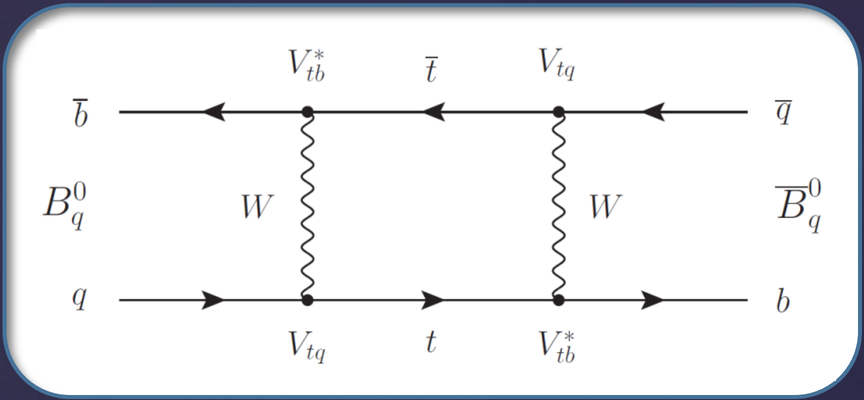
Measurements of semileptonic mixing asymmetries in $B^0_{(s)}$ mesons

BEACH Conference, Wichita, Kansas;
24th July 2012

Mark Williams, Lancaster University
On behalf of the D0 Collaboration

B Meson Oscillations and CPV

Neutral B mesons oscillate into their antiparticles via weak interactions:



Oscillations very well-established in both B^0 and B_s^0 systems:

$\Delta M_d = 0.507 \pm 0.004\ ps^{-1}$ ‘slow’ mixing: probability of oscillation prior to decay depends strongly on decay time;

$\Delta M_s = 17.69 \pm 0.08\ ps^{-1}$ ‘fast’ mixing: experimentally, ~50% oscillation probability regardless of decay time;

Complex phase in CKM matrix $\Rightarrow$ $\mathbf{P[B_{(s)}^0 \rightarrow \bar{B}_{(s)}^0] \overset{?}{\neq} P[\bar{B}_{(s)}^0 \rightarrow B_{(s)}^0]}$

Studies of asymmetries in mixing are a sensitive probe of the SM.

B Meson Oscillations and CPV

Define semileptonic mixing asymmetry:

$$a_{sl}^{q} = \frac{\Delta\Gamma_q}{\Delta M_q} \cdot \tan(\phi_q) = \frac{\Gamma(\bar{B}_q^0 \to B_q^0 \to \ell^+ X) - \Gamma(B_q^0 \to \bar{B}_q^0 \to \ell^- X)}{\Gamma(\bar{B}_q^0 \to B_q^0 \to \ell^+ X) + \Gamma(B_q^0 \to \bar{B}_q^0 \to \ell^- X)}$$

SM values for both B^0 and B^0_s are negligible compared to experimental precision:

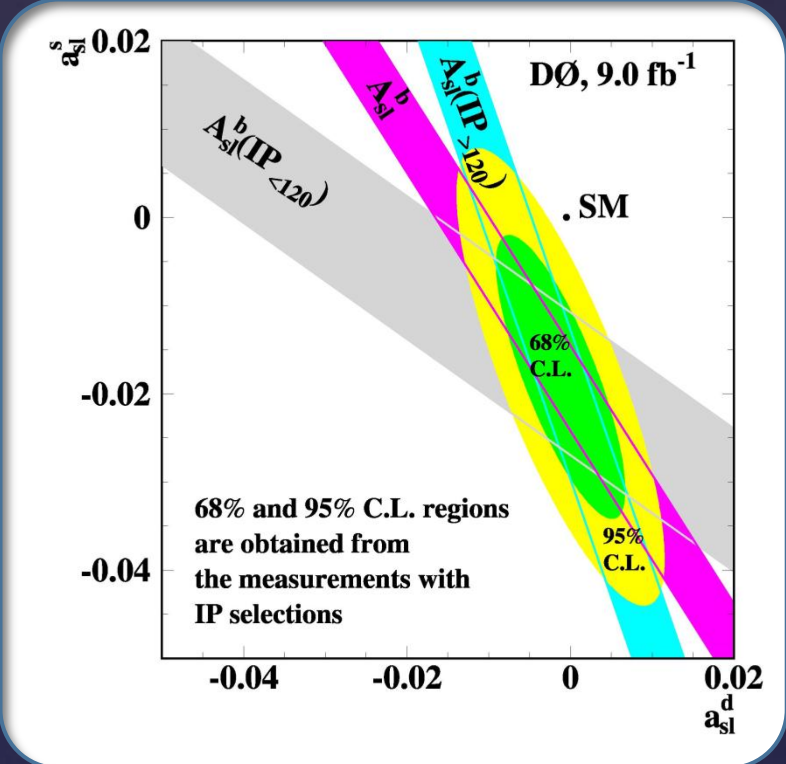
$a^d_{sl} = (-0.041 \pm 0.006)\%$ $a^s_{sl} = (-0.0019 \pm 0.0003)\%$	SM Predictions
$a^d_{sl} = (-0.05 \pm 0.56)\%$	Current WA value from B Factories
$a^s_{sl} = (-0.17 \pm 0.92)\%$	Previous D0 measurement

Any significant deviation from zero is hence a signal of new physics.

Same-sign Dimuon Asymmetry

D0, 2010-2011 (presented at BEACH 2010)

- Huge statistics;
- Need great care in understanding sources of muons, and related background asymmetries;
- Measure combination of semileptonic mixing asymmetries from B^0 and B_s^0;
- Use impact parameter dependence to measure a^d_{sl} and a^s_{sl} separately:



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

3.9σ disagreement with SM prediction

Need separate measurements of a^d_{sl} and a^s_{sl} – subject of this talk!

The D0 Detector

Tevatron accelerator located at the Fermilab site, 30 miles west of Chicago;

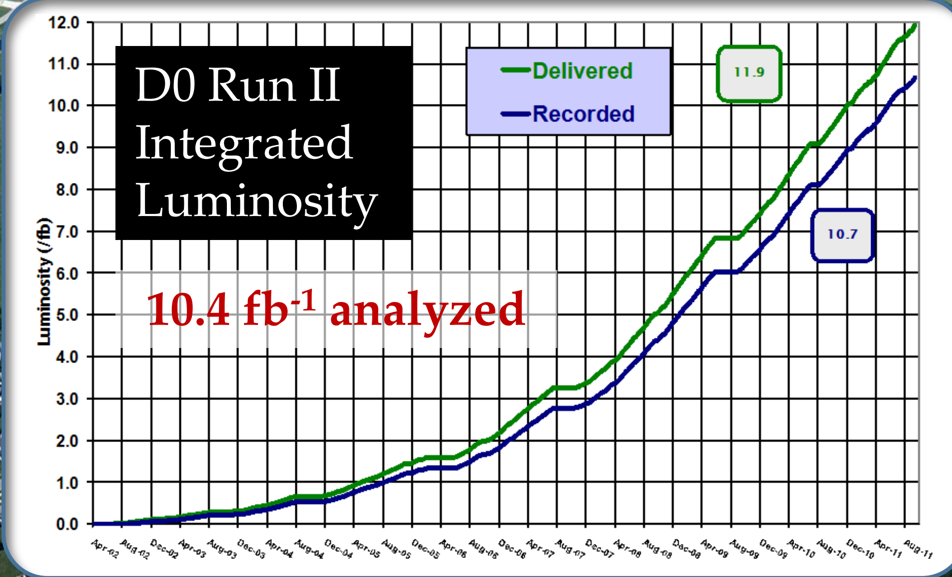
Collided protons and antiprotons at $\sqrt{s} = 1.96$ TeV

