Flavor & Symmetry measurements at D0

$B_s^0 \rightarrow \mu\mu$ and $A_{FB}(B^{\pm} \rightarrow J/\psi K^{\pm})$

MARJ CORCORAN MEMORIAL

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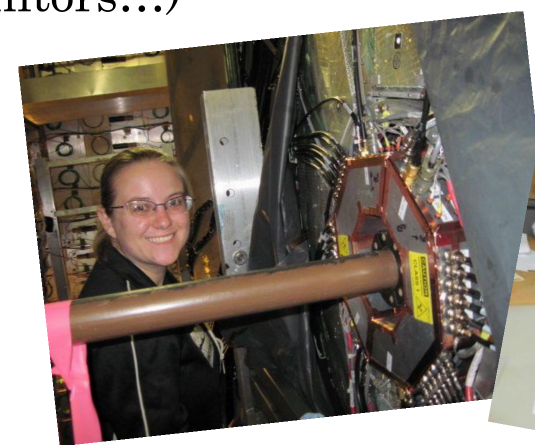
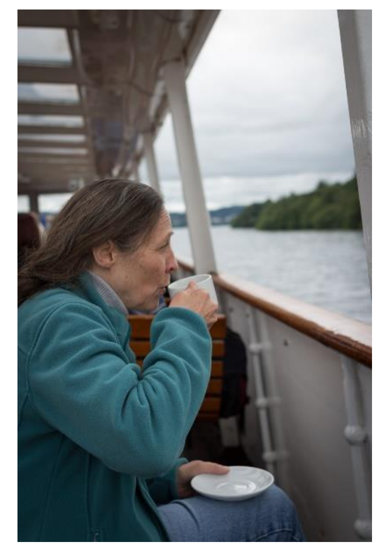
4/26/17

My perspective

Marj was deeply interested in flavor physics and measurements of fundamental symmetries like CP. She'd studied flavor in quarks for years, and was getting very excited about lepton flavor violation when I started at Rice.

She supervised many Rice graduate students through dissertations over the years – ending with Michelle's and mine (once we finished actual important things like building and installing luminosity monitors…)

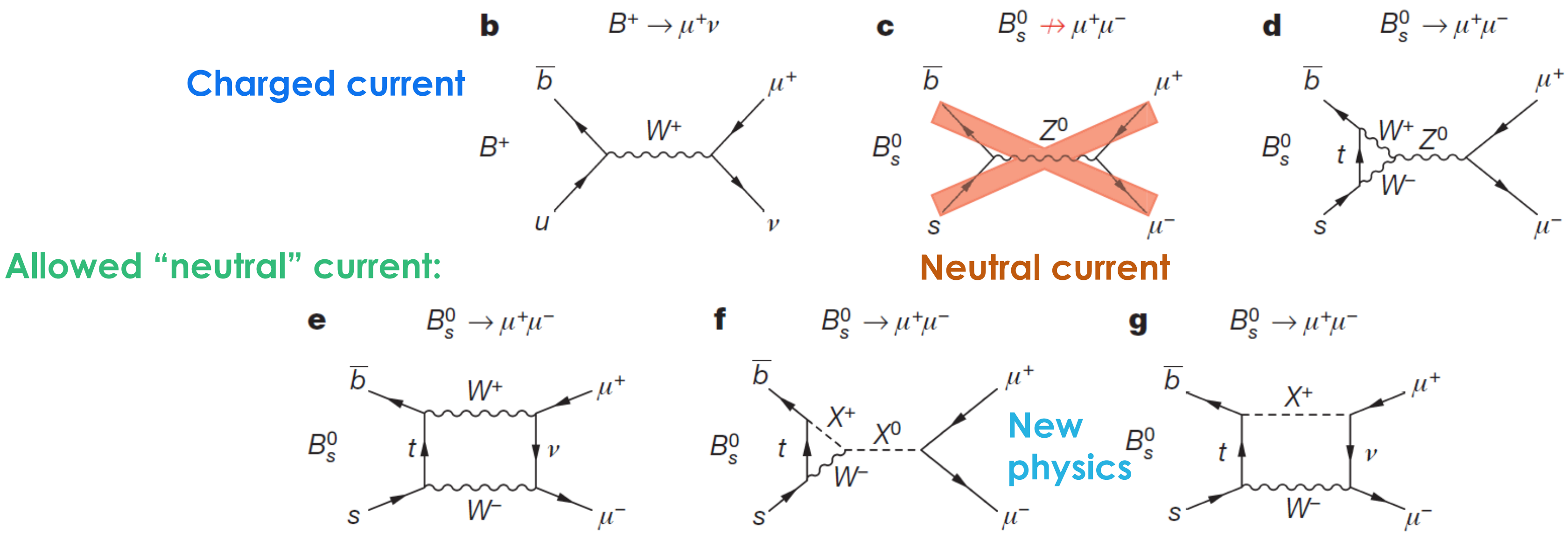




I'll share these two
final thesis analyses, which hit both of Marj's favorite topics

