CKM and CP violation results from the Tevatron

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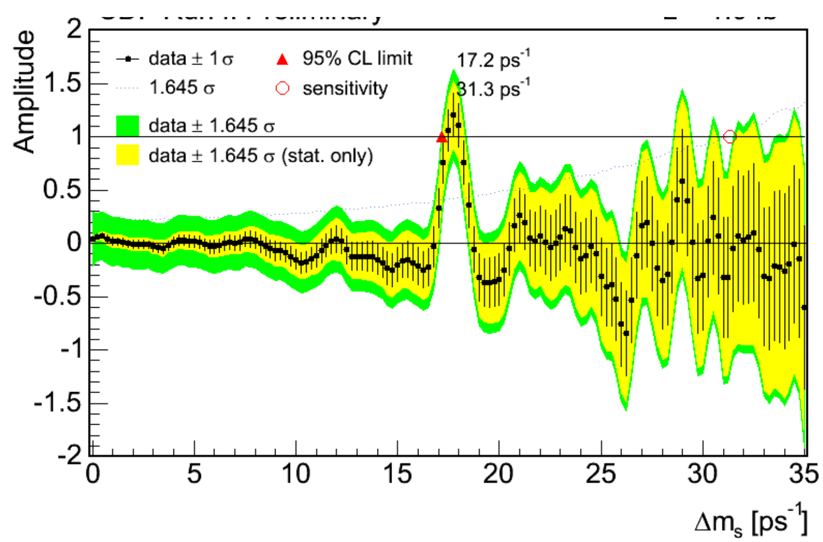
The Tevatron was a B-factory

- The Tevatron has a long legacy of significant B-physics measurements.
  - Pioneered usage of vertex detectors in hadron colliders (used in trigger!)
  - We have shown one can do B-physics alongside a high-pT program.
  - Probes higher mass states not available to e^+e^- machines, but has also been able to compete with them in B_d channels.
- B_s physics has been the forte of the Tevatron B-program
  - Δm_s measurement has been the highlight so far.
  - This measurement placed severe constraints on the CKM unitary triangle – The Standard Model (unfortunately) passed this test with flying colors.



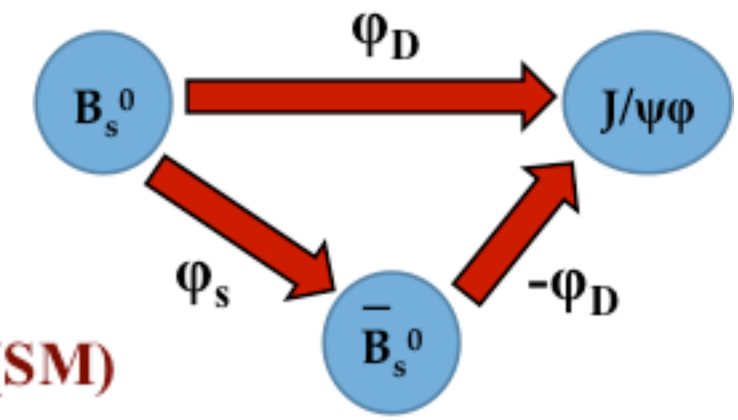
- CP violation in the B_s system is at the forefront of our current program

CP Violation Matters

- Matter and anti-matter were produced in equal amounts from the energy of the Big Bang, but the universe as we know it consists almost entirely of matter. Where did the anti-matter go?
- Some peculiar properties of particles and their interactions produced a small preference for matter (CP violation) which evolved into the present matter dominance.
- We have actually measured CP violation in weak quark decays in both the kaon and B_d meson systems, but at levels far too small to explain this.
- The CKM formalism of the SM predicts no other significant sources of CPV.
- But we exist! So we continue to search for chinks in the CKM armor and for other sources of CP violation.

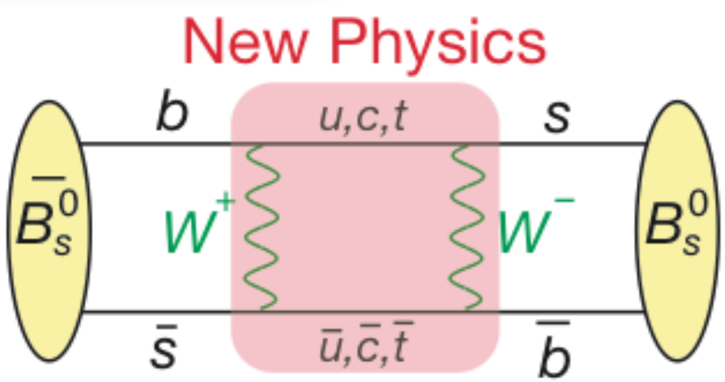
CP Violation in Interference $B_s^0 \to J/\psi\varphi$

- B_s equivalent to the classic $\sin 2\beta$ measurement.

