CP Violation Studies at D0

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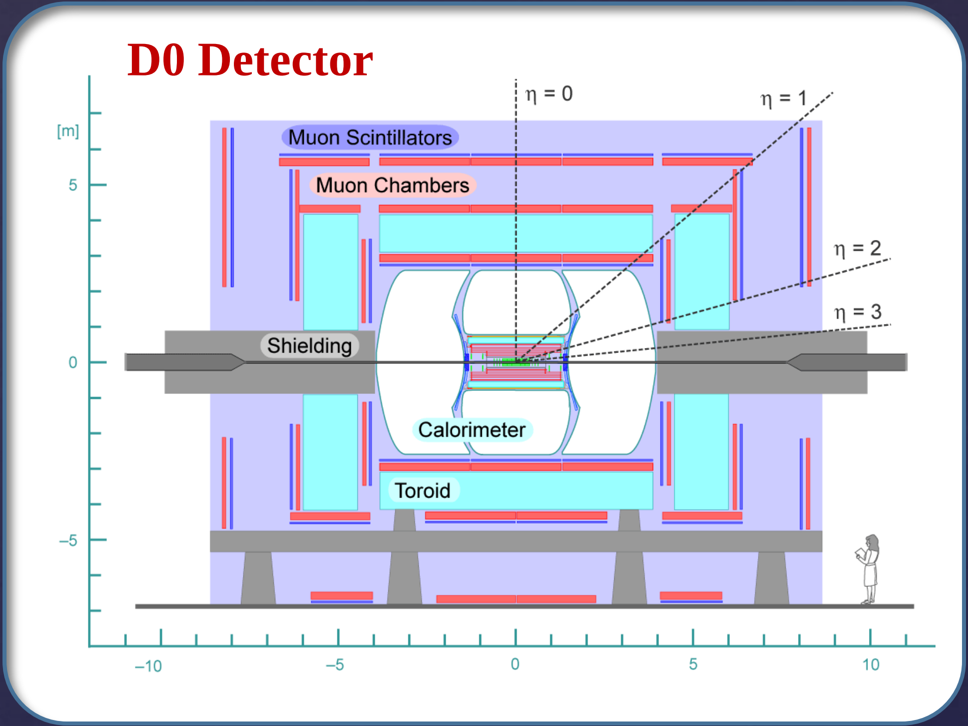
CP Violation @ D0

The D0 data set is uniquely suited for CPV searches / measurements:

- CP-symmetric initial state: no production asymmetries to disentangle;
- Symmetric tracker geometry (~same detection efficiencies for +ive, −ive tracks)
- Excellent muon system with wide acceptance (**$|\eta(\mu)| \leq 2$**); heavy shielding suppresses fake rate.



All analyses presented today use complete ~10.4fb^{-1} D0 data set

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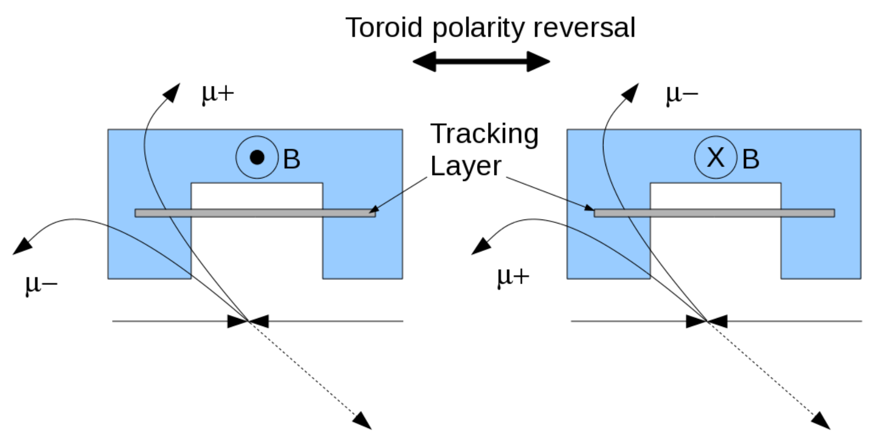
- Symmetric tracker geometry (~same detection efficiencies for +ive, −ive tracks)
- Excellent muon system with wide acceptance ($|\eta(\mu)| \leq 2$); heavy shielding suppresses fake rate.
- ~Equal exposure in all four magnet polarity configurations (muon toroid ⊗ tracker solenoid) removes any first-order detector asymmetries



Regular reversal of solenoid (tracking) and toroid (muon) magnets cancels detector asymmetries to first order

Typical tracking detectors have charge asymmetries of 1-3% (range-out, lorentz angle)

Detector Asymmetries

Important to make *independent measurements* of detector asymmetries

Largest asymmetry associated with charged kaon reconstruction

K^+ have smaller interaction cross-section than K^- in matter:

$K^- N \rightarrow Y\pi$

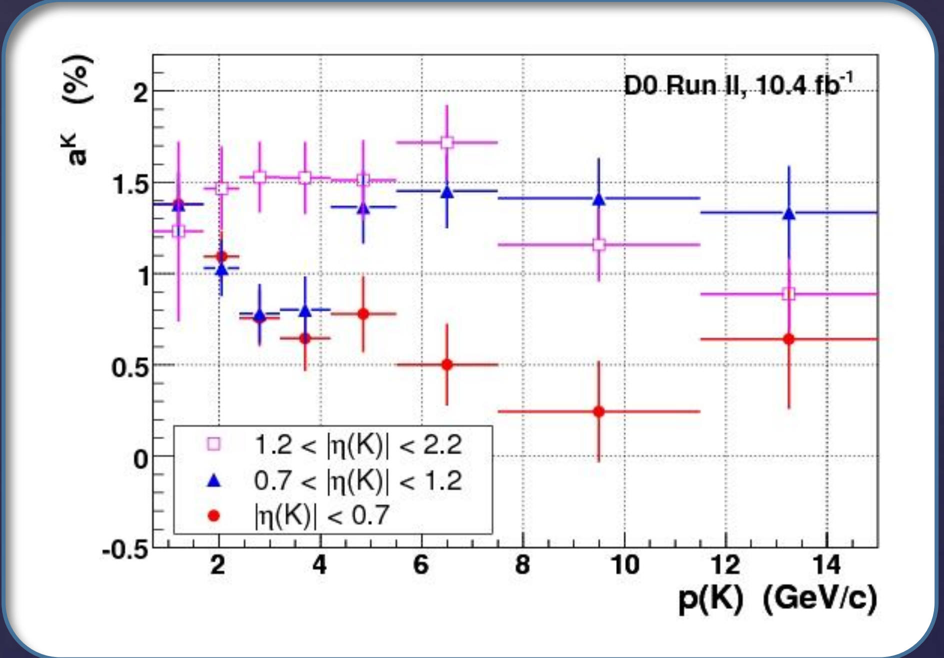
$K^+ N \rightarrow$ ✘

@ p(K) = 1 GeV

$\sigma(K^- d) \approx 80mb$

$\sigma(K^+ d) \approx 33mb$

K^+ have longer path length in tracker ⇒ higher track reconstruction efficiency.



