Heavy Flavour Results from D0 including CPV results

B_s Lifetime, B^+ F-B Asymmetry,
D_s & D CP Violation, Dimuon Asymmetry
(see Tuesday CDF Direct CPV results)

Iain Bertram

CKM 2014, Vienna, 11 September 2014

B_s Lifetime

- Test theoretical predictions
  - Heavy Quark Expansion: $\tau(B_s^0)/\tau(B_d^0) = 1.00 \pm 0.01$
    Phys. Rev. D **70**, 094031
  - … most recent, Lattice inputs: $= 1.001 \pm 0.002$
    Lenz review, arXiv:1405.3601
  - Need for understanding of complex B_s^0 mixed system
- Target
  - Lifetimes of B_d^0 and B^+ measured to < 1% precision at B-factories
  - Updating latest DØ measurement (precision 3.7%) with full data set ($0.4 \rightarrow 10.4\ fb^{-1}$)

B_s Lifetime

- B_s^0 lifetime depends on final state!
  - $\Delta m_s = B_s^H - B_s^L$ Mixing, mass eigenstates…
  - $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$ … with different lifetimes
  - $\Delta\Gamma_s = \Gamma_s^{CP\text{-even}} - \Gamma_s^{CP\text{-odd}}$ if no CP violation

$$\Gamma_s = \frac{\Gamma_s^L + \Gamma_s^H}{2}$$

define

$$\overline{\tau}(B_s^0) = 1/\Gamma_s$$

- Lifetimes
  - $B_s^0 \to J/\Psi f_0(980)$ Pure CP-odd, Only single lifetime, $\Gamma_s^{CP\text{-odd}}, \Gamma_s^H$
  - $B_s^0 \to K^+ K^-$ Pure CP-even, $\Gamma_s^{CP\text{-even}}, \Gamma_s^L$
  - $B_s^0 \to D_s^- \mu^+ \nu$ Flavour specific, 50% CP-even, CP-odd at t=0
  - $B_s^0 \to J/\Psi\phi$ complicated mix of CP-even and -odd, complex analysis to extract.

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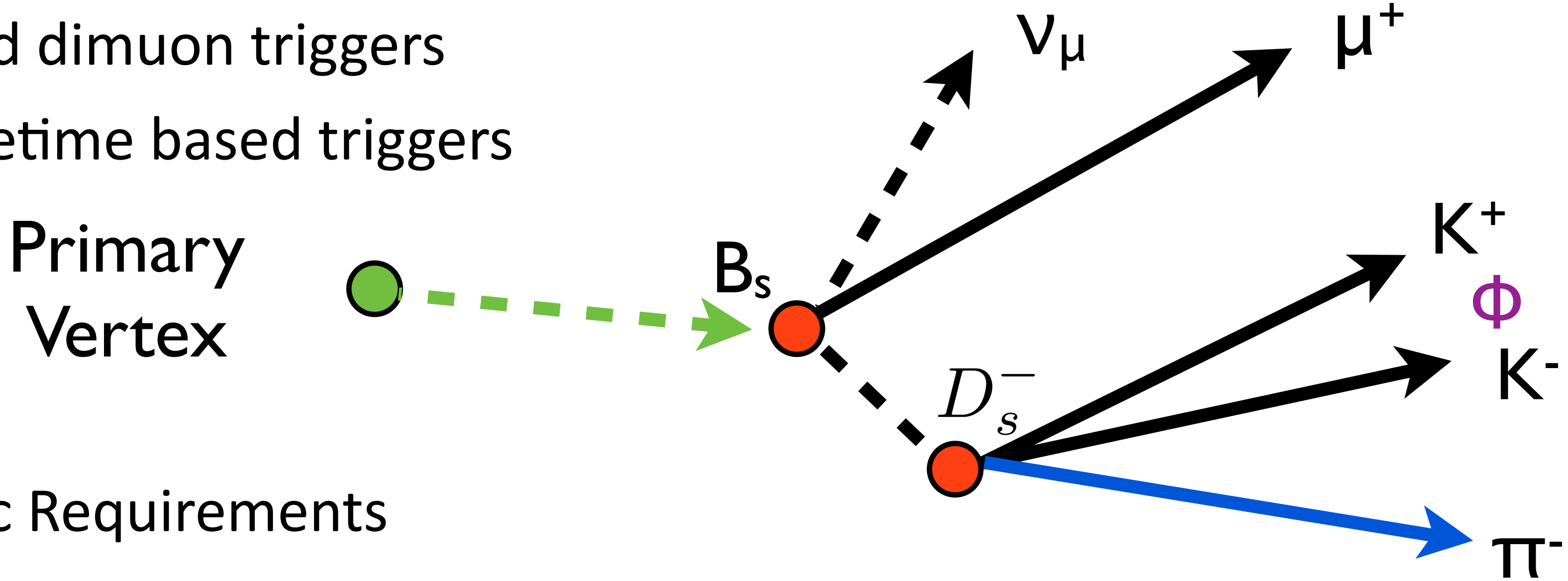
B_s Reconstruction

- Reconstruct B_s^0 using D_s^- with oppositely charged muon.
- Single and dimuon triggers
  - No lifetime based triggers

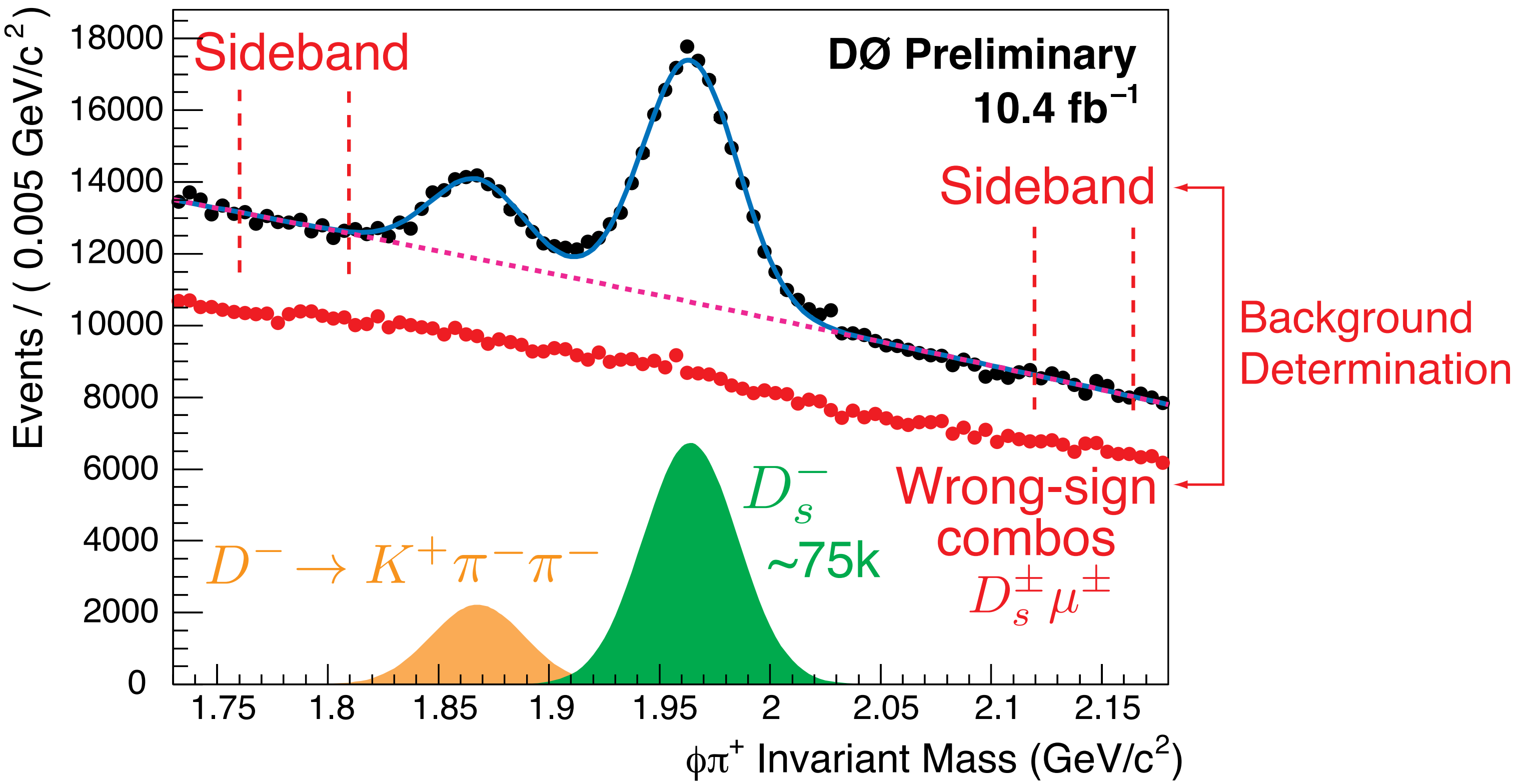


- Kinematic Requirements
  - $\mu^\pm$ with $p_T > 1.5$ GeV and $p_{tot} > 3.0$ GeV
  - ϕ: $K^\pm$ with $p_T > 1.0$ GeV and $1.08 \le m(KK) \le 1.32$ GeV
  - D_s: $\pi^\pm$ with $p_T > 0.7$ GeV and $1.6 \le m(\phi\pi) \le 2.3$ GeV
  - B_s: $2.5 \le m(\mu D_s) \le 5.5$ GeV

B_s Reconstruction

$$B_s^0 \to D_s^- \mu^+ \nu X$$
$$\hookrightarrow \phi\pi^-$$
$$\hookrightarrow K^+K^-$$

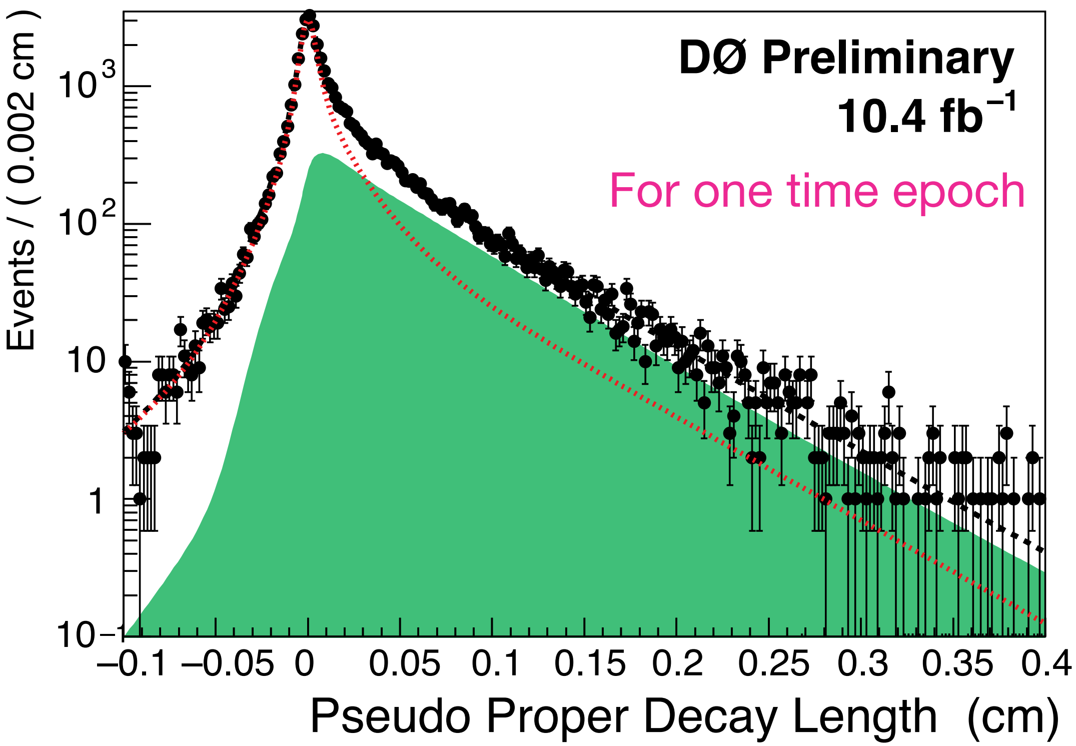
Reconstruct a D_s^- associated with a correct-sign muon



Likelihood

$$\mathcal{L} = \prod_{i \in \mathrm{sig.sample}} \left[f_{\mathrm{sig}} \mathcal{F}^i_{\mathrm{sig}} + (1 - f_{\mathrm{sig}}) \mathcal{F}^i_{\mathrm{bckg}} \right] \prod_{i \in \mathrm{bckg.sample}} \mathcal{F}^i_{\mathrm{bckg}}$$

- f_{sig} from D_s mass fit, $\boldsymbol{\mathcal{F}}_{bckg}$ Mass sidebands and WS signal.
- Lifetime models: convolved exponentials,
  cc : Gaussians, combinatorial: multiple exponentials



