Studies for a Level-3 Trigger at HERA-B

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Contents

- The HERA-B experiment
- Trigger system
- Operating environment of a Third Level Trigger (TLT)
- Monte Carlo studies for a TLT using the experiment’s Silicon Vertex Detector (SVD)

HERA-B

Measurement of CP violation in

$B \to J/\psi\, K_S$ (with $K_S \to \pi^+\pi^-$) and $B \to \pi^+\pi^-$

Consistency check of Standard Model description of CP violation

$$\sim \left(\overline{u}, \overline{c}, \overline{t}\right)_L \gamma_\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

CKM matrix

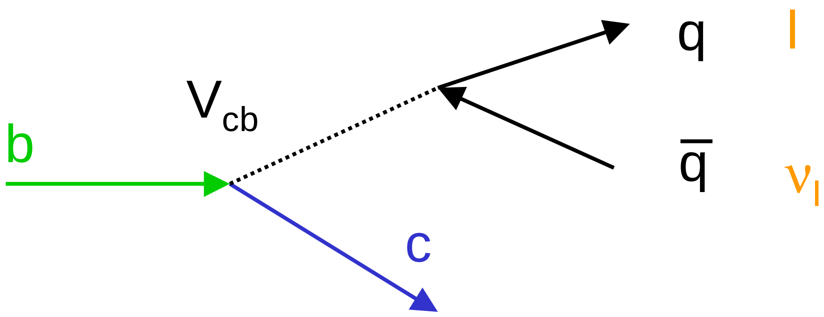
CP asymmetries:

$$\frac{N(B^0 \to f) - N(\overline{B}^0 \to f)}{N(B^0 \to f) + N(\overline{B}^0 \to f)}$$

$\to$ extract CKM phase

Semileptonic B Decays

- reduced hadronic uncertainties



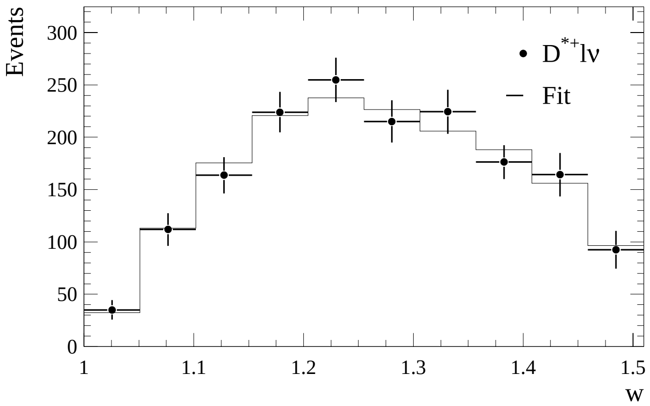
- B_d, B_s mixing, CKM elements, …
- example: V_{cb} measurement using

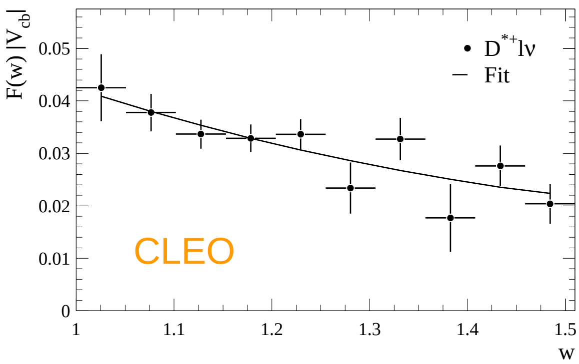
$$B^0 \rightarrow D^{*-} l^+ \nu_l$$
$$\hookrightarrow \overline{D}^0 \pi_s^-$$

$$\frac{d\Gamma}{dw} \propto G_F^2 K(w) \underbrace{|V_{cb}|^2 F^2(w)} \quad \text{with} \quad \mathrm{w} = \mathrm{v_B} \cdot \mathrm{v_{D^{*-}}}$$

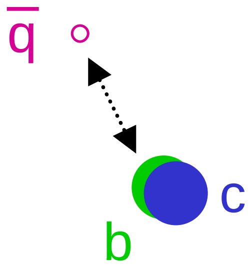
$\rightarrow$ measure as function of w and extrapolate to w=1

V_{cb} Measurement





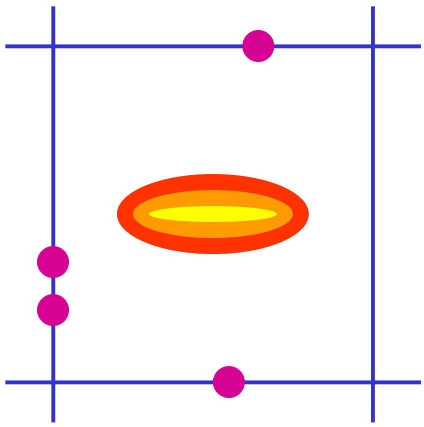
- at w=1 q^2 is maximal
- Heavy Quark Effective Theory predicts $F(1)=0.914 \pm 0.042$



- experimental challenge: K(1)=1 and π_s momentum is low near w=1 $\rightarrow$ poor reconstruction efficiency if overall boost is low

Hadronic B Factory

- proton-nucleon collisions at a wire target
- $\sqrt{s}$ = 42 GeV



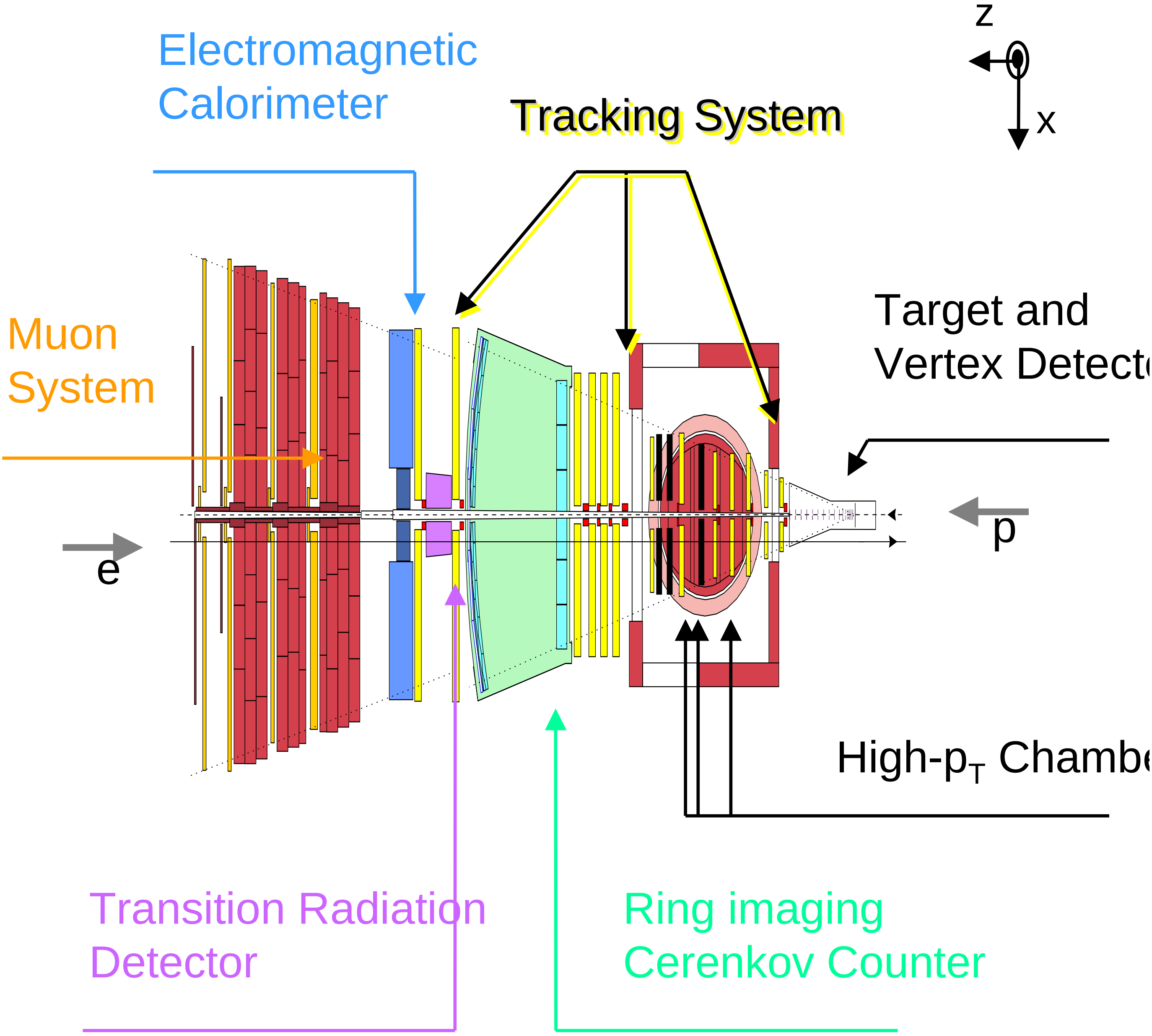
- branching ratios of sought channels in the order of 10^{-5}
- fraction of B events: $\frac{\sigma_{b\bar{b}}}{\sigma_{\text{inelastic}}} = \frac{\approx 10\,\text{nb}}{13\,\text{mb}} = 10^{-6}$

Experimental challenge:

- 10 MHz event rate and several superimposed interactions per event
- fast and radiation-hard detectors

→ Triggering is the key to B physics

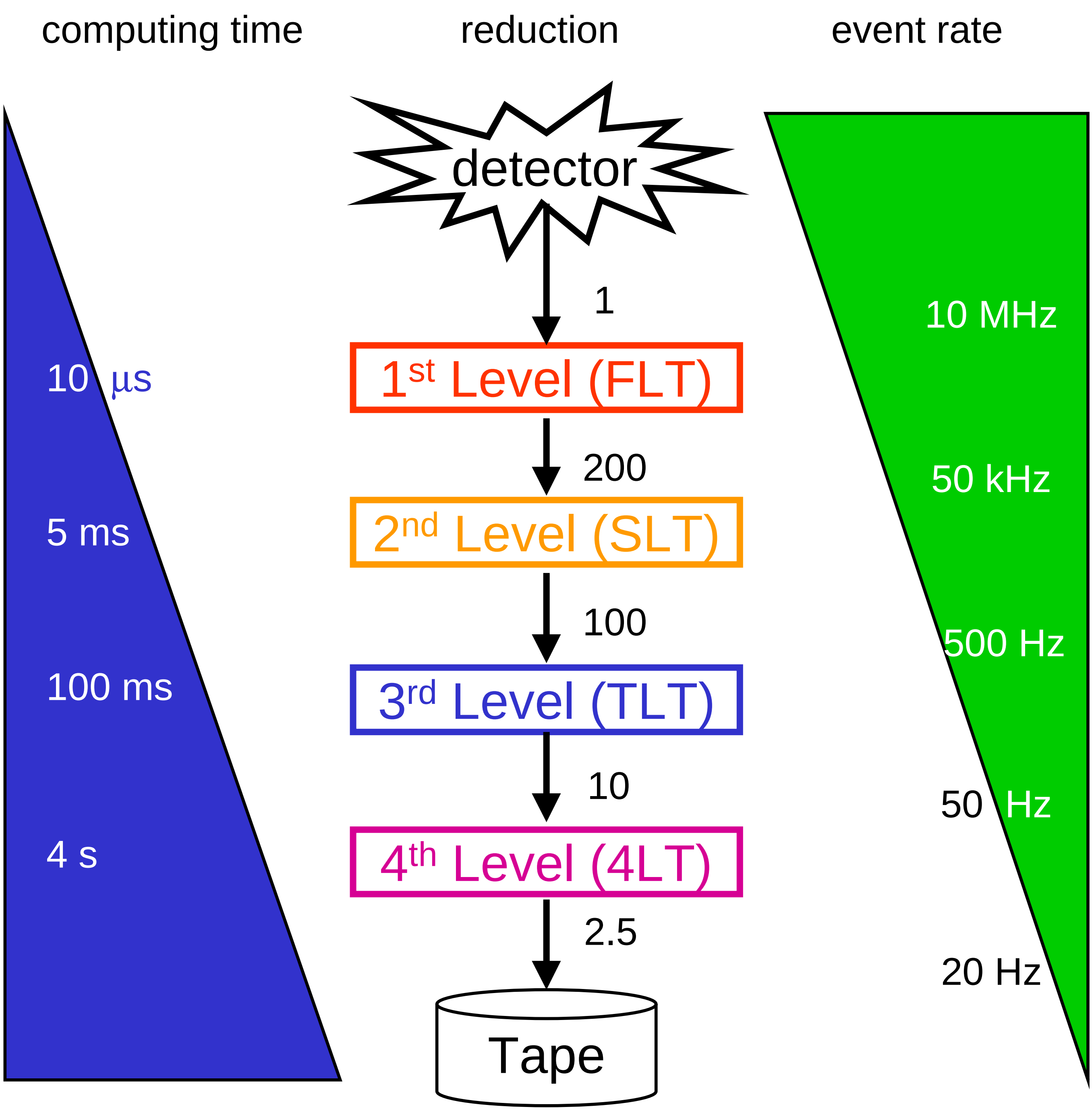
The HERA-B Detector



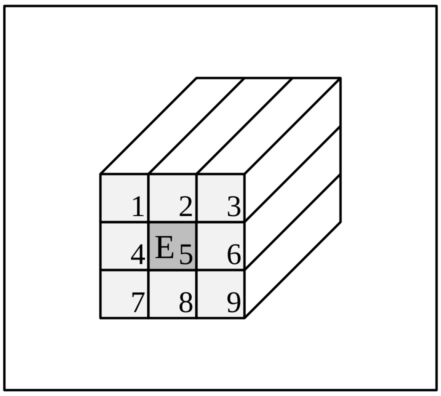
Trigger Strategy

- use pretrigger
- reconstruct electrons, muons and high-p_T hadrons in Regions of Interest (RoI)
- develop RoIs into tracks behind the magnet
- apply kinematic cuts
  - invariant mass trigger: two unlike-sign tracks of the same flavour ($B \rightarrow h^+h^-$, $J/\psi \rightarrow l^+l^-$)
  - count trigger: cut on p_T, combination of track charges and flavours
- refine kinematic cuts using more (and more precise) information about RoI particles
- use data outside of RoIs
  - when everything else fails

