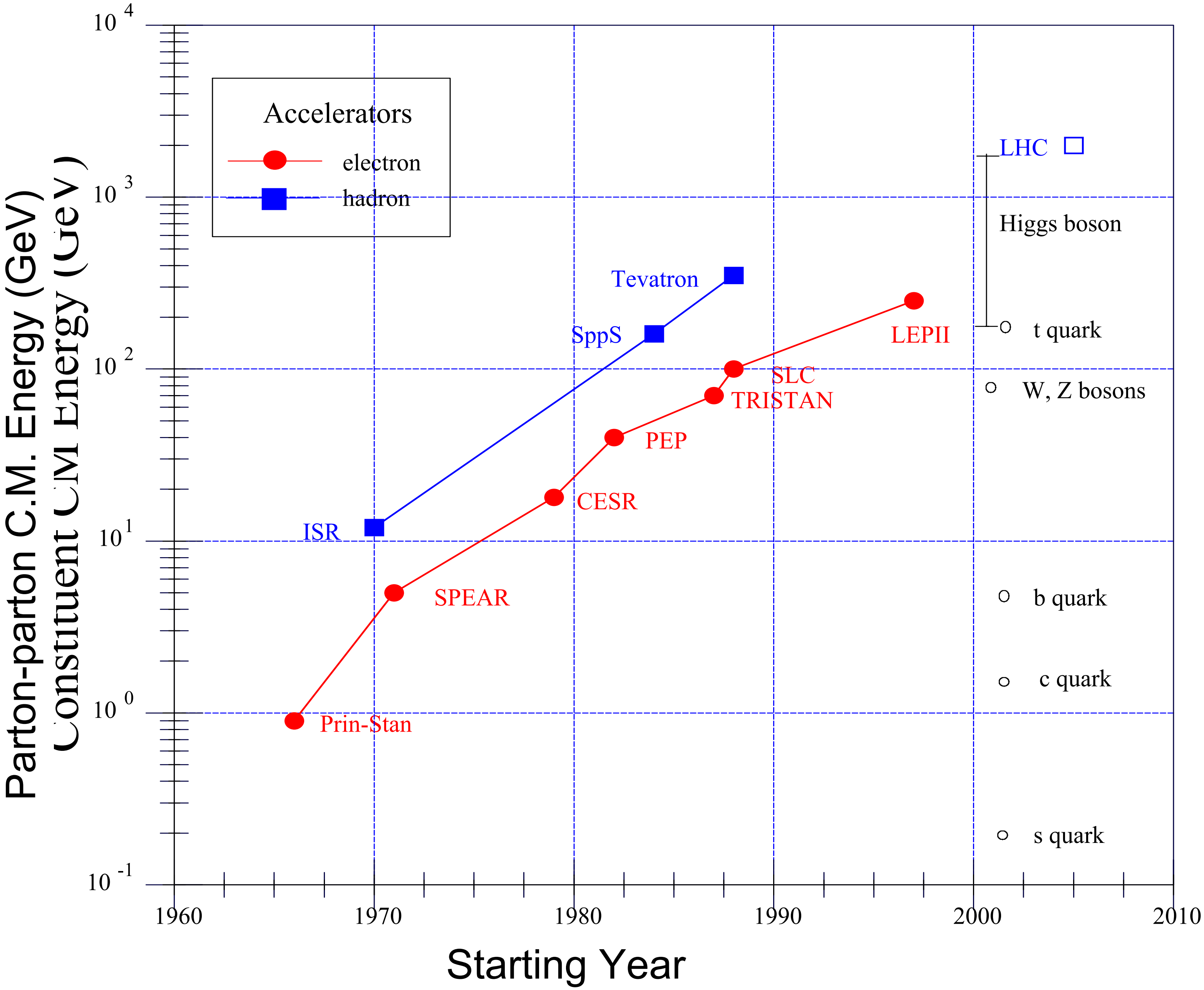
30 Years of Hadron Colliders

M. Della Negra/CERN

Split, 5 October 2004

Hadron & Electron Colliders



Intersecting Storage Rings, ISR

First hadron collider (p-p)

(approved by CERN Council Dec 1965)

First collisions in Jan 1971

$\sqrt{s}$ = 23, 30, 44, 53, 62 GeV

$L \sim 10^{31} cm^{-2} s^{-1}$

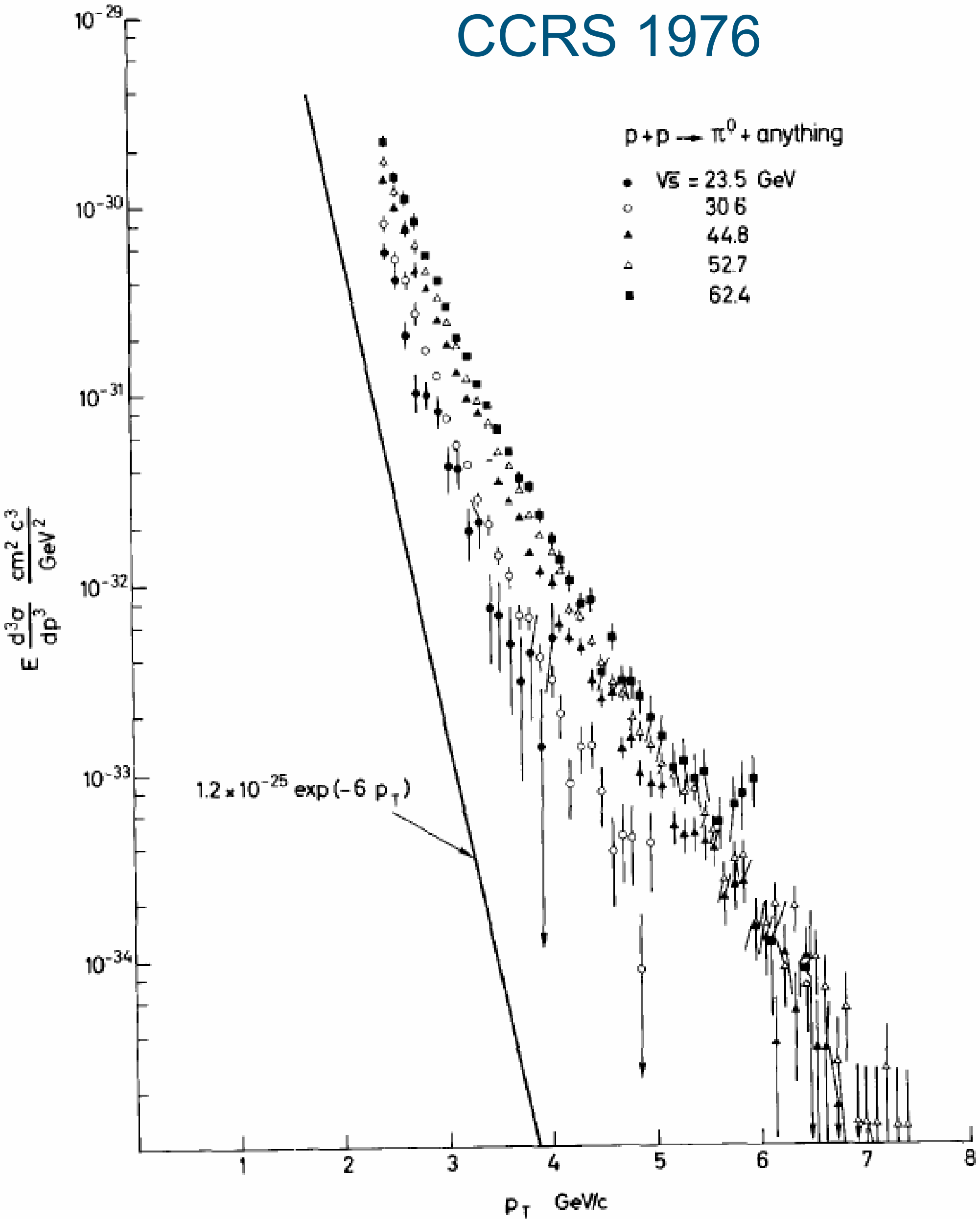
Most experiments: Inclusive spectra in small solid angle spectrometers looking at forward angles. Three Collaborations looked at large angle

BS, SS, CCR (1973)

Excess at large p_T

Parton-parton collisions?

CCRS 1976



ISR: the p_T^{-8} puzzle (1)

Expectations from the parton model:

From dimension arguments the parton-parton scattering cross-section should behave as

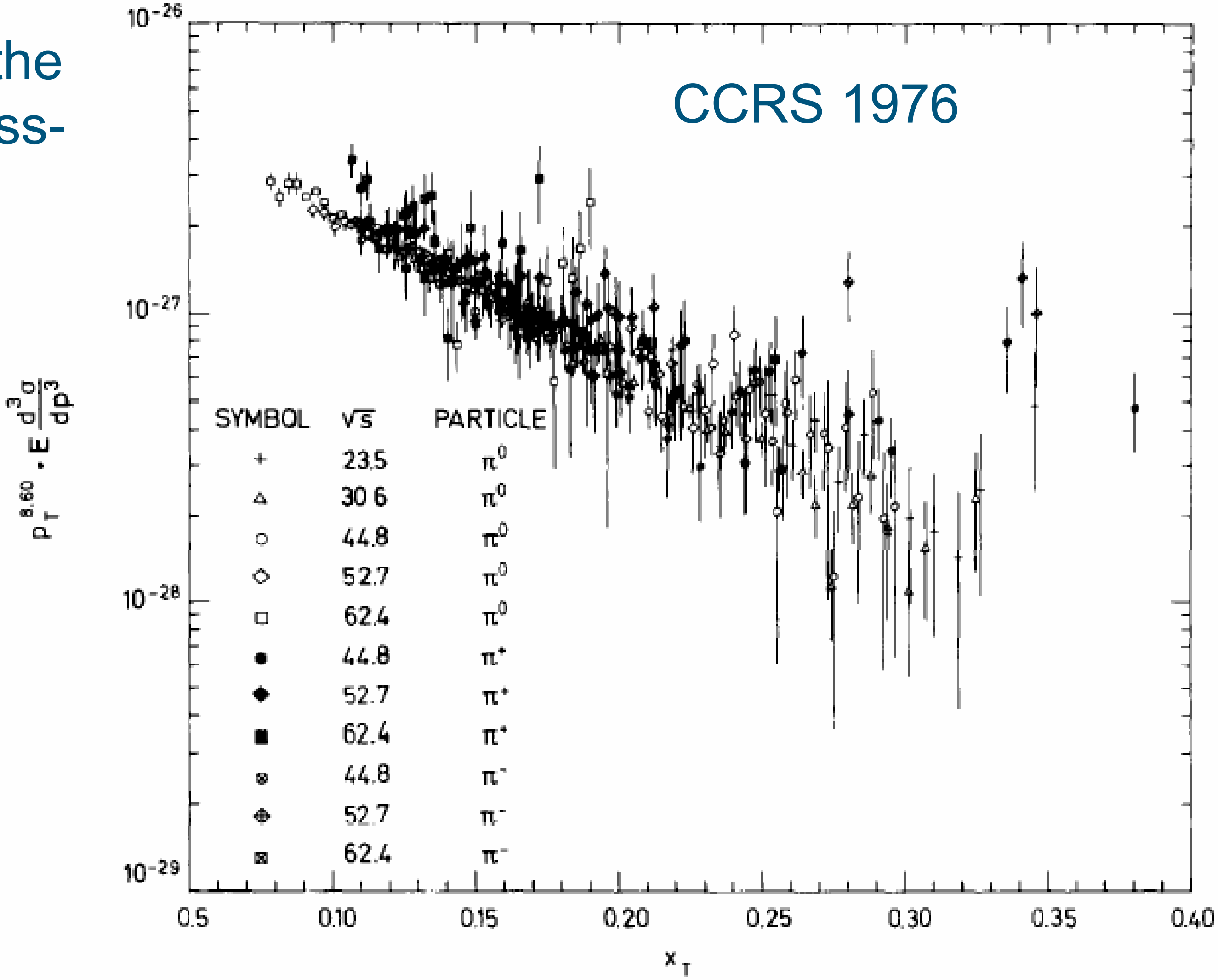
$$\frac{d\sigma}{d\hat{t}} = f(\hat{t}/\hat{s})\hat{s}^{-2}$$

Then the inclusive cross-section should behave as p_T^{-4} at fixed x_T:

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^4} f(x_T, \cos\theta)$$

with $$x_T = \frac{2p_T}{\sqrt{s}}$$

But CCRS data scale as p_T^{-8}



CCRS 1976

$$E\frac{d^3\sigma}{dp^3} \approx A\frac{1}{p_T^8}\exp(-26x_T)$$

ISR: the p_T^{-8} puzzle (2)

Force p_T^{-8} ?

meson+quark→ meson+quark (CIM)

or adhoc “black box” cross section (FF1)

$$\frac{d\sigma}{d\hat{t}} \propto \frac{1}{\hat{s}^2} \rightarrow \frac{1}{\hat{s}^4}$$

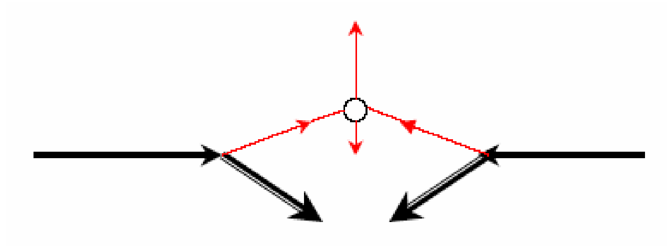
Or improve parton model :

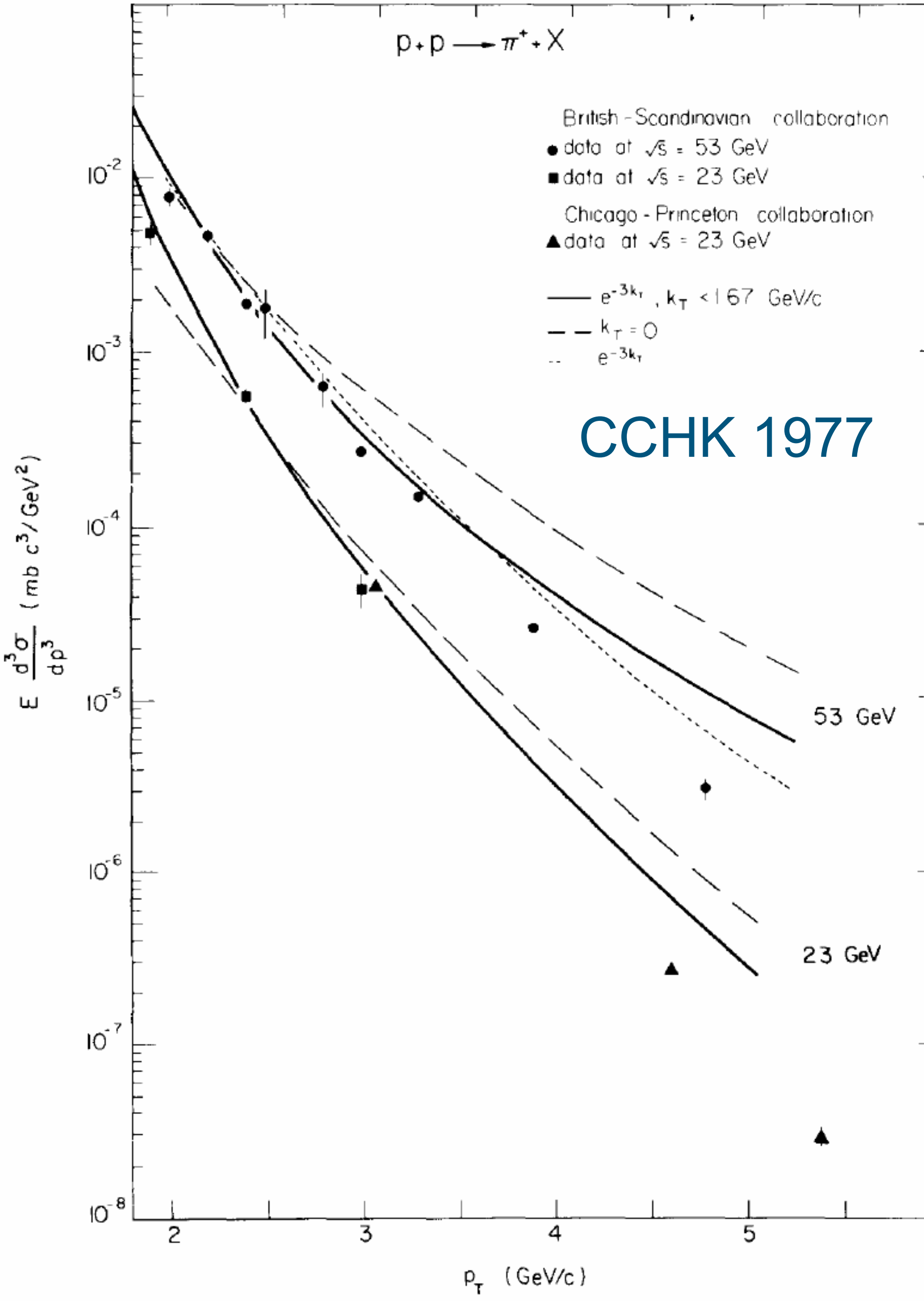
keep natural dimensional scaling for pointlike constituents.

$$\frac{d\sigma}{d\hat{t}} \propto \frac{1}{\hat{s}^2}$$

introduce k_T smearing of partons (CCHK):

$$d\sigma(P \rightarrow q) \approx \frac{(1-x)^3}{x} e^{-Ak_T} dx dk_T^2$$



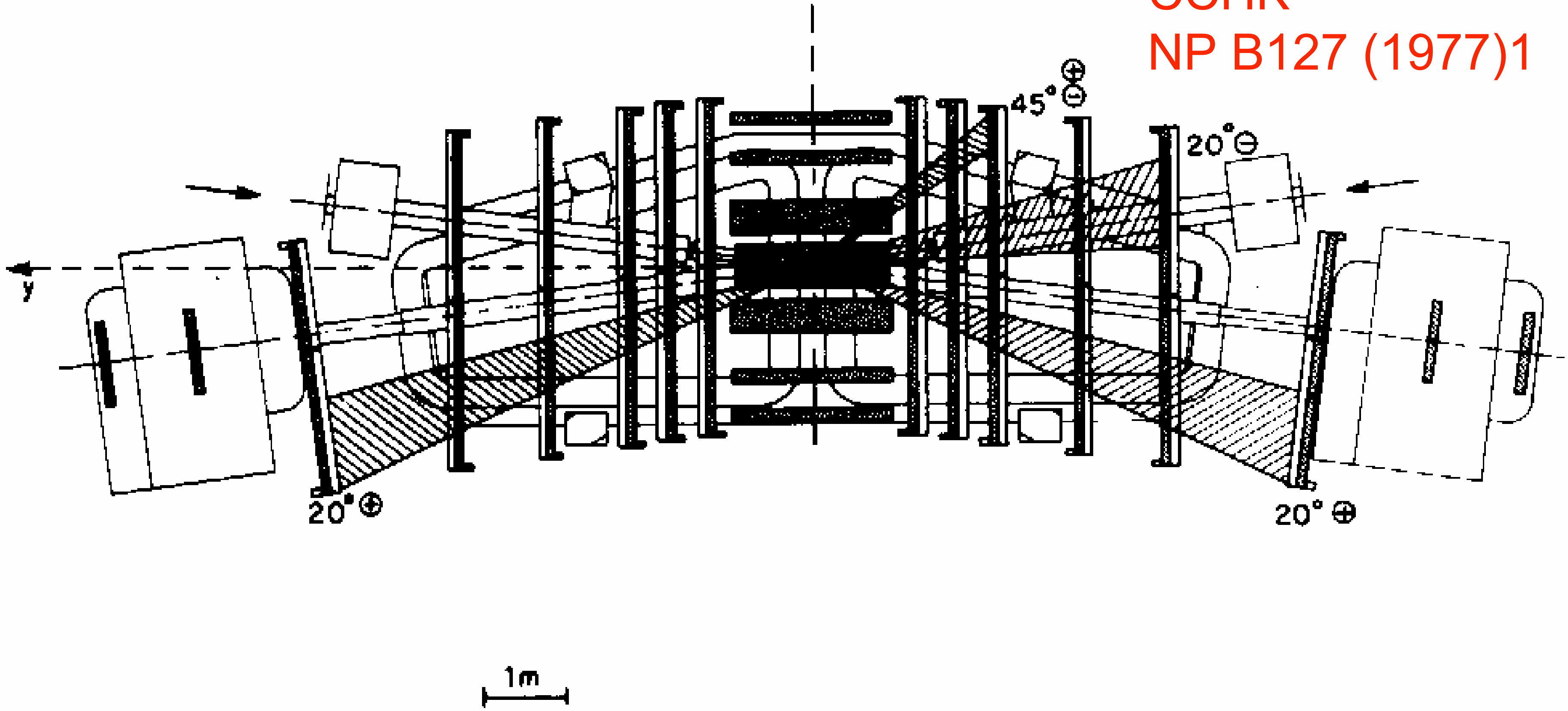


CCHK 1977

The Split Field Magnet (SFM) Detector

Can we see the parton jets?
Study full event structure: SFM the first “4π” collider detector. Charged particles only! 50,000 proportional wires.

CCHK
NP B127 (1977)1



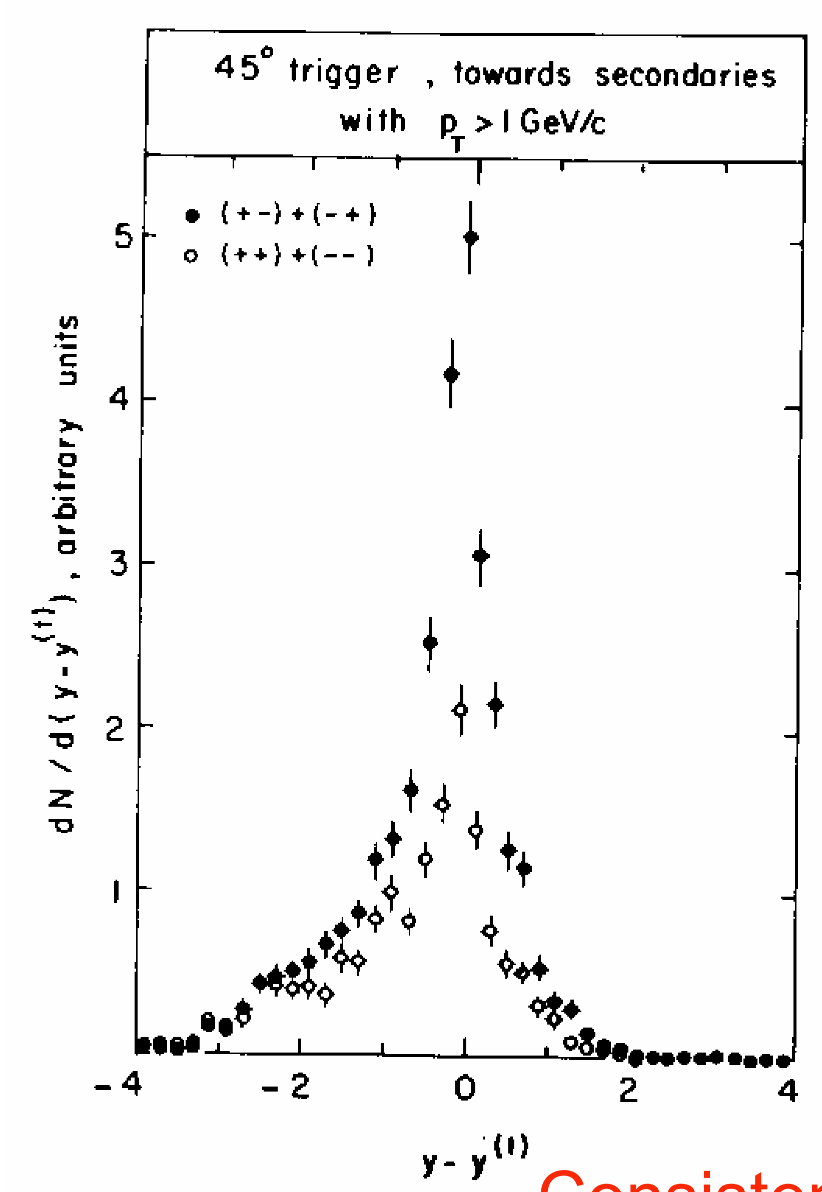
A large p_T charged particle trigger (at 20^0 and 45^0)was implemented using the proportional chambers in self-triggering mode.

