Highlights from LEP, Tevatron & LHC

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NIKHEF

Highlights of LEP, Tevatron & LHC

- Lecture 1,2: LEP physics results
  - Construction & running
  - Physics of the W and Z
  - QCD at LEP
- *Lecture 3,4: Tevatron results*
  - *Running D0 and CDF*
  - *QCD, jets, dijets*
  - *Heavy quarks, top quarks*
  - *W,Z physics, Higgs searches*
- Lecture 5,6: LHC physics programme & results
  - Construction & running of LHC
  - QCD, jets
  - W, Z physics, top quark
  - Higgs prospects

LEP

- LEP reached high precision in electroweak sector of the SM
  - Z mass, couplings, lepton universality, WWZ triple coupling
- But not only! High precision also in QCD
  - $e^+e^- \rightarrow 2$ jets
    - determination of the spin of quark
  - $e^+e^- \rightarrow 3$ jets
    - determination of the spin structure of the gluon
  - $e^+e^- \rightarrow 4$ jets
    - sensitive to triple gluon coupling
    - probing the gauge structure of QCD
    - unambiguous determination of SU(3) structure

Color factors

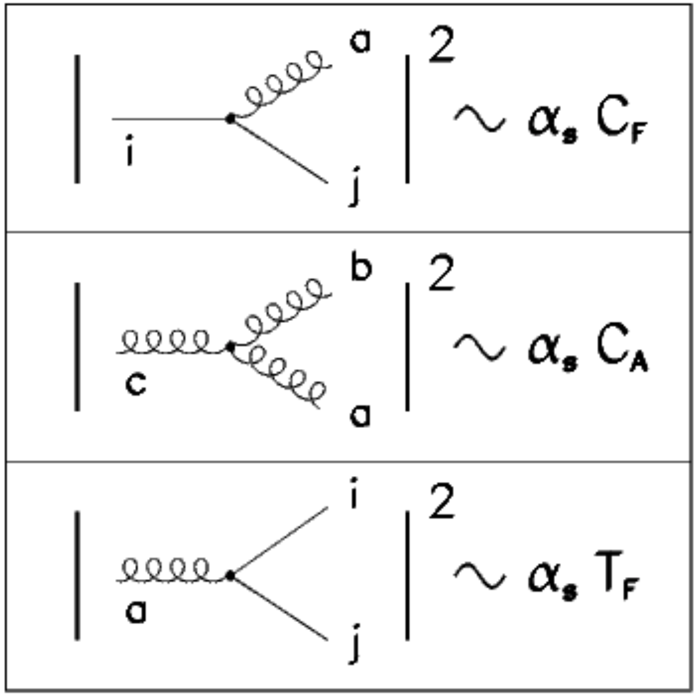
- QCD is SU(3) theory?

$$[T^a, T^b] = i f^{abc} T^c$$

$$\sum_{a=1}^{N_A} \left(T^a T^{\dagger a}\right)_{ij} = \delta_{ij} C_F$$

$$\sum_{a,b=1}^{N_A} f^{abc} f^{*abd} = \delta^{cd} C_A$$

$$\sum_{i,j=1}^{N_F} T^a_{ij} T^{\dagger b}_{ji} = \delta^{ab} T_F$$



T^a are the generators of the Lie group
N_F and N_A are dimensions of fundamental and adjoint representation

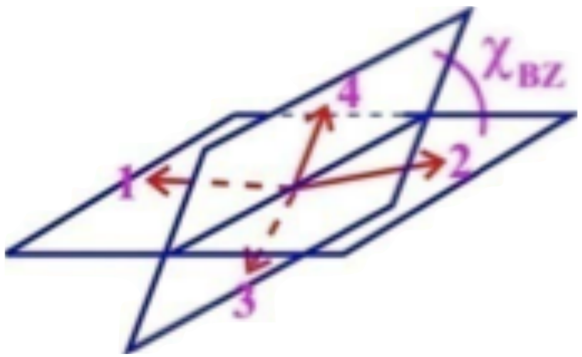
- For group *SU(N_C)*:

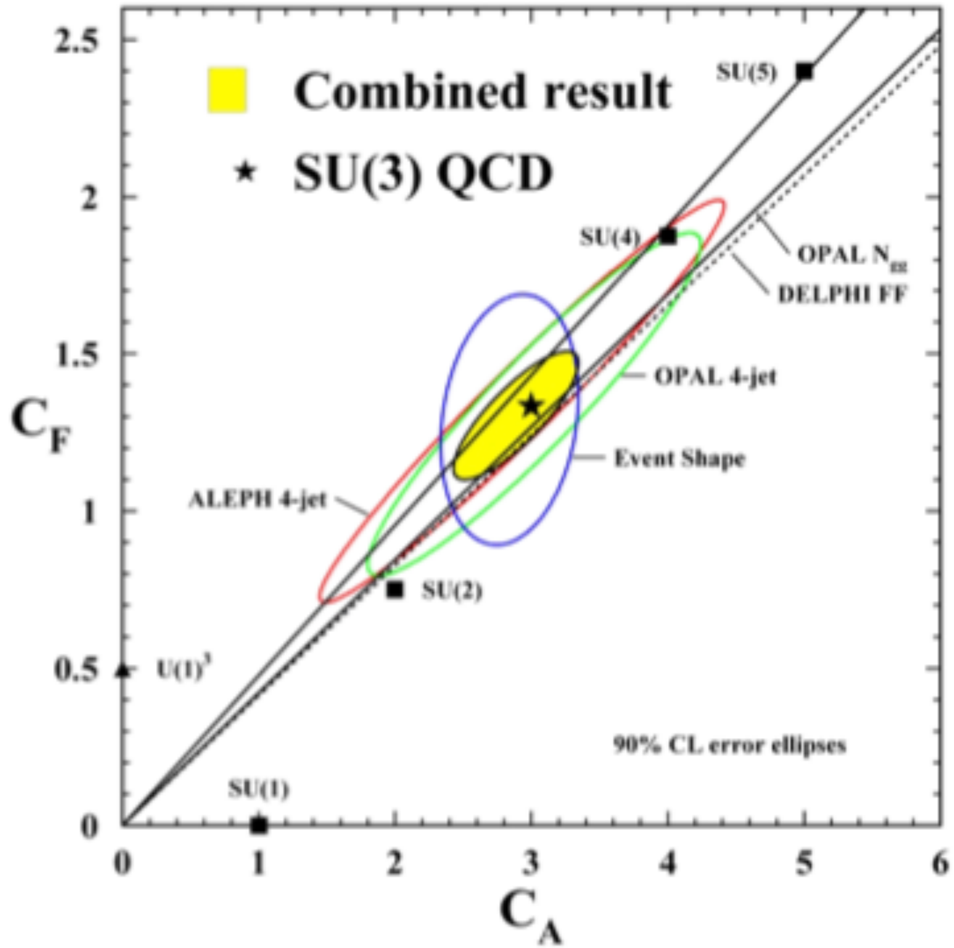
$$C_A = N_C \quad , \quad C_F = \frac{N_C^2 - 1}{2N_C} \quad , \quad T_F = 1/2 \,.$$

Color factors reflect basic properties of QCD. They are therefore measured to prove SU(3) is the gauge group of QCD

Ultimate precision color factors

- Construct observables to separate the contributions to the cross section
  - combine 4-jet and event shape results, accounting for correlations





  - Approx 8-14% accurcy on gauge structure QCD!

$C_A = 2.89 \pm 0.21$
$C_F = 1.30 \pm 0.09$

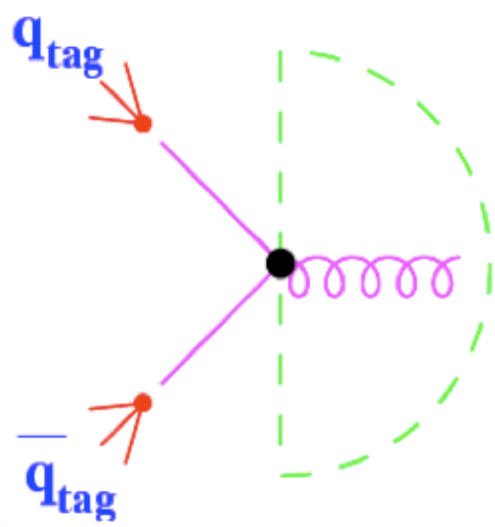
Difference quark and gluon jets

- Quark and gluon jets have different coupling strengths to emit gluons
  - Hence you expect 'gluon' and 'quark' jets to be different

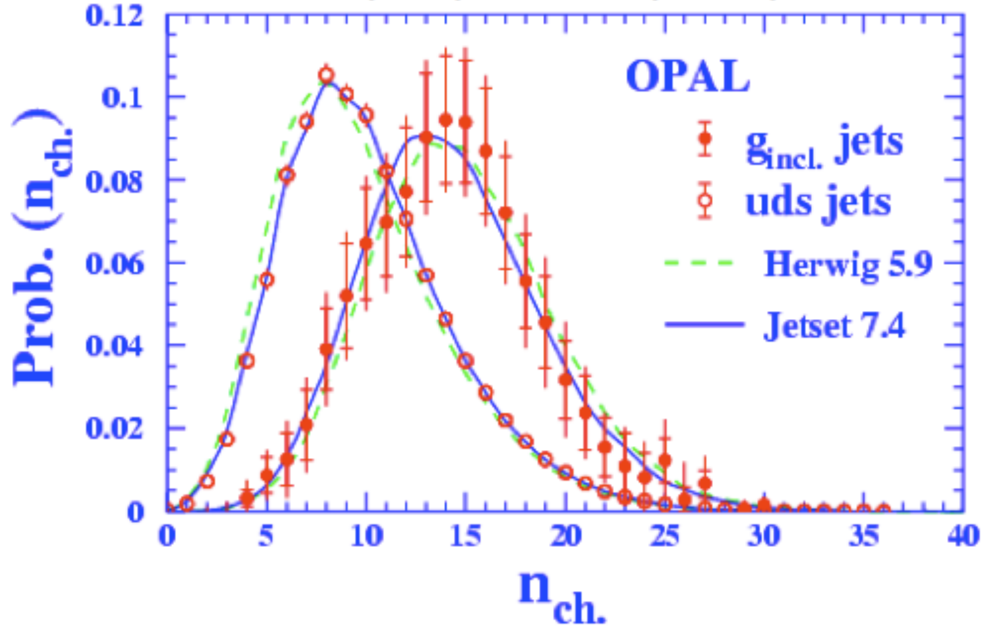
- Naive expectation: $r_{g/q} = \frac{\langle n_g \rangle}{\langle n_q \rangle} = \frac{C_A}{C_F} = 2.25$
  - Gluon jets have a larger multiplicity, softer fragmentation function, and are broader, than quark jets
  - Expect large differences, on order ~ 2

Particle multiplicity difference

- Eliminate jet-dependence
  - for quark jets its not so difficult:
    - define full hemisphere as “quark jet”
  - for gluon select specific topology:
    - using b-tagging in opposite hemisphere



OPAL (LEP), EPJC11(1999)217



$r_{G/Q}$ = 1.51±0.04

This is not the naive expectation of r=2.25

However, perfect agreement with NLL calculations

Determination of α_S

- Strong coupling
  - Rinning of the coupling (here leading order)
  - Natural scale Q^2

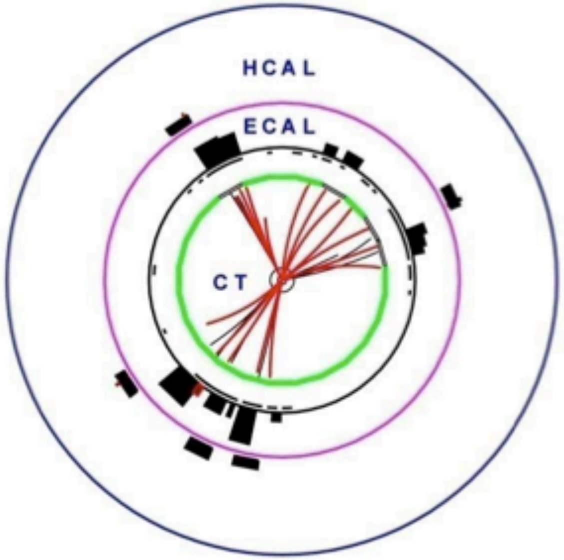
$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln(Q^2/\Lambda^2_{QCD})}$$

- Many methods at LEP have been used to measure
  - Each with own systematic and experimental challenges

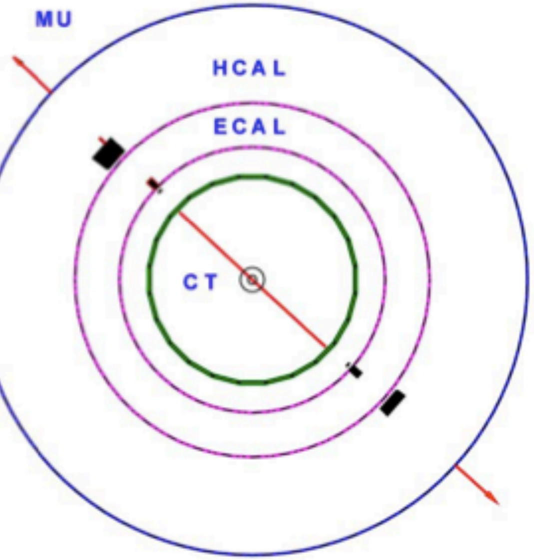
- A very straightforward (inclusive) and reliable method:
  - Just count the number of hadronic versus lepton events:

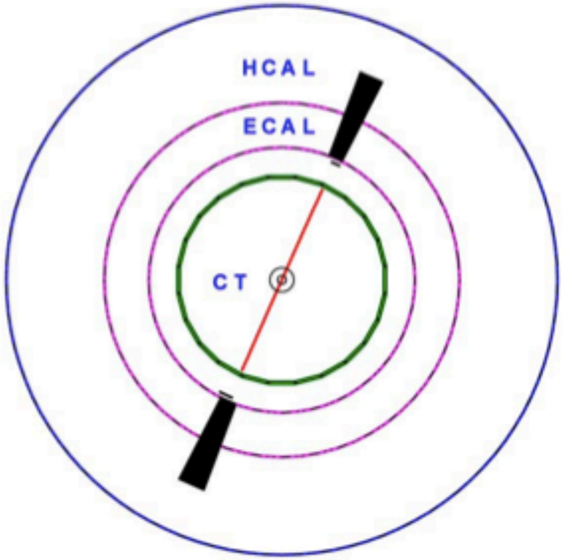
    $R_\ell = \Gamma\ [Z \rightarrow \text{hadrons}] / \Gamma\ (Z \rightarrow \ell^+\ell^-)$
  - based on event counting, known to α_S^3
  - small theoretical & experimental uncertainties, no hadronization corrections, etc

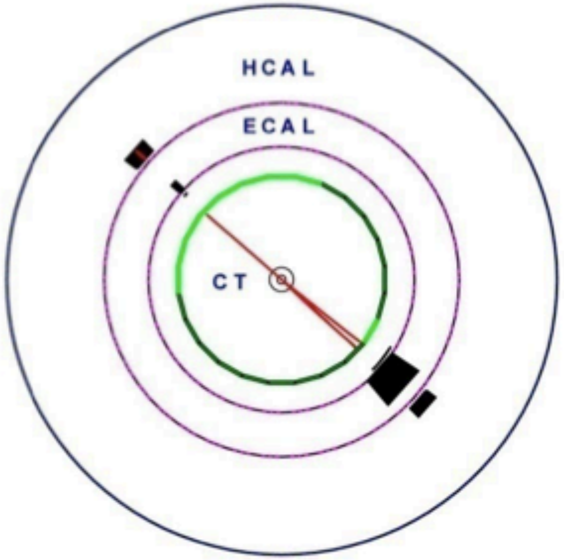
$R_\ell = \Gamma\,[Z \rightarrow \text{hadrons}] \,/\, \Gamma\,(Z \rightarrow \ell^+\ell^-)$



versus



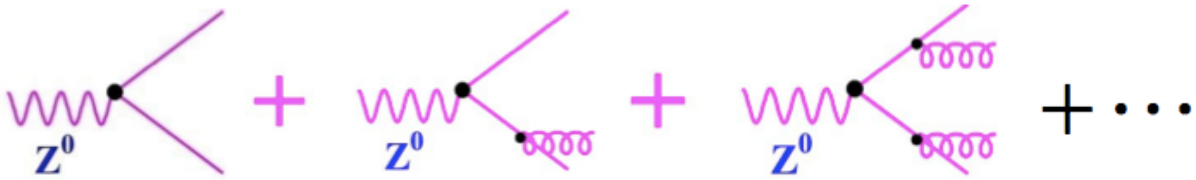




Calculations of R_l

- To get R_l you calculate:

$R_\ell \sim$



$$= R_\ell^0 (1 + \delta_{QCD})$$

  - explicit calculations show:

$$\delta_{QCD} = 0.333\alpha_S + 0.0952\alpha_s^2 + 0.484\alpha_s^3 \approx \underline{0.042}$$

- LEP and SLC determined:

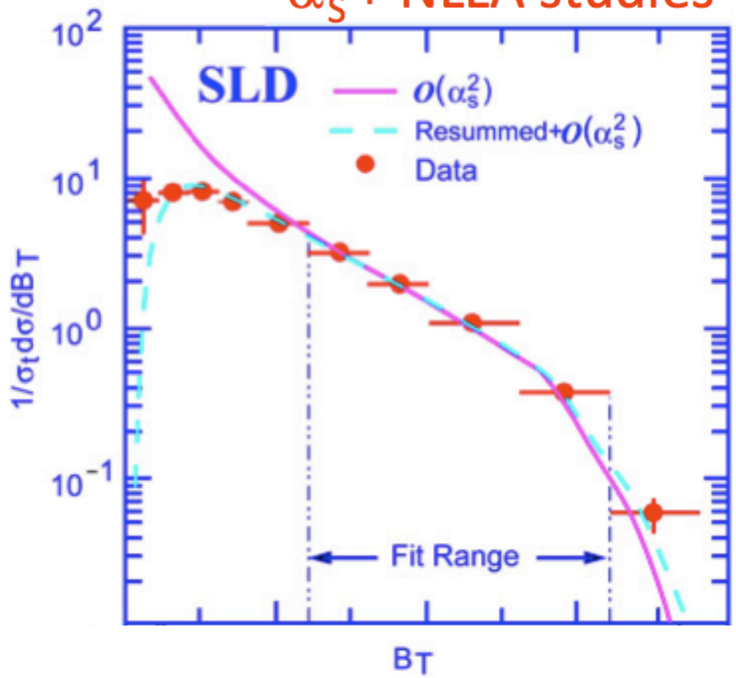
$$\alpha_S(M_Z) = 0.1189 \pm 0.0030$$

  - 2.5% precision, using all LEP data (12 million Z events)
  - experimental uncertainties dominate

One more determination α_S

- Look in the 'dynamics' of the events:
- Determine α_S from event shapes
  - Each events gets assigned one number "y" for an event shape

α_S^2 + NLLA studies



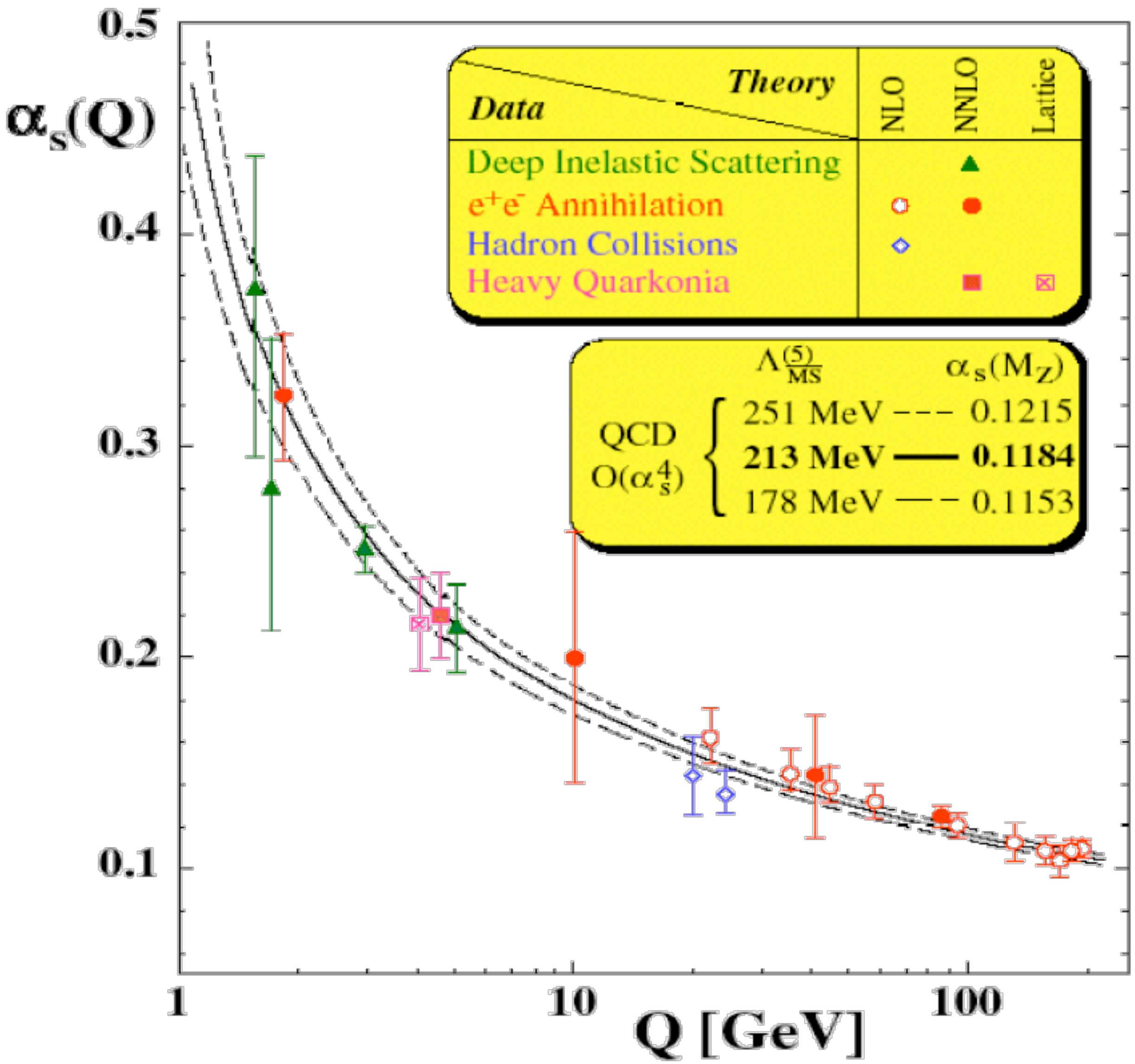
  - Look at: Thrust, Jet Broadening, Sphericity, ...

$$\alpha_S(M_Z) = 0.1192 \pm 0.0025\,(\text{expt.}) + 0.0070\,(\text{theor.})$$

  - 6% precision uncertainty, dominated by unknown higher order terms (dependence on assumption for renormalization scale)

Running coupling

- Beautiful agreement with theory
- shows the Gauge structure of QCD

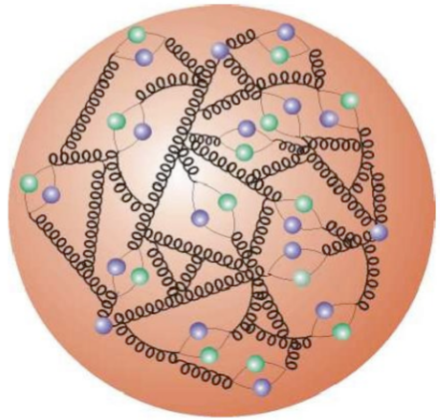


Summary

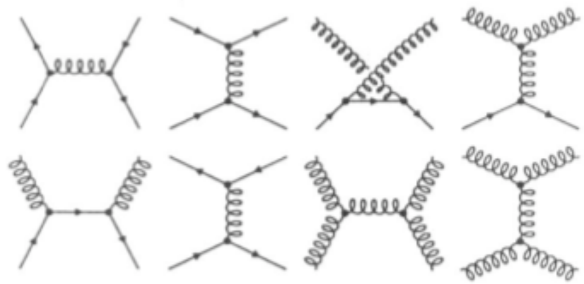
- LEP has been a fantastic machine:
  - Standard Model physics tested with unprecedented precision
  - Comparison experiment and theory at level of radiative corrections
    - Enormous boost to theoretical calculations
  - LEP gave complete understanding of the Standard Model
    - Gauge structure of Electro Weak physics
    - Gauge structure of QCD

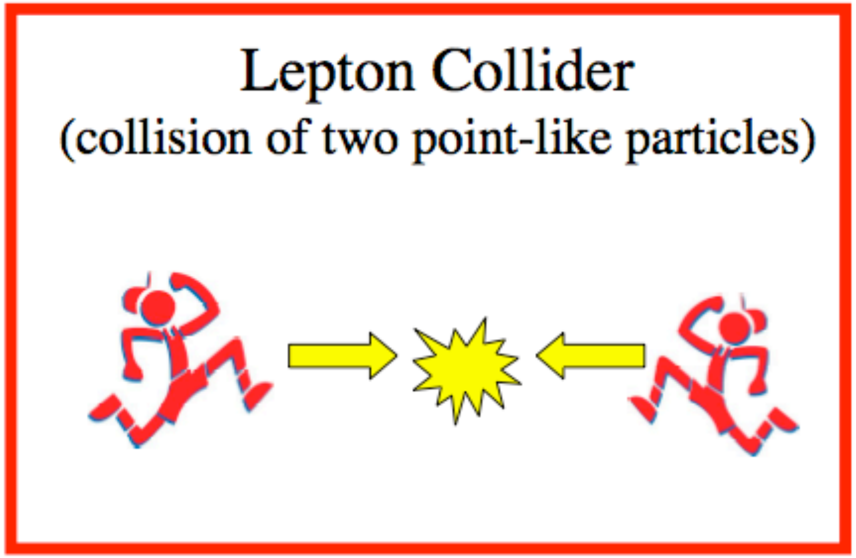
- Urging questions:
  - How is symmetry breaking realized?
  - Where is the Higgs?
  - How is Higgs mass stabilized?
  - Naturalness - hierarchy problem?

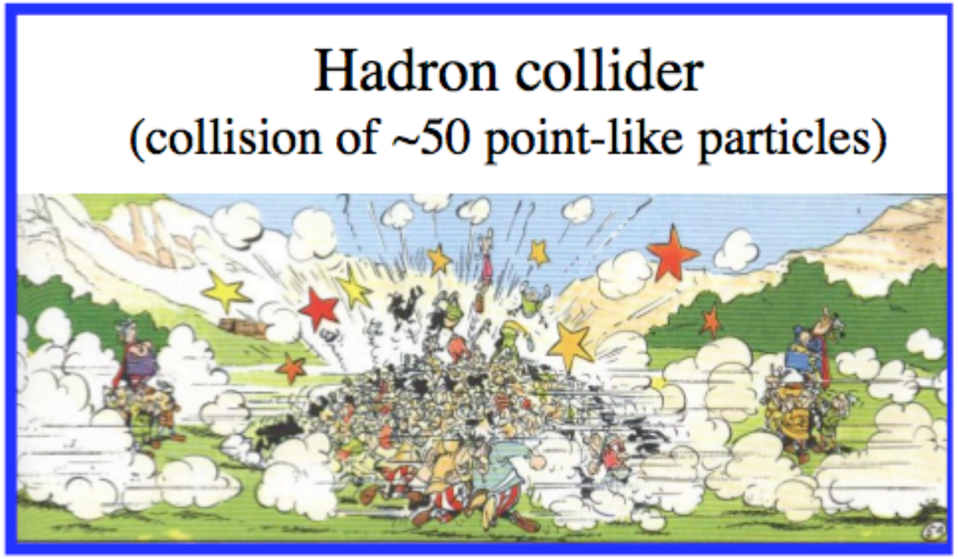
Why hadron collider?



