Flavor Tagging at Hadron Colliders

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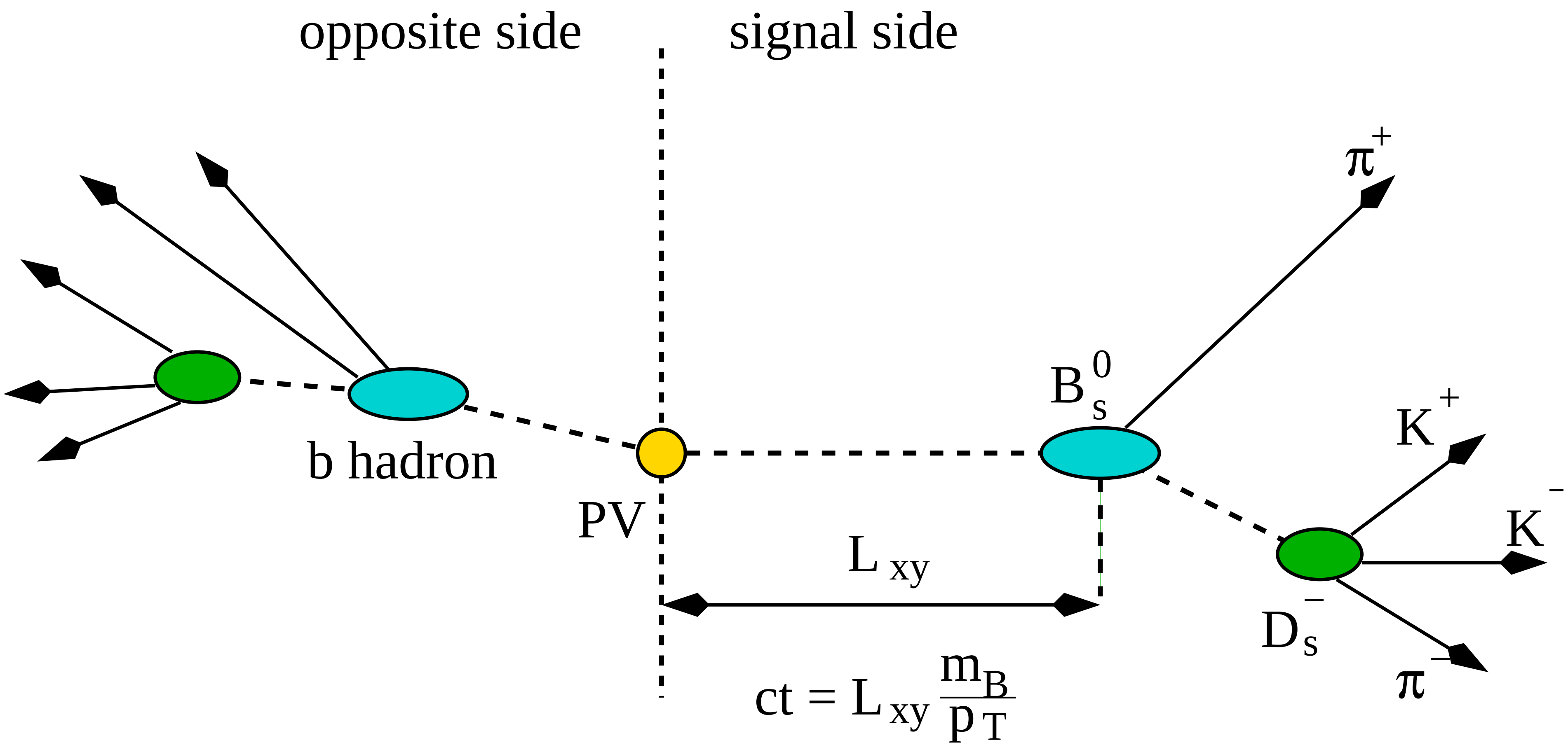
$B_s - \bar{B}_s$ Mixing Analysis



1) B_s selection & reconstruction

2) Measurement of proper decay time ct

3) Flavor tagging

Asymmetry Measurement

True asymmetry:

$$\mathcal{A}_{true}(t) = \frac{N_{RS}(t) - N_{WS}(t)}{N_{RS}(t) + N_{WS}(t)} = cos(\Delta m_s t)$$

N_{RS}: production flavor $=$ decay flavor

N_{WS}: production flavor $\neq$ decay flavor

Measured asymmetry:

$$\begin{aligned}
\mathcal{A}_{measured}(t) &= \frac{N'_{RS}(t) - N'_{WS}(t)}{N'_{RS}(t) + N'_{WS}(t)} \\
&= \frac{N_{RS}(t)(1 - P_{mt}) + N_{WS}(t)P_{mt} - N_{WS}(t)(1 - Pmt) - N_{RS}(t)P_{mt}}{N_{RS}(t) + N_{WS}(t)} \\
&= (1 - 2P_{mt})\frac{(N_{RS}(t) - N_{WS}(t))}{N_{RS}(t) + N_{WS}(t)} = (1 - 2P_{mt})\mathcal{A}_{true}(t)
\end{aligned}$$

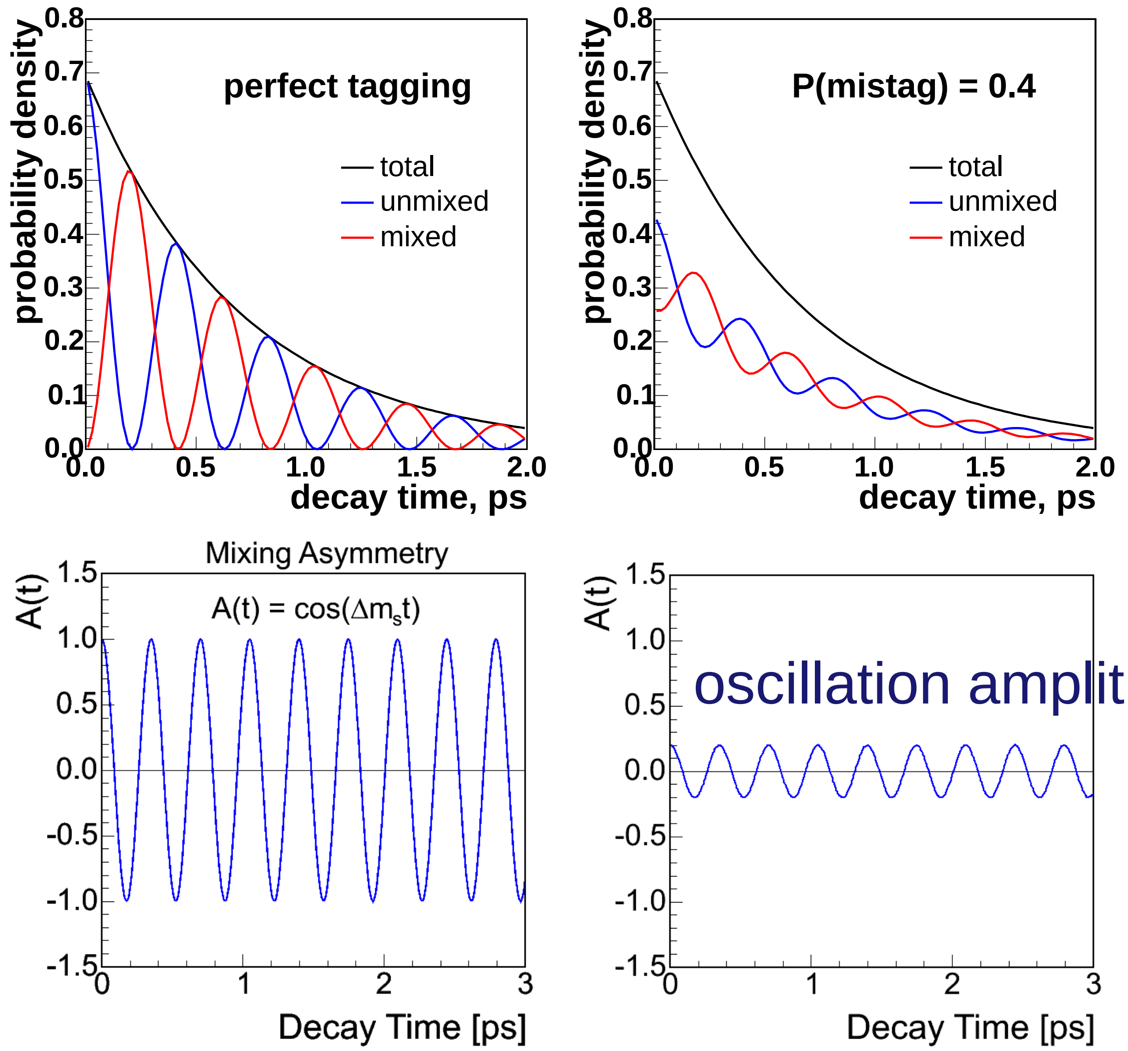
N'_{RS} : measured production flavor $=$ decay flavor