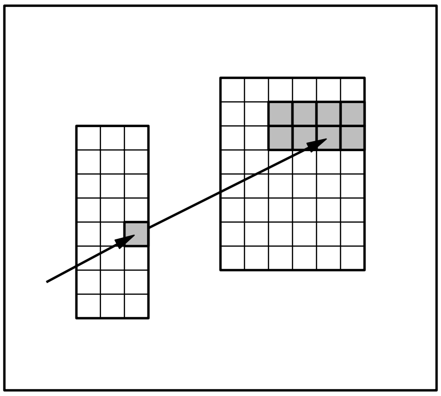
Trigger Levels



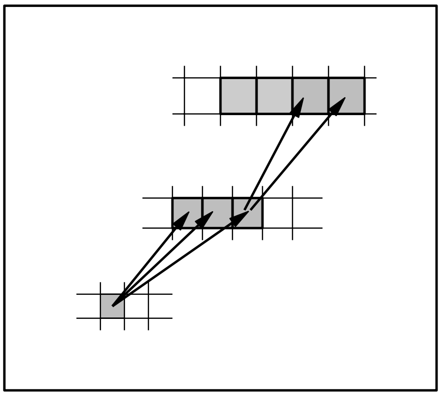
Pretrigger Sources



- Localised cluster in calorimeter above energy threshold
- $p_T \geq 1$ GeV

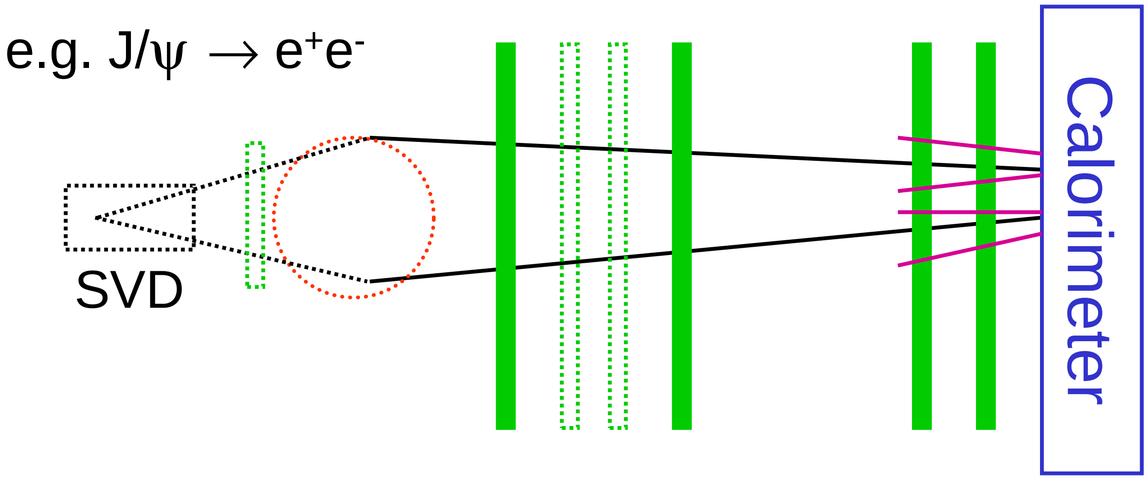


- muon track candidates
- combination of fired pads in the last two muon superlayers



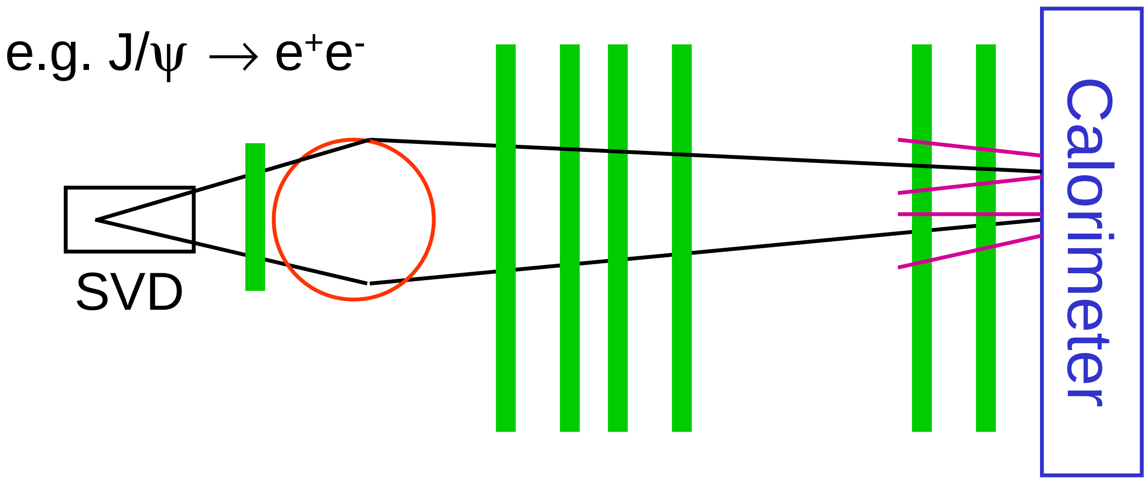
- High-p_T ($\geq$ 1.5 GeV) track candidates
- fired pads in the three high-p_T superlayers in the magnetic field

First Level Trigger



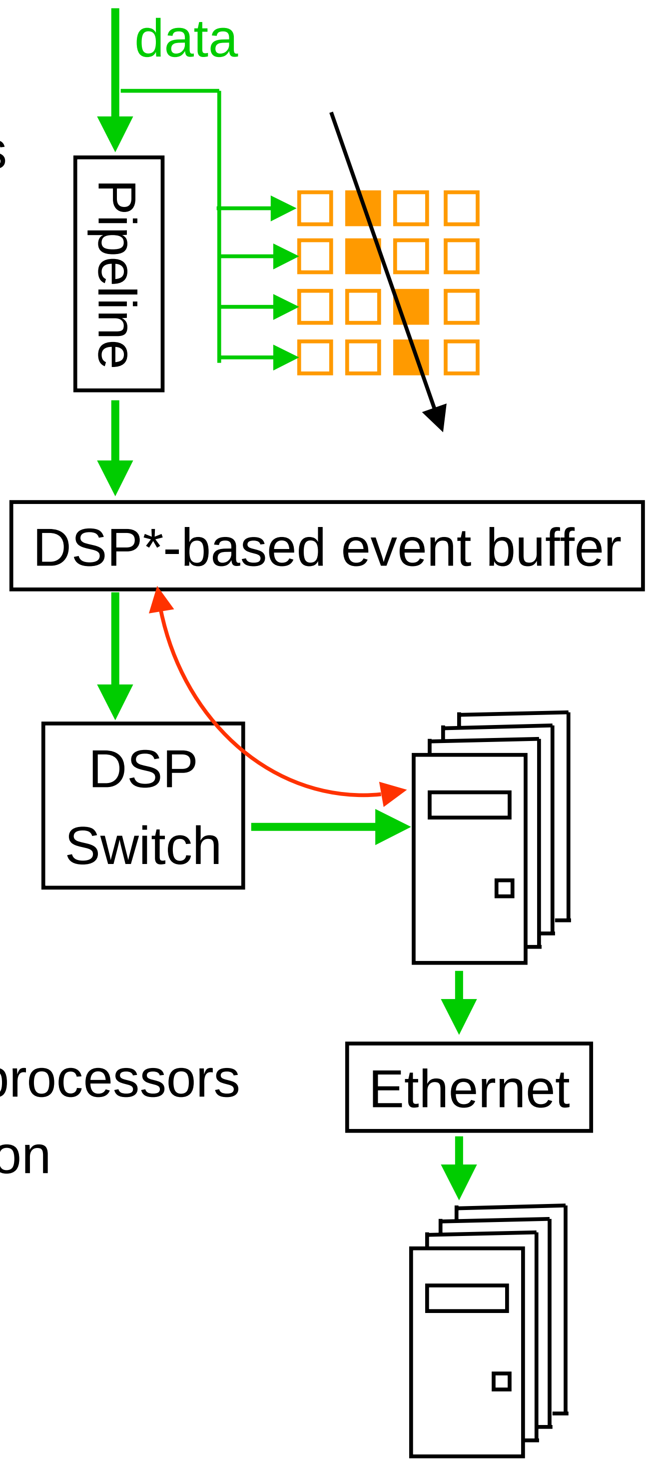
- develops RoIs supplied by the pretriggers into tracks behind the magnet
- uses hit data from selected superlayers
- estimate momentum using target constraint
- calculate invariant masses of track pairs and p_T

Second Level Trigger



- gets RoIs from FLT
- repeat tracking in RoIs using more superlayers and the full chamber resolution
- propagate RoI thru the magnetic field
- reconstruct trajectories in SVD RoIs
- vertexing with trigger particles or impact parameter cuts

Trigger Implementation



FLT

- custom-made electronics
- processors assigned to detector region

SLT

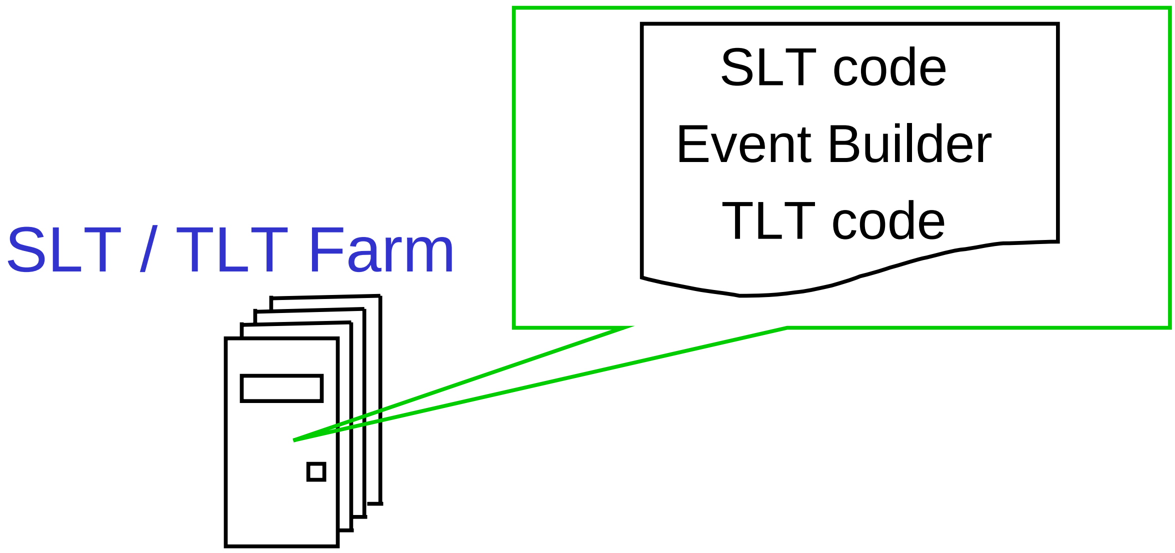
- Linux PC farm with 240 processors
- processors assigned to events

4LT

- Linux PC farm with 200 processors
- online event reconstruction
- check quality of run data

* Digital Signal Processor

Where is the TLT ?



- same processor which made the SLT decision
- after the event building
- has the full event data at its disposal
- input rate is 500 Hz
- expected reduction is 10
- available time per event is limited to 100 ms

What is the TLT ?