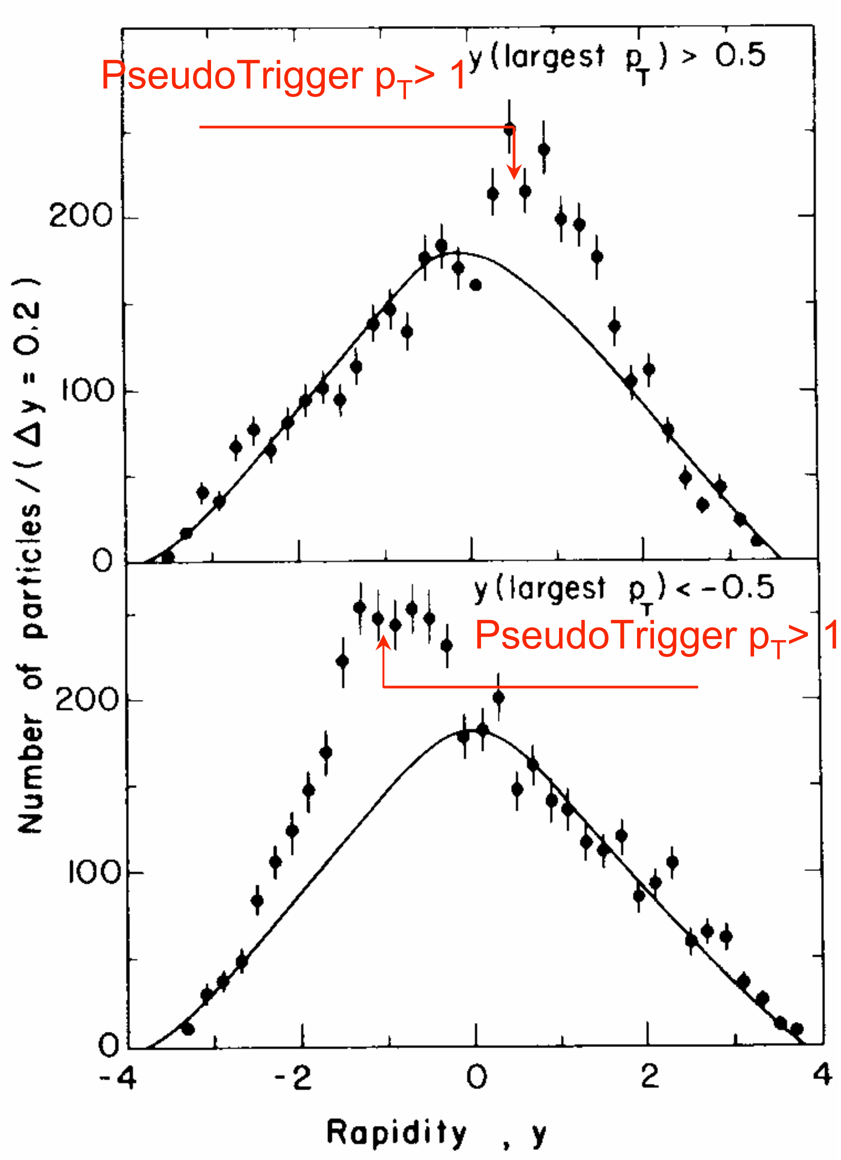
Structure of events with a large p_T trigger: $p_T > 2$ GeV

Towards

CCHK 1977

Away ($p_T > 0.8$)





PseudoTrigger $p_T > 1$

PseudoTrigger $p_T > 1$

Consistent with two-jet structure!

QCD and Large p_T Hadron Production

There is a new emerging theory giving grounds to the parton model: Quantum Chromodynamics with asymptotic freedom (1973).

$$\alpha_s(Q^2) \rightarrow 0 \quad as \quad Q^2 \rightarrow \infty$$

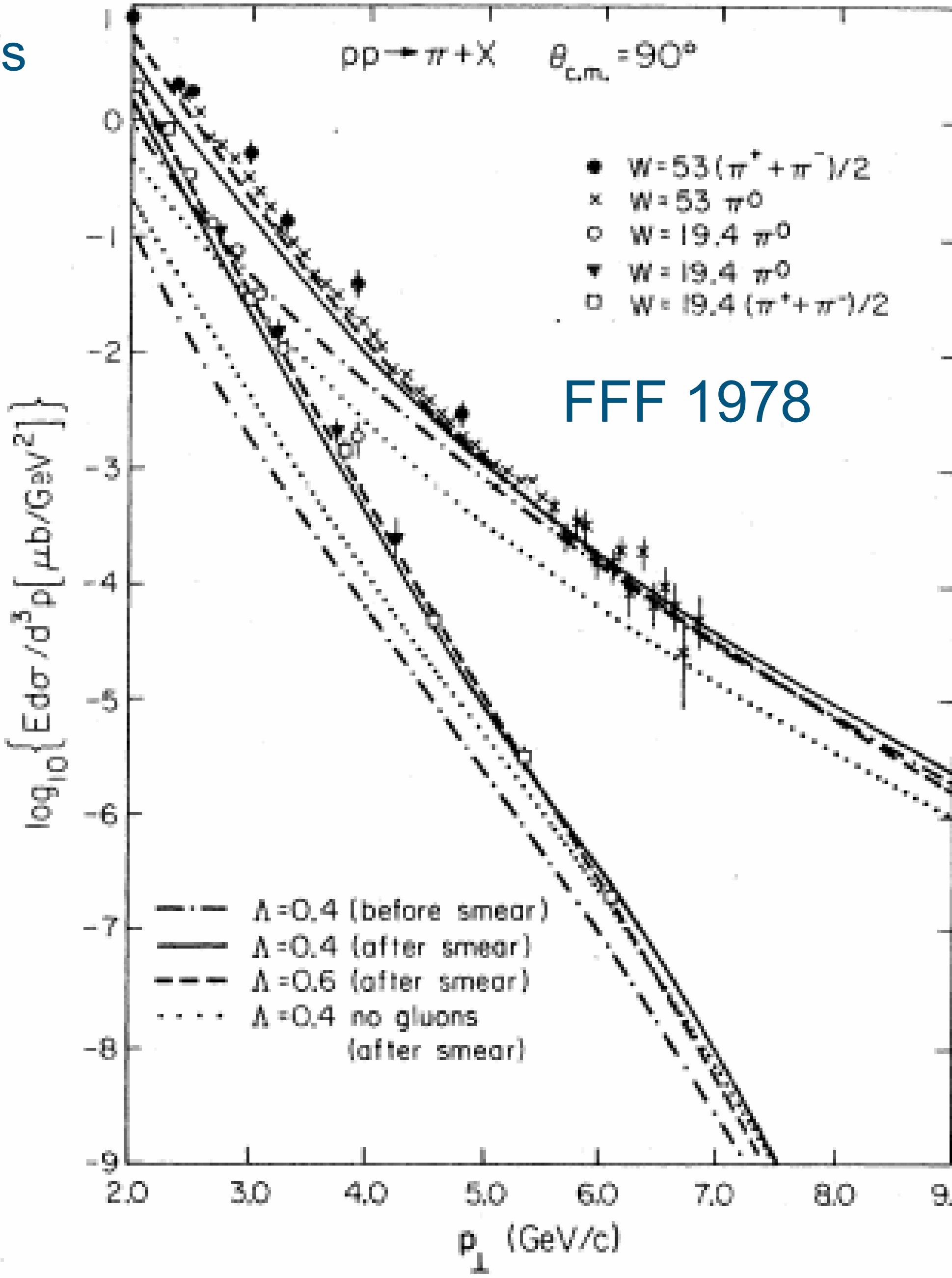
Feynman, Field and Fox (1978): QCD can fit quantitatively the ISR data!

1) k_T smearing a la CCHK
2) 2→2 process: qq, qg. gg
3) scaling violations

$$F(x) \rightarrow F(x,Q^2) \qquad D(z) \rightarrow D(z,Q^2)$$

$$\alpha_s \rightarrow \alpha_s(Q^2)$$

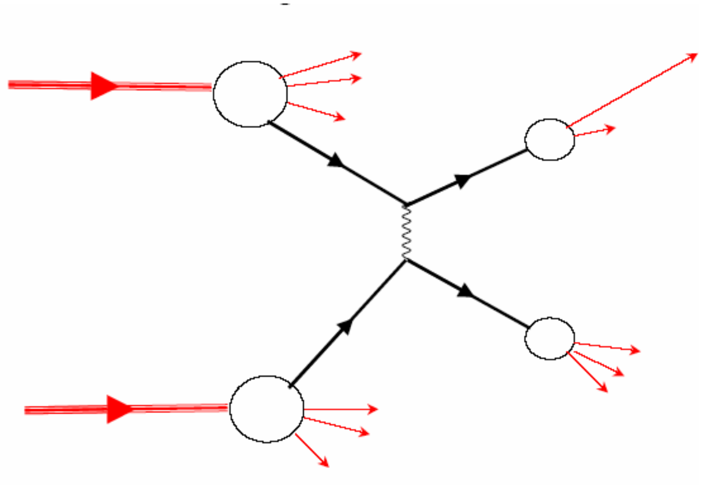
- k_T smearing necessary to explain the data at low p_T!
- Gluon contributions are needed. ISR jets are mainly gluon jets!
- Approximate p_T^{-8} scaling was not fundamental



FFF 1978

Summary: Large p_T phenomena at the ISR

Large p_T phenomena observed for the first time at the ISRs are consistent with 2→2 scattering of point like constituents.



Towards jet biased by single particle trigger

Away jet barely discernible from the underlying event

- p_T^{-8} approximate scaling was not fundamental.
- At low p_T cannot neglect effect of k_T of partons.
- Need higher p_Ts (and higher energies) to “see” jets.
- Need calorimeter trigger (unbiased jet trigger). Calo triggers also welcome higher E_Ts (energy resolution). R807 with 2π calorimetry came too late (1980).

S$p\bar{p}$S : a $p\bar{p}$ Collider in the SPS!

In 1976 Carlo Rubbia and others pointed out that the SPS could be transformed into a proton-antiproton collider capable of reaching a centre of mass energy of 2x270 GeV and a luminosity of ~ $10^{30}cm^{-2}s^{-1}$.

Exciting possibility: direct observation of the intermediate vector bosons: W and Z

3 working groups (1977):

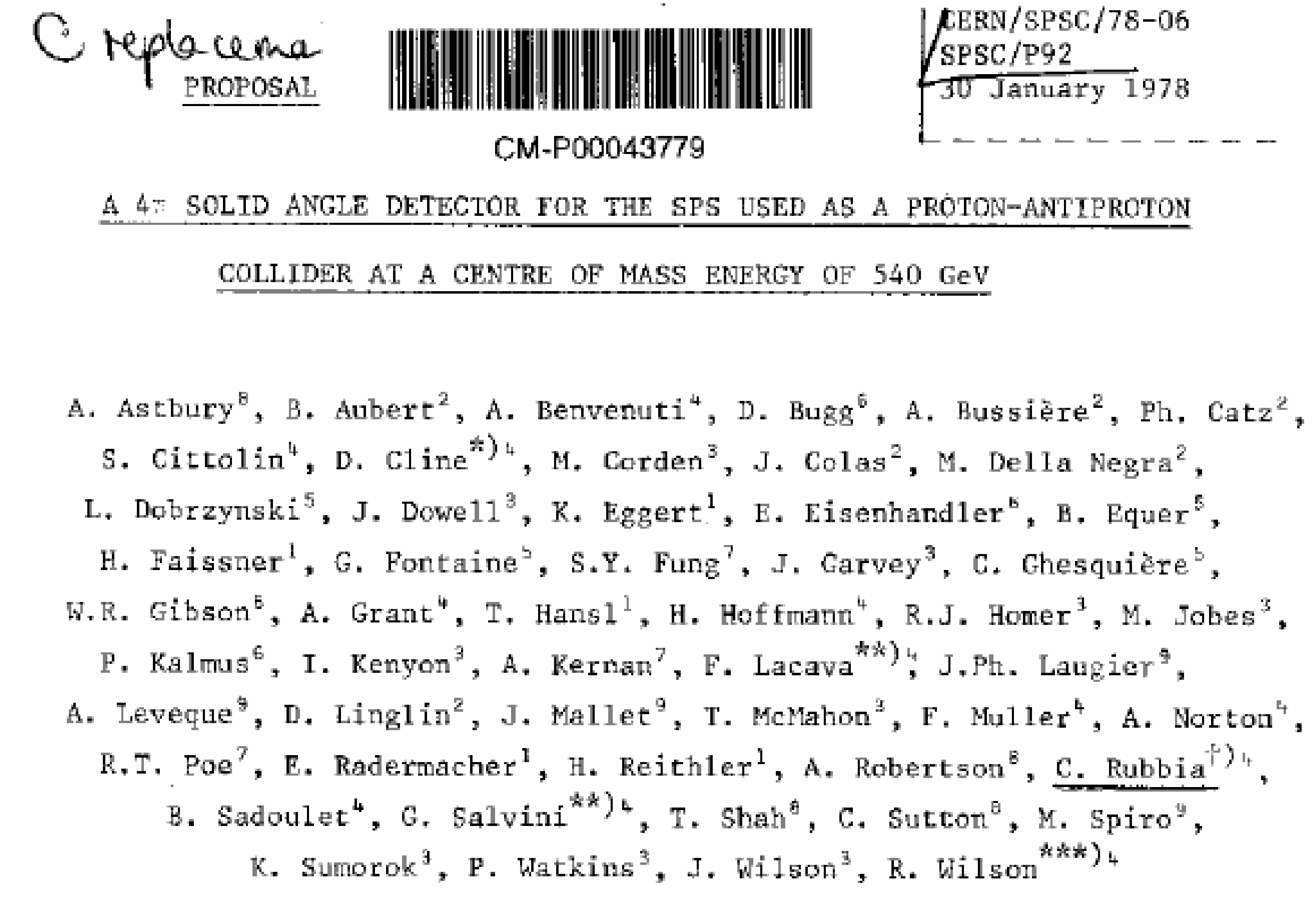
1)Antiproton source

2)Initial Cooling Experiment (ICE): S. Van der Meer

3)General Purpose Detector: C. Rubbia

Sp$\bar{p}$S : UA1 Proposal

The very first general purpose 4π detector (UA1) for a hadron collider was proposed in January 1978



C replacema

PROPOSAL

CM-P00043779

CERN/SPSC/78-06
SPSC/P92
30 January 1978

A 4π SOLID ANGLE DETECTOR FOR THE SPS USED AS A PROTON-ANTIPROTON COLLIDER AT A CENTRE OF MASS ENERGY OF 540 GeV

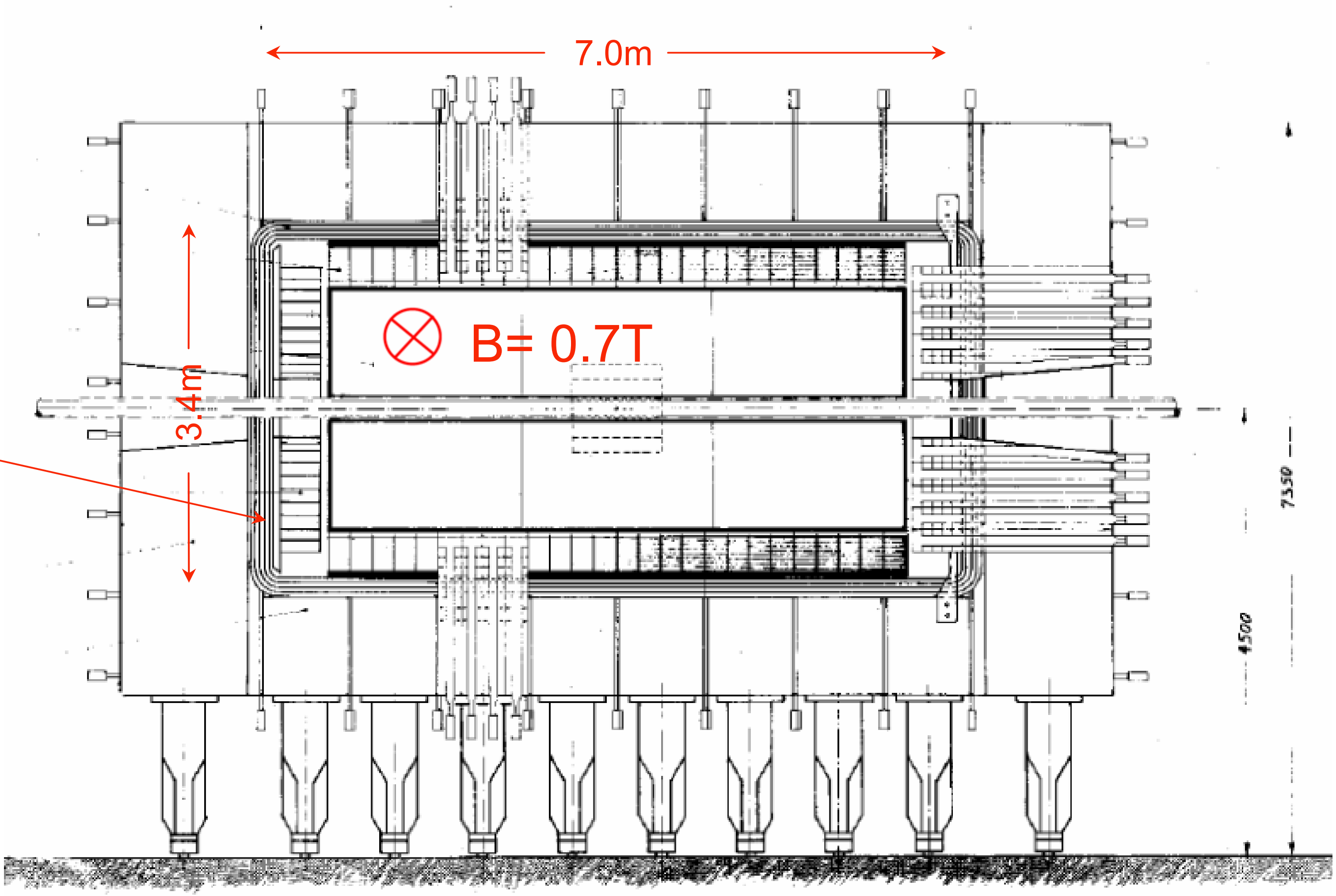
A. Astbury[8], B. Aubert[2], A. Benvenuti[4], D. Bugg[6], A. Bussière[2], Ph. Catz[2],
S. Cittolin[4], D. Cline*)[4], M. Corden[3], J. Colas[2], M. Della Negra[2],
L. Dobrzynski[5], J. Dowell[3], K. Eggert[1], E. Eisenhandler[6], B. Equer[5],
H. Faissner[1], G. Fontaine[5], S.Y. Fung[7], J. Garvey[3], C. Ghesquière[5],
W.R. Gibson[6], A. Grant[4], T. Hansl[1], H. Hoffmann[4], R.J. Homer[3], M. Jobes[3],
P. Kalmus[6], I. Kenyon[3], A. Kernan[7], F. Lacava**)[4]; J.Ph. Laugier[9],
A. Leveque[9], D. Linglin[2], J. Mallet[9], T. McMahon[3], F. Muller[4], A. Norton[4],
R.T. Poe[7], E. Radermacher[1], H. Reithler[1], A. Robertson[8], C. Rubbia†)[4],
B. Sadoulet[4], G. Salvini**)[4], T. Shah[8], C. Sutton[8], M. Spiro[9],
K. Sumorok[3], P. Watkins[3], J. Wilson[3], R. Wilson***)[4]

(52 authors)

UA1 Design

Magnetic Field: B=0 (UA2) or B≠0 (UA1) ?

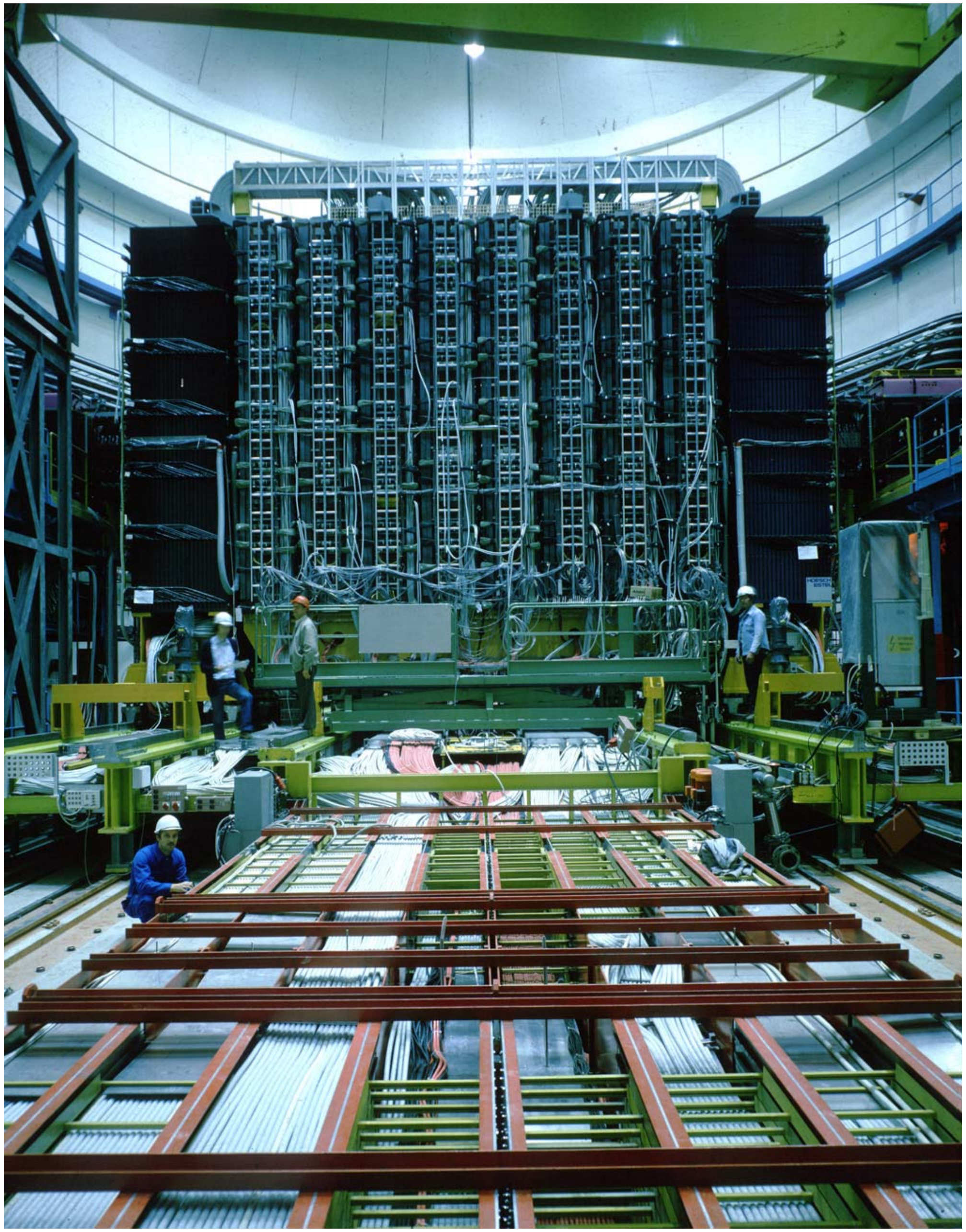
Choice of Magnet: Solenoid or Dipole? Difficult choice. Dipole selected for better forward tracking (hadron collider ≠ electron collider).



