CP-violation studies with the DZero detector

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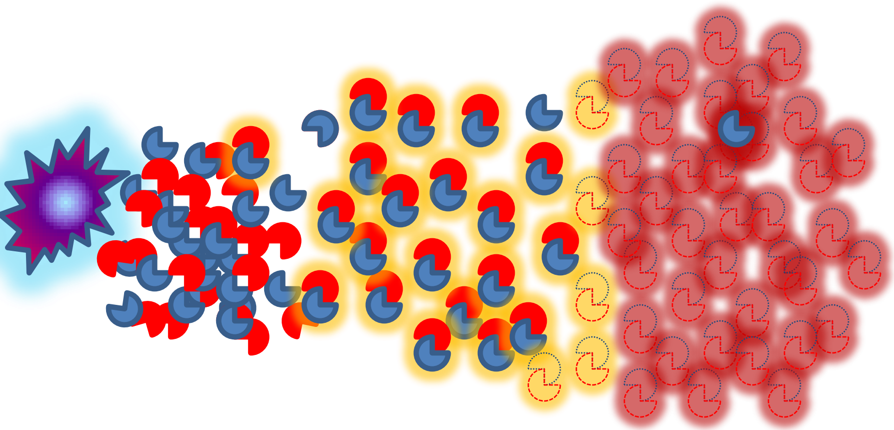
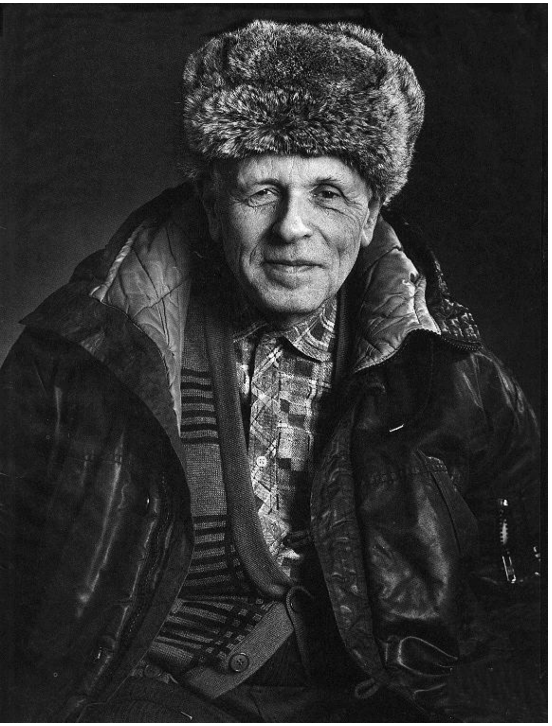
A Simplistic Theory of the Universe



1. Big Bang
2. Equal amounts of matter and antimatter
3. Some processes lead to slight dominance of matter over antimatter
4. Annihilation
5. We are left with a lot of photons and "few" baryons: $\frac{N_B}{N_\gamma} = 6\times10^{-10}$

Sakharov's conditions of our Universe existence

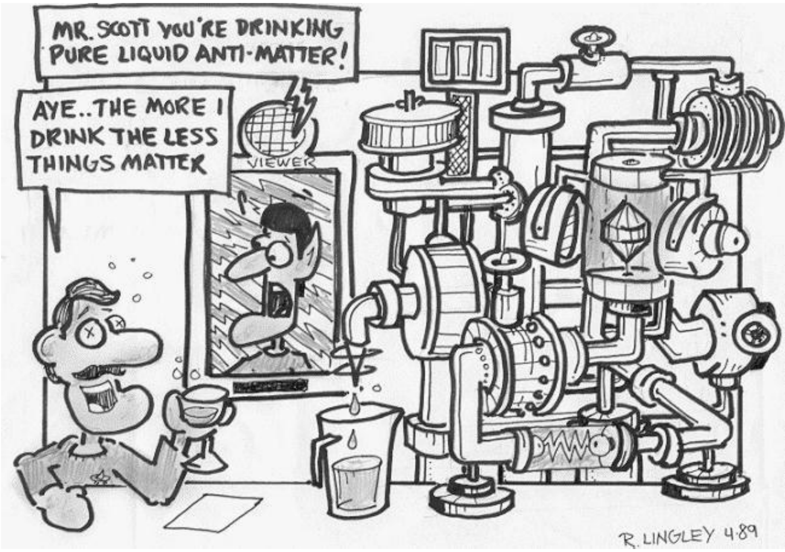


- They were formulated in 1967
- Inspired by the CP violation discovery in the kaon system

- Baryon number violation
- C, CP violation
- These processes happened when the Universe was not in thermal equilibrium

Baryon number violation

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



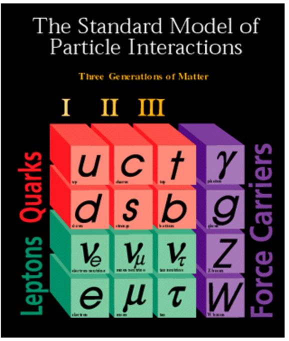
$$Now: \quad \frac{\Delta N_b}{N_\gamma} = (6.1 \pm 0.3) \times 10^{-10} \quad \text{(WMAP)}$$

- 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



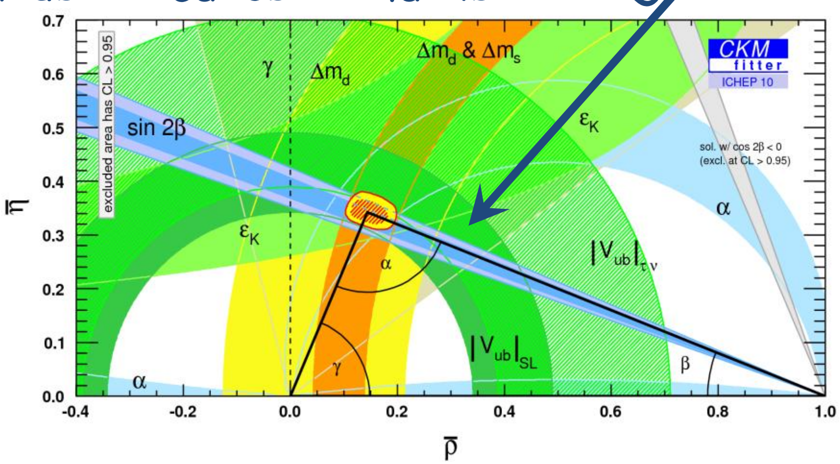
- Lagrangian

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

$$= V_{CKM}$$

Unitarity

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



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

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

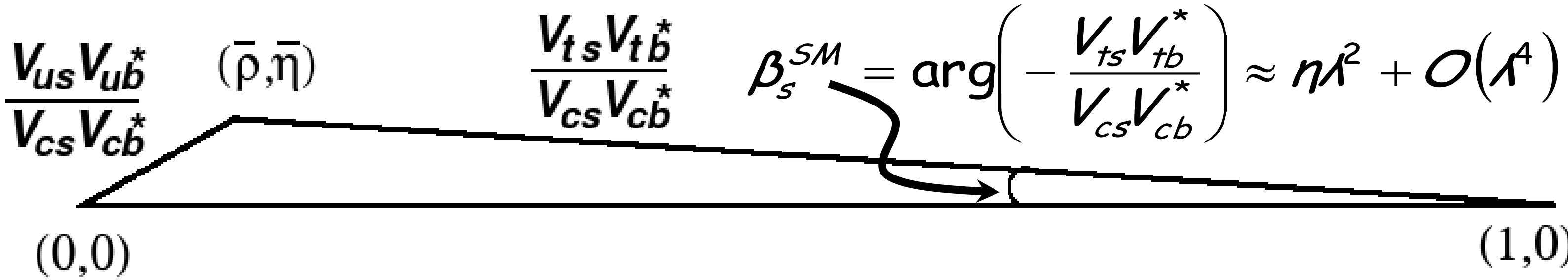
CPV: CKM matrix

- 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

$$\beta_s^{SM} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \approx \eta\lambda^2 + O(\lambda^4) \approx 0.02$$



- Angle β_s in SM small ➔ NP effects more visible

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

$$\frac{n_{\bar{\mathcal{B}}}}{n_\gamma} \cong 0 \qquad \boxed{\frac{n_{\mathcal{B}}}{n_\gamma} = (6.2 \pm 0.2) \times 10^{-10}}$$

WMAP

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

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

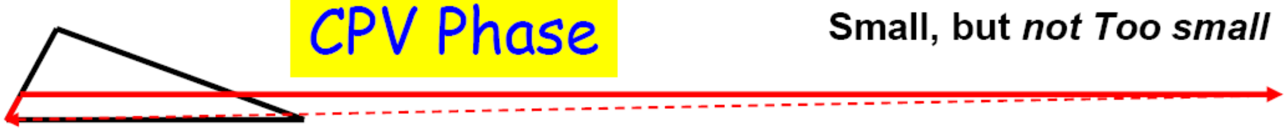
EW Phase Transition Temperature
~ v.e.v.

Masses too Small!

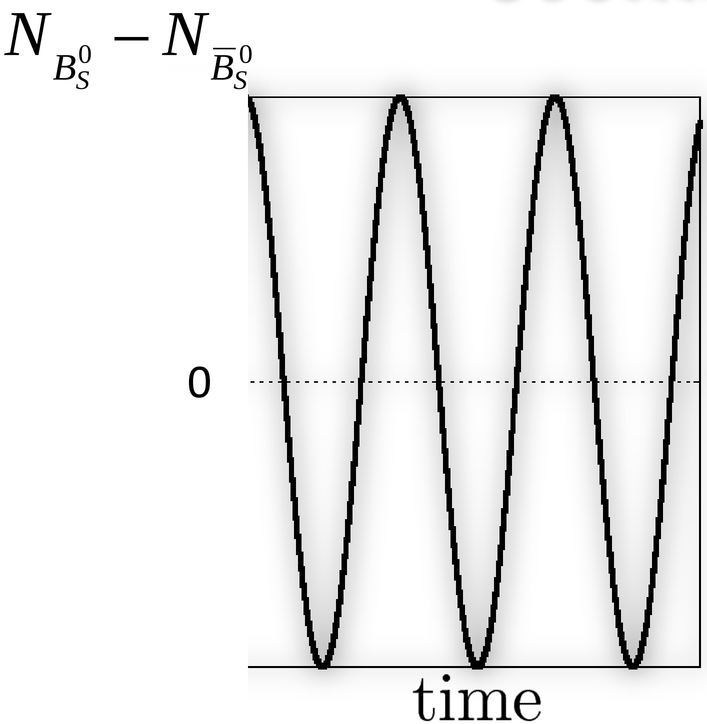
$A \sim 3 \times 10^{-5}$ in SM is common (unique) area of triangle

CPV Phase

Small, but *not Too small*



Oscillations of $B_{(s)}$ mesons



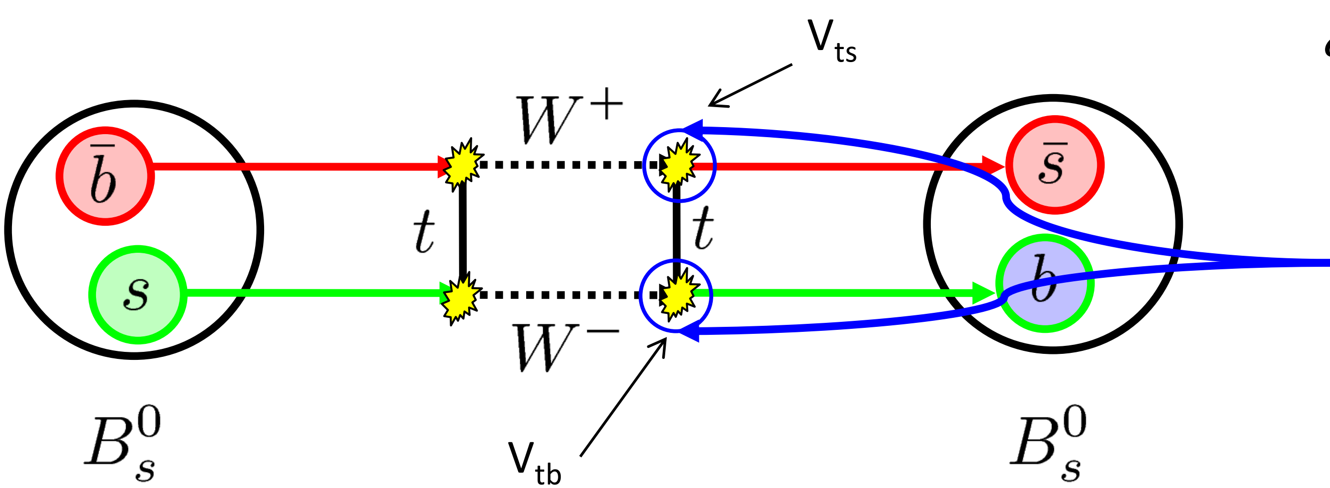
The B_s^0 meson spontaneously transforms into its antiparticle ($\overline{B}_s^0$) and vice-versa

