VELO Vertexing and Tracking Algorithms of the LHCb Trigger System

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Overview

- **The challenge at LHCb**
- **LHCb trigger overview**
- **L0**
  - Overview
  - Algorithms
- **L1**
  - Overview
  - Algorithms
  - Timing
- **Conclusions**

The challenge at LHCb

- **pp interactions at $s^{1/2}$ = 14TeV**
- **40MHz bunch crossing**
- **Average luminosity “modest” $2*10^{32}cm^{-2}s^{-1}$**
- **Visible interactions at 10MHz**
  - 100kHz $b\bar{b}$ events
  - 15% with all decay products of at least one **B** contained in detector
  - Branching ratio of interesting channels 10^{-3} to 10^{-7}
- **Write events at 200Hz**
  - Not just any old events but very interesting **b** ones of course!

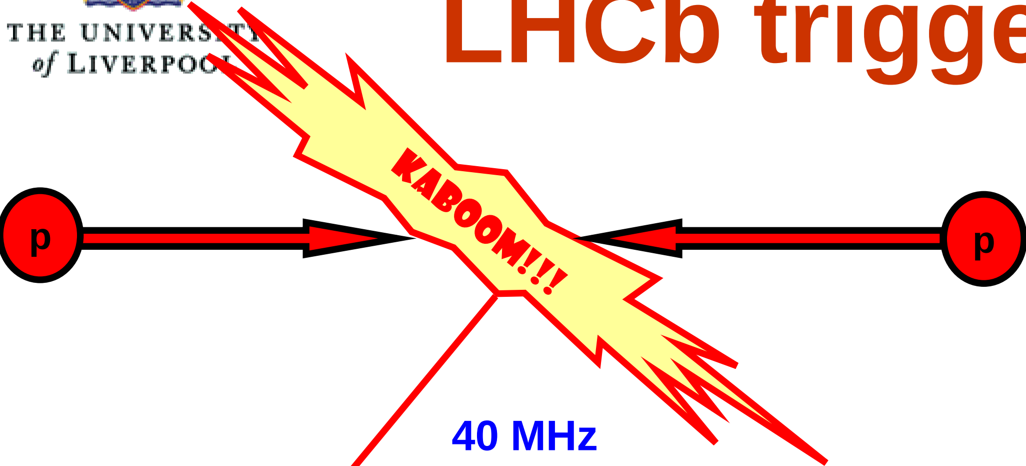
Meeting the challenge

LIKE LOOKING FOR A NEEDLE IN A SHARK-INFESTED OCEAN FULL OF HAYSTACKS

- **Fortunately B events have**
  - Displaced vertices
  - High p_T particles from B decays
- **Exploit this in a three-level trigger system**
  - **L0** hardware
  - **L1**, **HLT** software on dedicated PC farm

This talk will concentrate on the L0 and L1 vertexing and tracking algorithms

LHCb trigger overview



40 MHz

L0
Charged track multiplicity
Number of interactions
Total hadronic E_T
Large p_T, E_T lepton, hadron, γ

1MHz

L1
Track p_T
Impact parameter
$\mu\mu$ invariant mass
e, γ E_T

40kHz

HLT
High P_T, E_T
Displaced vertex
B candidate mass

200Hz

DISK

Hardware on customised electronics
Synchronous
Latency 4μs, 2μs for data processing

Software on Linux PC farm
Asynchronous
Latency up to 58 ms

Software on L1 PC farm
Use vacant CPU power
Close to offline quality reconstruction
Full LHCb tracking
Particle ID
Channel-specific event selection

