Search for new sources of CP violation at the DØ experiment

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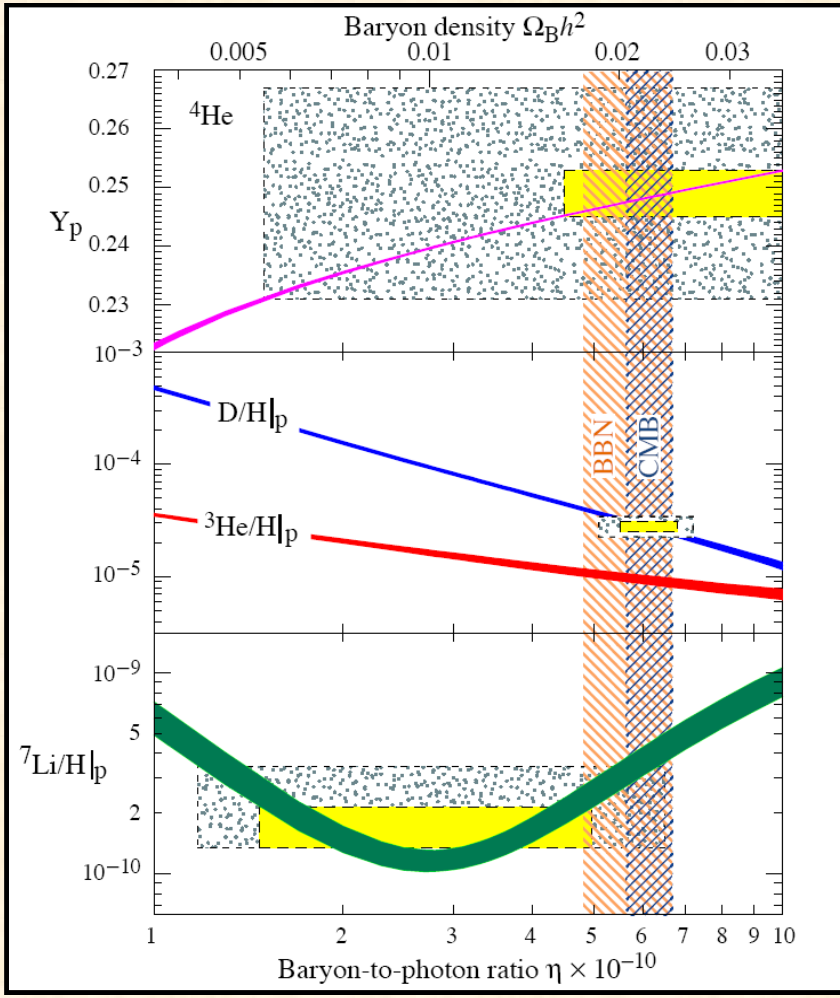
Baryon Asymmetry of the Universe

- **Baryon asymmetry *(BAU)* is one of the biggest obstacles in explaining the evolution of our Universe:**
  - **Big-bang nuclesynthesis *(BBN)* is very successful in describing the abundance of different elements in the Universe;**
  - **All results are consistent with $n(B)/n(\gamma) = (6.1\pm0.2)\times10^{-10}$ (WMAP);**
  - **However, $n(\bar{B})/n(\gamma) = 0$;**
- **Excess of matter over antimatter is a precondition, not a prediction of the BBN;**



Abundances of different elements as predicted by the BBN (B.D. Fields and S. Sarkar, PDG-2008)

Baryon Asymmetry of the Universe and CP violation

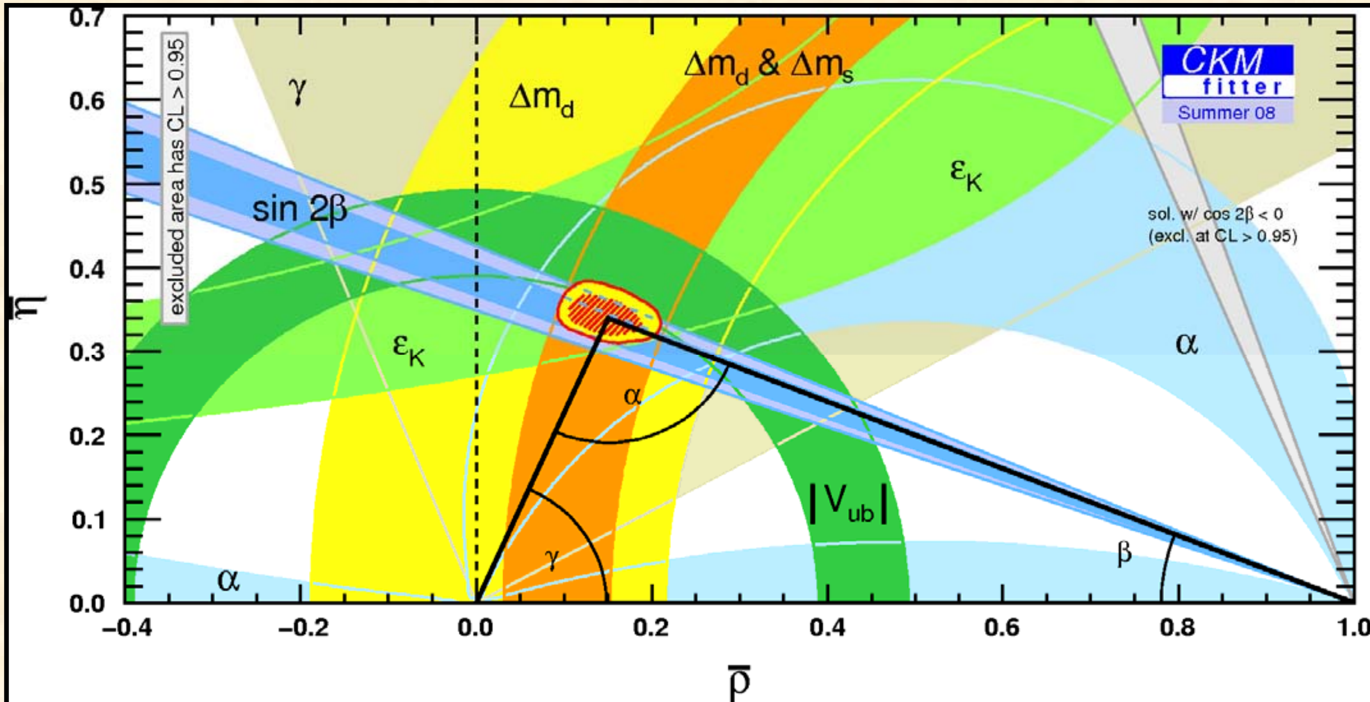
- **CP violation, or difference in properties of matter and antimatter, is the necessary ingredient to explain the BAU (and our existence):**
  - **Particles of antimatter could decay faster due to the CP violation, leaving only the particles of matter in our Universe;**
- **The only known source of CP violation is the complex quark-mixing CKM matrix:**

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$V_{ub} \neq V_{ub}^*; V_{td} \neq V_{td}^* \Rightarrow \textbf{CPV}$$

Standard Model CPV

- **In the SM with 3 generations the CKM matrix has just one complex phase:** $\gamma \equiv \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) = \arg(\bar{\rho} + i\bar{\eta})$
  - **All other complex parameters are determined by the unitarity relations, e.g.:** $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
- **Essentially all observed phenomena are described well by a single complex phase of the CKM matrix:**
  - **All measurements are consistent with a single crossing point in the *(ρ-η)* plane;**



Standard Model CPV

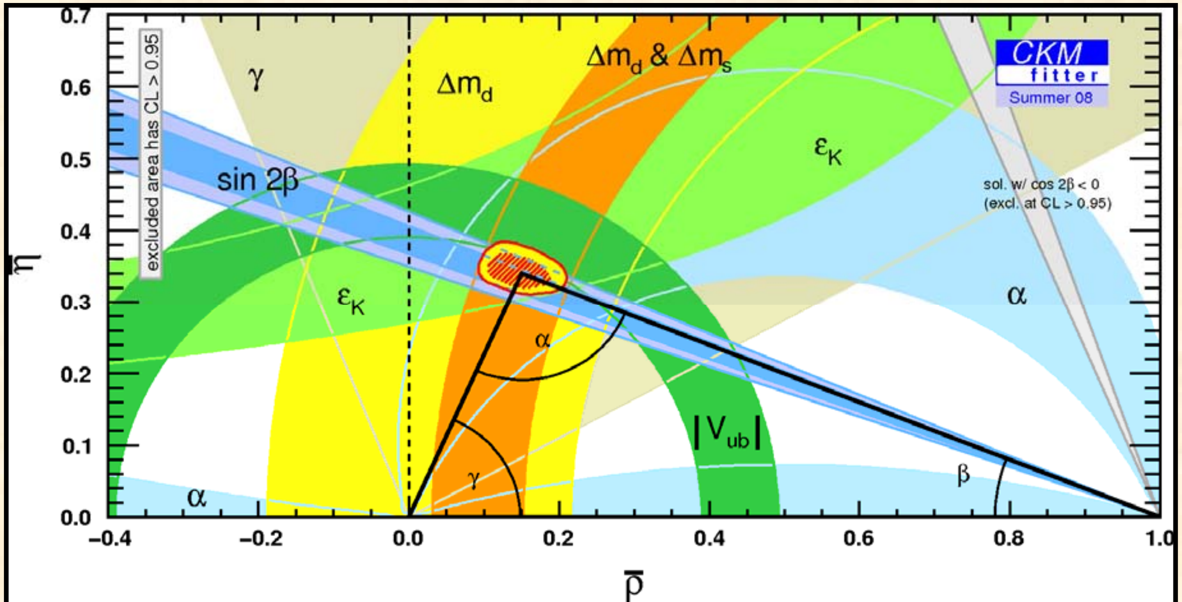
- **Notwithstanding this success of the SM in describing the CPV phenomena, the magnitude of the CP violation in the SM is too small (about 10 orders of magnitude) to explain the observed asymmetry between matter and antimatter;**
  - **see e.g. P. Suet, E. Sather, Phys.Rev.D51, 379-394 (1995);**

The fact of our existence calls for new sources of the CP violation beyond the standard model

- **The search of these sources is one of the main goals of current and future experiments;**

Search for new contributions

- **Identifying new sources of CP violation is complicated by large theoretical uncertainties in the SM prediction for many observables, or by large experimental uncertainties in their measurement:**
  - **E.g. angles α and γ of UT are known with large uncertainties, although the huge input statistics of B factories was used;**
  - **Conversion of $\Delta M_s/\Delta M_d$ to $|V_{ts}/V_{td}|$ includes large theoretical uncertainties much larger than the experimental error;**

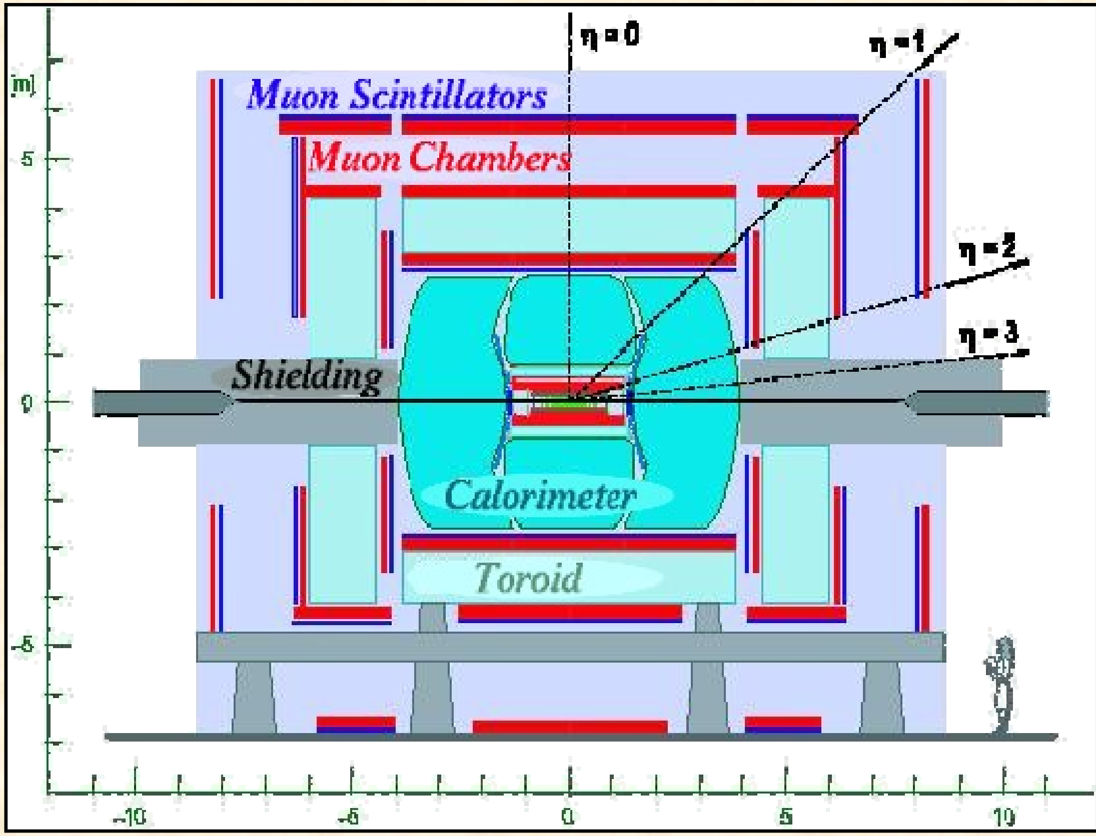


Strategy of search

- **A promising strategy of this search is to study the processes where the Standard Model predicts a small CP violation, while the extensions of the Standard Model predict large CP violating effects:**
  - **Deviation from the zero level is much easier to observe;**
  - **Small central value usually imply small theoretical uncertainties;**

This strategy is adopted by the DØ experiment

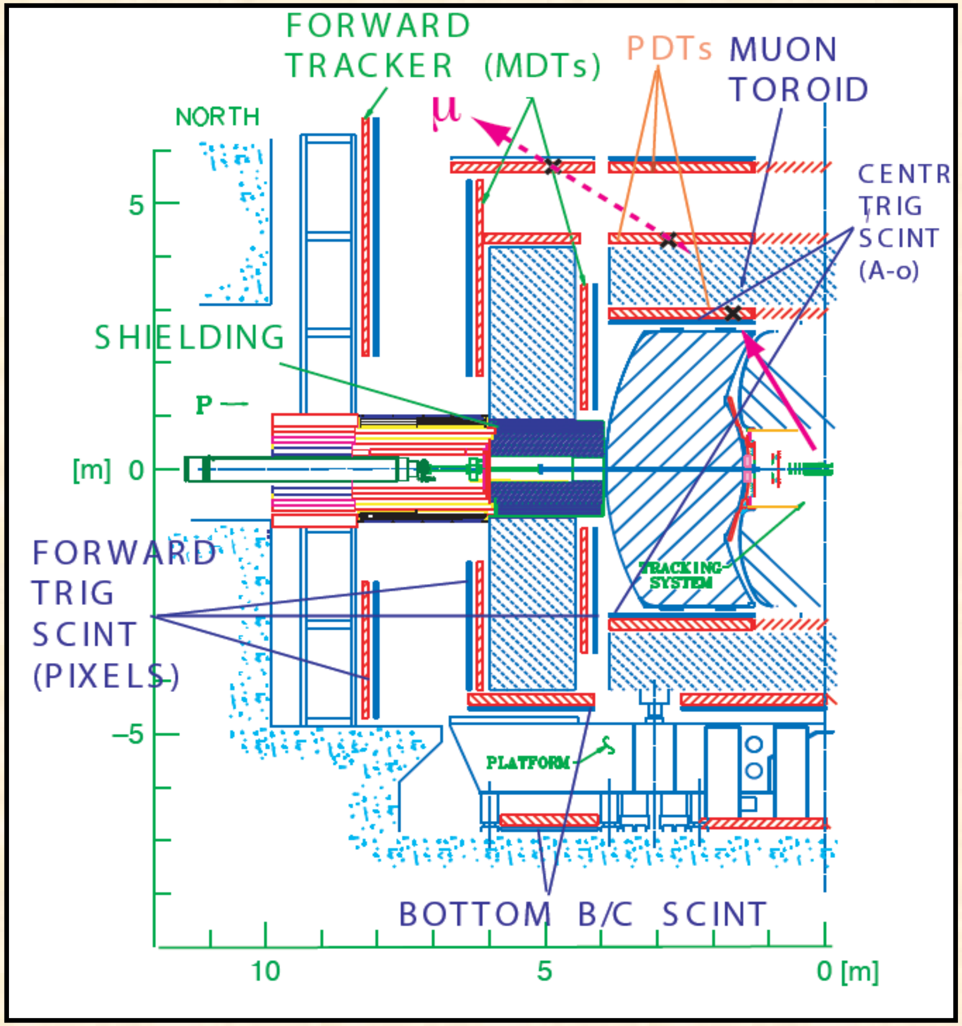
DØ Detector



Key elements for B-physics:

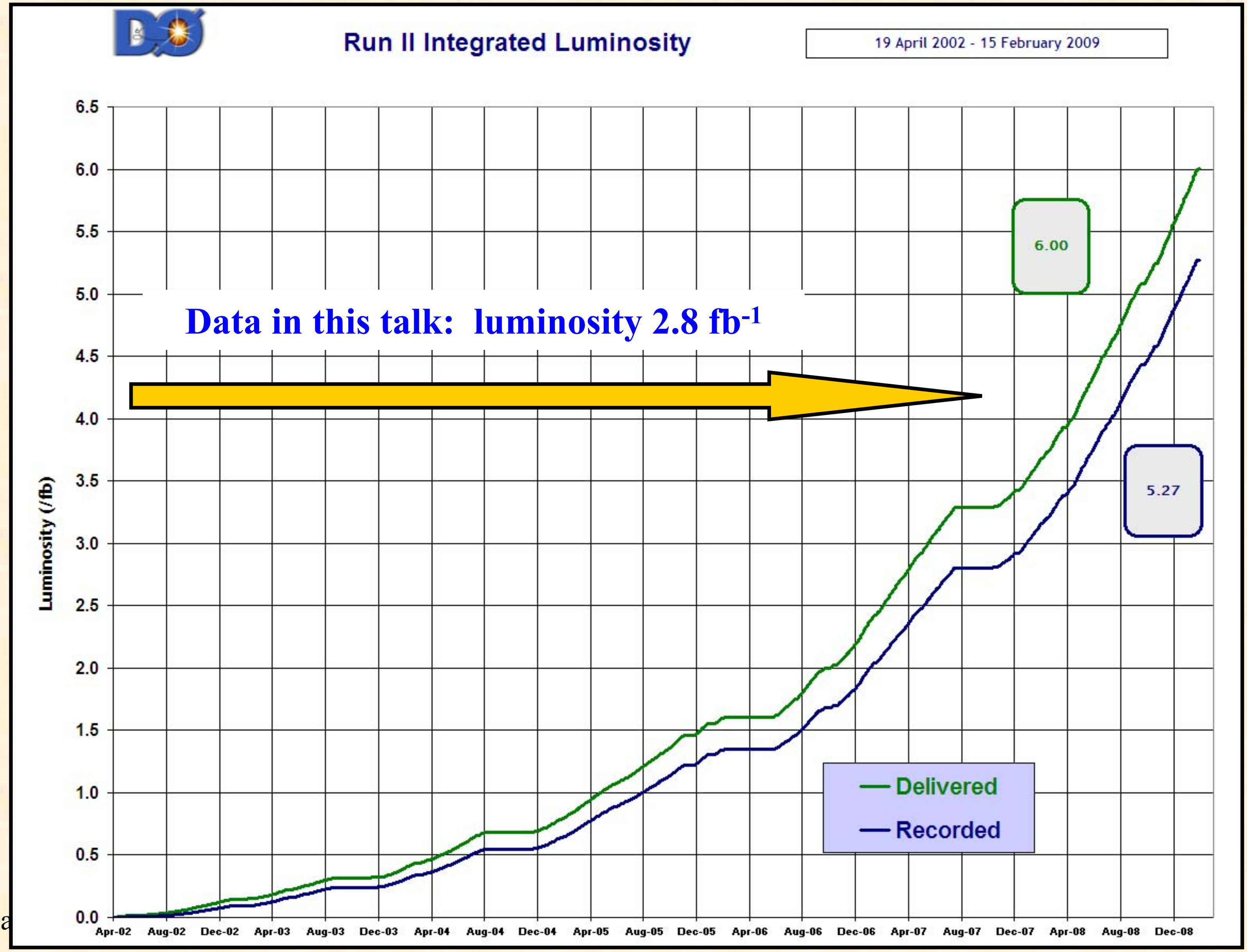
- **Muon system;**
- **Muon trigger;**
- **Solenoid + Toroid;**
- **Polarities of magnets are regularly reversed;**
- **Tracking with precise vertex detector;**
- **Wide acceptance up to $|\eta|<2$;**

DØ Muon System



- **Large acceptance |*η*|< 2.2;**
- **Excellent triggering;**
- **Cosmic ray rejection;**
- **Low punch-through;**
- **Local measurement of muon charge and momentum;**
- **High purity of muon ID;**

Available statistics



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In this talk

- **CP violation in $B_s \rightarrow J/\psi\ \varphi$ decay;**
- **Charge asymmetry in semileptonic $B_s \rightarrow \mu\nu D_s$ decay;**
- **Charge asymmetry in $B^{\pm} \rightarrow J/\psi\ K^{\pm}$ decay;**

CP violation in $B_s \rightarrow J/\psi\ \varphi$

Decay $B_s \to J/\psi\ \varphi$

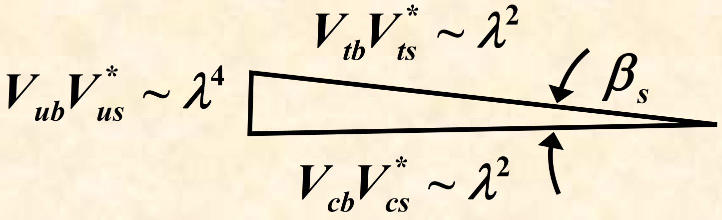
- The final system is the mixture of CP-even and CP-odd eigenstates;
- Both B_s and $\overline{B}_s$ decay to this system, and the interference between the decay and mixing $B_s \leftrightarrow \overline{B}_s$ produces the CP-violating effects;

$$\begin{tikzcd}
B_s \arrow[rr, bend left] \arrow[dr, bend right] & & J/\psi\ \varphi \\
& \overline{B}_s \arrow[ur, bend right] &
\end{tikzcd}$$

CP violating phase

- **CP violation in $B_s \rightarrow J/\psi\varphi$ decay is described by the phase ϕ_s;**
- **Within the SM ϕ_s is related with the angle of the (bs) unitarity triangle:**

$$\boxed{\phi_s^{SM} = -2\beta_s = 2\arg\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) = -0.038 \pm 0.002}$$



  - **M. Bona *et al.* (UTfit collab.), JHEP 0610,0811 (2006).**

- **From the values of CKM elements: $\beta_s \sim \lambda^2$ (λ=0.226);**

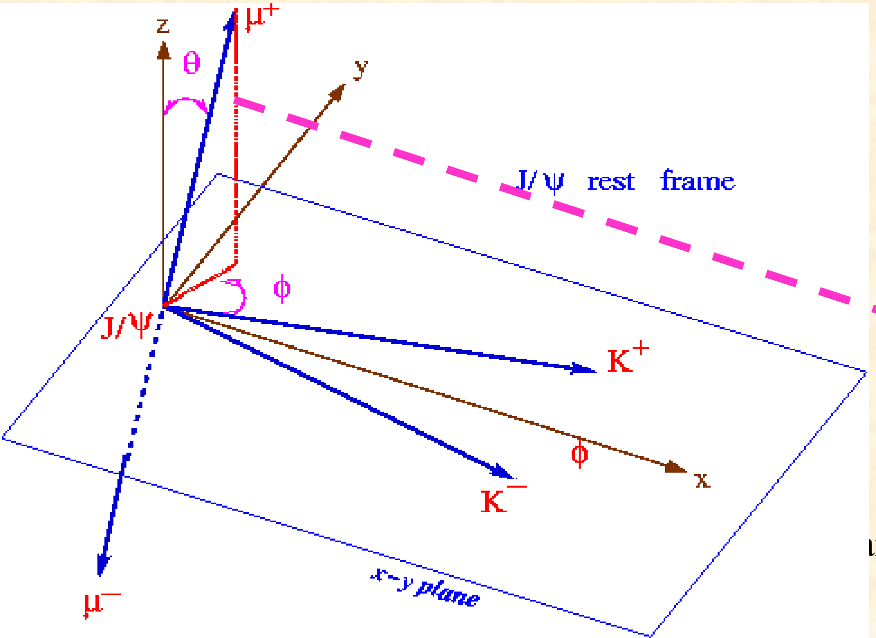
This phase is very small in the Standard Model

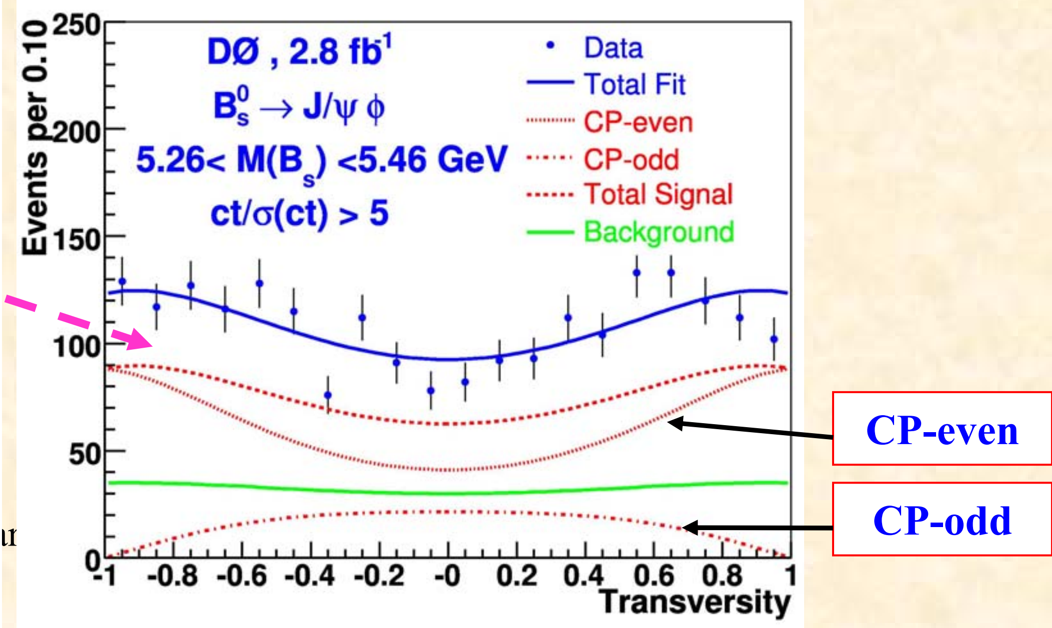
- **It can be significantly modified by the new physics contribution:**
  - **E.g. 4th generation of quarks: W. Hou, arxiv:0803.1234**

Any large non-zero value of the phase ϕ_s will be a clear and unambiguous indication of the new physics contribution

Polarization amplitudes

- Decay is described by 3 complex polarization amplitudes:
  - A_0, $A_\parallel$ amplitudes correspond to the CP-even eigenstate;
  - $A_\perp$ amplitude corresponds to the CP-odd eigenstate;
  - Absolute values of amplitudes and the strong phases $\delta_1 \equiv \arg\left\{A_\parallel^* A_\perp\right\}$; $\delta_2 \equiv \arg\left\{A_0^* A_\perp\right\}$ can be measured from the angular distribution of decay products;





Time evolution of amplitudes

- **The time evolution of decay rate for the initial B_s and initial $\overline{B}_s$ is different in presence of CP violation:**

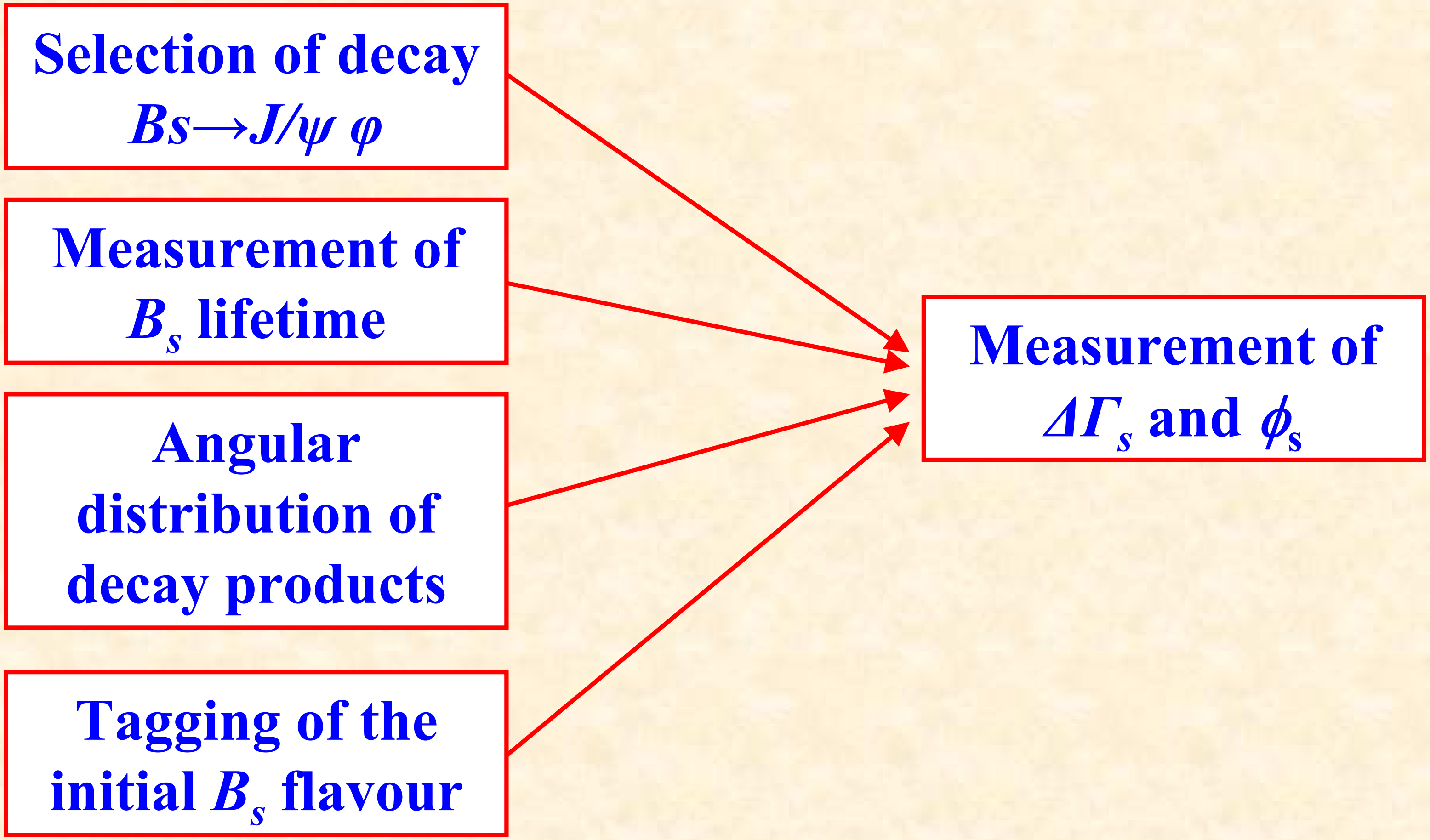
$$d\Gamma / dt \propto e^{-\overline{\Gamma}_s t}\left(\cosh\frac{\Delta\Gamma_s t}{2} + (|A_0|^2 + |A_\parallel|^2 - |A_\perp|^2)(f \cdot \sin(\Delta M_s t)\sin\phi_s - \sinh\frac{\Delta\Gamma_s t}{2}\cos\phi_s) \right)$$