$B_s^0 \to \mu\mu$

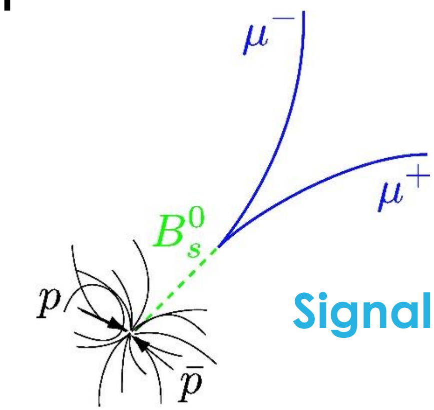
- Flavor-changing neutral currents (FCNC) are highly suppressed in the standard model – higher diagrams required:



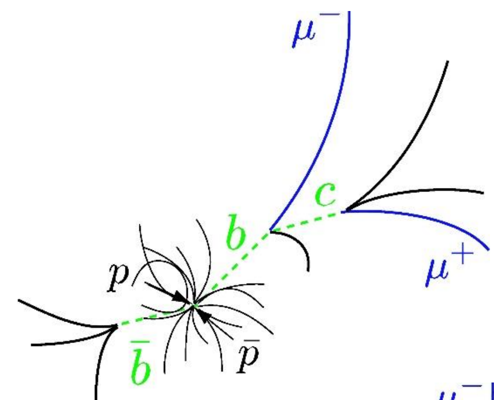
- $B_s^0 \to \mu\mu$ is a FCNC decay with SM branching fraction 3.5 x 10^{-9}
  - Suppressed because of requiring FCNC → 2 vertices become 4
  - Suppressed because of helicity requirements
- New physics particles in these loops could alter this branching fraction!

Dimuon event reconstruction

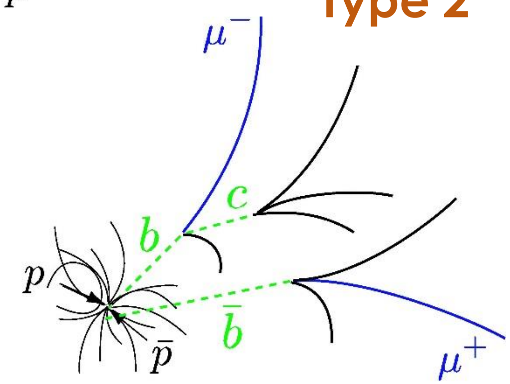
- Two high quality muons
  - Opposite charge
  - 3D vertex well separated from the $p\bar{p}$ interaction
- Large backgrounds from semileptonic b and c decays
  - Type 1: M($\mu\mu$) typically < M(B_s^0)
  - Type 2: M($\mu\mu$) typically > M(B_s^0)
  - Type 3: $B_s^0 \to hh \to \mu\mu$. Rare like signal and with a peaking structure…bad news!
  - No true $\mu\mu$ vertices, but often close enough to be reconstructed with a fake vertex
- B_s^0 candidate:
  - Small IP with $p\bar{p}$ interaction (μ's large)
  - $p_T(\mu\mu)$ points along vector from $p\bar{p}$ to B_s^0
  - Exploit all the differences with MVA methods



