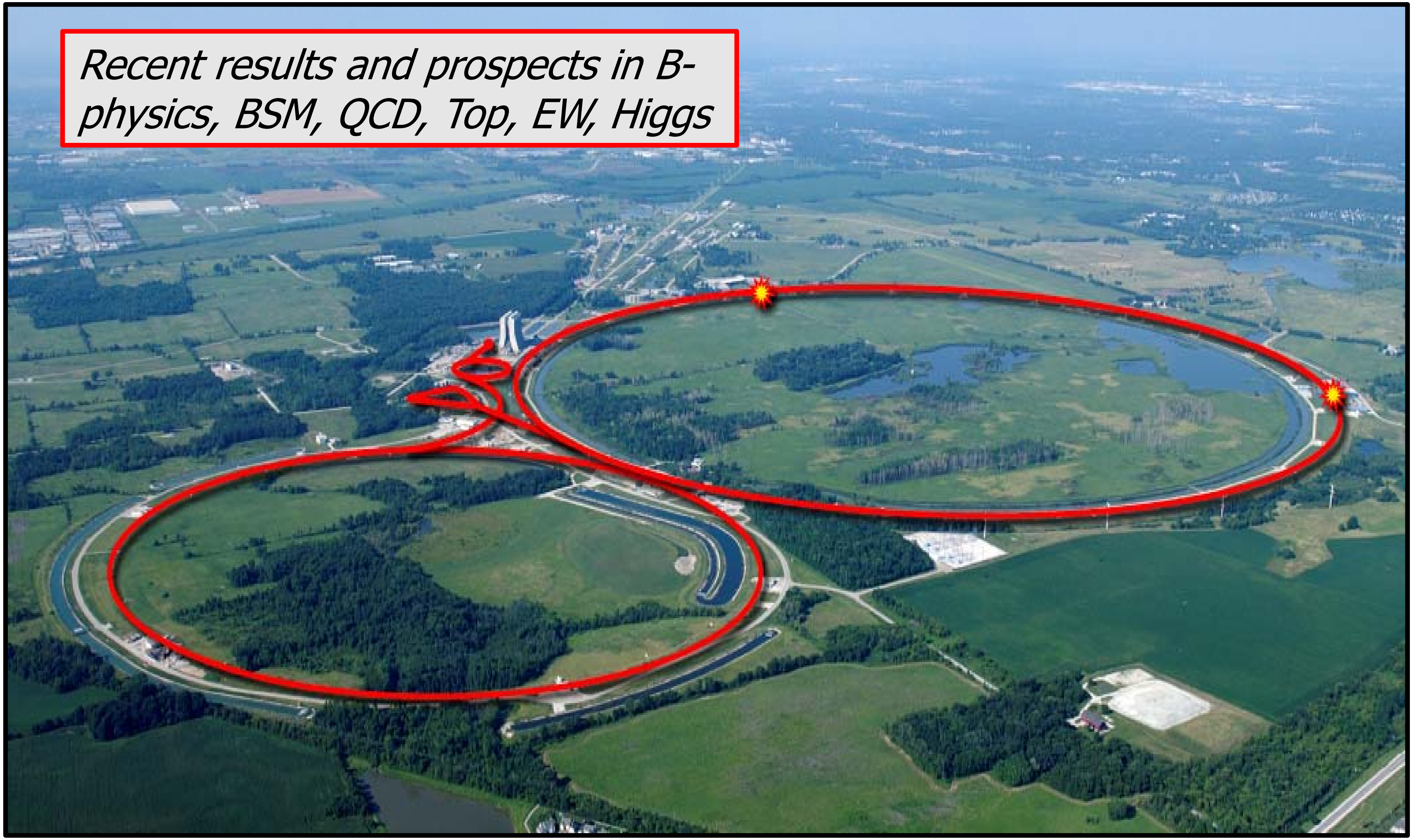
Tevatron Physics Results

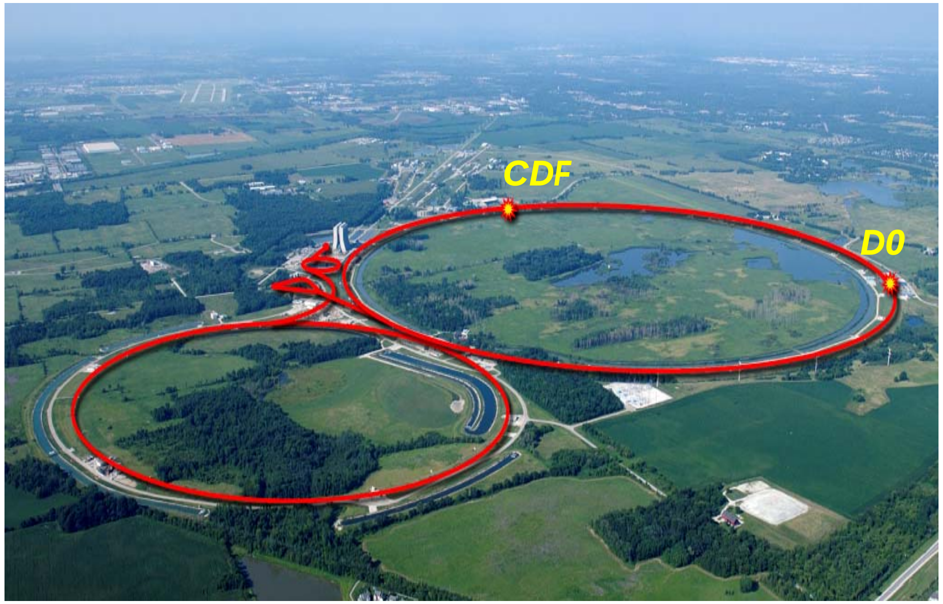


Gregorio Bernardi

on behalf of the D0 and CDF collaboration,

BNL Forum, May 1st 2013

Tevatron, Collaborations



Proton-antiproton collider operating at $\sqrt{s}$ = 1.96 TeV from 2002 to 2011 (Run II)

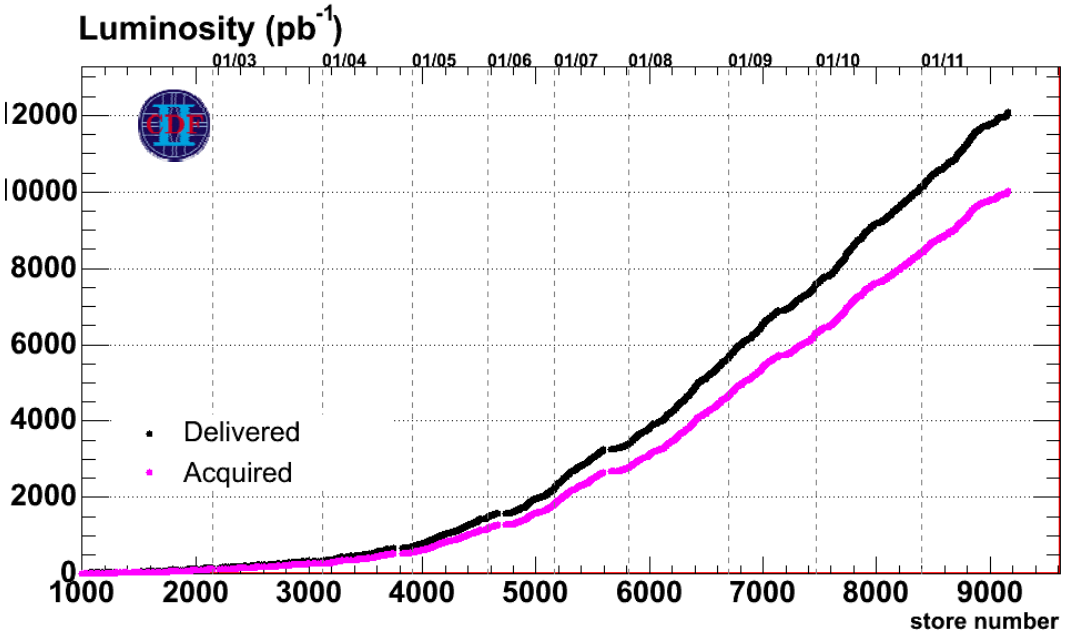
+ $\sqrt{s}$ = 300, 900 GeV in 9/2011

Currently
~400 + ~400 members
from ~60 + ~70 institutions

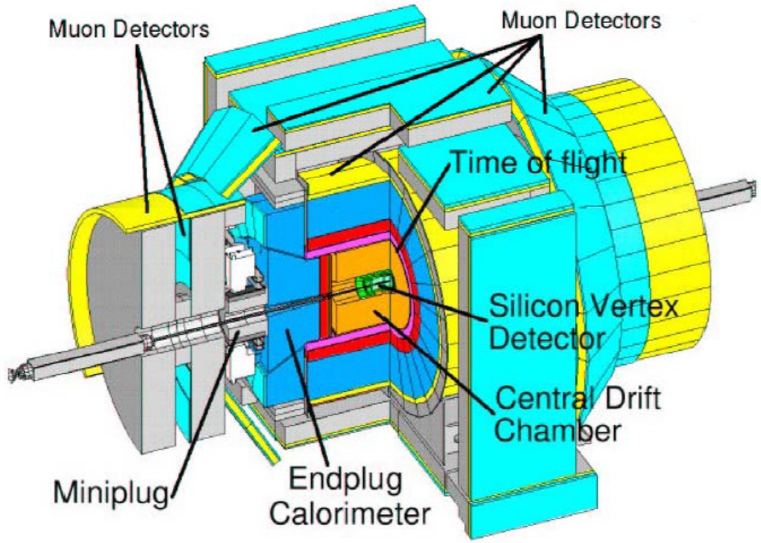
Samples, Detectors

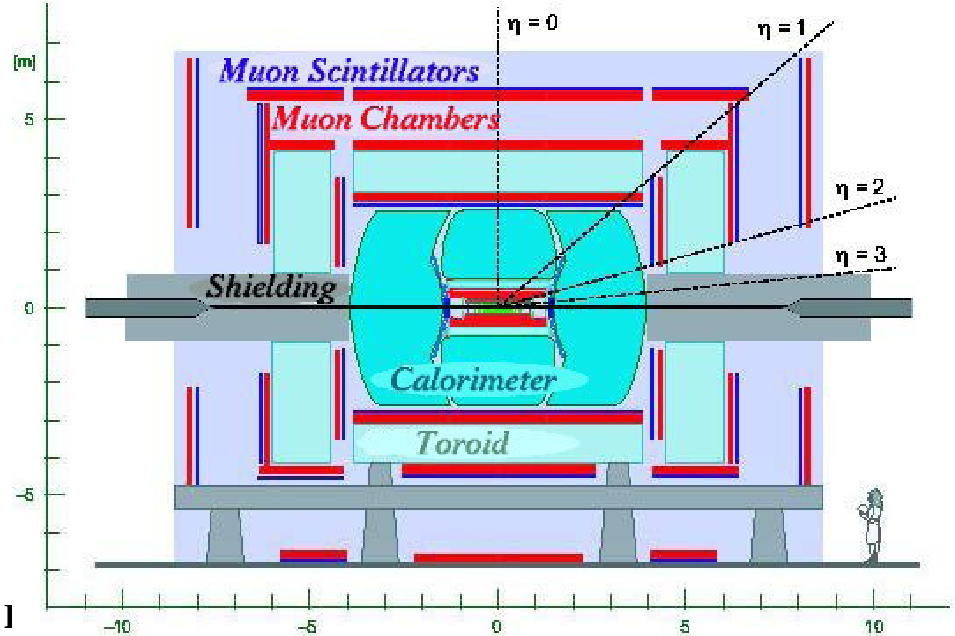
Delivered 12 fb^{-1}, Recorded 10 fb^{-1}/experiment

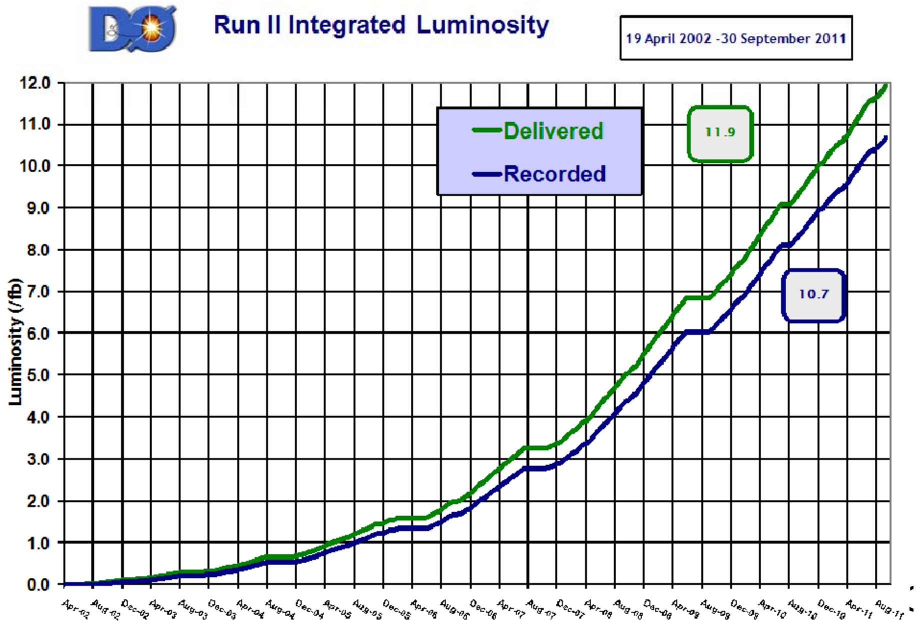
✧ 15B + 9B events total in Run II



CDF II Detector

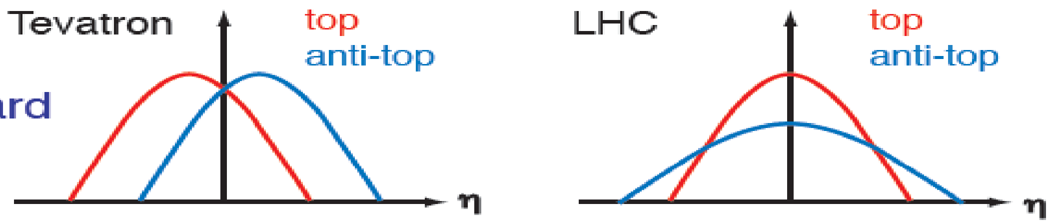






Tevatron Unique Dataset

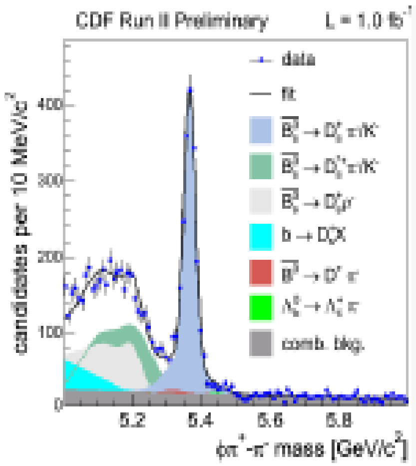
- Different collision energy, $\sqrt{s}_{\mathrm{eff}}$
  - Cross sections, asymmetries; e.g., top, electroweak
  - Different (QCD) backgrounds → Tevatron evidence for $H \longrightarrow b\bar{b}$
    (only evidence for direct coupling to fermion mass)
- $p\bar{p}$ collisions instead of pp
  - Top quark forward-backward asymmetries:

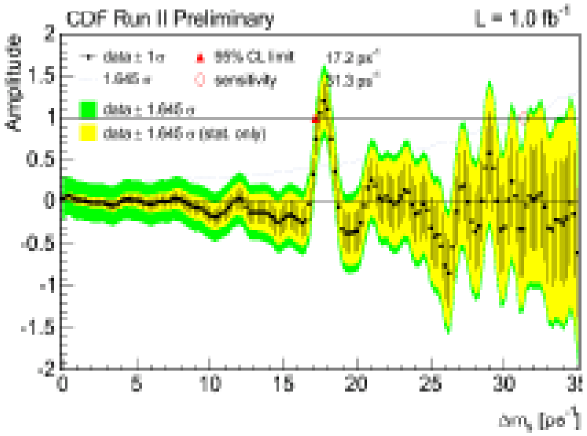


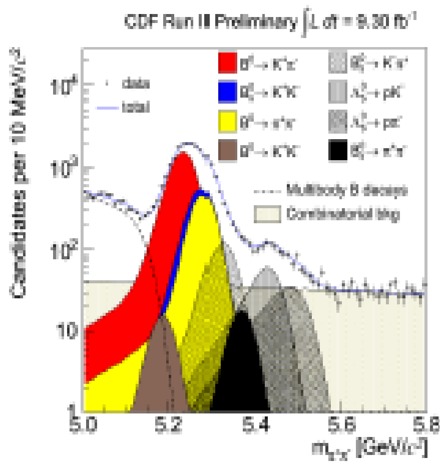
  - is an initial CP invariant state (*B* physics)
- Complementary! Production processes different mix of $q\bar{q}$ vs. gg collisions
  - $t\bar{t}$ spin correlations
- Well understood detector + *experts* (and their past inputs)
  (plus lower level of pileup, only getting worse at LHC)
  - *W* boson mass
  - top quark mass

  (with full data set)
  &
  (potential of reprocessed data)
- Clever detector operation,
  regular flipping of solenoid and toroid magnets
  - cancels charge tracking asymmetries to first order
    → competitive CP invariance tests in heavy flavor

Heavy Flavor physics @ Tevatron

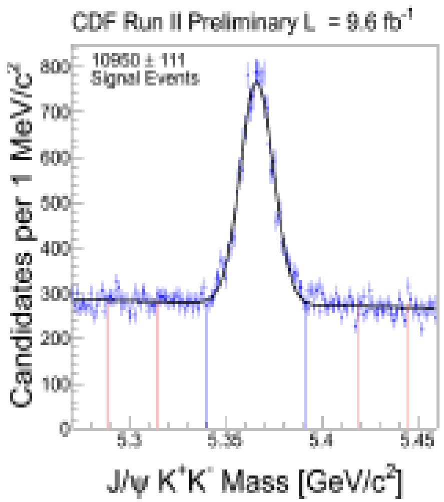


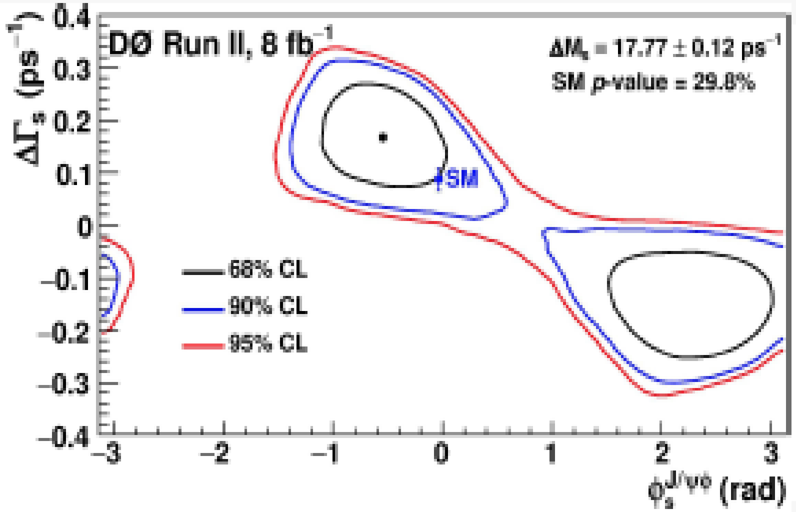




A lot of "first time" measurements:

- Spectroscopy, discovery of new states
- Precision lifetime measurements
- Bs mixing observation
- Hadronic trigger (@CDF)
- Many CP violation studies
- Stringent limits on Bs→reduced phase space for SUSY





Heavy Flavor recent highlights

2012:

CDF:

Measurement of the difference of CP-violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays
Measurement of CP-violation asymmetries in $D^0 \to K_s\pi^+\pi^-$,
Measurements of angular distributions of muons from upsilon meson decays..
Evidence for the charmless annihilation decay mode $B_s^0 \to \pi^+\pi^-$,

DZero:

Measurement of the Semileptonic Charge Asymmetry using B^0 meson mixing with the D0 detector
Measurement of the Semileptonic Charge Asymmetry using $B_s^0 \to D_s\mu X$ Decays
Observation of a Narrow State Decaying into $\Upsilon(1S) + \gamma$ in pp Collisions at $\sqrt{s} = 1.96$ TeV
Measurement of the Λ_b^0 Lifetime in the Exclusive Decay $\Lambda_b^0 \to J/\psi\Lambda^0$ in pp Collisions
Measurement of the CP-Violating Phase $\varphi_s^{J/\psi\,\varphi}$ using the Flavor-Tagged Decay $B_s^0 \to J/\psi\ \varphi$ in 8 fb^{-1}

2011:

CDF:

Observation of the Ξ_b^0 baryon
Measurement of CP-violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays at CDF
Measurements of direct CP violating asymmetries in charmless decays of strange b mesons/baryons

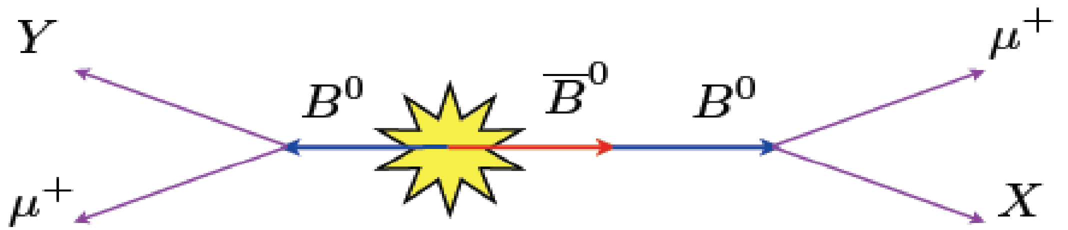
DZero:

