Collider Physics - Chapter 2

The $Sp\bar{p}S$ – $W^{\pm}$ and Z discovery

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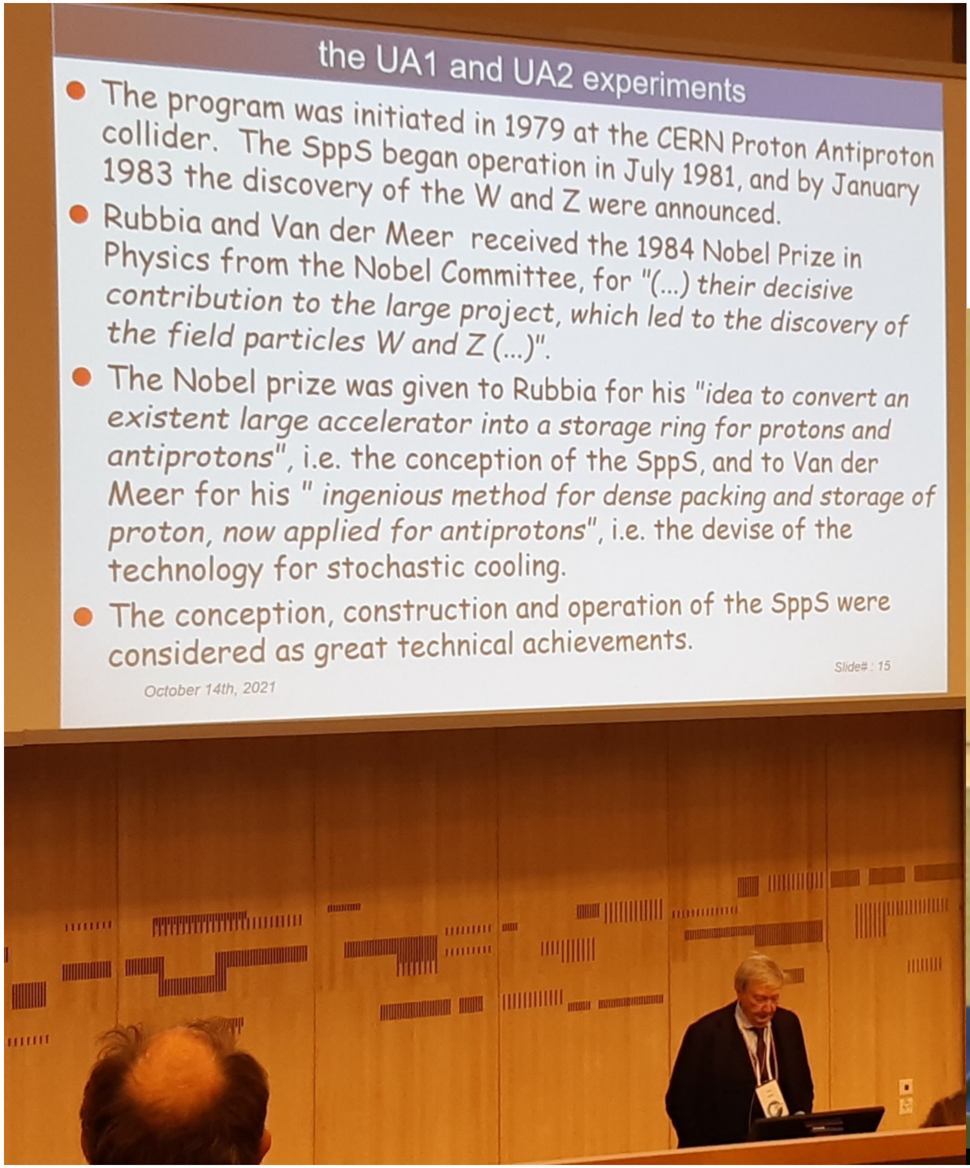
AA 21-22

last mod.
18-Oct-21

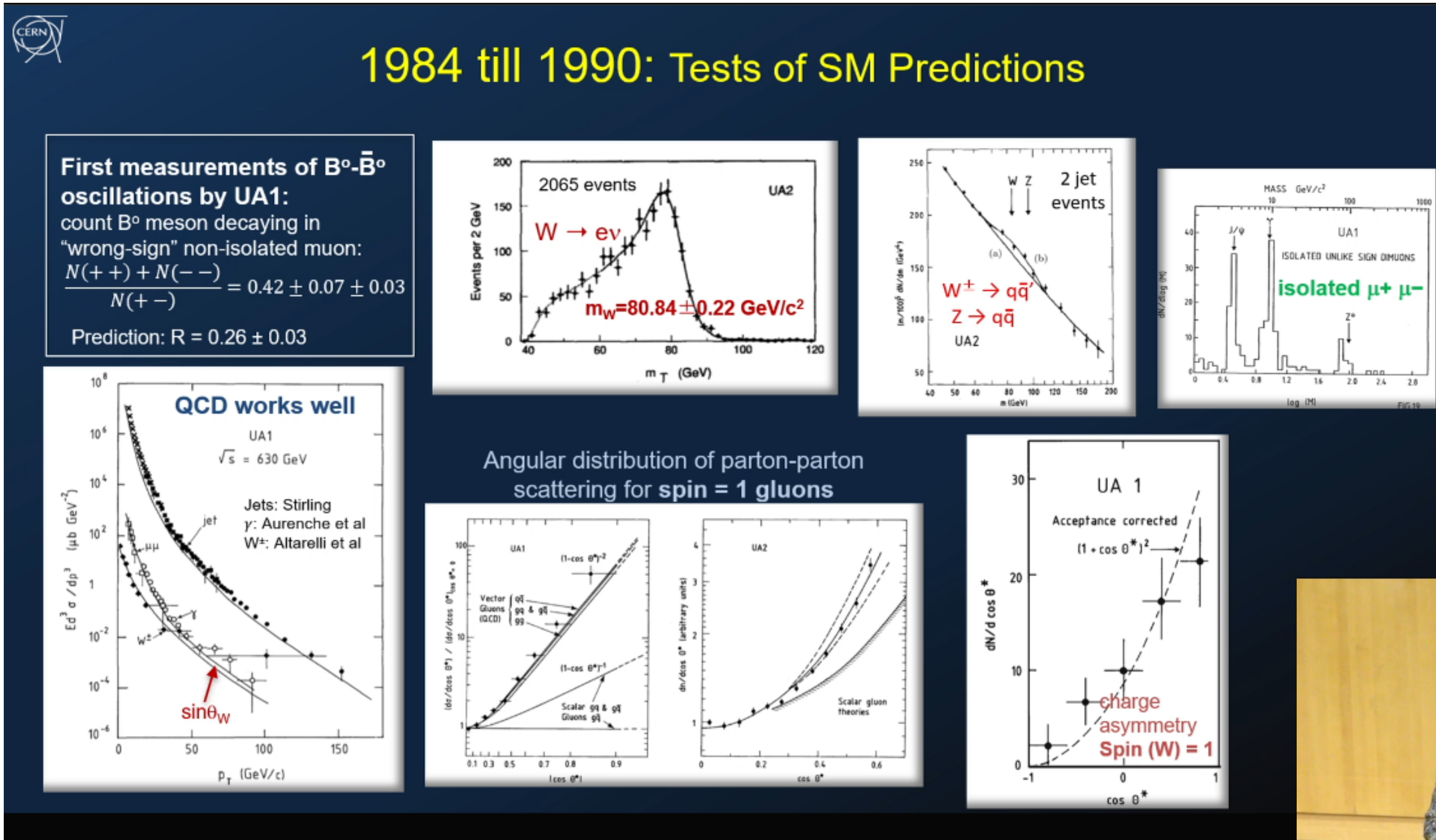
14/10/2021 - 50 years of Hadron Colliders at CERN

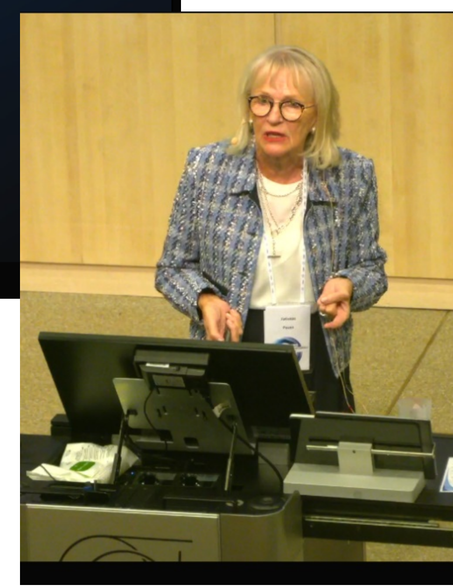


see:

https://indico.cern.ch/event/1068633/

14/10/2021 - 50 years of Hadron Colliders at CERN





Felicitas Pauss

14/10/2021 - 50 years of Hadron Colliders at CERN

Chris Llewellyn-Smith

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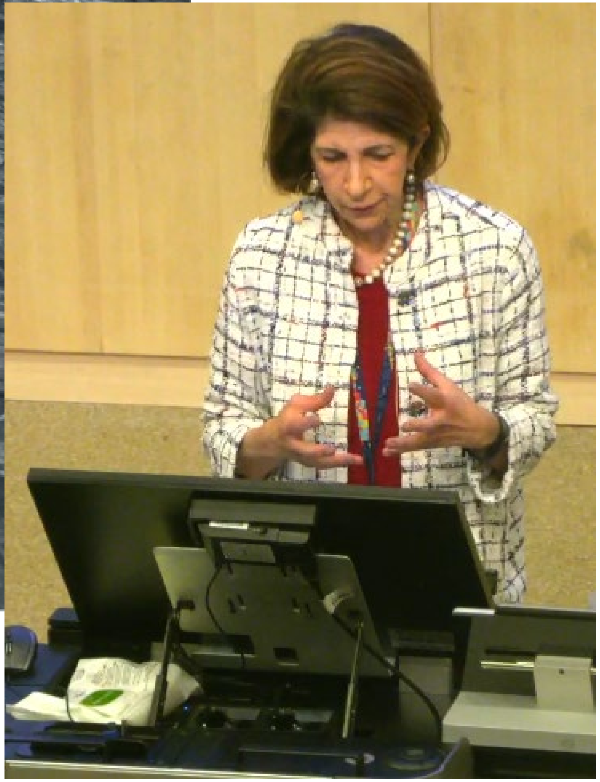
High-Luminosity LHC and beyond

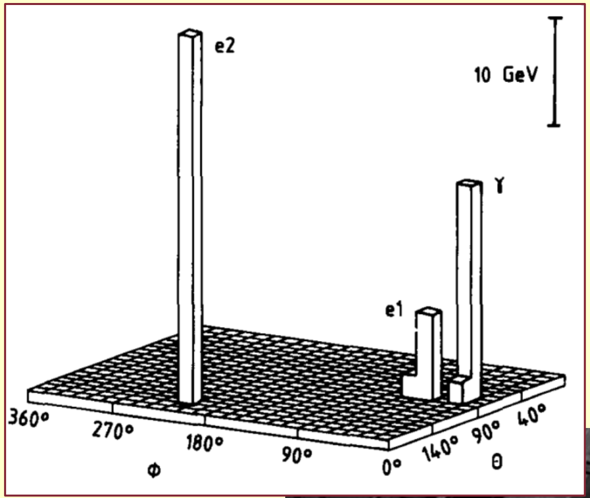
Fabiola Gianotti, 50th Anniversary of Hadron Colliders at CERN, 14 Oct 2021

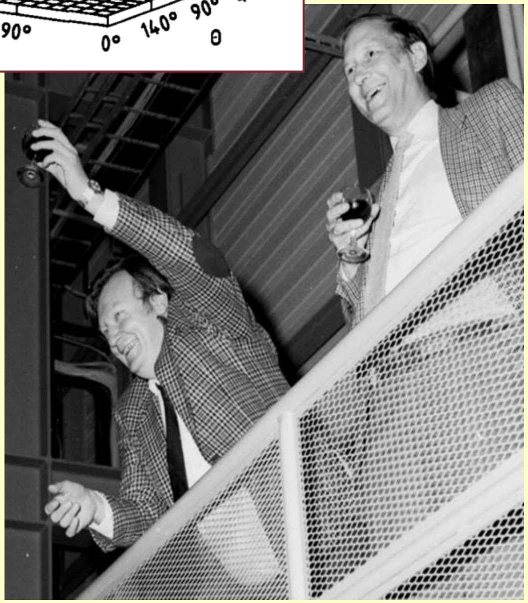


2 – The Sp$\bar{p}$S – W$^\pm$ and Z discovery

1. $\bar{p}$p collisions
2. The Sp$\bar{p}$S parameters
3. Detectors
4. Events
5. Hadronic interactions
6. The Drell-Yan process
7. W$^\pm$ discovery
8. Z discovery
9. W$^\pm$/Z properties(*)

(*) some of the properties of W$^\pm$ and Z are best studied in e^+e^- interactions [typical examples : Γ's and BR's] : their discussion is postponed to § LEP.





$\bar{p}p$ collisions: history

- The antiprotons ($\bar{p}$) are the antiparticles of the protons (p).
- Therefore **$\bar{p}p$** and **e^+e^-** colliders have similarities (e.g. one mag. channel with head-on collisions).
- … with the bonus of the lack of brem for $\bar{p}p$: in the same SPS tunnel, p/$\bar{p}$ were accelerated up to 273/315/450 GeV, while $e^\pm$ up to few GeV only.
- … and the disadvantage of compositeness → in high Q^2 collisions, partons$_{1,2}$ have a momentum $(x_{1,2}\sqrt{s}/2)$ and the energy of the parton collision is $\sqrt{\hat{s}} = \sqrt{s x_1 x_2}$.
- In addition $\bar{p}$'s are very scarce in our world (also e^+ are, but they are easy to produce and cheap).
- The real problem is the $\bar{p}$ "fabrication", accumulation and cooling, which has to happen before the acceleration process.
- It requires lot of clever ideas, both from Physics, Electronics, Engineering.

Once upon a time in 1976 …

Producing Massive Neutral Intermediate Vector Bosons with Existing Accelerators(*)

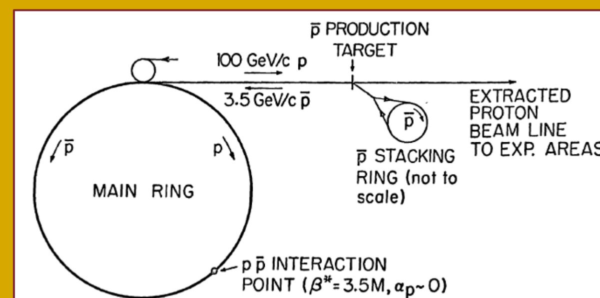
C. Rubbia and P. McIntyre
Department of Physics
Harvard University
Cambridge, Massachusetts 02138

and

D. Cline
Department of Physics
University of Wisconsin
Madison, Wisconsin 53706

March 1976

C. Rubbia, P. McIntyre and D. Cline, Proc. Int. Neutrino Conf., Aachen, 1976 (eds. H. Faissner, H. Reithler and P. Zerwas) (Vieweg, Braunschweig, 1977), p. 683.

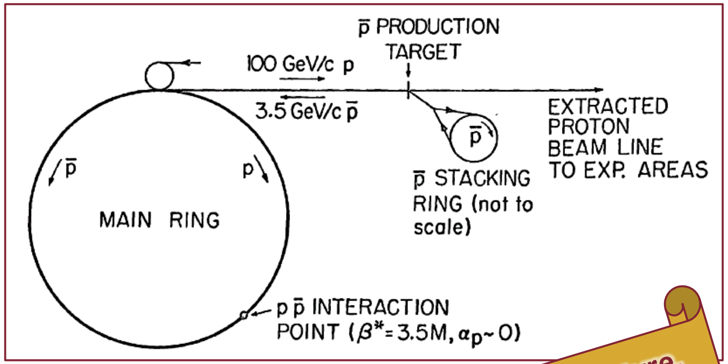


$\bar{p}p$ collisions: sequence

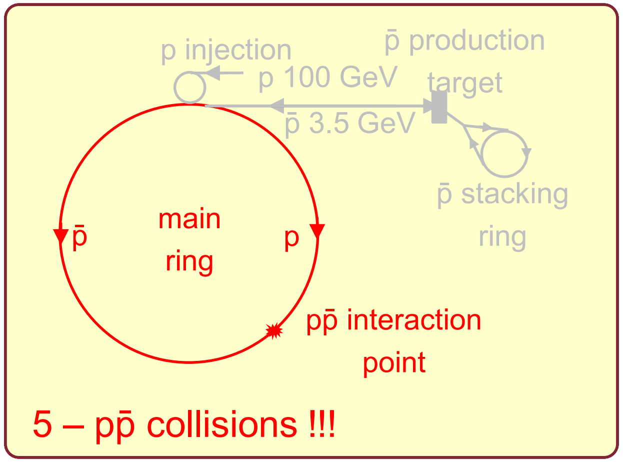
A little animation may help :

1. Protons are accelerated to an intermediate suitable energy [*the proposal says E_p = 100 GeV from Fermilab main ring, but it is NOT critical – at CERN E_p = 26 GeV from PS*] .
2. Then the p are extracted and sent onto a target, to produce high intensity collisions.
3. The resultant $\bar{p}$ (very rare) are collected and cooled ("stacked") in a lower energy ring [*at CERN $E_{\bar{p}}$ = 3.5 GeV – can't store $\bar{p}$'s at rest, despite Dan Brown*(*)].
4. After hours (days), when enough $\bar{p}$ are available, they are re-extracted and injected in the main ring, together with protons.
5. Both $\bar{p}$ and p are accelerated to the max energy, and then let collide.

Although every step requires ingenuity, step (3) and (4) are the real marvels; have a closer look.



Rubbia, McIntyre, Cline op.cit.

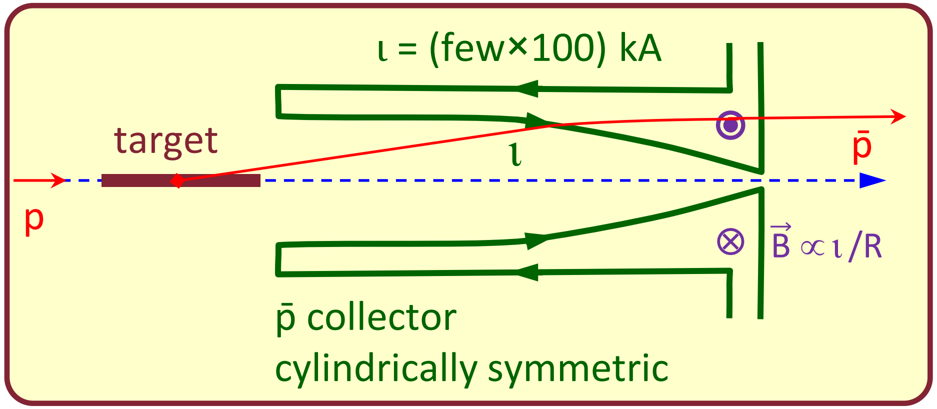


(*) *Penning traps work for few (< 10) particles.*

$\bar{p}p$ collisions: the making of $\bar{p}$

Rubbia et al. invented an innovative scheme for $\bar{p}p$ collisions(*).

- Carlo initially offered it to Fermilab, then he built it at CERN in 1978-81, later somebody else implemented it at Fermilab [*another turning point in particle physics, people thinks that Americans are more fast and flexible*].
- The key structures were the $\bar{p}$ collectors, which were a new design of the Van der Meer horn (see figs) …
- … and the AA (= Antiproton Accumulator), the ring where the $\bar{p}$ were collected, cooled, accumulated and stored for up to few days (next page).



