Measurement of the ratio of the $p\bar{p} \to W + c$ - jet cross section to the $p\bar{p} \to W +$ jets cross section

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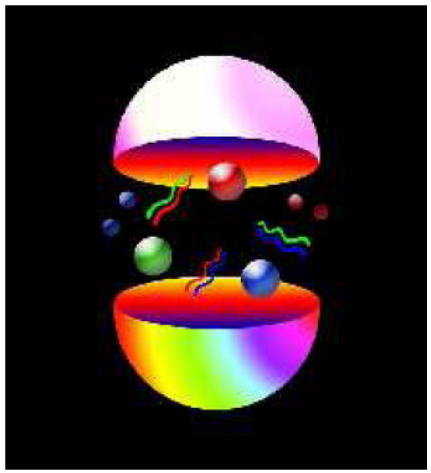
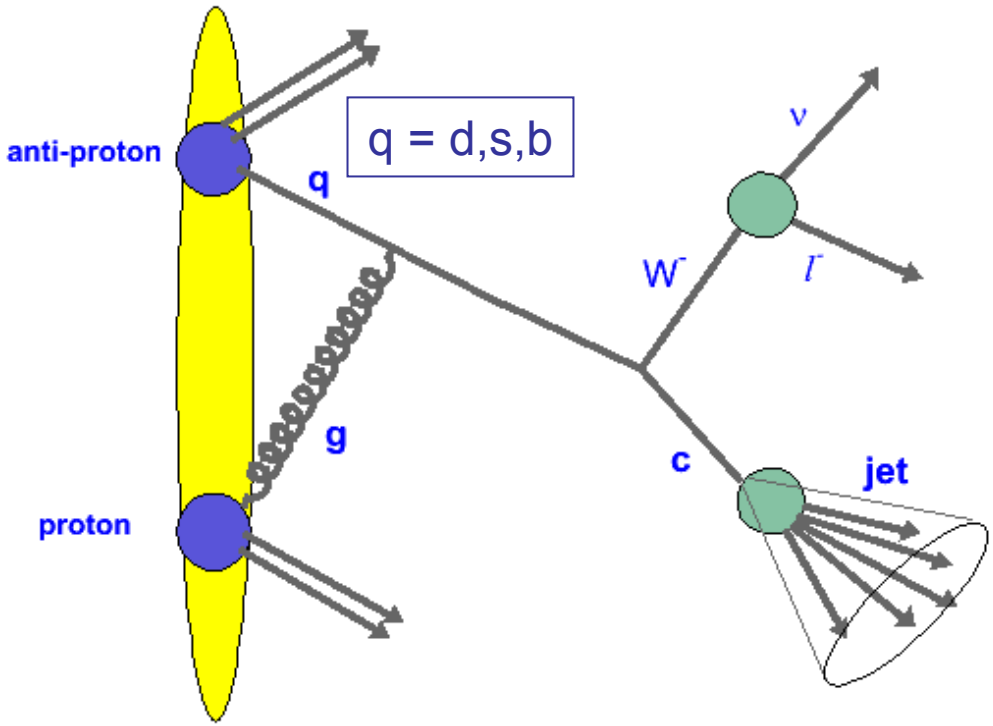
Overview

- Introduction
- W + c-jet production
- $\sigma(W + c\text{-jet}) / \sigma(W + \text{jets})$ ratio method
- Background processes
- c-jet extraction
- Result
- Summary & outlook

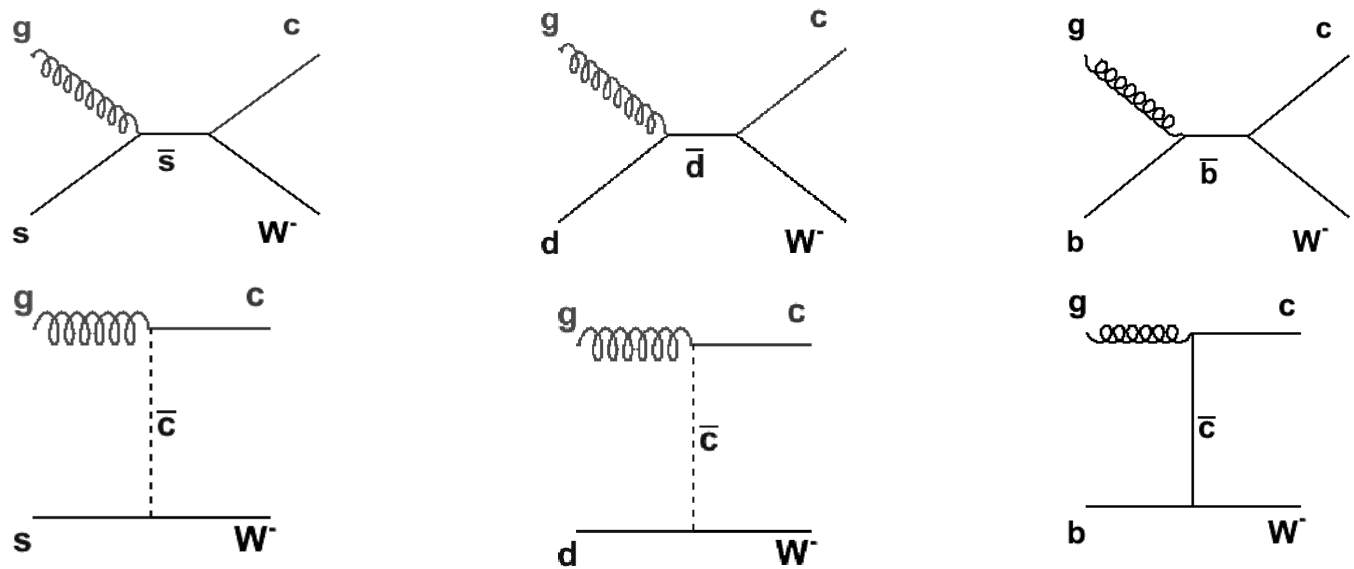
Introduction





- insight into the *s* quark content of the proton
  - important for reliable calculations of SM and new physics processes
- *W*+*c*-jet is a signature of many SM and new physics processes
  - Higgs boson production, top quark production, SUSY scalar top quark production, SUSY charged Higgs production etc…
- test of quantum chromodynamics and electroweak physics

W+c-jet production at leading order



$$\sigma(p\bar{p} \to W^- c) = \int\int dx_p \; dx_{\bar{p}} \; [s(x_p, Q^2) g(x_{\bar{p}}, Q^2) \hat{\sigma}(sg \to W^- c)$$
$$+ s(x_{\bar{p}}, Q^2) g(x_p, Q^2) \hat{\sigma}(gs \to W^- c) + s \leftrightarrow d + s \leftrightarrow b]$$

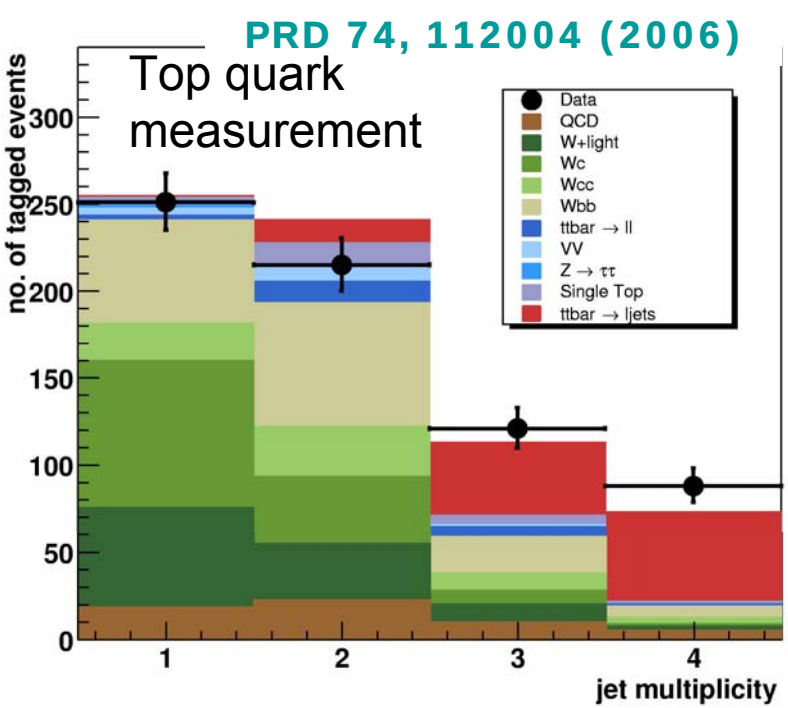
- $d(x,Q^2) > s(x,Q^2) > b(x,Q^2)$
- $V_{cs} > V_{cd} >> V_{cb}$
  - $\sigma(sg \to Wc) > \sigma(dg \to Wc) >> \sigma(bg \to Wc)$
- ~ 85% contribution to W+c production from s-quark
  - b-quark contribution is highly suppressed

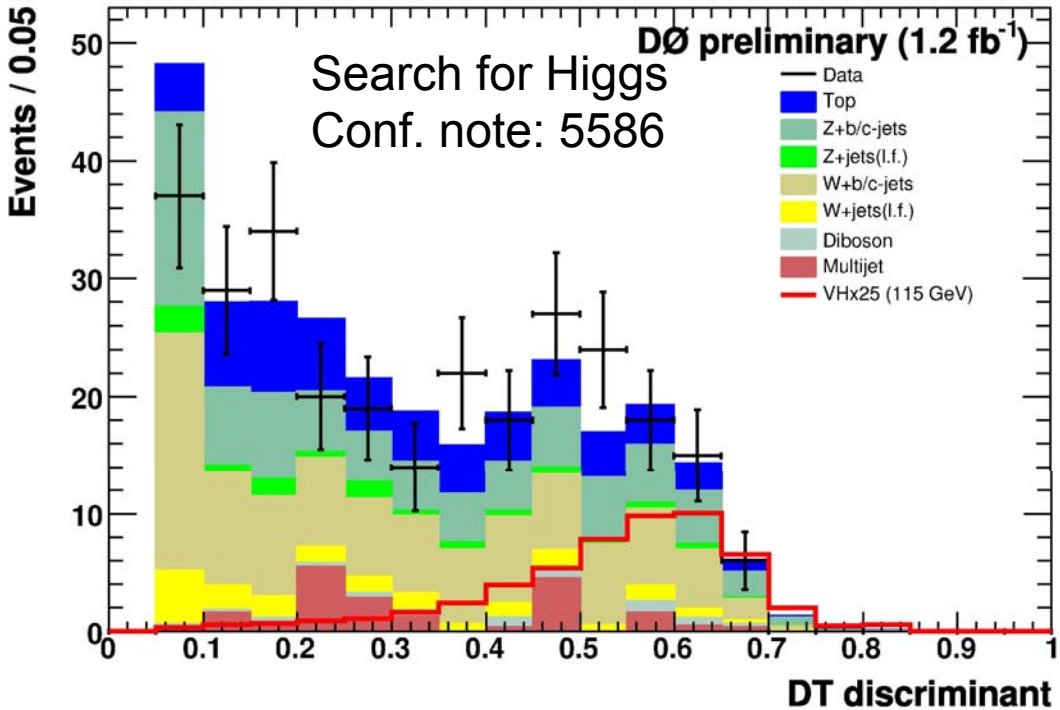
W+*c* is a signature of rare physics processes

- W+c-jet is among the significant sources of background to important processes
  - share the event selections for both SM and new physics processes

- theoretical uncertainty is more than 30%
  - ~10% V_{cs} uncertainty, ~20% scale uncertainty, ~20-30% PDF uncertainty

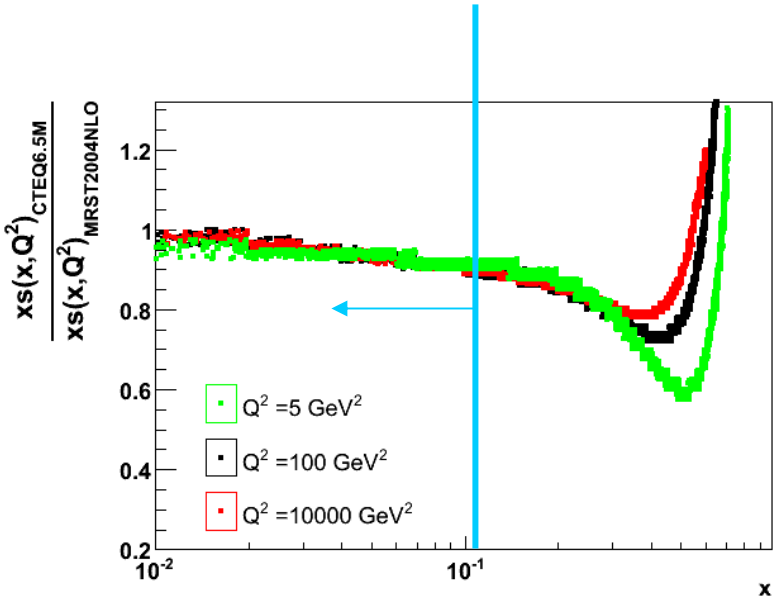
- quantify this background → increase the discovery potential

