Probing the origin of matter/antimatter asymmetry at DØ with

$5fb^{-1}$

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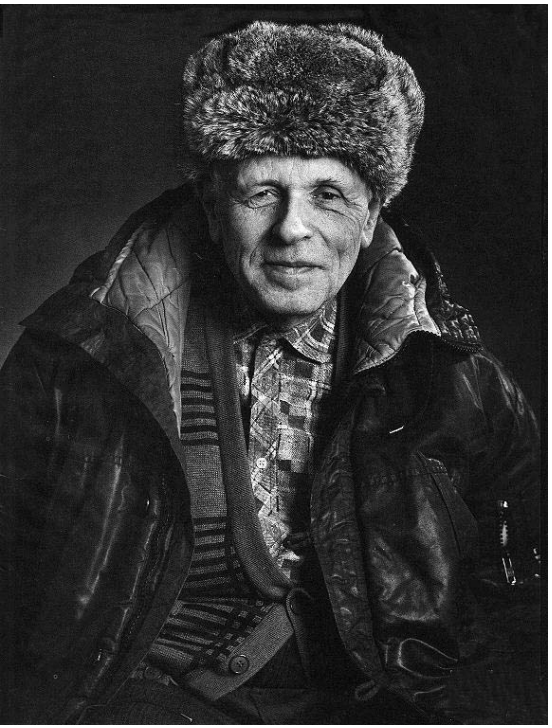
W&C

Fermilab

24 April 2009

Sakharov's conditions of our Universe existence



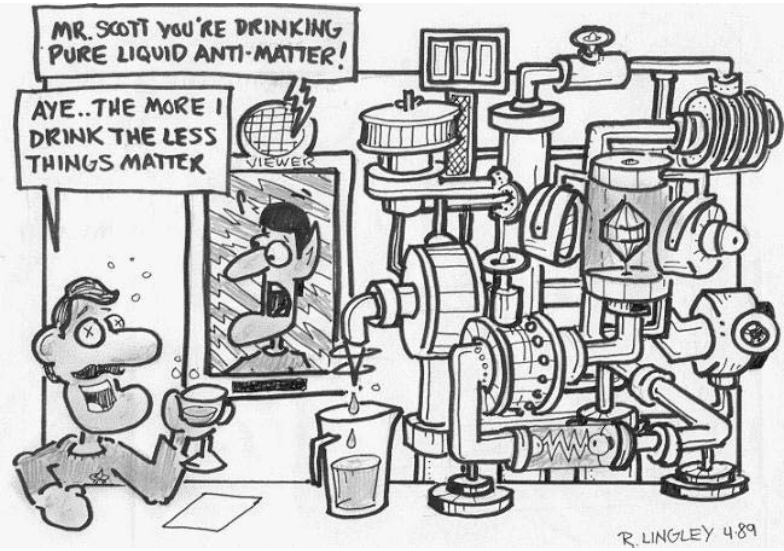
- They were formulated in 1967
- Inspired by the CP violation discovery in the kaon system

- Baryon number violation

- C, CP violation

- These processes happened when the Universe was not in thermal equilibrium

Baryon number violation



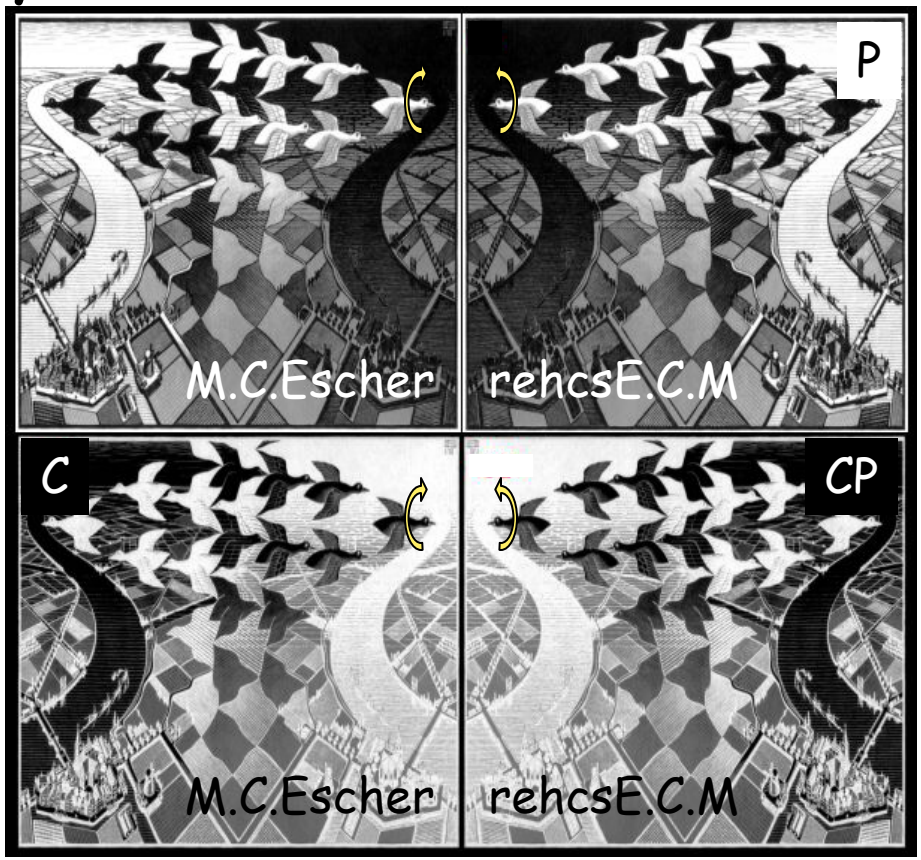
$$\frac{N_b(t) - N_{\bar{b}}(t)}{N_b(t) + N_{\bar{b}}(t)} \approx \frac{\Delta N_b}{N_\gamma}$$

$$Now: \quad \frac{\Delta N_b}{N_\gamma} = (6.1 \pm 0.3) \times 10^{-10} \quad \text{(WMAP)}$$

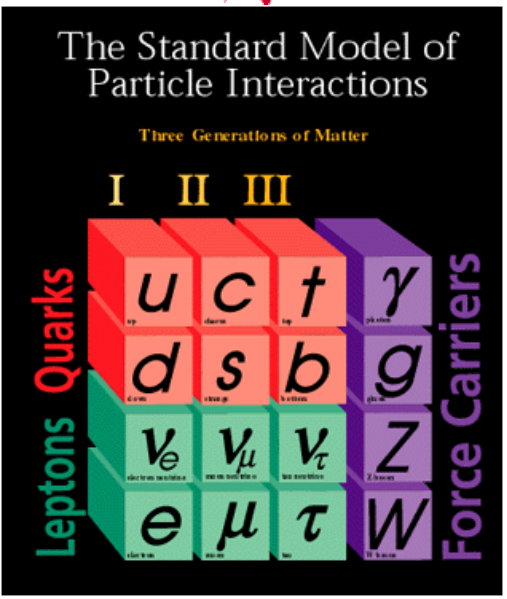
- Current estimates from the SM: ~10^{-20}
- 10 orders of magnitude difference

CP violation

- CP violation (CPV) – violation of symmetry of physics laws in combined Charge-conjugate and Parity transformation



Standard Model



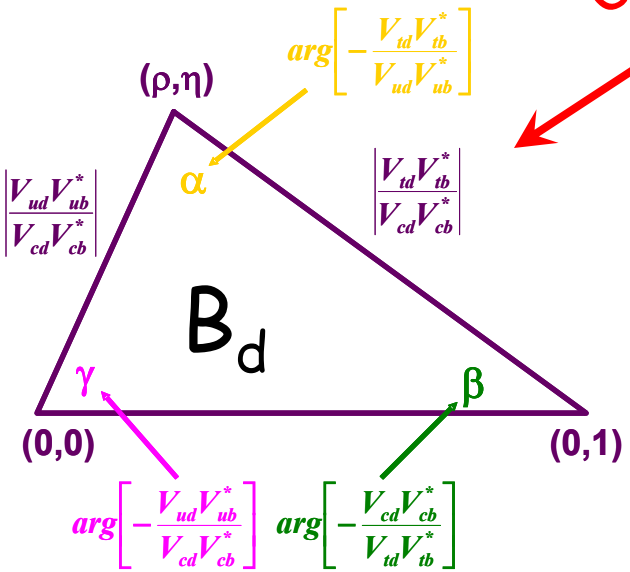
- Standard Model Lagrangian

$$L = \frac{g}{\sqrt{2}}\left(\overline{u},\overline{c},\overline{t}\right)_L \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma_\mu \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W^\mu + h.c.$$

$$= V_{CKM}$$

Unitarity

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



Area of the Unitarity Triangle is proportional to the CP violation in the Standard Model due to CKM Matrix

Sides and angles of the Triangle could be determined using many physics processes → Consistency check

Explanation by G.W.S.Hou @ W&C 2/6/2009

$$\frac{n_{\bar{\mathcal{B}}}}{n_\gamma} \cong 0$$

$$\frac{n_{\mathcal{B}}}{n_\gamma} = (6.2 \pm 0.2) \times 10^{-10}$$

WMAP

$$\mathrm{KM} \sim 10^{-20}$$

Too Small in SM

Jarlskog Invariant in SM3

(need 3 generation in KM)

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

Normalize by T ~ 100 GeV

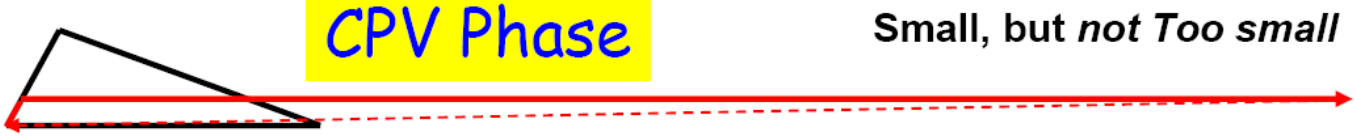
$$J/T^{12} \sim 10^{-20}$$

EW Phase Transition Temperature ~ v.e.v.

Masses too Small!

$$A \sim 3 \times 10^{-5}$$ in SM is common (unique) area of triangle

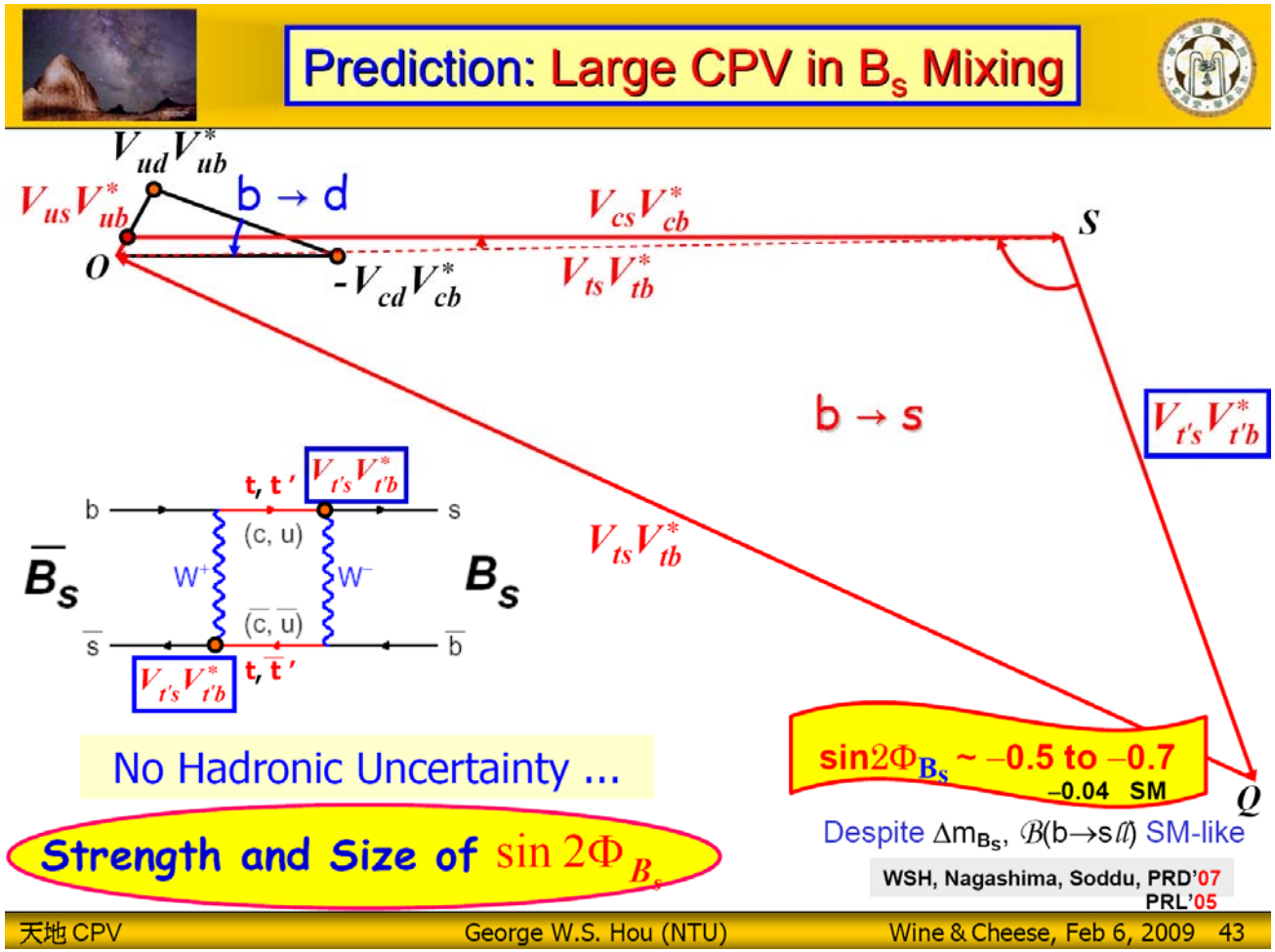
CPV Phase



Small, but *not Too small*

4th Generation helps!

