Selected Results from UA1 at the CERN Sp$\bar{p}$S Collider

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Little Doggie is watching you!

UTeV Lecture – 8 July 2004

My Experience in Particle Physics

- Aug. 82 to Aug. 83 – ISR experiment R608
- Jan. 84 to Jan. 89 – Graduate student on UA1
- Feb. 89 to Dec. 92 – Post. Doc. on Opal
- Jan. 93 to Jun. 97 – Wilson Fellow on CDF
- Jul. 97 to present – Professor at Penn

Current research is at Tevatron (CDF)

Future research will be on LHC (ATLAS)

Photo: 1st St. Ocean City, NJ. with Atlantic City in the background. 7 Feb. '04, H_20 is 1° C

Why Hadron Colliders

- In e^+e^- collisions collide pointlike constituents
- All $\sqrt{s}$ available to produce new particles
- The problem is synchrotron radiation

$$\delta E = \frac{4\pi}{3}\frac{e^2}{R}\beta^3\gamma^4 \propto \frac{E^4}{Rm^4}$$

If E → 2E, R → 16R, for same δE!

E Loss from Synchrotron Radiation

At LEP (R=4.24 km) with 100 GeV electrons:

$$\delta E(\mathrm{MeV}) = 8.85 \times 10^{-5} \frac{[E(\mathrm{GeV})]^4}{R(\mathrm{km})}$$

Aside: Does synch. rad. limit a linear e^+e^- collider?

= 2.1 GeV

At Tevatron (R= 1.0 km) with 1 TeV protons:

$$\delta E(\mathrm{KeV}) = 7.8 \times 10^{-3} \frac{[E(\mathrm{TeV})]^4}{R(\mathrm{km})}$$

Aside: What about the LHC – does it matter? Why or why not?

= 7.8 eV

So What Limits Proton Machines?

1. Larger momentum means higher field dipoles

LEP: 0.135 T (peak field)

TeV: 4.4 T (super conducting)

LHC: 8.3 T (super conducting)

Proton machines limited by dipole field strength

2. Why did Tevatron (and SppS) use antiprotons?

Only had one set of existing dipoles

Have to have countercirculating beams

What about the LHC?

Antiprotons

- They are not abundant – have to make them!
- Need extra components in accelerator complex
  - CERN "Antiproton Accumulator" or "AA"
    - Pioneered "stochastic cooling" S. Van der Meer
  - FNAL antiproton "Accumulator" and "Recycler"
- Antiprotons are the ultimate limit to luminosity
  - FNAL Run II: "Main Injector" built to increase rate of antiproton production by factor 3

Hadron Colliders

- Past: 1st proton collider CERN ISR (60 GeV)
- Past: 1st p $\bar{p}$ collider CERN Sp$\bar{p}$S (540 and 630 GeV, ramped to 900 GeV)
- Present: Fermilab Tevatron p $\bar{p}$ collider (1.8 and 1.96 TeV, also 630 GeV)
- Cancelled: SSC 40 TeV proton-proton
- Future: LHC 14 TeV proton-proton

Intersecting Storage Rings (ISR)

- Two separate rings, 300 m in diameter
- 8 intersection regions (called “R1”, …, “R8”)
- Storage ring, no acceleration, beams from PS
- Commissioned Jan. ’71, closed Jun. ’84
- 1st proton storage ring, proton-proton collider
- Center of mass energy about 60 GeV max.
- Also collided antiprotons on protons

CERN Accelerator Complex Early 80's

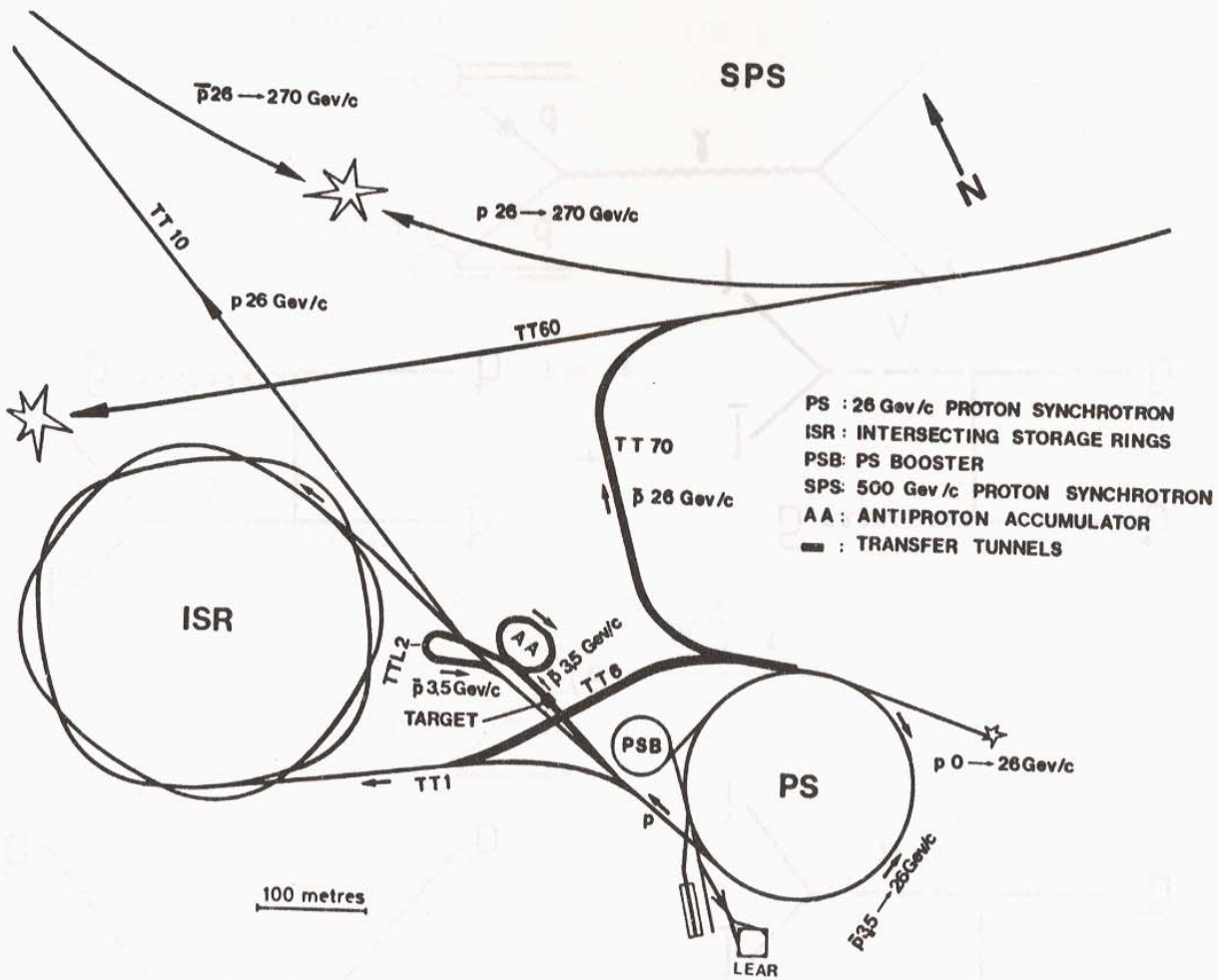


Fig. 8

Did not dig a tunnel
Buried under dirt

Two separate storage rings

CERN SPS (and Sp$\bar{p}$S)

- Began as a proton synchrotron ($2\pi R$=6.9 km)
- Commissioned in ’76 at 300 GeV, later 400
- Converted to proton antiproton collider in ’81
- $p\bar{p}$ center of mass 540 GeV, then 630
- “Ramping Run” went to 900 GeV
- Peak luminosity 6×10^{30} cm^{-2} s^{-1}
- 6×6 bunches, 3.8 μs between collisions
- Also accelerated e^+, e^-, heavy ions, etc.

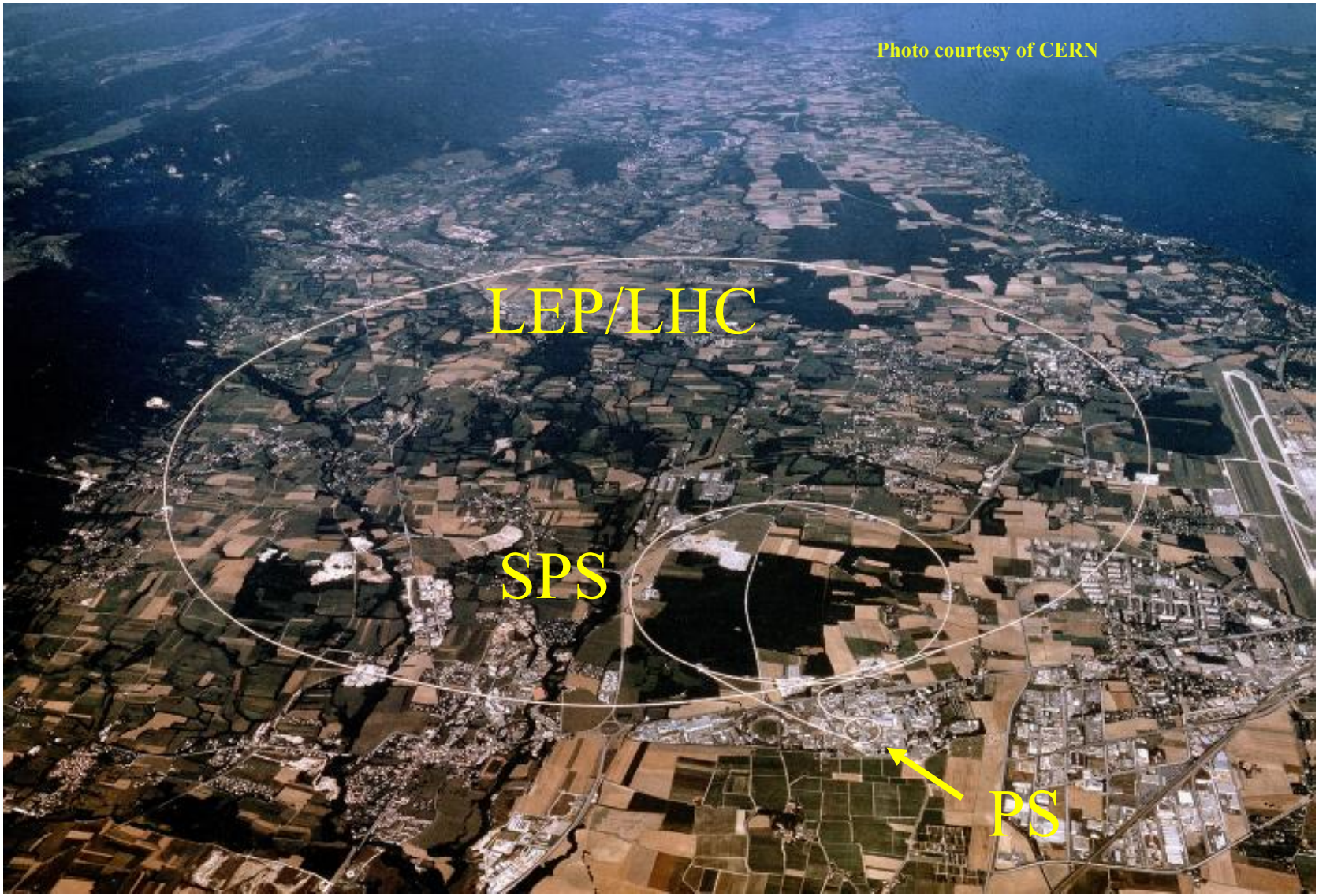


Photo courtesy of CERN
LEP/LHC
SPS
PS

The CERN Antiproton Accumulator & Antiproton Collector

Inside the SPS tunnel

Hadrons are Complicated

- Protons (and antiprotons) are not fundamental pointlike particles (like leptons and quarks)
- Constituents of the proton called "partons:"
  - Valence quarks: u, u, d
  - Sea quarks and antiquarks: u, $\bar{u}$, d, $\bar{d}$, s, $\bar{s}$, c, $\bar{c}$, …
  - Gluons: g (carry color and "anticolor")
- Partons described by "structure functions"
- Physics described by QCD (in principle)

Hadron Collisions Dominated by "Soft" Nonperturbative Processes

- **Elastic**
  - Proton and antiproton scatter like billiard balls
  - Kinetic energy conserved
- **Diffractive**
  - Either proton or antiproton breaks up (other intact)
  - Energy from shattered particle makes new particles
- **Inelastic**
  - Both proton and antiproton break up
  - Excess energy produces particles

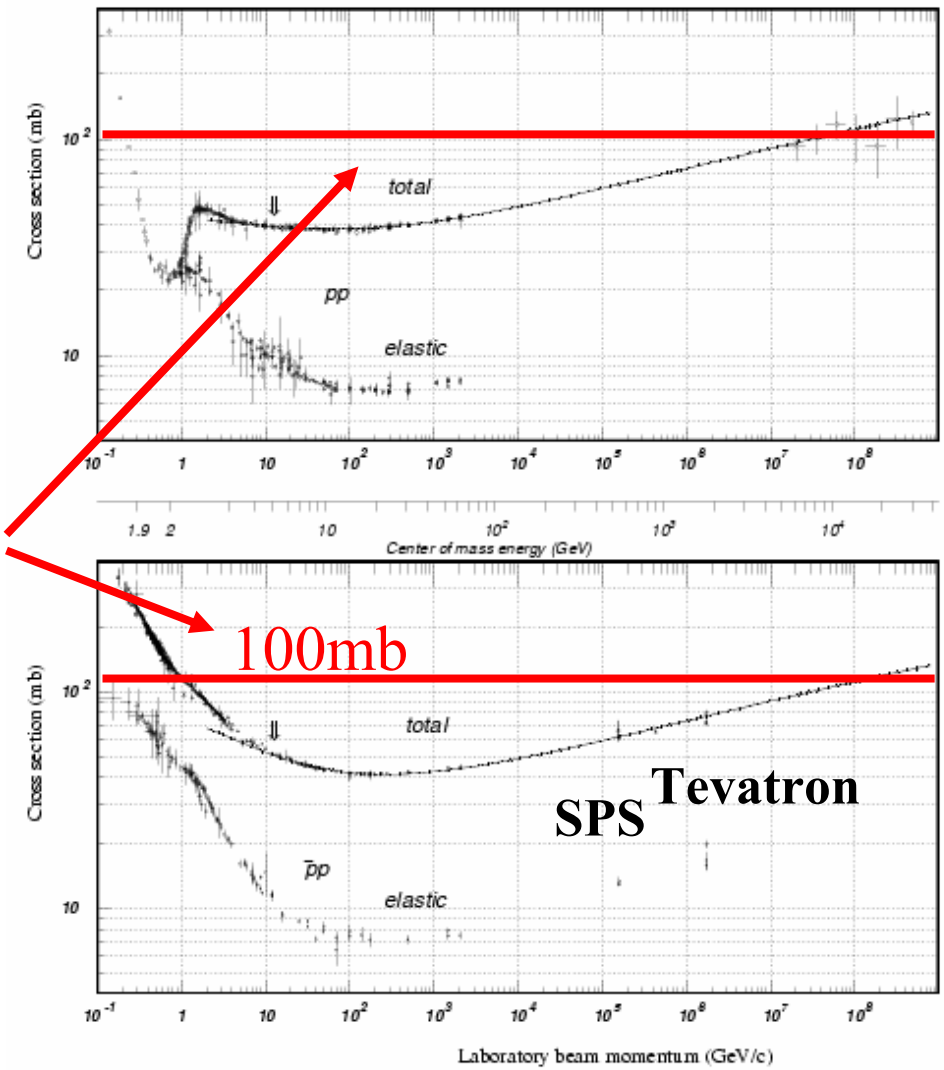
Total and Elastic Cross-section

Total is the sum of Elastic, diff., inelas.

$\sigma_{total} \sim 100$ mb

Rare processes (W, top, Higgs)
$\sigma \sim$ nb, pb, fb
$1{:}10^8$, $1{:}10^{11}$, $1{:}10^{14}$

Figures courtesy of PDG 2002



Convenient Variables

Inclusive particle cross sections:

$$\frac{Ed^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi p_T dp_T dy} \longrightarrow \frac{d^2\sigma}{\pi dp_T^2 dy}$$

Conveniently recast in p_T and y:

$$p_T = \sqrt{p_x^2 + p_y^2} \quad y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

z is the direction of the proton-antiproton beam axis

$$dy = \frac{dp_z}{E}$$

Rapidity and Pseudorapidity (η)

Rapidity change under Lorentz boost is constant

$$y \rightarrow y' = y + \tanh^{-1} \frac{v}{c}$$

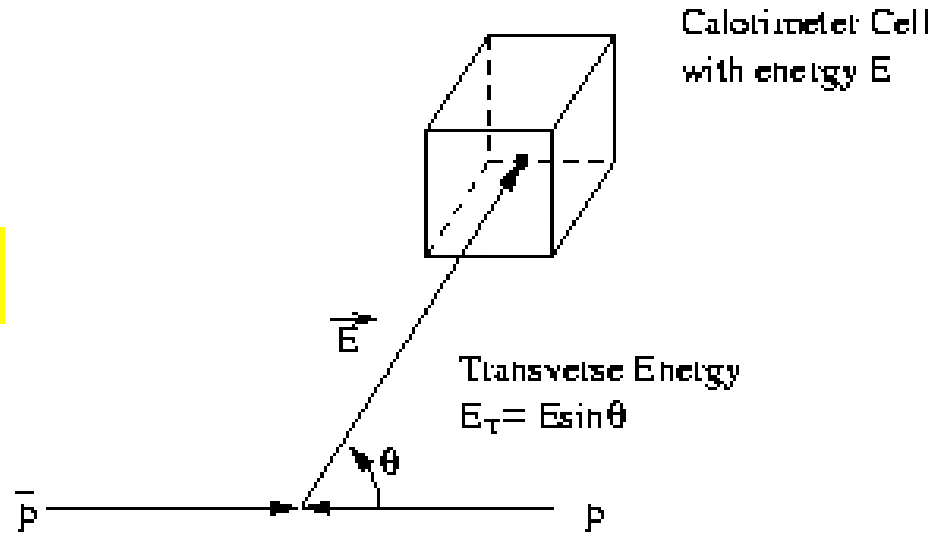
→ Rapidity differences cancel in Lorentz boost

For p>>m ("massless") use "pseudorapidity"

$$\eta = -\ln(\tan \frac{\theta}{2}) \qquad cos\theta = \frac{p_z}{p}$$

Transverse Energy E_T

Relativistic particles ($\beta \sim 1$) $E \approx pc$



Energy "vector"
- points from interaction pt to calorimeter cell
- magnitude is E

Transverse energy:
Component of Energy vector perpendicular to beam line

Scalar E_T sum $\sum E_T = \sum_{cells} |\vec{E}_T|$

Also Called: E_T^{ν} **Vector sum Missing E_T** $\Delta E_T = -\sum_{cells} \vec{E}_T$

Inclusive Particle production

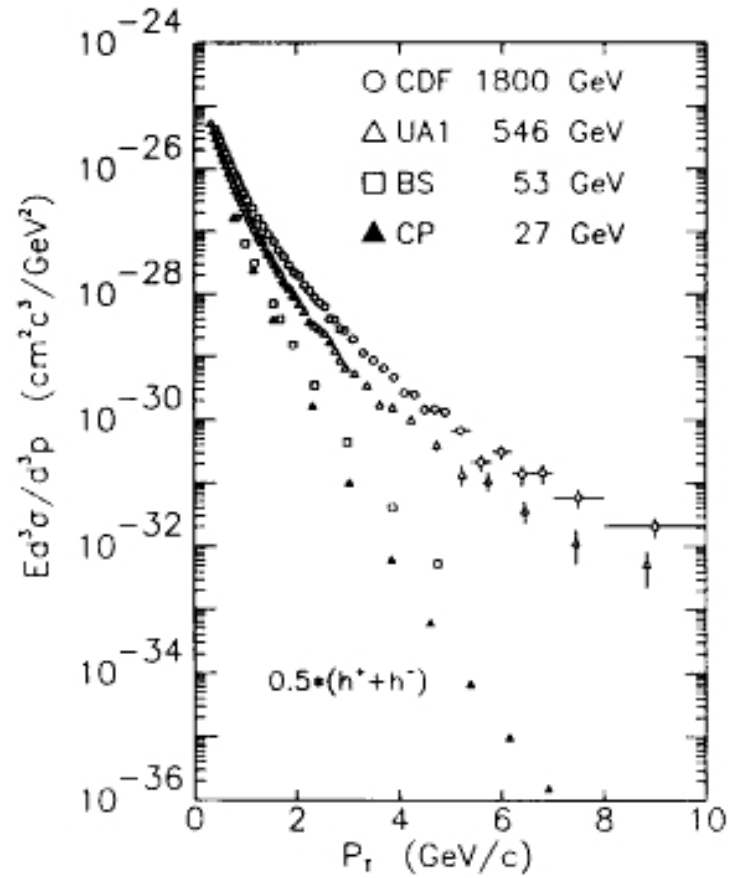
p_T spectrum steeply falling

$$E\frac{d^3\sigma}{d^3p} = A\frac{p_0^n}{(p_T+p_0)^n}$$

n is large ~ 10

TABLE I. Fit parameters of $E\,d^3\sigma/d^3p = Ap_0^n/(p_T+p_0)^n$. Quoted errors are purely statistical.