No production asymmetries: symmetric initial state

Collisions ended in September 2011

p

$\bar{p}$



The D0 Detector

D0: Typical general-purpose detector

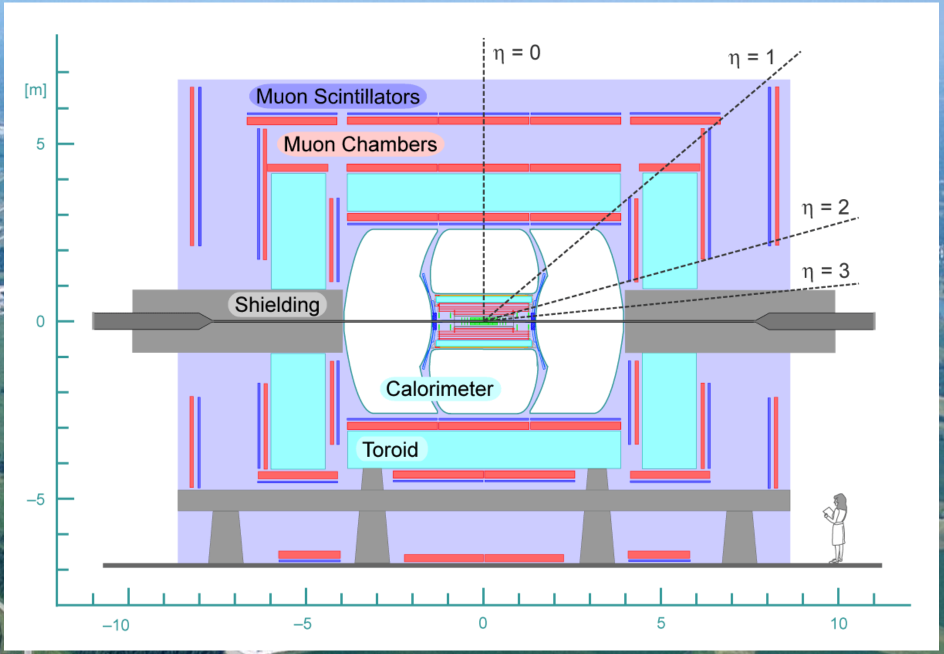
Silicon microstrip and scintillating fiber tracking system

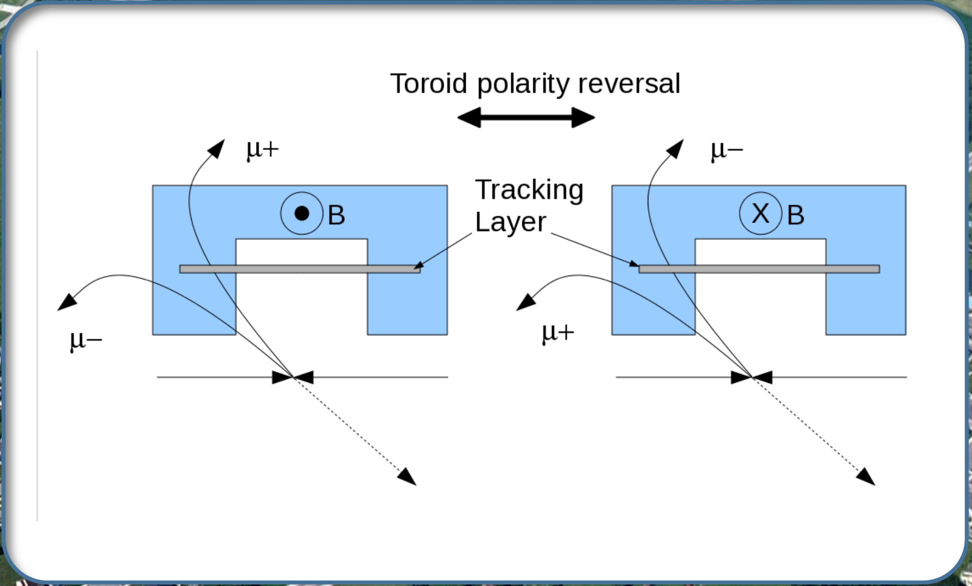
Muon tracking and scintillators located outside calorimeter, with thick shielding to suppress hadronic punchthrough

Wide acceptance $|\eta(\mu)| \leq 2$

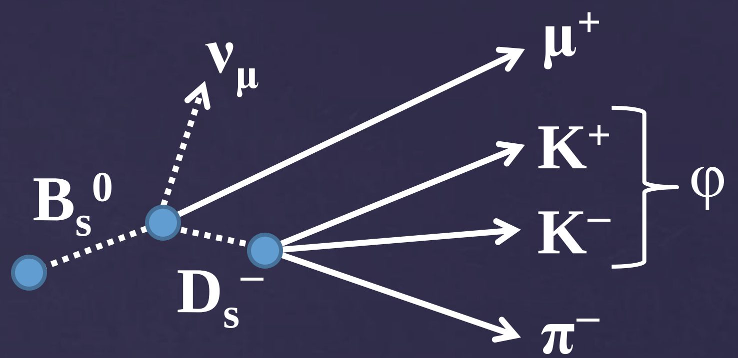
Polarities of tracking and muon magnets regularly reversed: removes first order detector asymmetries (e.g. due to range-out effects)

Events weighted to ensure equal contributions from all four polarity configurations





Analysis Overview



One decay channel for B_s^0:

$B_s^0 \rightarrow \mu^+ \nu D_s^- X$ with $D_s^- \rightarrow \varphi\pi^-$, $\varphi \rightarrow K^+K^-$

For each channel, raw asymmetry is extracted by fitting resonances in invariant mass to count $\mu D_{(s)}^{(*)\pm}$ signal yield:

$$A = \frac{N_{\mu^+ D^{(*)-}} - N_{\mu^- D^{(*)+}}}{N_{\mu^+ D^{(*)-}} + N_{\mu^- D^{(*)+}}} \equiv \frac{N_{\mathrm{diff}}}{N_{\mathrm{sum}}}$$

This is then related to the semileptonic mixing asymmetry via:

$$a_{\mathrm{sl}}^{q} = \frac{A - A_{\mathrm{BG}}}{F^{\mathrm{osc}}_{B^0_{(s)}}}$$

A_{BG}: detector-related asymmetries (e.g. positive kaons have higher detection efficiency).

F_B^{osc}: Many ‘signal’ events are from direct $B_{(s)}^0$ decays, B^+ decays, prompt $cc \rightarrow D^{(*)\pm}$ production, so dilute the sample.

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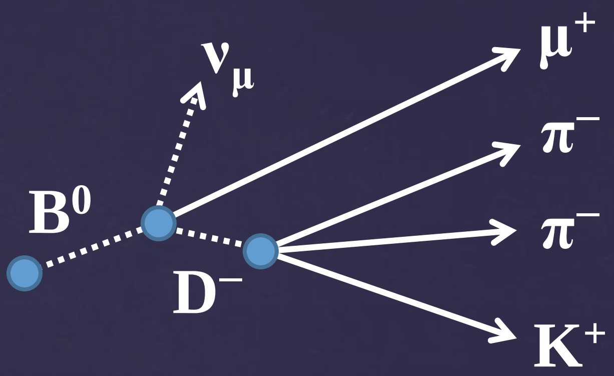

Two decay channels for B^0:

1) $B^0 \to \mu^+ \nu D^- X$ with $D^- \to K^+ \pi^- \pi^-$

2) $B^0 \to \mu^+ \nu D^{*-} X$ with $D^{*-} \to D^0 \pi^-$, $D^0 \to K^+ \pi^-$

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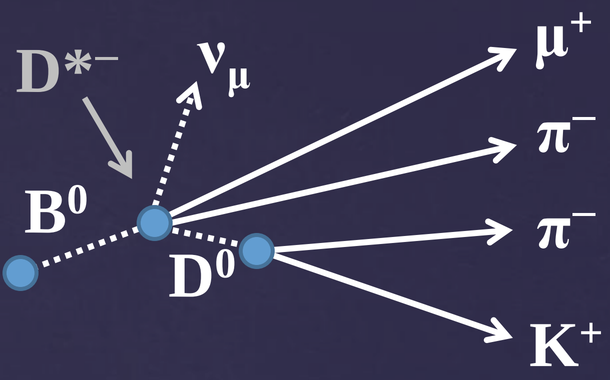

