$\Delta\Gamma_s$ and ϕ_s at the Tevatron

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On behalf of

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and the DØ and CDF collaborations

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Mixing in the B_s System

Time Evolution of neutral B mesons

$$|B_q^0(t)\rangle = g_+(t)\,|B_q^0\rangle + \frac{q}{p}\,g_-(t)\,|\overline{B}_q^0\rangle$$

$$|\overline{B}_q^0(t)\rangle = g_+(t)\,|\overline{B}_q^0\rangle + \frac{p}{q}\,g_-(t)\,|B_q^0\rangle$$

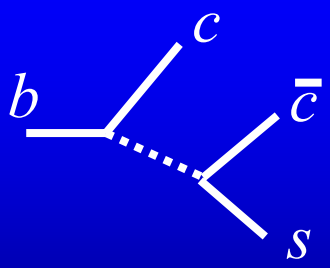
Three observables: Δm, $\Delta\Gamma$, ϕ

$$|g_\pm(t)|^2 = \frac{e^{-\Gamma_q t}}{2}\left[\cosh\left(\frac{\Delta\Gamma_q}{2}t\right) \pm \cos(\Delta m_q t)\right]$$

$$1 - \left|\frac{q}{p}\right|^2 \simeq \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)$$

$\Delta\Gamma$: dominated by b→ccs decays so don't expect new physics

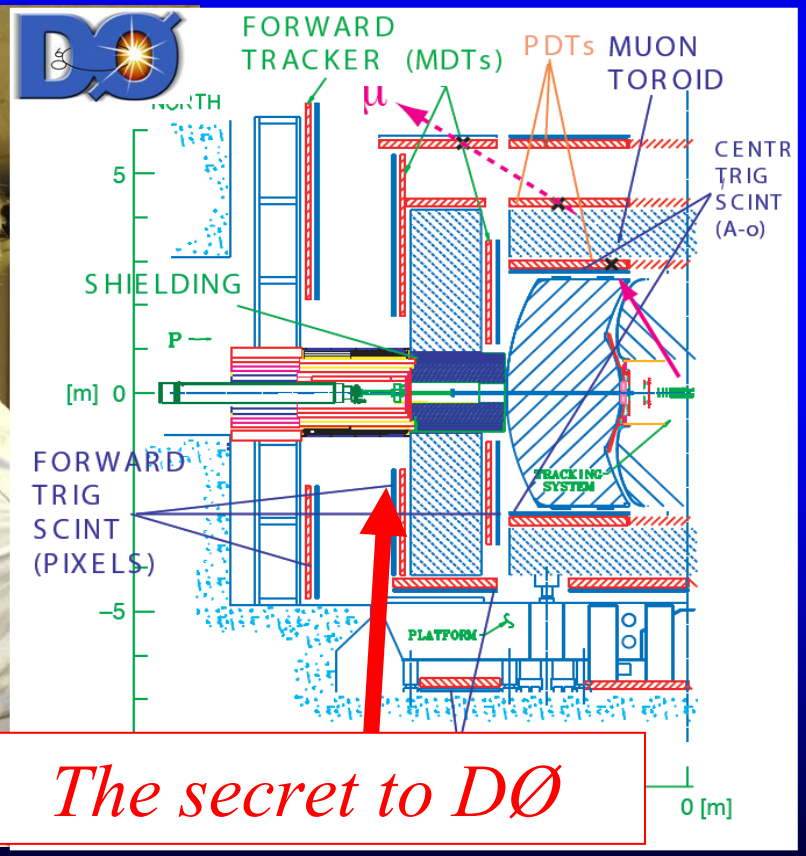
Interesting because it defines the phenomenology and experimental program. Order 10% $\Delta\Gamma/\Gamma$→ CPV studies without tagging



ϕ_s: small in SM but succeptible to new physics phase in the B_s mixing box diagrams

B physics at the Tevatron

- Large cross sections, all hadrons
- Many strengths to both but most important features:
  - DØ: muon system. CDF: displaced track trigger.
- Explore regions of parameter space inaccessible to B factories



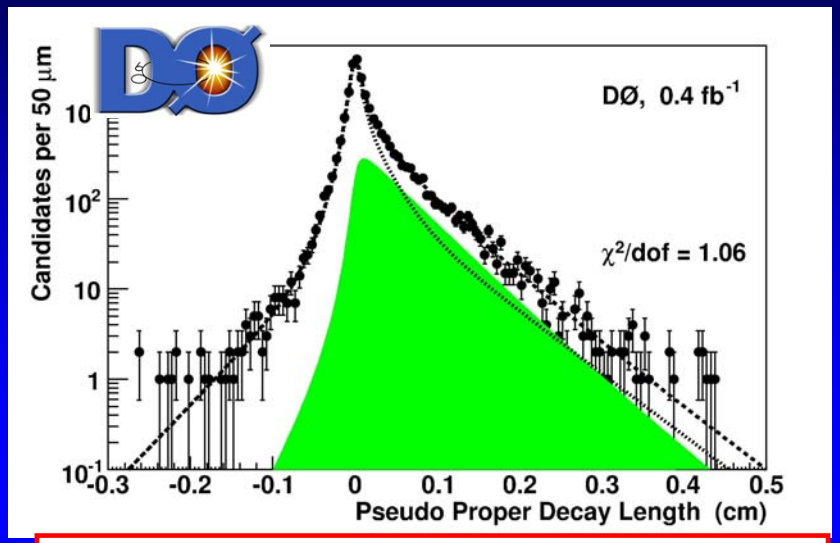
Signatures

- Flavor specific B_s lifetime in $D_s\mu\nu$ $\Rightarrow \Delta\Gamma$
  - CDF and DØ
- $B_s \rightarrow D_s^{(*)} D_s^{(*)}$ $\Rightarrow \Delta\Gamma$ (*so far assuming* $\phi_s = 0$ *& pure CP*)
  - DØ: $(\phi\pi)(\phi\mu\nu)$. CDF: $(\phi\pi)(\phi\pi)$
- CDF $\tau_L(B_s \rightarrow K^+K^-) \Rightarrow \Delta\Gamma$ (*so far assuming* $\phi_s = 0$)
- DØ Integrated semileptonic asymmetries $\Rightarrow \phi_s$
  - inclusive like-sign dimuons, exclusive $D_s\mu^{\pm}\nu$
- $B_s \rightarrow J/\psi\,\phi$ $\Rightarrow$ **$\Delta\Gamma$ and ϕ_s**
  - CDF: first measurement, ϕ_s set to zero
  - DØ: first measurement with ϕ_s as a free parameter

$B_s \to D_s \mu \nu$ Lifetime

Flavor specific decays carry equal amounts of B_H and B_L

$$\tau_{FS} = \frac{1}{\overline{\Gamma}_s}\left(\frac{1+y^2}{1-y^2}\right), y = \frac{\Delta\Gamma}{2\Gamma}$$



$$\tau_{FS}(B_s) = 1.398 \pm 0.044^{+0.028}_{-0.025}\, ps$$

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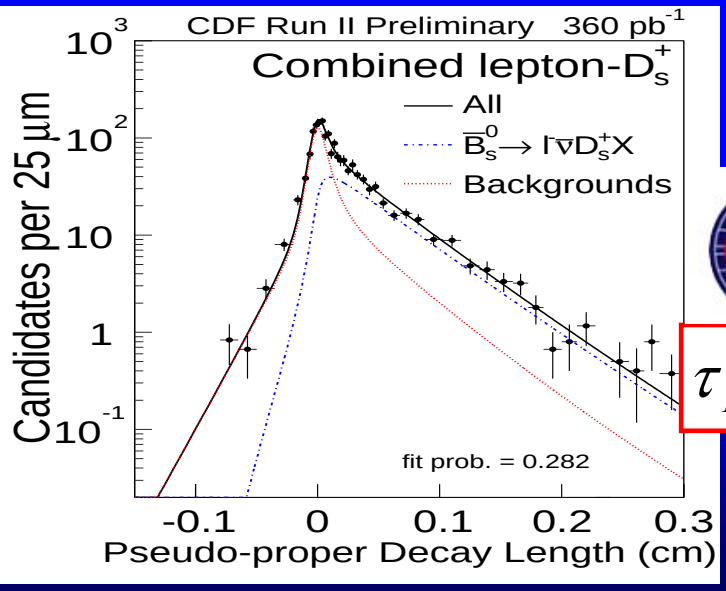


