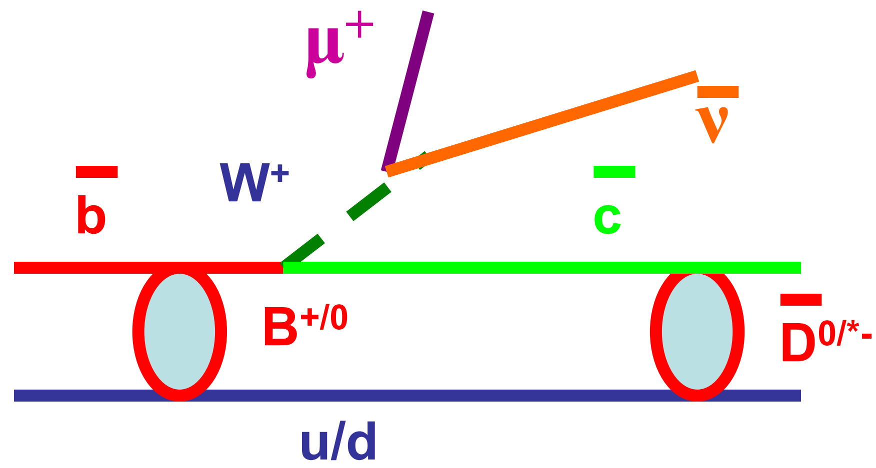
$B^{\pm}/B^0$ lifetime ratio and B^0 mixing at DØ

S.Burdin (Fermilab)
for DØ collaboration
Wine & Cheese
4/30/2004

- Data samples
- Subset of B-physics results:
  - $B^{\pm}/B^0$ lifetime ratio
  - B_d mixing
  - B_S semileptonic sample
- Conclusions

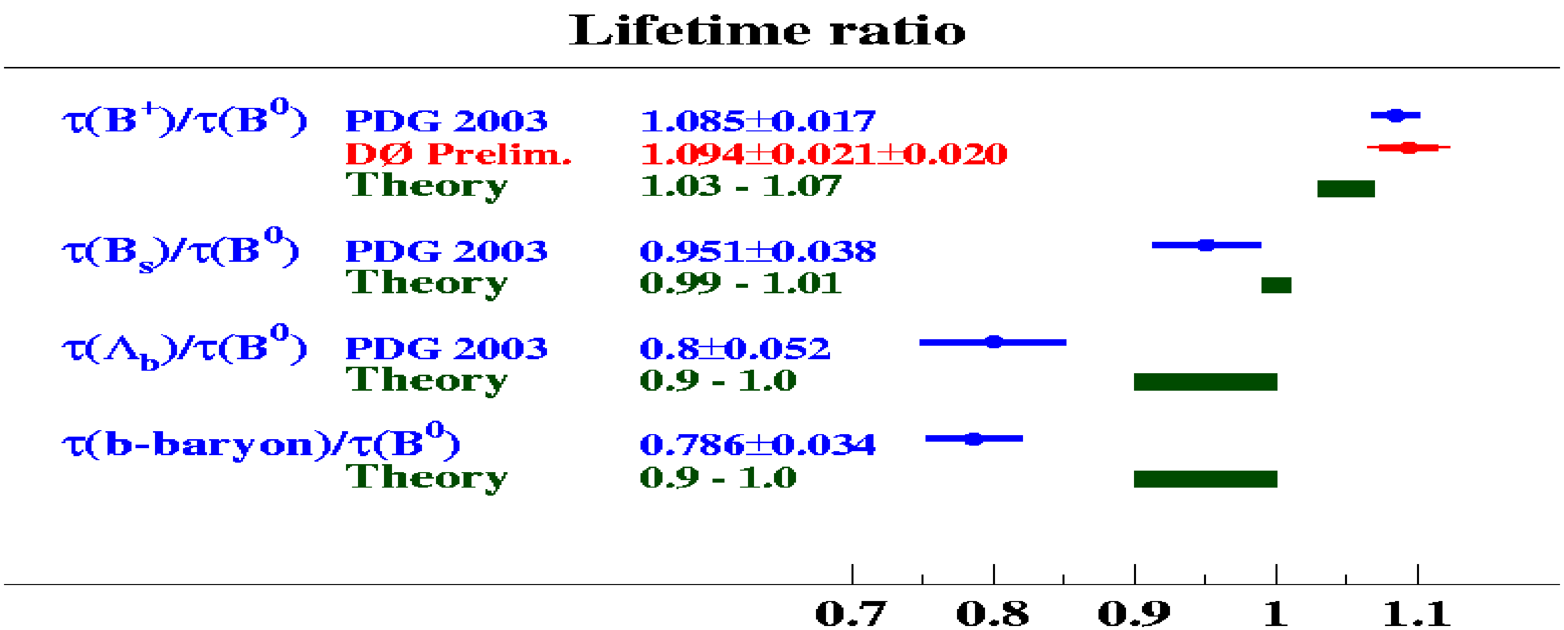
$\tau(B^+)/\tau(B^0)$: Motivation

spectator model:



- B^+ and B^0 lifetimes should be the same in naïve spectator model
- However there are differences at $O(1/m_b^3)$ level explained by Weak Annihilation (for B^0) and Pauli Interference (for B^+) diagrams (see *M.Beneke, G.Buchalla, C.Greub, A.Lenz and U.Nierste*, hep-ph/0202106)

$\tau(B^+)/\tau(B^0)$: Experiment VS. Theory

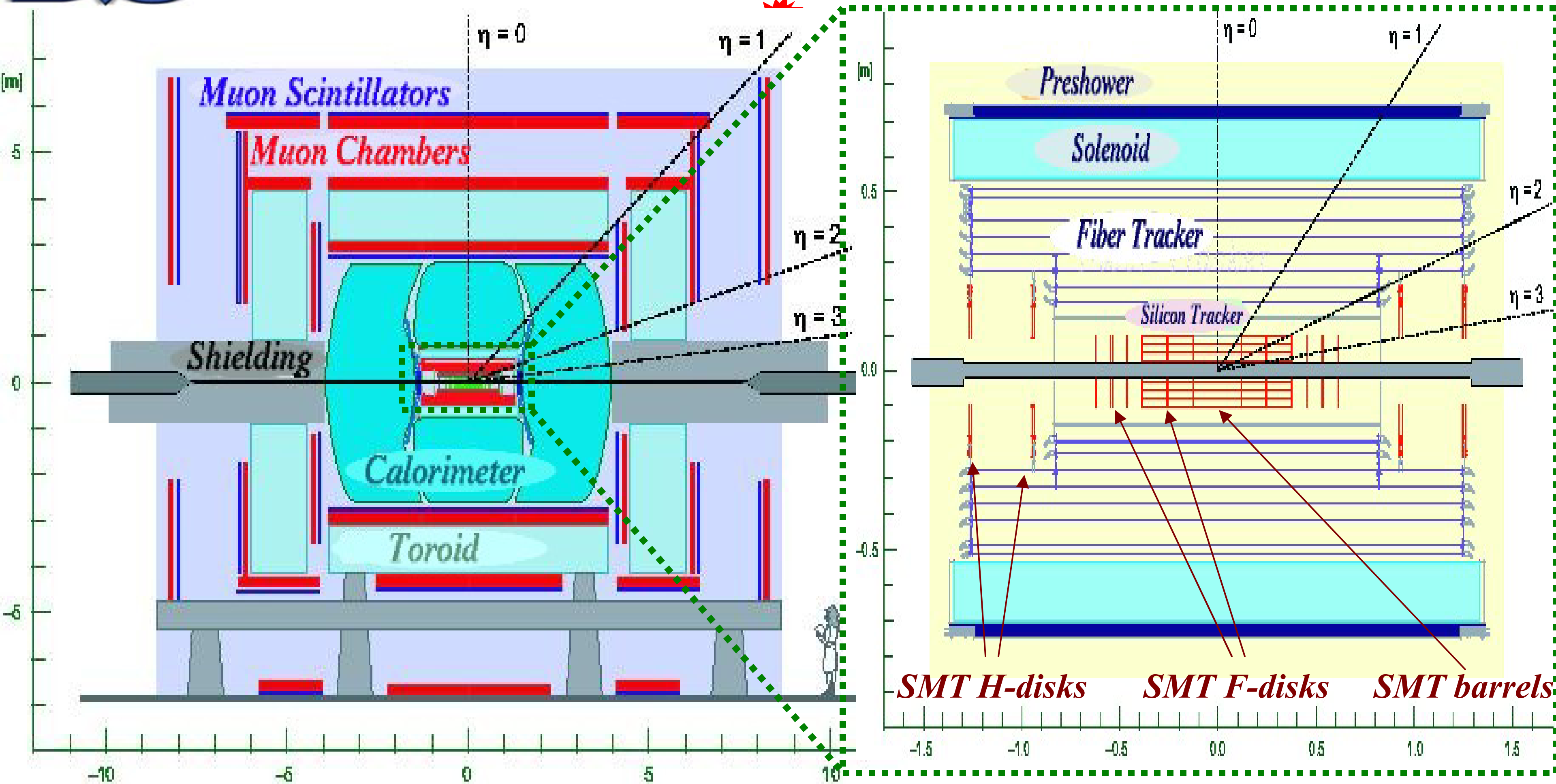


- In general theory prefers to deal with ratios
- Theoretical prediction (from hep-ph/0202106):

$$\tau(B^+)/\tau(B^0) = 1.053 \pm 0.016(\text{NLO+had}) \pm 0.017(m_B, V_{cb}, f_B)$$

- Further progress in theory is expected

DZero Detector



- Muon system with coverage |η|<2 and good shielding
- Trackers
  - Silicon Tracker: |η|<3
  - Fiber Tracker: |η|<2
- Magnetic field 2T

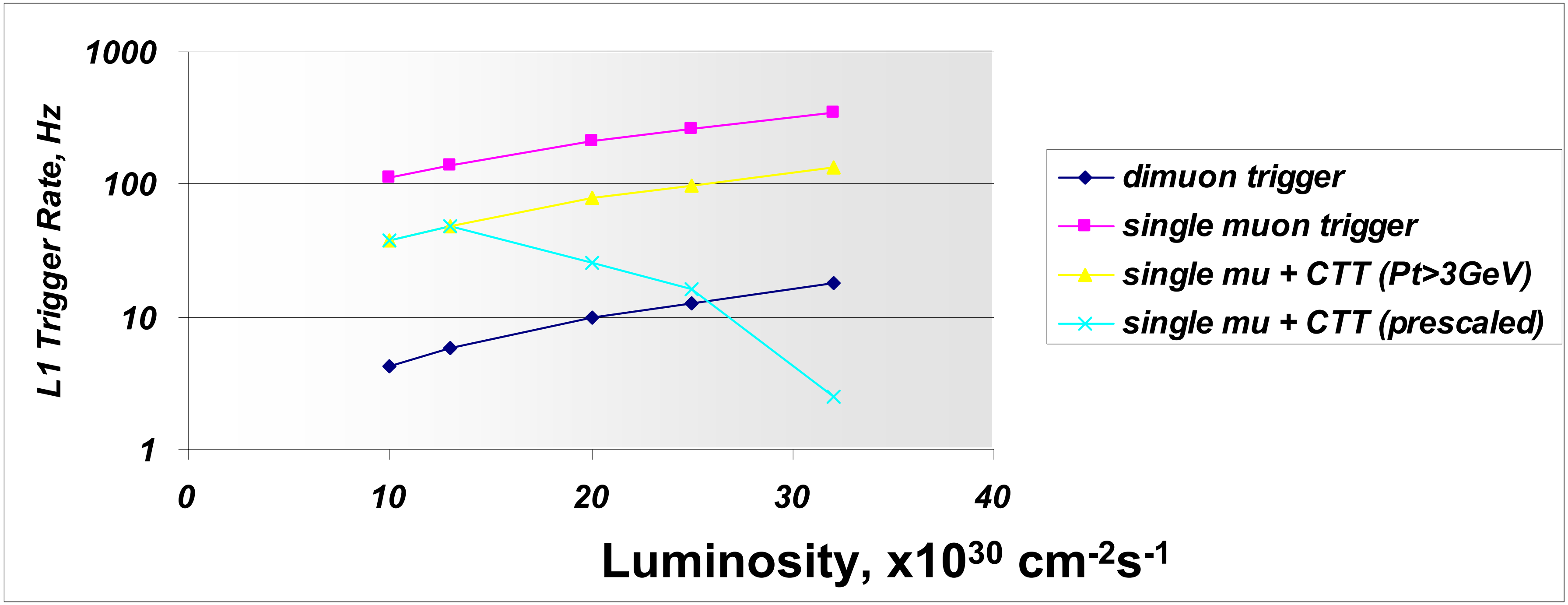
Triggers for B physics

- **Robust and quiet single- and di-muon triggers**
  - Large coverage $|\eta|<2$
  - Variety of triggers based on
    - L1 Muon & L1 CTT (Fiber Tracker)
    - L2 & L3 filters
- **Typical total rates at medium luminosity (40 10^{30} $s^{-1}cm^{-2}$)**
  - Di-muons : 50 Hz / 15 Hz / 4 Hz @ L1/L2/L3
  - Single muons : 120 Hz / 100 Hz / 50 Hz @ L1/L2/L3
    - Rates before prescaling: typically single muon triggers are prescaled or/and used with raised p_T threshold at L1
    - Muon purity @ L1: 90% - all physics!
  - Current total trigger bandwidth

