

# Hadron collider physics: a historical perspective

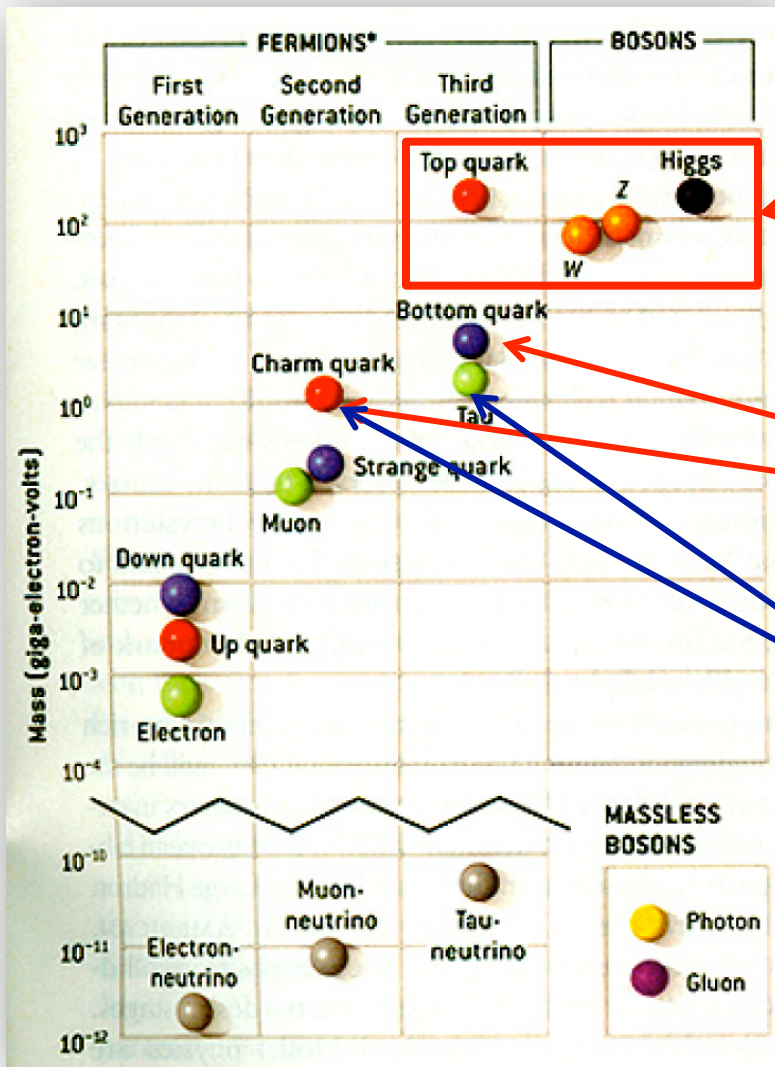
*Paris Sphicas  
CERN & NKUA (Athens)  
CERN, August 31, 2017*

- **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
- **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

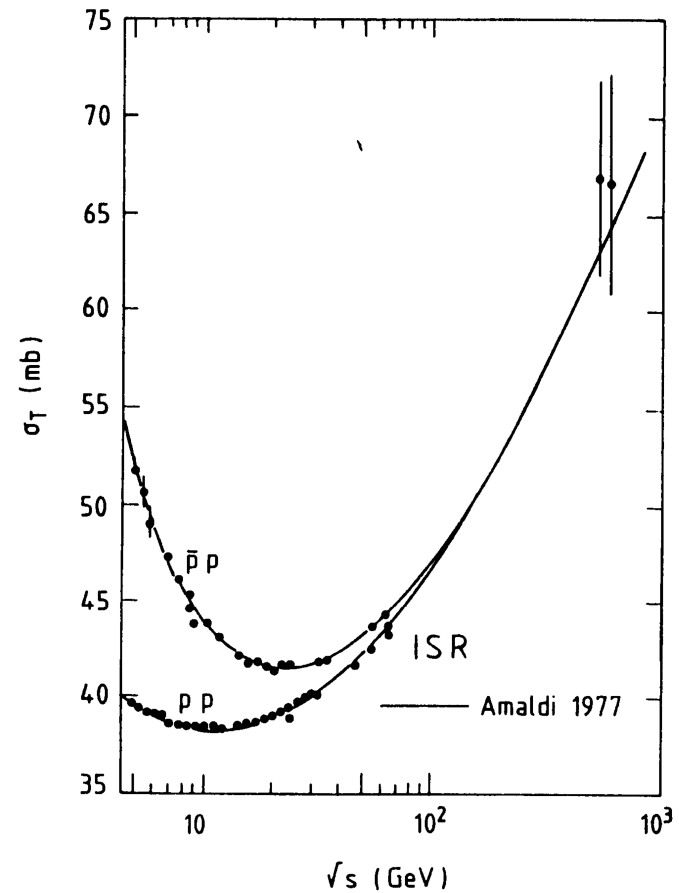
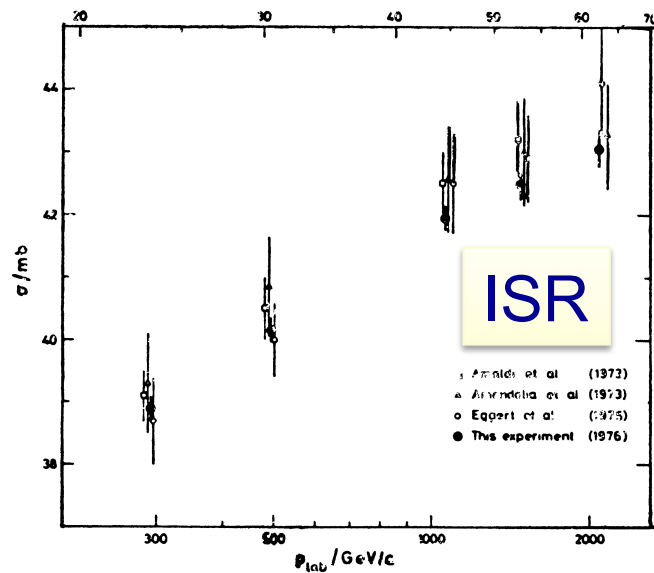
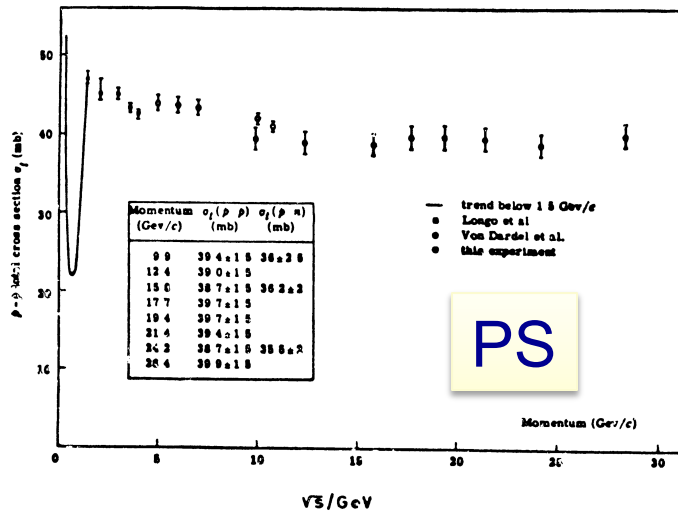
Hadron Collisions  
b quark: E288 @ FNAL  
c quark: pBe @ AGS

ee Collider  
c and  $\tau$  SPEAR

Not shown: probing the strong, weak and EM interactions

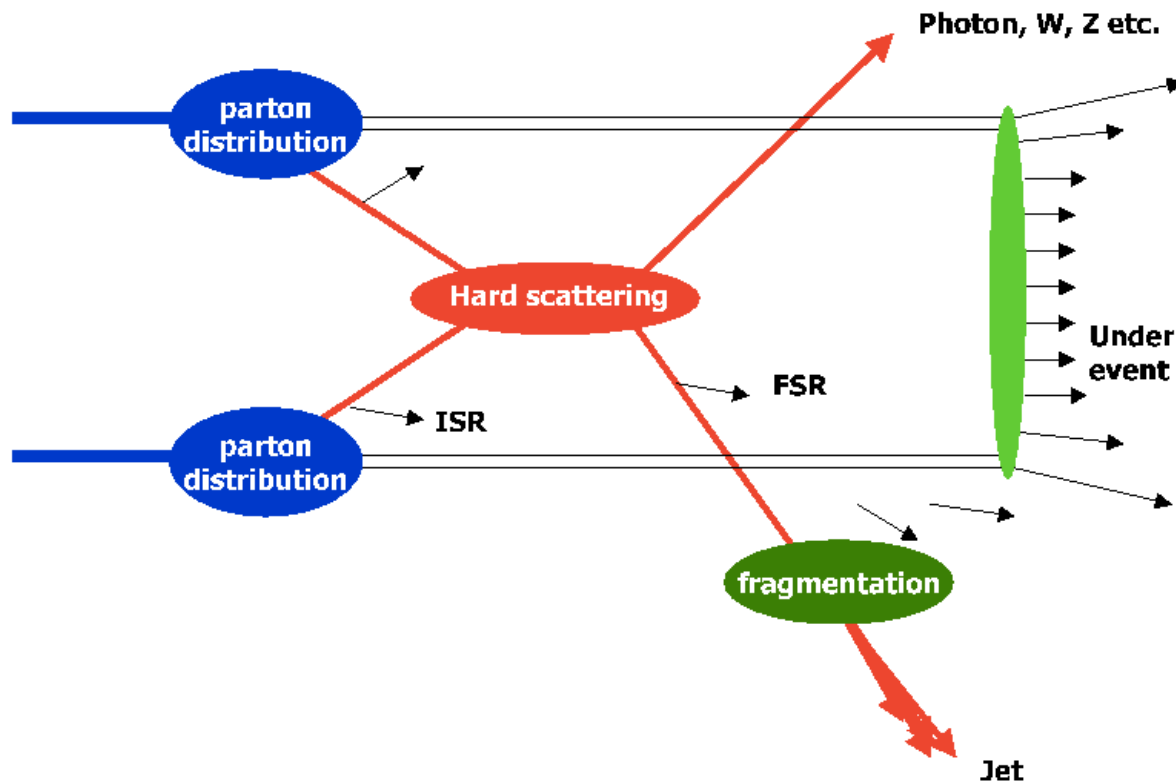
**The beginning: AGS and ISR;  
Two + one lessons**

# ISR discovery: rising pp and ppbar $\sigma$



# 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?

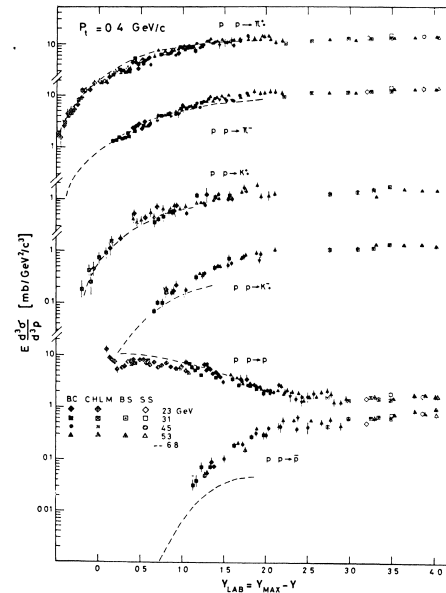
- CCR: inclusive particle spectra  
→ excess @ large  $P_T$ . Expected vs seen:

CIM

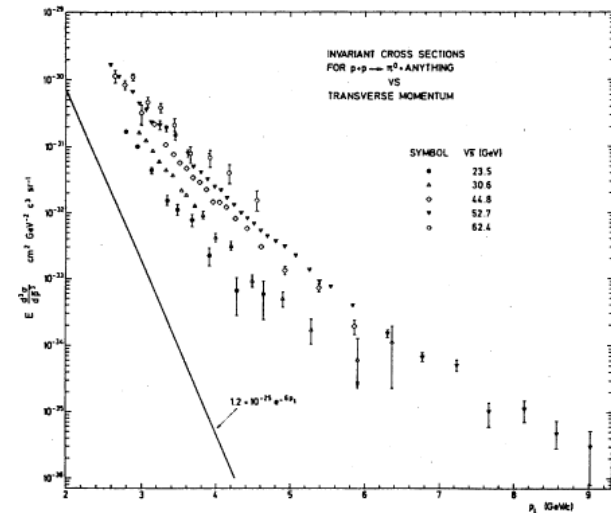
$$E \frac{d^3\sigma}{dp^3} \approx A \frac{1}{P_T^8} \exp(-26x_T)$$

points:

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



Feynman  
scaling &  
rapidity  
plateau



# “Jets” were missing...

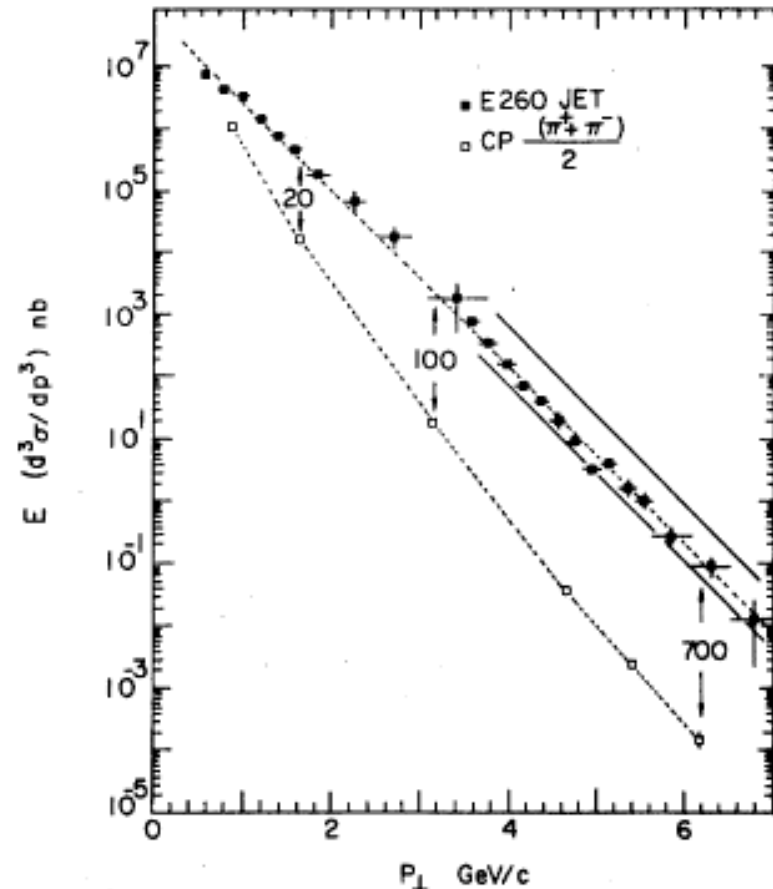
## ■ Killed by the trigger:

ISR: triggering on single particles, not global  $E_T$

1) Absence of CALO triggers (small  $E \rightarrow$  bad CALO response)

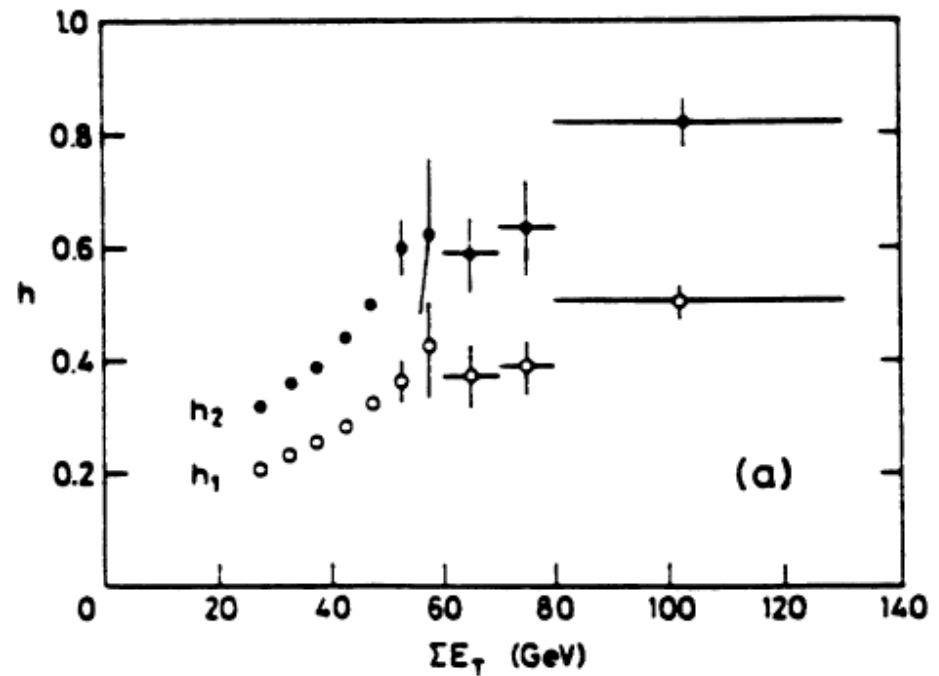
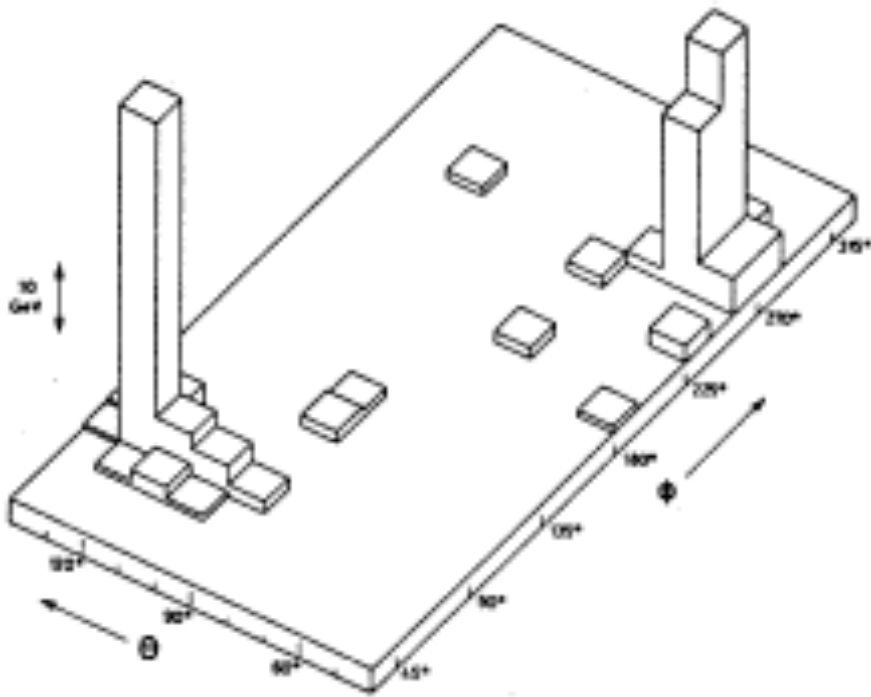
2) Jet spectrum: much steeper  $P_T$  spectrum than fragmentation  $\rightarrow$  particle of given  $P_T$  most likely the leading particle of a soft jet...

**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/ $\psi$

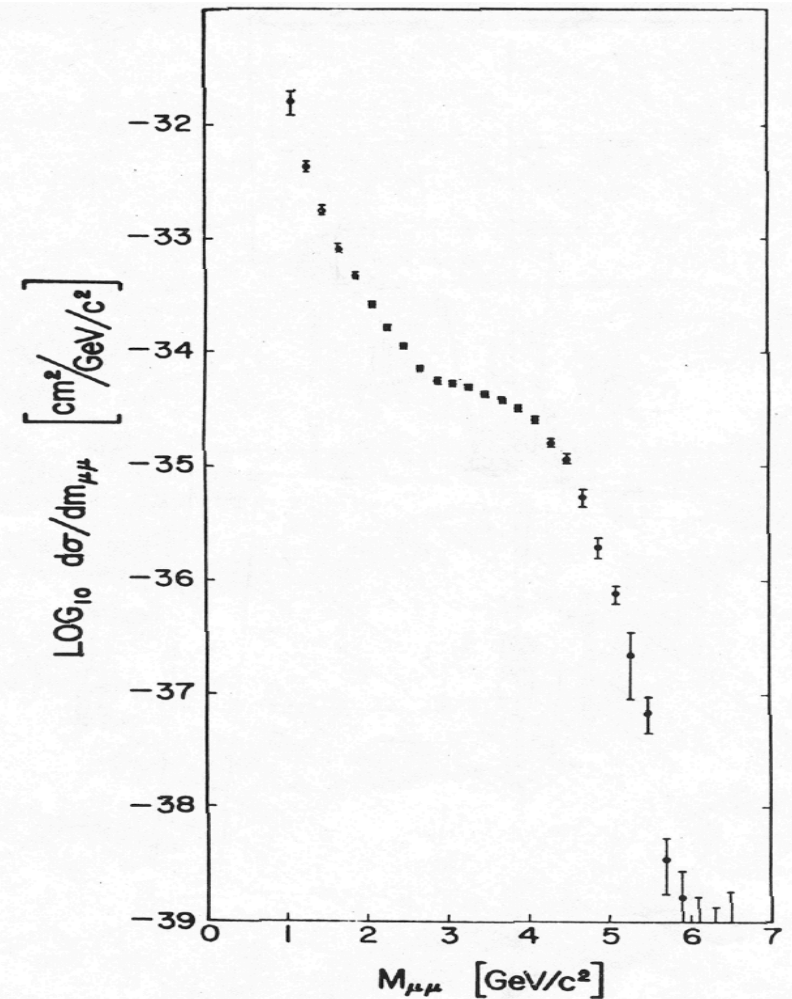
## ■ From Leon Lederman's autobiography at FNAL:

<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.”

