Measurement of the Forward-Backward Asymmetry in $B^{\pm}$ Meson Production in $p\bar{p}$ Collisions at DØ

PRL 114 05813 (2015)

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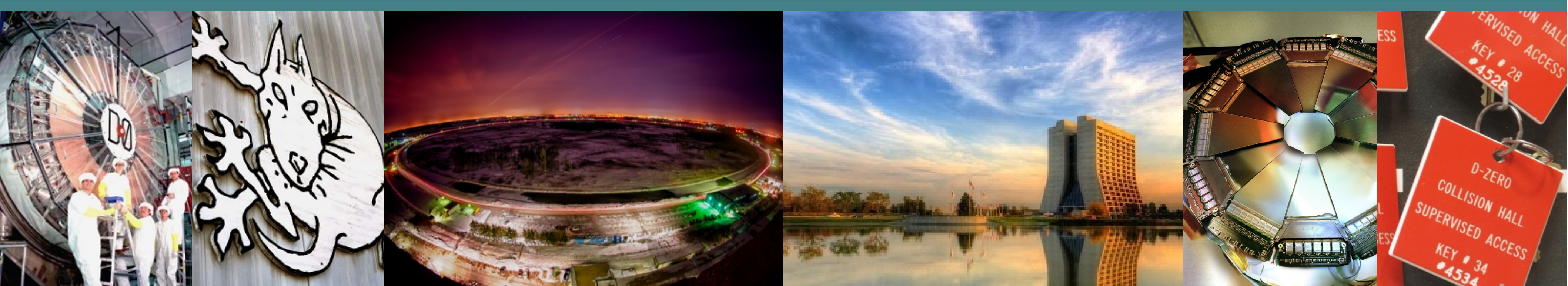

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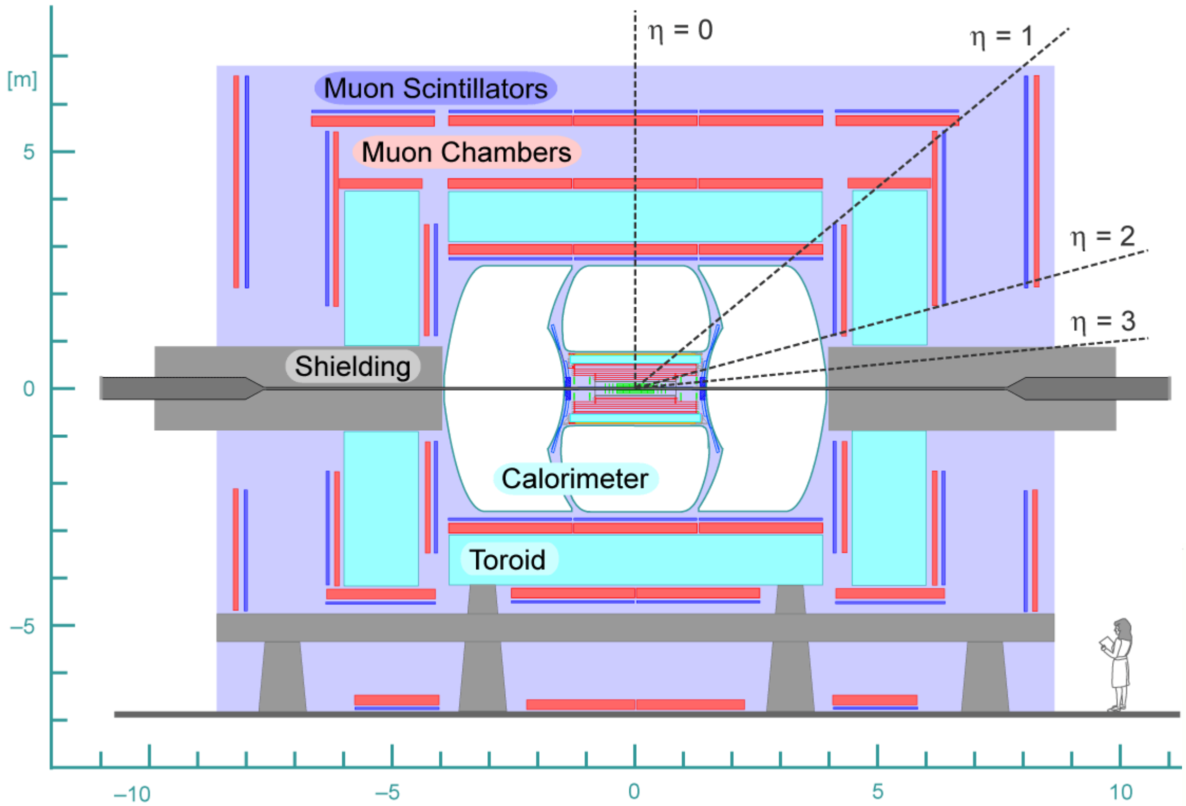
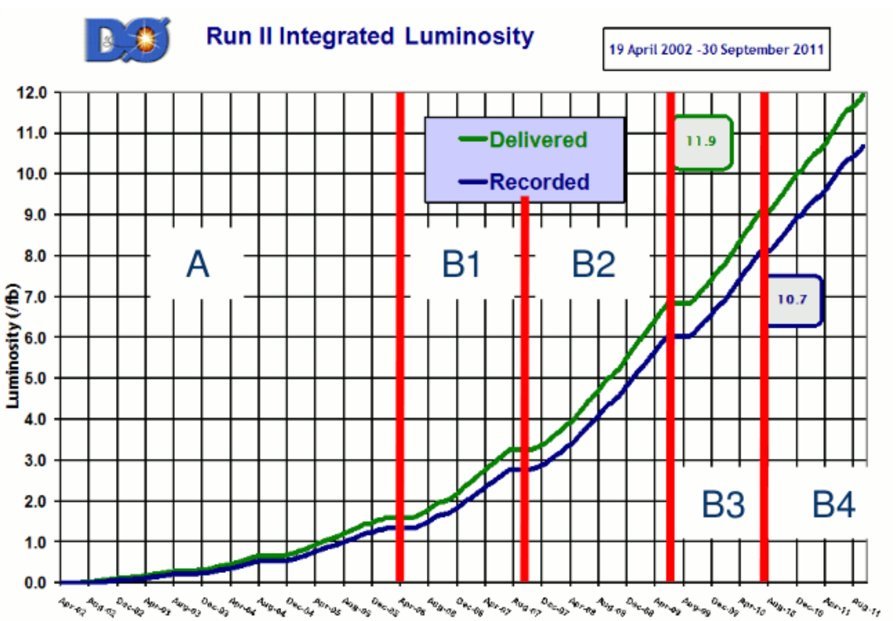
DØ Detector



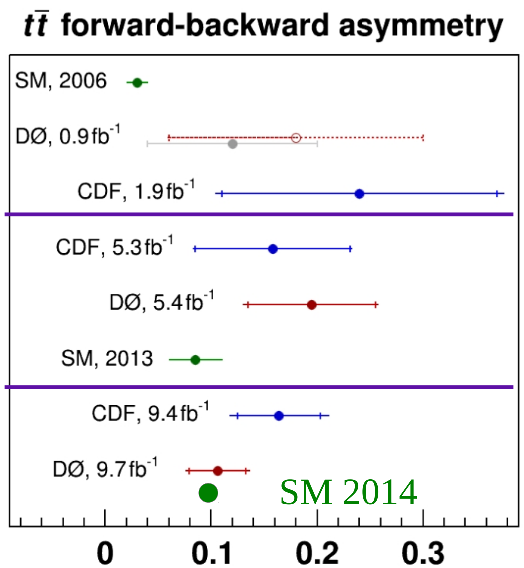
- Central tracking: silicon microstrip & fiber trackers
- Liquid argon / uranium calorimeter
- Independent muon tracking

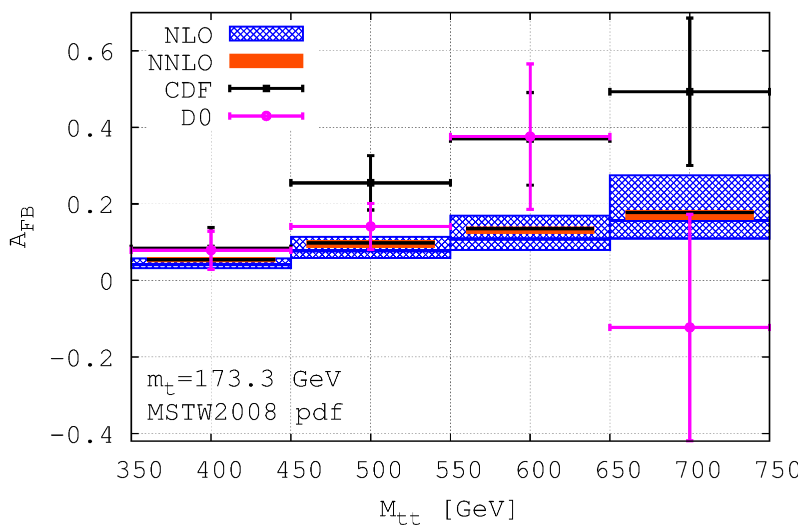


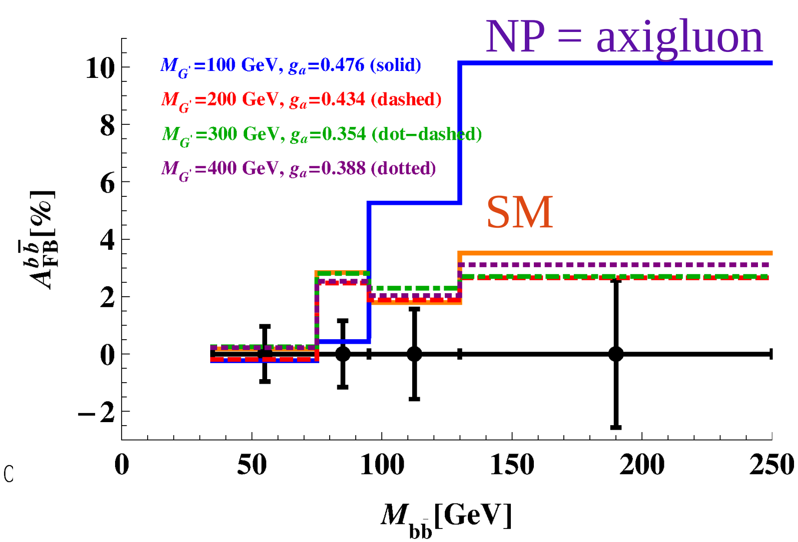
- Run II = 10 years of $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
- Data: 10.7 fb^{-1} recorded, this analysis uses 10.4 fb^{-1} (tracker+muon quality)

Motivation

- A_{FB} of $t\bar{t}$ production created a lot of interest
  - Early measurements >> SM, still some tension between CDF and SM
  - BSM models to explain excess can also predict $b\bar{b}$ asymmetry $\rightarrow$ same sources





