Collider Physics

Paris Sphicas
CERN & NKUA (Athens)
CHIPP Winter School of High Energy Physics
Adelboden, Jan 16-21, 2022

- **Introduction**
  - **Historical prelude; characteristics of colliders; from the ISR to the LHC.**
  - **Why ATLAS/CMS look the way they do**
  - **pp collisions: characteristics and kinematics; the environment and event reconstruction**
- **Some Standard Model processes**
  - **Jet production, W/Z production, top production**
- **Challenges in looking for New Physics**
  - **The case for data-driven estimates (and help from the Monte Carlo)**
- **Pseudo-summary 1**

Warning

1. The topic is vast
2. I have tried to cover a very wide range of topics
3. Whenever possible, I have tried to show the “method”

[but (3) works against (2)]

4. There is a “CMS twist” to this: I am more familiar with CMS results (and results are more readily accessible to me)

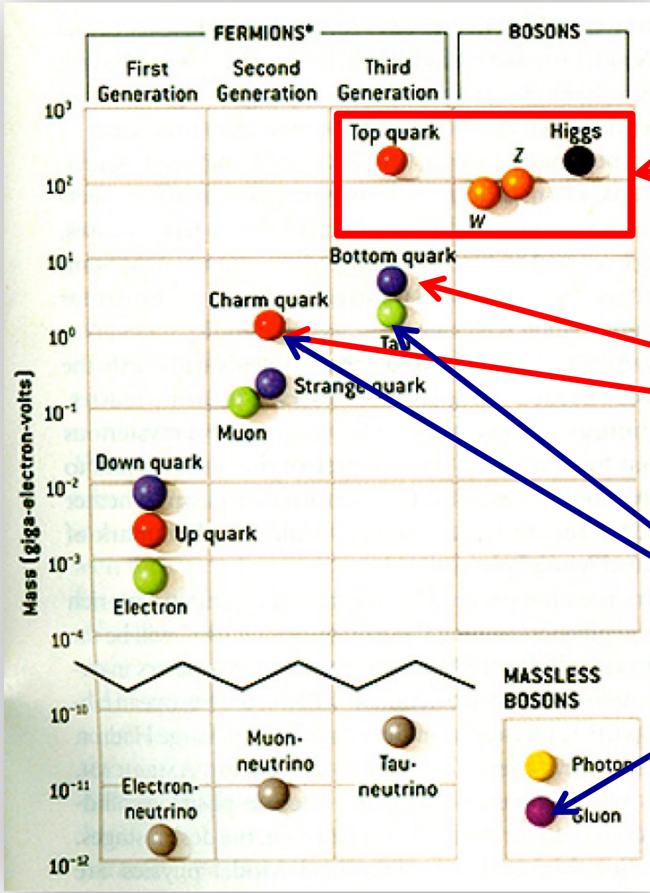
Introduction

Short historical prelude; characteristics of colliders; from the ISR to the LHC.

Short historical prelude (how the LHC came to be)

Why ATLAS/CMS look the way they do

The Standard Model and colliders



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

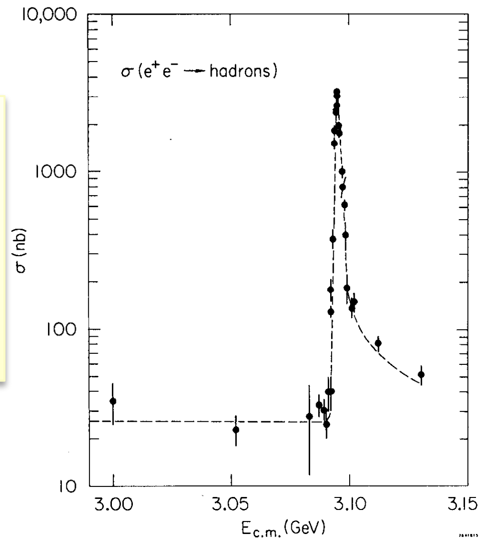
ee Colliders
c and τ @ SPEAR (SLAC)
g @ PETRA (DESY)

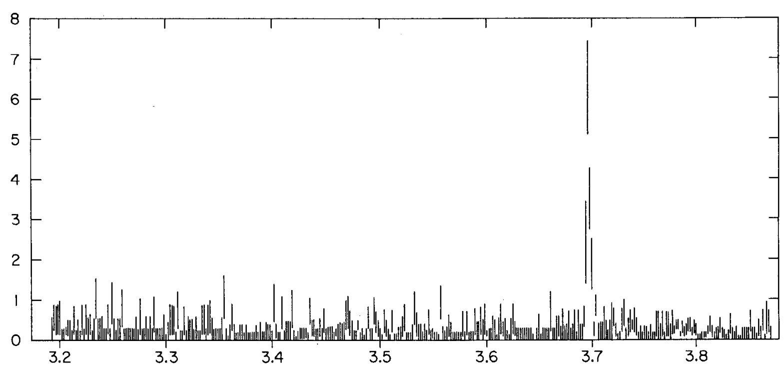
Not shown: probing/studying the strong, weak and EM interactions

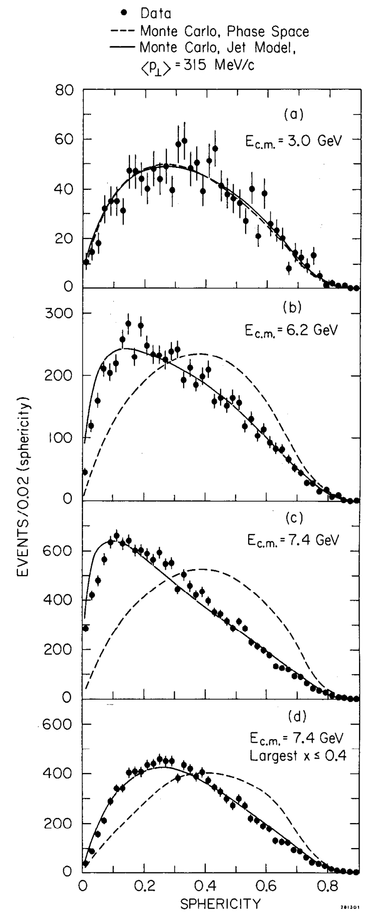
First high-energy e⁺e⁻ collider: SPEAR at SLAC

Very clean

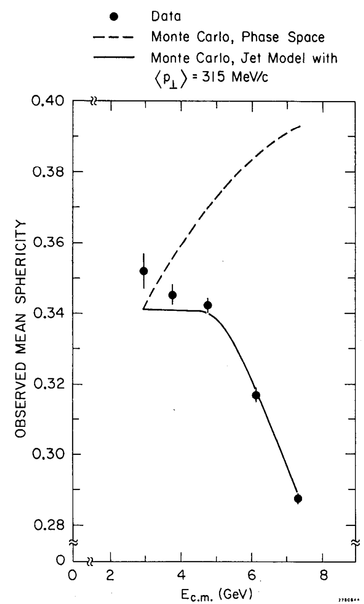
Fine tuning of beam energy
→ J/ψ, ψ(2S)





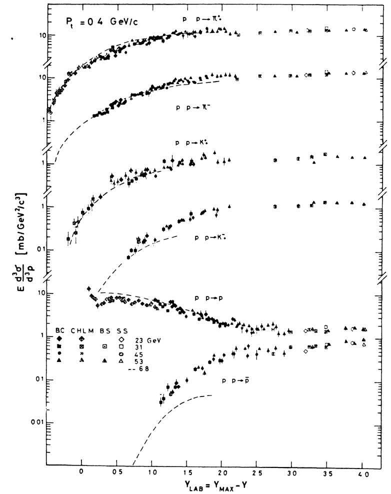


Discovery of hadronic jets (not as straightforward)



Proton-proton collisions; ISR: "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:**

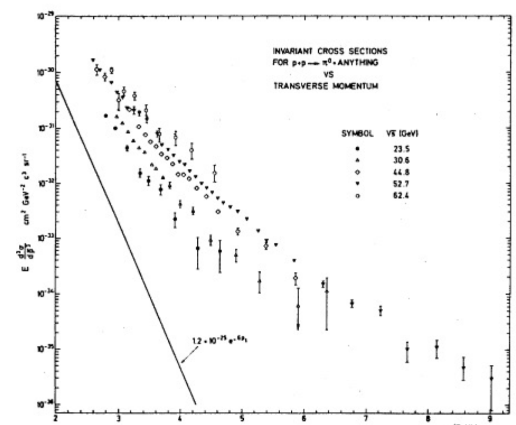
Consituent Interchange Model
D. Sivers, R. Blakenbecler and S. Brodsky, Phys.Reports 23, No. 1 (1976)

CIM*

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

points:

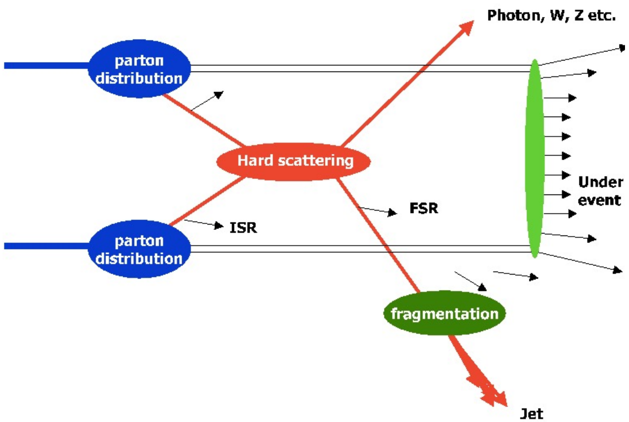
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{s^2}f(x_T,\cos\theta) = \frac{1}{P_T^{\,4}}g(x_T,\cos\theta)$$

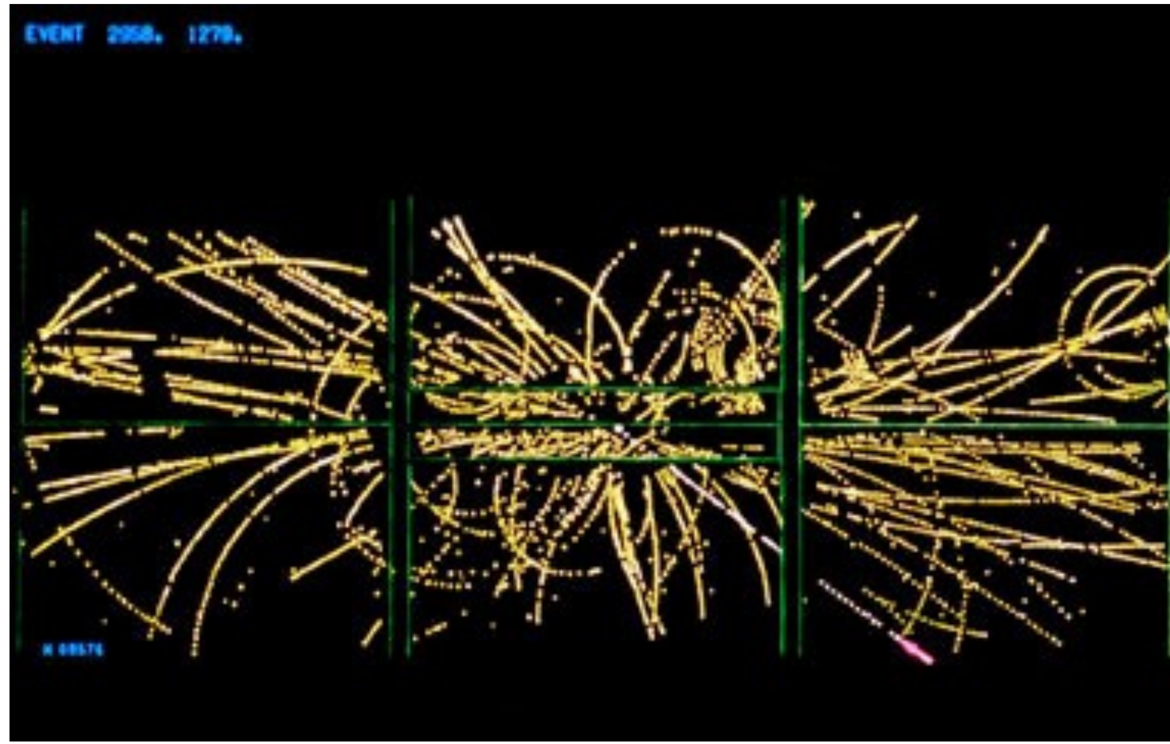


pp collisions :== parton-parton collisions

A clean (…) W decay at the SPS

20-60 GeV pp collisions





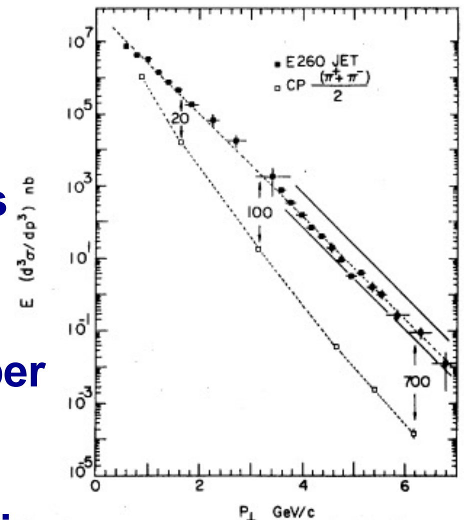
"Jets" were missing at the ISR… There at the SPS!

- **Killed by the trigger:**

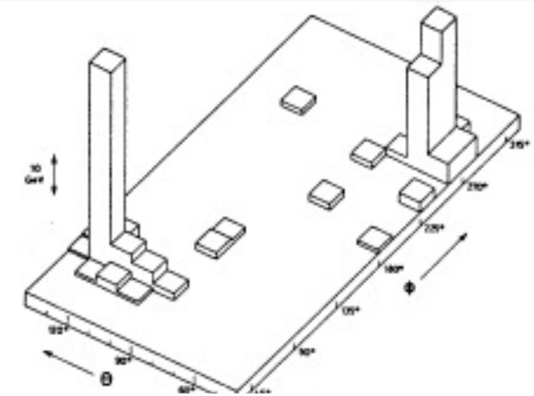
  ISR: triggering on single particles, not global E_T

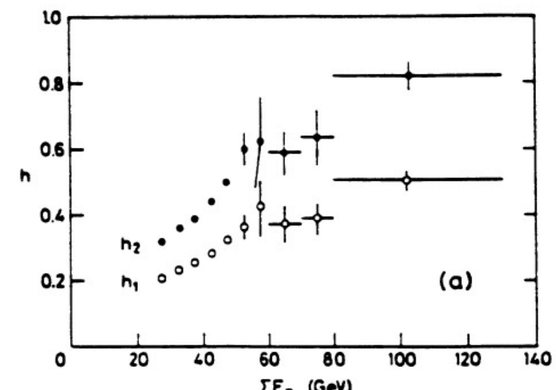
  1) Absence of CALO triggers (small E → bad CALO response)

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



UA2 experiment;
"Paris conference" 1982





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

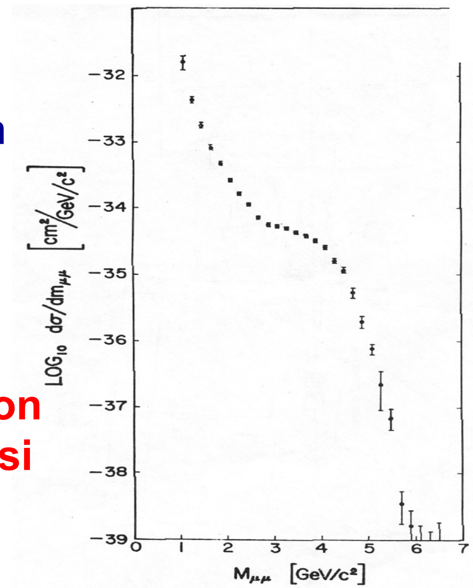
Discoveries missed: (well, AGS…) the J/ψ

- **From Leon Lederman's autobiography at FNAL:**

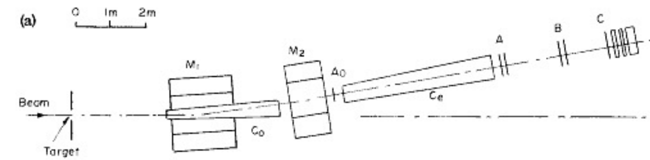
  http://history.fnal.gov/autobiography.html

  "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."



Brookhaven AGS: $p + Be \rightarrow e^+ e^- X$



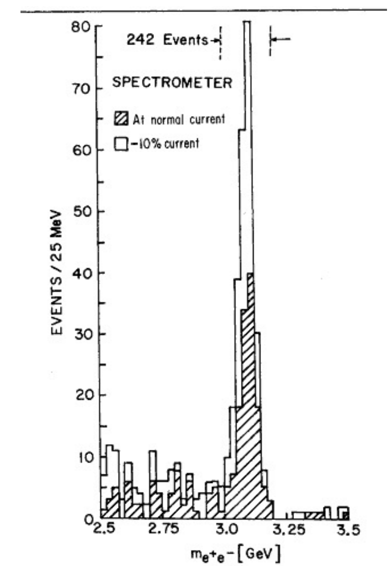


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

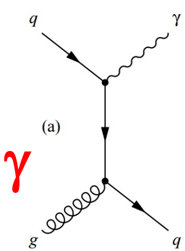
Hard Lesson #2: resolution is so important!

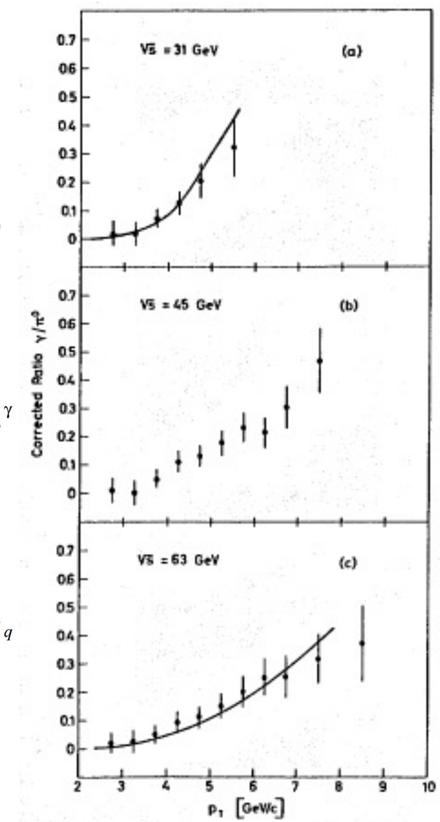
Evidence for the gluon (well...) SPS plans

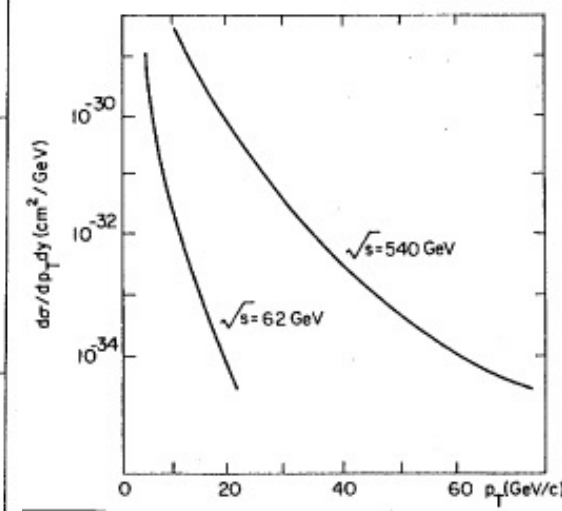
- **Prompt photons seen:**
  - ABCS: unambiguous rise of γ/π^0 ratio
  - Highly non-trivial (experimentally) exercise:
    - Huge background from decay photons...
- **In QCD picture:**

  quark+gluon → Quark + γ

- **Yet, so indirect… (π^0)…**



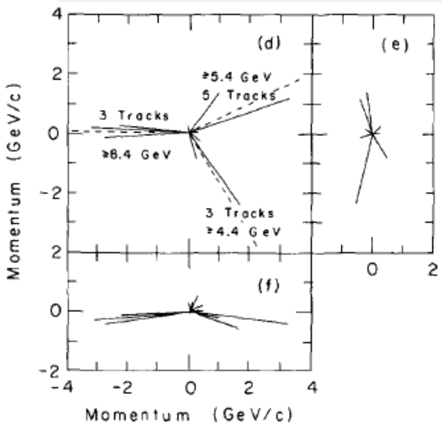




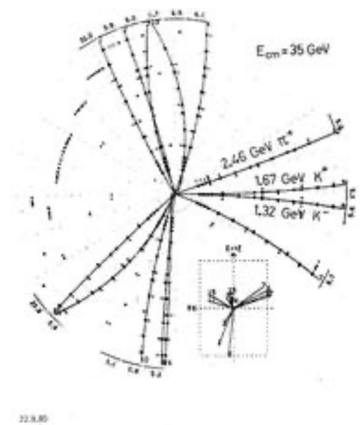
Meanwhile: SPS was in the works… Hard Lesson #3: energy helps…

Dicsovery of the gluon

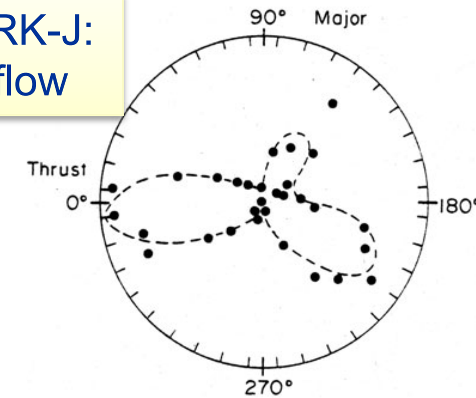
TASSO
Bergen, June 1979



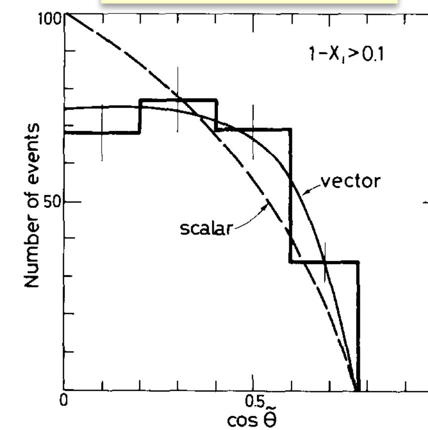
Two months later…
Lepton-Photon @ Chicago:
Clear three-jet events from
all four PETRA experiments



MARK-J:
E-flow

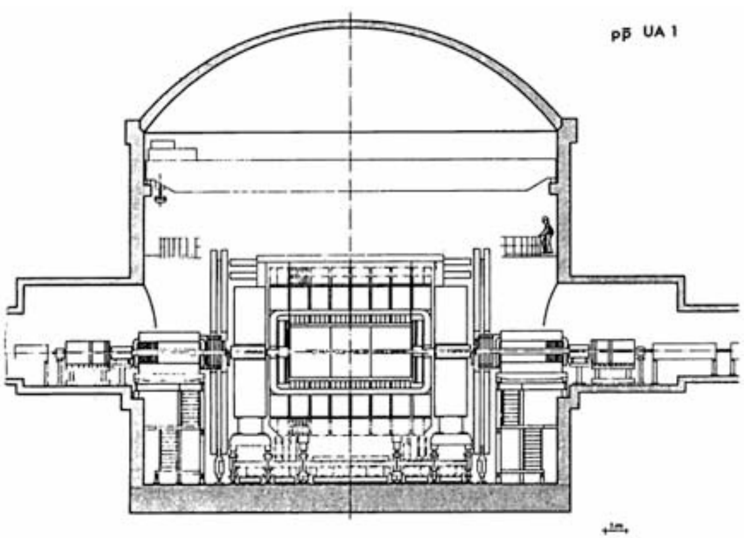


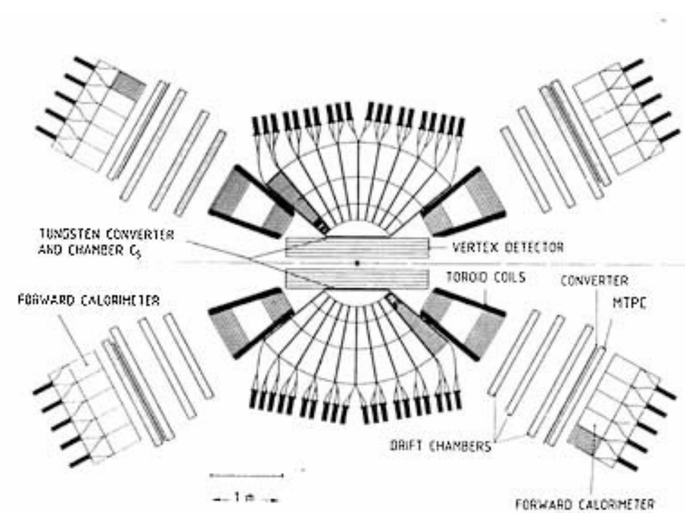
Measurement
of g spin



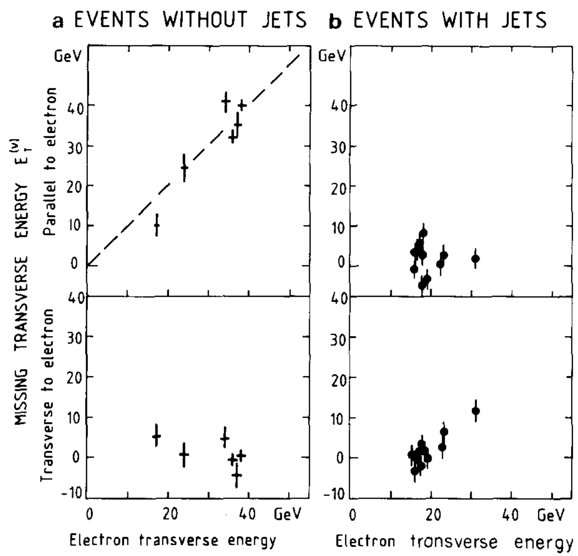
The first high-√s hadron collider and general-purpose experiments UA1 (and UA2)

- **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!



