Experimental observation of isolated large transverse energy electrons with associated missing energy at $\sqrt{s} = 540\,\text{GeV}$

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Overview of the paper

- $p\bar{p} \to e\nu$ events previously predicted to be mediated by W boson, as in:

$$p\bar{p} \to W^{\pm} \to e^{\pm} + \nu$$

- $p\bar{p}$ collision events at UA1 in the SPS at CERN investigated for $p\bar{p} \to e\nu$
- 6 events with high-energy electrons and a neutrino of equal and opposite transverse momenta found in $18\,\mathrm{nb}^{-1}$ data set; suggests two body decay $W \to e\nu$
- mass of W is determined experimentally as

$$m_W = \left(81^{+5}_{-5}\right)\,\mathrm{GeV/c^2}$$

- experimental mass and cross-section found to be in excellent agreement with Weinberg-Salam predictions

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Particle physics up to 1983

- 1897 - electron discovered
- 1932 - positron discovered
- 1937 - muon discovered
- 1956 - (electron) neutrino discovered
- 1962 - muon neutrino discovered
- 1968 - Glashow, Weinberg and Salam formulate unified electroweak theory
- 1969 - partons observed
- 1975 - tau discovered
- 1983 - ???

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Particle physics up to 1983

- 1897 - electron discovered
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- 1937 - muon discovered
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- 1968 - Glashow, Weinberg and Salam formulate unified electroweak theory
- 1969 - partons observed
- 1975 - tau discovered
- 1983 - W and Z bosons discovered

Predictions of W mass + cross-section

$$m_W = (82 \pm 2.4)\ \mathrm{GeV/c^2}$$

$$\sigma(p\bar{p} \to W^{\pm} \to e^{\pm} + \nu) \simeq 0.4 \times 10^{-33} k\ \mathrm{cm}^2 = 0.4k\ \mathrm{nb}$$

- k is an enhancement factor of ~ 1.5
- in $18\,\mathrm{nb}^{-1}$ sample, would expect $\sim 18 \times 0.4k = 7.2k$ events

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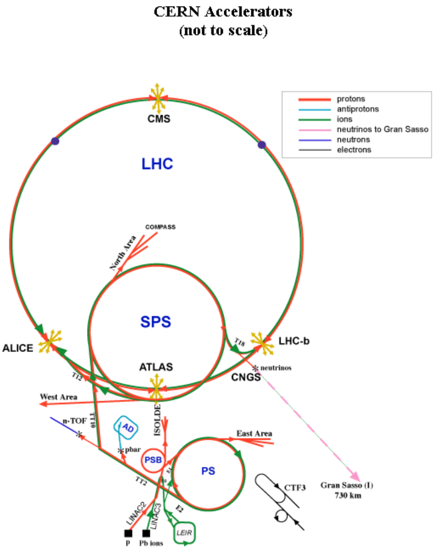
Super Proton Synchrotron (SPS) @ CERN



- 1957 - Synchrocyclotron starts up
- 1959 - Proton Synchrotron starts up
- 1976 - Super Proton Synchrotron starts up
- 1989 - LEP first injection
- 1999 - Antiproton Decelerator approved
- 2000 - LEP final shutdown
- 2008 - LHC starts up