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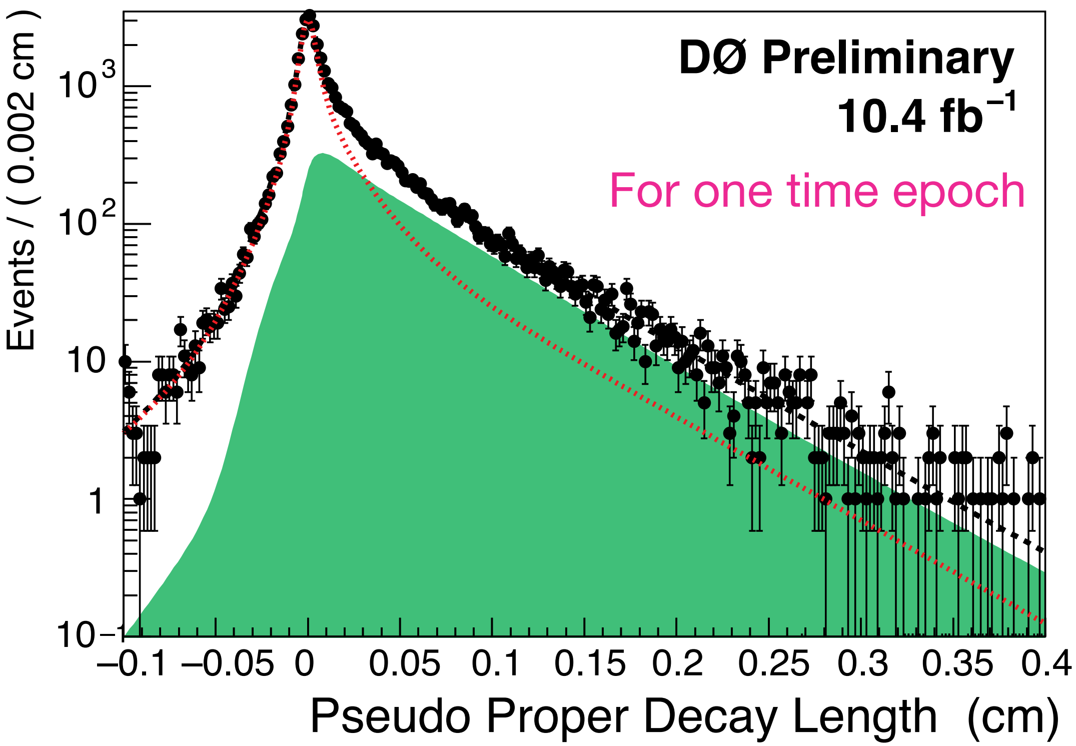
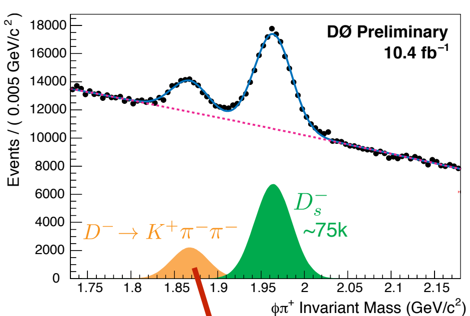




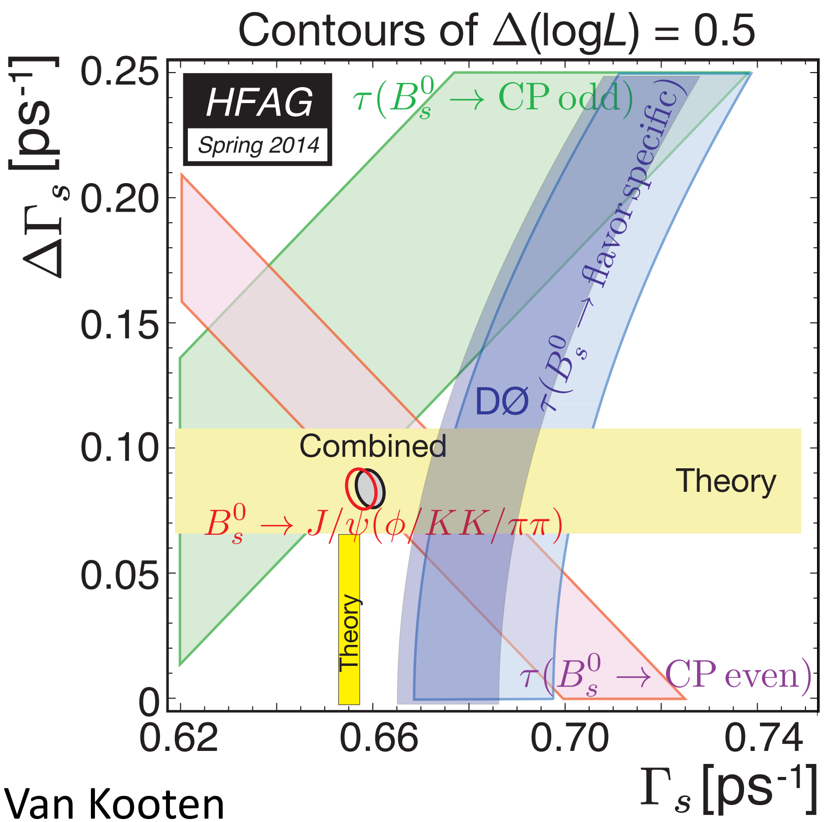
- Use $B_d \to D^-\mu^+\nu X$ peak fit for ratio $R = \tau(B_s^0)_{fs}/\tau(B_d^0)$

D0 Note 6442-CONF

B_s Lifetime

$$\tau\left(B_s^0\right)_{\rm fs} = 1.479 \pm 0.010 \pm 0.021 \text{ ps}$$

$$R = \tau\left(B_s^0\right)_{\rm fs} / \tau\left(B_d^0\right) = 0.964 \pm 0.013 \pm 0.007$$



$$\tau(B_s^0)_{\rm fs} = \frac{1}{\Gamma_s}\frac{1+(\Delta\Gamma_s/2\Gamma_s)^2}{1-(\Delta\Gamma_s/2\Gamma_s)^2}$$

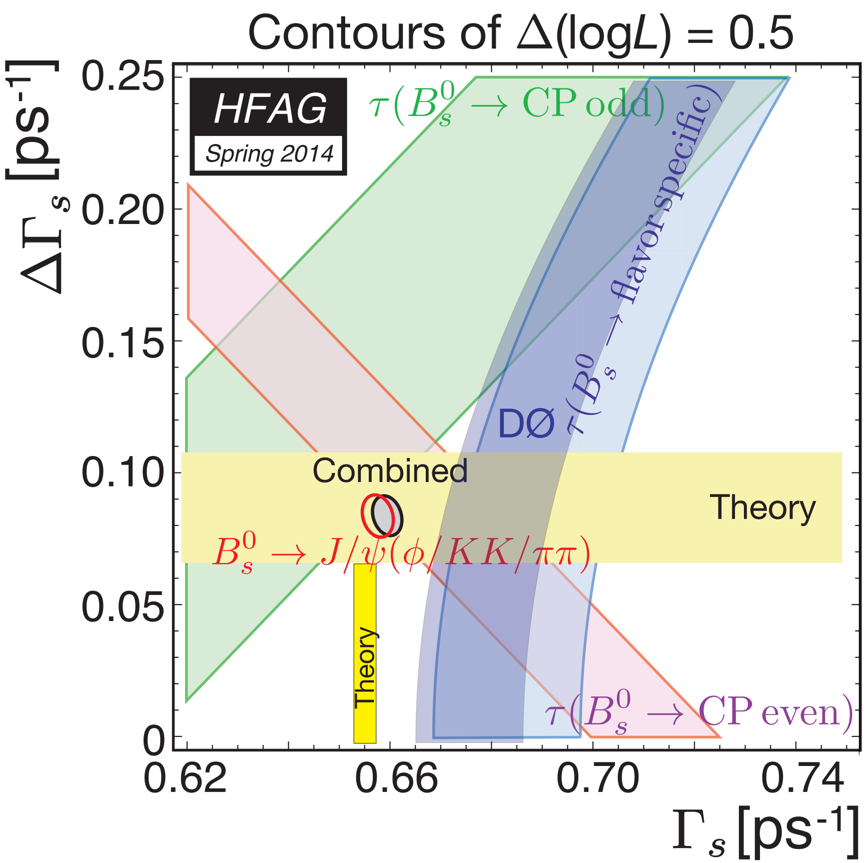
- Measurement precision better than previous world average
- DØ working on $B_s^0 \to J/\psi f_0(980)$ Pure CP-odd
- Stay tuned!

R Van Kooten

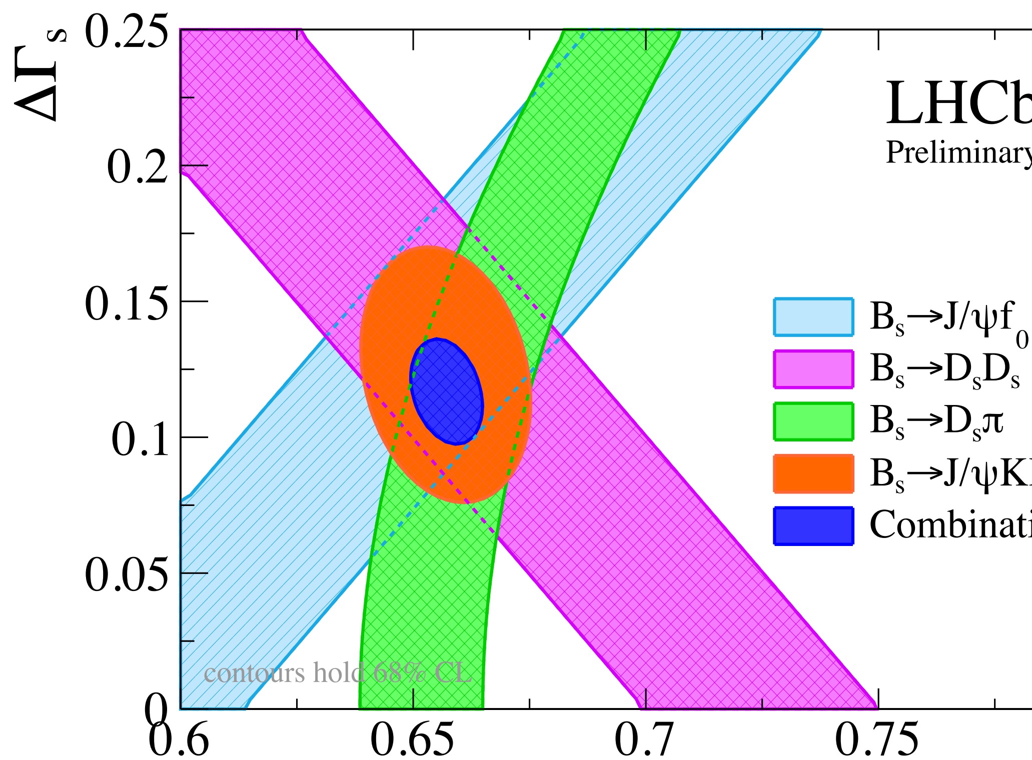
D0 Note 6442-CONF

B_s Lifetime

$$R = \tau\left(B_s^0\right)_{\mathrm{fs}} / \tau\left(B_d^0\right) = 0.964 \pm 0.013 \pm 0.007$$



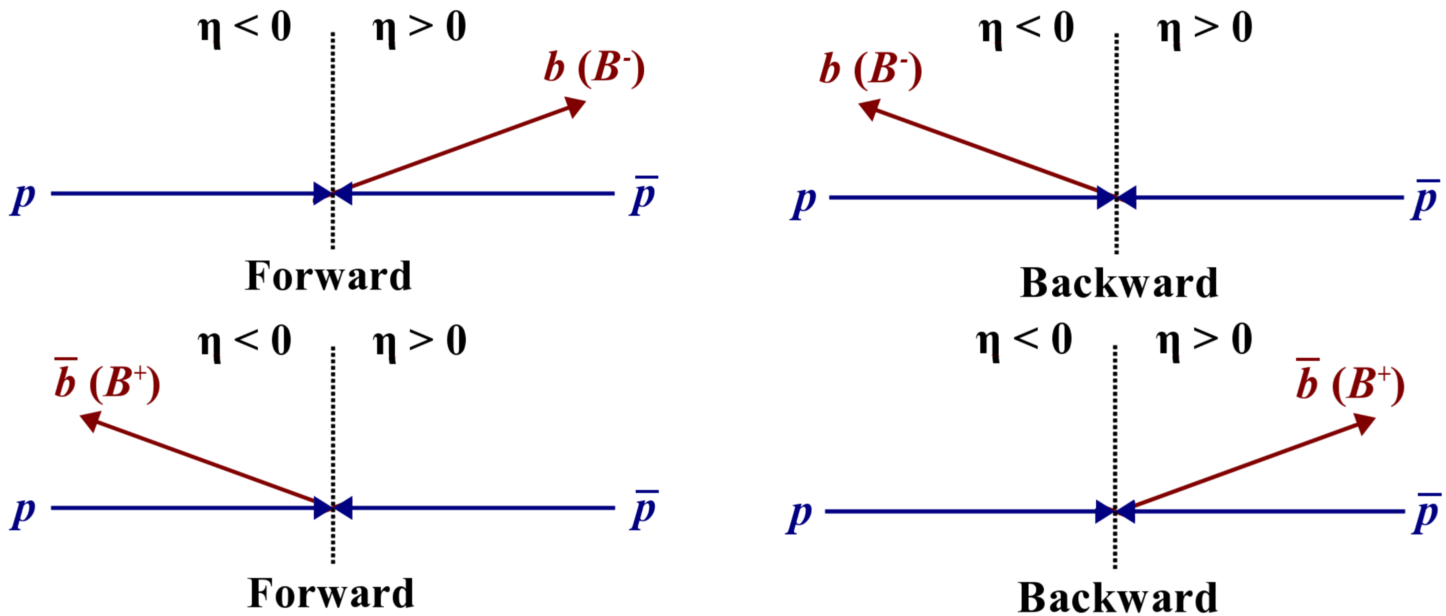
Dordei (Tuesday)



R Van Kooten

$B^{\pm}$ F-B Asymmetry

- Forward-backward asymmetry may probe for new physics.
- D0 uses $B^{\pm} \rightarrow J/\Psi K^{\pm}$ to probe asymmetry of b-quarks.



