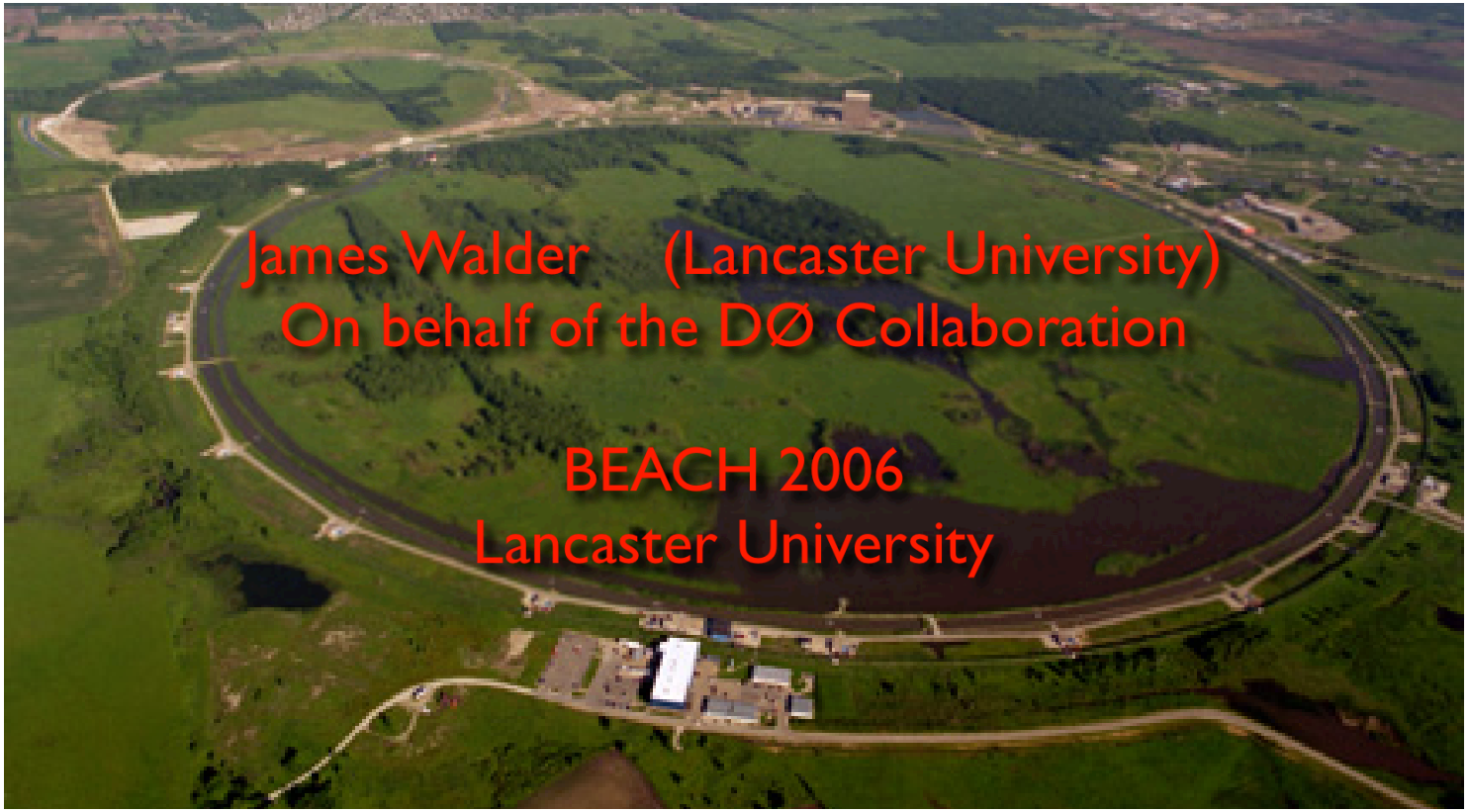
B_s Mixing at DØ



James Walder (Lancaster University)
On behalf of the DØ Collaboration

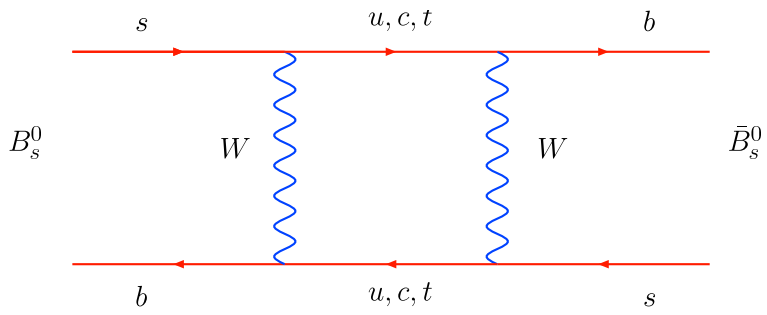
BEACH 2006
Lancaster University

Outline

- Motivation
- The DØ Detector
- Methodology
- Event Selection
- Initial Flavour Tagging
- Fitting procedure
- Results
- Summary

Motivation

- Neutral B mesons are able to transform between particle and anti-particle states - Mixing.



- The rate of mixing is governed by the mass difference between mass eigenstates.

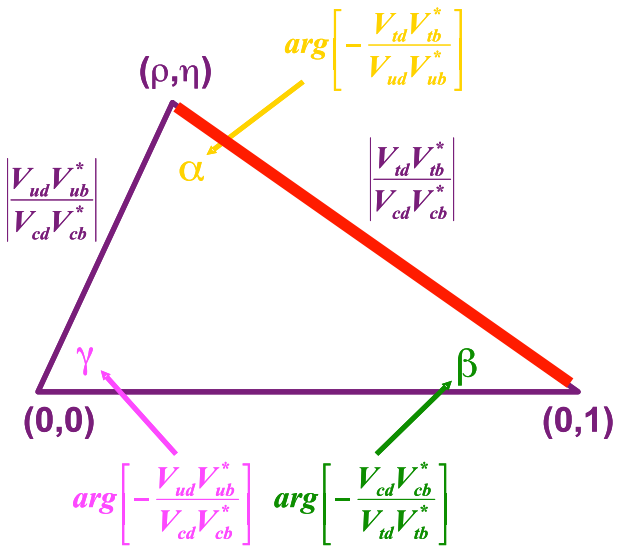
$$|B_H\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle + |\bar{B}^0\rangle)$$

$$|B_L\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle - |\bar{B}^0\rangle)$$

- Previous mixing results:
  - Kaons: CPV in weak sector,
  - Δm_d: top mass heavy (>> m_W),
  - Neutrinos - Mass!

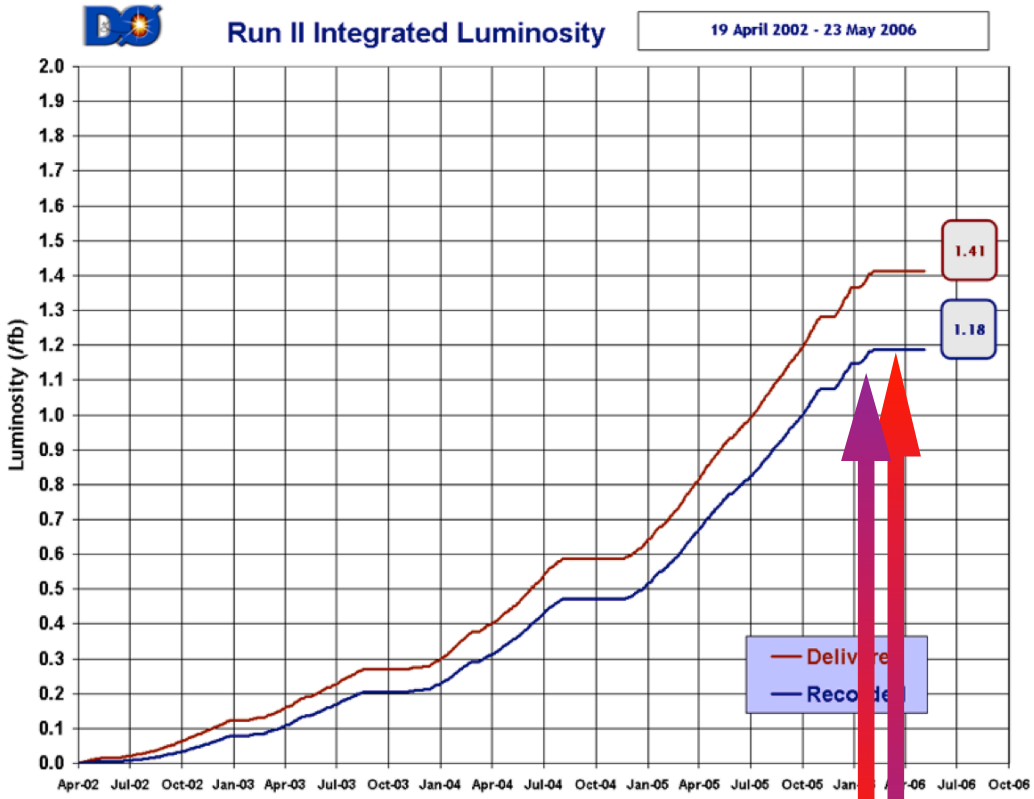
- New Physics can show up in B_S processes. Need mixing analysis for completeness.

CKM Triangle



- $\Delta m_d = |V^*_{tb} V_{td}|^2 \times$ (QCD)
- Many of the same QCD parameters appear in Δm_s.
- $\Delta m_s / \Delta m_d \propto |V_{ts} / V_{td}|^2$
- Allows determination of V_{td} with higher precision.

Tevatron Luminosity



Tevatron:
Proton anti-Proton collider.
$\sqrt{s}$ = 1.96 TeV

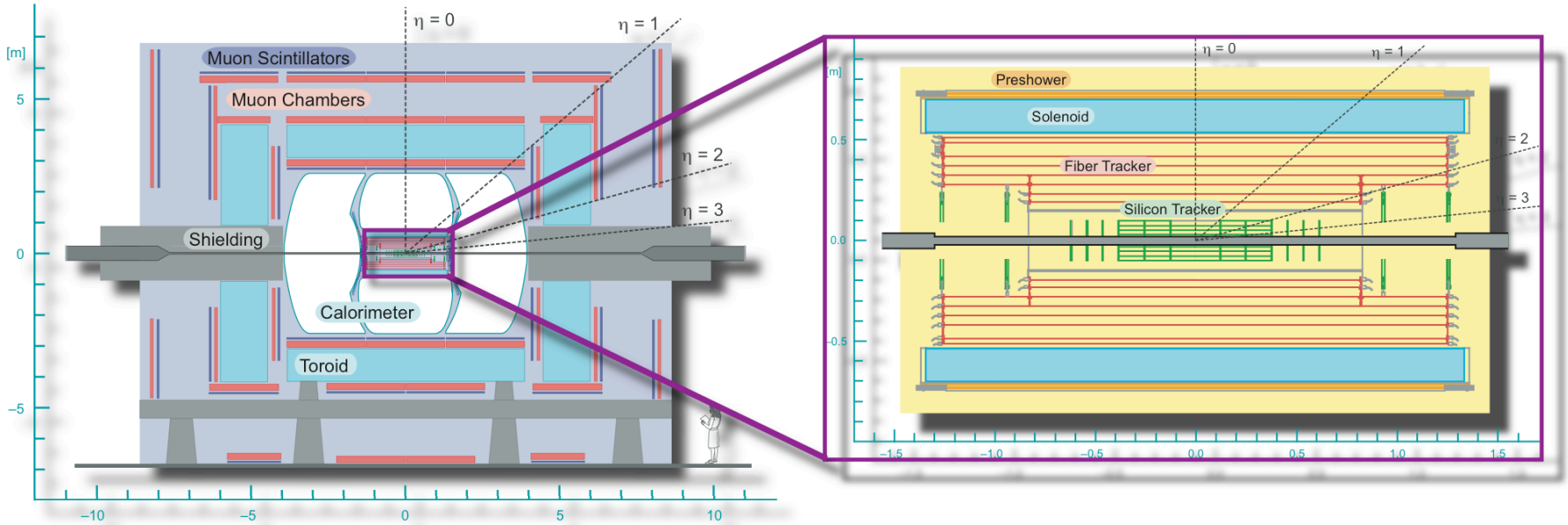
Peak instantaneous Luminosity:
172×10^{30} cm^{-2}s^{-1}

Average data taking efficiency ~ 85% over Run IIa.

Excellent performance from Tevatron.
1 fb^{-1} integrated luminosity used in Mixing analysis.
Special thanks to DØ Online and Offline personnel:
Turnaround <3 months from data collection to PRL submission.