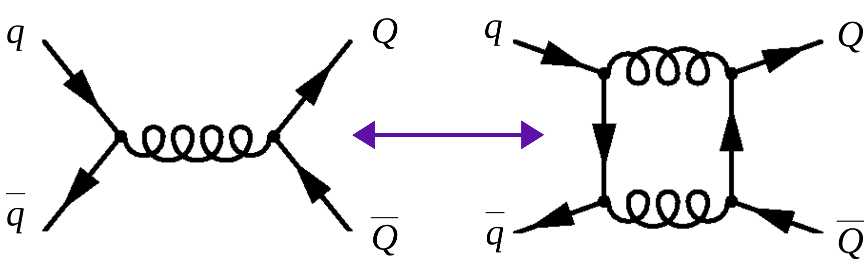


- This analysis was only the 2nd hadron collider measurement for $b\bar{b}$!
  - LHCb: forward-central asymmetry in mass range around Z peak (PRL 113 082003, 6/2014)
  - CDF: forward-backward asymmetry in M($b\bar{b}$) > 150 GeV; (arXiv:1504.06888, 4/2015)
    M($b\bar{b}$) > 40 GeV; (CDF Note 11156, 3/2015)

Figures: Ziqing Hong; arXiv:1411.3007; PRL 111 062003 (2013)

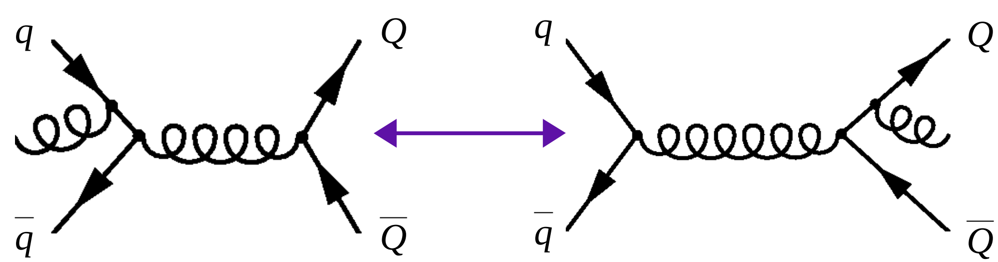
A_{FB} in $b\bar{b}$ Production

- Do heavy quarks have a preference to move in a specific direction?
  - At leading order QCD, no! In higher order $q\bar{q}$ interactions, yes!
- Asymmetry dominated by interference of tree-level and one-loop diagrams which are antisymmetric under $Q \leftrightarrow \bar{Q}$ exchange
  - Proportional to symmetric color factor d^2_{abc} (Kuhn/Rodrigo PRD **59**, 054017, 1999)
  - Secondary source is interference between ISR and FSR diagrams



Born / Box Interference: $A_{FB} > 0$

System is less perturbed if Q color flow follows incoming q



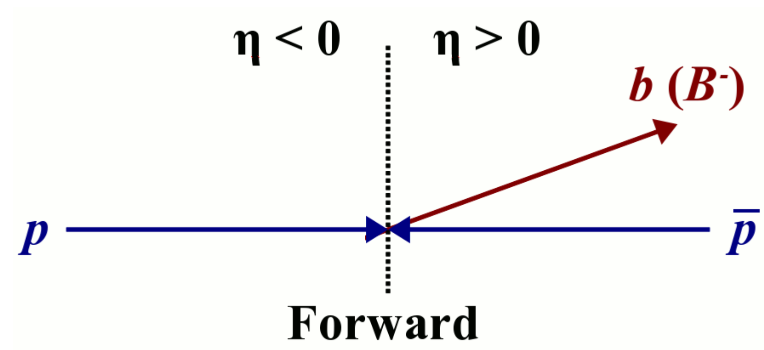
ISR / FSR Interference: $A_{FB} < 0$

Radiation requires "deceleration" of color flow – Q prefers to follow incoming $\bar{q}$

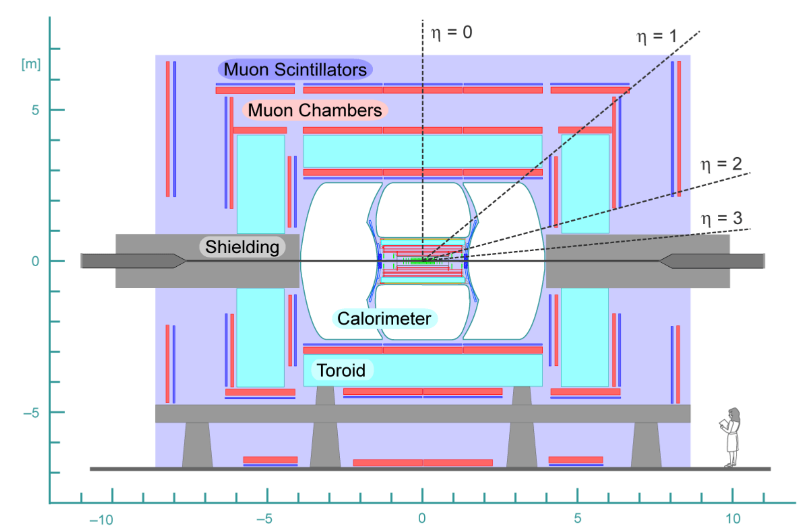
A_{FB} in $b\bar{b}$ Production

- In $p\bar{p}$ collisions, forward = b, B^- ($\bar{b}$, B^+) following p ($\bar{p}$) direction

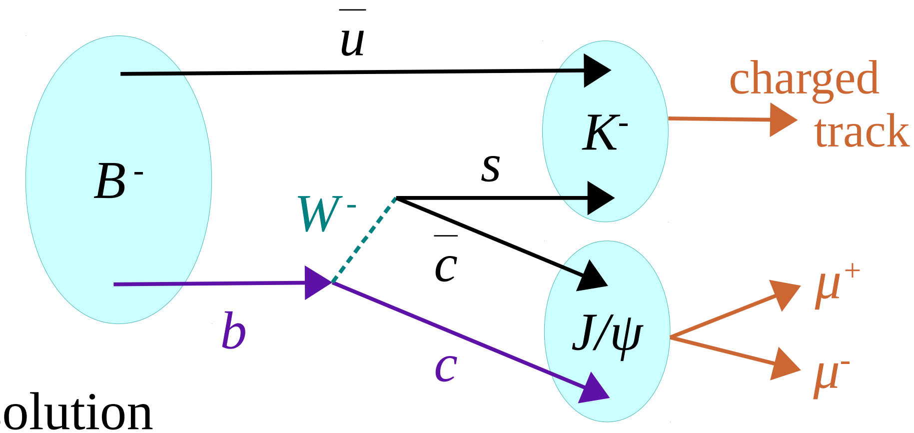
$$A_{FB}(B^{\pm}) = \frac{N(-q_B\eta_B > 0) - N(-q_B\eta_B < 0)}{N(-q_B\eta_B > 0) + N(-q_B\eta_B < 0)}$$



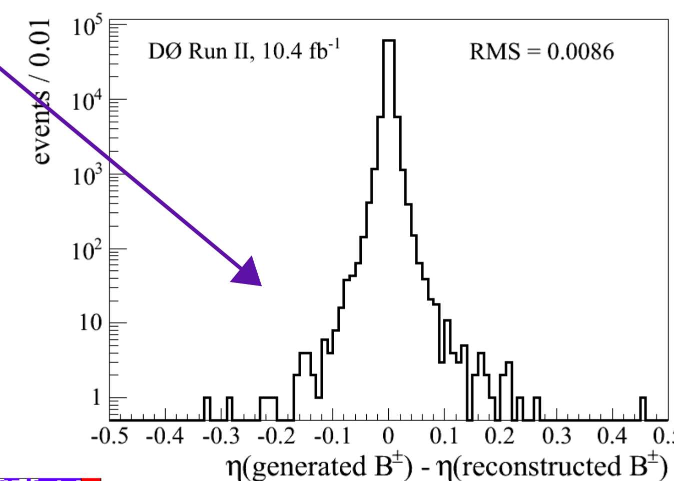
- Fully reconstructed $B^{\pm}$ decays tag $b/\bar{b}$ exactly
  - No precision lost to mis-tags, $B^0/\bar{B}^0$ oscillations
- DØ has many practical advantages:
  - History of precise CPV asymmetry results
  - $p\bar{p}$ initial state
  - reversing magnet polarities
  - extensive μ coverage



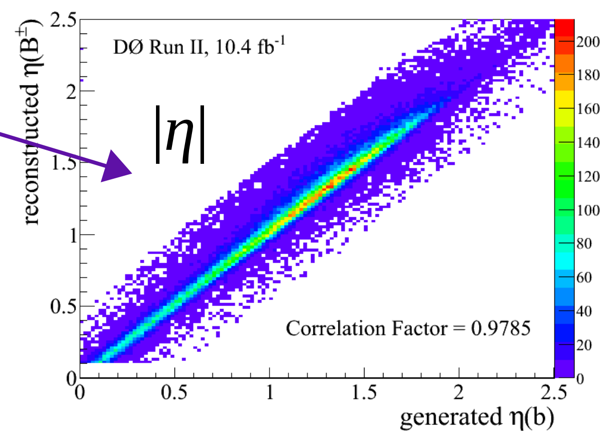
Reconstructing $B^{\pm} \rightarrow J/\psi\ K^{\pm}$

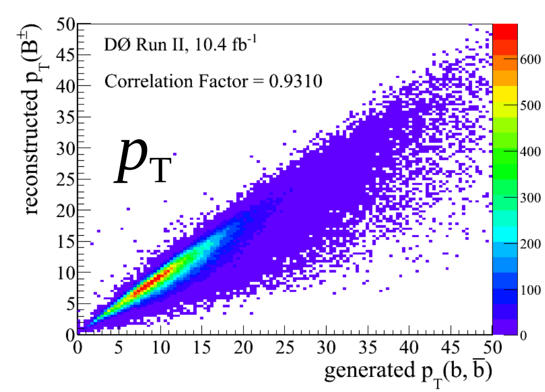


- $\mu^+\mu^-$ pair (J/ψ) + track ($K^{\pm}$) = $B^{\pm}$
  - $B^{\pm}$ decay length significance > 3σ
- F/B definition: $q_{FB} = -q_B\ \mathrm{sign}(\eta_B)$
  - Ambiguous near $|\eta|$ = 0 due to finite resolution