$$\tau_{FS}(B_s) = 1.381 \pm 0.055^{+0.052}_{-0.046}\, ps$$

$$\tau_{FS}(B_s, WA) = 1.440 \pm 0.036\, ps$$

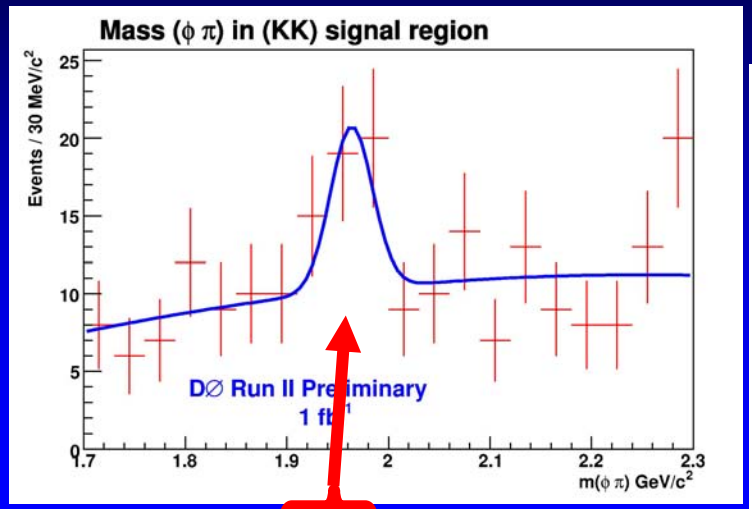
$B_s \to D_s^{(*)} D_s^{(*)}$

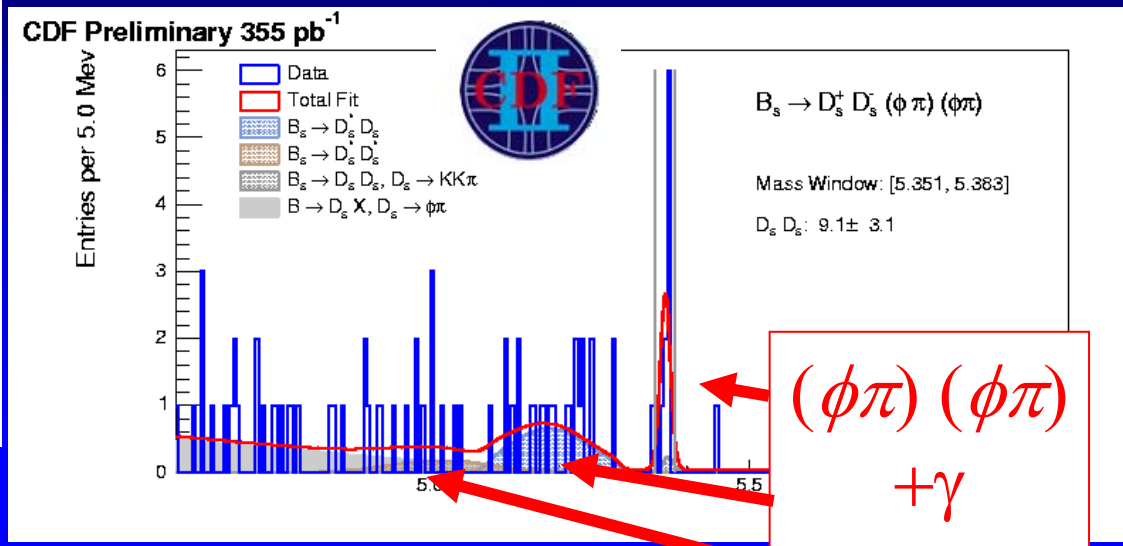
- Current assumption: ~all CP even ⇒saturates $\Delta\Gamma$
  - Can be verified with more data.

$$BF(B_s \to D_s^{(*)} D_s^{(*)}) = \left(\frac{\Delta\Gamma}{2\Gamma}\right)\left(1 + O\left(\frac{\Delta\Gamma}{\Gamma}\right)\right)$$

- DØ: partial reconstruction $D_s \to \phi\pi + D_s \to \phi\mu\nu$
  - Includes $D_s^* \to D_s\gamma$, direct measure of $\Delta\Gamma$
- CDF: full reconstruction $2\times D_s \to \phi\pi$
  - Doesn't include D_s^*, lower limit on $\Delta\Gamma$
- Both: error (and central value) dominated by $D_s \to \phi\pi$ BF

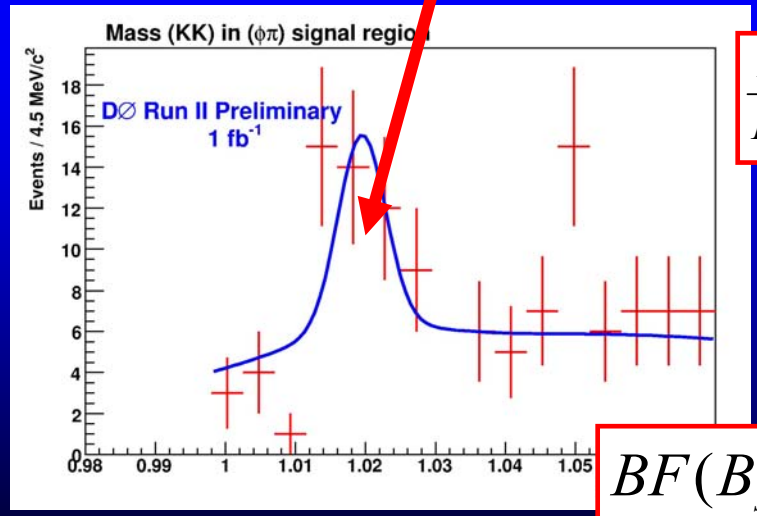
$B_s \to D_s^{(*)} D_s^{(*)}$





$(\phi\pi)\ (\phi\pi)$
$+\gamma$
$+\gamma\gamma$

$(\phi\pi)\ (\phi\mu\nu)$



$$\frac{BF(B_s \to D_s D_s)}{BF(B^0 \to D_s D^+)} = 1.67 \pm 0.41 \pm 0.12 \pm 0.24(f_s / f_d) \pm 0.39(BF)$$

$$BF(B_s \to D_s^{(*)} D_s^{(*)}) = 0.071 \pm 0.032^{+0.029}_{-0.025}$$

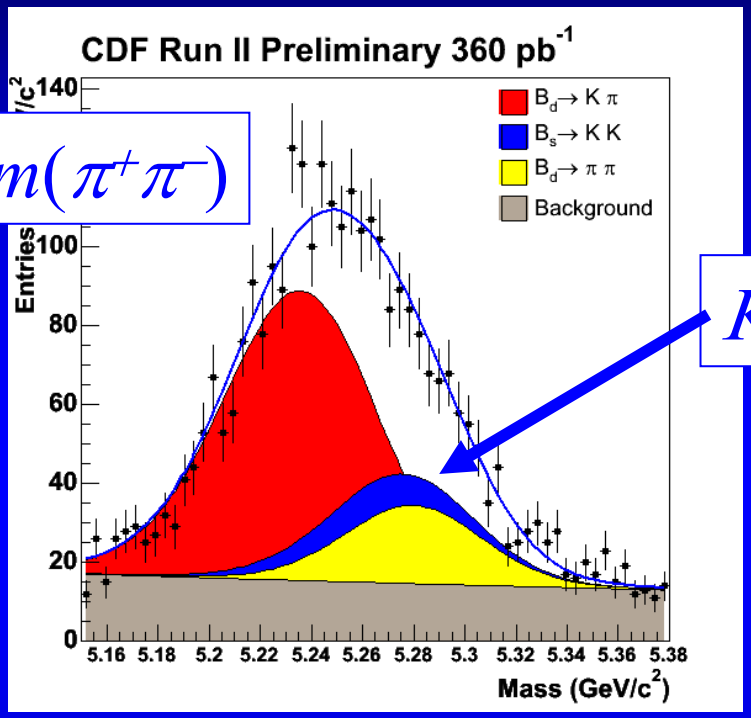
$B_s \to K^+K^-$

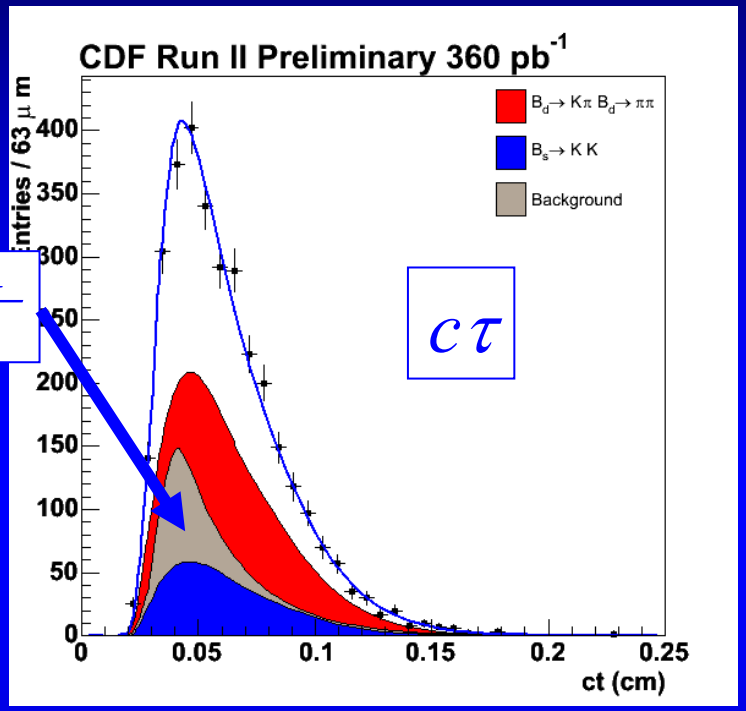
- Most straight forward measurement
  - Pure CP final state
  - Analog of $K_S \to \pi^+\pi^-$
  - No CPV: direct measure of τ_L
  - Future: any indication of K^+K^- on τ_H path
    $\Rightarrow$ *unambiguous CPV*