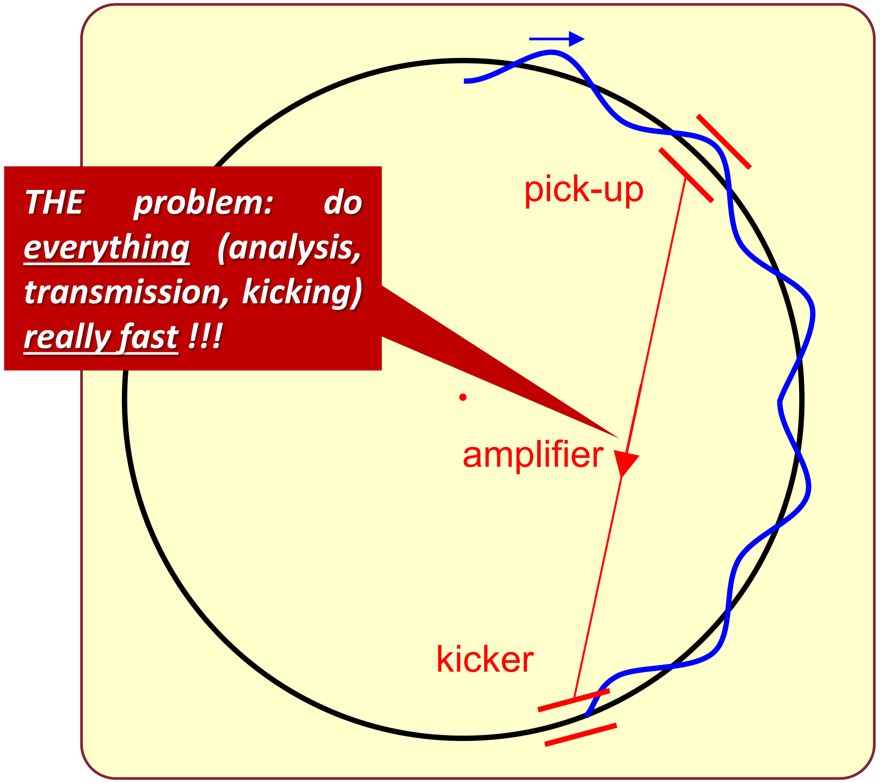
(*) *imho the creation of the $\bar{p}p$ machine (and not the relatively easy analysis of W and Z events) was the real achievement of the CERN $\bar{p}p$ Collider.*

look the ν horn in §ν (same author) and comment on the difference.

p̄p collisions: pickup+kicker

The main problem : the "cooling" of p̄ :

- [*why "cooling" ? in classical physics, the* *__temperature__* *of a gas is related to its motion in its CM frame : higher temperature means higher* (<v^2> - <v>^{2}) *velocity; so "gas cooling" means reducing the* ***__relative__*** *velocity of particles;*]
- analyze a single particle (——) circulating in a ring;
- it oscillates with "betatron oscillations" around the ideal particle (——);
- a "**pick-up**" electrode detects its position respect to the nominal orbit;
- this value, appropriately amplified, is transmitted to a "**kicker**", displaced by (n/2 + ¼) wavelengths;
- **the kicker corrects the orbit**;
- notice that the **space displacement** produces an **angle correction**;
- in reality, the pick-up and kicker are traversed by a large and incoherent number of particles at the same time;
- but if their average displacement is NOT zero, they get a correction and (**in average**) become closer to the ideal orbit.

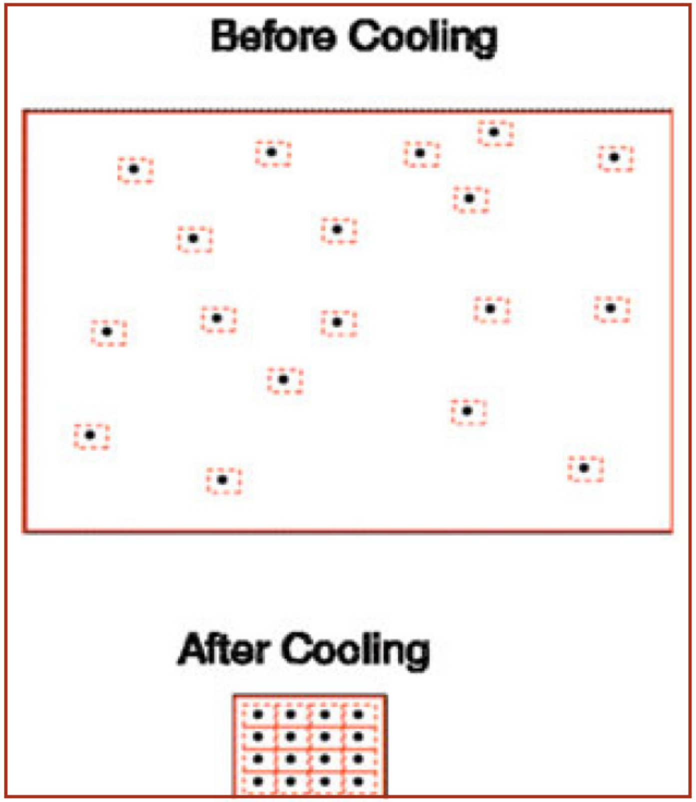


p̄p collisions: stochastic cooling

- Wikipedia : "***Liouville's theorem***, *[…] after the French mathematician Joseph Liouville, is a key theorem in classical statistical and Hamiltonian mechanics. It asserts that the phase-space distribution function is constant along the trajectories of the system.*"
- A principle well known to experts of beam optics : e.g. a quadrupole, or the principle of strong focusing.
- The cooling of p̄ "conflicts" with the theorem: e.g. a squeeze in transverse momentum should result in an increase in space dimensions.
- **Stochastic cooling** : [S. van der Meer, Nobel Lecture] "*Fortunately, there is a trick - and it consists of using the fact that particles are points in phase space with empty space in between. We may push each particle towards the center of the distribution, squeezing the empty space outwards. The small-scale density is strictly conserved, but in a macroscopic sense the particle density increases. This process is called cooling because it reduces the movements of the particles with respect to each other.*"

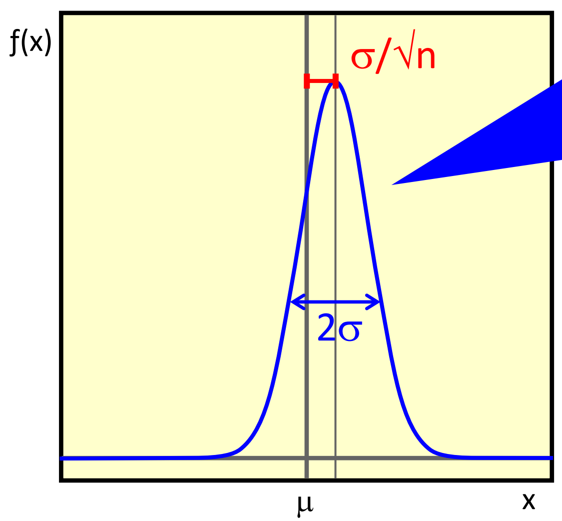
$\bar{p}p$ collisions: (how to avoid) Liouville theorem

Stochastic cooling



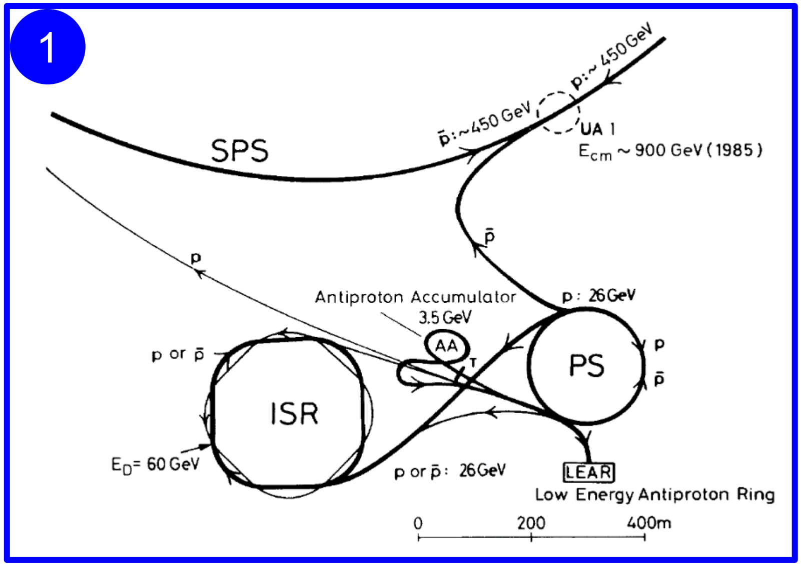
A cartoon by Carlo, to explain the previous sentence of van der Meer and the solution of the "Liouville problem".

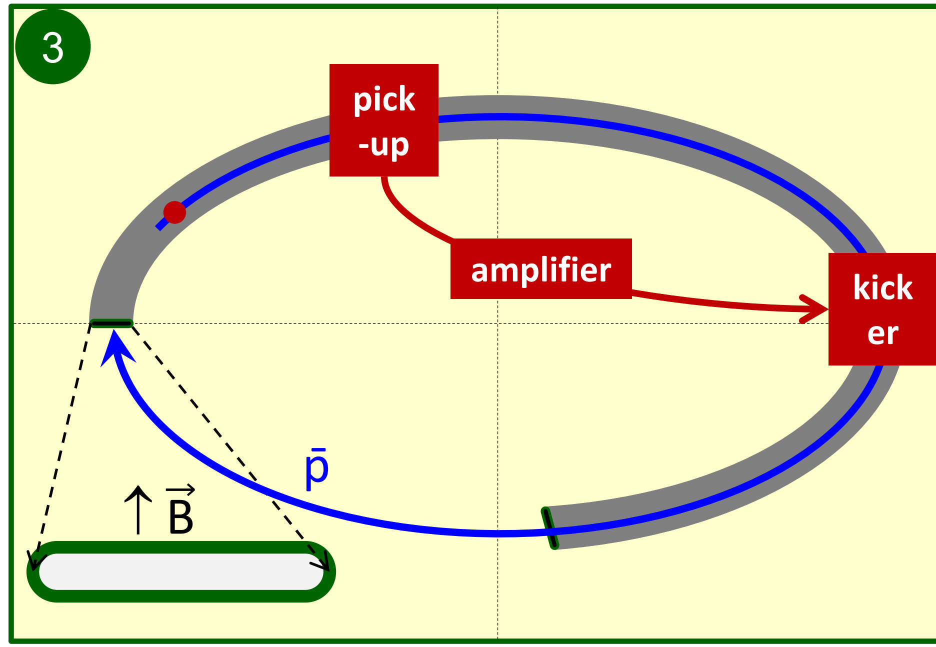
- *My understanding : cannot modify individual particle trajectories, but act on packets of n particles, small enough that their means be sensibly different from the ideal orbit ($1/\sqrt{n}$ not negligible).*
- it requires to divide the $\bar{p}$'s in small packets, act on each packet, and then reassemble the beam.
- *A completely different type of cooling exists, **electron cooling**, invented by G.I. Budker. It is used in other accelerators.*



"if a population of n elements is distributed according to a gaussian with average μ and rms σ, its mean is a random variable with average μ and rms = $\sigma/\sqrt{n}$."

$\bar{p}p$ collisions: the AA

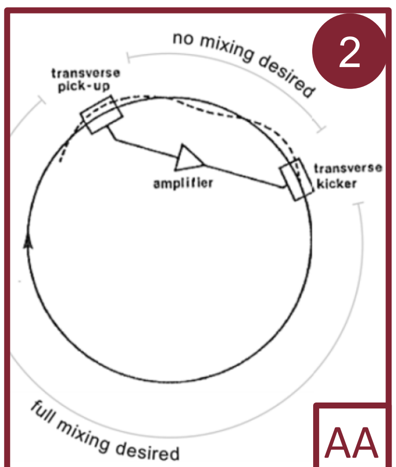




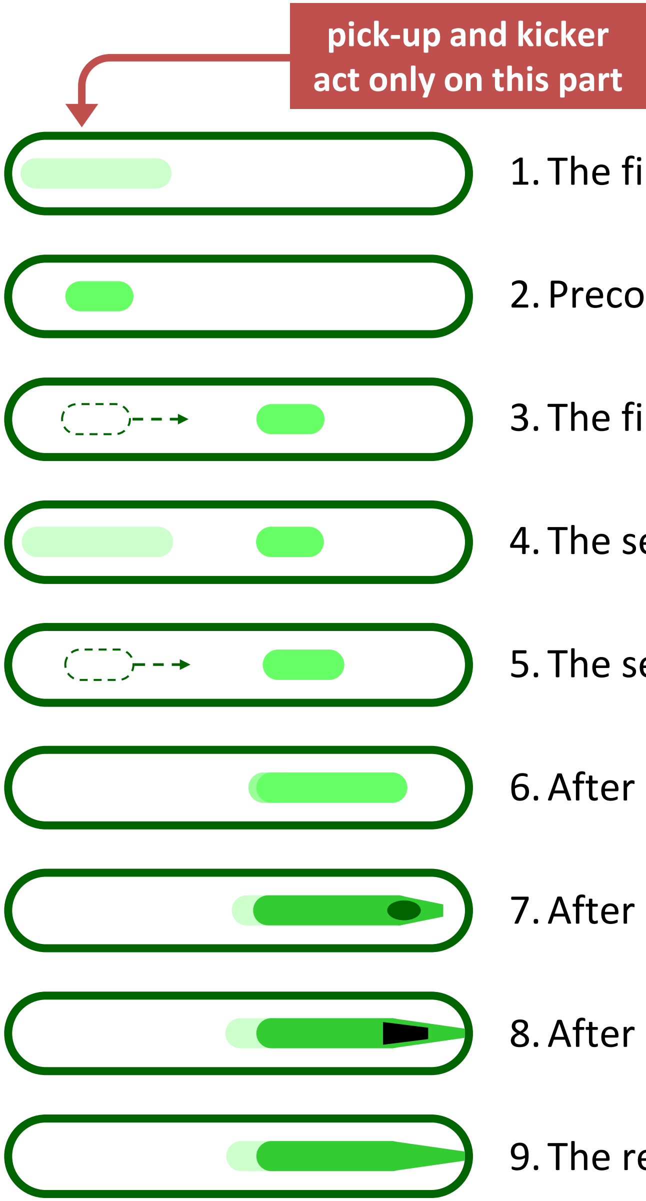
1. A view of the CERN $p\bar{p}$ complex in the '80s.

2. The AA and the its functioning principle.

3. A scheme of the AA operations.



$\bar{p}p$ collisions: the AA at work



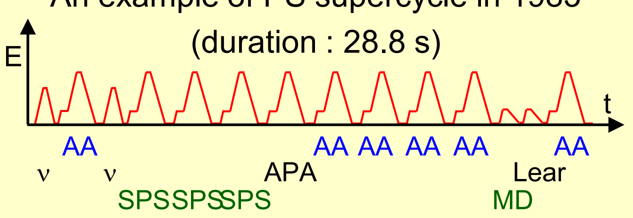
Time evolution of the $\bar{p}$ in the AA:

1. The first pulse of $7{\times}10^6$ $\bar{p}$ has been injected into the vacuum chamber.
2. Precooling has reduced the momentum spread.
3. The first pulse has been moved to the stack-tail region.
4. The second pulse is injected, 2.4 s later.
5. The second pulse, after having been precooled, is also stacked.
6. After 15 pulses, the stack contains 10^8 $\bar{p}$.
7. After 1 h, a dense core has formed inside the stack.
8. After 24 h, the core contains enough $\bar{p}$ for transfer to the SPS.
9. The remaining $\bar{p}$ are used to begin the next day of accumulation.

$Sp\bar{p}S$ parameters

1983 was the "golden year" of $Sp\bar{p}S$: performances still improving, $W^\pm$ and Z discovery. Notice :

- The rate of $\bar{p}$ production : a rate ~10^6 paid to convert matter into antimatter.
- The energy for $\bar{p}$ collection (3.5 GeV) was chosen because it is optimal for production σ and acceptance.
- The cross-section of the design, from an old experiment $\sigma(p\ {}_{74}W \to \bar{p}X)$, was higher. The project had margins to (barely) survive.
- The $Sp\bar{p}S$ performances were considered great, but LHC is × **10^5** in luminosity and × **20** in energy (**30** years later).



An example of PS supercycle in 1983 (duration : 28.8 s)

The $Sp\bar{p}S$ in 1983		
$p\ {}_{74}W \to \bar{p}\ X$	$\lvert\vec{p}\rvert$ = 26 GeV	10^{13} / 2.4 s
$\bar{p}$	$\lvert\vec{p}\rvert$ = 3.5 GeV	$1/(10^6\ p)$ → few × 10^9/h
$\bar{p}\ p$	$\sqrt{s}$ = 546 GeV (*)	$\mathscr{L} = 1.6\times10^{29}$ $cm^{-2}s^{-1}$
$\int\mathscr{L}dt$	153 nb^{-1}	
$N_{events}(\bar{p}p)$	8 × 10^9	
$W^\pm \to e^\pm\nu$	**90**	
$W^\pm \to \mu^\pm\nu$ (UA1 only)	**14**	
$Z \to e^+e^-$	**12**	
$Z \to \mu^+\mu^-$ (UA1 only)	**4**	

Don't confuse "${}_{74}W$" (tungsten,"wolfram") with "$W^\pm$", the IVB.

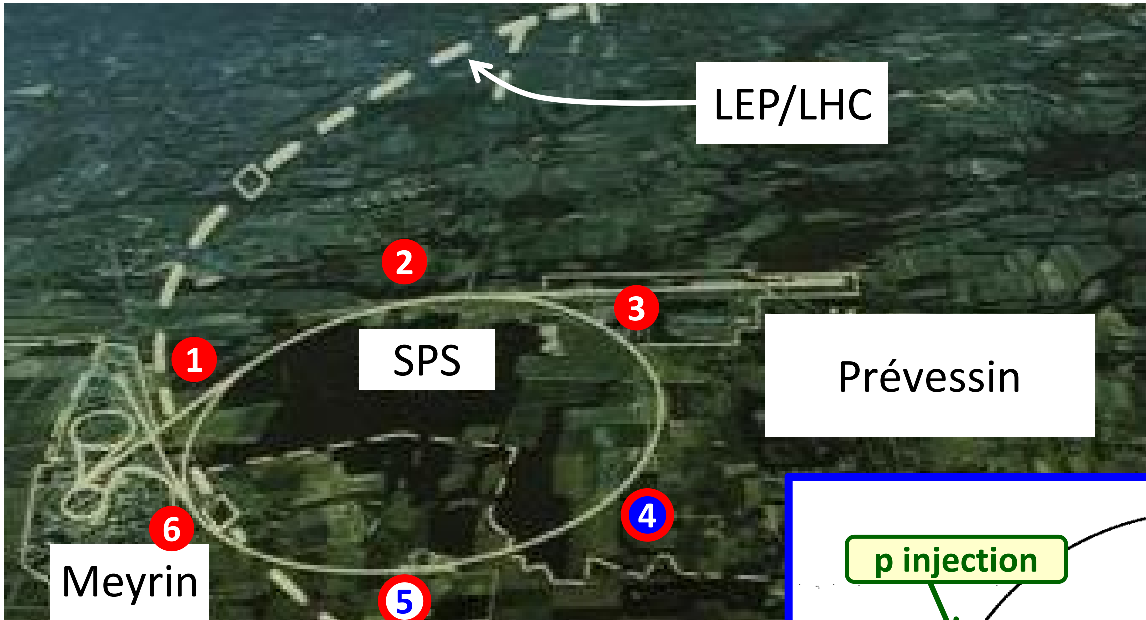
[*sorry, not my fault, only 26 letters available*]

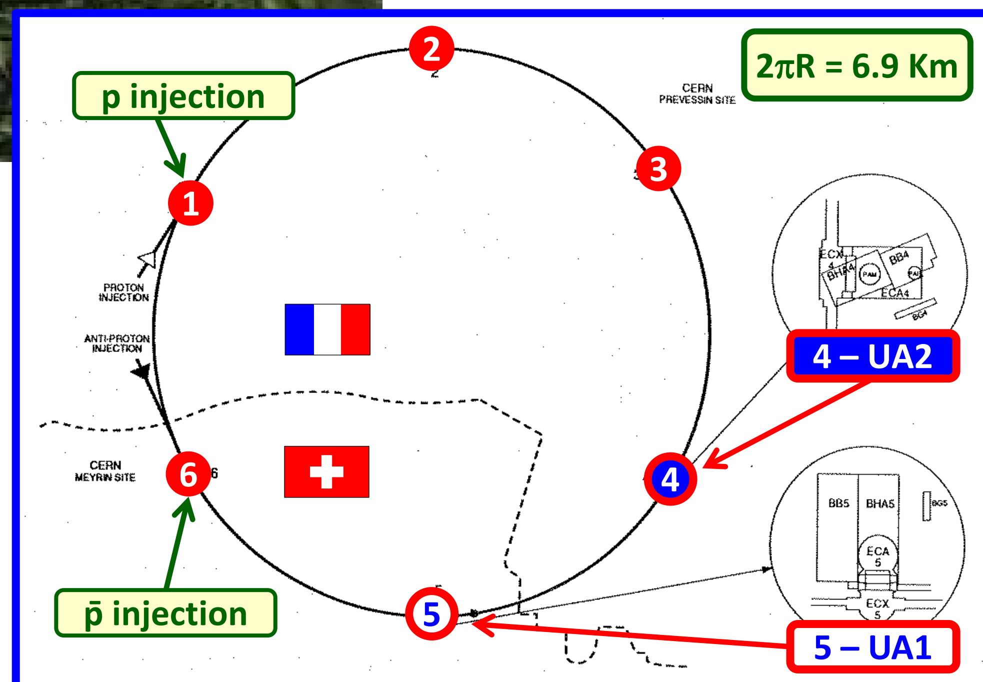
(*) $\sqrt{s}$ = 630 GeV in ≥ 1984.

