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Run-II B Workshop

Kaon Tagging and B_s^0 Mixing Projections for CDF in Run-II

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- Introduction
- B_s^0 Mixing
- Particle ID with Time-of-Flight
- Flavor Tagging with Particle ID:
  - Opposite Side Kaon Tagging
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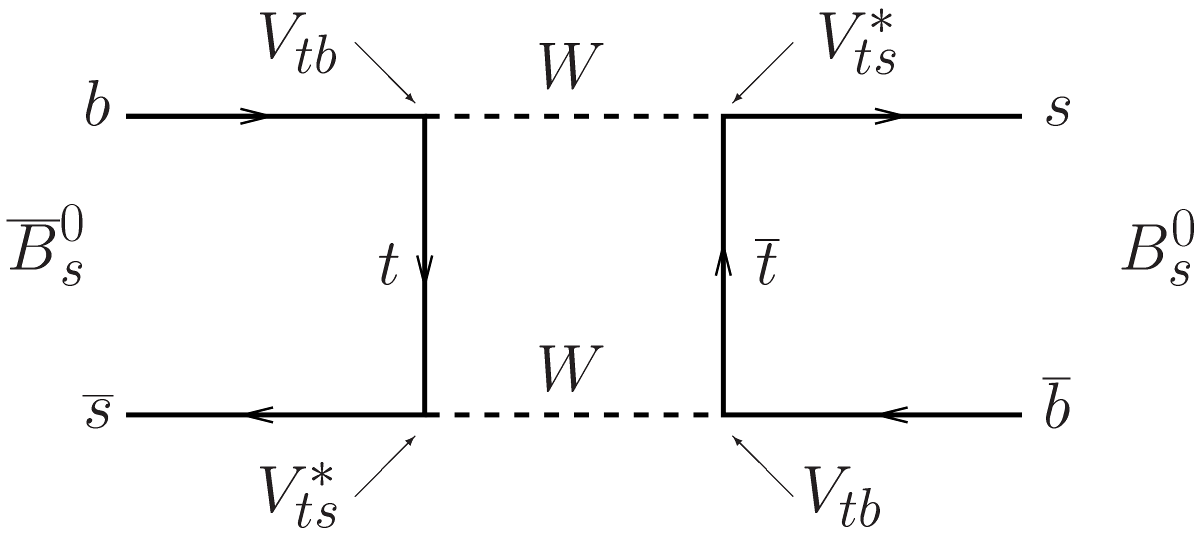
- B_s^0 Mixing Projections
- Conclusions

Introduction



CP Eigenstates: B_H^0 and B_L^0

Mass difference: $\Delta m_s = M(B_H^0) - M(B_L^0)$

$$\Delta m_s = \frac{G^2 M_W^2}{6\pi^2} m_{B_s} (B_{B_s} f_{B_s}^2) \eta_{QCD} S(z_t) |V_{ts}^* V_{tb}|^2$$

Probability of mixed state at decay:

$$\mathcal{P}_{\text{mixed}}(t) = \frac{1}{2}(1 - \cos \Delta m_s t)$$

Dimensionless mixing parameter:

$$x_s = \Delta m_s \tau(B_s^0)$$

Mixing Analysis

Elements of a mixing analysis:

1. Reconstruct B_s^0 decay,
   - Semileptonic: $B_s^0 \to D_s^- \ell^+ \nu_\ell X$
   - Hadronic: $B_s^0 \to D_s^- \pi^+$
2. Measure decay time,

$$t = m(B_s^0)\frac{L}{p}$$

$$(\delta t)^2 = \left(\frac{m}{p}\delta L\right)^2 \oplus \left(t\frac{\delta p}{p}\right)^2$$

3. Classify as mixed or unmixed
   - Decay flavor is unambiguous. . .
   - Production flavor is not.
4. Fit asymmetry for mixing frequency. . .

B_s^0 Mixing Analysis

True asymmetry:

$$A_{\rm true}(t) = \frac{N_{\rm mixed}(t) - N_{\rm unmixed}(t)}{N_{\rm mixed}(t) + N_{\rm unmixed}(t)}$$
$$= \cos(x_s t/\tau)$$

Measured asymmetry:

$$A_{\rm measured}(t) = \mathcal{D}_{\rm tag} e^{-(x_s\sigma_t/\tau)^2/2} A_{\rm true}(t)$$

