Single W and Z production, and W/Z+Jets at the Tevatron

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Fermilab

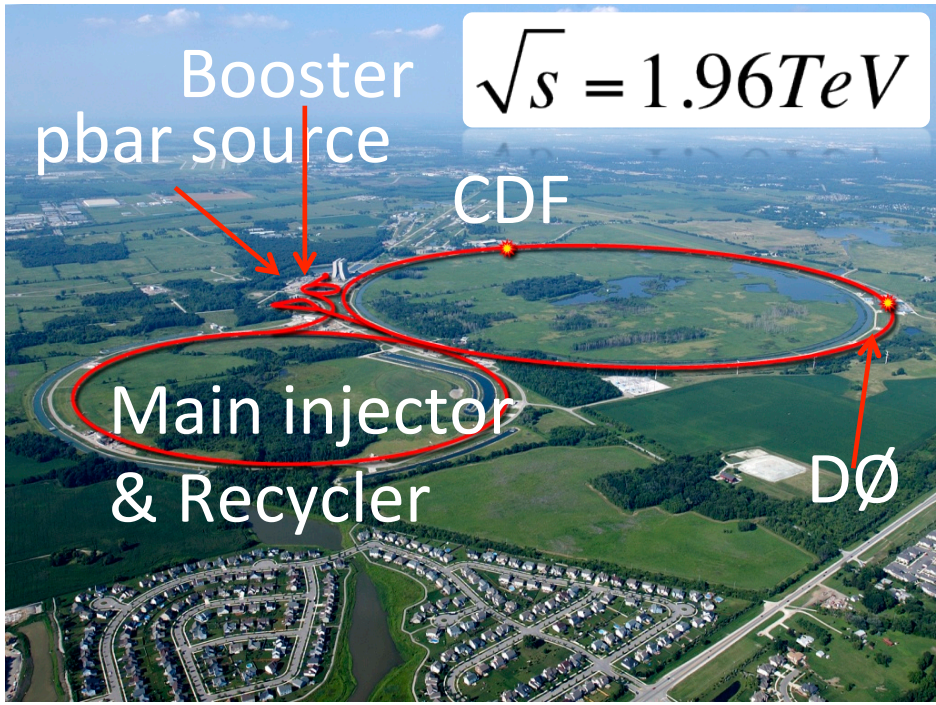
Moriond Electroweak Conference

March 8th, 2013

Introductions

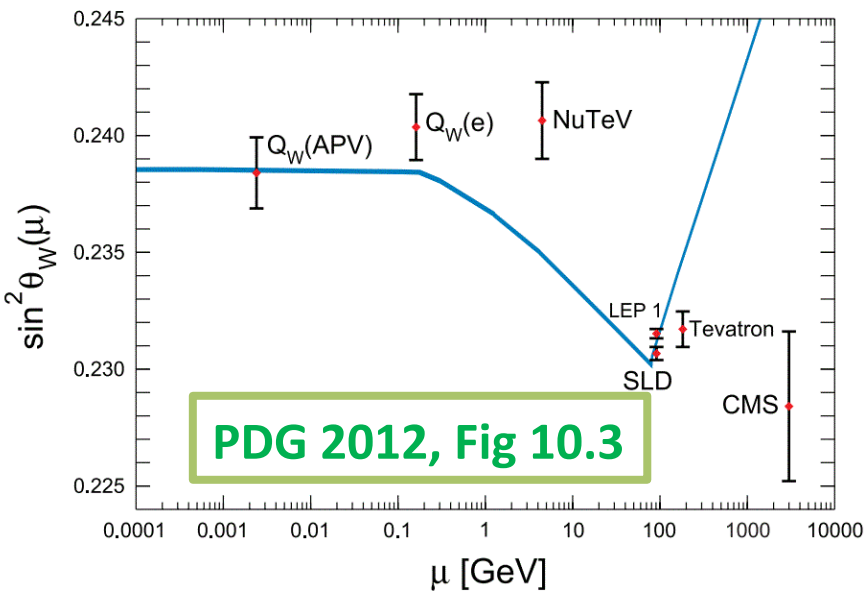
- ✓ Precision test on Standard Model (SM)
  - ➢ Parton distribution functions, initial state radiation, non-perturbative form factor
  - ➢ Background for many Searches, new physics

- ✓ Complementary to LHC
  - ➢ Tevatron: Valence quark annihilation
  - ➢ LHC: sea quark, and gluon contributions



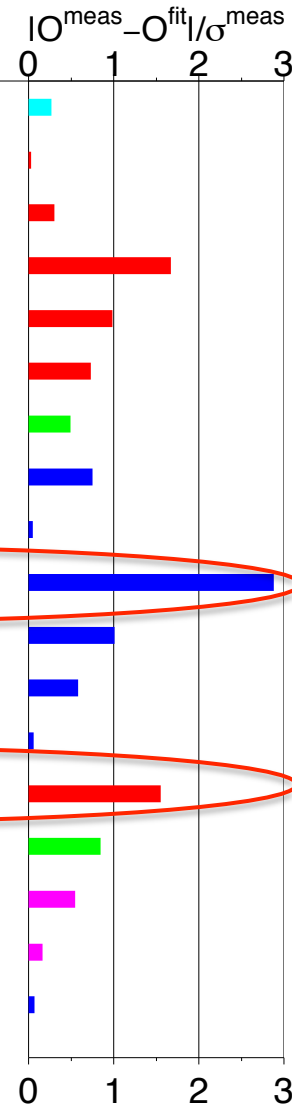
Weak mixing angle

- ✓ Fundamental parameter in the electroweak theory
- ✓ LEP A_{FB}^{b} and SLD A_{LR}: off by 3σ in opposite direction



PDG 2012, Fig 10.3

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

LEP, Winter 2012

Weak mixing angle

✓ In Collins-Soper frame, Z boson differential cross section:

$$\frac{dN}{d\Omega} \propto (1+\cos^2\vartheta) + A_0\,\frac{1}{2}\,(1-3\cos^2\vartheta) + A_1\,\sin 2\vartheta\cos\varphi + A_2\,\frac{1}{2}\,\sin^2\vartheta\cos 2\varphi + A_3\,\sin\vartheta\cos\varphi + A_4\,\cos\vartheta + A_5\,\sin^2\vartheta\sin 2\varphi + A_6\,\sin 2\vartheta\sin\varphi + A_7\,\sin\vartheta\sin\varphi\,.$$

In pQCD, A_5, A_6, A_7 near 0

A_1, A_3 are small

A_4 sensitive to $\sin^2\Theta_W$

With 2.1 fb^{-1} data of Z→ee events

Measure A_4 in different Z p_T bins, use the average value to extract weak mixing angle.

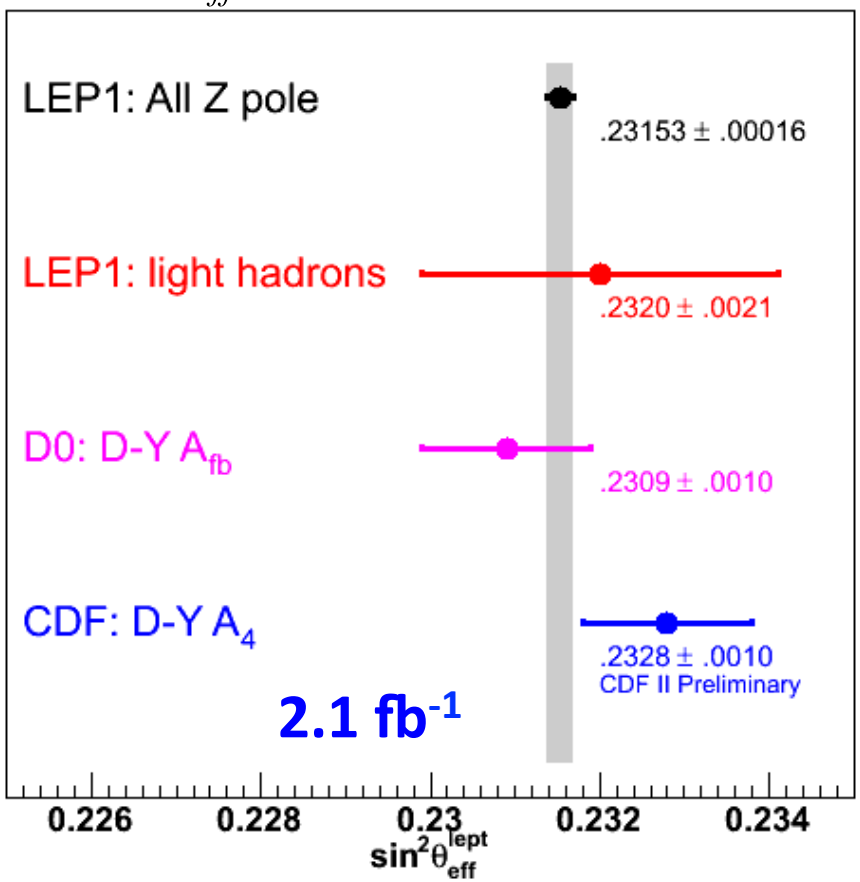
(PRL 106, 241801 (2011))