Kaon reconstruction asymmetry measured in $K^{*0} \rightarrow K^+\pi^-$ decays, in bins of $(p_K, |\eta_K|)$

⇒ 0.5% to 1.5% effect

Detector Asymmetries

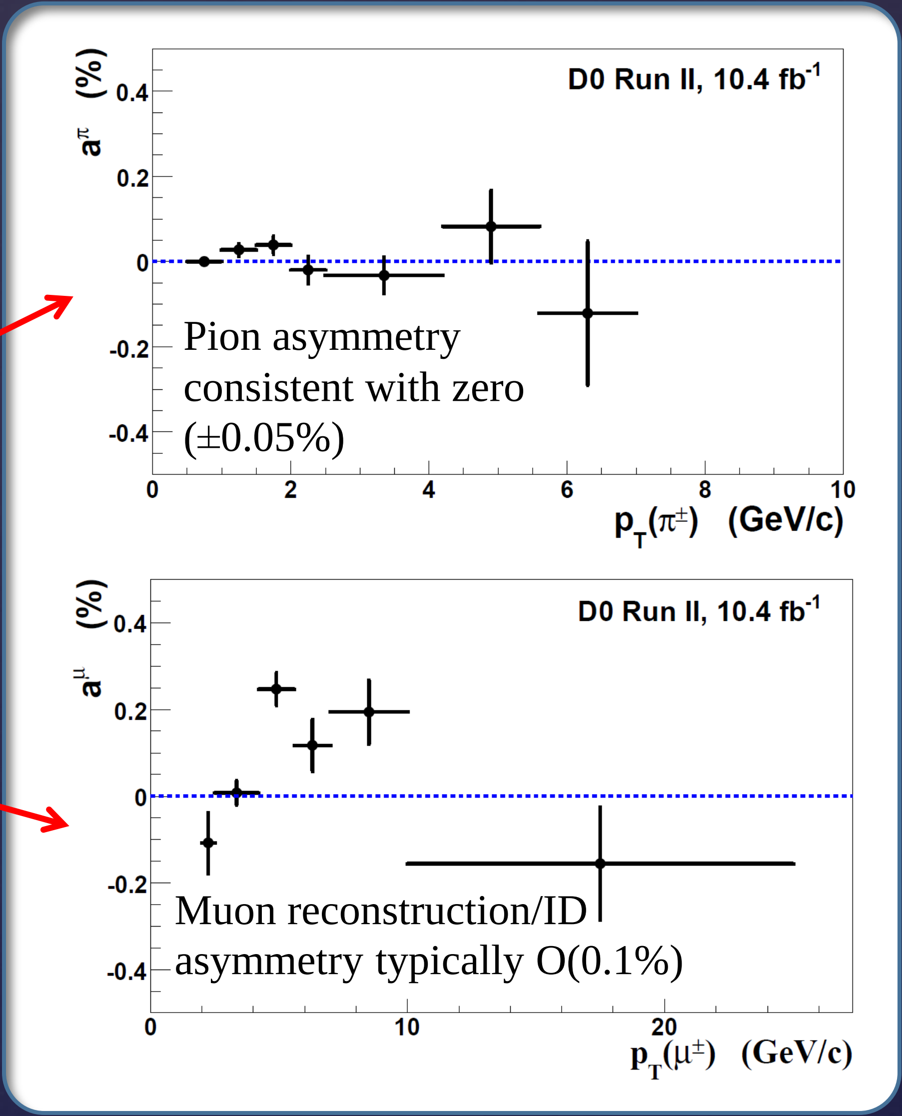
In contrast, muon and pion detection efficiencies are very small

Driven by detector effects, rather than by matter/antimatter interaction differences

Pion (i.e. track) reconstruction asymmetry measured using $K_S^0 \rightarrow \pi^+\pi^-$ and $K^{*+} \rightarrow K_S^0\pi^+$ decays

Muon reconstruction/ID asymmetry measured using $J/\psi \rightarrow \mu^+\mu^-$ decays

Both effects $\gtrsim$10x smaller than kaon asymmetry.

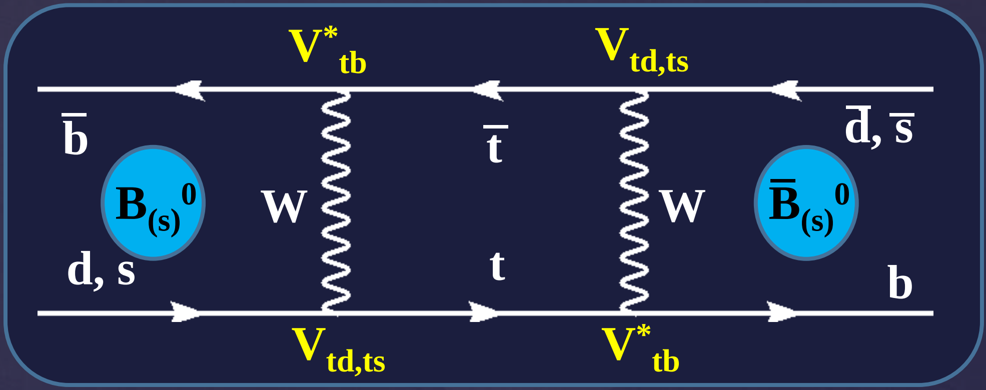


CPV in B Meson Mixing

Neutral B mesons oscillate into their antiparticles

Complex phase in CKM matrix can lead to asymmetry:

$$\Gamma[B_{(s)}^0 \to \bar{B}_{(s)}^0] \stackrel{?}{\neq} \Gamma[\bar{B}_{(s)}^0 \to B_{(s)}^0]$$



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 of a^q_{sl} are negligible compared to experimental precision:

$$a^d_{sl} = (-0.041 \pm 0.006)\%$$

$$a^s_{sl} = (-0.0019 \pm 0.0003)\%$$

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

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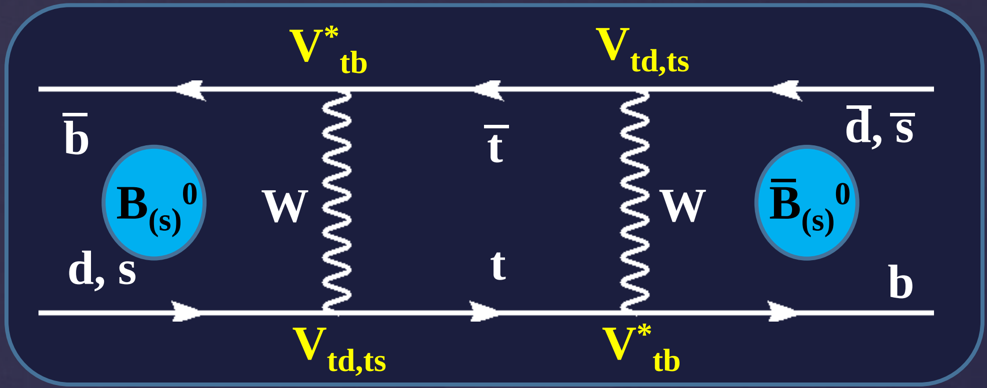
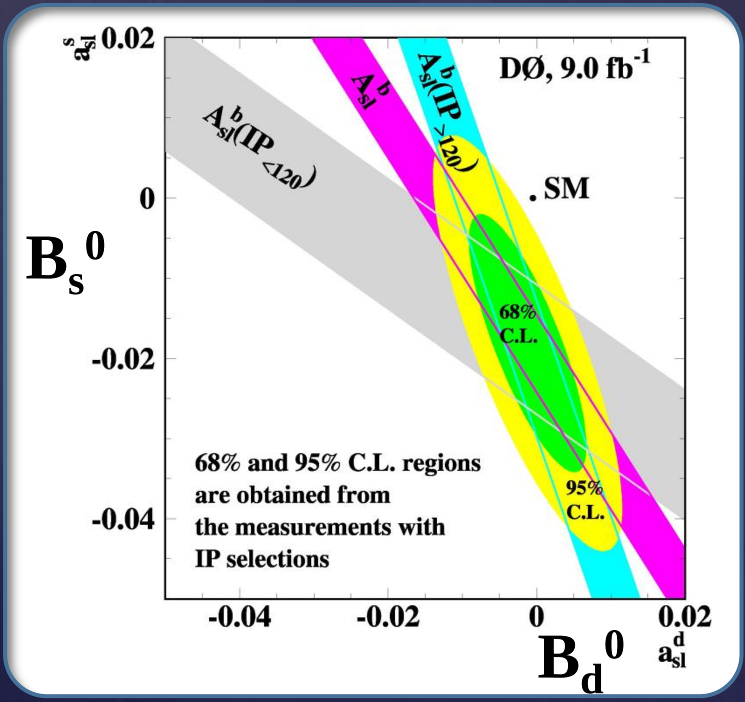




D0 experiment measures significant asymmetry in same-charge dimuons (2011)

