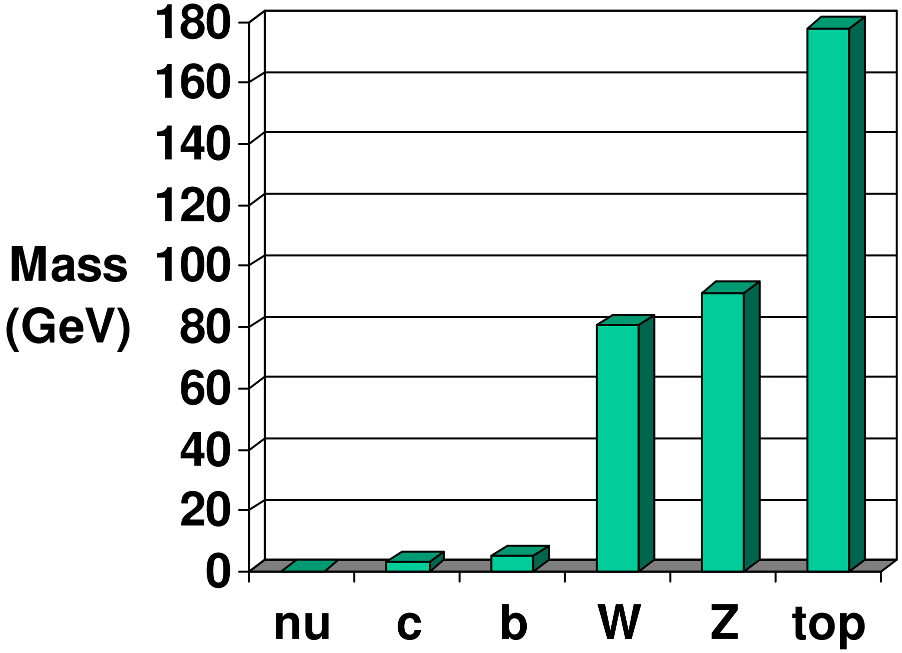
Top and Electroweak Physics

Recent developments from experiment, phenomenology and theory



Dave Rainwater will cover Electroweak Symmetry Breaking and Higgs

Evelyn J. Thomson

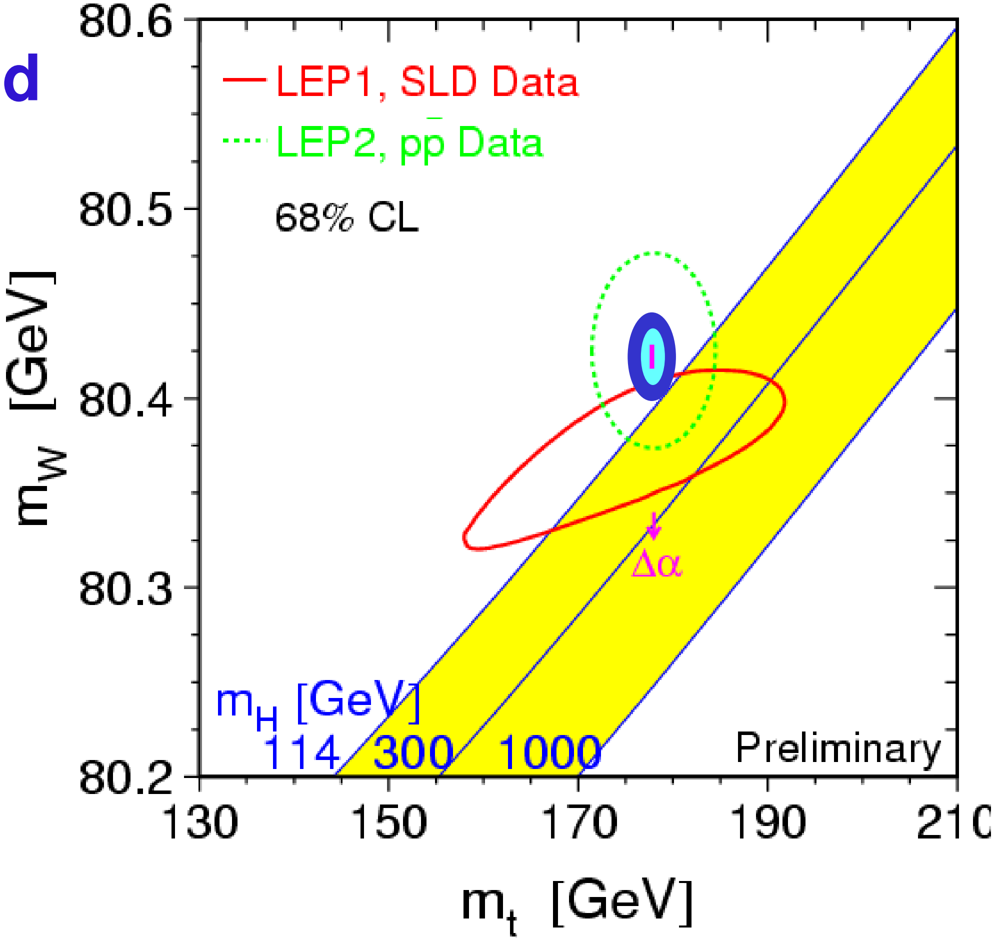
University of Pennsylvania/Ohio State University

DPF 2004 August 27

Motivation

- **Fundamental parameters of Standard Model**
- **Sensitive to Higgs mass and new physics through radiative corrections**
  - **Precision measurements**
  - **Theory challenges**
- **Standard Candles for detector calibration**
  - **Lepton identification**
  - **Energy/Momentum scale**
  - **Luminosity**
- **Backgrounds to many new physics signals**

TeVatron Run II, LHC, ILC

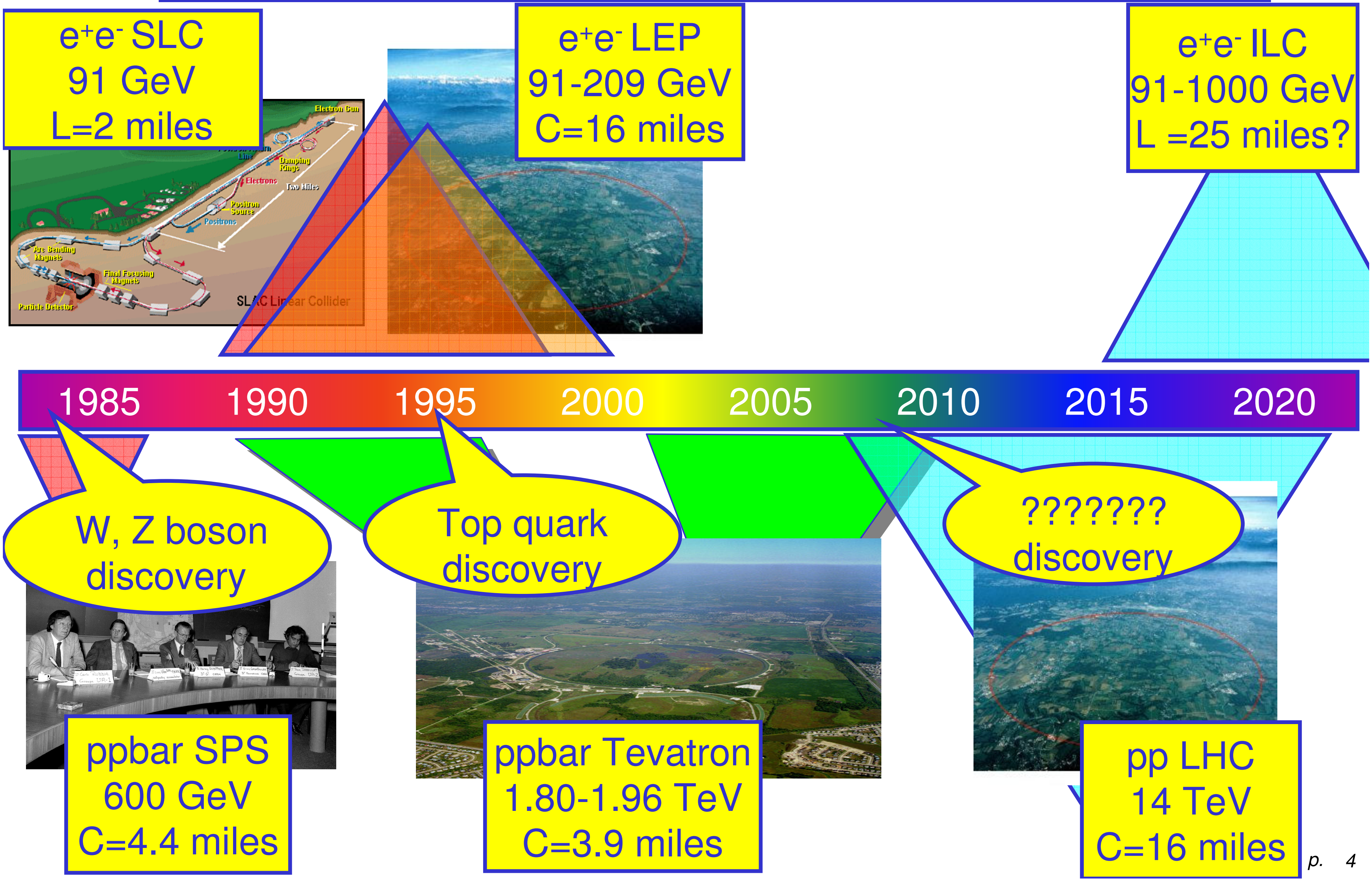


Outline

- Accelerators powerful enough to produce W, Z, top
  - Status
- W and Z physics
  - W and Z production cross-section
  - W width
  - W charge asymmetry
  - W mass
  - Diboson production and Triple Gauge Couplings
- Top physics
  - Top production cross-section
  - Top decays
  - Top mass
- Standard Model (and beyond) global fit

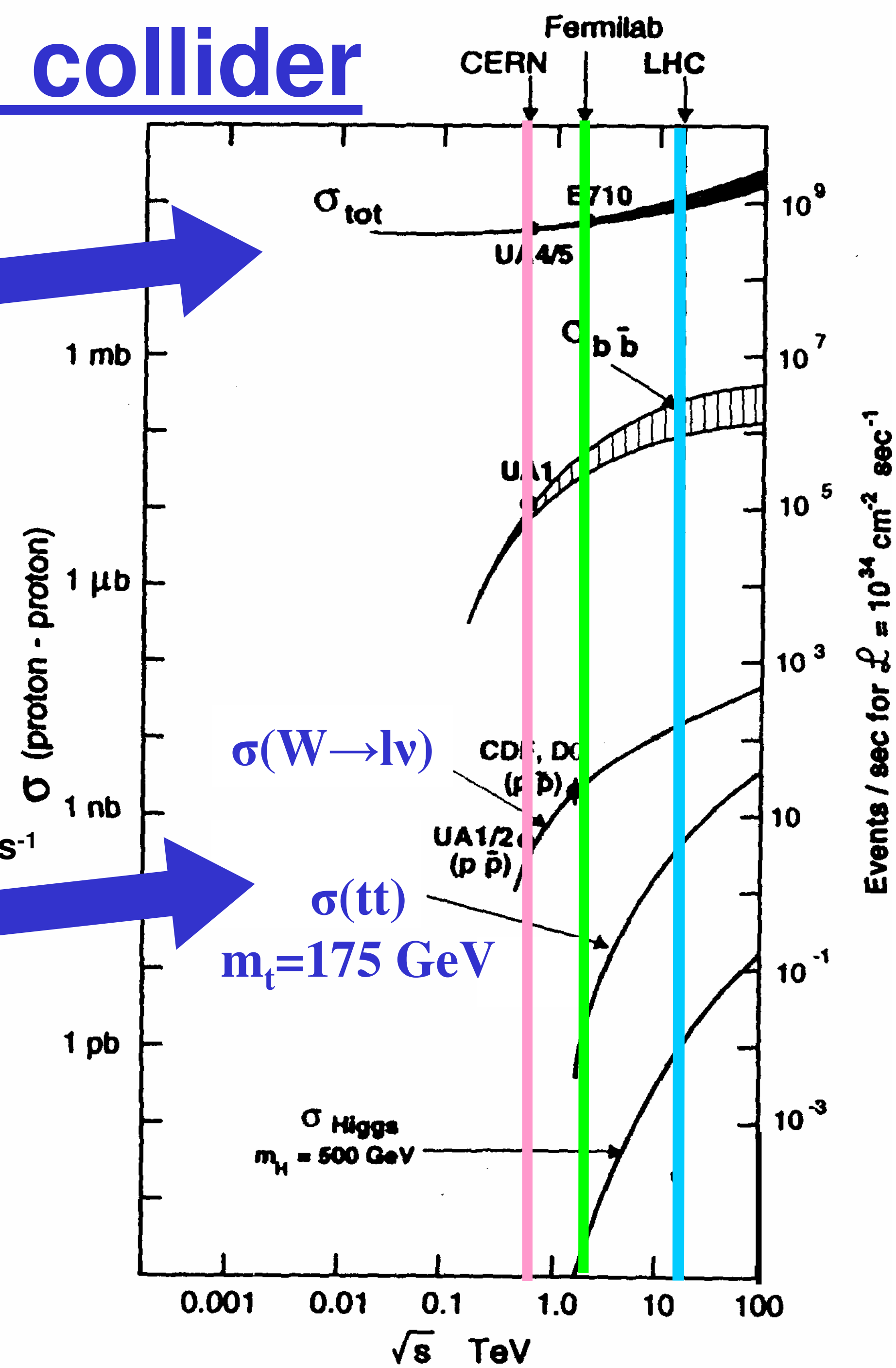
Will show selected results! See parallel top and electroweak sessions for all the details!

Accelerators: The decade of the Hadron Collider

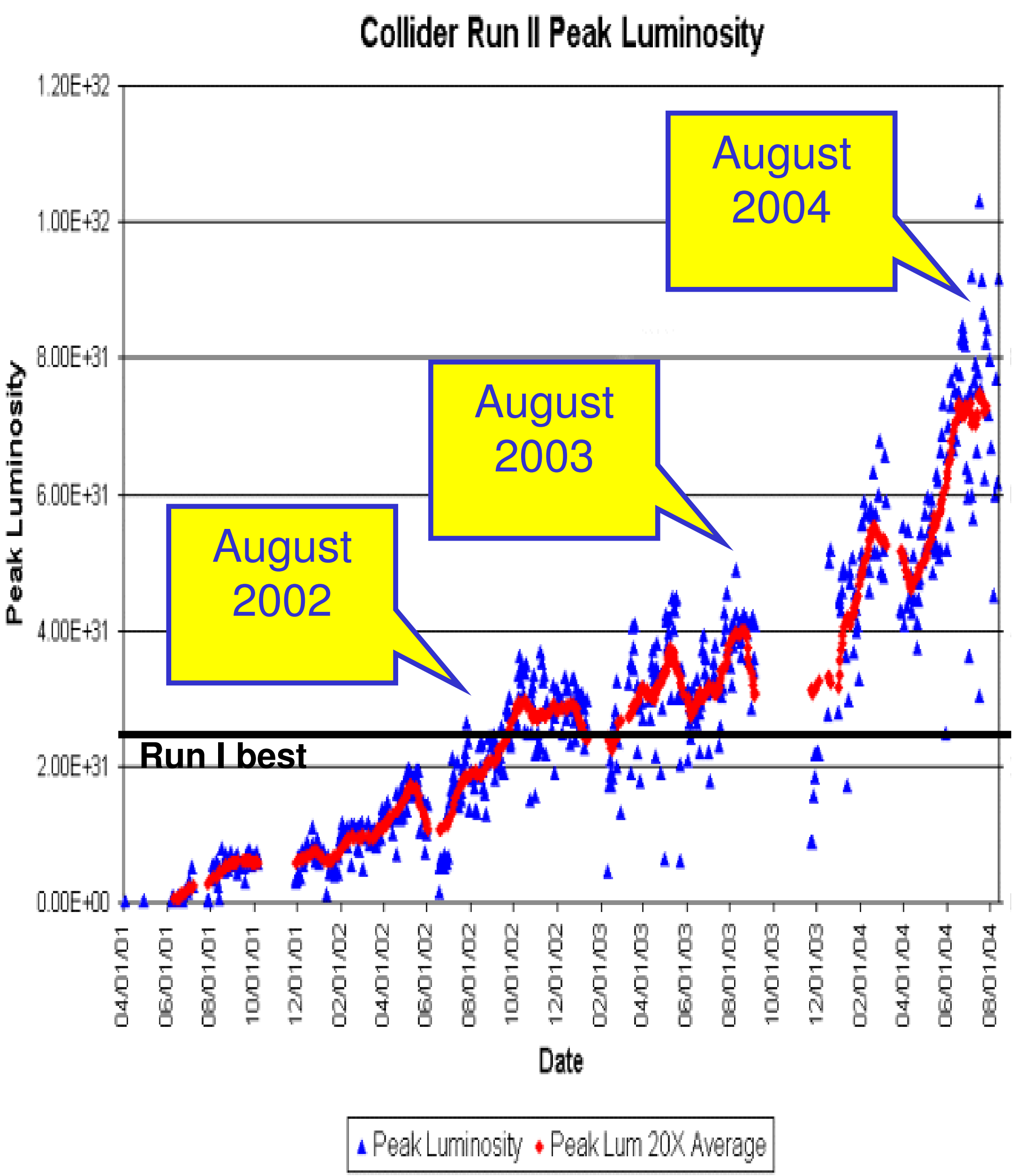


Physics at a hadron collider is like…

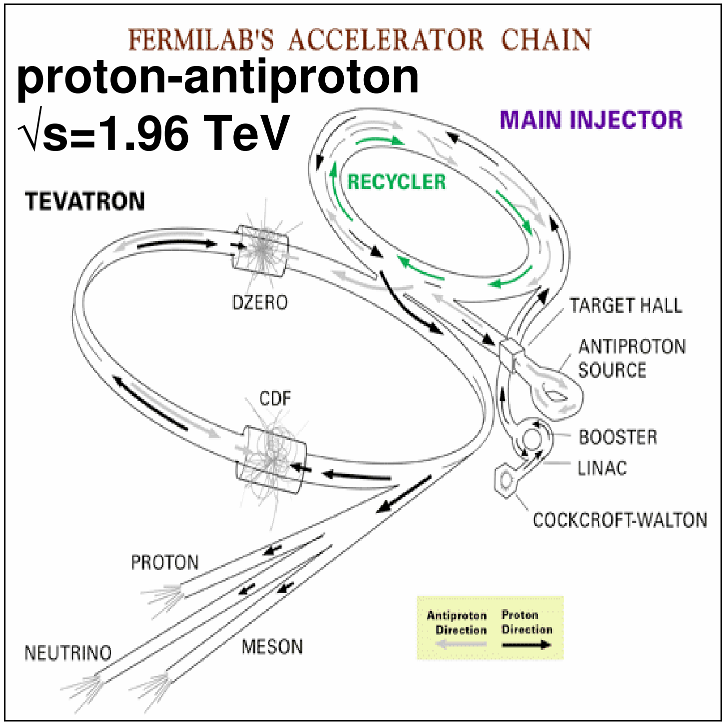
- Drinking from a firehose
  - Collision rate huge
    - Tevatron – every 396 ns
    - LHC – every 25 ns
  - Total cross section huge ~60mb
    - 2-3 interactions per collision
      - Tevatron $L=10^{32} cm^{-2}s^{-1}$
      - LHC initial/low lumi $L=10^{33} cm^{-2}s^{-1}$
    - 20 interactions per collision
      - LHC design/high lumi $L=10^{34} cm^{-2}s^{-1}$
- Panning for gold
  - W, Z, top are relatively rare
    - Need high luminosity
    - Trigger is crucial
      - Distinguish using high p_T leptons



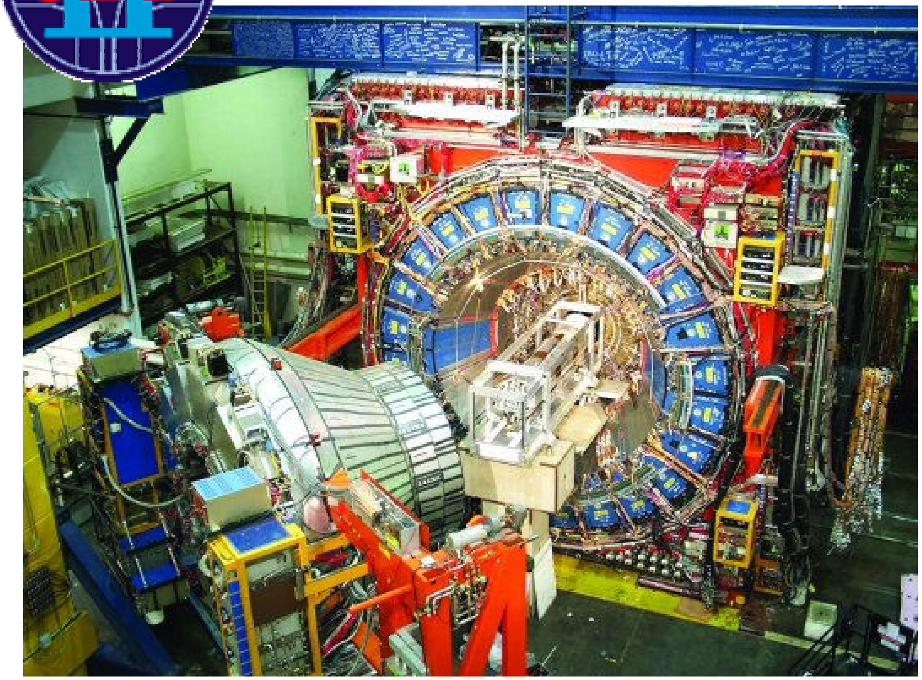
TeVatron Performance



- **Peak luminosity**
  - x2 increase since 2003
  - Reached $L=10^{32}cm^{-2}s^{-1}$
- **Future**
  - Run until 2009
  - Deliver 4-9 fb^{-1}



TeVatron Experiments



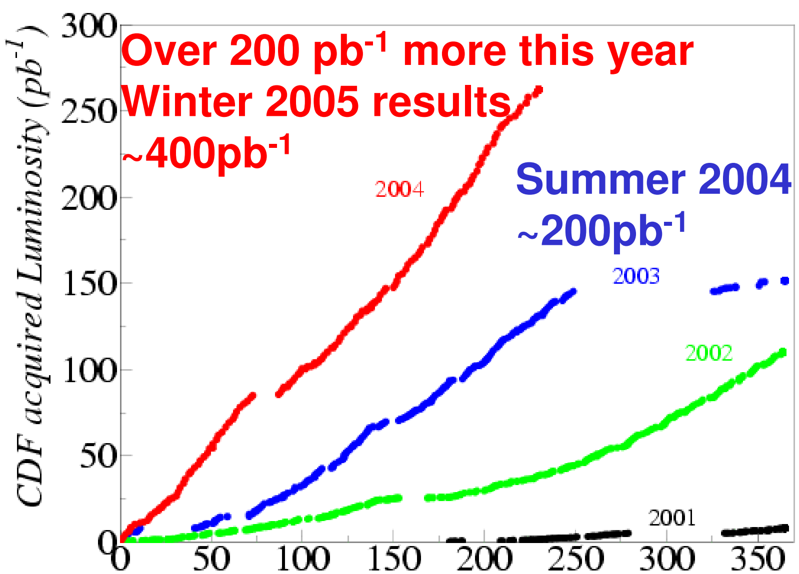
Top & Electroweak Physics need

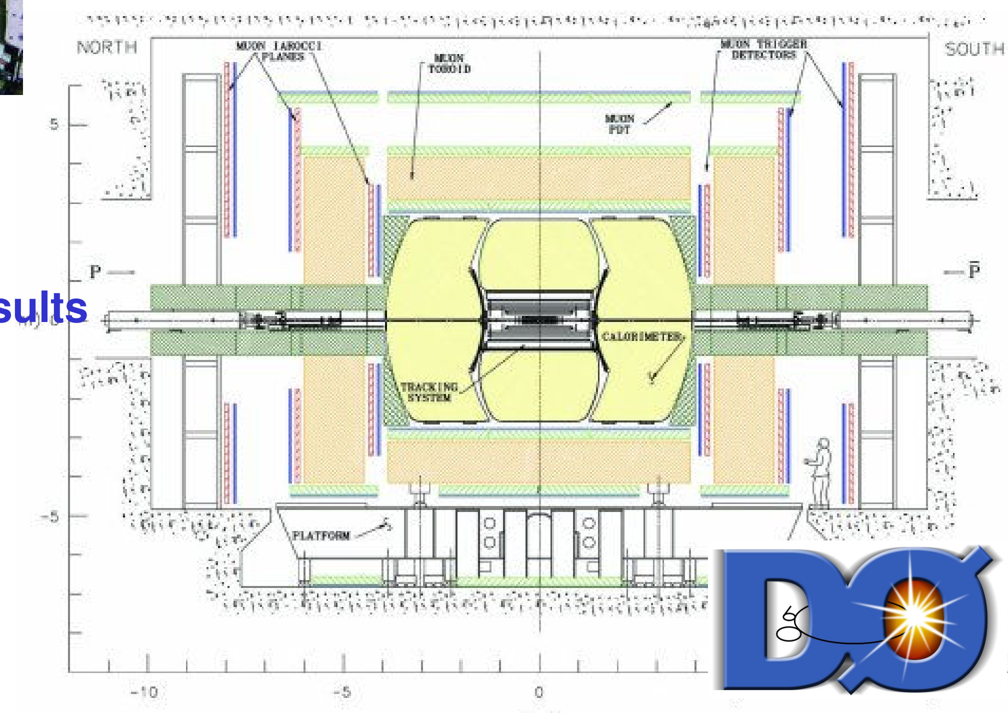
Trigger

Electron/Muon/Tau identification

Tracking and b tagging

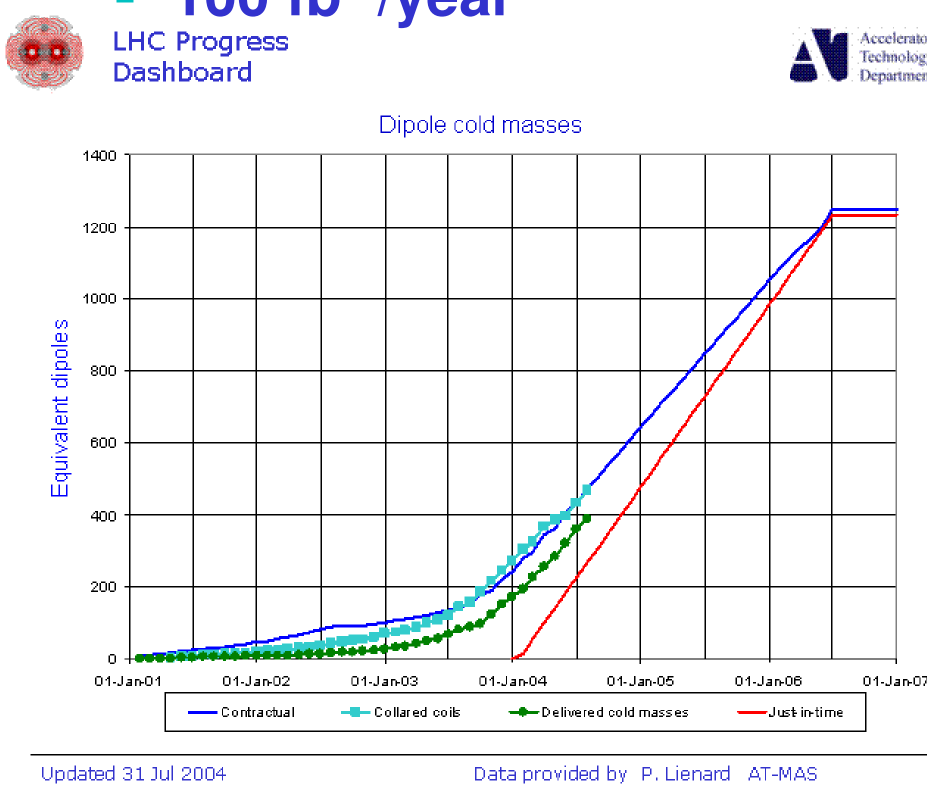
Calorimetry

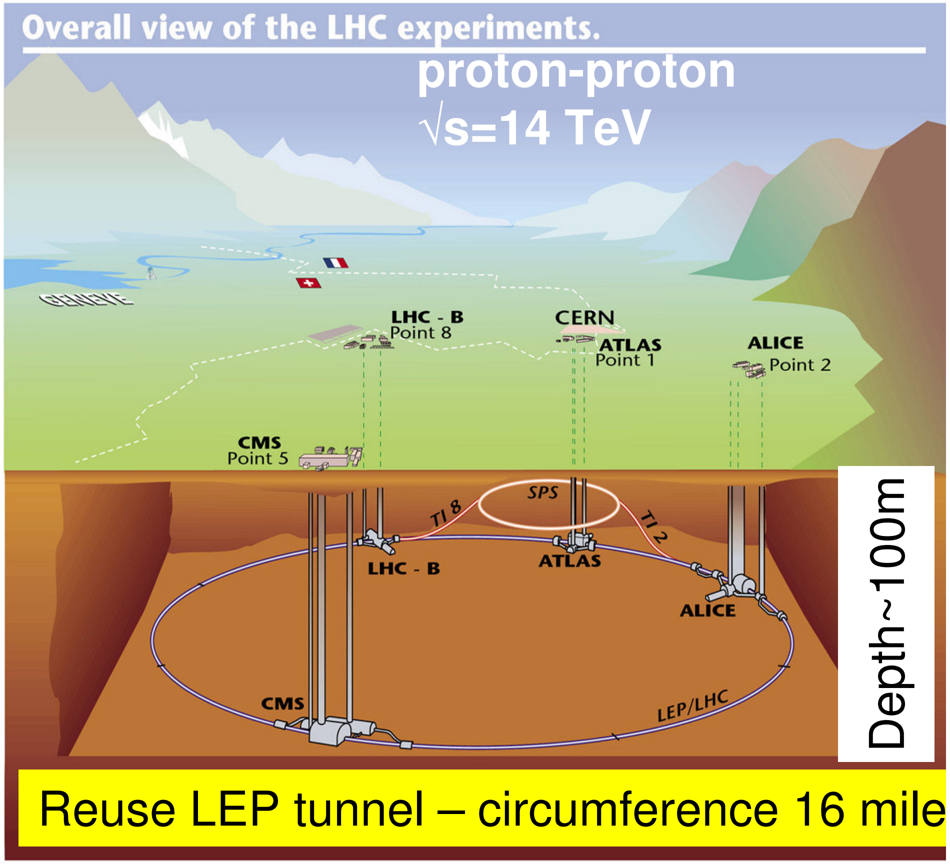




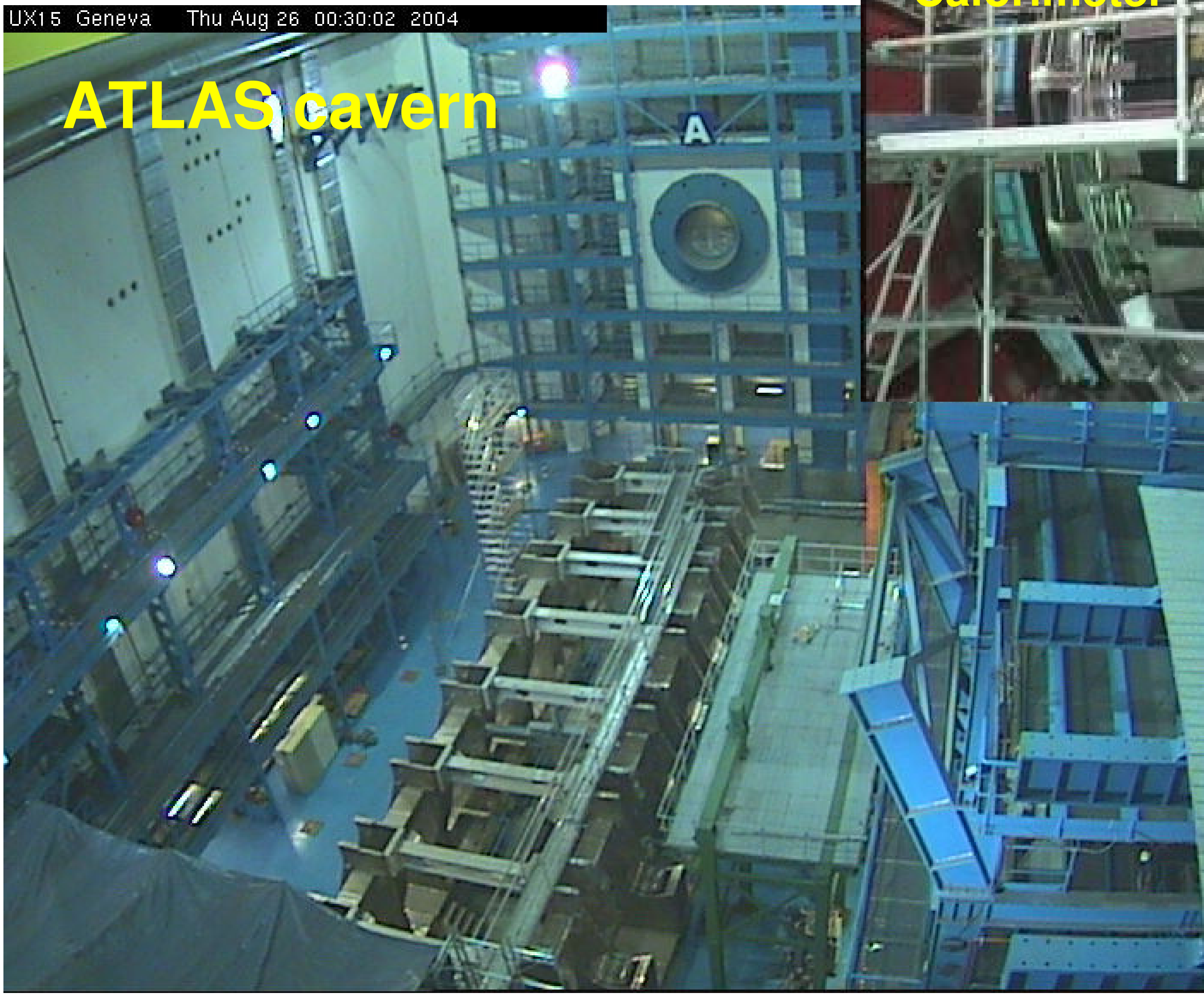
Large Hadron Collider (LHC)