- Straight forward to understand, hard to do.
  - Large and complicated h^+h^- sample
  - Lifetime biasing trigger

- Possible at CDF due to displaced track trigger

$B_s \to K^+K^-$



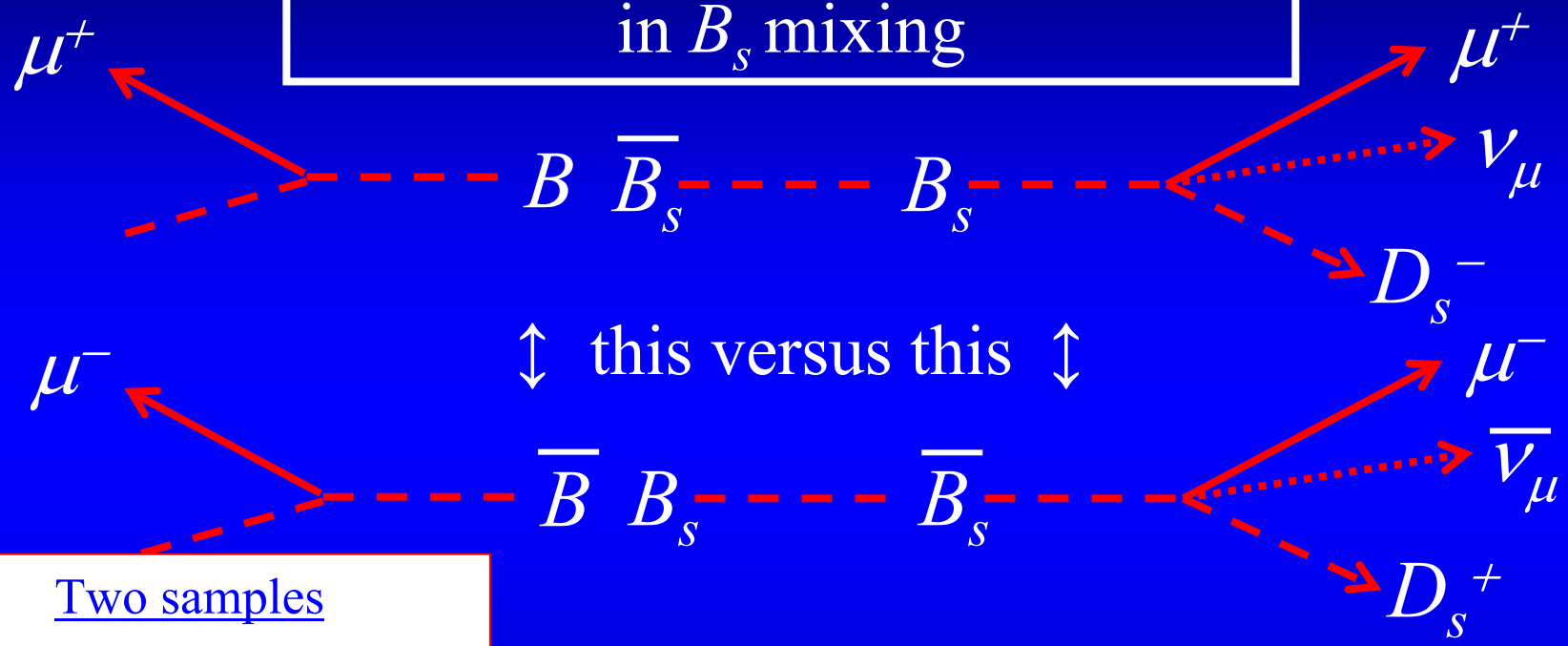


K^+K^-

$$\tau(B_s \to K^+K^-) = 1.53 \pm 0.18 \pm 0.02\, ps$$

A_{SL} Measurements

Direct measure of indirect CPV in B_s mixing



Two samples

Exclusive untagged $D_s\mu$

Inclusive like-sign $\mu\mu$

$$\frac{N(D_s\mu^+)-N(D_s\mu^-)}{N(D_s\mu^+)+N(D_s\mu^-)} = A_{SL}(untagged) \approx \frac{\Delta\Gamma}{\Delta m}\tan\phi$$

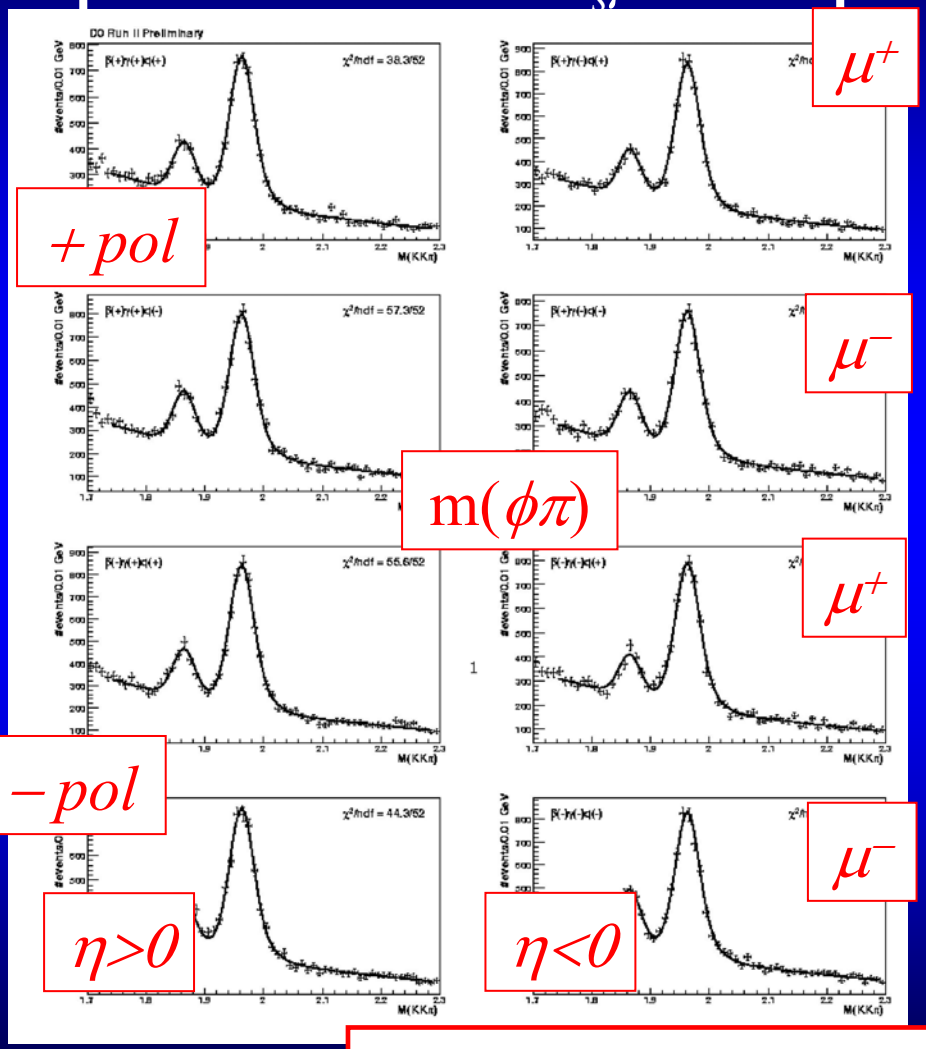
$$\frac{N(\mu^+\mu^+)-N(\mu^-\mu^-)}{N(\mu^+\mu^+)+N(\mu^-\mu^-)} = A_{SL}(tagged) = 2A_{SL}(untagged)$$