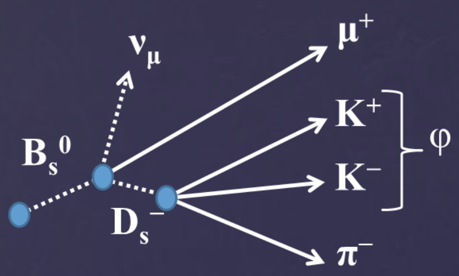
Interpreted as arising from asymmetry in B mixing and/or interference

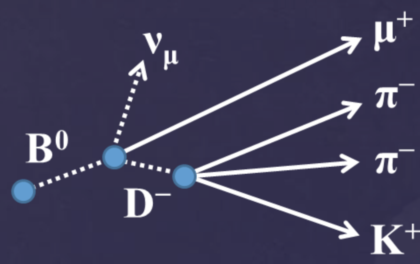
~50% contributions from B_d^0 and B_s^0

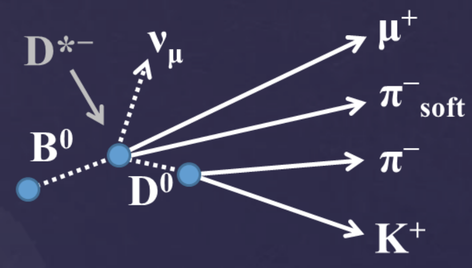
Important to make separate, independent measurements of a^d_{sl} and a^s_{sl}

(see talk by B. Hoeneisen, 19th July)

Analysis Overview







Three decay channels:

$B_s^0 \rightarrow \mu^+ \nu D_s^- X$ **$B^0 \rightarrow \mu^+ \nu D^- X$** **$B^0 \rightarrow \mu^+ \nu D^{*-} X$**

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

Detector-related asymmetries (a^K, a^π, a^μ):

$A_{BG}(B^0) = (1.18 \rightarrow 1.27)\%$

$A_{BG}(B_s^0) = (0.13 \pm 0.06)\%$

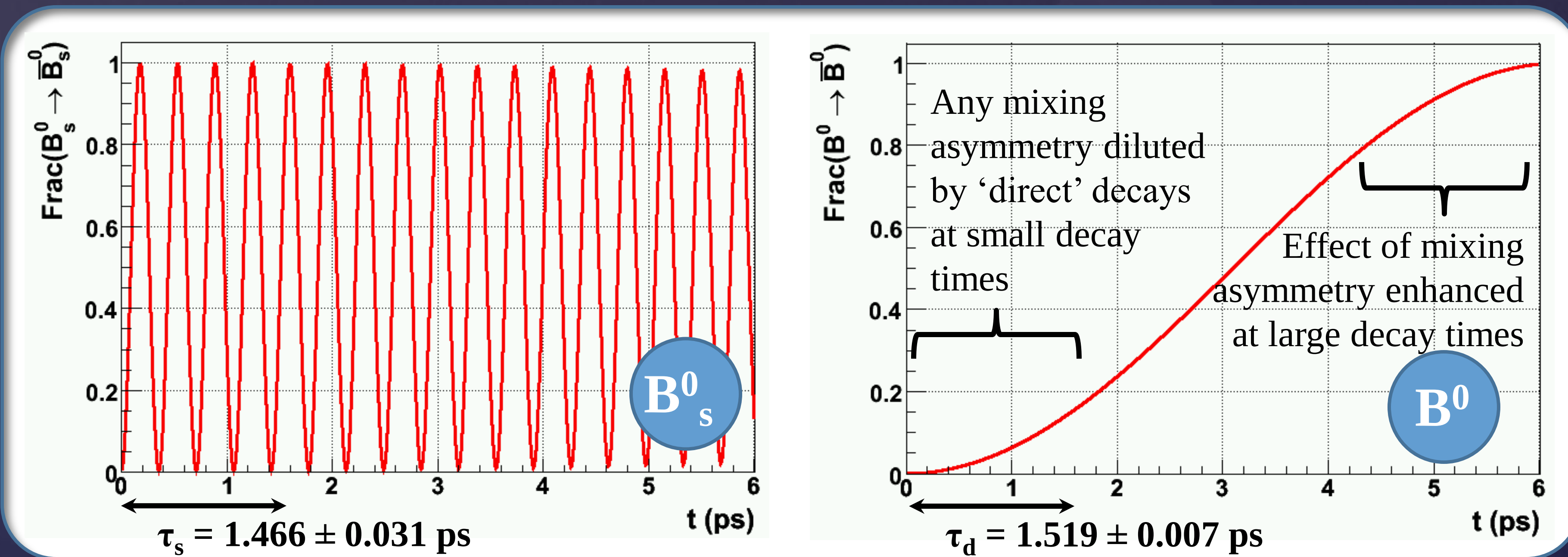
Raw asymmetry extracted by counting $\mu D_{(s)}^{(*)\pm}$ signal yields

Fraction of reconstructed $\mu D_{(s)}$ decays from oscillated $B^0_{(s)}$ mesons (assume other sources are charge symmetric).

Time Dependence

Meson-antimeson oscillation is a time-dependent process

$\Rightarrow$ non-zero a^q_{sl} manifests as **decay time-dependent asymmetry**

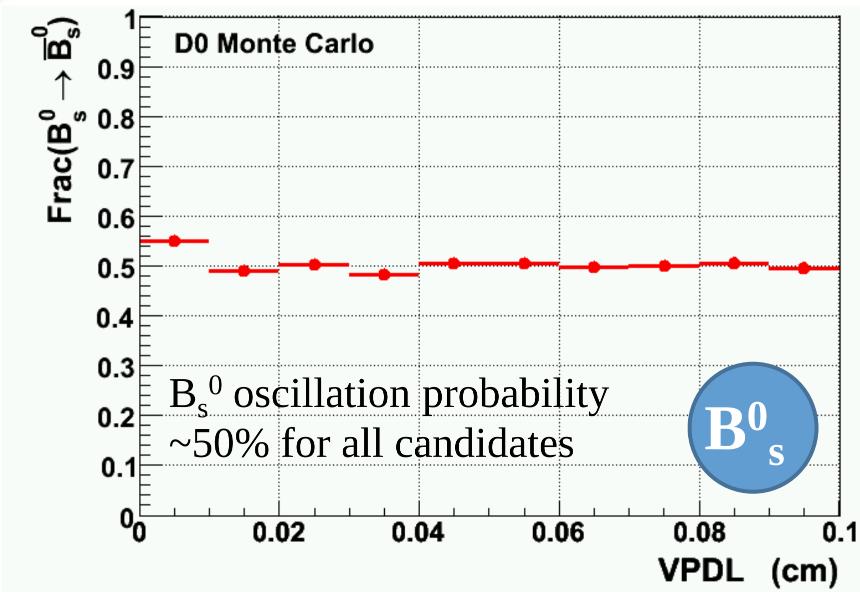


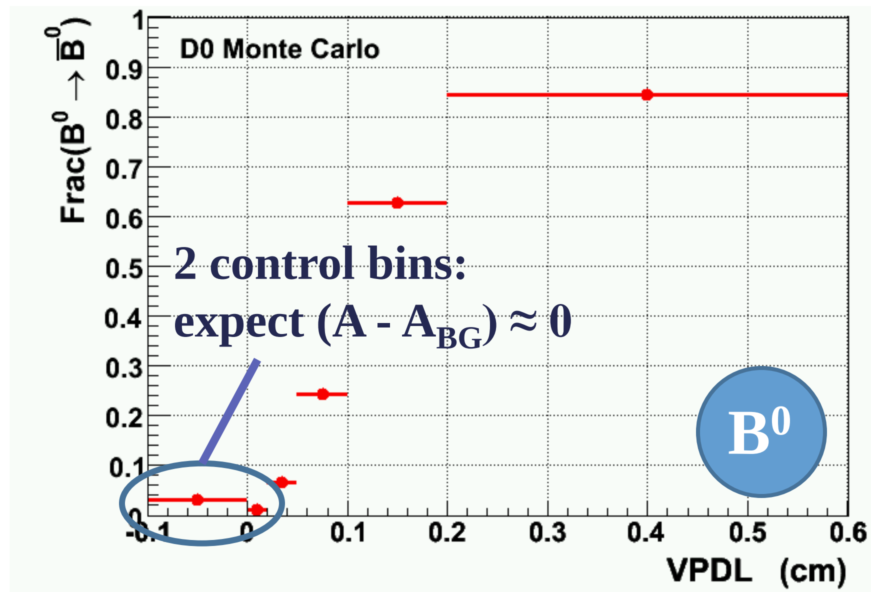
B^0_s mesons: 'fast' oscillation ($\tau_s \Delta m_s >> 1$)

B^0 mesons: 'slow' oscillation ($\tau \Delta m \approx 1$)

~~Time~~ VPDL Dependence

Measured ‘decay time’ (visible proper decay length = VPDL) is distorted by missing neutrino & detector resolution





Measure B^0 asymmetries in 6 bins of VPDL; Use MC simulation to extract $F^{osc}_{B^0}$ separately in each region – **exploit time dependence**.