$\sqrt{s}$ (GeV)	Fit interval (GeV/c)	A [10^{-24} cm^2/(GeV^2/c^3)]	p_0 (GeV/c)	n	χ^2	N_{DF}
1800	0.4–10.0	0.45 ± 0.01	1.29 ± 0.02	8.26 ± 0.08	102	64
	0.5–10.0	0.45 ± 0.01	1.29 ± 0.02	8.26 ± 0.07	90	62
	0.5–5.0	0.47 ± 0.01	1.25 ± 0.01	8.12 ± 0.05	86	59
630	0.4–4.0	0.27 ± 0.01	1.63 ± 0.13	10.2 ± 0.56	32	33
1800	0.4–10.0	0.45 ± 0.01	1.30 fixed	8.28 ± 0.02	103	65
630	0.4–4.0	0.33 ± 0.01	1.30 fixed	8.89 ± 0.06	39	34
546 (UA1)	0.3–2.0	0.46 ± 0.01	1.30 fixed	9.14 ± 0.02	29	32



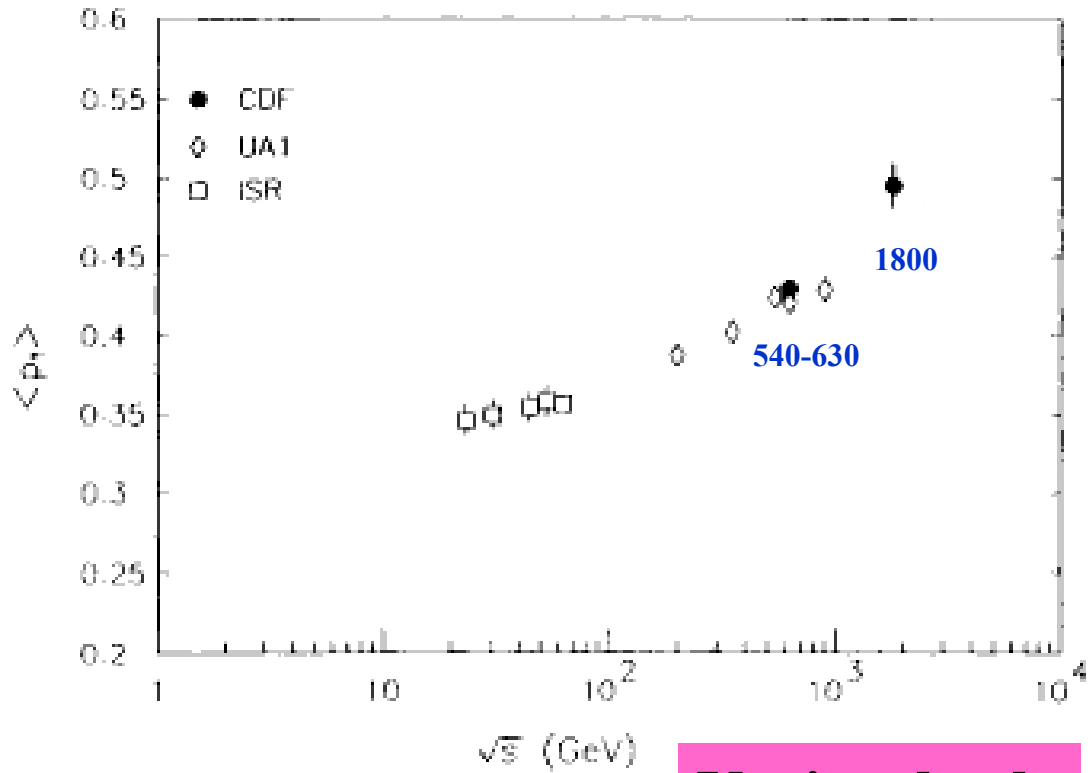
The CDF Collaboration
F. Abe *et al.* PRL 61 (1988) p. 1819

Inclusive Particle production

The CDF Collaboration
F. Abe *et al.* PRL 61 (1988) p. 1819

Average Transverse momentum

$\langle p_T \rangle$ ~ few 100 MeV



Varies slowly with √s

Inclusive Particle production

UA1 Collaboration
Phys. Lett. 118B (1982) p. 173

"Interesting" physics occurs at high p_T

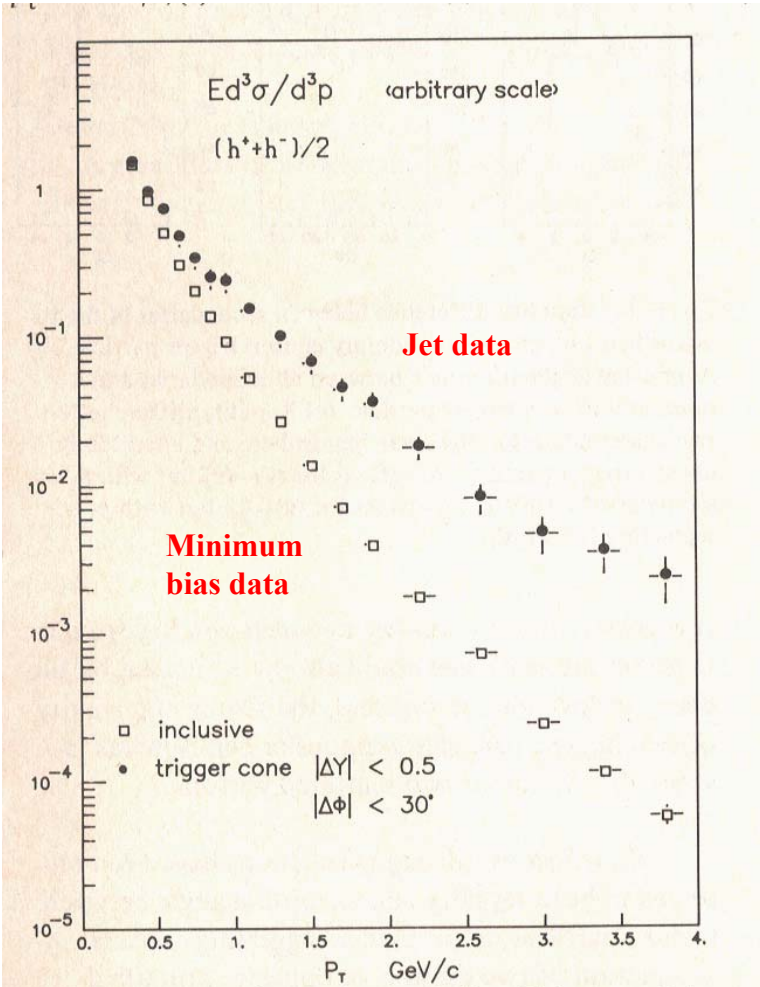
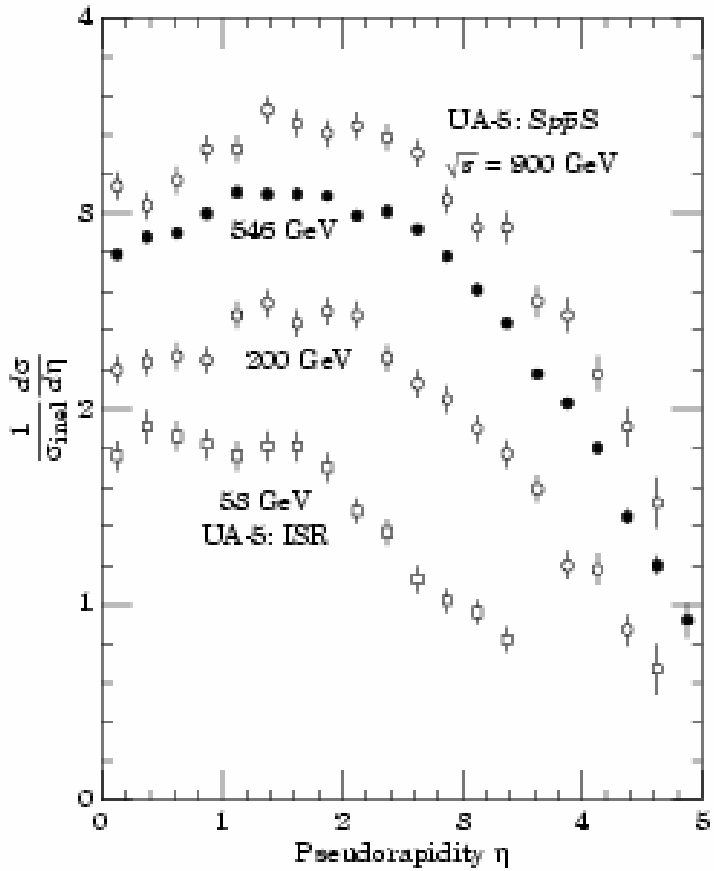


Fig. 3. p_T spectrum of towards secondaries within $\Delta y = \pm 0.5$

Inclusive Particle production

- Rapidity plateau
  - Height of plateau increases with √s
  - Extends out further in η with increasing √s

Heavy particles (b, t, W, …) are produced centrally



Hard Scattering

- Previous slides described "soft" phenomena

  not easily calculable with perturbation theory
- Hard scattering (large Q^2) $\rightarrow$ α_s becomes small

  perturbation theory applicable
- Determination of cross-section for specific process includes
  - Calculation of the fundamental process $d\sigma/dt$ (can be QCD or EW)
  - Convolution of $d\sigma/dt$ with parton distributions or structure functions *F*
  - Outgoing quarks and gluons must be evolved to hadrons (fragmentation or hadronization): described by a fragmentation function *D*
- QCD processes dominate the hard cross-section
- For these NLO processes can be important

Parton Distribution Functions

Protons consist of
- Valence quarks
- Sea quarks
- Gluons

How the parton distribution functions are mapped out

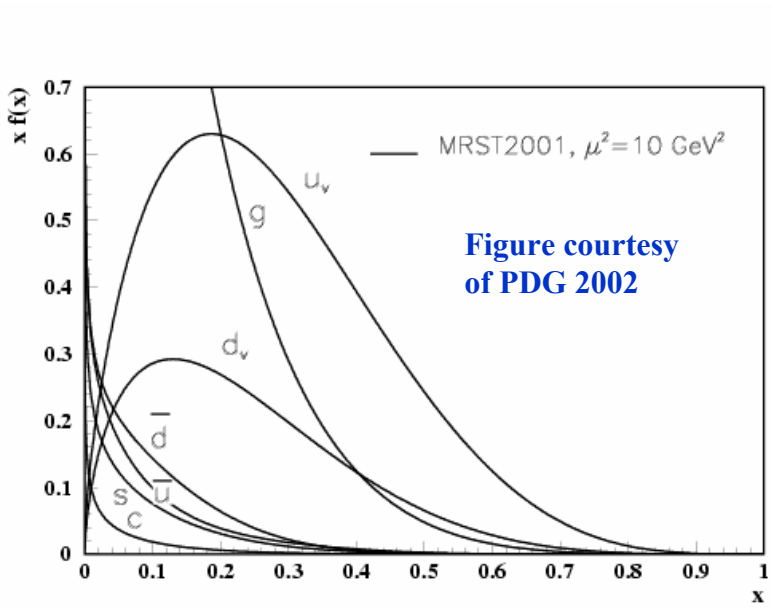


Figure courtesy of PDG 2002

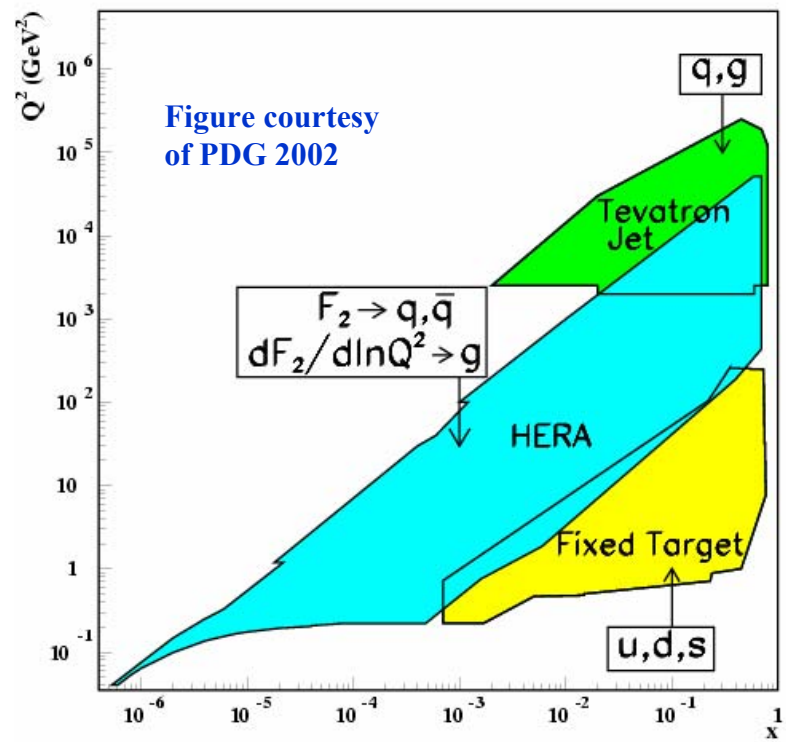


Figure courtesy of PDG 2002

Perturbative QCD Works Well!

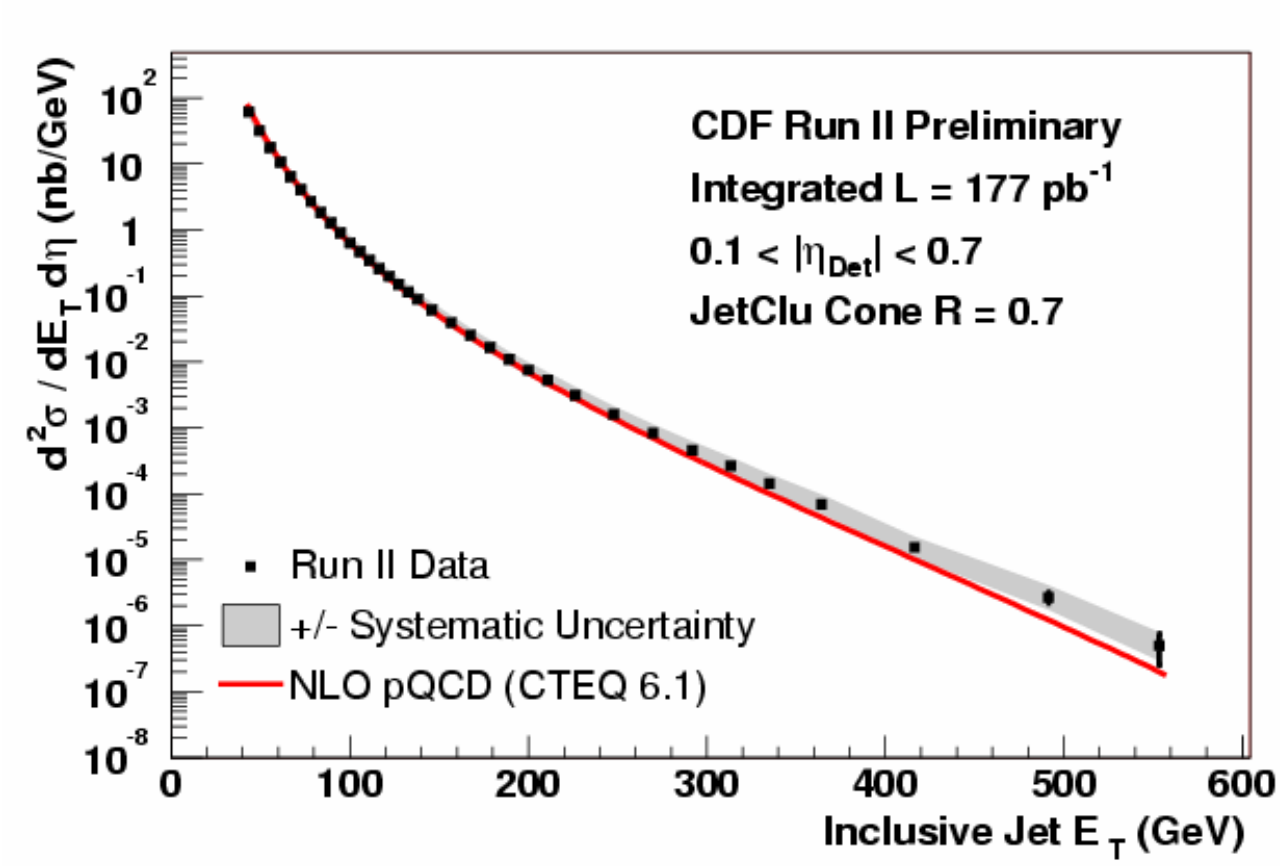
Preliminary inclusive jet cross section measurement from CDF II

Jets from scattered quarks and gluons

Triumph for exper. and theory

Measured over 9 orders of mag.