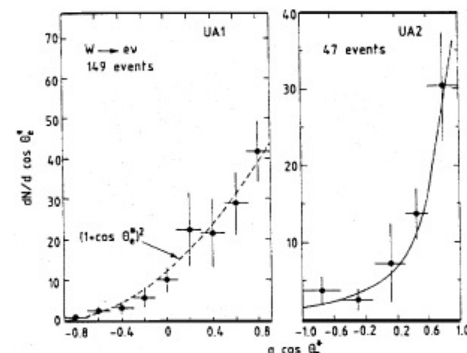


The rendez-vous with the W boson

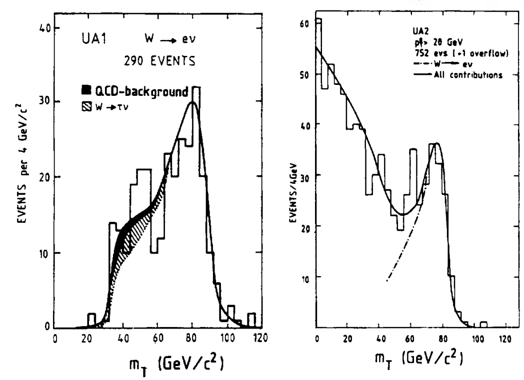


It was there, at the right time (number of events → rate → time of rendez-vous!)

And with the correct spin…

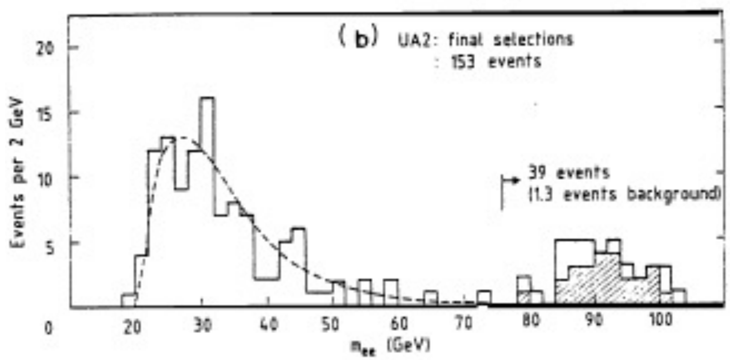


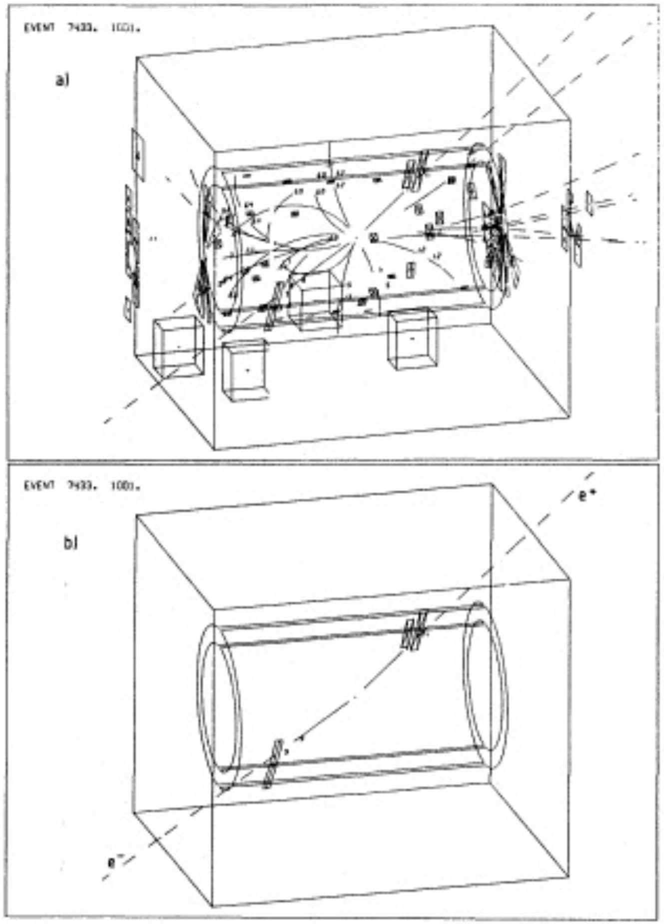
at the right mass:	$\text{UA1: } m_W = 81 \pm 5 \text{ GeV}$ $\text{UA2: } m_W = 81 \pm^{10}_{6} \text{ GeV}$



The similarly punctual cousin: the Z boson

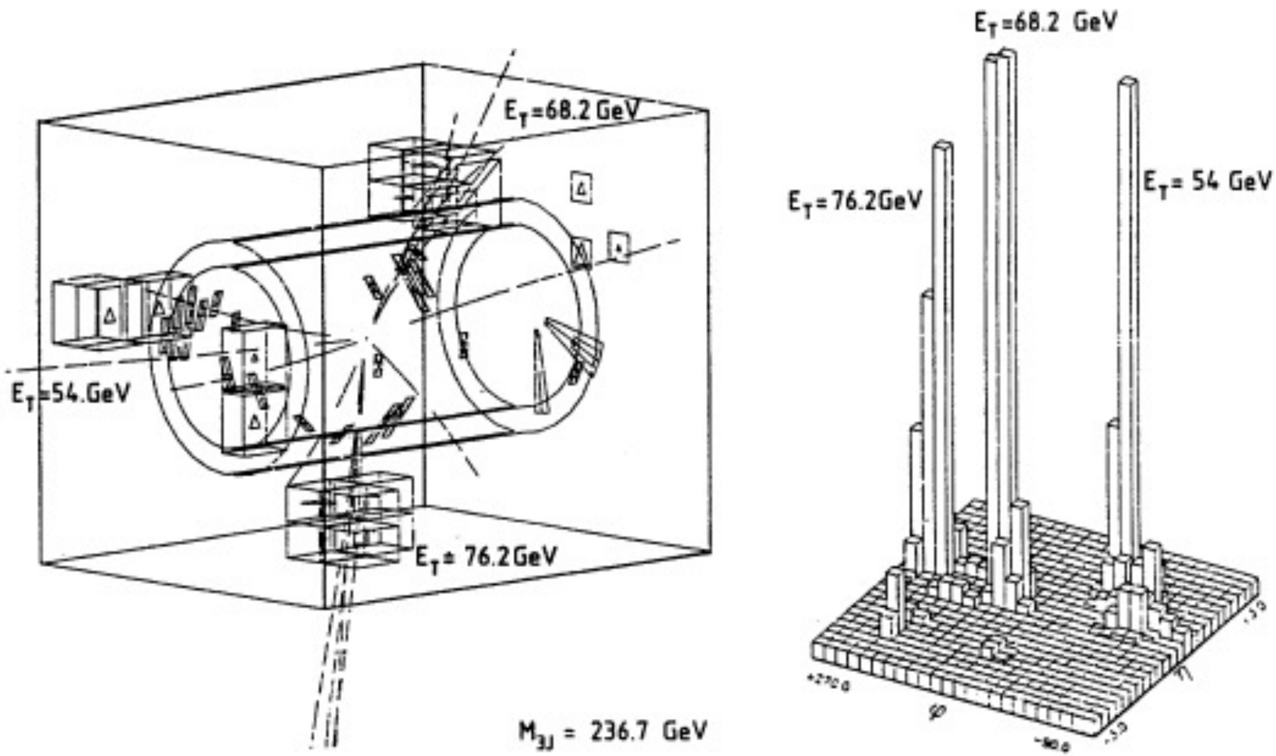
- **The Z boson was there as well**
  - Also at the right time
  - And at the right mass





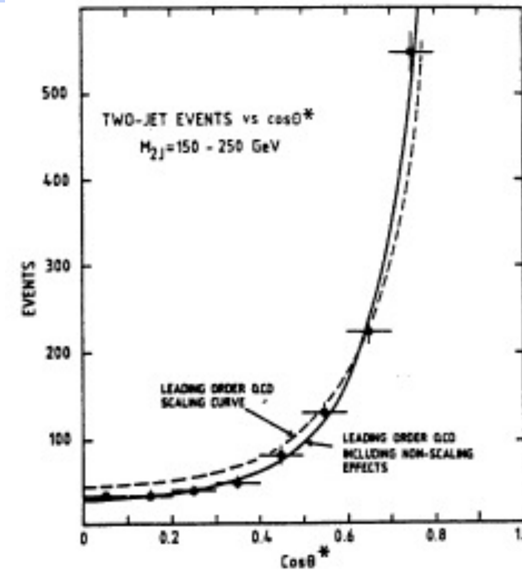
Jets in proton-antiproton collisions

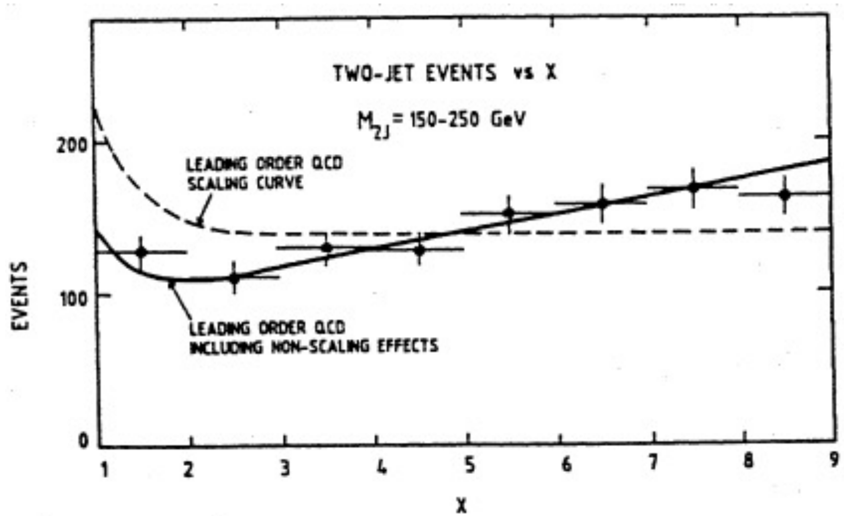
- Even the gluon was still there – in three-jet events!



SPS legacy: strong interaction

Partons inside protons do scatter a la Rutherford!

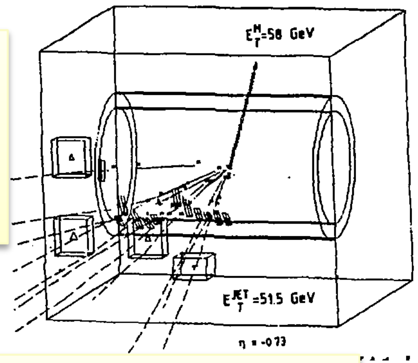




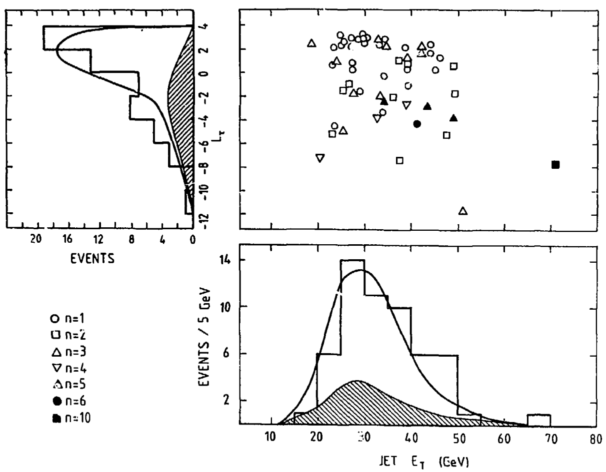
And the QCD "scaling violations" are, actually, visible – Q^2 dependence

Plus, some excitement (that subsided)

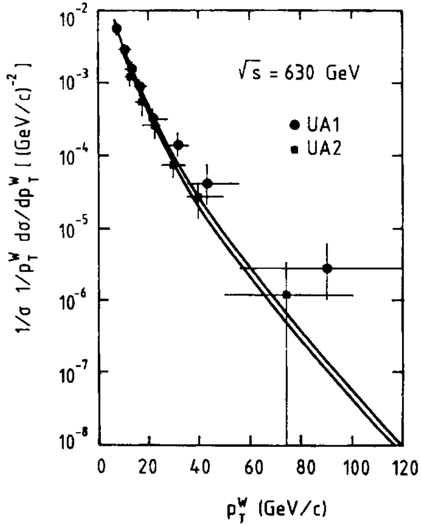
The Monojets! SUSY???

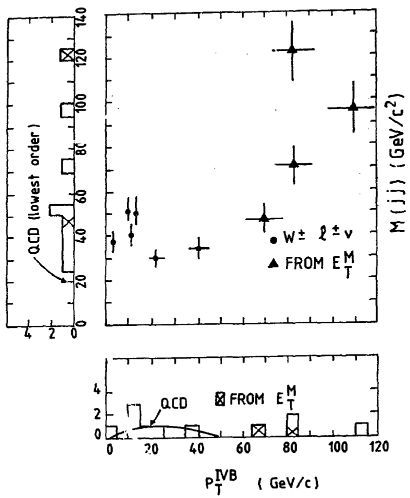


They turned out to be taus…



High-p_T Ws
New X→WW?





It was statistics + LO QCD…

End of the 80s, beginning 90s: Passing the baton to LEP (CERN) and the Tevatron (Fermilab)

LEP Overview: Luminosity, Energy, Precision

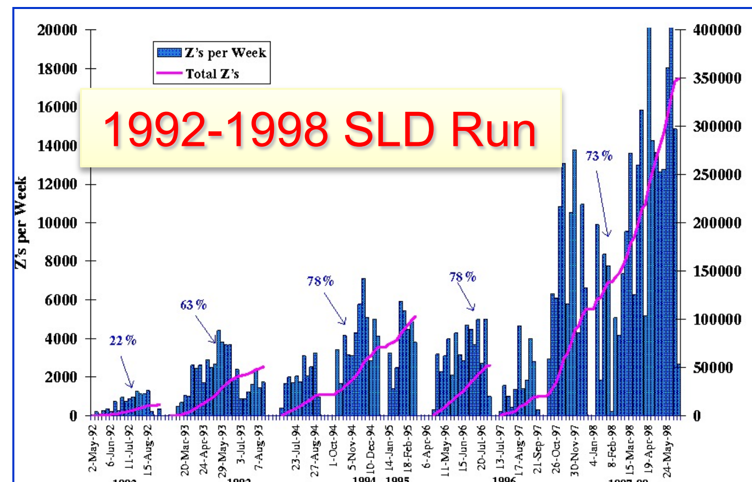
- Conventional collider e^+e^- ring;
- Energy upgradeable;
- Energy measurable;
- Four detectors (A,L,D,O);
- Large luminosity;
- 20 Million Z events.

- But…. Energy limited by synchrotron radiation loss ($\sim\gamma^4$). At the Z peak: 3 GeV/turn (replenished by the RF system)

Stanford Linear Collider and SLD

COMPLEMENTARY to LEP

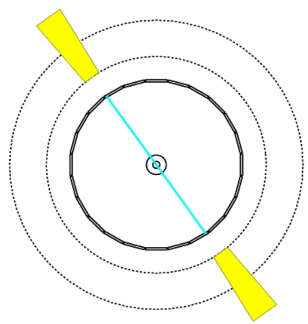
First (high √s) e^+e^- “linear” collider (+ arcs);
Reduced luminosity;
73% electron beam polarization;
Small transverse beam sizes;
and small beam pipe…
Only one detector (MarkII, SLD)
350,000 Z events



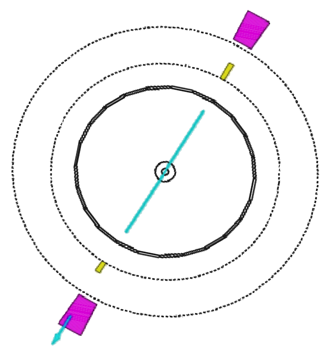
e⁺e⁻ collisions: clean, controlled environment

Total Luminosity: 1000 pb^{-1}

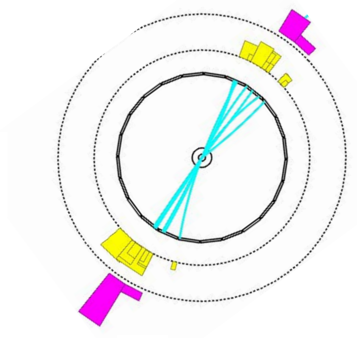
$e^+e^- \to Z \to e^+e^-$

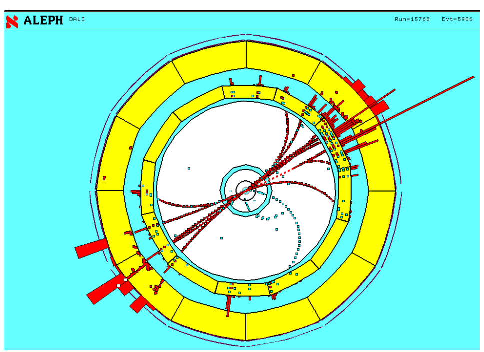


$e^+e^- \to Z \to \mu^+\mu^-$

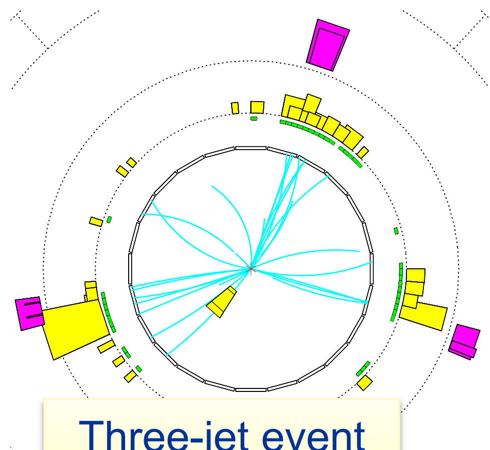


$e^+e^- \to Z \to$ hadrons

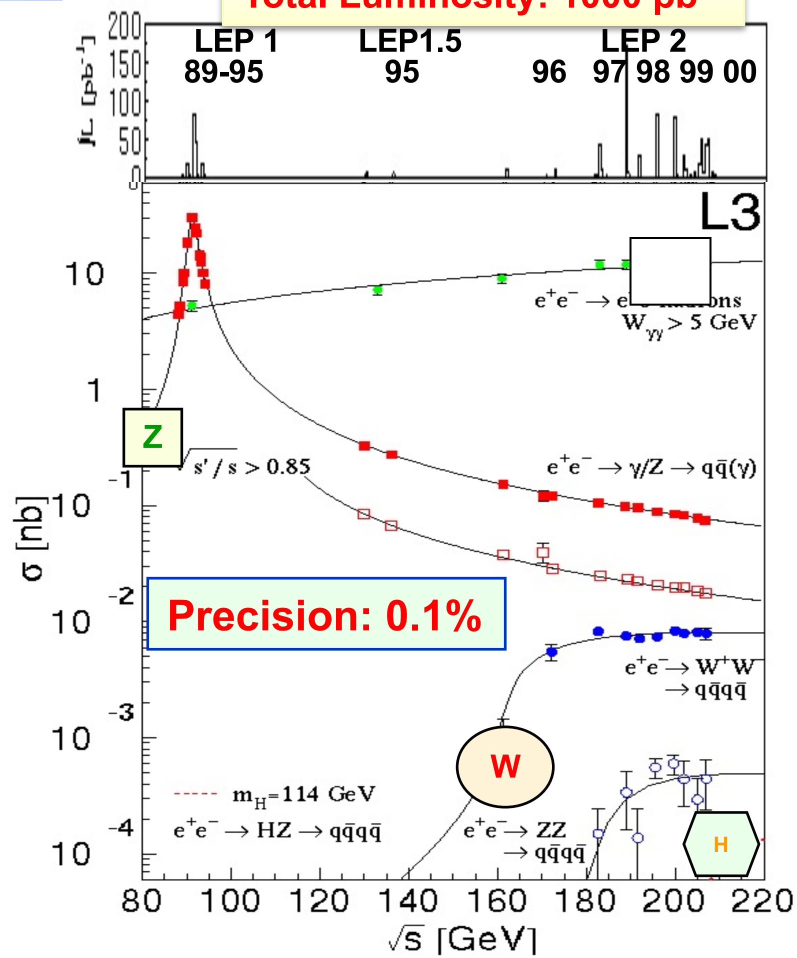




Two-jet event



Three-jet event



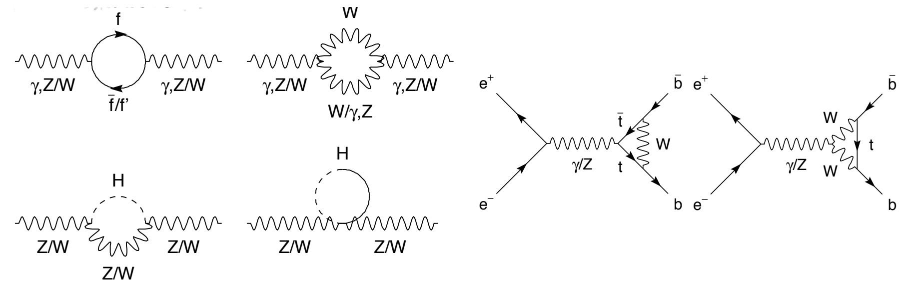
Energy: 88 → 209.2 GeV

The LEP legacy

LEP ran for over a decade
And delivered unprecedented precision on the Electroweak Theory.