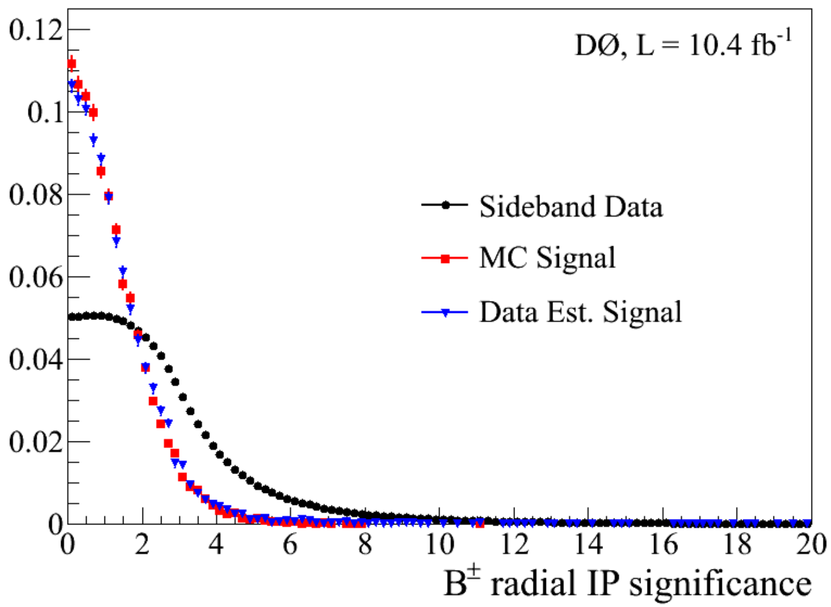


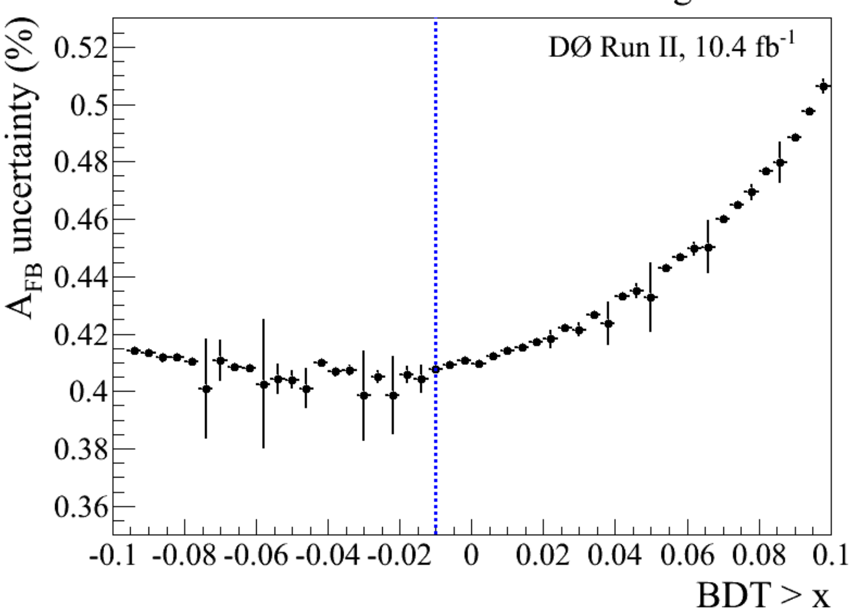
- Rejecting $|\eta_B| < 0.1$ (2% of data) gives:
  - 100% q_{FB}(MC@NLO $B^{\pm}$) = q_{FB}(reco $B^{\pm}$)
  - 99.5% q_{FB}(MC@NLO $b,\bar{b}$) = q_{FB}(reco $B^{\pm}$)
- $B^{\pm}$ kinematics closely match b kinematics:
  - Reco. $B^{\pm}$ vs generated $b,\bar{b}$
  - $A_{FB}(B^{\pm})$ affected minimally by hadronization





Boosted Decision Tree

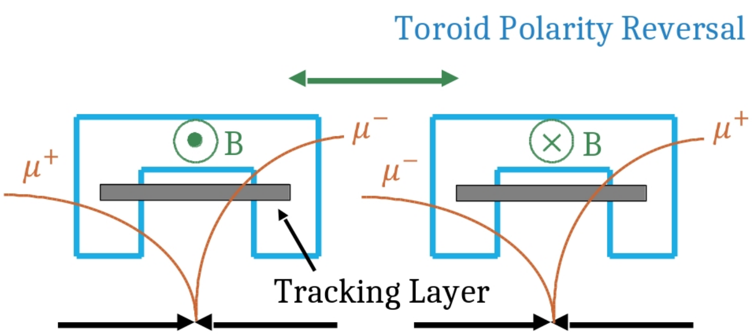




- Background taken from data in sidebands
  - Mostly partial reconstruction and combinatoric background
- Signal MC (leading-order) generated with Pythia
  - Match kinematics as closely as possible with expected data signal (from sideband subtraction) using weights
  - Ex: muon p_T, trigger effects aren't modeled
- BDT trained using 40 variables:
  - Momenta, decay lengths, impact parameters, pointing angles, vertex fit χ^2, isolation, and $\Delta\varphi$ for several particle pairs
- Cut on discriminant chosen to minimize $A_{FB}(B^{\pm})$ statistical uncertainty

Reconstruction Asymmetries

- Asymmetries in detector or reconstruction of J/ψ or $K^{\pm}$ must be corrected
- Forward-backward asymmetry is a combination of charge asymmetry and “north-south" asymmetry
- Deal with A_C: w_{magnet}
  - Equalize N($B^{\pm}$) in 4 magnet polarity settings to remove tracking asymmetries
  - Set N(B^{+}) = N(B^{-}) to correct for $K^{\pm}$ detector interaction cross-section differences → 1% A_C



- Deal with A_{NS}: $w_{J/\psi} w_K$
  - Measure asymmetries in samples without expected production asymmetry
  - set $\varepsilon_{\eta<0} = \varepsilon_{\eta>0}$ with a corrective weight, based on event-by-event kinematics
  - Effects on $A_{FB}(B^{\pm})$ are small: B^{+} and B^{-} on same side have opposite q_{FB}, so A_{NS} corrections mostly cancel

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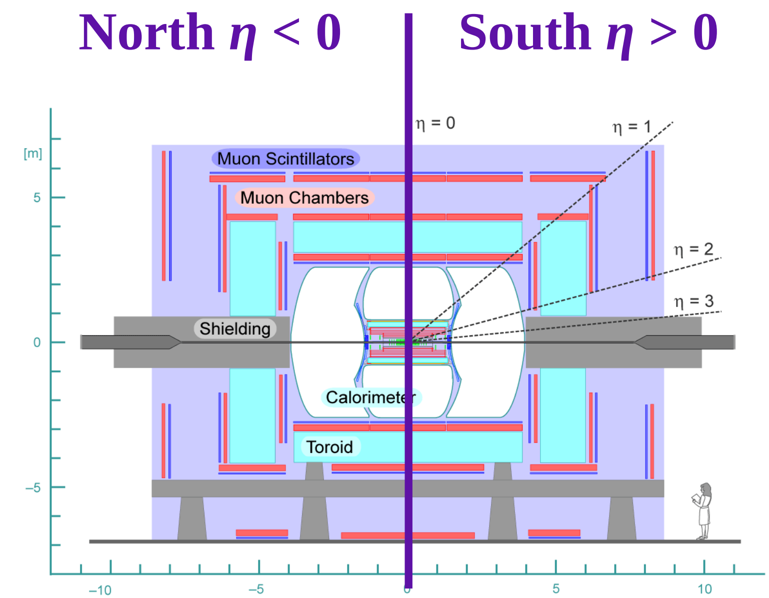
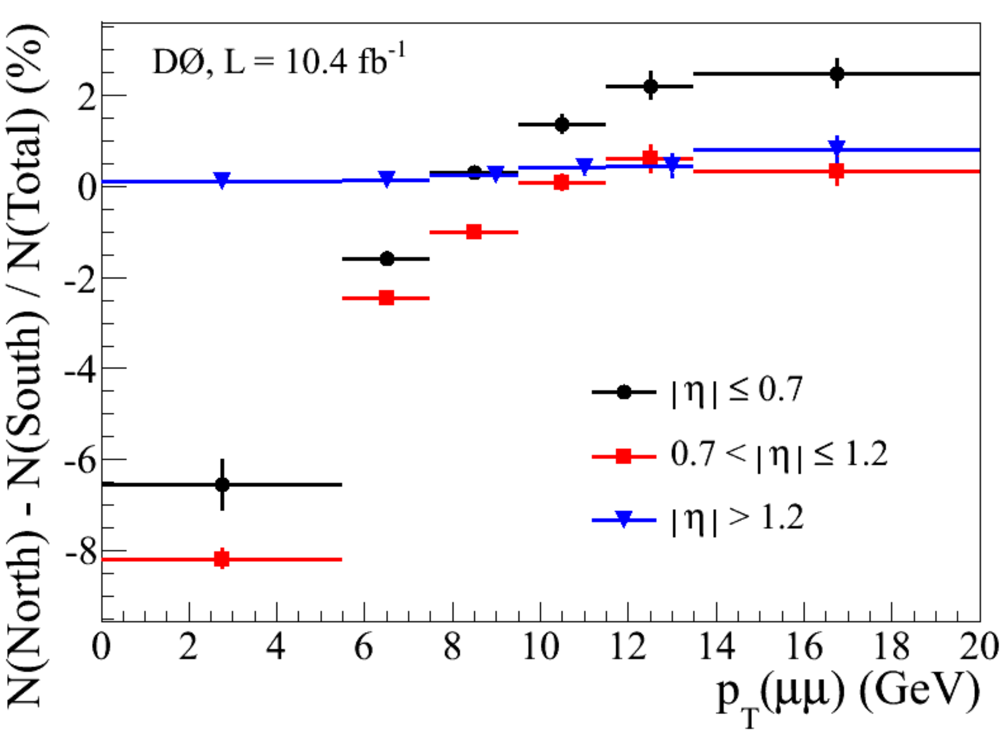
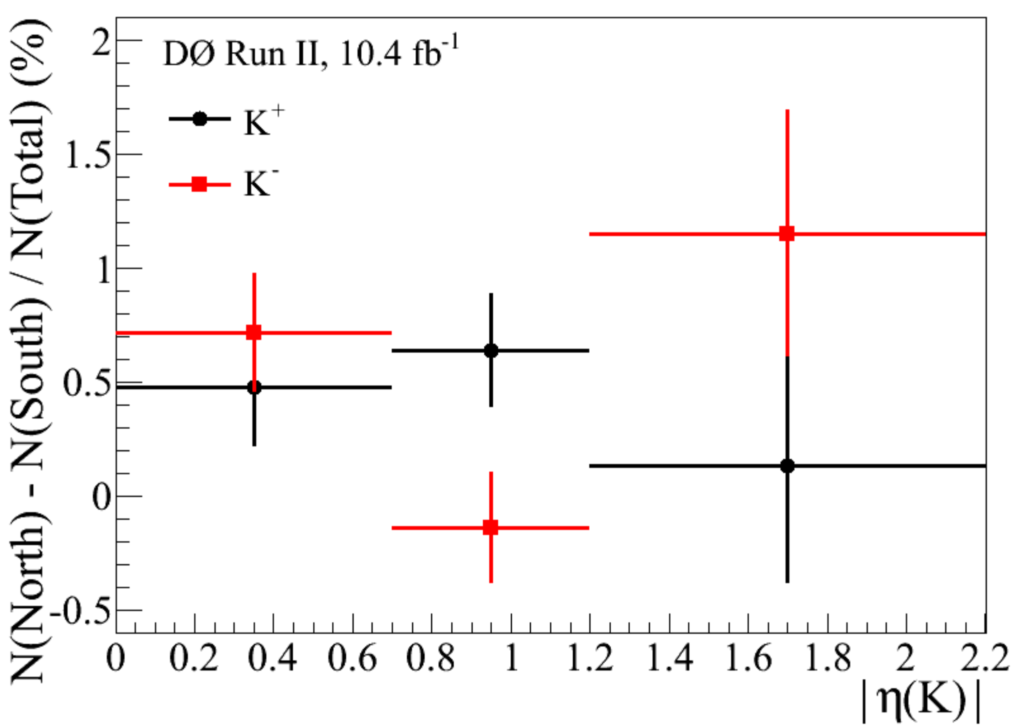