(Cheap) warm magnet with Al Coil

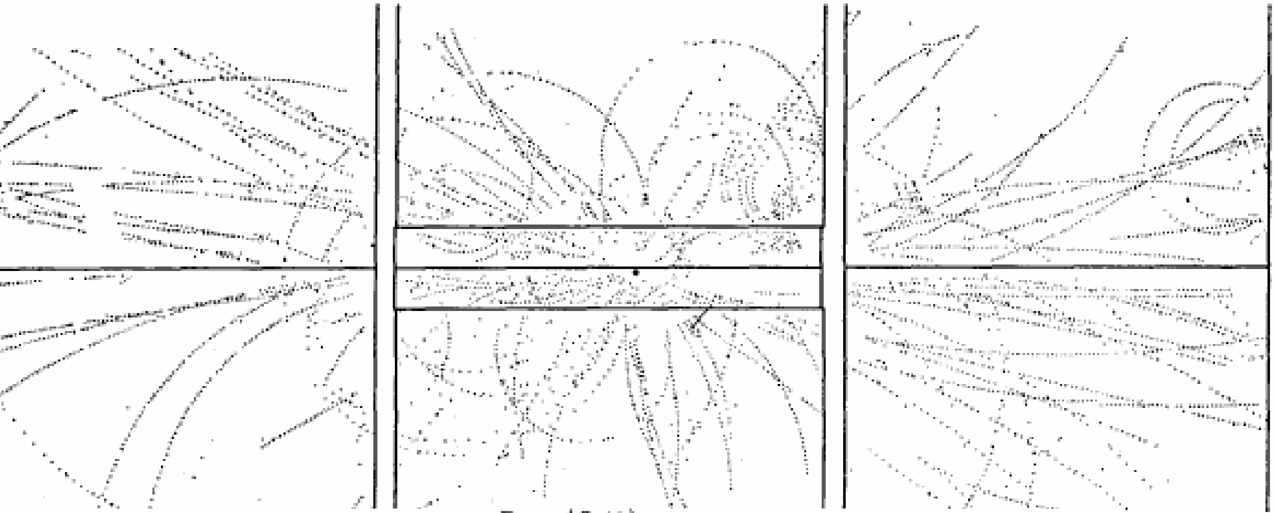
UA1 Detector

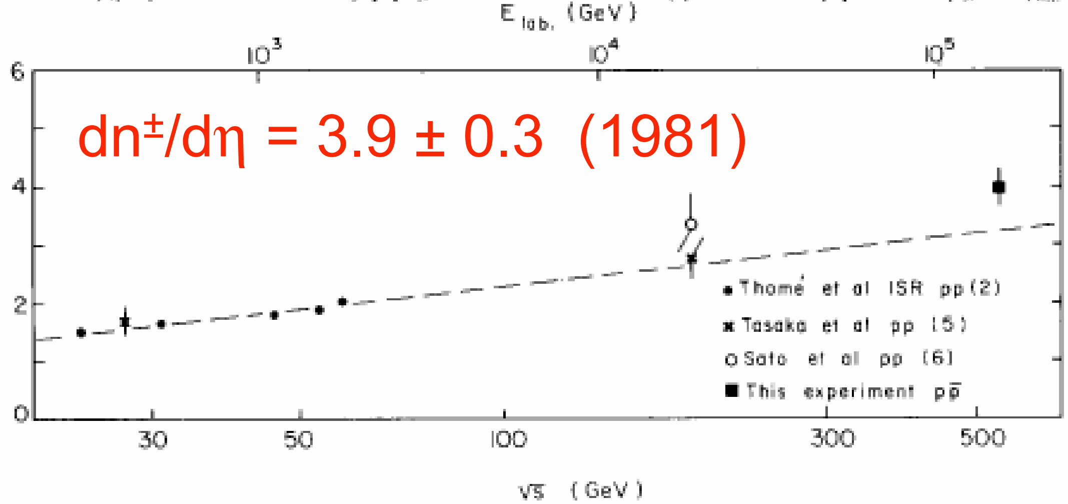
UA1 was built in less than 4 years!



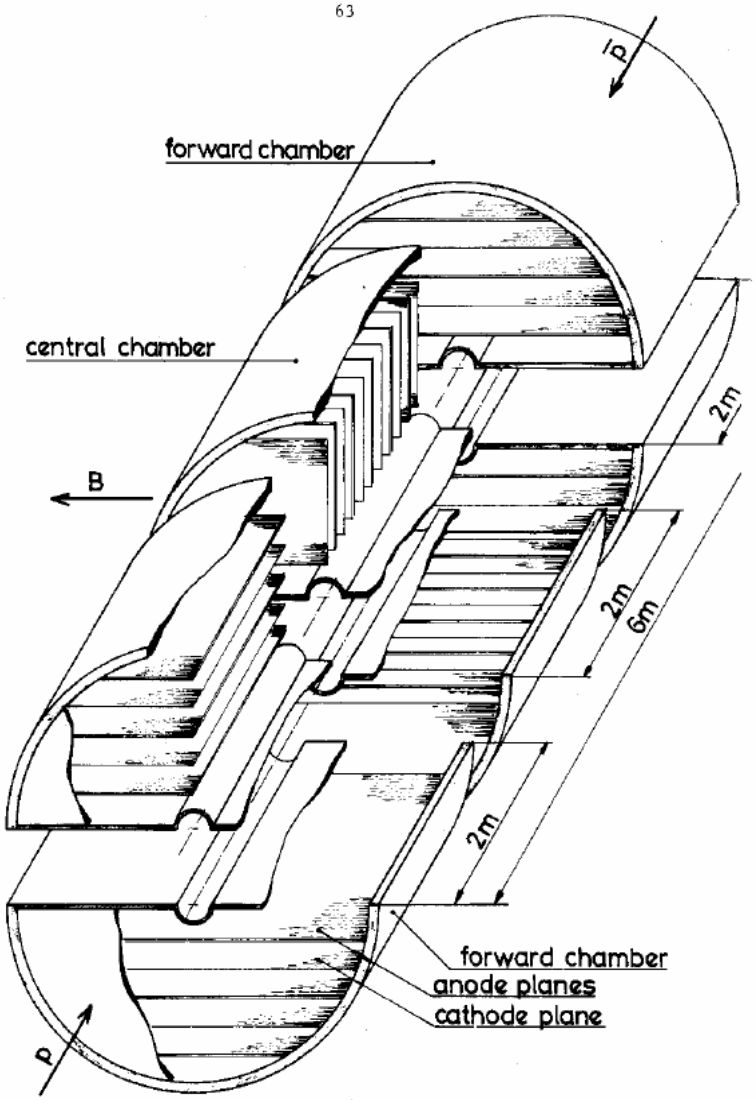
UA1 Central Tracking

Image Chamber (drift chamber): Bubble chamber picture quality! (10,700 wires, 20cm drift length, 4μs max drift time, ~ 300 μm accuracy)





$dn^{\pm}/d\eta = 3.9 \pm 0.3$ (1981)



First collisions at √s = 540 GeV observed in a pilot run in Oct 1981!

(less than 4 years after the proposal)

at L ~ 2 x 10^{25} $cm^{-2}s^{-1}$

UA1 Calorimetry

First Physics Run in Dec 1981 at 10^{26} Luminosity.

UA1 and UA2 started to turn on calorimeter triggers:

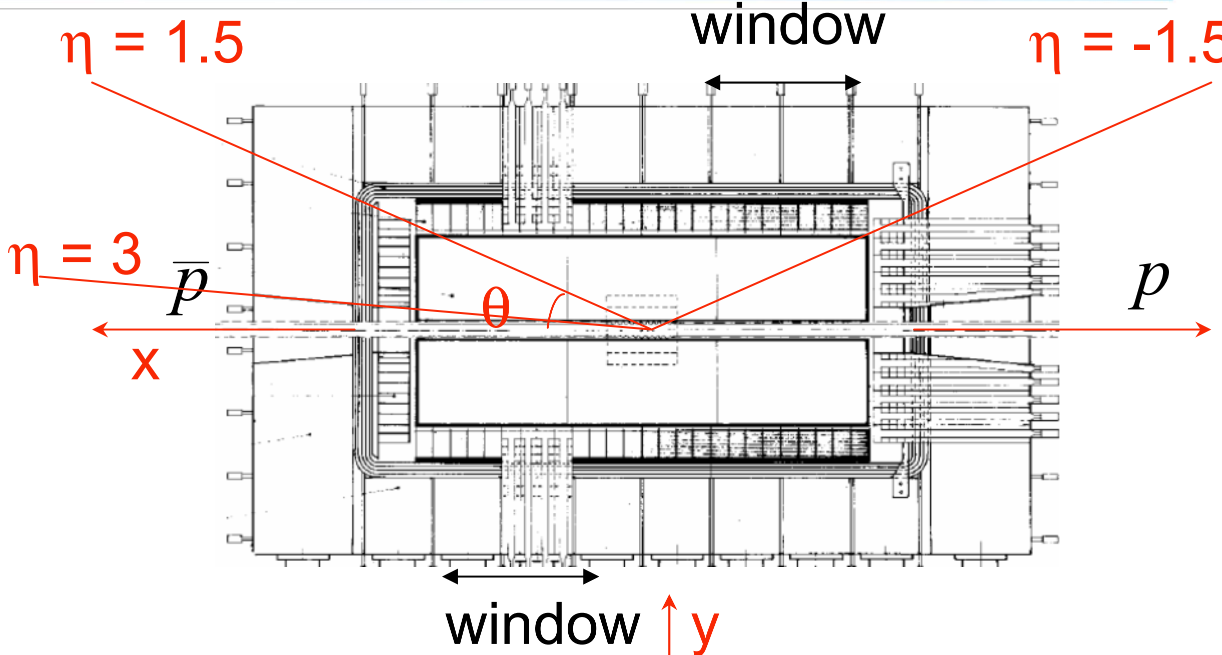
ΣE_T triggers instead of Jet trigger!

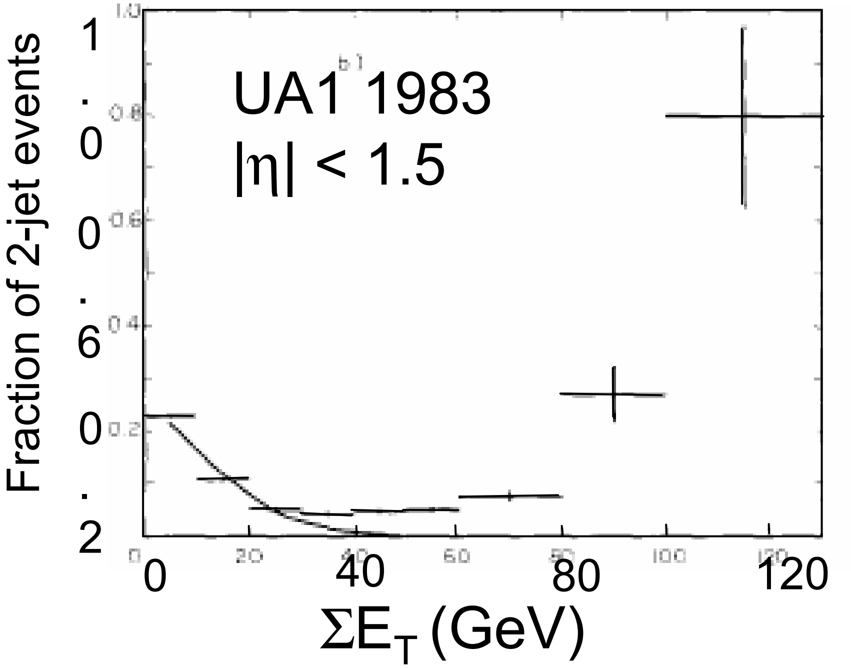
UA1: ΣE_T in $|\eta| < 3$

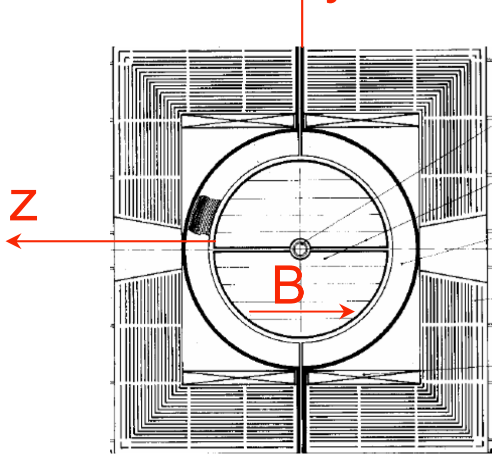
UA2: ΣE_T in $|\eta| < 1.5$ (no endcaps!)

UA2 saw the jets first !

(Paris, ICHEP1982):



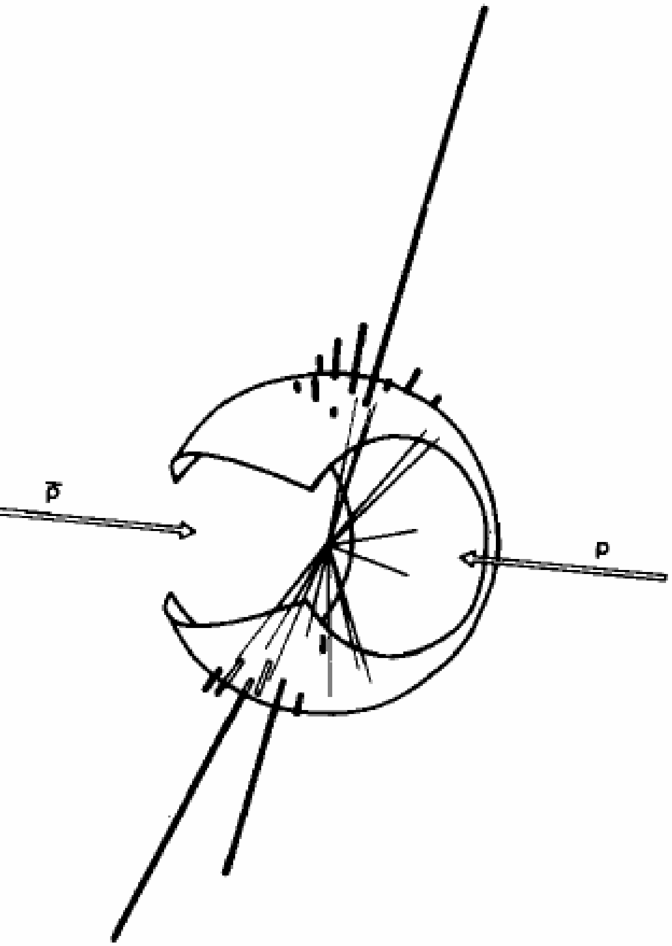


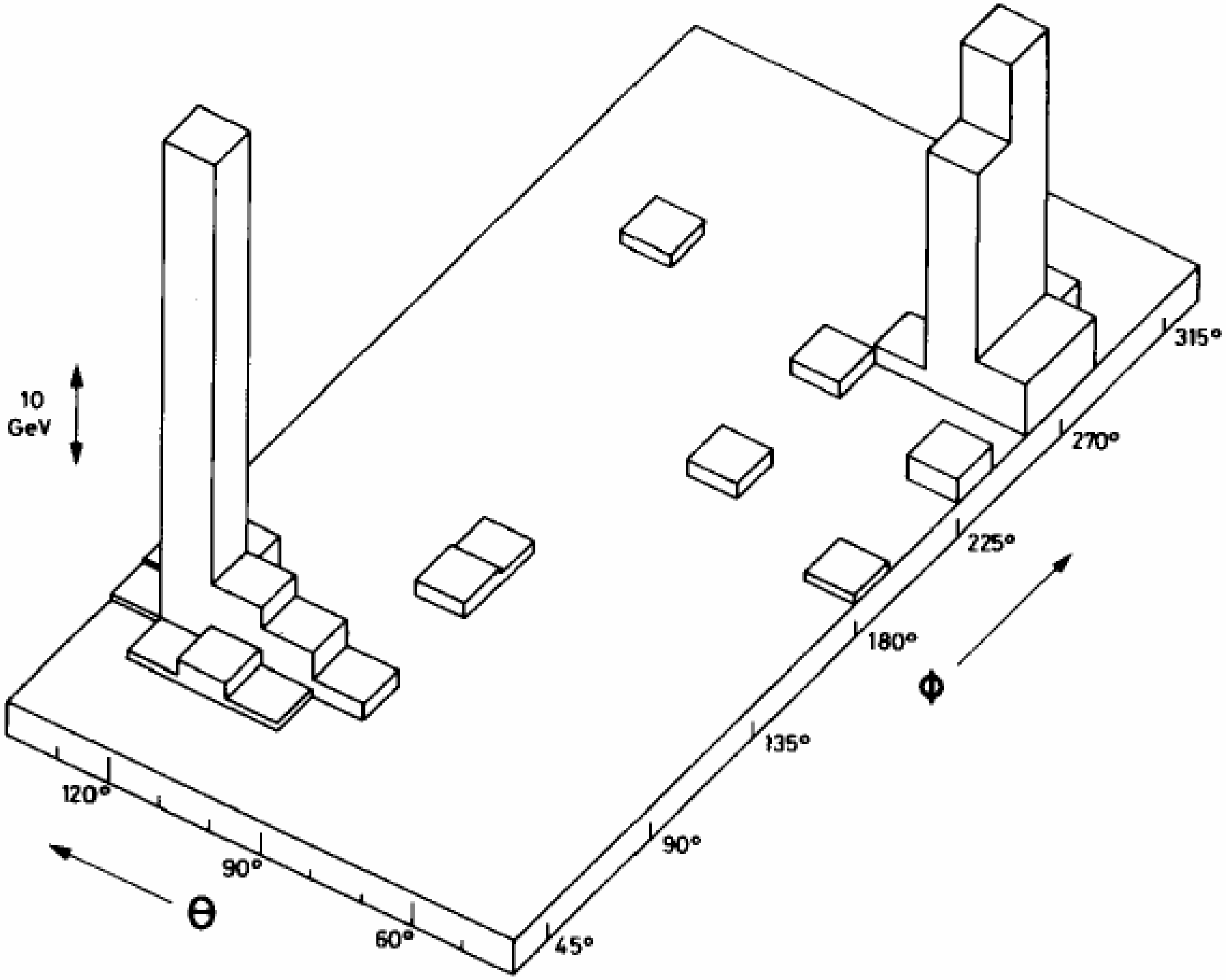


$|\eta| < 1.5$ versus $|\eta| < 3$, wont see jet

for $|\eta| < 3$ until $\Sigma E_T > 300$ GeV

UA2 first clear evidence for jets (Paris 1982)



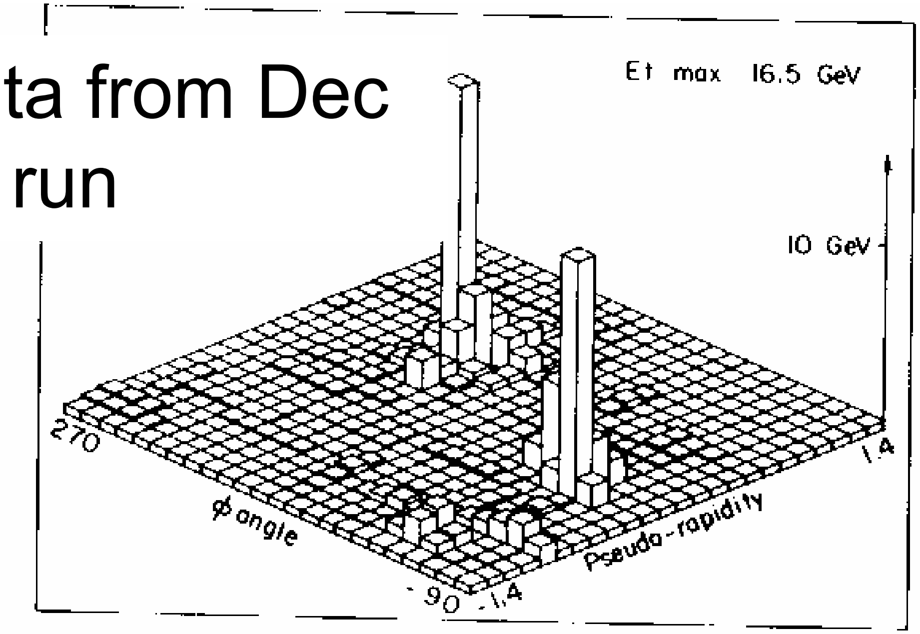


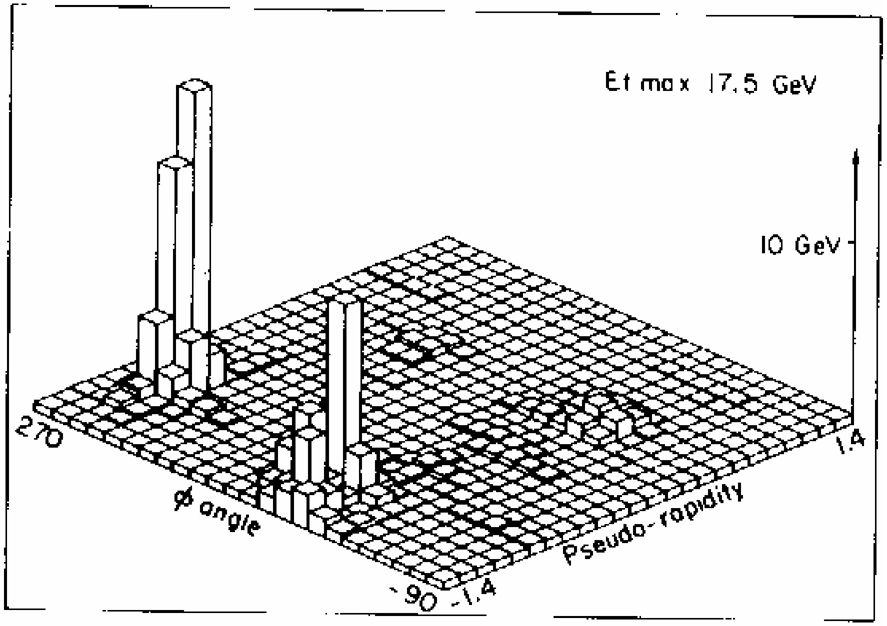
UA2 event with the largest ΣE_T ($|\eta|<1.5$): ΣE_T = 127 GeV

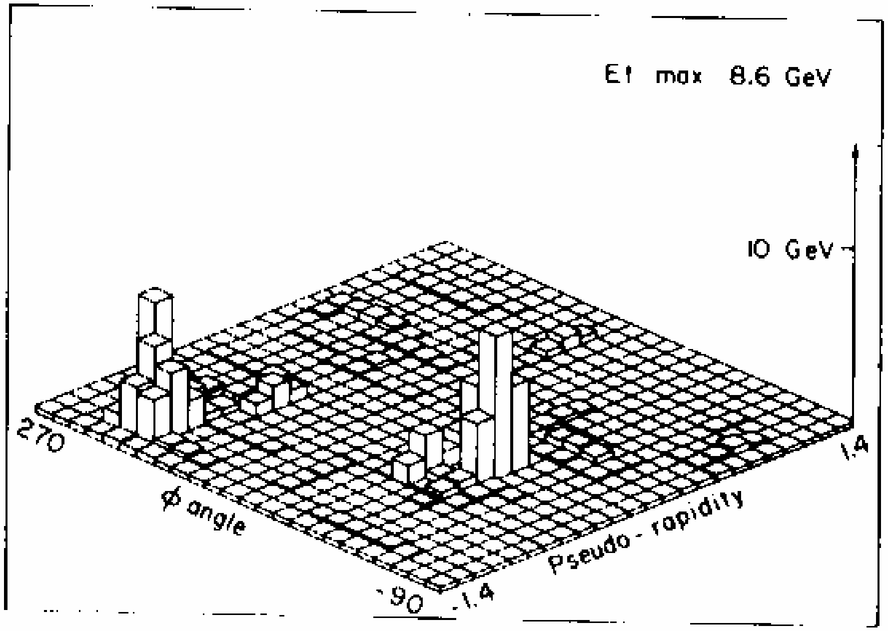
(Dec 1981 run, 79 μb^{-1})