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Analysis Overview

Three main ingredients for each channel:

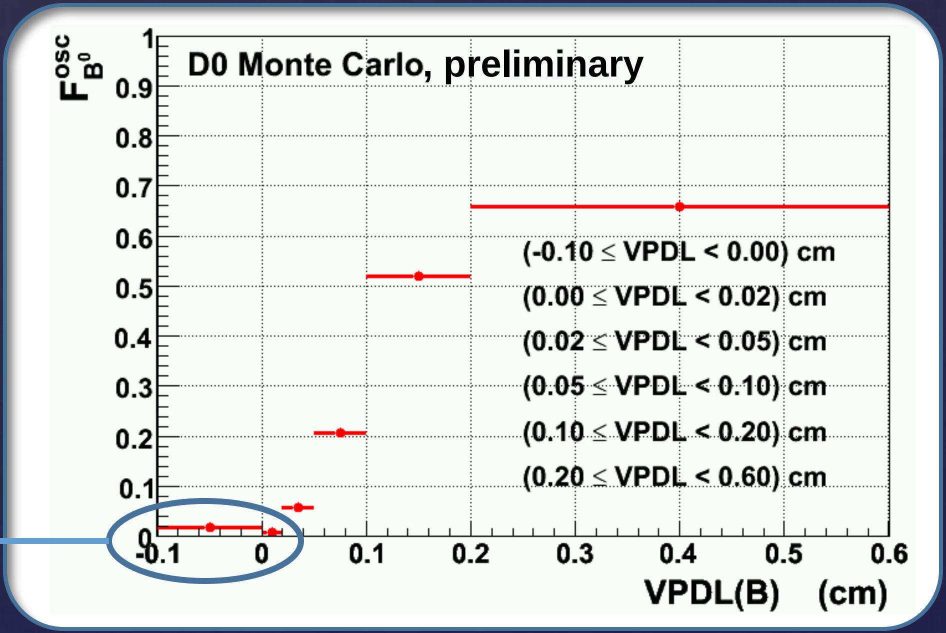
1) Measure **A** by fitting mass distributions for sum and difference;
2) Measure $\mathbf{A_{BG}}$ using data-driven methods from other channels;
3) Determine $\mathbf{F_B^{osc}}$ using simulation

…then combine inputs to extract a^q_{sl}.

Single time-integrated measurement for a^s_{sl}

Six measurements in bins of visible-proper-decay-length (VPDL) for a^d_{sl}: take advantage of 'turning on' of mixing signal for longer lifetimes.

First two bins used as **control region** – negligible signal.



Event Selection

Channels use **common selections** where possible:

- Single and dimuon **triggers** without impact parameter requirements;
- **High quality track in muon system, associated with central track**:
  - $p_T > 2$ GeV; $p_{tot} > 3$ GeV;
- **3 additional tracks** with total charge $q(ttt) = -q(\mu)$:
  - $p_T > 0.7$ GeV; ($p_T > 0.5$ GeV for pion in B_s^0 decay)
- Four tracks must be associated with same Primary Vertex;

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Preselection: Loose, channel-specific reconstruction/vertexing requirements;

Multivariate techniques for final selection.

Optimise to maximise signal significance $\mathbf{N_S / \sqrt{(N_S + N_B)}}$ – performed separately for each VPDL bin in a^d_{sl} measurement

Raw Asymmetry Extraction

$$a_{\rm sl}^{q} = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

Extracting Raw Asymmetries

$$a_{\rm sl}^q = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

Construct invariant mass distributions that can be fitted to extract $\mu D_{(s)}^{(*)\pm}$ yields:

- **M(φπ)** for $D_s^\pm$ channel;
- **M(Kππ)** for $D^\pm$ channel;
- **ΔM** = $M(D^0\pi) - M(D^0)$ for $D^{*\pm}$ channel.

Fill charge-specific histograms $H^\pm$ for each distribution, and use to construct sum and difference:

$$H_{\rm sum} = H^+ + H^-$$
$$H_{\rm diff} = H^+ - H^-$$

Perform simultaneous binned χ^2 fit of sum and difference to extract asymmetry:

$$\chi^2 = \sum_{\text{bin } i=1}^{N} \left[\left(\frac{H^i_{\rm sum} - F^i_{\rm sum}}{\sigma^i_{\rm sum}} \right)^2 + \left(\frac{H^i_{\rm diff} - F^i_{\rm diff}}{\sigma^i_{\rm diff}} \right)^2 \right]$$

$F^i_{\rm sum(diff)}$ are fit functions $F_{\rm sum(diff)}$ integrated over width of bin *i*.

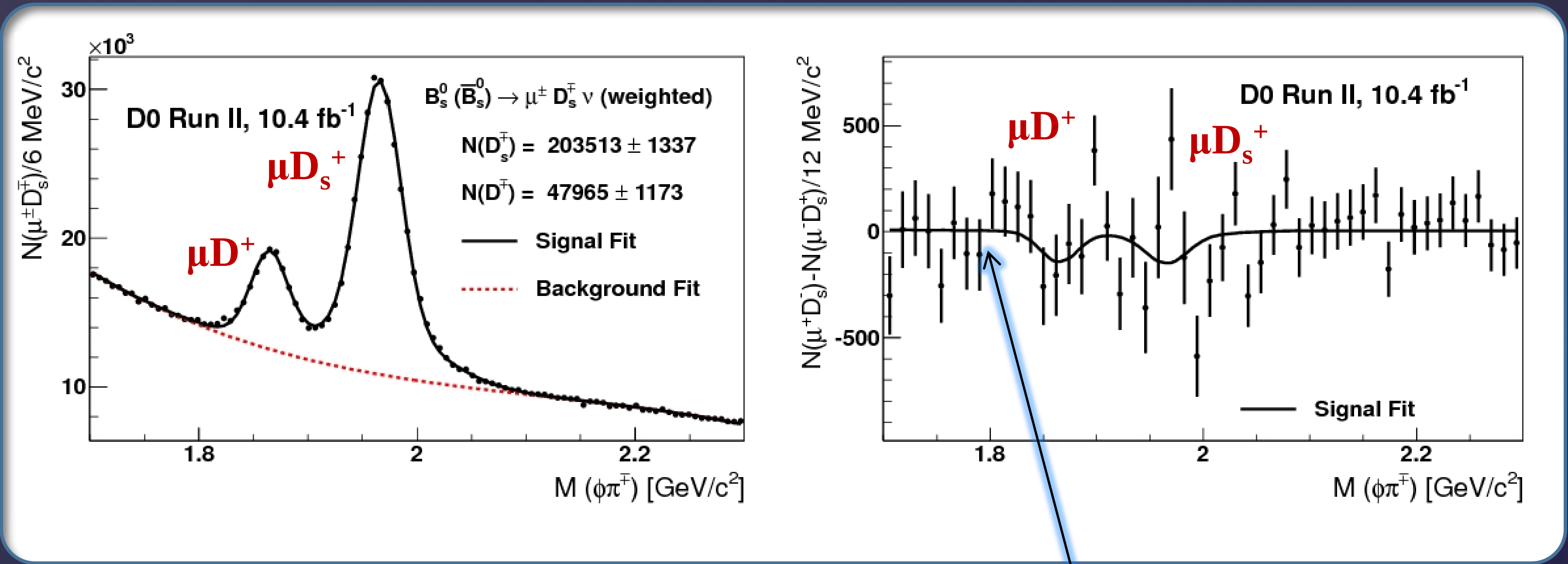
$\sigma^i_{\rm sum} = \sigma^i_{\rm diff} = \sqrt{H^i_{\rm sum}}$

Sum/Difference Fit: $D_s^{\pm}$

$$a_{\rm sl}^{q} = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

Single time-integrated fit

$A = (-0.40 \pm 0.33)$ %



Smaller peak from $B^0 \rightarrow \mu\nu D^+$

Also measure asymmetry in this component:

$A_{D+} = (-1.21 \pm 1.00)\%$

Negligible asymmetry in background

$A_{BG} = (0.00 \pm 0.11)\%$

Strong indication that track reconstruction asymmetry is small.

