Constraining the CKM Matrix at Hadron Machines

- The CKM matrix
- CP violation in $B \to J/\psi K_S^0$
- Trigger on hadronic B decays at CDF
  - CP violation in $B^0 \to h^+ h^-$
  - The search for $B_s^0 \overline{B}_s^0$ mixing

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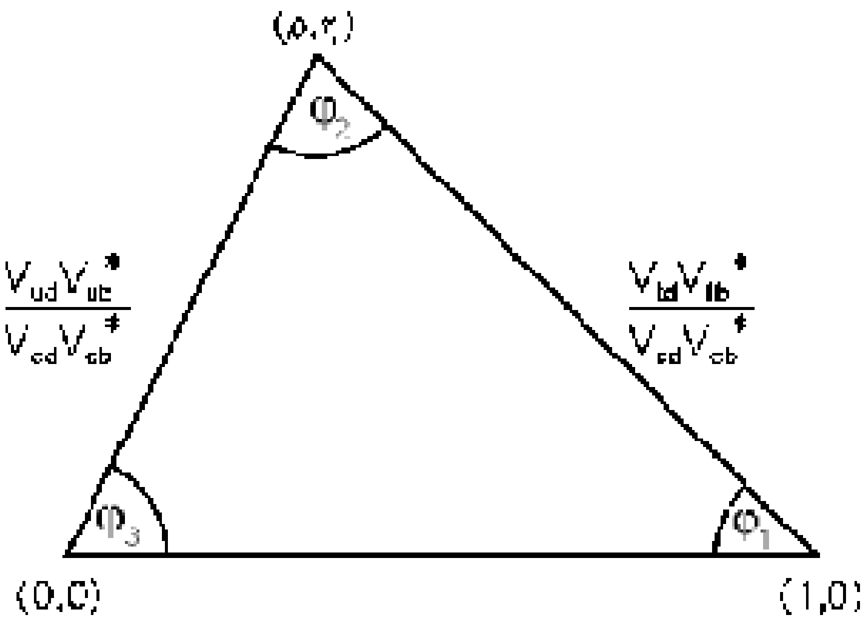
The CKM Triangle

Unitary CKM matrix governs weak decay of quarks

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



Wolfenstein parametrisation:

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitarity $\rightarrow V^\dagger V = 1$ gives:

$$V_{tb}^* V_{td} + V_{cb}^* V_{cd} + V_{ub}^* V_{ud} = 0$$

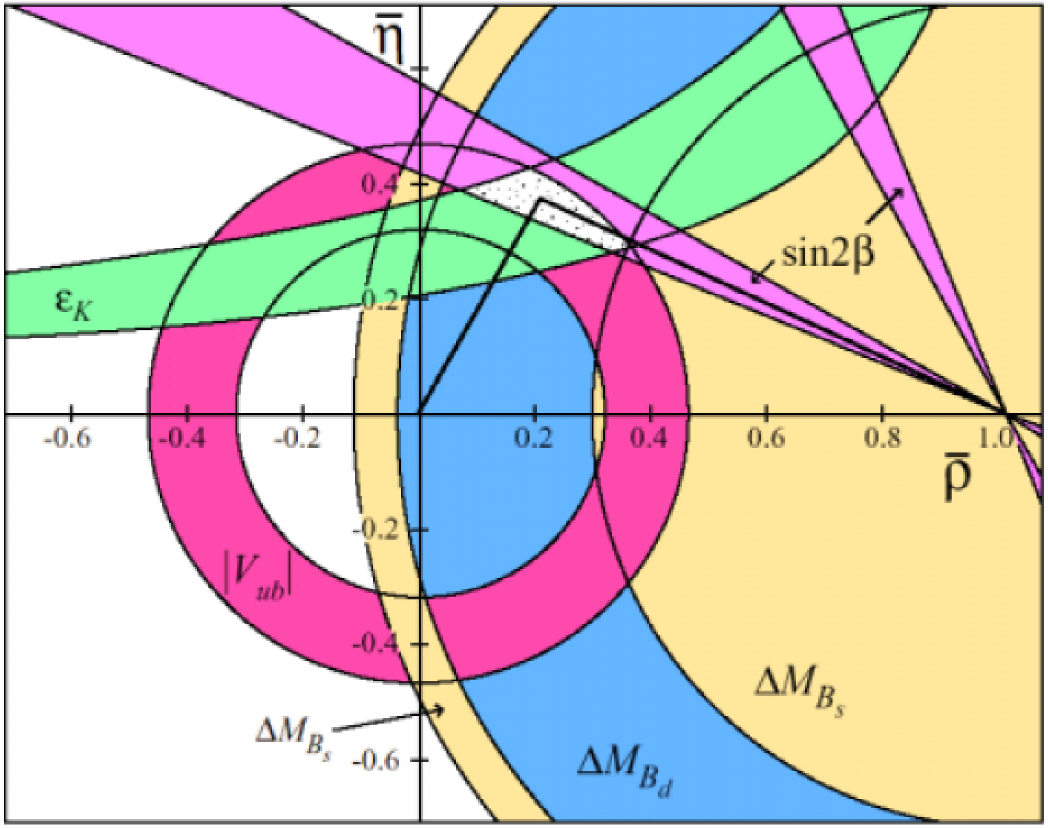
$$\phi_2 = \arg\left(\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \phi_1 = \arg\left(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\phi_3 = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

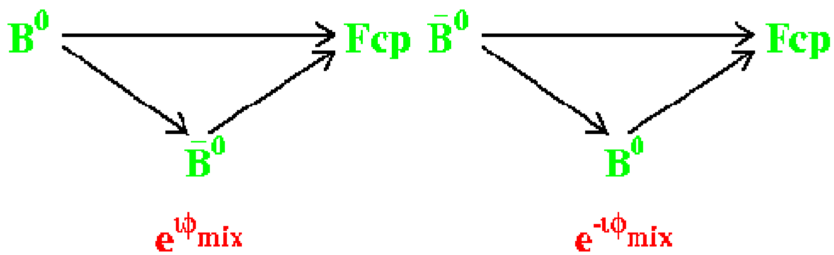
Constraining the Unitarity Triangle

- Three measurements discussed here

  1. CP asymmetry in $B^0 \to J/\psi K_S^0$ (ϕ_1)
  2. CP asymmetry in $B^0 \to h^+h^-$ (ϕ_2, ϕ_3)
  3. B_s^0 mixing ($\frac{|V_{td}|}{|V_{ts}|}$)



Indirect CP Violation

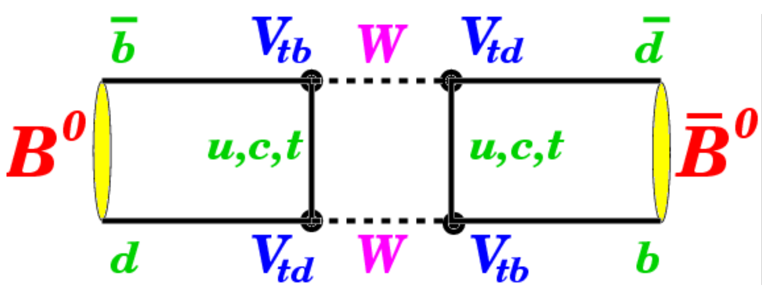


- Results in:

$$\frac{dN}{dt}(B^0 \rightarrow J/\psi K_S^0) \sim 1 - \sin\,2\phi_1 \sin\,\Delta m t$$

$$\frac{dN}{dt}(\overline{B}^0 \rightarrow J/\psi K_S^0) \sim 1 + \sin\,2\phi_1 \sin\,\Delta m t$$

- CP phase in CKM element V_{td}



- Tag B^0 flavour to see asymm.

$$A_{CP}^{obs} = \mathcal{D} A_{CP}$$

- $\mathcal{D}$ is the "tagging dilution"
  - $\mathcal{D} = (N_r - N_w)/(N_r + N_w)$
  - $N_r(N_w)$ are right/wrong tags
- Precision on $\sin\,2\phi_1$ given by

$$\delta \sin\,2\phi_1 \approx 0.47 \frac{1}{\sqrt{\varepsilon \mathcal{D}^2}} \sqrt{\frac{S+B}{S^2}}$$