Detectors in Trigger

VELO:
primary vertex
impact parameter
displaced vertex.
L1

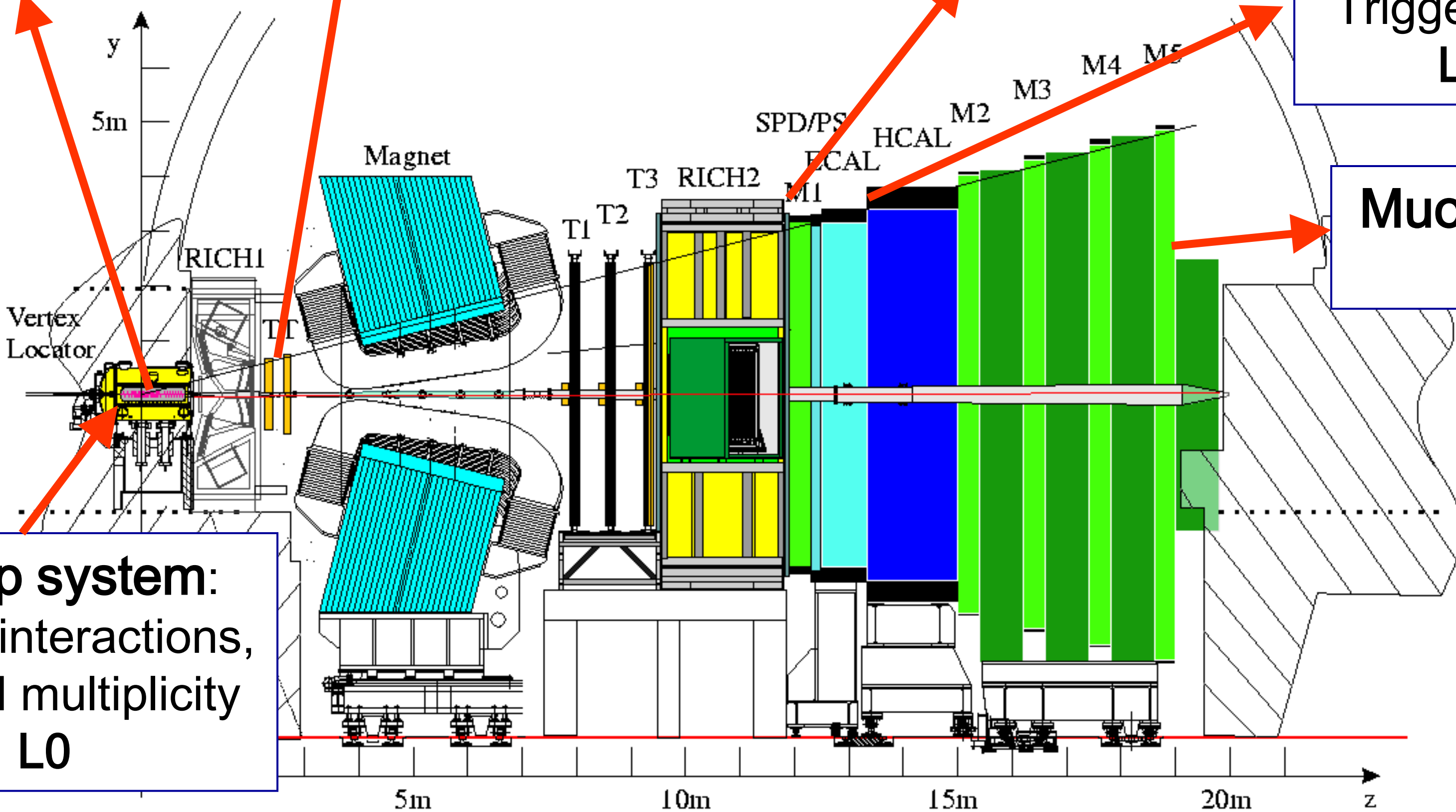
Trigger Tracker:
p, p_T
L1

SPD:
Charged multiplicity
L0

Calorimeters:
PID: e,γ, π^0
Trigger on hadr.
L0, L1

Muon System
L0, L1

Pile-up system:
multiple interactions,
charged multiplicity
L0



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L0 trigger in a nutshell

"L0 OBJECTS"

- **4×2 highest p_T muons**
  μ CHAMBERS
- **Highest E_T γ, electron, hadron candidates**
  CALORIMETERS

GLOBAL VARIABLES

- **ΣE_T**
  CALORIMETERS
- **z and # tracks in 1st, 2nd vertex**
  PILE-UP SYSTEM
- **Charged particle multiplicity**
  SPD, PILE-UP SYSTEM