Theory matches prediction well



Motivation for Sp$\bar{p}$S: Find $W^{\pm}$ & Z^0

With known constants:

$$\alpha \approx 1/137 \qquad G_F \approx 1.17 \times 10^{-5}\,\mathrm{GeV}^{-2}$$

$$\sin^2\theta_W \approx 0.23$$

At the time recently determined from ν and anti-ν scattering

Could predict M_W and M_Z

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad M_Z^2 = \frac{M_W^2}{\cos^2\theta_W}$$

$$M_W \approx 80\,\mathrm{GeV}/c^2 \quad M_Z \approx 90\,\mathrm{GeV}/c^2$$

Too heavy for existing accelerators

W & Z Production

Lowest order prod: quark anti-quark annihilation

$$u\bar{d} \rightarrow W^+ \quad d\bar{u} \rightarrow W^-$$

$$\sigma(p\bar{p} \rightarrow W^- X \text{ or } W^+ X) \sim 6\,\text{nb}$$

$$u\bar{u}, d\bar{d} \rightarrow Z^0 X$$

$$\sqrt{s} = 630\ \text{GeV}$$

$$\sigma(p\bar{p} \rightarrow Z^0 X) \sim 2\,\text{nb}$$

W & Z Detection

For discovery exploit leptonic decays:

$$W^- \to e^-\bar{\nu}_e, \mu^-\bar{\nu}_\mu$$ BF 11% per lepton

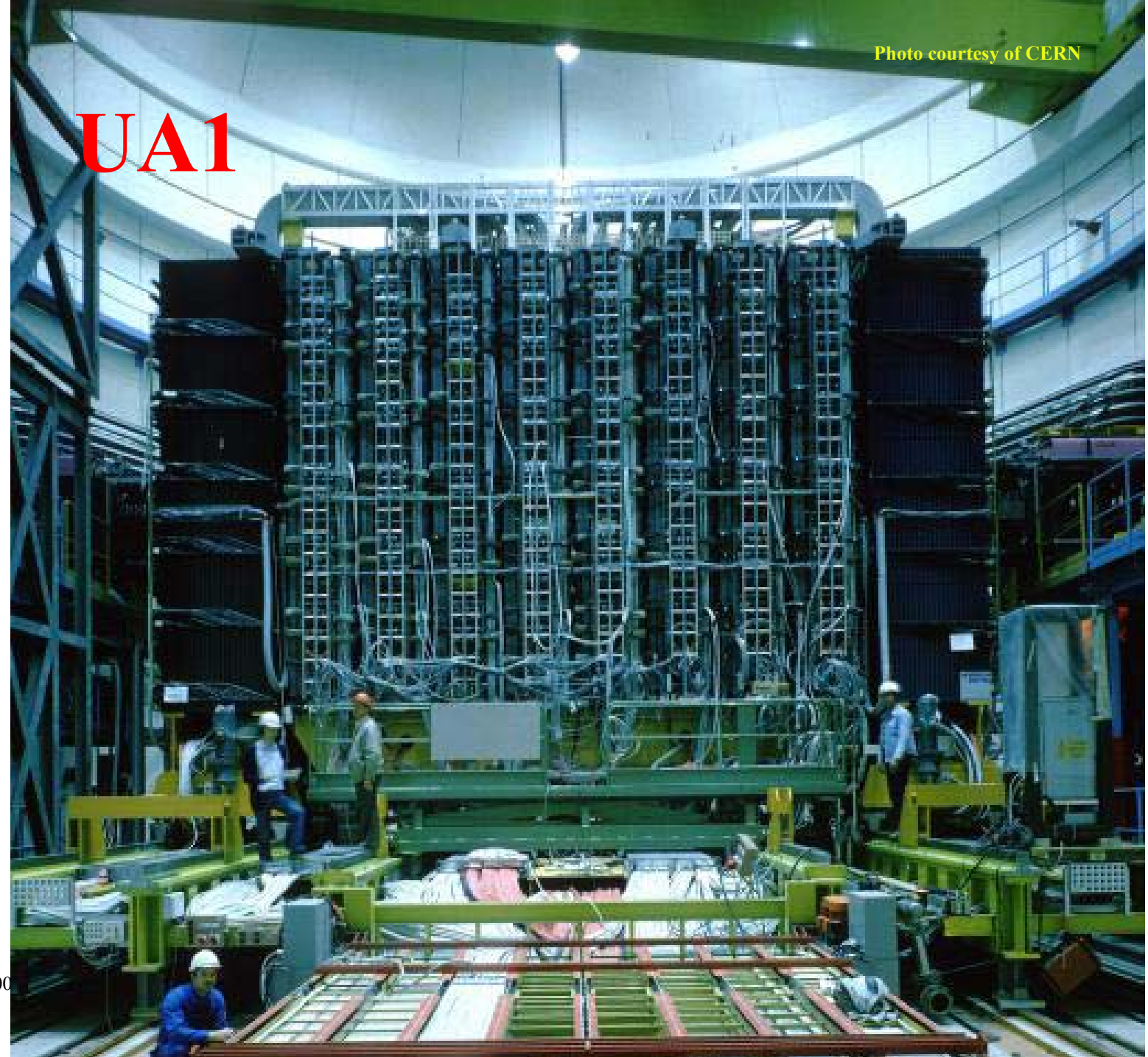
$$Z^0 \to e^+e^-, \mu^+\mu^-$$ BF 3% per lepton

$$\sigma(p\bar{p} \to W^- X, W^- \to e^-\bar{\nu}) \sim 0.3\,\mathrm{nb}$$

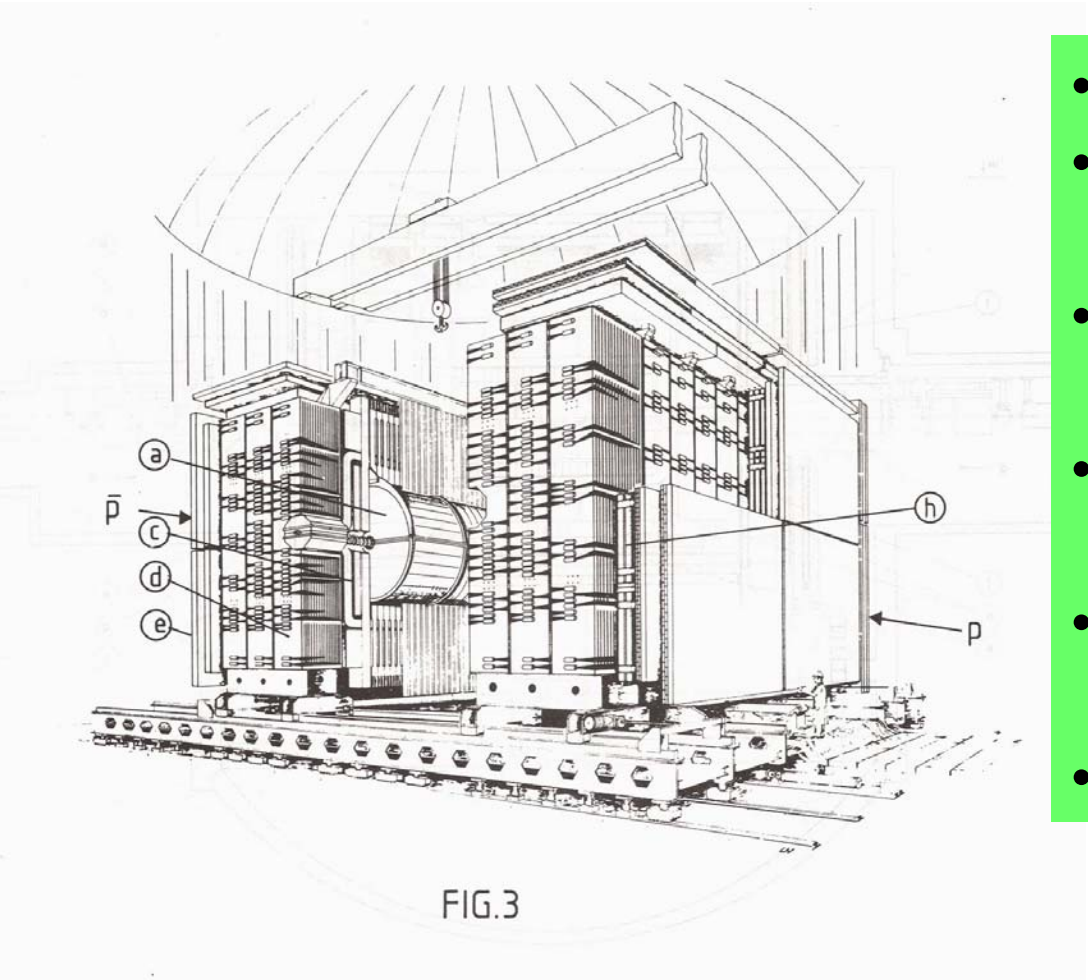
$$\sigma(p\bar{p} \to Z^0 X, Z^0 \to e^+e^-) \sim 60\,\mathrm{pb}$$

Fall '82 Run: 18 nb^{-1} for UA1

Expect handful of events


UA1
Photo courtesy of CERN

UA1: Key Features



- Dipole Field B=0.7T
- "Bubble chamber" quality drift chamber (CD)
- Calorimetry covered large fraction of solid angle
- Electromagnetic calorimeter seg. 4 layers in depth (26 X_0)
- hadronic calorimeter with 2 layers in depth (5 λ)
- Extensive μ detection

Cross-sectional View of UA1

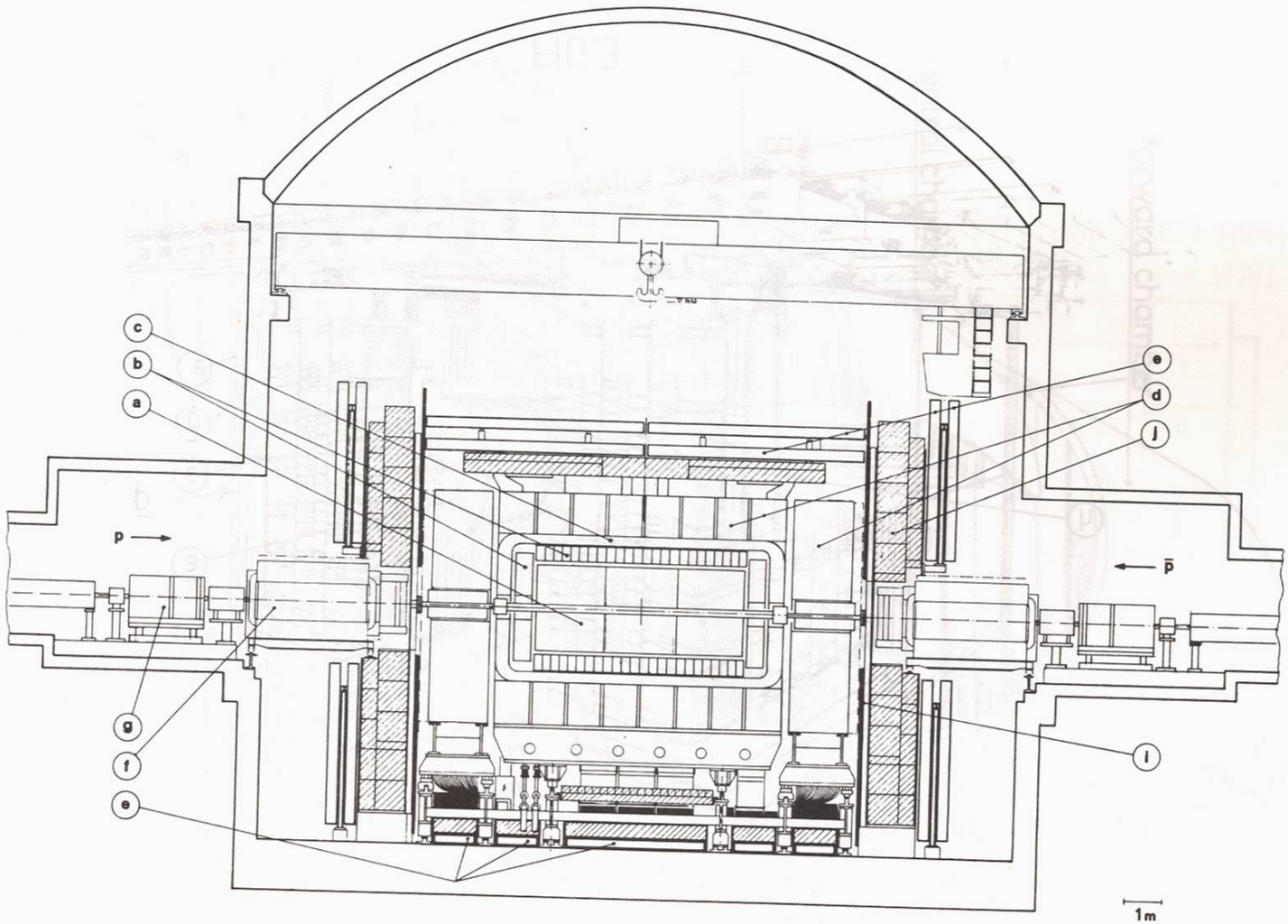
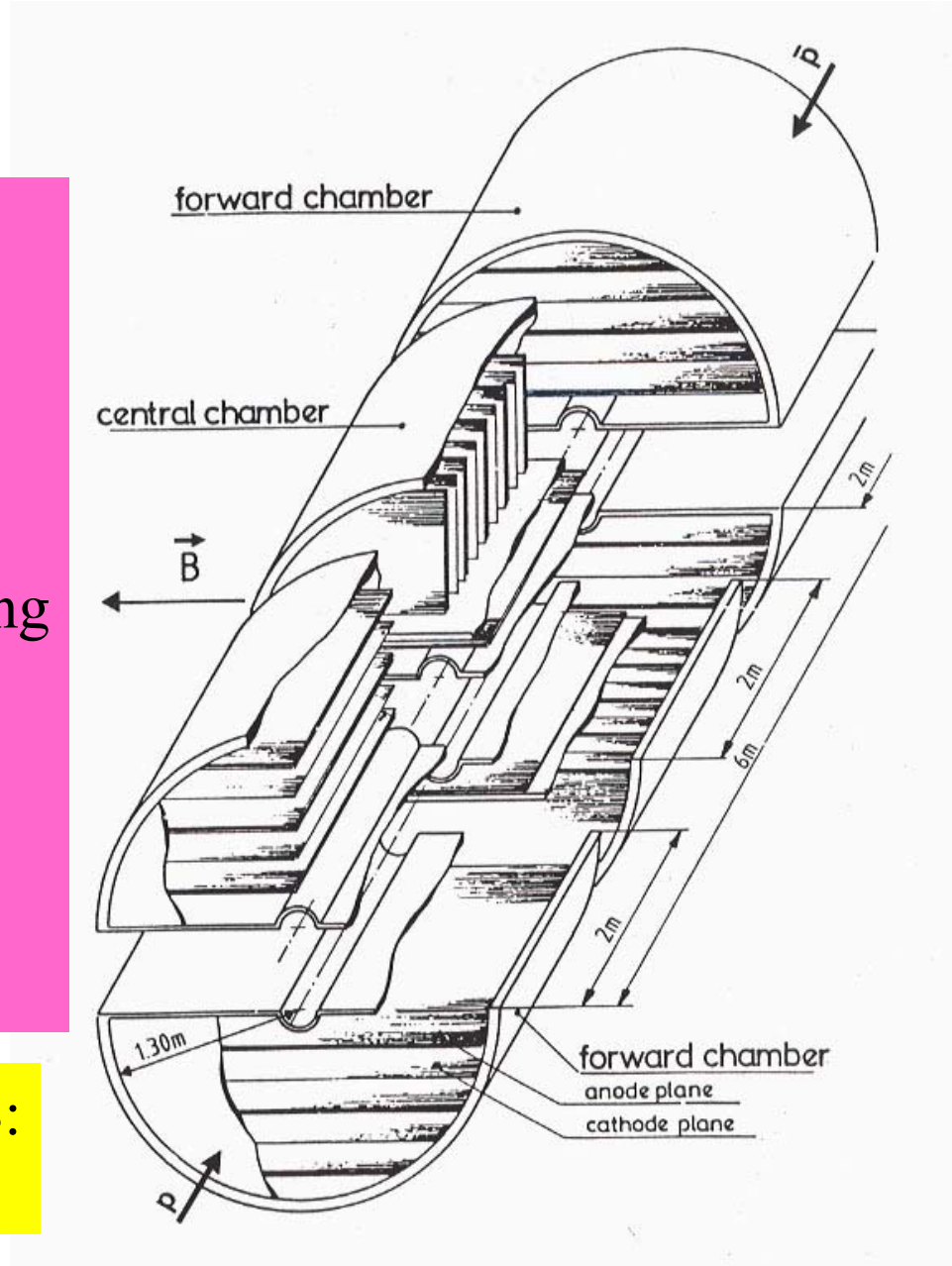


FIG.2

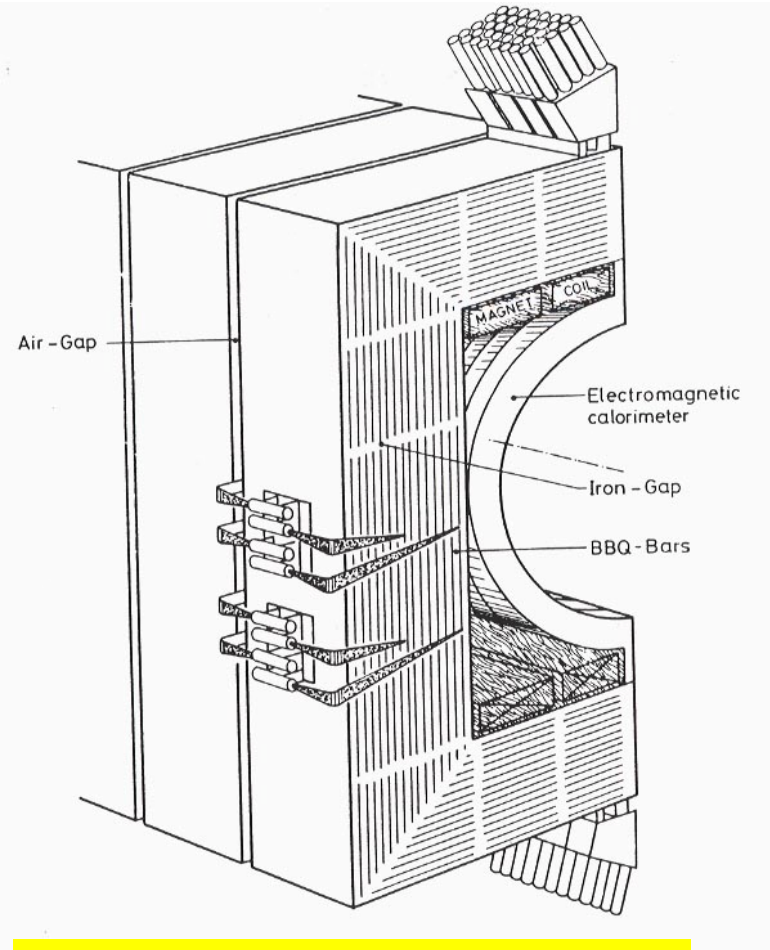
UA1 Central Tracking (CD)