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

$$\Delta m_s = M_{Heavy} - M_{Light} \approx 2|M_{12}|$$

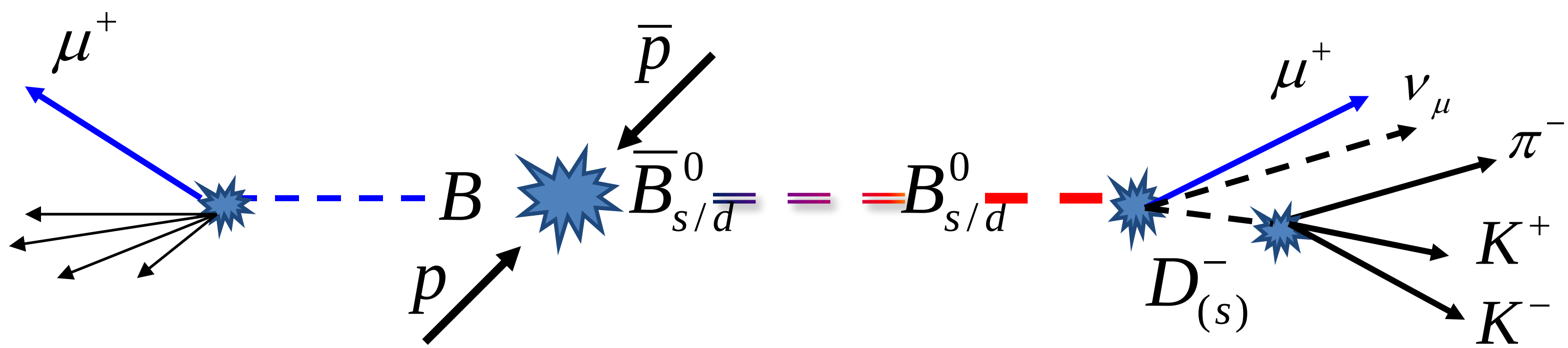
$$\Delta\Gamma_s = \Gamma_{Light} - \Gamma_{Heavy} \approx 2|\Gamma_{12}|\cos\varphi_s$$

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



The frequency of the oscillation is related to the quark mixing matrix elements

Di-muon events



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

The dimuon charge asymmetry of semileptonic *B* decays:

$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

CP Violation in Mixing

Direct decay rates:

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

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

Mixed decay rates:

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

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

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

Analysis with initial-state tagging

- Select only mixed decays

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

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

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

- Inclusive analysis: $$a_{sl}=\frac{\Gamma\left(\bar{B}(t)\to\mu^+X\right)-\Gamma\left(B(t)\to\mu^-X\right)}{\Gamma\left(\bar{B}(t)\to\mu^+X\right)+\Gamma\left(B(t)\to\mu^-X\right)}=A_{sl}^b$$
  - The asymmetry is “detectable” even without the initial-state tagging

A^{b}_{sl} at the Tevatron

- Since both B_d and B_s are produced at the Tevatron, A^{b}_{sl} is a linear combination of a^{d}_{sl} and a^{s}_{sl} :
  - Need to know production fractions of B_d and B_s mesons at the Tevatron
  - Measured by the CDF experiment

$$\boxed{A^{b}_{sl} = (0.506 \pm 0.043) a^{d}_{sl} + (0.494 \pm 0.043) a^{s}_{sl}}$$

Unlike the experiments at *B* factories, the Tevatron gives a unique possibility to measure the charge asymmetry of both B_d and B_s

Theoretical Predictions

- $a_{sl}^{s} = \Delta\Gamma_s / \Delta m_s \tan(\varphi_s)$

- New Physics parameterization (A.Lenz&U.Nierste)

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

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

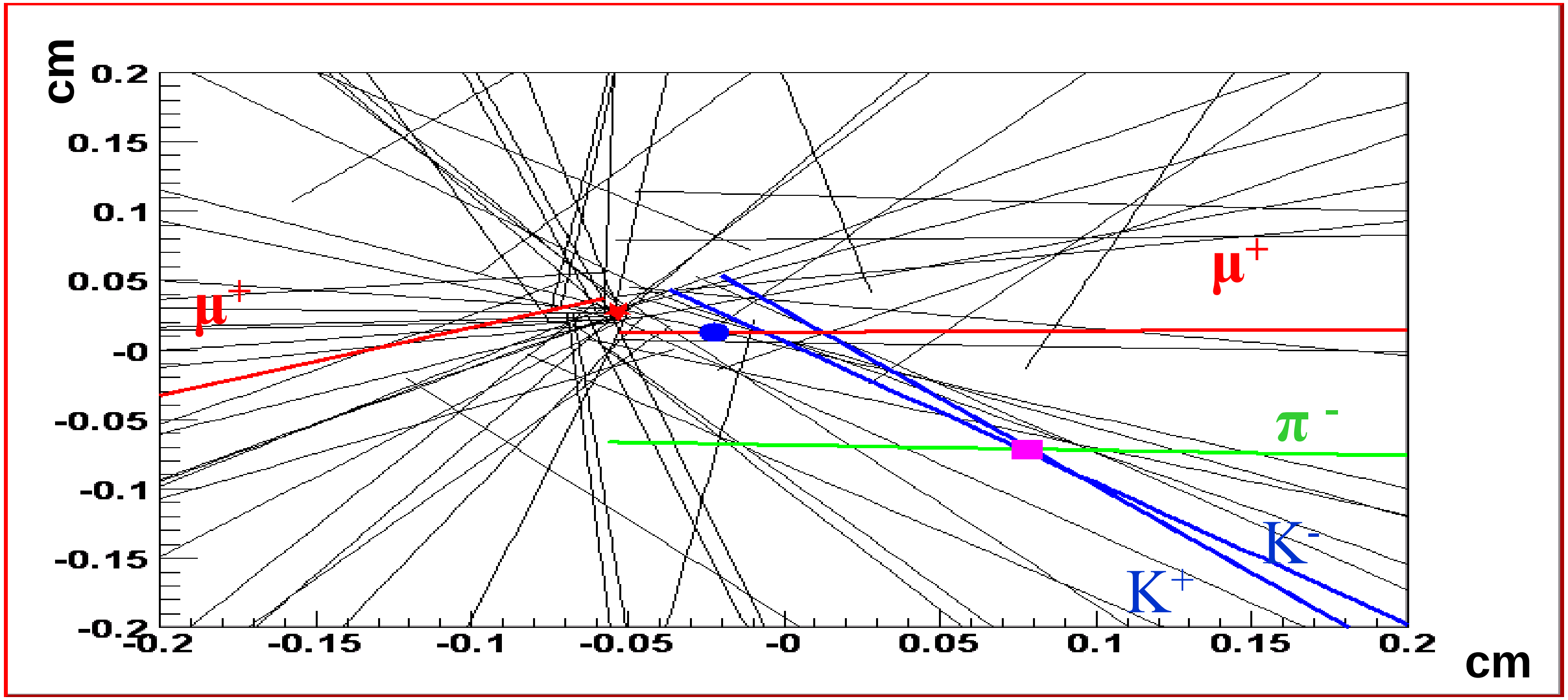
$$\Delta\Gamma_s = 2|\Gamma_{12}^{s}| \cos(\varphi_s^{SM} + \varphi_s^{\Delta}) = (0.096 \pm 0.039) ps^{-1} \cdot \cos(\varphi_s^{SM} + \varphi_s^{\Delta})$$

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

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

- a^{s}_{sl} is very small in the SM: $+2 \cdot 10^{-5}$
  - $a_{sl}^{d} = \left(-4.8^{+1.0}_{-1.2}\right) \cdot 10^{-4}$

Exclusive or Inclusive?

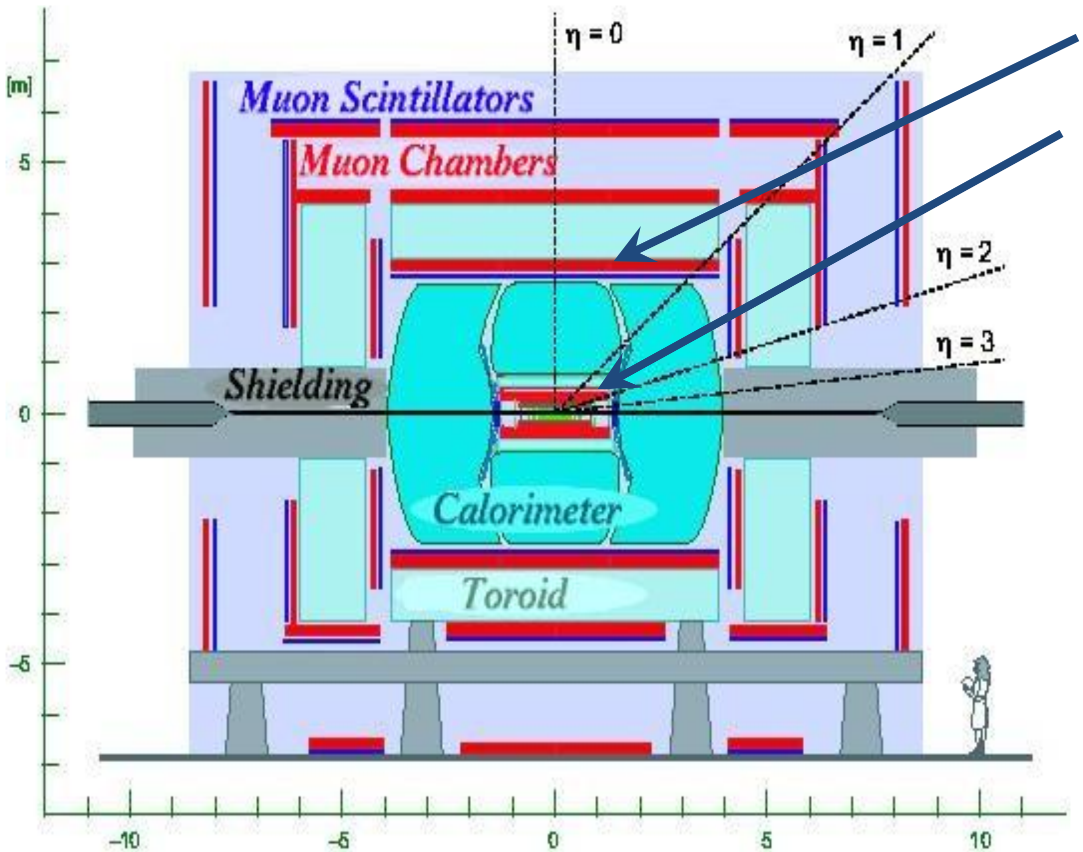


- Exclusive
  - Pros:
    - Access to decay-time information
    - Easier to understand backgrounds
  - Cons:
    - Much smaller statistics
- Inclusive
  - Pros:
    - Large statistics
  - Cons:
    - Backgrounds and sample composition are challenging

Inclusive Analysis

DZero Detector

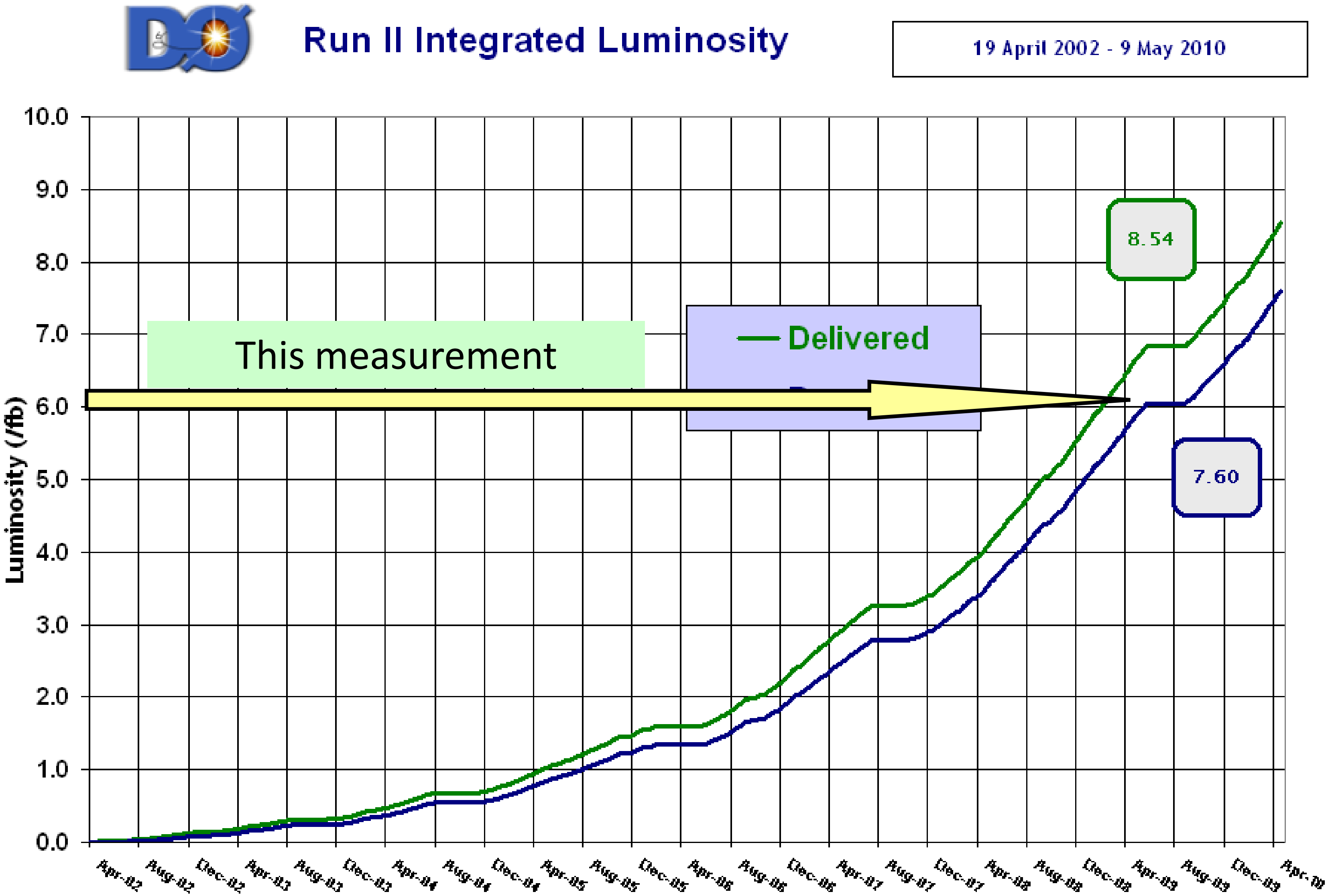
- Spectrometer : Fiber and Silicon Trackers in 2 T Solenoid
- Muons : 3 layer system & absorber in Toroidal field
- Hermetic : Excellent coverage of Tracking, Calorimeter and Muon Systems