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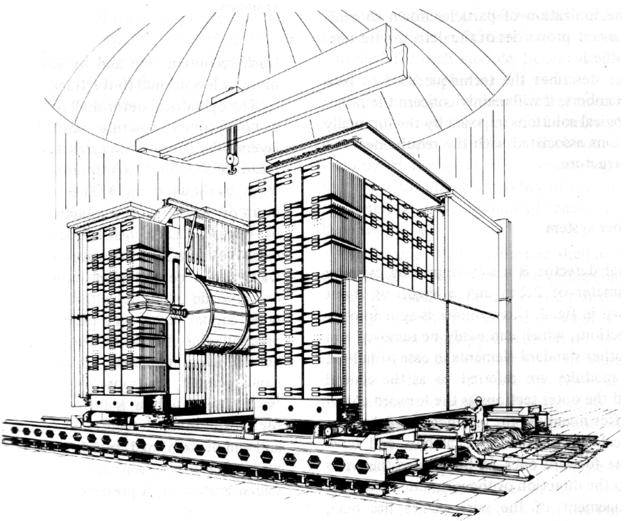
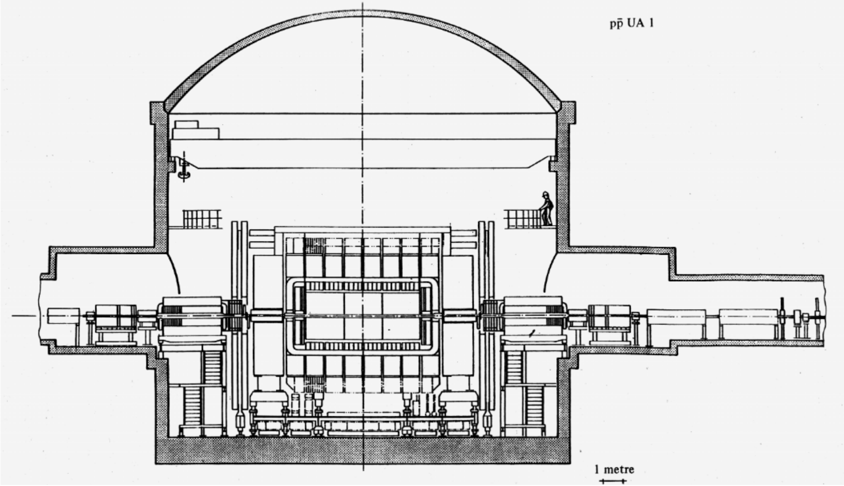
Underground Area 1 (UA1) - detector



Underground Area 1 (UA1) - detector



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Underground Area 1 (UA1) - detector

- ran from 1981 until 1990
- moveable detector (see also UA2) custom built around SPS for $p\bar{p}$ collisions
- could be rolled back to allow fixed-target operation of SPS

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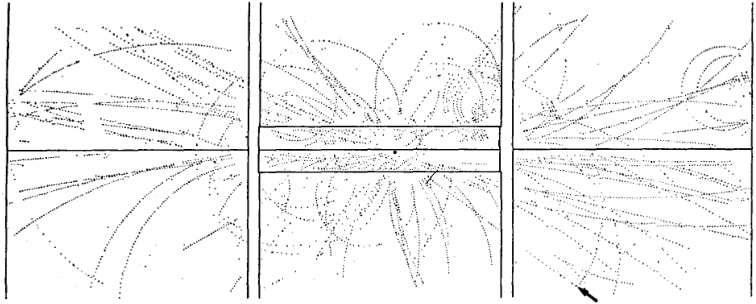
Underground Area 1 (UA1) - detector

- transverse dipole magnet produced uniform field of 0.7T over $7 \times 3.5 \times 3.5\text{m}^3$
- central detector = six-chambered cylinder, 5.8 m length, 2.3 m diameter
- produced bubble-chamber quality pictures of each interaction



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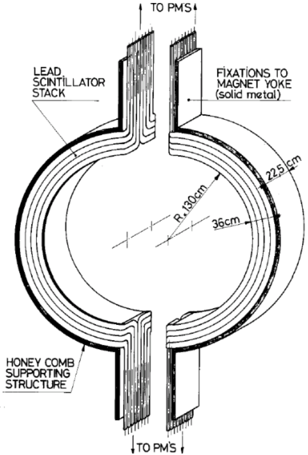
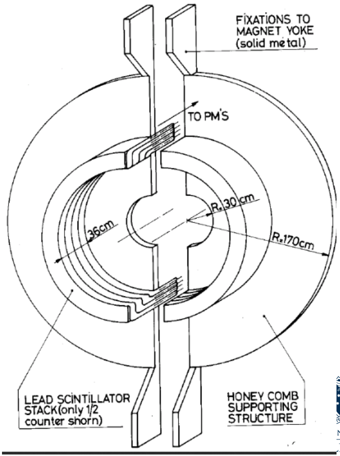
Underground Area 1 (UA1) - detector

- 48 barrel EM calorimeters, called 'gondolas'

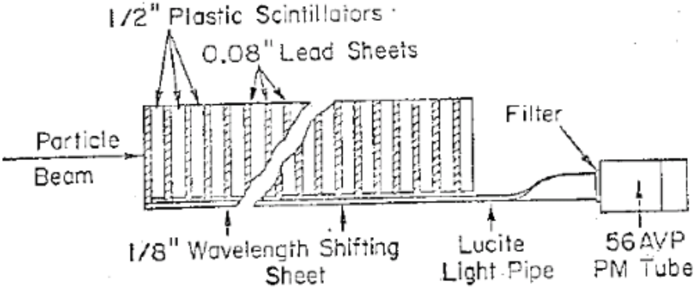


- 64 end-cap EM calorimeters, called 'bouchons'