Dilution: $\mathcal{D}_{\rm tag} = 2\mathcal{P}_{\rm tag} - 1$

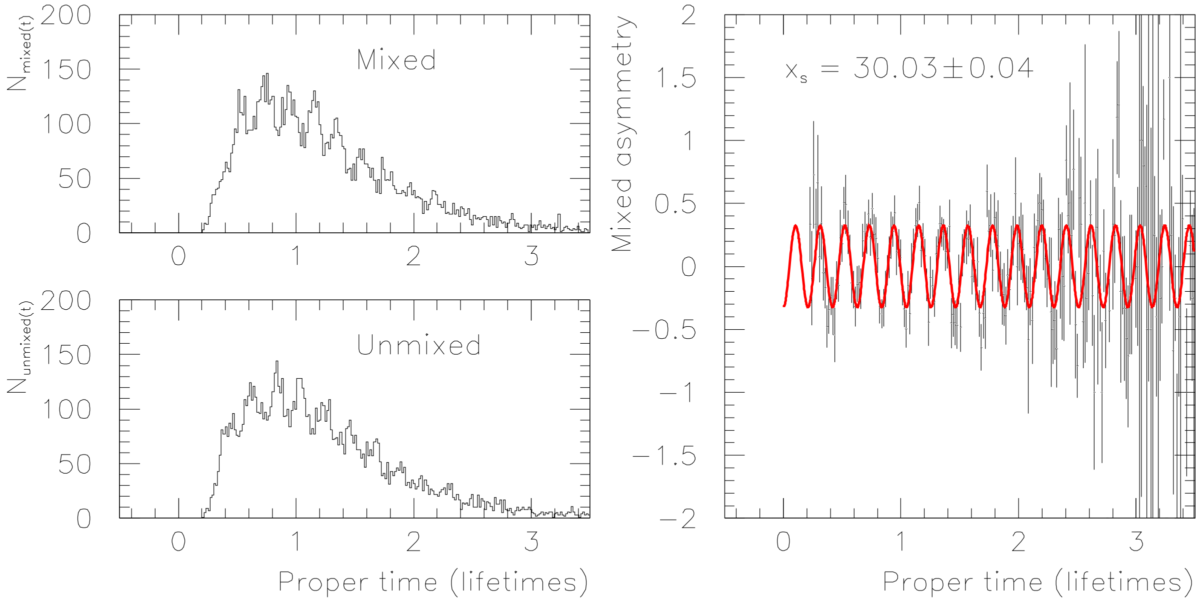


Figure of merit: $\epsilon\mathcal{D}^2_{\rm tag}$

A value of $\epsilon D^2 \sim 1\%$ is a good tag.

This Talk

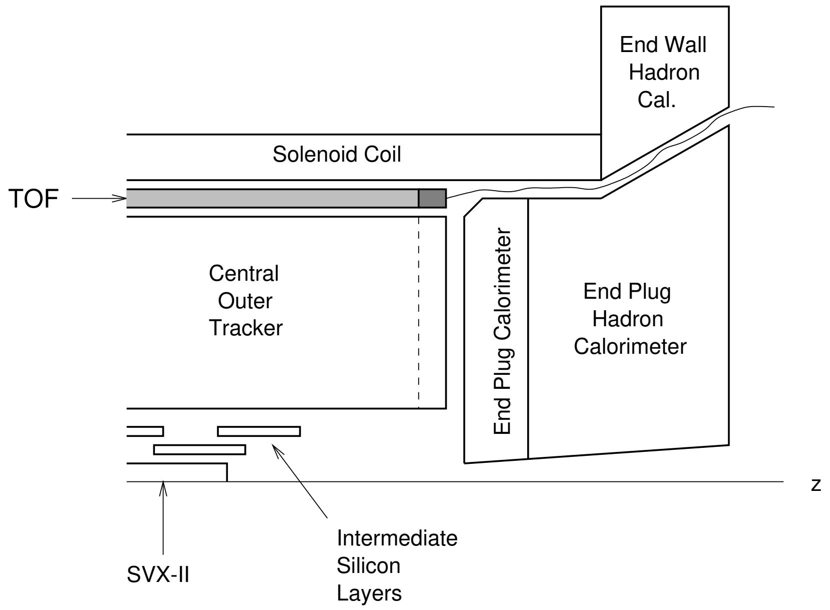
New flavor tags made possible by particle ID

$\Longrightarrow$ Particularly important for B_s^0 mixing

Outline

- CDF's Time-of-Flight detector,
- Particle identification,
- Flavor tags using particle ID,
- Projections for mixing sensitivity