Constraint on W mass

CDF note: 10952

Using A_4 to measure $\sin^2\Theta_W$

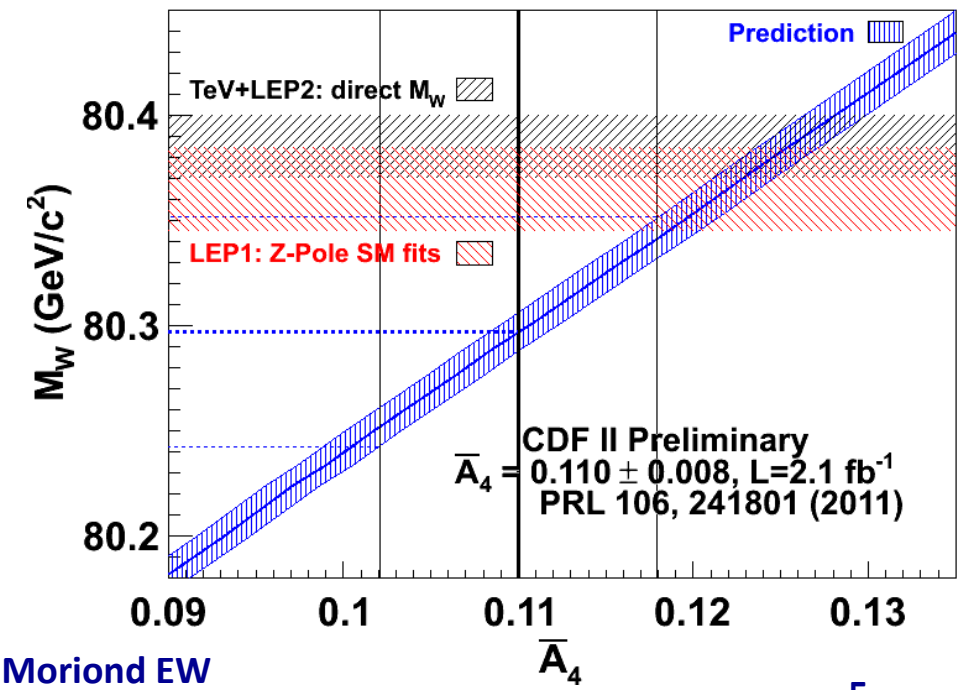
$$\sin^2\theta_{eff}^{lept} = 0.2328 \pm 0.0010$$



Using A_4 to constraint W mass

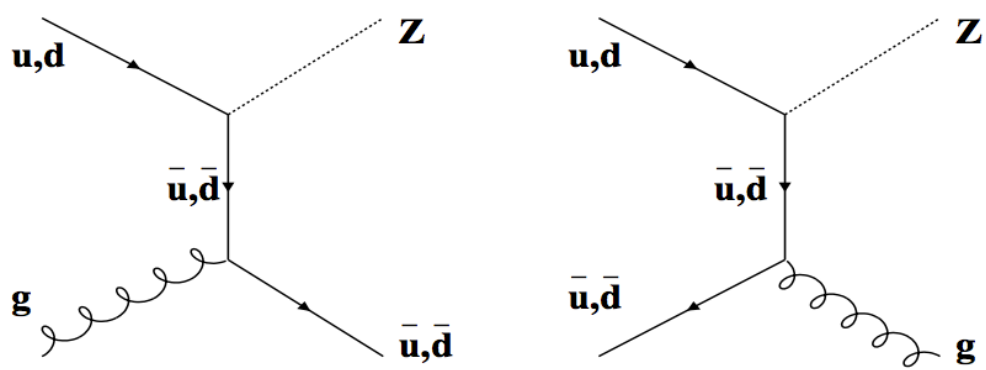
$$M_W = 80.297 \pm 0.055 \text{ GeV}/c^2$$

$$M_W = 80.385 \pm 0.015 \text{ GeV}/c^2, \text{ direct}$$
$$= 80.365 \pm 0.020 \text{ GeV}/c^2, \ Z \text{ pole},$$



Z boson p_T measurements

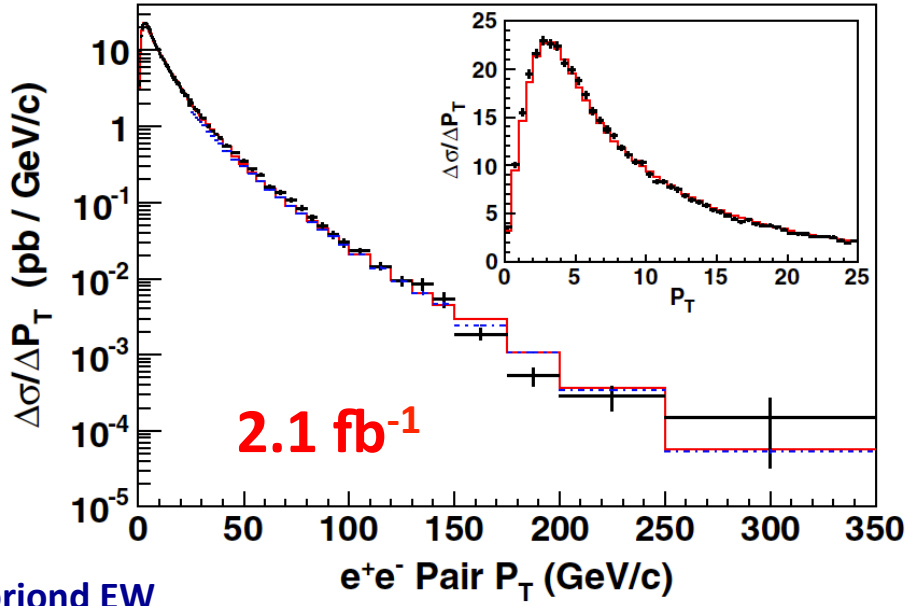
- ✓ Motivation:
  - ➢ Test the vector boson production formalism
  - ➢ Reduce theory uncertainty of the precision W mass measurement
  - ➢ Reduce uncertainties on searches with backgrounds from high p_T boson
- ✓ Z boson p_T: Comes from initial QCD radiation



Z boson p_T measurements

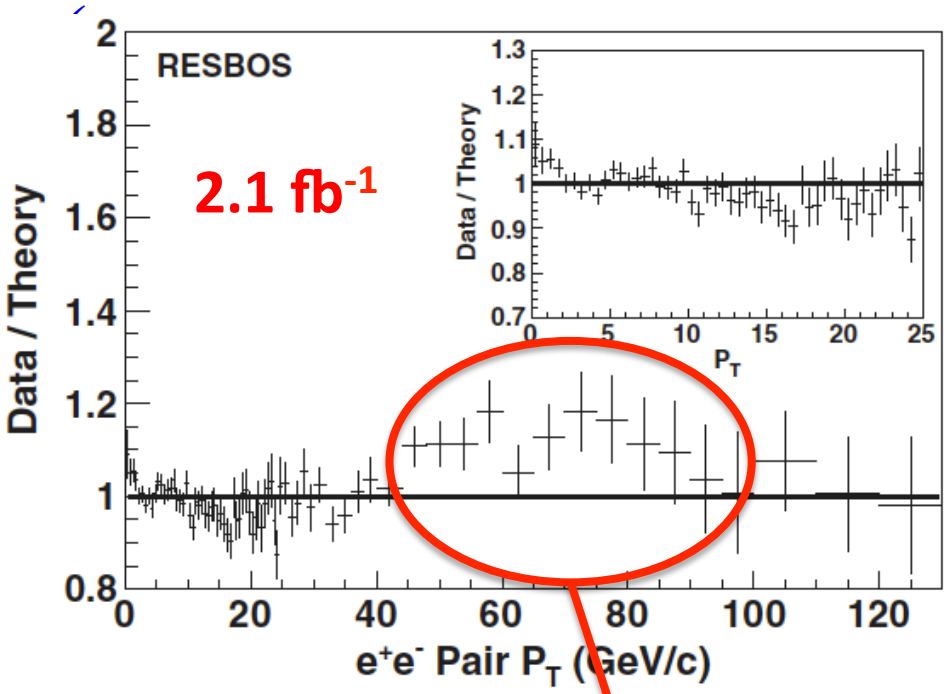
PRD 86,052010 (2012)

