Hadron collider physics: a historical perspective

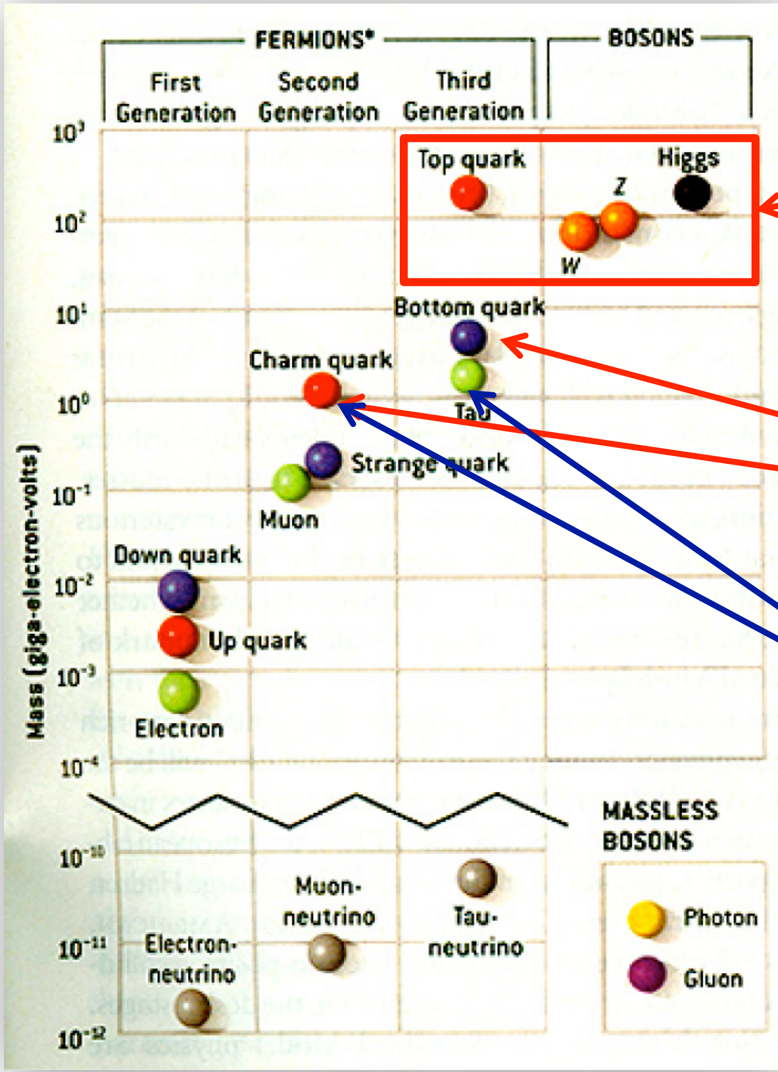
Paris Sphicas
CERN & NKUA (Athens)
Univ. Of Geneva, April 18, 2018

- **The first one: ISR**
  - **And some missed discoveries**
- **A matter-antimatter (p-pbar) collider, part I: SPS**
  - **EWK theory (unification!)**
- **A proton-antiproton collider, part II: Tevatron**
  - **Top quark & EWK & B physics in hadron collisions**
- **Towards the Higgs boson: pp collider(s)**
  - **From the SSC to the LHC – to the Higgs boson**
- **Outlook**

What hadron colliders have done for the Standard Model of Particle Physics

Not even an introduction…

The Standard Model and hadron collisions



Hadron Colliders
W/Z: UA1/UA2 @ SPS
Top: CDF/D0 @ Tevatron
H: ATLAS/CMS @ LHC

Hadron Collisions
b quark: E288 @ FNAL
c quark: pBe @ AGS

ee Collider
c and τ SPEAR

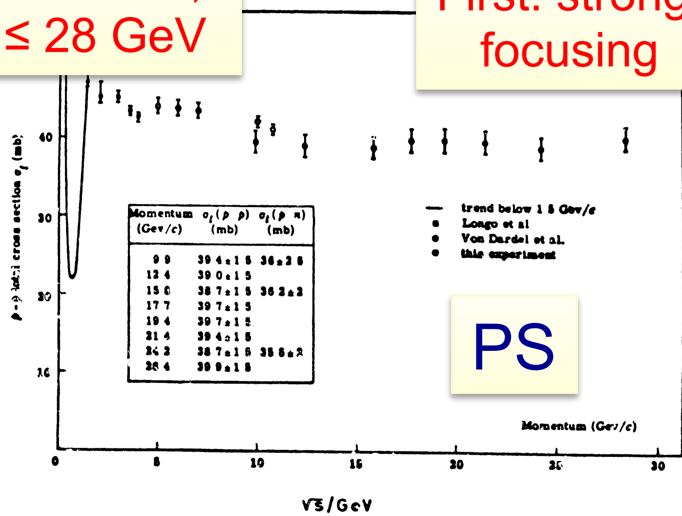
Not shown: probing the strong, weak and EM interactions

The beginning: AGS and ISR; Two + one lessons

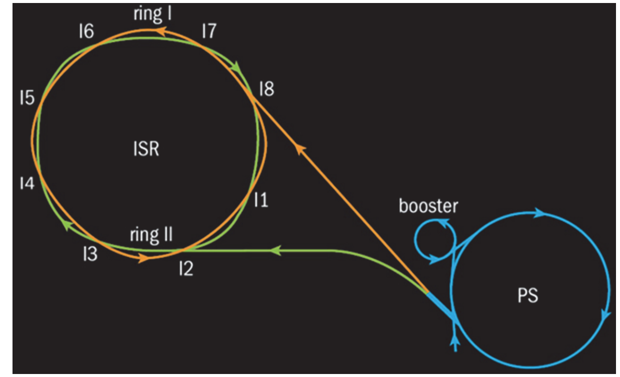
ISR discovery: rising pp and ppbar σ

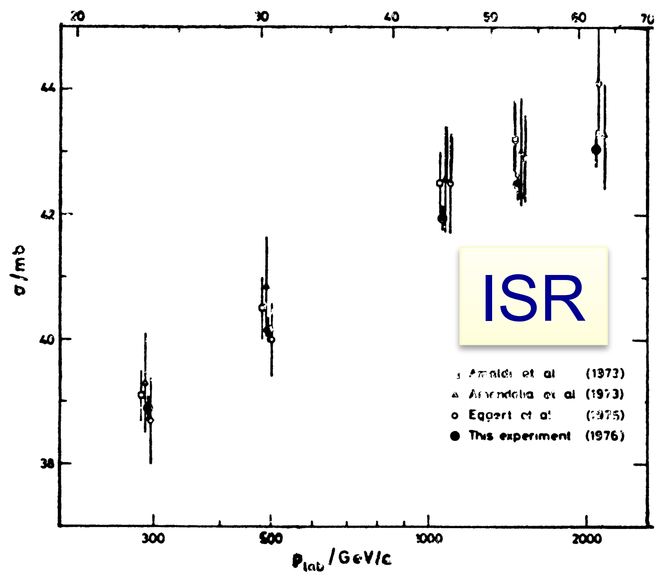
Synchrotron, √s ≤ 28 GeV

First: strong focusing



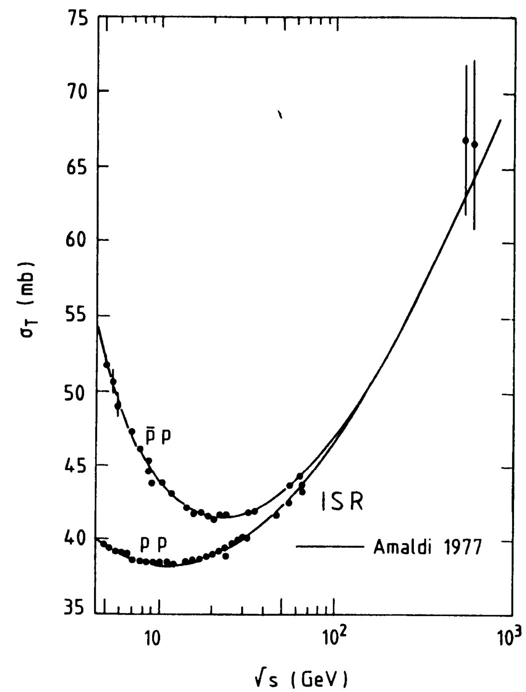
PS





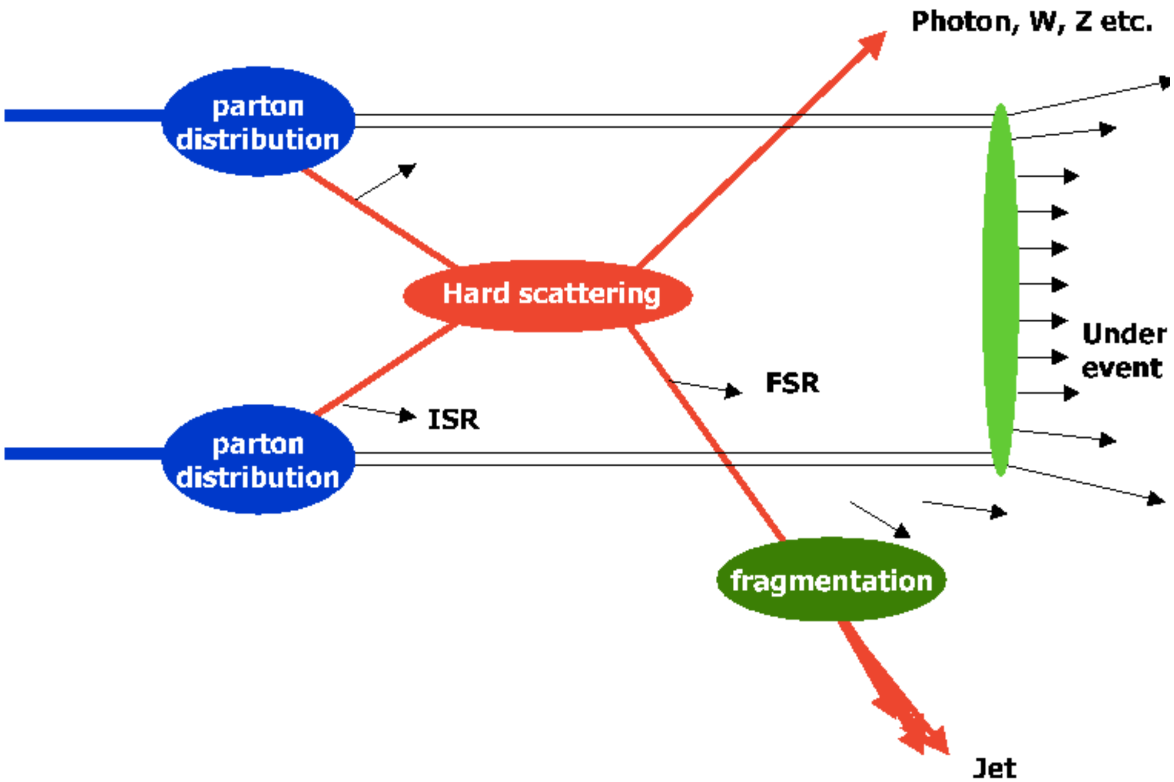
√2mE vs 2E…

ISR



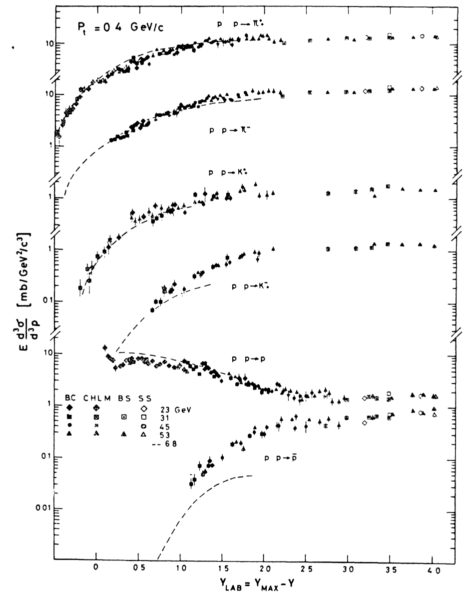
pp collisions :== parton-parton collisions

20-60 GeV pp collisions



Colliding watches

- Late 60's:
  - Parton model: infant stage
  - Successful in spectroscopy+ weak decays
  - Bjorken scaling + SLAC–MIT experiment
  - Question: is it applicable to hadron collisions?



Feynman scaling & rapidity plateau

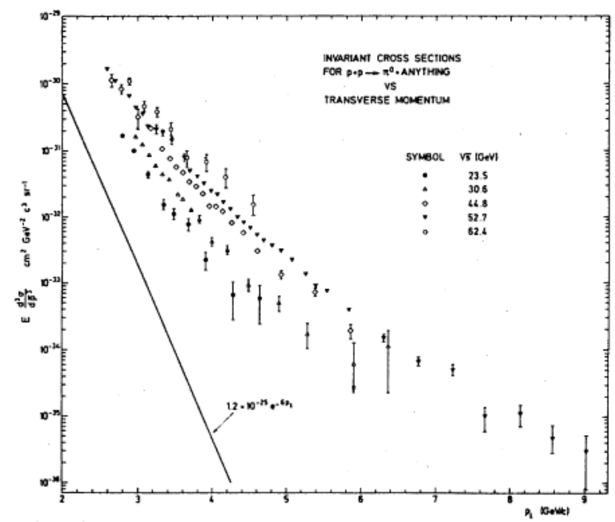
- CCR: inclusive particle spectra → excess @ large P_T. Expected vs seen:

CIM

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

points:

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{s^2}f(x_T,\cos\theta) = \frac{1}{P_T^{\,4}}g(x_T,\cos\theta)$$



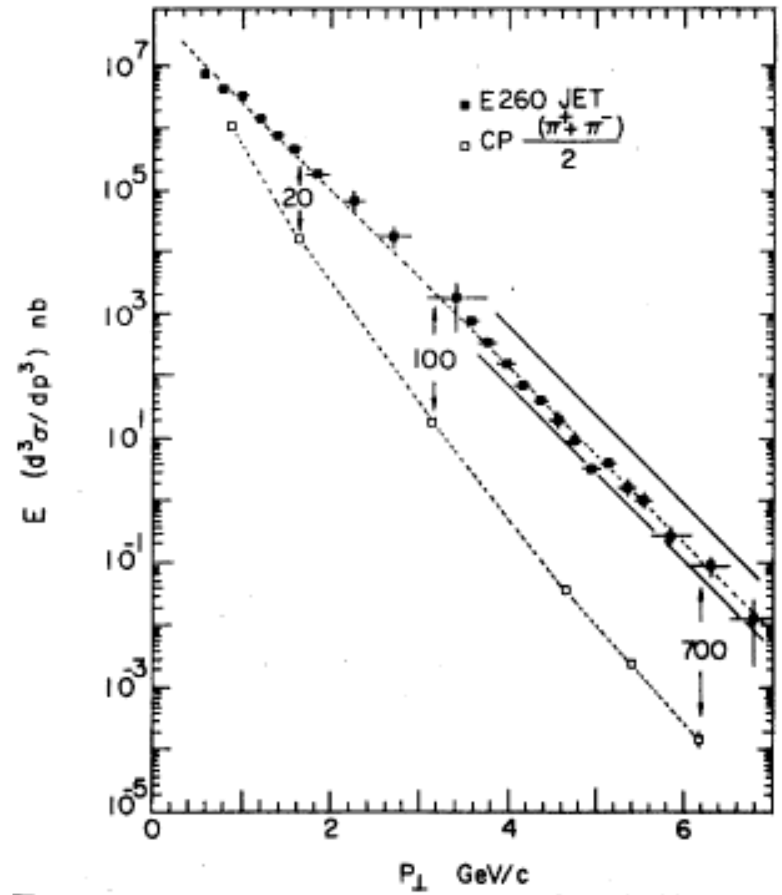
“Jets” were missing…

- **Killed by the trigger:**

  ISR: triggering on single particles, not global E_T

  1) Absence of CALO triggers (small E → bad CALO response)

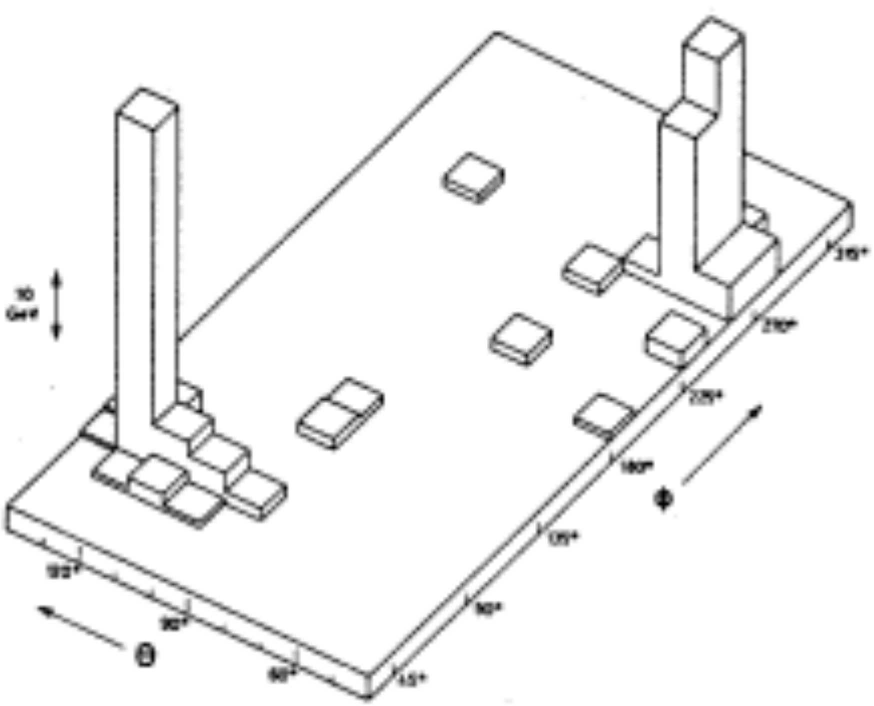
  2) Jet spectrum: much steeper P_T spectrum than fragmentation → particle of given P_T most likely the leading particle of a soft jet...

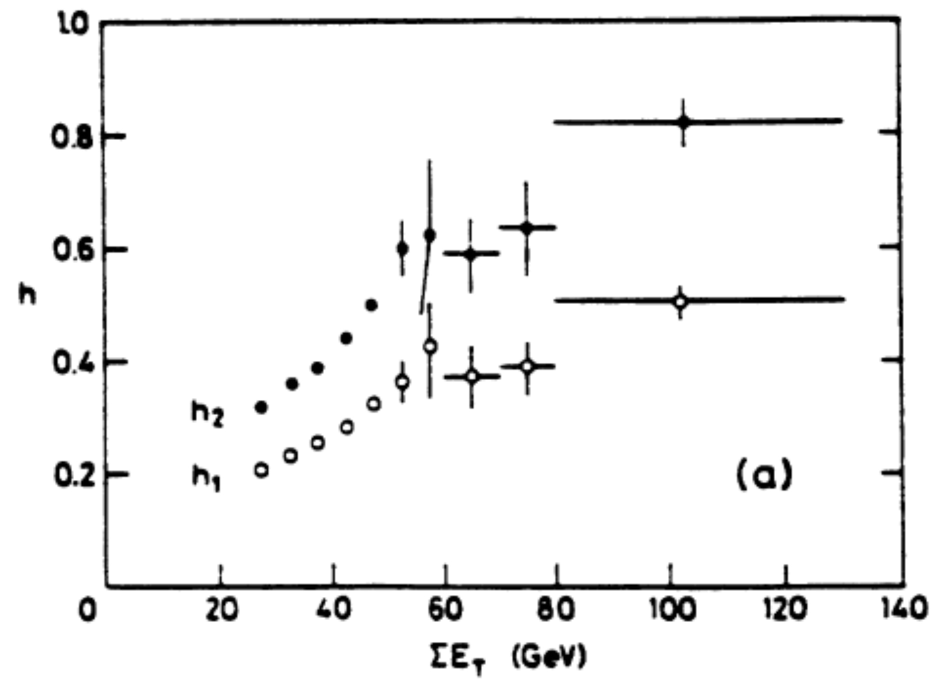


Lesson #1: triggering a risky and complicated activity; use inclusive triggers, e.g. based on the calorimeter!

The jets were there – but at the SPS…

- **UA2 experiment; "Paris conference" 1982**



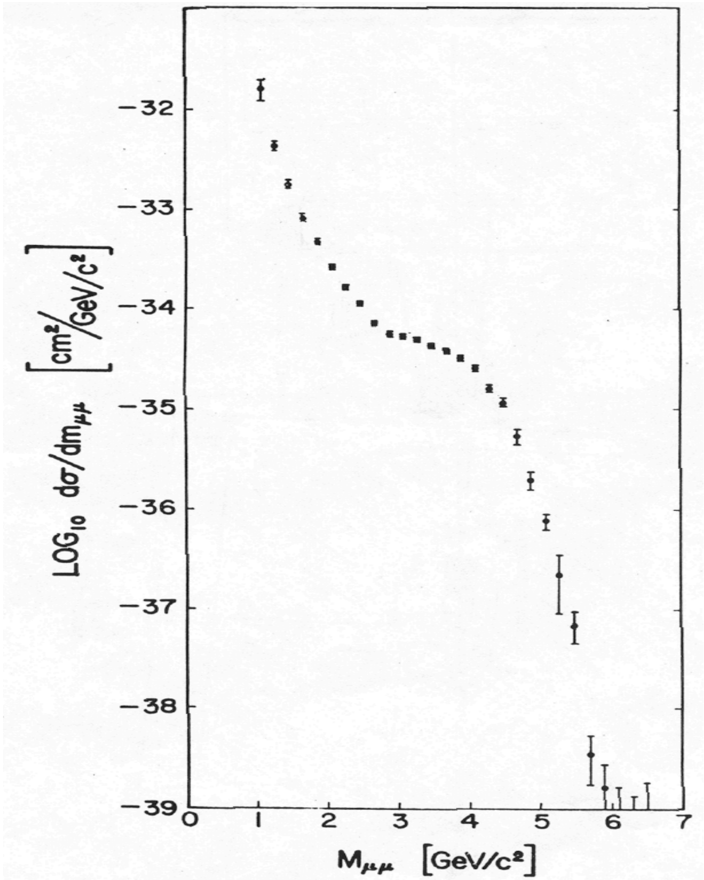


Discoveries missed: (well, AGS…) the J/ψ

- **From Leon Lederman's autobiography at FNAL:**
  http://history.fnal.gov/autobiography.html

  "In 1961 he worked under M. Schwartz and J. Steinberger on neutrinos. He was in charge of finding neutral currents. Schwartz was in charge of finding Lederman."