N'_{WS} : measured production flavor $\neq$ decay flavor

P_{mt}: mistag probability

Effect of Imperfect Tagging

Mis-tag dampens the observed oscillation!



oscillation amplitude: 1-2P(mistag)

(for this examples $\Delta m_s = 2.5$ ps^{-1})

Asymmetry Measurement

Tagging dilution $D = 1 - 2P_{mt}$

perfect tag $\leftrightarrow$ 100% dilution; random tag (P_{mt} = 50%) $\leftrightarrow$ 0% dilution;

Tagging efficiency $\epsilon = \frac{N_{tagged}}{N_{all}}$

Effective statistical size of a sample

$$\rightarrow N_{eff} = N_{all} \times \epsilon D^2.$$

Uncertainties on mixing currently statistical limited.

A few numbers ...

[%]	ϵD^2
D0/CDF	2.5 - 5.0
BABAR/BELLE	$\approx$ 30

e^+e^- experiments perform about an order of magnitude better!

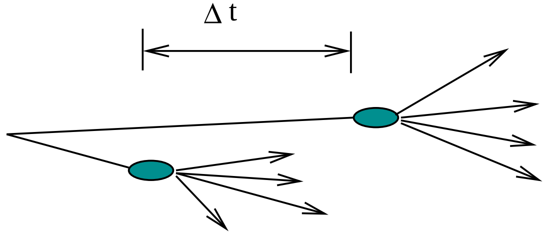
Why do Opposite Side Taggers worse @ $p\bar{p}$?

- Potential oscillation of OS B ($P_{mt} = 12\%$) introduces dilution.

OST (mainly) tag on decay flavor of opposite side b.

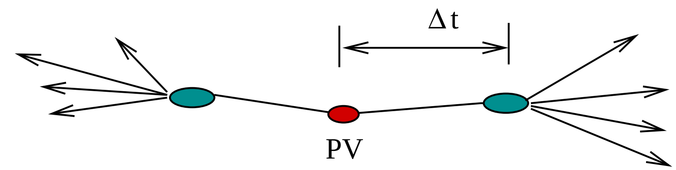
e^+e^- @ $Y(4S)$:

decay flavor of OS and “production” flavor of SS B correlated

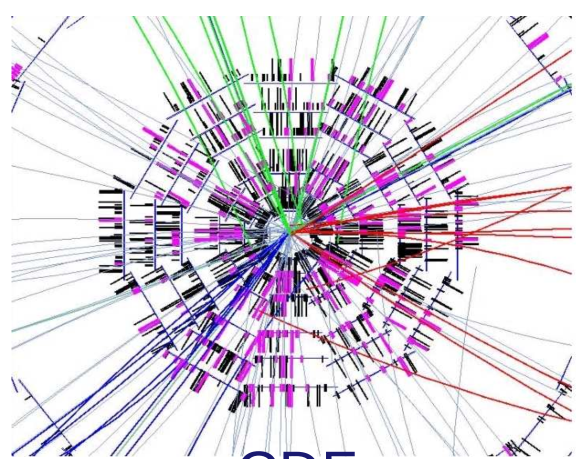


Hadron Collider:

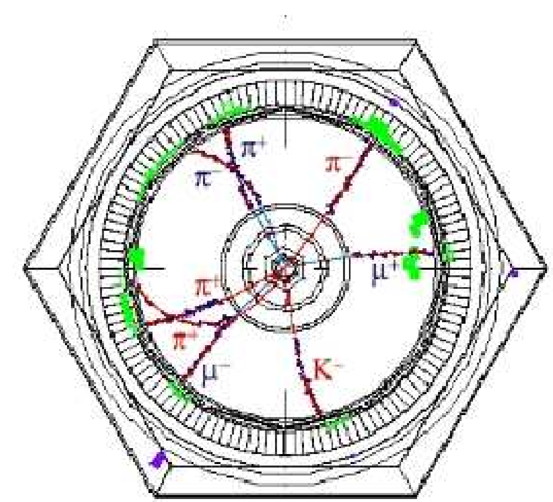
production flavor of OS and SS B correlated



- Busy environment, hard to identify (inclusive) OS B
- Longitudinal boost, loss of OS B in forward direction; Tag on false information



CDF

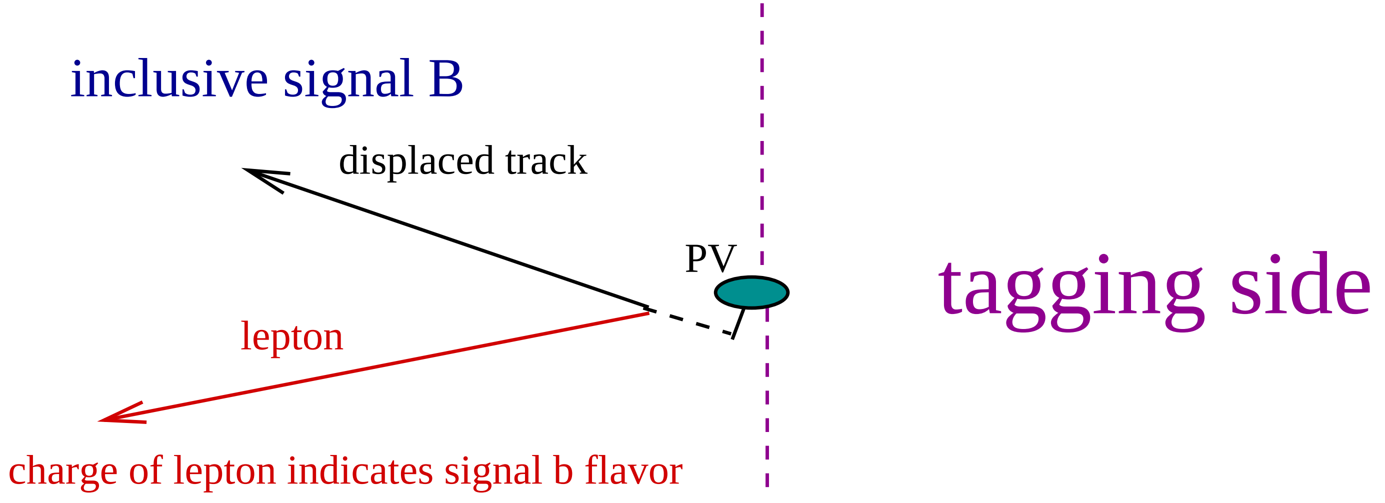


BABAR

OST: General Strategy

Need huge sample to develop and optimize tagging algorithm

Exploit that OST performance is independent of signal side.