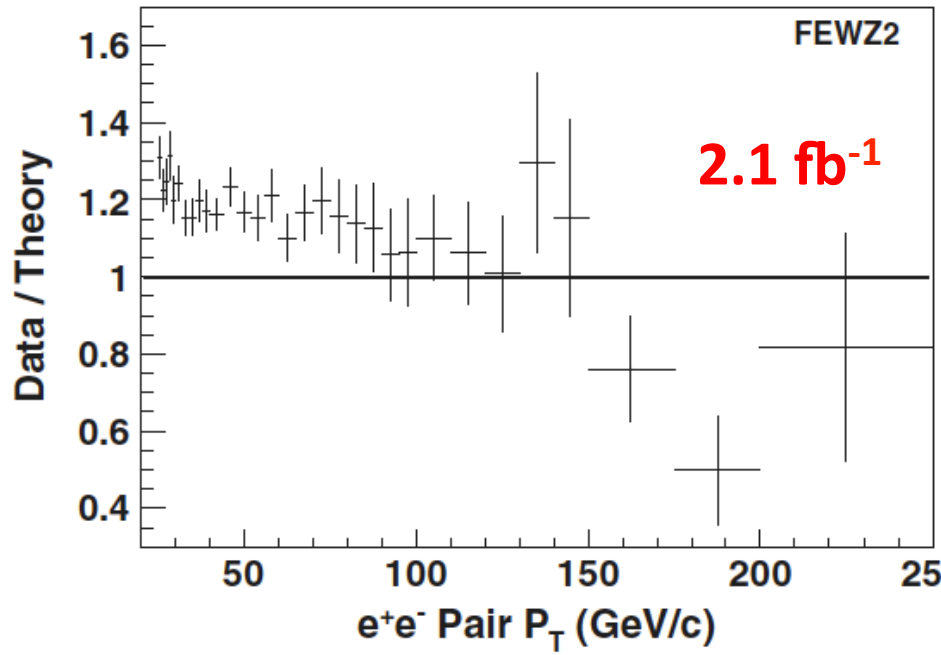
- ✓ Low p_T region: dominated by soft and collinear gluons emission, limited standard perturbative calculation
  - ➢ QCD resummation methods
- ✓ High p_T region: dominated by a single parton emission
  - ➢ Fixed-order perturbative calculations
- ✓ With 2.1 fb^{-1} data of Z→ee events



Z boson p_T measurements

PRD 86,052010 (2012)





Resbos: utilizes the Collins, Soper, and Sterman (CSS) resummation formalism.

FEWZ2: QCD fixed-order perturbative calculation at $O(\alpha_s)$ (NNLO)

Resummed calculation must be matching to the fixed-order pertubative calculation

W/Z+jets productions

- ✓ Motivations:
  - ➢ Important background for new physics search
  - ➢ Stringent test of perturbative QCD
  - ➢ Theoretical predictions suffer from large uncertainties
  - ➢ Constrain the quark PDF (W+c)

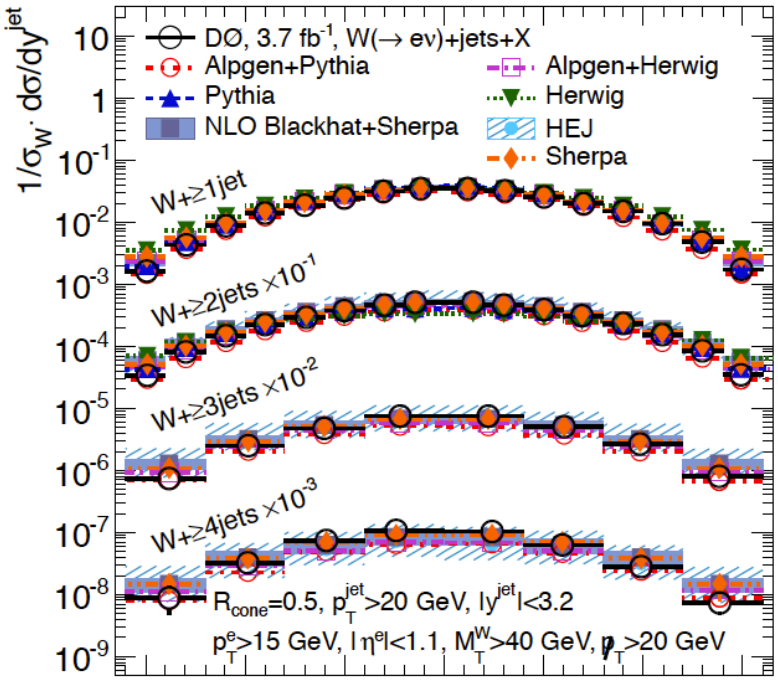
- ✓ Most of measurement are using CDF/DZero full data-set

W+jets

Submitted to PRD. arXiv: 1302.6508

- ✓ Theoretical uncertainty is the dominated uncertainty
- ✓ Results:
  - ➢ Compared with plenty of MC predictions
  - ➢ Interesting comparisons for plenty of variables
  - ➢ Smaller/equivalent uncertainties to the best predictions

With 3.7 fb^{-1} data



Jet Rapidity

W+b

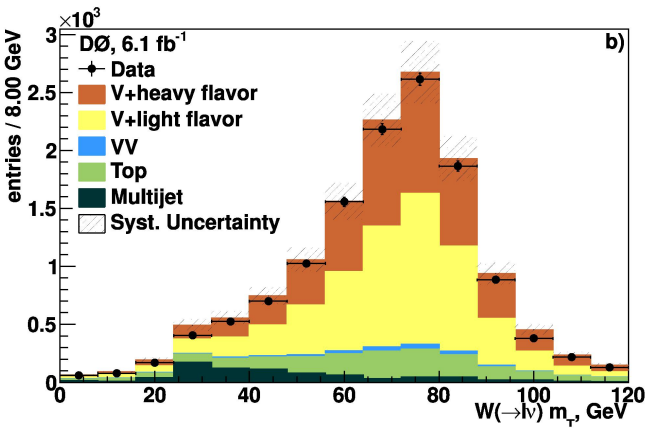
PLB 718,1314 (2013)

✓ Previous measurements:

➢ CDF: PRL 104, 131801 (2010)

Measured: $2.74 \pm 0.27\ (\text{stat.}) \pm 0.42\ (\text{syst.})\ \text{pb}$

Prediction: $1.22 \pm 0.14\ (\text{syst.})\ \text{pb}$

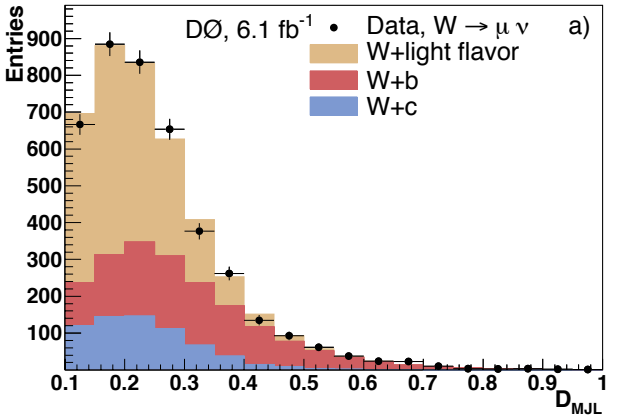


✓ **Dzero results with 6. 1 fb^{-1} data**

Measured: $\sigma(W+b)\cdot\mathcal{B}(W\to\ell\nu)$

$= 1.05 \pm 0.03\,(\text{stat.}) \pm 0.12\,(\text{syst.})\ \text{pb.}$

Prediction: $\sigma(W+b)\cdot\mathcal{B}(W\to\ell\nu) = 1.34^{+0.41}_{-0.34}\ (\text{syst.})\ \text{pb}$



