CP violation in B hadrons at the Tevatron

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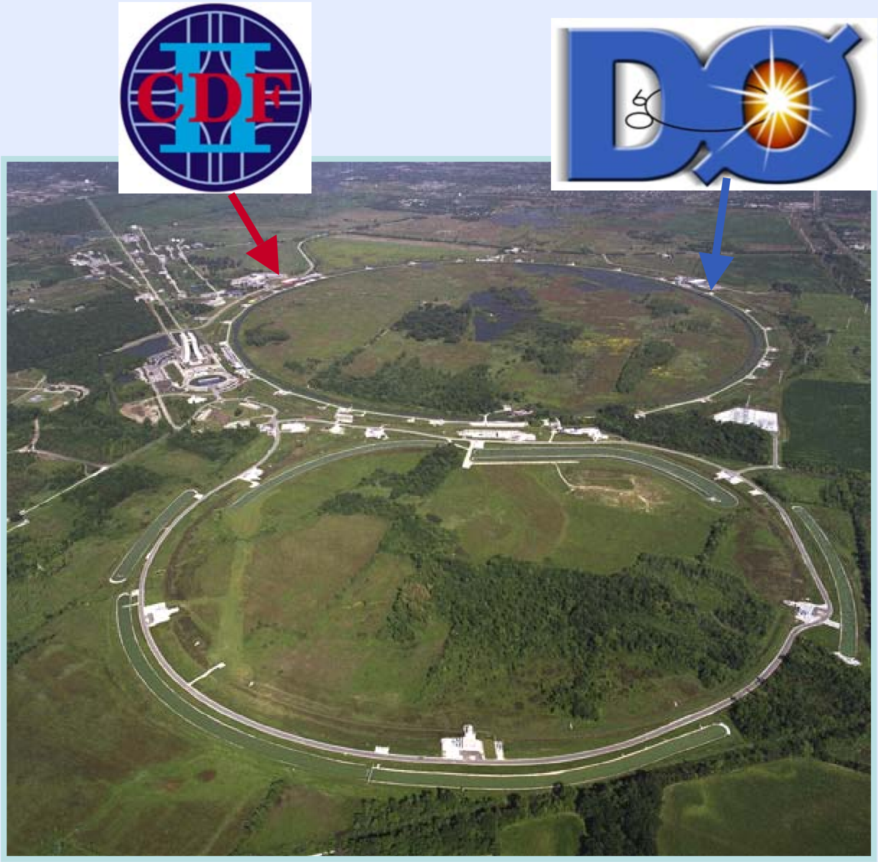
Overview

- CDF and DØ detectors at Fermilab
- *CP* violation in B_s decays
  - Neutral B_s system
  - Mixing induced *CP* violation
  - Phenomenology
  - Fit results
  - Combined results for *CP* violating parameter β_s
  - Preview of coming updates:
    - B flavour tagging improvements
    - inclusion of $B_s \rightarrow J/\psi$ KK (S-wave)
    - PID extension
- Summary



The Fermilab Tevatron

CP violation in neutral B_s system

Flavour eigenstates:

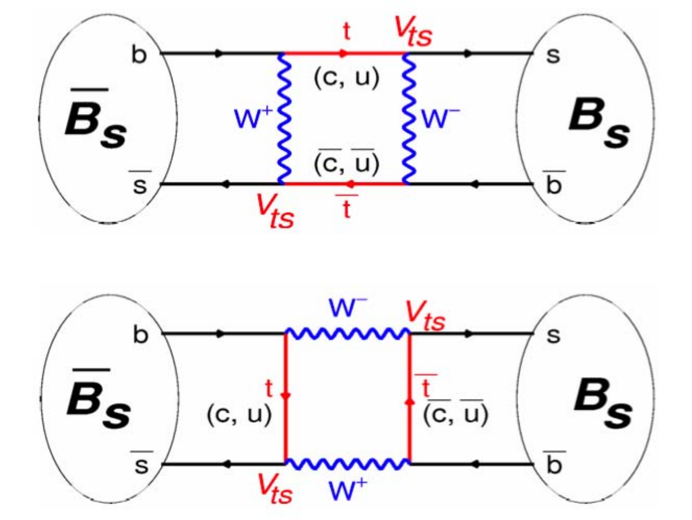
$$|B_s^0\rangle = (\bar{b}s)$$
$$|\bar{B}_s^0\rangle = (b\bar{s})$$

Mixing of flavour eigenstates is governed by:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = H \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} \equiv \Bigg[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2} \underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}} \Bigg] \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$

Flavour eigenstates are not mass eigenstates:

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle$$
$$|B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$



Different masses -> mixing frequency: $\Delta m_s = m_H - m_L \approx 2|M_{12}|$

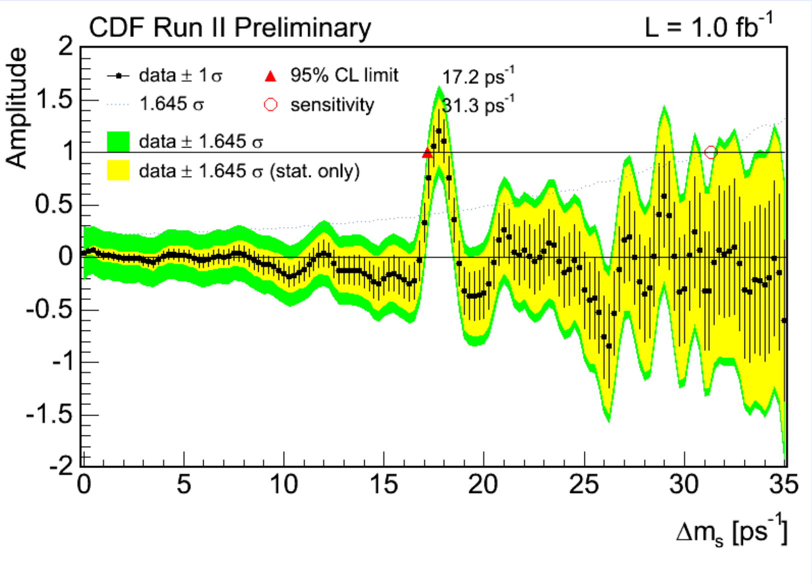
-> phase: $\varphi_s^{SM} = \arg(-M_{12}/\Gamma_{12}) \sim 0.04$