    1600 Hz / 800 Hz / 60 Hz @ L1/L2/L3
- **B-physics semi-muonic yields are limited by L3 filters and L3 bandwidth**

Muon Trigger Rates

❑ L1 Single and Di-Muon Trigger rates VS. luminosity



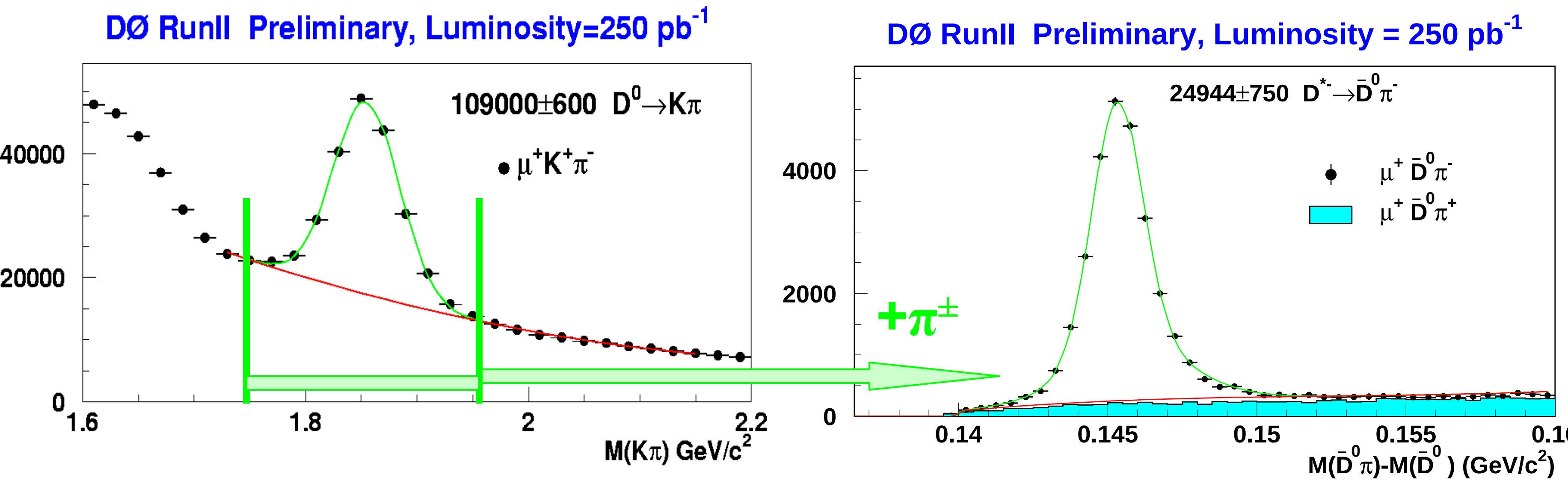
- ❑ CTT helps to reduce the single muon trigger rate by ~3 for Pt>3 GeV
- ❑ Single muon trigger is prescaled at high luminosities

Semileptonic Data Samples

- Looking for $B \rightarrow \mu^- \nu D^0 X$, $D^0 \rightarrow K^- \pi^+$
  - Charge conjugate always implied
- Select D^0 candidates
- Search for a pion track which gives D^* invariant mass in combination with D^0: $D^{*+} \rightarrow D^0 \pi^+$
- Divide the $\mu D^0 X$ candidates into 2 subsamples:
  - D^* was found: D^* sample
  - No D^*'s were found: D^0 sample

Semileptonic B_d sample

- 109k inclusive $B \to \mu\nu D^0$ candidates
  - 25k $B \to \mu\nu D^*$ candidates
    - ✓ D^* yield 50% higher for looser D^0 selections (not used for these analyses)



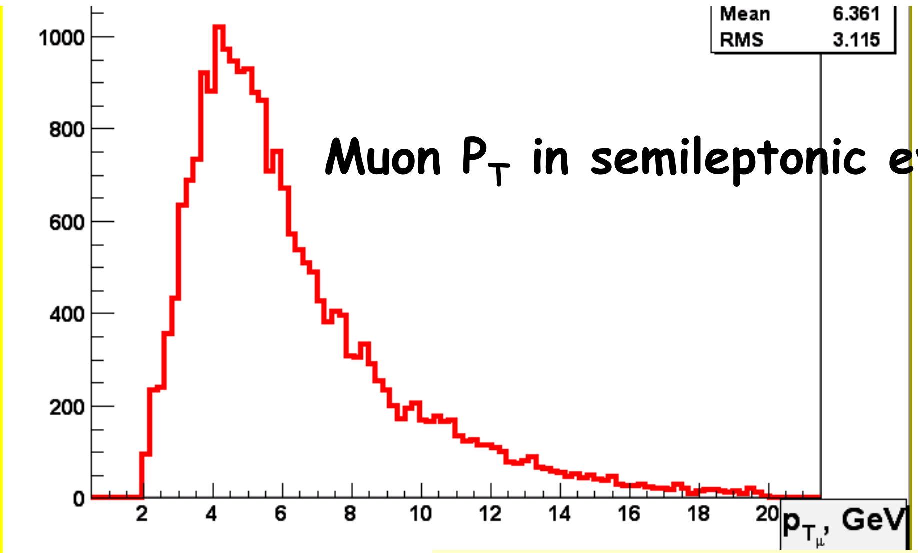
Dominated by B^+ decays

Dominated by B^0 decays

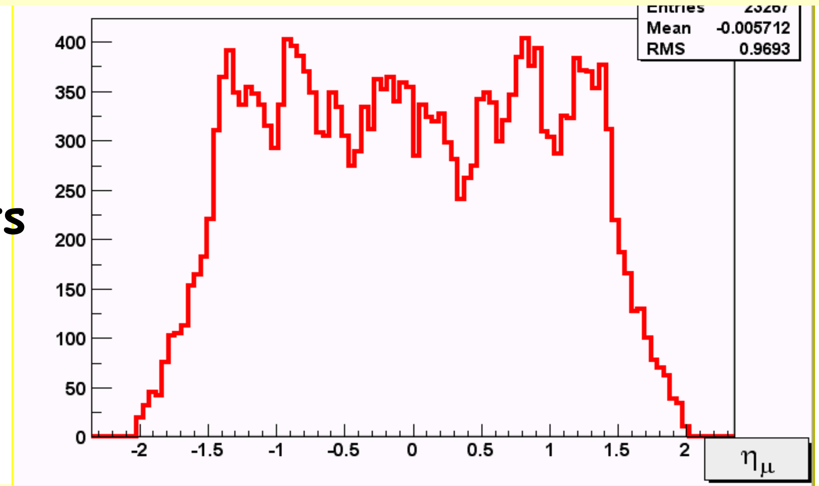
Muon Selections

- Tight muons with $|\eta|<2$ and $P_t > 2$ GeV

Muon P_T in semileptonic events



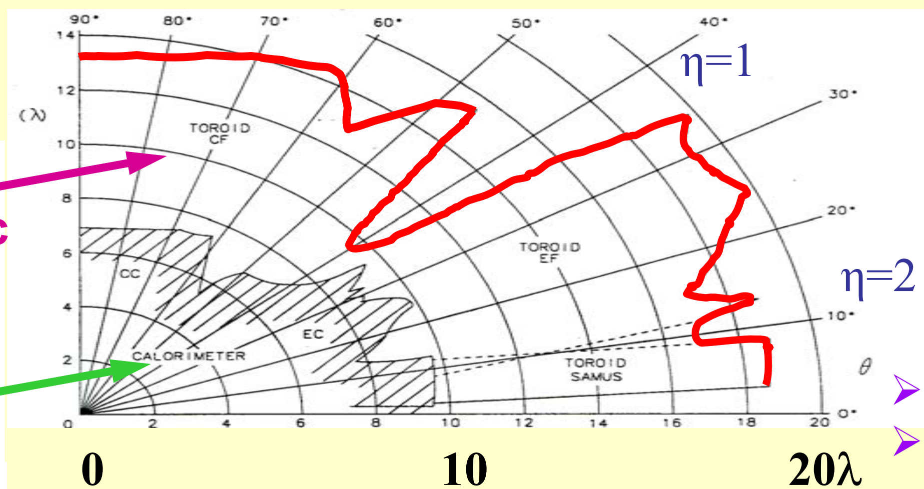
Muon η in semileptonic events



Coverage of Muon system is matched by L3/offline tracking

Turn-on shape determined by muon triggers

Interaction lengths VS. θ



Toroid = magnetic iron

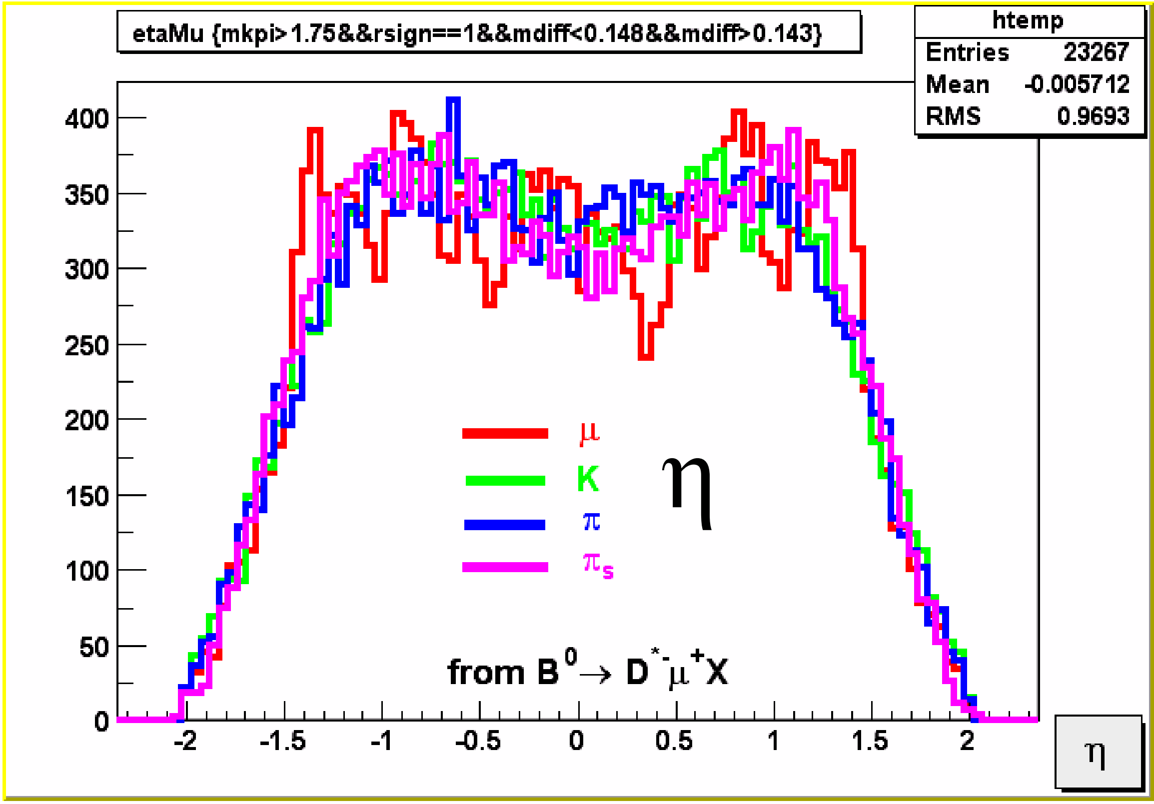
Calorimeter

Corresponds to muon P threshold:

- ~4.5GeV in central region
- ~5GeV in forward region

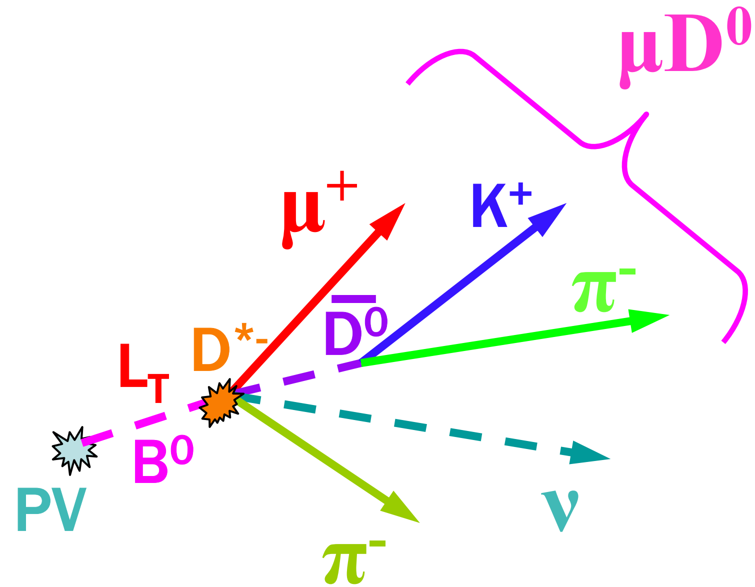
$D^0 \rightarrow K^-\pi^+$ Selections

- 2 tracks of opposite charge with P_T>0.7GeV, $|\eta|$<2 and in the same jet as the above muon
- Lifetime and topological selections
- η acceptance determined by Fiber Tracker
- Statistics is decreased by 2.3 if cut $|\eta|$<1 applied to all particles