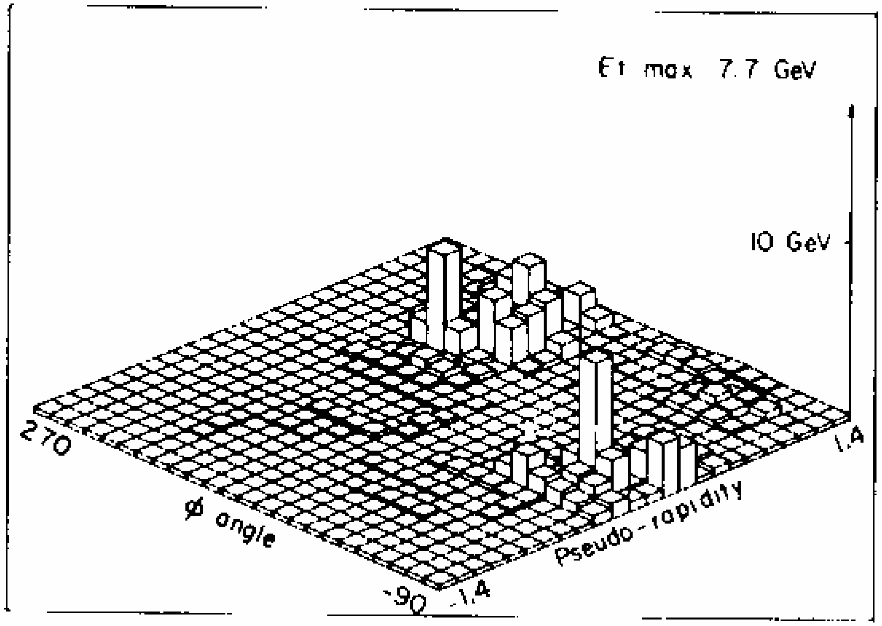
UA1: All Events are jet-like for $\Sigma E_T > 100$ GeV in $|\eta|<1.5$

Data from Dec 81 run









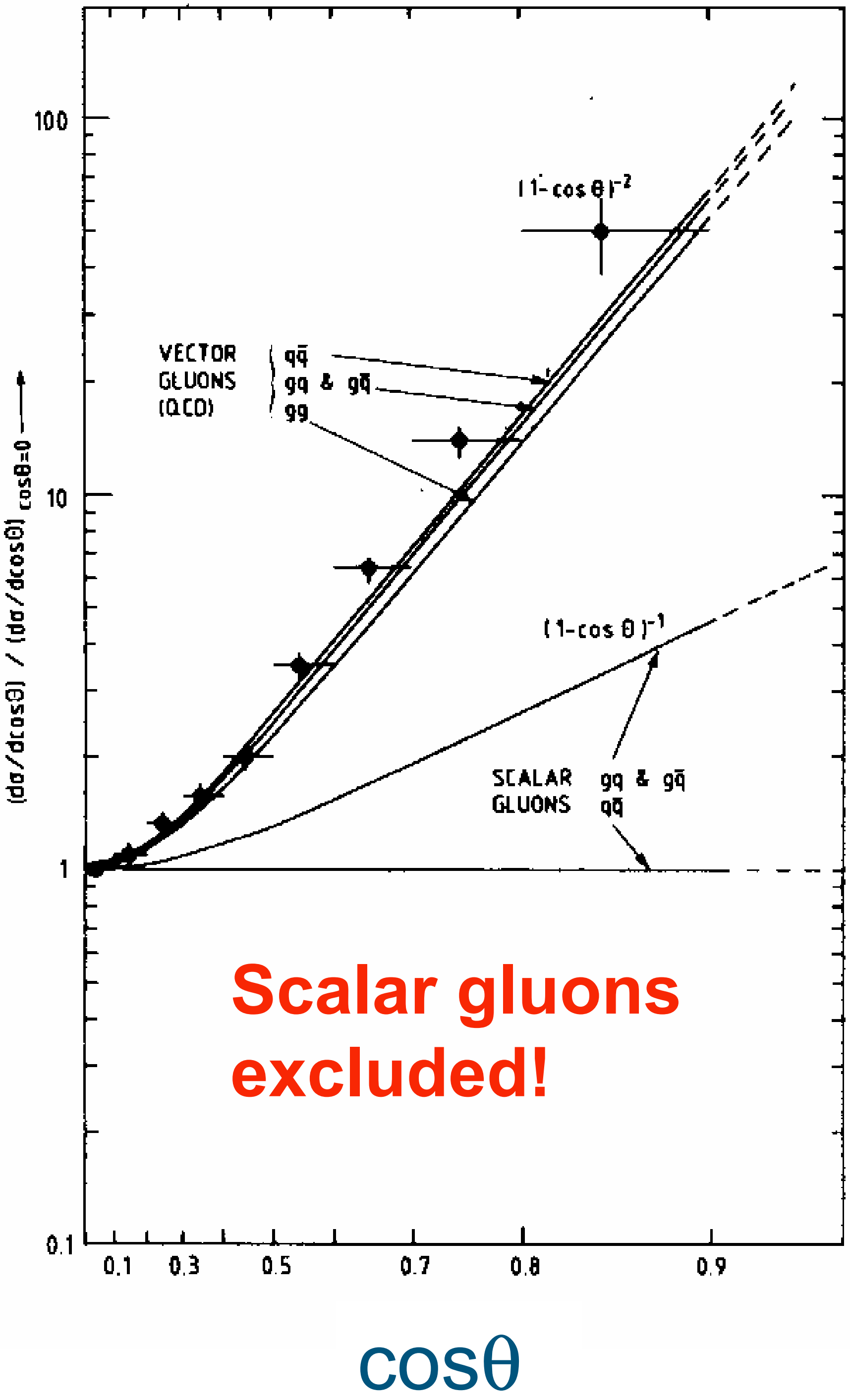
dN/dcosθ for 2-jet events

For the 1982 runs (Oct-Dec, 14 nb^{-1} at $L = 5 \times 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) localised energy jet triggers were used instead of ΣE_T triggers.

A large collection of 2-jet events with $E_T > 25$ GeV (both jets) in $|\eta| < 3$ was collected.

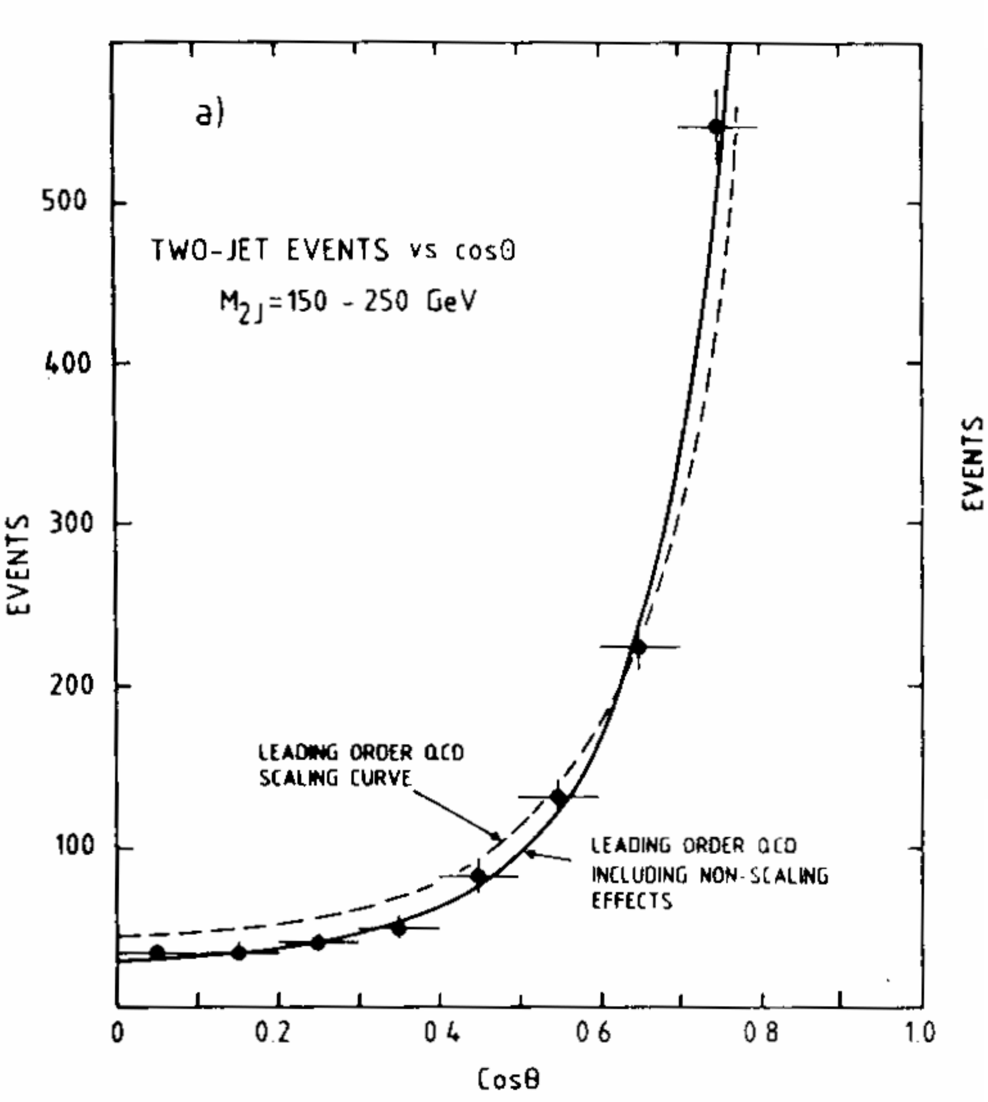
From the jet observables one can reconstruct the kinematics of the parton-parton scattering and extract x_1, x_2 and $\cos\theta$

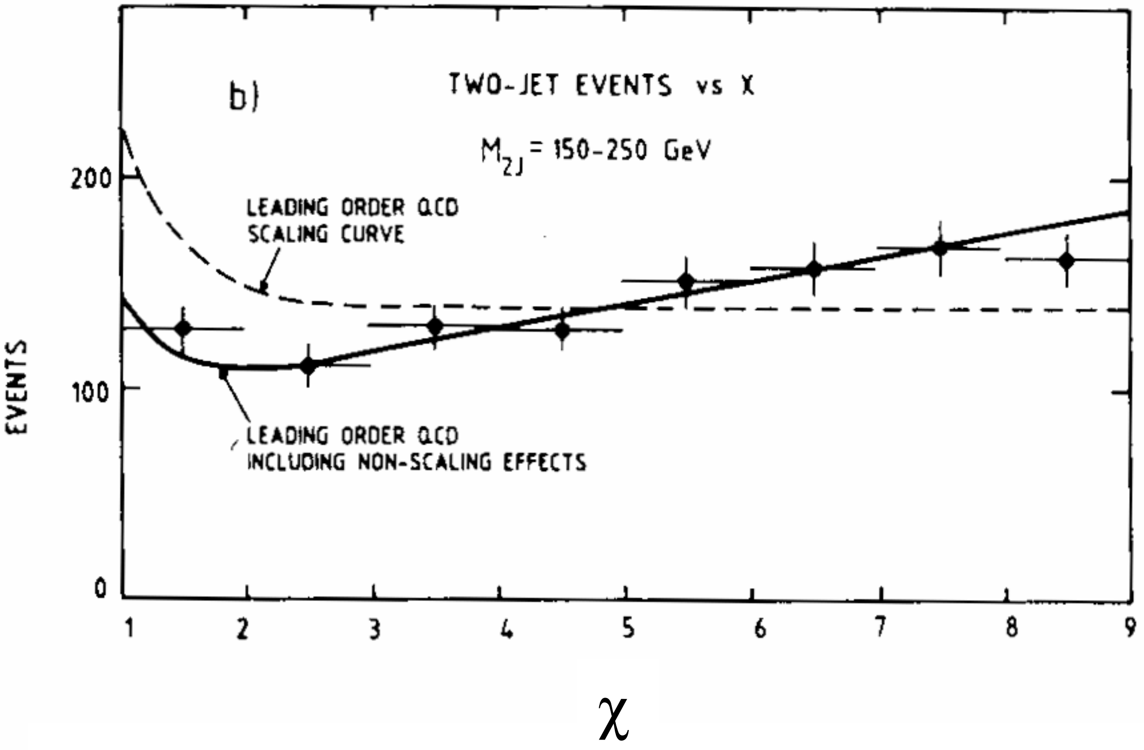
Partons inside protons do scatter a la Rutherford (vector gluon exchange):$1/(1-\cos\theta)^2$



Scalar gluons excluded!

Angular distribution for 2-jet events





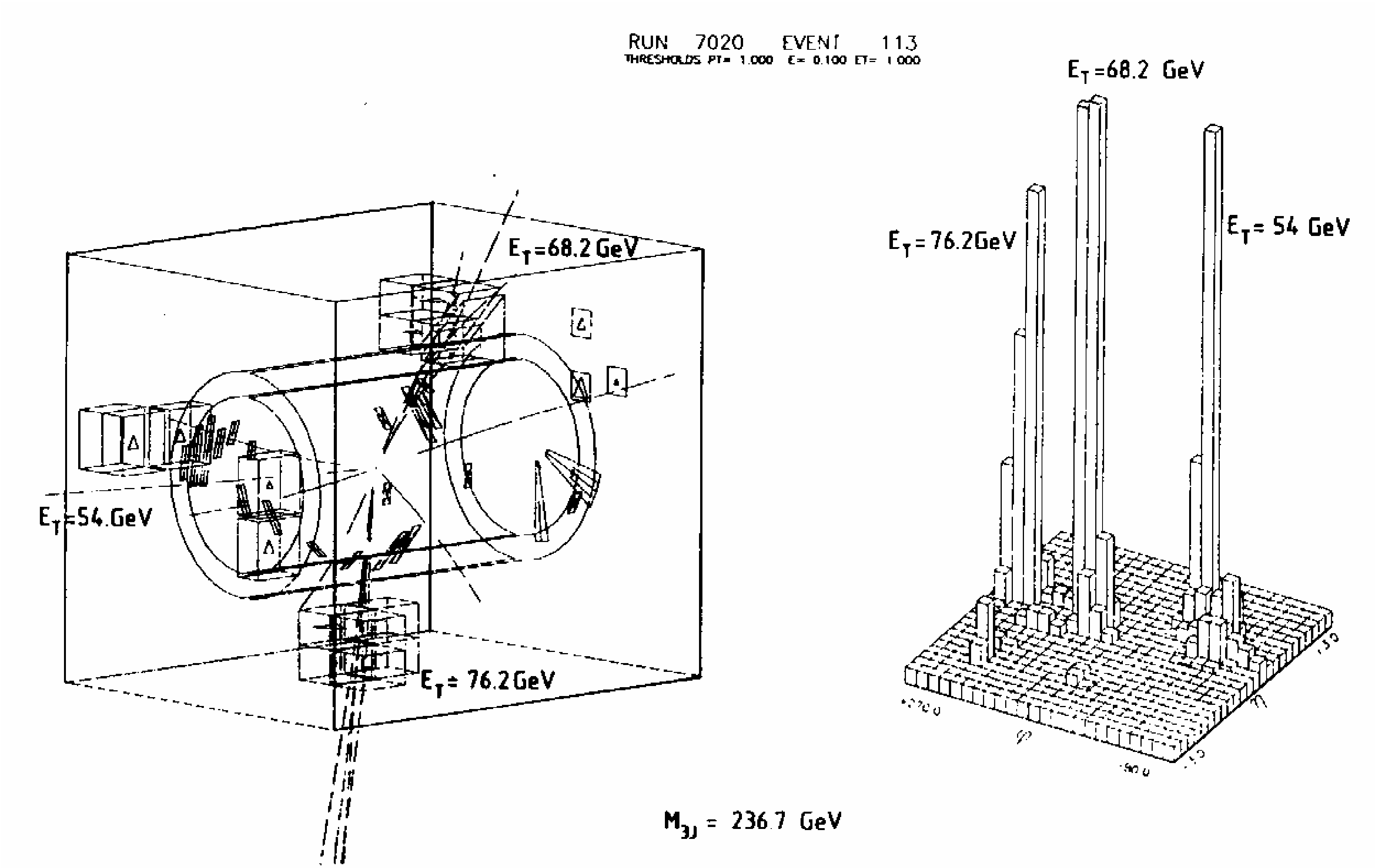
$$\chi = (1 + \cos\theta)/(1 - \cos\theta)$$

$$d\chi = 2\, d\cos\theta/(1 - \cos\theta)^2$$

Scaling violations are visible

Three-Jet events are also there

Direct Evidence for Gluon Bremstrahlung



First observation of W's

Main goal of UA1(and UA2!) was to observe W's and Z's as predicted by the Weinberg Salam theory. In 1982 the mass of the IVBs were predicted to be:

$\sin^2\theta_W = 0.23 \pm 0.01$ $M_W = 82 \pm 2.4\, GeV^2$ $M_Z = 94 \pm 2.5\, GeV^2$

The W/Z production cross-sections at √s = 540 GeV were computed in LO QCD

$\sigma(p\bar{p} \to W^{\pm} \to e^{\pm}\nu) \approx 0.5 nb$ $(u\bar{d} \to W^{+}\ or\ \bar{u}d \to W^{-})$

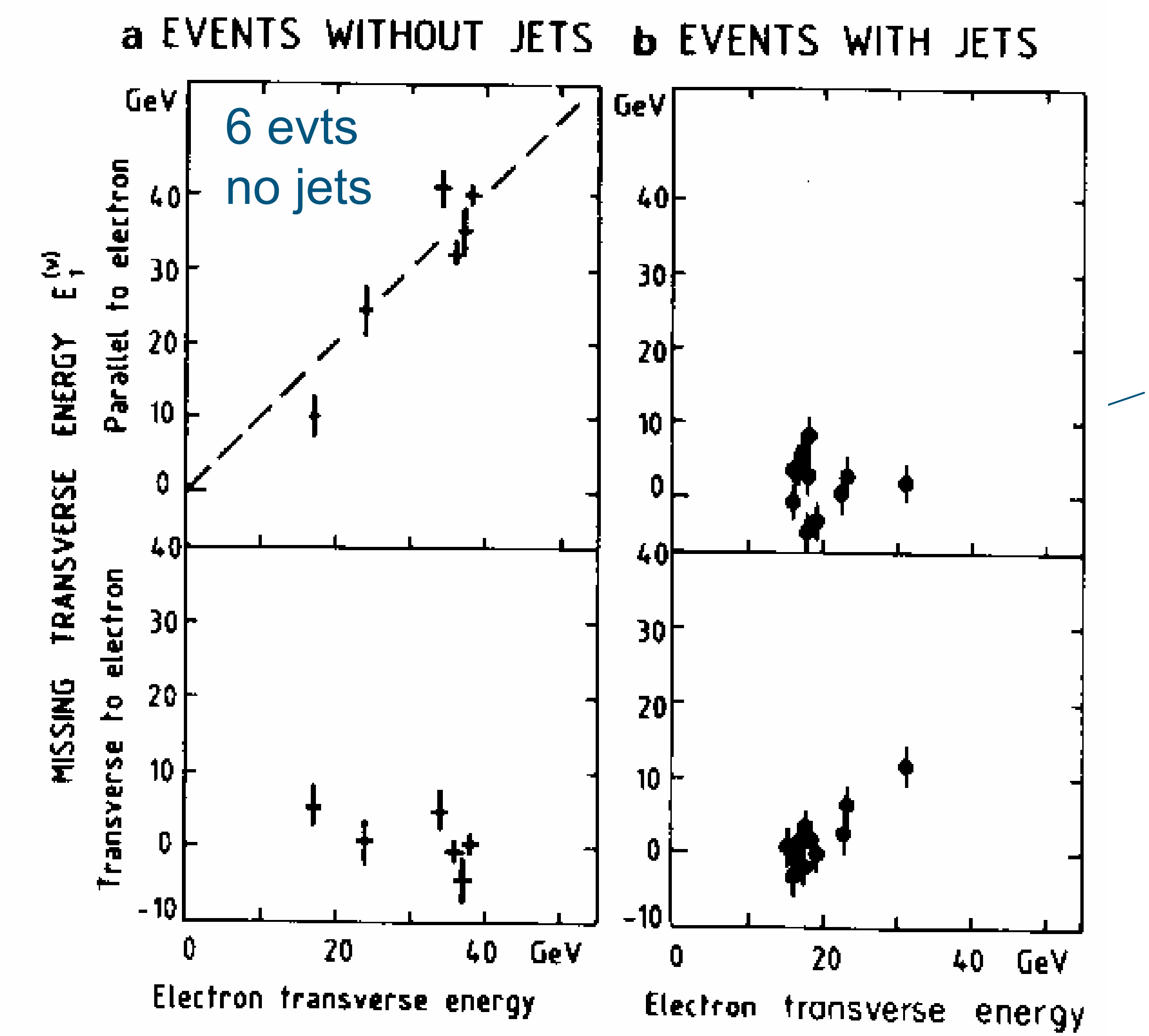
$\sigma(p\bar{p} \to Z^{0} \to e^{+}e^{-}) \approx 0.05 nb$ $(q\bar{q} \to Z^{0})$

Hence for the Nov-Dec 1982 run of 14 nb^{-1} , ~7 W's were expected and < 1 Z^0!

Indeed 6 W events were found in UA1 and published Feb 1983

UA1: Phys. Lett. 122B (1983) 103
And so did UA2!
UA2: Phys. Lett. 122B (1983) 476

First observation of W's



Inclusive electron selection E_T > 15 GeV: **find 6 events with no jet** and hence large missing transverse energy, E_T^{miss} ! Events with jets have no E_T^{miss}

Experimental aspects

Magnetic tracking is a fundamental tool for electron id:

Isolated track in CD

$|1/p_{CD}-1/E_{calo}| < 3\sigma$

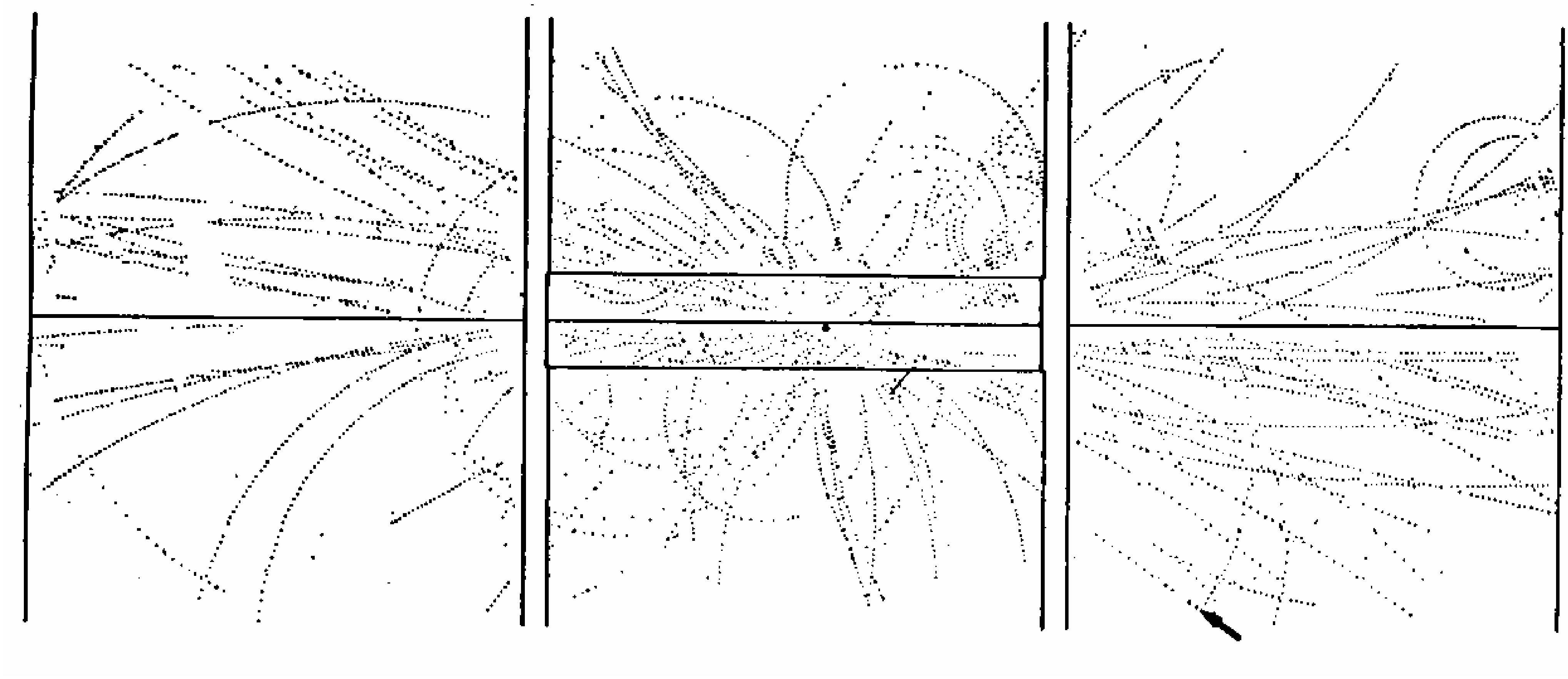
B field, 0.7T, a bit weak

$\Delta p/p=\pm 20\%$ at p_T= 40 GeV

Hermetic Calorimetry is a fundamental tool for E_T^{miss} measurement.

