Time of Flight @ CDF (II)

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Outline:

- TOF Offline Calibration
- TOF Reconstruction
- Validation/TOF Performance
- Physics with TOF
- 216 scintillator bars ($\approx 4 \times 4 \times 279.5 \text{ cm}^3$), as cylinder directly outside of the COT
- 1 photomultiplier-tube at each end
- PMT + readout electronics measure time when collected charge is above threshold
- integrates the charge within a time window ($\approx 10$ ns)
**Contribution to Time Measurement in the TOF System**

- \( t_{\text{speed}} = \frac{d}{s} \)
- \( d = L/2 \pm z \)
- \( (L=280\text{cm}) \)

TAC start

TDC

C_s : common stop

TAC stop

\[ TDC = C_s - (t_0 + \text{tof} + t_s + t_c + t_w) \]
TOF Calibration

- **Online Calibration**
  Pedestal subtraction and TAC calibration

- **Time Walk Effect** (slewing correction)
  Due to dependence of discriminator time on pulse height
  \( \approx 2 \text{ ns} \)

- **Speed of Signal Propagation in Bars**
  Time depend on z position of hit along the bar
  \( \approx 20 \text{ ns} \)

- **Channel-to-Channel Time Offset**
  Includes cable length and clock signals
  \( \approx 1 \text{ ns} \)

- **Residual Correction in z Position along the bar**
  \( \approx 200 \text{ ps} \)

(Design TOF resolution: 100 ps)
- Time difference East - West vs. \( z \)

\[
t_E - t_W = t_0^E - t_0^W - (t_{wE}(Q) - t_{wW}(Q)) + t_{cE} - t_{cW} + 2z/s
\]

\( s \): speed of signal propagation

Time walk dependence almost cancels in time difference of east/west. The **effective speed of light** comes from the fitted slope.

Channel-by-Channel offset doesn’t affect the slope, just causes a shift. The effective speed of light is fitted again after the time walk correction.

![Graph showing](image-url)
TOF Calibration: Time Walk Correction

- Time Walk Correction
  Due to leading edge discriminator: Larger pulses fire the discriminator at earlier time than smaller pulses. During calibration event $t_0$ is not yet known. Effect studied with tracks passing through two neighbouring bars (A,B):
  
  $t_A = t_A^0 + t_s A(z) + t_c A - \frac{\alpha A}{\sqrt{Q}}$;
  $t_B = t_B^0 + t_s B(z) + t_c B - \frac{\alpha B}{\sqrt{Q}}$;
  $\alpha A \approx \alpha B$
  $t_A - t_B \propto \alpha \times \left( \frac{1}{\sqrt{Q_A}} - \frac{1}{\sqrt{Q_B}} \right)$;

\[ t_{45} - t_{46} \text{ (ns)} \]
TOF occupancy is about 30% (average b-event)

Two thirds of the TOF signals are not related to a reconstructed track → significant background even for isolated tracks

Occupancy is present in data and MC → It is related to real particles in the detector
TOF-Track Matching

- extrapolate track into tof bar
- calibrate time according to z position of intersection
- measured charge and time on east and west side after calibration should be the same
- cut on $\chi^2 = \frac{(t_E-t_W)^2}{\sigma^2_E + \sigma^2_W} + \frac{(Q_E-Q_W)^2}{\sigma^2_{\Delta Q}}$
- charge has to be calibrated for attenuation length
- single track matching efficiency: 74% (average b-event)
- single track matching purity: 96% (average b-event)
Arrival-Time Resolution

Like to study arrival time resolution and track-matching independent of \( t_0 \).
Isolate calibration and matching effects from \( t_0 \) computation.

→ Study time difference of two muon legs of \( J/\Psi \) event \( (K_S \rightarrow \pi\pi, \ldots) \)

\[
\begin{align*}
\Delta t &= (t_{\mu_1} - t_{\mu_1}^{exp}) - (t_{\mu_2} - t_{\mu_2}^{exp}) \\
&= \left( t_{\mu_1} - t_0 - \frac{s_1}{c} \sqrt{1 + \frac{m_\mu^2}{p_1^2}} \right) - \left( t_{\mu_2} - t_0 - \frac{s_2}{c} \sqrt{1 + \frac{m_\mu^2}{p_2^2}} \right)
\end{align*}
\]

Errors on momentum (p) and arclength (s) are negligible compared to timing resolution.

Arrival time resolution:

\[
\sigma_t = \sigma_{\Delta t} / \sqrt{2}
\]

\( \sigma_t = 156 / \sqrt{2} \) ps = 110 ps
**Efficiency-Purity Definition**

- **Efficiency**: all $J/\Psi$s where both muon fulfill matching cut divided by number of $J/\Psi$s with both muons fiducial tof tracks
- **Purity**: $J/\Psi$ in narrow gaussian divided by all $J/\Psi$s which pass matching cuts
- Combined $\chi^2$ of time and charge works best
- Default cut: $\chi^2 \leq 14$
- Single track efficiency: 74%
- Single track purity: 96%

70% of all tracks are fiducial $\rightarrow$ absolute tof efficiency about 52%
A Closer Look at the Tails (1)

Bad Muons:

\[ |(Tof_{\mu_1} - Tof_{exp,\mu_1}) - (Tof_{\mu_2} - Tof_{exp,\mu_2})| \geq 500\text{ps} \ \& \]
\[ |Tof_{\mu_1/2} - Tof_{exp,\mu_1/2}| \geq |Tof_{\mu_2/1} - Tof_{exp,\mu_2/1}| \]

We measure more often too late than too early times
A Closer Look at the Tails (2)

Early tails:

- Another particle crosses the bar before the track we are interested in → time measurement is triggered too early

Late tails:

- Another particle crosses the bar while the gate is still open. Additional charge makes signal look larger as it is. → Time Walk Correction too small → corrected time is too late

Inefficiency:

- Another particle has triggered or polluted either the time or the charge measurement
The bunches @ CDF are long:

\[ \sigma_z \approx 30 \text{ cm} \rightarrow \Delta t = \sigma_z / c \approx 1 \text{ ns} \gg \sigma_{tof} \approx 110 \text{ ps} \]

Need to calculate \( t_0 \) event by event (vertex by vertex) to achieve good resolution.