$Sp\bar{p}S$ parameters: $\mathcal{L}_{int}$ / year

Year	1982	1983	1984	1985	1986	1987	1988	1989	1990
Beam energy (GeV)	273	273	315	315		315	315	315	315
β_h^* (m)	1.5	1.3	1	1		1	1	1	0.6
β_v^* (m)	0.75	0.65	0.5	0.5		0.5	0.5	0.5	0.15
# bunches	3+3	3+3	3+3	3+3		3+3 (6+6)	6+6	6+6	6+6
p/bunch (10^{10})	9.5	14	16	16			12	12	12
$\bar{p}$/bunch (10^{10})	1.2	1.5	2	2			4	6	7
$< \mathcal{L}_{initial} >$ (10^{30} cm^{-2}s^{-1})	0.05	0.17	0.36	0.39		0.35	1.3	1.8	3.1
$< \mathcal{L}_{int}$/coast > (nb^{-1})	0.5	2.1	5.3	8.2		2.8	31.5	40	70
# coasts/year	56	72	77	80	0	33	107	119	104
$< T_{coast} >$ (h)	13	12	15	17			11	12	10
$\mathcal{L}_{int}$ /year (nb^{-1})	**28**	**153**	**395**	**655**	**0**	**94**	**3608**	**4759**	**7241**

The detectors





UA1 and UA2 are placed at 60° wrt each other, in the region far from the injection from PS.

The detectors: hermeticity

- Modern Collider detectors cover a solid angle as close as possible to 4π;
- there are two reasons for that :
  - detect all the particles of the final state (e.g. to reconstruct a rare multibody state with high efficiency);
  - "detect" the invisible particles (e.g. ν's), which escape without interacting with the apparatus ("hermeticity", as Carlo used to call it);
- there is a fundamental difference between e^+e^- and pp ($\bar{p}p$) :
  - in hadronic colliders (NOT in e^+e^-), most of $\sqrt{s}$ (= $1-\sqrt{x_1 x_2}$) is lost in spectator fragments, which escape in the beam chamber without being detected;
  - the "visible energy" is a (small and variable) fraction of $\sqrt{s}$;
- therefore, in pp and $\bar{p}p$, the constraint of 4-mom conservation is not applicable in 4D;
- instead, a 2D constraint in the transverse plane is used;
- in the analysis, use the "missing transverse energy" $\not{E}_T$ (assume $\not{E}_T = |\vec{p}_T^{\,\nu}|$). [*"missing transverse momentum" looks more correct to me, but it is not widely used*].

Rules for trigger and analysis:

e^+e^- : "4D";

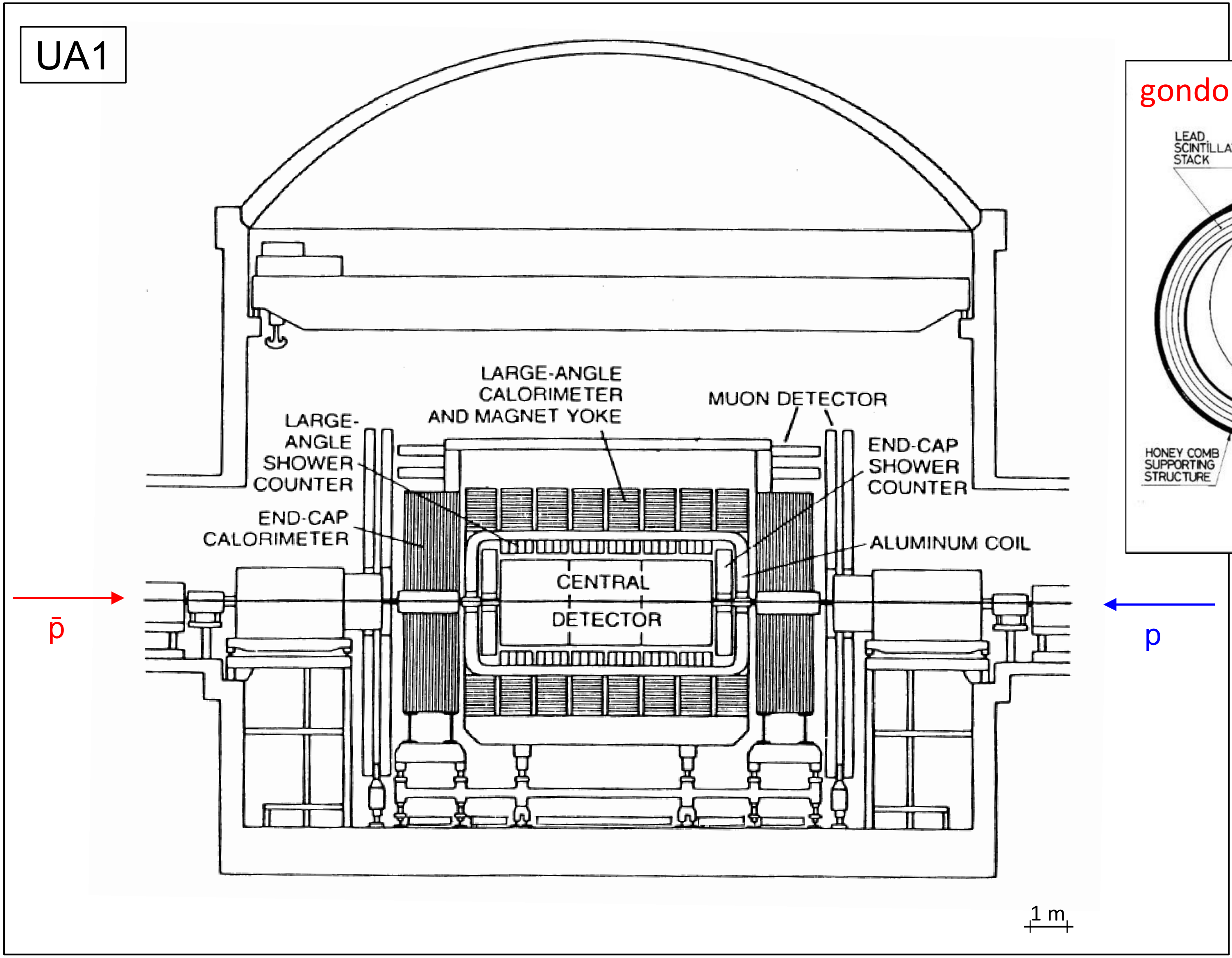
pp($\bar{p}p$) : "2D" :

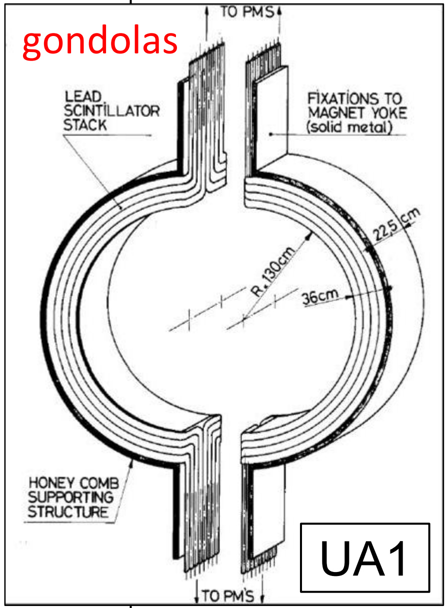
ν's $\rightarrow E_T$

spectators $\rightarrow E_\ell$

The detectors: UA1

The detectors: UA1 layout



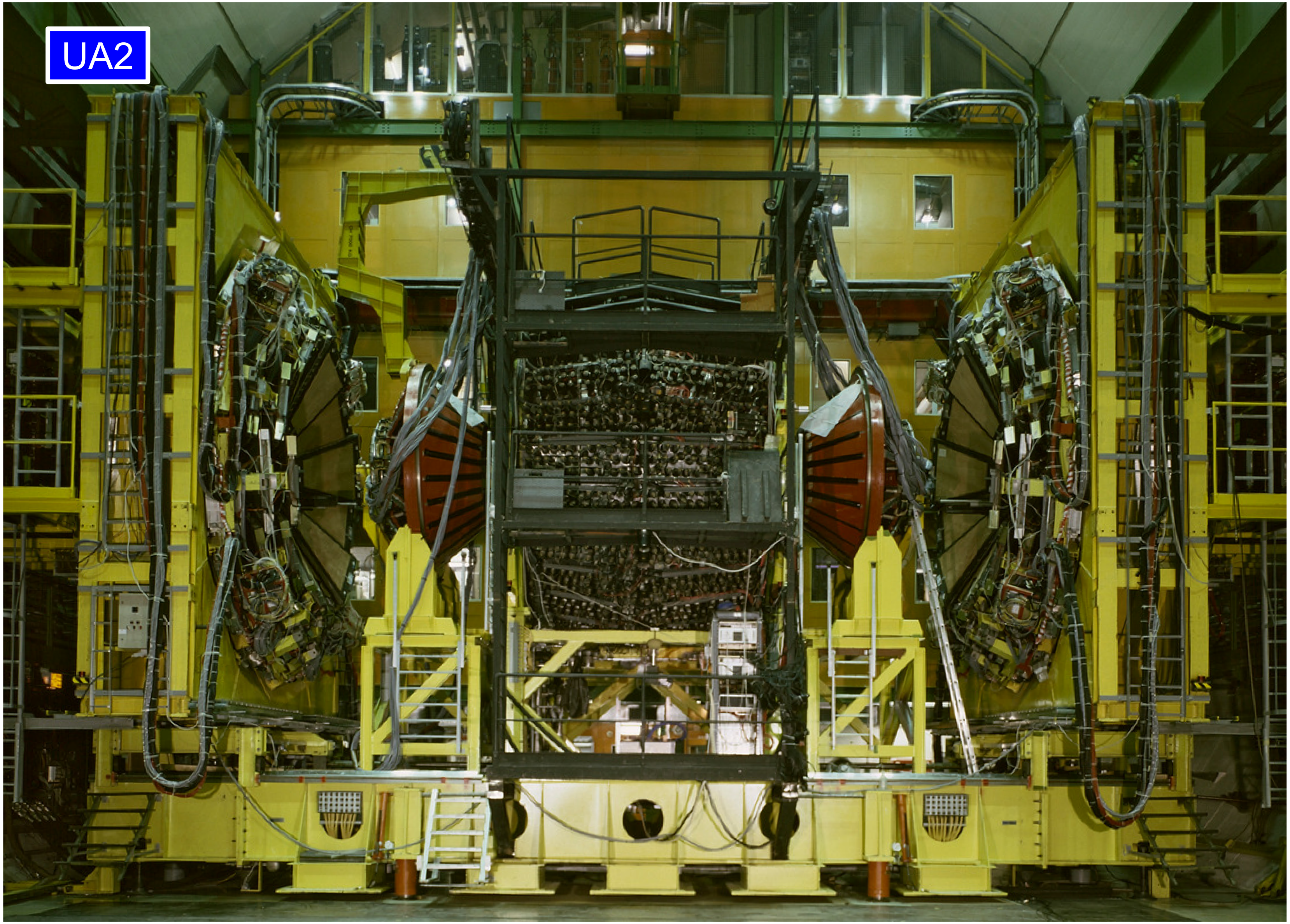


The detectors: UA1 parameters

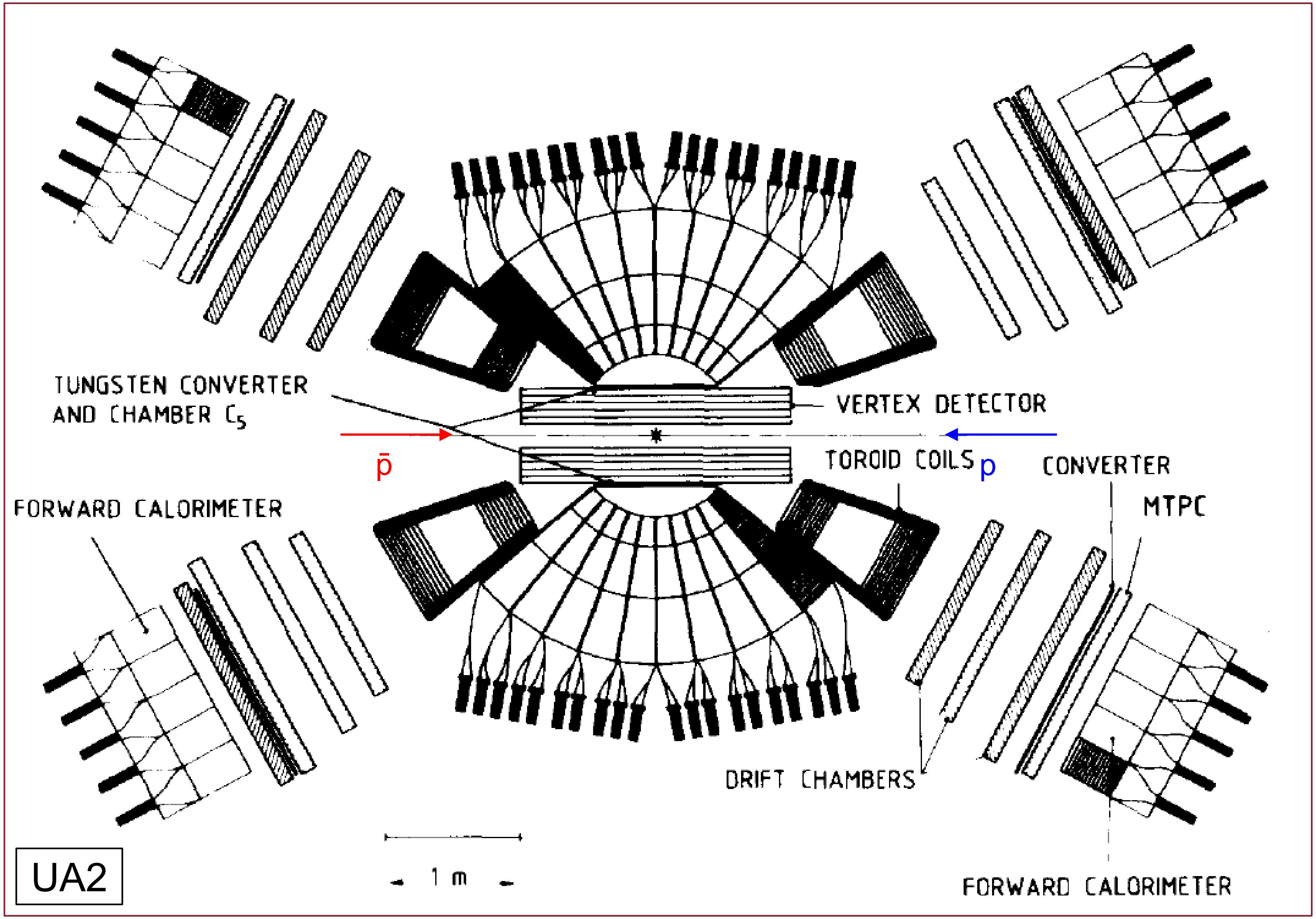
Central drift chamber	Gas	Field	v_{drift}	$\alpha_{Lorentz}$	$N_{sense\ wires}$
	Ar-ethane 40-60	1.5 kV/cm	53 μm/ns	23° @ 0.7 T	6110

UA1	Zenith θ	type	Name	e.m. rad-length	had. abs-length	Cell Δθ×Δϕ	σ_E/E
Central calorimeter	25°–155°	e.m.	gondolas	26.6/sinθ	1.1/sinθ	5°×180°	0.15/√E(GeV)
		had.	C's	–	5.0/sinθ	15°×18°	0.80/√E(GeV)
Endcap calorimeter	5°–25° 155°–175°	e.m.	bouchons	27/cosθ	1.1/cosθ	20°×11°	0.12/√E(GeV)
		had.	I's	–	7.1/cosθ	5°×10°	0.80/√E(GeV)