- Disadvantage:
  - Hadrons are complex objects
    - High multiplicity of other stuff
    - Energy and type of colliding parton unknown
      - Kinematics are not completely constrained
- Advantage:
  - Can access higher energies







e^+e^- versus hadron collider

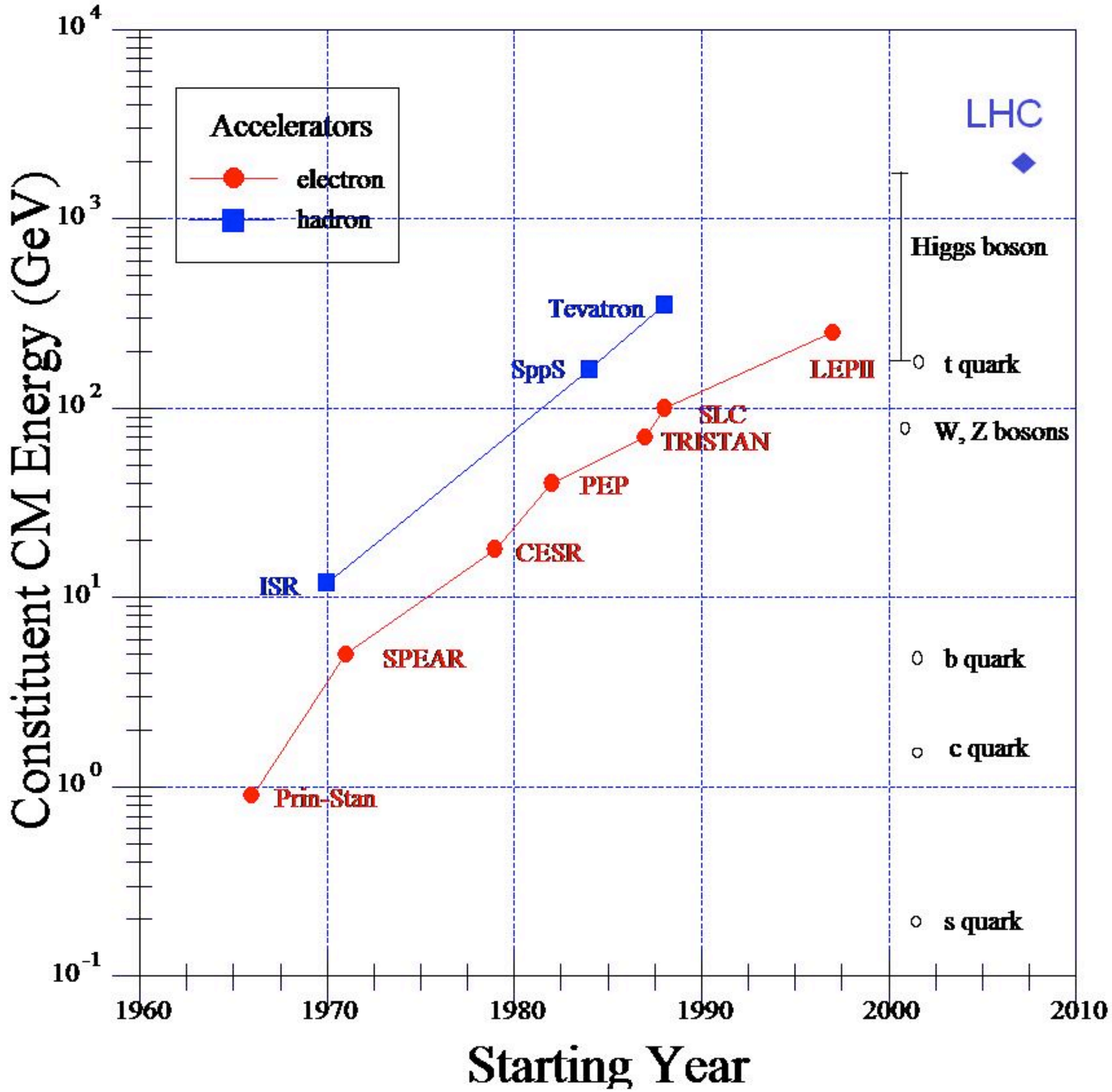
- Circular colliders
  - Pro:
    - Re-user their power on each turn
  - Con:
    - Synchrotron radiation reduces energy of particles
      - Problem worsens with m^4
  - Synchrotron radiation is not an issue for LHC

Energy loss per turn: $-\Delta E \approx \frac{4\,\pi\,e^2}{3\,R}\left(\frac{E}{mc^2}\right)^4$

Energy loss: e vs p $\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$

- Linear colliders
  - Particle sees each component just once
  - Now more cost-effective for electrons than circular collider:
    - ILC, CLICK

Average constituent CM Energies



LHC and Tevatron parameters

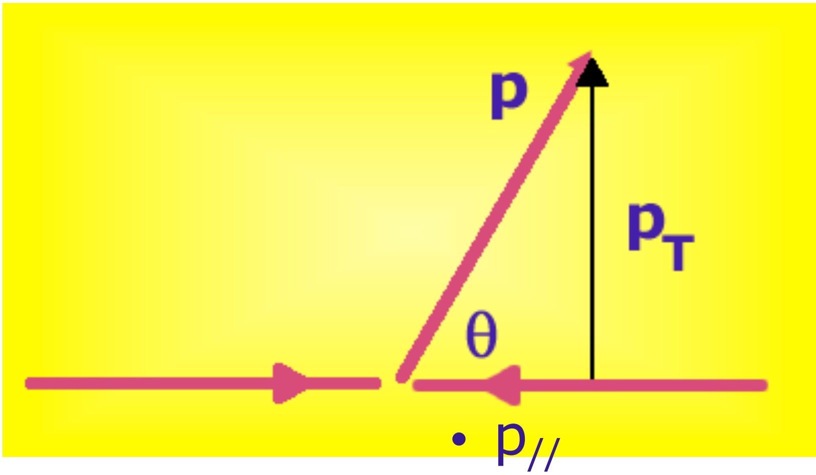
- LHC today
  - Runs at 7 TeV cm energy
  - I.e. 3.5 times higher energy wrt Tevatron
  - Has recorded a few pb^{-1}

	LHC (design)	Tevatron (achieved)
Centre-of-mass energy	14 TeV	1.96 TeV
Number of coll. bunches	2808	36
Energy stored in beam	360 MJ	1 MJ
Peak Luminosity (10^{30} $cm^{-2}s^{-1}$)	10000	400
Integrated Luminosity: $\int L dt$	>100 fb^{-1}	~9 fb^{-1}

- Depends on the process which machine is more powerful
  - But LHC will be taken over at some point....

Hadron collider kinematics

- Transverse momentum, p_T
  - Escaping particles ($\theta<3^o$) have $p_T \sim 0$
  - Visible transverse momentum conserved
- Longitudinal momentum and energy, $p_{//}$ and E
  - Particles that escape detection have large $p_{//}$
  - Visible $p_{//}$ is not conserved



Single particle kinematics

- Single particle phase space
  - Non relativistic: classical Maxwell-Bolzmann statistics
    - All Cartesian components equally probable:
      $d\vec{P} = dP_x dP_y dP_z = P^2 dP d\Omega = dP_{//} P_T dP_T d\phi$
  - Relativistic generalization
    - Four-dimensional momentum volume with mass constraint:
      $d^4 P \delta(E^2 - P^2 - m^2) = d\vec{P}/E = P_T dP_T d\phi dy$
    - where y is 'rapidity' $dy = dP_{//}/E$
      with is relativistic analogue of longitudinal velocity
  - Single particles are uniformly distributed in y
    - For particles in inelastic collisions occupying full phase space
      - i.e. for small momenta en small rapidity
      - One particle phase space uniform in (φ,y) for small y

Pseudorapidity $\left[\cosh^2 y - \sinh^2 = 1\right]$

- Expression for E, P and m:

$$E^2 - P^2 = m^2 \quad \rightarrow \quad E^2 - P_{//}^2 = P_T^2 + m^2 \equiv m_T^2$$

- from which we can write:

$$\begin{aligned} \sinh y &= \frac{P_{//}}{m_T} \\ \cosh y &= \frac{E}{m_T} \\ \tanh y &= \frac{P_{//}}{E} \end{aligned} \qquad m = 0 : \rightarrow \quad m_T = P_T = E \sin\theta \qquad \begin{aligned} \sinh y &= 1/\sin\theta \\ \cosh y &= 1/\tan\theta \\ \tanh y &= \cos\theta \end{aligned}$$

- Pseudorapidity: $e^{-y} = \tan(\theta/2) \equiv \eta$
  - equivalent to rapidity when neglecting mass wrt transverse momentum
  - proton collider detectors segmented into ‘pixels’ of equal size in space (η,φ), e.g. ATLAS & CMS
    - justification of the use of (η,φ) coordinates in plots.

Pseudorapidity

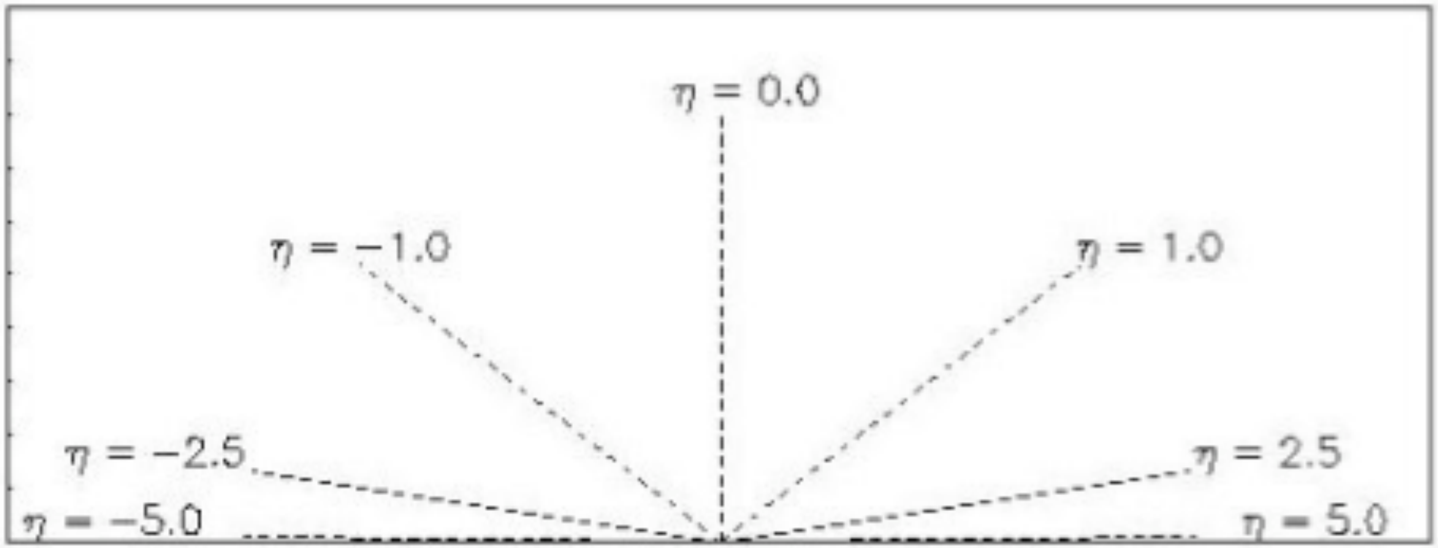
- Rapidity y
  - Rapidity y is:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

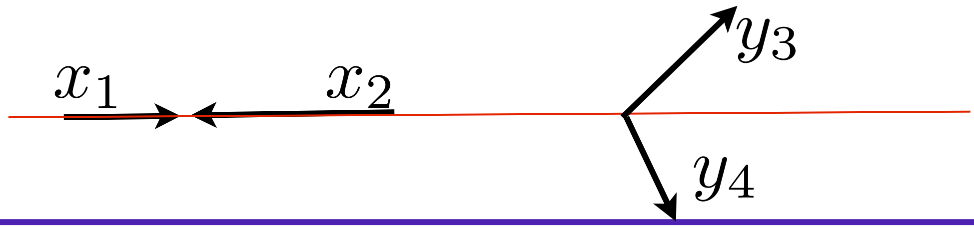
First year bachelors exercise:
prove that y is additive under Lorentz transformations

  - and pseudo-rapidity as m=0 limit

$$\eta = -\ln(\tan(\theta/2))$$

- 

2 particle system



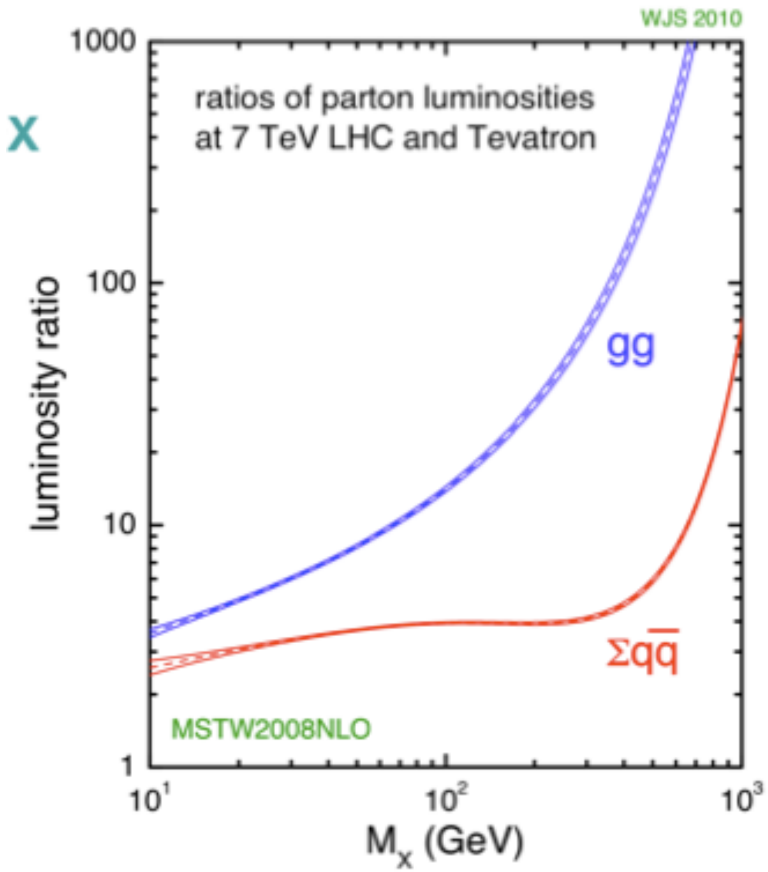
- Colliding partons
  - Parton momentum in CM frame of protons with momentum P
    $p_1 = x_1 P, \;\; p_2 = x_2 P$
  - The mass of the system: $\hat{s} = M^2 = 4P^2 x_1 x_2 = x_1 x_2 s$
    - for massless partons $\tau \equiv x_1 x_2 \;\;,\;\; x \equiv x_1 - x_2$
  - Typical production when $x_1 = x_2$ or $< x > \sim \sqrt{\tau}$
    - e.g. top-quarks at Tevatron at rest produced at $< x > \sim 0.2$
    - top-quarks at LHC at rest produced at $< x > \sim 0.025$
- Kinematics fixed for 2→2 system

$$M^2 = 2E_T^2 \left[\cosh(y_3 - y_4) - \cos(\phi_3 - \phi_4)\right]$$

  - which reduces to $M = 2E_T$
    for back-to-back final state with $y_3 = y_4$

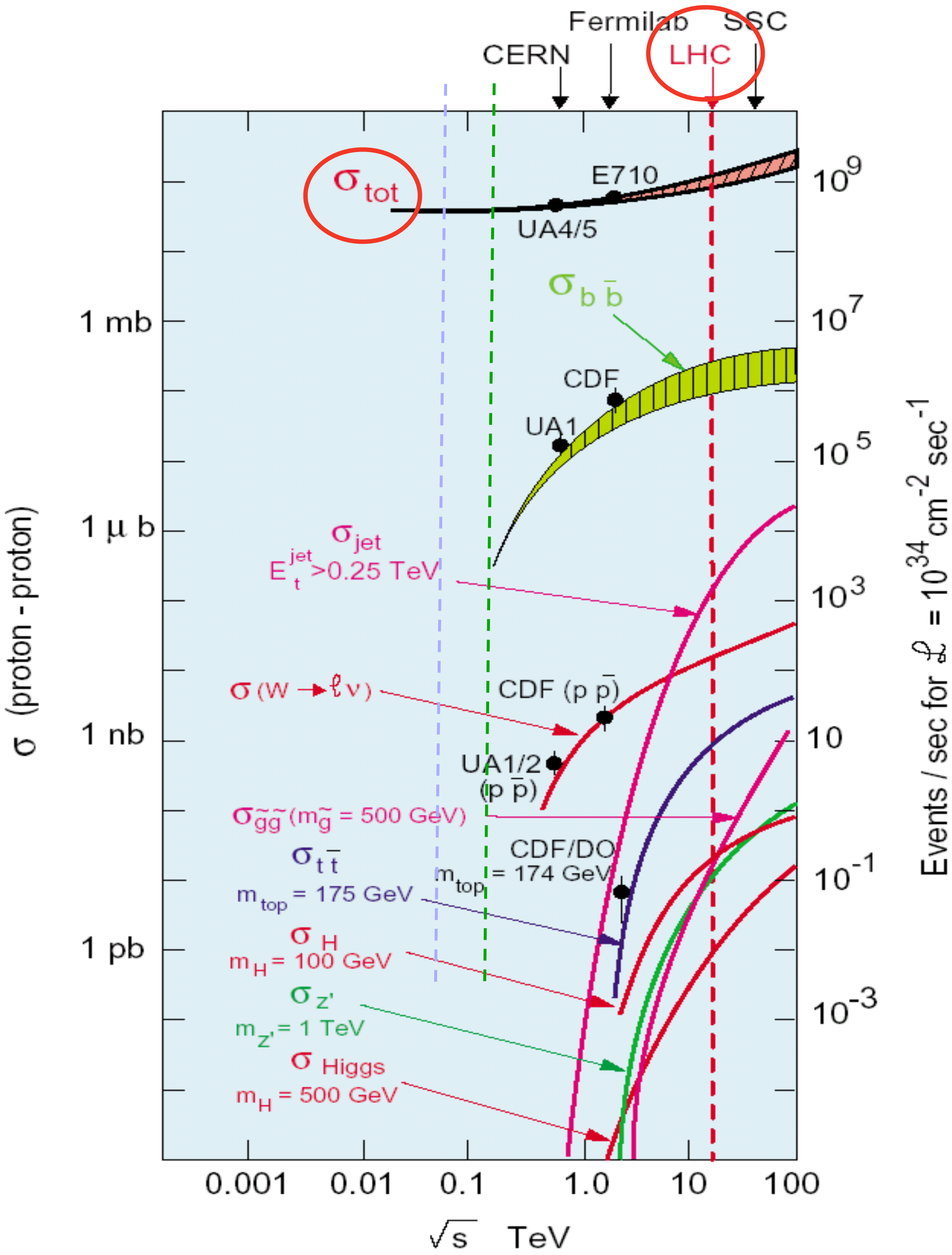
Tevatron vs LHC

- Parton densities
  - Rise dramatically towards low x
    - Results in larger cross sections for LHC
    - $\int L dt = 1\ fb^{-1}$ at LHC competitive with $10\ fb^{-1}$ at Tevatron for high mass processes
  - $\int L dt = 100\ pb^{-1}$ already interesting in some cases for LHC



Process	M_X	σ(LHC @ 7 TeV) / σ(Tevatron)
$q\bar{q} \to W$	80 GeV	3
$q\bar{q} \to Z'_{SM}$	1 TeV	50
$gg \to H$	120 GeV	20
$q\bar{q}/gg \to t\bar{t}$	2x173 GeV	15
$gg \to \tilde{g}\tilde{g}$	2x400 GeV	1000

Hadron Colliders in Summary



- Higher Energy
- Broadband production

⇒ Discovery machines

- Large physics cross-section
- What is interesting is *rare*
- The ability to find rare events is the consequence of evolved detector design and technological innovations

A bit of hadron collider history

A short interlude

Hadron Colliders History: ISR

The ISR (Intersecting Storage Rings, 300m diameter)

the world's first hadron collider, and ran from 1971 to 1984, with a maximum center of mass energy of 62 GeV.

"The ISR missed the J/ψ and later missed the Υ "

"...it took a long time to overcome two major difficulties of collider physics. The first… the relatively low luminosity… The second…the very wide angle spread over which particularly interesting events, such as lepton pair events, may occur…

The answer is, of course, sophisticated detectors covering at least the whole central region ($45^o < \theta < 135^o$) and full azimuth."

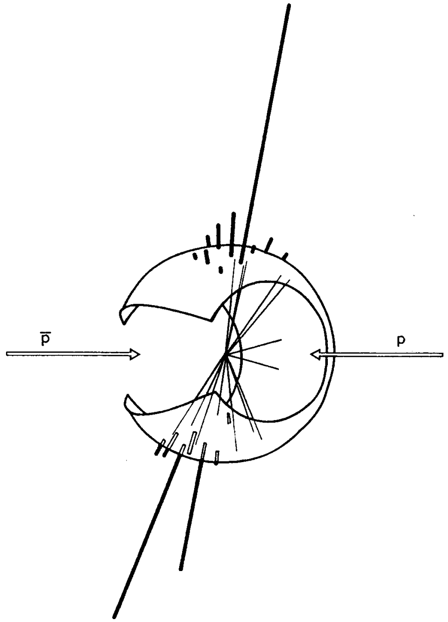
" …they stumbled on an unexpectedly strong hadron yield; large-p_T production had been discovered, a witness, as we now know, to the pointlike structure within hadrons.

- Early ISR experiments were not prepared for the J/ψ and later ones were too late for the Υ. They nevertheless learned a lot and paved the way for UA1 and UA2 which were well-prepared and on-time.

UA2 @ SppS

bulletin

WEEK MONDAY 30 AUGUST — N°35/82 — SEMAINE DU LUNDI 30 AOUT

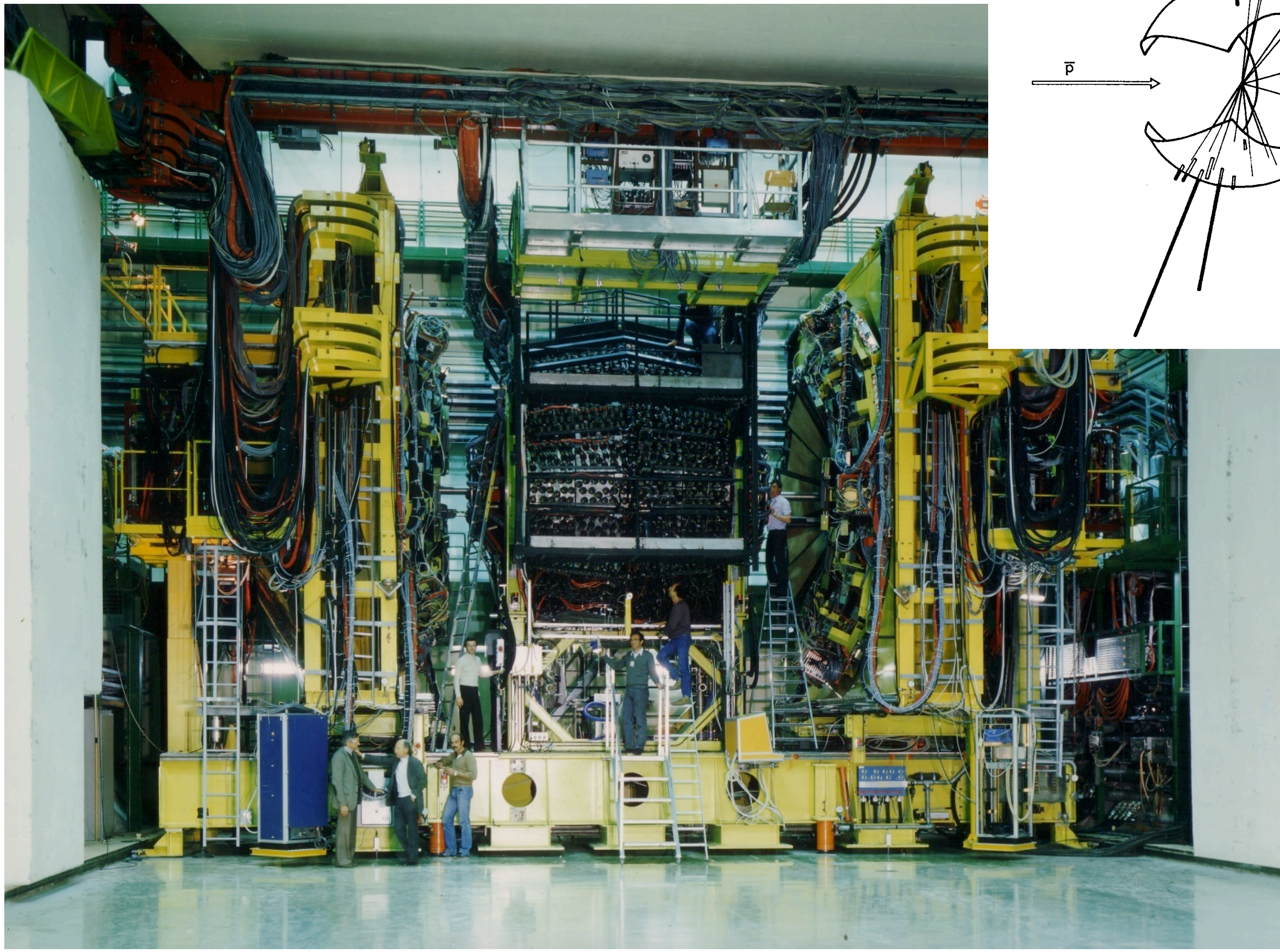


A spectacular 'jet' event seen by the UA2 experiment, in which the fragments of a violent 540 GeV proton-antiproton collision contained 127 GeV of energy flying off at right angles to the initial collision axis. The line lengths are proportional to particle energies.

Evénement spectaculaire 'en jet' observé au cours de l'expérience UA2 et dans lequel les fragments d'une violente collision proton-antiproton de 540 GeV contenaient une énergie de 127 GeV fusant à angle droit par rapport à l'axe initial de la collision. La longueur des lignes est proportionnelle à l'énergie des particules.