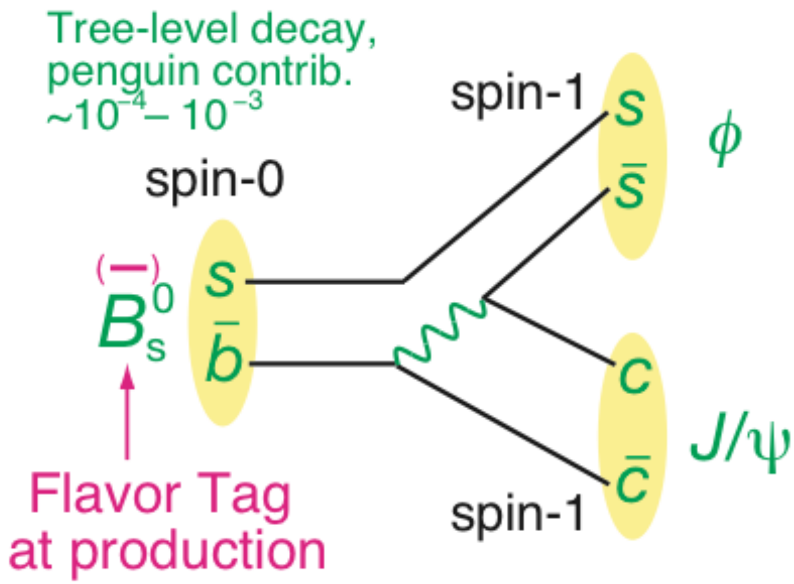


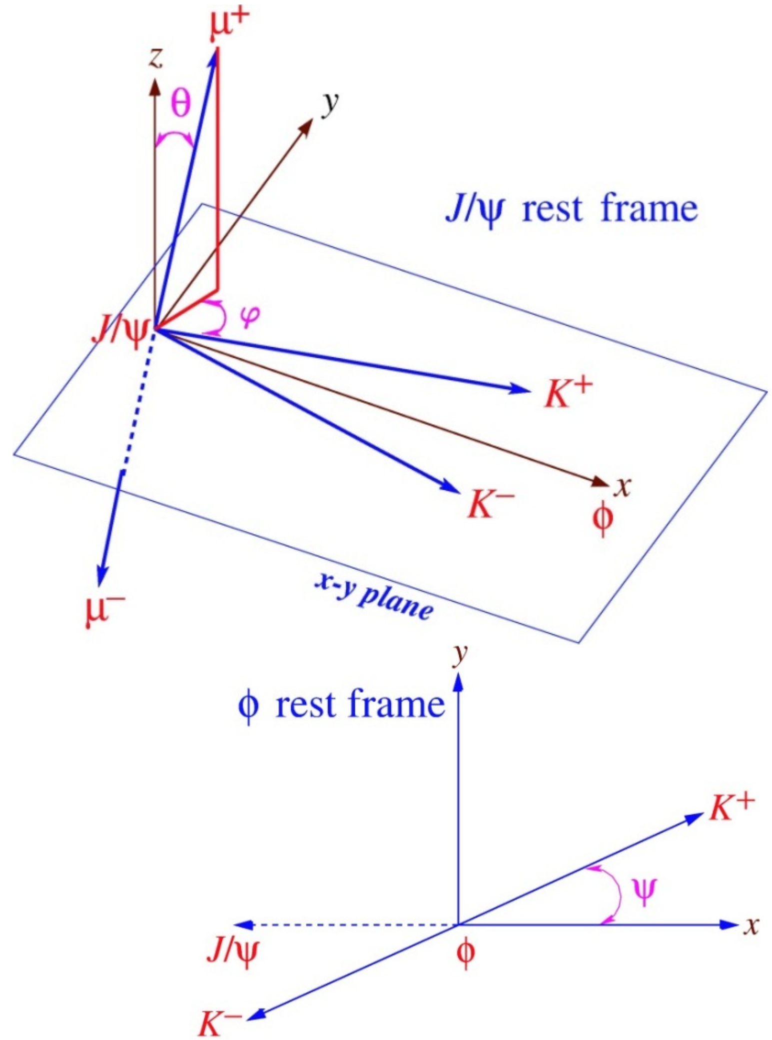
$$\varphi_s^{J/\psi\varphi} = -2\arg\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = -2\beta_s \approx -0.04\ (\text{SM})$$

- Sensitive to new physics in the box diagram.



CP Violation in $B_s^0 \to J/\psi\varphi$



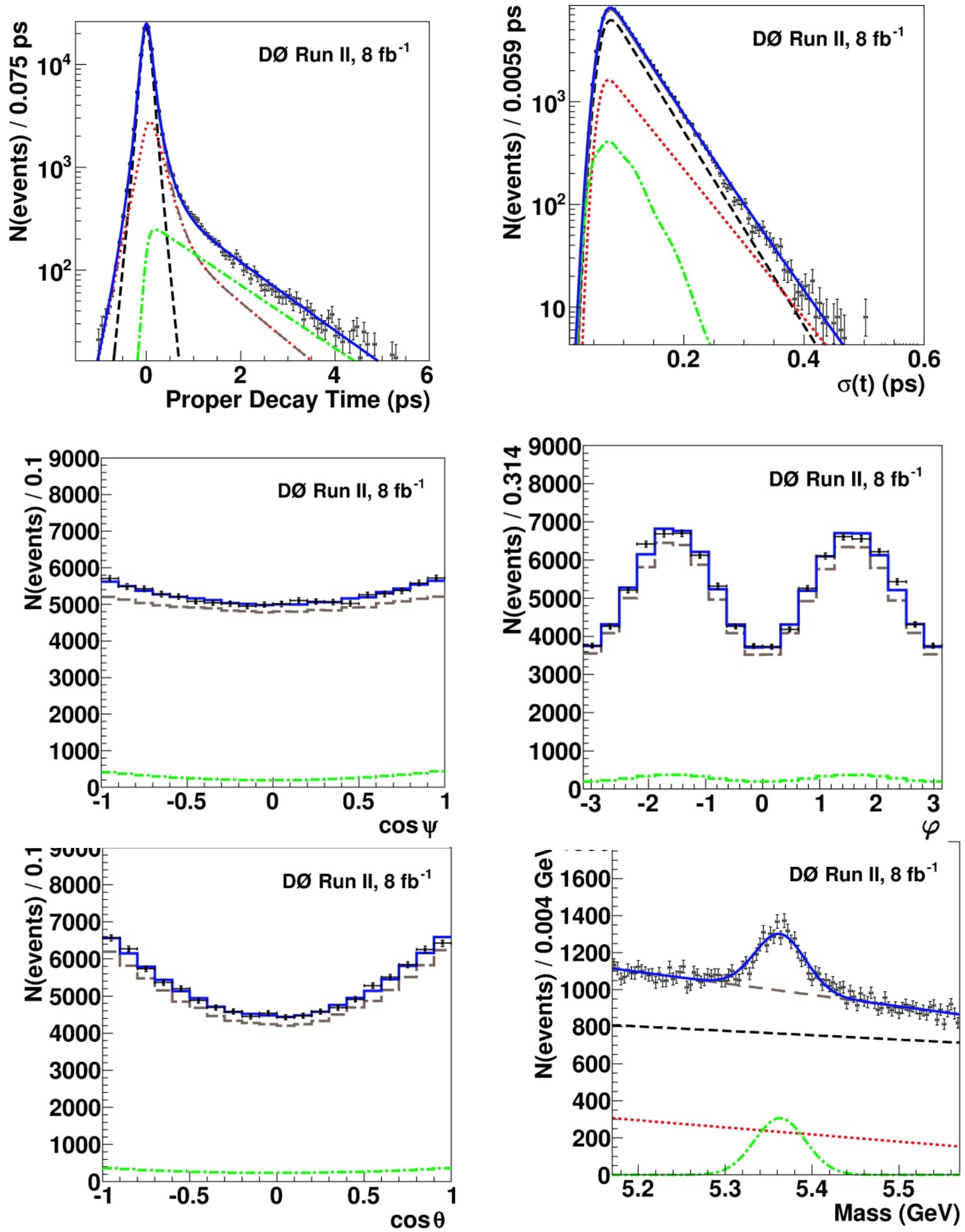


- B_s decays into two vector mesons that are either both CP even or CP odd
- B-tagged, angular analysis
- Measured by both CDF and DØ with several updates over the years – with as much as a 2.2 sigma discrepancy with the SM