Visible Proper Decay Length

- Determine distance between μD^0 vertex and primary vertex in transverse plane: L_T
- Determine transverse momentum of μD^0 system: $P_T(\mu D^0)$
- Calculate Visible Proper Decay Length:
  - $VPDL = L_T/P_T(\mu D^0) \cdot M_B$



1. B-meson produced at primary vertex
2. After passing L_T in transverse plane it decays to $D^{*-/0}\mu X$
   - D^{*-} decays immediately to $D^0\pi$
3. D^0 decays to $K\pi$ after passing some distance

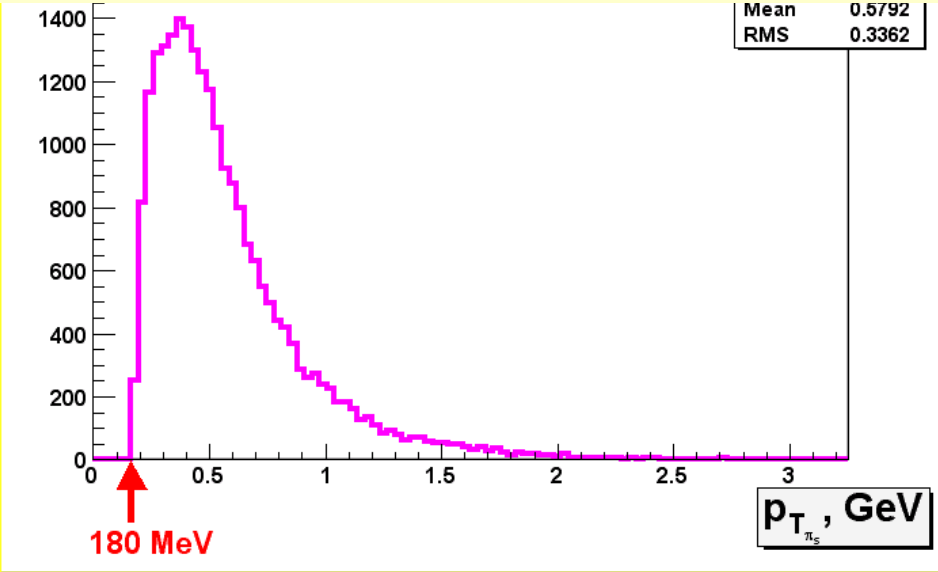
Novel Analysis Technique

- Measure directly ratio of lifetimes instead of measuring absolute lifetimes
  - Group events into 8 bins of Visible Proper Decay Length (VPDL)
  - Measure $r = N(\mu D^*)/N(\mu D^0)$ in each bin
    - ✓ In both cases fit D^0 signal in mass spectrum to extract $N(\mu D)$
      - ✓ no need to know VPDL distribution for background
  - Many systematics will cancel if relative reconstruction efficiencies of D^* wrt D^0 is the same in all VPDL bins (i.e. slow pion reconstruction efficiency)

D* Selections

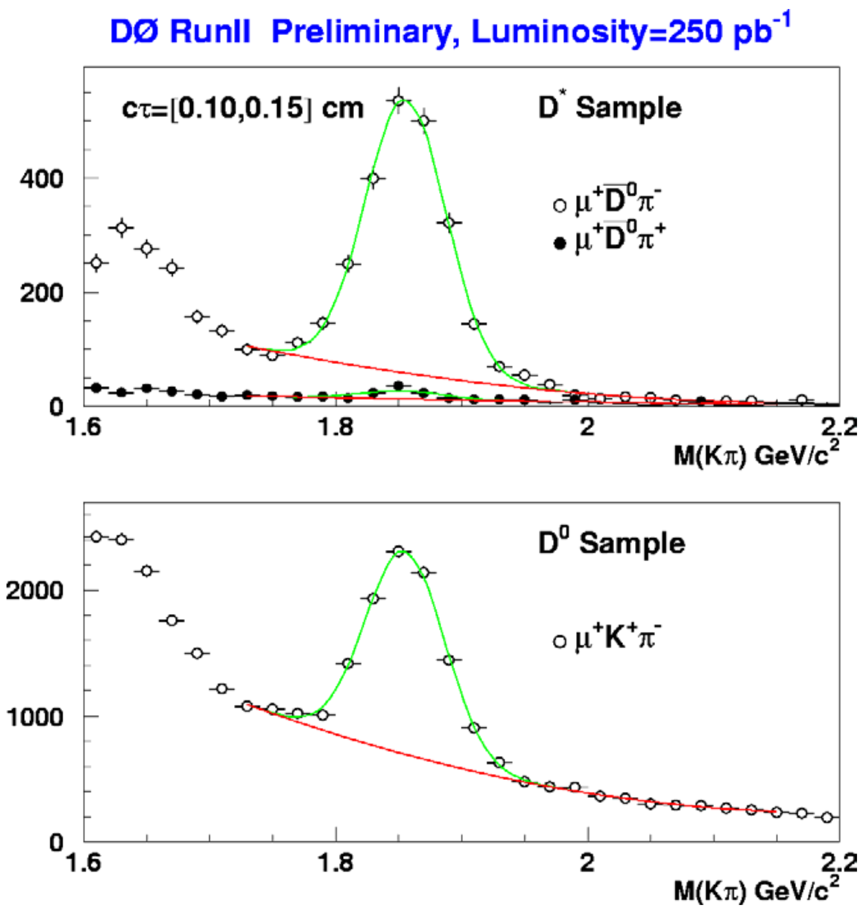
- Reconstruct slow pion from D* without biasing lifetime
  - ✓ Only requirement on slow pion is to give correct m(D*)-m(D^0) value
  - ✓ If slow pion is not reconstructed then the event goes to D^0 sample
    - Taken into account in the sample composition
  - ✓ Slow pion is
    - NOT used for calculation of VPDL
    - NOT used in B-vertex
    - NOT used in K-factors

p_T spectrum of soft pion candidate in $D^* \to D^0\pi$



Ratio of D^0 and D^* events

one example : VPDL bin [0.10 - 0.15 cm]



Fit function :

Gaussian + 2nd order polynomial

- In each VPDL bin

$$r_i = \frac{N_i(\mu^+ D^{*-})}{N_i(\mu^+ \bar{D}^0)} = \frac{N_i^{*R} - C \cdot N_i^{*W}}{N_i^0 + (1+C) \cdot N_i^{*W}}$$

- Fit D^0 mass peak in both cases in exactly same way
  - Decreases fit systematics
- Number of D^* events is corrected to account for combinatorial bkg
  - Estimated from wrong sign D^* combinations
  - Small correction because D^* S/B is good
- Number of D^0 events is corrected to account for genuine D^0's lost due to D^* window cut
  - Small correction as well

Fitting Procedure

$k \equiv \tau^+/\tau^0 - 1$ is determined from $\chi^2(N,k)$ minimisation:

measured

expected

$$\chi^2(N,k) = \sum_i \frac{(r_i - N \cdot r_i^e(k))^2}{\sigma^2(r_i)}$$

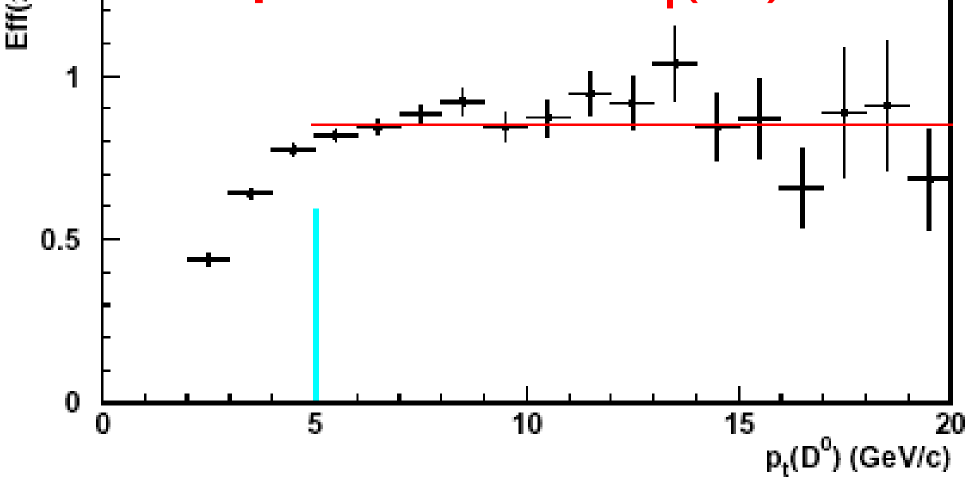
- Norm N and k are free parameters in minimisation;
- $\tau^+ = 1.674 \pm 0.018$ ps is taken from PDG;
- $\tau^0 = \tau^+/(1+k)$;
- Br_j are taken from PDG;
- $D_j(K)$, $Res_j(x)$ are taken from simulation;
- $Eff_{D^0}(x)$ is taken from simulation;
- $Eff_{D^*}(x) = C \cdot Eff_{D^0}(x)$ - verified in simulation;

Expected Ratio r^e_i

- **To calculate expected ratio in each VPDL bin**
  - **Sort decay channels between D^0 and D^* samples**
  - **For given decay channel determine the probability for B to have certain Visible Proper Decay Length according to**
    - ✓ Lifetime
    - ✓ K-factor which takes into account not reconstructed particles
    - ✓ Resolution
    - ✓ Efficiency
  - **Make a sum for each sample according to the branching rates**
  - **Integrate over the VPDL bin to get the number of events**
  - **Take the ratio**

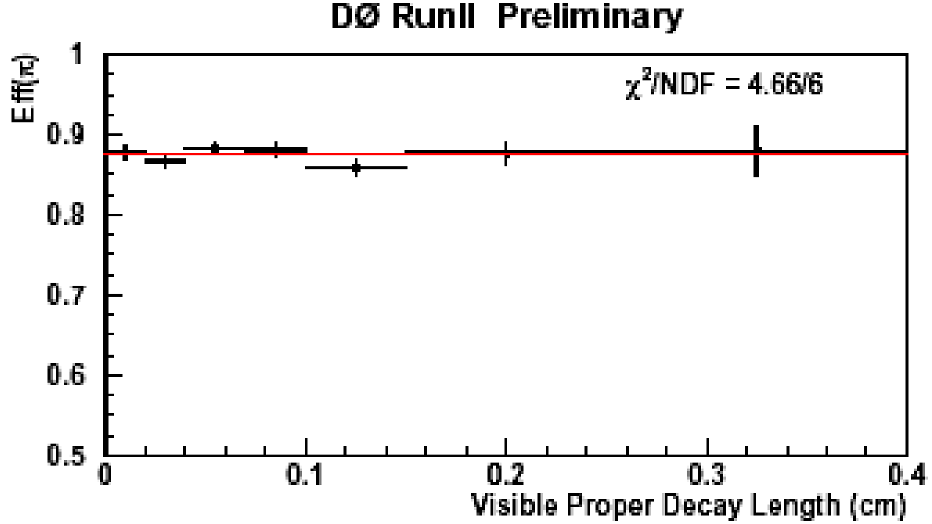
$\tau(B^+)/\tau(B^0)$: Efficiency for slow pion

Dependence on $P_T(D^0)$



- There is dependence of slow pion reconstruction efficiency from $P_T(D^0)$
- For $P_T(D^0)$>5GeV this dependence is small