- 6 independent half cylinders
- 5.8 m long, 2.3 m diameter
- total volume 25 m^3
- covered $5^o<\theta<175^o$
- 40% Argon, 60% Ethane
- wires: 6k sense, 17k field shaping
  - parallel to B field
  - organized in planes
  - horizontal in forward
  - vertical in central
- drift gap 18cm (3.6 μs)

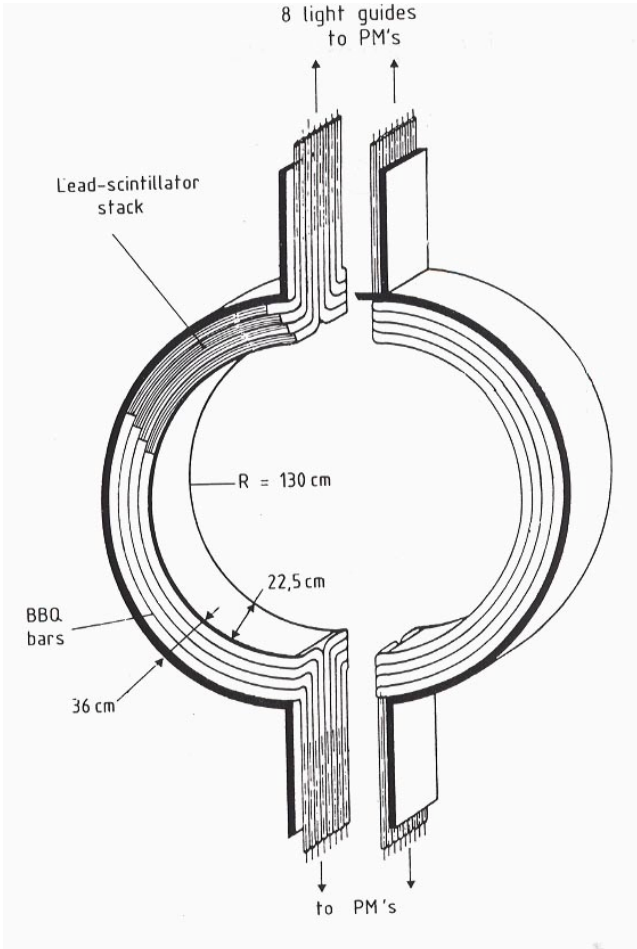
For 1 m track perpendicular to B:
$\Delta p/p^2 = 0.005\ (GeV/c)^{-1}$



UA1 Central Calorimetry



Central Hadronic "Cees"



Central EM "Gondolas

UA1 Calorimetry

Calorimeter	Angular coverage θ (deg)	Thickness		Cell size		Sampling step	Segmentation in depth	Resolution
		No. rad. lengths	No. abs. lengths	$\Delta\theta$ (deg)	$\Delta\phi$ (deg)			
barrel EM: gondolas	25 –155	26.4/sin θ	1.1/sin θ	5	180	1.2 mm Pb 1.5 mm scint.	3.3/6.5/10.1/6.5 X_0	$0.15/\sqrt{E}$
hadr.: c's	25 –155	–	5.0/sin θ	15	18	50 mm Fe 10 mm scint.	2.5/2.5 λ	$0.8/\sqrt{E}$
end-caps EM: bouchons	5 – 25	27/cos θ	1.1/cos θ	20	11	4 mm Pb 6 mm scint.	4/7/9/7 X_0	$0.12/\sqrt{E_T}$
hadr.: I's	155 –175	–	7.1/cos θ	5	10	50 mm Fe 10 mm scint.	3.5/3.5 λ	$0.8/\sqrt{E}$
calcom EM	0.7– 5	30	1.2	4	45	3 mm Pb 3 mm scint.	4 × 7.5 X_0	$0.15/\sqrt{E}$
hadr.	175 –179.3	–	10.2	–	–	40 mm Fe 8 mm scint.	6 × 1.7 λ	$0.8/\sqrt{E}$
very forward EM	0.2– 0.7	24.5	1.0	0.5	90	3 mm Pb 6 mm scint.	5.7/5.3/5.8/7.7 X_0	$0.15/\sqrt{E}$
hadr.	179.3–179.8	–	5.7	0.5	90	40 mm Fe 10 mm scint.	5 × 1.25 λ	$0.8/\sqrt{E}$

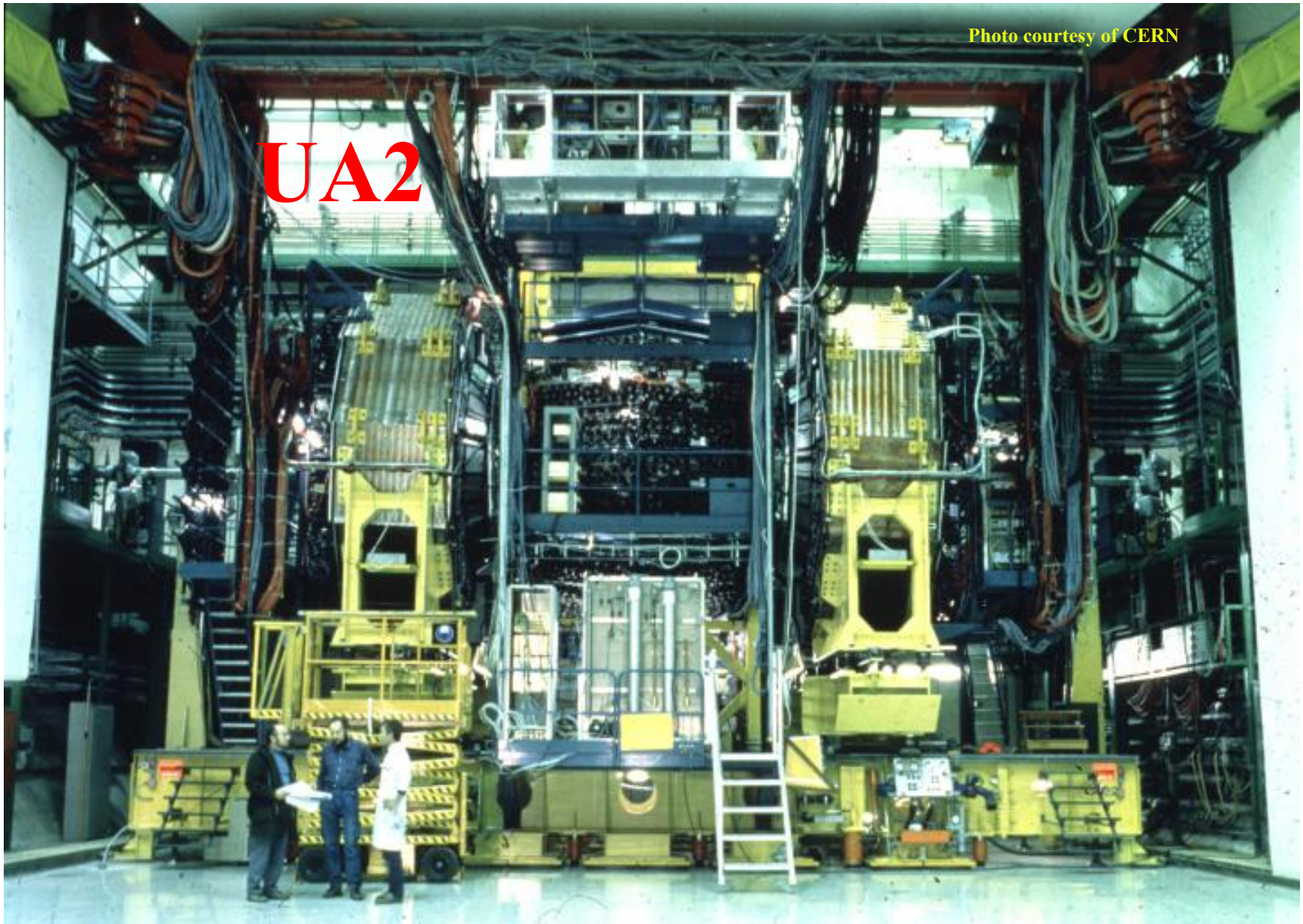


Photo courtesy of CERN
UA2

UA2: Key Features

- No magnet with central calorimeter
- Less 4π coverage
- Carefully calibrated central calorimeter (crucial for M_W)
- Finer segmentation
- Projective towers
- TRT for e/π sep (later – after upgrade)

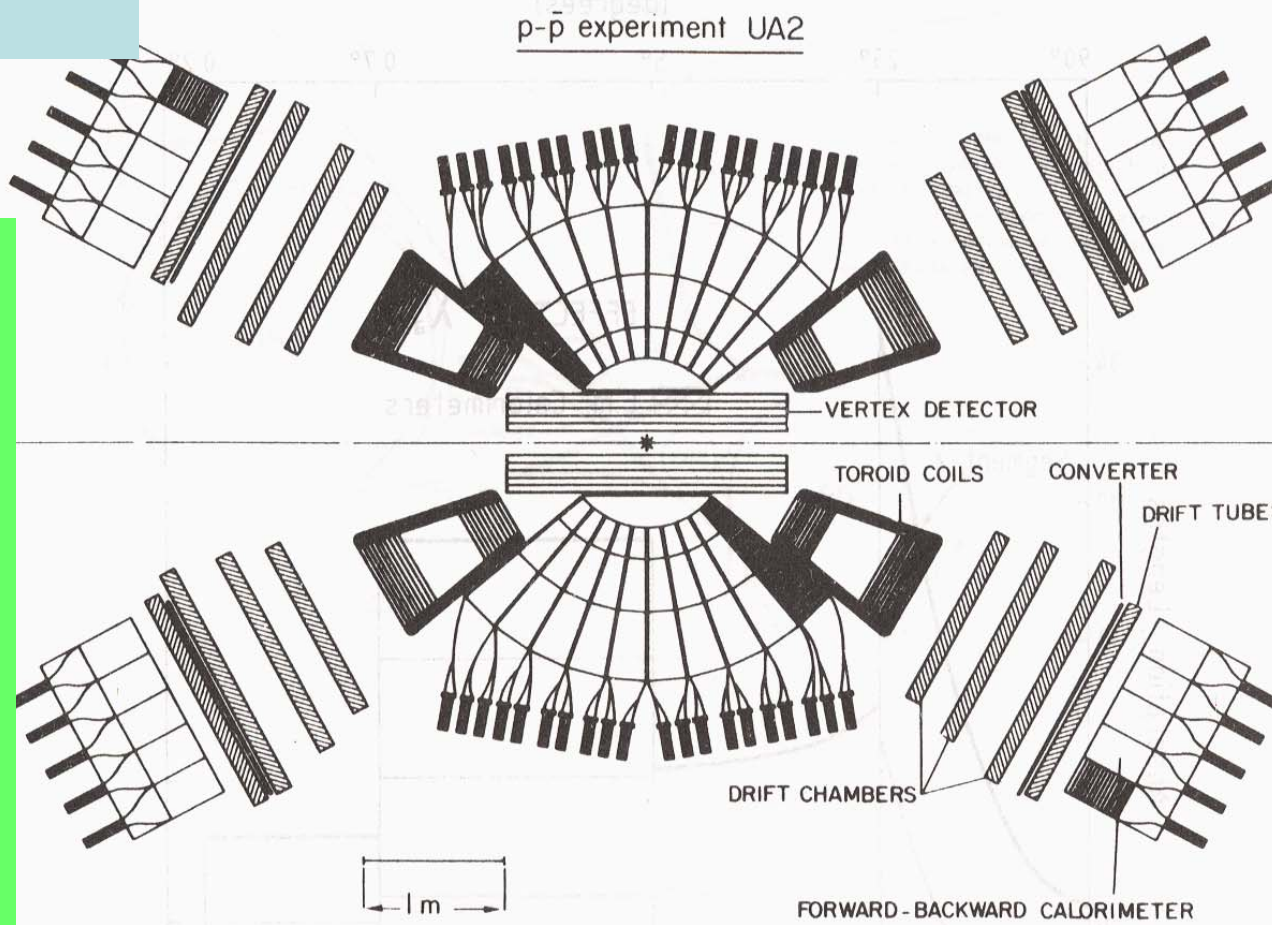


Fig. 11

UA2: 1st Evidence of Jets

79 μb^{-1} of data

Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982

A "small" experiment: 54 Authors

OBSERVATION OF VERY LARGE TRANSVERSE MOMENTUM JETS AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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Received 25 August 1982

The distribution of total transverse energy ΣE_T over the pseudorapidity interval $-1 < \eta < 1$ and an azimuthal range $\Delta\phi = 300°$ has been measured in the UA2 experiment at the CERN $\bar{p}p$ collider ($\sqrt{s} = 540$ GeV) using a highly segmented total absorption calorimeter. In the events with very large ΣE_T ($\Sigma E_T \geq 60$ GeV) most of the transverse energy is found to be contained in small angular regions as expected for high transverse momentum hadron jets. We discuss the properties of a sample of two-jet events with invariant two-jet masses up to 140 GeV/c^2 and we measure the cross section for inclusive jet production in the range of jet transverse momenta between 15 and 60 GeV/c.

1. Introduction. The suggestion that hard scattering of hadron constituents should result in two jets with the same momenta as the scattered partons [1] has motivated an intense experimental effort [2]. Earlier ISR experiments [3] have reported observations of such double-jet structures. However these jets were not as clearly identified as they are in the hadronic final states of high-energy e^+e^- annihilations [4], because in hadronic collisions the jets carry only a fraction of the total energy available. As a consequence, jets are accompanied by several soft hadrons which may make their identification more difficult and in general they are not collinear.

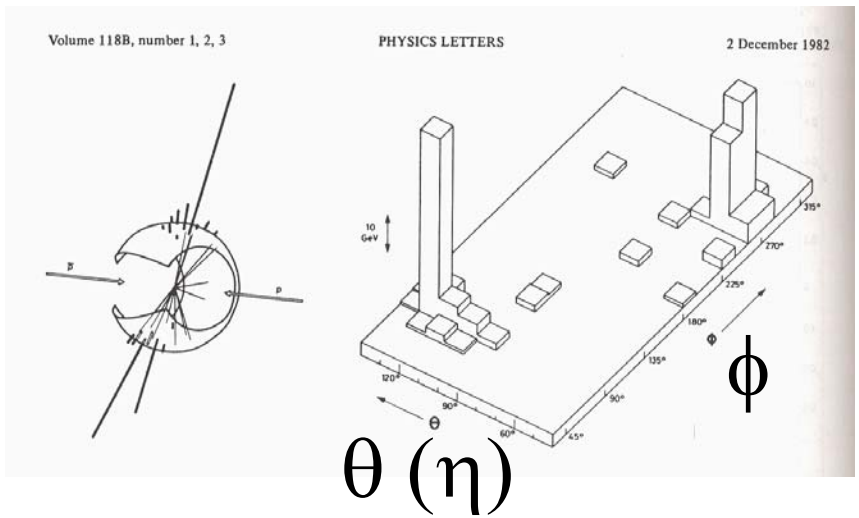
The recent successful operation of the CERN $\bar{p}p$ collider [5] has opened a new possibility to observe high transverse momentum hadron jets. At $\sqrt{s} = 540$ GeV the yield of jets with $E_T > 20$ GeV is expected to increase by about four orders of magnitude with respect to the top ISR energy [6] whereas the average particle density in the central region for an ordinary collision has increased by less than a factor of 2 [7].

We report here on results from the UA2 experiment at the CERN $\bar{p}p$ collider. This experiment uses a large

[1] Now also at Istituto di Fisica, Università di Udine, Italy.
[2] Now also at Istituto di Fisica, Università di Perugia, Italy.

ΣE_T concentrated in back to back regions not isotropic

Largest ΣE_T event



UA2 Collaboration, M. Banner *et al.*, Phys. Lett. 118B (1982) p. 203

Unroll calorimeter: "Lego Plot"

UA1: W Discovery Winter 83

Based on:

$$W \rightarrow e\nu$$

Two Searches:

1. Electron
2. Neutrino "Missing Energy"

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EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

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Aachen [a]–Annecy (LAPP) [b]–Birmingham [c]–CERN [d]–Helsinki [e]–Queen Mary College, London [f]–Paris (Coll. de France) [g]–Riverside [h]–Rome [i]–Rutherford Appleton Lab. [j]–Saclay (CEN) [k]–Vienna [l] Collaboration

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We report the results of two searches made on data recorded at the CERN SPS Proton–Antiproton Collider: one for isolated large-E_T electrons, the other for large-E_T neutrinos using the technique of missing transverse energy. Both searches converge to the same events, which have the signature of a two-body decay of a particle of mass ~80 GeV/c^2. The topology as well as the number of events fits well the hypothesis that they are produced by the process $\bar{p} + p \rightarrow W^{\pm} + X$, with $W^{\pm} \rightarrow e^{\pm} + \nu$; where $W^{\pm}$ is the Intermediate Vector Boson postulated by the unified theory of weak and electromagnetic interactions.

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W Event Selection

Electron Selection

- $E_T(e) > 15$ GeV in Calo.
- $p_T(e) > 7$ GeV in CD
- Isolated (no extra p)
- No leakage in Had.
- track/calor. match
  - position
  - E/p

Neutrino Selection

- $E_T(e) > 15$ GeV in Calo.
- $p_T(e) > 7$ GeV in CD
- Isolated (no extra p)
- $\Delta E_T > 15$ GeV
- stricter isolation
  - track
  - add calorimeter iso.