- lepton + displaced track as inclusively reconstructed signal side B, develop and calibrate taggers on opposite side.
- Cross check & correct tagger calibration on reconstructed B^+/B^0 sample $\longrightarrow$ determine overall dilution scale factor
- Finally, apply tagger to B_s sample

Lepton Tagging (I)

Exploit semileptonic decay on OS (BR: 10% each for e and μ)

Signal:

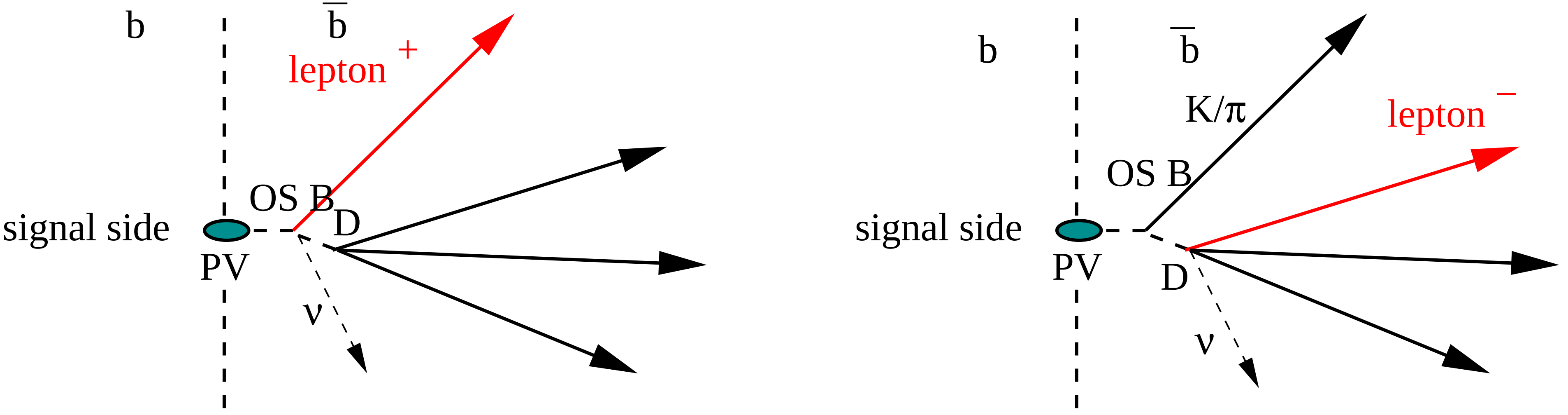
$b \rightarrow \ell^- X$

$\bar{b} \rightarrow \ell^+ X$

Background:

$b \rightarrow c \rightarrow X\ell^+$

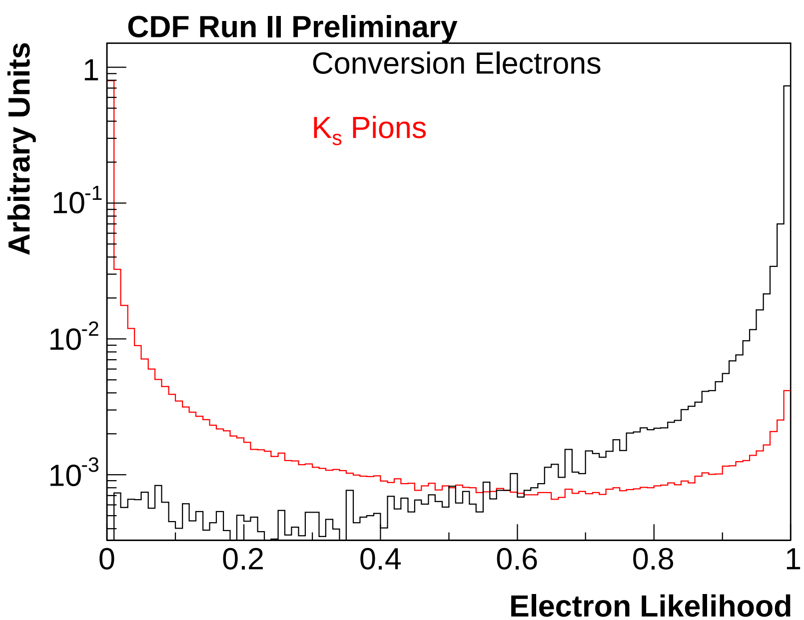
$\bar{b} \rightarrow c \rightarrow X\ell^-$

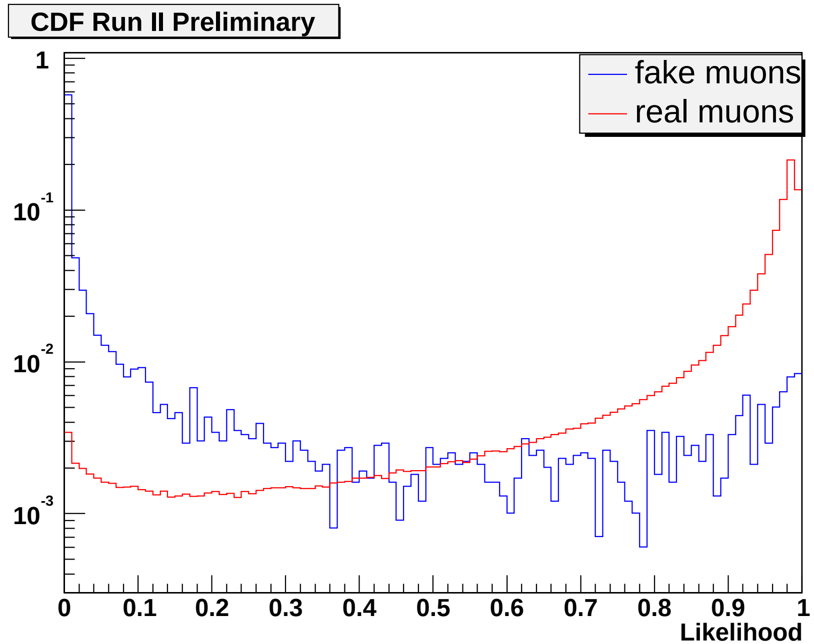


Lepton reconstruction is inclusive
(no secondary vertex is reconstructed).

Lepton Tagging (II)

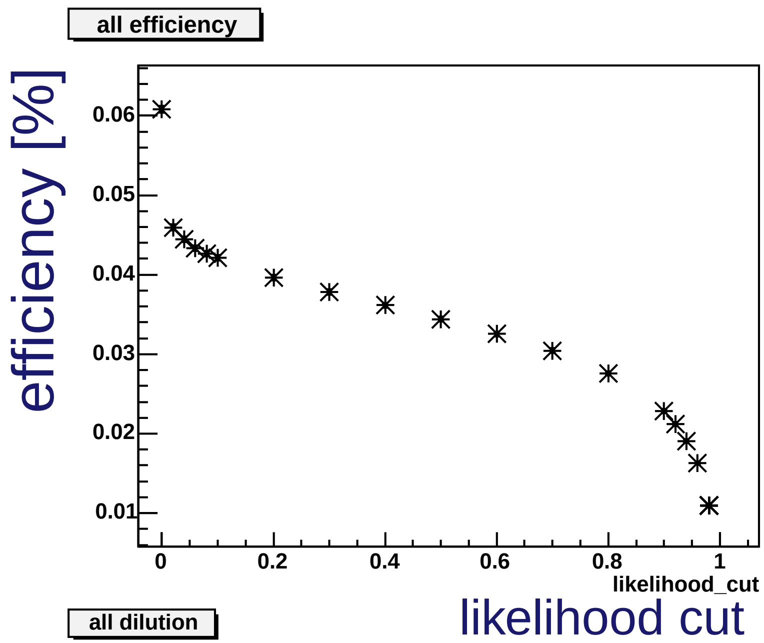
- Muon ID: Combined Likelihood of muon chambers, electromagnetic and hadronic calorimeter information
- Electron ID: Combined Likelihood of dE/dx in drift chamber, electromagnetic and hadronic calorimeter (suboptimal for momentum range of tagging electrons)

