QCD and B and charm Physics at the Tevatron

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On behalf of the CDF and DØ Collaborations

PLHC 2012, Vancouver

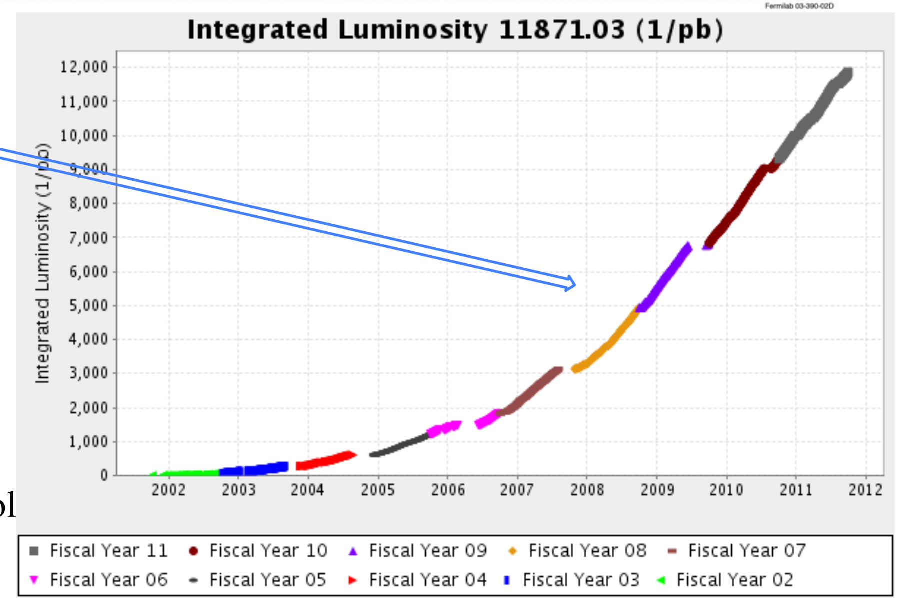
June 6, 2012

Overview

- Introduction
- Recent QCD results
  - Inclusive jets (DØ)
  - γ+b, γ+c jets (DØ, CDF)
- Heavy quark (b and c) physics
  - Fragmentation (CDF)
  - CP asymmetries in B and D physics (CDF)
  - Rare decays and new states (DØ, CDF)
  - Lifetimes (DØ)
- Summary

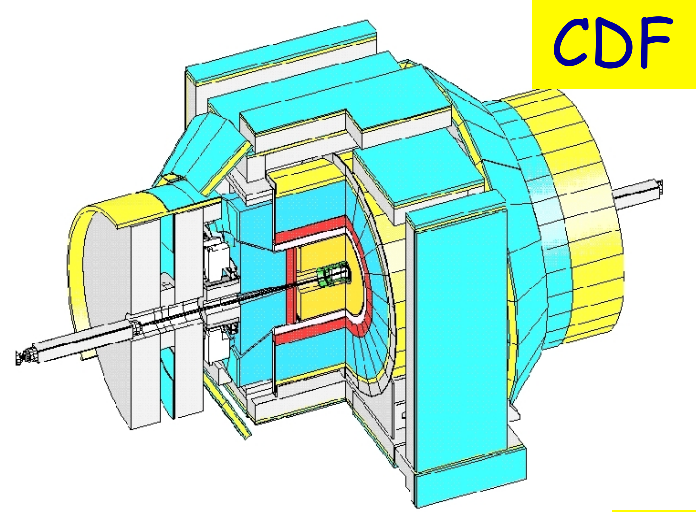
Tevatron Collider

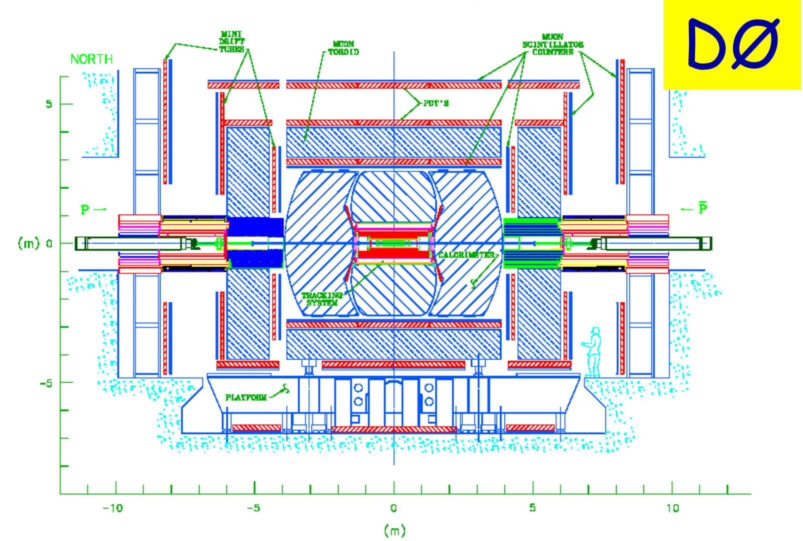
- The Tevatron Collider ran from 1985 to 2011 (with intervals of fixed-target running and upgrades)
- Run 2 covers the years from 2001 to 2011
- In Run 2 proton-antiproton collisions occurred at center of mass energy 1.96 TeV
- ≈10 fb^{-1} luminosity was recorded for each experiment
- This is a large and well-understood dataset



CDF and DØ Experiments

- The focus today will be on recent CDF and DØ measurements that satisfy one or more of the following:
  - Use the entire ~10 fb^{-1} dataset
  - Update previous results
  - Are significant new results in the areas of QCD or B and charm physics
- Take advantage of:
  - The p-pbar initial state
  - Higher luminosity and statistics
  - Specialized triggers
  - New analysis techniques
  - Improved understanding of the detectors and errors





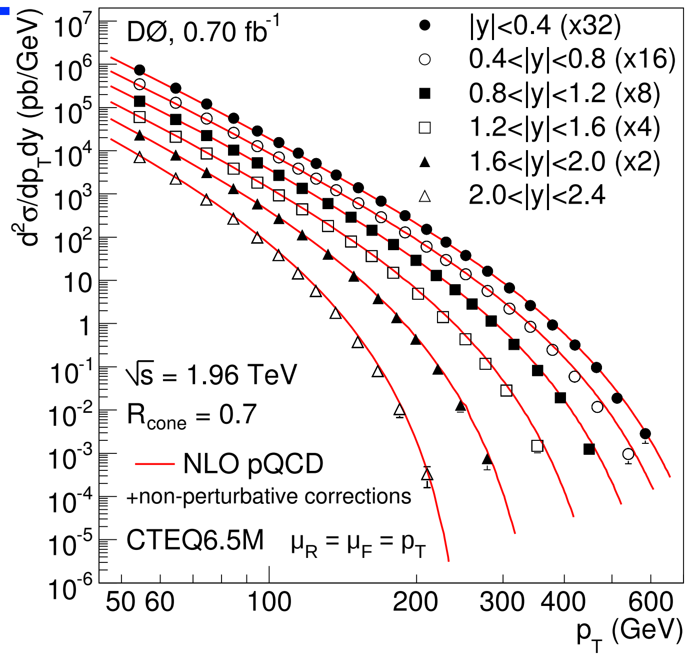
QCD PHYSICS

QCD

- The QCD analyses are primarily concerned with:
  - Parton Distribution Functions (pdfs)
  - Tests of QCD calculations (LO, NLO, NNLO, etc.)
  - Higher precision and new kinematic regions
  - Rarer processes only accessible now with larger datasets
  - Processes where p-pbar allow for interesting and potentially unique measurements
  - Many of the QCD analysis involve heavy quarks, and some of the heavy quark analyses have natural connections to QCD and fragmentation.

QCD Inclusive Jets

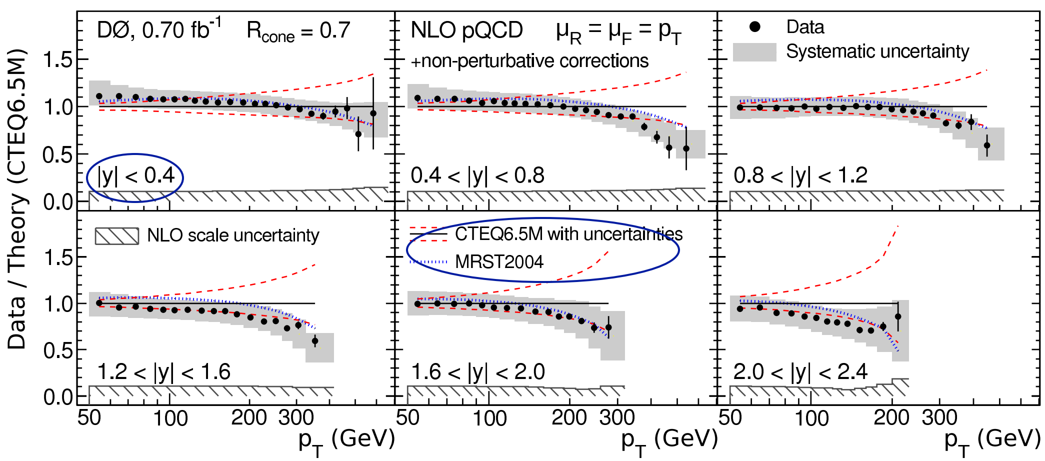
DØ

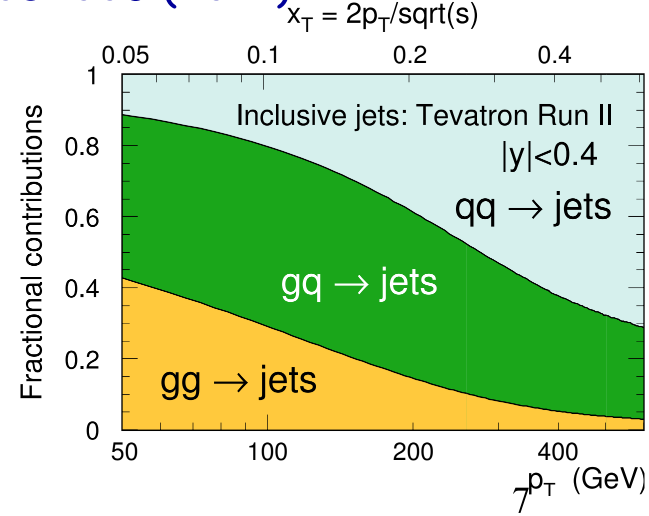


- Inclusive jets with:

$-2.4 < \eta < 2.4, 50\ \text{GeV} < p_T < 600\ \text{GeV}$

- Probe of parton distributions and qq, qg and gg subprocesses in $p\bar{p}$ collisions.
  - Contributions depend on the p_T of the jets (x_T of partons)
  - Measurements are sensitive to high x gluon distributions
- Agreement with CTEQ6.5M and MRST2004 pdf's is seen.
- PRD 85, 052006 (2012)

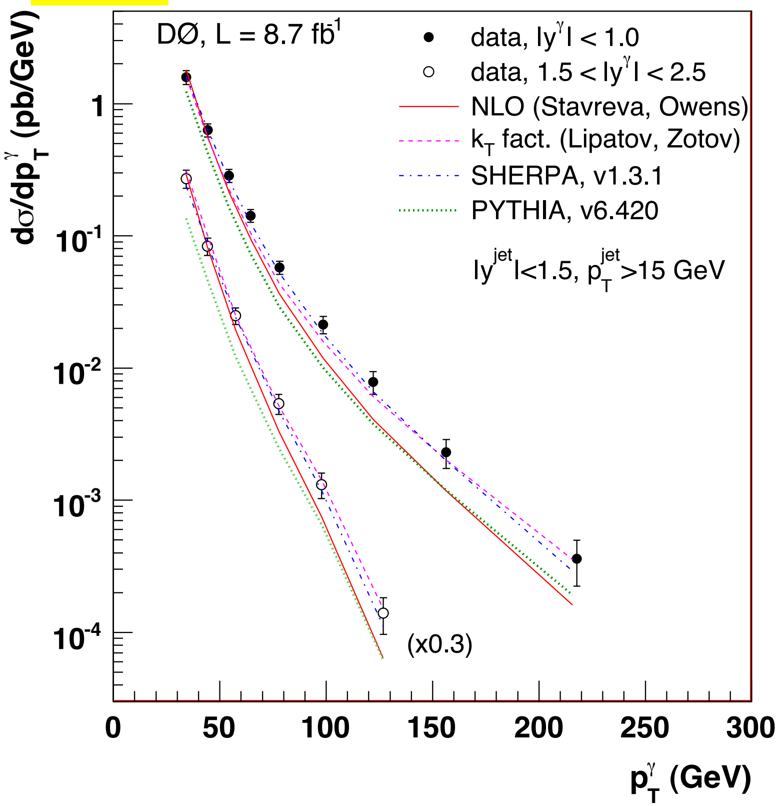




γ + b jets

(a) Compton scattering. (b) Annihilation.