First observation

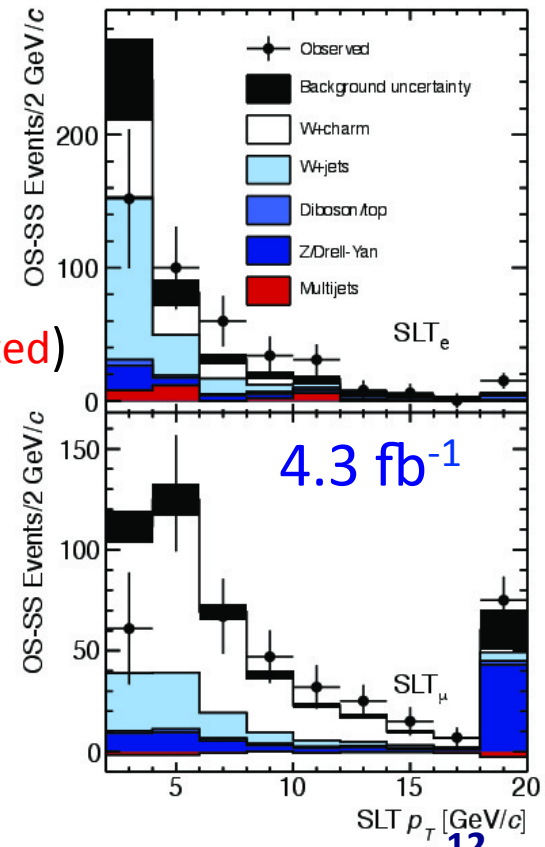
W+c

PRL 110, 071801 (2013)

- ✓ At Lowest order: quark-gluon fusion (*gq->Wc*), where *q = d, s, b* quark
- ✓ ~20% from *gd->Wc*: small quark-mixing matrix element. Same for *gb->Wc*
- ✓ Results:
  - ➢ Cross section: $13.6^{+3.4}_{-3.1}$ pb
  - ➢ NLO prediction: 11.4 ± 1.3 pb
  - ➢ Significance: 5.7 σ (hypothesis of no signal interpreted)
  - ➢ Given $\sigma_{Wc}^{theory} = 9.8(\pm 1.1)|V_{CS}|^2 + 2.1(\pm 0.2)pb$

  $|V_{cs}| = 1.08 \pm 0.16$
  - ➢ Restricting the range to [0,1],

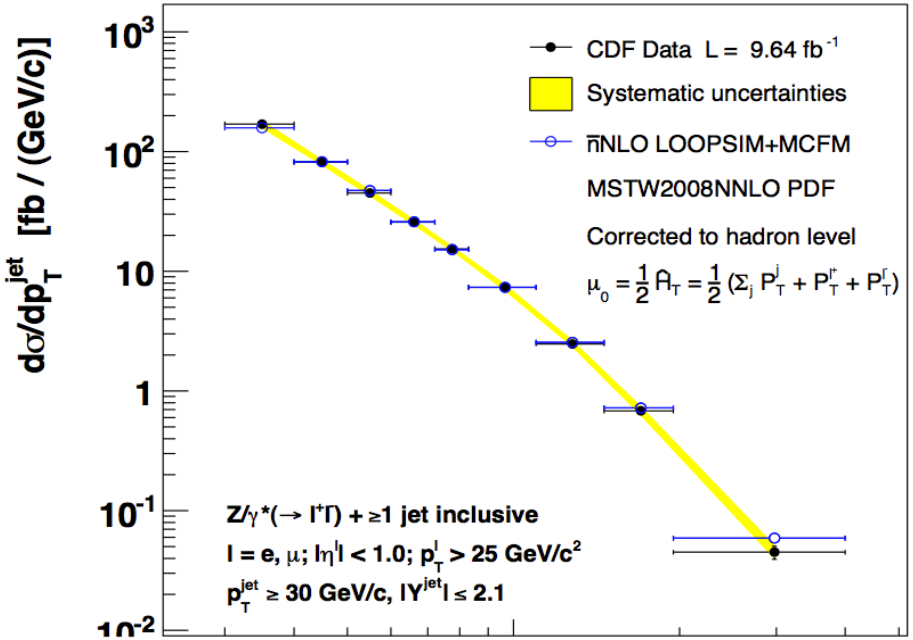
  extracted $|V_{cs}| > 0.71$ at 95% CL



Z+jets

CDF note: 10216

- ✓ Jet requirements: R = 0.7, p_T > 30 GeV, |y|< 2.1
- ✓ Results:
  - ➢ Z+≥1jets, Z+≥2 jets, Z+≥Njets, as function of plenty of variables
  - ➢ Compare results with next-to-leading order(NLO) pQCD predictions including non-perturbative corrections

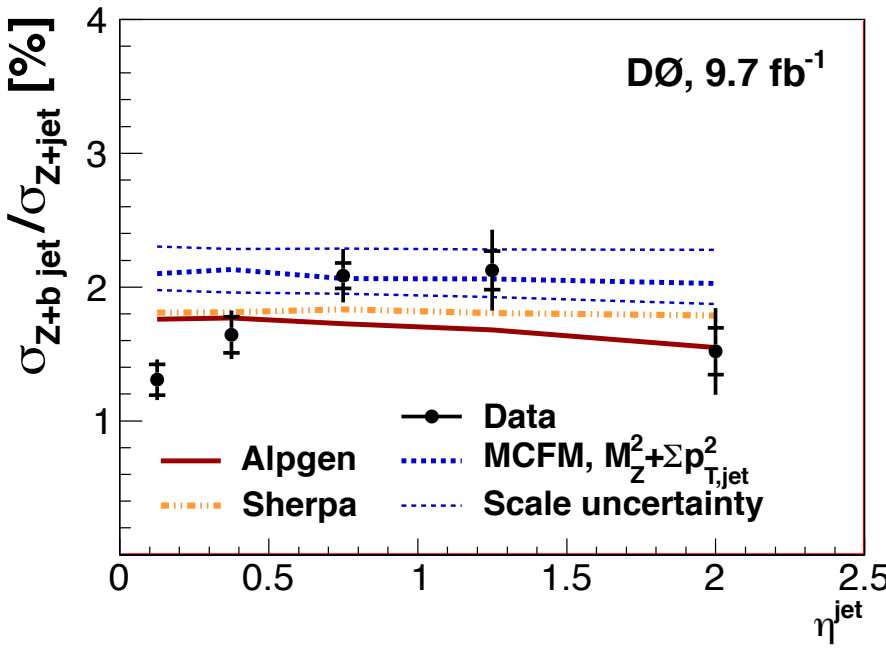


$p_T^{jet}[GeV/c]$

Z+b/Z+jet

Submitted to PRD. arXiv: 1301.2233

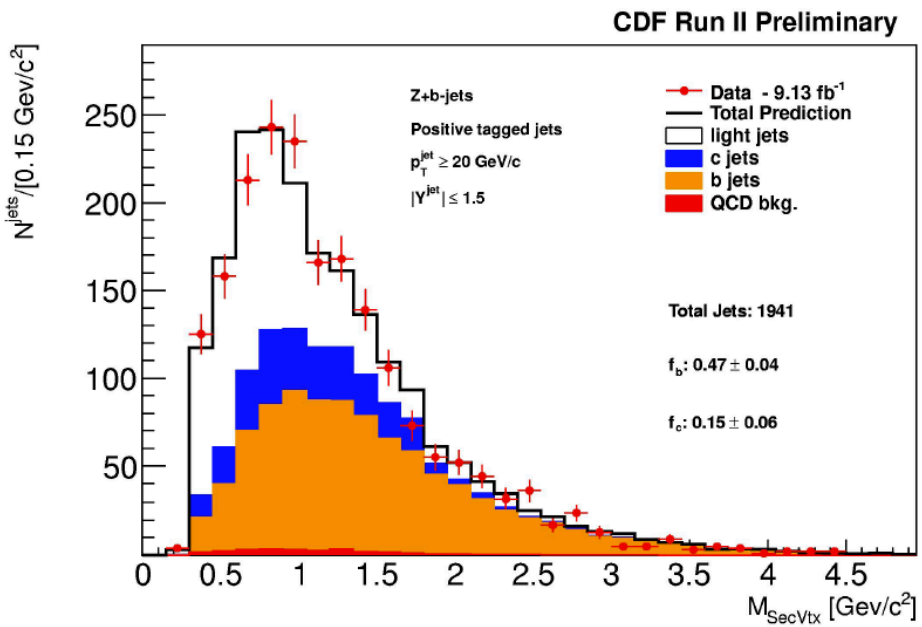
- ✓ Select events with Z->ee, μμ + b jet
- ✓ Results:
  - ➢ Ratio: $0.0202 \pm 0.0014\,(\text{stat.}) \pm 0.0018\,(\text{syst.})$
  - ➢ NLO prediction: $0.0206^{+0.0022}_{-0.0013}$
  - ➢ Differential cross section as function of p_T(jet), p_T(Z), η(jet), and ΔΦ(z, jet)