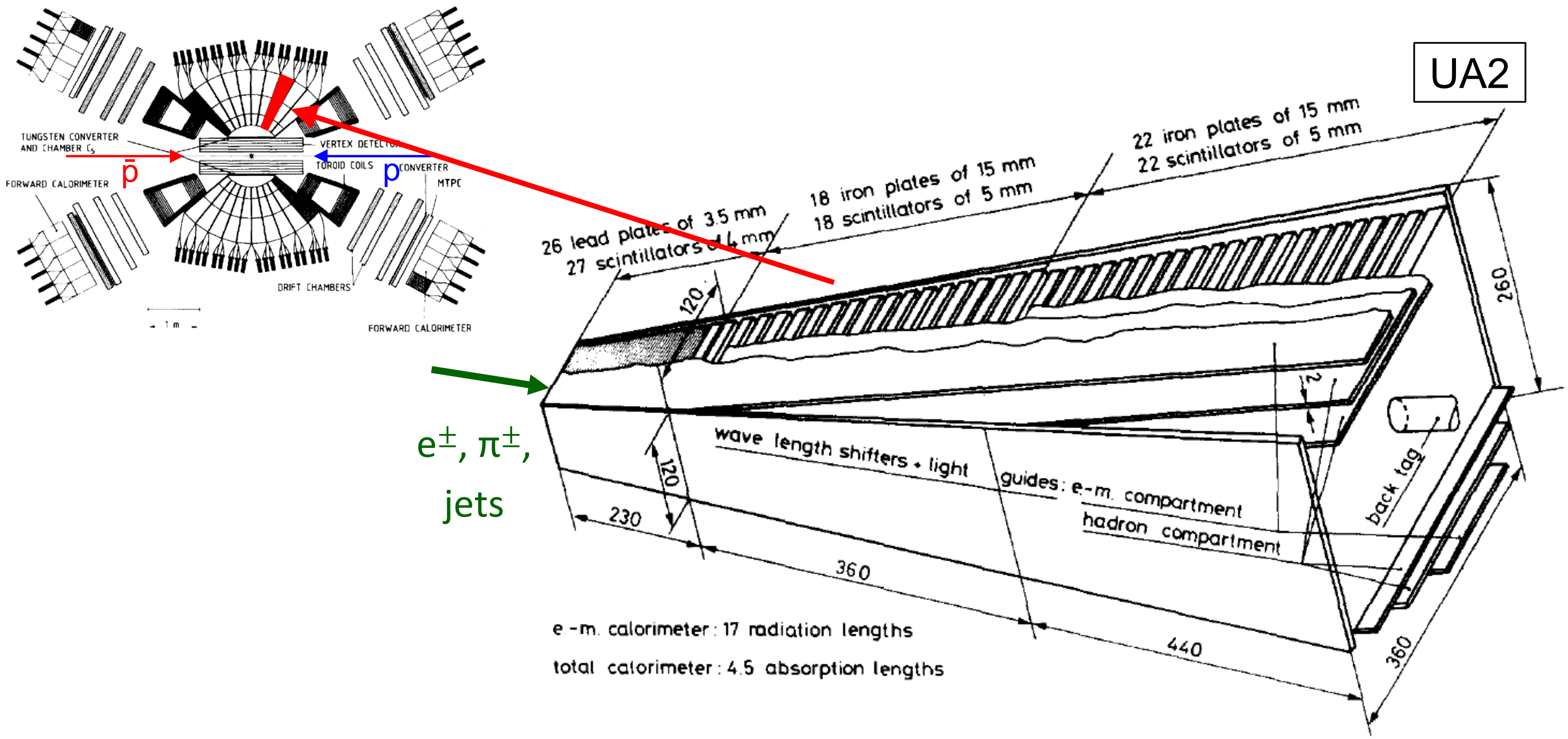
The detectors: UA2



The detectors: UA2 scheme



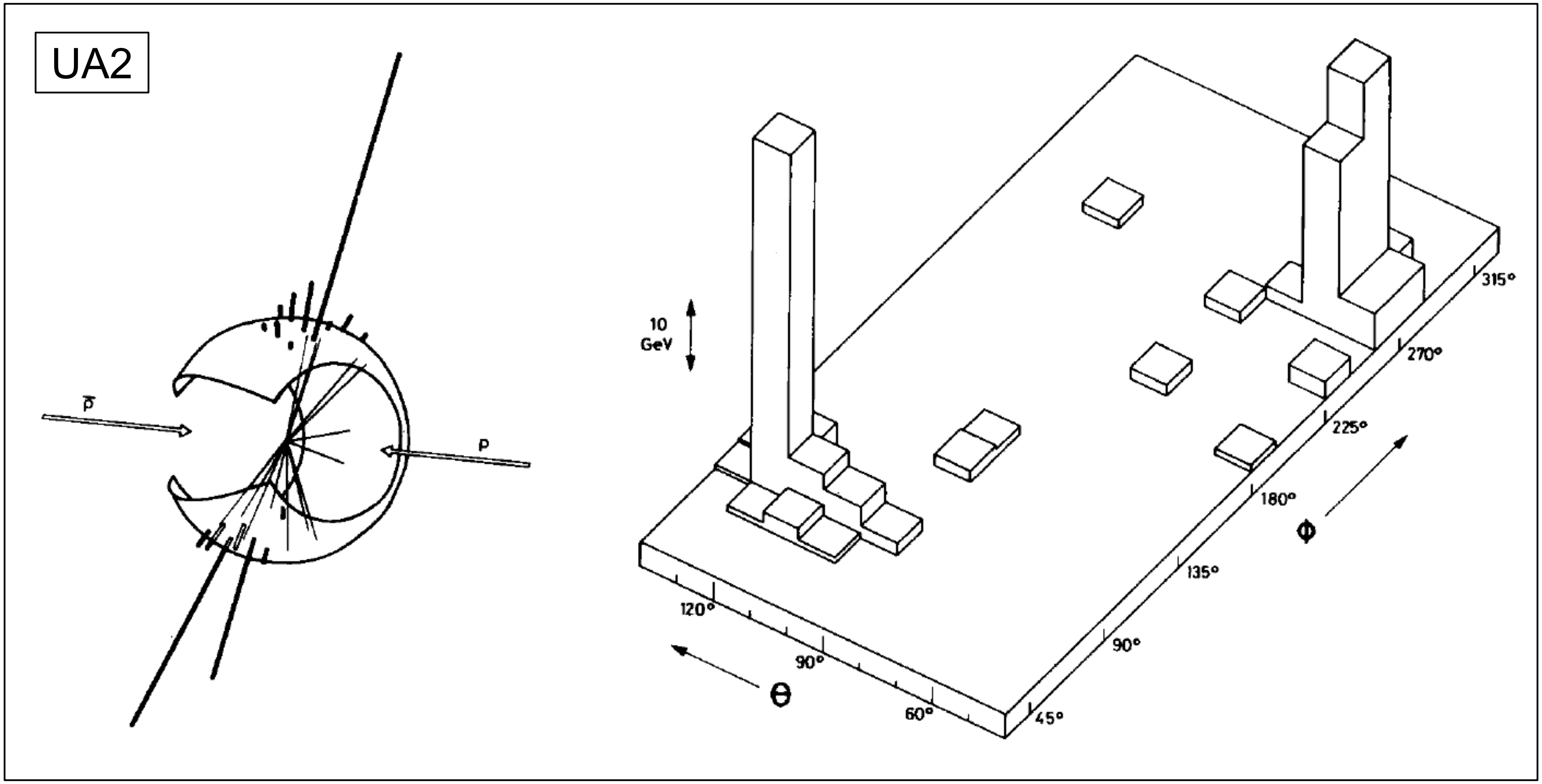
The detectors: UA2 calos



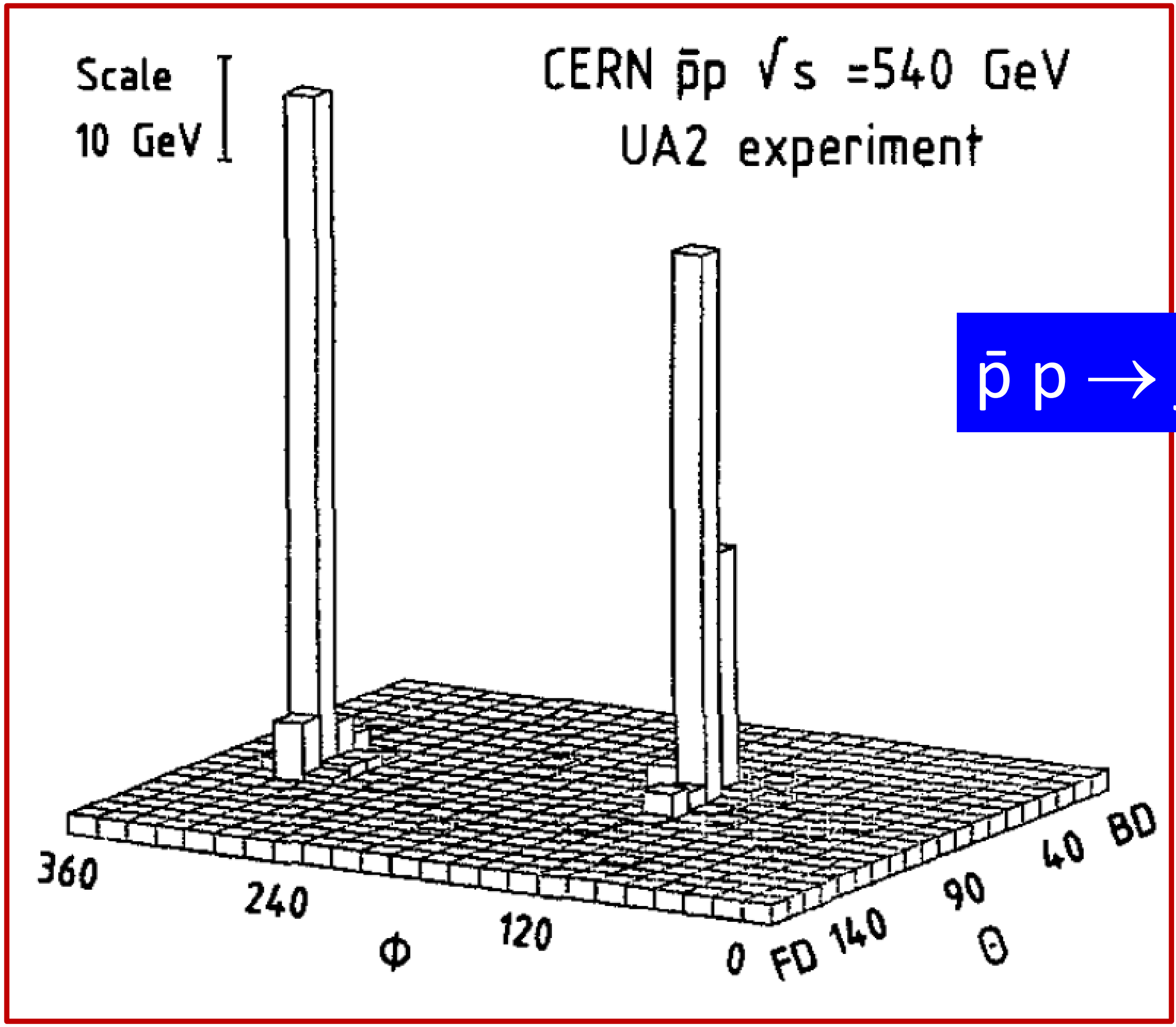
UA2 Central calorimeter	zenith θ	type	e.m. rad-length	had. abs-length	Cell Δθ×Δϕ	σ_E/E
	40°−140°	e.m.	17	~0.5	10°×15°	$0.14/\sqrt{E(GeV)}$
		had	–	2+2		32% – 11%

The events: jets discovery

Hadronic jets discovery :
UA2 - Paris conference, 1982



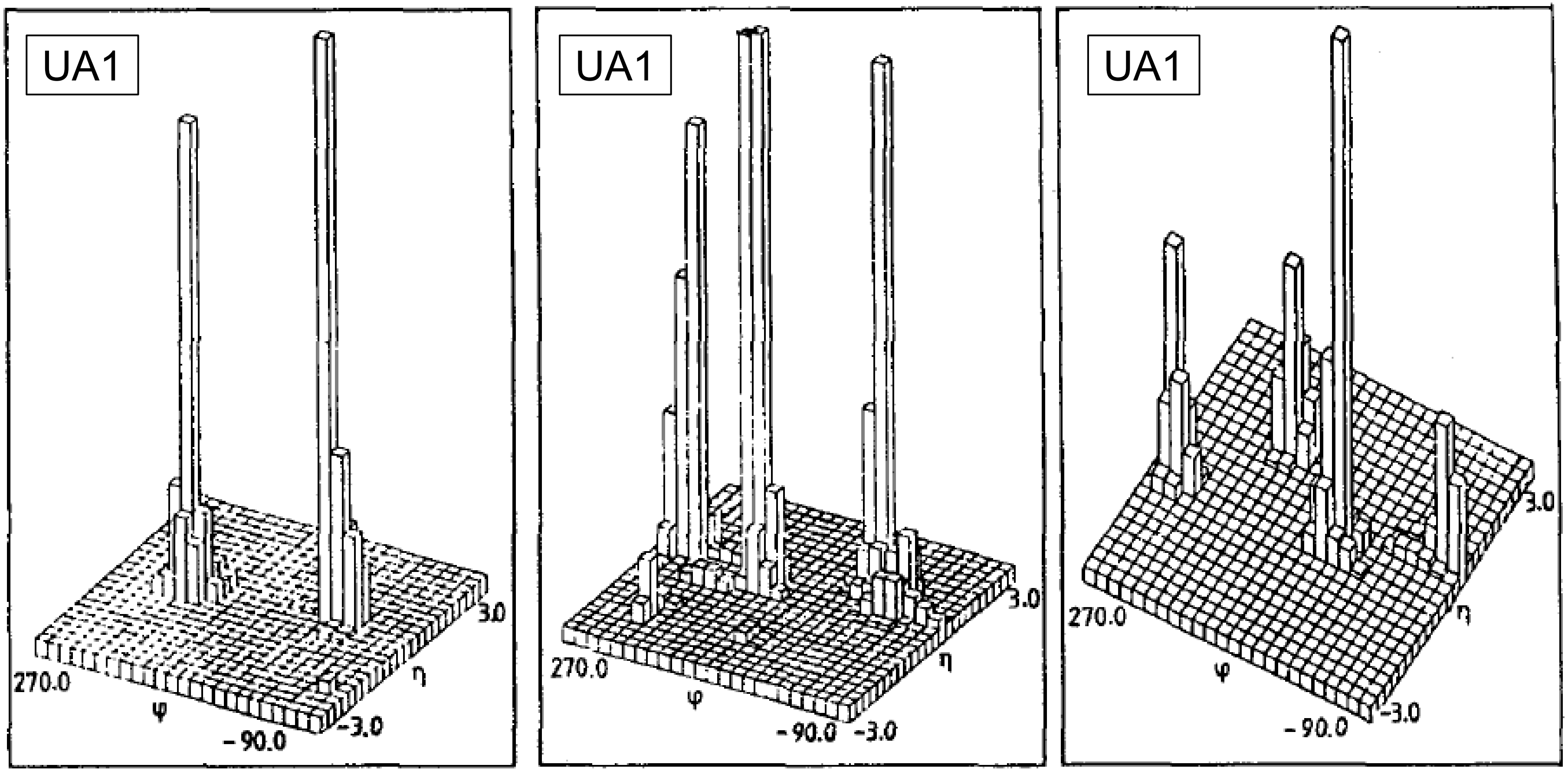
The events: UA2 jets



p̄ p → jet jet

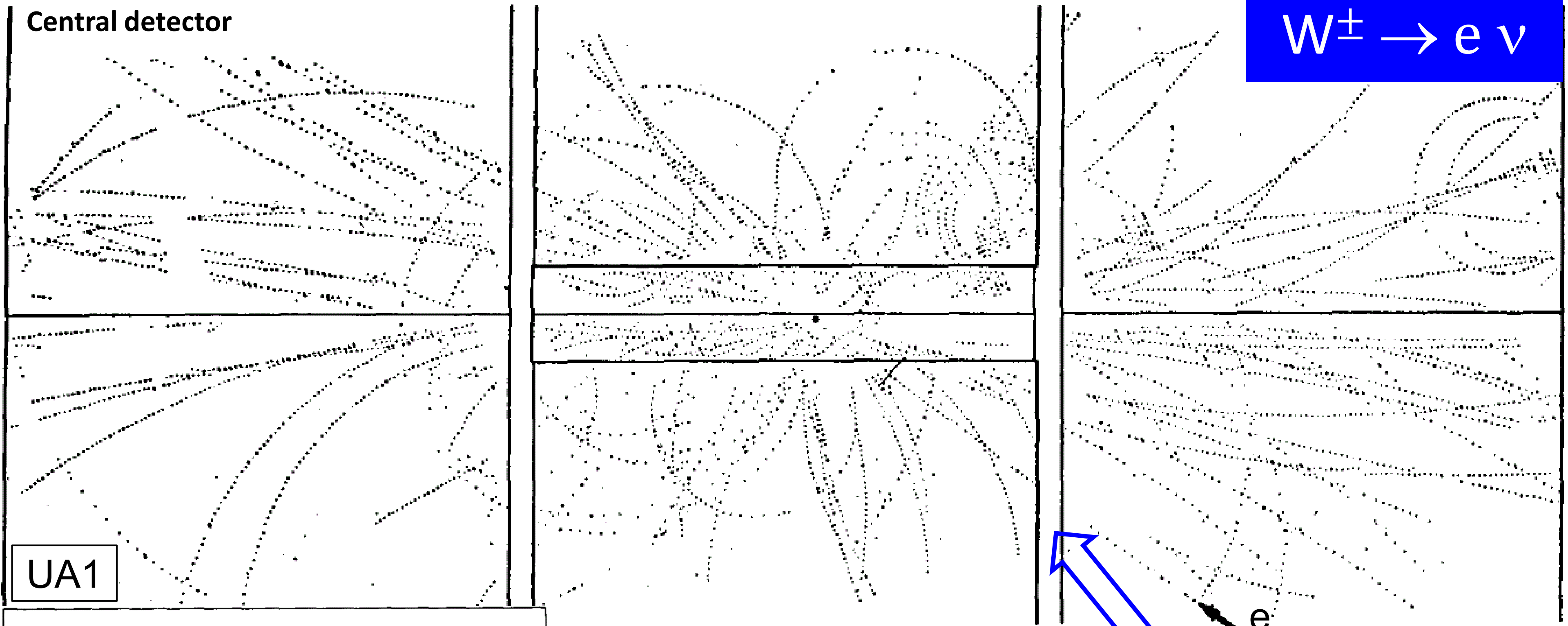
The events: UA1 jets

$\bar{p}p \to$ 2,3,4 jets



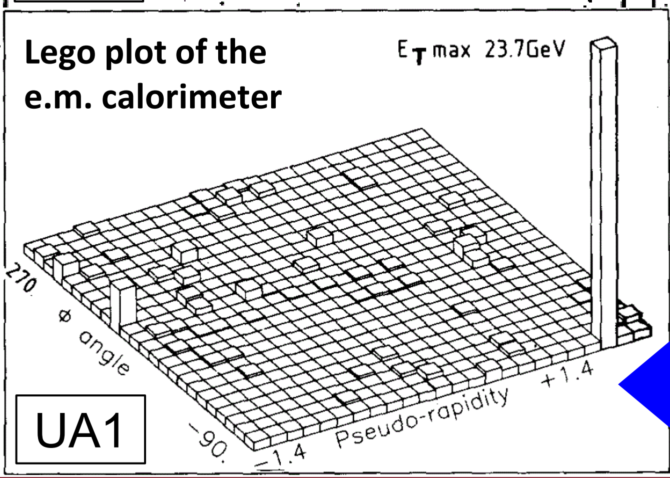
The events: UA1 $W^{\pm} \rightarrow e\nu$

Central detector



$W^{\pm} \rightarrow e\,\nu$

Lego plot of the e.m. calorimeter

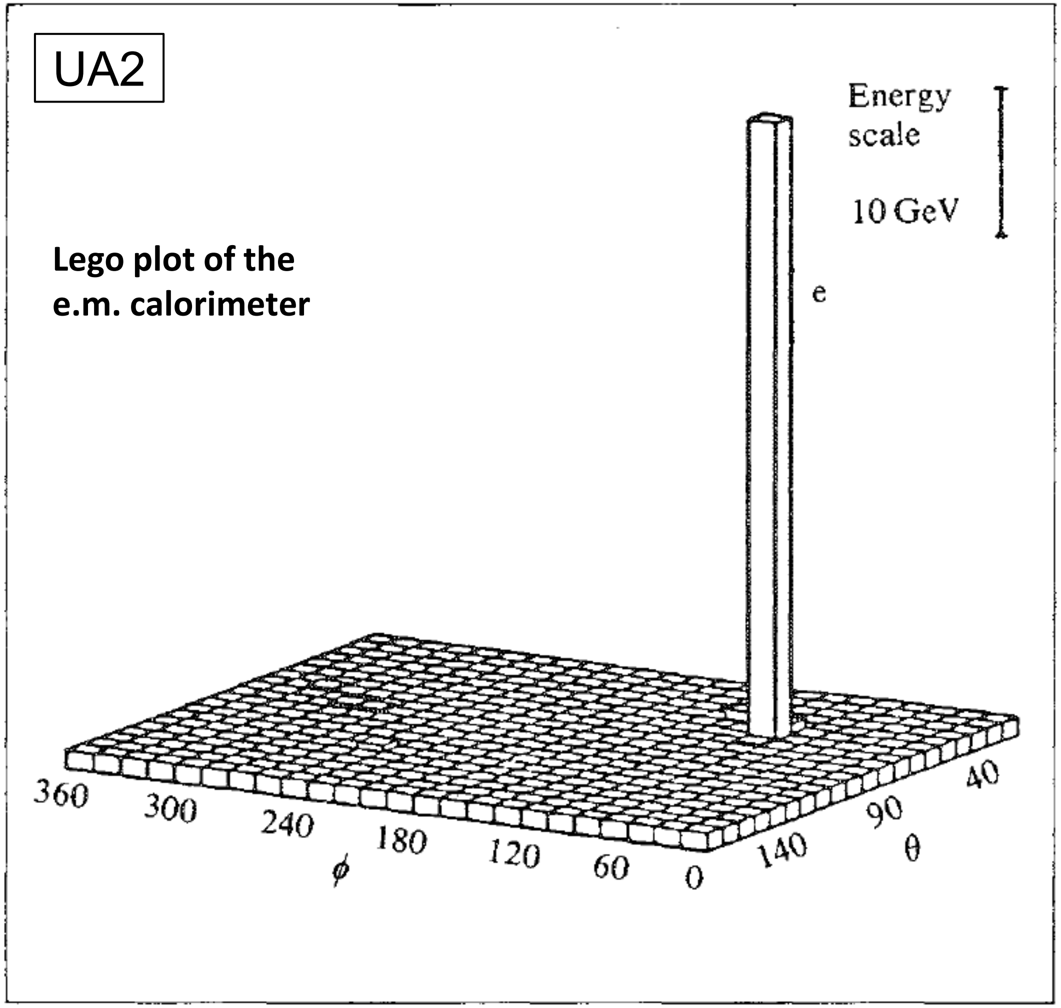


The original UA1 paper said "*Fig. 6. The digitization from the central detector for the tracks in (…) events which have an identified, isolated, well-measured high-p_T electron*".

The central detector is impressive, but the e.m. calo is definitely easier for event trigger, selection and analysis.