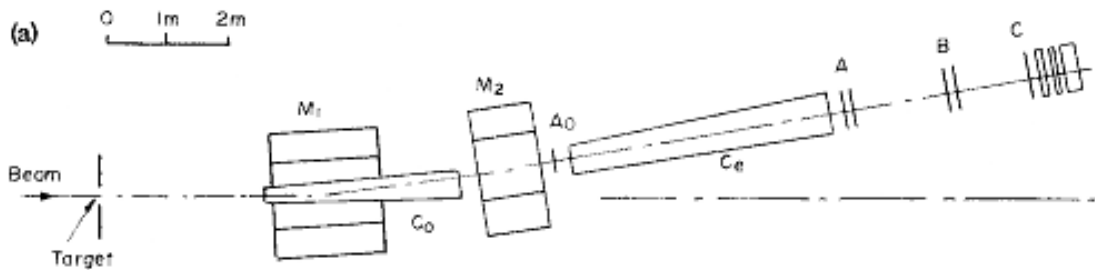
“In 1968 he invented the di-muon experiment and missed the J/ $\psi$  particle.”

**Lesson #2: resolution is so important!**



# Discoveries made: the $J/\psi$

## ■ Brookhaven AGS: $p + \text{Be} \rightarrow e^+ e^- X$



## ■ SPEAR at SLAC:

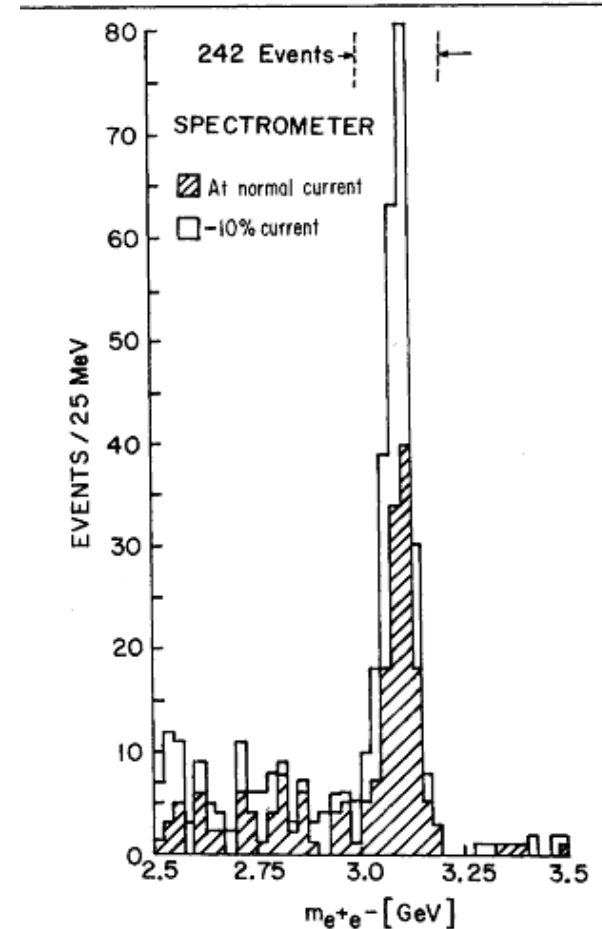
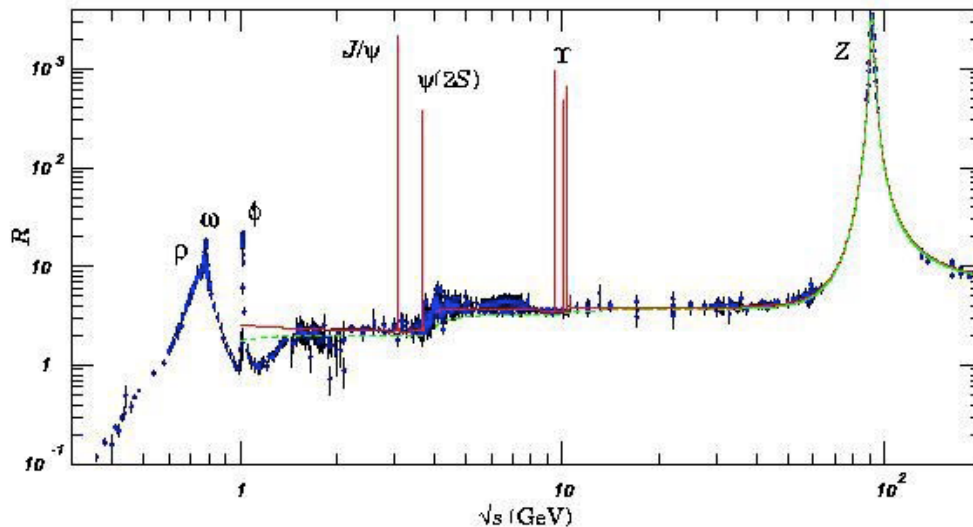


FIG. 2. Mass spectrum showing the existence of  $J$ . Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

# Evidence for the gluon (well...) SPS plans

## ■ Prompt photons seen:

- ◆ ABCS: unambiguous rise of  $\gamma/\pi^0$  ratio
- ◆ Highly non-trivial (experimentally) exercise:

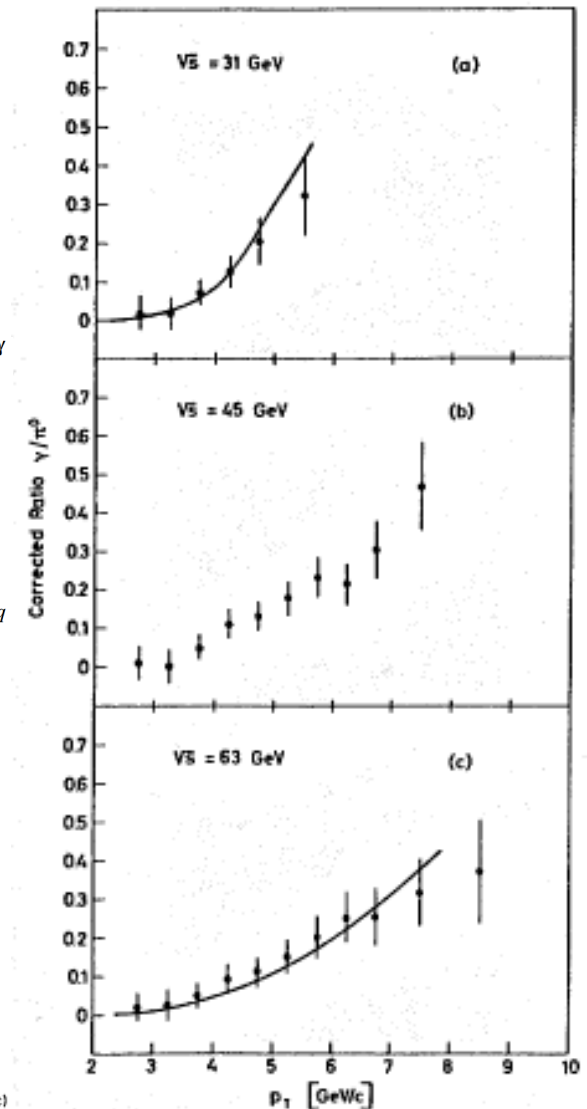
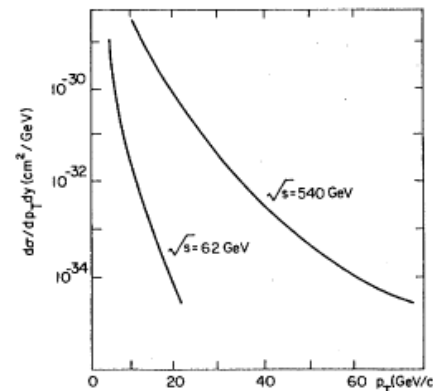
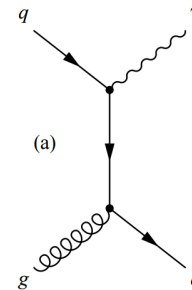
- Huge background from decay photons...

## ■ In QCD picture:

quark+gluon  $\rightarrow$  Quark +  $\gamma$

## ■ Yet, so indirect... ( $\pi^0$ )...

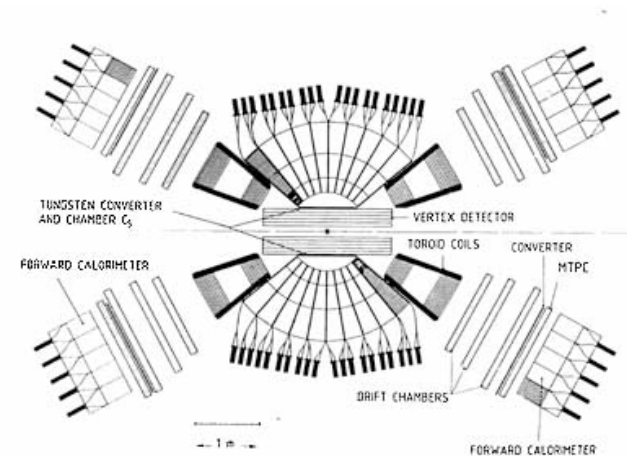
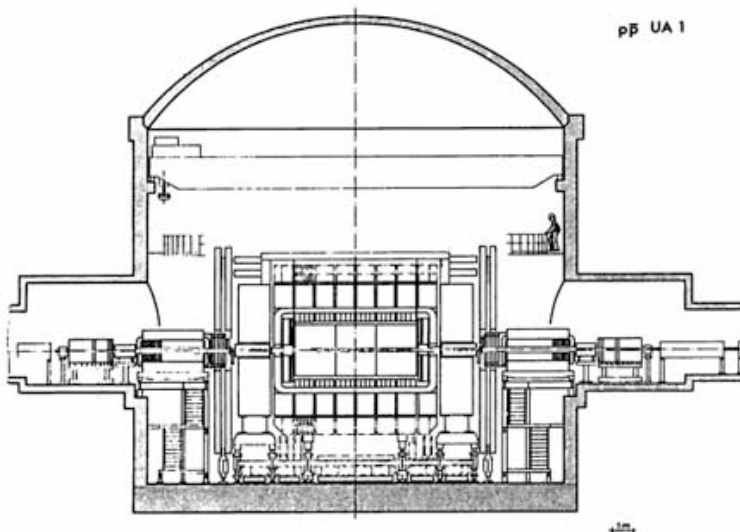
Meanwhile: SPS  
was in the works...  
Lesson #3: energy  
helps...



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

# UA1 (and UA2)

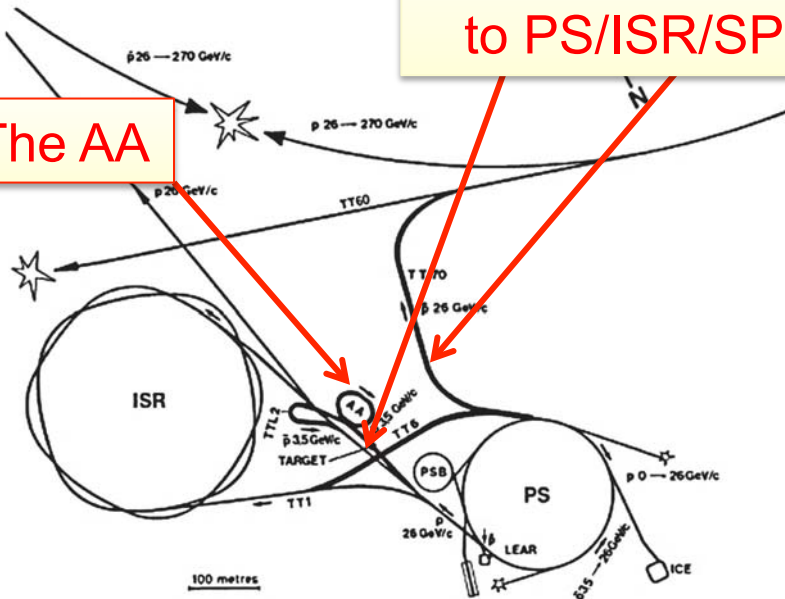
- **At the time, they were huge, very, very risky undertakings**
  - ◆ To begin with, the collider had to bring in protons and ANTI-protons to collide (cross section for W/Z production in pp was too small)
  - ◆ Second, and above all, the result was predicted to be a MESS
  - ◆ Third, they had to draw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



# The SPS and the magic of p-pbar collisions

New transfer lines  
to PS/ISR/SPS

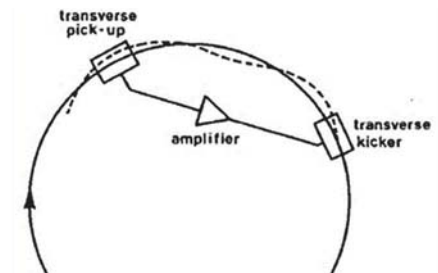
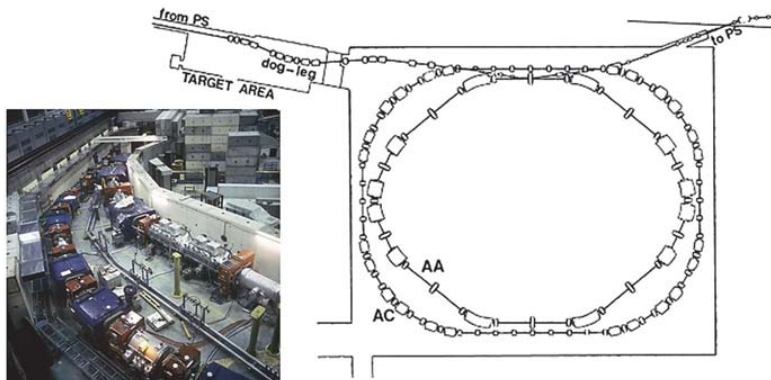
The AA



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

$N_i$  limits: injector; interaction with beam pipe; beam-beam interaction;  
p-pbar: limited by pbar injection  
Constraints: total  $I_b = k_b N_1$  (ee: RF;  
pp: losses in SC magnets; ppbar:  
pbar injection); transverse size! In  
hadron col:  $g_b \epsilon_n$  by injector.

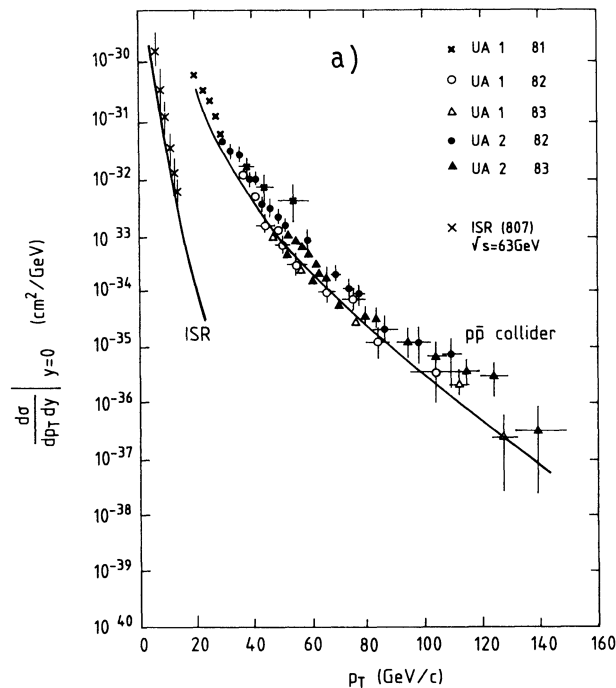
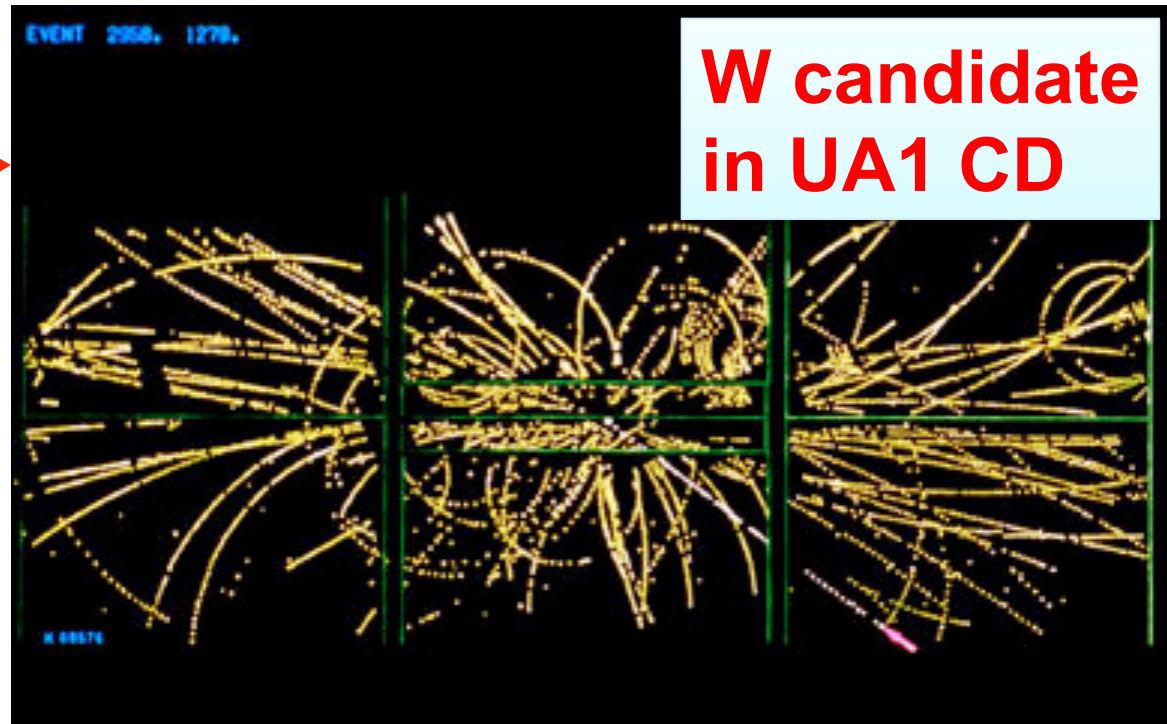
CERN  
Antiproton  
Accumulator  
(AA) ~end 70's



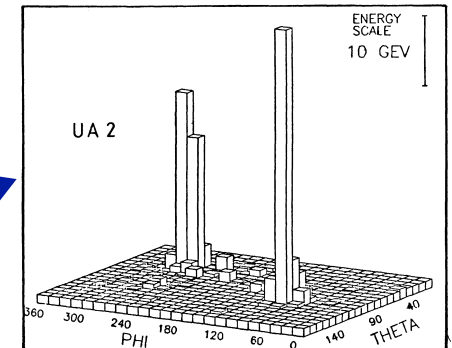
Stochastic Cooling  
(Simon van der Meer)