- Explains large CPV in Bs mixing
- Explains the Kπ puzzle in B_u/B_d: $\Delta A = A_{K^+\pi^0} - A_{K^+\pi^-} \sim 15\%$



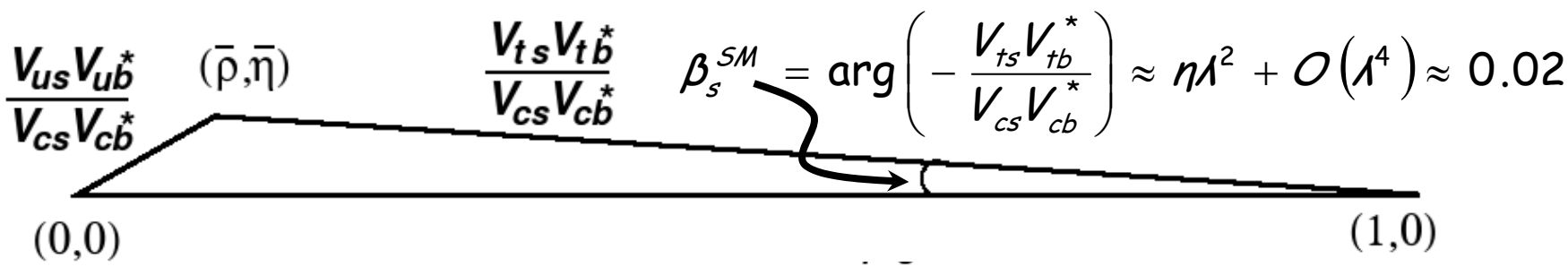
- Baryon asymmetry due to the new CKM^4 matrix could gain $\sim 10^{+15}$!

CPV: CKM matrix

- Wolfenstein parameterization of CKM matrix

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2\left(1-\frac{1-2\rho}{2}\lambda^2 + i\eta\lambda^2\right) & 1 \end{pmatrix} + O(\lambda^4)$$

- $\lambda = \sin(\theta_{Cabibbo}) \approx 0.23$
- $\eta \approx 0.35$ – CP violation in SM
- From unitarity ➔ $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$ for B_S system

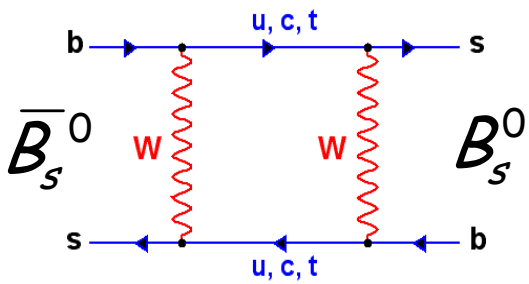


- Angle β_s in SM small ➔ NP effects more accessible

$B_s^0 - \overline{B_s^0}$ Mixing & CP parameters

Flavor eigenstates propagate according to the Schrödinger Eq.

$$i\frac{d}{dt}\begin{pmatrix} |B_s^0(t)\rangle \\ |\overline{B_s^0}(t)\rangle \end{pmatrix} = \begin{pmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M - i\frac{\Gamma}{2} \end{pmatrix}\begin{pmatrix} |B_s^0(t)\rangle \\ |\overline{B_s^0}(t)\rangle \end{pmatrix}$$



Mass eigenstates

$$|B_L\rangle = \frac{1}{\sqrt{p^2+q^2}}\left(p\,|B_s^0\rangle + q\,|\overline{B}_s^0\rangle\right)$$

$$|B_H\rangle = \frac{1}{\sqrt{p^2+q^2}}\left(p\,|B_s^0\rangle - q\,|\overline{B}_s^0\rangle\right)$$

$\rightarrow$

$$\Delta m_s = M_H - M_L \approx 2|M_{12}|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\varphi_s$$

If $q/p=1$ ➔ No CP violation

$$\textit{Phase} \quad \varphi_s^{SM} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \sim 0.004$$

- New Physics effects $\quad \varphi_s^{SM} \rightarrow \varphi_s^{SM} + \varphi_s^{\Delta}$

Semileptonic B_s asymmetry

- Directly related to the CPV:

$$a^s_{sl} = \frac{\Gamma\left(\bar{B}_s(t) \to f\right) - \Gamma\left(B_s(t) \to \bar{f}\right)}{\Gamma\left(\bar{B}_s(t) \to f\right) + \Gamma\left(B_s(t) \to \bar{f}\right)}$$

- $a^s_{fs} = a^s_{sl} = \Delta\Gamma_s / \Delta m_s \tan(\varphi_s)$
- New Physics parameterization (A.Lenz&U.Nierste)

$$M_{12}^s \equiv M_{12}^{SM,s} \cdot \Delta_s \qquad \Delta_s \equiv |\Delta_s| e^{i\varphi_s^\Delta}$$

$$\Delta m_s = \Delta m_s^{SM} |\Delta_s| = (19.30 \pm 6.74) ps^{-1} \cdot |\Delta_s|$$

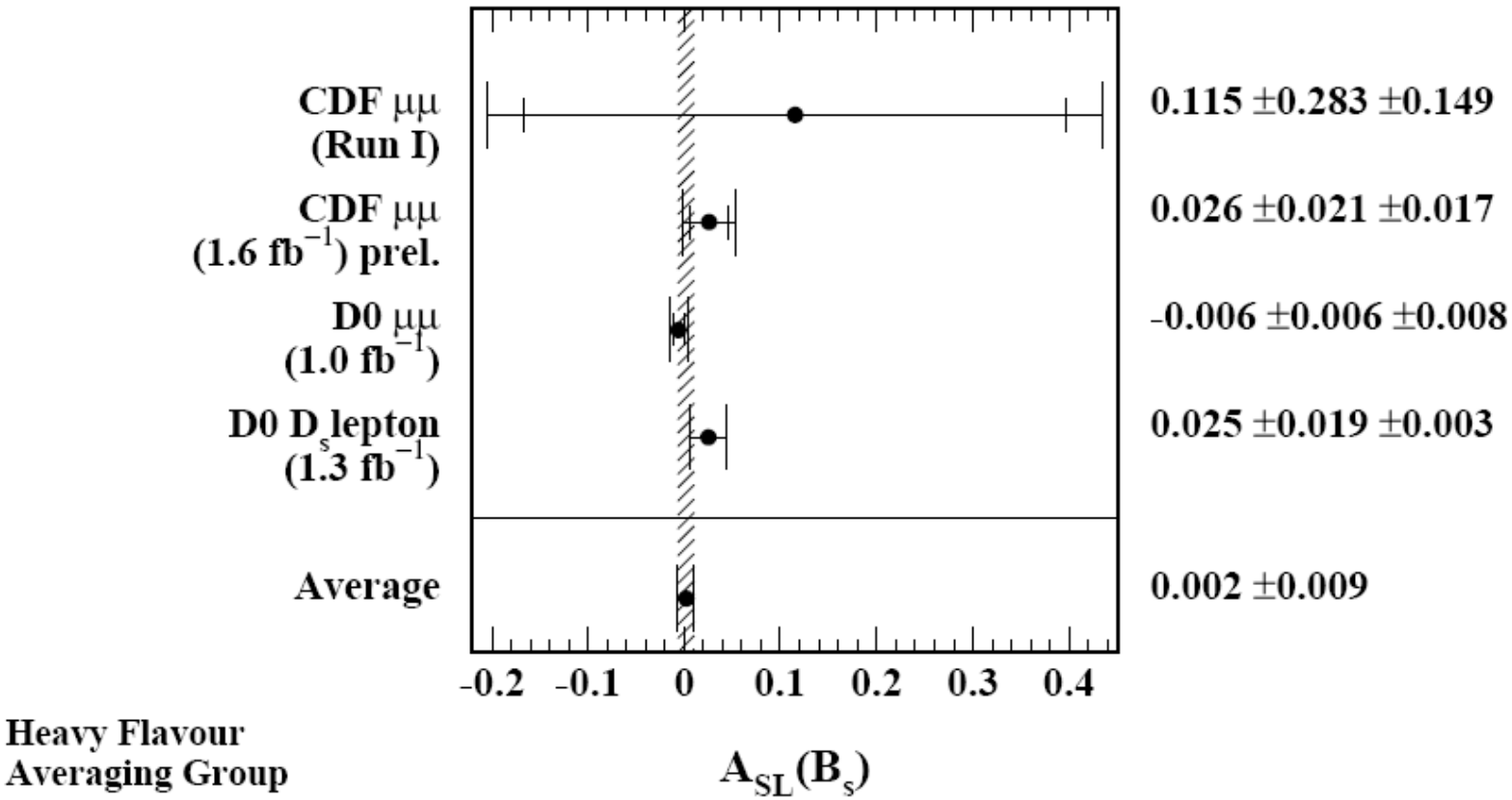
$$\Delta\Gamma_s = 2|\Gamma_{12}^s| \cos\left(\varphi_s^{SM} + \varphi_s^\Delta\right) = (0.096 \pm 0.039) ps^{-1} \cdot \cos\left(\varphi_s^{SM} + \varphi_s^\Delta\right)$$

$$a^s_{fs} = \frac{|\Gamma_{12}^s|}{|M_{12}^{SM,s}|} \cdot \frac{\sin\left(\varphi_s^{SM} + \varphi_s^\Delta\right)}{|\Delta_s|} = (4.97 \pm 0.94) \cdot 10^{-3} \cdot \frac{\sin\left(\varphi_s^{SM} + \varphi_s^\Delta\right)}{|\Delta_s|}$$

SM: $|\Delta_s| = 1$ and $\varphi_s^\Delta = 0$

- a^s_{sl} is very small in the SM: $+2 \cdot 10^{-5}$

Measurements of a^s_{sl}



- Estimate from $\Delta\Gamma_s$, ΔM_s and φ_s: $a^s_{sl}=-(8.4^{+5.2}_{-6.7})\cdot 10^{-3}$

Global fits

A.Lenz&U.Nierste

Just illustration...

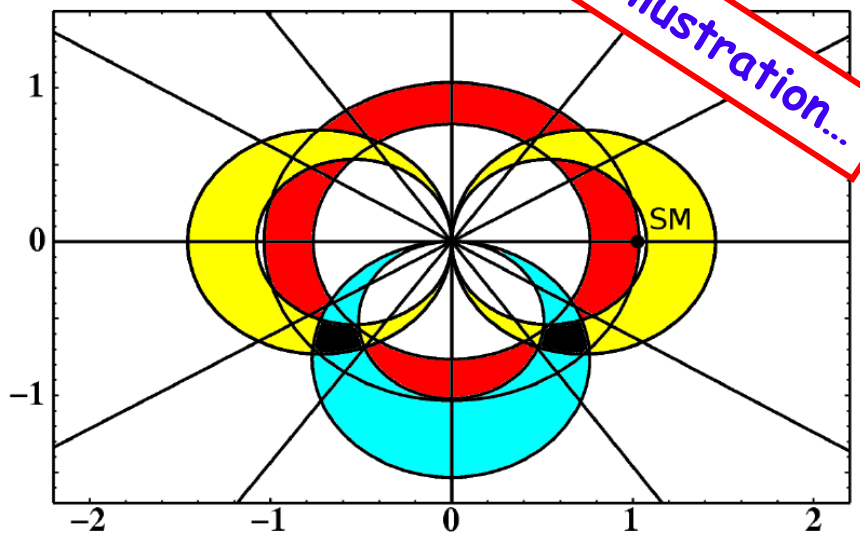
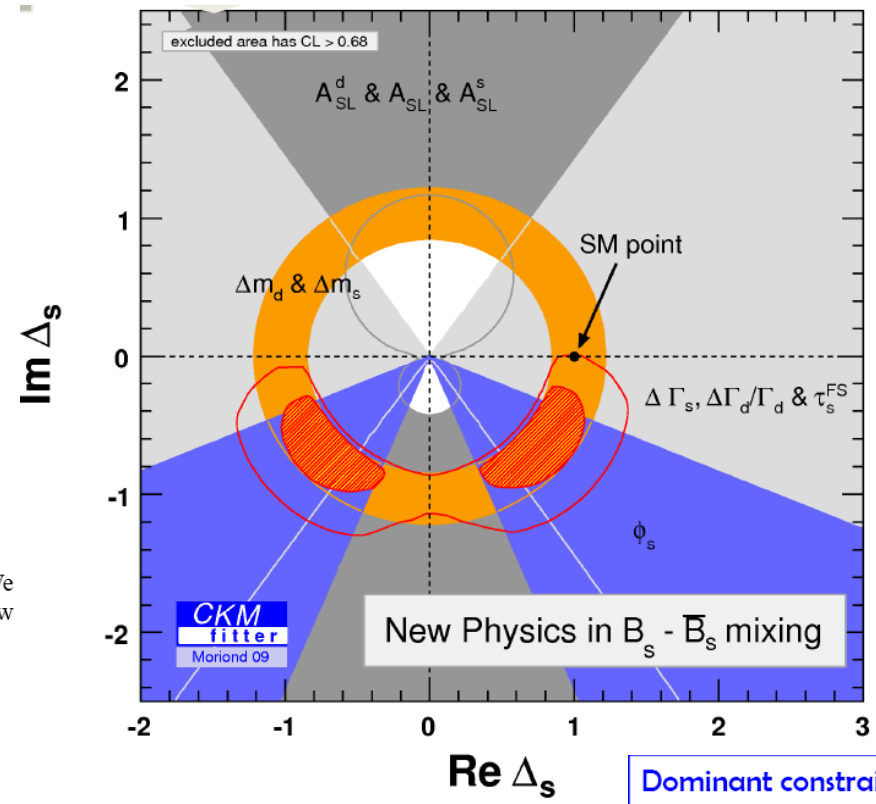


