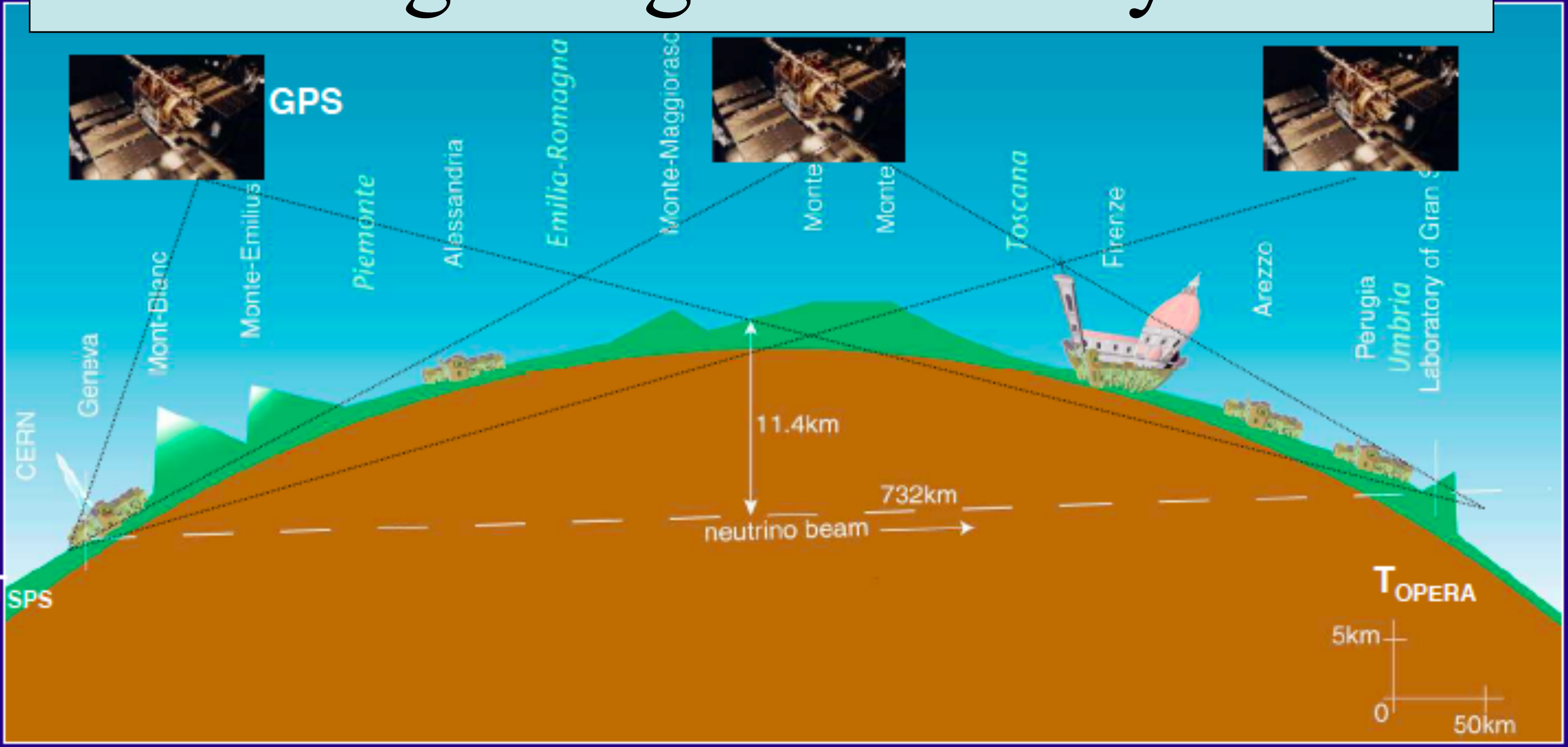
Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