Time-of-Flight in Run-II

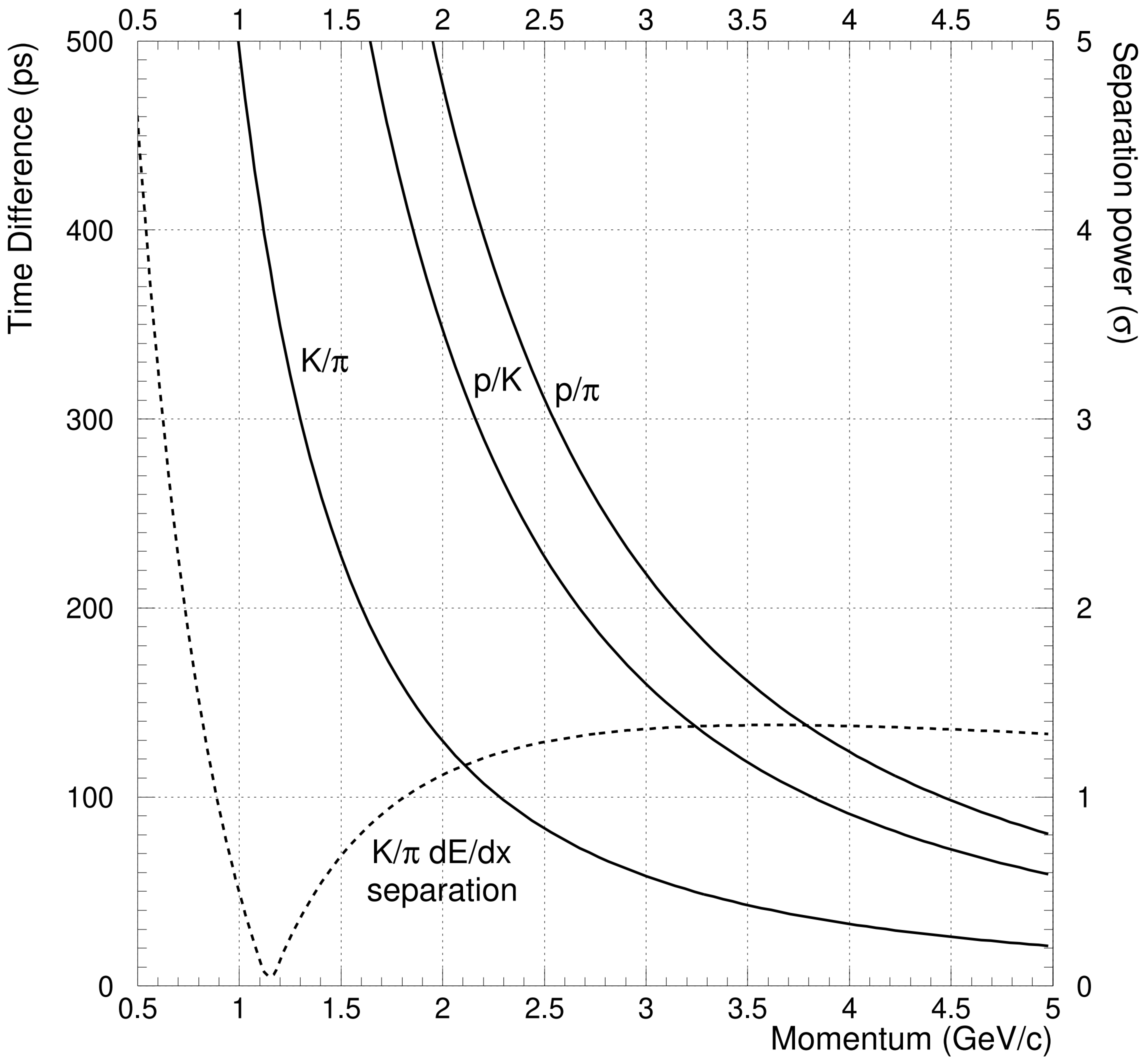


- 216 bars of Bicron BC-408 scintillator
- 432 Hamamatsu fine-mesh PMT's
- Rapidity coverage: $|\eta| < 0.9$
- Timing resolution: $\sigma_T \sim 100$ ps
- 2σ K/π separation for $p < 1.6$ GeV$/c$

Run-I prototype $\Longrightarrow$ realistic expectations

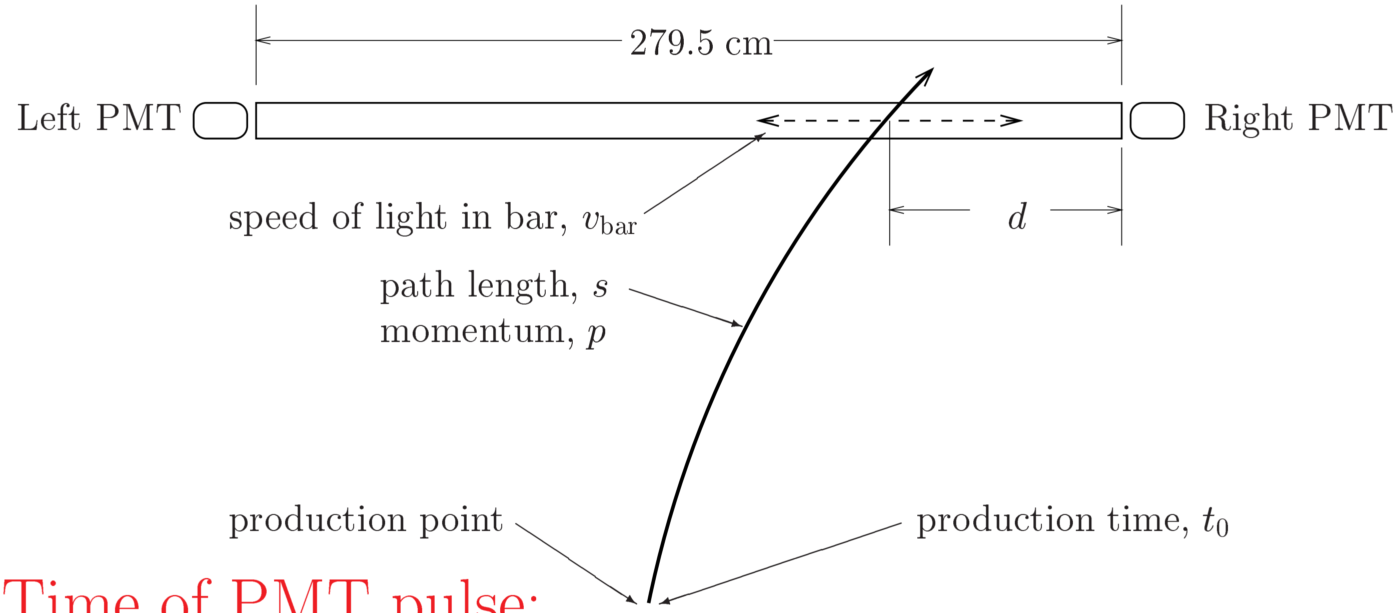
Full system ready for Run-II

Particle ID in Run-II



- $> 1.2\sigma$ K/π separation over all momenta
- *Statistical* separation possible for large p
- $> 2\sigma$ separation below ~ 1.6 GeV$/c$,

Time-of-Flight for Particle ID



Time of PMT pulse:

$$t_{\mathrm{hit}} = t_0 + \frac{s}{\beta c} + \frac{d}{v_{\mathrm{bar}}}$$

Measured mass:

$$m_{\mathrm{meas}} = \frac{p}{c}\sqrt{\frac{1}{\beta^2_{\mathrm{meas}}} - 1}$$

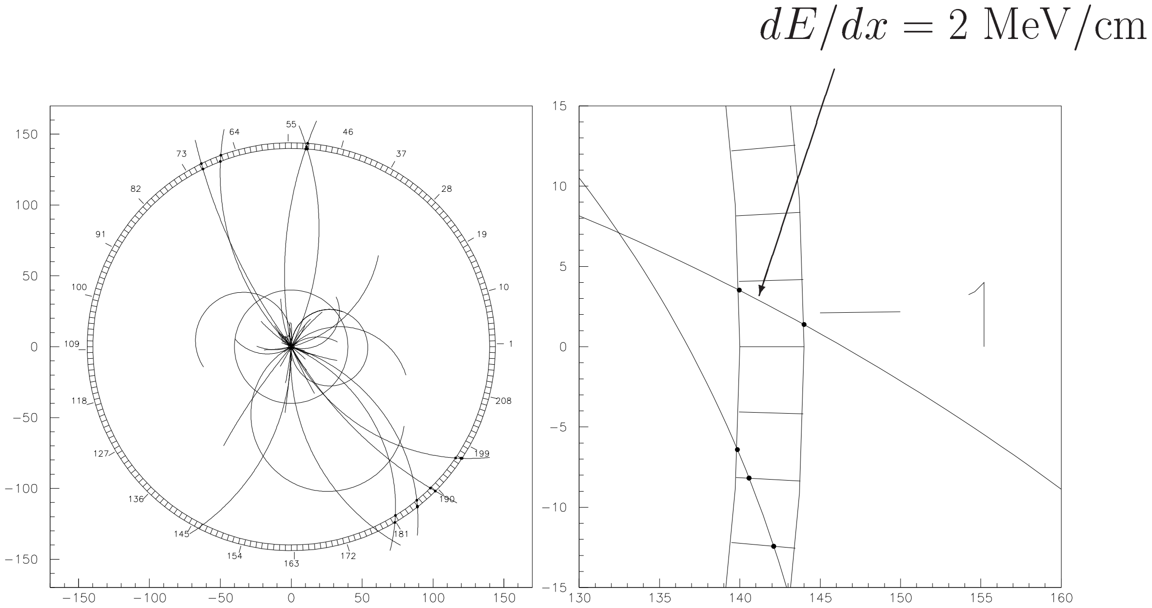
Expected time:

$$t_{\mathrm{exp}}(m) = t_0 + \frac{s}{c}\sqrt{1 + \frac{m^2c^2}{p^2}} + \frac{d}{v_{\mathrm{bar}}}$$

Test mass hypothesis using:

$$\chi^2_m = \frac{(t_{exp}(m) - t_{\mathrm{hit}})^2}{\sigma_t^2} \Longrightarrow w_m(\chi^2), \lambda_m(\chi^2, p_T, \ldots)$$

Parameterized Simulation

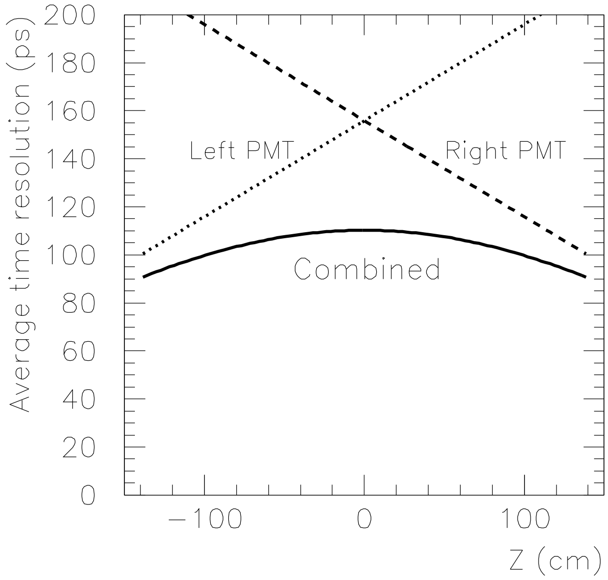


Attenuation of light:

$$Q = Q_0 e^{-d/\Lambda} \qquad \Lambda = 300 \text{ cm}$$

Timing resolution model:

$$\sigma_T = (\sigma_0 + \delta \cdot d) \cdot \sqrt{\frac{Q_{\rm MIP}}{Q}}$$
$$\sigma_0 = 100 \text{ ps}$$
$$\delta = 0.4 \text{ ps/cm}$$



Consistent with cosmic ray studies.

Measuring t_0

Measured time:

$$t_{\mathrm{hit}} = t_0 + \frac{s}{\beta c} + \frac{d}{v_{\mathrm{bar}}}$$

Long bunches: $\sigma_z \sim 30$ cm

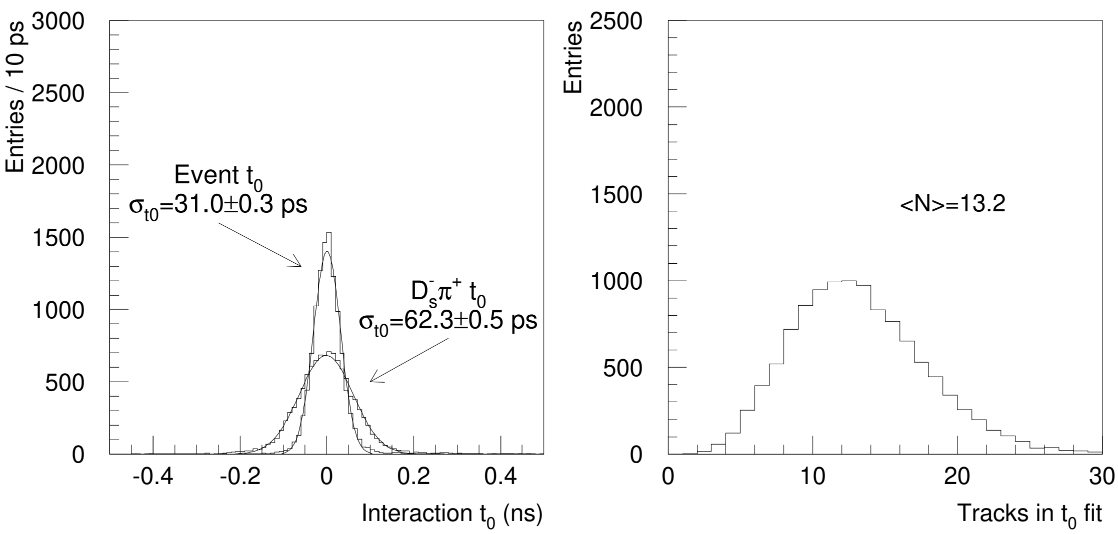
$$\Delta t_0 = \frac{\sigma_z}{c} \sim 1 \text{ ns} \gg \sigma_{t_{\mathrm{hit}}}$$

$\Longrightarrow$ Measure t_0 for each $p\bar{p}$ interaction:

1. Find $B^0 \to J/\psi K^0_S$, $B^0_s \to D^-_s \pi^+$, *etc...*
2. Find other tracks in primary vertex:

$$|z_0| < 1.0 \text{ cm} \qquad |d_0| < 0.5 \text{ cm}$$

3. Perform likelihood fit for t_0:



Only a small contribution to σ_{TOF}.