Figure 6: Illustration of the bounds in the complex Δ_s-plane for $|\Delta_s| = 0.9$ and $\phi_s^\Delta = -\pi/4$. We assume the following overall uncertainties: ΔM_s (red or dark-grey) : $\pm 15\%$, $\Delta\Gamma_s/\Delta M_s$ (yellow or light-grey): $\pm 15\%$, $a_{\rm fs}^s$ (light-blue or grey) : $\pm 20\%$ and ϕ_s^Δ (solid lines) : $\pm 20\%$.

V.Tisserand @ Moriond 09

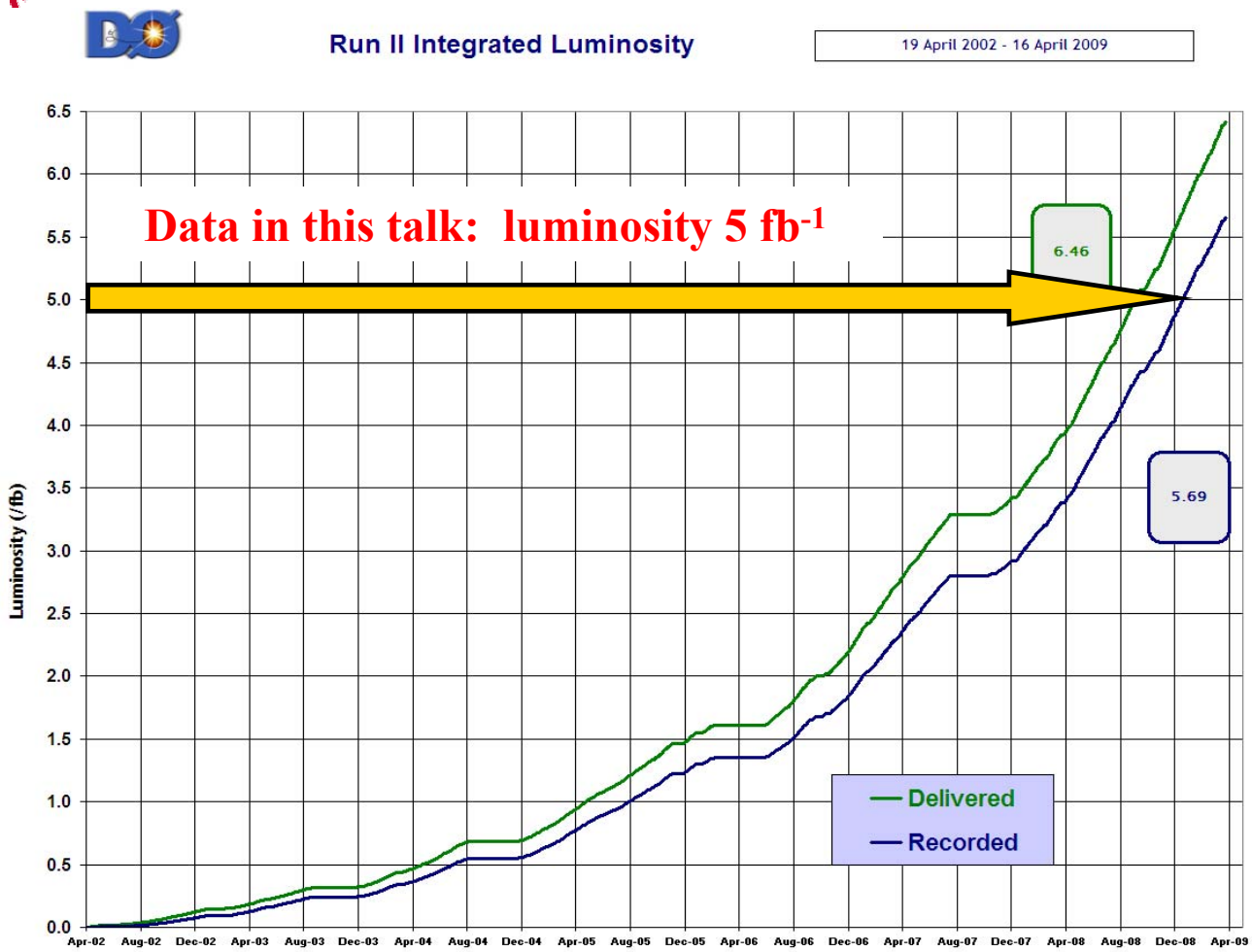


Dominant constraints:

- Δm_s agrees with SM.
- (ϕ_s=-2β_s,$\Delta\Gamma_s$) through time dependent angular analysis of Bs →J/ψφ by DØ/CDF (HFAG'08 update) is 2.2σ away from SM.

- The a_{sl} contributions are weak

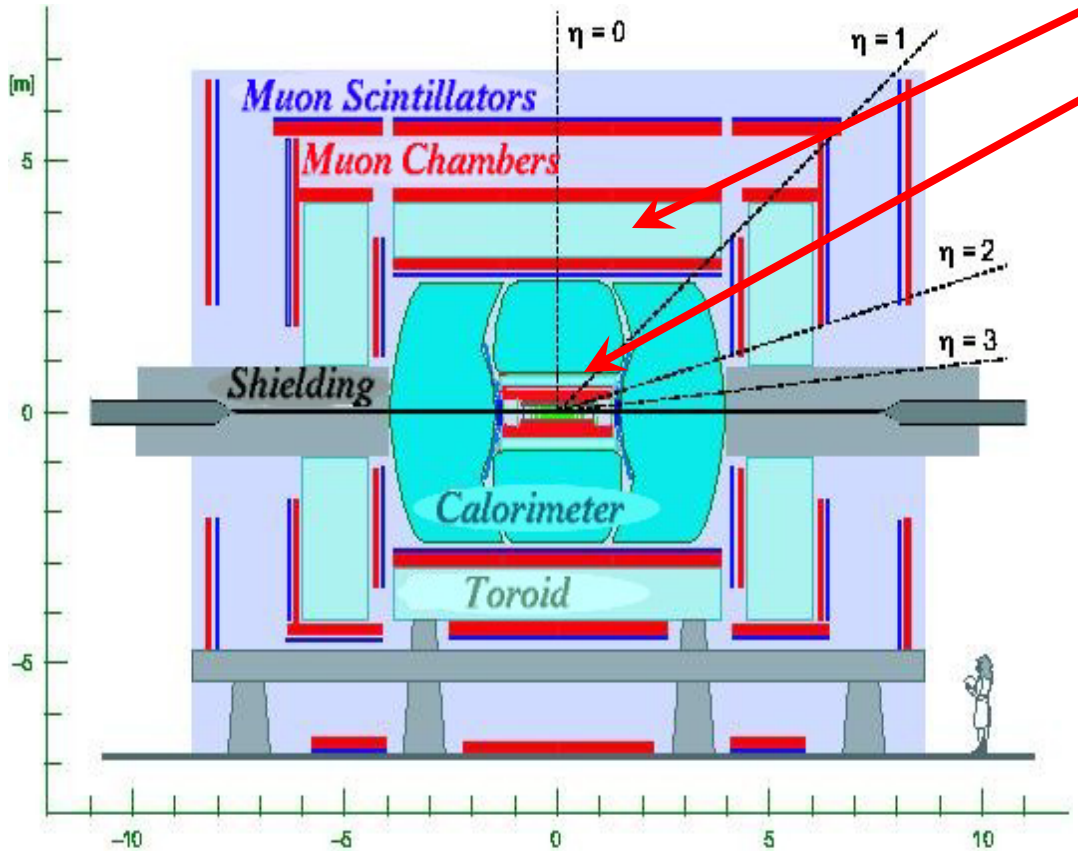
Available statistics



Thanks to the excellent performance of the Tevatron and the DZero detector

DZero Detector

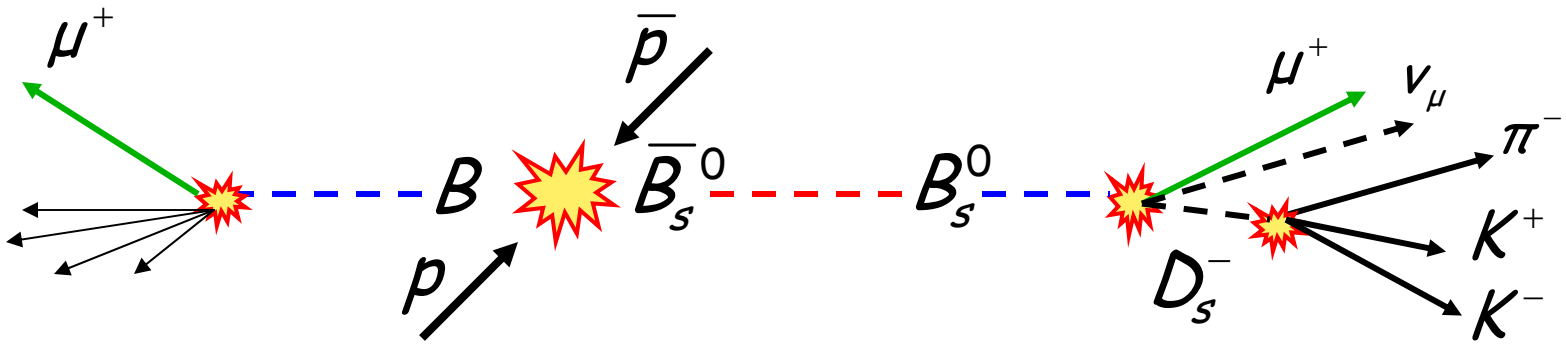
- Spectrometer : Fiber and Silicon Trackers in 2 T Solenoid
- Muons : 3 layer system & absorber in Toroidal field
- Hermetic : Excellent coverage of Tracking, Calorimeter and Muon Systems



Toroid & solenoid polarity flipped regularly

Low background single and dimuon triggers → large B→μX semileptonic samples

Analysis outline



- Charge of the muon at the same-side ➔ final state
- Charge of the muon at the opposite-side ➔ initial state

Truth level formulae for ΔM_s and CPV (fs case)

Direct decay rates:

$$\Gamma\left(B_s^0(t) \to \mu^+ X\right) = N_f \left|A_f\right|^2 e^{-\Gamma_s t} \left\{\cosh\frac{\Delta\Gamma_s t}{2} + \cos(\Delta M_s t)\right\} \Big/ 2$$

$$\Gamma\left(\overline{B}_s^0(t) \to \mu^- X\right) = N_f \left|\overline{A}_{\overline{f}}\right|^2 e^{-\Gamma_s t} \left\{\cosh\frac{\Delta\Gamma_s t}{2} + \cos(\Delta M_s t)\right\} \Big/ 2$$

Mixed decay rates:

$$\Gamma\left(\overline{B}_s^0(t) \to \mu^+ X\right) = N_f \left|A_f\right|^2 \left(1 + a_{sl}^s\right) e^{-\Gamma_s t} \left\{\cosh\frac{\Delta\Gamma_s t}{2} - \cos(\Delta M_s t)\right\} \Big/ 2$$

$$\Gamma\left(B_s^0(t) \to \mu^- X\right) = N_f \left|\overline{A}_{\overline{f}}\right|^2 \left(1 - a_{sl}^s\right) e^{-\Gamma_s t} \left\{\cosh\frac{\Delta\Gamma_s t}{2} - \cos(\Delta M_s t)\right\} \Big/ 2$$

No direct CP violation ➔ $\left|A_f\right| = \left|\overline{A}_{\overline{f}}\right|$