DØ Update

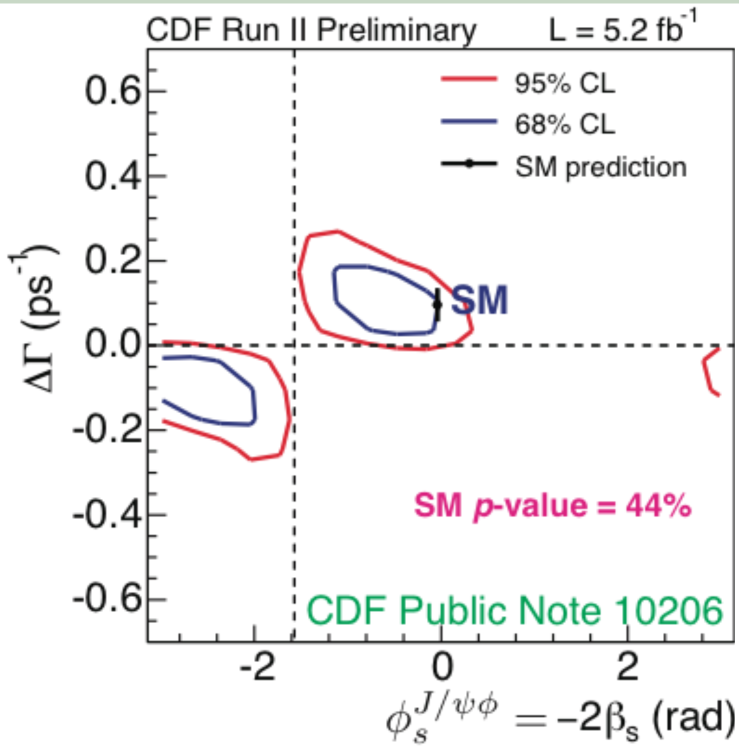
- DØ has updated their measurement using a boosted decision tree selection on 8 fb^{-1} of data.

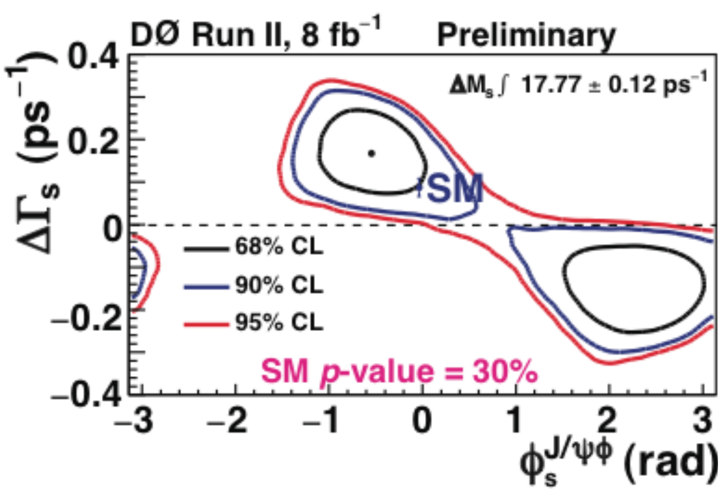
$$\overline{\tau}_s = 1.443^{+0.038}_{-0.035} \text{ ps},$$
$$\Delta\Gamma_s = 0.163^{+0.065}_{-0.064} \text{ ps}^{-1},$$
$$\phi_s^{J/\psi\phi} = -0.55^{+0.38}_{-0.36},$$
$$|A_0|^2 = 0.558^{+0.017}_{-0.019},$$
$$|A_{\parallel}|^2 = 0.231^{+0.024}_{-0.030},$$
$$\delta_{\parallel} = 3.15 \pm 0.22,$$
$$\cos(\delta_{\perp} - \delta_s) = -0.11^{+0.27}_{-0.25}.$$
$$F_S = 0.173 \pm 0.036,$$



Signal

CP Violation in $B_s^0 \to J/\psi\varphi$





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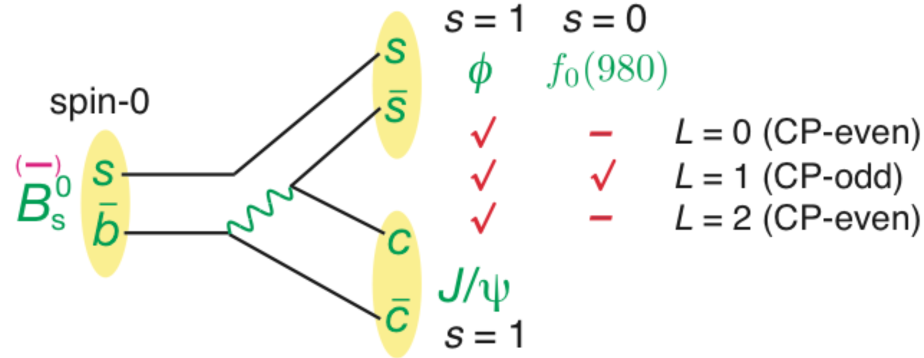
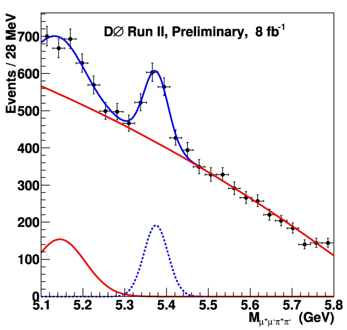
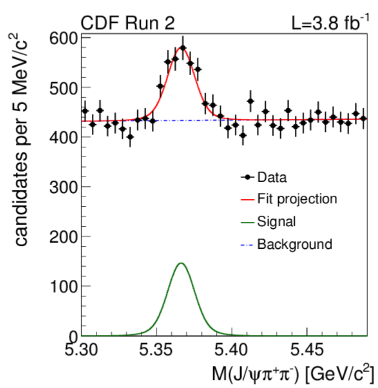
- DØ has updated their measurement using a boosted decision tree selection and has ~ 2 fb^{-1} of data to add.
- CDF will double statistics soon.
- Final Tevatron combination will be done.
- Discrepancy has shrunk, but both experiments show the same trend away from the SM value.