T. Adam[a], N. Agafonova[b], A. Aleksandrov[c,1], O. Altinok[d], P. Alvarez Sanchez[e], S. Aoki[f], A. Ariga[g], T. Ariga[g], D. Autiero[h], A. Badertscher[i], A. Ben Dhahbi[g], A. Bertolin[j], C. Bozza[k], T. Brugière[h], F. Brunet[l], G. Brunetti[h,m,2], S. Buontempo[c], F. Cavanna[n], A. Cazes[h], L. Chaussard[h], M. Chernyavskiy[o], V. Chiarella[p], A. Chukanov[q], G. Colosimo[r], M. Crespi[r], N. D'Ambrosio[s], Y. Déclais[h], P. del Amo Sanchez[l], G. De Lellis[t,c], M. De Serio[u], F. Di Capua[c], F. Cavanna[p], A. Di Crescenzo[t,c], D. Di Ferdinando[v], N. Di Marco[s], S. Dmitrievsky[q], M. Dracos[a], D. Duchesneau[l], S. Dusini[j], J. Ebert[w], I. Eftimiopolous[e], O. Egorov[x], A. Ereditato[g], L.S. Esposito[i], J. Favier[l], T. Ferber[w], R.A. Fini[u], T. Fukuda[y], A. Garfagnini[z,j], G. Giacomelli[m,v], C. Girerd[h], M. Giorgini[m,v,3], M. Giovannozzi[e], J. Goldberg[aa], C. Göllnitz[w], L. Goncharova[o], Y. Gornushkin[q], G. Grella[k], F. Grianti[ab,p], E. Gschewentner[e], C. Guerin[h], A.M. Guler[d], C. Gustavino[ac], K. Hamada[ad], T. Hara[f], M. Hierholzer[w], A. Hollnagel[w], M. Ieva[u], H. Ishida[y], K. Ishiguro[ad], K. Jakovcic[ae], C. Jollet[a], M. Jones[e], F. Juget[g], M. Kamiscioglu[d], J. Kawada[g], S.H. Kim[af,4], M. Kimura[y], N. Kitagawa[ad], B. Klicek[ae], J. Knuesel[g], K. Kodama[ag], M. Komatsu[ad], U. Kose[j], I. Kreslo[g], C. Lazzaro[i], J. Lenkeit[w], A. Ljubicic[ae], A. Longhin[p], A. Malgin[b], G. Mandrioli[v], J. Marteau[h], T. Matsuo[y], N. Mauri[p], A. Mazzoni[r], E. Medinaceli[z,j], F. Meisel[g], A. Meregaglia[a], P. Migliozzi[c], S. Mikado[y], D. Missiaen[e], K. Morishima[ad], U. Moser[g], M.T. Muciaccia[ah,u], N. Naganawa[ad], T. Naka[ad], M. Nakamura[ad], T. Nakano[ad], Y. Nakatsuka[ad], D. Naumov[q], V. Nikitina[ai], S. Ogawa[y], N. Okateva[o], A. Olchevsky[s], O. Palamara[s], A. Paoloni[p], B.D. Park[af,5], I.G. Park[af], A. Pastore[ag,u], L. Patrizii[v], E. Pennacchio[h], H. Pessard[l], C. Pistillo[g], N. Polukhina[o], M. Pozzato[m,v], K. Pretzl[g], F. Pupilli[s], R. Rescigno[k], T. Roganova[ai], H. Rokujo[f], G. Rosa[aj,ac], I. Rostovtseva[x], A. Rubbia[i], A. Russo[c], O. Sato[ad], Y. Sato[ak], A. Schembri[s], J. Schuler[a], L. Scotto Lavina[g,6], J. Serrano[e], A. Sheshukov[q], H. Shibuya[y], G. Shoziyoev[ai], S. Simone[ah,u], M. Sioli[m,v], C. Sirignano[s], G. Sirri[v], J.S. Song[af], M. Spinetti[p], N. Starkov[o], M. Stellacci[k], M. Stipcevic[ae], T. Strauss[g], P. Strolin[t,c], S. Takahashi[f], M. Tenti[m,v,h], F. Terranova[p], I. Tezuka[ak], V. Tioukov[c], P. Tolun[d], T. Tran[h], S. Tufanli[g], P. Vilain[al], M. Vladimirov[o], L. Votano[p], J.-L. Vuilleumier[g], G. Wilquet[al], B. Wonsak[w], J. Wurtz[a], C.S. Yoon[af], J. Yoshida[ad], Y. Zaitsev[x], S. Zemskova[q], A. Zghiche[l]