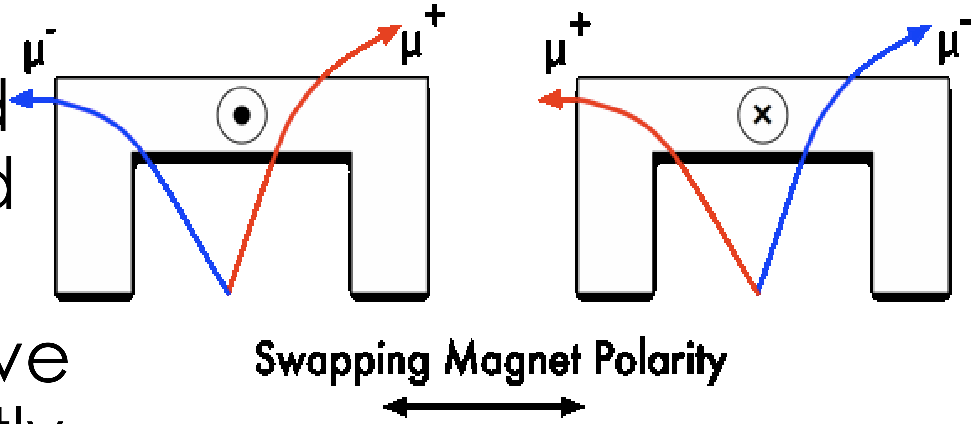
Toroid & solenoid polarity flipped regularly

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

Data in the analysis: 6.1 fb^{-1}



Reversal of Magnet Polarities



- Polarities of DØ solenoid and toroid are reversed regularly
- Trajectory of the negative particle becomes exactly the same as the trajectory of the positive particle with the reversed magnet polarity
- By analyzing 4 samples with different polarities (++, −−, +−, −+) the difference in the reconstruction efficiency between positive and negative particles is minimized from ~3% to ~0.1%
  – The parameters δ and Δ on the following slides

Event selection

- **Inclusive muon sample**:
  - Charged particle identified as a muon
  - $1.5 < p_T < 25$ GeV
  - muon with $p_T < 4.2$ GeV must have $|p_Z| > 6.4$ GeV
  - $|\eta| < 2.2$
  - Distance to primary vertex: <3 mm in axial plane; < 5 mm along the beam
- **Like-sign dimuon sample**:
  - Two muons of the same charge
  - Both muons satisfy all above conditions
  - Primary vertex is common for both muons
  - $M(\mu\mu) > 2.8$ GeV to suppress events with two muons from the same *B* decay

Blinded analysis

The central value of A^b_{sl} was extracted from the full data set only after the analysis method and all statistical and systematic uncertainties had been finalized

Experimental observables and A^b_{sl}

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

n^+, n^- – the number of muons with given charge

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

N^{++}, N^{--} – the number of events with two like-sign dimuons

- Semileptonic B decays contribute to both like-sign dimuon asymmetry A and inclusive muon asymmetry a;
- Both A and a linearly depend on the charge asymmetry A^b_{sl}

$$a = k\, A^b_{sl} + a_{bkg}$$

$$A = K\, A^b_{sl} + A_{bkg}$$

- In addition, there are detector related background contributions A_{bkg} and a_{bkg}

Analysis outline:

- **Determine the background contributions A_{bkg} and a_{bkg}**
- **Find the coefficients K and k**
- **Extract the asymmetry A^b_{sl}**

Raw asymmetries

$$\boxed{\begin{aligned} a &= k\,A_{sl}^{b} + a_{bkg} \\ A &= K\,A_{sl}^{b} + A_{bkg} \end{aligned}}$$

- Asymmetry in inclusive muon sample (1.495×10^{9} muons)

$$\boxed{a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}} = (+0.955 \pm 0.003)\%}$$

- Asymmetry in like-sign dimuon sample (3.731×10^{6} events)

$$\boxed{A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (+0.564 \pm 0.053)\%}$$

Background contribution

$$\boxed{\begin{aligned} a &= k\, A^b_{sl} + a_{bkg} \\ A &= K\, A^b_{sl} + A_{bkg} \end{aligned}}$$

- Sources of background asymmetries:
  - Background muons
    - Kaon and pion decays $K^+ \to \mu^+ \nu$, $\pi^+ \to \mu^+ \nu$ or punch-through
    - proton punch-through
    - False track associated with muon track
  - Asymmetry of muon reconstruction

Detailed description of background

$$\boxed{\begin{aligned} a &= k\,A_{sl}^{b} + a_{bkg} \\ A &= K\,A_{sl}^{b} + A_{bkg} \end{aligned}}$$

- Background asymmetry a_{bkg} in **inclusive muon sample**:

$$\boxed{a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta}$$

  - f_K, f_π, and f_p are the fractions of kaons, pions and protons identified as a muon in the inclusive muon sample
  - a_K, a_π, and a_p are the charge asymmetries of kaon, pion, and proton tracks
  - δ is the charge asymmetry of muon reconstruction
  - $f_{bkg} = f_K + f_\pi + f_p$

Detailed description of background

$$a = k\,A^b_{sl} + a_{bkg}$$
$$A = K\,A^b_{sl} + A_{bkg}$$

- Background asymmetry A_{bkg} in **like-sign dimuon sample**:

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

  - F_K, F_π, and F_p are the fractions of kaons, pions and protons identified as a muon in the like-sign dimuon sample
  - A_K, A_π, and A_p are the charge asymmetries of kaon, pion, and proton tracks
  - Δ is the charge asymmetry of muon reconstruction
  - $F_{bkg} = F_K + F_\pi + F_p$;

Kaon detection asymmetry

$$\boxed{a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta}$$

$$\boxed{A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta}$$

- The largest background asymmetry comes from the charge asymmetry of kaon track identified as a muon (a_K, A_K)
- Interaction cross section of K^+ and K^- with the detector material is different, especially for kaons with low momentum
  - e.g., for $p(K)$ = 1 GeV:

$$\boxed{\begin{array}{l}\sigma(K^- d) \approx 80\,\mathrm{mb} \\ \sigma(K^+ d) \approx 33\,\mathrm{mb}\end{array}}$$

- It happens because the reaction $K^- N \to Y\pi$ has no K^+N analogue

- K^+ meson travels further than K^- in the material, and has more chance of decaying to a muon
- Therefore, the asymmetries a_K, A_K **should be positive**
- All other background asymmetries are found to be about ten times less

Measurement of kaon asymmetry

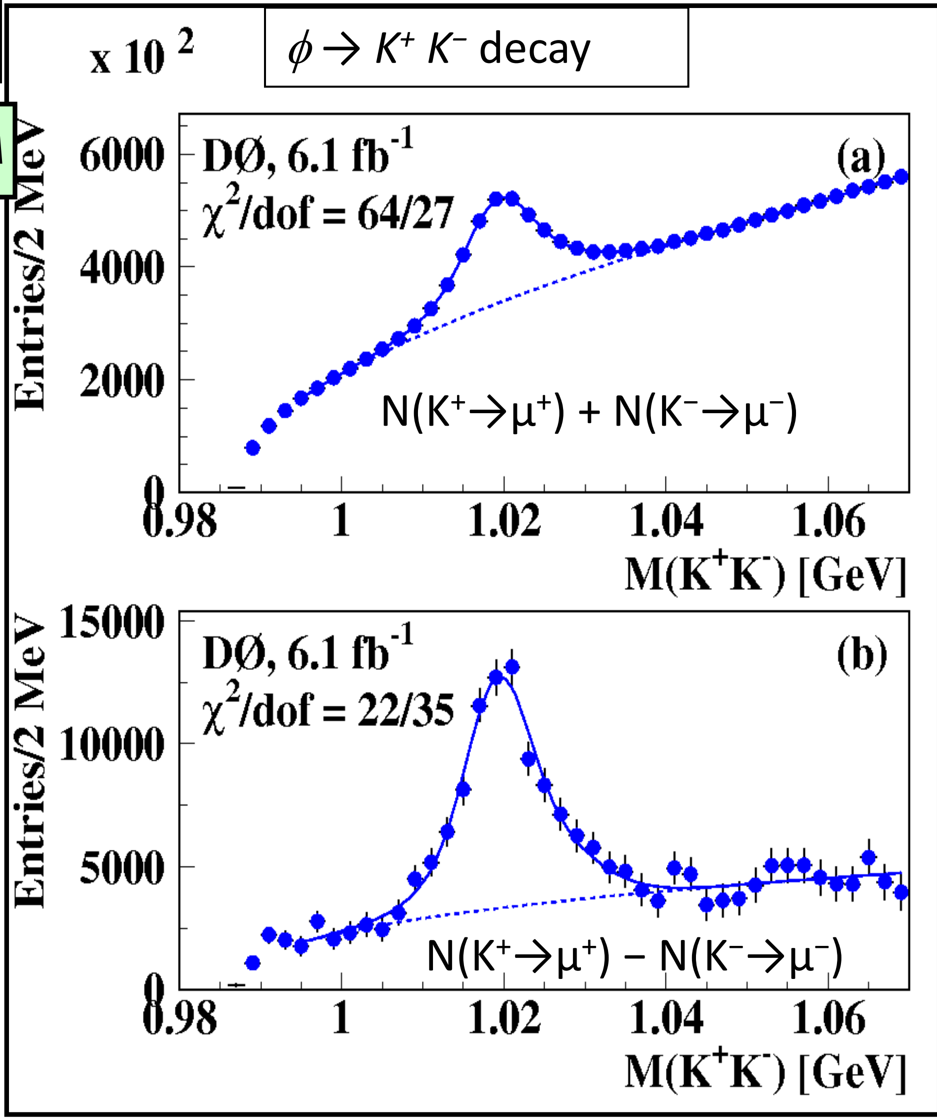
$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- Sources of kaons:

$$K^{*0} \to K^+\pi^-$$
$$\phi(1020) \to K^+K^-$$

- Require that the kaon is identified as a muon
- Build mass distributions separately for positive and negative K→μ samples
- Compute asymmetry in the number of observed events