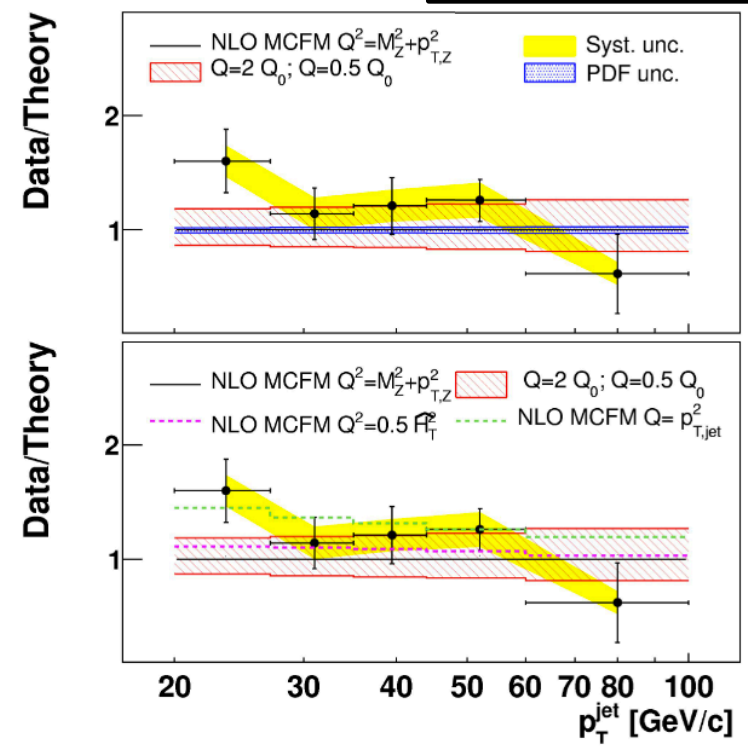


Z+b

✓ Select events with Z->ee, μμ + b jet

CDF note: 10594





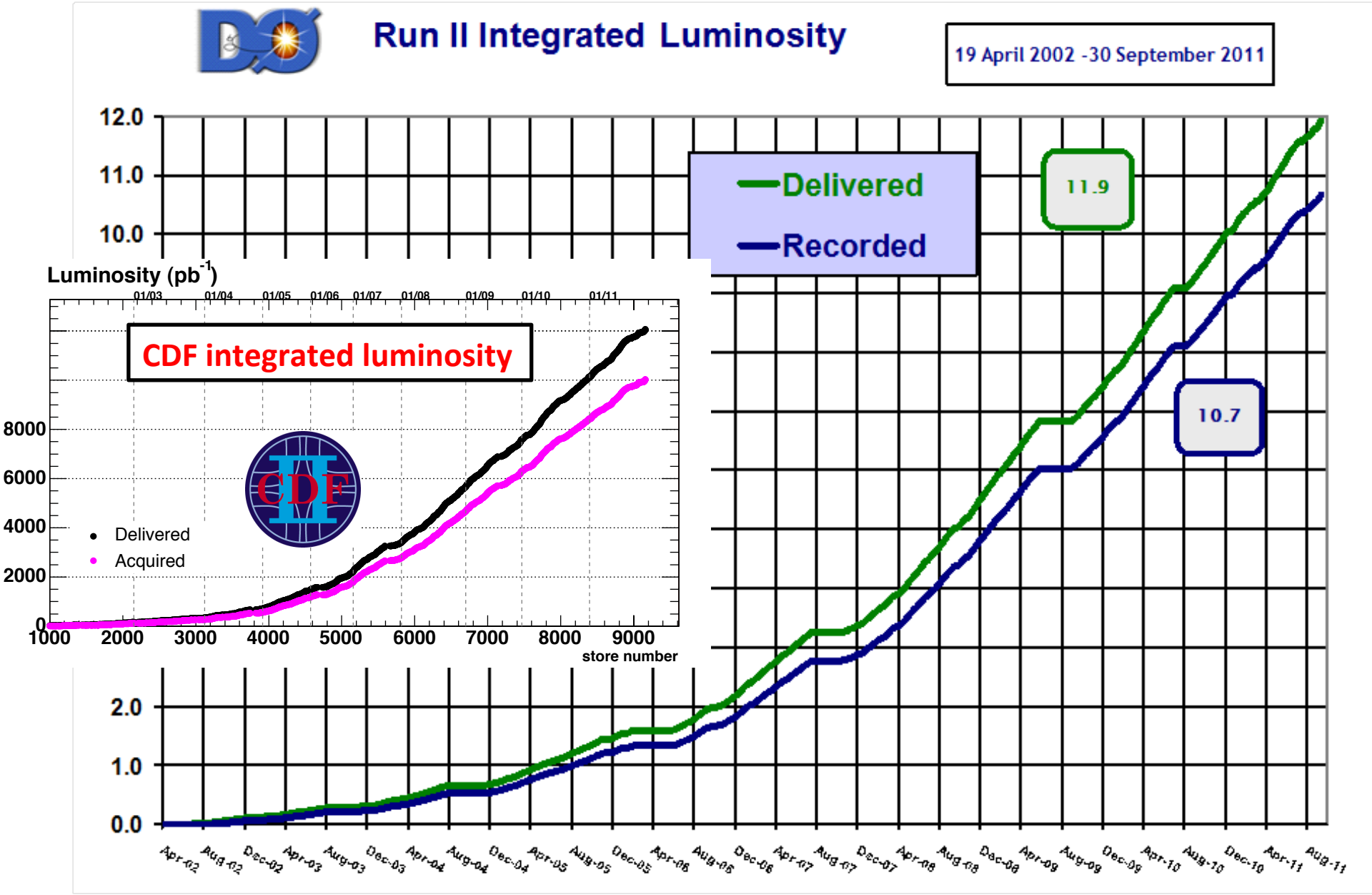
To compare with NLO prediction with MCFM:

	Data	$Q^2 = m_Z^2 + p_{T,Z}^2$	$Q^2 =< p_{T,jet}^2 >$
$\frac{\sigma_{Z,bjet}}{\sigma_Z}$	0.261 ± 0.023 (stat.) ± 0.029 (syst.) %	0.23%	0.29%
$\frac{\sigma_{Z,bjet}}{\sigma_{Z,jet}}$	2.08 ± 0.18(stat.) ± 0.27 (syst.) %	1.8%	2.2%

Summary

- ✓ At the Tevatron, precise measurement of W/Z boson production provides tests on the Standard Model
- ✓ Precise measurement of V+jets provides tests on the pQCD formalism
- ✓ Many W, Z properties measurements with full data-set are ongoing