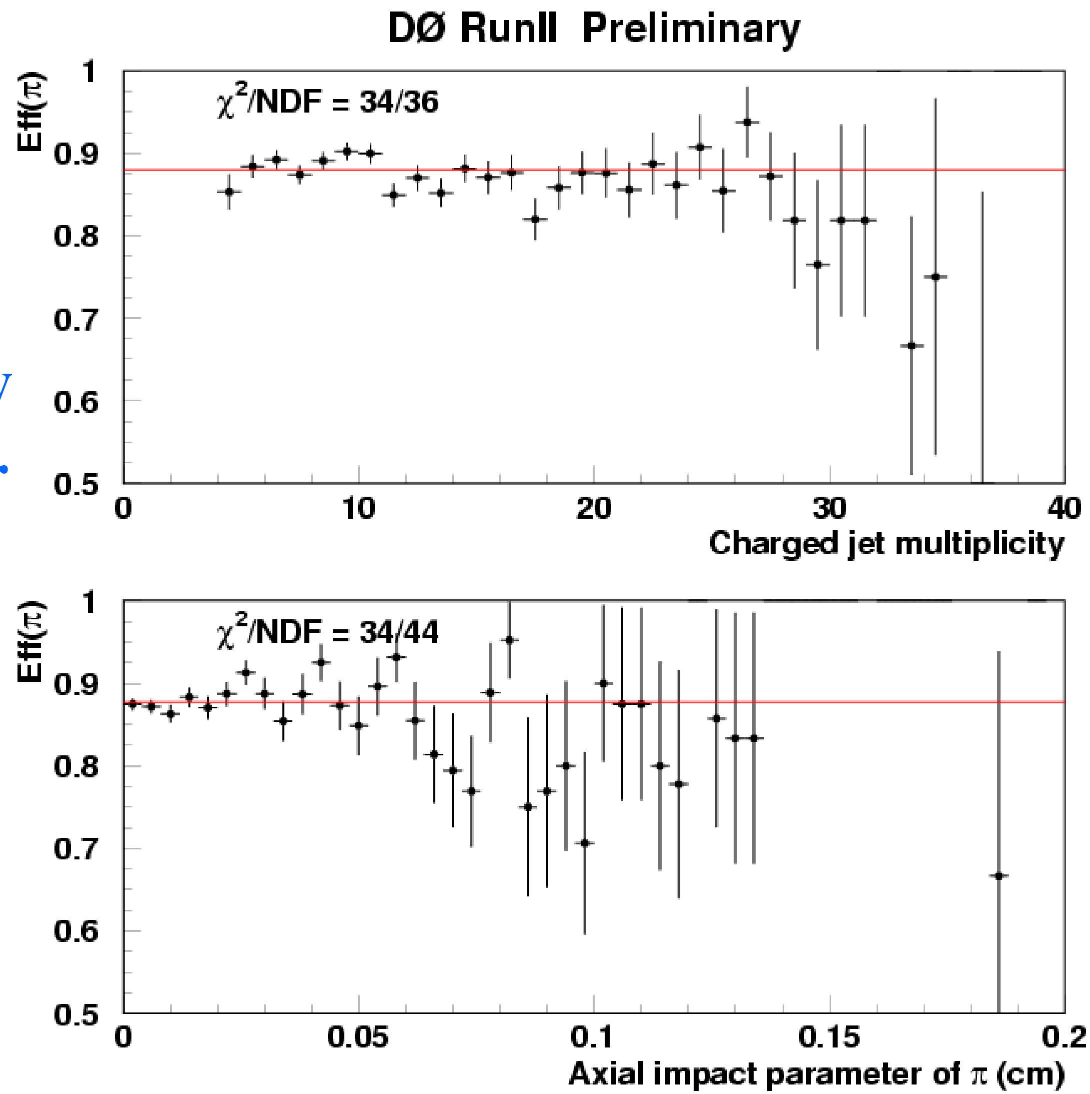
Dependence on VPDL



- After cut $P_T(D^0)$>5GeV the slow pion reconstruction efficiency is flat over all VPDL region under study
- So far gives the main contribution to systematic error
- Additional crosschecks in data in progress

$\tau(B^+)/\tau(B^0)$: Checks for slow pion efficiency

- **Do not see dependence in MC on**
  - Charged jet multiplicity
  - Axial impact parameter



Semileptonic Sample Composition

For D^* sample:

- $B^0 \to D^{*-}\mu\nu$;
- $B^0 \to D^{**}\mu\nu \to D^{*-}\mu\nu X$;
- $B^+ \to D^{**}\mu\nu \to D^{*-}\mu\nu X$;
- $B_s^0 \to D_s^{**}\mu\nu \to D^{*-}\mu\nu X$;

For D^0 sample:

- $B^+ \to D^0\mu\nu$;
- $B^+ \to D^{*0}\mu\nu$;
- $B^+ \to D^{**}\mu\nu \to D^0\mu\nu X$;
- $B^+ \to D^{**}\mu\nu \to D^{*0}\mu\nu X$;
- $B^0 \to D^{**}\mu\nu \to D^0\mu\nu X$;
- $B^0 \to D^{**}\mu\nu \to D^{*0}\mu\nu X$;
- $B_s^0 \to D_s^{**}\mu\nu \to D^0\mu\nu X$, $B_s^0 \to D_s^{**}\mu\nu \to D^{*0}\mu\nu X$;

Branching rates from PDG values for inclusive and exclusive measurements:

$$Br(B^+ \to \mu^+ \nu \overline{D}^0) = 2.15 \pm 0.22\%$$

$$Br(B^0 \to \mu^+ \nu D^-) = 2.14 \pm 0.20\%$$

$$Br(B^+ \to \mu^+ \nu \overline{D}^{*0}) = 6.5 \pm 0.5\%$$

$$Br(B^0 \to \mu^+ \nu D^{*-}) = 5.53 \pm 0.23\%$$

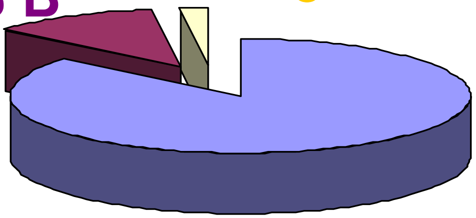
$$Br(B^+ \to \mu^+ \nu \overline{D}^{**0}) = 2.67 \pm 0.37\%$$

$$Br(B^+ \to \mu^+ \nu \overline{D}^{**0} \to l^+ \nu D^{*-} X) = 1.07 \pm 0.25\%$$

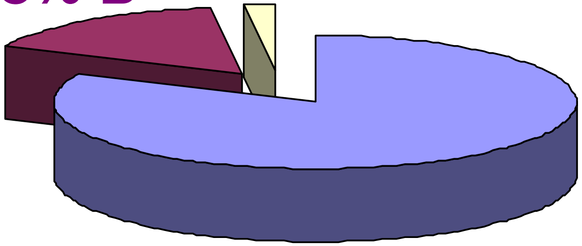
Important : D* decays dominate both D⁰ and D* samples

Sample Composition

- Based on above and after corrections for reconstruction efficiency
- D* sample composed of

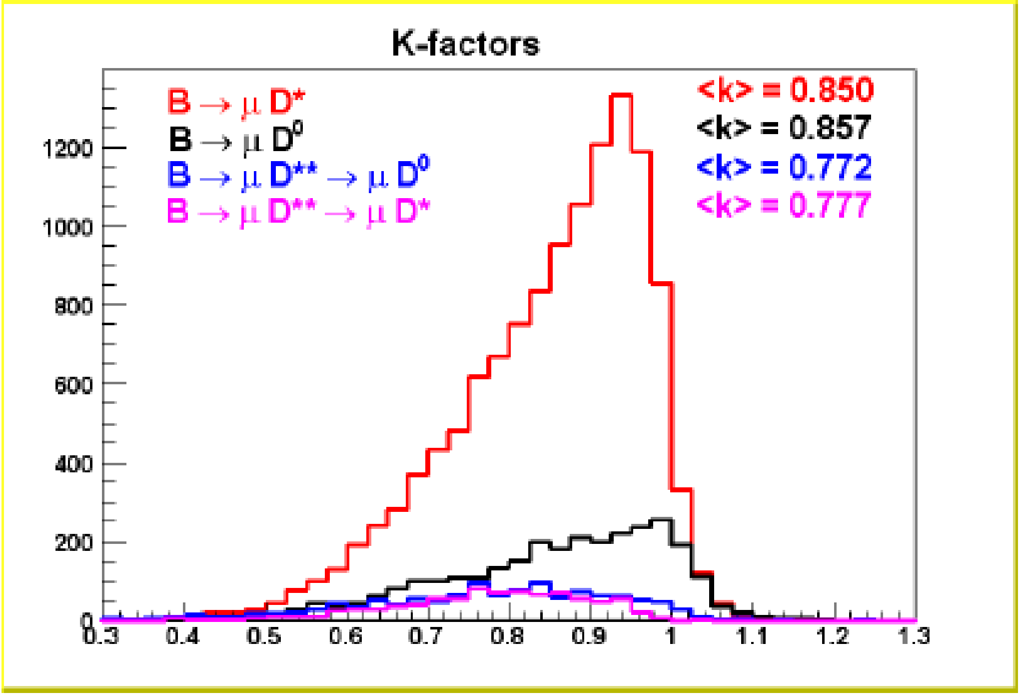


- D^0 sample composed of



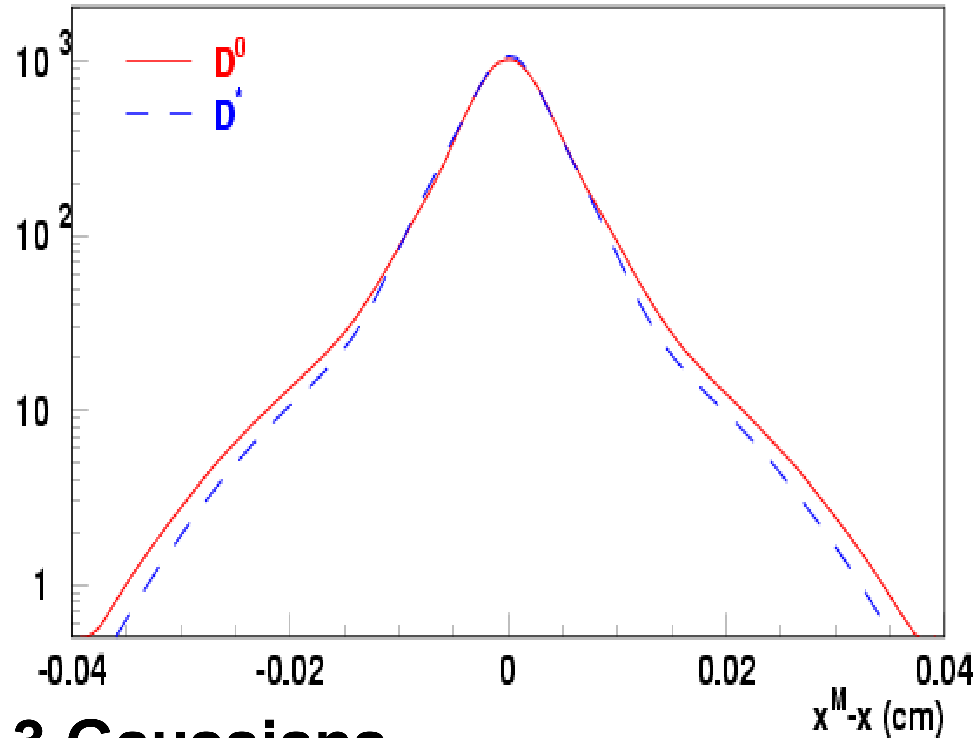
K-factors

- K-factors take into account not reconstructed particles
- Production $B \to D^* \mu \nu X$ dominates both for D^* and D^0 samples
- K-factors are computed as: $K = P_T(\mu D^0) / P_T(B)$, even for D^{*-} sample
  - K-factors are the same for $B^0 \to D^{*-} \mu \nu X$ and $B^+ \to D^{*0} \mu \nu X$ decays
    - ✓ Reduced systematics
- 4 groups of K-factors
  - $B \to D^* \mu$
    - ✓ $B^0 \to D^{*-} \mu \nu$
    - ✓ $B^+ \to D^{*0} \mu \nu$
  - $B \to D^0 \mu$
    - ✓ $B^+ \to D^0 \mu \nu$
  - $B \to D^{**} \mu \to D^0 \mu$
    - ✓ No D^{*-} reconstructed
  - $B \to D^{**} \mu \to D^{*-} \mu$



VPDL Resolution

- Determined from MC
  - Described by 3 Gaussians
- Ratio fitting procedure assumes resolution is the same for D^0 and D*
  - We do not use slow pion for B-vertex
- Resolution and tails of resolution were varied in wide range to study systematics due to resolution effects
- Not so important for B_d studies

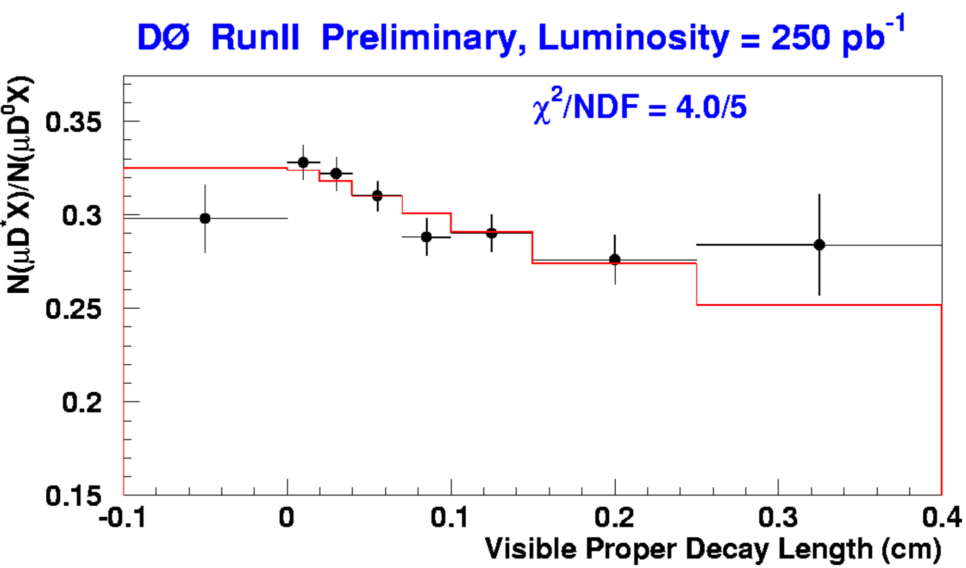


3 Gaussians

- σ_1= 22.2 μm – 28%
- σ_2= 47.3 μm – 57%
- σ_3= 131 μm – 15%

$\tau(B^+)/\tau(B^0)$: Result

Use binned χ^2 fit of event ratios to determine $\tau(B^+)/\tau(B^0)$



Main systematic errors:

Source	Δk
$Br(B^+ \to D^{*-}\pi^+\mu\nu X)$	0.0053
Resolution description	0.0042
Difference in resolution D^*,D^0	0.0041
$Eff(D^*)/Eff(D^0) \neq const$	0.0132
Efficiency of different B decays	0.0086
Energy scale of B-hadron	0.0072
Fitting of N^*, N^0	0.0060

Preliminary result:

$\tau(B^+)/\tau(B^0) = 1.093 \pm 0.021\ (stat) \pm 0.022\ (syst)$

$\tau(B^+)/\tau(B^0)$: Consistency Checks

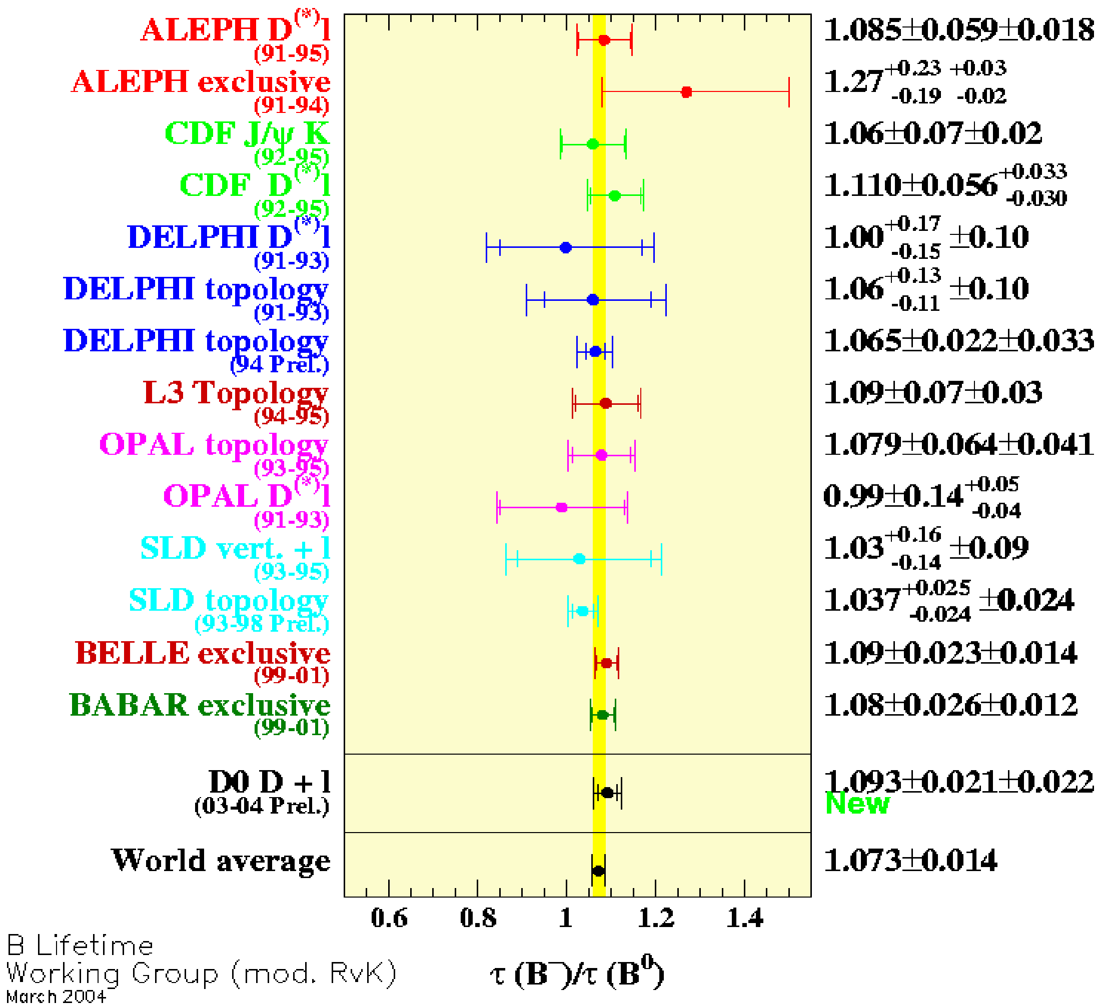
- Split data sample in two parts with respect to various parameters – all looks good

Consistency test	k
$\lvert Z_{PV}\rvert < 15cm$	0.099 ± 0.028
$\lvert Z_{PV}\rvert > 15cm$	0.091 ± 0.031
$\eta(muon) > 0$	0.107 ± 0.031
$\eta(muon) < 0$	0.079 ± 0.030
$p_T(\mathrm{D}^0) < 7.5$ GeV/c	0.105 ± 0.031
$p_T(\mathrm{D}^0) > 7.5$ GeV/c	0.083 ± 0.030
μ^+ only	0.088 ± 0.030
μ^- only	0.111 ± 0.031
$p_T(\mu) < 5.5$ GeV/c	0.104 ± 0.033
$p_T(\mu) > 5.5$ GeV/c	0.083 ± 0.028
Different intervals	0.086 ± 0.021
Without last VPDL interval	0.107 ± 0.024
Additional VPDL interval 0.4-0.8 cm	0.092 ± 0.021

- Invert magnetic field
  - ✓ Positive polarity:
    - ➢ *k=0.072±0.030*
  - ✓ Negative polarity:
    - ➢ *k=0.115±0.030*
  - ✓ Will be important cross-check for CP-measurements

- Measured ratio in MC = 0.073 ± 0.030 (input 0.070)

$\tau(B^+)/\tau(B^0)$: Comparison with other experiments

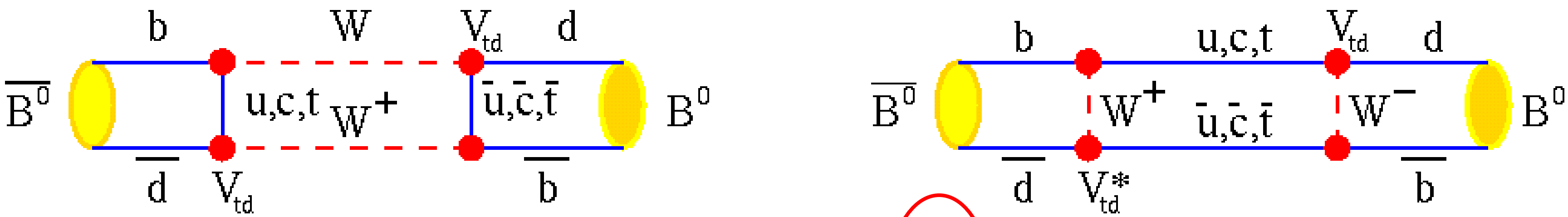


New DØ result

(average not updated, plot not official or approved by HFAG)

This is one of the most precise measurements to date

$B^0/\overline{B^0}$ mixing



B_d oscillation frequency:

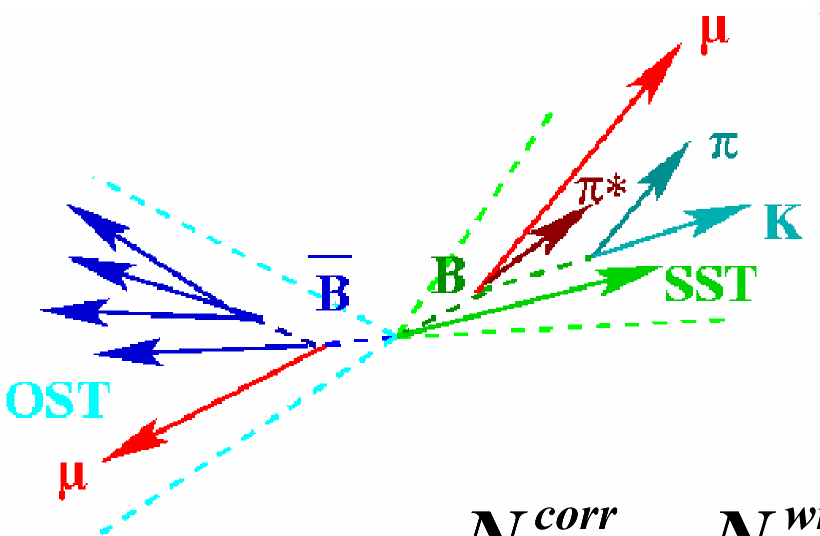
$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_B m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) \eta_{QCD} B_{B_d} f_{B_d}^2 \left| V_{tb}^* V_{td} \right|^2$$

If we measure Δm_s and Δm_d then:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s^0}}{m_{B_d^0}} \frac{B_{B_s^0} f_{B_s^0}^2}{B_{B_d^0} f_{B_d^0}^2} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

- We use our large sample of semileptonic B_d decays to measure Δm_d:
  - Use: 25k B→μ ν D* sample
  - Benchmark the initial state flavor tagging for later use in B_s and Δm_s measurements
  - Can also constrain more exotic models of b production at hadron colliders
    - ✓ light gluino & sbottom production (Berger *et al.*, Phys.Rev.Lett.86,4231(2001))

Initial State Tagging



Dilution= $\dfrac{N^{corr} - N^{wr}}{N^{corr} + N^{wr}}$

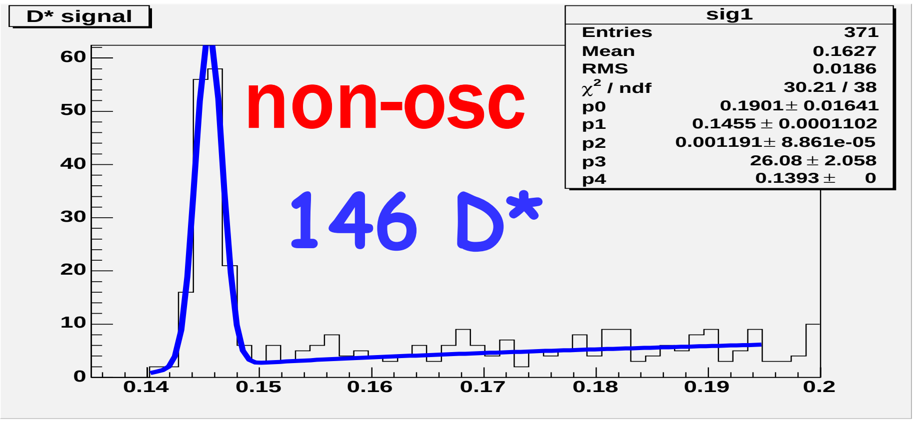
- B flavor tagging methods:
  - Opposite Side Lepton Tag
    - High Dilution: D=0.5
    - Low Efficiency: ε=0.05
  - Jet Charge Tag
    - Moderate Dilution: D=0.1-0.3
    - Moderate Efficiency: ε=0.5
  - Same Side Tag
    - Low Dilution: D=0.1-0.2
    - High Efficiency: ε=0.7-0.8
- Significance of mixing measurement: $S \propto \varepsilon D^2$
- The methods can be combined

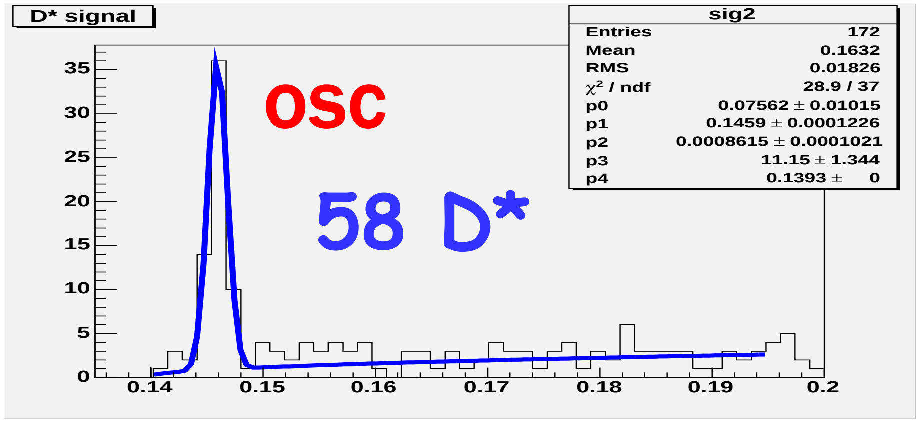
OS muon tagging

- ✓ For tag optimization used
  - Semileptonic B^+ sample
  - $B^+ \to J/psi\ K^+$ sample
- ✓ Adopted the following tagging procedure
  - Select certified muons
    - Track with # SMT hits > 1, # CFT hits > 1
    - Pt > 2.5 GeV
    - Nseg = 2 or 3 ← Good signal in muon system
    - Not from the same jet as B candidate
    - cos (ϕ angle between B and tag muon) < 0.5
    - Not from J/psi
  - If more than one candidate-choose muon with max Pt
  - Not oscillated: $Q_{\mu op} \cdot Q_{\mu} < 0$; oscillated: $Q_{\mu op} \cdot Q_{\mu} > 0$