Signal



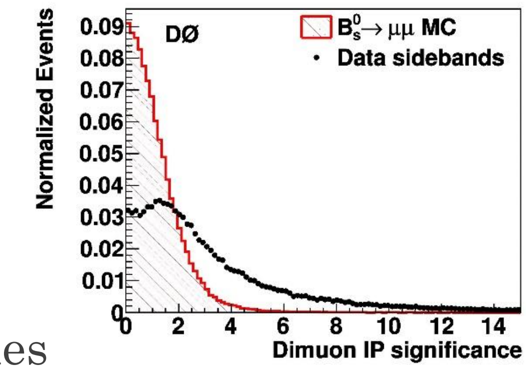
Type 1

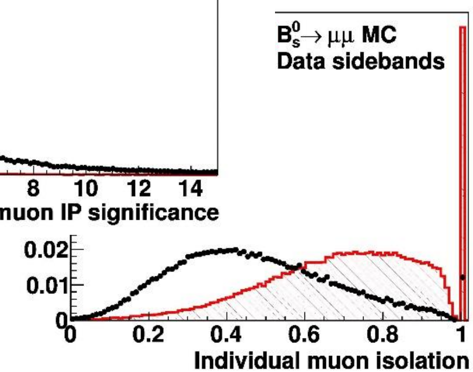


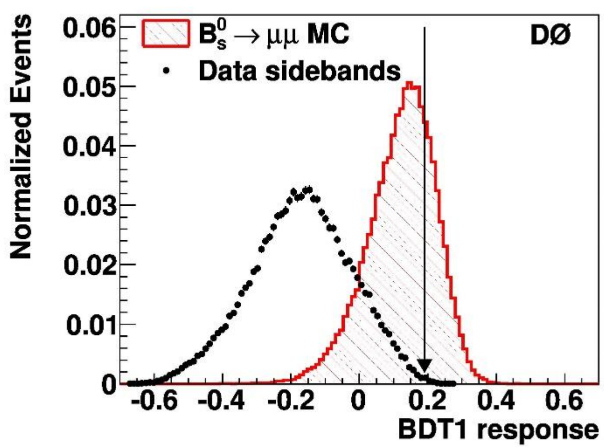
Type 2

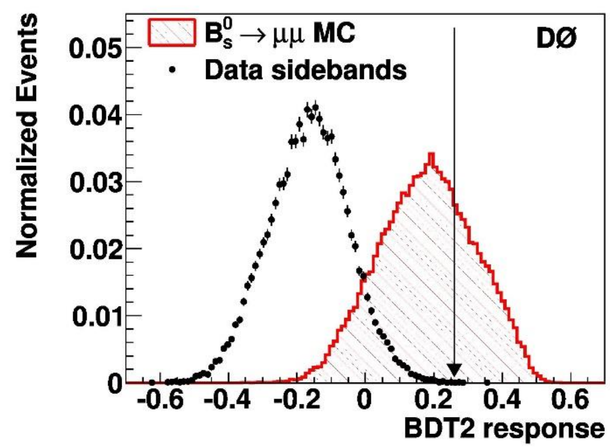
MVA method

- Train two Boosted Decision Trees on simulated signal and data from sidebands with M($\mu\mu$) = 4 – 4.9 GeV or 5.8 – 7.0 GeV
- 30 variables in each BDT:
  - Kinematics/topology of the $\mu\mu$ system
  - Isolation, measures of nearby radiation
  - Simulation validated in $B^{\pm} \to J/\psi K^{\pm}$
- 25% training, 25% testing, 50% of samples for determining expected S & B yield
- Optimize cuts by minimizing expected limit on $\mathcal{B}(B_s^0 \to \mu\mu)$







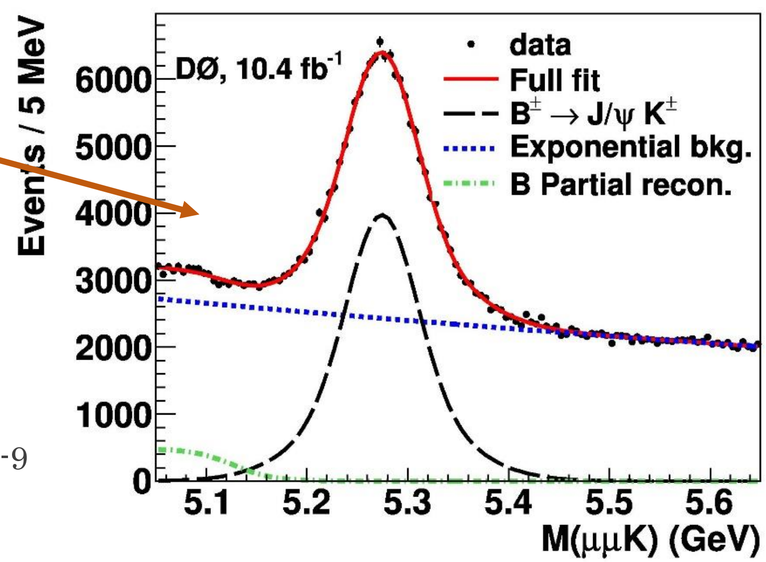


Event sensitivity

- Determine N($B_s^0 \to \mu\mu$) events expected by normalizing to "standard candle" channel $B^{\pm} \to J/\psi K^{\pm} \to \mu\mu K^{\pm}$ (dimuon with J/ψ mass + track)
- Define "single event sensitivity" as the branching fraction for which 1 event is expected in the dataset

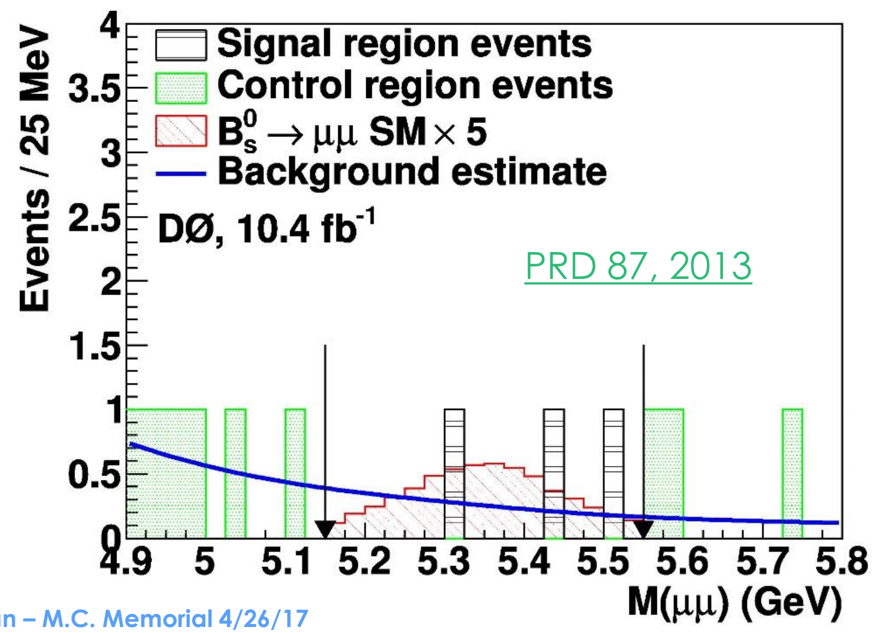
$$\text{SES} = \frac{1}{N(B^{\pm})} \times \frac{\epsilon(B^{\pm})}{\epsilon(B_s^0)} \frac{f(b \to B^{\pm})}{f(b \to B_s^0)} \times \mathcal{B}(B^{\pm} \to J/\psi K^{\pm}) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