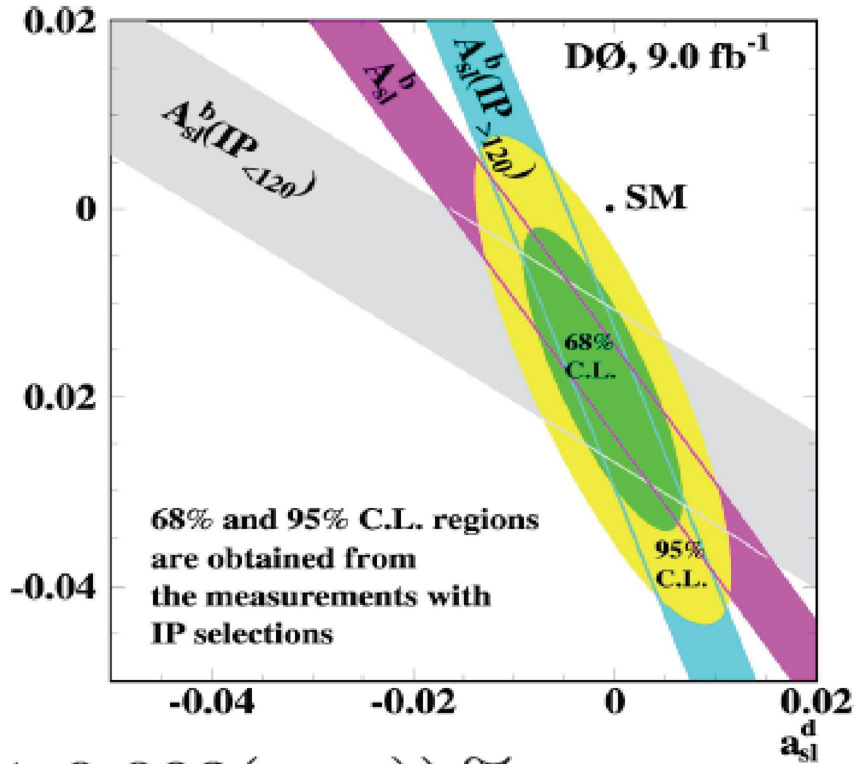
Measurement of the Anomalous Like-Sign Dimuon Charge Asymmetry with 9 fb^{-1} of pp Collisions
Measurement of the Production Fraction Times Branching Fraction $f(b \to \Lambda_b) \cdot B(\Lambda_b \to J/\psi\ \Lambda)$

CP Violation in Like-sign di-muon asymmetry

Tevatron initial state CP symmetric
Easier measurement of asymmetries in comparison to LHCb
Magnetic field reversal at DO helps keeping tracking asymmetry systematics at 10-3 level

Study dependence from impact parameter to change sensitivity to B0d and B0s contributions





$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$
$$= C_d a^d_{sl} + C_s a^s_{sl} \qquad \text{where } a^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

$C_{d(s)}$ is the fraction of $B_d(B_s)$ events in the data sample.

arxiv.org:1106.6308 PRD **84** 052007 (2011)

$$A^b_{sl} = (-0.787 \pm 0.172(\text{stat}) \pm 0.093(\text{syst}))\ \%$$

- Anomalous Dimuon - 3.9σ deviation from SM expectations
- Split the data (blue band, grey band):

$$a^d_{\rm sl} = (-0.12 \pm 0.52)\%,$$
$$a^s_{\rm sl} = (-1.81 \pm 1.06)\%.$$

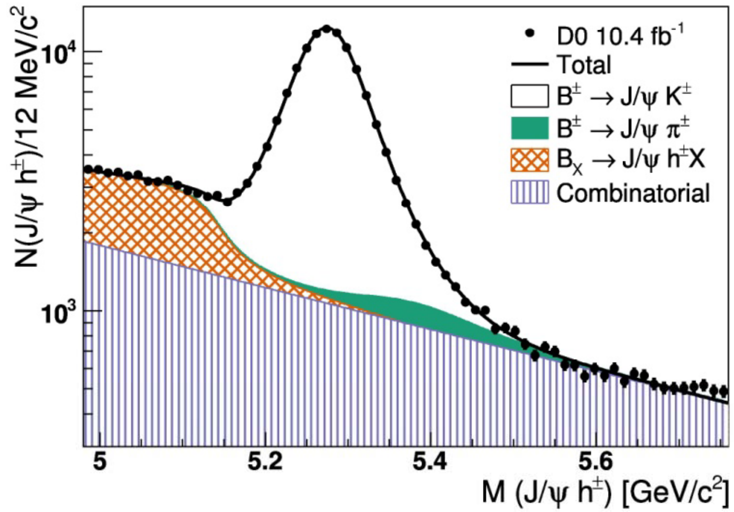
CP violation in interference between decays of B0d,s to same final states with / without mixing reduces significance of observation to ≈3 s.d.
arXiv.org:1303.0175

CPV search in $B^{\pm} \to J/\psi K^{\pm}$ & $B^{\pm} \to J/\psi \pi^{\pm}$

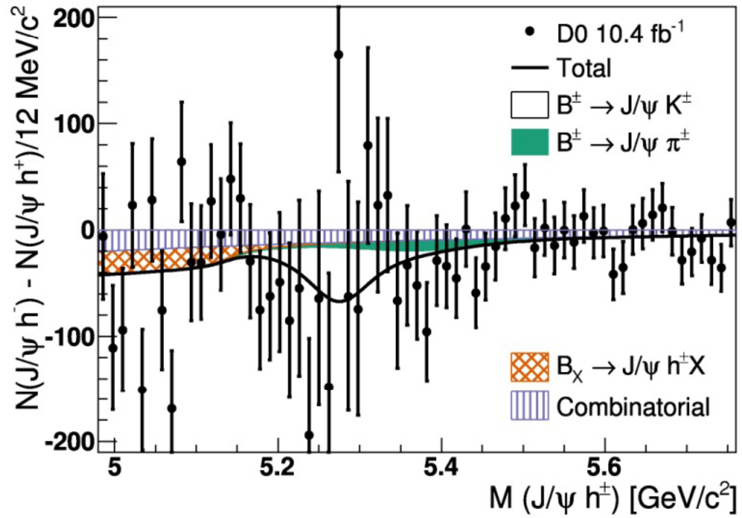
Measure exclusive asymmetries in Bs→Ds μ X decay

Analyzed $B^{\pm} \to J/\psi K^{\pm} \to \mu^+\mu^- K^{\pm}$
& $B^{\pm} \to J/\psi \pi^{\pm} \to \mu^+\mu^- \pi^{\pm}$

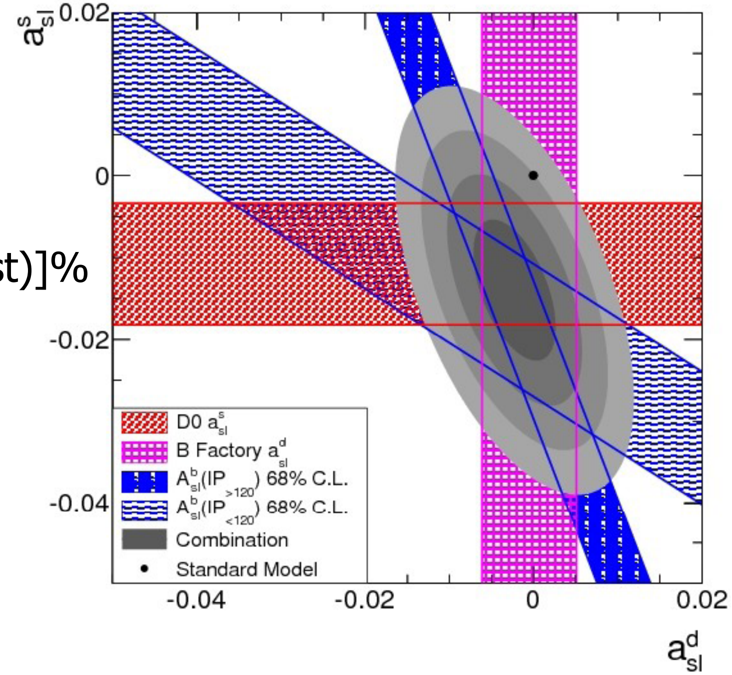
$A^{J/\psi K} = (0.59 \pm 0.36)\%$ $A^{J/\psi \pi} = (-4.2 \pm 4.8)\%$



Most precise measurement, thanks to the ability to reverse the magnetic fields at D0. Consistent with SM expectations and with di-muon result



$a^s_{sl} = [-1.12 \pm 0.74\ (stat) \pm 0.17 (syst)]\%$

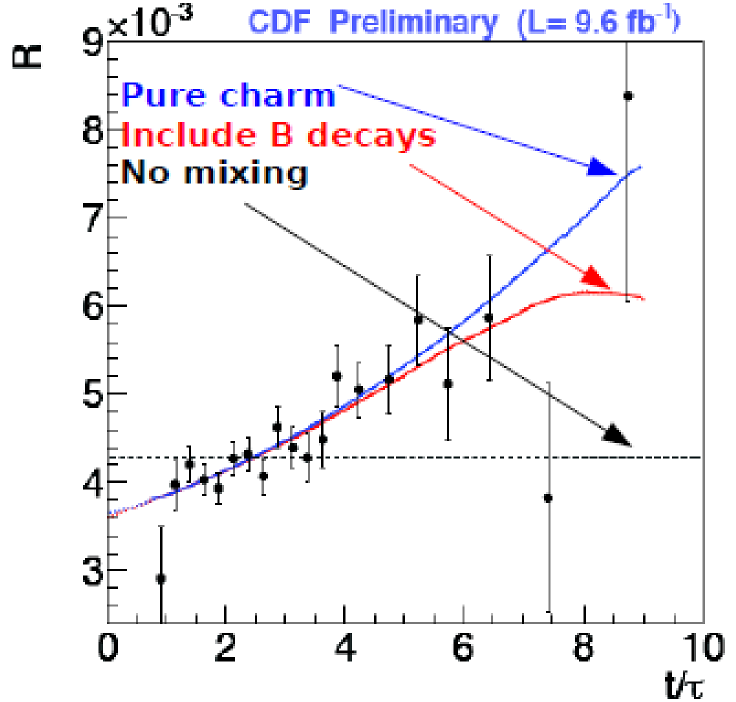


arXiv:hep-ex/1304.1655, submitted to PRL

Charm mixing in $D\bar{D}$ system

Study of DD mixing at CDF with full data set
8.10^6 $D^{*+} \rightarrow D^0 \rightarrow K^- \pi^+$ decays with slow π tag
Repeat fits in 20 different time bins

Experiment	R_D ($\times 10^{-3}$)	y' ($\times 10^{-3}$)	x'^{2} ($\times 10^{-3}$)	Excluding No-Mixing Significance (sigmas)	R_B ($\times 10^{-3}$)
Belle	3.64 ± 0.17	0.6 ± 4.0	0.18 ± 0.22	2.0	3.77 ± 0.09
BaBar	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9	3.53 ± 0.09
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13	**9.1**	4.25 ± 0.04
CDF	3.51 ± 0.35	4.27 ± 4.30	0.08 ± 0.18	**6.1**	4.30 ± 0.06



$$R(t/\tau) = R_D + (t/\tau)\sqrt{R_D}\,y' + (t/\tau)^2\,\frac{x'^2 + y'^2}{4}$$

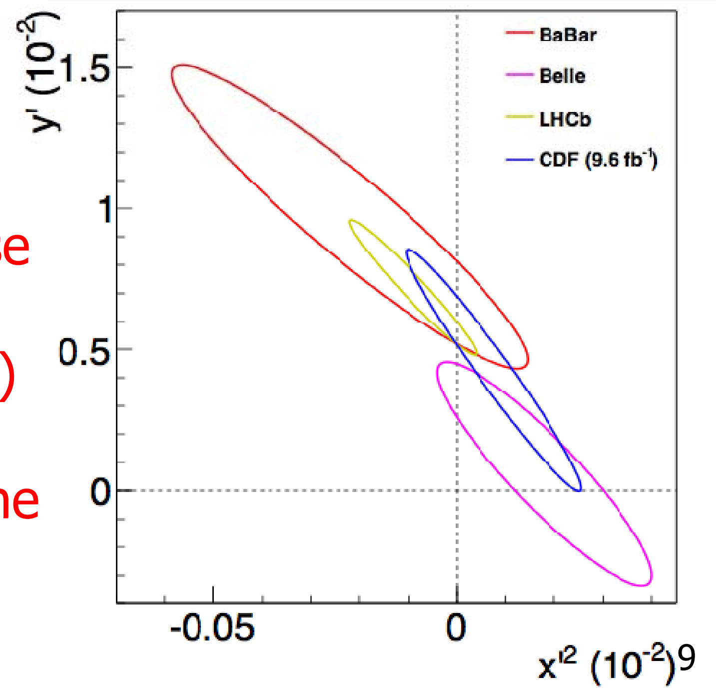
DCS to CF ratio — Interference — Mixing

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \qquad x \equiv \frac{M_2 - M_1}{\Gamma}$$

$$y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi} \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

Fit Type	χ^2 /ndof	Parameter	Fit Value (10^{-3})
		R_D	3.51 ± 0.35
Mixing	16.91/17	y'	4.3 ± 4.3
		x'^{2}	0.08 ± 0.18
No-mixing	58.75/19	R_B	4.30 ± 0.06

Two most precise measurements (LHCb and CDF) are compatible and overlap in the physics region



Heavy Flavor: prospects

2013:

- Bc lifetime in Bc→J/ψπ decays
- Evidence for Λ_b^*
- A_{CP} in B→hh′ decays with full sample
- Search for $B_{s,d}$→μμ with full sample
- BR(B_s→J/ψϕ) and fragmentation fractions
- K production associated D_s^+/D^+ mesons
- B^{**} decays
- Y cross section and polarization
- Charm production in minimum bias events
- Excited baryons (K_s^0, Λ0) in min. bias evts

>2013:

- Quarkonia (χ_b, χ_c fractions, Y+X spectroscopy, fragmentations in Y events, h_b searches, low mass Drell-Yan and J/ψ studies)
- Doubly charmed and bottom-charmed baryons
- Multiple heavy flavor production
- Baryon polarization
- Heavy flavor in jets

2013:

B_s lifetime in semileptonic decays
Final dimuon asymmetry paper
B_s →J/ψf_0 lifetime and CPV
Search for B_s →D_s μμX decays
Search for direct CPV in B^+→J/ψK^+ decays
Λ_b→ψ(2S)Λ_0 branching ratio
ψ(2S) →μμ cross-section

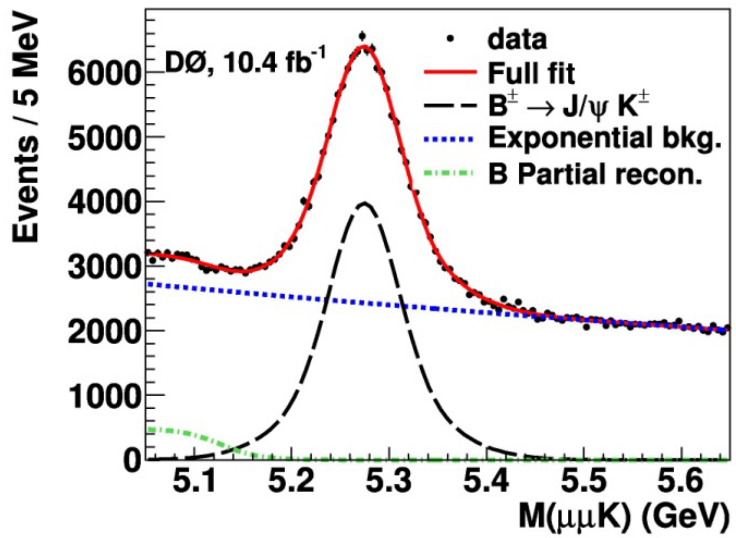
> 2013:

Exotic states, XYZ
J/ψ polarization
di-J/ψ production
CPV asymmetry in Charm (D^0→KμνX)
Search for B_c^+ →J/ψD_s^+
Λ(2S) →μμ cross-section

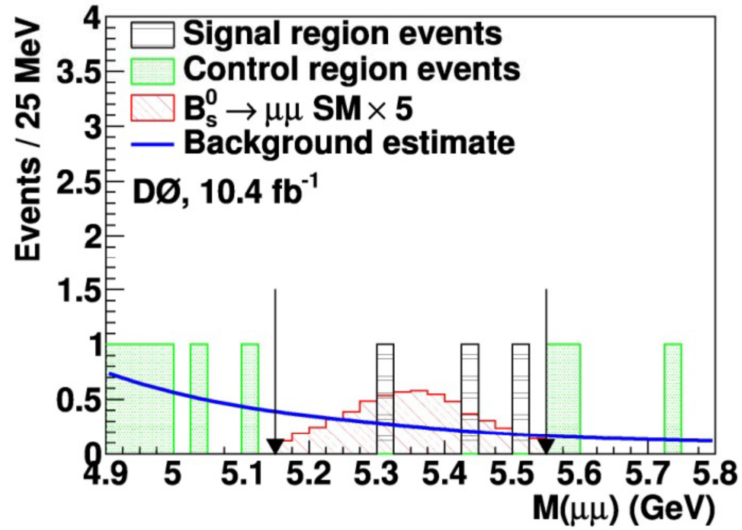
BSM: Search for $B^0_s \to \mu\mu$ decay

PRD 87, 072006 (2013)

- FCNC suppressed: $BR_{SM} = 3.5\times10^{-9}$
- Used $B^{\pm}_d \to J/\psi K^{\pm} \to \mu^+\mu^- K^{\pm}$ for normalization
- Trained BDT against MC for signal & data sidebands for background

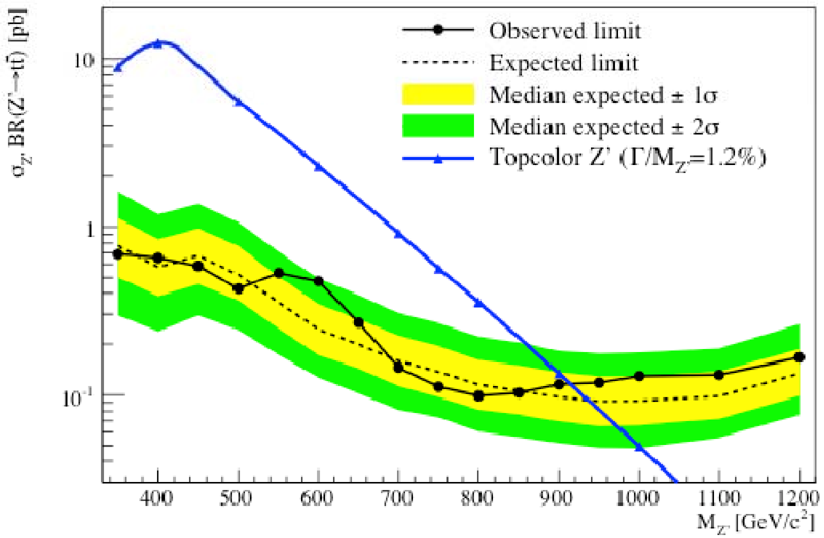


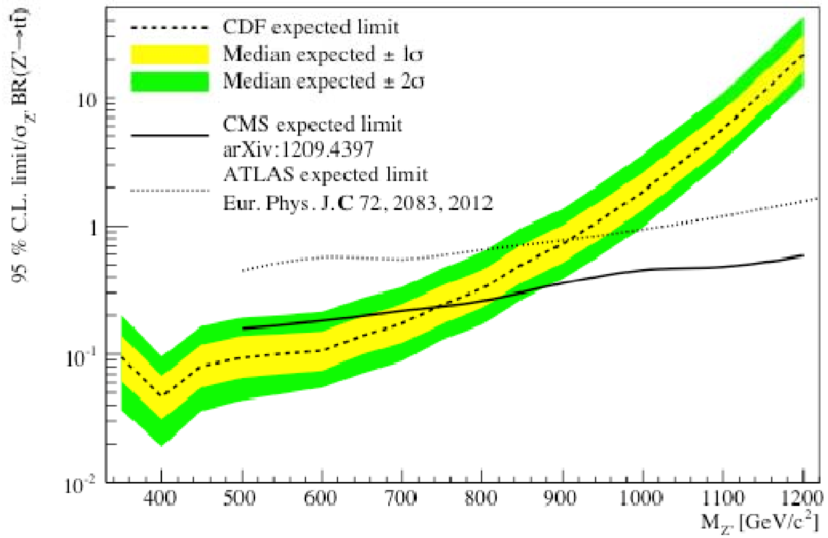
Experiment	Observed limits at 95% C.L. ($\times10^{-9}$)
ATLAS	22
CMS	7.7
LHCb	0.94 now evidence
CDF	13
D0	15



BSM: Search for top-pair resonances

PRL 110, 121802 (2013)





tt events selected in the l+jets channel (3j & ≥4j categories) requiring at least one b-tagged jet

- Topcolor model Z′ excluded up to 915 GeV @ 95% C.L.
- Best exclusion limit below 700 GeV

QCD recent highlights

2012:

CDF:

Observation of exclusive $\gamma\gamma$ production in pp-bar collisions at √s=1.96 TeV,
Study of substructure of high transverse momentum jets produced in ppbar collisions

DZero:

Measurement of the γ+c-jet cross section and the ratio γ+c and γ+b cross sections
Measurement of the pp to W + b + X production cross section at √s = 1.96 TeV
Measurement of the Differential Cross Section dσ/dt in Elastic pp Scattering at √s = 1.96 TeV
Measurement of the Photon + b-Jet Production Differential Cross Section in pp Collisions

2011:

CDF:

Measurement of event shapes in pp-bar collisions at √s=1.96 TeV
Measurement of the cross section for prompt isolated diphoton production in pp-bar
Diffractive W and Z production at the Fermilab Tevatron (2010)

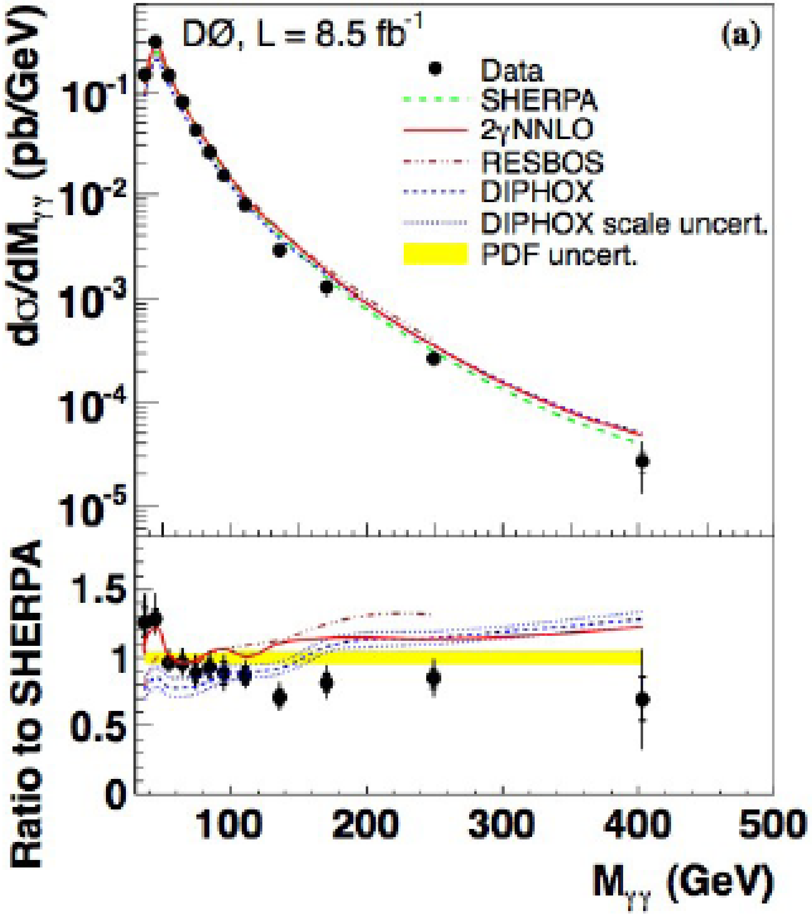
DZero:

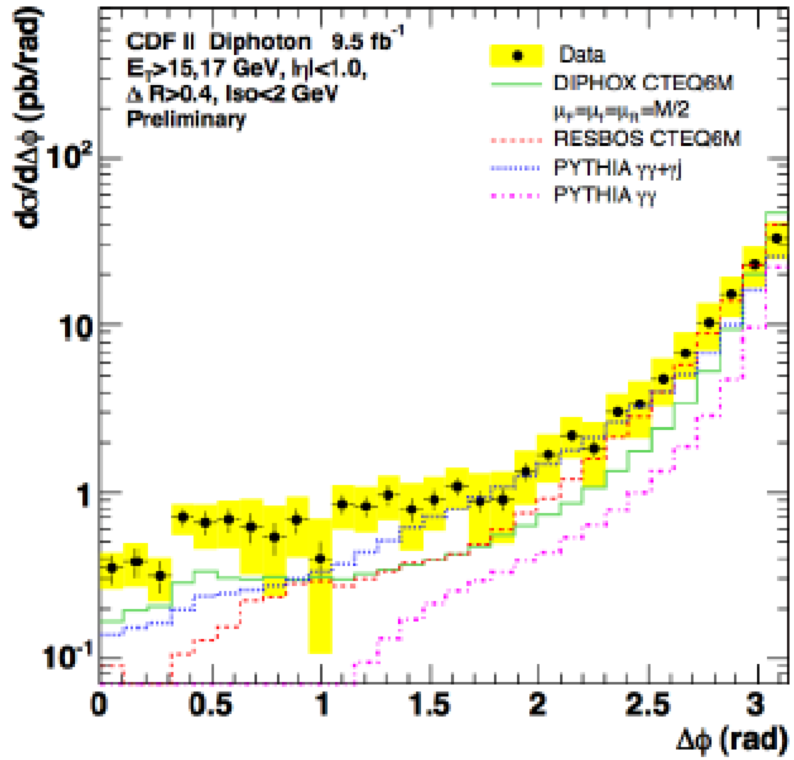
Measurement of the Inclusive Jet Cross Section in pp Collisions at √s = 1.96 TeV
High Mass Exclusive Diffractive Dijet Production in pp Collisions at √s = 1.96 TeV
Measurements of Inclusive W+Jets Production Rates as a Function of Jet Transverse Momentum

γγ differential cross sections

arXiv:hep-ex/1301.4536, submitted to PLB

At Tevatron, produced predominantly through $q\bar{q}$ annihilation and gg fusion, with gg→γγ important at low di-photon invariant mass and intermediate p_T





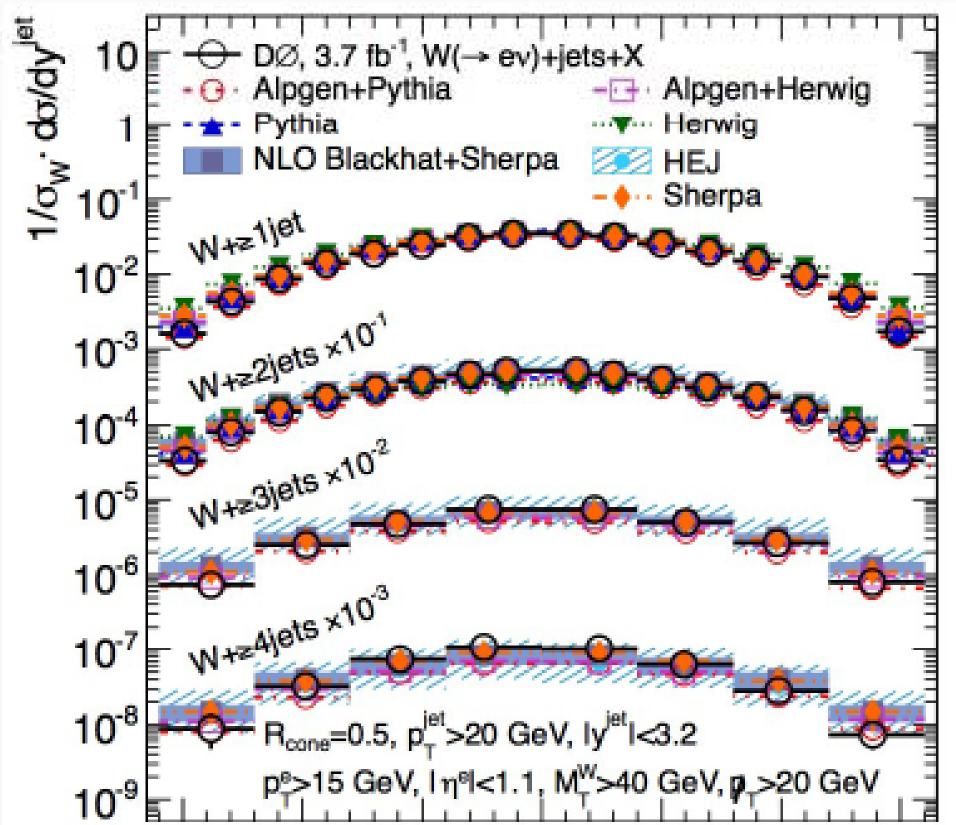
In low Δφ region fragmentation and higher order contributions important

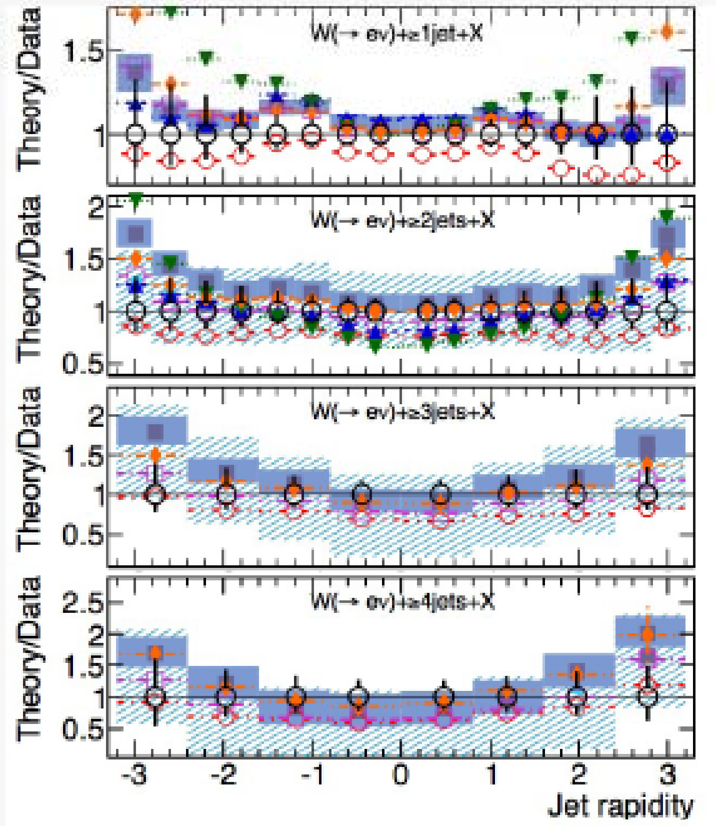
QCD@NNLO needed to describe the data

W(eν) + jets cross sections

arXiv:hep-ex/1302.6508, submitted to PRD

New comprehensive study of inclusive W+jets production (40 differential distributions), comparison with most recent MC models and theoretical calculations, important backgrounds for electroweak/top/Higgs measurements

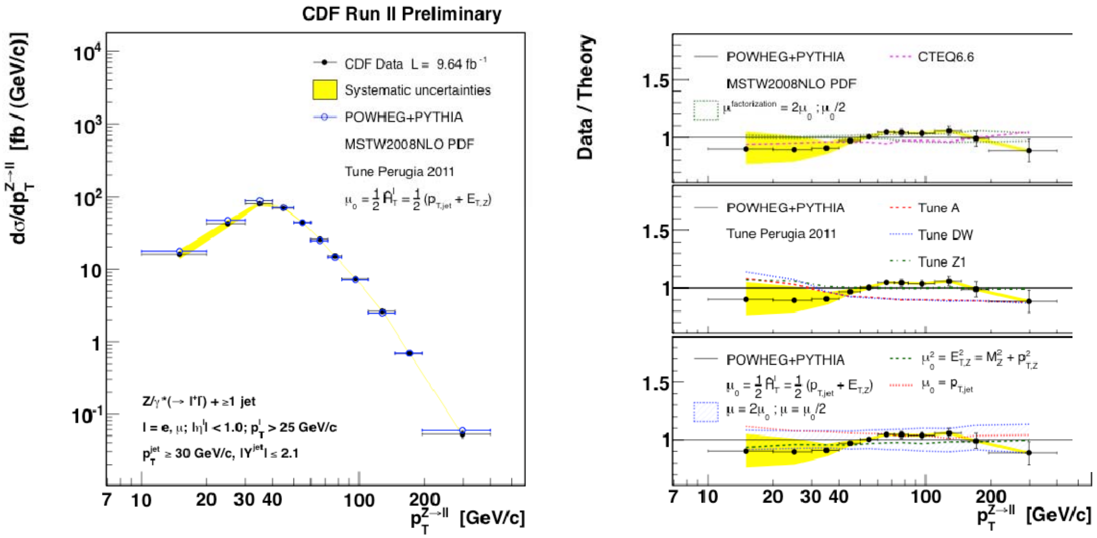


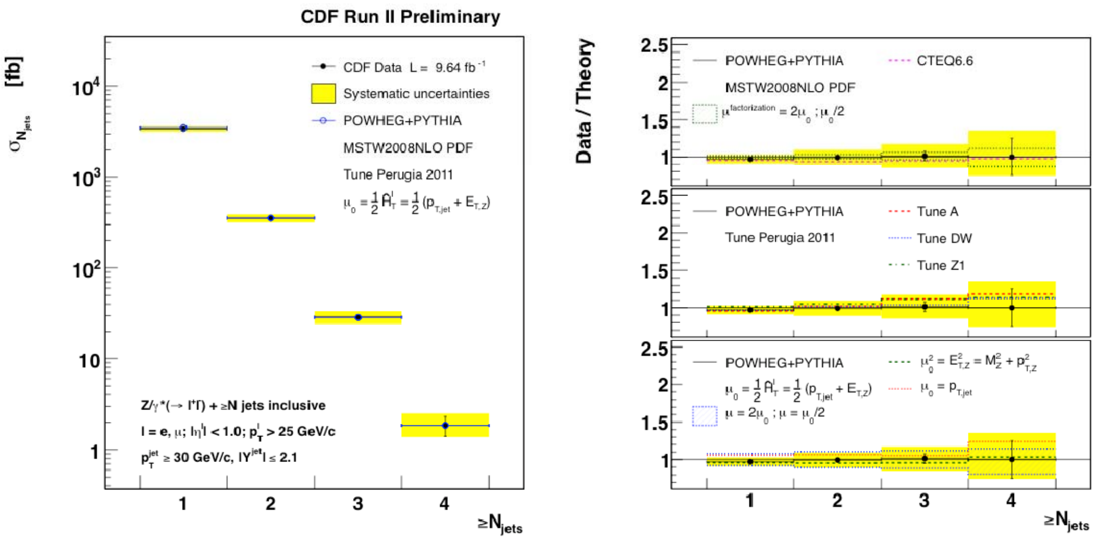


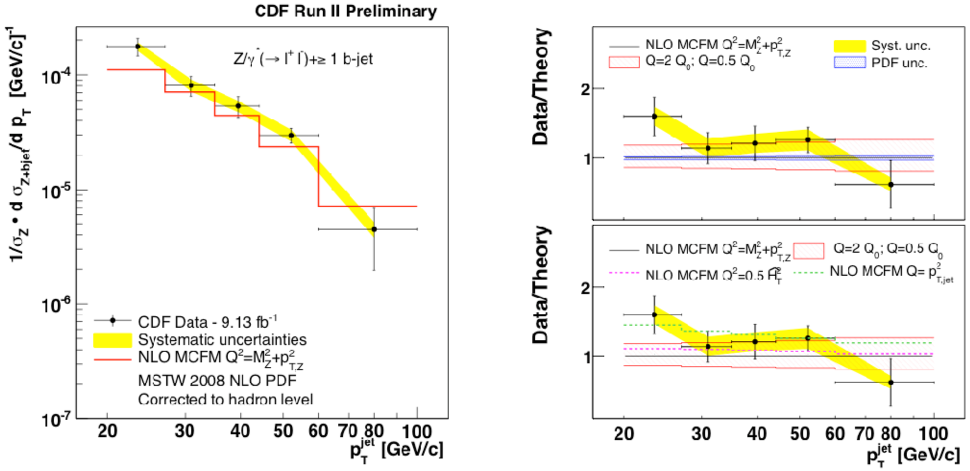
QCD@NLO works well

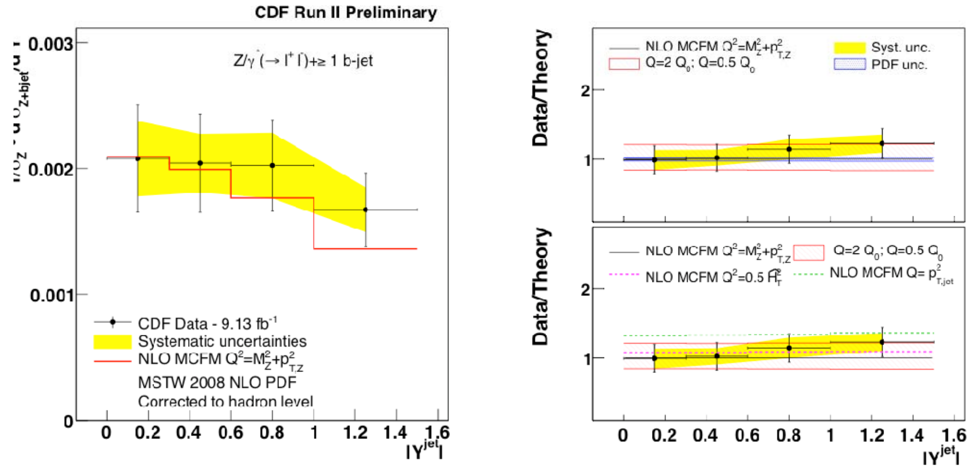
Z(ll) + jets cross sections

M_{ll} in [66,116] GeV/c^2, ΔR=0.7



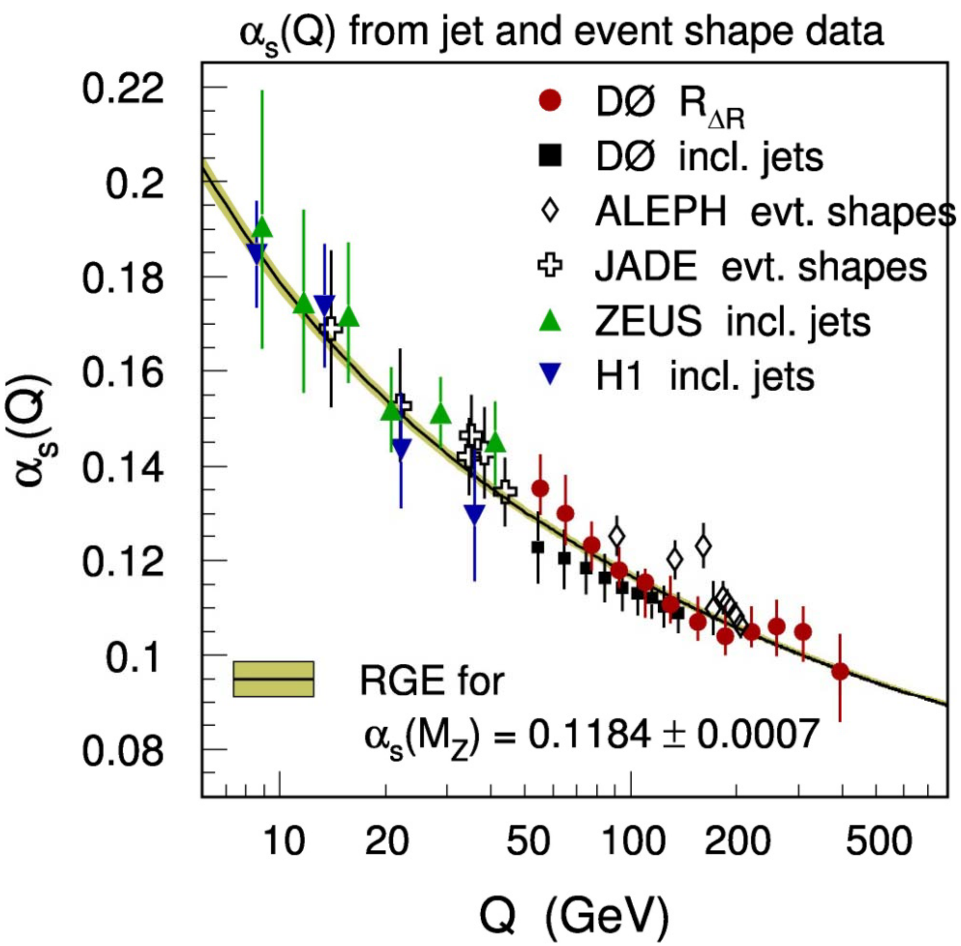


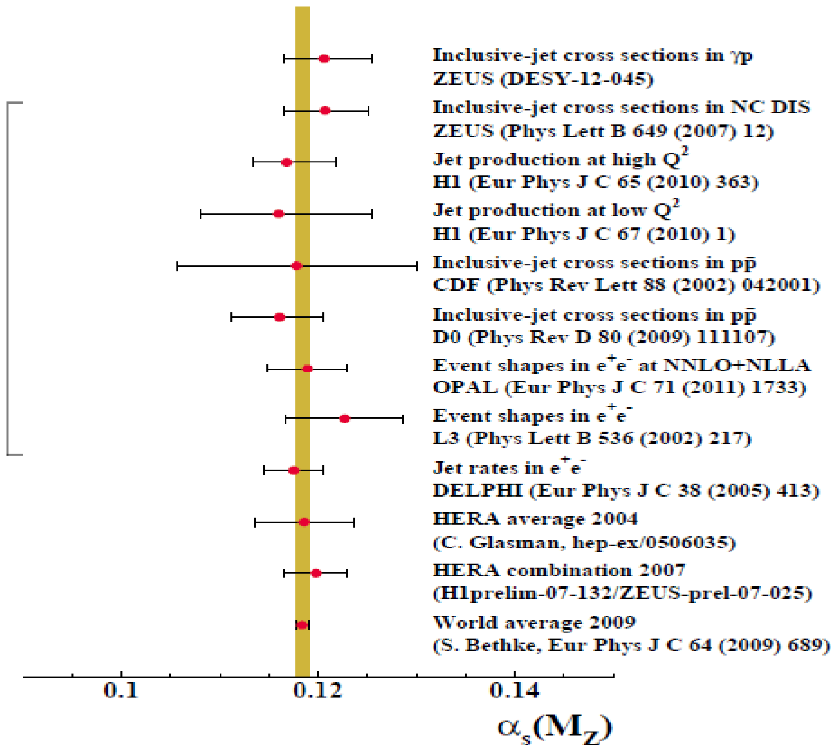




QCD@NLO works well

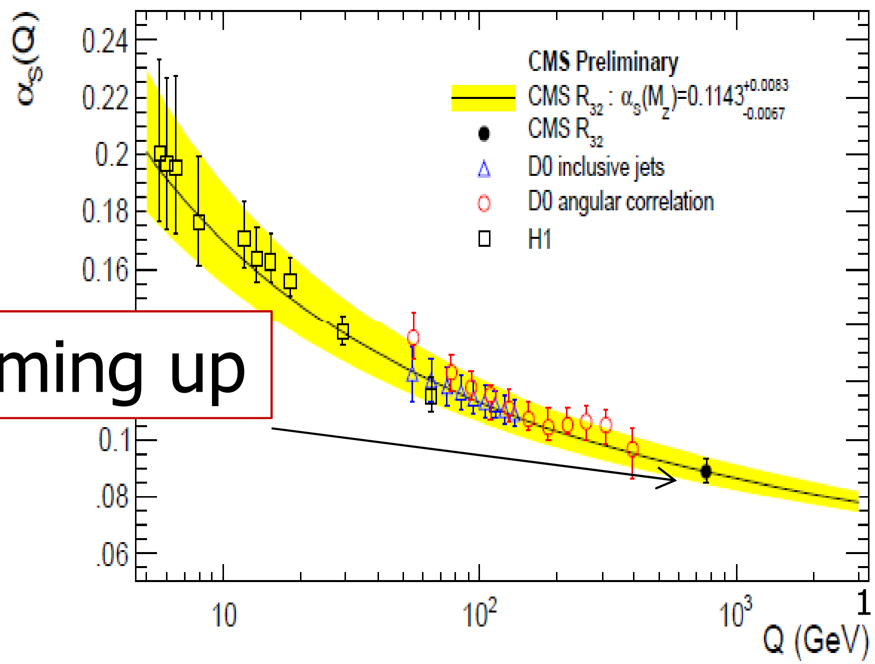
QCD: alpha_s from 3jet/2jet ratio @DZero