The DØ Detector

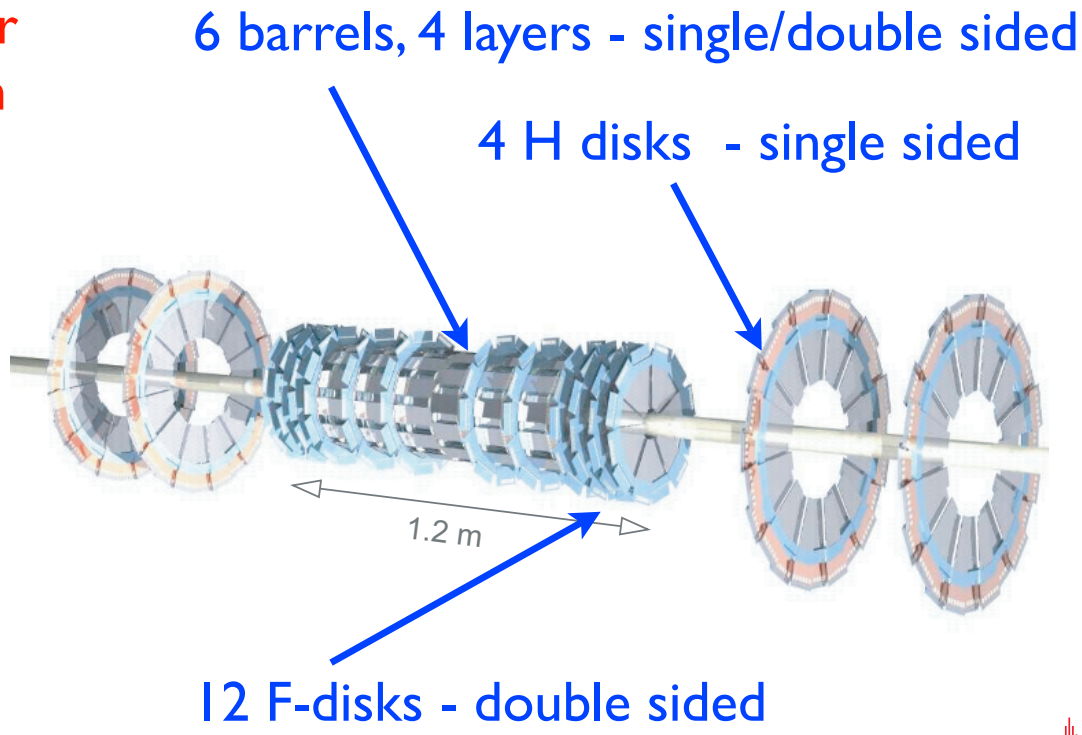
See L. Wealty-Rieger's Talk for detailed description. Fri. 09:20



- 3 Layer muon system with large |η| coverage.
- Liquid Argon/Uranium calorimeter and preshower.
- Silicon and fibre tracking volumes enclosed within 2T magnetic field.
- Layer 0 installed for Run IIb - improvement in vertex resolution.

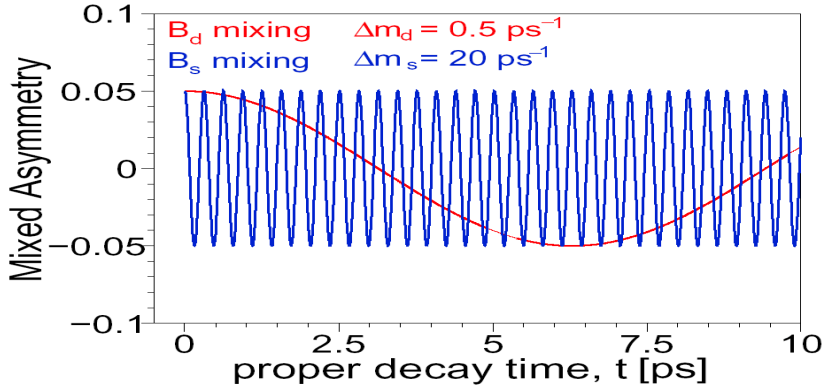
The DØ Detector

- Single inclusive muon and di-muon triggers used in analysis.
  $|\eta|<2.0$, $P_T>2,3,4$ GeV.
- Central Fibre Tracker provides momentum resolution.
- Lepton ID.
  muon chambers, calorimeter and preshower.
- Vertex resolution from silicon tracker.



Analysis Measurement

- Δm_s oscillations ~40 times faster than Δm_d.



- Need to reduce background whilst maintaining high statistics B_S sample.

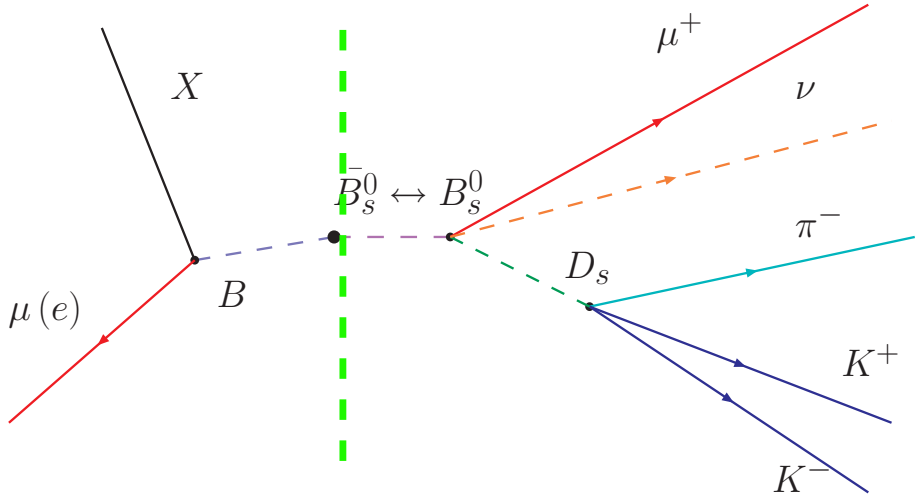
  Optimise significance:

$$\mathcal{S}_{ig} = \sqrt{\frac{S}{S+B}} \cdot \sqrt{\frac{S\epsilon\mathcal{D}^2}{2}} \cdot \exp\left\{-\frac{(\Delta m_s \sigma_\tau)^2}{2}\right\}$$

- Detector resolution effects reduce oscillation amplitude.

Analysis Outline

Opposite Side

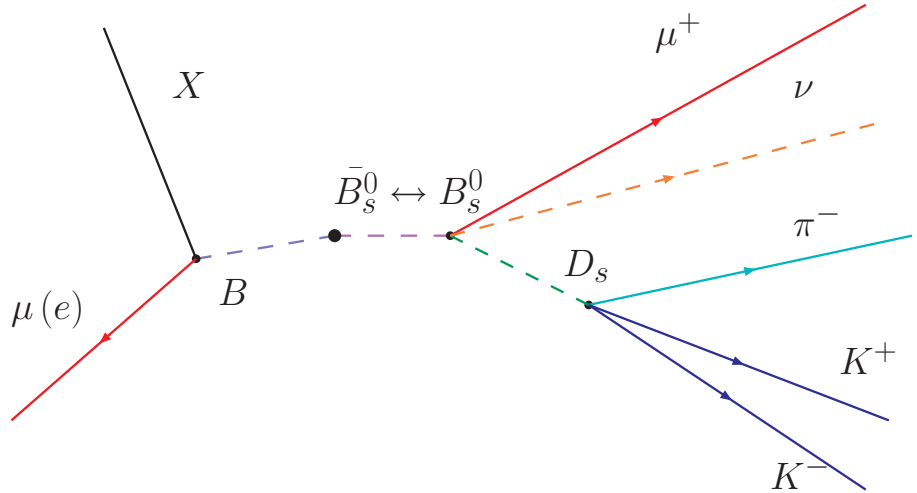


Reconstructed Side

- Select events from the decay $B_s \rightarrow D_s\,\mu$, $D_s \rightarrow \phi\pi$,
- Identify decay flavour (from charge of reconstructed muon),
- Tag initial flavour (from opposite side B-hadron),
- Determine transverse decay length L_T,
- Measure Visible Proper Decay Length (VPDL),
- Combine parameters in an unbinned likelihood fit.

Signal Selection

- Select events with a muon.
- Find two oppositely charged tracks in same jet, with a common vertex and mass compatible with a ϕ.



- Combine with third track, opposite charge to muon and combined vertex with kaons. Impact parameter cuts applied.
- Construct μ D_s vertex, with invariant mass constraints.

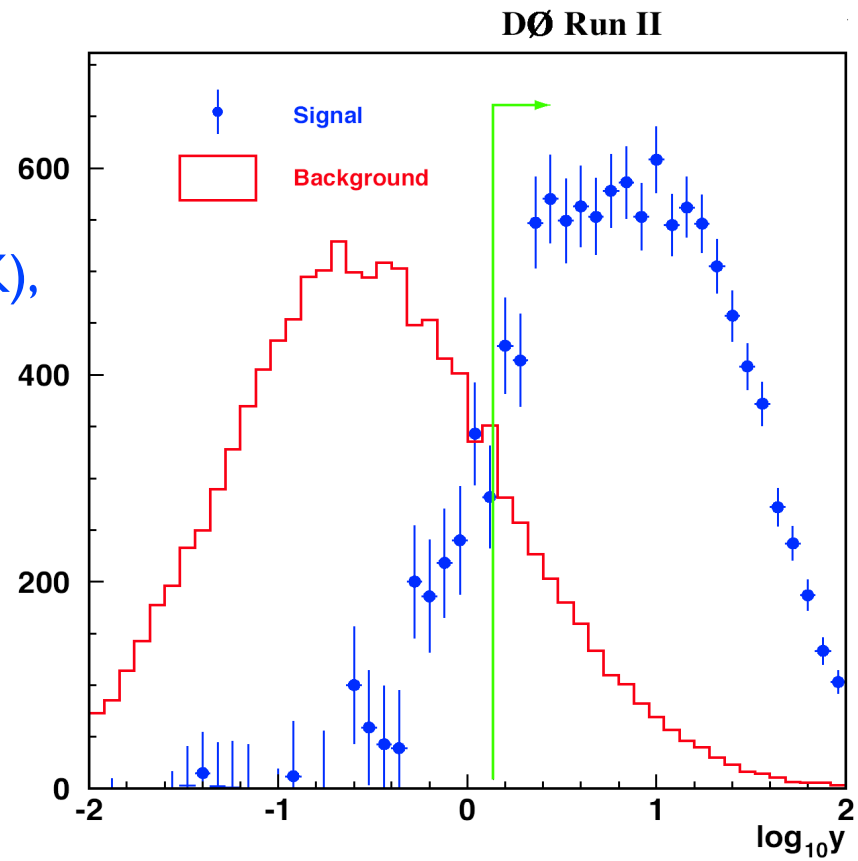
Likelihood Function

- Improve Significance with set of discriminating variables.
  Helicity (angle between Ds and K),
  P_T (KK), m(KK),
  m(μD_S),
  Isolation,
  X^2 of D_S vertex fit.

- Signal and Background PDFs taken from data.

$$y_i = \frac{\mathrm{PDF}^{\mathrm{s}}(x_i)}{\mathrm{PDF}^{\mathrm{b}}(x_i)}$$

- Apply cut on combined likelihood ratio.

