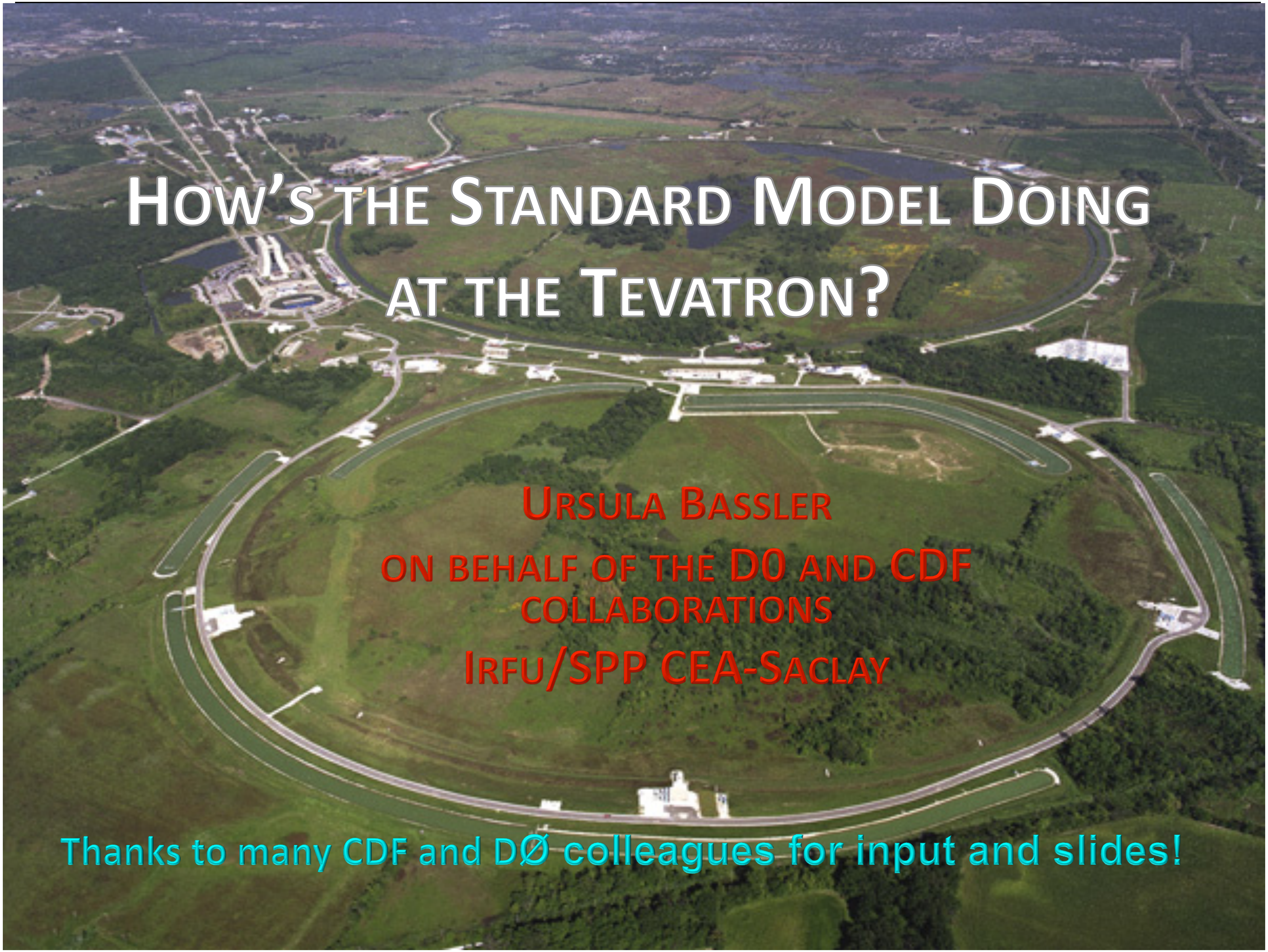


How's the Standard Model Doing at the Tevatron?

Ursula Bassler

on behalf of the D0 and CDF collaborations

Irfu/SPP CEA-Saclay

Thanks to many CDF and DØ colleagues for input and slides!

TEVATRON A DISCOVERY MACHINE

Luminosity delivered : ~ 9 fb^{-1}

on tape : 7.5 fb^{-1}/exp.

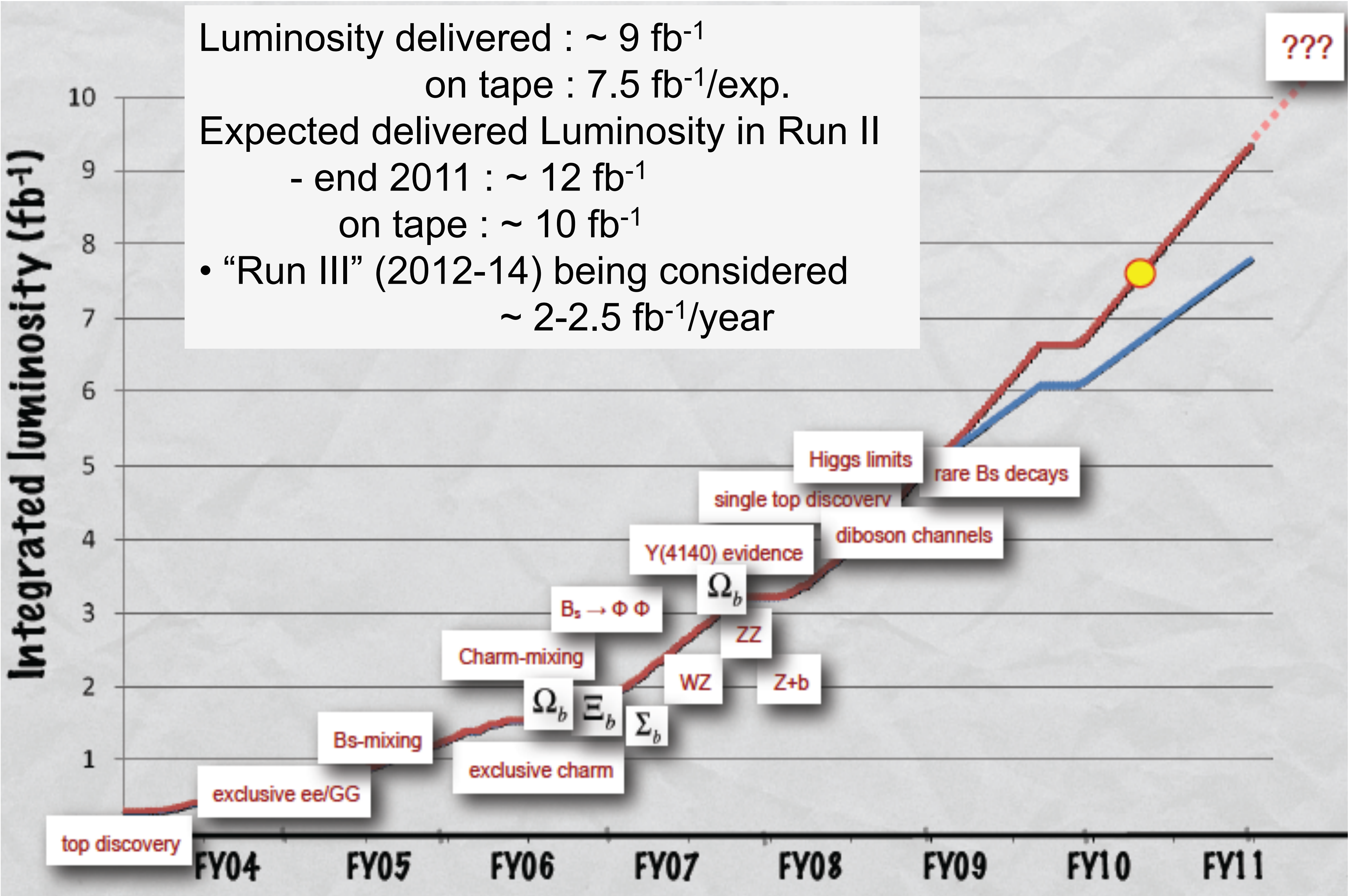
Expected delivered Luminosity in Run II

- end 2011 : ~ 12 fb^{-1}

on tape : ~ 10 fb^{-1}

• "Run III" (2012-14) being considered

~ 2-2.5 fb^{-1}/year



TEVATRON A "SM" DISCOVERY MACHINE

Luminosity delivered : ~ 9 fb^{-1}

on tape : 7.5 fb^{-1}/exp.

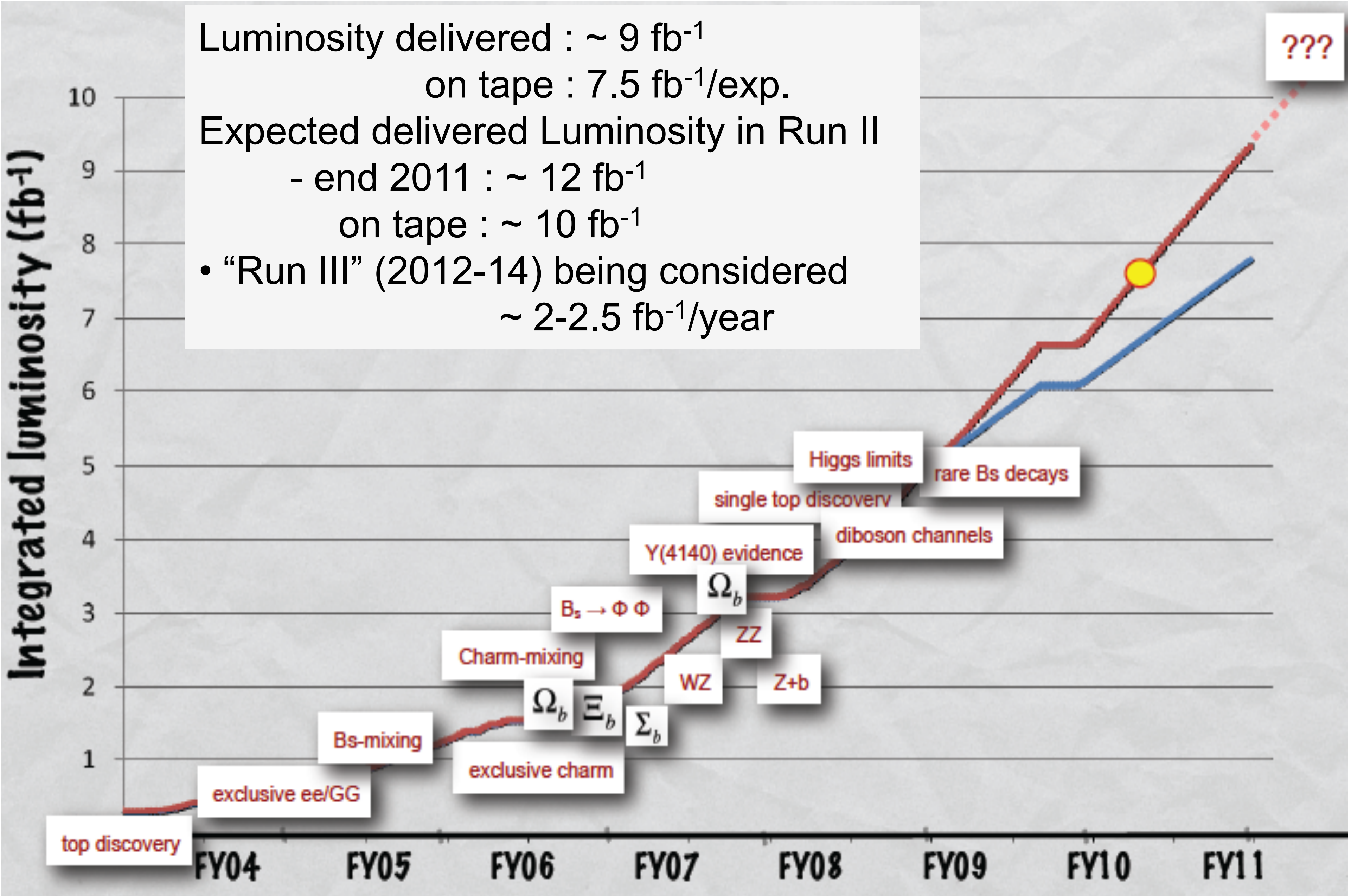
Expected delivered Luminosity in Run II

- end 2011 : ~ 12 fb^{-1}

  on tape : ~ 10 fb^{-1}

• "Run III" (2012-14) being considered

~ 2-2.5 fb^{-1}/year



What the Luminosity Allows Us to See

Luminosity on tape : ~ 7.5 fb^{-1} /exp. :

~ 10T Jets :

- ➔ pdf, alpha-s
- ➔ di-jet mass: substructure
- ➔ jet structure

~ 40 M W➔lv and 4M Z➔ll:

- ➔ W-mass measurement
- ➔ production asymmetries

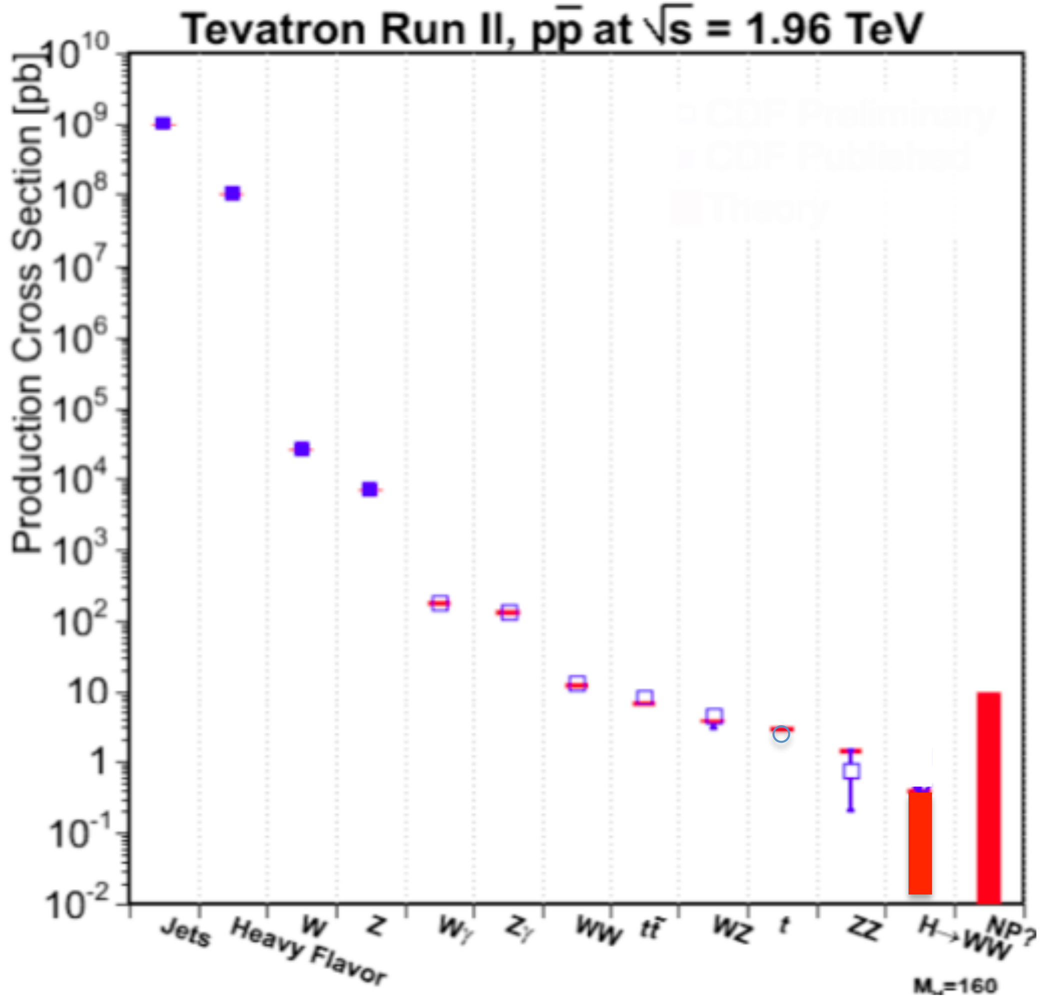
~ 20k top➔l+jets :

- ➔ Top cross-section and mass
- ➔ Single top production

~ 4k WWs➔llvv , 400 WZ➔lllv, 40 ZZ ➔ llll:

- ➔ observation

➔ Constraints on Higgs production



Dedicated Tevatron talks :

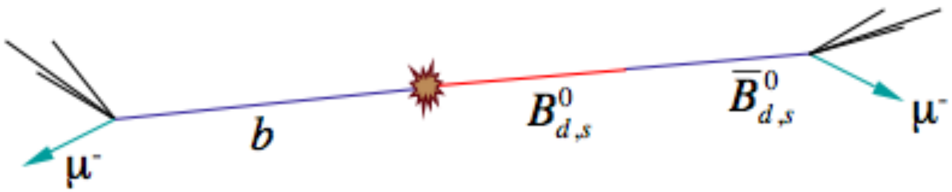
Top (Tommaso Dorigo) , Higgs (Mark Neubauer) and BSM searches (Sergey Uzunyan)