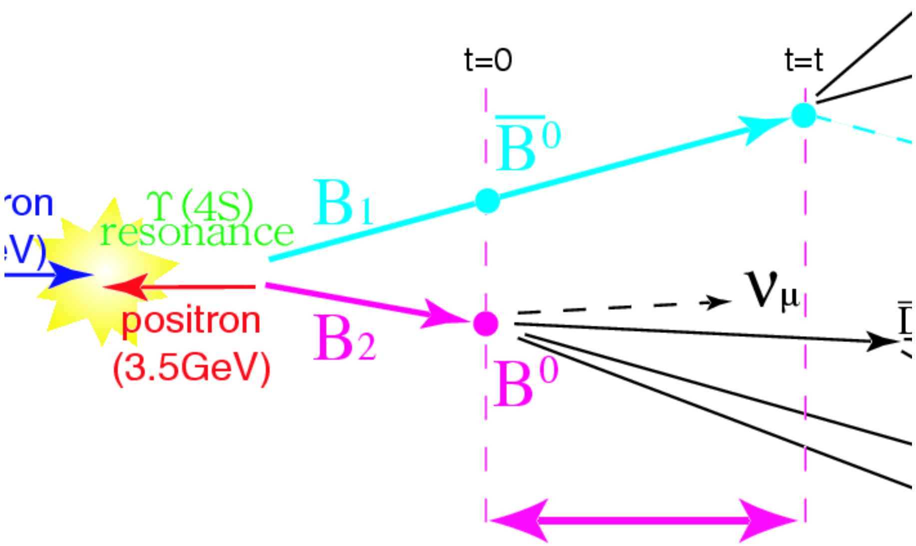
  - ε is tagged fraction
  - S is signal yield
  - B is background yield
- B^0 and $\overline{B}^0$ produced at equal rates develop asymmetry:

$$A_{CP}(t) = \frac{\frac{dN}{dt}(\overline{B}^0 \rightarrow J/\psi K_S^0) - \frac{dN}{dt}(B^0 \rightarrow J/\psi K_S^0)}{\frac{dN}{dt}(\overline{B}^0 \rightarrow J/\psi K_S^0) + \frac{dN}{dt}(B^0 \rightarrow J/\psi K_S^0)}$$

$$= \sin\,2\phi_1 \sin\,\Delta m t$$

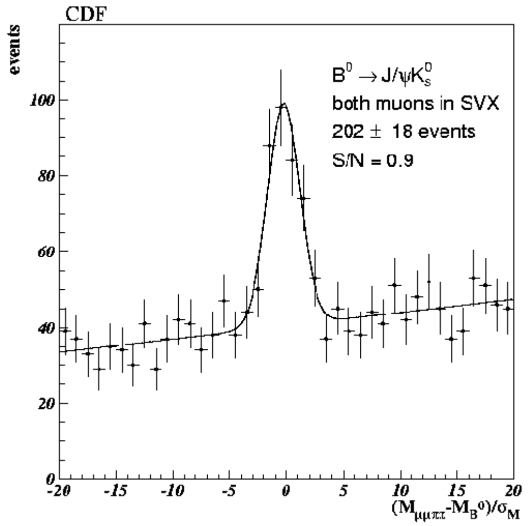
Experimental Environment Differences

- Production environment can be important
  - At hadron collider $b\bar{b}$ are not produced in coherent state
    - Time averaged asymmetry does not vanish
    - Time dependent measurement can improve precision
  - At B factory $B^0\overline{B}^0$ produced in coherent P-wave state
    - CP asymmetry builds after first B meson decays
    - Measure time dependence asymmetry to see CP asymmetry

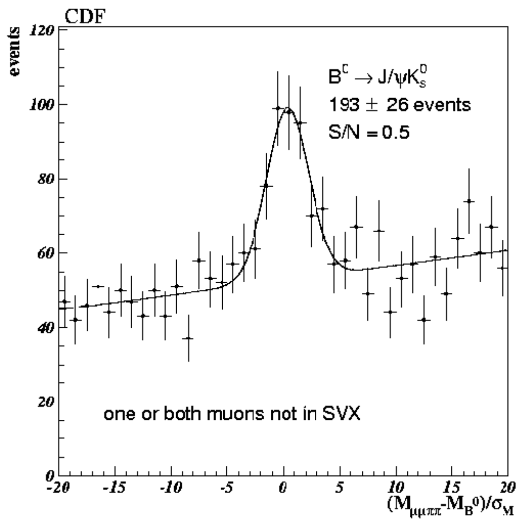


The CDF $J/\psi K_S^0$ Sample

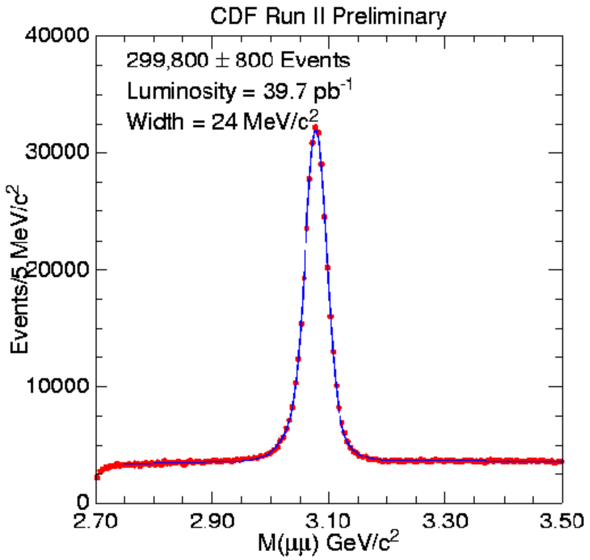
- CDF-I measurement:
  - Both J/ψ muons have silicon



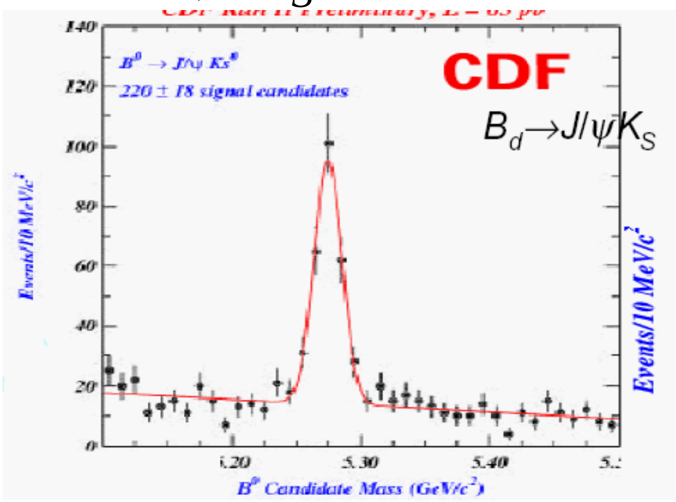
  - One J/ψ muon misses silicon



- CDF-II data sample is as big
  - 300000 J/ψ candidates

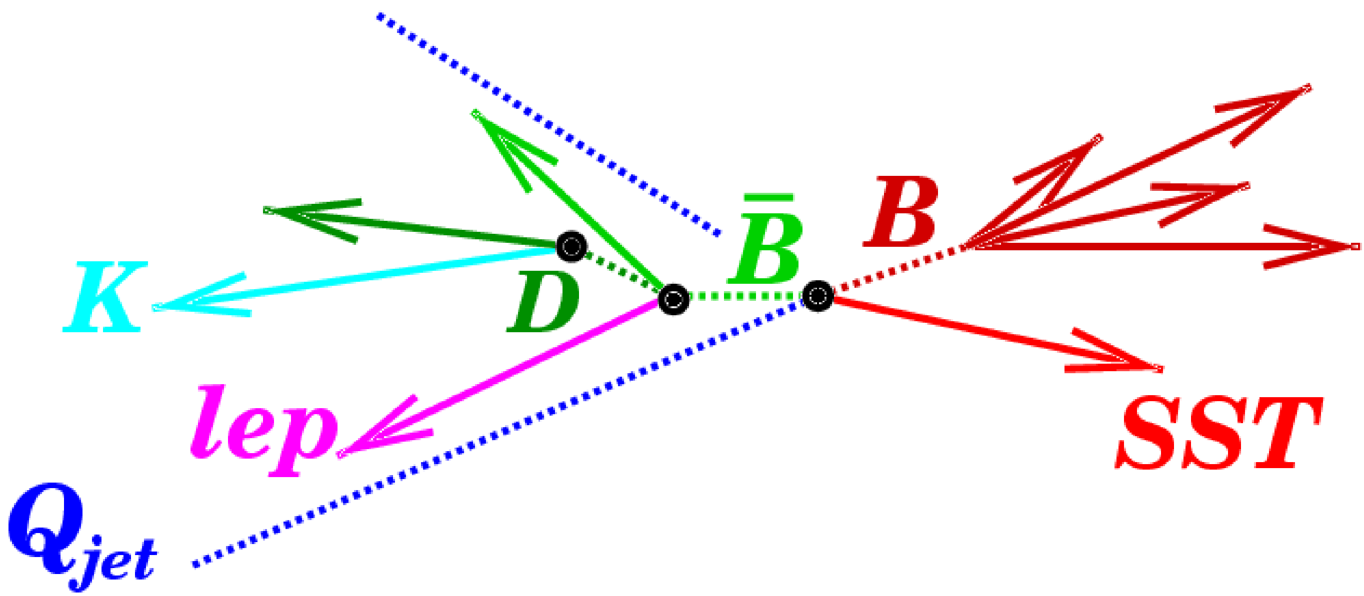


  - 220 $J/\psi K_S^0$ candidates



  - Focus on CDF-I measmt.