BACKUP


Run II Integrated Luminosity
19 April 2002 -30 September 2011
Delivered
Recorded
11.9
10.7
12.0
11.0
10.0
2.0
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Apr-02
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Dec-02
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Dec-10
Apr-11
Aug-11
Luminosity (pb-1)
CDF integrated luminosity
01/03
01/04
01/05
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01/07
01/08
01/09
01/10
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8000
6000
4000
2000
0
1000
2000
3000
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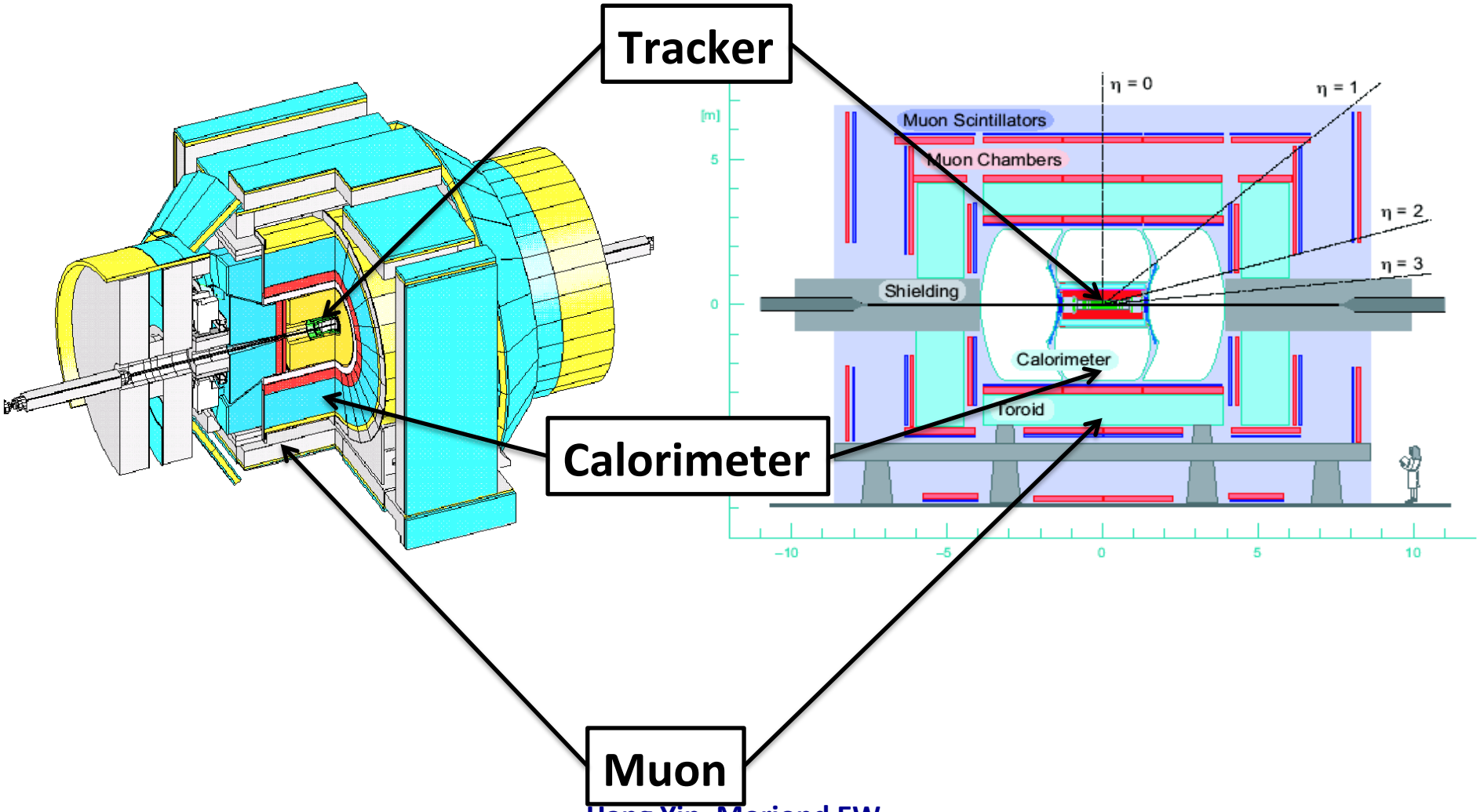
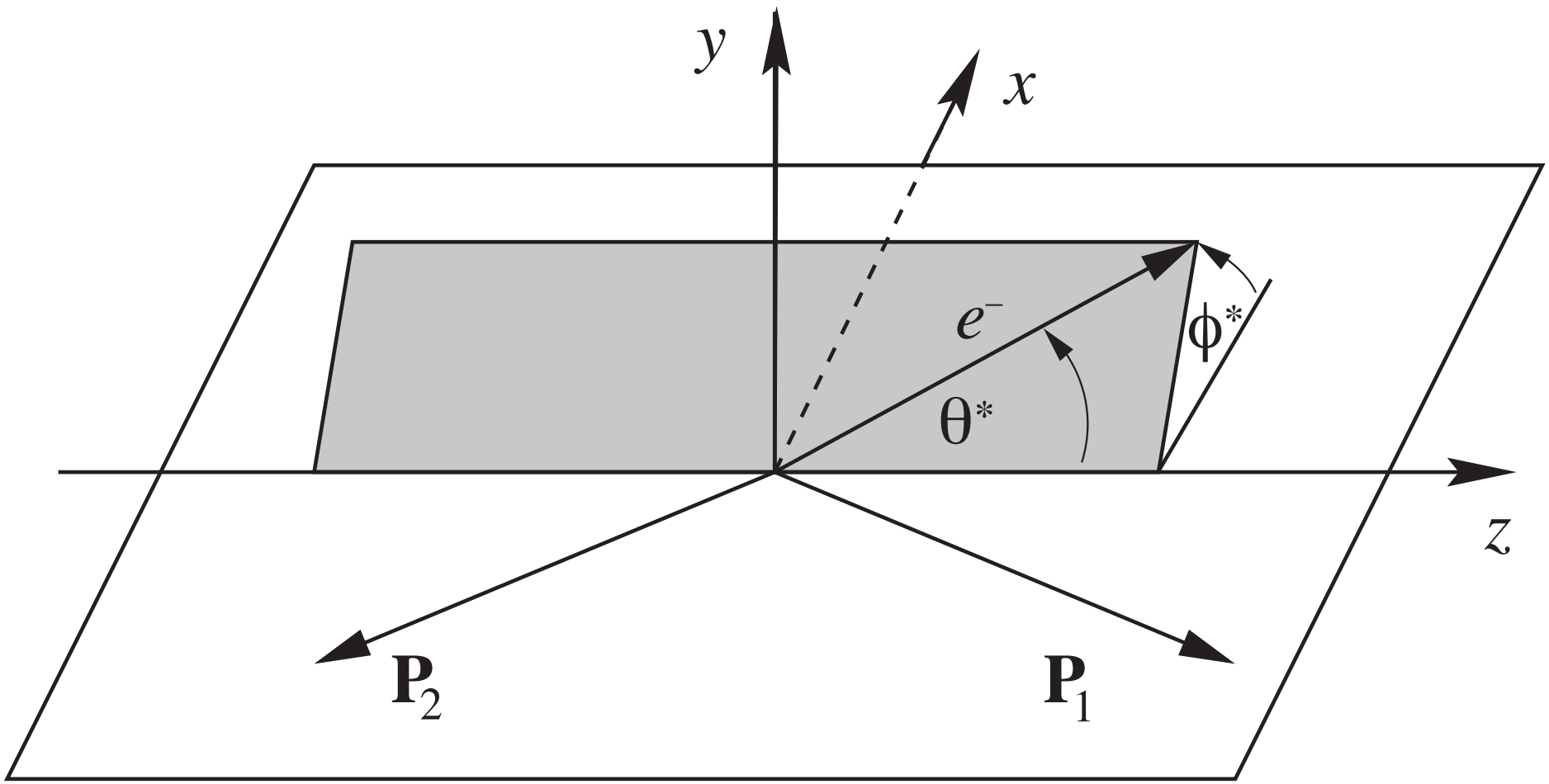
5000
6000
7000
8000
9000
store number
Delivered
Acquired
CDF II