A busy W event

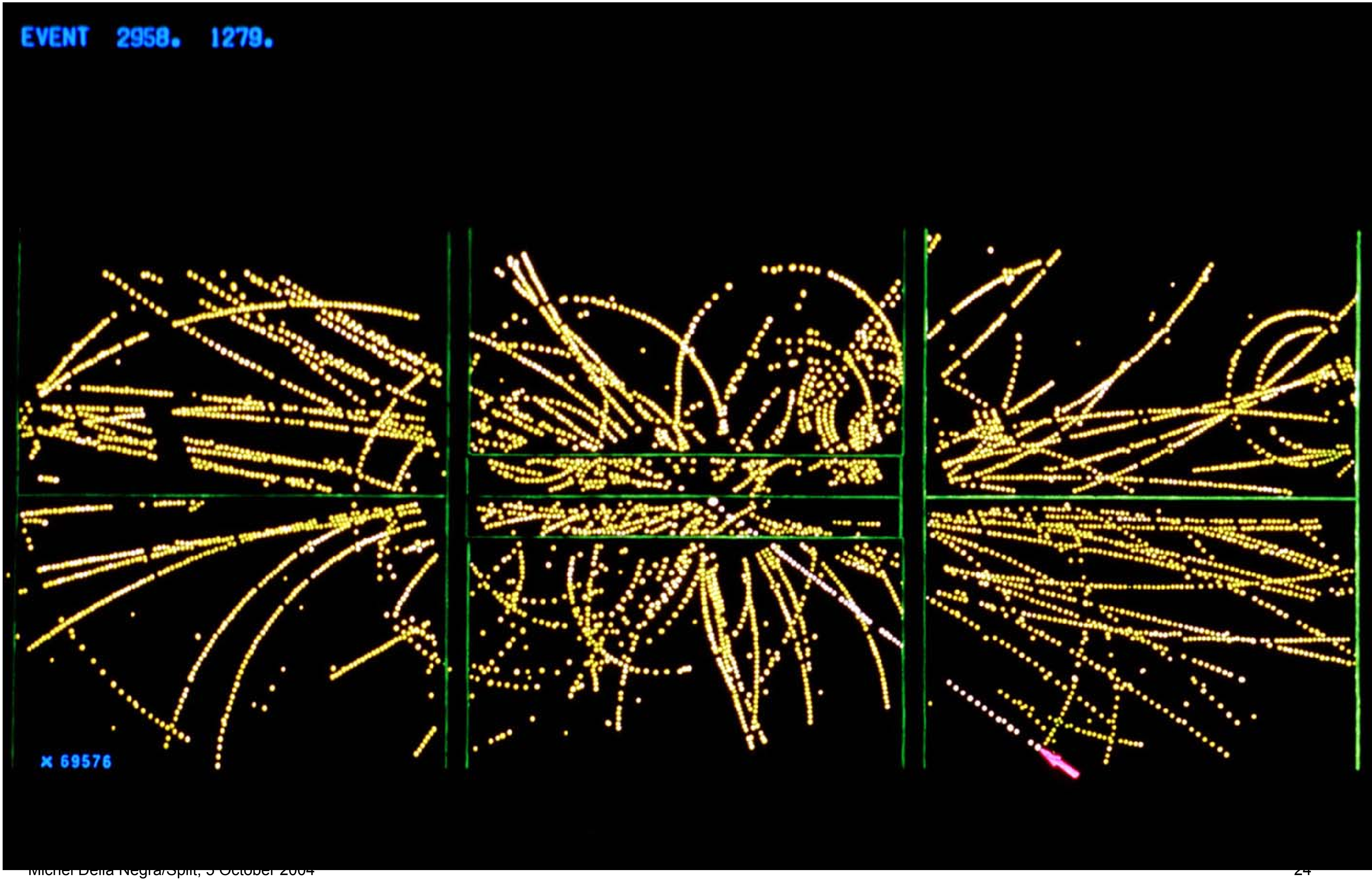
No visible jet on the away side!



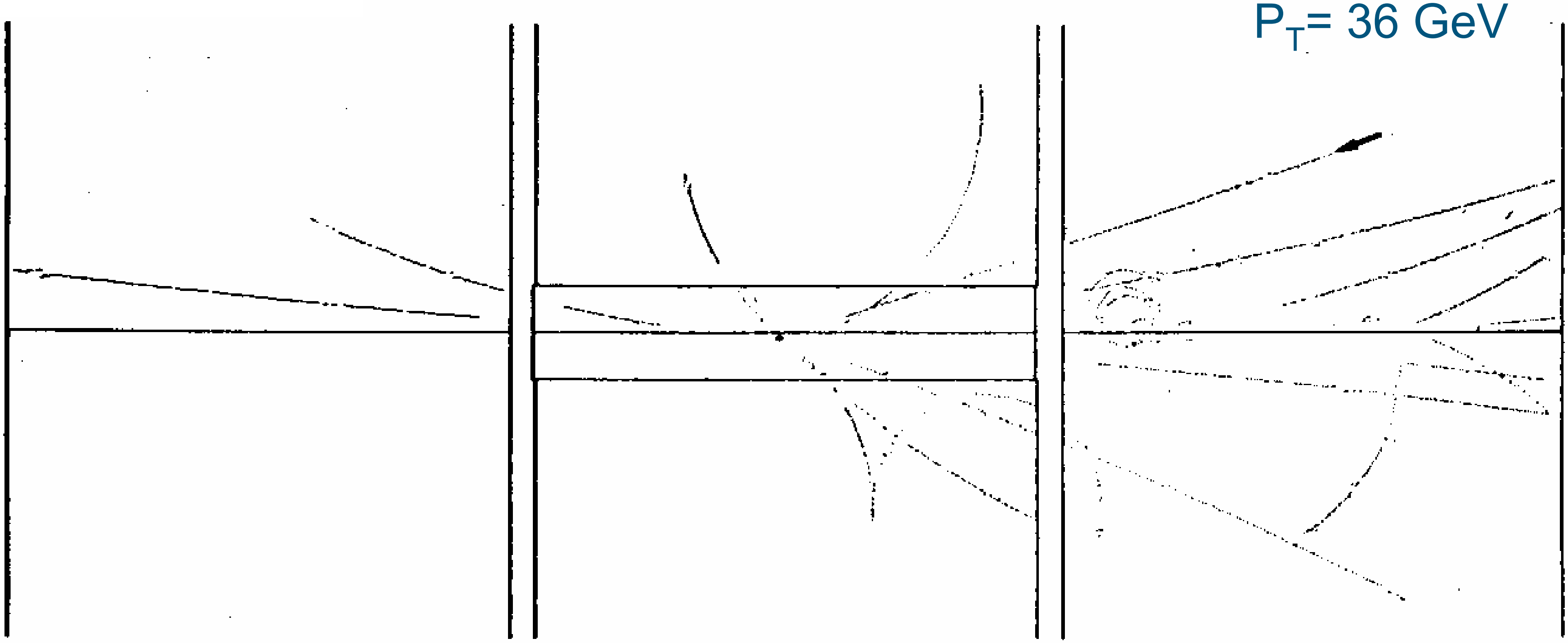
Electron

P_T= 24 GeV

Same busy W event (in color!)



A Quiet W Event



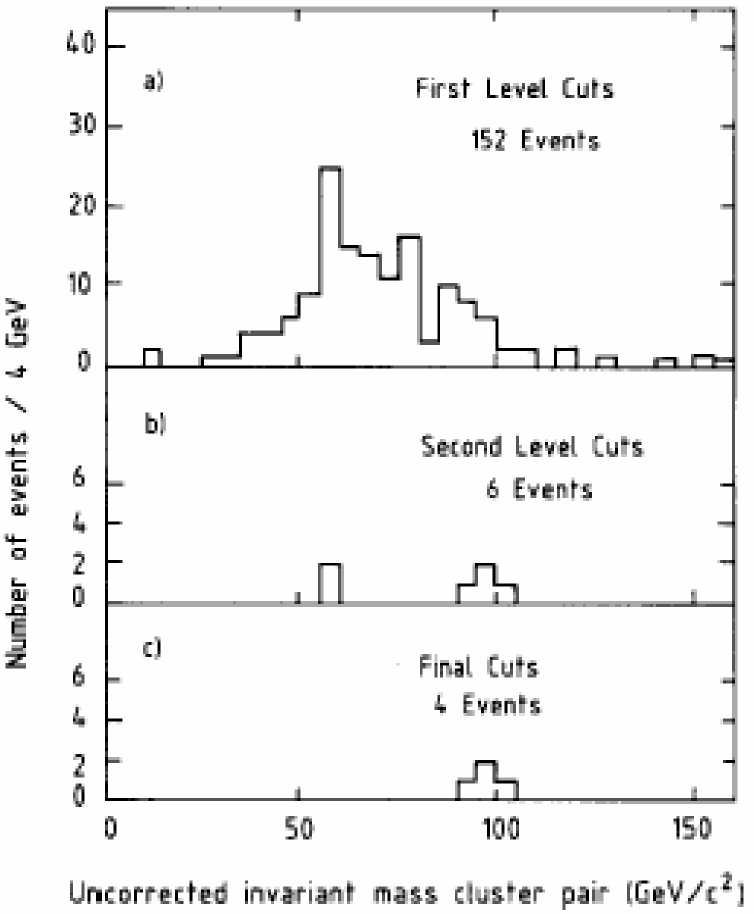
Electron

P_T= 36 GeV

No visible jet on the away side!

First observation of Zs

April-May 1983 run: 55nb^{-1}
Race open for the first observation of Zs!

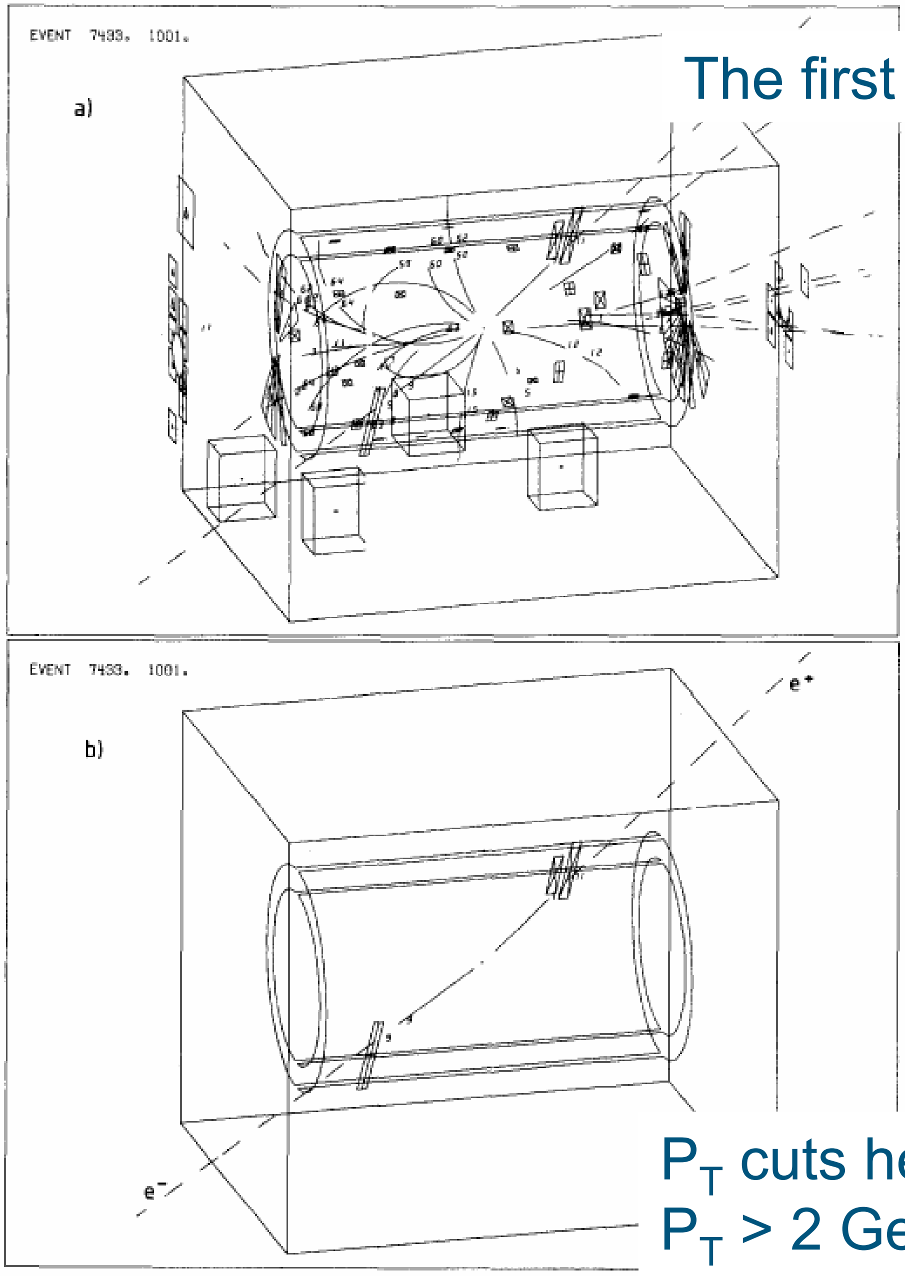


2 elm clusters
$E_T > 25$ GeV

1 charged track in CD
$P_T > 7$ GeV

2 charged tracks

"Four e^+e^- events survive the cuts with a common value of e^+e^- invariant mass"



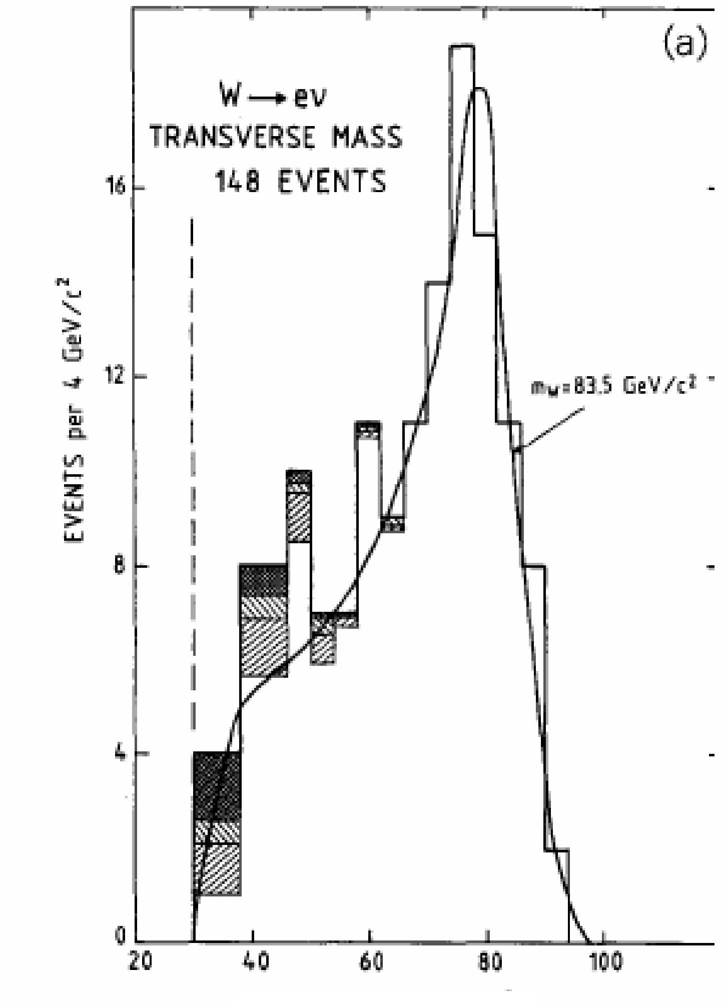
The first Z

P_T cuts hel
$P_T > 2$ GeV
$E_T > 2$ GeV

UA1: Phys. Lett. 126B (1983) 398
UA2: Phys. Lett. 129B (1983) 130

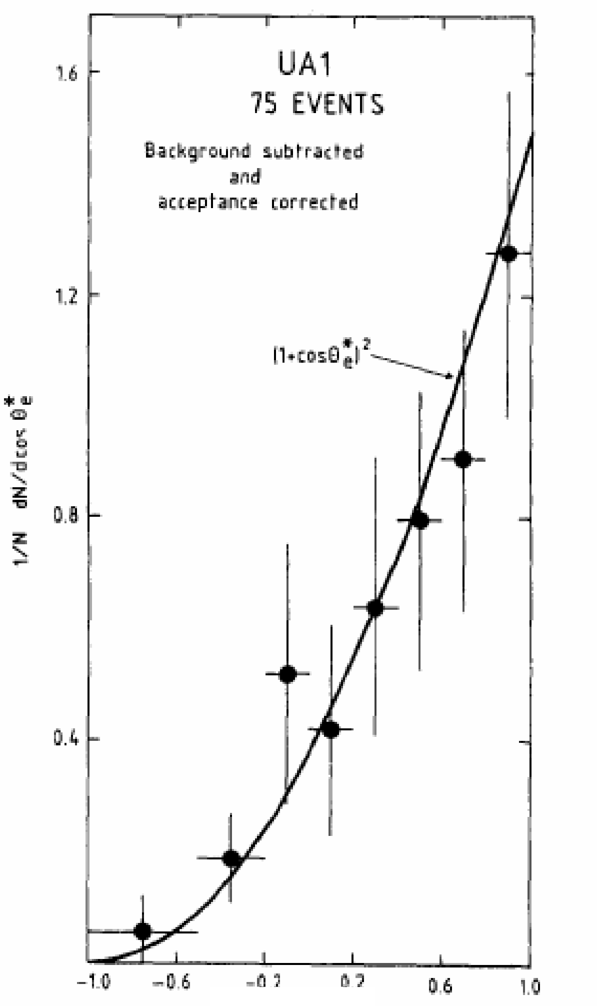
W/Z Mass and Spin

W mass



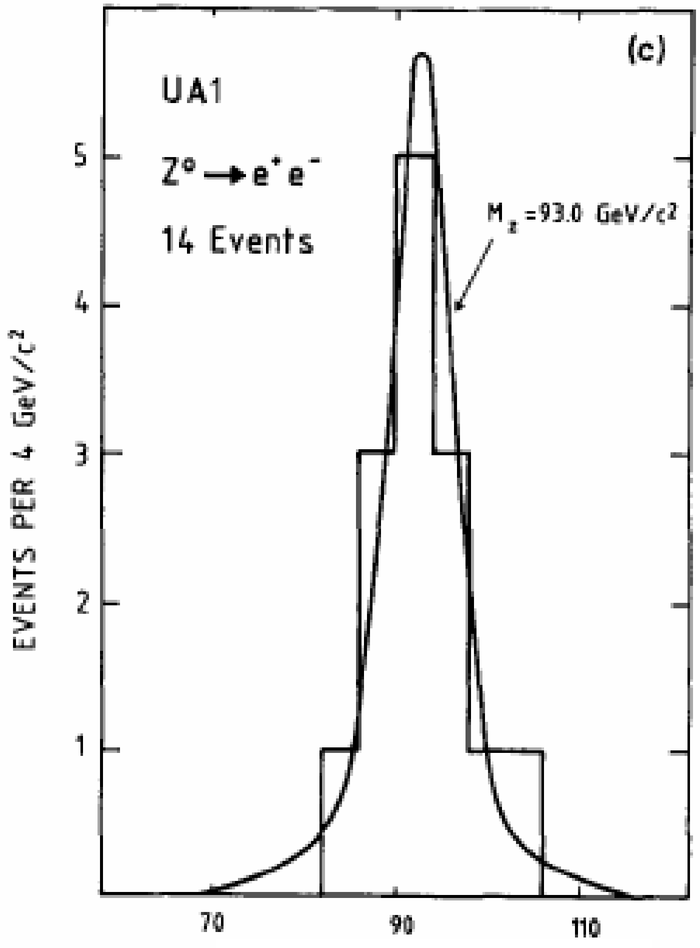
m_T (GeV)

W Spin



cosθ

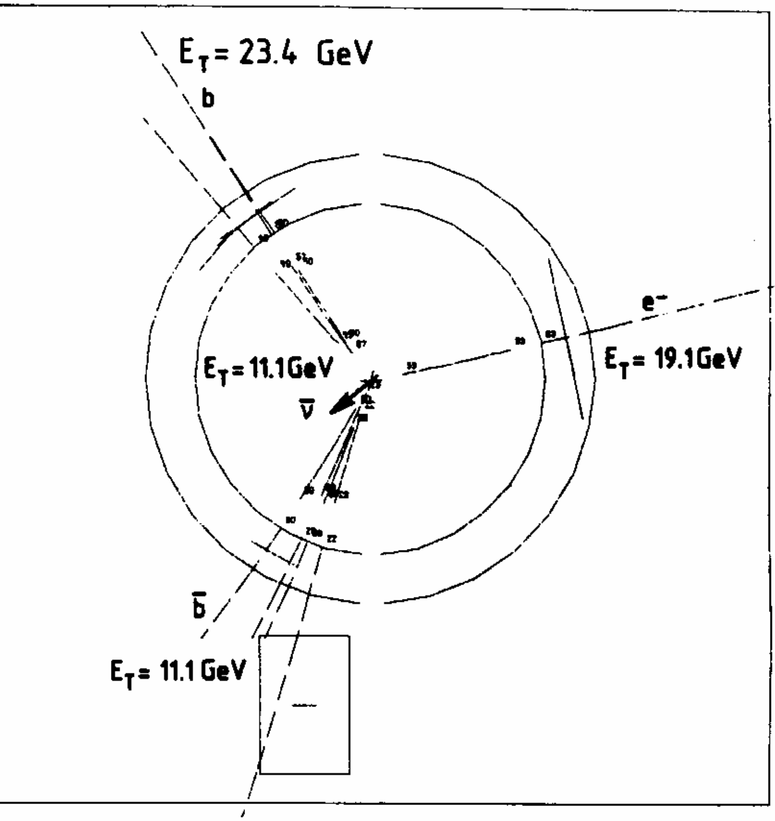
Z mass



$M(e^+e^-)$ (GeV)

1983 + 1984 data, 400 nb^{-1}: study W/Z properties

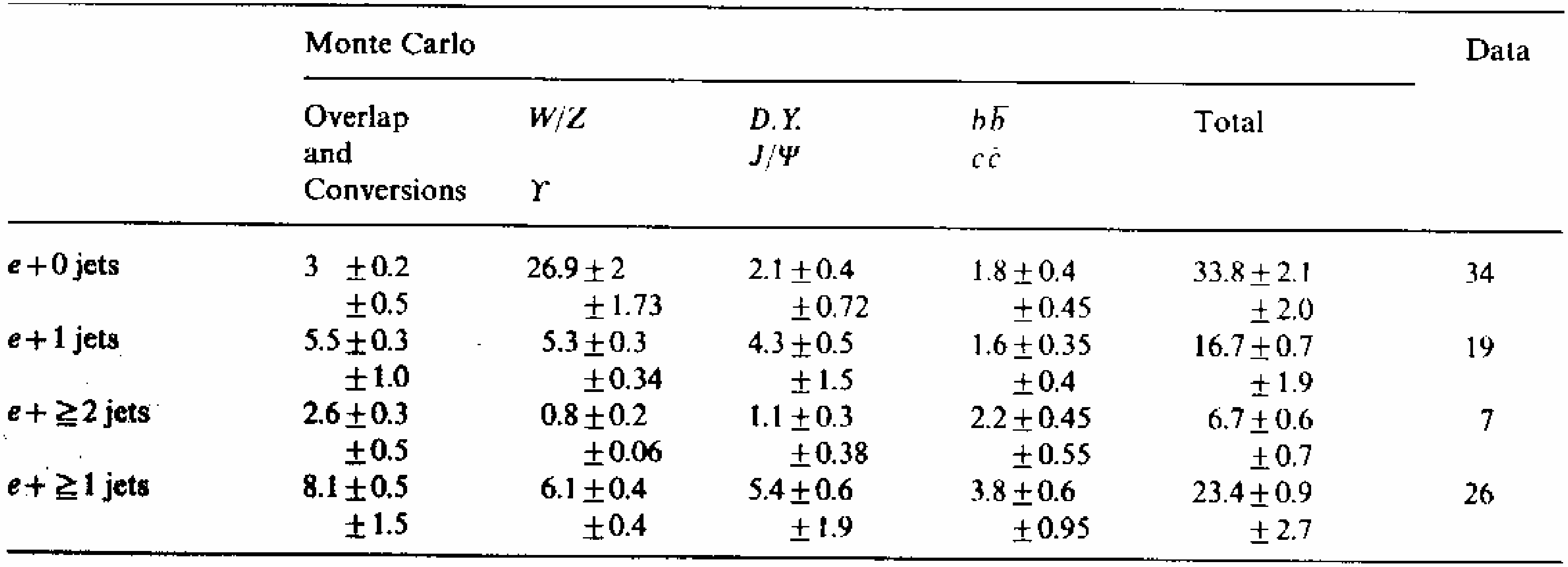
Top in UA1?