Main Systematics

- Detector related asymmetries:
  - Main asymmetry due to spectrometer geometry
  - Controlled by looking at charge asymmetry for different magnet polarities and different η regions.
- Kaon decay in flight:
  - Asymmetric due to hadronic interactions
  - Measured directly in data using kaons tagged from D^* decay

A_{SL} Results

Exclusive $D_s\mu$



$$A_{SL}(B_s) = 0.025 \pm 0.019 \pm 0.004$$

Inclusive dimuon

$$A_{SL} = -0.0092 \pm 0.0044 \pm 0.0032$$

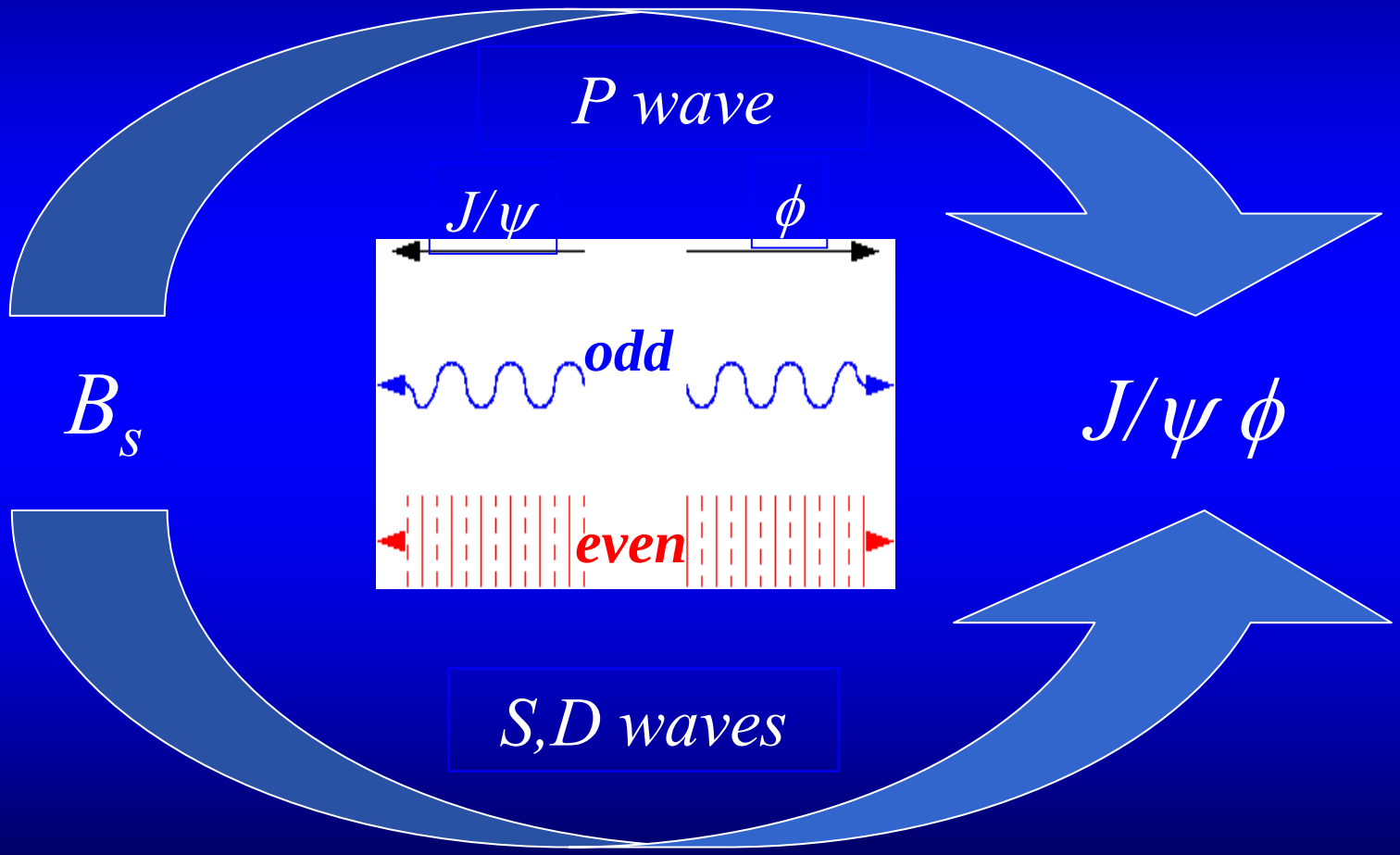
$$A_{SL} = A_{SL}(B_d) + \frac{f_s Z_s}{f_d Z_d} A_{SL}(B_s)$$

Using WA $A_{SL}(B_d)$:

$$A_{SL}(B_s) = -0.015 \pm 0.011$$

$B_s \rightarrow J/\psi\ \phi$

Analog to $B^0 \rightarrow J/\psi\ K_S$ but VV instead of VP



$B_s \rightarrow J/\psi\, \phi$

Time evolution: pure even case

$$\Gamma(t) \approx \left| A_{even}(t) \right|^2$$

$$f(t, even) \approx e^{-\Gamma_L t}$$

$B_s \rightarrow J/\psi\, \phi$

Time evolution: even plus odd components

$$\Gamma(t) \approx \left|A_{even}(t)\right|^2 + \left|A_{odd}(t)\right|^2$$

$$+ A^* A(CPC)$$

CP conserving interference

$$f(t, even) \approx e^{-\Gamma_L t}$$

$$f(t, odd) \approx e^{-\Gamma_H t}$$

CP states = heavy, light states

$B_s \to J/\psi\,\phi$

Time evolution: even plus odd plus CPV

$$\Gamma(t) \approx \left|A_{even}(t)\right|^2 + \left|A_{odd}(t)\right|^2$$

$$+ A^* A(CPC)$$

CP conserving interference

$$+ A^* A(CPV)$$

CP violating interference between two paths

$$f(t, even) \approx (1+\cos\phi_s)e^{-\Gamma_L t} + (1-\cos\phi_s)e^{-\Gamma_H t}$$

$$f(t, odd) \approx (1+\cos\phi_s)e^{-\Gamma_H t} + (1-\cos\phi_s)e^{-\Gamma_L t}$$

Heavy and light states are mixed CP

$B_s \to J/\psi\,\phi$

Time evolution: even plus odd plus CPV

$$\Gamma(t) \approx \left|A_{even}(t)\right|^2 + \left|A_{odd}(t)\right|^2$$

$$+ A^* A(CPC)$$

$$+ A^* A(CPV)$$

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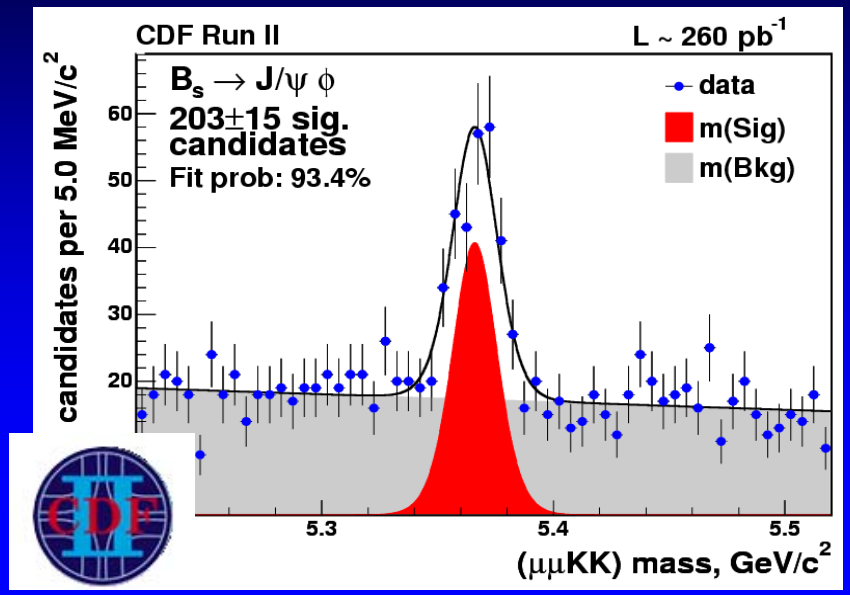
CP conserving interference