Reconstruction Asymmetries

- $A_{NS}(J/\psi)$: prompt $J/\psi \rightarrow \mu^+\mu^-$, measure in bins of $|\eta|$ and p_T
  - Est. 2% *B* decay fraction
  - Low p_T A_{NS} traced to inactive material causing $\langle p_T(\mu)\ \mathrm{N}\rangle > \langle p_T(\mu)\ \mathrm{S}\rangle$
- $A_{NS}(K^{\pm})$: $\varphi \rightarrow K^+K^-$ decays, bins of leading kaon charge and $|\eta|$
  - A_{NS} is a parameter in simultaneous fits to north and south side data





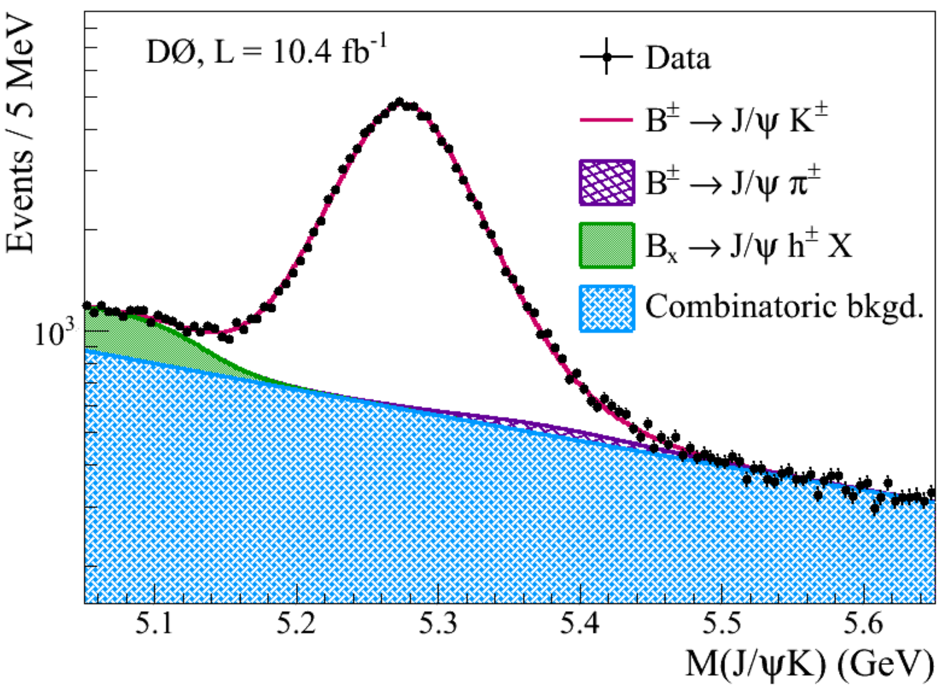
Maximum Likelihood Fit

$$\boxed{\mathrm{LLH} = -2\sum_{n=1}^{N} w_n \ln(\mathcal{L}_n)}$$

- Boosted Decision Tree to reduce background
- Unbinned fit over all $B^{\pm}$ candidates
- Events weighted to correct for reconstruction asymmetries (next slides)
- 4 components, each with an event fraction f and asymmetry A

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

$$\mathcal{L}_n = \alpha\Big[\underline{f_S(1+q_{\mathrm{FB}}A_S)S(M_{J/\psi K}, E_K)} + \underline{f_P(1+q_{\mathrm{FB}}A_P)P(M_{J/\psi K}, E_K)}$$
$$\underline{+ f_T(1+q_{\mathrm{FB}}A_T)T(M_{J/\psi K})}\Big]$$
$$\underline{+ [1-\alpha(f_S+f_P+f_T)](1+q_{\mathrm{FB}}A_E)E(M_{J/\psi K}, E_K)}$$



Signal: $B^{\pm} \rightarrow J/\psi\ K^{\pm}$ double Gaussian

Pion: $B^{\pm} \rightarrow J/\psi\ \pi^{\pm}$ shifted double Gaussian

Threshold: partial B reconstruction

Exponential: combinatoric background

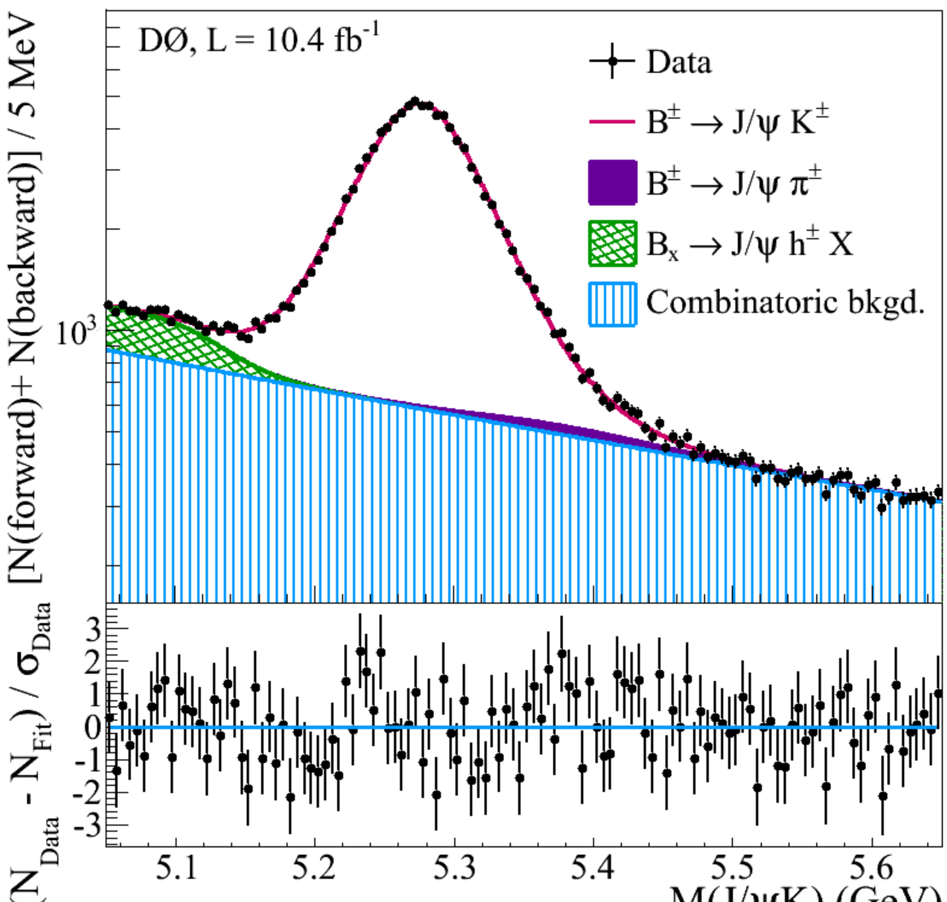
Extraction of $A_{FB}(B^{\pm})$

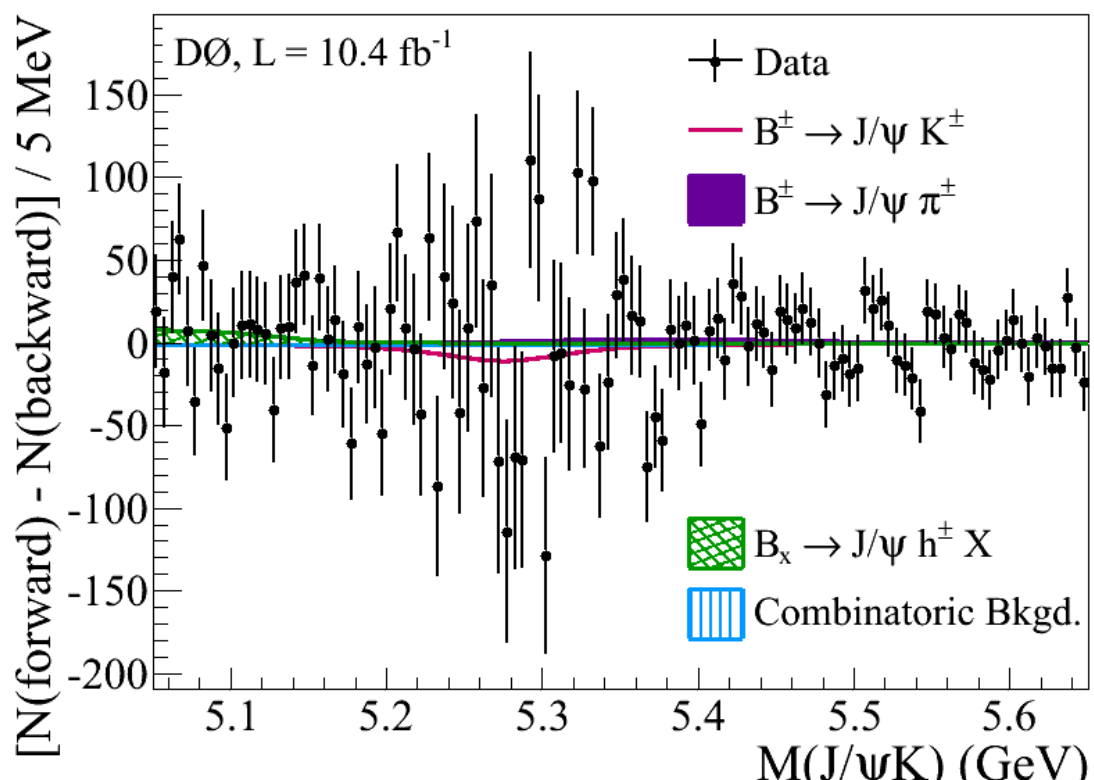
$A_{FB}(B^{\pm})$ = [-0.24 ± 0.41(stat) ± 0.19(syst)]%

- 89328 signal evts / 160360 candidates
- χ^2 / d.o.f = 249 / 214

TABLE I: Summary of uncertainties on $A_{FB}(B^{\pm})$ in data.