  - **$f = +1$ for initial B_s; $f = -1$ for initial $\overline{B}_s$;**

We can measure both $\Delta\Gamma_s$ and ϕ_s by studying the time evolution of the angular distributions of the decay products and detecting the initial flavour of B_s

  - **Dependence on angular variables is more complicated, and includes the terms $\sim \sinh(\Delta\Gamma \cdot t / 2)\sin\phi_s$;**
  - **It means that we are sensitive to ϕ_s even without the initial flavour tagging, provided there is a sizeable width difference $\Delta\Gamma_s$;**

Ingredients of analysis



Selection of decay $B_s \to J/\psi\ \varphi$

Measurement of B_s lifetime

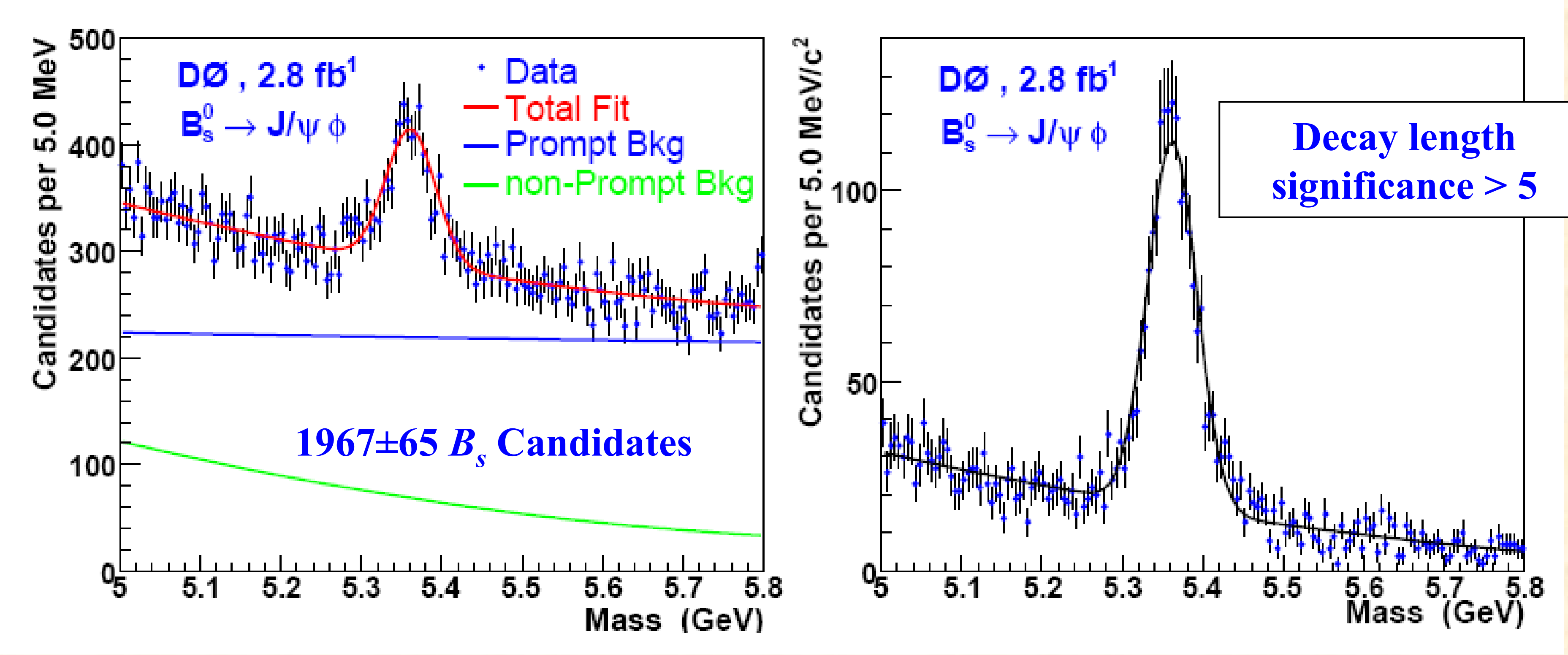
Angular distribution of decay products

Tagging of the initial B_s flavour

Measurement of $\Delta\Gamma_s$ and ϕ_s

Signal selection

- Select $J/\psi \rightarrow \mu^+\mu^-$ and $\varphi \rightarrow K^+K^-$;
- Sequential cuts on masses $M(\mu^+\mu^-)$, $M(K^+K^-)$ momenta of μ^+, μ^-, K^+, K^- and vertex quality;
- Applied cuts do not bias the lifetime distribution;



1967±65 B_s Candidates

Decay length significance > 5

Lifetime measurement

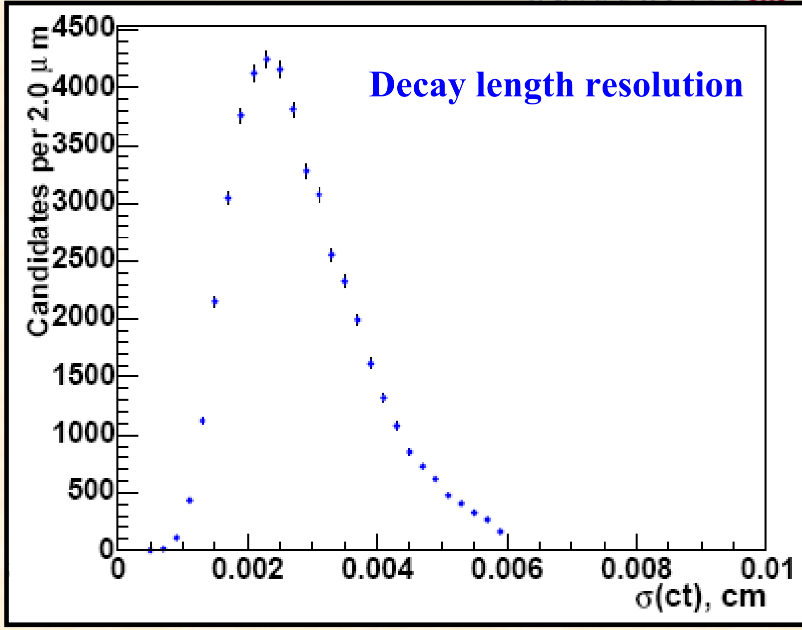
- **Proper decay length resolution: ct ~ 25 μm;**
- **Excellent description of lifetime distribution;**

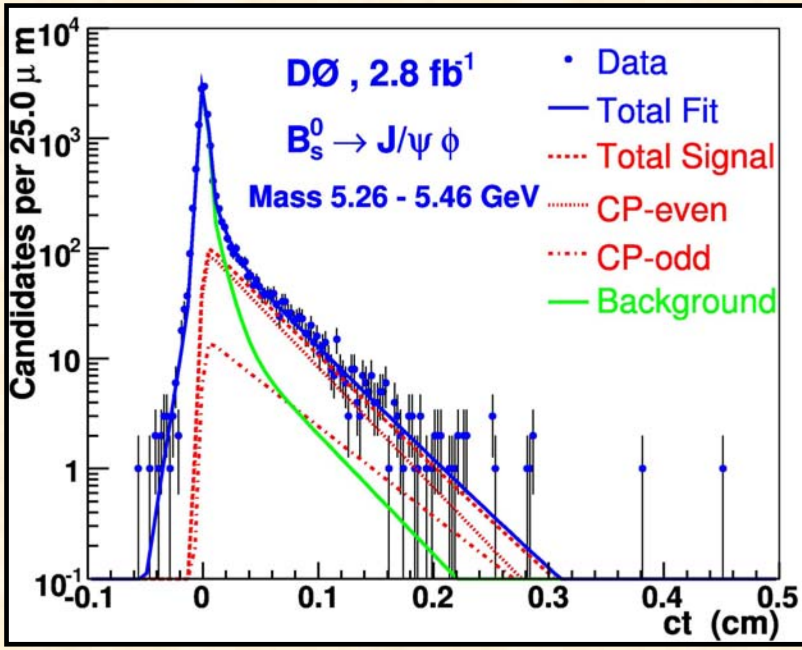
$$\bar{\tau}(B_s^0) = 1.52 \pm 0.05 \pm 0.01\,\mathrm{ps}$$

$$\Delta\Gamma_s = 0.19 \pm 0.07\,(\mathrm{stat})\,^{+0.02}_{-0.01}\,(\mathrm{syst})\,\mathrm{ps}^{-1}$$

- **Measured B_s lifetime is consistent with the world average value:**

$$\bar{\tau}(B_s^0) = 1.425 \pm 0.041\,\mathrm{ps}\ \ (\mathrm{PDG-2008})$$

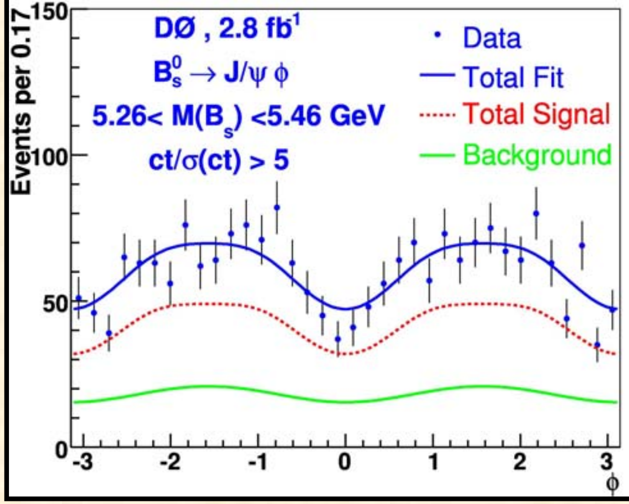


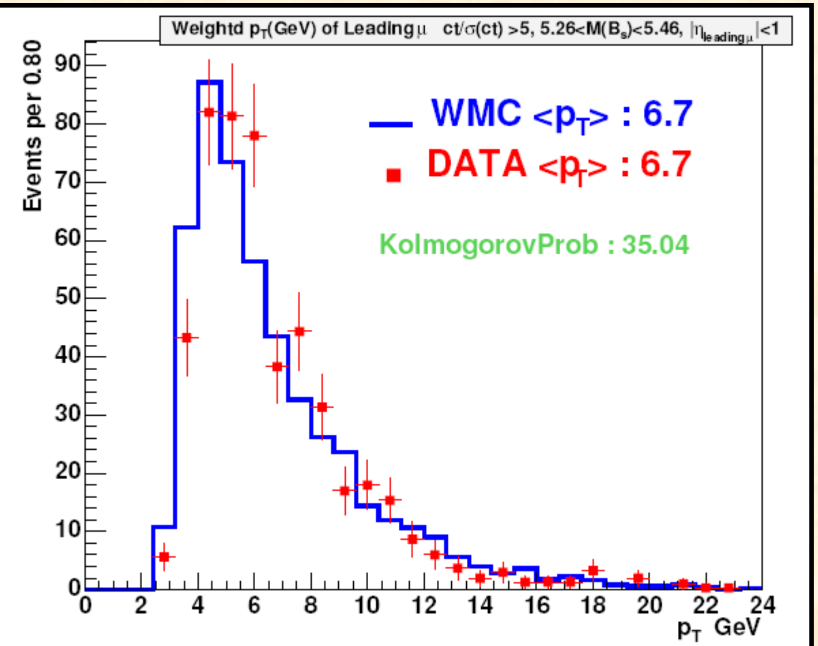


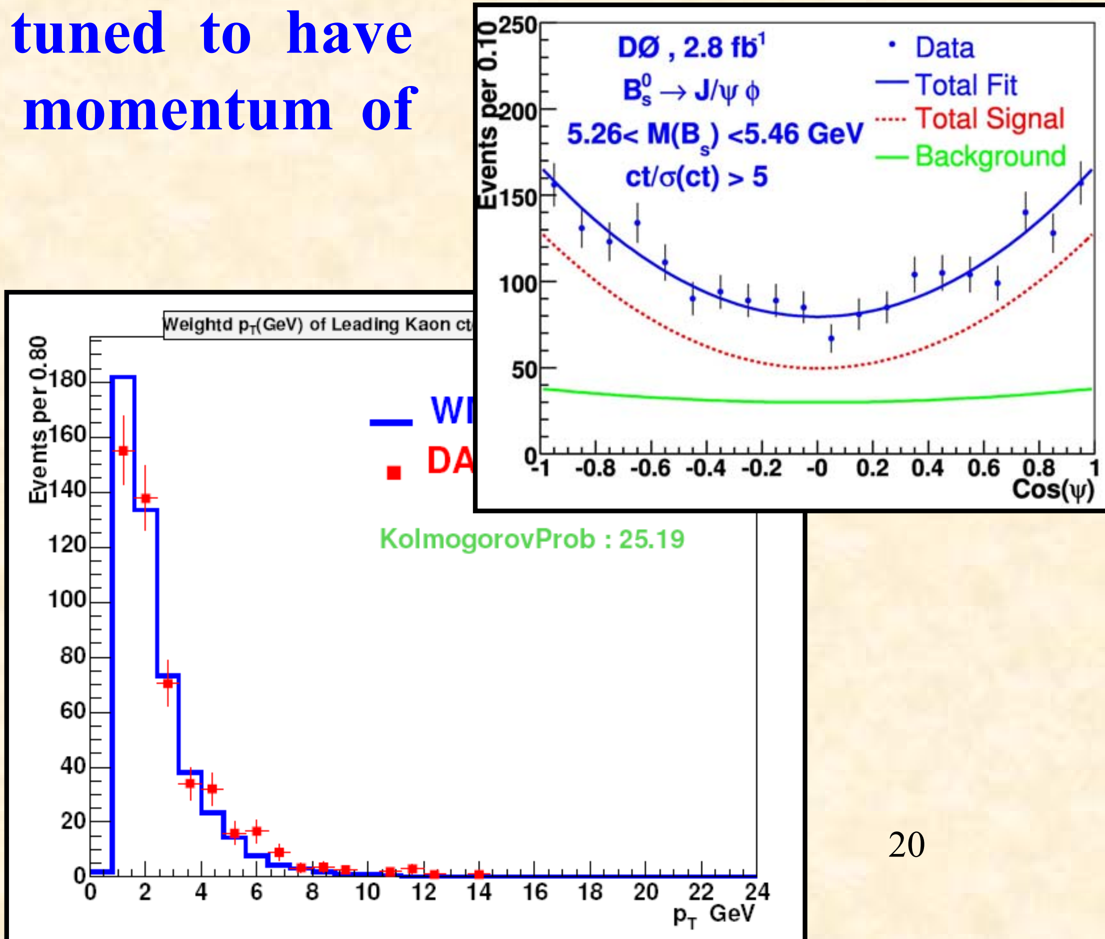
Decay length distribution

Angular distributions

- **Polarization amplitudes are obtained from angular distributions, and depend on the correct description of detector acceptance;**
- **Simulation was specially tuned to have the correct description of momentum of all particles;**