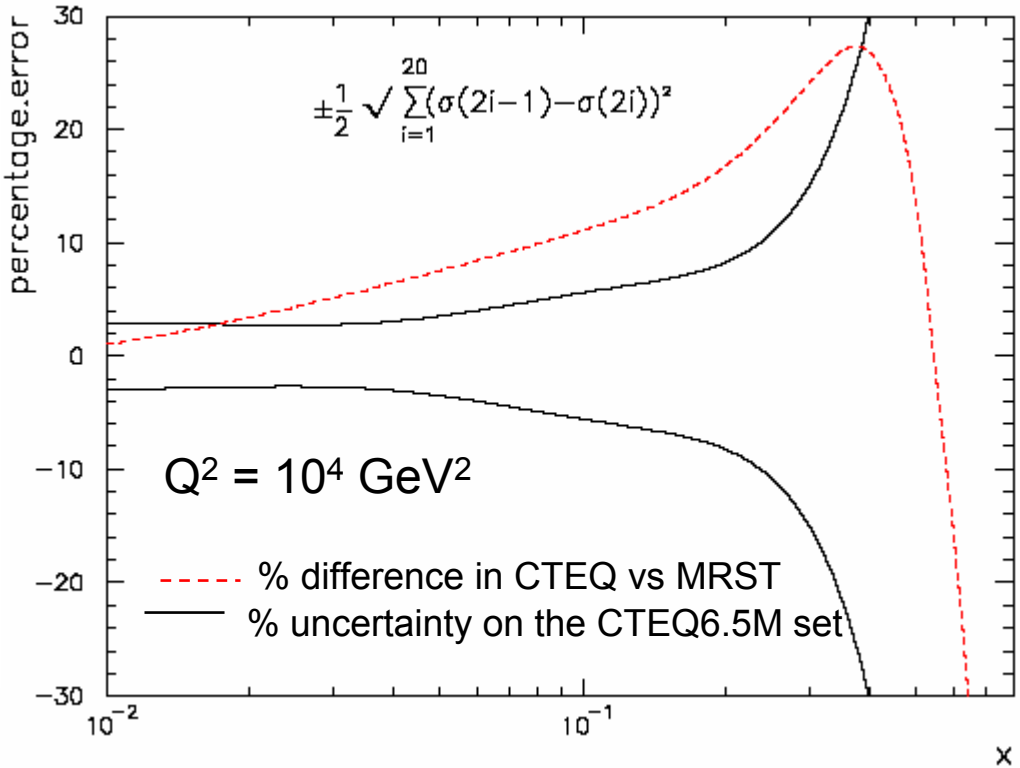




Comparison of CTEQ6.5M and MRSTNLO2004 parameterizations of the strange quark PDFs

PDFs HEP data
http://durpdg.dur.ac.uk/hepdata/pdf3.html





- not well constrained in the *x* region [0.01,1]
- still does not reflect a true uncertainty
- until this year no direct measurement at the hadron collider

CTEQ6.5M parameterizations of *s*-quark

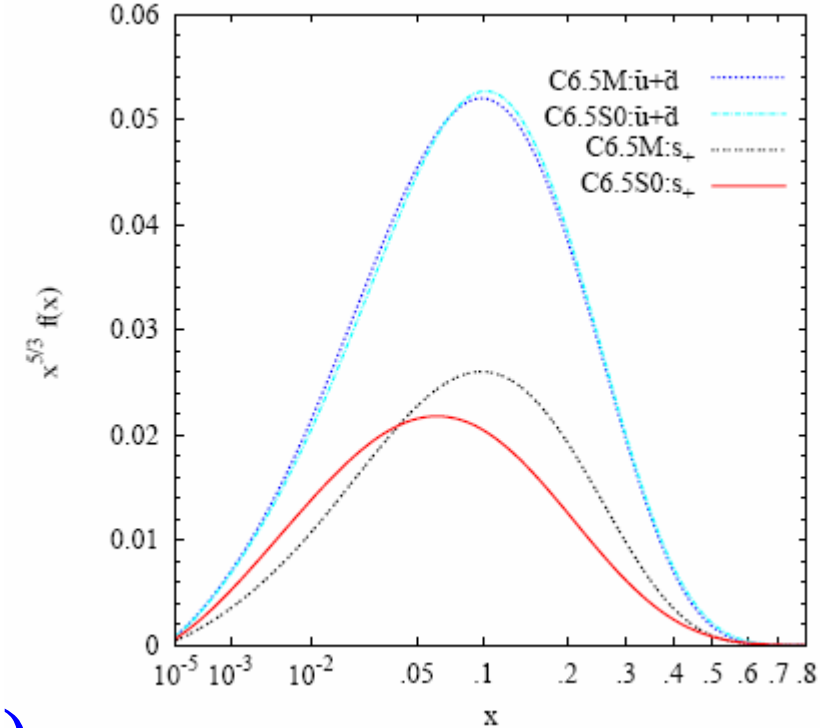
CTEQ6.5M:

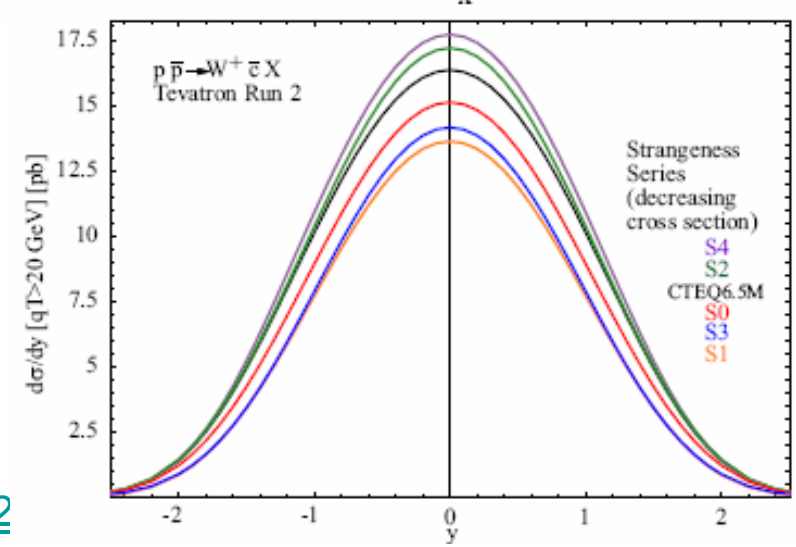
$$s(x) = \bar{s}(x) = r\,\frac{\bar{u}(x) + \bar{d}(x)}{2}$$

$$r = 0.5$$

CTEQ6.5S0:

$$s_+(x) = A_o x^{A_1} (1-x)^{A_2} P_+(x)$$





~30% variations in the central rapidity region

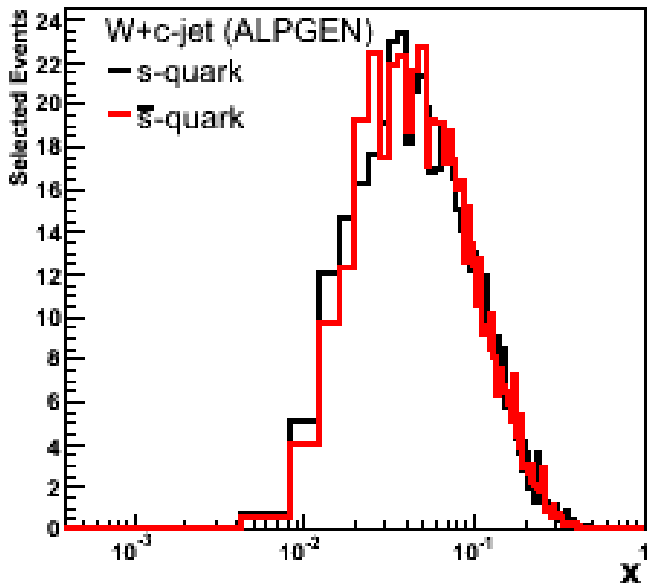
arXiv:hep-ph/0702268v2

Constraining the *s*-quark at the Tevatron

$$x_s x_g \geq \frac{M_W^2}{s} \approx 0.0017$$

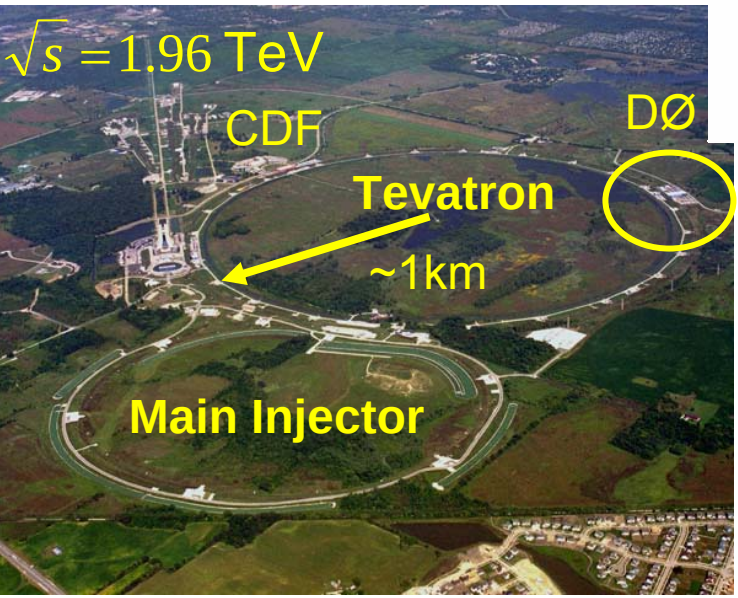
- fixed target (ν-N) experiments have measured the *s*-quark PDFs at low momentum scales
  - most recent publication:
    Phys. Rev. Lett. 99, 192001 (2007)

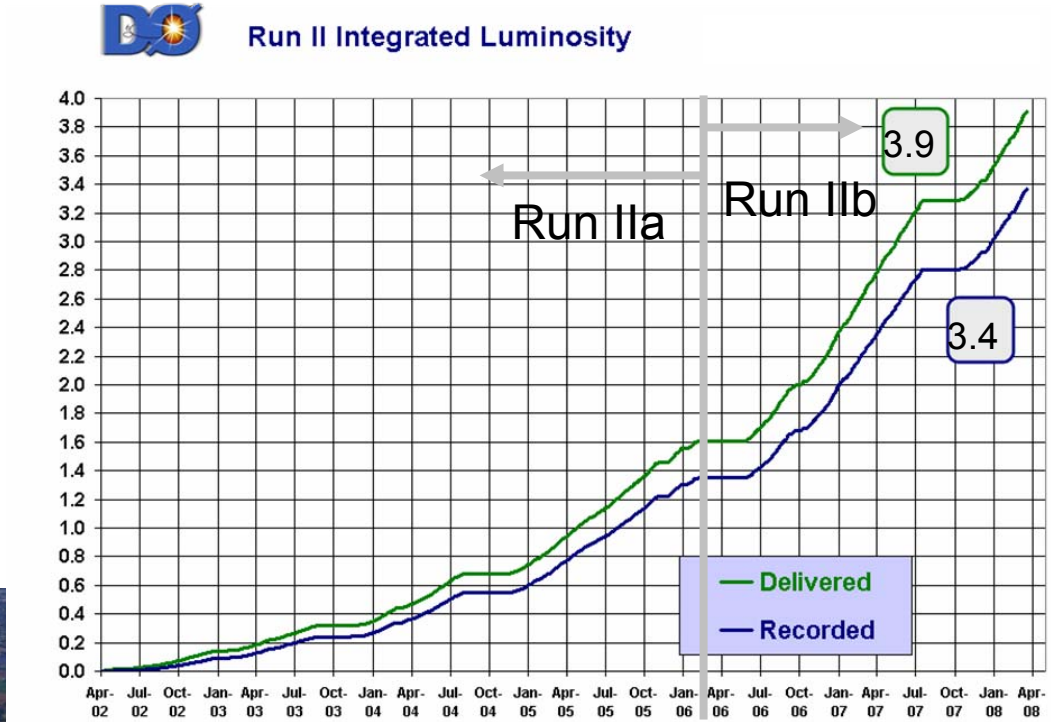
- constraining region at the Tevatron
  - $x \in [0.01, 0.1]$
  - Q scale of the order of M_W