Different decay widths: $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}| \cos(2\varphi_s^{SM})$

CP violation in $B_s \rightarrow J/\psi\phi$

Δm_s is already well determined by Tevatron measurements

CDF



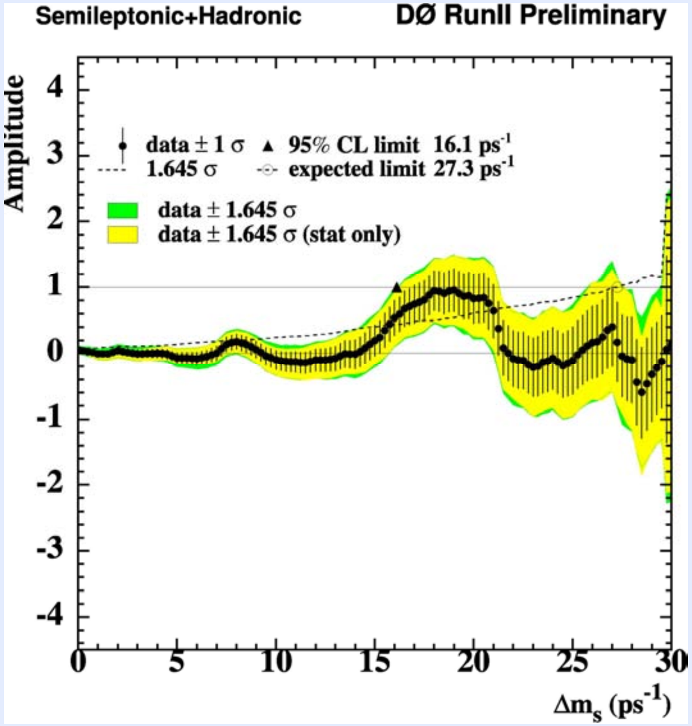
5σ observation

$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{stat}) ps^{-1}$$

DØ

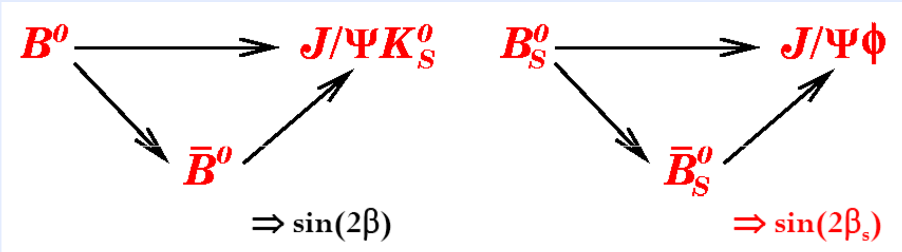
3σ evidence - in agreement with CDF

$$\Delta m_s = 18.52 \pm 0.91 ps^{-1}$$

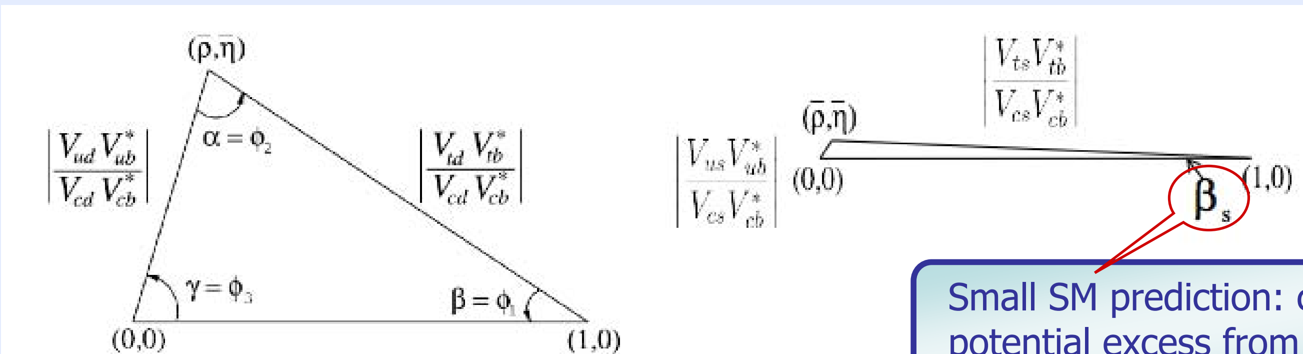


However, CP violation phase is not precisely known…

both are needed to constrain New Physics



CP violation in $B_s \rightarrow J/\psi\varphi$ occurs through interference of decays with and without mixing.



Small SM prediction: clear to see potential excess from NP

$$\beta_s = \beta' \equiv \arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right)$$

A New Physics effect would contribute to both the phases φ_s and β_s by introducing a new physics phase:

$$\varphi_s = \varphi_s^{SM} + \varphi_s^{NP} \text{ and } 2\beta_s = 2\beta_s^{SM} - \varphi_s^{NP}$$

So, if NP phase dominates we measure $2\beta_s \approx -\varphi_s \approx \varphi_s^{NP}$

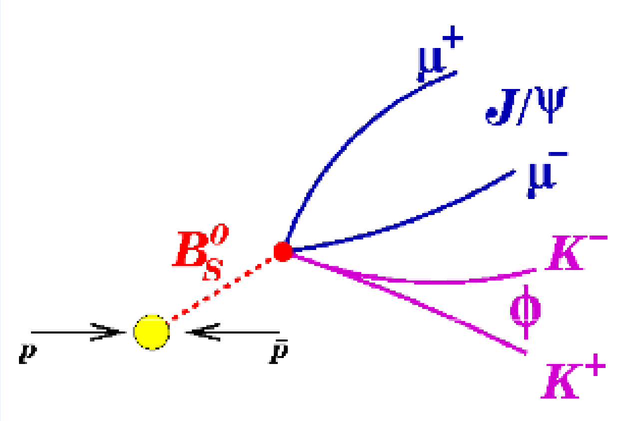
Can measure this in the CP asymmetry:

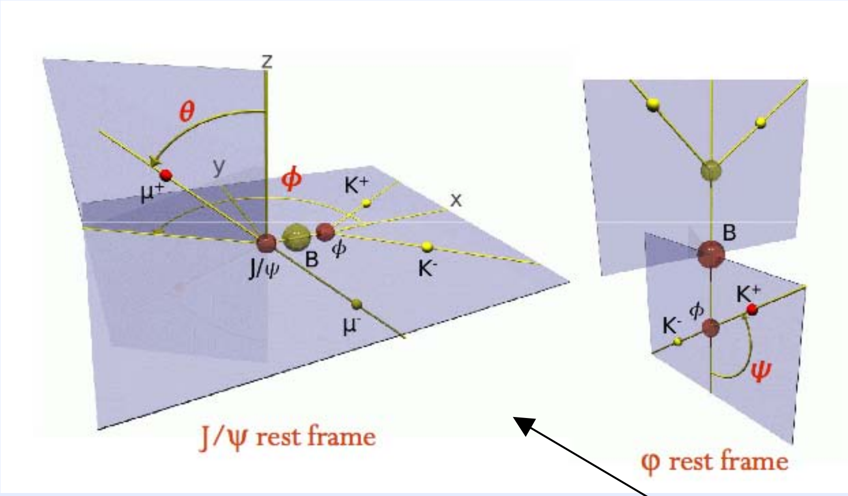
$$\mathcal{A}_{CP}(t) \equiv \frac{\bar{B}^0_s(t) - B^0_s(t)}{\bar{B}^0_s(t) + B^0_s(t)} = \sin(2\beta_s)\cdot\sin\Delta m_s t$$

$B_s \to J/\psi\phi$: experimental strategy

Reconstruct $B_s \to J/\psi(\to\mu^+\mu^-)\ \phi(\to K^+K^-)$

Final state is a mixture of CP even (~75%) and odd (~25%) states.





Three angular momentum states of J/ψ phi:

L=0	S-wave	**CP even**
L=1	P-wave	**CP odd**
L=2	D-wave	**CP even**

Can separate final CP states using angular analysis

Transversity basis describes these contributions as: A_0, $A_{//}$ (CP even), $A_{perp\ (CP\ odd)}$ according to their polarisation.

Can be separated using the angular distributions of the final state particles

Fit function

Use a multivariate fit combining angular analysis and time dependence

- Simplest case, fit without flavour tagging, has four fold ambiguity:
  - β_s and $\Delta\Gamma$ symmetric about zero
  - strong phases symmetric about pi

$$\phi_{\parallel} \equiv |A_{\parallel}^* A_0|$$
$$\phi_{\perp} \equiv |A_{\perp}^* A_0|$$

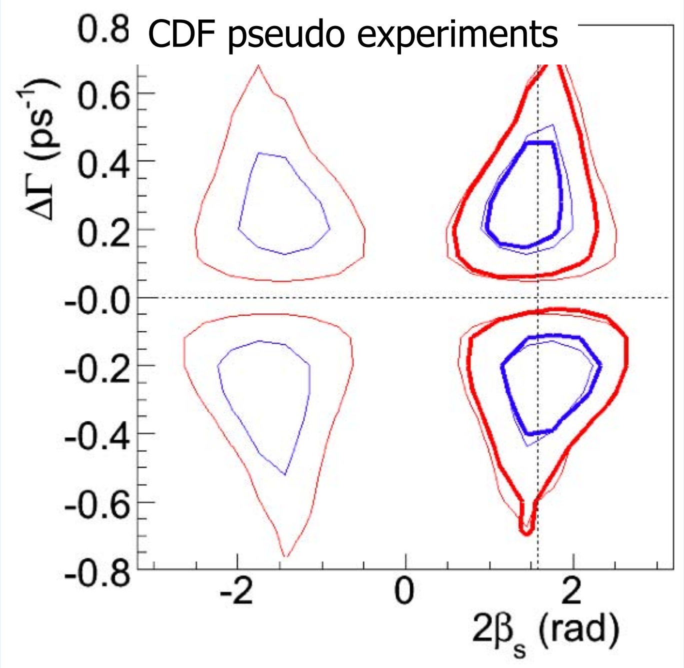
$$\begin{array}{lcl} \beta_s & \rightarrow & \frac{\pi}{2} - \beta_s \\ \Delta\Gamma & \rightarrow & -\Delta\Gamma \\ \phi_{\parallel} & \rightarrow & 2\pi - \phi_{\parallel} \\ \phi_{\perp} & \rightarrow & \pi - \phi_{\perp} \end{array}$$

- Addition of flavour tagging allows us to follow time dependence of B_s and $\overline{B}_s$ separately
- Removes insensitivity to sign of $\Delta\Gamma$ and β_s

  -> Removes half of the ambiguity

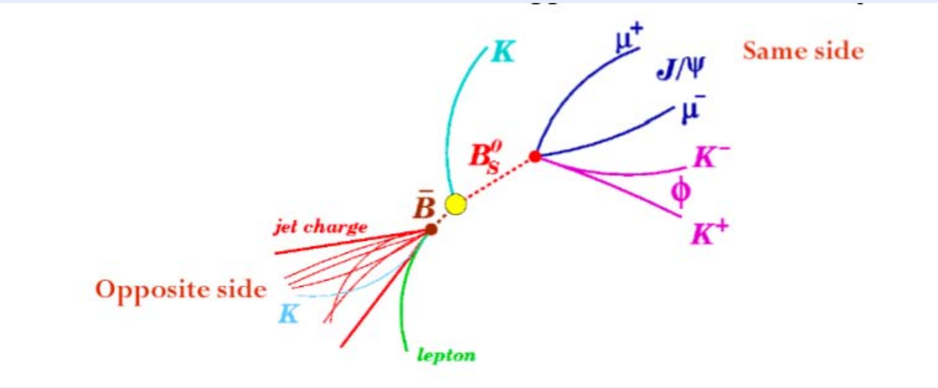
Plot shows CDF pseudo experiments

95% CL tagged fit
68% CL tagged fit
95% CL untagged fit
68% CL untagged fit



B flavour tagging

- Opposite side tag (OST):
  - b quarks are pair produced (flavour conservation)
  - Can deduce properties of the candidate B meson by looking at the decay of the B hadron formed by the pair produced partner of its b quark
- Same side kaon tag (SSKT):
  - Sign of kaon from primary vertex of candidate B_s can tag B_s flavour