Raw Asymmetries: B_s^0 Example

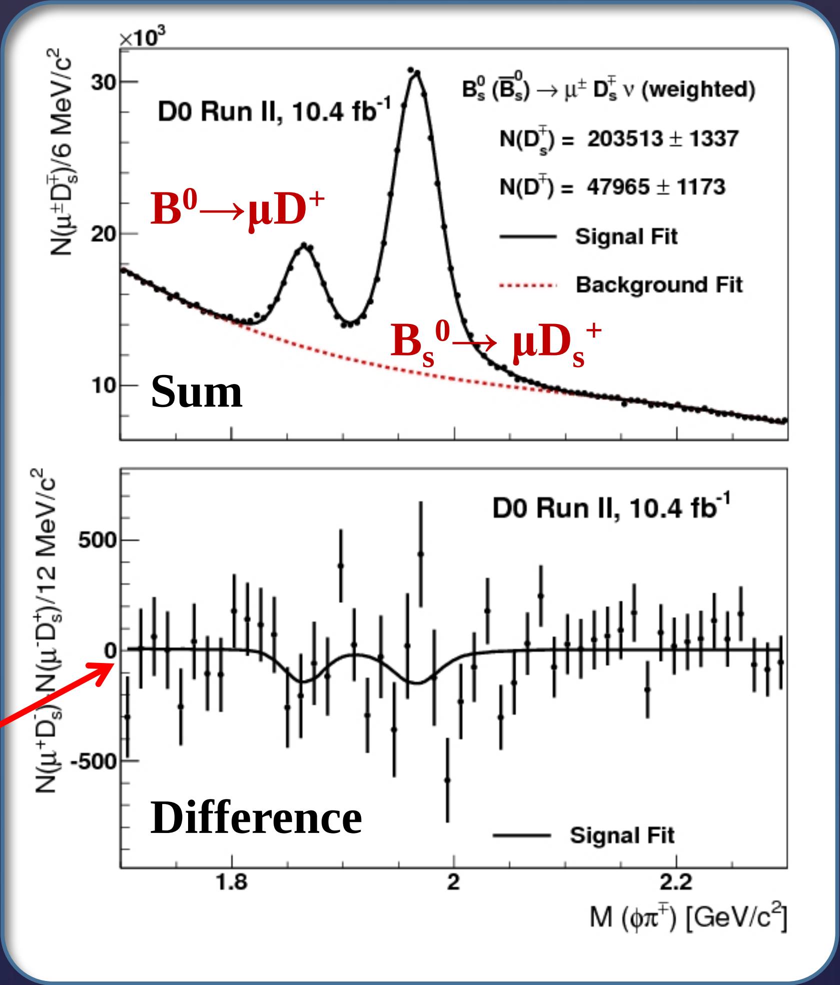
Simultaneous constrained fit of sum and difference distributions (single set of signal parameters)

$$A = \frac{N_{\mu^+ D_{(s)}^{(*)-}} - N_{\mu^- D_{(s)}^{(*)+}}}{N_{\mu^+ D_{(s)}^{(*)-}} + N_{\mu^- D_{(s)}^{(*)+}}} \equiv \frac{N_{\text{diff}}}{N_{\text{sum}}}$$

Validate using charge-randomised ensemble studies: fits are unbiased, with correct uncertainties

Negligible asymmetry in background region: strong indication that track reconstruction asymmetry is small.

$A(B_s^0 \to \mu^+ \nu D_s^- X) = (-0.40 \pm 0.33)\ \%$

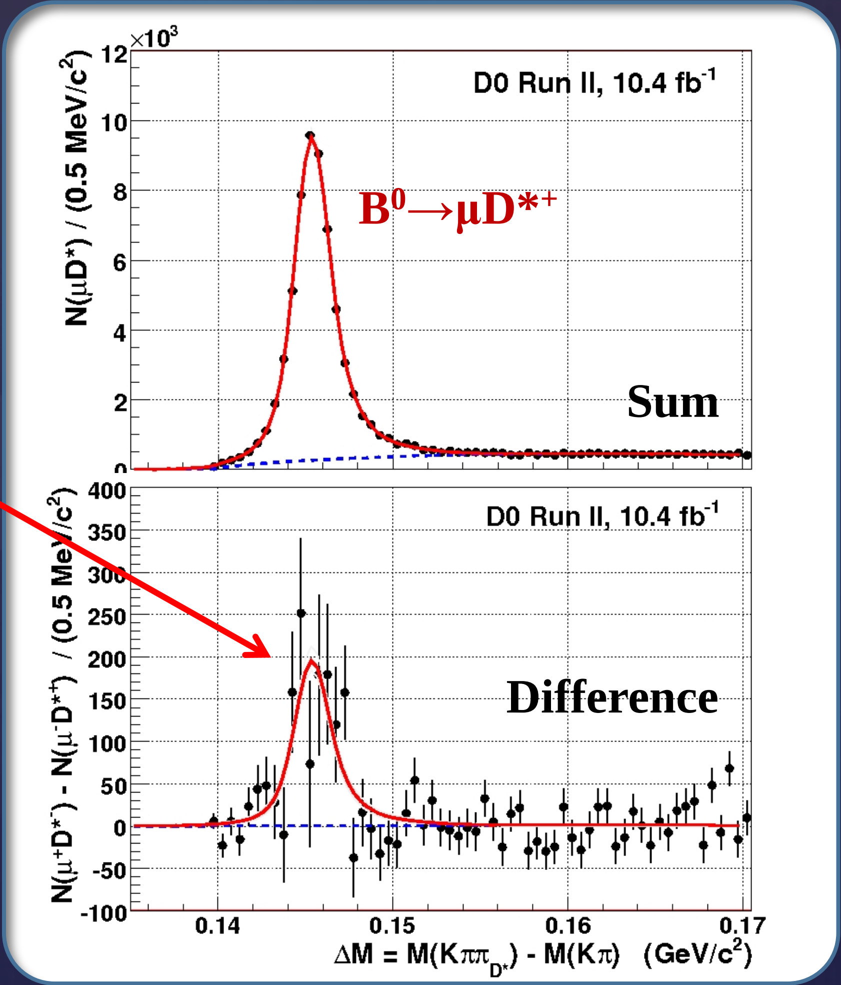


Raw Asymmetries: B^0 Example

For B^0 channels, 6 separate bins of VPDL (example is most sensitive VPDL bin for D* channel)

Single charge kaon in final state – expect large (~1%) raw asymmetry due to kaon reconstruction asymmetry

$A_4(B^0 \to \mu^+ \nu D^{*-} X) = (1.38 \pm 0.33)$ %



Results

Combining two B^0 channels, each with four signal VPDL regions, with correlations accounted for:

$$a_{\mathrm{sl}}^{d} \;=\; [0.68 \pm 0.45\ (\mathrm{stat.}) \pm 0.14\ (\mathrm{syst.})]\%$$

- Consistent with SM prediction
- More precise than previous WA from B-factories: $(-0.05 \pm 0.56)\%$

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

$$a_{\mathrm{sl}}^{s} = [-1.12 \pm 0.74\,(\mathrm{stat}) \pm 0.17\,(\mathrm{syst})]\,\%$$