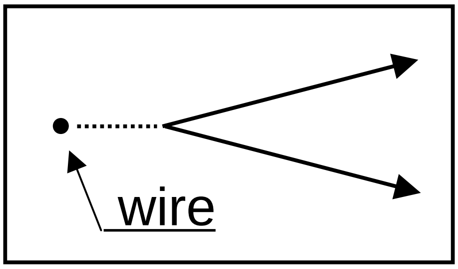
Definition (after Technical Design Report) :

A system which is to supply additional suppression when the information in the RoIs does not suffice to bring down the rate to an acceptable level (at a reasonable signal efficiency).

- uses data outside of the RoIs
- targeting at:
    - decay modes with potentially fewer kinematic constraints than $J/\psi \rightarrow l^+l^-$
    - trigger settings that are likely to require more suppression (in particular single FLT-SLT track triggers)
- extend HERA-B's physics program

Trigger Examples

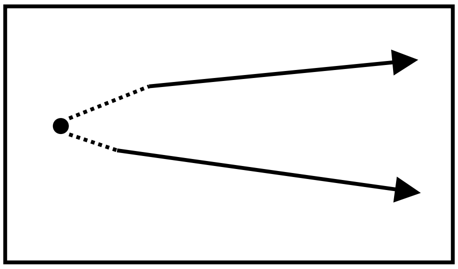
a) $B \to J/\psi(\to l^+l^-)\ X$



→ without TLT

- Pretrigger: lepton ID, p_T
- FLT: tracks, p_T,M_{inv}
- SLT: p_T, track quality, M_{inv}, same wire, vertex quality and position, momentum sum points back to wire

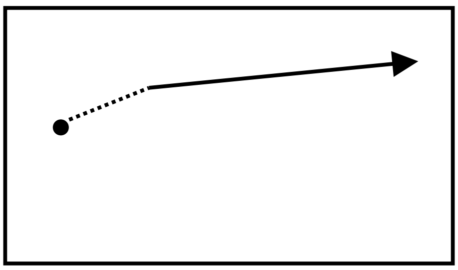
b) $BB \to ll\ XY$



→ TLT candidate

- Pretrigger: lepton ID, p_T
- FLT: tracks, p_T
- SLT: p_T, track quality, same wire, impact parameter cuts

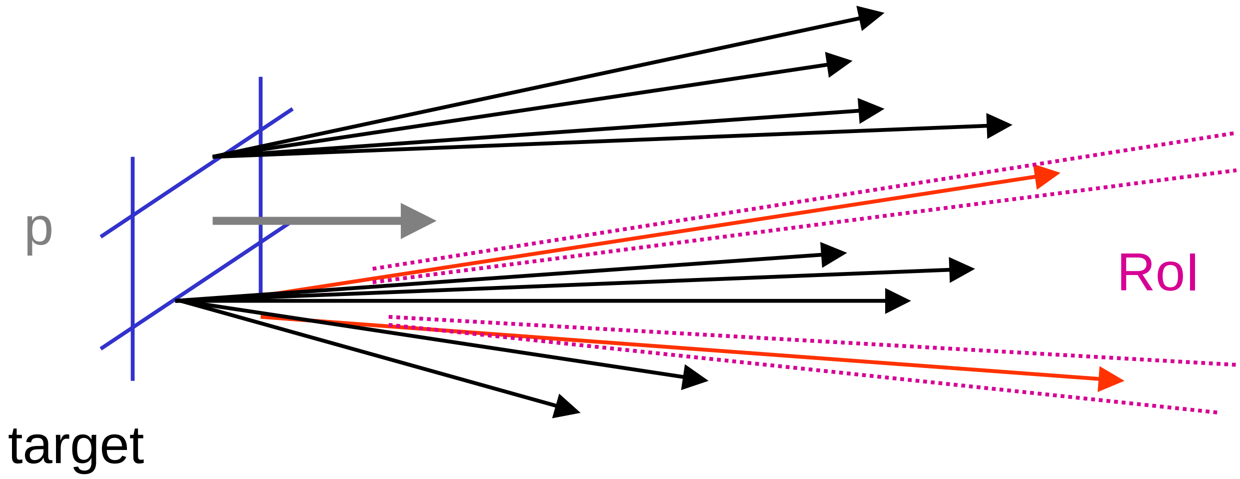
c) $B \to l\ X$



→ strong TLT candidate

- like (b)
- cuts can only be applied to one track

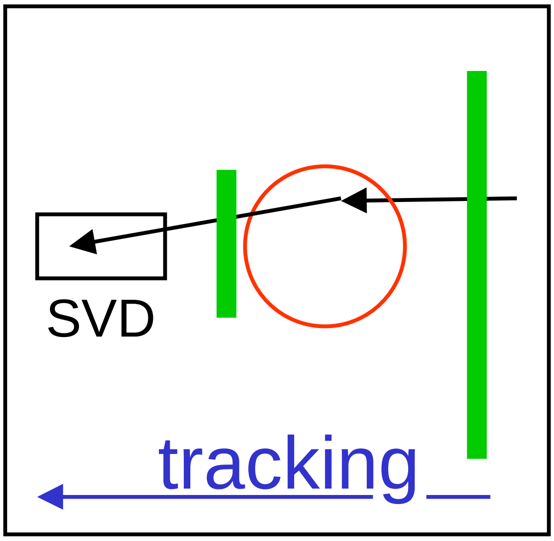
TLT Strategy

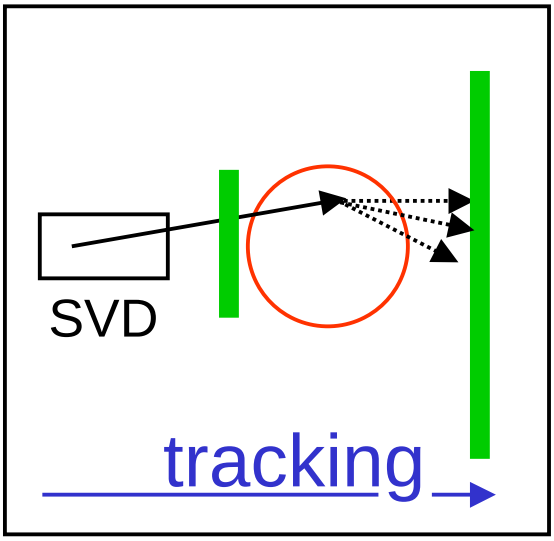


- local pattern recognition in subdetectors possible
- usage of more than one subdetector too close to complete event reconstruction
- interaction (i.e. target wire) which caused the trigger already known at SLT
- standalone information of PID devices (calorimeter, Cerenkov counter) difficult to relate to the triggered interaction

→ use Silicon Vertex Detector

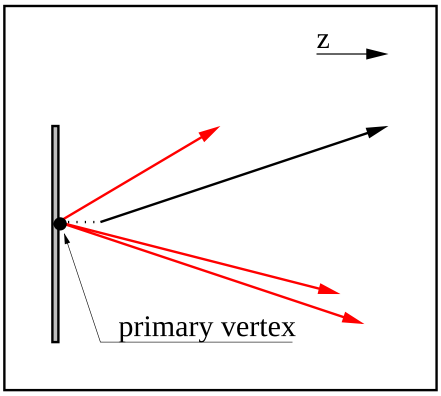
Silicon TLT



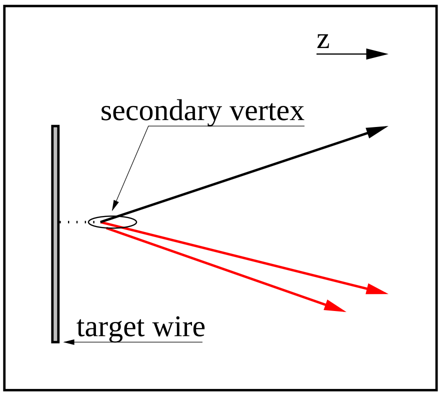


- Pros:
  - SLT information can partially be exploited as starting point
  - only tracks from SLT wire have to be reconstructed
- Cons:
  - no momentum information for found tracks
    - track resolution might suffer
    - no kinematic decay reconstruction
  - tracking SVD → Magnet more difficult than Magnet → SVD (target constraint usable)
    - prolongation of tracks complicated

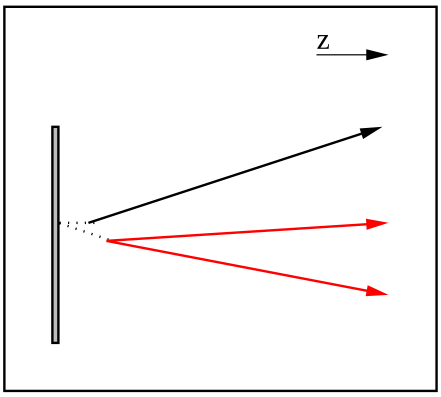
TLT Approaches



- find primary vertex
- place cuts on distance track-vertex instead on track-wire



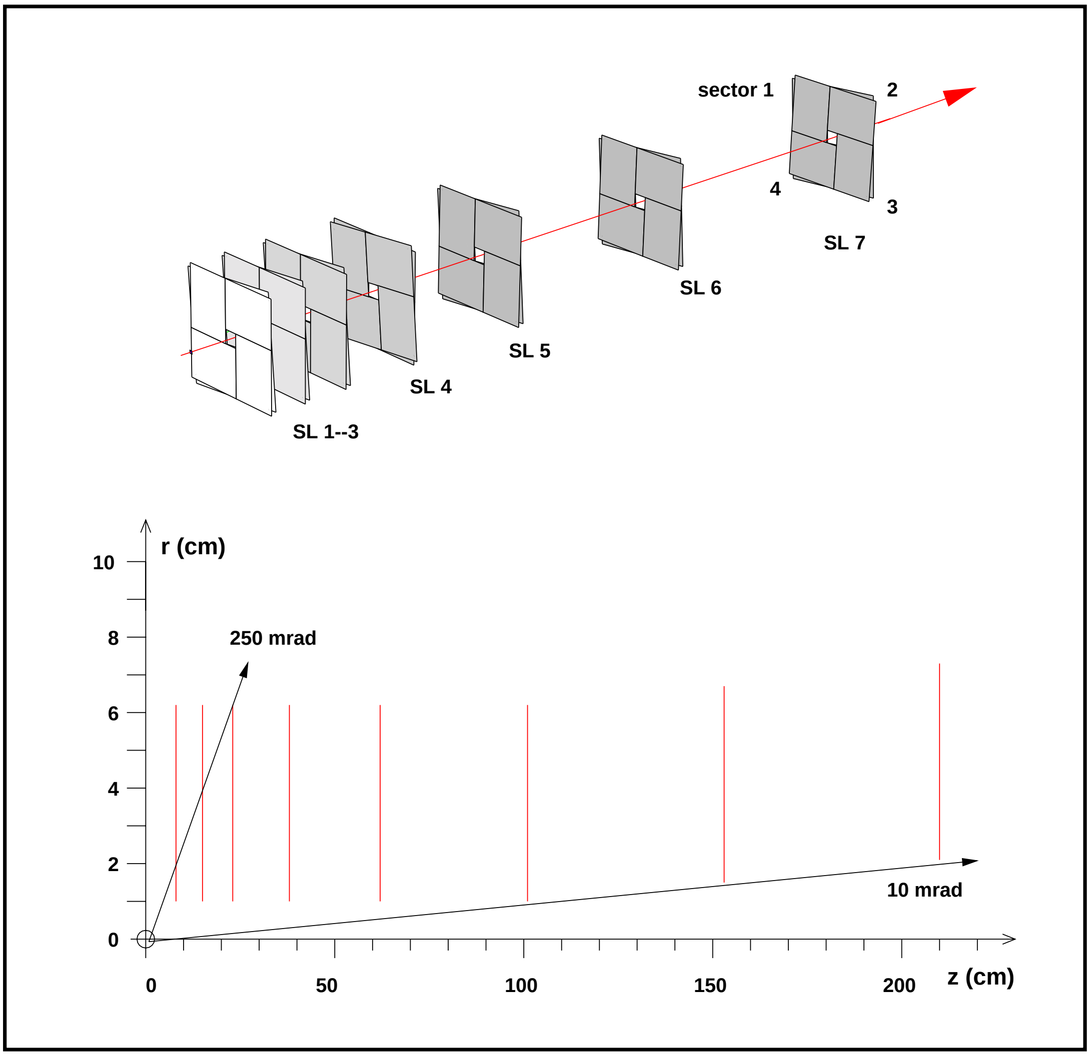
- search for secondary vertices downstream of target wire