CDF and DØ detector



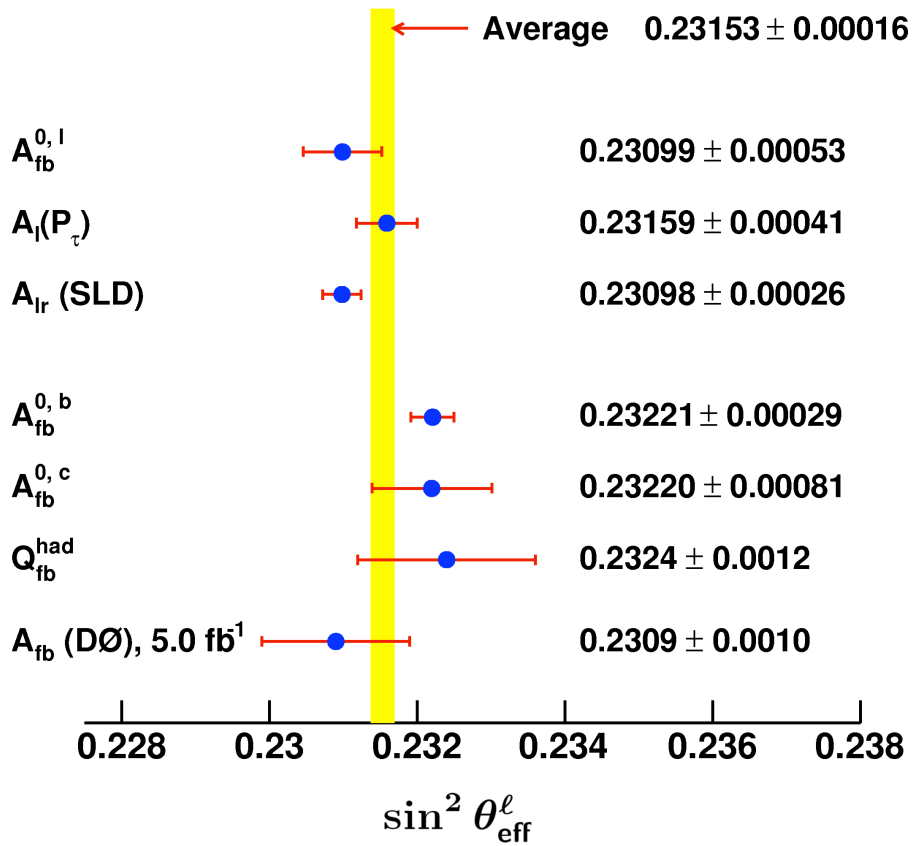
Collins-Soper frame



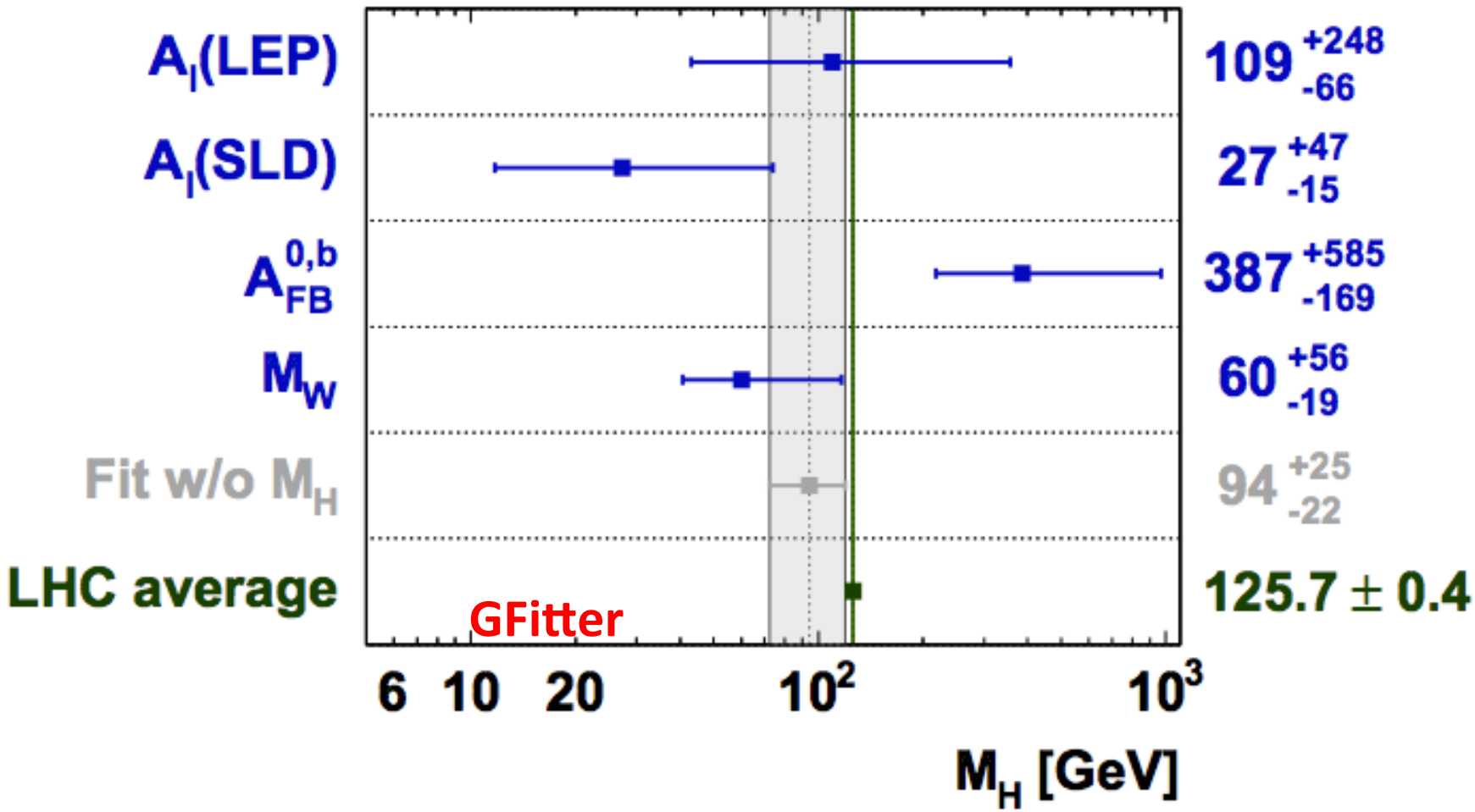
Weak mixing angle

$$g_V^f = T_3^f - 2Q_f \sin^2\theta_W$$

$$g_A^f = T_3^f$$



Weak mixing angle



Soft gluon resummation

- ✓ The differential cross section:

$$\frac{d^2\sigma}{dp_T^2} \sim \frac{\alpha_W \alpha_S}{p_T^2} \ln\left(\frac{Q^2}{p_T^2}\right)\left[\nu_1 + \nu_2 \alpha_S \ln^2\left(\frac{Q^2}{p_T^2}\right) + \nu_3 \alpha_S^2 \ln^4\left(\frac{Q^2}{p_T^2}\right) + \cdots\right]$$

- ✓ Collins, Soper, Sterman formalism: re-organize the ν_i terms in b-space

$$\frac{d^2\sigma}{dp_T^2} \sim \int_0^\infty d^2 b e^{i\vec{p_T}\bullet\vec{b}} W(b,Q) + Y(b,Q)$$

- ✓ *W(b, Q)*: sum to all orders the terms that are at least as singular as $1/p_T^2$
- ✓ *Y(b, Q)*: difference between the fixed-order perturbative result and part of the series that is as singular as $1/p_T^2$

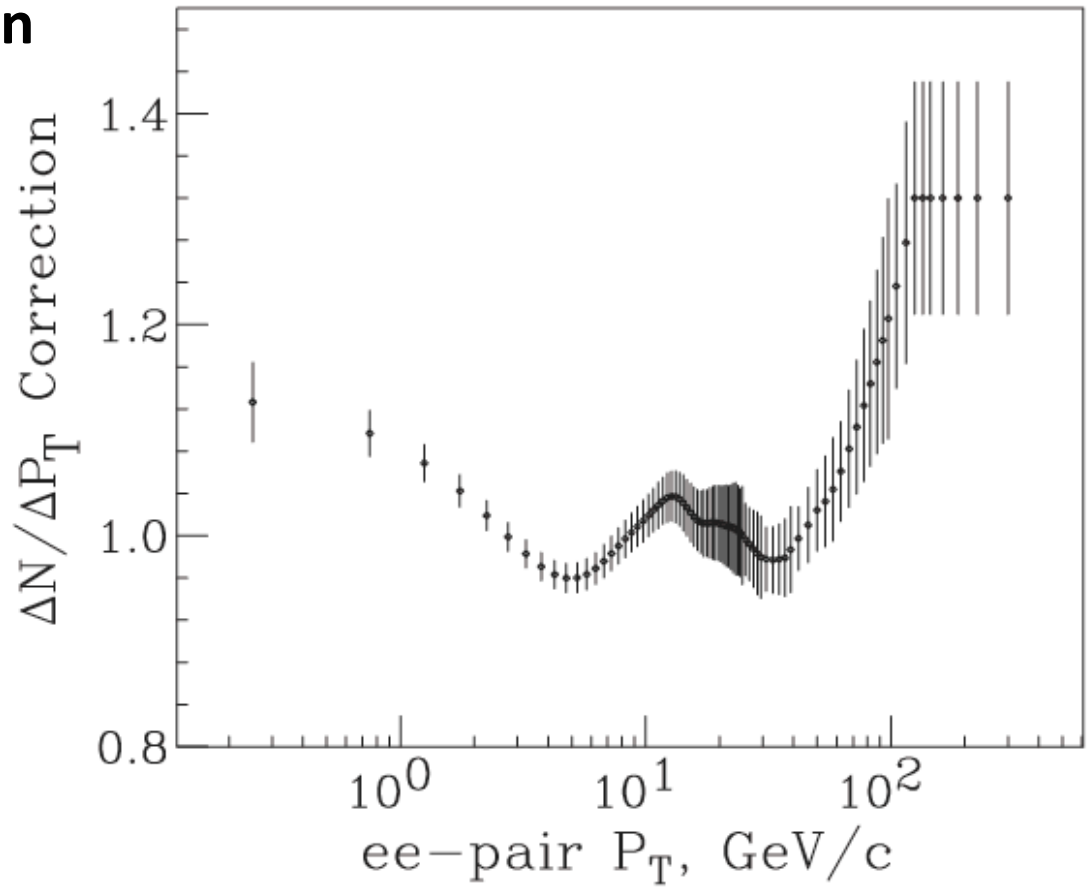
$$W(b,Q) = W(b_*,Q)e^{-S_{NP}(b,Q)}, \quad with \quad b_* = \frac{b}{\sqrt{1+(b/b_{\max})^2}}$$