➔ Some emphasis on EW and QCD results

B_s MIXING

Likesign Di-muon Asymmetry

Charge asymmetry in semi-leptonic B-decays:
like sign events tag B^0 oscillation



$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

Dimuon charge asymmetry of semileptonic b-decays measures CP-violation in B_s and B_d mixing

- N_b^{++}, N_b^{--} – number of events with two b hadrons decaying semileptonically and producing two muons of the same charge
- One muon comes from direct semileptonic decay $b \rightarrow \mu^- X$
- Second muon comes from direct semileptonic decay after neutral B meson mixing: $B^0 \rightarrow \overline{B}^0 \rightarrow \mu^- X$

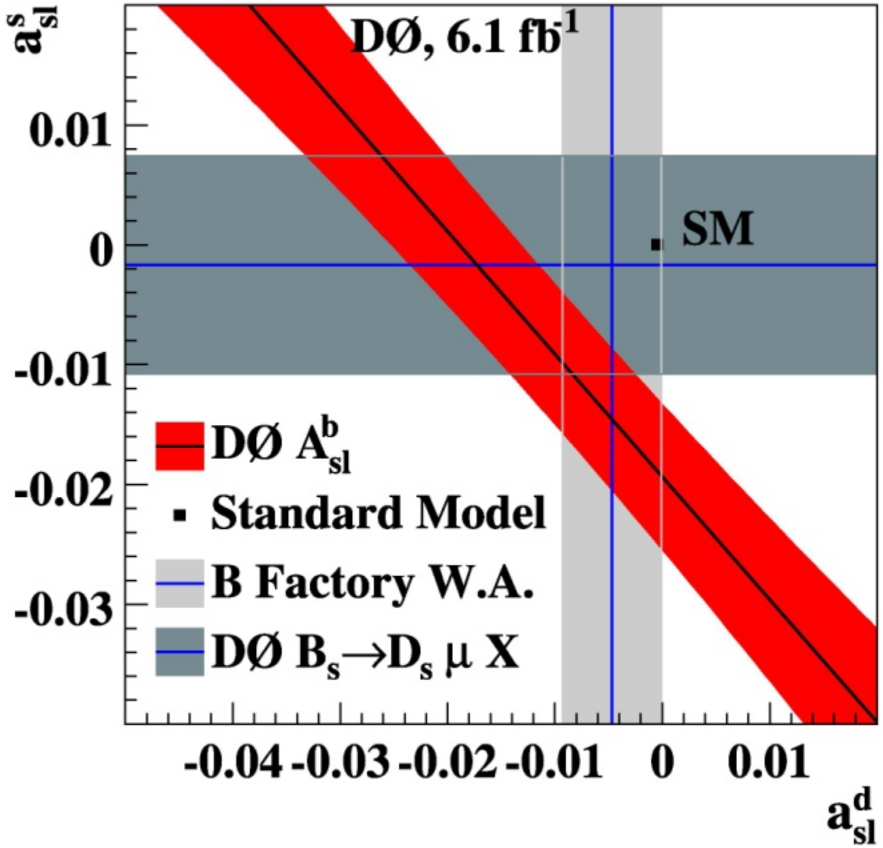
The measured value at DØ at 3.2σ from the SM expectation!

$$A^b_{sl} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

$$A^b_{sl}(SM) = (-0.023^{+0.005}_{-0.006})\%$$

Likesign Di-muon Asymmetry

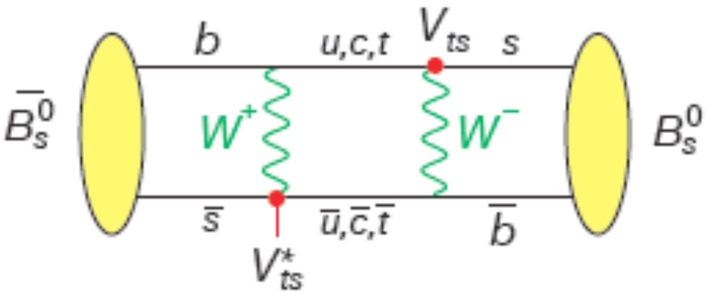
- At the Tevatron: production of B^0_d and B^0_s
- Fraction of B^0_d and B^0_s measured by CDF
- Charge asymmetry A_{sl} is a linear combination of a^d_{sl} and a^s_{sl}



$$A^b_{sl} = (0.506 \pm 0.043)a^d_{sl} + (0.494 \pm 0.043)a^s_{sl}$$

SM contribution negligible
- Signs of new physics?

B_s MIXING



2 mass eigenstates:

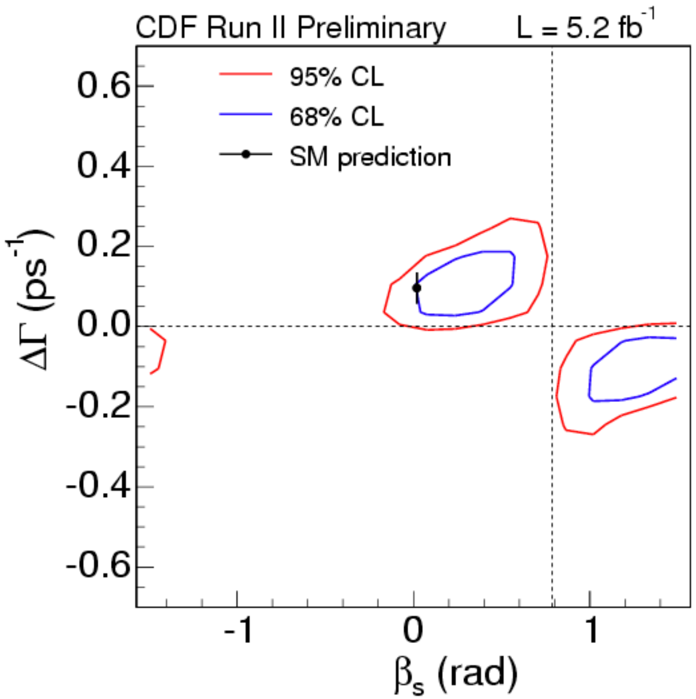
$|B_s\rangle = p\,|Bs\rangle - q\,|B_s\rangle$ $\quad |B_s\rangle = p\,|B_s\rangle + q\,|B_s\rangle$

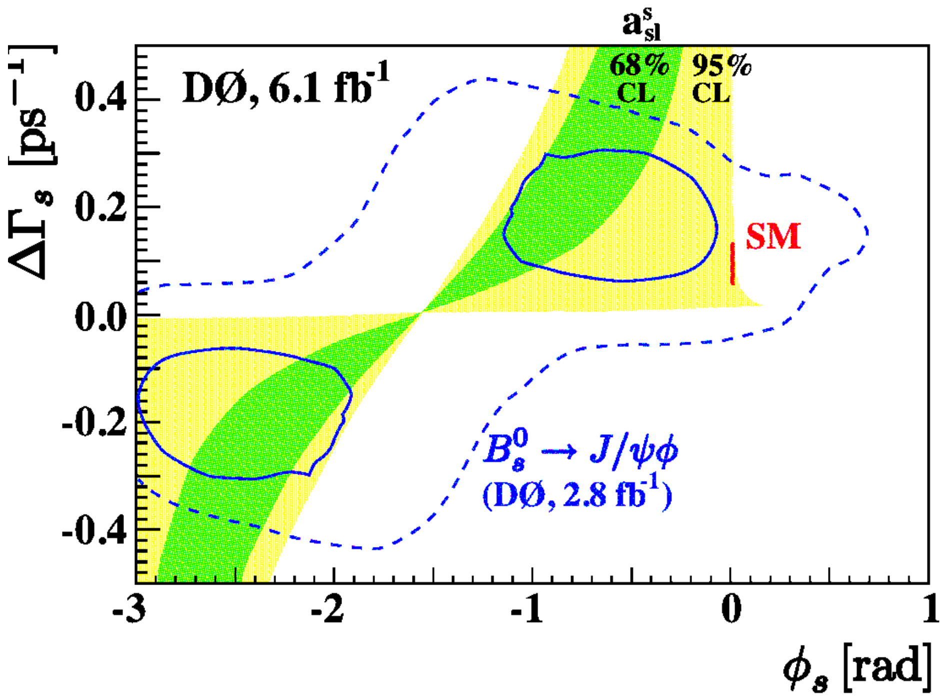
If CP is conserved then q = p

$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$ with $\phi_s = -2\beta_s$ mixing phase

New CDF and DØ result at 0.8σ and 1σ from SM ➔ closer than previous results

➔ LHCb: 5% precion expected with 500 pb^{-1}





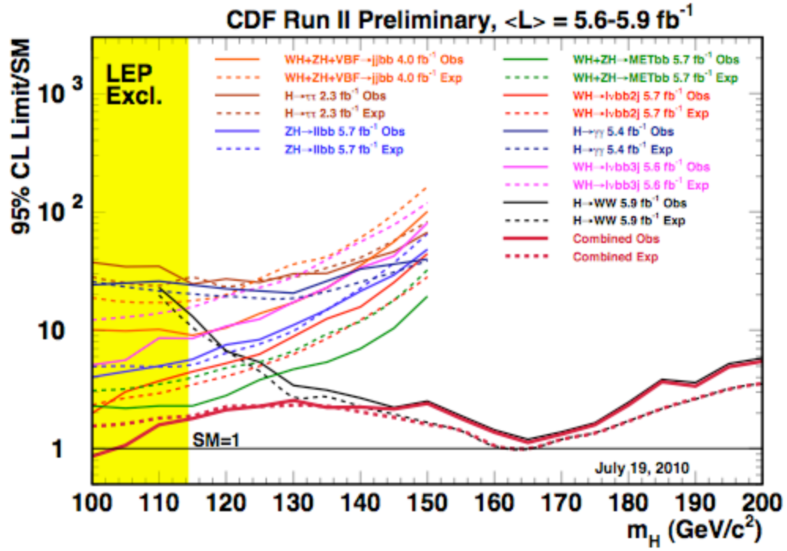
HIGGS SEARCH

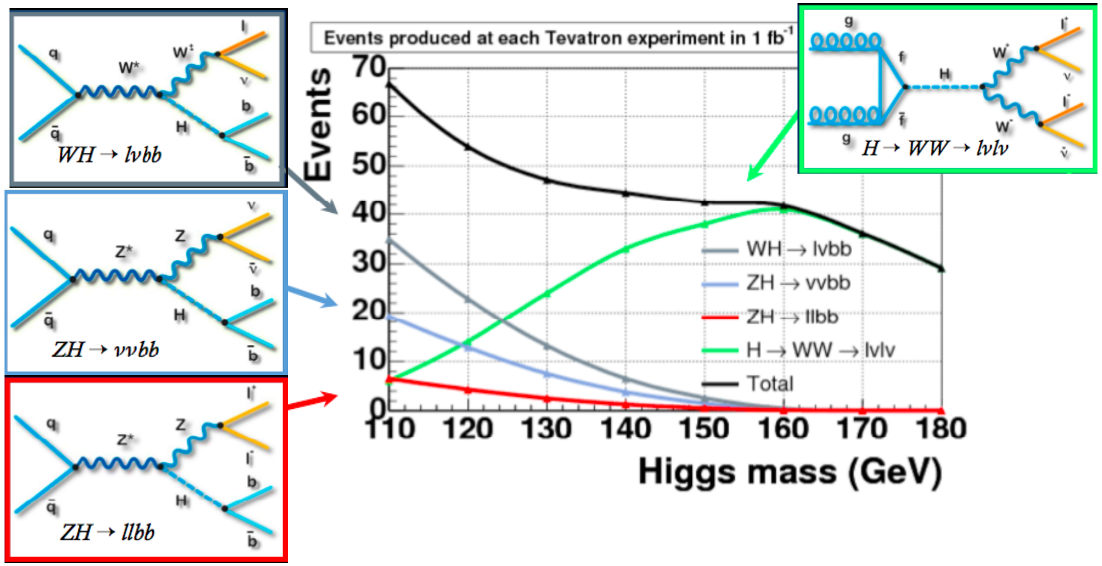
Higgs Search at the Tevatron

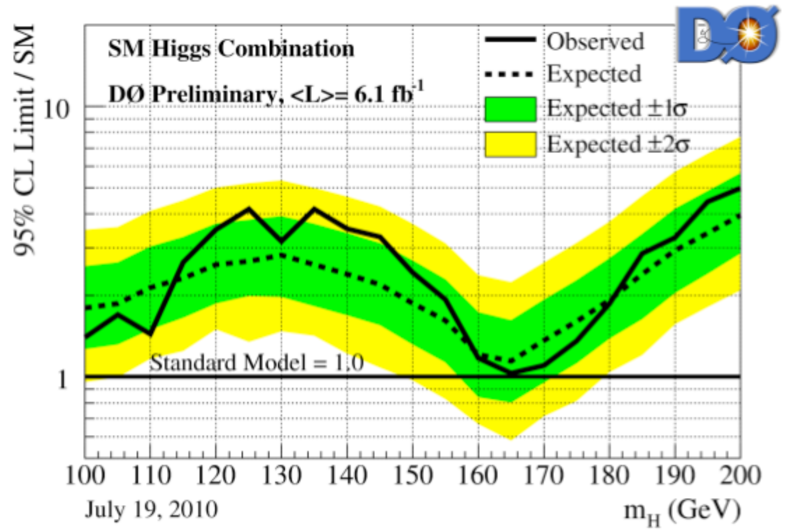
- **Low Mass Higgs (m_H ~<135 GeV)**
  - $H \rightarrow bb$, QCD bb background overwhelming
  - Use associated production to reduce background
- **High Mass Higgs (m_H ~>135 GeV)**
  - $H \rightarrow WW \rightarrow l\nu l\nu$ decay available
  - Take advantage of large $gg \rightarrow H$ production cross section

Threefold strategy

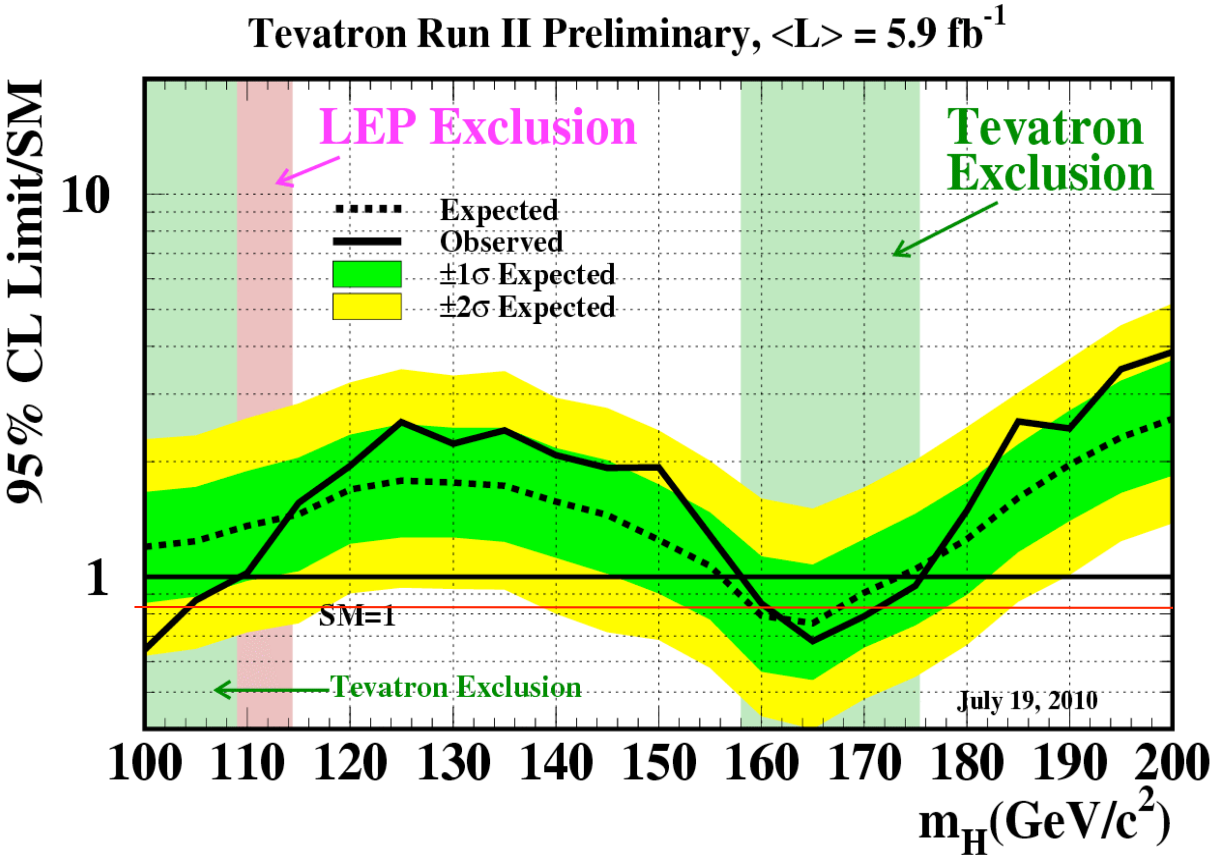
- Maximize signal acceptance, reduce background
- Employ multivariate techniques
- Combine all available channels of both experiments







COMBINED LIMIT ON HIGGS MASS



- Combined 95% CL exclusion values for $100 < m_H < 200$ GeV
- Sensitivity to low mass Higgs rapidly growing

➔ High mass exclusion between 158 and 175 GeV

- Weak dependence on the theoretical x-section :
  - with 20% less on gg→H exclusion still ~ 160-172 GeV
  - effect of large systematics even weaker.