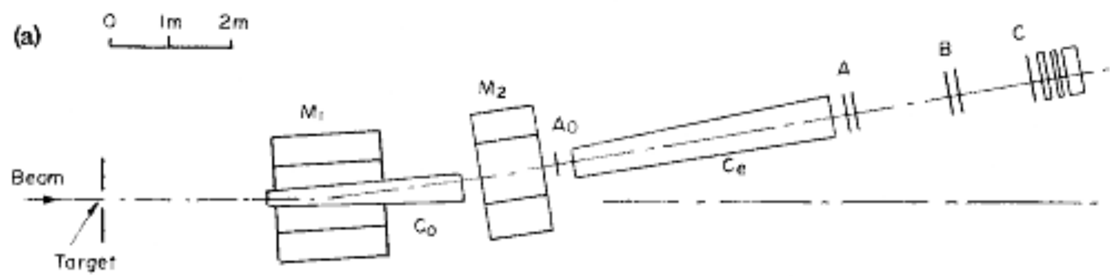
  "In 1968 he invented the di-muon experiment and missed the J/Psi particle."



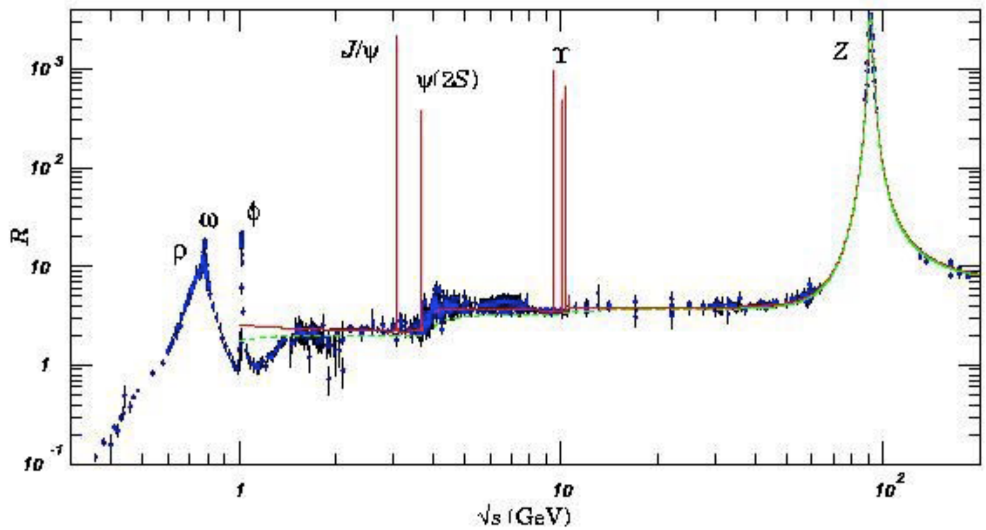
Lesson #2: (for colliders – ISR) central coverage! (for all) resolution ever so important!

Discoveries made: the J/ψ

- **Brookhaven AGS: p + Be → $e^+ e^-$ X**



- **SPEAR at SLAC:**



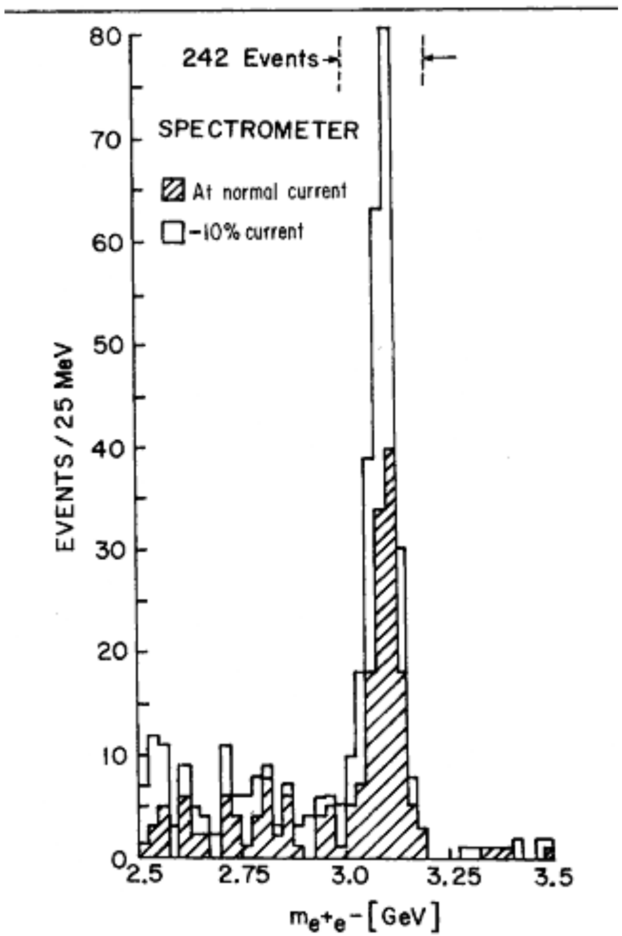
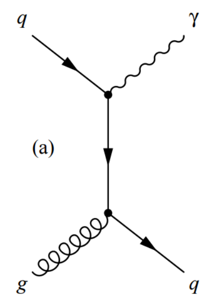
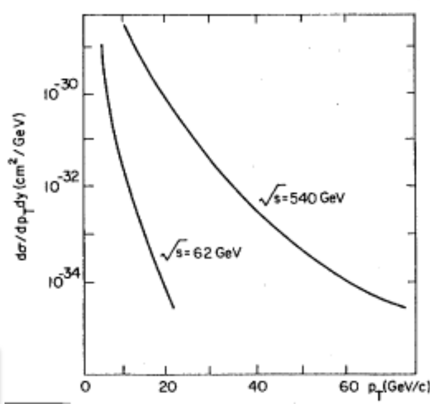


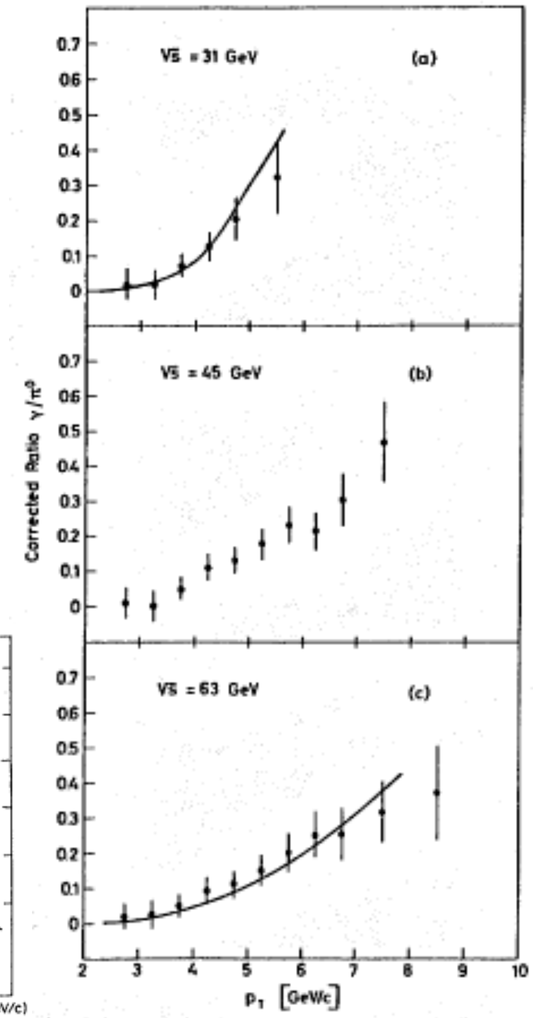
FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

Evidence for the gluon (well…) SPS plans

- **Prompt photons seen:**
  - ABCS: unambiguous rise of γ/π^0 ratio
  - Highly non-trivial (experimentally) exercise:
    - Huge background from $\pi^0 \rightarrow \gamma\gamma$…
- **In QCD picture: q+g → q + γ**
- **Yet, so indirect… (π^0)…**







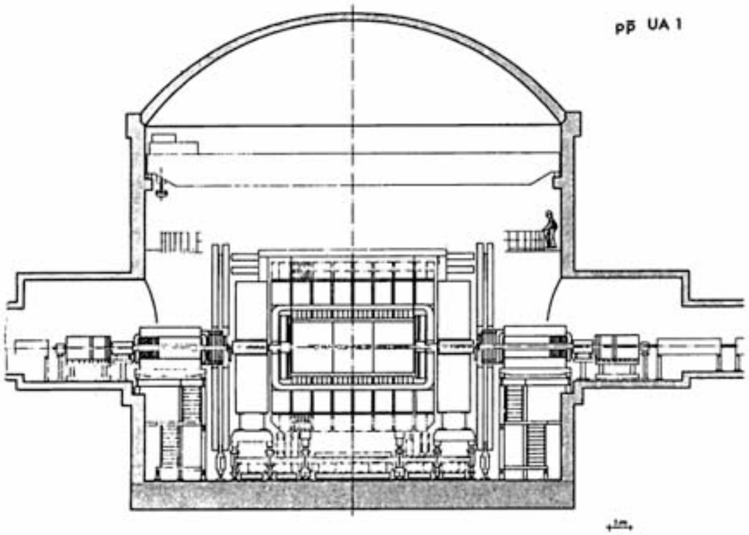
Meanwhile: SPS was in the works…
Lesson #3: energy helps…

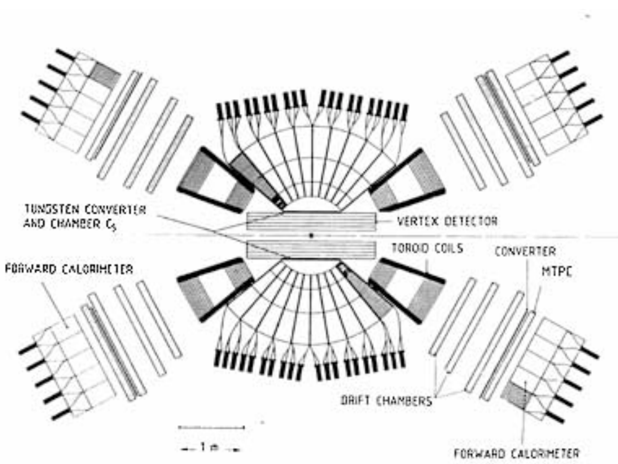
Important result to mention: <1 particle in 10^{10} has fractional charge

The SppS experiments: UA1 and UA2 and the glorious 80's

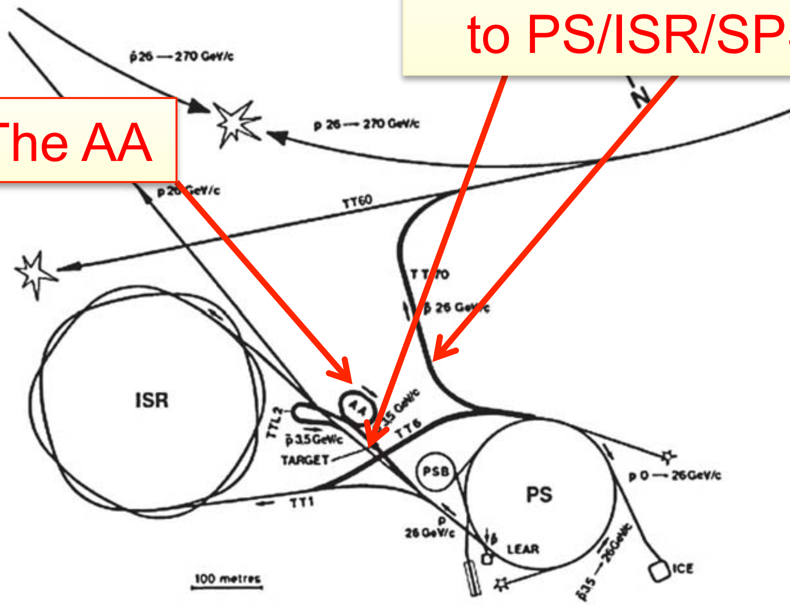
UA1 (and UA2)

- **At the time, they were huge, very, very risky undertakings**
  - **To begin with, the collider had to bring in protons and ANTI-protons to collide (cross section for W/Z production in pp was too small)**
  - **Second, and above all, the result was predicted to be a MESS**
  - **Third, they had to draw from the lessons learned!**





The SPS and the magic of p-pbar collisions



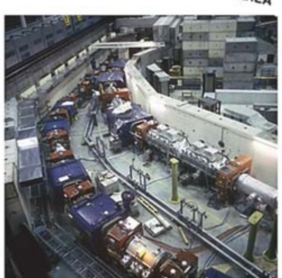
The AA

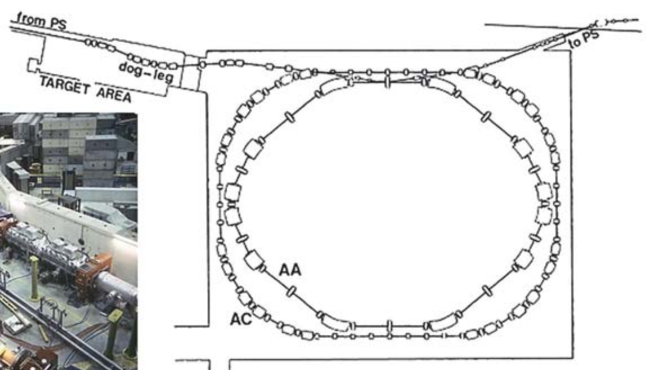
New transfer lines
to PS/ISR/SPS

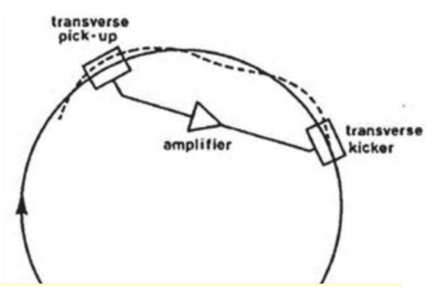
$$\mathcal{L} = \frac{N_1 N_2 k_b f \gamma}{4\pi\epsilon_n\beta^*}F$$

N_i limits: injector; interaction with beam pipe; beam-beam interaction; p-pbar: limited by pbar injection
Constraints: total I_b=k_bN_1 (ee: RF; pp: losses in SC magnets; ppbar: pbar injection); transverse size! In hadron col: $g_b\varepsilon_n$ by injector.

CERN Antiproton Accumulator (AA) ~end 70's



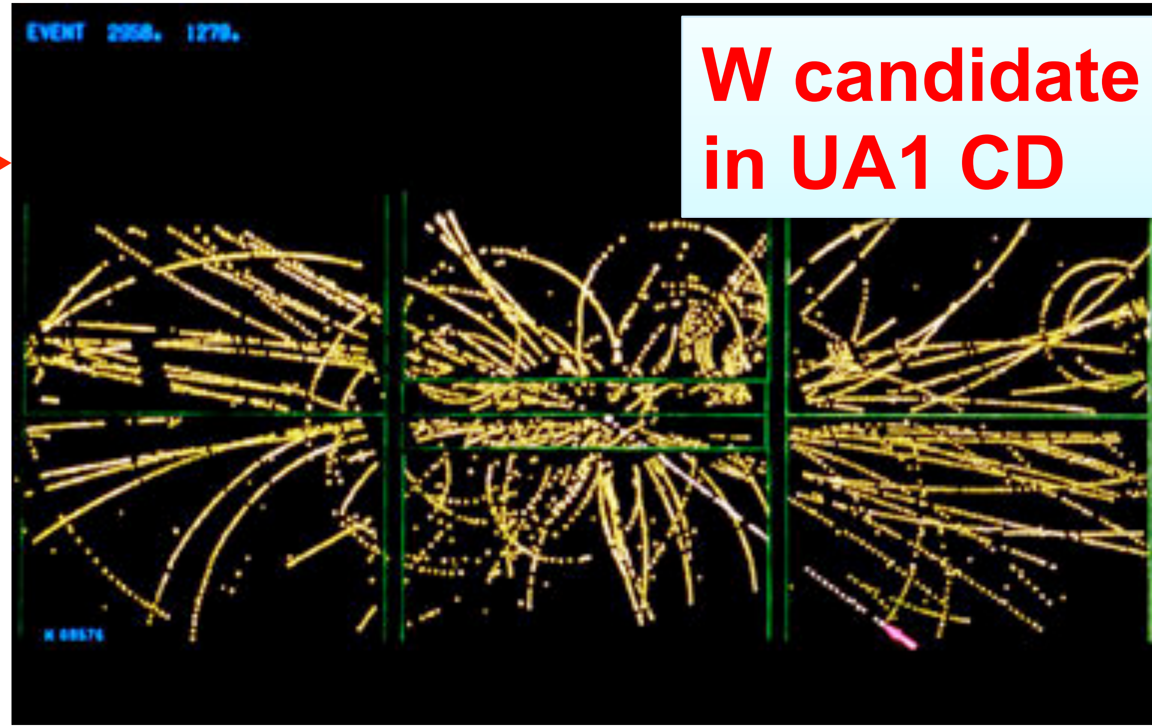




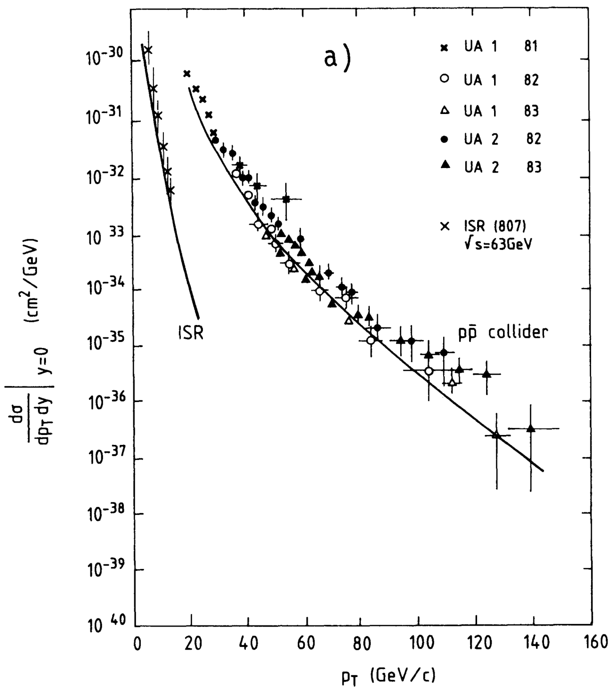
Stochastic Cooling
(Simon van der Meer)

A mess (or maybe not?)

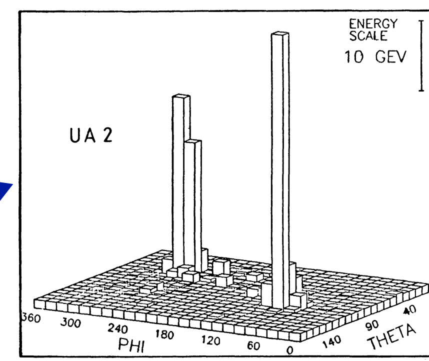
The power of precision tracking



W candidate in UA1 CD



The action is in the transverse plane



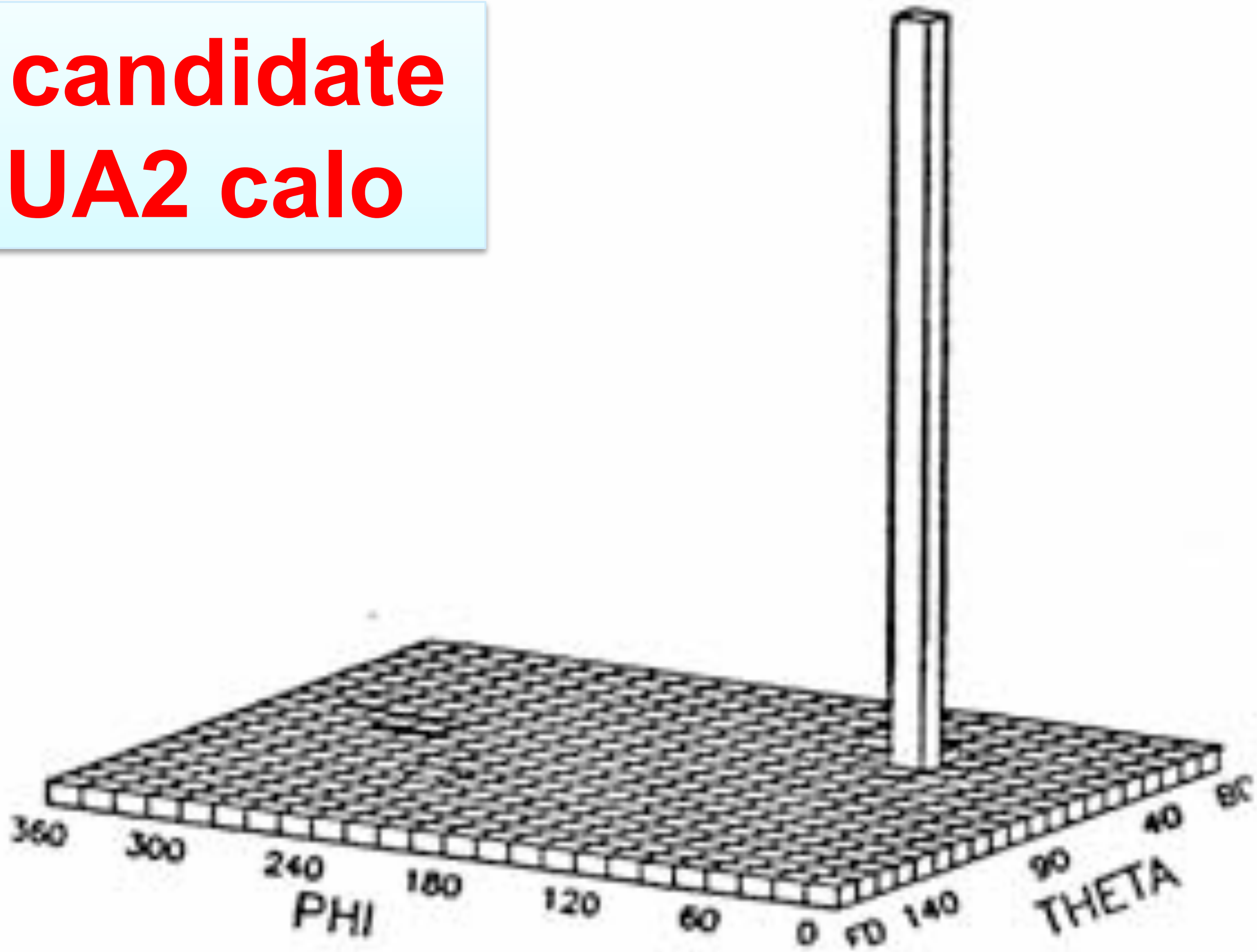
Hermeticity

Calorimeter (inclusive) trigger

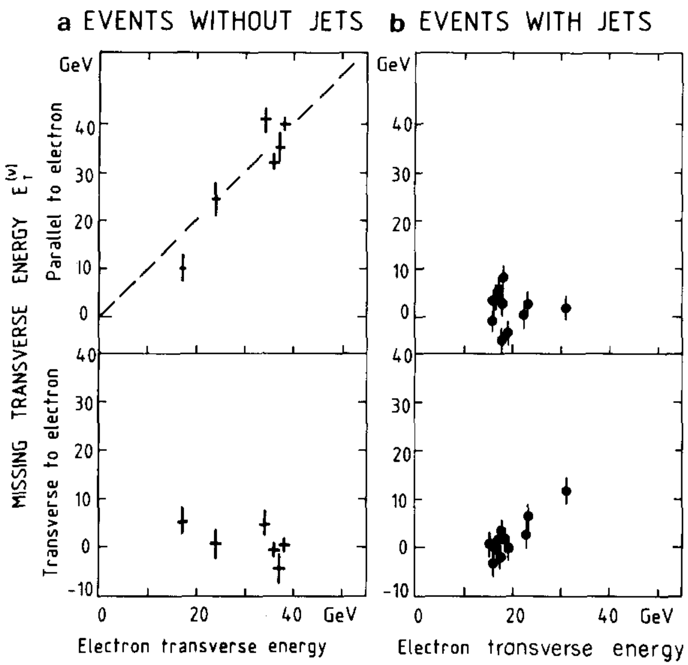
Precision tracking

SPS legacy: “Intermediate Vector Bosons”

W candidate in UA2 calo

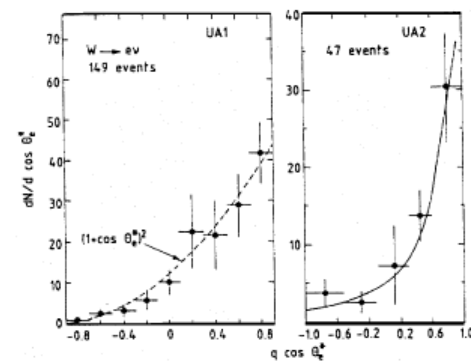


The rendez-vous with the W boson



It was there, at the right time (number of events → rate → time of rendez-vous!)