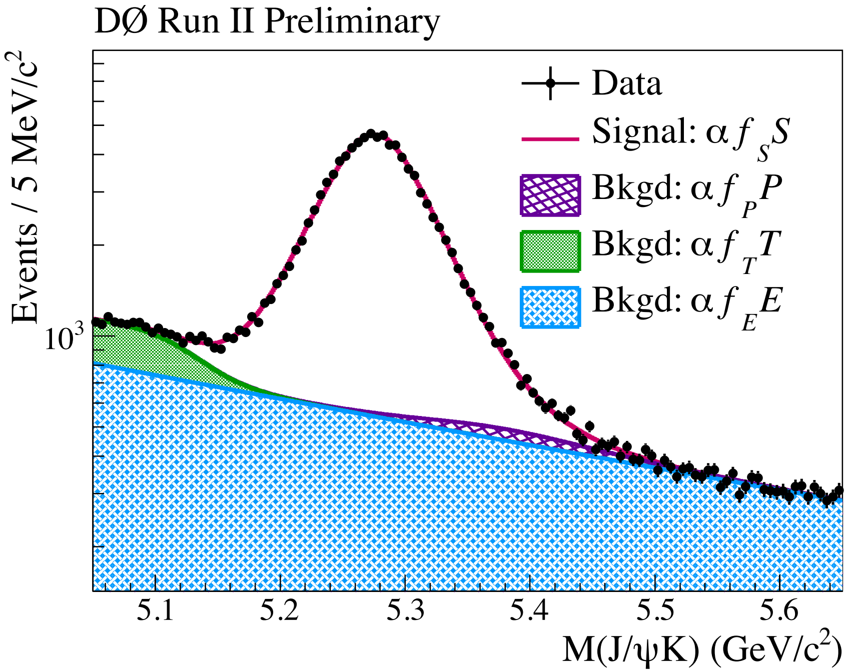
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

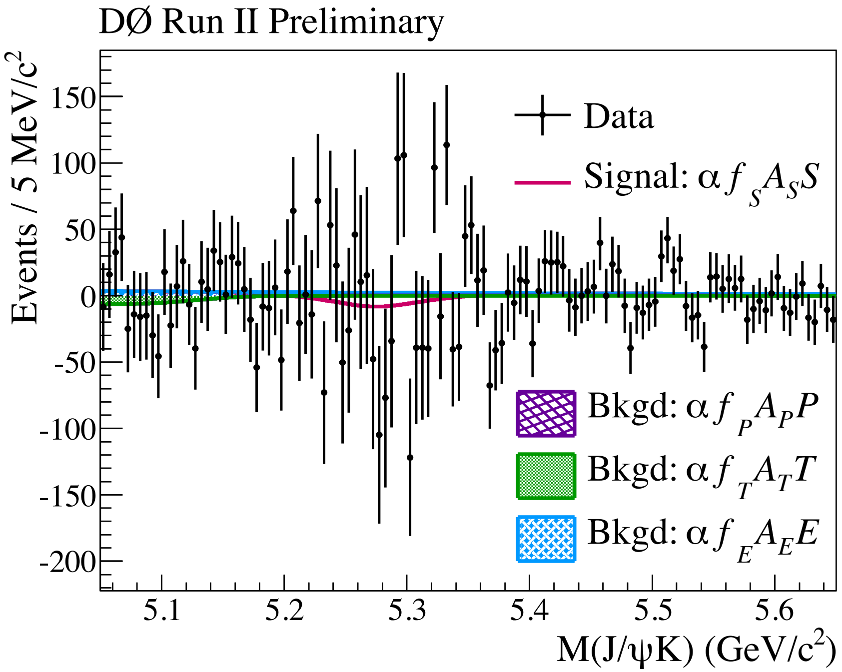
Forward: b-quark in same direction as proton
anti-b in same direction as anti-proton

D0 Note 6441-CONF

$B^\pm$ F-B Asymmetry

- An unbinned maximum likelihood fit is used to extract the number of B meson decays in each category.
- Unblinded projections: D0 Note 6441-CONF





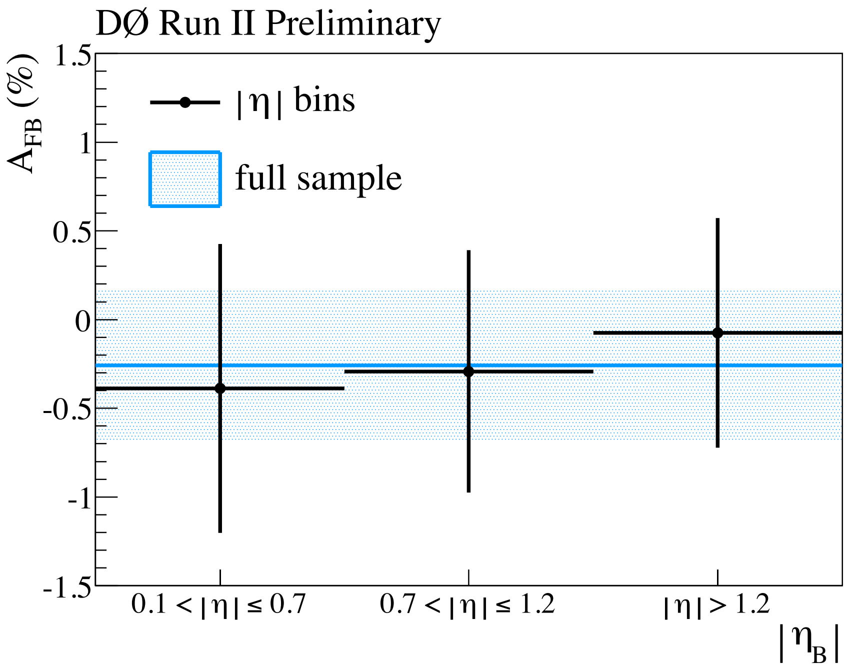
- Correct for F-B reconstruction asymmetries, muon and kaons using weights: A_{corr} = -0.06%.

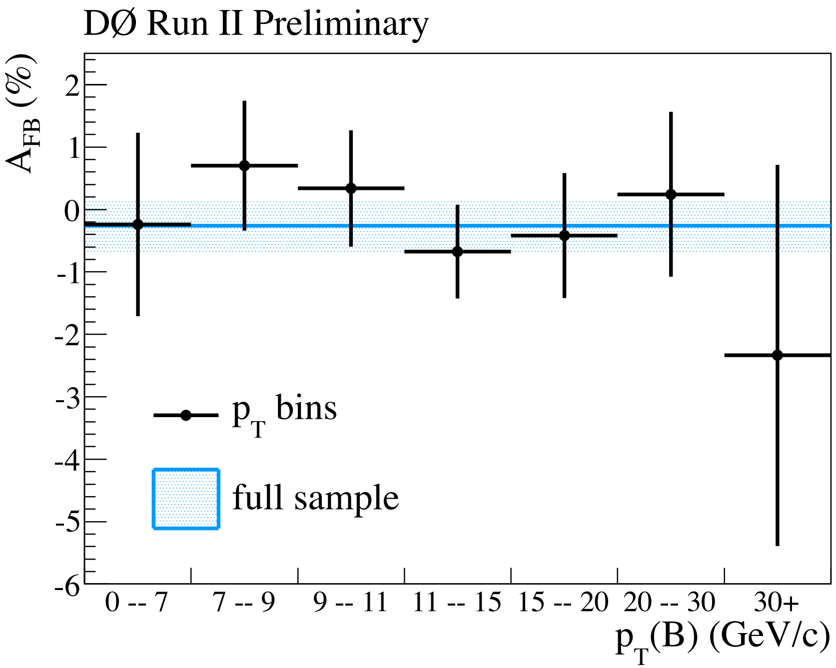
$B^{\pm}$ F-B Asymmetry

$$A_{FB} = [-0.26 \pm 0.41 \pm 0.17]\,\%$$

- Comparison with MC@NLO

$$A_{\mathrm{MC@NLO}} = [1.63 \pm 0.43 \pm X.XX]\,\%$$





- Theory systematics to come: different PDFs, renorm. scale. etc.

Direct CPV in $D_s^\pm \to \phi\pi^\pm$ & $D^\pm \to K^\mp\pi^\pm\pi^\pm$

- Motivation:
  - Direct CP violation can occur if tree and loop (penguin) can interfere with different strong and weak phases
  - No CP violation is expected in decay $D_s^\pm \to \phi\pi^\pm$ and $D^\pm \to K^\mp\pi^\pm\pi^\pm$ (all process have same weak phase)
  - Non-zero value implies new physics
- Motivation
  - Assume zero-CPV in many other analyses:

    e.g.: $B_s^0 \to \bar{B}_s^0 \to D_s\mu\nu$ — CPV in mixing

    $\sigma(D_s^\pm)$ — Production asymmetry (LHCb)
- e.g. Experimentally measure

$$A_{D_x} = \frac{N_{D_x^+} - N_{D_x^-}}{N_{D_x^+} - N_{D_x^-}}$$

Phys. Rev. Lett. 112, 111804 (2014)

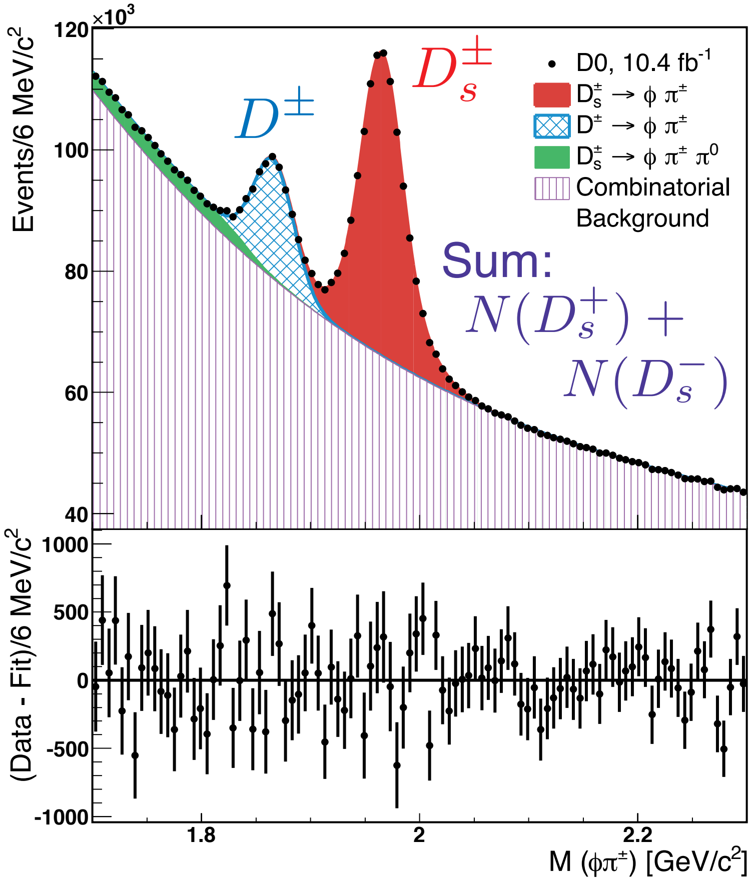
Direct CPV in $D_s^{\pm} \rightarrow \phi\pi^{\pm}$