The events : UA2 $W^{\pm} \rightarrow e\nu$

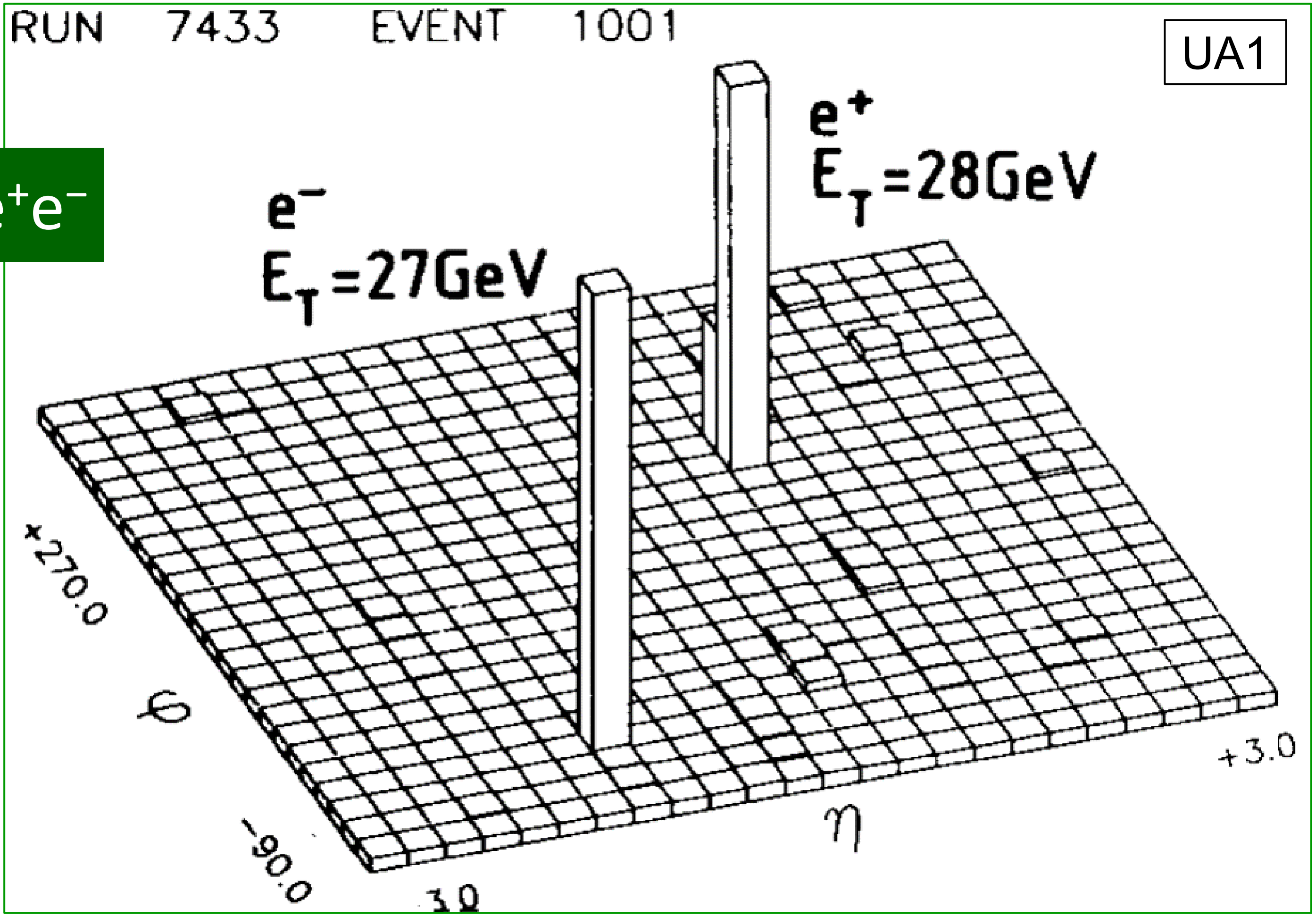
$W^{\pm} \rightarrow e\,\nu$



NB UA2 had a magnetic field only in the FB regions to measure $e^{\pm}$ asymmetry; in the central region, $e^{+} \leftrightarrow e^{-}$ were ambiguous.

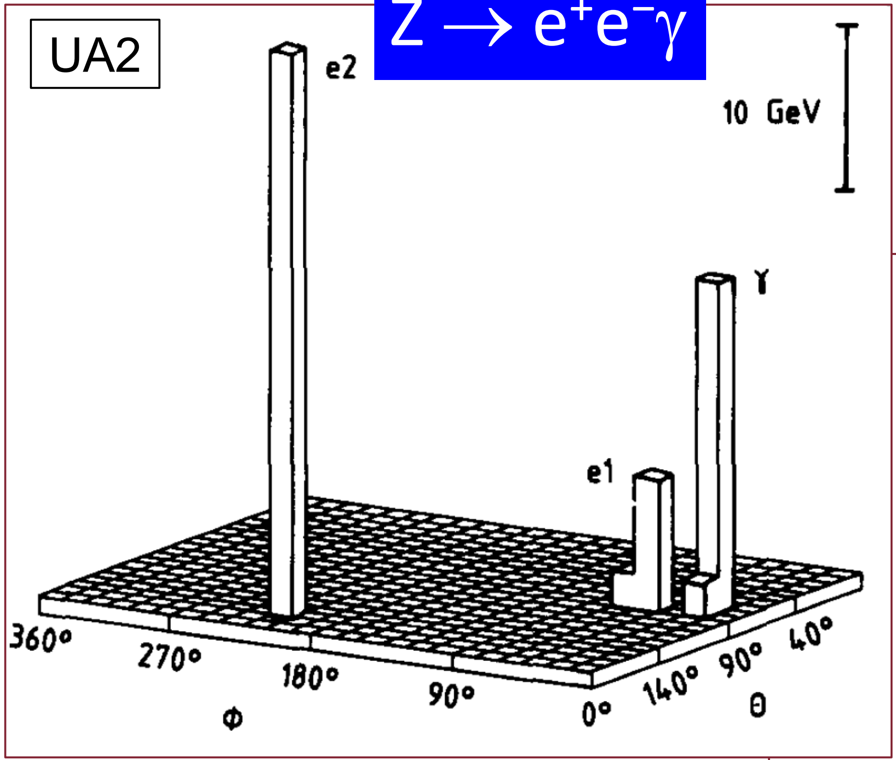
The events: UA1 $Z \to e^+e^-$

$Z \to e^+e^-$

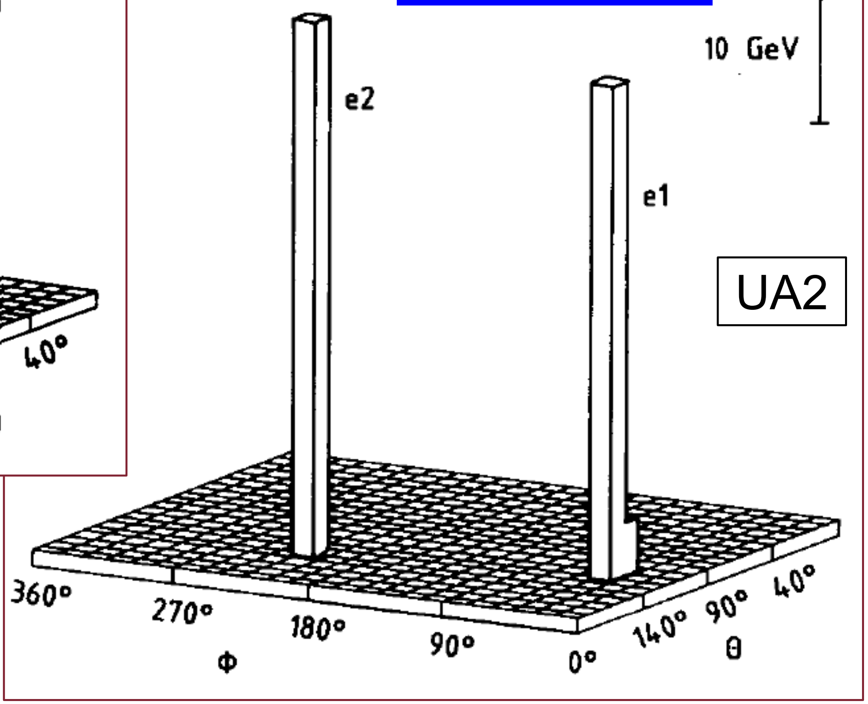


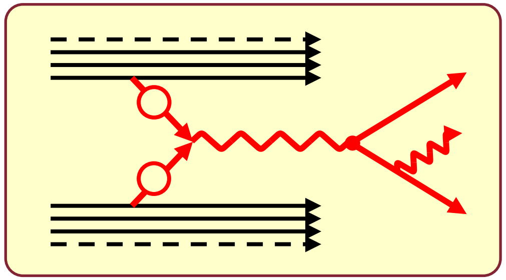
The events: UA2 $Z \rightarrow e^+e^-$

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



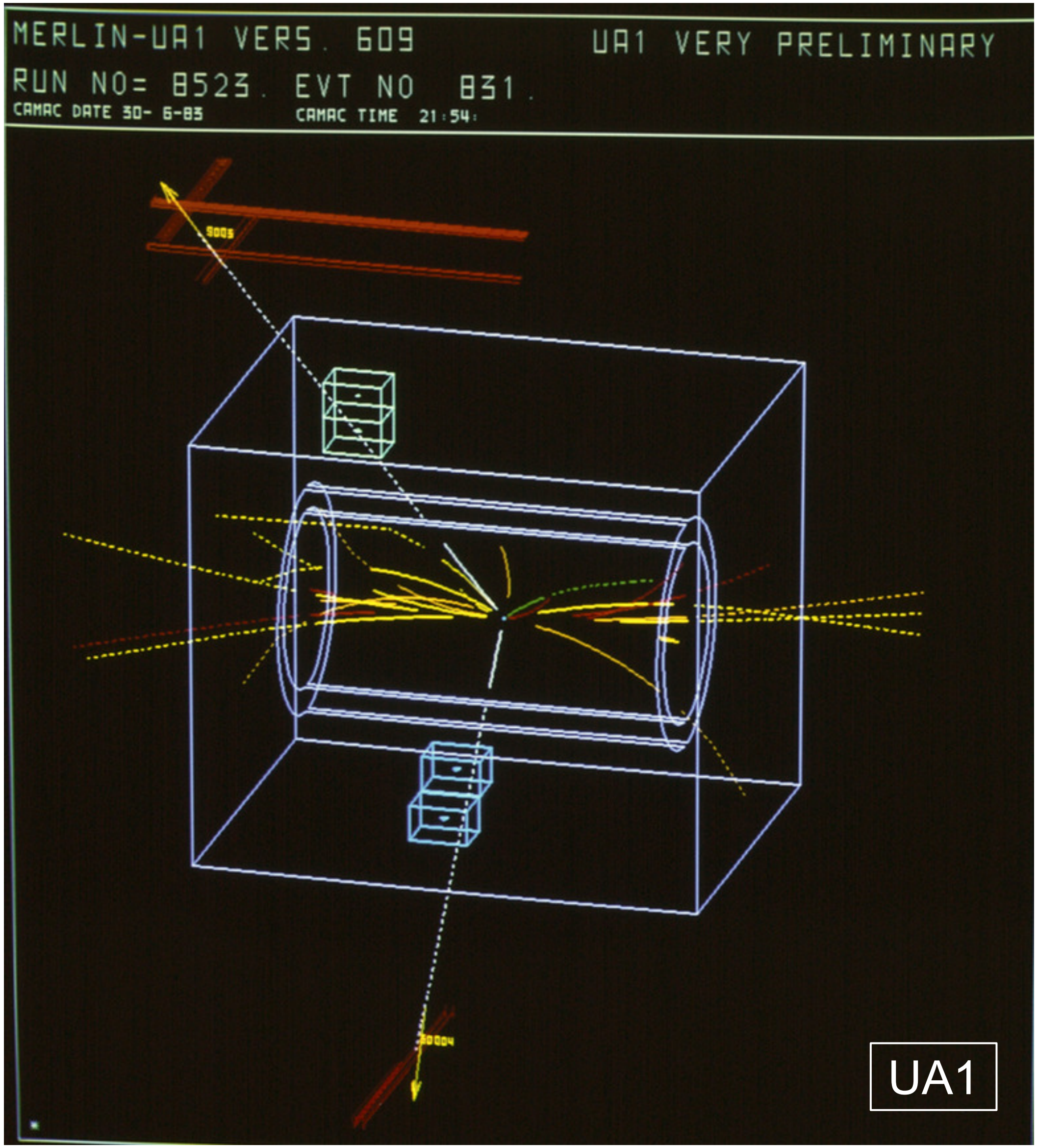
$Z \rightarrow e^+e^-$





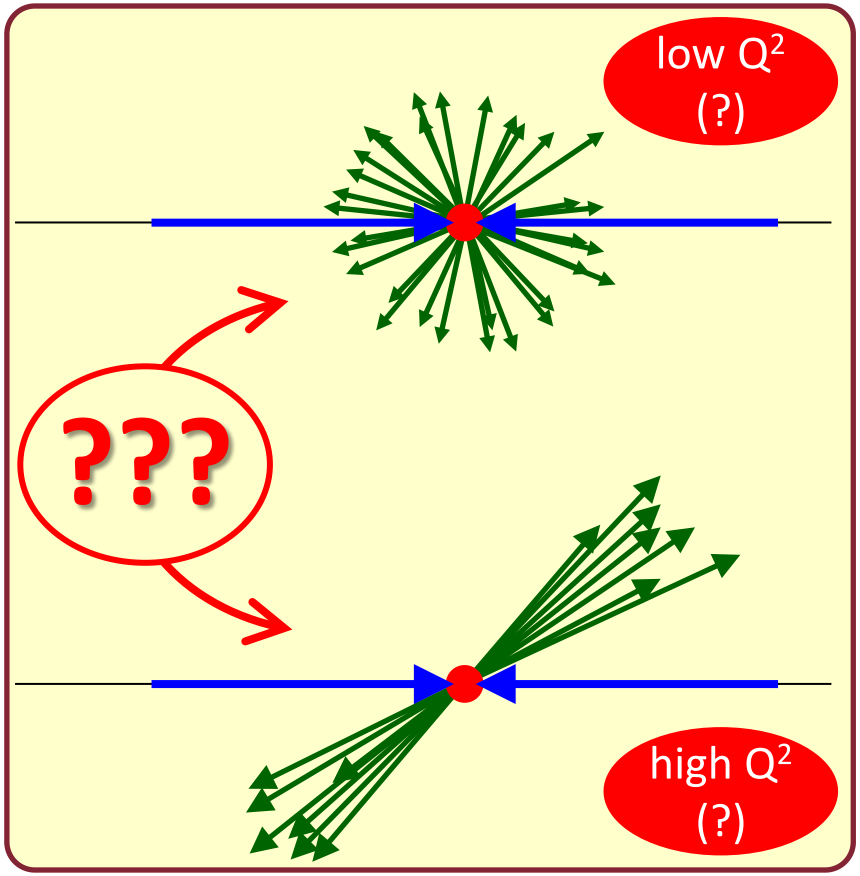
The events: UA1 $Z \rightarrow \mu^+\mu^-$

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



hadronic interactions

- At the time, the scheme of the quark-parton model (qpm) was established, but not shared by everybody .
- The expected signature of qpm is the "jettyness" of the hadronic events.
- If qpm and QCD hold, the expectation is a change of regime as a function of Q^2 :
  - at low Q^2, coherent $\bar{p}p$ collisions → final state hadrons spherically distributed;
  - at high Q^2, parton-parton collisions → two thin jets.
- Otherwise, expect all types of events at any Q^2, but most should be spherical.
- A difficult experimental challenge:
  - prove jettyness without a "trigger bias" (i.e. *"cherry-piking" the events*);
  - disentangle dynamics from kinematics (3-momentum conservation may simulate jettyness);
  - prove that the majority (?) of events at high Q^2 are "jet-like".



hadronic interactions: transition region

The solution :

- measure Q^2 independently from jets: define $\mathbf{\Sigma E_T}$ (total transverse energy, i.e. an unbiased (*) observable, in QCD $\propto \sqrt{Q^2}$) :

$$\Sigma E_T = \Sigma_k \, |E_T^{hadron-k}| = \Sigma_k \, E_k \, |\sin\theta_k|;$$

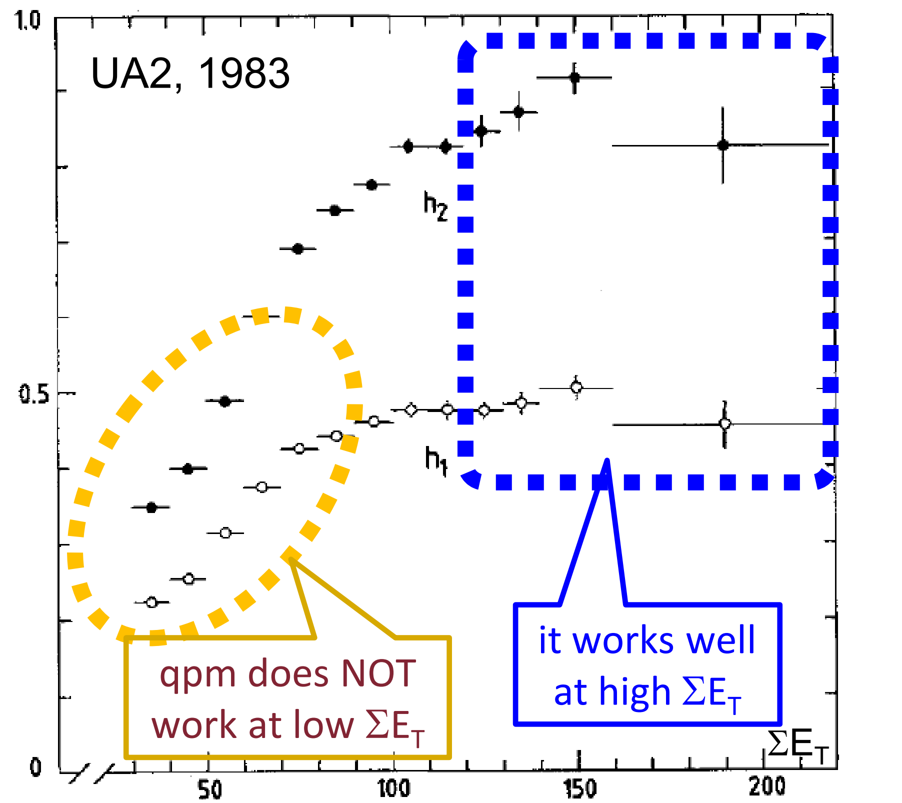
- identify the two highest jets of the events and their transverse energies E_T^1, E_T^2;
- plot, in bins of ΣE_T, the fractions :

$$h_1 = \langle E_T^1/\Sigma E_T \rangle;$$
$$h_2 = \langle (E_T^1 + E_T^2)/\Sigma E_T \rangle.$$

- In "ideal" qpm+QCD :
  - ➢ p̄p int. @ low Q^2 : both h_1,h_2 small;
  - ➢ qpm @ high Q^2 : $h_1 \approx 0.5$, $h_2 \approx 1$.