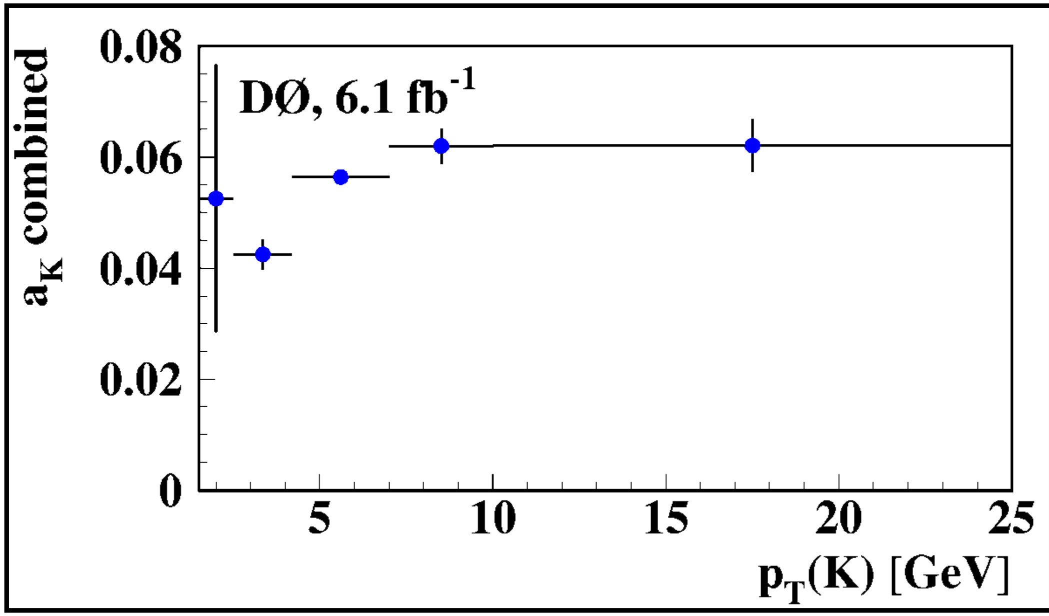


Measurement of kaon asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- Results from $K^{*0} \to K^+\pi^-$ and $\phi(1020) \to K^+K^-$ agree well
  - For the difference between two channels: $\chi^2/\mathrm{dof} = 5.4 / 5$
- Combination in p_T bins is used



Measurement of a_π, a_p

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

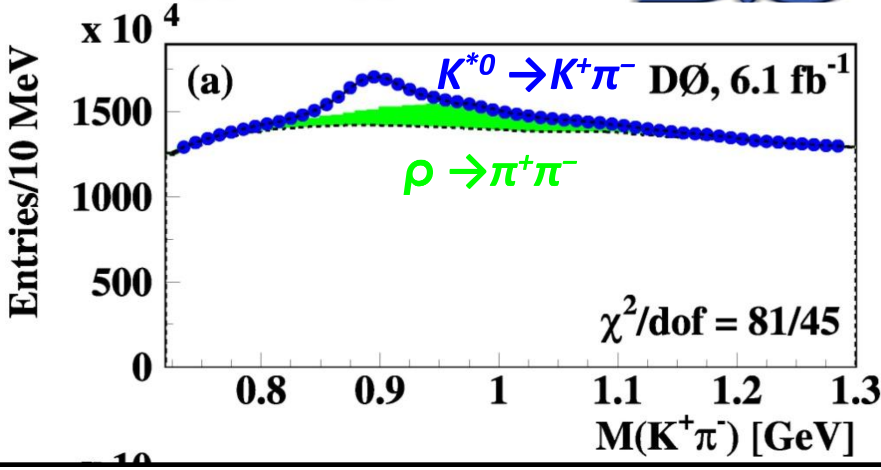
- The asymmetries a_π , a_p are measured using the decays $K_S \rightarrow \pi^+ \pi^-$ and $\Lambda \rightarrow p\, \pi^-$ respectively
- Similar measurement technique is used

	a_K	a_π	a_p
Data	$(+5.51 \pm 0.11)\%$	$+(0.25 \pm 0.10)\%$	$(+2.3 \pm 2.8)\%$

Measurement of f_K, F_K

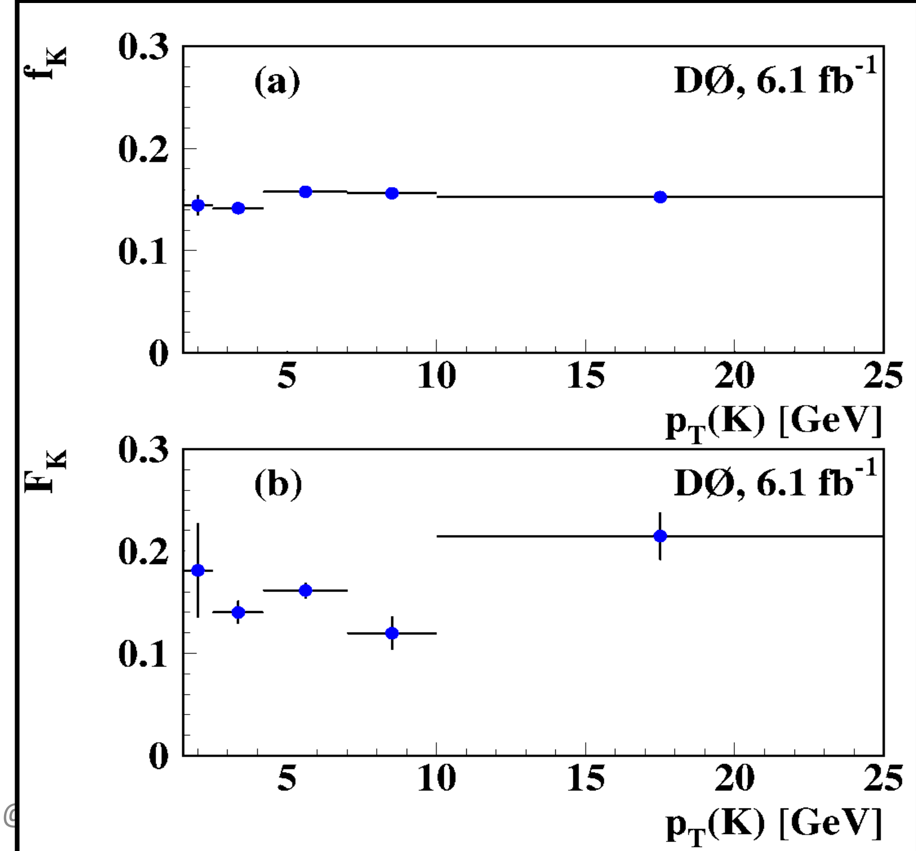
$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$



- Fractions f_K , F_K are measured using the decays $K^{*0} \to K^+\pi^-$

$$F_K, f_K = \frac{N(K_S)}{N(K^{*+} \to K_S \pi^+)} F_{K^{*0}}, f_{K^{*0}}$$

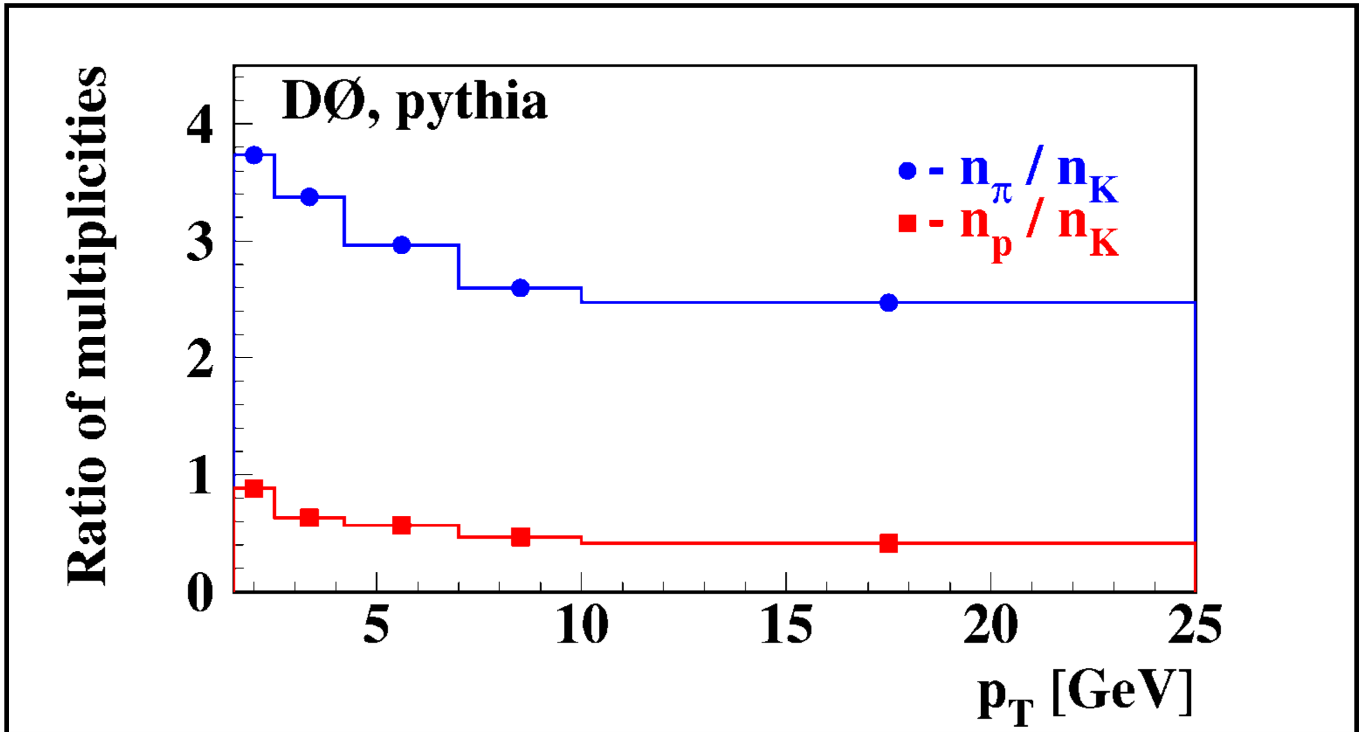


Measurement of f_π, f_p, F_π, F_p

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- Fractions f_π , f_p , F_π , F_p are obtained using f_K , F_K with an additional input from simulation on the ratio of multiplicities n_π / n_K and n_p / n_K



Muon reconstruction asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

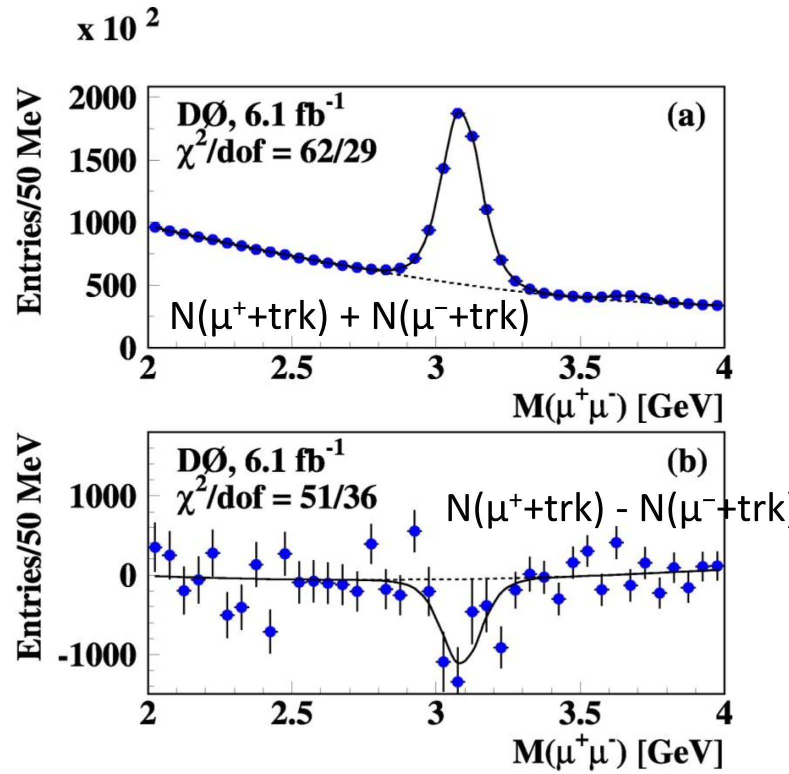
$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

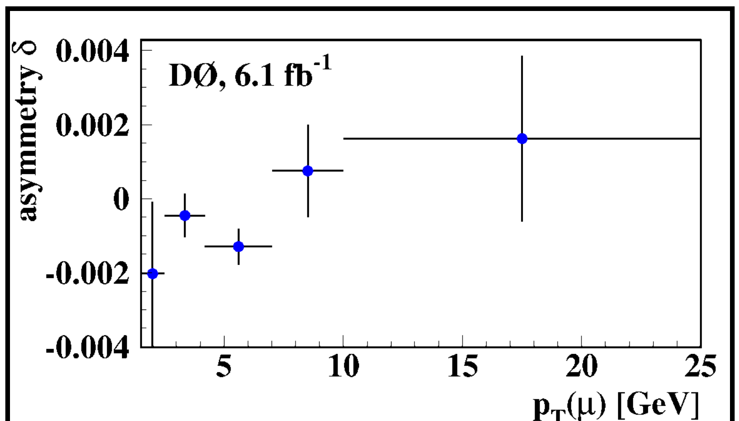
- We measure the muon reconstruction asymmetry using $J/\psi \to \mu\mu$ events
- Average asymmetries δ and Δ are:

$$\delta = (-0.076 \pm 0.028)\%$$
$$\Delta = (-0.068 \pm 0.023)\%$$

- To be compared with:

$$a = (+0.955 \pm 0.003)\%$$
$$A = (+0.564 \pm 0.053)\%$$





Summary of background contribution

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

	$(1-f_{bkg})$	f_K	f_π	f_p
MC	(59.0±0.3)%	(14.5±0.2)%	(25.7±0.3)%	(0.8±0.1)%
Data	(58.1±1.4)%	(15.5±0.2)%	(25.9±1.4)%	(0.7±0.2)%