Time-integrated analysis

- No initial state tagging:

$$\frac{\Gamma(B_s,\overline{B_s}(t)\to\mu^+X)-\Gamma(B_s,\overline{B_s}(t)\to\mu^-X)}{\Gamma(B_s,\overline{B_s}(t)\to\mu^+X)+\Gamma(B_s,\overline{B_s}(t)\to\mu^-X)}=\frac{a^s_{sl}}{2}\left[1-\frac{\cos(\Delta M_s t)}{\cosh(\Delta\Gamma_s t)}\right]$$

- Time integrated analysis

$$\frac{\Gamma(B_s,\overline{B_s}\to\mu^+X)-\Gamma(B_s,\overline{B_s}\to\mu^-X)}{\Gamma(B_s,\overline{B_s}\to\mu^+X)+\Gamma(B_s,\overline{B_s}\to\mu^-X)}=\frac{a^s_{sl}}{2}$$

- 1st D0 publication on the direct measurement of a^s_{fs}

Analysis with initial-state tagging

- Select only mixed decays

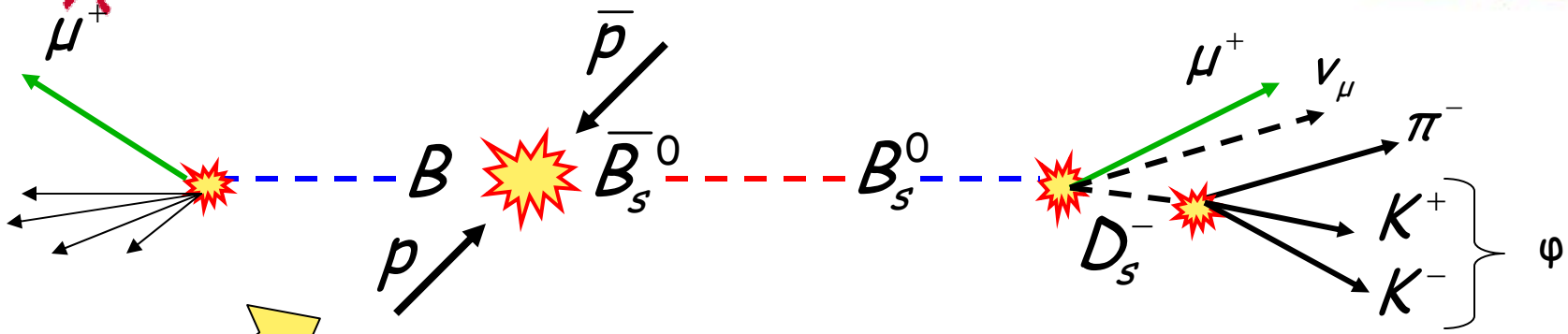
$$\Gamma\left(\overline{B}_s^0(t) \to \mu^+ X\right) = N_f \left|A_f\right|^2 \left(1 + a_{sl}^s\right) e^{-\Gamma_s t} \left\{\cosh\frac{\Delta\Gamma_s t}{2} - \cos\left(\Delta M_s t\right)\right\} \Big/ 2$$

$$\Gamma\left(B_s^0(t) \to \mu^- X\right) = N_f \left|\overline{A}_{\overline{f}}\right|^2 \left(1 - a_{sl}^s\right) e^{-\Gamma_s t} \left\{\cosh\frac{\Delta\Gamma_s t}{2} - \cos\left(\Delta M_s t\right)\right\} \Big/ 2$$

$$a_{sl}^s = \frac{\Gamma\left(\overline{B}_s(t) \to \mu^+ X\right) - \Gamma\left(B_s(t) \to \mu^- X\right)}{\Gamma\left(\overline{B}_s(t) \to \mu^+ X\right) + \Gamma\left(B_s(t) \to \mu^- X\right)}$$

- No time dependence!
  - Same-sign dimuon analyses
- Simple "counting" technique would work!
- Initial-state tagging is not 100% effective and accurate ➔ use events with no tagging
  - Include time dependence to improve accuracy

Detection level formulae



$$P^{-+} = \Gamma\left(B_s^0(t) \to f\right)\cdot\frac{1+|d|}{2} + \Gamma\left(\bar{B}_s^0(t) \to f\right)\cdot\frac{1-|d|}{2}$$

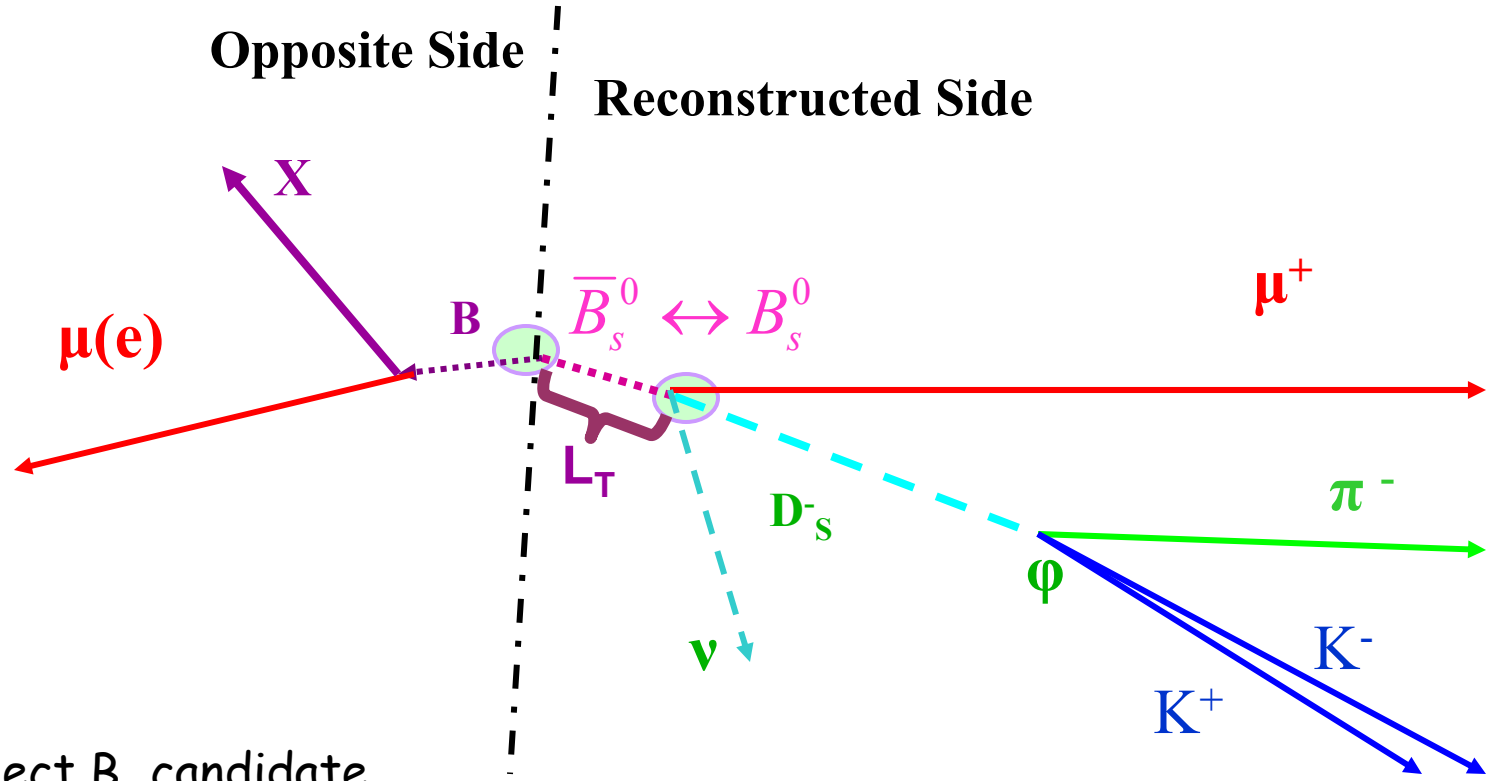
$$\boxed{P^{++} = \Gamma\left(\bar{B}_s^0(t) \to f\right)\cdot\frac{1+|d|}{2} + \Gamma\left(B_s^0(t) \to f\right)\cdot\frac{1-|d|}{2}}$$

$$P^{+-} = \Gamma\left(\bar{B}_s^0(t) \to \bar{f}\right)\cdot\frac{1+|d|}{2} + \Gamma\left(B_s^0(t) \to \bar{f}\right)\cdot\frac{1-|d|}{2}$$

$$P^{--} = \Gamma\left(B_s^0(t) \to \bar{f}\right)\cdot\frac{1+|d|}{2} + \Gamma\left(\bar{B}_s^0(t) \to \bar{f}\right)\cdot\frac{1-|d|}{2}$$

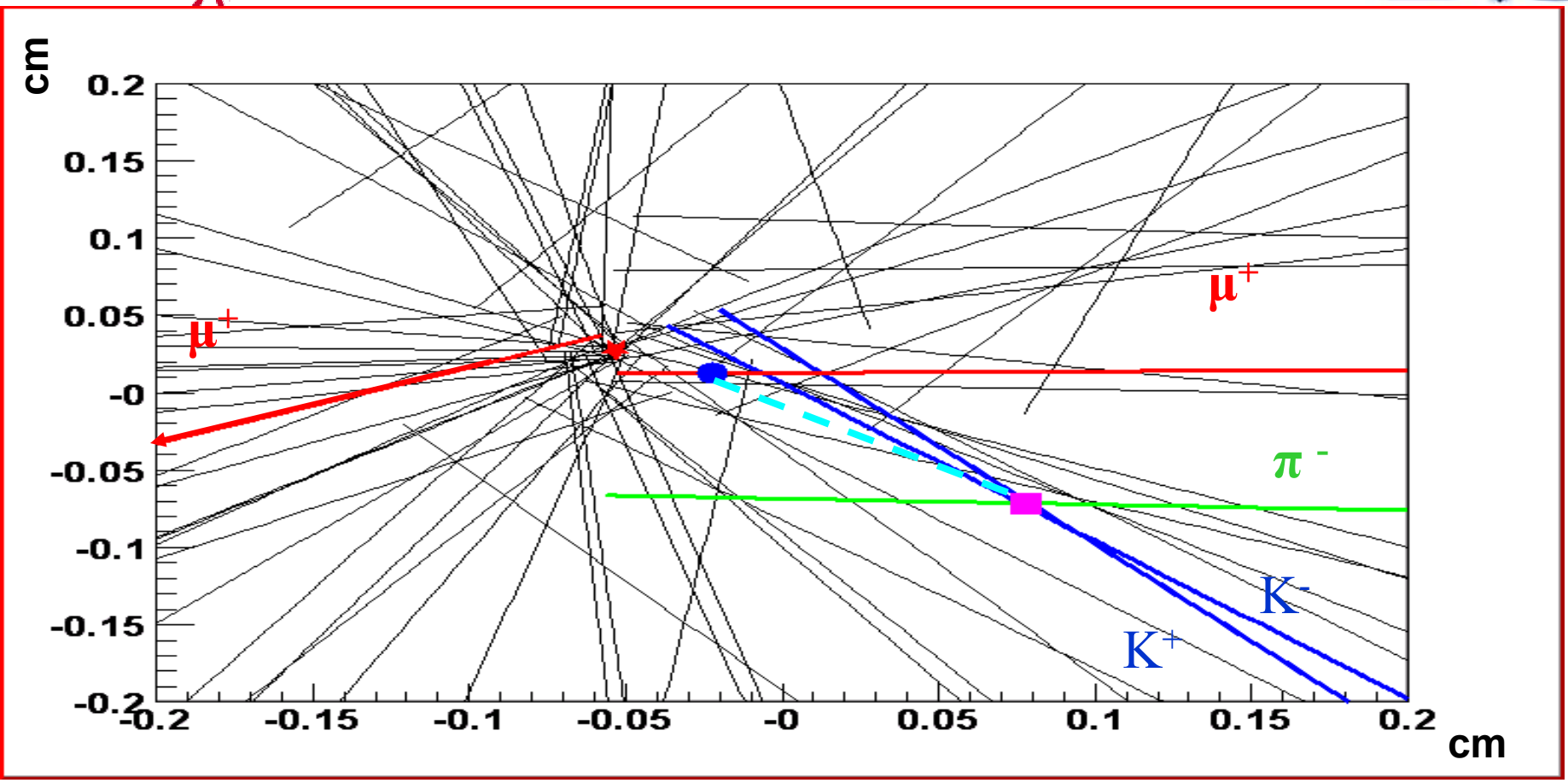
- d is the initial-state tagging dilution (OST)
  - d=0 ➔ no initial-state tagging (~80% of the events)
  - d=1 ➔ 100% accurate initial-state tagging

Analysis Outline
(more detailed)