- Goal: find the Higgs boson or new physics!
- Initial/low lumi $L<10^{33}cm^{-2}s^{-1}$ for first 3 years 2007-2009
  - <2 min bias/collision
  - 10 fb^{-1}/year
  - Time for precision top and electroweak measurements
- Design/high lumi $L=10^{34}cm^{-2}s^{-1}$
  - ~20 min bias/collision
  - 100 fb^{-1}/year



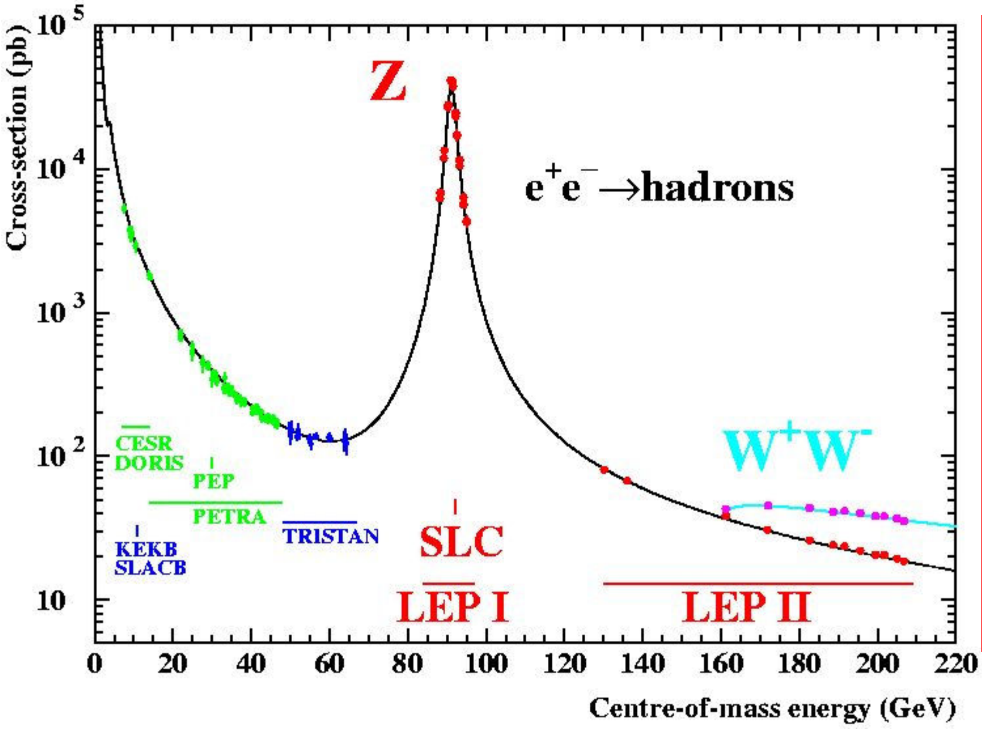


LHC detectors under construction



International Linear Collider (ILC)

- Decision to choose superconducting “cold” technology
  - Last week! See www.interactions.org/linearcollider/
- Design parameters
  - Total cross-section small at high energies
    - Need very high luminosities
  - Linear
    - Need high acceleration gradients



Precision measurements of Higgs or new physics…

International Linear Collider
e^+e^-
200-500 GeV
Upgrade to 1 TeV

W and Z Physics

Standard Candles

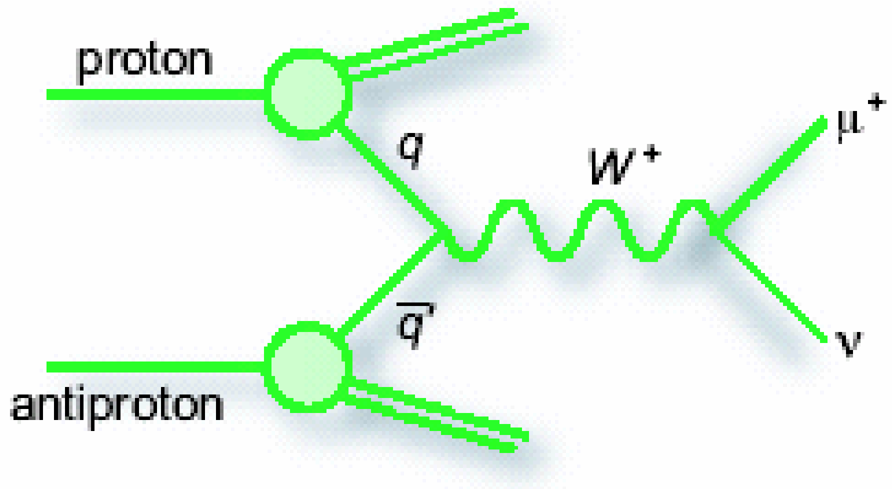
at Tevatron and LHC

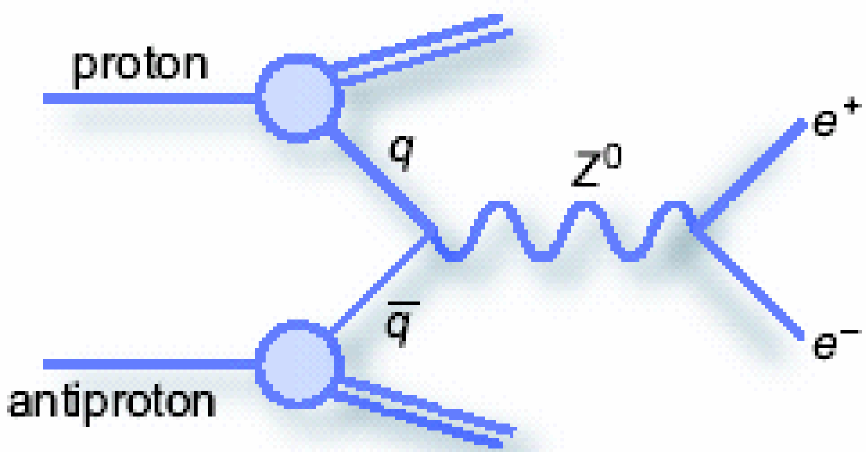
W/Z cross-sections → W width

W/Z asymmetries

W mass

WW, WZ, ZZ, Wγ, Zγ





Trigger on leptonic decays at Tevatron and LHC

Clean event signatures with low background

BR~11% per mode for W → ℓ ν
BR~3% per mode for Z→ $\ell^+\ell^-$

CDF(D0) W and Z Event Selection

$W \rightarrow e\nu$

1 electron E_T>25 GeV, $|\eta|$< 2.8(1.1)
High MET> 25 GeV

$Z^0 \rightarrow e^+e^-$

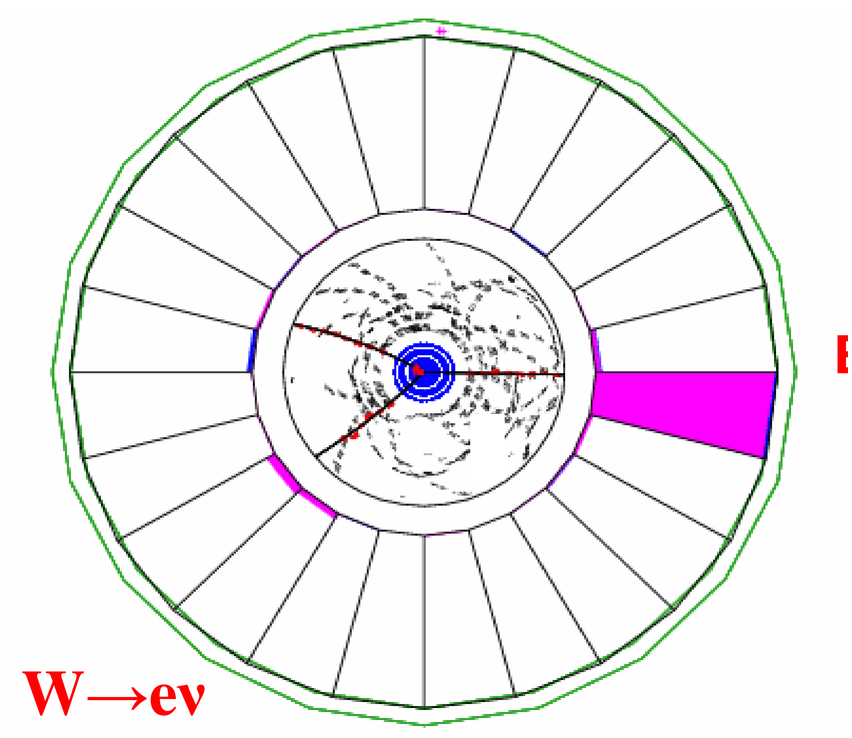
2 electrons E_T>20 GeV

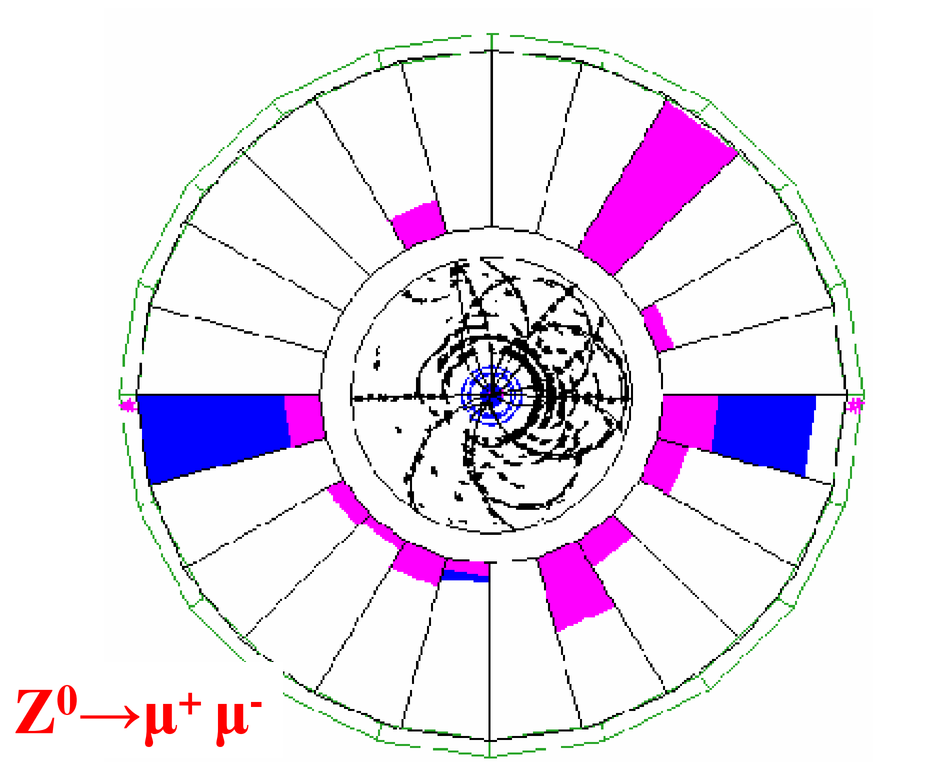
$W \rightarrow \mu\nu$

1 muon p_T>20 GeV, $|\eta|$< 1.0(1.5)
High MET>20 GeV

$Z^0 \rightarrow \mu^+ \mu^-$

2 muons p_T>20(15) GeV

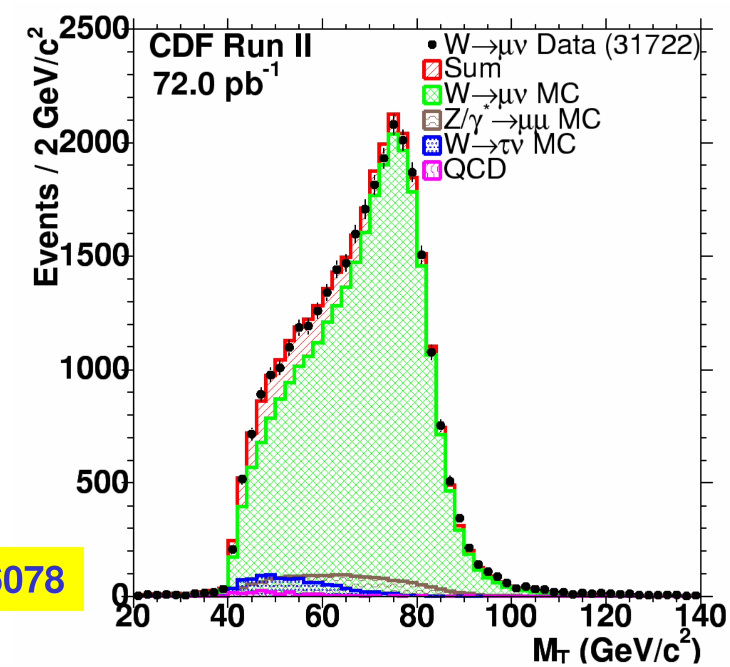


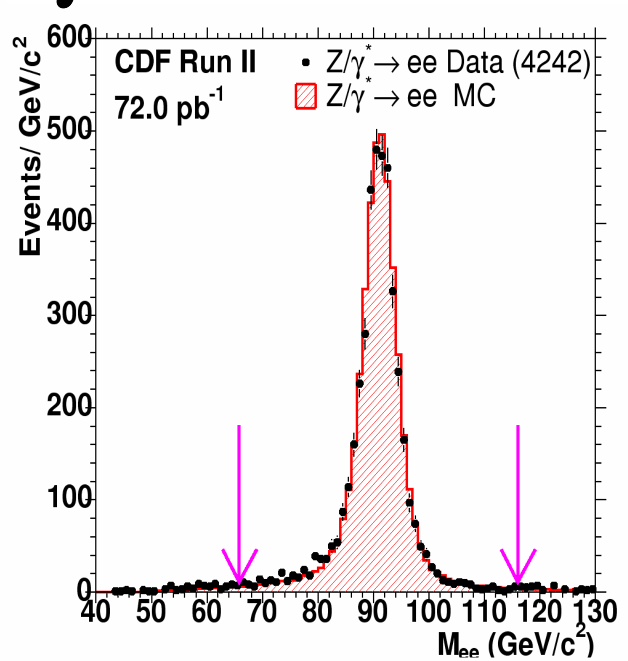


W and Z production cross section

$$\sigma \cdot B = \frac{N_{obs} - N_{bkg}}{\mathcal{A} \cdot \mathcal{E} \cdot \int \mathcal{L}}$$

Uses $\sigma_{inelastic}$ = 60.7± 2.4 mb (CDF+E811)





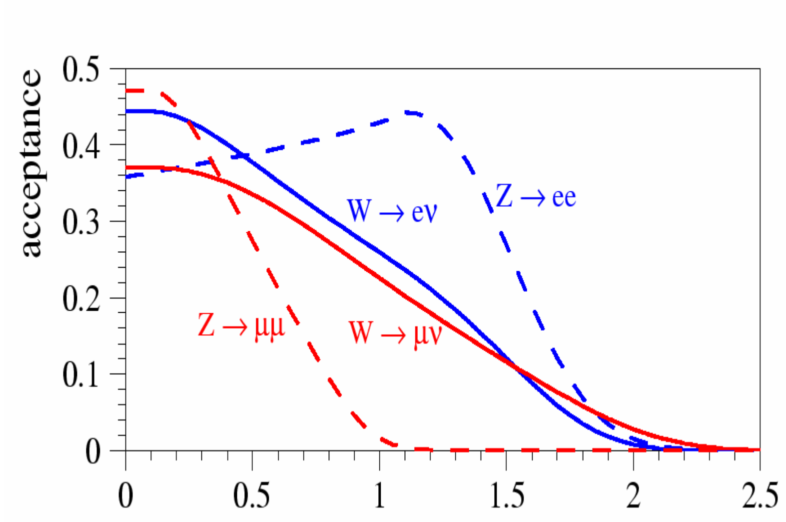
hep-ex/0406078

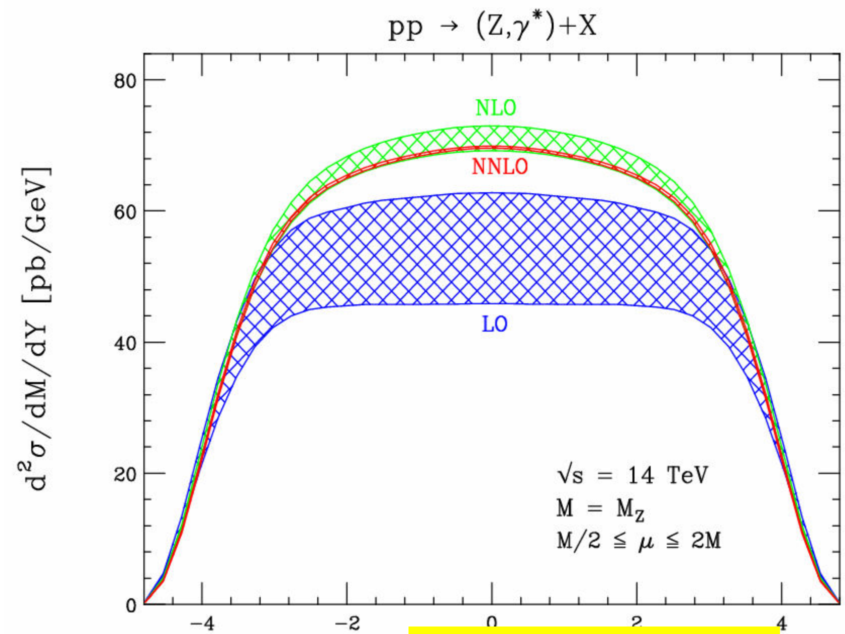
Precision	2.2%	2.4%	2.6%	3.9%
category / channel	$W \to e\nu$	$W \to \mu\nu$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
N candidates	37584	31722	4242	1785
acceptance	0.2397 ± 0.0036	0.1970 ± 0.0025	0.3182 ± 0.0040	0.1392 ± 0.0027
efficiency	0.749 ± 0.009	0.732 ± 0.013	0.713 ± 0.012	0.713 ± 0.015
background	1656 ± 300	2990 ± 140	62 ± 18	13 ± 13
cross section (pb)	$2780 \pm 14 \pm 60$	$2768 \pm 16 \pm 64$	$255.8 \pm 3.9 \pm 5.5$	$248.0 \pm 5.9 \pm 7.6$

Additional luminosity uncertainty of 6% is 166pb for W and 15pb for Z

$\mathcal{A}$: geometric and kinematic acceptance

- Key quantity is boson rapidity, y
- Calculate A(y) from PYTHIA with GEANT detector simulation
  - Dominant systematics
    - E_T,P_T scale <0.4%
    - Detector material < 1%
- Convolve with NNLO differential cross-section
  - First complete NNLO computation of a differential quantity for high energy hadron collider physics
    - Powerful new calculation, applicable to many observables
    - Important for LHC
  - Dominant systematics
    - PDFs CTEQ6M (0.7-2.1%)



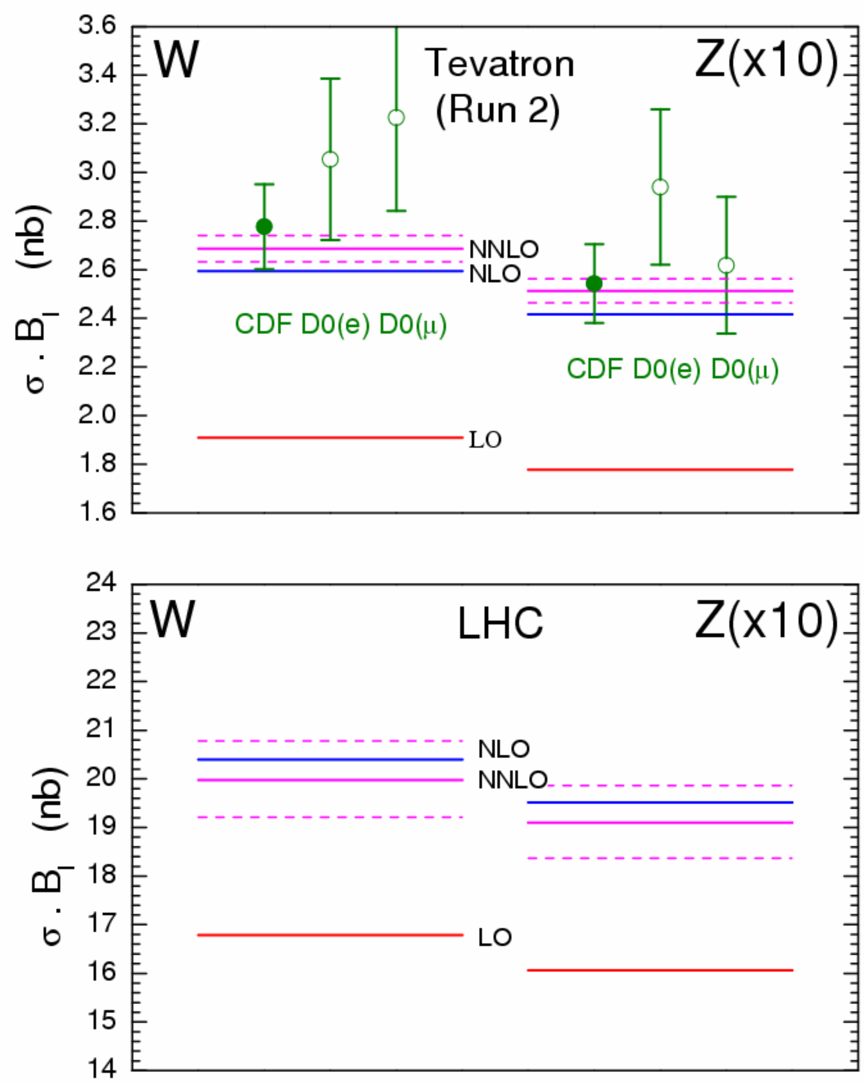


C. Anastasiou et al
hep-ph/0312266

Experiment vs theory

- Precision measurements vs precision NNLO predictions
  - Theoretical uncertainty 2%
  - Experimental uncertainty 2%
  - Luminosity uncertainty 6% from total cross section
- Future: instead use W and Z as a luminosity monitor at LHC

S. Frixione, M. Mangano
hep-ph/0405130

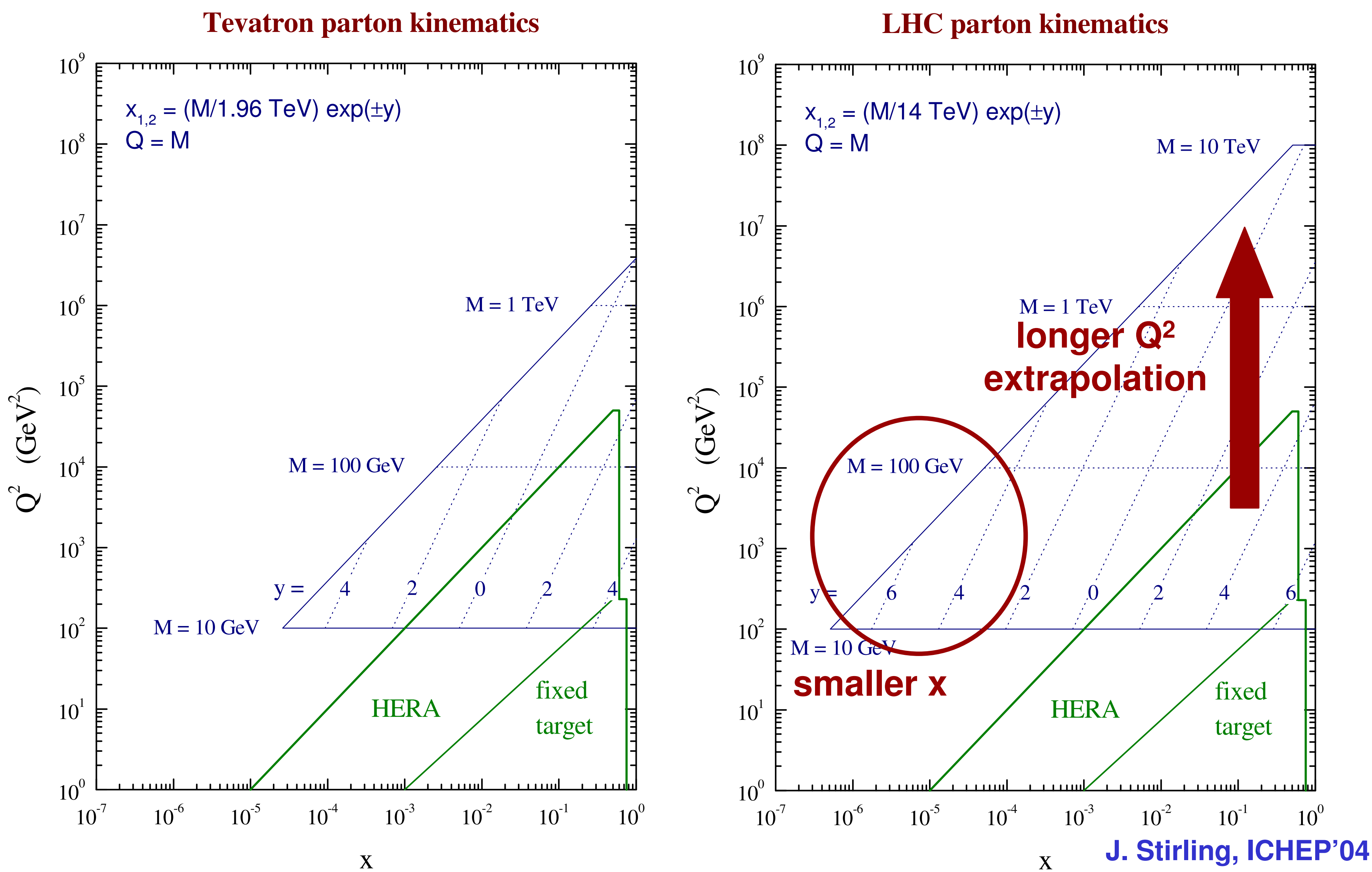


partons: MRST2002
NNLO evolution: Moch, Vermaseren, Vogt
NNLO W,Z corrections: van Neerven et al. with Harlander, Kilgore corrections