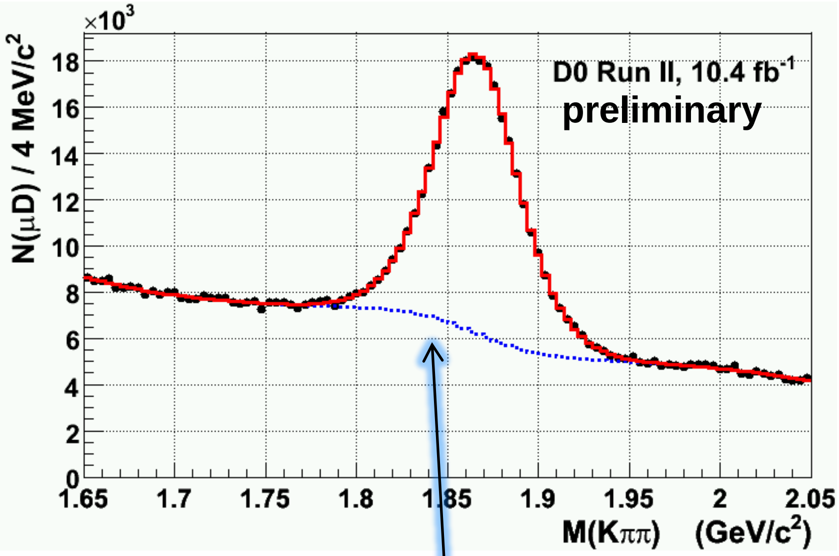
Example Fits: D±

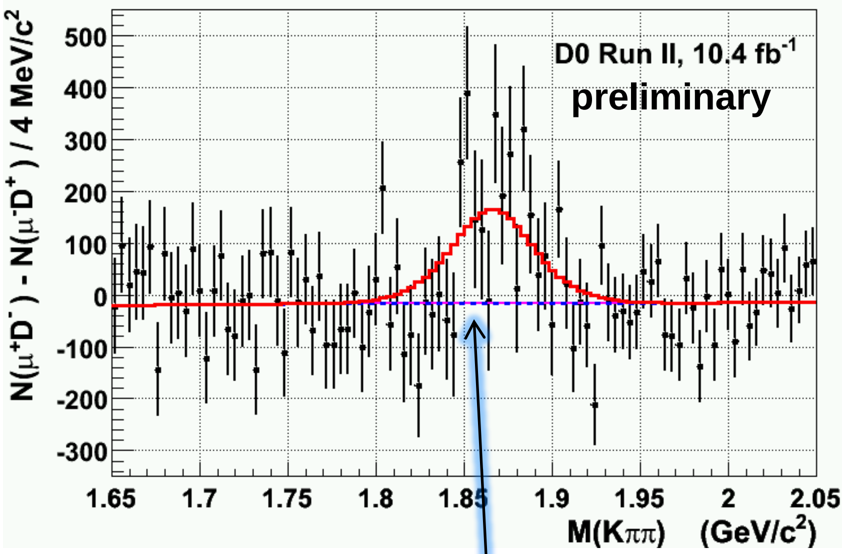
$$a^q_{\rm sl} = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

For [0.10 < VPDL(B) < 0.20] cm

(Bin with highest a^d_{sl} sensitivity)

A = 1.48 ± 0.41 %





Hyperbolic tangent models effects of partially-reconstructed decays (validated in MC), e.g.

$D^- \rightarrow K^+\pi^-\pi^-\pi^0$ (threshold at 1.70→1.75 GeV)

$D^{*-} \rightarrow \pi^- (D^0)K^+\pi^-\pi^0$ (threshold at 1.80→1.90 GeV)

Significant positive asymmetry: expected due to kaon reconstruction effects.

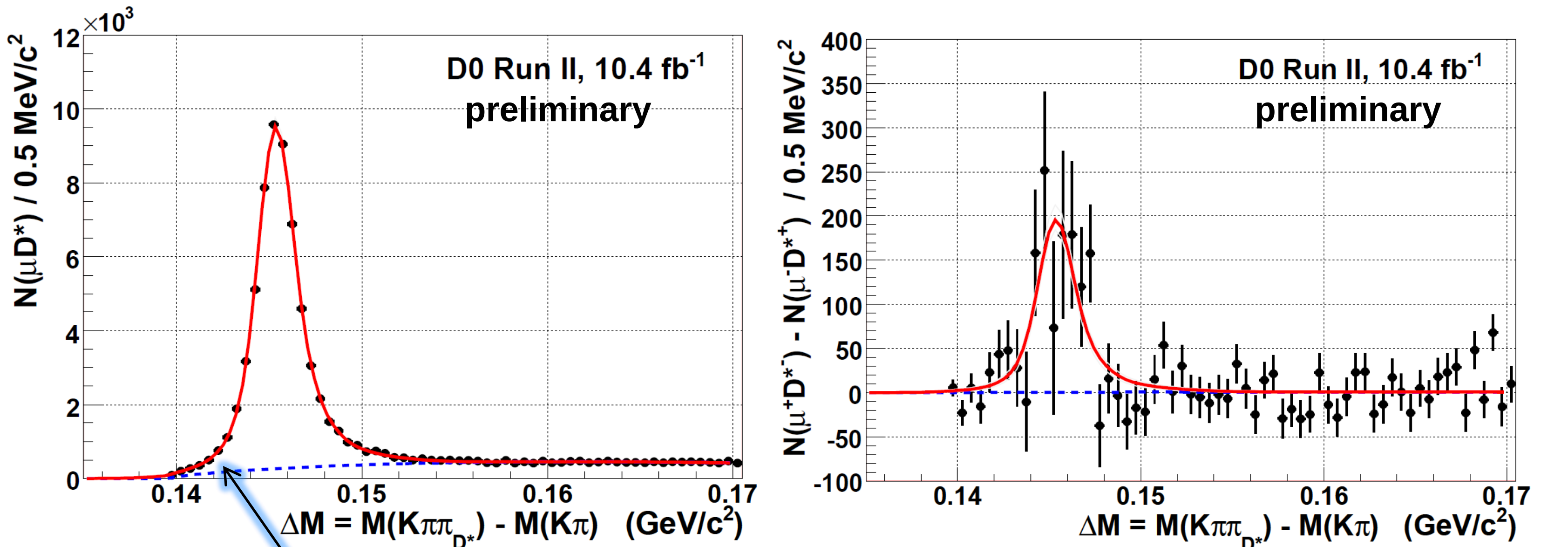
Example Fits: $D^{*\pm}$

$$a_{sl}^{q} = \frac{A - A_{BG}}{F^{osc}_{B^0_{(s)}}}$$

For [0.10 < VPDL(B) < 0.20] cm

(Bin with highest a^d_{sl} sensitivity)

A = 2.11 ± 0.44 %



Proximity of pion threshold skews shapes of signal and background, and necessitates studies to understand BG shape.

Charge-randomised ensemble tests confirm asymmetry extraction is unbiased, and with correct uncertainties (all channels)

Systematic Uncertainties

$$a_{\rm sl}^q = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

Allow simultaneous variations in several aspects of fits:

- Bin widths, upper and lower fitting limits
- Fitting functions (sum/diff for both signal and BG components)
- Alternative weighting scheme
- For D*, use different $M(D^0)$ mass window

Examine effect on final measured asymmetry over this set of fit variants.