  - Number of observed $B^{\pm}$ events in data: $(87.4 \pm 3.0) \times 10^3$ decays
  - Reconstruction efficiency ratio: $\varepsilon(B^{\pm})/\varepsilon(B_s^0) \approx (13.0 \pm 0.5)\%$
  - Fragmentation ratios and branching fractions taken from HFAG results
- Final SES after all cuts = (2.8 + 0.24) x 10^{-9}

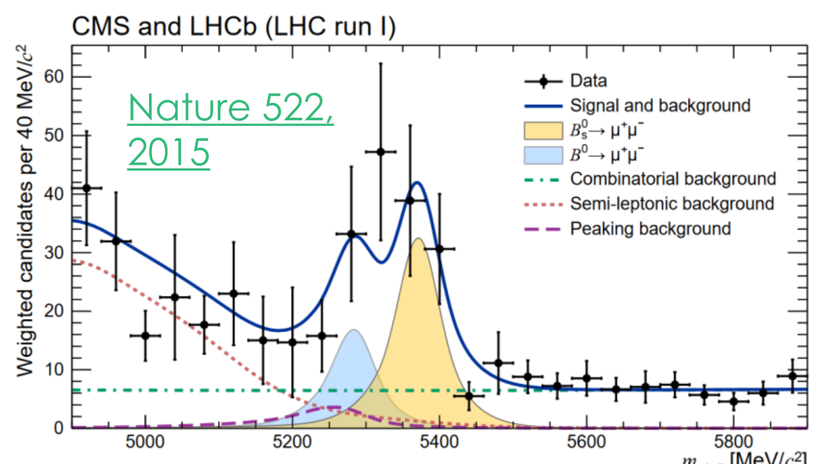


Results

- Region of $4.9 < M(\mu\mu) < 5.8$ GeV was blinded. Signal region inside was chosen as $M(B_s^0) \pm 200$ MeV by maximizing signal significance.
  - Final SES = $(2.8 + 0.24) \times 10^{-9}$ → **expect 1.23 ± 0.13 signal events**
  - Background ($\mu\mu$ + peaking): expect 4.3 ± 1.6 events
- **Observed 3 events** in the signal region! Consistent with B and S+B
- At 95% C.L., $\mathcal{B}(B_s^0 \to \mu\mu) < 15 \times 10^{-9}$ → almost twice the expected improvement from luminosity increase alone!

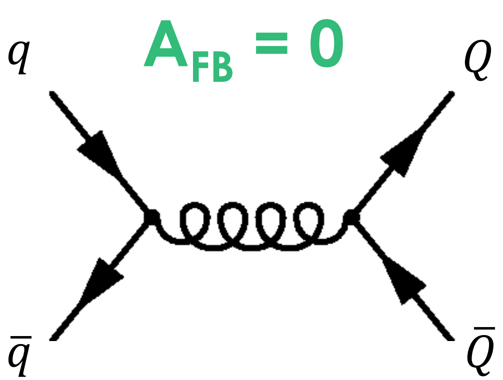


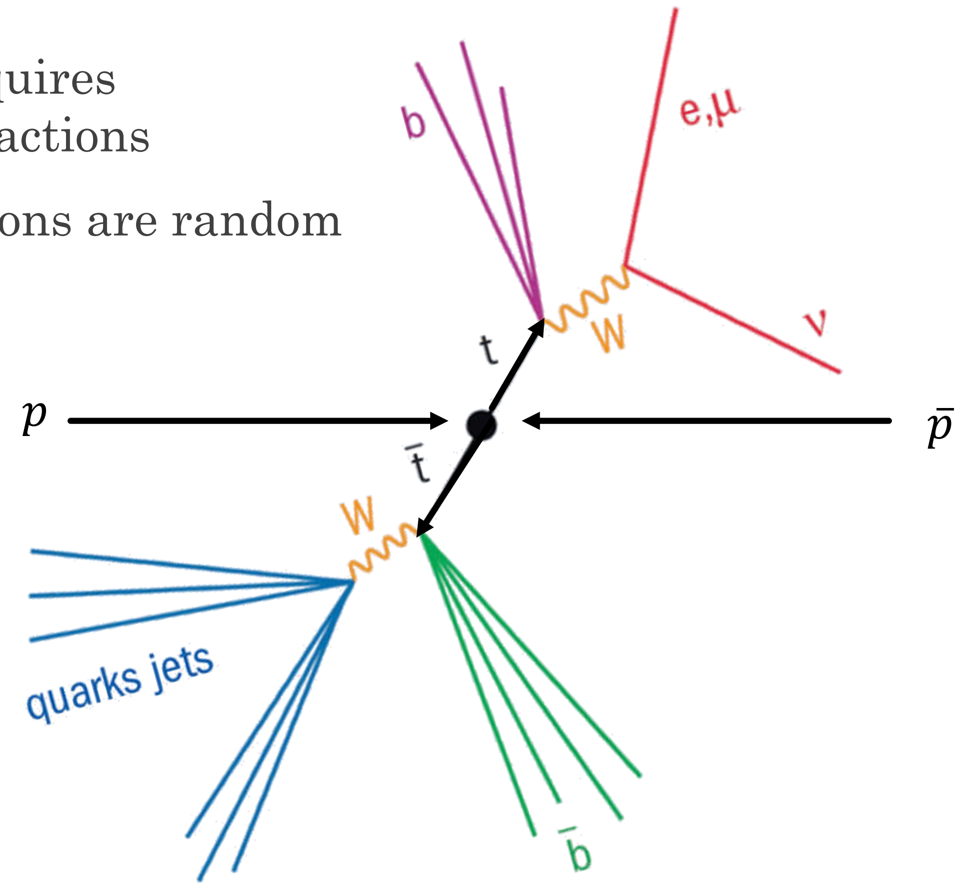
Process discovered in 2015 by CMS+LHCb:



A_{FB} in $B^{\pm} \to J/\psi K^{\pm}$

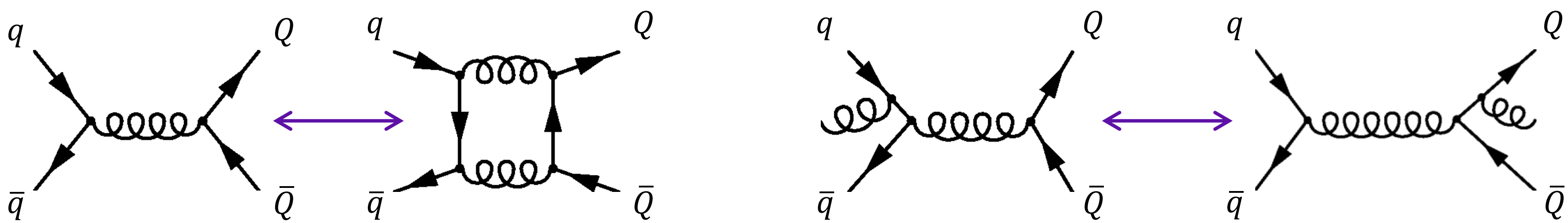
- The forward-backward asymmetry connects the "(anti)quark-ness" of a produced particle with the "(anti)quark-ness" of the initial particle
- **Do heavy (anti)quarks prefer to move in the direction of the (anti)proton?**
- Like $B_s^0 \to \mu\mu$, this question requires next-to-leading order SM interactions
- At leading order, the $q\bar{q}$ directions are random





A_{FB} in $B^{\pm} \rightarrow J/\psi K^{\pm}$

- What happens at next-to-leading order?
- Diagrams can interfere, breaking $Q \leftrightarrow \bar{Q}$ symmetry

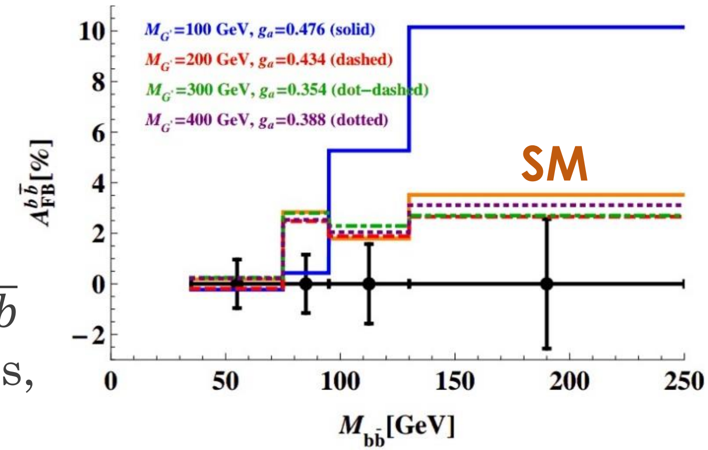


$A_{FB} > 0$, dominant at low p_T **$A_{FB} < 0$, grows with p_T**

- Measured first for top quarks → physics melodrama!
  - 7/2011: D0 + CDF measure asymmetry of 19.6 ± 6.5%, expected 5%
  - 11/2012: CDF measures anomalous increase of A_{FB} with mass & rapidity
  - 5/2014: D0 releases full dataset measurement of 10%
  - 11/2014: Theorists surprised by large NNLO correction: now expect 9.5% A_{FB}
- ***…Meanwhile, in the far-off land of B physics…***

A$_{\text{FB}}$ in $B^{\pm} \to J/\psi K^{\pm}$

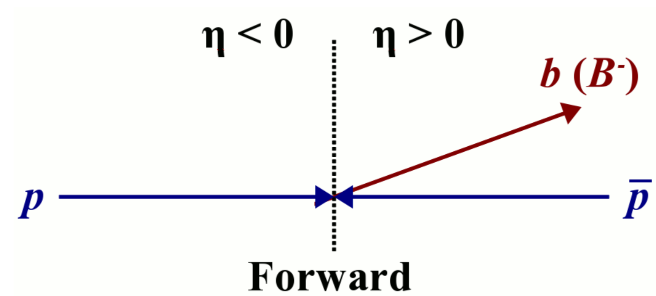
- If new physics is blowing up A$_{\text{FB}}(t)$, then A$_{\text{FB}}(b)$ should also be large!
- Axigluon models were popular ideas:
- Difficulty comes in precisely identifying b vs $\bar{b}$ jets! Semileptonic decays, $B^0 \leftrightarrow \bar{B}^0$ oscillations, several effects cloud flavor.