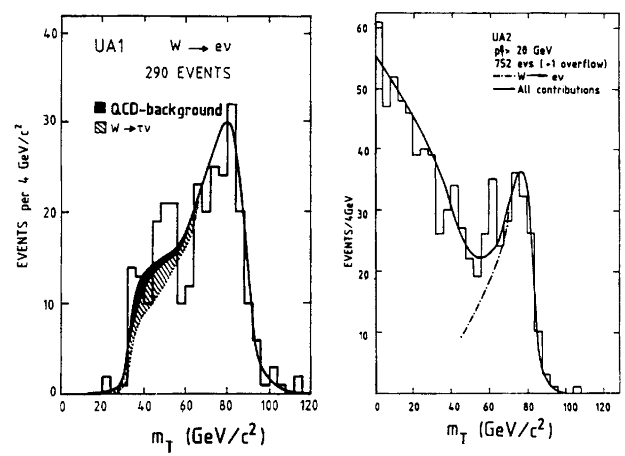
And with the correct spin…



at the right mass:

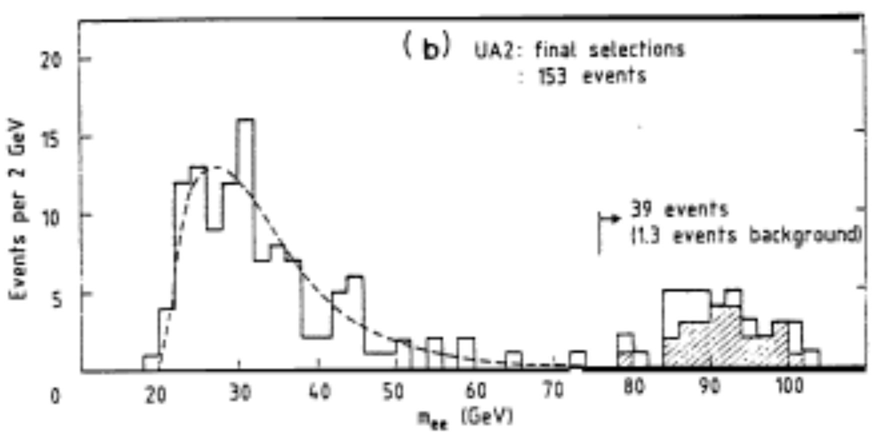
$$\text{UA1: } m_W = 81 \pm 5\ \text{GeV}$$

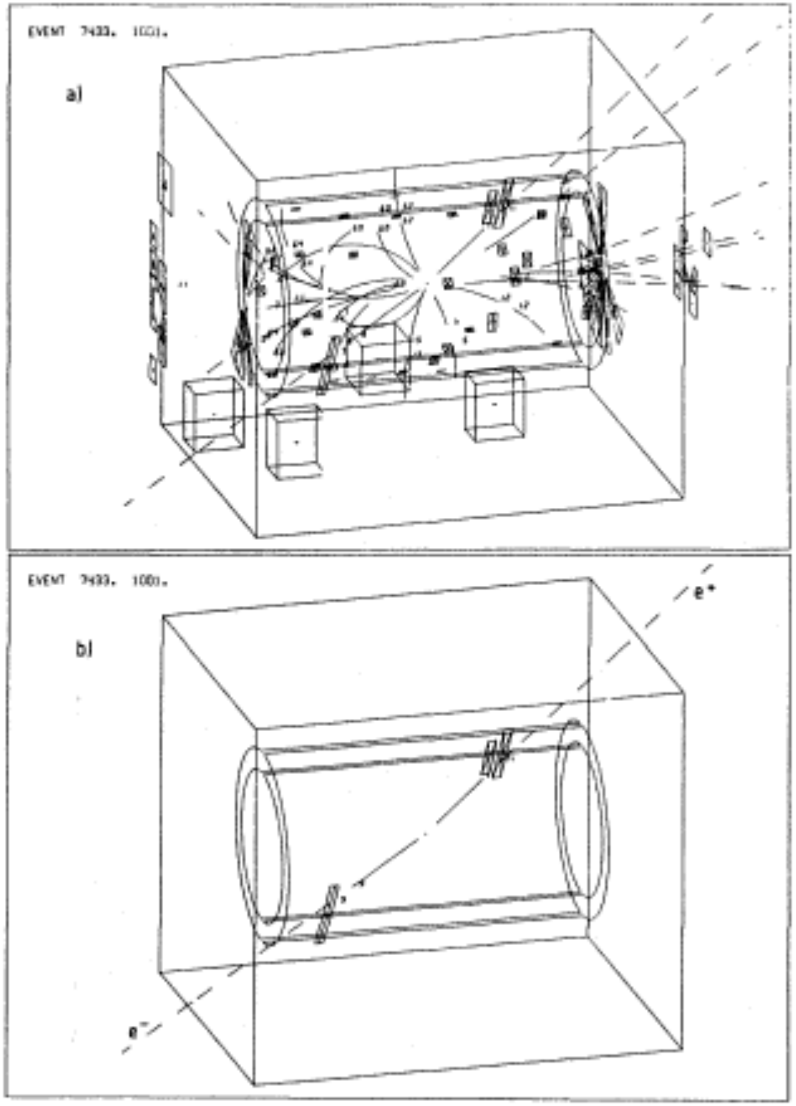
$$\text{UA2: } m_W = 81 \pm^{10}_{6}\ \text{GeV}$$



The similarly punctual cousin: the Z boson

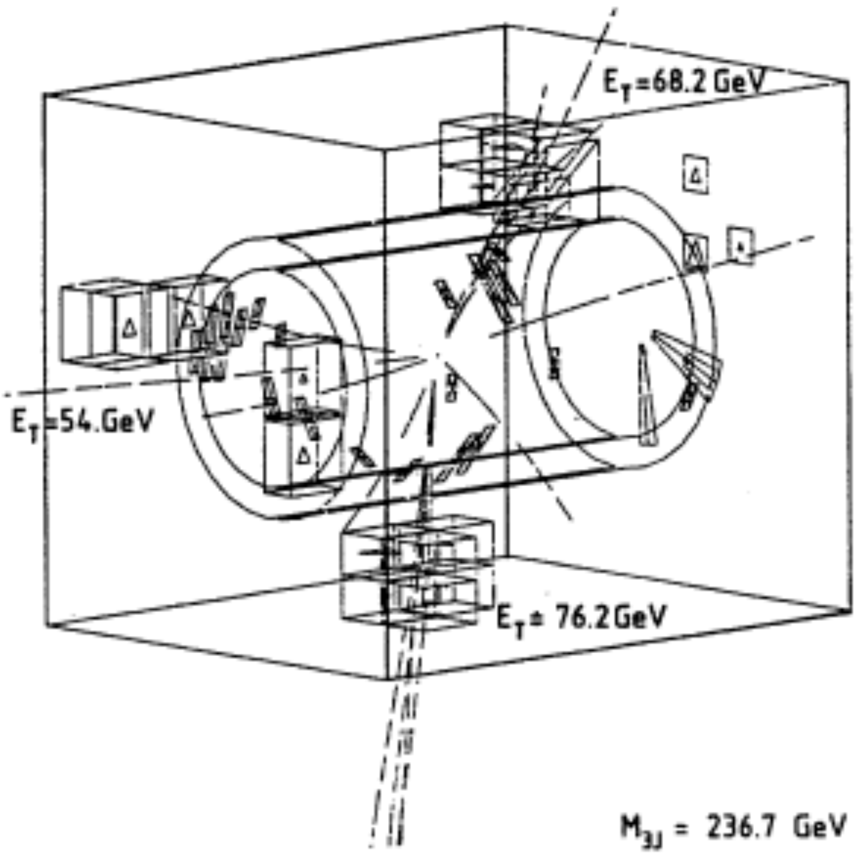
- **The Z boson was there as well**
  - **Also at the right time**
  - **At the right mass**

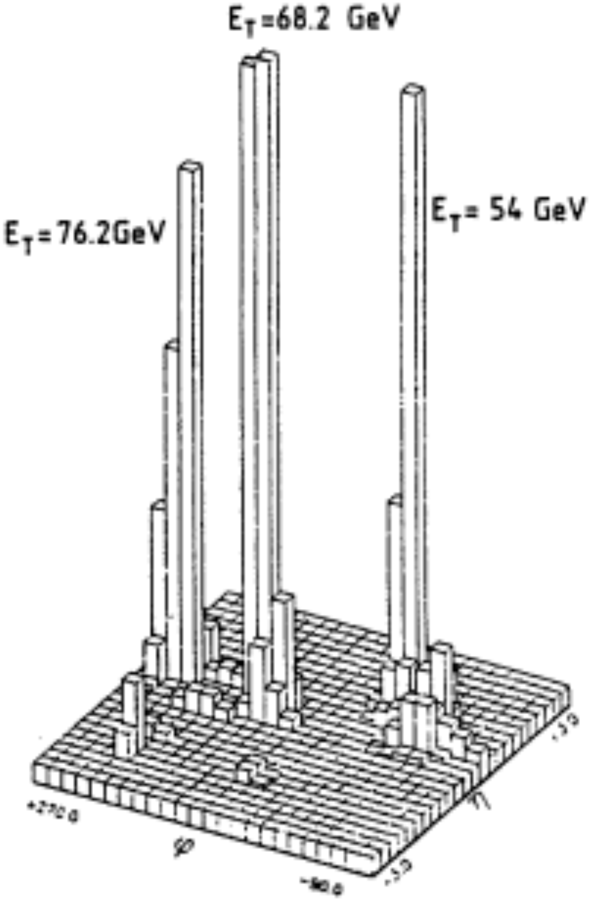




Jets in proton-antiproton collisions

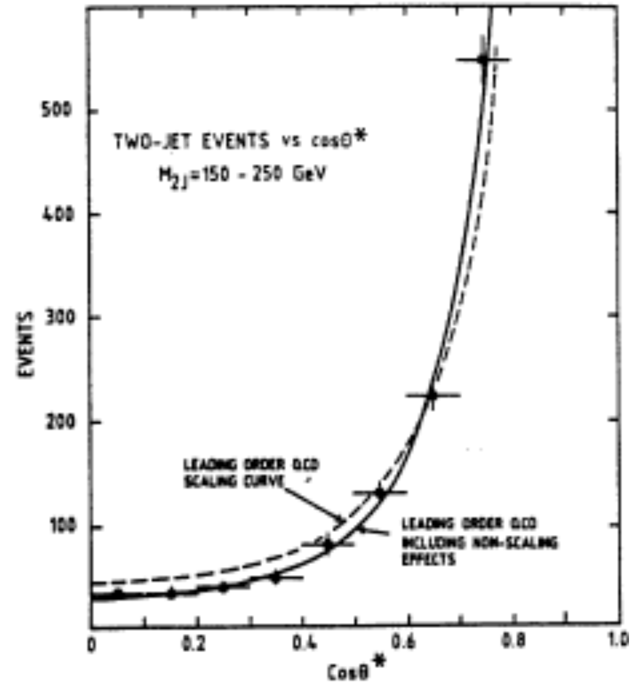
- **Even the gluon was still there – in three-jet events!**

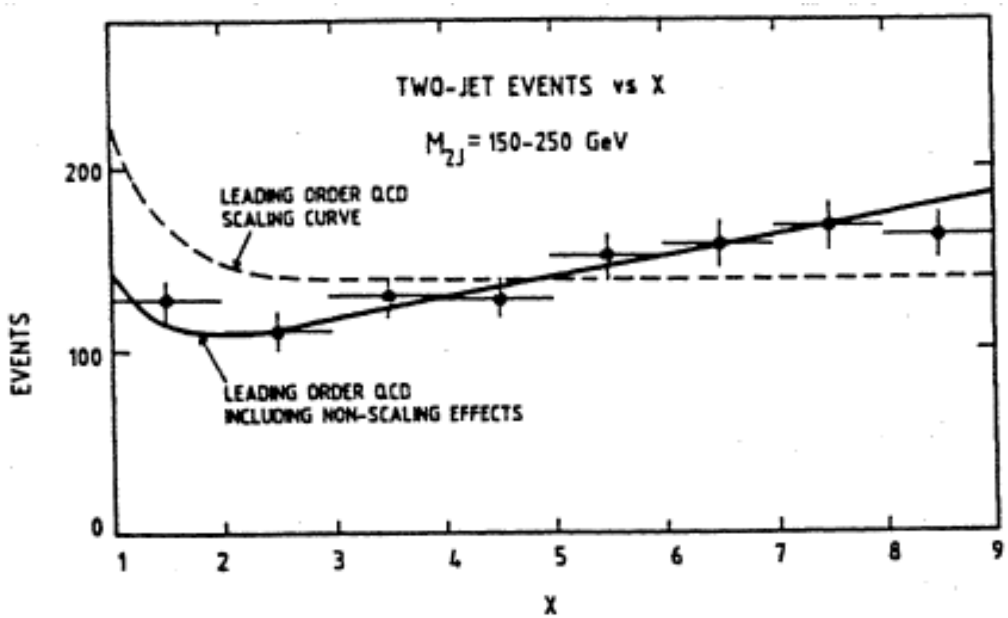




SPS legacy: strong interaction

Partons inside protons do scatter a la Rutherford!





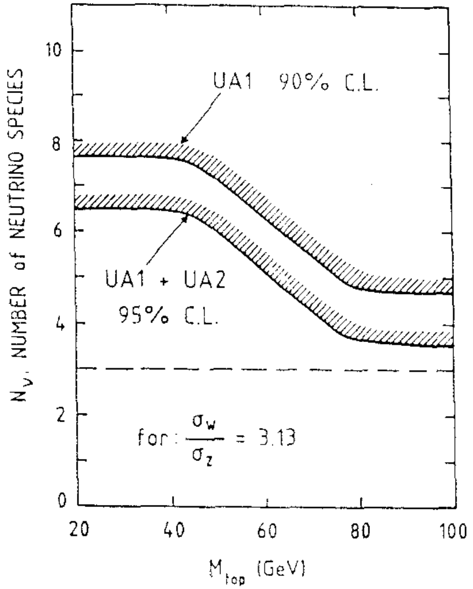
And the QCD "scaling violations" are, actually, visible – Q^2 dependence

SPS: we learned a lot more as well

- **≤ 6neutrinos!**
  - From W width

$$\frac{N(\mathrm{W}\to \mathrm{l}\nu)}{N(\mathrm{Z}\to \mathrm{l^+l^-})} = \frac{\sigma_\mathrm{W}\cdot \mathrm{BR}(\mathrm{W}\to \mathrm{l}\nu)}{\sigma_\mathrm{Z}\cdot \mathrm{BR}(\mathrm{Z}\to \mathrm{l^+l^-})},$$

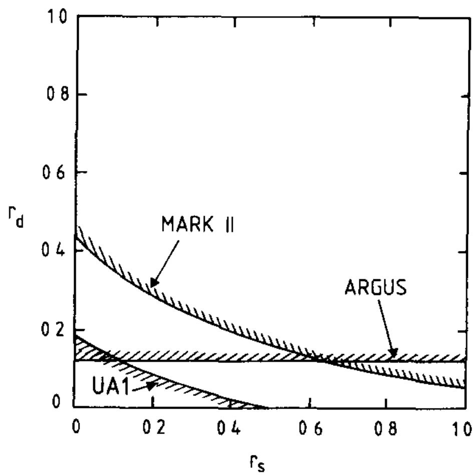
$$= \frac{\sigma_\mathrm{W}}{\sigma_\mathrm{Z}}\,\frac{\Gamma(\mathrm{W}\to \mathrm{l}\nu)}{\Gamma_\mathrm{W}}\Big/\frac{\Gamma(\mathrm{Z}\to \mathrm{l^+l^-})}{\Gamma_\mathrm{Z}}$$

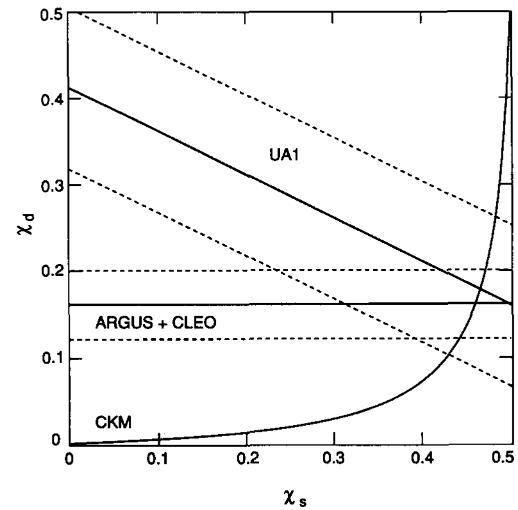


$$\Gamma_\mathrm{Z} = 2.7^{+0.4}_{-0.3}\ \mathrm{GeV}/c^2,$$

$$< 3.1\ \mathrm{GeV}/c^2 \quad (90\%\ \mathrm{CL})$$

- **And B mesons mix a lot:**
  - Observation of $\mu^+\mu^+$ and $\mu^-\mu^-$ events:



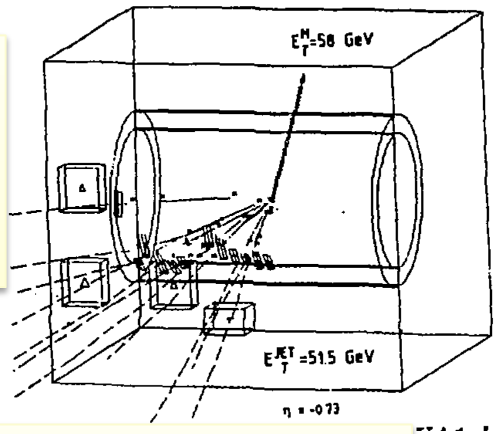


$$\chi = \frac{(\mathrm{BR})_\mathrm{d} f_\mathrm{d} \chi_\mathrm{d}}{\langle \mathrm{BR}\rangle} + \frac{(\mathrm{BR})_\mathrm{s} f_\mathrm{s} \chi_\mathrm{s}}{\langle \mathrm{BR}\rangle}$$

$$\chi_\mathrm{s} > 0.12 \text{ at } 95\%\ \mathrm{CL}, \quad \chi_\mathrm{s} > 0.17 \text{ at } 90\%\ \mathrm{CL}$$

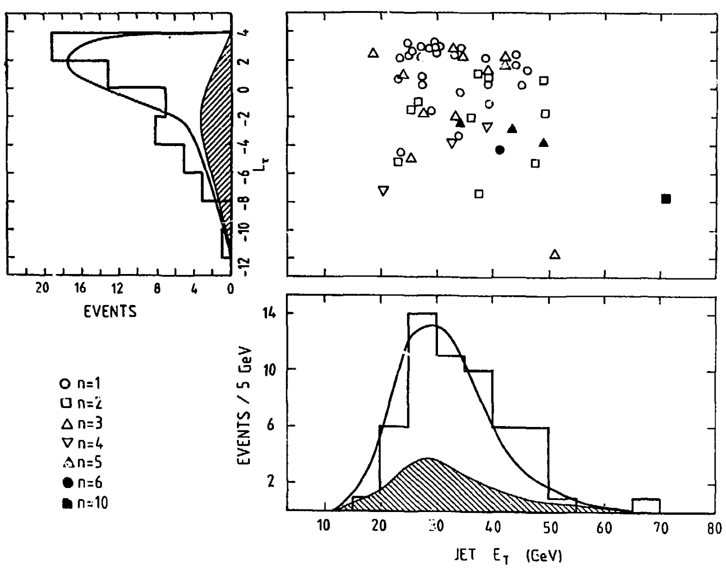
Plus, some excitement (that subsided)

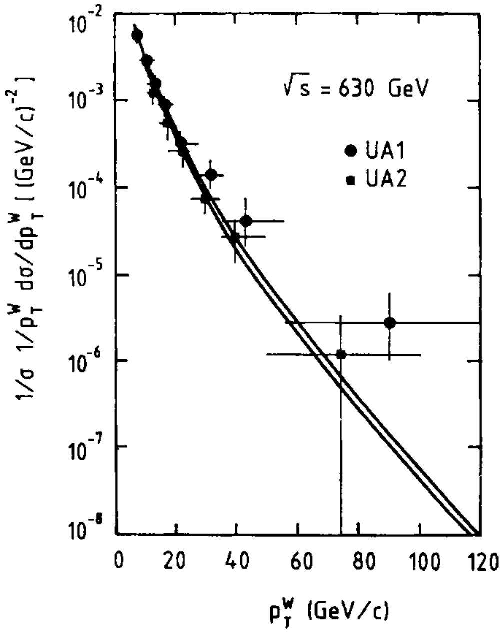
The Monojets! SUSY???