Fermilab Tevatron Collider

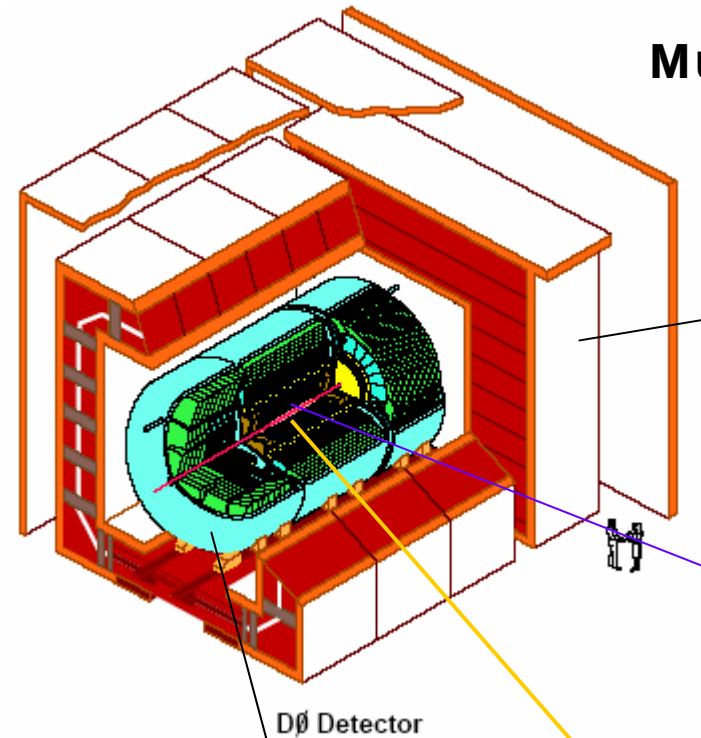
- proton anti-proton collisions at 1.96 TeV
  - 396ns bunch crossings



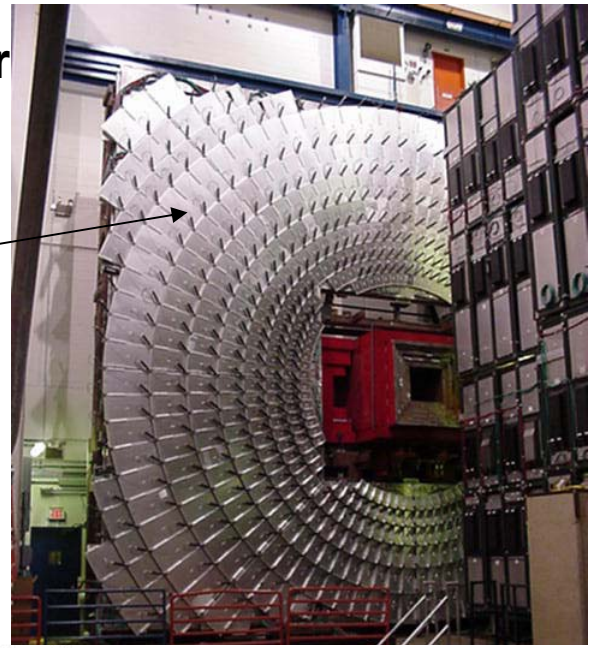


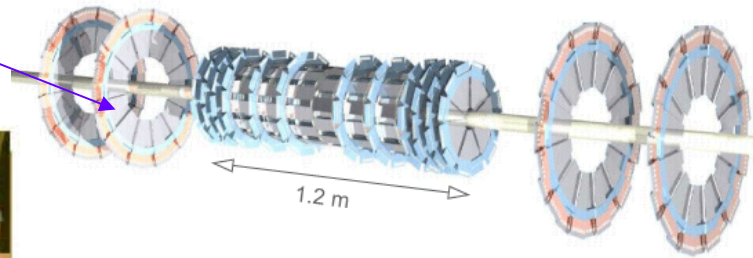
- $\int L\, dt \sim 3\ fb^{-1}$
  - $1\ fb^{-1}$ for this measurement
- Run II: 2001- 2009?
- anticipation for the LHC

The DØ detector



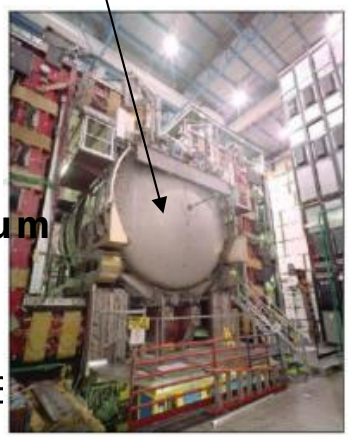
Muon spectrometer

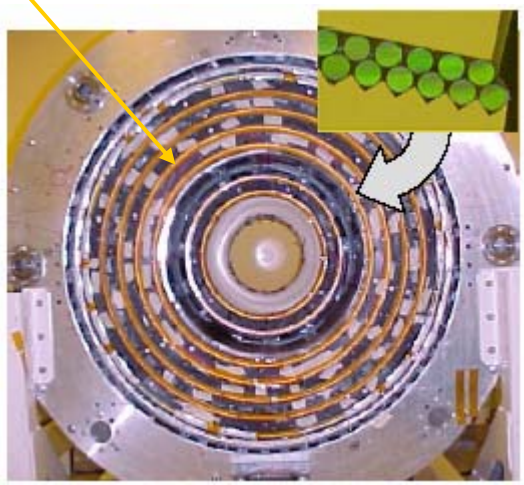




Silicon microstrip detector for tracking

LAr / Uranium calorimeter



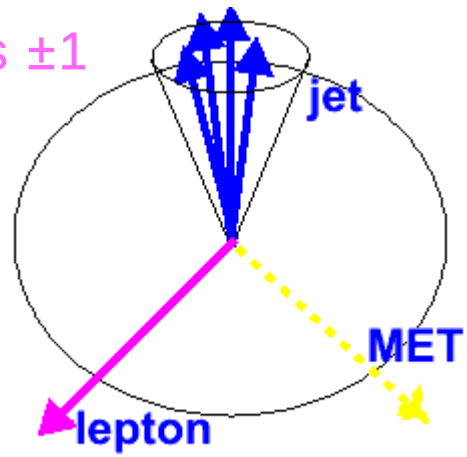


Central fiber tracker

$\sigma(W+c\text{-jet})/\sigma(W+\text{jets})$ ratio

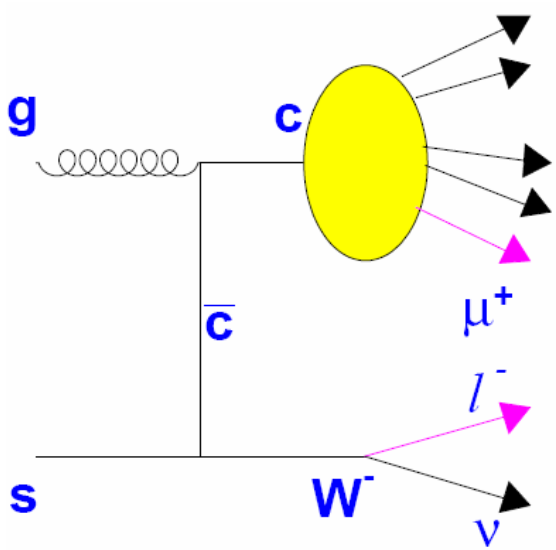
- event signature for an inclusive *W*+jets selection
  - isolated lepton + missing E_T + jet
  - $W \rightarrow e\,\nu$, $W \rightarrow \mu\,\nu$ and $W \rightarrow \tau(\rightarrow l\nu\nu)\nu$ modes
- *W*+*c*-jet signature:
  - isolated lepton + missing E_T + *c*-tagged jet
  - net charm quantum number in the final state is ±1

$$R = \frac{\sigma(W(\rightarrow l\nu)+c\text{-jet})}{\sigma(W(\rightarrow l\nu)+\text{jets})} = \frac{N(W(\rightarrow l\nu)+c\text{-jet})}{N(W(\rightarrow l\nu)+\text{jets})}$$



- many experimental (e.g. jet energy scale, efficiencies and luminosity) and theoretical uncertainties (PDF and scale uncertainties) cancel in ratio

$\sigma(W+c\text{-jet})/\sigma(W+\text{jets})$ ratio measurement strategy



W charge is opposite to the muon charge from recoiling charm

A simple counting measurement

$$R = \frac{N(W(\to l\nu)+c\text{-jet})}{N(W(\to l\nu)+\text{jets})}$$

$$= \frac{N^l_{OS} - f^l_c(N^l_{SS} - N^{l,nonWj}_{SS}) - N^{l,nonWj}_{OS}}{(1 - f^l_Z - f^l_{QCD}) \times N^l_{Wj} \times \varepsilon_c \times K_T}$$

N^l_{OS} = number of OS events

N^l_{SS} = number of SS events

$N^{l,nonWj}_{SS}$ = SS events from multijet, di-boson and top quark

N^l_{Wj} = number of observed W + jets candidates

f^l_c = correction to the BKD to W + c

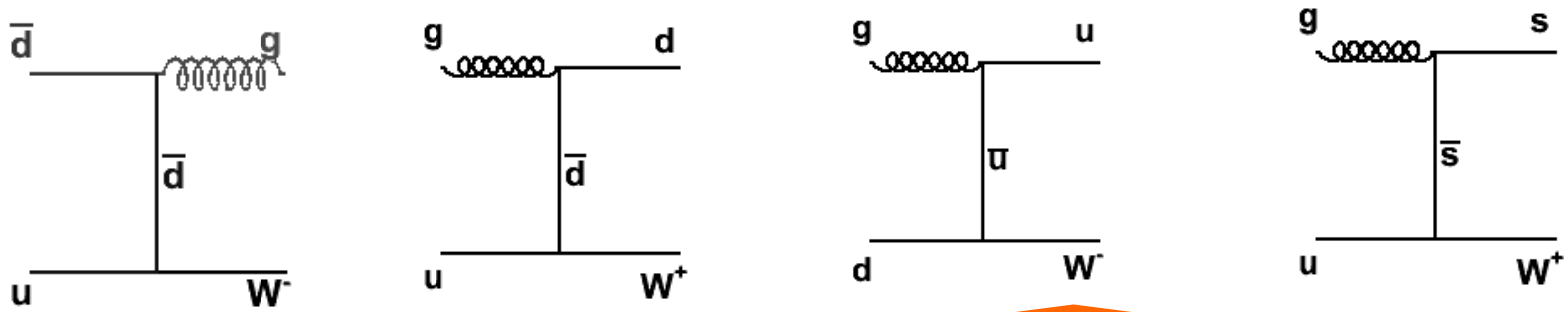
f^l_Z, f^l_{QCD} = fractions of Z + jets and multi-jet background to W + jets

ε_c = acceptance × efficiency of W + c relative to W + jets

K_T = correction for the trigger bias

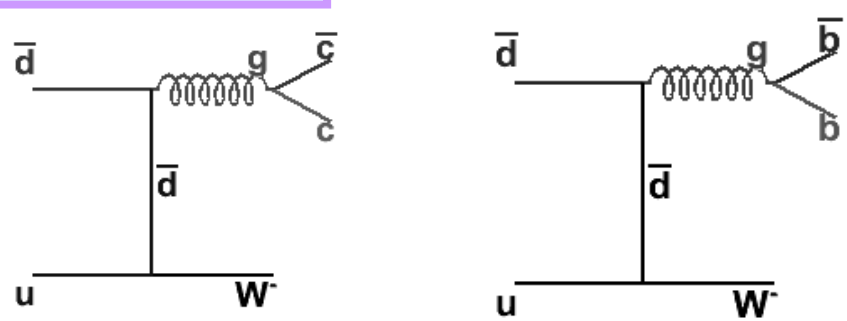
Major physics backgrounds to *W*+*c*-jet process

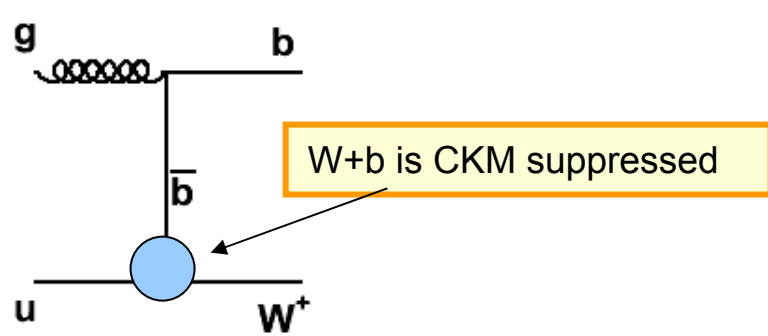
W+light jets



Contribute to signal due to "leading particle effect"
e.g. described in Phys. Rev. Lett. 78, 3442 (1997)