J. Stirling, ICHEP'04

PDFs at LHC

LHC-HERA workshop on PDFs



J. Stirling, ICHEP'04

Indirect Measurement of W Width

Measure W/Z cross section ratio: many systematics cancel

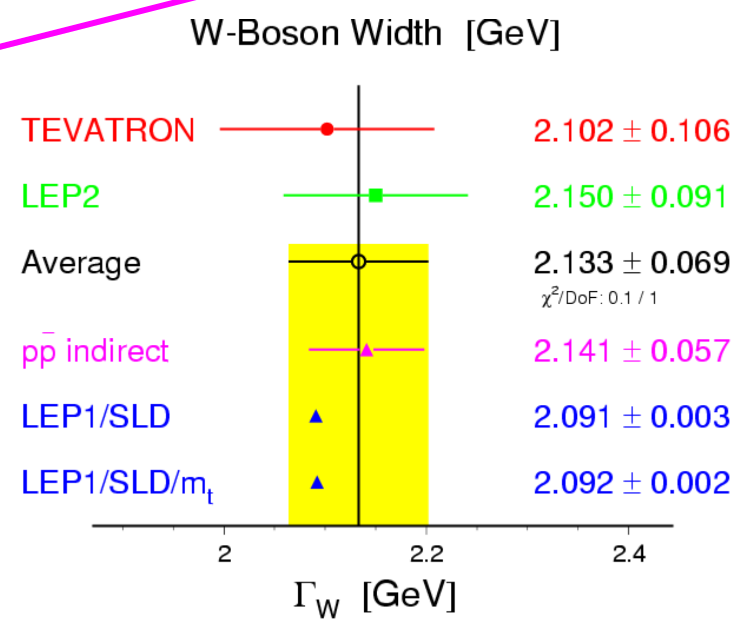
CDF	$e+\mu$	$72pb^{-1}$	$R = 10.92 \pm 0.15 \pm 0.14$
D0	e	$177pb^{-1}$	$R = 10.82 \pm 0.16 \pm 0.28$

Prediction **PDG**

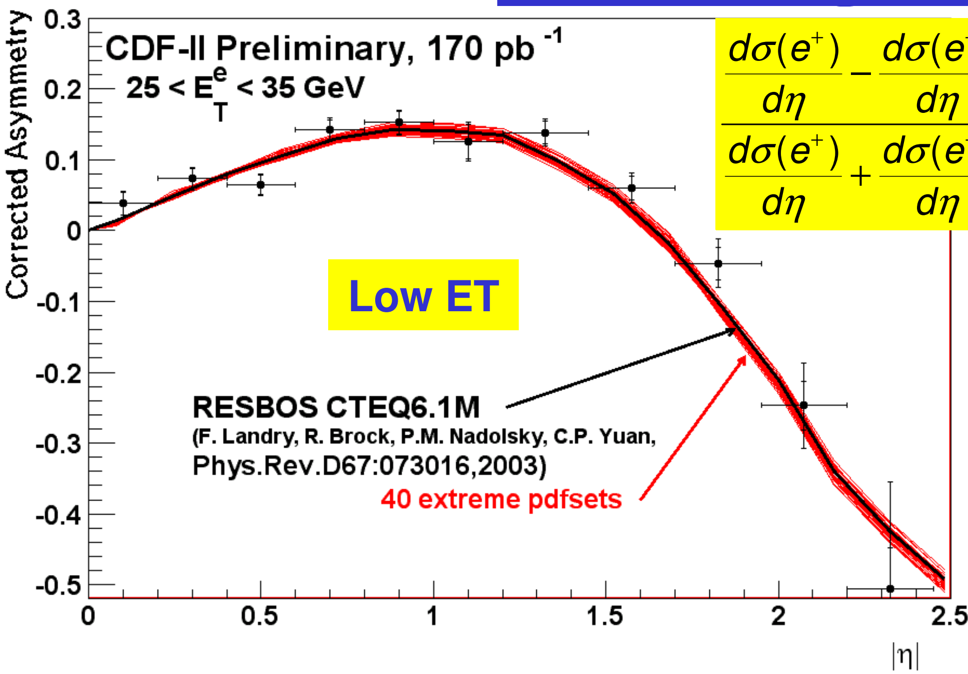
$$R = \frac{\sigma \cdot Br(p\bar{p} \to W \to \ell\nu)}{\sigma \cdot Br(p\bar{p} \to Z \to \ell^+ l^-)} = \frac{\sigma \cdot Br(p\bar{p} \to W)}{\sigma \cdot Br(p\bar{p} \to Z)} \times \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)} \times \frac{\Gamma(Z)}{\Gamma(Z \to \ell^+ l^-)}$$

Extract W boson width
CDF 2.079 ±0.041 GeV

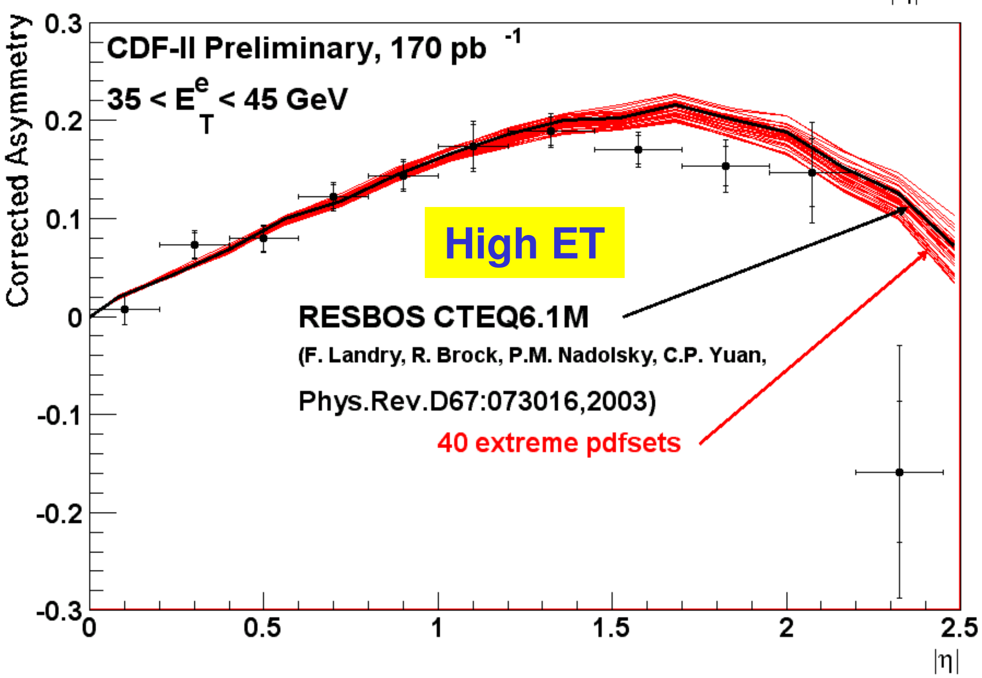
Compare to direct measurements



W charge asymmetry



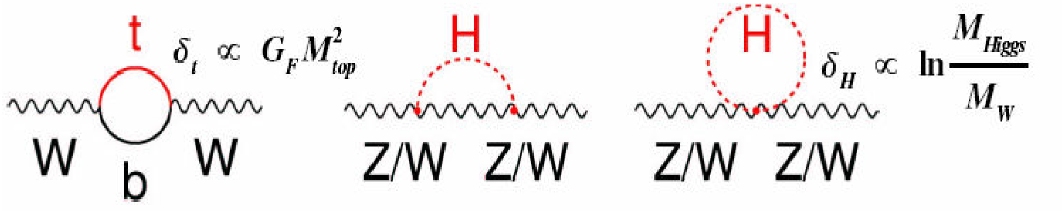
$$\frac{\frac{d\sigma(e^+)}{d\eta} - \frac{d\sigma(e^-)}{d\eta}}{\frac{d\sigma(e^+)}{d\eta} + \frac{d\sigma(e^-)}{d\eta}}$$



- u quark carries more of proton momentum, on average, than d quark
  - W^+ boosted along proton beam direction
  - W^- boosted along anti-proton beam direction
- W charge asymmetry sensitive to u/d quark ratio at large x
  - Count e^+ and e^- vs η
    - High E_T sensitive to PDFs
  - Calorimeter- seeded Silicon tracking for electrons with $|\eta|>1$
    - Charge mis-id < 2%

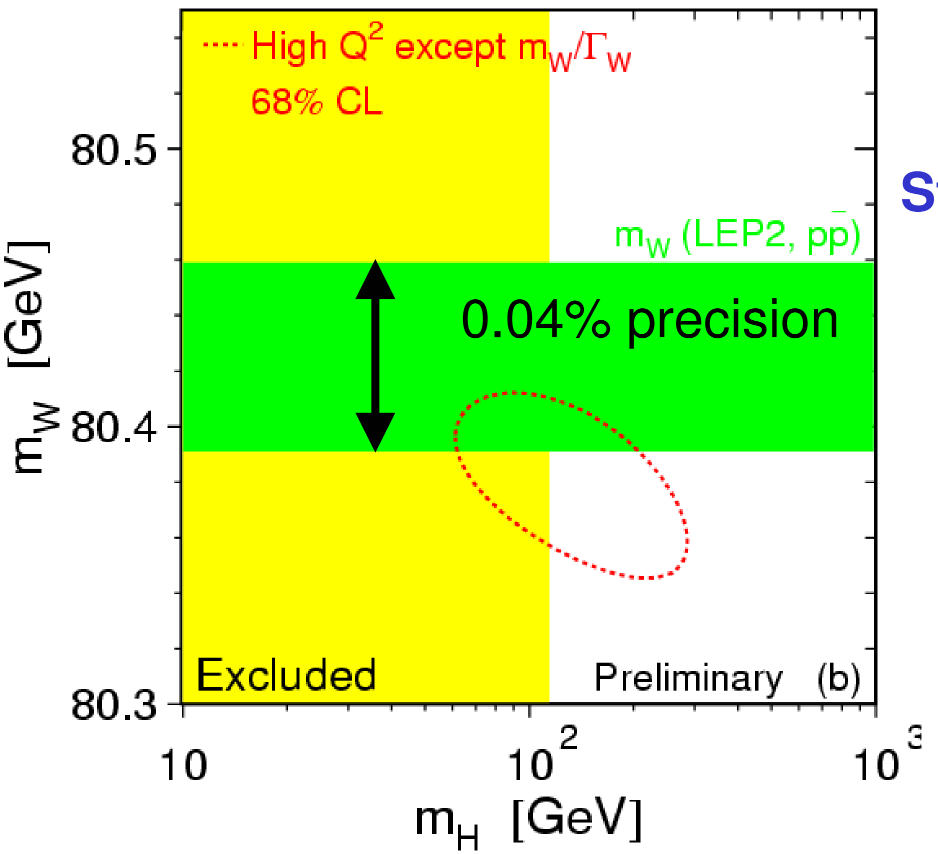
Standard Model prediction for W mass

Radiative corrections make W mass sensitive to top and Higgs mass



A. Freitas et al
hep-ph/0311148

Recent theoretical calculation of full two-loop electroweak corrections



$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

Standard Model prediction for W mass dominated by error on top mass

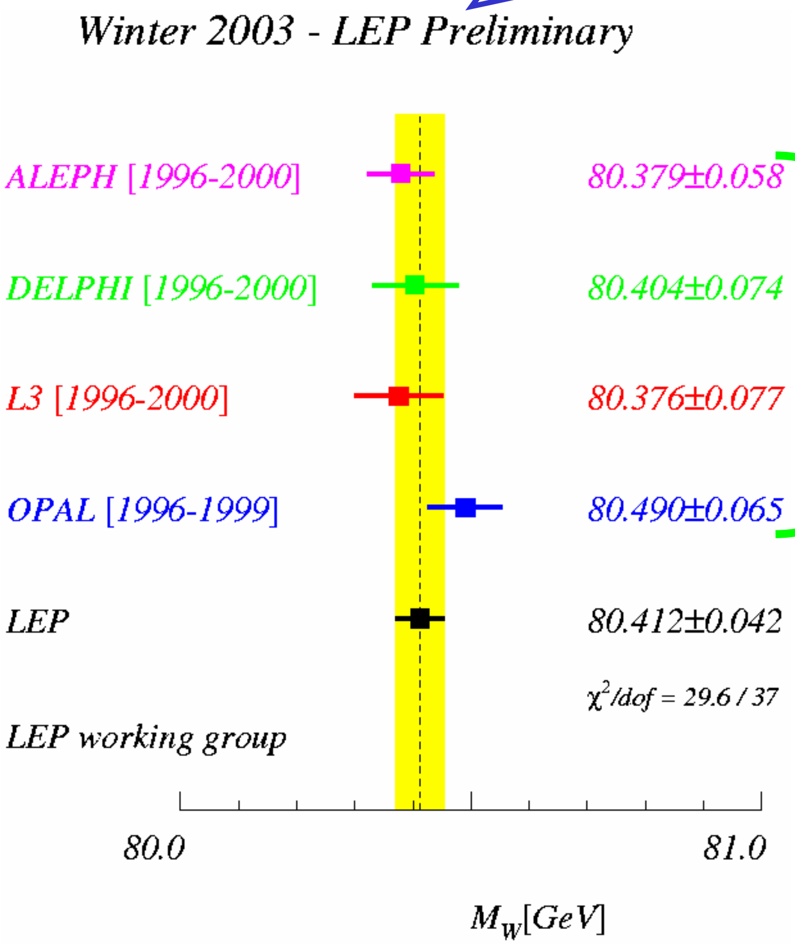
Contribution from error on top mass

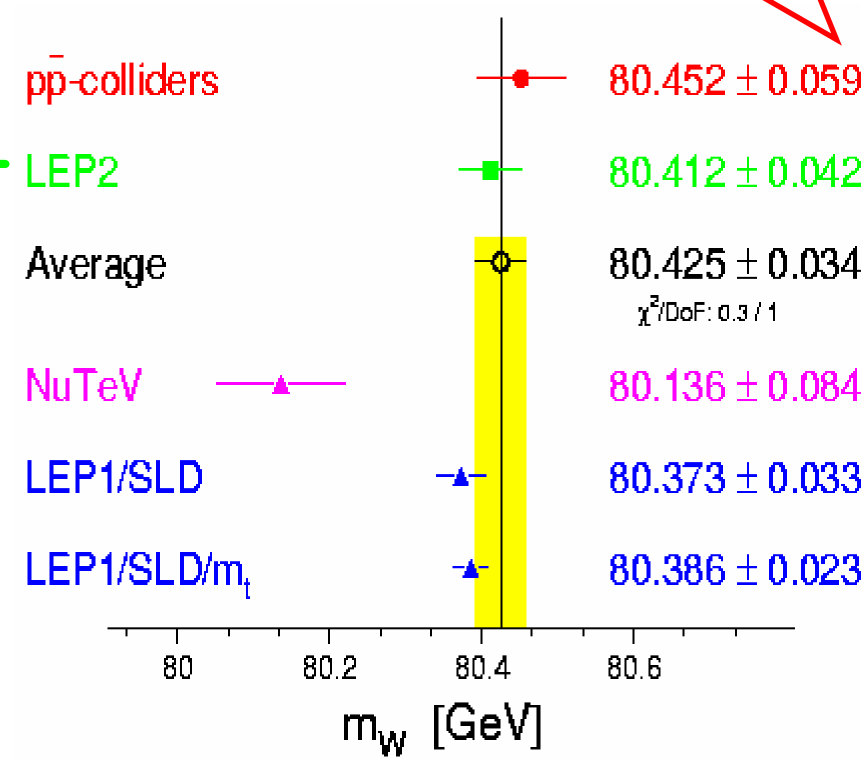
	Experiment δM_{top} (GeV)	Prediction δM_W (MeV)
Now	4.3	26
TeV	2.5	15
LHC	1.3	8
LC	0.1	-

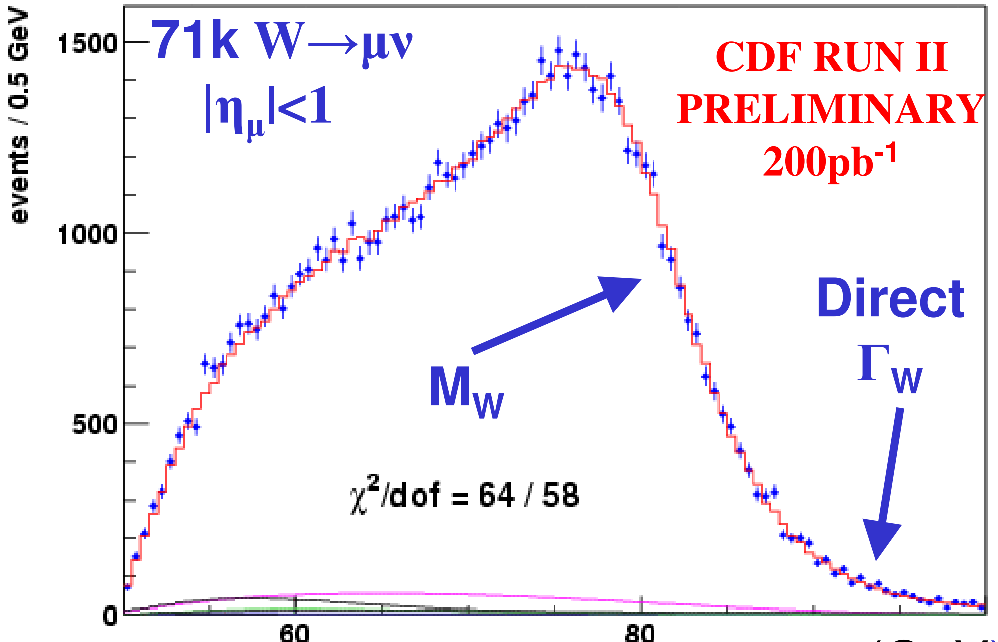
Experimental measurements of W mass

Limited by uncertainty from Final State Interactions in 4q
H. Ruiz ICHEP'04

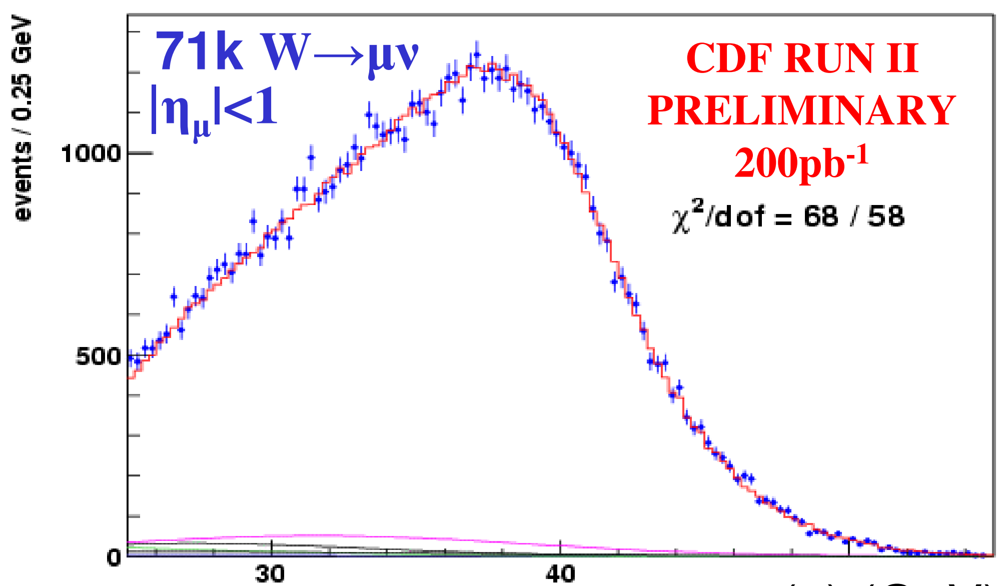
Final Run I hep-ex/0311039
First Run II soon!







$$M_T = \sqrt{2E_T^{\ell}E_T^{\nu}(1-\cos\phi_{\ell\nu})}$$



Tevatron/LHC

Measure W mass from fit to

- W Transverse mass
  - Hadronic recoil model
- Muon P_T or electron E_T
  - W p_T model

Run II fit results are still blinded!

- Statistical error 50 MeV per channel

Dominant systematic uncertainty from lepton energy/momentum scale and resolution

- Most time and effort spent on detector calibration
- This is a very difficult and demanding measurement

Run 1 W mass Systematic Uncertainties

Combined Run I uncertainty 59 MeV

How do we reach 40 MeV per experiment in Run II?

And 15 MeV per experiment at LHC?

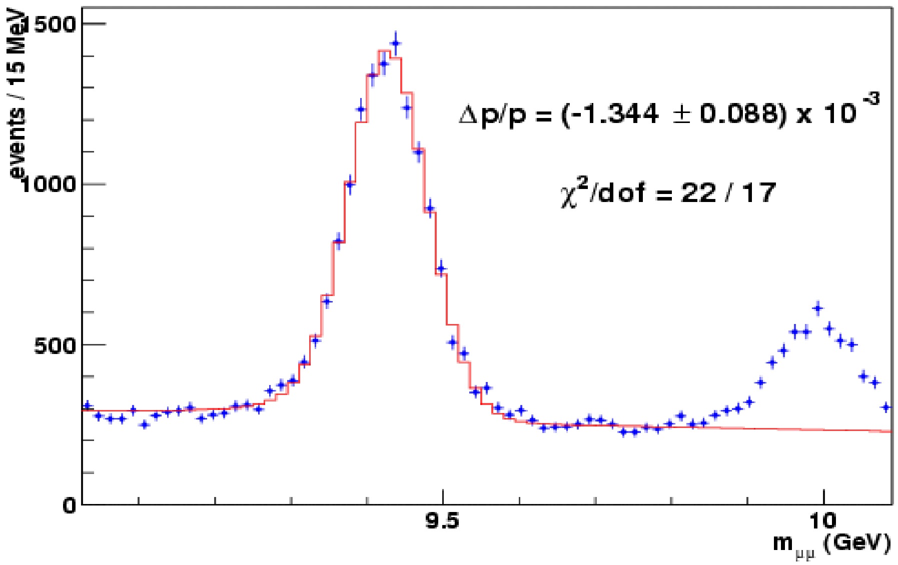
Most of the systematics are statistics-limited…get smarter with more data!

TeVatron Run 1	CDF $W\to\mu\nu$	CDF $W\to e\nu$	D0 $W\to e\nu$
W statistics	100	65	60
Lepton Energy scale	85	75	56
Lepton resolution	20	25	19
Selection bias	18	-	12
Backgrounds	25	5	9
Recoil model	35	37	35
PT(W)	20	15	15
PDFs	15	15	8
QED corrections	11	11	12
Γ_W	10	10	10

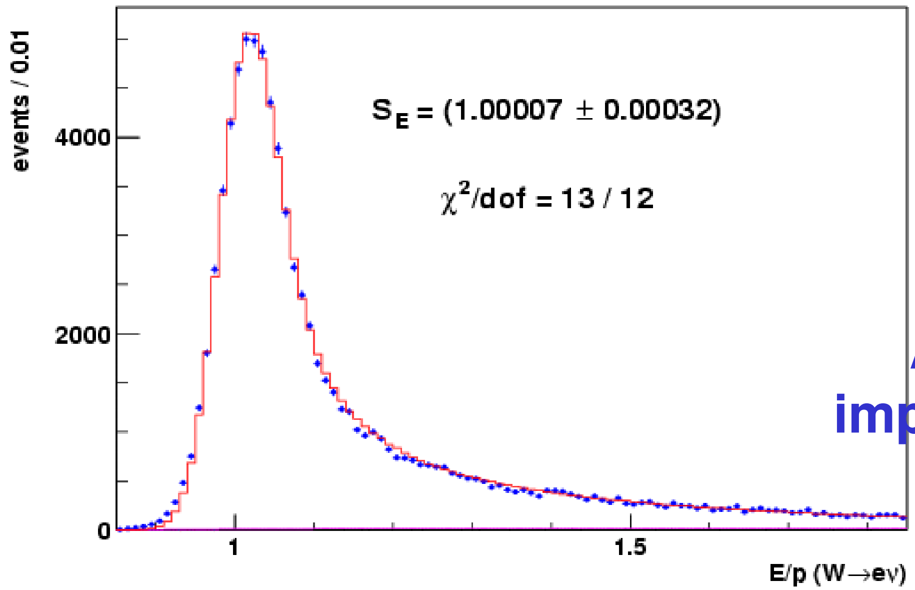
Correlated! (PDFs, QED corrections, Γ_W)

Lepton Energy scale

Some advantages to a hadron collider – many calibration samples!
And uncertainties decrease with higher statistics



Muon momentum scale/resolution
use J/ψ, Υ
cross-check with $Z \rightarrow \mu^+\mu^-$
Preliminary syst. 25 MeV !!! (87)

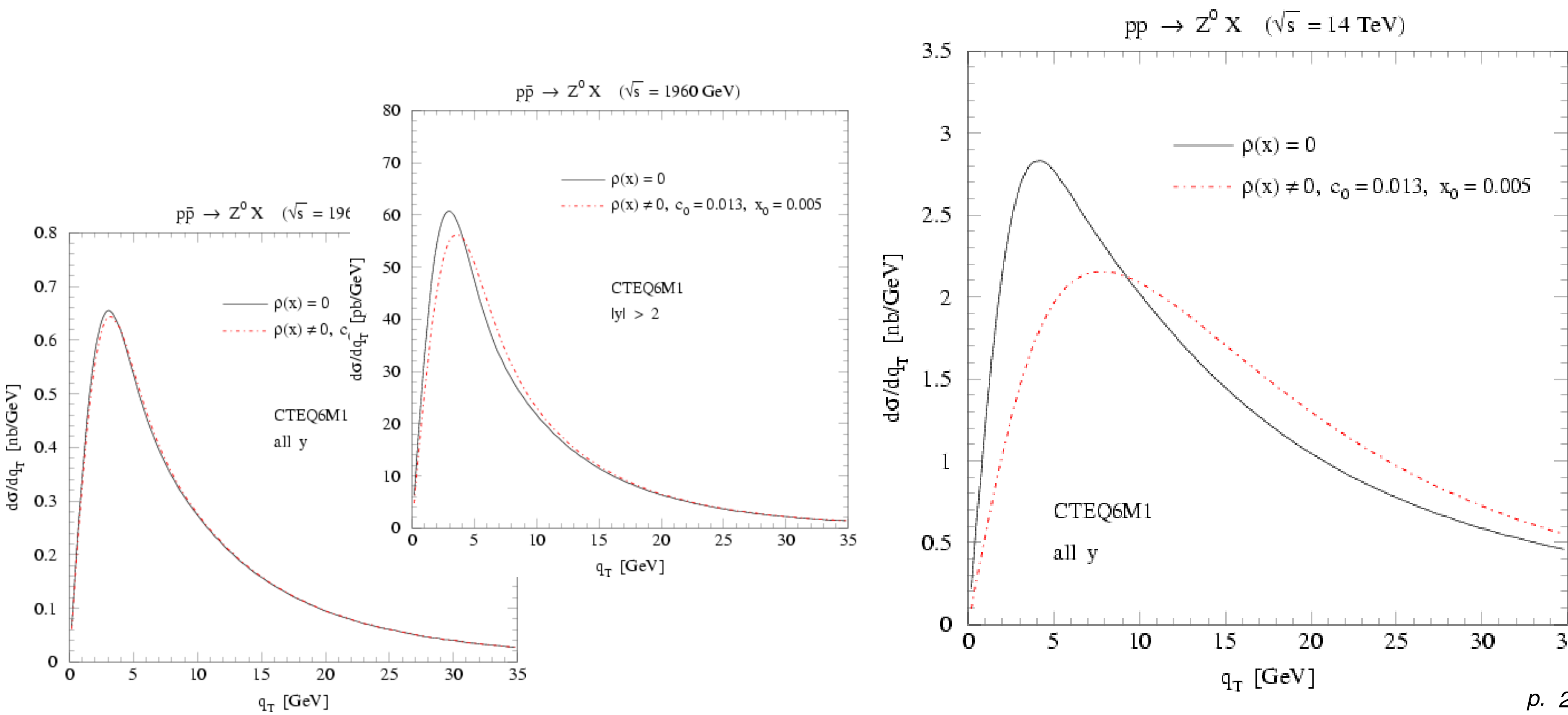


Electron energy scale/resolution
use E/p in $W \rightarrow e\nu$
cross-check with $Z \rightarrow e+e-$
Preliminary syst. 80 MeV (70)

Accurate model of detector material important due to electron bremsstrahlung
Source of 55 MeV uncertainty
ATLAS/CMS take note!

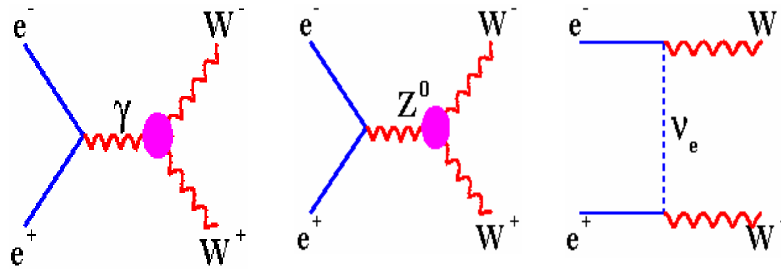
QCD & QED corrections

- QED radiative corrections
  - Multiple QED radiation — C. Calame et al hep-ph/0402235
  - QCD+QED(FSR) in RESBOS-A — Q. Cao, C.P.Yuan hep-ph/0401026
- Transverse momentum resummation at small-x?
  - TeVatron – may be visible at high rapidity — S. Berge et al., hep-ph/0401128 DPF parallel session
  - LHC important everywhere



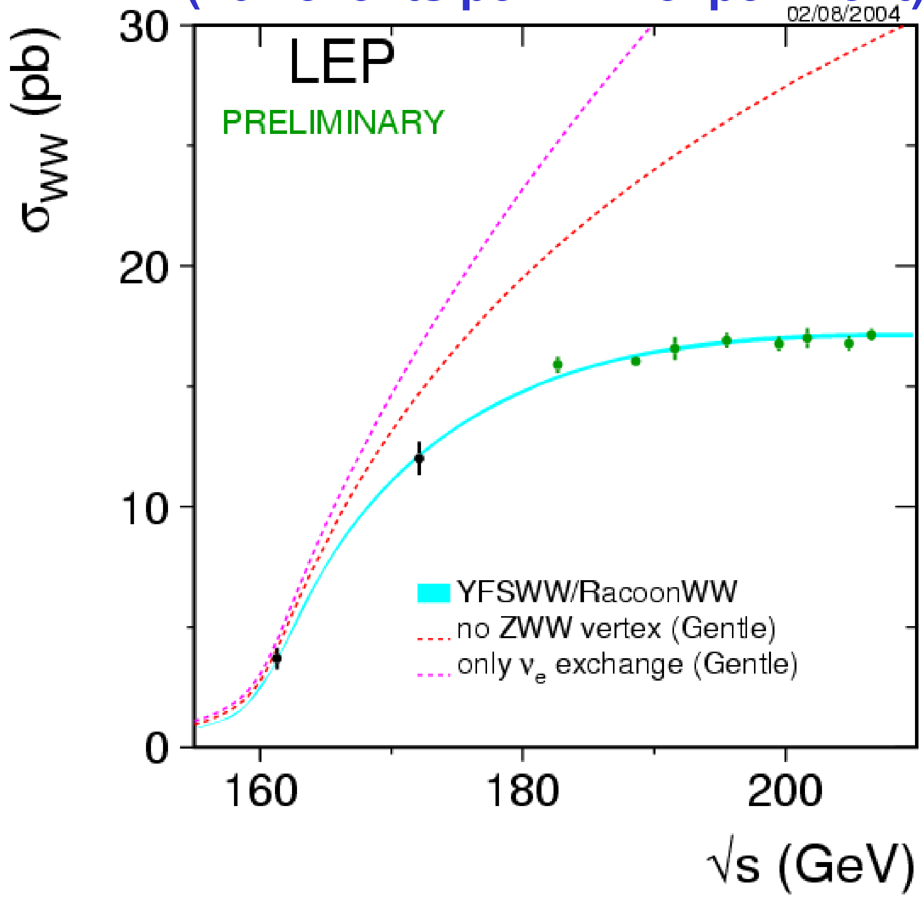
W mass ILC

- Direct reconstruction a la LEP above threshold
  - Higher statistics with ILC in qqlv channel
  - Experimental precision 5 MeV but beam energy calibration important
- Indirect from WW cross section near threshold
  - Experimental precision 6 MeV with 100 fb^{-1} and polarisation
  - But what is $\sqrt{s}$?
    - Beam spread
    - Beamstrahlung
    - ISR
  - Confident of 200ppm
    - Working on techniques to reach required 50ppm
  - Theory needs to reach 0.12% accuracy. Work needed but possible.