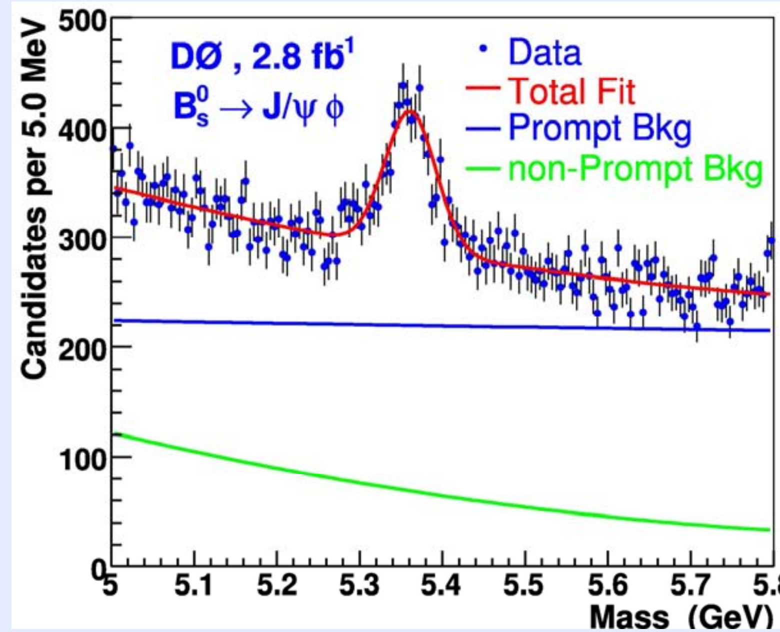


- CDF 2.8fb^{-1} result does not exploit SSKT beyond 1.4fb^{-1}
- Updated SSKT now validated and will be included in upcoming result
  - Significant improvement in tagging power
  - Reduces statistical errors of β_s - $\Delta\Gamma$ contours

CP violation in $B_s \rightarrow J/\psi\phi$:

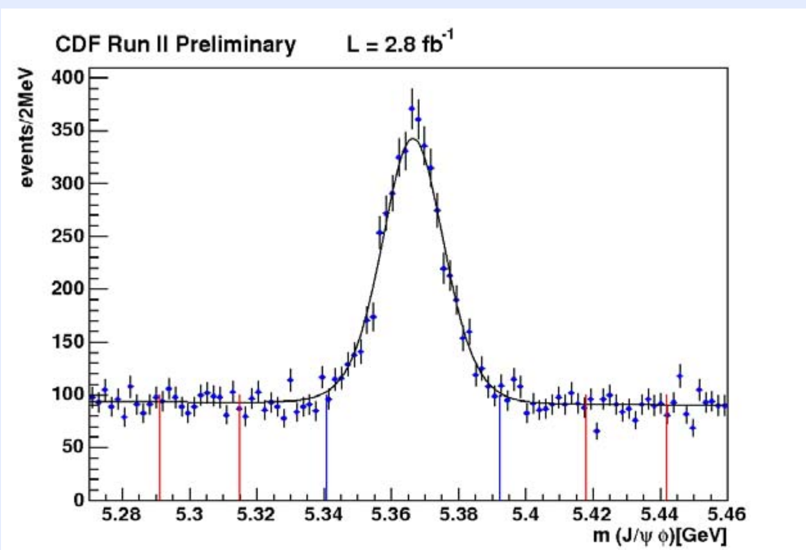
- *CDF and DØ results $L=2.8fb^{-1}$*
- *Tevatron combination*

Data sample and selection



DØ

- Dimuon trigger
- Cut based selection
- Signal events: 1967 ± 65
- Luminosity: 2.8fb^{-1}



CDF

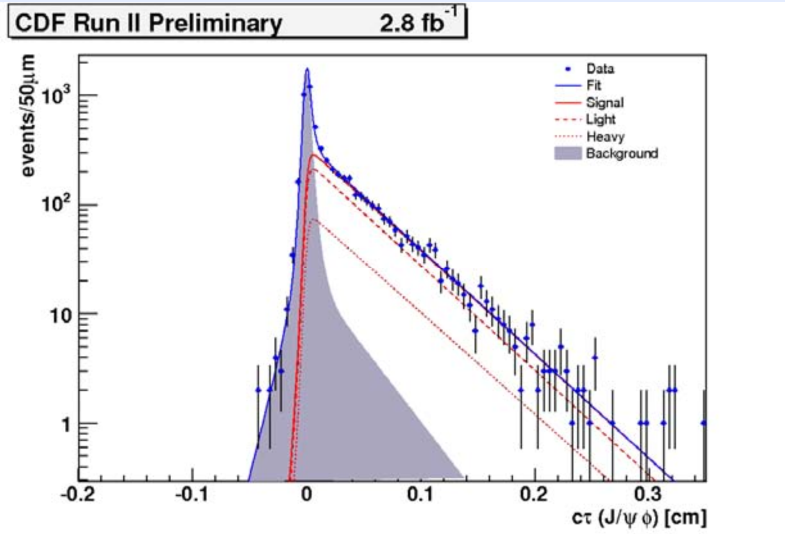
- Dimuon trigger
- Neural network selection
- Signal events: 3153 ± 55
- Luminosity: 2.8fb^{-1}