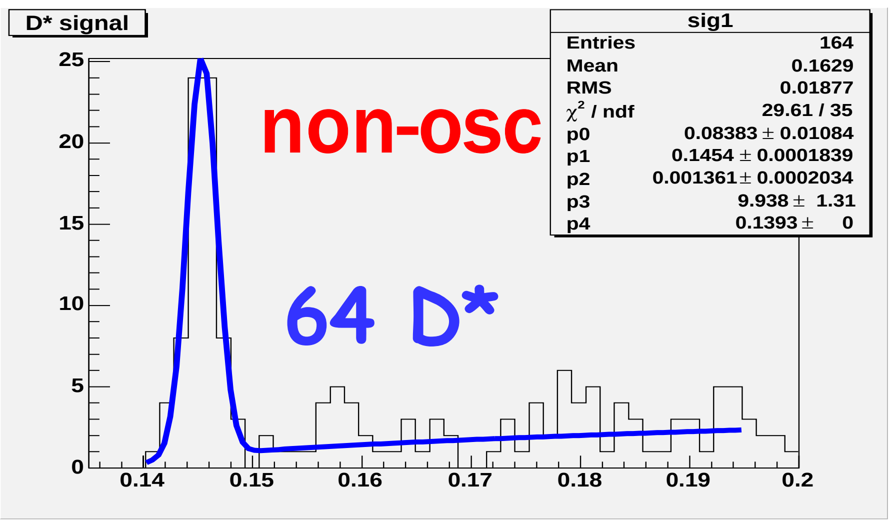
Number of events in different bins of Visible Proper Decay Length

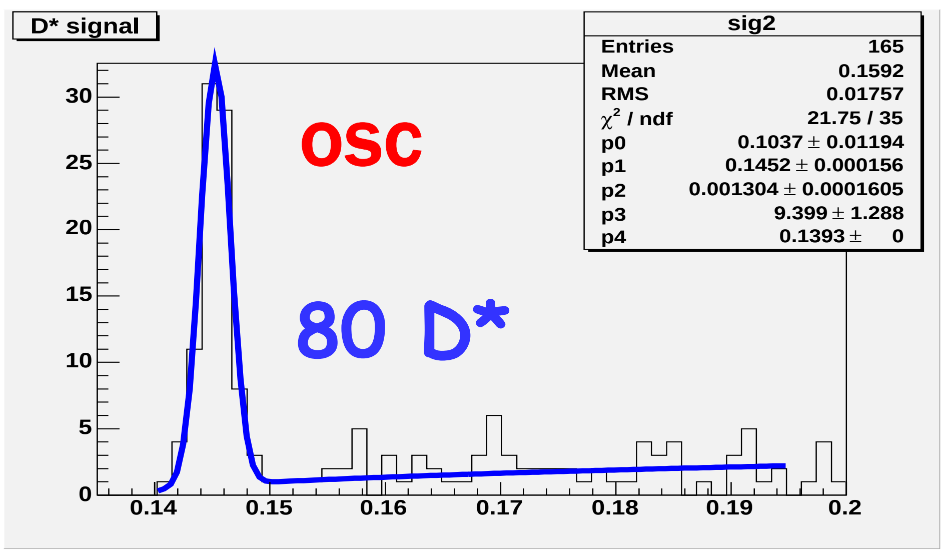
- First bin VPDL = [0.0 - 0.025 cm] or [0 – 0.83 ps]





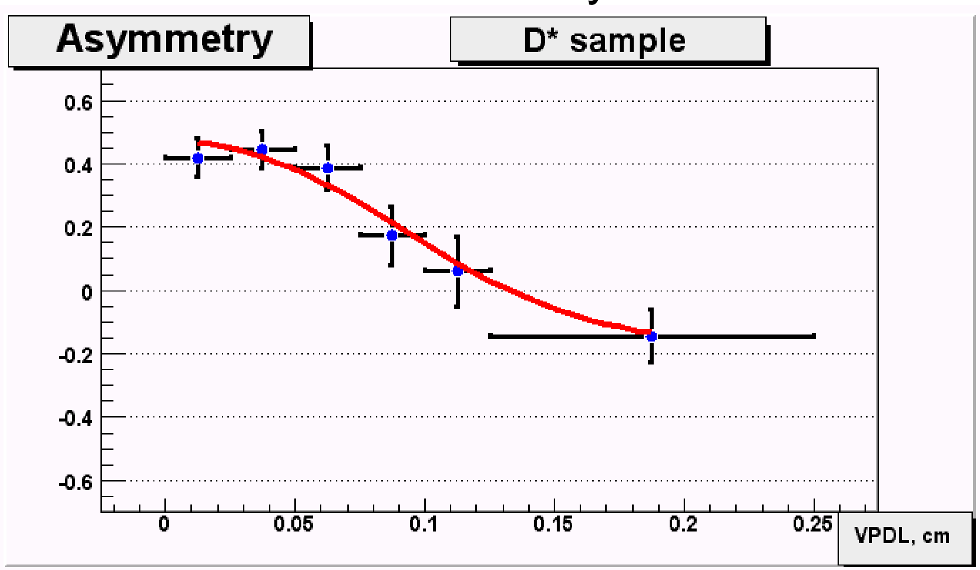
- Last bin VPDL = [0.125 - 0.250 cm] or [4.17 – 8.33 ps]

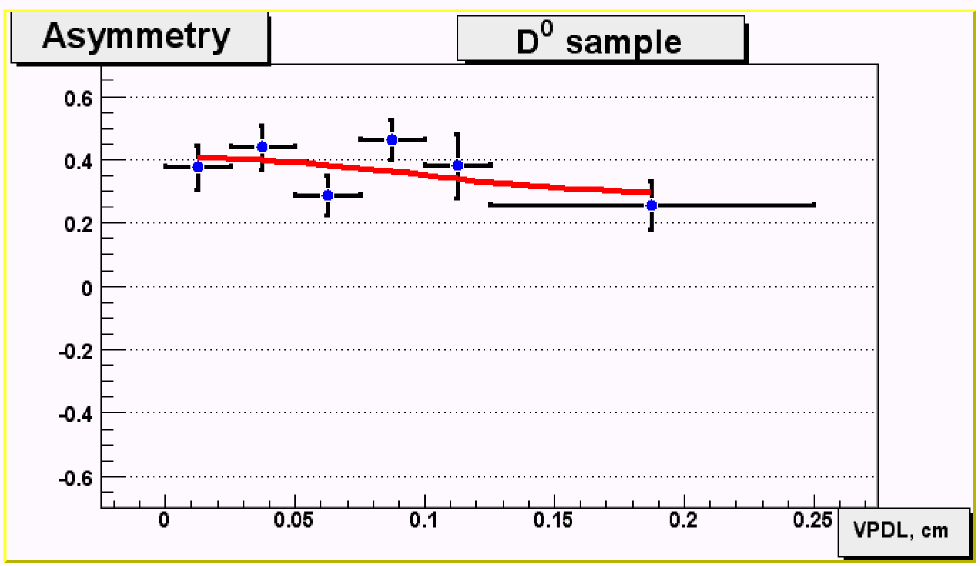




Oscillations in D^* and D^0 samples

DØ RunII Preliminary





- Expect to see oscillations
- Level is offset by B^+ contribution

- Expect to see no oscillations
- Some variation from oscillations due to B^0 contribution into sample composition

Fitting Procedure

- ✓ Need expression for expected asymmetry
  - Use exactly the same approach as in the lifetime ratio analysis
- ✓ First sort out how different B meson species behave wrt oscillation/tagging
  - ➢ Bd tagged as oscillated

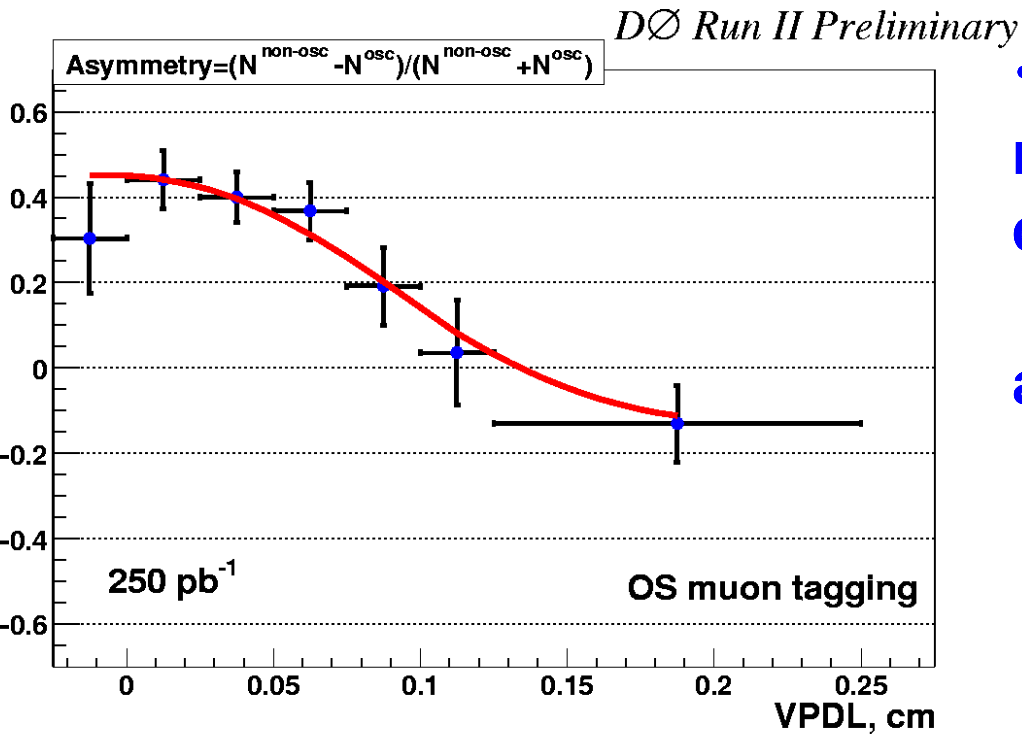
$$n_d^+ = \frac{K}{c\tau_{B_d}} \exp\left(-\frac{Kx}{c\tau_{B_d}}\right) \cdot 0.5 \cdot (1 + (2\eta - 1)\cos(\Delta m \cdot Kx / c))$$

  - ➢ Bd tagged as non-oscillated

$$n_d^- = \frac{K}{c\tau_{B_d}} \exp\left(-\frac{Kx}{c\tau_{B_d}}\right) \cdot 0.5 \cdot (1 - (2\eta - 1)\cos(\Delta m \cdot Kx / c))$$

  - Bd oscillates with frequency Δm
  - x is VPDL
  - η is tagging purity = fraction of correctly tagged events / total

$B^0/\bar{B}^0$ Mixing Results



- Already one of the best measurements at hadron collider
- Good prospects to improve accuracy
  - work in progress to decrease systematic uncertainty
  - use other tagging methods
    - oscillations observed with other tagging algorithms
  - add more D^0 decay channels

Preliminary results:

$$\Delta m_d = 0.506 \pm 0.055(\text{stat}) \pm 0.049(\text{syst})\ \text{ps}^{-1}$$