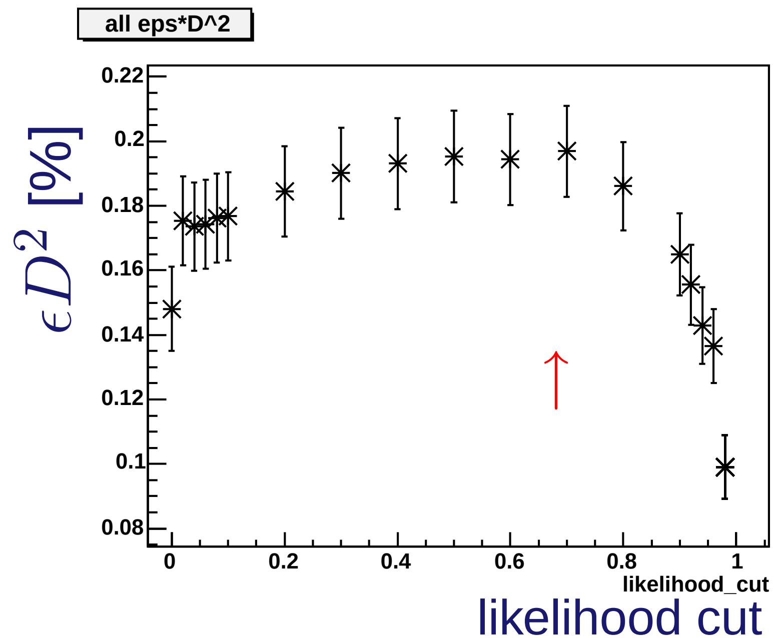


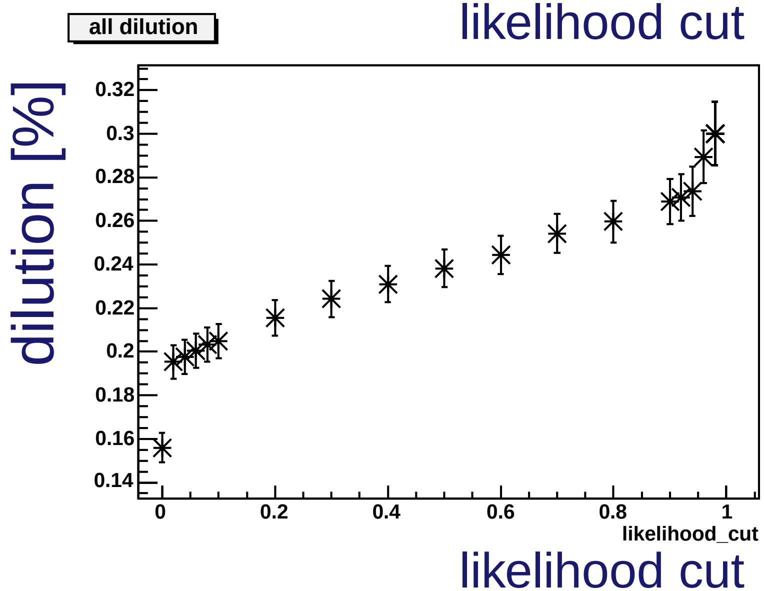


Electron/muon & background templates for all detectors needed.

Optimizing Muon Tagging







Cut based approach yields

ϵD^2 = 0.45% only ...

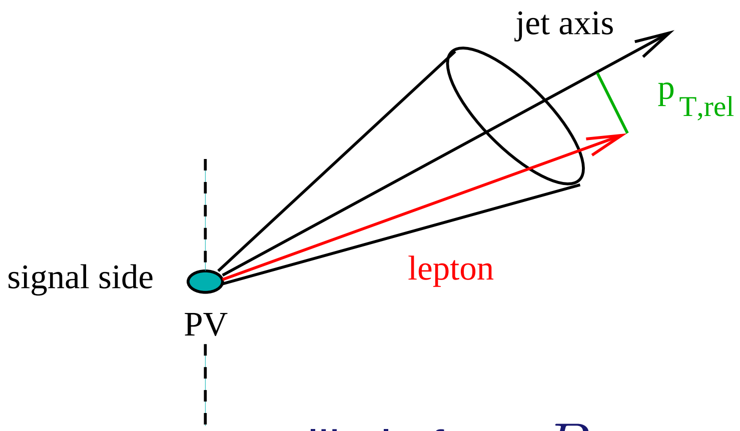
(raw dilution corrected by $\times$ 1.56)

Parameterization & Classification

Dilution depend on:

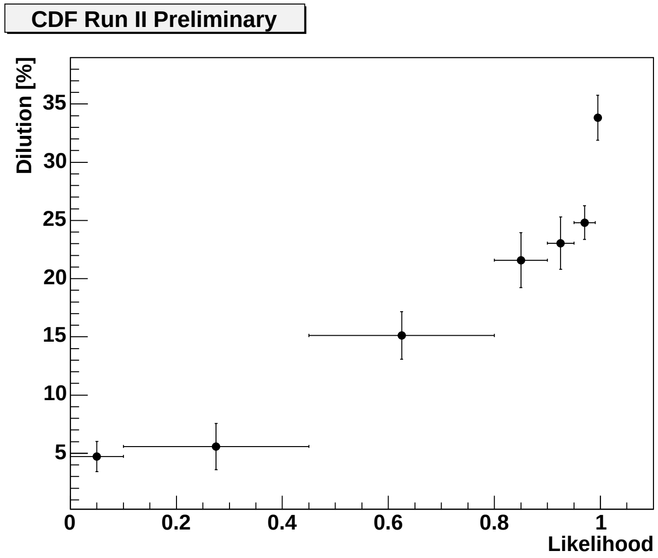
- Muon detector system
- Likelihood value
- $p_{T,rel}$ to OS B-jet

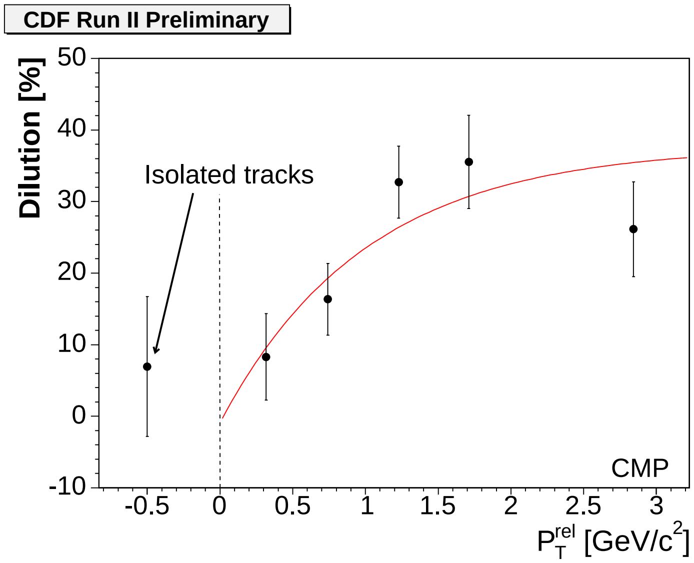
To exploit dependencies, large calibration sample needed !



large $p_{T,rel}$: μ likely from B

low $p_{T,rel}$: μ likely from D

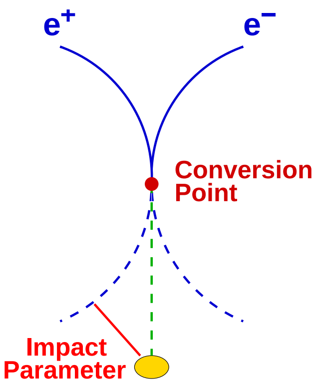




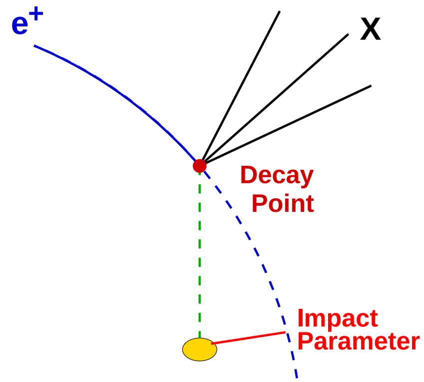
ϵD^2(OS muon tagger) = 0.7%

Electron Tagger

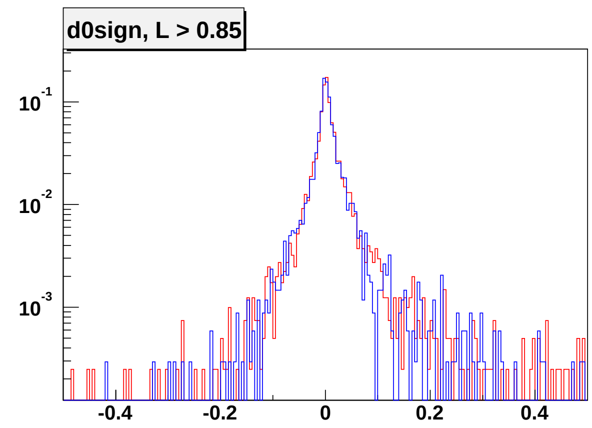
Additional background from non-identified conversion electrons