39 remaining events

34 back to back jet activity

5 ΔE_T balance $E_T(e)$ **Same 5 events here** → 7 no jet act.: E_{had} negligible

18 Remaining events

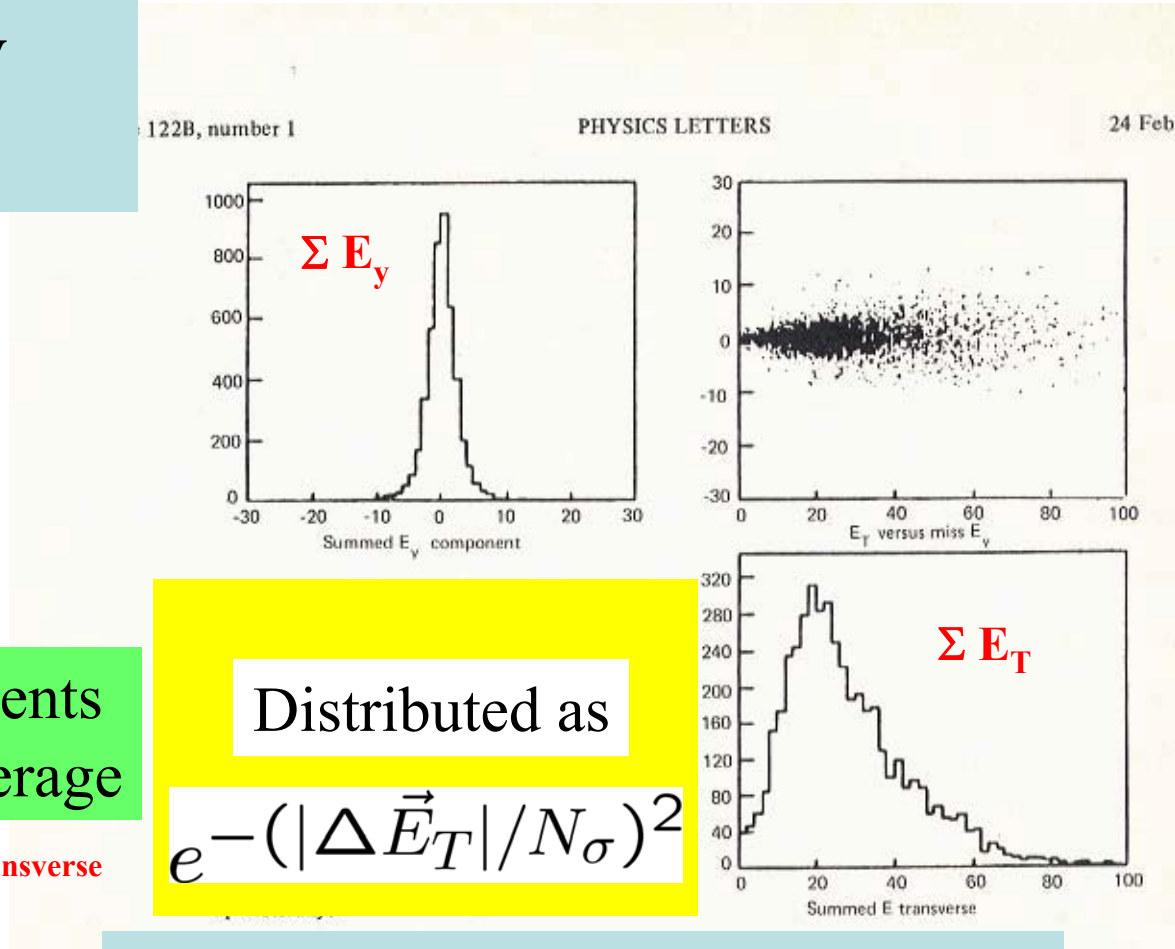
11 jet activity: E_{had} behind $E_T(e)$

Missing Energy Resolution

Evaluate resolution in ΔE_T using data collected with low trigger bias: "minimum bias data"

Expect transverse components ΣE_y, ΣE_z to balance on average

Careful: UA1 used x for beam axis, y&z were transverse



Distributed as

$$e^{-(|\Delta \vec{E}_T|/N_\sigma)^2}$$

Width of $\Sigma E_y, E_z$ Increased with ΣE_T Event "temperature"

Defined "missing E_T significance"

$$N_\sigma = |\Delta \vec{E}_T|/0.7\sqrt{\Sigma |E_T|}$$

Details of the W Candidates

	Run, event	Properties of the electron track										Calorimeter information					General event topology				
		E_T (GeV)	E (GeV)	p (GeV/c)	Δp a)	Q	dE/dx I/I_0	y b)	Track No.	Length (m)	Sagitta (mm)	Electromagnetic energy deposition: Sample 1 (GeV)	Sample 2 (GeV)	Sample 3 (GeV)	Sample 4 (GeV)	E_{had} (GeV)	E_{tot} (GeV)	Missing E_T (GeV)	$\Delta\phi$ c) (deg.)	Charged tracks	$\sum\|E_T\|$ (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).

Two of the 6 W Candidates

Displays of hits in Central Detector (CD)

Tracks easily seen by eye

Soft tracks bend in 0.7T dipole field

e candidates are straight indicating high p

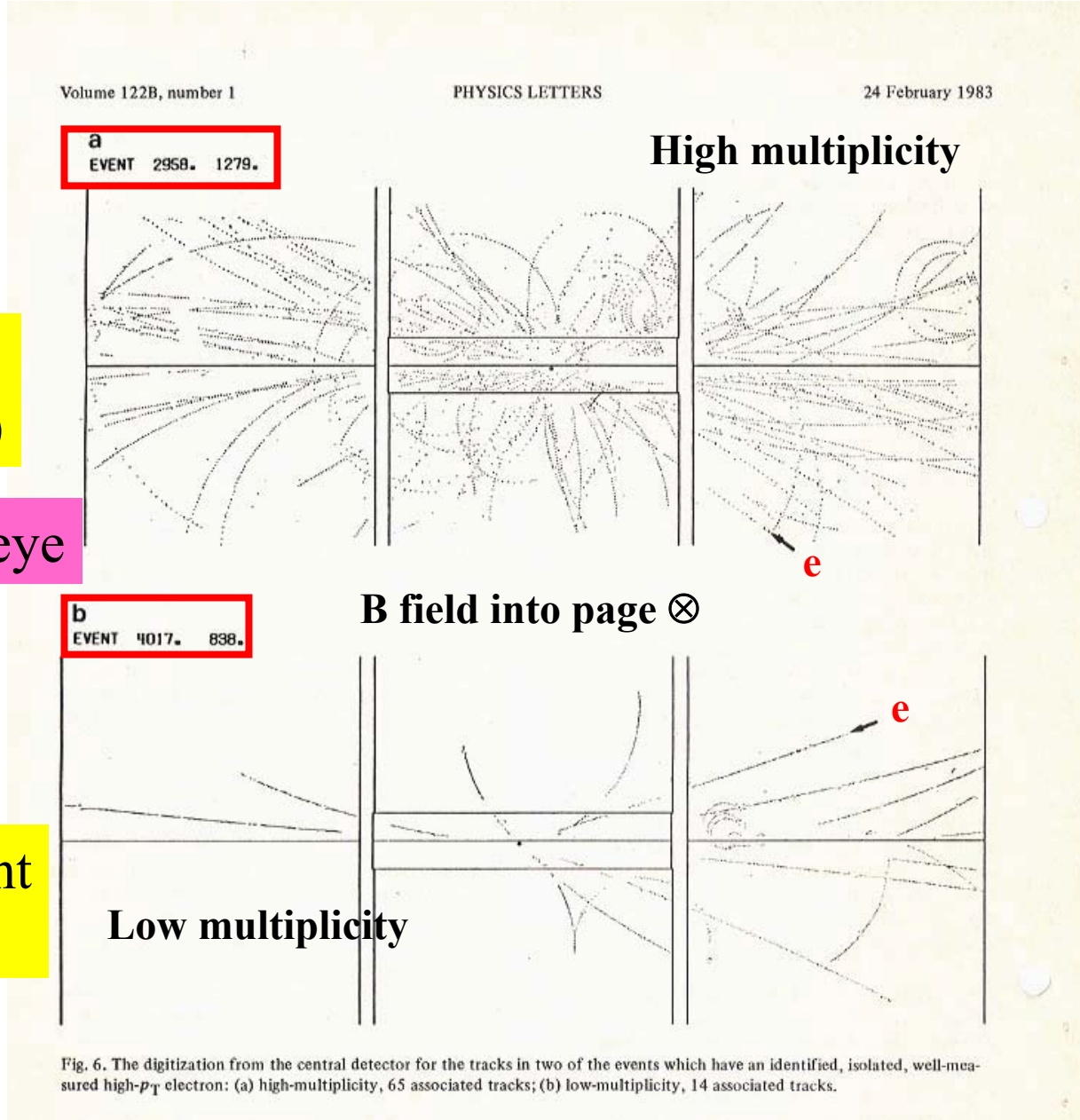


Fig. 6. The digitization from the central detector for the tracks in two of the events which have an identified, isolated, well-measured high-p_T electron: (a) high-multiplicity, 65 associated tracks; (b) low-multiplicity, 14 associated tracks.

Same 2 Candidates Lego plots

Unroll detector in ϕ and η

Isolated high E_T EM cluster

EM

High p_T track Matching in position and E/p

p_T

Very little hadronic E
n.b. reduced vertical scale

HAD

Minimal "back to back"activity
Implies *not* QCD jet background

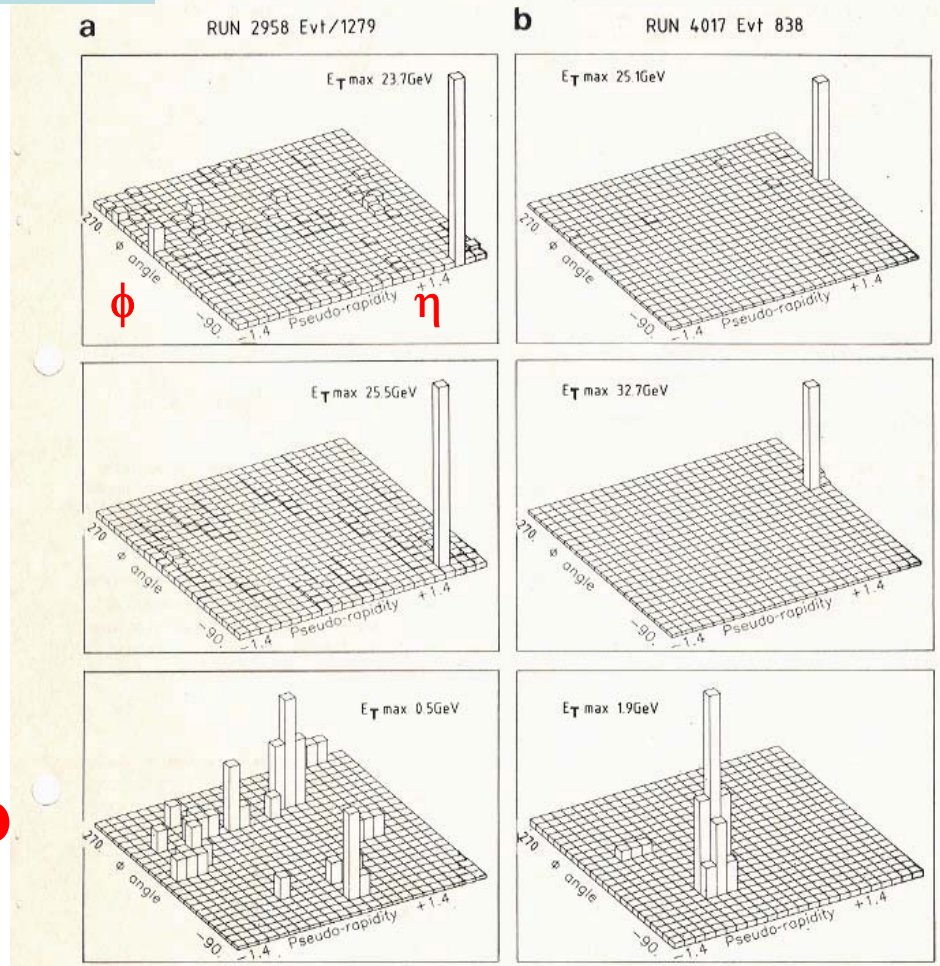
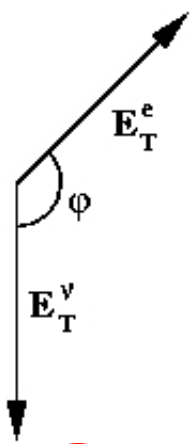


Fig. 7. The energy deposited in the cells of the central calorimetry and the equivalent plot for track momenta in the central detector for the two events of fig. 6. The top diagram shows the electromagnetic cells, the middle shows the central detector tracks, and the bottom plot, with a very much increased sensitivity, shows the energy in the hadron calorimeter. The plots reveal no hadronic energy behind the electron and no jet structure; (a) high-multiplicity; (b) low-multiplicity.

W Transverse Mass m_T

Only transverse components of ν reconstructed (unknown E escapes down BP)

Form transverse mass m_T



"Jacobian peak" characteristic of W decay

$$m_T^2 = 2E_T^e E_T^\nu (1 - cos\phi)$$

Based on the original 6 events UA1 quoted: M_W=81± 5 GeV/c²

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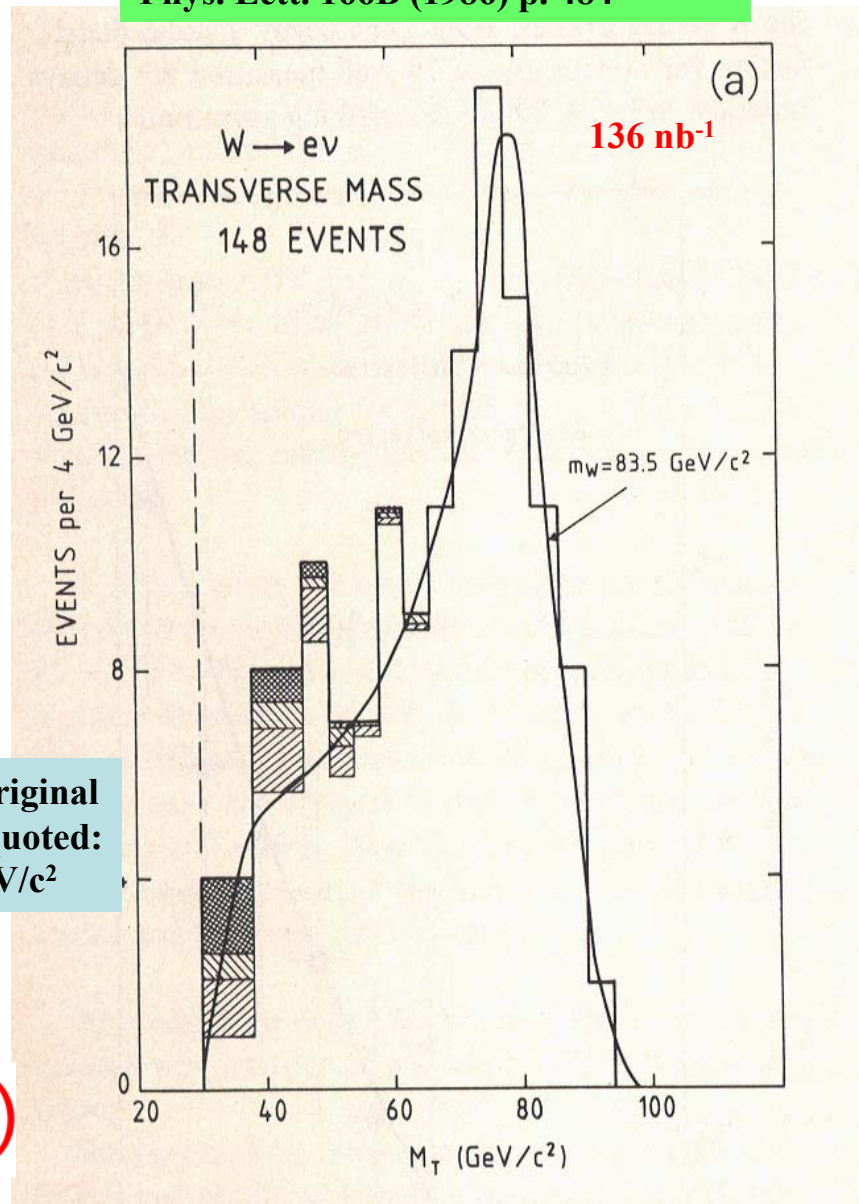
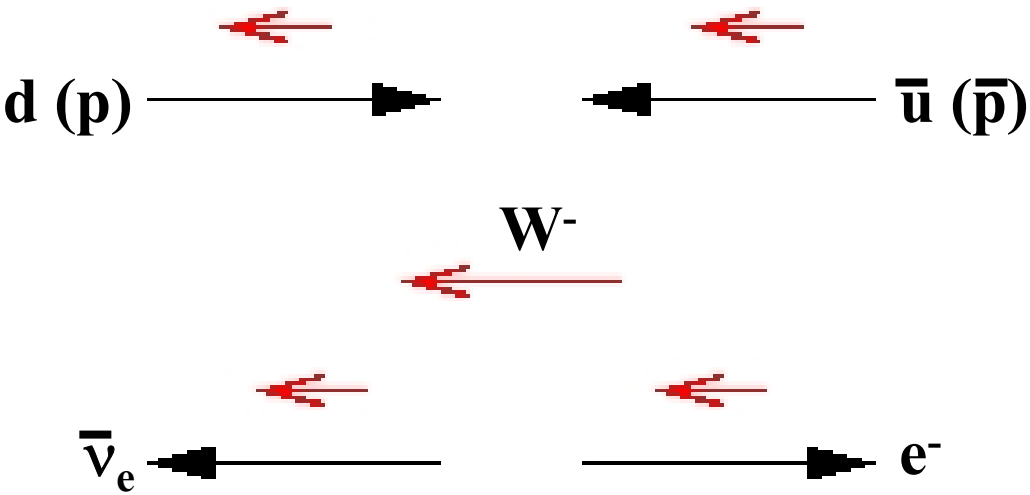


W Asymmetry (V-A)

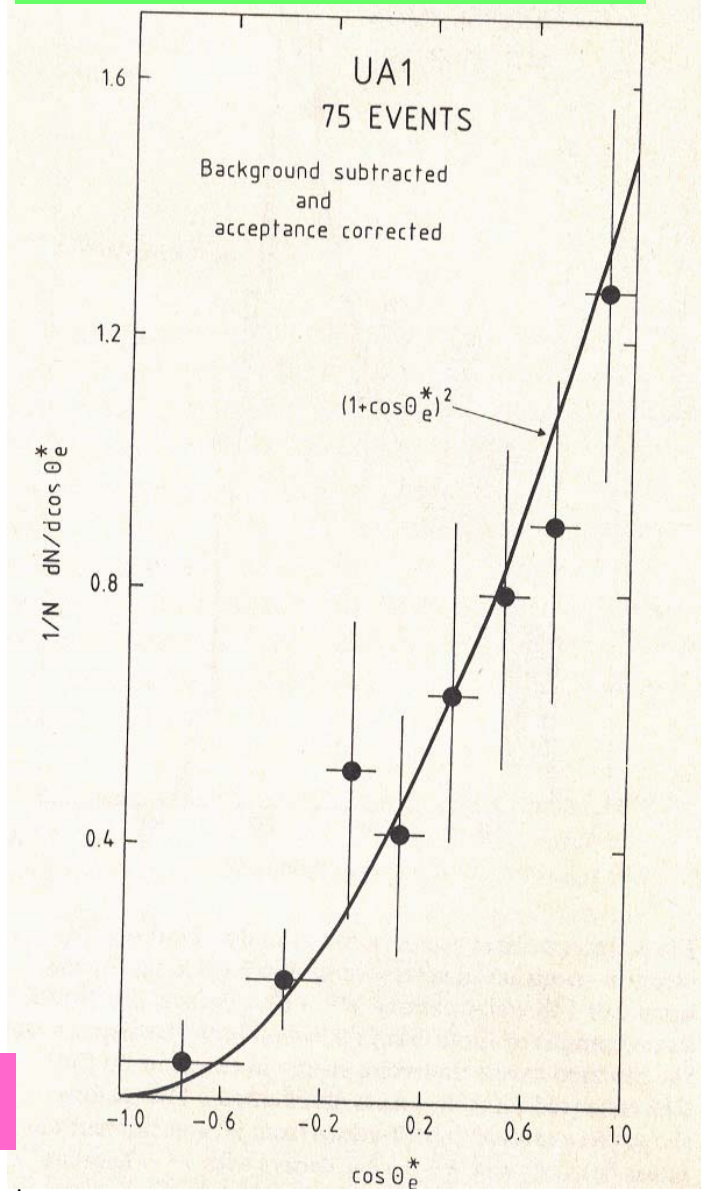
Due to V-A interaction
e^- (e^+) follows p (anti-p)