Results with SM assumption

CDF L=2.8fb^{-1}

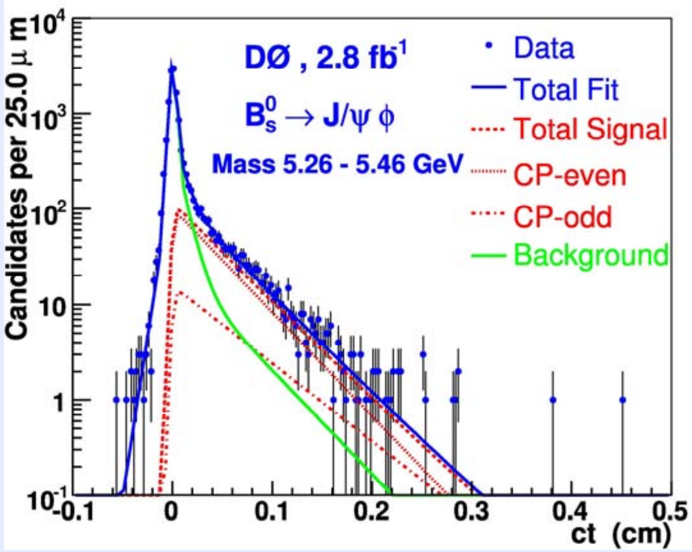
DØ L=2.8fb^{-1}

http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B58/



$$\tau_s = 1.53 \pm 0.04\ (\text{stat.}) \pm 0.01\ (\text{syst.}) ps$$
$$\Delta\Gamma = 0.02 \pm 0.05\ (\text{stat.})\ \pm 0.01\ (\text{syst.}) ps^{-1}$$
$$|A_\parallel|^2 = 0.241 \pm 0.019\ (\text{stat.}) \pm 0.007\ (\text{syst.})$$
$$|A_0|^2 = 0.508 \pm 0.024\ (\text{stat.}) \pm 0.008\ (\text{syst.})$$

$$\tau_s = 1.52 \pm 0.05\ (\text{stat.}) \pm 0.01\ (\text{syst.}) ps$$
$$\Delta\Gamma = 0.19 \pm 0.07\ (\text{stat.})\ ^{+0.02}_{-0.01}\ (\text{syst.}) ps^{-1}$$
$$|A_\parallel|^2 = 0.244 \pm 0.032\ (\text{stat.}) \pm 0.014\ (\text{syst.})$$
$$|A_0|^2 = 0.555 \pm 0.027\ (\text{stat.}) \pm 0.006\ (\text{syst.})$$



From untagged fit with $\beta_s = 0.0$

http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim

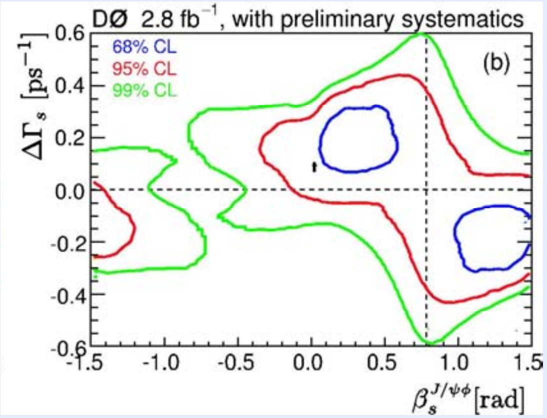
Combined CDF and DØ result $2.8 fb^{-1}$

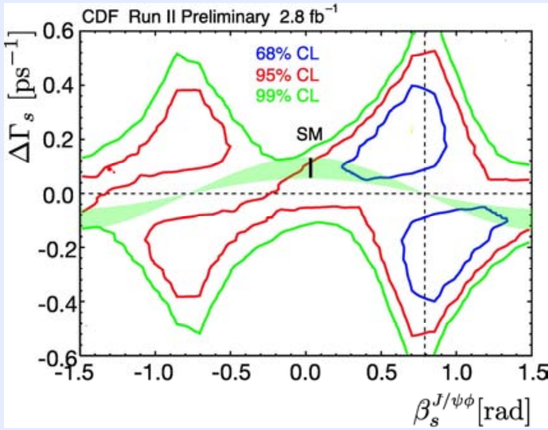
Cannot quote point value for β_s

- symmetries in likelihood
- non-Gaussian errors

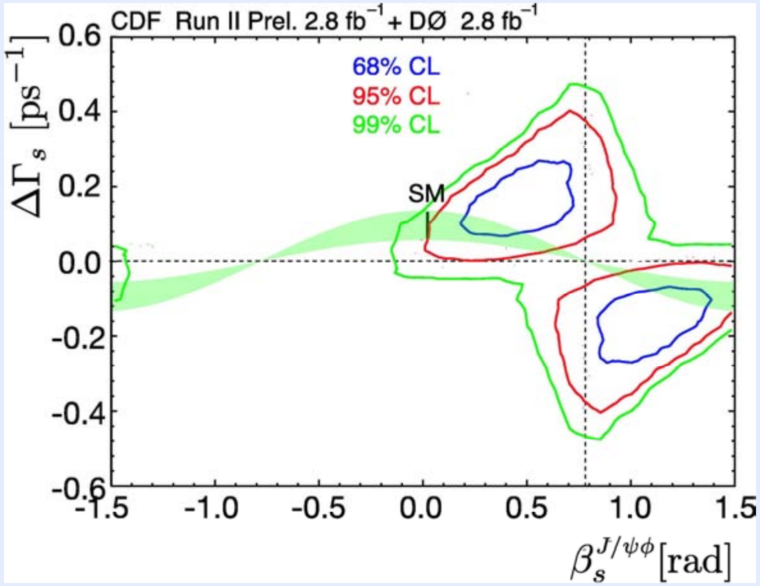
Show $\Delta\Gamma$-β_s likelihood contours

- errors adjusted by likelihood ratio ordering technique





DØ: $2.8fb^{-1}$ result
significance 1.7σ of deviation from SM



CDF: $2.8fb^{-1}$ result
P-value for SM point =7%
-> significance 1.8σ

Tevatron combination: probability of observed deviation from SM = 3.4% ($2.12\ \sigma$)