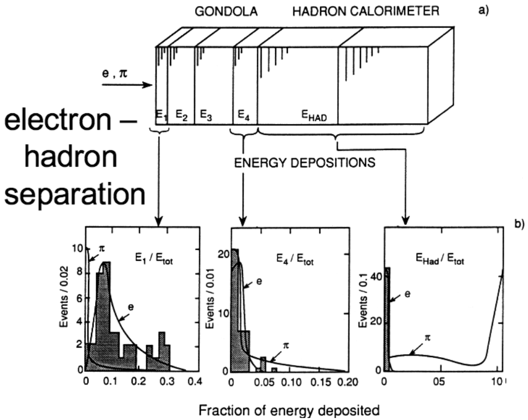
Underground Area 1 (UA1) - detector

- transverse energy E_T a very important variable; attenuation length of scintillators in calorimeter are arranged to match variation over $\sin\theta$
- from this $E_T = E \sin\theta$ can be directly measured



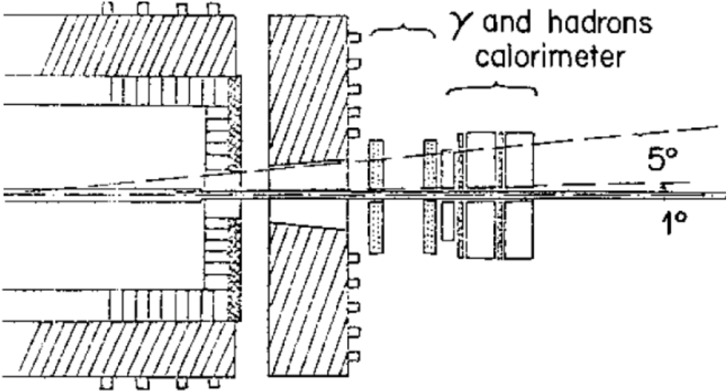
Electron/hadron separation

- electromagnetic showers identifed by characteristic transition curve
- 90% of electrons are detected



Neutrino identification

- emission of neutrinos signalled via missing energy
- calorimeters are completely hermetic down to 0.2° in forward regions



Data taking

- proton and anti-protons collided at $\sqrt{s} = 540\,\mathrm{GeV}$
- $18\,\mathrm{nb}^{-1}$ data set ($\sim 10^9$ collisions), collected at UA1
- recorded over 30 days during November and December 1982
- triggers were used to select events of interest

Triggers

- four initial event selections are performed:
  (1) at least 10 GeV of E_T in 2 gondolas or 2 bouchons
- with three other specific triggers for electron events:
  (2) jet trigger: ≥ 15 GeV of E_T in localised EM/hadron calorimeter
  (3) global E_T trigger: > 40 GeV of total E_T; $|\eta| < 1.4$
  (4) muon trigger: at least one track with $|\eta| < 1.3$

- of 9.75×10^5 events trigger, 1.4×10^5 passed the above trigger selection, i.e. characterised by electron trigger flag

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Offline selection

- number of events reduced to 27,000 after initial offline selection (using calorimeter)
    - $E_T > 15\,\text{GeV}$ in two gondolas, or
    - $E_T > 15\,\text{GeV}$ in two bouchons with valid position information
- again reduced with drift chamber reconstruction, requiring good quality, vertex-associated charged track of $p_T > 7\,\text{GeV/c}$
    - 2,125 events remaining

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Electron candidate selection

- from sample of 2,125 events, a final set of selections are applied to select for electrons
- three cuts are made in succession to reduce jet debris
  - 167 events remaining
- two cuts are made to optimise selection for electromagnetic properties
  - 39 events remaining

Electron candidate selection

- these 39 events are processed manually in Megatek and classified as:
  (1) 5 events - jetless
  (2) 11 events - jet opposite track within 30° angle of ϕ
  (3) 23 events - two jets (one containing electron candidate) or e^+e^- conversion pair
- events with jets show no missing energy; jetless events show missing transverse energy almost exactly back-to-back to electron candidate