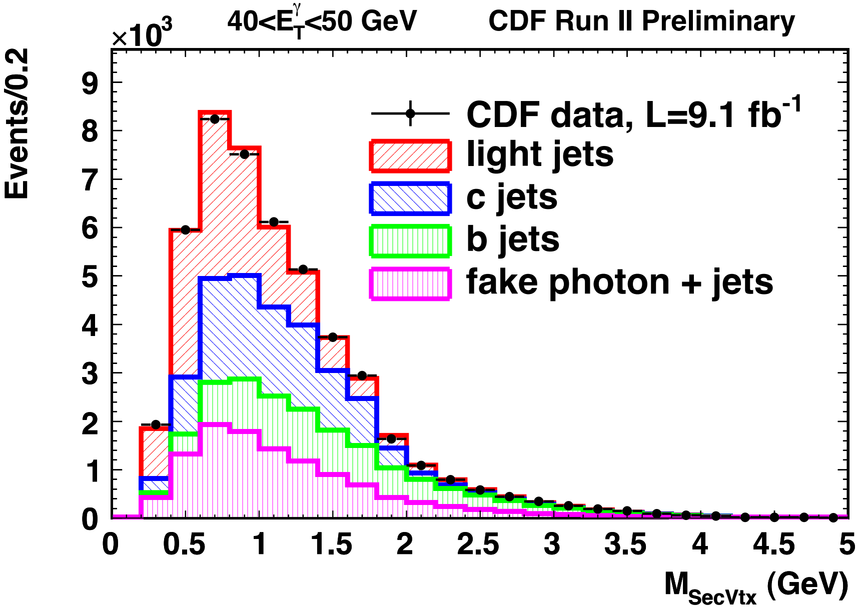
DØ



- DØ analysis uses 8.7 fb^{-1}
- Contributions from Qg->γQ (Compton) and qqbar->γQQbar (annihilation)
  - Probe of quark and gluon distributions in the proton
- Select central (|y|<1.0) and forward (1.5<|y|<2.5) photons.
- The differential cross section is measured as a function of photon p_T
- NLO QCD predictions show good agreement with data up to p_T < 70 GeV. Higher order QCD corrections are required at higher p_T

γ + b jets, γ + c jets

CDF



Luminosity 9.1 fb^{-1}

$30 < E_T^\gamma < 300, |y^\gamma| < 1.0$

$E_T^{jet} > 20, |y^{jet}| < 1.5$

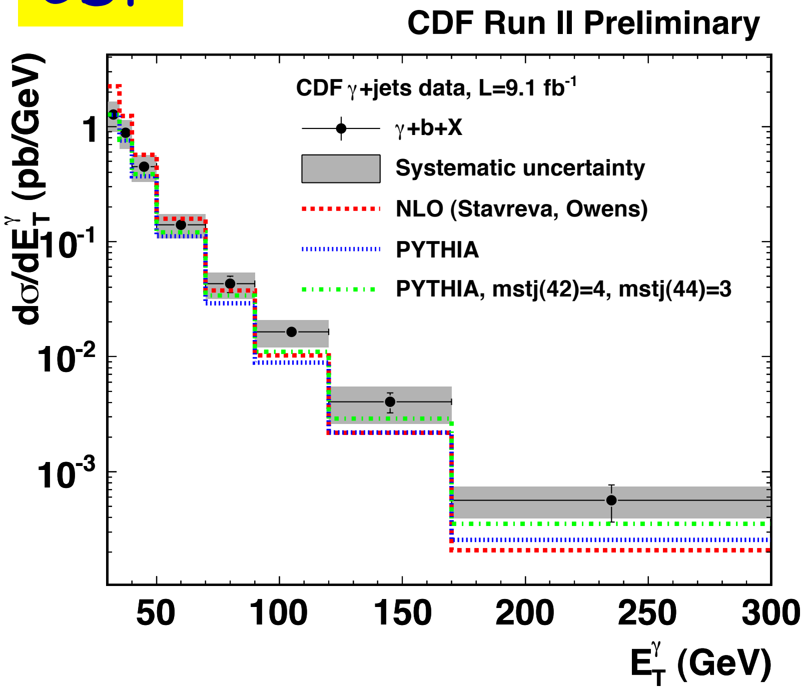
Fits to b, c, light quark jet fractions are made using templates from MC simulation.

Cross sections for γ+b and γ+c events are measured, taking into account efficiencies, unfolding, and other effects.

γ + b jets, γ + c jets

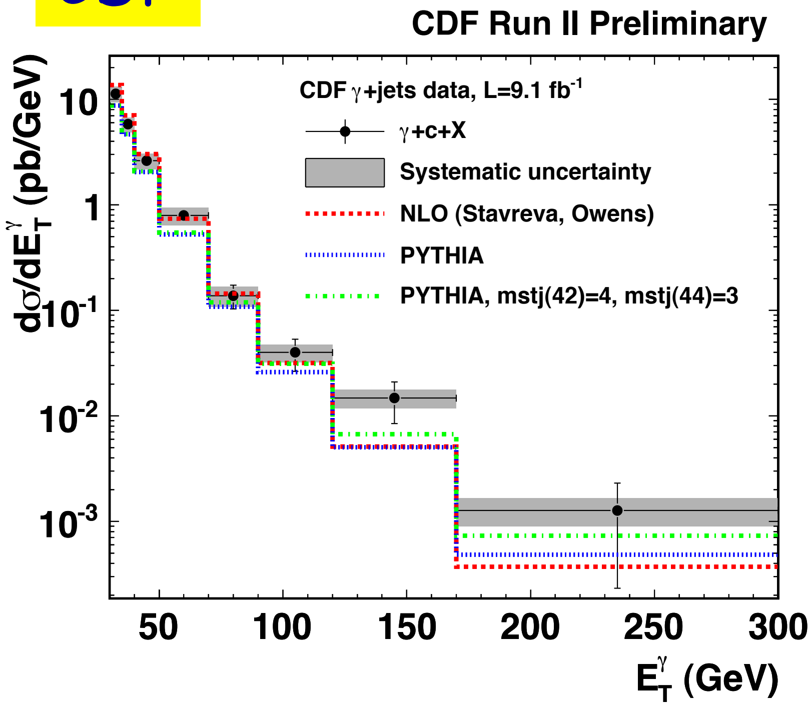
CDF

γ+b jets



CDF

γ+c jets



The NLO calculations match the data at low E_T, but fall below the data at high E_T, showing the need for higher order terms.

- Similar conclusion to the DØ results in γ+b jets.
- CDF Public Note 10818

HEAVY QUARK PHYSICS

Heavy Quark Physics

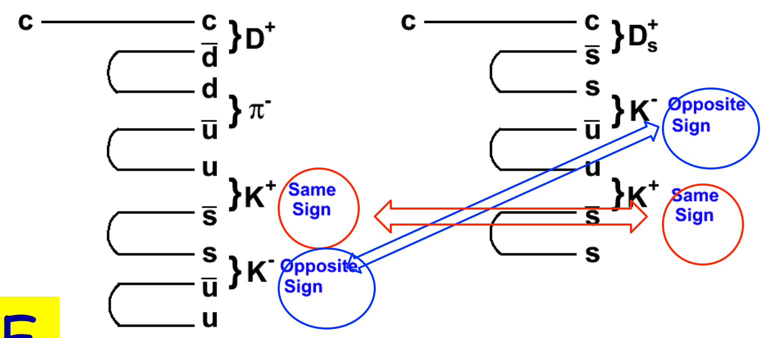
- Heavy Quark Physics
  - The study of heavy quark physics in p-pbar collisions provides valuable insight to HEP.
  - In particular, beyond standard model physics at higher energy scales can be accessed using low-energy, well-predicted flavor observables.
  - This talk will cover just a few results in the areas of:
    - Fragmentation
    - CP asymmetry
    - Decay modes
    - Lifetimes

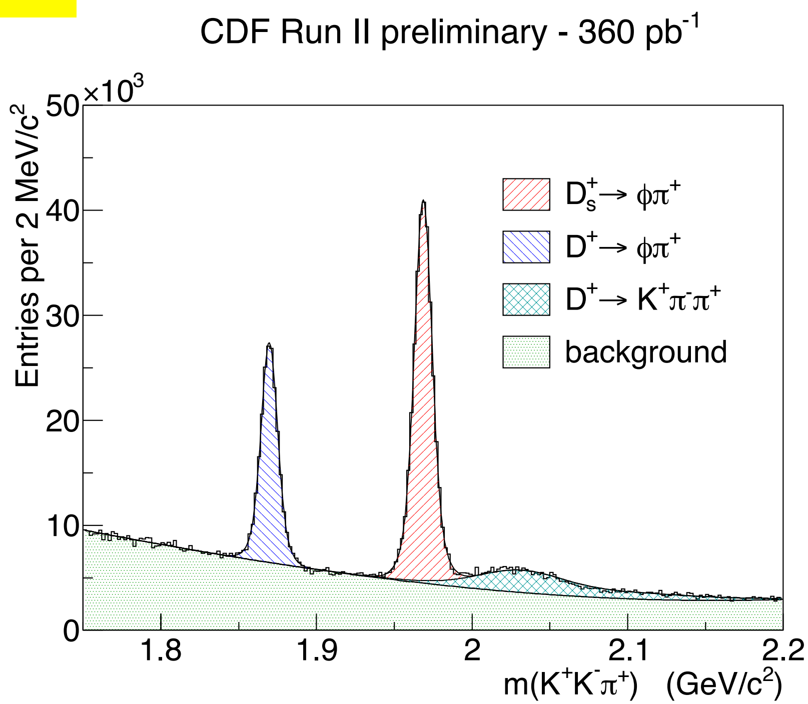
Quark fragmentation using K in association with D_s^+ /D^+

- A study of fragmentation looking at the charged K of same and opposite sign associated with D^+ and D_s^+
  - Expect to see differences in rates of opposite-sign and same sign K

CDF

- ~260,000 D_s^+ and 140,000 D^+ decaying to KKπ. The impact parameter distribution was used to separate prompt D_s^+/D^+ from D_s^+/D^+ from B decays.
- The results show expected qualitative behavior of opposite and like-sign K rates as a function of K p_T.





Quark fragmentation using K in association with D_s^+/D^+

Big difference between D_s (left) and D (right) in opposite sign K production.