Jets et particules

Parmi les nouveaux résultats de physique annoncés lors de la Conférence internationale de physique des particules qui s'est tenue récemment à Paris, le plus remar-



September 1981:
first (small) run
for UA2

First observation of
jets in hadronic collisions

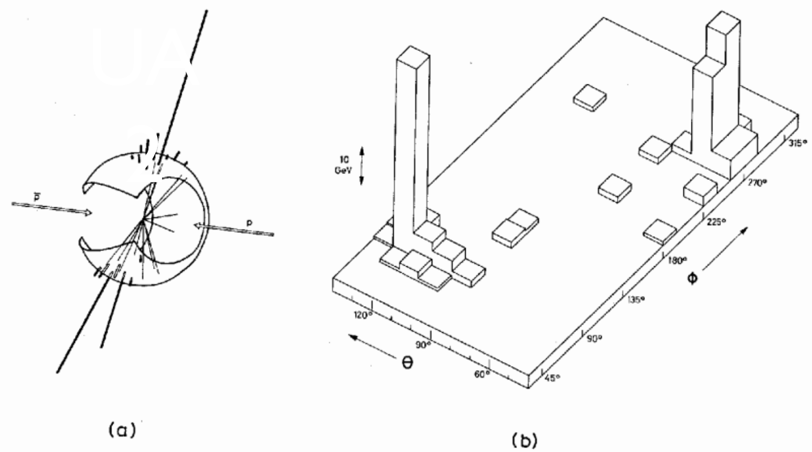
Hadron Colliders History: SppS

SPS Collider operation, 1982-1983

Operational features	1982	1983
Beam Energy (GeV)	273	273
β_H^* (m)	1.5	1.3
β_V^* (m)	0.75	0.65
Integrated luminosity (nb^{-1})		
average per store	0.5	2.1
average per day	0.4	1.8
per year	28	153
Luminosity (10^{29} $cm^{-2} \cdot s^{-1}$)		
peak	0.5	1.7
average per store	0.1	0.5
Hours scheduled	1750	2064
Hours realised	748	889
Number of stores	56	72
Average store duration (h)	13	12
% stores terminated by faults	41	40

- Engineering run 1981 ~1 nb^{-1}
  - 1st dijets at a hadron collider!
    - *Production and Properties of Jets…* Z.Phys.C20:117, 1982.
- Physics run 1982 ~20 nb^{-1}
  - Co-discovery of the W
    - *Observation of Single Isolated Electrons of High Transverse Momentum…* Phys.Lett.B122:476-485, 1983.
    - *Inclusive Charged Particle Production …* Phys.Lett.B122:322-328,1983.
- 1983 ~ 130 nb^{-1}
  - Co-discovery of the Z
    - *Evidence for $Z^0 \rightarrow e+e$* Phys.Lett.B129:130-140, Aug. 1983.

Discovery W and Z

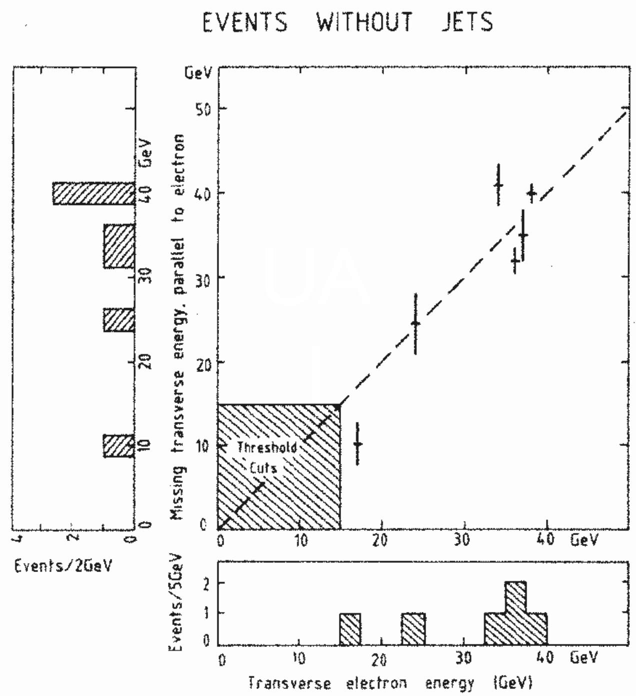


(a) (b)

Fig. 4

First dijets at a hadron machine

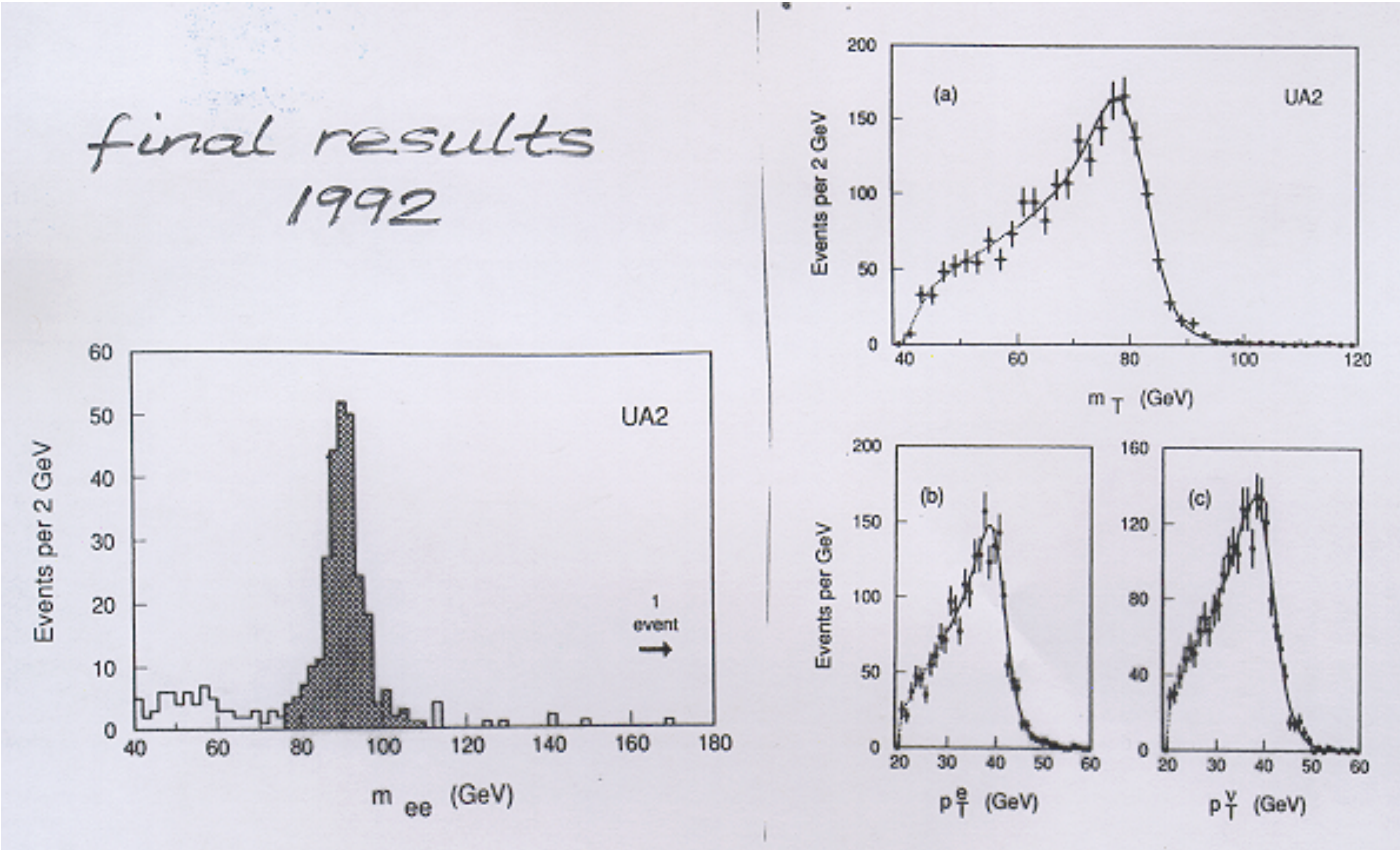
Publication came out of the 1981 run!



6 events in UA1 and the W was discovered!

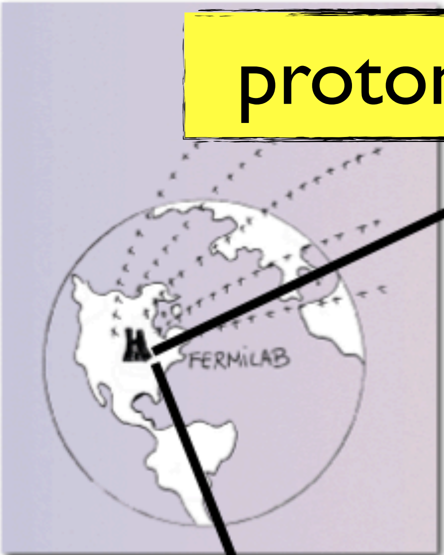
UA2 saw 4 W events: they obtained a central value of 80 GeV for M_W

Finish with accurate W/Z masses



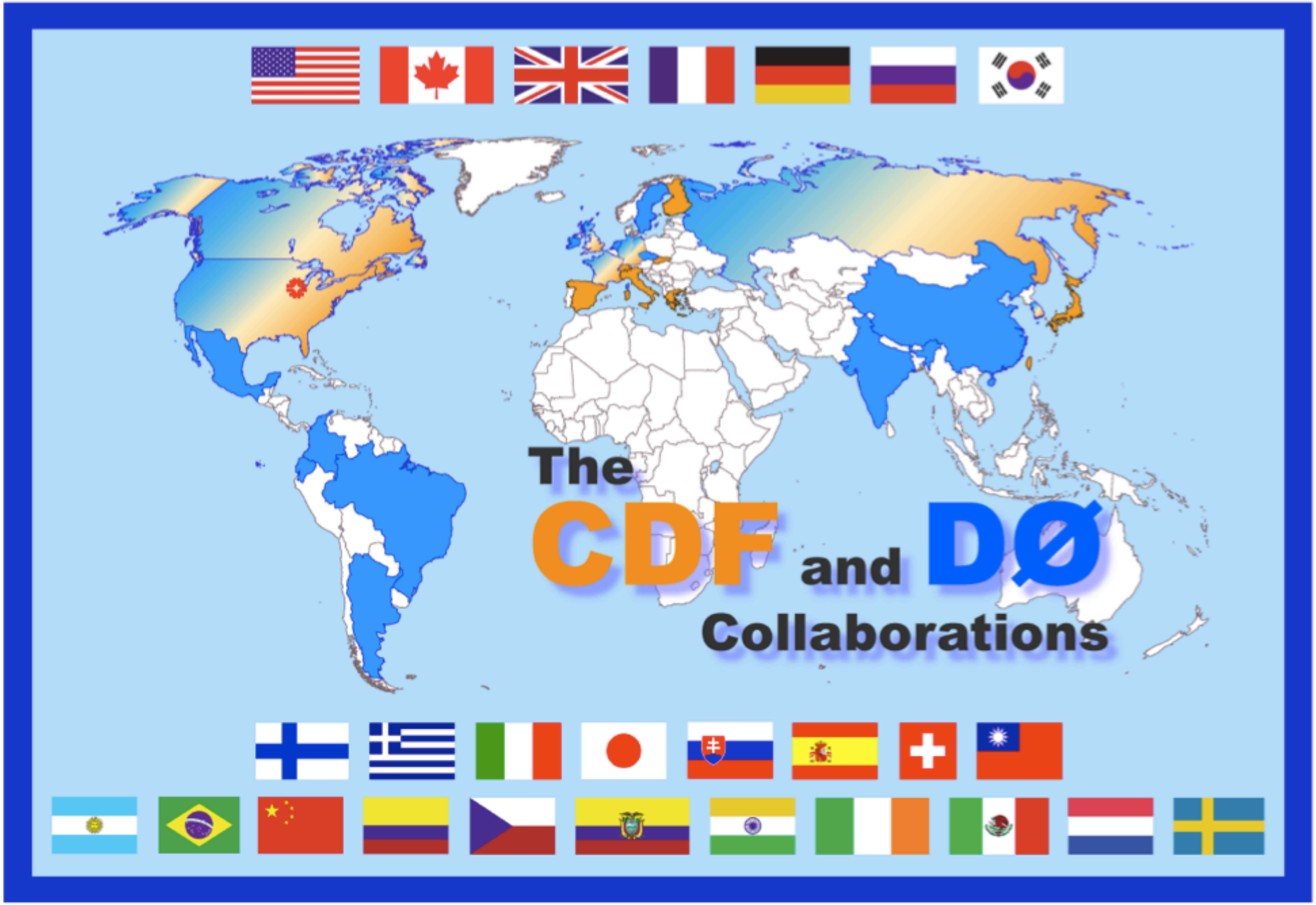
Fermilab's Tevatron

protons on anti-protons at cm energy 1.96 TeV



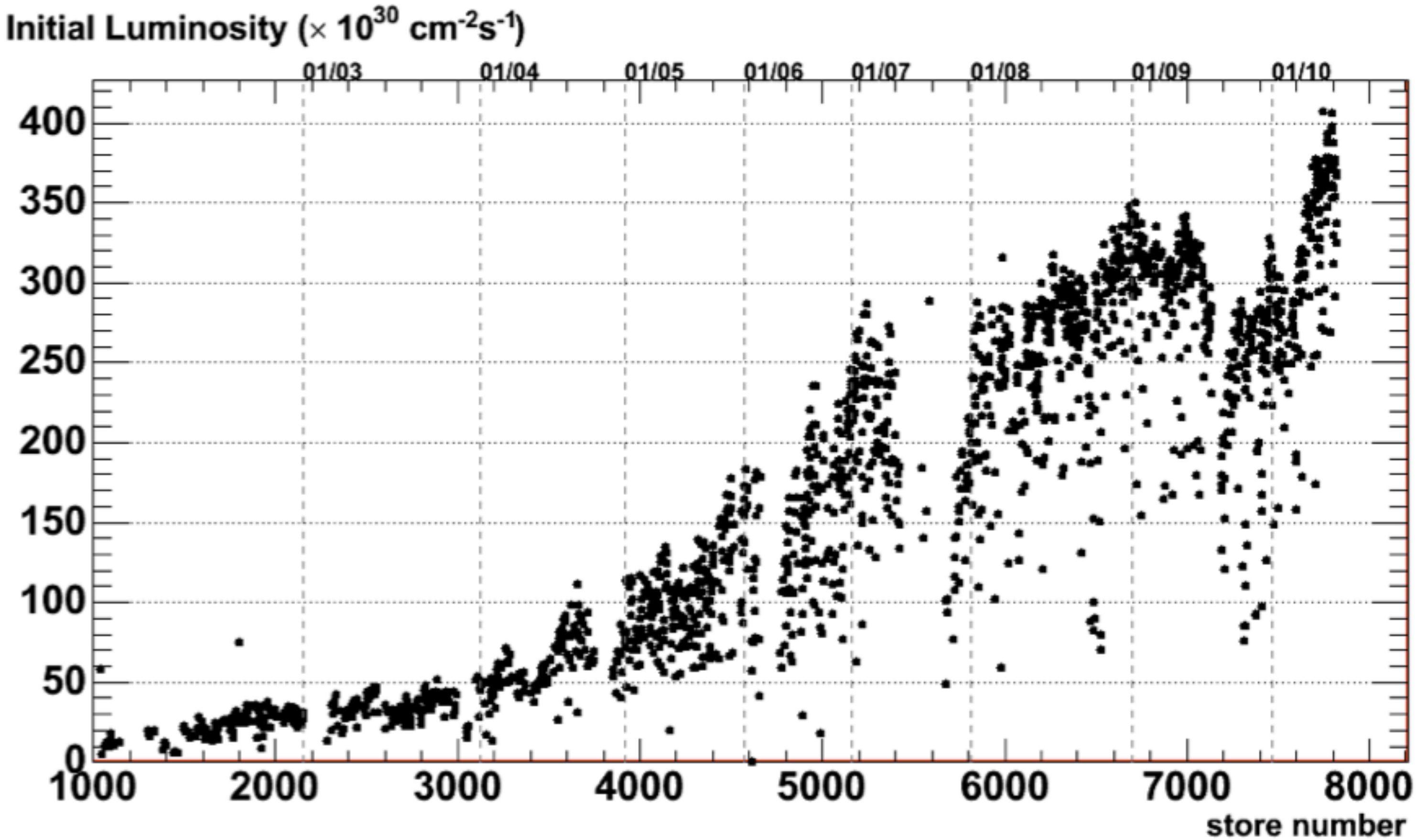
run-I:1990-1995
(1.8 TeV cm)

run-II: >2001
(1.96 TeV)


The
CDF and DØ
Collaborations

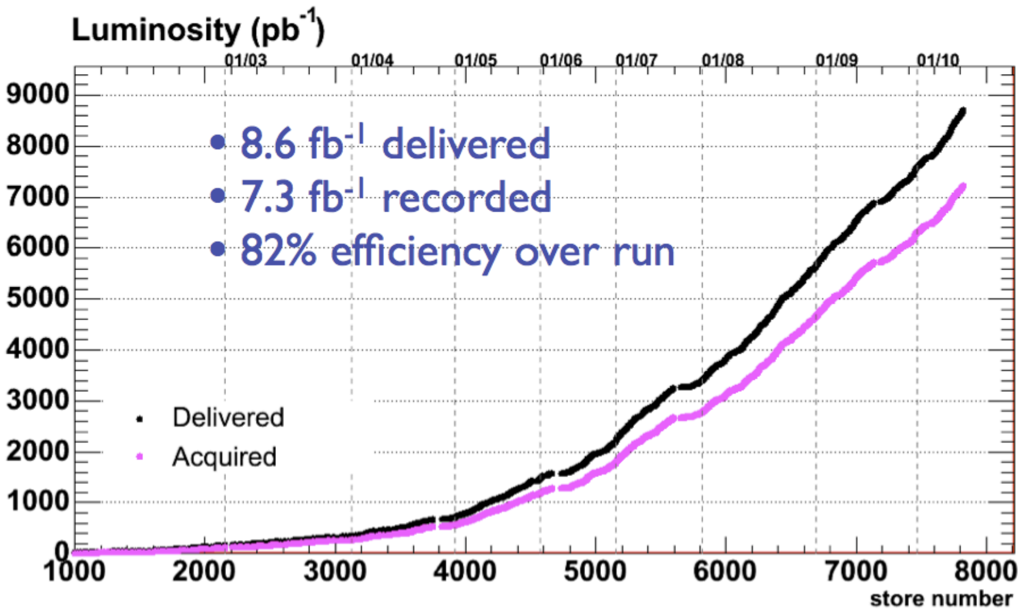
Tevatron performance

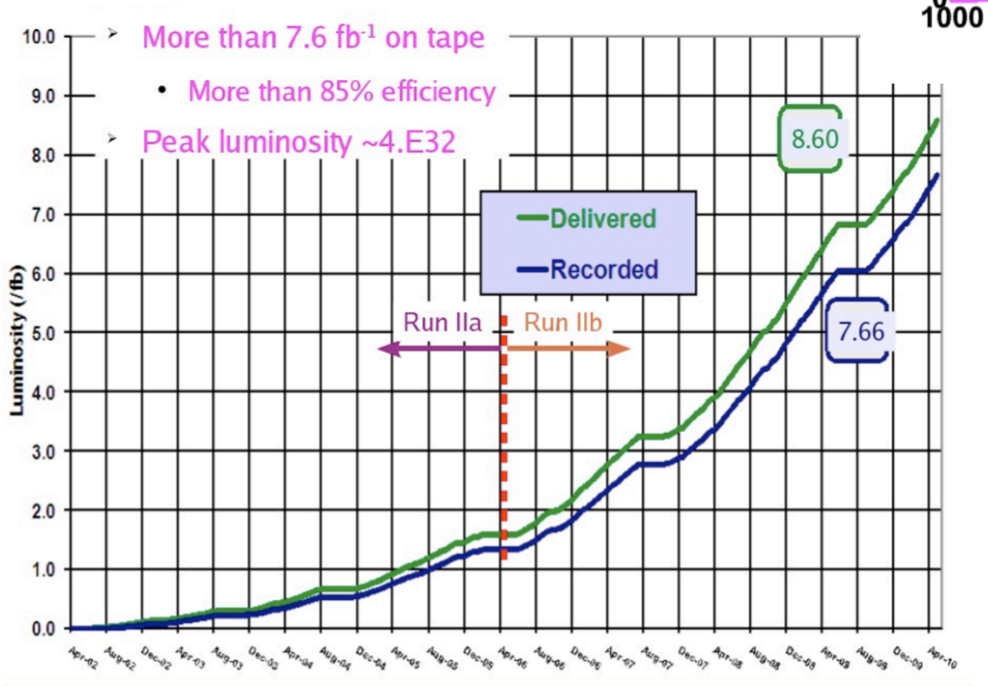
- Stores routinely come in at > 3 10^{32}
  - 60 – 70 pb-1 delivered/week is typical.
- Expect >2fb/year.



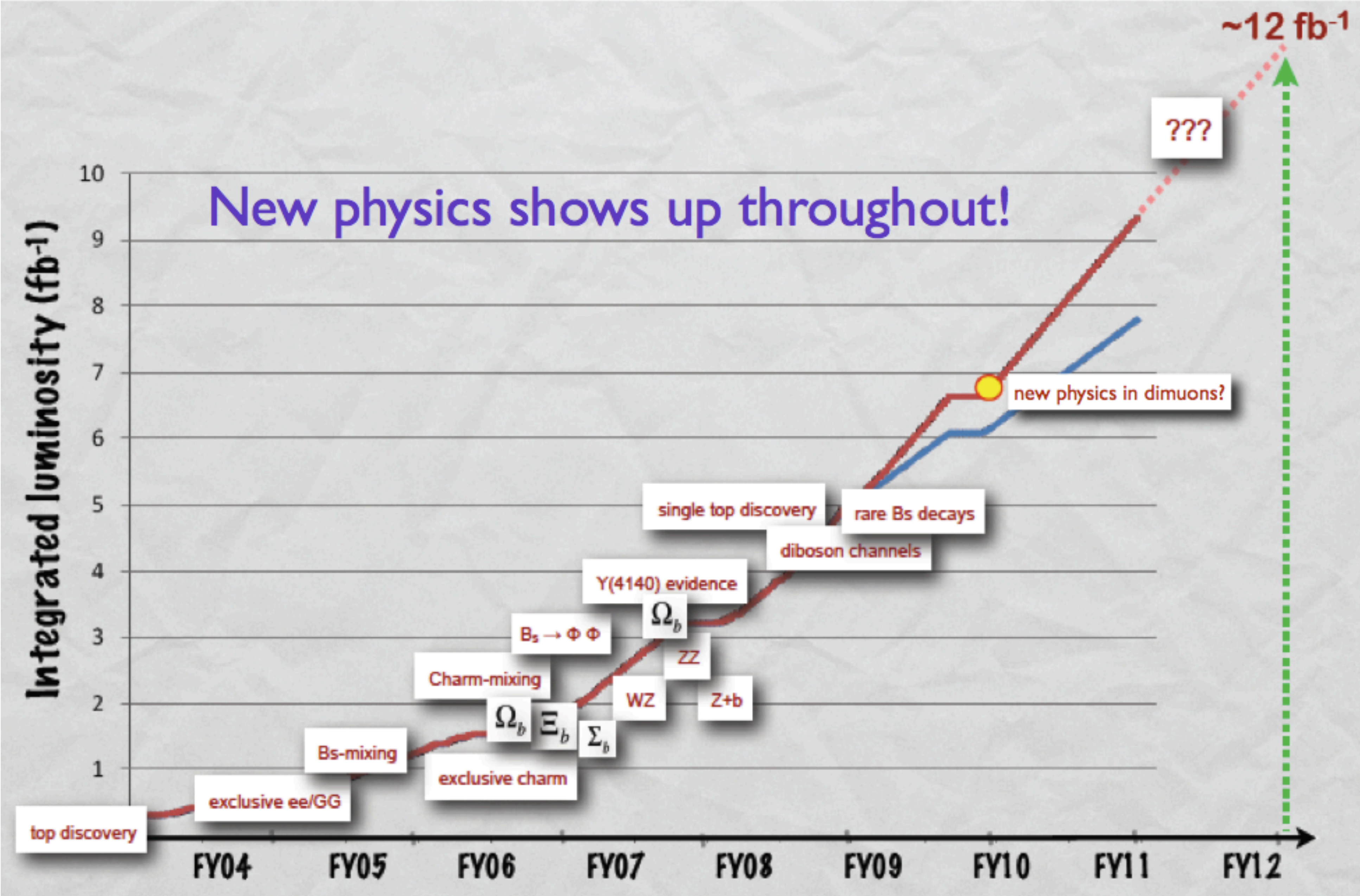
D0 and CDF luminosity profiles

- Recent numbers
  - Enormous amount of data on tape
  - Tevatron is performing very well





Discoveries still whowing up?



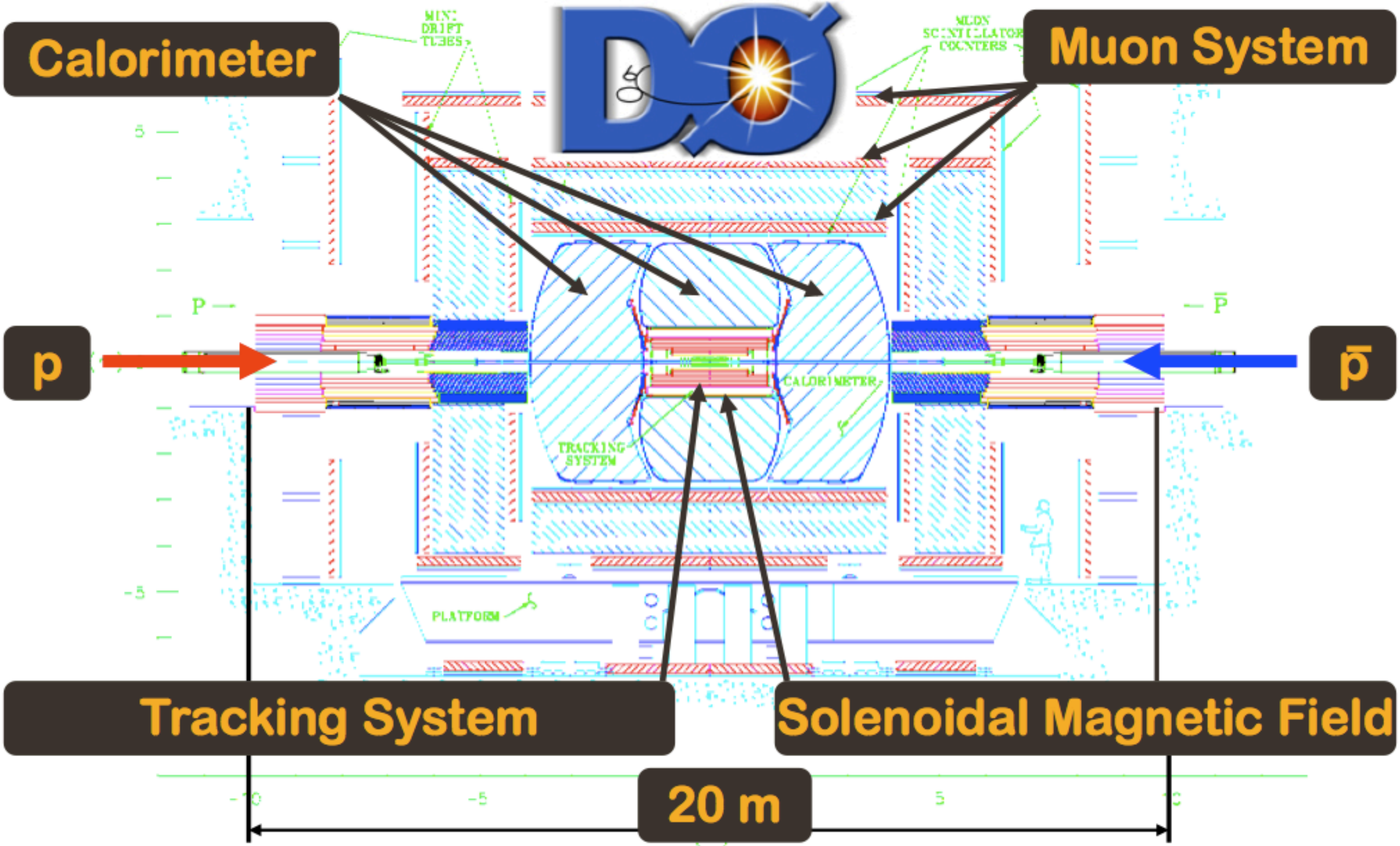
Tevatron Research Program

- Precision Measurements, New Reach for Discoveries
  - Mixing, CKM Constraints and CP Violation
  - Heavy Flavor Spectroscopy
  - New Heavy Baryon States
  - Tests of Quantum Chromodynamics
  - Di-Boson production and SM Gauge Couplings
  - New Exclusive/Diffractive Processes
  - Precise measurement of Top-quark and W-boson Masses
  - Top Quark Properties
- Unique Window into the unknown
  - Searches for Supersymmetry, Extra Dimensions, Exotica
  - Still at the Energy Frontier... for now
- Probing the Terascale with increased luminosity
  - The Standard Model Higgs Boson is almost within reach!