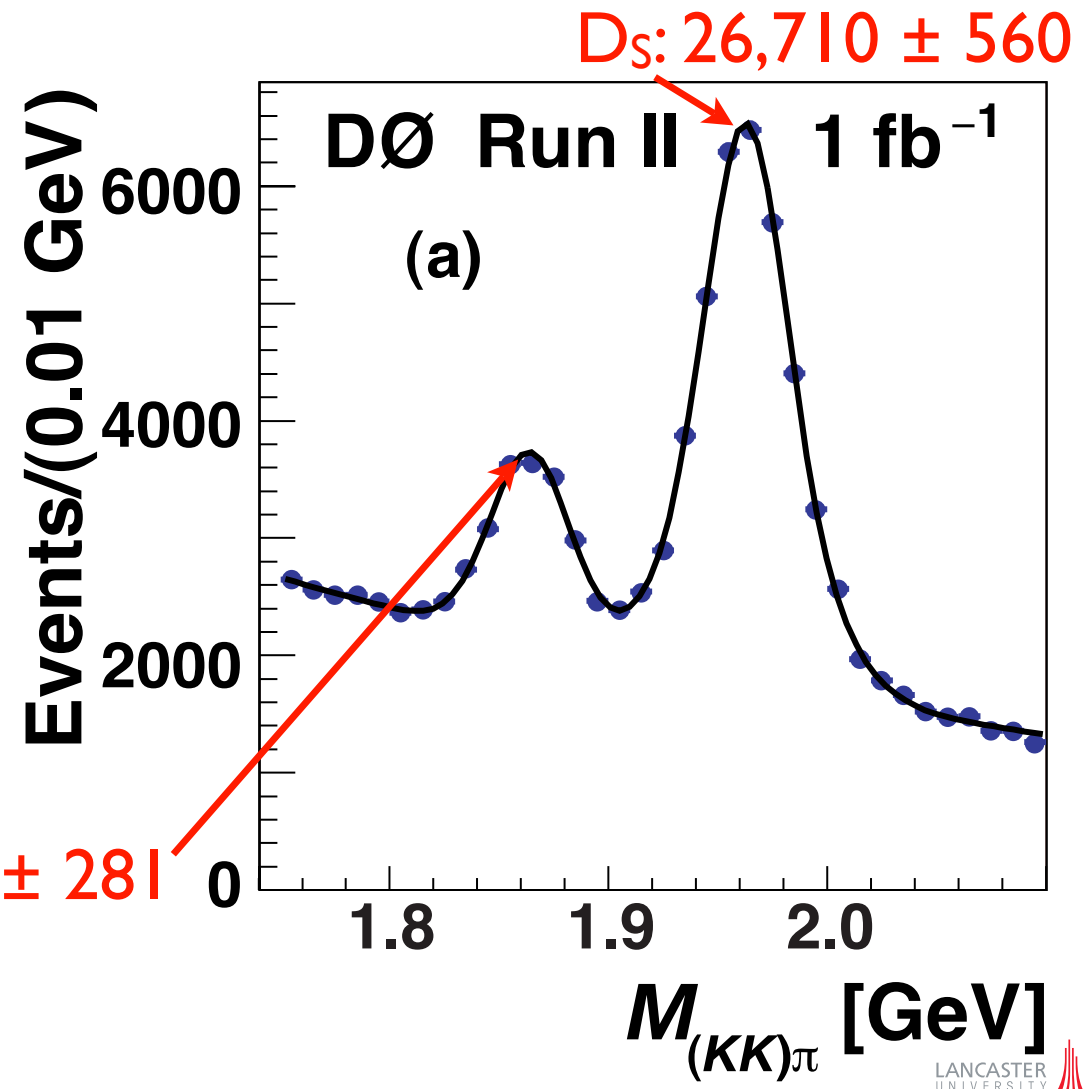


$$y = \prod_{i}^{N} y_i$$

Untagged Sample

Selected events from untagged sample.

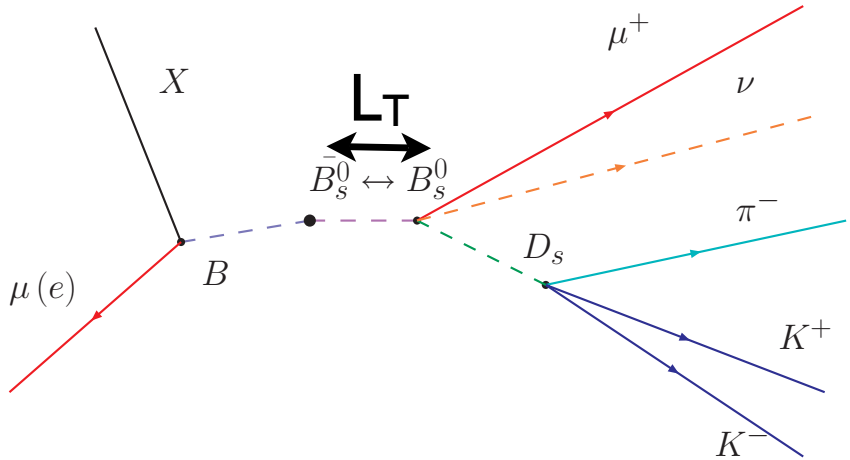
Gaussians for signal, Exponential background.



Proper Decay Length

- Due to non-reconstructed particles in event can measure the Visible Proper Decay Length.

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



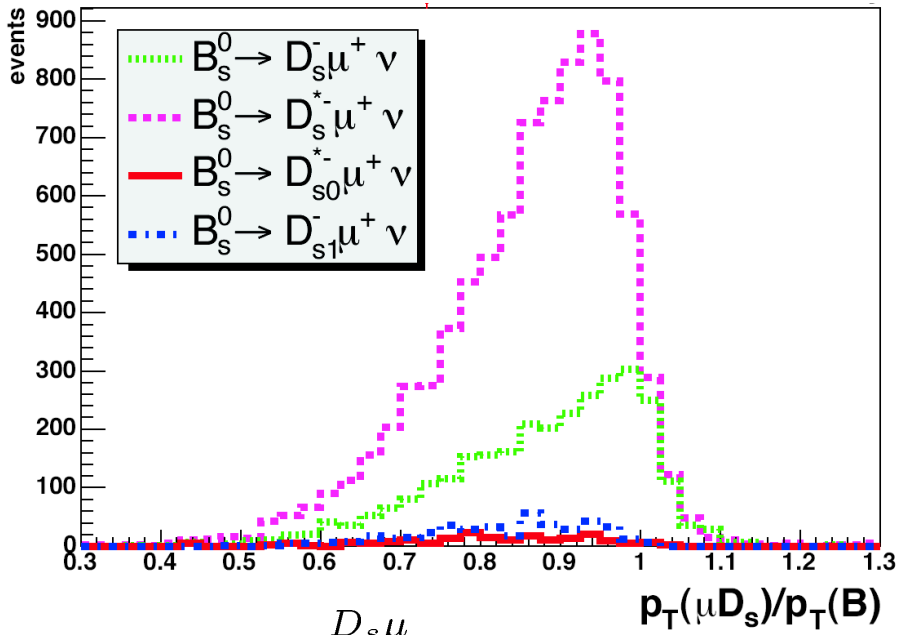
- Introduce K-factor, determined from MC to correct for bias.

$$K = \frac{p_T^{D_s\mu}}{p_T^{B_s}}$$

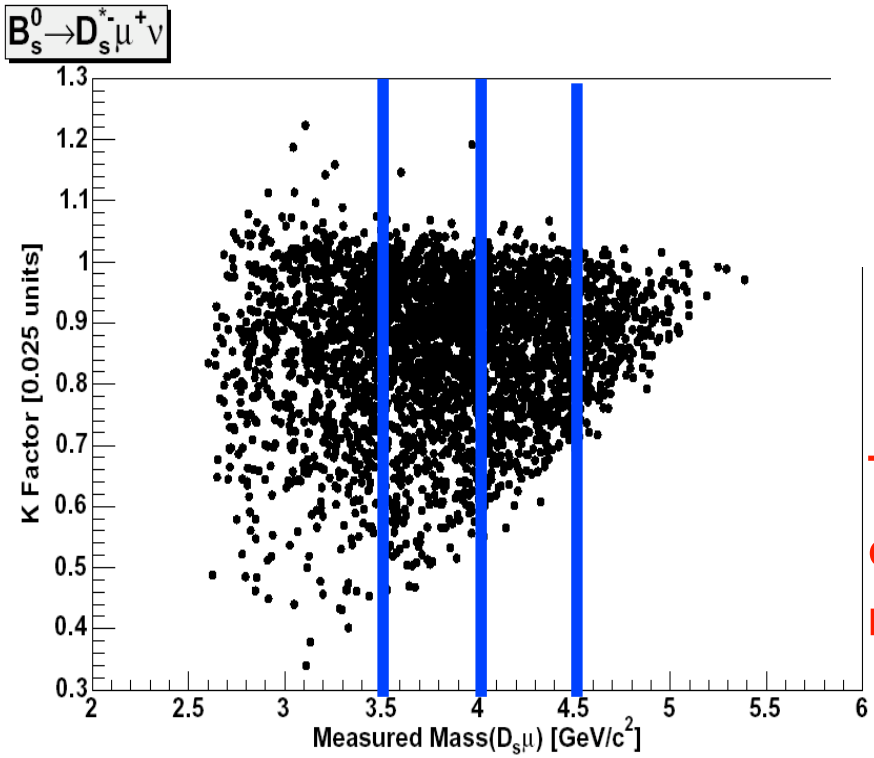
- Proper Decay Length: $ct = x^M \cdot K$

K-Factors

- K-Factor distributions for different decay modes.



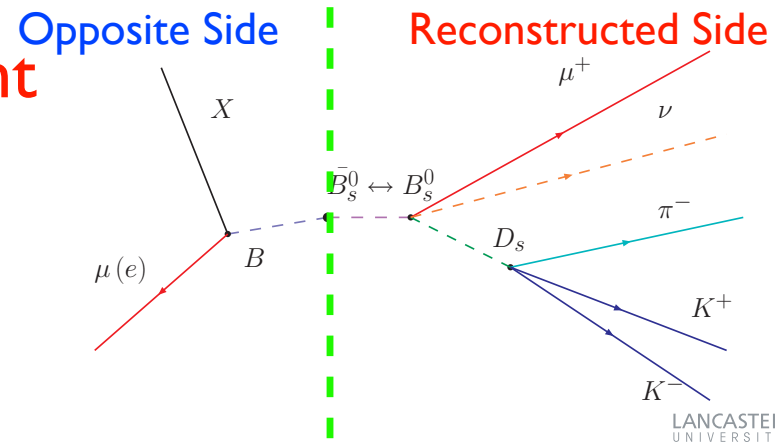
$$K = \frac{p_T^{D_s \mu}}{p_T^{B_s}}$$



To reduce error separate K-Factor distributions in to different μ D_S mass bins.

Initial State Flavour Tagging

- Reconstructed muon provides flavour at time of decay.
- Harder to identify flavour at production.
- As b $\bar{b}$ pairs produced at production, use opposite side of the event to determine initial flavour.
- Optimise with different tagging methods.



Flavour Tagging Variables

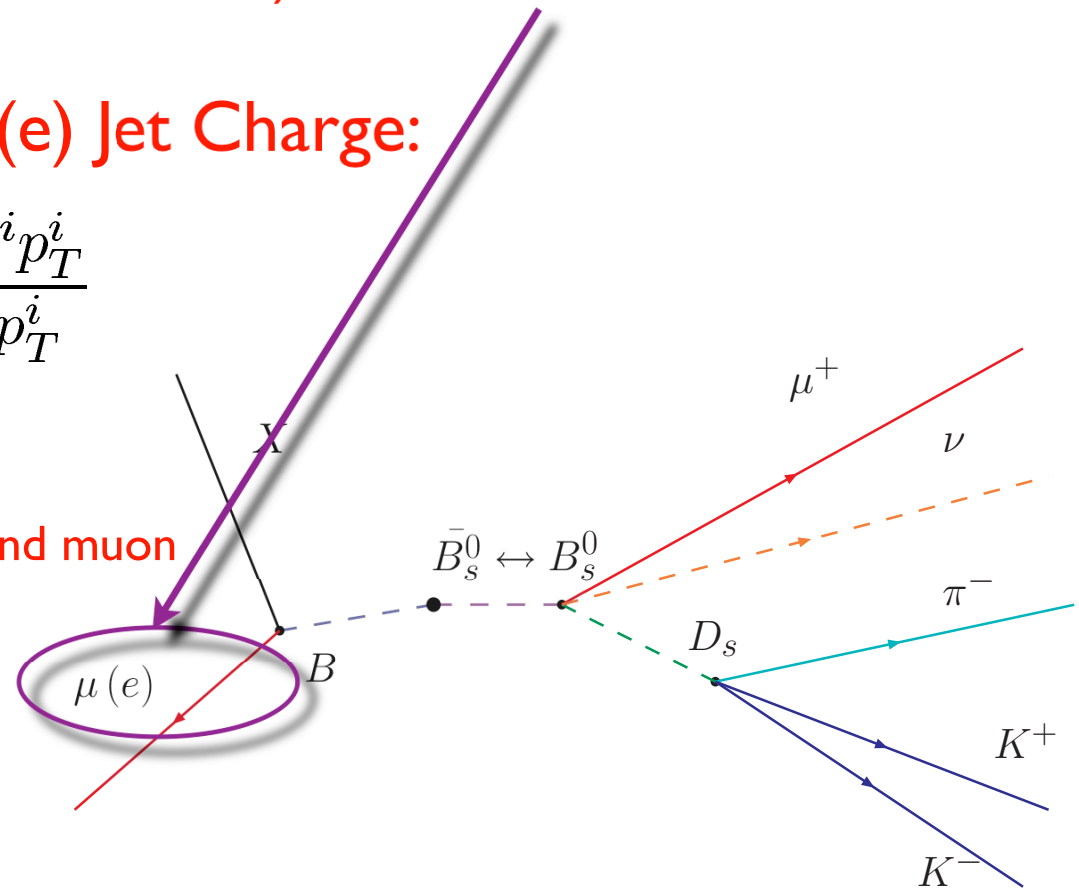
- If muon (or electron) is found:

Use muon (e) Jet Charge:

$$Q_J^{\mu(e)} = \frac{\sum_i q^i p_T^i}{\sum_i p_T^i}$$

Within cone ΔR < 0.5 around muon

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

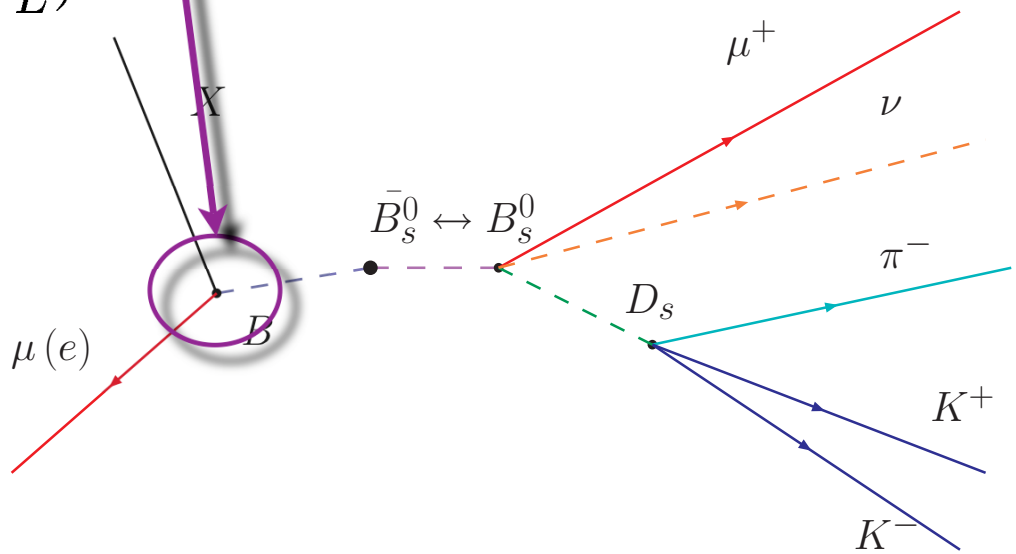


Flavour Tagging Variables

- Secondary Vertex:

  SV Charge:

$$Q_{SV} = \frac{\sum_i (q^i p_L^i)^k}{\sum_i (p_L^i)^k}, \quad k = 0.6$$

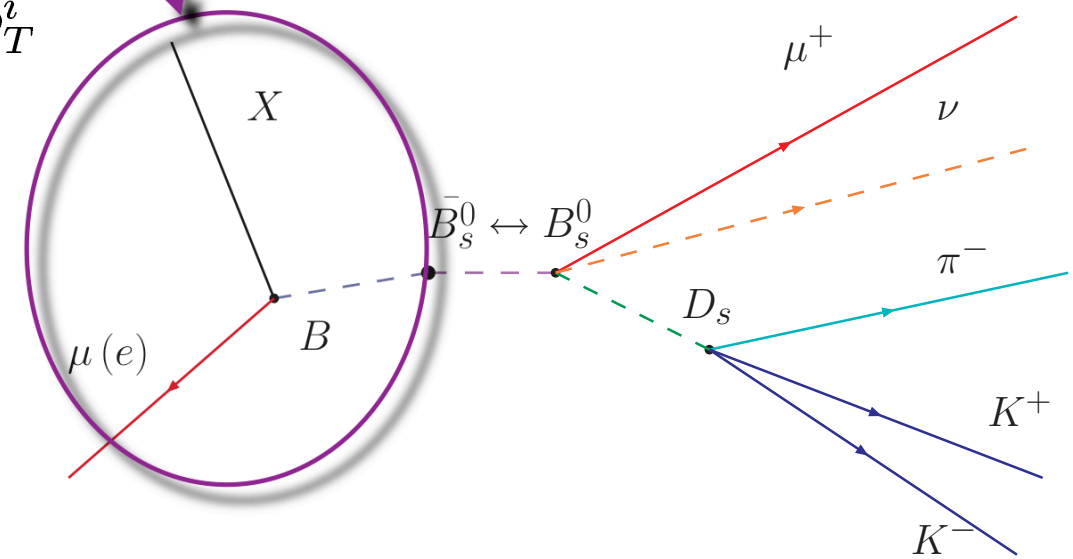


Flavour Tagging Variables

- Event Charge:

  Sum weighted charge of tracks in opposite side:

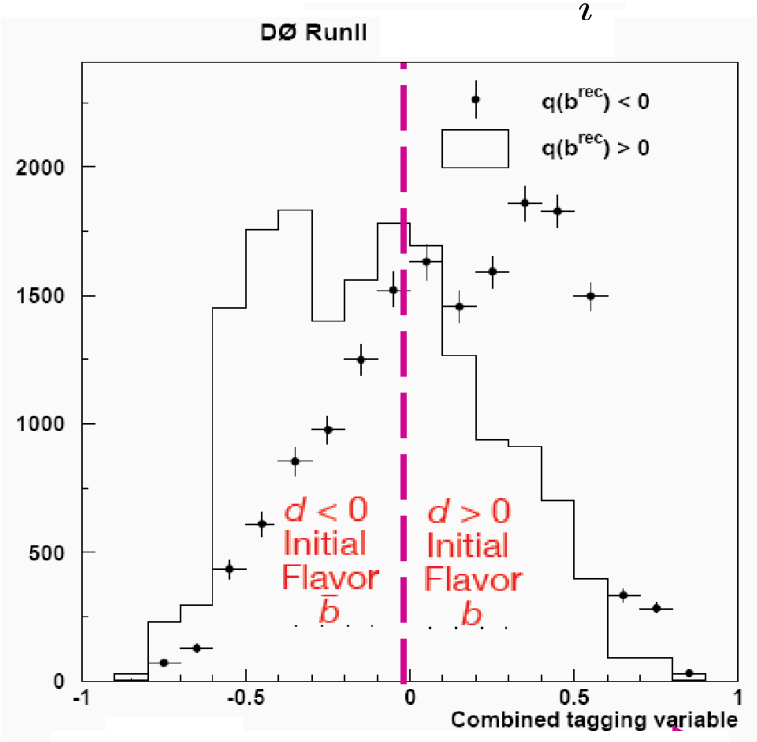
$$Q_{EV} = \frac{\sum_i q^i p_T^i}{\sum_i p_T^i}$$



Combined Flavour Tagging

- Use Likelihood ratio method:

$$d = \frac{1-y}{1+y} \qquad y = \prod_{i}^{N} y_i \qquad y_i = \frac{\mathrm{PDF}^{\bar{\mathrm{b}}}(x_i)}{\mathrm{PDF}^{\mathrm{b}}(x_i)}$$



d>0 Tagged as b,

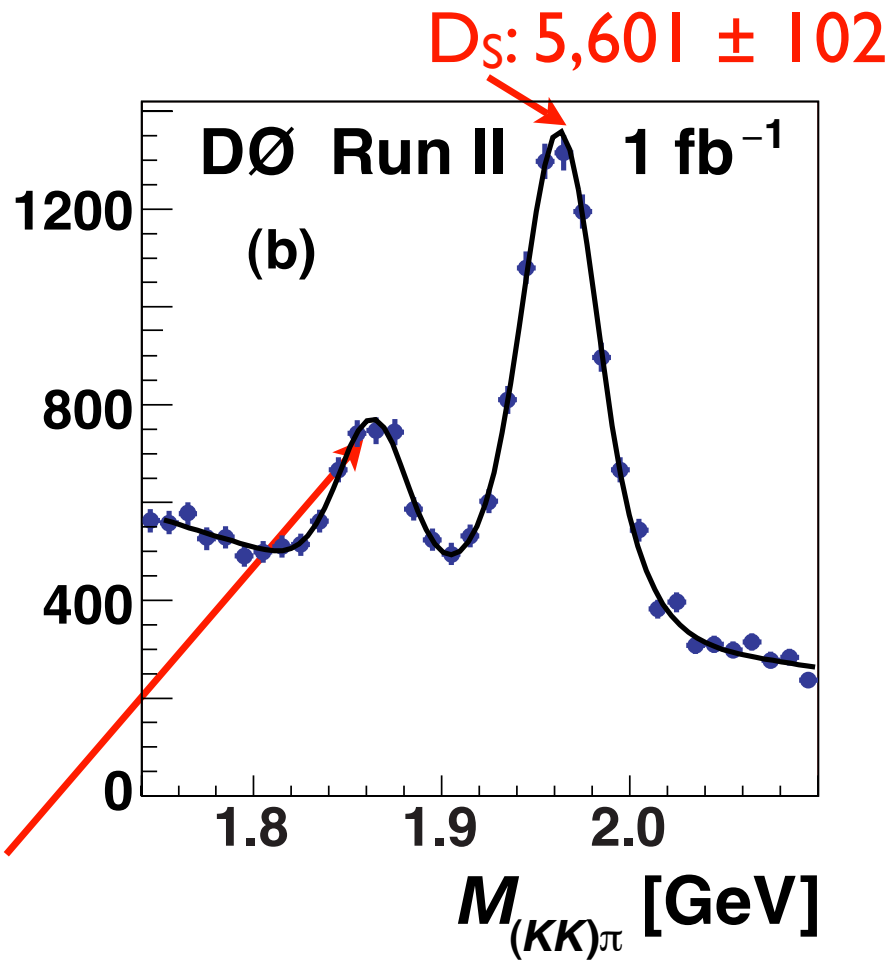
d<0 Tagged as $\bar{b}$.

Purity increases with larger |d|.

Tagged Sample

Selected events from tagged sample.

Tagging efficiency ~20%



Amplitude Method

$$P^{\text{non-osc/osc}} = \frac{K}{c\tau_{B_s}} \cdot \mathrm{e}^{-\frac{K}{c\tau_{B_s}} x^M} \cdot 0.5(1 \pm A \cdot \mathcal{D} \cos(\Delta m_s K x^M / c))$$

- Probability of oscillation.
  - Multiplicative factor *A*:
    A=1 for mixing,
    A=0 otherwise.
  - Ideal width Γ (1/τ), smeared out by detector resolution and K-factor effects.
- Scan over a range of Δm_s and fit for *A* at each point.

Likelihood Fit Inputs

$$-2\sum_i \ln f_i \qquad f_i = P^{x^M}(x^M, \sigma_{x^M}, d_{pr}) \cdot P^{\sigma_{x^M}} \cdot P^{d_{pr}} \cdot P^{m(\phi\pi)}$$

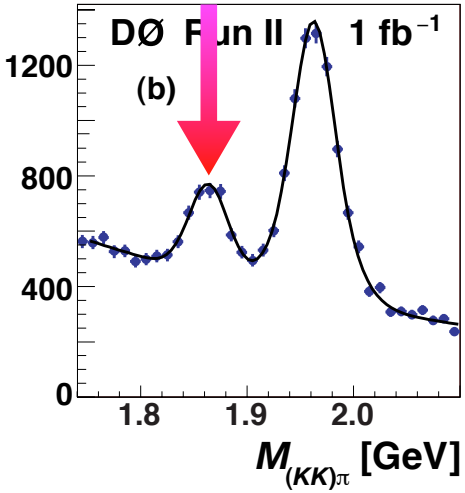
- Signal:

$$P_s^{(\mathrm{n})\mathrm{osc}}(x^M, \sigma_{x^M}, d_{pr}) = \int_{K_{\min}}^{K_{\max}} D(K)\mathrm{d}K \cdot \frac{Eff(x^M)}{N} \int_0^\infty \mathrm{d}x\, G(x - x^M, \sigma_{x^M}) \cdot p_s^{(\mathrm{n})\mathrm{osc}}(x, K, d_{pr})$$

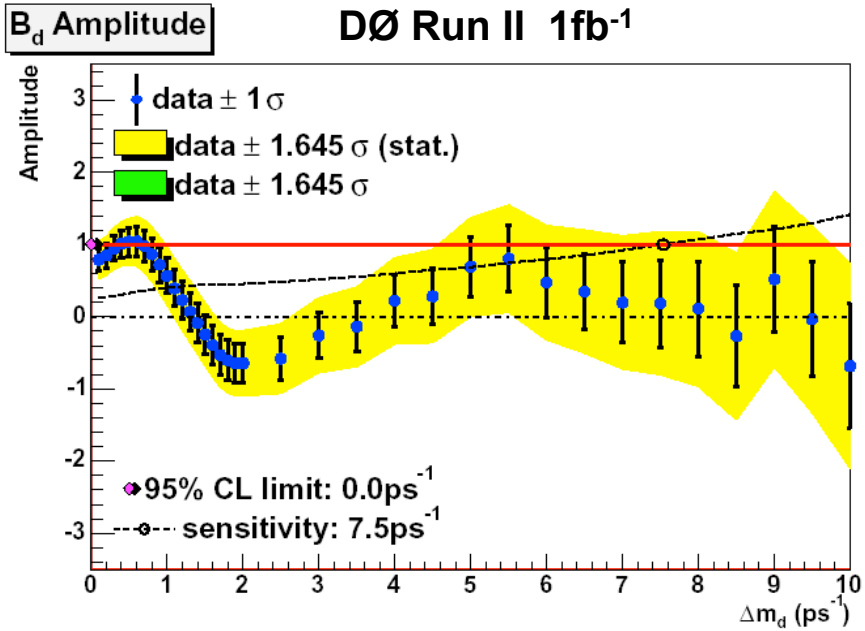
  - Likelihood function takes VPDL and error, mass of D_s and predicted dilution.
  - Includes contributions from all signal processes.