CNGS Beam Layout at CERN



Timing using the GPS System

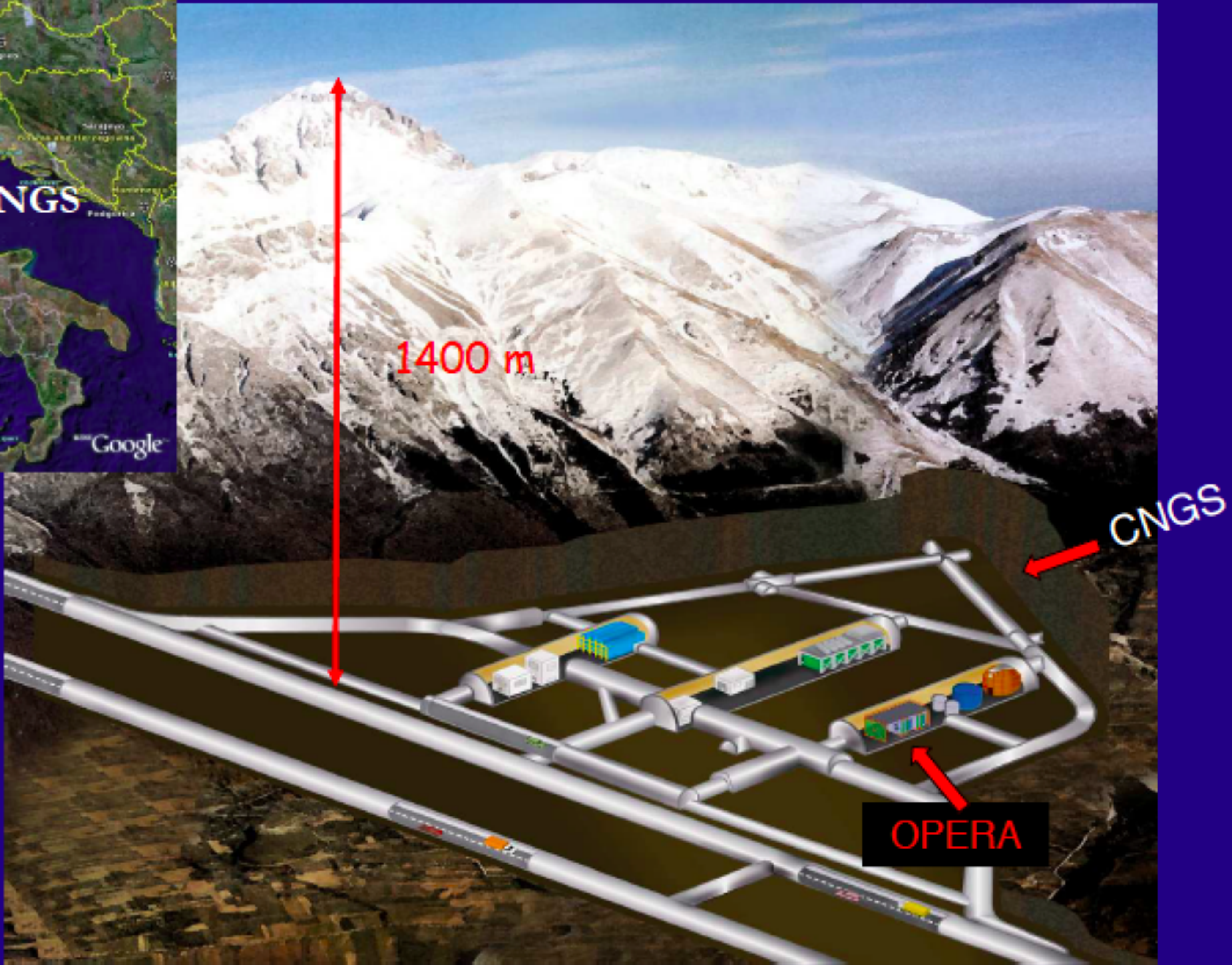


Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

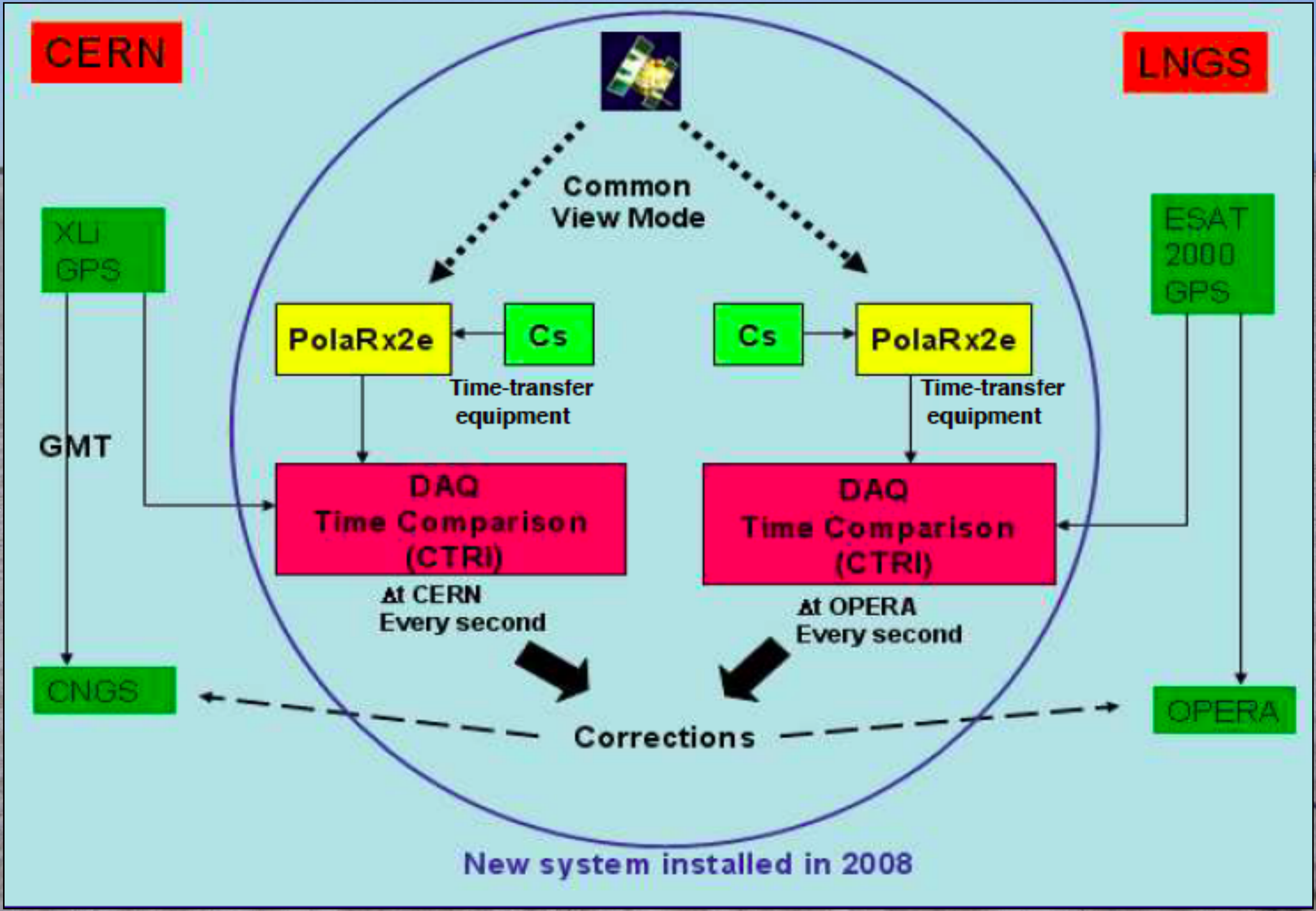
$$|T_{OPERA} - (T_{Kicker} + TOFc)| < 20\ \mu s$$

Synchronisation with standard GPS systems ~100 ns (inadequate for our purposes)