Impact Parameter Resolution

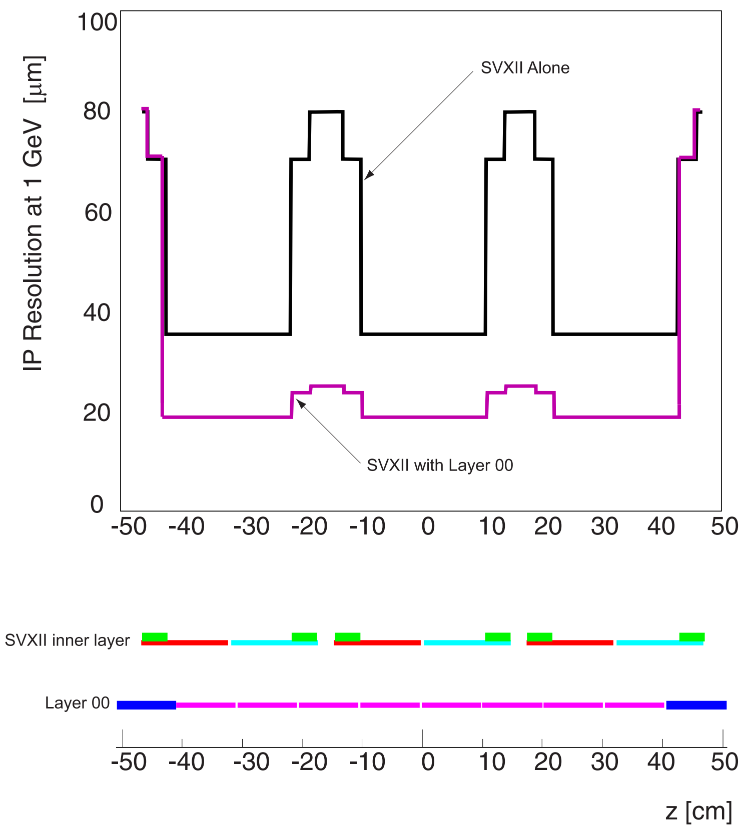
- SVX-II:

$$\sigma_{d_0} = \begin{cases} 13 + 40/p_T\ \mu\text{m} & \text{No SVX-II hybrid hit} \\ 13 + 80/p_T\ \mu\text{m} & \text{SVX-II hybrid hit} \end{cases}$$

$$\sigma_{z_0} = \begin{cases} 28 + 40/p_T\ \mu\text{m} & \text{No SVX-II hybrid hit} \\ 28 + 80/p_T\ \mu\text{m} & \text{SVX-II hybrid hit} \end{cases}$$

- SVX-II + Layer 00:

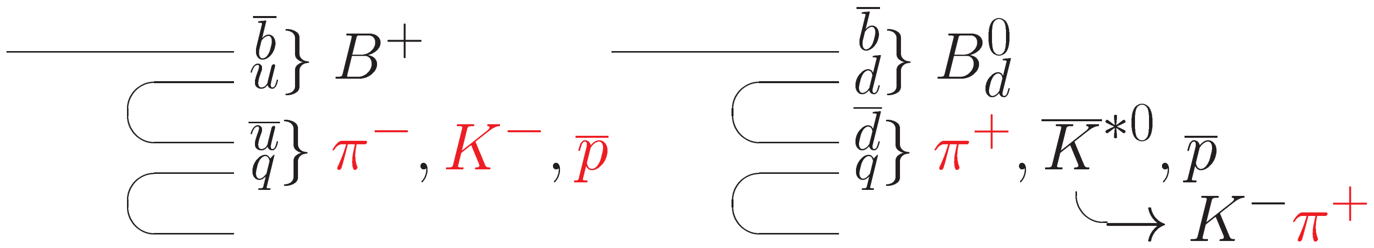
$$\sigma_{d_0} = 5.5 + 17/p_T\ \mu\text{m}$$



Methods of b Flavor Tagging

1. **Opposite Side Flavor Tags:**
   Identify flavor of *other* B in the event
   Infer flavor of B of interest.
   - lepton tag: $b \to \ell^- X$ but $\bar{b} \to \ell^+ X$
   - jet charge: $Q^b_{\rm jet} < 0$ but $Q^{\bar{b}}_{\rm jet} > 0$

   Acceptance for opposite side B is $\sim 40\%$.
2. **Same Side Flavor Tag (SST):**
   Exploit correlation from fragmentation
   or B^{**} decay.



i.e. π^+ tags B^0 but π^- tags $\overline{B}^0$.

Better acceptance than opposite side tag.

Opposite Side Kaon Tag

Identify decay flavor of the *other* B:

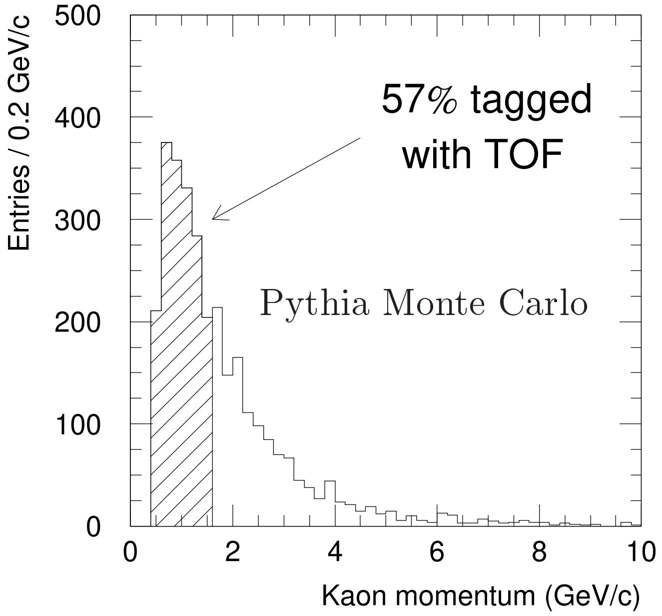
$$\overline{b} \to \overline{c} \to \overline{s} \to K^+$$

$$B \to K^+ X \text{ but } \overline{B} \to K^- X$$

Opposite side kaon tag:

- Identify kaons using TOF,
- Require separation from reconstructed B in η-φ,
- Reject tracks from the primary vertex.