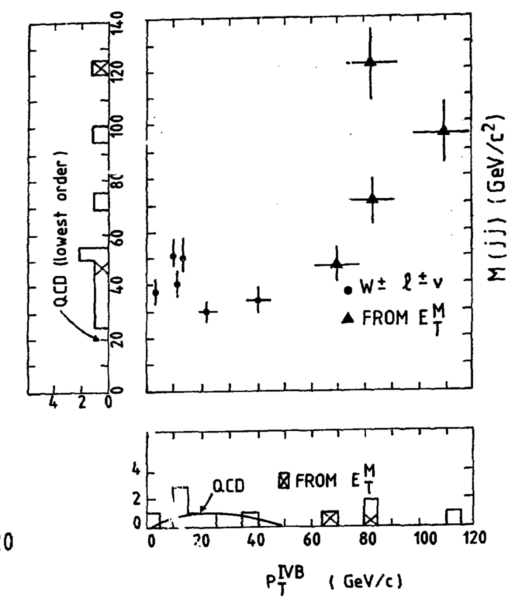


High-p_T Ws
New X→WW?

They turned out to be taus…





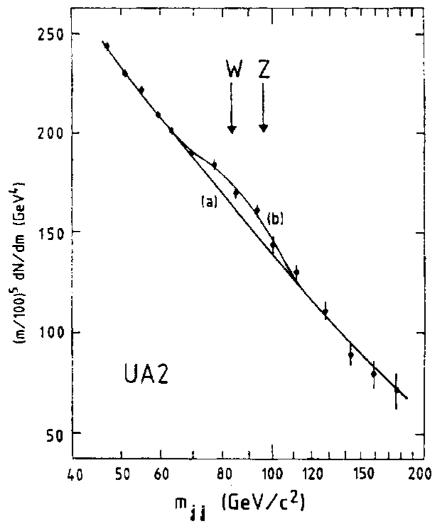


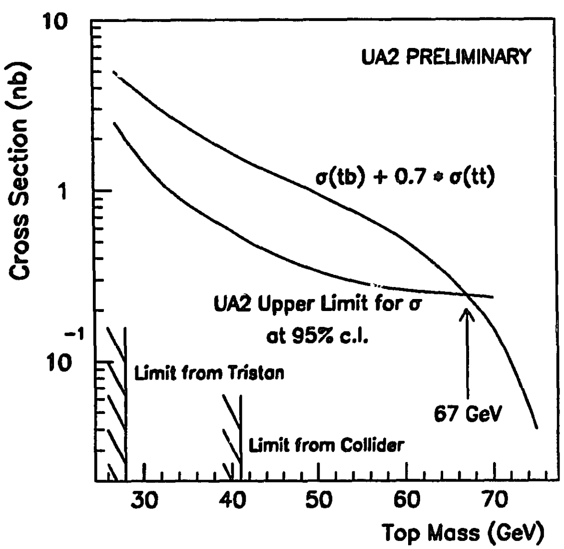
It was statistics + LO QCD…

Near the end…

Near the end, UA1 was running without EM calorimeter… The previous one had been removed, to make room for a new U-TMP calorimeter (prompted by the noble goal of a W mass measurement to ~100 MeV)
UA1 became a ≈ muon detector;
UA2 thrived and dominated

Special trigger (low-p_T jets)



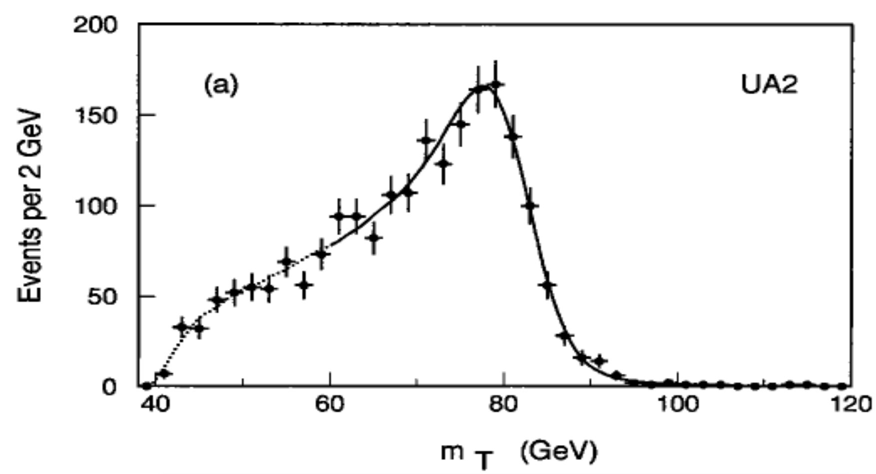


95% CL

$M_{top} > 67$ GeV
M b' > 53 GeV.

$M_{top} > 70$ GeV
M b' > 56 GeV.

90% CL

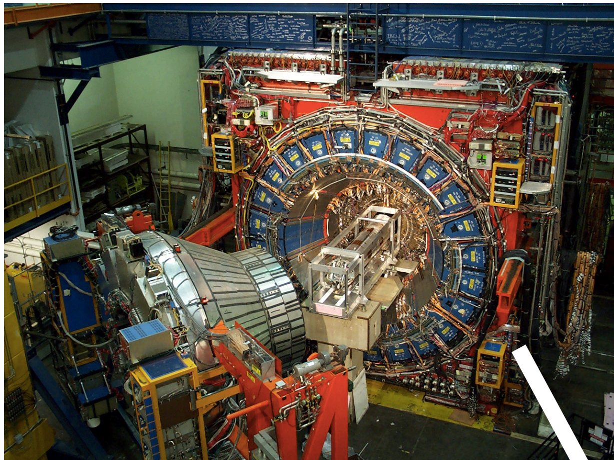


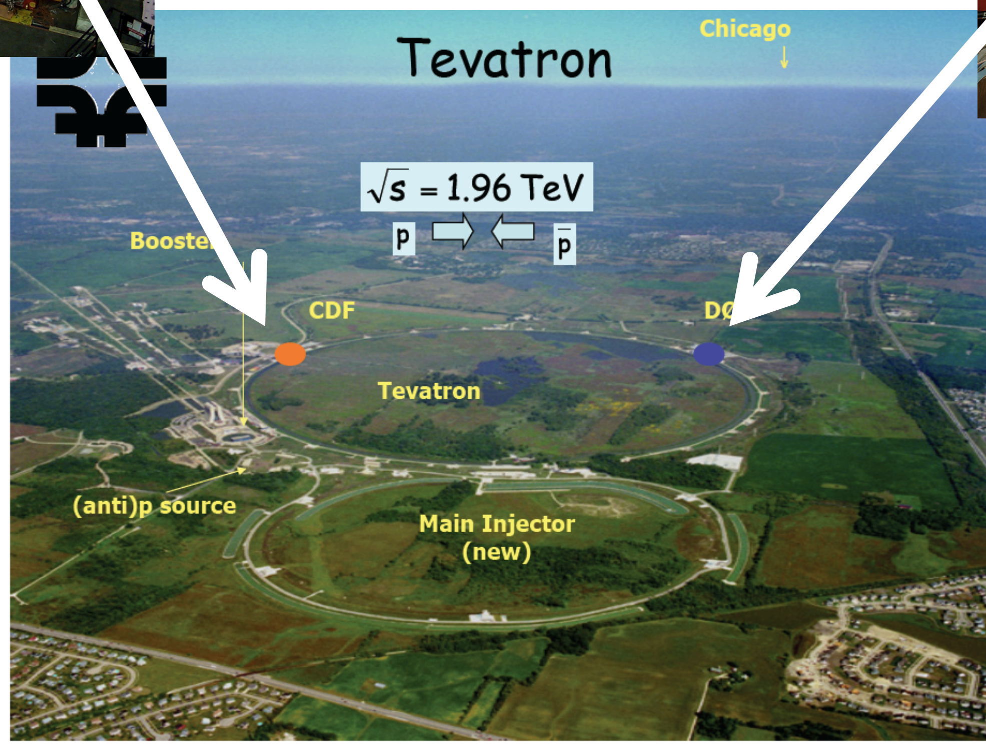
M_W=80.35±0.33±0.17 GeV

Passing the baton to Fermilab (end of the 80s)

aka "Go west my boy/girl, go west"

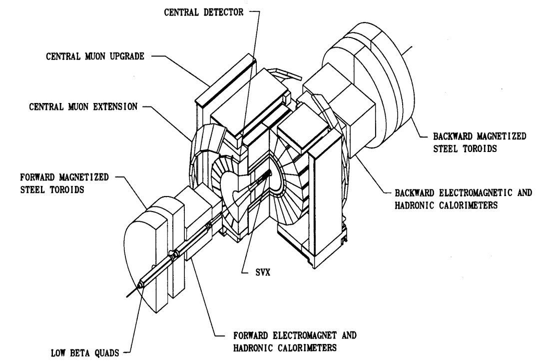
End of 80s, beginning of 90s: Tevatron



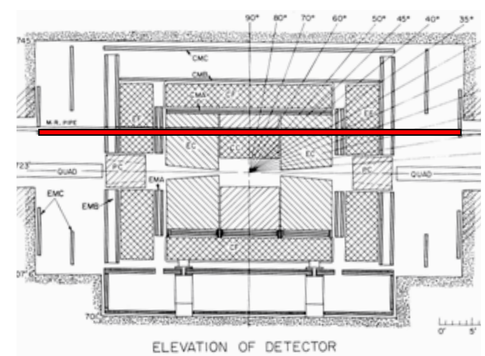


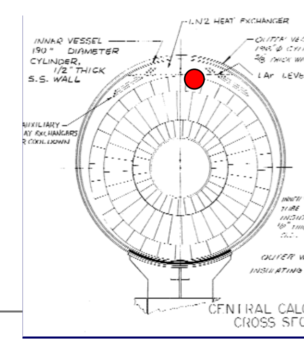
Tevatron experiments: a bit of history

- **CDF: design report in 1981**
  - US-Italy-Japan collaboration; 87 physicists from 13 institutes; construction project in 1983
  - Basic concept: magnetic detector (à la UA1); great tracking; hermetic but "normal" calorimeter coverage; central muon coverage; three-level trigger system.



- **1981: FNAL director call for detector at D0**
  - … something "small (to fit inside a 9m cube), simple, and clever". Add: moveable to/from beam line (D0: fixed target beam extraction); 12 proposals, all rejected
  - D0: 1983 proposal; 71 physicists from 12 institutes (all US); approved by DOE in 1984
  - Basic concept: non-magnetic detector (à la UA2); great (compensating) calorimeter (Lar-U); hermetic muon coverage; same trigger.

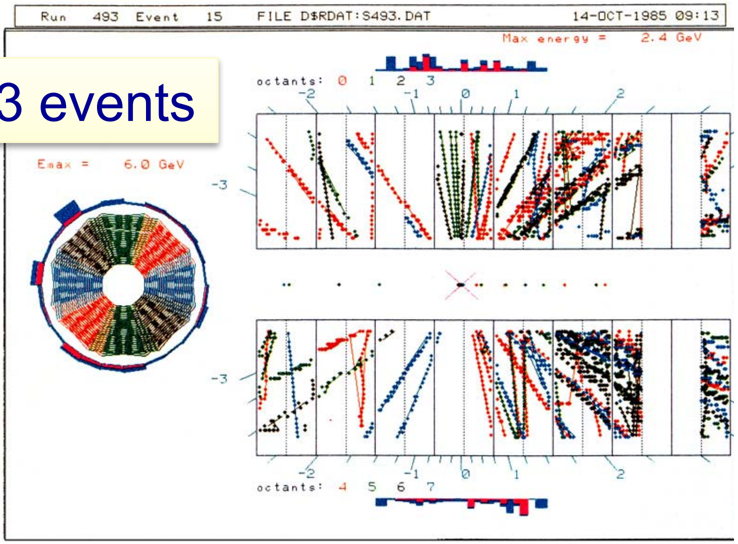




Tevatron evolution

First collisions: CDF, Oct 1985

23 events

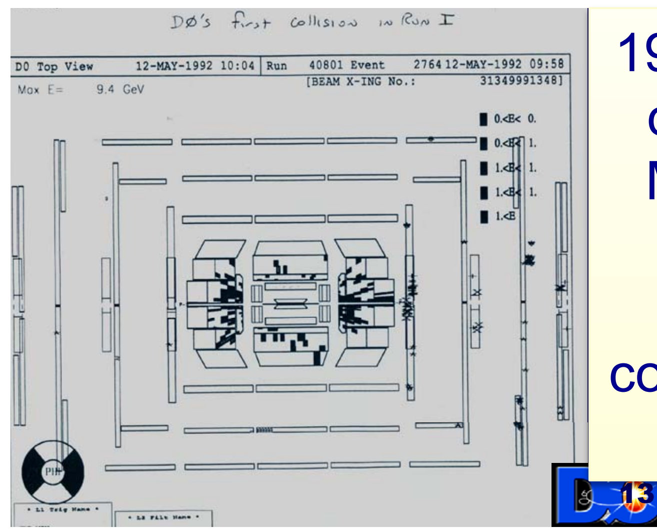


1987: Run 0; first run, CDF,
4pb^{-1} @ 1.8 TeV

1992-96: Run 1; CDF & D0,
120 pb^{-1} @ 1.8 TeV

2011: Run 2; upgraded CDF&D0
12 fb^{-1} @ 2.0 TeV

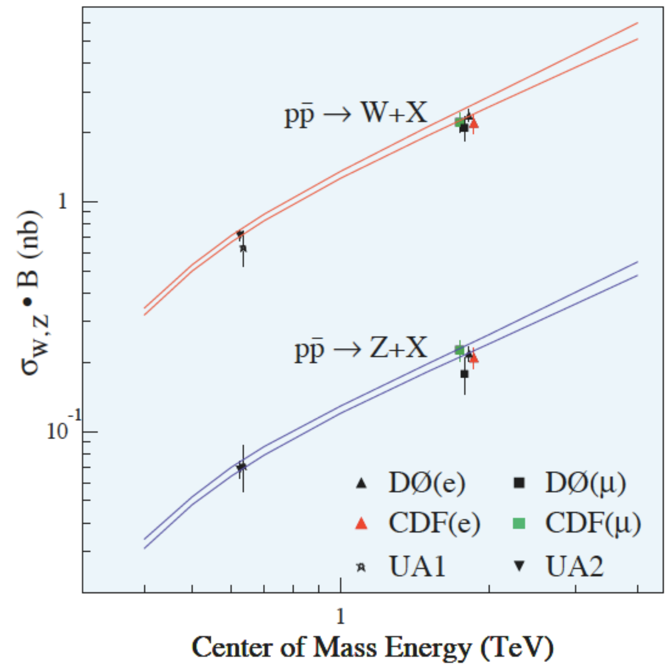
And D0 was just starting…

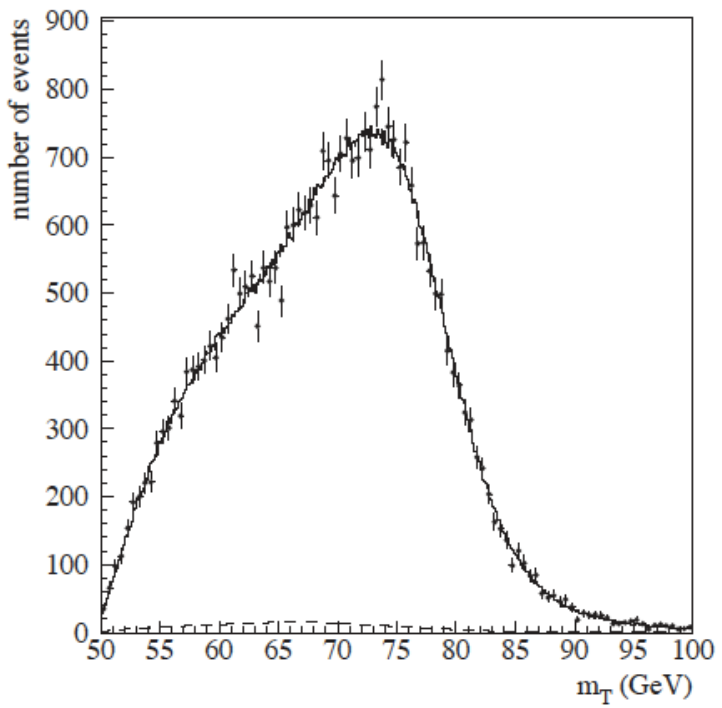


1992: start of Run I; May 12, 1992: first collisions at D0!

The Tevatron… W/Z physics, next-gen!

- **Higher Energy: big difference in production cross section of massive particles + high luminosity : Huge samples**

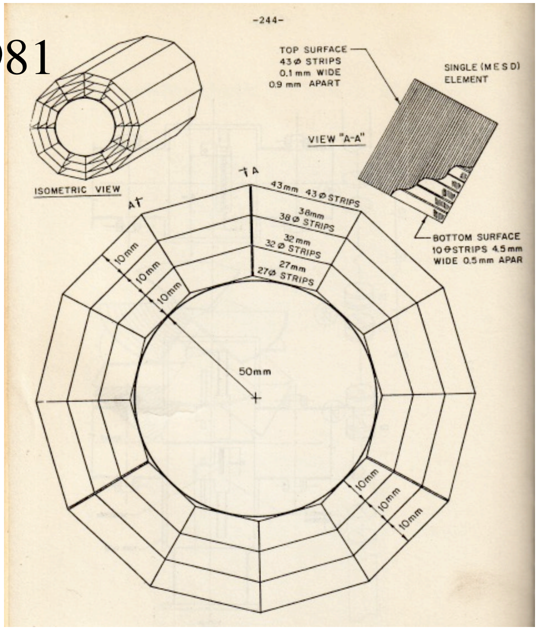


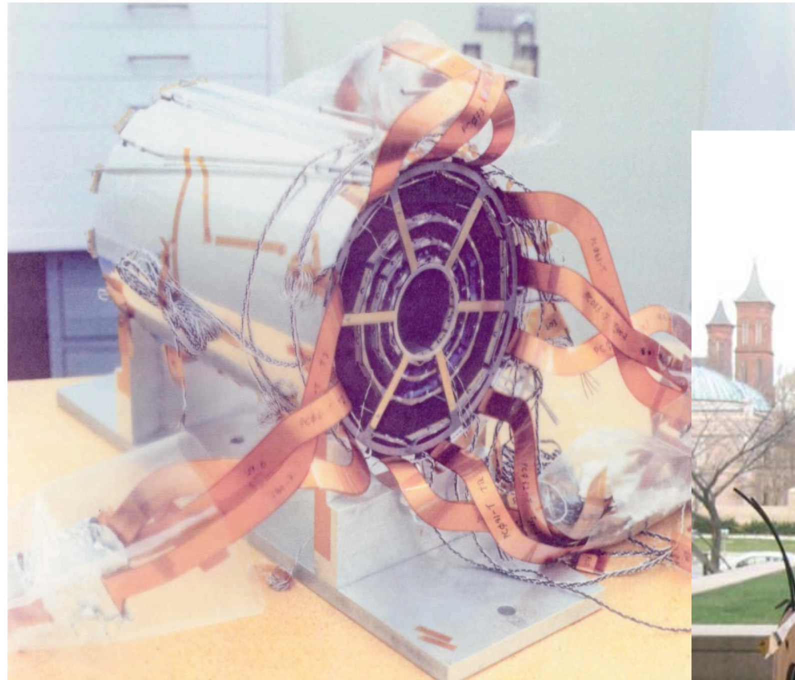


W boson transverse mass distribution from D0, circa 1997: 33,000 W candidates!