From CERN to the Gran Sasso



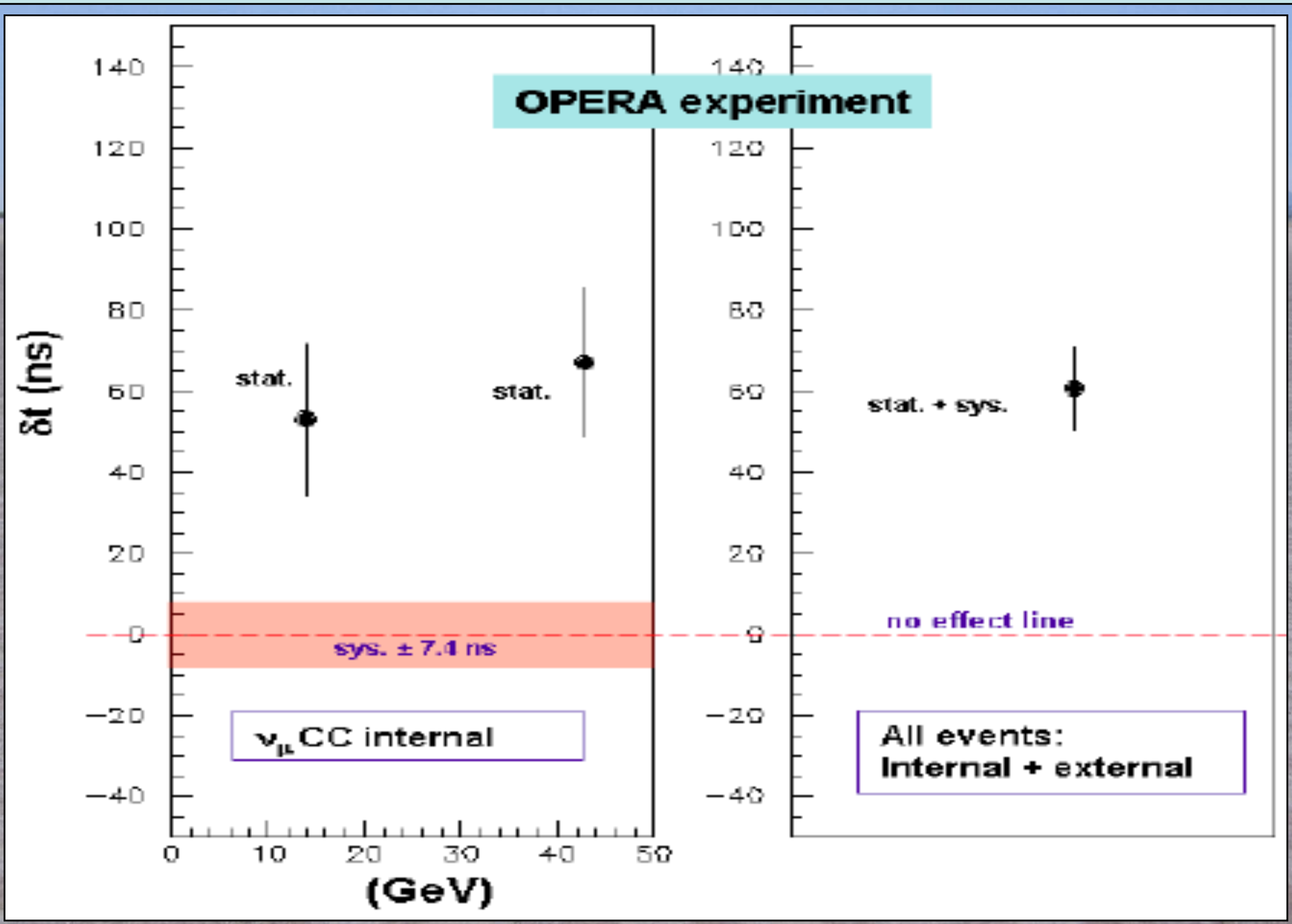
Summary of Synchronization Procedure



Summary of Timing Uncertainties

Item	Result	Method
CERN UTC distribution (GMT)	10085 ± 2 ns	• Portable Cs • Two-ways
WFD trigger	30 ± 1 ns	Scope
BTC delay	580 ± 5 ns	• Portable Cs • Dedicated beam experiment
LNGS UTC distribution (fibers)	40996 ± 1 ns	• Two-ways • Portable Cs
OPERA master clock distribution	4262.9 ± 1 ns	• Two-ways • Portable Cs
FPGA latency, quantization curve	24.5 ± 1 ns	Scope vs DAQ delay scan (0.5 ns steps)
Target Tracker delay (Photocathode to FPGA)	50.2 ± 2.3 ns	UV picosecond laser
Target Tracker response (Scintillator-Photocathode, trigger time-walk, quantisation)	9.4 ± 3 ns	UV laser, time walk and photon arrival time parametrizations, full detector simulation
CERN-LNGS intercalibration	2.3 ± 1.7 ns	• METAS PolaRx calibration • PTB direct measurement