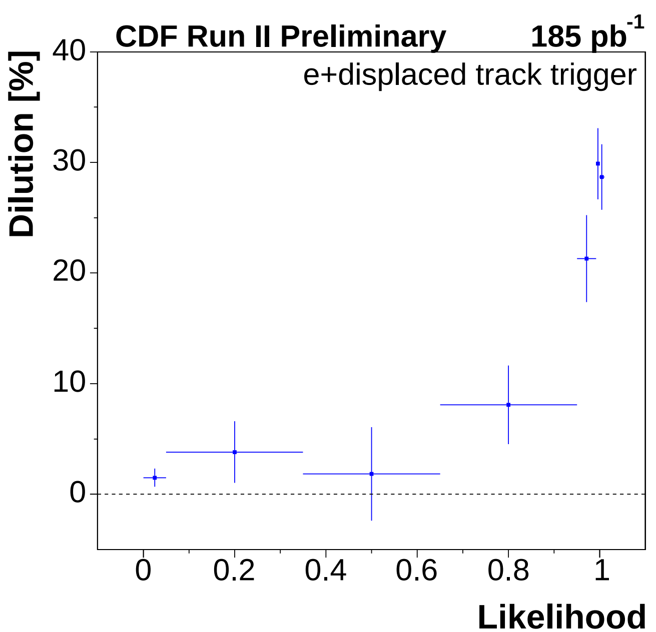
Positively Signed Impact Parameter

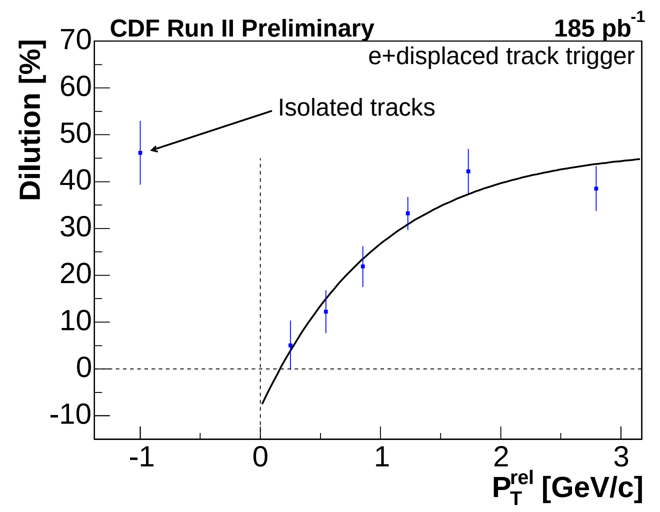


Negatively Signed Impact Parameter



Dilution higher for electrons with positive signed IP



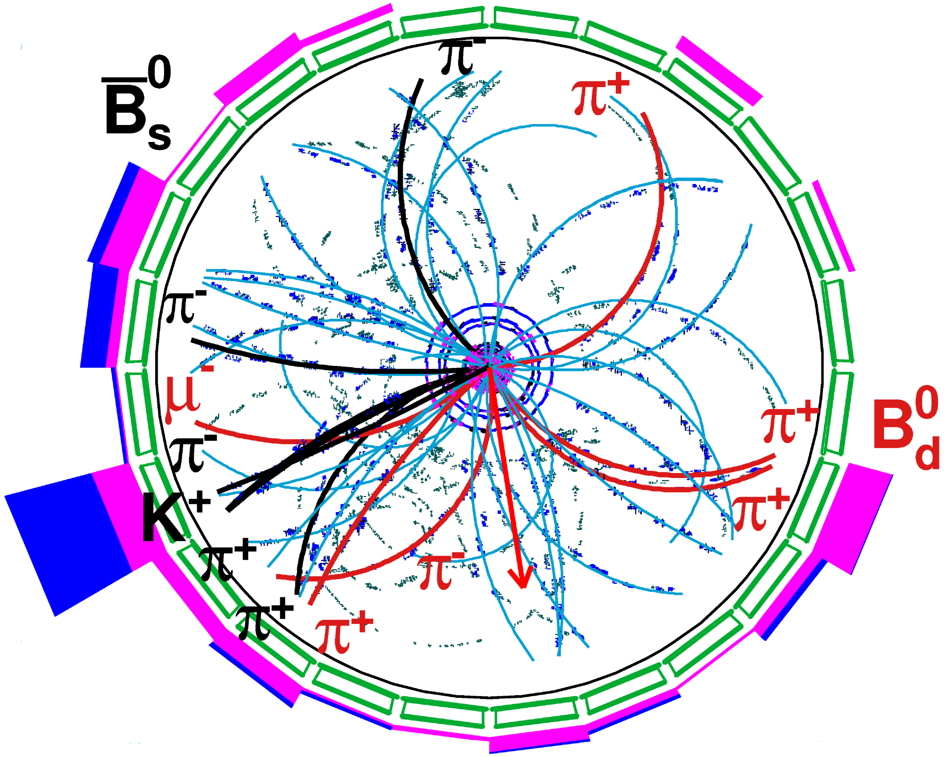


ϵD^2(OS electron tagger) = 0.4%

Jet Charge Tagger

Sum of charge of tracks in opposite side jet indicate OS flavor

(low dilution, high efficiency tagger)



Works best for $B^{\pm}$ on opposite side,

little information from q=$\frac{1}{3}$ as well for B^0

How do to define opposite side jet?

Neural Network Based JQT (I)

1) Reconstruct jet

2) Identify B daughter tracks in jets

- track impact parameter significance
- rapidity to jet axis
- track p_T
- ΔR to signal B
- ...

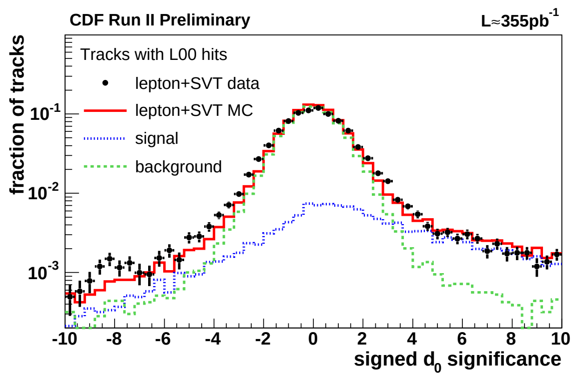
3) Select OS B jet

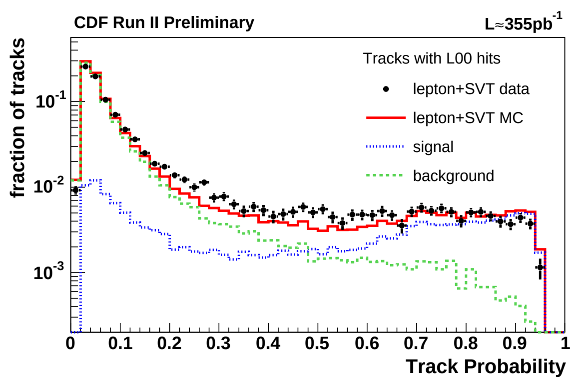
- track net output
- jet p_T
- secondary vtx in jet (χ^2)
- $\Delta\phi(jet,\ signal\ B)$
- ...

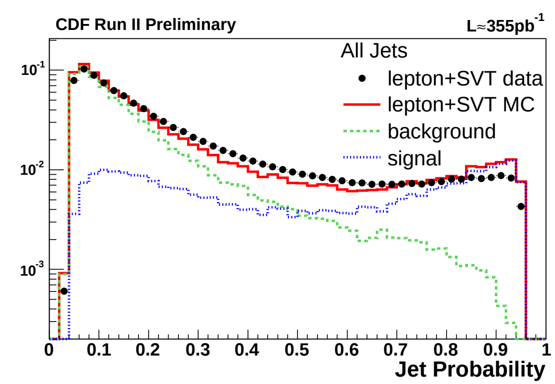
NN squeeze best out of correlated variables with each little separation power