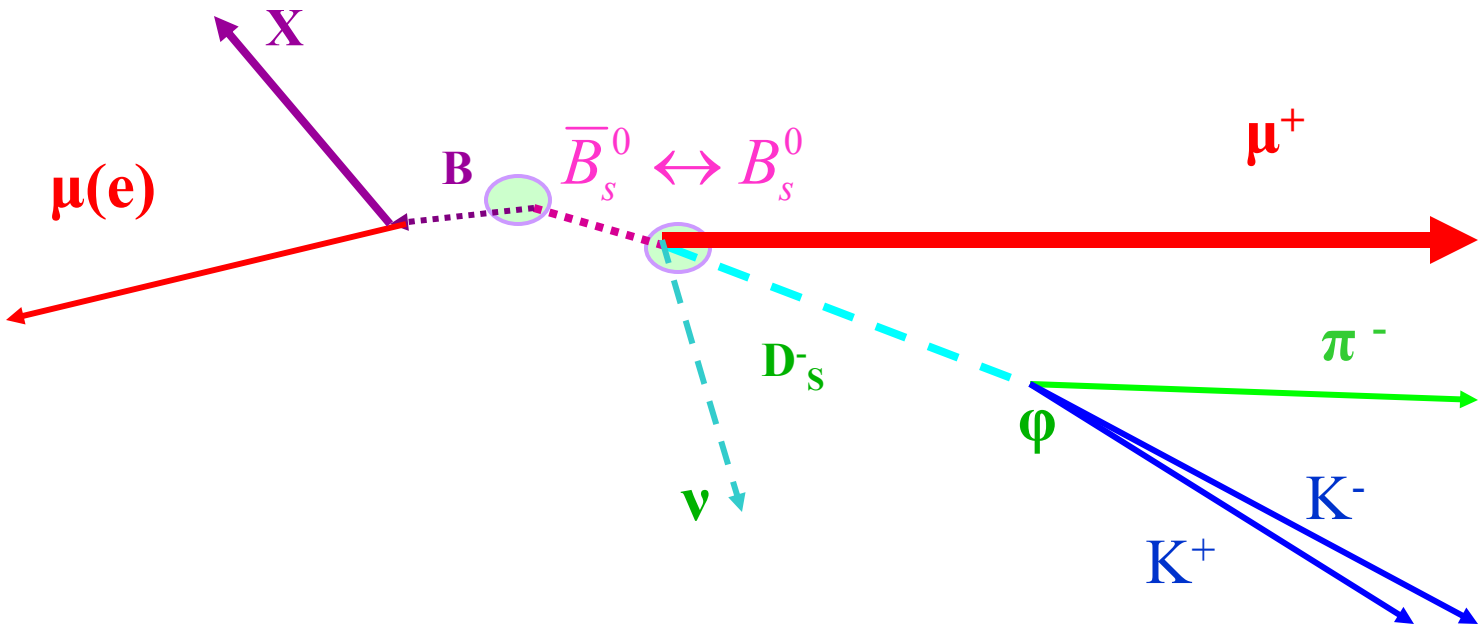
- Select B_s candidate
  - $B_s \rightarrow \nu\mu D_s(\rightarrow \varphi\pi$ or $K^*K)$
- For each B_s candidate
  - B_S flavor at decay time from muon sign at the reconstructed side
  - Transverse length L_T and its error
  - Transverse momentum $P_T(B_s)$ (use $P_T(D_s\mu)$)
  - B-hadron flavor at the opposite side (indicates B_S flavor at production time)

Challenge: High Track Multiplicity



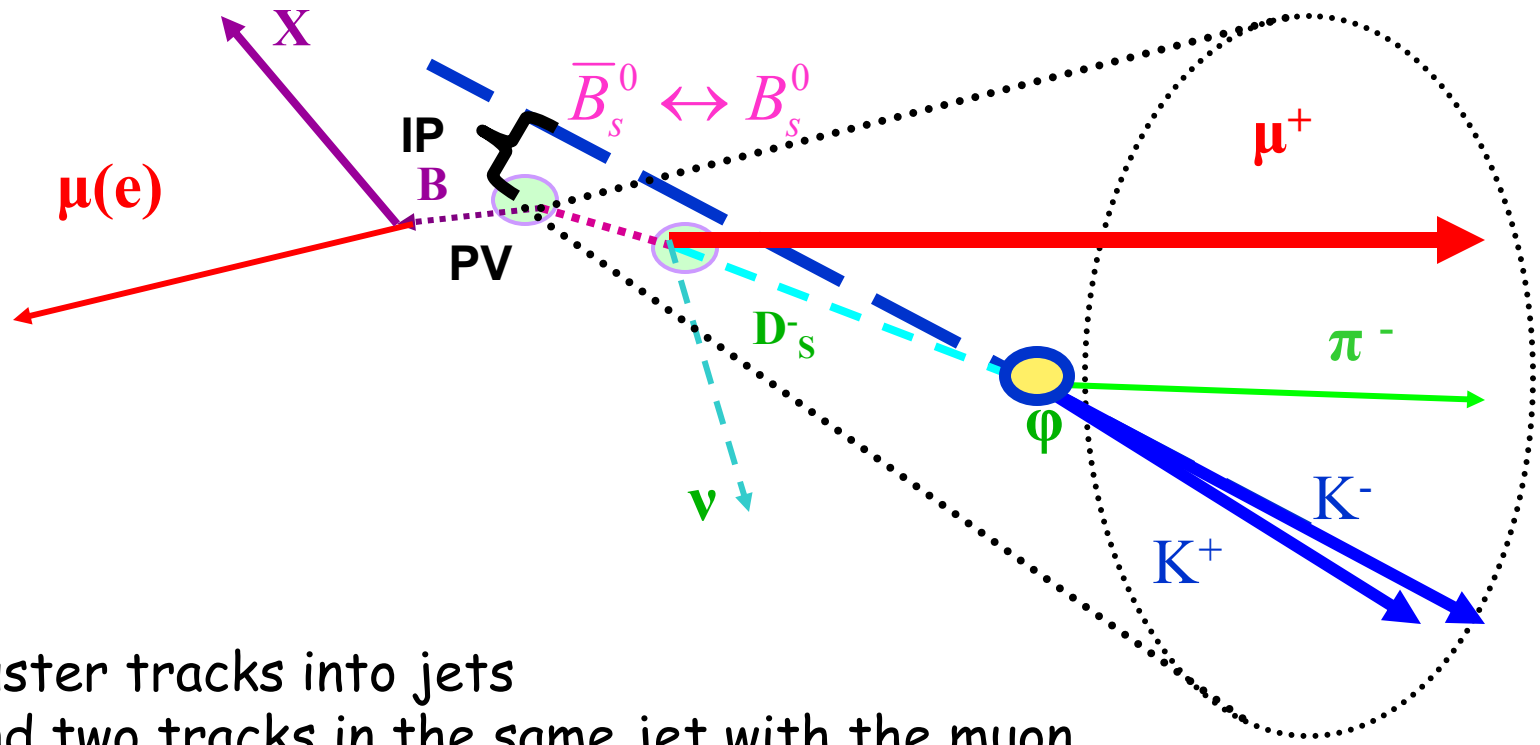
$$\overline{B}_s^0 \to B_s^0 \to \nu\mu^+ \overbrace{\pi^- \underbrace{K^+ K^-}_{\phi}}^{D_s^-}$$

Signal Selection



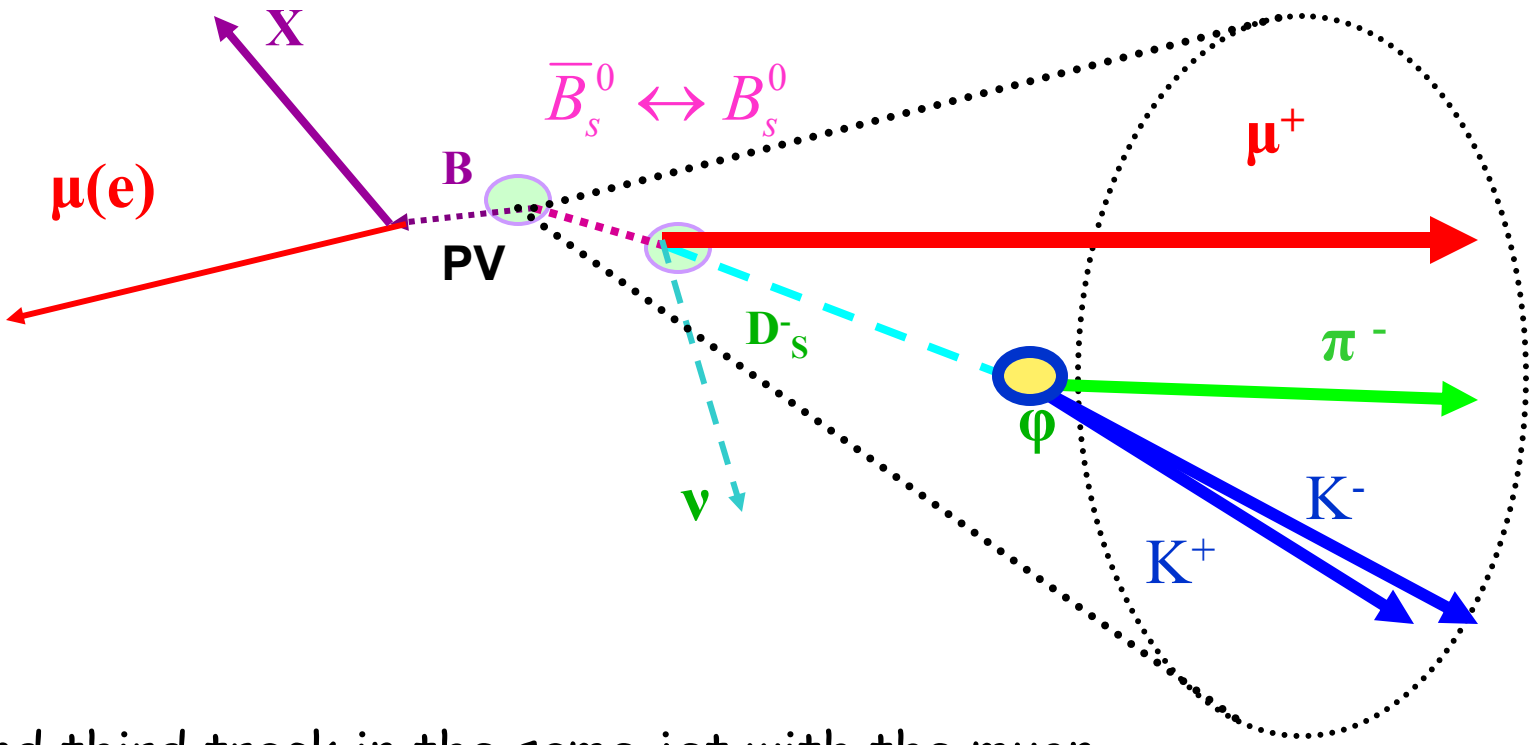
- Select events with a muon

Signal Selection



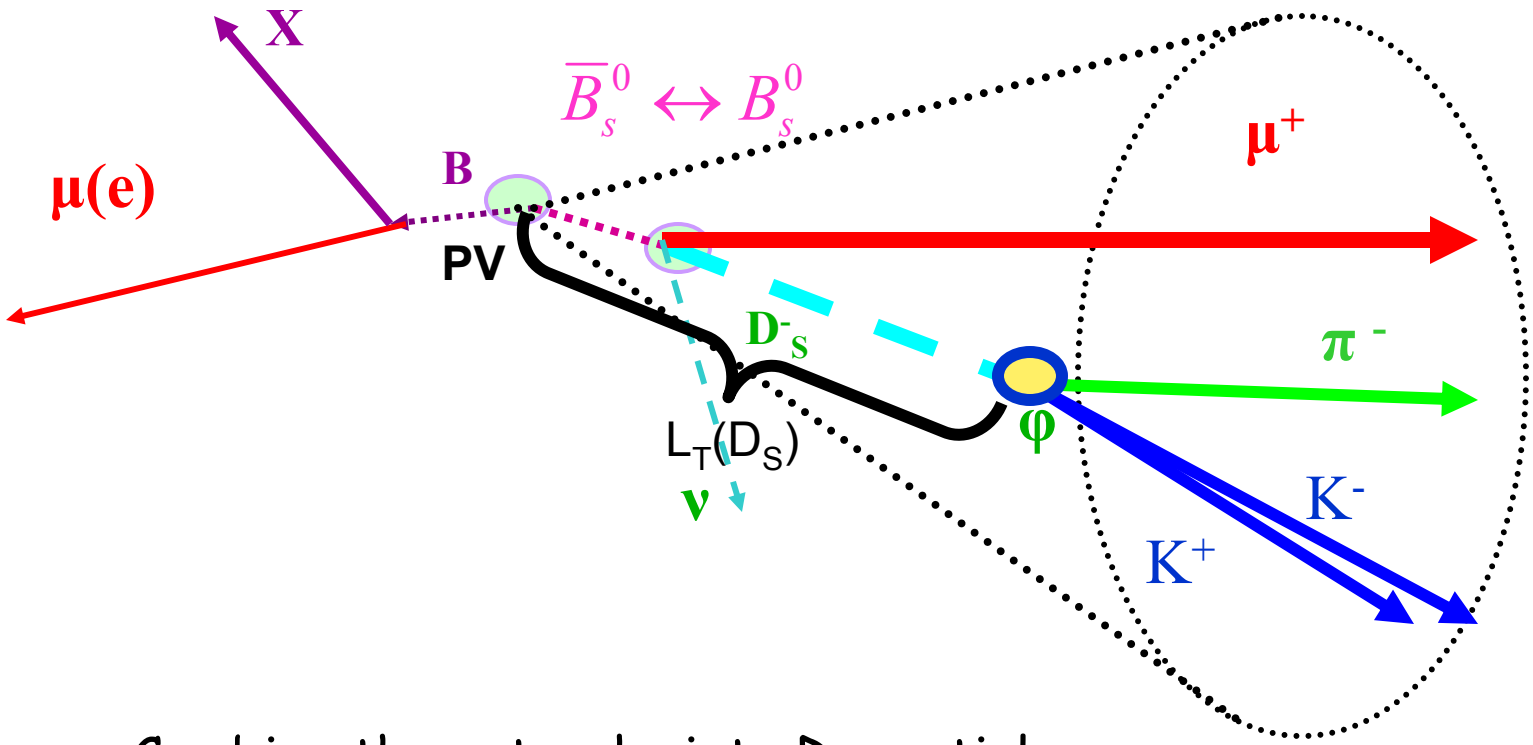
- Cluster tracks into jets
- Find two tracks in the same jet with the muon
  - different signs
  - Impact Parameter significances with respect to the Primary Vertex
  - common vertex
  - φ mass