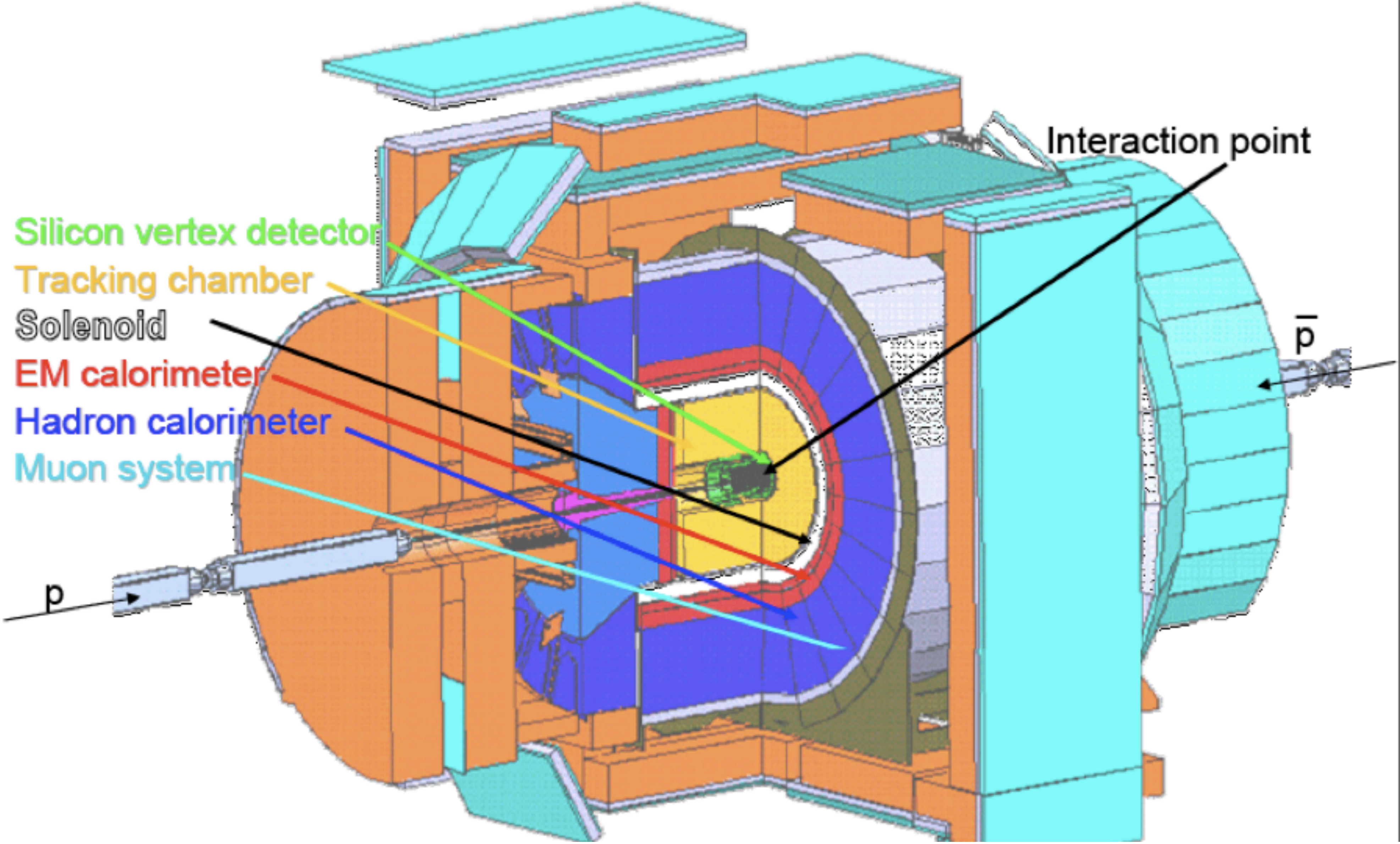
Tevatron versus LHC

- Tevatron is impressive:
- Results on SM physics are very hard to beat for the LHC
- Many analysis techniques very advanced after years of running experience
- Dont close your eyes to what happens at Tevatron!
  - (...but they wont find the Higgs...:-))

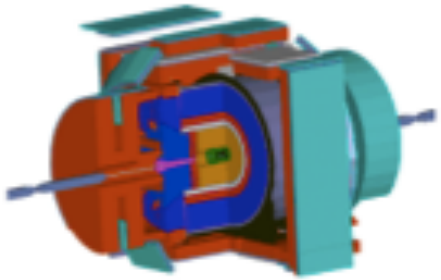
The DØ Detector

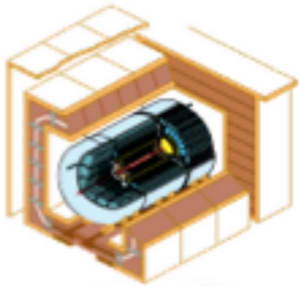


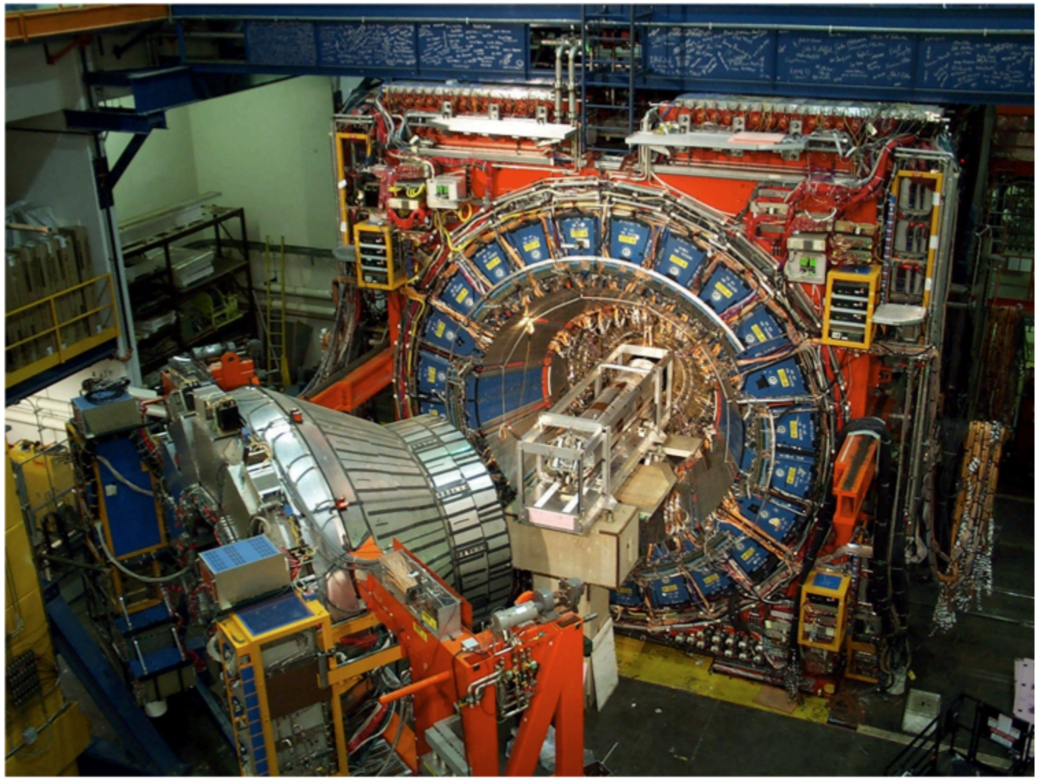
The CDF Detector



CDF & D0

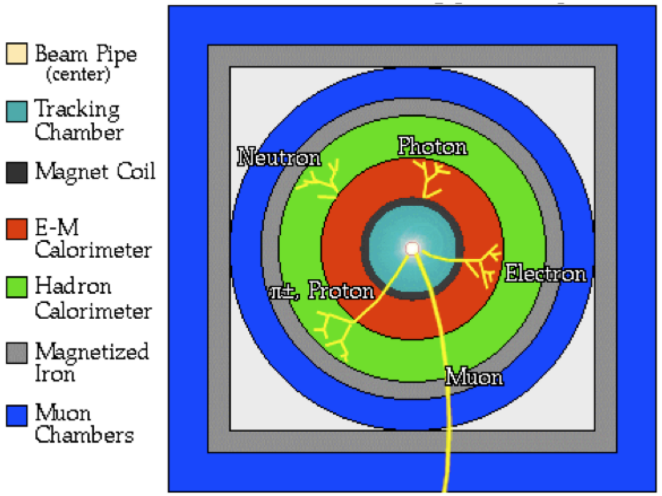






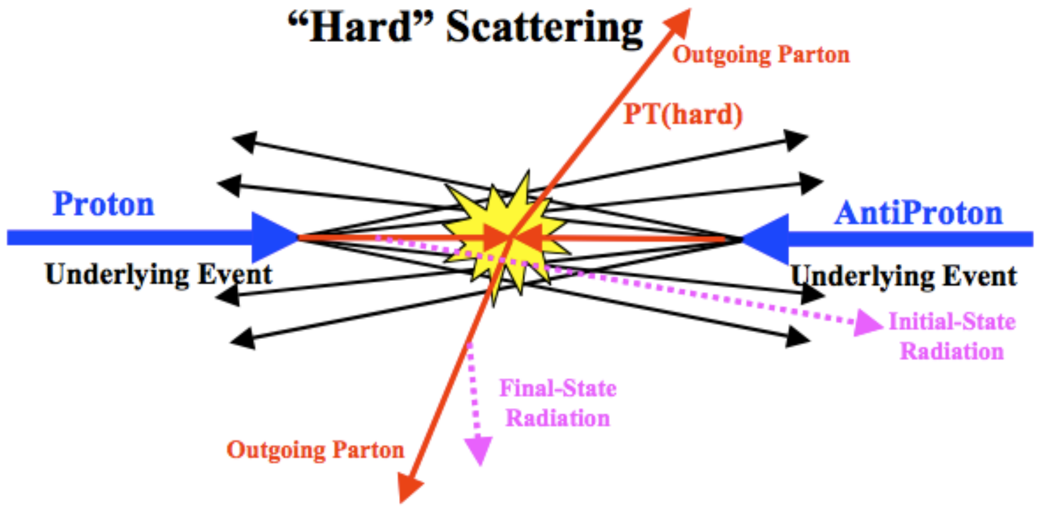
Particle ID

- D0:
  - Retained from Run I
    - Excellent muon coverage
    - Compact high granularity LAr CAL
  - New for run 2:
    - 2 Tesla magnet
    - Silicon detector
    - Fiber tracker
    - Trigger and Readout
    - Forward roman pots



- CDF:
  - Retained from Run I
    - Central Calorimeters
    - Central muon chambers
  - Major upgrades for Run II:
    - Drift chamber: COT
    - Silicon: SVX, ISL, L00
    - Forward calorimeters
    - Forward muon system
    - Time-of-flight
    - Preshower detector
    - Timing in EM calorimeter
    - Trigger and DAQ

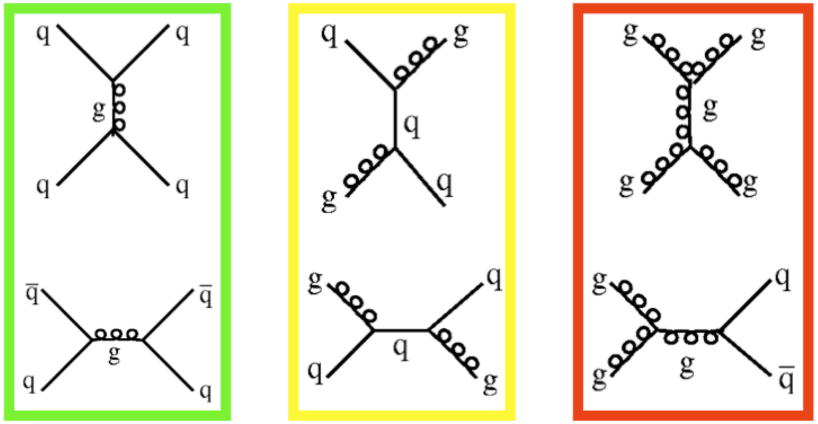
Complicated events

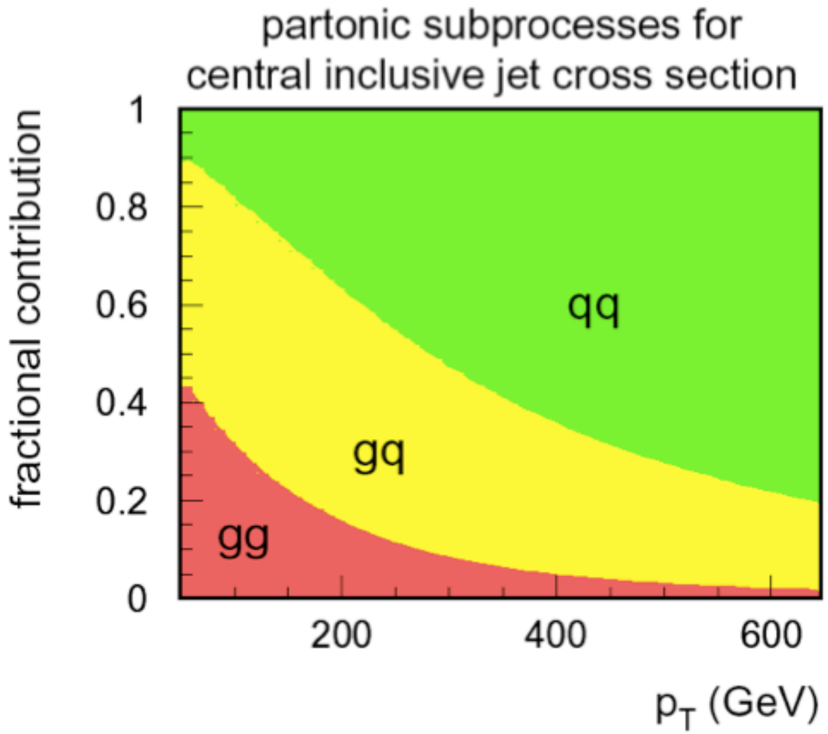


- "Underlying event":
  - Initial state radiation
  - Interactions of other partons in proton
- Additional pp interactions
  - LHC: ~1.5 (~23 at design values)
  - Tevatron: ~10
- Many forward particles escape detection
  - Transverse momentum ~0
  - Longitudinal momentum >>0

Jet cross sections @ Tevatron

- Inclusive jets
  - Underlying process from qq, qg, gg
  - Relative fraction depends on pdf's

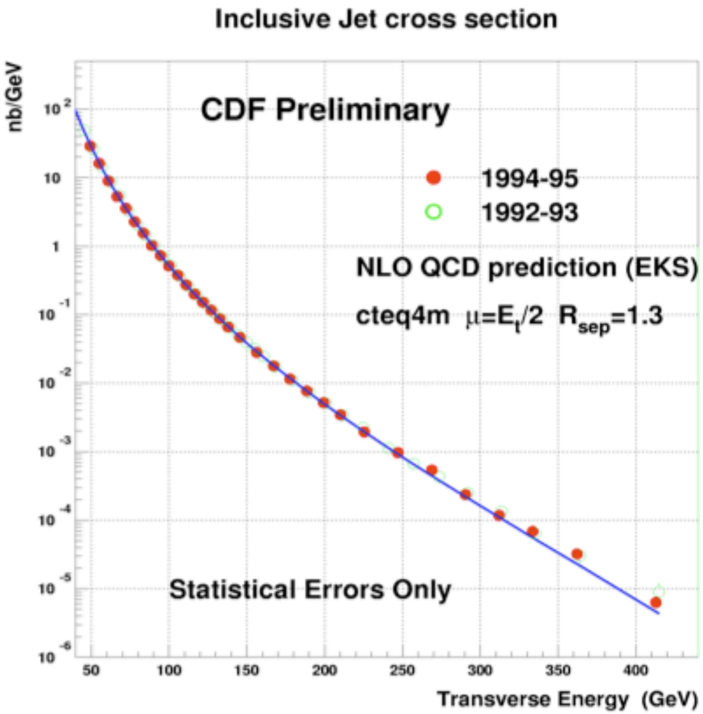




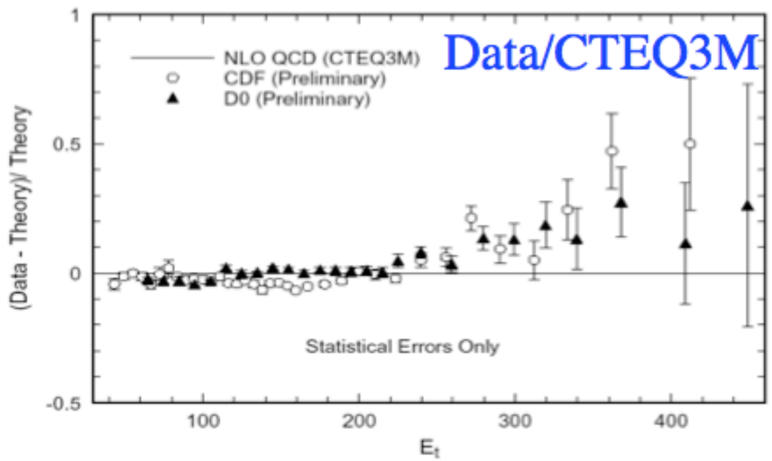
  - Highest E_T probes shortest distances
    - Tevatron: $r_q<10^{-18}$ m
    - LHC: $r_q<10^{-19}$ m
    - Could e.g. reveal substructure of quarks

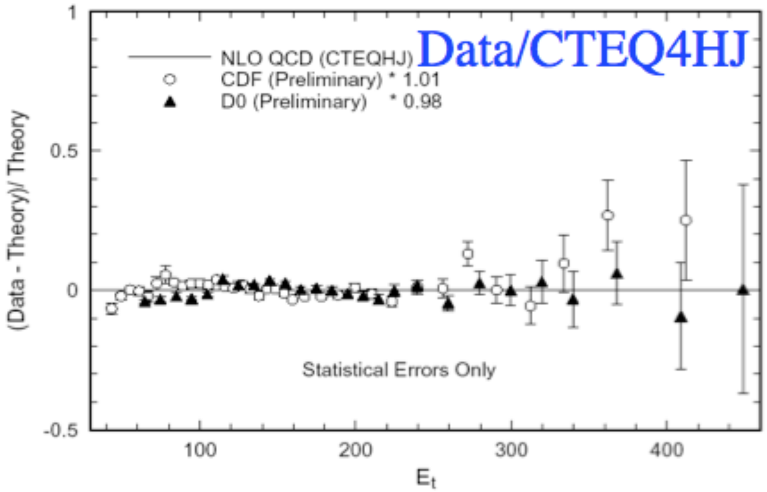
Tests perturbative QCD at highest energies

Famous story of ~1996



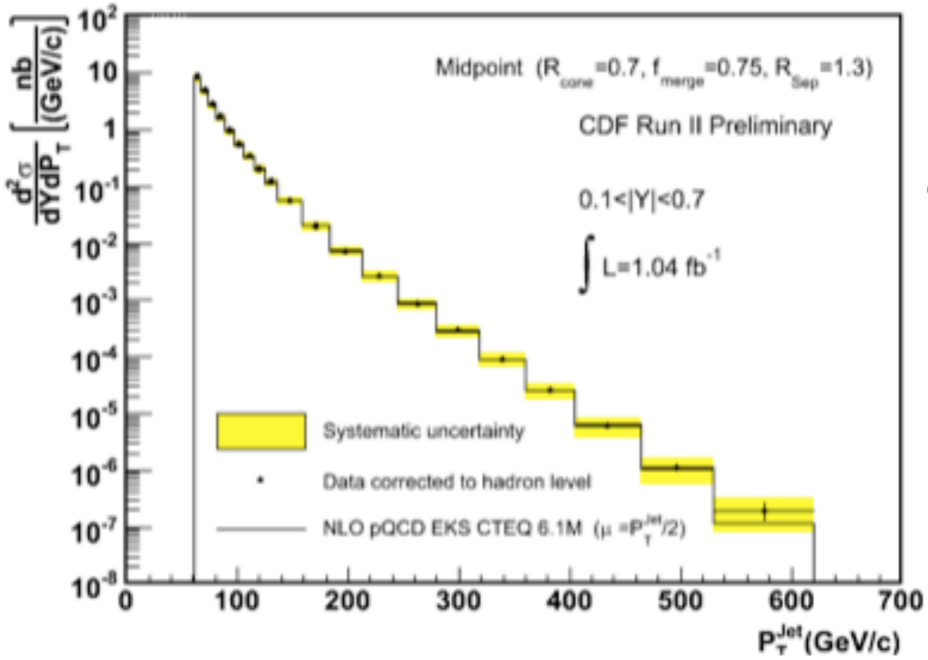
- Tevatron run1
  - Excess of events at very high E_T
  - Is this hint of quark sub-structure?
- Uncertainties in gluon pdf
  - No constraints at high-x
  - Inclusion gives good fit: signal gone!

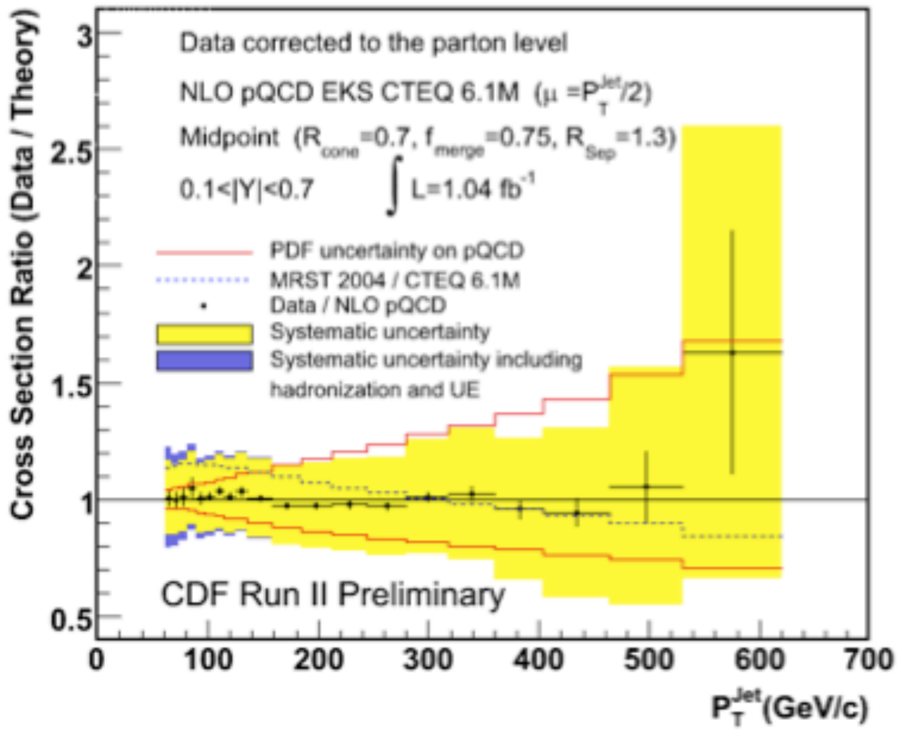




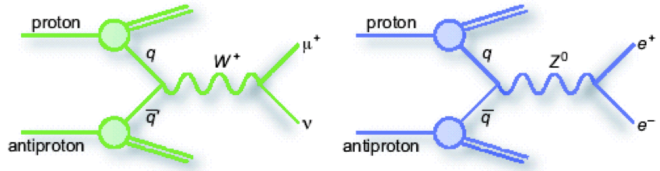
Jet physics

- Current status:
  - QCD remains valid upto 8 orders of magnitude
  - No sign of new resonances beyond QCD

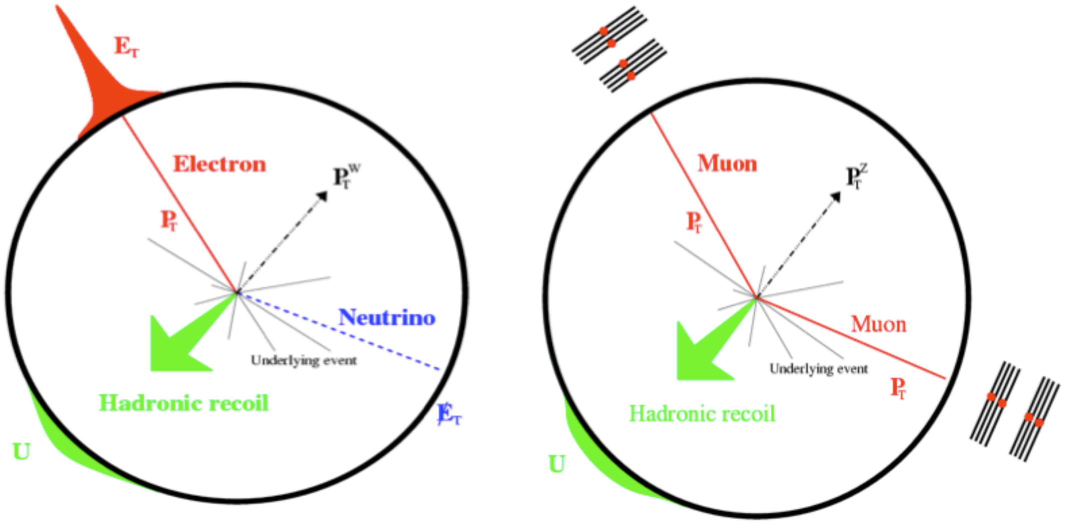




W and Z physics



- Leptonic decays
  - hadronic decays swamped by background
- Selection:
  - Z: Two leptons p_T>20 GeV
    - Electron, muon, tau
  - W: One lepton p_T>20 GeV
    - Large imbalance in transverse momentum
    - Missing E_T>20 GeV
      Signature of undetected particle (neutrino)

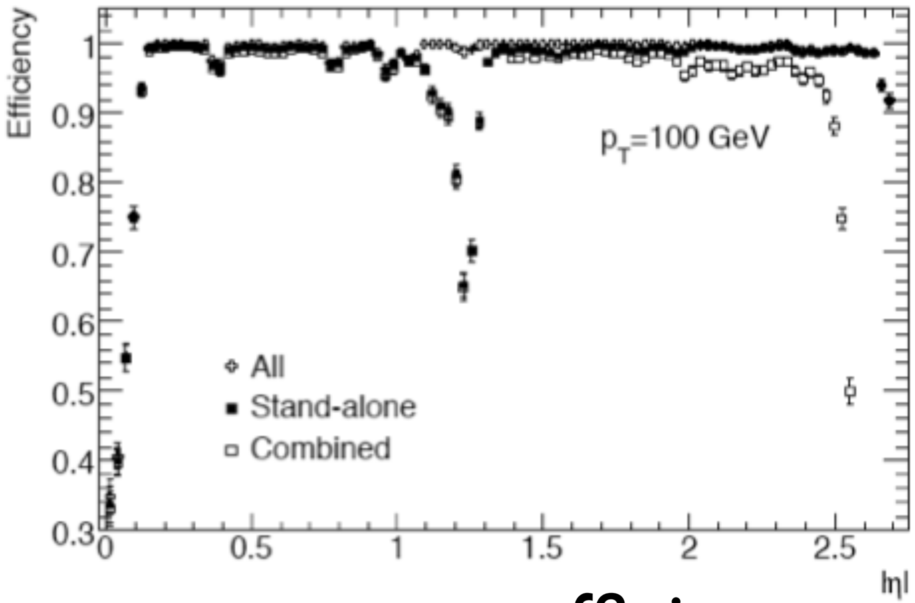


- Excellent calibration signal for many purposes:
  - Electron energy scale
  - Track momentum scale
  - Lepton ID and trigger efficiencies
  - Missing ET resolution
  - Luminosity .