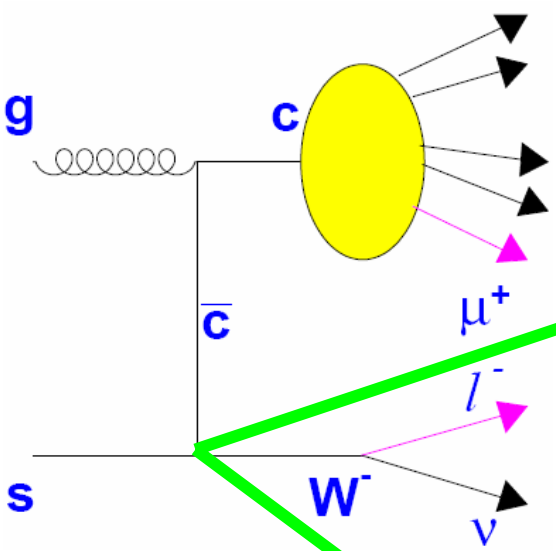
W+heavy flavor jets





Other relatively small background processes are di-boson and top quark productions

Event selection



- at least one jet defined using cone algorithm with radius 0.5
  - p_T > 20 GeV, others with p_T > 15 GeV
  - jet p_T is calibrated for the jet energy scale (JES)
- jet pseudorapidity $|\eta| < 2.5$
- muon-tagged jet contains a muon with p_T > 4 GeV
  - dR (jet, muon) < 0.5
  - veto on the Z/γ background

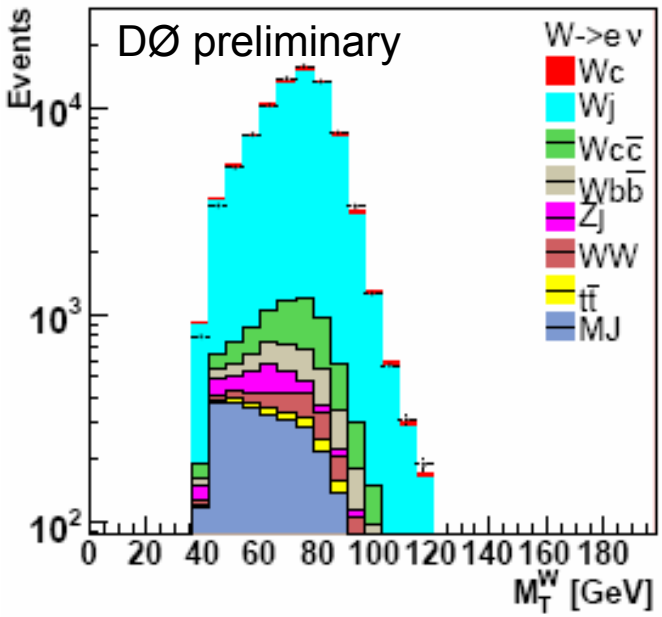
- pass single muon trigger
- one isolated muon p_T > 20 GeV
- veto on cosmic muons

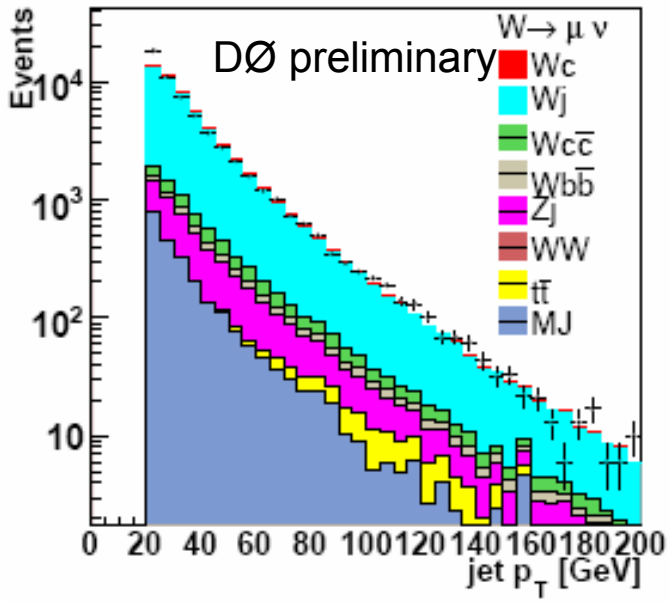
OR

- pass single electron trigger
- one isolated electron p_T > 20 GeV

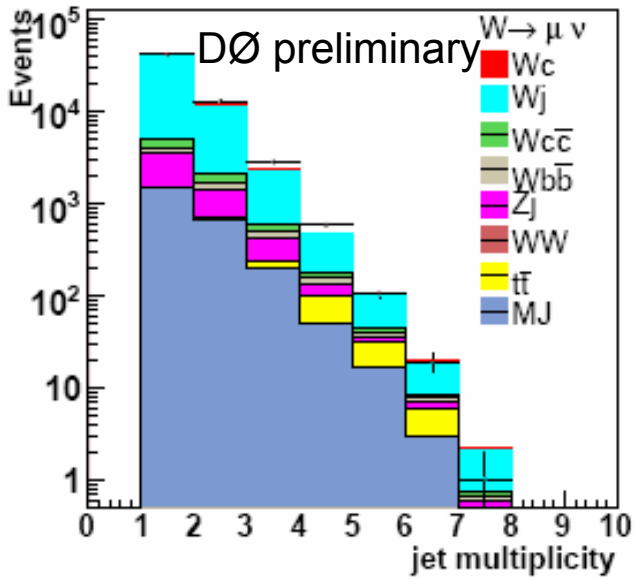
- Large missing E_T > 20 GeV
- W boson transverse mass [40, 120] GeV
- $|\Delta\varphi(\text{lepton}, \text{ETmiss})|$ > 0.4

W+jets Analysis





- sample composition: Wc, Wcc, Wbb, Wj, WW, Zj, ttbar, multijets
  - estimate multijets background from data
- data has reasonable agreement with the theoretical prediction
- theory: ALPGEN + PYTHIA
  - ALPGEN: tree level matrix element generator
  - PYTHIA: leading order + parton shower generator

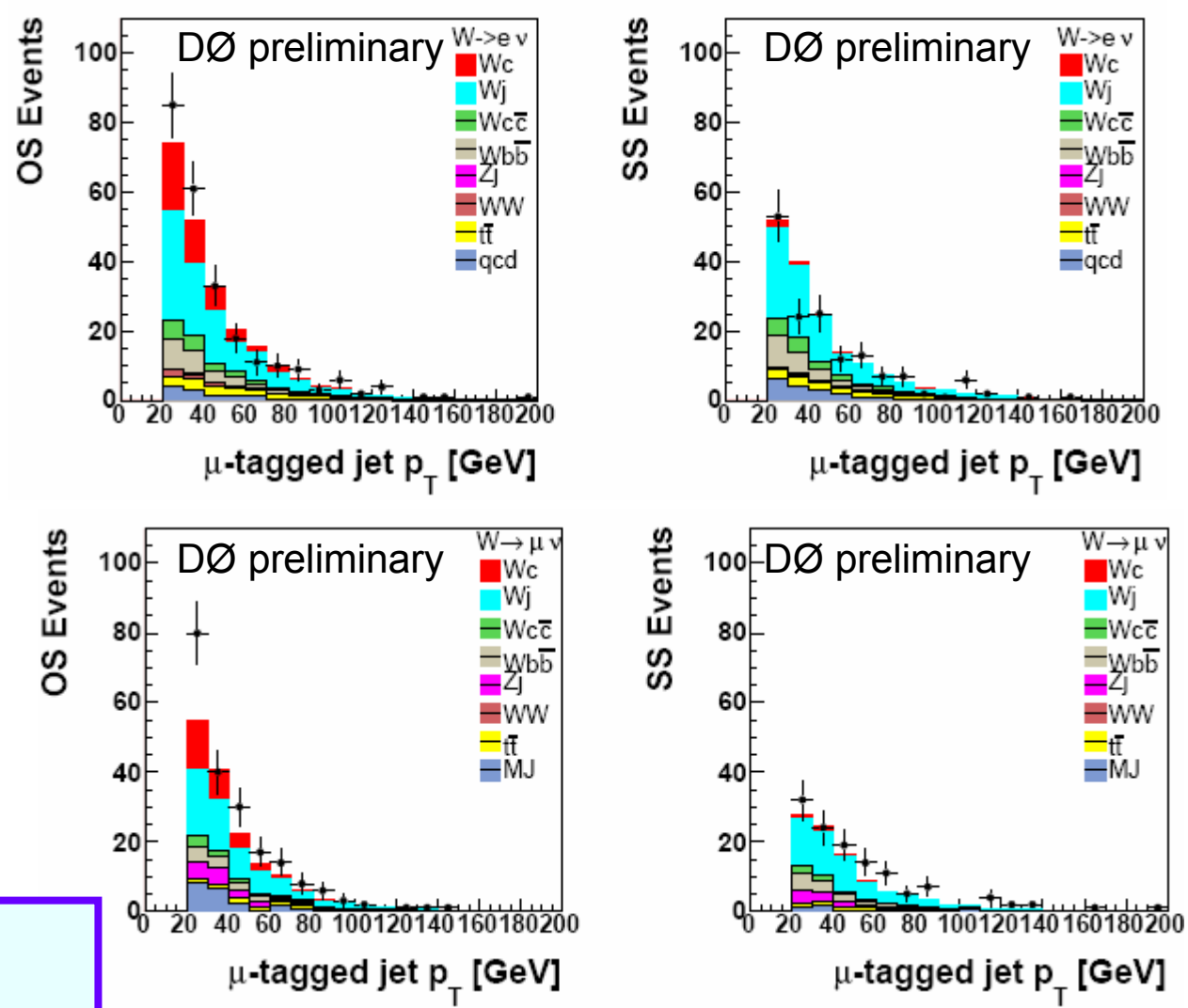


Muon-tagged jet p_T spectra

muon p_T > 4 GeV

Electron Channel

Muon Channel



excess of OS events is the signature of W+c!!

Background estimations

- events containing a soft muon-tagged jet enrich a sample with b/c or pion/kaon semileptonic decays
  - irreducible Wbb, Wcc backgrounds are SS events observed in data
    - OS = SS
    - well defined background, but just reduce the statistical precision of signal estimation
  - W+light jet background estimation needs a weakly model dependent small correction to SS events
    - OS = f * SS
  - multijet background is estimated from data
    - small correlation is observed due to b-bbar and c-cbar processes
  - other relatively small background estimated from MC simulation
    - WW, top quark pair productions, single top quark production etc
      - large correlations in OS and SS events, but small cross sections