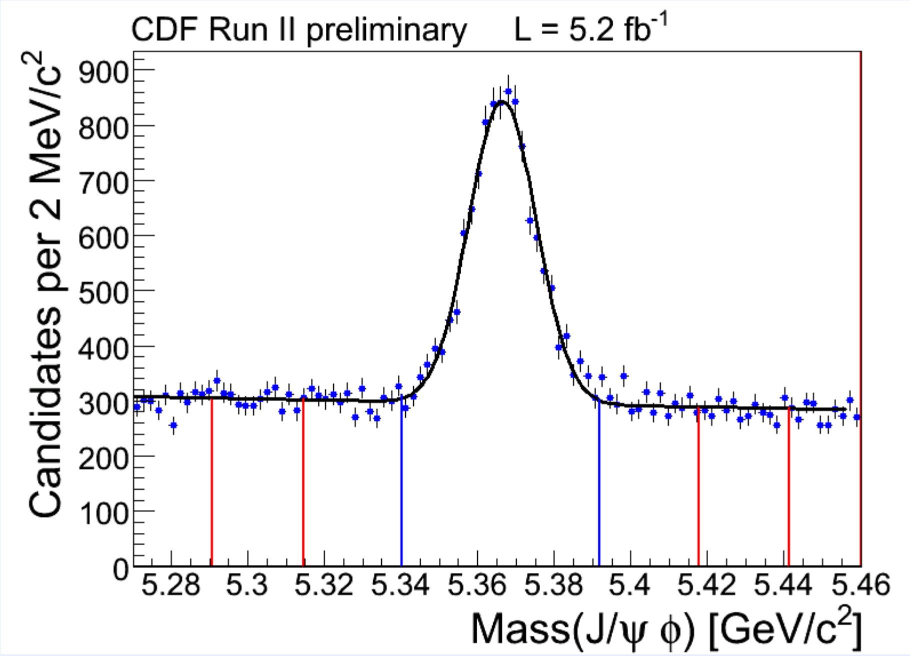
http://tevbwg.fnal.gov/results/Summer2009_betas/

Coming upgrades to β_s measurements

Coming soon!

DØ:

- Update to $L=6.1fb^{-1}$ from previous $2.8fb^{-1}$ result
- Will use boosted decision tree selection to improve signal to background ratio



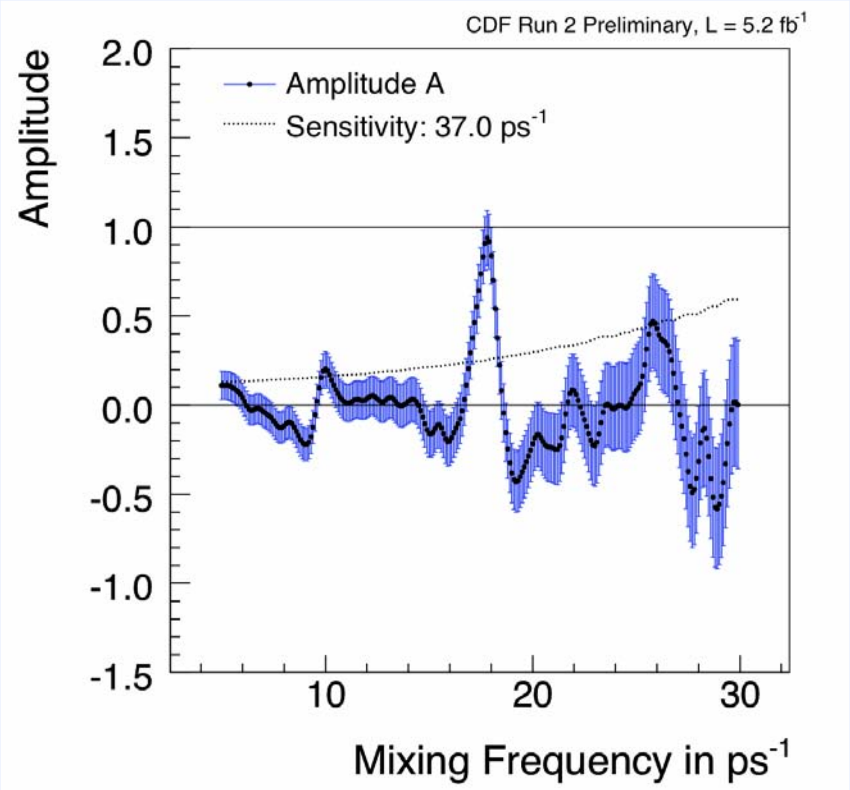
CDF:

- Update to $L=5.2fb^{-1}$
- Inclusion of PID for full dataset
  - previous update lacked PID after $1.4fb^{-1}$
  - dE/dx and TOF calibrated and extended
- Improved flavour tagging: addition of same side tag
- Account for $B_s \to J/\psi$ KK S-wave

SSKT calibration

- SSKT is calibrated on B_s mixing measurement
- Mixing amplitude ≈1 :
  - tagger assesses its performance accurately
- Amplitude > 1
  - tagger underestimates its power
- Amplitude < 1
  - tagger overestimates performance
- Uses several decay modes:

$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to \phi^0 \pi^-,\ \phi^0 \to K^+ K^-$$
$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to K^* K^-,\ K^* \to K^+ \pi^-$$
$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to (3\pi)^-$$
$$B_s^0 \to D_s^- (3\pi)^+,\ D_s^- \to \phi^0 \pi^-,\ \phi^0 \to K^+ K^-$$



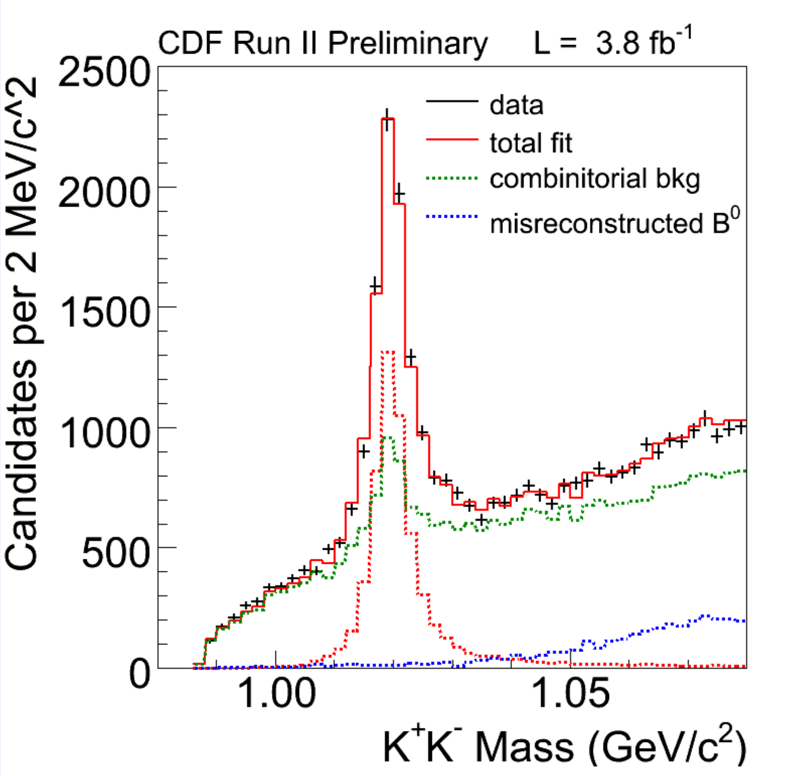
$$\mathcal{A} = 0.94 \pm 0.15\ (\text{stat.}) \pm 0.13\ (\text{syst.})$$