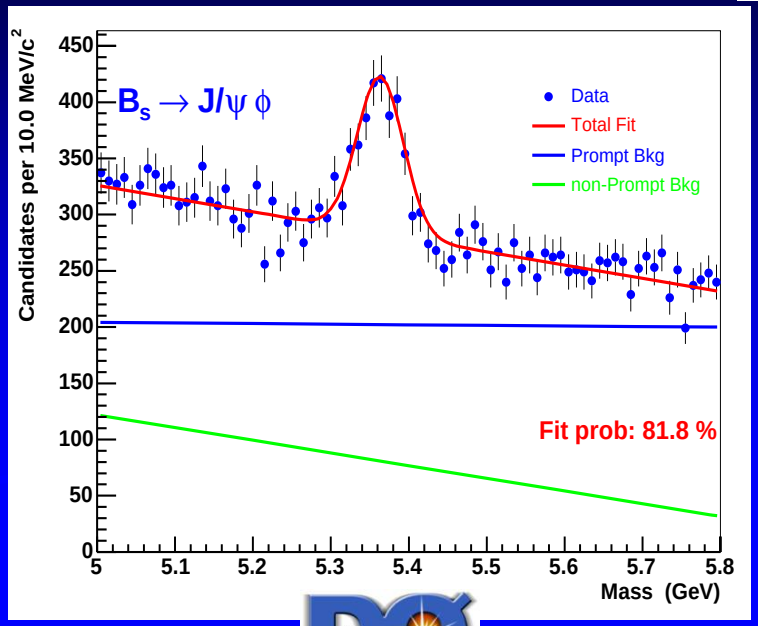
CP violating interference between two paths