  - Measure A$_{\text{FB}}$ at high momentum with large uncertainty from flavor tag
  - Measure A$_{\text{FB}}$ at lower momentum (smaller A$_{\text{FB}}$) but with highly precise flavor tag and large sample → B physics! **Use the B+ meson for a tag**
- Benefit from $p\bar{p}$ collisions, flipping magnet polarities, μ coverage
- In pp collisions, "forward" = b, B^- following the proton direction

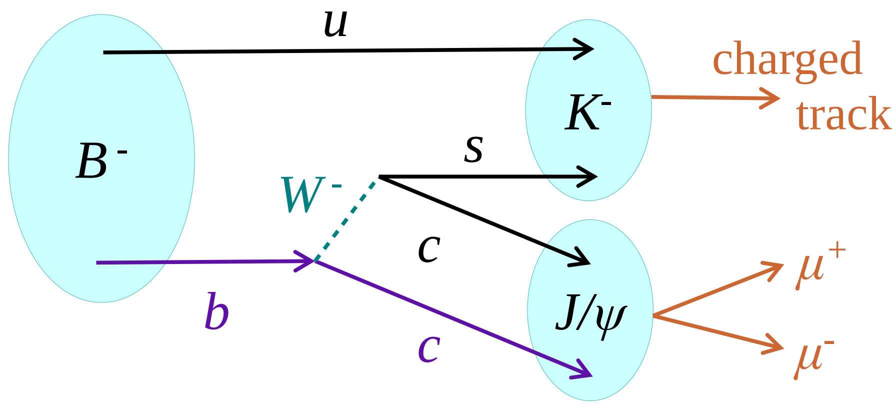
$$A_{FB}(B^{\pm}) = \frac{N(-q_B\eta_B > 0) - N(-q_B\eta_B < 0)}{N(-q_B\eta_B > 0) + N(-q_B\eta_B < 0)}$$

$$q_{\text{FB}} = -q_B \text{sign}(\eta_B)$$

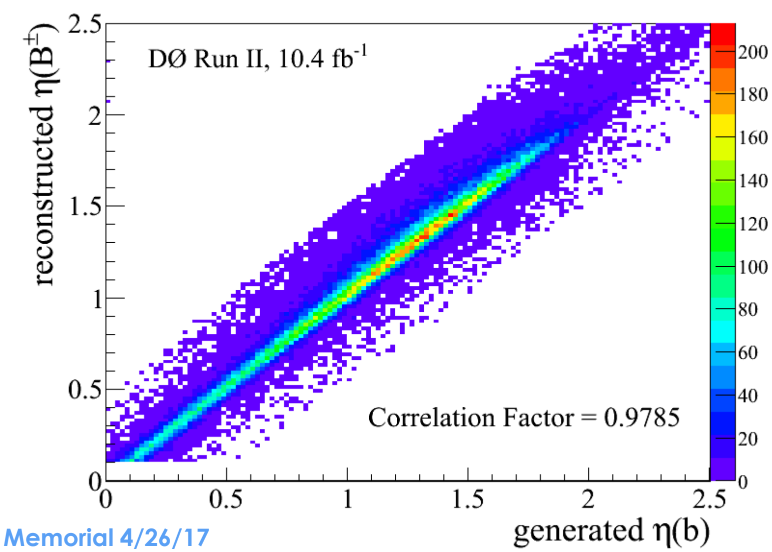


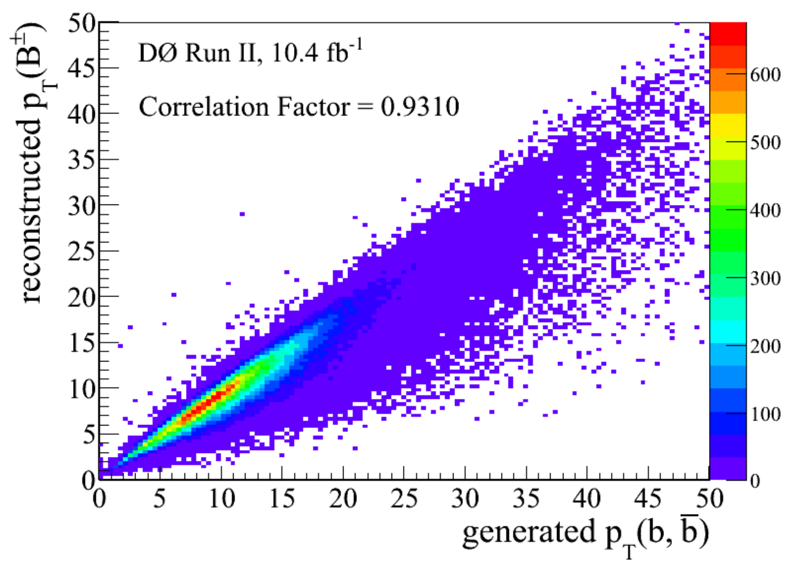
Reconstructing $B^{\pm} \rightarrow J/\psi K^{\pm}$