On several observables, 0.1%

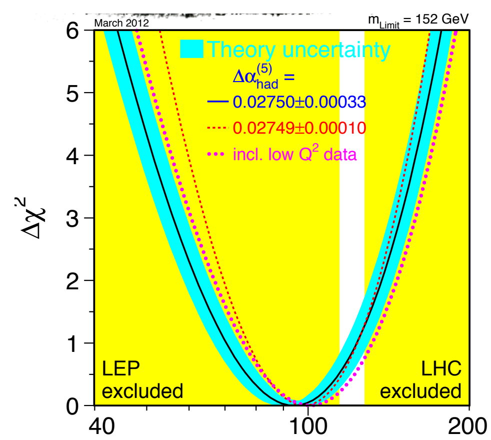
Precision gives access to loops



We also learned that:

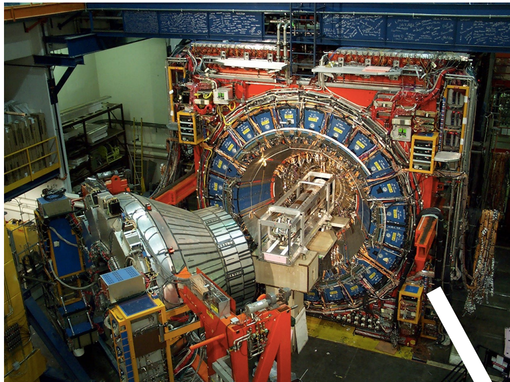
There are at most three neutrino species lighter than M_Z. $N_\nu = 2.9919 \pm 0.0081$

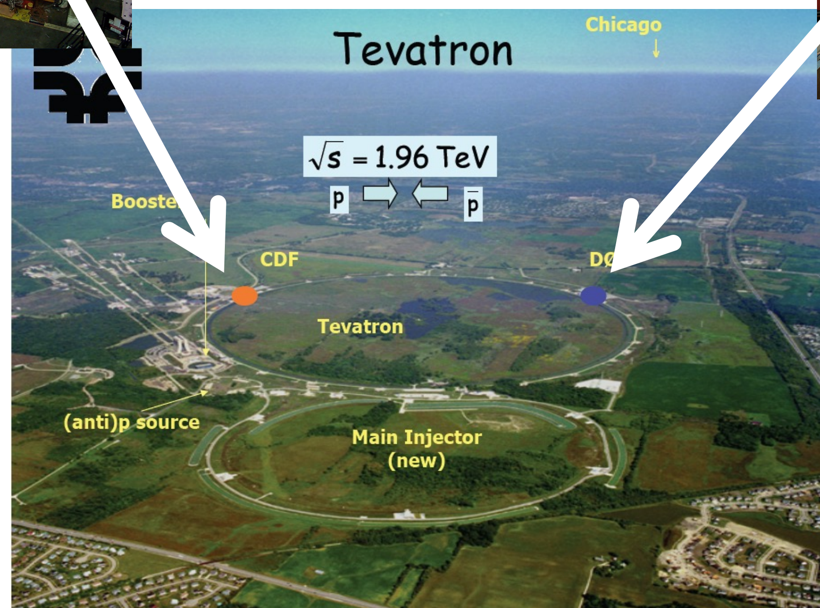
Higgs boson heavier than 114.5 GeV
SUSY not there for masses <~100-110 GeV.



Highest √s attained: 209.2 GeV.
K. Hubner Phys. Reports 403-404 (2004)
The maximum energy of LEP2 was determined by the decision in 1996 to discontinue the production of the SC cavities…

End of 80s, beginning of 90s: Tevatron

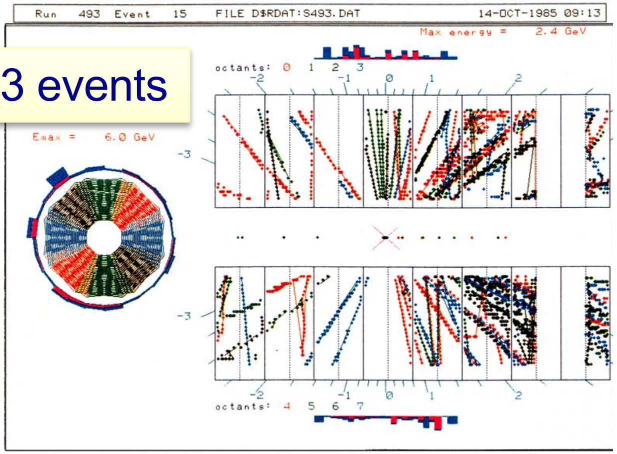




Tevatron evolution

First collisions: CDF, Oct 1985

23 events

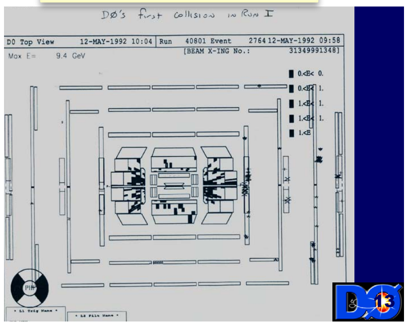


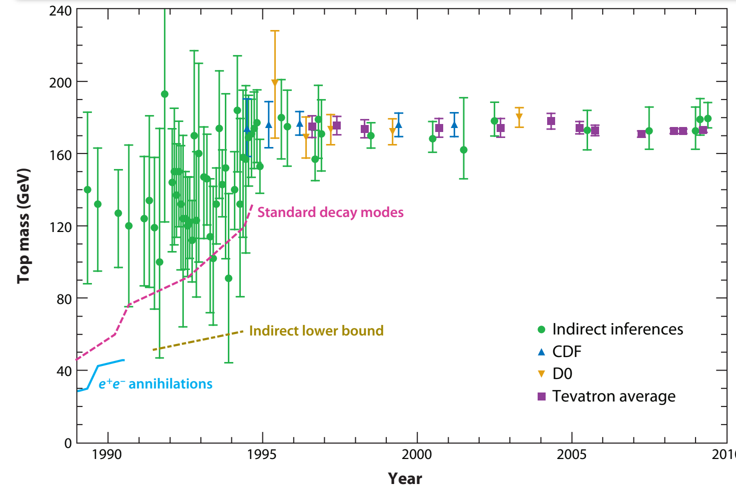
1987: Run 0; first run, CDF,
4pb^{-1} @ 1.8 TeV
1992-96: Run 1; CDF & D0,
120 pb^{-1} @ 1.8 TeV
2011: Run 2; upgraded CDF&D0 12 fb^{-1} @ 2.0 TeV

With LEP providing precision physics at the Z, the Tevatron target was mainly the top quark

And D0 was just starting…

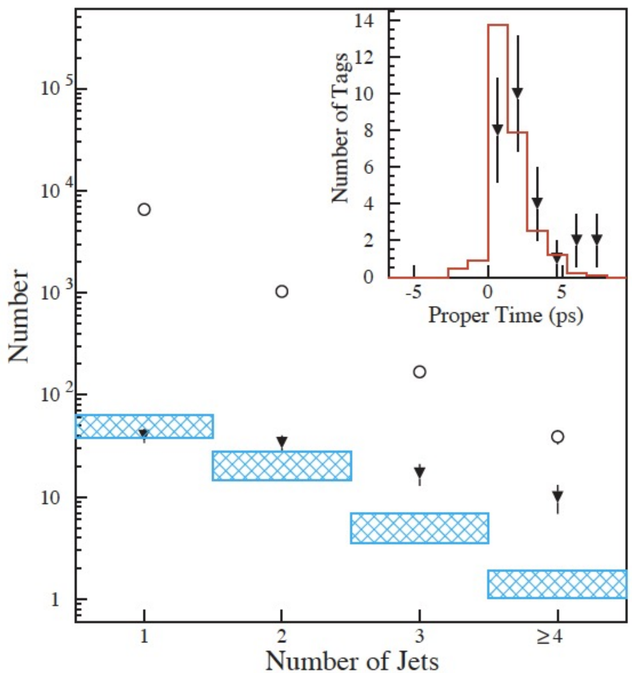
Eventually started in 1992 (Run I)

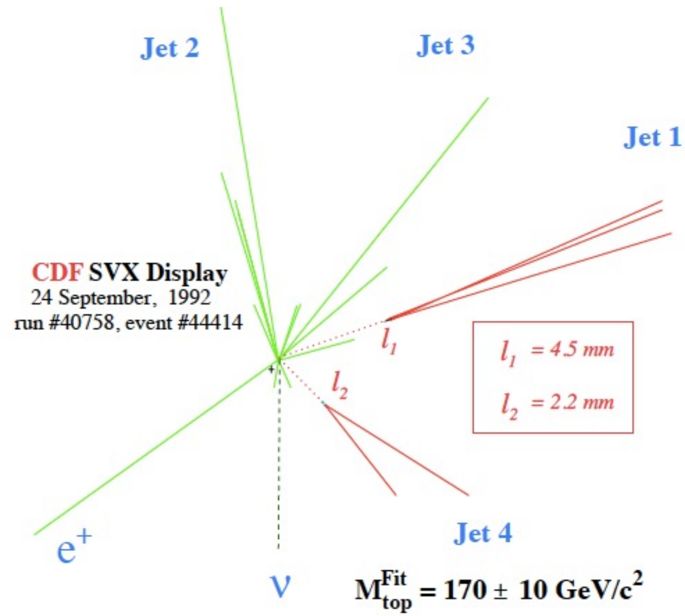




The Tevatron discovery: the top quark (I)

- 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!

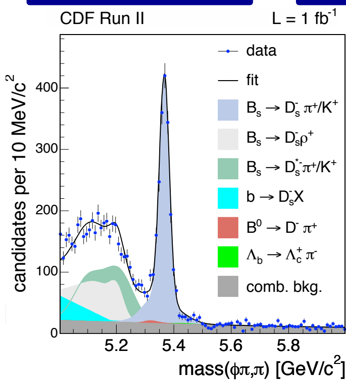


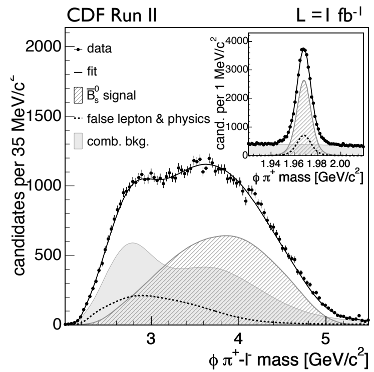


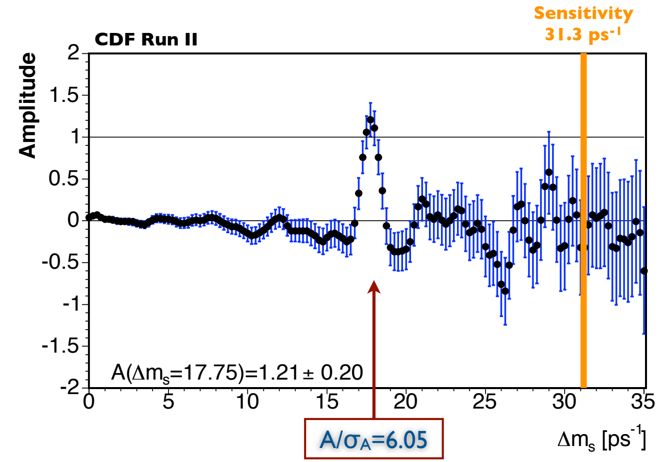
Jewel of B physics @ hadron colliders: B_s

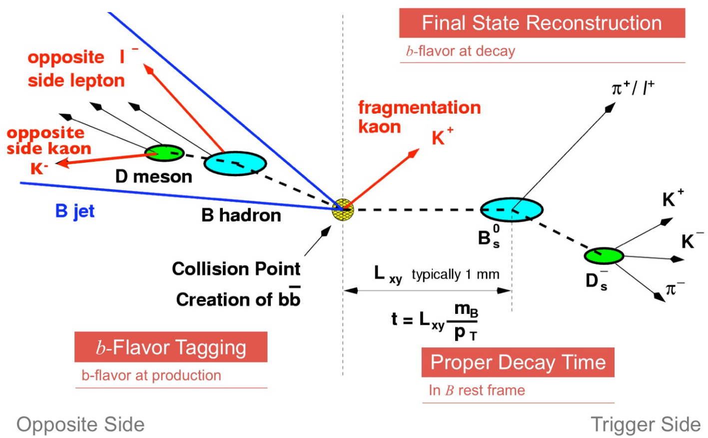
$\boxed{B_s \to D_s \pi}$ $\boxed{D_s \to \phi\pi}$ $\boxed{B_s \to \ell(\nu) D_s}$

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

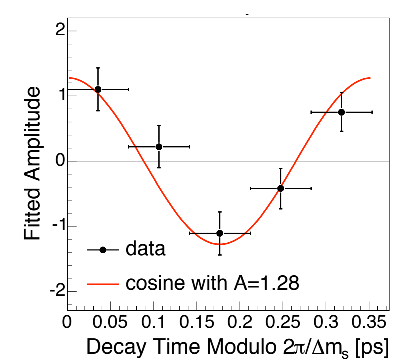






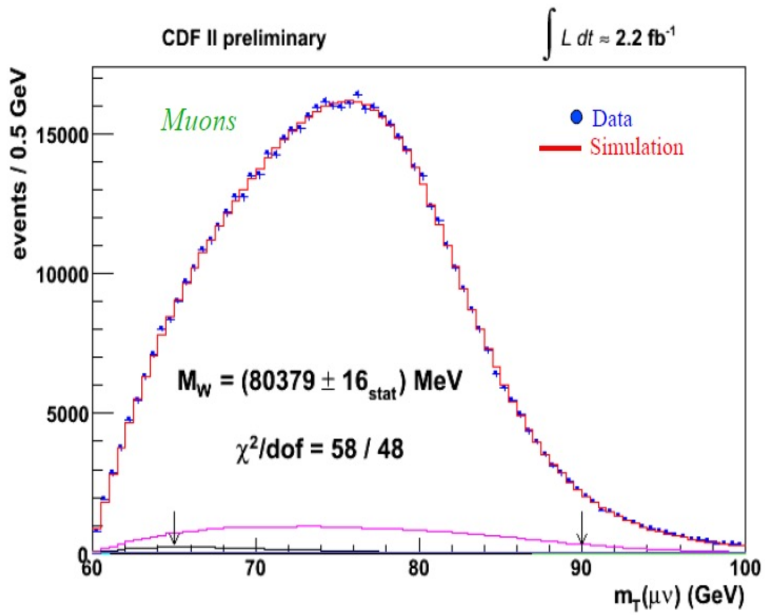


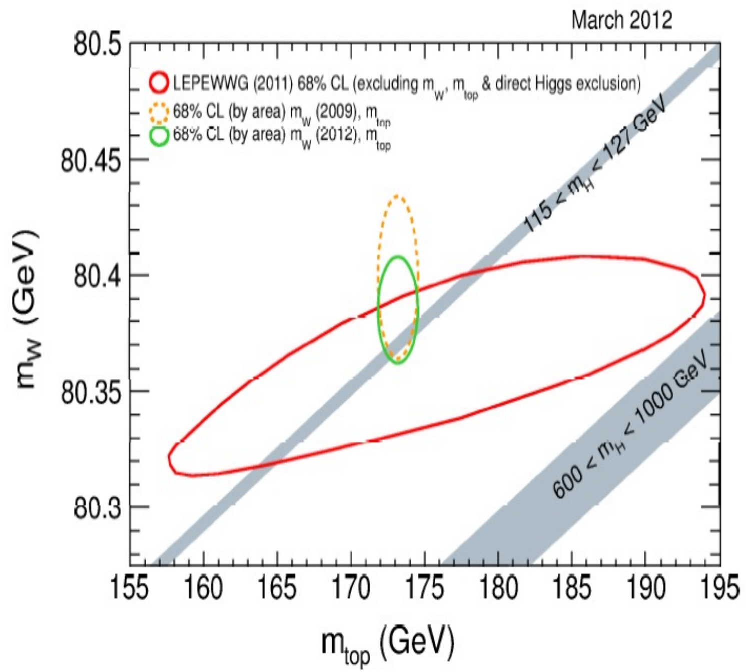
Major tools:
SVXII, PID
(TOF, dE/dx)



The surprise: very high precision on M_W

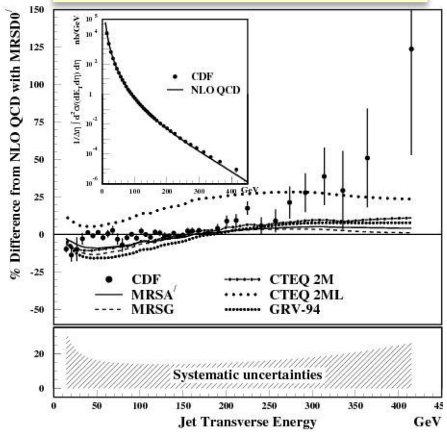
- A measurement with a relative error of 0.24×10^{-3}
  - $M_W = 80387 \pm 19$ MeV/c^2 ($\rightarrow \pm 12$ (stat.) ± 15 (syst.))

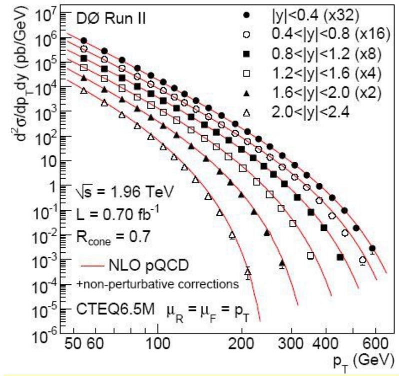




There was also excitement... (I)

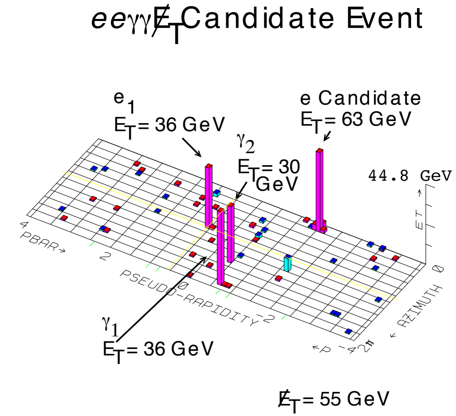
Compositeness?

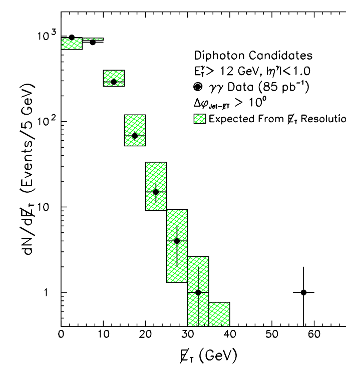




Nope; mainly PDFs… (plus JEC/JES)

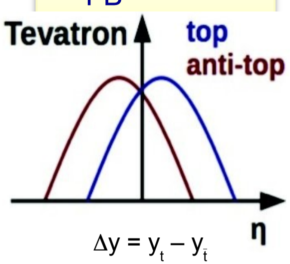
SUSY? Selectron pairs?

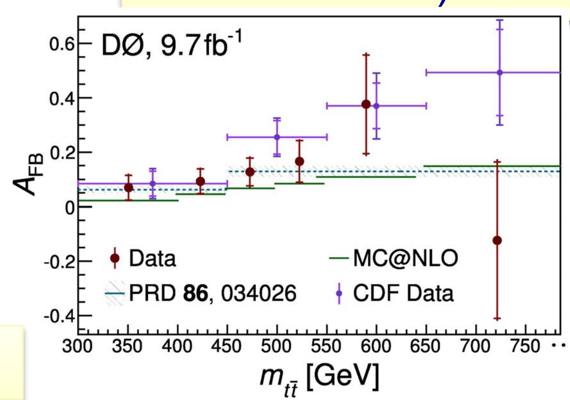




Bkg: $\sim 10^{-6}$

$A_{FB} \rightarrow Z'$?





Nope; stats+the

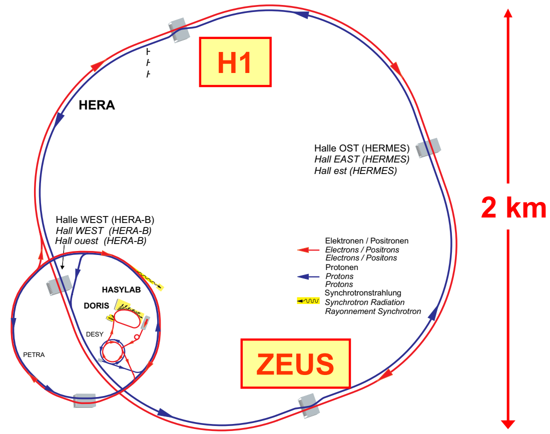
Nope; stats…(?)