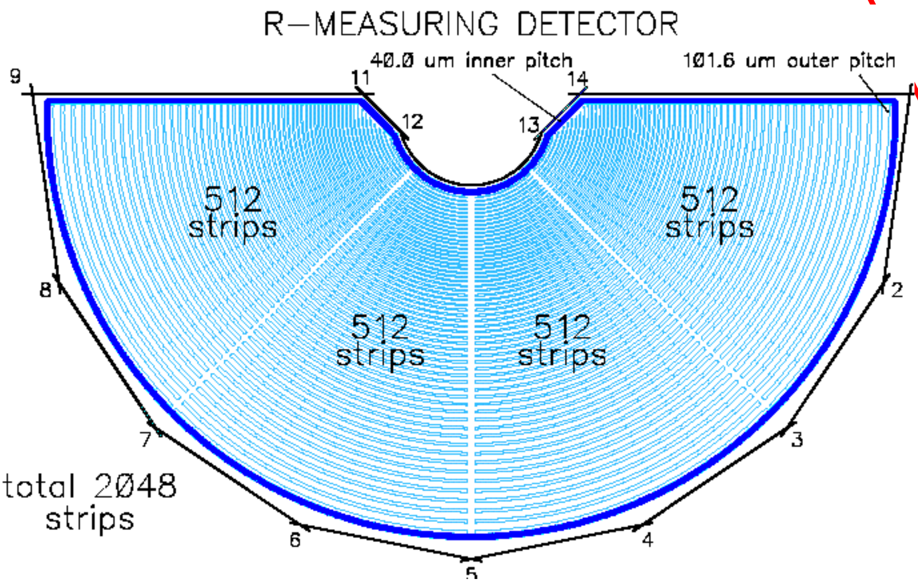
→ **L0 decision unit L0DU**

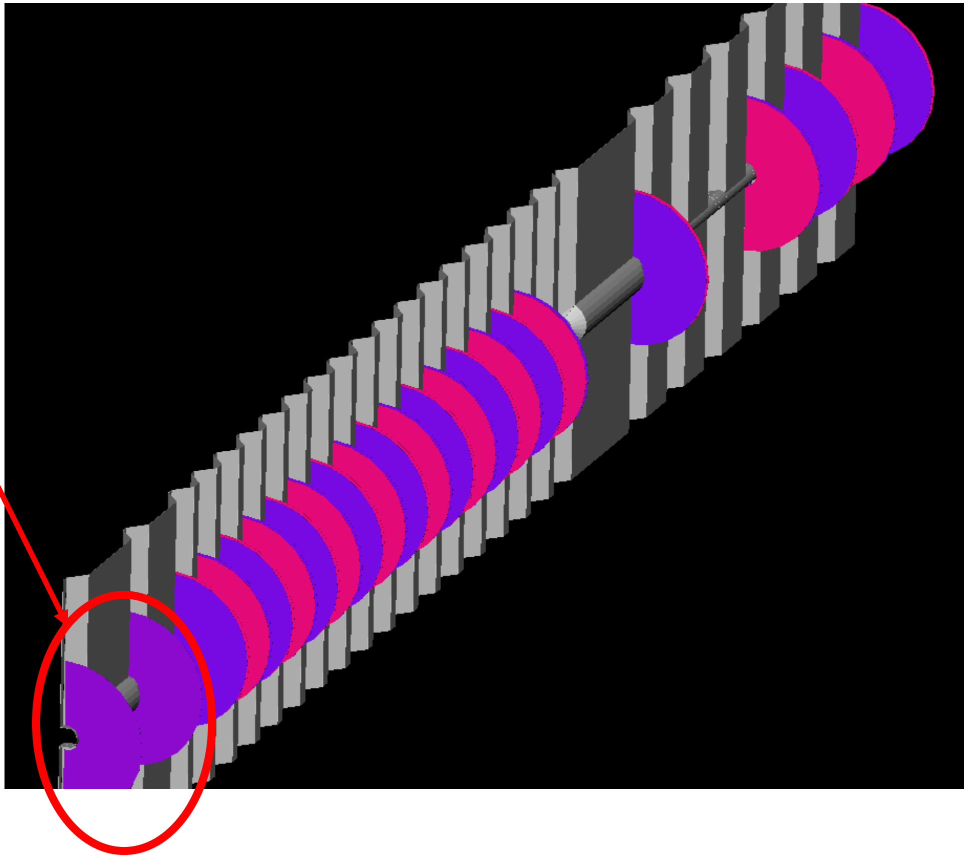
BUT HOW DOES IT ALL WORK?