# A mess (or maybe not?)

The power  
of precision  
tracking



The action is in the  
transverse plane



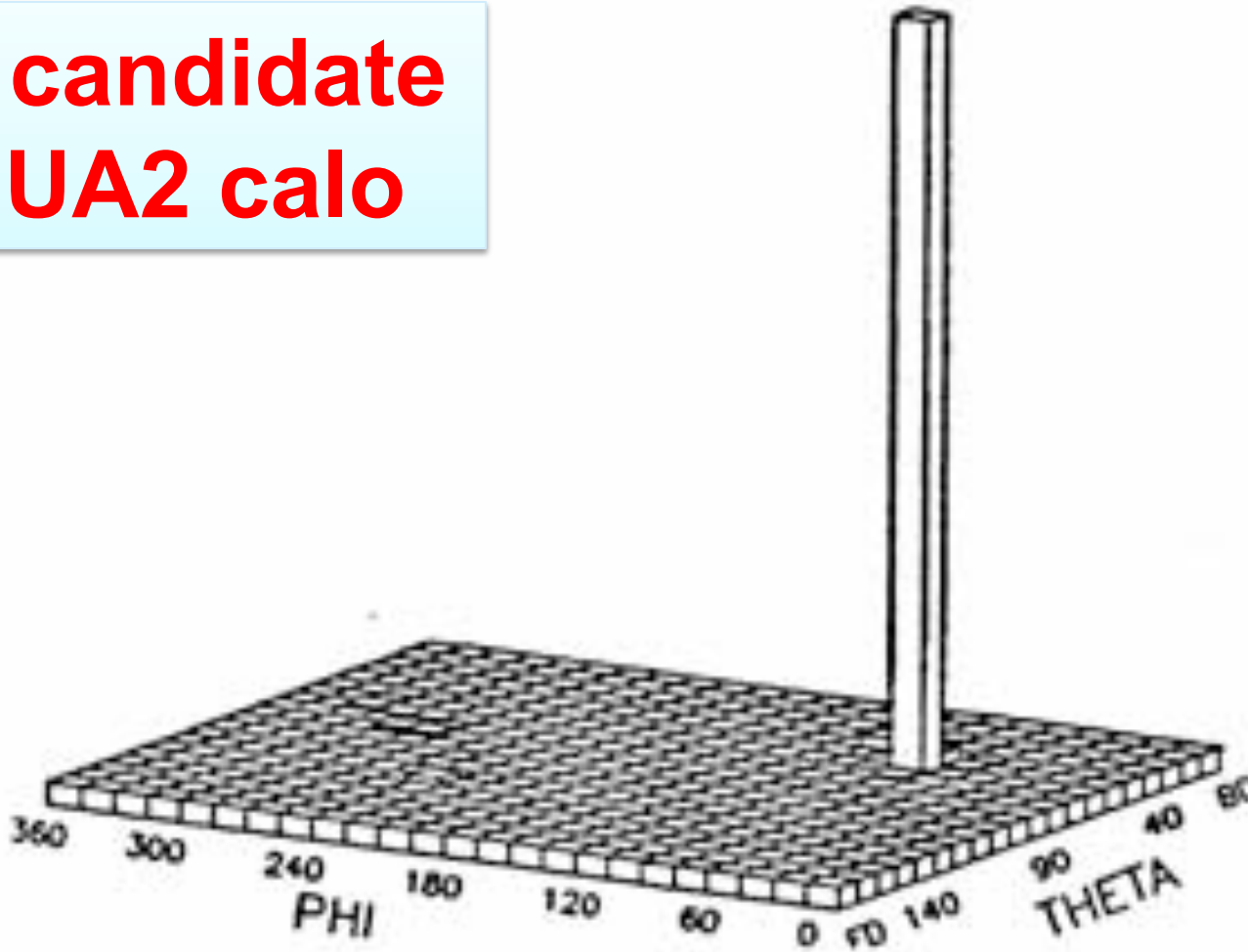
**Hermeticity**

**Calorimeter (inclusive) trigger**

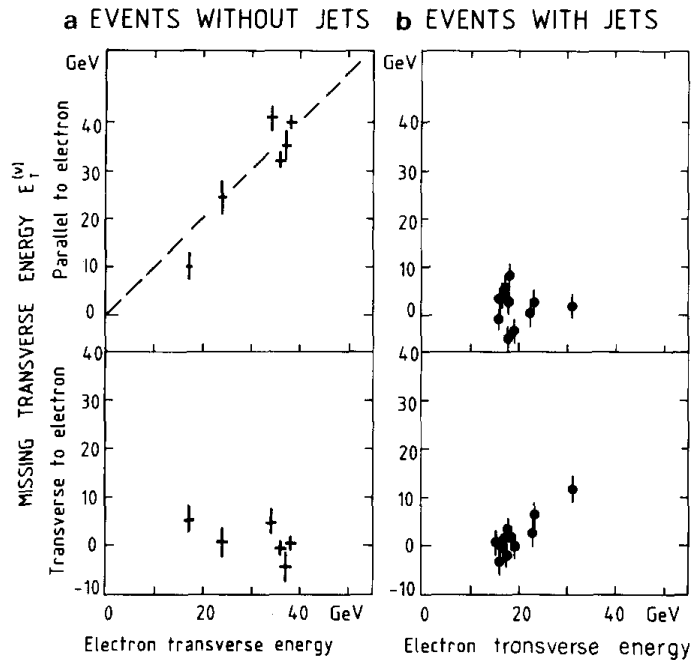
**Precision tracking**

# SPS legacy: “Intermediate Vector Bosons”

**W candidate  
in UA2 calo**

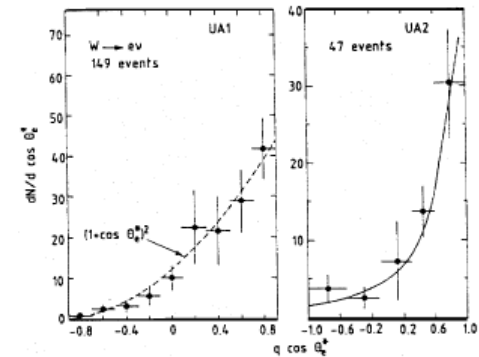


# The rendez-vous with the W boson



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

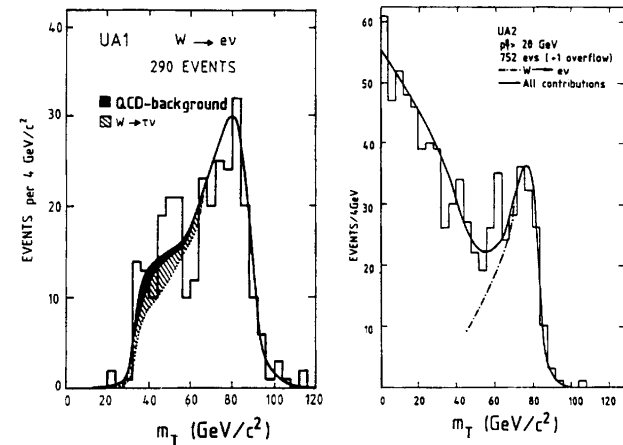
And with the  
correct spin...



at the  
right  
mass:

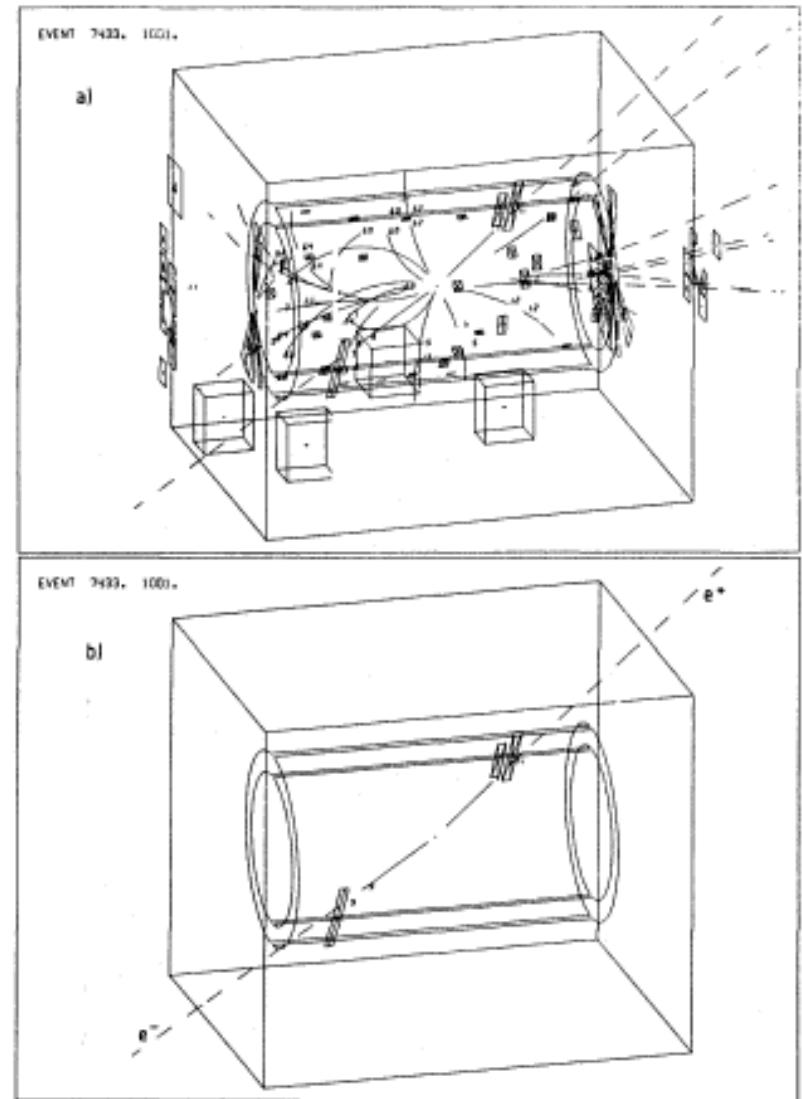
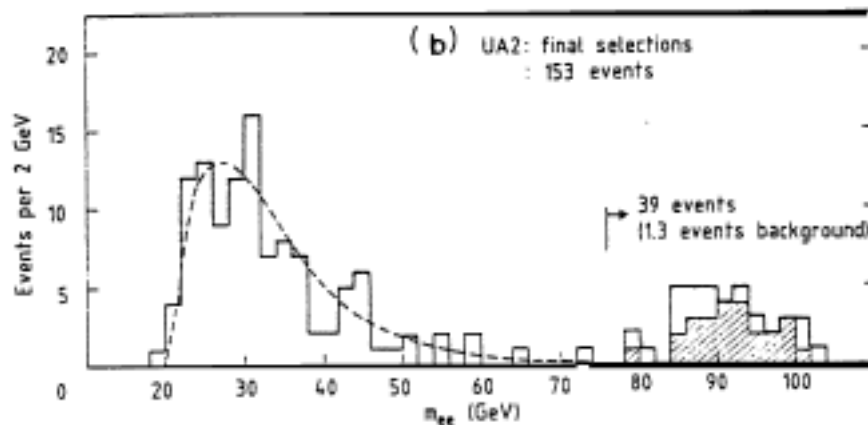
$$\text{UA1: } m_W = 81 \pm 5 \text{ GeV}$$

$$\text{UA2: } m_W = 81 \pm_{-6}^{+10} \text{ GeV}$$



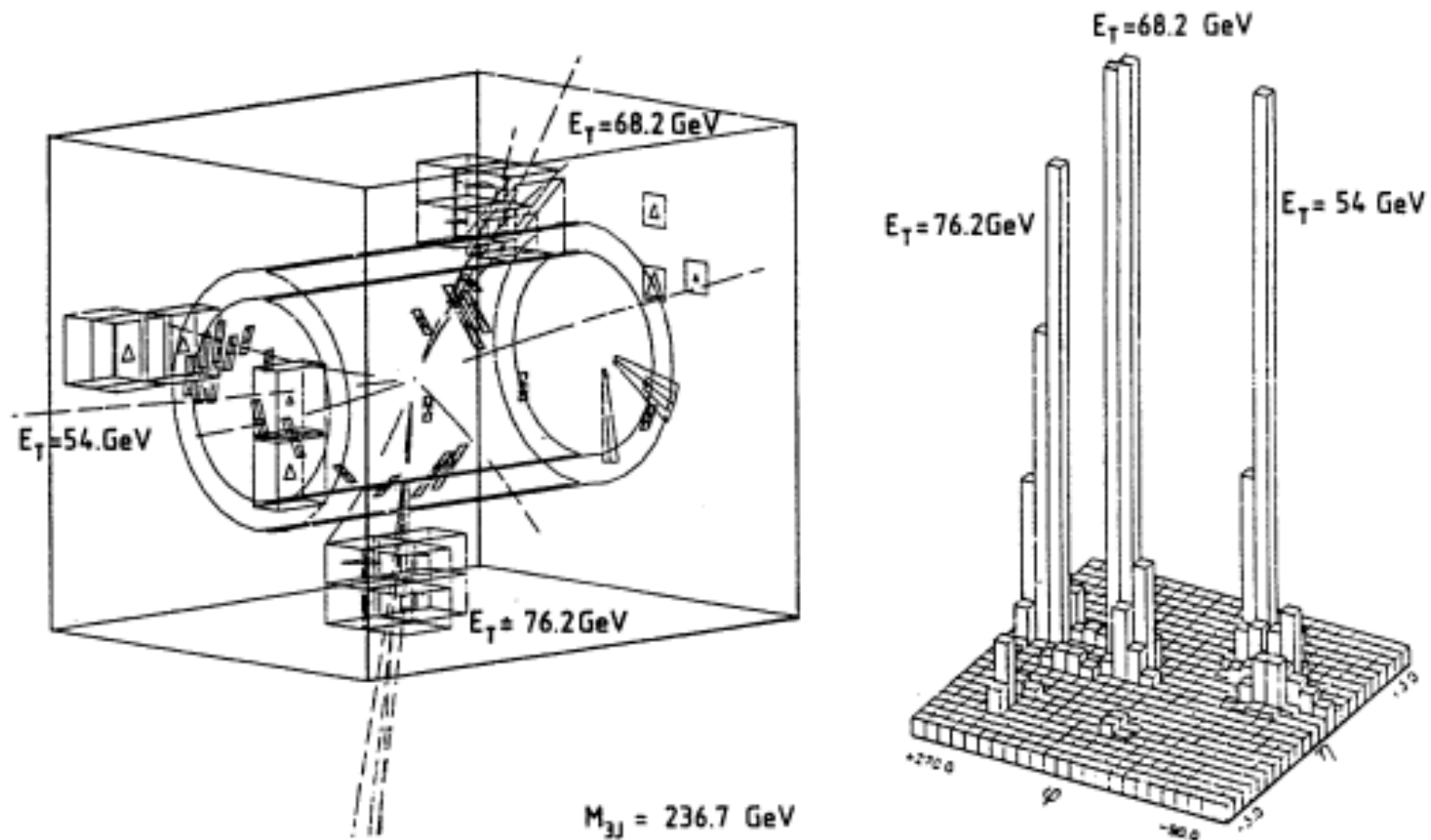
# The similarly punctual cousin: the Z boson

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



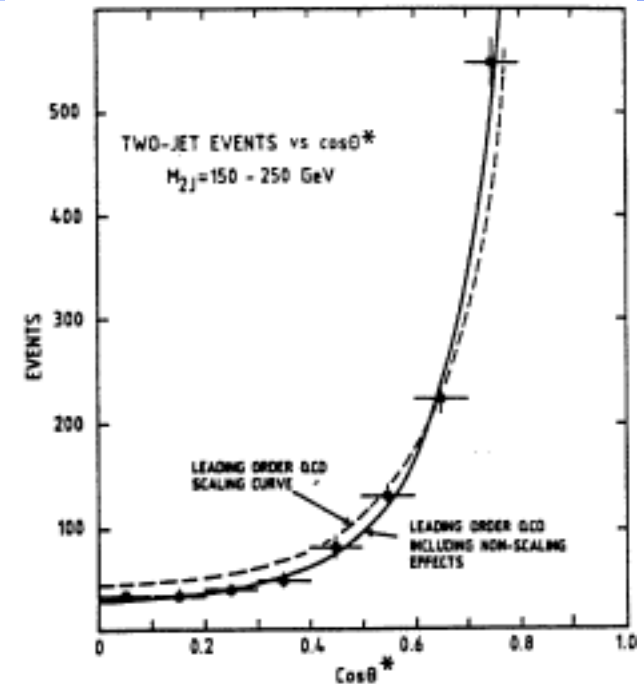
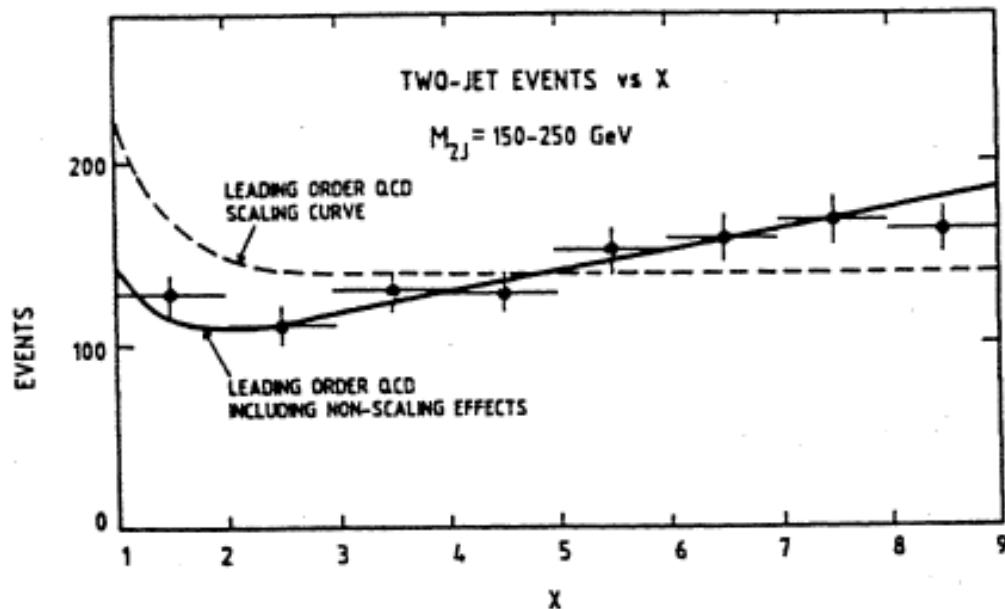
# Jets in proton-antiproton collisions

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



# SPS legacy: strong interaction

**Partons inside protons do scatter a la Rutherford!**



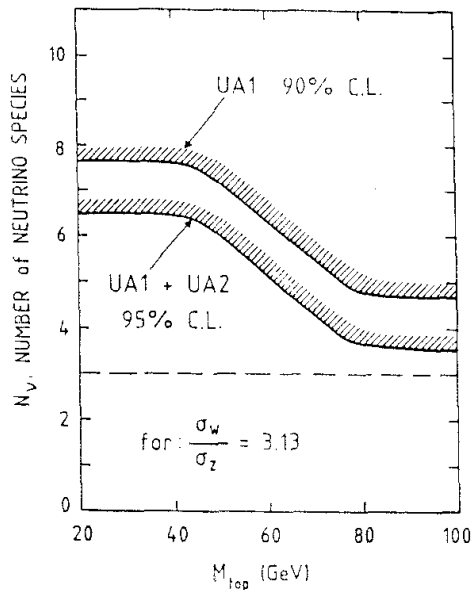
**And the QCD “scaling violations” are, actually, visible –  $Q^2$  dependence**

# SPS: we learned a lot more as well

## ■ $\leq 6$ neutrinos!

### ◆ From W width

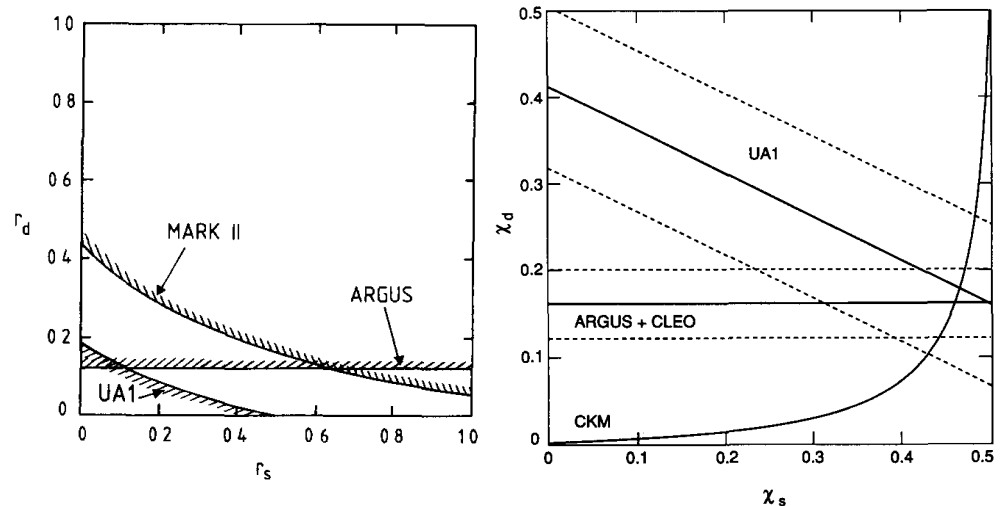
$$\begin{aligned} \frac{N(W \rightarrow l\nu)}{N(Z \rightarrow l^+l^-)} &= \frac{\sigma_W \cdot \text{BR}(W \rightarrow l\nu)}{\sigma_Z \cdot \text{BR}(Z \rightarrow l^+l^-)}, \\ &= \frac{\sigma_W}{\sigma_Z} \frac{\Gamma(W \rightarrow l\nu)}{\Gamma_W} \bigg/ \frac{\Gamma(Z \rightarrow l^+l^-)}{\Gamma_Z} \end{aligned}$$



$$\begin{aligned} \Gamma_Z &= 2.7_{-0.3}^{+0.4} \text{ GeV}/c^2, \\ &< 3.1 \text{ GeV}/c^2 \quad (90\% \text{ CL}) \end{aligned}$$

## ■ And B mesons mix a lot:

### ◆ Observation of $\mu^+\mu^+$ and $\mu^-\mu^-$ events:

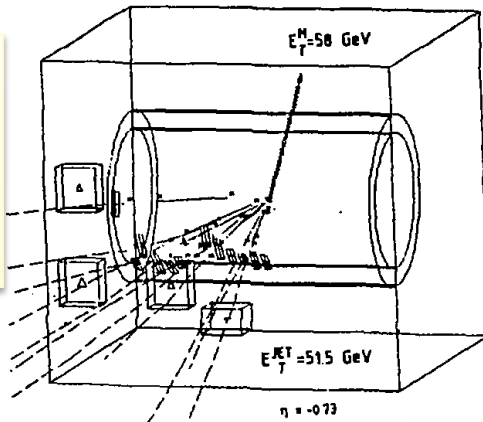


$$\chi = \frac{(\text{BR})_d f_d \chi_d}{\langle \text{BR} \rangle} + \frac{(\text{BR})_s f_s \chi_s}{\langle \text{BR} \rangle}$$

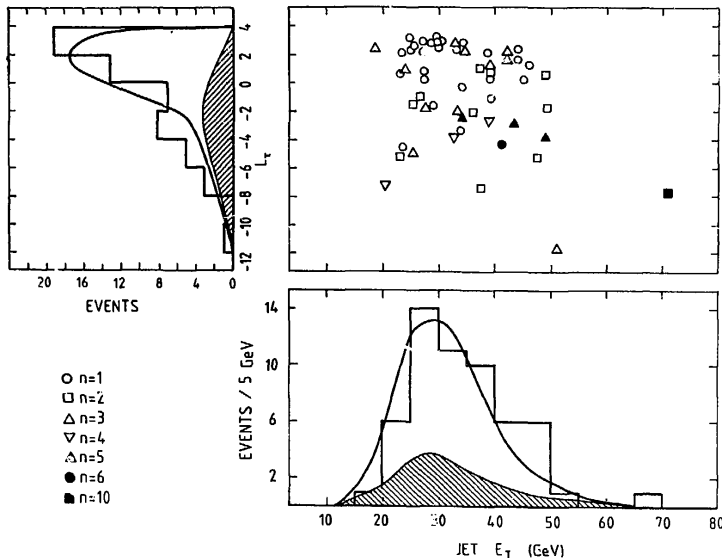
$$\chi_s > 0.12 \text{ at } 95\% \text{ CL}, \quad \chi_s > 0.17 \text{ at } 90\% \text{ CL}$$

# Plus, some excitement (that subsided)

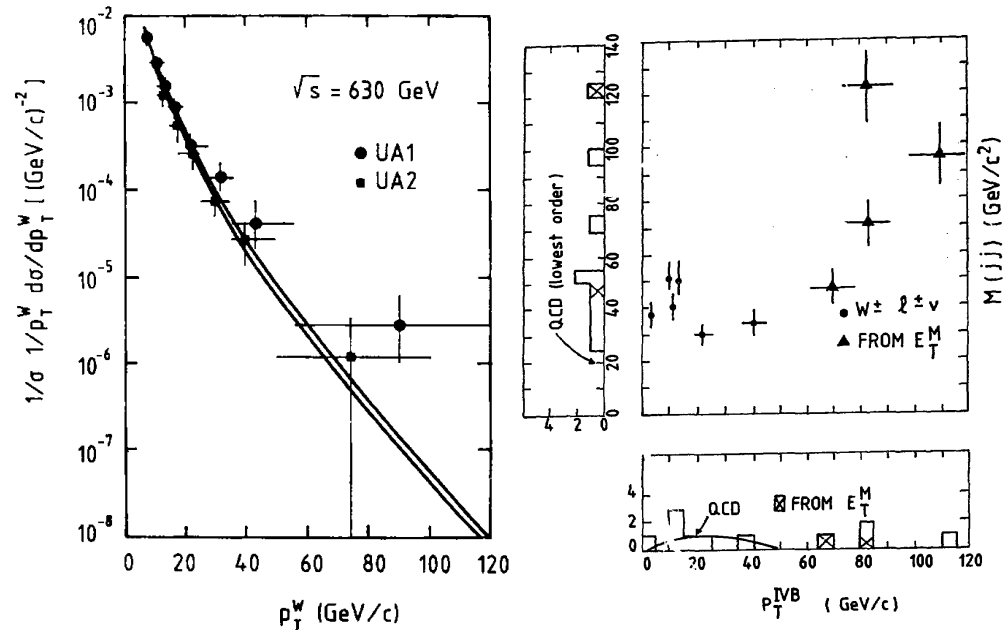
The  
Monojets!  
SUSY???