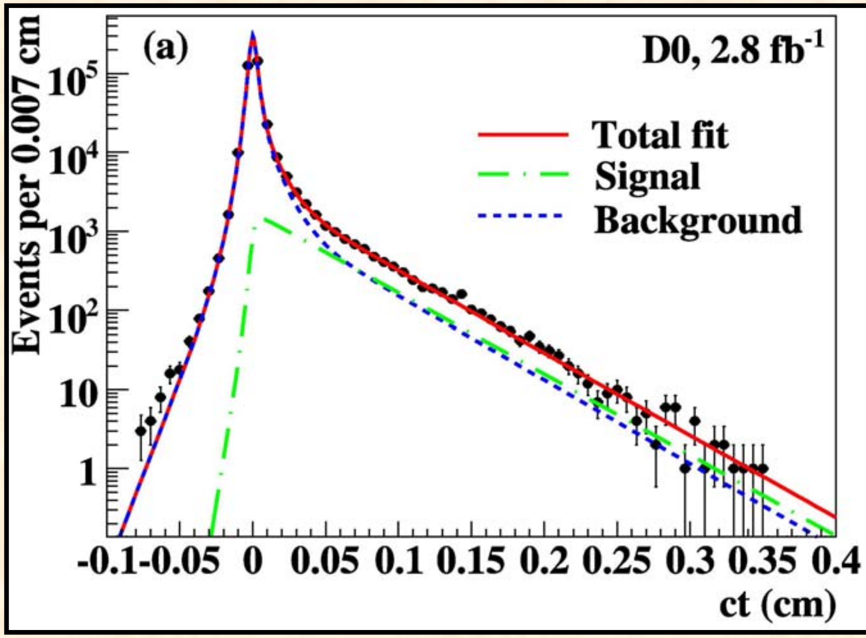






Test with $B_d \to J/\psi K^*$

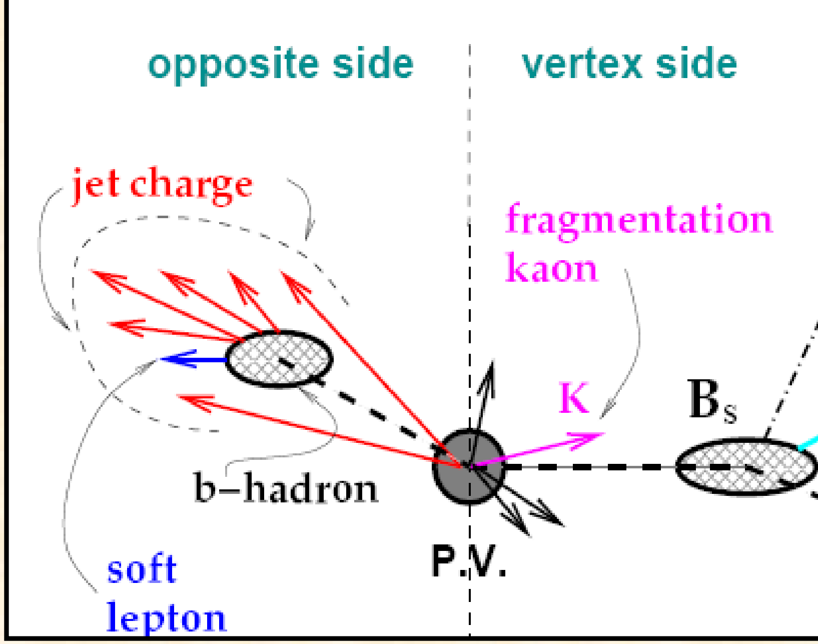
- **We verified the description of angular distributions by measuring the polarization amplitudes in a similar decay $B_d \to J/\psi K^*$:**
  - **Much larger statistics;**
  - **Can be compared with the results from B factories:**



Decay length distribution for $B_d \to J/\psi K^*$ sample

$B_d \to J/\psi\ K^*$ (D0)	$B_d \to J/\psi\ K^*$ (HFAG-2008)
$\lvert A_0 \rvert^2 = 0.587 \pm 0.011 \pm 0.013$	$\lvert A_0 \rvert^2 = 0.56 \pm 0.01$
$\lvert A_\parallel \rvert^2 = 0.230 \pm 0.013 \pm 0.025$	$\lvert A_\parallel \rvert^2 = 0.219 \pm 0.009$
$\delta_\perp = 3.21 \pm 0.06 \pm 0.09$	$\delta_\perp = 2.92 \pm 0.04$
$\delta_\parallel = -2.69 \pm 0.08 \pm 0.09$	$\delta_\parallel = -2.91 \pm 0.06$

Flavour tagging



- Flavour tagging is obtained by the combination of the information from the same and opposite side to the B_s;
- From opposite side:
  - soft lepton (electron or muon);
  - Jet charge of the secondary vertex;
  - Total jet charge;
- From the same side:
  - Charge of track closest to B_s direction;
  - Jet charge of tracks from primary vertex;

- Tagging power:

$$P = \varepsilon D^2$$

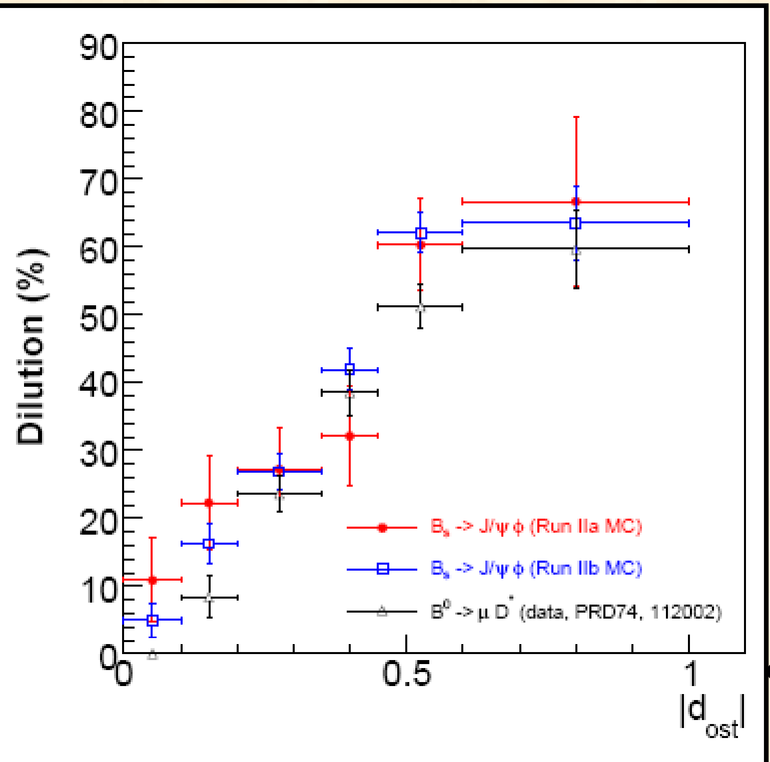
$$\varepsilon = \frac{N_{cor} + N_{wr}}{N_{tot}} \; ; D = \frac{N_{cor} - N_{wr}}{N_{cor} + N_{wr}}$$

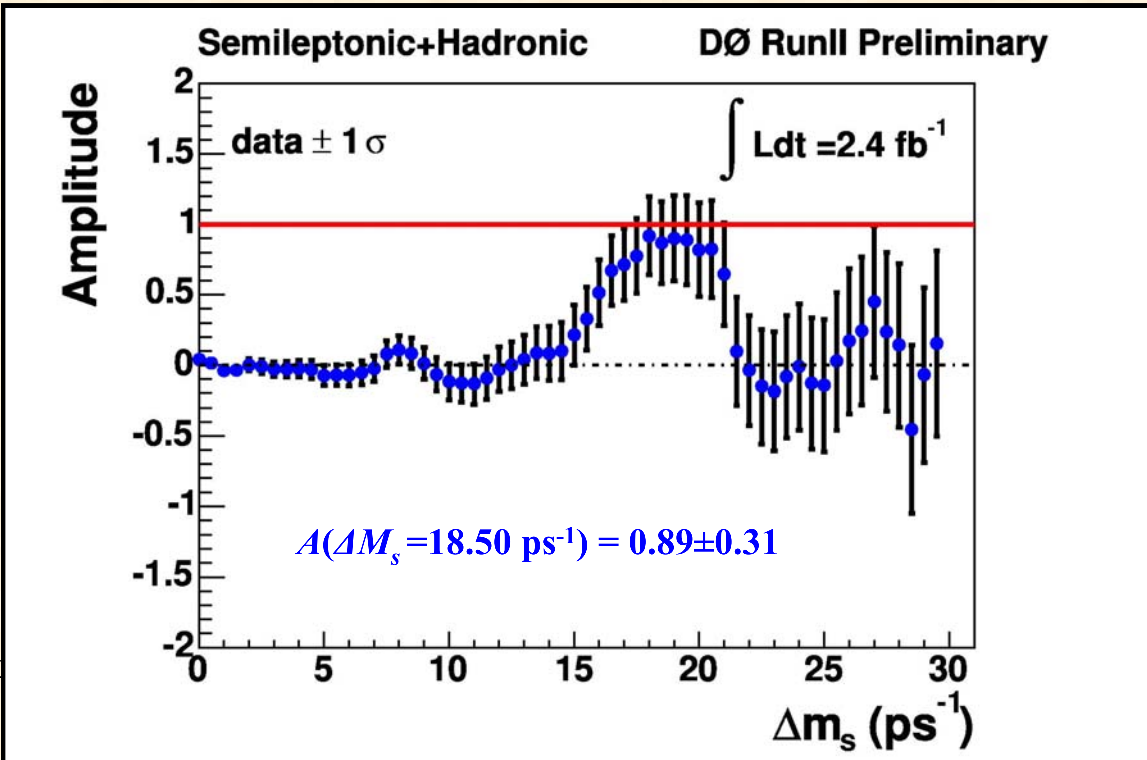
  - N_{tot} – total number of events;
  - N_{cor} – number of correct tags;
  - N_{wr} – number of wrong tags;
- In this analysis:

$$P = \varepsilon \cdot D^2 = (4.68 \pm 0.54)\%$$

Calibration of flavour tagging

- Opposite side flavour tag is calibrated with real data $B_d \rightarrow \mu\nu D^*$ events and compared with MC;
- Calibration of the same side tagging can be done only with MC;
- Performance can be verified in ΔM_s measurement, where same flavour tagging is used;





$A(\Delta M_s = 18.50\ \text{ps}^{-1}) = 0.89 \pm 0.31$

Results

- **We obtain:**

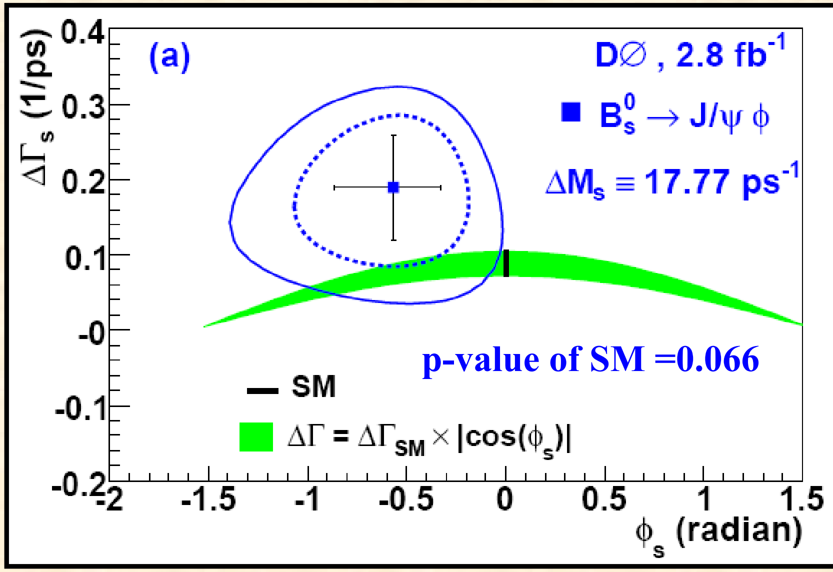
$$\phi_s = -0.57^{+0.24}_{-0.30}\,(\text{stat})^{+0.07}_{-0.02}\,(\text{syst})$$

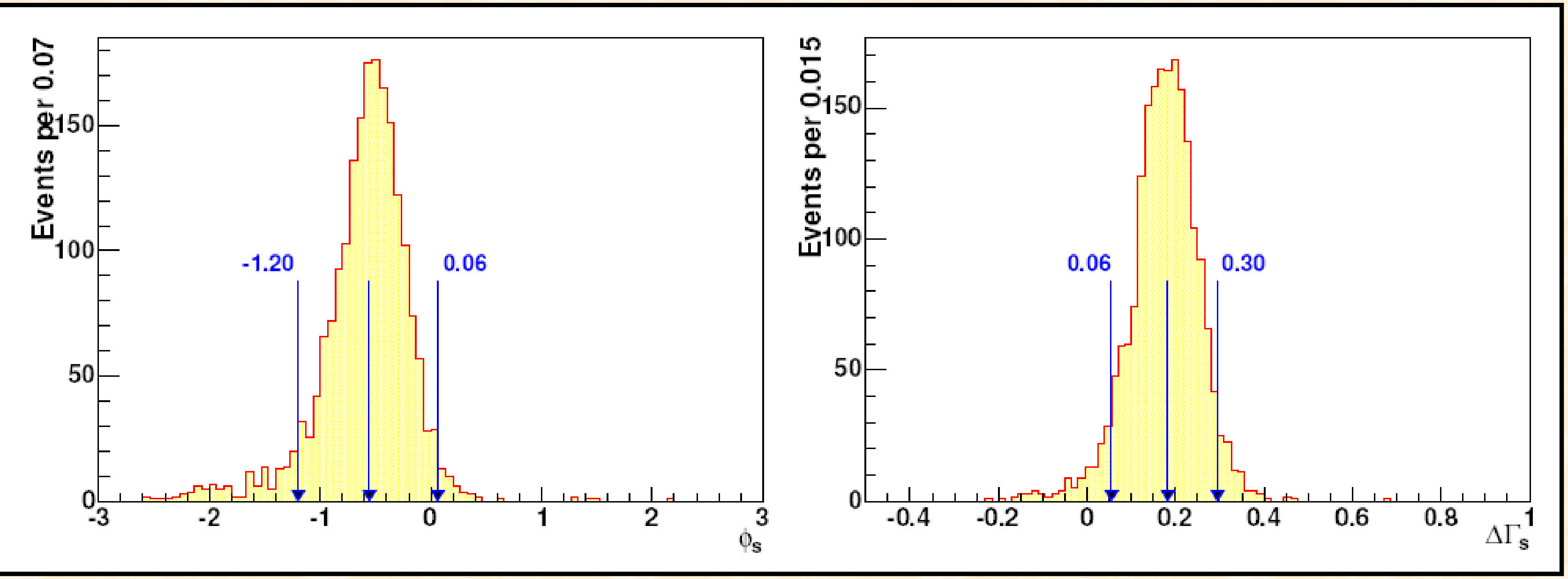
$$\Delta\Gamma_s = 0.19 \pm 0.07\,(\text{stat})\,^{+0.02}_{-0.01}\,(\text{syst})\,\text{ps}^{-1}$$