———————————————

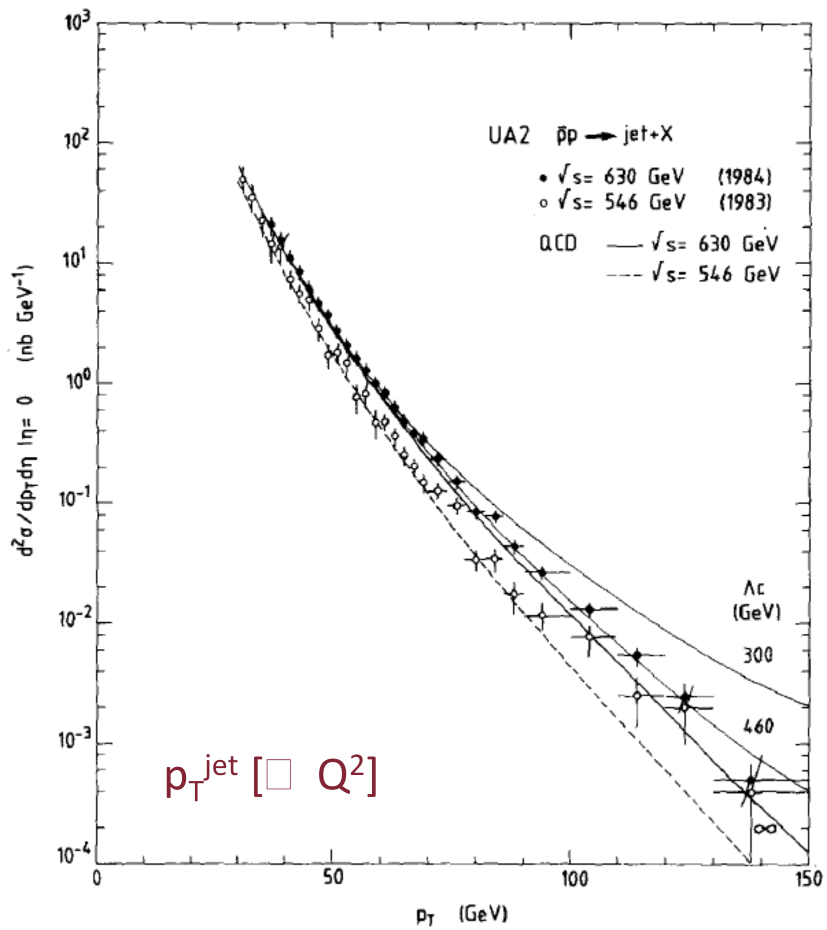
(*) events selected (triggered) by ΣE_T are unbiased respect to shape; moreover, if qpm holds, $\Sigma E_T \propto \sqrt{Q^2}$.

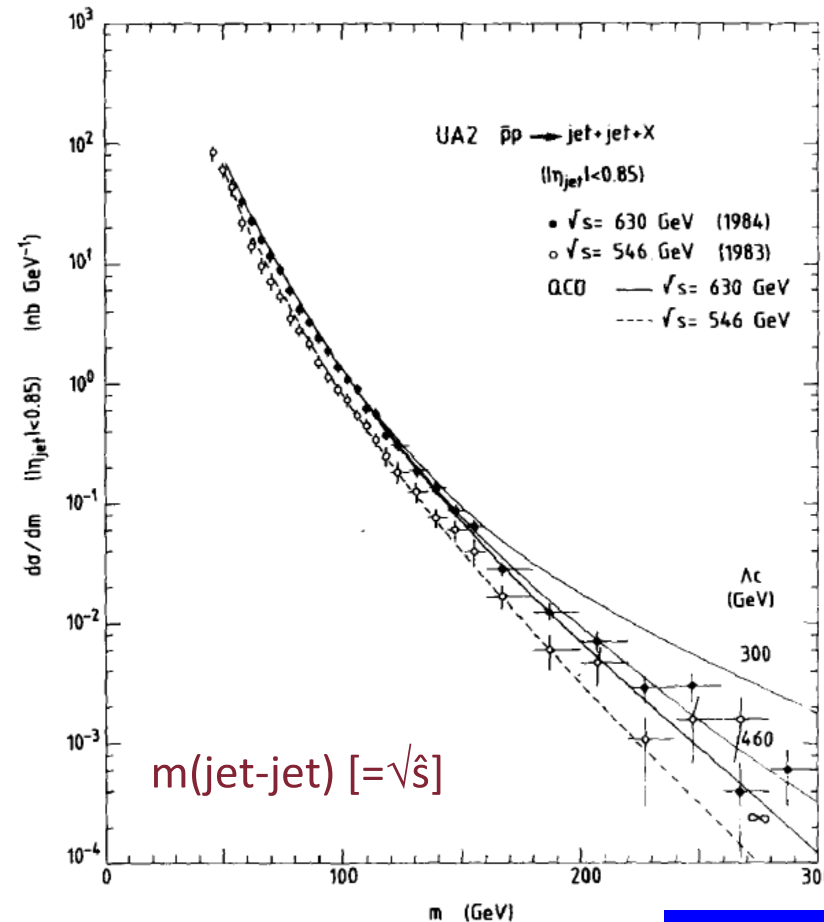


Success !!! As a function of ΣE_T , (i.e. $\sqrt{Q^2}$), the events change in the expected way; the qpm region is not precisely defined, but

$$\Sigma E_T > \sim 100 \text{ GeV } (\ell < \sim 10^{-18} \text{ m}).$$

hadronic interactions: $d^2\sigma/dp_T d\eta|_{\eta=0}$





Already discussed. Just notice :

- the increase as a function of √s;
- the comparison with pQCD;

- limit on $\Lambda \geq$ 370 GeV @ 95% CL (1/Λ hypothetical scale of a sub-structure : $(370\ \text{GeV})^{-1} \approx 5\times10^{-19}$ m.

for higher limits on Λ, see § LHC.

hadronic interactions: dσ/dcosθ

The ($\mathbb{L}$-invariant) angular variable χ:

$$\chi \equiv \frac{\hat{u}}{\hat{t}} = \frac{1+\cos\theta^*}{1-\cos\theta^*}; \;[\chi \text{ large} \leftrightarrow \theta \text{ small}]$$

The variable χ "flattens" the Rutherford angular cross-section, i.e. $d\sigma/d\cos\theta^* \propto \hat{t}^{-2} \propto (1 - \cos\theta^*)^{-2}$ $\rightarrow d\sigma/d\chi$ = const. [*box*].

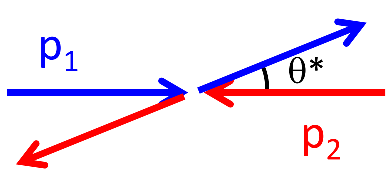
$$\frac{d\chi}{d\cos\theta^*} = \frac{1}{1-\cos\theta^*} + \frac{1+\cos\theta^*}{(1-\cos\theta^*)^2} = \frac{2}{(1-\cos\theta^*)^2};$$

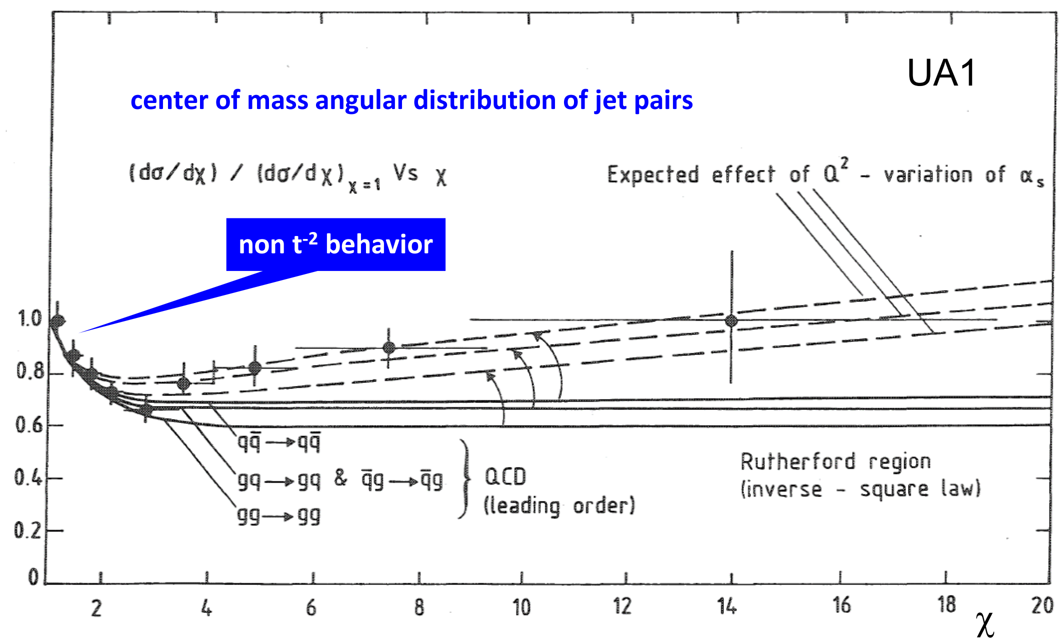
$$\frac{d\sigma_{\text{Rutherf.}}}{d\chi} = \left(\frac{d\sigma}{d\cos\theta^*}\right)\left|\frac{d\chi}{d\cos\theta^*}\right|^{-1} \propto \left(\frac{1}{\hat{t}^2}\right)\left|\frac{d\chi}{d\cos\theta^*}\right|^{-1} \propto$$

$$\propto \frac{1}{(1-\cos\theta^*)^2}(1-\cos\theta^*)^2 = \text{const.}$$

The data (UA1 1983, actually Bill Scott) show :

- $d\sigma/d\chi$ is remarkably "quasi flat";
- good agreement with pQCD: $d\sigma/d\chi$ not constant because of α_s running : χ large $\rightarrow$ θ small $\rightarrow$ Q^2 small $\rightarrow$ α_s larger $\rightarrow$ σ larger);
- in addition, non-$\hat{t}^{-2}$ processes at small χ (large θ).





The "Drell-Yan" process

- Drell and Yan in 1971 computed in qp model:

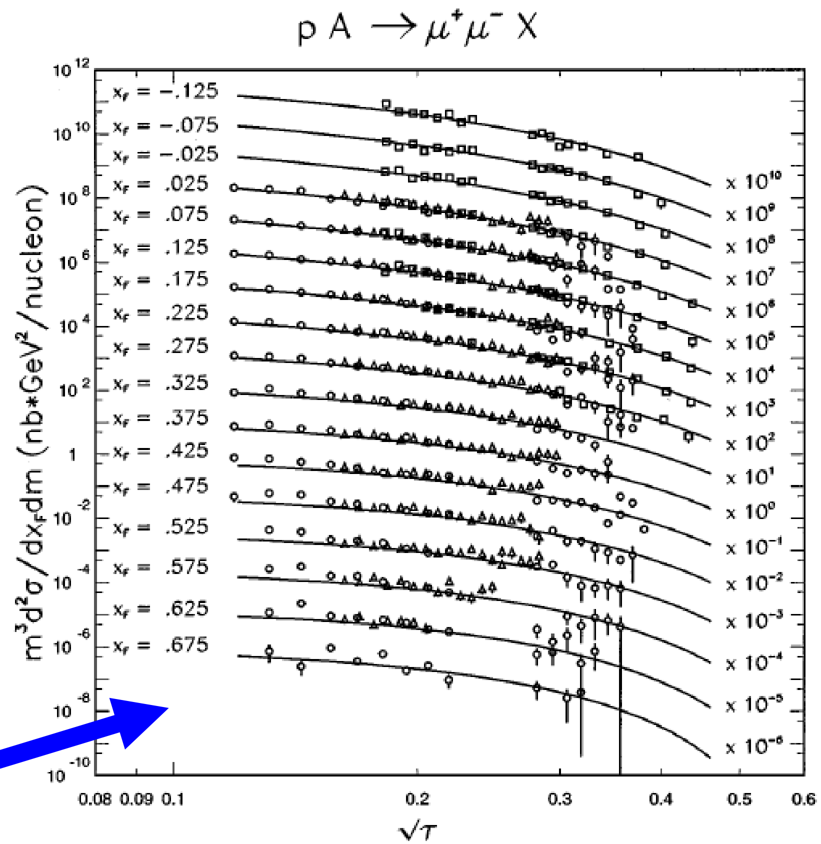
  $q\,\bar{q} \rightarrow \gamma^* \rightarrow \ell^+\ell^-, \quad \ell = e, \mu, \tau;$

- they found :

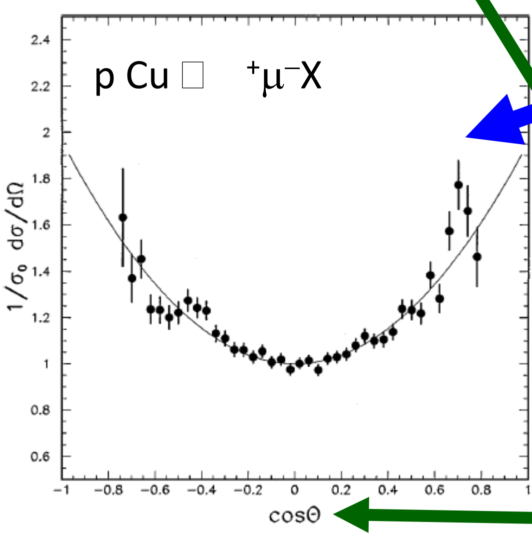
$$\frac{d^2\sigma}{dm_{12}^2 dx_F} = \frac{4\pi\alpha^2}{9m_{12}^2 s}\frac{1}{(x_1+x_2)} \times$$

$$\times \sum_i e_i^2 \left[q_i(x_1)\bar{q}_i(x_2) + \bar{q}_i(x_1) q_i(x_2) \right];$$

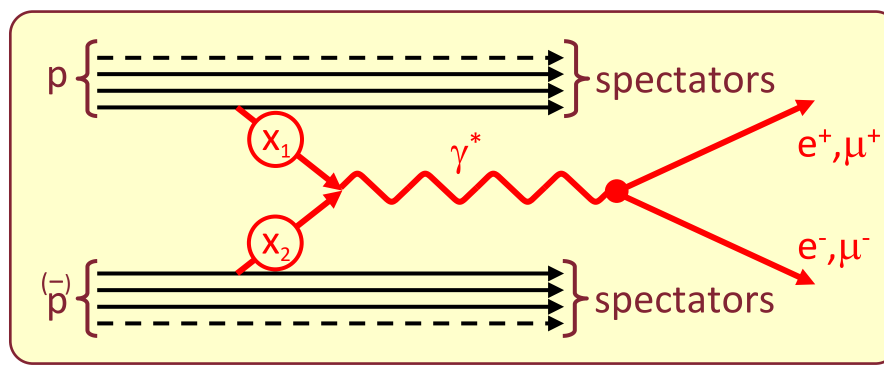
$$\frac{d\sigma}{d\Omega} = \sigma_0\left(1+\cos^2\theta\right); \quad x_F = x_1 - x_2; \quad \tau = m_{12}^2/s.$$



Ann.Rev.Nucl.Part.Sci. 49:217 (1999) [fixed-target exp.]



"θ" is the angle in the ℓ⁺ℓ⁻ frame, should be "θ*".



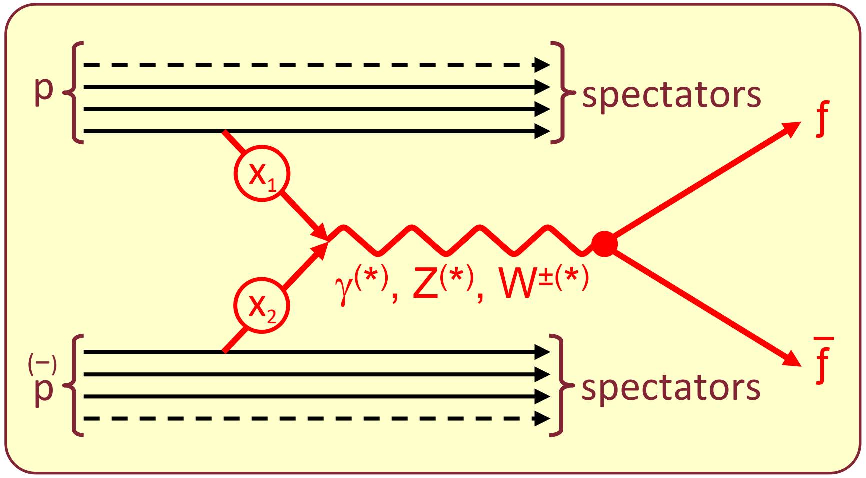
The "Drell-Yan" process: definition

- by extension, in hadronic interactions, the name "DY" was also used for processes with two leptons mediated by a (heavy) vector bosons :

  $d\bar{u} \to W^- \to \ell^-\bar{\nu}$, (+ any $q\bar{q}' \to$ leptons);

  $u\bar{u} \to Z \to \ell^-\ell^+$, $\square^-$, $q\bar{q}$ (+ ...);

- by a further extension, it is also used for all processes with a fermion-antifermion pair in the final state, mediated by an electro-weak vector boson, either real or virtual ($\gamma^{(*)}$, $Z^{(*)}$, $W^{\pm(*)}$), e.g. $d\bar{u} \to W^- \to q\bar{q}'$;
- i.e. "DY" = production of a $f\bar{f}$ pair in a hadronic interaction with an electro-weak spin-1 mediator in the s-channel;
- when the γ^* is replaced by another IVB, at parton level the electro-magnetic process has to be replaced by the appropriate electro-weak cross-section;
- a DY process is calculable with the usual [qpm + QCD/EW] scheme;
- computations of the DY processes were at the origin of the $Sp\bar{p}S$ proposal, and the main ingredient of the comparison data-theory;
- since then, this scheme has been technically improved without basic modifications.



$W^{\pm}$ discovery

On 25 January 1983 CERN announced the discovery of the W boson. Left to right: Carlo Rubbia, Simon van der Meer, Herwig Schopper, Erwin Gabathuler, Pierre Darriulat (Image: CERN)

W$^{\pm}$ discovery: UA1

$W^{\pm} \rightarrow e^{\pm}\nu$

Phys. Lett. 122B (1983)

Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

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

UA1 Collaboration, CERN, Geneva, Switzerland

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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

W± discovery: UA2

$W^\pm \to e^\pm \nu$

Phys. Lett 122B (1983)

Volume 122B, number 5,6 PHYSICS LETTERS 17 March 1983

OBSERVATION OF SINGLE ISOLATED ELECTRONS OF HIGH TRANSVERSE MOMENTUM IN EVENTS WITH MISSING TRANSVERSE ENERGY AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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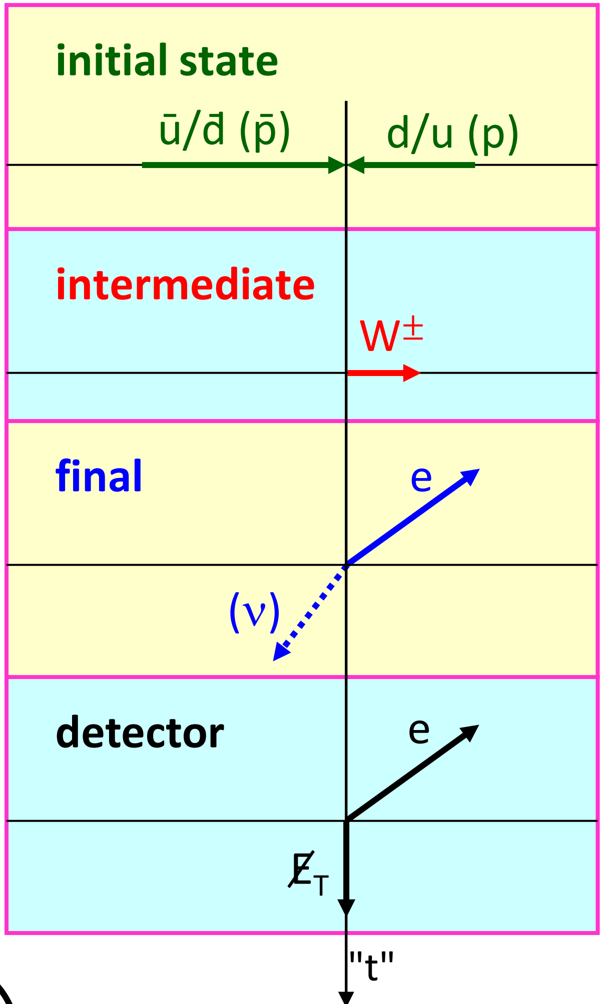
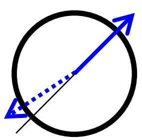
[f] *Centre d'Etudes nucléaires de Saclay, France*

$W^{\pm}$ discovery: method

- production (assume only valence) : $\bar{u}d \to W^- \to \ell^-\bar{\nu}$
  [the case ($u\bar{d} \to W^+ \to \ell^+\nu$) is similar, *mutatis mutandis*];
- ℓ = e/μ, study the "e" case (original discovery, μ similar);
- the hadronic decay modes are dominant (see **§ LEP**), but essentially invisible at the Sp$\bar{p}$S, but an attempt by UA2;
- qpm $\to p_T(W^{\pm}) \approx 0$; $p_z(W^{\pm})$ unknown and varying;
- ν not detected (but $\not{E}_T$);
- data selection :
  - trigger in E_T electromagnetic ($e^{\pm}$) : E_T > 8 GeV [UA2];
  - also possibly large $\not{E}_T$ ($\to p_T^{\nu}$);
  - … and a true $e^{\pm}$ (from its e.m. shower);
  - reconstruct p_T^e, p_T^{ν} (= $\not{E}_T$), $\to E_T^{tot}$, p_T^{tot};
  - compute : m_T ["transverse mass"] :
    $m_T^2 \equiv \left(E_T^{\ell} + E_T^{\nu}\right)^2 - \left(\vec{p}_T^{\,\ell} + \vec{p}_T^{\,\nu}\right)^2 \approx 2E_T^{\ell}E_T^{\nu}\left(1 - \cos\Delta\phi_{\ell\nu}\right)$;
- analysis :
  - select clean $W^{\pm}$ decays, i.e. high-p_T $e^{\pm}$ + $\not{E}_T$;
  - correlate $m_T \to m_W$, e.g. via montecarlo.