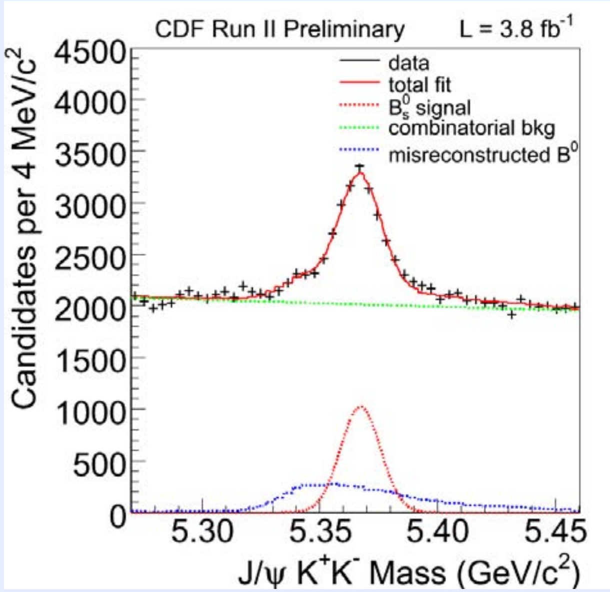
$$\Delta m_s = 17.79 \pm 0.07\ ps^{-1}$$
$$\epsilon \mathcal{A}^2 D^2 \approx 3.2 \pm 1.4\ \%$$

Agreement between this and the published CDF measurement is very good

Inclusion of $B_s \rightarrow J/\psi KK$

- Potential contamination of B_s signal by S-wave: B_s->J/ψ KK (KK non-resonant) and B_s->J/ψ f^0
- Predicted up to 10-15% contamination could bias towards SM value of β_s
- Next CDF update will include non-resonant component in the likelihood





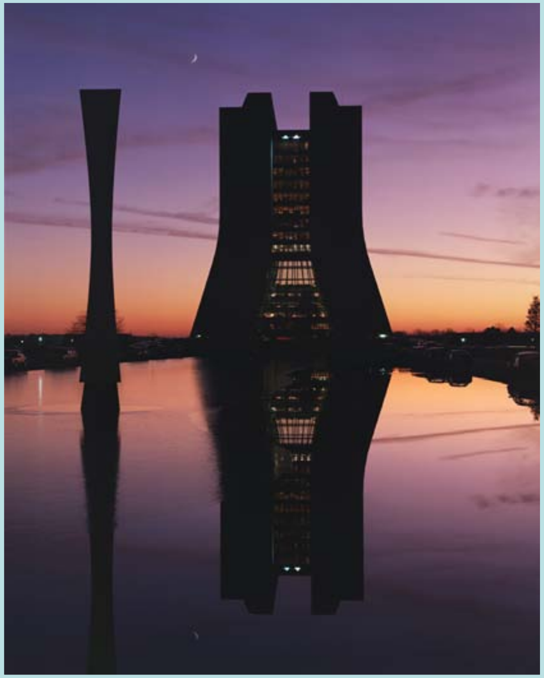
Invariant KK mass (above)

- combinatorial background from B_s sidebands
- B^0 reflections modelled from MC
- Fractions fixed from B_s mass fit (left)

-> little evidence from this distribution for additional component

Summary

- B_s system is rich source of information about *CP* violation, accessible to Tevatron experiments
- DØ and CDF produced precision measurements of B_s mixing frequency
- Both experiments have constrained *CP* violating phase β_s
  - More powerful result achieved from Tevatron combination
- Forthcoming updates from CDF and DØ to utilize full datasets doubling current statistics



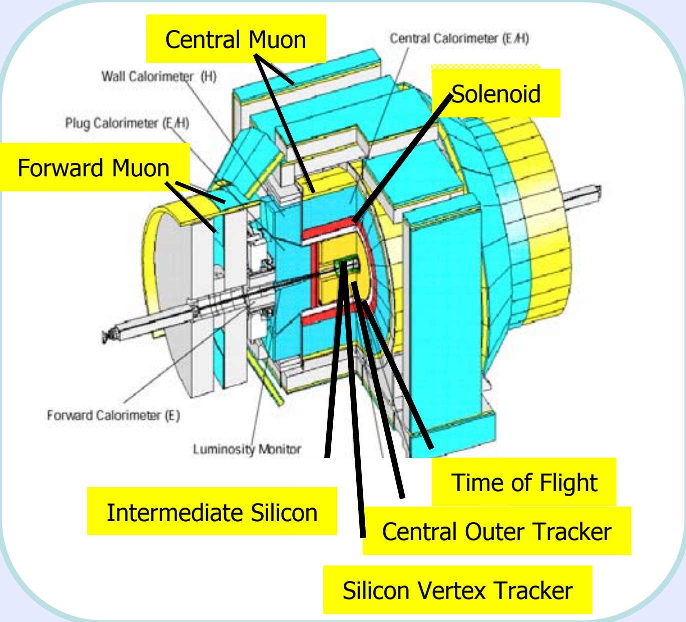
More news on this important measurement soon!