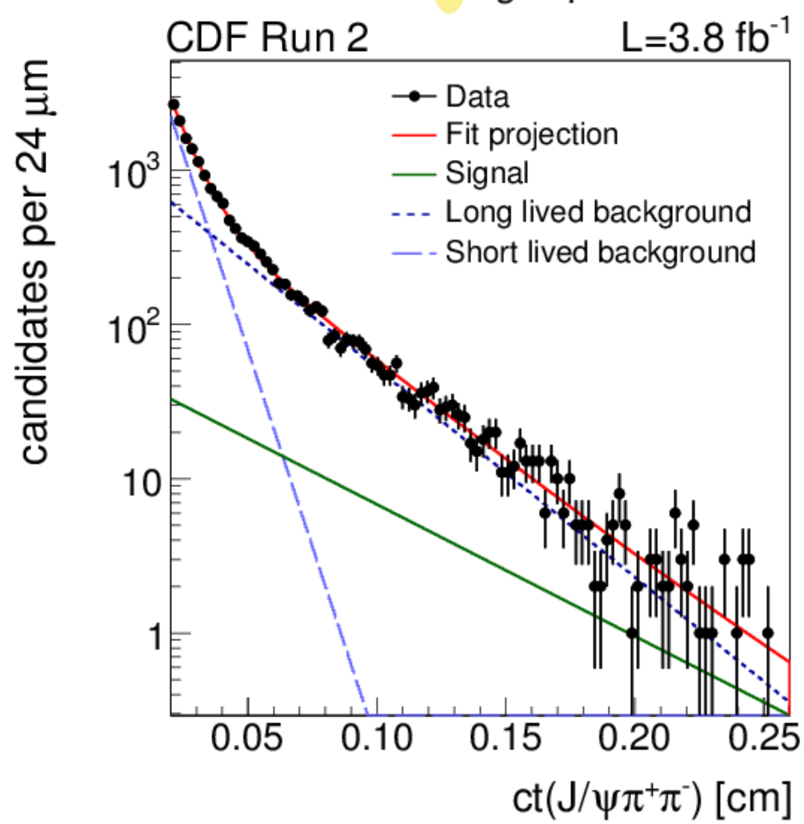
CP Violation in $B_s^0 \rightarrow J/\psi f^0$

- Very interesting decay mode – much smaller BR, but no need for angular analysis.
- Can help resolve two-fold ambiguity
- DØ and CDF have measured BR
- CDF has measured lifetime – a direct measurement of the CP odd lifetime!





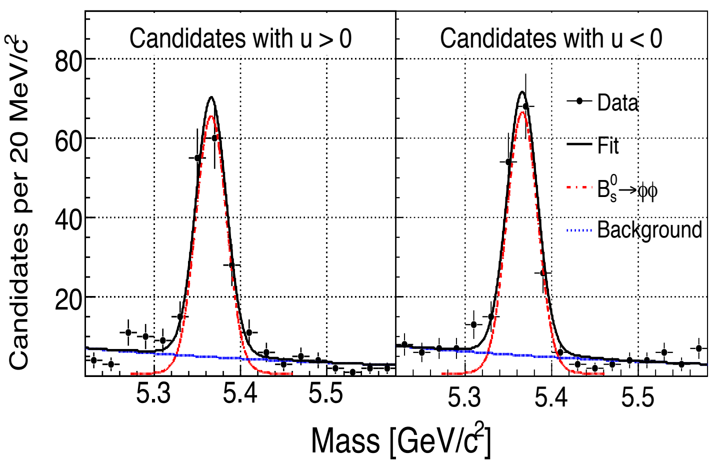


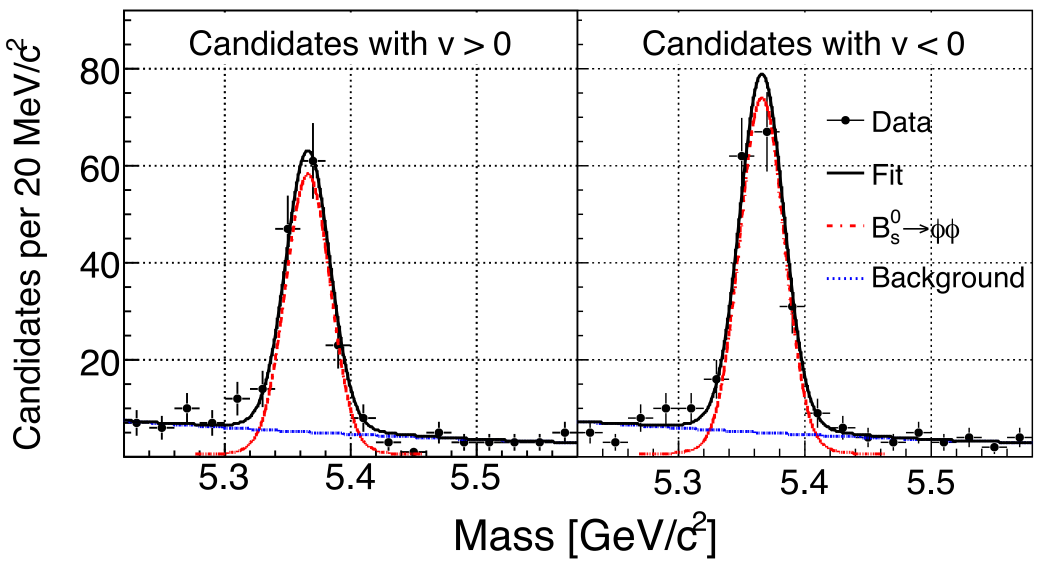


$$\tau = (1.7 + 0.12 - 0.011 \pm 0.03)\ \text{ps}$$

CP Violation in $B_s^0 \rightarrow \phi\phi$

- Not enough statistics to do a mixing induced CPV analysis, but CDF has looked at triple product asymmetries which can be non-zero if there is new physics.



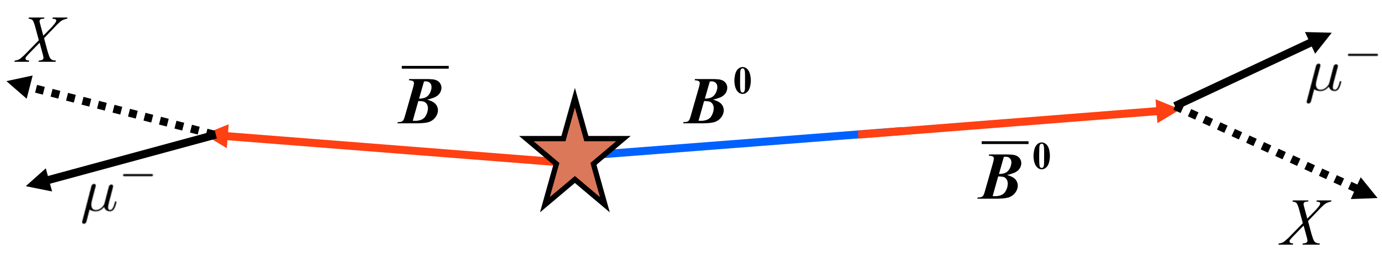


$$TP = \vec{p} \cdot (\vec{q}_1 \times \vec{q}_2)$$

A_u = -0.007±0.064 (stat) ±0.018 (syst)

A_v = -0.120±0.064 (stat) ±0.016 (syst)

CP violation in B meson mixing A^b_{sl}



- We search for CP violation in mixing in the like-sign dimuon charge asymmetry of semileptonic B decays.