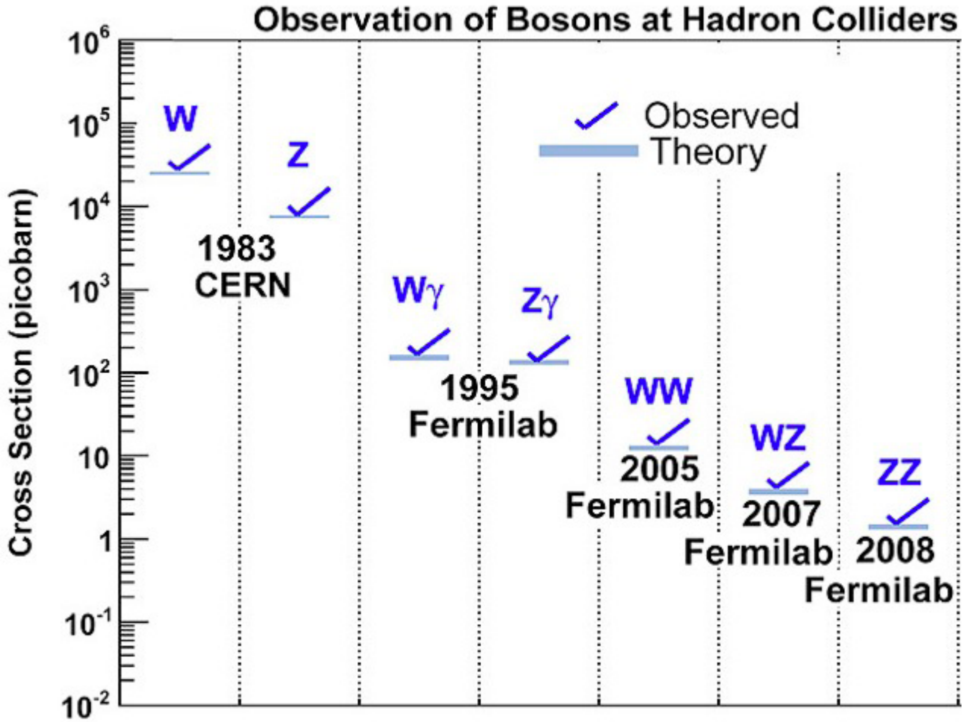
➔ no hint of a signal in the 155-175 GeV region where you would expect a > 2 sigma excess

Towards the Higgs

DI-BOSONS

DIBOSONS PHYSICS

- **Probe of electroweak sector of the standard model**
  - cross sections
  - gauge boson couplings
- **Background for Higgs searches**
- **“Validation” of multivariate analysis techniques**



Charged Triple Gauge Couplings

- probed by WW, WZ, Wγ

5 TGC parameters:

$g1^Z$, κ_γ, κ_Z = 1 in SM

λ_γ, λ_Z = 0 in SM

Neutral Triple Gauge Couplings

- probed by ZZ, Zγ

4 TGC parameters:

$h3^\gamma$, $h3^Z$, $h4^\gamma$, $h4^Z$ all 0 in SM !

WW+WZ+ZZ → 2 jets + mE_T

CDF ($3.5fb^{-1}$): σ= 18.2 ± 3.7pb

observation at 5.3σ

WW+WZ→ lν + 2 jets

DØ ($1.1fb^{-1}$): σ= 20.2 ± 4.5 pb **evidence at 4.4σ**

CDF($4.6fb^{-1}$): σ= $16.5^{+3.3}_{-3.0}$ pb **observation at 5.4σ**

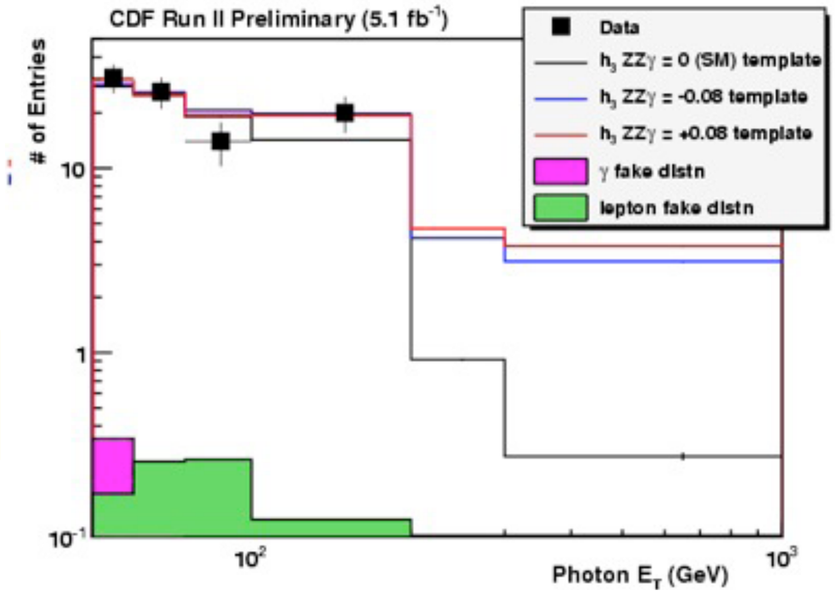
Zγ and ZZ

Zγ→ eeγ, μμγ, ννγ (5fb^{-1})

- Cross sections in good agreement with SM
- γ E_T spectrum used to set limits on TGC

➔ Most stringent limits (λ=1.2 TeV)

	h_3^γ	h_3^Z	h_4^γ	h_4^Z
CDF	-0.022,0.021	-0.018, 0.020	-0.0009, 0.0010	<0.0009

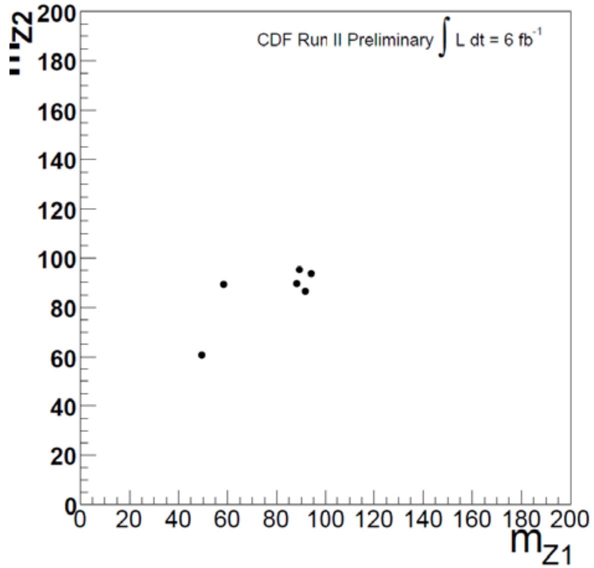


- **ZZ signature well established by both collaborations**

ZZ→ lll'l' (6fb^{-1})

CDF: $\sigma= 1.7^{+1.20}_{-0.7} \pm 0.2$ pb

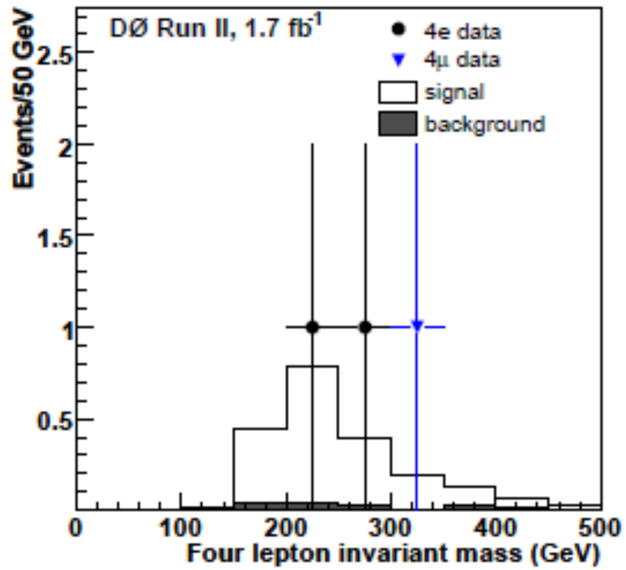
observation at 5.7σ



ZZ→ lll'l' and ZZ→llνν (2.7fb^{-1})

DØ : σ= 1.60 ± 0.65 pb

observation at 5.7σ



WZ

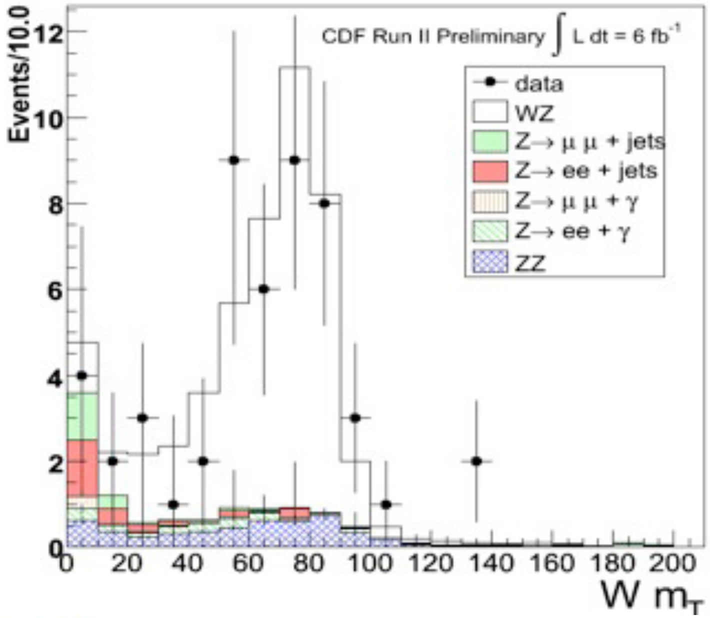
- **Triple lepton final state WZ→ lll'v**

CDF: $\sigma = 3.7^{+0.6}_{-0.4} \pm 0.6$ pb (ML fit to NN output) **($6fb^{-1}$)**

CDF : $\sigma = 4.1 \pm 0.7$ pb (Normalized to NNLO Z cross-section)

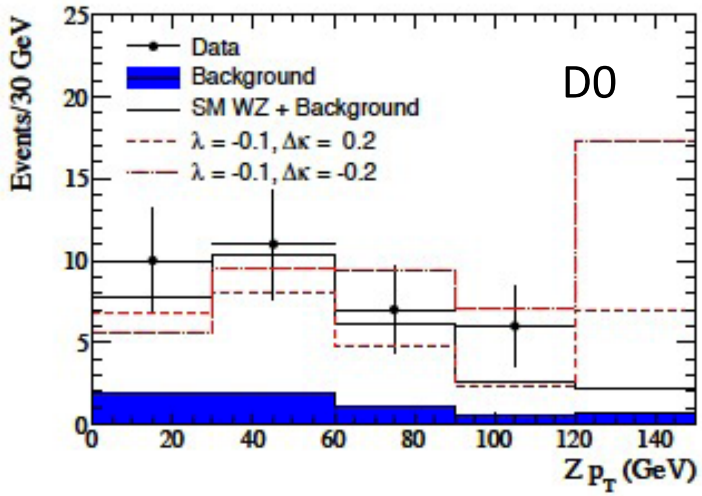
DØ : $\sigma = 3.9^{+1.0}_{-0.9}$ pb **($4.1fb^{-1}$)**

- Cross-section in agreement with NLO: $\sigma_{WZ} = 3.46 \pm 0.21$ pb



Extract limit on WWZ coupling from DØ Zp_T distribution:

λ_Z	Δg_1^Z	$\Delta \kappa_Z$
-0.075, 0.093	0	0
0	-0.053, 0.156	0
0	0	-0.376, 0.686



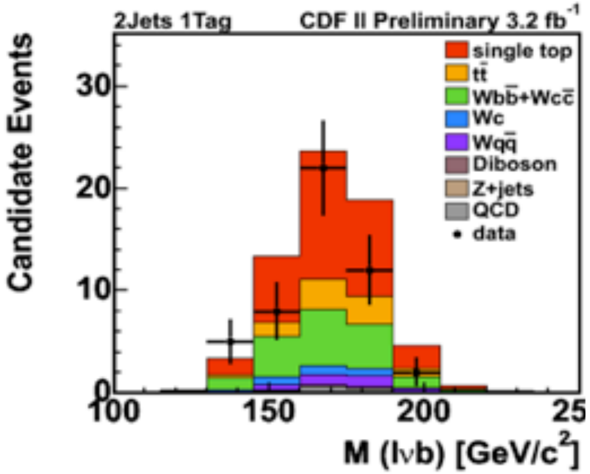
Most stringent limits from direct study of WZ production!

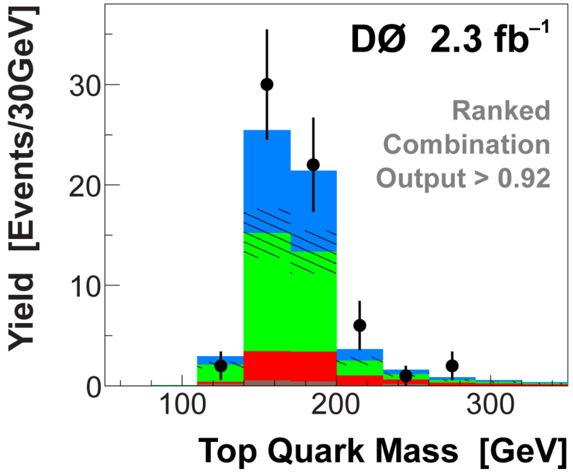
Towards the Higgs

SINGLE TOP

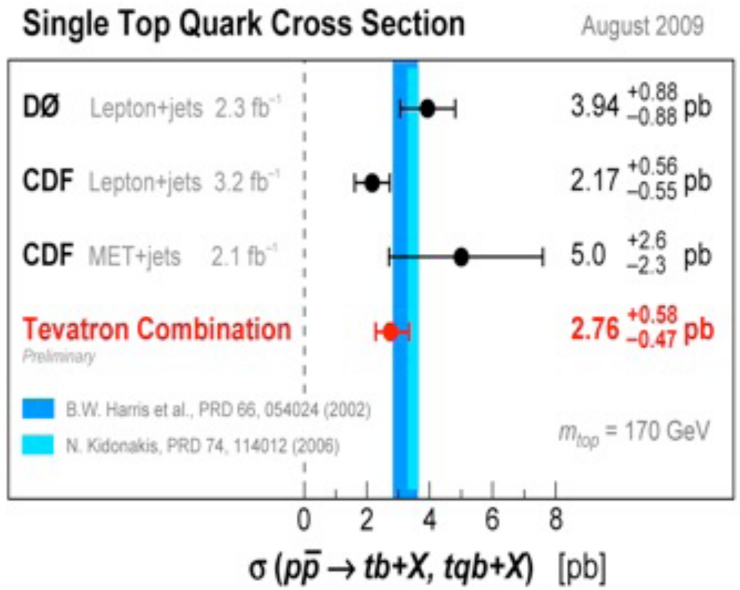
SINGLE TOP PRODUCTION

Single Top Cross Section	Signal Significance Expected	Signal Significance Observed
DØ 2.3 fb^{-1} arXiv:0903.0850 m_{top} = 170 GeV		
3.94 ± 0.88 pb	4.5 σ	5.0 σ
CDF 3.2 fb^{-1} arXiv:0903.0885 m_{top} = 175 GeV		
$2.3^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ

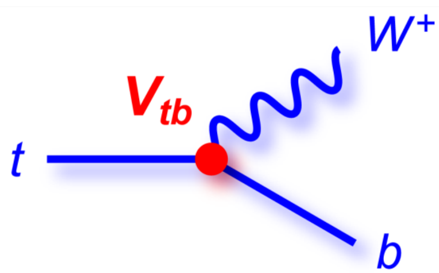




- Tevatron s- and t-channels production
- Observed by CDF and D0 in 2009, 14 years after top discovery :
  - small cross section
  - large background with large uncertainties
  - multivariate techniques necessary



$\sigma = 2.76^{+0.58}_{-0.47}$(stat + syst) pb



- Allows to measure $|V_{tb}|$:

$|Vtb| = 0.91 \pm 0.08$ (stat+syst)