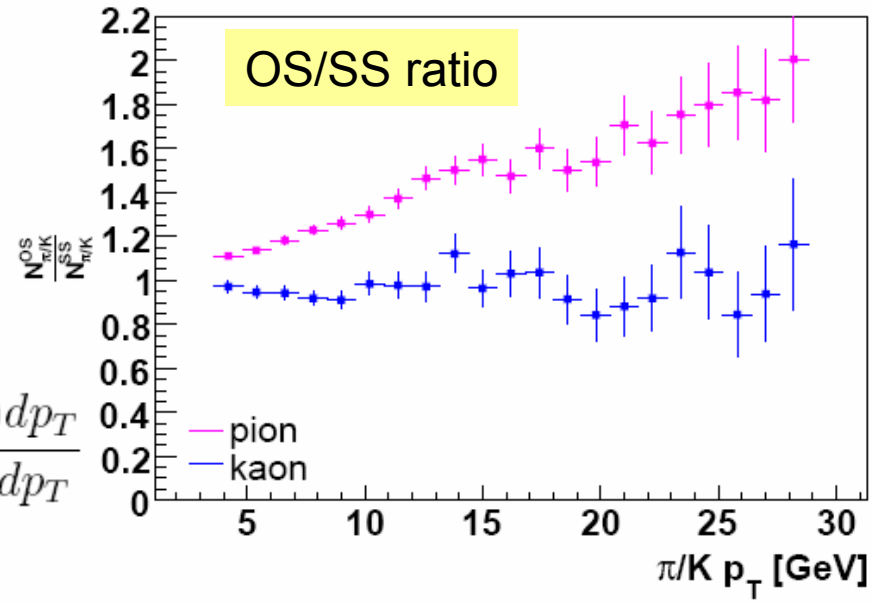
W+light-jet background

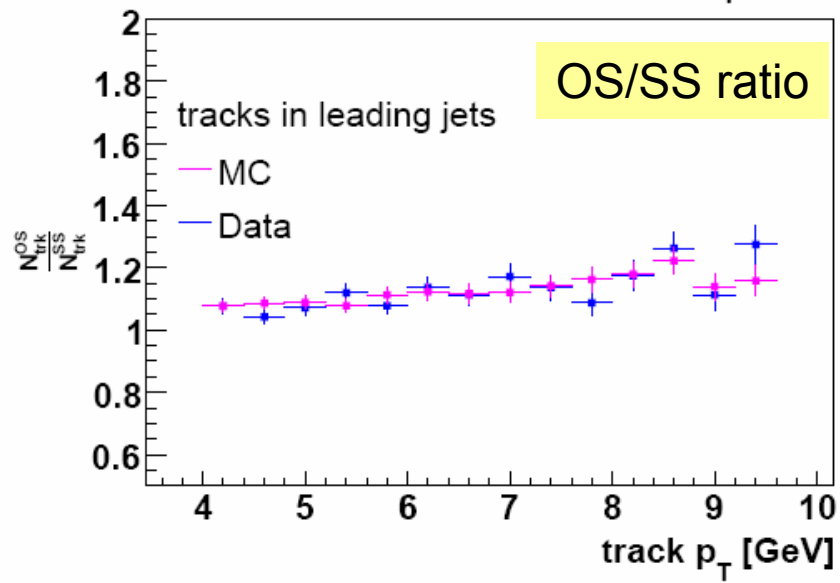
- dominant background
  - ~50% of all sources
- apply weakly model dependent correction to SS events

$$f_c^\ell = \frac{\int w_\pi(p_T) N_\pi^{\mathrm{OS}}(p_T) dp_T + \int w_K(p_T) N_K^{\mathrm{OS}}(p_T) dp_T}{\int w_\pi(p_T) N_\pi^{\mathrm{SS}}(p_T) dp_T + \int w_K(p_T) N_K^{\mathrm{SS}}(p_T) dp_T}$$

- correction depends on relative $K^\pm/\pi^\pm$ multiplicity per jet
  - OS/SS for the tracks shows fairly good agreement in the data and MC

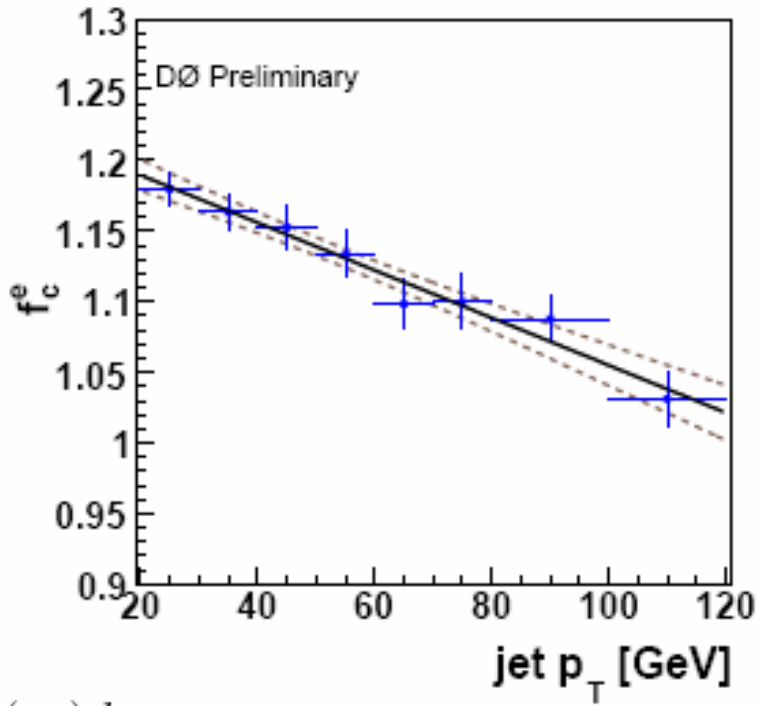
Kaons has less correlation than pions





W+light-jet background (cont'd.)

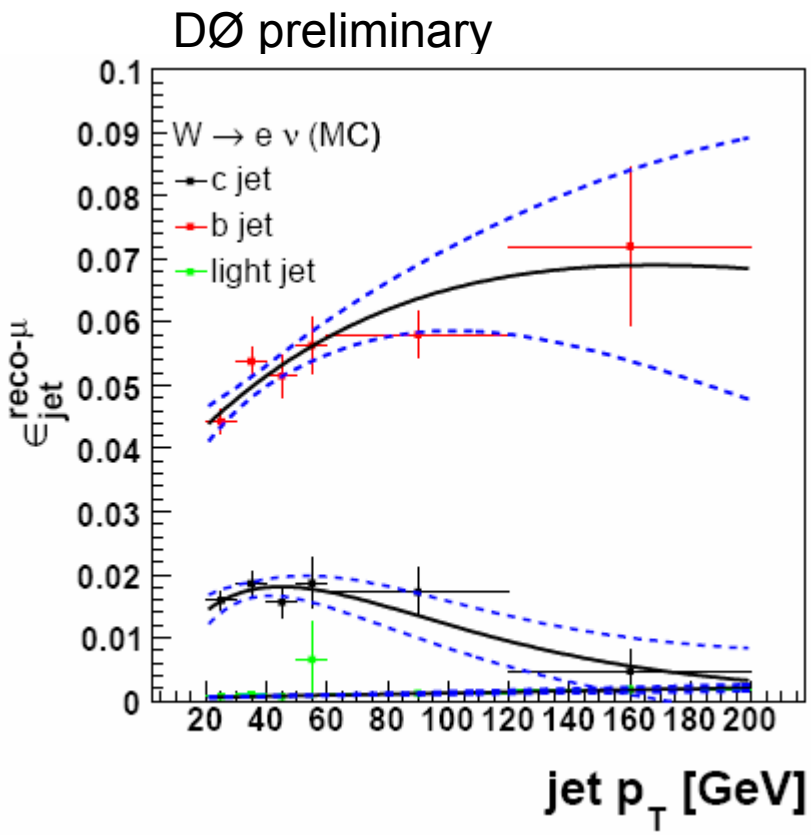
- correction factor, f_c^{ℓ}, decreases with jet p_T
- W+g process dominates over W+q at high p_T

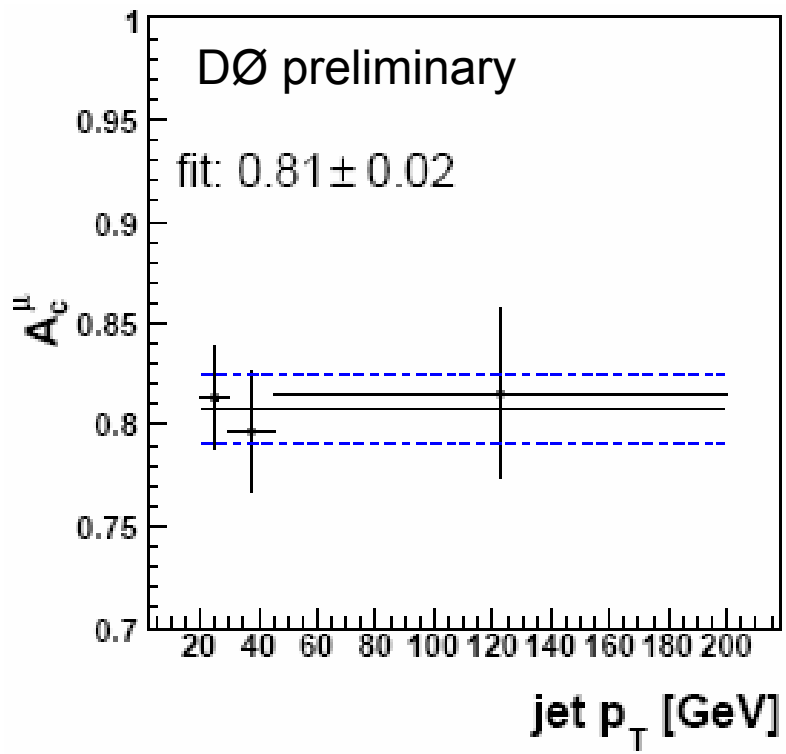


$$f_c^{\ell} = \frac{\int w_\pi(p_T) N_\pi^{\mathrm{OS}}(p_T) dp_T + \int w_K(p_T) N_K^{\mathrm{OS}}(p_T) dp_T}{\int w_\pi(p_T) N_\pi^{\mathrm{SS}}(p_T) dp_T + \int w_K(p_T) N_K^{\mathrm{SS}}(p_T) dp_T}$$

Relative efficiency of *W*+*c*-jet selection

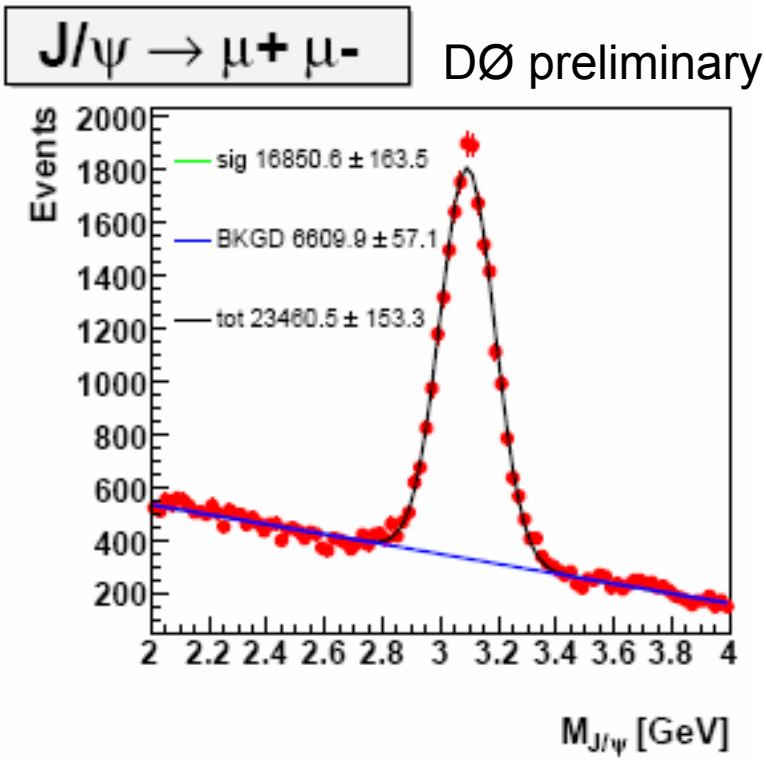
- includes BF($c \rightarrow \mu$), muon identification and reconstruction, kinematical selection, jet momentum corrections for muon and neutrino energy losses in the jet, and efficiency for charge correlation
  - presence of muon from pion/kaon decays in c-jet in the *W*+*c*-jet sample degrades the correlation in final state leptons from 100% → 80%

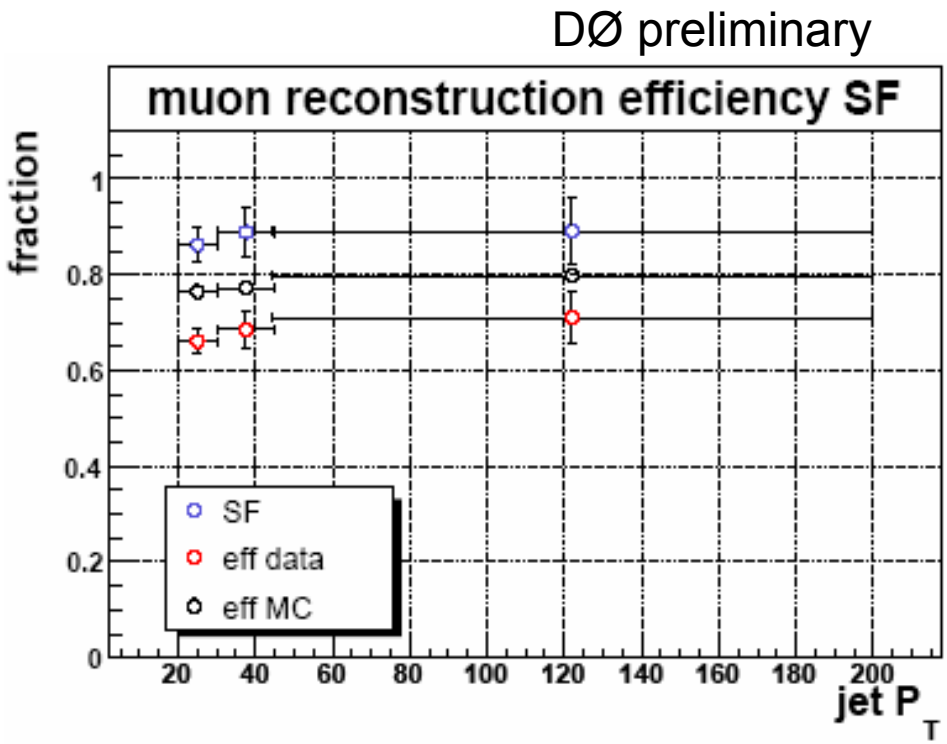




Scale factor for efficiency correction

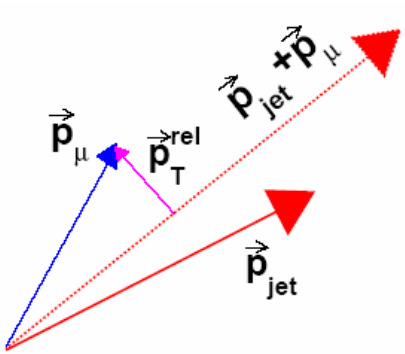
- muon tagging efficiency estimated from models needs corrections to account for the residual detector effects
- use a large data sample of $J/\psi \rightarrow \mu^+\mu^-$ to estimate the muon reconstruction efficiencies
  - use tag and probe method to determine the efficiencies
  - ~10% correction is required to recover the data-MC discrepancies