Flavour Tagging the b Quark



- Determine the flavour (B^0 vs $\bar{B}^0$) at time of production

  Opposite-Side Tagging

  - Charge of opposite-side jet (JETQ)
  - Soft e or μ tag from semi-leptonic decay of opposite B (SLT)

  Same-Side Tagging

  - Same-side SVX and non-SVX pion tagging (SST)

Jet Charge Tagging (JETQ)

- Opposite-side b quark can fragment into any B meson
- Identify flavour of b quark through charge of opposite jet
- Use a variant of *JADE* track cluster algorithm
  - optimised for low p_t jets
- Weight track charges by
  - transverse momentum
  - impact parameter ($T_i \approx 0$ for displaced tracks)

$$Q_{jet} = \frac{\Sigma q_i p_i (2 - T_i)}{\Sigma \ \ p_i (2 - T_i)}$$

- Tagging regions
  - $Q_{jet} > 0.2 \longrightarrow b$
  - $Q_{jet} < -0.2 \longrightarrow \bar{b}$
  - $|Q_{jet}| < 0.2 \longrightarrow$ **no tag**
- 40% of $J/\psi K_S^0$ have a JETQ tag

  $\mathcal{D} = 0.235 \pm 0.069$

  - Calibrate on $J/\psi K^{\pm}$ data

Soft Lepton Tagging (SLT)

- Identify flavour of opposite B hadron through $b \to l\nu X$ decay
- Semileptonic branching ratio leads to $\approx 6\%$ efficiency
- Electron selection
  - Central track ($p_t > 1$ GeV/c) matched to EM shower
- Muon selection
  - Central track ($p_t > 2$ GeV/c) matched to muon stub
- Calibrate this on $J/\psi K^{\pm}$ sample

$$\mathcal{D} = 0.625 \pm 0.146$$

Same Side Tagging (SST)

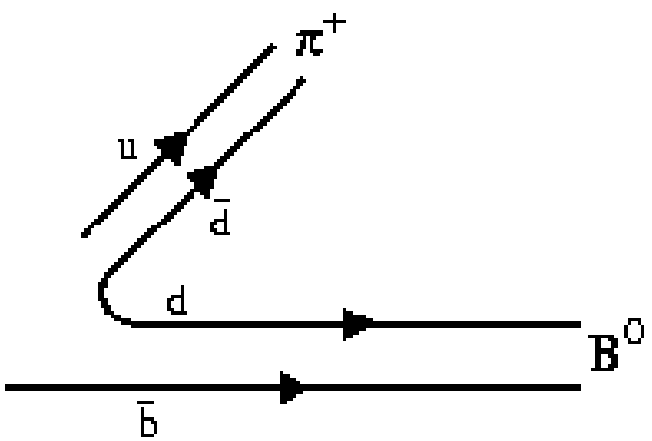
- Opposite tagging limited
  - Other b is central only 50% of the time
  - Other b is B^0 or B_s^0 it mixes
- Exploit correlated fragmentation on same side

- Use semi-leptonic B meson decays to calibrate SVX sample

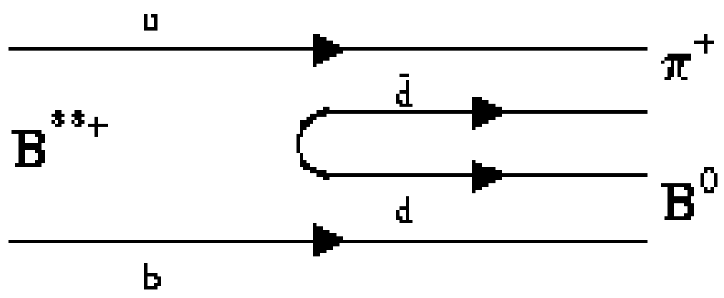
$$\mathcal{D} = 0.166 \pm 0.022$$

- Use $B^{\pm} \to J/\psi K^{\pm}$ sample to calibrate non-SVX sample

$$\mathcal{D} = 0.174 \pm 0.036$$



fragmentation



via B**

Summary of Flavour Tagging

Tagger	Events	efficiency (ε)	Dilution ($\mathcal{D}$)
SST	SVX	35.5 ± 3.7 %	16.6 ± 2.2 %
SST	non-SVX	38.1 ± 3.9 %	17.4 ± 3.6 %
SLT	all	5.6 ± 1.8 %	62.5 ± 14.6 %
JETQ	all	40.2 ± 3.9 %	23.5 ± 6.9 %

- All algorithms have similar statistical power:

Tagger	$\varepsilon\mathcal{D}^2$
SST	2.1 ± 0.5 %
SLT	2.2 ± 1.0 %
JETQ	2.2 ± 1.3 %

- Combine algorithms (with correlations) to give:

$$\varepsilon\mathcal{D}^2 = 6.3 \pm 1.7\%$$

- ~ 400 $J/\psi K_s^0$ events equivalent to $\sim$ 25 perfectly tagged events

Combining Different Taggers

- Example: SST ($\mathcal{D} = 16.6\%$) and JETQ ($\mathcal{D} = 23.5\ \%$)
  - If the taggers agree:

$$\mathcal{D}_{eff} = \frac{(\mathcal{D}_{\mathrm{SST}}+\mathcal{D}_{\mathrm{JETQ}})}{(1+\mathcal{D}_{\mathrm{SST}}\mathcal{D}_{\mathrm{JETQ}})} = \frac{(0.235+0.166)}{(1+0.235*0.166)} = 39\ \%$$

  - If the taggers disagree:

$$\mathcal{D}_{eff} = \frac{(\mathcal{D}_{\mathrm{SST}}-\mathcal{D}_{\mathrm{JETQ}})}{(1-\mathcal{D}_{\mathrm{SST}}\mathcal{D}_{\mathrm{JETQ}})} = \frac{(0.235-0.166)}{(1-0.235*0.166)} = 7\ \%$$

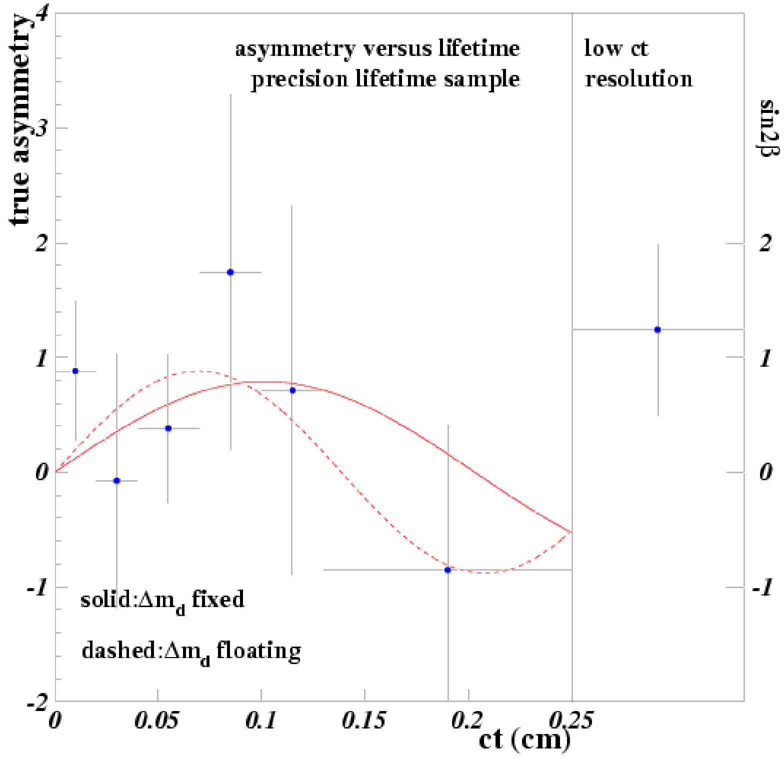
  - JETQ determines flavour

- Each event is weighted in the fit by its effective dilution
  - SLT has much higher dilution $\rightarrow$ over-rules others if present

Fitting $\sin 2\phi_1$

- Combine all information in maximum likelihood fit
- Allow for charge asymmetries in efficiencies and dilution
  - possible charge biases in tracking at low p_t
  - $K^{\pm}$ interaction rate differences
  - Charge asymmetric backgrounds (beampipe spallation)
- No significant asymmetries observed
- Likelihood function includes event-by-event probabilities for
  - Observed decay length
  - Reconstructed candidate mass
  - Efficiency and tagging probability
- Include constraints from other data ($B^+ \rightarrow J/\psi K^+$)
  - tagging efficiencies
  - dilutions
- Take external inputs for τ_{B^0}, Δm_d, m_B
  - Allow them to float within their errors

CDF's Current Measurement of $\sin 2\phi_1$



$$\sin\ 2\phi_1 = 0.91 \pm 0.37(stat. + sys.)$$

Effect	Evaluated	$\delta \sin\ 2\phi_1$
$\mathcal{D}$	in fit	0.18
Δm_d	in fit	0.01
τ_{B^0}	in fit	0.01
m_B	refit	0.01
charge bias	external	negligible
K_L^0 regen.	external	negligible

- Split off systematic uncertainty

$$\sin\ 2\phi_1 = 0.91 \pm 0.32(stat) \pm 0.18(syst)$$

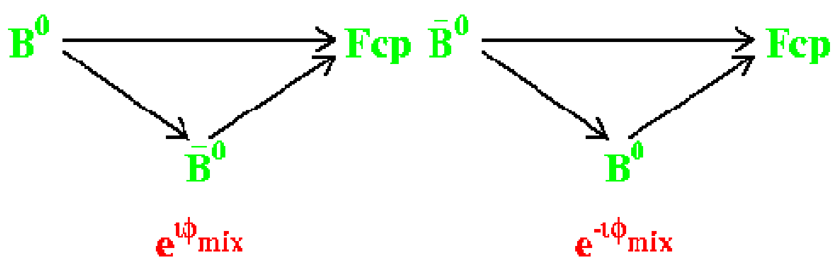
Improvements from Run II

- State of the art when published
  - CP violated at 90 % CL
- Superseded by B factories

Expt	$\sin 2\phi_1$
BaBar	$0.741 \pm 0.067(stat) \pm 0.034(sys)$
Belle	$0.719 \pm 0.074(stat) \pm 0.035(sys)$
CDF	$0.91 \pm 0.37(stat + sys)$