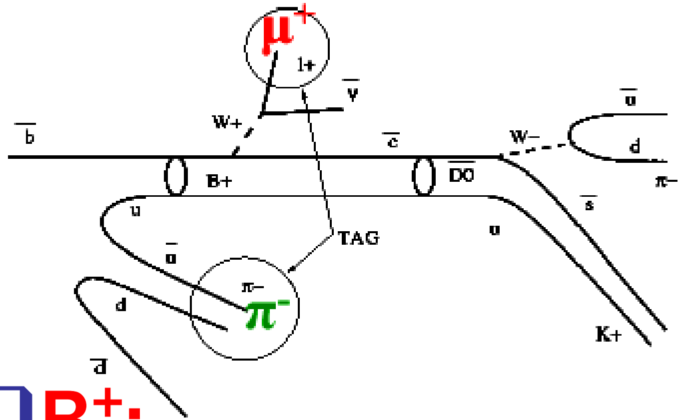
Tagging efficiency: 4.8 +/- 0.2 %

Tagging purity: 73.0 +/- 2.1 %

Systematics for the mixing

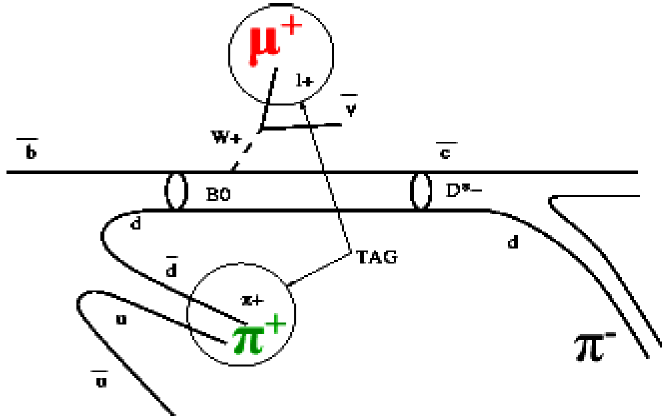
Source	$\sigma_{\Delta m}^{syst}$, ps^{-1}	σ_{η}^{syst}
$Br(B_d \to D^{*-}\mu^+\nu)$	0.003	0.0006
$Br(B \to D^*\pi\mu\nu X)$	0.009	0.0002
$Br(B_S \to D_S\mu^+\nu X)$	0.001	0.0040
B lifetime	0.004	0.0020
Resolution function	0.017	0.0040
Alignment	0.007	0.0040
K-factor	0.009	0.0004
Mass peak fitting procedure	0.041	0.0020
Total	0.049	0.0083

B_d mixing with Same Side Tagging



❑ B^+:

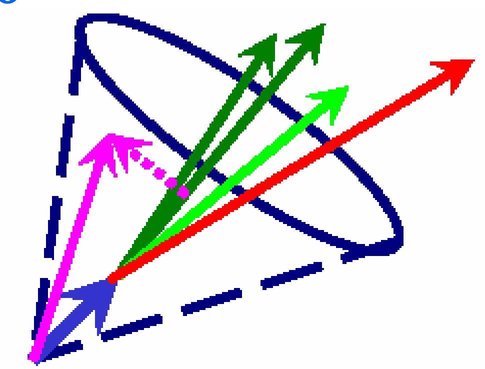
➢ Correct tag: Qt·Qμ<0



❑ B^0:

➢ Correct tag: Qt·Qμ>0

Tagging track:

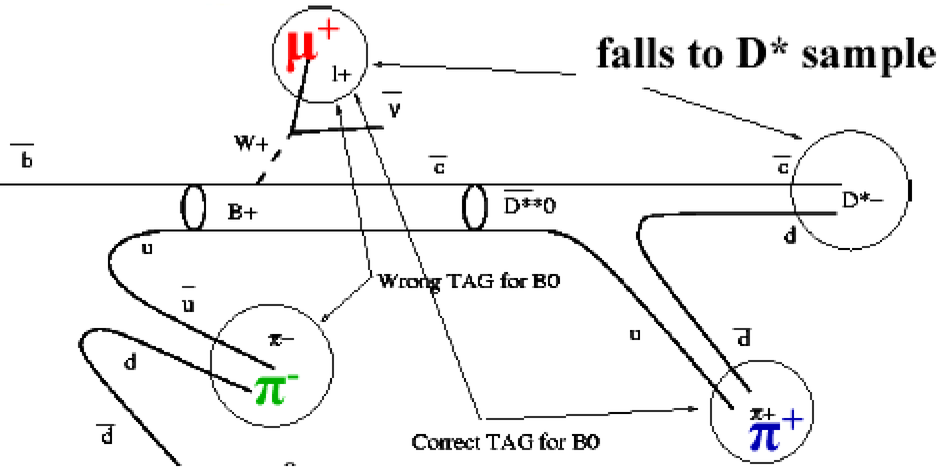


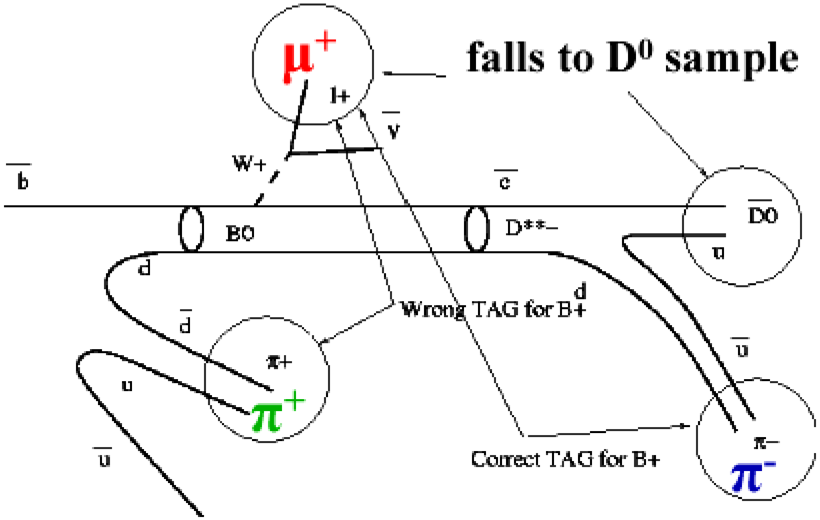
Lowest Pt_{rel} track wrt B-meson in $\Delta R<0.7$ cone around B

✓Used by CDF in Run I

✓Other algorithms are being considered also

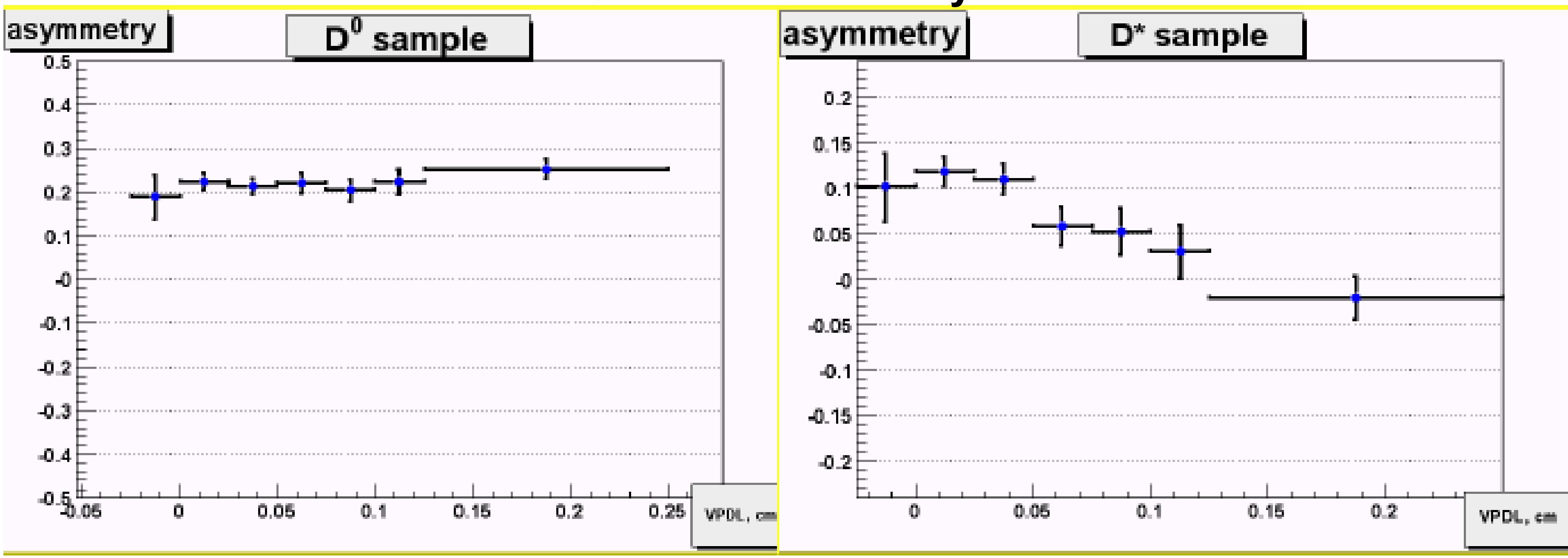
D^{**} contribution





- **Difficulties arise due to D^{**} contribution**
  - Charged pion from D^{**} can be taken as a tag
- **Evaluated from D^{**} topological analysis**
  - Use impact parameter of pion from $D^{**} \rightarrow D^{*}\pi$

DØ RunII Preliminary

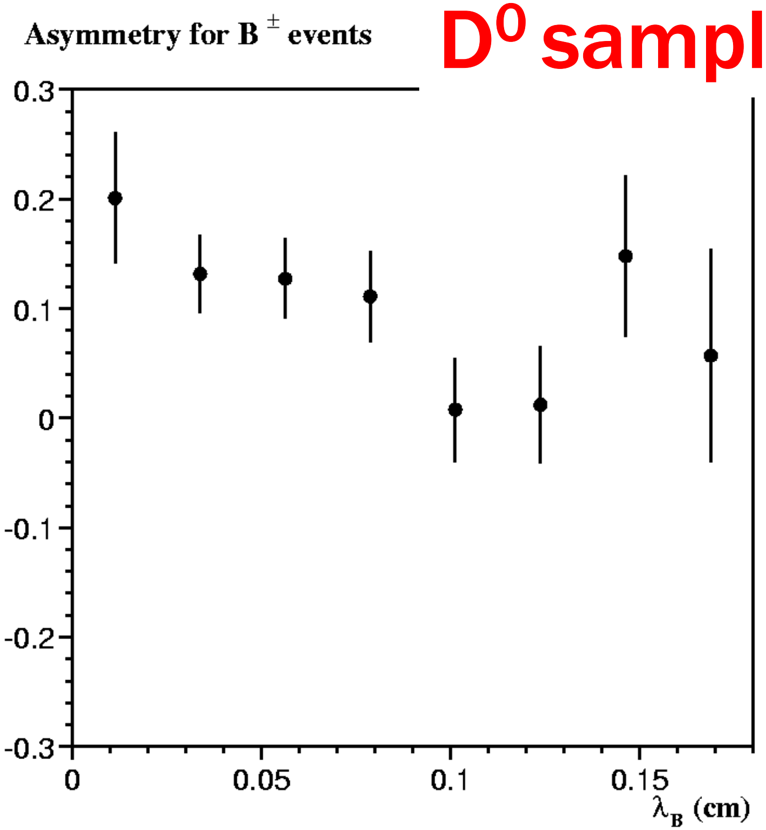


- ✓ No oscillations in the D^0 sample
- ✓ There are oscillations in the D* sample