$\mu D^{\pm}$ (similar for other channels)

Source	Bin 1 −0.10 – 0.00 cm	Bin 2 0.00 – 0.02 cm	Bin 3 0.02 – 0.05 cm	Bin 4 0.05 – 0.10 cm	Bin 5 0.10 – 0.20 cm	Bin 6 0.20 – 0.60 cm
μD channel						
Bin width	0.09%	0.01%	0.01%	0.01%	0.00%	0.05%
Fit limits	0.17%	0.06%	0.08%	0.05%	0.03%	0.12%
Magnet weighting	0.02%	0.00%	0.00%	0.00%	0.00%	0.01%
Signal model	0.03%	0.03%	0.01%	0.04%	0.01%	0.01%
Background model (sum)	0.03%	0.00%	0.01%	0.01%	0.01%	0.00%
Background model (diff)	0.01%	0.00%	0.01%	0.00%	0.01%	0.02%
Combined systematic	±0.19%	±0.07%	±0.08%	±0.07%	±0.05%	±0.13%
Statistical	±1.28%	±0.35%	±0.32%	±0.33%	±0.41%	±0.88%

For all measurements, systematic uncertainty considerably smaller than statistical.

Detector Asymmetries

$$a_{\mathrm{sl}}^{q} = \frac{A - A_{\mathrm{BG}}}{F_{B^0_{(s)}}^{\mathrm{osc}}}$$

Detector Effects – Introduction

Final-state particles can have different detection efficiencies for particles and antiparticles. Two causes:

1) 'Physics' asymmetries due to different interaction cross-sections of particles in the detector (matter) material.

Negatively charged **kaons** interact with nucleons to produce hyperons
$\Rightarrow$ shorter path length
$\Rightarrow$ lower reconstruction efficiency
$\Rightarrow$ positive kaon asymmetry

2) Residual asymmetries remaining after magnet polarity weighting, e.g. due to imperfect cancellation of (time-dependent) inactive detector elements.

For B^0 channels ($\mu^+K^+\pi^-\pi^-$): $\mathbf{A_{BG} = a^{\mu} + a^{K} - 2a^{\pi}}$

For B_s^0 channel ($\mu^+\varphi\pi^-$): $\mathbf{A_{BG} = a^{\mu} - a^{\pi}}$

$$a^X \equiv \frac{\varepsilon^{X^+} - \varepsilon^{X^-}}{\varepsilon^{X^+} + \varepsilon^{X^-}}$$

Kaon Reconstruction Asymmetry

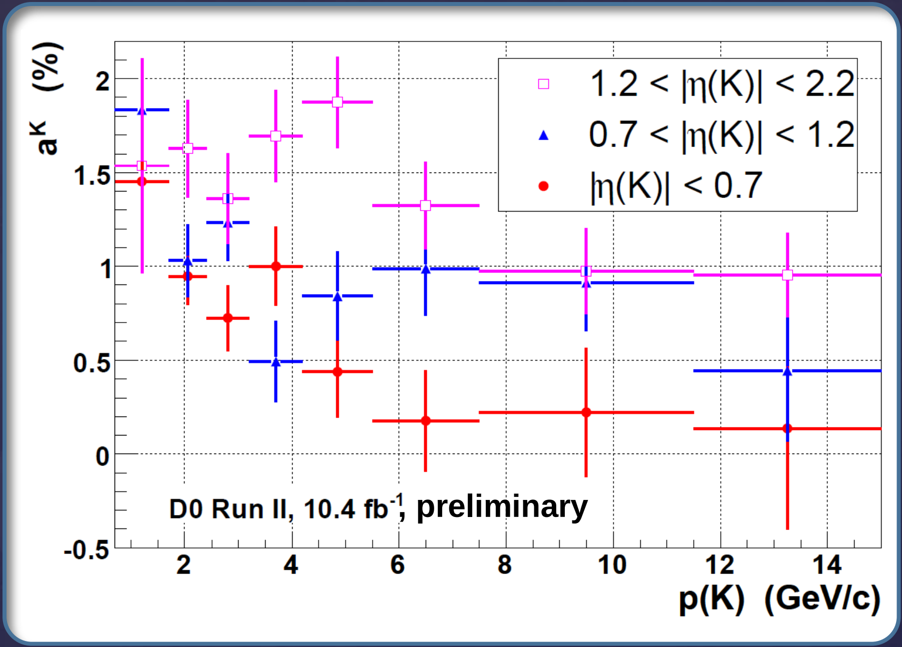
Only affects B^0 channels

Use dedicated channel $\mathbf{K^{*0} \to K^+ \pi^-}$

Also includes possible **asymmetry** in reconstruction of opposite-charge **pion**.

Study difference $N(K^+\pi^-) - N(K^-\pi^+)$ and fit invariant mass distribution to extract asymmetry in p(K) bins.

Convolute a^K distribution with p(K) for each channel and each VPDL bin to obtain final kaon correction.



$$A_{BG}(B^0) = a^\mu + a^K - 2a^\pi$$

Muon Reconstruction Asymmetry

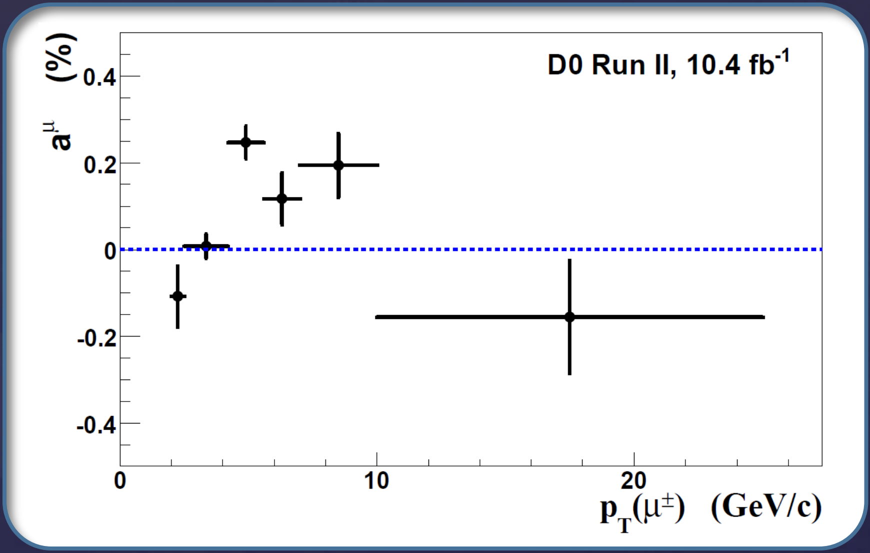
Affects all three channels

Dedicated channel $\mathbf{J/\psi \rightarrow \mu^+\mu^-}$

Insensitive to track asymmetry – only local muon reconstruction;

Study difference $N(\mu^+t^-) - N(\mu^-t^+)$ and fit invariant mass distribution to extract asymmetry in $p_T(\mu)$ bins;

10x smaller than kaon asymmetry.