- Sensitive to new physics

Higgs Constraints

SM CONSISTENCY

Higgs: SM Consistency Check

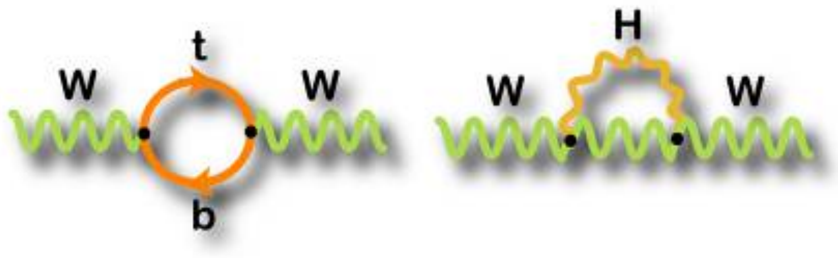
Derive W boson mass from precisely measured electroweak quantities

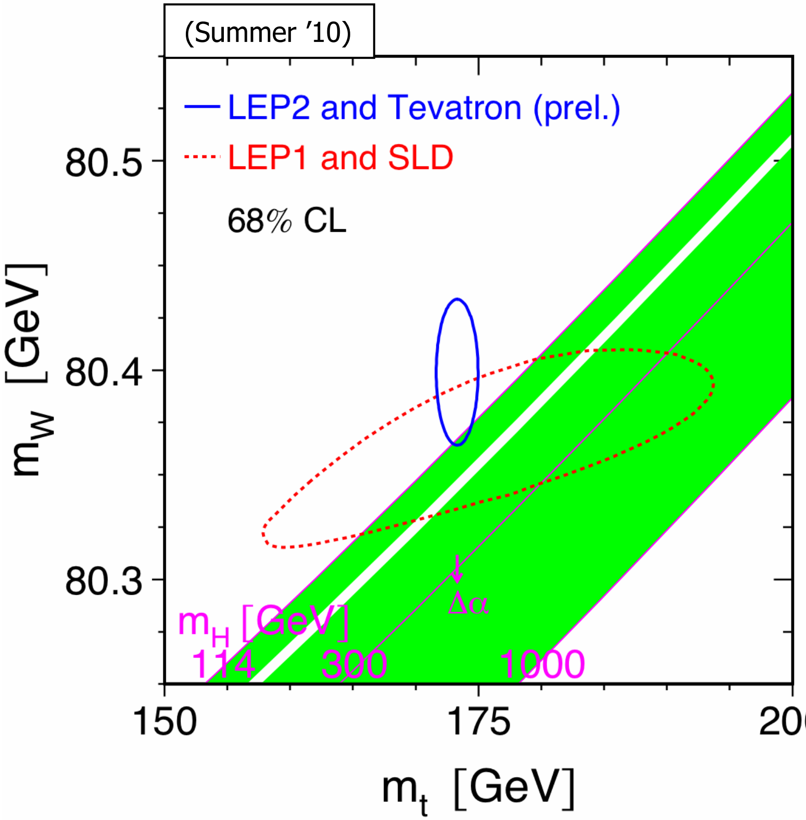
known to 0.015%

$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_F}\,\frac{1}{1-M_W^2/M_Z^2}\,\frac{1}{1-\Delta r}$$

known to 0.0009% M_Z known to 0.002%

Δr: - large radiative corrections
- dominated by *tb* and Higgs loops
- sensitive to new physics





m_{top}=(173.3 ± 1.1) GeV (0.6%)
m_W =(80.399±0.023) GeV (0.028%)
➔ Δm_W ~ 0.006 x Δm_{top} ~ 7 MeV for equal weights in Higgs limits

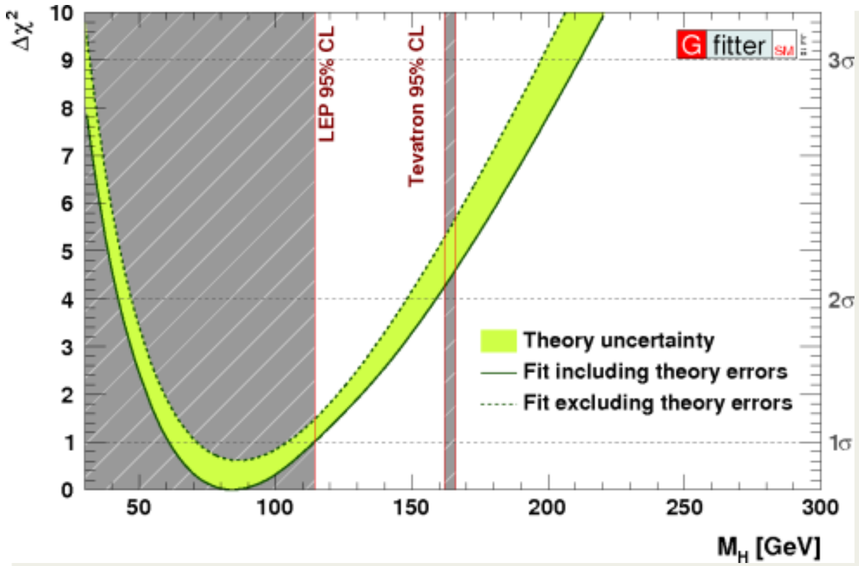
=> Prediction of the Higgs boson mass and consistency check of SM

CONSTRAINTS ON HIGGS MASS

- **Indirect limits:**

Electroweak precision measurement

Precision EW fit:
m_H = [47,159] GeV@95%CL

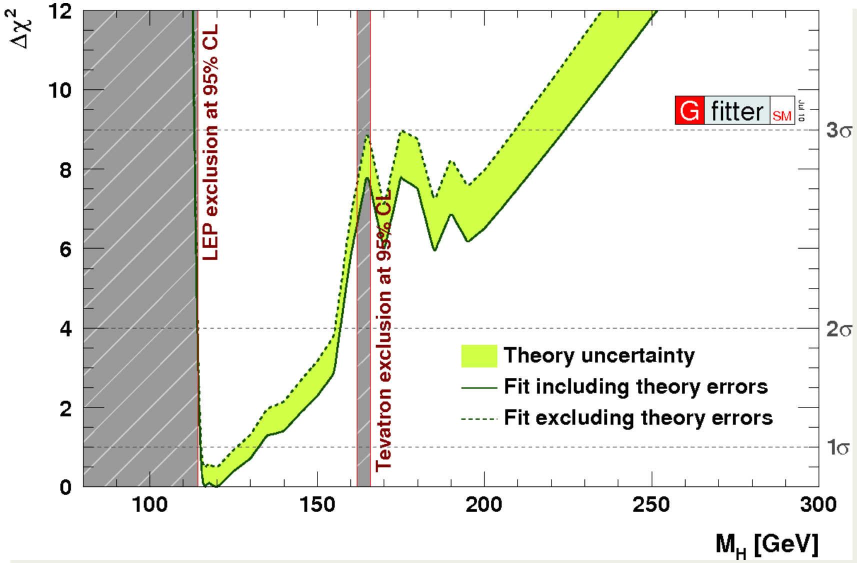


- **Direct limits:**

LEP: m_{Higgs} > 114 GeV @ 95% CL
TEV: m_{Higgs} ≠ [158;175] GeV @ 95% CL

Combining Direct and Indirect Limits GFITTER :

m_H= [114, 157] GeV @ 95 % CL



Higgs Constraints

TOP MASS

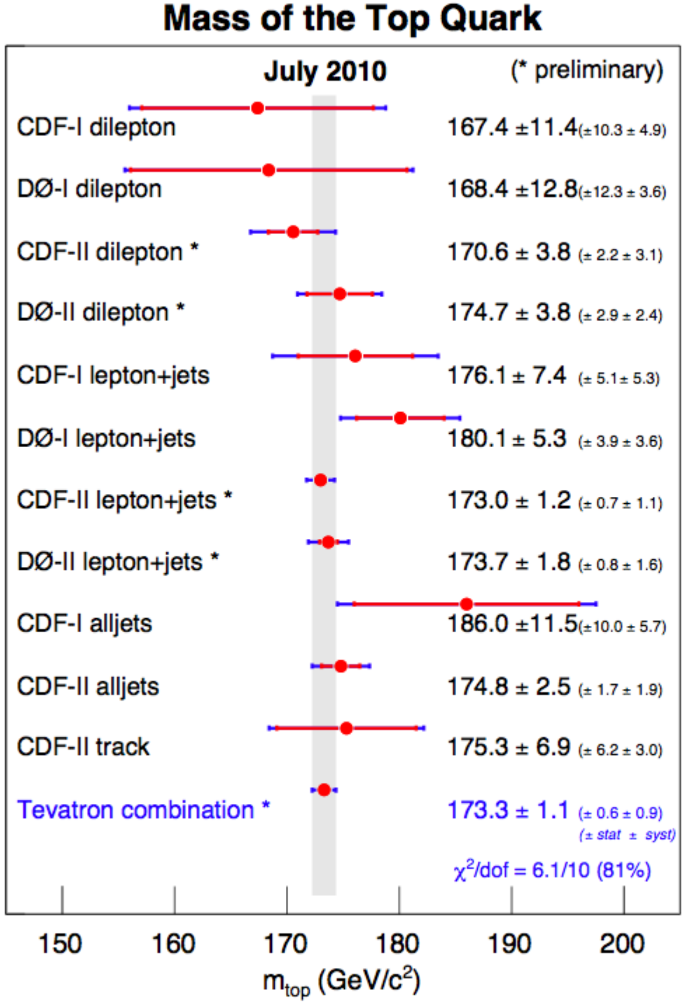
Top Quark Mass

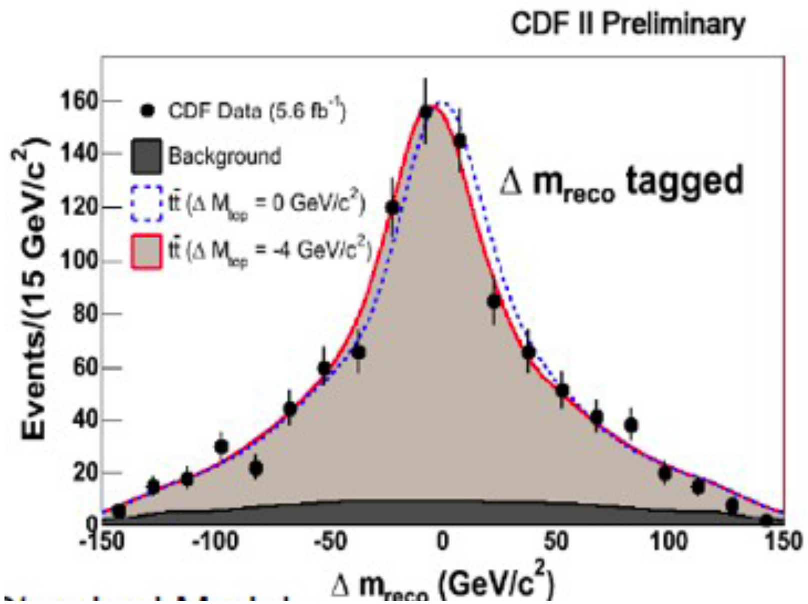
- Measurement in different channels consistent
- Different methods produce consistent results

m_{top}=173.3±1.1(total) GeV

- 0.6% relative uncertainty
- Precision is now limited mainly by systematics

➔ joint effort on improving its understanding





Probing CPT:
Is top quark mass equal to anti-top quark mass?

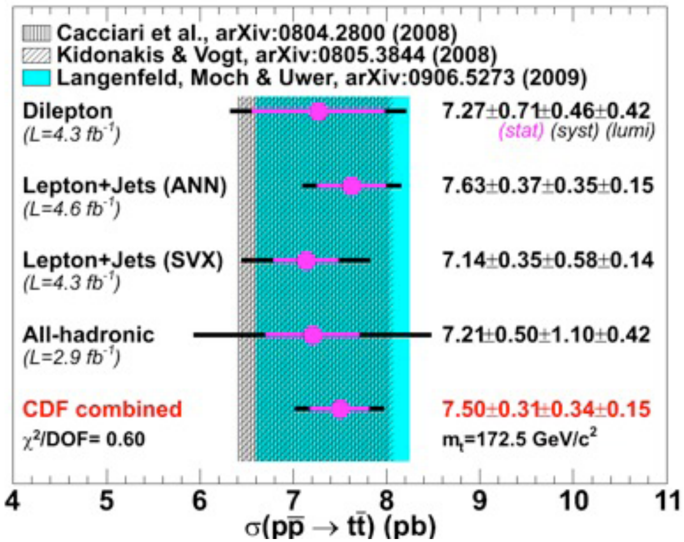
CDF : ΔM_{top} = -3.3 ± 1.4(stat.) ± 1.0 (syst.) GeV (5.6 fb^{-1})

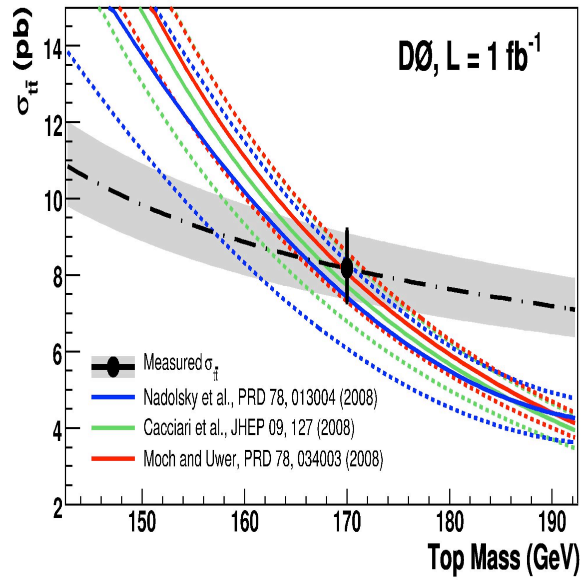
DØ : **ΔMtop = 3.8±3.7 GeV** (1 fb^{-1})

First measurements of mass difference of bare quarks

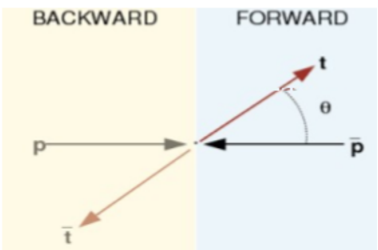
TOP QUARK PAIR PRODUCTION

- Top pair production cross-section measured in all channels except $\tau_{had}\tau_{had}$
- Combined CDF cross-section has a precision of 6% ➔exceeds precision expected for the Tevatron





➔ mass from cross-section $169.1^{+5.1}_{-5.2}$GeV consistent with direct mass measurement



$$A_{fb} = \frac{F - B}{F + B}$$

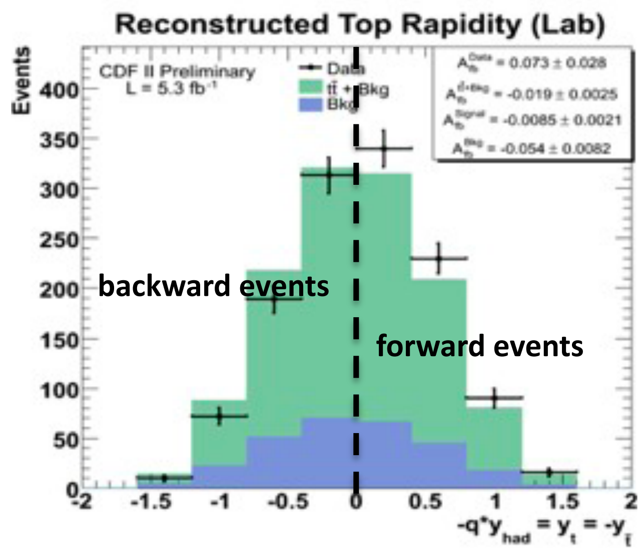
- New physics could give rise to asymmetry
- due to interference effects

CDF ($5.3fb^{-1}$): A_{fb}=15.0±5.0 (stat) ±2.4 (syst) %

SM prediction A_{FB} = 5±1.5 % (NLO QCD)

DØ ($4.3fb^{-1}$): A_{fb}^{raw} =8±4 (stat) ±1 (syst) %

MC prediction $A_{FB}^{raw} = 1^{+2}_{-1}$ % (MC@NLO)