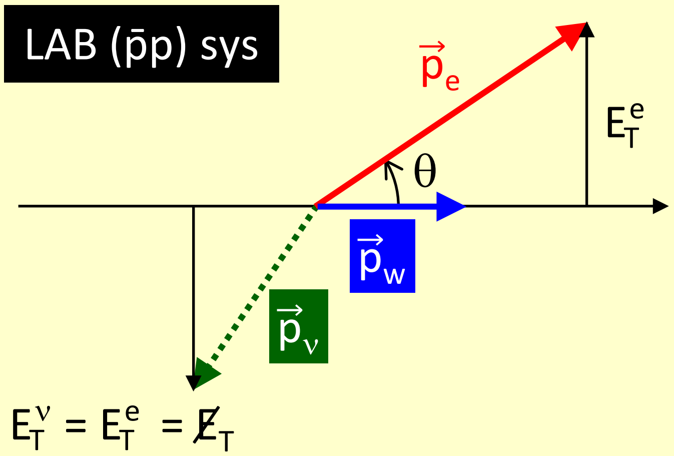
ideally $E_T^{\ell} = E_T^{\nu} \equiv E_T$,
□ =180°, $m_T = 2E_T$.



$W^{\pm}$ discovery: kinematics

Problem : in a $W \rightarrow e\nu$ event, only $\vec{p}_e$ and $\not{E}_T$ are detected. Is it possible to get $\vec{p}_W$ and $\vec{p}_\nu$?

[$\vec{p}_W$ necessary to boost $\theta \rightarrow \theta^*$, i.e. to test e.w. theory]



... but:

- Γ_W neglected $\rightarrow \Delta p_W^{sys}$;
- possibly : $\vec{p}_T^{\,W}$ = "$\not{E}_T$(2D)" – $\vec{p}_T^{\,e}$ (but large error from spectators).

$$W: \quad \left(\sqrt{m_W^2 + p_W^2}, \qquad p_W, \qquad 0\right);$$

because of q.p.m.

$$e: \quad (k, \qquad k\cos\theta, \qquad k\sin\theta);$$

e almost massless

$$\nu: \quad \left(\sqrt{m_W^2 + p_W^2} - k, \quad p_W - k\cos\theta, \quad -k\sin\theta\right);$$

measured: $k, \theta, \not{E}_T$;

unknowns: m_W, p_W;

check: $\not{E}_T \left[\approx E_T^\nu \approx E_T^e\right] \approx k\sin\theta$ [+ planarity];

$$m_\nu^2 \approx 0 \rightarrow \left(\sqrt{m_W^2 + p_W^2} - k\right)^2 = \left(p_W - k\cos\theta\right)^2 + k^2\sin^2\theta;$$

$\rightarrow$ one equation, two unknowns $\rightarrow$ no solution.

But, if m_W known: e.g. from the jacobian [next slide]

$$m_W^2 + p_W^2 + k^2 - 2k\sqrt{m_W^2 + p_W^2} = p_W^2 + k^2 - 2p_W k\cos\theta;$$

$$\left(2k\sqrt{m_W^2 + p_W^2}\right)^2 = \left(m_W^2 + 2p_W k\cos\theta\right)^2;$$

$$4\boxed{p_W^2}\,k^2\left(1 - \cos^2\theta\right) - 4\boxed{p_W}\,k m_W^2\cos\theta + 4k^2 m_W^2 - m_W^4 = 0;$$

$\rightarrow$ two solutions for $\boxed{p_W}$ and for $\boxed{\vec{p}_\nu}$.

$W^\pm$ discovery: the jacobian peak

- m_W from the "jacobian peak" ["*" = W c.m.] :

$$p_T^e{}^* = p_T^e = p^e{}^*\sin\theta^* = \tfrac{1}{2} m_w \sin\theta^*;$$

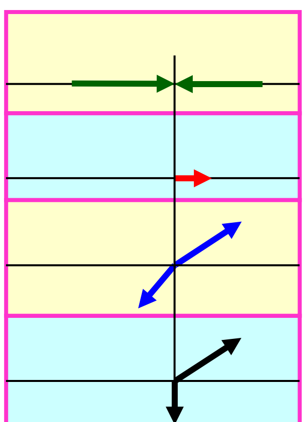
$$\cos\theta^* = \sqrt{1-\left(2p_T^e/m_w\right)^2} = \sqrt{m_w^2-4\left(p_T^e\right)^2}\,/m_w;$$

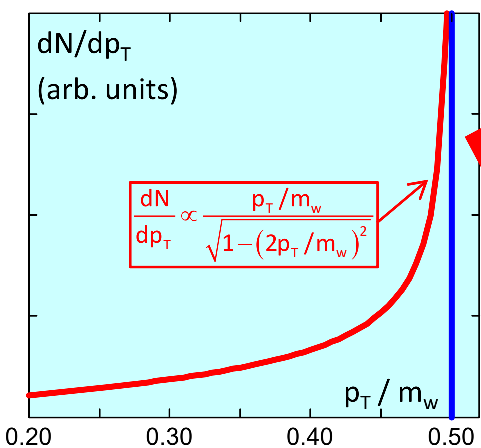
$$dN/dp_T^e = \left(dN/d\cos\theta^*\right)\times\left|d\cos\theta^*/dp_T^e\right| \propto$$

$$\propto \left(1+\cos\theta^*\right)^2\times\frac{4p_T^e}{m_w}\times\frac{1}{\sqrt{m_w^2-4\left(p_T^e\right)^2}}.$$

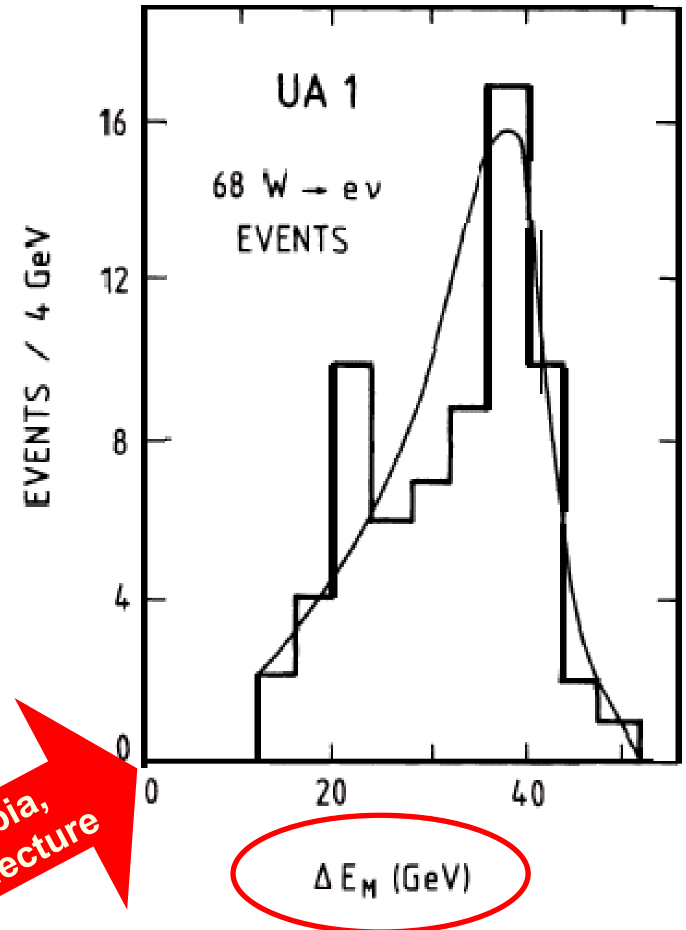
= $f(p_T^e, m_W)$ smooth, no-peak

- therefore the "jacobian" $|d\cos\theta^*/dp_T^e|$ produces a sharp peak at $p_T^e \approx m_W/2$, modulated by $\Gamma_W \oplus$ (detector).



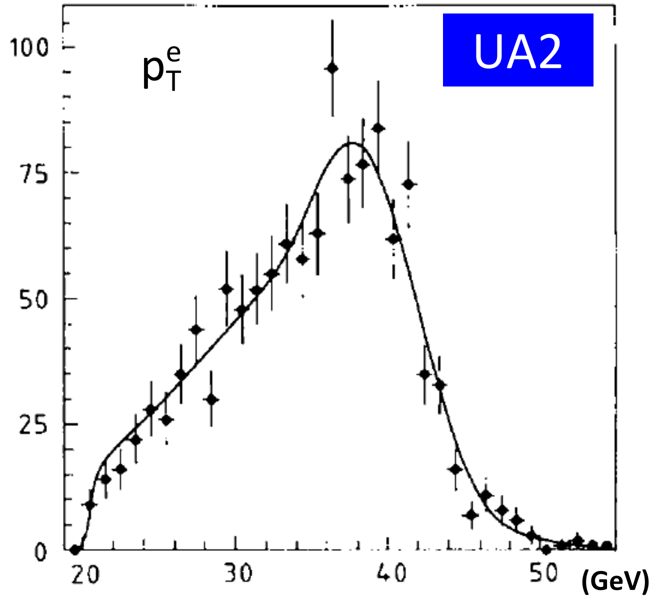


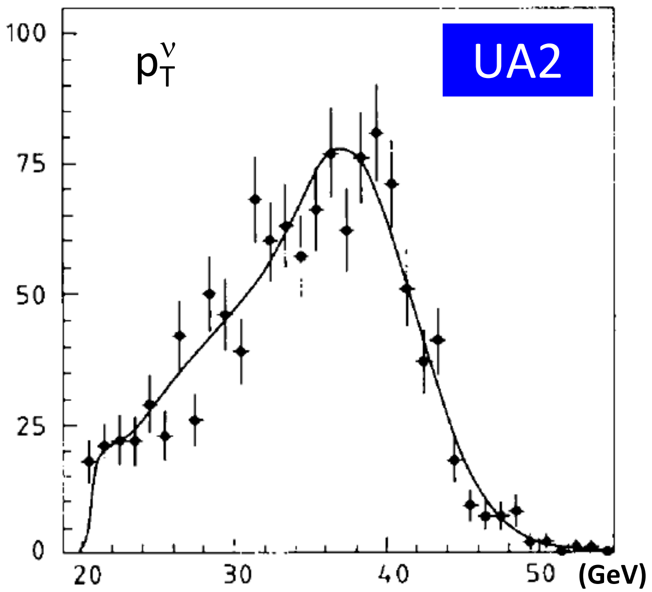
C.Rubbia, Nobel lecture



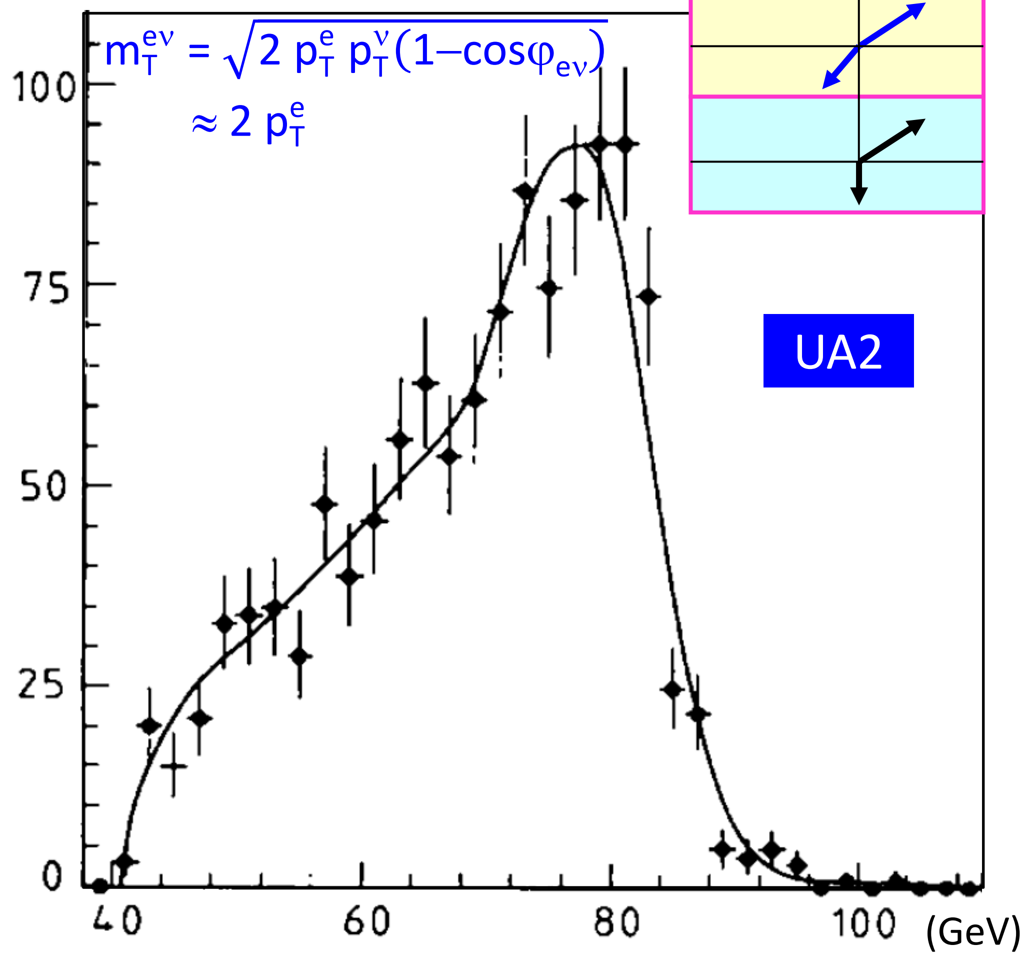
technicality : the plot shows "ΔE_M" $\equiv \not{E}_T \approx E_T^\nu$, which follows exactly the same kinematics as p_T^e.

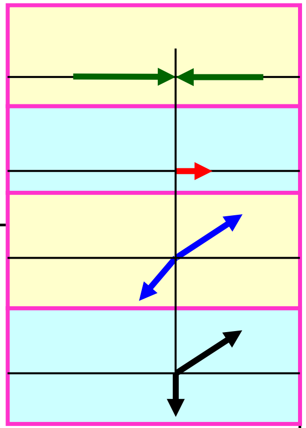
$W^{\pm}$ discovery: the jacobian peak



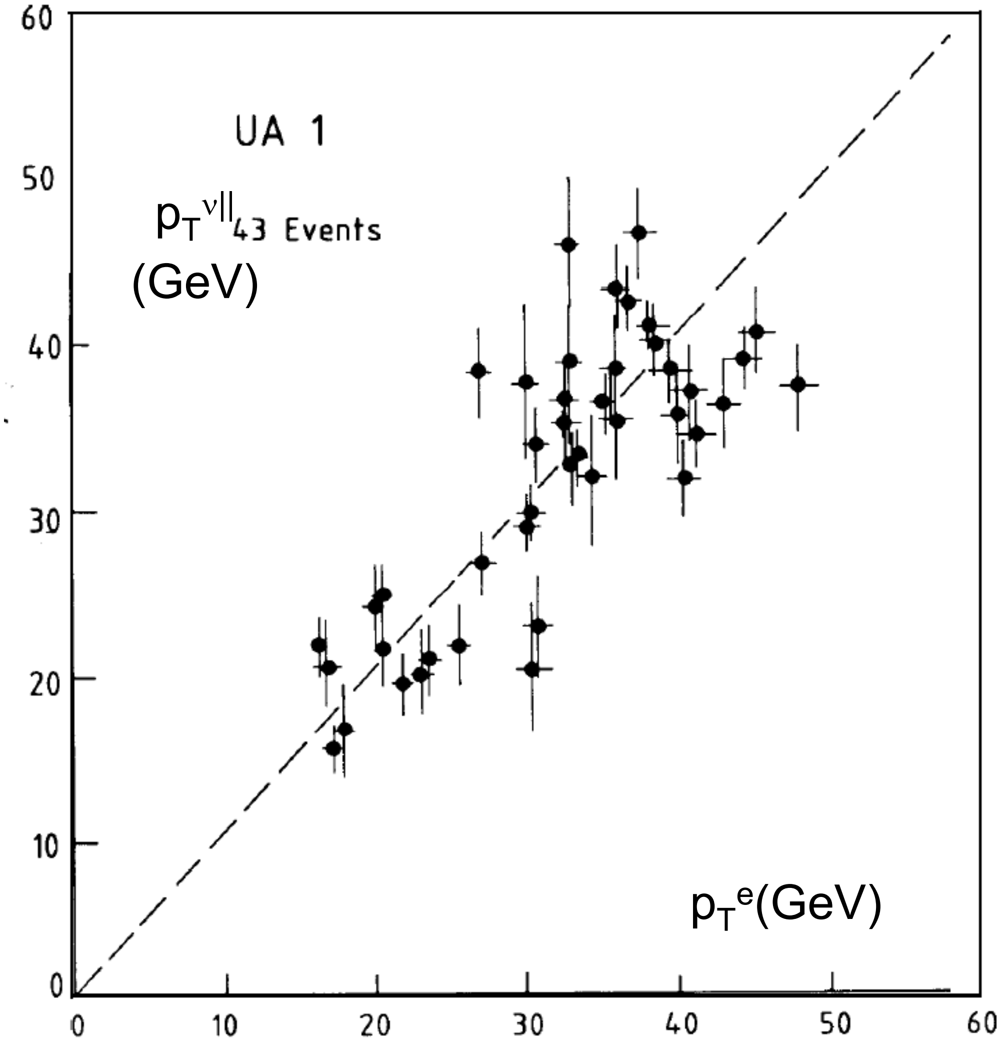


after many years of data-taking, with the full $\mathcal{L}_{int}$.