- search for tracks with large impact parameters outside of the RoIs

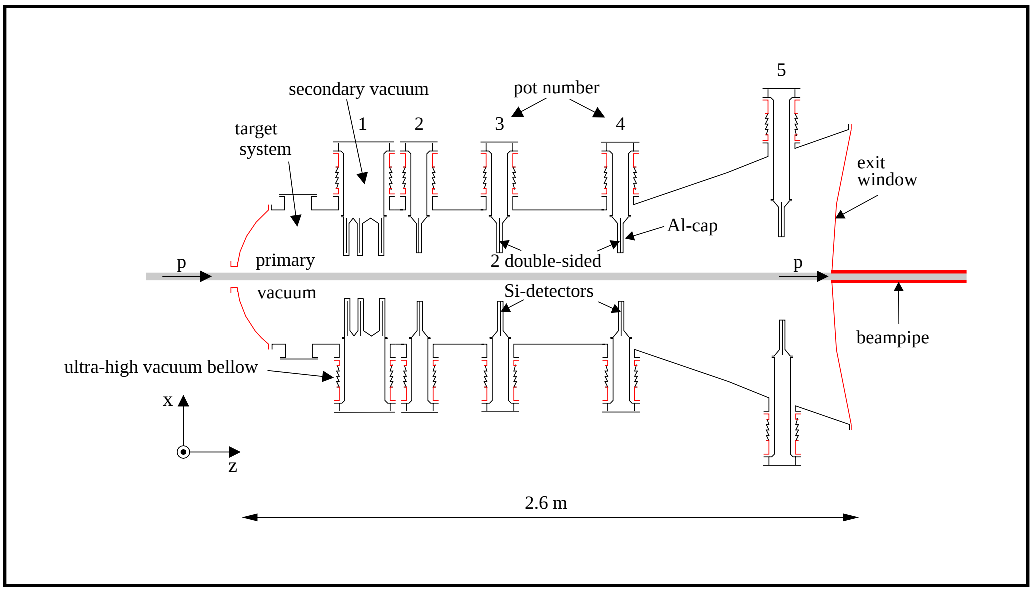
SLT tracks / TLT tracks

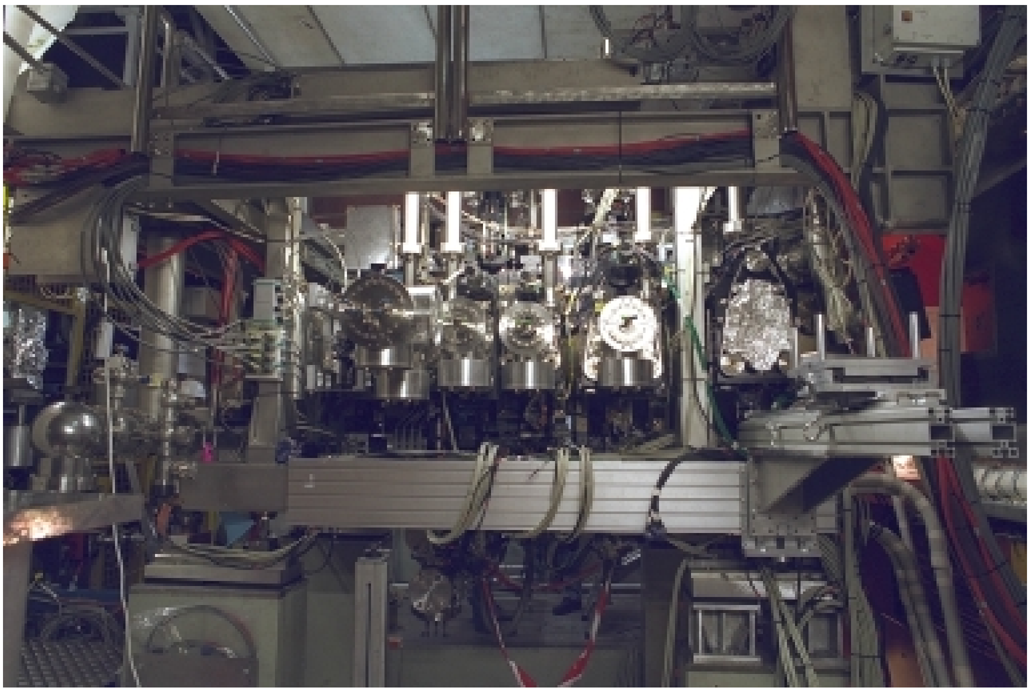
Silicon Vertex Detector



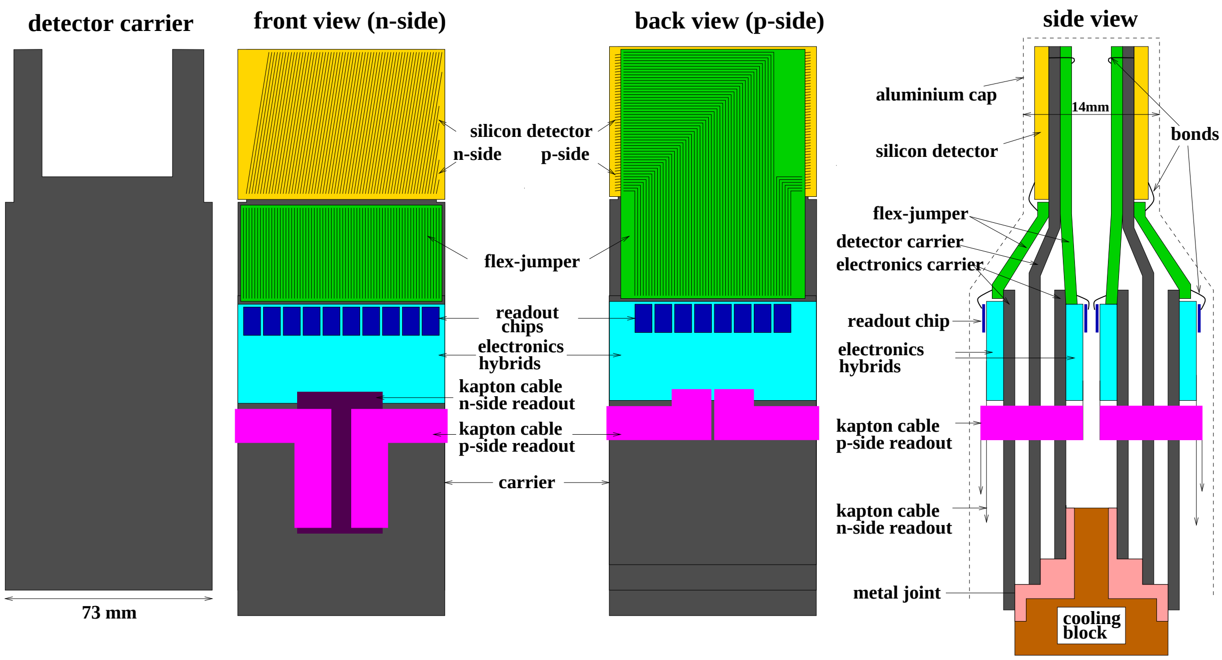
- 7+1 superlayers
- 150,000 readout channels
- acceptance 10 - 250 mrad
- 4 sectors per superlayer

Vertex Vessel





SVD Modules

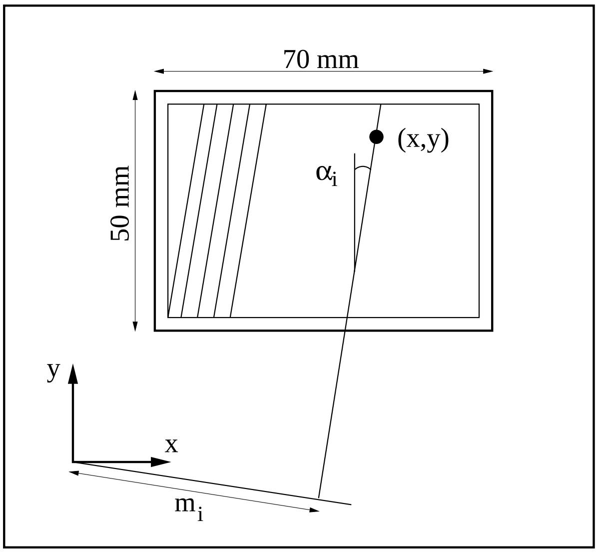


- double-sided silicon detectors (280 µm)
- 50 µm readout pitch
- 4 stereo angles: ±2.5° with respect to x- and y-axis

Work on TLT Studies

- SVD pattern recognition
  - TLT tracking by S. Scharein
    - sufficiently fast
    - reconstructed tracks online, used on the 4LT farm for data quality checks
  - standard SVD reco CATS
    - better efficiency than TLT tracking
    - competitive timing
- track fit
  - Kalman filter
- trigger algorithms

Track Fit

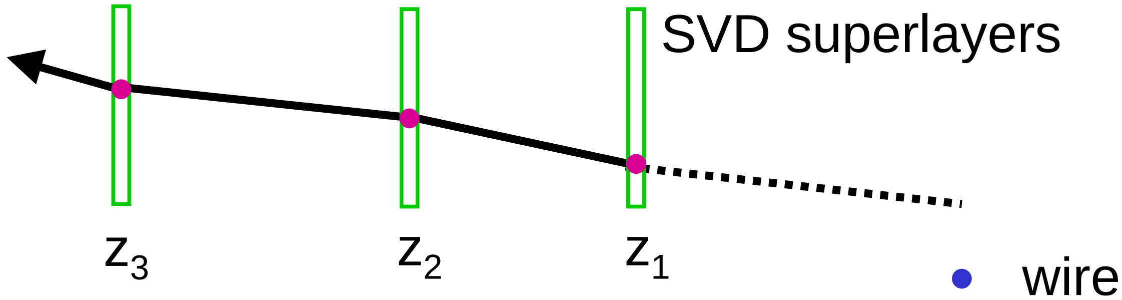


- determine track parameters at target
- track resolution is limited by MS in detector material
  - single hit resolution is 12 μm
  - MS angle for 1 GeV particle in 280 μm Si is 0.7 mrad → 70 μm offset when extrapolating over 10 cm
- 4-dim. track vector:

$$t = (x(z_{ref}), y(z_{ref}), t_x, t_y)$$

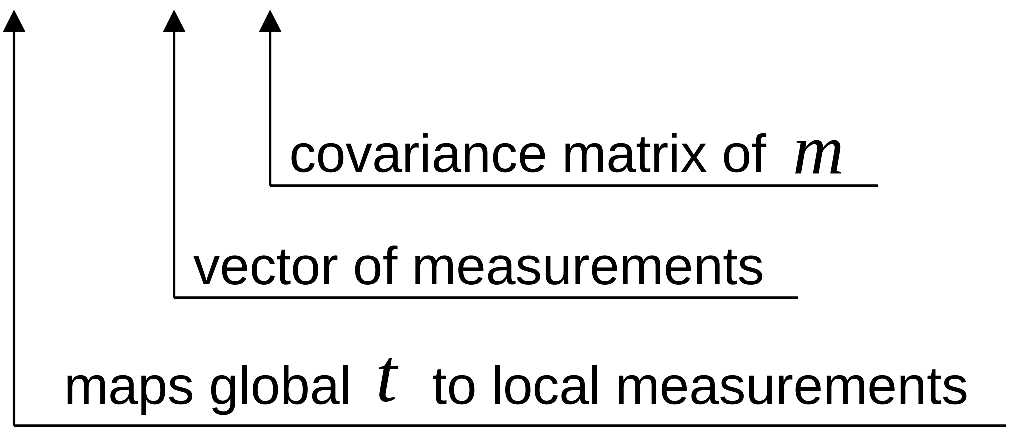
- measurement: $m_i = x \cos \alpha_i - y \sin \alpha_i$

Global Track Fit



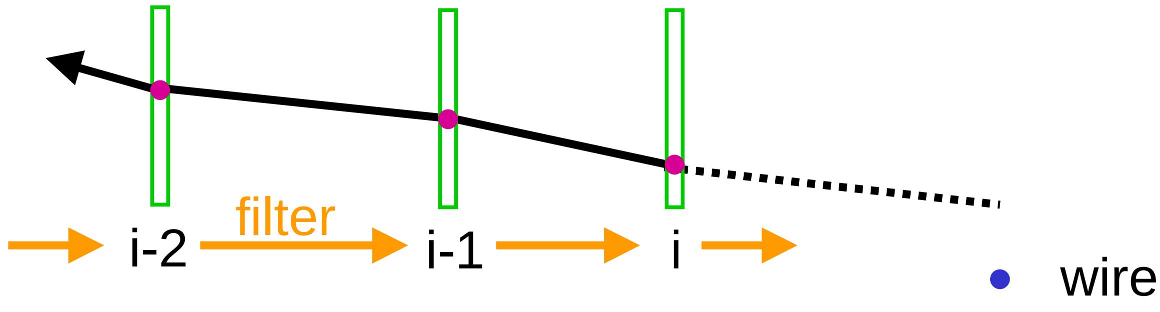
- obtains global track parameters

$$(Ht - m)^T V^{-1} (Ht - m) \rightarrow \min$$



- only applicable for tracks which do not suffer much from MS (p_{track} > 8 GeV)