Agrees with models

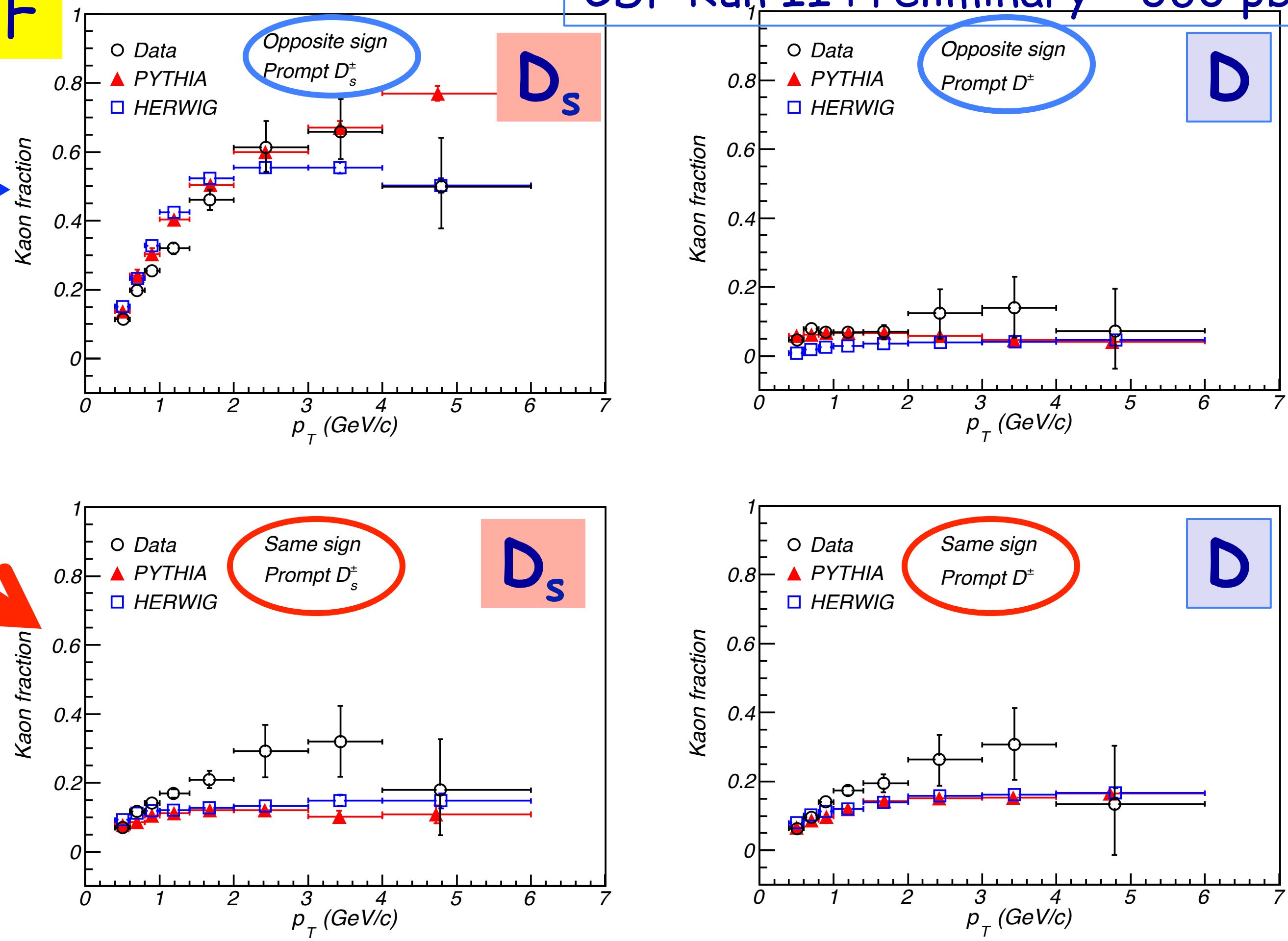
D_s and D similar in same sign K production

Disagrees with fragmention models

- Valuable input for further tuning of models.

CDF

CDF Run II Preliminary – 360 pb^{-1}



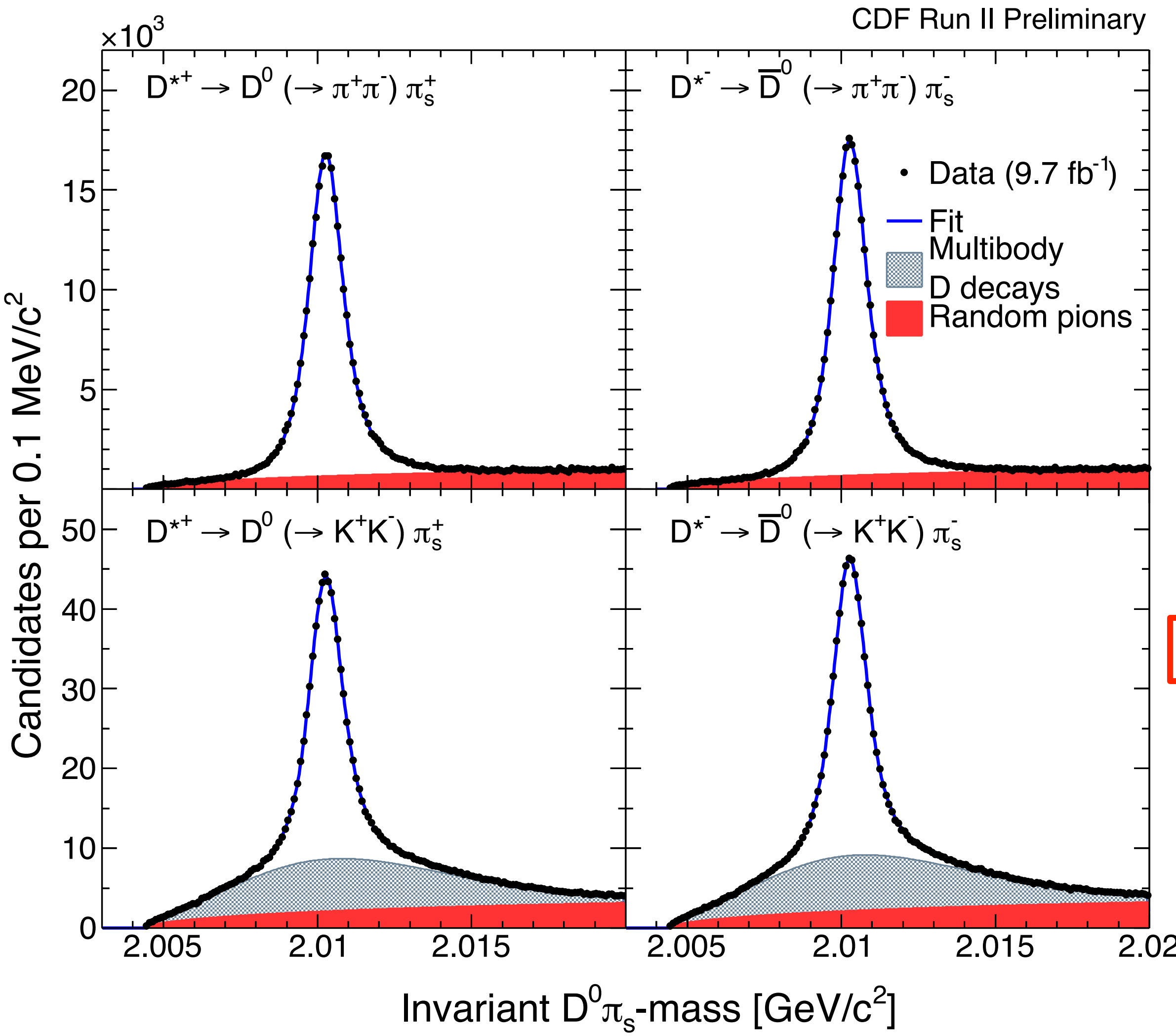
CDF Public Note 10704

CP Asymmetry in Heavy Quark Decay: $\Delta A_{cp}(D^0\text{->}hh)$

- CDF measured $A_{cp}(D^0\text{->}KK)$ and $A_{CP}(D^0\text{->}\pi\pi)$, as well as the difference in the two quantities, $\Delta A_{cp}(D^0\text{->}hh)$ in 5.9 fb^{-1}
  - $A_{cp}(D^0\text{->}KK) = [-0.24 \pm 0.22(stat) \pm 0.10(sys)]\%$
  - $A_{CP}(D^0\text{->}\pi\pi) = [0.22 \pm 0.24(stat) \pm 0.11(sys)]\%$
  - $\Delta A_{cp}(D^0\text{->}hh) = [-0.46 \pm 0.31(stat) \pm 0.12(sys)]\%$
    (PRD 85, 012009 (2012))
- The analysis for ΔA_{cp} has been updated with the full Run 2 dataset
- The event selection is relaxed due to cancellation of systematics in the difference measurement, leading to more signal events
- D^0 flavor is determined by the $D^*\text{->}D^0\pi_s$ decay
- Detector effects are canceled by using the difference of raw asymmetries of the KK and ππ decays:

➔ $\Delta A_{cp} = A(KK^*)-A(\pi\pi^*) = A_{cp}(K^+K^-)-A_{cp}(\pi^+\pi^-)$

$\Delta A_{cp}(D^0\text{->}hh)$



CDF

- ~550K D* tagged $D^0\text{->}\pi^+\pi^-$
- ~1.21M D* tagged $D^0\text{->}K^+K^-$
- Fits were used to extract the signal, BG, and multibody decays.
- $A(\pi\pi^*) = (-1.71\pm0.15)\%$
- $A(KK^*) = (-2.33\pm0.14)\%$
  - (Raw quantities)

$\Delta A_{CP}=[-0.62\pm0.21 \pm0.10]\%$

2.7σ different from 0

CDF public note 10784

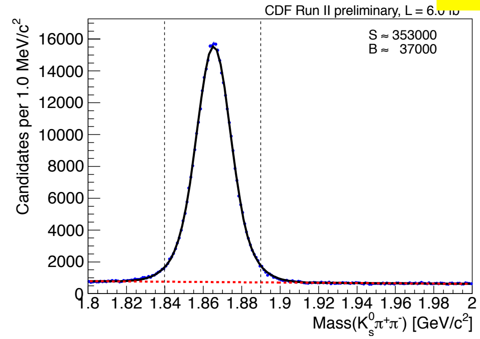
This result is a confirmation of LHCb measurement:

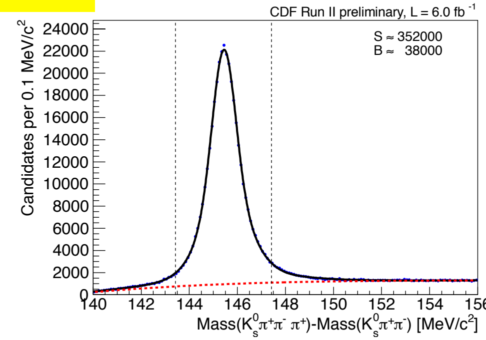
$\Delta A_{cp}=[-0.83\pm0.21\pm0.11]\%$

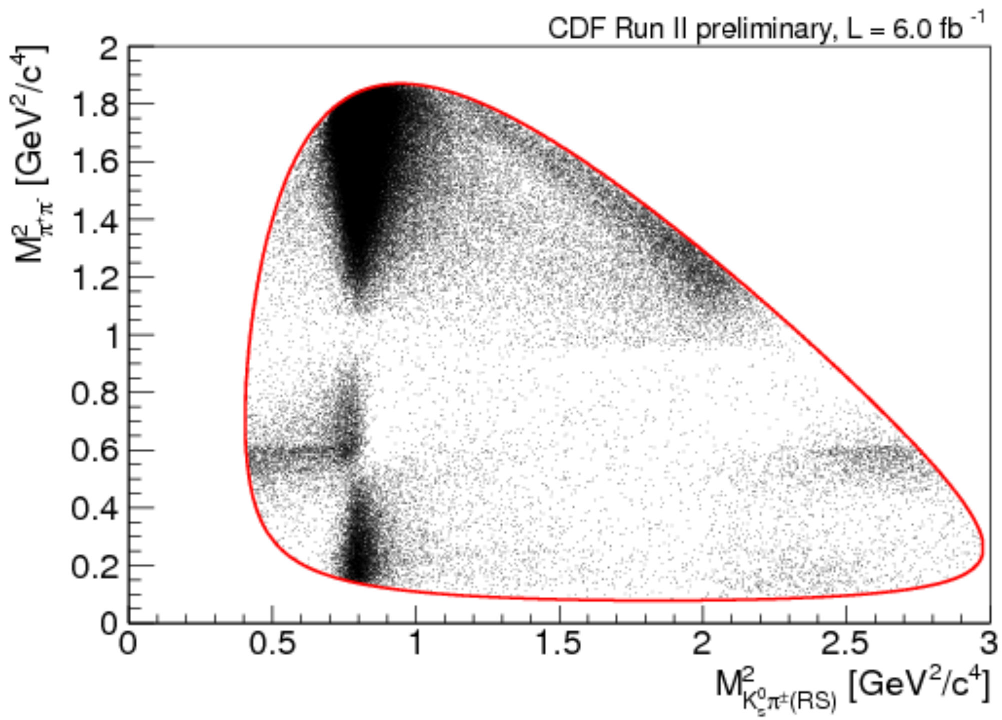
A_{cp} in $D^0 \to K_s\pi\pi$

CDF

- A_{cp} is also measured in CDF in D^0 decay to $K_s\pi\pi$
  - Standard Model expectations ~10^{-6}
- D* tag is used to determine D^0 flavor
- Two methods are used:
  - *A full Dalitz fit using the isobar model*
  - *A model independent bin-by-bin comparison of D^0 and D^0-bar plots.*
- From the fits A_{cp} is extracted