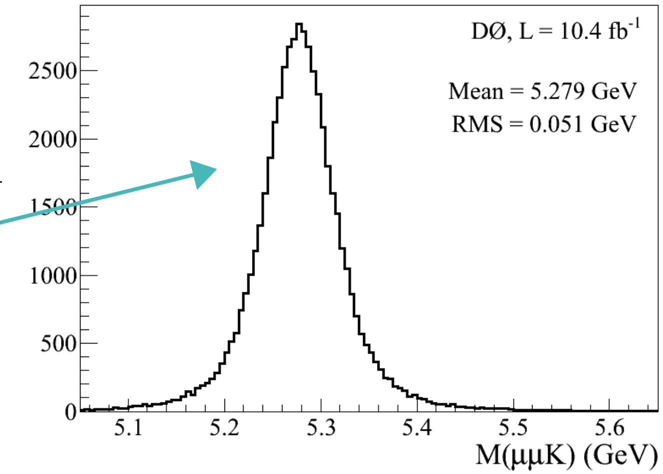
Source	Uncertainty
Statistical	0.41%
Alternative BDTs and cuts	0.17%
Fit Variations	0.06%
Reconstruction Asymmetries	0.05%
Fit Bias	0.02%
Systematic Uncertainty	0.19%
Total Uncertainty	0.45%





$A_{FB}(B^{\pm})$ Estimate from MC

- 16M QCD $p\bar{p} \rightarrow b\bar{b}X$ events generated with MC@NLO + HERWIG for hadronization
- Identical $B^{\pm} \rightarrow J/\psi\, K^{\pm}$ selection as in data
  - Add requirement that $J/K^{\pm}$ reconstructed tracks match generated $B^{\pm} \rightarrow J/\psi\, K^{\pm}$ tracks (leaves only signal)
  - Correct for unmodeled muon trigger effects
  - Correct for MC reconstruction asymmetries

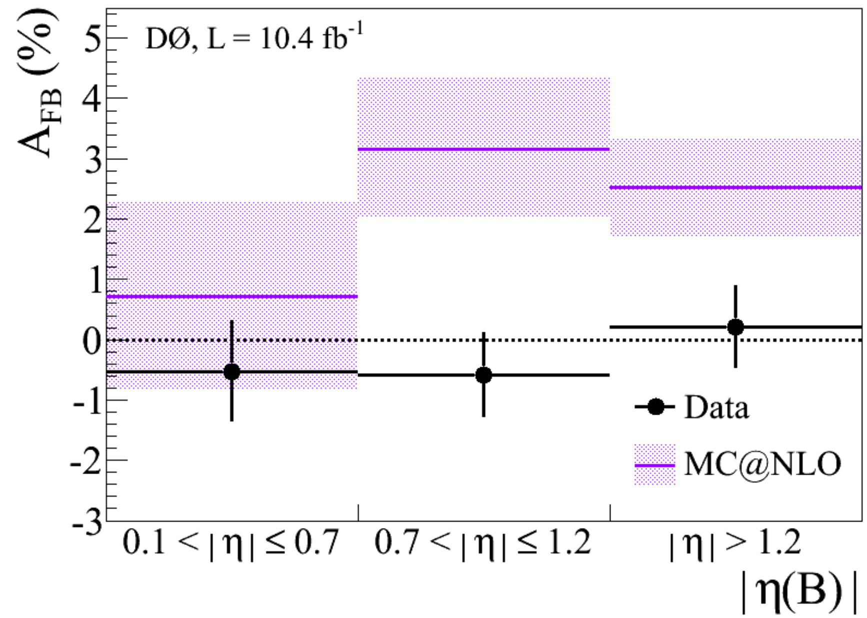


- Systematic uncertainties: PDF, energy scale, fragmentation
  - Renormalization & factorization energy scale variations: 0.44%
  - Fragmentation model variations: 0.25%
  - PDF eigenvector uncertainty shifts: 0.03%

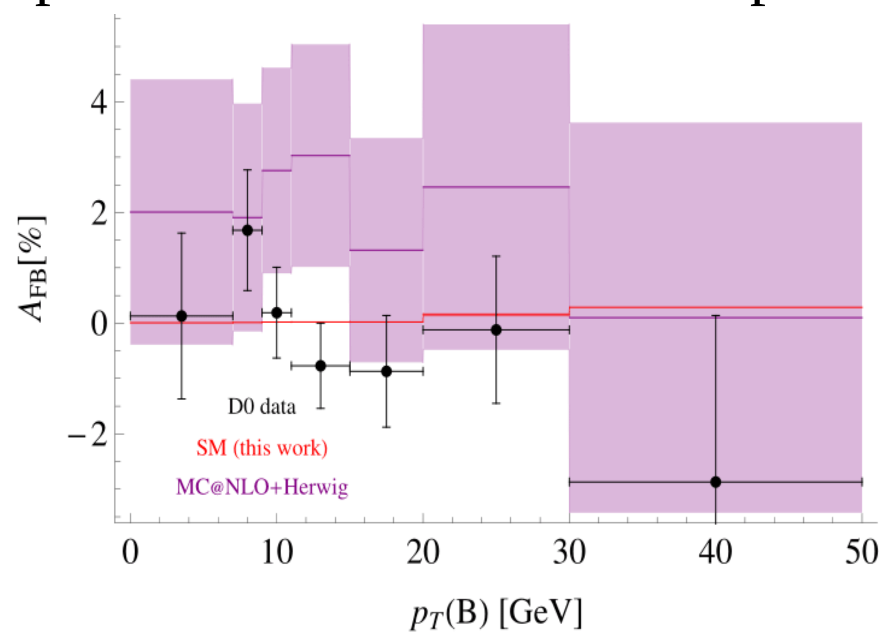
$$\boxed{A_{FB}(B^{\pm}) = [2.31 \pm 0.34(\text{stat}) \pm 0.51(\text{syst})]\%}$$

$A_{FB}(B^{\pm})$ Estimate from MC

- Also measured in bins of $|\eta|$ and p_T
  - $\langle p_T(B^{\pm})\rangle$ = 12.9 GeV
  - General discrepancy from MC @ NLO
  - 3σ disagreement in inclusive sample



- Our conclusion: “...more rigorous SM predictions are need to interpret these results.”
- And they came!
  - Consistent with the SM (red) within small uncertainties
  - Also consistent with CDF low and high mass measurements



Summary

- First Tevatron measurement of a forward-backward asymmetry in the *b* sector

$$\boxed{A_{FB}(B^{\pm}) = (-0.24 \pm 0.41 \pm 0.19)\%}$$

  - Precision reflects DØ's excellent heavy flavor asymmetry program
  - Agrees with new SM theory predictions → asymmetry consistent with zero
  - Extended and complemented by recent CDF measurements

- After developments of the last two years, there is much less room for new physics to appear in anomalous forward-backward asymmetries!

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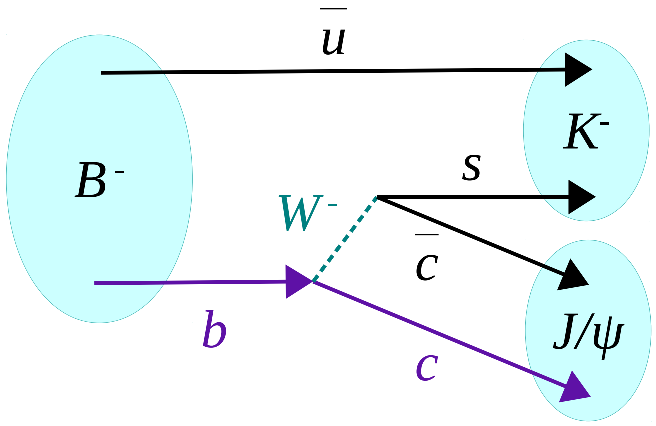
Thank You!

Backup

References

- DØ analysis: PRL **114** 05813 (2015), arXiv:1411.3021
- $A_{FB}(q\bar{q})$ theory: Kuhn/Rodrigo, PRD **59**, 054017 (1999)
- $A_{FB}(t\bar{t})$ SM prediction: Czakon/Fiedler/Mitov, arXiv:1411.3007
- LHCb measurement: PRL **113**, 082003 (2014)
- CDF measurements:
  - High mass: arXiv:1504.06888
  - Low mass: CDF note 11156
- Theory Predictions
  - $A_{FB}(B^{\pm})$ prediction: Murphy, arXiv:1504.02493
  - New physics models: Grinstein/Murphy, PRL **111**, 062003 (2013)

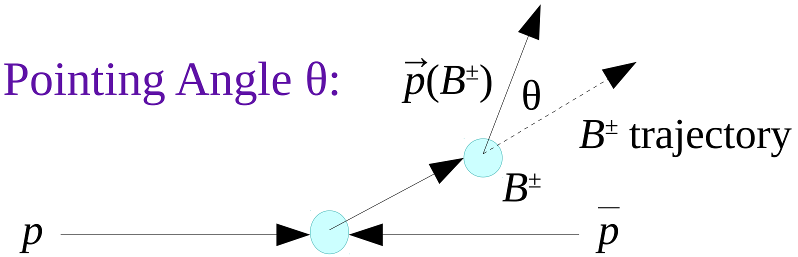
Reconstructing $B^{\pm} \rightarrow J/\psi\ K^{\pm}$

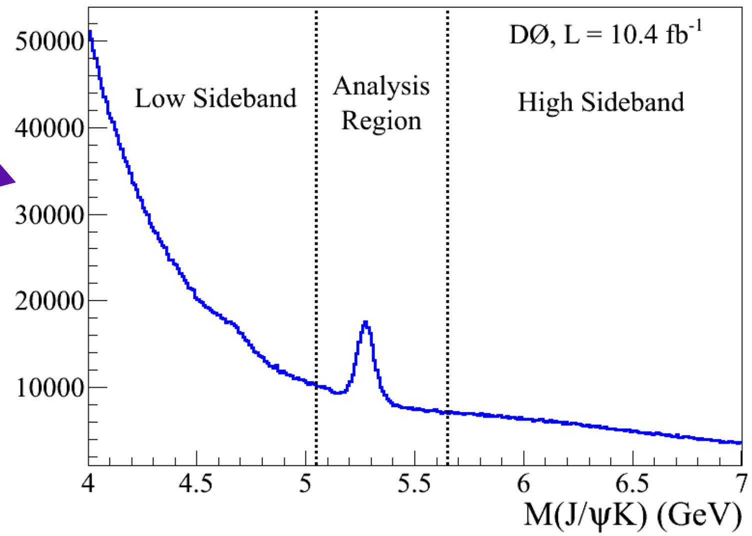


- All DØ data from Tevatron Run II, 10.4 fb^{-1}
- $\mu^+\mu^-$ pair (J/ψ) + track ($K^{\pm}$) = $B^{\pm}$ candidate
- $\mu^{\pm}$: $p_T > 1.5$ GeV; $|\eta| < 2.1$
- $K^{\pm}$: $p_T > 0.7$ GeV; $|\eta| < 2.1$
- J/ψ: Mass = 2.7 – 3.45 GeV
  - Decay length uncertainty < 0.1cm
  - cos(2D Pointing Angle) > 0
- $B^{\pm}$: Mass = 4.0 – 7.0 GeV
  - decay length significance > 3
  - vertex fit $\chi^2 < 16 / 3$ d.o.f
  - cos(2D Pointing Angle) > 0.8