- Run II data gets us back in game
  - 1 fb^{-1} we expect to have
  - 4000 $J/\psi K^0_S$ candidates
  - $\delta \sin 2\phi_1 \approx \pm 0.09$ on
- Tagging improvements may be possible
  - Ultimate precision may be better
- Despite poorer flavour tagging hadron colliders
  - Remain competitive
  - Sample size 5x those of e^+e^- machines

The $B^0 \rightarrow \pi^+\pi^-$ Asymmetry



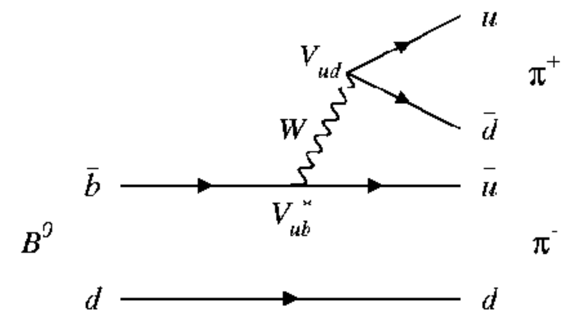
- More than one path $B^0 \rightarrow F_{\mathrm{CP}}$
  - Direct CP violation possible

$$A_{CP}(t) = \frac{\frac{dN}{dt}(\overline{B}^0 \rightarrow F_{\mathrm{CP}}) - \frac{dN}{dt}(B^0 \rightarrow F_{\mathrm{CP}})}{\frac{dN}{dt}(\overline{B}^0 \rightarrow F_{\mathrm{CP}}) + \frac{dN}{dt}(B^0 \rightarrow F_{\mathrm{CP}})}$$

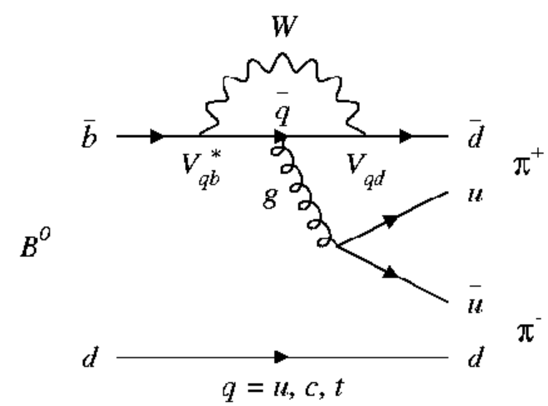
$$= S_F \sin \Delta m t + A_F \cos \Delta m t$$

- $B^0 \rightarrow \pi^+\pi^-$ final states have contributions from:

Tree



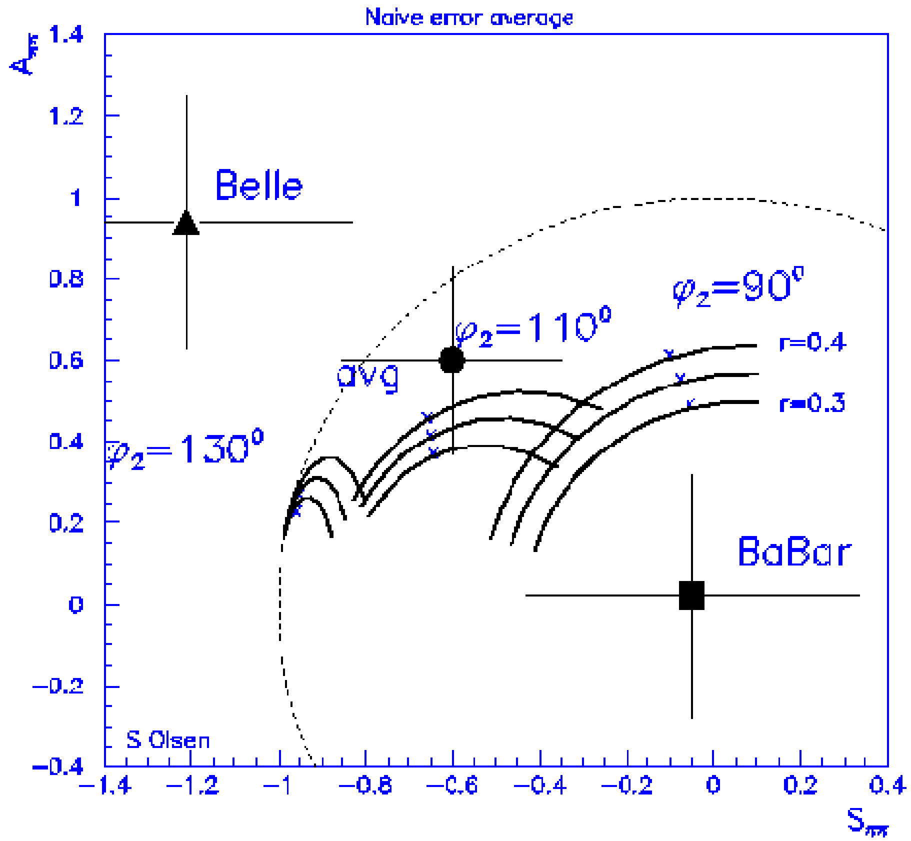
Penguin



- $S_{\pi\pi} = \sin(2\phi_2 + \theta) \neq \sin(2\phi_2)$
- Direct CP violation: $A_{\pi\pi} \neq 0$

The Interest in $B^0 \to \pi^+\pi^-$

- Not just another CKM angle
- Interest in this mode
  - BaBar and Belle disagree by two sigma on θ
  - Belle has $A_{\pi^+\pi^-} \approx 3\delta A_{\pi^+\pi^-}$
- Hadron collider measurements may arbitrate
  - Huge B cross-section
  - Trigger efficiently on fully hadronic/charged states



Triggering on $B^0 \to \pi^+\pi^-$ at a Hadron Machine

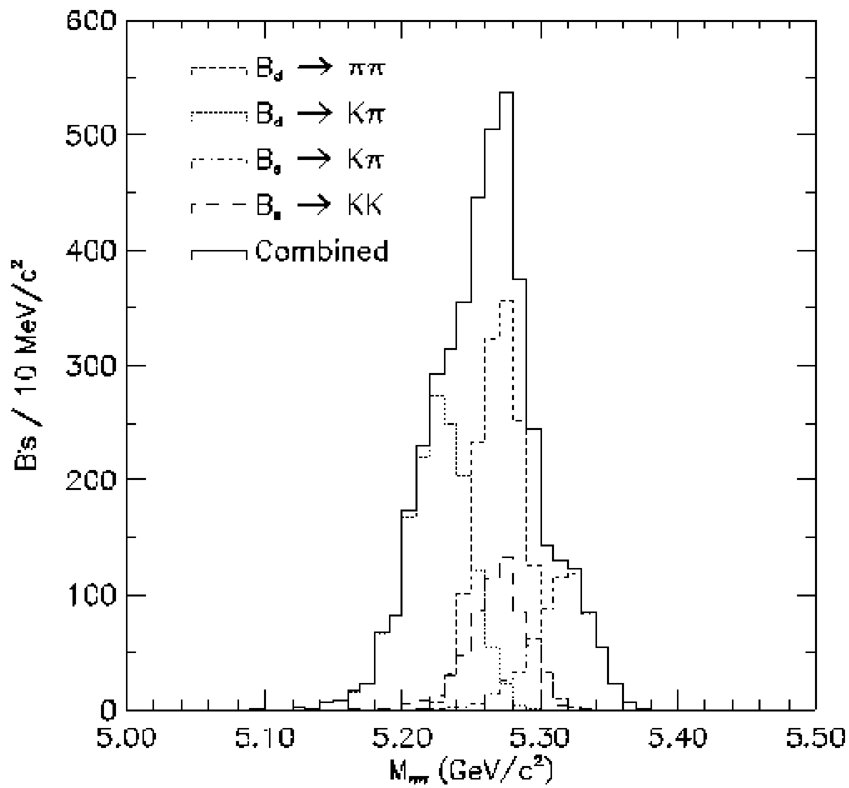
- Level 1: 2 tracks $p_t > 2$ GeV/c
  - $\sigma_{p_t} \approx 0.02 p_t^2$
  - L1 can run up to 30 kHz deadtimeless
- Level 2: Both tracks $d > 120\ \mu$m
  - $\sigma_d \approx 20 \oplus 40/p_t\ \mu$m
  - Beamspot 25 μm
- Level 3: Use full reconstruction
  - Further reduction by 2-5

Luminosity	T_{cross} (ns)	$\overline{N_{p\bar{p}}}$	L1 (kHz)	L2 (Hz)
0.4×10^{32}	396	1	18	300
0.7×10^{32}	396	2	18	39
2.0×10^{32}	132	2	30	67
1.7×10^{32}	396	5	28	38

- Predicted yield in 2 fb^{-1}:
  - 4000 - 7000 $B^0 \to \pi^+\pi^-$
  - 16000 - 28000 $B^0 \to K^+\pi^-$