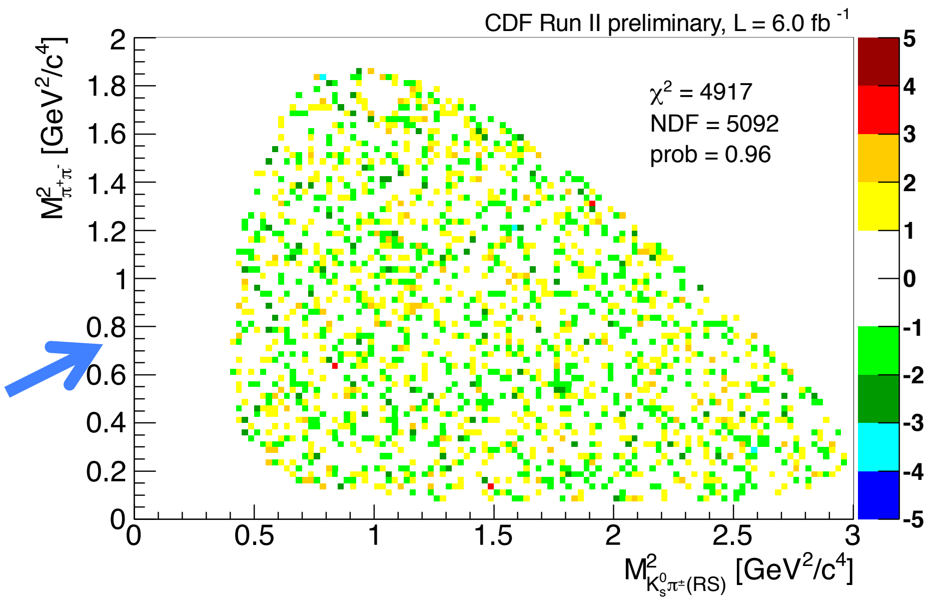




A_{cp} in D^0->$K^0\pi\pi$

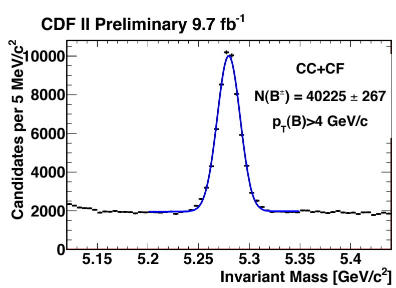
- Resonance substructure (amplitude and phases) are measured
  - No evidence for CP violation is found in any sub resonance, with resolutions better than previous experiments.
- A model-independent difference bin-by-bin subtraction is also measured
- Integrating over all modes:
- A_{cp} = -0.0005 ± 0.0057 ± 0.0054

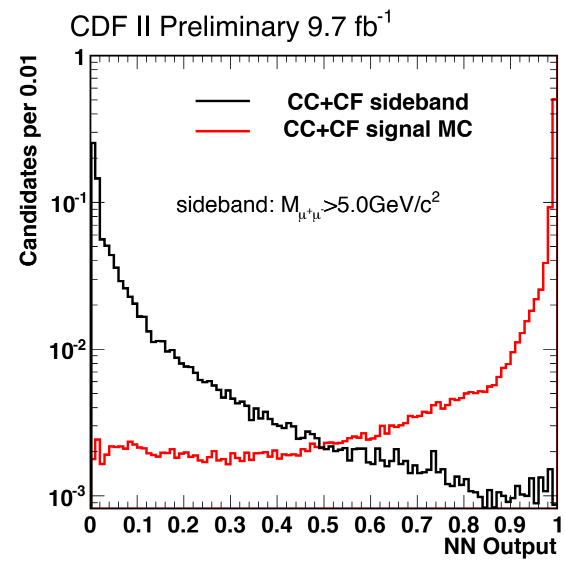
  Assuming no direct CP asymmetry one can derive:
- A_{cp}^{ind} = -0.0002+-0.0025+-0.0024



$B \to \mu^+\mu^-$

- Processes involving FCNC are an excellent way to search for new physics
- SM predictions: $BR(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$, $BR(B_d \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$
- CDF published results using 7 fb^{-1} (PRL 107, 191801 (2011))
  - $BR(B_d \to \mu^+\mu^-) < 6.0 \times 10^{-9}$ at 95% C.L.
  - $BR(B_s \to \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$
- The CDF analysis was extended to full Run 2 dataset (9.7 fb^{-1})
  - No change to analysis methods
  - NN to discriminate signal from background
  - Normalize to $BR(B^+ \to J/\psi K^+)$:

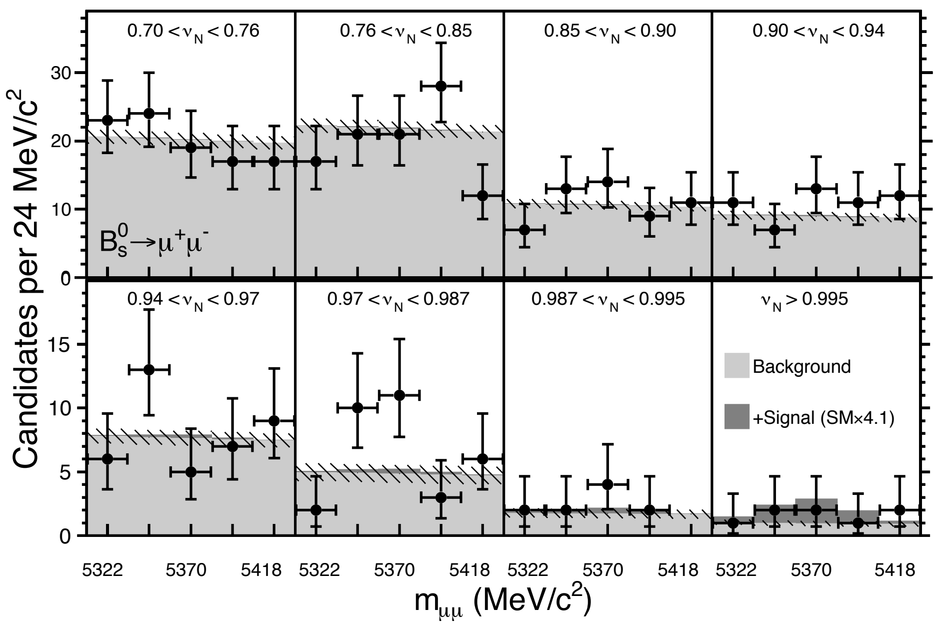




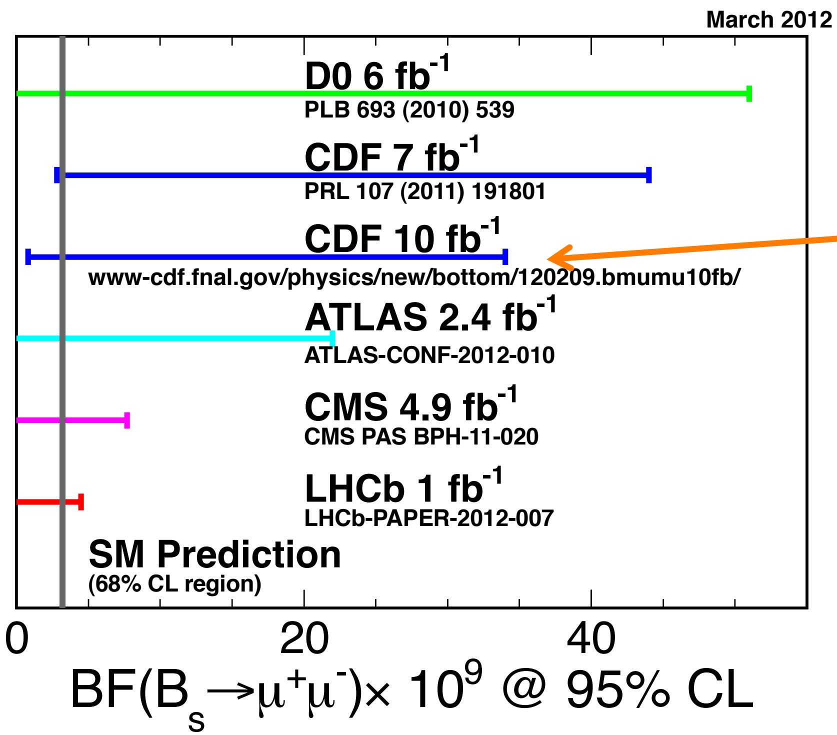
B->μ+μ⁻

- The challenge is to reject a large background while keeping most of the signal
- 14 discriminating variables were used to build an optimized neural net classifier to separate signal from background
- Combinatorial background is estimated from mass sidebands
- Fake muon background estimated from B->hh and D->Kπ

CDF Preliminary 9.7 fb^{-1} **CDF**



$B_s \to \mu+\mu^-$



Results:

- $BR(B_d \to \mu^+\mu^-) < 4.6 \times 10^{-9}$ (95% CL)
- $BR(B_s \to \mu^+\mu^-) = (1.3^{+0.9}_{-0.7}) \times 10^{-8}$
- $0.8 \times 10^{-9} < BR(B_s \to \mu^+\mu^-) < 3.4 \times 10^{-8}$ (95% CL)
- $BR(B_s \to \mu^+\mu^-) < 3.1 \times 10^{-8}$ (2.7×10^{-8}) 95% (90%) CL