The Main Result

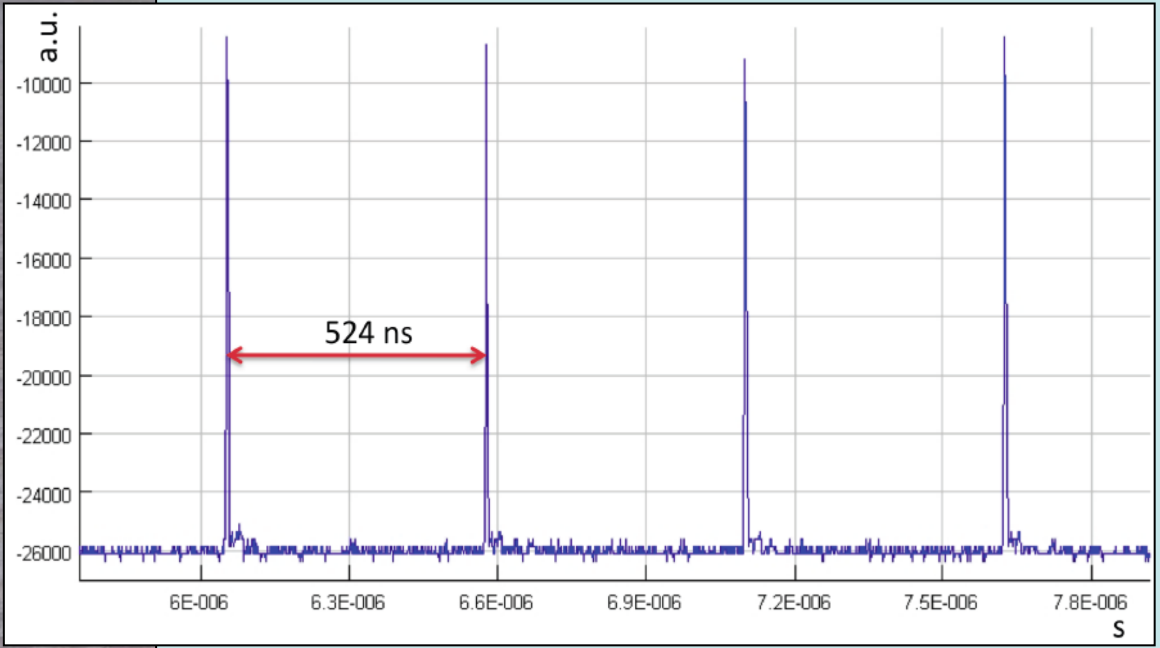


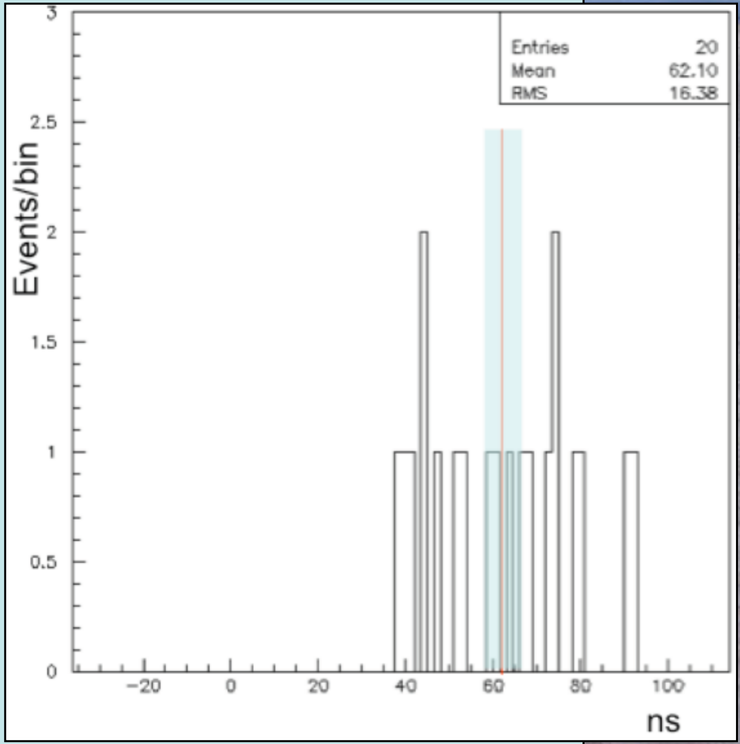
$\delta t = (60.7 \pm 6.9 \text{ (stat.)} \pm 7.4 \text{ (sys.)})$ ns

$(v-c)/c = \delta t / (TOF'_c - \delta t) = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^{-5}$

Test with Bunched Beam

- Avoid problem of modelling spill by using bunched beam:





- Reproduce same timing advance

Special and General Relativity

- Sagnac effect (rotation of Earth during travel):

$$\delta t \simeq \frac{\vec{\omega} \cdot (\vec{r}_1 \times \vec{\Delta r})}{c^2}$$: **δt = + 2.16 ns**

- Tends to increase travel time
- Smaller than total error, taken into account
- Schwartzschild effects ~ $\epsilon = \frac{r_s}{L} = \frac{2GM_e}{Lc^2} \simeq 1.2 \times 10^{-8}$