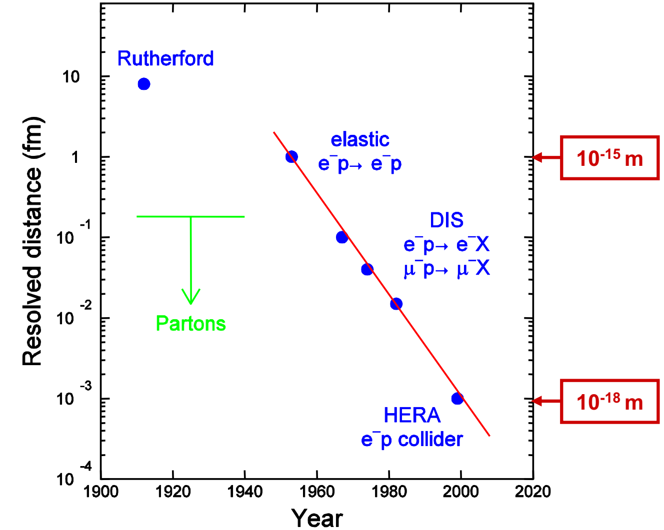
Electron-proton collider” HERA at DESY

★ DESY (Deutsches Elektronen-Synchroton) Laboratory, Hamburg, Germany

$e^{\pm}$ 27.5 GeV → ← 820 GeV p

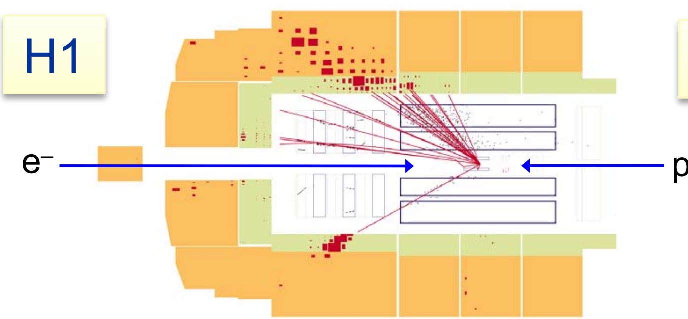
$\sqrt{s}$ = 300 GeV



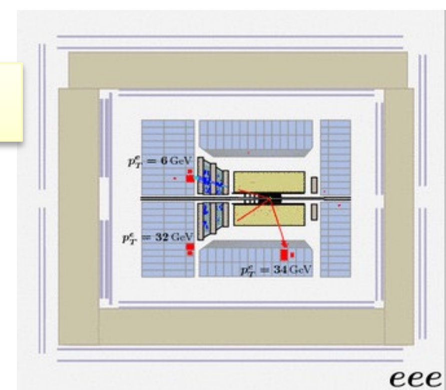


★ Two large experiments : H1 and ZEUS

H1



ZEUS



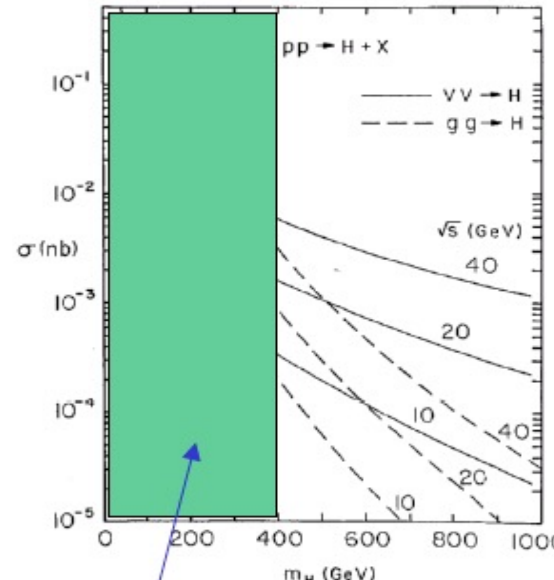
1992-2007
Proton pdfs
QCD
WK interaction

LEP and the Tevatron were huge successes

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

A machine for EWSB

- **Superconducting Supercollider (SSC) √s=40 TeV…**
  - **By now: would have had 4th-gen results**
- **So: use existing LEP tunnel at CERN**
  - **Replace: e by p; increase bending power**
    - **Large Hadron Collider**

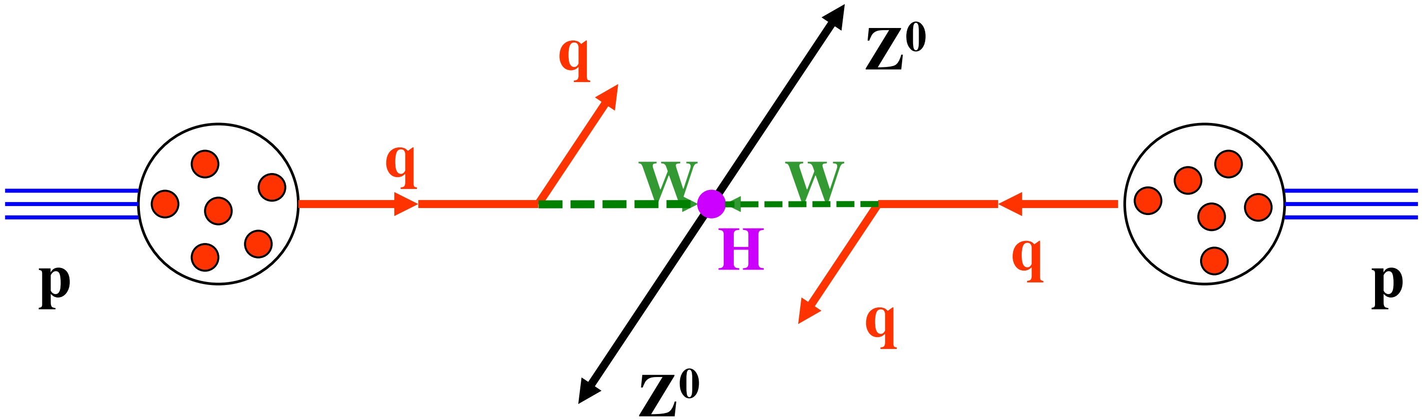


D.Dicus, S. Willenbrock

Phys.Rev.D32:1642,1985

Not true any more (M_T=175 GeV)

Higgs Production in pp Collisions



$M_H \sim 1000$ GeV

$E_W \geq 500$ GeV

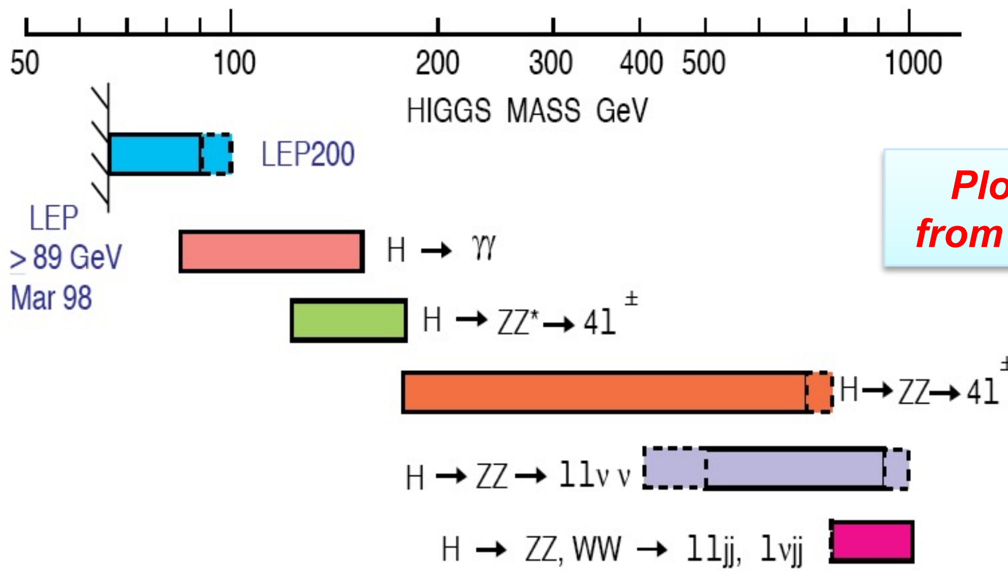
$E_q \geq 1000$ GeV (1 TeV)

$E_p \geq 6000$ GeV (6 TeV)

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

Designing LHC detectors

- **Using Higgs boson as driver of requirements:**
  - **SM did not provide information on M_H, so a broad range of masses – and thus signatures – had to be considered**



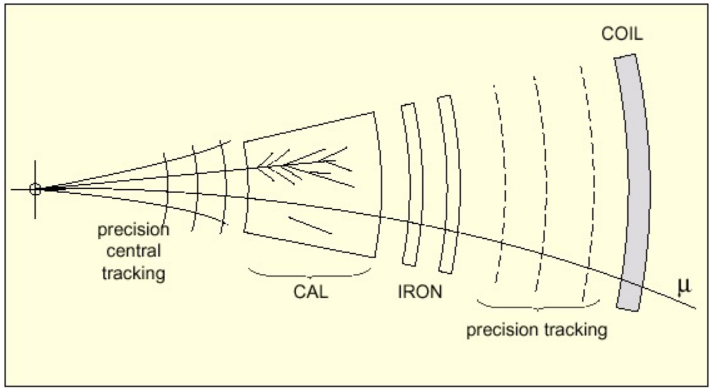
Plot/slide from the 90's

- **Need "4π, general-purpose detectors"**

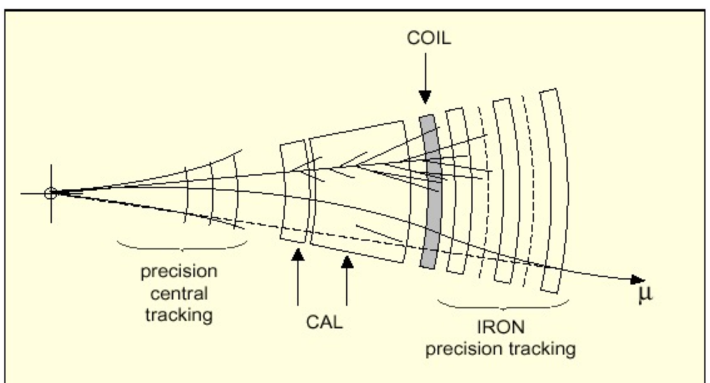
Designing an LHC experiment

- **THE issue: measure momenta of charged particles (e.g. muons); so which measurement "architecture"?**

Note: B in z in both cases



Standalone p measurement;
safe for high multiplicities;
Air-core toroid
Property: σ flat with η

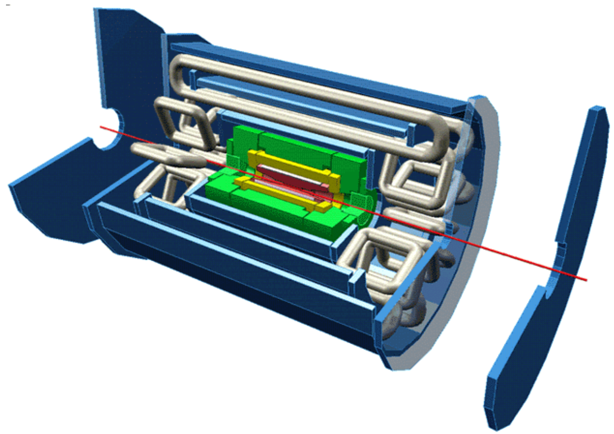


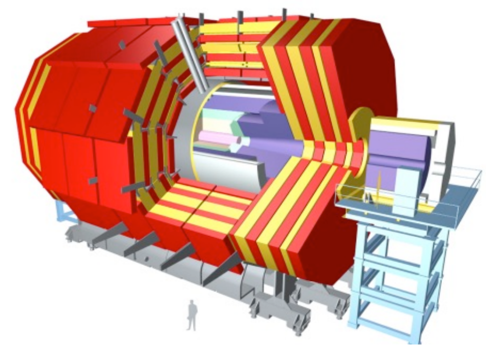
Measurement of p in tracker and B return flux;
Iron-core solenoid
Property: muon tracks point back to vertex

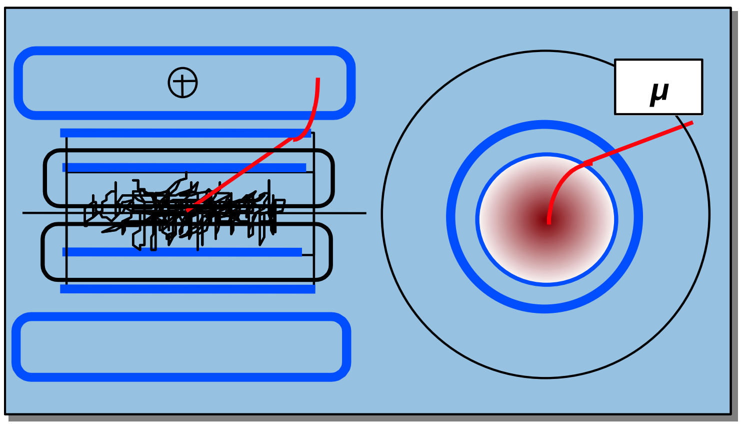
LHC: pp general-purpose experiments

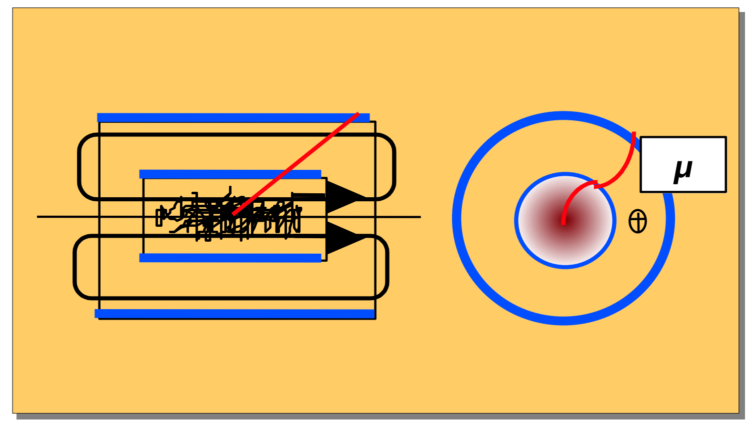
ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid



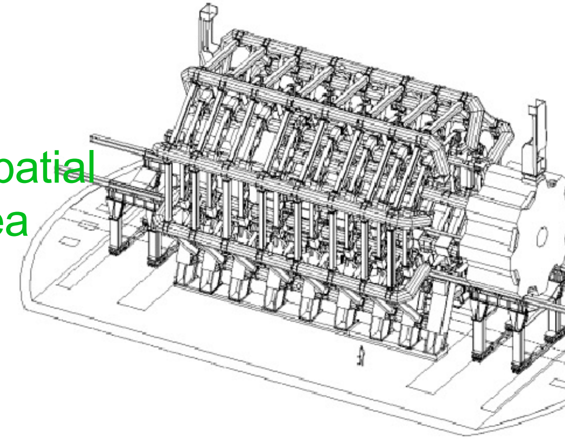




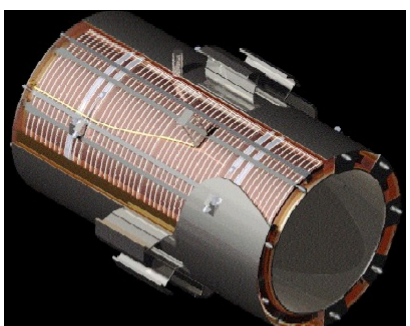


Choice of magnet (I)

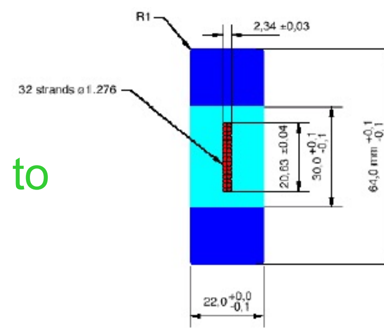
- **Basic goal: measure 1 TeV muons with 10% resolution**
  - **ATLAS: <B>~0.6T over 4.5 m → s=0.5mm → need σ_s=50μm**
    - Ampère's thm: $2\pi RB=\mu_0 nI \longrightarrow nI=2\times10^7$ At
    - With 8 coils, 2x2x30 turns: I=20kA (superC)
    - Challenges: mechanics, 1.5GJ if quench, spatial & alignment precision over large surface area



  - **CMS: B=4T (E=2.7 GJ!)**

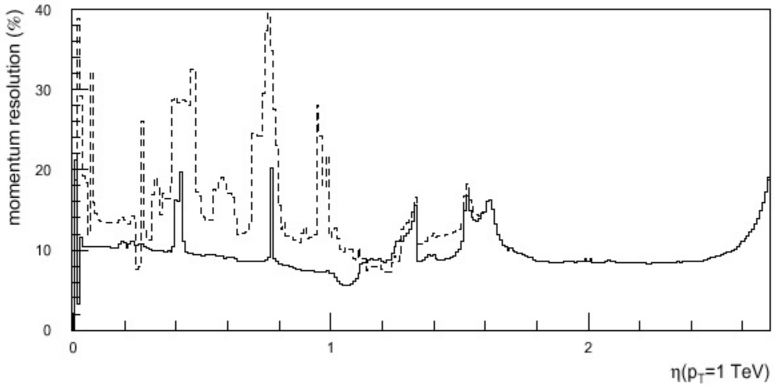


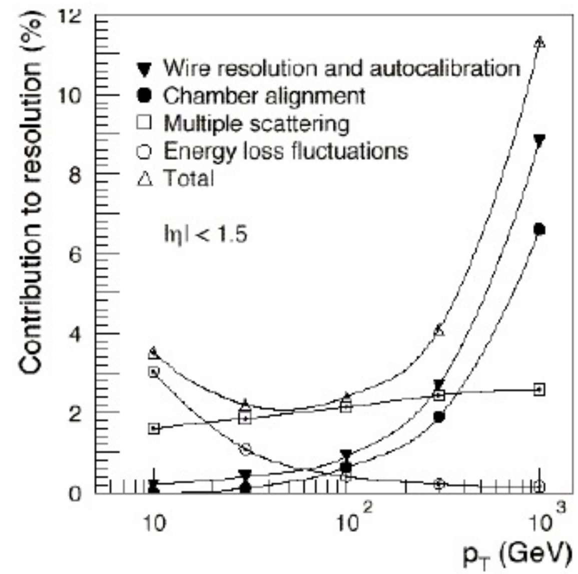
- $B=\mu_0 nI$; @2168 turns/m $\longrightarrow$ I=20kA (SuperC)
- Challenges: 4-layer winding to carry enough I, design of reinforced superC cable



Choice of magnet (II): air-core torroid

- Torroid: gives flat σ vs η:





(a) External meas. does not benefit From beam spot (20 μm @ LHC)

(b) need additional solenoid for internal track measurement

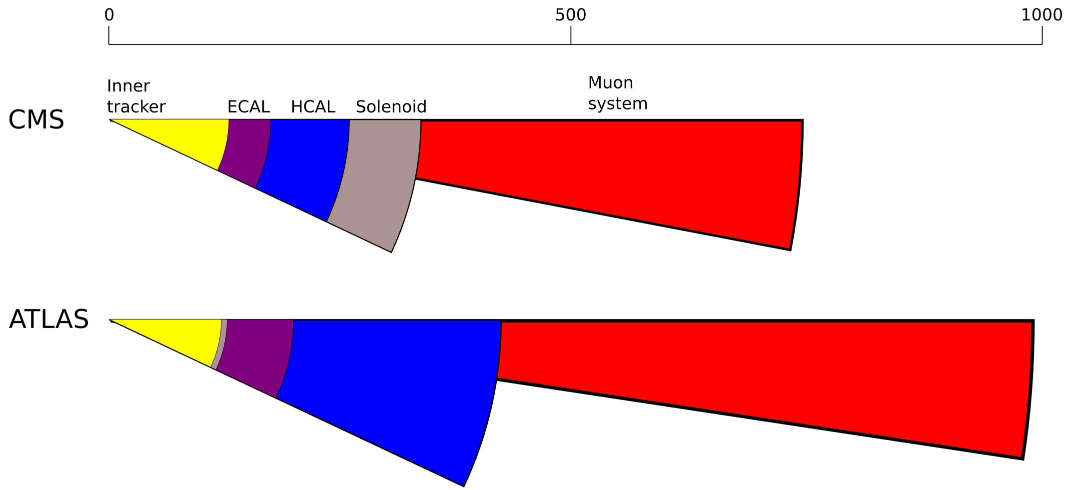
- **ATLAS: B=2T solenoid**

○ **Calorimetry: a new question: inside or outside solenoid?**

- **ATLAS: outside; CMS: inside**

Choice of magnet (IV)

- **Side effects: size of things…**
  - **External measurement:**
    - **Need space: solenoid + toroids → complicated field configuration**
    - **Lower field in tracker (2T)**
  - **Internal measurement:**
    - **Very compact → no space**

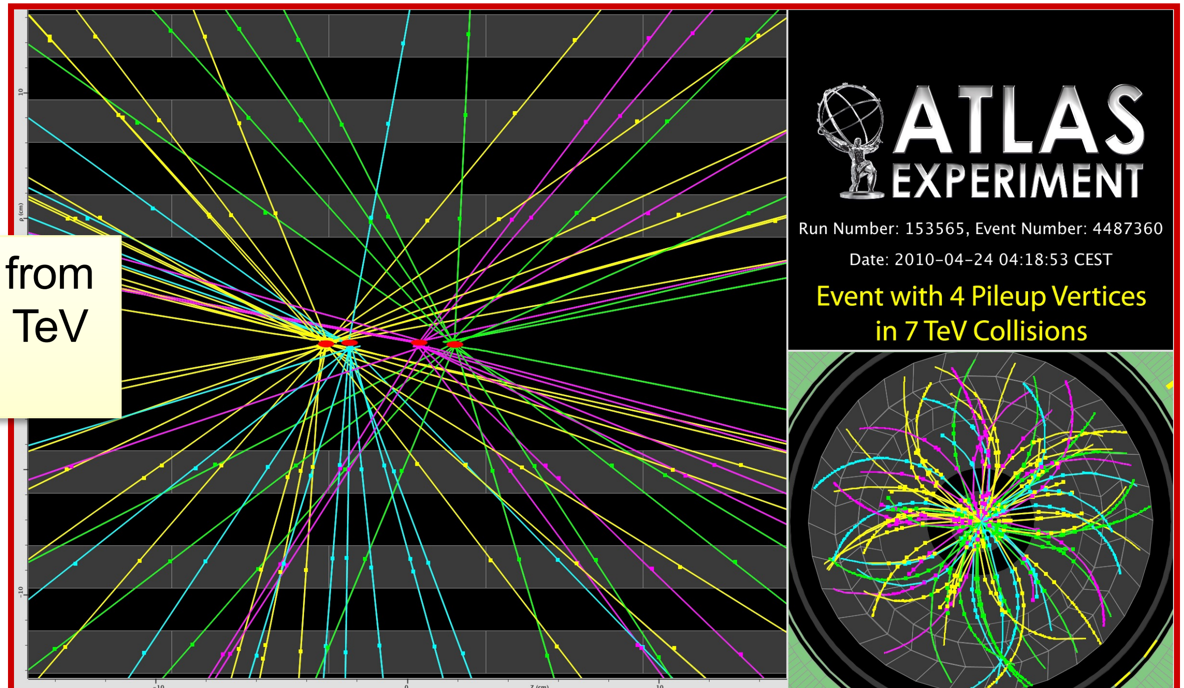


  - **HCAL: shallow in CMS; deep (and better) in ATLAS**
    - **ATLAS: 60%/√E; CMS: 120%/√E → naively expect, ATLAS ~twice better for jets and ME_T**

The environment

- Lower cross section → need higher luminosity.
  - But then, probability that more proton pairs interact during a crossing rises

Example from earliest 7 TeV collisions



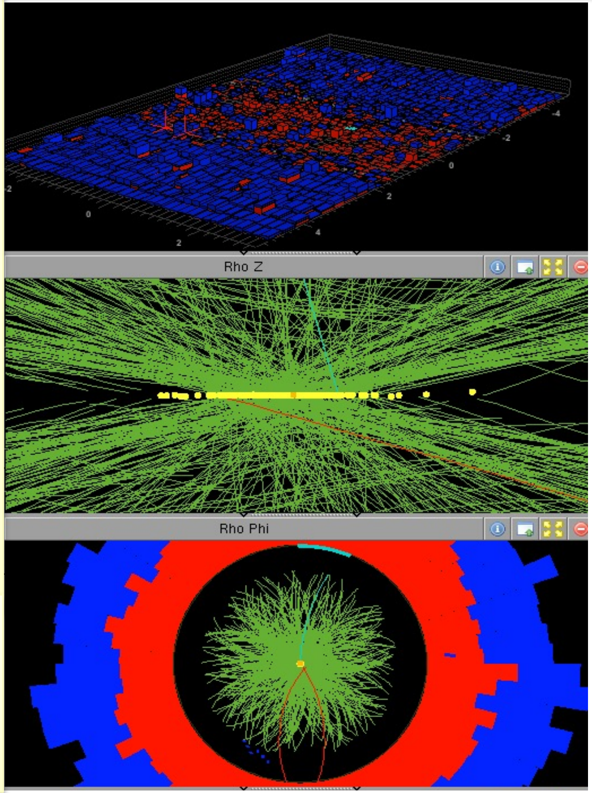
- This is referred to as “pileup”.