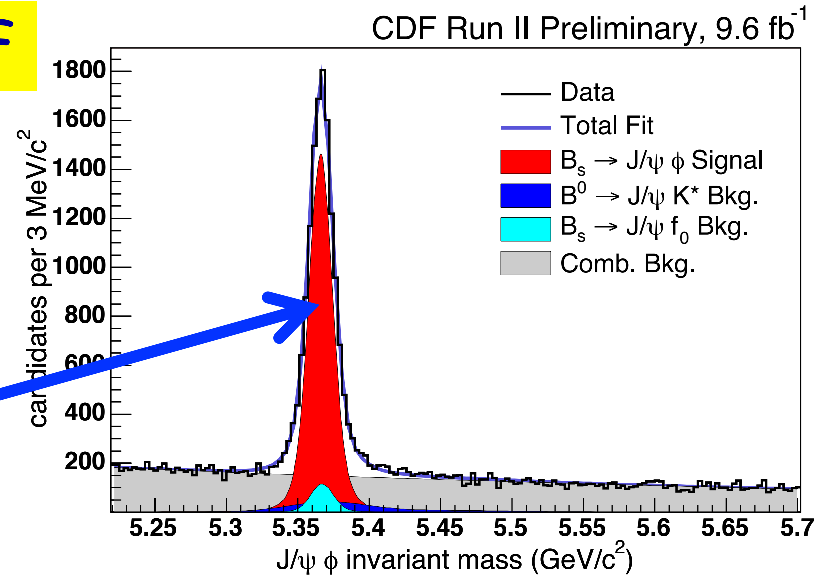
CDF publication is in preparation

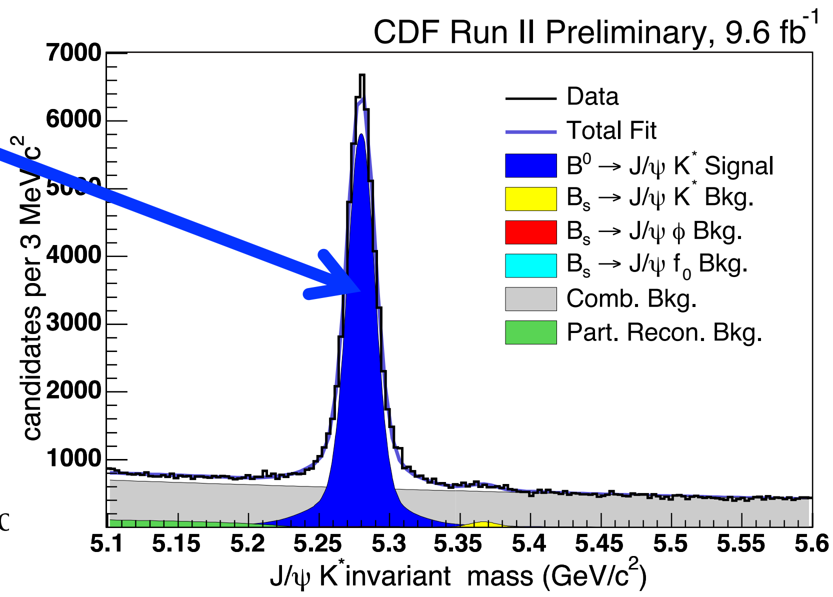
Getting closer to a measurement of the $B_s \to \mu\mu$

$BR(B_s \to J/\psi\phi)$ and f_s/f_d

CDF

- Using the full Run 2 dataset CDF measures the ratio:
  - $R = (f_s * BR(B_s \to J/\psi\, \varphi)/ f_d * BR(B^0 \to J/\psi\, K^*))$
- Selection is optimized by maximizing $S/\sqrt{S+B}$.
- A binned log likelihood fit is made to signal shape templates and background functions:
  - ~11,000 $J/\psi\varphi$
  - ~57,000 $J/\psi K^*$
- Final result, corrected for acceptance:
  - $R = 0.239 \pm 0.003 \pm 0.019$
- Using CDF fs/fd and PDG $BR(B^0 \to J\psi K^*)$ we can extract:
  - $BR(B_s \to J/\psi\varphi) = (1.18 \pm 0.02 \pm 0.09 \pm 0.014 \pm 0.05) * 10^{-3}$
  - World's best measurement.

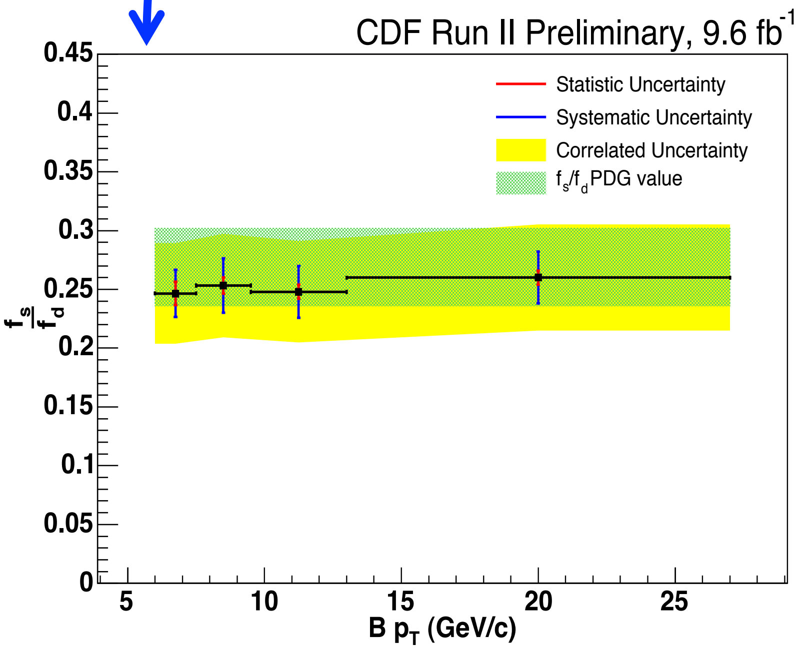


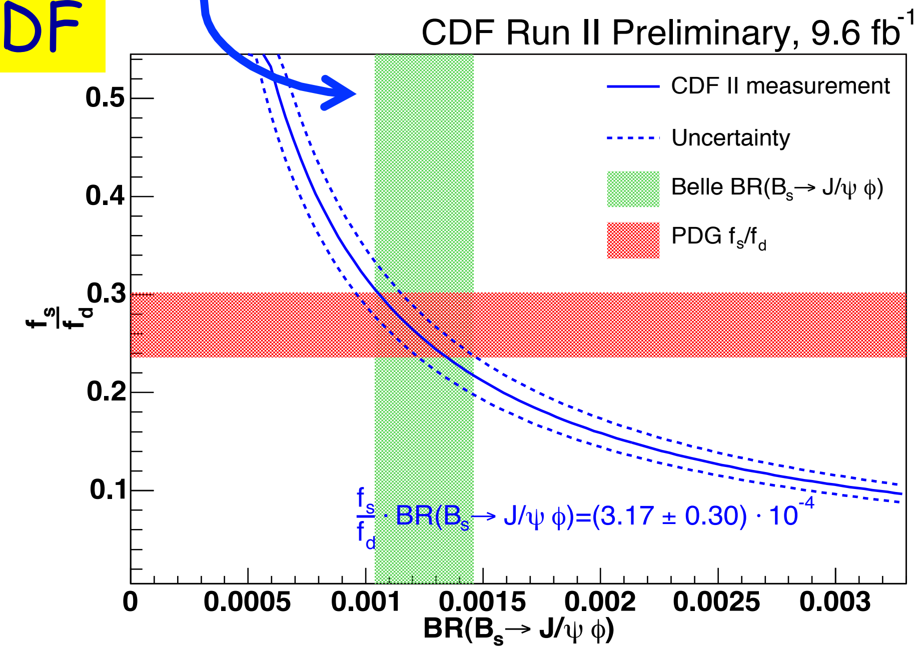


$BR(B_s \to J/\psi\phi)$ and f_s/f_d

- The fits to B_s->$J/\psi\varphi$ and B_s->$J/\psi K^*$ are performed in 4 p_T ranges
- $f_s/f_d(p_T)$ can be extracted using Belle's latest BR(B_s->$J/\psi\varphi$)
- This is the first measurement of f_s/f_d as a function of p_T
- Averaging over all p_T: f_s/f_d=0.254±0.003±0.020±0.044
- More generally, the CDF measurement of f_s/f_d is a function of BR (B_s->$J/\psi\varphi$) and is shown below

CDF



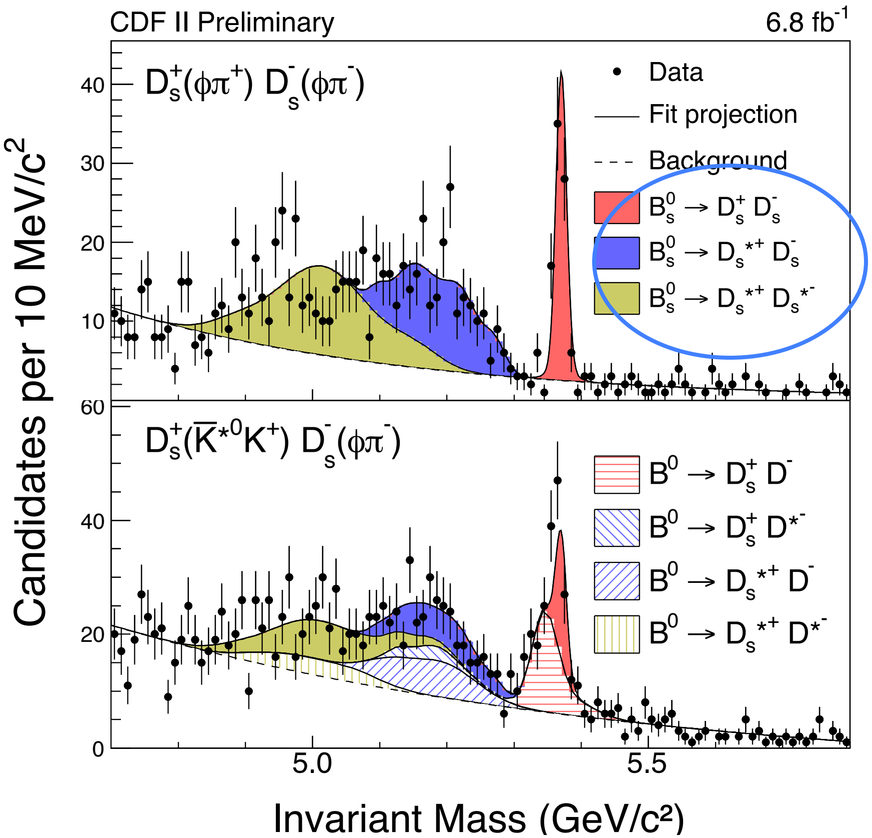


$B_s \to D_s^{(*)+} D_s^{(*)-}$

- CDF has measured the BR's of B_s decays:
  - (B_s->$D_s^+D_s^+$), (B_s->$D_s^{*+}D_s^+$), (B_s->$D_s^{*+}D_s^{*+}$)
    - where: (D_s->$\varphi\pi$), (D_s->$K^{*0}K$)
- These measurements may provide information on $\Delta\Gamma_s$
- A neural net is used to separate signal and background contributions.
- The final sample contains ~750 B_s->$D_s^{(*)}D_s^{(*)}$ decays
- A simultaneous fit is made to B_s and B_d decays to separate the decay contributions. BR's were normalized to well-measured B_d -> D_sD BR's.
  - The fitting procedure accounts for partially reconstructed D_s^* decays in the fit using mass shapes.

$B_s \to D_s^{(*)+} D_s^{(*)-}$

CDF



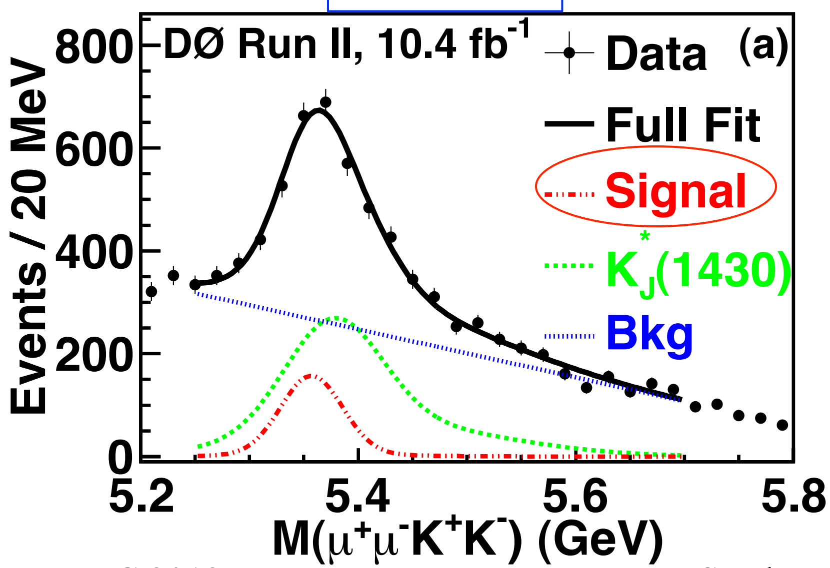
- World's best measurements of the BR's.
- Published in PRL 108, 201801 May 14,2012
- $Br(B^0_s \to D^+_s D^-_s) = (0.49 \pm 0.06 \pm 0.05 \pm 0.08)\%$
  $Br(B^0_s \to D^{*+}_s D^-_s) = (1.13 \pm 0.12 \pm 0.19 \pm 0.09)\%$
  $Br(B^0_s \to D^{*+}_s D^{*-}_s) = (1.75 \pm 0.19 \pm 0.17 \pm 0.29)\%$
  $Br(B^0_s \to D^{(*)+}_s D^{(*)-}_s) = (3.38 \pm 0.25 \pm 0.30 \pm 0.56)\%$

- Values are lower than but consistent with recent Belle result.
- These provide important constraints for indirect searches for new physics.