They turned out to be taus...



High- $p_T$  Ws  
New  $X \rightarrow WW$ ?

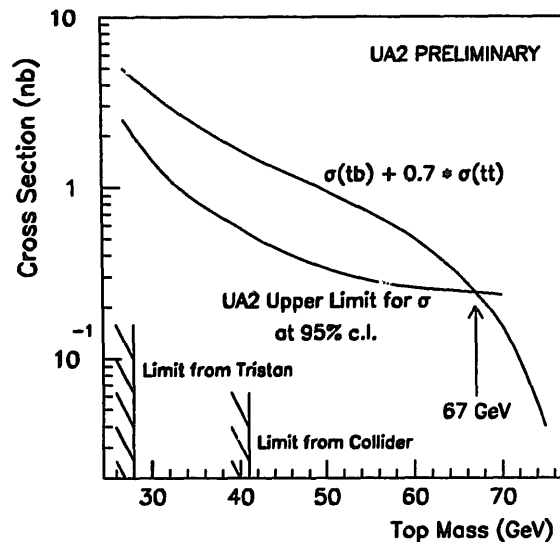
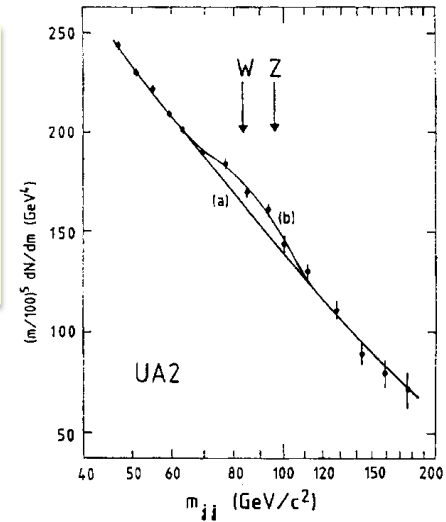


It was statistics + LO QCD...

# 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  $\sim 100$  MeV)  
 UA1 became a  $\approx$  muon detector;  
 UA2 thrived and dominated

Special trigger  
 (low- $p_T$  jets)

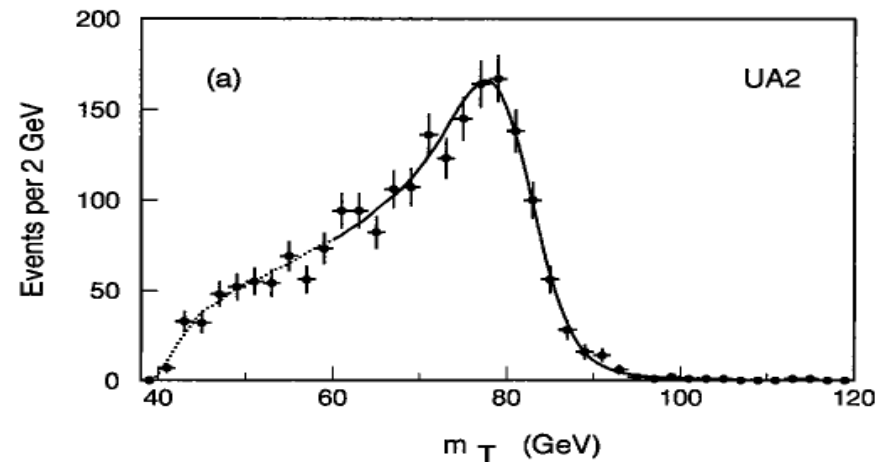


95% CL

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

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

90% CL

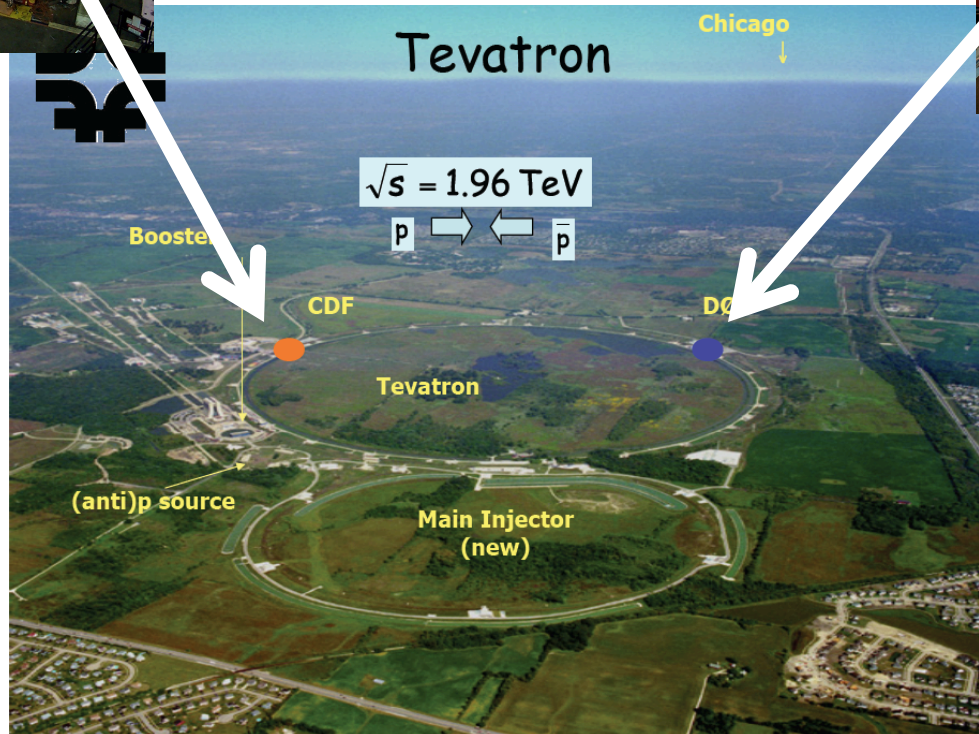
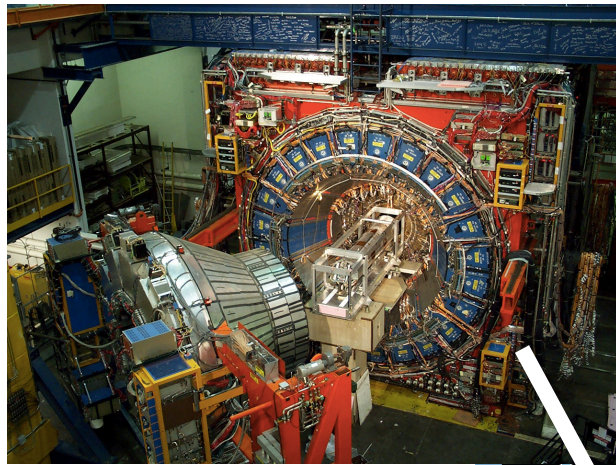


$M_W = 80.35 \pm 0.33 \pm 0.17$  GeV

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

**aka “Go west my boy/girl, go west”**

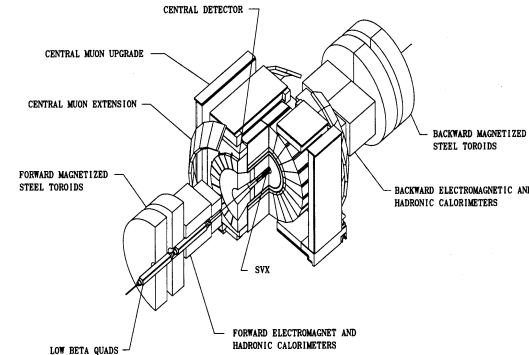
# End of 80s, beginning of 90s: Tevatron



# Tevatron experiments: a bit of history

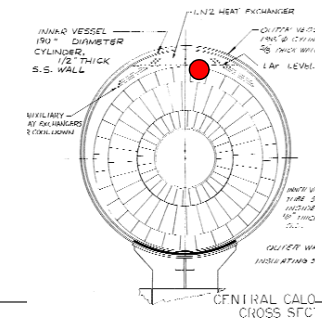
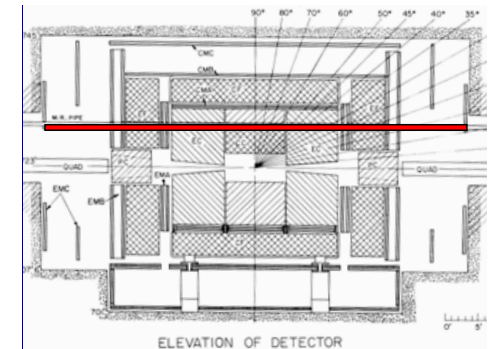
- **CDF: design report in 1981**

- ◆ **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.**



- **1985: FNAL director call for detector at D0**

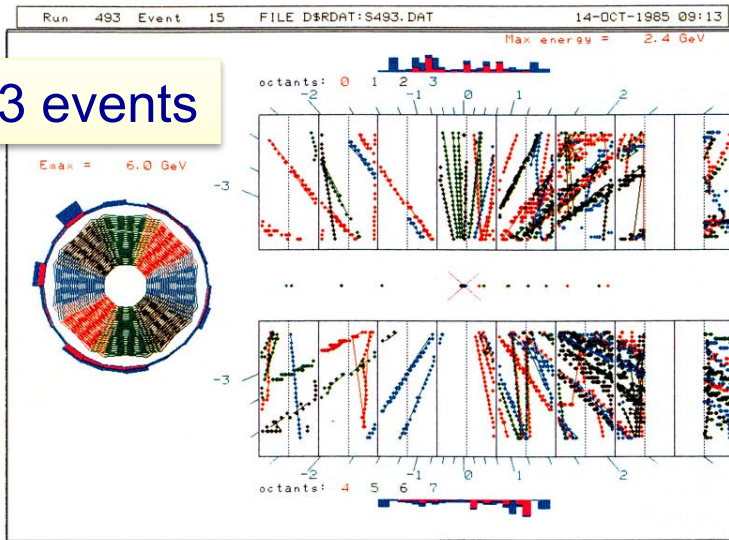
- ◆ ... something “small (to fit inside a 9m cube), simple, and clever”. Add: moveable to/from beam line (D0: fixed target beam extraction); 12 proposals, all rejected
- ◆ D0: 1983 proposal; 71 physicists from 12 institutes (all US); approved by DOE in 1984
- ◆ Basic concept: non-magnetic detector (à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



# Tevatron evolution

First collisions: CDF, Oct 1985

23 events



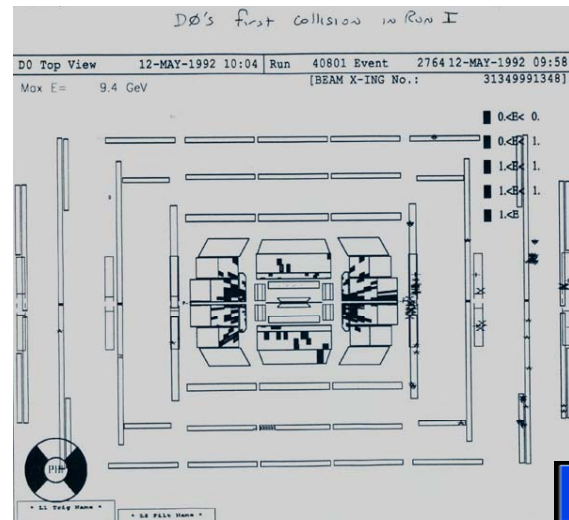
And D0 was just starting...



**1987: Run 0;** first run, CDF,  
4pb<sup>-1</sup> @ 1.8 TeV

**1992-96: Run 1;** CDF & D0,  
120 pb<sup>-1</sup> @ 1.8 TeV

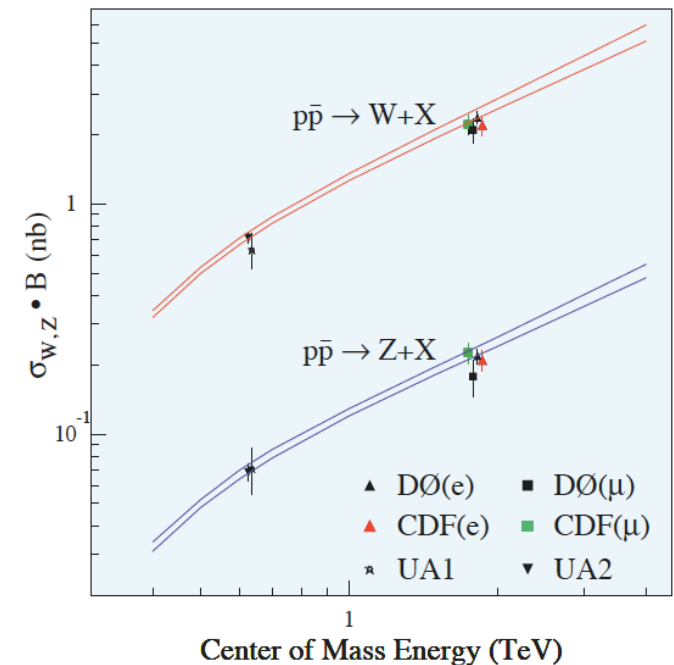
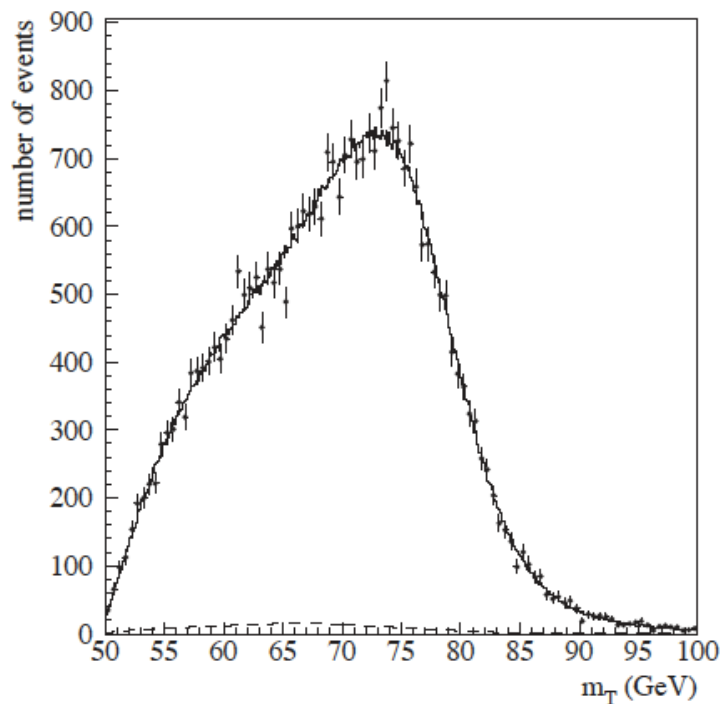
**2011: Run 2;** upgraded CDF&D0  
12 fb<sup>-1</sup> @ 2.0 TeV



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

# The Tevatron... W/Z physics, next-gen!

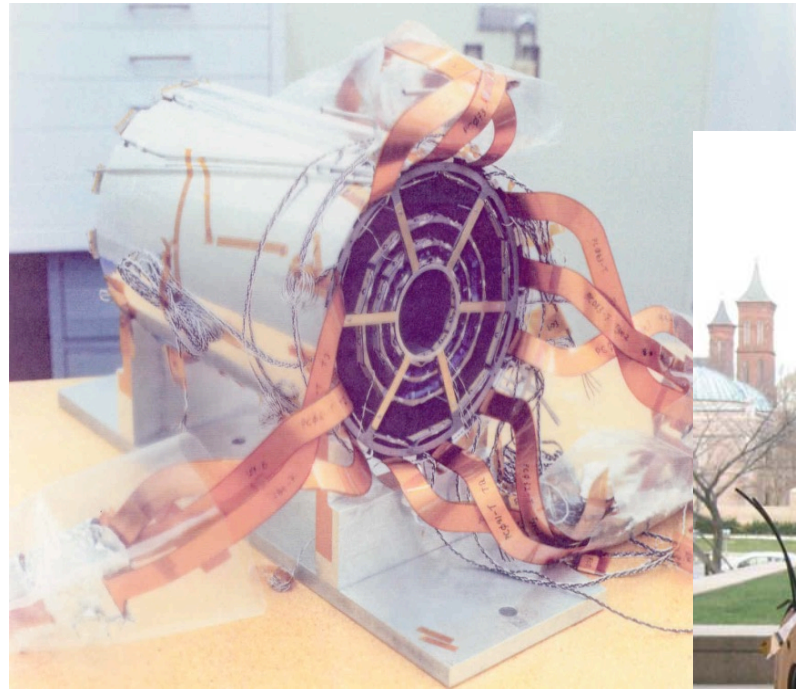
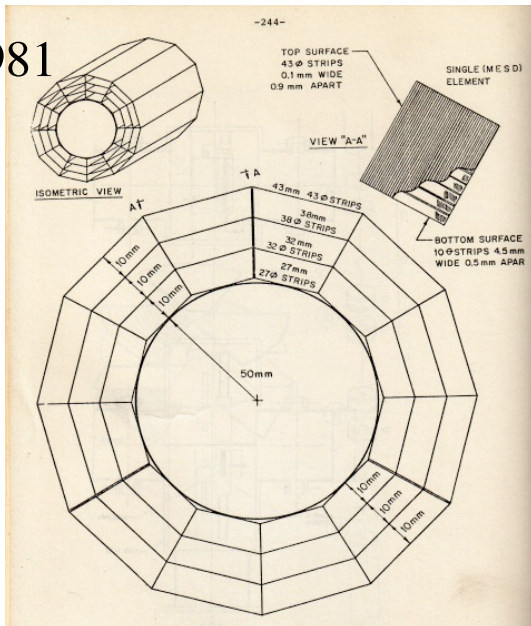
- Higher Energy: big difference in production cross section of massive particles + high luminosity : Huge samples



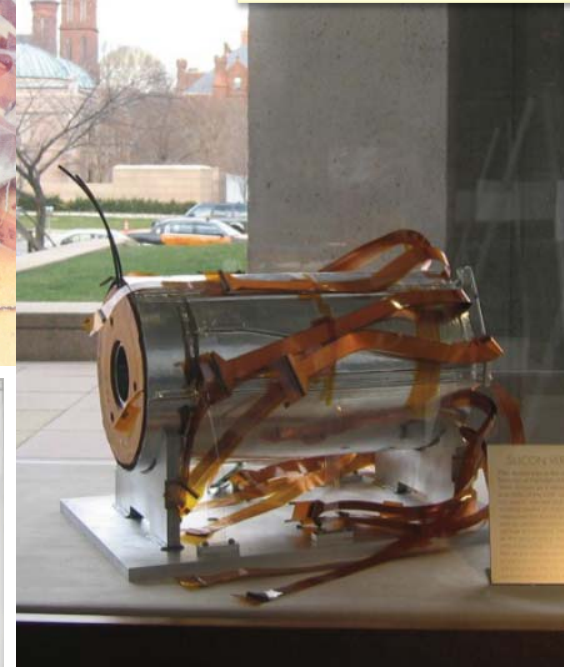
**W boson transverse mass distribution from D0, circa 1997: 33,000 W candidates!**