good data/MC agreement needed

But tagger can NOT be wrong, only suboptimal

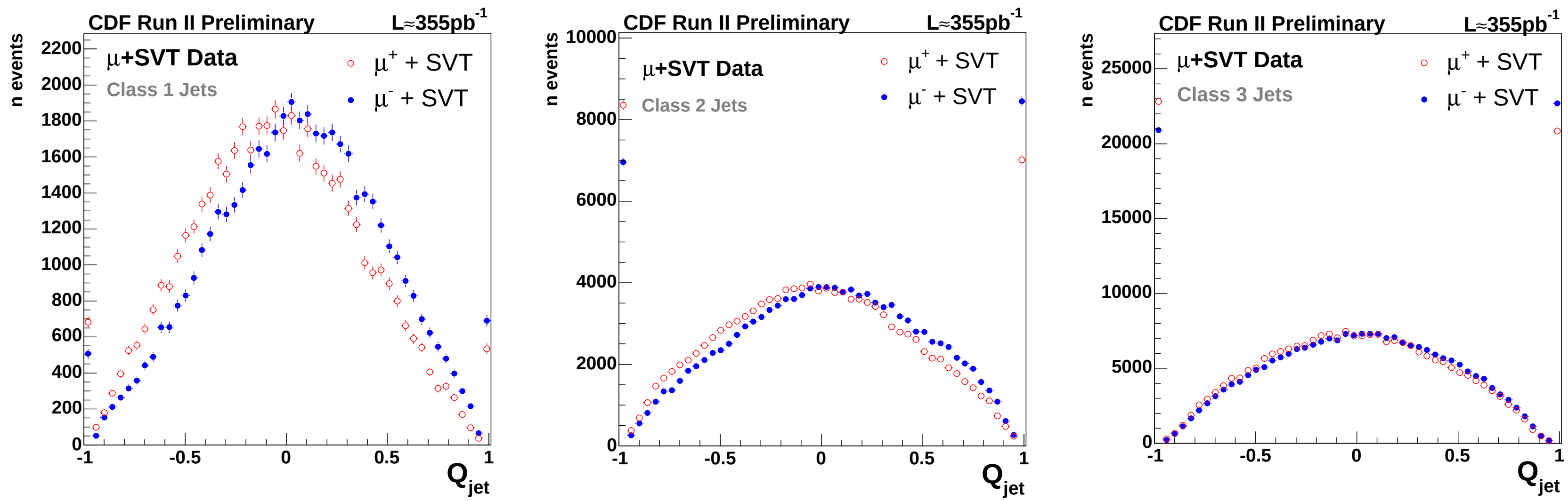


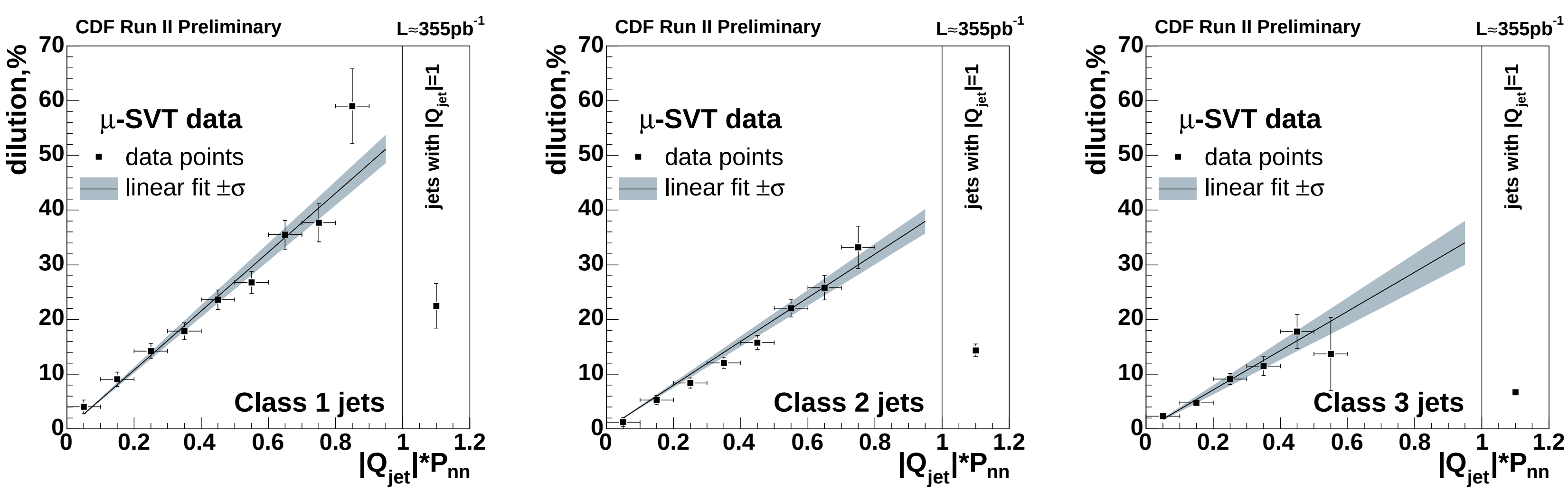




Neural Net JQT (II)

4) Compute Jet Charge: $Q_{jet} = \frac{\Sigma_i Q_i p_{T,i}(1+t_i)}{\Sigma_i p_{T,i}(1+t_i)}$, ($t_i$: track net output)

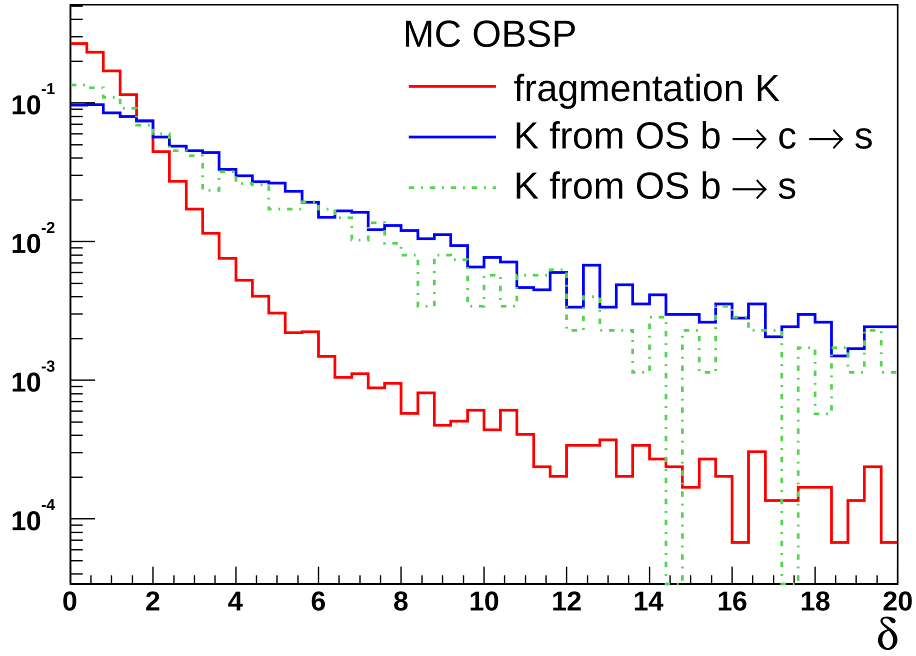




P_{nn}: jet net output; ϵD^2(JQT) = 0.9%

OST Kaon Tagging

Due to large CKM elements $b \to c \to s$ transition is favored.
Charge of kaon indicates B flavor.



Limiting factor is NOT kaon ID nor detector acceptance BUT separation of primary/secondary kaons.
Very poor standalone tagging power (ϵD^2 (OSKT) $<$ 0.2%), better used as additional input to JQT NN or to combined OST approach.

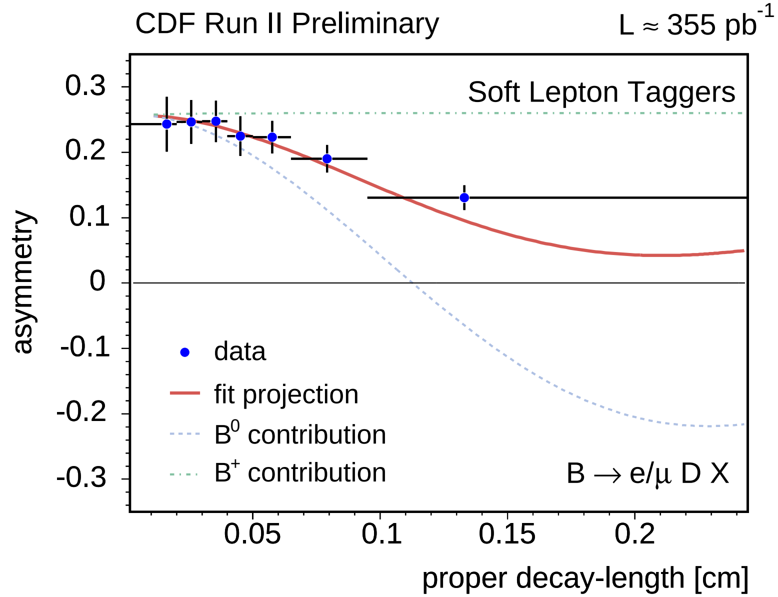
OST in B^+ & B^0

Use (partially) reconstructed B^+/B^0 and known mixing frequencies to cross check tagger calibration.