(more background reduction not shown in the plot)

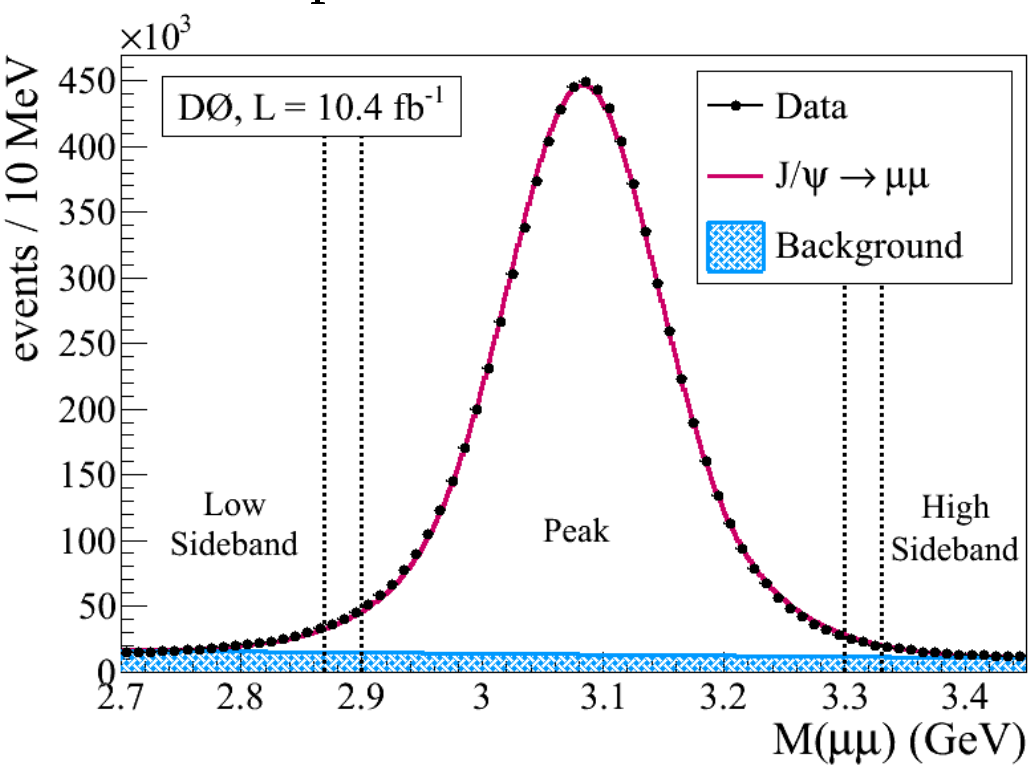
Pointing Angle θ:

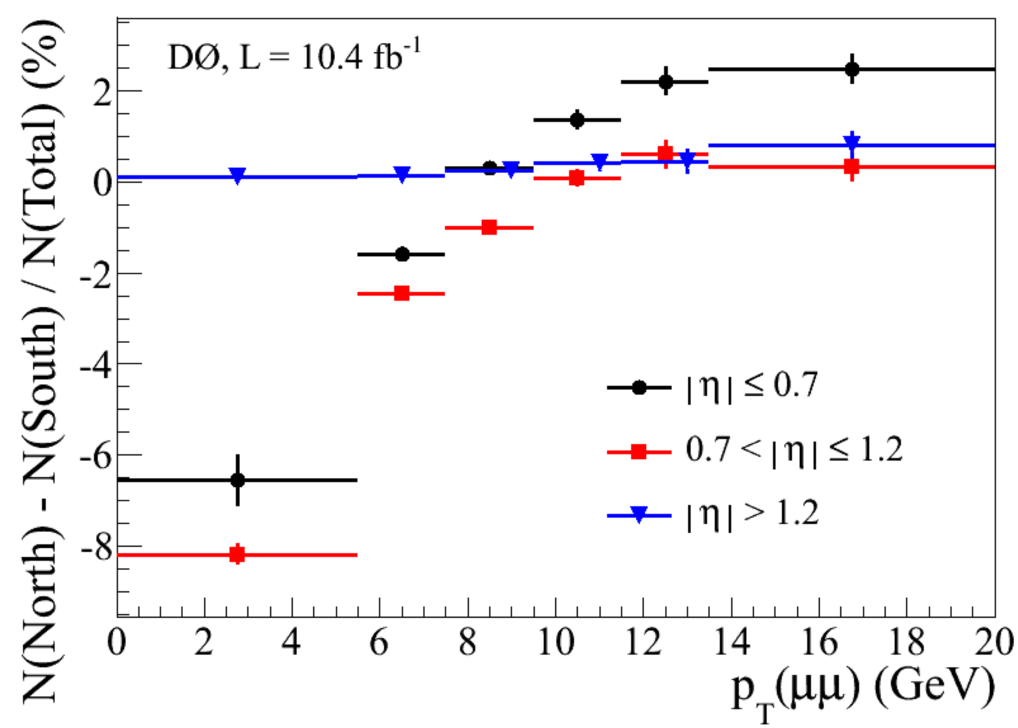




Reconstruction Asymmetries

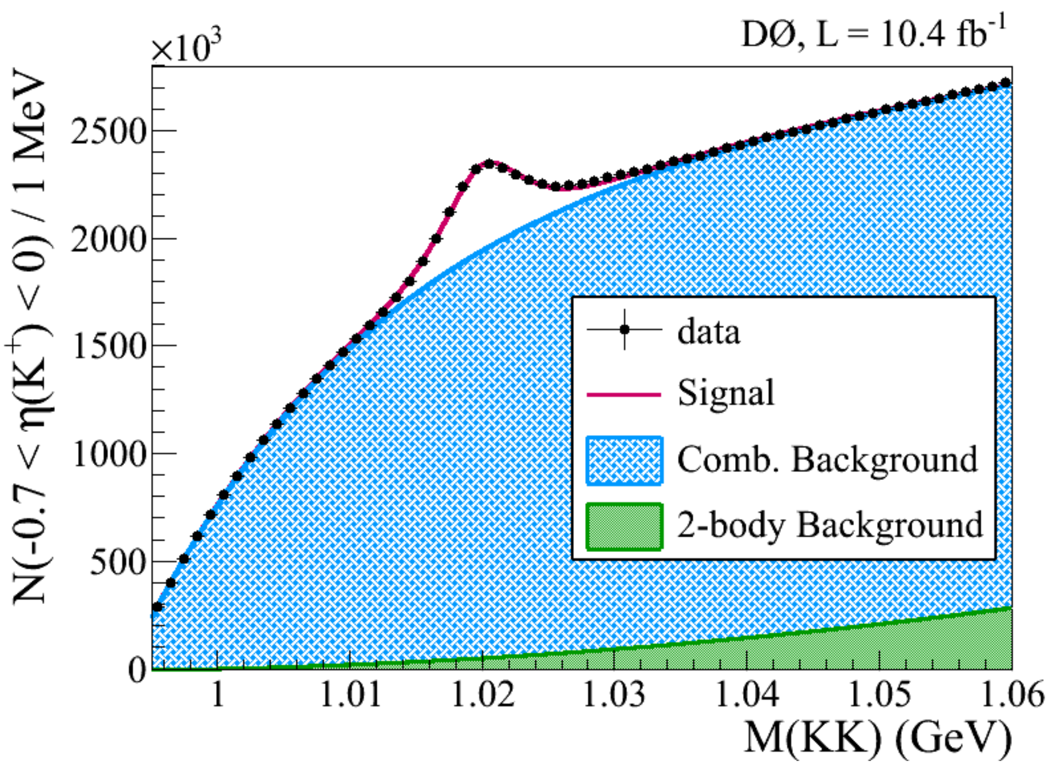
- $A_{NS}(J/\psi)$: prompt $J/\psi \rightarrow \mu^+\mu^-$, measure in bins of $|\eta|$ and p_T
  - identical selection with requirement of low decay length significance
  - Est. 2% *B* decay fraction
- A_{NS} calculated by counting after sideband subtraction in each bin of $|\eta|$
- Low p_T A_{NS} traced to inactive material causing $\langle p_T(\mu)\ N\rangle > \langle p_T(\mu)\ S\rangle$