# The true novelty: silicon vertex detector

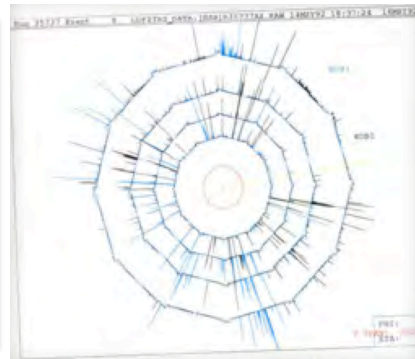
1981



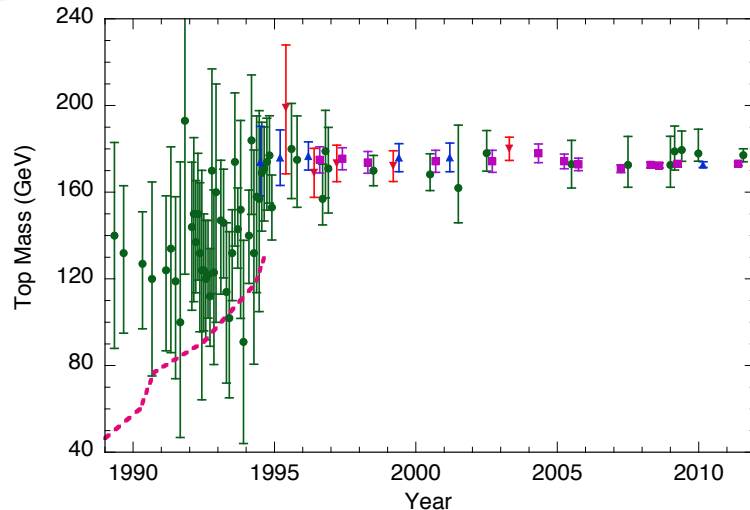
Smithsonian  
Museum,  
Washington



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

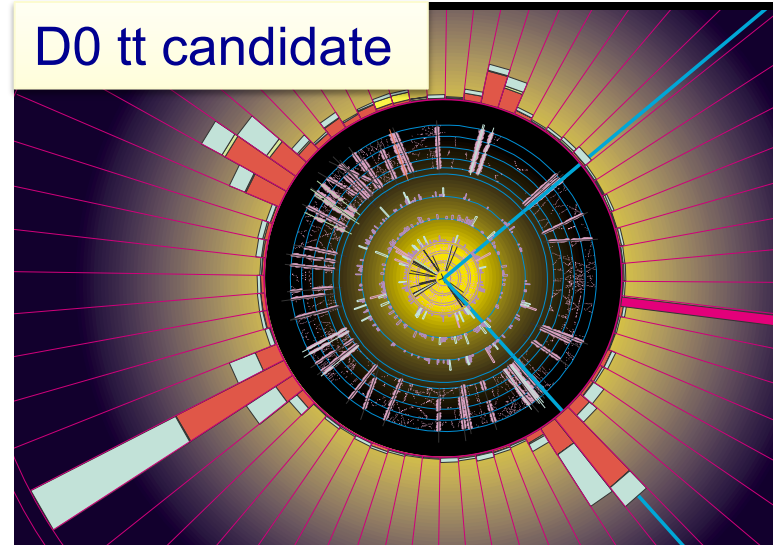


# Towards the top quark

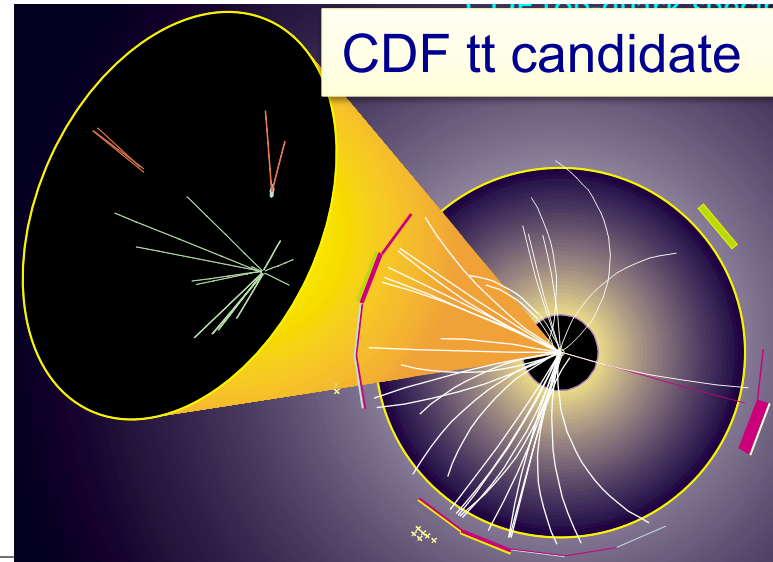


80's:  $m_t > 23$  GeV (Petra); 30 GeV (Tristan)  
1984: Weak evidence for  $W \rightarrow tb$  @  $m_t \sim 40$  GeV (UA1)  
1990:  $m_t > 91$  GeV (CDF) so no  $W \rightarrow tb$   
1994:  $m_t > 131$  GeV (D0)  
4/1994: CDF evidence  $m_t \sim 175$  GeV,  $2.8\sigma$ .  
7/1994: DØ sees  $\sim 2\sigma$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

D0  $t\bar{t}$  candidate

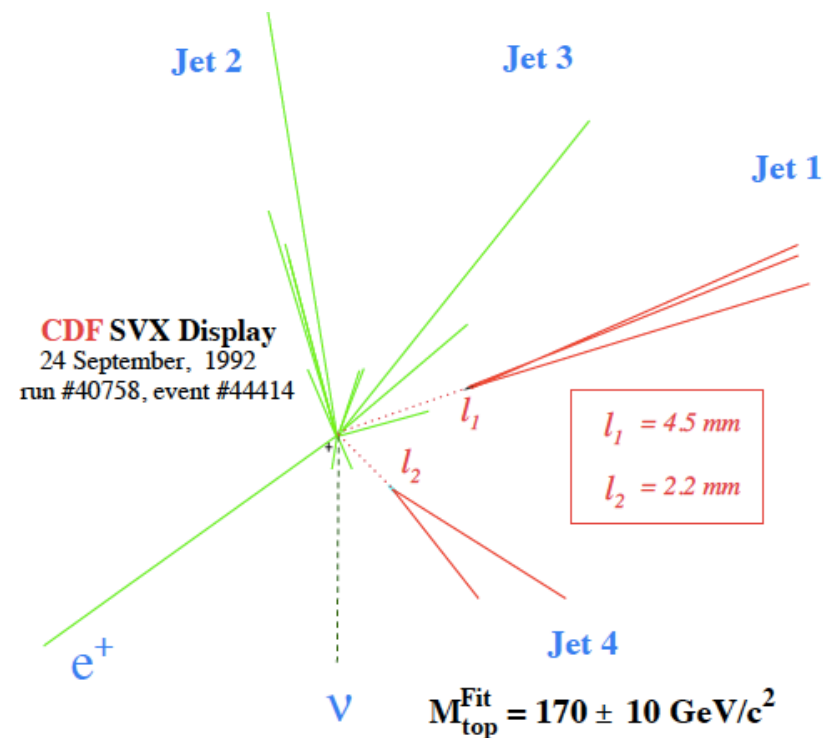
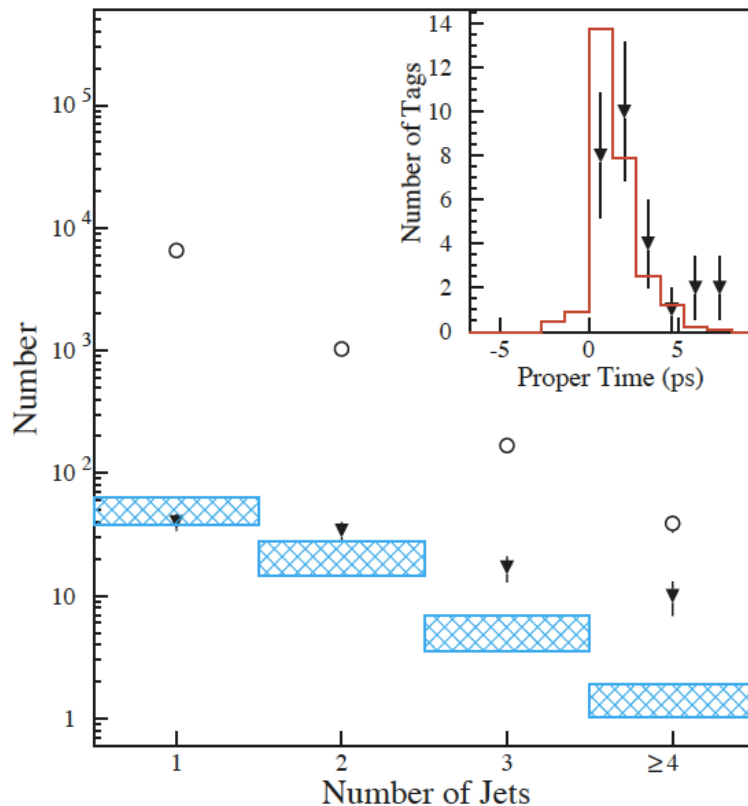


CDF  $t\bar{t}$  candidate



# 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)

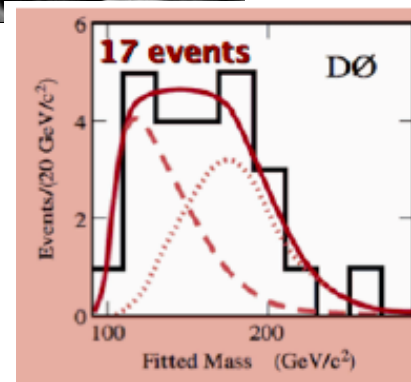
Mar 2, 1995



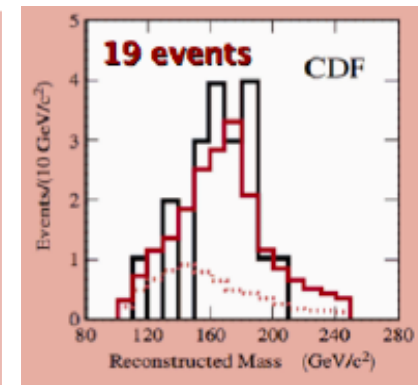
D0:  
Obs: 17 evts;  
Exp bkg:  $3.8 \pm 0.6$   
Prob =  $2 \times 10^{-6}$  ( $4.6\sigma$ )

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

CDF: Prob =  $1 \times 10^{-6}$  ( $4.8\sigma$ )



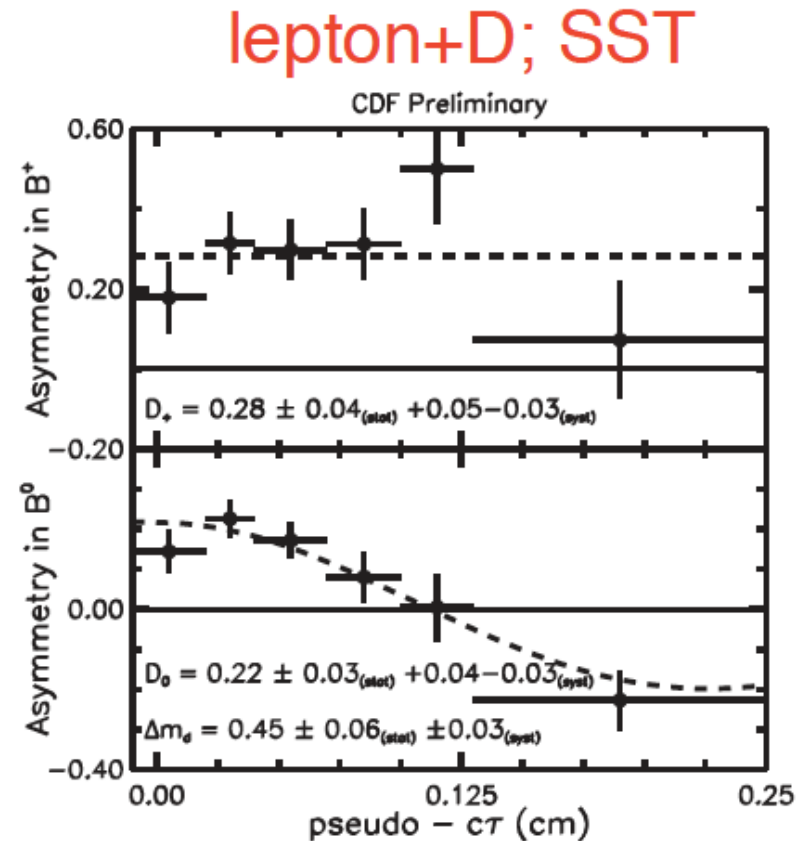
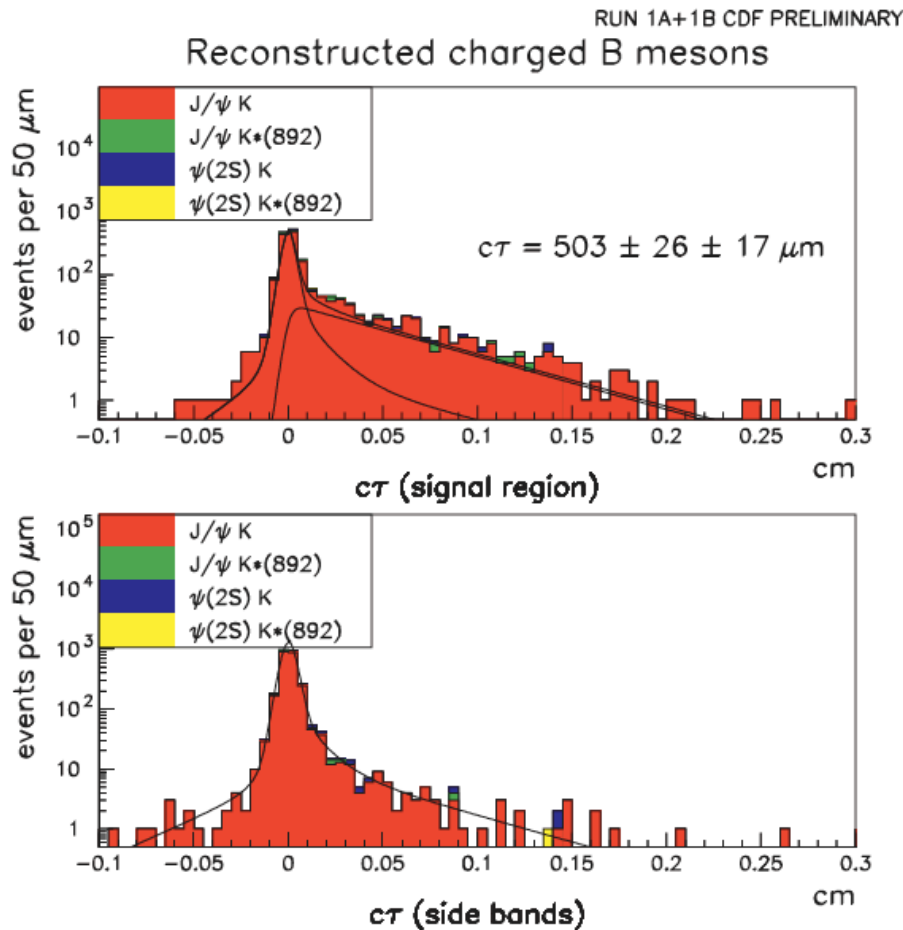
PRL 74, 2632 (1995)



PRL 74, 2626 (1995)

# And then came the rich B physics program

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



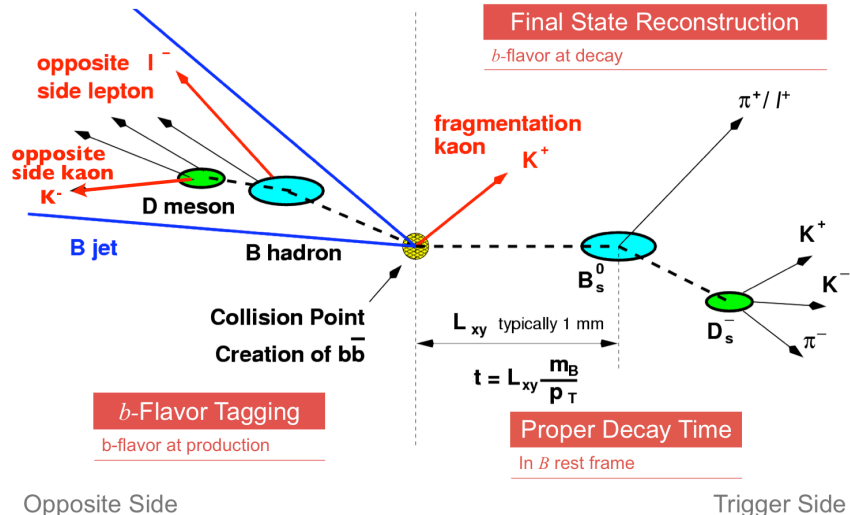
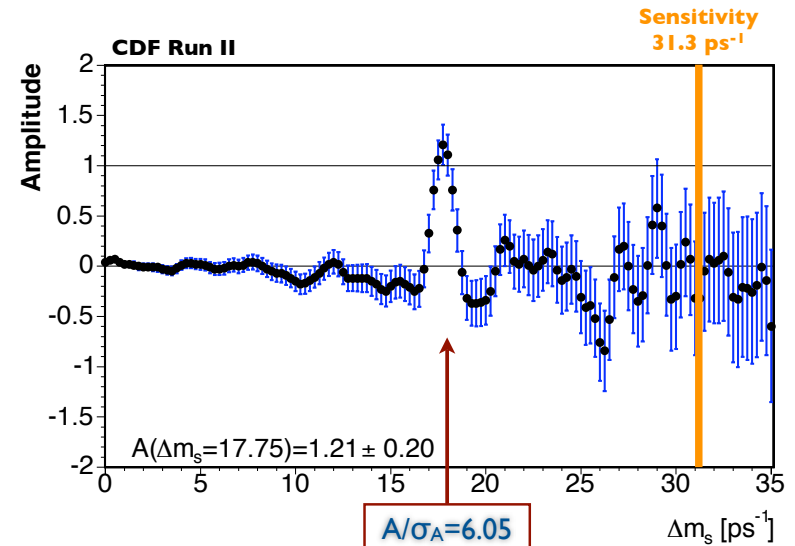
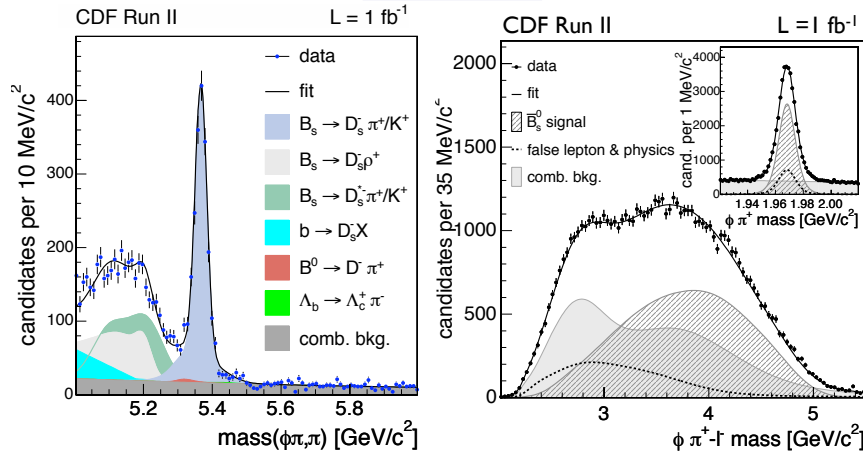
# Jewel of B physics @ hadron colliders: $B_s$

$$B_s \rightarrow D_s \pi$$

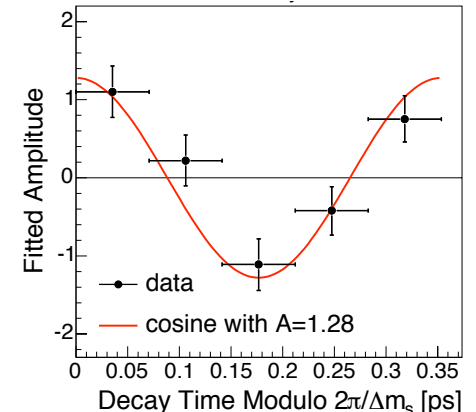
$$D_s \rightarrow \phi \pi$$

$$B_s \rightarrow \ell(\nu) D_s$$

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

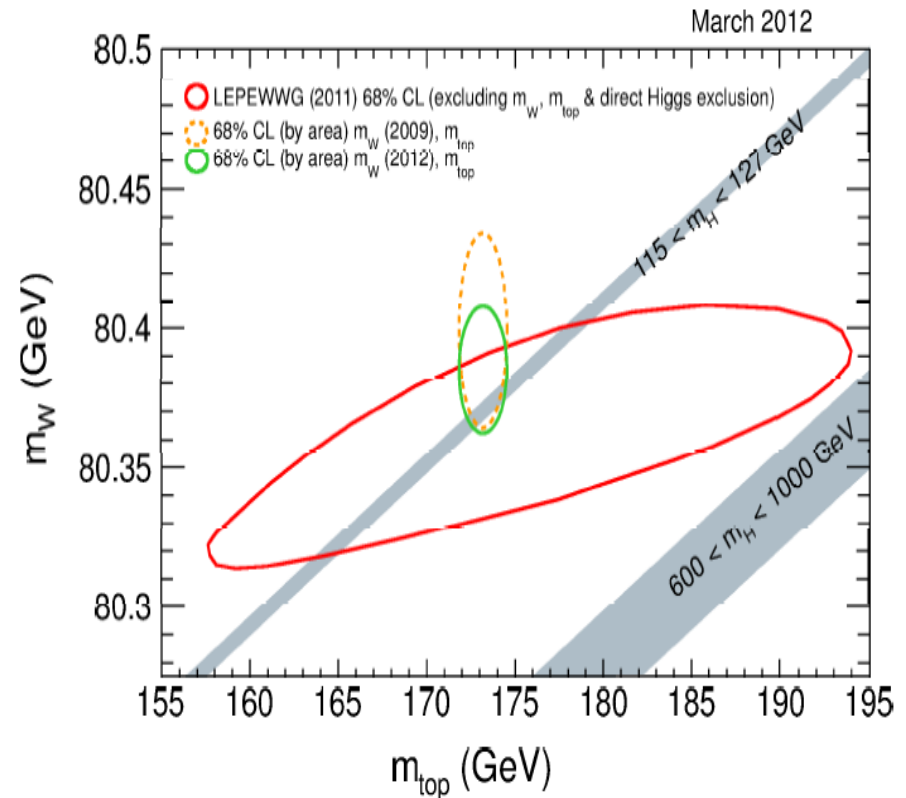
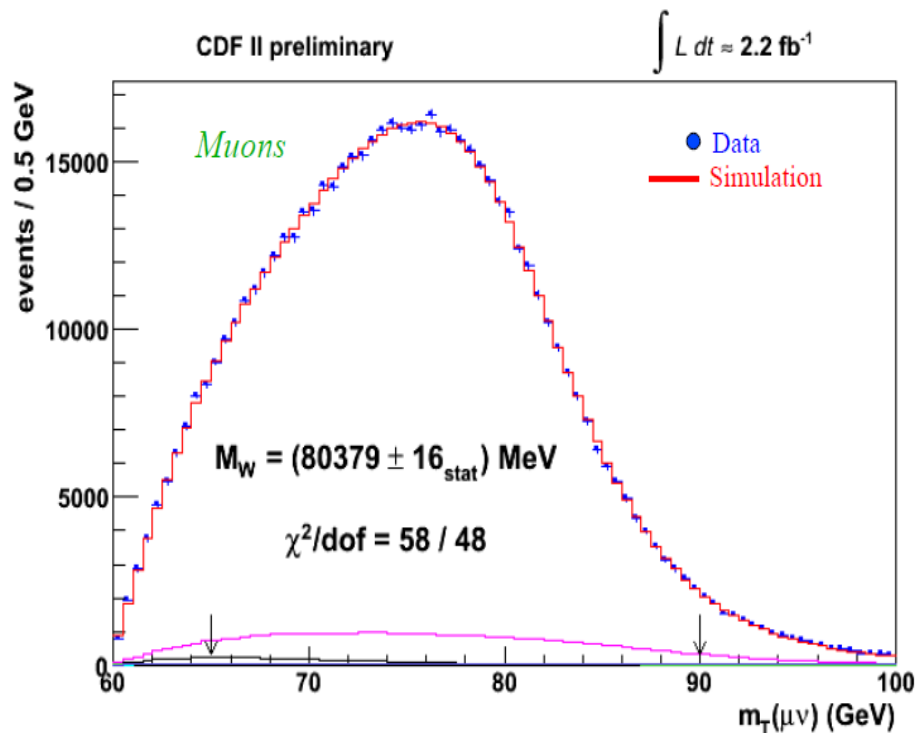