The environment (II)

# of interactions/crossing:

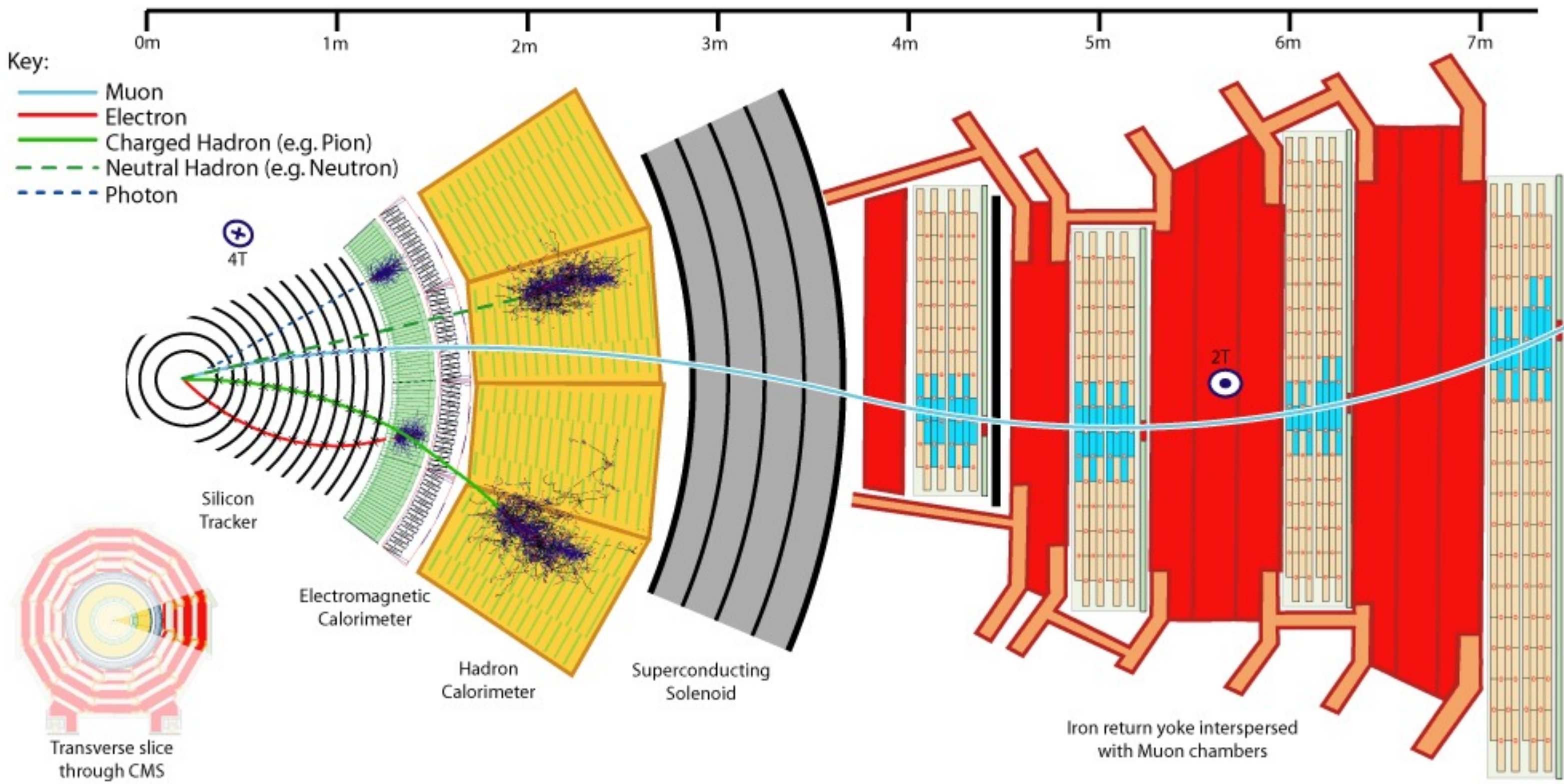
- **Interactions/s:**
  - **Lum = 10^{34} cm^{-2}s^{-1}=10^{7}mb^{-1}Hz**
  - **σ(pp) = 80 mb**
  - **Interaction Rate, R = 8×10^{8} Hz**
- **Events/beam crossing:**
  - **Δt = 25 ns = 2.5×10^{-8} s**
  - **Interactions/crossing=20**
    - **For 50 ns operation: 40!**
- **Not all p bunches full**
  - **2835 out of 3564 only**
  - **Interactions/"active" crossing = 20 x 3564/2835 = 25**

CMS event with 78 reconstructed vertices and 2 muons…



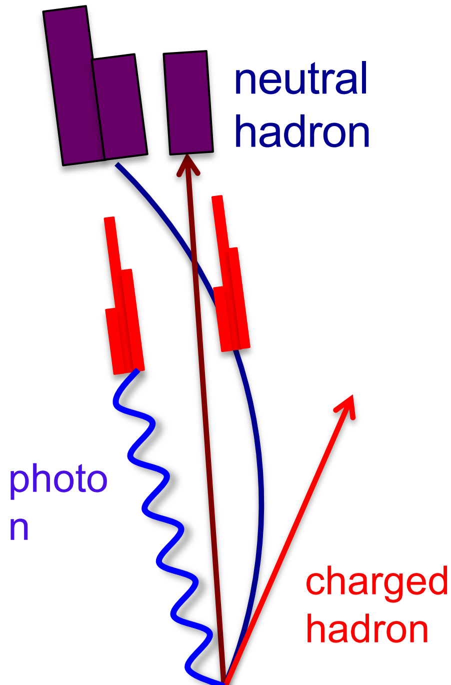
Operating conditions at LHC design time (summary):
(1) A "good" event containing a Higgs or SUSY decay +
(2) ~ 25 extra "bad" (minimum bias) interactions

Particle detection/identification in CMS



What has to be reconstructed: particle flow

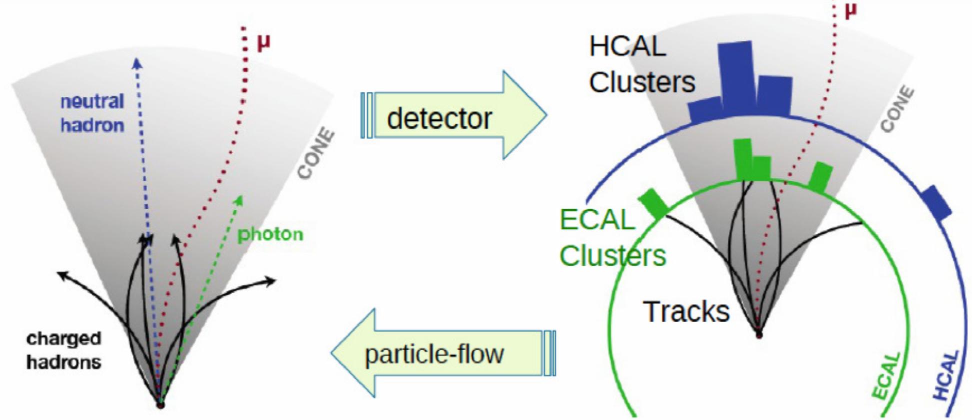
- **Types of particles:**



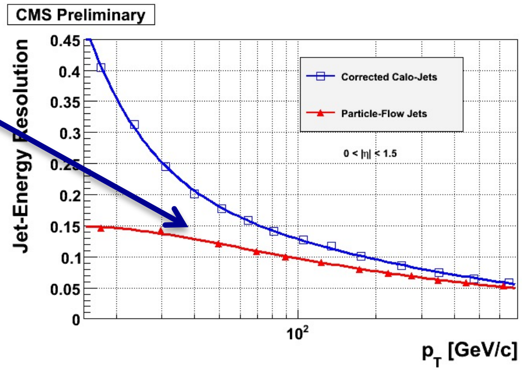
- **Calorimeter jet:**
  - $E = E_{HCAL} + E_{ECAL}$
  - σ(E) ~ calo resolution to hadron energy: 120 % / √E
  - direction biased (B = 3.8 T)
- **Particle flow jet:**
  - 65% charged hadrons
    - σ(pT)/pT ~ 1%
    - direction measured at vertex
  - 25% photons
    - σ(E)/E ~ 5-10% / √E
    - good direction resolution
  - 10% neutral hadrons
    - σ(E)/E ~ 120 % / √E
  - Need to resolve the energy deposits from the neutral particles…

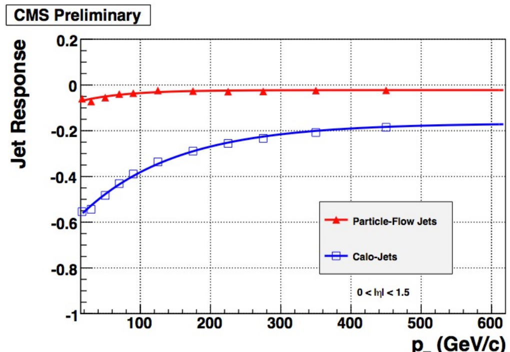
New (unforeseen in the 90's) element: particle flow

- Combine information from all detectors. Trade information from low-res detectors to high-res detectors, depending on physics object



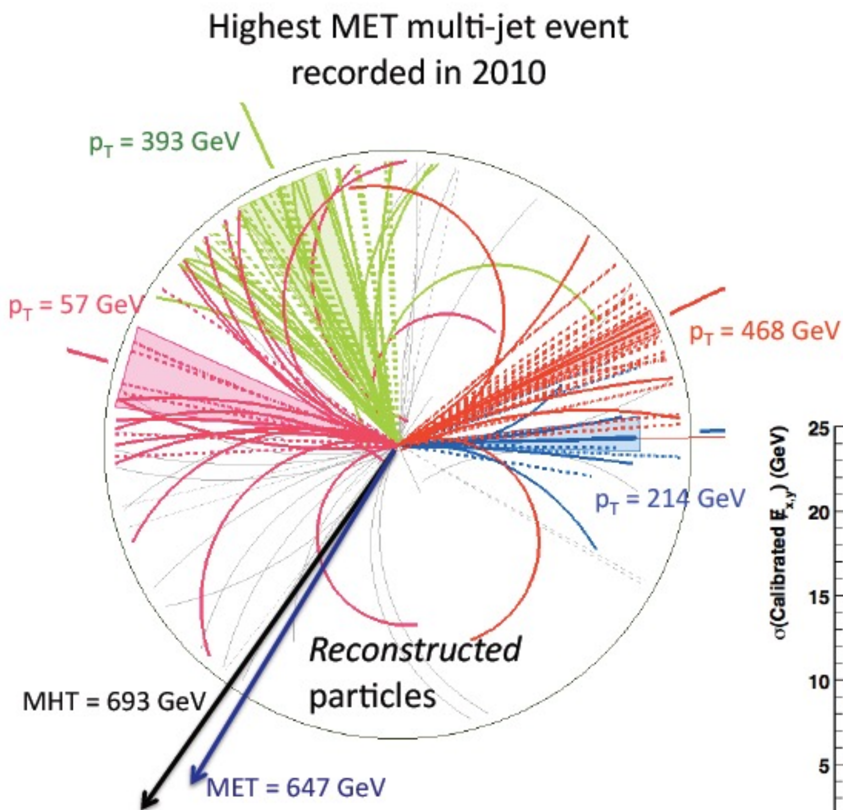
Large improvement in resolution at low p_T





Jet particles calibrated → response close to 1 *before* any jet energy correction

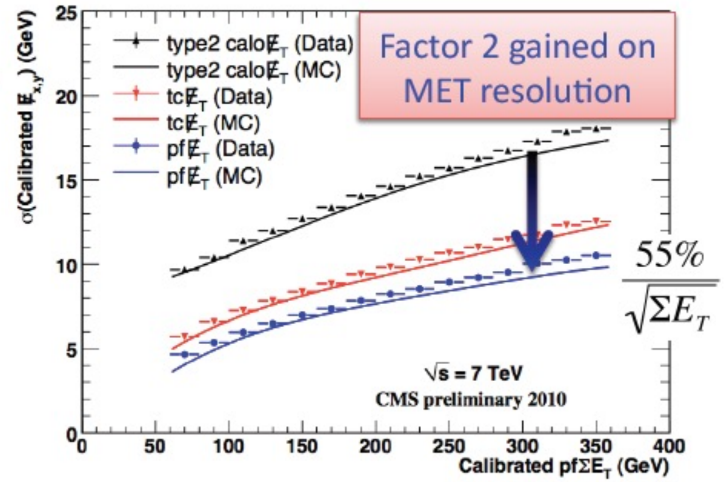
Hadronic variables: definition



$$\vec{E}_T^{miss} = \overrightarrow{MET} = -\sum_{\text{All particles}} \vec{p}_T$$

$$\overrightarrow{MHT} = -\sum_{\text{Jets}} \vec{p}_T$$

$$HT = \sum_{\text{Jets}} p_T$$

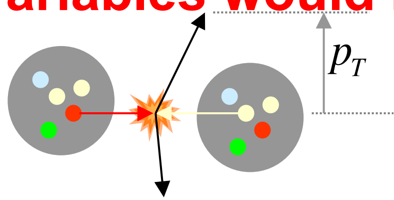


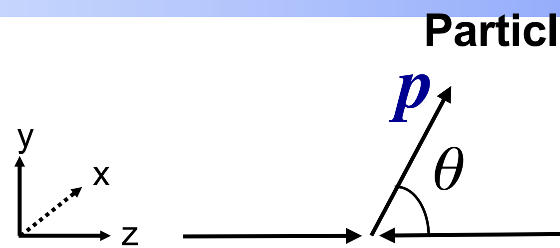
pp collisions

characteristics and kinematics;
the environment and event reconstruction

pp collisions: kinematics (I)

- "Natural" variables would be p, θ, ϕ

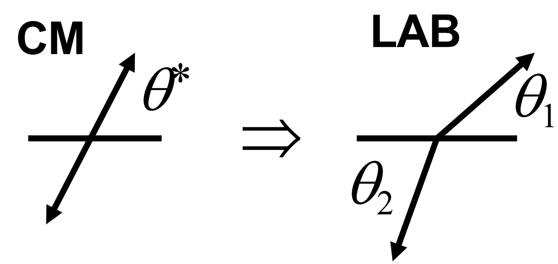




  - Longitudinal momentum & energy, p_z & E: not useful
    - Particles escaping detection have large p_z; visible p_z not conserved: $\sum_i p_{z,i} \neq 0$
  - More useful: transverse momentum, p_T
    - Particles escaping detector (low θ) have $p_T \approx 0$; visible p_T conserved: $\sum_i p_{T,i} \approx 0$
- LAB ≠ parton-parton CM system

Parton CM (energy)$^2 \rightarrow \hat{s} = x_1 x_2 s$

Worse: p, θ not invariant under Lorentz boosts along z (not good, especially in two-particle correlations)

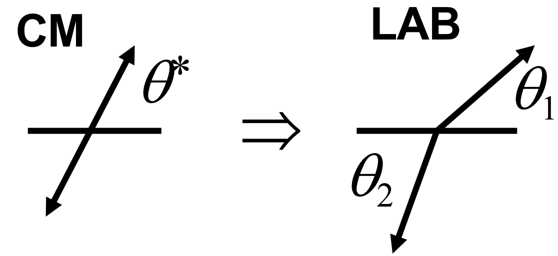


pp collisions: kinematics (II)

- **LAB ≠ parton-parton CM system**

$$\boxed{\text{Parton CM (energy)}^2 \rightarrow \hat{s} = x_1 x_2 s}$$

$$\boxed{p_z(\text{parton-parton}) = x_1 - x_2 \sqrt{\hat{s}}}$$



- **And since we cannot use $\sum_i p_{z,i}=0$, we cannot infer the overall boost in z of the parton-parton system**
  - **New problem: boost in z → p_T is invariant; p_z is not; since**

$$\tan\theta = p_z / p_T;\ p = \sqrt{p_T^2 + p_z^2}$$

→ so p, θ not invariant under Lorentz boosts along z

  - **Not good, especially in two-particle correlations: e.g. angle between two particles not the same in CM and LAB frames. We measure in LAB (but we to connect to calculation, we need z boost – to connect to the CM frame)**

pp collisions: kinematics (III)

- Need to introduce another "measure" of θ; rapidity:

Rapidity (y)

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

Pseudo-rapidity (η)

$$\beta \to 1\ (m << p_T):\ \eta \equiv -\ln\tan\frac{\theta}{2}$$

  - Lorentz boost in z direction:

$$y \to y' = y + \log\sqrt{\frac{1-\beta}{1+\beta}} = y - \tanh^{-1}(\beta) \Rightarrow \Delta y' = \Delta y$$

- Angular distance(two particles):

  use Δy(or $\Delta\eta$) and $\Delta\phi$

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

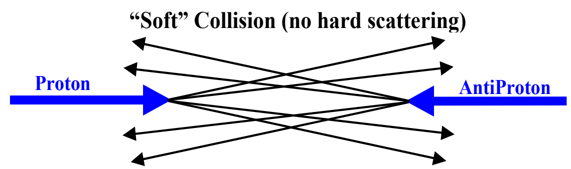
- Particle description: p_T, y, φ

  LI factor:

$$E dy = dp_z \Rightarrow \frac{d^3p}{E} = p_T dp_T dy d\varphi = \pi dy dp_T^2$$

The “underlying event"

- The UE consists of the “beam remnants” and from particles arising from soft or semi-soft multiple parton interactions (MPI)
  - The underlying event is not the same as a minimum bias event



No hard scattering
“Min-Bias” event

- Modeling of UE: important ingredient for jet physics and lepton isolation, energy flow, object tagging, etc

à la R. Field

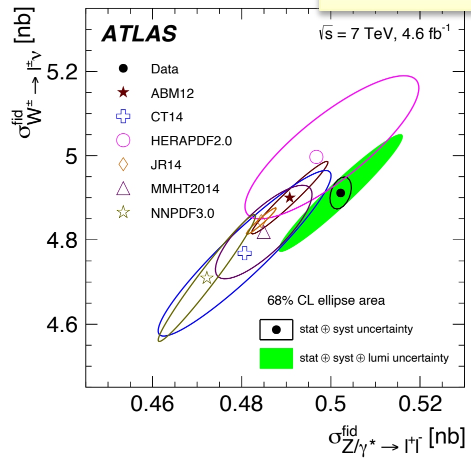
Luminosity and cross sections

- **Luminosity: the most valuable variable in our analysis**
  - **That everyone takes for granted (and they should not)**
  - **Definition of cross section: number of scatters (e.g. in solid angle, per unit time) divided by incoming flux.**
  - **Luminosity, L: N = σ x L. We measure σ = N/L. Error on L → directly on σ.**
- **Traditionally: has not been easy to determine with high accuracy**
  - **Yet, it's important for absolute cross section measurements.**

Machine	δL/L (%)
ISR	1.0-1.6
SppS	3-6
Tevatron	4-6
LHC	2.4 (1.4)

SM parameter measurements @ LHC limited by δL:
$\sigma_{top}(m_t,\alpha_S)$; $\sigma_{Z/W}(\alpha_S)$; σ_{ggH}
tt, W and Z cross sections already limited by L
HL-LHC: stat $\delta\sigma_{ggH}/\sigma_{ggH}$ <1%

arXiv:1612.03016



Luminosity, LHC bunch structure, operation

Instantaneous Lumi: $dN/dt = \sigma\, dL/dt = \sigma \mathcal{L}$

Units: $cm^{-2}s^{-1}$. Better: $fb^{-1}s^{-1}$; $nb^{-1}s^{-1}$

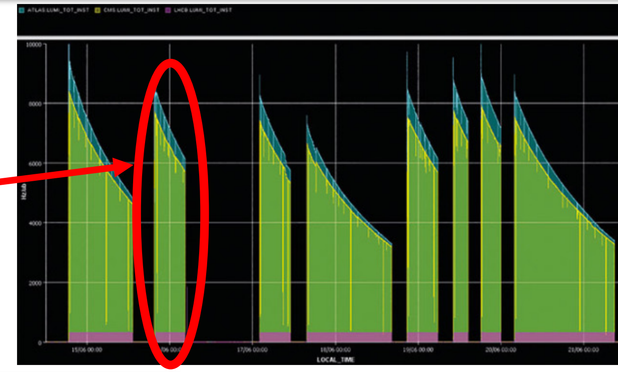
Integrated Lumi: $N = \sigma L$; $L = \int \mathcal{L} dt$

Units: $cm^{-2}s^{-1}$. Better: fb^{-1}; nb^{-1}

Linst drops with time (beam p eaten up)

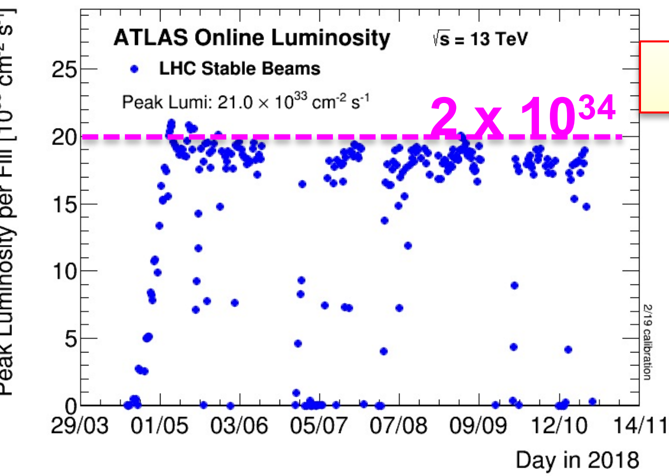
One LHC "fill"

Inst. Lumi

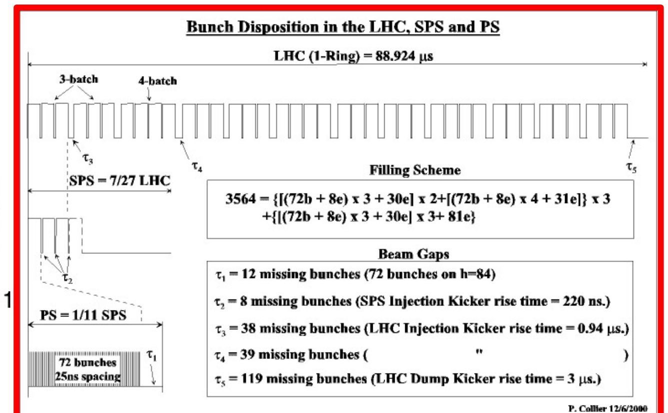


time

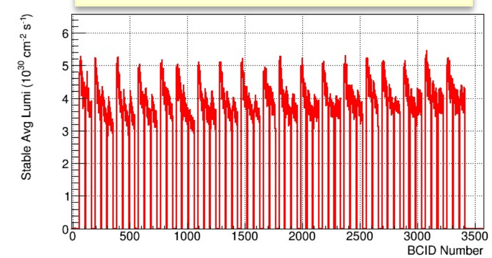
Run II: 2018



LHC "Orbit": 89 μs (3600 bunches)



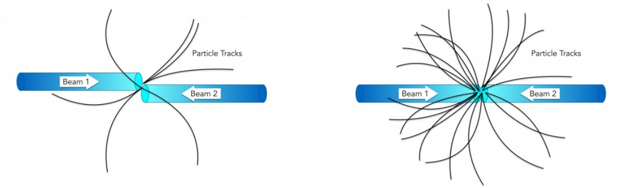
Example from ATLAS



Luminosity and cross sections

- **Luminosity: measures "flux" of particles**

$$\mathcal{L}_\mathrm{b} = f_\mathrm{r}\, n_1 n_2 \int \hat{\rho}_1(x,y)\,\hat{\rho}_2(x,y)\,\mathrm{d}x\,\mathrm{d}y$$



a). When the proton beams only overlap slightly there are few interactions and few tracks.
b). When the two beams overlap completely there are many interactions and many tracks.
(Image: Katharine Leney/ATLAS Experiment)

- **Assume factorization:** $\hat{\rho}(x,y) = \rho_x(x)\,\rho_y(y)$.