$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

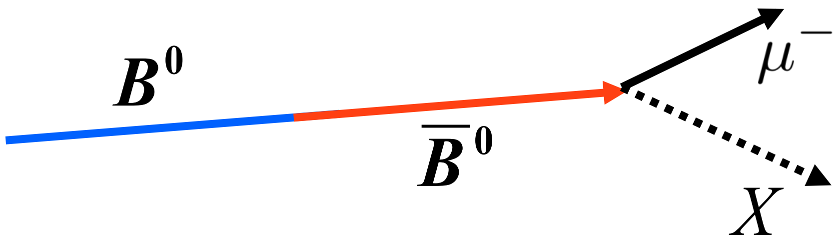
$$A^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q}\tan(\varphi_q)$$

  - The SM predicts small values and the B_d contribution has been measured to be small at the B factories.
  - As with $B_s^0 \rightarrow J/\psi\varphi$, new physics can enhance the value of the CPV phase. The NP contributions are in fact the same in these two cases.

- In summer of 2010, DØ measured a value 3.2σ away from the SM

Semileptonic Charge Asymmetry

- $A^b{}_{sl}$ is also equal to the charge asymmetry of "wrong sign" semileptonic B decays Y. Grossman, Y. Nir, G. Raz, PRL 97, 151801 (2006)



  - "Right sign" decay is $B \to \mu^+ X$
  - "Wrong sign" decays can happen only due to flavor oscillation in B_d and B_s mesons

$$\boxed{a^b_{sl} \equiv \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)} = A^b_{sl}}$$

A^b_{sl} Measurement Strategy

- Measure raw single and like-sign dimuon asymmetries:

$$\boxed{a \equiv \frac{n^+ - n^-}{n^+ + n^-}} \qquad \boxed{A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}}$$

- Determine detector and reconstruction related backgrounds, the remaining mixing contributions are equivalent.
- The single muon asymmetry is dominated, however, by background so we do NOT take a weighted average. We use it instead to effectively subtract the background from the purer dimuon measurement by taking a linear combination of the two.
- DØ's frequent switching of both magnet's polarities is crucial to reduce detector acceptance effects – very small systematic uncertainties.
- Improvements since the first measurement
  - Dominant background is now measured by data completely.
  - More data, better trigger efficiency.
  - Cleaner muon selection – less background.
  - Impact parameter studies.

New Dimuon Asymmetry Result

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

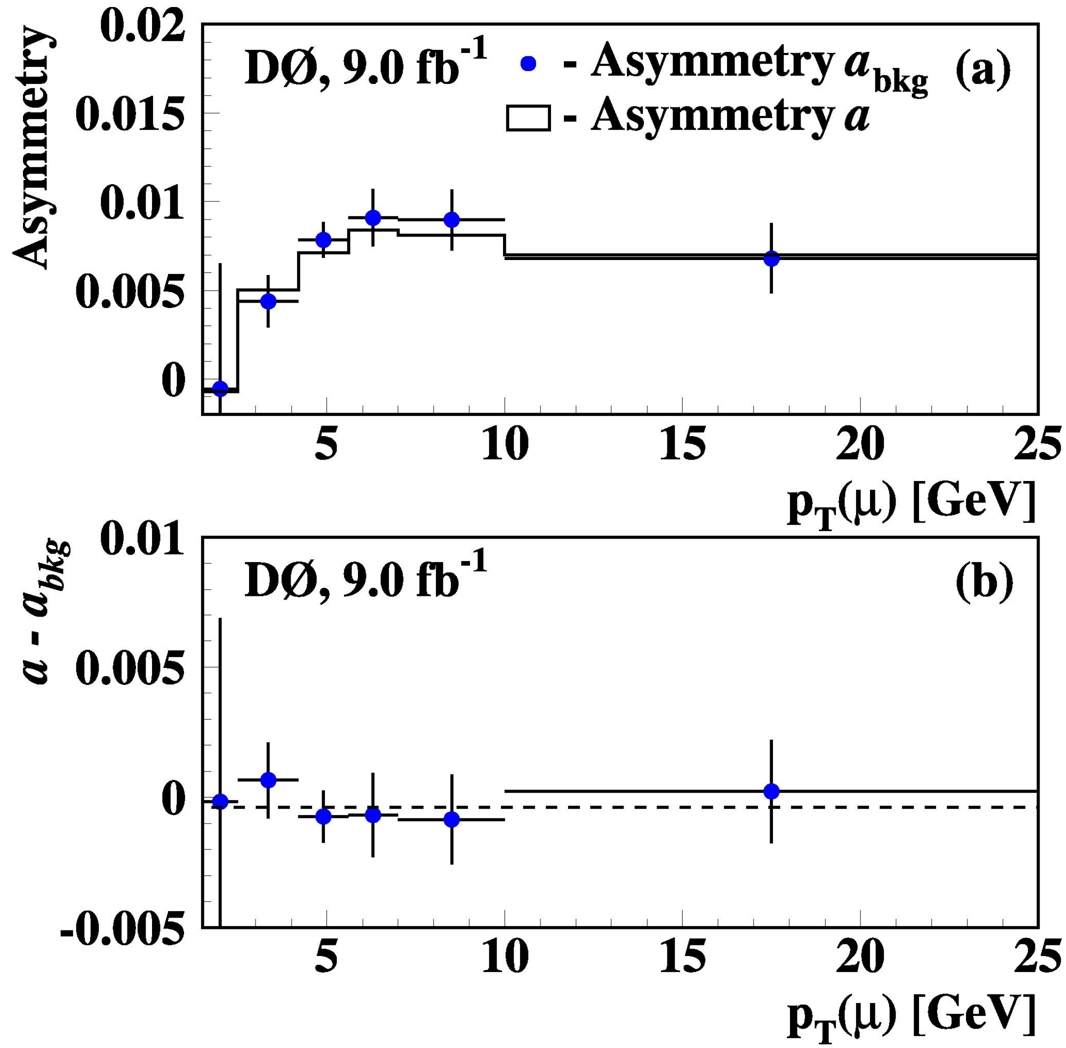
- To be compared with the SM prediction:

$$\boxed{\boldsymbol{A_{sl}^{b}(SM) = (-0.023^{+0.005}_{-0.006})\%}}$$

- This result is two orders of magnitude larger than the SM prediction; ~ 3.9σ away from it.
- Consistent with previous result.
- In the correct direction to explain matter dominance.