- ✓ b_* marks the region where one crosses from a (reasonable) well defined perturbative region into the non-perturbative region
- ✓ *W(b*, Q)*: perturbative part and can be calculated by perturbative expansions
- ✓ S_{NP}: non-perturbative Sudakov form factor (Ladinsky-Yuan form):

$$S_{NP}(b,Q) = g_1 b^2 + g_2 b^2 \ln\left(\frac{Q^2}{2Q_0^2}\right) + g_1 g_3 b \ln(100 x_i x_j)$$

Z boson p_T measurements

Generator level correction: make flat ratio between data and MC.



W+b

- ✓ Electron : $p_T > 20$ GeV, $|\eta| < 1.1$ && $1.5<|\eta|<2.5$, shower shape cuts, isolation cuts, Eoverp cut
- ✓ Muon : $p_T > 20$ GeV, $|\eta| < 1.7$, isolated in both tracker and calorimeter, reject cosmic rays
- ✓ Jet: $|\eta| < 1.1$, $p_T > 20$ GeV, in a cone of 0.5
- ✓ MET > 25 GeV

- ✓ Largest uncertainty from luminosity, jet energy resolution, jet modeling, detector effects
  - ➢ 6.1%, 2.5%, 3%, 4%
- ✓ MCFM v6.1, with central scale of M_W+2m_b, mb = 4.7 GeV
  - ➢ Include renormalization and factorization scales by a factor of two in each direction
  - ➢ m_b 4.2 – 5 GeV, and PDF sets
  - ➢ CDF prediction: J. Campbell, F. Febres Cordero, L. Reina, private communication(2009)

W+c

- (NLO-LO)/LO ~ 50%, at the Tevatron, 10-20% uncertainties
- Charm quark is identified through the semileptonic decay of the charm hadron into an electron or muon (soft leptons)
  - Electron/muon within the jet
  - Charge conservation allow only: *W^++anti-c, W^-+c*
  - OS and SS events: based on the charge of lepton from W, and the charge of soft-lepton from charm

$$\sigma_{Wc} = \frac{N_{tot}^{OS-SS} - N_{bkg}^{OS-SS}}{SAL}$$

  - A : acceptance
  - L : luminosity
  - S : dilution matrix

$$S = \frac{N_{Wc}^{OS} - N_{Wc}^{SS}}{N_{Wc}^{OS} + N_{Wc}^{SS}}$$

W+c

- ✓ A and S are derived from a MC
  - ➢ Require $p_T c > 20$ GeV, $|\eta| < 1.5$
  - ➢ W+ccbar not considered in the acceptance: cancel out in the same-sign subtraction, owing to the largely charge-asymmetry detector response
- ✓ Selection cuts:
  - ➢ Lepton pt > 20 GeV, $|\eta| < 1.1$, MET > 25 GeV, one jet pt > 20 GeV, $|\eta| < 2.0$, Mt > 20 GeV
  - ➢ Soft lepton:
    - Muon: matching trajectories of trks of the jet, pT > 3 GeV, $\Delta R < 0.6$
    - Electron: pt > 2 GeV, $\Delta R < 0.4$

W+c

- ✓ Signal: LO+PS, HQ decay from EVTGEN
- ✓ Bkgs:
  - ➢ Y/Z→μμ: remove mass between 8-11, 70-110 GeV
  - ➢ Z→ee: remove mass > 45 GeV
  - ➢ QCD: azimuthal angular (MET, jet) <0.3, reject
  - ➢ W+jets: pre-tag - signal,bkgs Times mis-tag prob
  - ➢ Mis-tag probalility: using a data Sample of pions, kaons, and protons from Λ^0 and D^{*+} tagged D^0 decays.

Percentage

Source	SLT_μ	SLT_e
SLT uncertainties	**±9.2**	**±16.6**
QCD multijet estimate	**±6.3**	**±9.9**
Initial and final state radiation	±6.0	±6.0
Background cross sections	±5.7	±4.7
c quark hadronization	±4.6	±4.6
PDFs	±3.6	±3.6
W-lepton ID	±2.2	±2.2
Jet energy calibration	±2.0	±2.0
Factorization, renormalization scales	±1.3	±1.3
Total	±15.4	±21.8
Luminosity	±7.9	±8.3

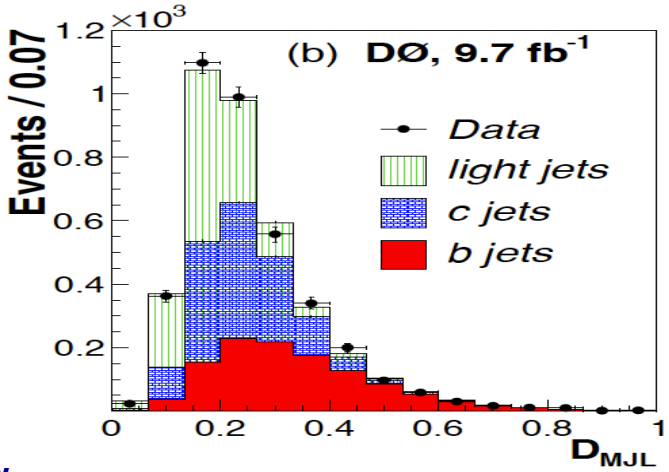
Z+jets

- ✓ CTEQ6.1M, $Q^2 = M_Z^2 + p_T^2(Z)$

- ✓ Jet energy: 5% in low jet pt region, 12% at high jet pt region
- ✓ Background: 1%-5%

Z+b/Z+jets

- ✓ Electron channel: $p_T > 15$ GeV, $|\eta| < 1.1$ && $1.5<|\eta|<2.5$
- ✓ Muon channel: $p_T > 10$ GeV, $|\eta| < 2$
- ✓ Jet: $p_T > 20$ && $|\eta| < 2.5$
- ✓ **$D_{MJL} = 0.5*(M_{SV}/5\ \text{GeV} - \ln(\text{JLIP})/20)$**
  - MSV: the invariant mass of the charged particles associated with the secondary vertex
  - JLIP: Jet Lifetime Probability, is the probability that tracks associated with the jet originate from the ppbar interaction vertex
- ✓ Largest uncertainties from b jet energy calibration, (jet energy resolution, jet energy scale)
- ✓ Extraction of b fraction:
  - Fit negative tagged jets: negative values for the decay legth significance and/or Impact parameter, caused by detector resolution effects
  - Different between data and MC as uncer.



Z+b

- ✓ Electron channel: $p_T > 20$ GeV, $66 < M_{ee} < 116$ GeV/c^2, one electron in central $|\eta| < 1$, another electron can be 1.2-2.8, ANN
- ✓ Muon channel: ANN cuts
- ✓ b jet: secondary vertex, named TIGHT SECVTX algorithm
- ✓ b jet fraction:
  - ➢ a binned maximum likelihood fit, based on the invariant mass of all charged tracks reconstructed at the secondary vertex.
- ✓ NLO: MCFM generator
- ✓ Largest uncertainty from Light jet template

W/Z differential cross section

✓ Z: $$\frac{d\sigma}{d(\cos\theta)} = A(1+\cos^2\theta) + B\cos\theta$$

✓ W: $$\begin{aligned}\frac{d\sigma}{d(p_T^W)^2 dy d\cos\theta d\phi} &= \frac{3}{16\pi}\frac{d\sigma^u}{d(p_T^W)^2 dy}[(1+\cos^2\theta) \\ &+ \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi \\ &+ \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi \\ &+ A_4\cos\theta + A_5\sin^2\theta\sin 2\phi \\ &+ A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi] \quad (1)\end{aligned}$$