Fit for global correction factor S_D: $P(t)_{B^0 \to \bar{B}^0} \propto \frac{1 - S_D D \cos(\Delta m t)}{2}$

hadronic analysis:

[%]	S_D
muon tagger	93.6 ± 4.0
electron tagger	107.2 ± 4.8
JQT 1	91.7 ± 6.0
JQT 2	100.1 ± 6.6
JQT 3	83.8 ± 11.5

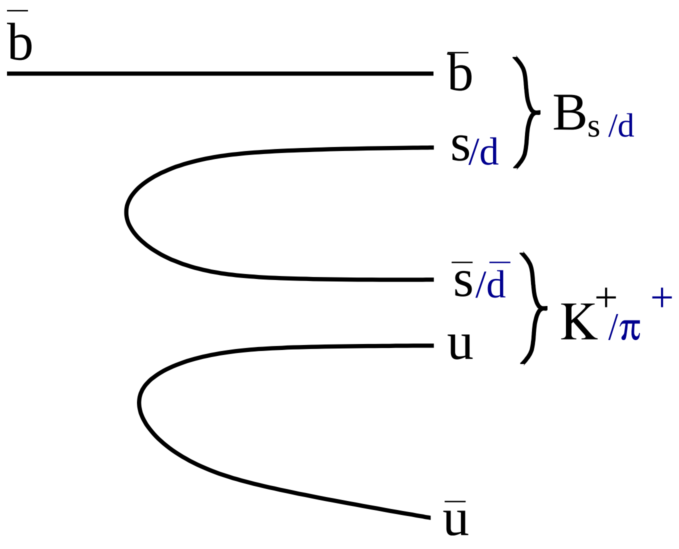


$\epsilon S_D^2 < D^2 > (combined,\ semil.) = 1.54 \pm 0.06\%$

$\epsilon S_D^2 < D^2 > (combined, hadr.) = 1.55 \pm 0.09\%$

OST algorithms are applied in hierarchical order (largest D first).
(NN combination of OST algorithms indicate ϵD^2 up to 2.0%.)

Same Side Tagger (I)

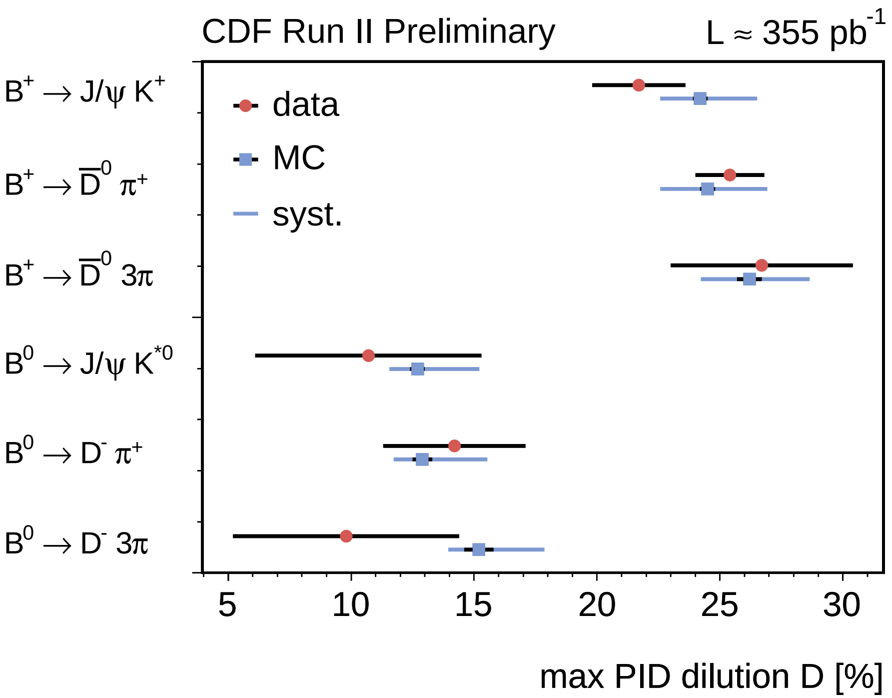


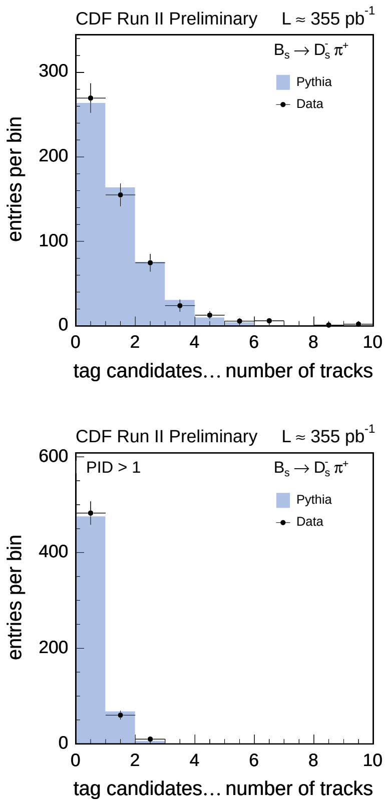
Charge of closest fragmentation track correlated to B production flavor

- SST performance depends on B type. It is different for B^+, B^0 and B_s. (+ different contributions from B^{**} decays)
- No inclusive samples can be used for calibration ...
  $\longrightarrow$ Monte Carlo samples instead (prompt charm from data ?)
- Till mixing is well established calibration can not be checked on data (this is more or less obsolete by now ...)

Same Side Tagger (II)

Most effort in this analysis spent on evaluating data/MC agreement and systematics.





track multiplicity with and w/o cut on PID

$B_s \to D_s \pi$

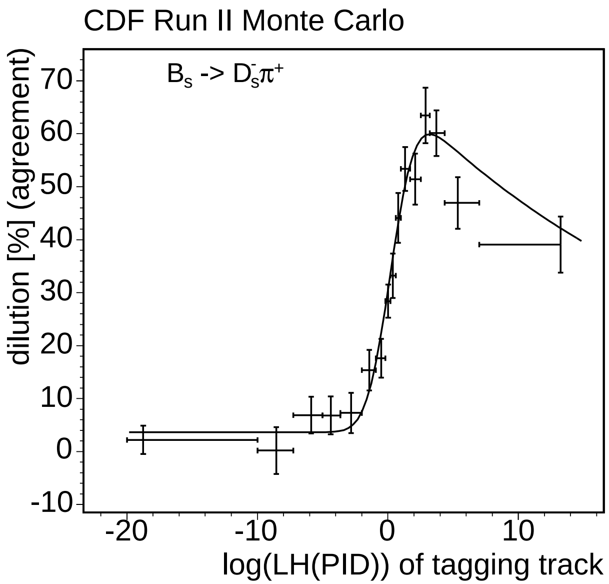
This was important for potentially setting a limit.

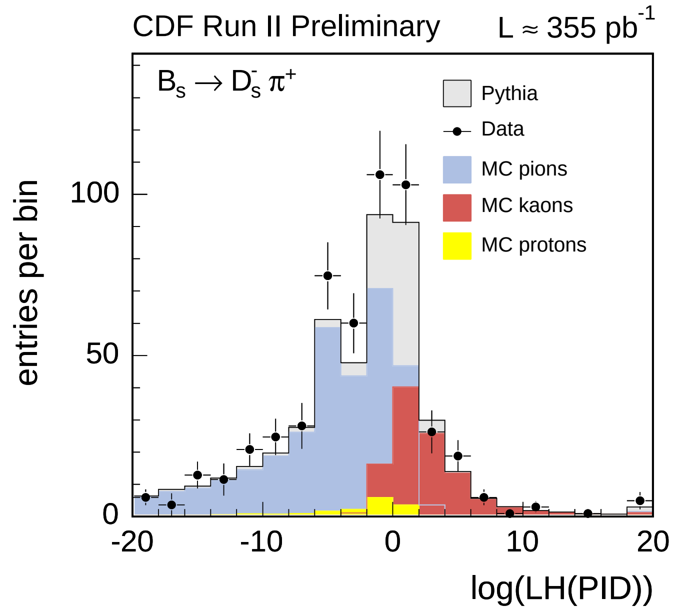
Too optimistic tagger estimates $\longrightarrow$ exclusion of Δm_s regions, to which we are not sensitive.