- Use similar techniques for CP asymmetries as other DØ analyses

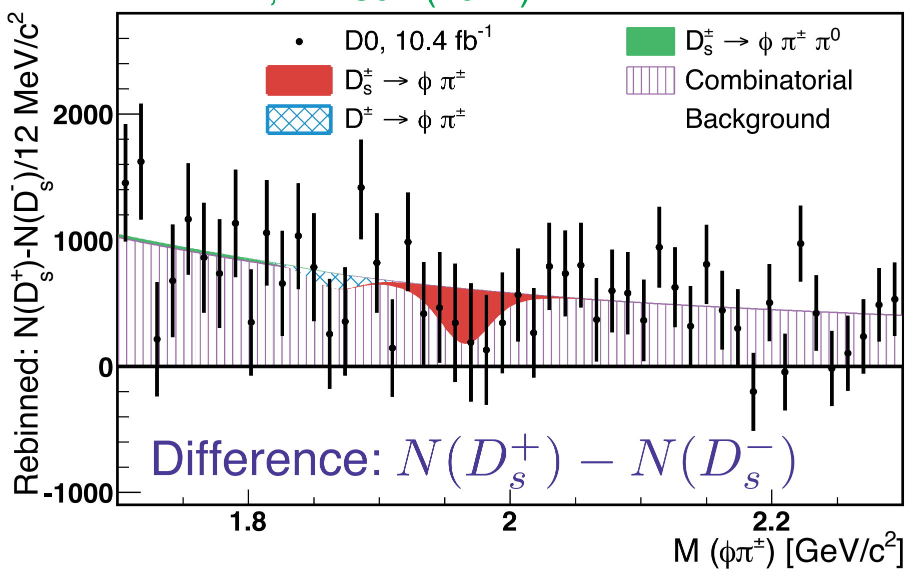
- $D_s^{\pm} \rightarrow \phi\pi^{\pm}$, $\phi \hookrightarrow K^{\oplus}K^{\ominus}$ — Dominant kaon charge asymmetry ~cancels!

$$A_{\mathrm{CP}} = A_{D_s} - A_{\mathrm{det}} - A_{\mathrm{phys}}$$

(A_{det}: small)



PRL **112**, 111804 (2014)



$$A_{\mathrm{CP}} = (-0.38 \pm 0.26 \pm 0.08)\%$$

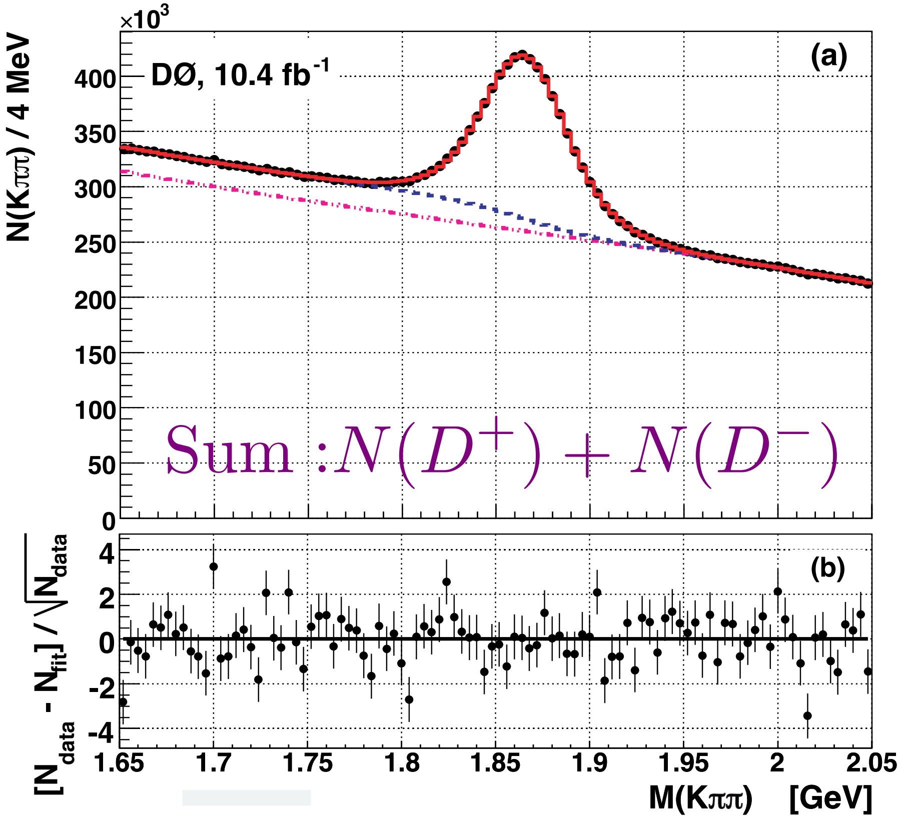
- Most precise measurement
- Consistent with zero

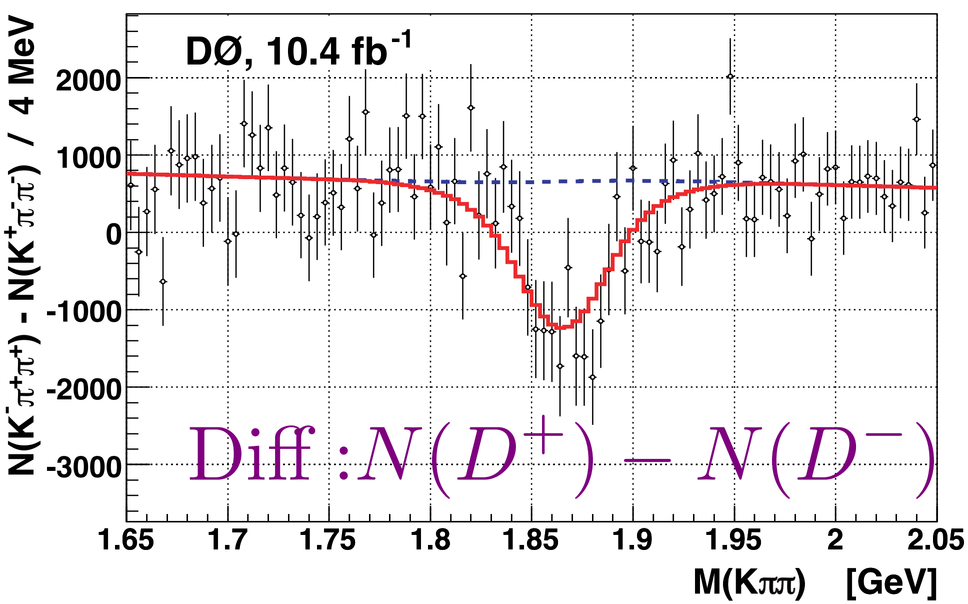
NEW arXiv:/1408.6848 PRD-RC

Direct CPV in $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$

Lancaster University

- Same methodology as $D_s^{\pm} \to \phi\pi^{\pm}$ (correction for unmatched K)





$$A_{\rm CP} = A_{D^+} - A_{\rm det} - A_{\rm phys}$$

$$A_{\rm det} = [-1.11 \pm 0.08]\,\%$$

$$A_{\rm phys} = [-0.014 \pm 0.023]\,\%$$

$$A_{\rm CP} = [-0.16 \pm 0.15({\rm stat}) \pm 0.09({\rm syst})]\,\%$$

Dimuon Charge Asymmetry

Direct semileptonic decay

Neutral *B* meson oscillation and then semileptonic decay

- CP violation *in mixing*: $\Gamma(B^0_{(s)} \to \bar{B}^0_{(s)} \to \mu^- X) \neq \Gamma(\bar{B}^0_{(s)} \to B^0_{(s)} \to \mu^- X)$
- Measure via

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

Inclusive single muons

$$a^{\mathrm{raw}} = \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)}$$

Mostly background

Constrain backg.

Reduce syst.

$$A^b_{sl} = \frac{N_b(\mu^+\mu^+) - N_b(\mu^-\mu^-)}{N_b(\mu^+\mu^+) + N_b(\mu^-\mu^-)}$$

Correct for backgrounds, fraction from *b*'s

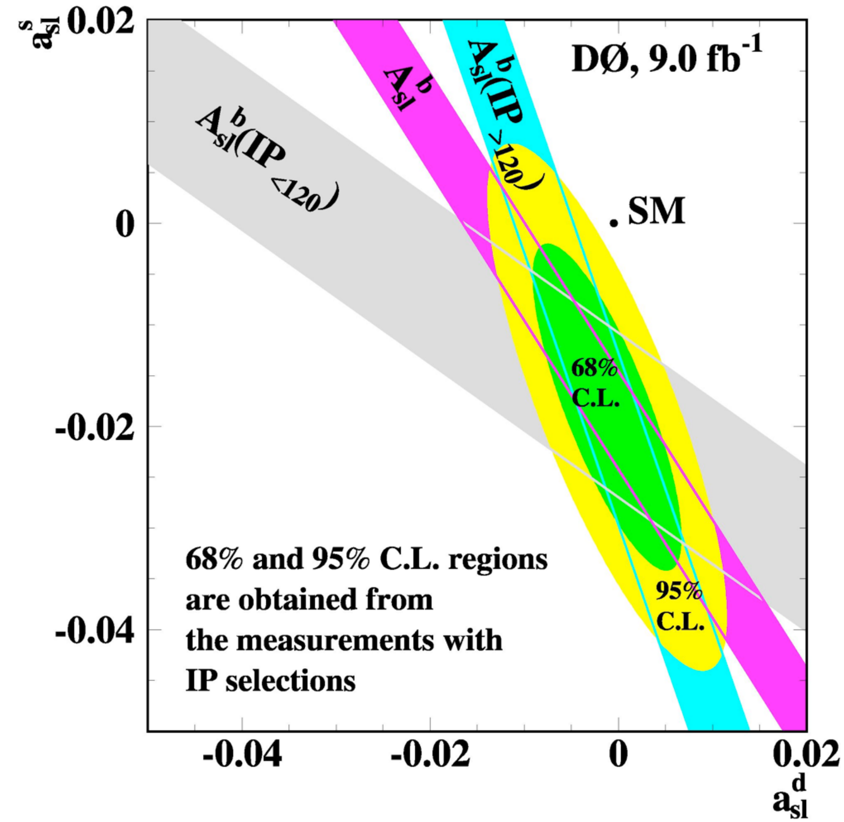
- Asymmetry is a linear combination semileptonic charge asymmetries of B^0_d and B^0_s

$$A^b_{sl} = C_d a^d_{sl} + C_s a^s_{sl} \quad ; \qquad a^b_{sl} = \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)}$$

Dimuon: 2011 Result

$$A_{sl}^{b} = (-0.787 \pm 0.172(\text{stat}) \pm 0.093(\text{syst}))\,\%$$

- 9.0 fb^{-1} → 10.4 fb^{-1}
- More detailed study of asymmetry dependence on impact parameter (IP) on each muon
- More detailed study of asymmetry dependence on muon (p_T, η)
- Another cross check using independent alternative way to measure background
- Additional CP-violating process included to interpret result



PRD **84** 052007 (2011)

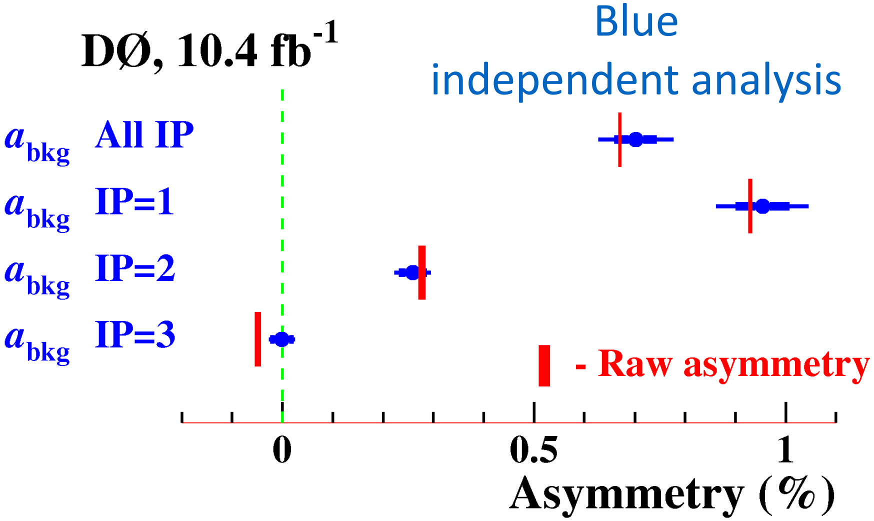
CPV in interference of decays w/ and w/o mixing & special decay class

Dimuon Charge Asymmetry

IP Sample	Muon IP (μm)
IP=1	0-50
IP=2	50-120
IP=3	120-3000

More backgrounds due to K→μ,π→μ which result in an asymmetry since σ(K^-N) > σ(K^+N)