The true novelty: silicon vertex detector

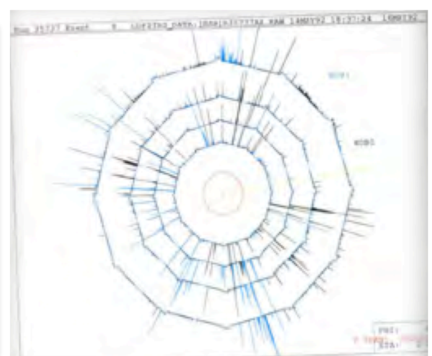
1981



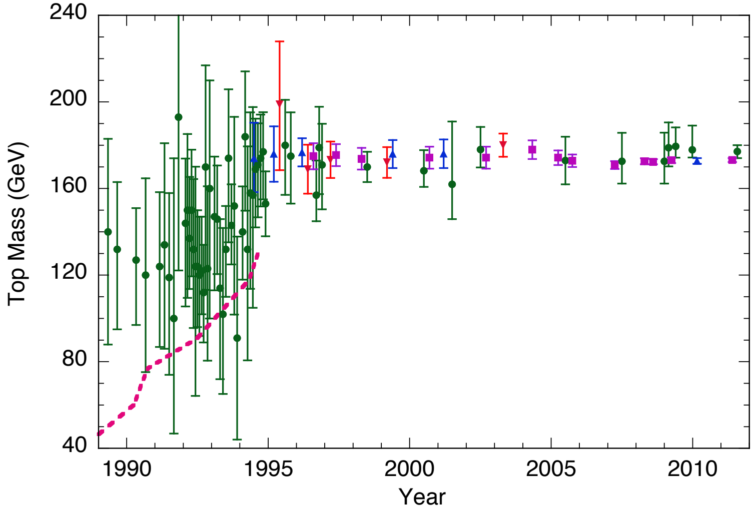


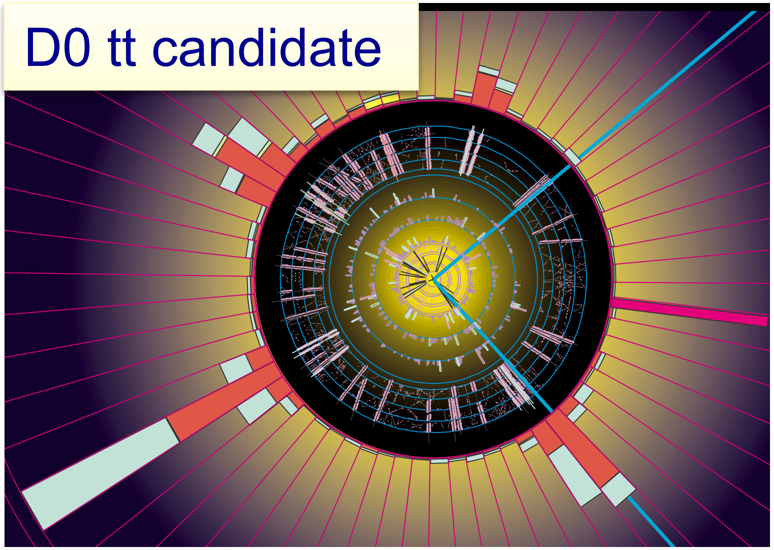
Smithsonian Museum, Washington

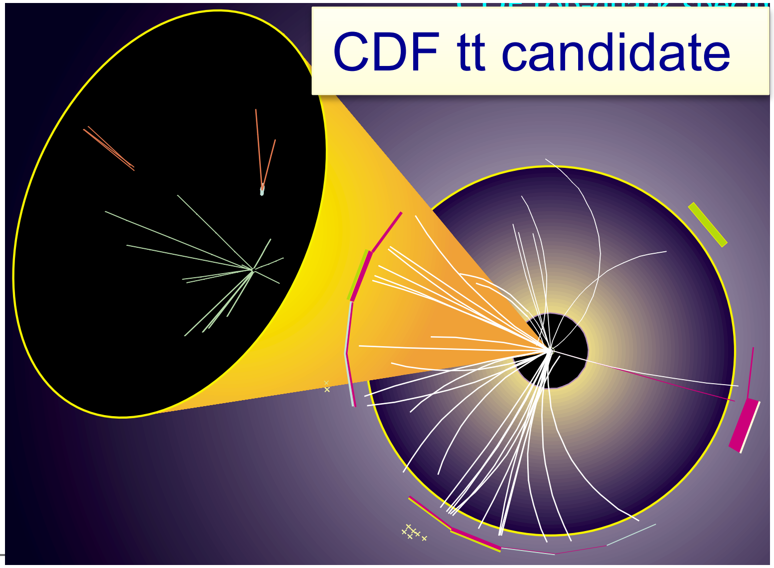
The SVX was the first silicon vertex detector and gave CDF a whole new physics capability



Towards the top quark



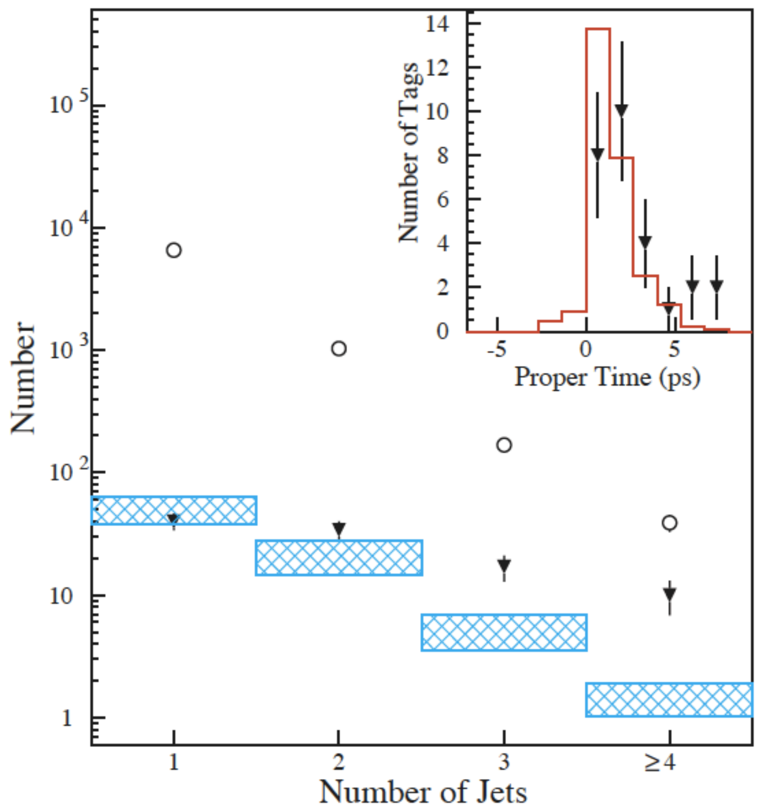


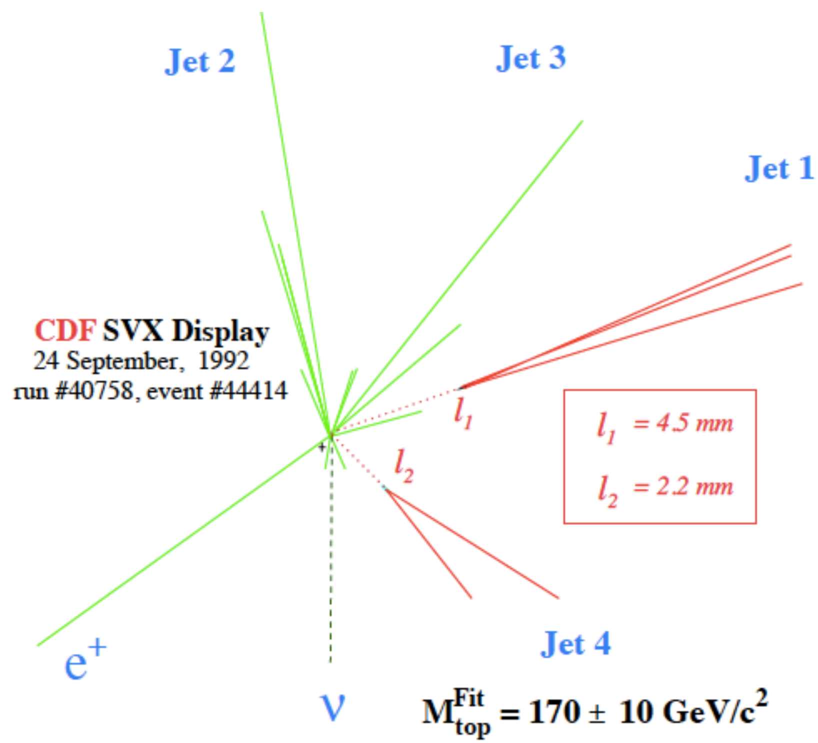


80's: M_t>23 GeV (Petra); 30 GeV (Tristan)
1984: Weak evidence for W→tb @ m_t~40 GeV (UA1)
1990: m_t > 91 GeV (CDF) so no W→tb
1994: m_t > 131 GeV (D0)
4/1994: CDF evidence m_t~175 GeV, 2.8σ.
7/1994: DØ sees ~2σ.
Feb. 17, 1995: CDF warning → 1 wk clock.
Feb. 24, 1995: CDF and DØ discovery

The Tevatron discovery: the top quark (I)

- **The crowning moment for the Tevatron experiments: the observation of the Top quark**
  - **The most complicated signature up to that point in time; leptons, jets, missing transverse energy, and b-tagging!**





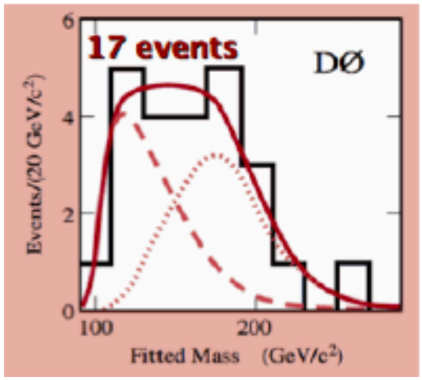
The Tevatron discovery: the top quark (II)

Mar 2, 1995

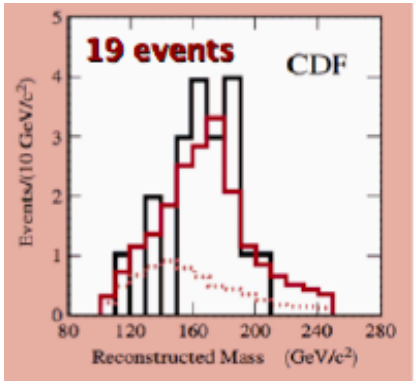
D0:
Obs: 17 evts;
Exp bkg: 3.8±0.6
Prob=2×10^{-6} (4.6σ)

Channel	SVX	SLT	Dilepton
Observed	27 tags	23 tags	6 events
Exp. bkg	6.7±2.1	15.4±2.0	1.3±0.3
Probability	2×10^{-5}	6×10^{-2}	3×10^{-3}

CDF: Prob=1×10^{-6} (4.8σ)



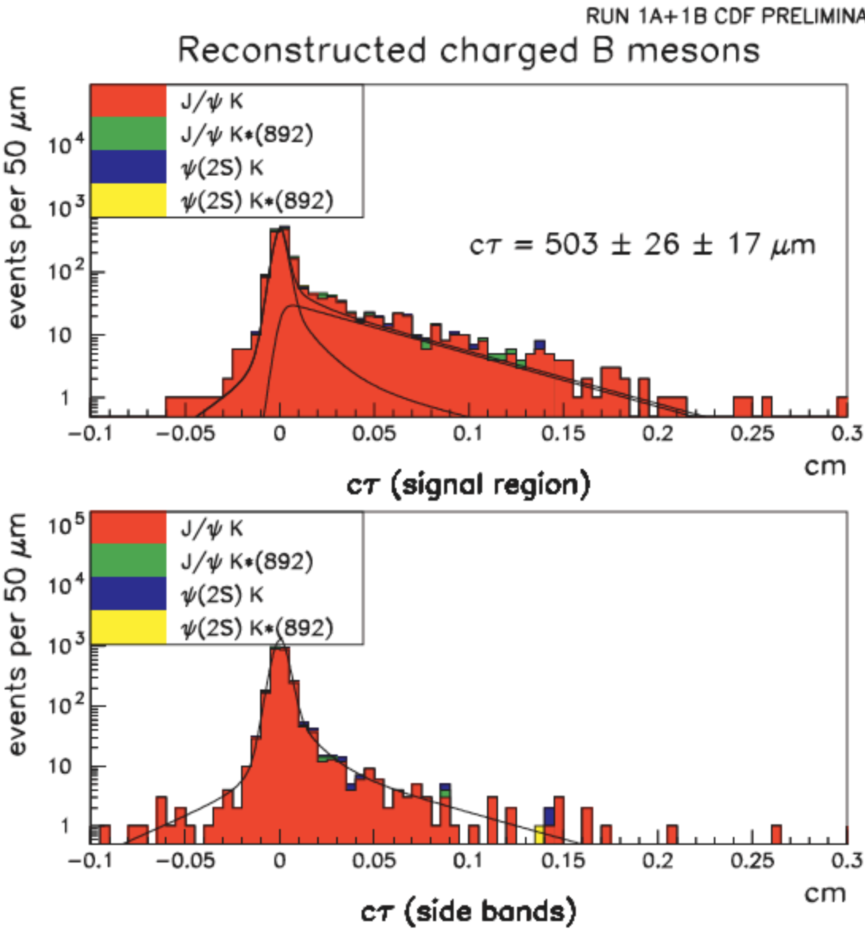
PRL 74, 2632 (1995)



PRL 74, 2626 (1995)

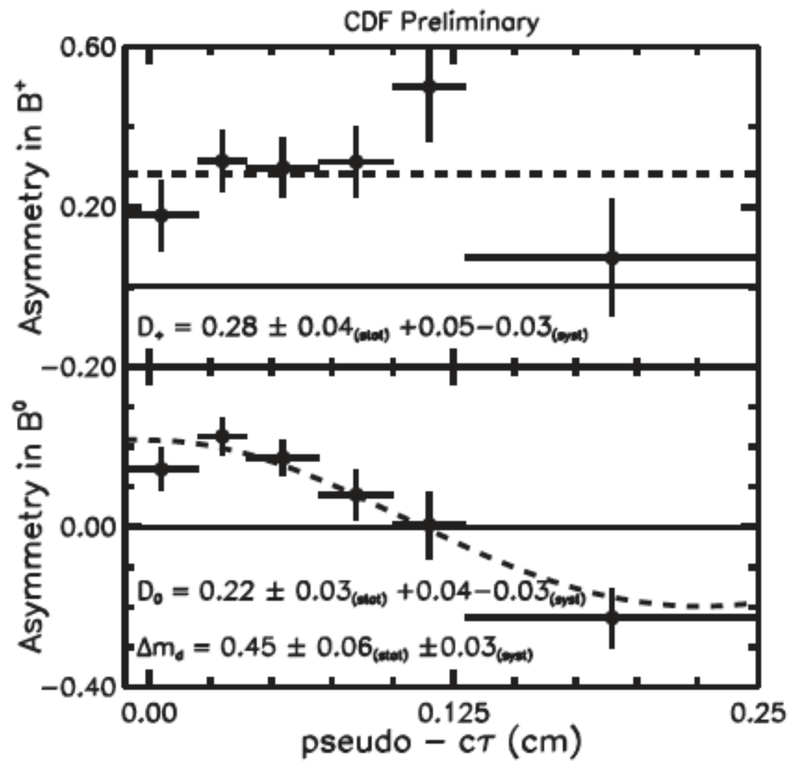
And then came the rich B physics program

- Directly "see" B meson decay; also flavor-tag (B/B-bar)



$B^+ \rightarrow J/\psi\ K^+$

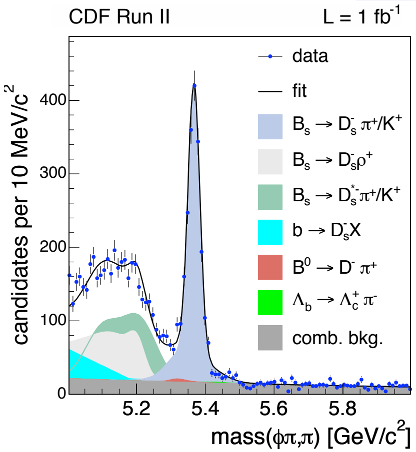
lepton+D; SST

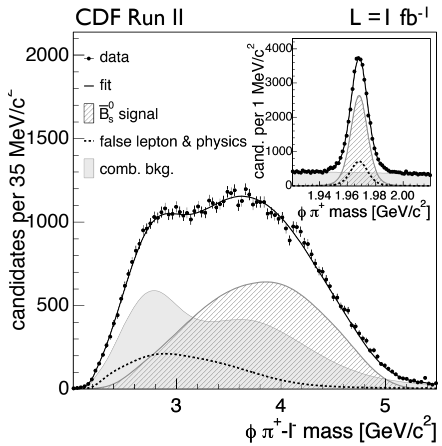


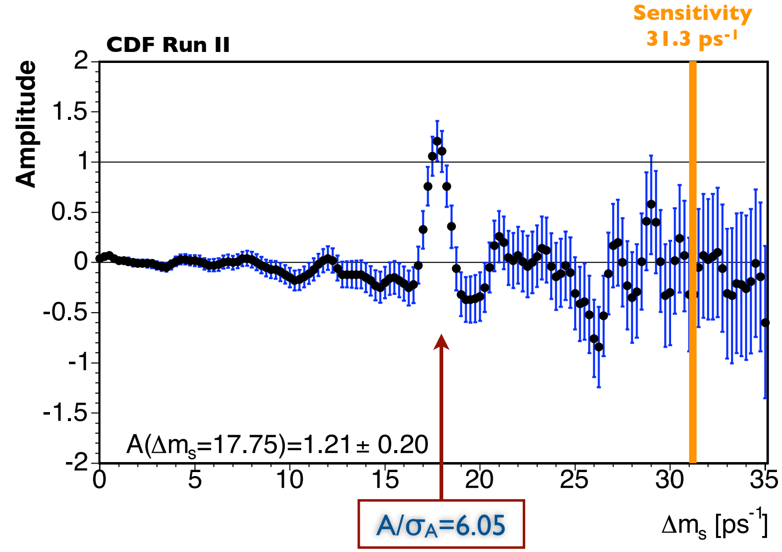
Jewel of B physics @ hadron colliders: B_s

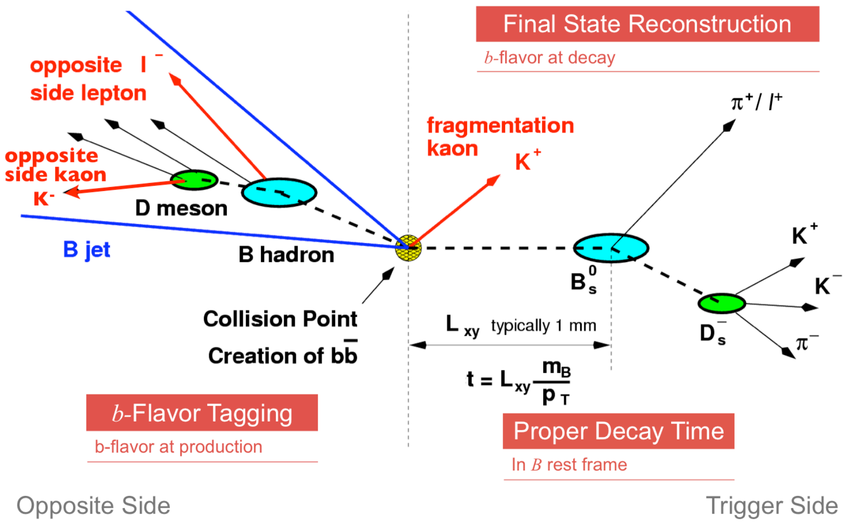
$B_s \to D_s \pi$ $\quad$ $D_s \to \phi\pi$ $\quad$ $B_s \to \ell(\nu) D_s$

$$\sigma_A = \sqrt{\frac{2}{\epsilon D^2}} \frac{\sqrt{B+S}}{S} e^{(\Delta m\, \sigma_t)^2/2}$$

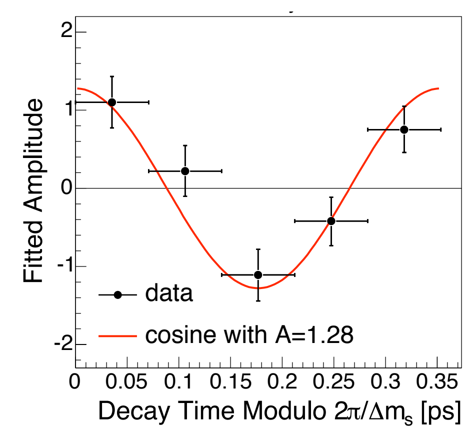






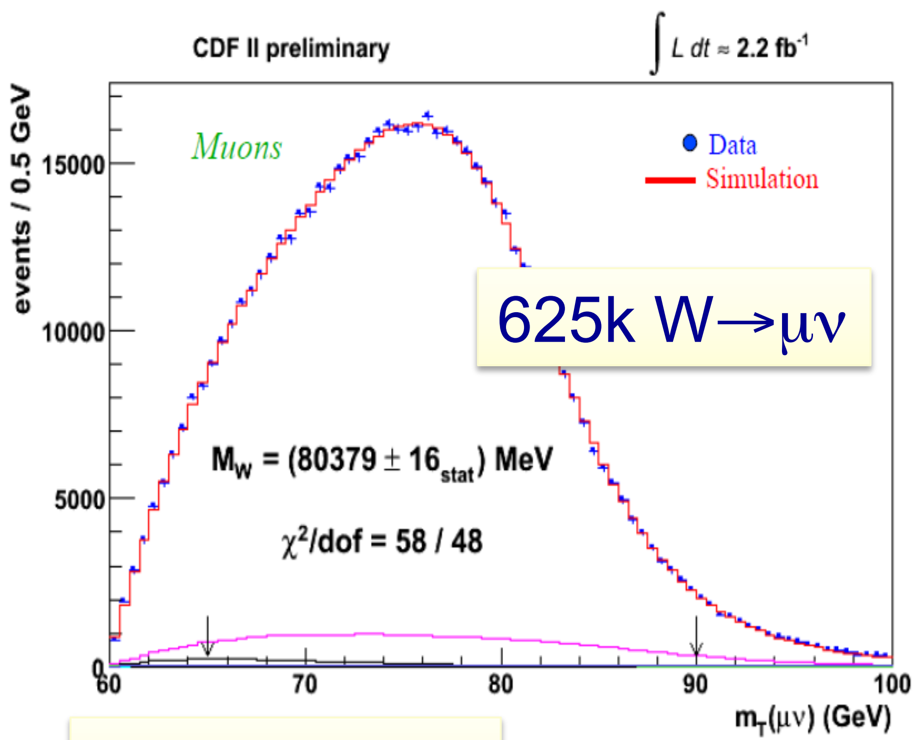


Major tools:
SVXII, PID
(TOF, dE/dx)



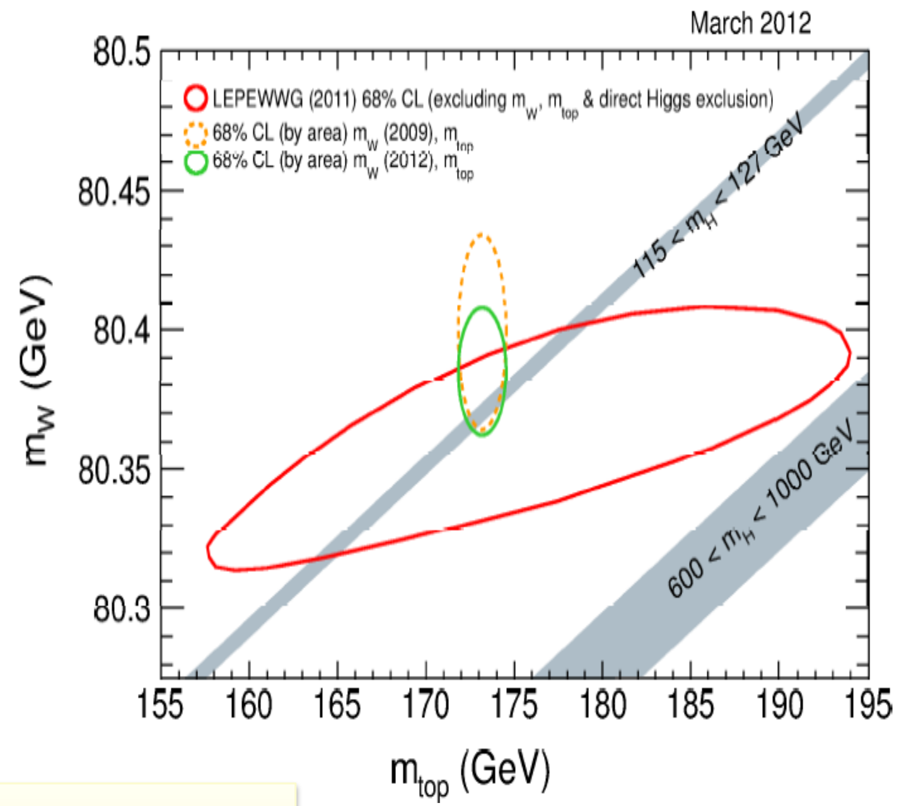
The surprise: very high precision on M_W

- **A measurement with a relative error of 0.24×10^{-3}**
  - $M_W = 80387 \pm 19$ MeV/c^2 ($\rightarrow \pm 12$ (stat.) ± 15 (syst.))