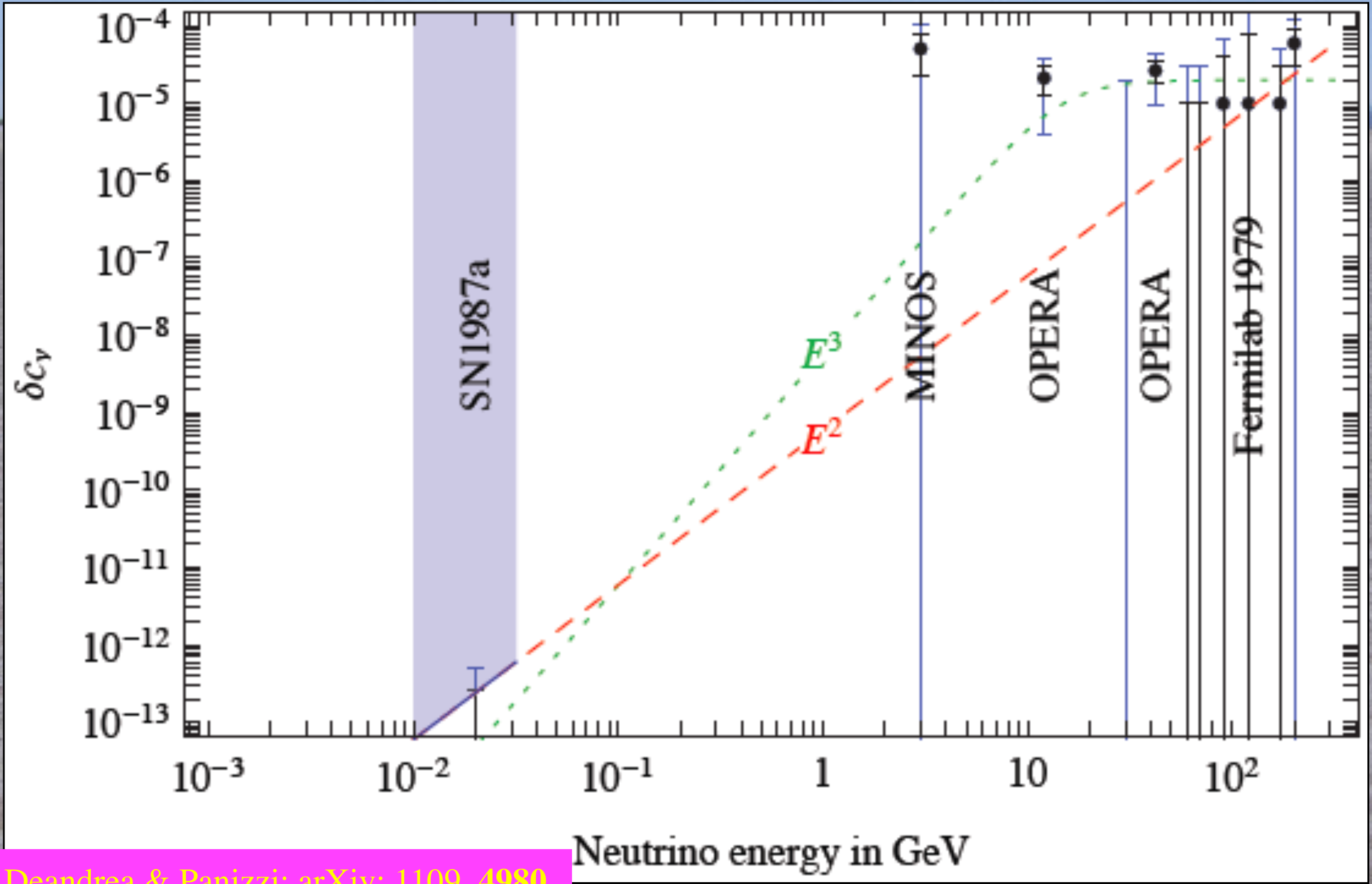
Neutrinos follow geodesic, re-evaluate Euclidean distance

$$\delta_e^{(1)} \simeq \delta_e^{(2)} = -1.22 \times 10^{-9} \quad , \quad \delta_e^{(2)} - \delta_e^{(1)} \approx \times 10^{-12}$$

- Non-inertial effects, redshifts of clocks, dipole field, frame-dragging all negligible

Kiritsis & Nitti: OPERA public note 136

Comparison of Neutrino Constraints



Cacciapaglia, Deandrea & Panizzi: arXiv: 1109. **4980**

Giudice, Sibiryakov & Strumia: arXiv: 1109. **5682**

Alexandre, JE & Mavromatos: arXiv: 1109.6296

SN1987a excludes δv ~ E or E^2

Could Neutrinos be Tachyons?

- v would approach c from above as E increases
- No non-trivial finite-dimensional unitary representations of Lorentz group for $m^2 < 0$
  - i.e., no spin-1/2 spinors
- Should spin 0 be quantized as bosons?
  - *"No"* (Feinberg) vs *"Yes"* (Sudarshan)
- Problem of causality!
  - Reinterpret backward emission of $E < 0$ as forward emission of $E > 0$?
- **Deform/break Lorentz symmetry?**

Lifshitz-Type Field Theory

- Time and space dimensions scale differently (Interesting for quantum gravity, mass generation)
- Anisotropy parameter *z*

J. Alexandre: arXiv: 1109.5629

- Model for neutrino velocity: $[t] = -z = -3,\ [x] = -1$
- Action: $S_{4ferm} = \int dt d\vec{x} \left(\overline{\psi} i \gamma_0 \dot{\psi} - \overline{\psi}(M^2 - \Delta)(i\vec{\partial} \cdot \vec{\gamma})\psi + g(\overline{\psi}\psi)^2 \right)$ $\Delta \equiv -\partial_i \partial^i = \vec{\partial} \cdot \vec{\partial}$
- Dispersion relation: $\tilde{\omega}^2 = \mu_{dyn}^2 + p^2 + \frac{2}{M^2} p^4 + \frac{p^6}{M^4}$
- Group velocity: $v_g = \frac{\partial \tilde{\omega}}{\partial p} > c$
- Superluminal propagation: $\delta v \sim E^2$

Alexandre, JE & Mavromatos: arXiv: 1109.6296

Čerenkov Radiation by Neutrinos

$$\nu_\mu \longrightarrow \begin{cases} \nu_\mu + \gamma \\ \nu_\mu + \nu_e + \overline{\nu}_e \\ \nu_\mu + e^+ + e^- \end{cases}$$