1983 data (108 nb^{-1}): Observe 5 isolated electrons + ≥ 2 Jets events (SM background: 0.1 fake e + 0.15 bbg) consistent with

$$W \to t\bar{b} \to e\nu b\bar{b} \qquad (m_t \approx 40 \text{ GeV})$$

1983-85 data (715 nb^{-1}): Observe 7 isolated electrons + ≥ 2 Jets events consistent with SM background of 6.7 evts



	Monte Carlo					Data
	Overlap and Conversions	W/Z Υ	D.Y. J/Ψ	$b\bar{b}$ $c\bar{c}$	Total	
$e+0$ jets	3 ±0.2 ±0.5	26.9 ± 2 ± 1.73	2.1 ± 0.4 ± 0.72	1.8 ± 0.4 ± 0.45	33.8 ± 2.1 ± 2.0	34
$e+1$ jets	5.5 ± 0.3 ± 1.0	5.3 ± 0.3 ± 0.34	4.3 ± 0.5 ± 1.5	1.6 ± 0.35 ± 0.4	16.7 ± 0.7 ± 1.9	19
$e+\geq 2$ jets	2.6 ± 0.3 ± 0.5	0.8 ± 0.2 ± 0.06	1.1 ± 0.3 ± 0.38	2.2 ± 0.45 ± 0.55	6.7 ± 0.6 ± 0.7	7
$e+\geq 1$ jets	8.1 ± 0.5 ± 1.5	6.1 ± 0.4 ± 0.4	5.4 ± 0.6 ± 1.9	3.8 ± 0.6 ± 0.95	23.4 ± 0.9 ± 2.7	26

Top in UA1?

Upgrade of the machine. New antiproton collector ACOL. L= $2 \times 10^{30} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

Upgrade of UA1? New em calorimeters U-TMP not ready. Old em calos removed.

UA1 1988-1989: 4.7 pb^{-1} of data muons only.

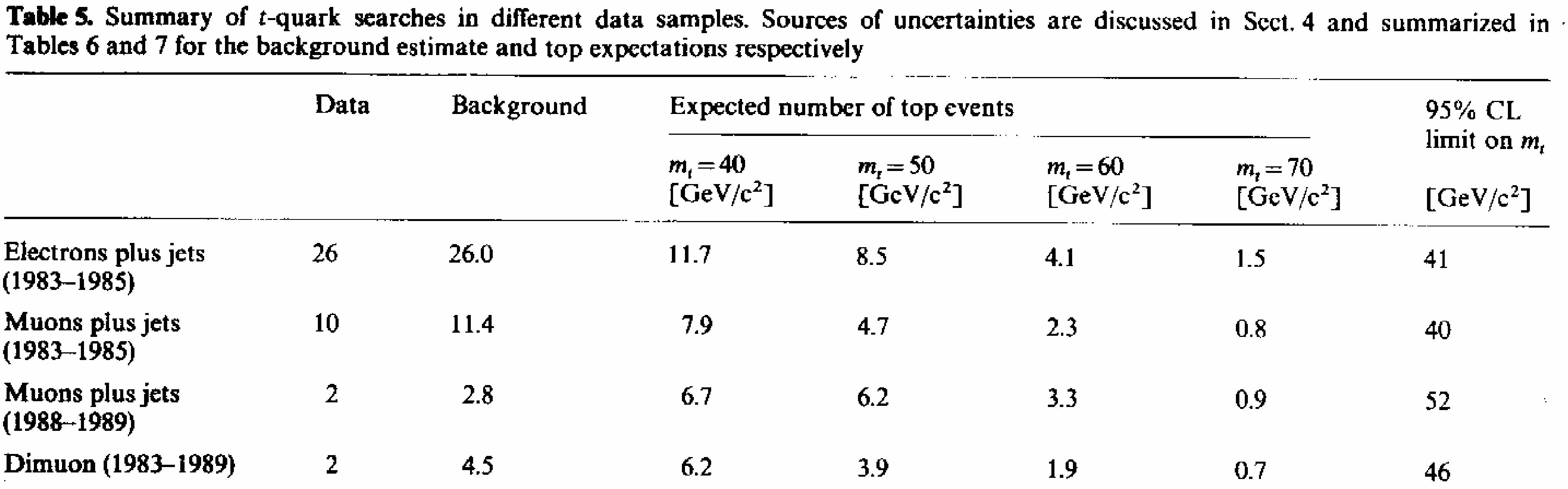


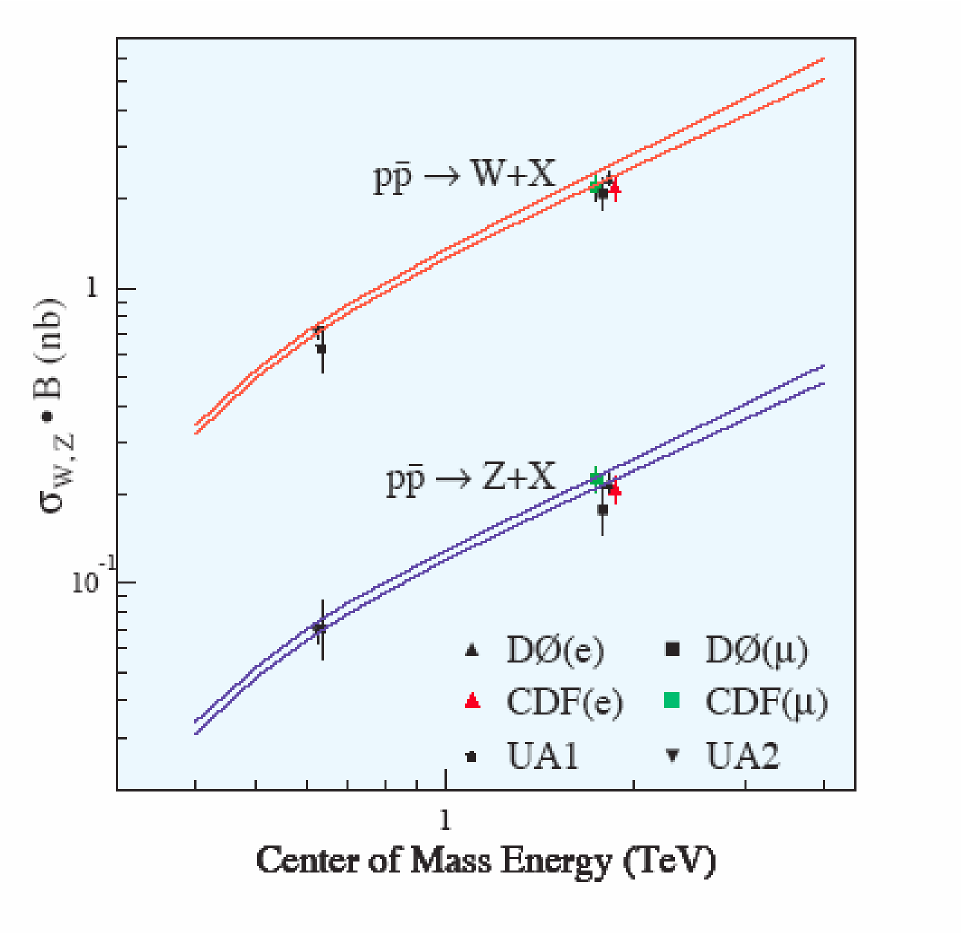
Table 5. Summary of *t*-quark searches in different data samples. Sources of uncertainties are discussed in Sect. 4 and summarized in Tables 6 and 7 for the background estimate and top expectations respectively

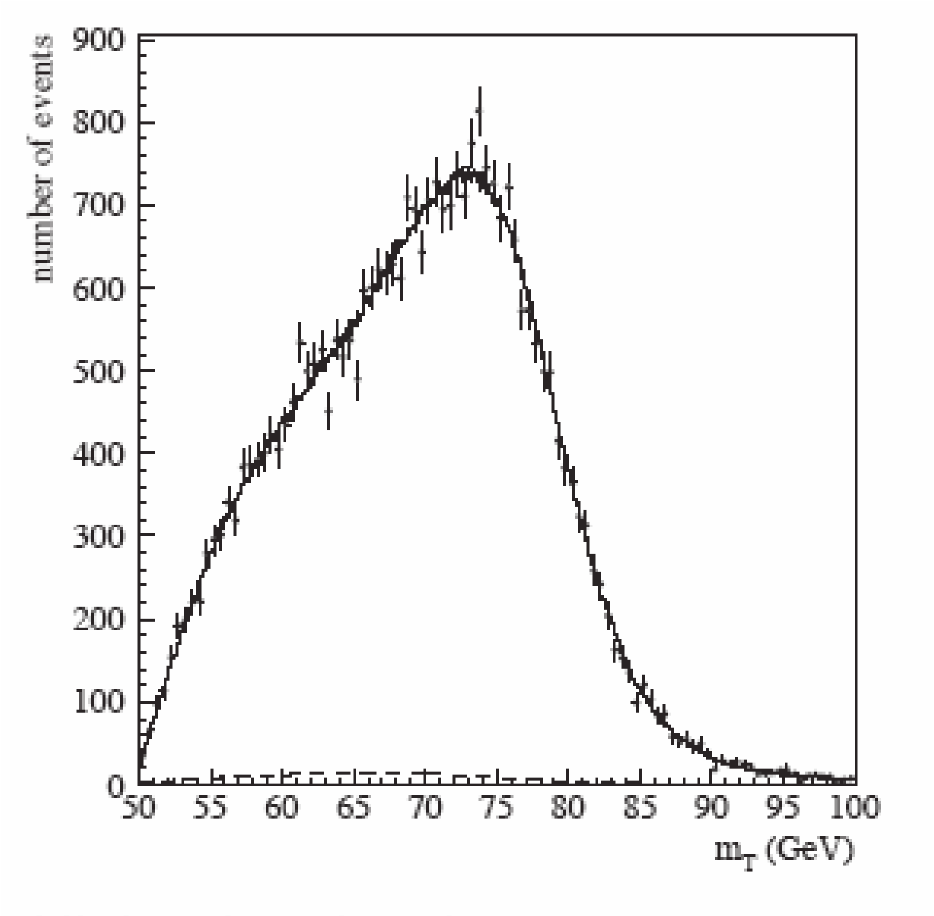
	Data	Background	Expected number of top events				95% CL limit on m_t
			$m_t=40$ [GeV/c^2]	$m_t=50$ [GeV/c^2]	$m_t=60$ [GeV/c^2]	$m_t=70$ [GeV/c^2]	[GeV/c^2]
Electrons plus jets (1983–1985)	26	26.0	11.7	8.5	4.1	1.5	41
Muons plus jets (1983–1985)	10	11.4	7.9	4.7	2.3	0.8	40
Muons plus jets (1988–1989)	2	2.8	6.7	6.2	3.3	0.9	52
Dimuon (1983–1989)	2	4.5	6.2	3.9	1.9	0.7	46

Combining all UA1 data (5.4 pb^{-1}): $m_t > 60$ GeV (95% CL).

But… CDF (Tevatron) had already started its search for the top and was getting already a better limit: $m_t > 77$ GeV (95% CL).

The Tevatron era

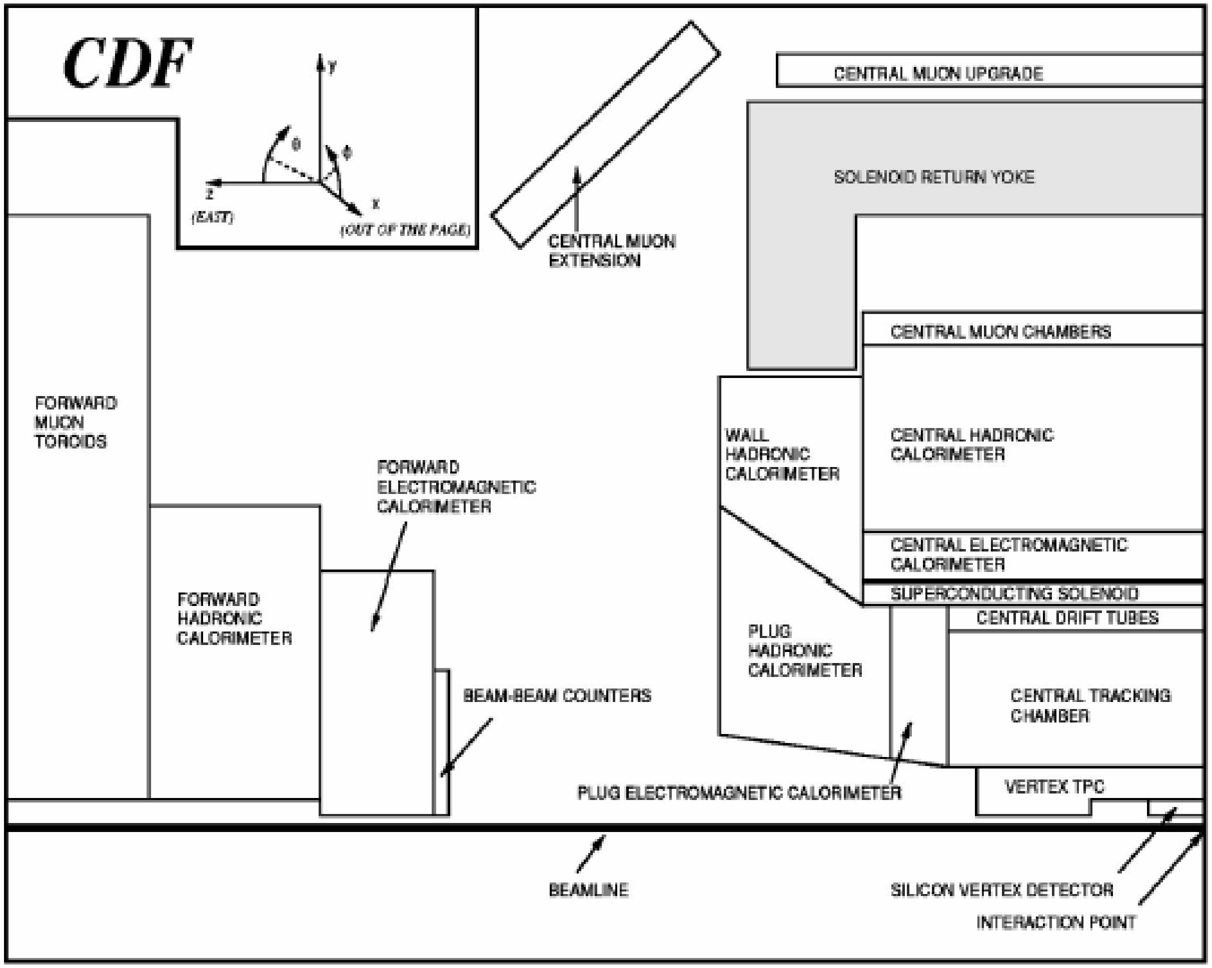




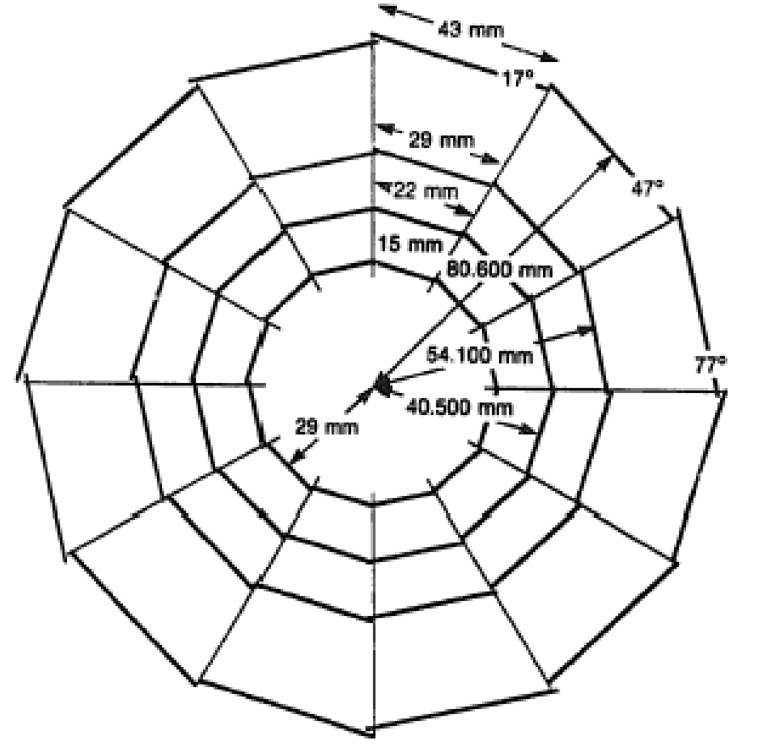
Higher Energy: Increase the production cross-section for massive particles

Higher Luminosity:
SPS 10^{30}→Tevatron 10^{32}
Huge samples available
D0: 30,000 Ws
$M_W = 80.482 \pm 0.091$

The CDF detector



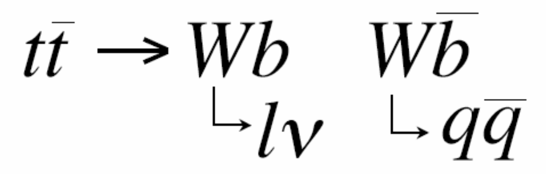
The Silicon Vertex Detector of CDF



With a Silicon Vertex Detector (SVD) CDF has demonstrated that b tagging is possible at a hadron collider!

Tevatron: the Top

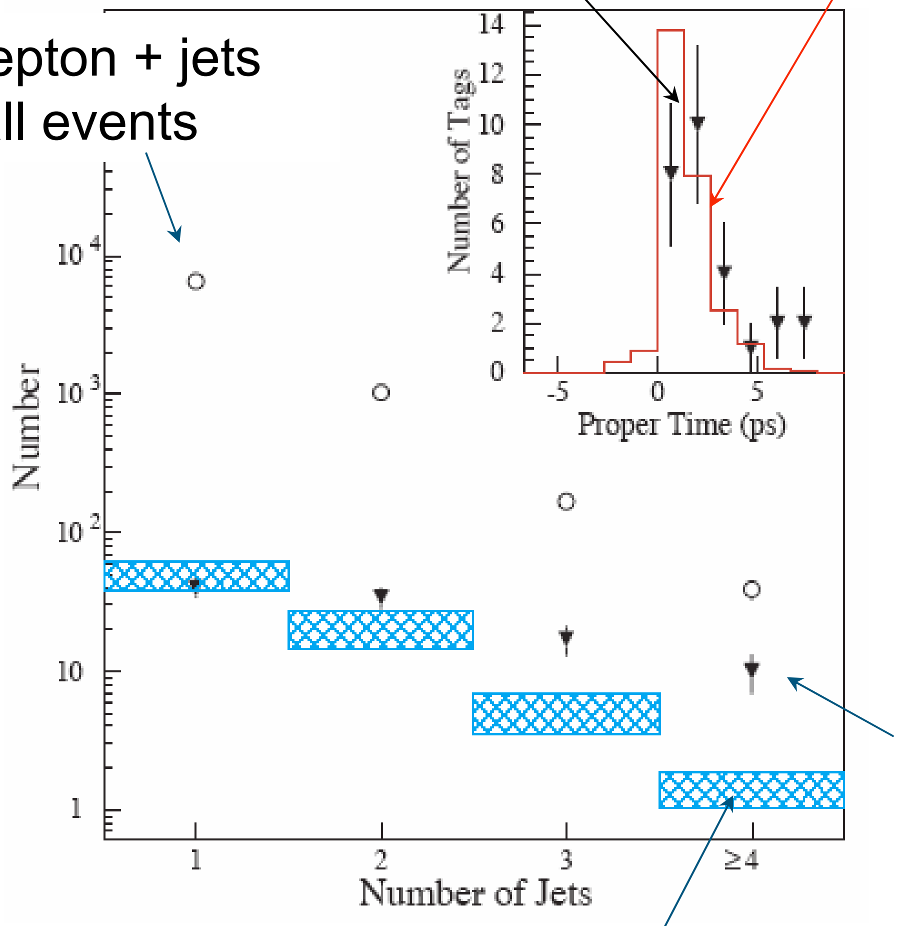
CDF 1995



$$\begin{array}{llll} t\bar{t} \rightarrow & Wb & & W\bar{b} \\ & \;\llcorner\!\rightarrow l\nu & & \;\llcorner\!\rightarrow q\bar{q} \end{array}$$

Look for leptons (e or μ) + ≥ 3 jets

Important feature of the CDF Detector: the Silicon Vertex Detector allows to SEE the b quarks (b tag).