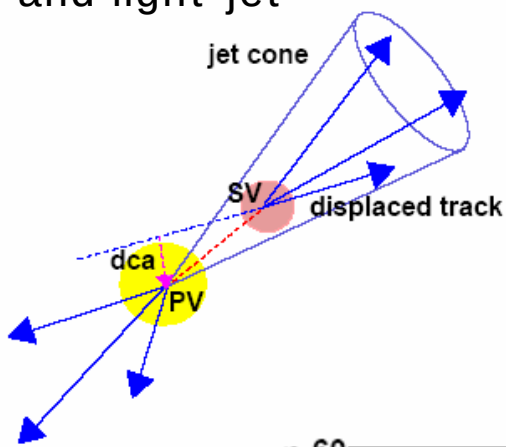


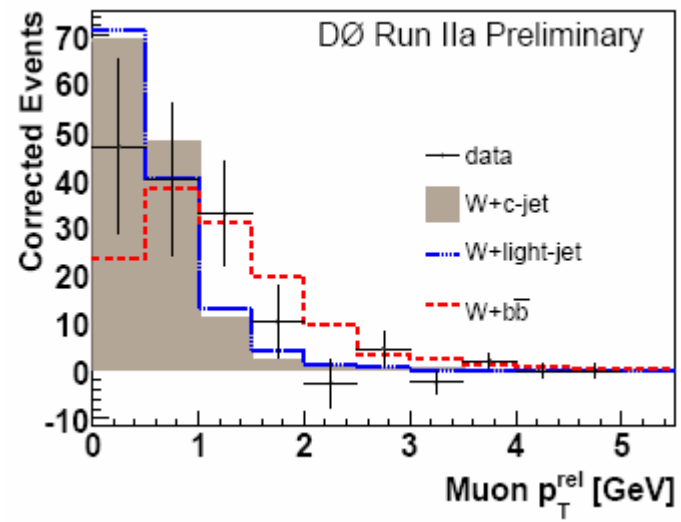


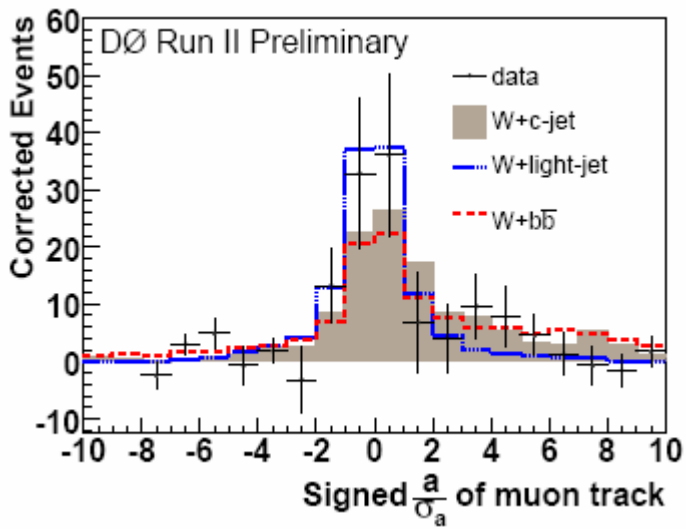
Comparison of *c*-jet & non-c-jet shapes

- seek variables for discrimination of the charm jet in events with W boson, examples:
  - p_T^{rel} of muon track
  - significance in impact parameter of muon with respect to the primary vertex
- Hard to tell c-jet from b-jet and light-jet



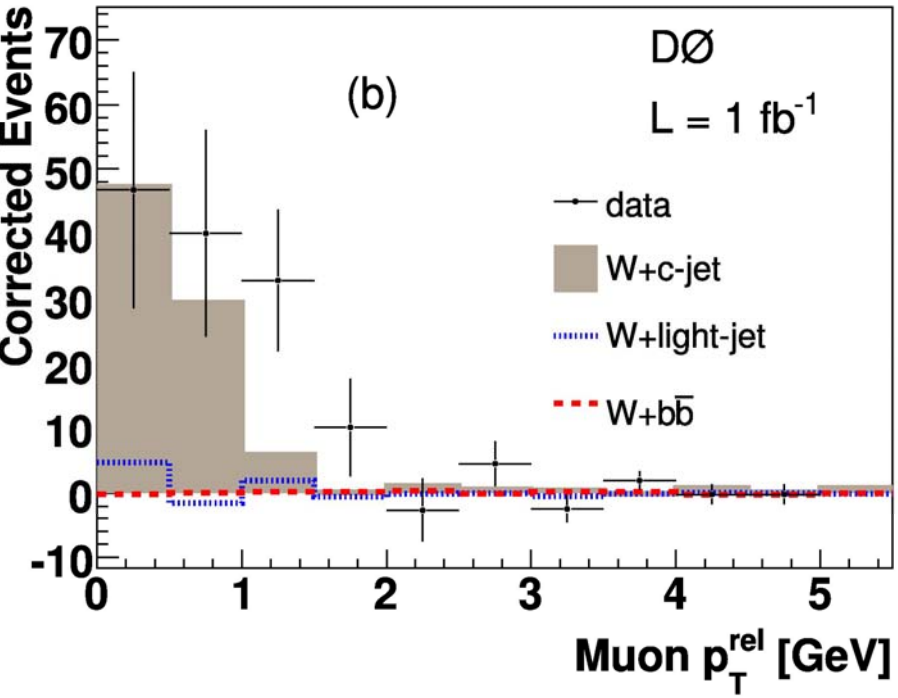


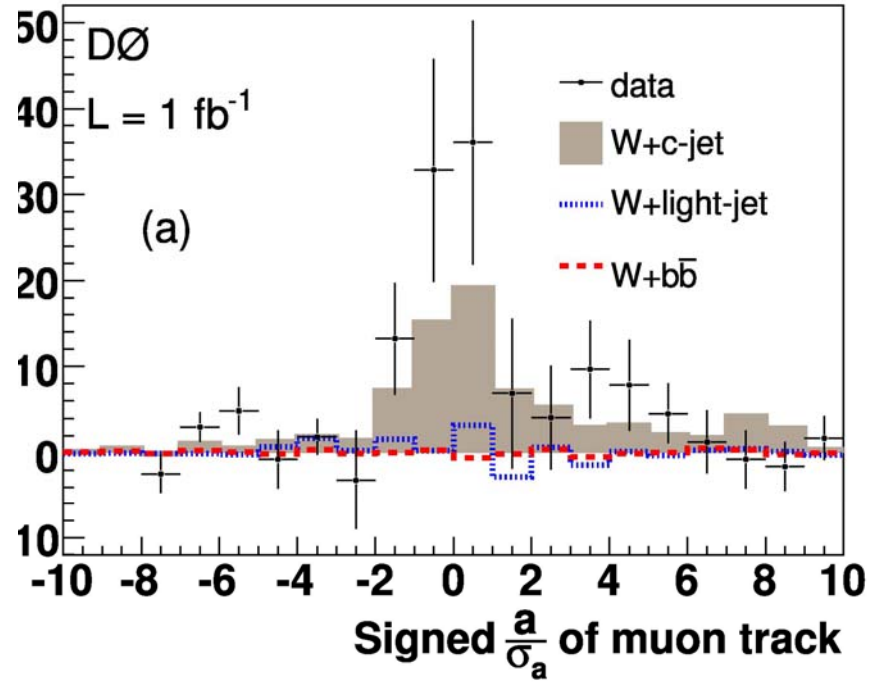




Consistency for the *c*-jet

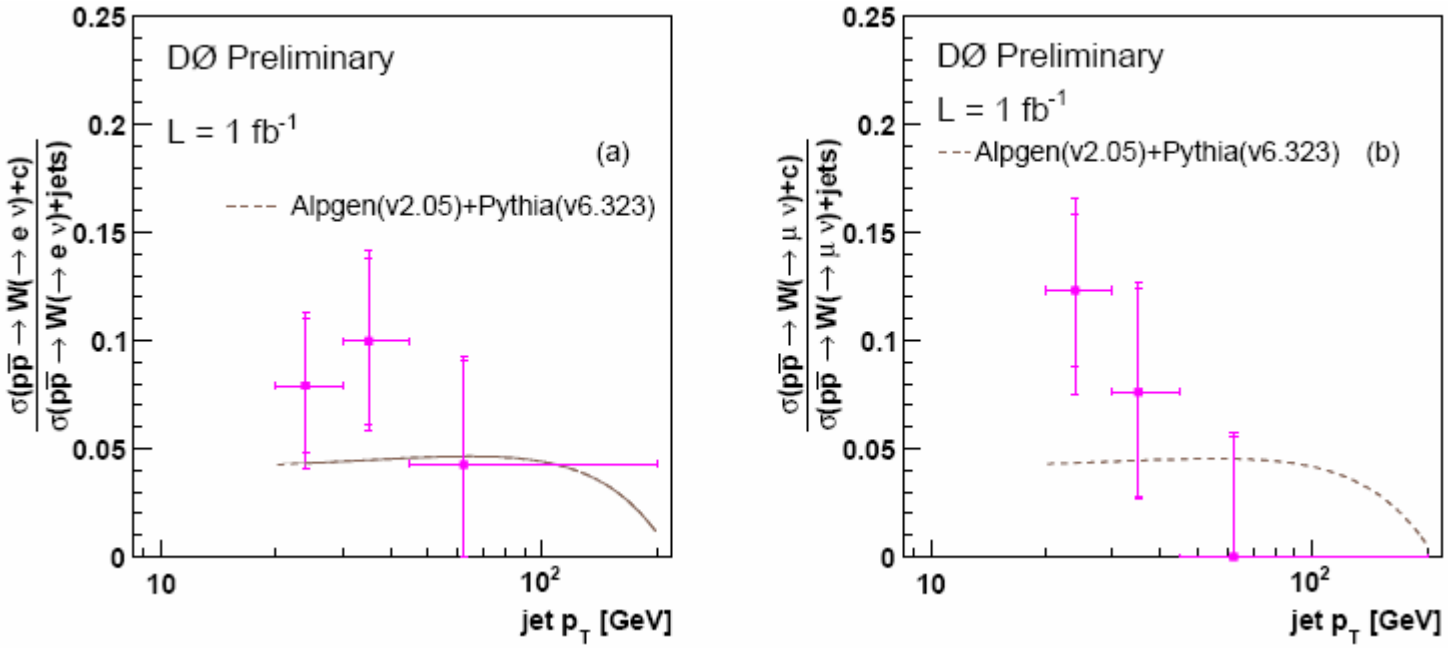
arXiv:0803.2259v1 [hep-ex]





- background-subtracted data favors the shape for the charm jet variables
- *b*-jet contamination is small
- light-jet contribution is indeed subtracted out