- Background:
  - Prompt ($c\bar{c}$) contribution,
  - Background from secondary vertices,
  - Long-lived, exponential $\otimes$ resolution.

Cross-Check: B_d



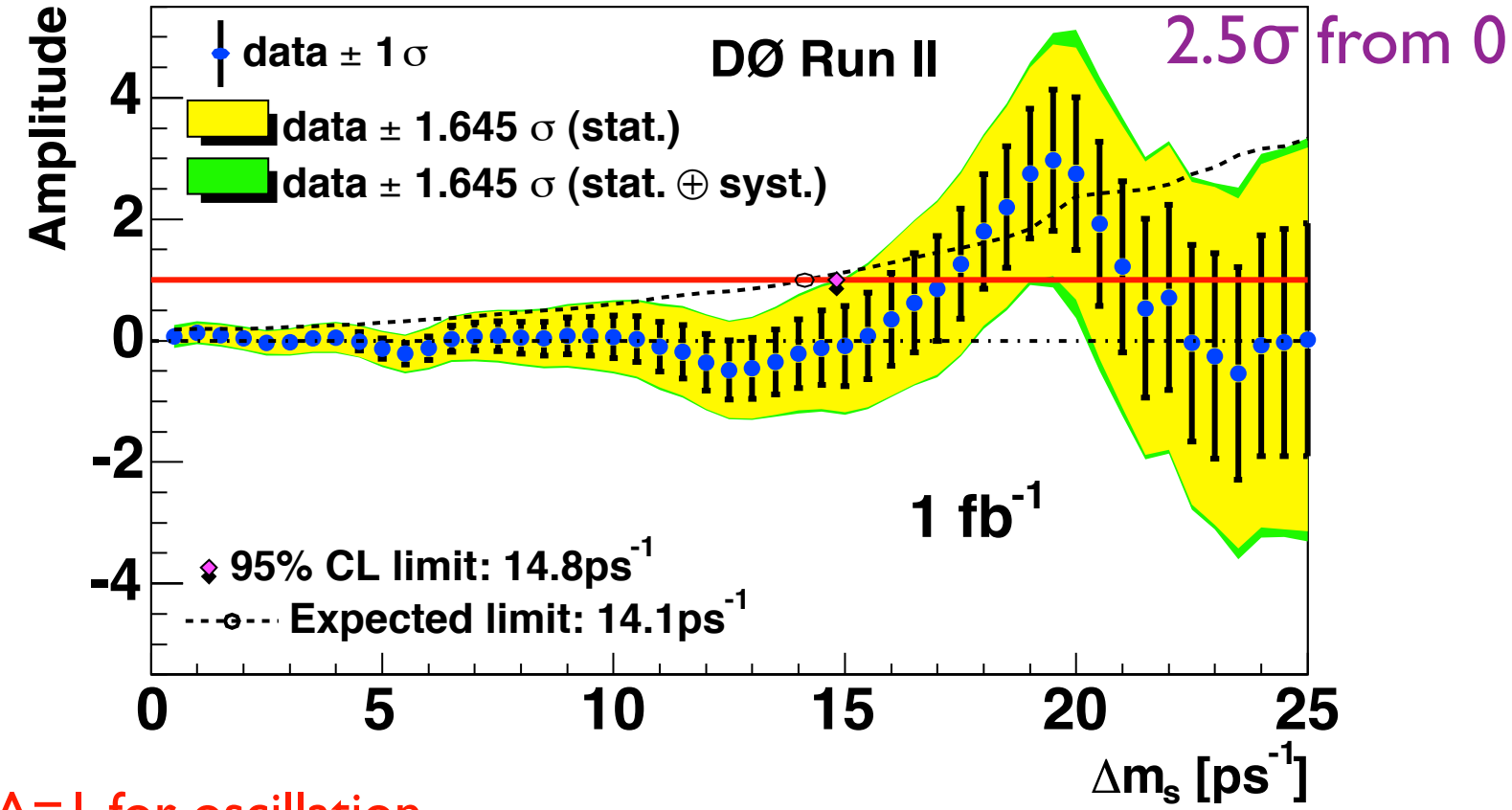
$B_d \rightarrow \mu D^{\pm}$



- Amplitude scan for B_d oscillations.
- $\Delta m_d = 0.506 \pm 0.020$ (stat) ps^{-1}.
- $\epsilon = (19.9 \pm 0.2$ (stat)) %
- $\epsilon D^2 = (2.48 \pm 0.21$(stat)) %

B_d sample used as calibration for OST in B_s analysis.

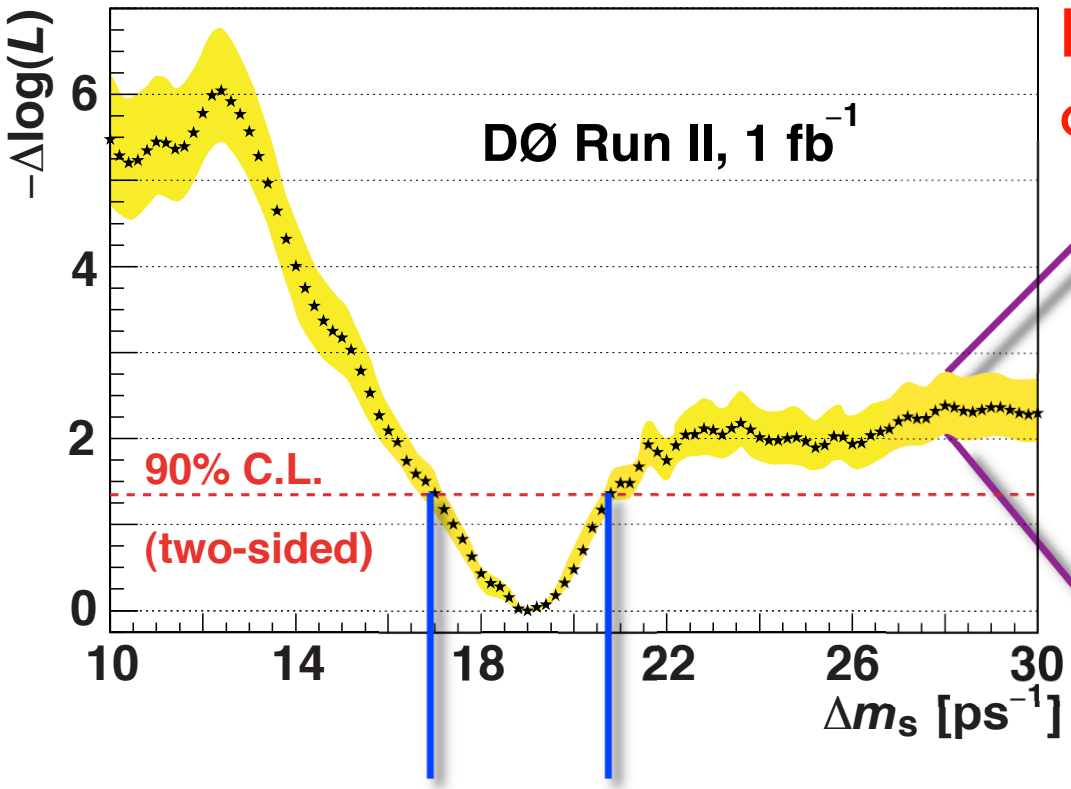
Amplitude Scan



A=1 for oscillation,
Clear deviation from A=0 observable around Δm_s = 19 ps^{-1}.

- Δm_s > 14.8 ps^{-1} at 95% CL.

Log Likelihood Scan



First time bounded on two sides.

$$\sigma_A^{\text{sys}} = \Delta A + (1 - A)\frac{\Delta\sigma_A}{A}$$

Resolution
K-factor
Branching ratio
VPDL model

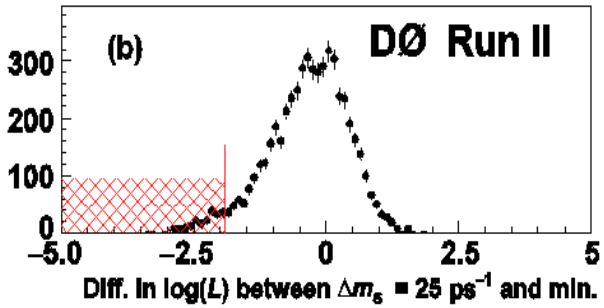
$17 < \Delta m_s < 21$ ps^{-1} , 90% CL.

Maximum Likelihood for $\Delta m_s = 19$ ps^{-1}.

Paper accepted by PRL!

Ensemble Tests

- Just how likely is this?
- Build Toy MC model incorporating resolution, K-Factors etc.
- Δm_s<16 ps^{-1} has been previously experimentally excluded.
- No sensitivity above 22 ps^{-1}.
- Probability to observe $\Delta\log(L)>1.7$ (as found from this measurement) in range $16<\Delta m_s<22$ ps^{-1}:
  - Simulate $\Delta m_s = \infty$ by randomising flavour tagging sign. Probability is 5% (with systematics) (from data).
  - With Δm_s = 19 ps^{-1}, probability ~15% (from MC).