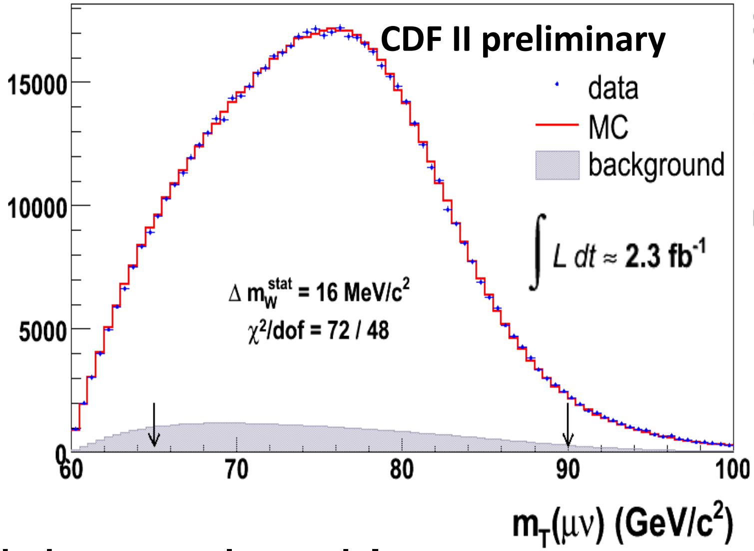
Higgs Constraints

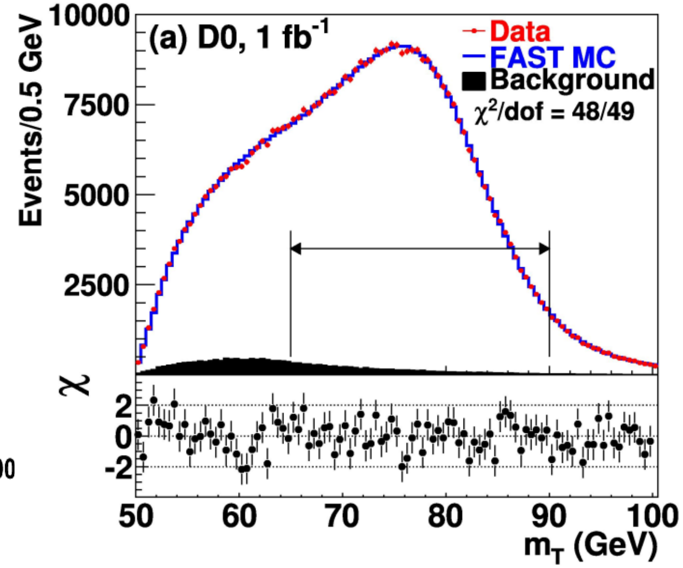
W MASS

Tevatron W Mass Combination

LEP legacy:

M_W=80367±33 MeV





Tevatron:

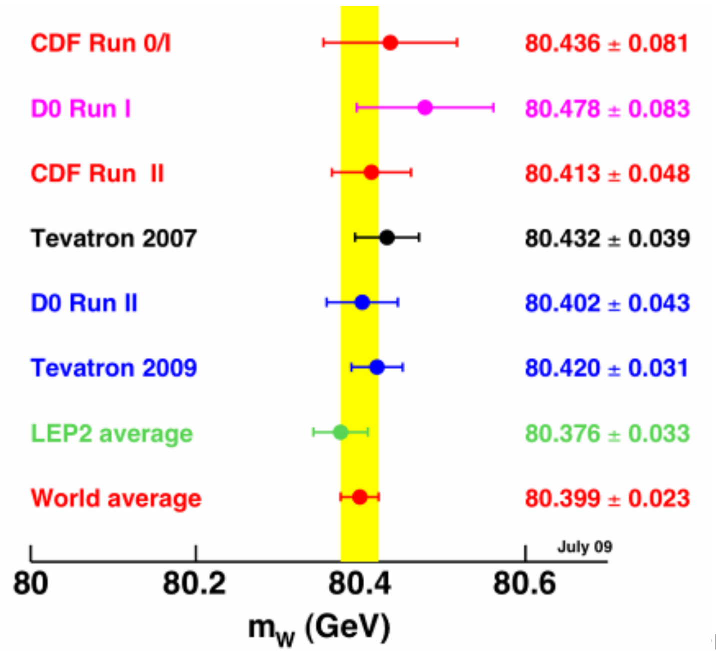
~ 500 000 W→eν candidates analysed !

- **Tevatron combination:**

  m_W=80420±31MeV (0.038%)

- Precision still statistical limited by Z calibration sample!
- **World Average (Summer 2009)**

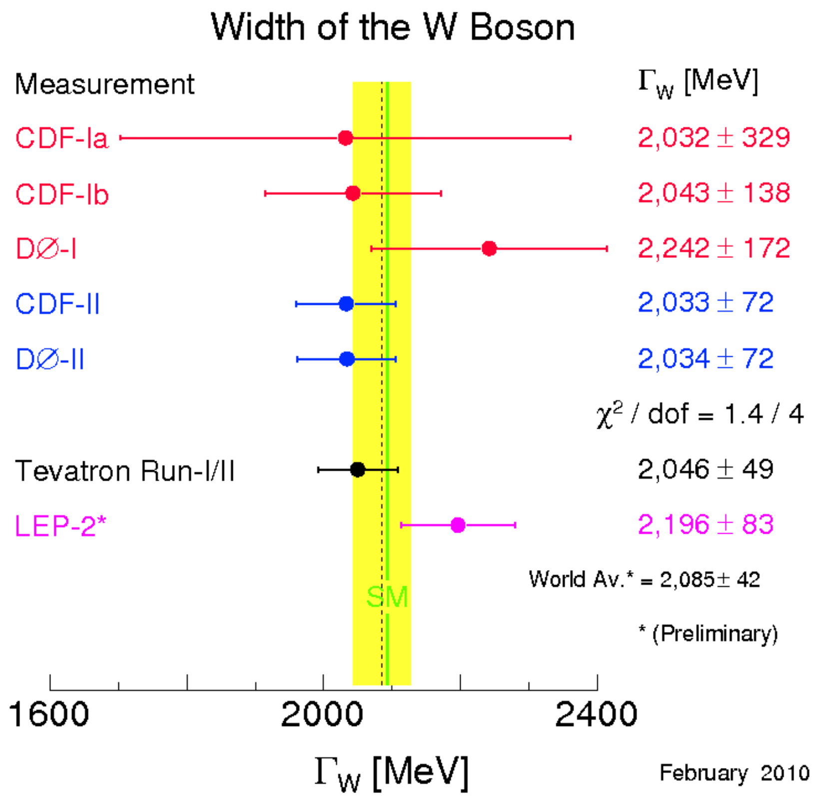
  m_W=80399 ± 23 MeV

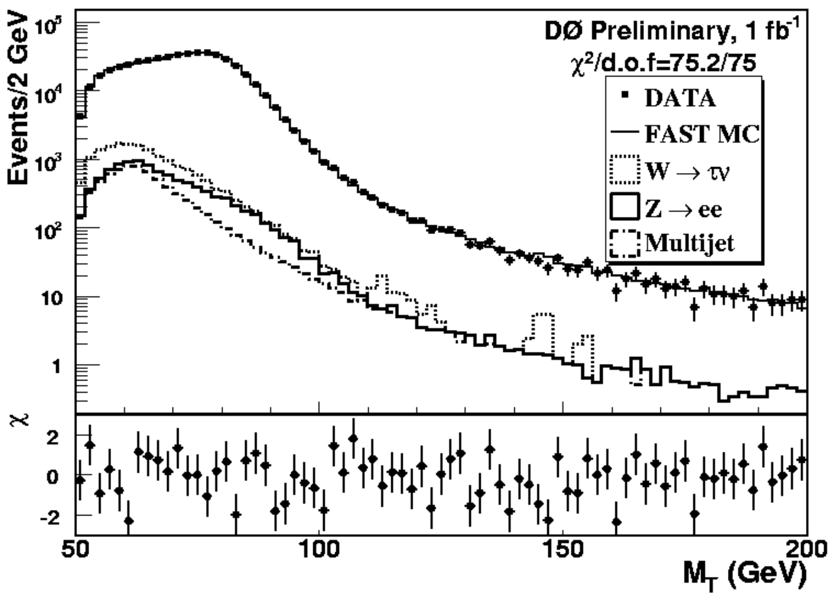


W-Width Γ_W

- The high m_T tail contains information on Γ_W
  - Exploit slower falloff of Breit-Wigner compared to Gaussian resolution
- Γ_W is expected to agree with SM almost irrespective of any new physics

$$\Gamma_W \approx (3 + 2f_{QCD})\frac{G_F M_W^3}{6\sqrt{2}\pi}(1+\delta_{SM}) = 2.089 \pm 0.002 \text{ GeV}$$





New world average:

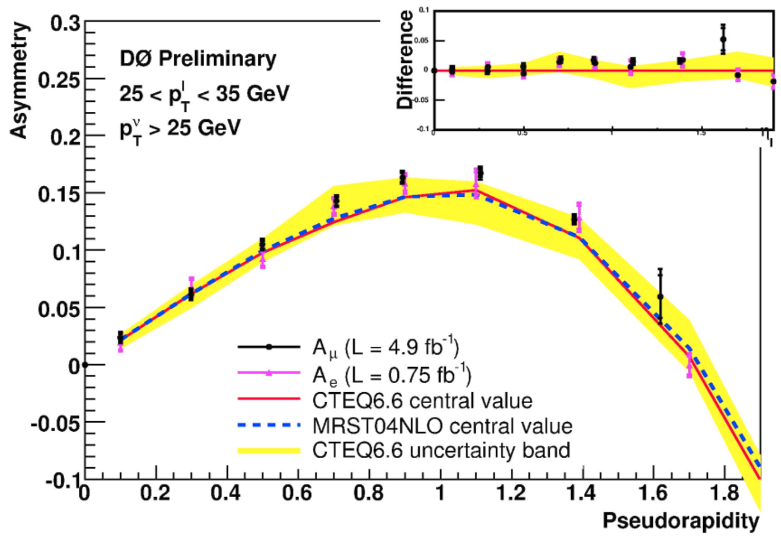
Γ_W = 2085 ± 42 (stat + syst) MeV

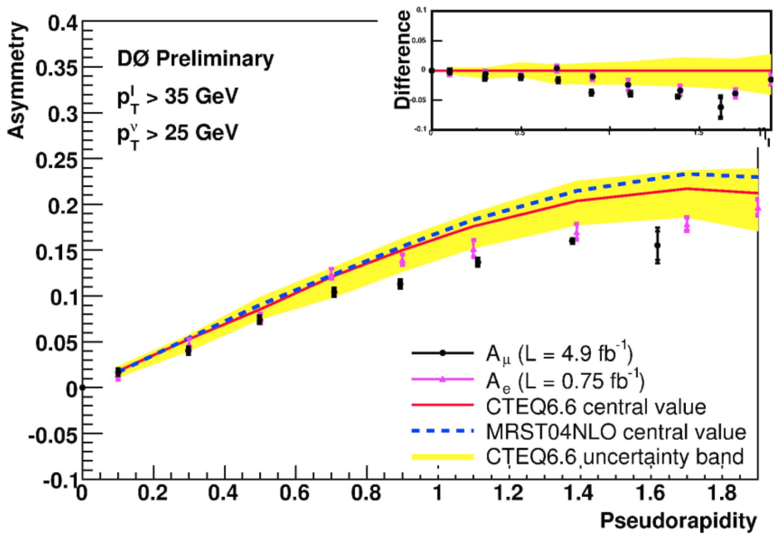
Theory: Γ_W = 2089 ± 2 MeV

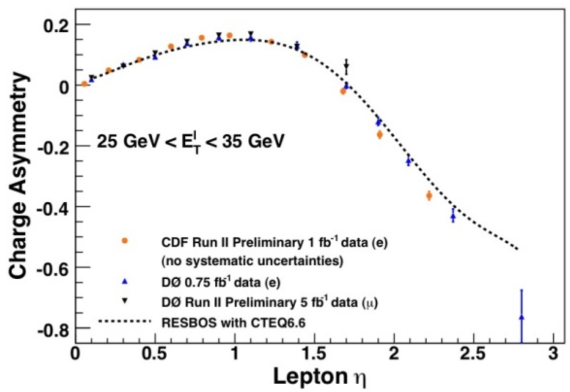
EW-PHYSICS

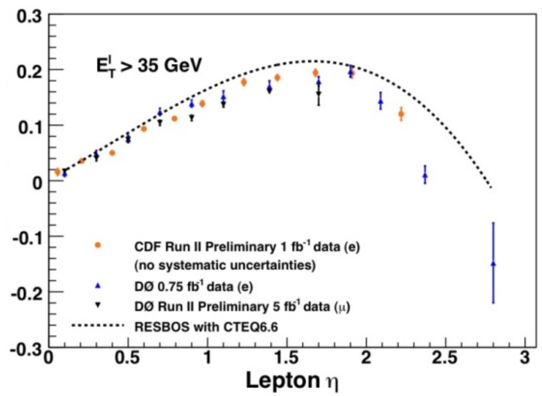
W and Lepton Charge Asymmetry

- New high statistics D0 muon charge asymmetry data confirms previous deviation from theory at high p_T^l
- Global fitters (MSTW,CTEQ) have problems incorporating D0 lepton charge asymmetry results :
  - Tension with low-x data
- Preliminary re-analysis of CDF result $A(y_W) \rightarrow A(\eta_l)$ confirms D0 result!
- Currently being investigated by theorists and experimental teams

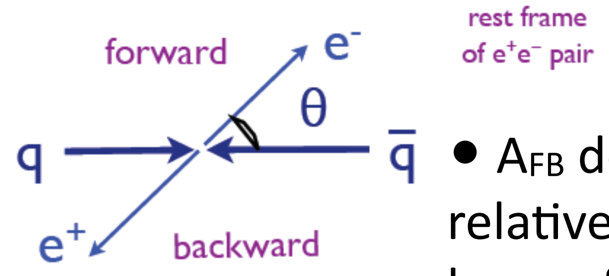






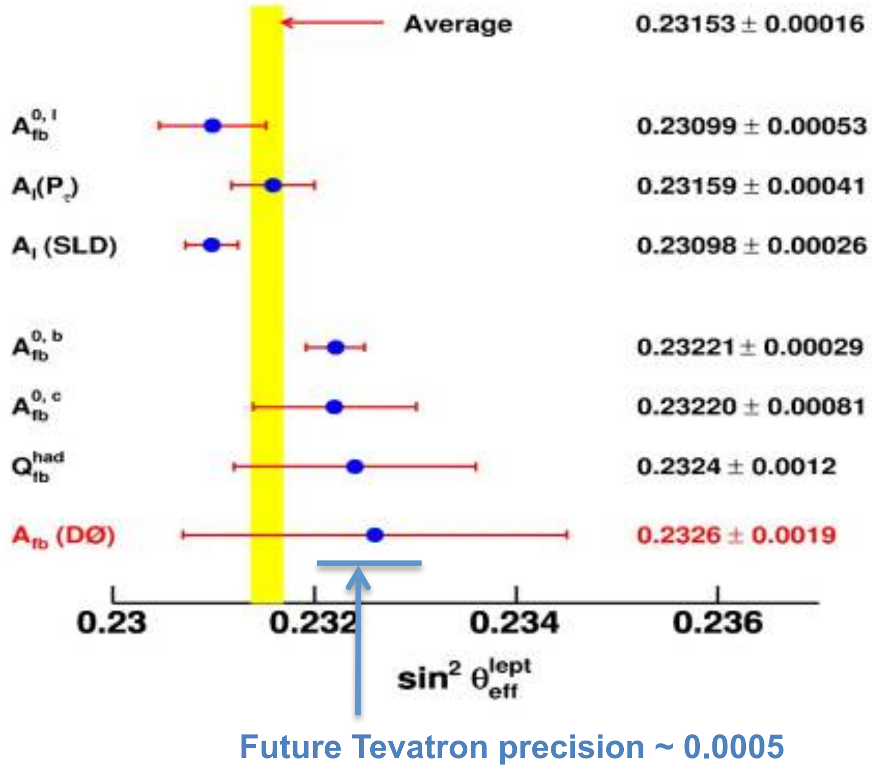


Z Forward Backward Asymmetry A_{FB}

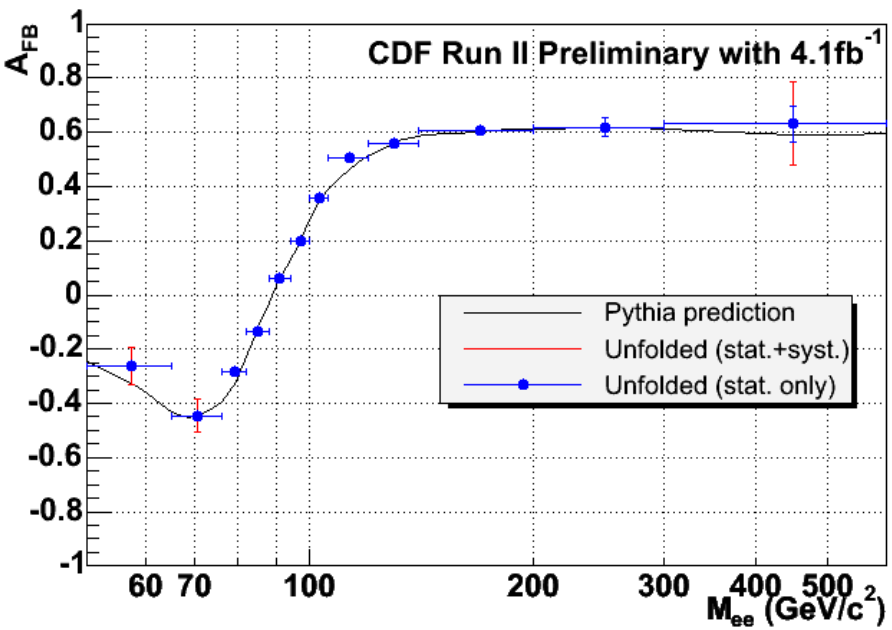


$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- A_{FB} determines the relative strengths of V-A boson-fermion couplings as well as $\sin^2 \theta_W$