Need at least two tof tracks excluding the track of interest in order to compute unbiased \( t_0 \).
\[ L = P(\pi) \cdot L(\pi) + P(K) \cdot L(K) + P(p) \cdot L(p) \]

Likelihood fit function \( L(\pi/K/p) \) consists of two gaussian distributions:

- mean: \( t_0 = \text{arrival time} - \text{expected time} (\pi/K/p) \)
- narrow gaussian corresponding to tof resolution (\( \approx 110 \text{ ps} \))
- broad gaussian to take misreconstructed/mismatched tracks into account (600 ps)
- ratio narrow/broad gaussian: 0.9:0.1
- weight Likelihood with particle probability obtained by COT \( dE/dx \) and apriori probability (0.8:0.1:0.1)
Define a Metric for $t_0$ Studies

- Split number of tracks per vertex into two subsets with $n/2$ tracks
- Compute $t_0$ for both subsets
- Plot the difference, fit the distribution with double gaussian

- **resolution**: size of narrow gaussian divided by $\sqrt{2}$
- **purity**: square-root of the fraction of vertices where $|t_{01} - t_{02}| \leq 3\sigma$
The $t_0$ resolution is a strong function of number of tracks used in the fit (statistical $\propto 1/\sqrt{N}$)

Average $t_0$ resolution is about 50 ps
Average $t_0$ purity is about 99%.
TOF Resolution

tof contains contributions from arrival time and $t_0$ resolution

- $\sigma = 119$ ps  
  (design value: 100 ps)
- 4.5% in tails ($|\text{tof-exp.tof}| \geq 0.3$ ns)

Separation of different particle species is a function of tof resolution but tails cause background e.g. for kaon-tagging or CHAMPS search
Protons: $\Lambda \rightarrow p\pi$

$2\text{GeV} \leq pT \leq 2.5\text{GeV}$

$2.5\text{GeV} \leq pT \leq 3.5\text{GeV}$

$pT \geq 2.5\text{GeV}$

$\Lambda \rightarrow p\pi$ candidates, mass[GeV]

proton pt[GeV/c]

Armin Scheurer (Karlsruhe)
Soft Pions: $D^* \to D^0(\to K\pi)\pi_s$

$pt \leq 0.5\text{GeV}$

$0.5\text{GeV} \leq pt \leq 0.75\text{GeV}$

$0.75 \leq pt \leq 1.0\text{GeV}$

$pt \geq 1.0\text{GeV}$

Kurt Rinnert (Karlsruhe)
Combining TOF and dE/dx PID

TOF works better for low momentum tracks, COT dE/dx works for very low or high momentum.

separation of protons/pions ($\Lambda \rightarrow p\pi$)

$\Lambda^0_b \rightarrow \Lambda_c (\rightarrow pK^-\pi^-)\pi^+$

Mass of potential $\Lambda^0_b$ candidates

Mass with combined PID for proton

Paula Squillacioti (Pisa)

Dmitry Litvintsev (FNAL)
• Background Rejection: e.g. penta quark search (proton)

• CHAMPS search (looking for very massive and slow particles)

• Monopole search (highly ionizing particles, curving along the B field (z)), TOF trigger

• B-Flavour Tagging
  
  • Opposite-Side-Kaon Tagging:
    It is more likely that a $\bar{B}$ meson contains a $K^-$ than a $K^+$ in the final state
  
  • Same-Side-Tagging ($B_s$)
    $B_s$ is likely to be accompanied close by a $K^+$ from fragmentation

\[
\begin{align*}
\bar{B} & \left[ \begin{array}{c} b \\ \bar{q} \end{array} \rightarrow \begin{array}{c} c \\ \bar{s} \end{array} \right] K^- \\
B & \left[ \begin{array}{c} \bar{b} \\ q \end{array} \rightarrow \begin{array}{c} \bar{c} \\ \bar{s} \end{array} \right] K^+ \\
& \left[ \begin{array}{c} \bar{b} \\ \bar{s} \end{array} \right] B_s \\
& \left[ \begin{array}{c} \bar{s} \\ \bar{u} \end{array} \right] K^+ \\
& \bar{u}
\end{align*}
\]
Summary

- TOF calibration and reconstruction are interwoven
- TOF inefficiency and impurity are caused by high occupancy in the detector (30%, 10% track related)
- $t_0$ has to be computed event-by-event
- TOF separation power does not only depend on resolution but on tails of the measured arrival time and the $t_0$ computation: $\sigma \approx 120$ ps, fraction of tails ($|\text{tof}-\text{tof}_\text{exp}| \leq 300$ ps) about 4.5%.
- TOF works well for low momentum (up to about 1.6 GeV) and is complemented by dE/dx for higher momentum.
- PID is started to be used @ CDF
- Further development of TOF reconstruction code is going on