Major tools:  
SVXII, PID  
(TOF,  $dE/dx$ )

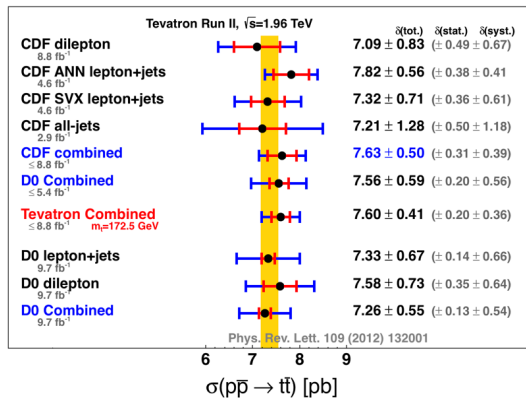
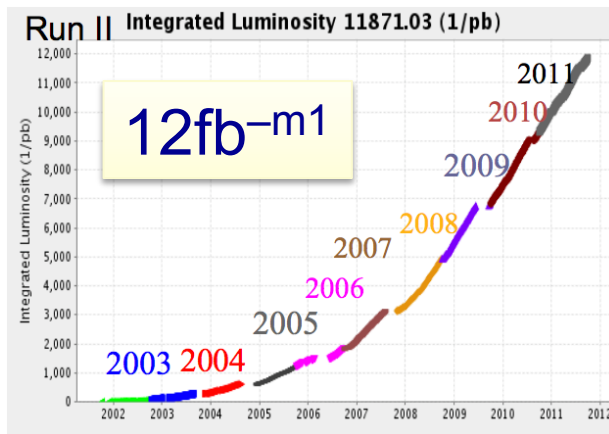


# The surprise: very high precision on $M_W$

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



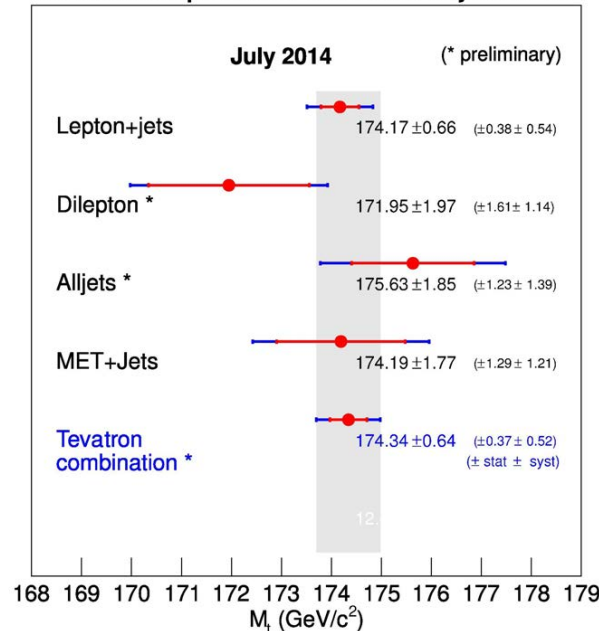
# Tevatron: sole source of t quarks for ~10 years



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

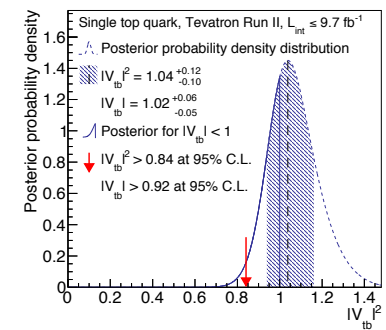
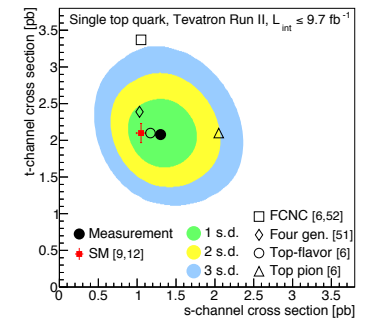
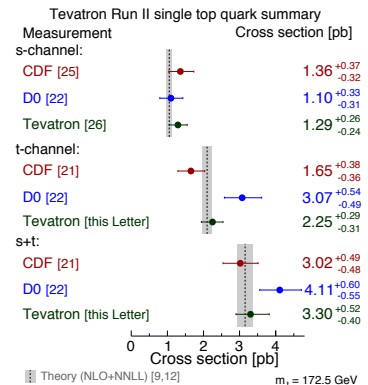
$$\Delta\sigma/\sigma = 5.4\%$$

## Mass of the Top Quark in Different Decay Channels



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

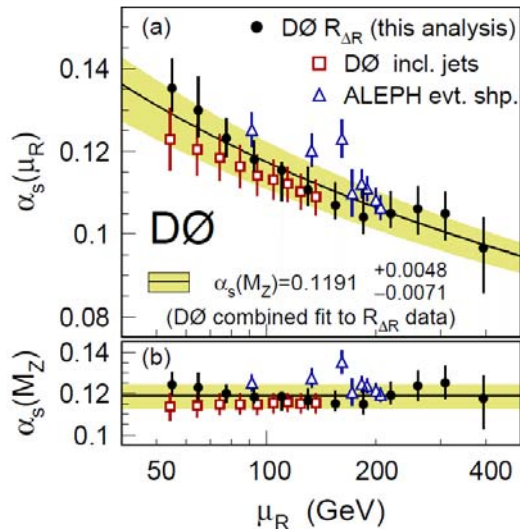
$$\Delta m/m = 0.37\%$$



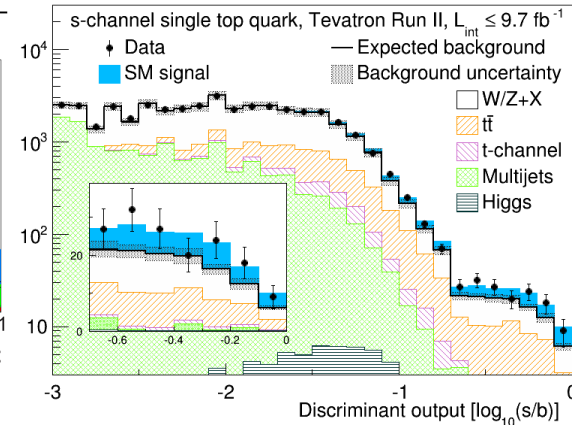
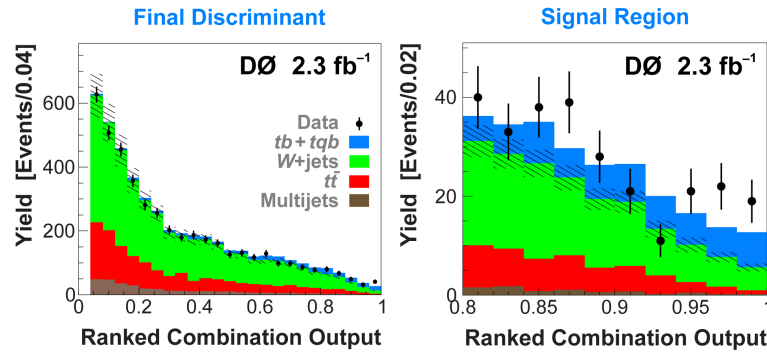
$$V_{tb} > 0.92$$

# Plus some new techniques

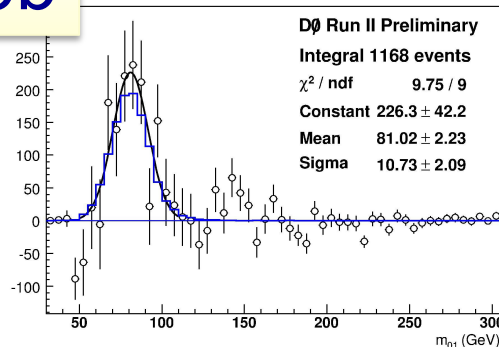
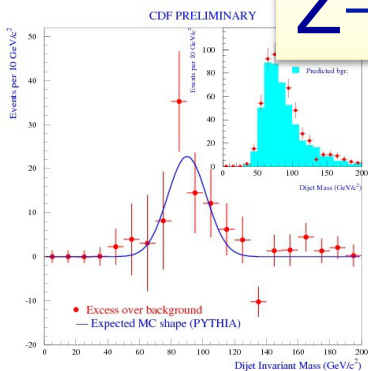
## $\alpha_s$ measurement



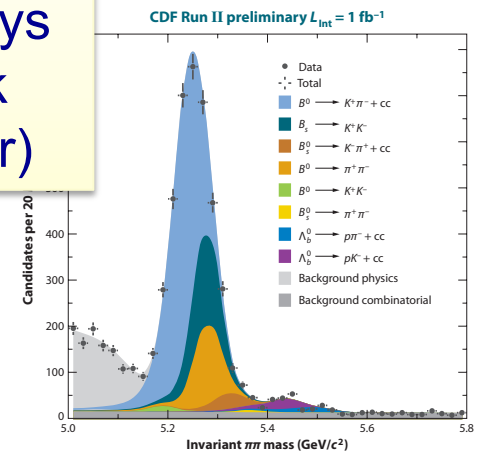
## MVA and single-top



## $Z \rightarrow b\bar{b}$

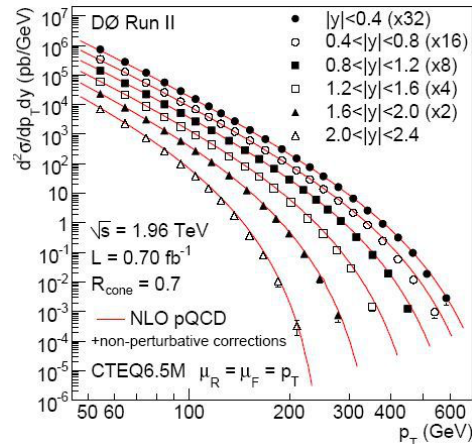
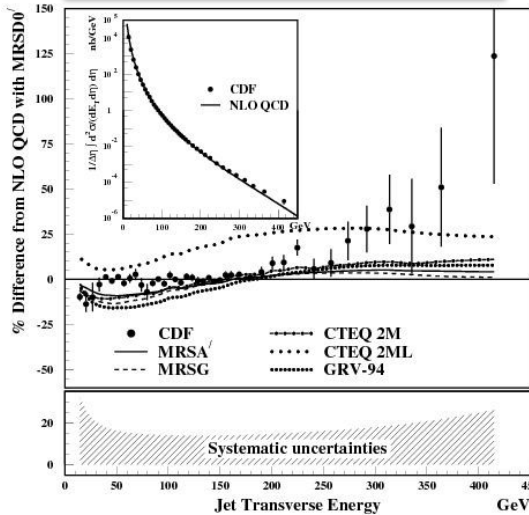


## Hadronic B decays (track trigger)



# There was also excitement... (I)

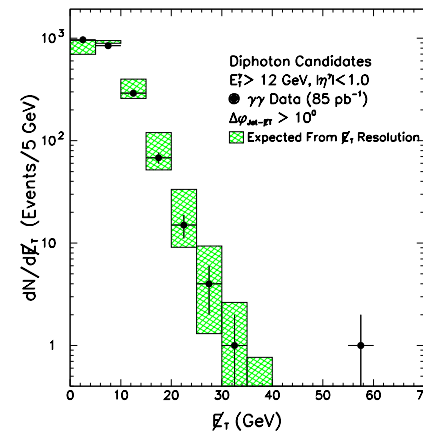
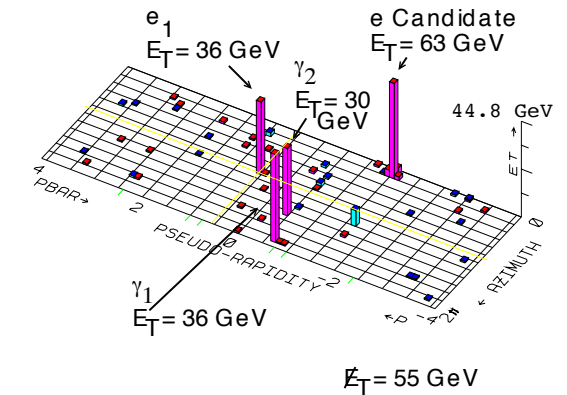
## Compositeness?



Nope; mainly PDFs...  
(plus JEC/JES)

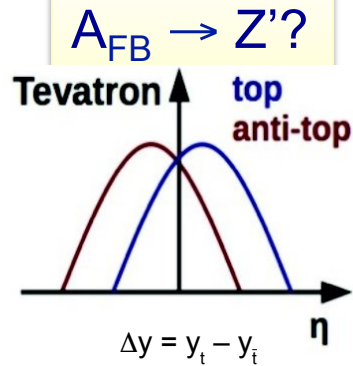
## SUSY? Selectron pairs?

$e e \gamma \gamma \bar{E}_T$  Candidate Event

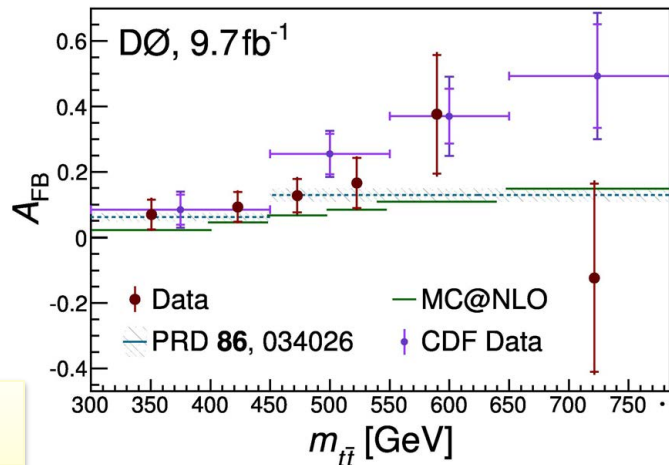


Bkg:  
 $\sim 10^{-6}$

Nope; stats...(?)

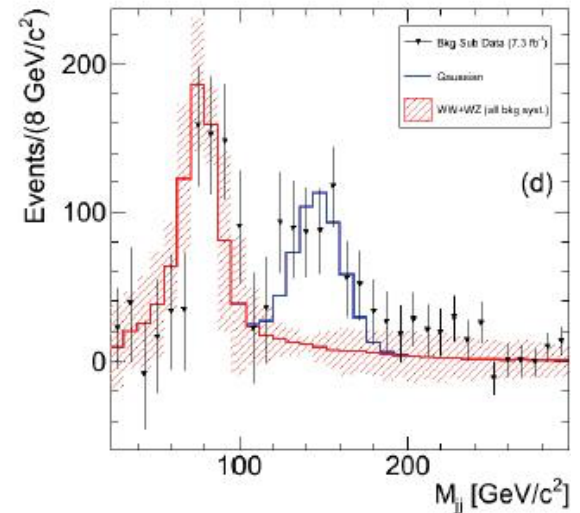
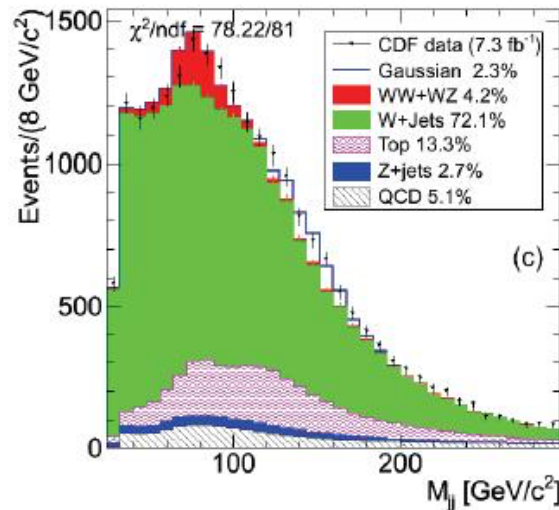


Nope; stats+the

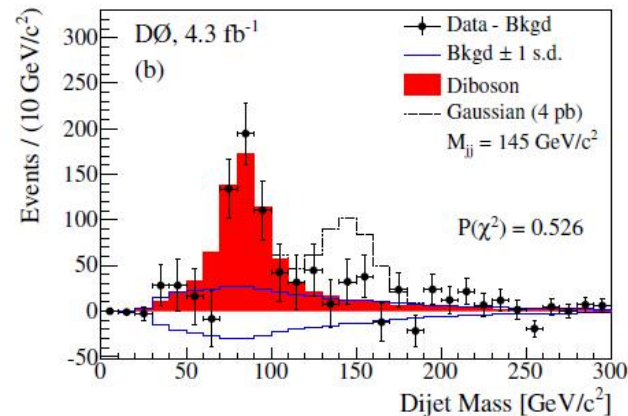


# There was also excitement... (II)

W+jj events...  
New resonance, X,  
with  $X \rightarrow jj$  and  
 $m_X \approx 145 \text{ GeV}$ ?