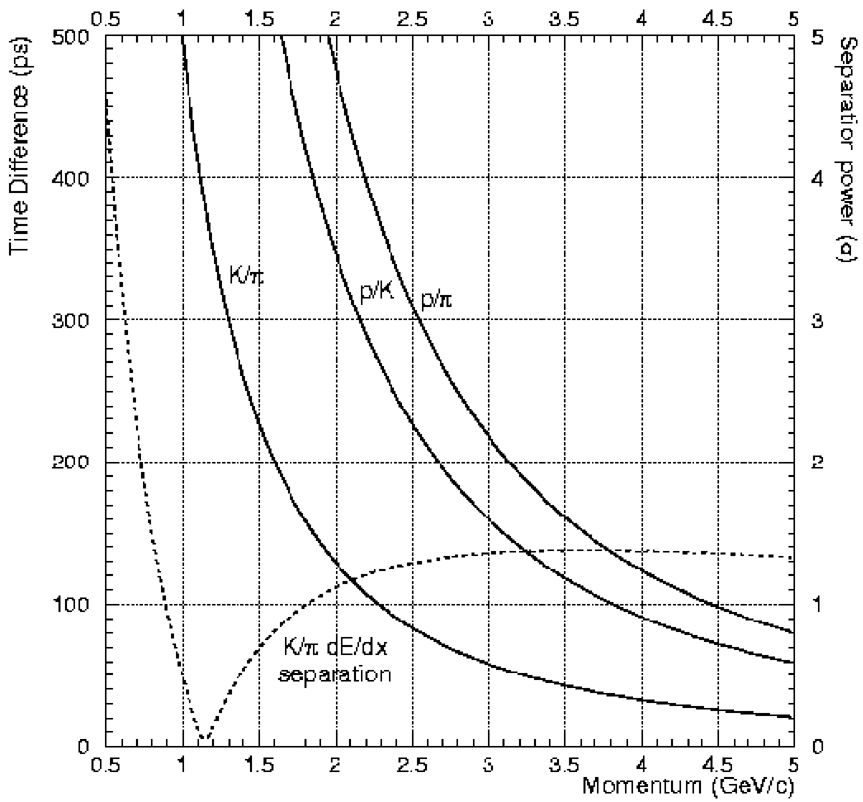
Projected Signal for $B^0 \to \pi^+\pi^-$

- Physics backgrounds
  - Use invariant mass to distinguish $\pi\pi$ from $K\pi$ and KK



- Also use
  - dE/dx in tracking chamber
  - Will have TOF but ...
    - ∗ One sigma $\pi - K$ separation up to 1.6 GeV/c
    - ∗ Mainly for flavour tagging (add $\varepsilon\mathcal{D}^2 \sim 2.4\%$)
- $K\pi$ has $\cos\Delta m_d t$ dependence
- Expect $\delta A_{\pi^+\pi^-} \sim 0.13$
  - For 5000 $\pi^+\pi^-$ candidates

A Word About TOF at a Collider



- Time of Flight (TOF) works best at low momenta
- Trigger tracks: $p_t > 2$ GeV/c
- More useful to distinguish $K^{\pm}$ from $\pi^{\pm}$ in fragmentation
  - Useful for flavour tagging
  - Especially B_s^0 decays

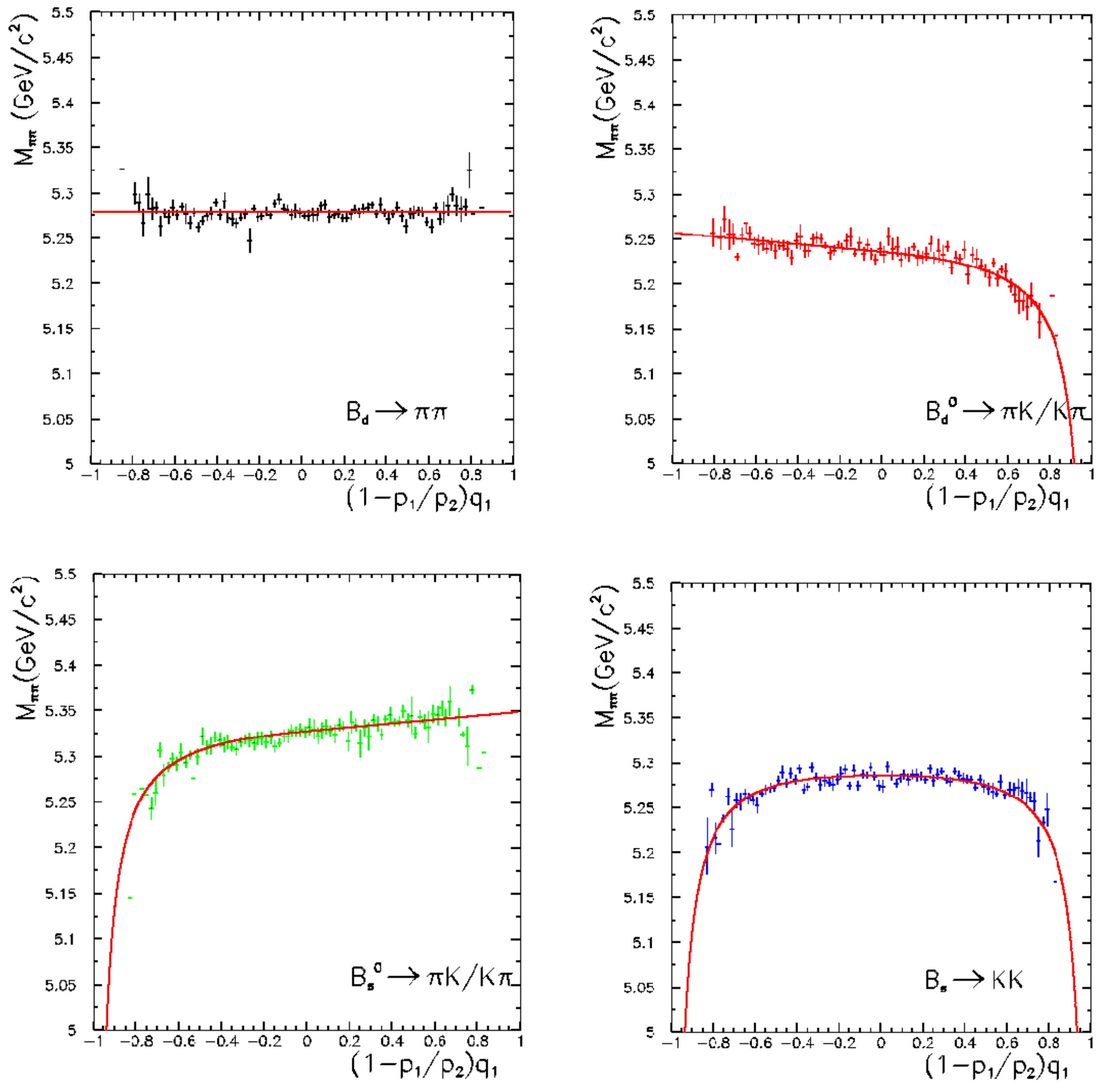
Optimal Separation of $B^0 \to h^+h^-$

- Exploit decay kinematics
  - Use a variable that distinguishes between daughter masses

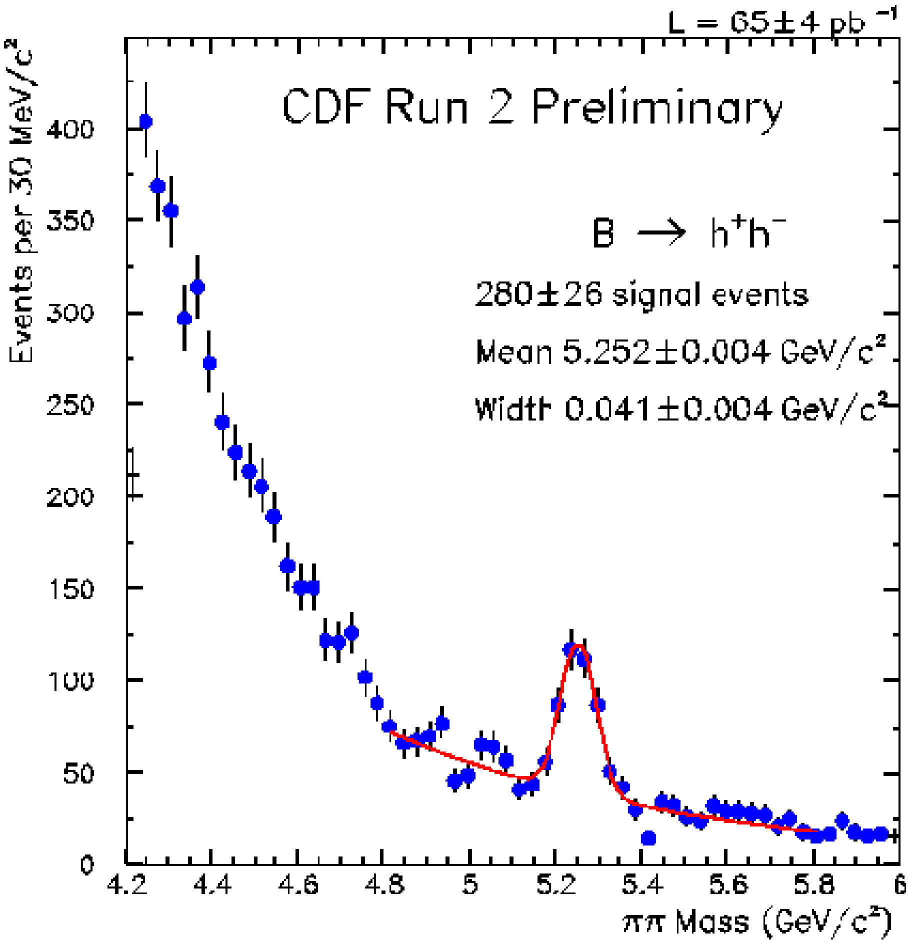
$$\alpha = (1 - p_1/p_2)q_1$$

$$p_1 < p_2$$

Channel	Event Yield
$B^0 \to K^+\pi^-$	148 ± 17
$B^0 \to \pi^+\pi^-$	39 ± 14
$B_s^0 \to K^+K^-$	90 ± 17
$B_s^0 \to K^+\pi^-$	3 ± 11