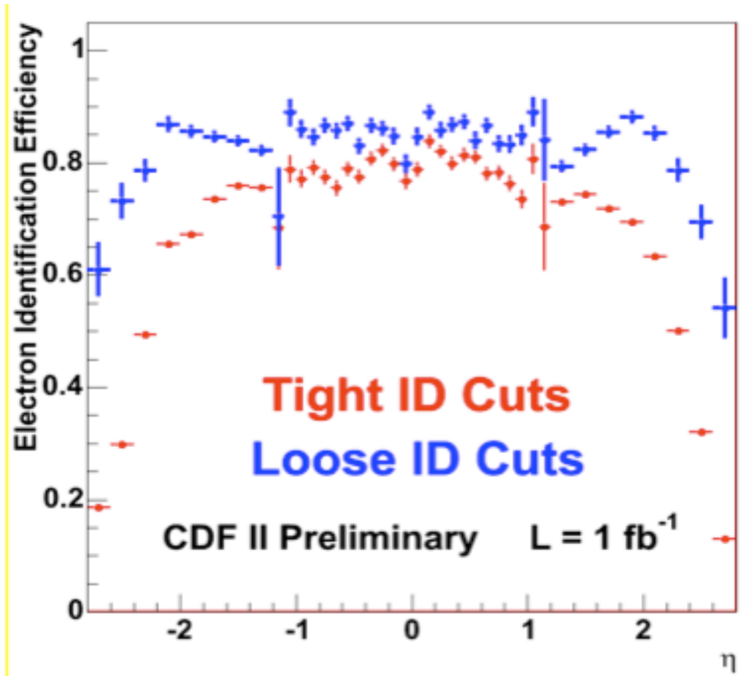
Electron and muon identification

- High efficiency for isolated electron
- Low misidentification of jets

- Performance:
  - Efficiency: 60-100% depending on |η|
  - Measured using Z's



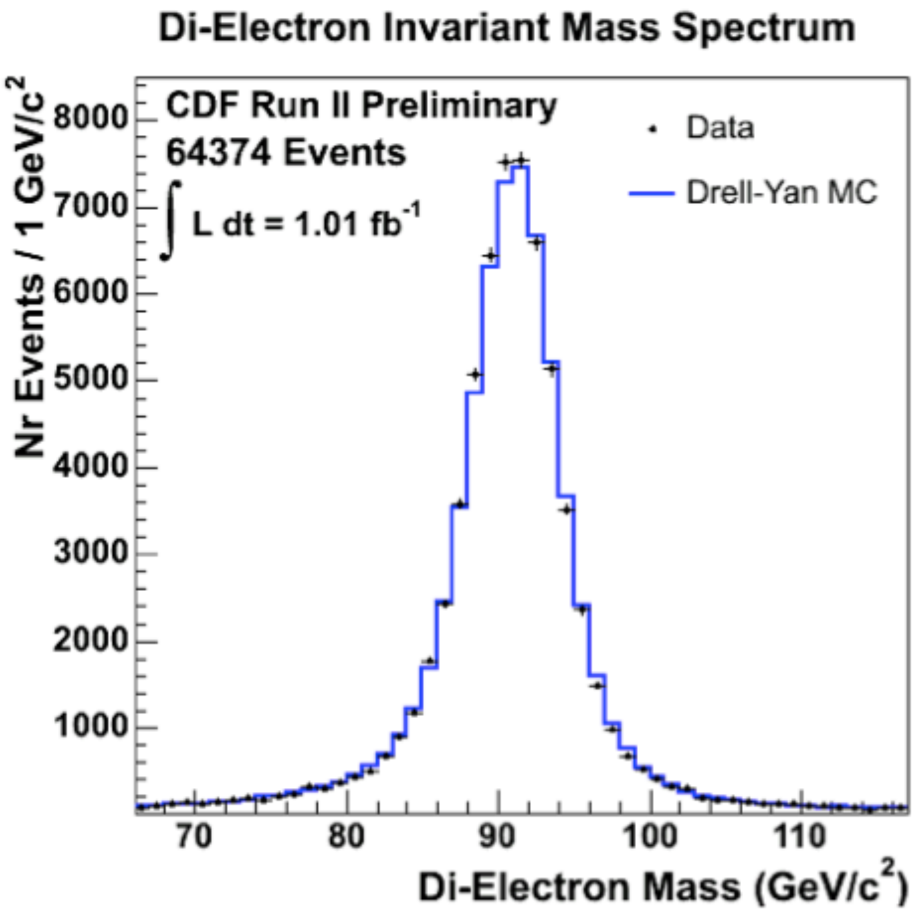
muon reco efficiency



electron reco efficiency

Z-mass reconstruction

- Z mass reconstruction
  - Invariant mass of two leptons
- The target at Tevatron is not to beat the LEP accuracy
  - Use MZ to calibrate electron energy scale by comparison to LEP measured value of MZ

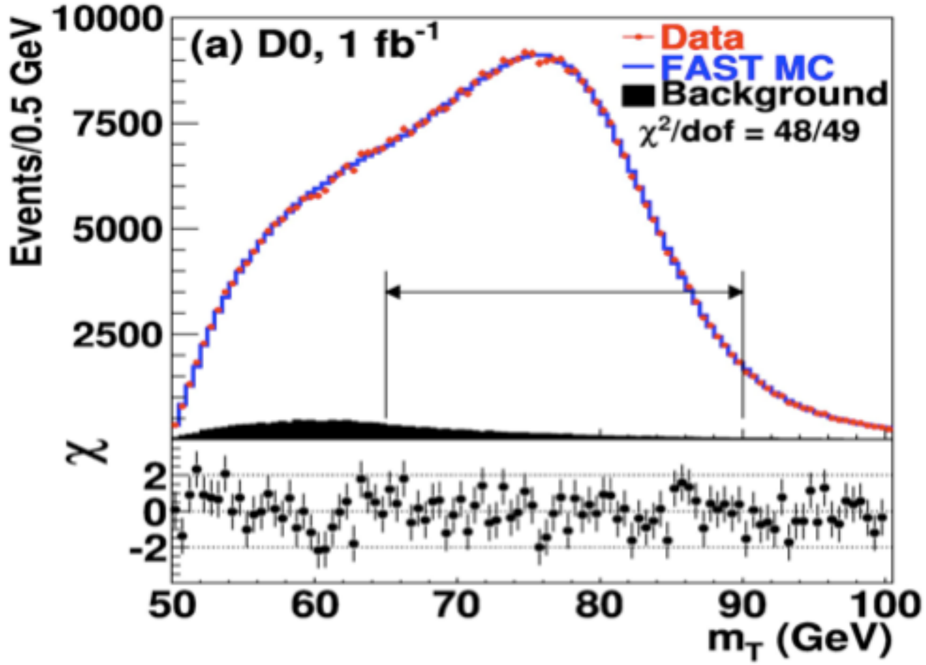


$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

W-boson mass measurement

- Requirements:
  - Precise EM calorimeter calibration with Z events
  - Detailed model of recoiling particle production and detector response
- E.g. W→eν mode in 1 fb^{-1}
  - 499,830 W's

$$m_T = \sqrt{|p_T^l|^2 + |p_T^\nu|^2 - (\vec{p}_T^l + \vec{p}_T^\nu)^2}$$



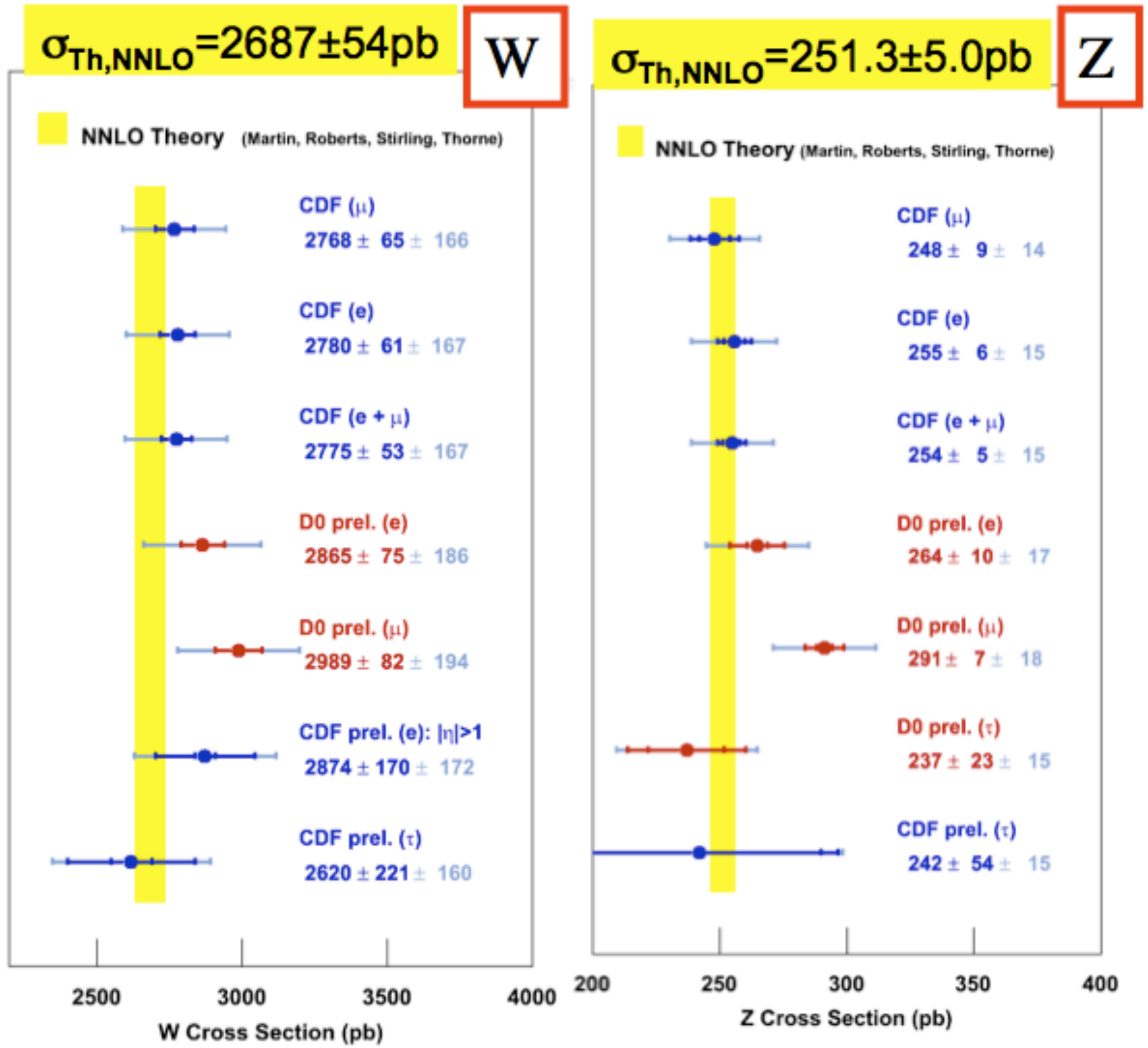
- M_W = 80.401± 0.021(stat) ± 0.038(syst) GeV

- Analysis in p_T , E_T^{miss} and m_T
  - Systematics: for m_T method 34 MeV for electron calibration out of 37 MeV total
  - Uncorrelated...combination

This morning new combined D0&CDF paper on MW: better than LEP

W and Z cross sections

- Uncertainties:
  - Experimental: 2%
  - Theoretical: 2%
  - Luminosity: 6%
- Can we use these processes to normalize luminosity?
  - Is theory reliable enough?



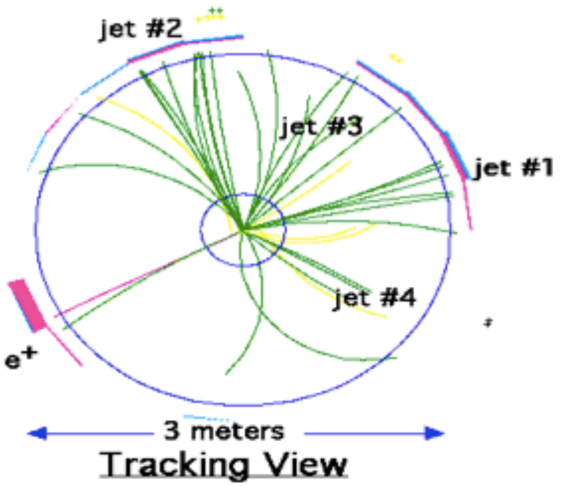
1995: discovery of the top-quark

Physicists Discover Top Quark

News Release - March 2, 1995

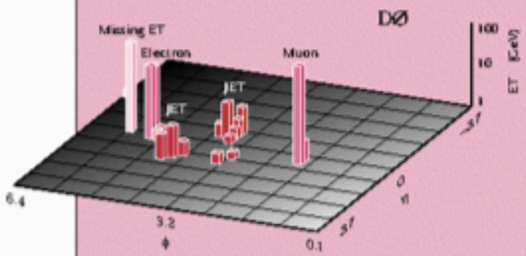
PHYSICISTS DISCOVER TOP QUARK

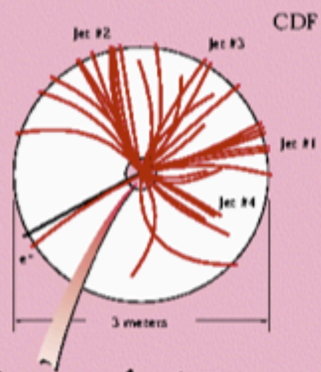
Batavia, IL--Physicists at the Department of Energy's Fermi Natic
subatomic particle called the top quark, the last undiscovered qua
sought the top quark since the discovery of the bottom quark at Fe
of the structure of matter.

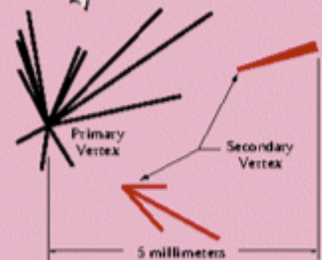


CDF AND DØ RESULTS

THE RESULTS FROM THE TWO COLLABORATIONS were remarkably similar. CDF found 6 dilepton events with a background of 1.3; 21 single-lepton events in which 27 cases of a *b* quark tag by the vertex detector (with 6.7 background tags expected); and 22 single-lepton events with 23 cases of a *b* tag through leptonic decay (with 15.4 background tags expected). DØ found 3 dilepton events (0.65 background events); 8 single-lepton events with topological tagging (1.9 background events); and 6 single-lepton events with *b*-to-lepton tags (1.2 background events). A particularly striking example of a dilepton event with very energetic electron, muon, and missing E_T (due to the neutrinos), plus two jets, is shown below from the DØ data. The plot shows the detector unfolded on to a plane, with the energy of the various objects indicated by the height of the bars. This event has a very low probability to be explained by any known background. The probability that background fluctuations could explain the observed signal was one-in-a-million for CDF and two-in-a-million for DØ—sufficiently solid that each experiment was able to claim the observation of the top independently.



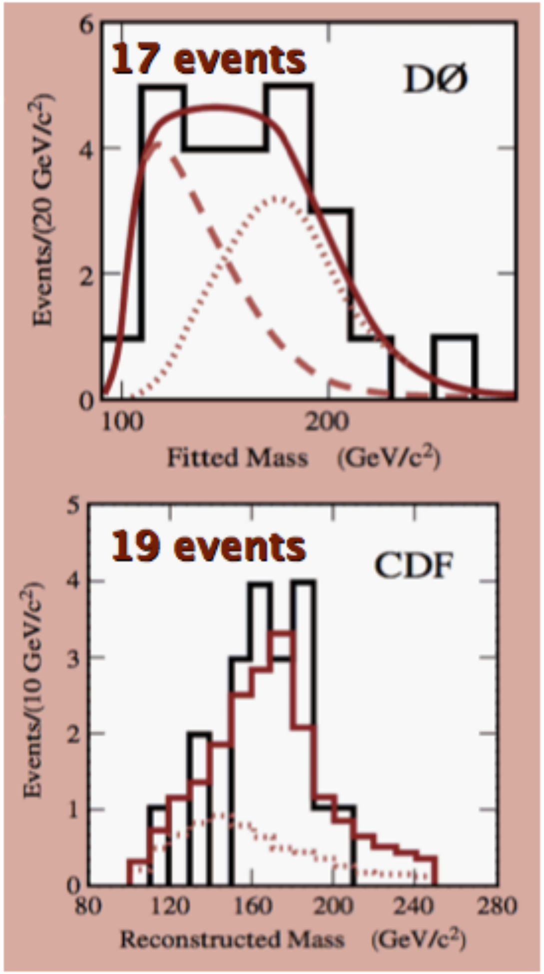




Additional studies helped to establish that the new signal

by the need to identify the correct combination of jets with parent quarks in the decay and to accommodate the tendency of the strong interaction to generate additional jets. The two experiments obtained consistent results for this

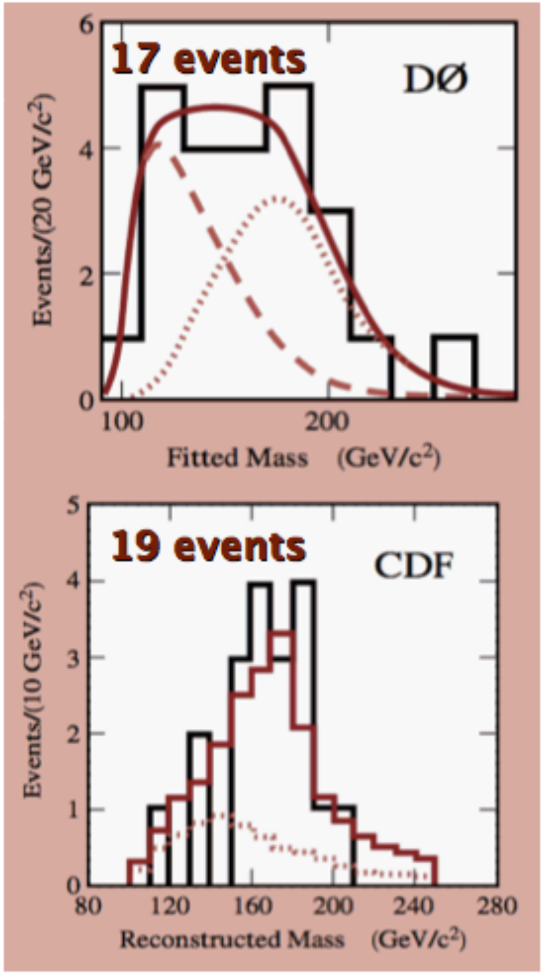
Top-quark discovery



1995, CDF and DØ experiments, Fermilab

- discovery in 1995 by CDF and D0

Top-quark discovery

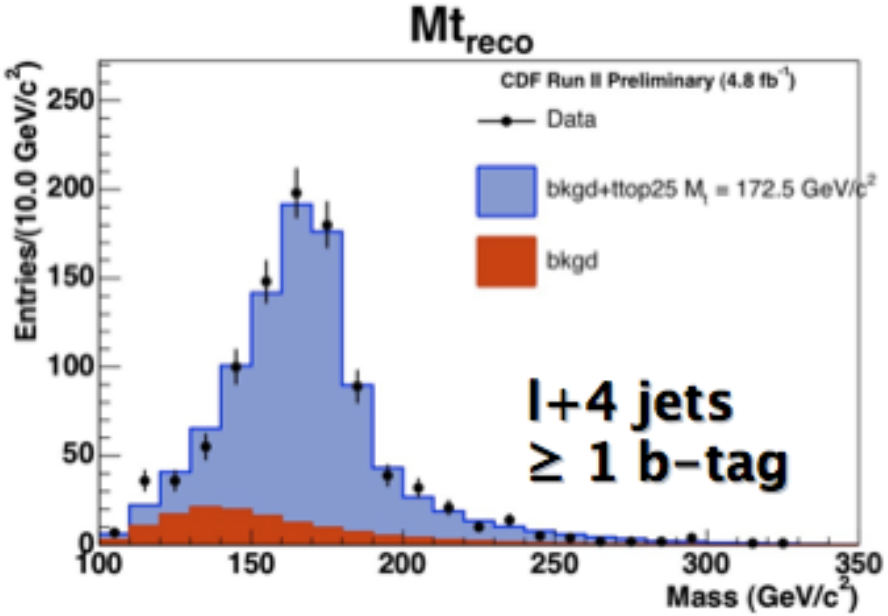


1995, CDF and DØ experiments, Fermilab

- discovery in 1995 by CDF and D0

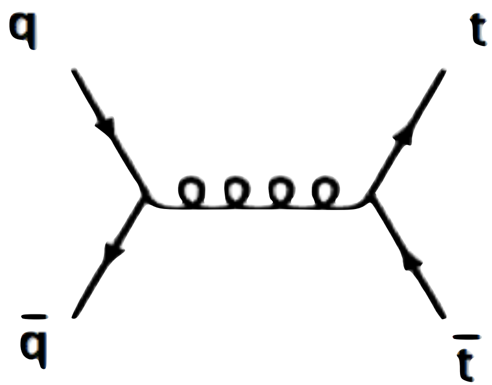
Today:

~1000 events

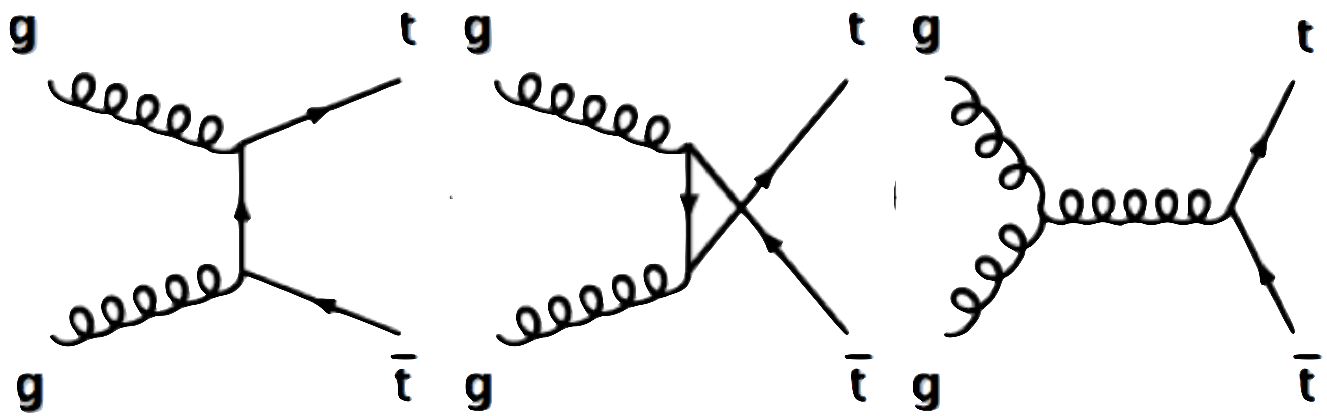


Top production

- Dominated at Tevatron by quark annihilation



85%

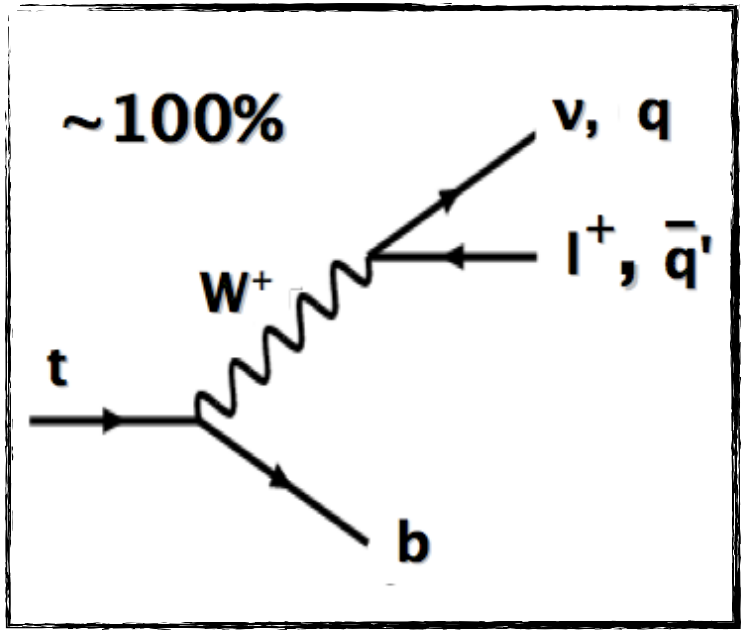


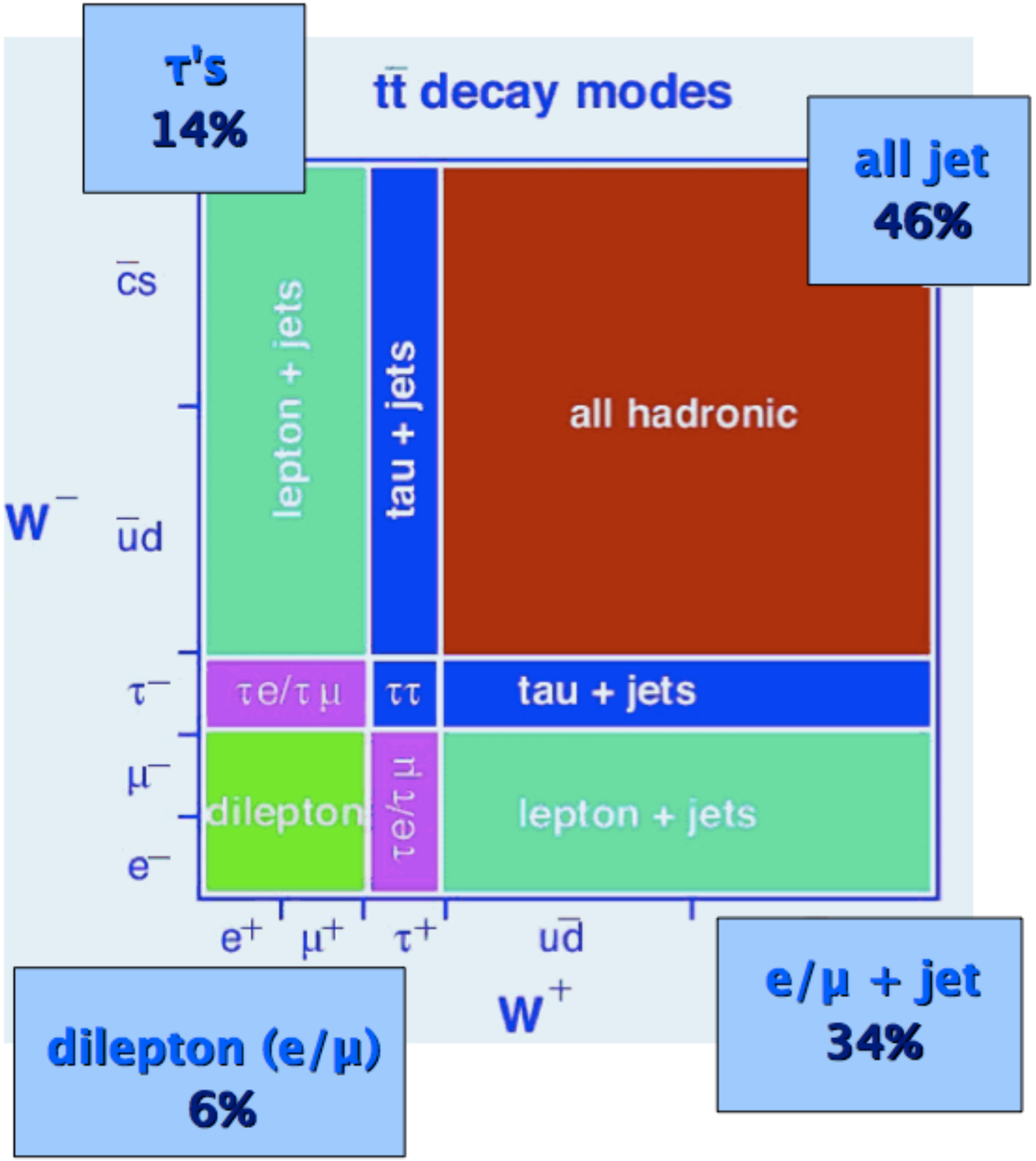
15%

$\sigma_{t\bar{t}} = 7.46^{+0.48}_{-0.67}$ pb in NNLO$_{approx}$
(m_{top} = 172.5 GeV)