Dimuon Asymmetry Closure Test

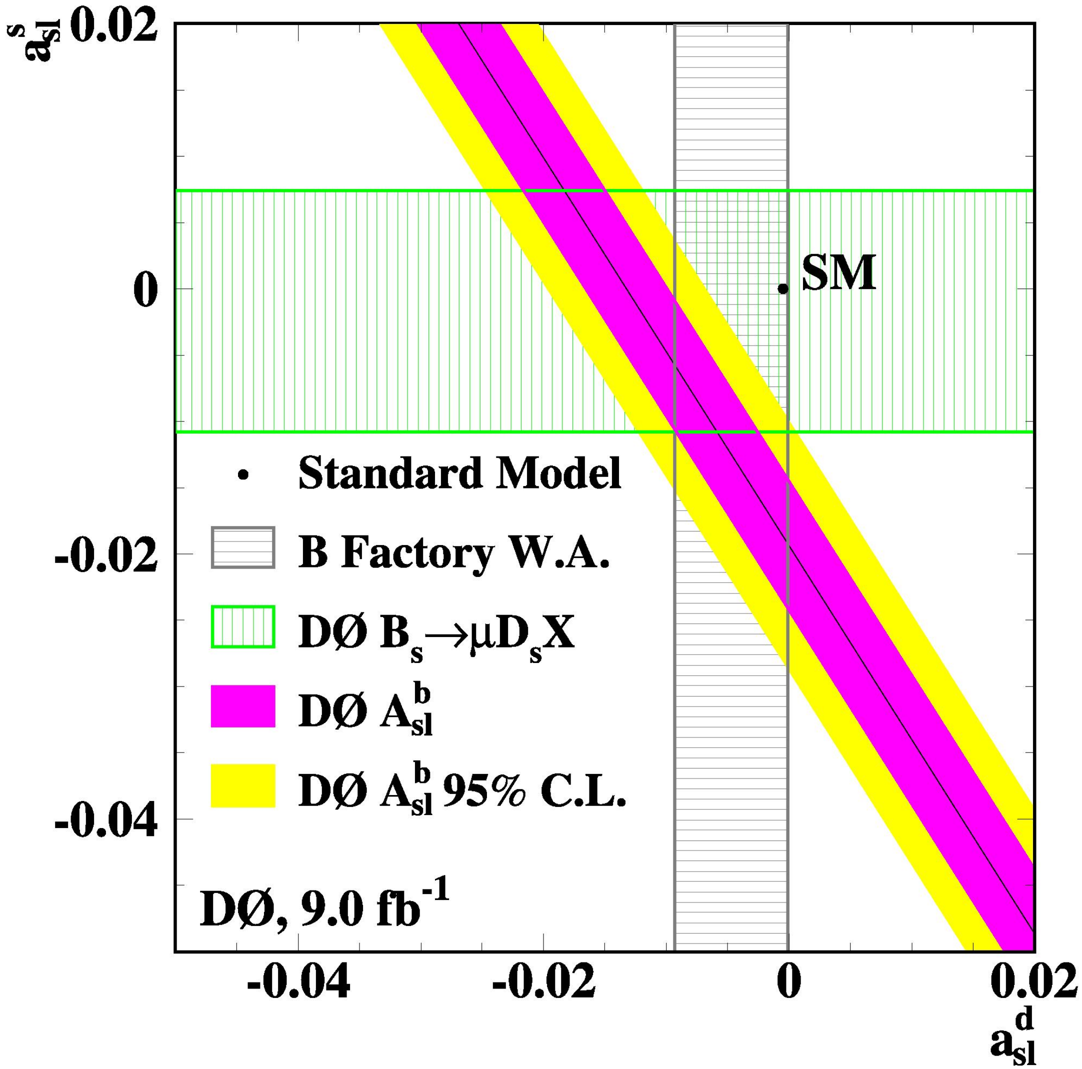
- The raw inclusive muon asymmetry a is dominated by background.
- We determine a_{bkg} independently from data and compare it to the raw asymmetry.
- We see that the background determination matches the asymmetry data quite well - even describing the pT dependence correctly.



$A^b_{\rm sl}$ at the Tevatron

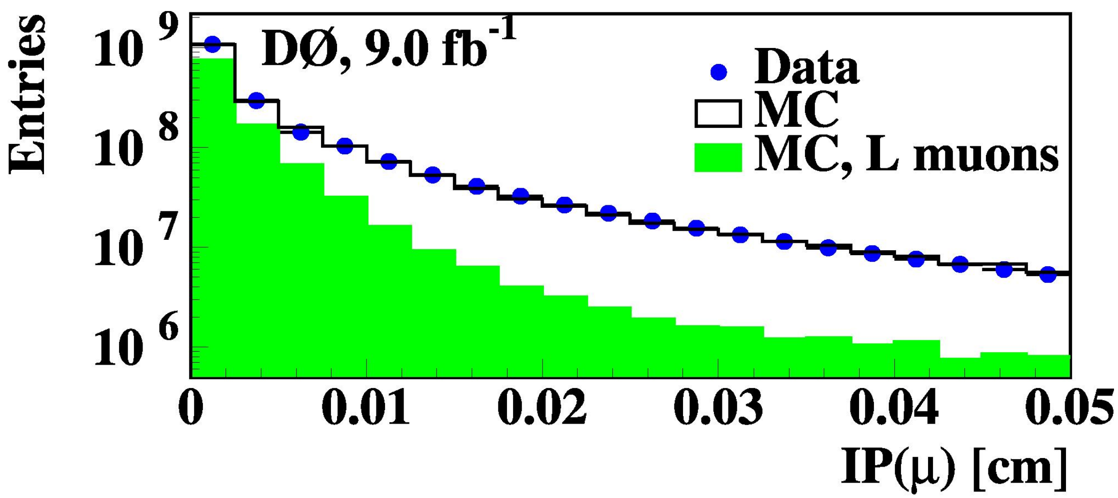
$$A^b_{sl} = (0.594 \pm 0.022) a^d_{sl} + (0.406 \pm 0.022) a^s_{sl}$$

- Both B_d and B_s are produced at the Tevatron, $A^b_{\rm sl}$ is a linear combination of $a^d_{\rm sl}$ and $a^s_{\rm sl}$
  - Relies on mixing probability and production fractions measurements of B_d and B_s mesons.
  - LEP HFAG values used, consistent with LHCb and CDF update
- Only a ~ 12% B_s production fraction, but large mixing probability leads to a large B_s contribution.