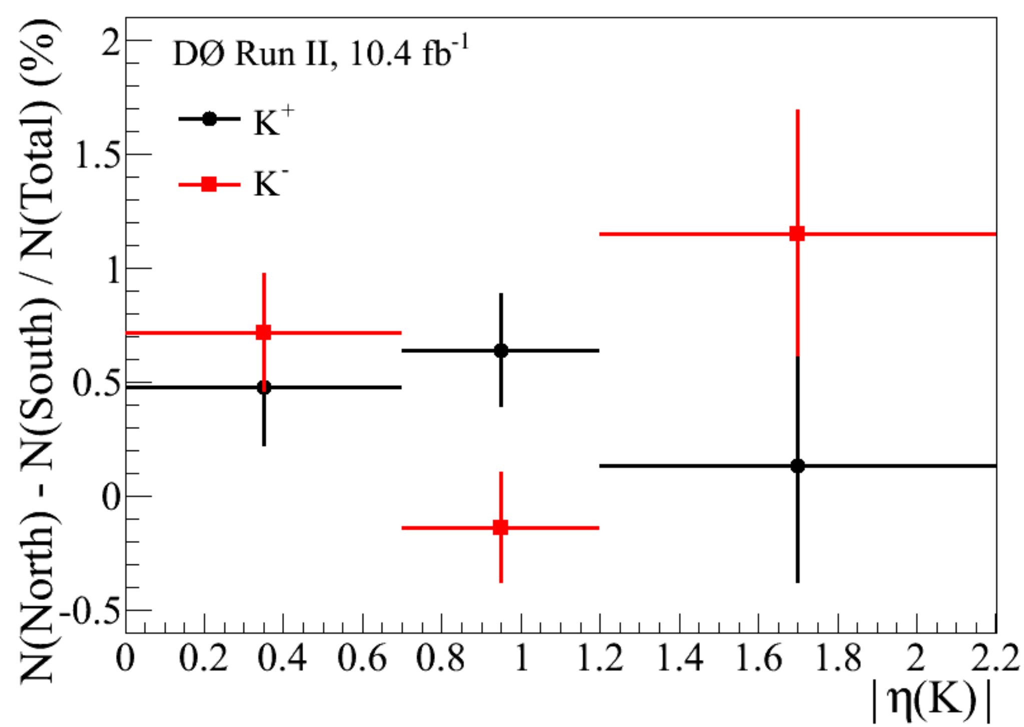




Reconstruction Asymmetries

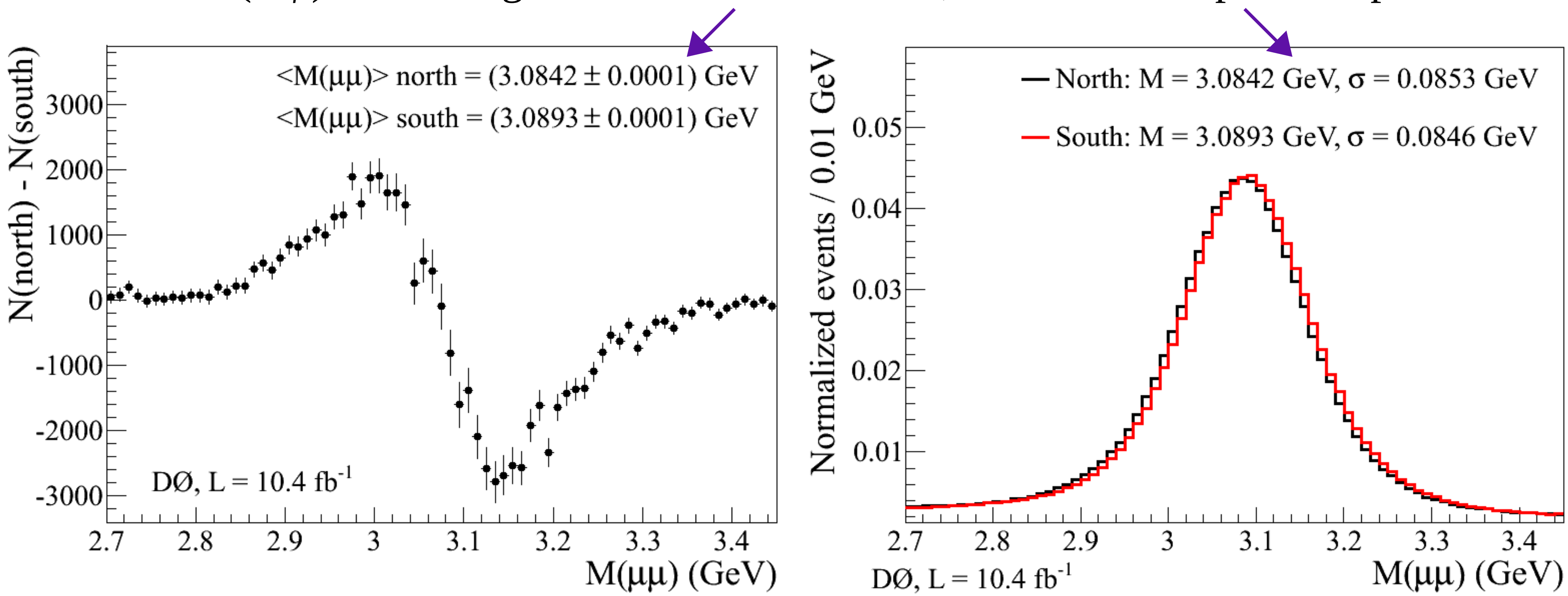
- $A_{NS}(K^{\pm})$: sample of $\varphi \rightarrow K^{+}K^{-}$ decays selected to reproduce kinematics of kaons in $B^{\pm} \rightarrow J/\psi\ K^{\pm}$
- Binned by charge and $|\eta|$ of leading kaon
- A_{NS} is a parameter in simultaneous χ^2 fits to north and south side data in each $|\eta|$ bin:





Maximum Likelihood Fit

- Particle masses don't match between north ($\eta < 0$) and south ($\eta > 0$) sides of the detector: M(north) always < M(south)
  - Ex: M(J/ψ) → ΔM significant based on errors, but small compared to peak width:



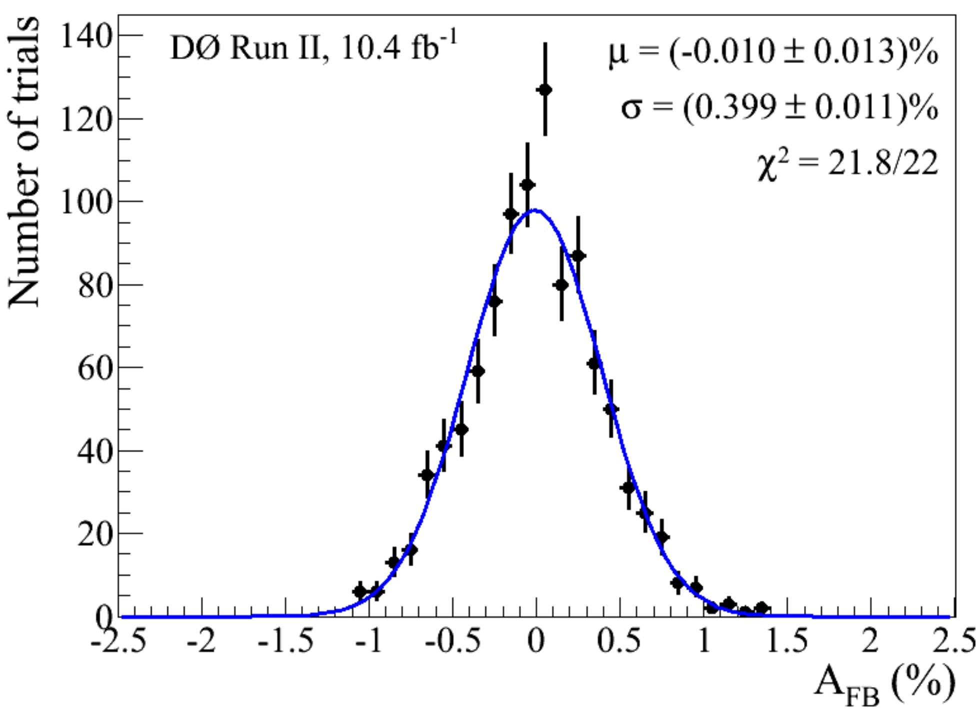
- Solenoid field asymmetric along z, but not included in the field map
- Solution: signal distribution has a unique parameter set on each side

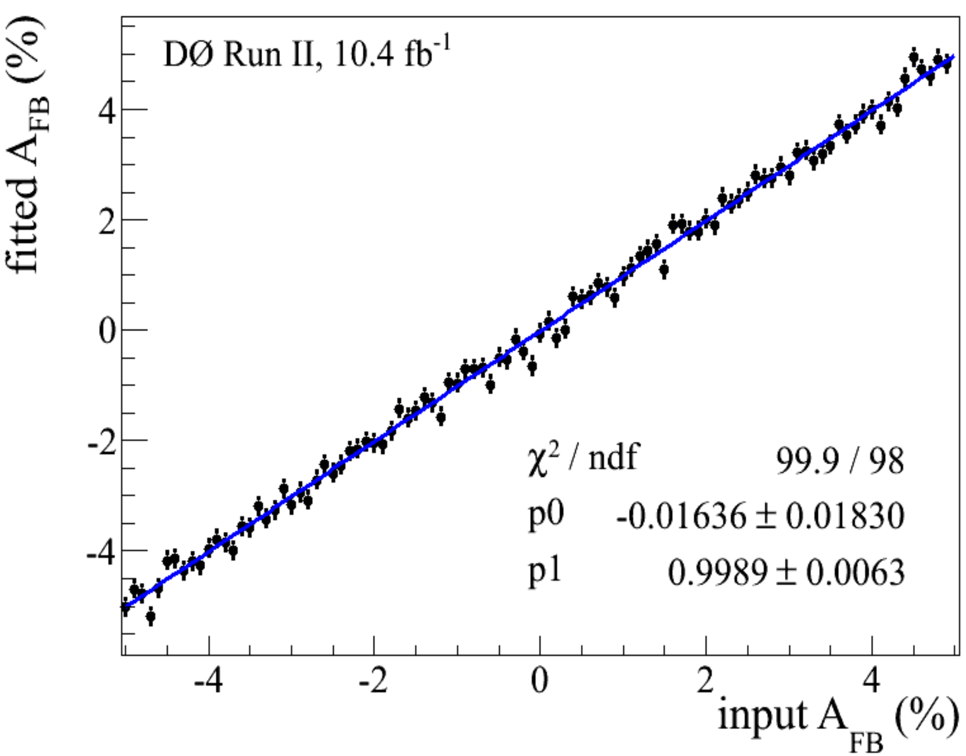
Maximum Likelihood Fit

- Until the analysis methods were approved, asymmetries were blinded by randomizing sign(η) of the $B^{\pm}$

- Statistical uncertainty from the fit is 0.41%, confirmed with an ensemble of 1000 trials

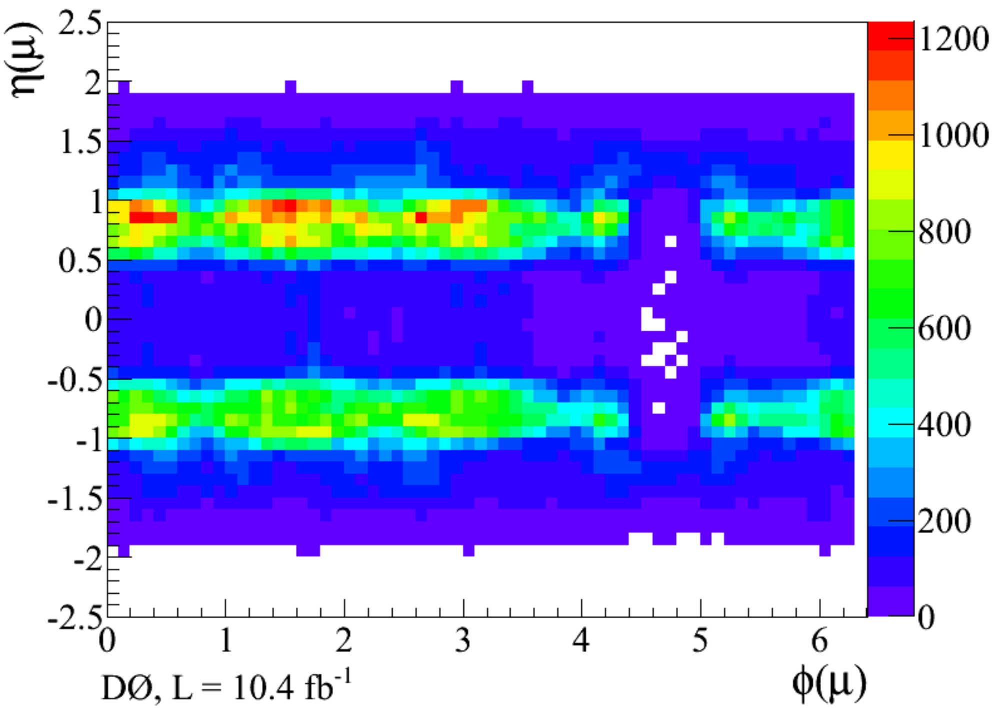
- Performance of the algorithm is tested by injecting asymmetries and comparing with fit results