$$\bar{\tau}(B^0_s) = 1.52 \pm 0.05 \pm 0.01\,\text{ps}$$

$$-1.20 < \phi_s < 0.06,$$

$$0.06 < \Delta\Gamma_s < 0.30\,\text{ps}^{-1}\ \text{at 90\% C.L.}$$

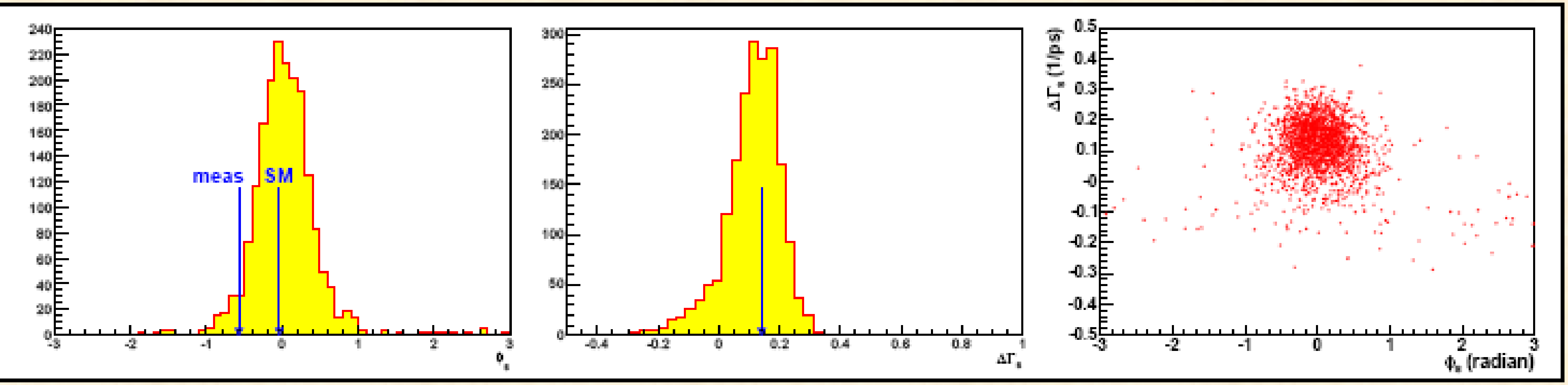




Measured values of ϕ_s and $\Delta\Gamma_s$ in 2000 MC pseudo-experiments.

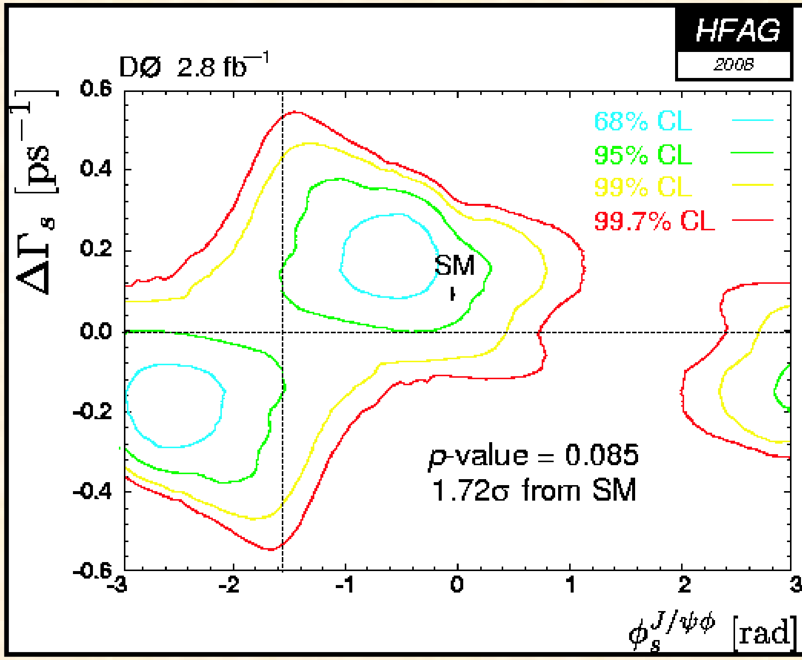
Consistency with the SM

- To test the consistency of our results with the standard model we performed 2000 MC pseudo-experiments with the true value of ϕ_s set to the SM prediction (-0.04);
- With the measured value ϕ_s = -0.57, the P-value for the SM hypothesis is 6.6%



Dependence on strong phases

- **In this result we assume that the strong phases $\delta_1 \equiv \arg\{A_\parallel^* A_\perp\}$; $\delta_2 \equiv \arg\{A_0^* A_\perp\}$ in $B_s \rightarrow J/\psi\varphi$ are the same as in $B_d \rightarrow J/\psi K^*$;**
- **This assumption on the strong phases is supported theoretically:**
  - **M. Gronau, L.Rosner, arxiv:0808.3761**
- **For combination with CDF we repeated the analysis of our data without this assumption;**
- **The result is consistent, the main effect is the second minimum, corresponding to:**



$$\boxed{\begin{array}{l} \Delta\Gamma_s \leftrightarrow -\Delta\Gamma_s; \quad \phi_s \leftrightarrow \pi - \phi_s; \\ \delta_1 \leftrightarrow \pi - \delta_1; \quad \delta_2 \leftrightarrow \pi - \delta_2 \end{array}}$$

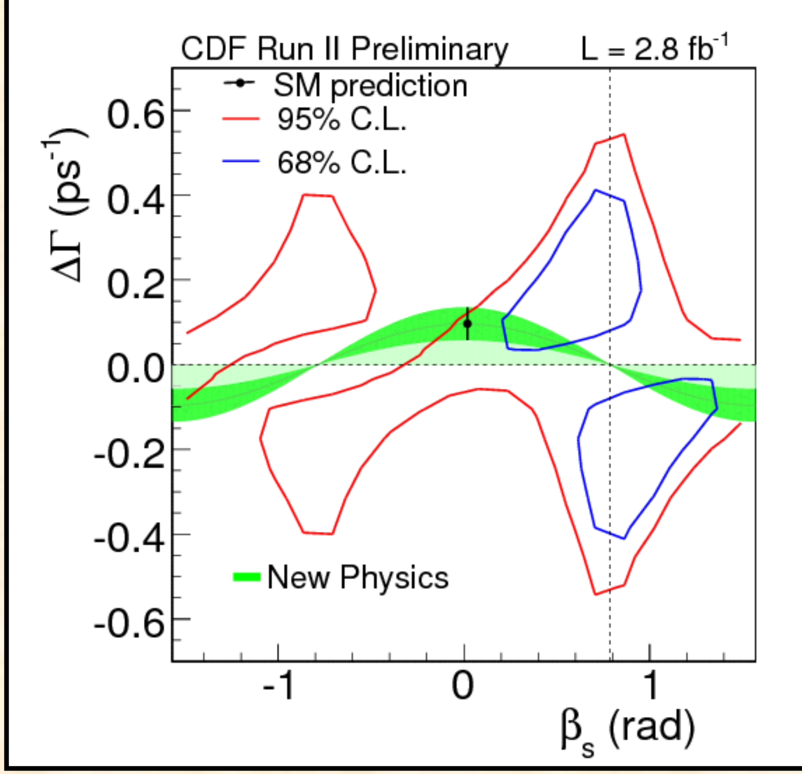
Combination with CDF

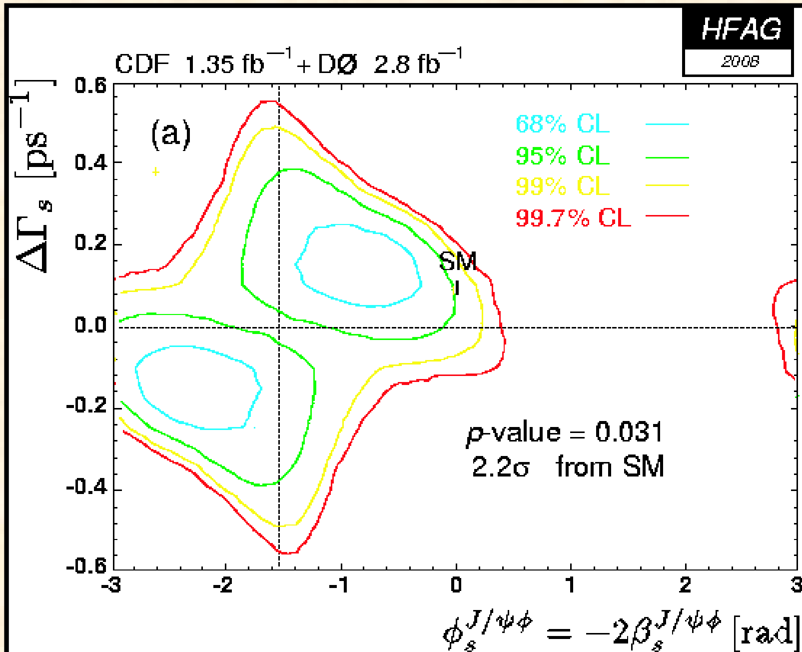
- CDF made a similar measurement of $\beta_s = -\phi_s/2$; p-value of SM is 0.07;
- Both results are consistent;
- Each of them shows ~1.8σ deviation from the SM;
- Their combination is performed by HFAG:

$$\Delta\Gamma_s = 0.154^{+0.054}_{-0.070}\ \text{ps}^{-1}$$

$$\phi_s = -0.77^{+0.29}_{-0.37}$$

  - The most recent CDF result is not included yet;
- p-value of combination =0.031 or 2.2σ from SM;





Charge asymmetry in $B_s \to D_s \mu \nu$ decay

Semileptonic Charge Asymmetry

- **Charge asymmetry of "wrong-sign" decays is defined as:**

$$A_{SL}^{s} = \frac{d\Gamma/dt(\bar{B}_s \to l^{+}X) - d\Gamma/dt(B_s \to l^{-}X)}{d\Gamma/dt(\bar{B}_s \to l^{+}X) + d\Gamma/dt(B_s \to l^{-}X)}$$

- **Non-zero value of $A_{SL}{}^{s}$ means the CP violation in mixing;**
- **$A_{SL}{}^{s}$ is related with the complex CP-violating phase $\phi_s{}^{12}$ of the B_s mixing matrix:**

$$A_{SL}^{s} = \frac{\Delta\Gamma_s}{\Delta M_s}\tan(\phi_s^{12})$$

  - **Definition of $\phi_s{}^{12}$:** **M_{12} and Γ_{12} are the elements of complex mass matrix *(M-$i\ \Gamma/2$)* of B_s system**

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

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

$$\phi_s^{12} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

$$\bar{\Gamma}_s = \frac{1}{2}(\Gamma_L + \Gamma_H)$$

$$i\frac{d}{dt}\begin{pmatrix} B_s(t) \\ \bar{B}_s(t) \end{pmatrix} = \left(\begin{bmatrix} m & M_{12}^{s} \\ M_{12}^{s*} & m \end{bmatrix} - \frac{i}{2}\begin{bmatrix} \Gamma & \Gamma_{12}^{s} \\ \Gamma_{12}^{s*} & \Gamma \end{bmatrix}\right)\begin{pmatrix} B_s(t) \\ \bar{B}_s(t) \end{pmatrix}$$

CP-violating phase ϕ_s^{12}

- Standard model predicts a very small value for ϕ_s^{12} and A_{SL}^s

$$\boxed{\begin{aligned}(\phi_s^{12})^{SM} &= (4.2 \pm 1.4) \times 10^{-3}\\ (\Delta\Gamma_s / \Delta M_s)^{SM} &= (4.97 \pm 0.94) \times 10^{-3}\\ (A_{SL}^s)^{SM} &= (2.1 \pm 0.3) \times 10^{-5}\end{aligned}}$$

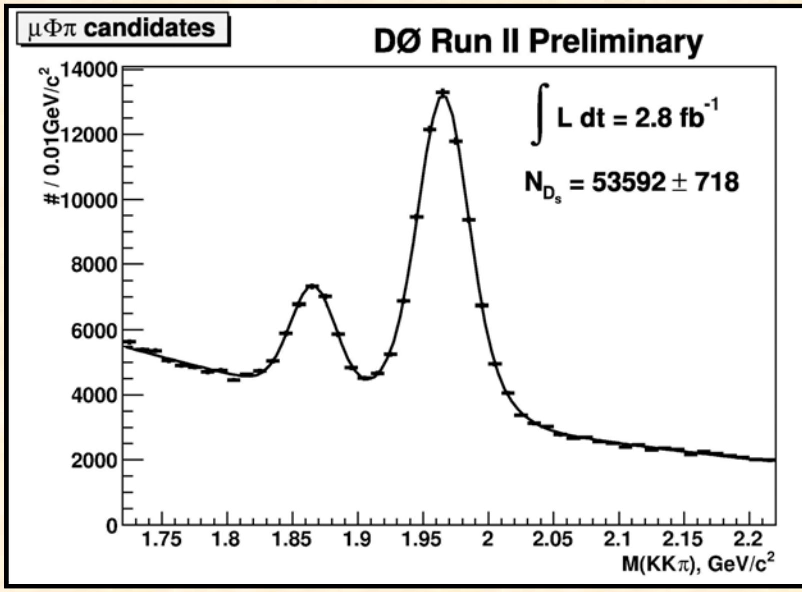
  - All numbers are from A. Lenz, U. Nierste, arxiv: hep-ph/0612167
- Contribution of the new physics can significantly modify this value;
- This contribution is the same as for the phase ϕ_s:

$$\boxed{\begin{aligned}\phi_s &= \phi_s^{SM} + \phi_s^{\Delta}\\ \phi_s^{12} &= \phi_s^{12,SM} + \phi_s^{\Delta}\end{aligned}}$$

- Assuming the experimental (HFAG) values of $\Delta\Gamma_s$, ΔM_s, ϕ_s, we can expect that: $\boxed{A_{SL}^s = -(7.3 \pm 5.4) \times 10^{-3}}$

Measurement of A_{SL}

- We use the same sample of $B_s \rightarrow \mu\nu D_s$, $D_s \rightarrow \varphi\pi$ events, and the same analysis technique, as in the measurement of ΔM_s;
- **Important difference**: events without flavour tag are still sensitive to A_{SL} (contrary to ΔM_s measurement):