→ First α_s results above 208 GeV, obtained at LEP

CMS coming up

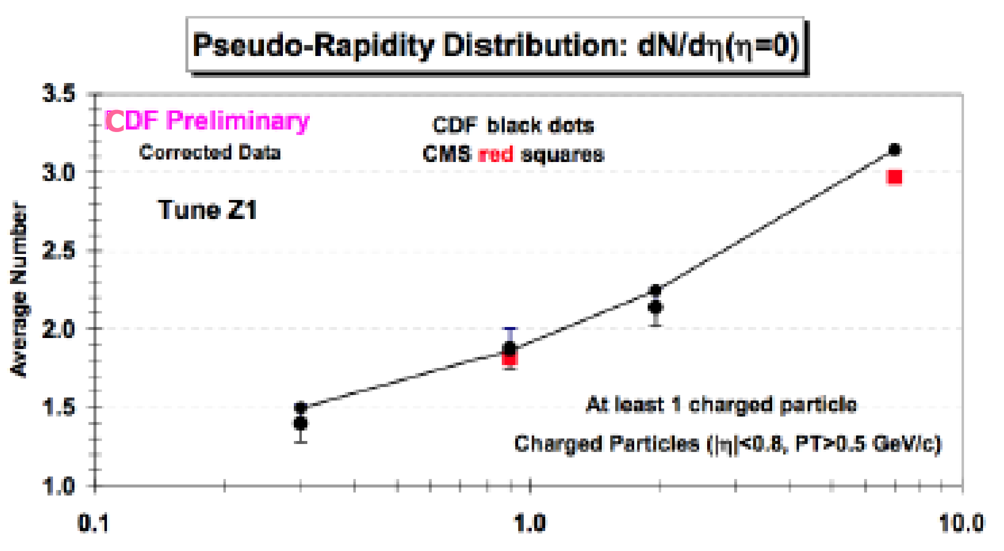


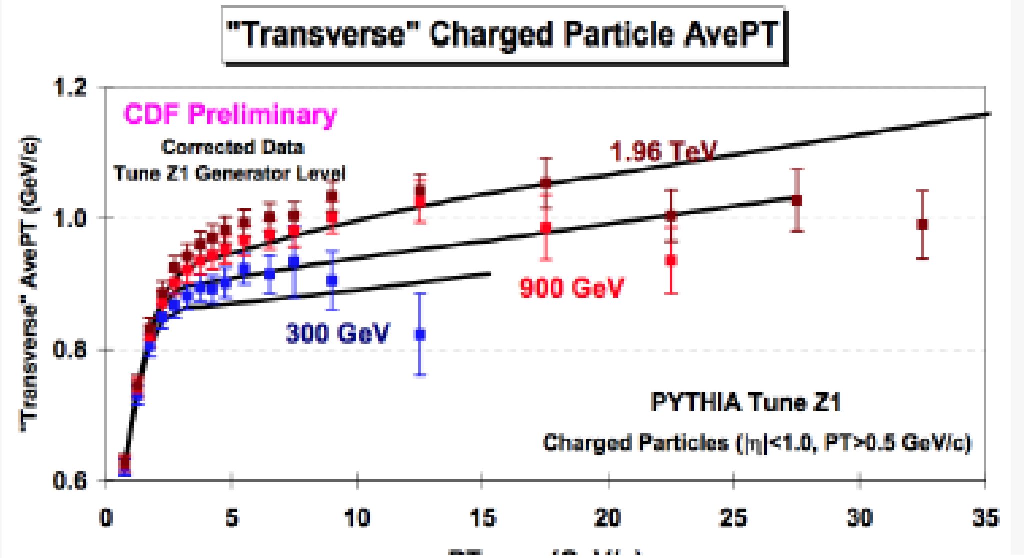
– x-Q^2 regions accessible at fixed target, DIS, Tevatron and LHC are complementary

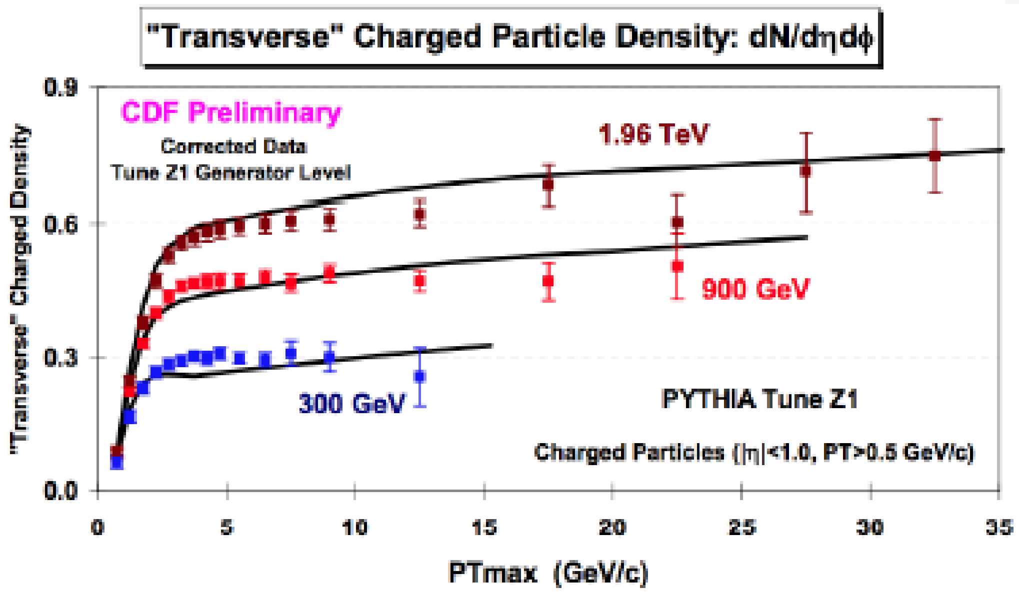
– Tevatron jet data are main source constraining gluon PDF at high x

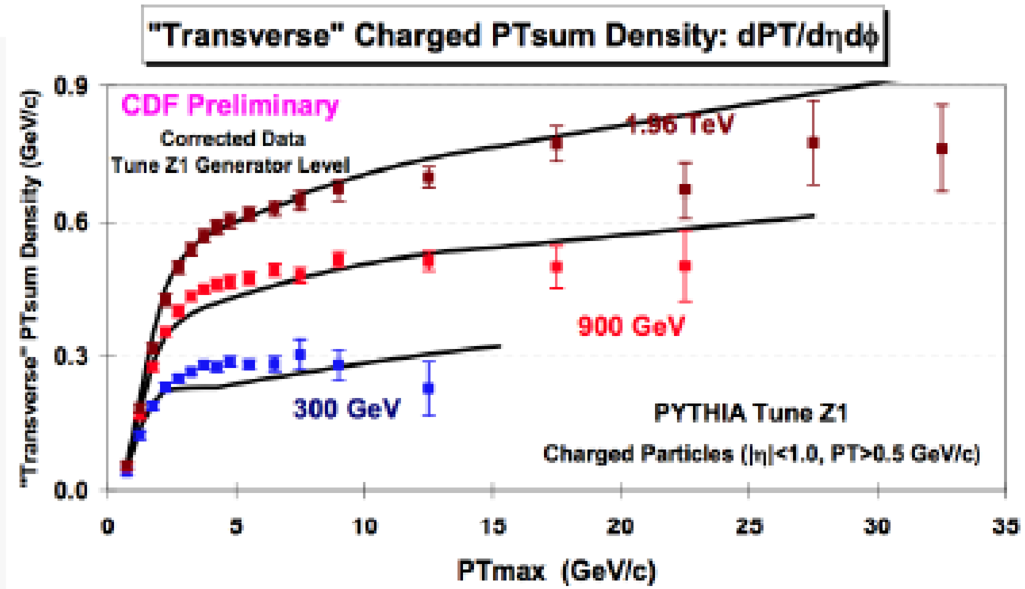
Soft QCD Physics

Data from short Tevatron energy-scan run @ 300 GeV & 900 GeV combined with 1.96 TeV data to study underlying event:









QCD: prospects

In preparation or just submitted

- γ+b, γ+c production with full sample
- $\gamma\gamma$ production with full sample
- W+light flavor cross section
- Observation of W+c production

2013 and beyond:

- Inclusive γ production with full sample
- Double parton interactions
- Double pomeron exchange in exclusive hadron
. production
- Underlying event studies with 3 collision energ.
- γ+light flavor production with full sample
- Studies of minimum bias events at 3 collision en.
- Diffraction studies (Bose-Einstein correlations,
.exclusive hadron production, pomerons in jet evts)

In preparation or just submitted

- Ratio of Z+b/Z+jet differential cross sections
- Rapidity dependence of $\Delta\phi$ in Dijet events
- Diphoton differential cross sections
- W+jets differential distributions
- Photon+jet triple differential cross section
- Ratios of Z+c/Z+jet & Z+c/Z+b cross sections

2013 and beyond:

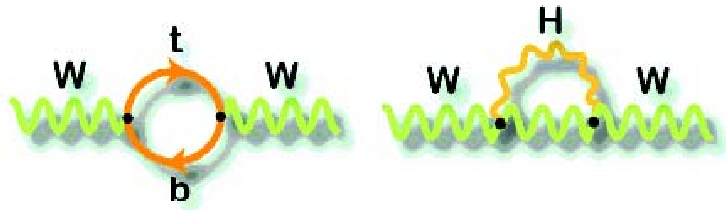
- alpha_s combination from jet measurements
- Single diffraction diff. cross section
- W+c/b differential cross sections
- J/ψ+J/ψ cross section
- Double parton (DP) interactions in ψ+HF+2jets
- Di-b-jet/Dijet mass cross section ratio
- Triple jet differential cross section
- Jet event shapes
- Inclusive jet cross section
- DP interactions in $\gamma\gamma$+jj - DP in J/ψ+J/ψ events
- γ+bb(cc) diff. cross section
- FB asym. In b+bbar(c+cbar) events

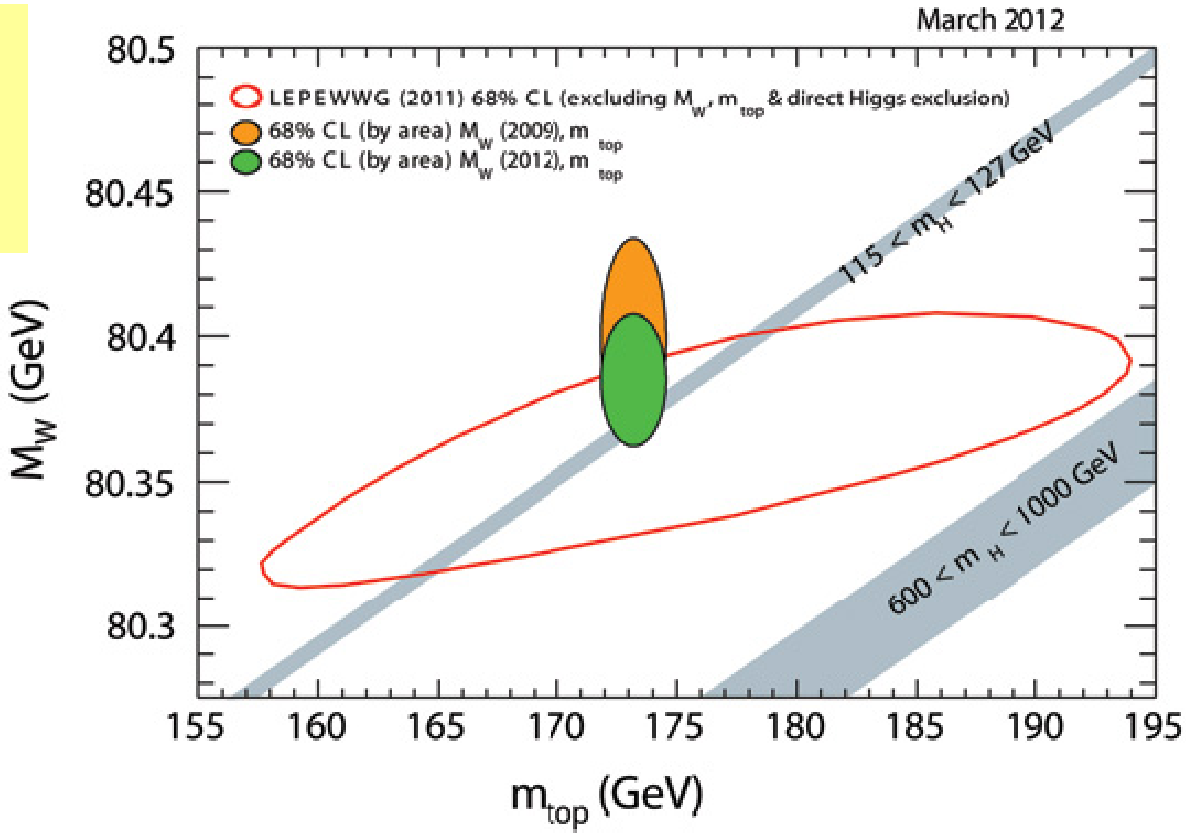
Indirect SM Higgs constraints

Recently updated top quark and W boson mass measurements from the Tevatron

$m_W = 80385 \pm 15$ MeV

$m_t = 173.2 \pm 0.9$ GeV





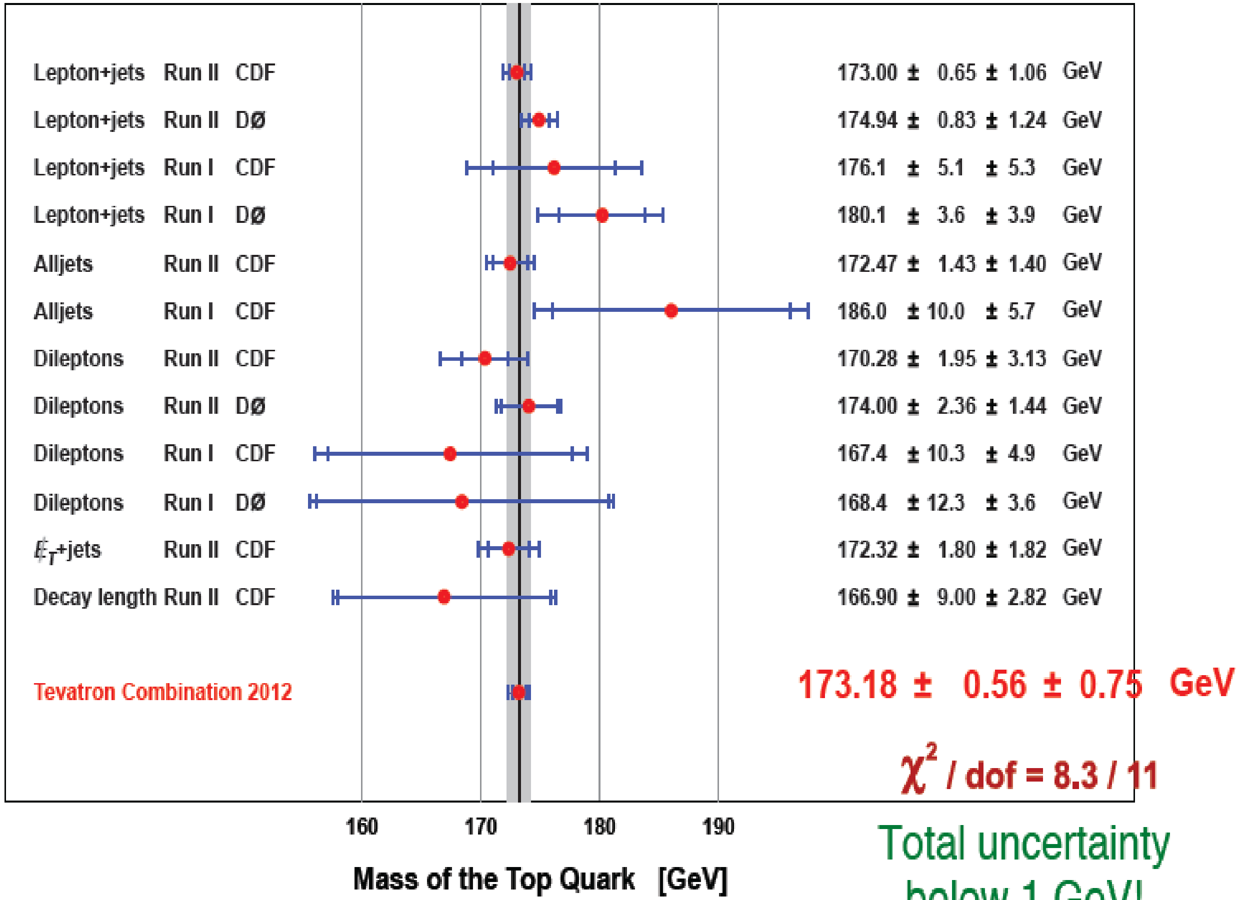
The particle discovered at the LHC and seen at the Tevatron looks like the SM Higgs also from the indirect point of view.

Tevatron has unique opportunity to check it

Top Mass and cross sections

- Top mass Tevatron combination recently published in PRD (on about half of the statistics), more precise than latest preliminary LHC combination (HCP-2012).

	Top Mass (GeV)
Tevatron	$173.2 \pm 0.6 \pm 0.8$
LHC	$173.3 \pm 0.5 \pm 1.3$

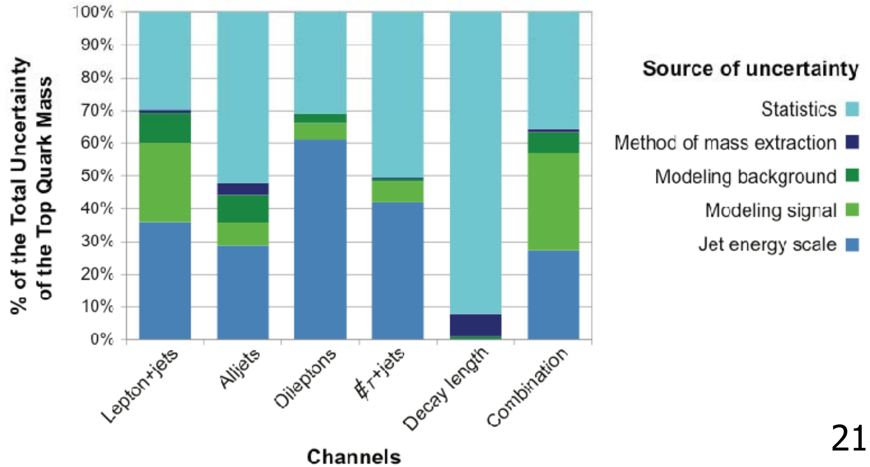


Total uncertainty below 1 GeV!

- New measurements and combination in preparation (2013), with full dataset

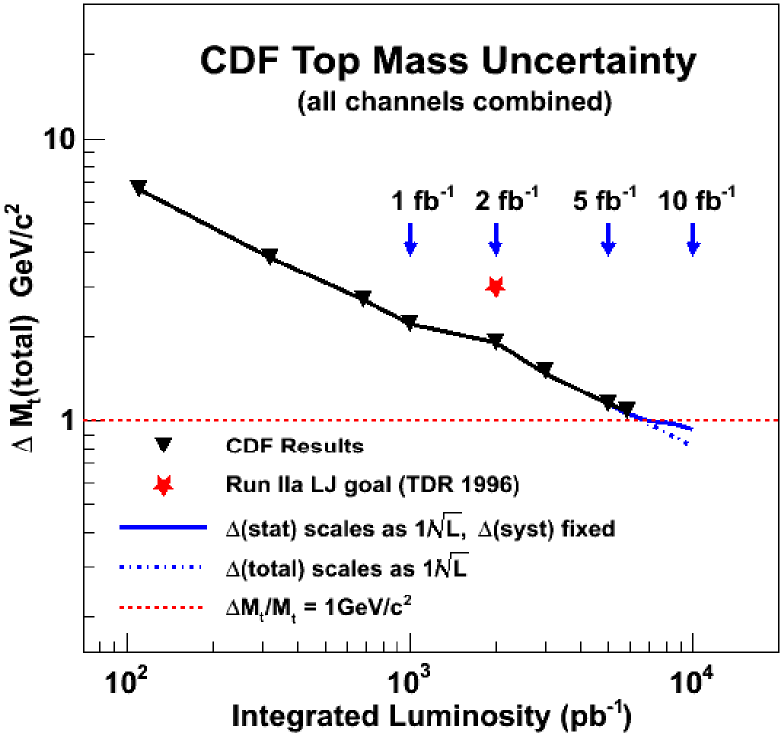
Moriond update: M_{top} = (173.20 ± 0.87) GeV

➔ 0.50% precision, more to come

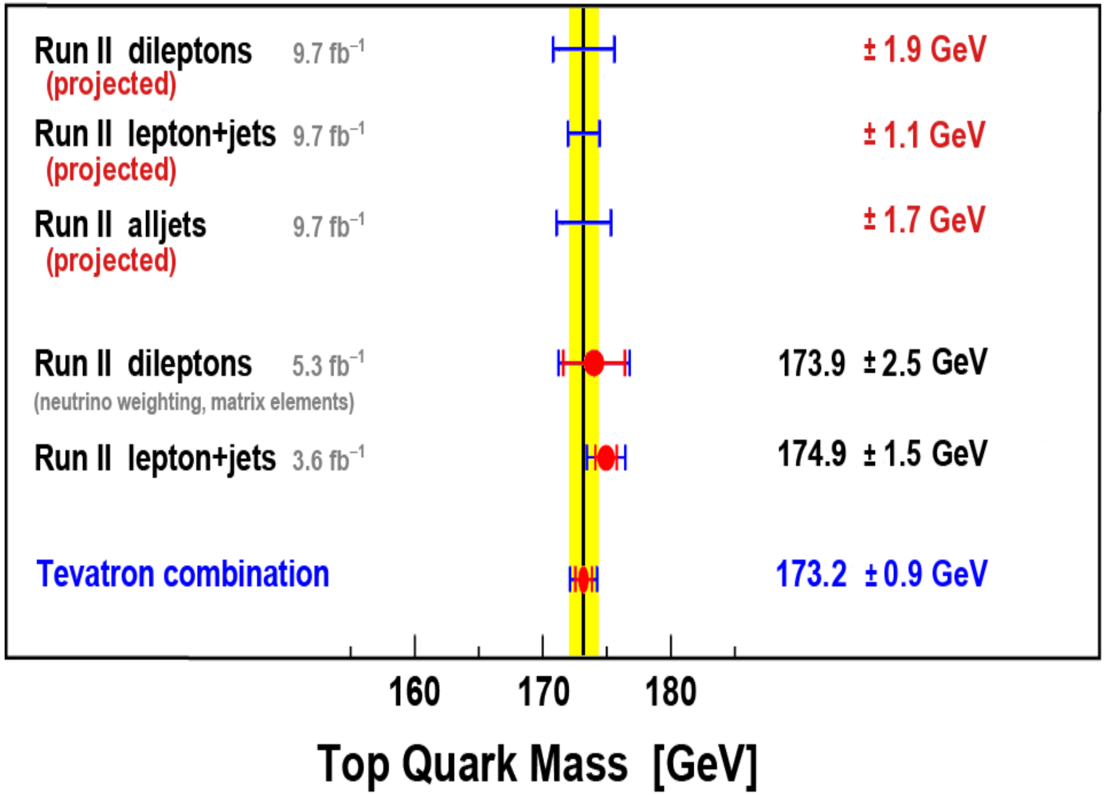


Tevatron top-pair production cross section combination soon to be released, unique to Tevatron energy

Expected Top mass precision



Dzero Top Mass uncertainty (projected and achieved)



With the improvements achieved or planned at CDF (~30% in b-tagged dilepton channel, 20 and 27% in lepton and MET+jet channels, 10% in all jets) and at Dzero (~30% in dilepton and lepton+jets, and a new result in all jets) we expect a ~20% improvement in the new Tevatron combination,

from 0.9 GeV (2011) down to 0.7 GeV with the full sample

Top physics recent highlights

2012:

Combination of the top-quark mass measurements from the Tevatron collider

. Combination of CDF and D0 measurements of the W boson helicity in top quark decays,

CDF:

Measurements of the top-quark mass and the tt-bar cross section in the hadronic τ+jets channel
Precision top-quark mass measurements at CDF
Measurement of the top quark mass in the all-hadronic mode at CDF

DZero:

Measurement of Leptonic Asymmetries and Top Quark Polarization in tt Production
Measurement of the Top Quark Mass in pp Collisions using Events with Two Leptons
Improved Determination of the Width of the Top Quark
Evidence for Spin Correlation in tt Production

2011

CDF:

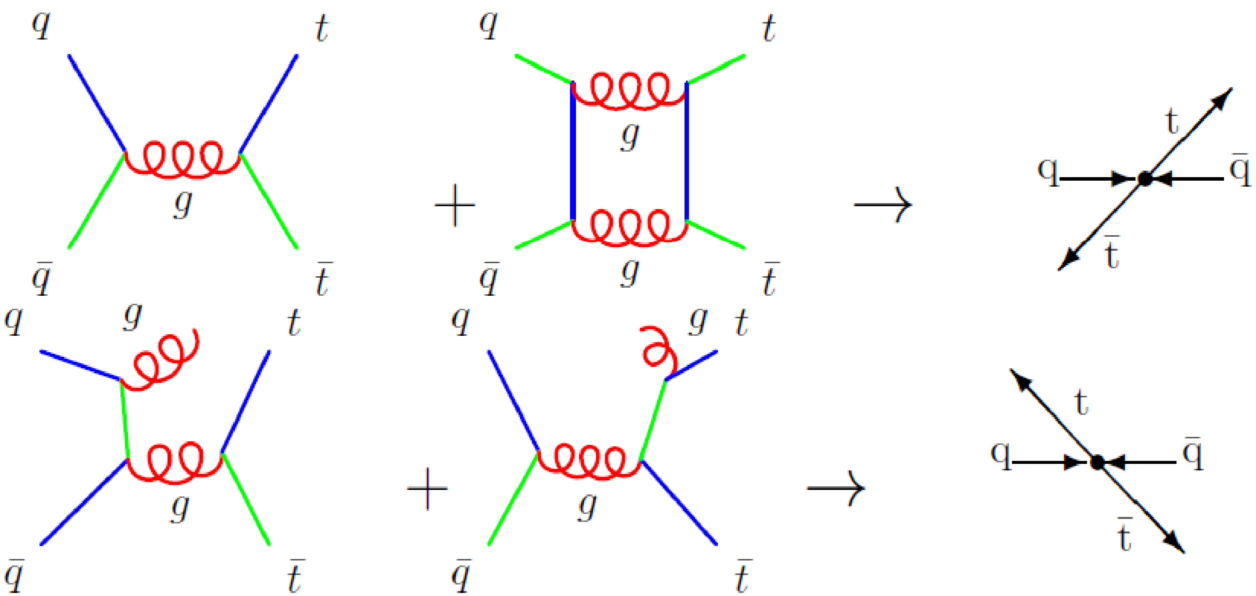
Evidence for a mass dependent forward-backward asymmetry in top quark pair production
. Search for a very light CP-odd Higgs boson in top quark decays from p-anti-p collisions

DZero:

Forward-Backward Asymmetry in Top Quark-Antiquark Production
Measurements of Single Top Quark Production Cross Sections and $|V_{tb}|$ in pp Collisions

Forward-backward top asymmetry

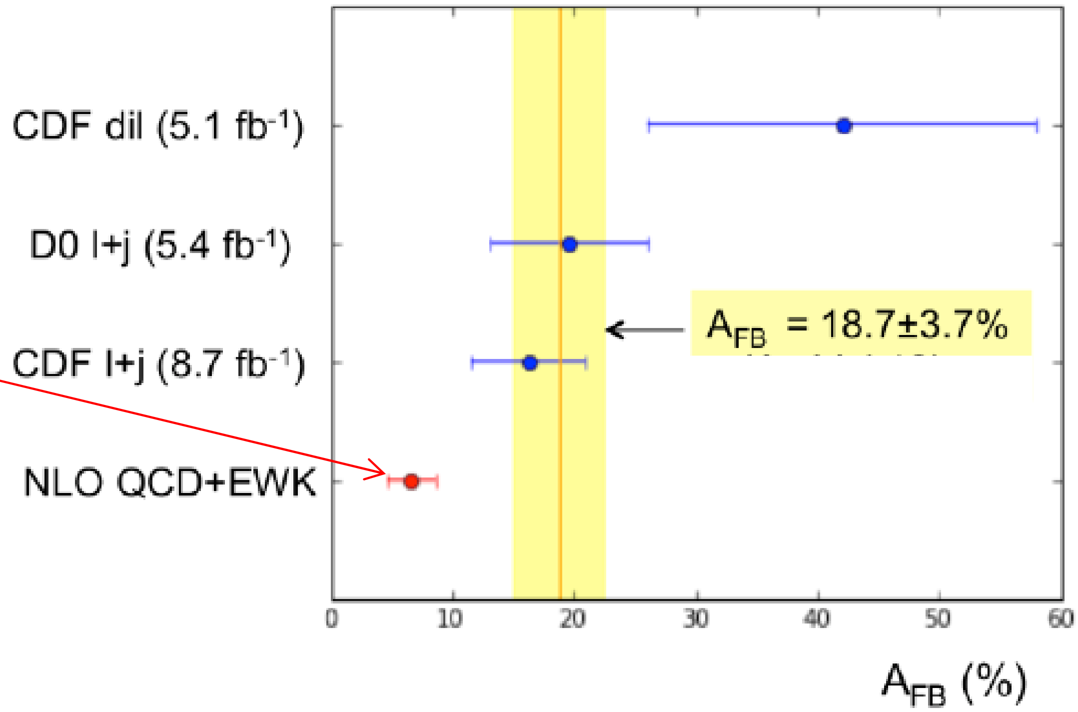
- In the SM, this effect only happens for $q\bar{q}$ initial states
- SM predicts no asymmetry at LO in QCD, and a small asymmetry at NLO



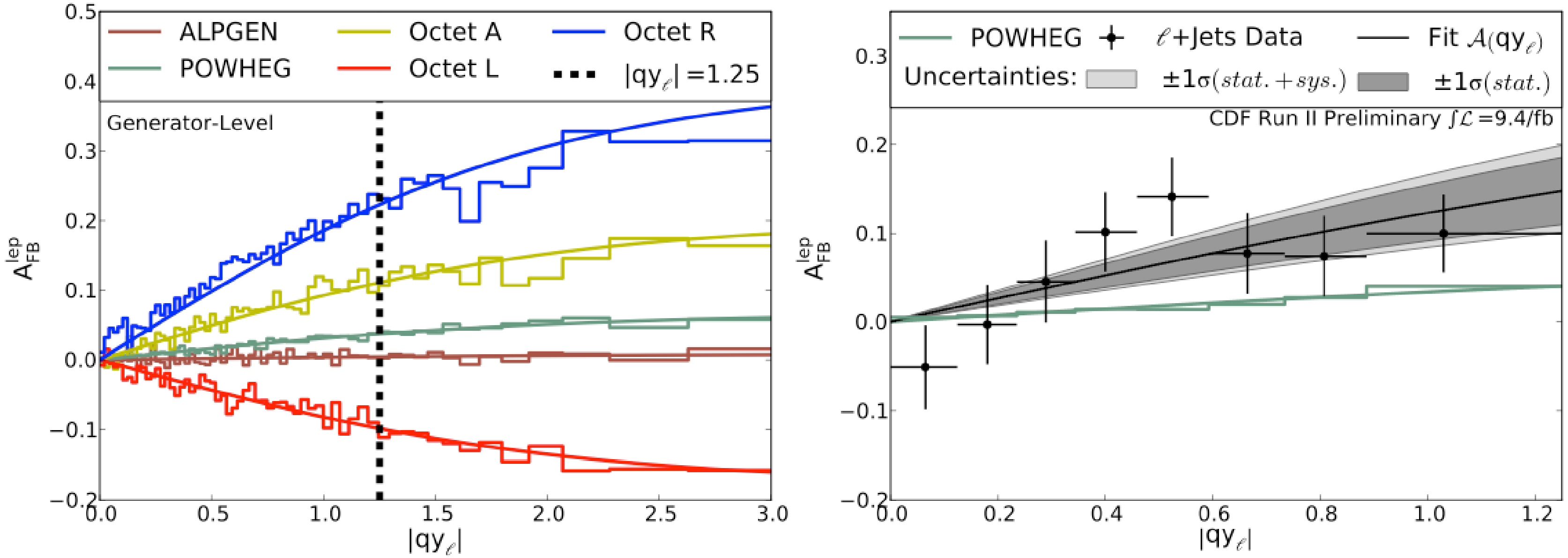
Effects at LHC are "diluted" by a factor ~10, →more difficult to measure

Combination of measured asymmetries is ~3.3σ from NLO QCD+EWK predictior

kinematics dependence under study (invariant mass dependence)



Leptonic A_{FB} in $tt \rightarrow l$+jets decays



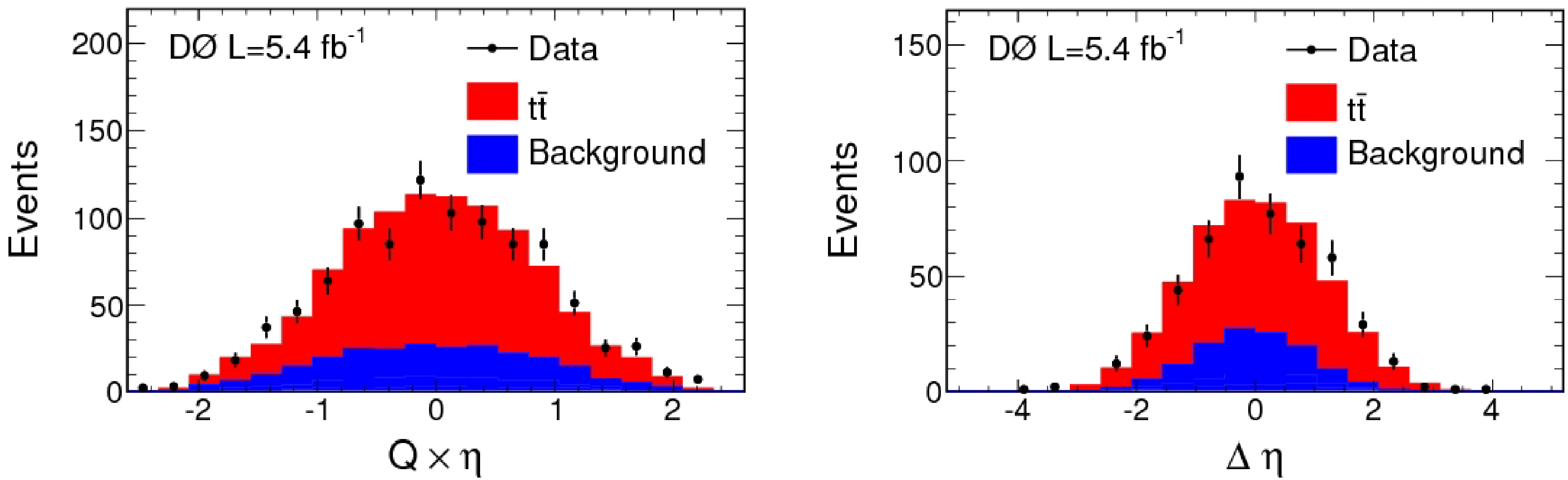
Partially correlated with A_{FB}(tt) (if tt production polarized), essentially free of event reconstruction uncertainties

- Measured total A_{FB}^{lep} = 0.094 ± 0.032_{stat} ± 0.029_{syst}
- SM@NLO A_{FB}^{lep} = 0.036

CDF public note 10975

Leptonic A_{FB} in tt→dilepton decays

PRD 87, 011103(R) (2013)

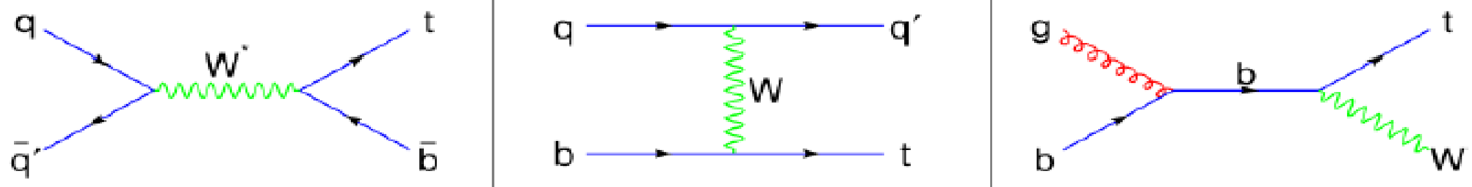


- Measured total $A_{FB}^{lep} = 0.058 \pm 0.051_{stat} \pm 0.013_{syst}$
- Combined with DZero lepton+jets result, $A_{FB}^{lep} = 0.112 \pm 0.032$
- SM@NLO $A_{FB}^{lep} = 0.047$

Results in all channels on full statistics from CDF and D0 soon available

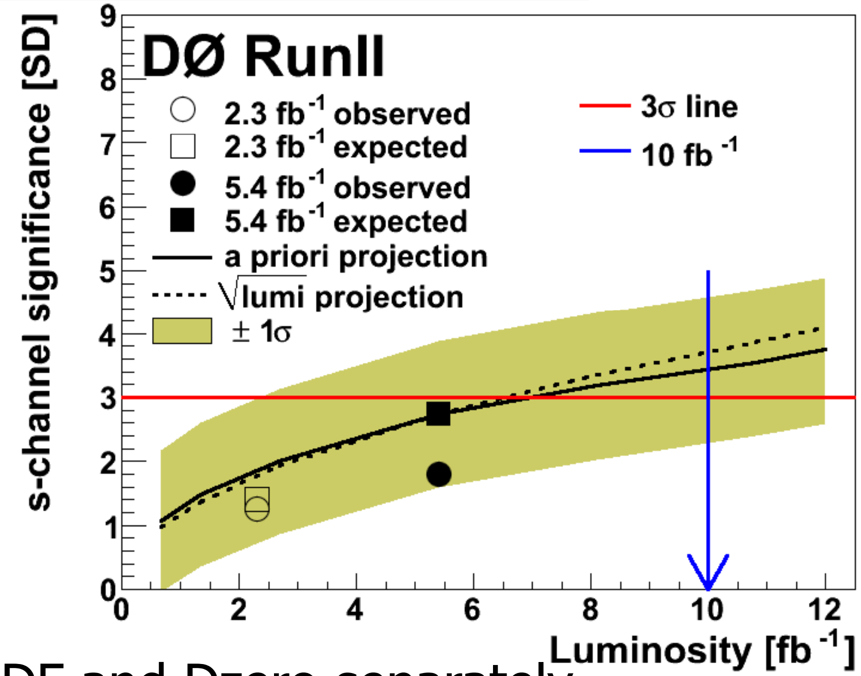
Expected s-channel single top significance

TeV: 1.04±0.06 pb	2.1±0.1 pb	0.1 pb
LHC8: 5.6±0.2pb	87±3 pb	22±2 pb



Kidonakis, MSTW2008, NNLO approximation, for m_t=173 GeV

Difficult channel at LHC ($q\bar{q}$ annihilation)
Important channel since BSM effects may manifest differently in s and t channel



We expect ~4σ s-channel significance from CDF and Dzero separately
(combining lepton+jets and MET+jets decay modes using full data sample)

With Tevatron combination a 5σ significance (observation) is within reach

Top physics: prospects

In preparation or just submitted

- Top charge in l+jets channel with full sample
- Top mass in MET+jets channel
- Top pair cross section in dilepton channel
- BR($t \rightarrow Wb$)/BR($t \rightarrow Wq$) in l+jets channel
- Top pair cross section in e/μ+τ channel
- Top mass in dilepton channel (Dalitz-Goldstein method)
- Top pair cross section Tevatron combination

2013 and beyond:

- Direct top width measurement in l+jets channel
- Top pair differential cross sections in l+jets
- A_{FB} in dilepton channel
- A_{FB} in high-p_T bottom pairs
- Spin correlations/top polarization in dileptons
- Top charge in dilepton channel
- Single top x-section in l+jets channel & MET+jets
- BR($t \rightarrow Wb$)/BR($t \rightarrow Wq$) in dilepton channel
- Top mass in dilepton channel (φ_v-weighting method)
- Top mass in all-jets channel
- Top pair cross section in l+jets channel
- Combinations (M_{top}, σ_{tt}, A_{FB}, single top)

In preparation or just submitted

- FB asymmetry in dilepton channel
- Top pair cross section Tevatron combi.

2013 and beyond

- differential ttbar cross sections
- inclusive cross section
- l+jets ME top mass
- s-channel single top
- leptonic asymmetry in l+jets
- top charge
- all-jets top mass
- *ttbar spin correlations*
- Combinations (M_{top}, σ_{tt}, A_{FB}, single top)

Electroweak physics recent highlights

2012:

CDF:

Precise measurement of the W-boson mass with the CDF II detector
Measurement of ZZ production in leptonic final states at √s of 1.96 TeV at CDF
Search for the rare radiative decay W→πγ in pp-bar collisions at √s=1.96 TeV

DZero:

Limits on anomalous trilinear gauge boson complings from WW, WZ and Wγ production
Measurement of the WZ and ZZ Production Cross Sections using Leptonic Final States
Measurements of WW and WZ Production in W+jets Final States in pp Collisions
Measurement of the W Boson Mass with the DØ Detector

2011:

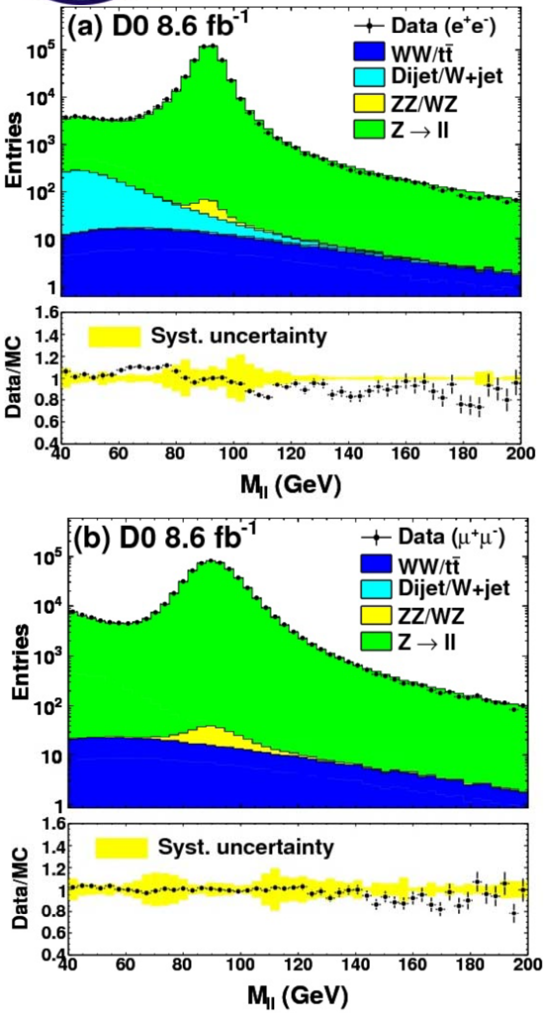
CDF:

First measurement of the angular coefficients of Drell-Yan e^+e^- pairs in the Z mass region
Limits on anomalous trilinear gauge couplings in Zγ events from pp-bar collisions at √s=1.96 TeV

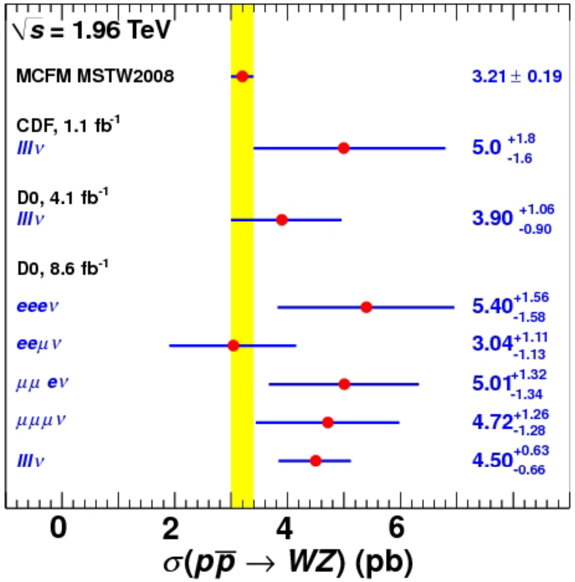
DZero:

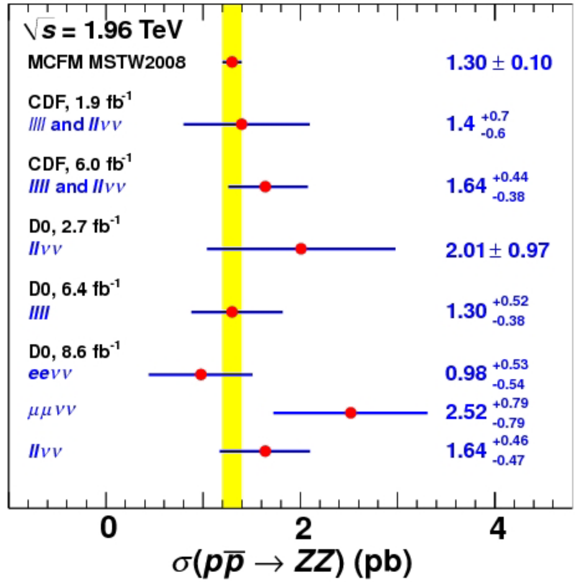
Wγ Production and Limits on Anomalous WWγ Couplings in pp Collisions at √s = 1.96 TeV
Measurement of the $\sin^2\theta^l_{eff}$ and Z-Light Quark Couplings using the FB Charge Asymmetry in $pp \rightarrow Z/\gamma^* \rightarrow e^+e^-$
Measurement of the ZZ Production Cross Section in pp Collisions at √s = 1.96 TeV

WZ & ZZ cross sections



PRD 85, 112005 (2012)



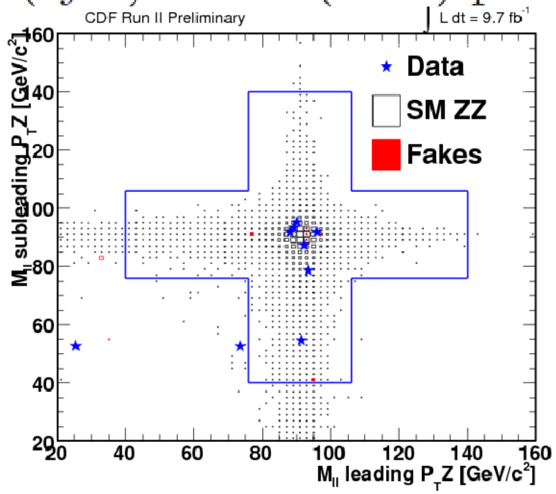


-WZ→lνll & ZZ→llνν: measured relative to Z→ll, then normalized to theory

→ DZero Combining ZZ→llνν with just submitted ZZ→llll(9.8 fb^{-1}):

$$\sigma(p\bar{p} \to ZZ) = 1.32^{+0.29}_{-0.25}\ (\mathrm{stat}) \pm 0.12\ (\mathrm{syst}) \pm 0.04\ (\mathrm{lumi})\ \mathrm{pb}$$

$^{+0.31}_{-0.28}$ (Total)