Back up

Detectors

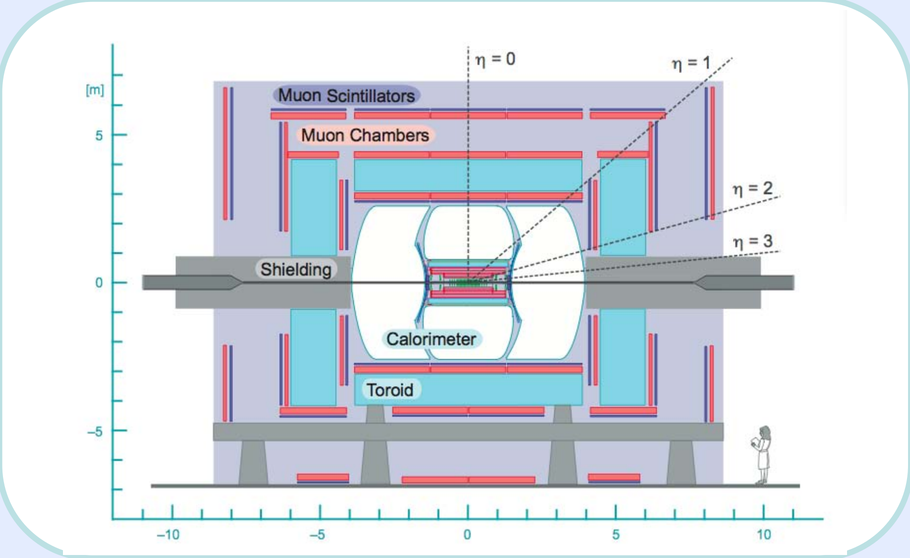
B physics at CDF:

- Particle ID: dE/dx and TOF
- Excellent vertex resolution ~23μm and p_T resolution: $\sigma(p_T)/p_T^2 \sim 0.1\ (\mathrm{GeV}/c)^{-1}$
- Trigger level silicon tracking



B physics at DØ:

- Solenoid (2TeV) polarity reversed weekly
- Strengths in semileptonic and J/ψ decays
- Excellent calorimetry and electron ID



Hadron colliders vs B factories:

\+ Much larger B production cross section, phase space, range of Bs generated
\- Higher background, don't know initial state
-> Larger signal for B_s at hadron machines but need sophisticated trigger and selection

Fit function

Use a multivariate fit combining angular analysis and time dependence

- Simplest case: fit without flavour tagging:

$$\mathcal{L}_i = f_s \cdot P_s(m) \cdot T(t,\psi,\theta,\phi) \cdot P_s(\sigma_t) + (1-f_s) \cdot P_b(m) \cdot P_b(t,\sigma_t) \cdot P_b(\sigma_t) \cdot P_b(\psi) \cdot P_b(\theta) \cdot P_b(\phi)$$

signal

background

mass terms — time dependence and angular terms — lifetime error terms

- Untagged likelihood has four fold ambiguity:
  - β_s and $\Delta\Gamma$ symmetric about zero
  - strong phases symmetric about pi

$$\phi_{\|} \equiv |A_{\|}^* A_0|$$
$$\phi_{\perp} \equiv |A_{\perp}^* A_0|$$

$$\beta' \rightarrow \frac{\pi}{2} - \beta', \quad \Delta\Gamma \rightarrow -\Delta\Gamma, \quad \phi_{\|} \rightarrow 2\pi - \phi_{\|}, \quad \phi_{\perp} \rightarrow \pi - \phi_{\perp}.$$

- Addition of flavour tagging allows us to follow time dependence of B_s and B_s separately
- Removes insensitivity to sign of $\Delta\Gamma$ and β_s

-> Removes half of the ambiguity

$$\mathcal{L}_i = f_s \cdot P_s(m) \cdot P_s(\xi) \cdot T(t,\psi,\theta,\phi,\mathcal{D},\xi) \cdot P_s(\sigma_t) \cdot P_s(\mathcal{D}) + (1-f_s) \cdot P_b(m) \cdot P_b(\xi) \cdot P_b(t,\sigma_t) \cdot P_b(\psi) \cdot P_b(\theta) \cdot P_b(\phi) \cdot P_b(\sigma_t) \cdot P_b(\mathcal{D})$$

terms altered or added by tag decision or tagging dilution

Coverage adjustment

Use same likelihood ratio ordering technique to account for non-Gaussian behaviour (to ensure we do not undercover the confidence regions) and to include effect of systematics on the errors:

- Generate pseudo experiments at the SM point in the $\Delta\Gamma$-β_s plane.
- Fit with all parameters floating
- Fit again with $\Delta\Gamma$ and β_s fixed to the SM point
- Form a likelihood ratio:

$$\mathcal{LR} = 2\log\frac{\mathcal{L}(\beta_s^{J/\psi\phi}, \Delta\Gamma, \vec{\xi})}{\mathcal{L}(\vec{\xi})}$$

- By integrating and normalising the distribution of likelihood ratios, and taking the log of this distribution, get the distribution (1-confidence level)
- This distribution can be used to adjust the likelihood to correspond to that expected from Gaussian errors, for a given confidence level.
- For systematic adjustment of the errors, pseudo experiments are generated for an ensemble of 16 “alternative universes”, for each the nuisance parameters are generated within +/- 5sigma of the measured value. The “universe” with the most extreme variations is used the adjustment at each point.

Transversity basis

Polarisation of vector mesons w.r.t direction of motion:

$|A_0|^2$: polarisation longitudinal, parallel

$|A_{//}|^2$: polarisation transverse, parallel

$|A_{perp}|^2$: polarisation transverse, perpendicular

We let the $A's$ be normalized such that $|A_0|^2 + |A_{\|}|^2 + |A_{\perp}|^2 = 1$.

The predicted angular distributions can be found from the following prescription Let $\hat{n}$ be the unit vector in the direction of the l^+ (J/ψ rest frame),

$$\hat{n} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta),$$

and let A be a complex vector defined as

$$\mathbf{A} = (A_0 \cos\psi, -\frac{A_{\|}\sin\psi}{\sqrt{2}}, i\frac{A_{\perp}\sin\psi}{\sqrt{2}}).$$

The angular distributions are governed by the probability density

$$P(\theta, \phi, \psi) = \frac{9}{16\pi}|\mathbf{A} \times \hat{n}|^2.$$

This is normalized such that

$$\int\int\int \frac{9}{16\pi}|\mathbf{A} \times \hat{n}|^2 \ \sin\theta d\theta \ d\phi \sin\psi \ d\psi = 1.$$