$$A_{BG}(B^0) = a^\mu + a^K - 2a^\pi$$

$$A_{BG}(B_s^0) = a^\mu - a^\pi$$

Track Reconstruction Asymmetry

Affects all three channels

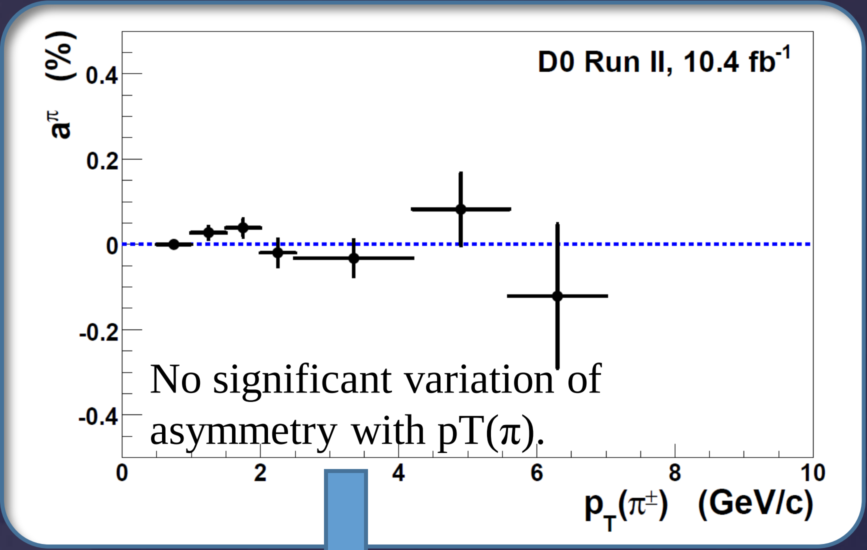
Use $\mathbf{K^0_S \rightarrow \pi^+\pi^-}$ decays to test relative track asymmetries versus pT(track)

Charge-symmetric process: insensitive to absolute charge asymmetry;

Symmetry breaks down when dividing into separate pT samples.

Additional dedicated channel ($K^{*\pm} \rightarrow K_S{}^0\pi^\pm$) finds no evidence for an absolute asymmetry.

Assign $a^\pi = (0.00 \pm 0.05)\%$



1) Overall track asymmetry will cancel in signal final states ($\mu^+\pi^-$)

2) Suggests negligible absolute asymmetry, since any effect should be pT dependent

Final A_{BG} Corrections

- Kaon asymmetry x10 larger than muon asymmetry
- Asymmetries consistent across VPDL bins
- Small differences between channels due to different kinematics

For B_s^0 channel:

$A_{BG} = (0.11 \pm 0.06)\%$

For $B^0 \to \mu D^{\pm}$ channel, **$A_{BG} = 1.17\% \to 1.23\%$ $\pm 0.06\%$**

	Bin 1 $-0.10 - 0.00$ cm	Bin 2 $0.00 - 0.02$ cm	Bin 3 $0.02 - 0.05$ cm	Bin 4 $0.05 - 0.10$ cm	Bin 5 $0.10 - 0.20$ cm	Bin 6 $0.20 - 0.60$ cm
			μD channel			
A (%)	2.70 ± 1.28 ± 0.19	1.02 ± 0.35 ± 0.07	1.16 ± 0.32 ± 0.08	1.50 ± 0.33 ± 0.07	1.48 ± 0.41 ± 0.05	1.20 ± 0.88 ± 0.13
a^K (%)	1.076 ± 0.051 ± 0.016	1.061 ± 0.048 ± 0.015	1.093 ± 0.047 ± 0.016	1.101 ± 0.047 ± 0.016	1.117 ± 0.047 ± 0.017	1.114 ± 0.048 ± 0.017
a^μ (%)	0.102 ± 0.025 ± 0.008	0.105 ± 0.027 ± 0.009	0.107 ± 0.029 ± 0.012	0.107 ± 0.029 ± 0.013	0.108 ± 0.028 ± 0.011	0.108 ± 0.028 ± 0.009
$a^K + a^\mu$ (%)	1.178 ± 0.057 ± 0.018	1.166 ± 0.055 ± 0.017	1.200 ± 0.055 ± 0.020	1.208 ± 0.055 ± 0.021	1.225 ± 0.055 ± 0.020	1.222 ± 0.056 ± 0.019

For $B^0 \to \mu D^{*\pm}$ channel, **$A_{BG} = 0.99\% \to 1.04\%$ $\pm 0.07\%$**

Oscillated $B_{(s)}^0$ Fraction

$$a_{\rm sl}^q = \frac{A - A_{\rm BG}}{F_{B^0_{(s)}}^{\rm osc}}$$

Dilution from non-mixed B mesons

Semi-inclusive event selection: missing neutrino prevents unique identification of $B_{(s)}0$ mesons;

Some $\mu D_{(s)}^{(*)}$ candidates arise from other sources:

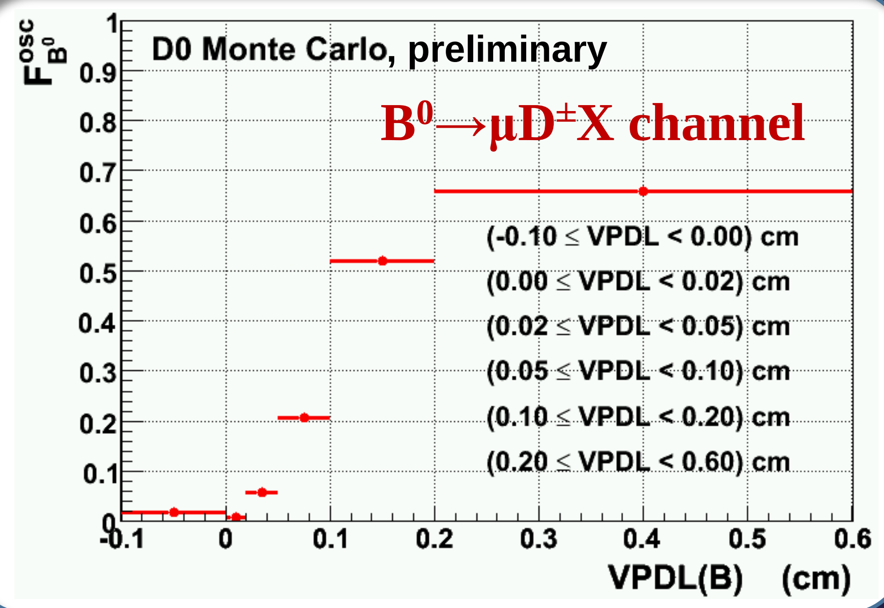
- Prompt $c \rightarrow D$
- B^+ decays
- B^0 in B_s^0 channel / B_s^0 in B^0 channel
- b baryons (negligible)

Need to model oscillations for both B^0 and B_s^0, for all three channels

Use **MC simulation**.

For B_s^0 channel:

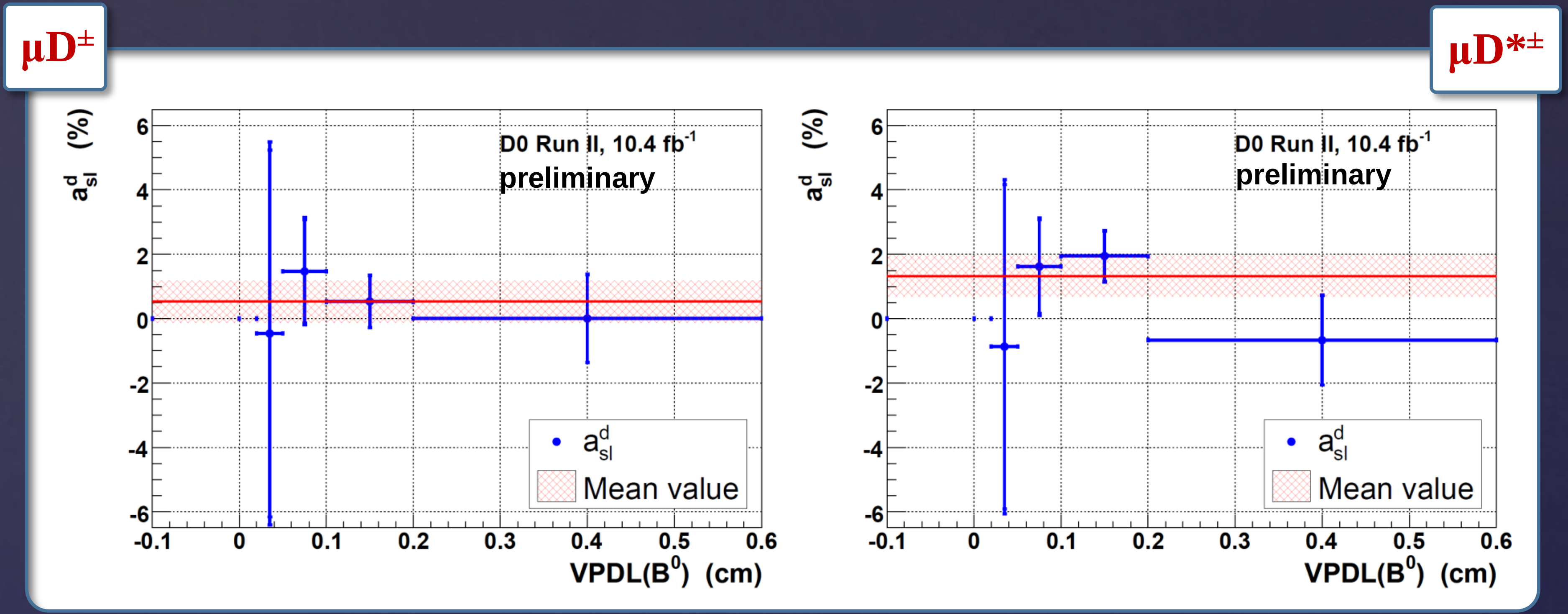
$$F^{osc}_{B_s^0} = 0.465 \pm 0.017$$



Final Results & Combination

$$a_{\rm sl}^{q} = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

a^d_{sl} versus VPDL



Combine within each channel taking all correlations into account (via pseudo-experiment ensembles):

$$a^d_{\rm sl}(\mu D) = [0.53 \pm 0.63 \text{ (stat.)} \pm 0.16 \text{ (syst.)}]\%$$
$$a^d_{\rm sl}(\mu D^*) = [1.32 \pm 0.62 \text{ (stat.)} \pm 0.16 \text{ (syst.)}]\%$$

Dependence on VPDL

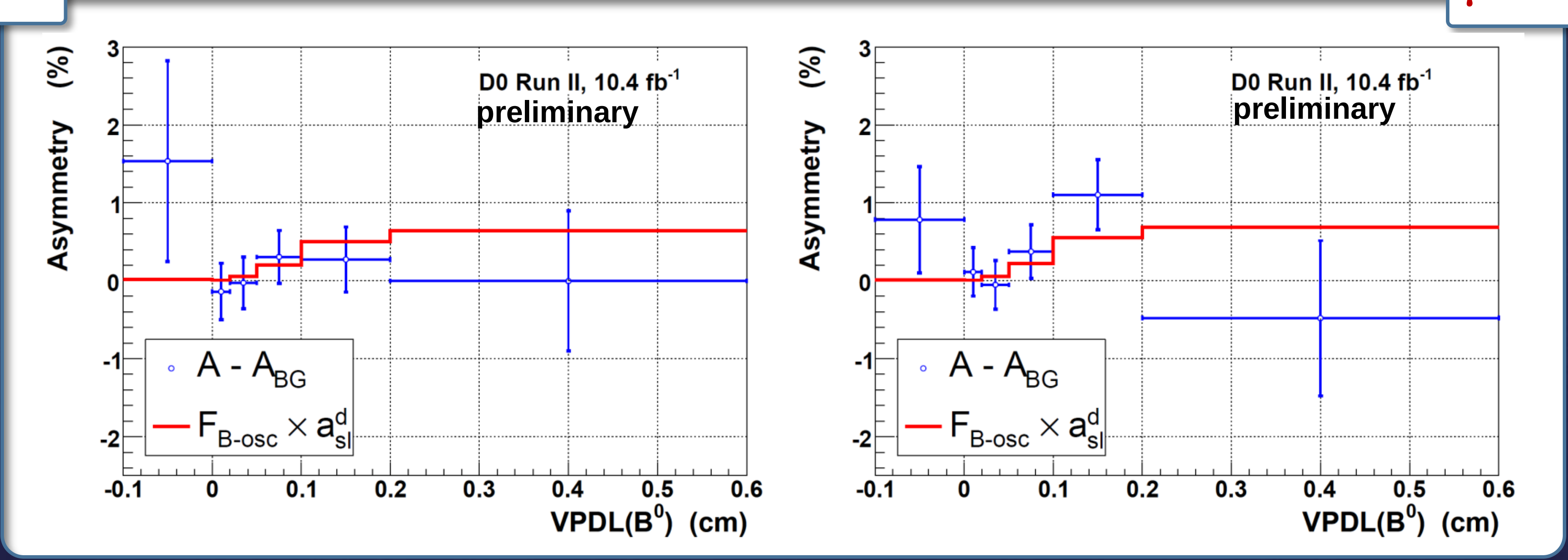
F_B^{osc} is strong function of VPDL

$\Rightarrow$ Any real physical asymmetry from B^0 mixing should be VPDL dependent;

Plot $(A - A_{BG})$ versus VPDL, to look for dependence:

$\chi^2 = 2.6$ (4.7) for a^d_{sl} from this measurement; 3.0 (9.4) for SM a^d_{sl}.

$\mu D^{\pm}$ **$\mu D^{*\pm}$**



Final Results

Combine two $\mathbf{a^d_{sl}}$ measurements, with correlations accounted for:

$$a^d_{\text{sl}} = [0.93 \pm 0.45\ (\text{stat.}) \pm 0.14\ (\text{syst.})]\%$$

- Consistent with SM at 2σ level
- More precise than existing WA from B-factories: (−0.05 ± 0.56)%
- Paper in preparation

Corresponding time-integrated measurement of $\mathbf{a^s_{sl}}$:

$$a^s_{\text{sl}} = [-1.08 \pm 0.72\,(\text{stat}) \pm 0.17\,(\text{syst})]\,\%$$

- Supersedes previous worlds-best measurement (D0, 2009)
- Consistent with results of dimuon asymmetry…
- Submitted to Phys. Rev. Letters (arXiv:1207.1769 [hep-ex])

Combination

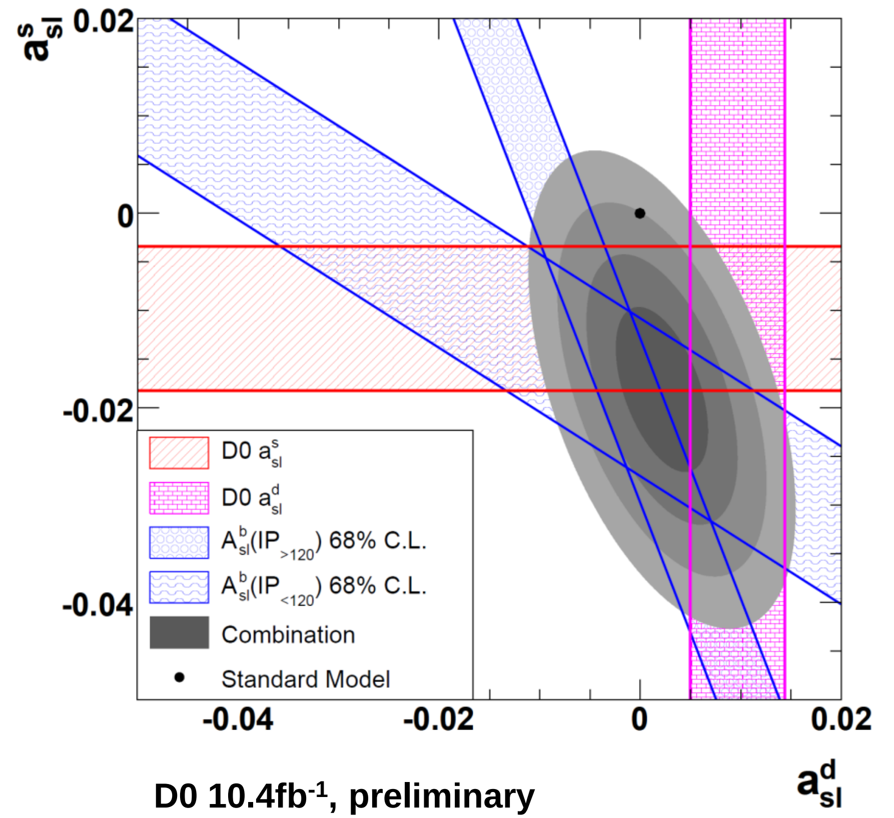
Combine D0 results from dimuon asymmetry (2011), a^d_{sl} and a^s_{sl}:

$$a^d_{\rm sl}(\text{comb.}) = (0.22 \pm 0.30)\%,$$
$$a^s_{\rm sl}(\text{comb.}) = (-1.81 \pm 0.56)\%,$$