	$f_K a_K$ (%) or $F_K A_K$ (%)	$f_\pi a_\pi$ (%) or $F_\pi A_\pi$ (%)	$f_p a_p$ (%) or $F_p A_p$ (%)	$(1-f_{bkg})\delta$ (%) or $(2-F_{bkg})\Delta$ (%)	a_{bkg} or A_{bkg}
Inclusive	0.854±0.018	0.095±0.027	0.012±0.022	−0.044±0.016	0.917±0.045
Dimuon	0.828±0.035	0.095±0.025	0.000±0.021	−0.108±0.037	0.815±0.070

- All uncertainties are statistical
- Notice that background contribution is similar for inclusive muon and dimuon sample: $A_{bkg} \approx a_{bkg}$

Signal contribution

$$k\,A^b_{sl} = a - a_{bkg}$$
$$K\,A^b_{sl} = A - A_{bkg}$$

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

- After subtracting the background contribution from the "raw" asymmetries *a* and *A*, the remaining residual asymmetries are proportional to A^b_{sl}

All processes except $\overline{B}^0_q \to B^0_q \to \mu^+ X$ don't produce any charge asymmetry, but rather dilute the values of *a* and *A* by contributing in the denominator of these asymmetries

	Process		
T_1	$b \to \mu^- X$		
T_{1a}	$b \to \mu^- X$ (non-oscillating)		
T_{1b}	$\bar{b} \to b \to \mu^- X$ (oscillating)	$\to A$	A^b_{sl}
T_2	$b \to c \to \mu^+ X$	$\to A$	
T_{2a}	$b \to c \to \mu^+ X$ (non-oscillating)		
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (oscillating)		A^b_{sl}
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$		
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$		
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$\to A$	
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$		

Coefficients k and K

$$k\,A_{sl}^{b} = a - a_{bkg}$$
$$K\,A_{sl}^{b} = A - A_{bkg}$$

- Coefficients *k* and *K* take into account this dilution of "raw" asymmetries *a* and *A*
- They are determined using the simulation of *b*- and *c*-quark decays
  - These decays are currently measured with a good precision, and this input from simulation produces a small systematic uncertainty
- Coefficient *k* is found to be much smaller than *K*, because many more non-oscillating *b*- and *c*-quark decays contribute to the asymmetry *a*:

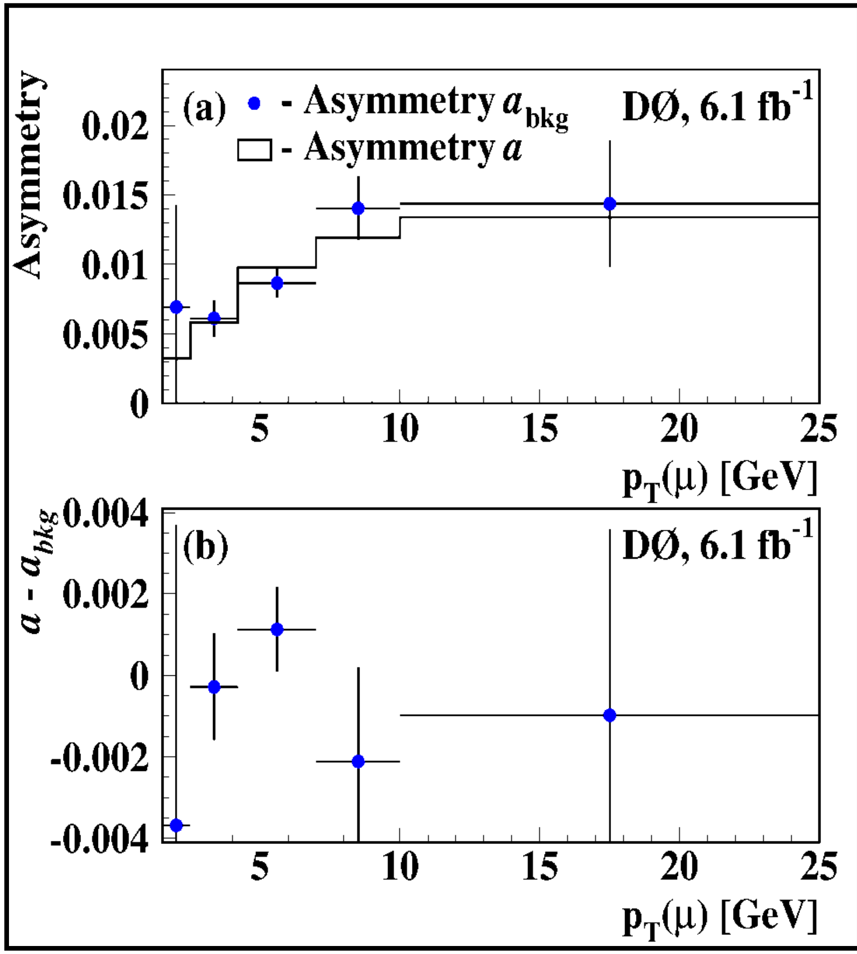
$$k = 0.041 \pm 0.003$$
$$K = 0.342 \pm 0.023$$

$$\frac{k}{K} = 0.12 \pm 0.01$$

Closure test

$$k\,A^b_{sl} = a - a_{bkg}$$

- The contribution of A^b_{sl} in the inclusive muon asymmetry a is suppressed by k = 0.041±0.003
- The value of a is mainly determined by the background asymmetry a_{bkg}
- Raw asymmetry: a=(+0.955±0.003)%
- Background asymmetry from data: a_{bkg}=(+0.917±0.045)%
- What about p_T dependences of the background asymmetries?



Agree well!

Bringing Everything Together

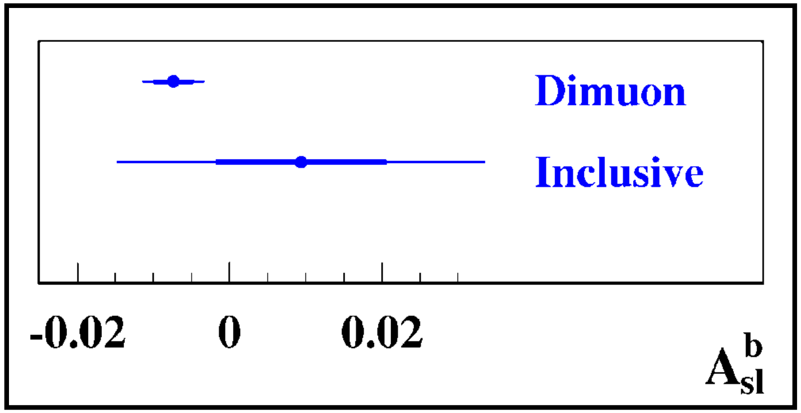
Using all results on background and signal contribution we get two separate measurements of A^b_{sl} from inclusive and like-sign dimuon samples:

$$A^b_{sl} = (+0.94 \pm 1.12\ (stat) \pm 2.14\ (syst)\ )\% \quad \text{(from inclusive)}$$

$$A^b_{sl} = (-0.736 \pm 0.266\ (stat) \pm 0.305\ (syst)\ )\% \quad \text{(from dimuon)}$$

Uncertainties of the first result are much larger, because of the small coefficient $k = 0.041 \pm 0.003$

Dominant contribution to the systematic uncertainty comes from the f_K and F_K fractions



Background subtraction

$$k\,A_{sl}^{b} = a - a_{bkg}$$

$$K\,A_{sl}^{b} = A - A_{bkg}$$

- Many background uncertainties in the inclusive muon and in the like-sign dimuon samples are correlated
- We subtract the background using the linear combination:

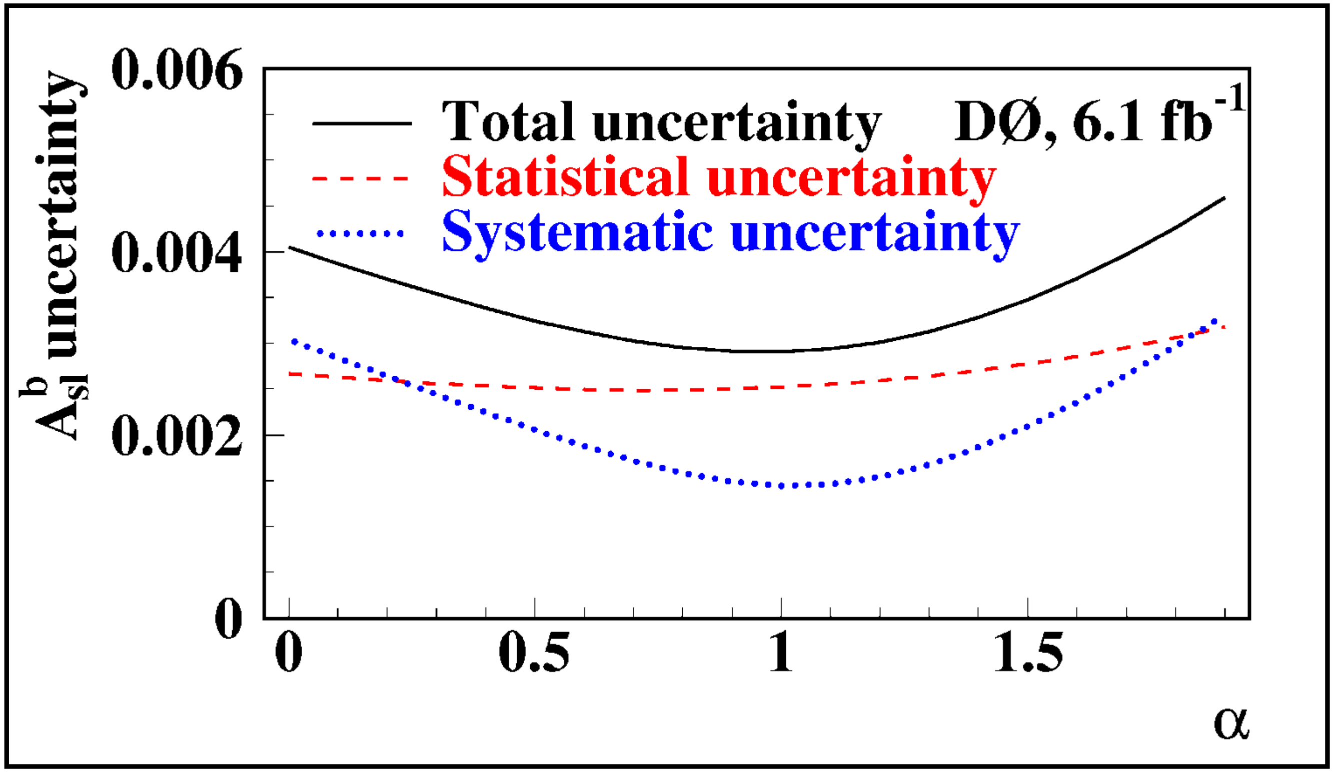
$$A' \equiv A - \alpha a = (K - \alpha k)A_{sl}^{b} + (A_{bkg} - \alpha a_{bkg})$$

  - The parameter α is selected such that the total uncertainty of A^{b}_{sl} is minimized
- Since $A_{bkg} \approx a_{bkg}$ and the uncertainties of these quantities are correlated, we can expect the cancellation of background uncertainties in A' for $\alpha \approx 1$
- The signal asymmetry A^{b}_{sl} does not cancel in A' for $\alpha \approx 1$ because:

$$k << K$$

Background subtraction

- Optimal value of *a* is obtained by the scan of the total uncertainty of A^b_{sl} obtained from *A'*
- The value α = 0.959 is selected:



Final result

- From $A' = A - \alpha\, a$ we obtain A^{b}_{sl} :

$$\boxed{A_{sl}^{b} = 0.506 \cdot a_{sl}^{d} + 0.494 \cdot a_{sl}^{s} = (-0.957 \pm 0.251\,(\mathrm{stat}) \pm 0.146\,(\mathrm{syst}))\%}$$

- To be compared with the SM prediction:

$$\boxed{A_{sl}^{b}(SM) = (-0.023^{+0.005}_{-0.006})\%}$$

- This result differs from the SM prediction by ~3.2 σ

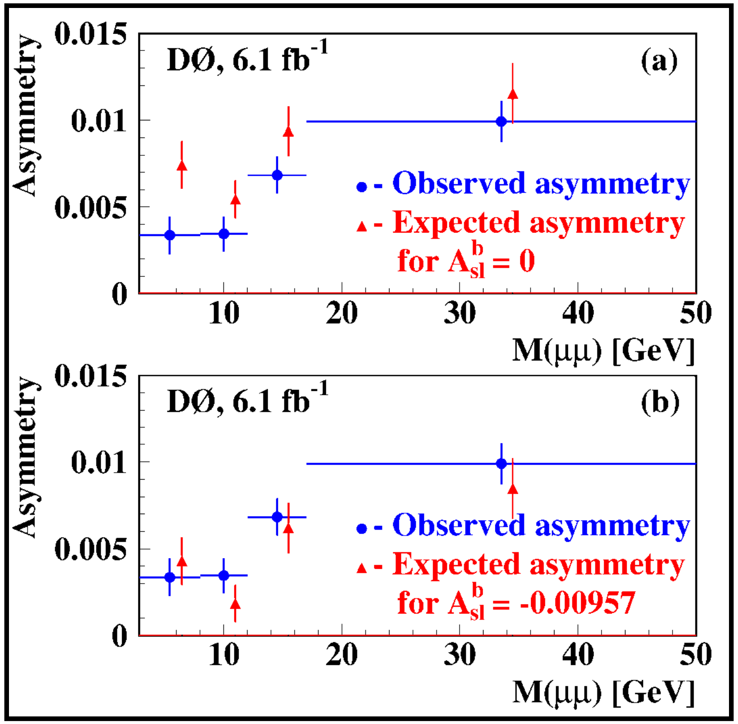
Statistical and systematic uncertainties