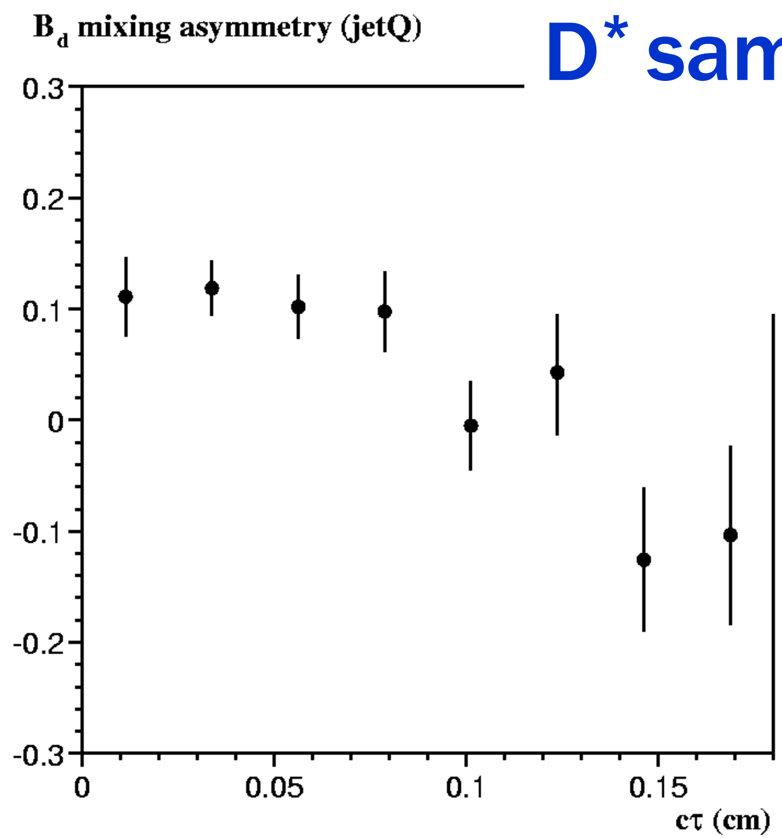
- ❑ Work in progress to measure Δm

Oscillations with Jet Charge Tagging

DØ RunII Preliminary



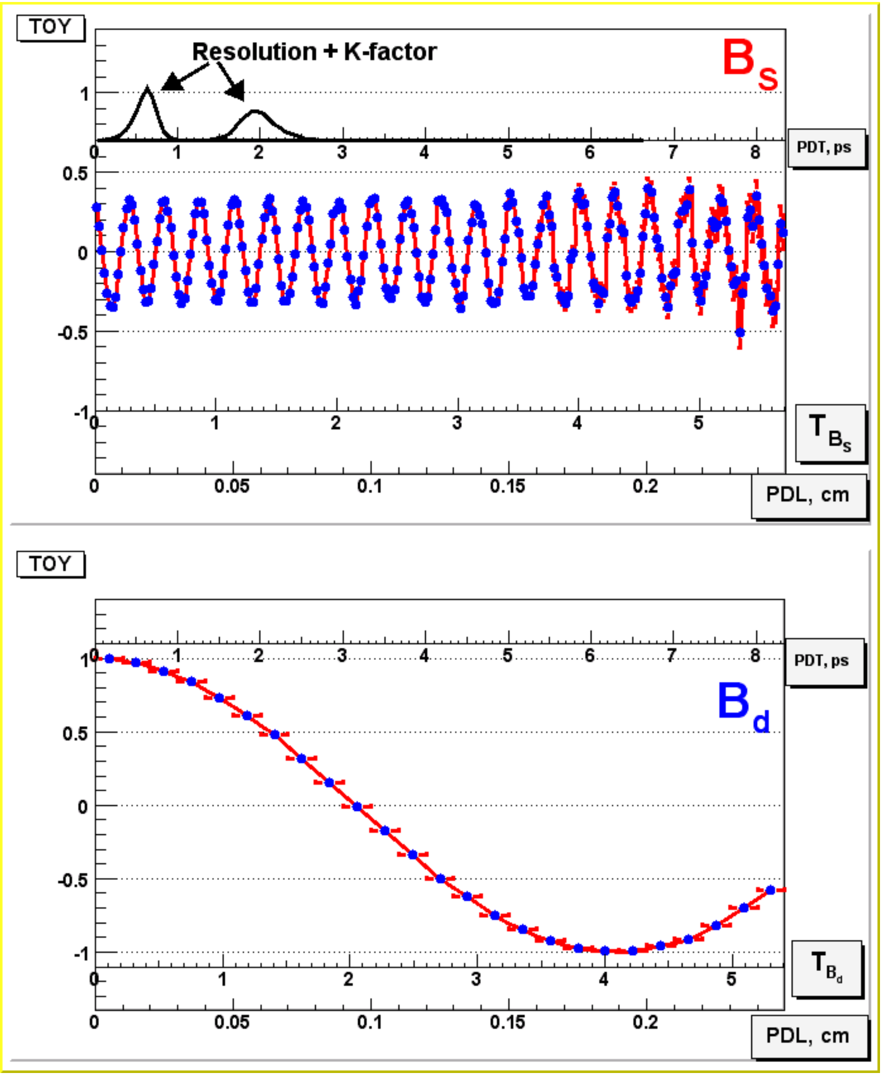
D^0 sample



D^* sample

- See oscillations

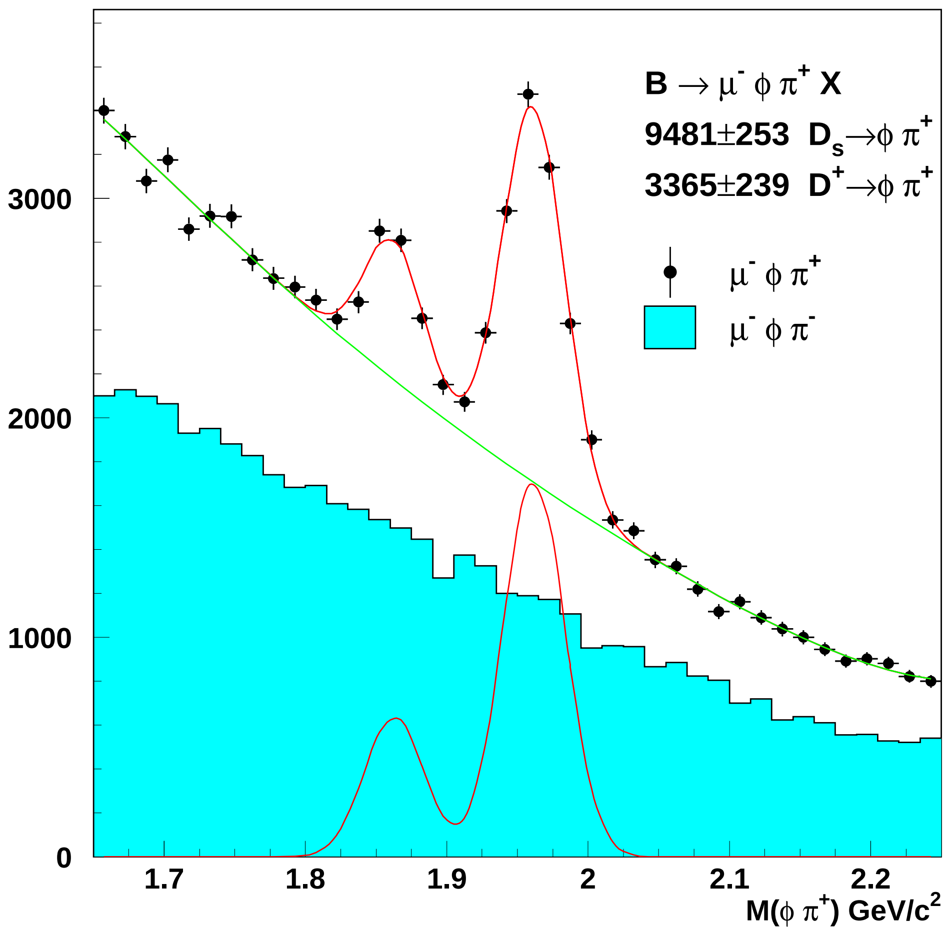
B_s mixing



- B_s oscillation frequency is more than 30 times higher than B_d's one
- Ability to measure the Δm_s deteriorates due to detector resolution and smearing of proper time because of neutrino
  - Try to find ways to improve resolution and evaluate K-factor on event by event basis
- No smearing due to neutrino in hadronic channels

Semileptonic B_s sample

DØ RunII Preliminary, Luminosity = 250 pb^{-1}



$B_s \rightarrow \mu\, \nu\, D_s$

$\rightarrow \phi\, \pi$

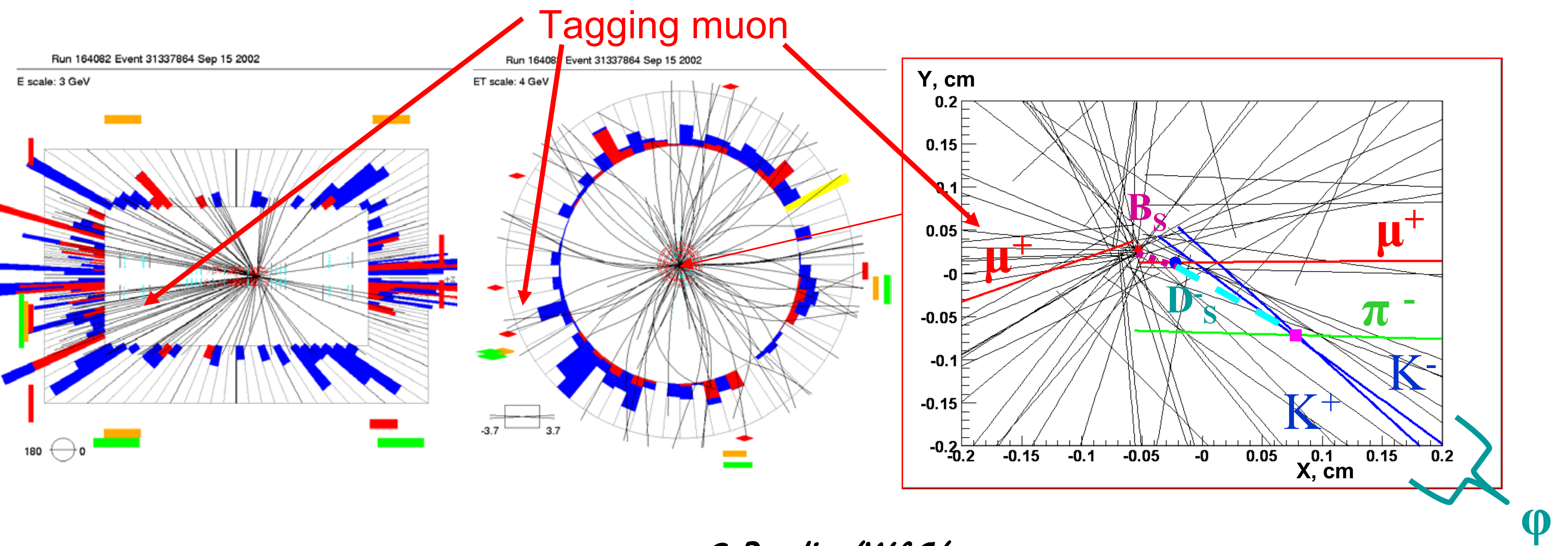
$\rightarrow K^+K^-$

- Excellent yield : **9500 candidates in 250 pb^{-1}**
- $\phi\pi$ invariant mass plot: some lifetime cuts applied

Work in progress to measure
- B_s/B_d lifetime ratio
- first results on B_s mixing
  - need to fully understand time resolution

Oscillated B_s candidate in Run 164082 Event 31337864

- **OS muon tagging was used for semileptonic B_s sample**
- **An example of tagged B_s candidate is shown**
  - **Two same sign muons are detected**
    - ✓ **Tagging muon has η=1.4**
    - ✓ **See advantage of muon system with large coverage**
  - **M_{KK}=1.019 GeV, $M_{KK\pi}$=1.94 GeV**
  - **$P_T(\mu_{Bs})$=3.4 GeV; $P_T(\mu_{tag})$=3.5 GeV**



Conclusions

- The semileptonic B-sample was used for
  - Precise measurement of B^+/B^0 lifetime ratio
    - ✓ $\tau(B^+)/\tau(B^0) = 1.093 \pm 0.021$ (stat) ± 0.022 (syst)
    - ✓ The result is competitive with B-factories
  - Measurement of B_d mixing parameter
    - ✓ $\Delta m_d = 0.506 \pm 0.055$(stat)$\pm 0.049$(syst) ps-1
    - ✓ Have potential for the best single measurement at hadron colliders
- The semileptonic B_S-sample will be used for B_S lifetime and oscillations measurements
- Plan to increase the L3 bandwidth to 100 Hz or higher to write more B mesons to tape

B Physics Program at DØ

- Unique opportunity to do B physics during the current run
- Complementary to program at B-factories (KEK, SLAC)

- B_S mixing, $\Delta\Gamma_S/\Gamma_S$
- Rare decays: $B_S \to \mu^+\mu^-$ Large tanβ SUSY models enhance rate

- Beauty Baryons, Λ_b lifetime, Ξ_b …
  - $\tau(\Lambda_b)/\tau(B_d^0)$ expt: 0.80±0.06 (SL modes), theory ~ 0.95

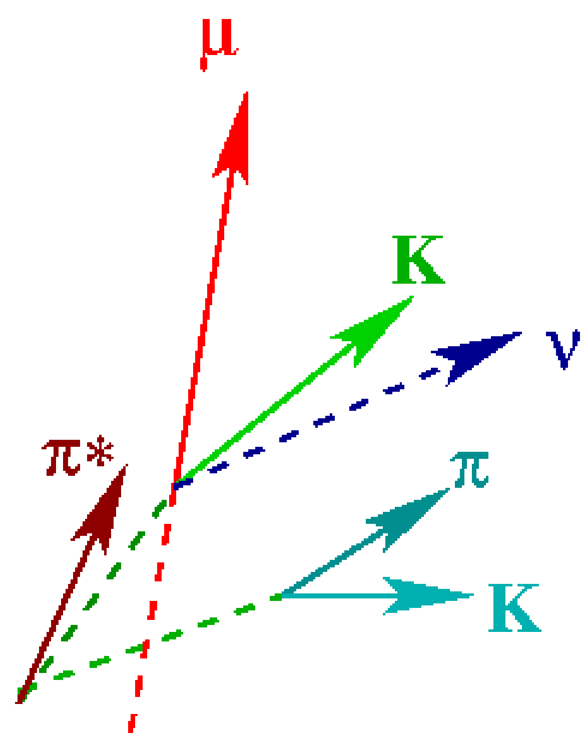
- B_C , B^{**} , B lifetimes, B semi-leptonic, CP violation studies
- b production cross-section: In Run I, measd. Rates x(2-3) higher
- Quarkonia - $J/\psi, \Upsilon$ production, polarization …

Backup Slides

$c\bar{c}$ contamination

- Can mimic the signal
- Looking for ways to estimate
- One of possibilities is below

$\bar{c}c \to D0\ X$
- $\to K\ \pi$
- $\to D^*\ X$
  - $\to D0\ \pi$
    - $\to K\ \mu\ \nu$



- So far established the lower limit ~10%