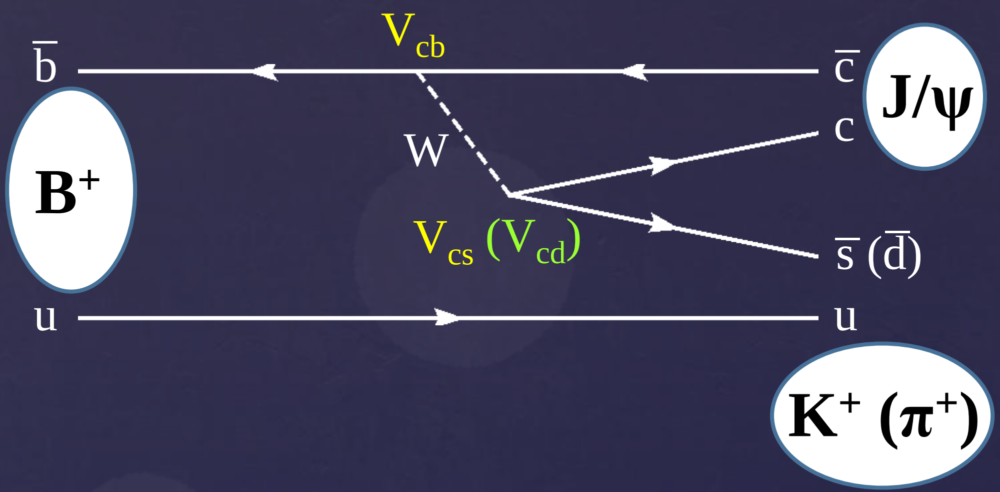
- Supersedes previous worlds-best measurement (D0, 2009)
- Consistent with results of dimuon asymmetry, and with SM.
- LHCb (preliminary): $a^{s}_{sl} = (-0.24 \pm 0.54 \pm 0.33)\%$

Direct CPV in $B^+ \to J/\psi K^+(\pi^+)$

CPV in **$B^+ \to J/\psi K^+$** expected to be small in SM, $\mathcal{O}(0.1\%)$

Same phases in tree and penguin diagrams: suppresses effects of any weak phase enhancements from BSM

Provides 'standard candle' of CPV measurements.



$B^+ \to J/\psi \pi^+$ more sensitive to any BSM contributions

Measure direct CPV parameter A_{CP} for both decays:

$$A^{J/\psi K} = \frac{\Gamma\left(B^- \to J/\psi K^-\right) - \Gamma\left(B^+ \to J/\psi K^+\right)}{\Gamma\left(B^- \to J/\psi K^-\right) + \Gamma\left(B^+ \to J/\psi K^+\right)}$$

$$A^{J/\psi \pi} = \frac{\Gamma\left(B^- \to J/\psi \pi^-\right) - \Gamma\left(B^+ \to J/\psi \pi^+\right)}{\Gamma\left(B^- \to J/\psi \pi^-\right) + \Gamma\left(B^+ \to J/\psi \pi^+\right)}$$

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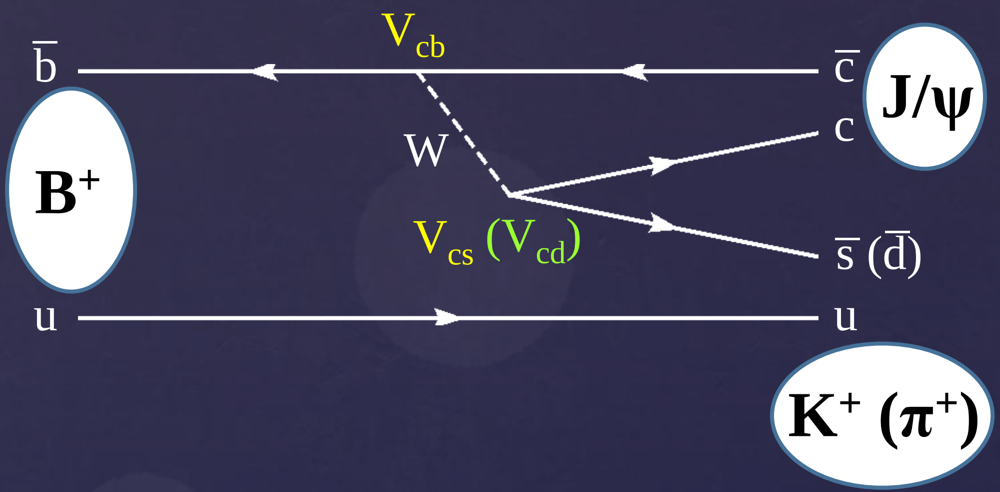


Measure direct CPV parameter A_{CP} for both decays:

Existing best measurements:

$A^{J/\psi K} = (-0.76 \pm 0.55)\ \%$ (Belle, 2010)

$A^{J/\psi \pi} = (-0.5 \pm 2.9)\ \%$ (LHCb, 2012)

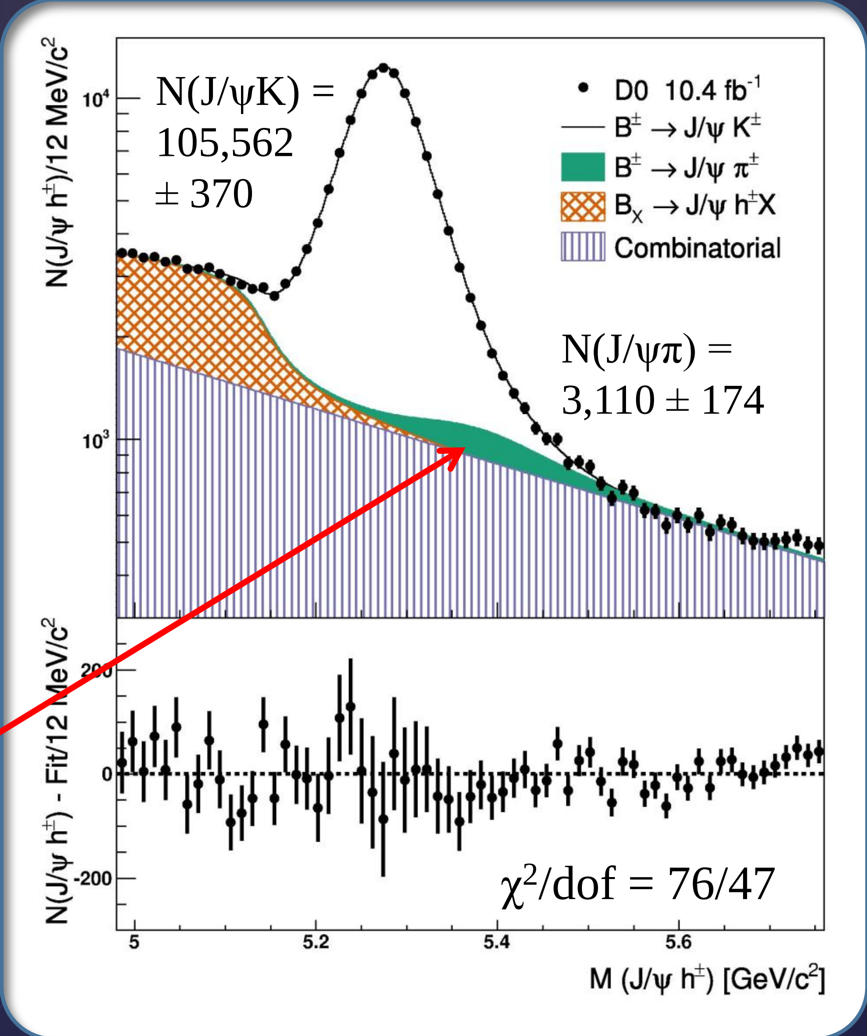
Analysis Strategy

Same principle as a^q_{sl} measurements:

1. Extract raw asymmetry from data, via simultaneous UML fit to sum and difference distributions
2. Correct for BG asymmetries (dominated by charged kaon reconstruction)

Multivariate event selection; charge-randomised ensemble tests to choose cut with best sensitivity.