Signal Selection



- Find third track in the same jet with the muon
  - sign opposite to the muon
  - Impact Parameter significance with respect to the Primary Vertex
  - common vertex with kaons
  - D_S mass

Signal Selection



- Combine three tracks into D_s particle
  - Decay Length significance with respect to the Primary Vertex
  - common vertex with the muon
  - some constraints on the μD_S invariant mass

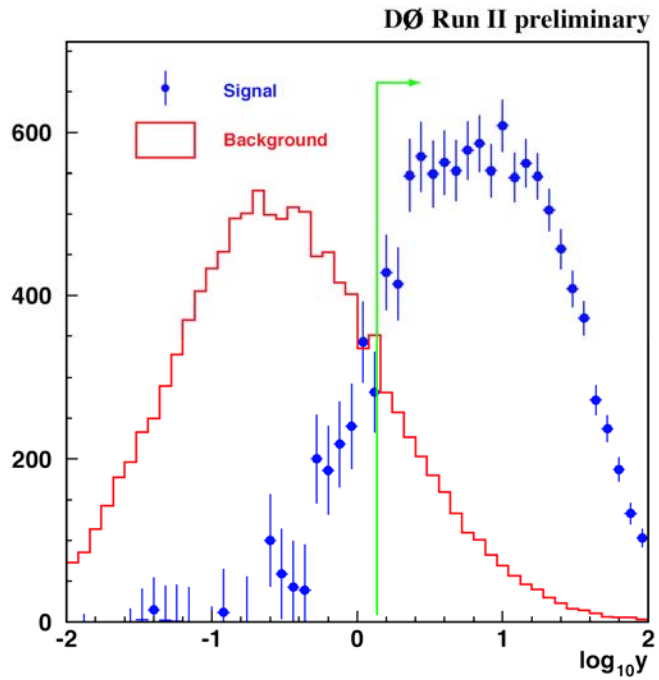
Signal Selection Function

Further improvement in S/B following initial vertex, lifetime & mass window cuts:

- Set of discriminating variables x_i constructed for each event
- Cut on combined variable, product of likelihood ratios

(PDFs for background and signal from data):

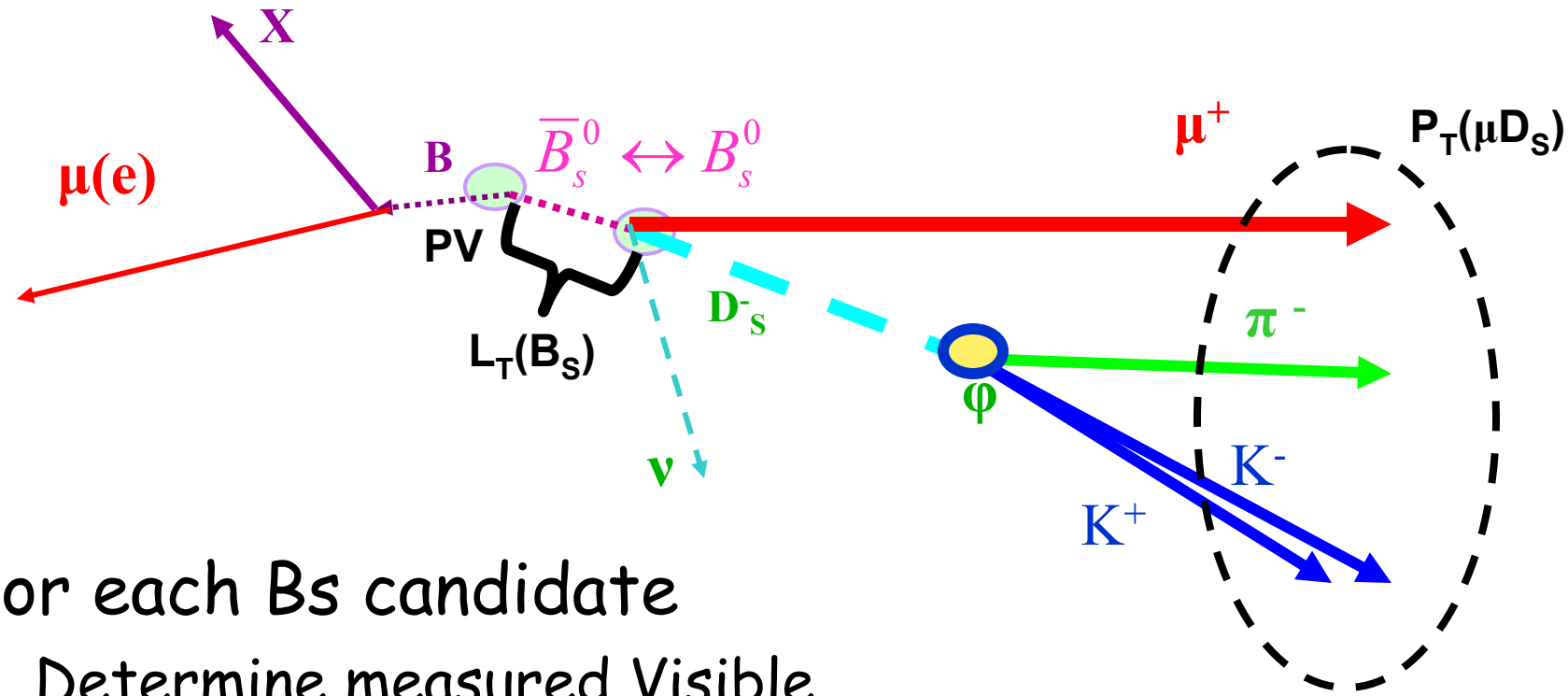
$$y = \prod_i^n y_i \; ; \qquad y_i = \frac{PDF_i^s(x_i)}{PDF_i^b(x_i)}$$



The following discriminating variables were used:

- Helicity angle;
- Isolation;
- $p_T(K^+K^-)$;
- Invariant mass, $M(\mu D_s)$;
- $M(K^+K^-)$

Signal Selection



- For each Bs candidate
  - Determine measured Visible Proper Decay Length

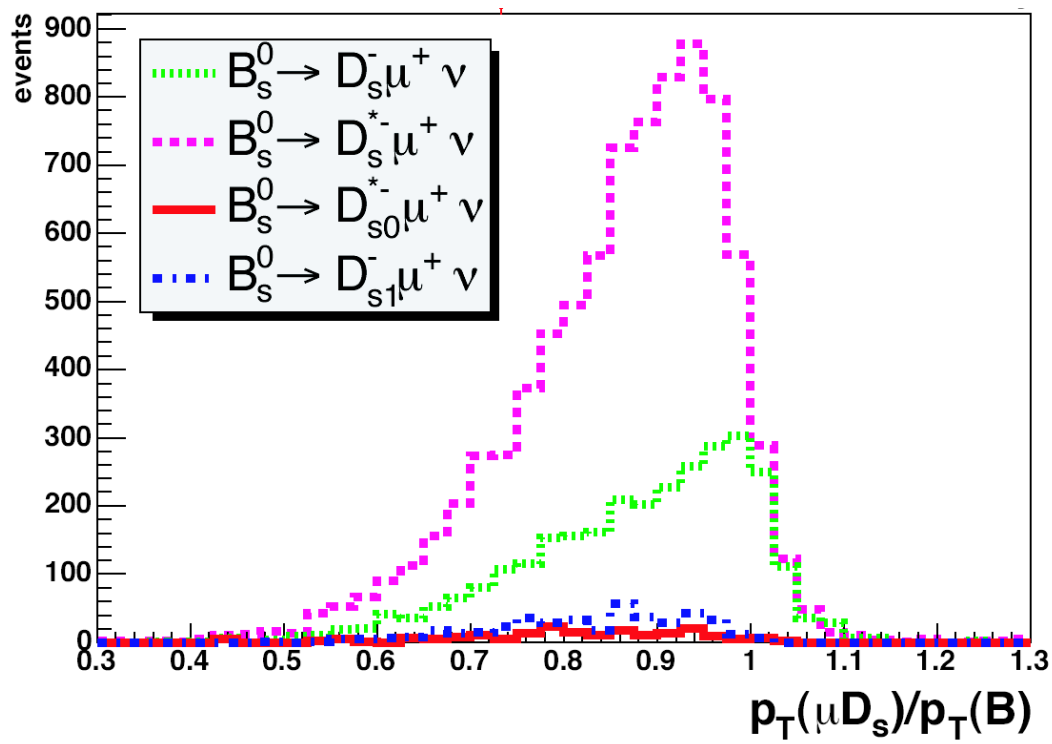
$$x^M = m_{B_s} \cdot \left(\vec{L}_T \cdot \vec{p}_T^{\,D_s\mu}\right) \Big/ \left(p_T^{D_s\mu}\right)^2$$

Proper Decay Length

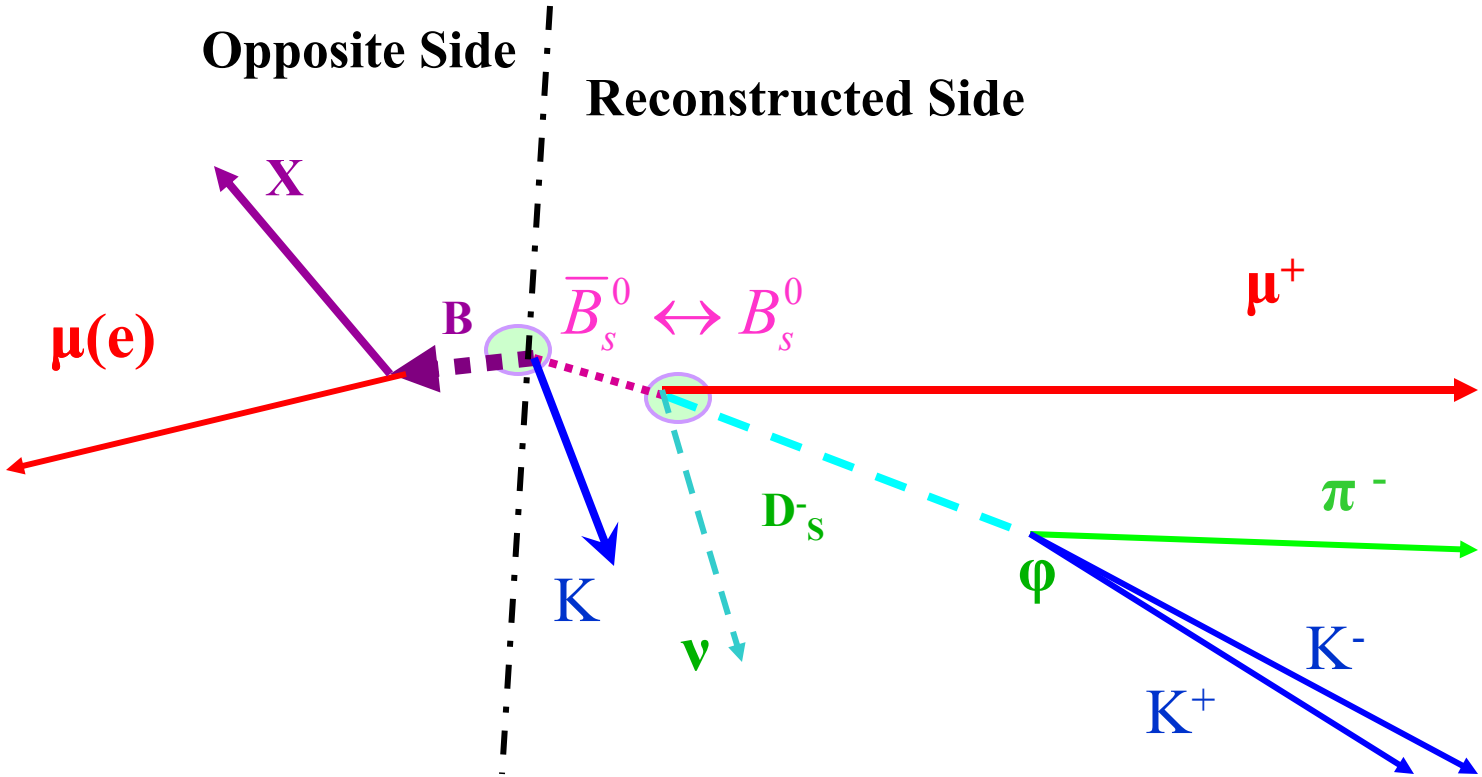
- Proper Decay Length is determined from the Visible Proper Decay Length
- K Factor takes into account the escaping neutrino and other missing particles
  - $B_s^0 \to D_s^{*-} \mu^+ \nu$, $D_s^{*-} \to D_s^- \gamma$
- From MC, each decay mode

$$ct_{B_s} = x^M K$$

$$K = p_T^{D_s \mu} \Big/ p_T^{B_s}$$



Initial State Tagging



- Use Opposite Side B-hadron
  - $b\bar{b}$ pairs are produced
- Same-side tagging for Bs requires reconstruction of a kaon → charge asymmetry in Initial State Tagging due to different cross-sections with the detector material