- A_{FB} sensitive to new resonance (f.g Z') via interference with $Z/\gamma*$



D0 1.1fb^{-1}:

$\sin^2\theta_W = 0.2326 \pm 0.0018(\text{stat.}) \pm 0.0006(\text{syst.})$

World = 0.23153 ±0.00016

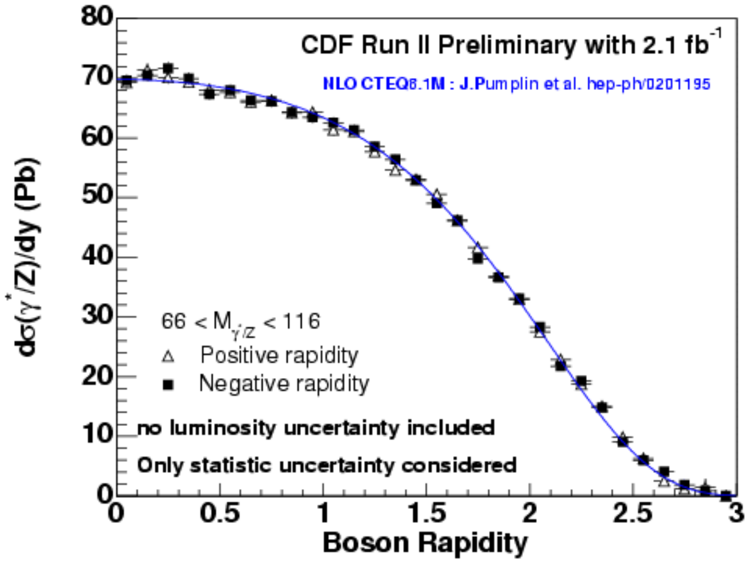
QCD

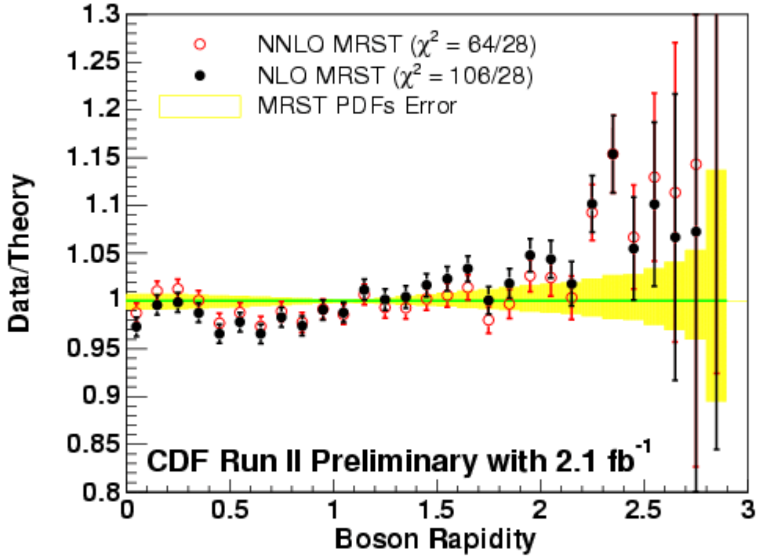
EW-BOSON PRODUCTION

Z-CROSS SECTION AND RAPIDITY

- Z-Boson rapidity reconstructed from leptonic decays

- High rapidity (y) probes high-x region
➔ sensitivity to d_v





- Shape well described by NLO QCD

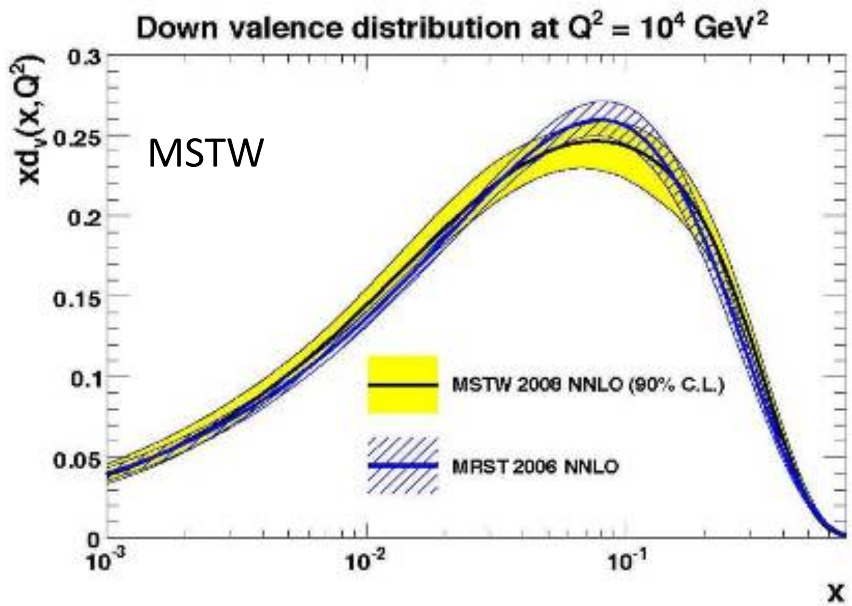
Total cross section |y| <2.9:

σ=256.0±0.7(stat)±2.0(syst) pb ± 6% (lumi)

σ(y>0) = 256.4 ± 1.0(stat) pb

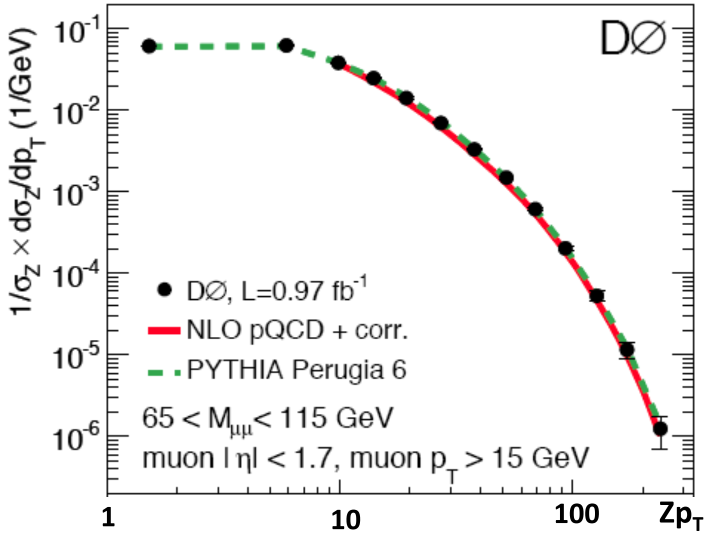
σ(y<0) = 256.9 ± 0.9(stat.) pb

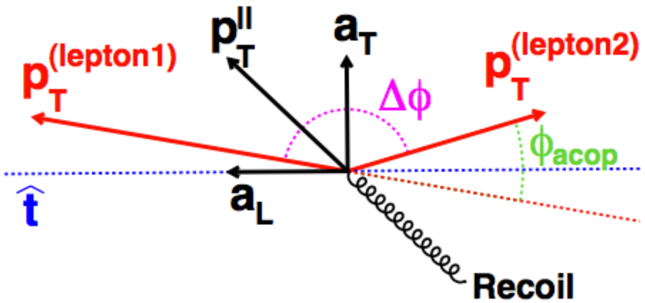
236.1±1.93 pb NLO CTEQ6M
252.6 ±3.1 pb NNLO MRST 2006



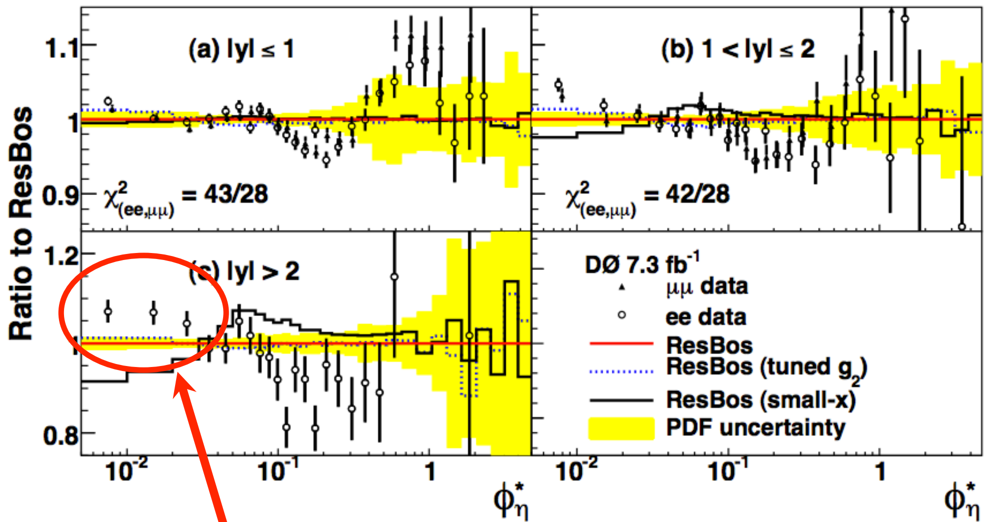
$Z/\gamma^*\ p_T$

- Vector boson p_T spectrum sensitive to initial state radiation => stringent QCD test (reweighting)
- Low p_T spectrum sensitive to multiple soft gluon emission => requires resummation techniques/mode
- Recent D0 result (7.3 fb^{-1}) uses new variable $\Phi^*=a_T/$ m_{ll} based on the two lepton directions





=> less vulnerable to detector resolution limiting precision of $p_T(Z)$ measurement

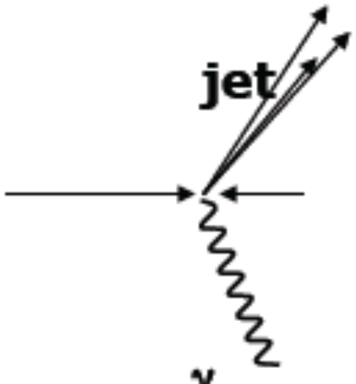


Data does NOT support "small-x broadening"

QCD

PHOTOPRODUCTION

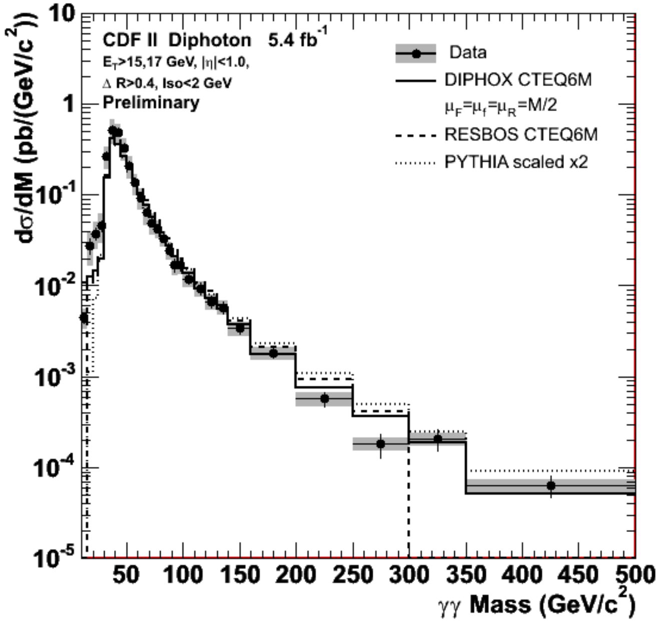
PHOTON AND DIPHOTON PRODUCTION



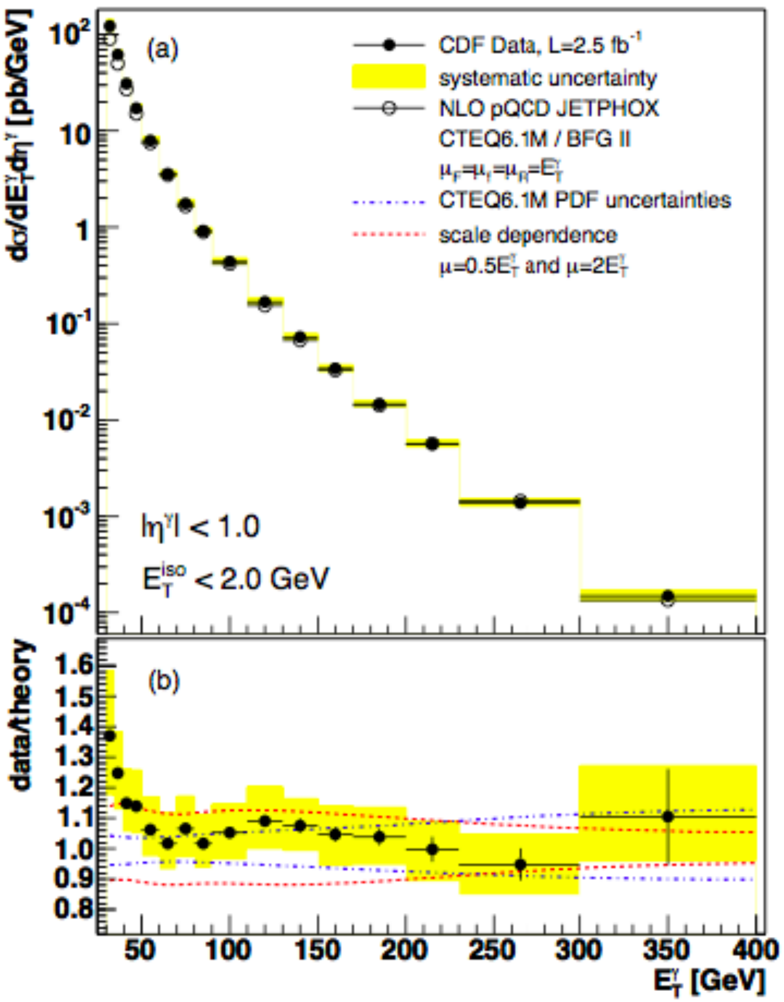
Study of QCD dynamics:
- know quark couplings
- sensitivity to gluon pdf
- no need of jet definition

But: experimentally difficult du to π^0 background

- **Signature for very interesting physics processes : Diphoton+X model independent BSM searches**
- **Invariant mass distribution measured with good precision**



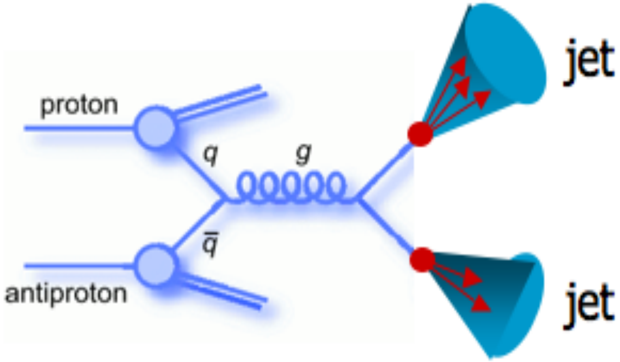
Higher order corrections (beyond NLO) needed as well as resummation to all orders of soft and collinear initial state gluons