Kalman Filter



- provides the best estimate for the local track parameters at each z_i

transport of track parameters

$$\hat{t}(z_i) = F(z_i, z_{i-1})\, t(z_{i-1})$$

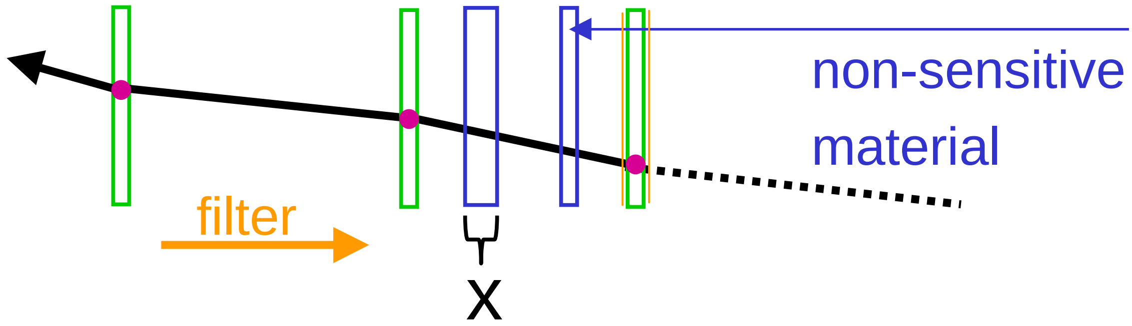
$$C(z_i) = F(z_i, z_{i-1})\, C(z_{i-1})\, F^T(z_i, z_{i-1})$$

covariance matrix of $t(z_{i-1})$

$$\underbrace{(t-\hat{t})^T C'^{-1} (t-\hat{t})^T}_{\text{old/new trackparam.}} + \underbrace{(H_i t - m_i) V^{-1} (H_i t - m_i)^T}_{\text{local measurement}} \rightarrow \min$$

- filter proceeds from measurement to measurement
- predicted track parameters are regarded as additional measurements at each z_i

Multiple Scattering



- MS dilutes knowledge of track parameters between two measurements
- covariance matrix of track parameters is updated according to amount of MS*:

$$C'(z_i) = C(z_i) + Q_{MS}$$

$$\sigma^2(t_x) := \sigma^2(t_x) + \theta^2(x/x_0)$$

$$\sigma^2(t_y) := \sigma^2(t_y) + \theta^2(x/x_0)$$

$$\theta(x/x_0) = \frac{13.6\ \mathrm{MeV}}{\beta cp}\hat{z}\sqrt{x/x_0}$$

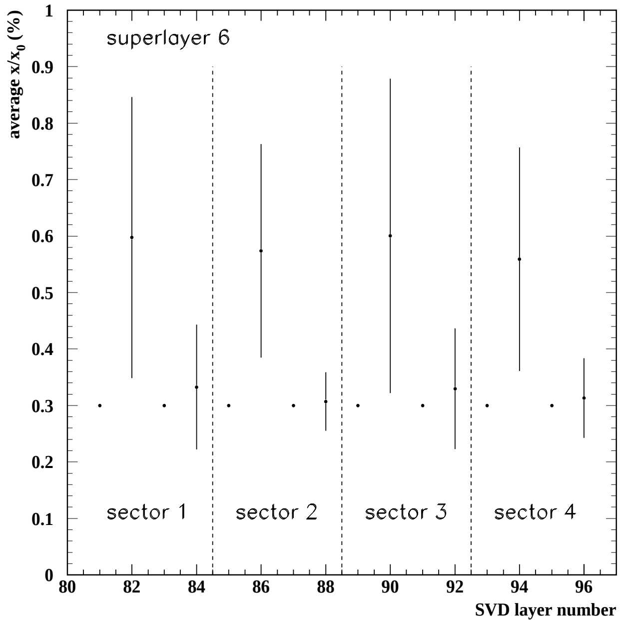
Problems:

momentum not known

evaluation of all scatterers is too time-consuming

* assumes $t_x^2 \approx t_y^2 \approx t_x t_y \approx 0$

Approximating x/x_0

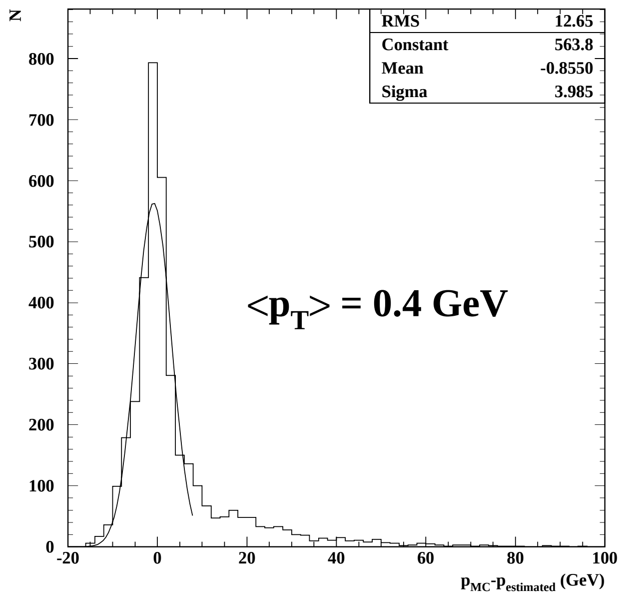


- MC tracks are followed through SVD
- consecutive scatterers are combined into one effective scatterer:

$$\left.\frac{x}{x_0}\right|_{\text{effective}} = \sum_{i=1}^{M} \frac{x^{(i)}}{x_0^{(i)}}$$

- material traversed between two measurements averaged over counter surface according to radial distribution of MC tracks

Approximating p

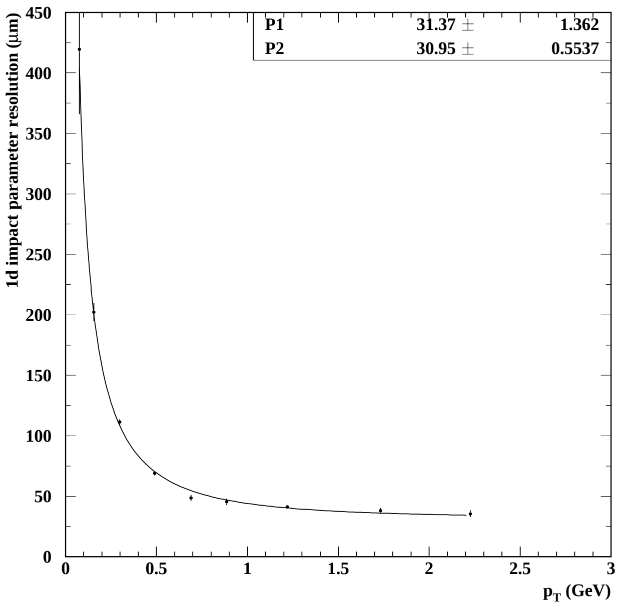


- t_x and t_y are only available information
- momentum is estimated as:

$$p_{\text{estimated}} = \langle p_T \rangle \sqrt{1 + \frac{1}{t_x^2 + t_y^2}}$$

- average p_T is adjusted to result in ‘reasonable’ pulls $(t_x - t_x^{MC})/\sigma(t_x)$ for the track parameters
- average p_T is roughly 0.4 GeV

Impact Parameter Resolutions



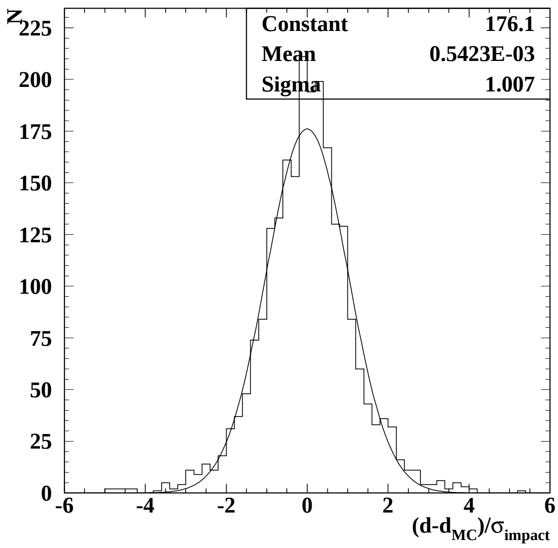
- impact parameter resolution (A,B=const., [A]=μm, [B]= μm·GeV):

$$\sigma(\mathrm{d}) = \sqrt{\mathrm{A}^2 + (\mathrm{B}/p_T)^2}$$

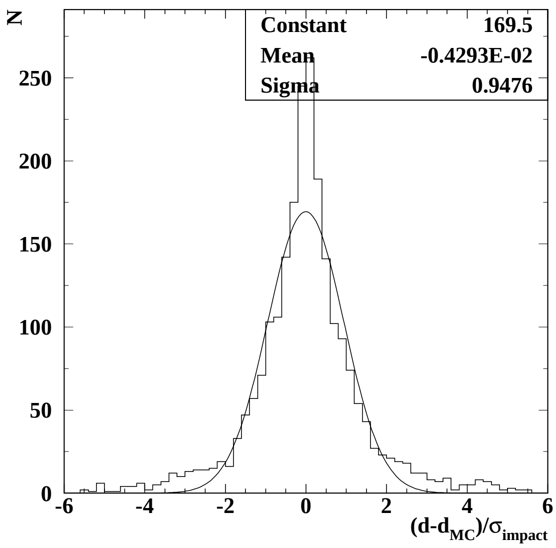
- results:

	σ(d) (μm)
Ideal PR, p known	$23 \oplus 31/p_T$
Ideal PR, p estimated	$31 \oplus 31/ p_T$
TLT tracking	$31 \oplus 31/ p_T$
HERA-B Proposal	$25 \oplus 30/ p_T$

Pulls of Impact Parameters

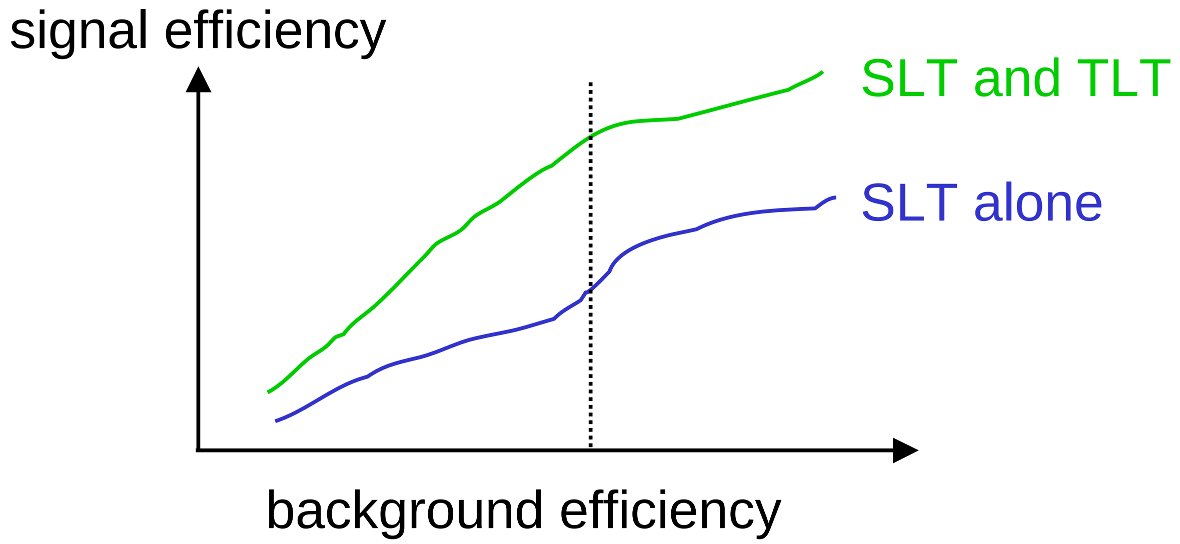


- ideal pattern recognition
- momentum known



- ideal pattern recognition
- momentum estimated

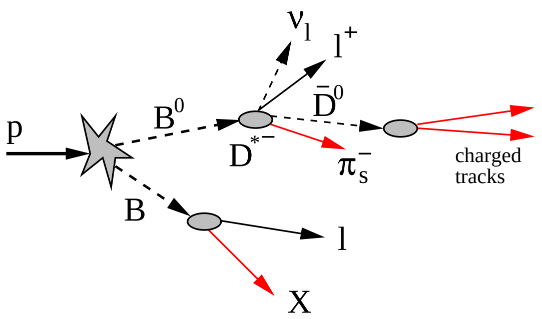
TLT Studies



- cuts which will be applied by SLT not precisely known
- even modest cuts on e.g. impact parameters reduce the available MC statistics severely
- investigate whether the joint effort of SLT and TLT results in a higher signal efficiency at the same background suppression