Initial-state tagging dilution

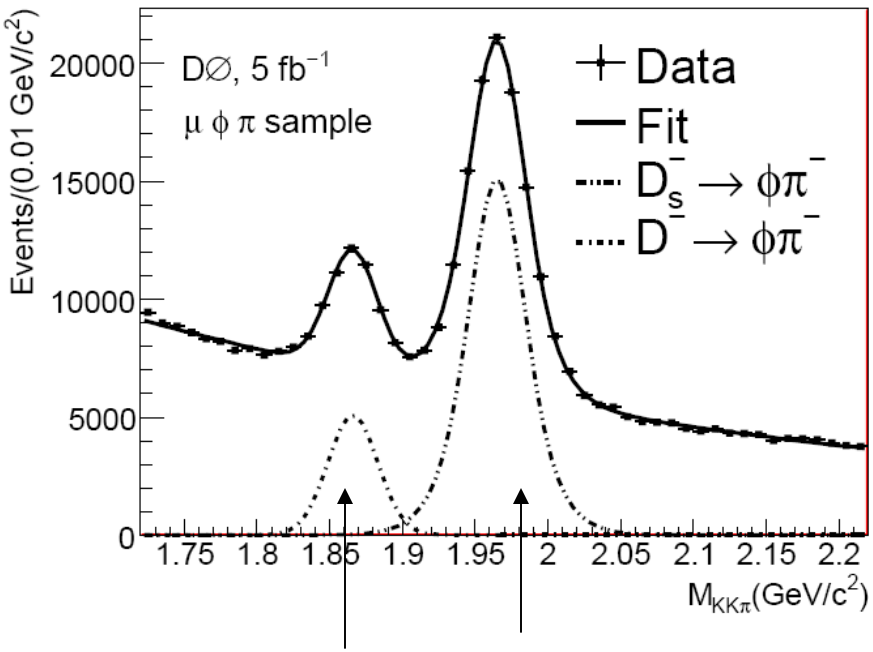
- Initial-state flavor discriminating variables have different PDFs for b and bbar quarks
  - OST μ^+ ➔ b-quark at the reconstructed side and reverse
- Construct ratios for each variable

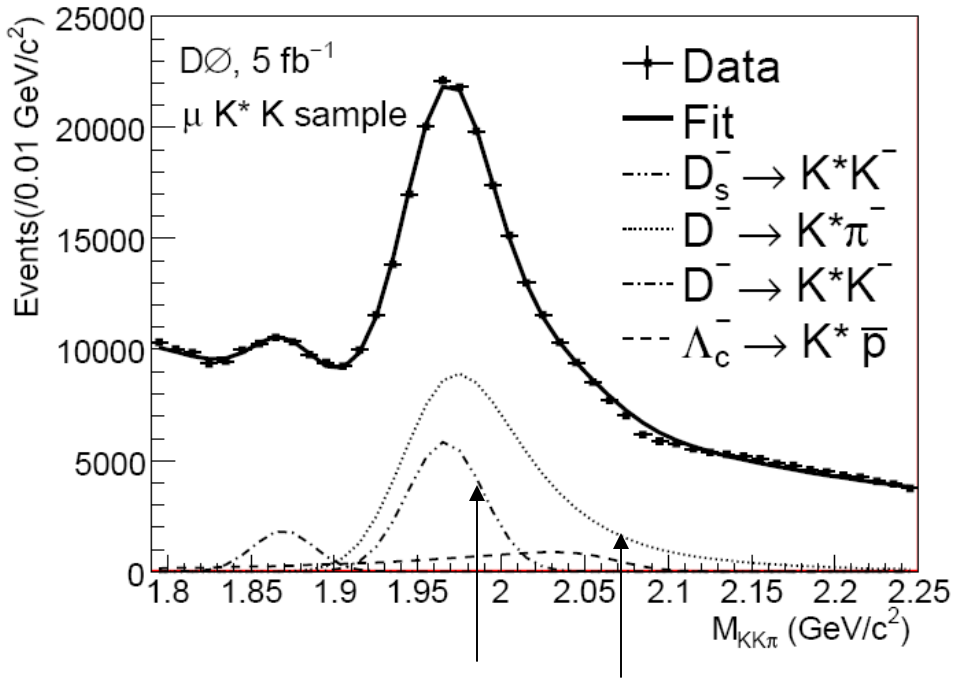
$$y_i = \frac{PDF_i^{\bar{b}}(x_i)}{PDF_i^{b}(x_i)}; \qquad y = \prod_i^n y_i$$

- Dilution d=(1-y)/(1+y)
  - $\varepsilon d^2=(2.48\pm0.21)\%$

Data samples

- Semileptonic samples at D0
  - Bs→μφπX: 81 394±865 (5fb^{-1})
  - Bs→μK*K: 33 557±1200 (5fb^{-1})





Good mass separation between B_s and B_d

B_s and B_d overlap

- ~85% are used for the B_s asymmetry measurement
  - The remaining ~15% are coming either from Bu, Bd, Bs →D(s)Ds or from different b or c quarks and not usable for the measurement

Fitting procedure

- Likelihood function for N events

$$L = \prod_{j=1}^{N} \sum_{i} \left[A_{\mu} A_{\mu_{OST}} f_i \cdot P_i^{l_M} \cdot P_i^{\sigma_{l_M}} P_i^{y_{sel}} P_i^{M(KK\pi)} P_i^{d_{tag}} \right]$$

- where f_i is the fraction of the ith source, l_M is the measured VPDL, σ_{lM} – its uncertainty, y_{sel} – selection variable, d_{tag} – initial state tagging dilution, $A\mu$ and $A\mu_{OST}$ – detector asymmetries

- PDF P^{lM} is constructed from the decay rate formulae and the remaining PDFs were taken from data.

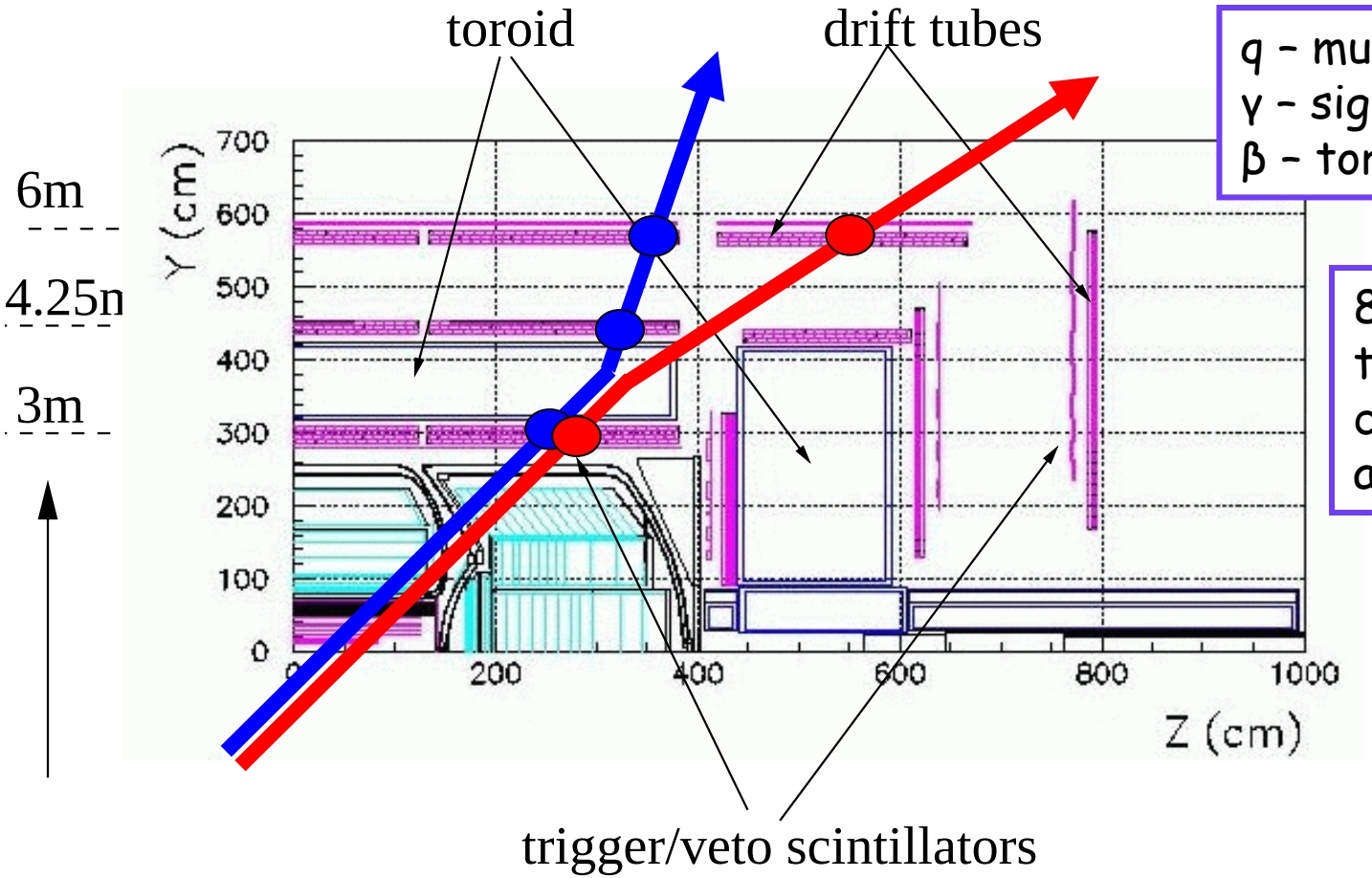
- Minimize -2lnL

Description of asymmetries

- A_{fb} – production forward-backward asymmetry
  - Should be 0 at Tevatron
- A_{det} – detector (material) north-south asymmetry
- A_{ro} – range-out asymmetry
  - change in acceptance and range-out of muon tracks that bend toward, or away from, the beam line
- $A_{q\beta}$ – detector asymmetry between tracks bending north and tracks bending south
- $A_{\beta\gamma}$ – second-order detector asymmetry
  - Non-zero if A_{ro} and physics asymmetries are non-zeros
- These asymmetries are fully determined from the data because the toroid polarity is flipped regularly
  - 1% precision for entire D0 sample
- **Totally: 5 detector + 1 physics = 6 asymmetries**

Detector asymmetries

- Detector asymmetries were taken into account using a technique developed for the dimuon analysis
  - $A_\mu=(1+q\gamma A_{fb})(1+\gamma A_{det})(1+q\beta\gamma A_{ro})(1+\beta\gamma A_{\beta\gamma})(1+q\beta A_{q\beta})$



q – muon charge
γ – sign of muon η direction
β – toroid polarity

8 samples allow to determine all detector asymmetries

Kaon and muon asymmetries

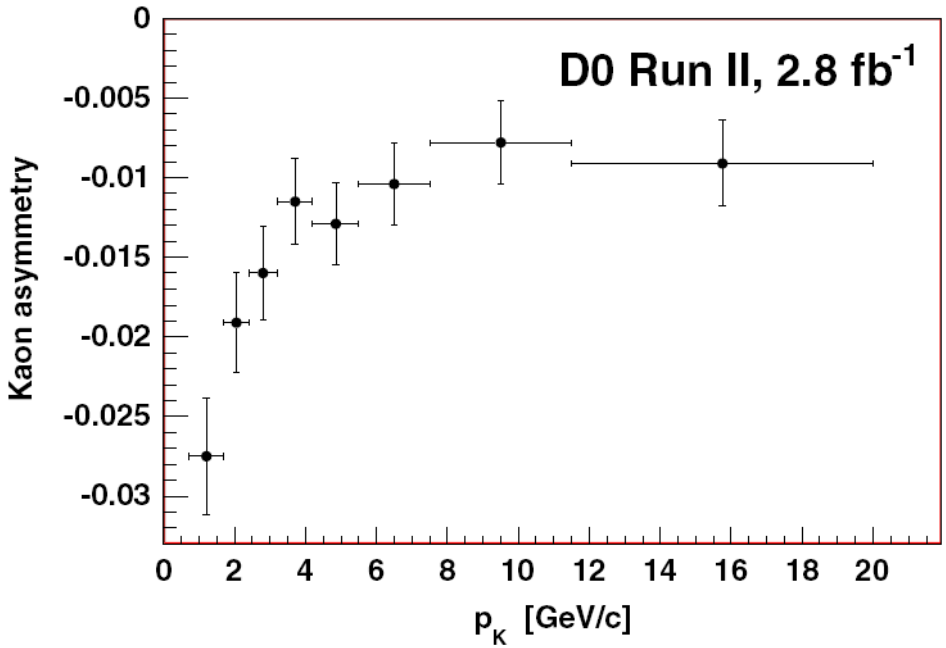


FIG. 3 (color online). Dependence of the kaon asymmetry, $A_K = [N(K^-) - N(K^+)]/[N(K^-) + N(K^+)]$, on the kaon momentum p_K in eight bins of approximately equal statistics. Errors are statistical.