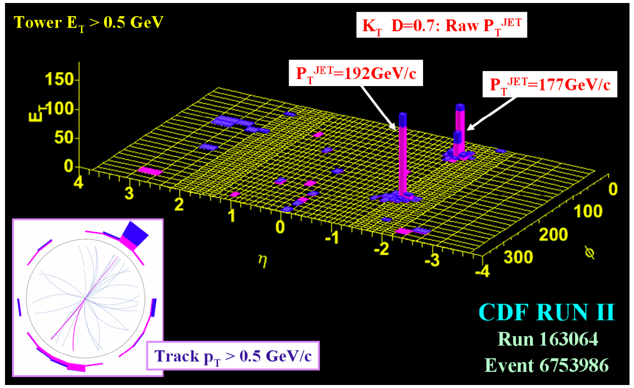
QCD

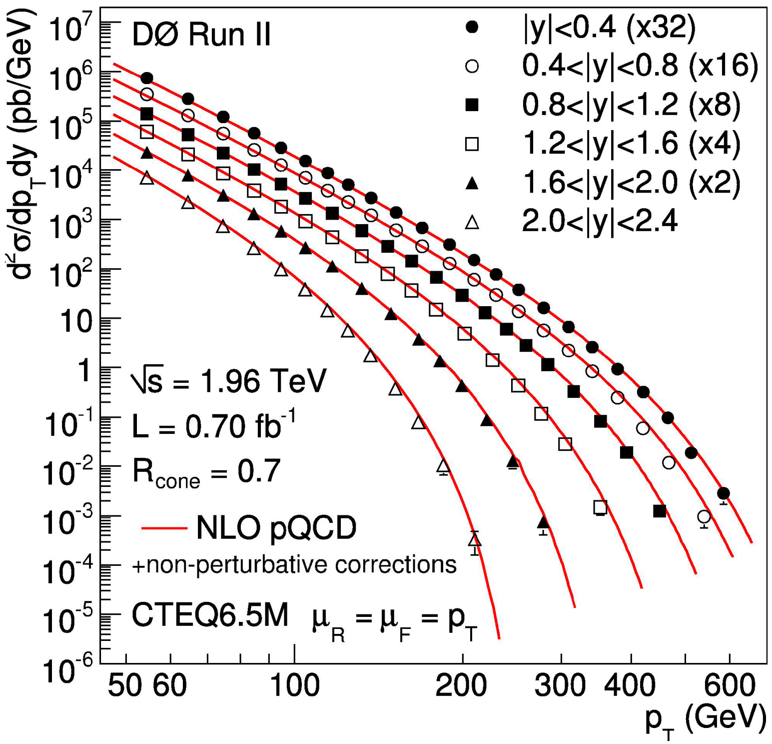
JET PHYSICS

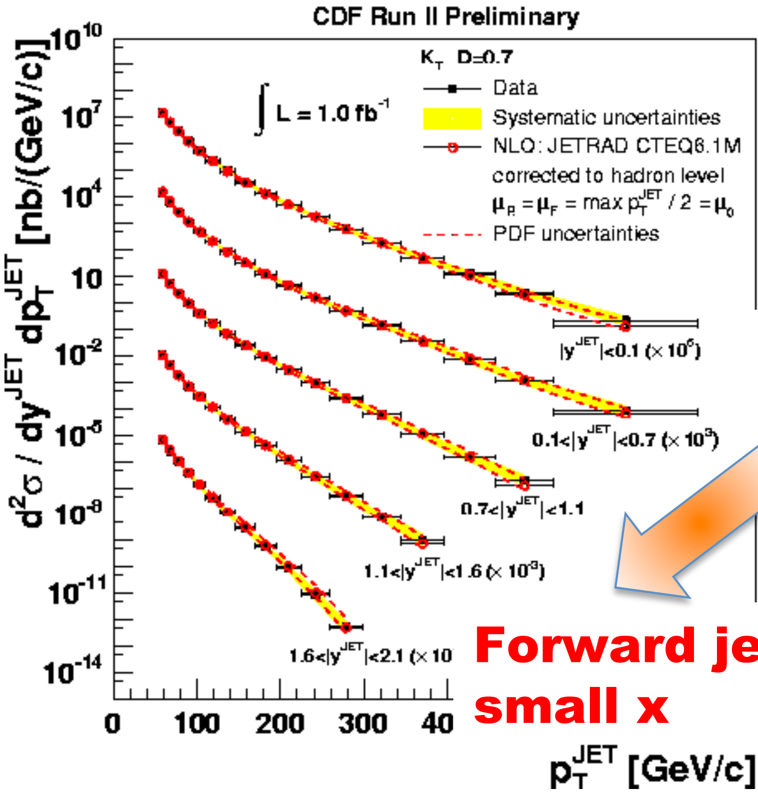
Jets at the Tevatron



Collimated jet of particles originating from quark and gluon fragmentation





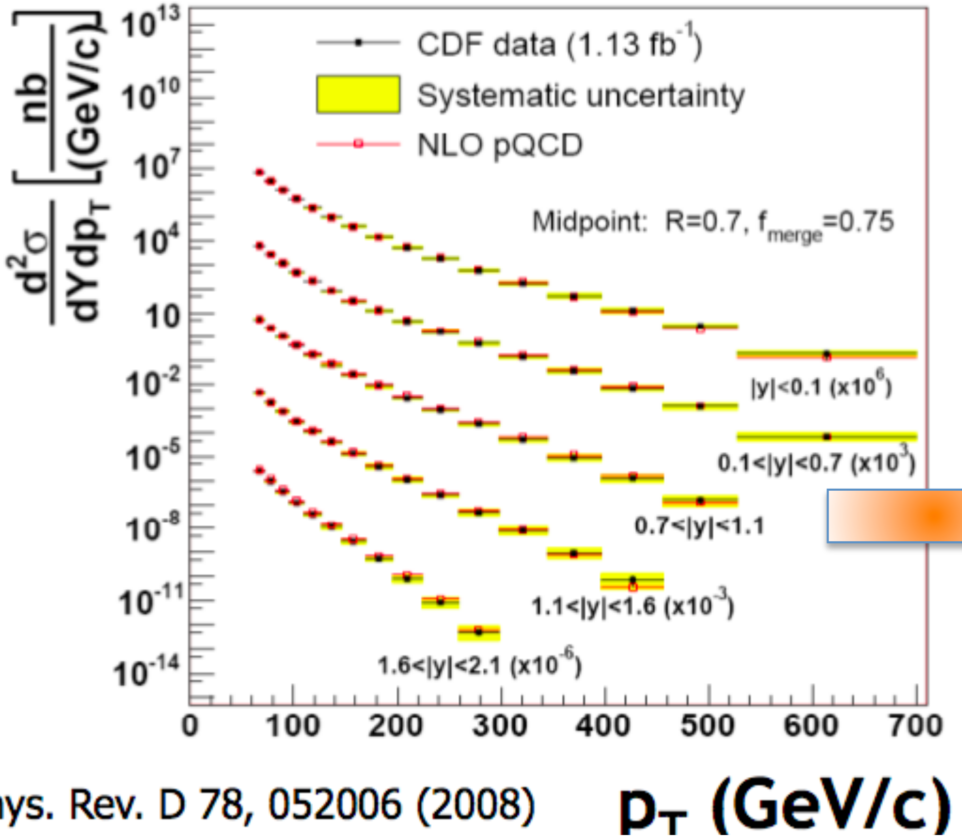


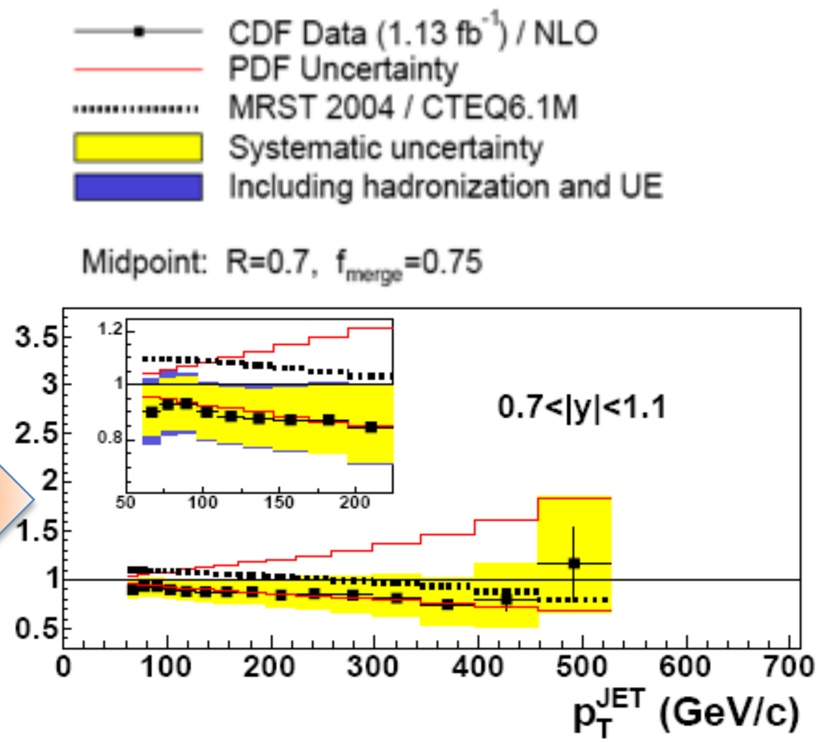
Jet reconstruction : cone based algorithms (CDF,DØ), k_T algorithm (CDF)

Central jets : high x

Forward jets : small x

INCLUSIVE JET PRODUCTION



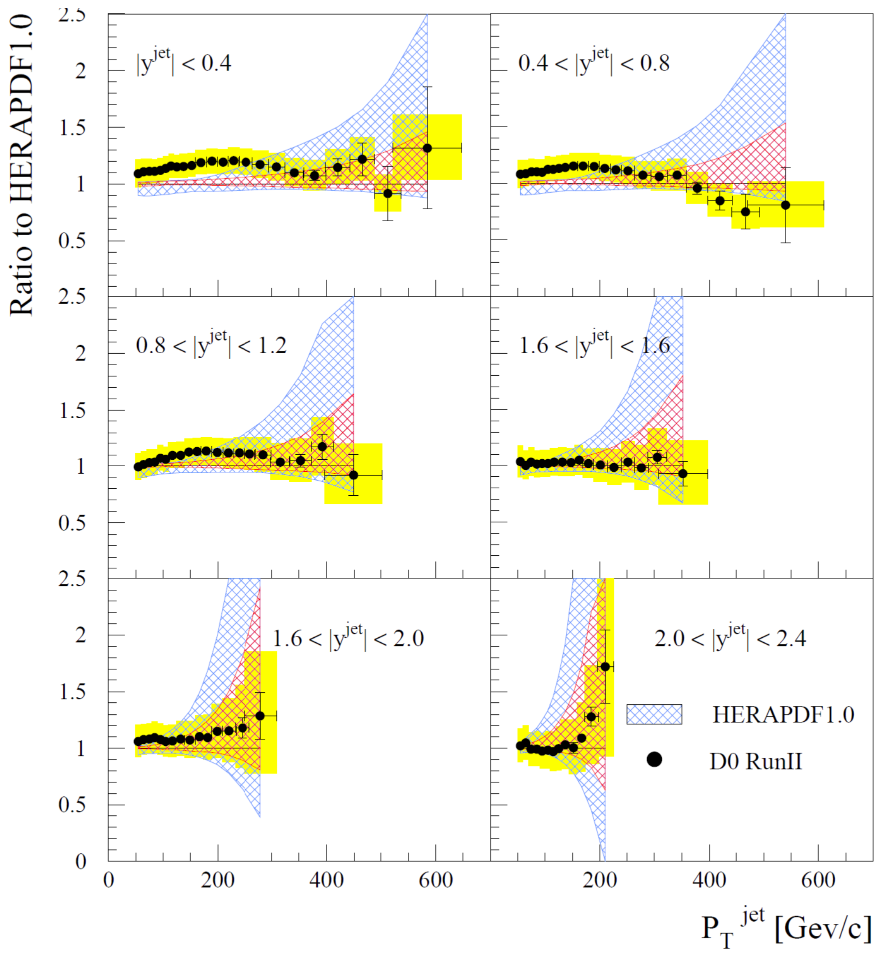


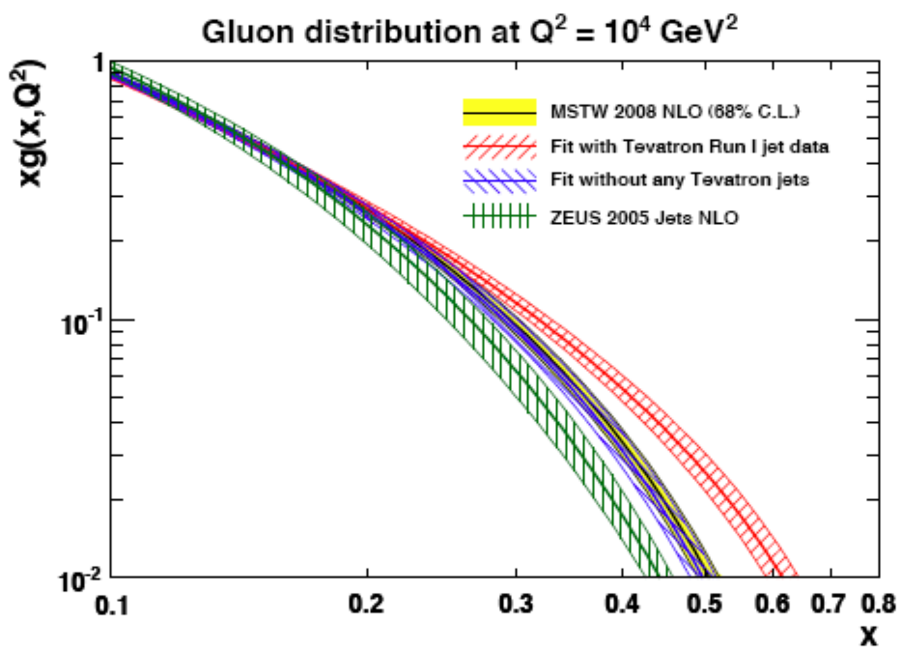
Phys. Rev. D 78, 052006 (2008)

- k_T and cone-based algorithms in good agreement with NLO
- Improved Jet Energy Scale (error 1.2-2%)
- Data corrected for effects from the underlying event and hadronisation
- PDF uncertainty exceeds now experimental error!

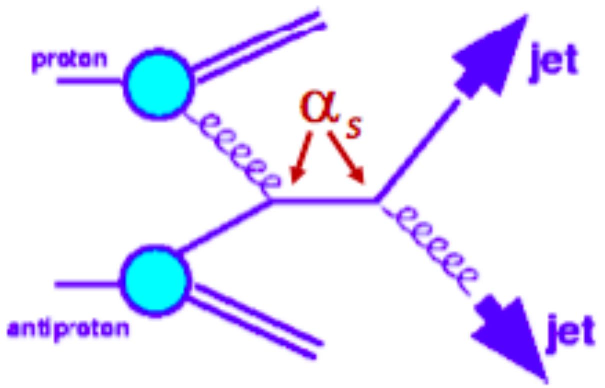
Gluon Density at High x

• Tevatron jet measurements complement HERA measurement: unique constrain on gluon density at high x
in MSTW08-fit : lower gluon density at high x from Run II data compared with Run I
• CTEQ fit about to come



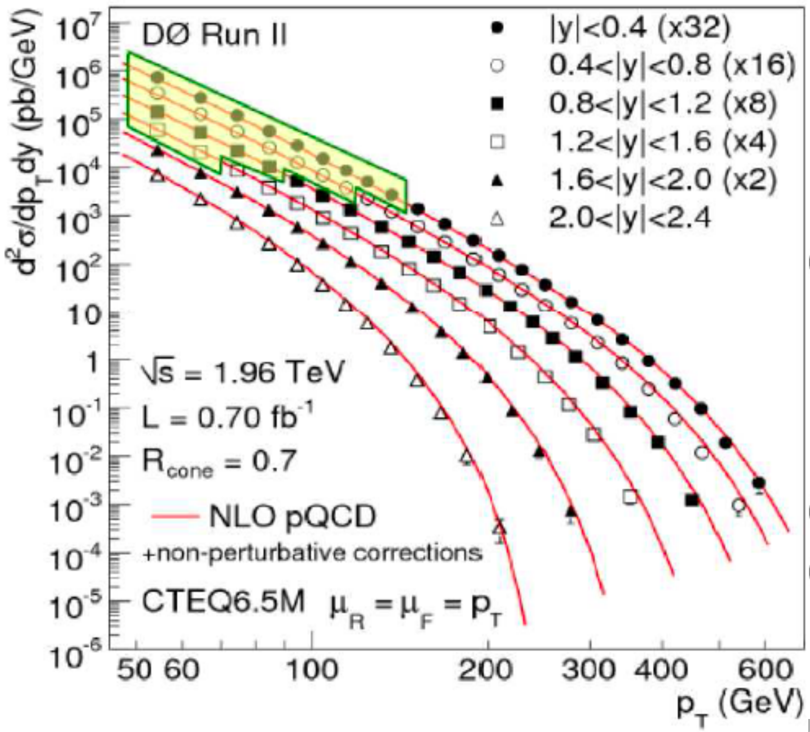


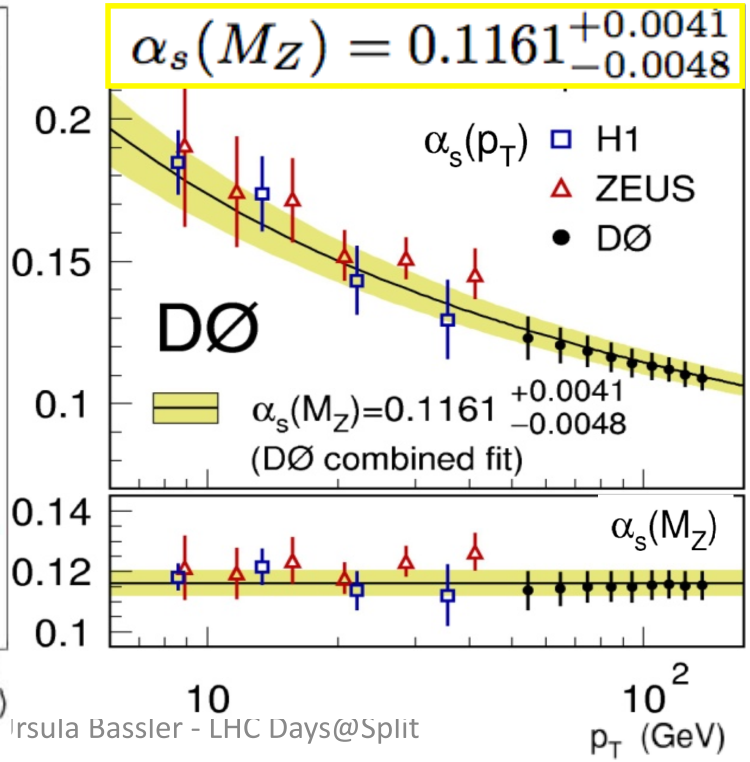
ALPHA$_S$ FROM JETS



- uses the P_T dependence of the jet x-section
- χ^2 minimization of data/theory points :
  - 22/110 points on the inclusive jet cross section
  - 50 < P_T < 145 GeV (high p_T excluded to minimize PDF correlations)
  - medium x-region (0.2-0.3)