WW pair production

(10k events per LEP experiment)

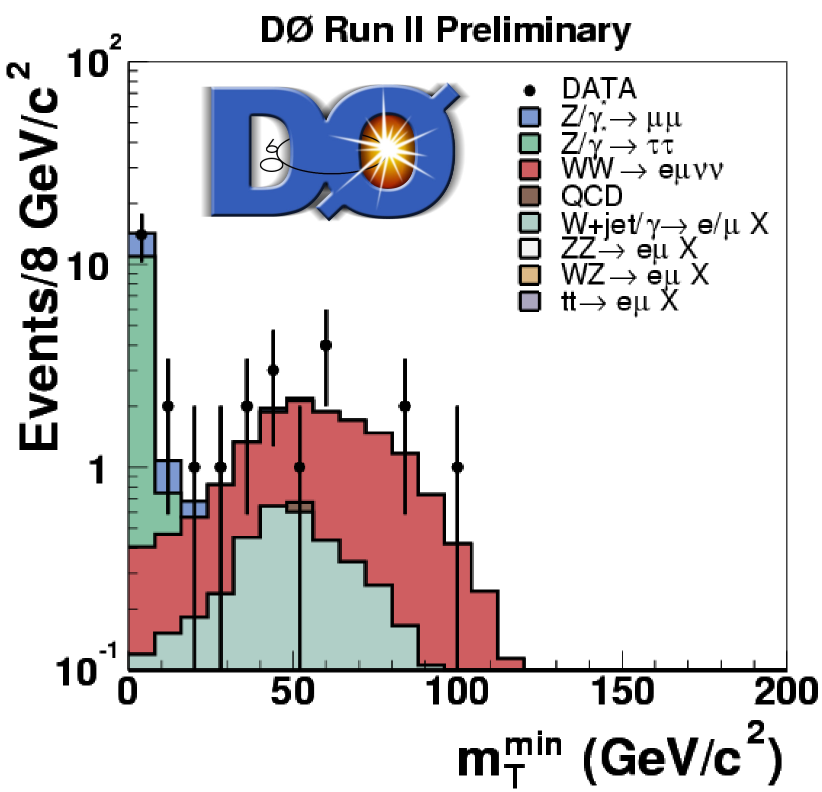


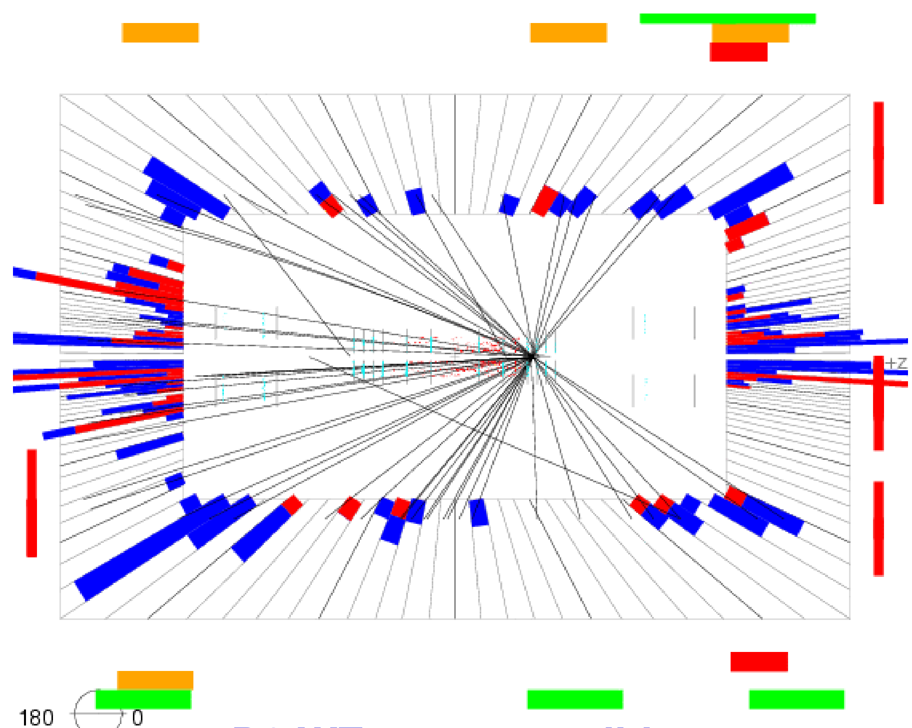
WW, WZ, ZZ production

- First observation of WW production at a hadron collider
  - TGC - Hard to beat LEP with 40k WW pairs
  - Important background to Higgs search!
- Still searching for WZ

CDF $\sigma(WW) = 14.3 \pm^{5.6}_{4.9} \pm^{1.8}_{1.8}\, pb$ $\qquad \sigma(WZ) < 13.9\, pb @ 95\%\ C.L.$

D0 $\sigma(WW) = 13.8 \pm^{4.3}_{3.8} \pm^{1.3}_{1.2}\, pb$ $\qquad \sigma(WZ) < 15.1\, pb @ 95\%\ C.L.$





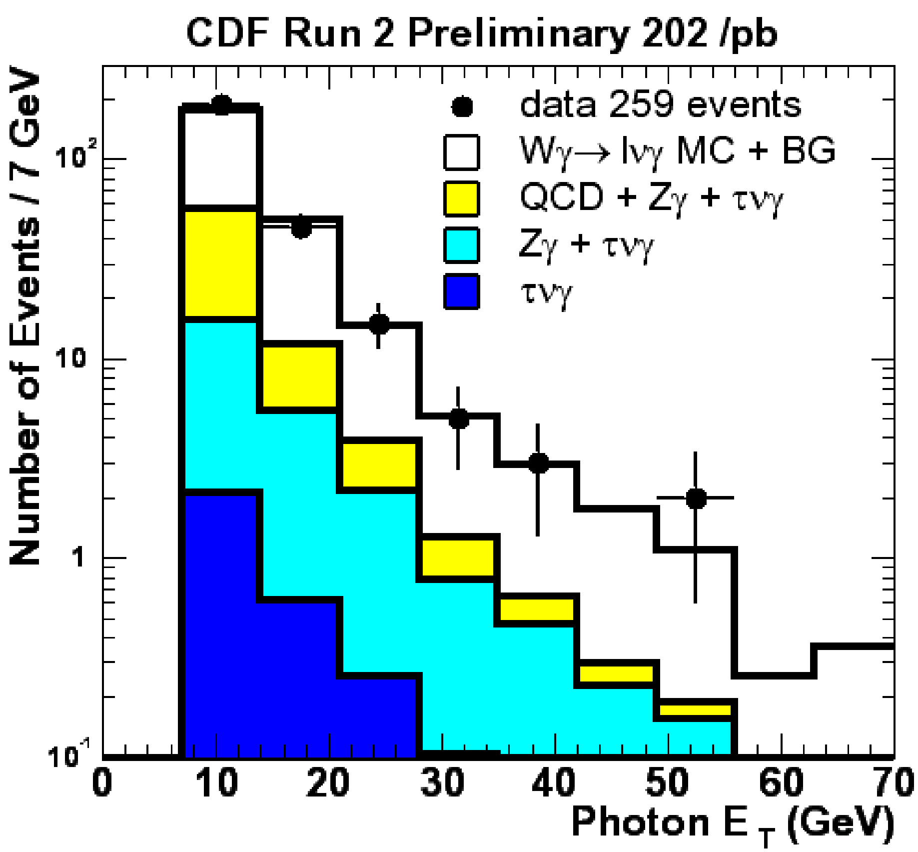
D0 WZ→μνμμ candidate

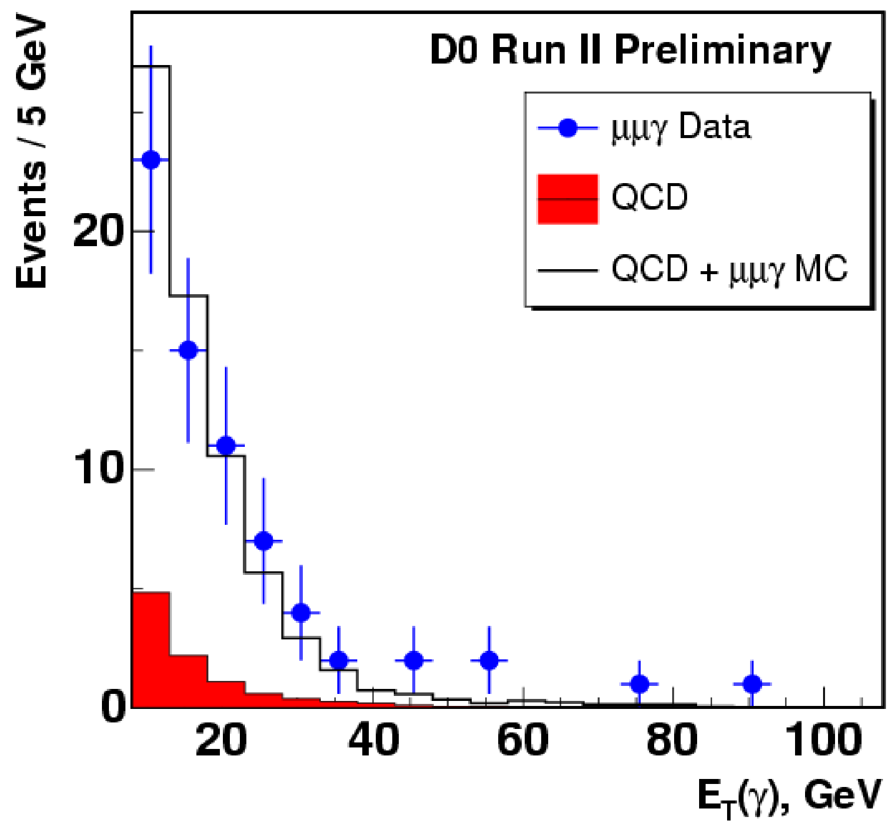
Wγ and Zγ production

- Photon p_T – sensitive to TGC
- LHC with 30 fb^{-1} improve LEP limits by factor 3-10

CDF $\sigma(W\gamma) = 19.7 \pm 1.7 \pm 2.3 pb$ $\qquad$ $\sigma(Z\gamma) = 5.3 \pm 0.6 \pm 0.4 pb$

D0 $\sigma(W\gamma) = 19.3 \pm 6.7 \pm 1.3 pb$ $\qquad$ $\sigma(Z\gamma) = 3.9 \pm 0.5 \pm 0.3 pb$





Top Physics

Top discovered by CDF and D0 in 1995

Very heavy! Top mass = 178.0 ± 4.3 GeV

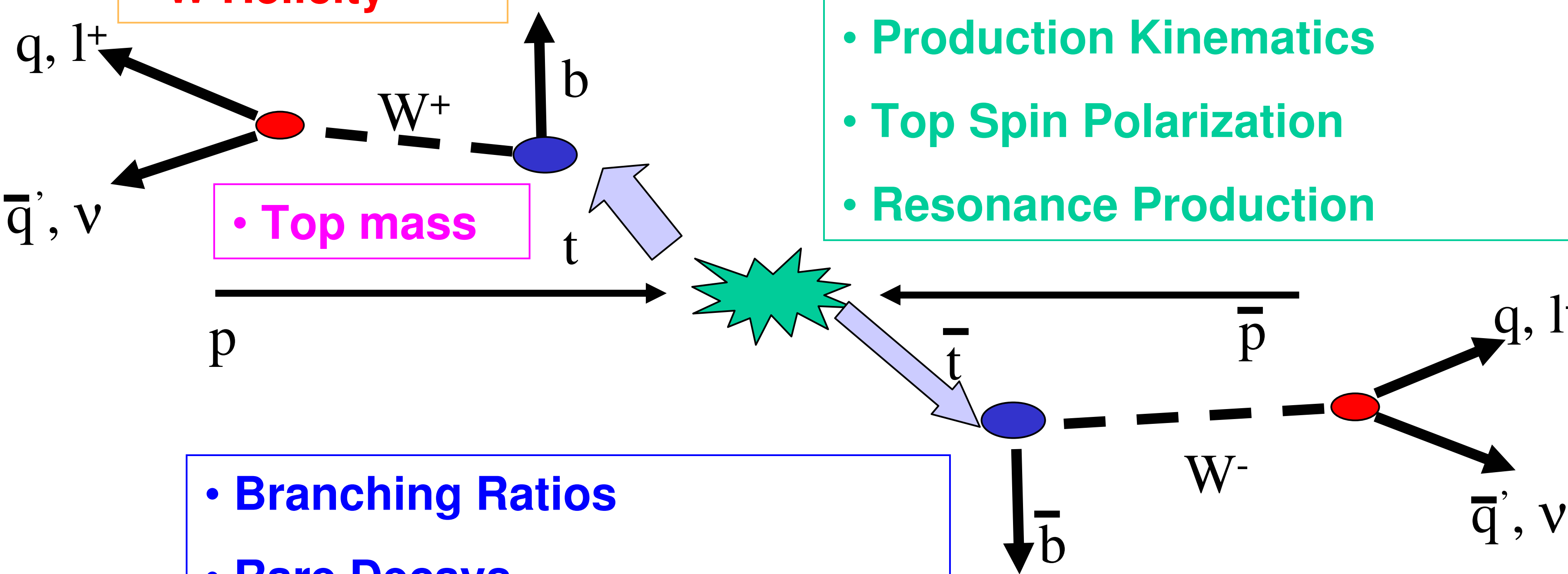
But only ~30 events per experiment

!!!Want more top events to study properties!!!

Run II σ 30% higher at $\sqrt{s}$=1.96 TeV

Similar mass to Gold atom! 35 times heavier than b quark

- **W Helicity**
- **Top mass**



- **Production Cross Section**
- **Production Kinematics**
- **Top Spin Polarization**
- **Resonance Production**

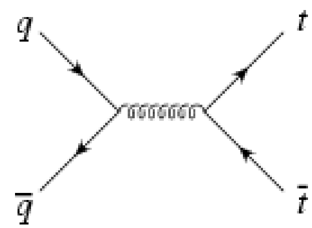
- **Branching Ratios**
- **Rare Decays**
- **Non-SM decay ($t \rightarrow H^+ b$)**

Top Production

Top pairs via strong interaction

LHC √s=14 TeV
833 ± 100 pb

0.8 events per second at initial/low lumi LHC



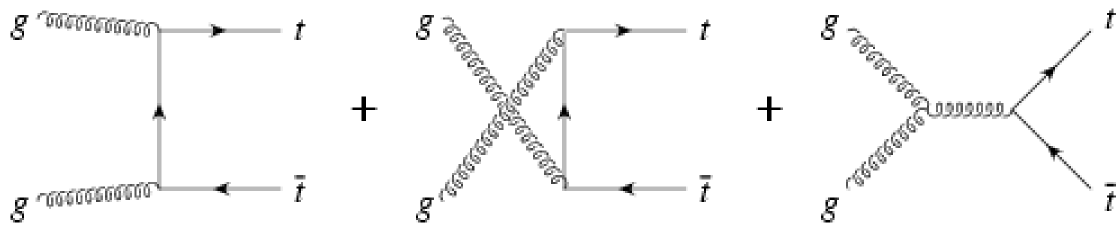
85% qq 15% gg
10% qq 90% gg

TeVatron √s=1.96 TeV

m_t (GeV)	- PDF	NLO σ(pb)	+PDF
170	6.8	7.8	8.7
175	5.8	6.7	7.4
180	5.0	5.7	6.3

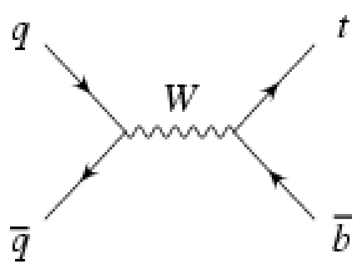
0.8 events per hour at recent lumi

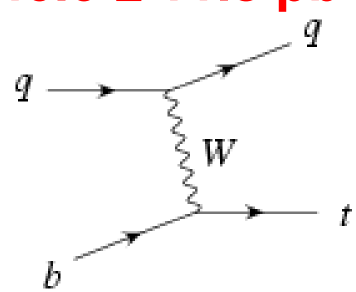
Bonciani et al hep-ph/0303085
Kidonakis et al PRD 68 114014

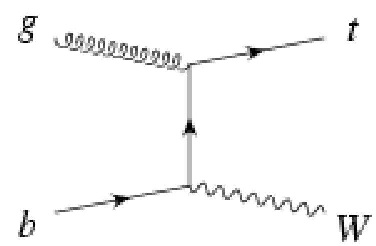


Single top via weak interaction

0.88 ± 0.11 pb	1.98 ± 0.25 pb	<0.1 pb
10.6 ± 1.1 pb	246.6 ± 11.8 pb	62.0+16.6-3.6 pb





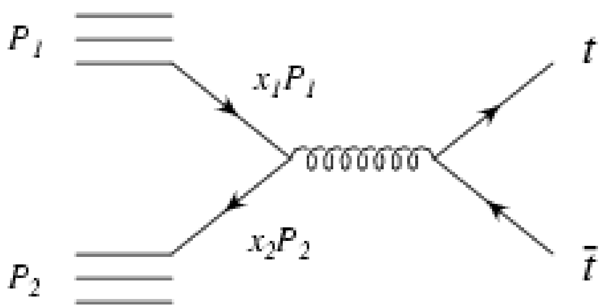


Z. Sullivan hep-ph/0408049

A.Belyaev et al PRD 63, 034012

Top pair production

- **Why is qq annihilation dominant at the TeVatron but gg fusion at LHC?**
- **Why does cross section increase by x100 for only x7 increase in √s?**

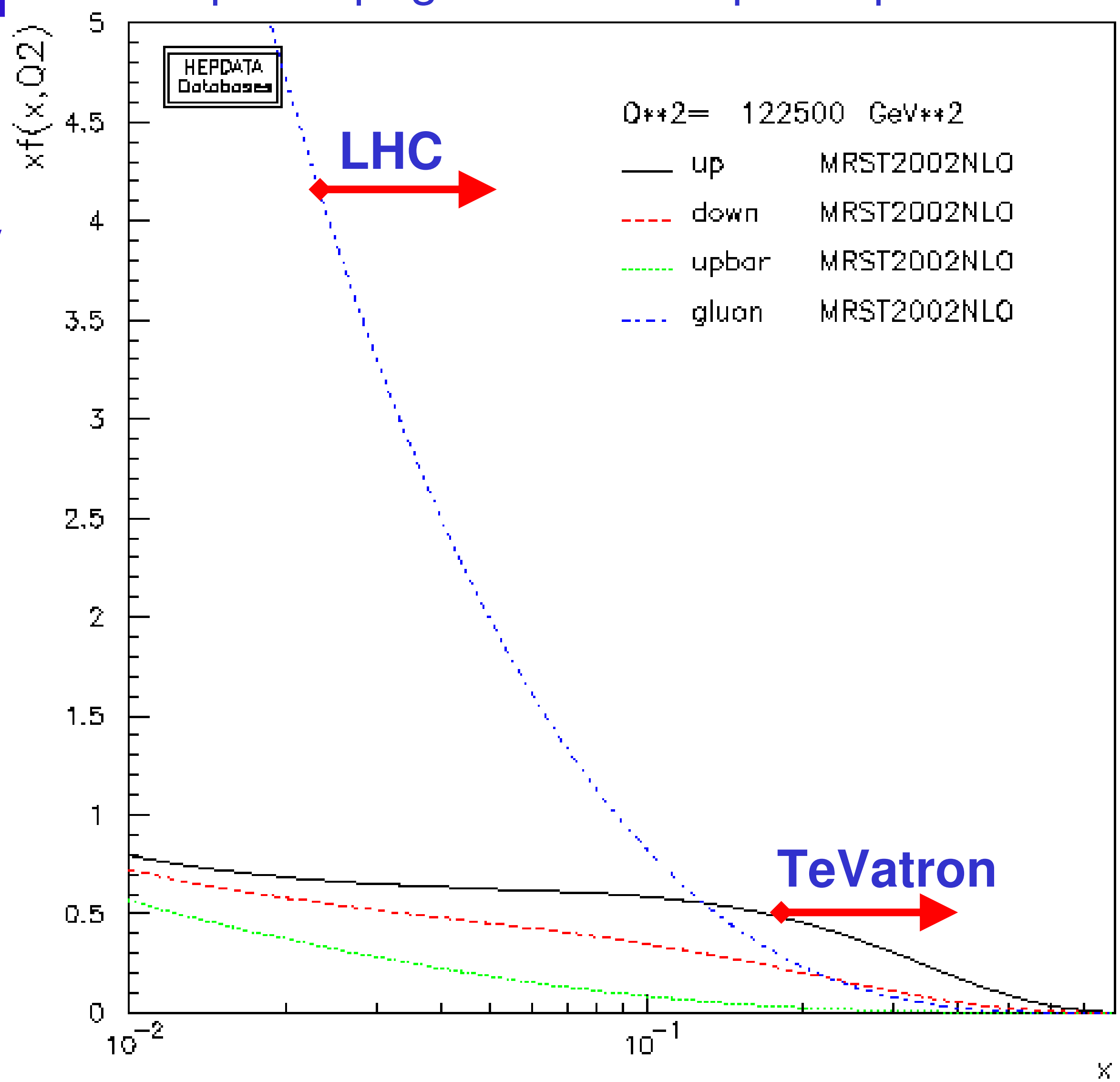


$$x \approx \frac{m_t}{\sqrt{s}/2}$$

$$\sqrt{s} = 1.96\,TeV\; x \approx 0.18$$

$$\sqrt{s} = 14\,TeV \quad x \approx 0.025$$

http://durpdg.dur.ac.uk/hepdata/pdf3.html

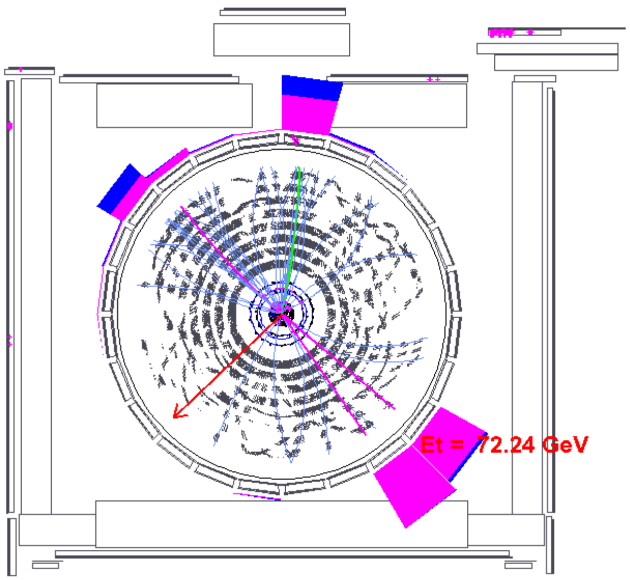


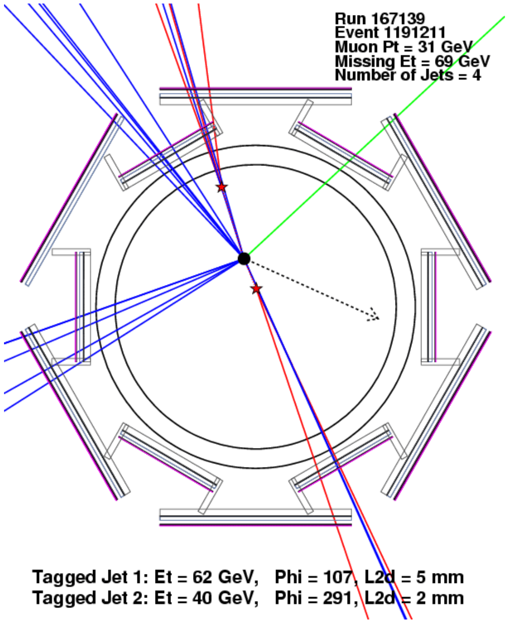
Top Decay

- BR(t→Wb) ≈ 100% in Standard Model
- Top lifetime 10^{-25} s (Γ(t→Wb)=1.5 GeV)
  - No top mesons or baryons (Λ_{QCD}=0.1 GeV)
  - Top spin observable via decay products

Final States in Top Pair Production

5% Dilepton	30% Lepton+Jets	46% All hadronic
Both W → lν (l=e or μ)	One W → lν (l=e or μ)	Both W → qq
2 leptons	1 lepton	
Missing ET	Missing ET	
2 b-jets	4 jets (2 b-jets)	6 jets (2 b-jets)





2 Lepton/isolated track p_T>20 GeV
MET>25 GeV
MET>40 GeV if m_{ll} [76,106] GeV
≥2 jets E_T>20 GeV

Dilepton

Observe 19 lepton/isolated track events in 200 pb^{-1}
Estimated background 6.9 ± 1.7 events
Observe 13 lepton/lepton events in 200pb-1
Estimated background 2.7 ±0.7 events

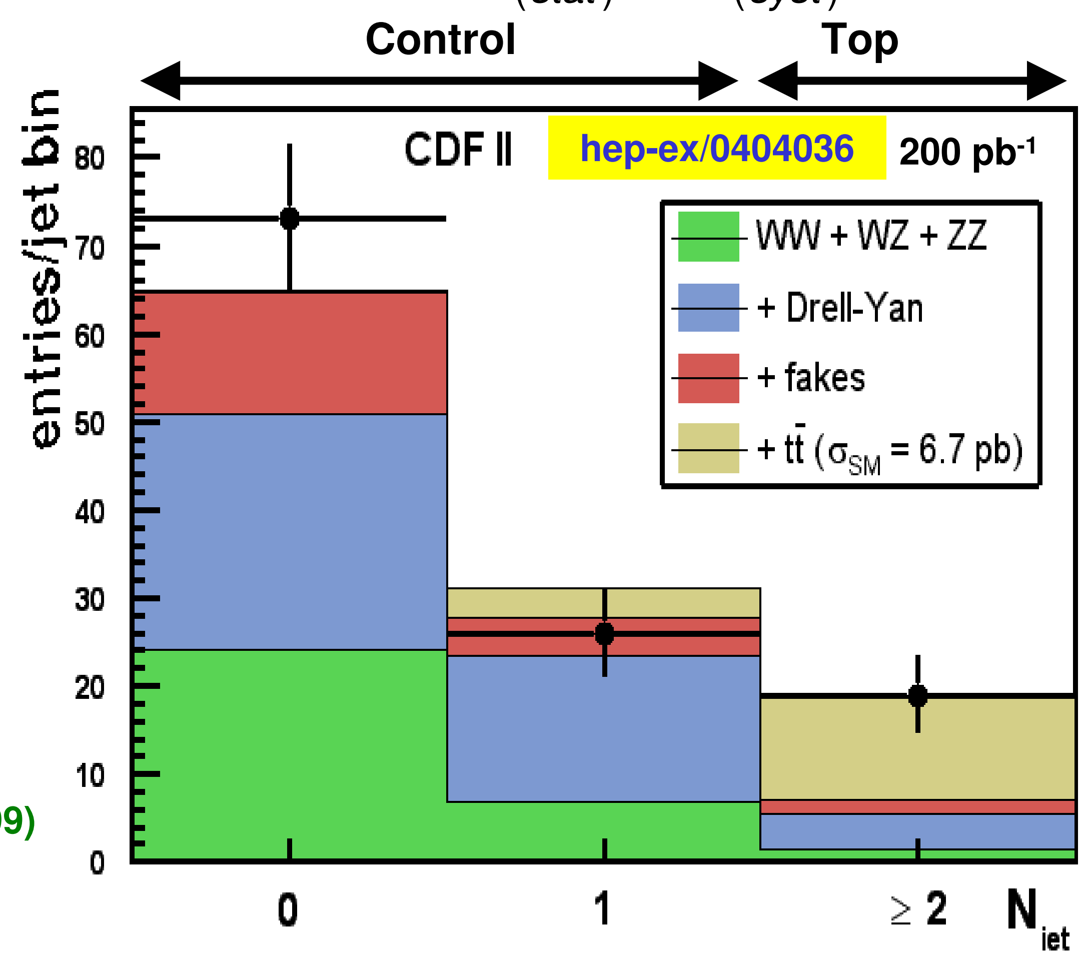
$$\sigma(t\bar{t}) = 7.0 \pm^{2.4}_{2.1(stat)} \pm^{1.6}_{1.2(syst)} \textbf{pb}$$