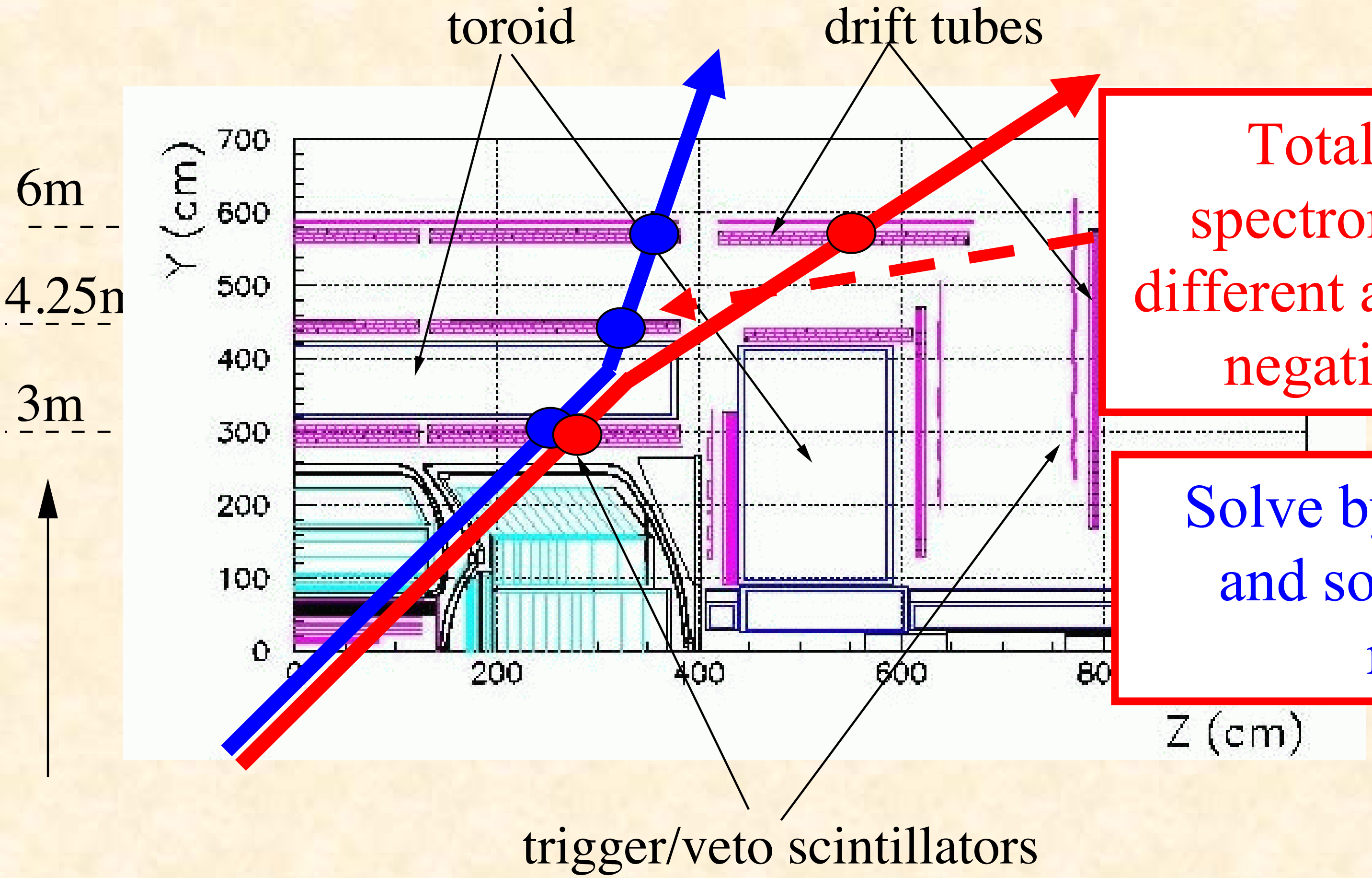


$$\boxed{\frac{d\Gamma/dt(B_s,\overline{B}_s \to l^+X) - d\Gamma/dt(B_s,\overline{B}_s \to l^-X)}{d\Gamma/dt(B_s,\overline{B}_s \to l^+X) + d\Gamma/dt(B_s,\overline{B}_s \to l^-X)} = \frac{A^s_{SL}}{2}\left[1 - \frac{\cos(\Delta M_s t)}{\cosh(\Delta\Gamma_s t)}\right]}$$

- **Important complication**: detector asymmetry in reconstruction of events with different charge can significantly bias the result;

Detector Systematics

Main difference in reconstruction efficiency is due to geometry of muon detector

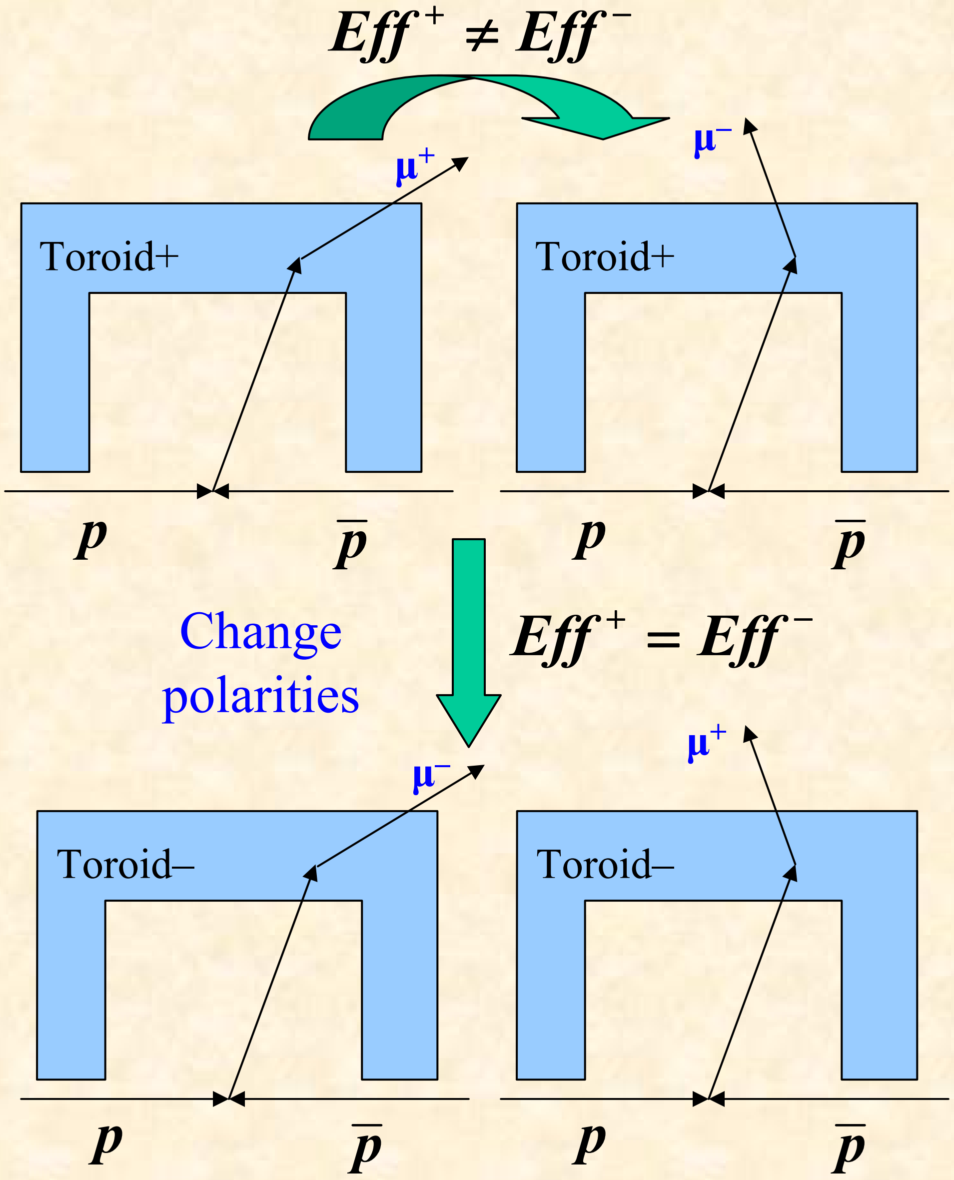


Total material and spectrometer geometry different along positive and negative trajectories

Solve by flipping toroid and solenoid polarity regularly

Reversing Magnet Polarities

- Polarities DØ solenoid are reversed regularly;
- Trajectory of the negative particle is exactly the same as the trajectory of the positive particle with the reversed magnet polarity;
- This cancels the first order detector effects;



$Eff^+ \neq Eff^-$

Change polarities

$Eff^+ = Eff^-$

Changing Magnet polarities is an important feature of DØ detector, which reduces significantly systematics in CP violation measurements

Result

- After processing ~2.8 fb^{-1} of our statistics we get:

$$\boxed{A_{SL}^{s} = -0.0024 \pm 0.0117^{+0.0015}_{-0.0024}}$$

- The only direct measurement of A_{SL}^{s};
- Systematic uncertainty is significantly reduced due to the special features of DØ detector;
- Precision will be improved in the nearest future after adding more statistics and other channels;
- Result is consistent with other measurements of A_{SL}^{s}:

$$\boxed{A_{SL}^{s} = +0.0016 \pm 0.0085 \quad \text{(HFAG - 2008)}}$$

- Result is consistent with the $B_s \to J/\psi\varphi$ measurement, from which we can expect: $\boxed{A_{SL}^{s} = -(7.3 \pm 5.4) \times 10^{-3}}$

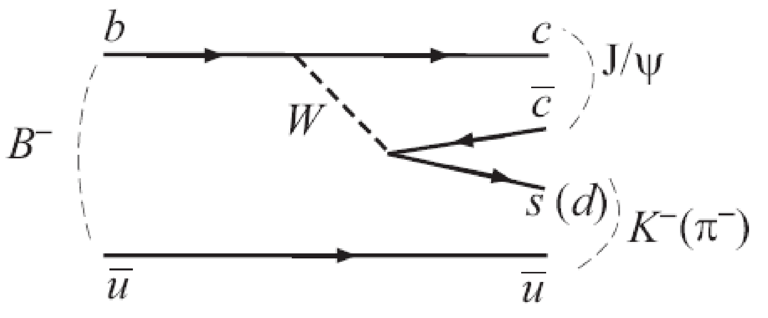
Measurement of direct CP violation in $B^{\pm} \to J/\psi\ K^{\pm}$ decay

Motivation

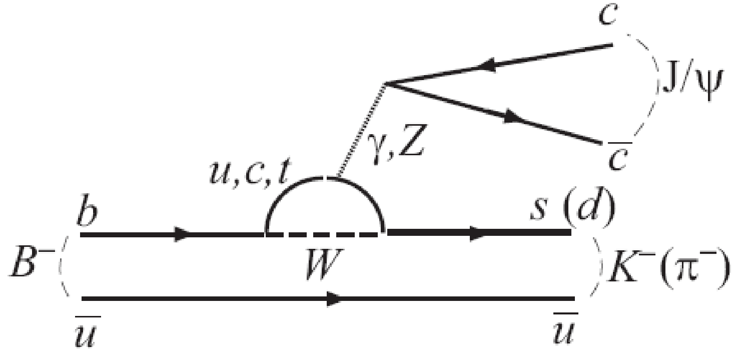
- **Direct CP asymmetry in $B^+ \to J/\psi\, K^+$ decay is defined as:**

$$A_{CP}(B^+ \to J/\psi(1S)K^+) = \frac{\Gamma(B^- \to J/\psi K^-) - \Gamma(B^+ \to J/\psi K^+)}{\Gamma(B^- \to J/\psi K^-) + \Gamma(B^+ \to J/\psi K^+)}$$

  - **Notice the charge convention for this asymmetry!**
- **CP violation is due to the interference of the tree and penguin diagrams:**



(a) Tree $\sim V_{cb}V^*_{cs}$



(b) Penguin $\sim V_{ub}V^*_{us} \times \text{loop}$

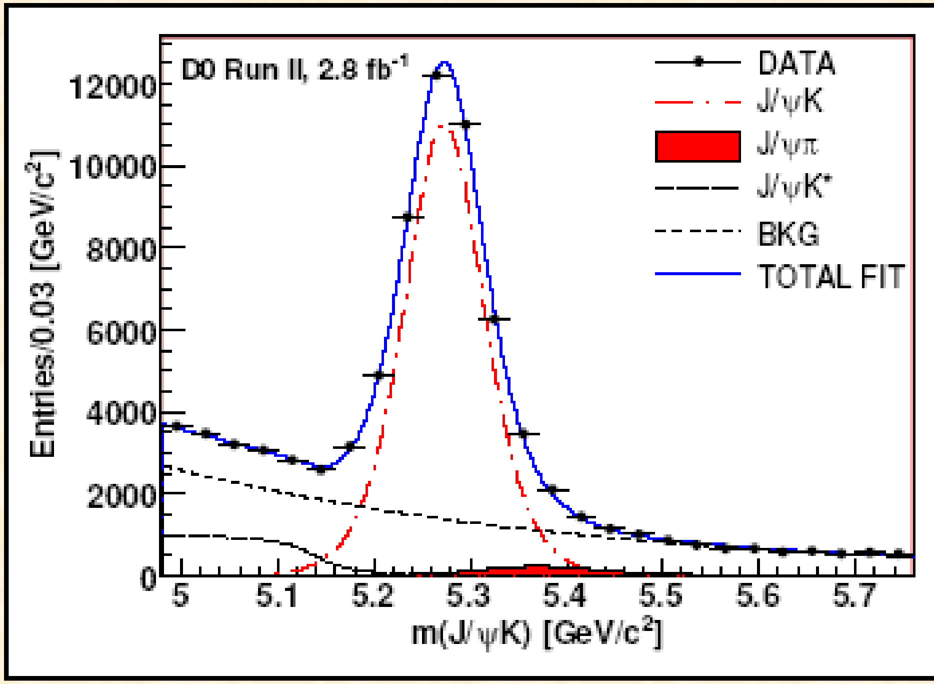
- **It is expected to be very small in the SM ~λ^2×loop (~10^{-3});**

Motivation

- **Adding new particles in the loop can significantly increase the value of CP asymmetry;**
- **Many new models predict a value of the order of 1%:**
  - **Flavour-violating Z';**
  - **Different Two-Higgs doublet models;**
  - **Fourth generation;**
- **CP asymmetry at the ~1% level would clearly indicate the presence of new physics;**

Decay $B^+ \to J/\psi\ K^+$ in DØ

- ~40K events with 2.8 fb^{-1};
- Will be increased to >100K events by the end of Fermilab;
- Overlap of $J/\psi\ K^+$ and $J/\psi\ \pi^+$ decays due to the detector resolution;
- Use $J/\psi \to \mu^+ \mu^-$ decay only;
- High precision ($\sim 3 \times 10^{-3}$) of CP asymmetry can be achieved;



Detector Asymmetries

- **Intrinsically, the measurement is very simple: just count the number of events with positive and negative kaon and compute the asymmetry:**