Asymmetry less pronouced at larger √s due to more sea quark W production



Asymmetry sensitive to structure functions

UA1 Collaboration, G. Arnison *et al.*, Phys. Lett. 166B (1986) p. 484



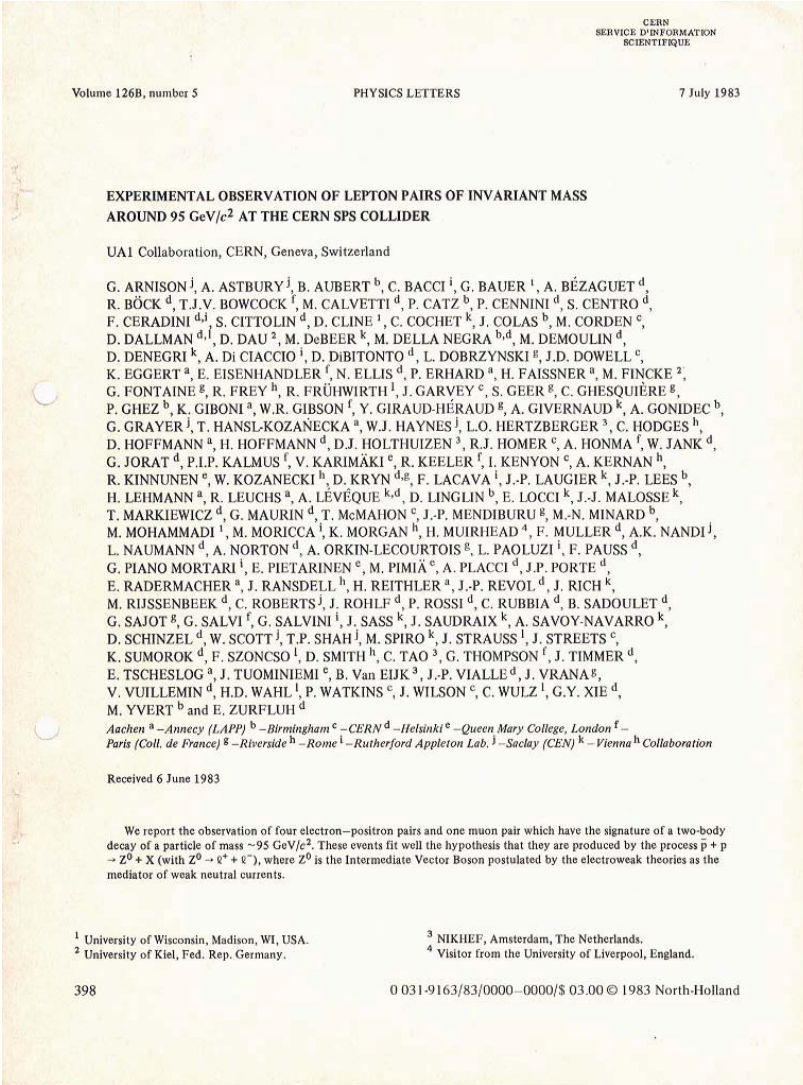
Z Discovery Spring 83

Based on 55 nb^{-1}

$\sigma \times$BR factor 10 less than W

Very clean signature, however
- 2 high p_T leptons
- opposite charge
- isolated
- invariant mass ~ 90 GeV/c^2

Discovery based on
- 4 e^+e^- pairs
- 1 $\mu^+\mu^-$ pair



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Volume 126B, number 5 PHYSICS LETTERS 7 July 1983

EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c^2 AT THE CERN SPS COLLIDER

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Received 6 June 1983

We report the observation of four electron–positron pairs and one muon pair which have the signature of a two-body decay of a particle of mass ~95 GeV/c^2. These events fit well the hypothesis that they are produced by the process $\bar{p} + p \to Z^0 + X$ (with $Z^0 \to \ell^+ + \ell^-$), where Z^0 is the Intermediate Vector Boson postulated by the electroweak theories as the mediator of weak neutral currents.

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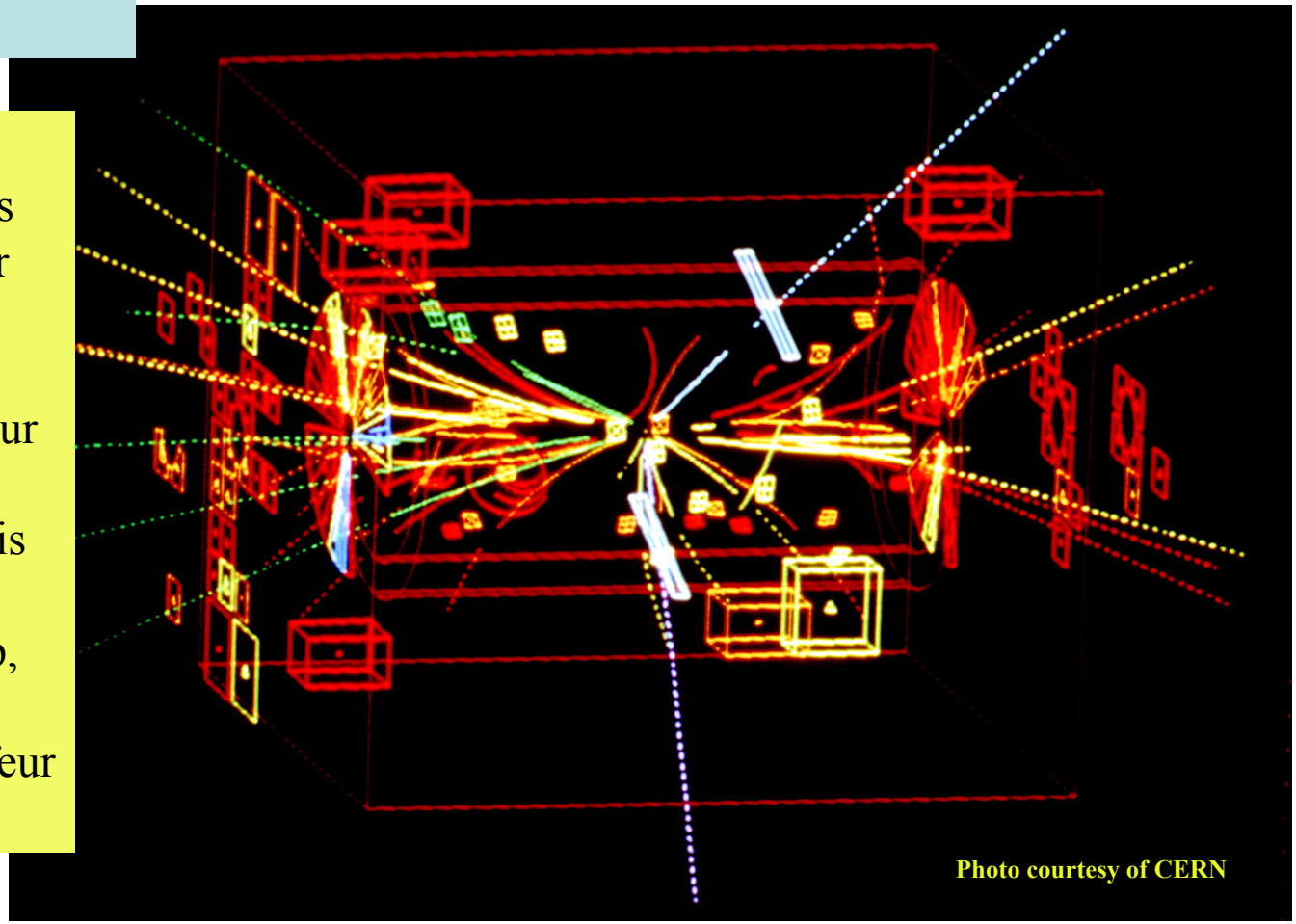
Megatek Display of First Z^0

This event had a problem: *E* did not match *p* on one leg, but the invariant mass of the two calorimeter clusters was about 90 GeV

Dr. Marie Noel Minard (LAPP-Annecy) saw this event on a print-out after arriving back at Annecy from a shift at CERN. She had the Lab chauffeur drive her back to CERN *at midnight* to look at this event on the Megatek. When the event came up, she closed her eyes, so, in fact, it was the chauffeur who saw the first Z^0



Another $Z \rightarrow e^+e^-$ Candidate

High p_T "discovery" physics sits well above underlying soft collision fragments

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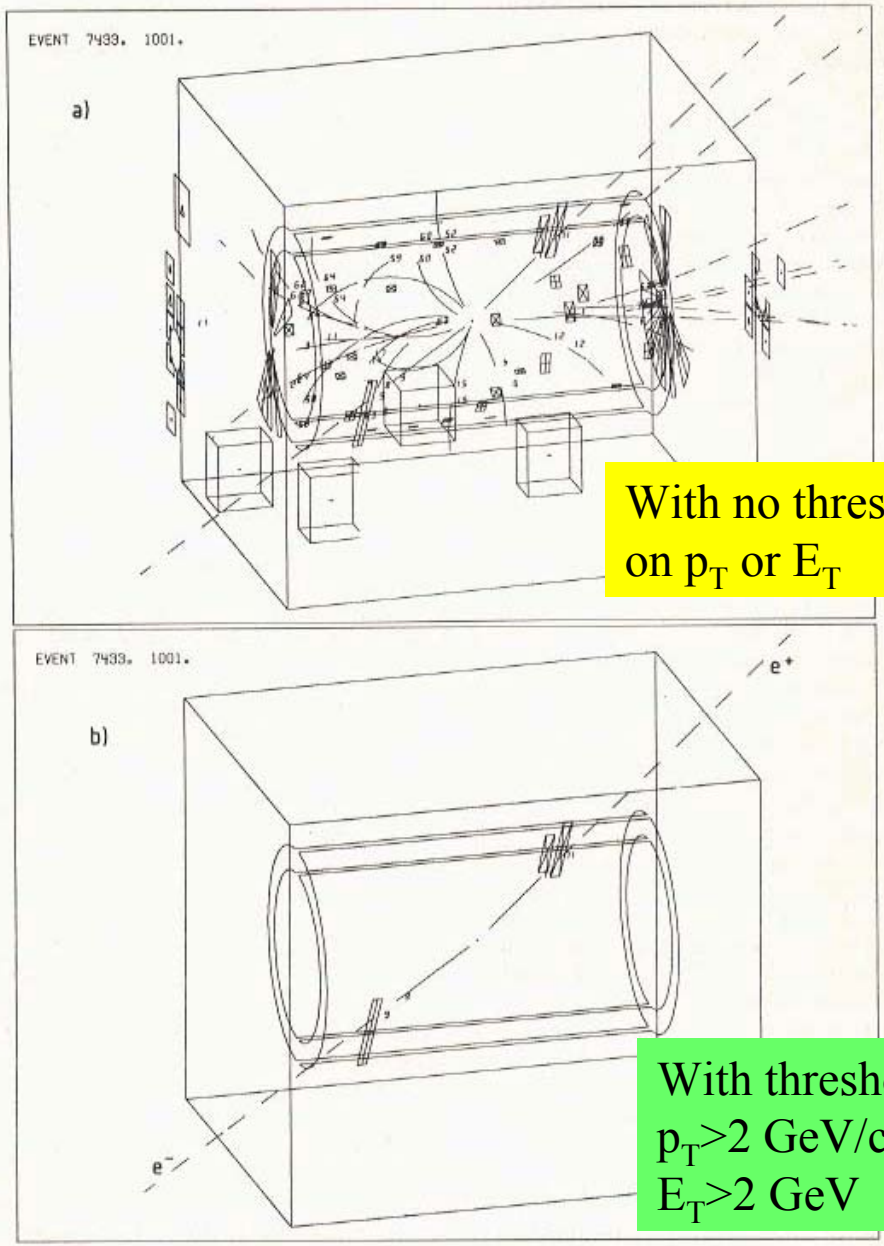

With no threshold on p_T or E_T

With thresholds: p_T>2 GeV/c E_T>2 GeV

Fig. 2. (a) Event display. All reconstructed vertex associated tracks and all calorimeter hits are displayed. (b) The same, but thresholds are raised to $p_T > 2$ GeV/c for charged tracks and $E_T > 2$ GeV for calorimeter hits. We remark that only the electron pair

Lego plots of 4 $Z^0 \rightarrow e^+e^-$

Like W's except
2nd e instead of ΔE_T

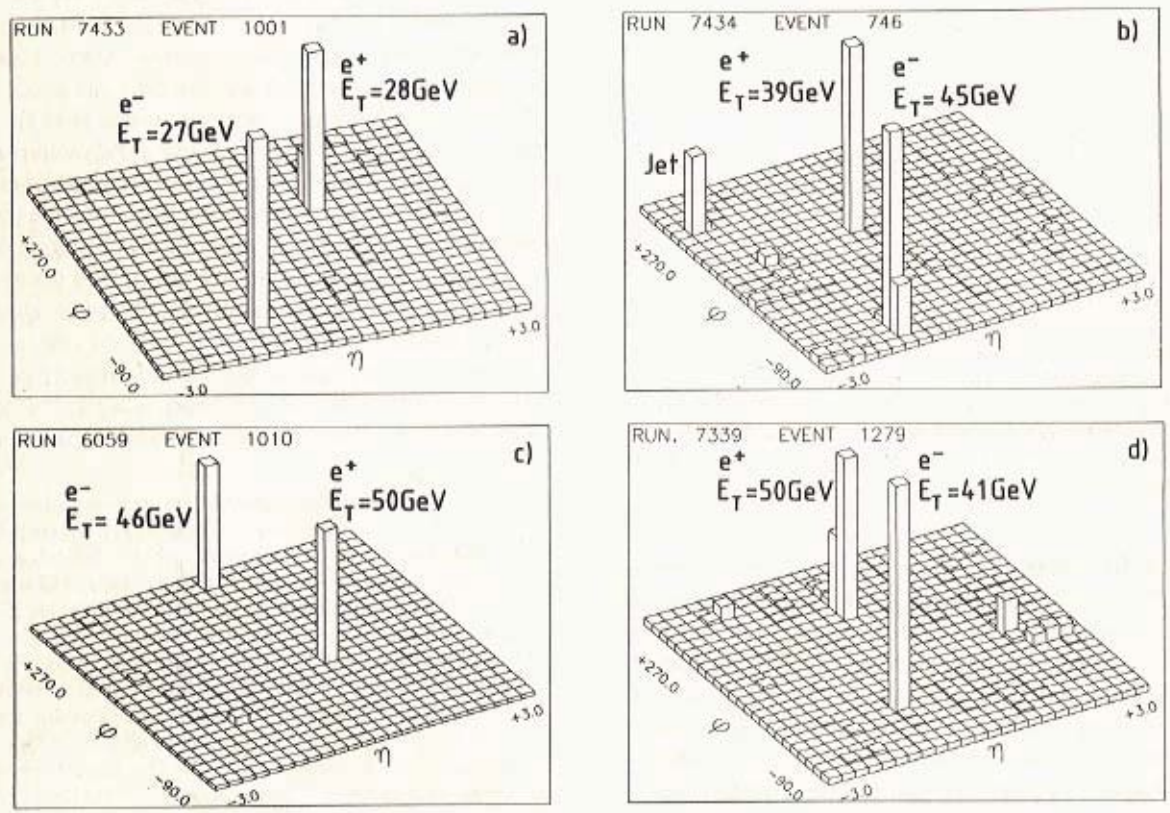

Fig. 3. Electromagnetic energy depositions at angles >5° with respect to the beam direction for the four electron pairs.

Properties of the individual electrons of the pair events

Table 1
Properties of the individual electrons of the pair events.

3.3 6.6 9.9 6.6 X_0

Run, event	Drift chamber measurement						Shower counter measurement					
	p (GeV)	Δp a) (GeV)	Q	dE/dx b)	y c)	φ (deg)	E_{tot} (GeV)	Electromagnetic samples (GeV) S_1	S_2	S_3	S_4	Had. energy H
A 7433 1001	33	+9 −6	+	1.8 ± 0.3	1.01	144	44	14	27	3	0.0	0.0
	63	+23 −13	−	1.7 ± 0.2	−1.19	−31	48	6	37	4	0.2	0.0
B 7434 746	27	+19 −8	+	1.6 ± 0.3	−0.36	131	42	2	18	20	1.3	0.1
	93	+66 −28	−	1.8 ± 0.2	−1.45	−60	102	42	56	4	0.2	0.0
C 6059 1010	32	+11 −6	+	1.3 ± 0.2	0.64	67	61	1	37	22	0.6	0.0
	9	+1 −1	−	1.4 ± 0.1	0.24	−121	48	1	23	23	1.3	0.0
D 7739 1279	d)	d)	d)	d)	−0.19	169	51	1	13	34	2.4	0.0
	50	+50 −17	−	1.5 ± 0.2	−0.79	−9	55	8	38	9	0.0	0.1

a) ±1σ including systematic errors.
b) Ionization loss normalized to minimum ionizing pion.
c) The rapidity y is defined as positive in the direction of outgoing $\bar{p}$.
d) Unmeasured owing to large dip angle.