We see very good agreement between data/MC

Same Side Tagger (III)

Exploit PID system (time-of-flight + dE/dx drift chamber) for selecting fragmentation kaon.





Current algorithm:

Select particle with largest kaon probability in vicinity of B_s

(no kinematical information used sofar)

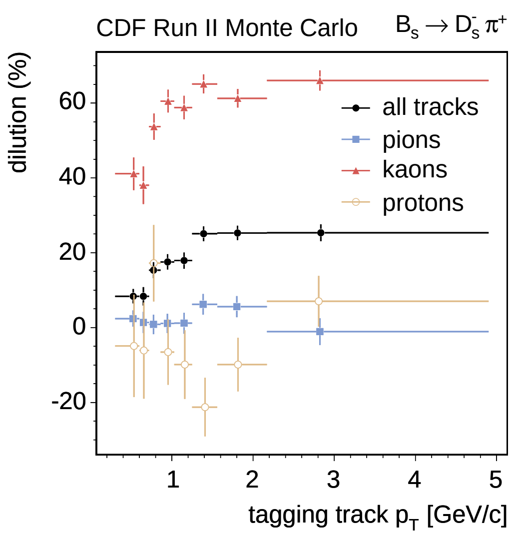
$\sqrt{< D^2 >}$ = 28.8%; ϵ = 48.2%; $\epsilon < D^2 >$ = 4.0%

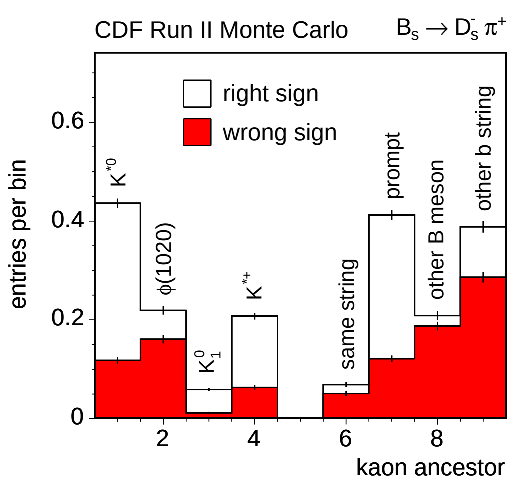
Tagging performance 2-3 $\times$ larger than for OST!

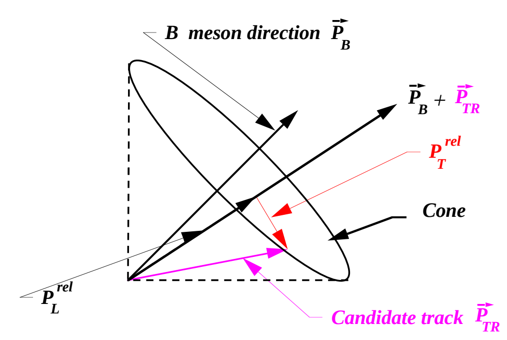
Same Side Kaon Tagging (IV)

- SST track (almost) every time in detector acceptance
- Little background, restricted search region
- No effect of oscillation, no limiting OS BR
- Main limitation right now suboptimal kaon ID

Optimal PID (Monte Carlo): potential performance $\epsilon D^2 \approx$ 10-12%







$p_{L,rel}$ or p_T good variables to select THE right kaon.

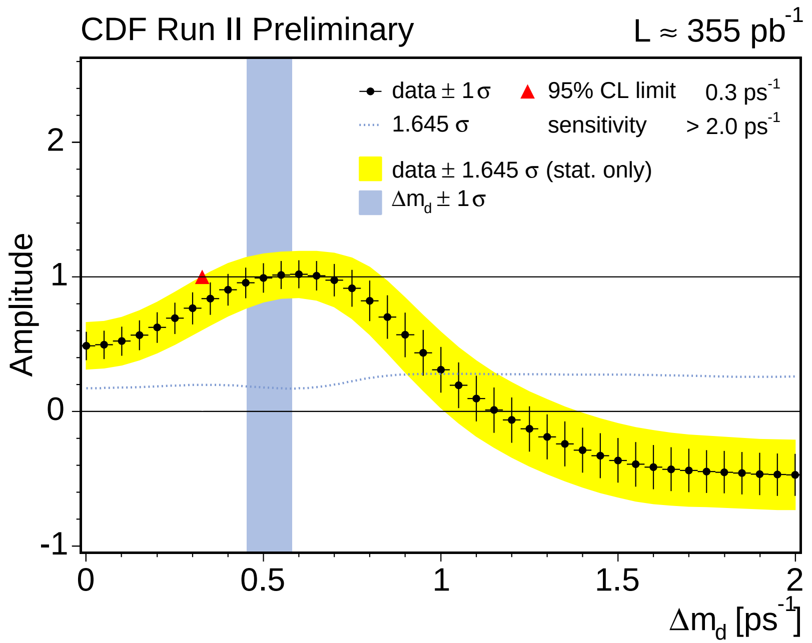
Combined PID and $p_{l,rel}$ SSKT algorithm under development.

After all, it work's ...

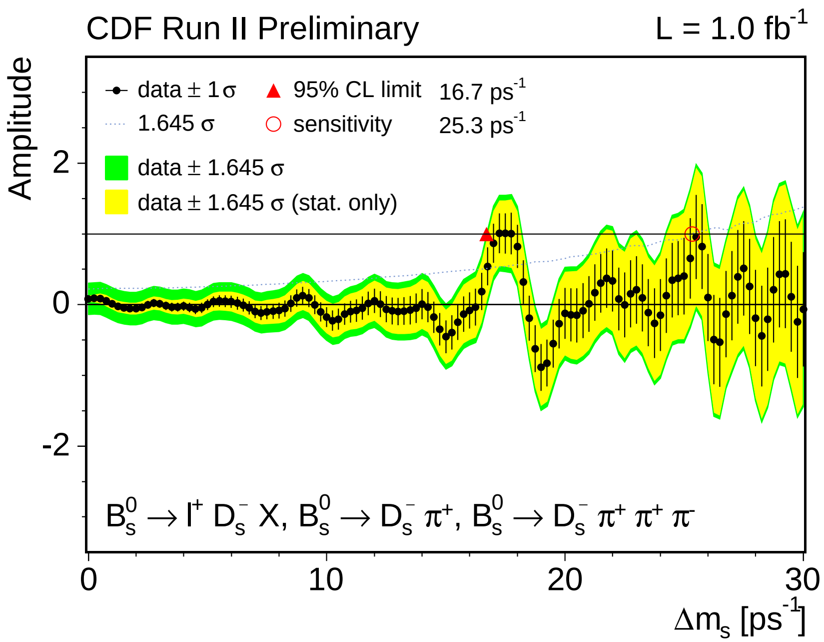
Fit for mixing amplitude with fixed dilution D:

$$P(t)_{B \to \bar{B}} \propto \frac{1 - AD\cos(\Delta m t)}{2}$$

scan for Δm_d



scan for Δm_s



A = 1 at signal $\Delta m \to$ taggers are properly calibrated!

Outlook

LHCb is optimized for B physics and flavor tagging:

- Larger acceptance in forward direction
- Better particle ID (RICH detector)
- $\times$ 2 better vertex resolution

ϵD^2 [%]	CDF	D0	LHCb expectation
Electron tagger	0.4	0.2	0.4-0.6
Muon tagger	0.7	1.5	0.7-1.8
Jet Charge tagger	0.9	0.5	0.9-1.3
OS kaon tagger	(0.2)	no kaon ID	1.6-2.4
OST combined	1.5	2.5	3.0-4.0
Same side kaon tagger (B_s)	3.5-4.5	not implemented	2.7-3.3
Same side tagger (B^0)	2.5-3.5	not implemented	0.8-1.0

LHCb expectations are based on non optimized algorithms but use (most likely) too optimistic detector simulation.

SSKT has to work better than OST!

Summary

- Flavor tagging is crucial for mixing and CP analysis
  $N_{eff} = N \times \epsilon D^2$
- Almost all detector systems are used for tagging,
  tagging will not work “out-of-the-box”
- Flavor tagging in hadronic environment very tough, but
  dedicated algorithms can squeeze info out of data
- Large tagger calibration samples needed for optimization
  (e.g. tuned MC (underlying physics + detector simulation))
- $\epsilon D^2 \approx$ 5% compared to $\approx$ 30% at B factories
- SS(K)T work potentially best