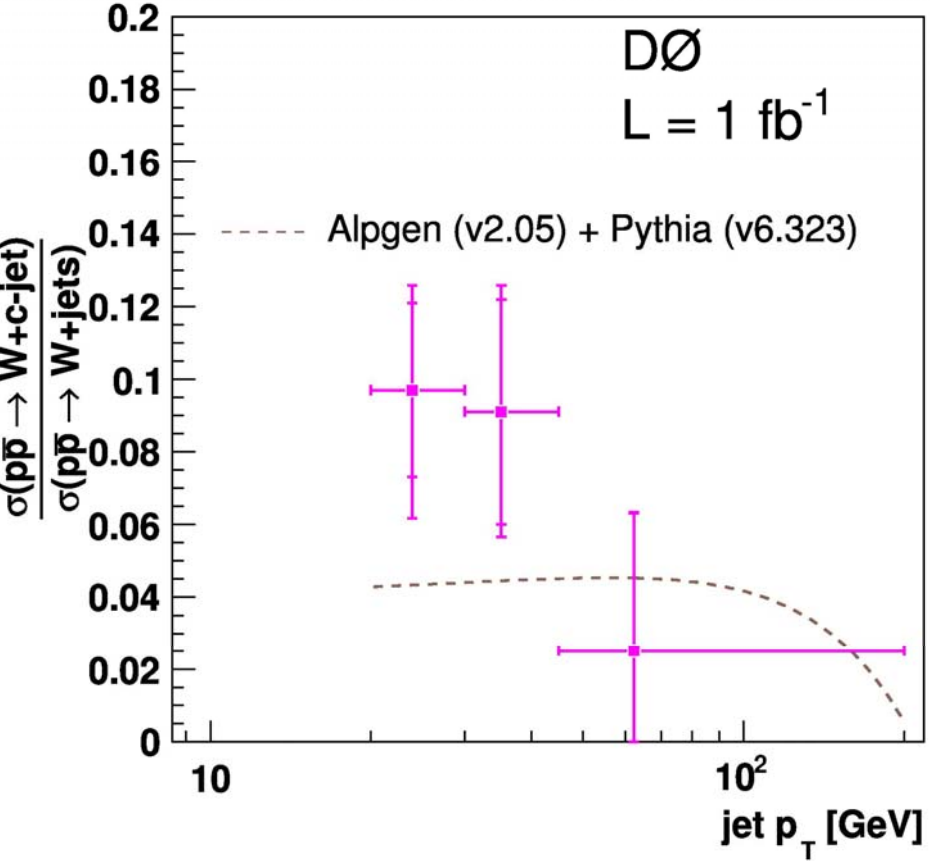
Results from W→eν and W→μν channels



$$\frac{\sigma(W(\to l\nu)+c\text{-jet})}{\sigma(W(\to l\nu)+\text{jets})} = \frac{N_{OS}^{l} - f_c^{l}(N_{SS}^{l} - N_{SS}^{l,nonWj}) - N_{OS}^{l,nonWj}}{(1 - f_Z^{l} - f_{QCD}^{l}) \times N_{Wj}^{l} \times \varepsilon_c \times K_T}$$

- jet pT is corrected to the particle level
- measurement compared with the theory
  - ALPGEN: for tree level matrix element calculation
  - PYTHIA: for parton shower
  - uncertainty due to CTEQ 6.5M PDFs is 6%
- both channels have consistent results

Result



- jet p_T is corrected to the particle level
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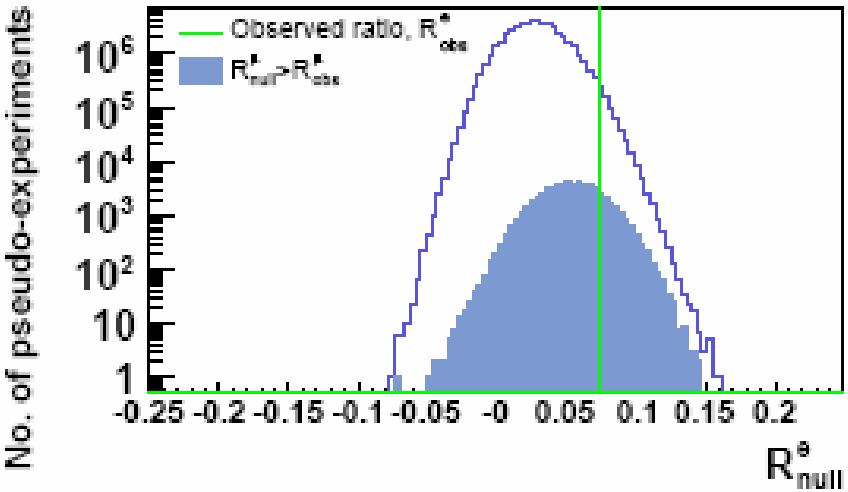
- recently submitted to
  - Physics Letters B
  - arXiv:0803.2259v1 [hep-ex]
  - Fermilab-Pub-08/062-E
- CDF's recently published result:
  - Phys. Rev. Lett. 100, 091803

- integrated over all p_T and all bins with $|\eta| < 2.5$

0.074 ± 0.019 (stat.) + 0.012 -0.014 (syst.)

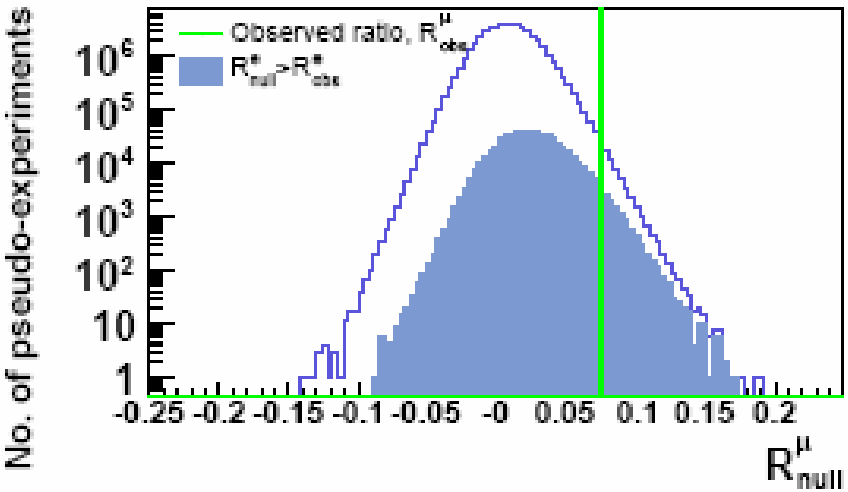
- no significant deviation from the theoretical prediction

Significance of the result



DØ Preliminary

Null Hypothesis
p-Value = 0.00025
N-σ = 3.5



- follow Bayesian approach
- include all systematic uncertainties and their correlations
- ensemble test for null hypothesis
  - probability that background fluctuations could produce equal to greater than the observed signal rate
- $2.5 \times 10^{-4} \rightarrow 3.5\ \sigma$ significance

Summary & outlook

- The measurement of $\sigma(W+c\text{-jet})/\sigma(W+\text{jets})$ ratio provides a probe of the strange quark inside proton and is a test of perturbative QCD and electroweak predictions

- We find good agreement within uncertainties with
  - the LO perturbative QCD predictions
  - the s quark evolved from the Q^2 scale that is two orders of magnitude below that of this measurement

- Direct evidence for the quark-gluon interactions that will be more important at the CERN LHC collider

- The DØ detector is operating well, already have ~3 fb^{-1} data on tape, expected to reach 6 fb^{-1} by the end of 2009.

- The precision of measurement can be improved to less than 15% at 6 fb^{-1}

THANK YOU!

Event yields

	W→eν +jets			W→μν +jets		
Samples	**before μ tag**	**OS**	**SS**	**before μ tag**	**OS**	**SS**
W+c	**4301.4 ± 27.3**	**58.7 ± 3.2**	**5.6 ± 0.9**	**2576.1 ± 18.9**	**32.3 ± 2.2**	**4.6 ± 0.8**
W+cc	2683.6 ± 13.4	15.8 ± 1.1	14.6 ± 1.1	1623.4 ± 9.3	8.2 ± 0.7	6.2 ± 0.6
W+bb	1229.5 ± 5.7	24.5 ± 0.8	23.6 ± 0.8	728.2 ± 3.9	12.3 ± 0.5	12.6 ± 0.5
W+j(udsg)	71561.6 ± 112.2	97.4 ± 3.8	84.4 ± 3.4	45204.7 ± 79.8	60.8 ± 2.7	51.2 ± 2.5
Z+j	711.7 ± 12.1	0.9 ± 0.3	1.6 ± 0.5	2649.1 ± 21.1	12.2 ± 1.4	9.3 ± 1.2
WW	539.0 ± 3.7	6.2 ± 0.4	1.9 ± 0.2	417.7 ± 3.3	4.1 ± 0.3	1.2 ± 0.2
ttbar	213.5 ± 1.0	18.3 ± 0.3	15.9 ± 0.3	119.7 ± 0.7	9.2 ± 0.2	8.1 ± 0.2
single-top	111.9 ± 0.3	6.3 ± 0.1	4.6 ± 0.1	75.7 ± 0.3	4.2 ± 0.1	3.0 ± 0.1
Multi-jet	2650 ± 64	13.3 ± 2.3	19.3 ± 2.9	2360 ± 178	12.2 ± 4.6	8.8 ± 5.4
Background	**79588.9 ± 130.6**	**176.3 ± 5.2**	**161.4 ± 4.7**	**53102.8 ± 196.5**	**118.9 ± 5.6**	**97.4 ± 6.1**
Sig+BKD	**83890.3 ± 124.7**	**235.0 ± 6.1**	**167.0 ± 4.8**	**55678.9 ± 197.4**	**198.5 ± 6.0**	**102.0 ± 6.2**
Data	**82747**	**245**	**154**	**57944**	**203**	**122**

Systematics summary

source	fractional uncert. % $W \rightarrow e\nu$ channel	fractional uncert. % $W \rightarrow \mu\nu$ channel
jet energy scale	+0, -9.0	+5.9, -2.4
jet mometum resolution	+2.3, -4.5	+4.7, -7.1
f_c^l	+4.5, -5.2	+3.1, -4.3
Relative acceptance times efficiency, ϵ_c^l	+15.1, -15.0	+14.9, -15.7
trigger correction, K_T^l	-	±10
total	+16.4, -19.2	+20.0, 22.7

sources	uncertainty
BF($c \rightarrow \mu$)	9.5%
c-jet fragmentation	4.5%
A_c^μ	6%
muon p_T resolution	+4.1%, -4.4%
jet energy correction	4.3%
efficiency scale factor	7%

Systematics summary

sources	uncertainty
jet energy scale	+2.3%, -6.5%
jet momentum resolution	+3.2%, -5.5%
f_c^l	+4.0%, -4.8%
Relative acceptance times efficiency, $\in_c^l$	+15.0%, -15.3%
trigger correction, K_T^l	3.9%
total	+16.5%, -18.6%

sources	uncertainty
BF($c \rightarrow \mu$)	9.5%
c-jet fragmentation	4.5%
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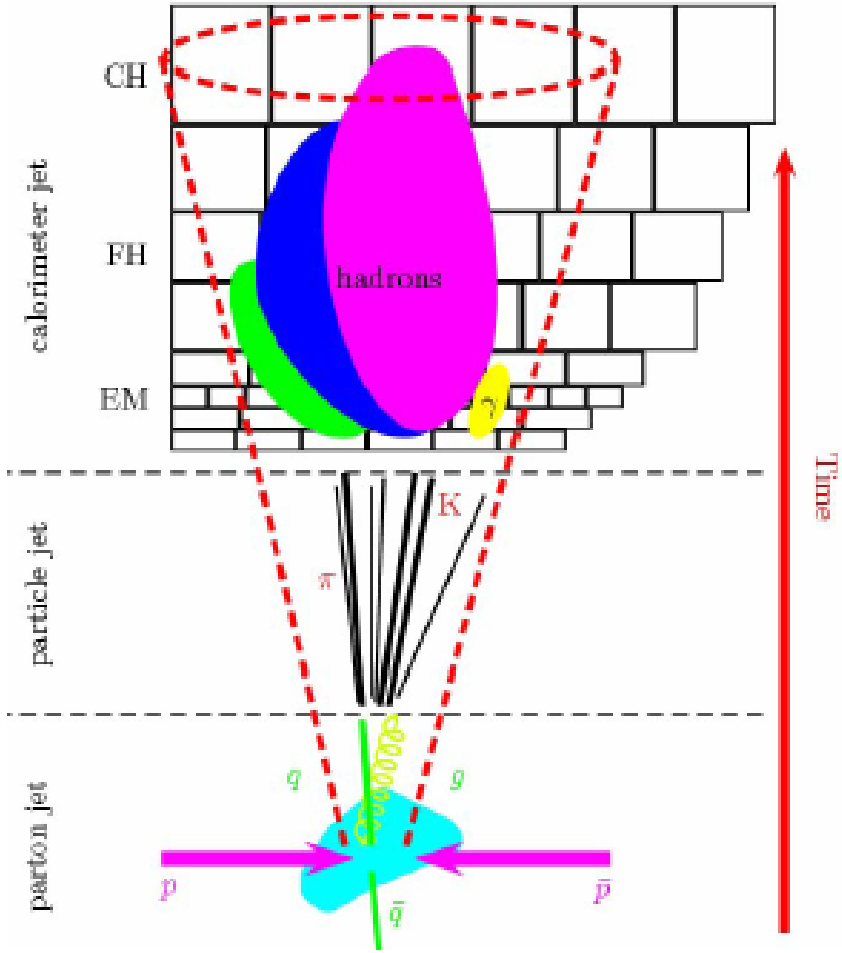
Objects identifications