$Z^0 \rightarrow \mu^+\mu^-$ Candidate

Trickier than e^+e^-: only have p

$$\frac{\Delta p}{p^2} = 0.005(\mathrm{GeV}/c)^{-1}$$

$$\frac{\sigma_E}{E} = \frac{0.15}{\sqrt{E\ (\mathrm{GeV})}}$$

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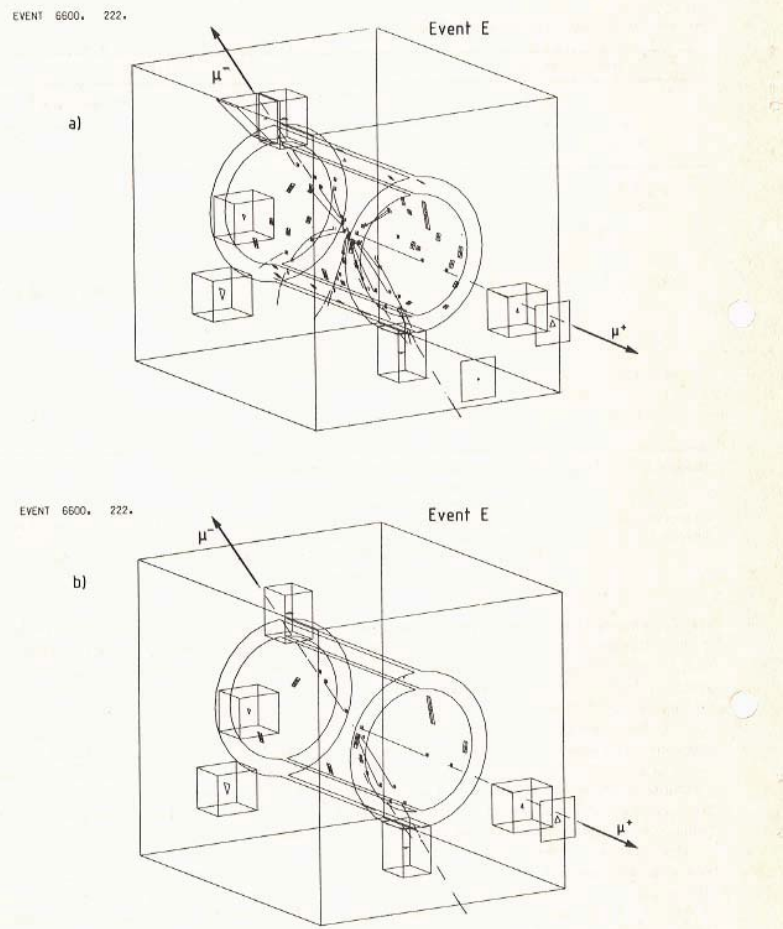

Fig. 5. Display for the high-invariant-mass muon pair event: (a) without cuts and (b) with $p_T > 1$ GeV thresholds for tracks and $E_T > 0.5$ GeV for calorimeter hits.

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Table 2
Properties of the muons of the dimuon event 6600-222.

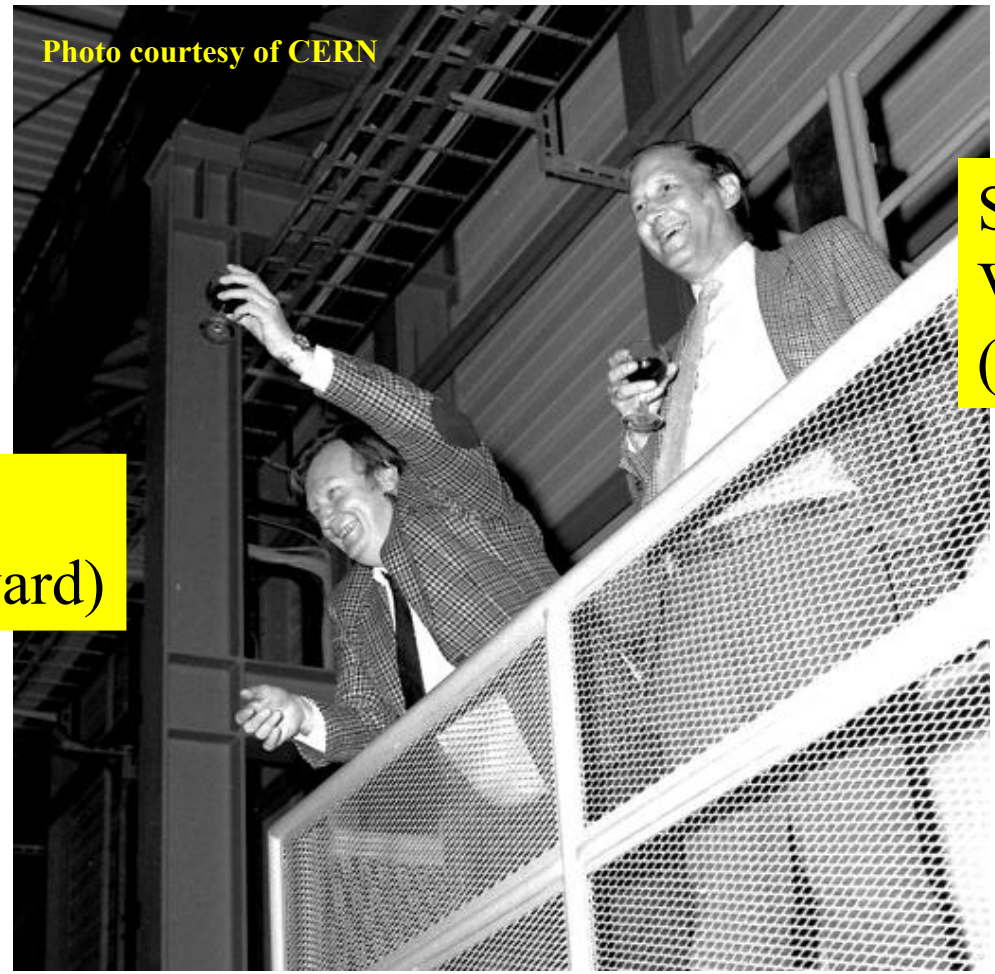
Track parameters					Muon identification				
					Normalized ionization I/I_s			μ/CD matching [d]	
Q	p (GeV/c)	ℓ (cm)	y	ϕ (°)	e.m. calorimeter	Hadron calorimeter	λ_{abs}	Position (cm)	Angle (mrad)
	58.8^{+8}_{-6} [a]								
+	60.3 ± 10.8 [b]								
	$59.2^{+6.4}_{-5.2}$ [c]	170	1.19	-27.6	0.8 ± 0.5	1.2 ± 0.5	10.2	$\Delta X_1 = -1.3 \pm 1.9$ $\Delta X_2 = 11.6 \pm 10.7$	$\Delta\phi = -2 \pm 6$ $\Delta\Lambda = 11 \pm 14$
	63.6^{+30}_{-15} [a]								
-	43.1 ± 6.2 [b]								
	$46.1^{+6.1}_{-5.7}$ [c]	80	-0.28	119.1	1.2 ± 0.9	1.6 ± 0.8	11.1	$\Delta X_1 = -0.1 \pm 8.0$ $\Delta X_2 = -8.0 \pm 8.5$	$\Delta\Phi = -6 \pm 3$ $\Delta\Lambda = -9 \pm 14$

Momentum determination: [a] Central detector and μ chamber (statistical errors only);
[b] Transverse momentum balance;
[c] Weighted average of (a) and (b).

μ-CD matching: [d] Difference between the extrapolated CD track and the track measured in the μ chambers (see fig. 6).

Remarks: The acceptance of the single muon trigger starts at a transverse momentum of about 2.5 GeV/c and reaches its full efficiency of 97% at 5.5 GeV/c. The geometrical acceptance of the dimuon trigger, used in this analysis, reduced the acceptance for Z^0 events to about 30%.

1984 Nobel Prize in Physics



Simon
Van der Meer
(CERN)

Carlo Rubbia
(CERN & Harvard)

Search for New Particles in UA1 Data Using a Missing Transverse Energy Analysis*

Many candidates for new physics produce stable weakly interacting particles leading to ΔE_T

Example: heavy lepton L^-

$$p\bar{p} \rightarrow W^- X \qquad W^- \rightarrow L^- \bar{\nu}_L$$

L decay

$$L^- \rightarrow \text{hadrons} \quad \nu_L \qquad L^- \rightarrow \ell^- \nu_L \bar{\nu}_\ell$$

"Monojet" signature: jet + ΔE_T

Signature like leptonic W decay

* adapted from talk presented at XXII Recontre de Moriond 8-15 Mar 1987

Another Example: SUSY

R parity conserved $\Rightarrow$ LSP stable & weakly interacting
Decay of SUSY particles eventually produces LSP $\therefore$ ΔE_T

UA1 considered models with the photino as the LSP

Sleptons

$$p\bar{p} \to W^- + X \qquad W^- \to \tilde{\ell}^- \tilde{\nu}_{\tilde{\ell}}$$

$$\tilde{\ell} \to \ell\tilde{\gamma} \qquad \tilde{\nu}_{\tilde{\ell}} \to \nu_\ell \tilde{\gamma}$$

W like signature: lepton plus ΔE_T

Squarks and gluinos

$$p\bar{p} \to \tilde{q}\bar{\tilde{q}}, \tilde{g}\tilde{q}, \tilde{g}\tilde{g}$$

Decay produces quarks, gluons, and photinos
Signature: multijets plus ΔE_T

Aside: discovery of new heavy particle (W) opens searches for more new particles (heavy lepton, sleptons)

Top decay an important avenue for new particle production in Run II

Focus on Jets Plus ΔE_T signature

When it's a single jet: "monojet"

Lepton + ΔE_T overwhelmed by SM W production

Standard Model Backgrounds

W production

$$W \to \tau\nu_\tau \qquad \tau \to \text{hadrons } \bar{\nu}_\tau$$

$$p\bar{p} \to W + \text{jets} \qquad W \to \ell\nu_\ell \longleftarrow$$

lepton "lost" in jet

Z^0 production

$$p\bar{p} \to Z^0 + \text{jets} \qquad Z^0 \to \nu\bar{\nu} \longleftarrow$$

Rate increased by extra ν families

$Z^0 \to \nu_L\bar{\nu}_L$

Heavy flavor

$p\bar{p} \to c\bar{c}, b\bar{b}$ with semileptonic decay, *e.g.* $b \to c\ell\nu_\ell X$

Instrumental backgrounds

- cosmic rays, beam halo
- cracks, reconstruction problems
- **mismeasurement of QCD jets**

QCD background most difficult to estimate:

- cross section orders of magnitude above signal
- Fakes signal when jets "fluctuate" to tails of $\sigma(\Delta E_T)$

Selection must reduce this background to such a small level that it does not matter if error on estimate is very large

Selection criteria

- at least one jet $E_T > 12$ GeV CD validated
- $|\Delta \vec{E}_T| > 15$ GeV $N_\sigma > 4$
- isolated $\Delta \vec{E}_T$
- veto e & μ

QCD Background Determination

"Jet fluctuation" Monte Carlo

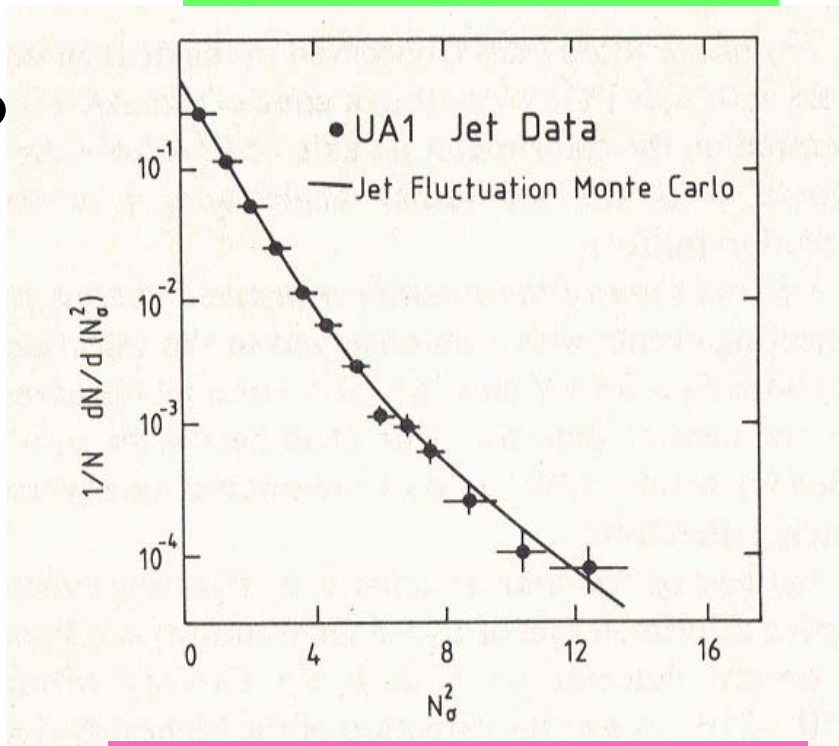
UA1 Collaboration, G. Albajar *et al.*, Phys. Lett. 185B (1987) p. 233

Use jet data as input to Monte Carlo

Fluctuate jets in data
According to jet resolution

Validate: compare predicted shape to data in N_σ

Normalize: for $N_\sigma < 3$
Extrapolate to $N_\sigma > 4$



Systematic on extrapolation: 100%

Data and MC shape agree

W → τν Selection

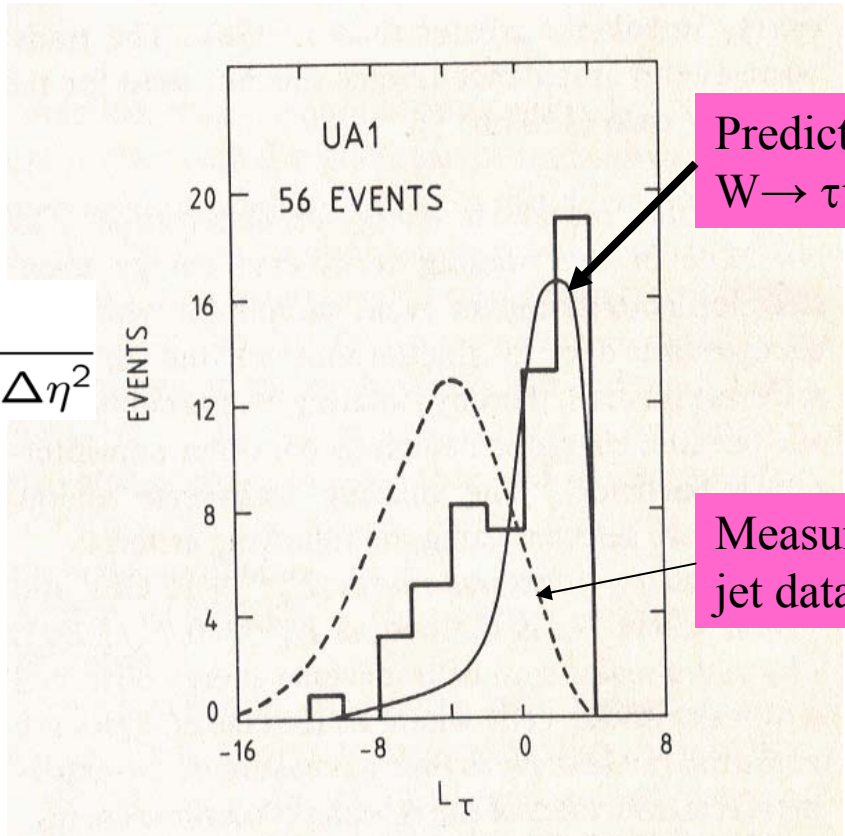
Boosted τ from W decay produces collimated low multiplicity jet

UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. 185B (1987) p. 233

Form τ Likelihood L_τ
Based on 3 inputs:

1. *Fraction of jet energy* in cone ΔR<0.4 vs ΔR<1.0 (expect peaking towards 1)
2. *Angular separation* Leading track and jet axis (expect peaking towards 0)
3. *Charged particle multiplicity* (expect predom. 1 or 3)

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$



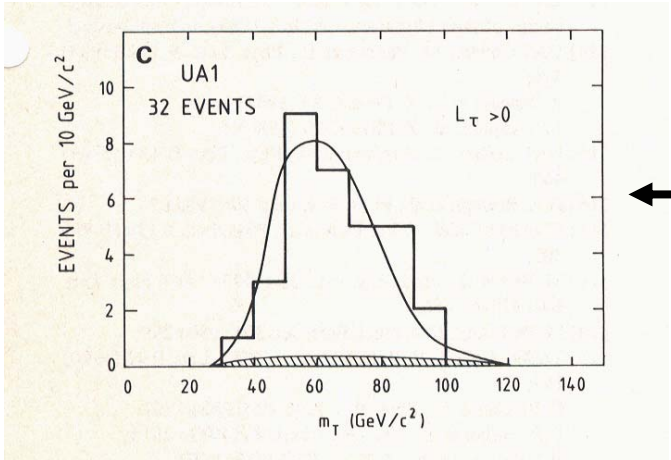
Predicted by W→ τν MC

Measured in jet data

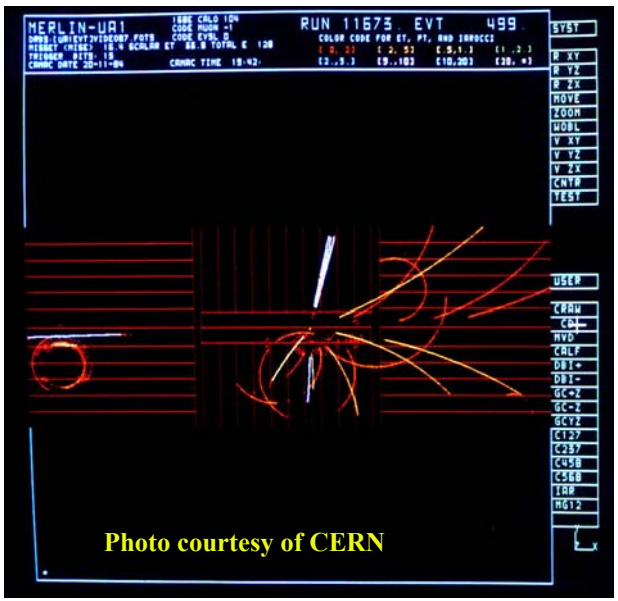
τ sample: $L_\tau > 0$

W → τν Candidates

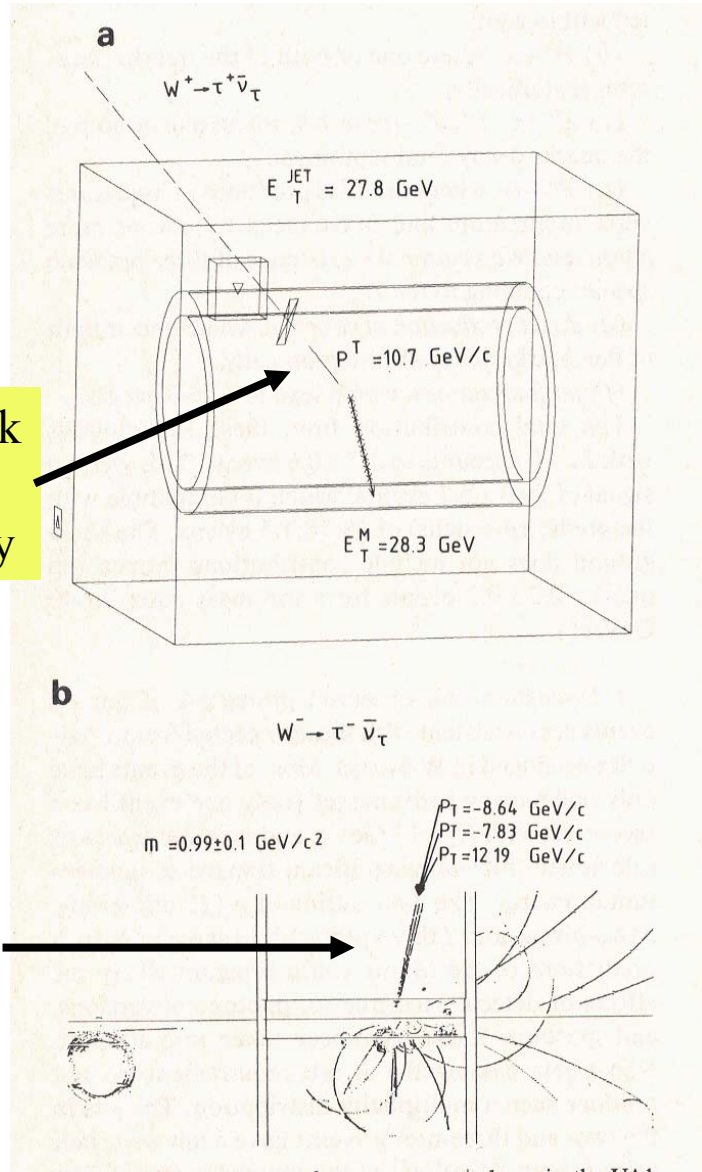
UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. 185B (1987) p. 233