Background estimates

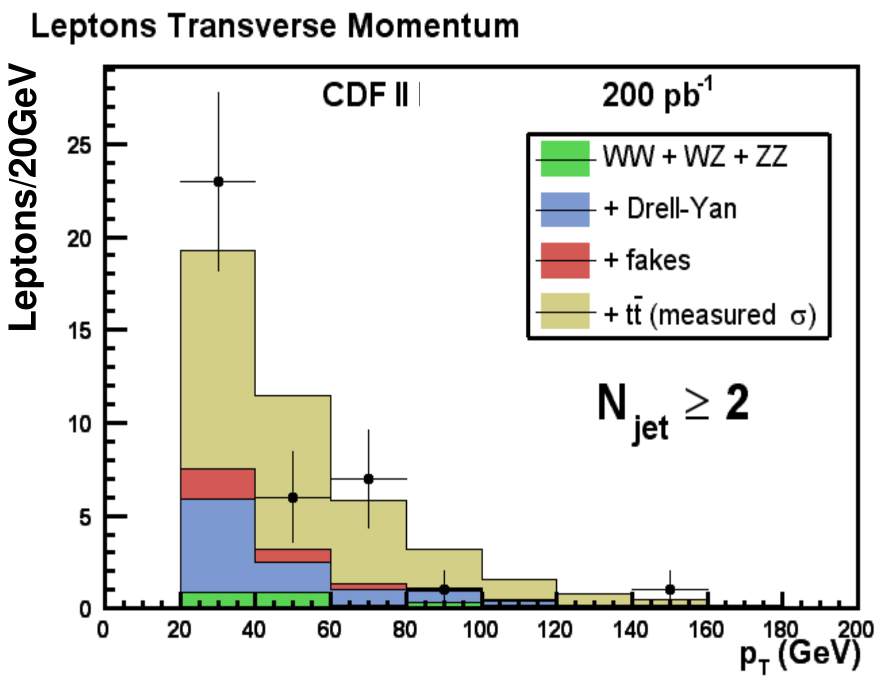
Data

Shape PYTHIA MC
Normalisation from data
Statistics-limited

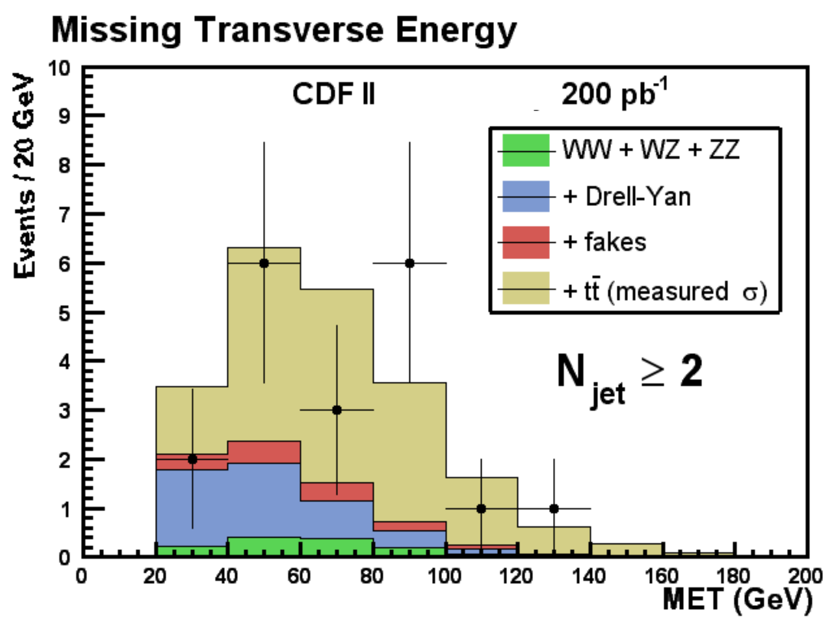
Shape PYTHIA MC
Normalisation from NLO
Campbell, Ellis
PRD60 113006 (1999)

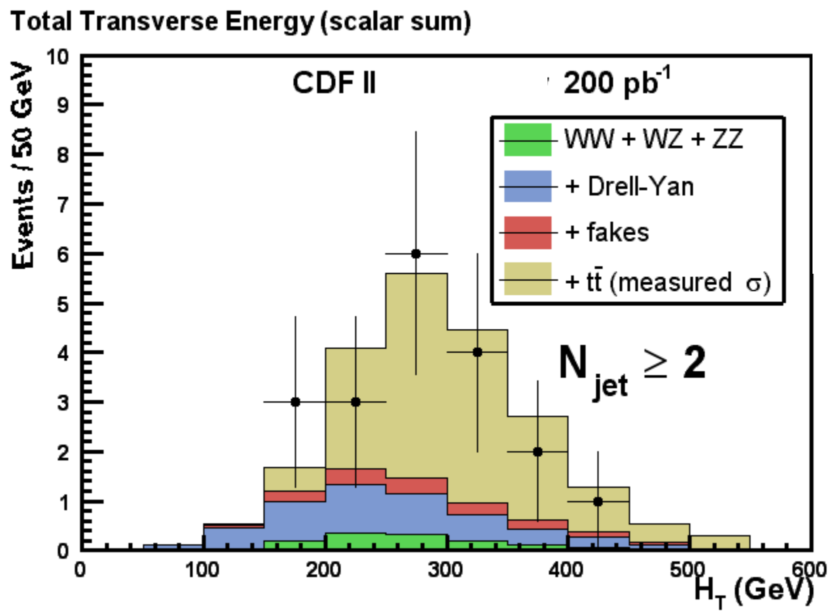


Dilepton kinematics



Kinematics consistent with Standard Model so far

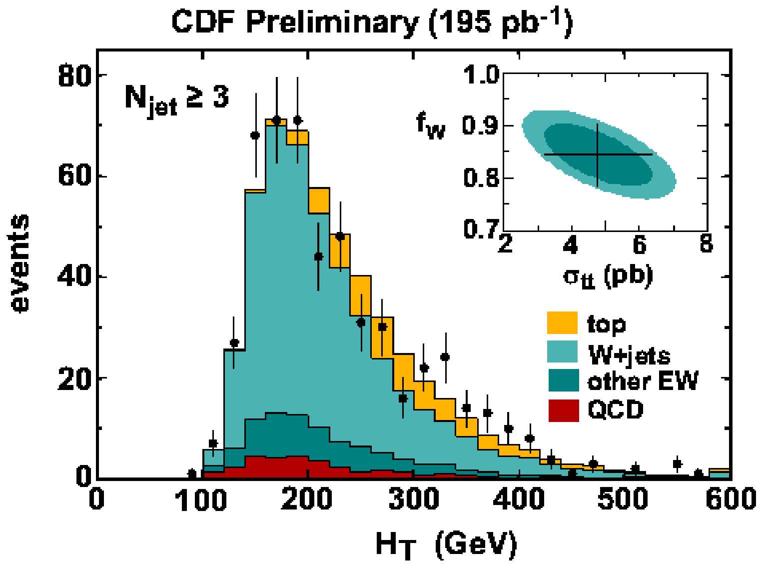


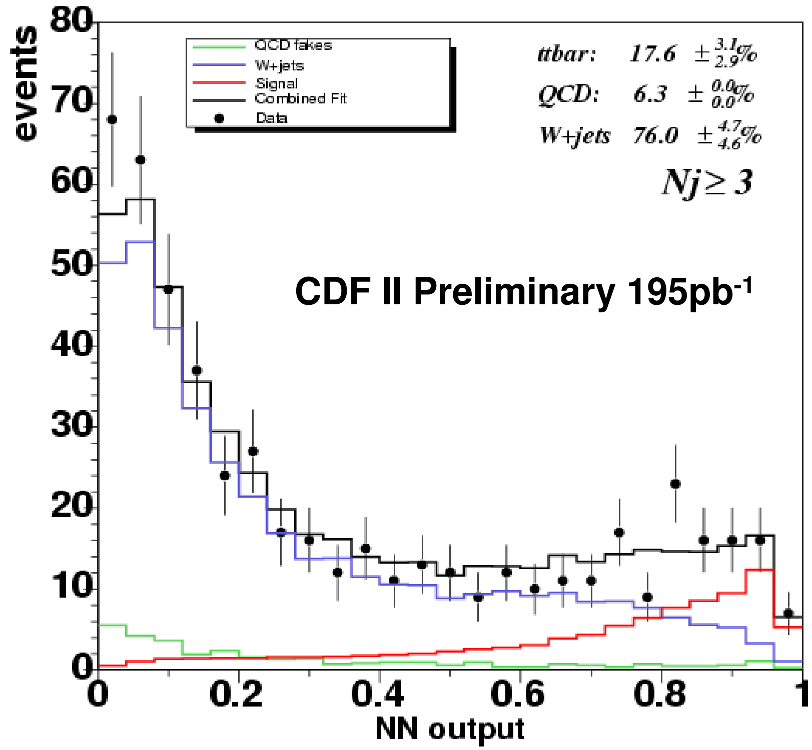


H_T is scalar sum of transverse energies of jets, leptons and MET

Lepton+Jets

1 Lepton p_T>20 GeV
MET>20 GeV
≥3 jets E_T>15 GeV, |η|<2.0





Dominant background from W+jets

Go beyond single variable like H_T
Combine seven kinematic variables in a 7-7-1 neural network to improve discrimination

Top shape from PYTHIA

W+jets background shape from ALPGEN+HERWIG MC

Observe 519 events
Fit result 91.3 ± $15.6_{(stat)}$ top events

$$\sigma(t\bar{t}) = 6.7 \pm 1.1_{(stat)} \pm 1.6_{(syst)}\,\textbf{pb}$$

Dominant systematics are
Jet energy scale uncertainty
Q^2 scale for W+jets MC

b-Tagging: Vertices and Soft Muons

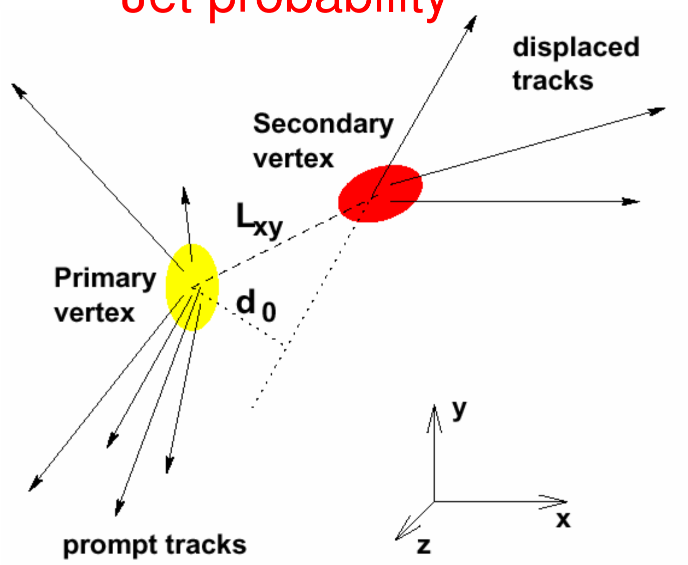
Recall Standard Model $t \to Wb$ branching ratio is ~100%

- Every top signal event contains 2 B hadrons
- Only 1-2% of dominant W+jets background contains heavy flavor

Improve S:B by exploiting knowledge that B hadrons

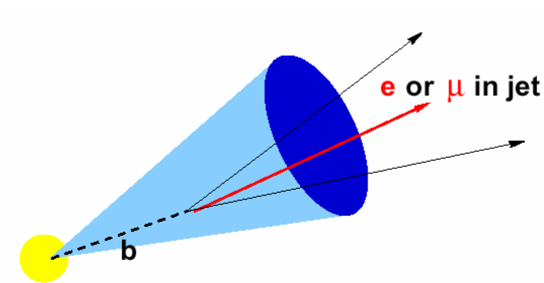
are long-lived and massive

Vertex displaced tracks
Jet probability



may decay semileptonically

Identify low-p_T muon



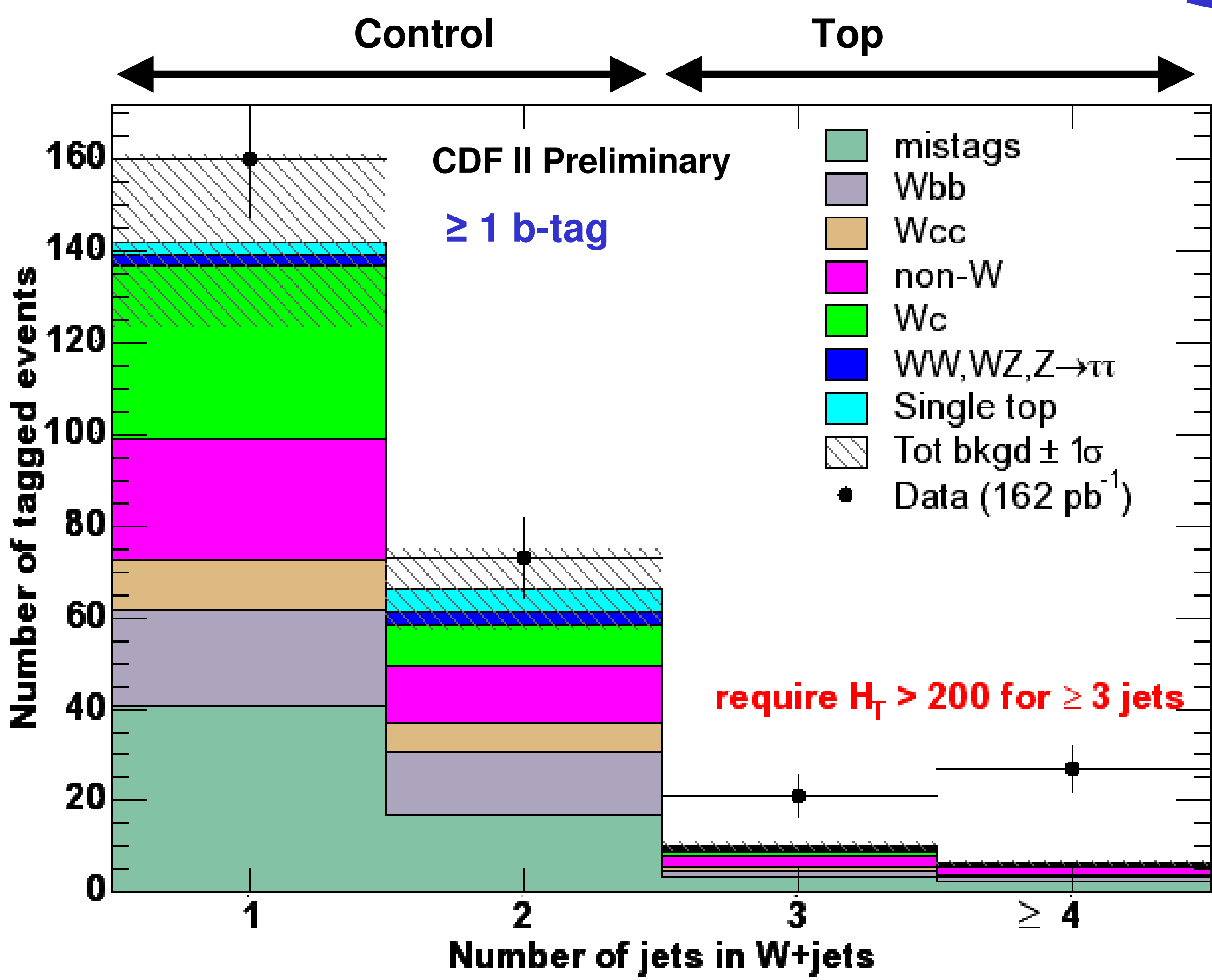
- $b \to \ell \nu c$ (BR ~ 20%)
- $b \to c \to \ell \nu s$ (BR ~ 20%)

55%	Top Event Tag Efficiency	15%
0.5%	False Tag Rate (QCD jets)	3.6%

Lepton+Jets: ≥1 SVX b-tag

Observe 48 events with H_T>200 GeV in 162 pb^{-1}
Estimated background 13.8 ±2.0 events

$$\sigma(t\bar{t}) = 5.6 \pm^{1.2}_{1.0(stat)} \pm^{1.0}_{0.7(syst)} pb$$



Background estimate
b-tag efficiency

Mistags from W+light flavour
Parameterise from Data
f(E_T, η, φ, ntracks, ΣE_T)

W+heavy flavour
Assume fraction
well-predicted by MC

$$\varepsilon^{Wbb}_{b-tag} \; \frac{\sigma^{LO}(Wbb)}{\sigma^{LO}(W + jets)}$$

Non-W from data

Diboson, Single top
Shape PYTHIA MC
Normalisation from NLO

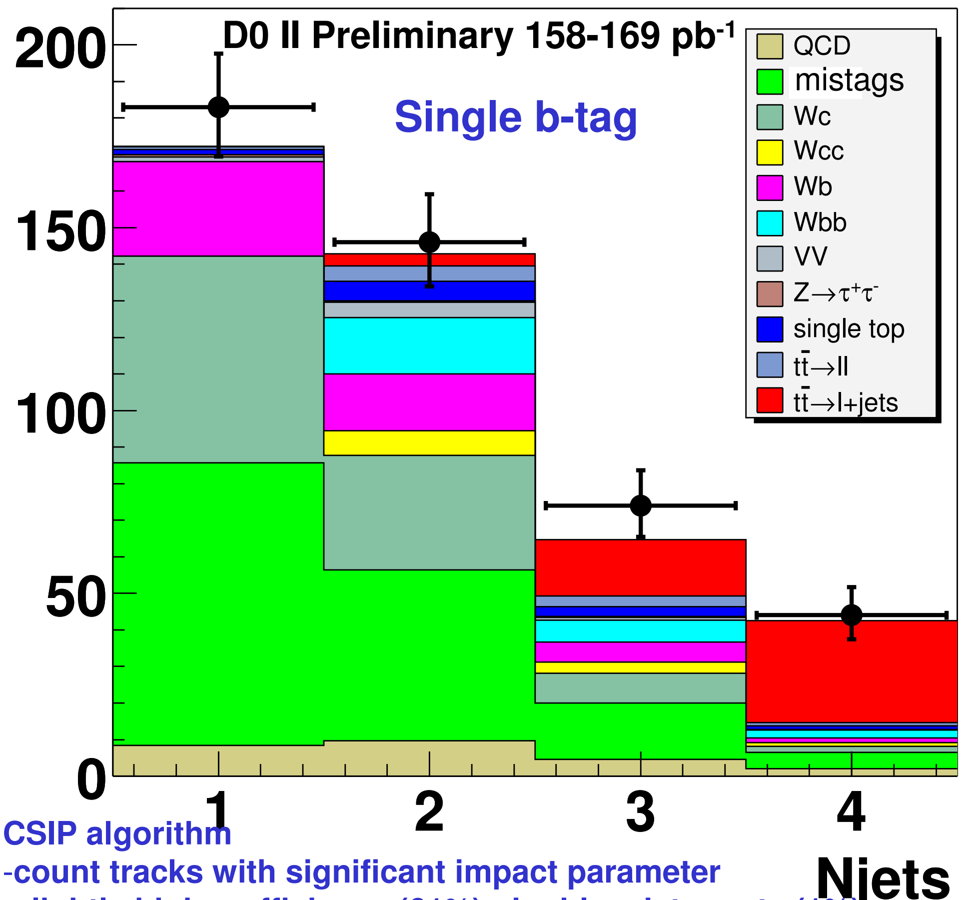
Lepton+Jets: Single vs Double b-tags

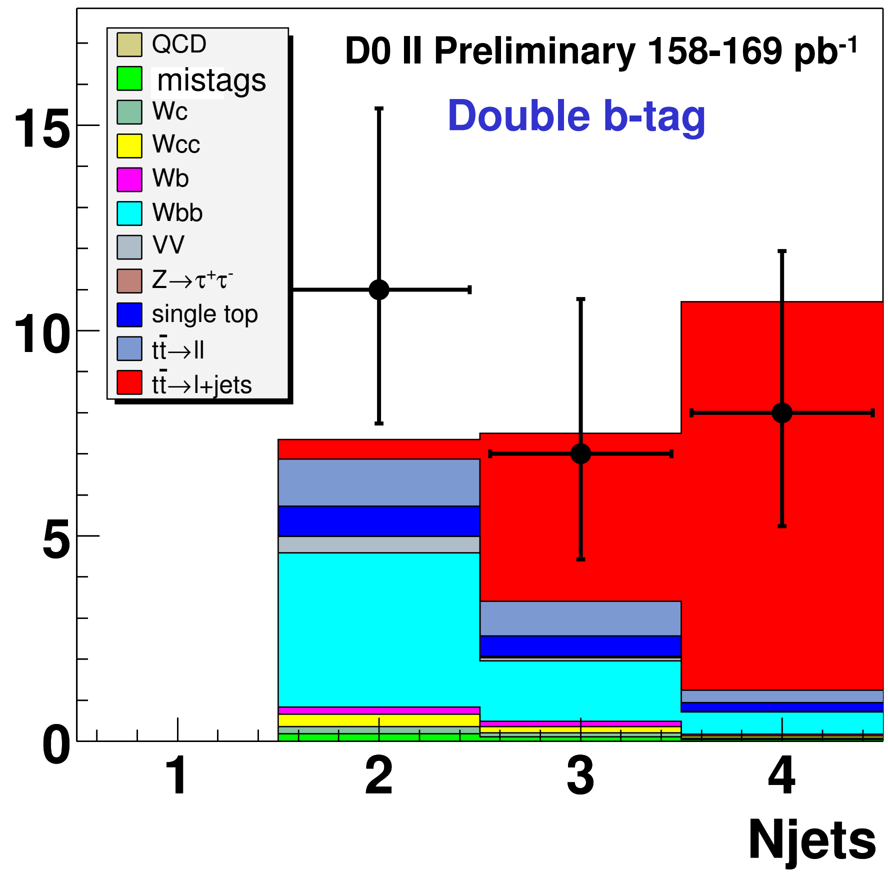
Double-tagged events – cleanest sample of top quarks!

Separate into 8 subsamples – single or double tag, 3 or ≥4 jets, e or μ

$$\sigma(t\bar{t}) = 7.2 \pm^{1.3}_{1.2(stat)} \pm^{1.9}_{1.4(syst)} pb$$

Background estimate
b-tag efficiency





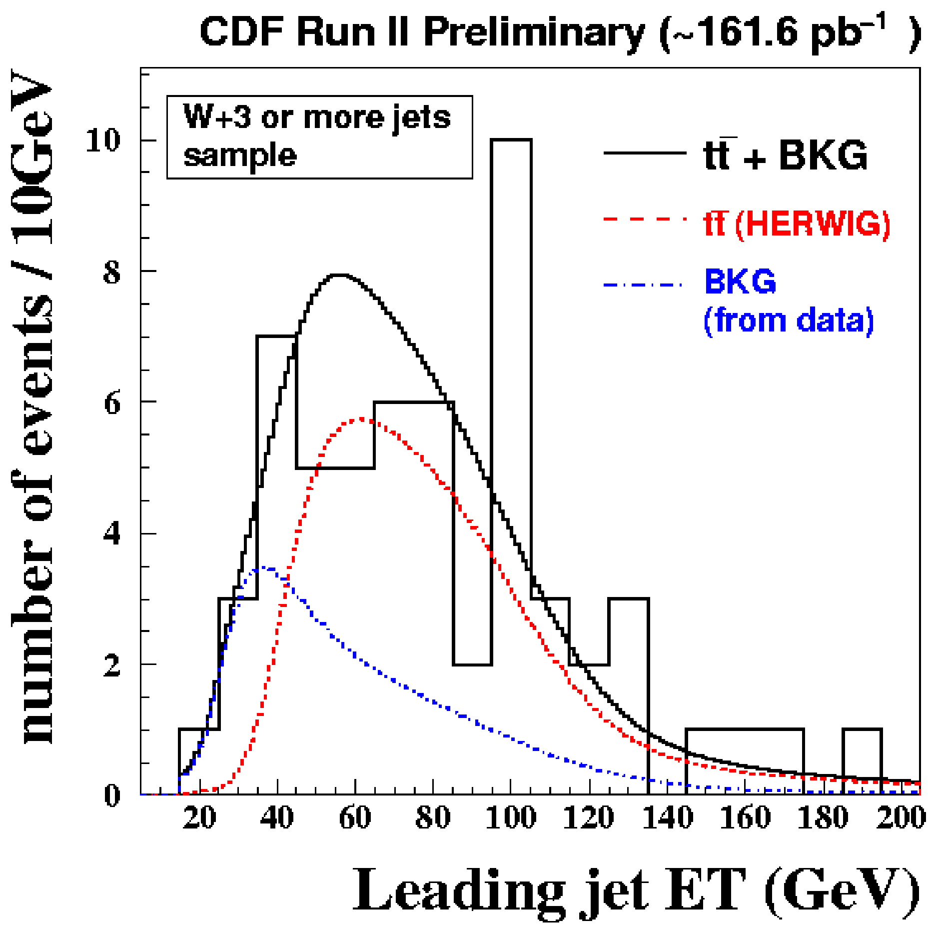
CSIP algorithm
-count tracks with significant impact parameter
-slightly higher efficiency (61%), double mistag rate (1%)

Lepton+jets: ≥1SVX b-tag & kinematics

Avoid dependence on W+jets MC
Use 0-tag data to model W+jets background shape

$$\sigma(t\bar{t}) = 6.0 \pm^{1.5}_{1.8(stat)} \pm 0.8_{(syst)}\, pb$$

Top acceptance
Background statistics

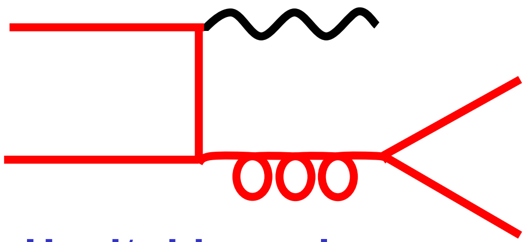


Top acceptance and shape
from PYTHIA MC
Try MC@NLO in future

However
Experimental systematics dominate:
jet energy scale uncertainty
b-tag efficiency uncertainty
Both will decrease with more data

MC issue #1: How to use LO ME?

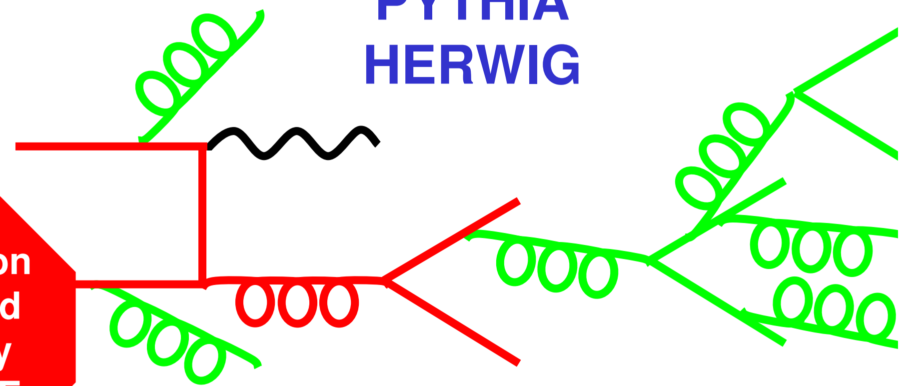
Leading Order Matrix Element
ALPGEN W,Z+≤6 jets
MADGRAPH W+≤9 jets



Good: Hard/wide-angle
Bad: Soft/collinear (ME diverges)

STOP!
Hard gluon described better by W+3p ME

Parton Shower MC
PYTHIA
HERWIG

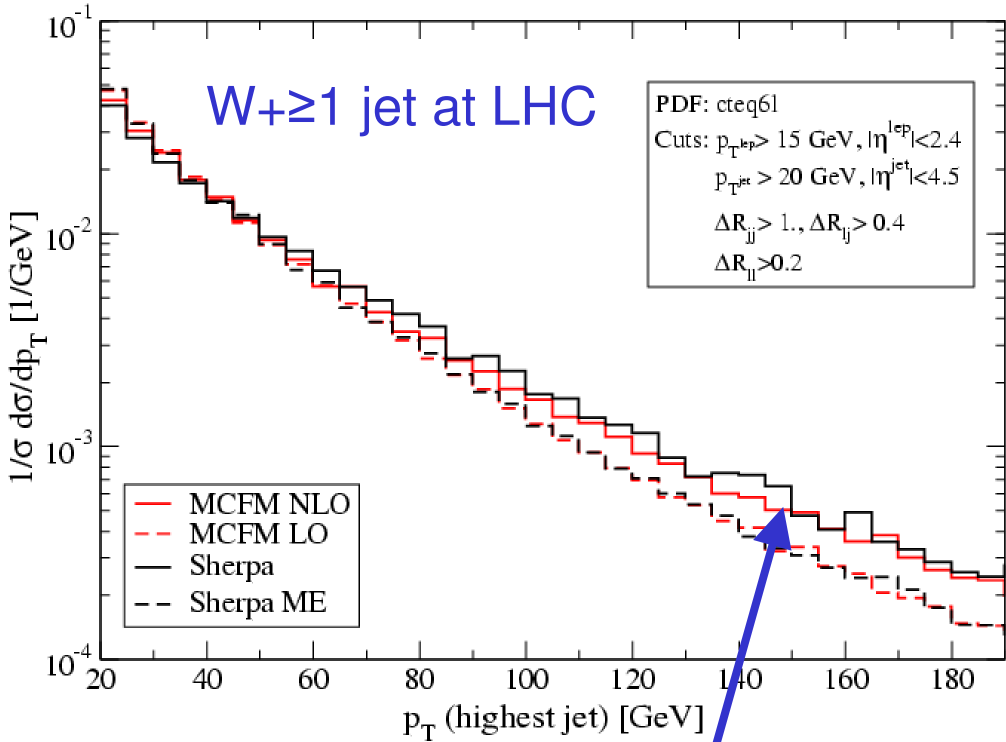


Bad: Hard/wide-angle
Good: Soft/collinear

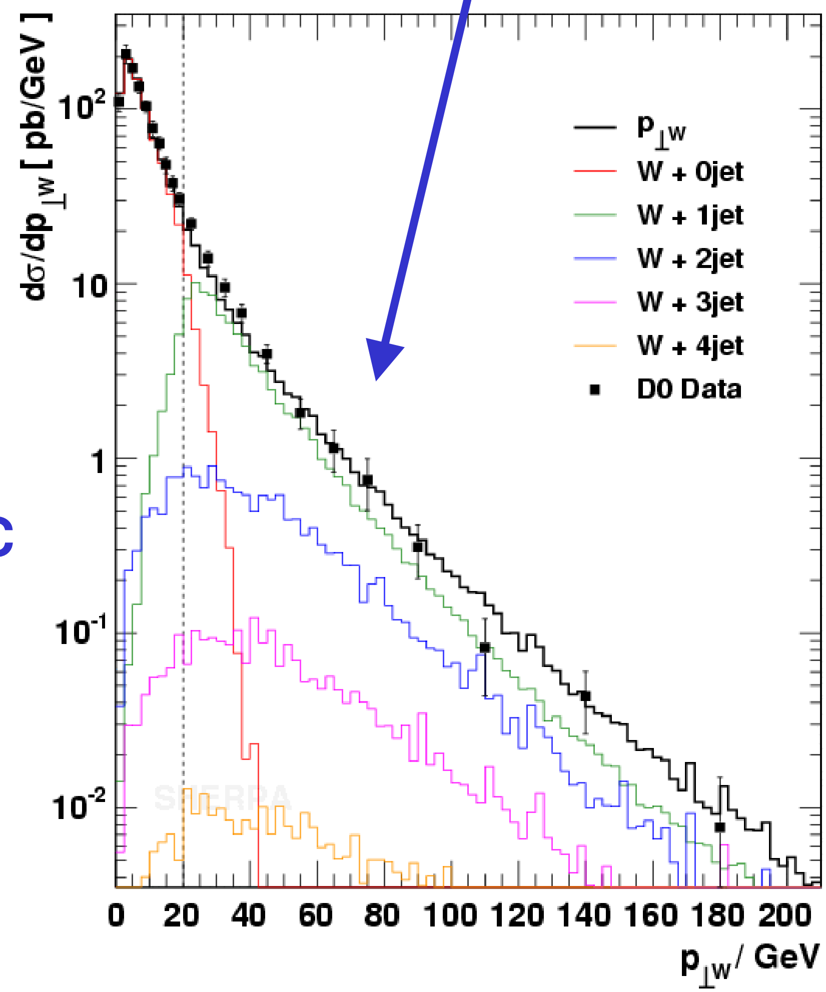
Interpolation needed!
"matching"
Veto hard emissions in Parton Shower
that are already accounted for by Matrix Element
"avoid double-counting"

CKKW for e+e- hep-ph/0109231
Adapted to hadron collider
PYTHIA/HERWIG S. Mrenna, P. Richardson hep-ph/0312274
SHERPA F. Krauss hep-ph/0407365
Alternative approach from M. Mangano

MC issue #1: how to use LO ME?