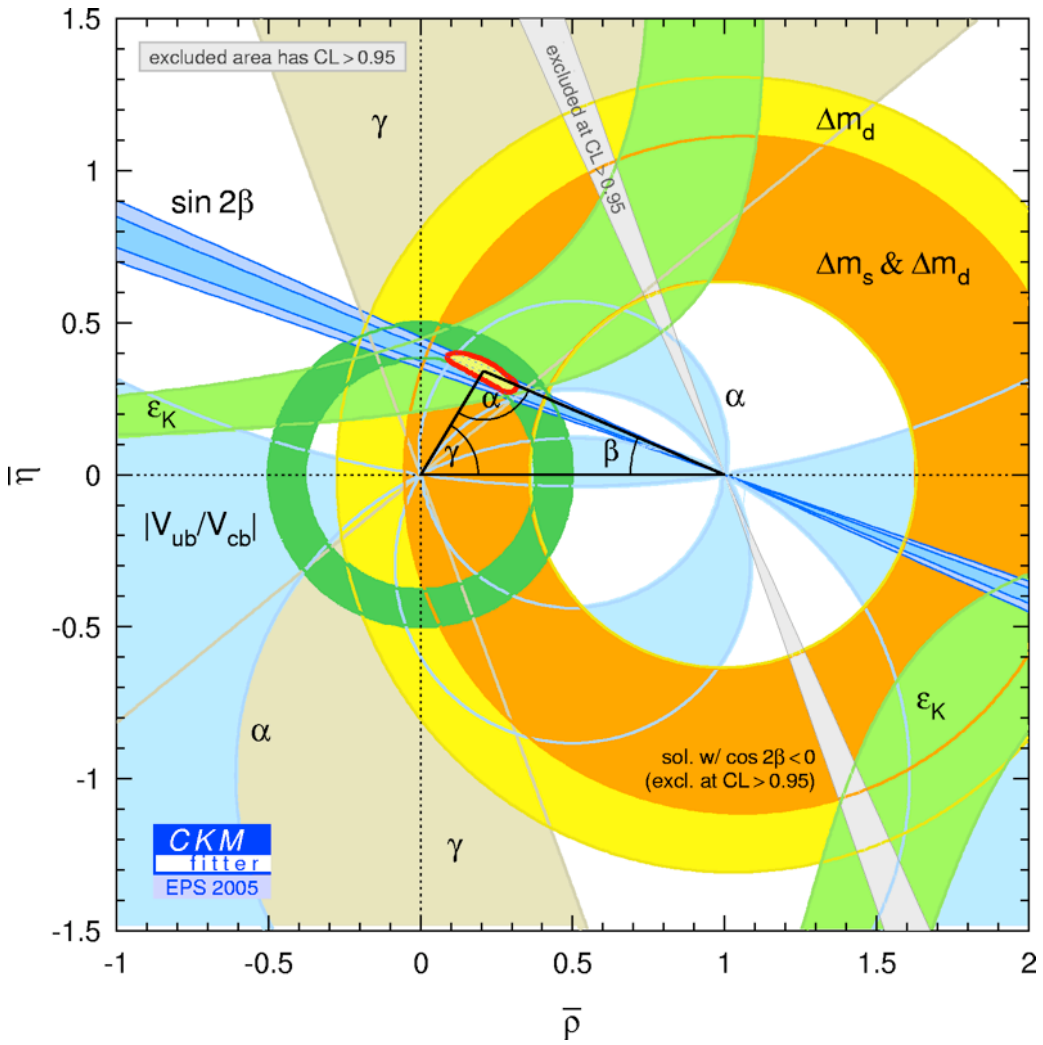


Summary

- First direct two-sided bound for Δm_s, with a
- 90% CL. for the range $17 < \Delta m_s < 21 ps^{-1}$.
- 2.5 σ deviation from amplitude of 0 at 19 ps^{-1}.
- Has been accepted by PRL.
- Analyses in progress:
  - More semileptonic decay modes (K^*K, $D_s e$),
  - Hadronic modes,
  - Same-Side Tagging methods.
- Upgraded Detector for Run IIb.
- Tevatron to provide more exciting results.

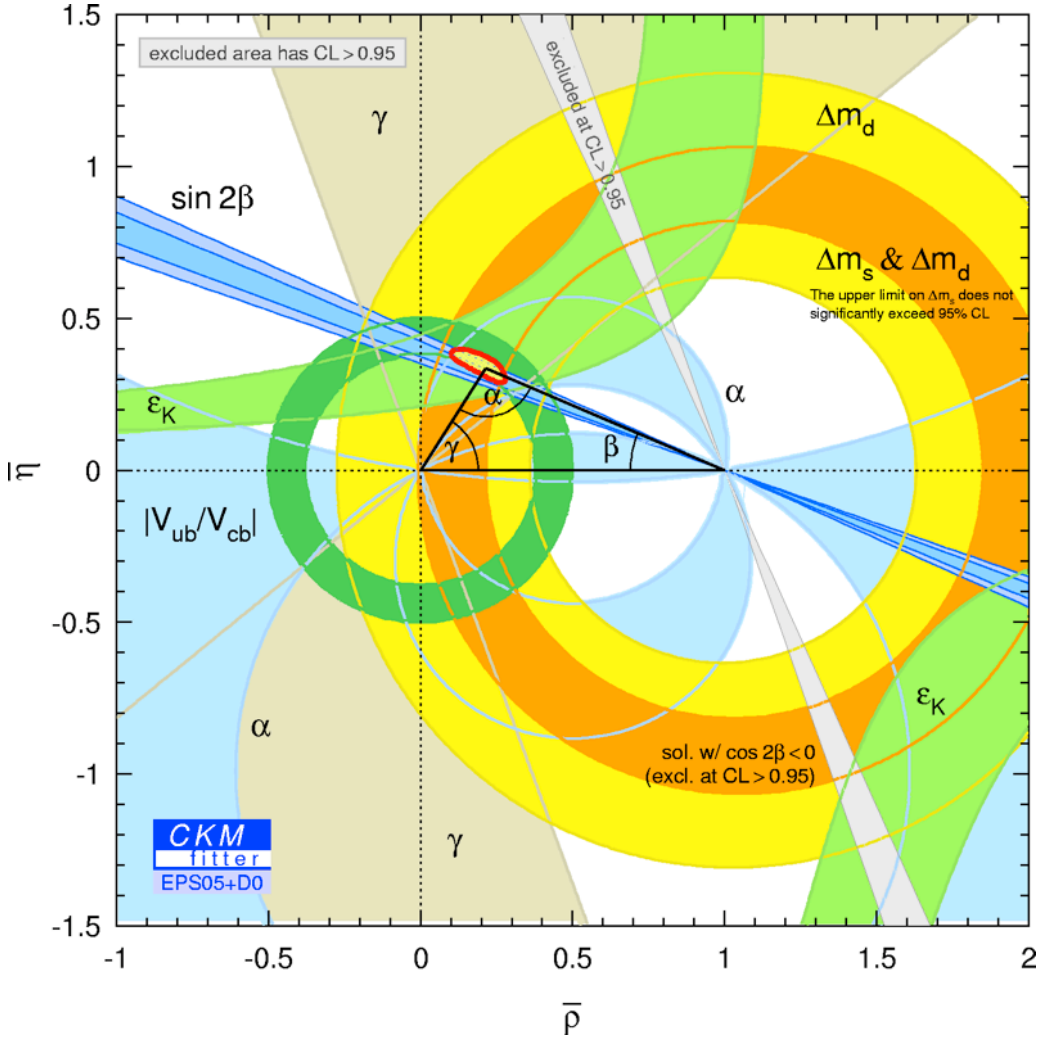
CKM Fitter Results

- Before DØ result.



CKM Fitter Results

- With DØ result.



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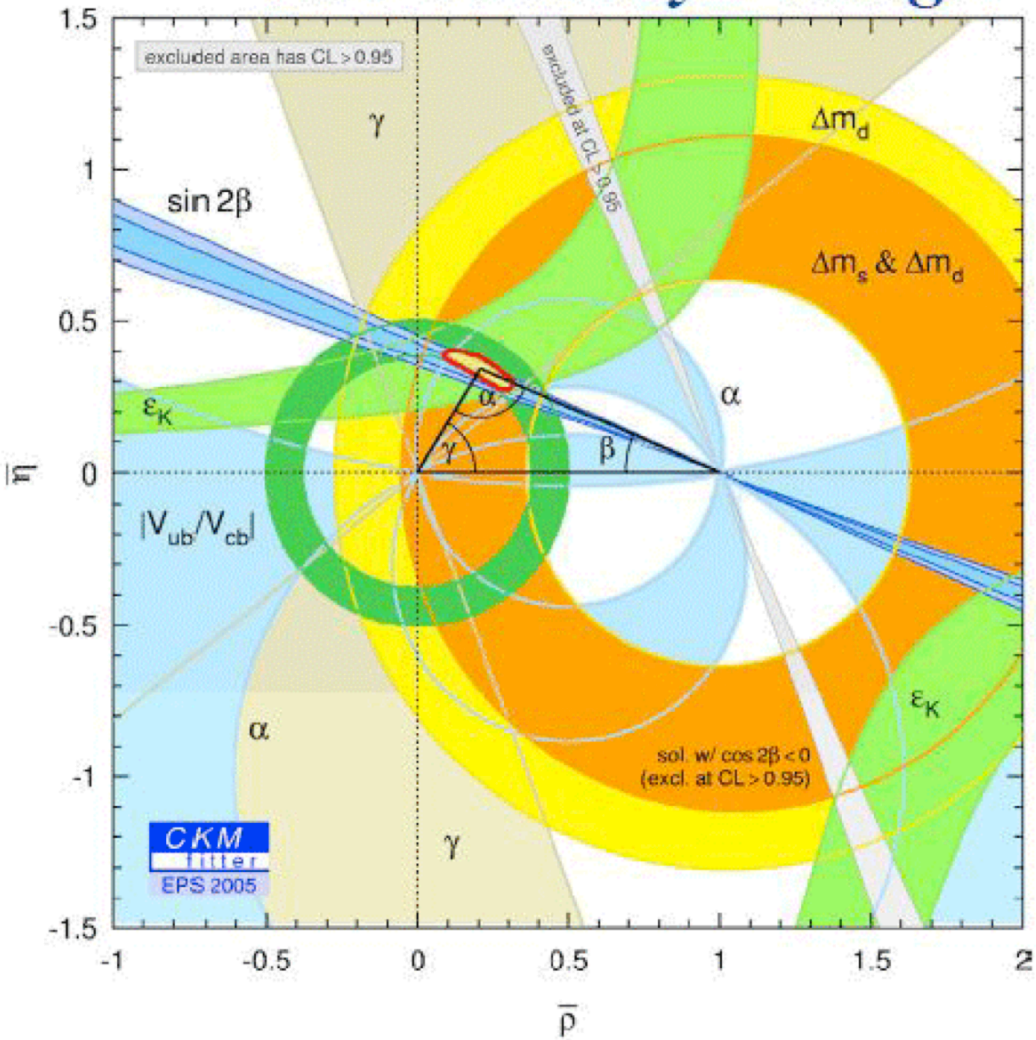
Backup Slides