m_T consistent with W decay



Single high p_T track with significant EM and had energy



Narrow low-mass 3-prong jet in CD

Missing E_T Signal Sample

UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. 185B (1987) p. 241

118 nb^{-1} @ 540 GeV, 597 nb^{-1} @ 630

56 events observed
32 τ's ($L_\tau > 0$)
24 $L_\tau < 0$

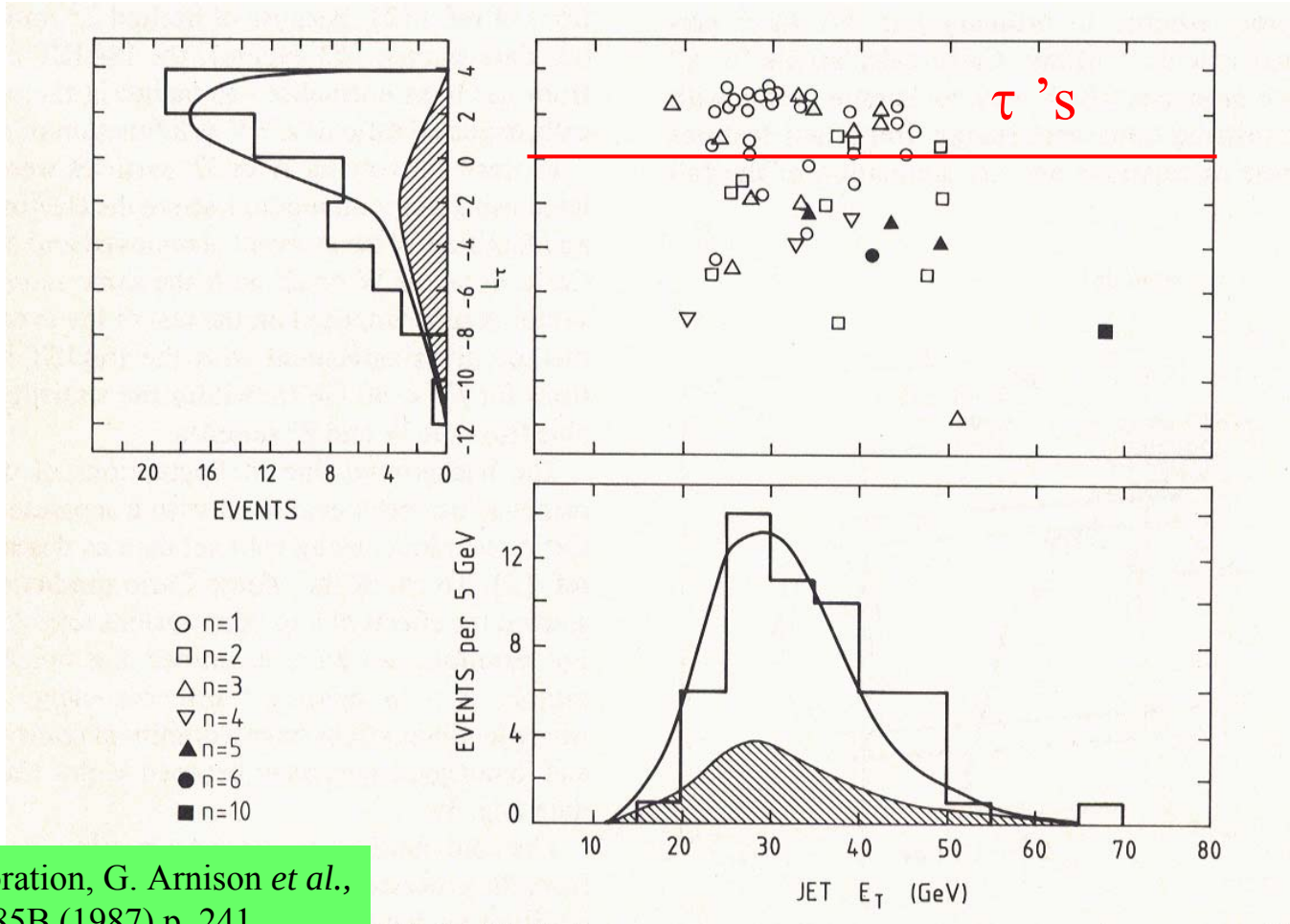
Good agreement with expectations

Comment:
Good example of several SM processes of comparable size adding up to a much larger total contribution ("Altarelli cocktail")

events passing all event selection cuts.

Process	Events (total	Events with $L_\tau < 0$	Events with $L_\tau < 0$ and $E_T^{jet} < 40$ GeV
$W \to e\nu$			
$W \to \mu\nu$	3.6	2.0	1.4
$W \to \tau\nu \to$ leptons			
$W \to \tau\nu$	36.7	8.0	7.1
$\to \nu\bar{\nu}$ + hadrons	<0.1	<0.1	<0.1
$W \to c\bar{s}$	0.5	0.1	0.1
$Z^0 \to \tau^+\tau^-$			
$Z^0 \to \nu\bar{\nu}$	7.4	7.1	5.6
(3 neutrino species)	<0.1	<0.1	<0.1
$Z^0 \to c\bar{c}$ and $b\bar{b}$	0.2		
$c\bar{c}$ and $b\bar{b}$		0.2	0.2
(direct production)	3.8		
jet fluctuations		3.4	3.4
(fake missing energy)			
total	52.2	**20.8** $\pm 5.1 \pm 1.0$	**17.8** $\pm 3.7 \pm 1.0$

L_τ versus Jet E_T for 56 Events



UA1 Collaboration, G. Arnison *et al.*, Phys. Lett. 185B (1987) p. 241

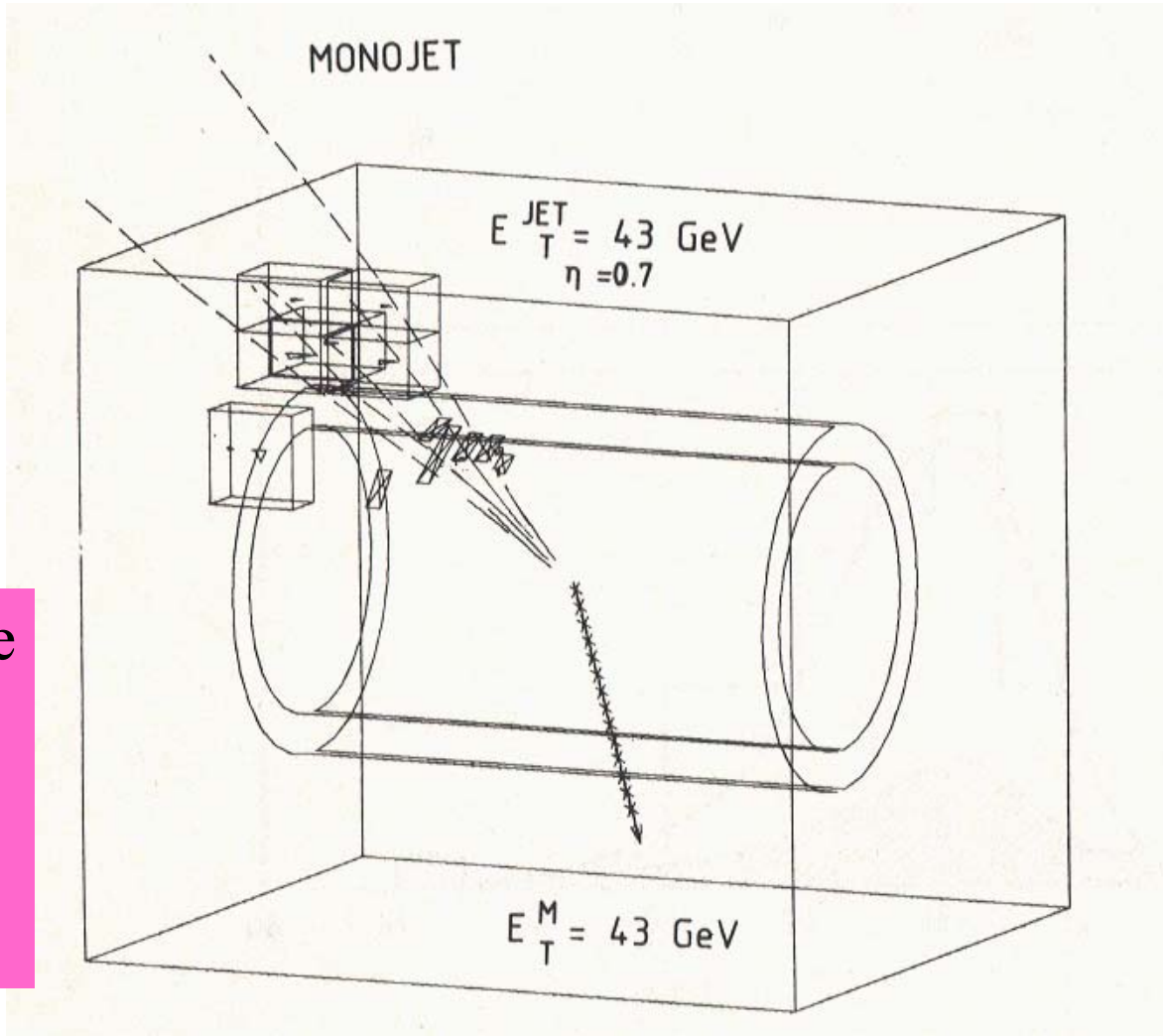
One of the 56 Signal Events

UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. 185B (1987) p. 241

This jet has $L_\tau < 0$

For display set thresholds at p_T, $E_T > 1$ GeV

Some of the signal came in on energy imbalance trigger only
(this example probably Fired jet trigger too)



Some Results from ΔE_T Analysis

1st observation of $W \rightarrow \tau\nu$

1st direct test of lepton universality (at high Q^2):

$$\frac{g_\tau}{g_e} = 1.01 \pm 0.09 \pm 0.05$$

$$\frac{g_\mu}{g_e} = 1.05 \pm 0.07 \pm 0.08$$

Aside: with 32 observed τ events, why is the statistical error so small?

$m_L > 41$ GeV/c^2 @ 90% C.L.

$n_\nu \leq 7$ @ 90% C.L.

Of course, then LEP came along and …

Squark and Gluino Searches

SUSY Model

Photino is the LSP, stable, massless

5 squarks are mass degenerate (no stop!)

Ignore wino, zino, higgsino, sleptons

2 parameters: $m_{\tilde{q}}, m_{\tilde{g}}$

Signature

Two or more jets with ΔE_T

Decay Scenarios

$$m_{\tilde{g}} > m_{\tilde{q}}$$

$$\tilde{g} \rightarrow q\bar{\tilde{q}} \rightarrow q\bar{q}\tilde{\gamma}$$

$$\tilde{q} \rightarrow q\tilde{\gamma}$$

$$m_{\tilde{q}} > m_{\tilde{g}}$$

$$\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$$

$$\tilde{q} \rightarrow q\tilde{\gamma} \quad \text{or}$$

$$\tilde{q} \rightarrow q\tilde{g} \rightarrow qq'\bar{q}'\tilde{\gamma}$$

Modified Selection for SUSY

Missing E_T selection described previously inefficient for SUSY

Isolation criteria too severe

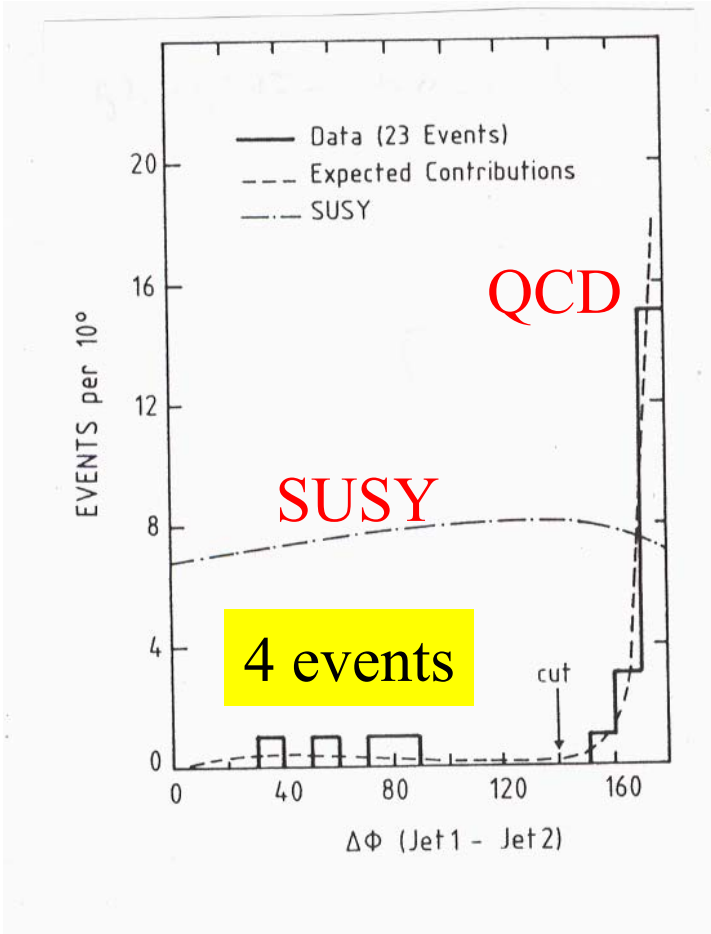
$\Rightarrow$ Require $\geq$ 2 Jets with $E_T > 12$ GeV

$\Rightarrow$ Eliminate back-to-back topology From mismeasured QCD jets:

$$|\phi_{\mathrm{jet1}} - \phi_{\mathrm{jet2}}| < 140^\circ$$

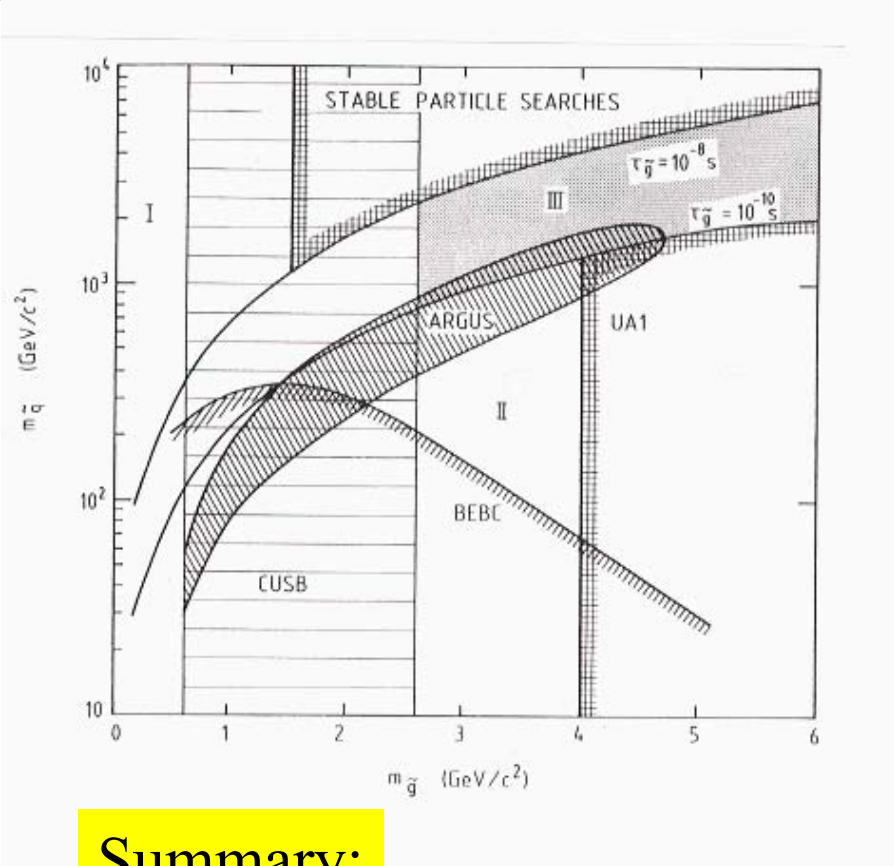
Expect 5.2±1.9±1.0 events (again from several sources)

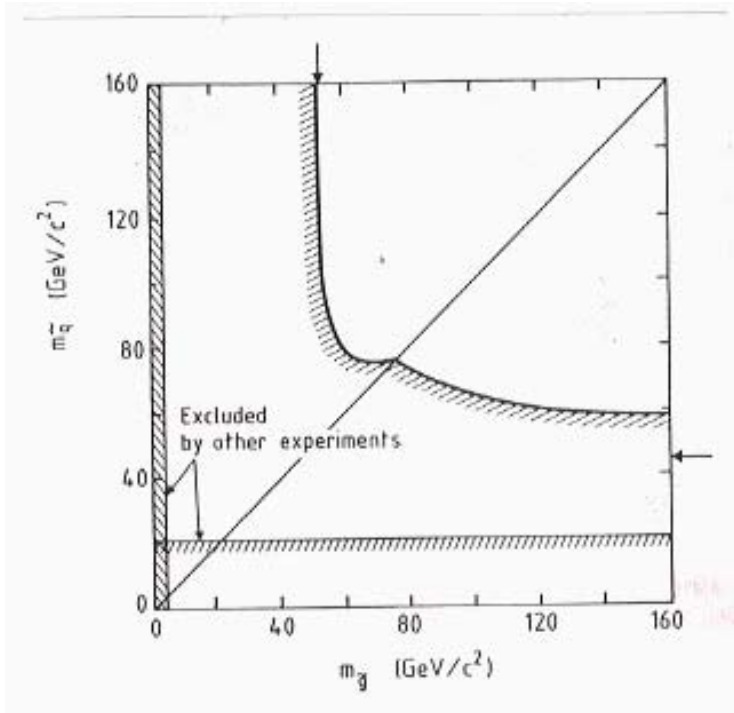
UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. 198B (1987) p. 261



Limits on squark & gluino masses

UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. 198B (1987) p. 261





Summary:

$$m_{\tilde{q}} > 45\ \mathrm{GeV}/c^2 \qquad m_{\tilde{g}} \to \infty$$

$$m_{\tilde{g}} > 53\ \mathrm{GeV}/c^2 \qquad m_{\tilde{q}} \to \infty$$

Caution: various qualifiers apply:
- Photino mass
- Gluino lifetime and acceptance
- No systematic on cross-section