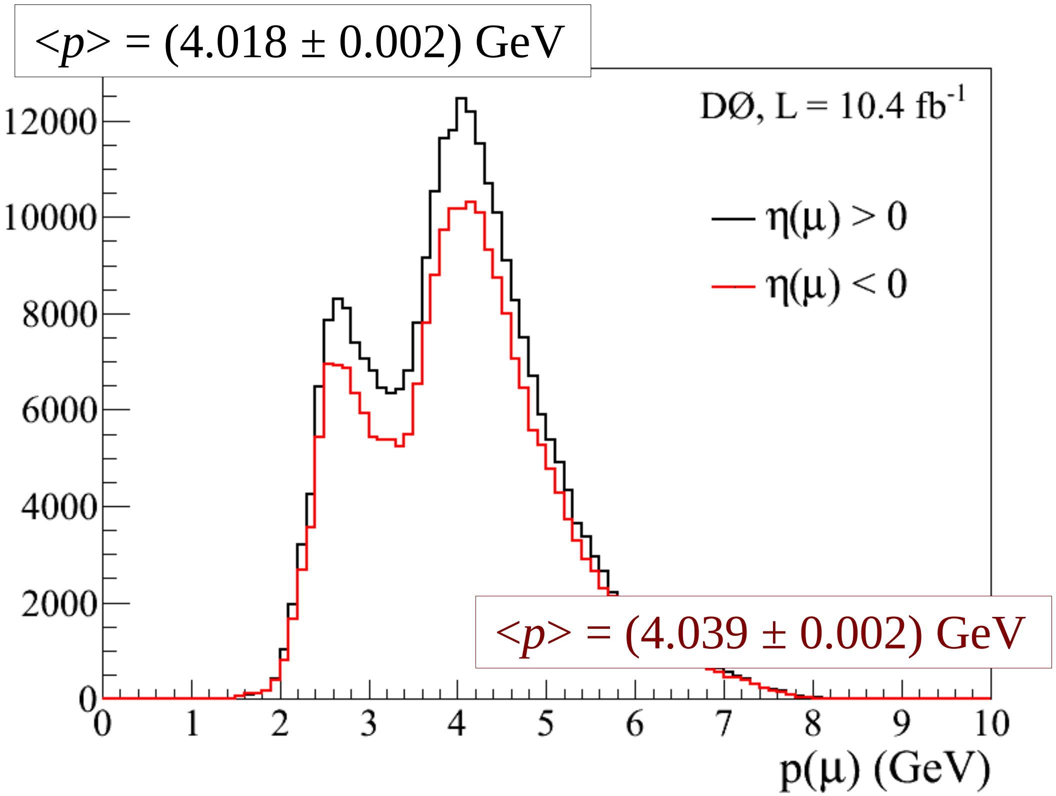




Reconstruction Asymmetries

- Large negative asymmetries at low momentum appear to be caused by extraneous detector material asymmetries (cable bunches, etc)
- Excess of low p_T muons on the south side, and that side has lower average p → momentum threshold is higher on the north side





Reconstruction Asymmetries

- Standard method:
- A(physics) = A(raw) – A(reco)
  - 1st order simplification of multiplying efficiencies
  - A(reco) calculated from a weighted average over A_{NS} bins:

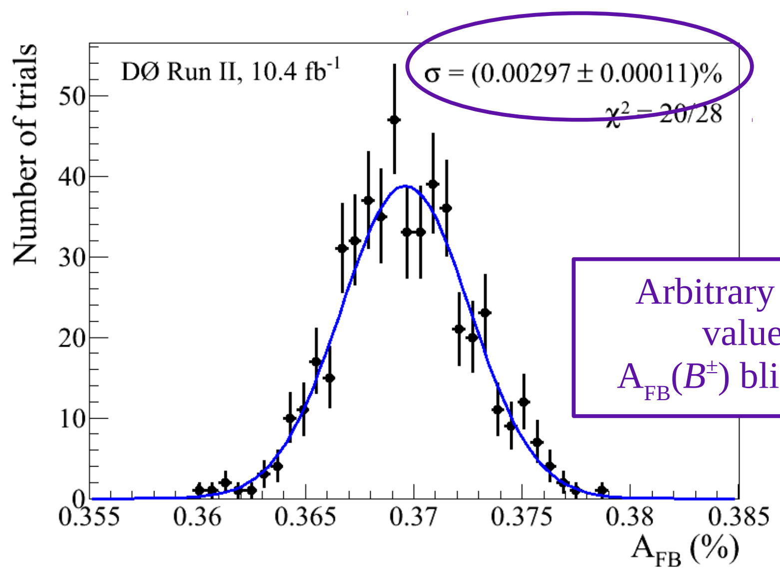
$$A_{\mathrm{FB}}(\mathrm{reco}) = \frac{1}{N}\sum_{\mathrm{bins}} n_i A_i$$

- Cross-check → A(reco) agrees with new weight method
- Uncertainty: ~0.13%
  - Directly from A_{NS} errors in A(reco)

- Our method: weight so $\varepsilon_{\eta<0} = \varepsilon_{\eta>0}$:

$$w_{\mathrm{north}} = \frac{1 - A_{NS}}{1 + A_{NS}}$$

- Event kinematics determine the bin of $A_{NS}(J/\psi)$ and $A_{NS}(K^{\pm})$
- Uncertainty: 0.003%
  - Ensemble of Gaussian variations to A_{NS}



Arbitrary mean value from $A_{FB}(B^{\pm})$ blinding

Extraction of $A_{FB}(B^{\pm})$

- Result is stable over time and with B^+/B^- fitted separately
- Background asymmetries also consistent with zero
- $A_{FB}(B^{\pm})$ = [-0.24 ± 0.41(stat) ± **0.19(syst)**]%

- Trained with different background samples or variables
- Mass range, E_K dependences, float/fix specific parameters
- Alternate fits, cuts, bins, etc
- Test of injecting asymmetries into blinded data

TABLE I: Summary of uncertainties on $A_{\mathrm{FB}}(B^{\pm})$ in data.

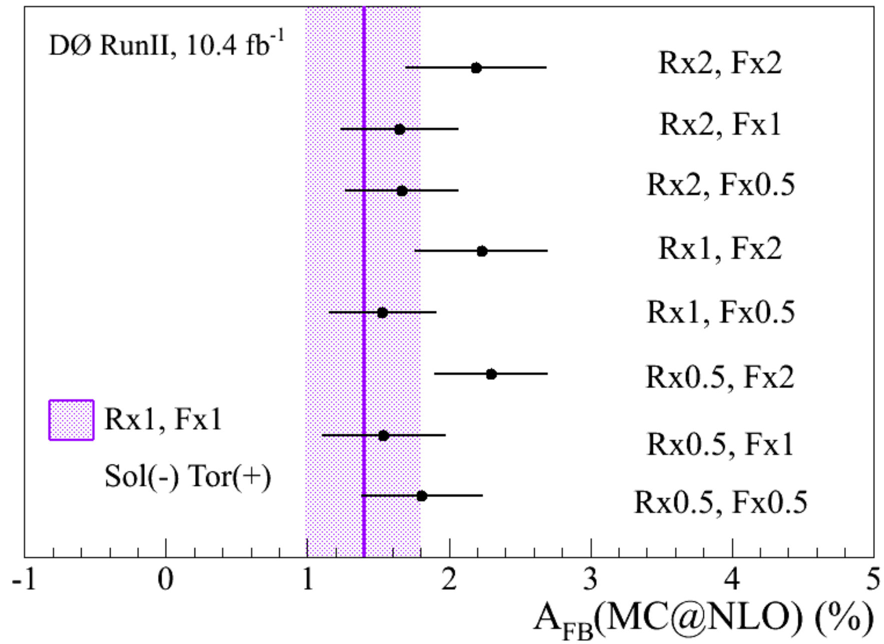
Source	Uncertainty
Statistical	0.41%
Alternative BDTs and cuts	0.17%
Fit Variations	0.06%
Reconstruction Asymmetries	0.05%
Fit Bias	0.02%
Systematic Uncertainty	0.19%
Total Uncertainty	0.45%

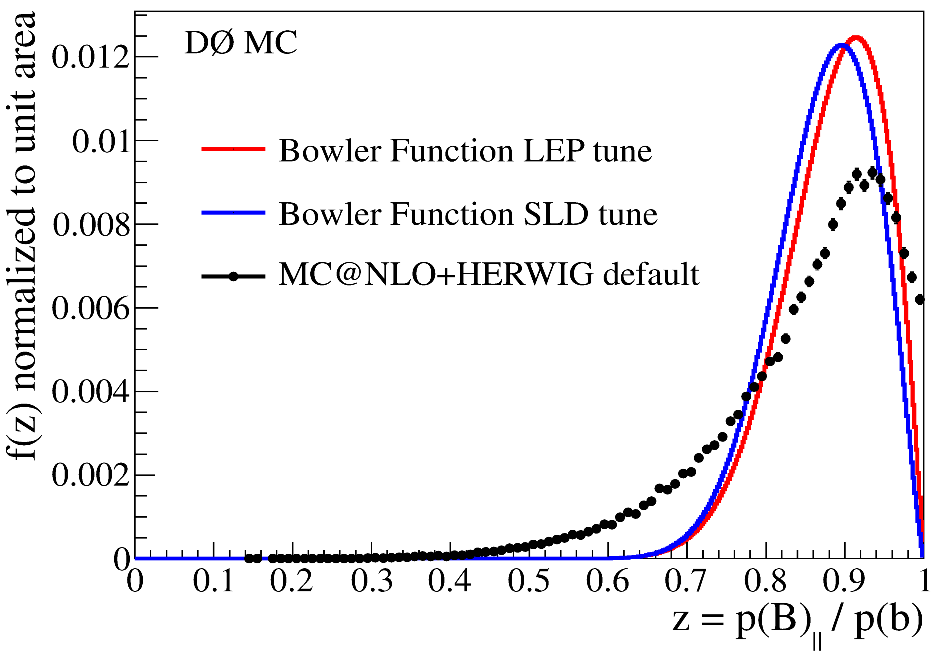
$A_{FB}(B^{\pm})$ Estimate from MC

- Energy scale choice: 0.44%

$$\mu_0 = \sqrt{\frac{1}{2}\left[2m^2(b) + p_T^2(b) + p_T^2(\bar{b})\right]}$$

  - Vary renormalization and factorization scales from $\mu_0/2$ to $2\mu_0$
  - Compared to default magnet polarity: $A_{FB}(B^{\pm}) = (1.39 + 0.40)\%$





- Fragmentation function: 0.25%
  - Weight $z = p(B)_{\parallel} / p(b)$ to match LEP or SLD tuned Bowler function

$$f_B(z) \propto \frac{1}{z^{1+bm_q^2}}(1-z)^a \exp(-bm_T^2/z)$$