Significant fraction of K's in acceptance:



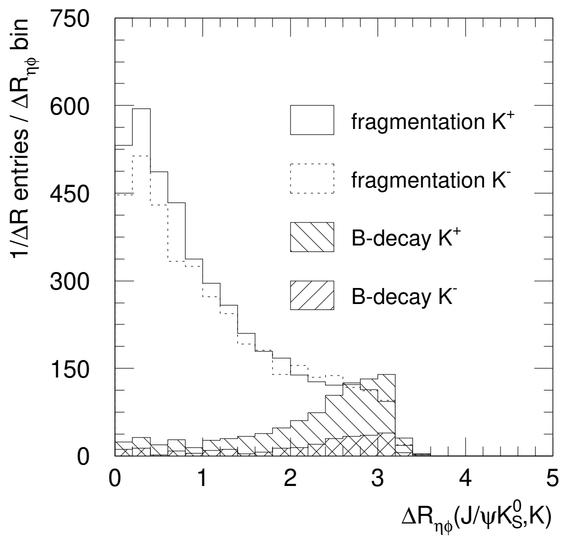
Opposite Side Kaon Tag

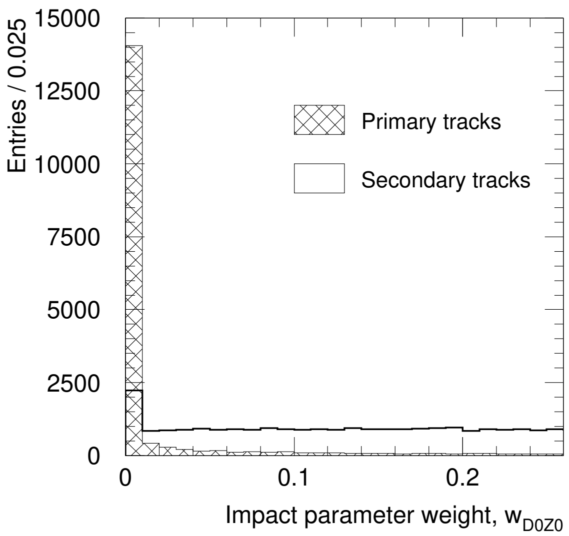
- Studied for $B_d^0 \to J/\psi K_S^0$ decays
- Kaon identification: $\lambda_K > 0.25$
- Opposite side isolation:

$$\Delta R_{\eta\varphi} = \sqrt{\Delta\eta^2 + \Delta\varphi^2} > 1,$$

- Displaced vertex:

$$\text{require } \chi^2_{d_0 z_0} = d_0^2/\sigma^2_{d_0} + z_0^2/\sigma^2_{z_0} > 9$$





$$\epsilon D^2 = (2.4 \pm 0.2)\%$$

Same Side Tag

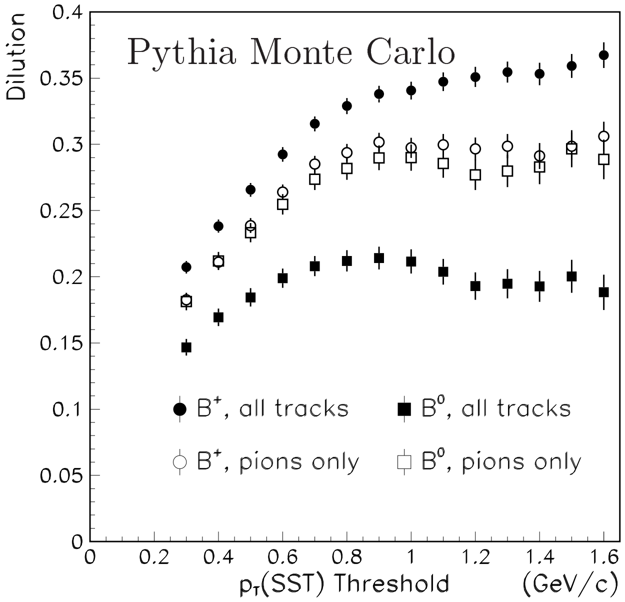
Find *the* track produced in association with B:

$\left.\begin{matrix}\bar{b}\\ u\end{matrix}\right\} B^+$ $\quad$ $\left.\begin{matrix}\bar{u}\\ q\end{matrix}\right\} \pi^-, K^-, \bar{p}$

$\left.\begin{matrix}\bar{b}\\ d\end{matrix}\right\} B_d^0$ $\quad$ $\left.\begin{matrix}\bar{d}\\ q\end{matrix}\right\} \pi^+, \overline{K}^{*0}, \bar{p}$

$\hookrightarrow K^-\pi^+$

Tagging dilution is *different* for B^+ and B^0.



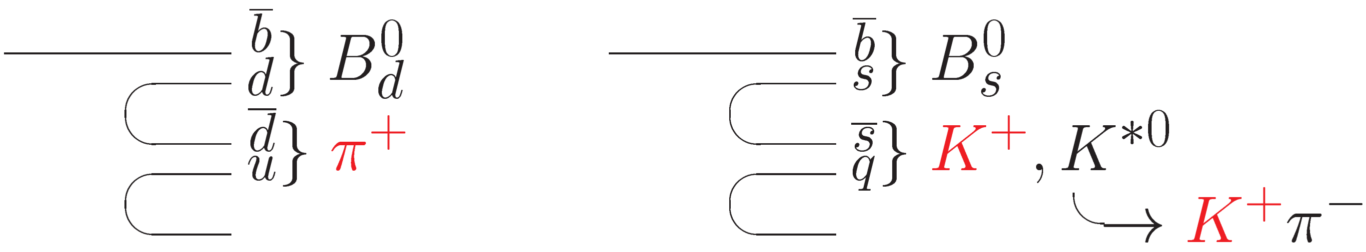
Clean up B^0 tag by rejecting K^- and $\bar{p}$:

- Identify SST track as before, but...
- Reject if TOF information inconsistent with pion hypothesis.

$$\epsilon D^2(J/\psi K_S^0) = \begin{cases} (1.4 \pm 0.1)\% & \text{without TOF} \\ (1.9 \pm 0.1)\% & \text{with TOF} \end{cases}$$

Same Side Kaon Tag for B_s^0

Same Side Tag for B_s^0:



Same SST algorithm as before except:

- We *require* TOF information,
- We *require* kaon identification, $\lambda_K > 0.25$.