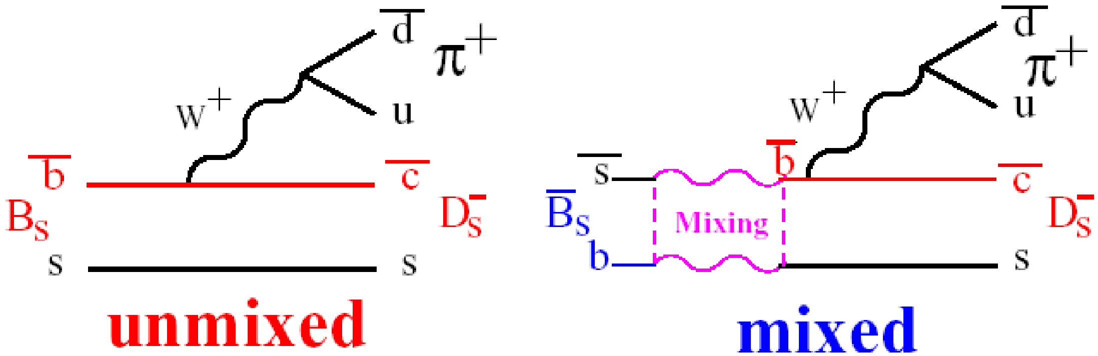


$B^0 \to h^+h^-$ Yields



- Design yield 2 $B^0 \to \pi^+\pi^-$ per pb
- Seeing 1 $\pi^+\pi^-$ candidate per pb
- The peak is an amalgam of
  - $B^0 \to \pi^+\pi^-; \pi^+K^-$
  - $B_s^0 \to K^+K^-; \pi^+K^-$
- Branching ratios for B^0 decays consistent with those seen at B factories
- $B_s^0 \to K^+K^-$ yield appears healthy
  - May give access to ϕ_3
  - (Fleischer, PLB 459 (1999) 306)
- Preliminary measurement of $\mathcal{A}_{K\pi}$ consistent with 0 ($\delta\mathcal{A} \approx 15\%$)

The CKM Prediction for B_s^0 Mixing

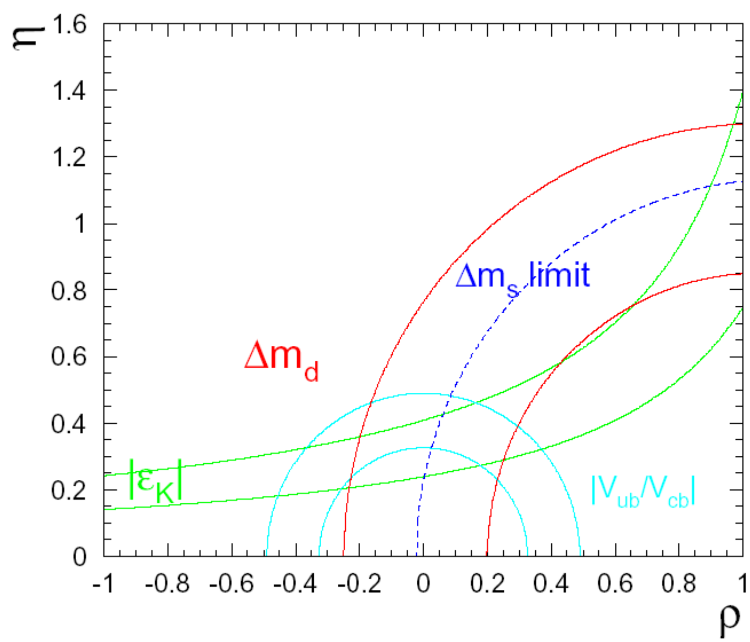


- Decay rate depends on amplitude difference of these two diagrams
  - Mixing box diagram brings in a factor of V_{ts}
- Observed decay rate for B_s^0 oscillates with

$$A_{\text{mix}} \equiv \frac{N_{\text{unmixed}}(t) - N_{\text{mixed}}(t)}{N_{\text{unmixed}}(t) + N_{\text{mixed}}(t)}$$

$$= \cos(\Delta m_s \cdot t)$$

$$\Delta m_s \approx \left(\frac{|V_{td}|}{|V_{ts}|}\right)^2 \Delta m_d$$



The Key to B_s^0 Mixing Formulae

- Measurement requires the:
  - Proper decay time, t
  - B_s^0 production flavour
  - Flavour at decay

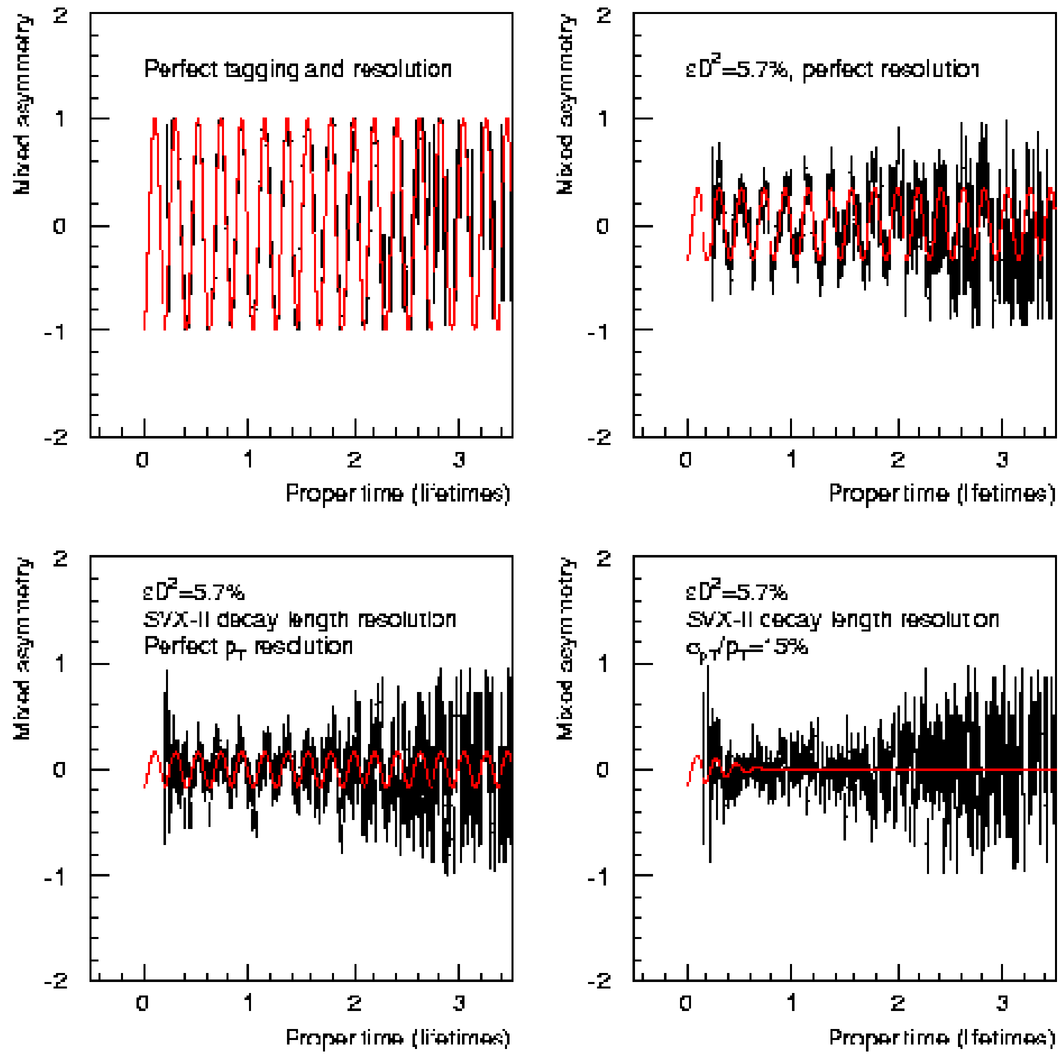
$$A_{\text{mix}}^{\text{observed}} \equiv \mathcal{D} \cos(\Delta m_s \cdot t)$$

- Where:
  - $\mathcal{D}$ is tag dilution $(\mathcal{D} = 2P - 1)$
  - $t = m\,\frac{L}{p}$ is decay time

- Proper time uncertainty:

$$\sigma_t^2 = (\frac{m}{p}\sigma_L)^2 + (t\frac{\sigma_p}{p})^2$$

- Fully reconstructed B_s^0 candidates have best time resolution
- Example with Δm_s = 20 ps^{-1}