No Particle ID – disentangle $J/\psi K$ and $J/\psi\pi$ from different signal shapes in fit



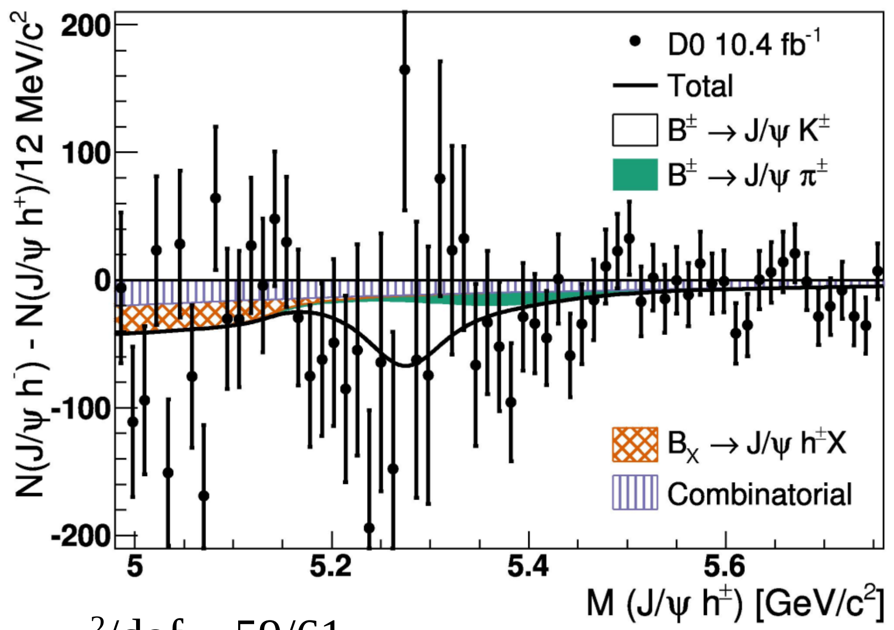
N(B⁻) – N(B⁺)

Raw asymmetries:

$A^{J/\psi K}_{raw}$ =
[−0.46 ± 0.36 (stat.) ± 0.05 (syst.)] %

$A^{J/\psi \pi}_{raw}$ =
[−4.2 ± 4.4 (stat.) ± 1.8 (syst.)] %

Systematic uncertainties from fitting model and range



Use standard kaon/pion reconstruction asymmetries in kinematic bins, to determine BG asymmetries:

$A^{J/\psi K}_{BG}$ = [1.05 ± 0.04] %

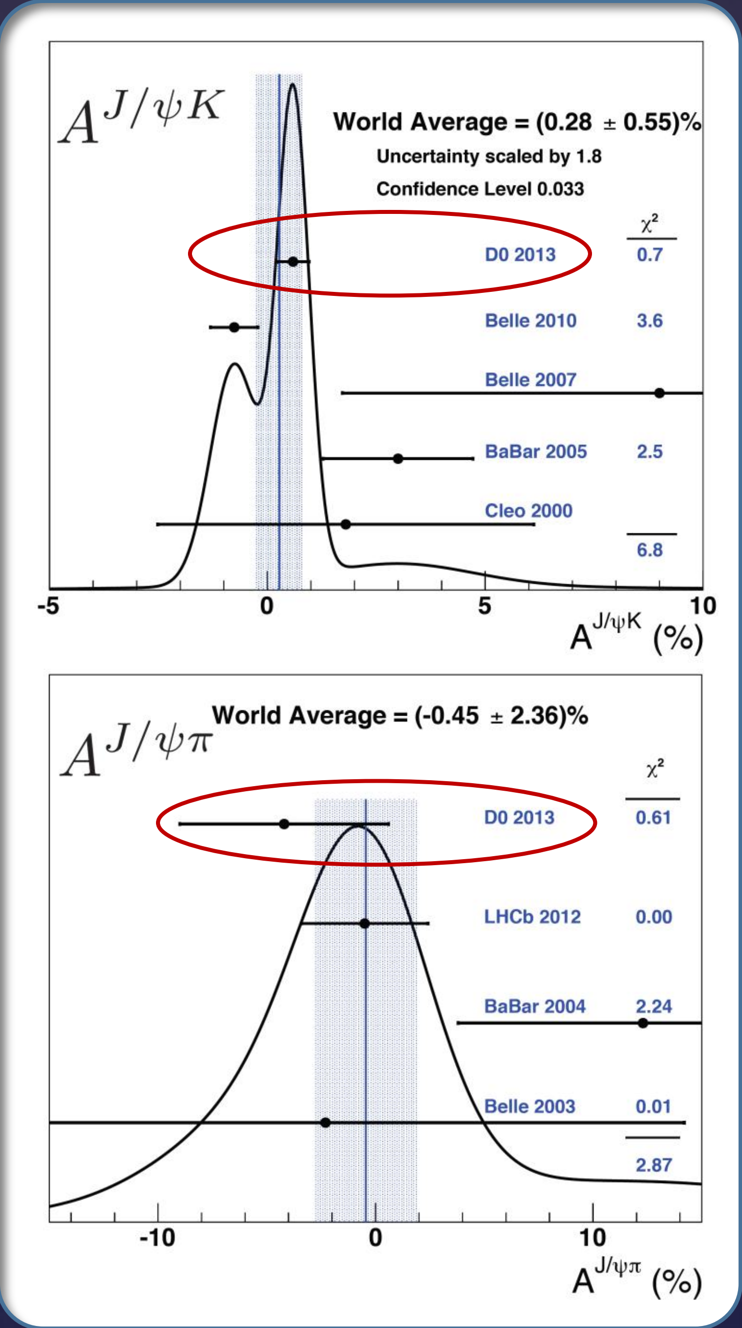
$A^{J/\psi \pi}_{BG}$ = [0.00 ± 0.05] %

Final Results

$A^{J/\psi K} = [0.59 \pm 0.36\,(\text{stat.}) \pm 0.08\,(\text{syst.})]\ \%$

$A^{J/\psi\pi} = [-4.2 \pm 4.4\,(\text{stat.}) \pm 1.8\,(\text{syst.})]\ \%$

- Most precise measurement of $A^{J/\psi K}$, consistent with zero (in line with SM);
- Competitive direct measurement of $A^{J/\psi\pi}$, also consistent with zero;
- Stability tests performed by dividing data sample into sub sets (low/high pT, forward/backward etc) – result stable in all cases



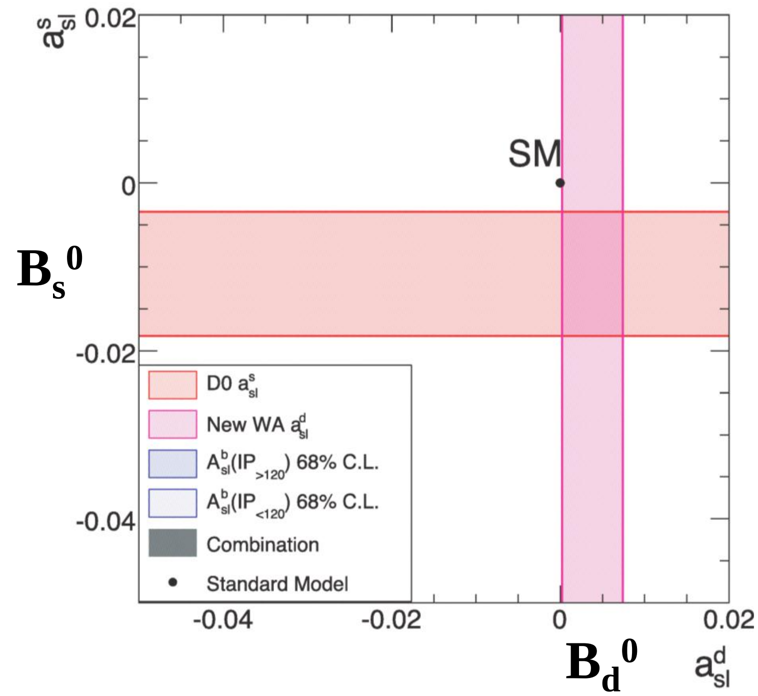
Summary

The **unique** D0 data set still being exploited to test our understanding of CPV in the SM, and provide important standard candles for future measurements

World-leading precision in several channels

Semileptonic mixing asymmetries from B^0 and B_s^0 consistent with SM, and with dimuon asymmetry analysis.