Correlation coefficient: −0.50

χ^2/dof = **4.7/2**

p-value of SM: **0.29% (3.0σ)**



B^0 meson: consistent with SM (zero)

B_s^0 meson: **>3σ evidence** for anomalous CPV

Conclusions

- We present new precise measurements of the semileptonic mixing asymmetry in B^0 and B_s^0 mesons:

$$a_{\rm sl}^d = [0.93 \pm 0.45\ (\text{stat.}) \pm 0.14\ (\text{syst.})]\%$$

$$a_{\rm sl}^s = [-1.08 \pm 0.72\,(\text{stat}) \pm 0.17\,(\text{syst})]\,\%$$

- When combined with dimuon asymmetry result, **3σ evidence of anomalously large CPV in B_s^0 mixing**
- Data-driven methods, using strengths of D0 detector.
- Limited input from MC.
- Many cross-checks validate measurement;
- Paper submitted to PRL (a^s_{sl}), Extended PRD in preparation for a^d_{sl}.

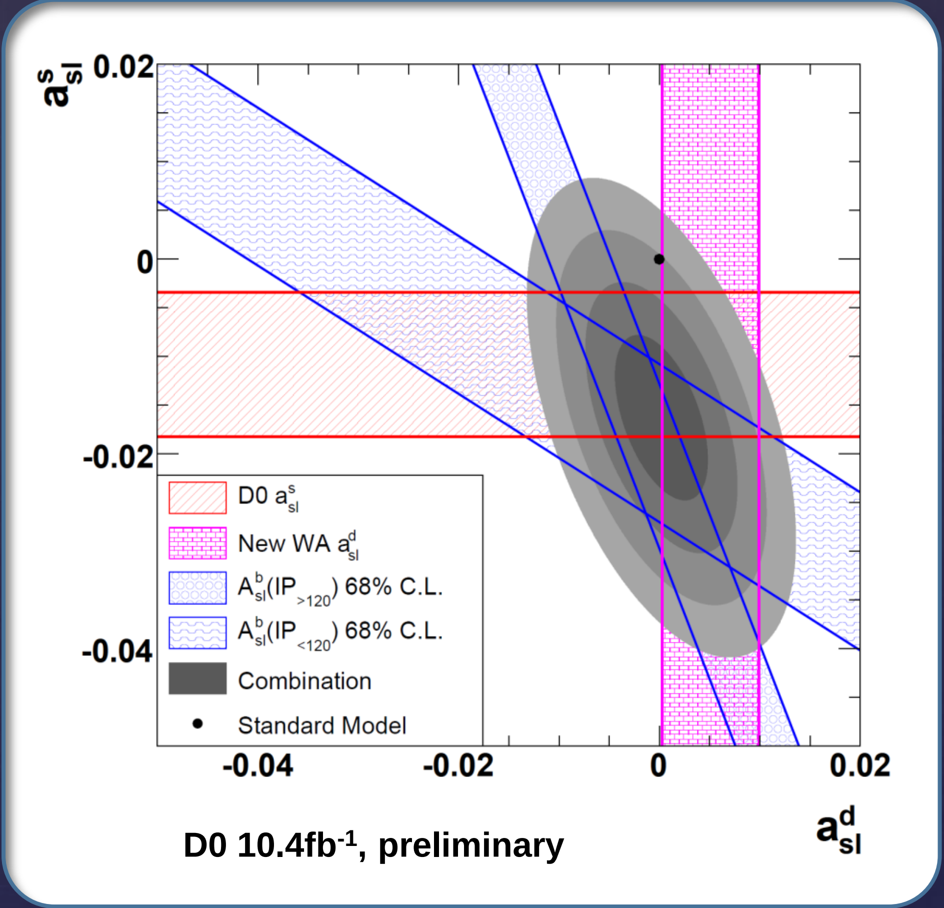
Extra Slides

- Additional combination
- Cross-checks
- Fit results (tables)

Combination (including B-fac a^d_{sl})

Combine D0 results from dimuon asymmetry (2011), a^d_{sl} and a^s_{sl}:, and existing WA of a^d_{sl} from B-factories.

$$a^d_{sl}(\text{comb.}) = (0.02 \pm 0.30)\%,$$
$$a^s_{sl}(\text{comb.}) = (-1.63 \pm 0.56)\%,$$



Correlation coefficient: −0.51

χ^2/dof = **2.1/2**

p-value of SM: **0.26%**

B^0 meson: consistent with SM (zero)

B_s^0 meson: **>3σ evidence** for anomalous CPV

Magnet Polarity Weighting

Events are weighted such that sum of weights W is same for four (solenoid, toroid) = (±, ±) polarity configurations.

$$W(\pm,\pm) \;=\; N_{\mathrm{min}}/N(\pm,\pm)$$

Default method: $N = N_{tot}$ (by event counting);

Alternative weights: $N = N_{sig}$ (from fits);

Weights determined separately in each VPDL bin, and for each channel.

Effective statistical loss of around 3-5%

$N(\mu D^{\pm})$: 740,000 → 722,000 (2.4% loss)
$N(\mu D^{*\pm})$: 545,000 → 519,000 (4.8% loss)
$N(\mu D_s^{\pm})$: 216,000 → 203,000 (6.0% loss)

Systematic Uncertainties on F_B^{osc}

- Vary B^0 decay branching ratios within uncertainties;
- Vary B meson lifetimes within uncertainties;
- Vary ΔM_d within uncertainties;
- Vary B^0 and B^+ fraction to account for precision in production fractions.

	Bin 1 −0.10 – 0.00 cm	Bin 2 0.00 – 0.02 cm	Bin 3 0.02 – 0.05 cm	Bin 4 0.05 – 0.10 cm	Bin 5 0.10 – 0.20 cm	Bin 6 0.20 – 0.60 cm
$F_{B^0}^{osc}(\mu D)$						
Branching Ratios	± 0.001	± 0.000	± 0.001	± 0.004	± 0.009	± 0.015
Production Fractions	± 0.000	± 0.000	± 0.000	± 0.001	± 0.002	± 0.003
B meson lifetimes	± 0.000	± 0.000	± 0.000	± 0.001	± 0.003	± 0.007
ΔM_d	± 0.000	± 0.000	± 0.001	± 0.003	± 0.005	± 0.002
Total	± 0.001	± 0.000	± 0.001	± 0.005	± 0.011	± 0.017
$F_{B^0}^{osc}(\mu D^*)$						
Branching Ratios	± 0.001	± 0.000	± 0.001	± 0.001	± 0.004	± 0.006
Production Fractions	± 0.000	± 0.000	± 0.001	± 0.001	± 0.001	± 0.002
B meson lifetimes	± 0.000	± 0.000	± 0.001	± 0.001	± 0.003	± 0.005
ΔM_d	± 0.000	± 0.000	± 0.001	± 0.003	± 0.005	± 0.003
Total	± 0.001	± 0.000	± 0.002	± 0.003	± 0.007	± 0.009