CDF: ZZ→llll: counting experiment; ZZ→llνν: NN fit

$$\sigma(p\bar{p} \to ZZ) = 1.38 \pm 0.19(\mathrm{stat.})^{+0.20}_{-0.19}(\mathrm{syst.})\ \mathrm{pb} = 1.38^{+0.28}_{-0.27}\ \mathrm{pb}$$

Next step: combine CDF/D0 measurements → Legacy

WWZ & WWγ anomalous couplings

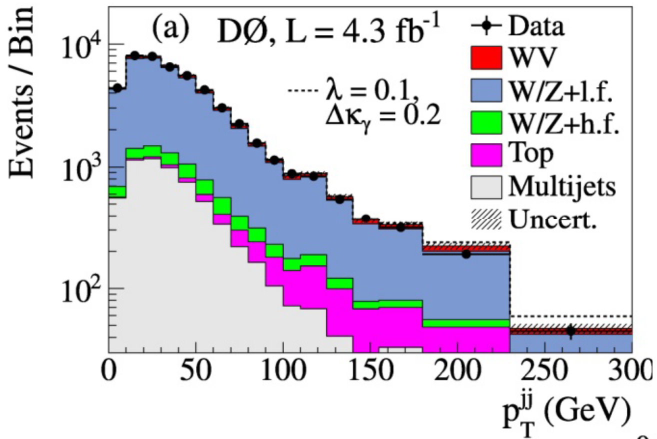
PLB 718, 451 (2012)

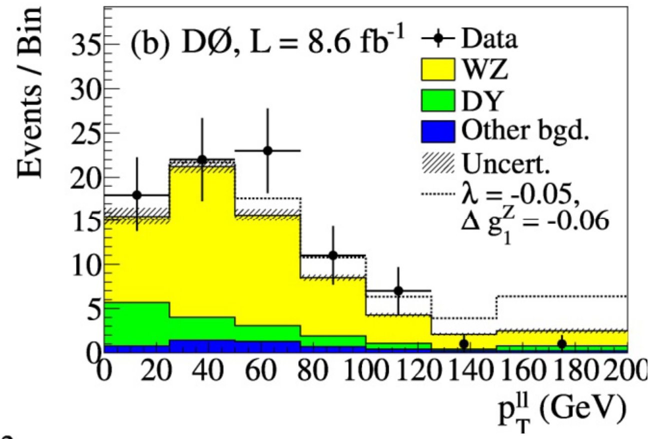
$$-i\frac{L_{VWW}}{g_{VWW}} = g_1^V\left(W^+_{\mu\nu}W^{\mu}V^{\nu} - W^+_{\mu}V_{\nu}W^{\mu\nu}\right) + \kappa_V W^+_{\mu}W_{\nu}V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^+_{\rho\mu}W^{\mu}_{\nu}V^{\nu\rho}$$

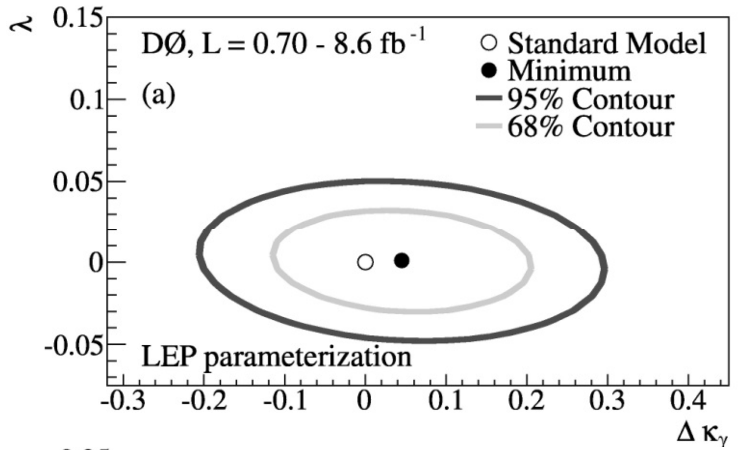
$$\mathrm{SM:}\quad \lambda_\gamma = \lambda_Z = 0 \qquad g_1^Z = \kappa_\gamma = \kappa_Z = 1$$

$$g_{\gamma WW} = -e \qquad g_{ZWW} = -e\cot\theta_W \qquad \mu_W = \frac{e}{2M_W}\left(1+\kappa_\gamma+\lambda_\gamma\right) \qquad q_W = \frac{e}{2M_W^2}\left(\lambda_\gamma - \kappa_\gamma\right)$$

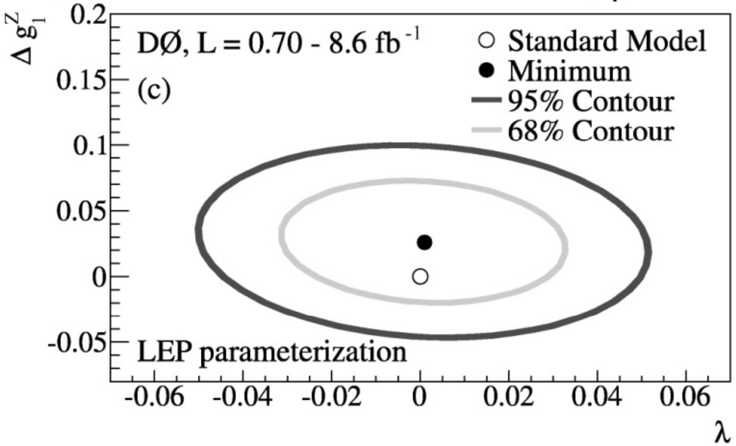
$$\mathrm{ATGC:}\quad \Delta\kappa_V = \kappa_V - 1 \qquad \Delta g_1^Z = g_1^Z - 1$$

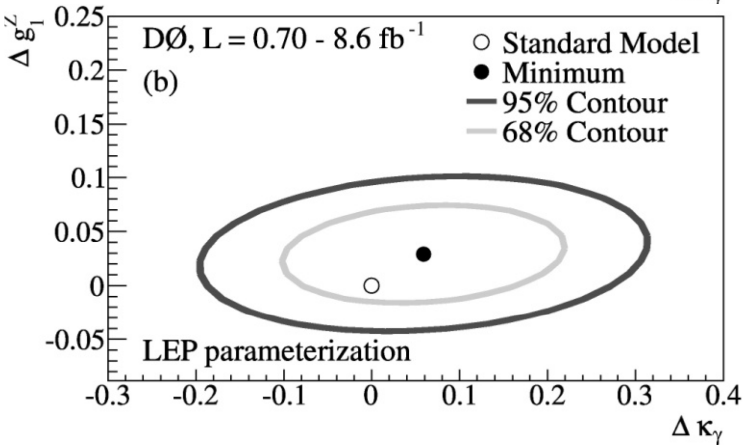






- WW+WZ→lνjj
- WW→lνlν
- WZ→lνll
- Wγ→lνγ
- Λ= 2 TeV





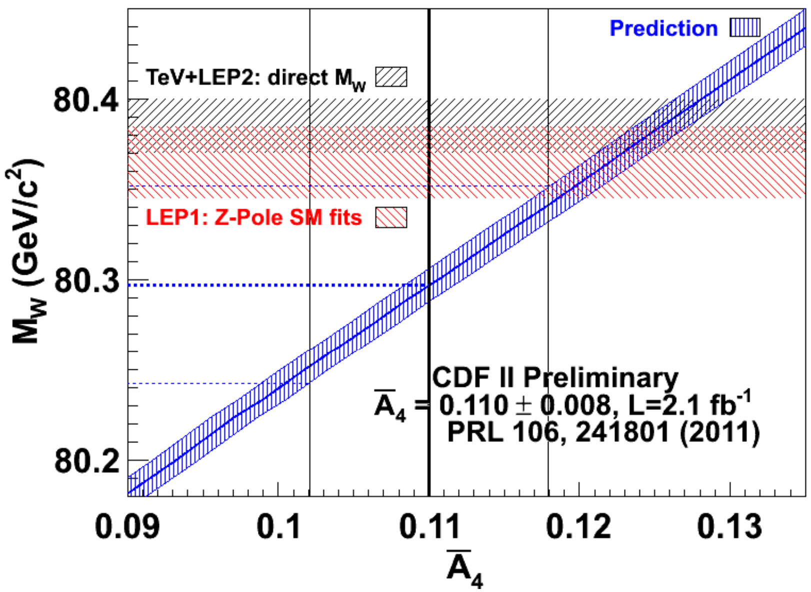
$$\mathrm{LEP:}\quad \Delta\kappa_\gamma = 0.048^{+0.106}_{-0.105} \qquad \Delta g_1^Z = 0.022^{+0.032}_{-0.030} \qquad \lambda = 0.007^{+0.021}_{-0.022} \qquad \mu_W = 2.012^{+0.035}_{-0.034}\ e/2M_W \qquad q_W = -0.995^{+0.042}_{-0.043}\ e/M_W^2$$

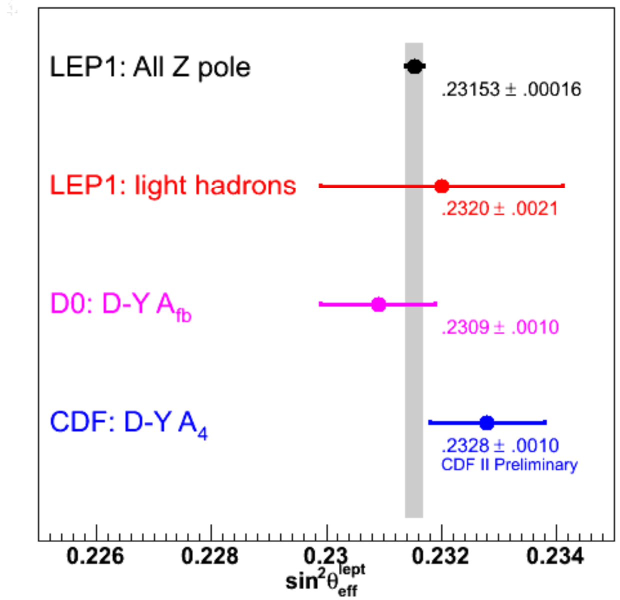
$$\mathrm{Equal\ couplings:}\quad \Delta\kappa = 0.037^{+0.044}_{-0.044} \qquad \lambda = 0.008^{+0.020}_{-0.025} \qquad \mu_W = 2.016^{+0.034}_{-0.034}\ e/2M_W \qquad q_W = -1.009^{+0.039}_{-0.041}\ e/M_W^2$$

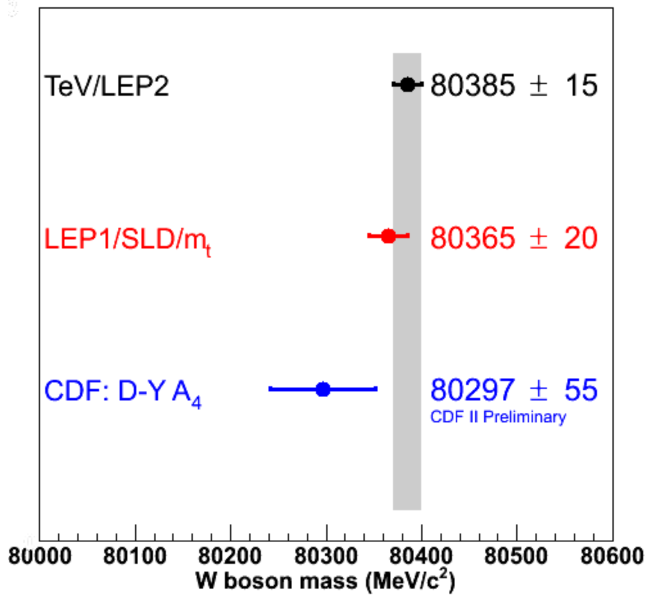
$\sin^2\theta_W$ (or M_W)

PRL 106, 241801 (2011)
CDF public note 10952

$$\frac{M_W^2}{M_Z^2} = 1 - \sin^2\theta_W$$







- ✧ Measured A_4 (V-A interference) from cosθ term of the angular distribution of e^+e^- pairs with M_{ee} in [66,116] GeV/c^2
- ✧ Derived $\sin^2\theta_{eff}^{lep}$ and M_W from A_4 and ResBos prediction

Electroweak physics: prospects

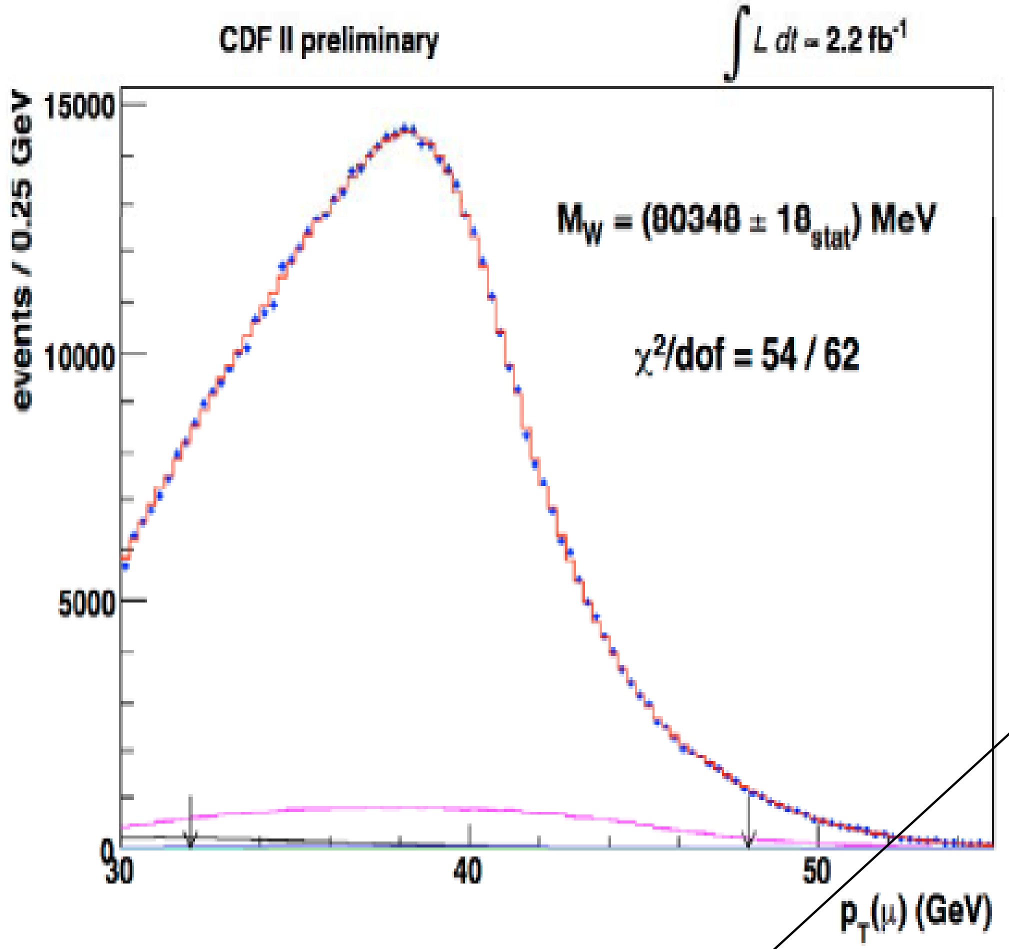
2013:

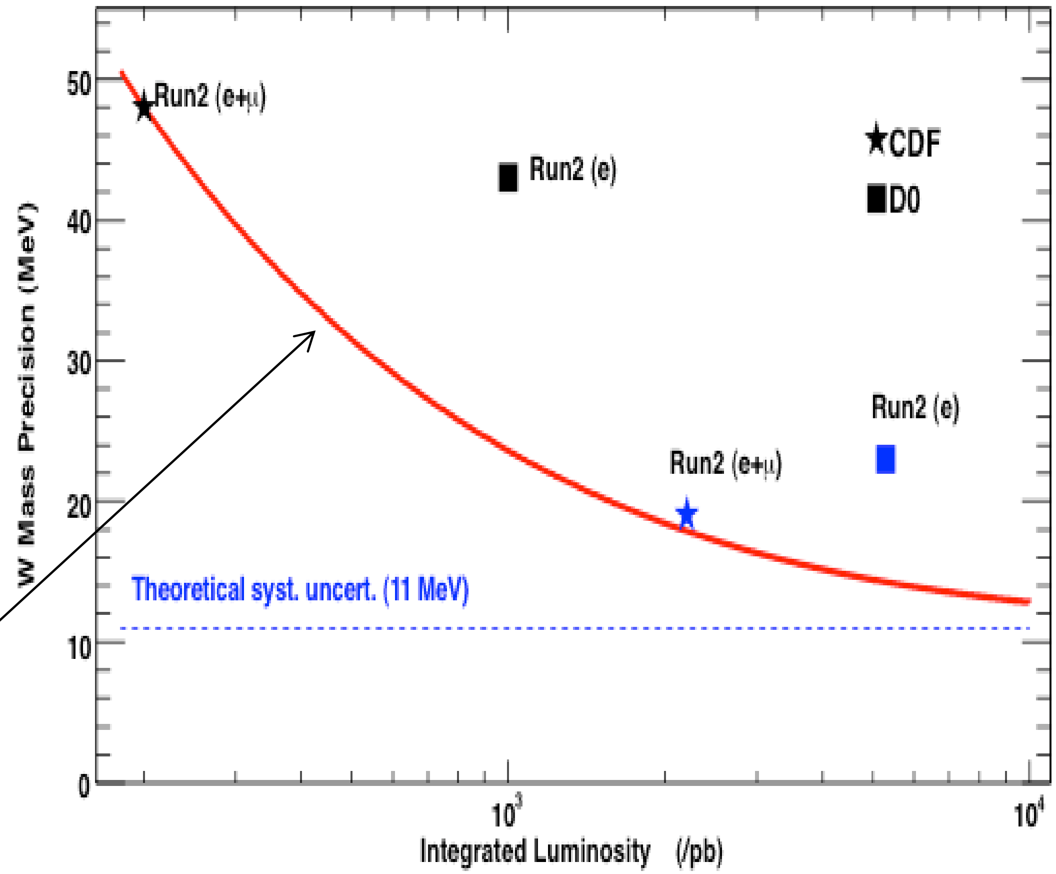
- W+jets differential cross sections with full sample (CDF)
- Search for $Z \rightarrow \gamma\gamma$ with full sample (CDF)
- W Charge asymmetry (D0)
- Z boson angular coefficients (D0)
- Z boson Forward-Backwards Asymmetry (D0)
- Z boson rapidity (D0)

>2013:

- W mass with full sample
- W width with full sample
- W mass Tevatron combination
- W mass with forward electrons (D0)
- Search for rare decays ($Z \rightarrow J/\psi\gamma$, $W \rightarrow \pi\gamma$) with full sample (CDF)

Expected W mass precision





Assumptions:

– The red curve starts from the 200 pb^{-1} total uncertainty and scales all uncertainties (except the theoretical ones) down as √L

– The theory blue line is from the most recent analysis:

  – 4 MeV from QED and 10 MeV from PDFs

  it is expected to go down, and is lower for forward leptons

W-mass projected systematic uncertainties

CDF projected uncertainties (MeV)

Source	0.2/fb (MeV)	2.2/fb (MeV)	10/fb (MeV)	
Lepton energy scale	23	7	3	→ Assume 50% reduction in BC-NBC and QED/energy loss uncertainties
Lepton energy resolution	4	2	1	} Assume the same scaling as 0.2/fb → 2.2/fb
Recoil energy scale	8	4	2	
Lepton removal	6	2	1	
Backgrounds	6	3	2	
pT(W) model	4	5	2	→ Assume 1/ √L scaling
PDFs	11	10	5	→ Assume 50% reduction in PDF uncertainty
QED radiation	10	4	4	→ Assume the same QED
Total systematics	34	15	8	
W statistics	34	12	6	→ Assume 1/ √L scaling
Total	48	19	→ 10	

Limiting factors:
1). PDFs (and QED)
2). BC-NBC difference
3). QED/energy loss modeling

DZero projected uncertainties (MeV)

Source (Unit in MeV)	Published (2012) 4.3 fb^{-1} CC	Projection improved 10 fb^{-1} CC	Projection improved 10 fb^{-1} CC+EC
Statistical	**13**	**9**	**8**
Experimental syst.			
Electron energy scale	16	11	10
Electron energy resolution	2	2	2
Electron energy nonlinearity	4	2	2
W and Z electron energy loss differences	4	2	2
Recoil model	5	3	2
Electron efficiencies	1	1	1
Backgrounds	2	2	2
Exp. Syst. Subtotal	18	12	11
Theoretical syst.			
PDF	11	11	5
QED	7	3	3
Boson pT	2	2	2
Theo. Syst. Subtotal	13	12	6
Systematic total	**22**	**17**	**13**
Total	**26**	→ **19**	→ **15**

Electron channel only

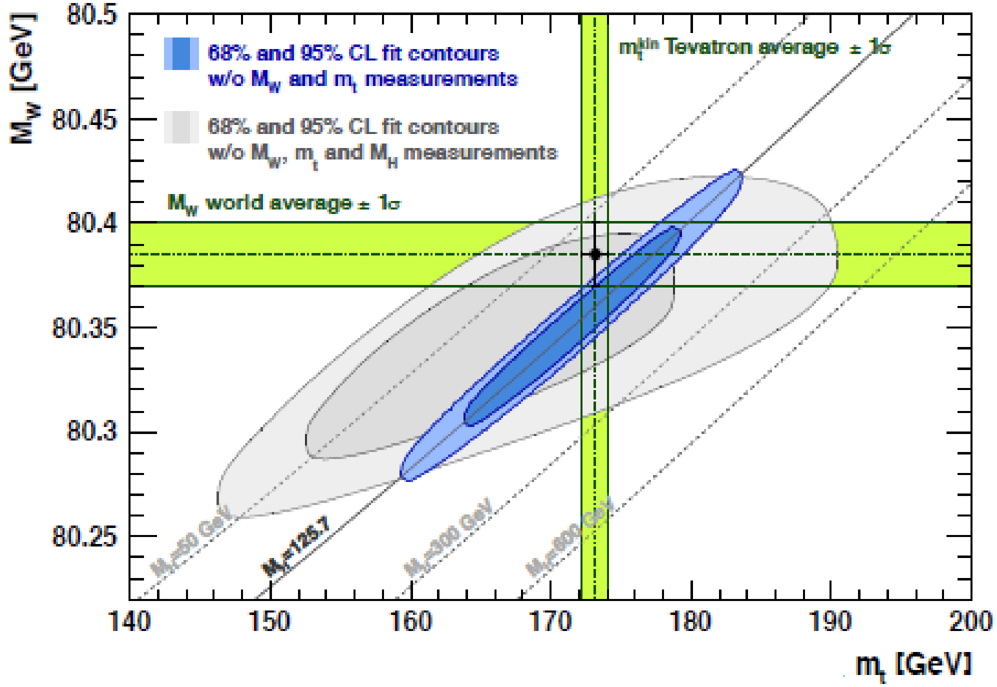
W-mass : how far can we go?