The Unitarity Triangle

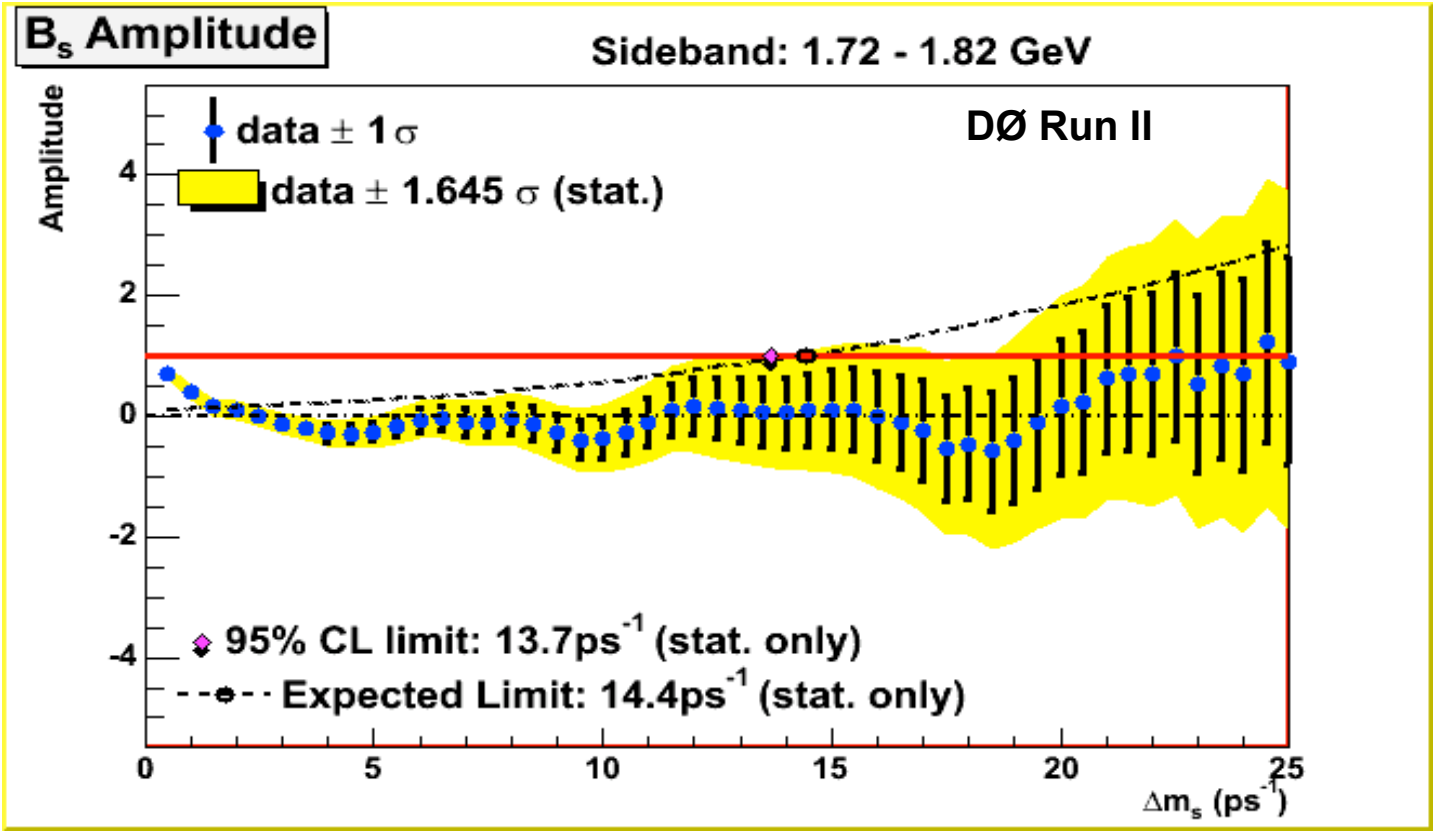


http://gordonwatts.wordpress.com

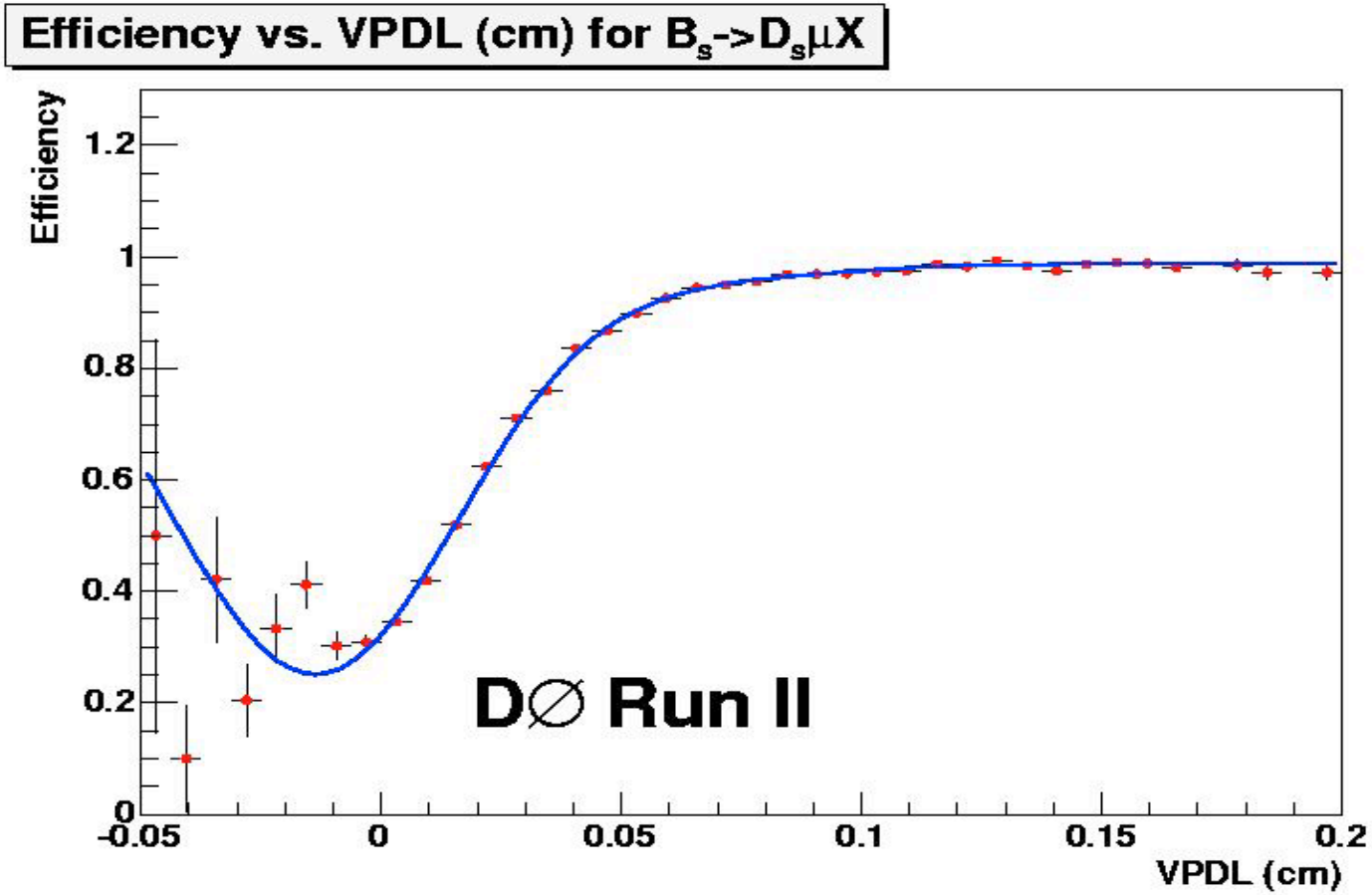
Tagging Performance

Tagger $\|d\|>0.3$	ϵD^2 (stat.) %
Muon	1.48±0.17
Electron	0.21±0.07
SV charge	0.5±0.11
Combined	2.19±0.22
Total OST	2.48±0.21

Sideband Region

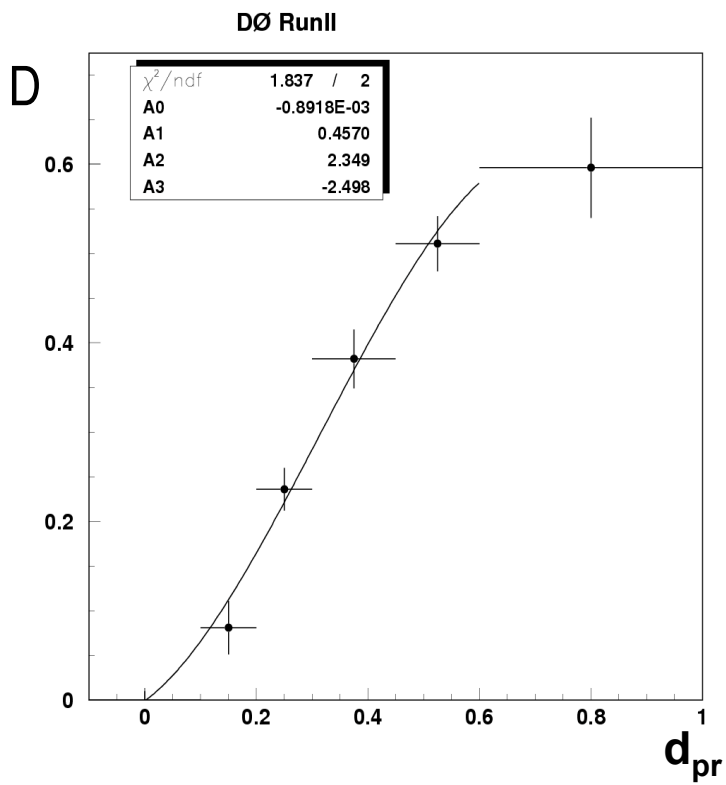


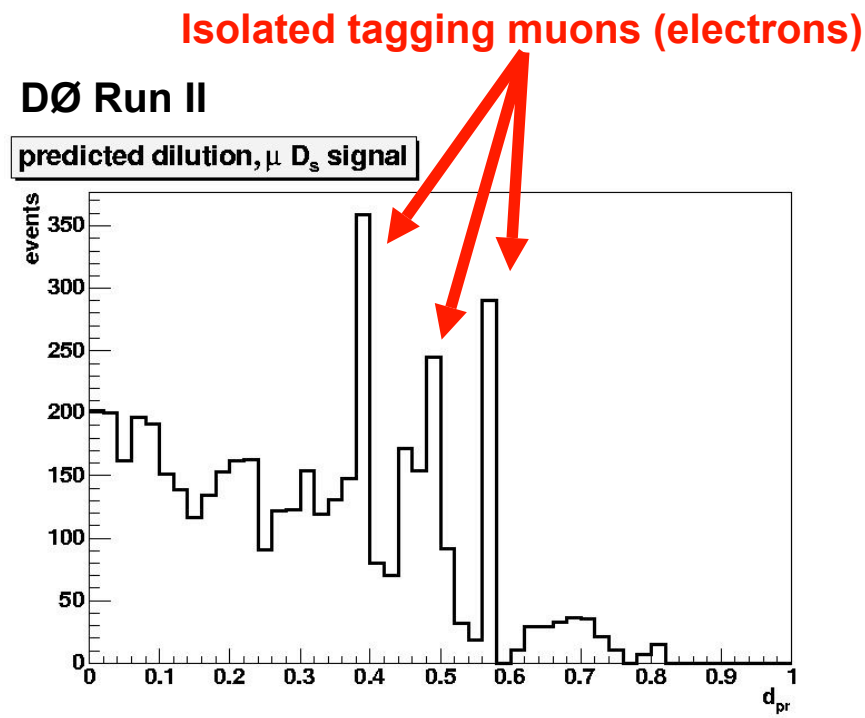
Eff. Dependence on VPDL



Taken from MC, cross-checked and tuned using data.

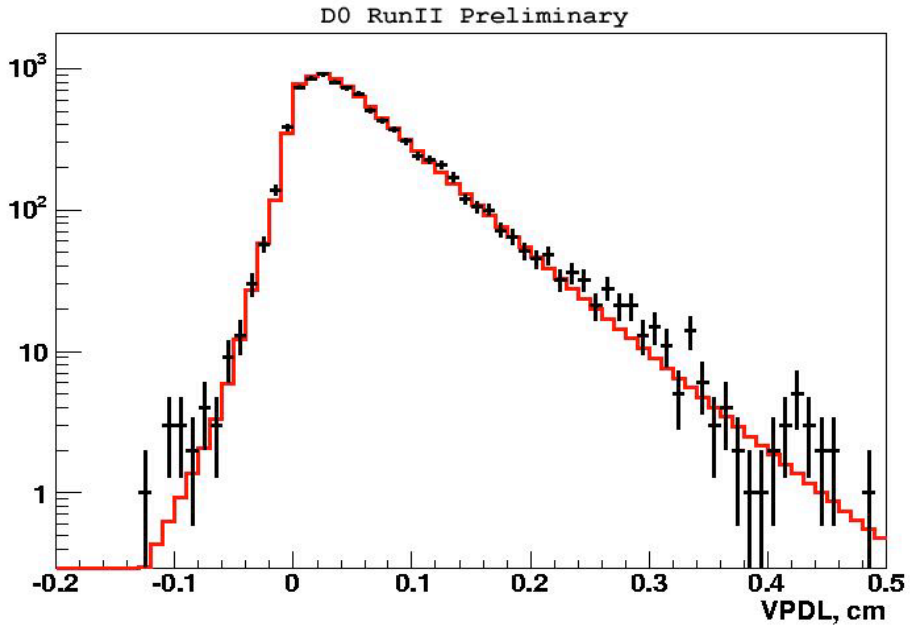
Dilution





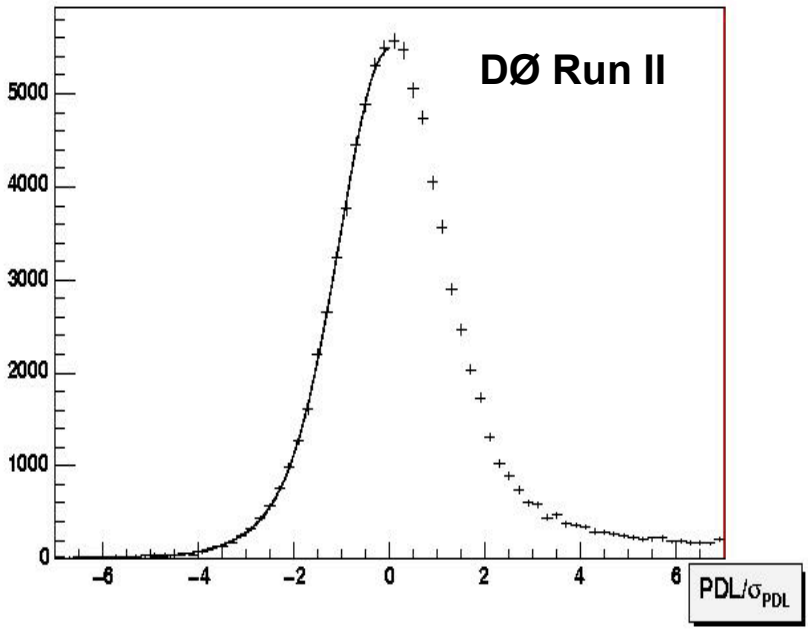
Dilution enters into Likelihood fit in an event by event basis.