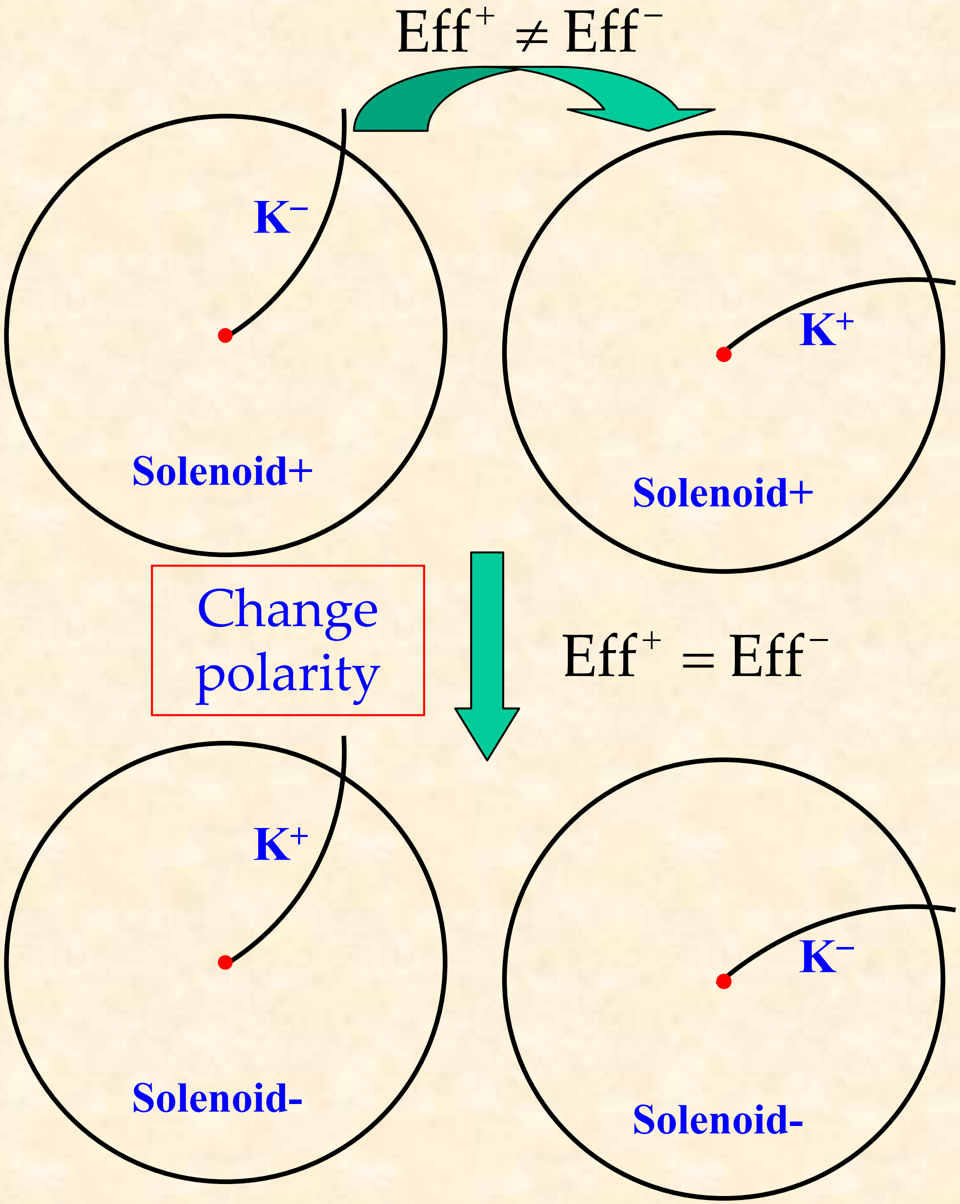
$$\boxed{A_{CP} = \frac{N(K^-) - N(K^+)}{N(K^-) + N(K^+)}}$$

- **In practice, the number of reconstructed events with positive and negative kaon can be different due to the detector effects and/or differences in properties of positive and negative particles;**

Reversing Magnet Polarities

- Reversal of magnet polarities also helps in this measurement to reduce the systematics;
- Polarities DØ solenoid are reversed regularly;
- Trajectory of the negative particle is exactly the same as the trajectory of the positive particle with the reversed magnet polarity;
- This cancels the first order detector effects;

Changing Magnet polarities is an important feature of DØ detector, which reduces significantly systematics in CP violation measurements



Extracting physics asymmetry

- If the samples with opposite polarities are equal, all detector asymmetry should cancel, and the simple counting gives a correct result:

$$\boxed{A_{CP} = \frac{N(K^-) - N(K^+)}{N(K^-) + N(K^+)}}$$

- More involved computations are used in practice, to take into account the small differences in the samples with opposite magnet polarities;

Physics asymmetry

- **Using this method we obtain for $B^{\pm} \rightarrow J/\psi K^{\pm}$:**

$$\boxed{A = -0.0070 \pm 0.0060\,(\mathrm{stat})}$$

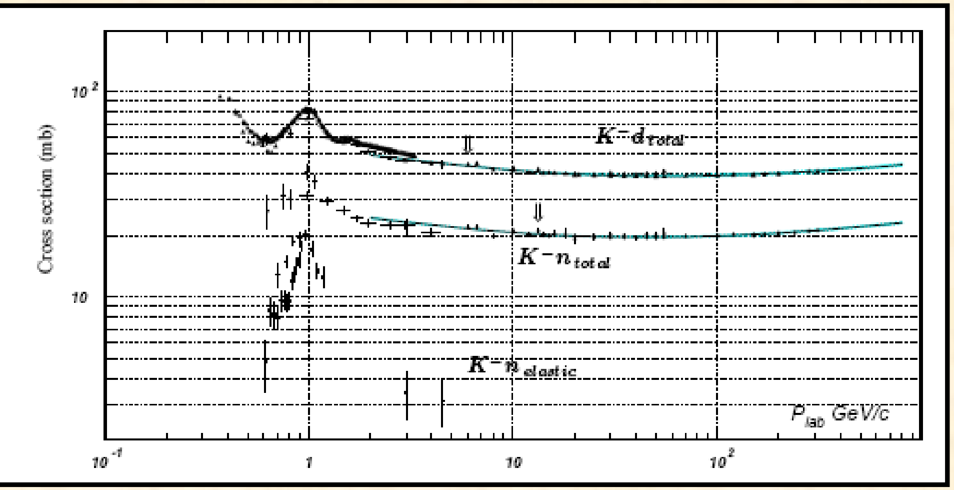
- **With the same sample we also measure the CP asymmetry in the decay $B^{\pm} \rightarrow J/\psi \pi^{\pm}$:**

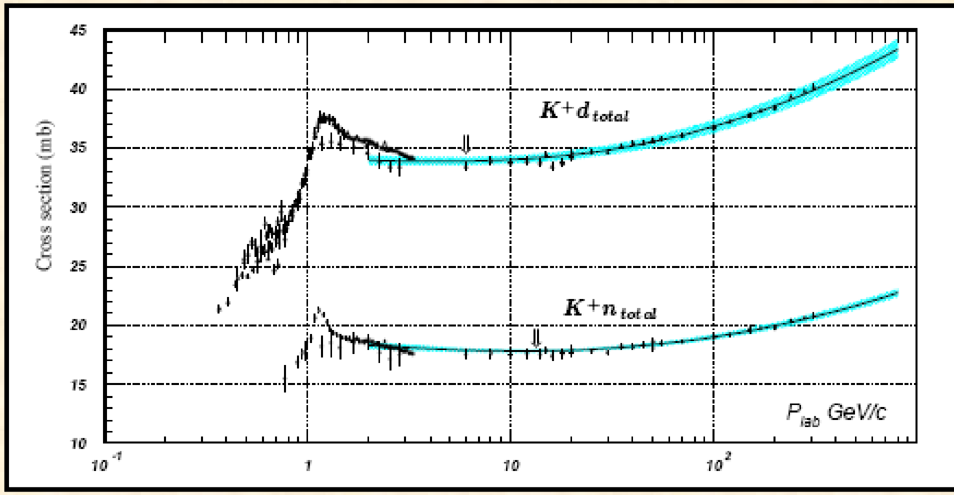
$$\boxed{A(B^{+} \rightarrow J/\psi\pi^{+}) = -0.089 \pm 0.081\,(\mathrm{stat}) \pm 0.028(\mathrm{syst})}$$

- **Not the end of the story for $B^{\pm} \rightarrow J/\psi K^{\pm}$ (yet), we should correct this result by the kaon detection asymmetry.**

Kaon detection asymmetry

- Interaction of K^+ and K^- with the detector material is different, especially for kaons with low momentum;

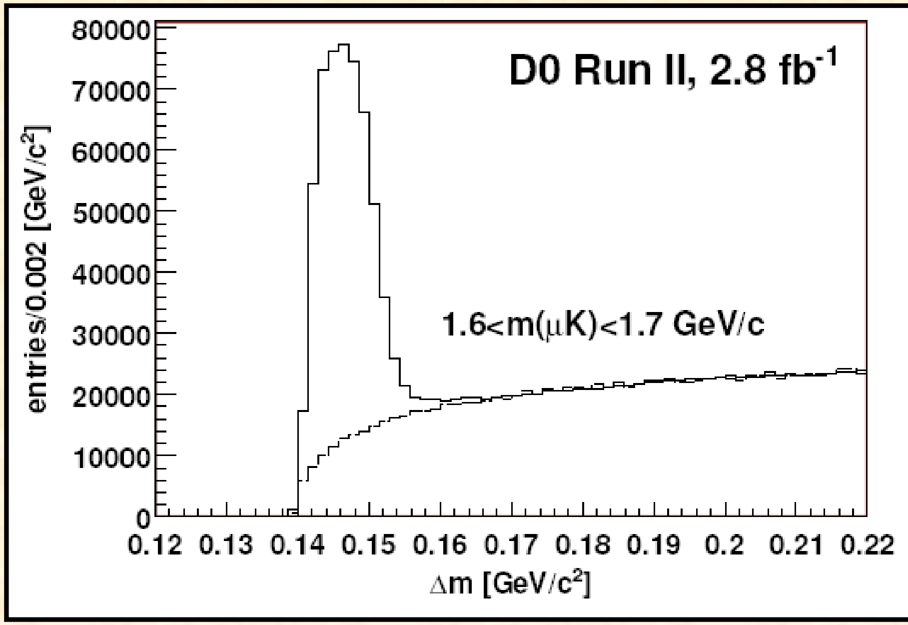




- It is because the reaction $K^-N \rightarrow Y\pi$ has no K^+N analogue;
- K^- has more chance to interact with the detector material and therefore it has lower reconstruction efficiency;
- This asymmetry is difficult to model, and it is better to measure it directly in data;

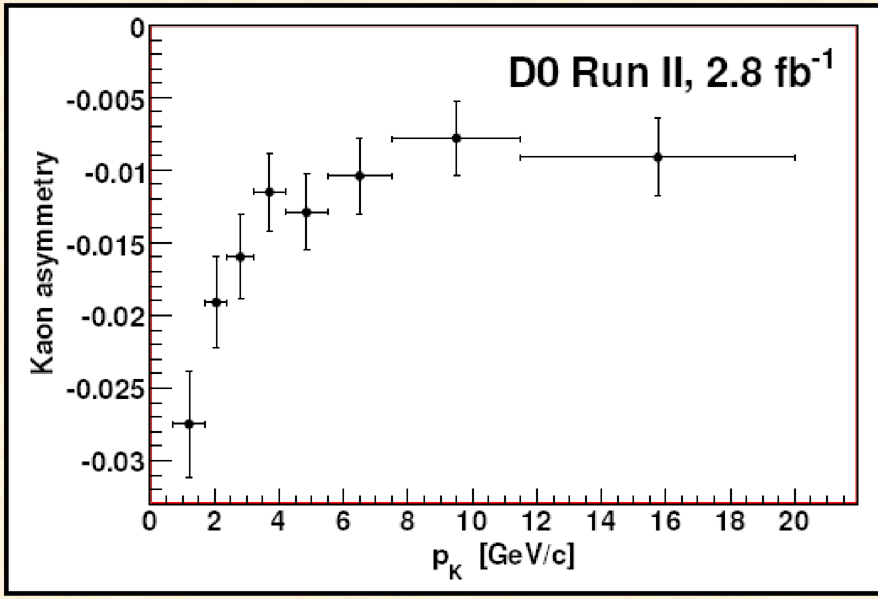
Measuring Kaon Asymmetry

- Kaon asymmetry can be measured using decay in which we don't expect the physics CP asymmetry;
- In case of DØ we selected the decay $D^{*+} \to D^0 \pi^+$; $D^0 \to \mu^+ \nu K^-$:
  - Muon provides the trigger;
  - All charged particles can be uniquely identified;
  - Easy and clean selection: signal is observed as the peak in the mass difference $\Delta M = M(\mu K \pi) - M(\mu K)$;
  - Good control of background;
  - High statistics ($\sim 10^7$ events);



Measuring Kaon Asymmetry

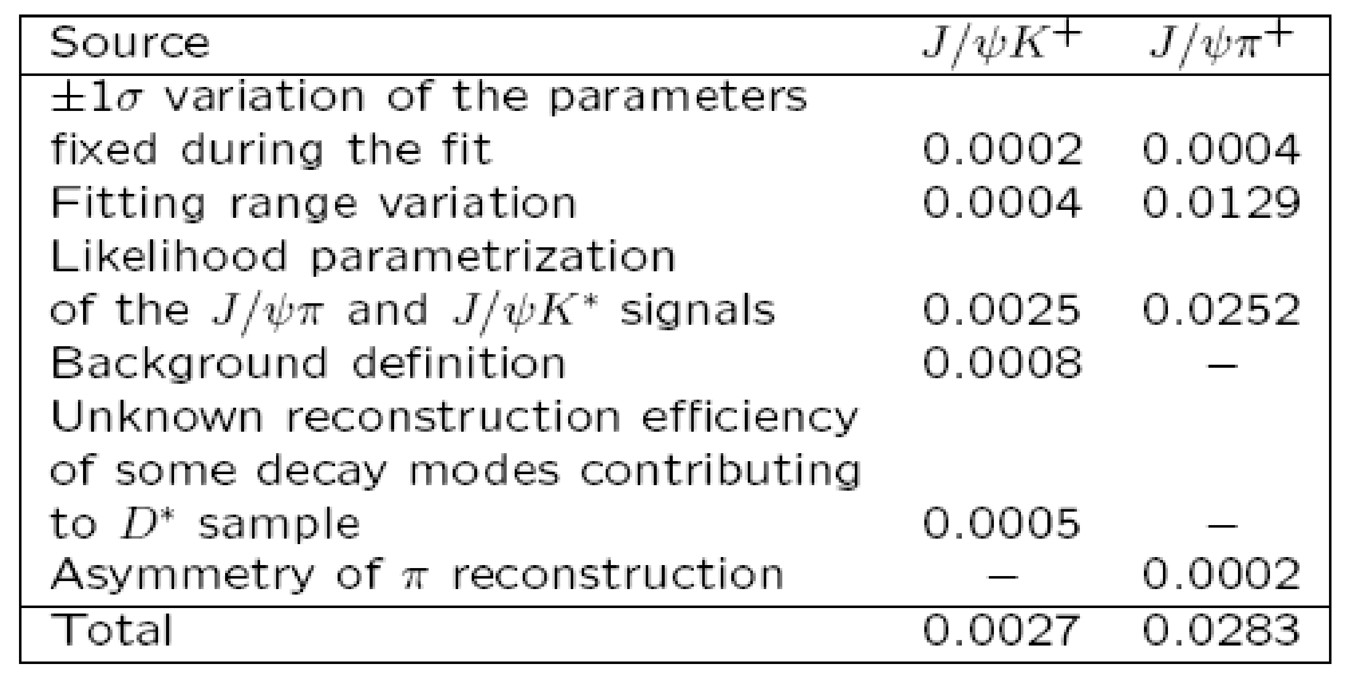
- We determine: $$\boxed{A_K = \frac{N(K^+) - N(K^-)}{N(K^+) + N(K^-)}}$$



- The reversal of magnet polarity eliminates the detector effects also in this case;
- Statistics is sufficient to measure the asymmetry as a function of Kaon momentum - we expect a strong dependence on the Kaon momentum (see the cross-section plots);
- Resulting Kaon asymmetry in $B^+ \to J/\psi K^+$ decay is momentum-weighted according to the Kaon momentum distribution;

Systematic uncertainties

- **Measurement of the kaon asymmetry in data eliminates the most important source of systematic uncertainty;**
- **All other sources of systematics are very small;**



Source	$J/\psi K^+$	$J/\psi\pi^+$
$\pm 1\sigma$ variation of the parameters fixed during the fit	0.0002	0.0004
Fitting range variation	0.0004	0.0129
Likelihood parametrization of the $J/\psi\pi$ and $J/\psi K^*$ signals	0.0025	0.0252
Background definition	0.0008	–
Unknown reconstruction efficiency of some decay modes contributing to D^* sample	0.0005	–
Asymmetry of π reconstruction	–	0.0002
Total	0.0027	0.0283