Possible if speed > light

dominant process e^+e^- Bremsstrahlung

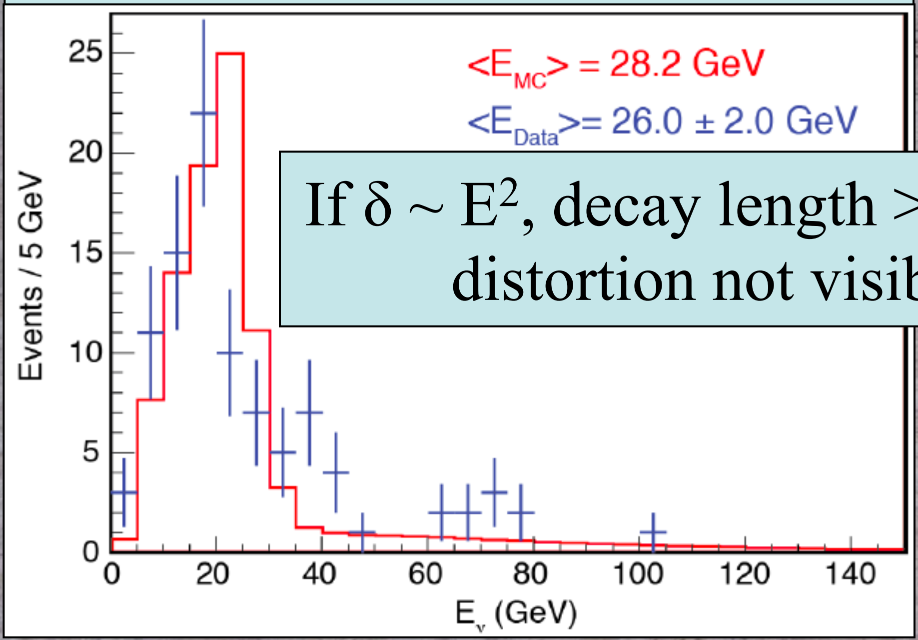
Energy loss rate: $\frac{dE}{dx} = -k\frac{G_F^2}{192\pi^3}E^6\delta^3$ $: \ k = 25/448$

- Difference between initial/final energies, terminal energy E_T: $E^{-5} - E_0^{-5} = 5k\delta^3\frac{G_F^2}{192\pi^3}L \equiv E_T^{-5}$
- Sensitive to $\delta = 2\ \delta v$ and its E dependence
- Applied to IceCube data suggests $\delta < 1.7 \times 10^{-11}$
- Does not apply to models with distorted metrics, nonlinear deformations of Lorentz symmetry