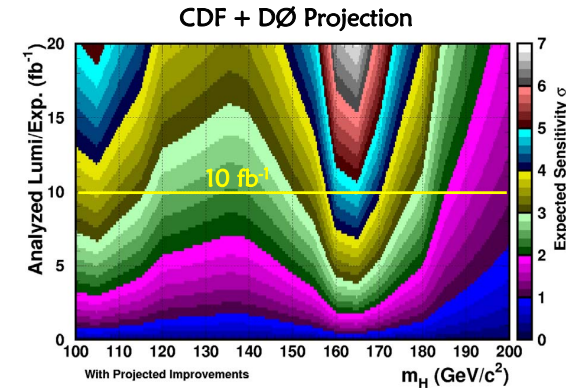
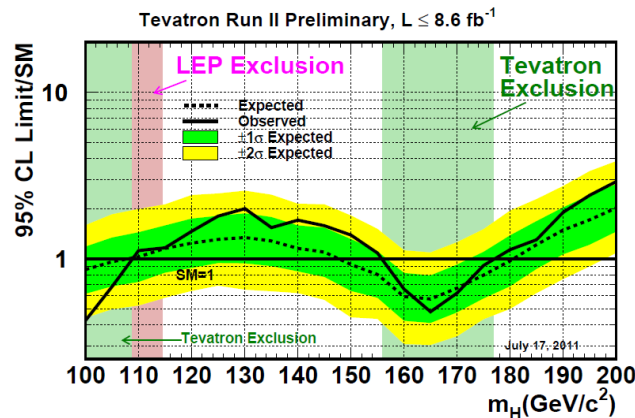
Nope; excluded  
by D0...  
Mainly JEC and  
JES and q/g  
differences



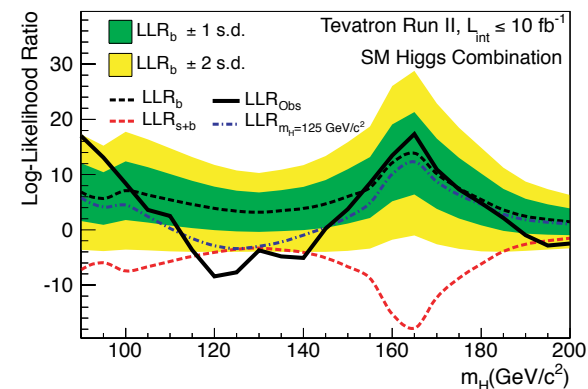
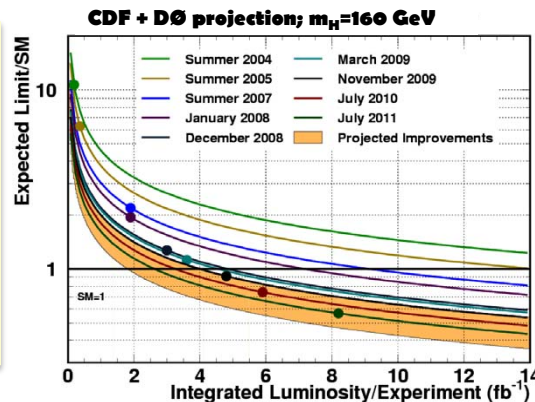
# The end of the Tevatron: the Higgs

- 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  $\sqrt{L}$ : 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

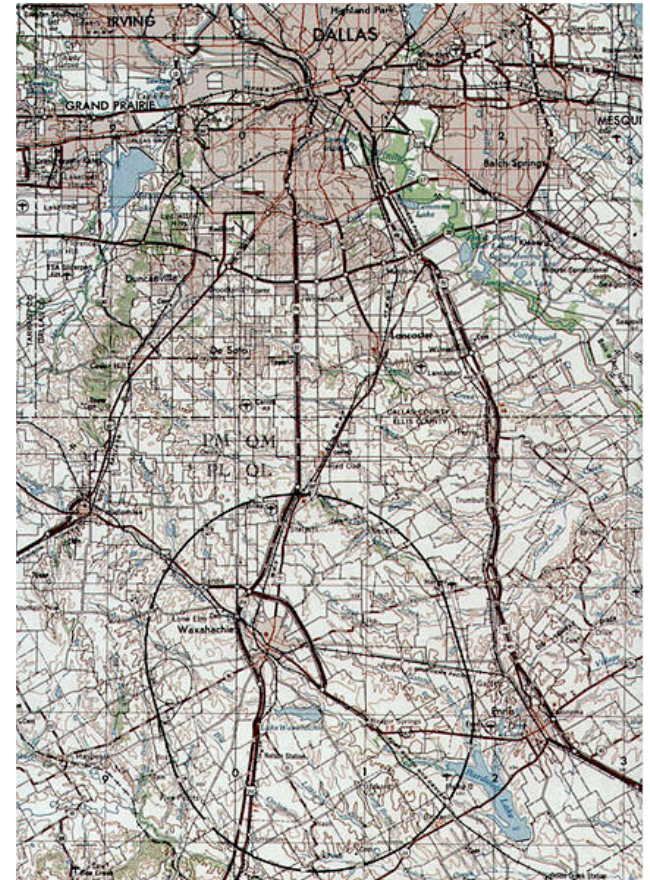
**As far back as in early 90's,  
people realized a new machine  
would be needed**

**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:

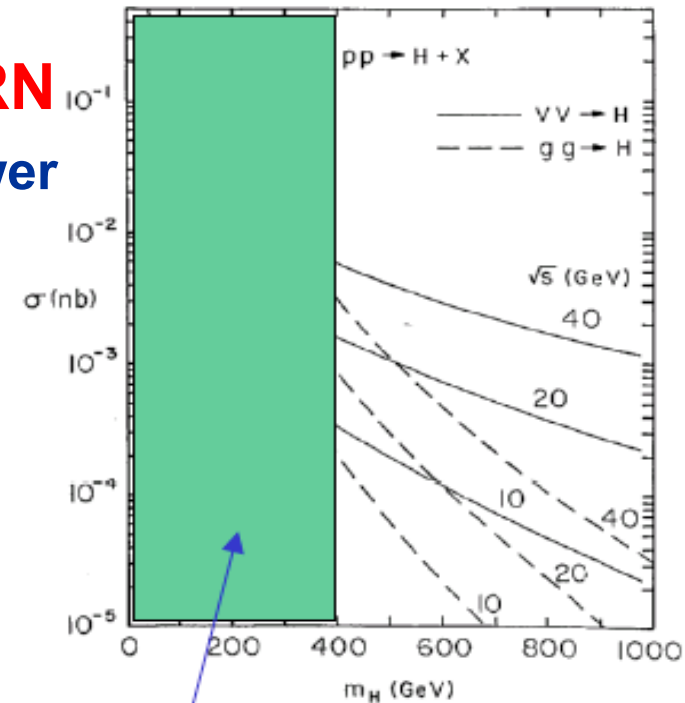
**“Congress soon will be deciding the fate of the Superconducting Super Collider—the \$11 billion Department of Energy atom smasher.**

**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

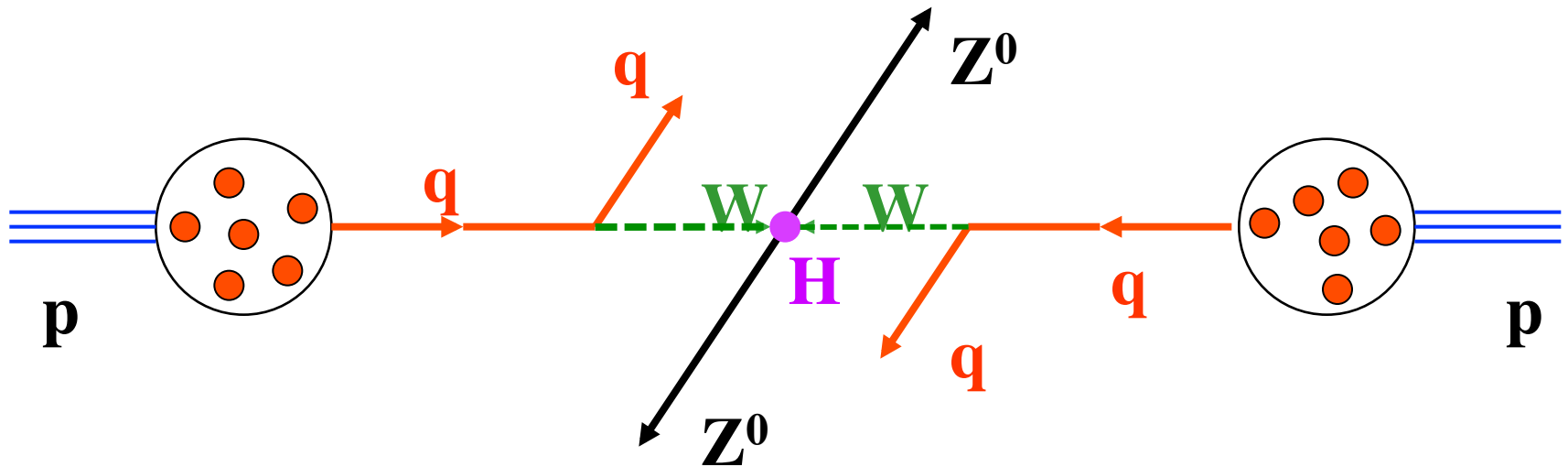
- **Superconducting Supercollider (SSC)  $\sqrt{s}=40$  TeV...**
  - ◆ Would have started in 1999 (!)
- **So: use existing LEP tunnel at CERN**
  - ◆ Replace: e by p; increase bending power
    - ➔ Large Hadron Collider



D.Dicus, S. Willenbrock  
Phys.Rev.D32:1642,1985

Not true any more ( $M_T=175$  GeV)

# Higgs Production in pp Collisions

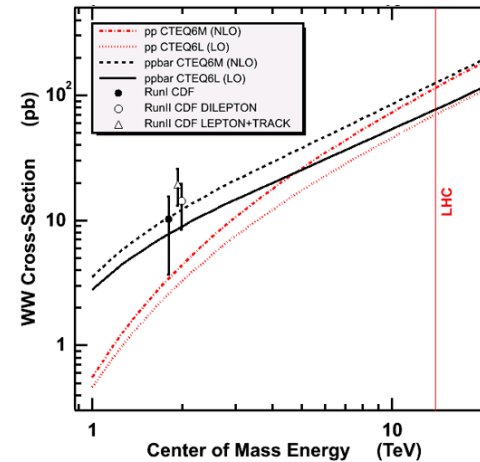


$$M_H \sim 1000 \text{ GeV}$$

$$E_W \geq 500 \text{ GeV}$$

$$E_q \geq 1000 \text{ GeV (1 TeV)}$$

$$E_p \geq 6000 \text{ GeV (6 TeV)}$$



No need for  
p-pbar...

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

# pp collisions at 14 TeV at $10^{34} \text{ cm}^{-2}\text{s}^{-1}$

## Interactions/x-ing:

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

$$\sigma(\text{pp}) = 70 \text{ mb}$$

$$\boxed{?} R_{\text{interactions}} = 7 \times 10^8 \text{ Hz}$$

$$\text{Time/BC, } \Delta t = 25 \text{ ns}$$

$$\text{Interactions/BC} = 17.5$$

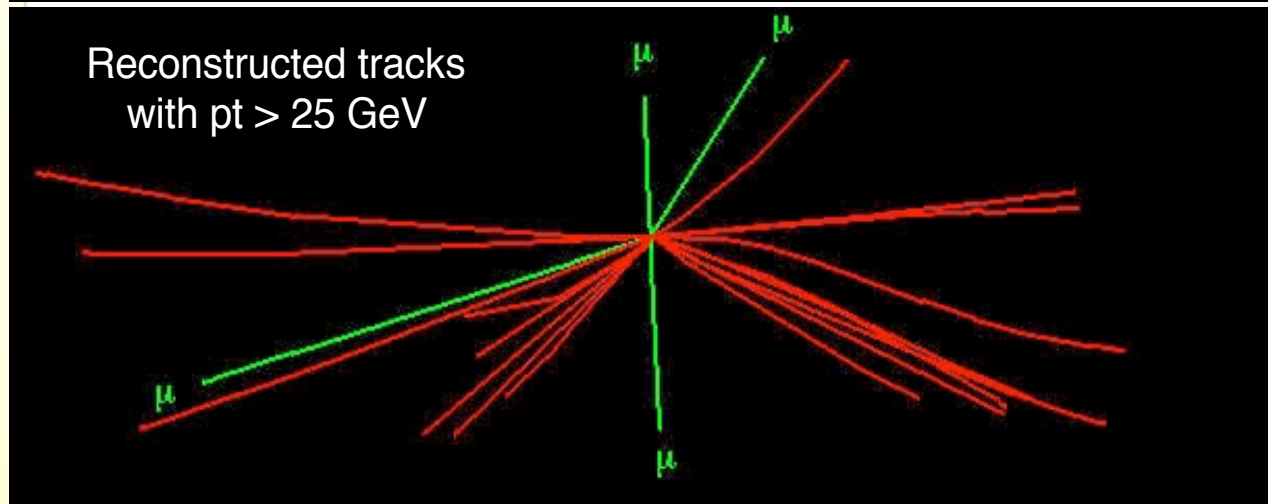
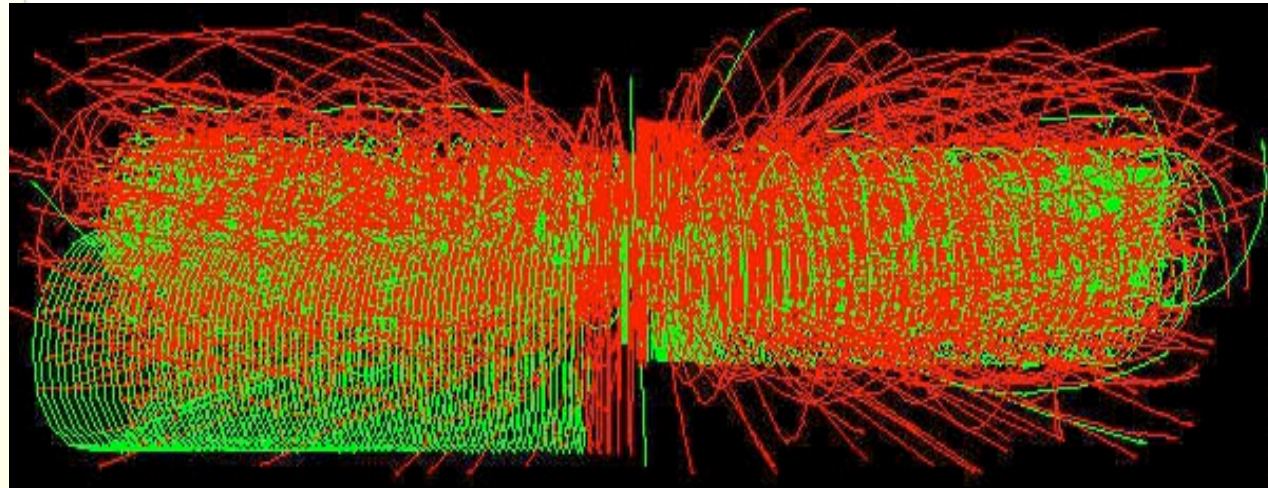
80% bunches full:

$$17.5 \times 5/4 = 23$$

**~ 20 min-bias  
events overlap!**

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

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



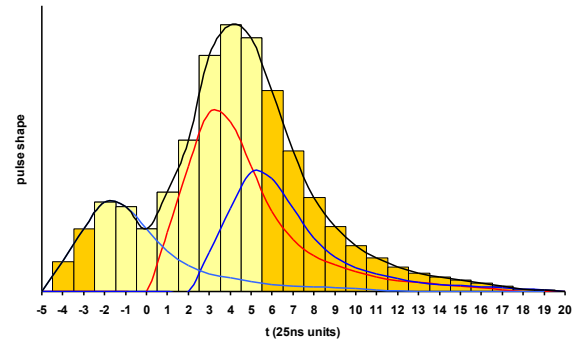
**And this (not the H...) would repeat every 25 ns**

# **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**



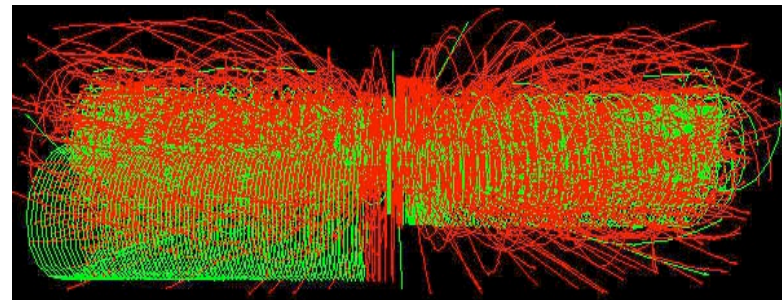
## ■ LHC detectors must be highly granular

- ◆ 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!**

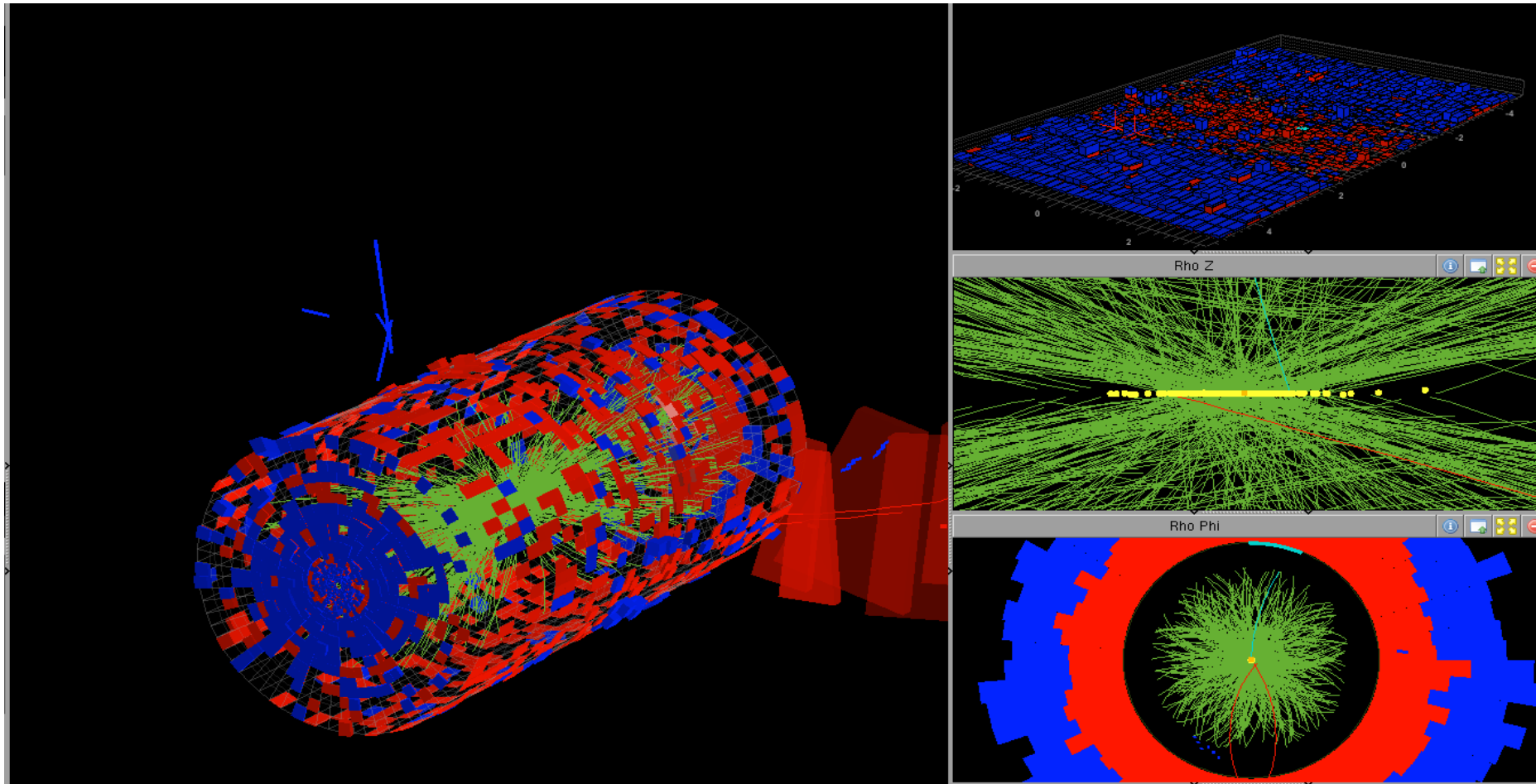
## ■ LHC detectors must be radiation-resistant:

- ◆ 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<sup>2</sup> [ $10^7$  Gy; 1 Gy = 1 Joule/Kg]**



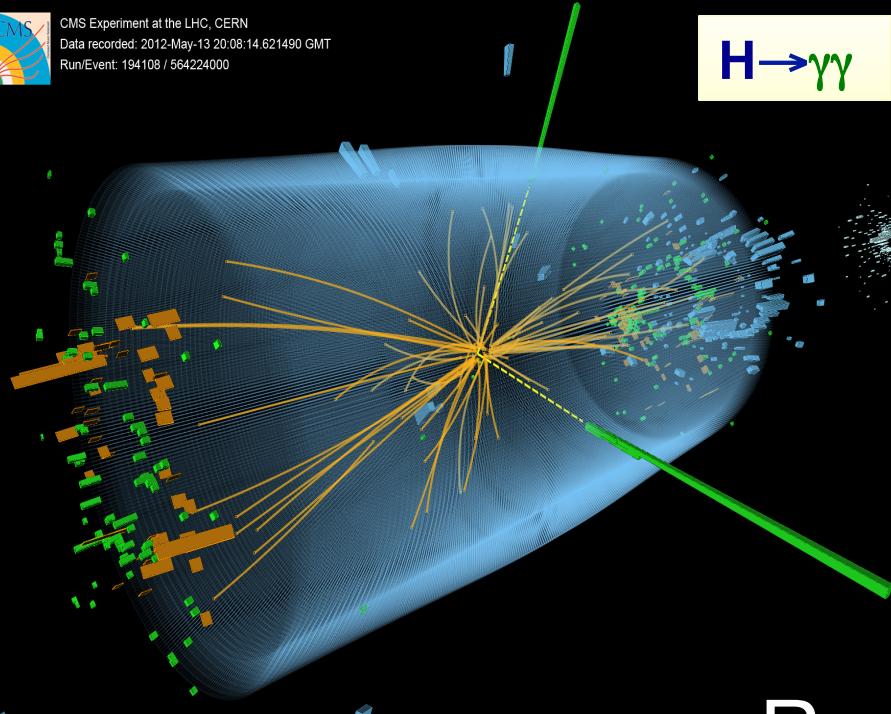
# Going beyond design conditions

**CMS event with 78 reconstructed vertices and 2 muons...**

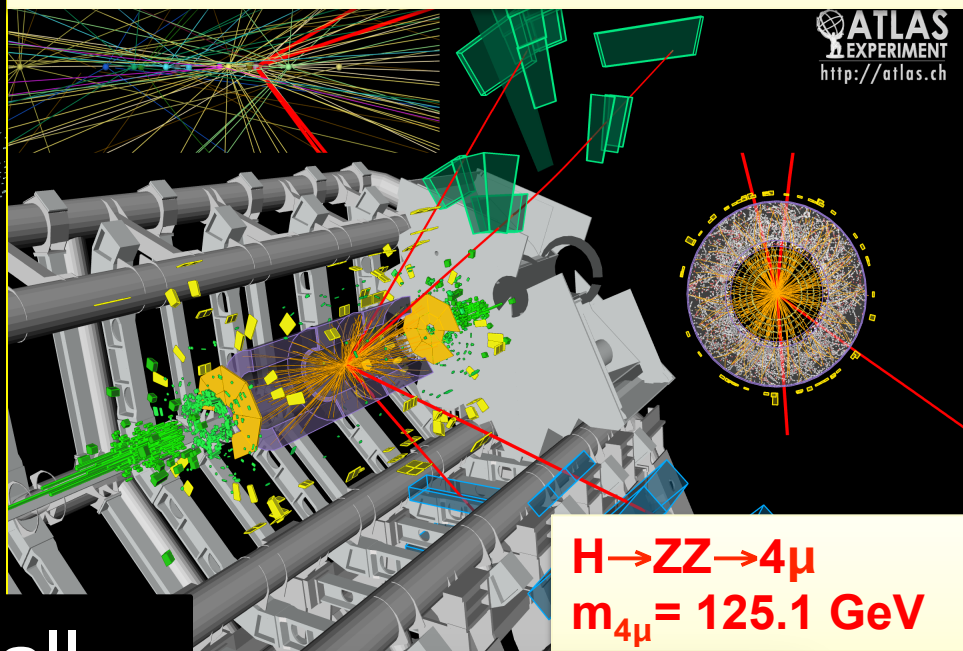




$H \rightarrow \gamma\gamma$



$p_T(\mu) = 36, 48, 26, 72 \text{ GeV}; m_{12} = 86.3 \text{ GeV}, m_{34} = 31.6 \text{ GeV}$



$H \rightarrow ZZ \rightarrow 4\mu$   
 $m_{4\mu} = 125.1 \text{ GeV}$

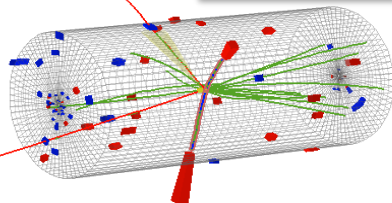


$\mu^+$ : 43 GeV

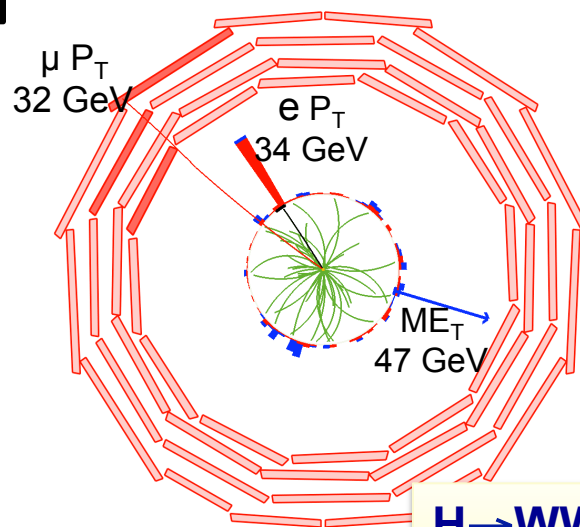
Recall...