- Kaon asymmetry was determined in "Study of Direct CP Violation in $B^\pm \to J/\psi K^\pm(\pi^\pm)$ Decays"
  - Phys. Rev. Lett. **100**, 211802 (2008)
- Important for the $\mu^+K^-K^*(\to K^+\pi^-)$ sample
  - K^+ and K^- have different p_T thresholds
- In the $\mu^+\pi^-\varphi(\to K^+K^-)$ sample the kaons are symmetric

- Muon reconstruction ID asymmetry $A(\mu)$ originates from the local fit convergence (needed to reconstruct the muon parameters) and was determined from the $J/\psi \to \mu\mu$ sample at the level $(-1.90 \pm 0.45) \cdot 10^{-3}$

Proper Decay Length

- Signal

$$P_{sig}^{x^M} = \int_{K_{min}}^{K_{max}} D(K)dK\left(\frac{1}{N}\right)Eff\left(x^M\right)\int_0^\infty dx \cdot G\left(x - x^M, s\sigma_{x^M}\right) \cdot p^{+-/++/-+/--}$$

- Combinatorial background
  - Long-lived background
    - Non-sensitive to the tagging
    - Sensitive to the tagging
      - Non-oscillating
      - Oscillating with Δm_d frequency
  - Prompt background
    - Width depends on resolution
    - Constant width

Fit

- Free fit parameters

a_{fs}^{s} - B_s semileptonic asymmetry

a_{fs}^{d} - B_d semileptonic asymmetry

a_{bg} - asymmetry in the combinatorial background. Was included into the oscillating long-lived term.

- All detector asymmetries: A_{fb}, A_{det}, A_{ro}, $A_{\beta\gamma}$, $A_{q\beta}$

Results

- Results of the asymmetry fit with statistical uncertainties

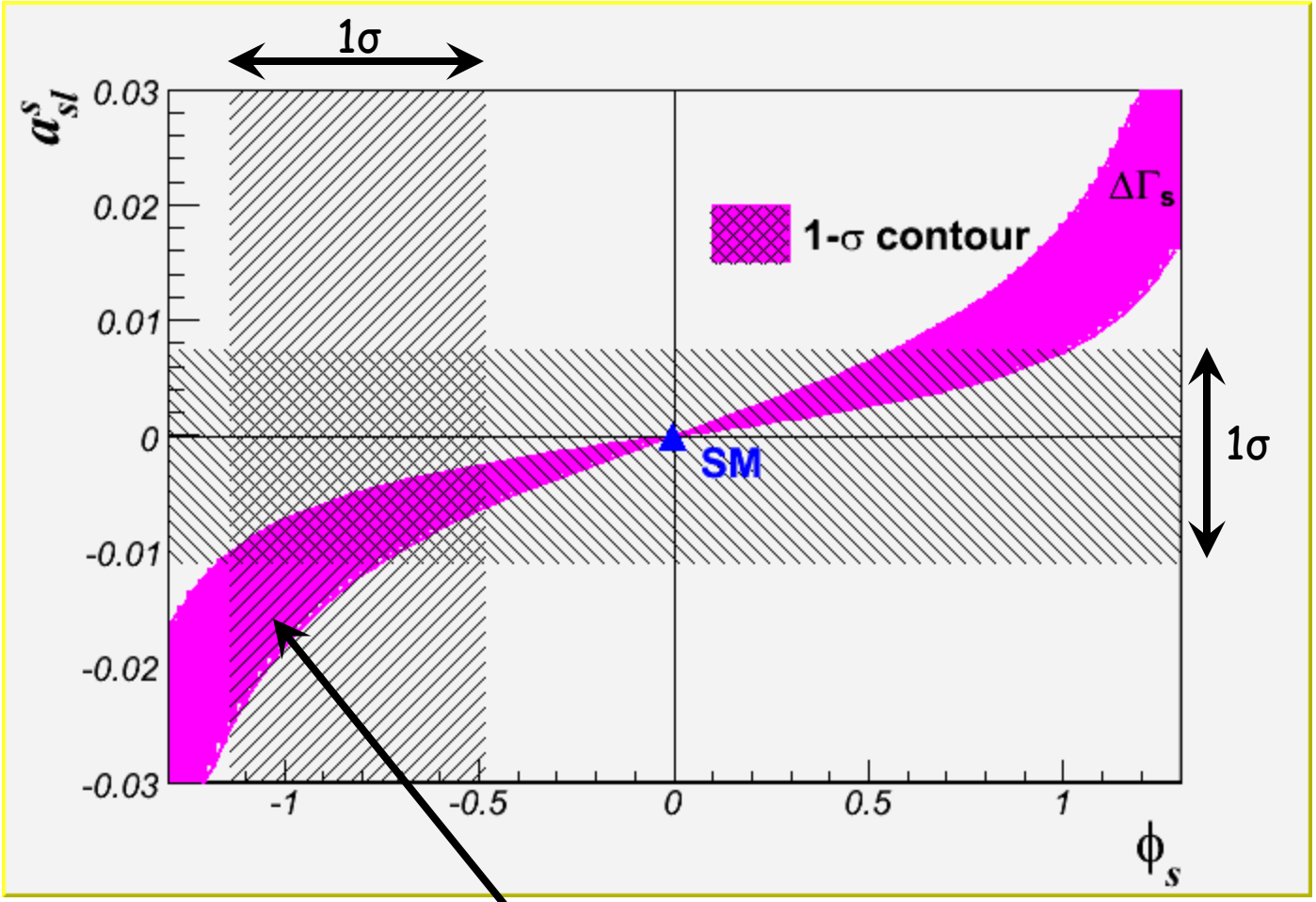
	$\mu^+\phi\pi^-$	$\mu^+K^{*0}K^-$	Combined
$a^s_{fs} \times 10^3$	-7.0 ± 9.9	20.3 ± 24.9	-1.7 ± 9.1
$a^d_{fs} \times 10^3$	-21.4 ± 36.3	50.1 ± 19.5	40.5 ± 16.5
$a_{bg} \times 10^3$	-2.2 ± 10.6	0.1 ± 13.5	-3.1 ± 8.3
$A_{\rm fb} \times 10^3$	-1.8 ± 1.5	-2.0 ± 1.5	-1.9 ± 1.1
$A_{\rm det} \times 10^3$	3.2 ± 1.5	3.1 ± 1.5	3.1 ± 1.1
$A_{\rm ro} \times 10^3$	-36.7 ± 1.5	-30.2 ± 1.5	-33.3 ± 1.1
$A_{\beta\gamma_\mu} \times 10^3$	1.1 ± 1.5	0.2 ± 1.5	0.6 ± 1.1
$A_{q_\mu\beta} \times 10^3$	4.3 ± 1.5	2.0 ± 1.5	3.1 ± 1.1

Systematic uncertainties

- Negative contributions:
  - Mass fitting procedure: -0.0008
  - Total branching fraction of Bs→Dsμν: -0.0001
  - Lifetime fit: -0.0001
  - Opposite-side tagging: -0.0022

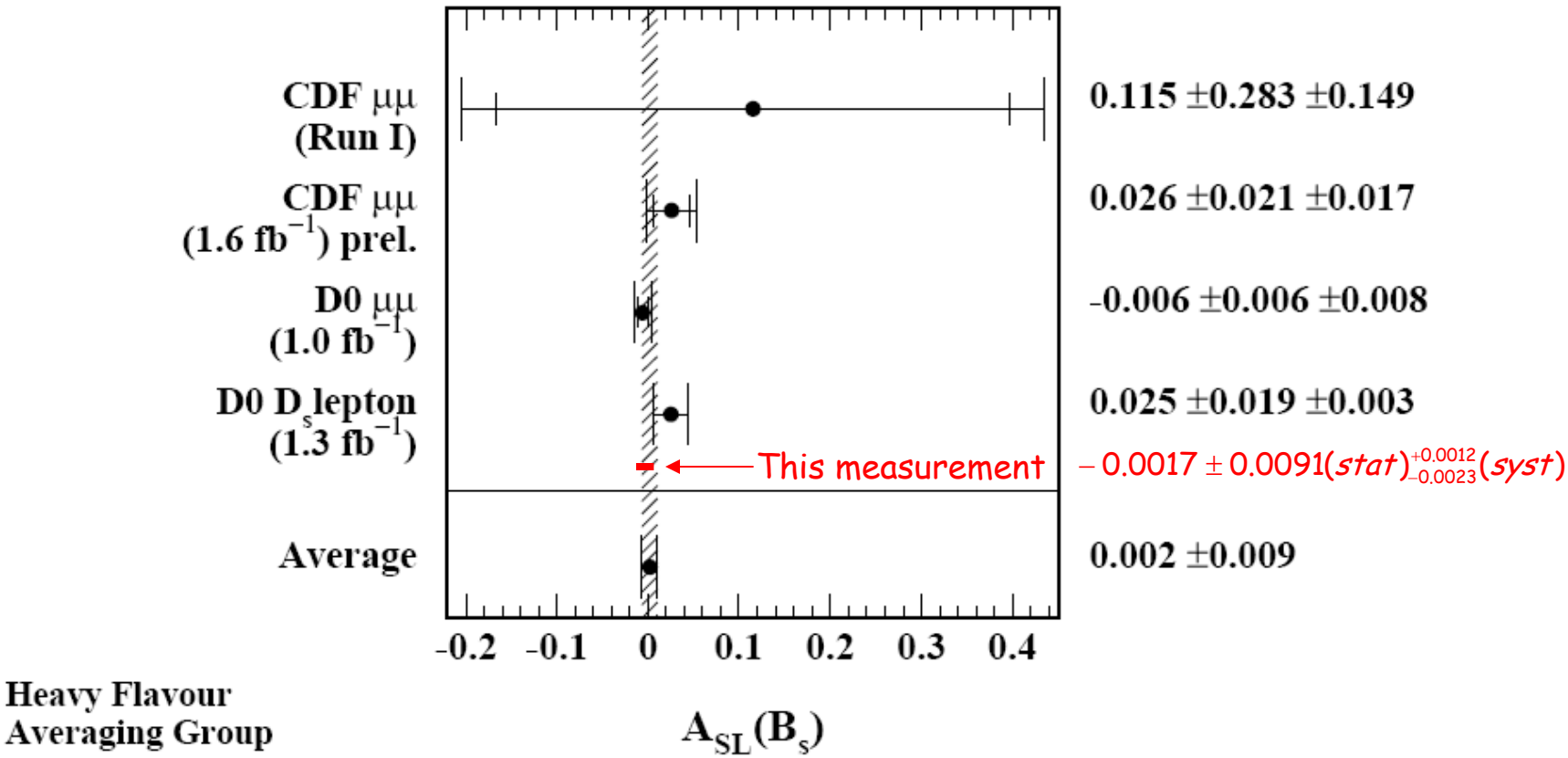
- Positive contributions
  - The a^d_{sl} from the fit is 2.5σ away from the SM and it could affect the a^s_{sl} in the μK*K mode due to the correlation (no mass separation). Set it to 0 to estimate the systematic error. Contribution is +0.0012

1-σ contour



- Unfavoured $\Delta\Gamma_s$ – φ_s combinations

Measurements of a^s_{sl}



- Estimate from $\Delta\Gamma_s$, ΔM_s and φ_s: $a^s_{sl}=-(8.4^{+5.2}_{-6.7})\cdot 10^{-3}$

Conclusion

- The Bs semileptonic asymmetry was measured using $5fb^{-1}$

$$a^s_{sl} = -0.0017 \pm 0.0091(stat)^{+0.0012}_{-0.0023}(syst)$$

  - Fermilab-Pub-09-140-E
  - arXiv: 0904.3907
  - Submitted to PRL
- Improves (and supersedes) the previous result by more than factor of 2
- Agrees and will be combined with the dimuon result
  - The precision improves by more than 30%
- Complements the Bs→J/ψ φ CP violation results
- Improves a^s_{sl} limits on new physics

- More statistics is being collected thanks to excellent performance of the Tevatron and detector.

- Stay tuned!