If we use the measured mass of the Higgs-like boson to constrain the W boson mass based on SM, we get:

$m_W = 80.359 \pm 0.011$ GeV

Comparing with the current world average directly measured value:

$m_W = 80.385 \pm 0.015$ GeV



With a world average around 10 MeV dominated by the Tevatron, and no change in central values, test direct and indirect Higgs mass values.

Significant anomaly could be detected if central value would slightly move apart, while reducing uncertainties .

Currently we have good agreement !!!

test SM consistency via m_W m_{top} m_{Higgs} at > 2 sigma level

Final Higgs combination from Tevatron

Combination: arXiv:hep-ex/1303.63416; submitted to Phys. Rev. D

All SM channels searched

Full luminosity used in almost all channels

CDF

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(5 b-tag categories)		9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2×(4 b-tag categories)	$H \to b\bar{b}$	9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels 2×(4 b-tag categories)		9.45	90–150
$WH + ZH \to jjb\bar{b}$ (2 b-tag categories)		9.45	100–150
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$ (4 jets,5 jets,≥6 jets)×(5 b-tag categories)		9.45	100-150
$H \to W^+W^-$ 2×(0 jets)+2×(1 jet)+1×(≥2 jets)+1×(low-$m_{\ell\ell}$)		9.7	110–200
$H \to W^+W^-$ (e-τ_{had})+(μ-τ_{had})		9.7	130–200
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)	$H \to W^+W^-$	9.7	110–200
$WH \to WW^+W^-$ (tri-leptons with 1 τ_{had})		9.7	130–200
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet,≥2 jets)		9.7	110–200
$H \to \tau^+\tau^-$ (1 jet)+(≥2 jets)	$H \to \tau^+\tau^-$	6.0	100–150
$H \to \gamma\gamma$ 1×(0 jet)+1×(≥1 jet)+3×(all jets)	$H \to \gamma\gamma$	10.0	100–150
$H \to ZZ$ (four leptons)	$H \to ZZ$	9.7	120–200

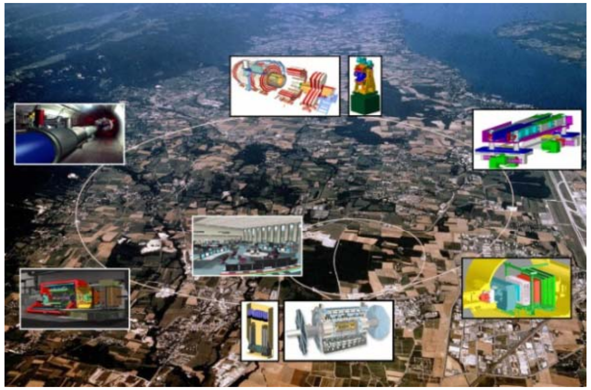
DØ

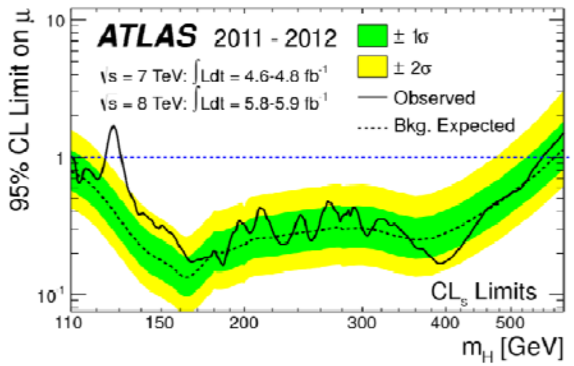
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ (4 b-tag categories)×(2 jets, 3 jets)		9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)	$H \to b\bar{b}$	9.5	100–150
$ZH \to \ell^+\ell^- b\bar{b}$ (2 b-tag categories)×(4 lepton categories)		9.7	90–150
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ (0 jets,1 jet,≥2 jets)		9.7	115–200
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{had}\nu$		7.3	115–200
$H \to W^+W^- \to \ell\bar{\nu}jj$ (2 b-tag categories)×(2 jets, 3 jets)	$H \to W^+W^-$	9.7	100–200
$VH \to e^\pm\mu^\pm + X$		9.7	100–200
$VH \to \ell\ell\ell + X$		9.7	100–200
$VH \to \ell\bar{\nu}jjjj$ (≥4 jets)		9.7	100-200
$VH \to \tau_{had}\tau_{had}\mu + X$	$H \to \tau^+\tau^-$	8.6	100–150
$H+X \to \ell^\pm\tau^\mp_{had}jj$		9.7	105–150
$H \to \gamma\gamma$		9.6	100-150

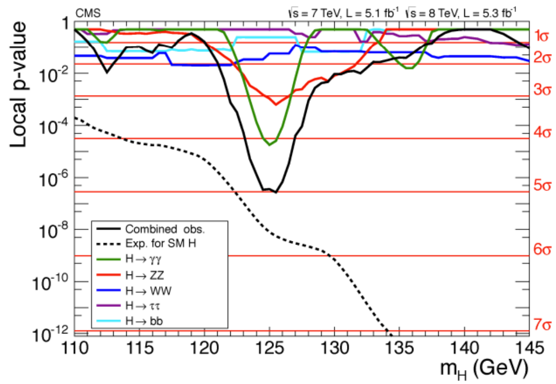
Higgs: Historical perspective and current Status

- **Tevatron Run II (2002 – 2011, 2 TeV):**
  - First post-LEP 95%CL exclusion (july 2009)
  - First evidence of a Higgs-like particle decaying to a pair of b-quarks (July 2012)

- **LHC (2011 – 2012, 7 - 8 TeV):**
  - Excluded wide mass range (111 – 122 GeV and 127 – 600 GeV)
  - **Discovered the new Higgs-like boson mainly through γγ and ZZ decays (July 2012)**



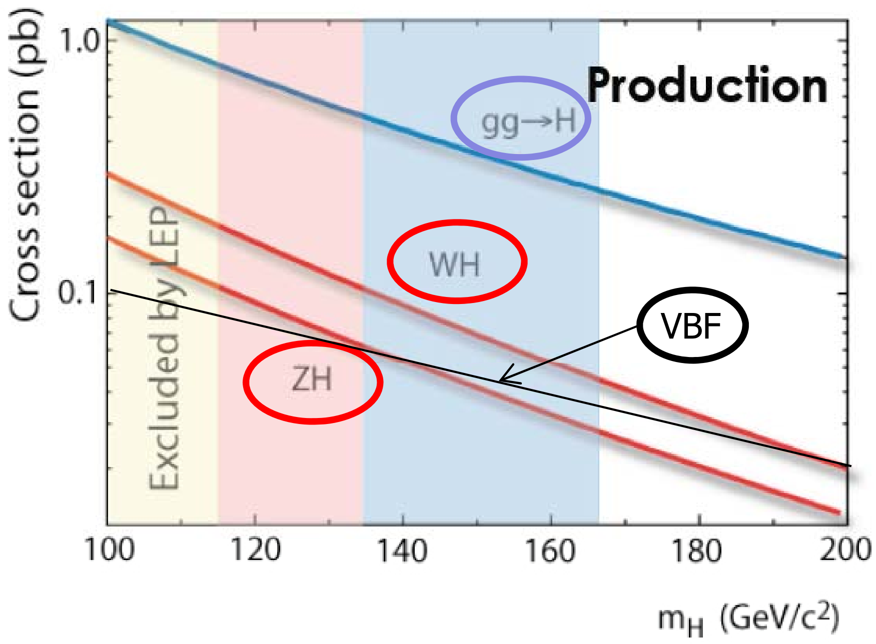


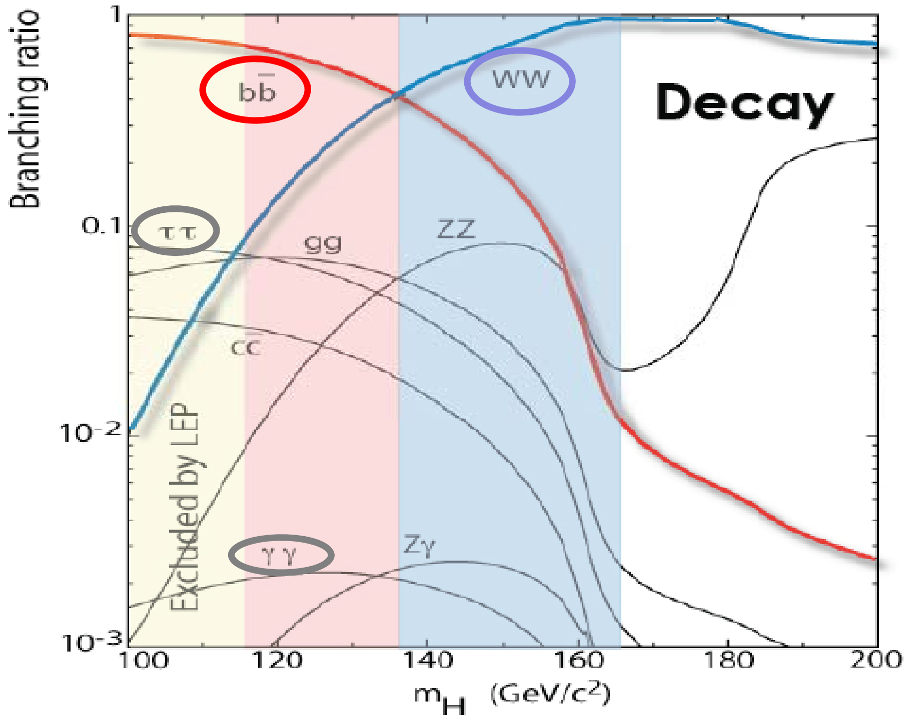


- **LHC ("full 2011-2012 dataset"):**
  - Since July 2012 progress in each channel, Observation confirmed in bosonic channel
  - ATLAS: m_H = 125.5 ± 0.2 (stat) ± 0.6 (sys) GeV, CMS: m_H = 125.8 ± 0.4 (stat) ± 0.4 (sys) GeV
  - H→bb, with ~18 fb^{-1} : data deficit at Atlas and ~2.2 σ excess at CMS
  - strong indications (2.9 σ)of fermionic decays at LHC from CMS H→ττ (full stat) but low ATLAS signal (1.1σ, 1.7σ expected, 18fb^{-1})

  ➔ **While it "is" a Higgs boson, the fermionic decays are not yet firmly established.**

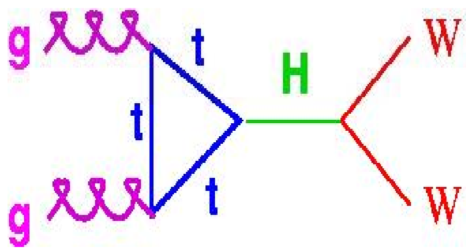
Higgs Production and Decay at the Tevatron





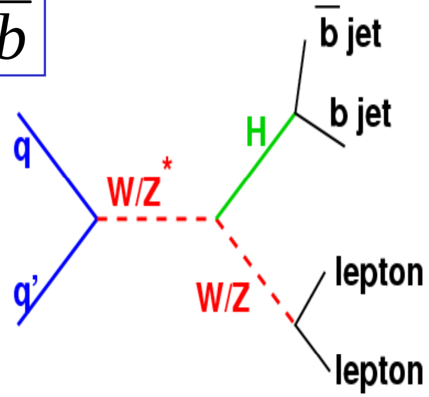
"High" mass (m_H > 135 GeV) dominant decay:

$H \rightarrow WW^{(*)}$ $\quad gg \rightarrow H \rightarrow WW \rightarrow \ell\nu\ell'\nu'$



Low mass (m_H < 135 GeV) dominant decay:

$H \rightarrow b\bar{b}$



$WH \rightarrow \ell\nu b\bar{b}$

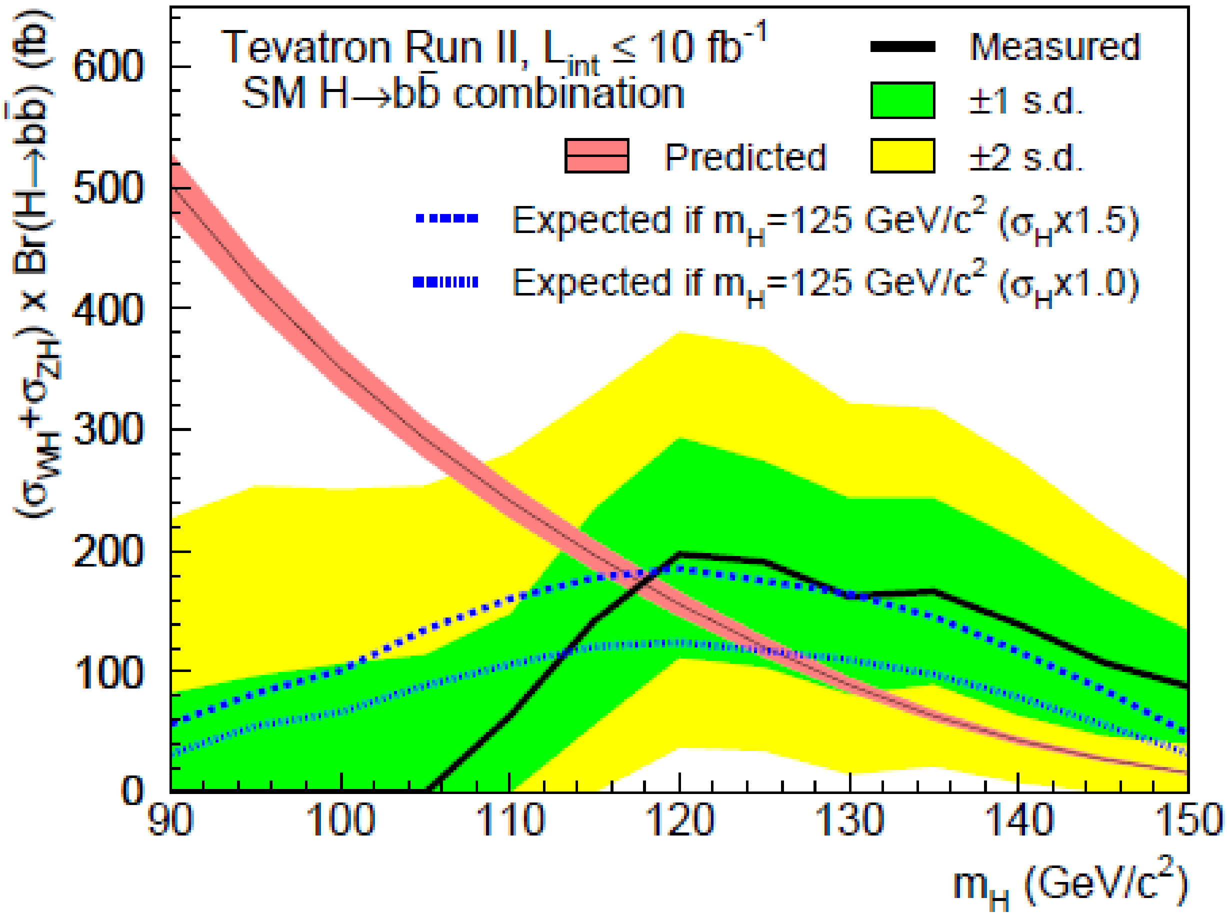
$ZH \rightarrow \ell^+\ell^- b\bar{b}$

$ZH \rightarrow \nu\bar{\nu} b\bar{b}$

use associated production modes to get better S/B

These are the main search channels, but there is an extensive program of measurements in other channels to extend the sensitivity to a SM Higgs

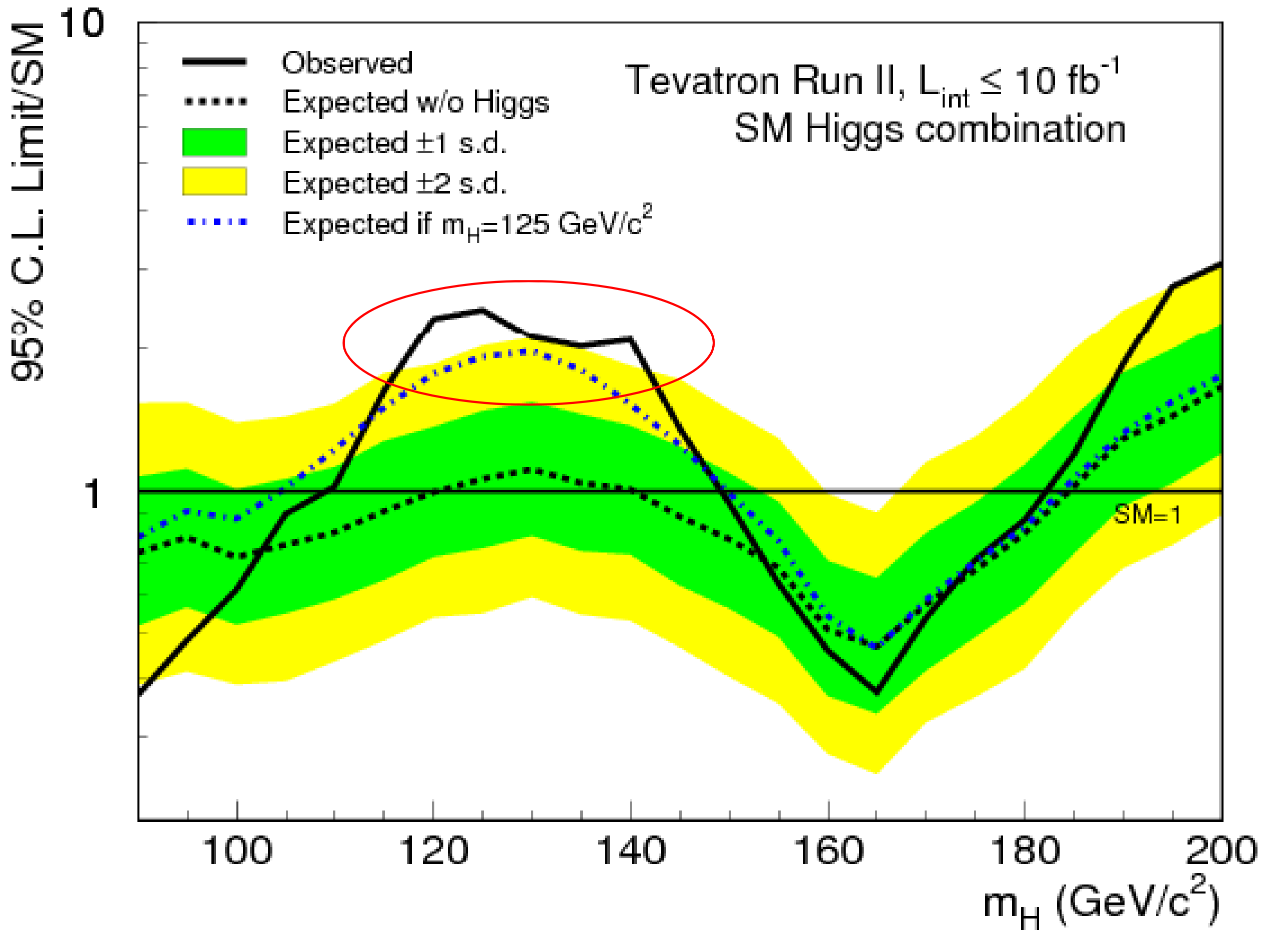
Cross section*BR measurement for WH/ZH with H→bb



$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \rightarrow b\bar{b})$ = 0.19 ± 0.09 $(\mathrm{stat} + \mathrm{syst})$ pb

SM Higgs @ 125 GeV: 0.12 ± 0.01 pb

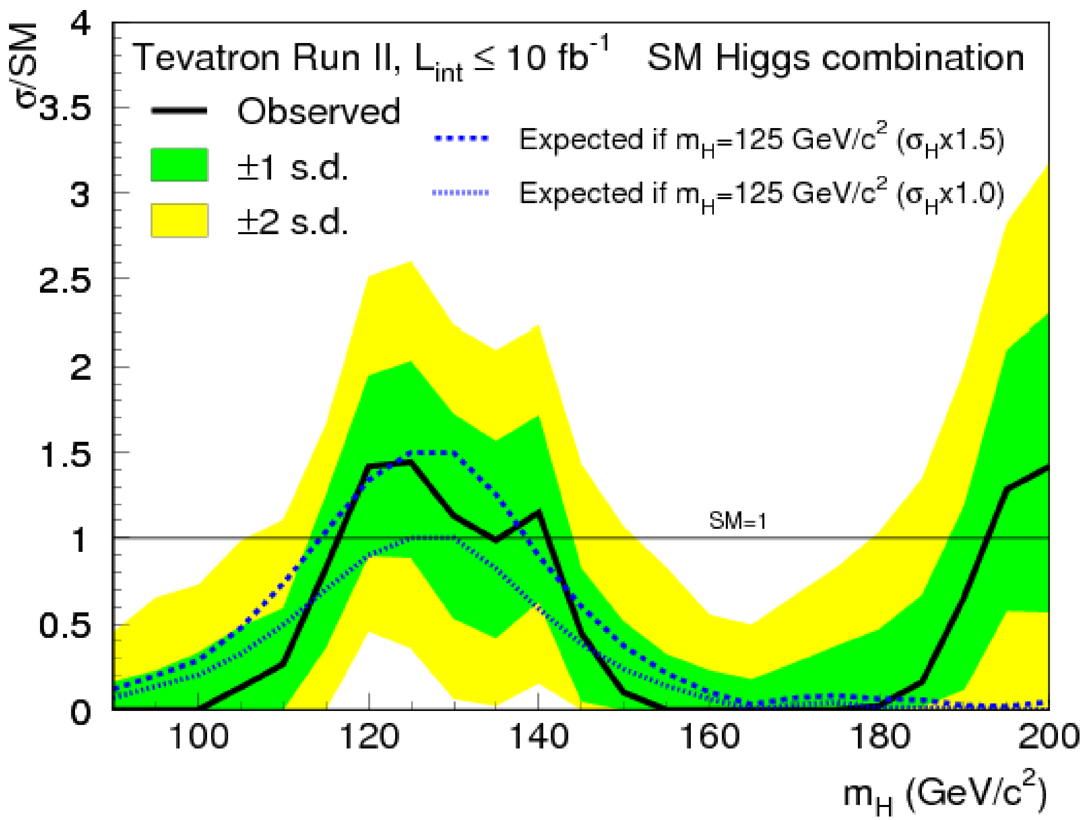
Full Tevatron combination

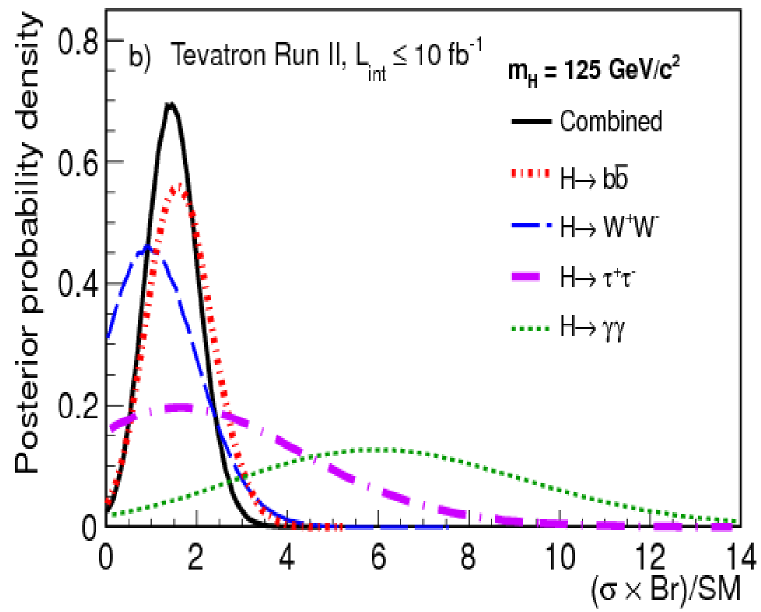


Significant excess, 2-3 sigma for 115→140 GeV

- Expected exclusion: 90 < m_H < 121 GeV, 140< m_H < 184 GeV
  Observed exclusion: 90 < m_H < 107 GeV, 149 < m_H < 182 GeV
- 95% CL limit at m_H=125 GeV: 1.09xSM (expected), 2.49xSM (observed)

Quantifying the signal: Best Fit Signal Rate



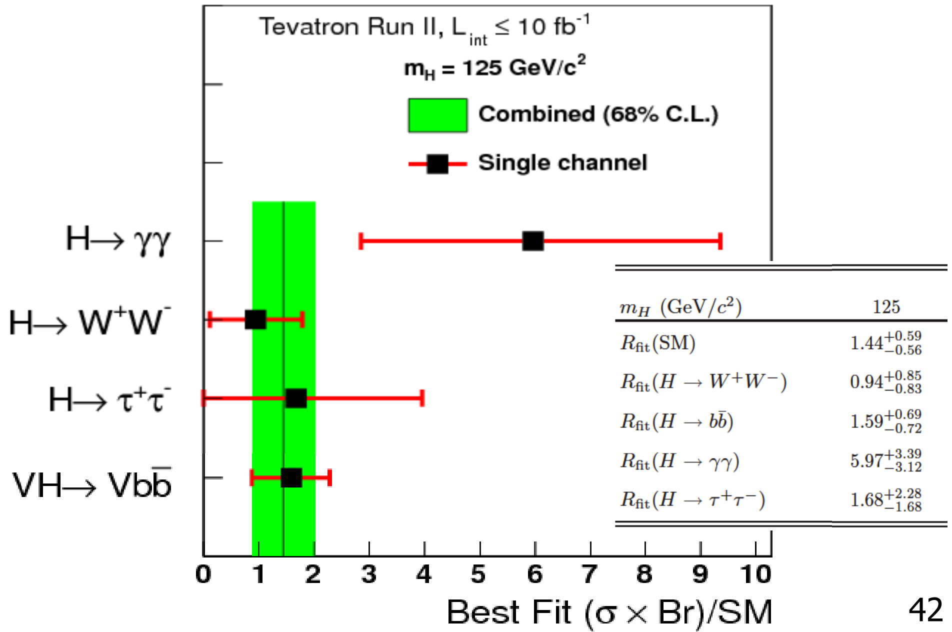


- Maximum likelihood fit to data with signal rate as free parameter.
- Best-fit signal rate at m_H=125 GeV:

$$\sigma_{fit} / \sigma_{SM} = 1.44 \pm 0.59$$

Consistent with SM Higgs.