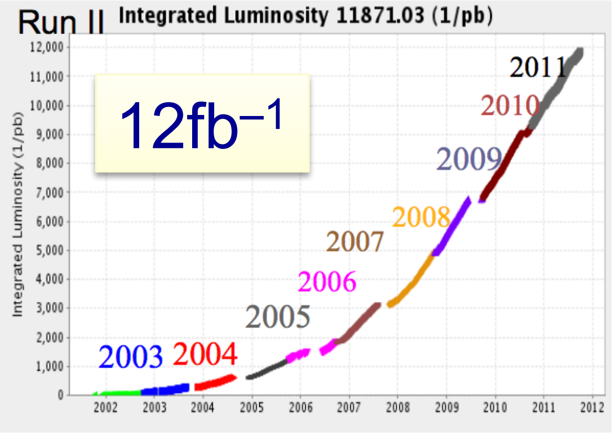
625k W→μν

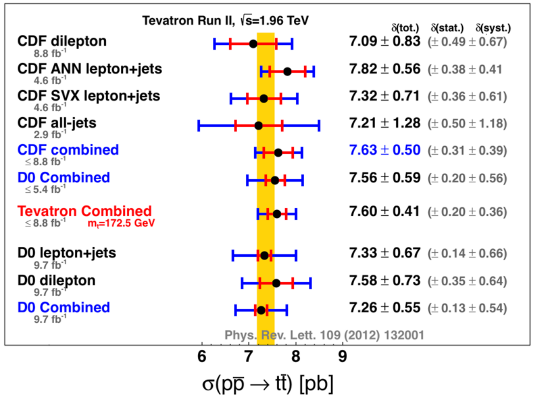
+470k W→eν



D0: 1.4M W→eν

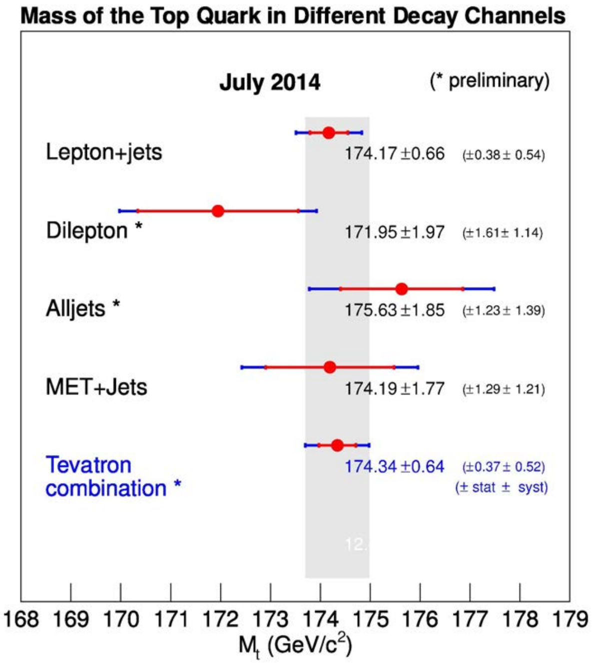
Tevatron: sole source of t quarks for ~10 years





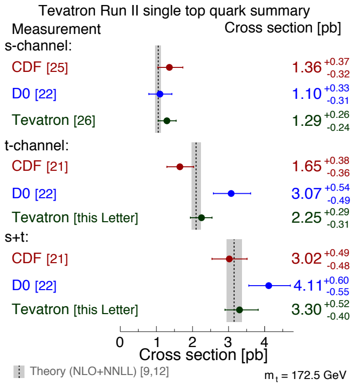
$$\sigma_{t\bar{t}} = 7.60 \pm 0.41\,\text{pb}$$

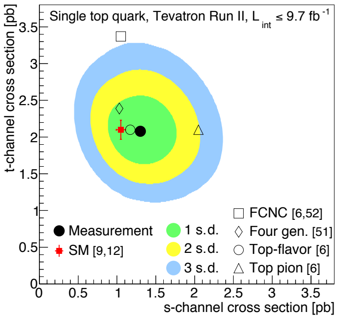
$\Delta\sigma/\sigma$ = 5.4%

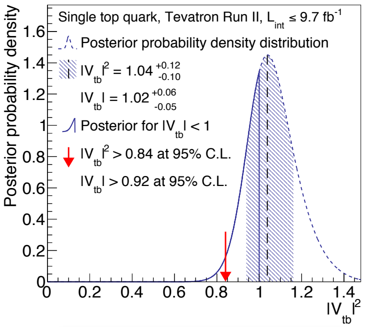


$$m_t = 174.34 \pm 0.64\ \text{GeV}$$

$\Delta m/m$ = 0.37%



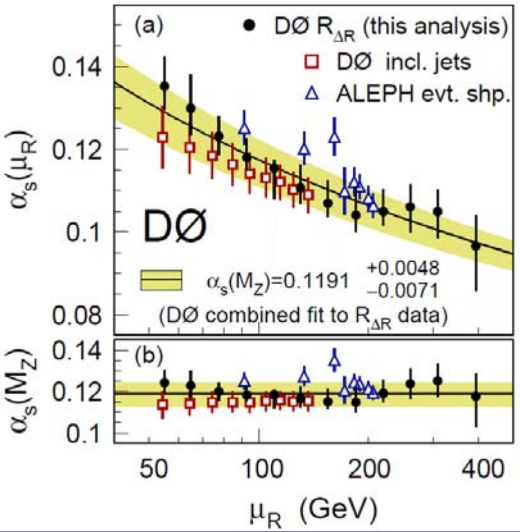




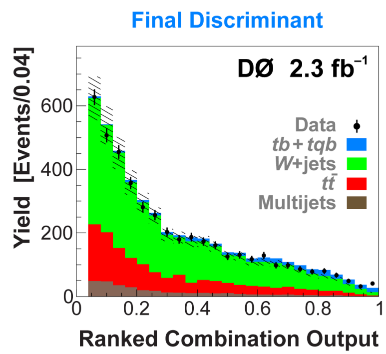
$V_{tb} > 0.92$

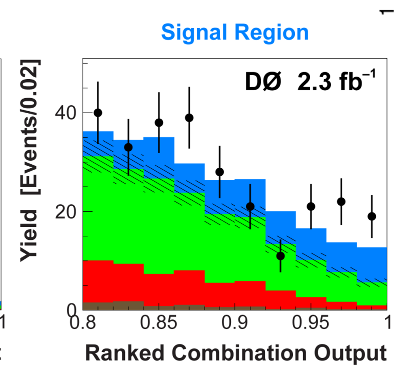
Plus some new techniques

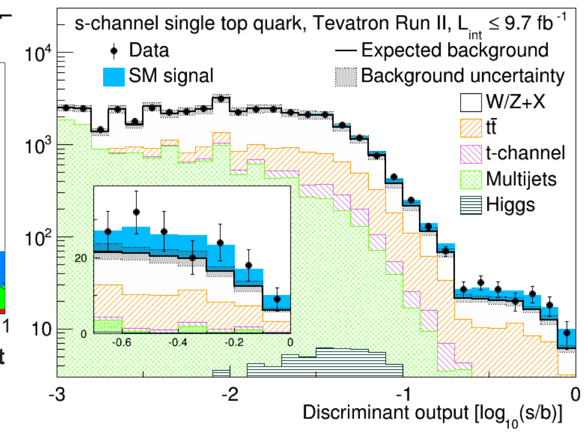
α_S measurement



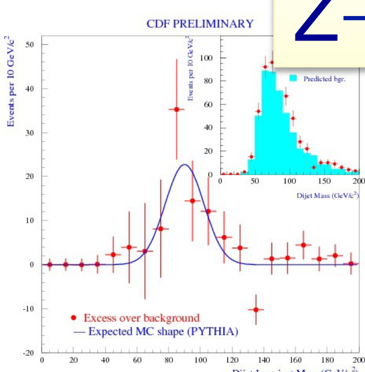
MVA and single-top

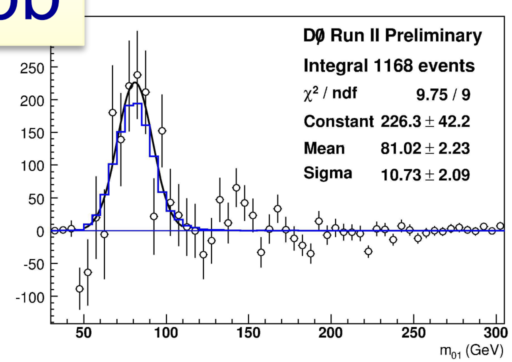




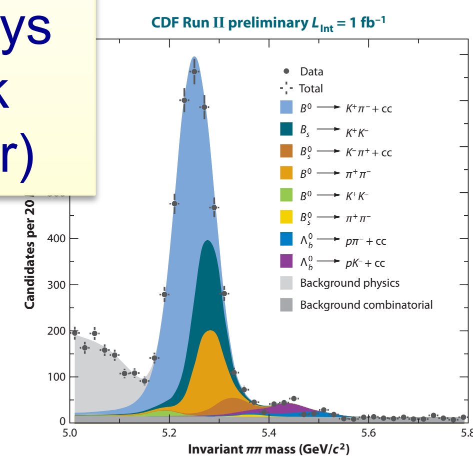


Z→bb



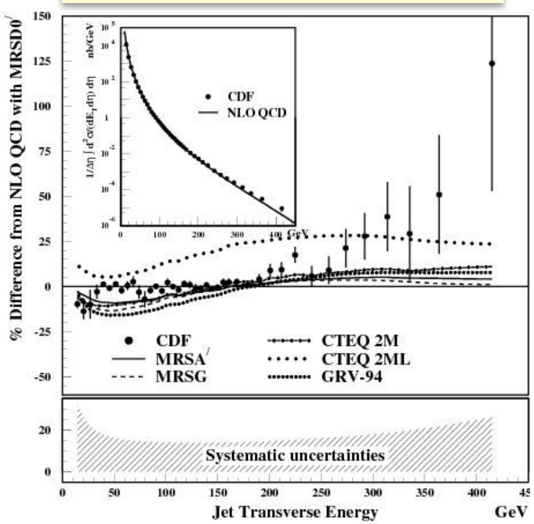


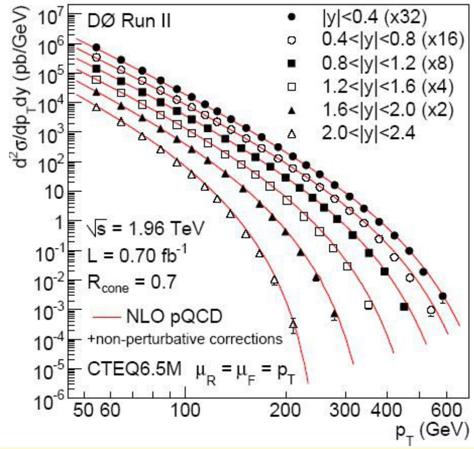
Hadronic B decays (track trigger)



There was also excitement... (I)

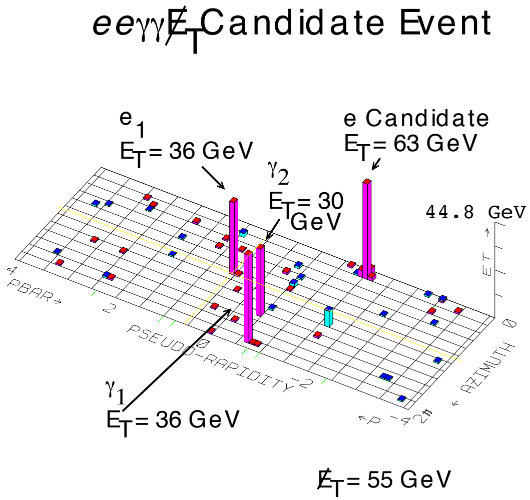
Compositeness?



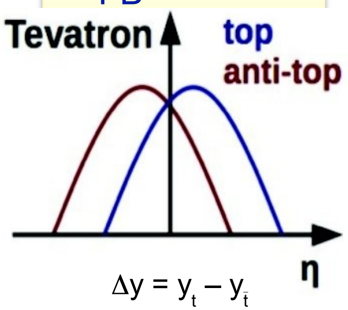


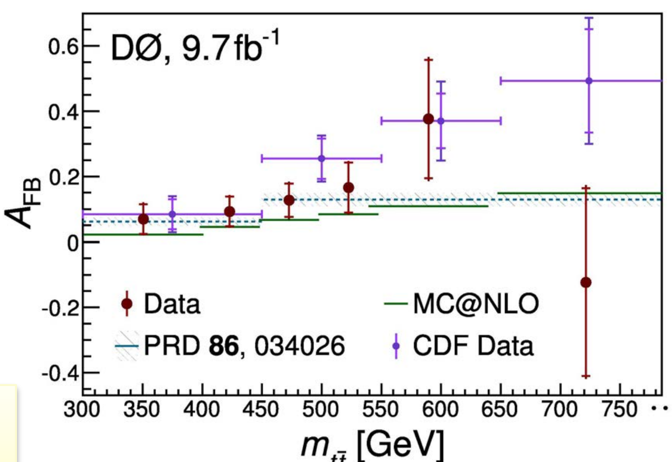
Nope; mainly PDFs…
(plus JEC/JES)

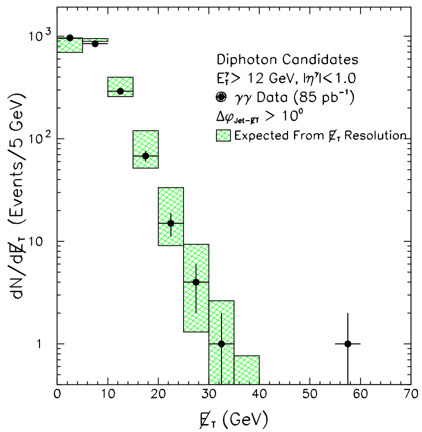
SUSY? Selectron pairs?



$A_{FB} \to Z'$?







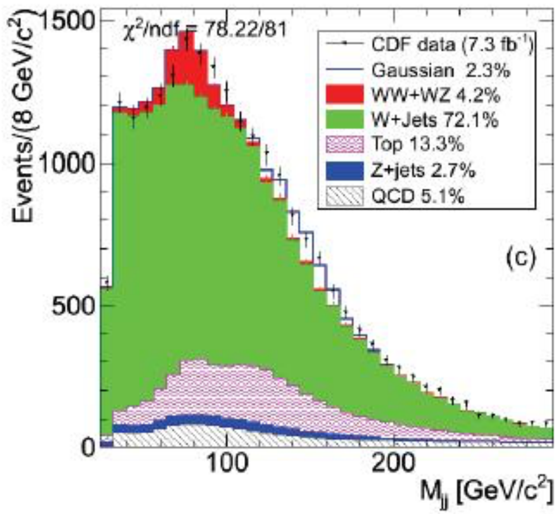
Bkg: ~10^{-6}

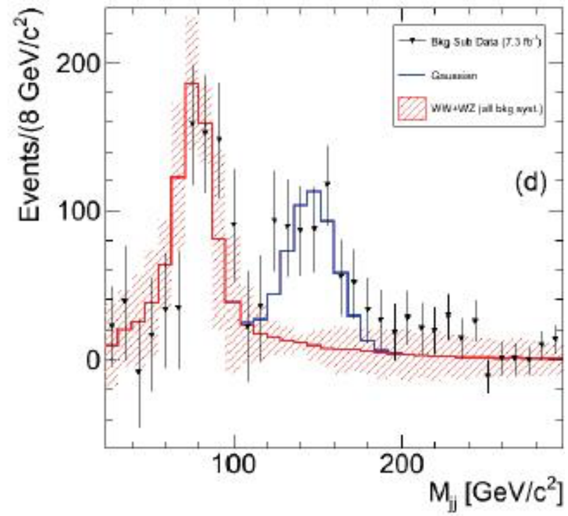
Nope; stats+the

Nope; stats…(?)

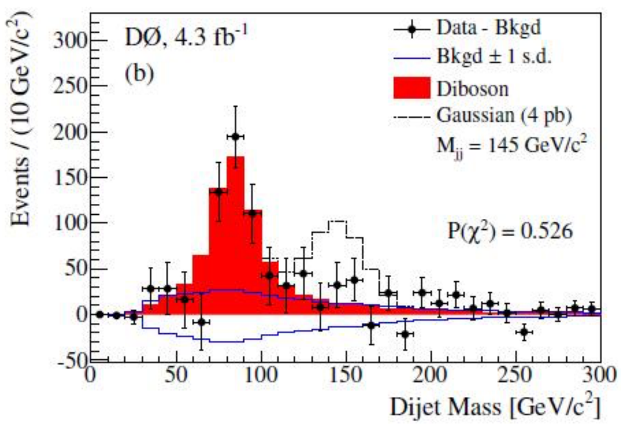
There was also excitement... (II)

W+jj events…
New resonance, X, with X→jj and m_X≈145 GeV?





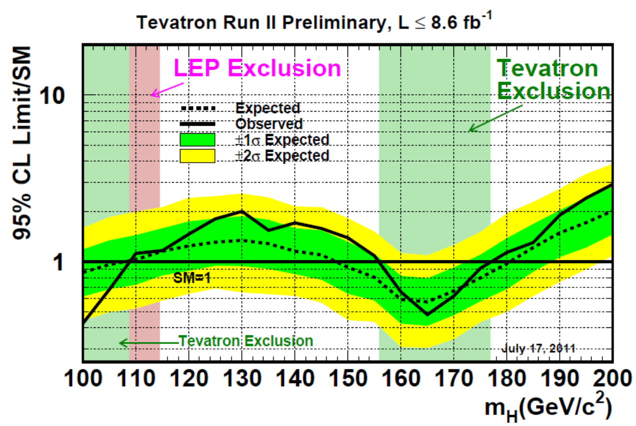
Nope; excluded by D0…
Mainly JEC and JES and q/g differences

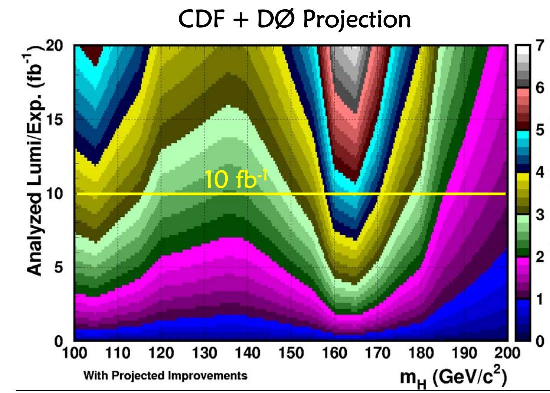


The end of the Tevatron: the Higgs

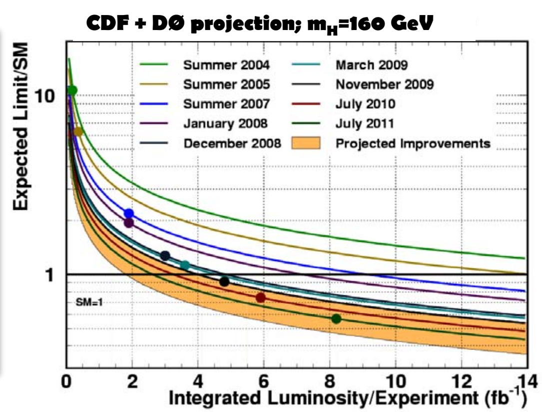
- **By end of Tevatron era: only one missing element in the Standard Model, the Higgs boson**

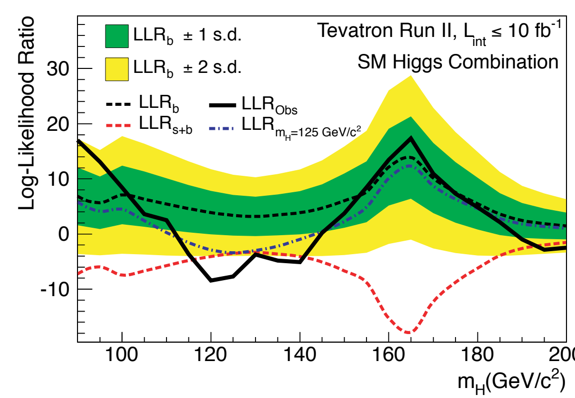
Summer 2011: $108<m_H<156$ or $m_H>177$





With time, limits improved faster than √L: new channels, better b-tagging, lepton ID/eff, jet resolutions…





The Tevatron

The word "success" does not do justice
Yet… the Higgs Boson did not show up

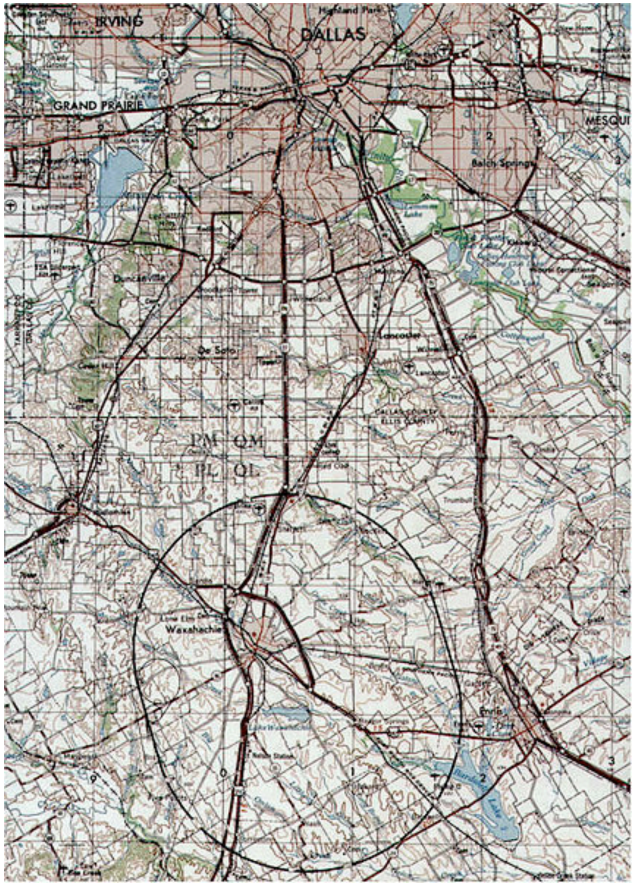
As far back as in mid 80's, people realized a new machine would be needed

The Superconducting Supercollider (SSC)

aka "the HIGGSatron"

The machine what was not meant to be

- The dream of the 90s: "today's physics at the Tevatron, tomorrow's physics at the SSC"
- Provided much of the motivation for crossing the Atlantic (towards the Atlantic in the early 90s
- SSC: a machine like no other
  - 87 km! 40 TeV! (Tevatron was 2 TeV!)