Top-quark decay

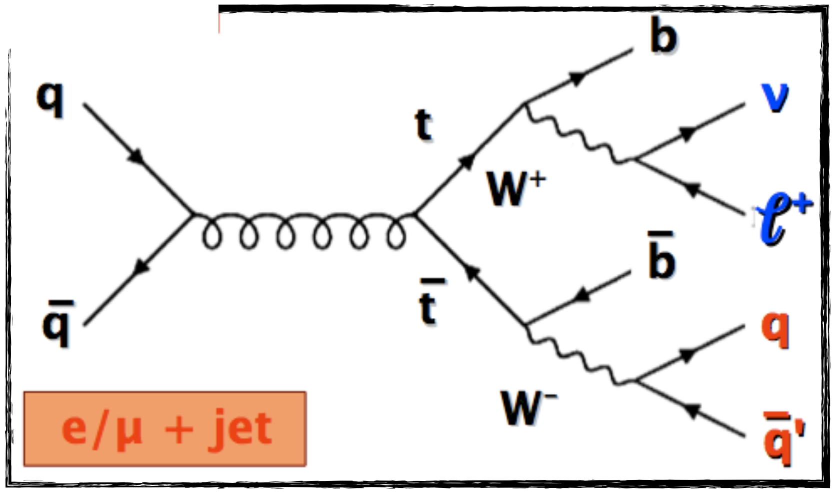
- Top-quark decay:
  - full 100% to b-quark plus W-boson
  - Decay of W-boson determined signature
    - lepton+neutrino
    - quarks



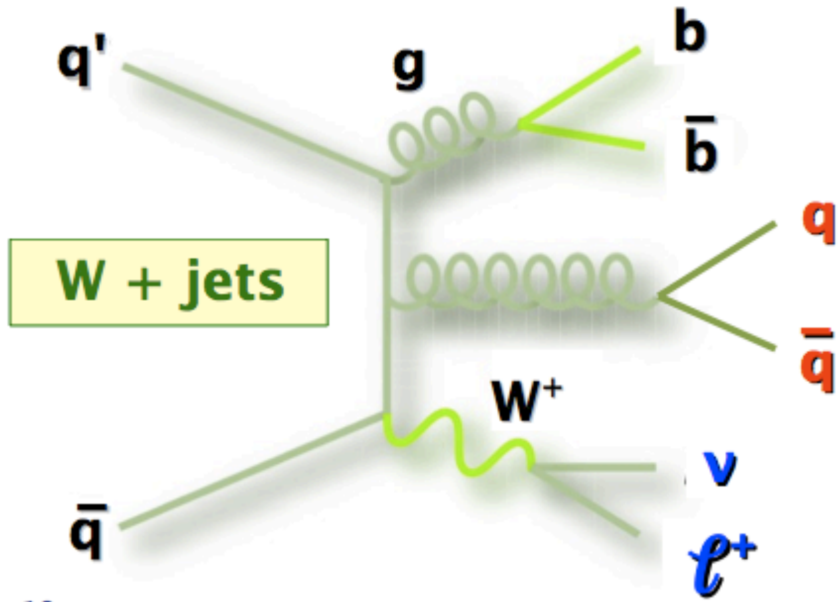


Lepton+jets: signal + background

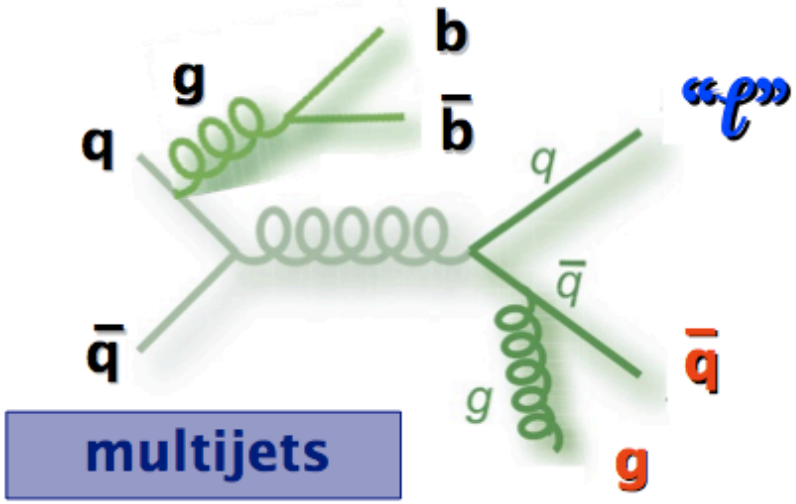
- Signal with electron or muon:
  - Easy trigger
- background
  - W+jets
  - multijet-events



3000 times higher rate



10^{10} times higher rate

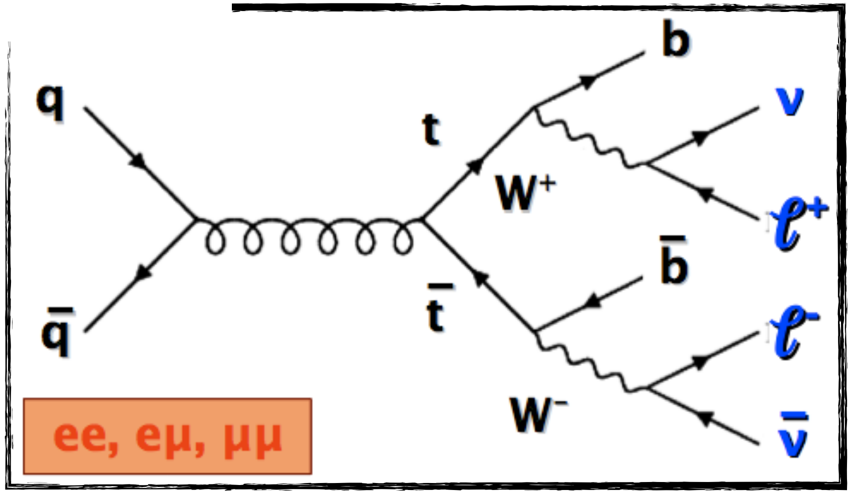


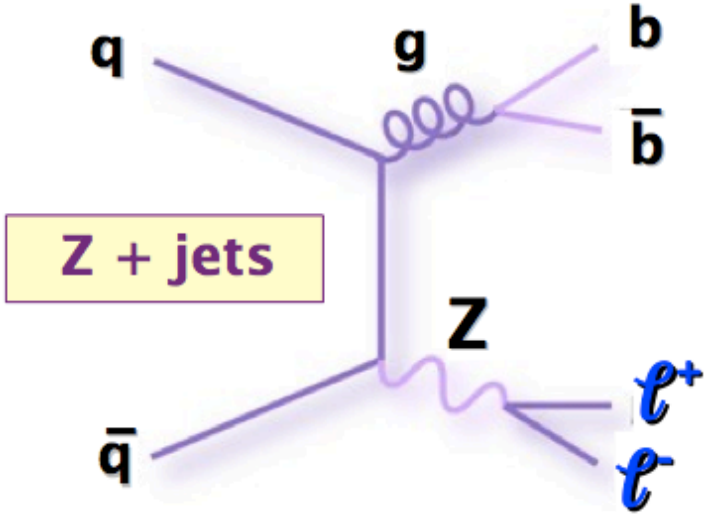
Di-lepton signatures: signal and bkgnd

- Signal with 2 leptons
  - 2 leptons, with 2 neutrino's
  -

background

300 times higher rate

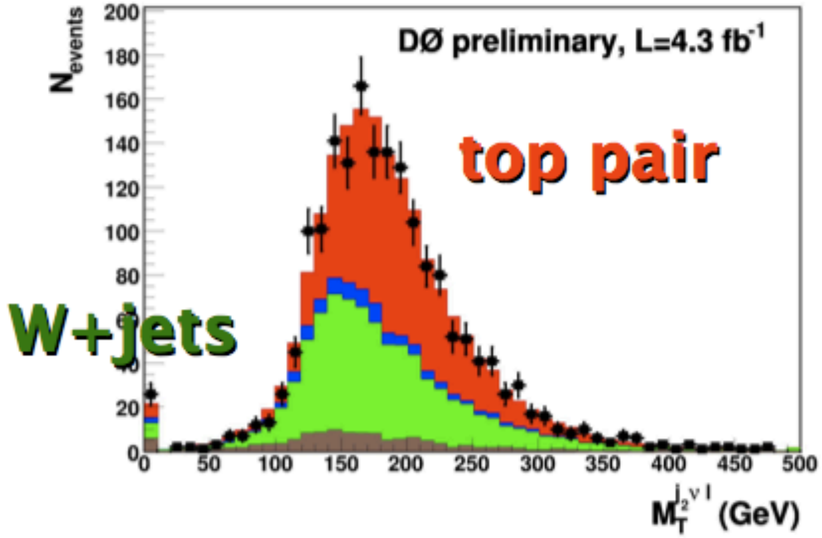


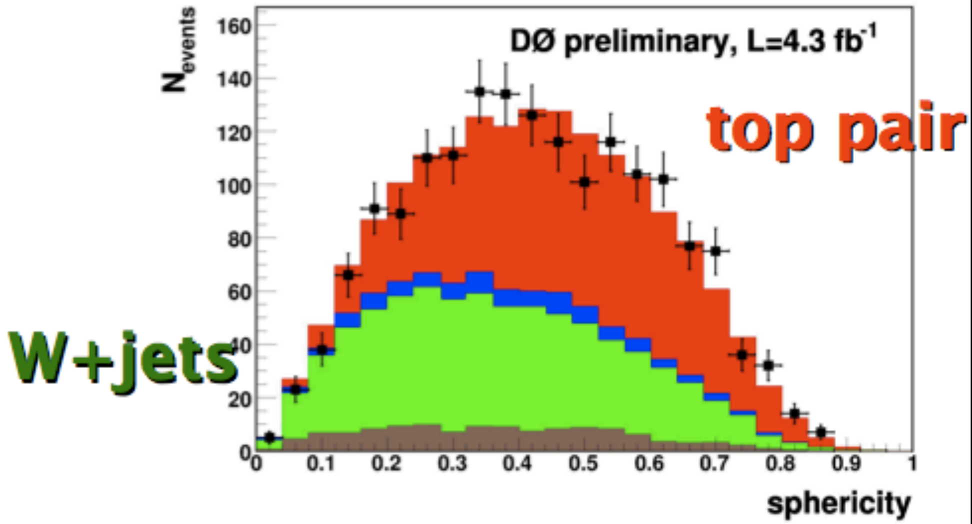


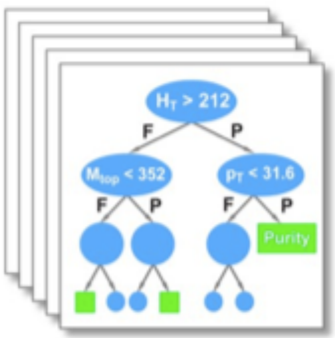
- less statistics
- less background

Top-quark cross section

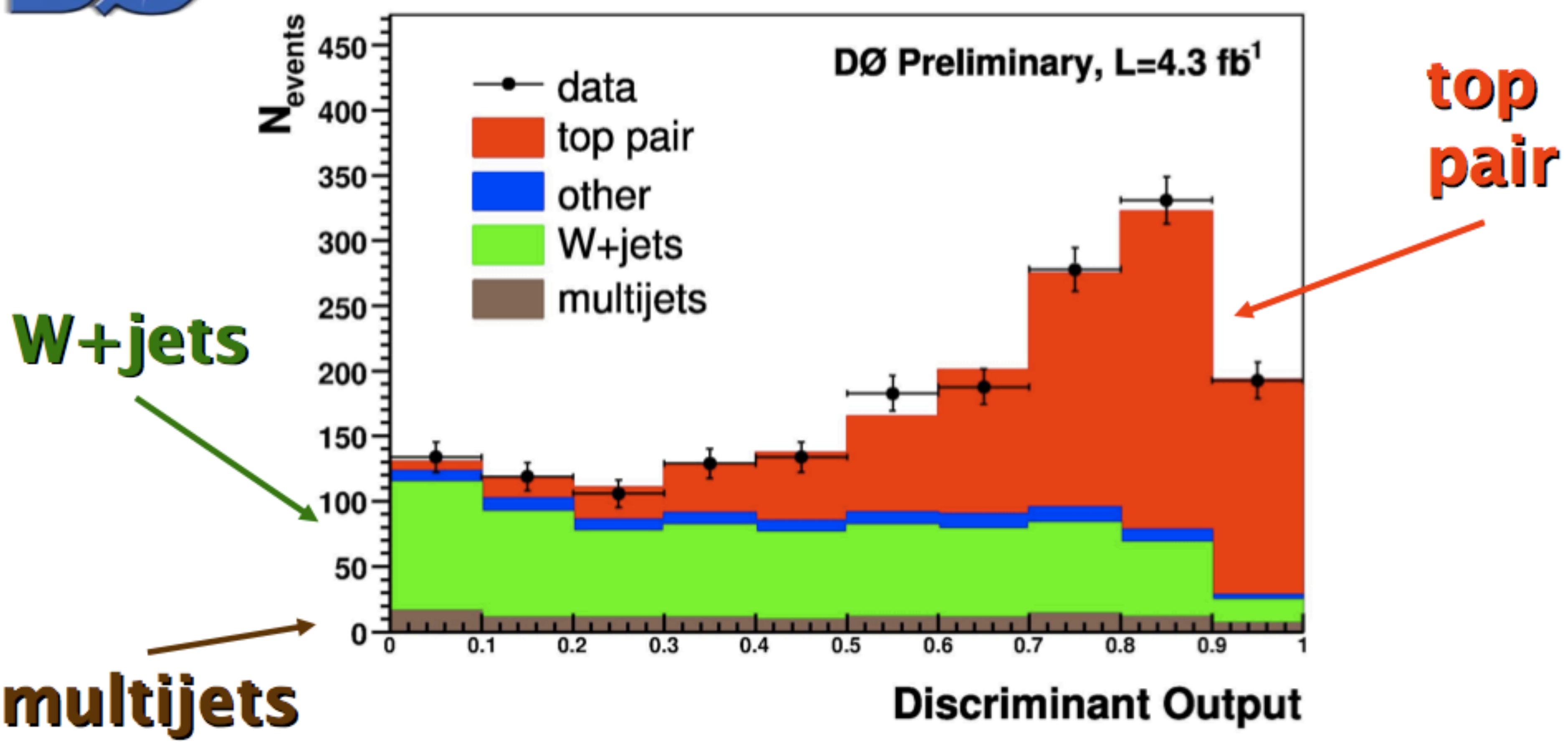
- Measure production rate
  - is as predicted by NLO QCD?
- kinematic properties
  - allow separation between signal and background
  - use energy-dependent quantities:
    - e.g. Transverse mass of leptonic
    - e.g. sphericity e.g. sphericity
- Boosted Decision Trees







Determination cross section

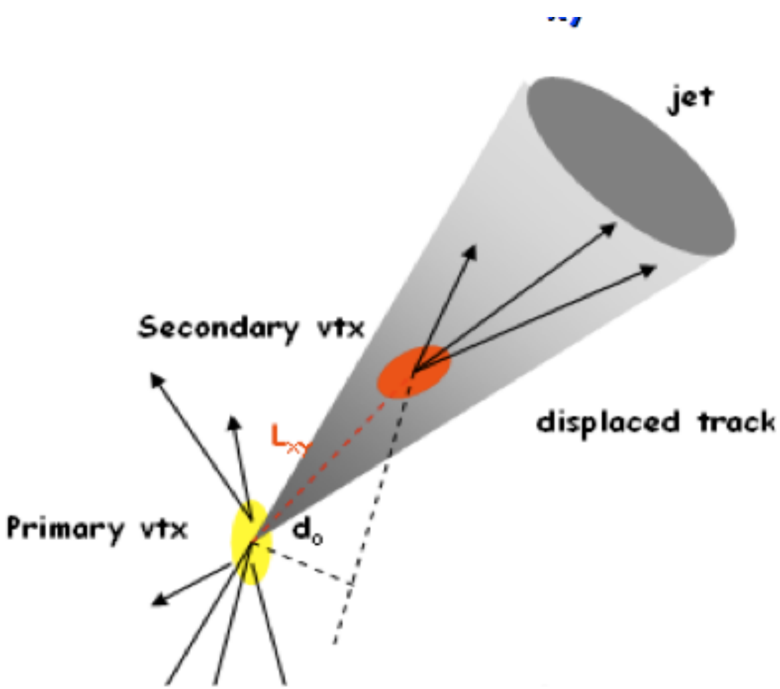


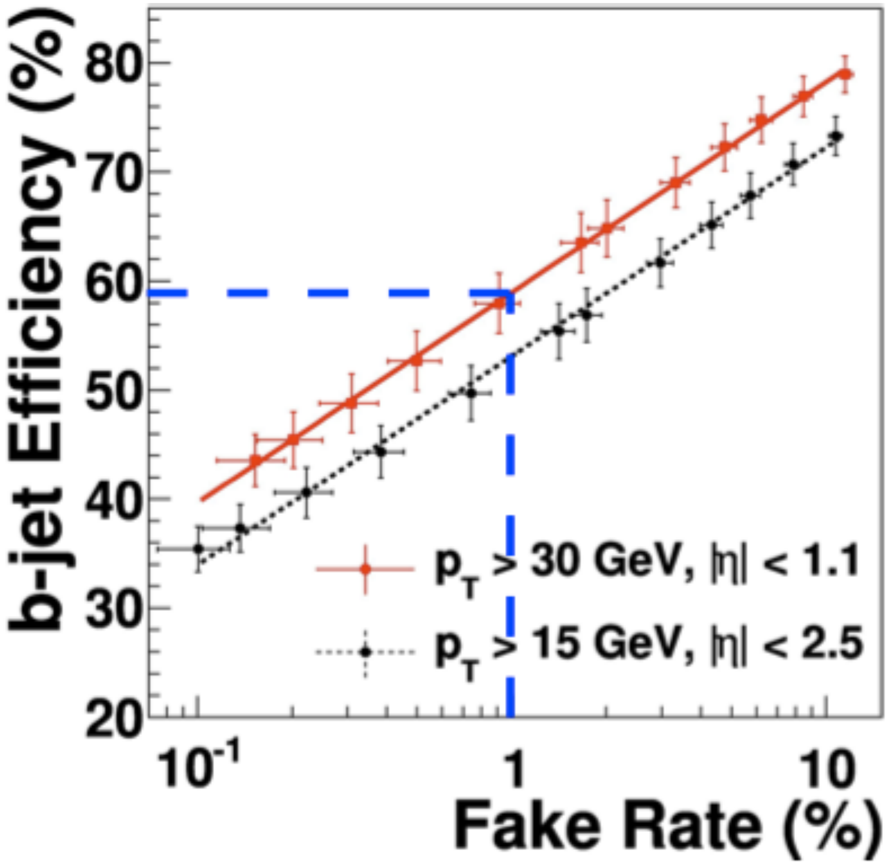
m_{top} = 172.5 GeV

$$\sigma_{t\bar{t}} = 7.70^{+0.70}_{-0.79} \text{ (stat+syst+lumi) pb}$$

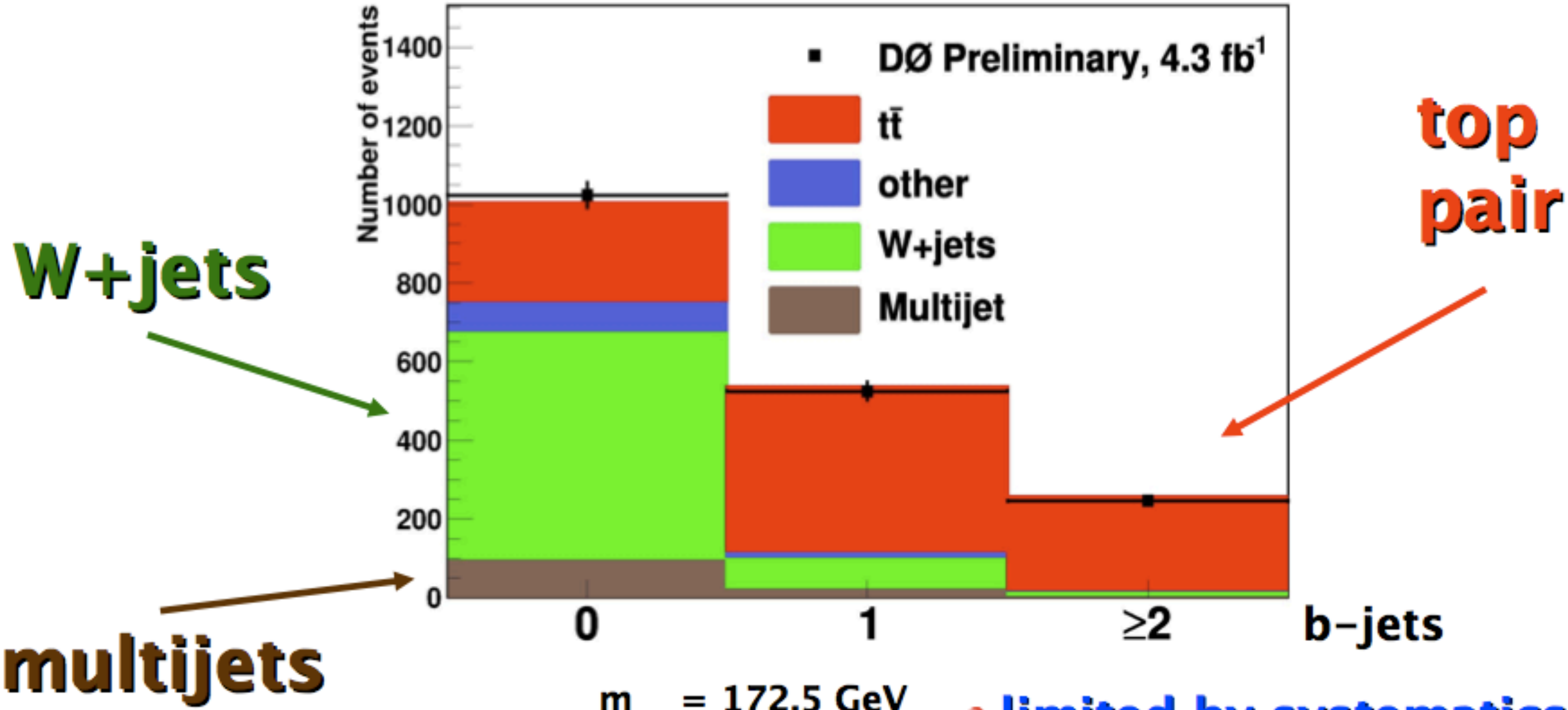
b-tagging

- B hadron lifetime τ ~ 1 ps
  - B hadrons travel L_{xy} ~ 3 mm before decay
  - Secondary vertex tagger 50-60% b-jet tagging efficiency
    - with fake rate of 1%





top-quarks with b-tagging



m_{top} = 172.5 GeV

$$\sigma_{t\bar{t}} = 7.93^{+1.04}_{-0.91} \text{ (stat+syst+lumi) pb}$$

- limited by systematics
- luminosity dominates at ~6%
- b-tagging second largest