Blue
independent analysis



$a_{CP} = a_{raw} - a_{det}$

Similar result if bin in (η, p_T)
where there are 27 independent bins

Dimuon Charge Asymmetry

IP Sample	Muon IP (µm)
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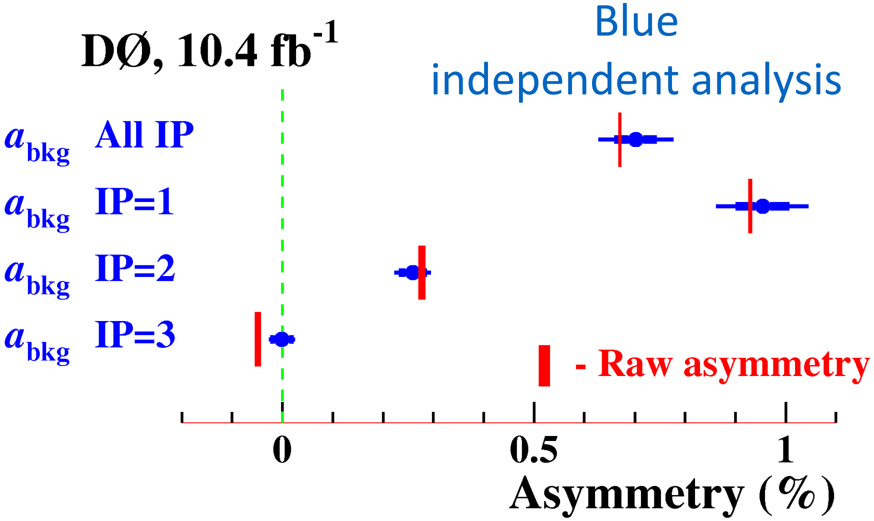
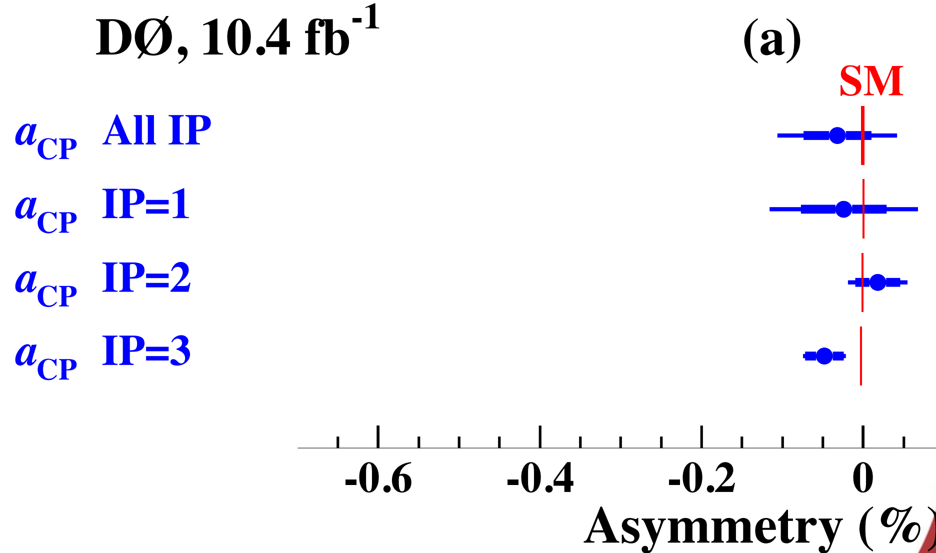
↑ More backgrounds due to K→µ,π→µ which result in an asymmetry since σ(K⁻N) > σ(K⁺N)

Blue independent analysis





Similar result if bin in (η, p_T)
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Phys. Rev. D 89, 012002 (2014)

Dimuon Charge Asymmetry

IP Sample	Muon IP (μm)
IP=1	0-50
IP=2	50-120
IP=3	120-3000

Using same sign dimuons

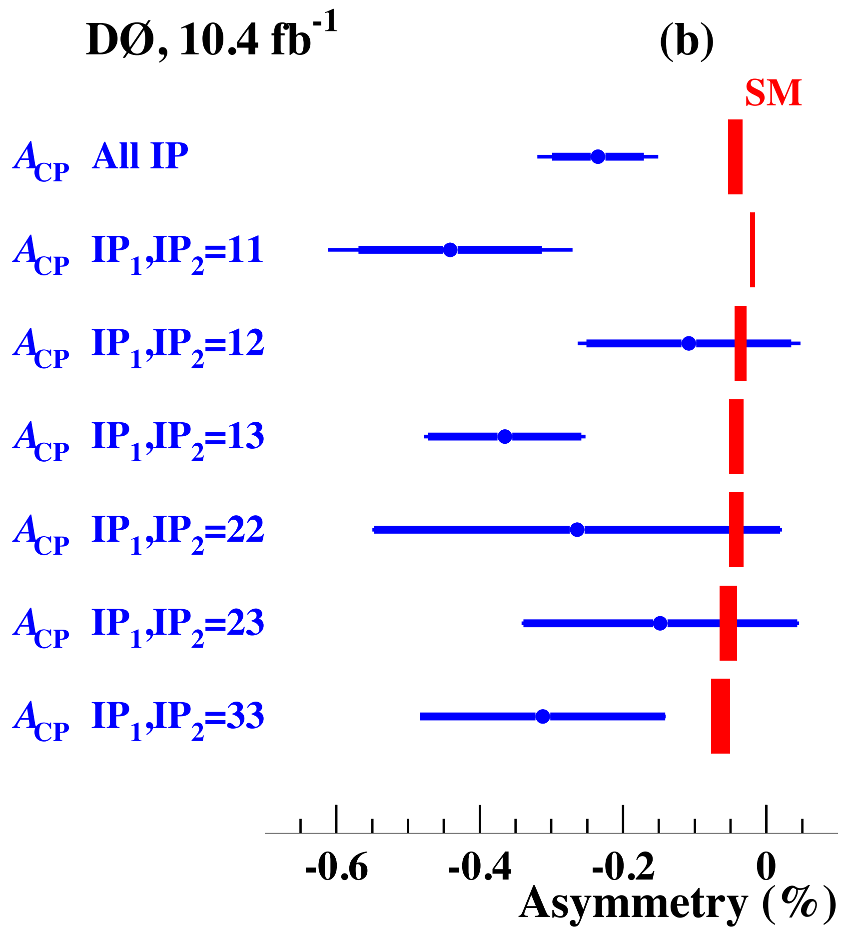
A_{CP} = (-0.235 ± 0.064 ± 0.055)%

3.6σ deviation from SM

$$A_{CP}^{mix}(SM) + A_{CP}^{int}(SM)$$

$$(-0.8 \pm 0.1) \times 10^{-4} + (-3.5 \pm 0.8) \times 10^{-4}$$

PRD 87, 074020 (2013)

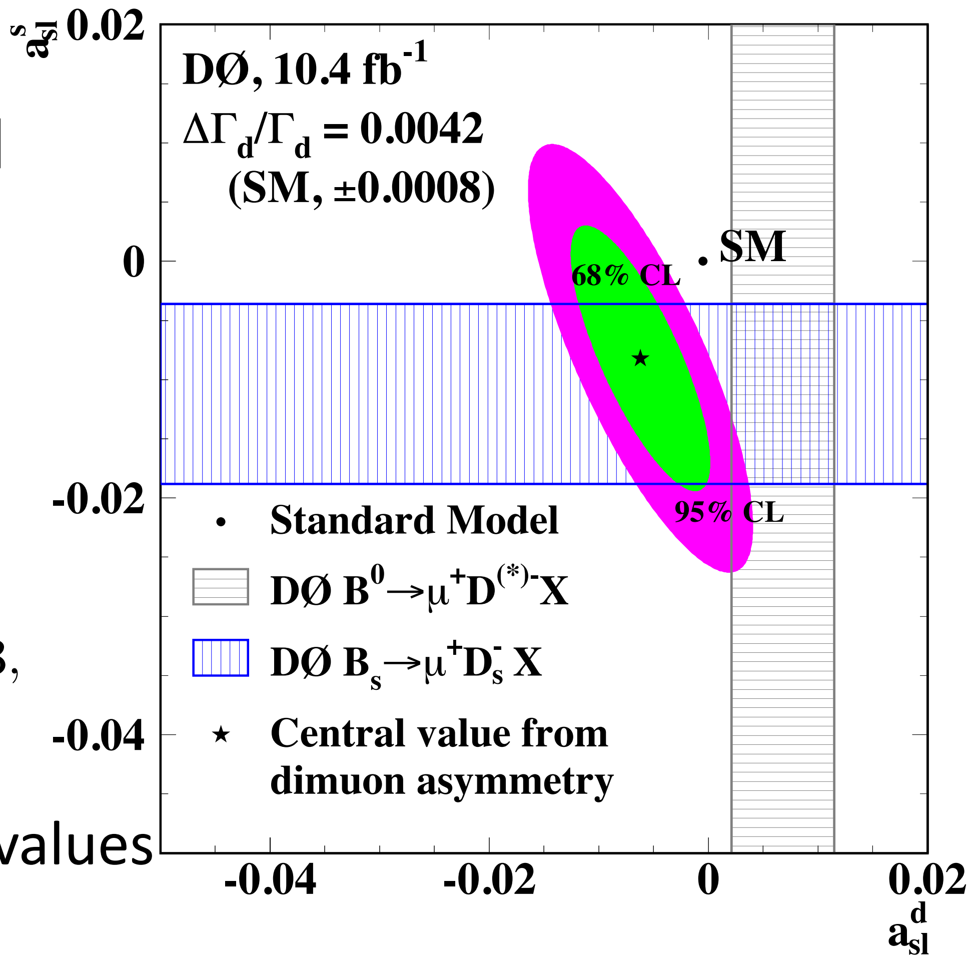


Phys. Rev. D 89, 012002 (2014)

Dimuon Charge Asymmetry

- Interpretation & results
  - Fractional mix of B_s and B_d in each IP bin and A_{CP} proportional to $\Delta\Gamma_d$

$$a^s_{sl} = (-0.82 \pm 0.99)\,\%,$$
$$a^d_{sl} = (-0.62 \pm 0.43)\,\%,$$
$$\Delta\Gamma_d/\Gamma_d = (+0.50 \pm 1.38)\,\%,$$
$$\rho_{s,d} = -0.61, \qquad \rho_{d,\Delta\Gamma} = -0.03,$$
$$\rho_{s,\Delta\Gamma} = +0.66.$$