- **The total systematic uncertainty in A_{CP} is 2.7×10^{-3}**

Final Result

- We get:

$$A = -0.0070 \pm 0.0060\ (\text{stat})$$
$$A_K = -0.0145 \pm 0.0010\ (\text{stat})$$

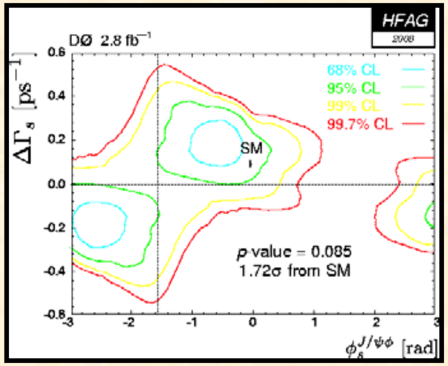
- Correcting our result on the Kaon asymmetry we get:

$$A_{CP}(B^+ \to J/\psi K^+) = A - A_K = +0.0075 \pm 0.0061\ (\text{stat}) \pm 0.0027\ (\text{syst})$$

- Consistent with PDG-2008 average: +0.015±0.017
- Has much better precision;
- Systematic uncertainty is very small, result will be improved with the increase of statistics;
- Hope to achieve the precision at the level of the SM prediction, the SM can be tested soon;

Conclusions

- DØ experiment is very active in the search for new sources of CP violation;
- World leading results in CP violation study are obtained:
  - CP asymmetry in $B_s \rightarrow J/\psi\varphi$ decay:



  - Semileptonic charge asymmetry:

$$\boxed{A_{SL}^{s} = -0.0024 \pm 0.0117^{+0.0015}_{-0.0024}}$$

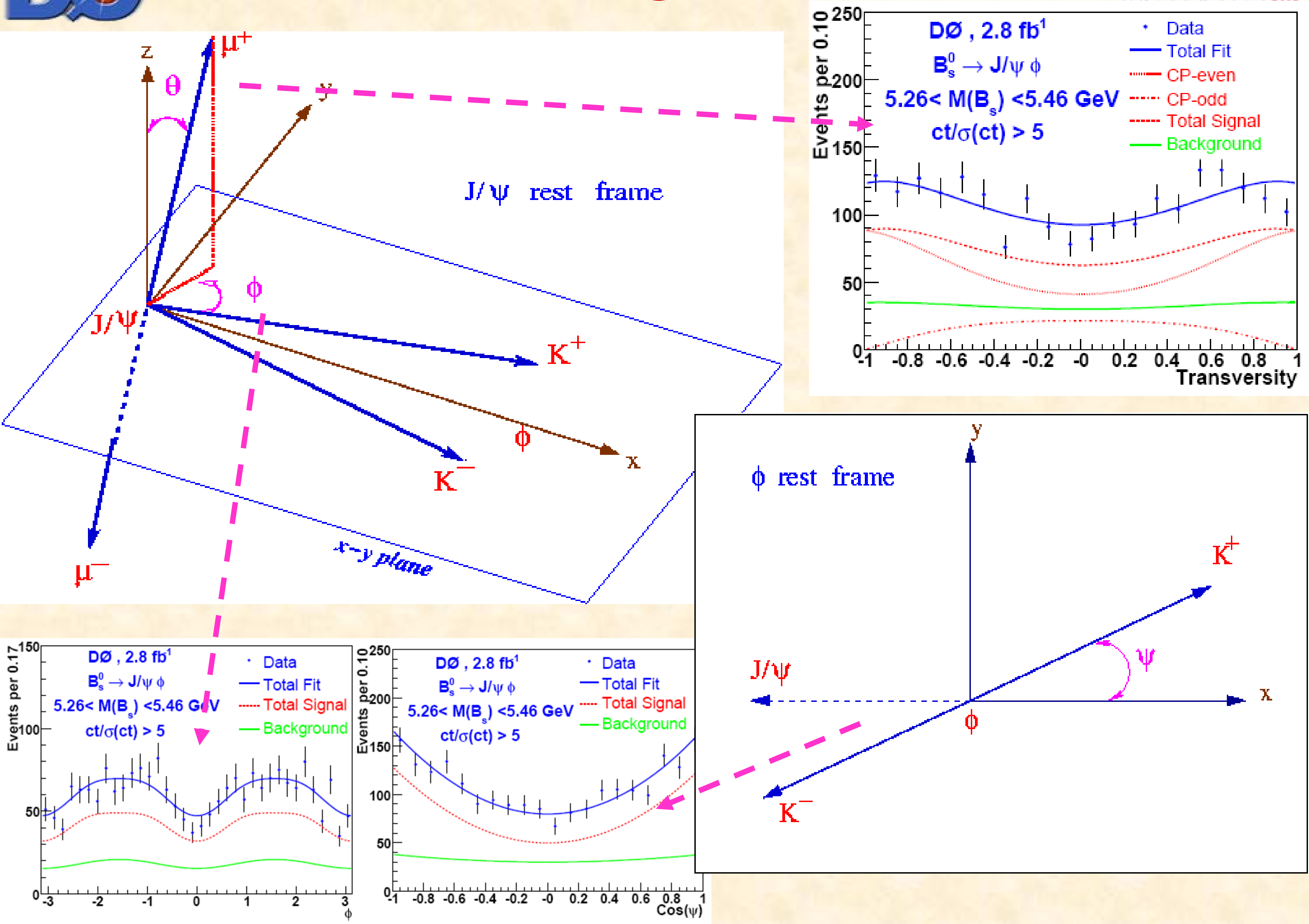
  - Direct charge asymmetry in $B^{\pm} \rightarrow J/\psi\, K^{\pm}$:

$$\boxed{A_{CP} = +0.0075 \pm 0.0061\,(\text{stat}) \pm 0.0027\,(\text{syst})}$$

Precision of all results will be improved by ~2 times with the full Tevatron statistics, which can help to establish the new sources of CP violation

Backup

3 angles


z
μ+
θ
y
J/ψ rest frame
J/ψ
φ
K+
φ
x
K−
x−y plane
μ−
DØ , 2.8 fb^{-1}
$B_s^0 \to J/\psi\ \phi$
5.26< M(B_s) <5.46 GeV
ct/σ(ct) > 5
Data
Total Fit
CP-even
CP-odd
Total Signal
Background
Events per 0.10
0
50
100
150
200
250
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
Transversity
φ rest frame
y
K+
ψ
J/ψ
x
φ
K−
DØ , 2.8 fb^{-1}
$B_s^0 \to J/\psi\ \phi$
5.26< M(B_s) <5.46 GeV
ct/σ(ct) > 5
Data
Total Fit
Total Signal
Background
Events per 0.17
0
50
100
150
-3
-2
-1
0
1
2
3
φ
DØ , 2.8 fb^{-1}
$B_s^0 \to J/\psi\ \phi$
5.26< M(B_s) <5.46 GeV
ct/σ(ct) > 5
Data
Total Fit
Total Signal
Background
Events per 0.10
0
50
100
150
200
250
-1
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
1
Cos(ψ)

Angular Distributions

$$\frac{d^4\Gamma(B_s(t)\to J/\psi(\to\mu^+\mu^-)\phi(\to K^+K^-))}{dt\cdot d\cos\theta\cdot d\cos\psi\cdot d\varphi}\propto$$

$$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)\cdot|A_0(t)|^2$$

$$+\sin^2\psi(1-\sin^2\theta\sin^2\varphi)\cdot|A_{||}(t)|^2$$

$$+\sin^2\psi\sin^2\theta\cdot|A_\perp(t)|^2$$

$$+(1/\sqrt{2})\sin 2\psi\sin^2\theta\sin 2\varphi\cdot\Re(A_0^*(t)A_{||}(t))$$

$$+(1/\sqrt{2})\sin 2\psi\sin 2\theta\cos\varphi\cdot\Im(A_0^*(t)A_\perp(t))$$

$$-\sin^2\psi\sin 2\theta\sin\varphi\cdot\Im(A_{||}^*(t)A_\perp(t)).$$

- **Evolution of amplitudes in time for $B_s(0)$ (upper sign) and for $\overline{B}_s(0)$ (lower sign):**

$$
\begin{aligned}
|A_0(t)|^2 &= |A_0(0)|^2 \left[\mathcal{T}_+ \pm e^{-\overline{\Gamma} t} \sin\phi_s \sin(\Delta M_s t)\right], \\
|A_\parallel(t)|^2 &= |A_\parallel(0)|^2 \left[\mathcal{T}_+ \pm e^{-\overline{\Gamma} t} \sin\phi_s \sin(\Delta M_s t)\right], \\
|A_\perp(t)|^2 &= |A_\perp(0)|^2 \left[\mathcal{T}_- \mp e^{-\overline{\Gamma} t} \sin\phi_s \sin(\Delta M_s t)\right],
\end{aligned}
$$

where

$$
\mathcal{T}_\pm = (1/2)\left[(1 \pm \cos\phi_s)e^{-\Gamma_L t} + (1 \mp \cos\phi_s)e^{-\Gamma_H t}\right].
$$

- **Here the CP violating phase $\phi_s = -2\beta_s + \phi_s^\Delta$; ϕ_s^Δ is the possible contribution of new physics;**

Evolution of amplitudes in time (continued)

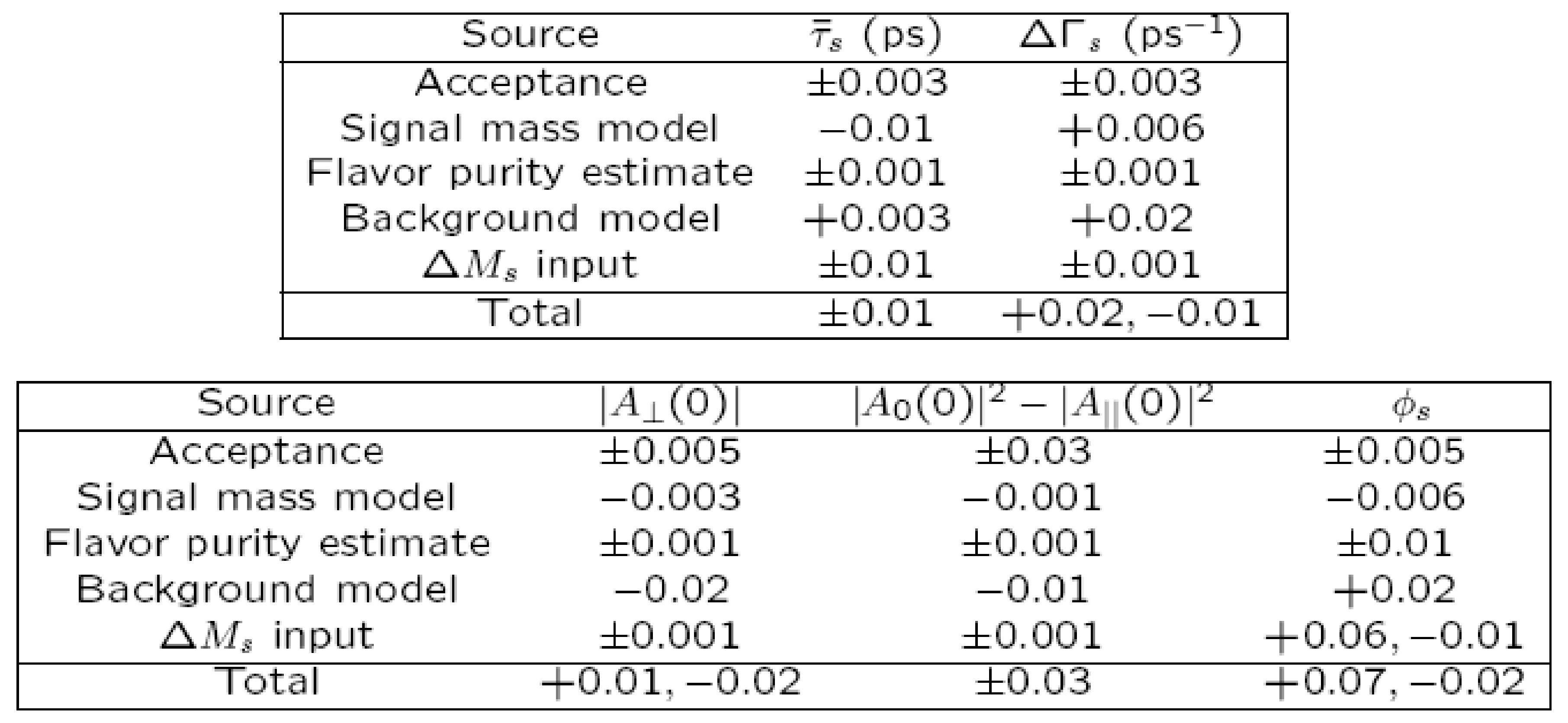
$$\begin{aligned}
\Re(A_0^*(t)A_\parallel(t)) &= |A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)[\mathcal{T}_+ \\
&\qquad \pm\ e^{-\overline{\Gamma}t}\sin\phi_s\ \sin(\Delta M_s t)],
\end{aligned}$$

$$\begin{aligned}
\Im(A_0^*(t)A_\perp(t)) &= |A_0(0)||A_\perp(0)|[\ e^{-\overline{\Gamma}t}(\ \pm\sin\delta_2\cos(\Delta M_s t)\ \mp \\
&\cos\delta_2\sin(\Delta M_s t)\cos\phi_s) - (1/2)\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\sin\phi_s\ \cos\delta_2],
\end{aligned}$$

$$\begin{aligned}
\Im(A_\parallel^*(t)A_\perp(t)) &= |A_\parallel(0)||A_\perp(0)|[\ e^{-\overline{\Gamma}t}(\ \pm\sin\delta_1\cos(\Delta M_s t)\ \mp \\
&\cos\delta_1\sin(\Delta M_s t)\cos\phi_s) - (1/2)\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\sin\phi_s\ \cos\delta_1],
\end{aligned}$$

- **Here:** $\delta_1 \equiv \arg\left\{A_\parallel^*(0)A_\perp(0)\right\};\quad \delta_2 \equiv \arg\left\{A_0^*(0)A_\perp(0)\right\}$
- **Normalization at t=0:** $|A_0(0)|^2+|A_\parallel(0)|^2+|A_\perp(0)|^2=1$

Systematic uncertainty for $B_s \to J/\psi\varphi$ analysis



Source	$\bar{\tau}_s$ (ps)	$\Delta\Gamma_s$ (ps^{-1})
Acceptance	± 0.003	± 0.003
Signal mass model	-0.01	$+0.006$
Flavor purity estimate	± 0.001	± 0.001
Background model	$+0.003$	$+0.02$
ΔM_s input	± 0.01	± 0.001
Total	± 0.01	$+0.02, -0.01$

Source	$\lvert A_\perp(0)\rvert$	$\lvert A_0(0)\rvert^2 - \lvert A_\parallel(0)\rvert^2$	ϕ_s
Acceptance	± 0.005	± 0.03	± 0.005
Signal mass model	-0.003	-0.001	-0.006
Flavor purity estimate	± 0.001	± 0.001	± 0.01
Background model	-0.02	-0.01	$+0.02$
ΔM_s input	± 0.001	± 0.001	$+0.06, -0.01$
Total	$+0.01, -0.02$	± 0.03	$+0.07, -0.02$