- The standard candle is back!
  - Dimuon (J/ψ mass) + track
  - $B^{\pm}$ separated from $p\bar{p}$ interaction
  - $|\eta_B| < 0.1$ for reliable directions



- $B^{\pm}$ is a fantastic tag of the initial b quark:
  $A_{FB}(B^{\pm})$ is a very close estimate of $A_{FB}(b)$ even after hadronization.
- BDT used to form a clean sample of $B^{\pm} \rightarrow J/\psi K^{\pm}$

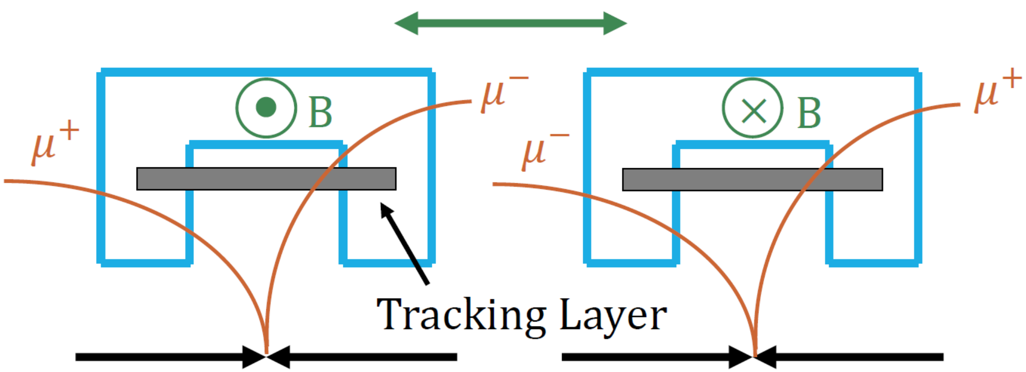




Reconstruction asymmetries

- A_{FB} is a convolution of a charge asymmetry and a "north/south" asymmetry – have to remove detector asymmetries from both sources
- A_C (w_{magnet}):
  - Equalize N($B^{\pm}$) in 4 polarities, removes tracking asymmetries
  - Set N(B^{+}) = N(B^{-}) to correct $K^{\pm}$-nucleon interaction differences (1% A_C)

Toroid polarity reversal:



- A_{NS} ($w_{J/\psi} w_K$):
  - Dedicated corrections
  - Correction based on event kinematics – sneaky asymmetric effects like extra inactive material (e.g. cables) can stop low p_T muons! Saw up to 8% asymmetry in J/ψ reconstruction
  - Mostly cancels in A_{FB} since B^+/B^- on the same side have opposite q_{FB}

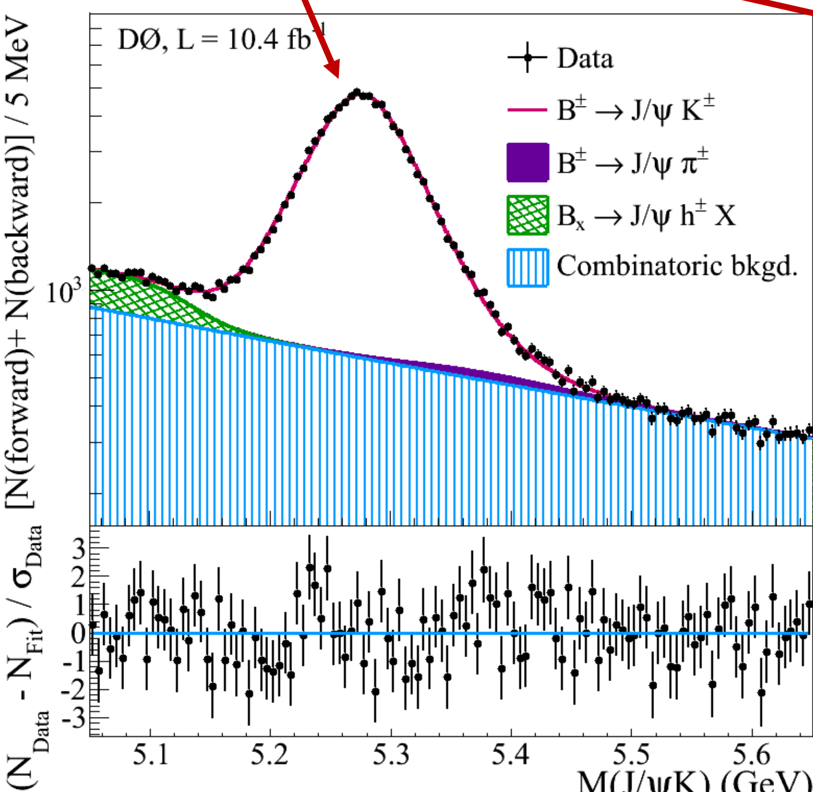
$$w_n = w_{magnet} w_{J/\psi} w_{K^{\pm}}$$