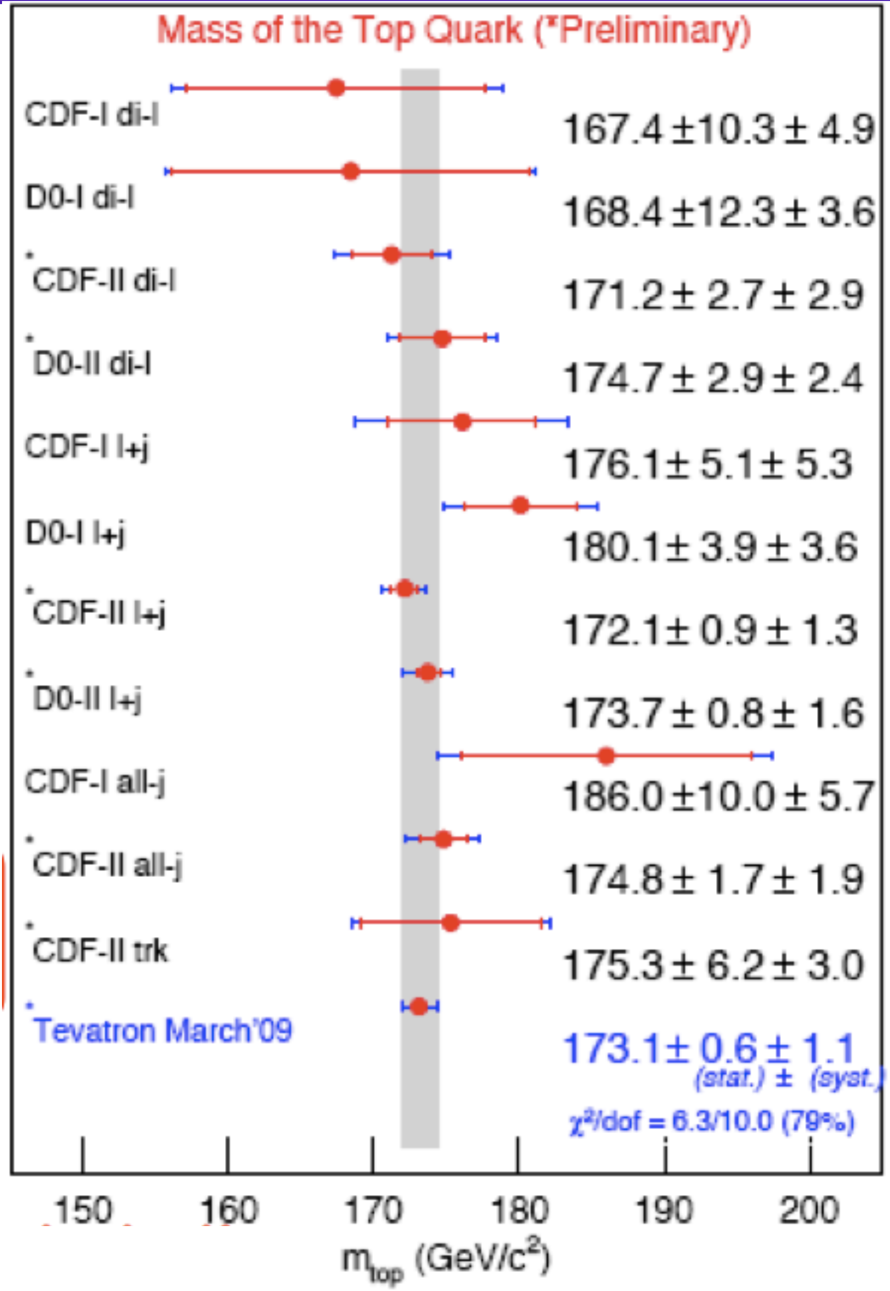
Mass of the top-quark

- Many advanced method being exercised
  - Lepton + jets dominate the world average
    - matrix methods
    - template methods
  - All methods consistent

$$M_t = 173.1 \pm 0.6\ (\text{stat.}) \pm 1.1\ (\text{syst.})\ \text{GeV}/c^2$$
$$M_t = 173.1 \pm 1.3\ \text{GeV}/c^2$$

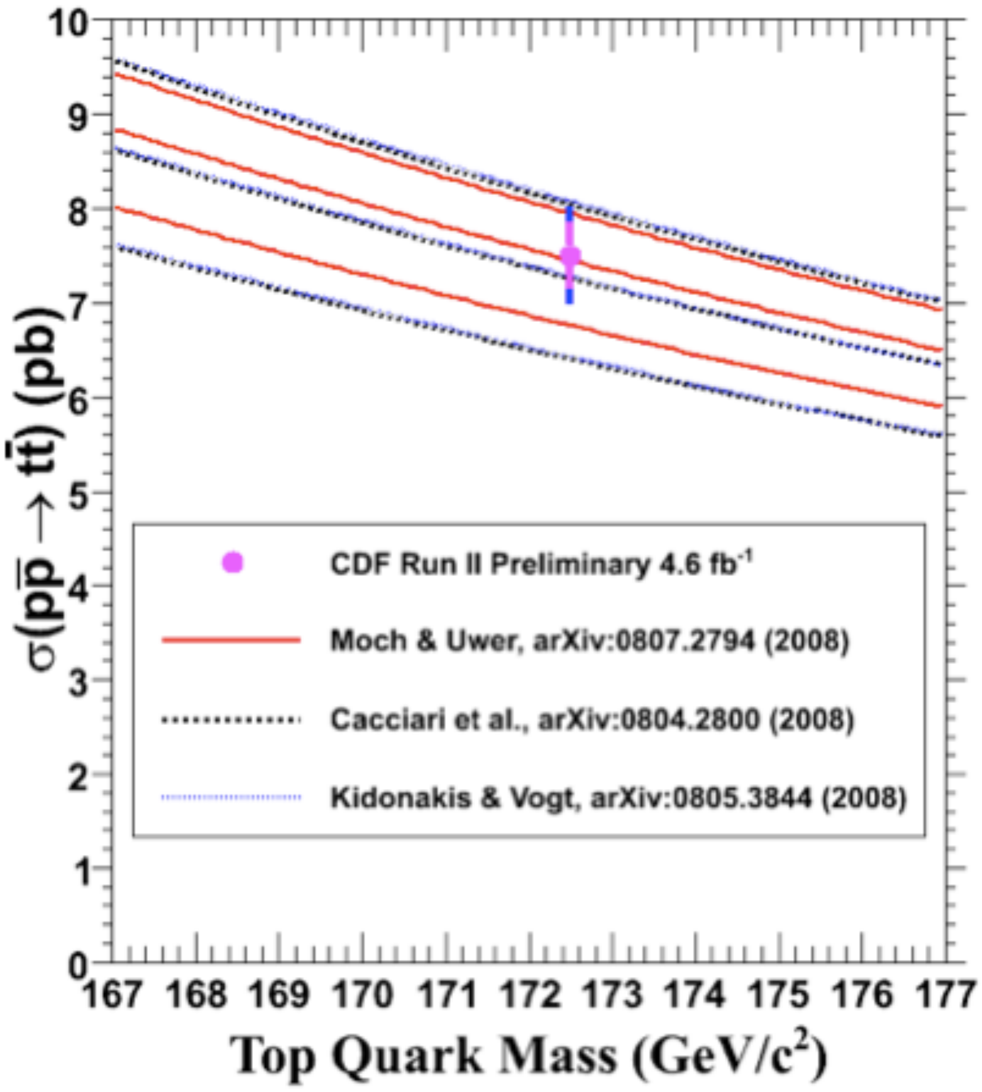
  - Top mass known to 0.75% precision
  - Approaching 1 GeV!

Hard to beat for LHC!

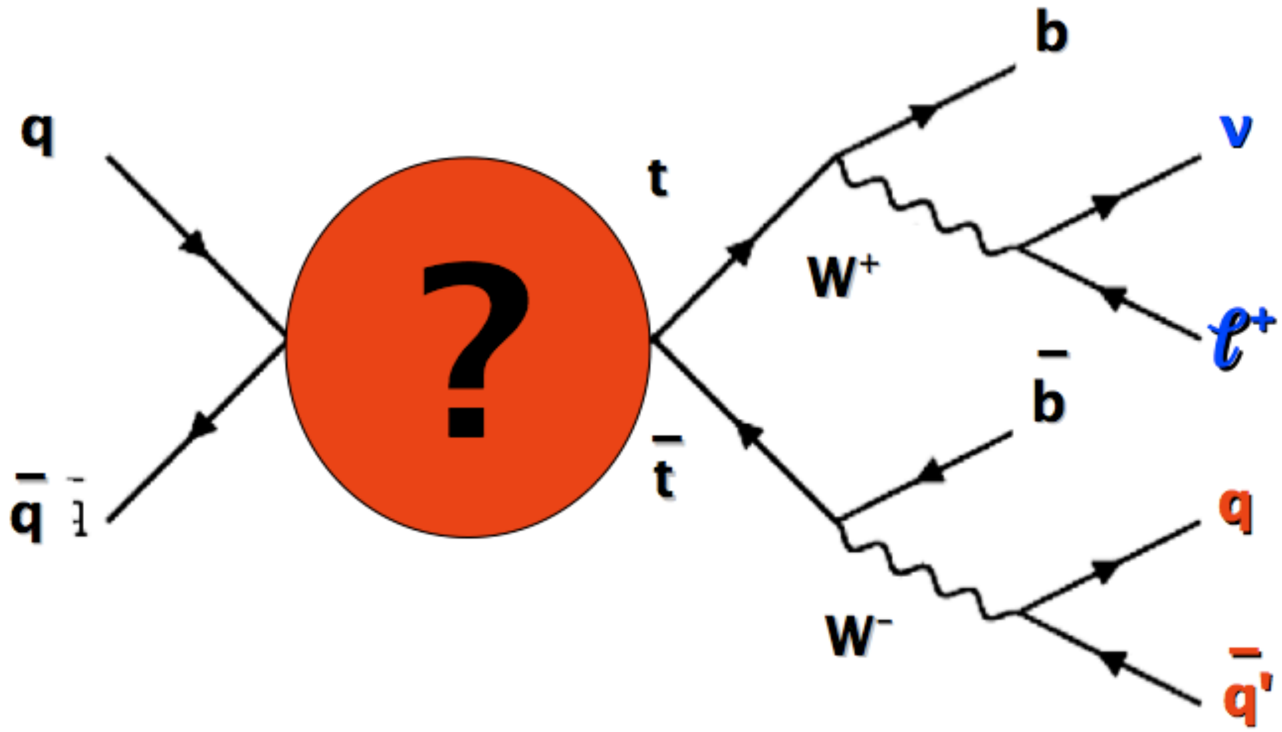


Precision M_{top} and σ(tt)

- Compare measured mass and cross section
  - Related via cross section calculations with Mtop as input
  - State of the art in NNLO calculations
  - Uncertainty bands due to unknown higher orders in theory (beyond NNLO) comparable to experimental uncertainties
    - Renormalisation scale dependence
    - Progress in theory needed!

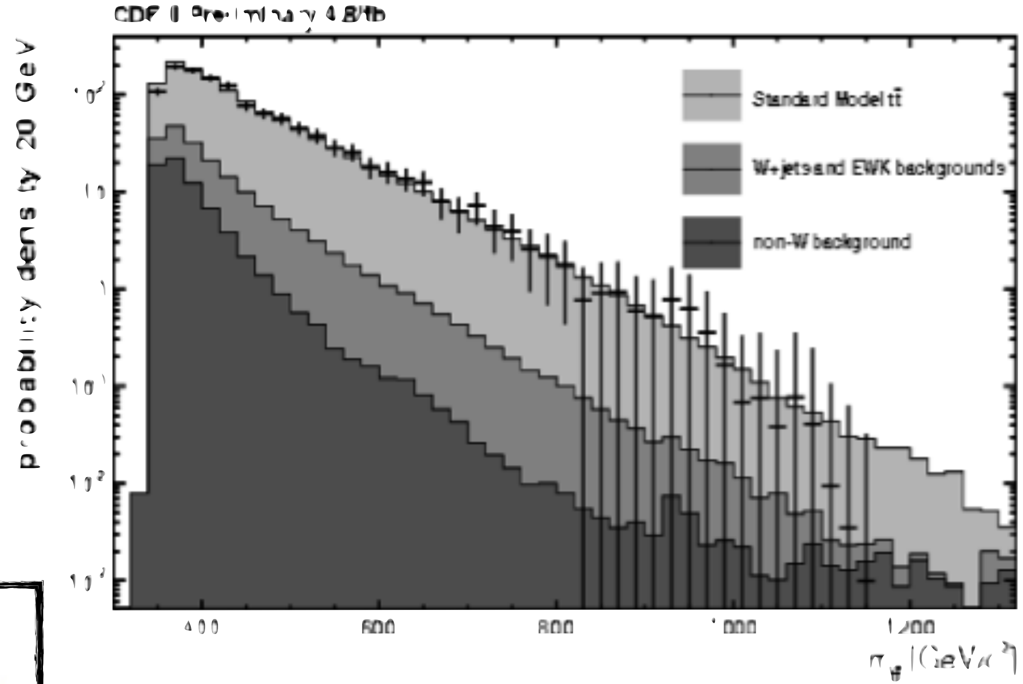


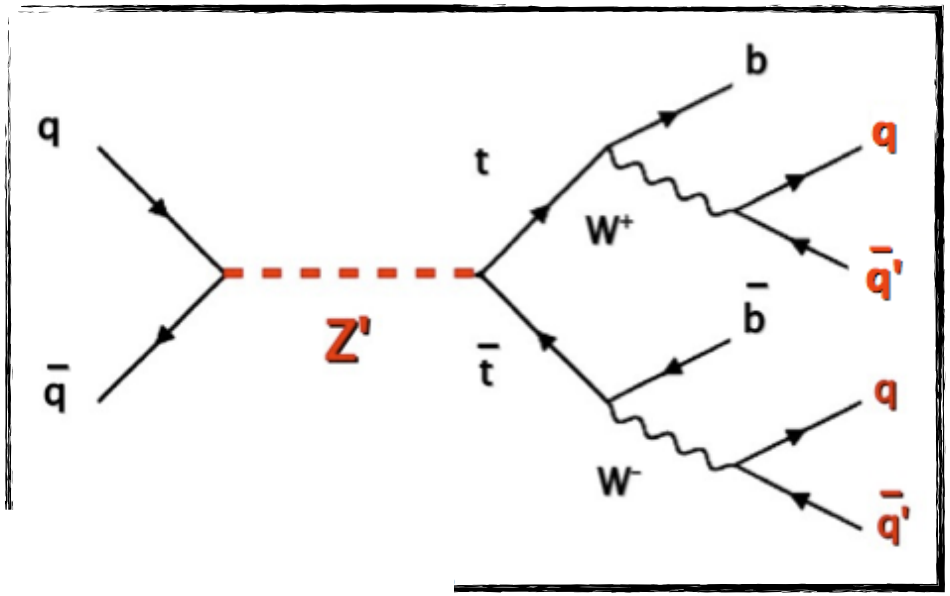
Search for new physics in top



Search for new physics

- no resonance production in tt system is expected
  - some models predict tt bound states: e.g. leptophobic Z' with strong 3 generation coupling





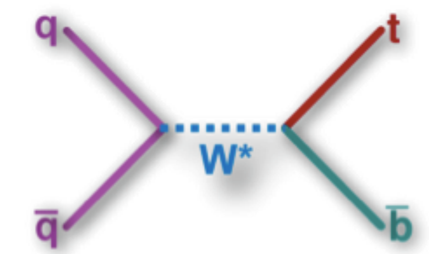
Search for bumps in tt reconstructed mass spectrum:

$M_{Z'} > 800\text{-}900$ GeV

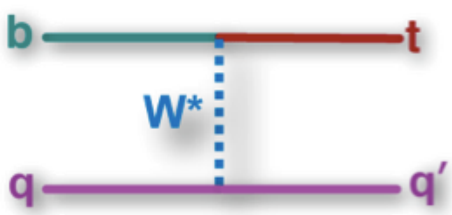
Single top production

- Electroweak production of top quarks
  - probe on CKM matrix element V_{tb}

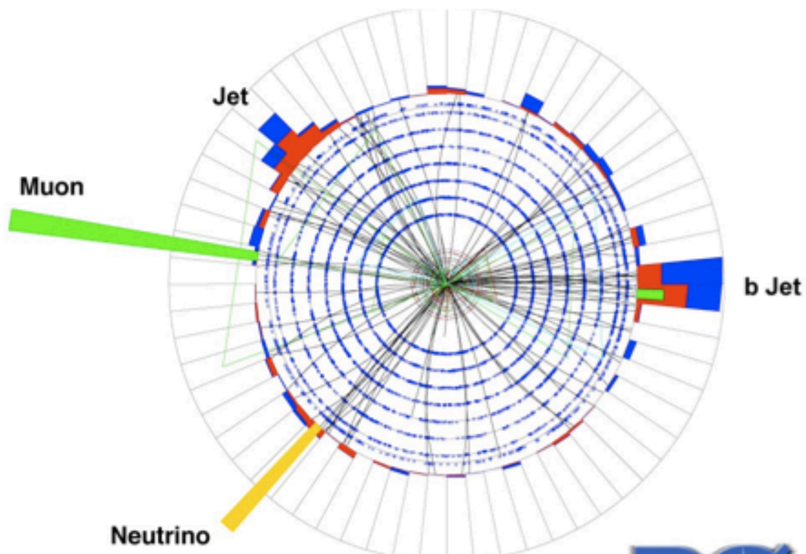
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



s-channel ~1 pb



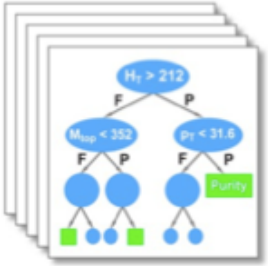
t-channel ~2 pb



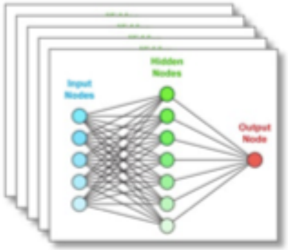
- Experimental challenge
  - Single top backgrounds very large:
  - Only 0.5 out of 10^{10} events contains a single top

Multivariate analyses

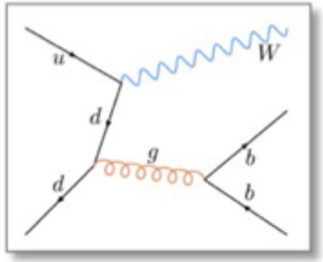
Boosted Decision Trees



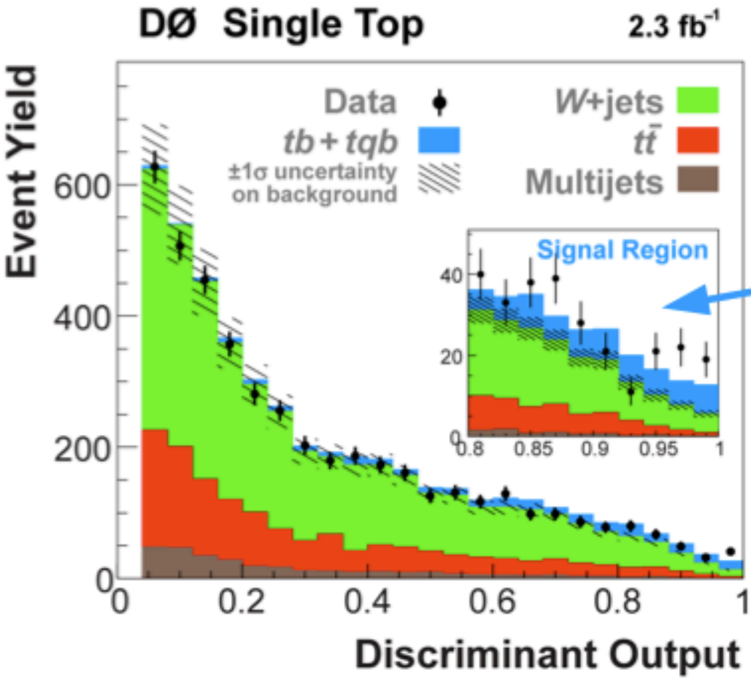
Boosted Neural Networks

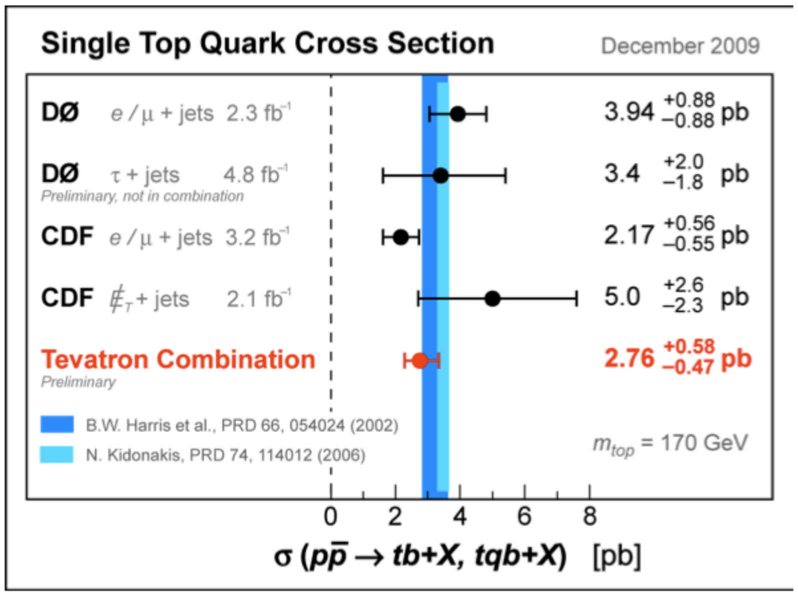


Matrix Elements



- Small but convincing signal

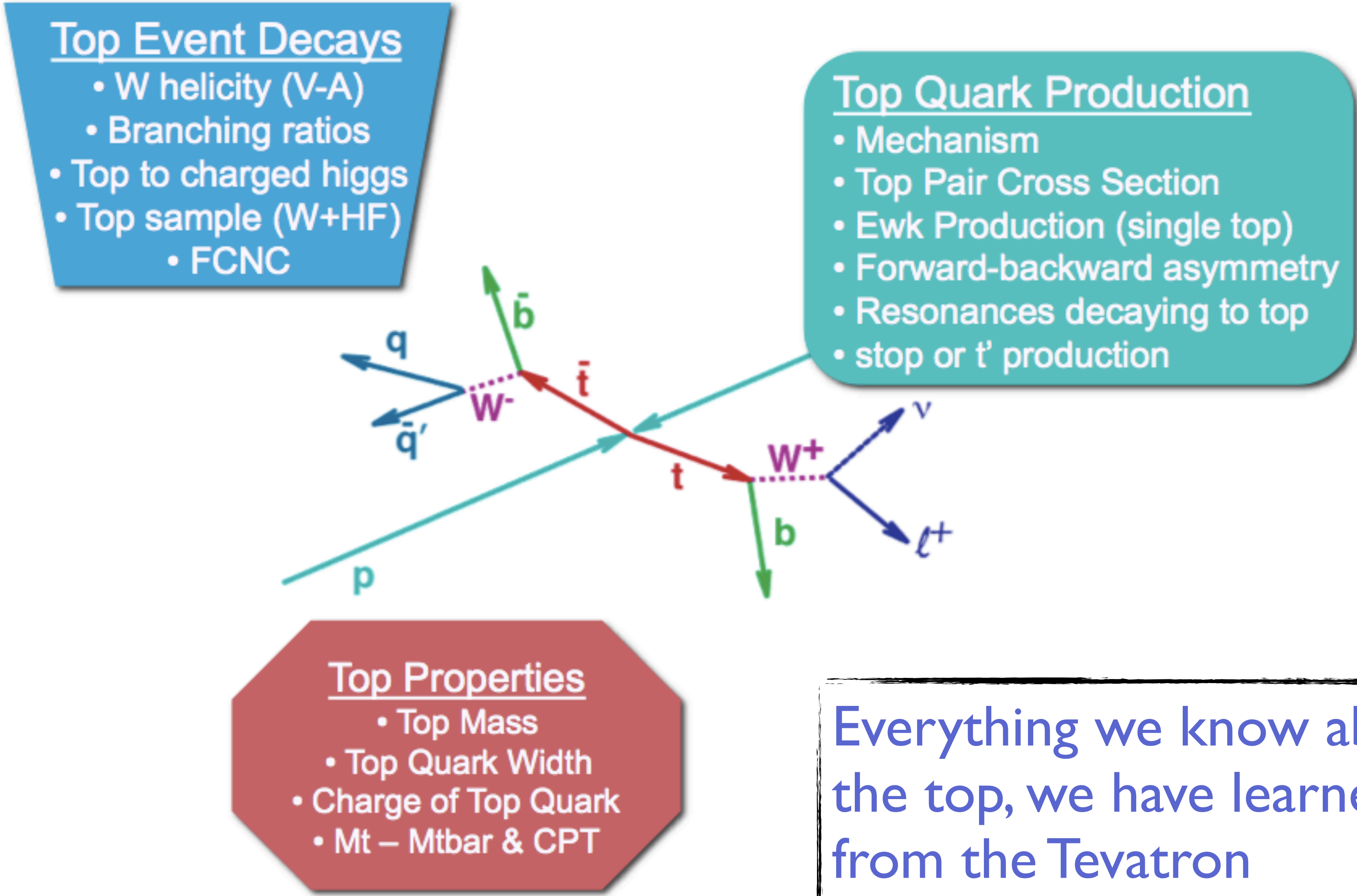




$|V_{tb}| = 0.88 \pm 0.07$

arXiv:0908.2171 [hep-ex]

Lessons of the top quark

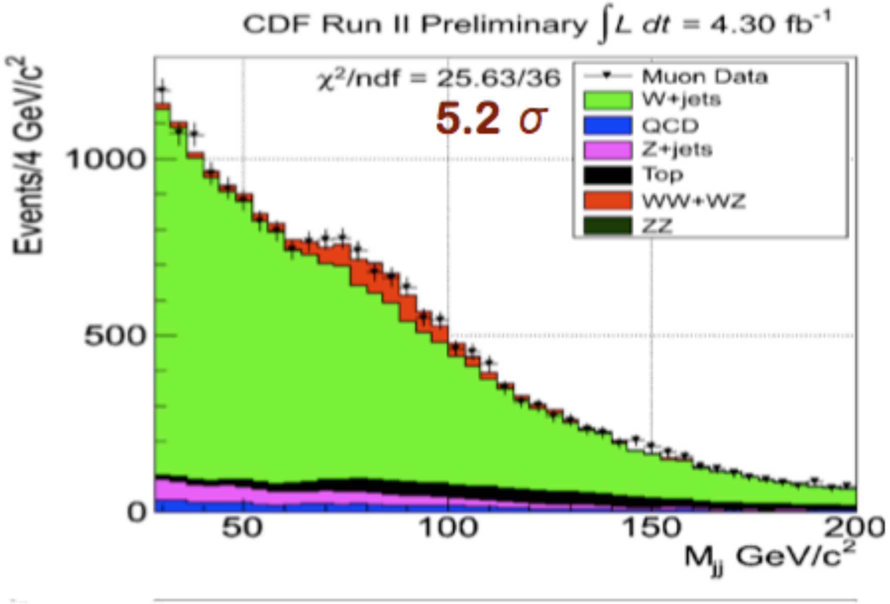


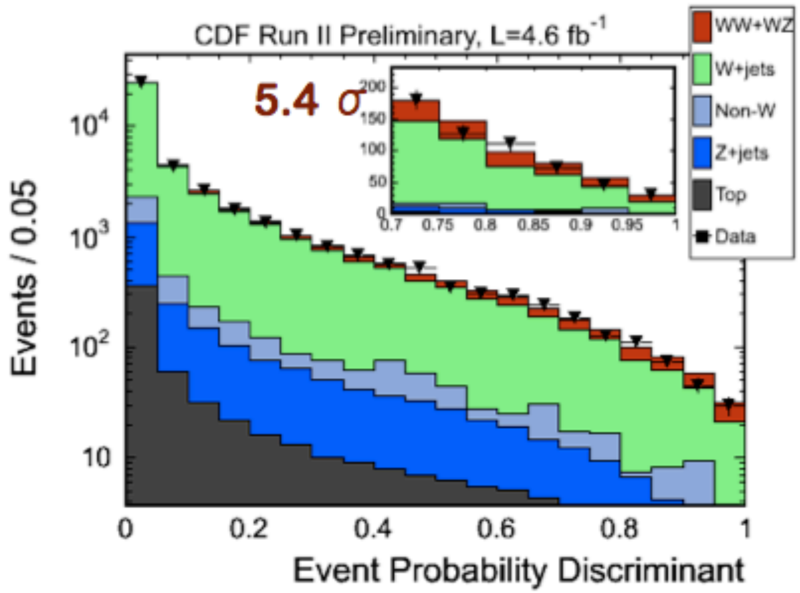
Everything we know about the top, we have learned from the Tevatron