Add matched LO Matrix Element MC from 0 to n partons to obtain inclusive W+jet model!



Leading jet pT in W+≥1 jet
Shape of Matched LO Matrix Element MC agrees with NLO prediction
Total rate still needs scale-factor

Important for modeling of kinematics at TeVatron and LHC

SHERPA F. Krauss hep-ph/0407365

MC issue #2: how to use NLO?

NLO theory up to W+2jets and Wbb

MCFM J. Campbell, R.K. Ellis http://mcfm.fnal.gov

Calculations still needed

W+3jets (a distant goal)

Nagy & Soper, hep-ph/0308127
Giele & Glover, hep-ph/0402152

Inclusion of b mass effects in Wbb

W. Beenaker et al., hep-ph/0211352
S. Dawson et al., hep-ph/0311216

	Good	Bad	Users
NLO NNLO	Hard emissions Total rates W+jets Heavy flavour fraction at NLO J. Huston, J. Campbell hep-ph/0405276	Soft&collinear emissions Hadronisation No events	Theorists
MC	Soft&collinear emissions Hadronisation Outputs events	Hard emissions Total rates For example, W+4jets is $O(\alpha_s^4)$ Scale uncertainty of 10% leads to 40% uncertainty on total rate	Experimentalists

MC ∩ NLO = Ø ?

(From S. Frixione, HCP'04)

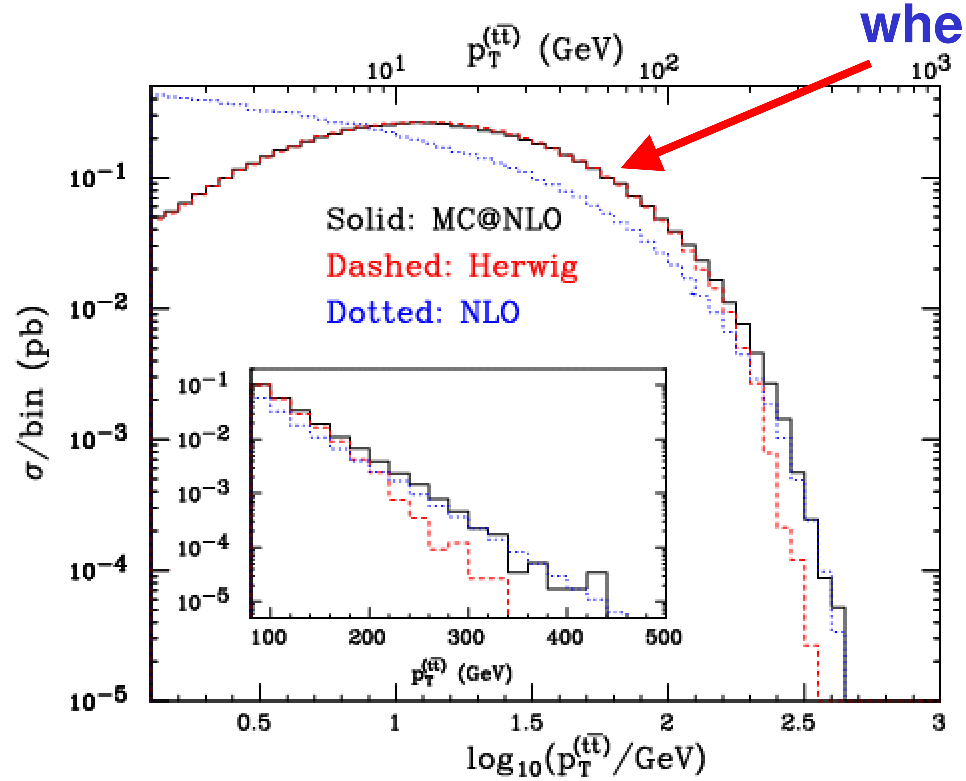
MC issue #2: how to use NLO?

MC@NLO

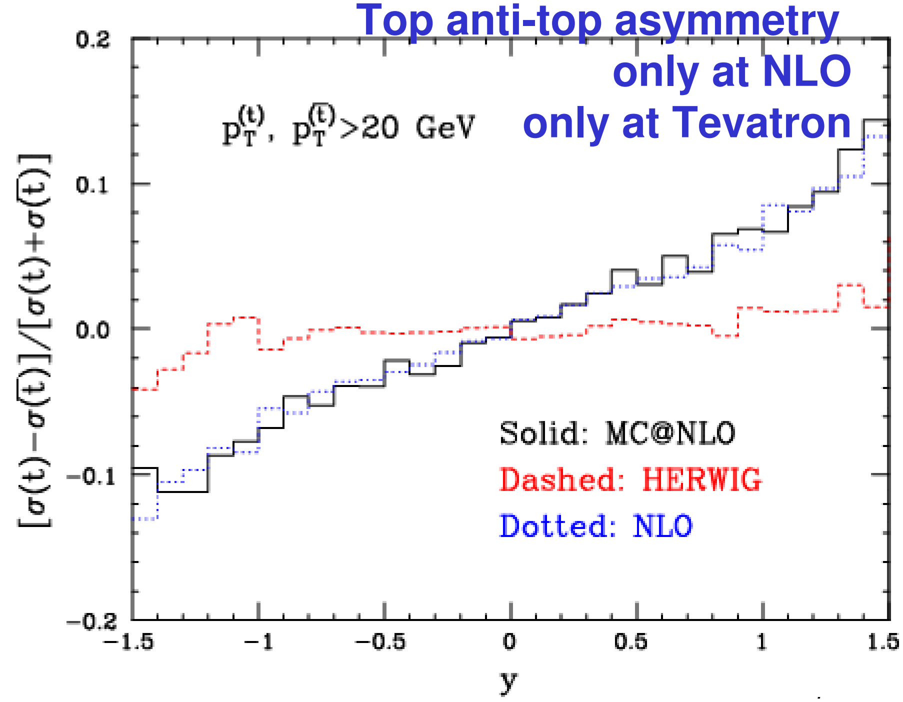
S. Frixione, P. Nason, B. Webber
hep-ph/0305252

Studies with realistic experimental cuts for these processes:
Single vector boson W, Z – no W/Z+jets yet!
Diboson WW, WZ, ZZ
Top pairs
Higgs
Lepton pairs

Top acceptance and kinematics at NLO
e.g. p_T of ttbar system at the Tevatron
MC@NLO rate= NLO rate
MC@NLO and MC predicted shapes are identical
where MC does a good job



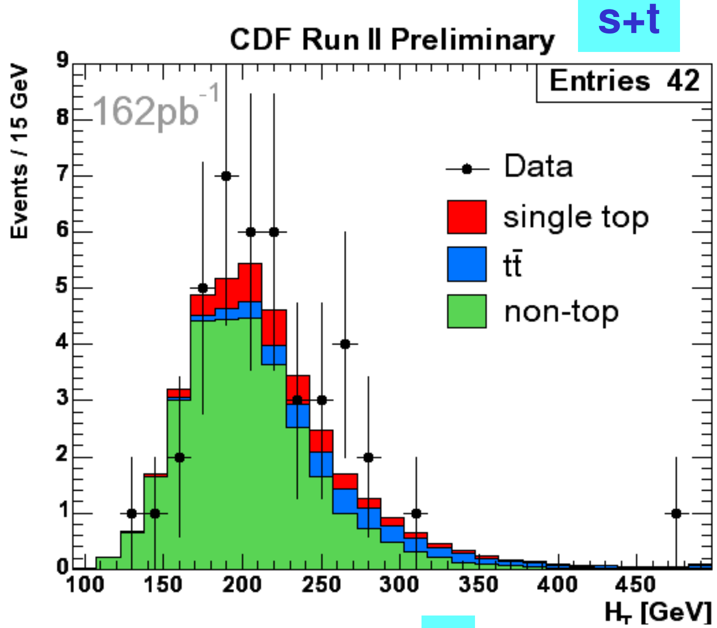
Top anti-top asymmetry
only at NLO
only at Tevatron



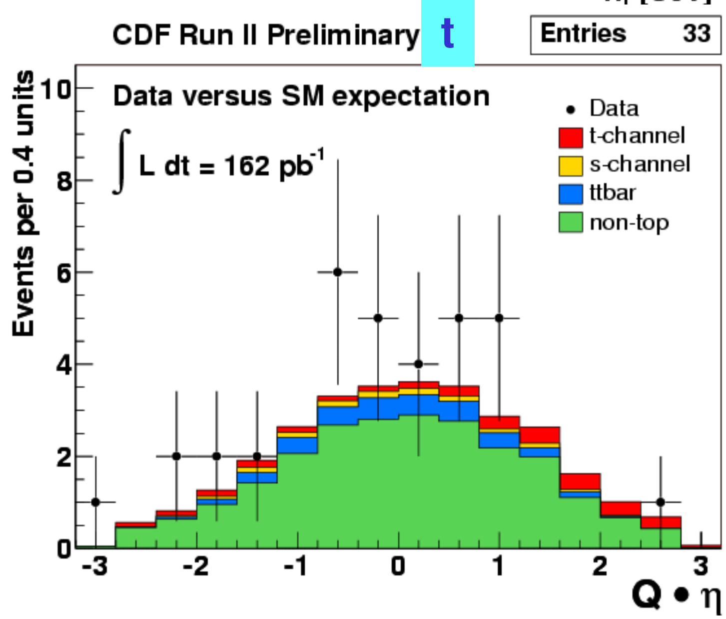
Search for Single Top

1 Lepton p_T>20 GeV
MET>20 GeV
Exactly 2 jets E_T>15 GeV $|\eta|$<2.8
≥ 1 b-tag
$M_{l\nu b}$ [140,210] GeV

s+t

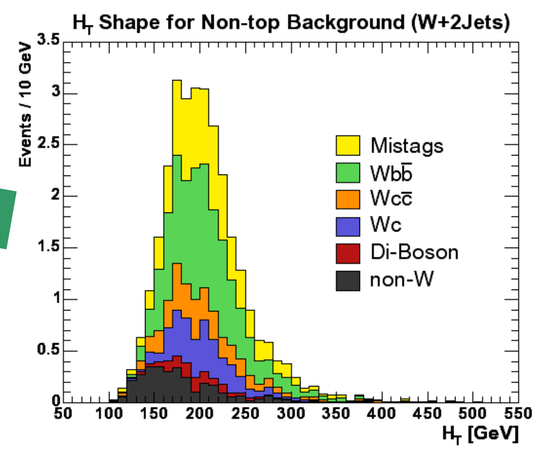


t



Single top is kinematically between W+jets and top pair production
NLO calculations for rate and shape very important, especially at LHC

R.K. Ellis, J. Campbell hep-ph/0408158

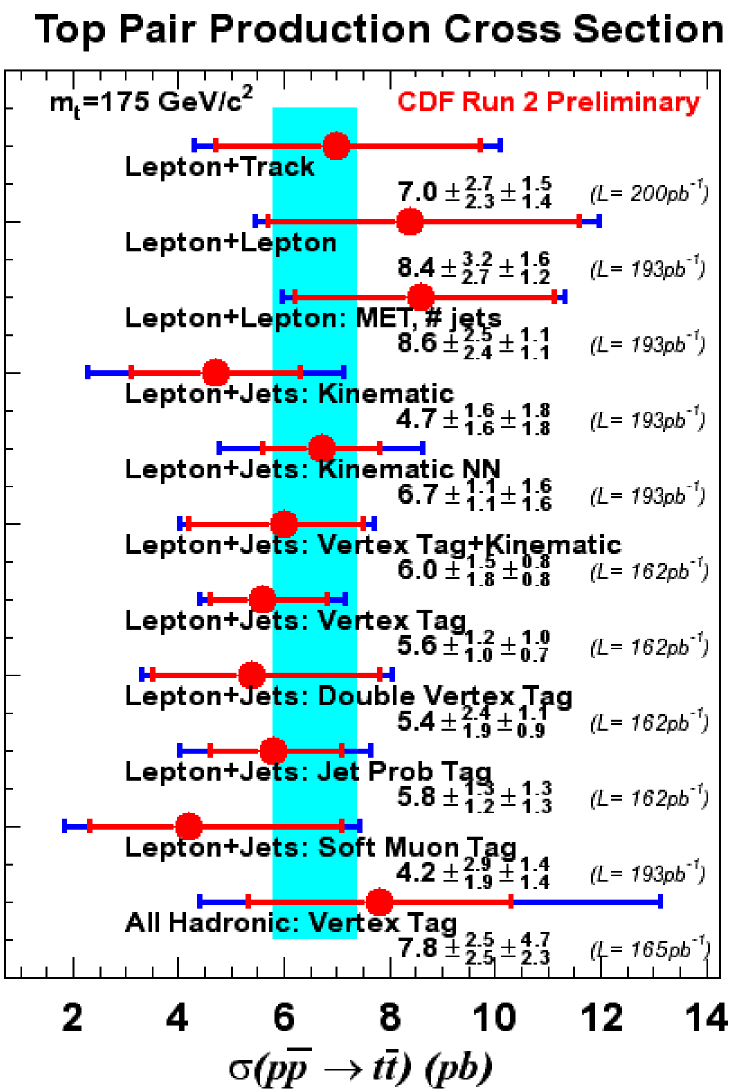


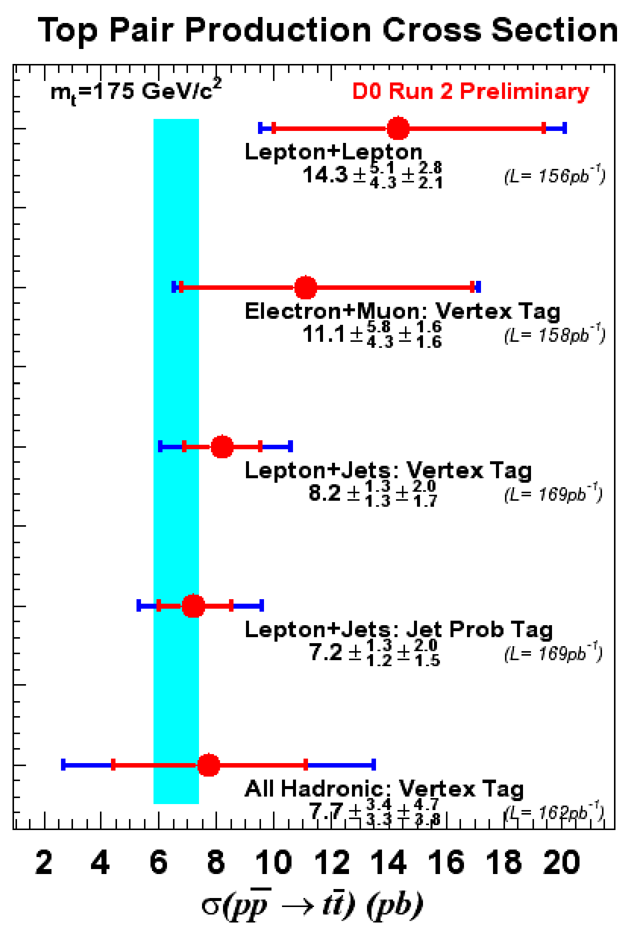
95% C.L. limits Observed (Expected)

Channel	CDF (pb)	D0 (pb)
s+t	<17.8 (13.6)	<23 (20)
t	<10.1 (11.2)	<25 (23)
s	<13.6 (12.1)	<19 (16)

Top pair production: Summary

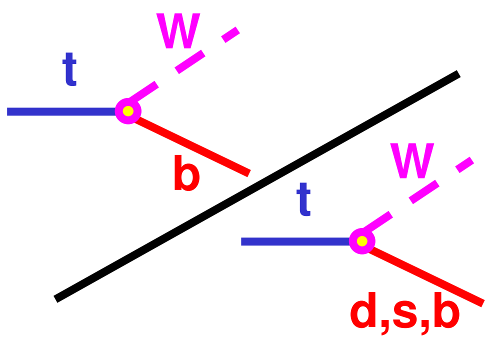
- **Many different measurements**
  - **Test different assumptions**
  - **Compare to look for new physics**
  - **Combination ~20% precision**
  - **Currently statistics-limited**





Top Decay: BR(t→Wb) ≈100%?

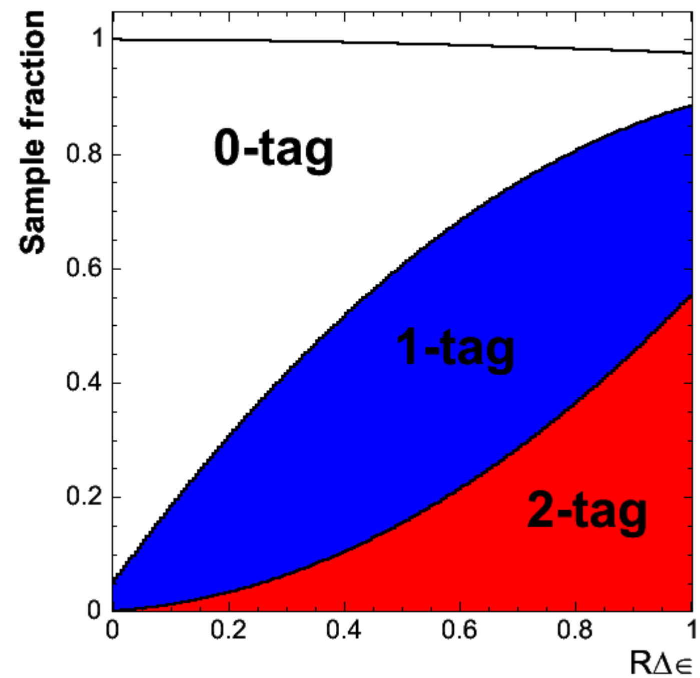
- Does top decay always produce a b quark?
  R=BR(t→Wb)/BR(t→Wq) ≈1

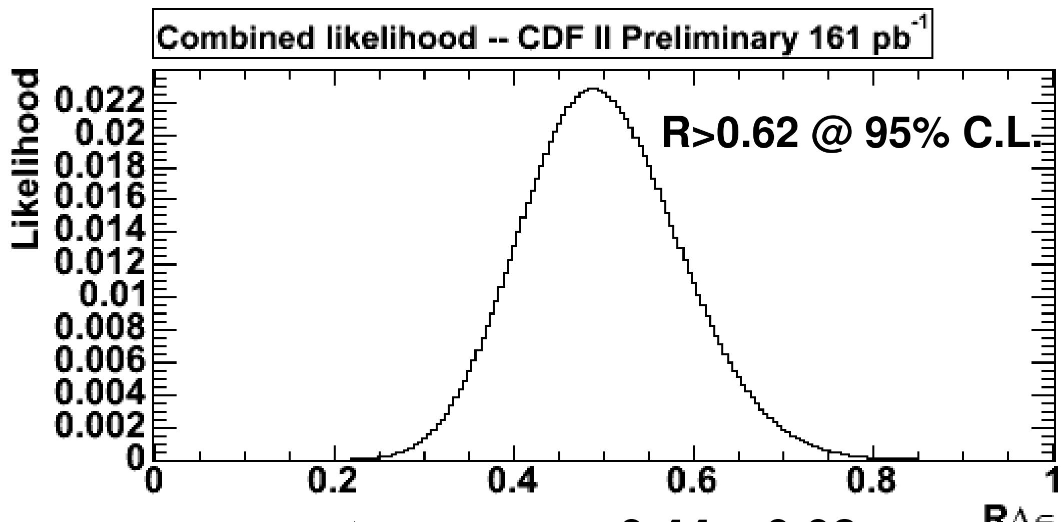


- Ratio of single/double b-tags sensitive to R
  - Lepton+jets
- CDF: 0-tags provide powerful constraint
  - Dilepton
  - Lepton+jets NN

$$R = 1.11 \pm^{0.21}_{0.26}$$ CDF 161 pb^{-1}

$$R = 0.70 \pm^{0.29}_{0.19}$$ D0 169 pb^{-1}

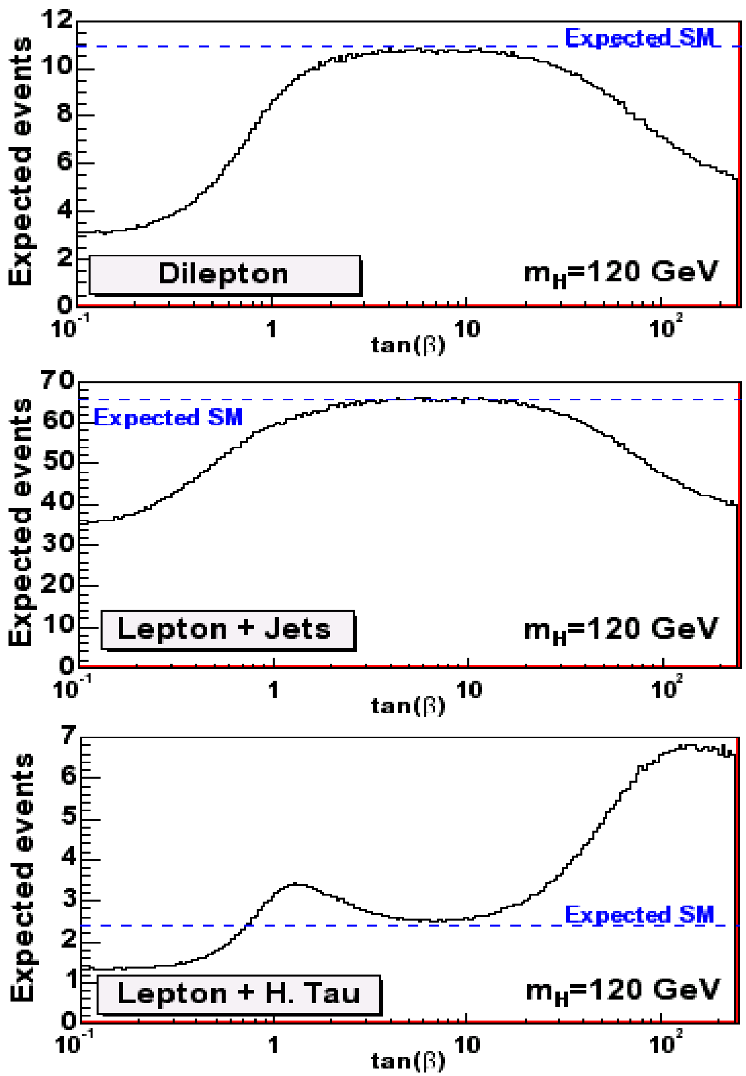


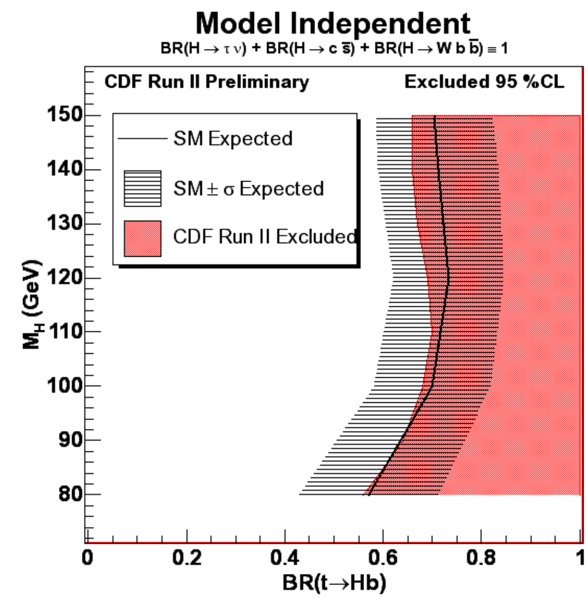


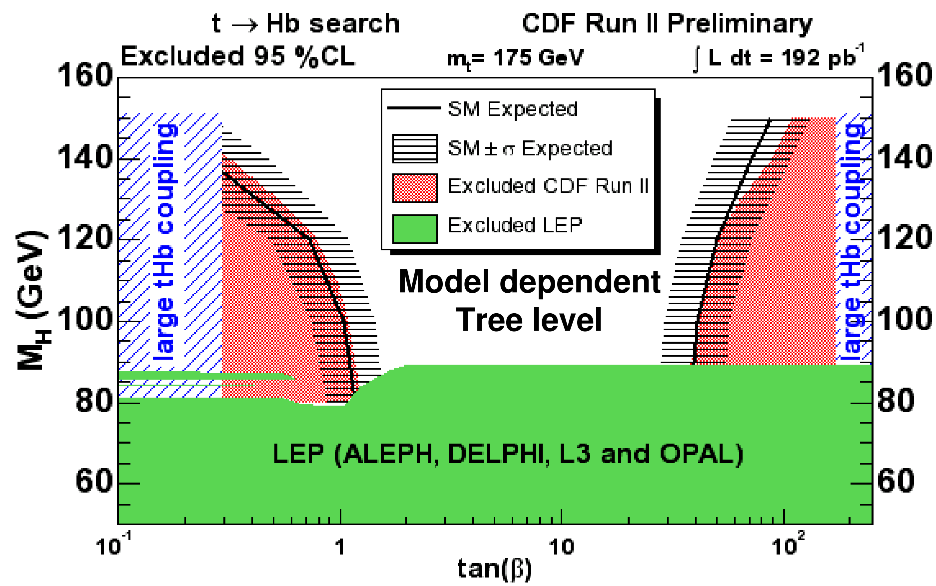
$\Delta\varepsilon = \varepsilon_b - \varepsilon_{light} = 0.44 \pm 0.03$

Top Decay: BR($t \rightarrow H^+ b$)?