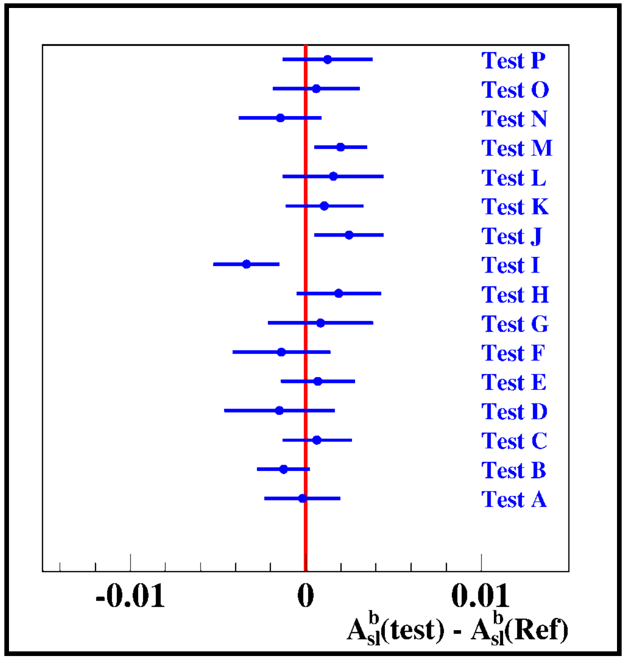
Source	A^b_{sl} inclusive muon	A^b_{sl} dimuon	A^b_{sl} combined
A or a (stat)	0.00066	0.00159	0.00179
f_K or F_K (stat)	0.00222	0.00123	0.00140
$P(\pi \to \mu)/P(K \to \mu)$	0.00234	0.00038	0.00010
$P(p \to \mu)/P(K \to \mu)$	0.00301	0.00044	0.00011
A_K	0.00410	0.00076	0.00061
A_π	0.00699	0.00086	0.00035
A_p	0.00478	0.00054	0.00001
δ or Δ	0.00405	0.00105	0.00077
f_K or F_K (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
c_b or C_b	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	0.02415	0.00405	0.00290

Dominant uncertainties

Consistency Checks

- No lifetime or flavour tagging
  - Is the asymmetry from B's?
  - Kinematical check





Modify selection, split sample tests, changes raw asymmetry by up to 150% due to variations in background

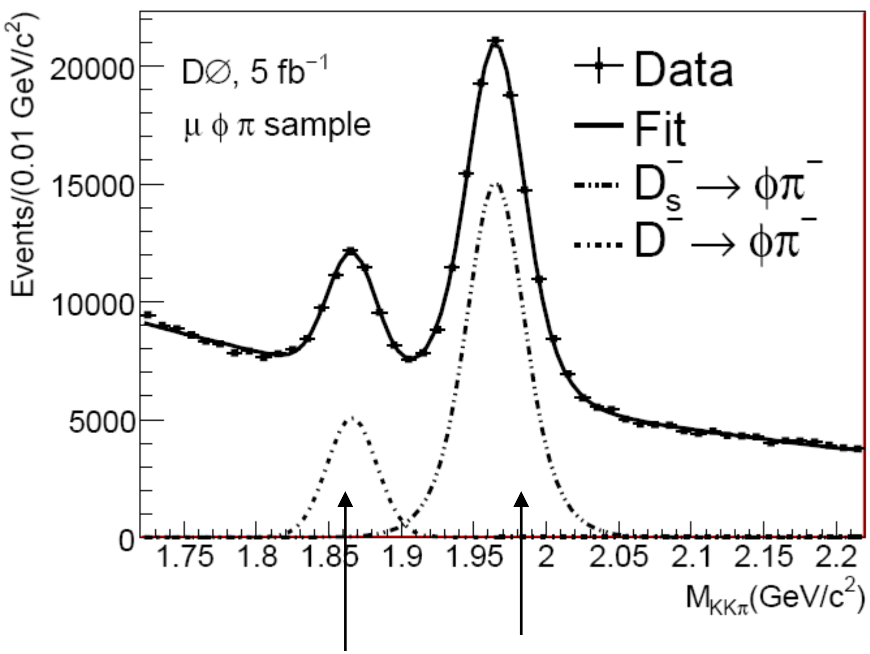
Measured value of A^b_{sl} remains stable

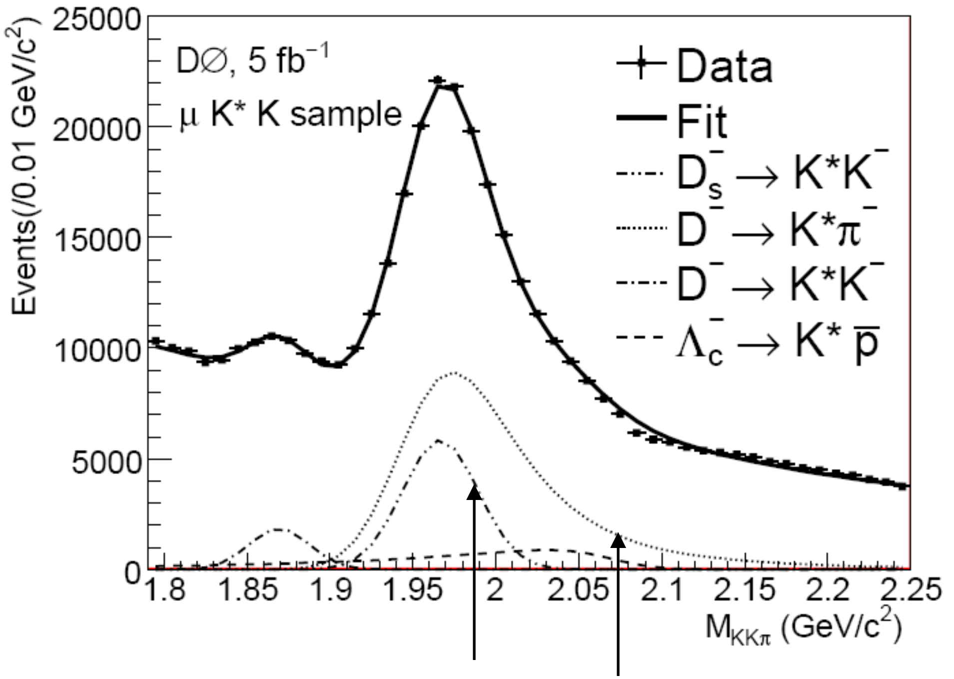
Exclusive Analysis

Exclusive analysis

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

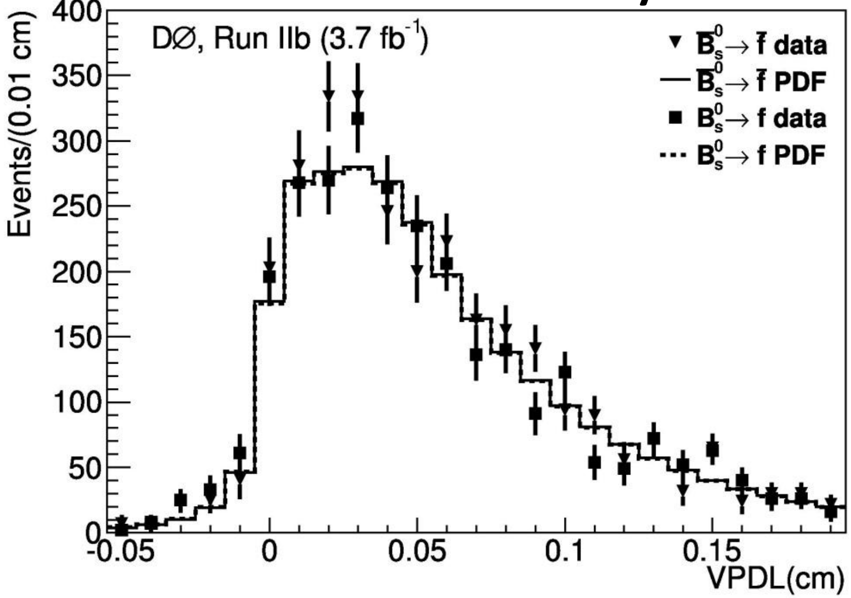
B_s and B_d overlap

- ~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

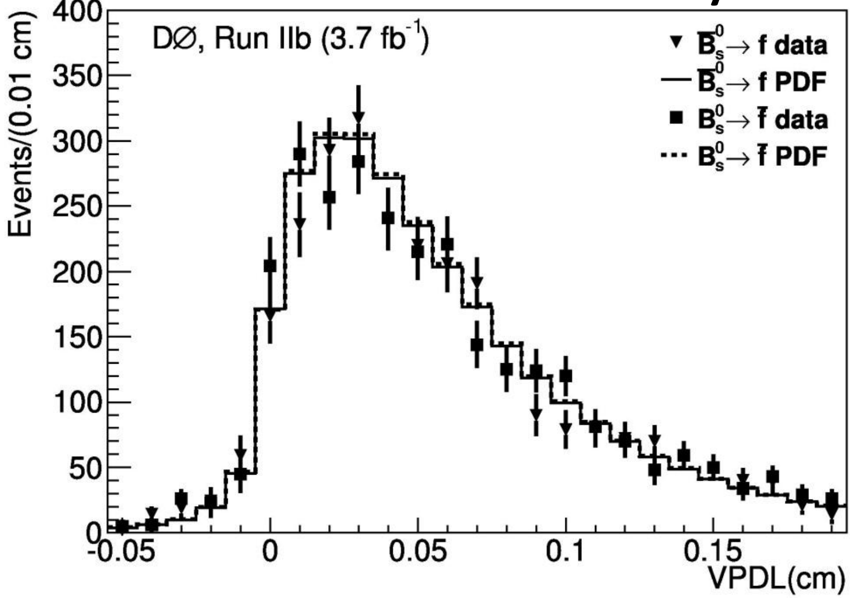
Exclusive analysis

Decay-length dependence

Direct decays



Mixed decays



Exclusive Analysis Results

TABLE II: Asymmetries 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
$A_{\mathrm{fb}} \times 10^3$	-1.8 ± 1.5	-2.0 ± 1.5	-1.9 ± 1.1
$A_{\mathrm{det}} \times 10^3$	3.2 ± 1.5	3.1 ± 1.5	3.1 ± 1.1
$A_{\mathrm{ro}} \times 10^3$	-36.7 ± 1.5	-30.2 ± 1.5	-33.3 ± 1.1
$A_{\beta\gamma} \times 10^3$	1.1 ± 1.5	0.2 ± 1.5	0.6 ± 1.1
$A_{q\beta} \times 10^3$	4.3 ± 1.5	2.0 ± 1.5	3.1 ± 1.1