$B_s^0 \to J/\psi f_2'(1525)$

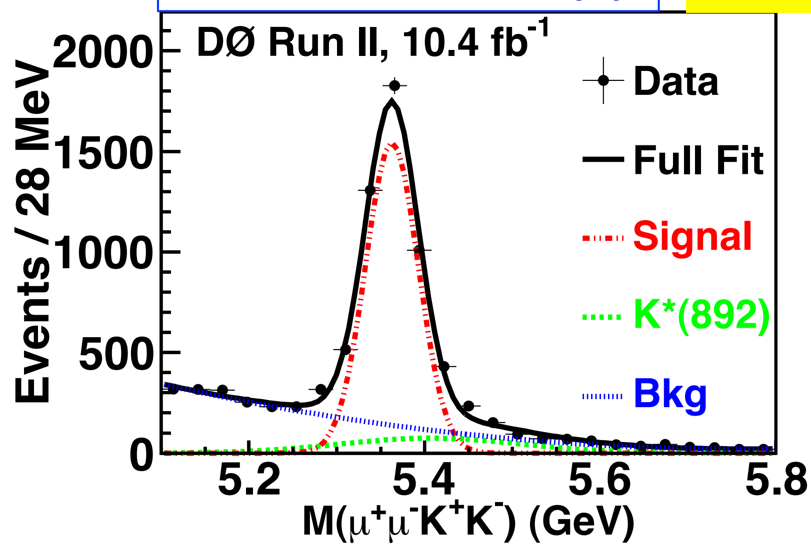
- This measurement uses the full Run 2 dataset : 10.4 fb-1
- Require a 4 track vertex, where the $\mu^+\mu^-$ consistent with J/ψ, and 1.35<M(K^+K^-)<2.0 GeV
- MC templates used to separate contributions from (J/ψ f_2'(1525)), (J/ψ φ), (J/ψ K_2*(1430)), (J/ψ K^0*(1430))
- Fitting is done as a function of K^+K^- mass to extract the f_2(1525) contribution. Contributions from K^0*(1430) and f_2'(1525) are seen.

Final Fit

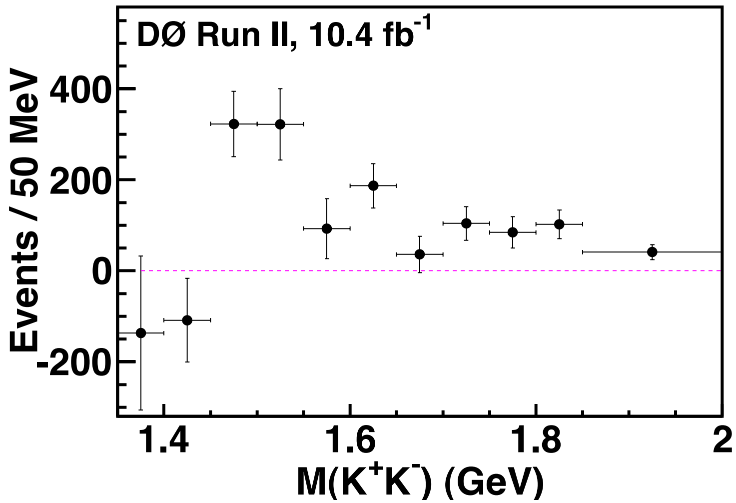


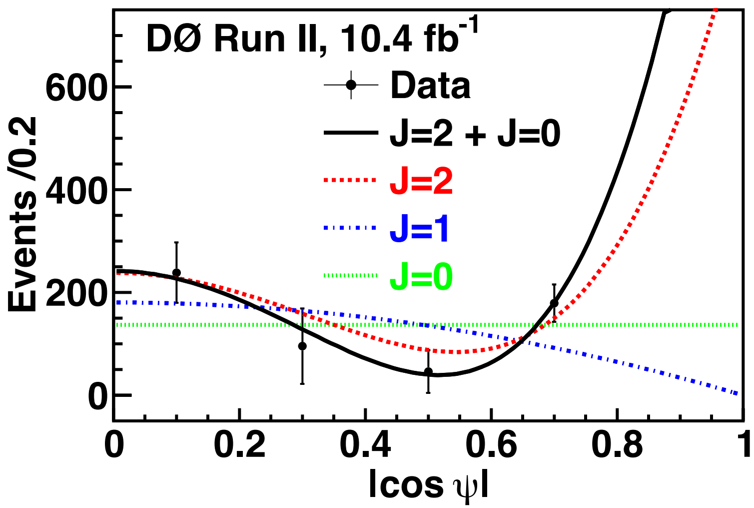
Normalization $J/\psi\phi$

DØ



$B_s^0 \to J/\psi f_2'(1525)$





DØ

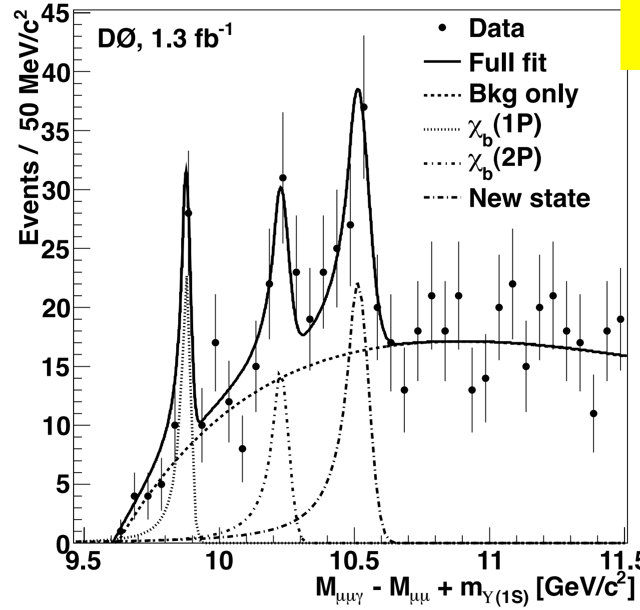
- Spin of K^+K^- is studied and is consistent with a combination of spin 0 and spin 2 and is inconsistent with spin 1.
- R = BR(B_s->J/ψ f_2'(1525))/BR(B_s->J/ψ φ) = 0.22±0.05±0.04
  - arXiv:1204.5723 (submitted to Phys. Rev. D)
- R(LHCb) = 0.26±0.027±0.024

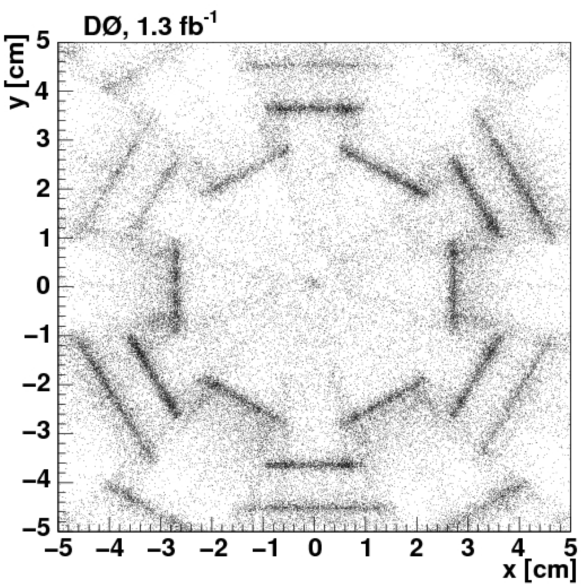
$\chi_b \rightarrow \Upsilon(1S) + \gamma$

DØ

Υ candidates in the mass range 9.1<M<9.7 are combined with photons identified by their conversions into e^+e^-- pairs.

3 peaks in the mass difference $M_{\mu\mu\gamma}$-$M_{\mu\mu}$ are seen corresponding to $\chi_b(1P)$, $\chi_b(2P)$ and a new state with significance 5.6σ, consistent with a state seen by ATLAS.





M(new state)=10.551±0.014±0.017

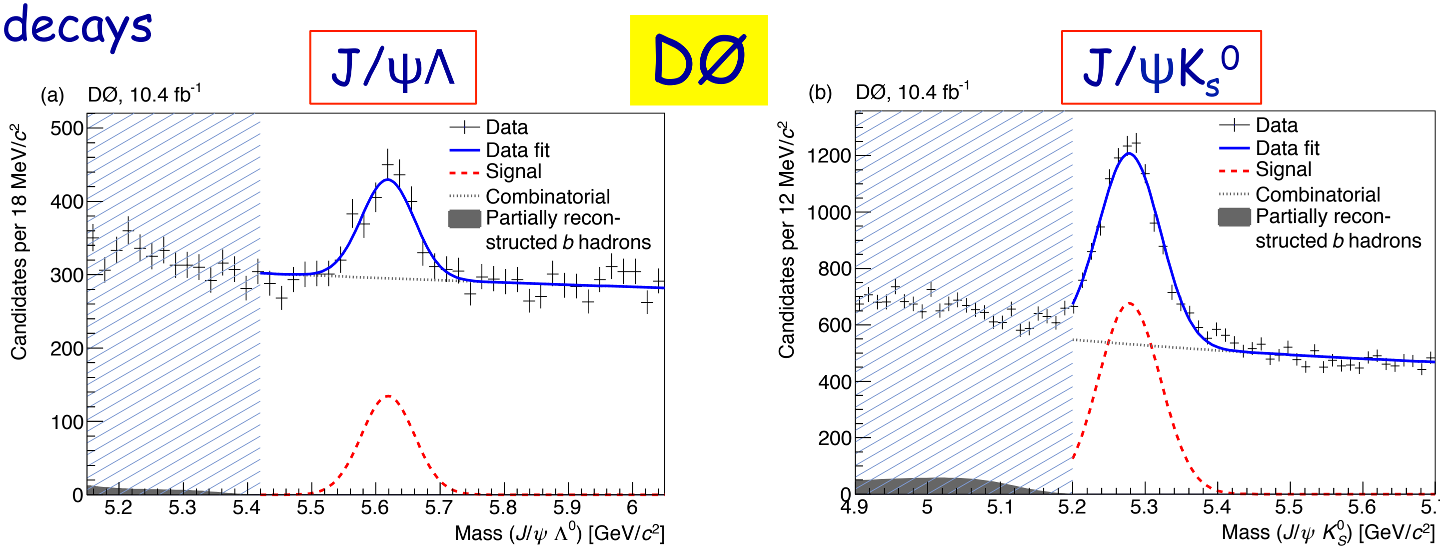
arXiv:1203.6034 (Submitted to PRD RC)

ATLAS: M=10.530±0.005±0.009

(PRL 108, 152001 (2012))