Reasonably consistent across channels.



m_H (GeV/c²)	125
R_{fit}(SM)	$1.44^{+0.59}_{-0.56}$
$R_{fit}(H \to W^+W^-)$	$0.94^{+0.85}_{-0.83}$
$R_{fit}(H \to b\bar{b})$	$1.59^{+0.69}_{-0.72}$
$R_{fit}(H \to \gamma\gamma)$	$5.97^{+3.39}_{-3.12}$
$R_{fit}(H \to \tau^+\tau^-)$	$1.68^{+2.28}_{-1.68}$

Probing Higgs Boson Couplings

- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult
- A better option: measure deviations of couplings from the SM prediction (arXiv:1209.0040).
  Basic assumptions:
  - there is only one underlying state at m_H~125 GeV,
  - it has negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).

  Additional assumption made in this study:
  - no additional invisible or undetected Higgs decay modes.
- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.
  Examples:

$$\sigma(gg \to H)BR(H \to WW) = \sigma_{SM}(gg \to H)BR_{SM}(H \to WW)\frac{\kappa_g^2\kappa_W^2}{\kappa_H^2}$$

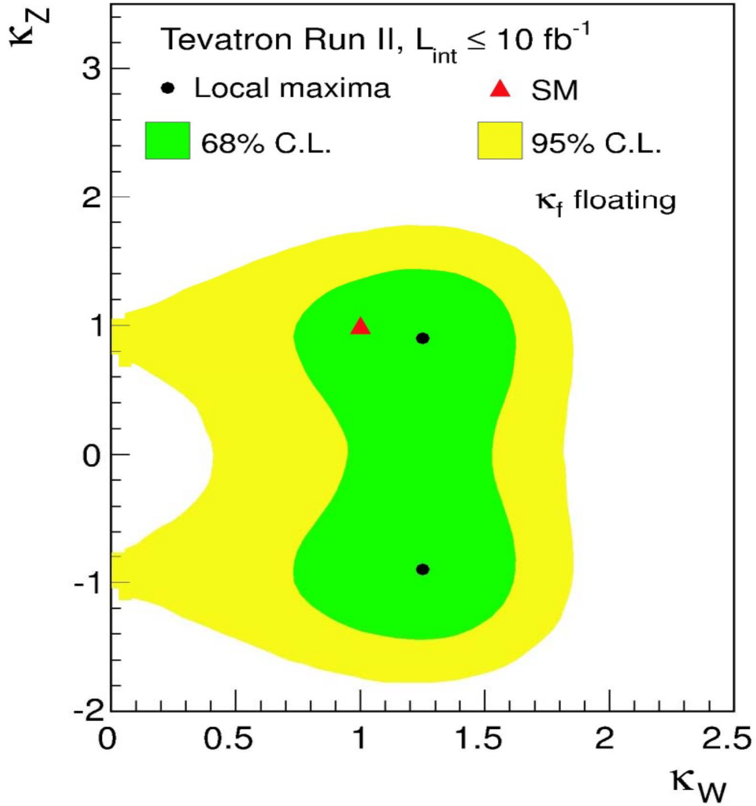
$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2\kappa_b^2}{\kappa_H^2}$$

$$\kappa_g = f(\kappa_t, \kappa_b, M_H)$$

$$\kappa_H = f'(\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, M_H)$$

Probing Higgs Boson Couplings (I)

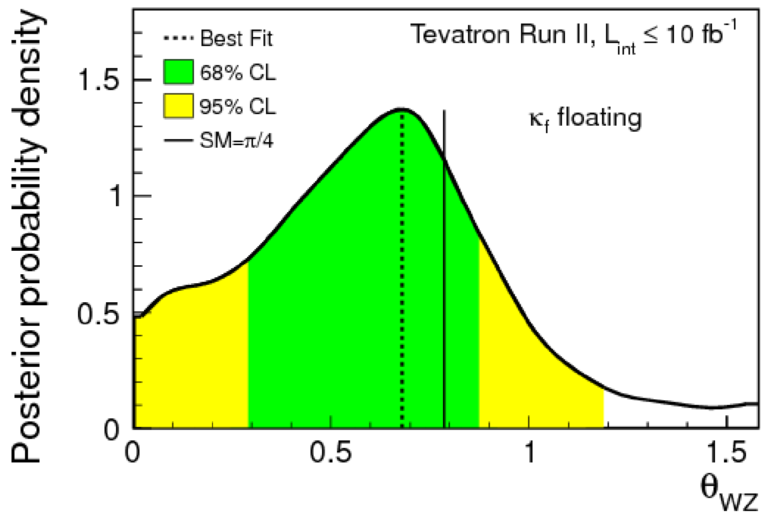
- With simplest scenario of measuring one coupling deviation at a time assuming SM values for the others, results consistent with SM
- When both κ_W and κ_Z vary independently ➔
  - κ_f integrated over
  - Best fit: $(\kappa_W, \kappa_Z) = (1.25, \pm 0.90)$
- The point $(\kappa_W, \kappa_Z) = (0, 0)$ corresponds to NO Higgs boson production or decay in the most sensitive search modes at the Tevatron and is not included within the 95% C.L. region due to the significant excess of events in the SM Higgs boson searches @ 125 GeV



Probe $SU(2)_V$ custodial symmetry by measuring the ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$

Measure $\theta_{WZ} = \tan^{-1}(\kappa_Z/\kappa_W) = \tan^{-1}(1/\lambda_{WZ})$

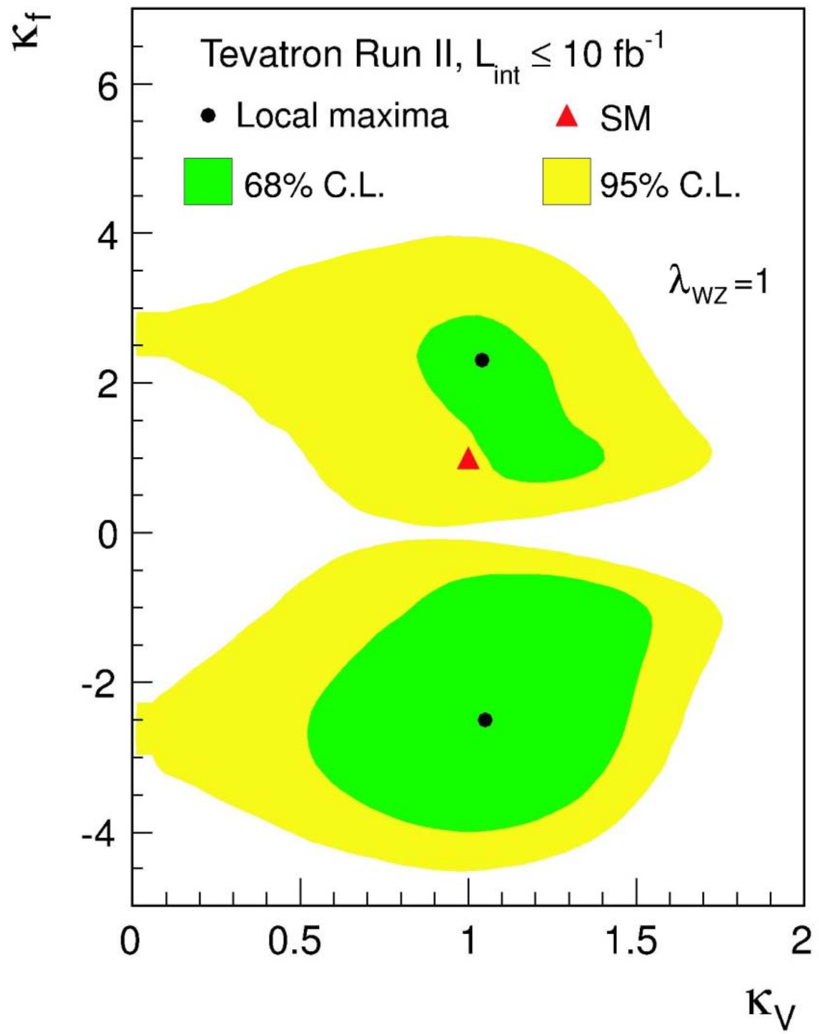
$$\theta_{WZ} = 0.68^{+0.21}_{-0.41} \rightarrow \lambda_{WZ} = 1.24^{+2.34}_{-0.42}$$



Probing Higgs Boson Couplings (II)

- Measure simultaneously κ_V and κ_f (assuming λ_{WZ}=1).

- Asymmetry comes from the excess in $H \rightarrow \gamma\gamma$
- Two minima:
  $(\kappa_V, \kappa_f)=(1.05,-2.40)$ and
  $(\kappa_V, \kappa_f) = (1.05, 2.30)$
- The integral of the posterior density in the (+,+) quadrant is 26% of the total, while the remaining 74% of the integral of the posterior density is contained within the (+,–) quadrant
- Good consistency with SM



Higgs Summary and Outlook

- Latest Tevatron results based on full Run II dataset in all major search channels are now submitted to PRD.

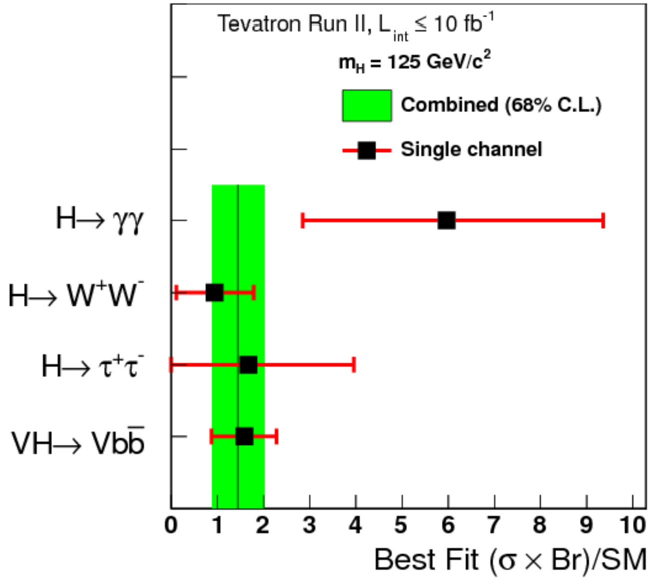
- Previously published evidence for WX/ZX production with X→bb, where X is consistent with a SM Higgs boson of 125 GeV, as the newly discovered particle by ATLAS & CMS is so far the only evidence for fermionic decays of the Higgs

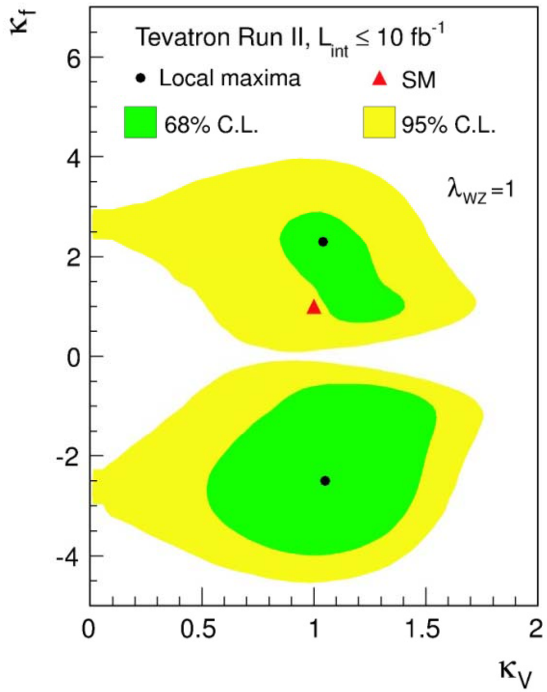
- The H→bb channel is unlikely to be seen at the 5 sigma level before the 2015 LHC Run, except maybe through combination of all results available (Tevatron and LHC)

.

- Signal strenghts in 4 decay channels, and results on Higgs couplings to fermions, W & Z, are consistent with the SM.

- Despite the impressive progress on Higgs physics at LHC, the Tevatron has still some valuable information to provide (spin-parity results under preparation, targetting LHCP).





Future

Priorities: Tevatron-relevant measurements with full luminosity, including combinations of results (CDF + D0 and LHC + Tevatron, when appropriate)

BSM: Relevant searches where triggers/backgrounds favor Tevatron vs. LHC

SM: Exhaust precision limits of legacy measurements (M_W, M_{top}, A_{FB}, s-channel σ_t)

Flavor: Exploit advantage in production with CP-invariant initial state

Conclusions

The CDF and Dzero collaboration keep producing milestones results and are exploiting this unique 10 fb^{-1} proton-antiproton dataset, with optimized reconstruction, simulation and analysis methods

Major results are world best (Top mass, W mass, $H \rightarrow bb$ significance) , often with only a subset of the full Data sample, progress in front of us.

Anomalies (Top Afb, Dimuon Asymmetry..) uniquely studied at the Tevatron need final results on complete dataset

Looking forward, there are several important achievements to be realized, including for each collaboration ~50 publications and ~40 theses.

We are writing the legacy of the Tevatron, and contributing to answer several open questions of high energy physics

CDF Milestone papers to come

- **QCD**
  - Photon production (γ inclusive, γ +light or heavy flavor, $\gamma\,\gamma$)
  - Diffraction studies at 3 collision energies (300, 900, 1960 GeV)
  - Double parton interactions

- **Heavy Flavor**
  - CP violation in the charm sector (D^+, D_s, A_{SL})
  - BR($B \rightarrow hh$)

- **Top**
  - Forward-backward asymmetry, differential cross sections
  - Single top observation in s-channel combining l+j and ν+j decay modes
  - M_{top} with all data in all decay modes (all-jets, l+jets, ν+jets, ll)
  - Combinations (CDF, Tevatron)

- **Electroweak**
  - W+jets differential cross sections
  - θ_W with all data
  - M_W with all data, combination (Tevatron)

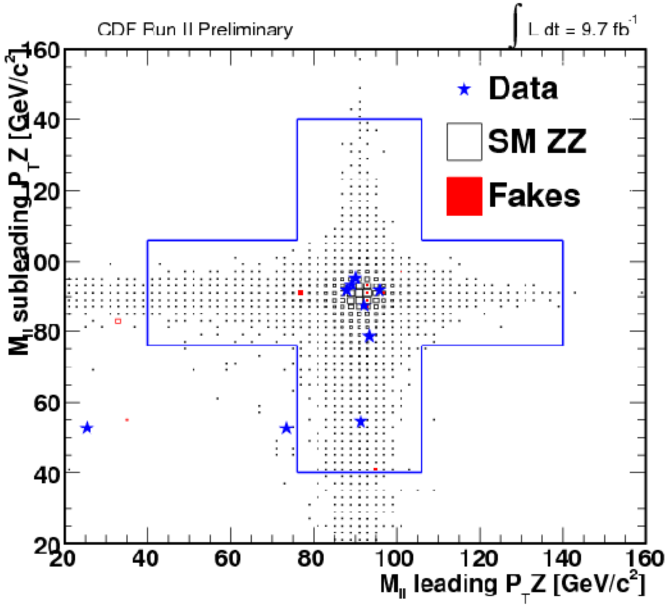
- **Higgs**
  - Couplings, spin and parity determination, combinations (CDF, Tevatron)

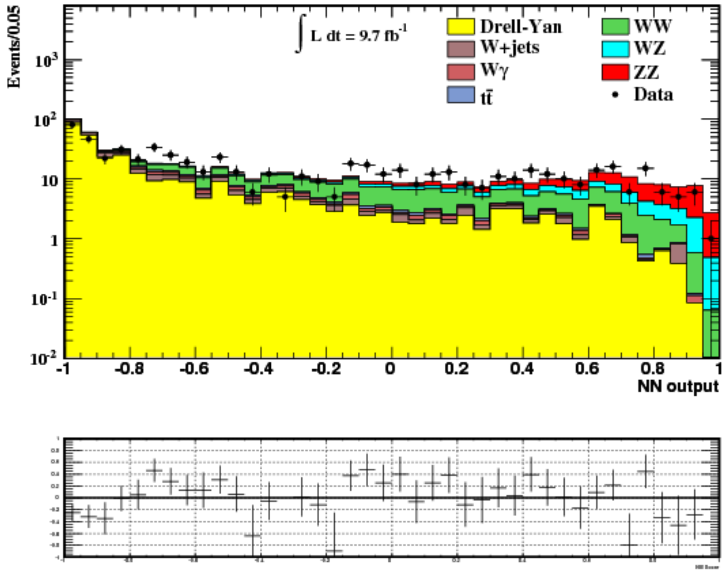
Dzero Milestone papers to come

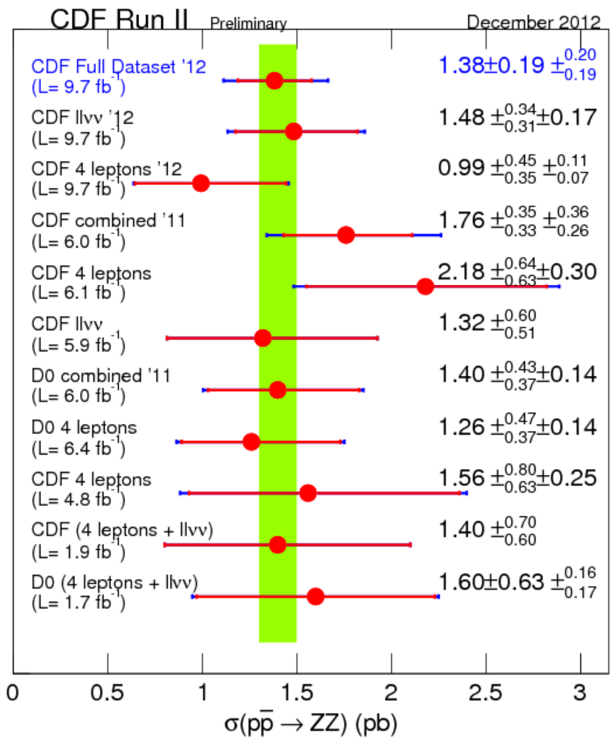
- **QCD**
  - di-b-jet/di-jet cross section ratio
  - V+Heavy flavor differential measurements
  - Double parton interactions
  - Jet event shapes
- **B Physics**
  - Final dimuon asymmetry measurement (D0)
  - Search for direct CPV in $B^+ \rightarrow j/Psi\ K^+$
- **Top**
  - Mass with full dataset (Tevatron combination)
  - Forward-Backward asymmetry (combination of leptons and l+jets, Tevatron comb)
  - Observation of single top s-channel (Tevatron combination)
- **Electroweak**
  - Forward-backward aymmetries (PDF constraints, θ_W)
  - W mass (~10 MeV precision), tests of the Standard Model (Tevatron combination)
- **Higgs**
  - Measurement of Hbb couplings, determination of Spin-Parity
  - Tevatron combinations

ZZ cross section

CDF public note 10957







ZZ→llll: counting experiment; ZZ→llνν: NN fit

- ZZ→llll $\quad \sigma(p\bar{p} \to ZZ) = 0.99^{+0.45}_{-0.35}(\text{stat.})^{+0.11}_{-0.07}(\text{syst.})\ \text{pb} = 0.99^{+0.45}_{-0.35}\ \text{pb}$
- ZZ→llνν $\quad \sigma(p\bar{p} \to ZZ) = 1.48^{+0.34}_{-0.31}(\text{stat.}) \pm 0.17(\text{syst.})\ \text{pb} = 1.48^{+0.38}_{-0.35}\ \text{pb}$
- Combined $\quad \sigma(p\bar{p} \to ZZ) = 1.38 \pm 0.19(\text{stat.})^{+0.20}_{-0.19}(\text{syst.})\ \text{pb} = 1.38^{+0.28}_{-0.27}\ \text{pb}$