Applied to $\overline{B}_s^0 \to J/\psi\phi$ (Lepton trigger):

$$\epsilon D^2 = (2.6 \pm 0.3)\%$$

Applied to $\overline{B}_s^0 \to D_s^+\pi^-$ (all hadronic trigger):

$$\epsilon D^2 = (4.2 \pm 0.5)\%$$

Summary of Tagging Results for Run-II

Tag	$B^0 \to J/\psi K_S^0$	$B_s^0 \to J/\psi \phi$	$B_s^0 \to D_s^- \pi^+$
Soft lepton tag (μ)	1.0	1.0	1.0
Soft lepton tag (e)	0.7	0.7	0.7
Jet Charge	3.0	3.0	3.0
Opposite Side Kaon Tag	2.4	2.4	2.4
Same Side Tag (pion)	1.9	—	—
Same Side Tag (kaon)	—	2.6	4.2
Total	9.0%	9.7%	11.3%

B_s^0 Mixing

To resolve B_s^0 oscillations we require:

$$\sigma_t < 1/\Delta m_s$$

$$\sigma_t^2 = \left(\frac{m}{p}\delta L\right)^2 \oplus \left(t\frac{\delta p}{p}\right)^2$$

Fully reconstructed B_s^0 decays: $\delta p/p = 0.4\%$.

The XFT + SVT Trigger

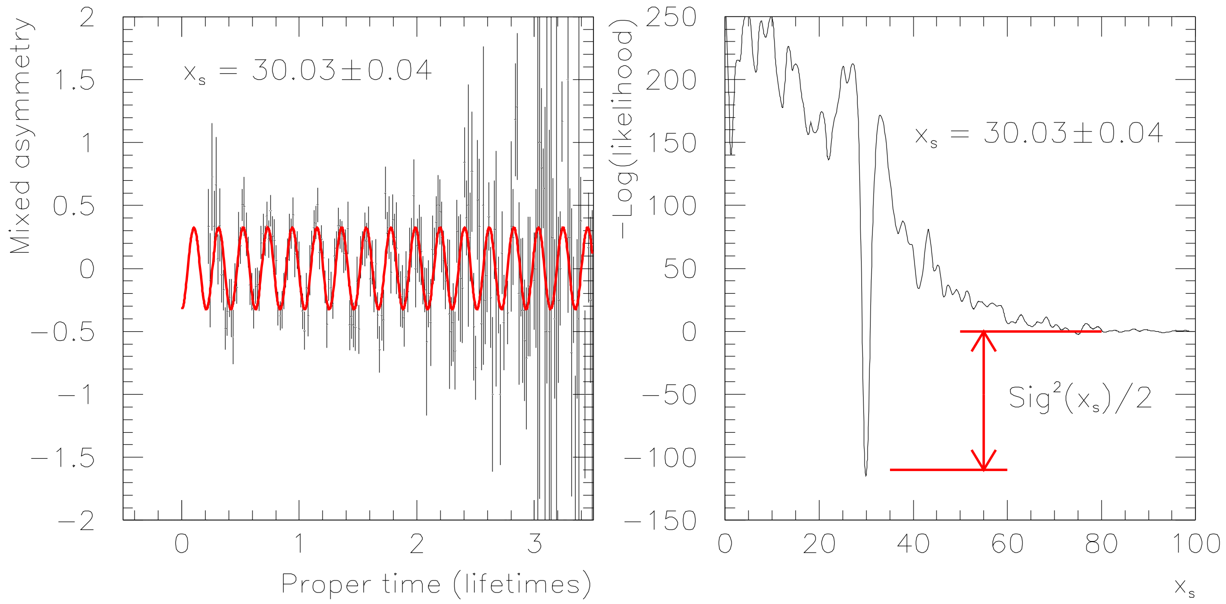
Level 1:	$p_T^{(1)}, p_T^{(2)} > 2$ GeV$/c$, $p_T^{(1)} + p_T^{(2)} > 5.5$ GeV$/c$, $\delta\phi \leq 135°$, Opposite charge.
Level 2:	$120\ \mu$m $< \lvert d \rvert < 1$ mm, $p_T(B) \cdot X_v \geq 0$, $2° < \delta\phi < 90°$.

Expect $\mathcal{O}(20,000)$ decays recorded:

$$B_s^0 \rightarrow D_s\pi, \quad B_s^0 \rightarrow D_s 3\pi$$

with $D_s \rightarrow \phi\pi, \quad D_s \rightarrow K^* K$

x_s Reach Projections



Average significance of x_s measurement:

$$\mathrm{Sig}(x_s) = \sqrt{\frac{N\epsilon D^2}{2}} \cdot e^{-(x_s\sigma_t/\tau)^2/2}\sqrt{\frac{S}{S+B}}$$

where

N = 20,000 B_s^0 decays in 2 fb^{-1} (N=S+B)