Projected B_s^0 Yields

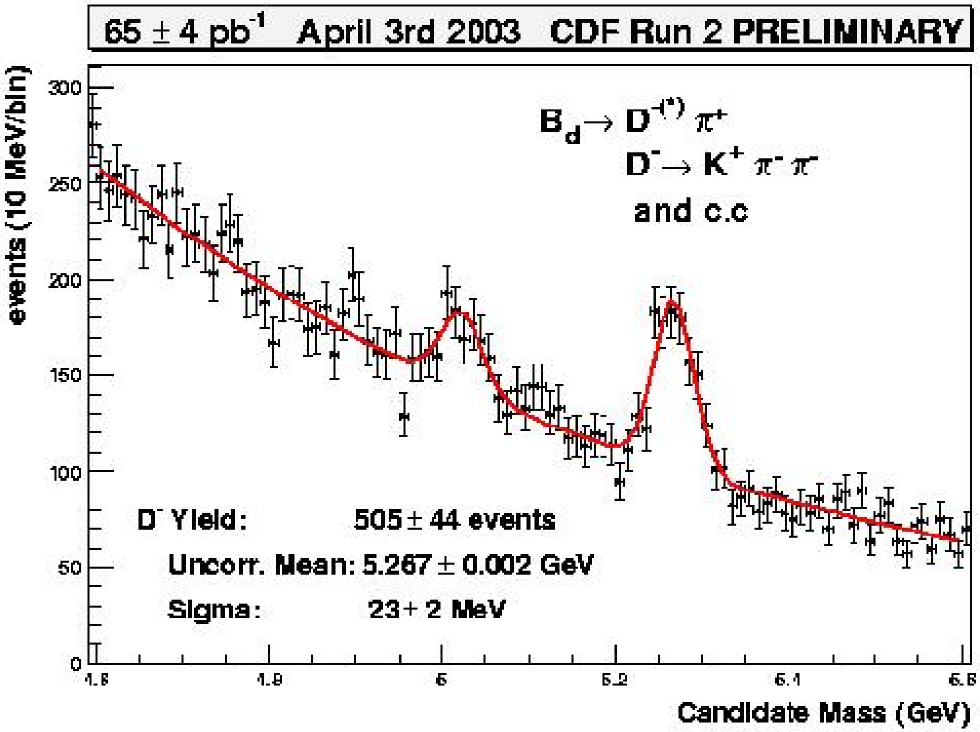
- Projections prior to the start of Run predicted yields like

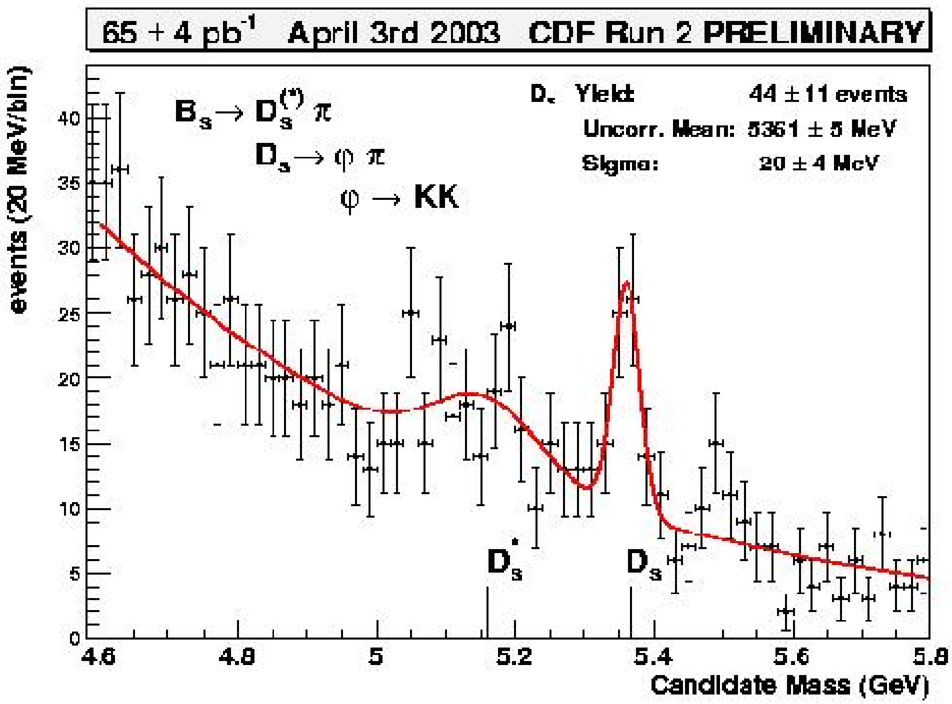
B_s^0 Channel	D_s^+ Channel	Yield in 1 fb^{-1}
$D_s^{\pm}\pi^{\mp}$	$\phi\pi^+$	8000
	$K^{*0}K^+$	7000
	$\pi^+\pi^-\pi^+$	2700
total		18200
$D_s^{\pm}\pi^+\pi^-\pi^{\mp}$	$\phi\pi^+$	8500
	$K^{*0}K^+$	7500
	$\pi^+\pi^-\pi^+$	3000
total		19000

- Currently have yields that are a factor 5 below this

Fully Reconstructed B_s^0 Decays

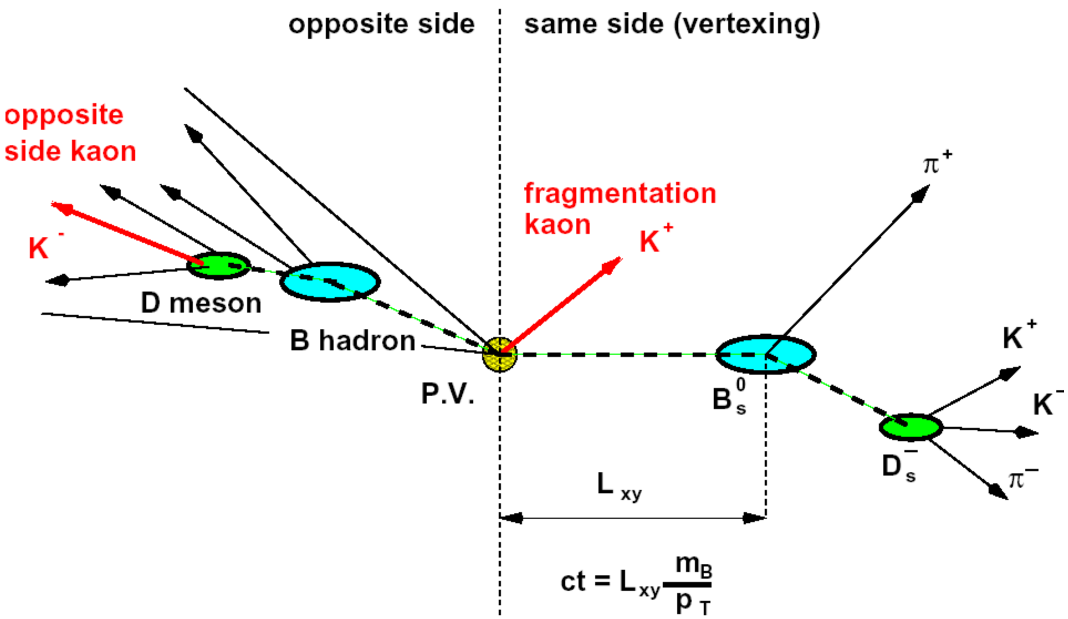
- Another goal of the impact parameter trigger was B_s^0 mixing
  - Several hundred pb^{-1} necessary for $\Delta m_s = 20 - 30$ ps^{-1}





- Evaluating yields and proper time resolution with early data
  - Will not look for B_s^0 oscillations until we have a suitable sensitivity

Flavour Tagging for B_s^0 Mixing

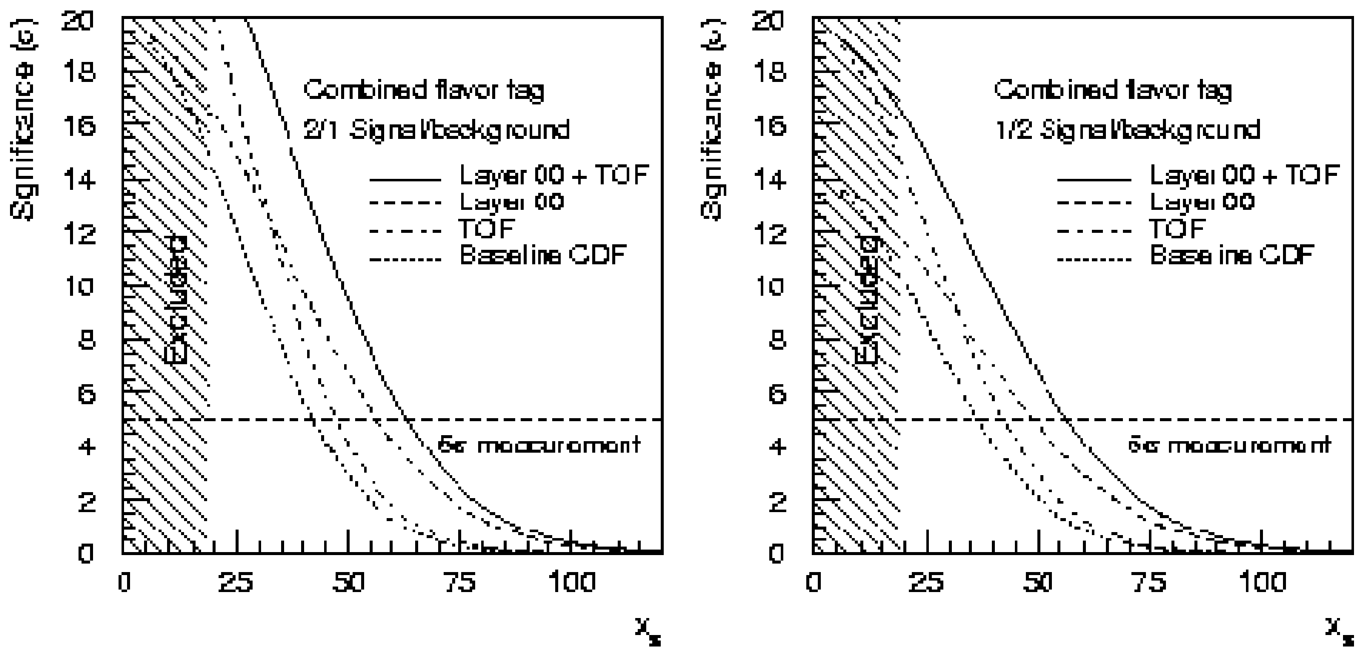


Flavour Tag (εD^2 %)	Run I	Run II
Same Side	1.0	4.2
Soft Leptons (e, μ)	1.7	1.7
Jet Charge	3.0	3.0
Opposite Side Kaon	-	2.4
Total	5.7	11.3