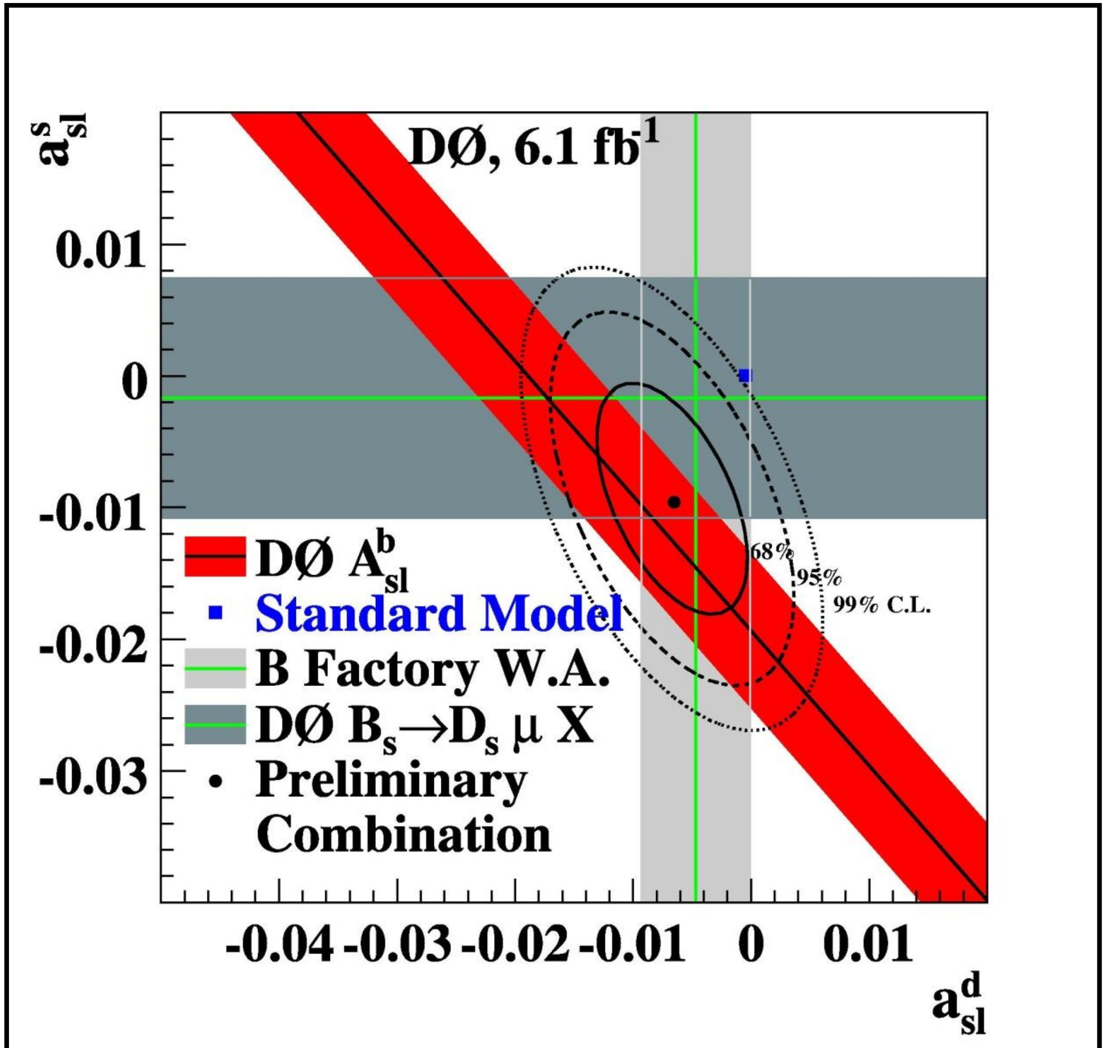
Exclusive analysis

TABLE III: Systematic uncertainties.

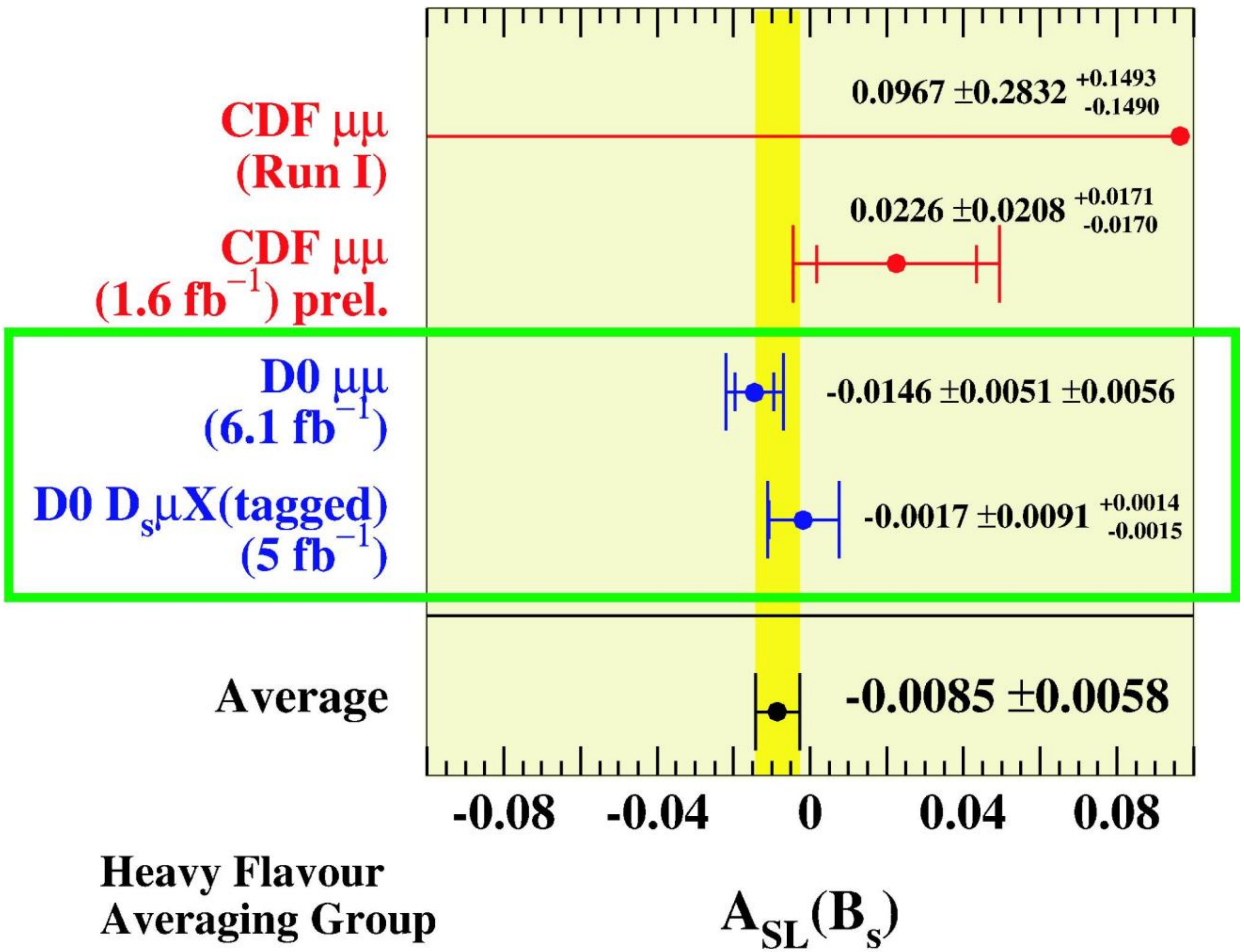
	$\sigma(a^s_{fs}) \times 10^3$
Kaon asymmetry set to 0	-1.24
Kaon asymmetry scaled by 2	1.30
Signal fraction -1σ	-0.76
Signal fraction $+1\sigma$	0.47
Dilution scaled by 0.9	-0.19
Dilution scaled by 1.1	0.21
μ trigger efficiency low	-0.03
μ trigger efficiency high	0.00
Decay-time dependent efficiency low	0.15
Decay-time dependent efficiency high	-0.01
VPDL resolution scaled by 0.95	0.03
VPDL resolution scaled by 1.05	-0.03
BF $B^0_s \to D^-_s D^+_s$	0.00
BF $B^0_s \to \mu^+ D^{(*)-}_s X$	-0.10
Relative BF $B^0_s \to \mu^+ \nu_\mu D^-_s$ low	0.01
Relative BF $B^0_s \to \mu^+ \nu_\mu D^-_s$ high	-0.05
B^0_d fraction in $\mu^+ D^-$ candidates set to 93%	-0.24
Fake vertex background low	-0.13
Fake vertex background high	-0.04
Prompt combinatorial background low	0.01
Prompt combinatorial background high	-0.01
$\Delta\Gamma_s$ -1σ	0.00
$\Delta\Gamma_s$ $+1\sigma$	-0.01
Δm_s -1σ	-0.01
Δm_s $+1\sigma$	0.02
Total	$^{+1.41}_{-1.50}$

Combination

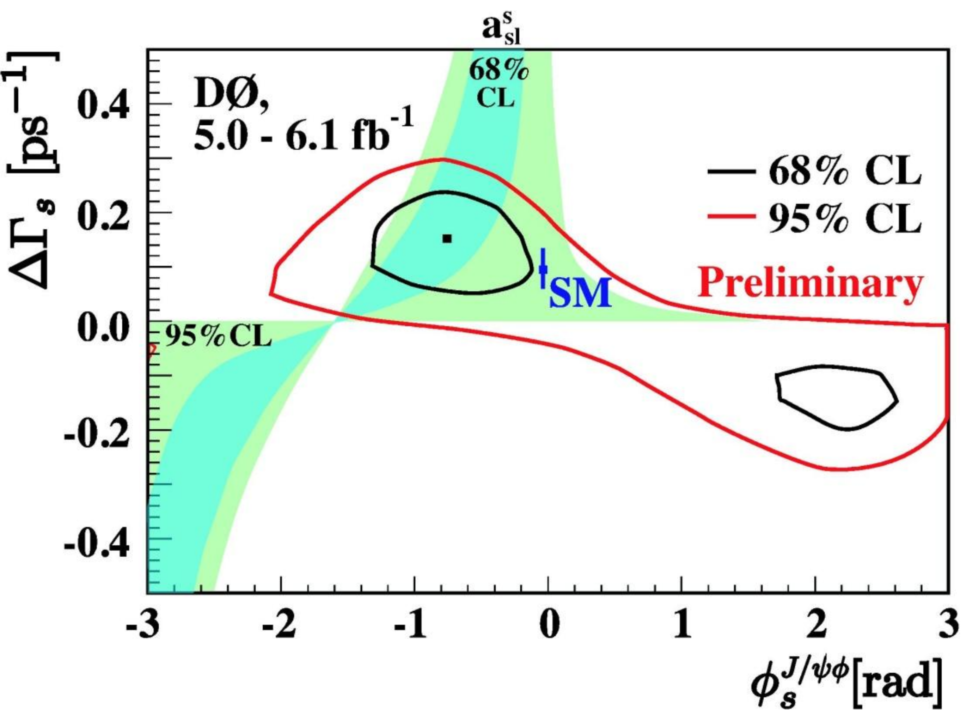
- Combination of measurements of semileptonic charge asymmetries