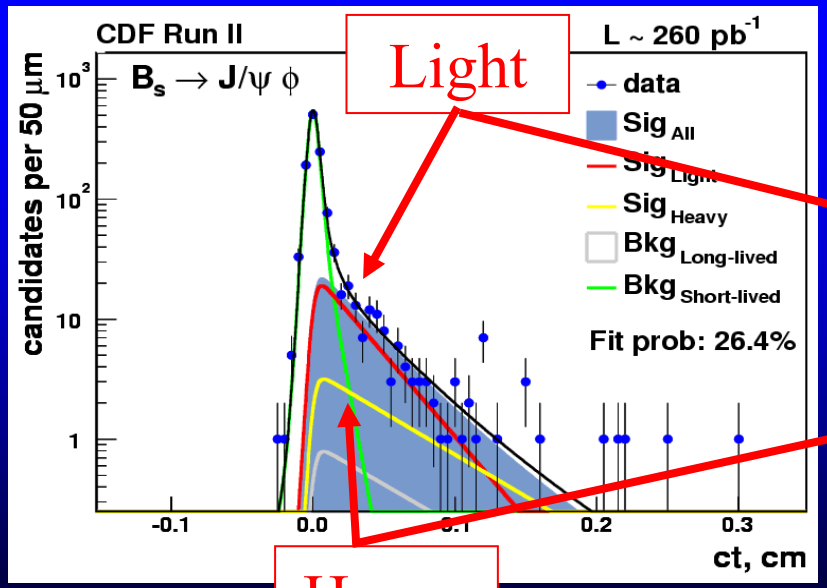
Heavy and light states are mixed CP

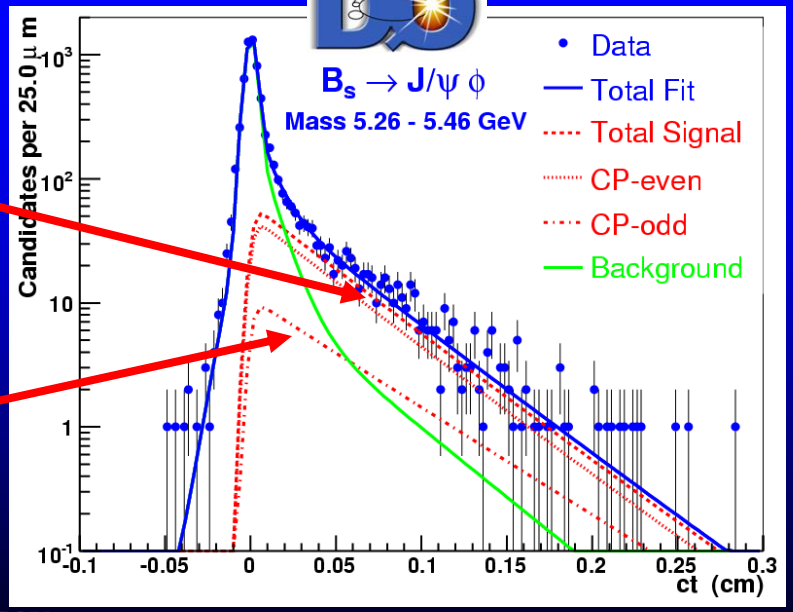
Same as seeing $K_L \to \pi^+\pi^-$

$B_s \rightarrow J/\psi\ \phi$ Results

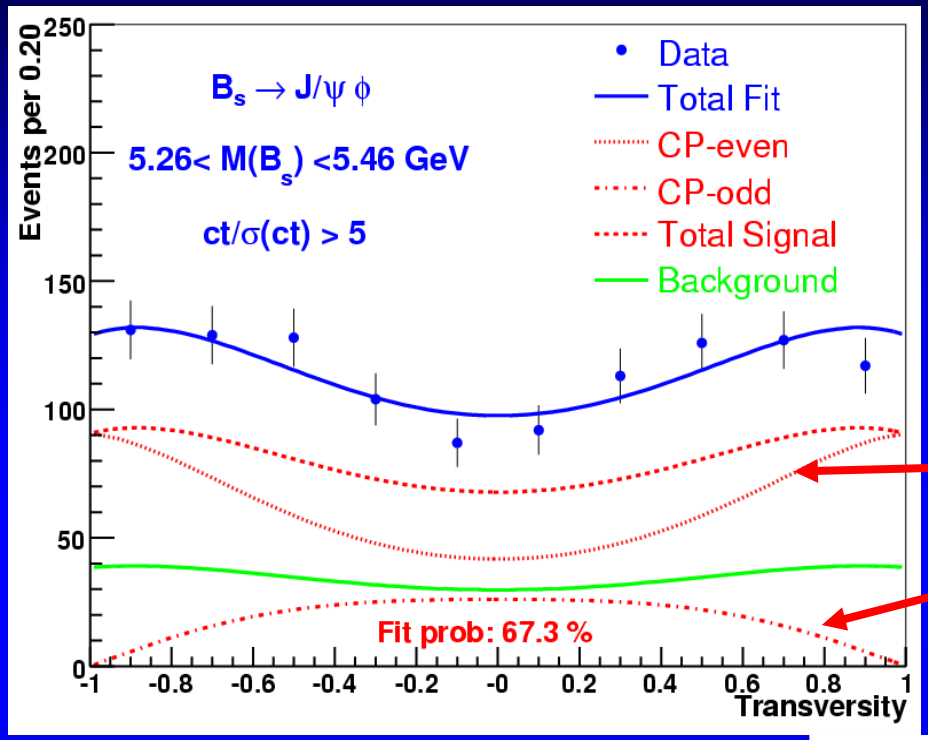








$B_s \to J/\psi\,\phi$ Results



even

odd

$$\Delta\Gamma_s = 0.17 \pm 0.09 \pm 0.03\, ps^{-1}$$

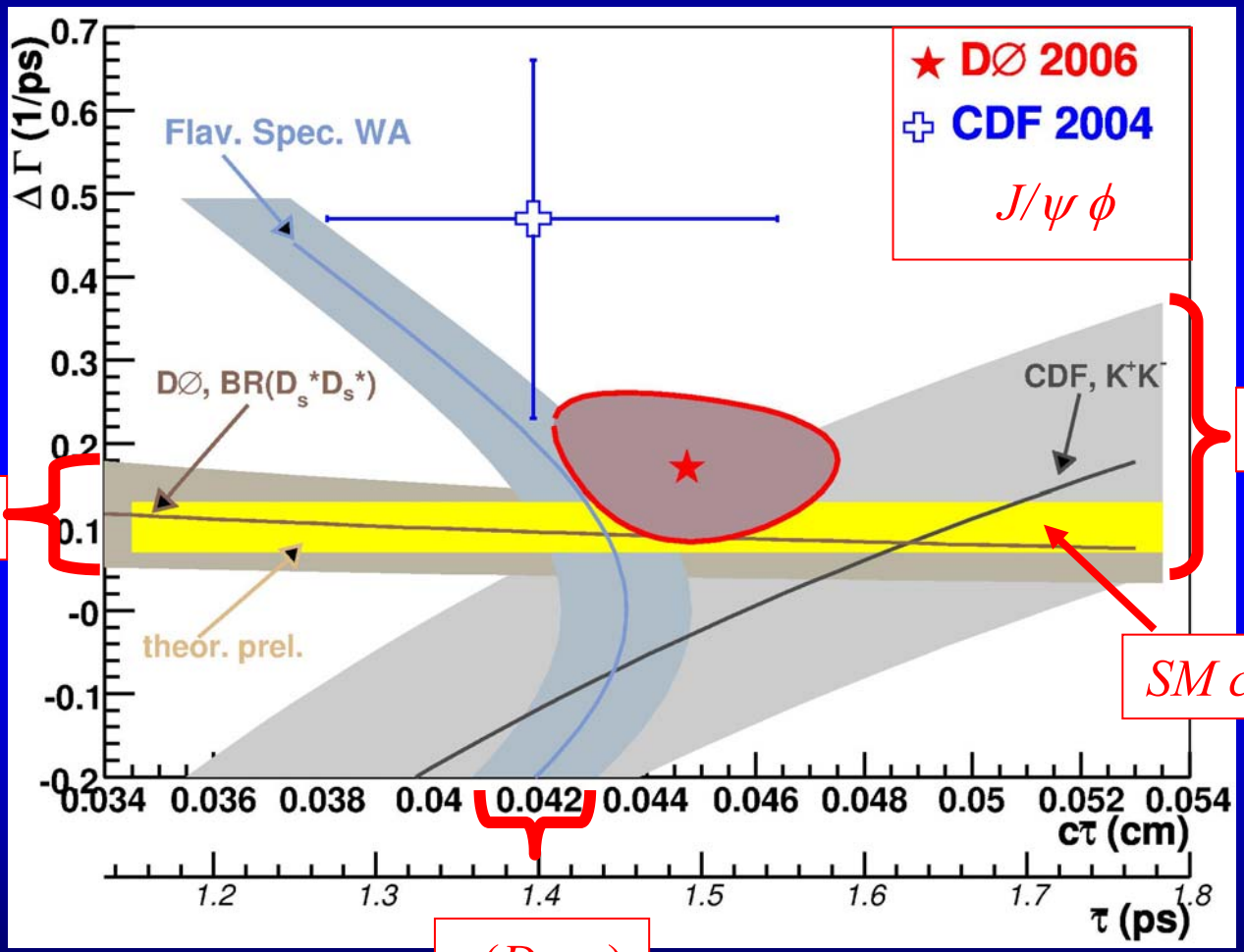
$$\phi_s = -0.79 \pm 0.56 \pm 0.01$$

$$\tau_s = 1/\Gamma_s = 1.49 \pm 0.08^{+0.01}_{-0.03}\, ps$$

ΔΓ Results

(Only DØ J/ψ φ allows $\phi_s \neq 0$ in his plot)

ΔΓ (ps^{-1})



$BF(D_s^{(*)}D_s^{(*)})$

$\tau(K^+K^-)$

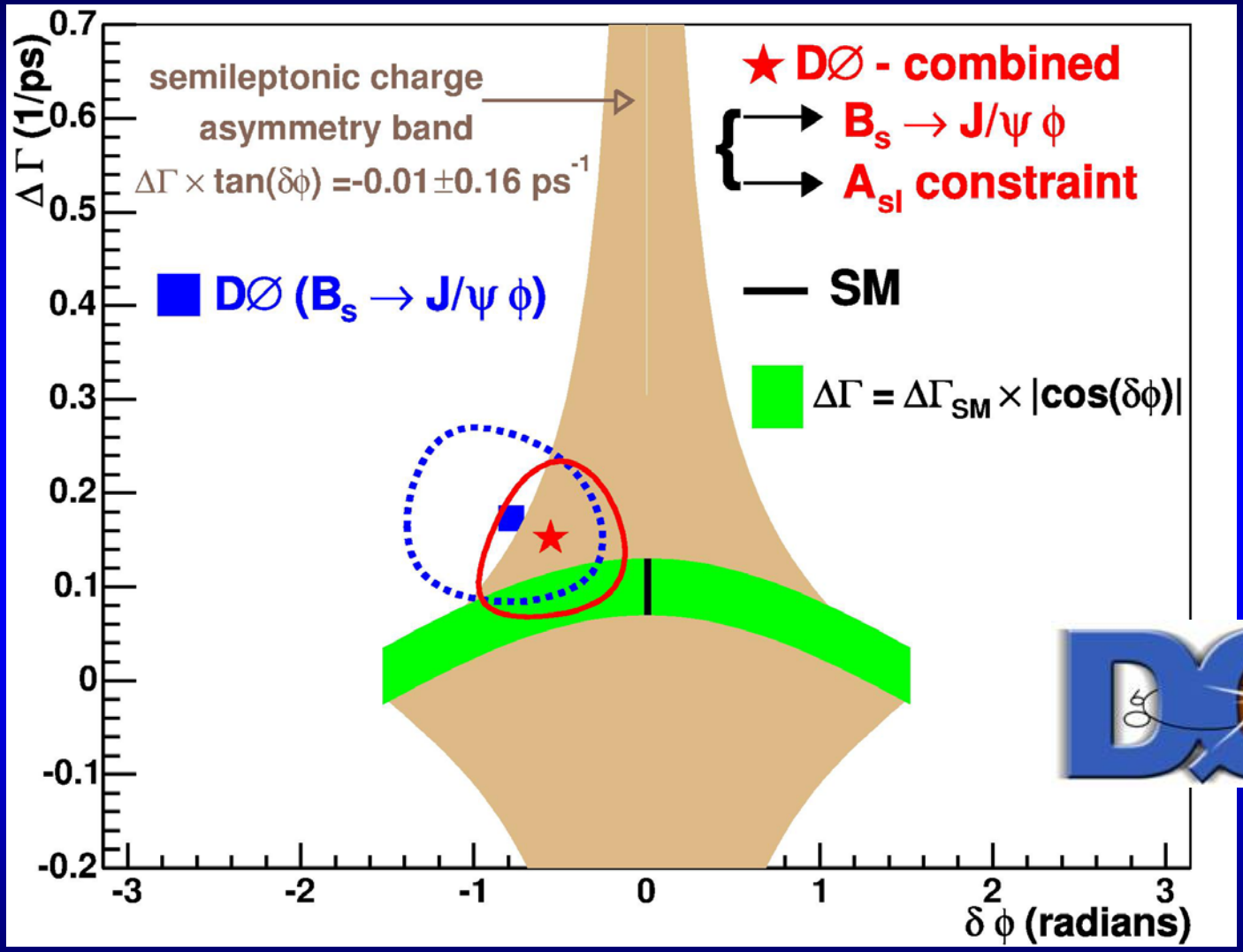
SM calculation

$\tau(D_s\mu\nu)$

Average τ

ϕ_s Results

$\Delta\Gamma$ (ps^{-1})



ϕ_s

Conclusions

- Now have information on all B_s mixing parameters from the Tevatron experiments.
  - Very diverse program giving consistent results:
    - Δm_s consistent with SM/CKM expectations
    - $\Delta\Gamma$ consistent with SM calculations
    - Interesting ϕ_s parameter space accessible at the Tevatron
    - Excellent example of the complementary aspects of the DØ and CDF programs
- Expect rapid improvements in precision on ϕ_s
  - Doubling data set
  - Results from both experiments based on full data set
  - New modes and new techniques