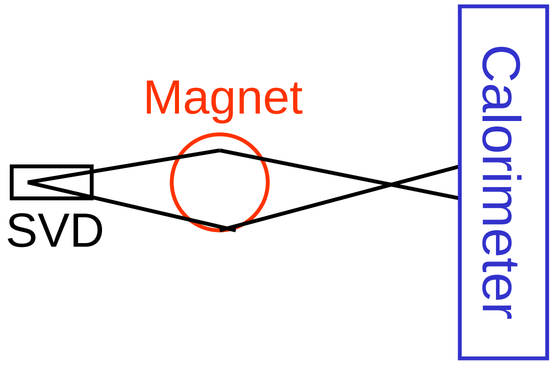
Data Samples

Signal Sample



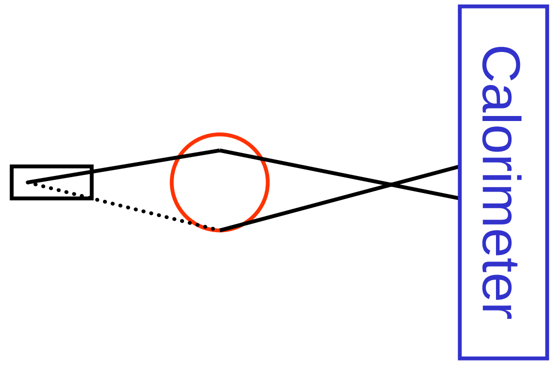
- Double-semileptonic B decays
- $B^0 \to l\nu_l\ D^{*-}(\to D^0\pi^-)$
- $p_T^{Leptons} > 1$ GeV

Misidentification Sample



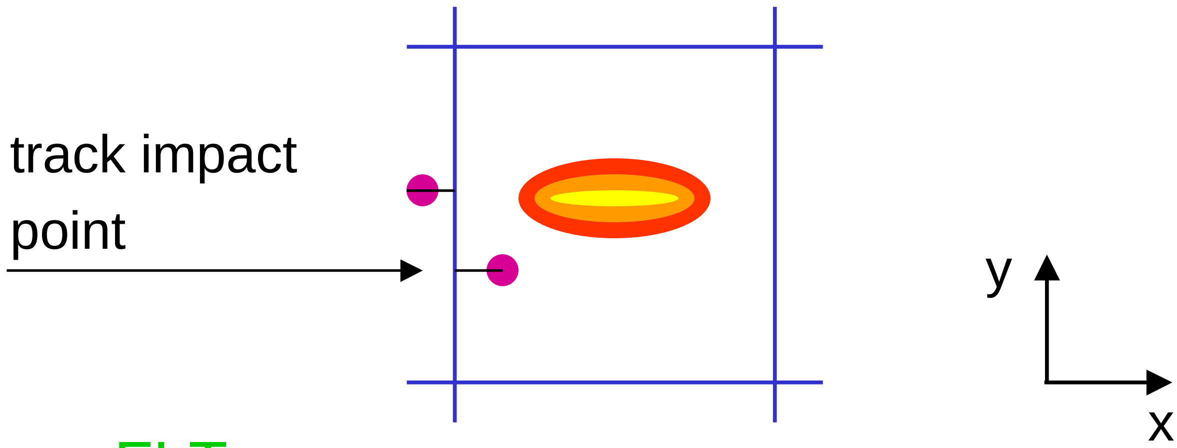
- High-p_T inelastic events
- two hadrons misidentified as leptons
- $p_T^{Fake\ leptons} > 1$ GeV

Tracking Error Sample



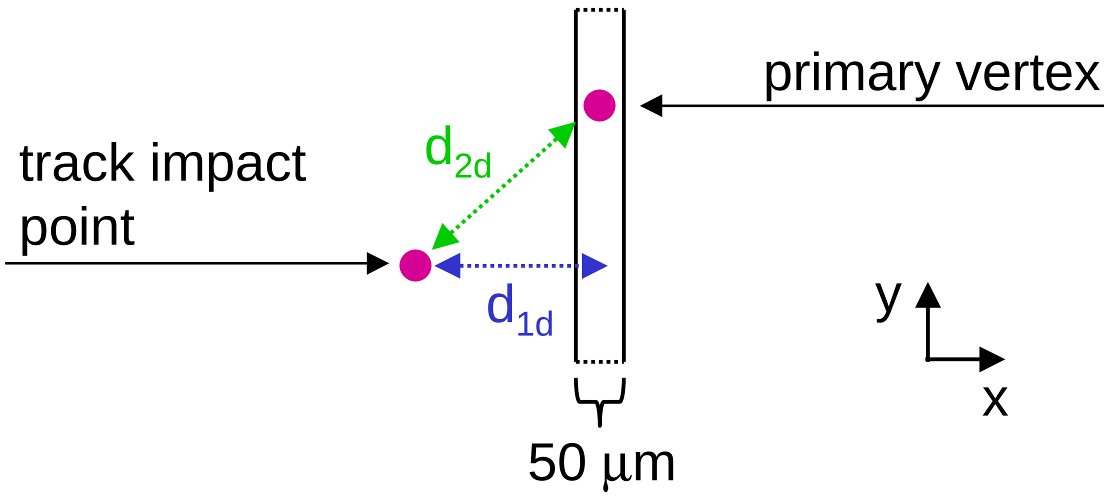
- Like misid sample, but SLT finds one wrong track segment in SVD
- randomly selected 2^{nd} trigger particle

Trigger Simulation



- FLT
  - does not resolve target region
  - count trigger assumed
    - p_T cut on trigger particles
    - any flavour combination
- SLT
  - ideal pattern recognition for trigger particles
  - acceptance: at least three hits in both x- and y-view
  - Kalman fit using MC momentum
  - assigned to same target wire (DCA<3 mm)
- TLT
  - discards tracks sharing >50% of hits with trigger tracks

Primary Vertex Finding

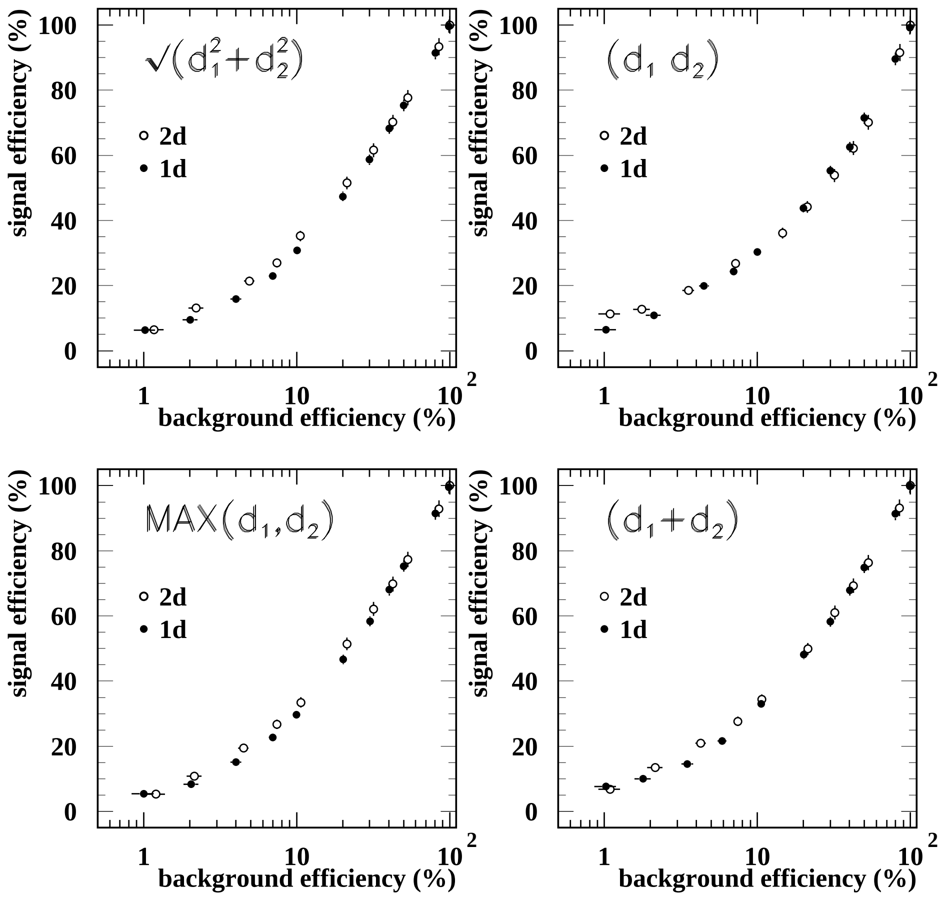


- resolution of primary vertex:
  - σ_x=14 μm, σ_y=28 μm, σ_z=143 μm
- combining IPs d_1 and d_2 of the two trigger particles in four ways:

$$f(d_1, d_2) = \sqrt{d_1^2 + d_2^2}, d_1 \cdot d_2, \max(d_1, d_2), d_1 + d_2$$

- accept events with $f(d_1,d_2)$>cut for both d_{1d} and d_{2d}
- vary cut to obtain desired background suppression

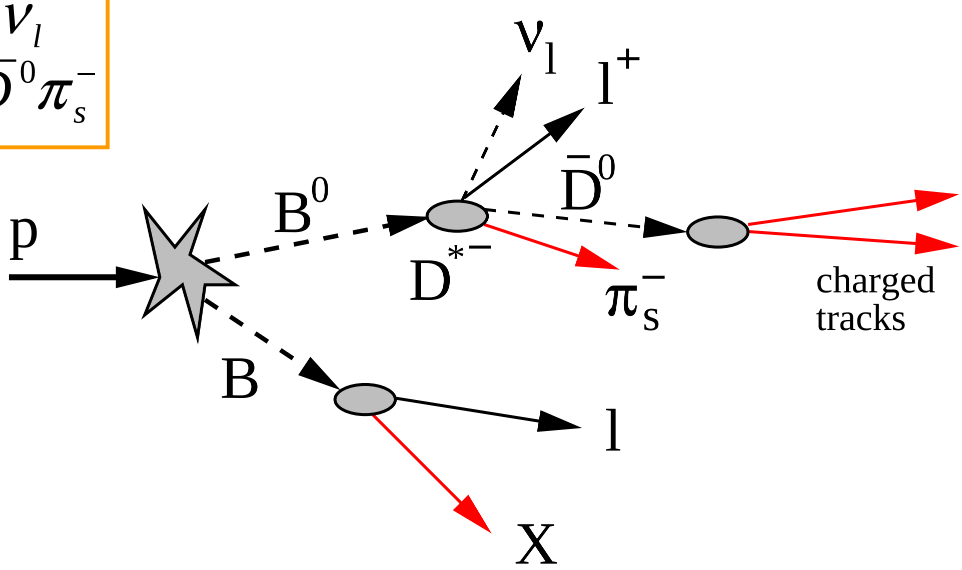
Result



- only weak dependence on choice of $f(d_1,d_2)$
- using d_{2d} instead of d_{1d} does not result in an efficiency gain

Vertex Finding

$$B^0 \rightarrow D^{*-} l^+ \nu_l$$
$$\quad \hookrightarrow \bar{D}^0 \pi_s^-$$



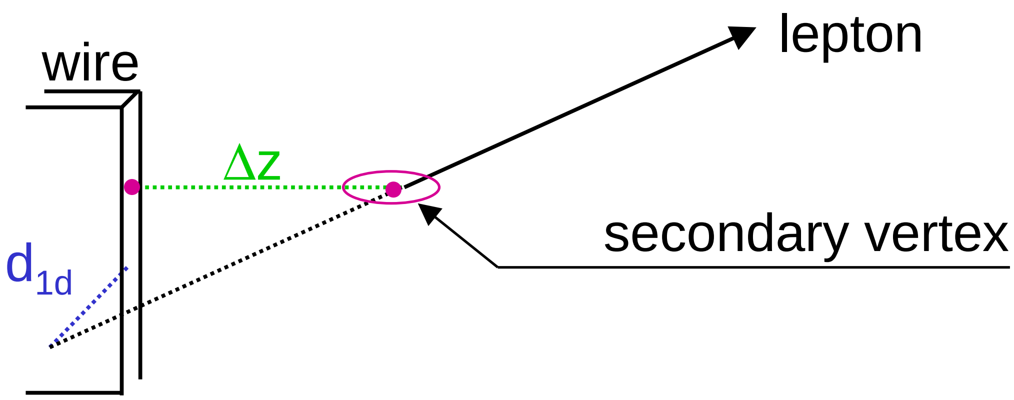
- general-purpose vertex search extremely challenging
- vertexing with SLT leptons in above channel

particle	cτ (μm)	βγτc (mm)	⟨p (GeV)	⟨p_T (GeV)
B^0	468	11.2	131	2.4
D^{*-}	≅0	≅0.0	67	1.6
D^0	124	4.2	63	1.5