$e^+$ : 21 GeV  
 $e^-$ : 10 GeV

$H \rightarrow ZZ \rightarrow 2\mu 2e$   
 $m_{4l} = 126.9 \text{ GeV}$



$\mu^+$ : 24 GeV



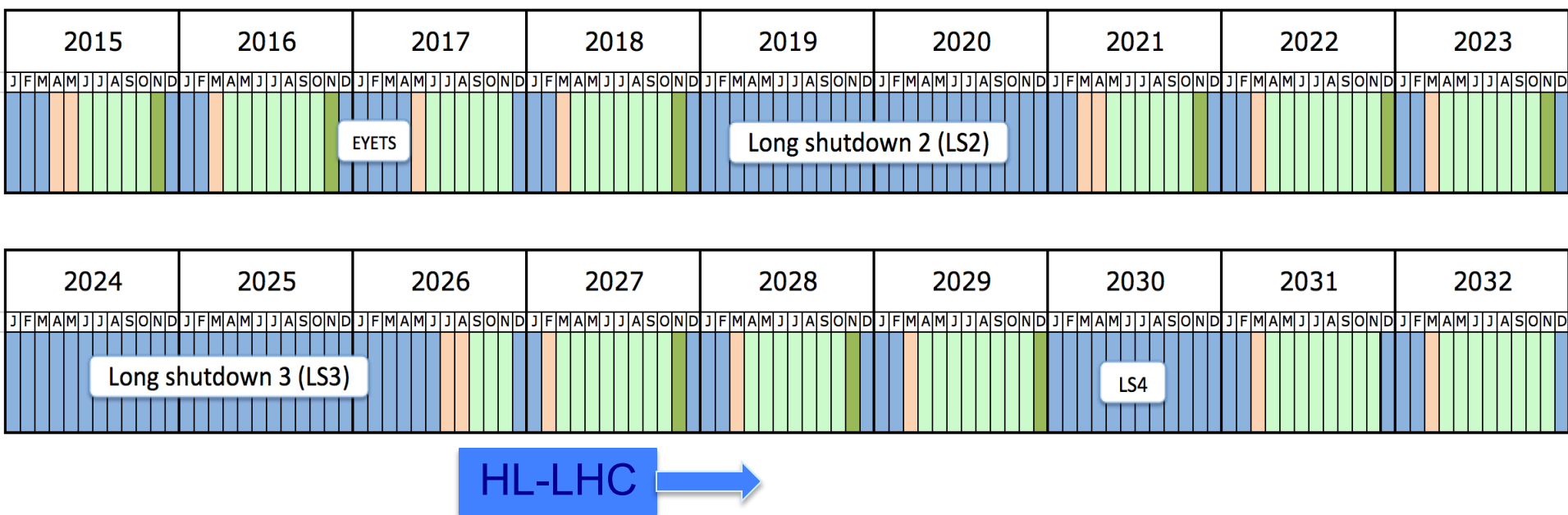
$H \rightarrow WW \rightarrow \mu\nu e\nu$

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

# LHC plan

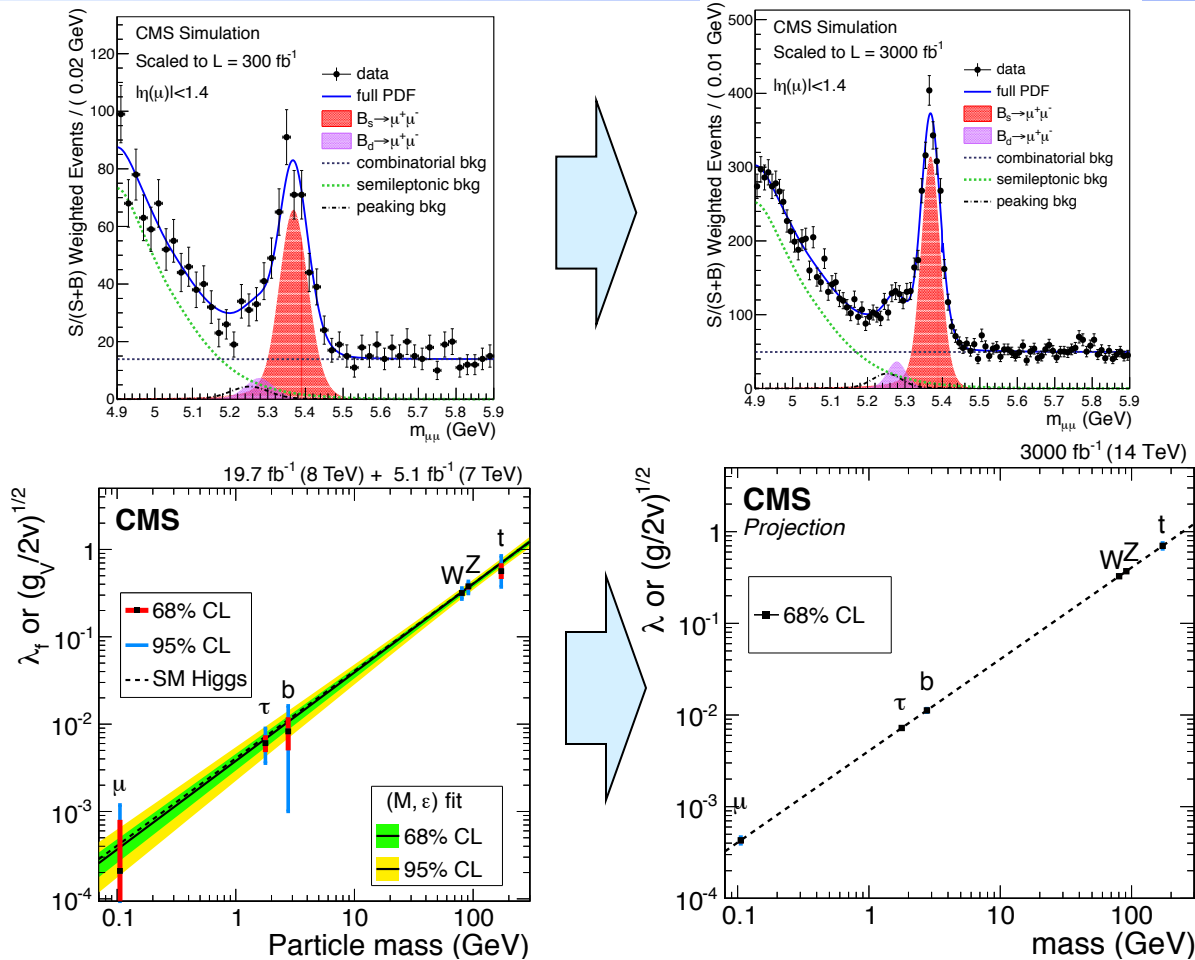
Run 2

Run 3



HL-LHC

# There is power (and physics) in these improvements

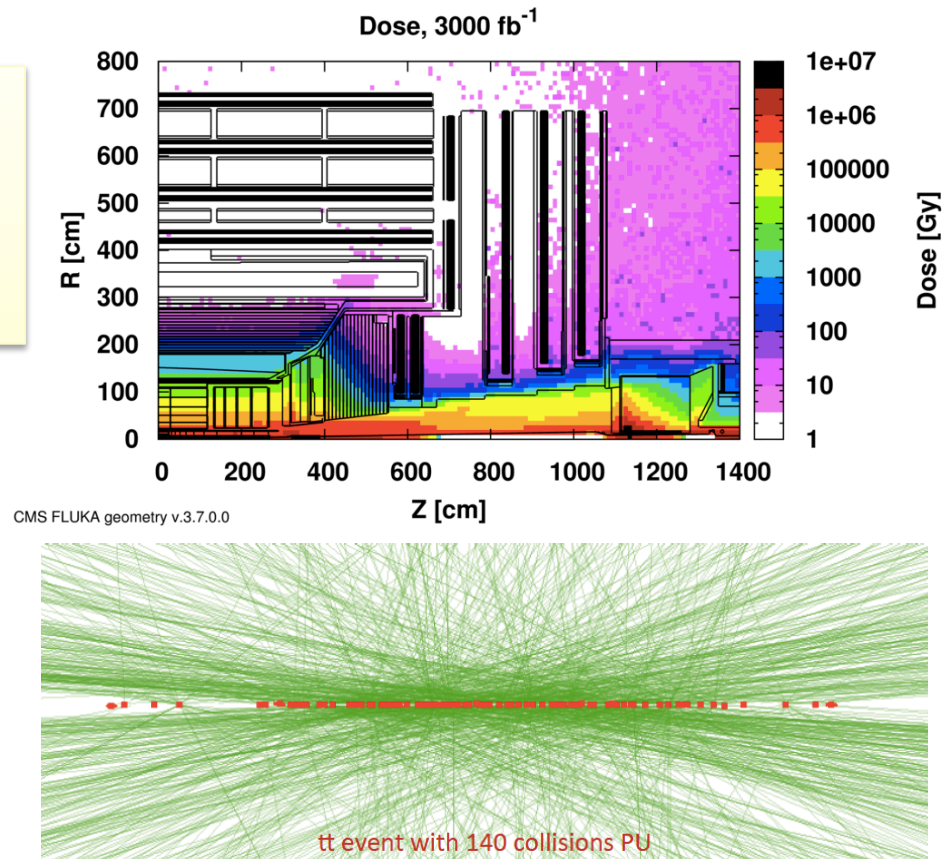


En route to these: new detector elements that represent major new technology & instrumentation breakthroughs

# HL-LHC challenges

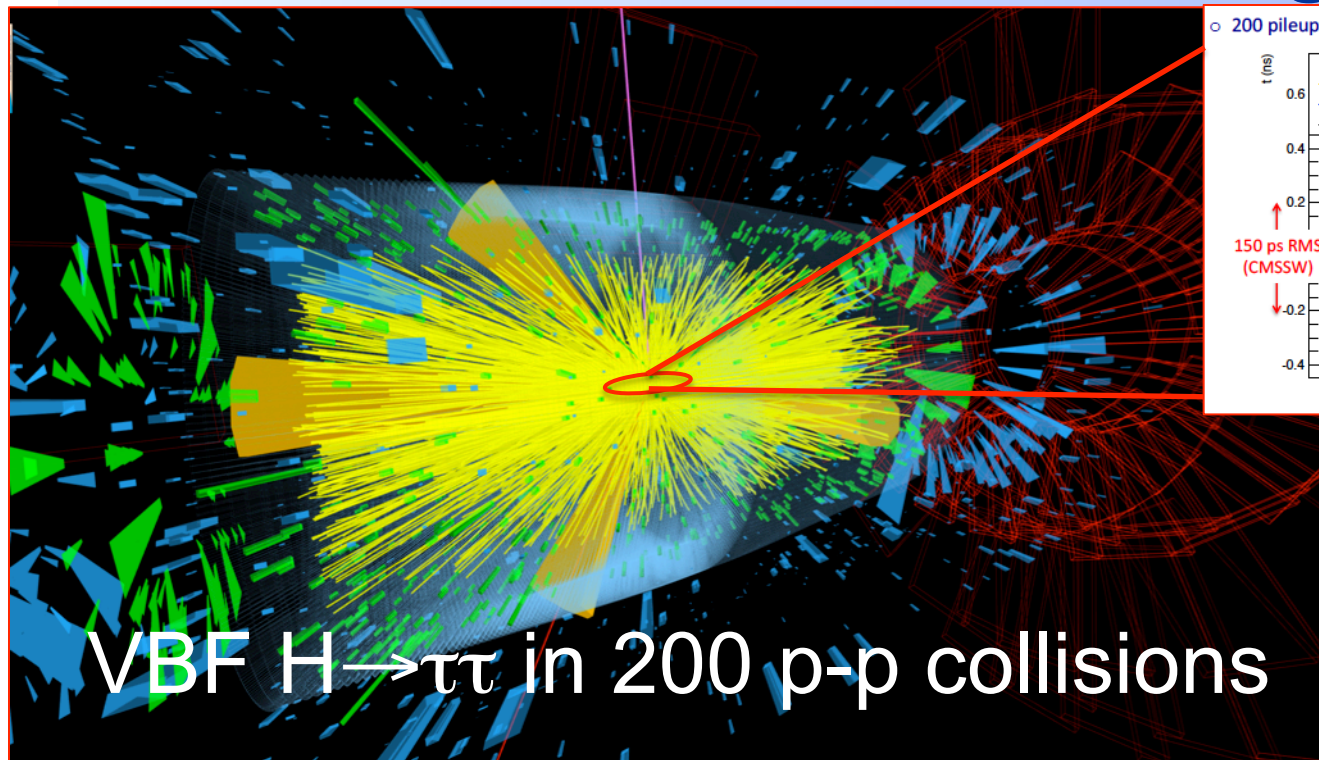
Annual dose at HL-LHC:  
similar to total dose from  
LHC start to LS3

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

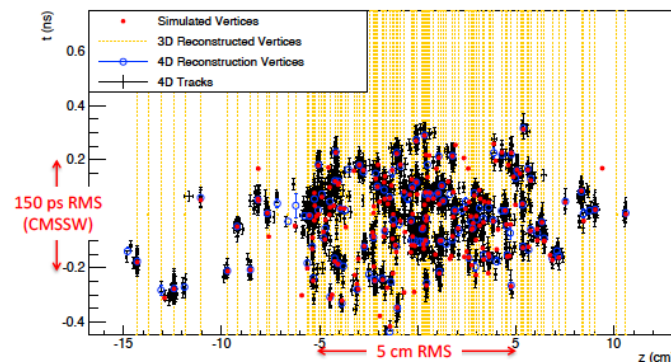


**Upgrade several detector components**  
**Redesign some electronics, Trigger and DAQ**

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

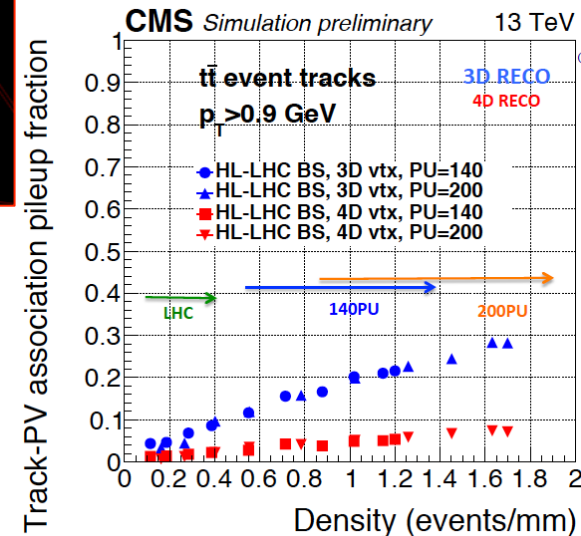


200 pileup collisions



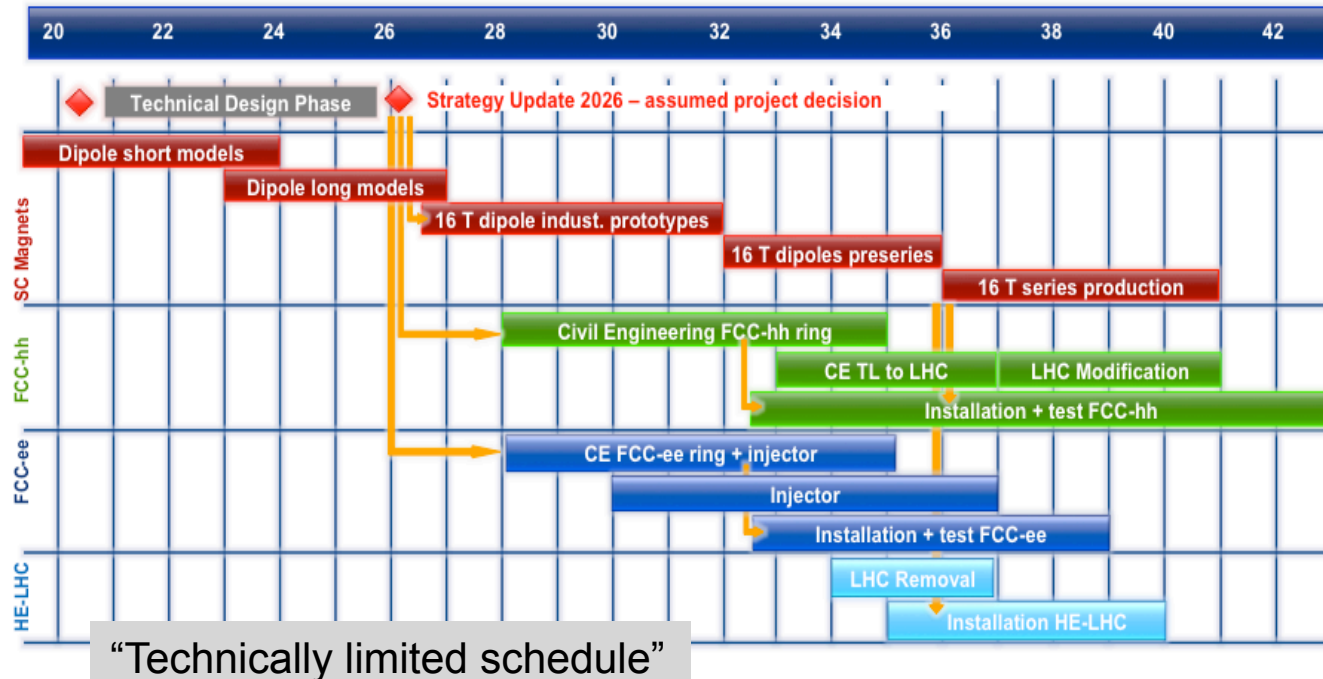
Time of flight precision  $\approx 30 \text{ ps}$ ,  $|\eta| < 3$ ,  $p_T > 0.7 \text{ GeV}$   
 “Provide a factor 4-5 effective pile-up reduction”

- $\approx 15\%$  merged vertices reduce to  $\approx 1.5\%$
- Low pileup track purity of vertices recovered



# **Long-term Outlook**

# Towards a new machine

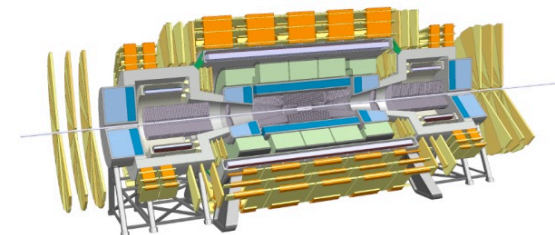


FCC: 100 TeV  
HE-LHC: 27 TeV

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.

- Provide firm Yes/No answers 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?



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

# 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!”**