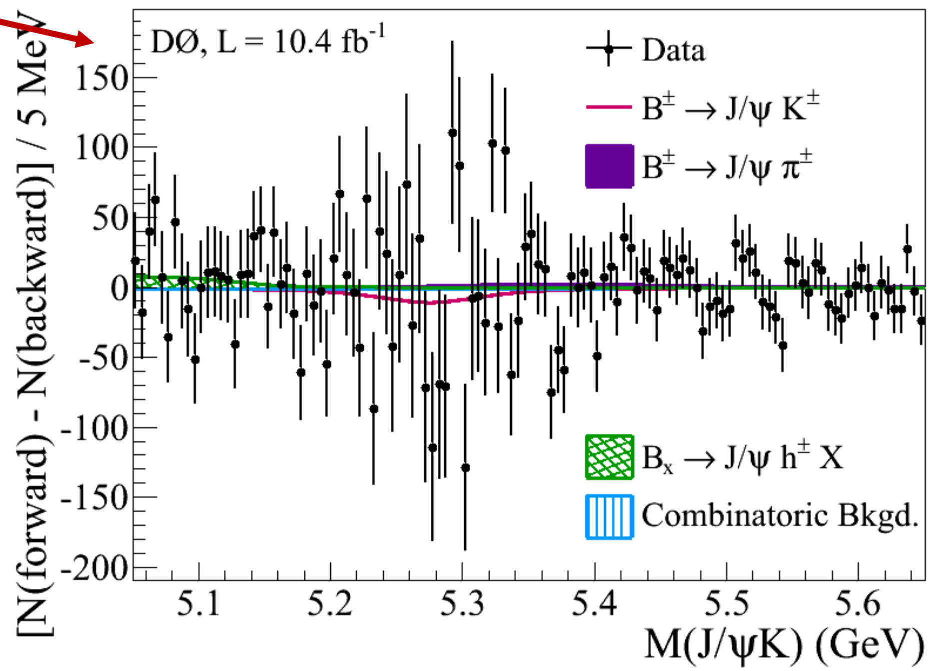
Results

- Measure A_{FB} in unbinned 2D maximum likelihood fit to weighted events with signal + 3 backgrounds:

$$\mathcal{L}_n = \alpha\left[f_S(1 + q_{FB}A_S)S(M_{J/\psi K}, E_K) + \dots \right.$$

Signal: $B^\pm \to J/\psi K^\pm$ double Gaussian
$B^\pm \to J/\psi \pi^\pm$ shifted double Gaussian
Partial B reconstruction
Combinatoric background

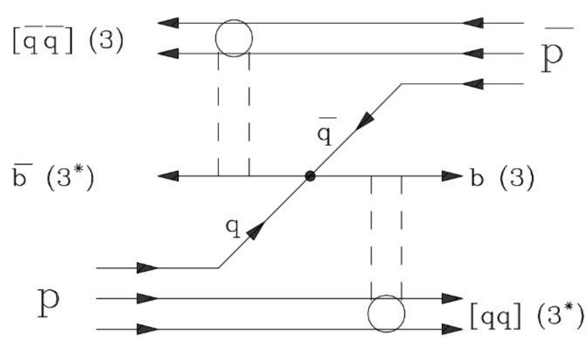


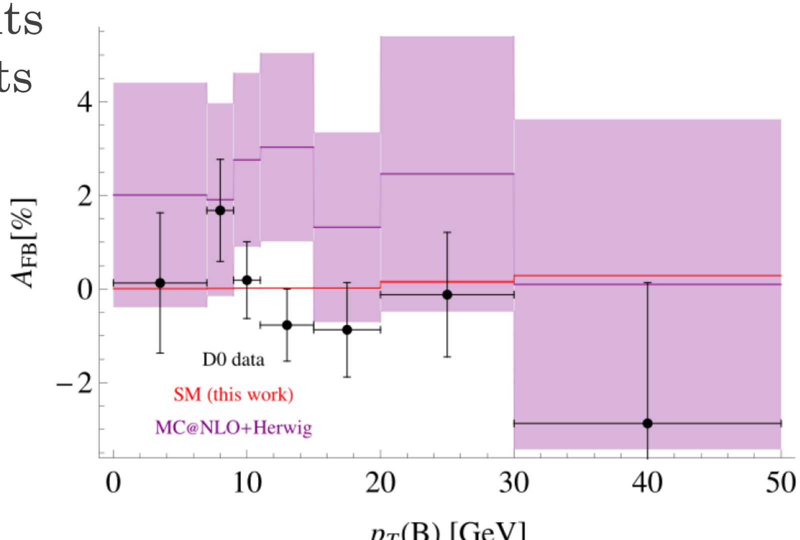


$A_{FB}(B^\pm)$ = [-0.24 ± 0.41(stat) ± 0.19(syst)]%

Interpretations

- Marj called this our "double-blind study", since we did a blind measurement of a quantity that had no SM prediction
- Generated MC@NLO+Herwig MC to estimate the SM value (NLO a requirement!), measuring asymmetry of $(2.3 \pm 0.61)\%$
- Post-publishing, theorist responded with a calculation that shows this measurement is **consistent with the SM**
- At the end of the $A_{FB}(t)$ saga, the door is essentially closed on new physics in anomalous heavy flavor forward-backward asymmetries
- $A_{FB}(B^{\pm})$ prompted other D0 measurements of A_{FB} in B baryons which probed concepts like string drag in proton collisions.





Thank you Marj!