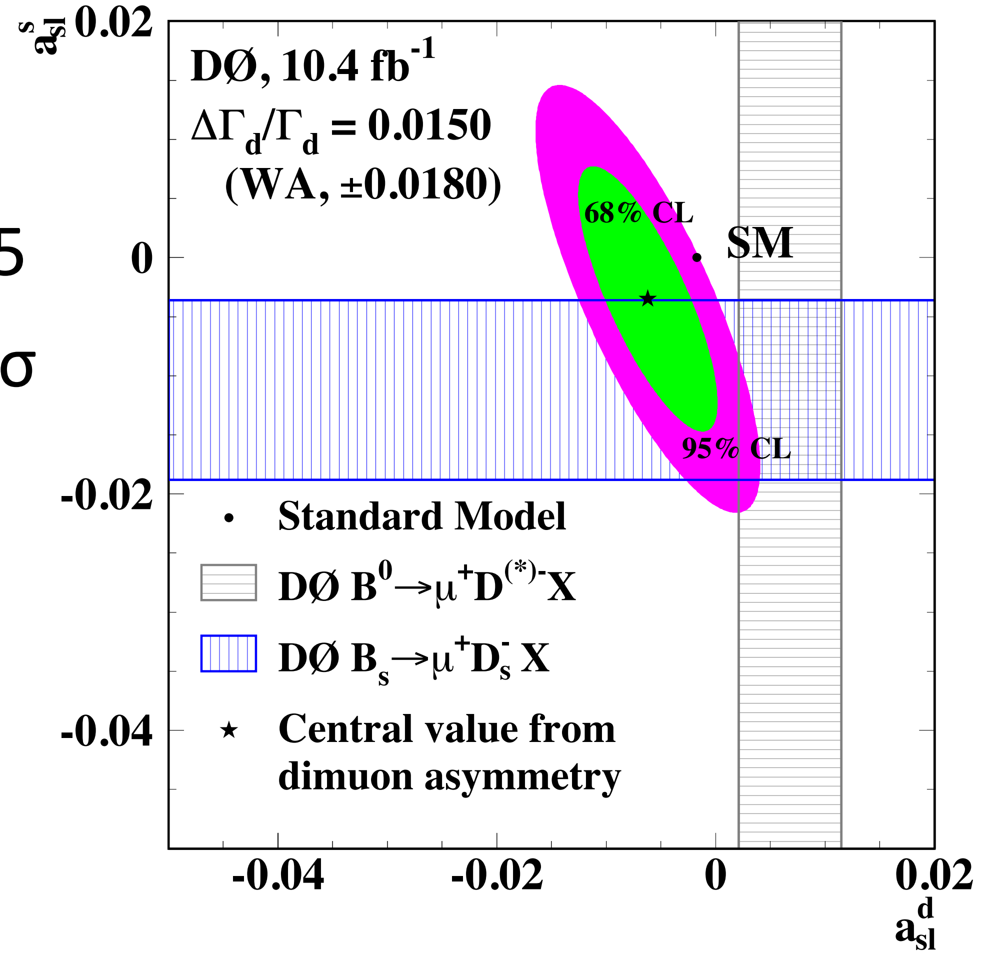
3.0σ deviation from SM of three values

Result consistent with D0 measurements of a^s_{sl} and a^d_{sl}

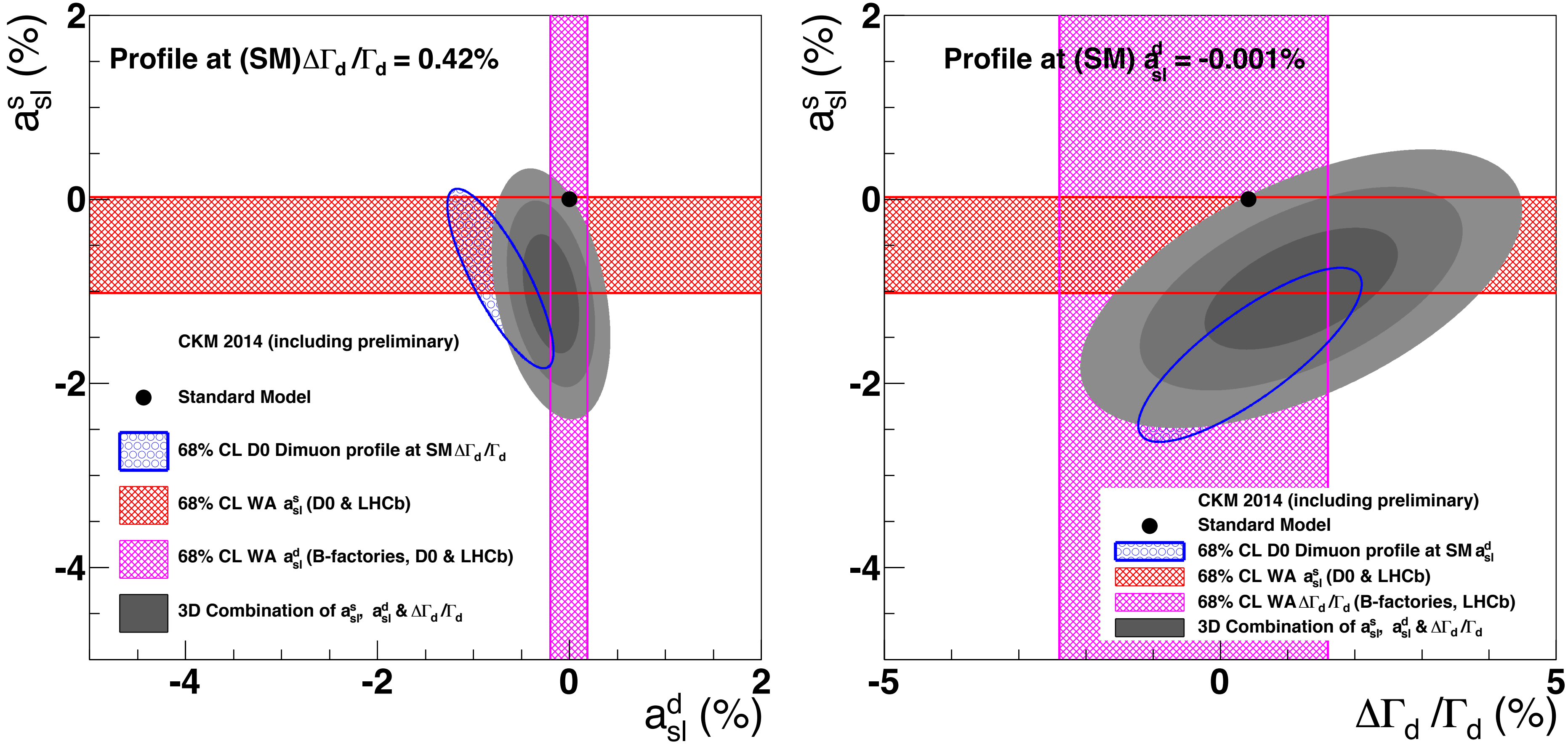
Phys. Rev. D 89, 012002 (2014)

Dimuon Charge Asymmetry

- Interpretation & results
  - Sensitive to $\Delta\Gamma_d/\Gamma_d$
  - Fix to WA $\Delta\Gamma_d/\Gamma_d = 0.015$
  - Deviation now only 1.9σ



Semi-Leptonic CPV WA



$$a_{\rm sl}^s = (-0.88 \pm 0.43)\,\%,$$
$$a_{\rm sl}^d = (-0.17 \pm 0.17)\,\%,$$
$$\Delta\Gamma_d/\Gamma_d = (+1.03 \pm 0.92)\,\%,$$

$$\rho_{s,d} = -0.20, \quad \rho_{d,\Delta\Gamma} = +0.19, \quad \rho_{s,\Delta\Gamma} = +0.50.$$

$$\chi^2(\text{comb}) = 3.47/3\text{d.o.f.}$$

2.9σ deviation from SM

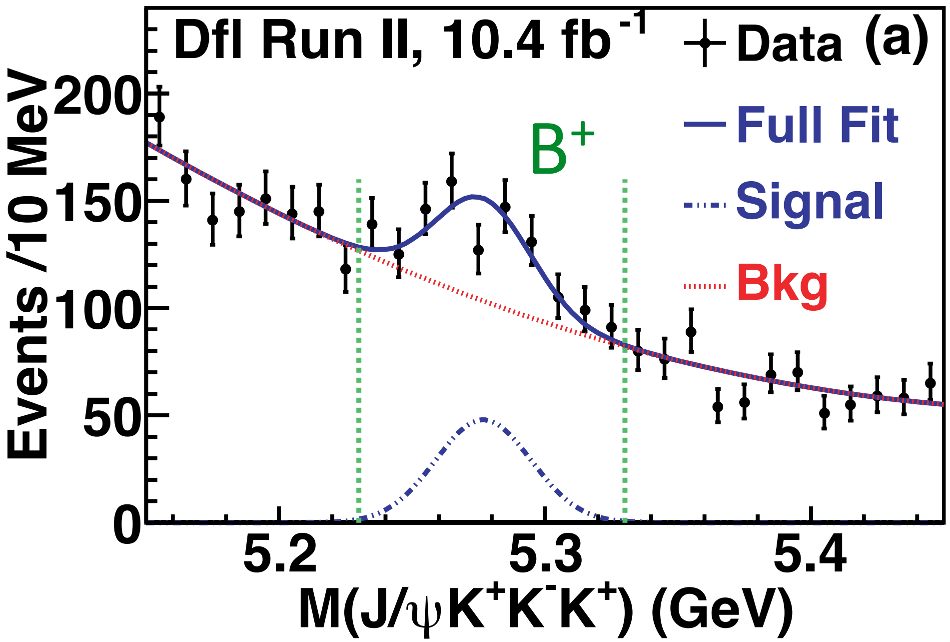
Summary

- DØ has a well understood detector & dataset with well developed analysis techniques.
  - small levels of pile-up
  - p–anti-p CP symmetric initial state
  - regular flipping of magnet polarities
- Still producing results that are complimentary to the LHC in niche areas.
  - new tests of CPV and FB asymmetries
  - Leaving Dimuon charge asymmetry puzzle
    - New Physics
    - Is $\Delta\Gamma_d/\Gamma_d$ the solution?

Backup Slides

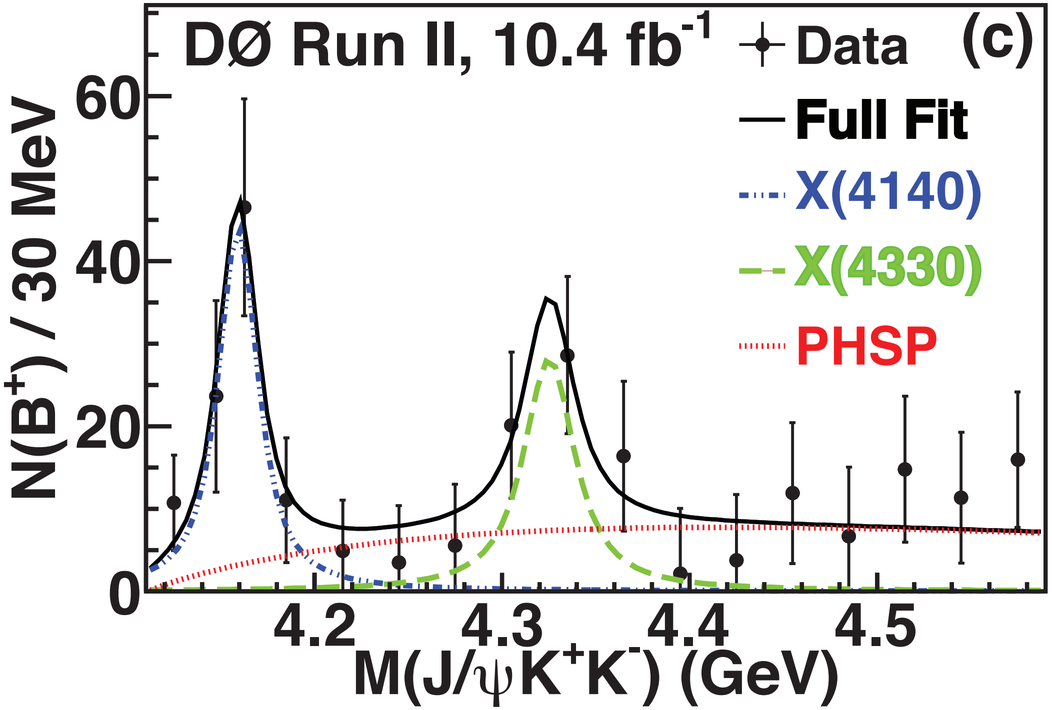
Search for X(4140)

- $B^+ \to J/\psi\phi K^+$: resonance $X(4140) \to J/\psi\phi$
  - Standard quark model does not predict a state at this mass
  - Decay suggests cc, but mass is above open charm threshold
- Reconstruct $B^+ \to J/\psi\phi K^+$ (where $J/\psi \to \mu\mu$ and $\phi \to KK$)
  - veto $\psi(2S)$ and check for J/ψ + K or π structures
  - Fit for B^+ yield in bins of $M(J/\psi KK)$



Phys. Rev. D 84, 012004 (2014)

Search for X(4140)



- Evidence for X(4140) at 3.1σ

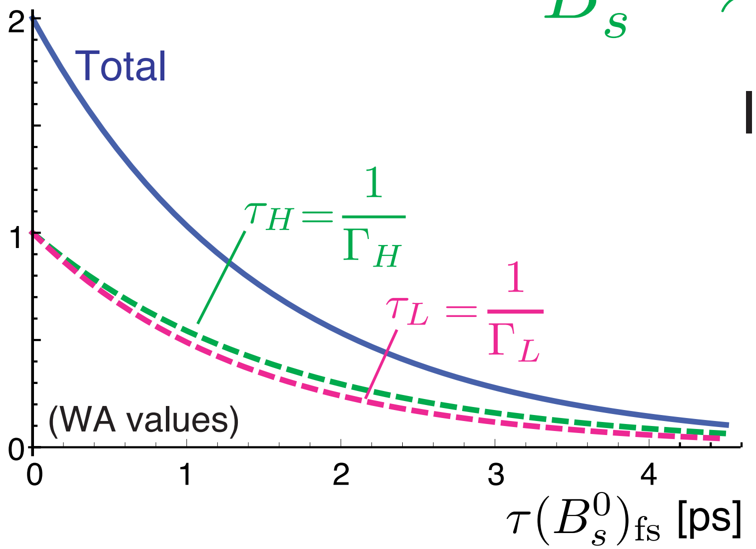
$$M = 4159.0 \pm 4.3 \pm 6.6 \text{ MeV}$$
$$\Gamma = 19.9 \pm 12.6^{+3.0}_{-8.0} \text{ MeV}$$

$$\frac{\mathcal{B}(B^+ \to X(4140)K^+)}{\mathcal{B}(B^+ \to J/\Psi\phi K^+)} = (19 \pm 7 \pm 4)\%$$

- Status
  - First evidence at CDF (Y(4140)) at 3.8σ
    No evidence at Belle γγ → J/ψϕ in but higher mass state reported
    No evidence at LHCb
    Evidence at CMS at >5σ