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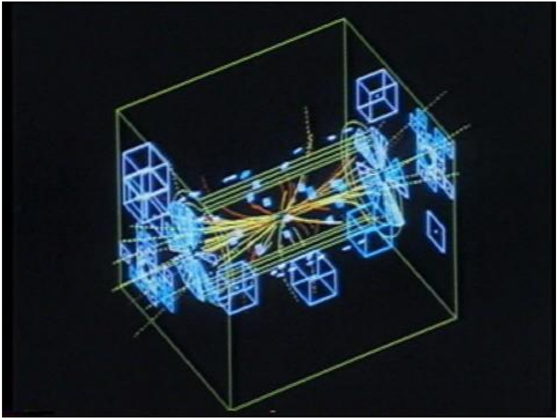
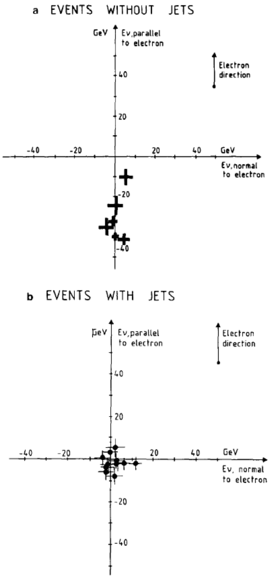
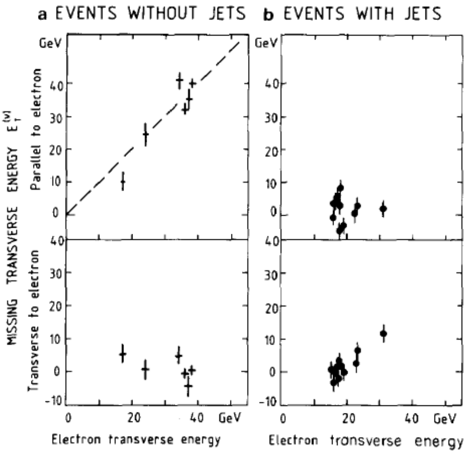
An aside - Megatek



- Megatek examples (short movie) available at `bit.ly/2236tws`

Electron candidate selection





Energetic neutrino candidate selection

- from sample of 2,125 events, a different set of selections are applied to search for energetic neutrinos
- based exclusively on presence of missing E_T
- two simple cuts are made to select high missing E_T and candidate track not part of jet
  - 70 events remaining
- remaining events are processed manually, and two more cuts are applied
  - 18 events remaining

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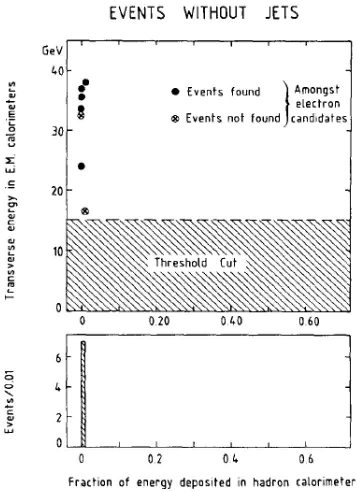
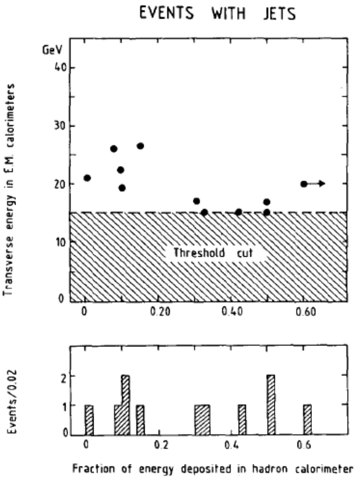
Energetic neutrino candidate selection





Energetic neutrino candidate selection

- from E_c consideration, events with jets are deduced as hadronic events; the jetless events constitute an electron sample
- five of the seven jetless events match the jetless events from electron candidate selection

Detailed event description

Table 2
Main parameters of electron events with a large missing transverse energy.