PRD **86**, 072009 (2012)
PRL **110**, 011801 (2013)



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Direct CPV parameters in $B^+ \to J/\psi K^+(\pi^+)$ also consistent with SM expectations

PRL **110**, 241801 (2013)

+ more to come…

Extra Material

CP Violation and the SM

CKM Quark mixing matrix: 3 mixing angles and one *complex phase* δ

Nonzero complex phase ↔ CP violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{\mathrm{CKM}}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Our aim: Make measurements of observables with **precise (and/or small) SM prediction**, where NP effects can (must) cause significant changes

Three categories of CP violation:

1) **Direct** $\Gamma(A \to f) \neq \Gamma(\bar{A} \to f)$ e.g. $A_{CP}(B^+ \to J/\psi \pi^+)$, $A_{CP}(B^+ \to J/\psi K^+)$

2) **In mixing** $\Gamma(A \to \bar{A}) \neq \Gamma(\bar{A} \to A)$ e.g. a^d_{sl}, a^s_{sl}

(1 and 2: **Covered in this talk**)

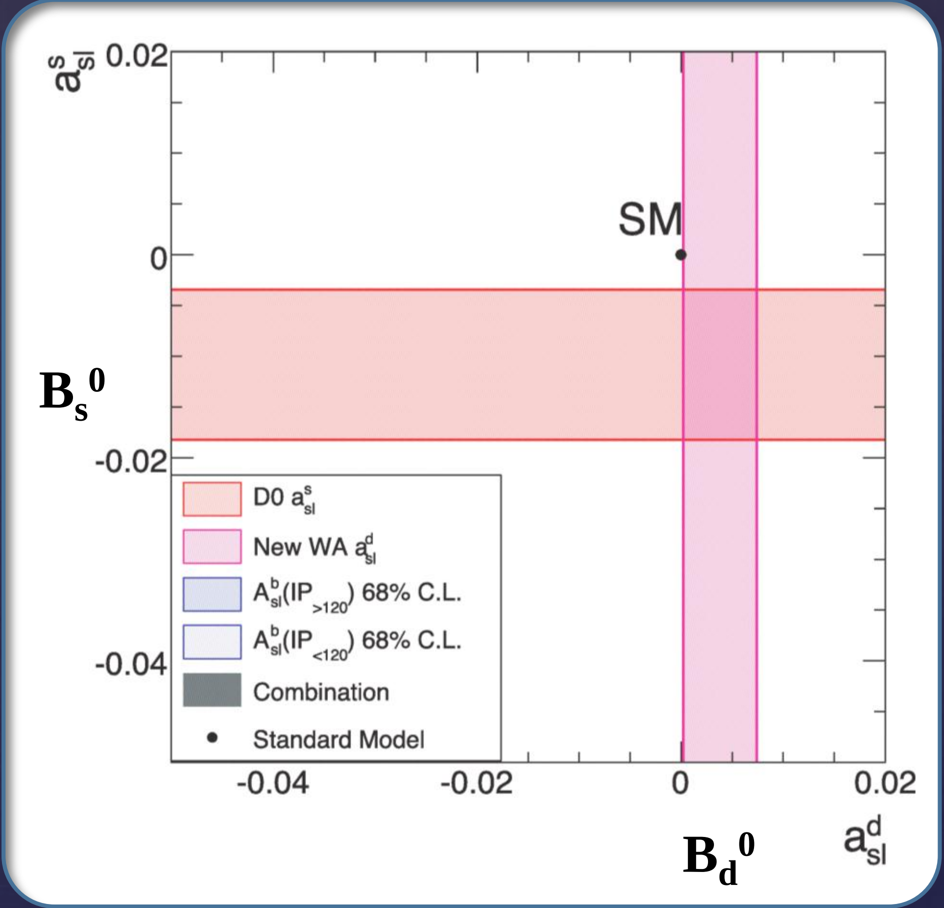
3) **In interference between mixing and decay**

a^q_{sl} Combination

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

$$a^d_{sl}(\text{comb.}) = (0.07 \pm 0.27)\%,$$
$$a^s_{sl}(\text{comb.}) = (-1.67 \pm 0.54)\%$$

2.9σ from SM point



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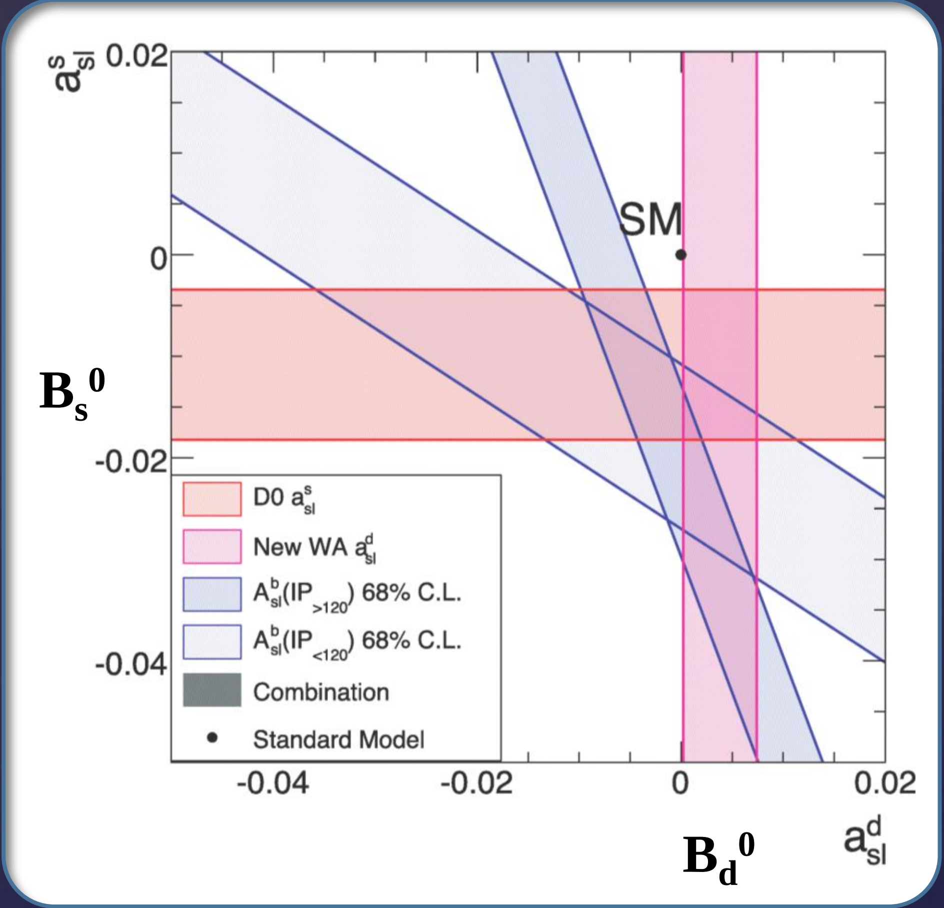