Backup B_s Lifetime

$$B_s^0 \rightarrow D_s^- \ell^+ \nu X$$



If fit with a single exponential, measure:

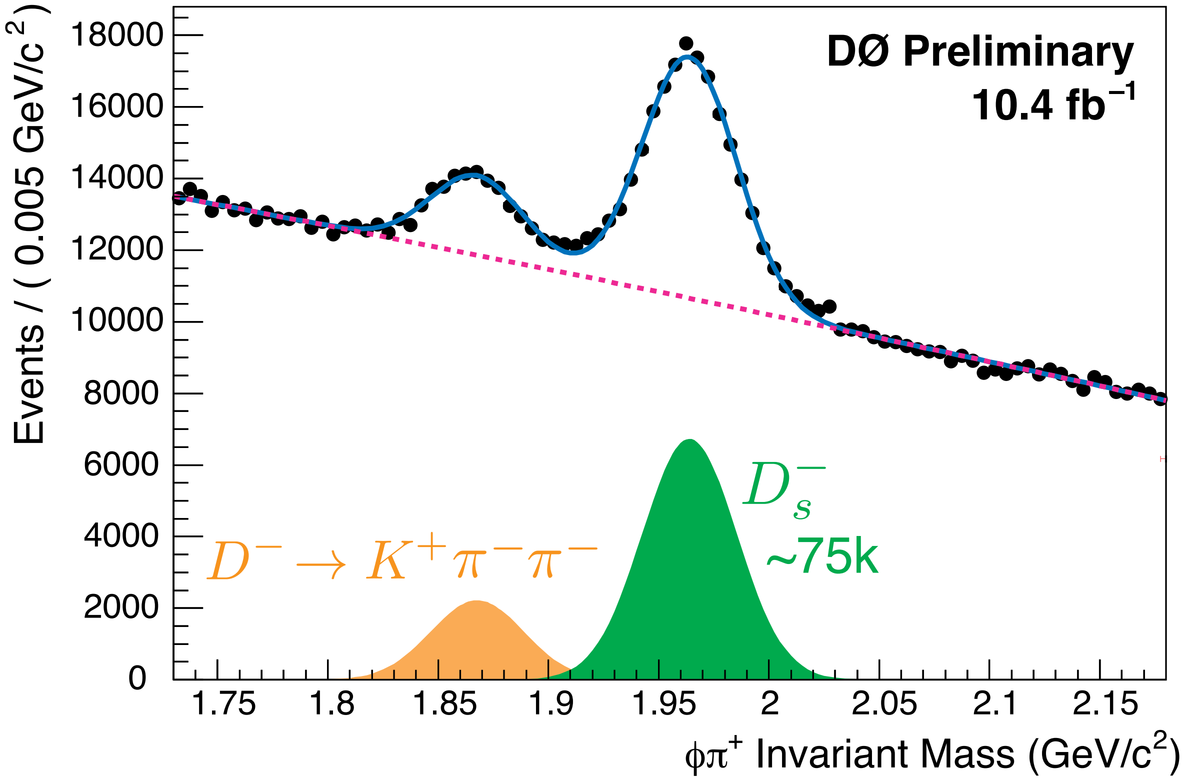
$$\tau(B_s^0)_{\rm fs} = \frac{1}{\Gamma_s} \frac{1+(\Delta\Gamma_s/2\Gamma_s)^2}{1-(\Delta\Gamma_s/2\Gamma_s)^2}$$

Difficult to distinguish two exponentials in a stable fit...

B_s Reconstruction

$$B_s^0 \to D_s^- \mu^+ \nu X$$
$$\hookrightarrow \phi\pi^-$$
$$\hookrightarrow K^+K^-$$

Reconstruct a D_s^- associated with a correct-sign muon

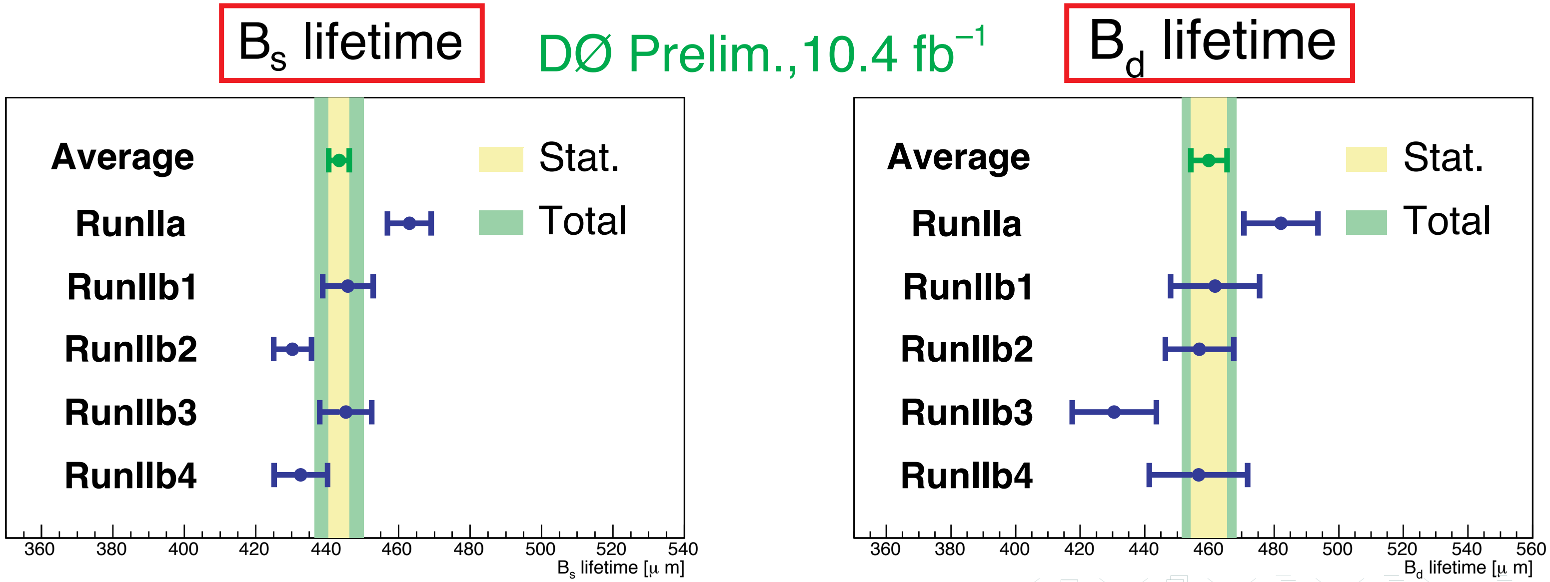


B_s Lifetime Systematics

- Decay length resolution
  Replace double-Gaussian model with single + exponential tails
- Combinatorial Background
  Use single samples (each of mass side-bands, wrong-sign)
- *K* factors
  Use different MC, vary composition and relevant lifetimes within uncertainties
- Non-Combinatorial Background
  Vary composition within uncertainties
- Detector Alignment
  Use different silicon microvertex detector alignment files with sensors moved within uncertainties
- Signal fraction
  Varied within uncertainties from mass fit, different mass models

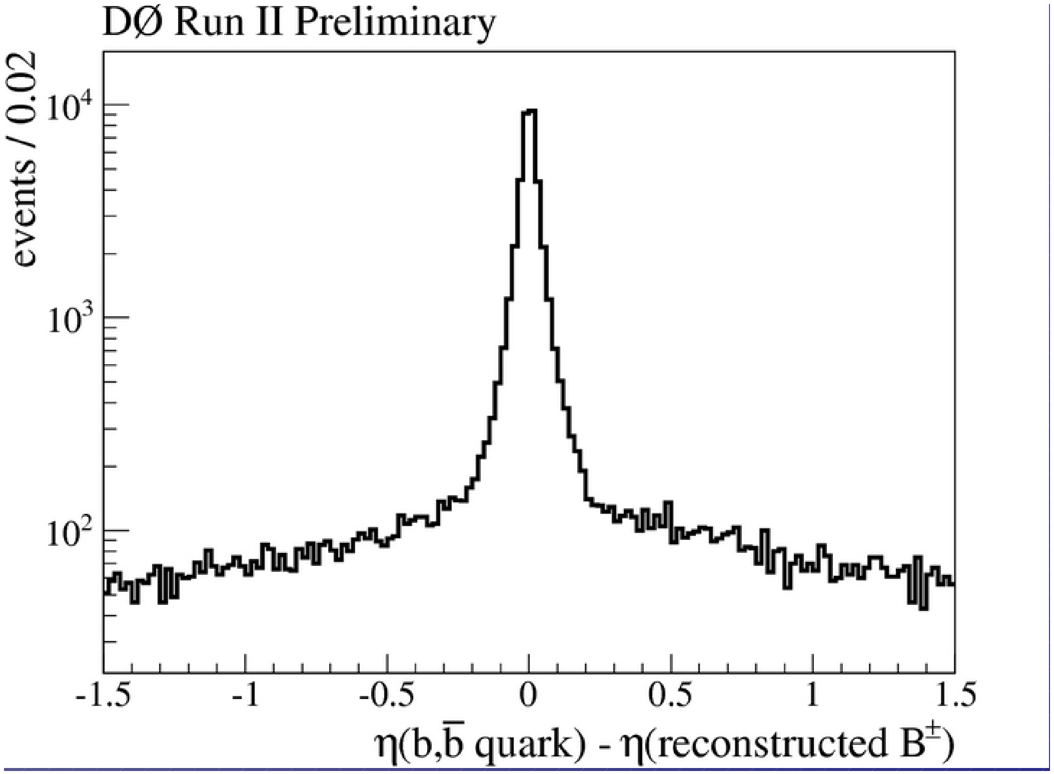
Systematics

Uncertainty source	B_s^0 (μm)	B^0 (μm)	Δ R
Resolution Model	0.7	2.1	0.003
Combinatorial Background Model	5.0	4.9	0.001
K-factor determination	1.6	1.3	0.006
Non-Combinatorial Background	2.6	2.0	0.001
Signal Fraction	1.0	1.8	0.002
Alignment of the detector	2.0	2.0	0.000
Total	**6.3**	**6.4**	**0.007**



$B^{\pm}$ F-B Asymmetry

- Correlation between parent b-quark and reconstructed B meson from MC@NLO. About 80% of the time, the B meson tracks the parent b-quark.

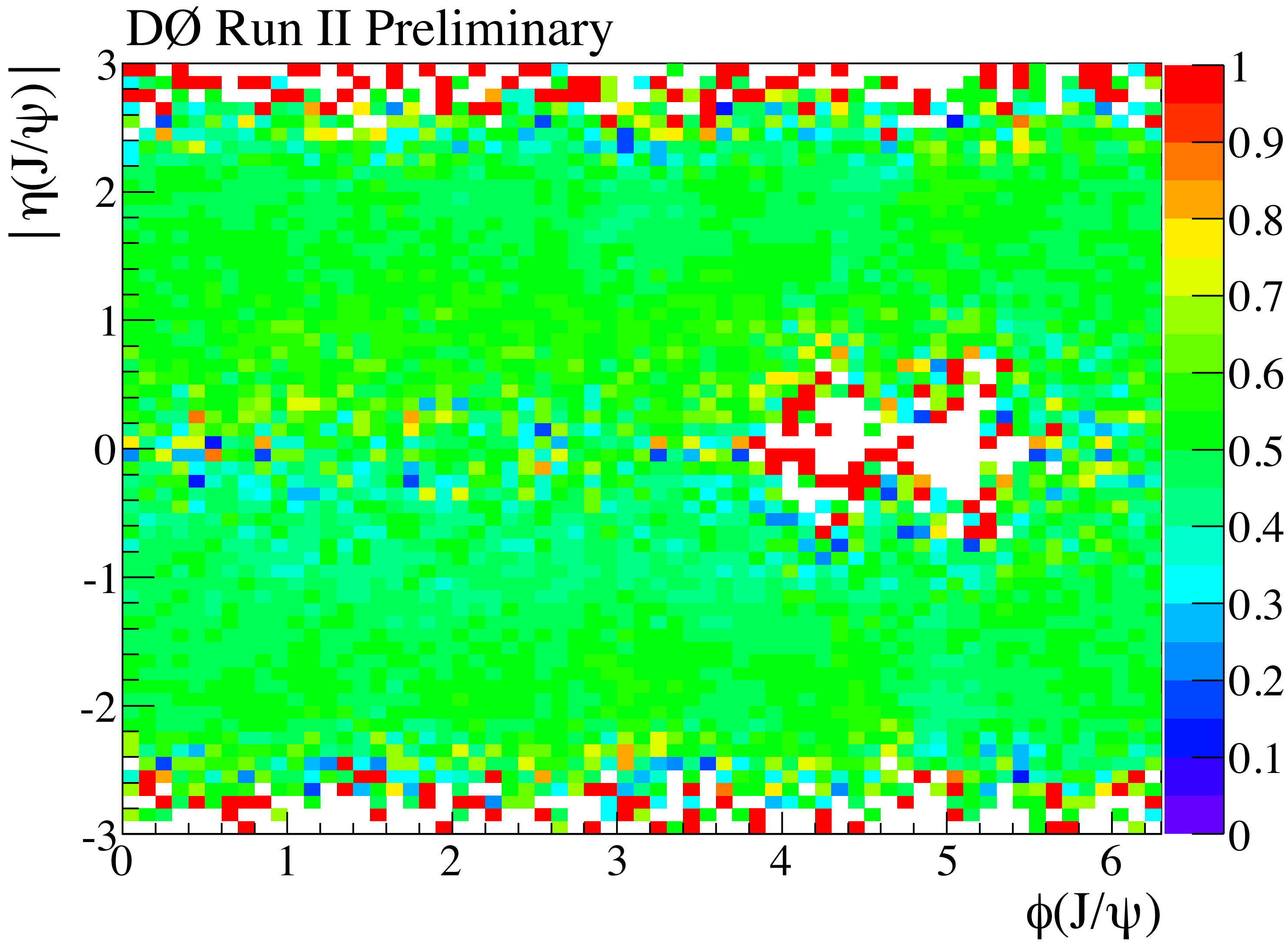


$B^{\pm}$ F-B Asymmetry

BDT Variations	0.14%
Fit Variations	0.080%
Polarity Weighting	0.0001%
Detector Asymmetries	0.058%
Systematic	0.17%
Statistical	0.41%
Total	0.44%