Tevatron’s top its raison d’etre

Last step before Higgs:

- WW and WZ di-boson final states





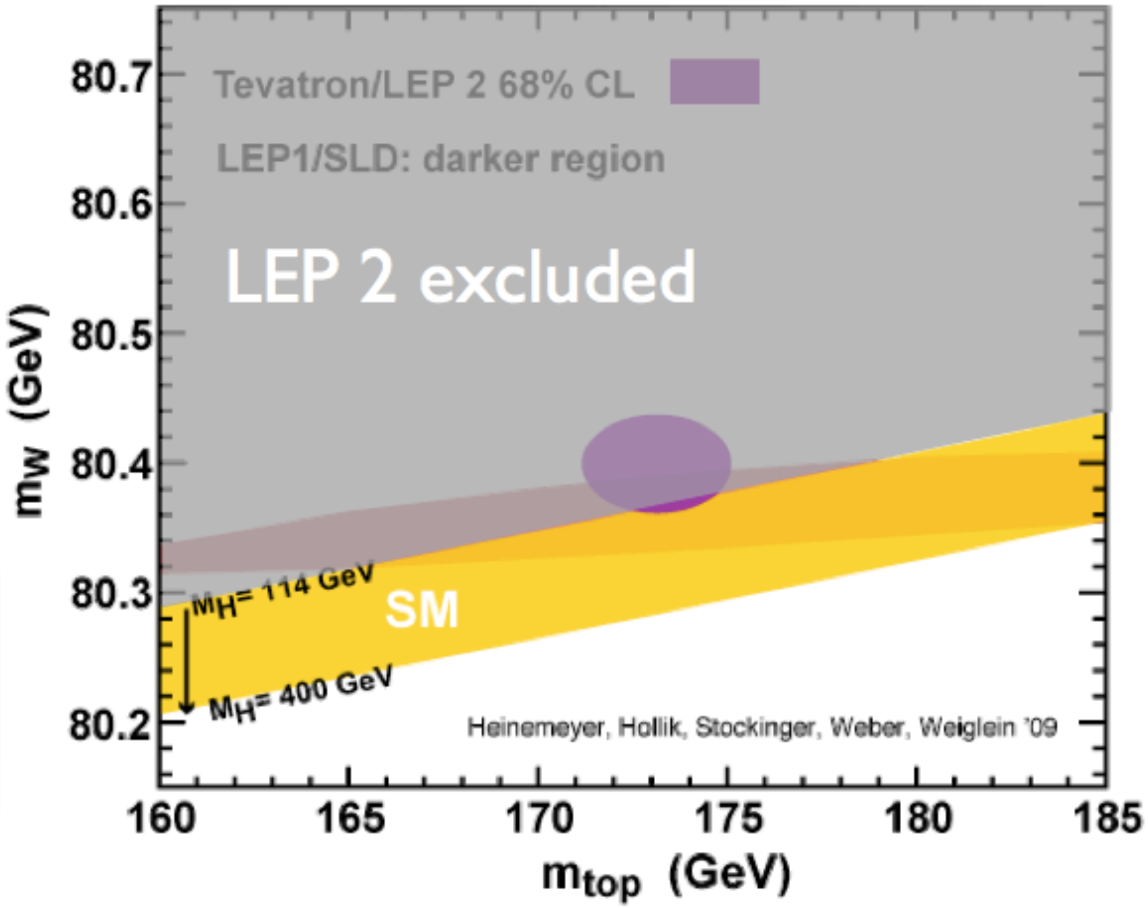
$\sigma = 18.1 + 3.3_{stat} \pm 2.5_{sys}$ pb

$\sigma = 16.5 +3.3/-3.0_{stat} \pm 3.5_{sys}$ pb

- WW/WZ measurements in Lepton + Jets
- Using matrix element techniques and mjj calibration with 4.3-4.6 fb^{-1}

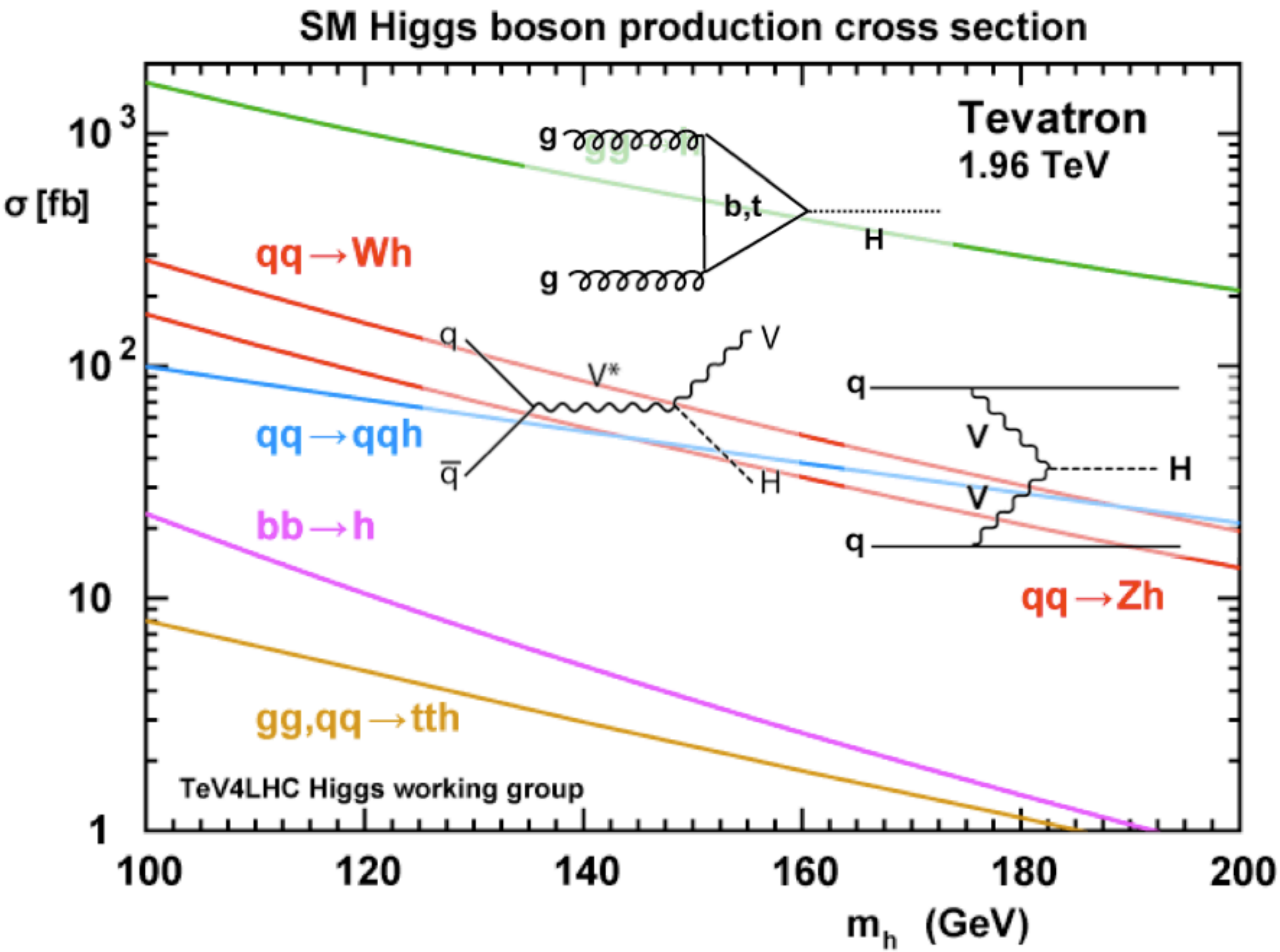
Where is the Higgs?

- Use latest results on M_{top} and M_W
  - push Higgs mass to even lighter values



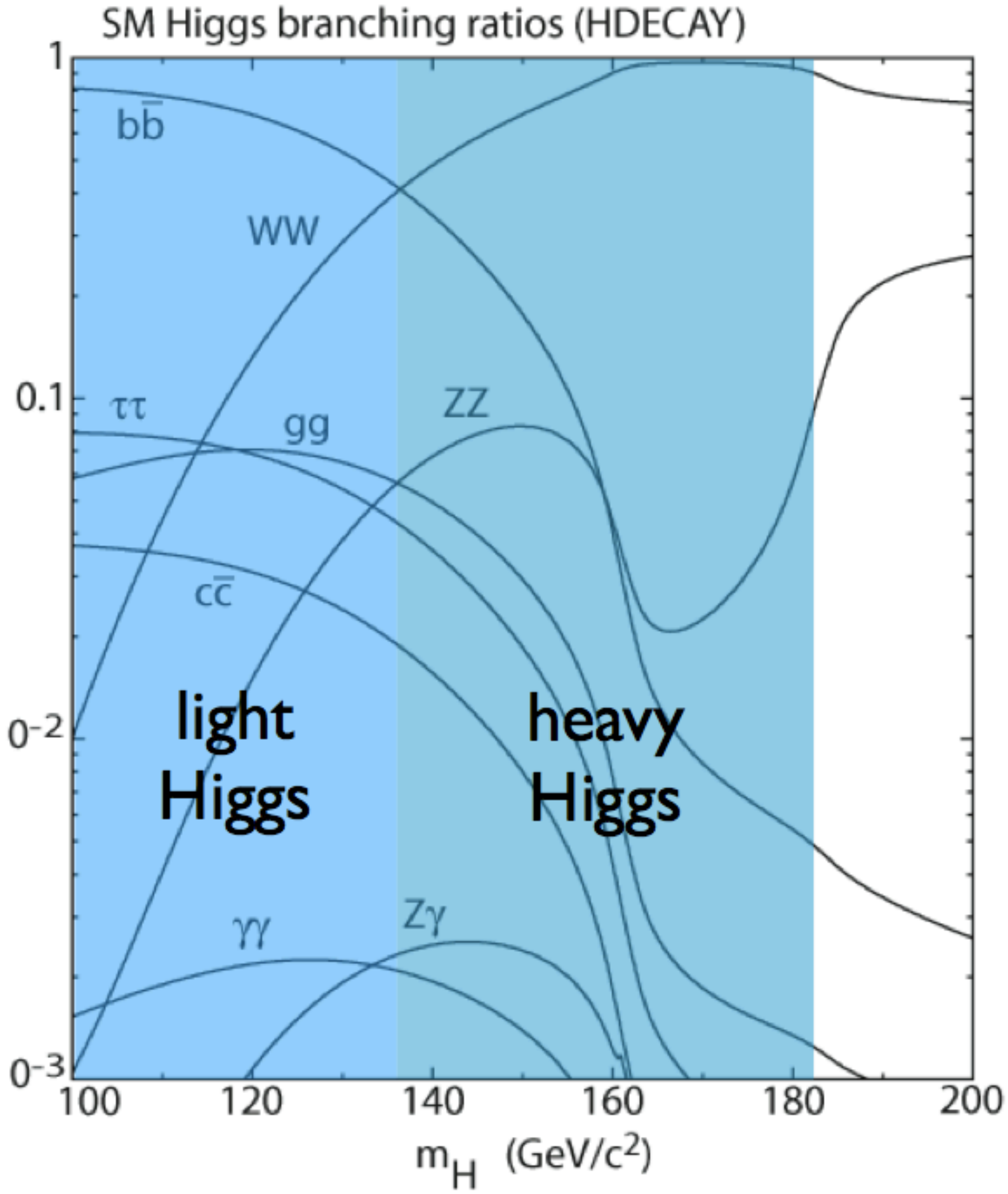
$$m_H = 87 \pm^{35}_{26} \text{ GeV}$$
$$m_H < 157 \text{ GeV} @ 95\% \text{C.L.}$$
$$m_H > 114 \text{ GeV(direct)}$$

Higgs production



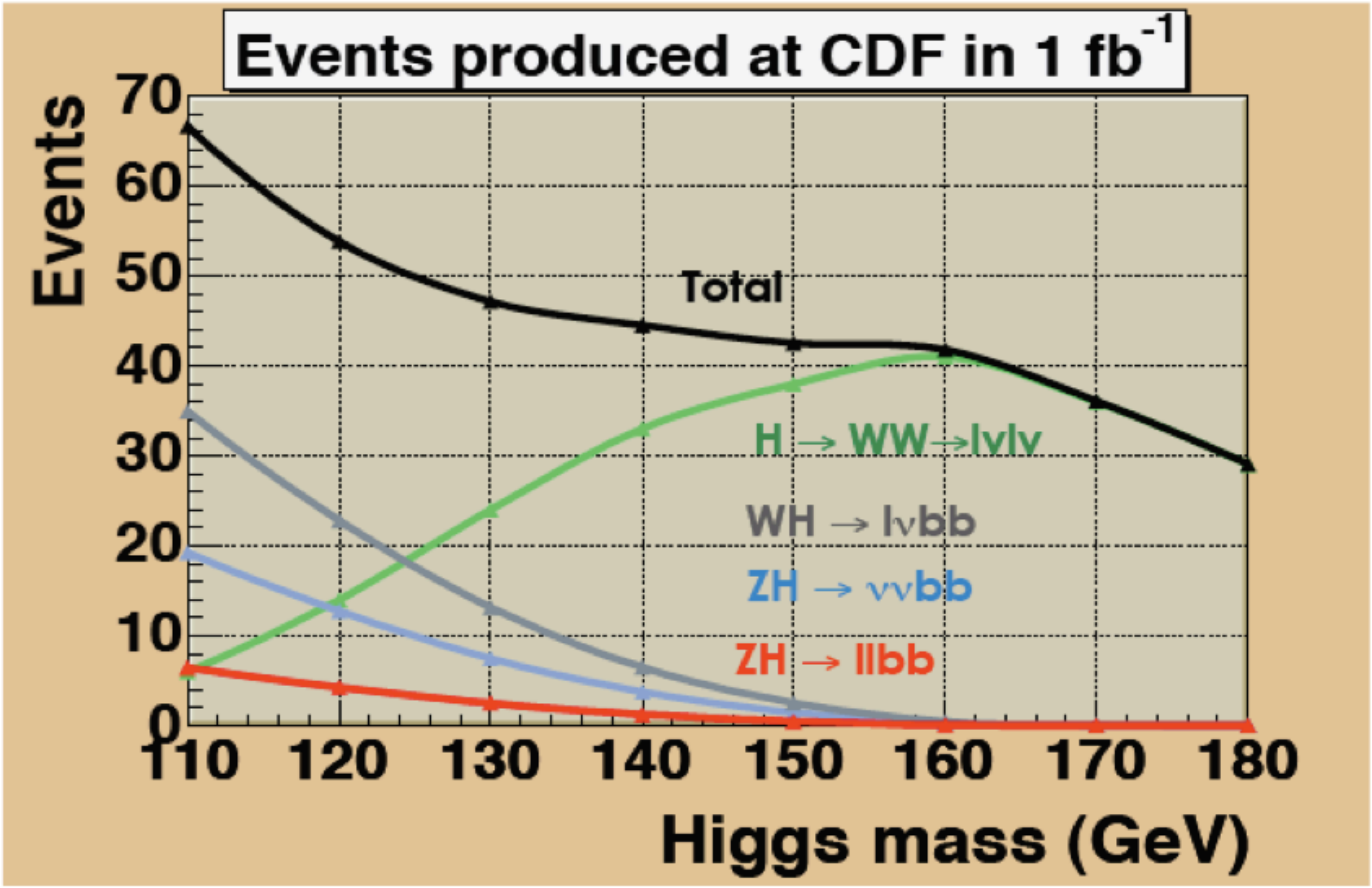
Higgs signatures

- Light Higgs:
  - bb dominates
  - tau playes a role
- Heavy Higgs
  - WW dominant
  - ZZ with leptons in the final state has too small branching ratio



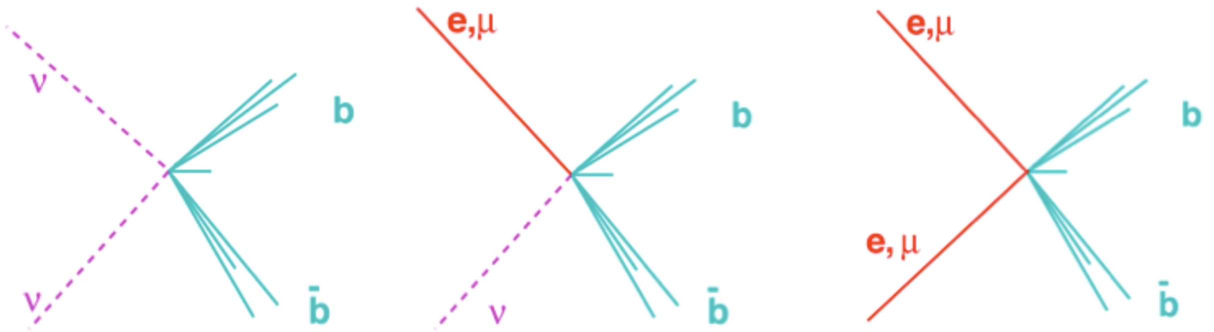
Events: the challenge

- These are production numbers
  - – trigger, acceptance, ID efficiency not yet factored in.

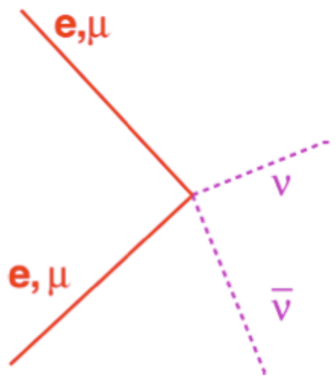


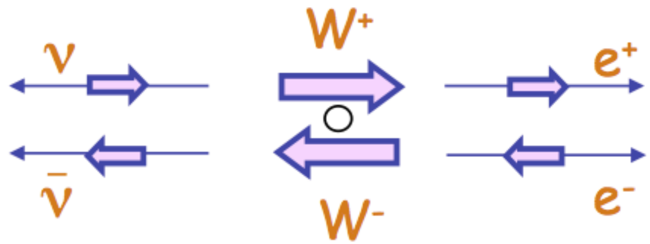
Tevatron channels

- gg→H→bb/ττ suffer too much background

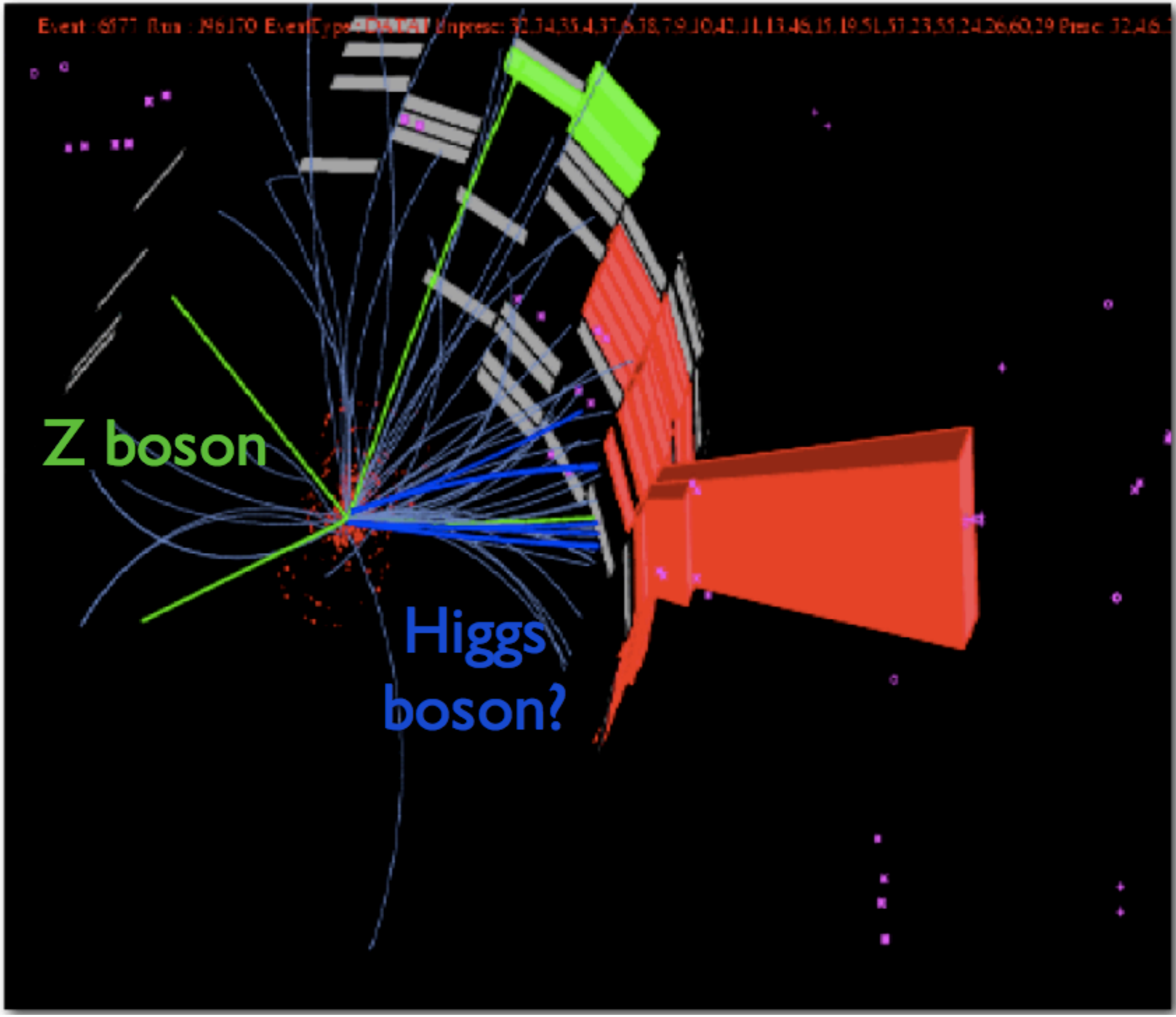


- ⇒ low mass channels: WH and ZH (with leptons)

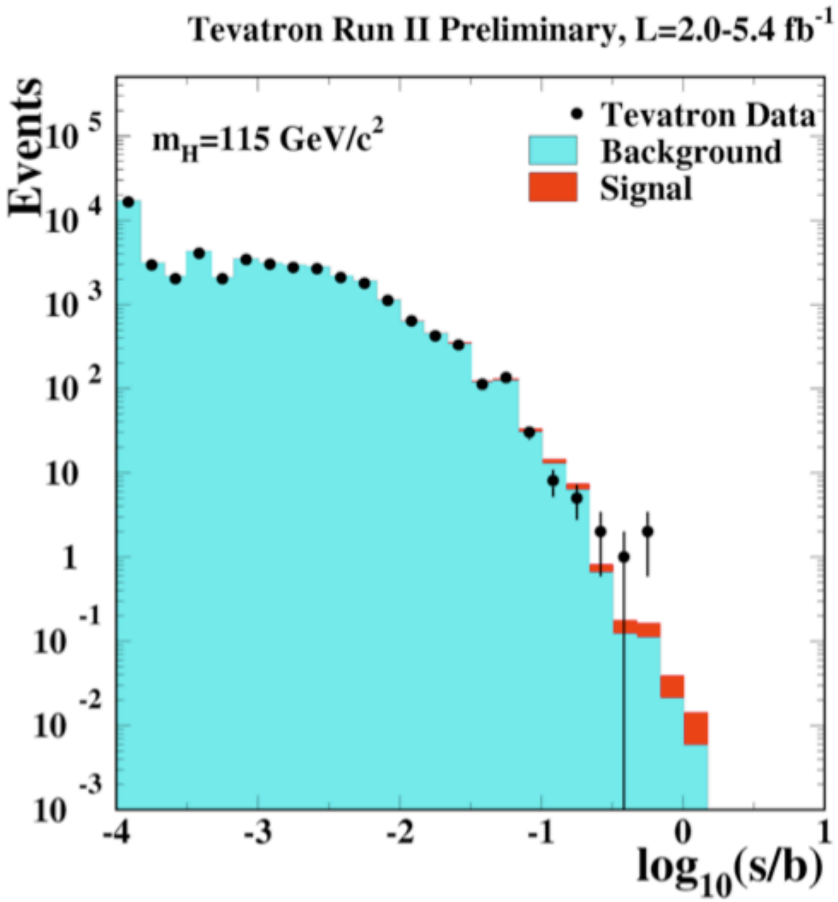




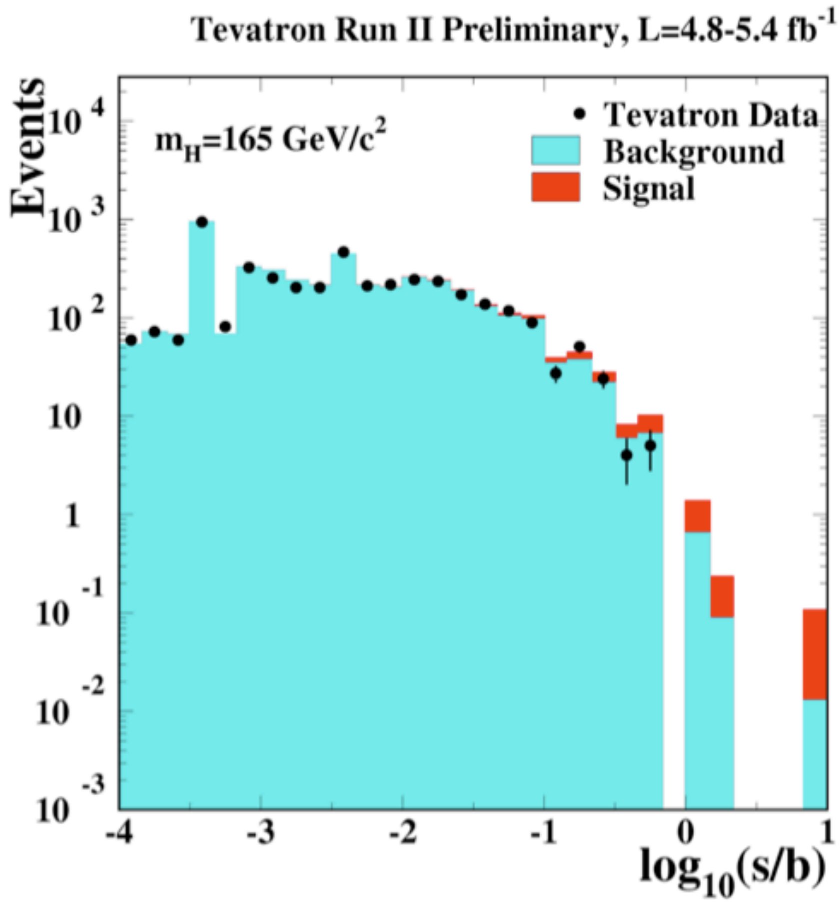
- ⇒ high mass channels: H→WW and VH→VWW


Z boson
Higgs boson?

Combined Tevatron Results



Low mass Higgs



High mass Higgs