Run, event	Properties of the electron track										Calorimeter information					General event topology				
											Electromagnetic energy deposition									
	E_T	E	p	Δp a)	Q	dE/dx I/I_0	y b)	Track No.	Length	Sagitta	Sample 1	Sample 2	Sample 3	Sample 4	E_{had}	E_{tot}	Missing E_T	$\Delta\phi$ c)	Charged tracks	$\sum\lvert E_T\rvert$
	(GeV)	(GeV)	(GeV/c)						(m)	(mm)	(GeV)	(GeV)	(GeV)	(GeV)	(GeV)	(GeV)	(GeV)	(deg.)		(GeV)
A 2958 1279	26	42	33.8	+6.3 −4.6	−	1.22 ±0.2	+1.1	36	1.36	1.7	4	35	3	0.2	0	278	24.4 ± 4.6	179	65	81
B 3522 214	17	46	47.5	+8.2 −6.1	−	1.37 ±0.16	+1.7	18	1.64	1.5	2	32	10	0.5	0	296	10.9 ± 4.0	219	49	60
C 3524 197	34	45	21.6	+21.8 −7.2	−	1.37 ±0.3	−0.8	26	1.25	2.11	1	30	14	0.2	0	367	41.3 ± 3.6	187	21	68
D 3610 760	38	40	33.4	+33.0 −11.1	−	1.64 ±0.34	+0.3	9	0.98	0.75	3	9	26	2.2	0.4	111	40.0 ± 2.0	181	10	47
E 3701 305	37	37	56.2	+121.3 −22.8	+	1.54 ±0.28	−0.1	12	0.95	0.4	1	18	17	0.9	0	363	35.5 ± 4.3	173	39	87
F 4017 838	37	70	53.1	+6.6 −5.3	−	1.30 ±0.26	+1.4	3	2.01	2.0	19	48	3	0.3	0	177	32.3 ± 2.4	179	14	49
G 3262 1108	40	40	6.7	+1.9 −1.2	−	1.23 ±0.28	0.0	21	0.85	3.0	2	22	15	0.9	0	218	33.4 ±2.9	172	21	63

a) Including 200 μm systematic error. b) y is defined as positive in the direction of the outgoing $\bar{p}$.
c) Angle between electron and missing energy (neutrino).

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Background evaluations

- possible backgrounds:
  (1) high p_T $\pi^{\pm}$ misidentified as an electron or overlapping with one or more π^0
  (2) high p_T π^0, η^0 or γ converted to e^+e^- pair with one side missed
  (3) heavy quark production, with $Q_1 \to e(\nu X)$ and $Q_2 \to \nu(\ell X)$ and only the electron and neutrino being detected
- none of these background processes were shown to have occured; the final events are concluded to be high-energy electron events

A promising conclusion?

- presence of electron and neutrino of approximately equal and opposite transverse momenta suggests two body decay
- e.g. $W \to e + \nu_e$

Determining W mass

- lower limit on m_W can be determined through $m_W \geq m_T$

$$m_T^2 = 2p_T^{(e)}p_T^{(\nu)}(1 - \cos\phi_{\nu e})$$

$$m_W > 73\,\mathrm{GeV/c^2}\text{at } 90\%\text{ CL}$$

Table 3
Transverse mass and transverse momentum of a W decaying into an electron and a neutrino computed from the events of table 2.

Run, event	$p_T^{(e)}$ of electron (GeV/c)	$p_T^{(\nu)}$ = missing E_T (GeV)	Transverse mass (GeV/c)^2	$p_T^{(W)} = \lvert p_T^{(e)} + p_T^{(\nu)} \rvert$ (GeV)
A 2958 1279	24 ± 0.6	24.4 ± 4.6	48.4 ± 4.6	0.6 ± 4.6
B 3522 214	17 ± 0.4	10.9 ± 4.0	26.5 ± 4.6	10.8 ± 4.0
C 3524 197	34 ± 0.8	41.3 ± 3.6	74.8 ± 3.4	8.6 ± 3.7
D 3610 760	38 ± 1.0	40.0 ± 2.0	78.0 ± 2.2	2.1 ± 2.2
E 3701 305	37 ± 1.0	35.5 ± 4.3	72.4 ± 4.5	4.7 ± 4.4
F 4017 838	36 ± 0.7	32.3 ± 2.4	68.2 ± 2.6	3.8 ± 2.5

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Determining W mass

- final fit corrects for transverse W motion and uses Drell-Yan predictions with no smearing
- mass given for fit on electron energy and angle and neutrino E_T is

$$m_W = \left(81^{+5}_{-5}\right)\ \mathrm{GeV/c^2}$$

- excellent agreement with Weinberg-Salam model expected mass ($m_W = (82 \pm 2.4)$ GeV/c^2)
- number of observed events (6) consistent with cross-section estimates ($\sim 7.2k$)

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End

- Thank you for your attention
- Questions?