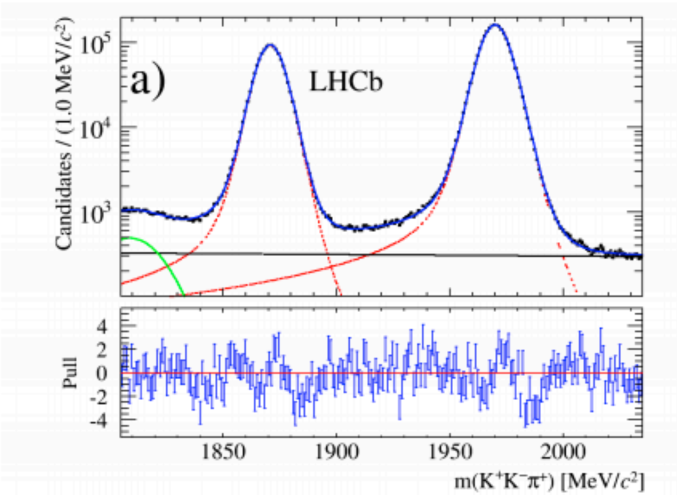
$B^{\pm}$ F-B Asymmetry

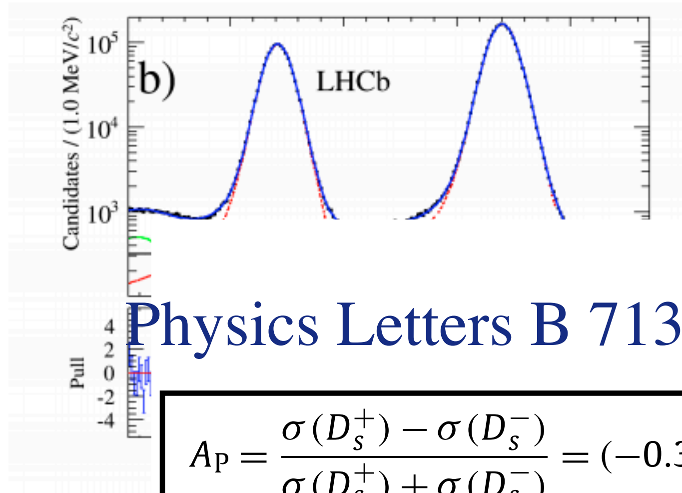
- Detector Asymmetry



Determination of the raw asymmetries: D$^{\pm}$→ϕπ$^{\pm}$

L=3fb^{-1} D^{+}→ϕπ^{+} D^{-}→ϕπ^{-}





– signal
– combinatorial bkg

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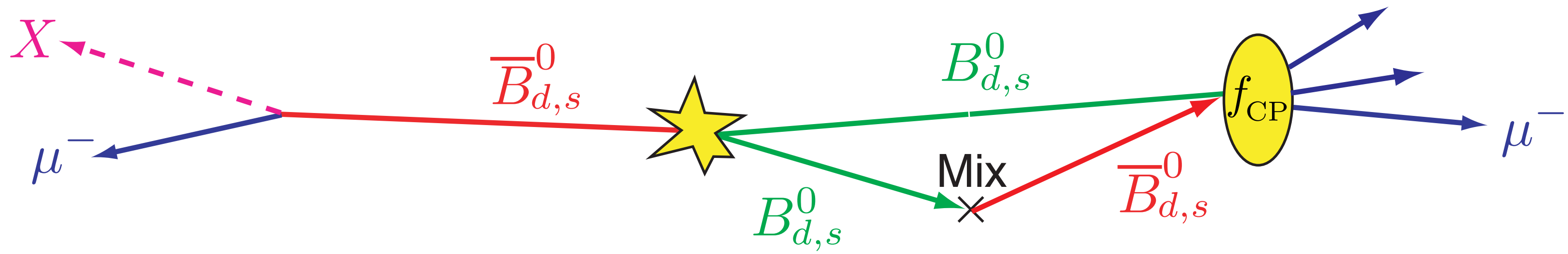
$$A_P = \frac{\sigma(D_s^+) - \sigma(D_s^-)}{\sigma(D_s^+) + \sigma(D_s^-)} = (-0.33 \pm 0.22 \pm 0.10)\%.$$

Decay Mode	Yield
$D^{\pm} \to K_S^0\pi^{\pm}$	$4\,834\,440 \pm 2\,555$
$D_s^{\pm} \to K_S^0\pi^{\pm}$	$120\,976 \pm 692$
$D^{\pm} \to K_S^0K^{\pm}$	$1\,013\,516 \pm 1\,379$
$D_s^{\pm} \to K_S^0K^{\pm}$	$1\,476\,980 \pm 2\,354$
$D^{\pm} \to \phi\pi^{\pm}$	$7\,020\,160 \pm 2\,739$
$D_s^{\pm} \to \phi\pi^{\pm}$	$13\,144\,900 \pm 3\,879$

[%] Asymmetry	Total
$\mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0\pi^{\pm}}$	-0.95 ± 0.05
$\mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0\pi^{\pm}}$	-0.15 ± 0.46
$\mathcal{A}_{\rm meas}^{D^{\pm}\to K_S^0K^{\pm}}$	$+0.01 \pm 0.19$
$\mathcal{A}_{\rm meas}^{D_s^{\pm}\to K_S^0K^{\pm}}$	$+0.27 \pm 0.11$
$\mathcal{A}_{\rm meas}^{D_s^{\pm}\to \phi\pi^{\pm}}$	-0.41 ± 0.05

Additional Source of CPV in Like-Sign Dimuons

Borissov, Hoeneisen, arXiv:1303.0175v1 [hep-ex],
Understanding the like-sign dimuon charge asymmetry in pp(bar) collisions



e.g.,

$$B^- B^0 \text{ with } B^- \to \mu^- X, \quad B^0 \to D^+ D^-, \quad D^- \to \mu^- X$$

$$B^+ \bar{B}^0 \text{ with } B^+ \to \mu^+ X, \quad \bar{B}^0 \to D^+ D^-, \quad D^+ \to \mu^+ X$$

but due to interference between mixing and decay in *B* system:

$$\Gamma(B^0 \to D^+ D^-) \neq \Gamma(\bar{B}^0 \to D^+ D^-) \qquad \mathcal{A} = -\sin(2\beta)\frac{x_d}{1+x_d^2}$$

$$\mathcal{A}^{\rm mix}_{\rm CP}(SM) = (-0.8 \pm 0.1) \times 10^{-4}$$

$$\mathcal{A}^{\rm int}_{\rm CP}(SM) = (-3.5 \pm 0.8) \times 10^{-4}$$ ← additional

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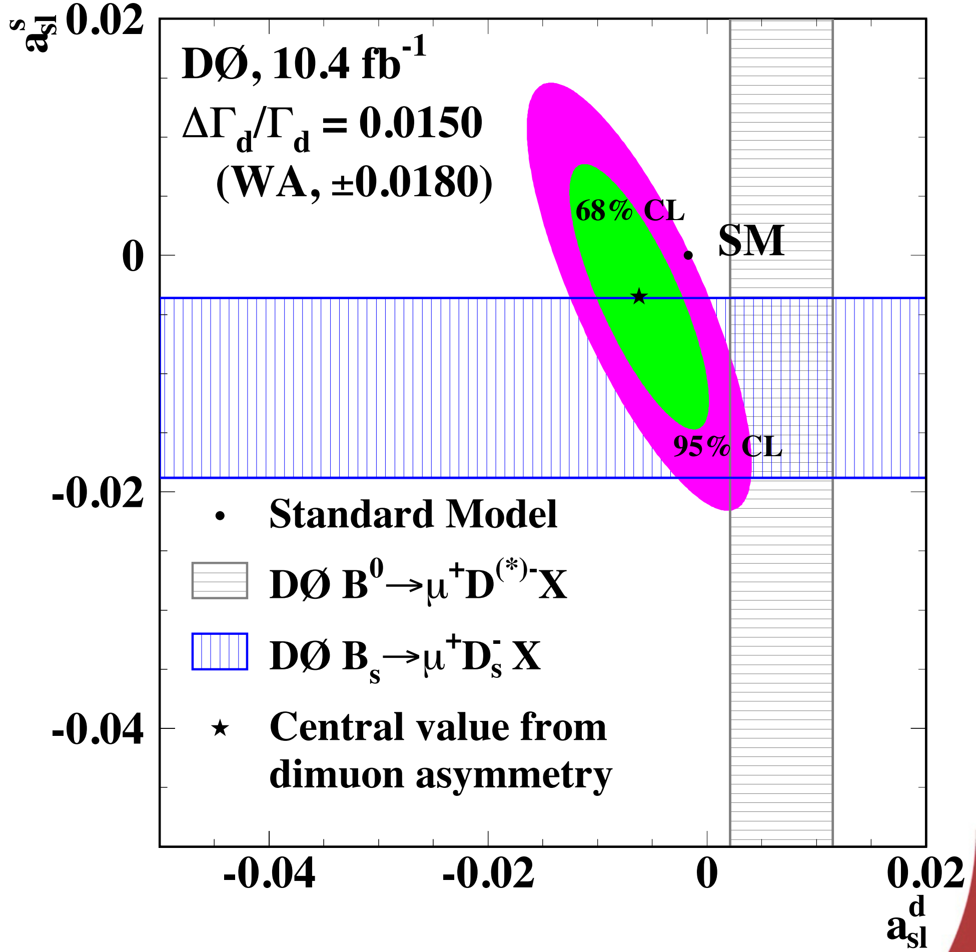
Dimuon Charge Asymmetry

- Average of all three D0 semi-leptonic charge asymmetries

$$a^s_{\rm sl} = (-1.33 \pm 0.58)\,\%,$$
$$a^d_{\rm sl} = (-0.09 \pm 0.29)\,\%,$$
$$\Delta\Gamma_d/\Gamma_d = (+0.79 \pm 1.15)\,\%,$$
$$\rho_{s,d} = -\,0.34, \qquad \rho_{d,\Delta\Gamma} = +0.24,$$
$$\rho_{s,\Delta\Gamma} = +\,0.55.$$

3.1σ deviation from SM



Semi-Leptonic CPV WA

- Direct Measurements of a^d_{sl} = (-0.01 ± 0.19)%
  - Previous B-factory results HFAG arXiv:1207.1158 (-0.59 ± 1.06)%*
  - DØ: PRD 86, 072009 (2012) (+0.68 ± 0.47)%
  - BaBar: PRL 111, 101802 (2013) (+0.06 ± 0.38)%
  - LHCb: (L Grillo Tuesday, CKM) (+0.02 ± 0.35)%
  - BaBar: CKM Dilepton (Cheng, Tuesday, CKM) (-0.39 ± 0.40)%

* removed old BaBar dilepton

- Direct Measurements of a^s_{sl} = (+0.50 ± 0.52)%
  - DØ: PRL 110, 011801 (2013) (-1.12 ± 0.76)%
  - LHCb: PLB 728C (2014) (-0.06 ± 0.63)%
- Direct Measurements of $\Delta\Gamma_d/\Gamma_d$ = (-0.4 ± 2.0)%
  - Previous B-factory results, HFAG, arXiv:1207.1158 (+1.15 ± 1.80)% (Belle, BaBar, [DELPHI])
  - LHCb: JHEP04(2014)114 (-4.4 ± 2.7)%
- Dimuon Charge Asymmetry (see talk)