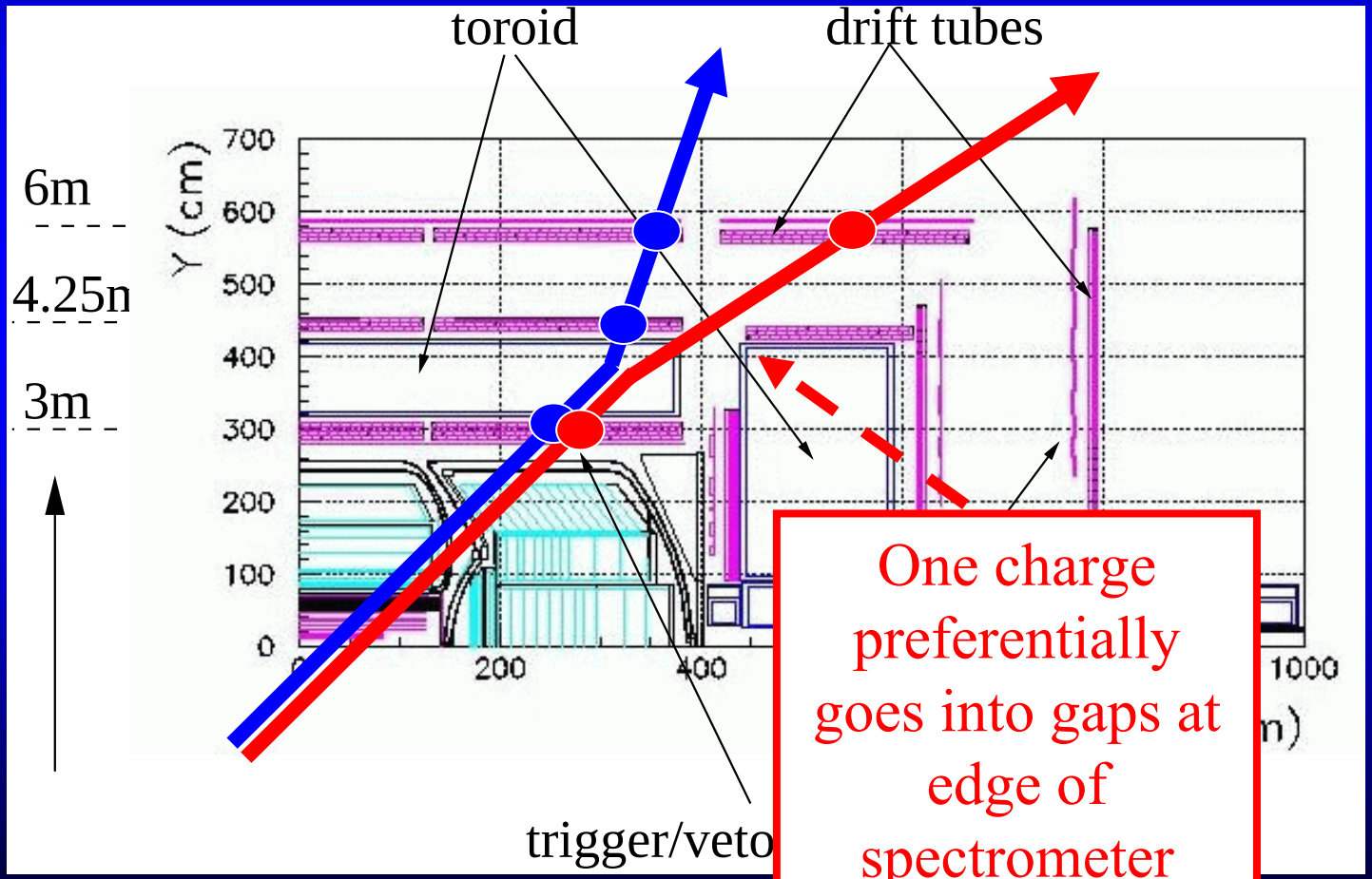
Backup

$B_s \to K^+K^-$

- More details:
  - K^+K^- is always CP even
  - No indirect CPV: even state = light state
  - Also need to worry about direct CPV in the $b \to u$ tree
    - Tree pollution complicates the translation to $\Delta\Gamma$

Detector Systematics

Main detector related systematic is due to geometry in muon spectrometer

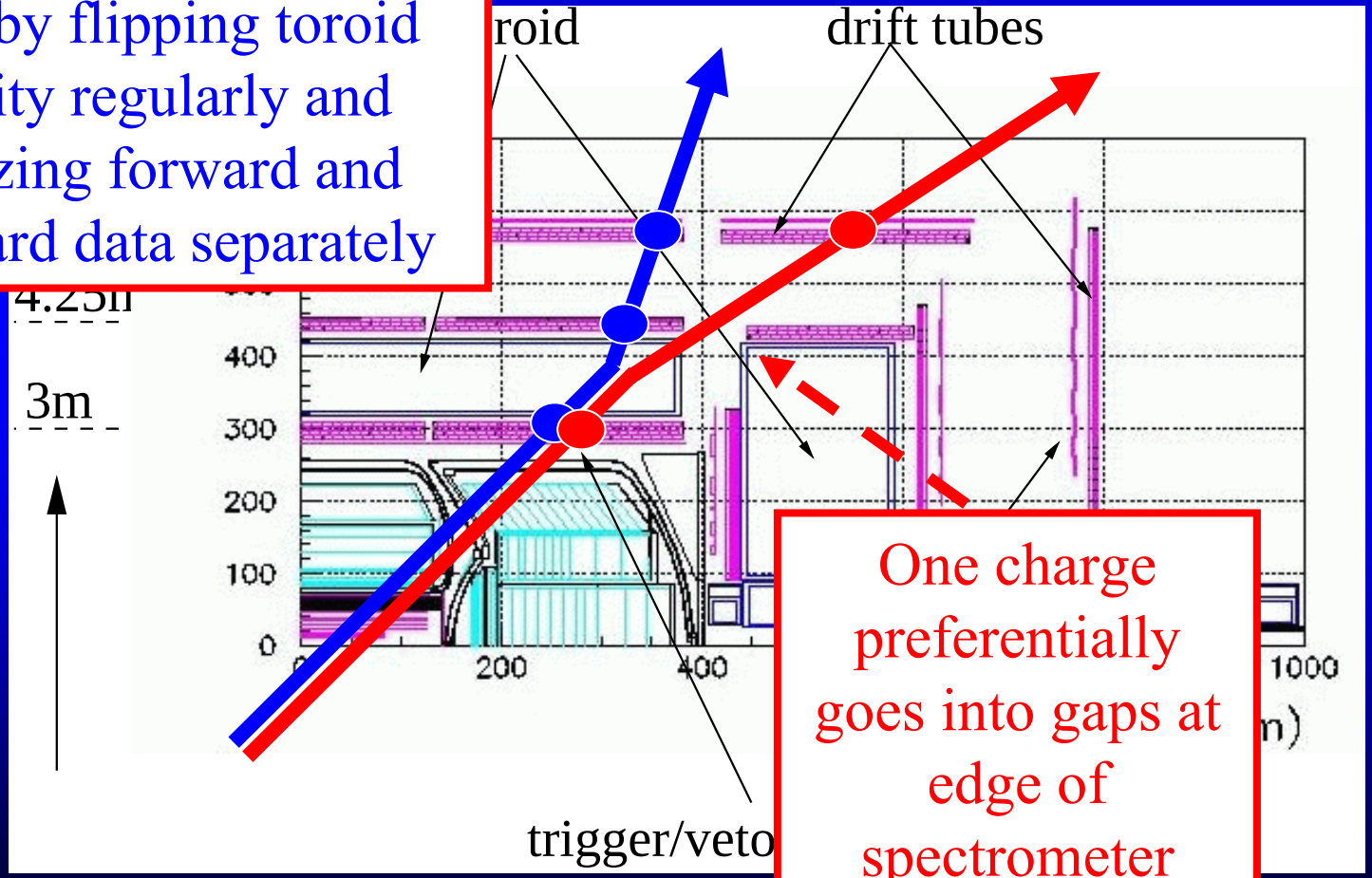


One charge preferentially goes into gaps at edge of spectrometer

Detector Systematics

Main detector related systematic is due to geometry in muon spectrometer

Solve by flipping toroid polarity regularly and analyzing forward and backward data separately



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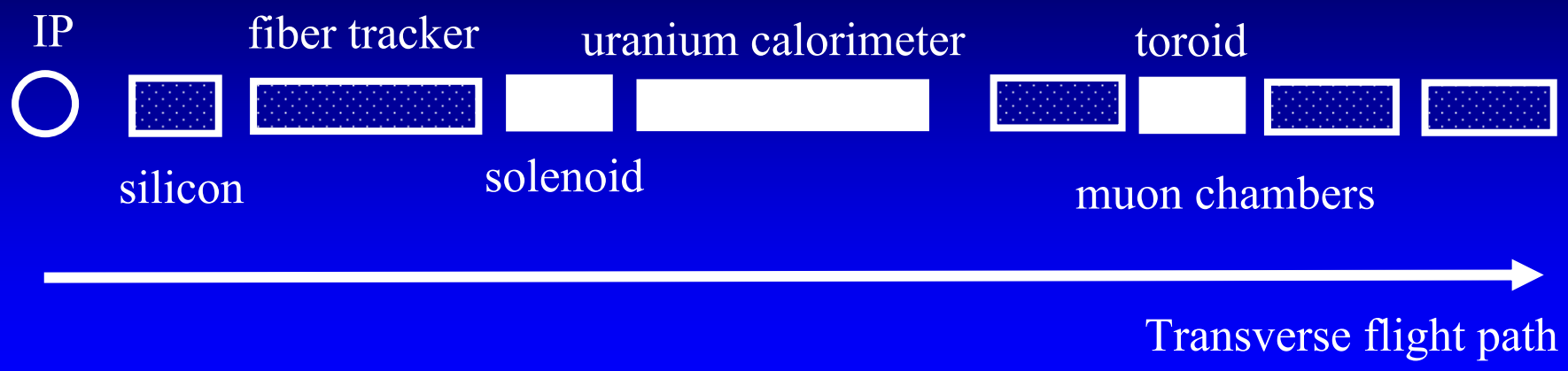
Physics Systematics: Kaon Decay