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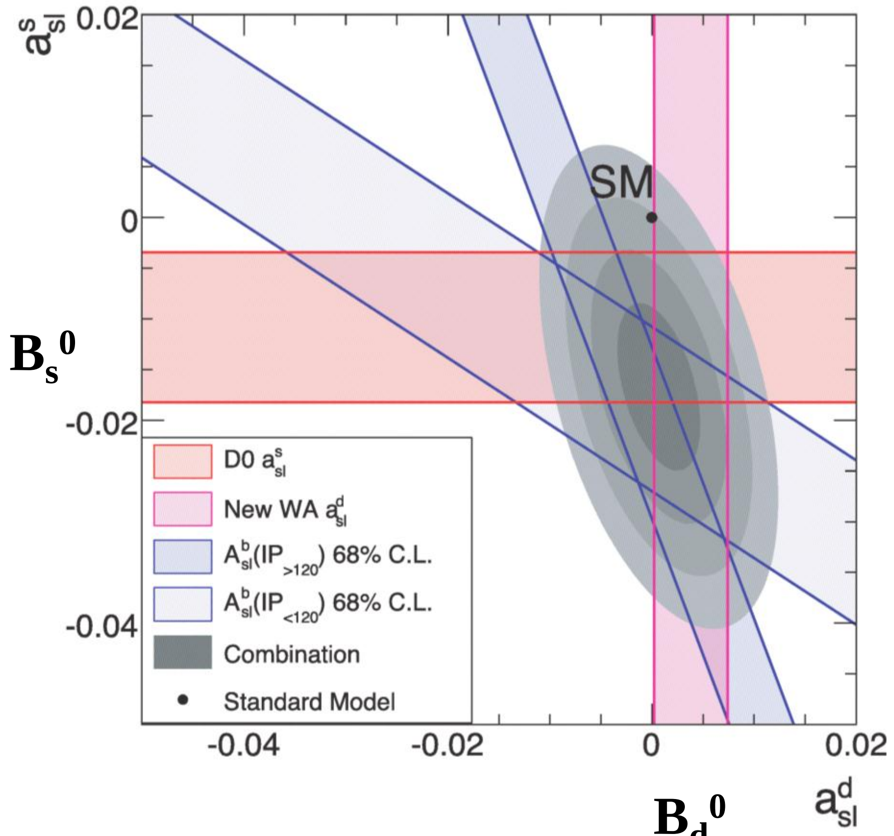

B_s^0

B_d^0

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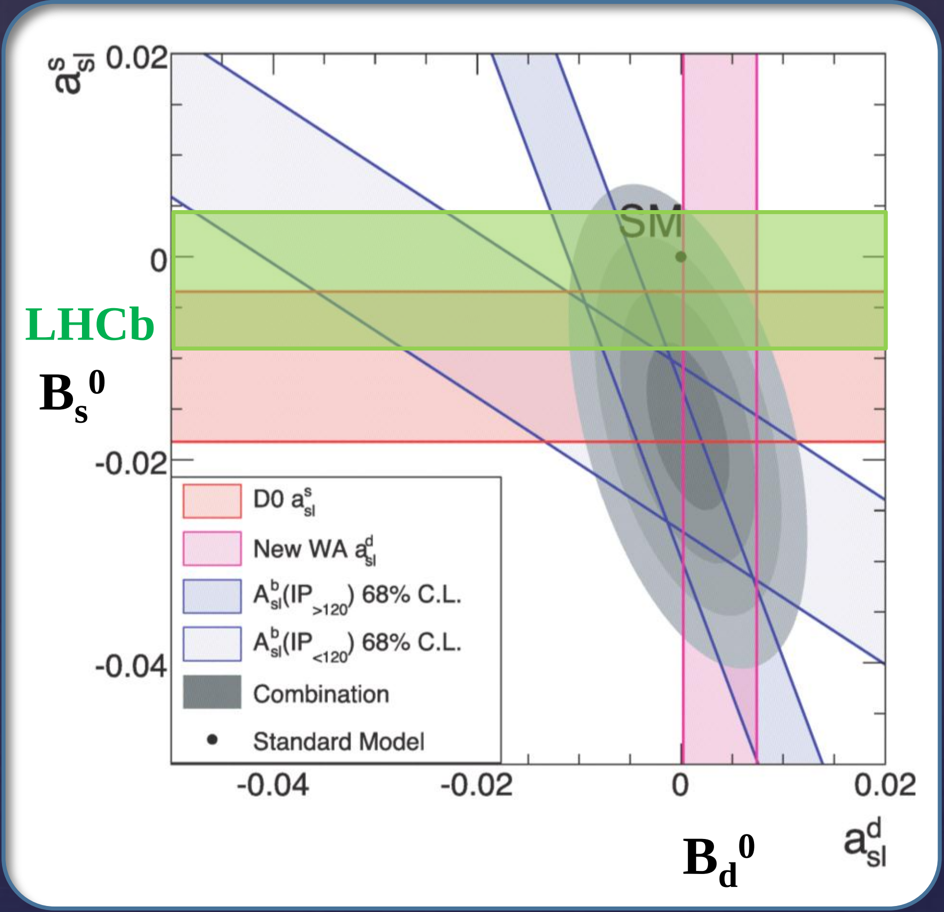
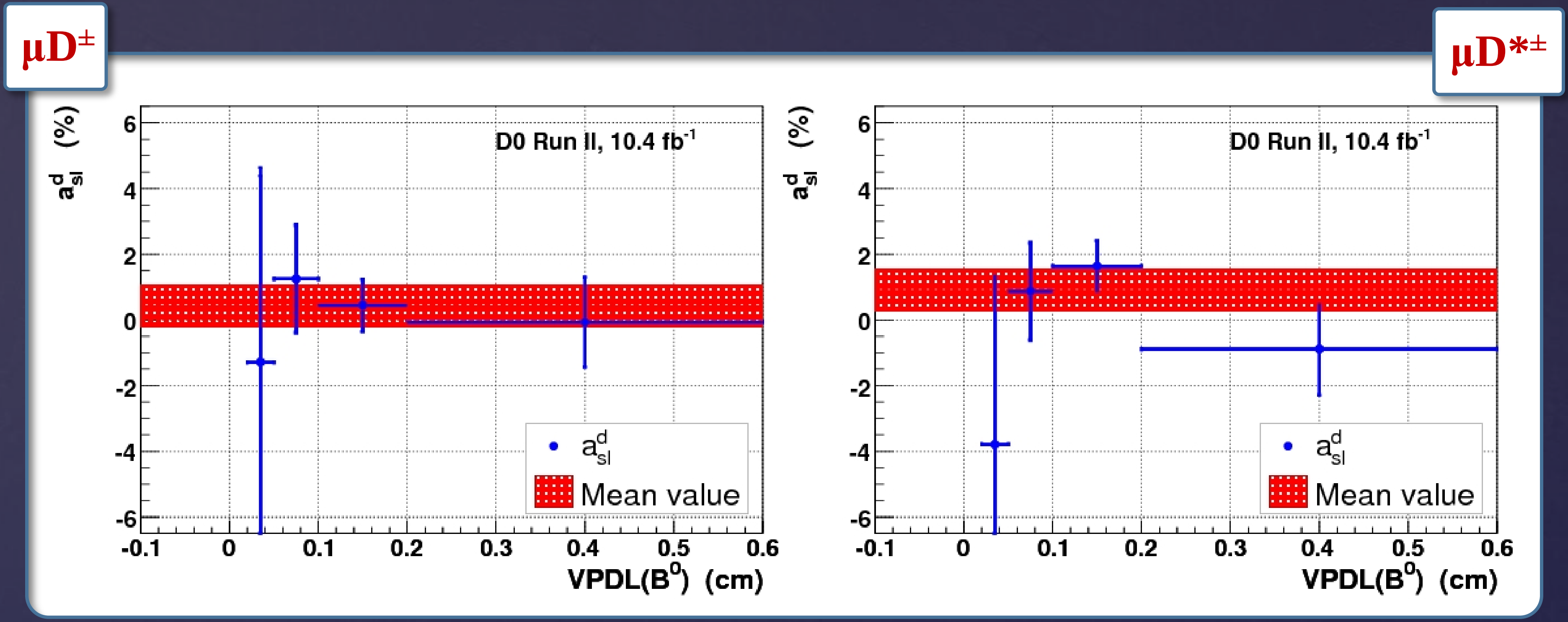


a^s_{sl}(LHCb) *also shown for comparison*

$(-0.24 \pm 0.63)\%$

a^d_{sl} Results: by channel



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

$$a^d_{\rm sl}(\mu D) = [0.43 \pm 0.63\ ({\rm stat.}) \pm 0.16\ ({\rm syst.})]\%$$
$$a^d_{\rm sl}(\mu D^*) = [0.92 \pm 0.62\ ({\rm stat.}) \pm 0.16\ ({\rm syst.})]\%$$