27 tagged jets

Expected for b from t

lepton + jets all events

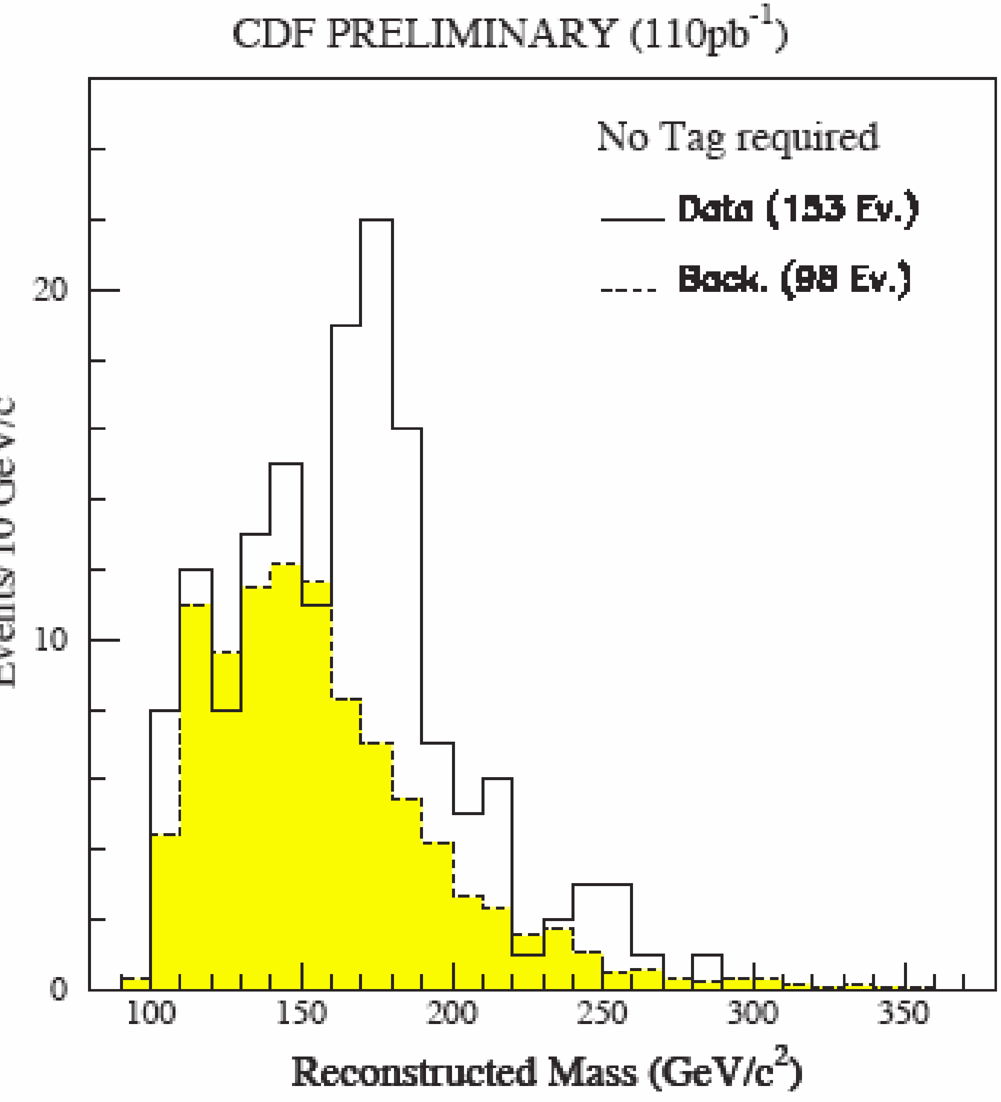
lepton + jets b tag only

Background (fake b-tags)

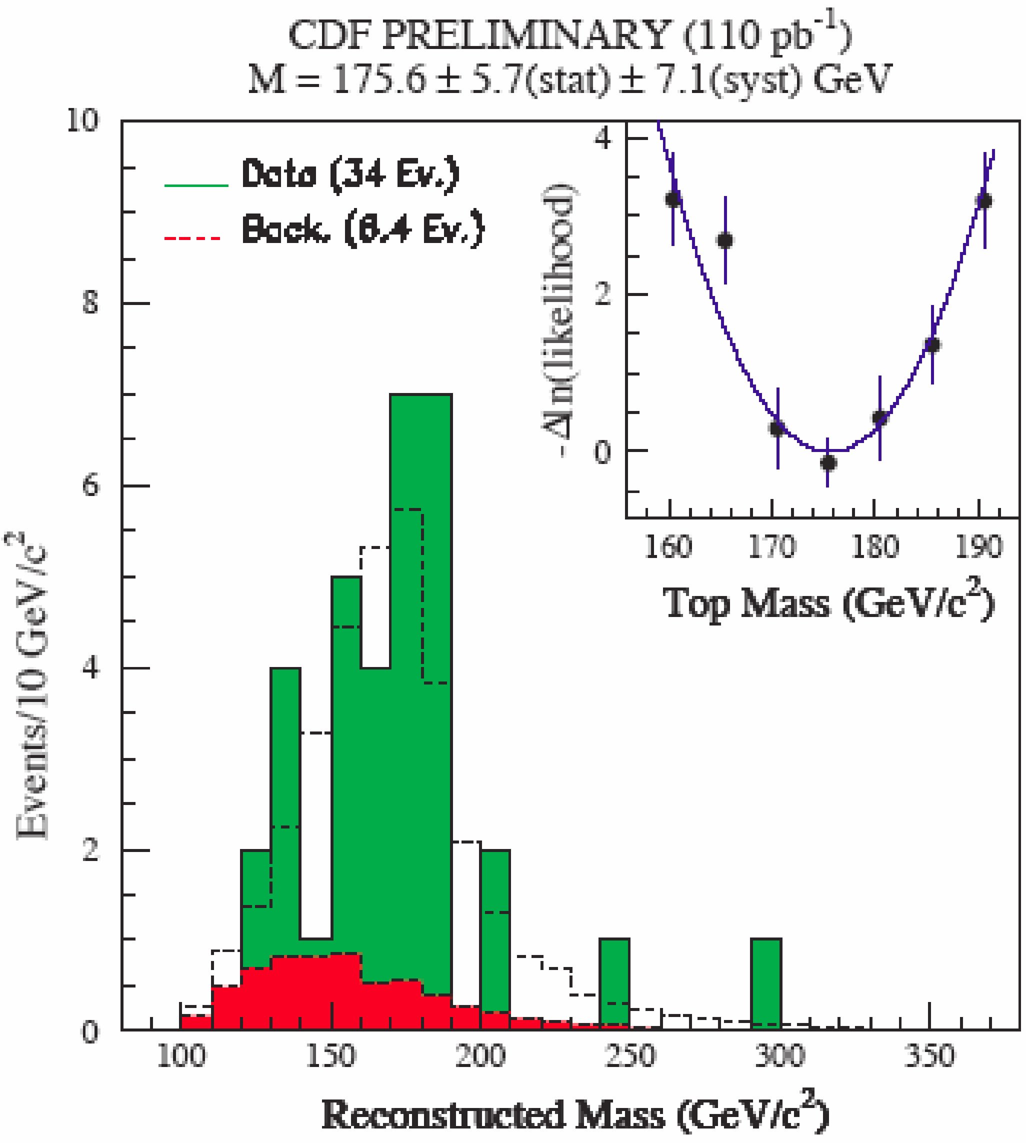
The Top is Heavy 175 GeV!

CDF 1995
Run I

Without b tag

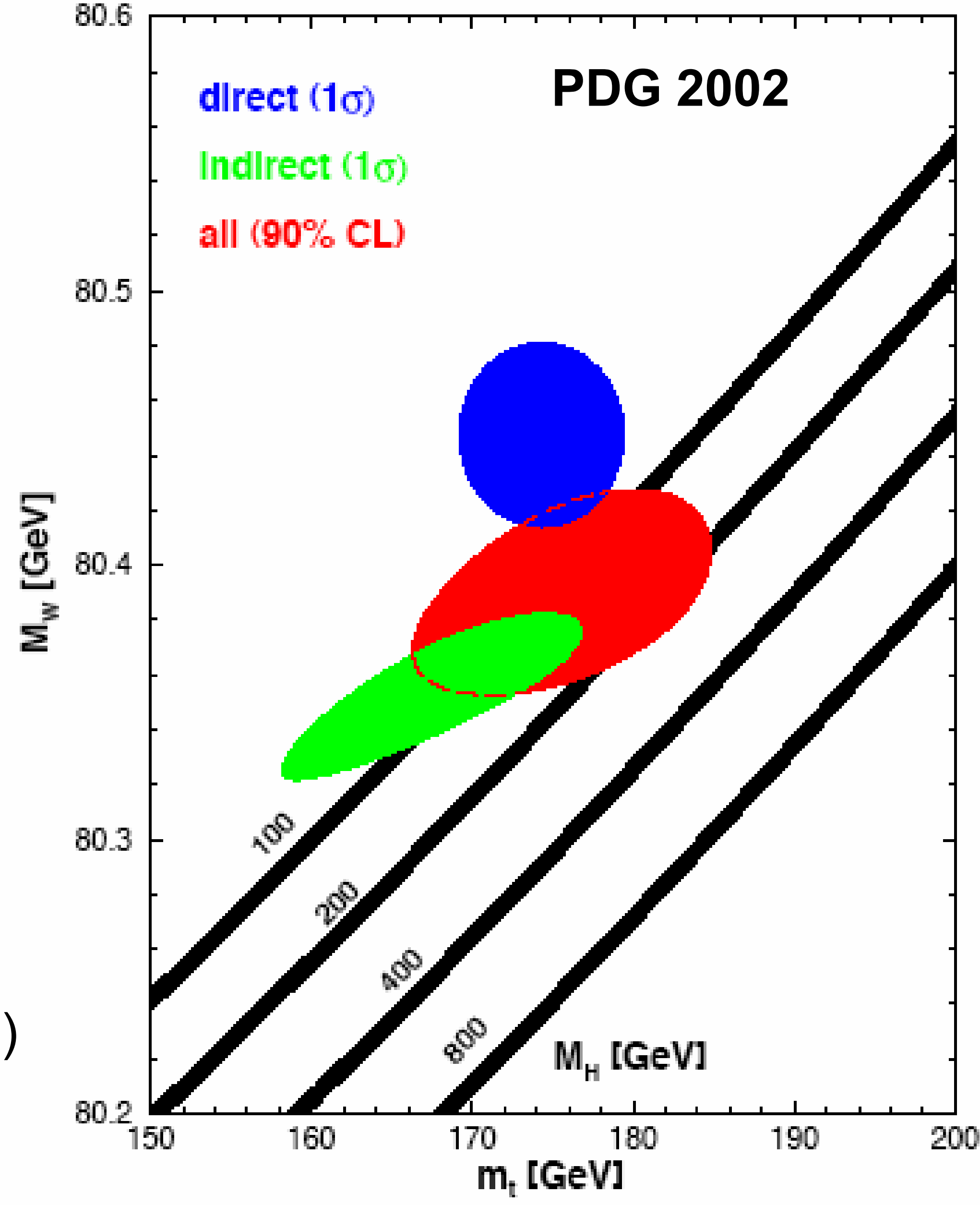


With b tag



Summary Hadron Colliders

- QCD looks like the theory of strong interactions
- W and Z properties as expected
- All the known/expected fermions are there
- All is well with the Standard Model



PDG 2002

m_t= 174.3±5.1 GeV (CDF, D0)

m_W= 80.454±0.060 GeV (CDF, D0, UA2)

m_W= 80.451±0.033 GeV (CDF, D0, UA2, LEP)

Higgs Mass (SM, PDG2002)

Experimental Limits

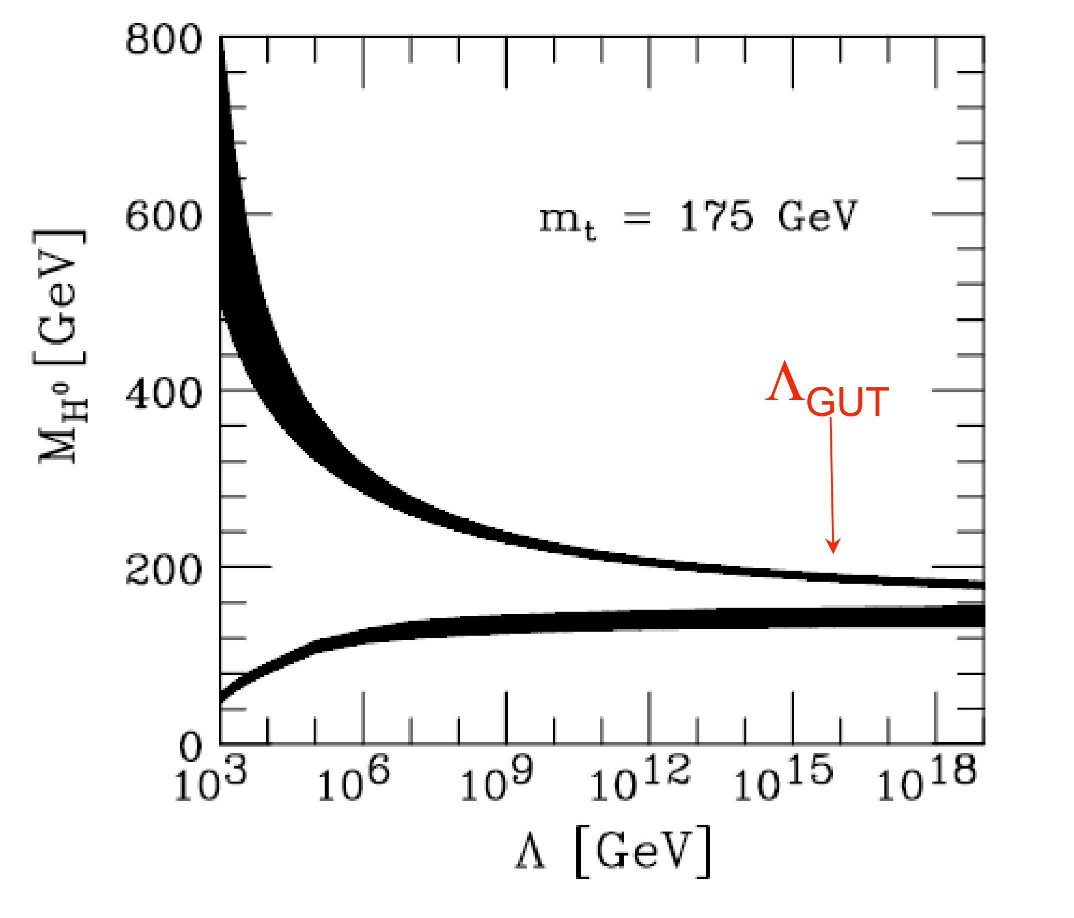
Direct Search at LEP

$m_H > 114.1$ GeV (95% CL)

Indirect experimental bound radiative corrections EW data, m_t and m_W

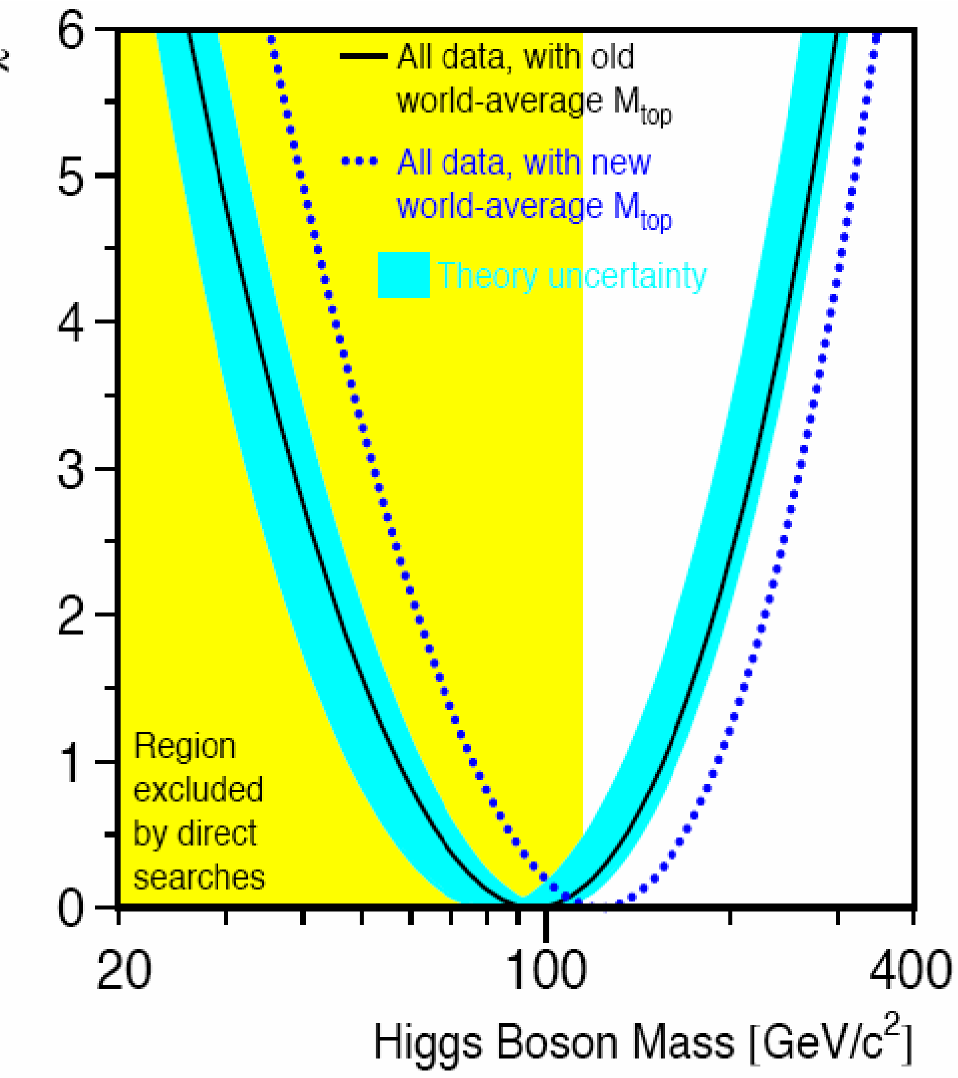
$m_H < 196$ GeV (95% CL)

Theoretical Limits



SM self consistent up to $\Lambda_{GUT} \approx 10^{16}$ GeV implies: **130 GeV < m_H < 190 GeV**

New top mass from Tevatron



The top mass is drifting up!

New value of top mass CDF Run II

http://www-cdf.fnal.gov/people/links/KoheiYorita/TopMassDLM_public.htm

m_t = 177.8 +4.5-5.0 (stat.) ± 6.2(syst.) GeV

New analysis of D0 Run I:

http://moriond.in2p3.fr/EW/2004/transparencies/2_Tuesday/2_1_morning/2_1_3_Kulik/Kulik.pdf

m_t= 180.1 ± 3.6(stat) ± 3.9(syst) GeV

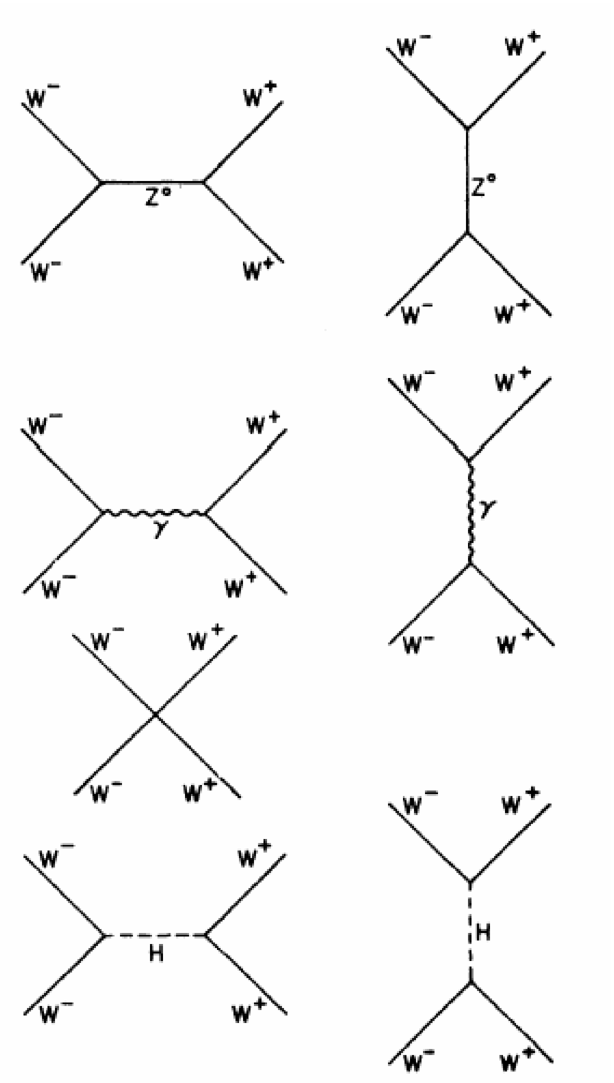
Favors slightly higher Higgs mass

LEPEWWG'04

Assume standard model global fit

$$\Rightarrow M_{\mathrm{H}} = 117^{+67}_{-45}\ \text{GeV}$$

WW Scattering



Lee, Quigg and Thacker, PRD16 (1977) 1519

1) Need H exchange to cancel divergences at large s

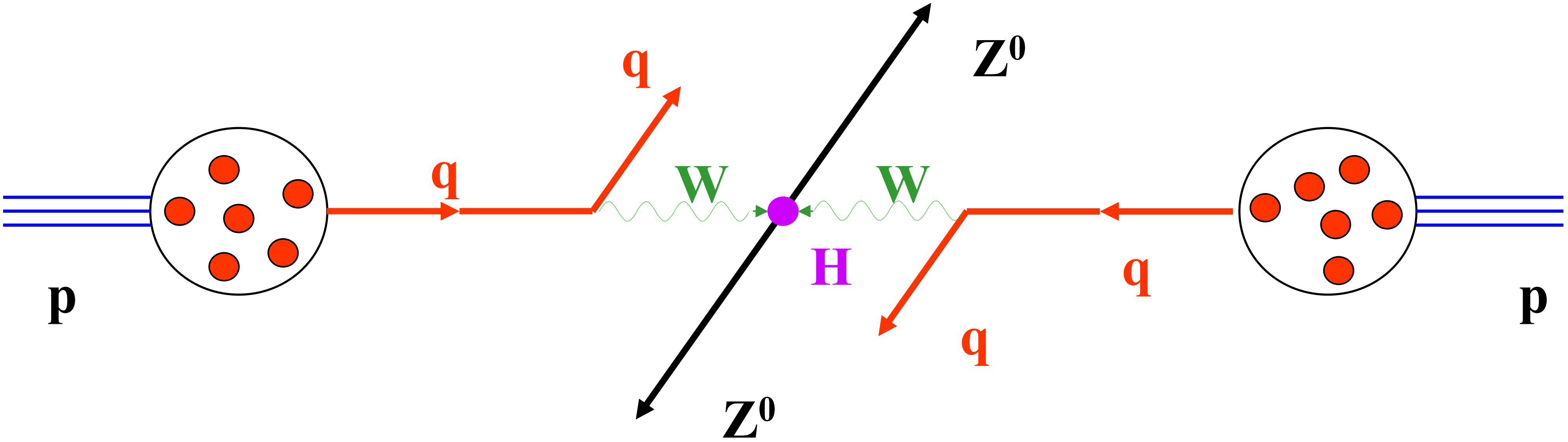
2) Partial wave unitarity bounds lead to limits on Higgs mass:

$$m_H^2 \leq \frac{8\pi\sqrt{2}}{3G_F} \quad \Rightarrow \quad m_H \leq 1\ TeV$$

G_F is the Fermi constant: $G_F^{-1/2} \approx 300\ GeV$

No lose theorem:
An accelerator able to probe WW scattering up to √s≈1 TeV will necessary elucidate the Higgs mechanism in the Standard Model.