Projections for B_s^0 Mixing Measurement

- Expected signal: 20,000 candidates
- Proper time resolution: $45 - 60\ \text{fs} \oplus t\frac{\sigma_p}{p}$
- Flavour tagging effectiveness: $\varepsilon\mathcal{D}^2 = 5.7 - 11.3\%$
- Signal to Background: $2:1 \rightarrow 1:2$

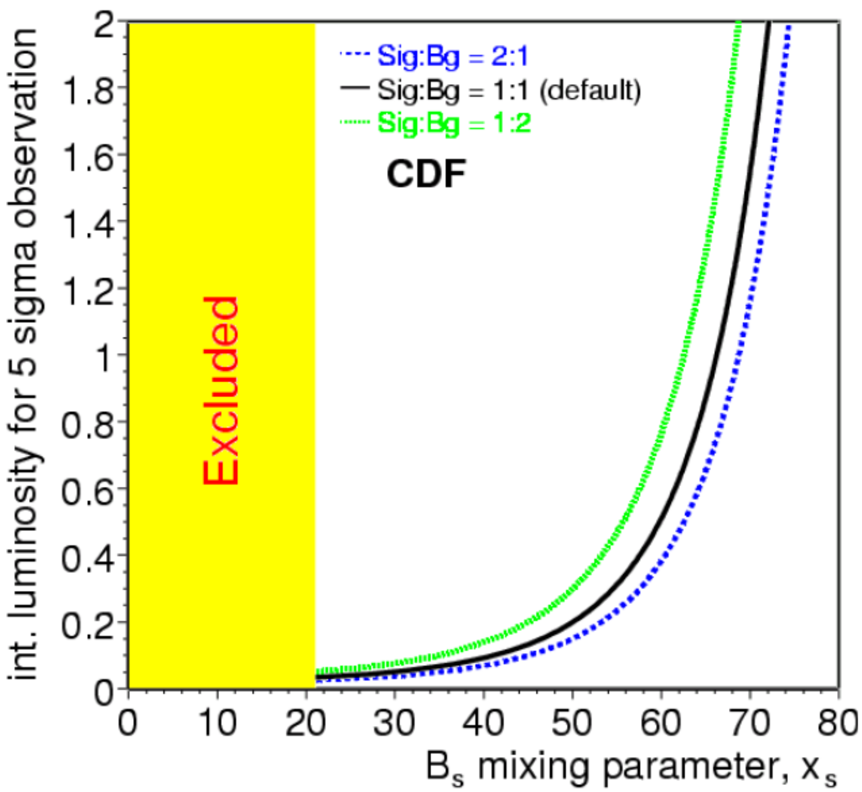
$$\text{Significance}(\Delta m_s) = \sqrt{\frac{S\varepsilon\mathcal{D}^2}{2}}\, e^{-\frac{1}{2}(\Delta m_s \sigma_t)^2} \sqrt{\frac{S}{S+B}}$$



$$x_s = \Delta m_s \cdot \tau_B$$

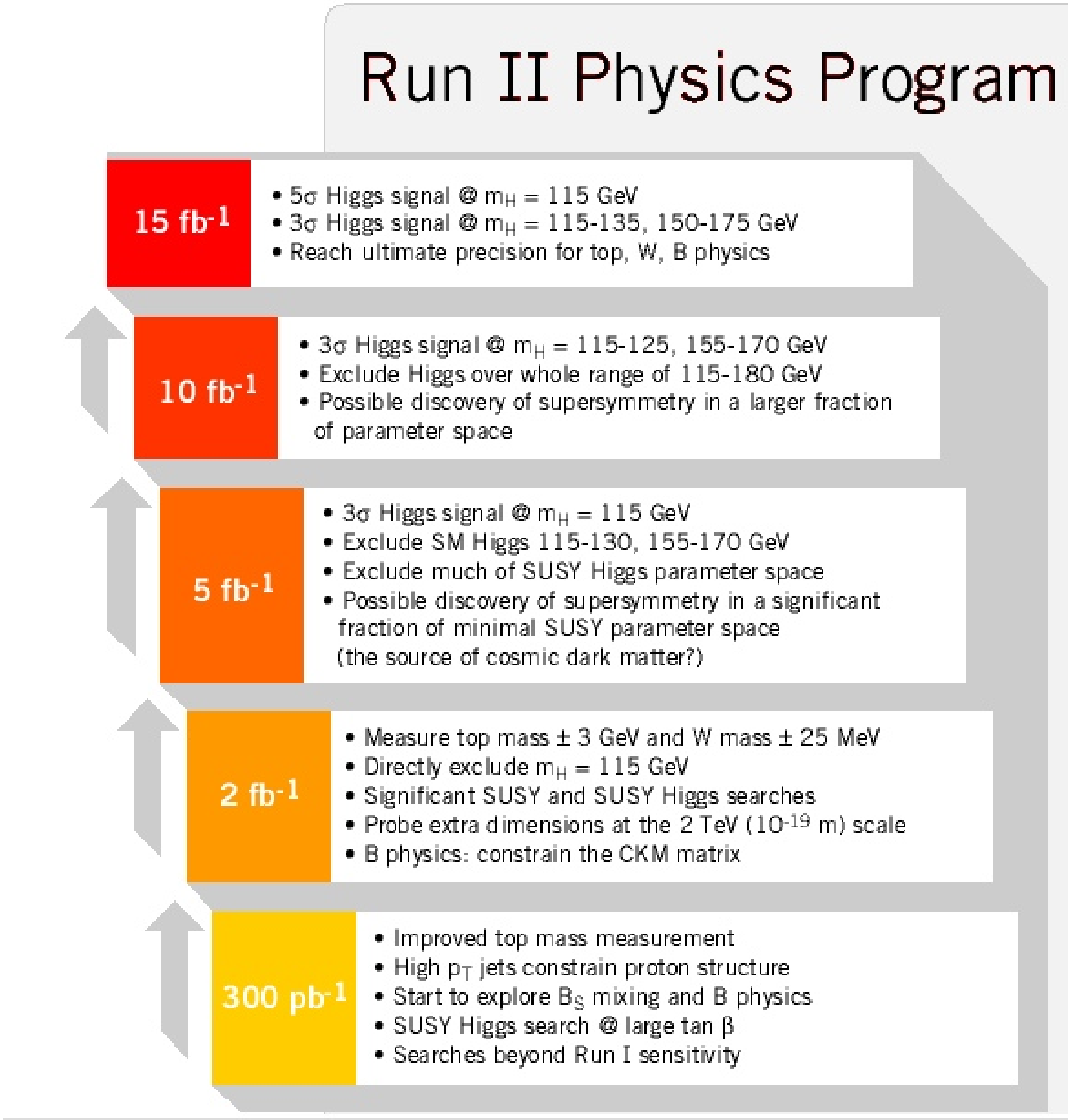
Prospects for Pinning Down Δm_s

- Plot based on run II projections
- Some not working out as well as hoped
  - Trigger yield (2.4)
  - Offline sample selection (2)
  - So far $B_s^0 \rightarrow D_s^{\pm}\pi^{\mp}$ only (2)
  - Impact parameter (1.5)
  - Flavour tagging eff (2)
- Working to on each factor
- Will not "open box" until
  - Sensitive to new Δm_s regime



Summary and Prospects

- Hadron colliders are potentially competitive place to do B physics
- CDF/D0 just getting into new luminosity regime
- BTeV/LHCb will take up the relay towards the end of the decade



Last Exercise

- B_s^0 mixing prospects:

  I suggest you explore the formula that parametrises the projected significance of the B_s^0 mixing measurement at CDF. In particular it might be prudent to explore less optimistic inputs.

  - In 500 $^{-1}$ (that we should have in the next 1.5 to 2 years) it looks like we might get more like 3000-5000 candidates.
  - Given $\frac{\sigma_p}{p} \approx 3\%$ (typical of fully reconstructed B mesons with a transverse momentum of 3 GeV in CDF) you could use a time resolution of $45 \rightarrow 60 \oplus 45$ fs, where the range in the first number corresponds to using (or not using) our inner-most silicon layer.
  - Flavour tagging should reach $\varepsilon\mathcal{D}^2 = 6\%$, eventually. Maybe take $6 \rightarrow 9$ % as a reasonable range.
  - We have S/B of about 1:2 now. Perhaps we will get to 1:1 in the not too distant future.

  Try to estimate what the B_s^0 mixing significance will be for one or more of these more realistic scenarios. As a bonus question you might explore which of the four inputs above is likely to give the bigest gain in B_s^0 mixing sensitivity – although we are working on improving all of them!