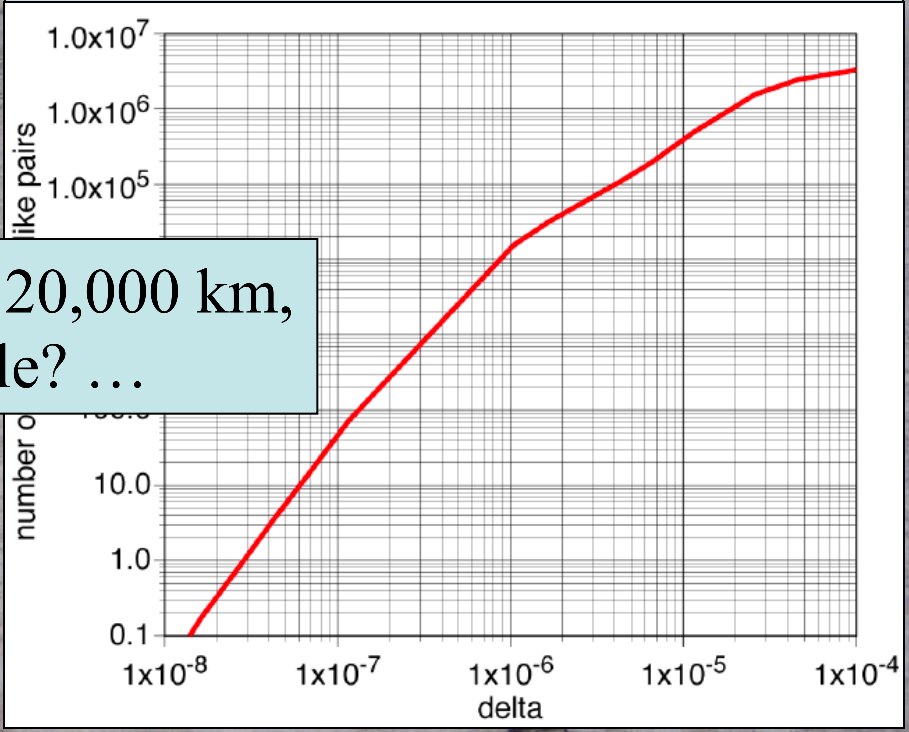
Cohen & Glashow: arXiv: 1109.6562

Constraints from ICARUS

- No visible distortion of neutrino energy spectrum



- No excess of e^+e^- pairs



If $\delta \sim E^2$, decay length > 20,000 km, distortion not visible? …

Cohen & Glashow: arXiv: 1109.6562

ICARUS Collaboration: arXiv: 1110.3763

Mohanty & Rao: arXiv: 1112.2981

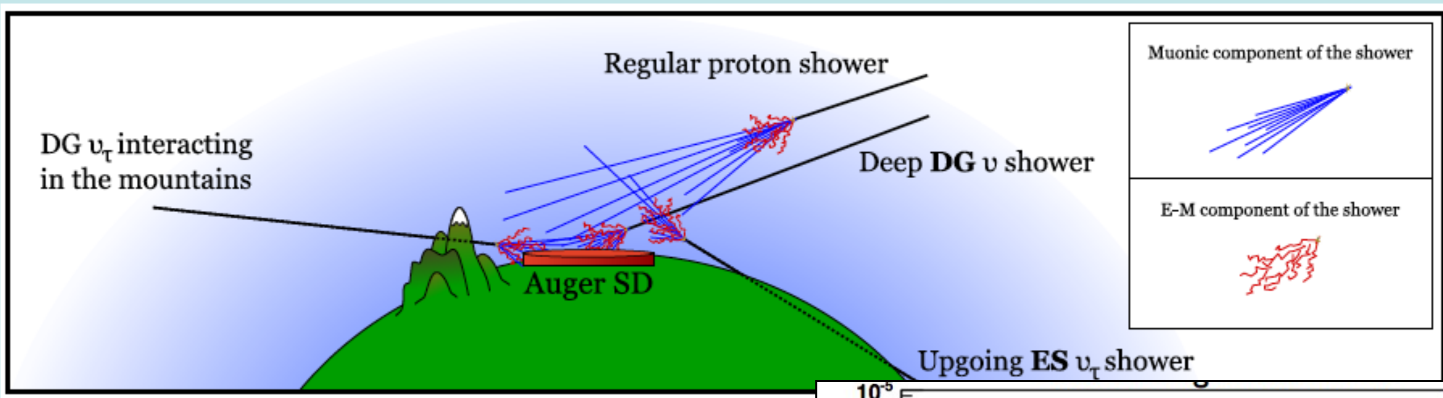
… but expect ~ 10^5 events in OPERA

The Story so far

- No technical error found
  - OPERA carried out test with separated bunches
- No theoretical error found
- Difficult to reconcile with other constraints (SN1987a, Cohen-Glashow radiation, …)
- No direct contradiction with other experiments
- Other experiments are preparing to check
- **This is how science should be done (technical scrutiny, verification, tests, theory)**

GZK Neutrinos?

- Independent probe of GZK mechanism
- Search underway with Auger, IceCube et al

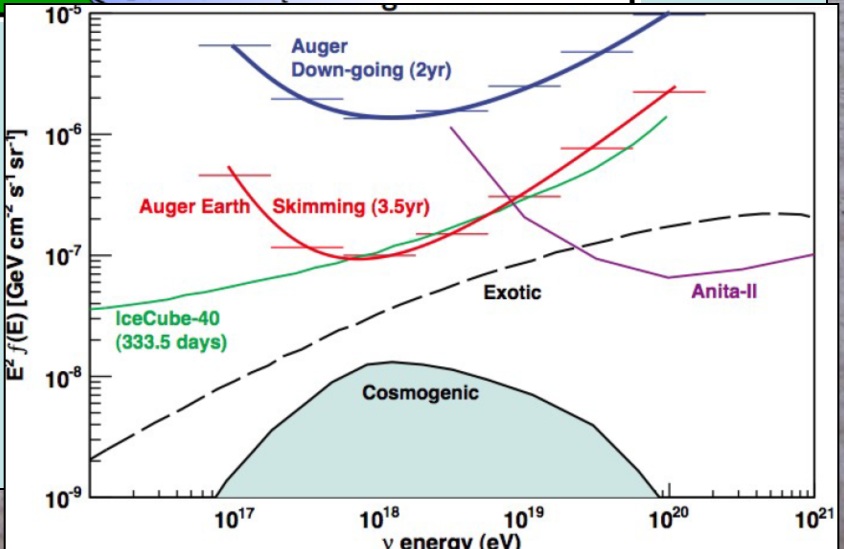


- But flux uncertain,

other possible sources

- Could also be affected by

Lorentz violation



Sensitivity to Lorentz Violation

- GZK neutrinos would be degraded by Cohen-Glashow effect (if it exists):

$$E^{-5} - E_0^{-5} = 5k\delta^3 \frac{G_F^2}{192\pi^3} L \equiv E_T^{-5}$$

- OPERA $\delta \sim 5 \times 10^{-5}$: max $E_\nu = 12.5$ GeV
- Superkamiokande limit ($E_\nu \sim 1$ TeV, $L = 10^4$ km):

  $\delta < 1.4 \times 10^{-8}$

- IceCube limit ($E_\nu \sim 16$ TeV, $L = 500$ km):

  $\delta < 3.7 \times 10^{-10}$

- GZK neutrinos (10^{20} eV, 10^8 Pc) sensitive to

  $\delta \sim 10^{-27}$

GZK Photons?

- GZK collisions also produce photons:

$$p + \gamma \rightarrow \Delta \rightarrow p + \pi^0 \rightarrow \gamma\gamma$$

- These would be absorbed by background γ's:

$$\gamma + \gamma \rightarrow e^+e^-$$

- But not in some models with Lorentz violation: conflict with Auger limit?

Maccione, Liberati & Sigl: arXiv:1003.5468

- Constraint avoided in D-brane model of space-time foam

JE, Mavromatos & Nanopoulos: arXiv:1004.4167

- Test this model via time delays in arrivals of high-energy γ's from GRBs and AGNs

Amelino-Camelia, JE, Mavromatos, Nanopoulos & Sarkar: astro-ph/9712103

Summary

- UHECR the most extreme environment for studying particle physics
  - Energy ~ 10^{11} GeV at production
  - Centre-of-mass energy in collision > 100 TeV
- No evidence of any exotic physics
  - Stay on the look-out!
- Exotic physics always possible
- Be aware of complementary experiments
  - Not just LHC, also OPERA, …

What's New? Exuberance for Novelty Has Benefits

By JOHN TIERNEY

Novelty-seeking, a personality trait long associated with trouble, turns out to be one of the crucial predictors of emotional and physical well-being.

Viktor