L0: pile-up system

- For CP studies, multiple collisions aren't favored (potential issues with tagging or primary vertex association)
- Cut out events with multiple vertices

- Two planes of R-measuring sensors
- Identical to VELO sensors
- Places up-stream from interaction point
- Strips ORed in groups of 4
    - Determines R resolution

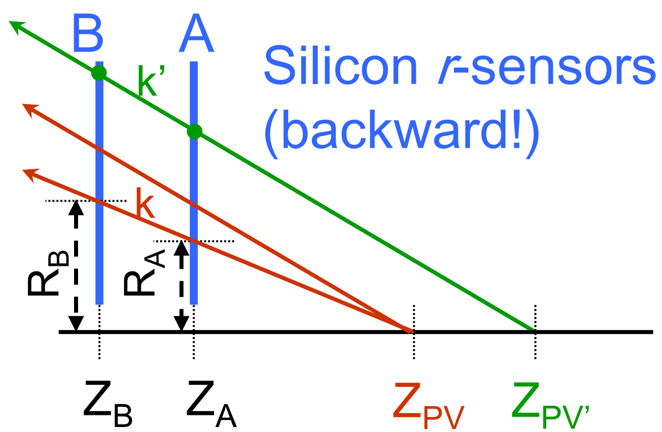


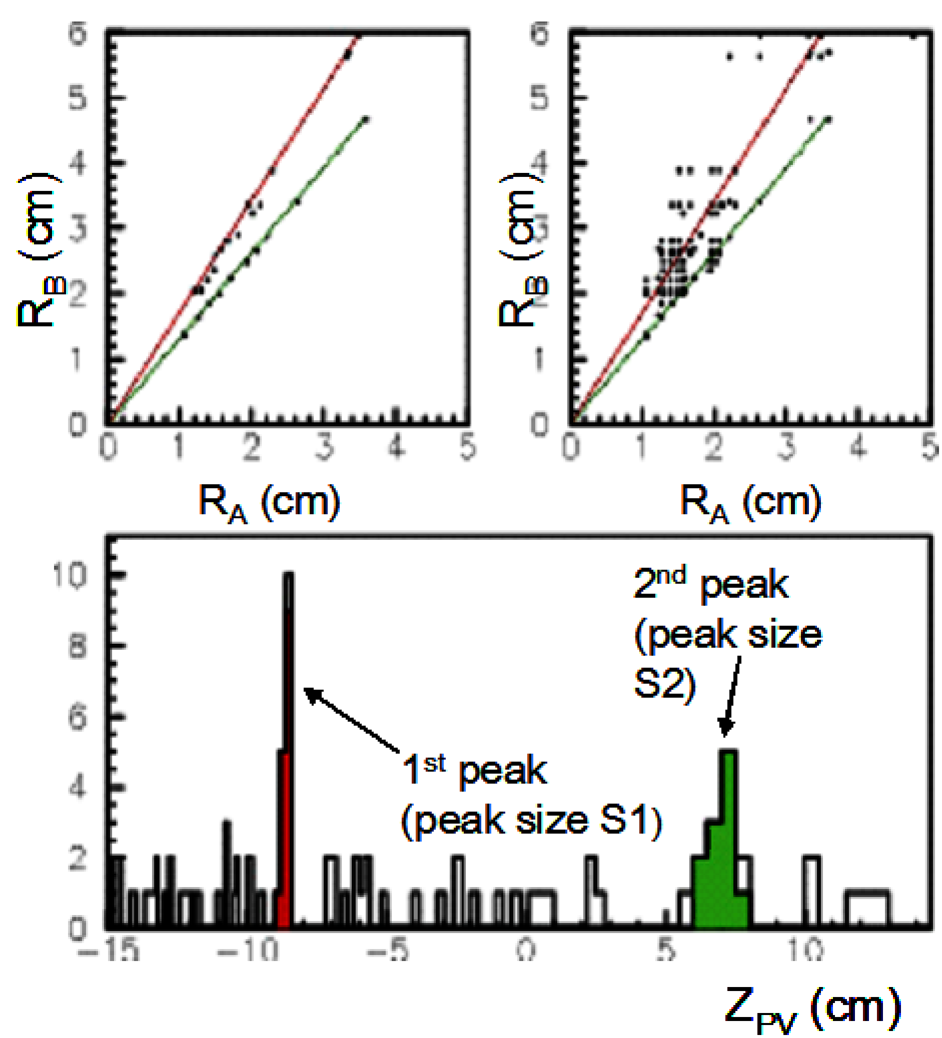


Pile-Up Veto: principle

Tracks from same Z_{PV} have the same ratio k