HERA results extended to high P_T

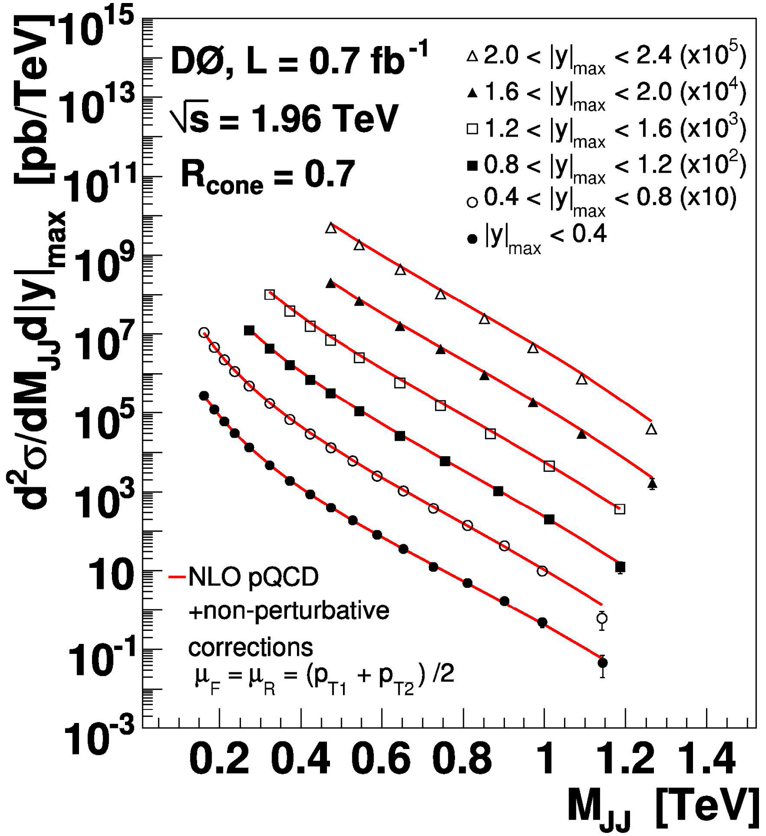


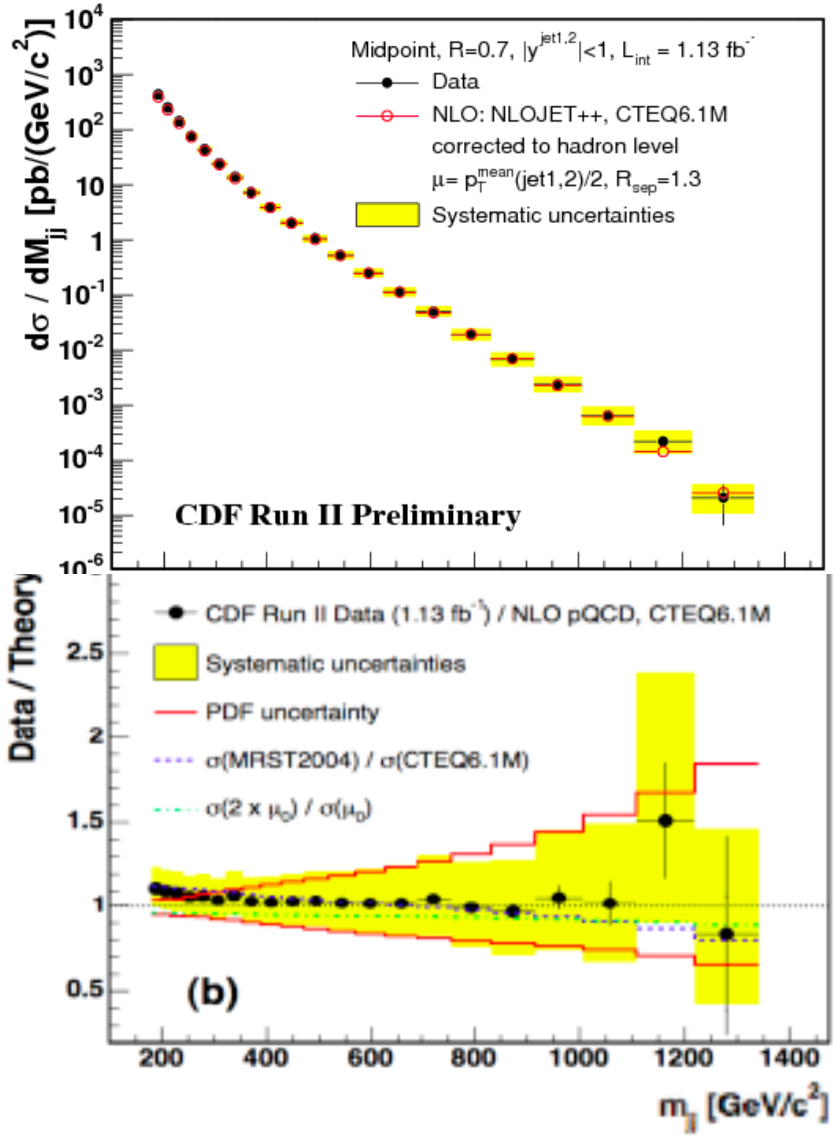


- NLO+2 loop thresholds corrections
- PDF: MSTW2008 NNLO

Highest precision from hadron collider!

Dijet Production and Mass Distributions





- Di-jet mass distribution scanned for resonances ➔ new physics (compositeness, Extra Dimensions, Z' production)
- In good agreement with NLO calculation

➔Distributions now taken over by LHC!

MULTIJET PRODUCTION

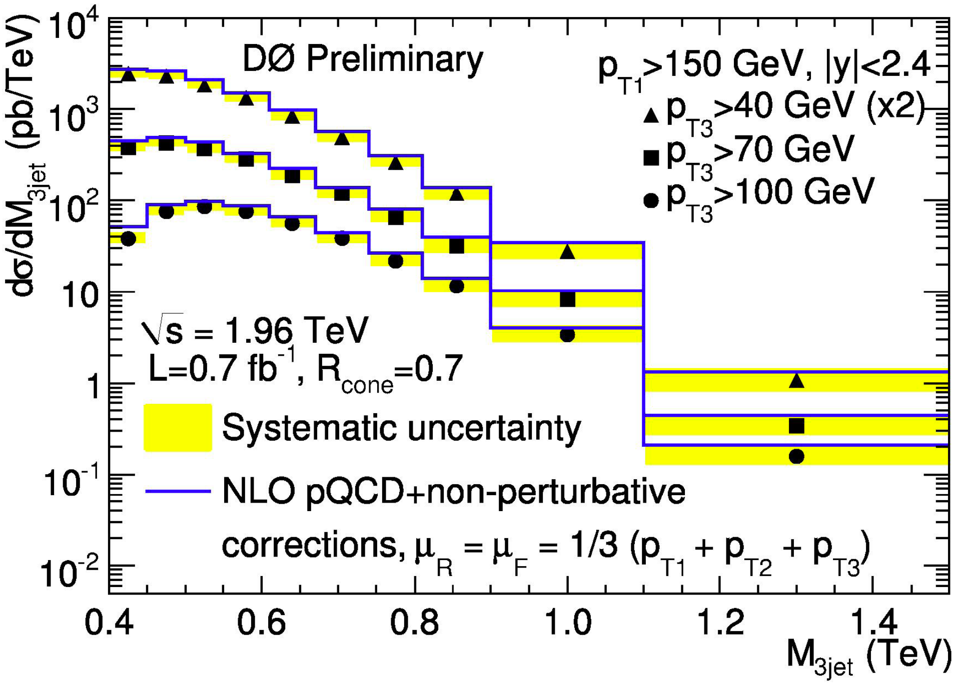
Sensitive to QCD radiation: test of MC models at NLO

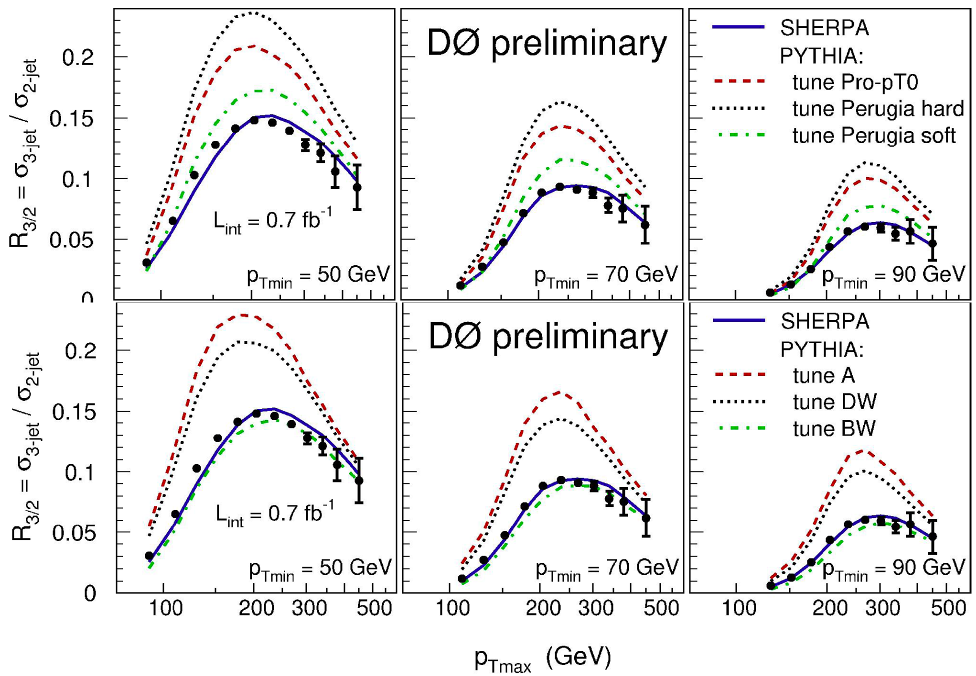
Three-jet mass cross section
- well separated jets (R_{ij} > 1.4)
- different regions of p_{T3}

➔ **reasonably well described**

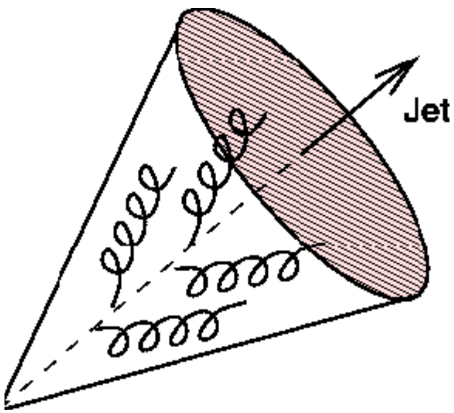
Ratio R(3jets/2jets) vs p_T leading jet
- $p_{Tmax} > p_{Tmin}$ + 30 GeV

➔ **Best description by Sherpa**



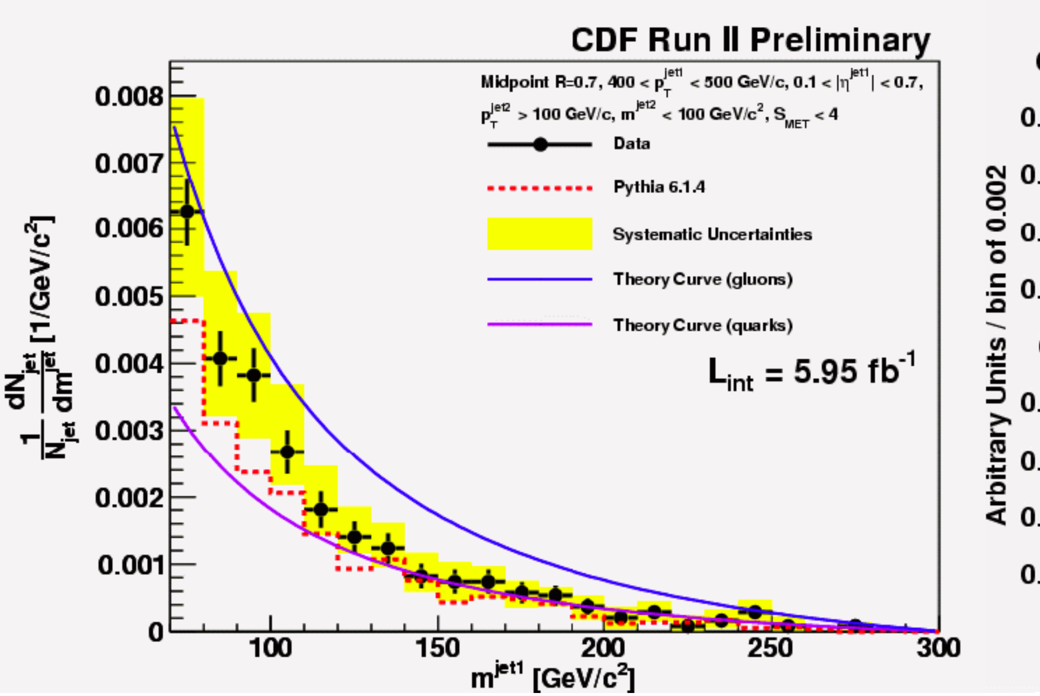


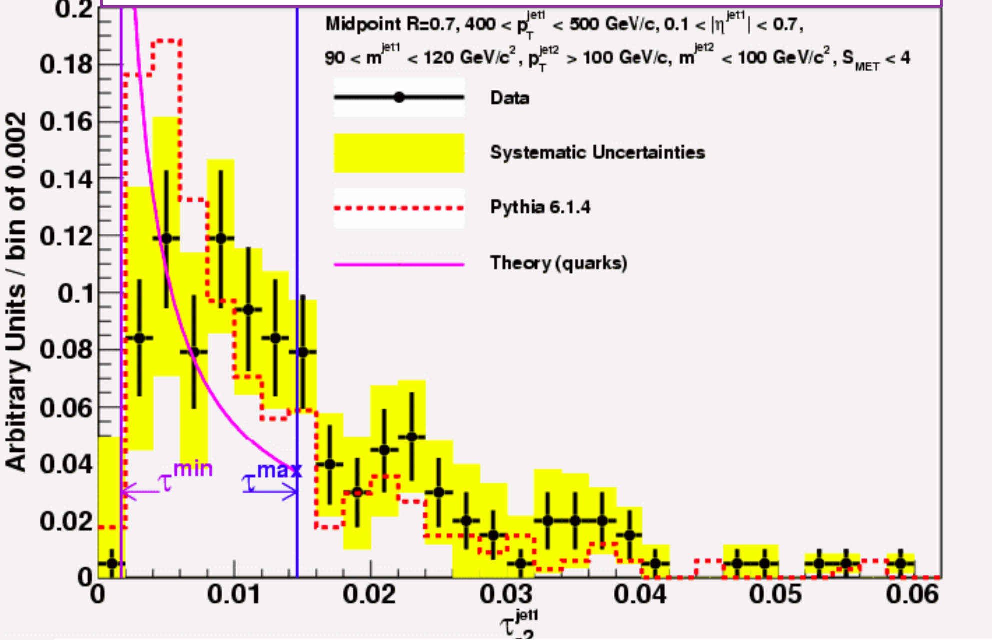
SUBSTRUCTURE OF HIGH P_T JETS



- Selection of jets with p_T > 400 GeV
- Invariant mass of leading jet (80% quark induced expected) :
  - low masses not described by Pythia
- energy distribution within the jet : search for boosted objects
  - jets energy less concentrated than in Pythia
  - influence of underlying events?

$$\tau_a(R, p_T) = \frac{1}{m_J} \Sigma_i \omega_i \sin^a \theta_i \left[1 - \cos \theta_i\right]^{1-a}$$





Conclusions

The Tevatron tests extensively the Standard Model

– Despite its age, it keeps performing very well!

- **A wide range of physics processes are studied:**

– Precision measurements in QCD jet physics

– The most precise hadron colliders measurement of α_s

– Precision measurement of the top quark and W masses at < 1%

➔ **Critical input to EW theory fit for Higgs boson mass**

- Small cross-section phenomena now accessible due to large luminosity: Maybe new physics in B_s mixing?

- CDF and D0 are working very hard searching the Higgs

➔ Evidence for it in the mass range favored by current theoretical fits of EW data is within reach at the Tevatron

… especially if the machine will continue to run beyond 2011