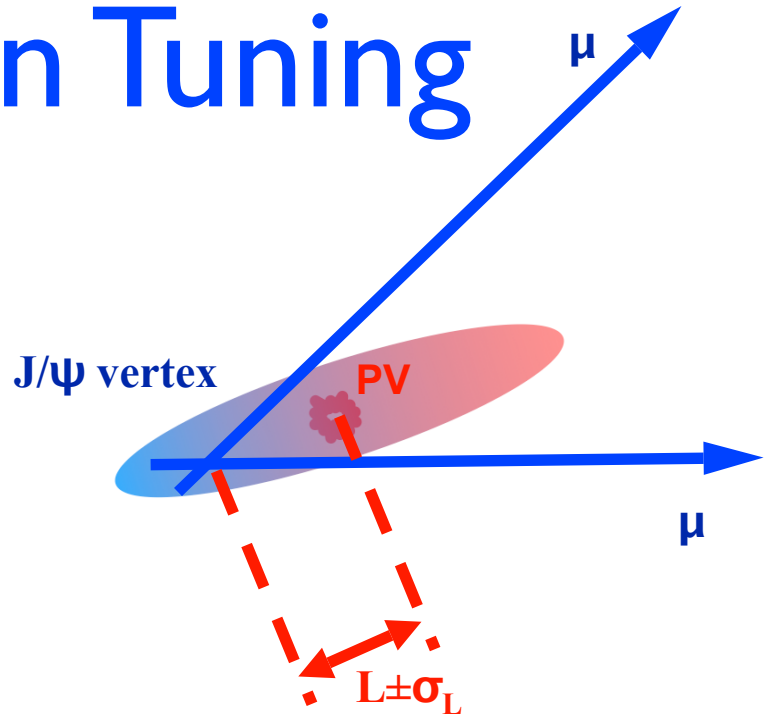
Lifetime Fit



- Lifetime measurement does not directly influence lifetime oscillation measurement.
- Trigger Biases have been studied. Different efficiency models used.
- $c\tau$ = 404 - 416 μm. Stat. error ~10 μm. (HFAG: $c\tau$ ~ 438±12 μm.)

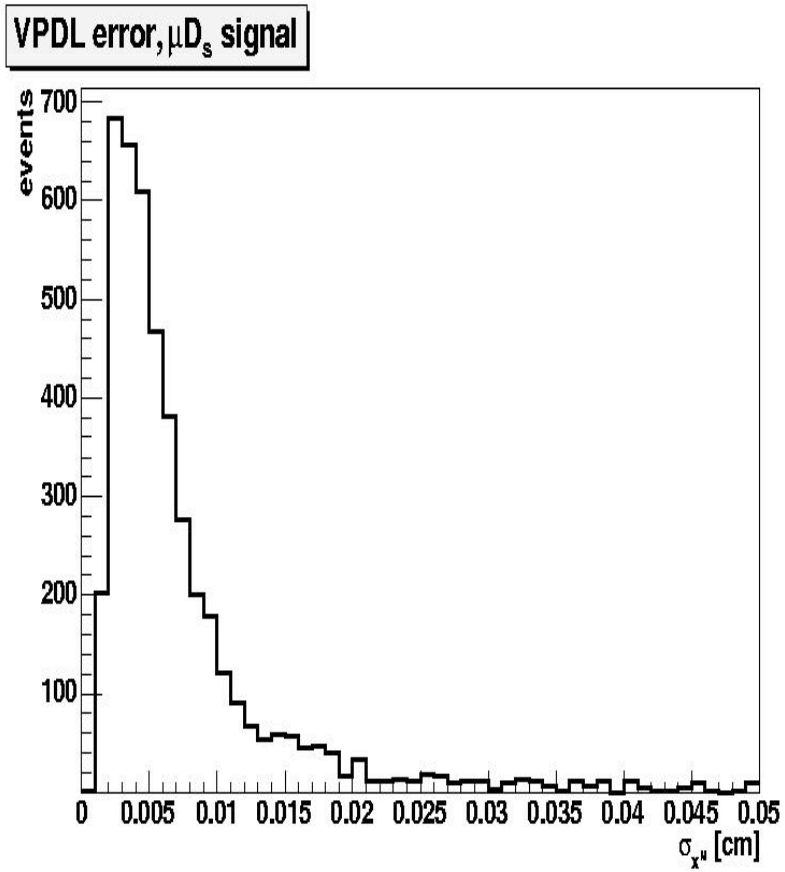
Resolution Tuning





- Double Gaussian fit to J/ψ proper decay length.
- Resolution scale factor is 1.0 for 72% of events, 1.8 for other 28%

Vertex Resolution



Determined from vertex fitting procedure

Systematic Uncertainties

Osc. frequency		1 ps^{-1}	3 ps^{-1}	5 ps^{-1}	7 ps^{-1}	9 ps^{-1}	11 ps^{-1}	13 ps^{-1}	15 ps^{-1}	17 ps^{-1}	19 ps^{-1}	21 ps^{-1}	23 ps^{-1}	25 ps^{-1}
$\mathcal{A}$		0.128	−0.025	−0.134	0.073	0.079	−0.100	−0.459	−0.093	0.858	2.749	1.218	−0.253	0.018
Stat. uncertainty		0.090	0.124	0.167	0.231	0.299	0.410	0.504	0.659	0.864	1.068	1.413	1.690	1.920
$\mathrm{Br}(D_s D_s) = 4.7\%$	$\Delta\mathcal{A}$	−0.003	+0.000	+0.003	−0.002	−0.002	+0.003	+0.010	+0.001	−0.022	−0.059	−0.021	+0.012	+0.009
	$\Delta\sigma$	−0.002	−0.003	−0.004	−0.005	−0.006	−0.009	−0.010	−0.014	−0.018	−0.023	−0.029	−0.035	−0.040
$\mathrm{Br}(D_s \mu X) = 6.7\%$	$\Delta\mathcal{A}$	+0.006	−0.003	−0.005	−0.004	−0.001	−0.003	−0.011	−0.004	+0.012	+0.046	+0.023	−0.001	+0.011
	$\Delta\sigma$	+0.002	+0.002	+0.003	+0.004	+0.005	+0.007	+0.009	+0.011	+0.015	+0.019	+0.024	+0.030	+0.035
$p_{T_\mu} > 6$ GeV/c	$\Delta\mathcal{A}$	−0.015	+0.009	+0.013	+0.010	−0.001	+0.010	+0.029	+0.013	−0.045	−0.124	−0.044	−0.023	−0.019
	$\Delta\sigma$	−0.004	−0.006	−0.008	−0.011	−0.014	−0.019	−0.024	−0.031	−0.042	−0.054	−0.066	−0.081	−0.093
K-factor variation	$\Delta\mathcal{A}$	−0.000	+0.006	−0.024	+0.001	+0.010	−0.041	+0.045	+0.104	+0.231	+0.207	−0.380	+0.006	−0.001
2%	$\Delta\sigma$	+0.000	+0.001	+0.002	+0.004	+0.007	+0.012	+0.011	+0.027	+0.025	+0.059	+0.040	+0.049	+0.050
K-factor distribution	$\Delta\mathcal{A}$	+0.000	−0.000	−0.001	+0.001	−0.002	+0.013	+0.006	+0.036	+0.028	−0.003	+0.171	+0.033	+0.032
smoothed	$\Delta\sigma$	+0.000	+0.000	+0.000	+0.000	+0.001	+0.001	+0.002	+0.003	+0.003	+0.005	+0.004	+0.008	+0.009
K-factor from	$\Delta\mathcal{A}$	−0.000	−0.001	+0.003	+0.001	−0.009	+0.026	+0.003	+0.055	+0.048	−0.021	+0.248	+0.003	−0.050
measured momenta	$\Delta\sigma$	+0.000	+0.000	+0.000	+0.001	+0.001	+0.002	+0.003	+0.005	+0.004	+0.006	+0.006	+0.005	+0.011
Fraction of peaking bkg.	$\Delta\mathcal{A}$	+0.002	+0.001	−0.000	−0.001	−0.000	+0.000	−0.000	+0.001	+0.004	+0.012	+0.007	+0.002	+0.008
(combinatorial bkg.)	$\Delta\sigma$	+0.000	−0.000	−0.000	+0.000	+0.000	+0.000	+0.001	+0.001	+0.001	+0.001	+0.003	+0.004	+0.004
Fraction of peaking bkg.	$\Delta\mathcal{A}$	+0.001	−0.000	−0.002	−0.000	−0.002	−0.007	−0.016	−0.013	+0.004	+0.055	+0.014	−0.035	−0.021
(signal)	$\Delta\sigma$	+0.001	+0.001	+0.001	+0.002	+0.002	+0.004	+0.005	+0.007	+0.012	+0.014	+0.026	+0.034	+0.039
$c\tau_B_s$	$\Delta\mathcal{A}$	+0.001	+0.001	+0.002	−0.000	−0.001	+0.003	+0.003	−0.001	−0.010	−0.029	+0.003	+0.013	+0.000
	$\Delta\sigma$	−0.000	−0.000	−0.001	−0.001	−0.002	−0.002	−0.003	−0.004	−0.006	−0.007	−0.011	−0.014	−0.015
uncertainty in	$\Delta\mathcal{A}$	−0.002	+0.001	−0.001	+0.001	+0.002	+0.002	−0.001	−0.003	+0.000	+0.008	+0.008	+0.002	−0.001
reflection	$\Delta\sigma$	+0.000	+0.000	+0.000	+0.001	+0.001	+0.001	+0.001	+0.001	+0.002	+0.002	+0.003	+0.004	+0.004
Stat. fluctuation of	$\Delta\mathcal{A}$	−0.001	+0.000	+0.000	+0.001	−0.000	−0.001	−0.000	+0.003	+0.008	+0.016	+0.011	+0.004	+0.009
N_D_s	$\Delta\sigma$	+0.000	+0.001	+0.001	+0.001	+0.001	+0.002	+0.002	+0.003	+0.004	+0.004	+0.008	+0.009	+0.009
resolution	$\Delta\mathcal{A}$	+0.001	+0.002	+0.004	+0.010	+0.007	−0.000	−0.019	−0.012	+0.019	+0.075	+0.040	+0.025	+0.076
(signal)	$\Delta\sigma$	+0.000	+0.001	+0.002	+0.004	+0.007	+0.012	+0.016	+0.023	+0.035	+0.046	+0.068	+0.087	+0.102
resolution	$\Delta\mathcal{A}$	+0.001	−0.001	−0.001	−0.001	−0.001	−0.001	−0.001	−0.002	−0.003	−0.006	−0.009	−0.009	−0.011
(bkg.)	$\Delta\sigma$	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.001	−0.001
dilution	$\Delta\mathcal{A}$	−0.005	−0.002	+0.008	+0.021	−0.010	−0.006	+0.001	+0.002	−0.015	−0.042	+0.037	+0.112	+0.129
	$\Delta\sigma$	−0.001	−0.001	−0.001	−0.002	−0.003	−0.005	−0.004	−0.005	−0.004	−0.002	−0.017	−0.018	−0.018
Fr_tsens	$\Delta\mathcal{A}$	−0.010	+0.006	+0.003	+0.003	+0.003	+0.000	−0.002	−0.004	−0.005	−0.004	−0.000	+0.001	−0.005
	$\Delta\sigma$	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	+0.000	+0.000	−0.000
Fr_osc	$\Delta\mathcal{A}$	−0.005	−0.000	+0.000	−0.001	−0.001	−0.001	−0.001	−0.002	−0.002	−0.003	−0.004	−0.006	−0.006
	$\Delta\sigma$	+0.000	+0.000	+0.000	+0.000	0.000	+0.000	−0.000	−0.000	+0.000	+0.000	0.000	−0.000	0.000
Fit to	$\Delta\mathcal{A}$	+0.008	+0.010	+0.014	+0.030	+0.041	+0.044	+0.004	+0.026	+0.129	+0.379	+0.291	+0.149	+0.363
VPDL distribution	$\Delta\sigma$	+0.002	+0.001	+0.001	+0.003	+0.006	+0.013	+0.021	+0.034	+0.045	+0.043	+0.100	+0.147	+0.179
Non-zero $\Delta\Gamma$	$\Delta\mathcal{A}$	+0.000	+0.000	+0.001	+0.000	+0.000	+0.001	+0.001	+0.000	−0.001	−0.005	−0.003	+0.001	−0.001
	$\Delta\sigma$	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.000	−0.001	−0.001	−0.001	−0.002	−0.002	−0.002
Total syst.	σ_{tot}^{sys}	0.071	0.057	0.056	0.068	0.090	0.106	0.117	0.194	0.286	0.337	0.565	0.309	0.497
Total	σ_{tot}	0.115	0.137	0.176	0.241	0.313	0.423	0.517	0.687	0.910	1.119	1.522	1.718	1.983