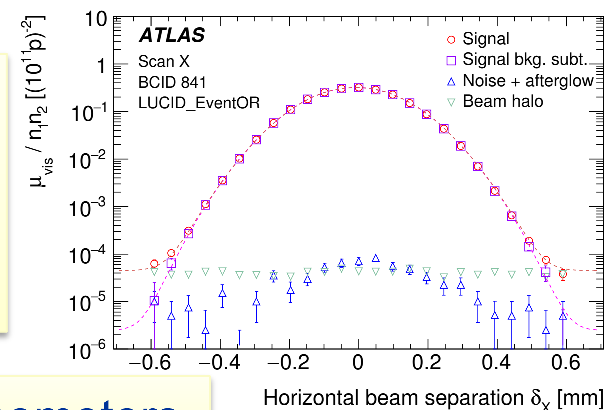
$$\mathcal{L}_\mathrm{b} = f_\mathrm{r}\, n_1 n_2\, \Omega_x(\rho_{x1},\rho_{x2})\, \Omega_y(\rho_{y1},\rho_{y2}) \qquad \Omega_x(\rho_{x1},\rho_{x2}) = \int \rho_{x1}(x)\,\rho_{x2}(x)\,\mathrm{d}x$$

→ Need: a counting method and a beam overlap measurement

- **Counting can be done from dedicated (or other) detectors**
- **Beam overlap measurement through "Van Der Meer scans"**

Van Der Meer: $$\Omega_x(\rho_{x1},\rho_{x2}) = \frac{R_x(0)}{\int R_x(\delta)\,\mathrm{d}\delta}$$

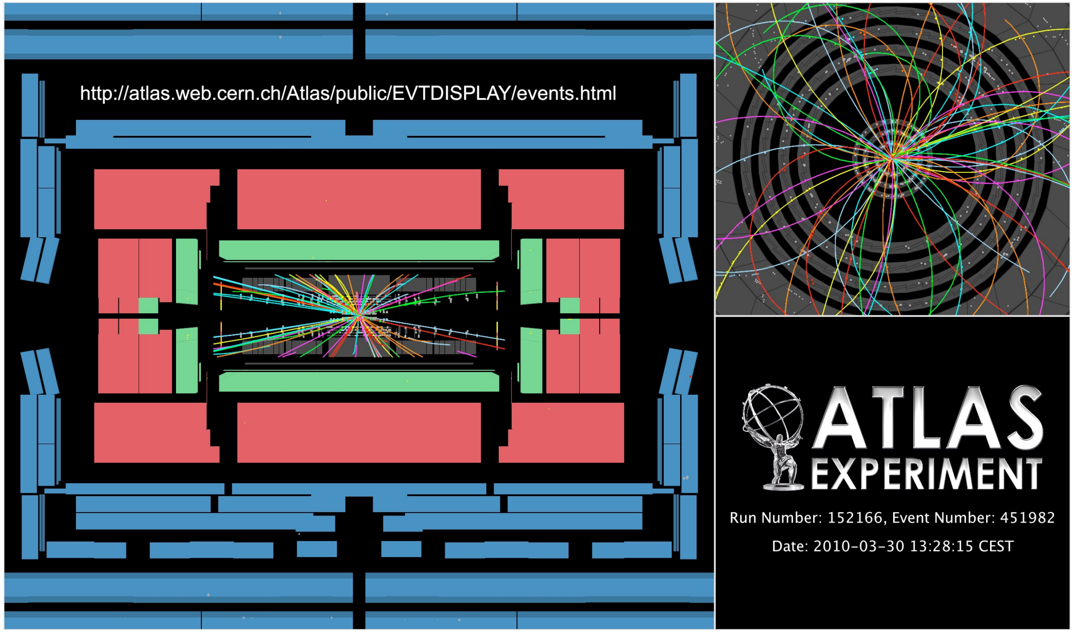
Measure visible interaction rate μ_{eff} as a function of beam separation δ



Topic for (some other) full lecture: luminometers

Inelastic pp collisions: characteristics

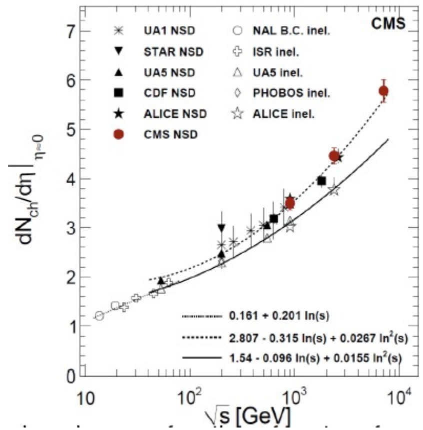
- One of the earliest collisions at 7 TeV

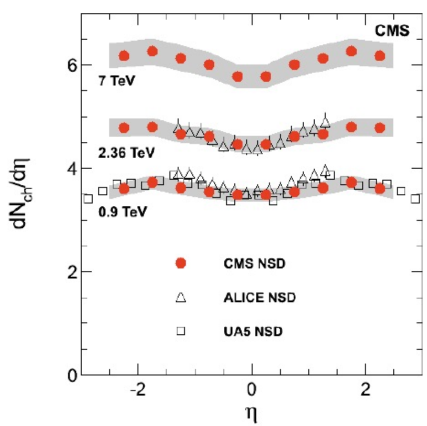


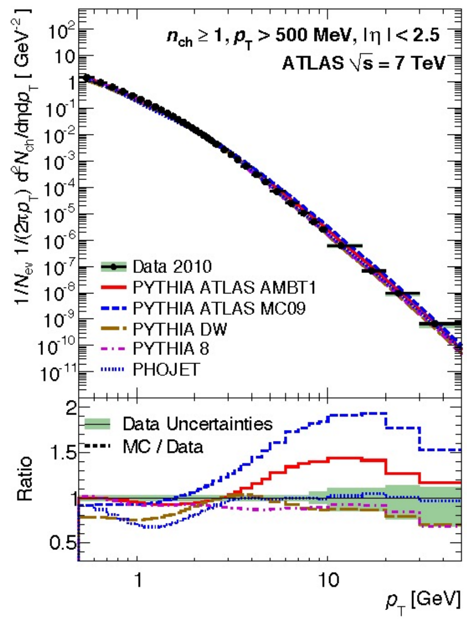
- "Minimum-bias" collisions ~ model/input for "underlying event"
- Properties to study: particle multiplicities; particle momenta and correlations; energy flow, especially in transverse plane

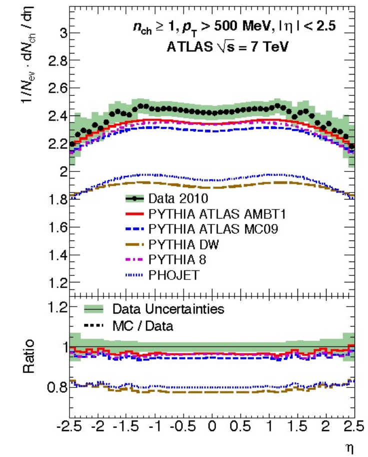
Minimum bias interactions

- Inelastic collisions (protons break)

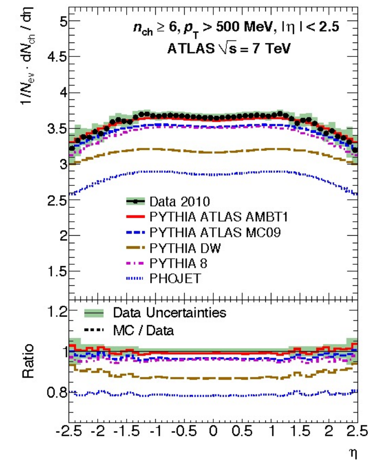








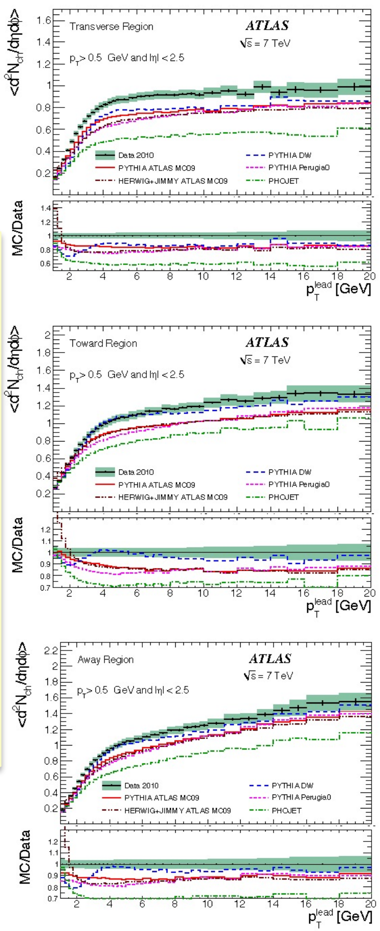
$N_{ch} \geq 1$



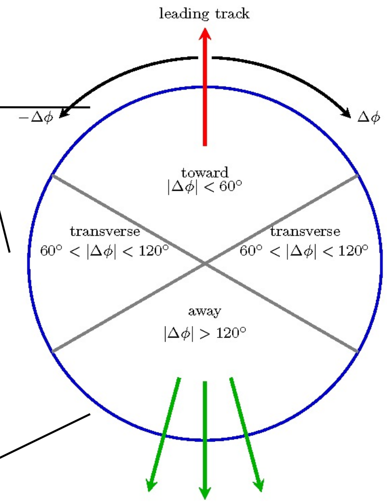
$N_{ch} \geq 6$

Underlying event (I)

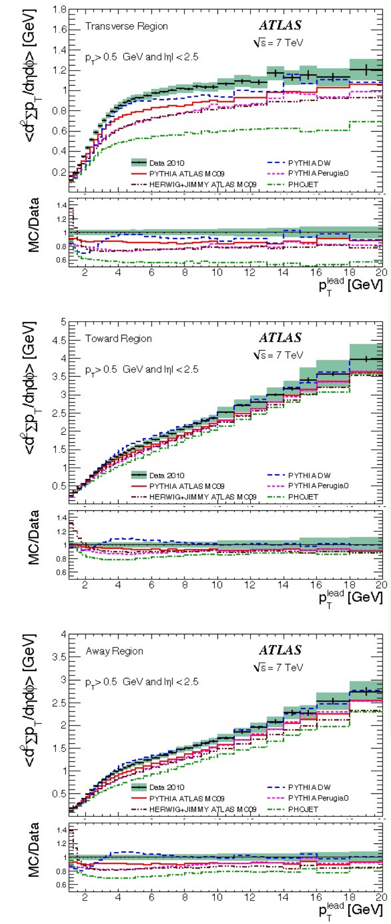
Multiplicity vs P_T



Particle momentum flow in regions defined wrt leading track



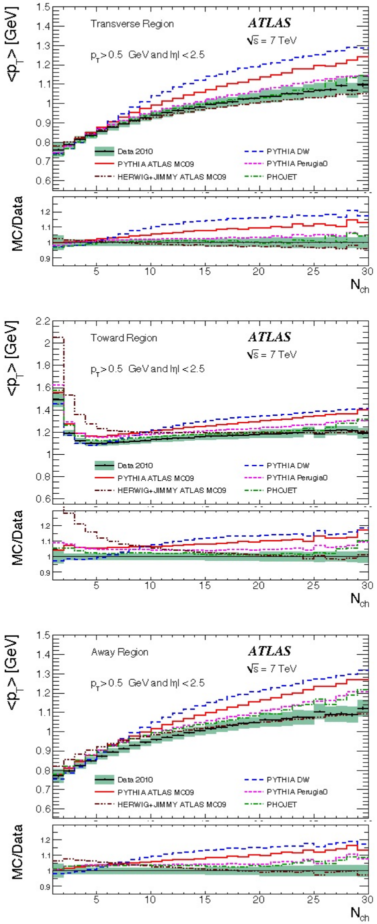
arXiv:1012.0791



Sum P_T vs P_T

Underlying event (II)

Mean P_T vs Multiplicity

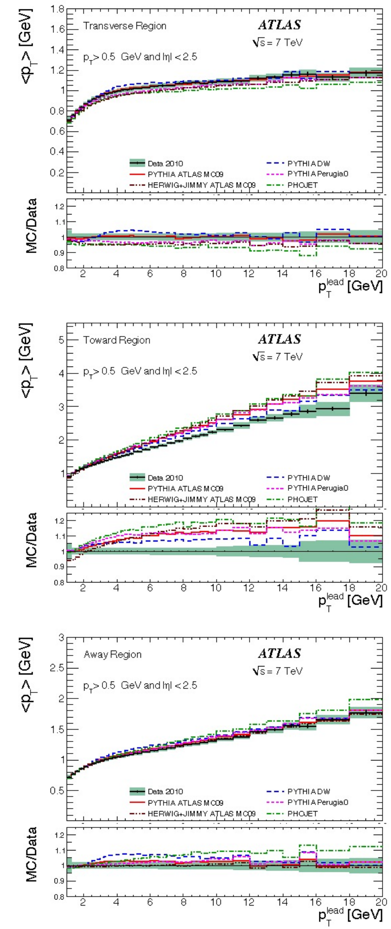


From these comparisons: determine best "tunes" for underlying event.

In practice: tuning of soft QCD model in PYTHIA

Tuning is important for data-MC agreement further down; particle isolation (e.g. in lepton identification) and missing energy (ME_T)

Mean P_T vs P_T



Some Standard Model processes

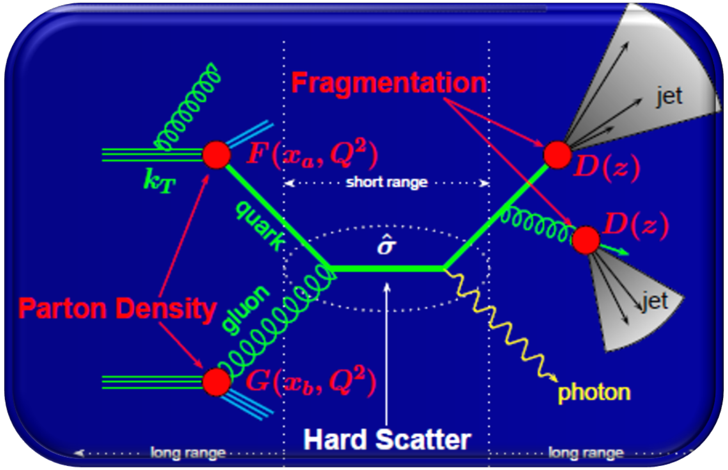
Jet production

W/Z production

top production

QCD: parton-parton scattering

- Picture of pp interactions:

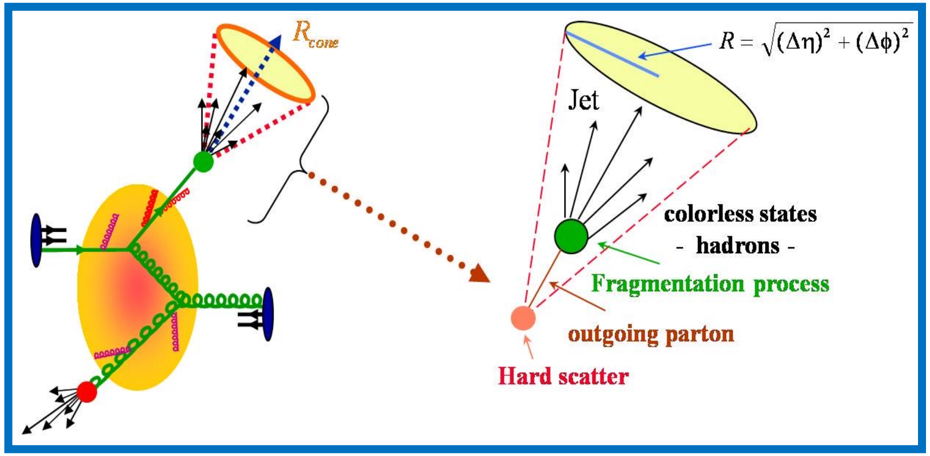


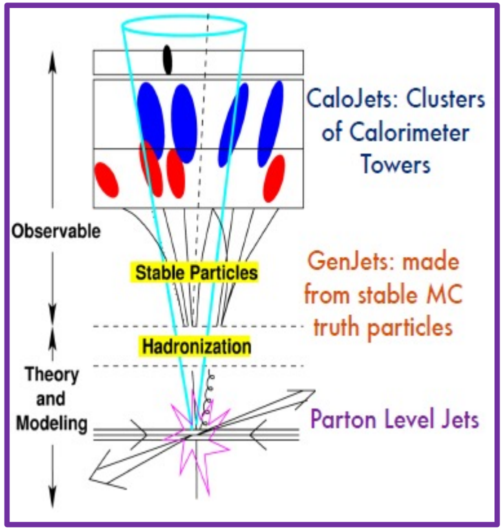
- Basis of all calculations & Monte Carlo simulations: the QCD factorization theorem

$$d\sigma_{pp}\left(p_1, p_2, M\right) = \sum_{a,b} \int_0^1 dx_a dx_b \;\; d\hat{\sigma}_{ab \to F+X}\left(x_a p_1, x_b p_2, M, \mu\right)$$
$$\times F_{a/p}\left(x_a, \mu\right) \;\; F_{b/p}\left(x_b, \mu\right)$$

Jets

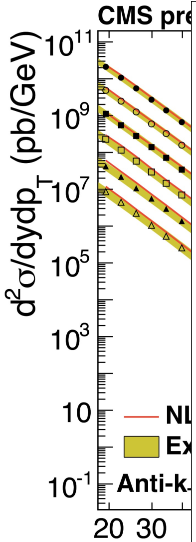
- Colored partons from hard scatter "evolve" via soft quark and gluon radiation and and then hadronize to form a "spray" of roughly collinear colorless hadrons –> Jets
  - Jets: localized clusters of energy (or particles)
  - Jets: experimental signature of quarks & gluons

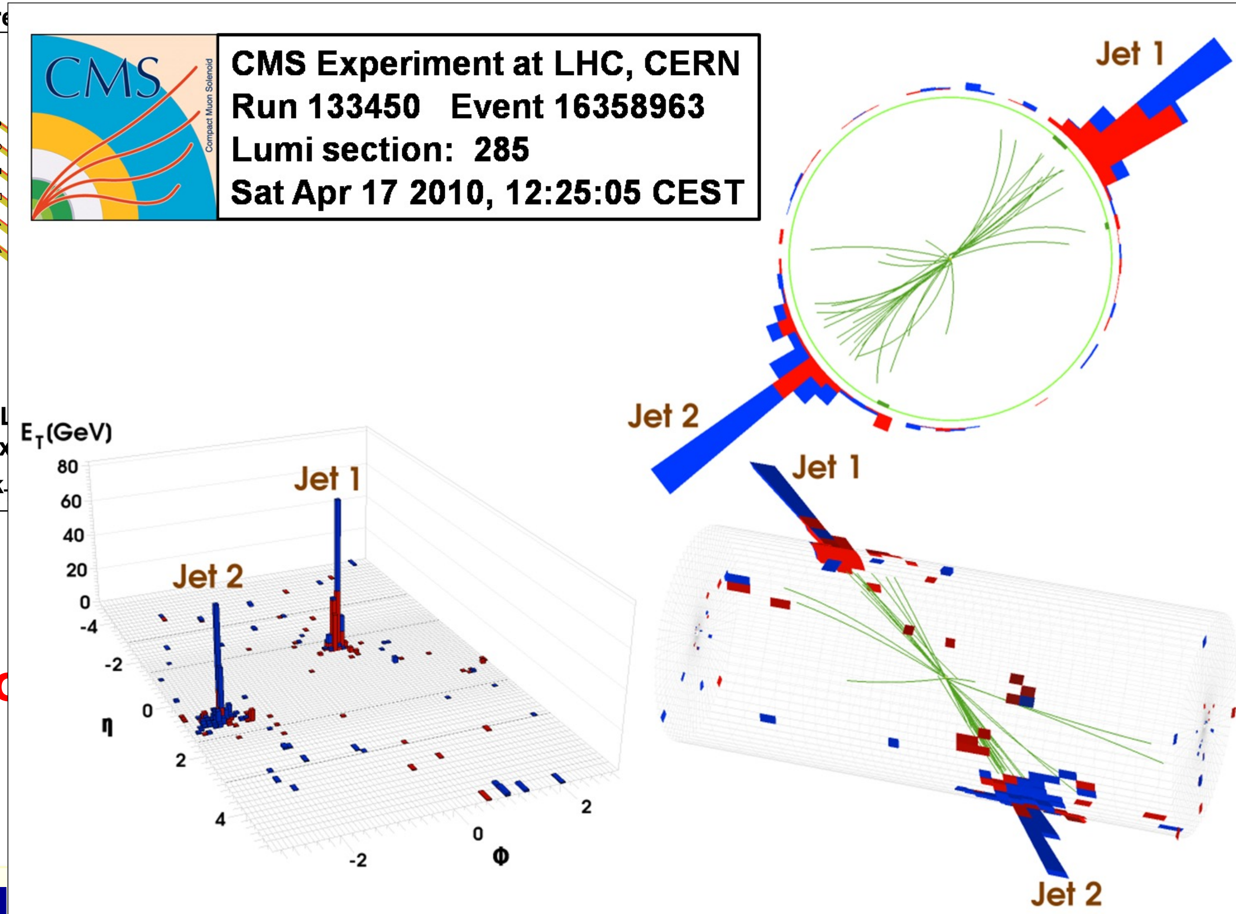


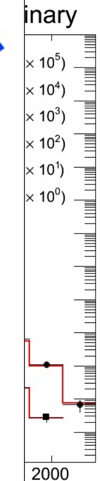


- Two types of measurements, probing:
  - The hard scatter: jet P_T and η, dijet correlations, dijet mass,…
  - Jet internals: energy flow, comparison of quark vs gluon jets,…

Jets







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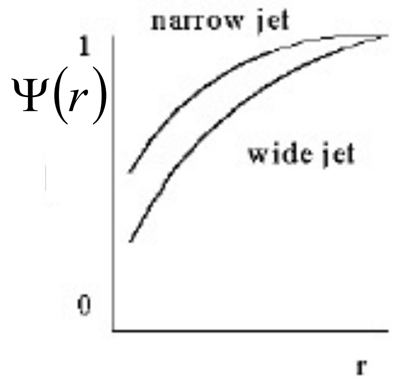
1-2%)

Excel

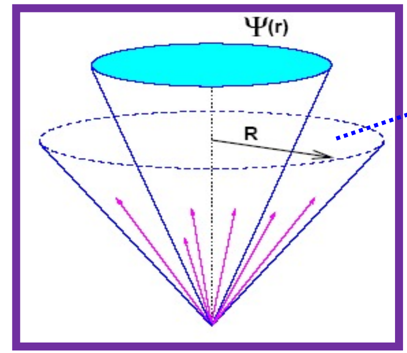
Jet shapes

- Integrated Jet Shape definition: average fraction of jet transverse momentum inside a cone of radius R concentric to the jet axis; measure of jet "narrowness"