CATO report

- **May 92:**

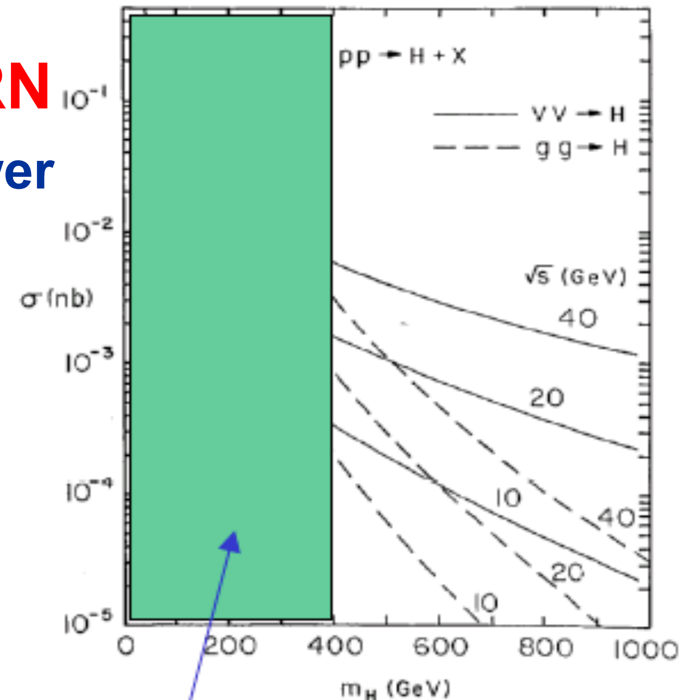
  "Congress soon will be deciding the fate of the Superconducting Super Collider—the $11 billion Department of Energy atom smasher.

  After five years of skyrocketing cost estimates and increasing skepticism about the scientific merit of the SSC, there is now growing support on Capital Hill for pulling the plug on what would be one of the most expensive science projects ever undertaken by the federal government.

  The administration, however, has been lobbying furiously to spare the SSC from the budget knife and even proposes a 30 percent increase in the project's budget…"

A machine for EWSB

- **Superconducting Supercollider (SSC) $\sqrt{s}$=40 TeV...**
  - **Would have started in 1999 (!)**
- **So: use existing LEP tunnel at CERN**
  - **Replace: e by p; increase bending power**
    - ➨ **Large Hadron Collider**

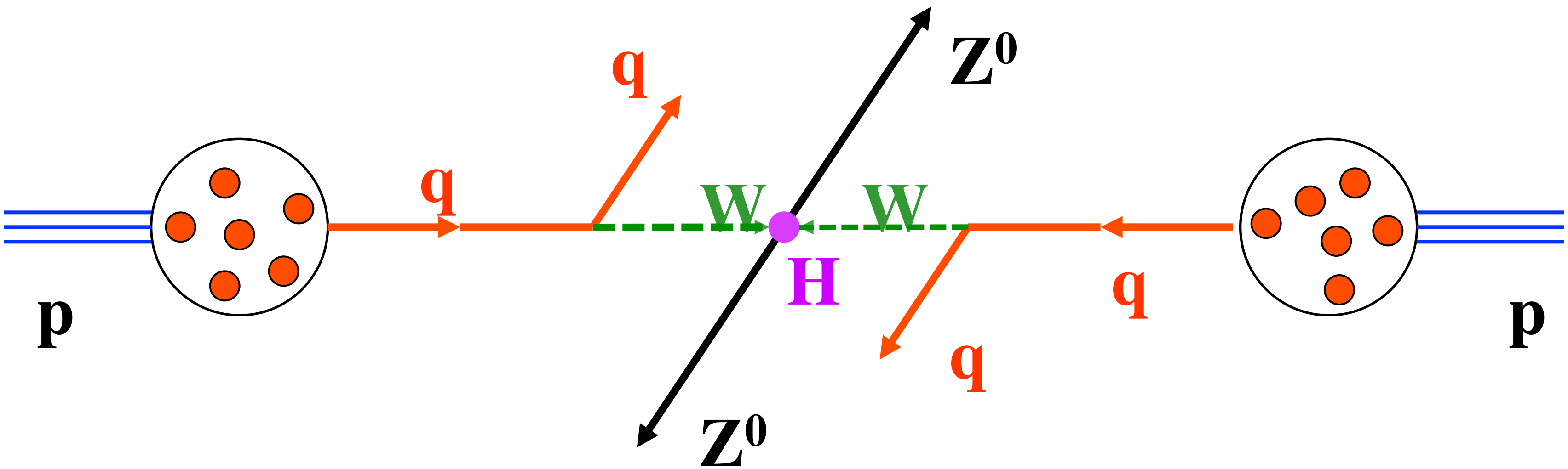


D.Dicus, S. Willenbrock

Phys.Rev.D32:1642,1985

Not true any more (M_T=175 GeV)

Higgs Production in pp Collisions

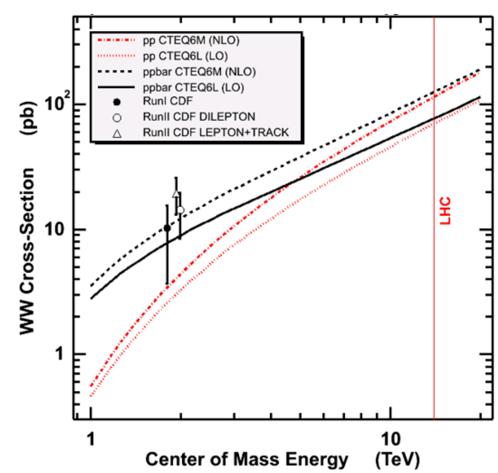


M_H ~ 1000 GeV

$E_W \geq$ 500 GeV

$E_q \geq$ 1000 GeV (1 TeV)

$E_p \geq$ 6000 GeV (6 TeV)



No need for p-pbar…

→ Proton Proton Collider with $E_p \geq$ 6-7 TeV

pp collisions at 14 TeV at 10^{34} cm^{-2}s^{-1}

Interactions/x-ing:

$L = 10^{34}$ cm^{-2}s^{-1}

$\sigma(pp)$ = 70 mb

→ $R_{interactions} = 7\times10^{8}$ Hz

Time/BC, Δt = 25 ns

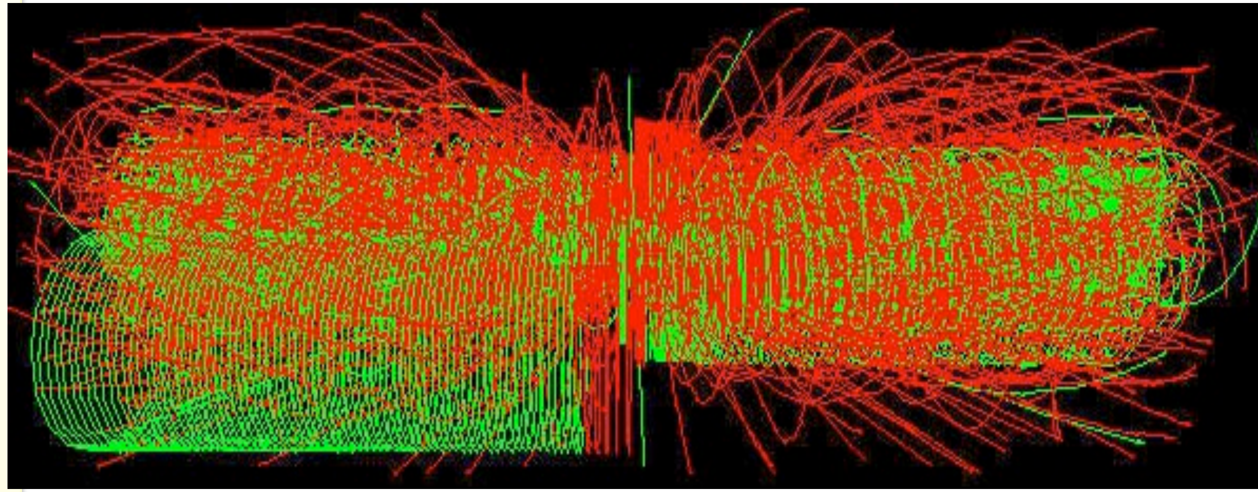
Interactions/BC=17.5

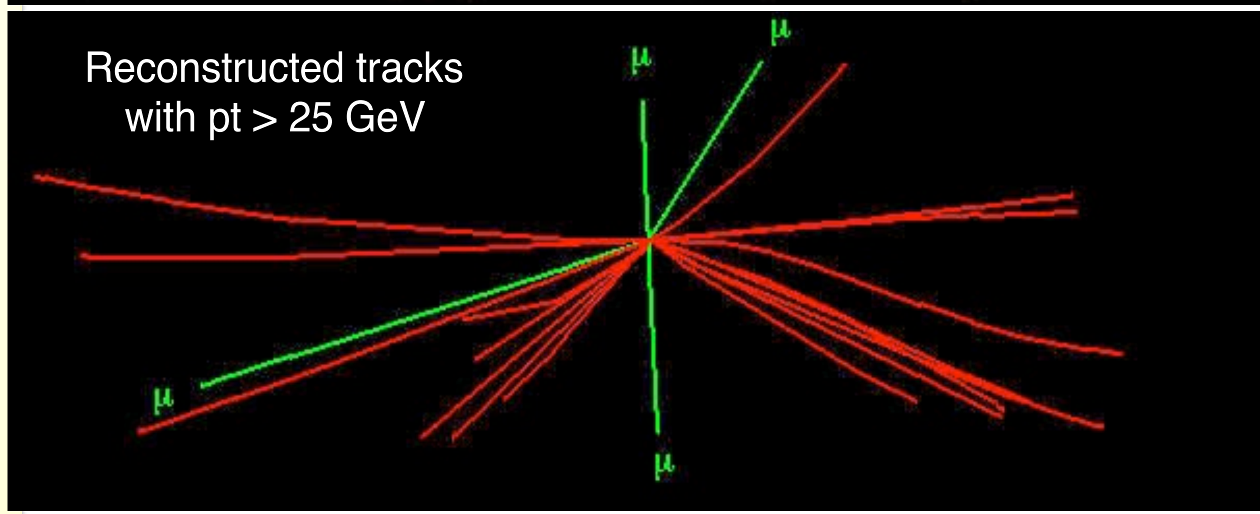
80% bunches full:
17.5x5/4 = 23

~ 20 min-bias events overlap!

Example: the cleanest ("golden") Higgs signature:

$H \rightarrow ZZ$, $Z \rightarrow \mu\mu$, $H \rightarrow 4\mu$:



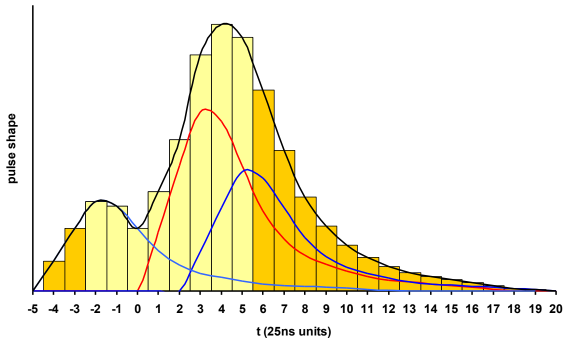


And this (not the H...) would repeat every 25 ns

The LHC challenge

LHC challenges: detector design

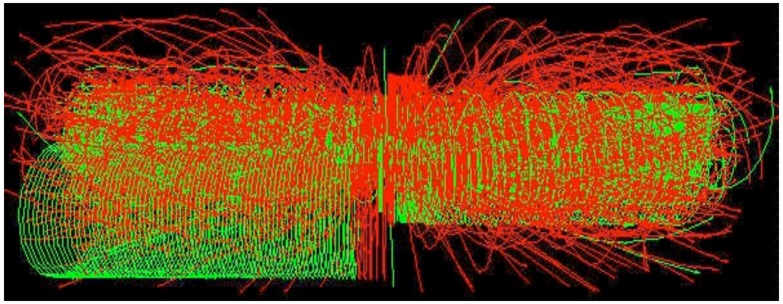
- **LHC detectors must have fast response**
  - Otherwise will integrate over many bunch crossings → large "pile-up"
  - Typical response time : 20-50 ns
    - → challenging readout electronics



- **LHC detectors must be highly granular**
  - Minimize probability that pile-up particles be in the same detector element as interesting object
    - → large number of electronic channels; high cost

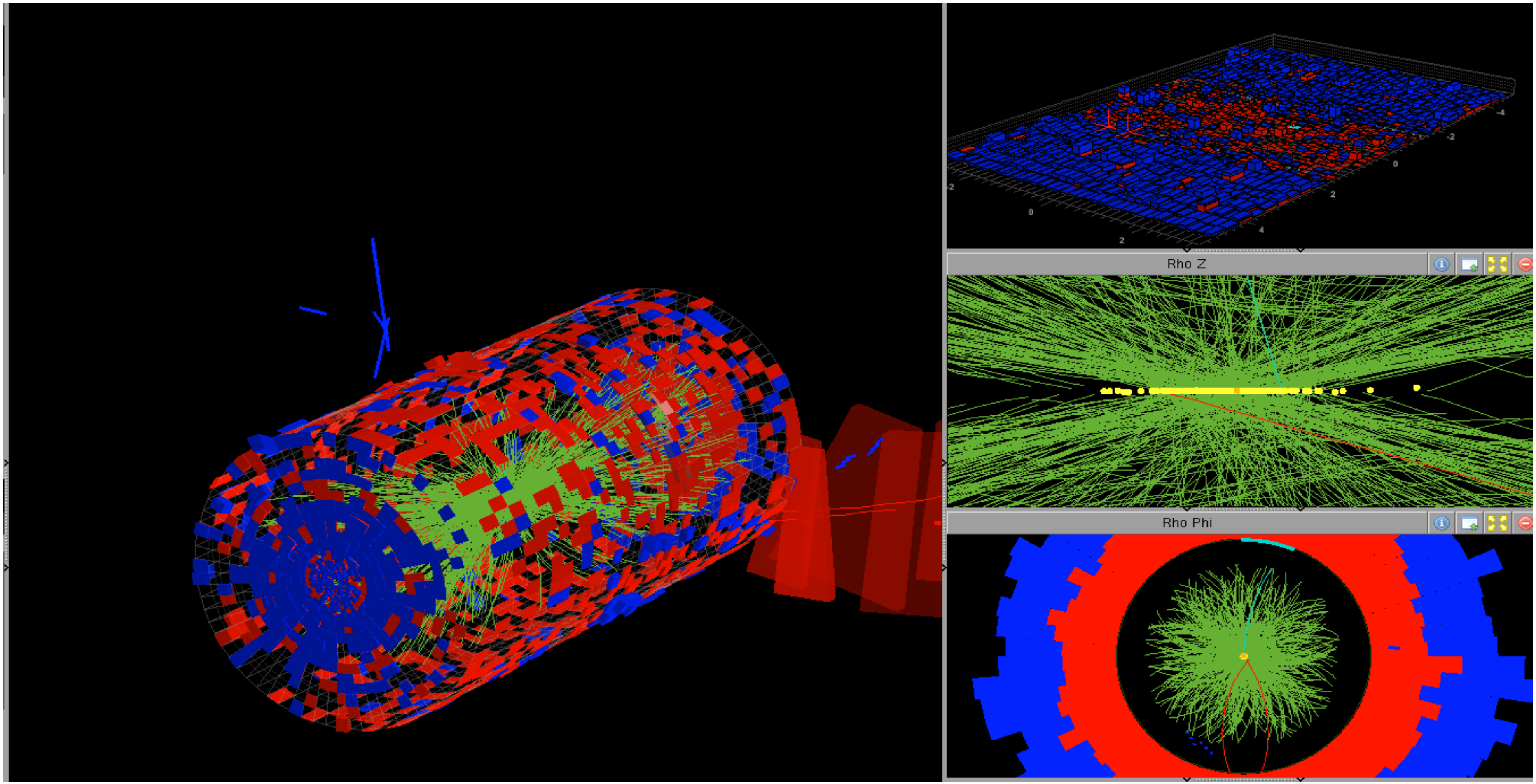
100 million channels per detector!

- **LHC detectors must be radiation-resistant:**
  - high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters in 10 yrs of LHC:
    - up to 10^{17} n/cm^2 [10^7 Gy; 1 Gy = 1 Joule/Kg)

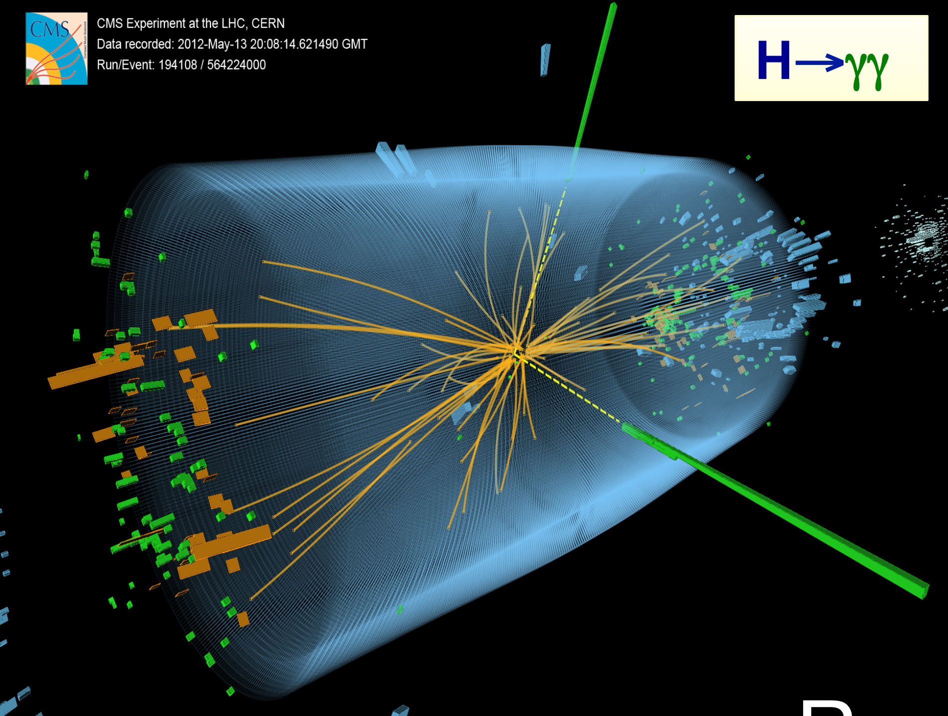


Going beyond design conditions

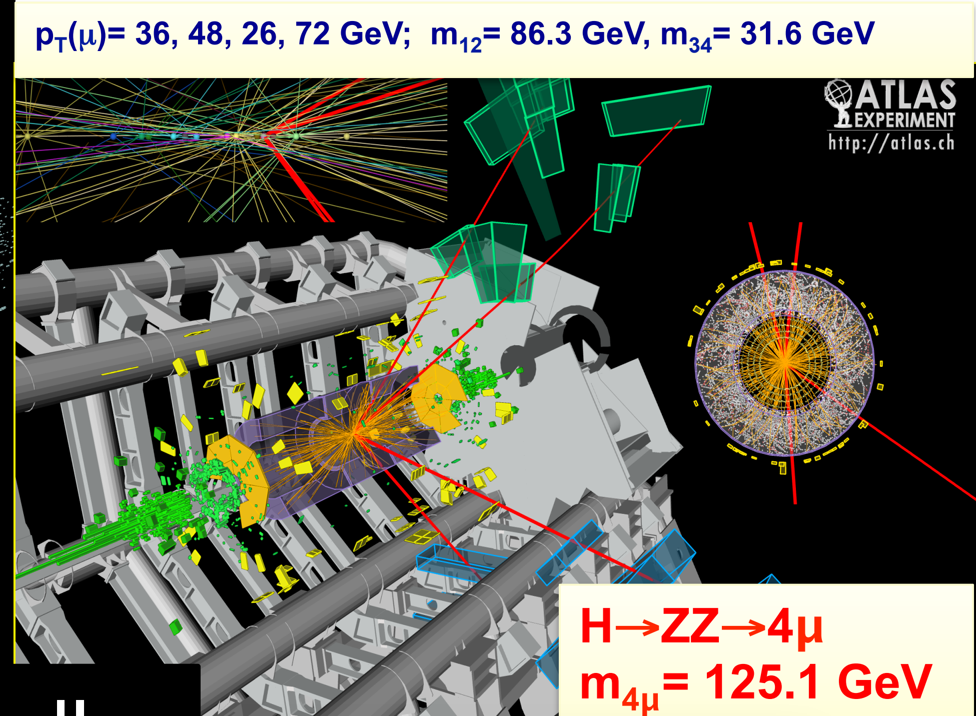
CMS event with 78 reconstructed vertices and 2 muons…