- studied vertex resolution and vertex recognition

Vertex Resolution

Can cuts on Δz compete with impact parameter cuts?



significance of d_{1d} for trigger lepton with $p_T \geq 1$GeV:

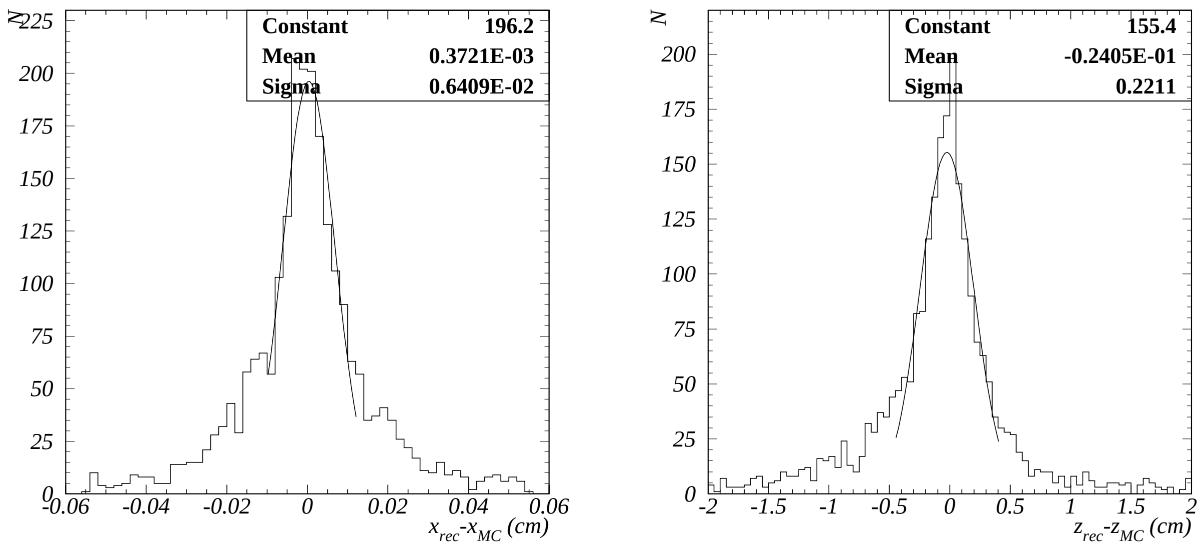
$$\frac{d}{\sigma(d)} \cong \frac{468\ \mu\text{m}}{\sqrt{2}\cdot 39\ \mu\text{m}} = 8.5$$

required resolution of the vertex coordinate in z:

$$8.5 = \frac{\Delta z}{\sigma(\Delta z)} = \frac{\langle c\tau\beta\gamma\rangle}{\sigma(\Delta z)} = \frac{11.2\ \text{mm}}{\sigma(\Delta z)} \qquad \sigma(\Delta z) \cong 1.3\ \text{mm}$$

$J/\psi \to l^+l^-$ has $\sigma(\Delta z) \approx 500\ \mu$m ....

Lepton-π_s Vertex

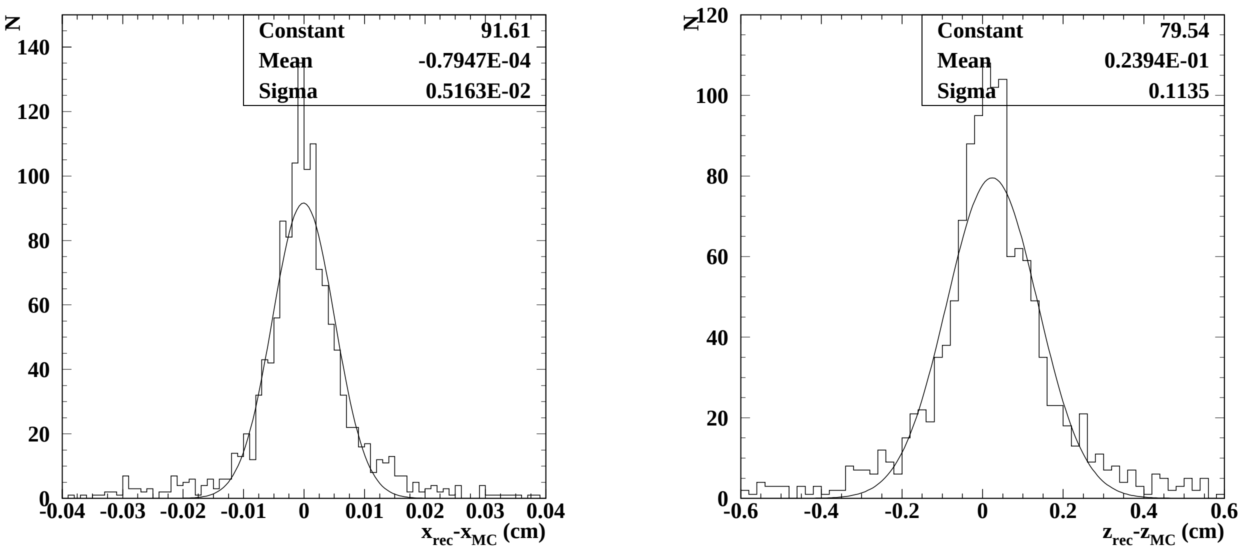


- ideal pattern recognition of tracks
- lepton fitted with p_{MC}, π_s with momentum approximation
- ideal vertex recognition

particle	p (GeV)	⟨p_T (Gev)	$\sigma_{x,y}$ (µm)	σ_z (µm)
l^+	31.9	1.73		
π_s	3.5	0.15	65	2200

→ poor resolution in z due to low π_s momentum

Lepton-Kaon Vertex



trigger lepton and kaon from D^0

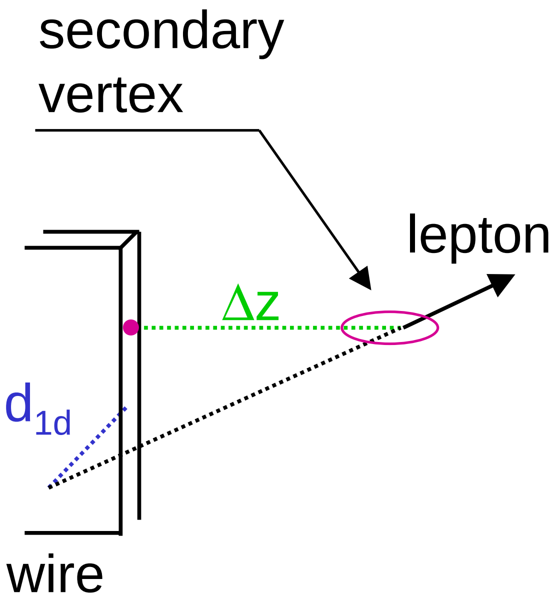
- e.g. $D^0 \rightarrow K\ \pi$
- ideal recognition of tracks and vertices

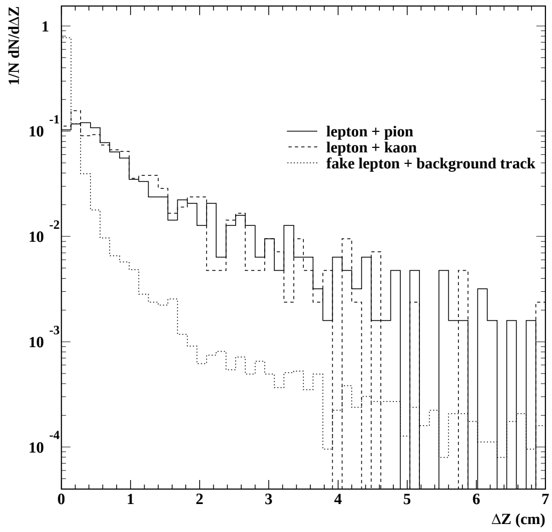
particle	p (GeV)	⟨p_T (Gev)	$\sigma_{x,y}$ (μm)	σ_z (μm)
l^+	31.9	1.73		
K	17.5	0.84	50	1100

$\rightarrow$ reproduces position of B vertex better than the π_s

$\rightarrow$ systematic shift in z of $\approx$200 μm

Vertex Recognition

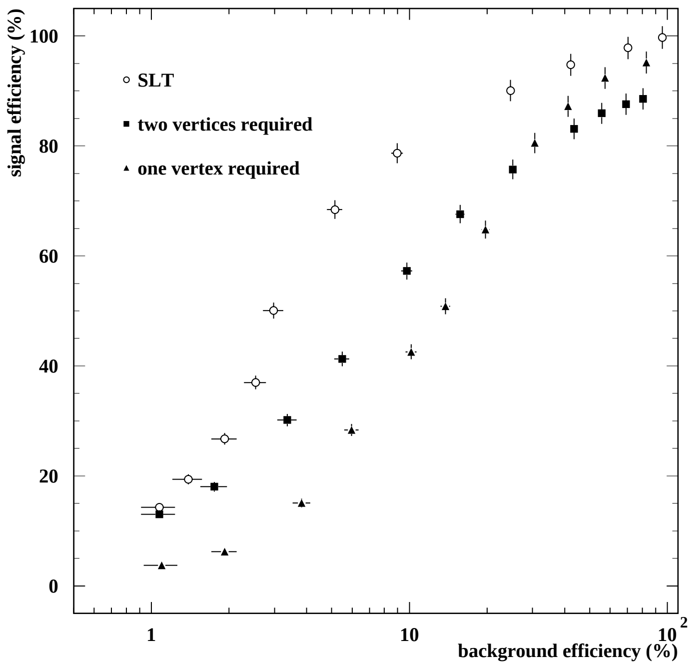




DCA < 500 μm

- ideal pattern recognition of tracks
- weak angular correlations between decay particles → not exploited
- cut on DCA of particles and quality of vertex candidates
- no cut on IP of candidate tracks

Efficiency

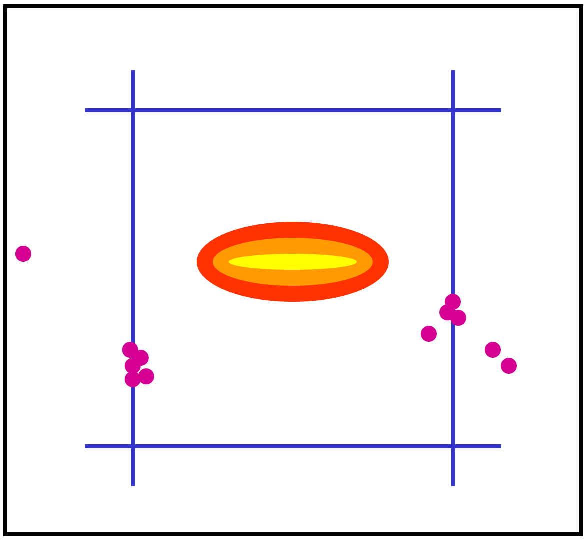


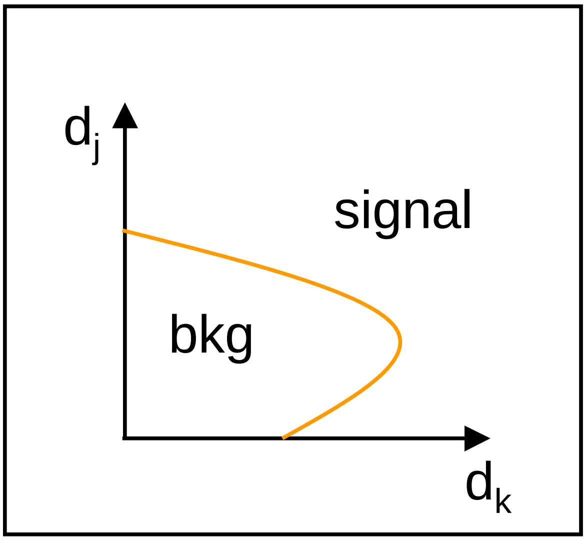
- accept vertices in window 0≤ Δz ≤ 7 cm
- vary lower edge to reject fake vertices
- SLT assumed to cut on $\sqrt{d_1^2 + d_2^2}$