- Jets:
  - iterative seed based midpoint cone algorithm with cone radius 0.5
    - use four momentum information of all particles in the cone to estimate the jet momentum
    - collinear and infrared safe
- Electrons:
  - simple cone algorithm
  - shower in the EM part of calorimeter
- Muons:
  - identified both in the outer muon spectrometer and in the central tracker

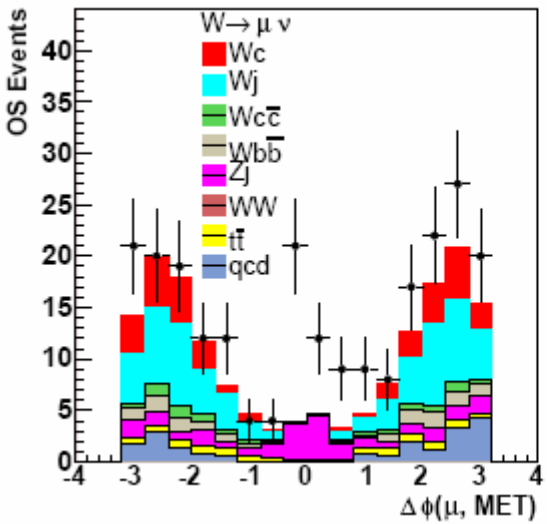
Jet reconstruction

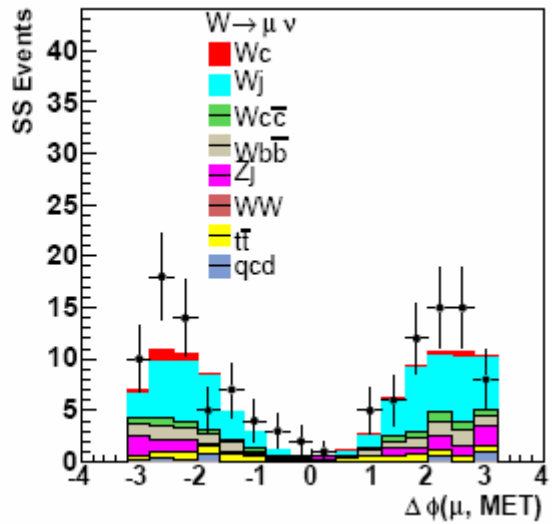
- jets constructed using the iterative seed based mid point cone algorithm
  - cone radius 0.5
  - using 4-momentum information of all particles within the jet cone
  - collinear and infrared safe
  - split/merge on the
- jet momentum is calibrated to the particle level after correcting for
  - Offset: pile-ups, noise, underlying events, multiple particle interactions etc..
  - jet response
  - Out-of-cone showering



Z/γ background suppression

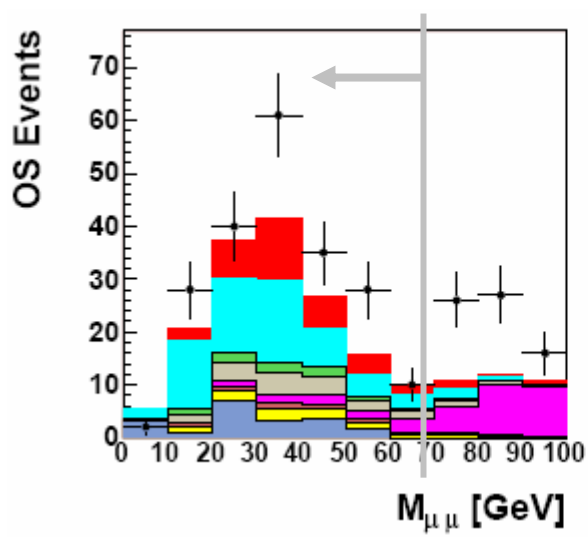
- peak close to zero is an indication of the Drell-Yan background, highly suppressed by the $|\Delta\varphi| < 0.4$ cut

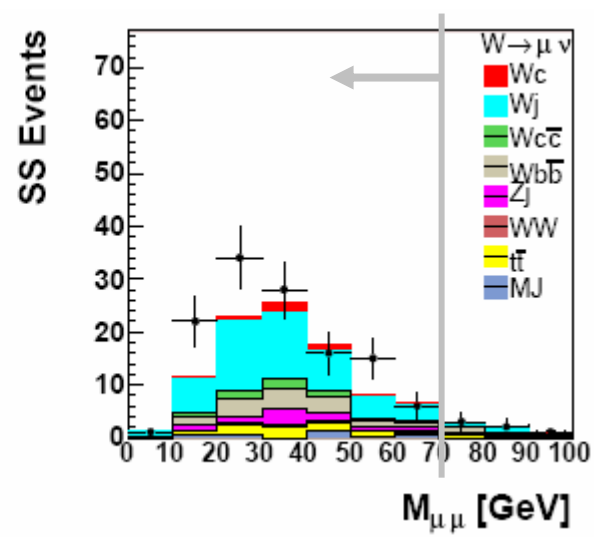




$\Delta\varphi(\mu, \text{MET})$ comparison

$M_{\mu\mu}$ comparison

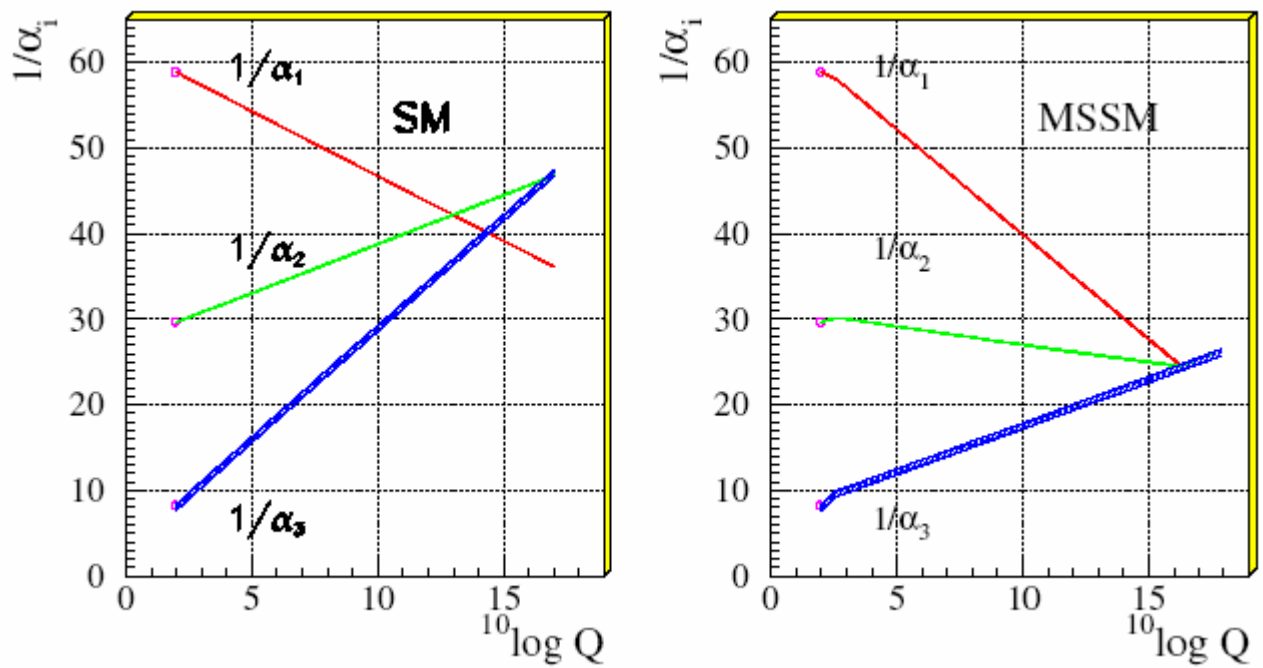




Measurement summary

	$W \to e\nu$ decay channel	$W \to \mu\nu$ decay channel
N^{ℓ}_{Wj}	82747	57944
N^{ℓ}_{OS}	245	203
N^{ℓ}_{SS}	154	122
$N^{\ell,\mathrm{MJ}}_{\mathrm{OS}}$	13.3±2.6±3.4	12.2±4.6±8.7
$N^{\ell,\mathrm{MJ}}_{\mathrm{SS}}$	19.3±2.9±4.9	8.8±5.4±6.3
$N^{\ell,WW}_{\mathrm{OS}}$	6.2±2.1	4.2±1.6
$N^{\ell,WW}_{\mathrm{SS}}$	1.9±0.5	1.2±0.4
$N^{\ell,t\bar{t}}_{\mathrm{OS}}$	18.8±4.5	9.3±2.2
$N^{\ell,t\bar{t}}_{\mathrm{SS}}$	16.1±3.9	8.1±1.9
$N^{\ell,t\bar{b}}_{\mathrm{OS}}$	6.3±1.8	4.2±1.2
$N^{\ell,t\bar{b}}_{\mathrm{SS}}$	4.6±1.3	3.1±0.9
f^{ℓ}_{c}	1.149±0.007±0.017	1.148±0.007±0.013
ϵ^{ℓ}_{c}	$0.0124\pm0.0012^{+0.0019}_{-0.0019}$	$0.0122\pm0.0012^{+0.0018}_{-0.0019}$
K^{μ}_{T}	-	1.18±0.02±0.12
$\frac{\sigma[W(\to\ell\nu)+c\text{-jet}]}{\sigma[W(\to\ell\nu)+\text{jets}]}$	$0.073\pm0.023^{+0.012}_{-0.014}$	$0.075\pm0.031^{+0.015}_{-0.017}$

Unification of fundamental interactions

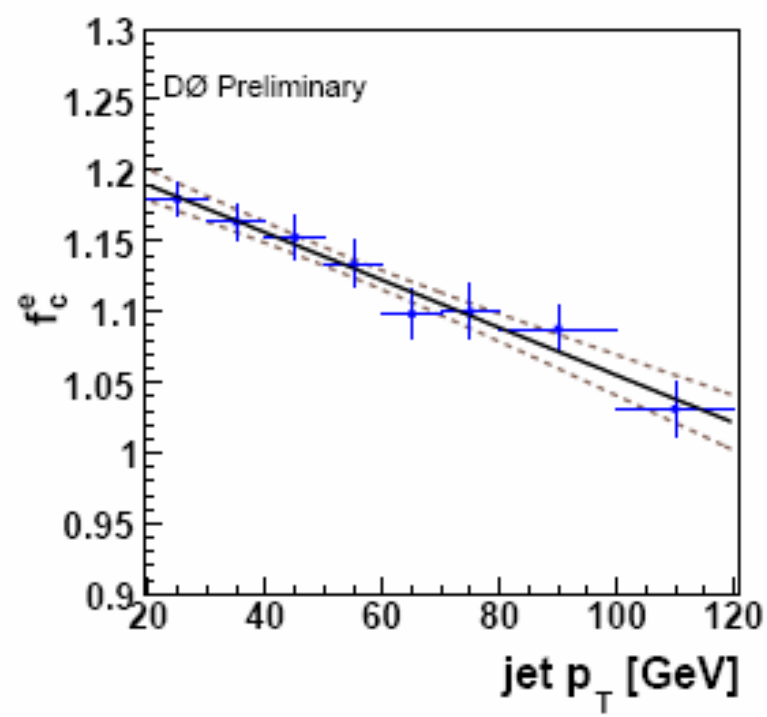


- In SM running coupling constants do not exactly converge at one scale
- With the extension to SM, e.g SUSY, the running coupling constant converges at one scale 10^{16}

Background estimations

- events containing a soft muon-tagged jet enrich a sample with b/c or pion/kaon semileptonic decays
  - irreducible Wbb, Wcc backgrounds are SS events observed in data
  - W+light quark jet background estimation needs a weak model dependent small correction to SS events
  - multijet background is estimated from data
  - other relatively small background estimated from MC simulation

W+g dominates over W+q at high p_T



$$f_c^\ell = \frac{\int w_\pi(p_T) N_\pi^{OS}(p_T) dp_T + \int w_K(p_T) N_K^{OS}(p_T) dp_T}{\int w_\pi(p_T) N_\pi^{SS}(p_T) dp_T + \int w_K(p_T) N_K^{SS}(p_T) dp_T}$$