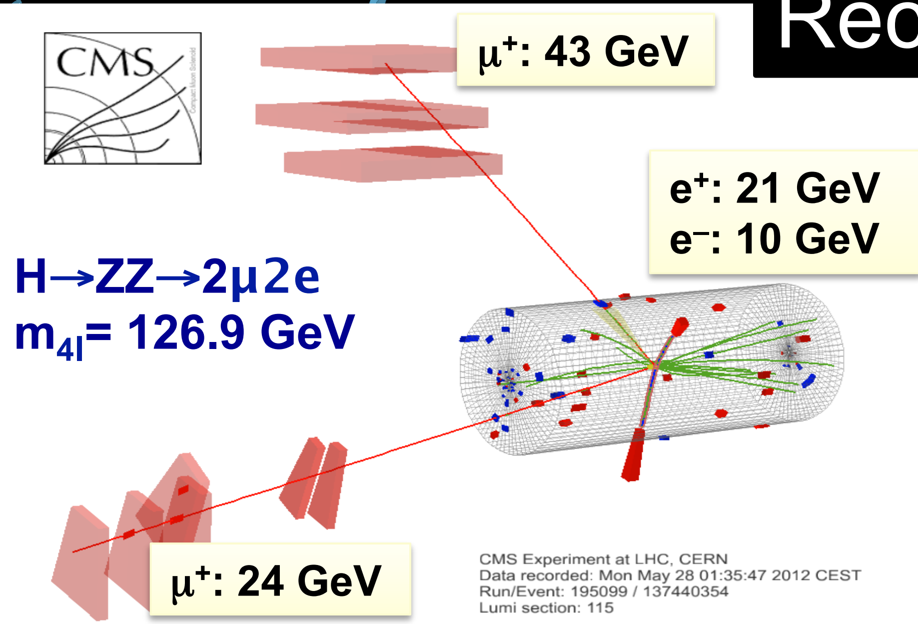
Recall…



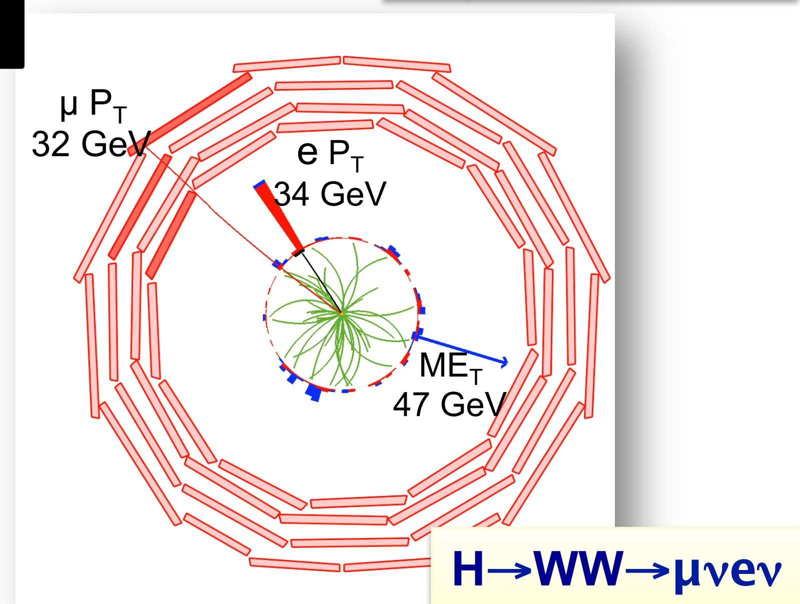
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H→γγ



$p_T(\mu)$= 36, 48, 26, 72 GeV; m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
ATLAS EXPERIMENT
http://atlas.ch
H→ZZ→4μ
$m_{4\mu}$= 125.1 GeV



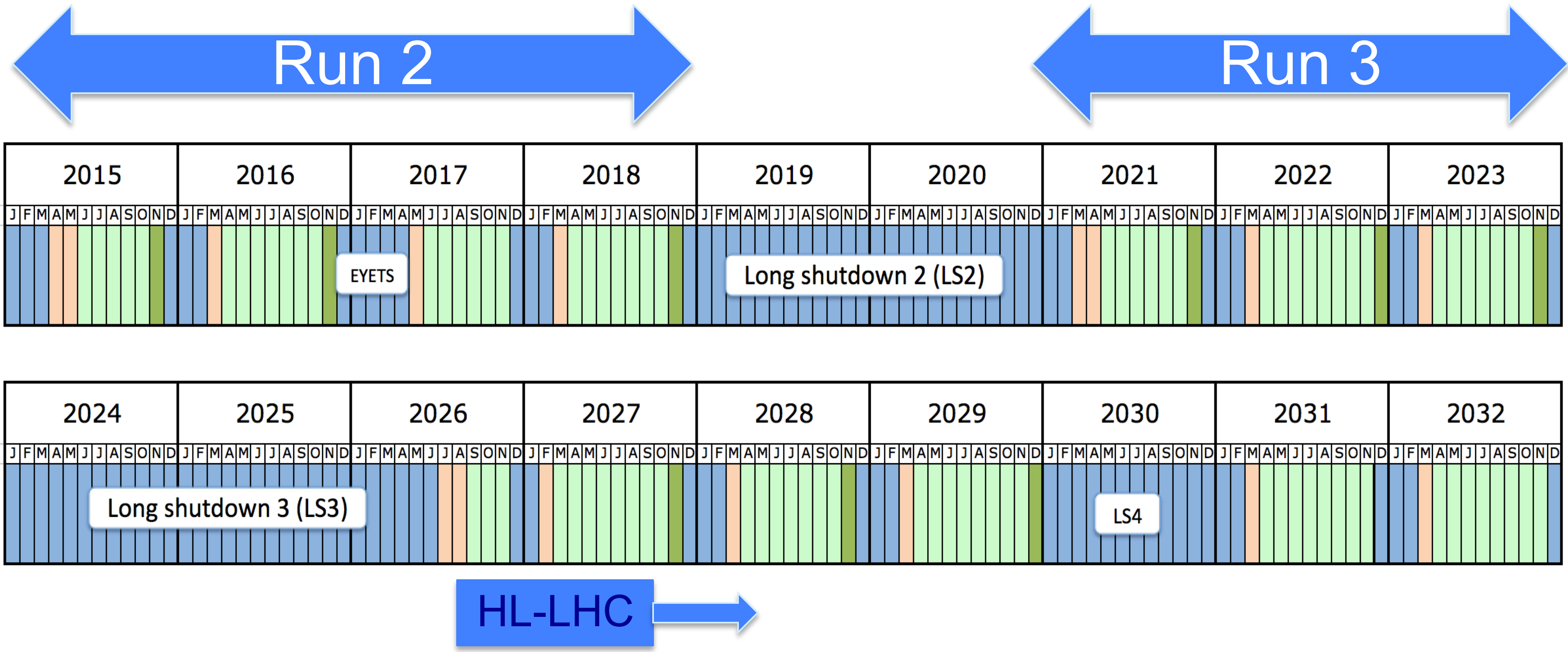
CMS
μ⁺: 43 GeV
e⁺: 21 GeV
e⁻: 10 GeV
H→ZZ→2μ2e
m_{4l}= 126.9 GeV
μ⁺: 24 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115



μ P_T
32 GeV
e P_T
34 GeV
ME_T
47 GeV
H→WW→μνeν

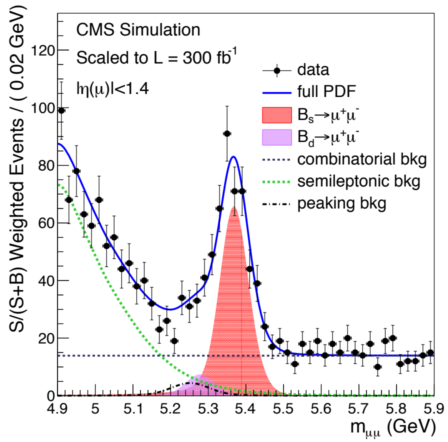
Short-term Outlook
(LHC at 13-14 TeV & at very high luminosity)

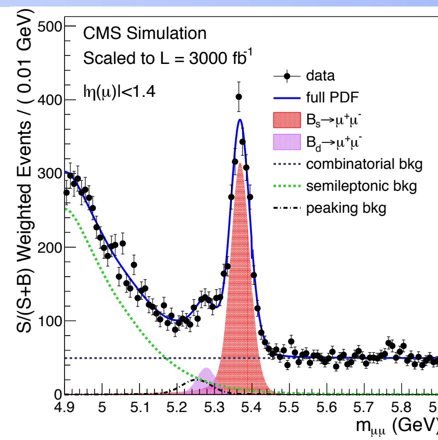
LHC plan

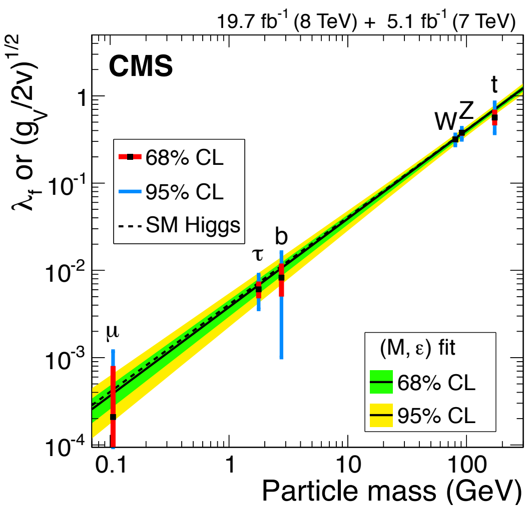


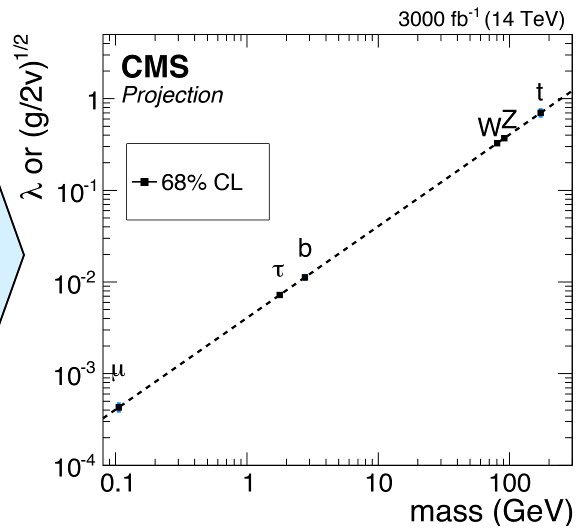
Run 2
Run 3
2015
2016
2017
2018
2019
2020
2021
2022
2023
EYETS
Long shutdown 2 (LS2)
2024
2025
2026
2027
2028
2029
2030
2031
2032
Long shutdown 3 (LS3)
LS4
HL-LHC

There is power (and physics) in these improvements





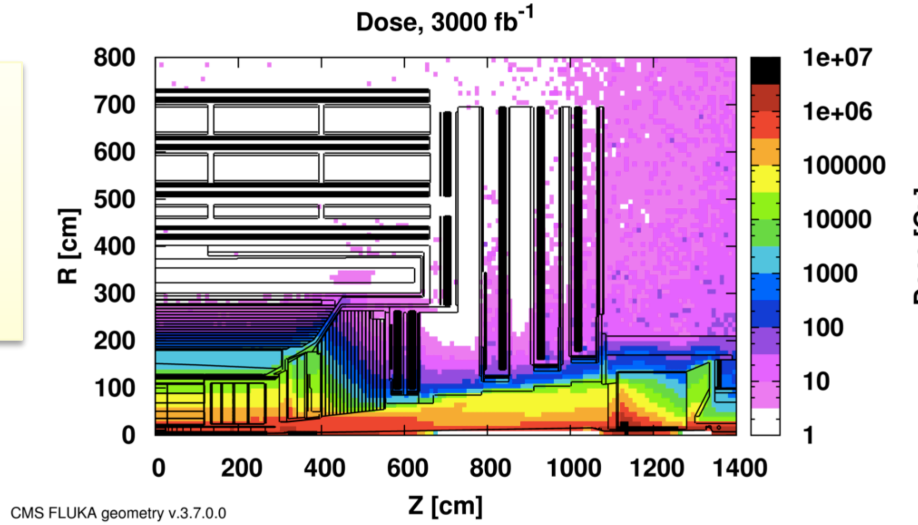




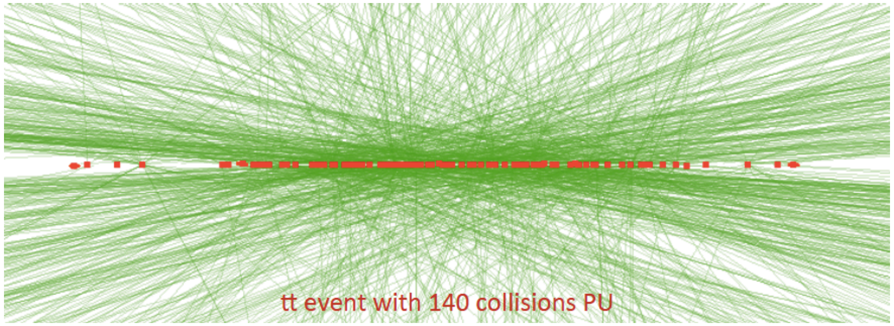
En route to these: new detector elements that represent major new technology & instrumentation breakthroughs

HL-LHC challenges

Annual dose at HL-LHC: similar to total dose from LHC start to LS3



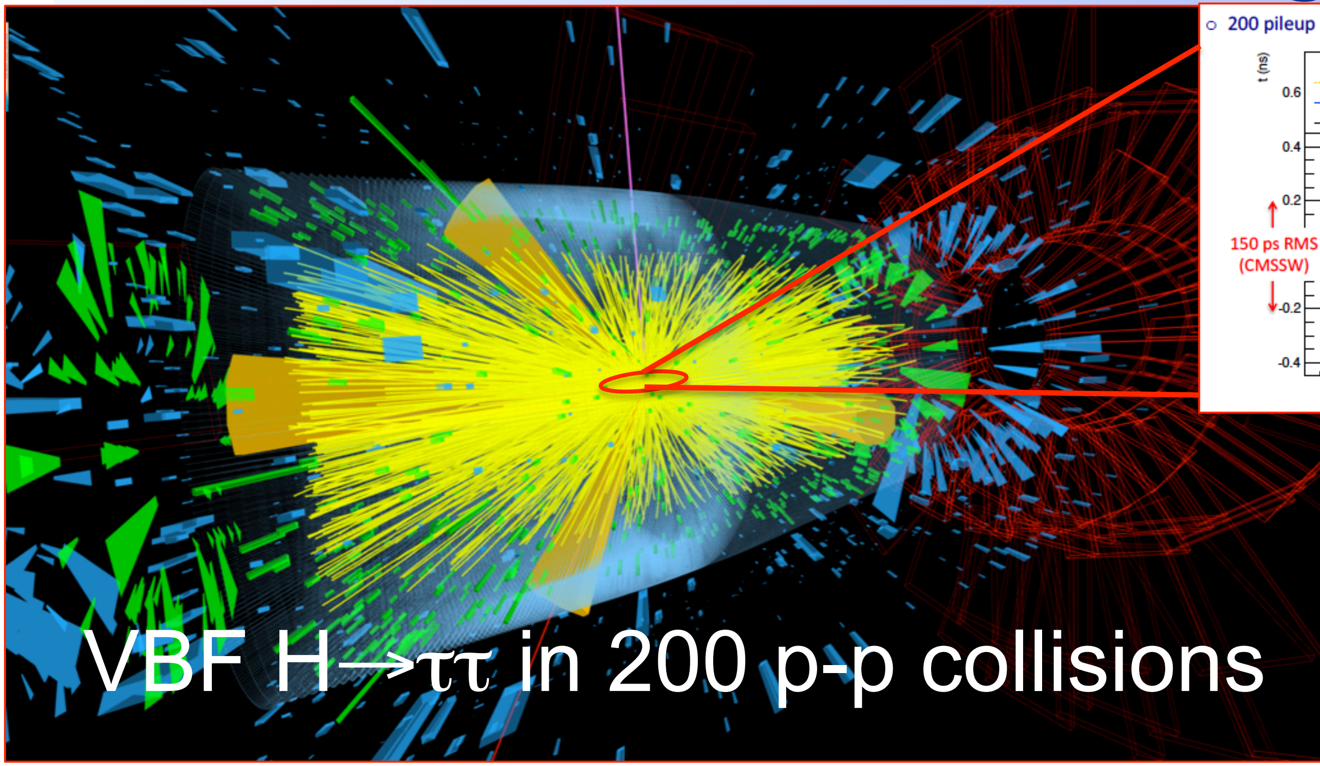
Key to physics: maintain detector performance in the presence of much higher pileup (140-200!)

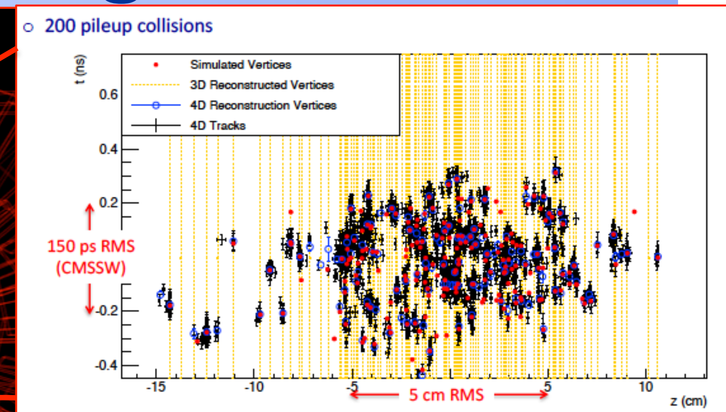


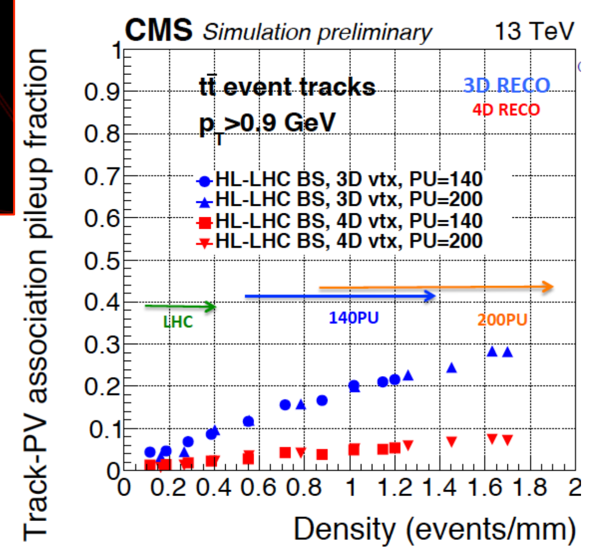
Upgrade several detector components

Redesign some electronics, Trigger and DAQ

Example of cool new stuff: 4D reconstruction & Timing Detector







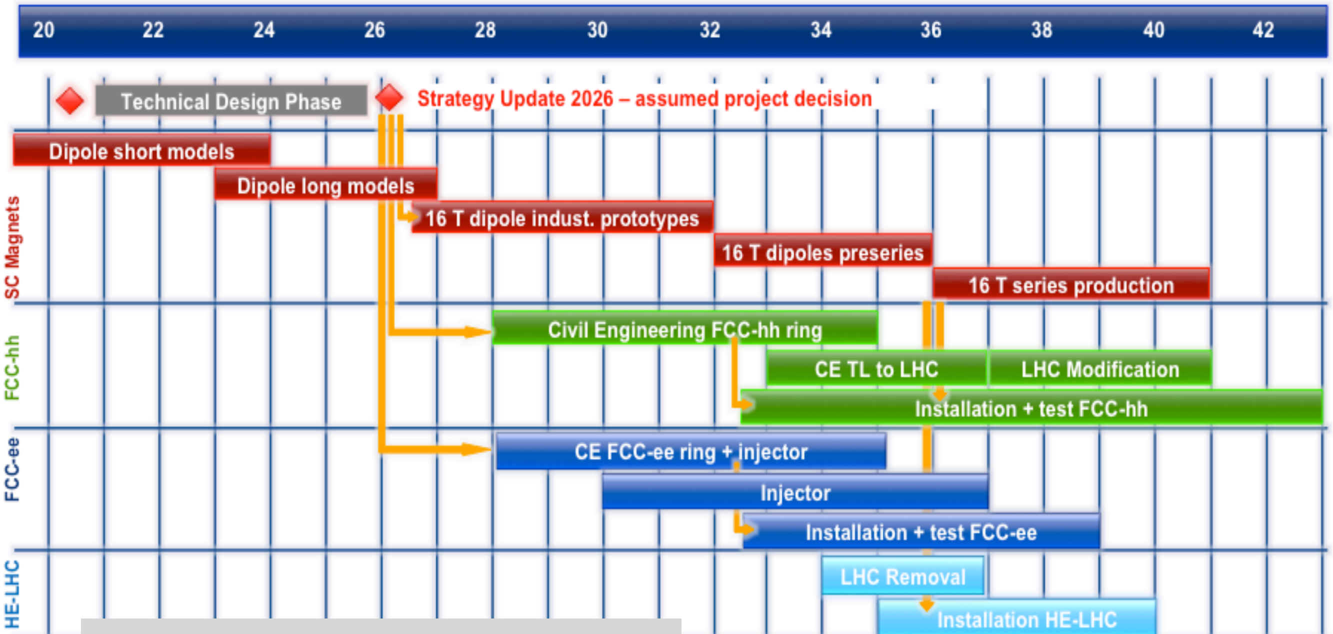
Time of flight precision ≃ 30 ps, $|\eta|$< 3, p_T > 0.7 GeV

"Provide a factor 4-5 effective pile-up reduction"

- ≃ 15% merged vertices reduce to ≃ 1.5%
- Low pileup track purity of vertices recovered

Long-term Outlook

Towards a new machine



"Technically limited schedule"

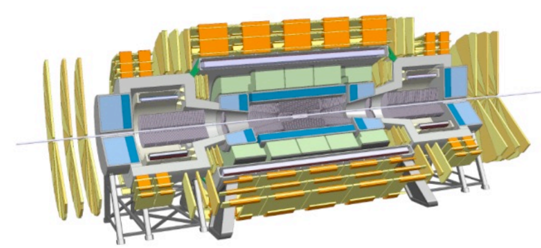
FCC: 100 TeV
HE-LHC: 27 TeV

Pileup: 1000
Data: 10^3 PB/s

Next step in energy: driven by magnets… begs for more investment on this front

And of course on new acceleration methods.

- <u>Provide firm Yes/No answers</u> to questions like:
  - is the SM dynamics all there is at the TeV scale?
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - did baryogenesis take place during the EW phase transition?



$$\left|\psi_{FCC-hh}\right\rangle = \sum c_i \left|\psi_{LHC,i}\right\rangle$$

Summary

- **Over the past 40 years experiments at hadron colliders have pushed the energy frontier**
  - **Including pBe collisions, we got three new quarks (c, b, t) two gauge bosons (W, Z) and a new boson (H). The latter appears to be a particle like no other!**
- **Currently: the biggest, greatest HEP instrument thus far, the LHC and its experiments**
  - **Beautiful physics-producing engines! Plus, a new portal: the Higgs boson with mass 125 GeV**
    - **We are only beginning to probe its properties**
    - **Plus, there are huge reasons to believe that new physics should be within reach; just note down the lessons learnt as we move towards the next machine(s)**
- **F. Dyson: "New directions in science are launched by new tools more often than by new concepts. The effect of a concept–driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained!"**