Higgs Production in pp Collisions



M_H ~ 1000 GeV

⇙ $E_W \geq 500$ GeV

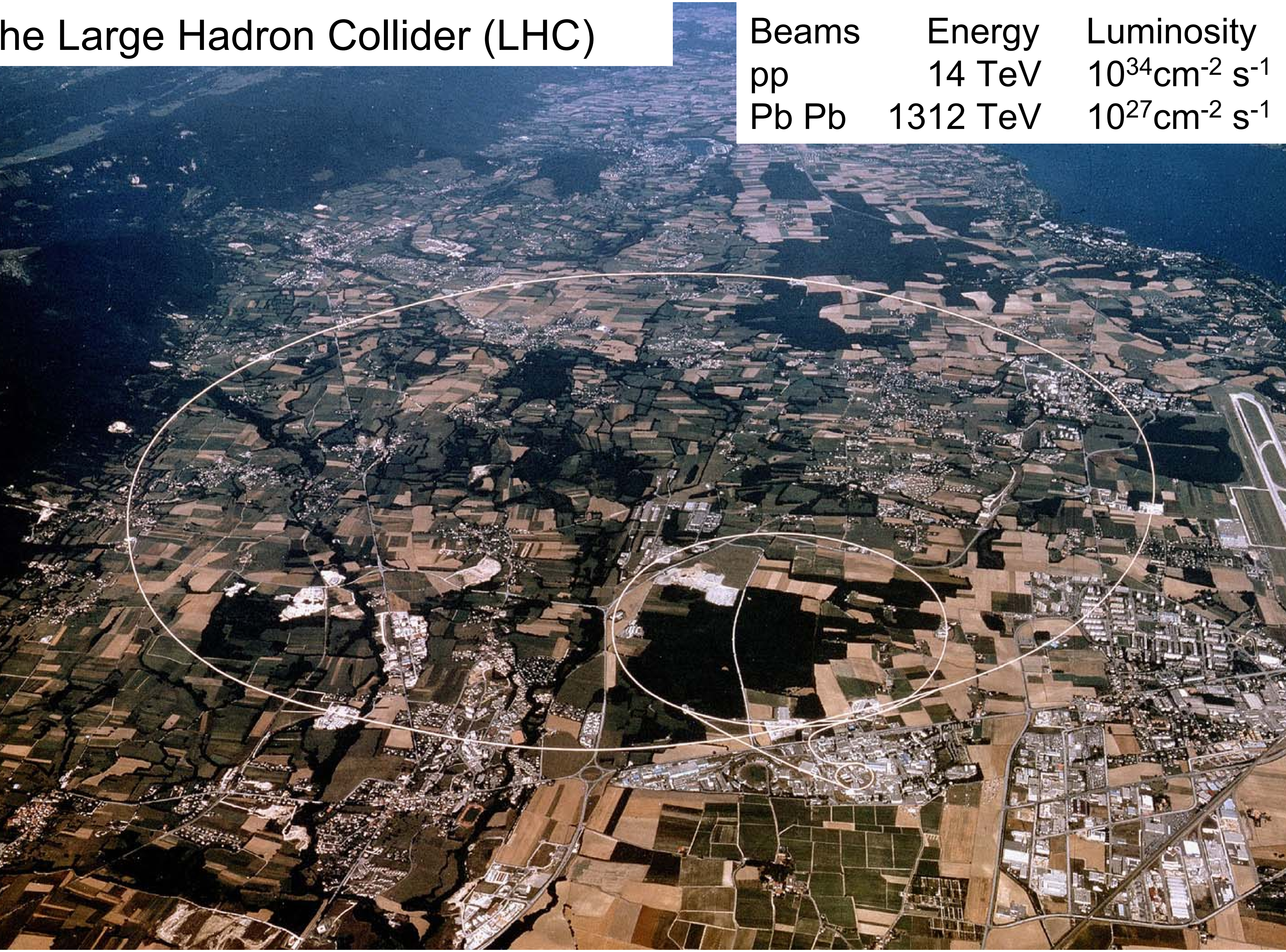
⇙ $E_q \geq 1000$ GeV (1 TeV)

⇙ $E_p \geq 6000$ GeV (6 TeV)

⇧ **Proton Proton Collider $E_p \geq 7$ TeV @ 10^{34}cm^{-2}s^{-1} Luminosity**

he Large Hadron Collider (LHC)

Beams	Energy	Luminosity
pp	14 TeV	$10^{34} cm^{-2} s^{-1}$
Pb Pb	1312 TeV	$10^{27} cm^{-2} s^{-1}$



1232 Superconducting Dipole Magnets 8.3 T

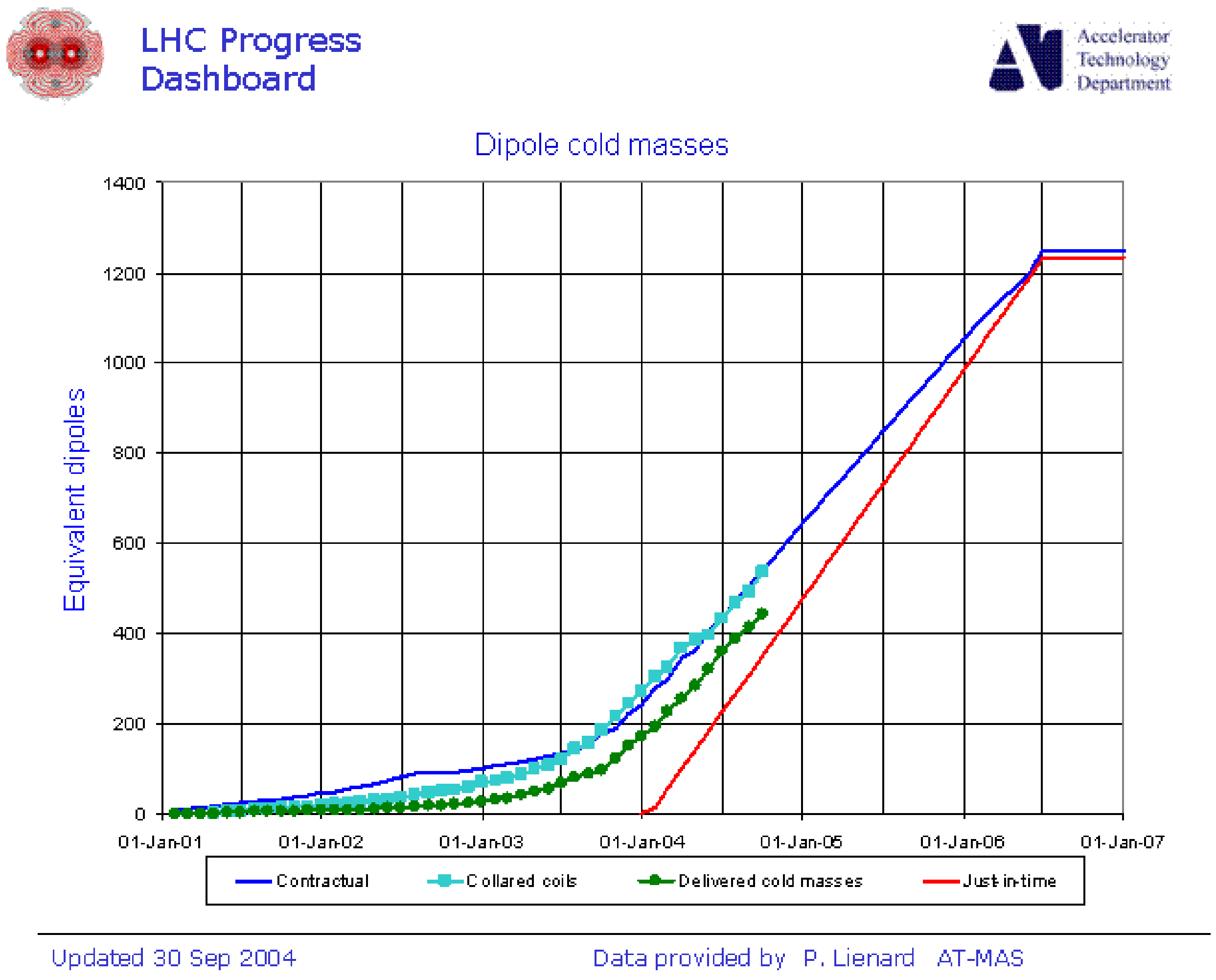
Machine Schedule

- **Official schedule:**
  Collisions in Summer 2007

- **Dipole production is not critical**
  ~400 dipoles (32%) cold tested ready for installation.

- **Critical Path:**
  Repair and Installation of Cryogenic lines.

- **New Machine Schedule**:
  Dec 04



LHC Progress Dashboard

Accelerator Technology Department

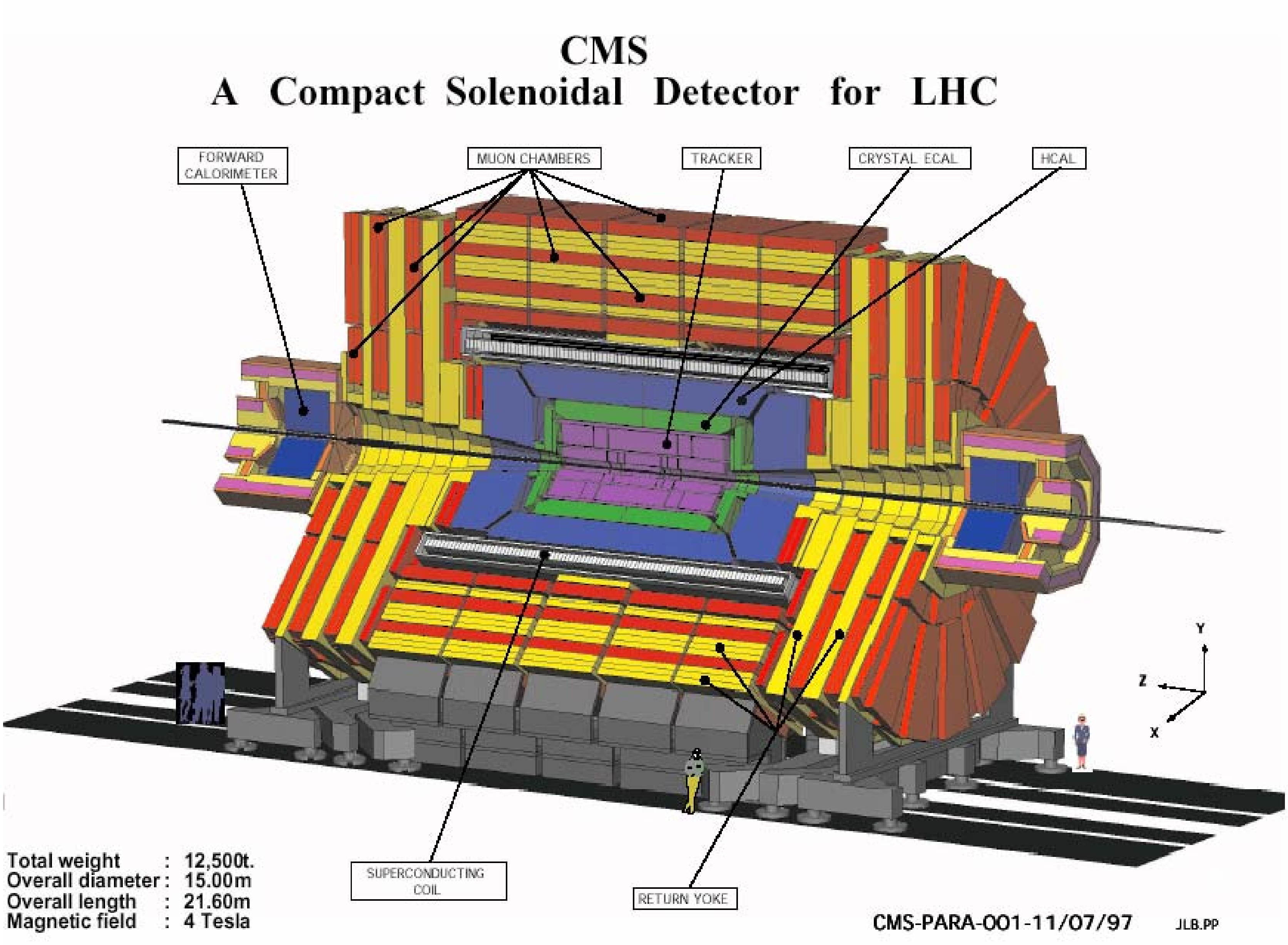
Dipole cold masses

Updated 30 Sep 2004 Data provided by P. Lienard AT-MAS

Design of LHC Detectors

- Two specialised detectors: Alice (Heavy Ions) and LHCb (B physics)
- Two general purpose detectors: ATLAS and CMS
  - Not clear that a general purpose detector could work at 10^{34} luminosity:
    - Fast detectors (25ns between bunch crossings)
    - Radiation Hard (more than 10 Mrad forward)
    - Very high granularity: minimize cell occupancy and pile-up
    - Event size and rate, trigger selection, bandwidth of readout network
- R&D started in ~1990 (Aachen workshop).

The CMS Detector

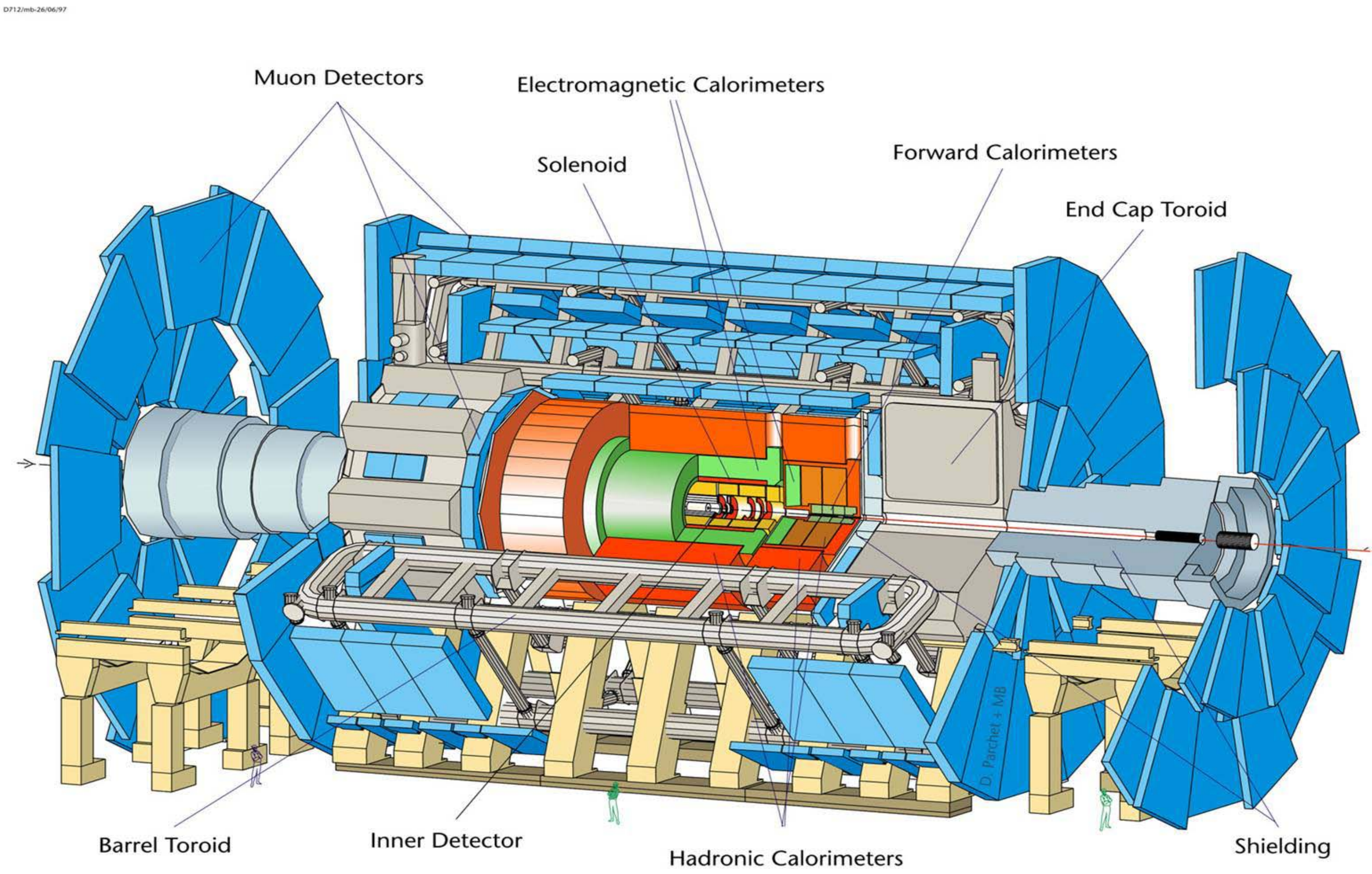


CMS
A Compact Solenoidal Detector for LHC

Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

CMS-PARA-001-11/07/97 JLB.PP

The ATLAS Detector



Diameter	***25 m***
Barrel toroid length	***26 m***
End-cap end-wall chamber span	***46 m***
Overall weight	***7000 Tons***


μ
6.920 m
5.635 m
4.645 m
3.850 m
2.950 m
2.864 m
1.840 m
1.320 m
Y
φ
X
Towards Center of LHC
CMS-TS-00079
Transverse View
40
40

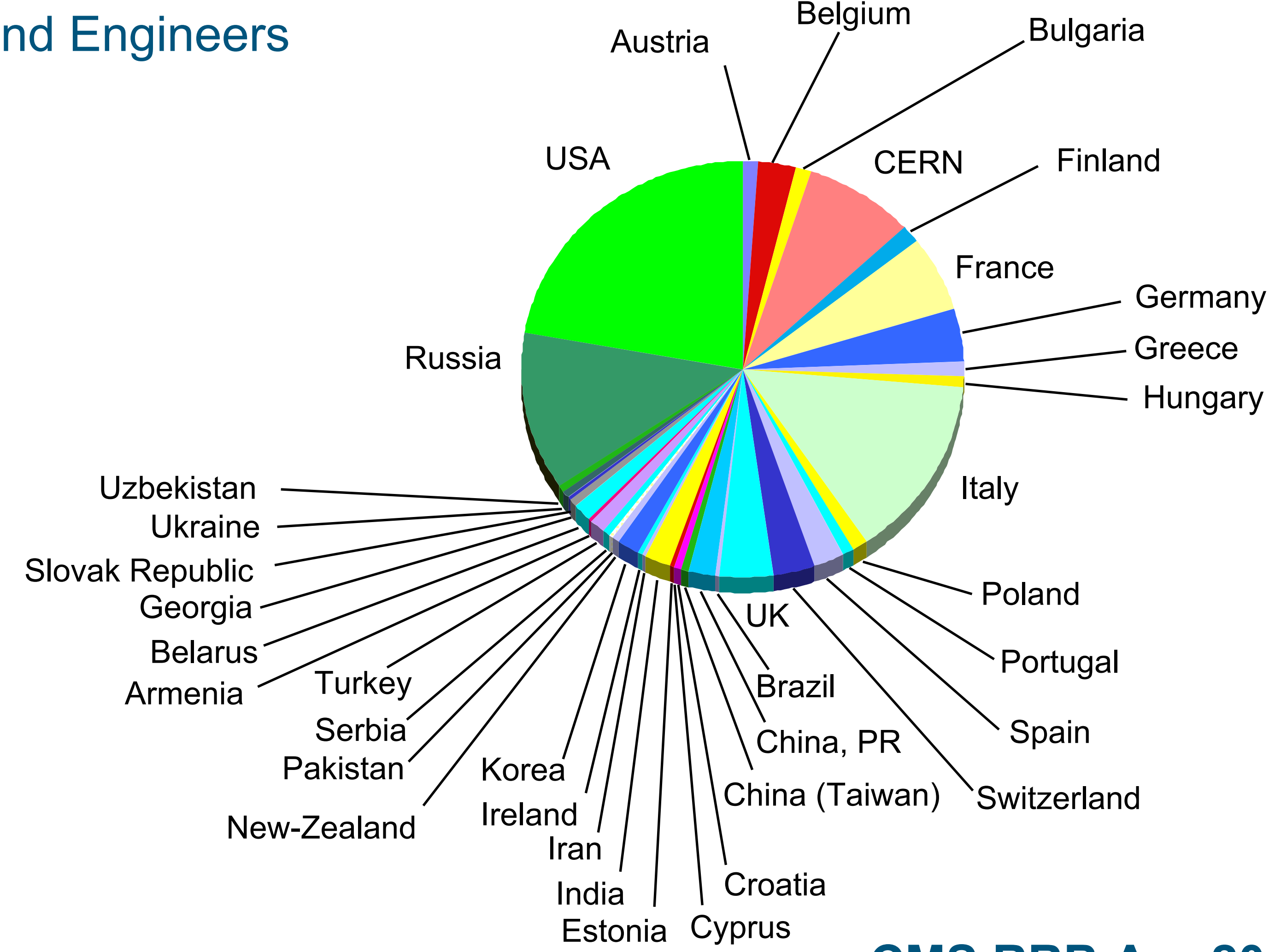
CMS Collaboration

CMS Letter of Intent, Oct 1992:

443 Physicists and Engineers

23 Countries

49 Institutions



CMS RRB Apr 2004

1976 Physicists and Engineers

36 Countries

153 Institutions

April, 05 2004/gm

http://cmsdoc.cern.ch/pictures/cmsorg/overview.html

LHC Detector Innovations

LHC challenges have led to dramatic detector progress

- Precise and fast Electromagnetic Calorimeters; high granularity (~100,000 channels), radiation hard.
  - ATLAS: Liquid Argon – “accordeon” for high speed operation
  - CMS: PbWO4 – fast crystal calorimetry, radiation resistant; more precise than Lar, but more difficult to calibrate.
- Huge Supraconducting Magnets
  - CMS: 4T Solenoid – HPD, APD photodetectors working at 4T
  - ATLAS: Muon Toroids – precision momentum over an enormous volume.
- All silicon tracking – 200 m^2 (10 M strips, 60 M pixels)
- Silicon pixels at p-p colliders for b tagging.
- Deep Submicron (0.25μm) electronics – radiation hard
- Optical data transfers – fast, hermetic - Gigabit Optical Links.

Physics at Startup

ATLAS and CMS will be ready for first collisions in 2007.

Example SM Higgs Discovery Reach (5σ): ATLAS +CMS

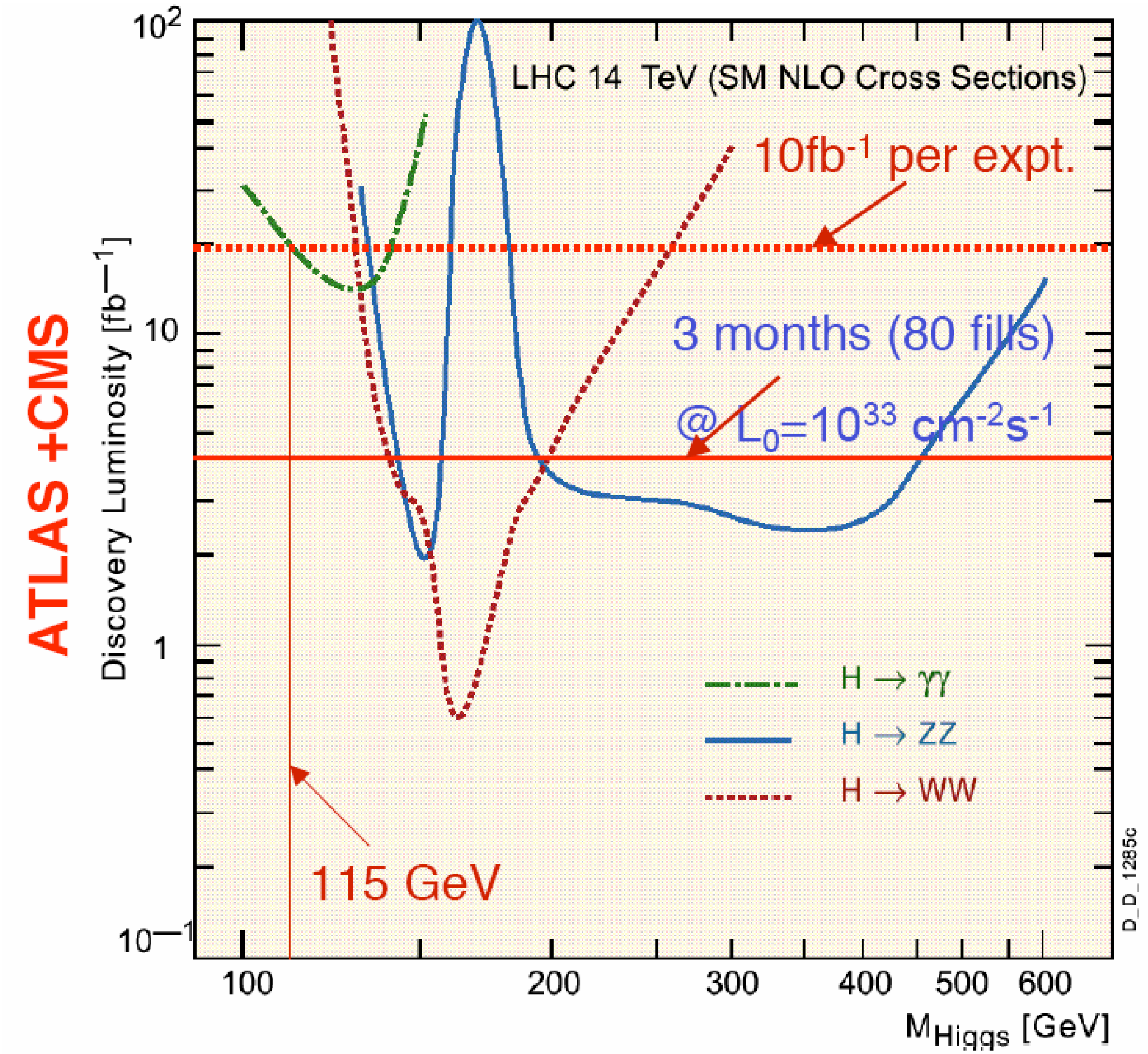
At $L_0=10^{33}$ cm^{-2}s^{-1}

1 month ~ 0.7 fb^{-1}

At $L_0= 3.10^{33}$ cm^{-2}s^{-1}

1 month ~ 2 fb^{-1}

Assumptions: 14hr run
and 10hr to refill
i.e. 1 fill/day
t_L ~ 20 hr, Efficiency of 2/3



Conclusion

Hadron Colliders are discovery machines.

- **ISR:** large PT phenomena, first indications of strong parton-parton interactions.
- **Sp$\bar{p}$S UA1/UA2:** Jet Physics establish QCD as theory of strong interactions. Confirmation of the EW theory with the observation of the IVBs (Ws and Zs) and the study of their properties.
- **Tevatron CDF/D0:** Discovery of the Top quark. The top is heavy!
- **LHC CMS/Atlas:** Probe the 1 TeV mass scale for the first time. The Standard Model has been precisely tested at LEP. Theory needs experimental input.

  There are no firm predictions: Higgs? Supersymmetry? Extra-dimensions? Something new will be discovered, we don’t know exactly what and this is very exciting.

  Rendez-vous in 2007 for the first collisions at LHC