S/B signal-to-bkg ratio, 1:2–2:1

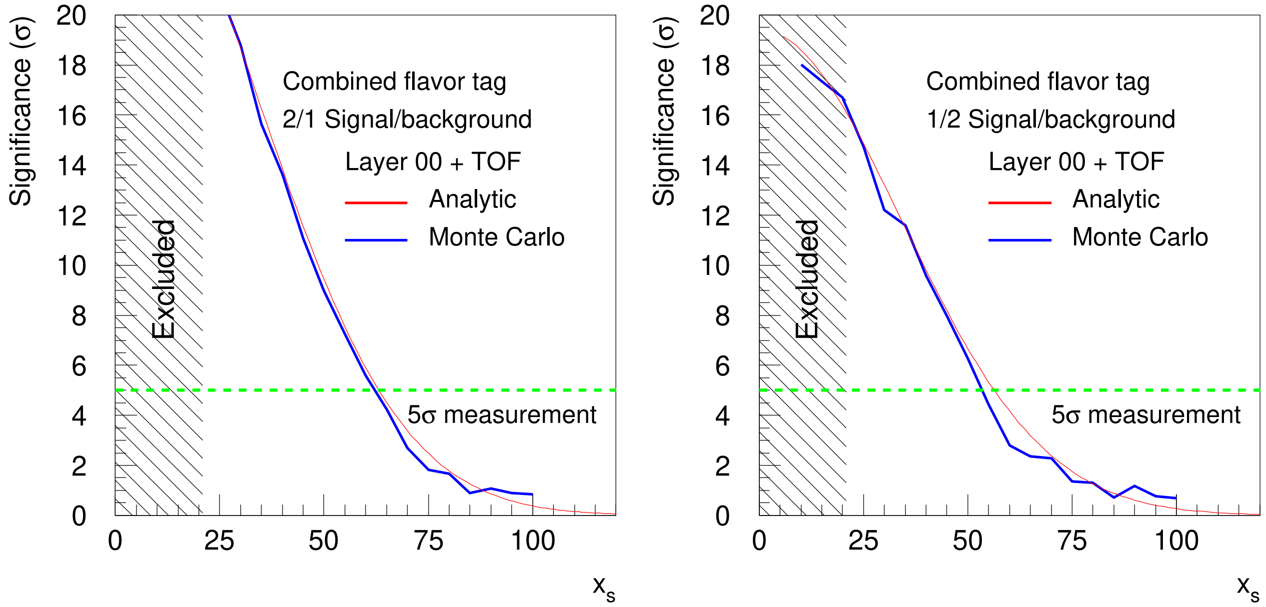
ϵD^2 tagging efficiency = 11.3%

σ_t proper time resolution, 45 fs

τ B_s^0 lifetime

B_s^0 Oscillation Sensitivity

On *average*, what is the limit of sensitivity?



$$\text{Maximum } x_s = \begin{cases} 63 & \text{for } S/B = 2:1 \\ 56 & \text{for } S/B = 1:2 \end{cases}$$

- Optimist:

  "5% of the time we could make a 5σ observation for $x_s = 73$!"

- Pessimist:

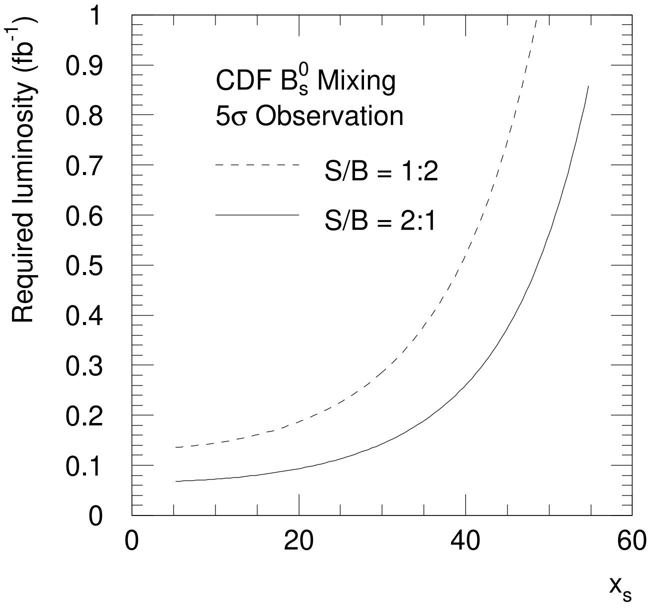
  "5% of the time we would fail to make a 5σ observation even if $x_s = 53$."

Global fits:

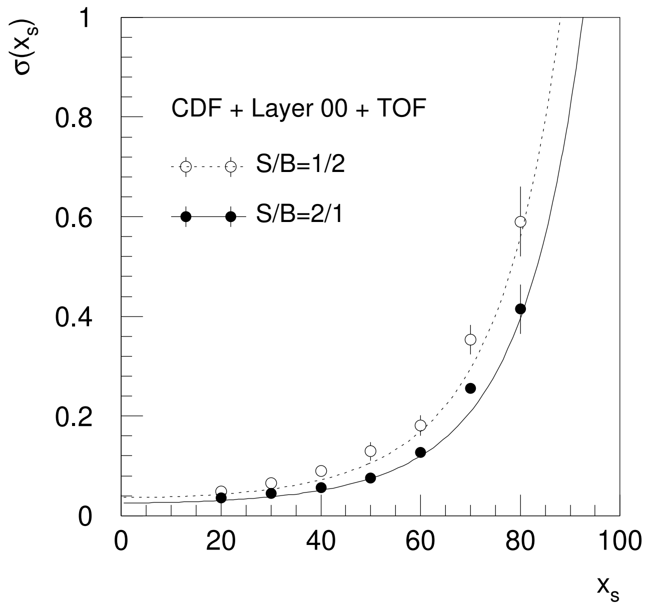
$$22.0 < x_s < 30.8 \text{ @ } 95\% \text{ C.L.}$$

B_s^0 Oscillation Sensitivity

Integrated luminosity required for 5σ observation:



Once oscillations are observed, x_s will be measured *extremely* precisely.



Conclusions

A new B_s^0 physics program in Run-II

- Time-of-Flight for particle ID
  - Two new flavor tags
  - Particularly relevant for B_s^0
- Hadronic trigger
  - Fully hadronic B_s^0 decays
  - Excellent proper time resolution
- Very large sample sizes expected
  - Might see B_s^0 mixing *early* in Run-II
- Only the beginning of a rich B_s^0 program:
  - $B_s^0 \to J/\psi\phi$
  - $B_s^0 \to K^+K^-$
  - $B_s^0 \to D_s^- K^+$