$$k \equiv \frac{R_A}{R_B} = \frac{Z_{PV} - Z_A}{Z_{PV} - Z_B}$$

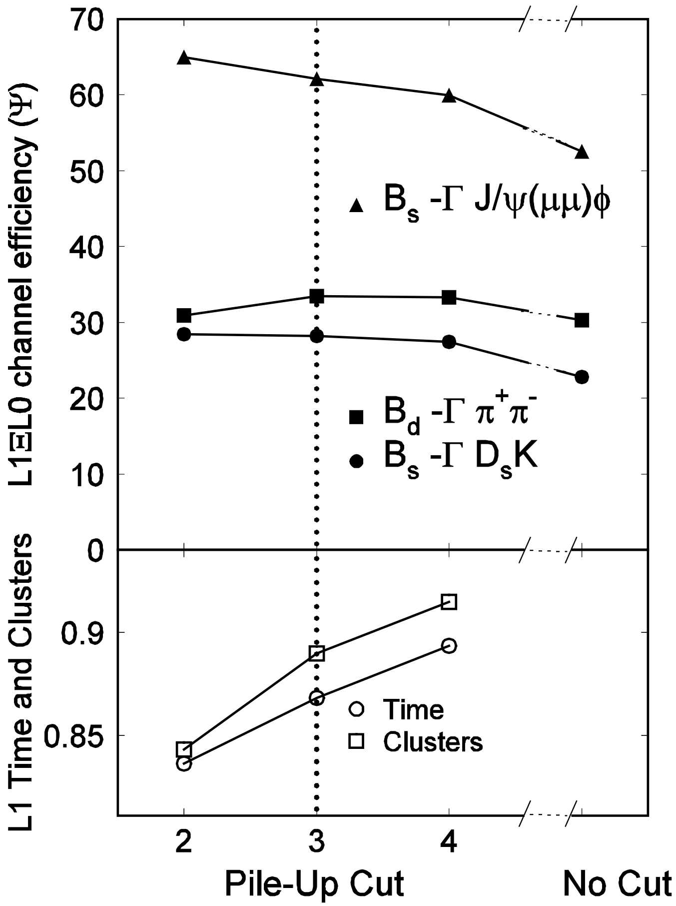


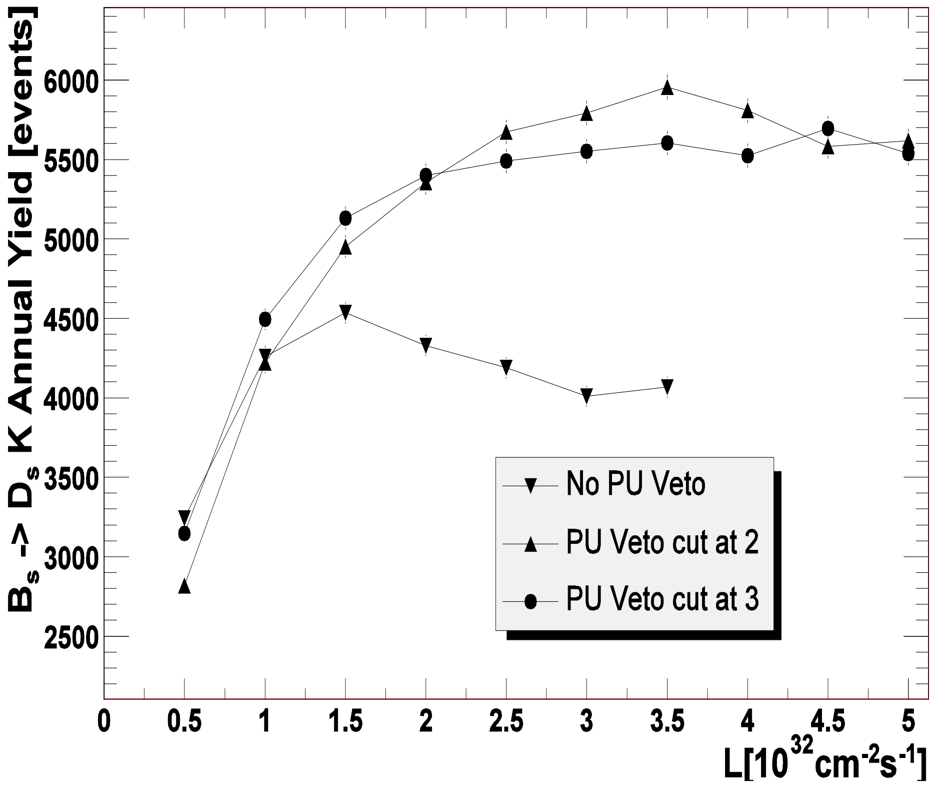


- **Calculate vertex for all combinations of 2 points a and b.**
- **Find highest peak (= prim.vtx)**
- **Remove the hits and find 2nd peak**
- **Veto if peak>threshold**
- **$\sigma(Z_{vtx}) \approx 2.8$ mm, $\sigma(\text{beam}) \approx 53$ mm**

2nd peak mult. cut tunable parameter

Pile-up Veto performance





L0*L1 efficiency for different channels as a function of PU cut on 2nd peak multiplicity.