→ factor 10 suppression reached for Δz > 4 mm

→ but SLT gives better signal efficiency at same background suppression

Track Trigger





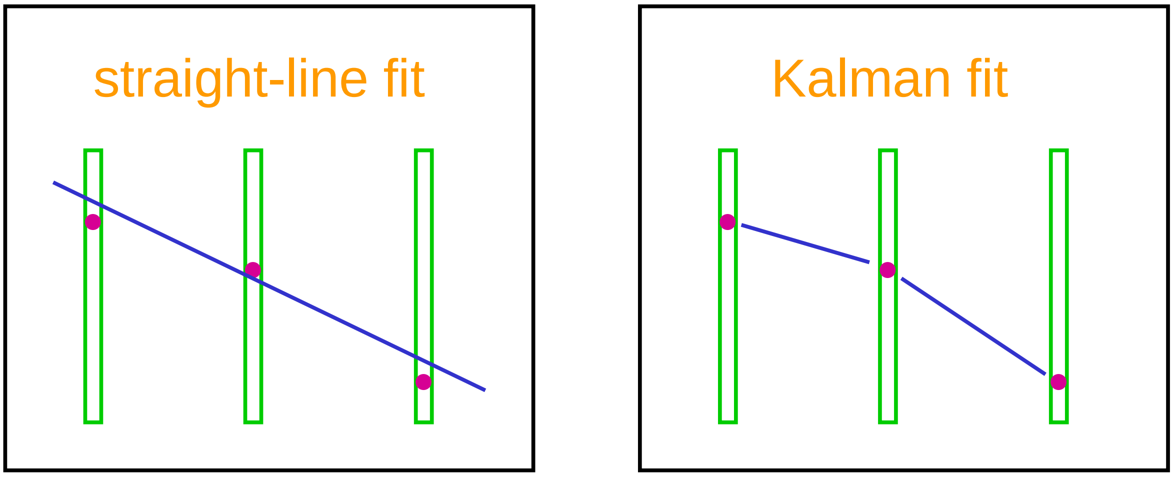
- based on measured impact parameters of additional tracks
- find a discriminator function

$$S = F(d_1, \ldots, d_N; \sigma_1, \ldots, \sigma_N; \ldots)$$

- accept events with $S > S_{cut}$ (if large S denote likely signal events)
- ansatz:

$$S = \frac{1}{N} \sum_{i=1}^{N} w_i \left(\frac{d_i}{\sigma(d_i)} \right)^q$$

Track Selection

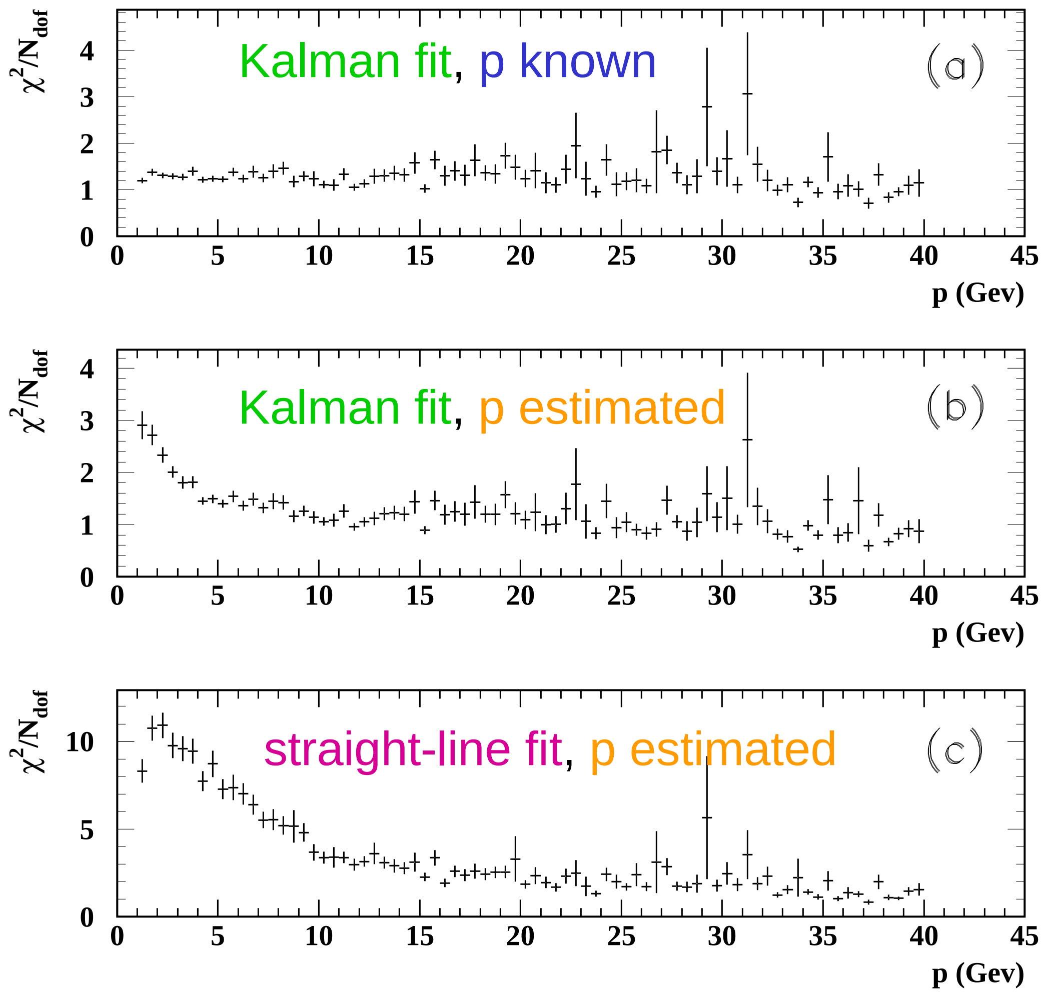


- exclude likely ghost tracks and trigger tracks from hadron decays in flight: d_{max}<1 mm
- exclude tracks with small impact parameters (smaller than IP of trigger particles)
- empirical: q=1 is a good choice
- adjust weights

$$w_i = \frac{1}{\sqrt{\chi^2 / N_{dof}}}$$

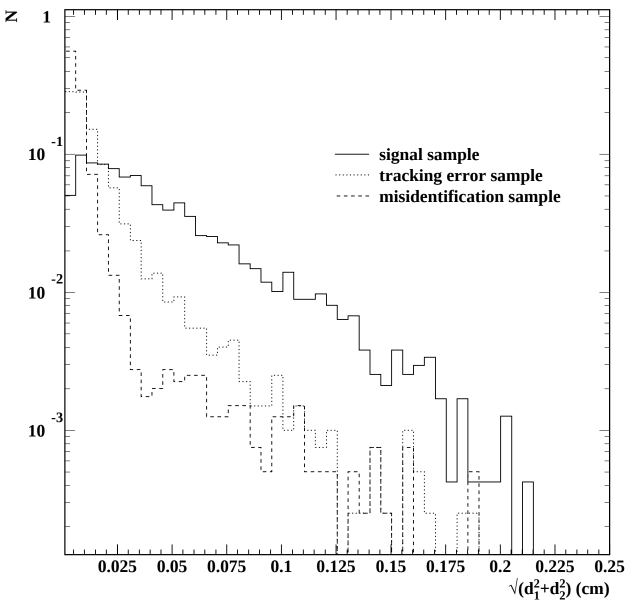
  - χ^2 of straigh-line fit
  - Kalman fit hides multiple scattering

χ^2/dof



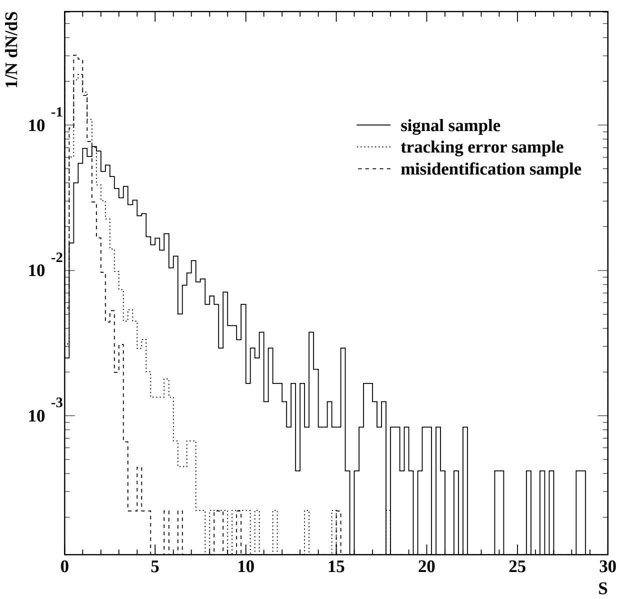
χ^2/N_{dof}
Kalman fit, p known
(a)
p (Gev)
Kalman fit, p estimated
(b)
straight-line fit, p estimated
(c)

Cut Quantities



SLT only:

cut on $\sqrt{d_1^2 + d_2^2}$



SLT and TLT:

SLT imposes no cut

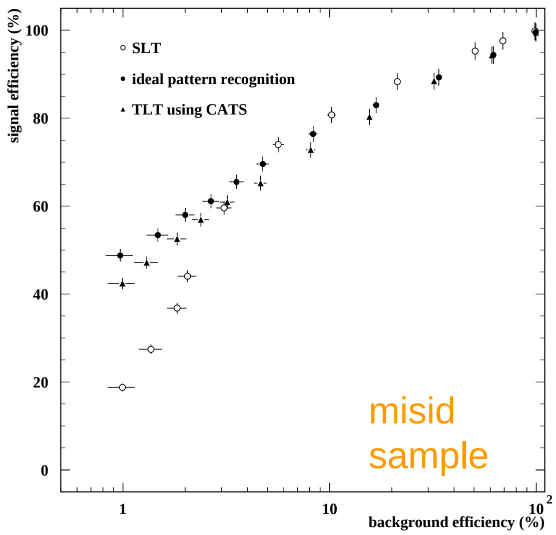
TLT calculates S

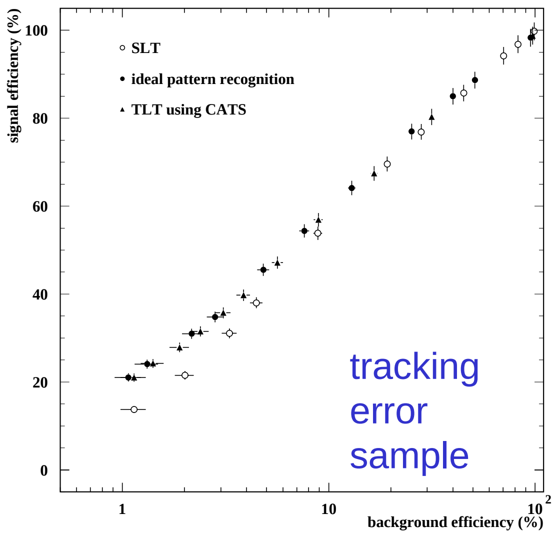
S(signal) = 3.8

⟨S(misid) = 0.9

⟨S(track-err) = 1.3

Efficiency





- tracking error sample is a more serious background
- at a suppression of 10:
  - signal efficiency 75% for misid sample
  - signal efficiency 55% for tracking error sample
  - but: SLT gave all events to TLT without imposing impact parameter cut

→ TLT tracks contribute at large suppressions

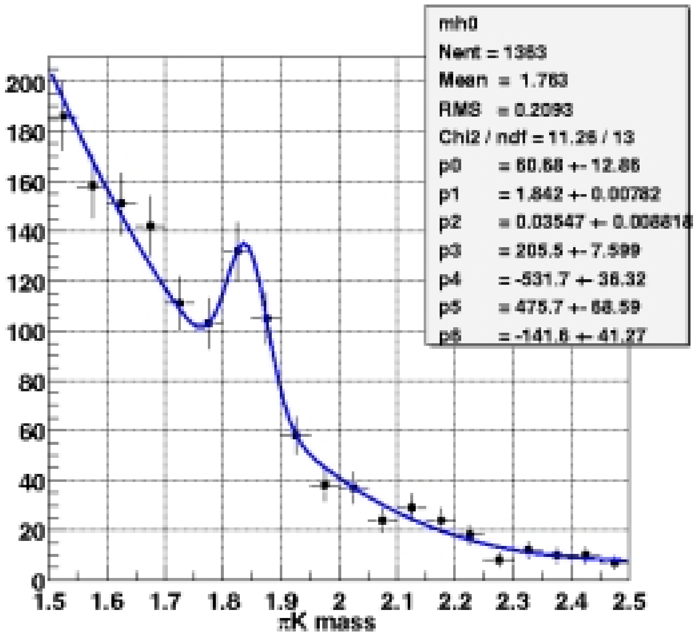
→ efficiency grows by factor 1.5 and 3

Conclusion

- Reconstruction of SVD tracks within 100 ms possible.
- Missing momentum information and not accurately known material distribution in SVD do not rule out a Silicon TLT.
- The reconstruction of the primary vertex is not of great help.
- MC studies indicate that vertexing with SLT tracks is a less promising approach than the search for more tracks from the decays cascade of B hadrons.
- Gain in signal efficiency depends on SLT cuts and nature of background samples.

$\rightarrow$ Silicon TLT can help to record data at increased signal efficiency.

Outlook



D. Dujmic

- investigate other approaches (e.g. neural networks)
- data samples for TLT studies became available in this year's data taking
- study single-lepton trigger data
  - one muon with p_T > 1.2 GeV
  - identify events with lifetime by reconstructing charm