Does top decay to a charged Higgs instead of a W?
Compare observed number of events in 3 final states







All lower

Lepton+τ higher

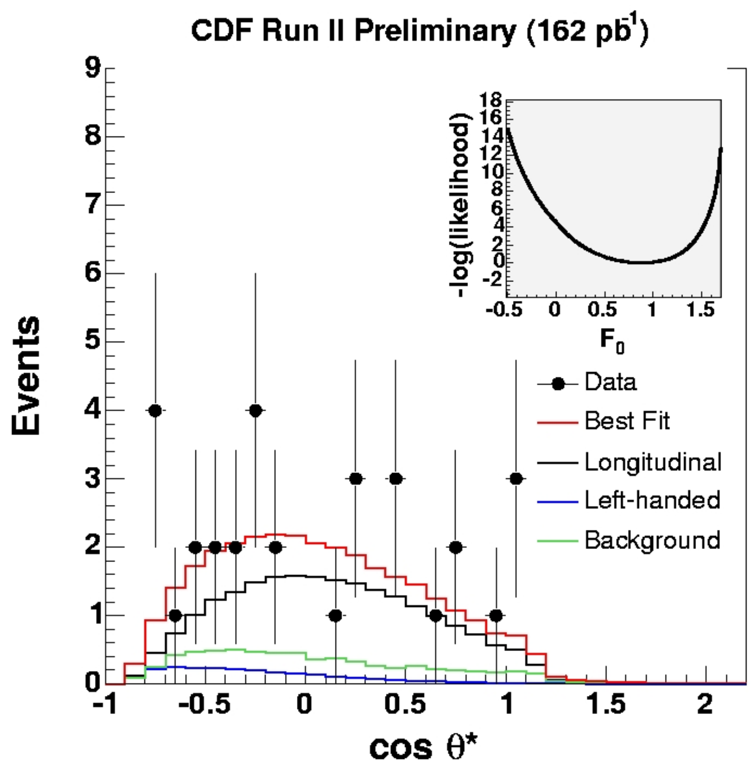
Helicity of W from top decays

Standard Model is V-A theory: predicts W from top are
F_0=70% longitudinal, F_-=30% Left-handed

- **Assume F_+=0.0 (ie no V+A)**
  - **Measure F_0**

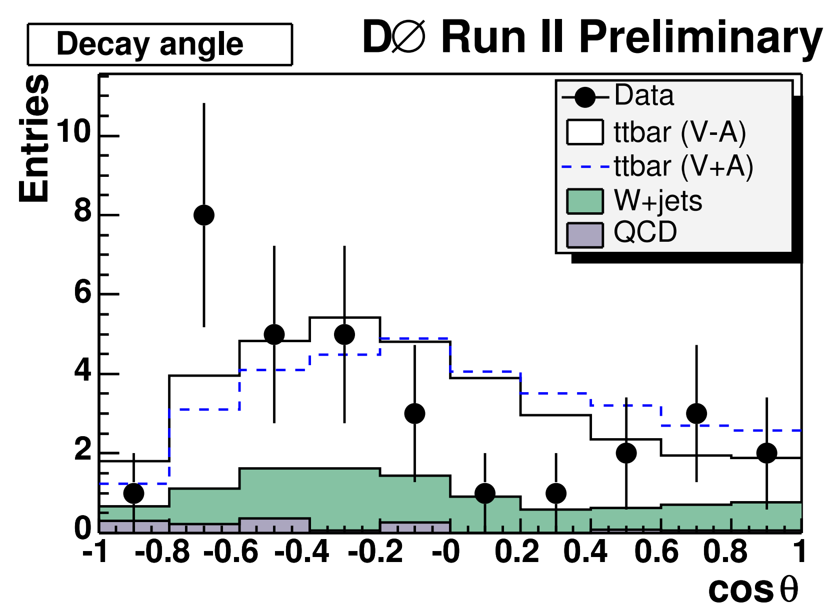
$$F_0 = 0.89 \pm^{0.30}_{0.34} \pm 0.17$$

  - **F_0>0.25 @ 95% C.L.**



"Who says it's a fermion?"
Top squark could mimic final state but W polarisation would be different

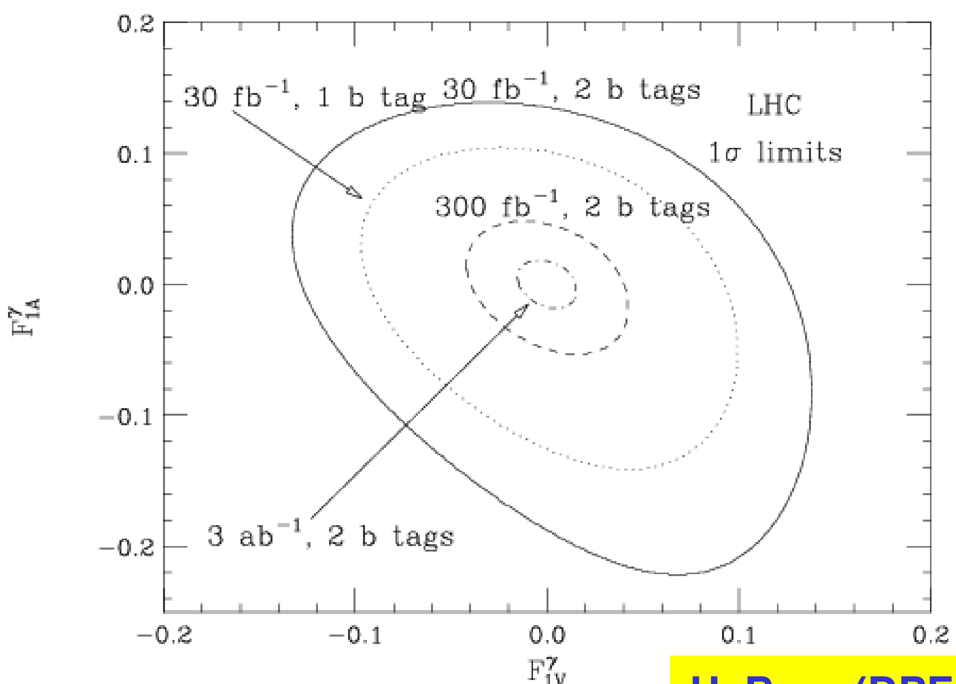
- **Assume F_0=70%**
  - **Set limit on V+A fraction**
  - **F_+<0.269 @ 90% C.L.**

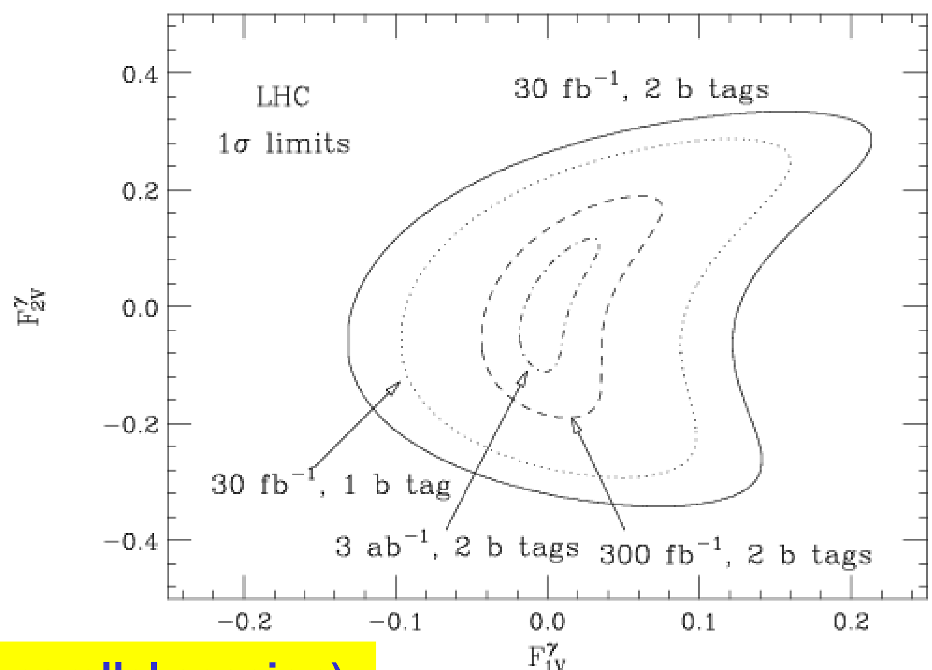


Top Charge and ttγ coupling

Standard Model top charge +2/3 implies $t \rightarrow W^{+}b$
Exotic top charge -4/3, then $t \rightarrow W^{-}b$ instead!

- Examine photon p_T and angular distributions
- Measure ttγ coupling at LHC to 3-10%
  - More difficult at Tevatron due to QED ISR from qq
  - Difficult at $e^{+}e^{-}$ linear collider to disentangle ttγ and ttZ



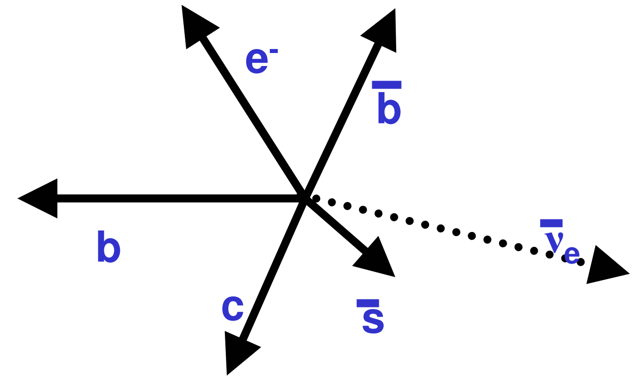


U. Baur (DPF parallel session)
A. Juste, L. Orr, D. Rainwater

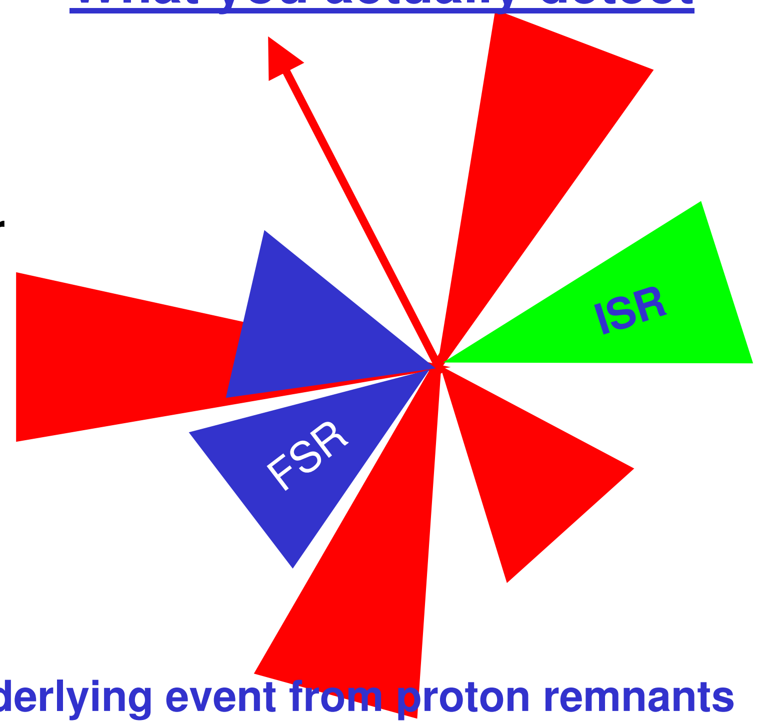
Top Mass: Reconstruction

- Lepton+Jets
  - Neutrino undetected
    - P_x, P_y from energy conservation
    - 2 solutions for P_z from $M_{l\nu}=M_W$
  - Combinatorics of 4 highest E_T jets
    - 12 ways to assign jets to partons
    - 6 if 1 b-tag
    - 2 if 2 b-tags (beware of charm!)
  - ISR
    - Extra jets
    - 4 highest E_T jets not always from top decay
  - FSR
    - Poorer resolution if extra jet not included or jet clustering leaves no well-defined jet-parton match
- Dilepton
  - Lower statistics
  - Two undetected neutrinos
  - Fewer combinations – only 2 jets
  - ISR/FSR as above

Final state from LO matrix element



What you actually detect



+underlying event from proton remnants
+ multiple interactions!

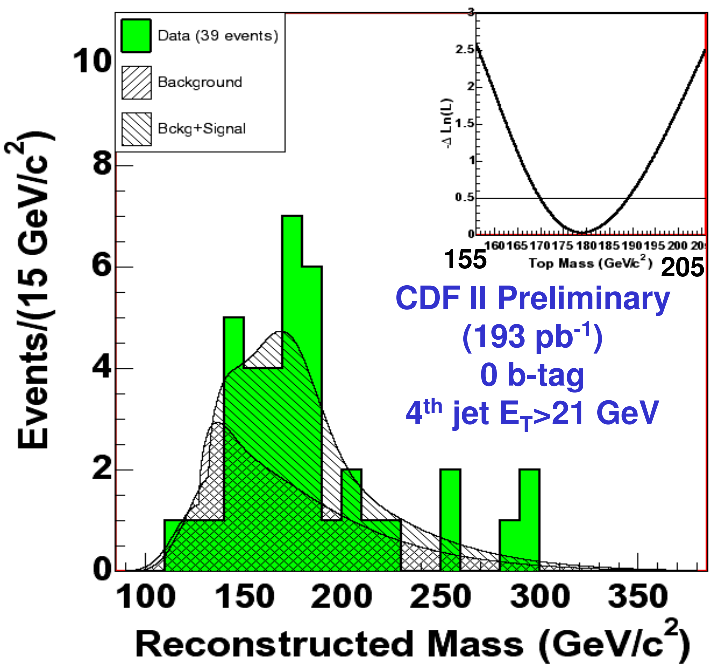
1 Lepton p_T>20 GeV
MET>20 GeV
>3 jets E_T>15 GeV, $|\eta|$<2.0

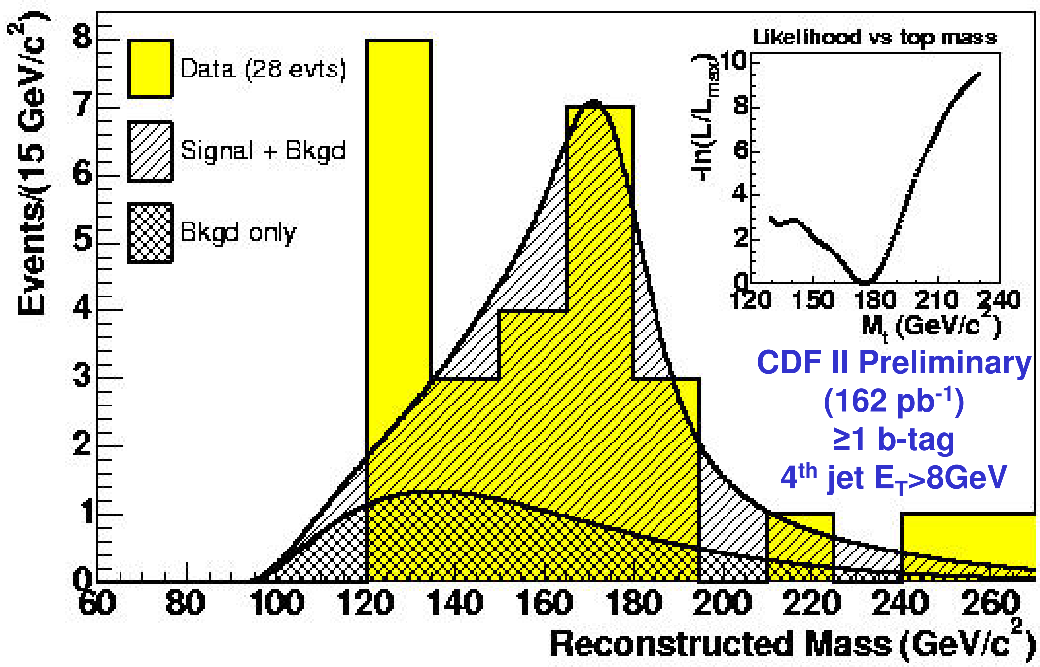
Top Mass: MC Template

$$\mathcal{P}(\text{measurement}|\text{mtop}) = \underbrace{\mathcal{P}(\text{measurement}|\text{partons}) \propto \mathcal{P}(\text{partons}|\text{mtop})}_{\text{MC + GEANT detector simulation + reconstruction}}$$

- Choose best combination and neutrino solution with a kinematic fit
  - $M_{fit}=m_{top}=m_{\overline{top}}$, $M_W(l\nu)=M_W(qq)$, transverse energy of tt+X system
  - Require χ^2 consistent with hypothesis
  - Performance: correct combination 30%, incorrect 26%, ill-defined (ISR/FSR) 44%
- Parameterise reconstructed mass shape with MC
  - top mass dependence – MC with different input top masses
  - Background shape
- Maximise Likelihood

$$m_{top} = 176.7 \pm^{6.0}_{5.4} \pm 7.1\ \text{GeV/c}^2$$





1 Lepton p_T>20 GeV
MET>20 GeV
==4 jets E_T>15 GeV, |η|<2.0
No b-tagging

Top Mass: Matrix Element

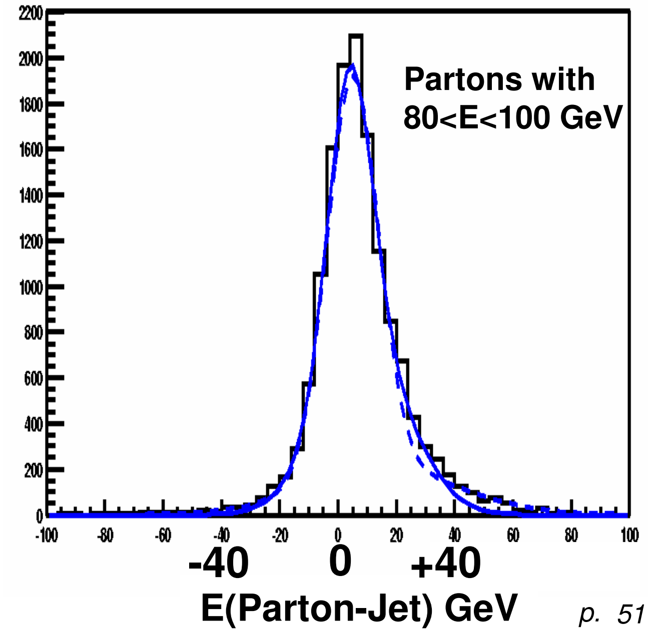
$\mathcal{P}$(measurement|mtop) = $\underbrace{\mathcal{P}\text{(measurement|partons)}}_{\text{GEANT detector simulation + reconstruction}} \propto \underbrace{\mathcal{P}\text{(partons|mtop)}}_{\text{LO matrix element}}$

$$P_{t\bar{t}} = \frac{1}{\sigma_{tot}} \int dp_{jet1} dm^2_{top1} dM^2_{w1} dm^2_{top2} dMw^2_2 \sum_{comb,\nu} W_{jet}(x,y) \frac{f(q_1)f(q_2)}{|q_1||q_2|} \phi_6 |M|^2$$

Updated D0 Run I measurement

- Use LO matrix element…
  - Exactly 4-jets for final state
  - Background from W+jets VECBOS
- …but LO matrix element needs partons
  - 20 parameters to describe initial (2) and final state (18)
  - Measure lepton momentum (3) and jet angles (8)
  - Energy and momentum conservation (4)
  - Integrate over 5 unknowns
    - Choose W and top masses (4) and a jet momentum (1)
    - Relate poorly-measured jet energies to partons with transfer functions from MC
- Advantages
  - Use all 24 combinations – correct one always included
  - Well-measured events carry more weight
  - 2x statistical power!
  - Systematic from jet energy scale reduced by 40%

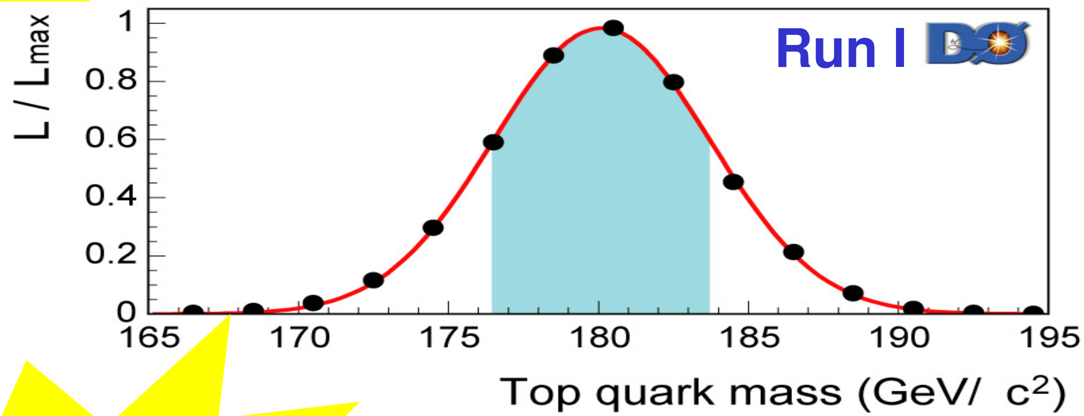
D0 91 events ≥4 jets	Events	(top, bkg)
Template χ^2 cut	77	(29,48)
ME ==4 jets	71	(16,55)
ME ==4 jets and $\mathcal{P}_{bkg}$	22	(12,10)



Top Mass: Matrix Element

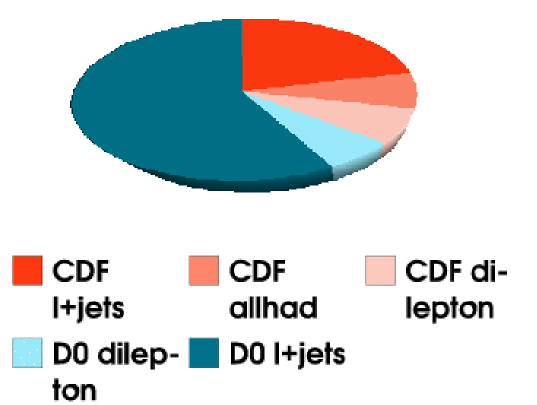
Nature 429 638-642
06/10/2004

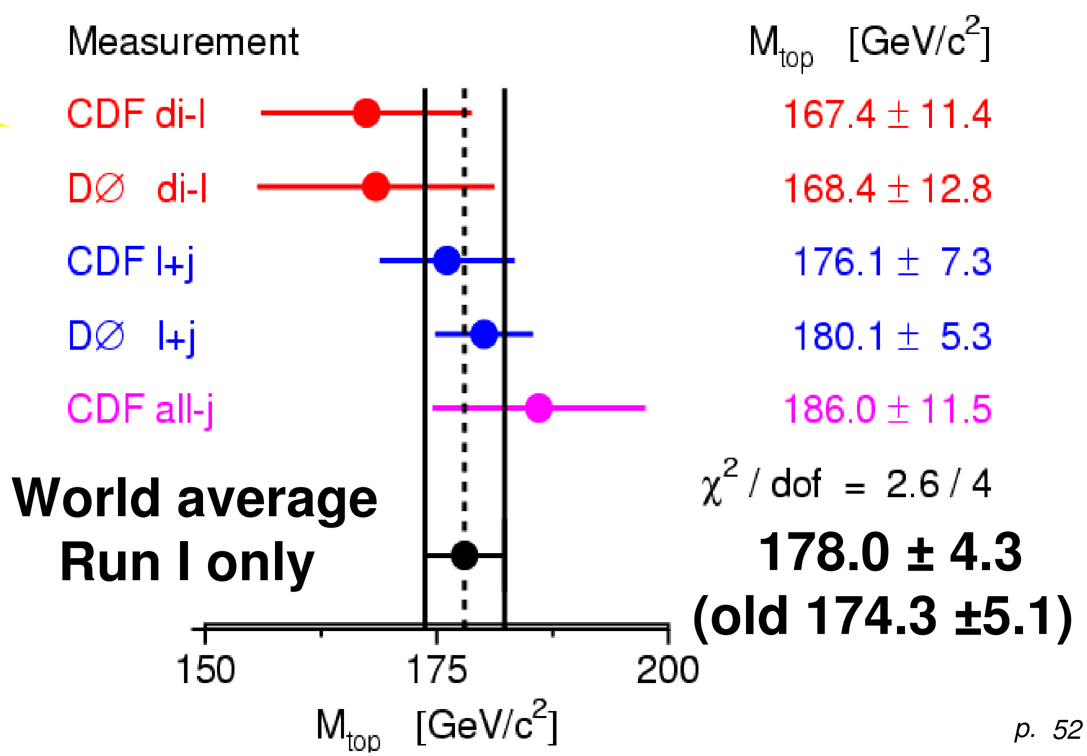
$$m_{top} = 180.1 \pm 3.6 \pm 3.9 \text{ GeV/c}^2$$



New world average
April 2004
hep-ex/0404010

Relative weight in top mass average





Global Standard Model Fit

Changes since Summer 2003

Only use high Q^2 measurements from LEP, SLC and Tevatron

Theory input

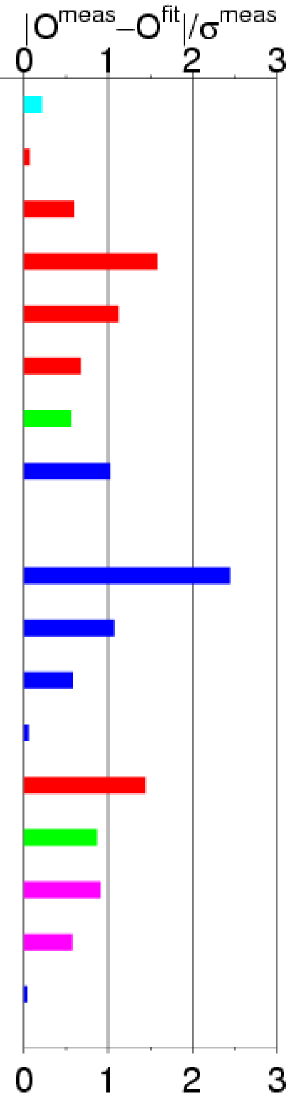
Complete two-loop for M_W
hep-ph/0311148
Fermionic two-loop for $\sin^2\theta^{eff}_{lept}$
hep-ph/0407317

Experimental input

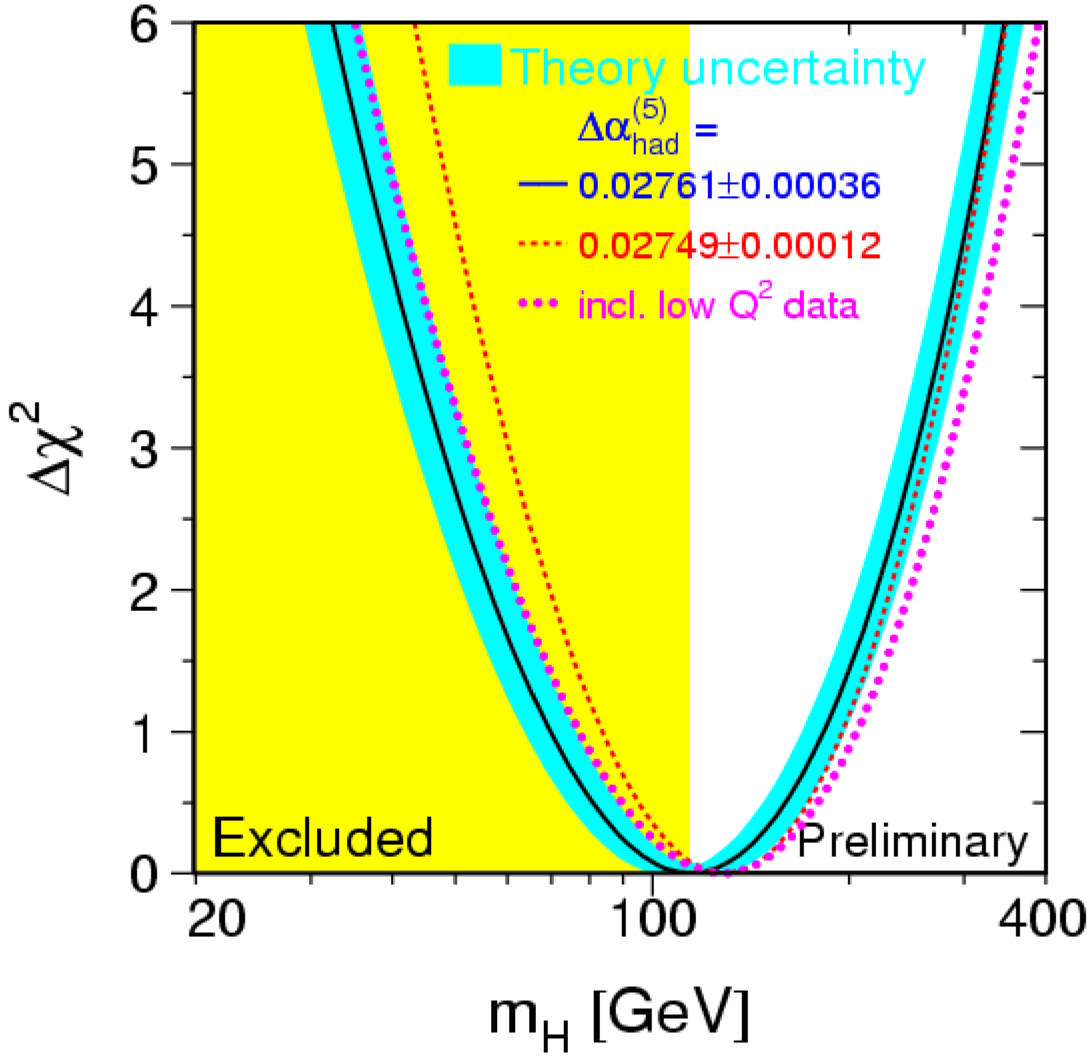
HF combination (LEP/SLC)
W mass combination (CDF/D0)
top mass (D0)

Summer 2004

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A^{0,b}_{fb}$	0.0998 ± 0.0017	0.1040
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2



SM constraint on Higgs boson mass

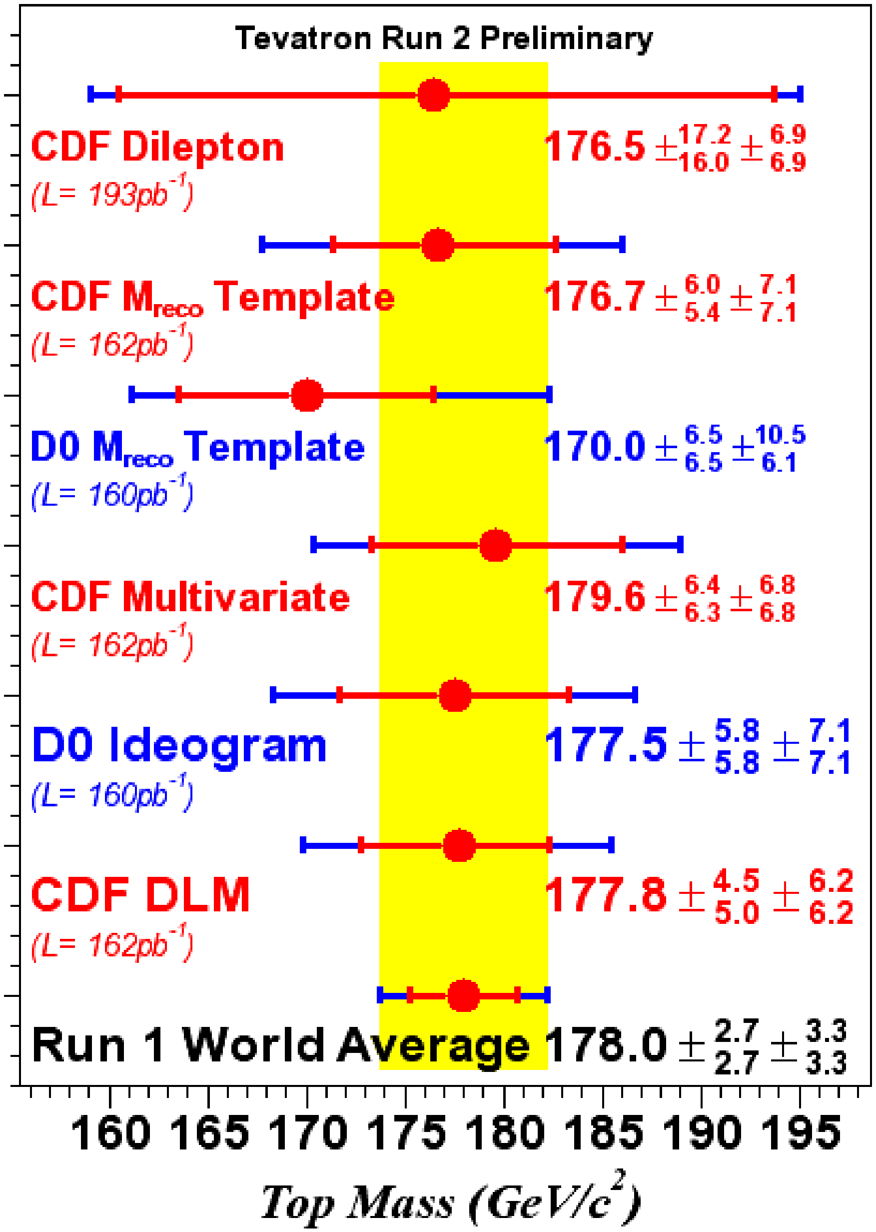


M_H=114 +69 – 45 GeV

M_H<260 GeV @ 95% C.L.