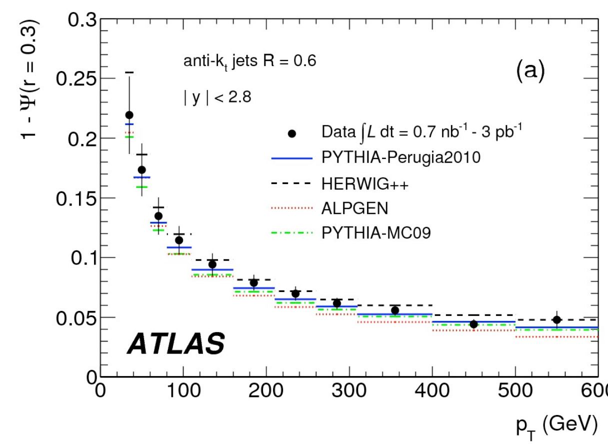
$$\Psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{p_T(0,r)}{p_T(0,R)}; \quad \left(\Psi(R) = 1\right)$$



Quark jets are narrower than gluon jets

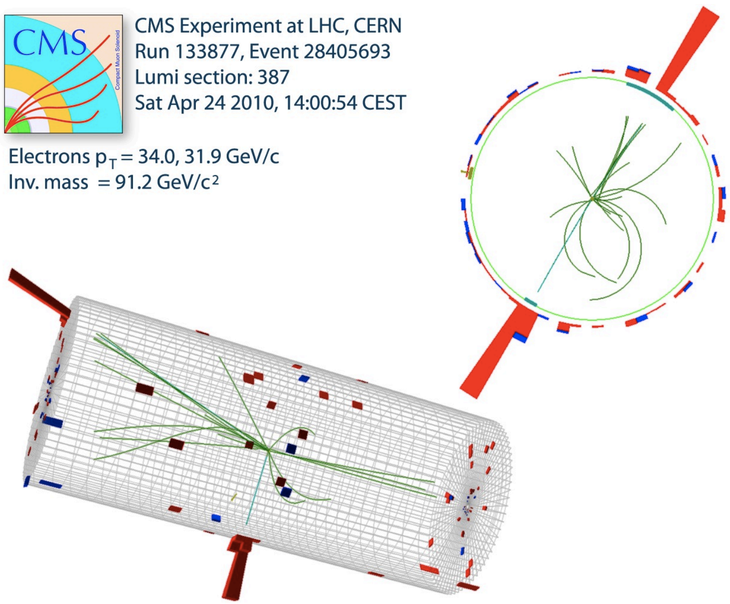


1-Ψ(r)

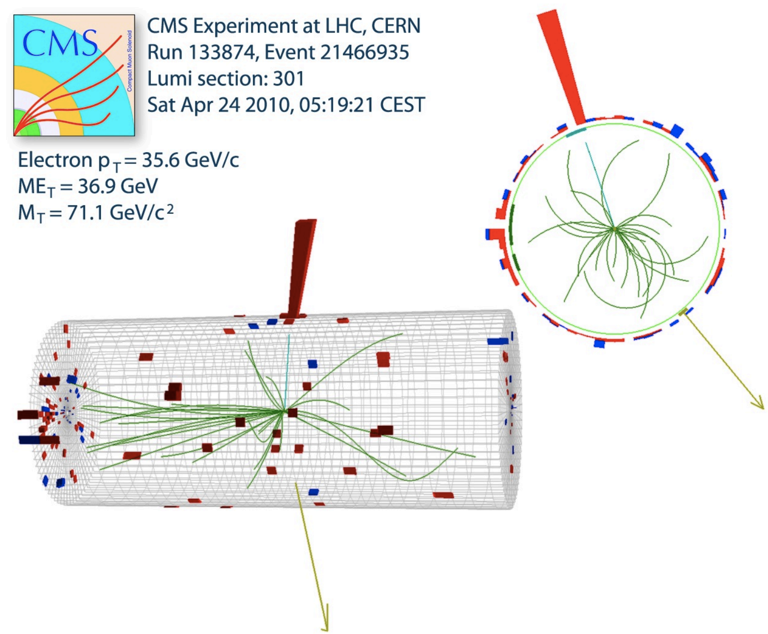


Mass, MET & transverse mass

Z → electron + positron



W → electron + neutrino



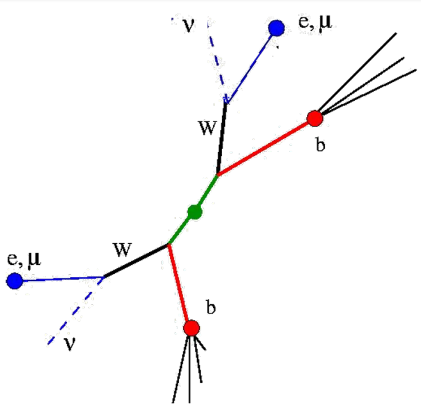
Transverse Mass,

$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1 - \cos\Delta\phi_{e,miss}}$$

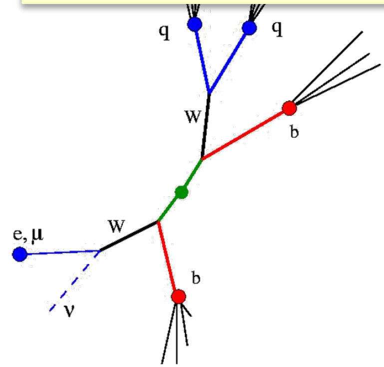
The top

- If the J/ψ, Υ, W and Z are standard candles, then the top is a candelabra*
  - Leptons, missing E_T, additional jets; and b-tagging
  - Analysis requires all that has gone into the W and Z, plus increased QCD background (because of higher jet multiplicity).
    - Plus interplay with W/Z+jets production

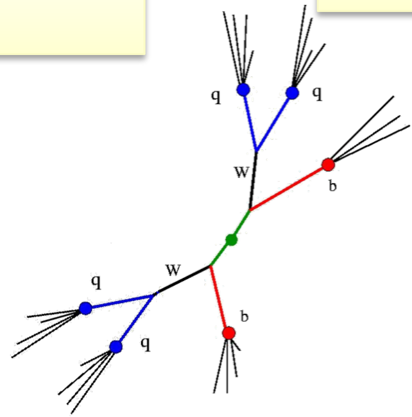
Dilepton: cleanest but Br~4/81



1-lepton: semi-clean; Br~8/27

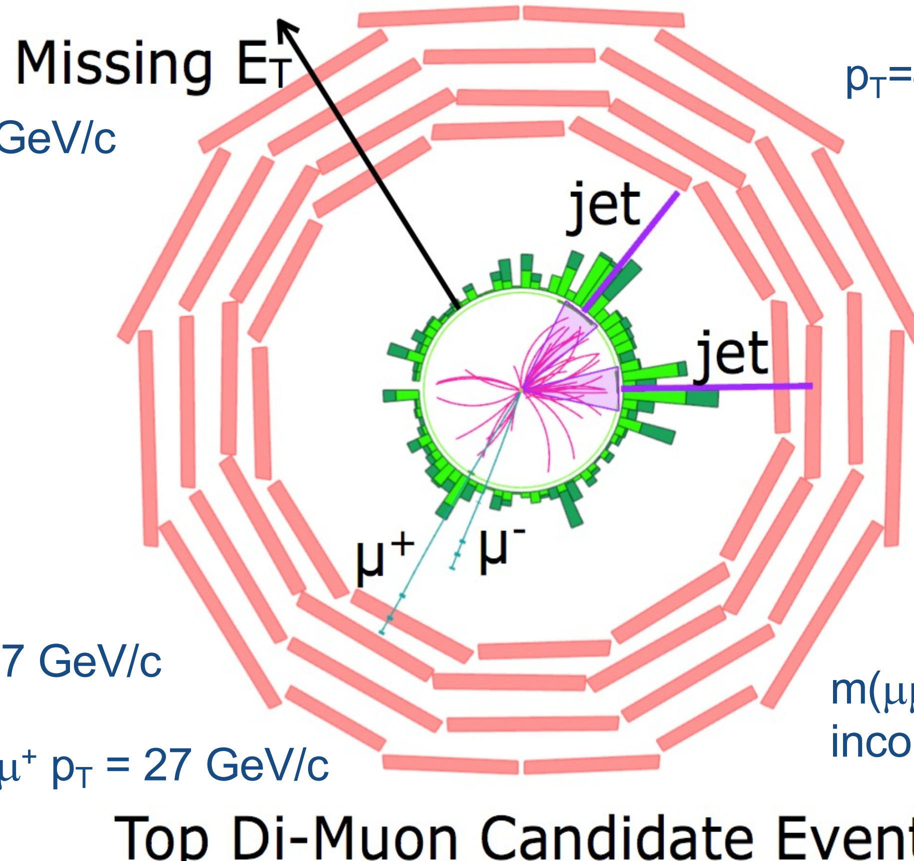


0-lepton: not-clean; Br~4/9



*: first heard this from Ken Bloom, U of Nebraska

top quark candidates: dilepton



MET= 57 GeV/c

p_T=45 GeV/c

p_T = 56 GeV/c

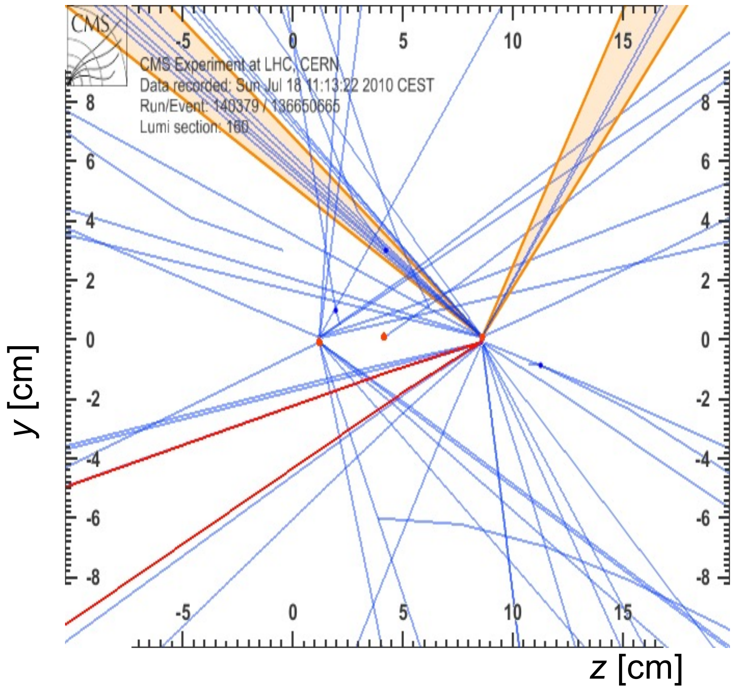
μ^- p_T = 57 GeV/c

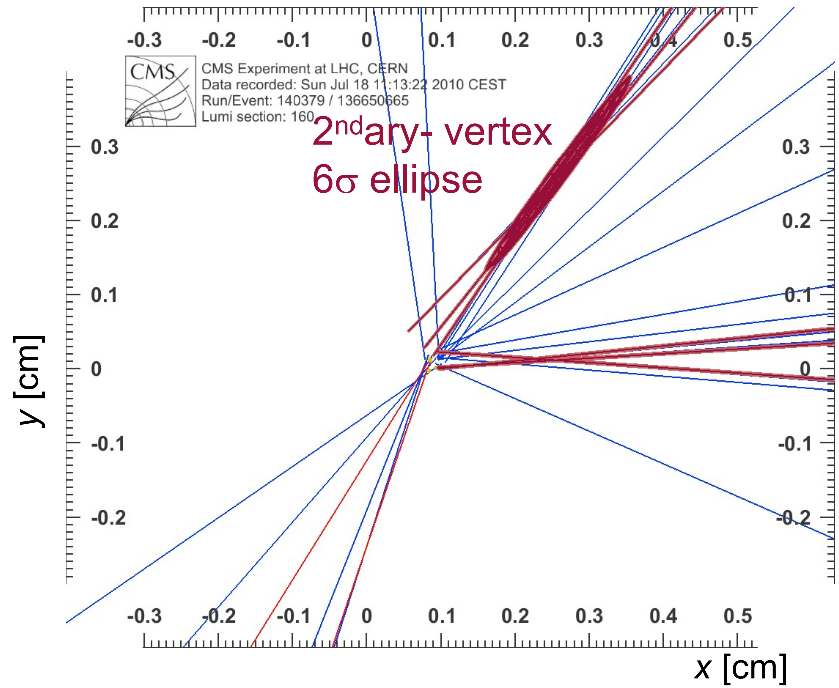
μ^+ p_T = 27 GeV/c

$m(\mu\mu)$ = 26 GeV/c^2
incompatible with Z

top quark candidates: dilepton (cntd)

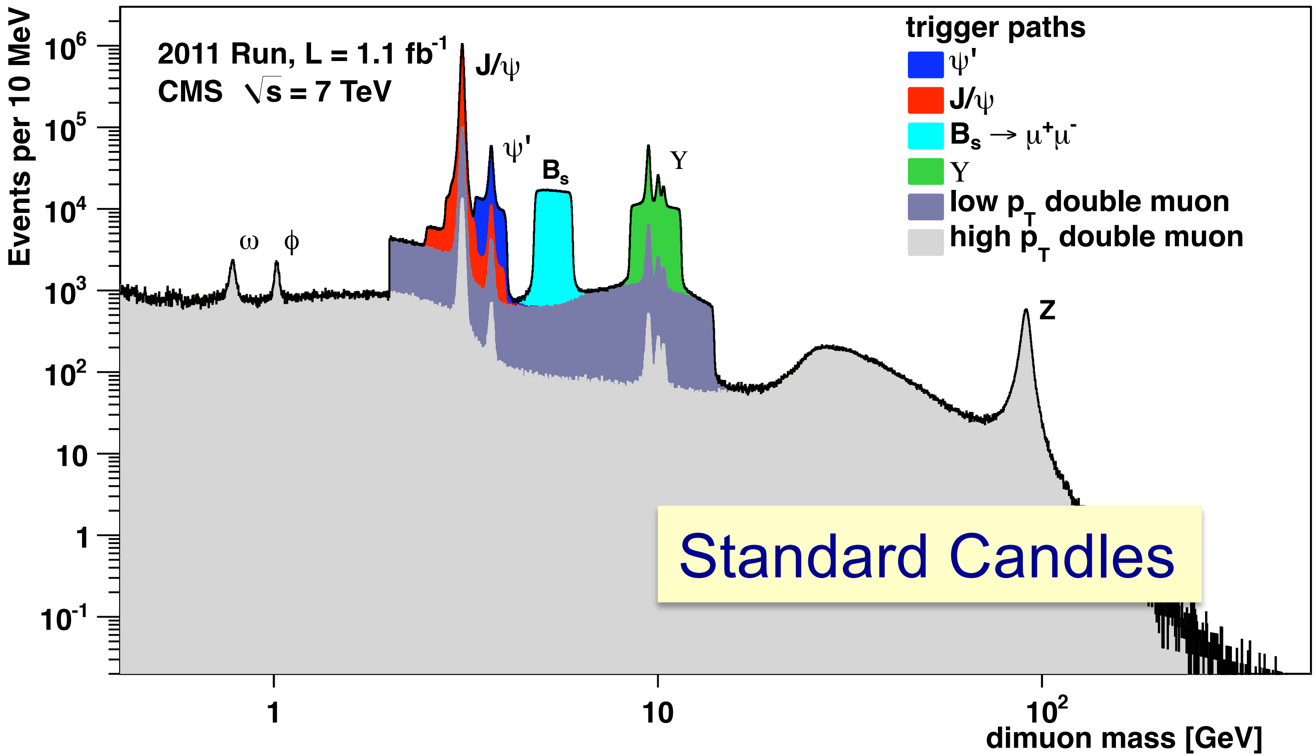
- **In addition: the two jets have good/clear *b*-tags**
- **Important cross check: muons and jets coming from the same interaction vertex.**



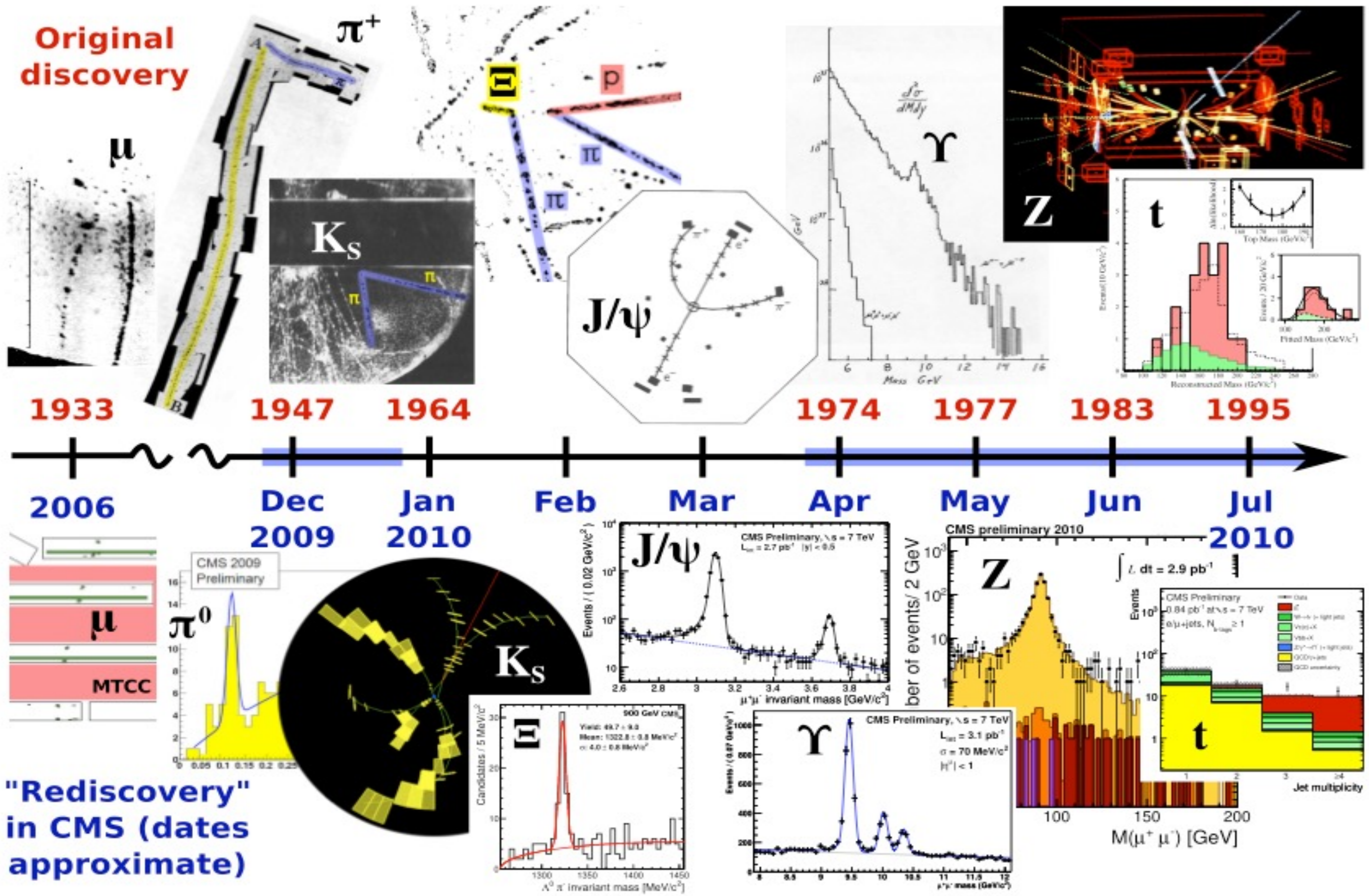


Detector performance

- The startup of the LHC experiments was the biggest discontinuity with the past: it was fast and efficient.

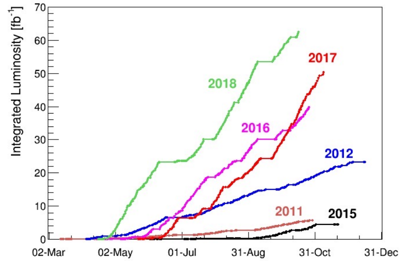


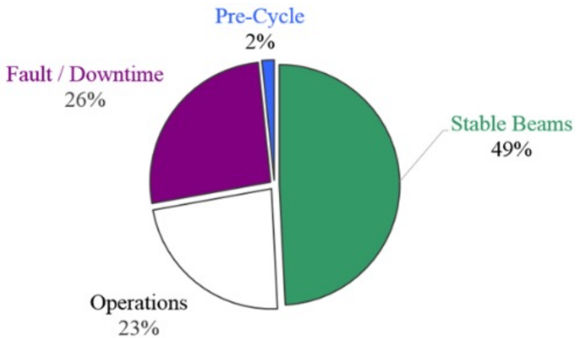
Around the standard model in 7 months

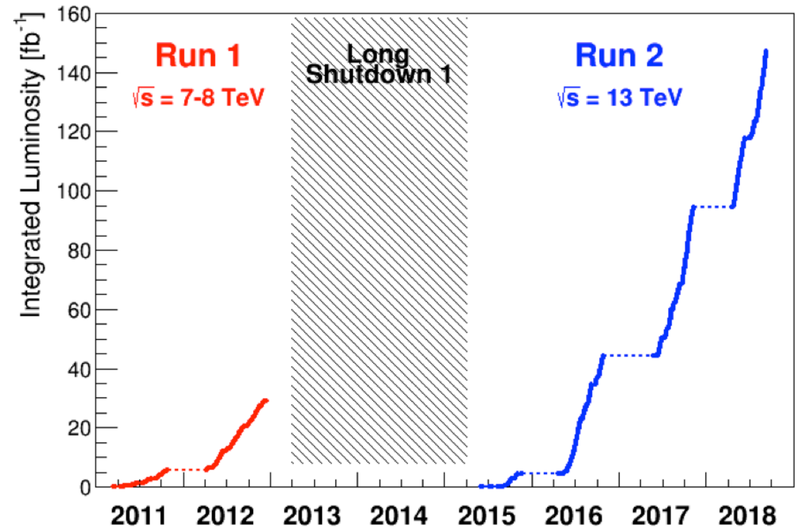


What followed: a very successful decade…

LHC t_0=2009
Run I: 2010–11: 7 TeV;
2012: 8 TeV
LS1: 2013–14
Run II: 2015–18: 13 TeV







≈153 days physics ≈3738.7 hours

	Duration [h]
Stable Beams	1839.5
Fault / Downtime	980.0
Operations	857.9
Pre-Cycle	61.3