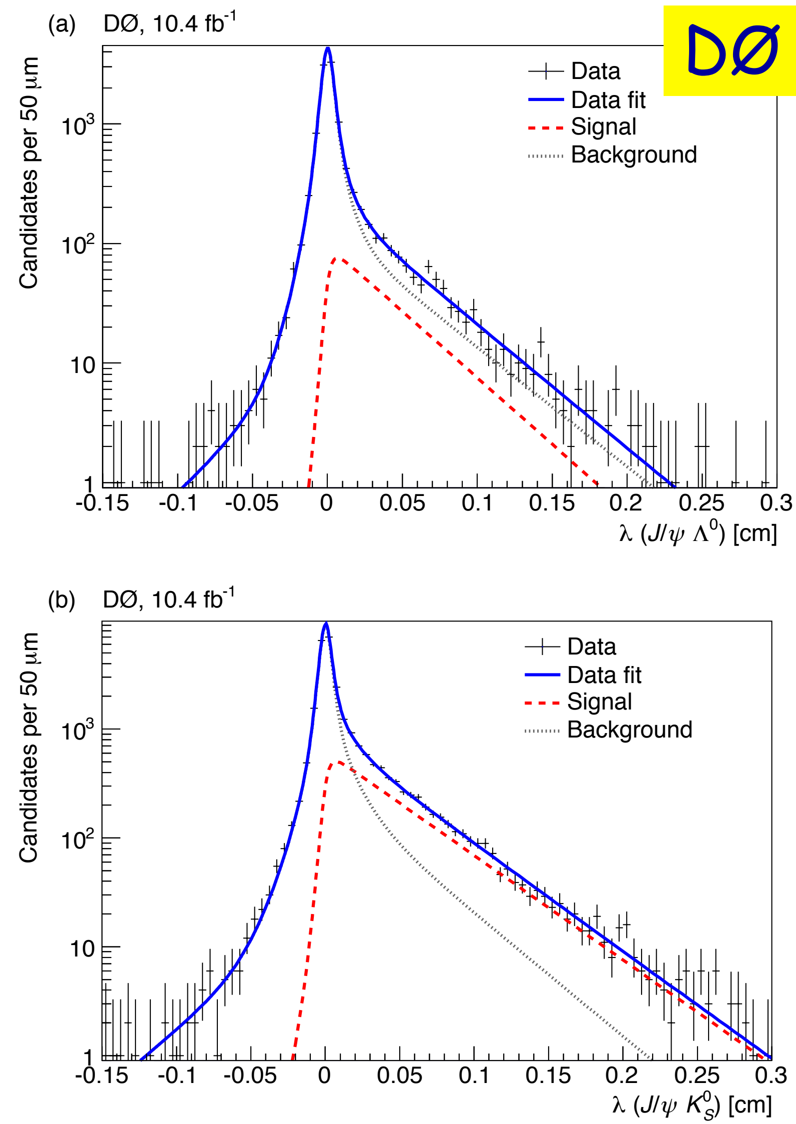
Λ_b Lifetime

- Λ_b lifetime is a puzzle, measurements don't agree, deviations from predictions.
  - New measurements are needed to help resolve the mystery.
- New DØ analysis of the Λ_b lifetime
- Uses full Run 2 Dataset – 10.4 fb^{-1}
- This analysis measures lifetimes in two similar decay modes:
  - $\Lambda_b \to J/\psi\Lambda$, $B^0 \to J/\psi K_s^0$
- Separate fits to both Λ_b and B^0 lifetimes in topologically similar decays



Λ_b lifetime

- Final fit results:
  - $\tau(\Lambda_b)$ = 1.303 ± 0.075 ± 0.035 ps
  - $\tau(B^0)$ = 1.508 ± 0.025 ± 0.043 ps
  - $\tau(\Lambda_b)/\tau(B^0)$ = 0.864 ± 0.052 ± 0.033
- arXiv:1204.2340, accepted by PRD
- Compare to other values (2011):
  - $\tau(\Lambda_b)$ = 1.425 ± 0.032 ps (PDG 2011)
  - $\tau(\Lambda_b)$ = 1.537 ± 0.045 ± 0.014 ps (CDF, PRL 106, 121804 (2011))
- There remains disagreement among the measurements in the value of $\tau(\Lambda_b)$
  - Puzzle is not yet resolved



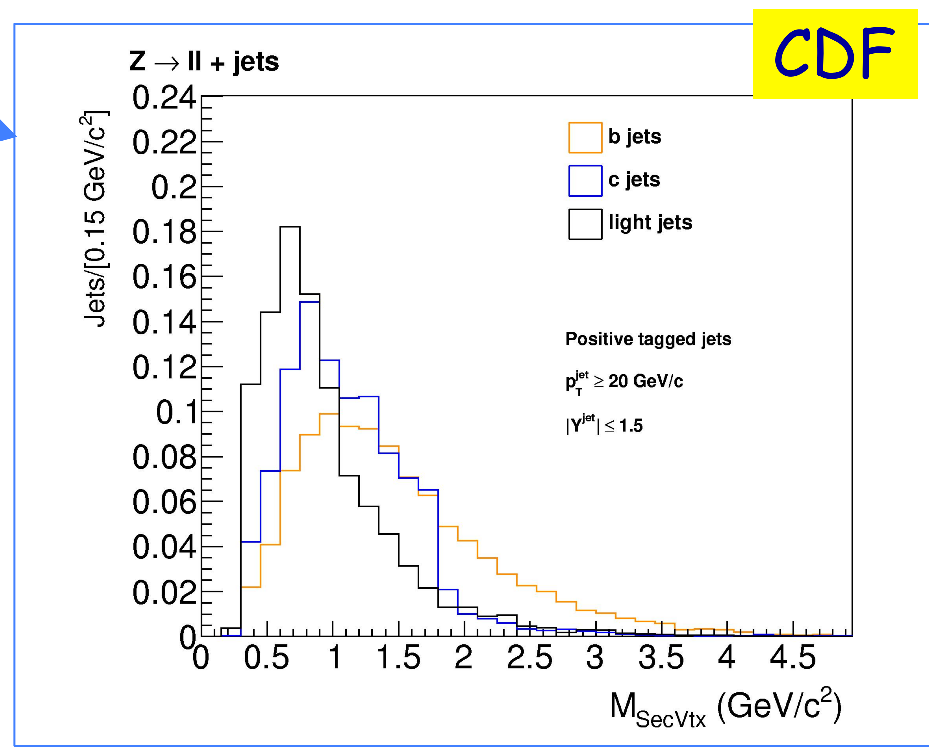
Summary and Prospects

- DØ and CDF have new and important results on many areas of QCD and heavy quark physics.
  - Many results are world's best or the only measurements of these quantities.
- Both experiments continue analysis of the full Run 2 dataset.
- The emphasis will be on higher precision and use of the unique capabilities of the Tevatron datasets.
- You can expect to see important and interesting results for some time to come.

Backup/Extra topics

Z + b jets

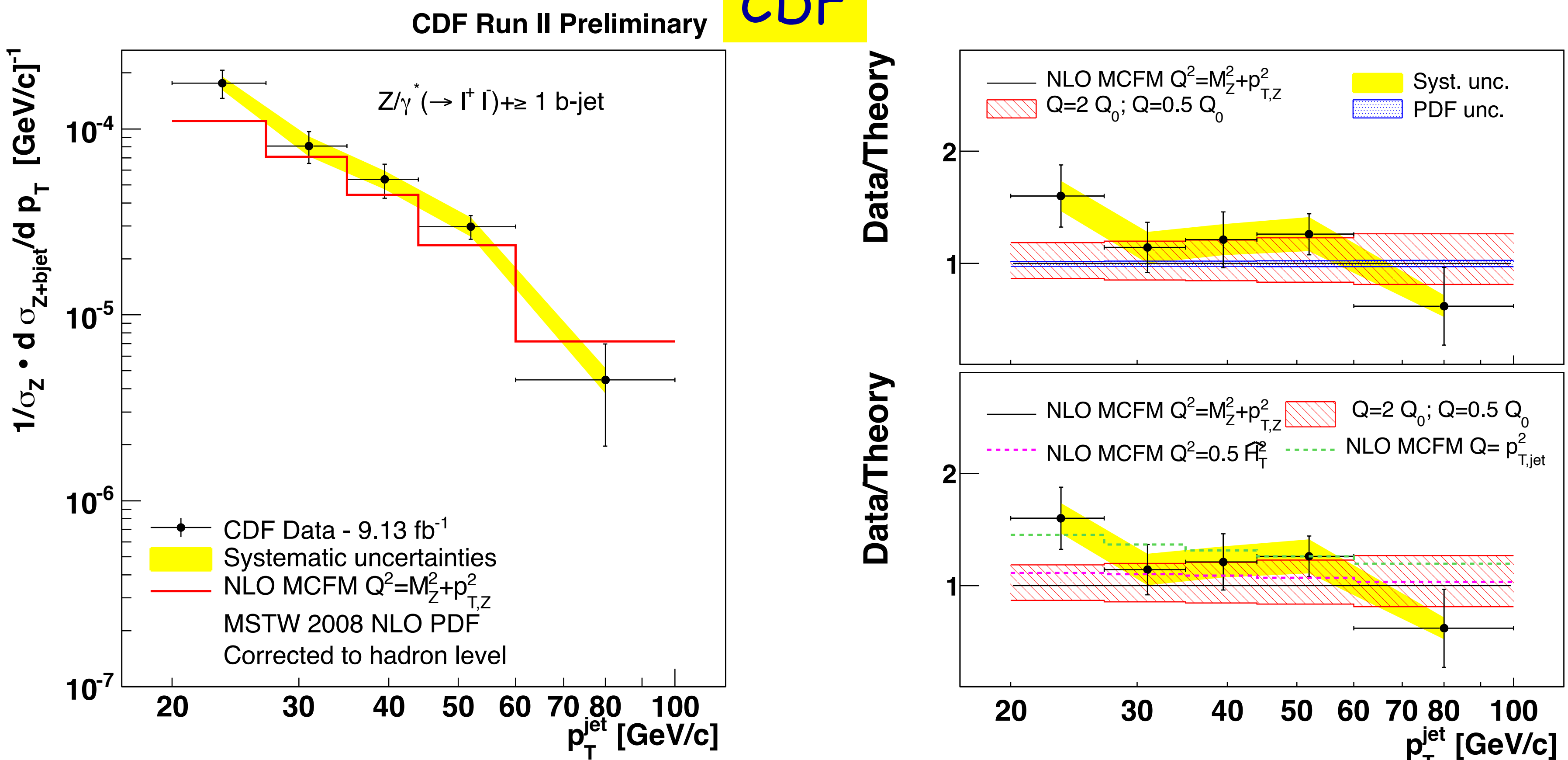
- Full CDF Run 2 dataset is used (9.1 fb-1)
- Z->μμ and Z->ee events are selected using an ANN
- Templates are used to fit b jet, c jet and light jet contributions
- Total Z+b jet cross section is normalized to Z+inclusive jets and Inclusive Z events
- The results for the differential cross section is calculated and agrees with MCFM NLO calculations



$$R = \frac{\sigma(Z(\to ll) + b\ jets)}{\sigma(Z \to ll)} = \frac{A_Z^{MC}}{A_{Z+bjet}^{MC}} \cdot \frac{N_{Z+bjets}^{data}}{N_Z^{data}}$$