$W^{\pm}$ discovery : p_T vs $\not{E}_T$



Results (see § LEP) :

UA1 pre-LEP :

m_W = 82.7 ± 1.0 (stat) ± 2.7(syst) GeV;

Γ_W < 5.4 GeV;

UA2 pre-LEP :

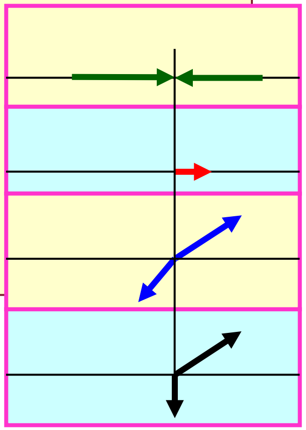
m_W = 80.2 ± 0.8 (stat) ± 1.3(syst) GeV;

Γ_W < 7 GeV;

[PDG 2020] :

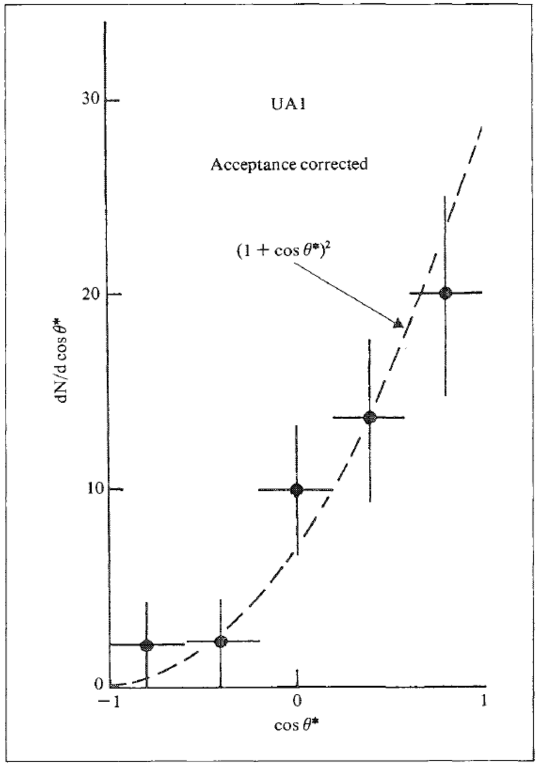
m_W = 80.379 ± .012 GeV;

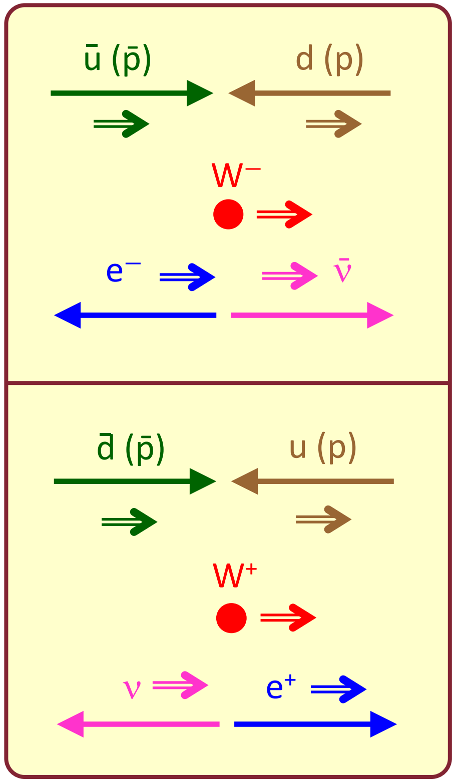
Γ_W = 2.085 ± .042 GeV;



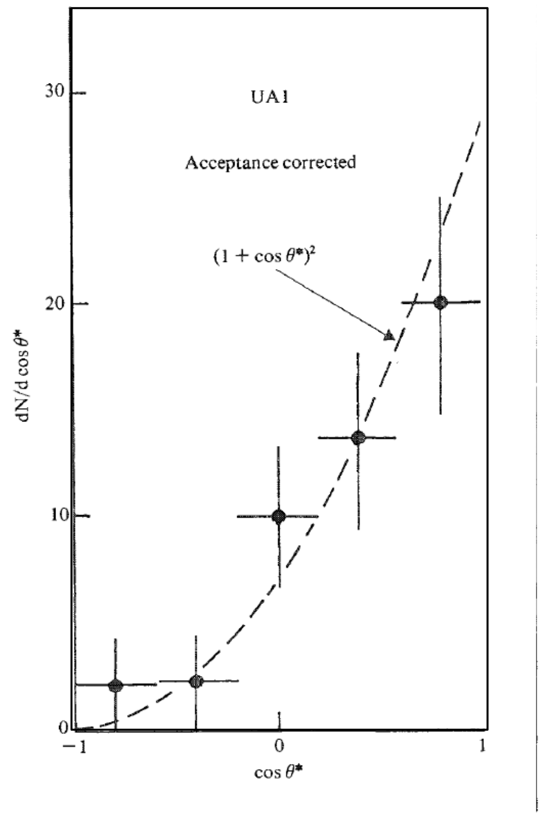
$W^\pm$ discovery : asymmetry

- Assume that the main process be valence-valence. The large values of the $W^\pm$ mass makes all the other masses negligible. Thus the particles have –ve helicity and the antiparticles +ve helicity.
- Then, the (V–A) structure of the CC favor the collinearity (e^-p), ($e^+\bar{p}$), i.e. $\cos\theta^* \approx 1$.
- As in many similar processes, $d\sigma/d\cos\theta^* \propto (1+\cos\theta^*)^2$.
- The process is a simple and powerful test of the theory …
- *… does it discriminate between* **V / A / (V–A) / (V+A)** *?* *[think and answer]*





$W^{\pm}$ discovery: asymmetry results



- As important as the pure discovery [*less media impact, of course*].
- This beautiful effect is only evident at the Sp$\bar{p}$S [$m_w^2 = sx_1x_2$ → increasing $\sqrt{s}$, the value of $x_{1,2}$ decreases, and therefore sea-quarks become dominant].
- [*probably one of the few advantages in hadronic colliders for a low value of* $\sqrt{s}$].
- At LHC, the initial state is pp, completely symmetric, so the effect is completely absent. The W^+ yield is more abundant, especially at large x, where the valence quarks are dominant [*do not confuse difference in initial state with parity violation*].
- At LHC, cross-section larger → more precise m_w, Γ_w measurements.
- A method to increase the asymmetry at high $\sqrt{s}$ is the selection of "low-p_T" $W^{\pm}$ ($q\bar{q} \to W^{\pm}$), with respect to "high p_T" $W^{\pm}$ (qg, $\bar{q}g \to W^{\pm}$ jet).

Z discovery: UA1

$Z \to e^+e^-$

Phys. Lett 126B (1983)

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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Z discovery: UA2

$Z \to e^+e^-$

Phys. Lett. 129B (1983)

Volume 129, number 1,2 PHYSICS LETTERS 15 September 1983

EVIDENCE FOR $Z^0 \to e^+e^-$ AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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Z discovery: mass computation

- production ūu (đd) → Z → $\ell^+\ell^-$;
- both selection and analysis easier than in the $W^\pm$ case [despite smaller cross-section] :
  - ➢ require two well identified, opposite-charge, same-flavor leptons;
  - ➢ use fake eμ to study bckgd [*NOT existent, NO bckgd, the easiest search ever*];
- compute :

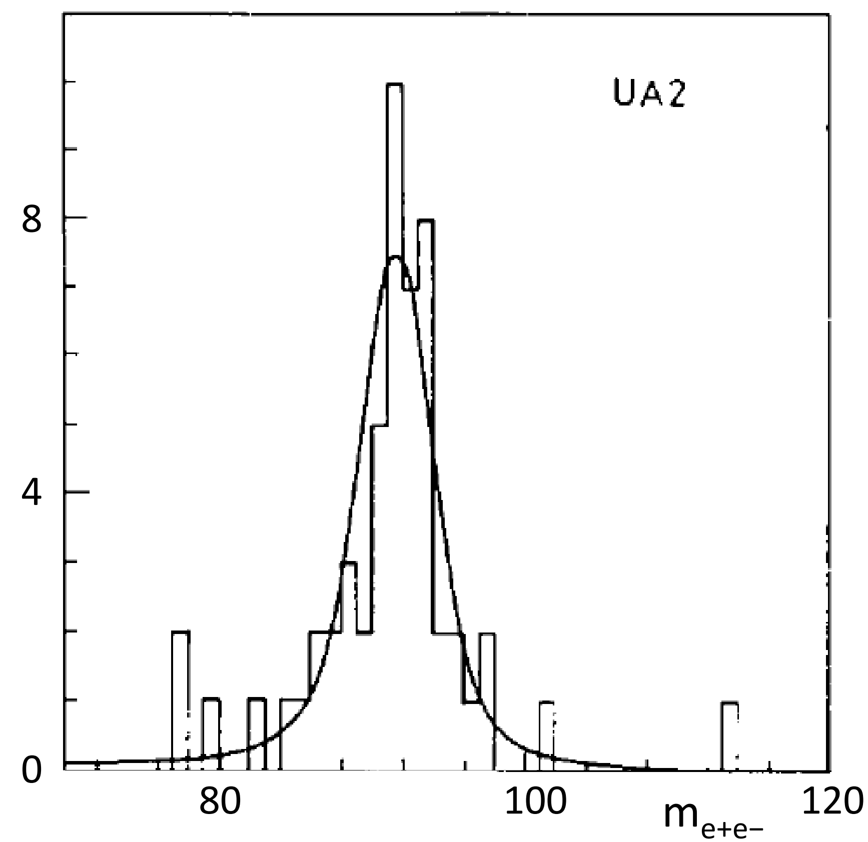
$$m(\ell^+\ell^-) \approx \sqrt{2E_+E_-(1-\cos\alpha)} = 2\sqrt{E_+E_-}\sin(\alpha/2);$$

$$\frac{\partial m}{\partial E_\pm} = \frac{m}{2E_\pm}; \qquad \frac{\partial m}{\partial \alpha} = \frac{m}{2\tan(\alpha/2)};$$

$$\left(\frac{\Delta m}{m}\right)^2 = \frac{1}{4}\left[\left(\frac{\Delta E_+}{E_+}\right)^2 + \left(\frac{\Delta E_-}{E_-}\right)^2 + \left(\frac{\Delta\alpha}{\tan(\alpha/2)}\right)^2\right];$$

$$\left\{E_+ \approx E_- \approx \frac{m}{2}; \alpha \approx 180°\right\} \rightarrow \frac{\Delta m}{m} \approx \frac{1}{\sqrt{2}}\frac{\Delta E}{E}$$

$$\rightarrow \Delta m \approx \sqrt{2}\Delta E \approx 1 \div 2 \text{ GeV}.$$



- no approx. → typically Δm ≈ 2 GeV for a single event.

$\Delta m_{exp} \sim \Gamma_{TOT}$

Z discovery: results

[interpretation and comparison with SM in § LEP]

Results :

UA1 :

m_z = 93.1 ± 1.0 (stat) ± 3.0(syst) GeV;

Γ_z = 2.7 $^{+1.2}_{-1.0}$ (stat) ± 1.3 (syst) GeV;

UA2 :

m_z = 91.74 ± .28 (stat) ± .93(syst) GeV;

Γ_z = 2.7 ± 2.0 (stat) ± 1.0 (sys) GeV;

[PDG 1995-2020, i.e. LEP] :

m_z = 91.1876 ± .0021 GeV;

Γ_z = 2.4952 ± .0023 GeV.

Comparison with SM :
- m_w/m_z;
- sin θ_w;
- SM checks;
- SM predictions (e.g. top mass);
- "bSM" physics.

the e^+e^- machine improves by >100 in m_z and >1000 in Γ_z !

... but the discovery was in $\bar{p}p$ (!!!)

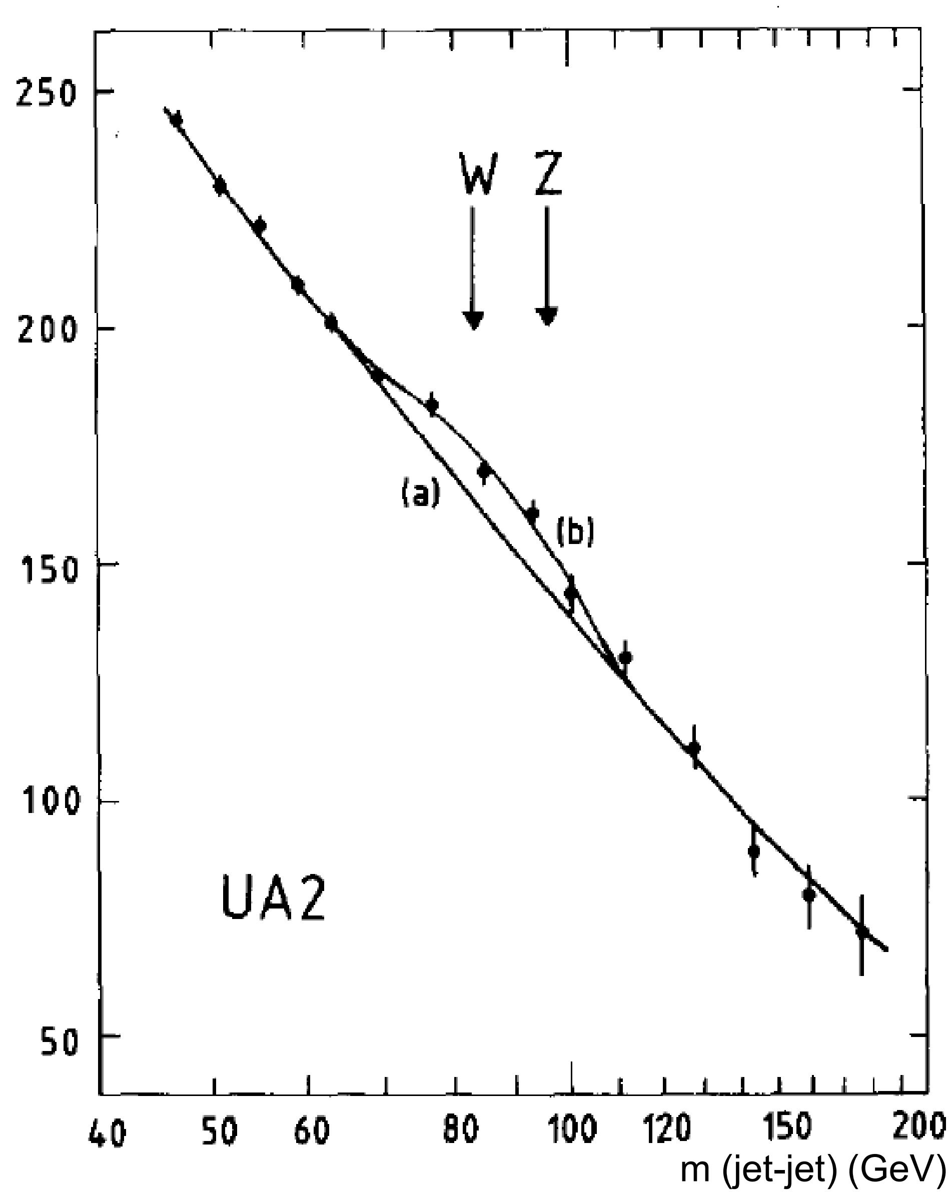
W± / Z properties: decay → q$\bar{q}$' / q$\bar{q}$

- The dominant decays of W/Z are into quark pairs :

  $W^+ \to u\bar{d}$ (, $\to c\bar{s}$);

  $W^- \to \bar{u}d$ (, $\to \bar{c}s$);

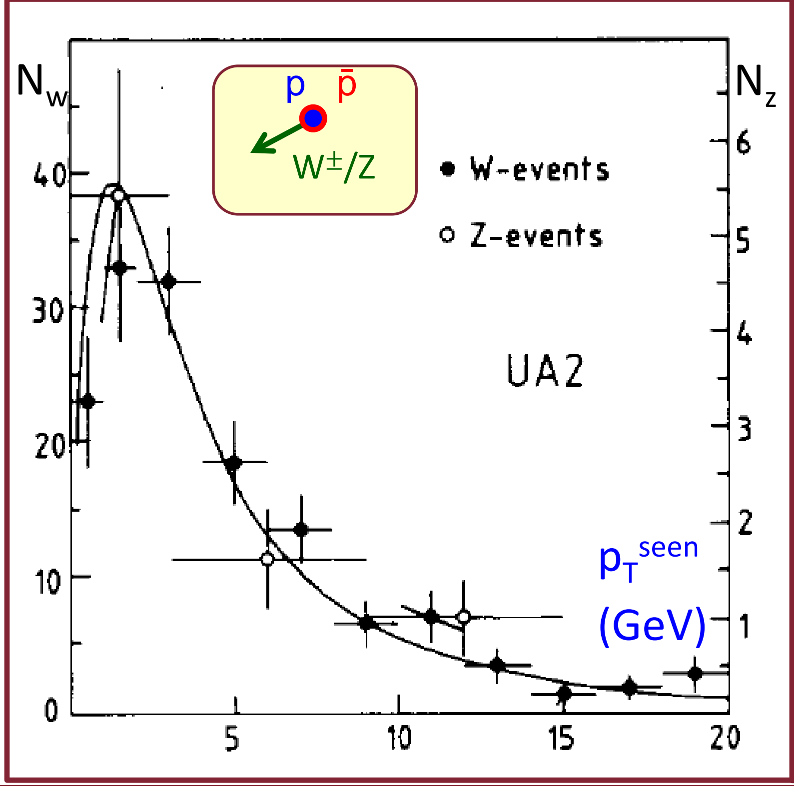
  $Z \to u\bar{u}, \to d\bar{d}$ (, $\to s\bar{s}$, …)
- but they are overwhelmed by the dominant QCD two-jet processes;
- the only analysis [*to my knowledge*] to select them by UA2, shown here;
- the first attempt of "jet spectroscopy", important as a method, but still quite rudimental in 1986.

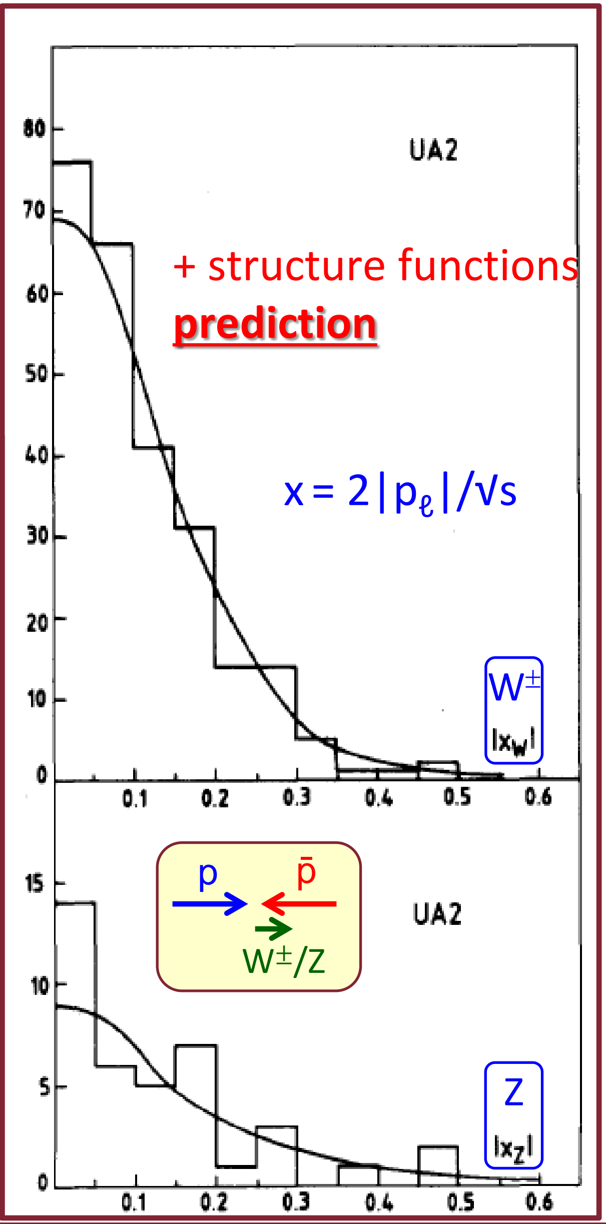


$W^{\pm}$ / Z properties: SM checks

Check the qpm with $W^{\pm}$ and Z :

- NOT a joke : if unsuccessful, serious breakdown both of the theory and the experimental method;
- x : the same variable as in structure functions and qpm;
  - the qpm **predicts** the x distribution, both for W and Z;
  - **ok**.
- p_T : the transverse momentum :
  - in qpm, NOT predicted (≈ 0);
  - expected to be "small";
  - heavily affected by detector;
  - "prediction" is a mixture of theory and exp.
  - **ok**.





References

1. all textbooks, e.g. [BJ 14], [Perkins 7-8], …
2. $Sp\bar{p}S$: Phys. Rep. 403 (2004) 91;
3. Drell-Yan : Ann. Rev. Nucl. Part. Sci. 49:217 (1999);
4. UA2 ΣE_T analysis : Phys. Lett. B165 (1985).
5. UA1 jets : Phys. Lett. B177 (1986) 244.
6. UA2 jets : Phys. Lett. B118 (1982) 203, Phys. Lett. B160 (1985) 349.
7. UA1 W,Z : C.Rubbia, Nobel Lecture 1984.
8. UA2 W,Z : Phys. Lett. B241 (1990) 150.
9. UA2 W,Z $\rightarrow q\bar{q}$: Phys. Lett B186 (1987) 452.

NB original papers are quoted everywhere; these are reviews – usually easier to understand.

AA antiproton production target

The first version of the antiproton production target was a tungsten rod, 11 cm long (actually a row of 11 rods, each 1 cm long) and 3 mm in diameter. The rod was embedded in graphite, pressure-seated into an outer casing made of stainless steel. The casing had fins for forced-air cooling. In this picture, the 26 GeV high-intensity beam from the PS enters from the right, where a scintillator screen, with circles every 5 mm in radius, permits precise aim at the target centre.

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End of chapter 2