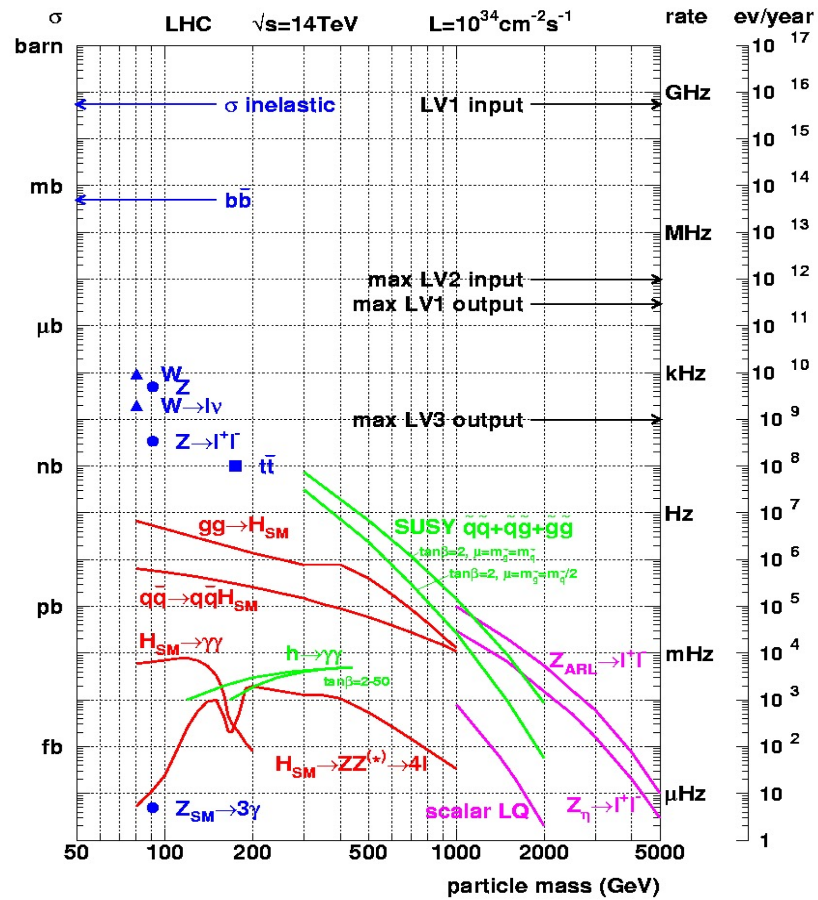
Run I: 2010-2012; total L~30 fb^{-1}.
Run II: 2015-2018 (150 fb^{-1})
Peak lumi ≈ 2.1 x 10^{34} cm^{-2}s^{-1} (2018)

Challenges in searching for new physics

The case for using the data AMAP

The LHC: signals much smaller than "bkg"

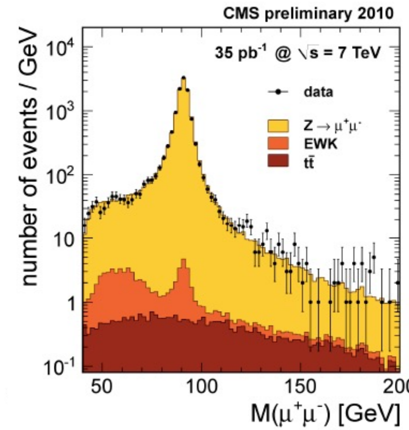
- General event properties
- Heavy flavor physics
- Standard Model physics
  - QCD jets
  - EWK physics
  - Top quark
- Higgs physics
- Searches for SUSY
- Searches for 'exotica'



Summary of high-P_T & high-mass probes

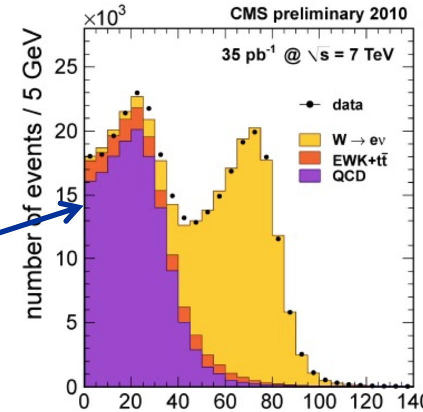
- **High-P_T di-objects: jets, leptons and photons**
  - **Mass($\ell\ell$)**
  - **Mass(jet-jet)**
  - **Mass($\gamma\gamma$)**

$$m_{\ell\ell} = \sqrt{2p_{\ell 1}p_{\ell 2}\left(1-\cos\Delta\theta(\ell_1,\ell_2)\right)}$$

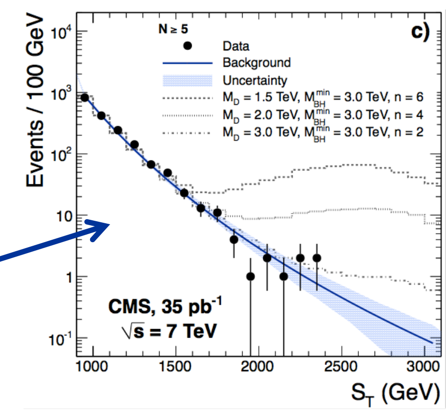


- **High-P_T lepton + ME_T (e.g. from ν)**
  - **Transverse mass**

$$m_T = \sqrt{2p_{T\ell}p_T^{miss}\left(1-\cos\Delta\phi(\ell,p_T^{miss})\right)}$$



- **Combination of objects, e.g. as in SUSY and BH searches**
  - **Various sums of transverse energies in the event**
  - **H_T: sum of all hadronic jets**
  - **S_T: sum of p_T of all objects (add leptons, photons, ME_T)**
    - **Also called "effective mass" (M_{eff}) in past LHC publications**

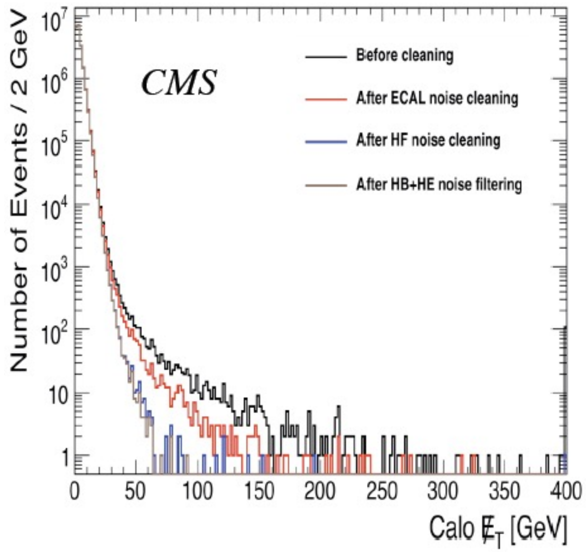


Understanding the detector (I)

- Example 1: understand reconstruction of physics objects [e.g. for electrons or muons]
  - Suppose Grand Theory X342 implies that we should be looking for a signature of one muon, plus 3 jets
    - Naturally: use a combination of Monte Carlo simulation of all known processes [e.g. W+3 jets; $W \to \mu\nu$] that give this signature plus data events with 1μ+3jets
    - But what about another background: Z+3 jets, for which we lose one lepton from the $Z \to \mu\mu$ decay?!
  - Worse: we can only get a *feeling* for the size of the effect from Monte Carlo and detector simulation
    - *But this [MC+simu] will never get the answer quite right*
    - One needs to find a way of calculating this efficiency from the only source that speaks the absolute truth: the data!
- Thus, we refer to "data-driven" methods / techniques

Understanding the detector (II)

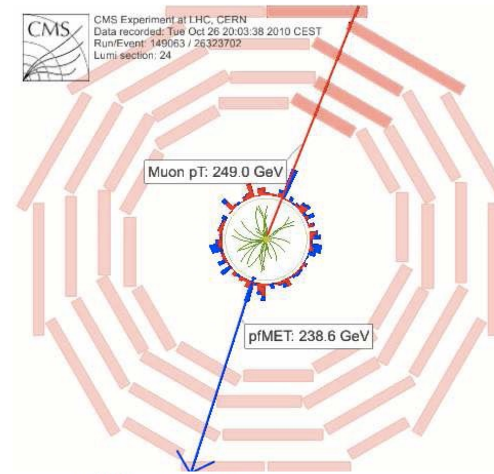
- **Example 2: understand missing transverse energy**
  - There are many instrumental sources of MET!
  - Calorimeter Noise
    - Need “noise filter”
  - Beam halo [particles from the beams]
    - Need “halo filter”
  - Cosmic muons traversing detector!
    - Can shower in the calorimeter!
    - Use tracks, topological cuts

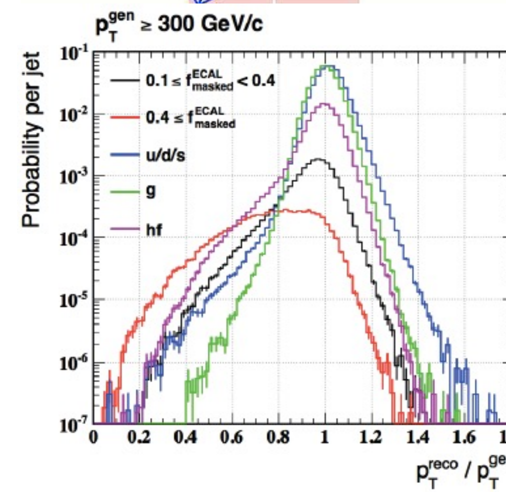


  - Here, for certain, simulation is of little help!
- **Again, one needs to rely on data**

Understanding the detector – ME_T (III)

- **Even worse: “honest mistakes”**
  - A misreconstructed muon can do damage: since muons leave only MIP energy in the calorimeter, in correcting the MET from the calos, one has to add the muon momentum! But if the muon is fake, one is correcting in error!
- **Tails of jet response!**
  - Effects of 1:10,000?
  - Detector cracks!
    - A jet that’s heading straight into a detector crack will lose quite a bit of energy – and thus there will be a fake ME_T reconstructed [because the E_T will not be reconstructed!]

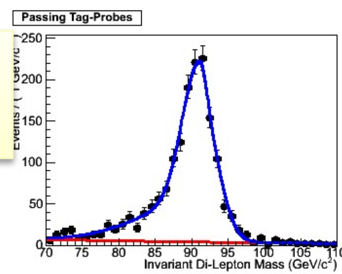


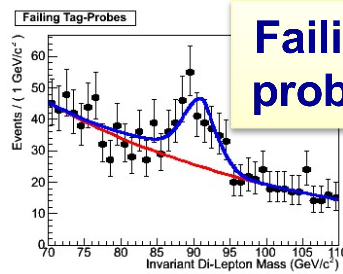


Obtaining (in)efficiencies from data

- What is the efficiency of the tight muon identification cuts? Or of the trigger? Use "tag and probe" method in, e.g. $Z \rightarrow \mu\mu$ decays:
  - Make a selection based on one muon that "tags" the type of event (e.g. passes tight cuts; or passes the trigger)
  - Then demand that second muon does the same

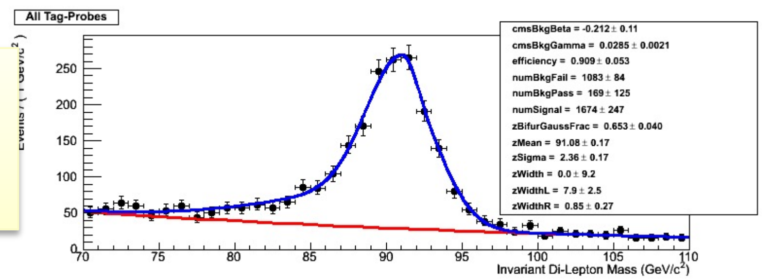
Passing probes

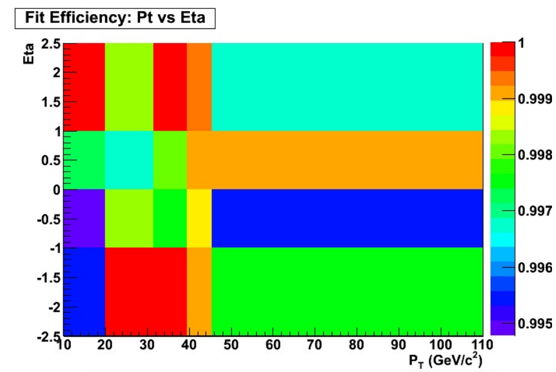




Failing probes

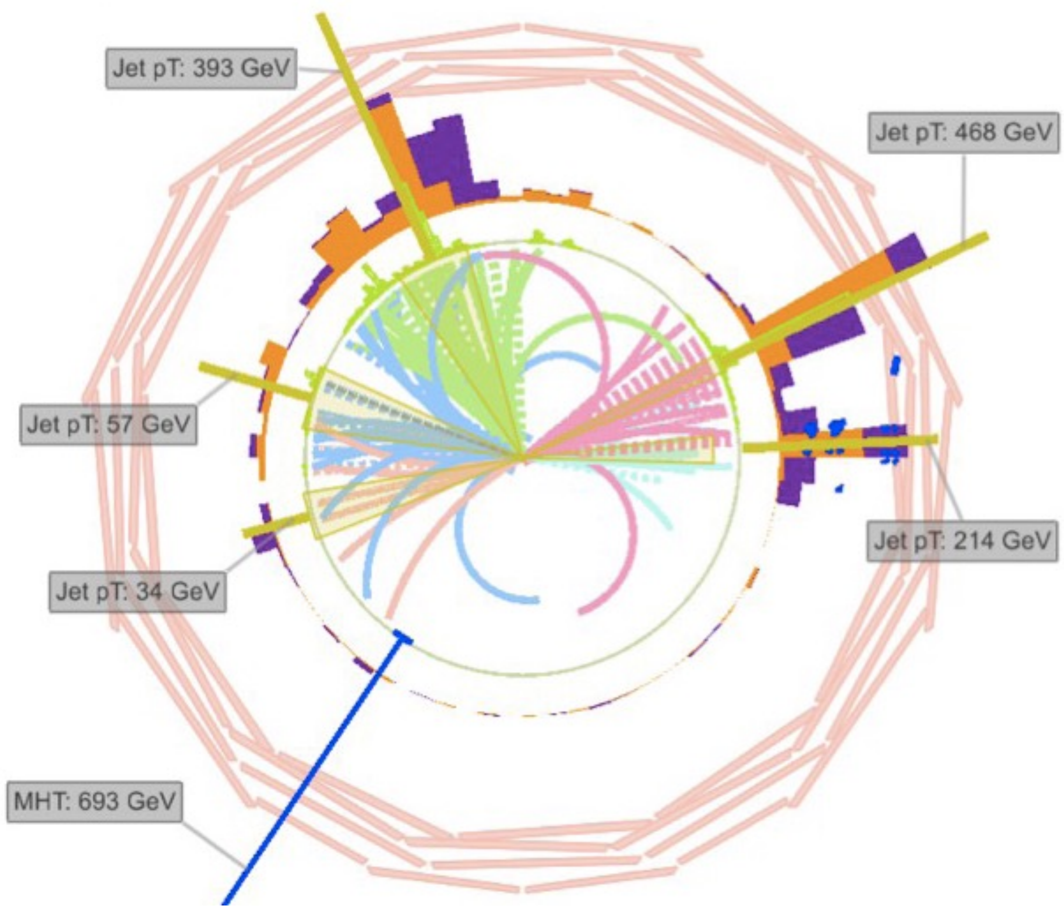
All combi-nations





Obtain efficiency map

Understanding the physics background (I)



Understanding the physics background (II)

- **Suppose one is searching in the "jets + MET" signature**
  - We will encounter this later in the SUSY searches
  - Even after understanding the "reducible backgrounds" – i.e. detector response, the filters, etc, -- there are "irreducible backgrounds" from physics

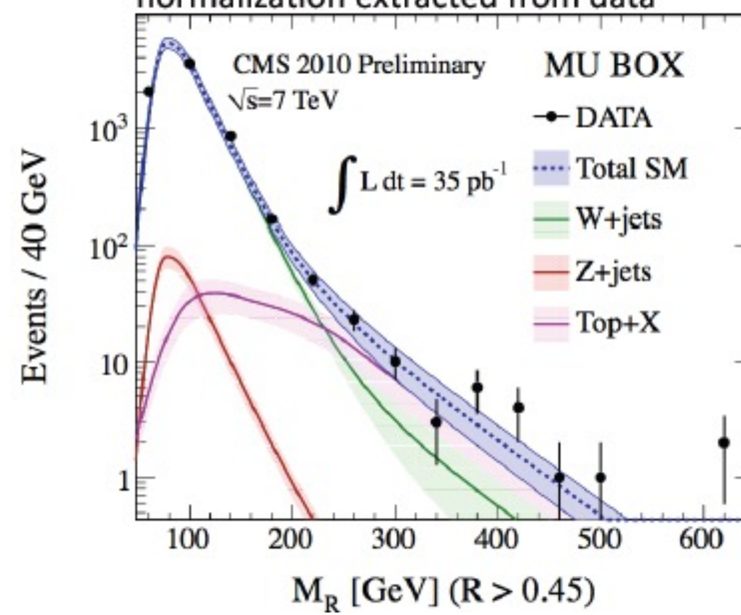
    processes which give the

    same signature

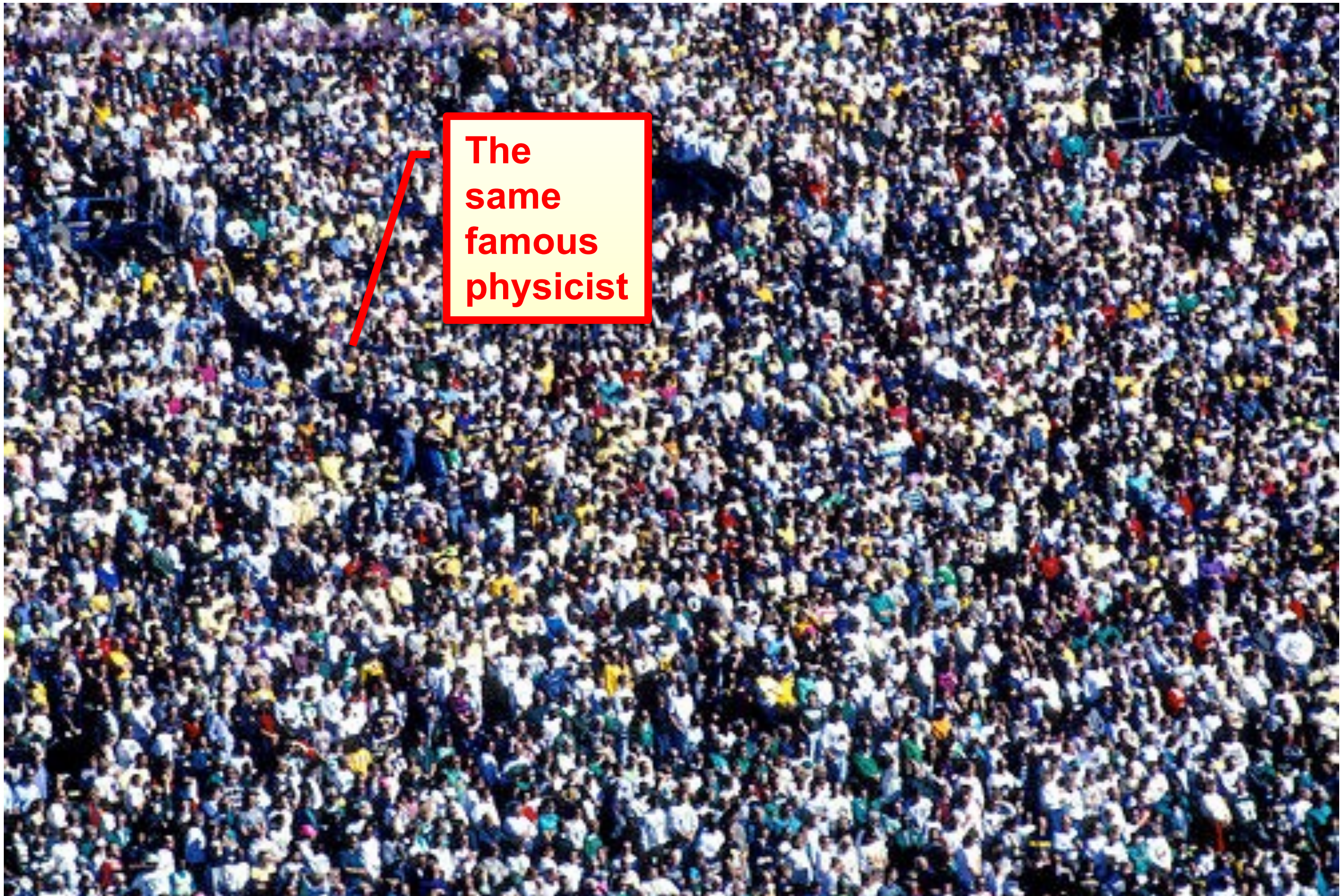
  Prime example 1: Z+jets
  And the Z decays to neutrinos
  So the MET is genuine!
  Prime example 2: t-tbar
  And one of the two W's decays
  to a tau and a neutrino

- **Cannot rely (only) on MC+simu!**

Background Shapes and normalization extracted from data



The problem: the background



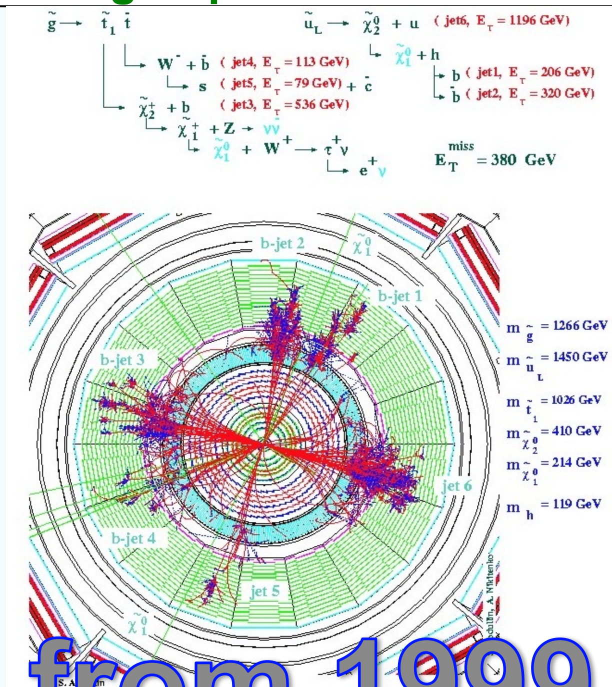
Huge background: implications

- Very difficult to select the “right” event(s); what are the criteria? Cannot interview every single person
  - Need an automated procedure; by necessity, it will rely on a set of successive approximations
  - One has to design these selection steps; and one has to ensure that they are unbiased!
    - Very difficult to avoid biases in the selection process!
    - Particularly important in the online trigger system!
- Number of “input” events is so large that one expects all abnormalities to show up
  - Even with a probability of occurrence of 1:10,000, in a crowd of 1,000,000 people, there will be 100 “cases”!
  - In practice, implies a new level of understanding – cannot rely on Monte Carlo to simulate things at this level of detail

"Turn on the LHC and… find Higgs & SUSY"

- ATLAS and CMS were designed to do this; they were "guaranteed" to find the Higgs – period; right away
  - In fact: SUSY is strongly produced, so will be observed first
    - For the "impatient": join SUSY physics group

- Many hard Jets
- Large missing energy
  - 2 LSPs
  - Many neutrinos
- Many leptons
- In a word **Spectacular!**



Text & simu from 1999

So what has transpired?

- Next three lectures!
- Lecture 2: Standard Model Physics
  - Jets and QCD measurements
  - Electroweak Theory
  - Top physics
- Lecture 3: EWSB Physics
  - The scalar sector, the great discovery
  - Searches for extensions to the scalar sector
  - Measurement of the W and top-quark masses; overall consistency of SM
- Lecture 4: Searches for New Physics
  - Supersymmetry
  - Exotica
  - Summary

Pseudo-summary I

Pseudo-summary I

- Hadron colliders: despite complexity of events, the interesting ones do stand out
  - Some limitations (e.g. $\Sigma p_z \neq 0$) but effective ways around it
  - Detector and event reconstruction: a huge job, to which we have done no justice in this lecture
- The LHC was conceived to probe the physics of the ~TeV region
  - Energy at "14" TeV $\rightarrow$ need for higher luminosity
    - Several unprecedented challenges to detectors. More in detector lectures.
- ATLAS & CMS: two different solutions for the same mission
  - With similar physics reach
- Proton-proton collisions: thankfully, hard scatter is clearly visible, and one can study the strong and electroweak interactions.
  - And search for new physics, Beyond the Standard Model