Top mass and Higgs mass 70% correlated in SM Vital to measure top mass well

Top Mass: Tevatron Summary

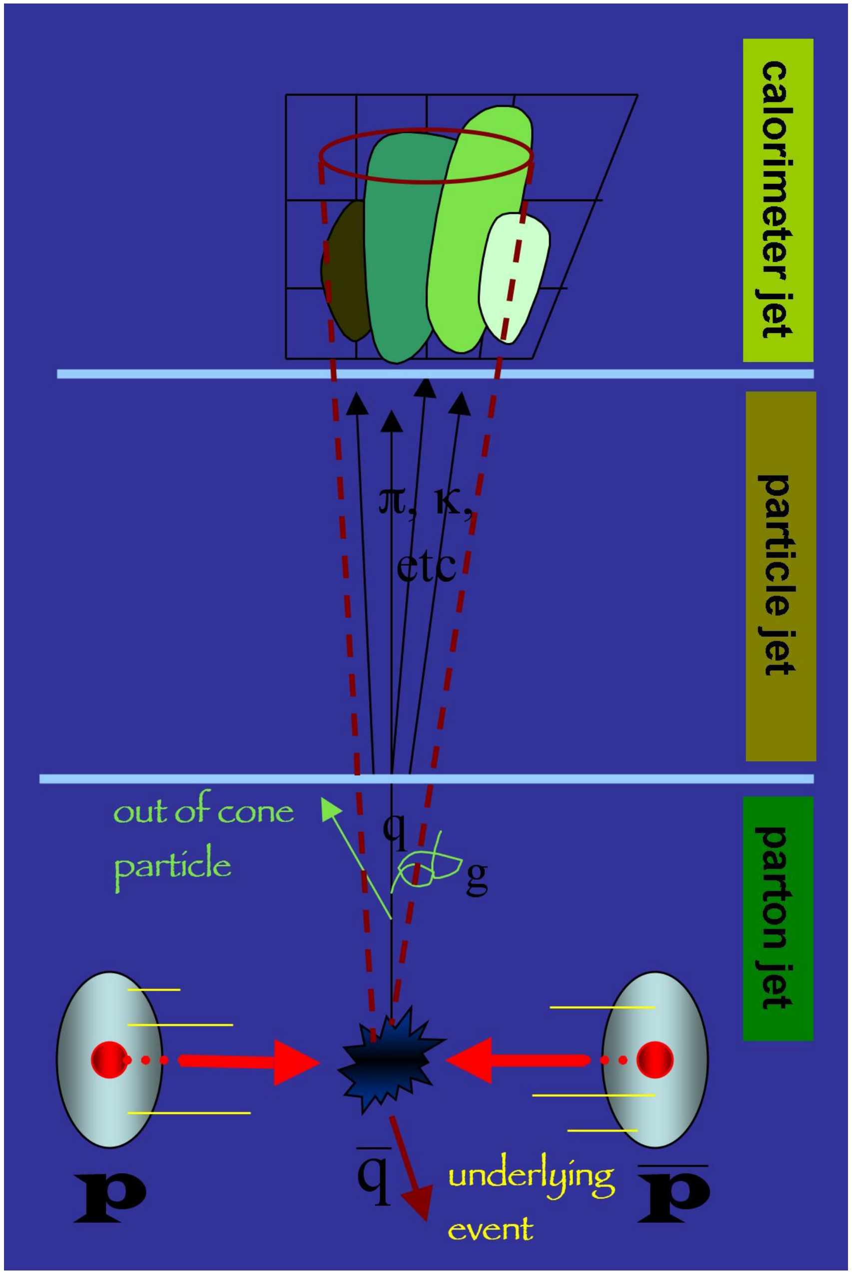


Run II goal is 2.5 GeV per experiment

Dominant systematic from jet energy scale

None of the Run II preliminary measurements are in the world average

Jet Energy Scale



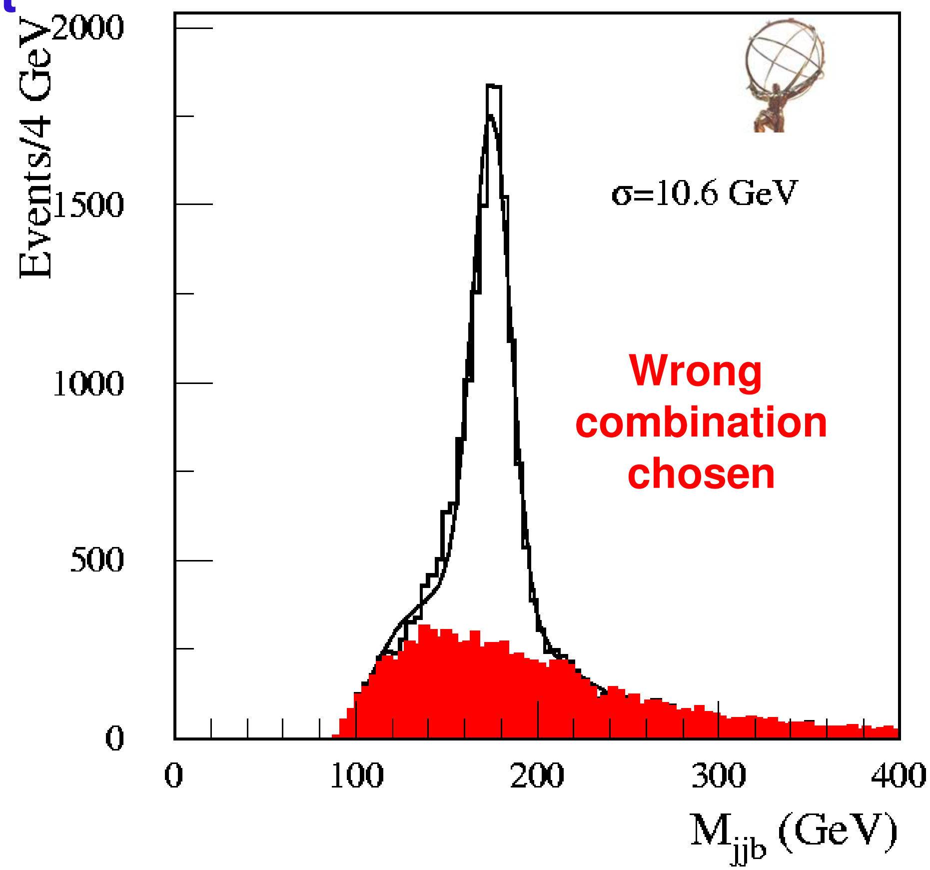
- **Absolute energy scale is the key!**
  - **Must tune Calorimeter simulation at single particle level**
  - **Accurate material description important – extra from new Silicon**
  - **New GEANT simulation**
  - **New forward calorimeter**
  - **Data γ-jet balance – statistics-limited**
- **Relative response**
  - **Data di-jet balance - calibrate relative to central**
- **Expect systematic to decrease soon**
  - **Improved simulation**
  - **Get smarter with more statistics**

1 Lepton p_T>20 GeV
MET>20 GeV
≥ 4 jets E_T>40 GeV, $|\eta|$<2.5
2 b-tags

Top mass @ LHC

- Much higher statistics…can reduce systematics
  - Double b-tags: reduce background and combinatorics
    - 87,000 top with S/B~78 with 10 fb^{-1}
  - Calibrate jet energy scale *in situ* using hadronic W decay!
  - b-jets – achieve 1% calibration with Z+b?
- Precision 1 GeV per experiment

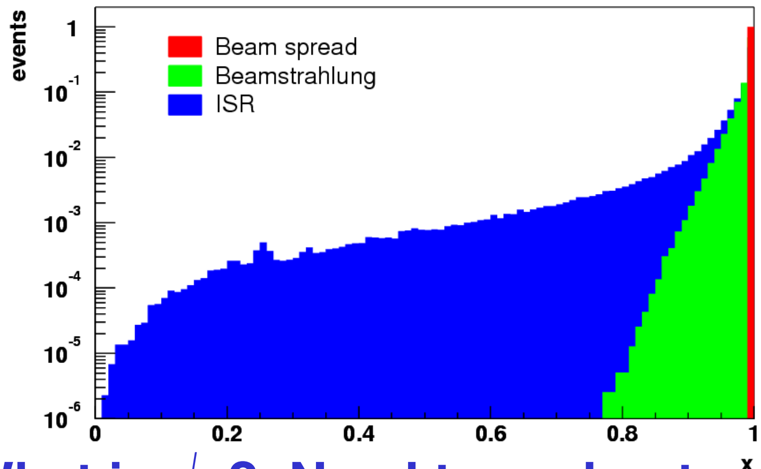
Source of uncertainty	Hadronic δM_{top} (GeV)	Fitted δM_{top} (GeV)
Light jet scale	0.2	0.2
b-jet scale	0.7	0.7
b-quark fragmentation	0.1	0.1
ISR	0.1	0.1
FSR	1.0	0.5
Combinatorial bkg	0.1	0.1
Total	1.3	0.9
Stat	0.1	0.1



SN-ATLAS-2004-040

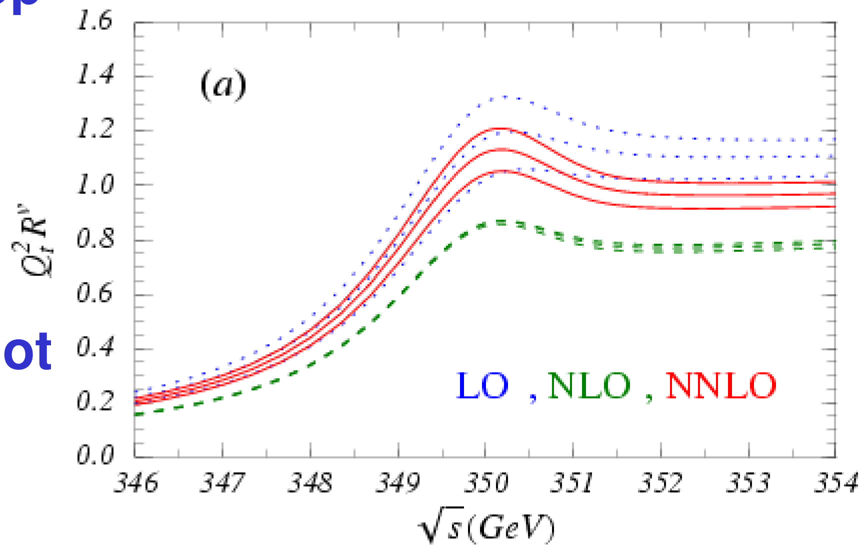
Top mass @ ILC

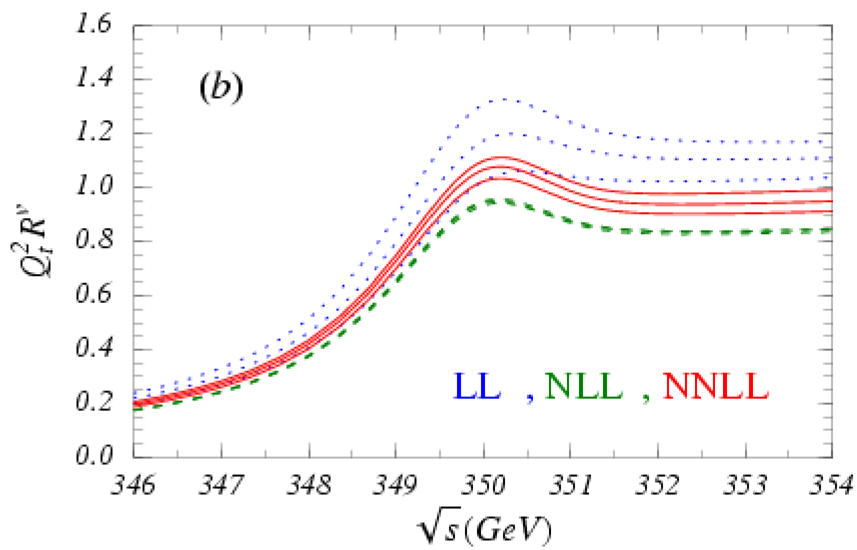
- Scan cross-section at threshold for top pair production
  - Theory calculation in good shape
  - Choose safe definition
- Ultimate limit of 100 MeV
  - Top carries colour charge, mass not well-defined below 100 MeV



- What is √s? Need to understand
  - Beam energy spread
  - Beamstrahlung
  - ISR

D. Miller, S. Boogert
http://www.linearcollider.ca/victoria04/





A. Hoang, hep-ph/0310301

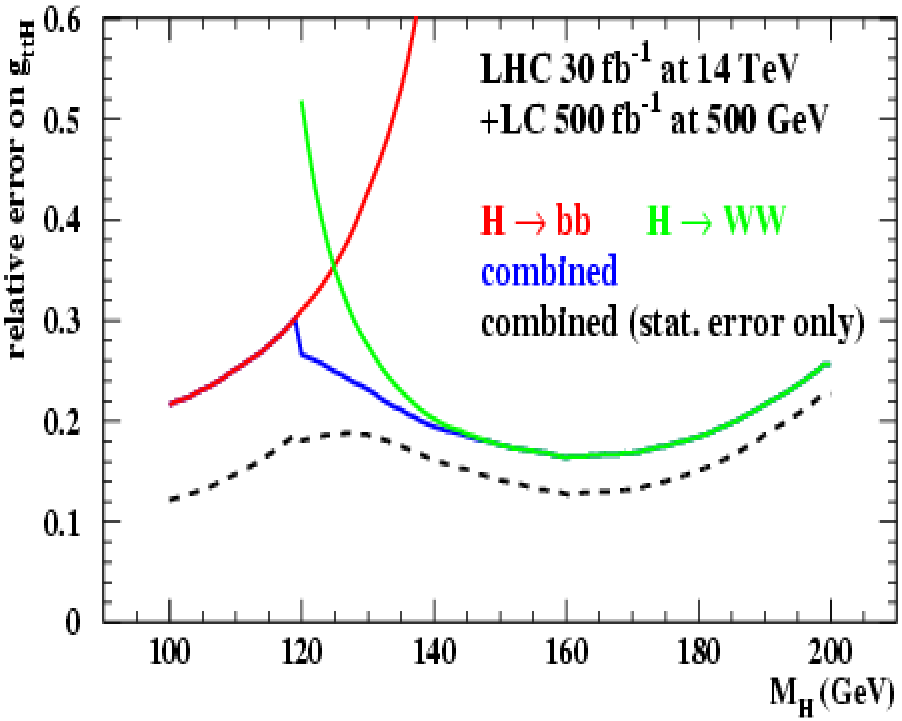
K. Desch
M. Schumacher
hep-ph/0407159

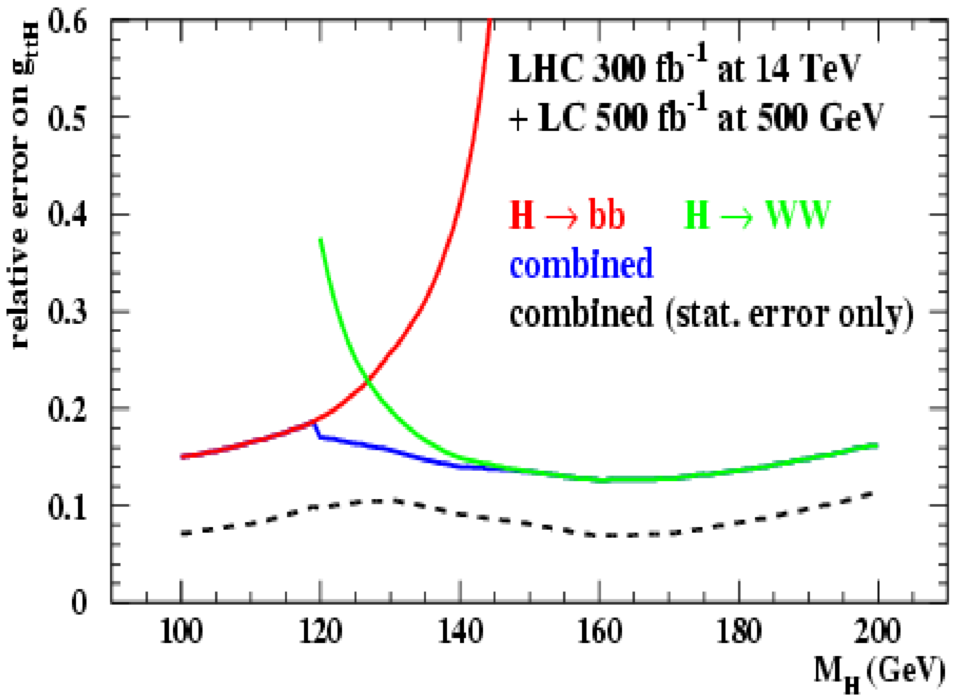
Top Yukawa Coupling

SM prediction is $$g_{ttH} = \frac{\sqrt{2} m_{top}}{246\ GeV} = 1.02 \pm 0.02$$

- **Important to test coupling between Higgs and top quark**
- **Combine LHC and LC for model independent measurement**
  - **LHC: pp →ttH+X – measure σ(ttH)xBR(H→WW) to 20-50%**
  - **ILC: e^+e^-→ZH - measure BR(H→WW) to 2%**
    - **Can do with 500 GeV Linear Collider**

$$\sigma(ttH) \propto g_{ttH}^2$$

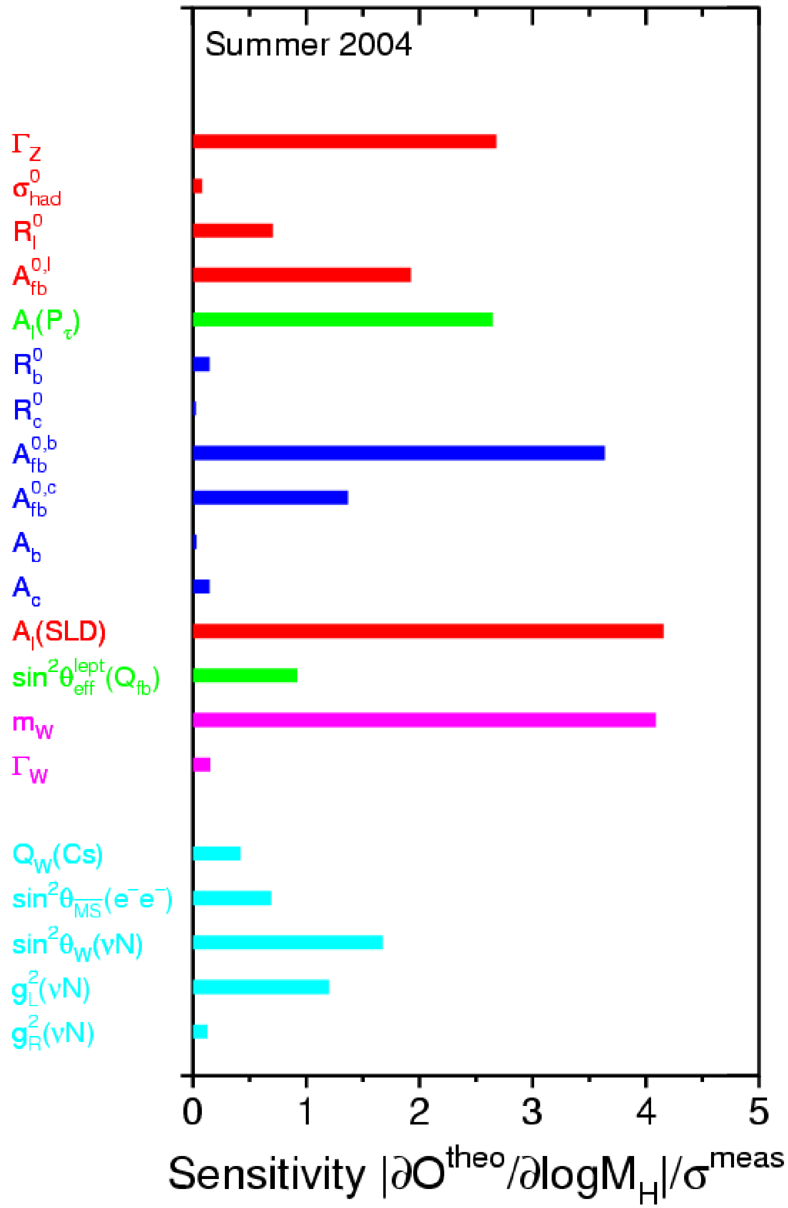




Conclusions

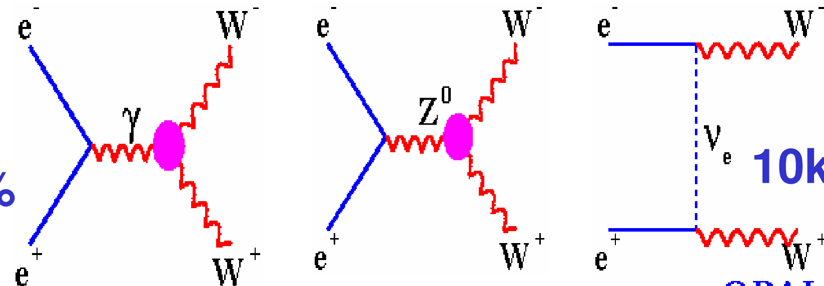
- Next few years shaping up to be very interesting
  - Tevatron delivering high luminosities – expect 4-9 fb^{-1}
    - More W bosons and top quarks than ever before
    - Precision measurements of top properties – is it really top?
  - Very fruitful interaction between theorists and experimentalists
    - NLO and beyond calculations important for precision measurements and searches for new physics
  - Promote interaction between Tevatron and LHC
    - Tev4LHC year-long workshop
- LHC first beam expected 2007, first physics 2008
- ILC accelerating towards reality

SM Higgs sensitivity



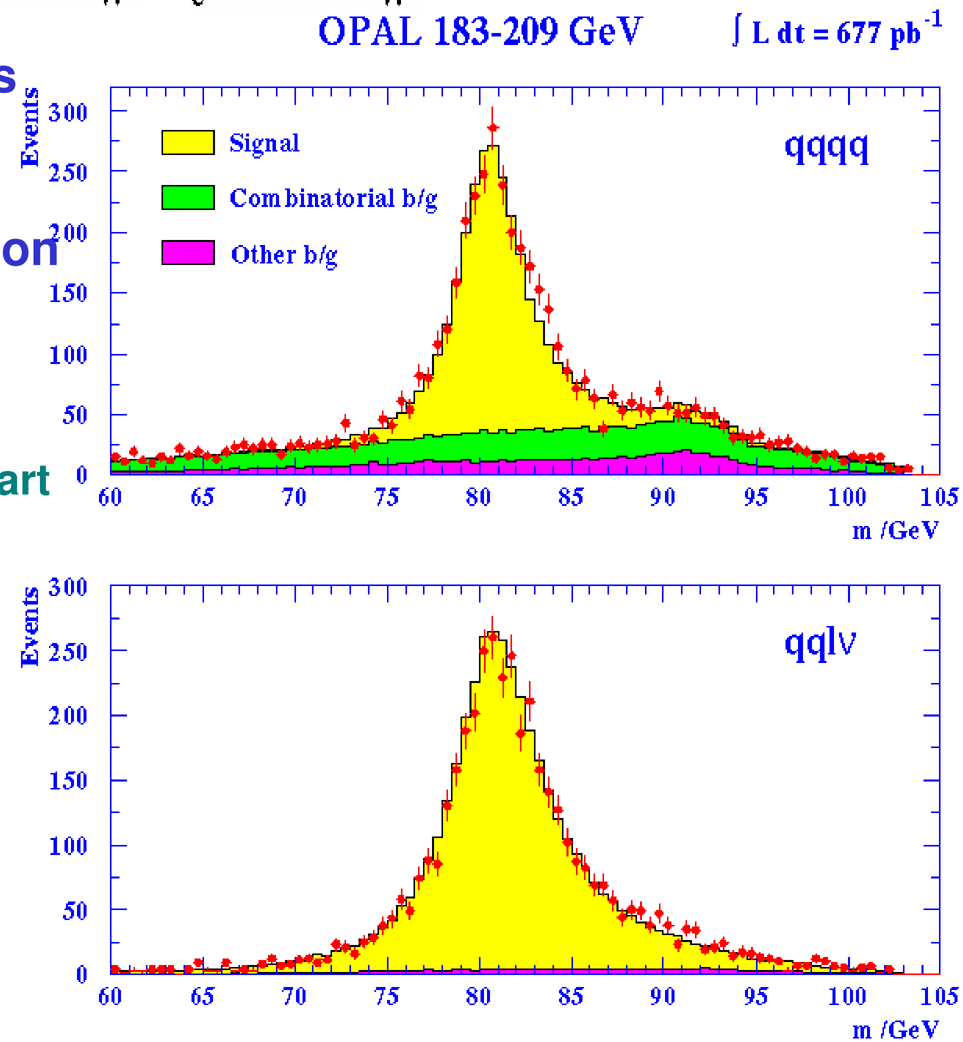
W mass at LEP

e⁺e⁻ collider
Measured √s
Trigger efficiency 100%

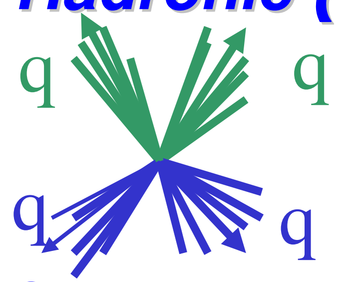


WW pair production
10k events per experiment

Direct reconstruction of W invariant mass from W decay products.
Improve resolution by kinematic fit with powerful constraints from E,P conservation

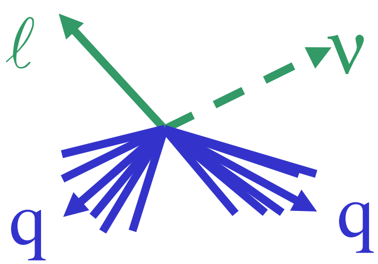


46% Hadronic (4q)



W's decay 0.1 fm apart
Decay products can interact!

44% Semileptonic (qqlν)

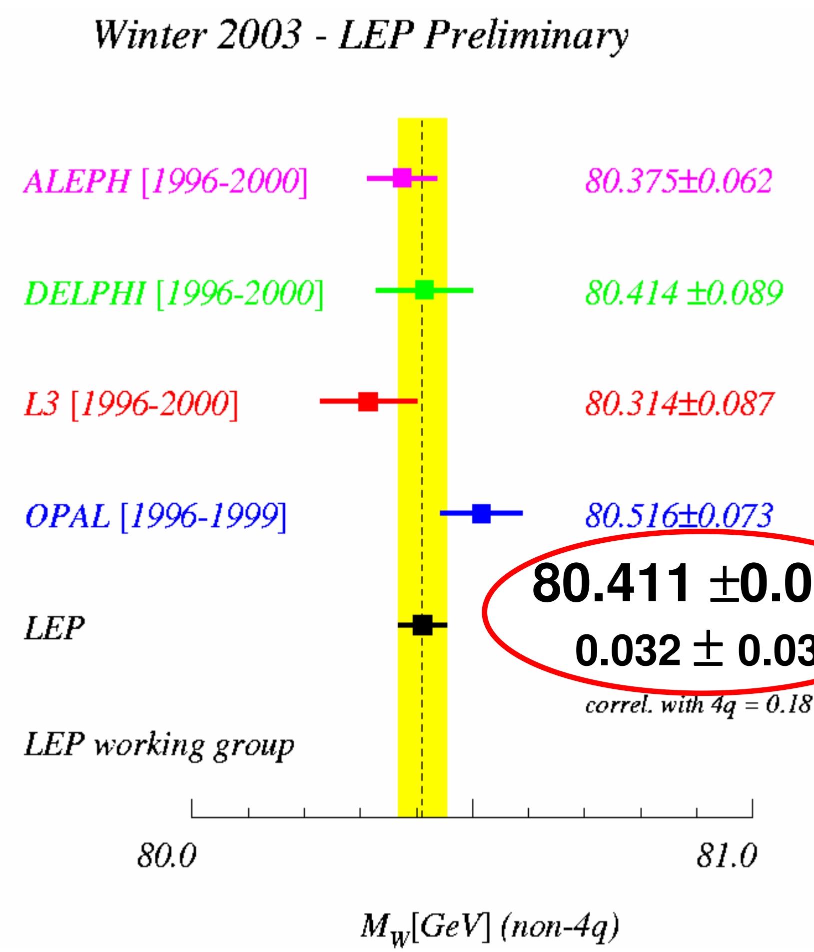


W mass at LEP

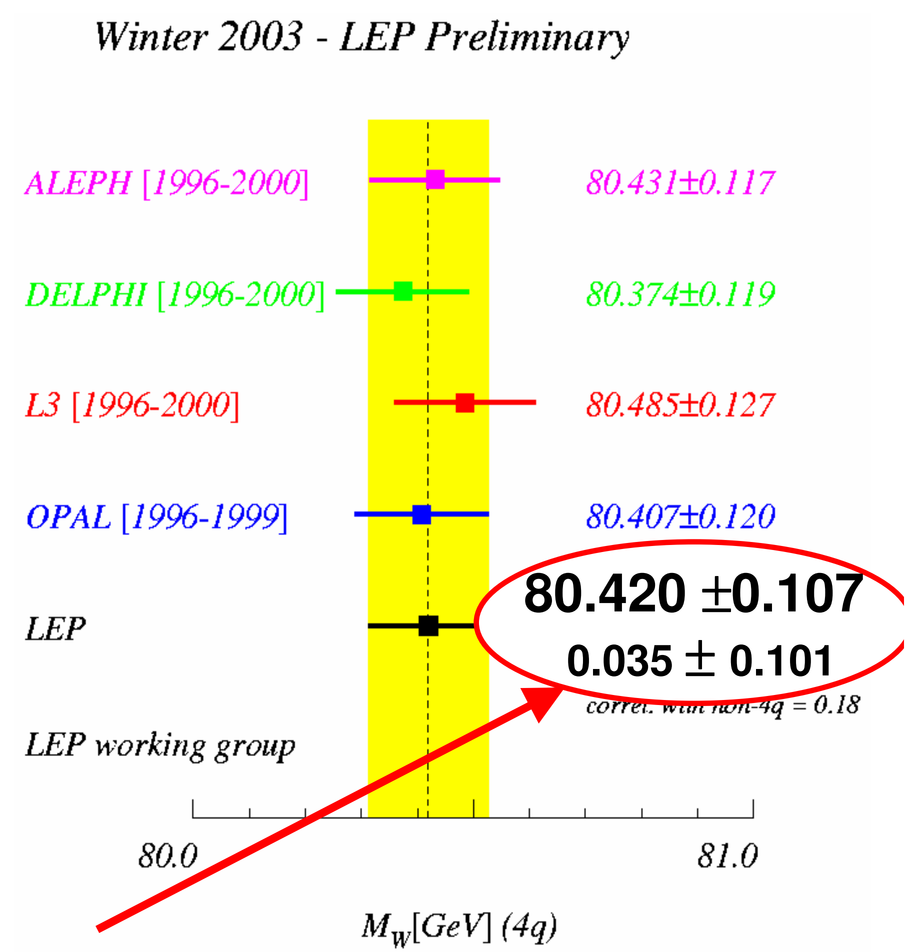
CERN-EP/2003-091

LEPEWWG/2003-02

Non-4q



4q



Similar statistical uncertainties
Trouble is…Final State Interactions in 4q