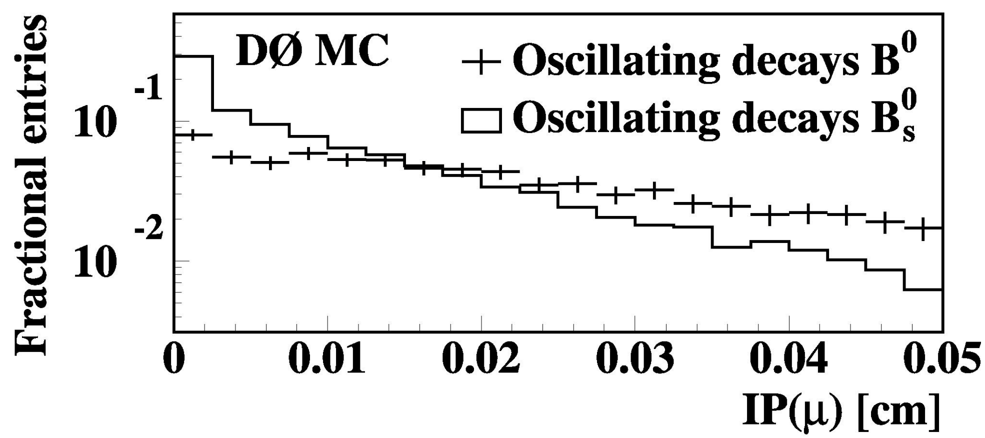


Impact Parameter Dependence of A^{b}_{sl}

- In order to further pin down the contributions to A^{b}_{sl}, we study the impact parameter distribution



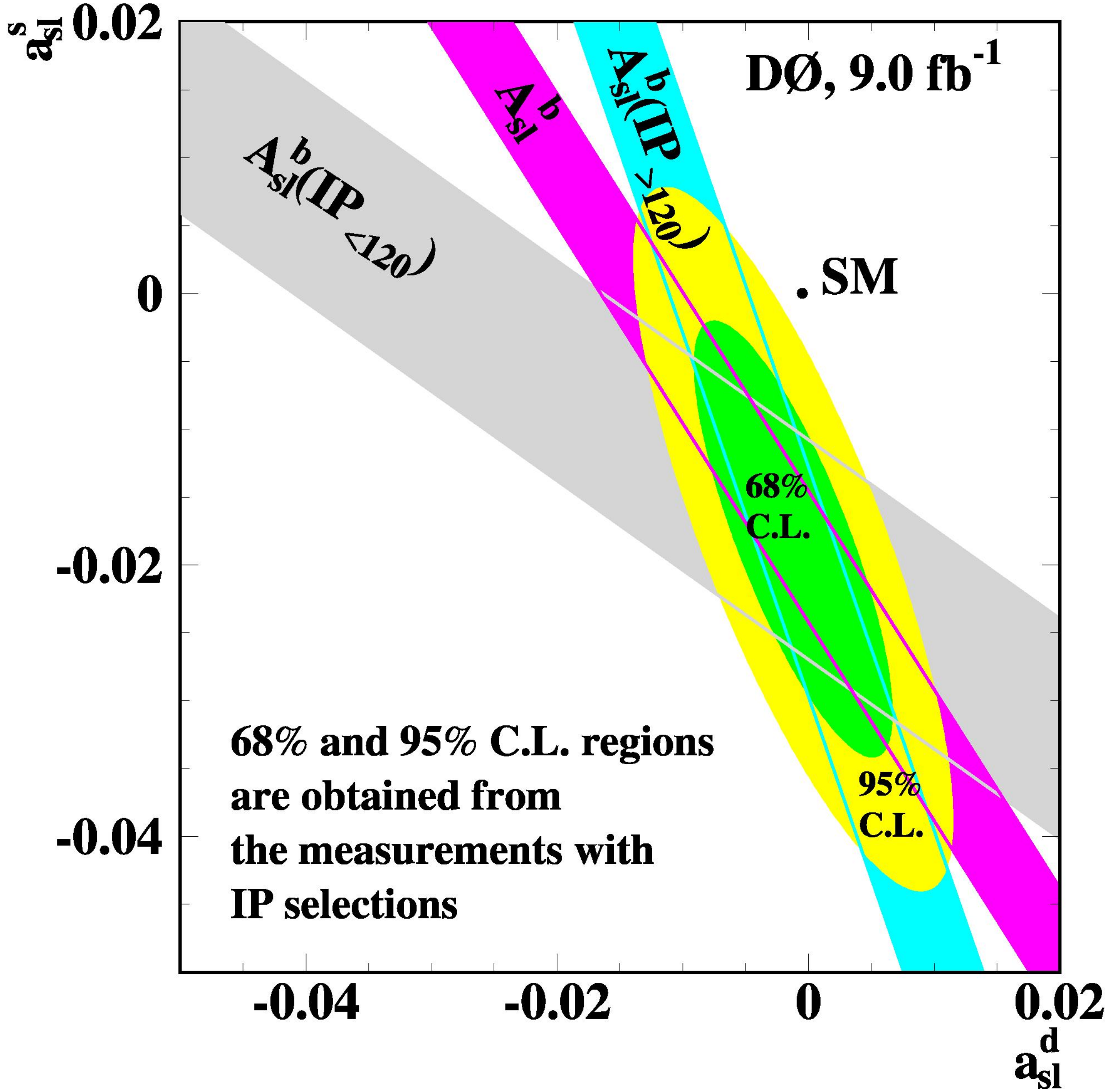
- IP > 120 μm
  - b enriched, with larger B_d contribution due to longer oscillation frequency
- IP < 120 μm
  - more background, but larger B_s contribution