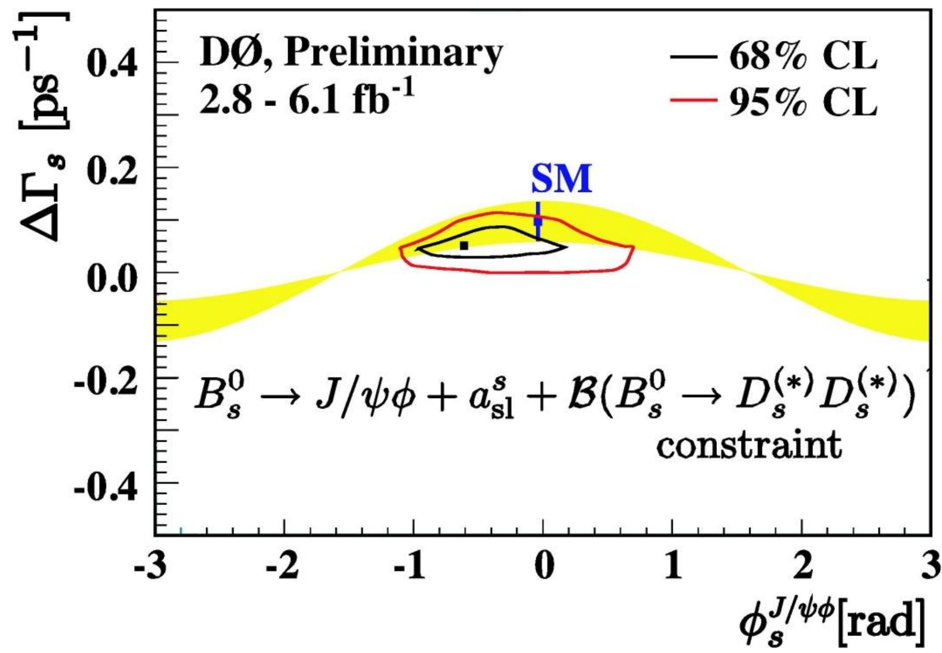


a^s_{sl} measurements

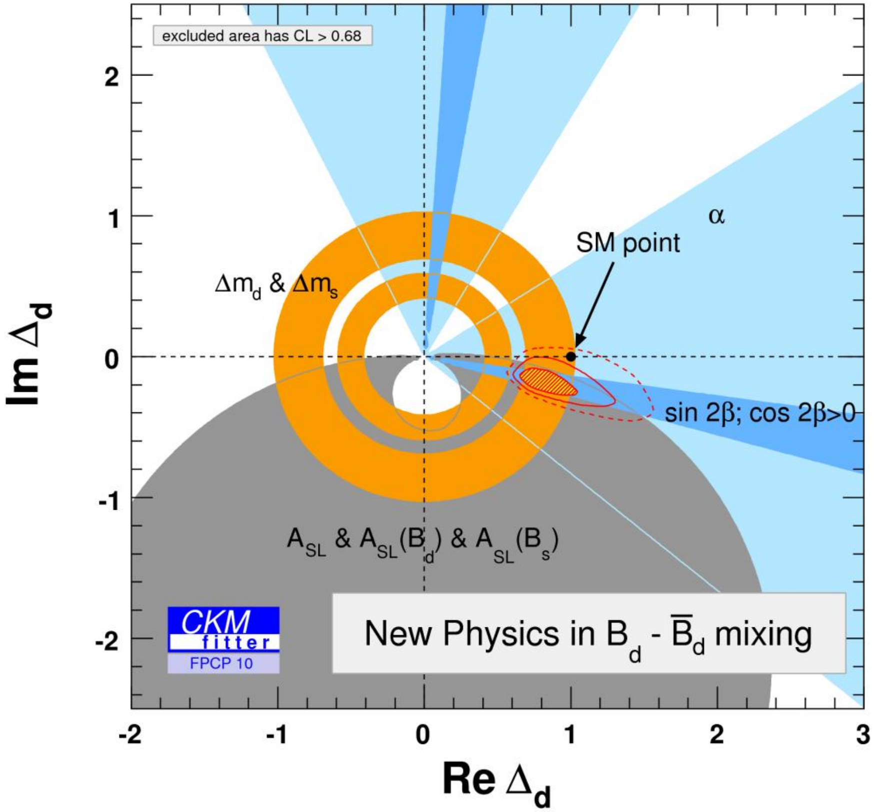


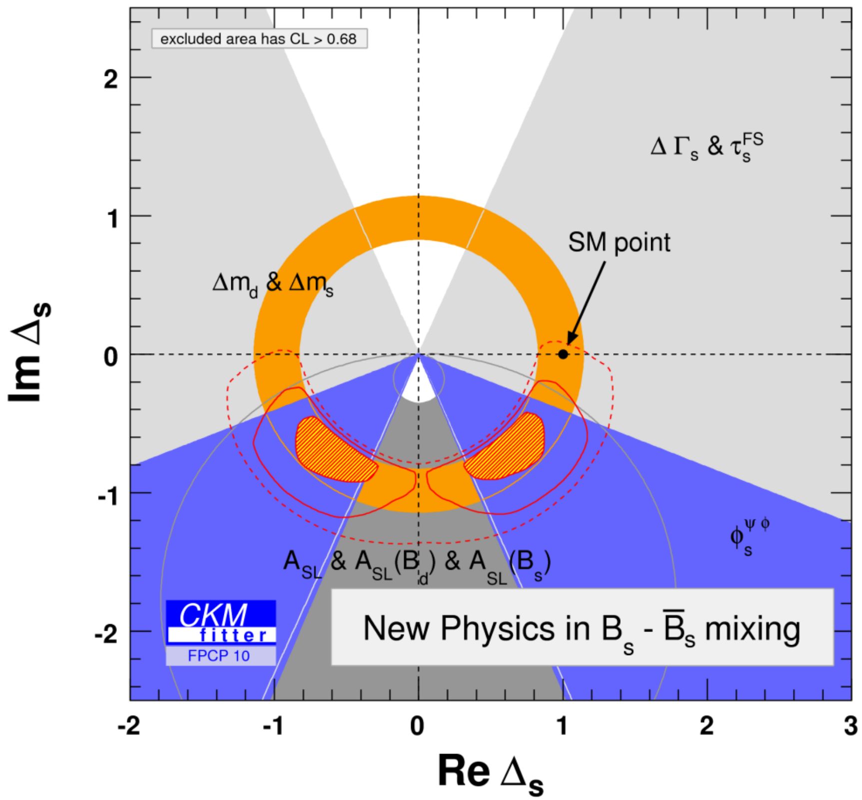
Combination with the Dzero $B_s \to J/\psi\varphi$ and $B_s \to D^{(*)}_s D^{(*)}_s$ analyses





Global Fits

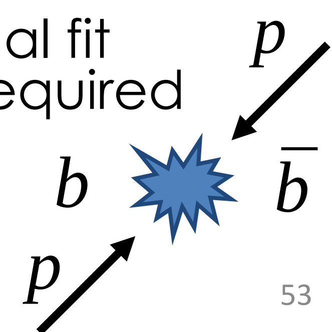




- 2.5-σ deviation from SM
- 2.7-σ deviation from SM

Perspectives

- New $B_s \rightarrow J/\psi\varphi$ results from the Tevatron and LHC experiments
- New A^b_{sl}, a^s_{sl} and a^d_{sl} results from DZero
- Model-independent measurements of semileptonic asymmetries at LHC is more challenging due to $B_{s/d/u}$ production asymmetries
  - Initial state is not symmetric anymore due to valence quarks (u and d only)
  - This leads to asymmetric hadronisations to $B_{u,d,s} - \overline{B}_{u,d,s}$ mesons
  - The asymmetries are different for B_d, B_u and B_s mesons
    - Can't measure for B_u and apply to $B_{d/s}$
    - Estimates from Pythia give (J.Damet&G.Ingelman):
      - ATLAS: A_{Bd}=(0.01→1.36)%, A_{Bu}=(0.04→1.57)%, A_{Bs}=(-1.41→0.06)% depending on model
      - LHCb: A_{Bd}=(0.09→2.19)%, A_{Bu}=(0.15→1.59)%, A_{Bs}=(-2.15→0.08)%
  - Exclusive analysis with initial state tagging and additional fit parameters describing the production asymmetries is required
    - See formulae on p. 11
    - The asymmetries enter the initial state tagging as well…



Conclusions

- Measurement of A^{b}_{sl} differs from the SM by 3.2σ

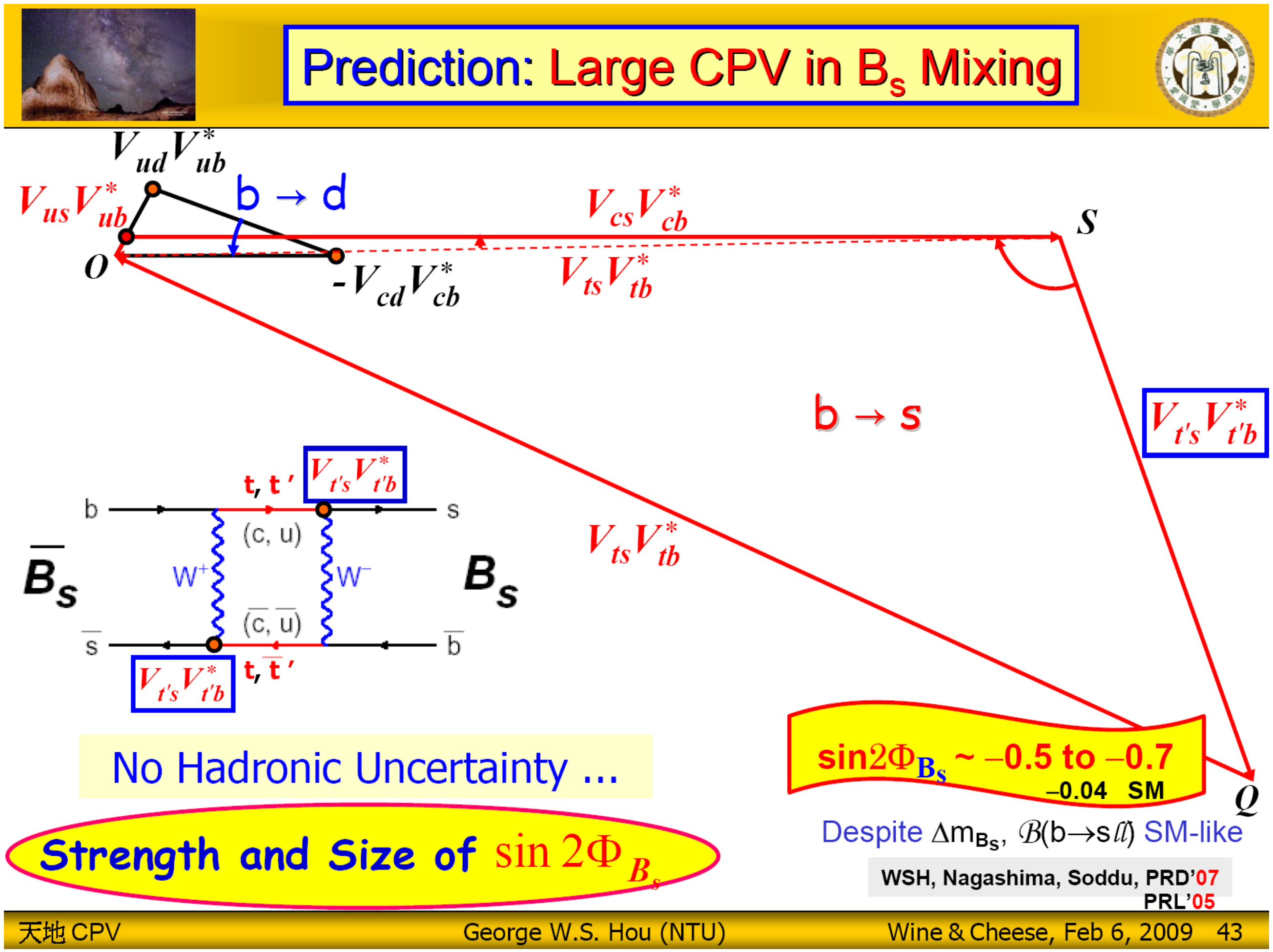
$$\boxed{A^{b}_{sl} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%}$$

- Almost all relevant quantities are obtained from data with minimal input from simulation
- Dominant uncertainty is statistical – precision can be improved with more luminosity
- Result is consistent with other measurements of CP violation in mixing
- High potential for new measurements of A^{b}_{sl} , a^{s}_{sl}, a^{d}_{sl} and φ^{s}_{sl} at Tevatron
- LHC experiments should be able to start contributing soon but model-independent measurements of semileptonic asymmetries will not be easy

Extra Slides

4^{th} Generation helps!

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

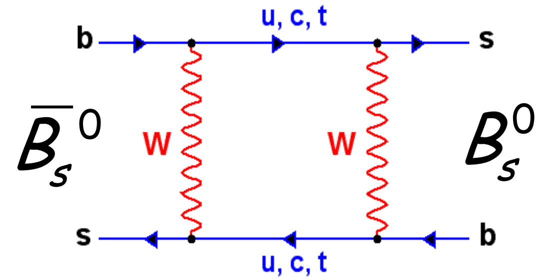


- Baryon asymmetry due to the new CKM^4 matrix could gain ~10^{+15}!

$B_s^0 - \overline{B_s^0}$ 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

$$\left.\begin{aligned} |B_L\rangle &= \frac{1}{\sqrt{p^2+q^2}}\left(p\,|B_s^0\rangle + q\,|\overline{B}_s^0\rangle\right) \\ |B_H\rangle &= \frac{1}{\sqrt{p^2+q^2}}\left(p\,|B_s^0\rangle - q\,|\overline{B}_s^0\rangle\right) \end{aligned}\right\} \rightarrow \begin{aligned} \Delta m_s &= M_H - M_L \approx 2|M_{12}| \\ \Delta\Gamma_s &= \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\varphi_s \end{aligned}$$

If q/p=1 ➔ No CP violation

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

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

$$
\begin{aligned}
N^{\pm\pm} \quad \propto & \qquad F_{SS}(1 \pm A_S)(1 \pm \Delta)^2 \\
+ & \sum_{x=K,\pi,p} F_{SL}^{x}(1 \pm A_x)(1 \pm a_S)(1 \pm \Delta) \\
+ & \sum_{x,y=K,\pi,p;\ y \geq x} \sum F_{LL}^{xy}(1 \pm A_x)(1 \pm A_y)
\end{aligned}
$$

$$
A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = F_{SS}A_S + F_{SL}a_S + (2 - F_{bkg})\Delta + F_K A_K + F_\pi A_\pi + F_p A_p
$$

$$
F_K = F_{SL}^{K} + F_{LL}^{K\pi} + F_{LL}^{Kp} + 2F_{LL}^{KK}
$$

$$
F_{bkg} = F_K + F_\pi + F_p = F_{SL} + 2F_{LL}
$$

$$
F_{SS} + F_{bkg} - F_{LL} = 1
$$

Sample Composition

TABLE XI: Heavy quark decays contributing to the inclusive muon and like-sign dimuon samples. Abbreviation "nos" stands for "non-oscillating," and "osc" for "oscillating." All weights are computed using the MC simulation.

	Process	Weight
T_1	$b \to \mu^- X$	$w_1 \equiv 1.$
T_{1a}	$b \to \mu^- X$ (nos)	$w_{1a} = (1-\chi_0)w_1$
T_{1b}	$\bar{b} \to b \to \mu^- X$ (osc)	$w_{1b} = \chi_0 w_1$
T_2	$b \to c \to \mu^+ X$	$w_2 = 0.113 \pm 0.010$
T_{2a}	$b \to c \to \mu^+ X$ (nos)	$w_{2a} = (1-\chi_0)w_2$
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (osc)	$w_{2b} = \chi_0 w_2$
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_3 = 0.062 \pm 0.006$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$	$w_4 = 0.021 \pm 0.001$
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_5 = 0.013 \pm 0.002$
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_6 = 0.660 \pm 0.077$