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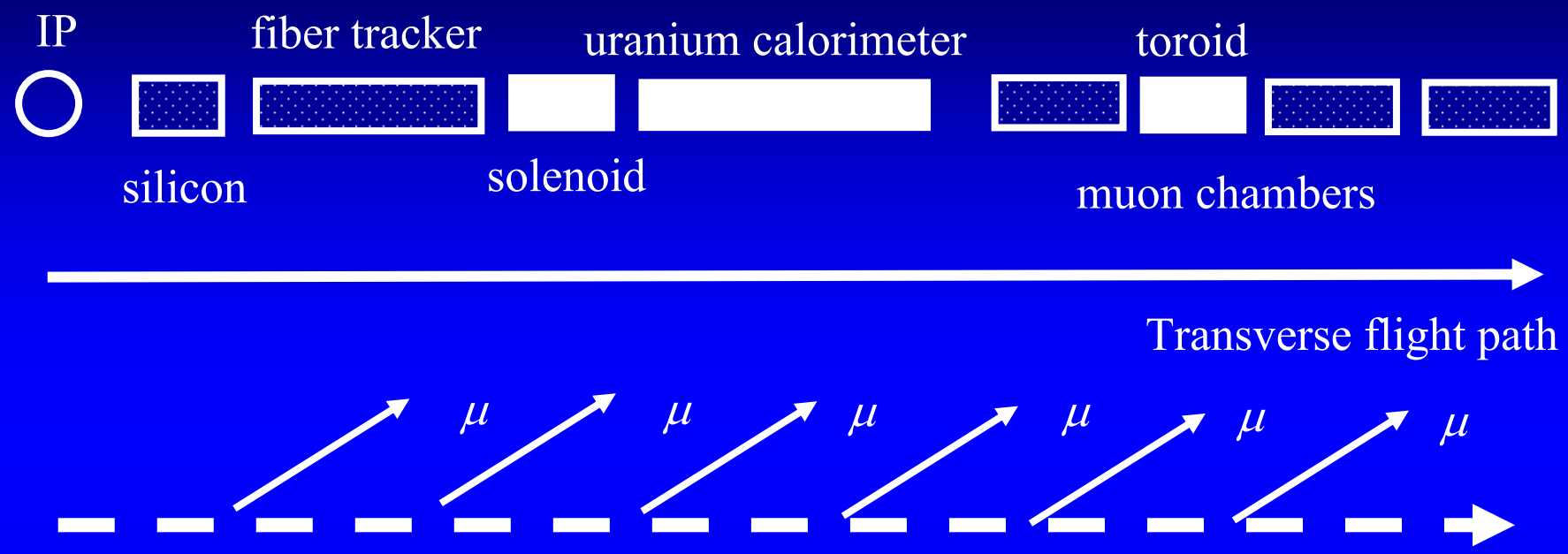
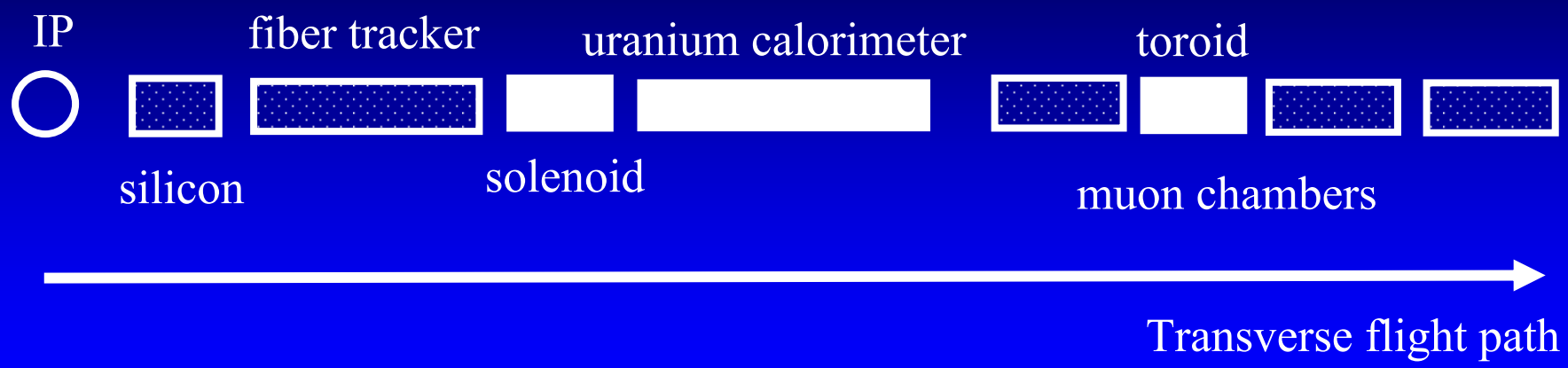


K^+ produce μ^+ from weak decay

Physics Systematics: Kaon Decay



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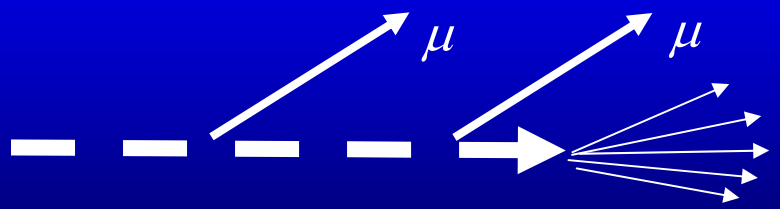
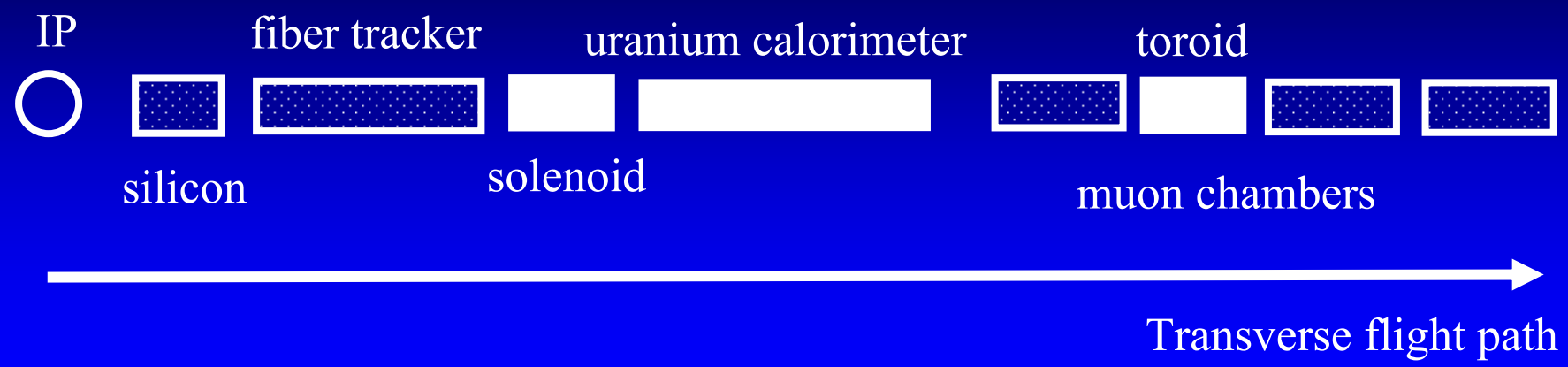
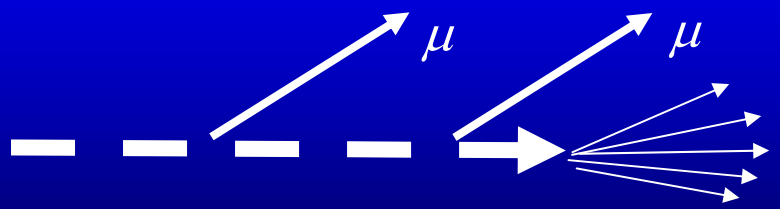


K^- stop more frequently in calorimeter from $K^- + N \rightarrow Y + \pi$ nuclear interactions. (No K^+ analog)

Physics Systematics: Kaon Decay



K^+ produce μ^+ from weak decay



Measured directly in data using kaons tagged from D* decay

K^- stop more frequently in calorimeter from $K^- + N \rightarrow Y + \pi$ nuclear interactions. (No K^+ analog)