Impact Parameter dependence of A^{b}_{sl}

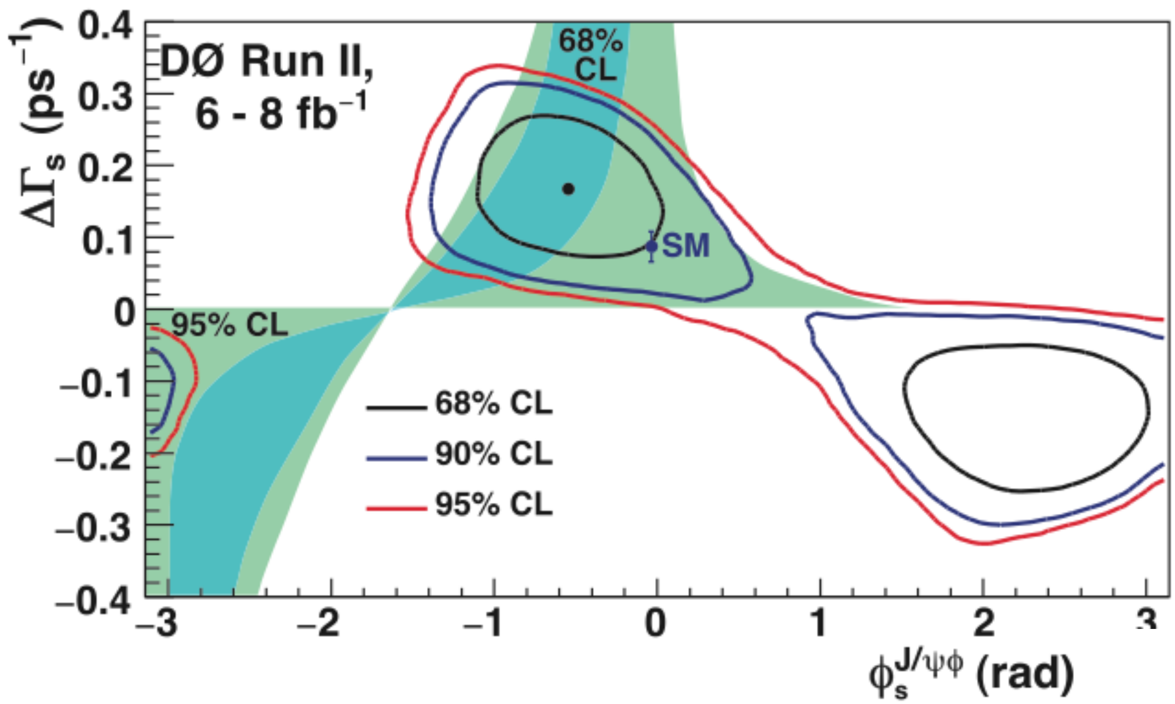
$$a_{sl}^{d} = (-0.12 \pm 0.52)\%$$

$$a_{sl}^{s} = (-1.81 \pm 1.06)\%$$



Putting it (almost) all together

- The value of a^s_{sl} can be translated into the measurement of the CP violating phase ϕ_s and $\Delta\Gamma_s$ which is in excellent agreement with an independent measurement of ϕ_s and $\Delta\Gamma_s$ in $B_s \rightarrow J/\psi\phi$ decays.
- This result is also consistent with the CDF measurement.
- LHCb already has considerable weight here as well, they are also planning an orthogonal measurement of A^b_{sl}.



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Conclusion

- The Tevatron remains a wonderful place to do B-physics (even though we have stopped running)
- We are at the peak of our analyses with one more round of major updates soon to come.
  - Updated and combined Tev meaurement of ϕ_s in $B_s \to J/\psi\phi$
  - Update of dimuon charge asymmetry with more sophisticated IP analysis – with a likely 5 sigma reach
- There are dozens of CKM and CPV analyses that I have not covered, and there are tons of data available for new ideas
- Remember Chris Quiggs's advice this morning:
  - "Stay Hungry, Stay Foolish"
  - We are pretty full, but there is always room for desert.
  - Staying foolish has never been a problem for us….

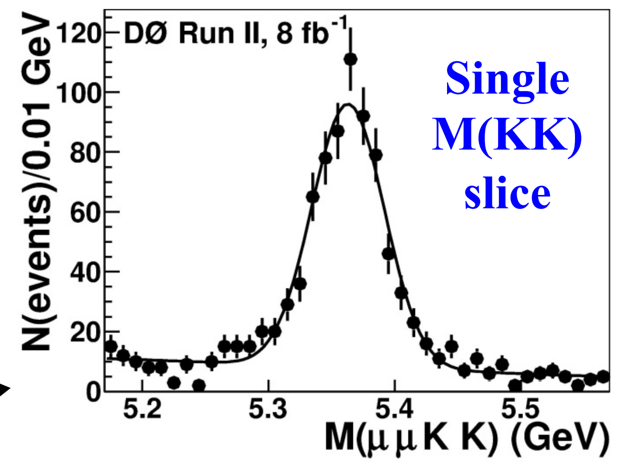
Backups

S-wave Contribution

Fraction (F_S) and phase (δ_S) of non-resonant S-wave K^+K^- contribution are free parameters in the fit.

Alternative method based on mass fit gives cross-check of F_S measurement.

- Divide data into slices in $M(K^+K^-)$;
- Fit the $M(\mu^+\mu^-K^+K^-)$ distribution in each slice, to extract B_s^0 signal;



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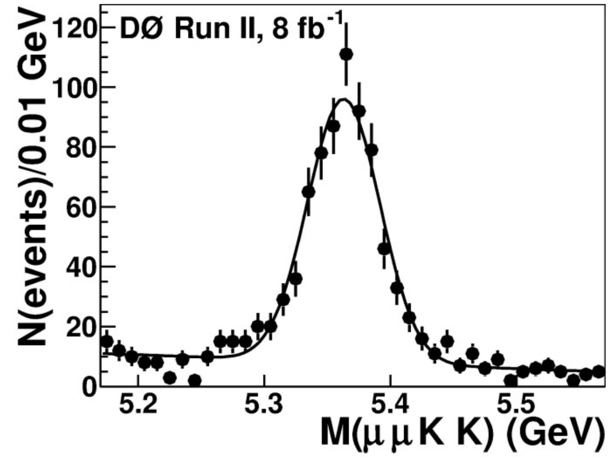

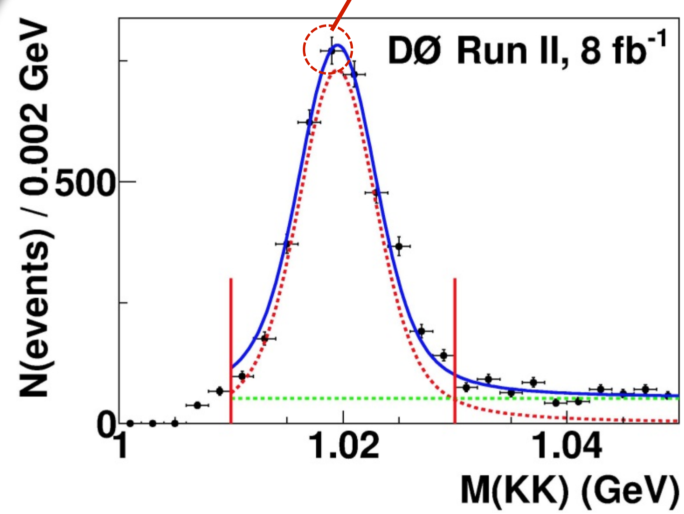

B_s^0 signal has two components:

1) **Clear resonance at φ(1020) – 'P-wave'**

2) **Uniform non-resonant contribution – 'S-wave'.**

Fitting to a number of different models yields:

$F_S = (12 \pm 3)\ \%$