Z + b jets

CDF



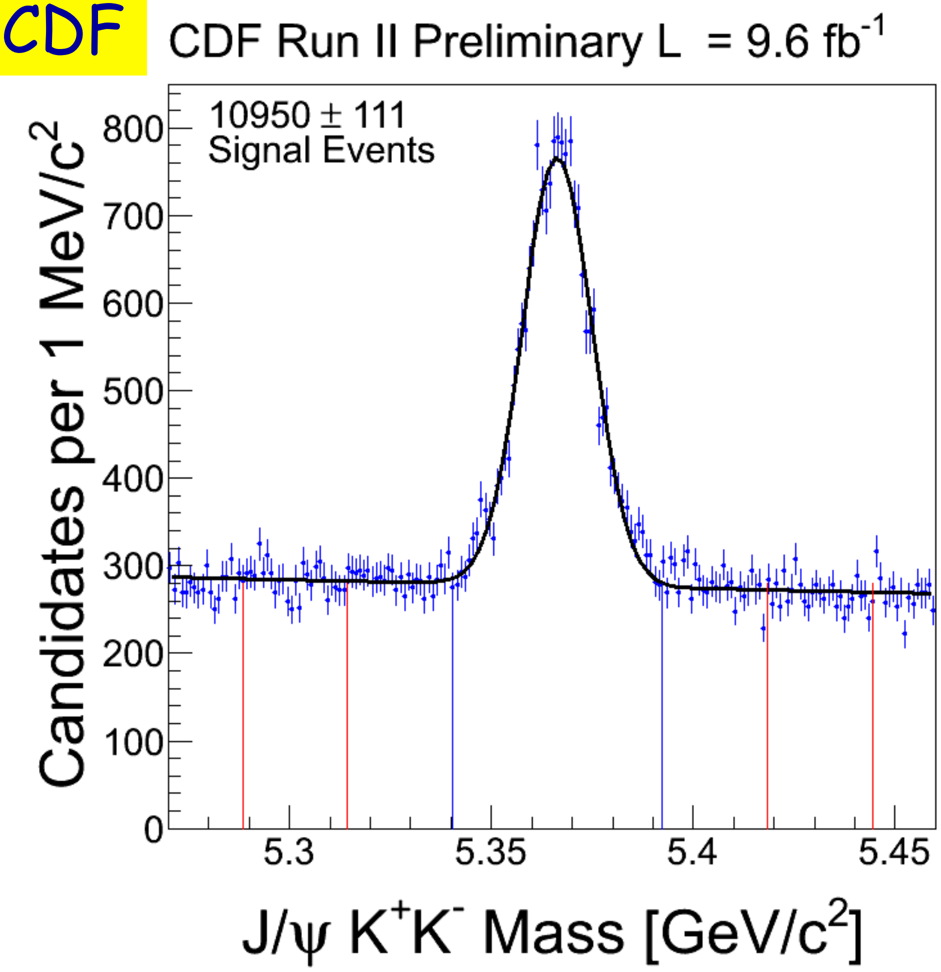
- $\sigma(Z\text{+b-jet})/\sigma(Z) = [0.261 \pm 0.023 \pm 0.29]\%$
- $\sigma(Z\text{+b-jet})/\sigma(Z) = 0.23\%$ (NLO + MCFM, $Q^2=m_Z^2+p_{T,Z}^2$)

  0.29% (NLO + MCFM, $Q^2=\langle p_{T,jet}\rangle^2$

$B_s \to J/\psi\phi$

CDF

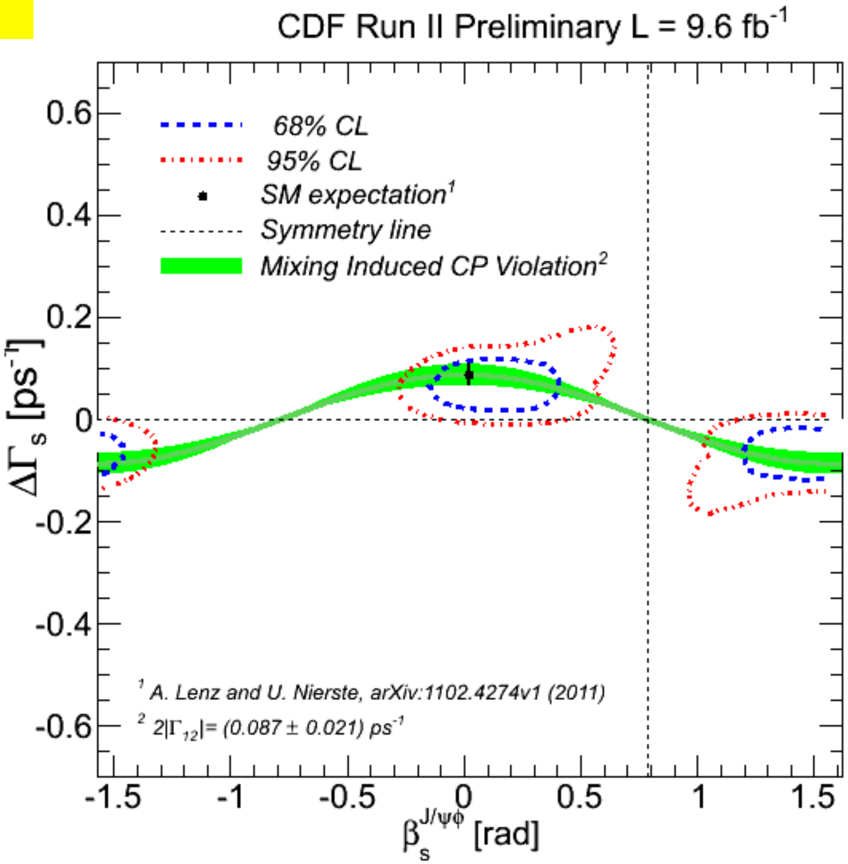
- Analysis uses full CDF dataset
- Neural-net used to separate signal and background
- ~11,000 $J/\psi\varphi$ events are analyzed
- A Likelihood fit was used to extract parameters:
  - $\Delta\Gamma_s$ and $\beta_s^{J/\psi\varphi}$



$B_s \to J/\psi\phi$

CDF

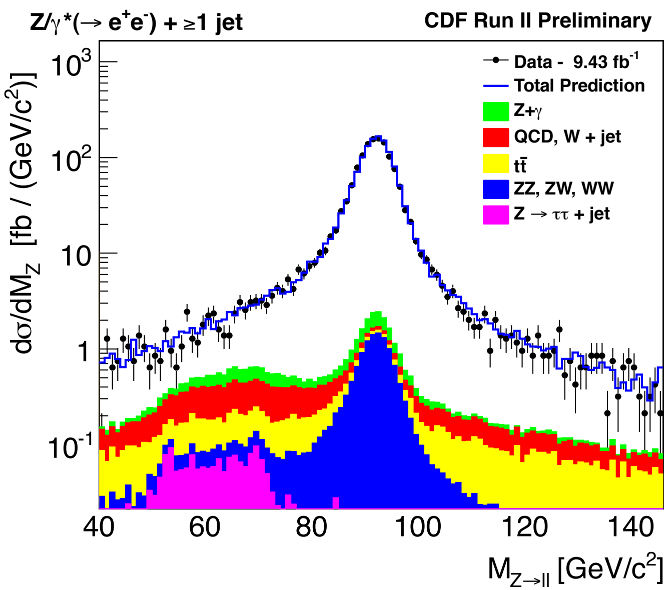
- CDF update of $\beta_s^{J/\psi\varphi}$ measurement
- The confidence interval of φ_s is measured to be [-0.60, 0.12] rad at 68% CL, in agreement with the CKM value and recent LHCb and DØ values.

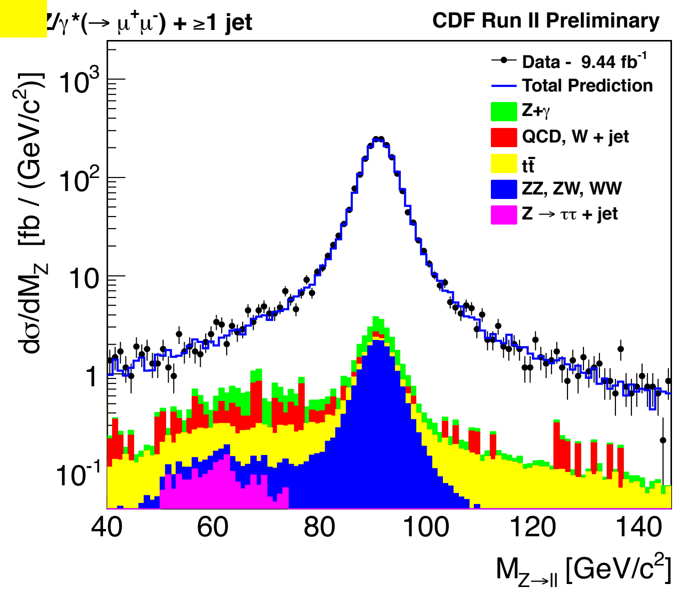


Z/γ* + jets

- Full CDF Run 2 dataset (9.4 fb-1)
- Jets are reconstructed using midpoint algorithm with R=0.7 and p_T jet>30 GeV and $|y_{jet}|$<2.1
- Z/γ*->μμ or ee
- Backgrounds estimated using MC and data-driven techniques

CDF

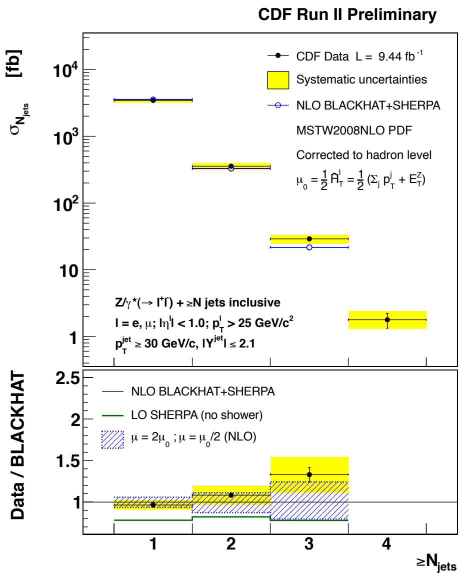


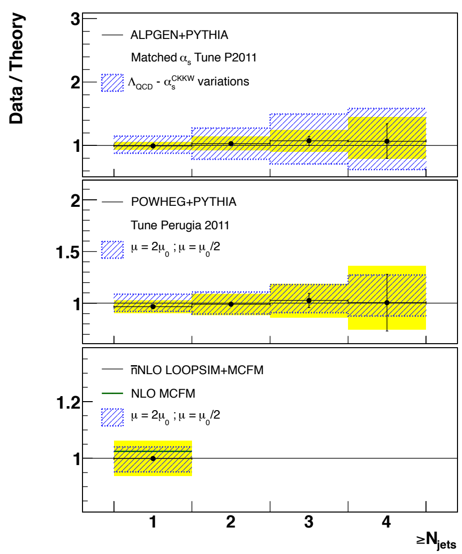


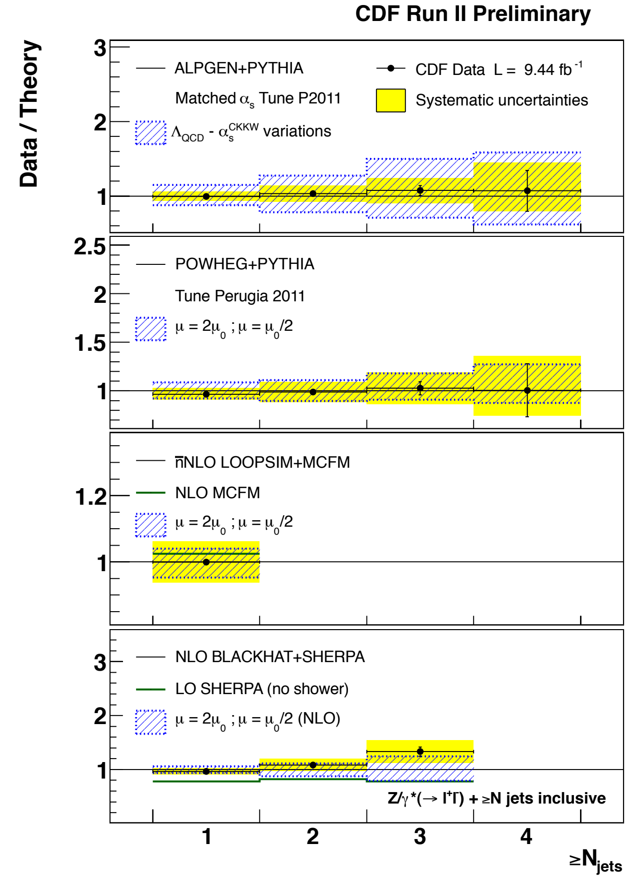
Z/γ* + jets

- Results are unfolded to hadron level and compared to several theoretical predictions
- Comparisons are made with theory.

CDF







$\Delta A_{cp}(D^0\text{->}hh)$

- Result:

$\Delta A_{CP}=[-0.62\pm0.21 \pm0.10]\%$

2.7σ different from 0

CDF public note 10784

Using the equation:

$A_{cp}=A_{cp}^{dir}+(<t>/\tau)A_{cp}^{ind}$

One can plot:

ΔA_{cp}^{dir} vs A_{cp}^{ind}

This result is a confirmation of LHCb measurement:

$\Delta A_{cp}=[-0.83\pm0.21\pm0.11]\%$