All other L0 cuts are modified to fill the allowed bandwidth

Expected annual yield for B ⇨D_sK as a function of luminosity for different PU cuts

L0 decision

GLOBAL VARIABLES

Tracks in 2nd vertex
Pile-up system multiplicity
SPD multiplicity
Total HCAL E_T

Reject events that are busy, empty or having multiple interactions

B DECAY CANDIDATE THRESHOLDS

E_T of hadrons, electrons, γ, π^0
p_T of μ

Good B-decay candidate

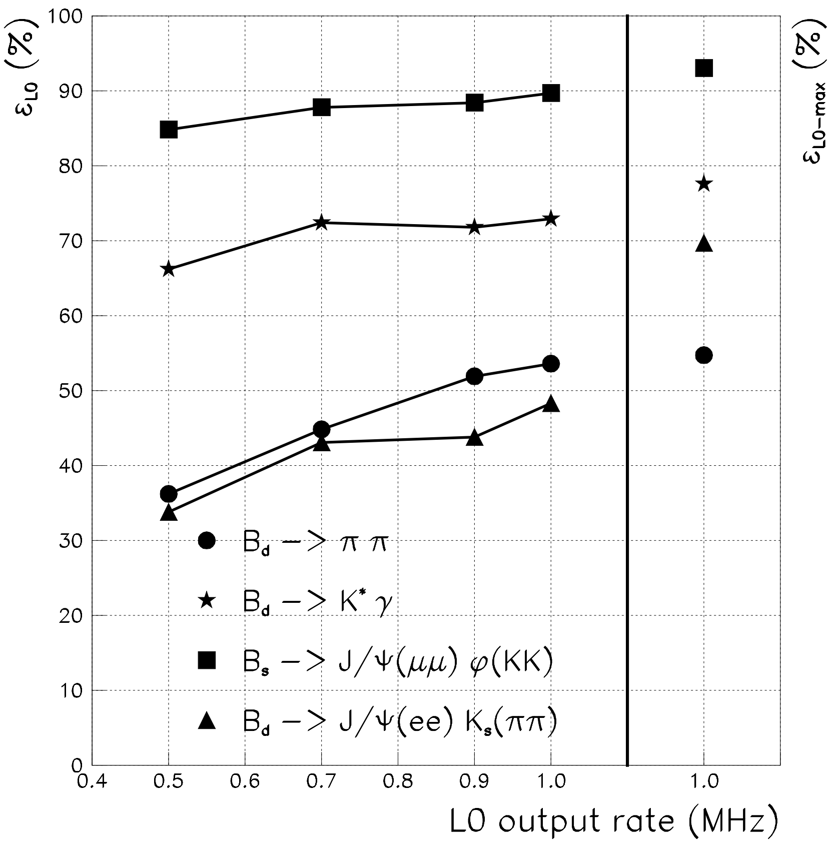
Σp_T of two highest p_T μ

Special di-muon trigger

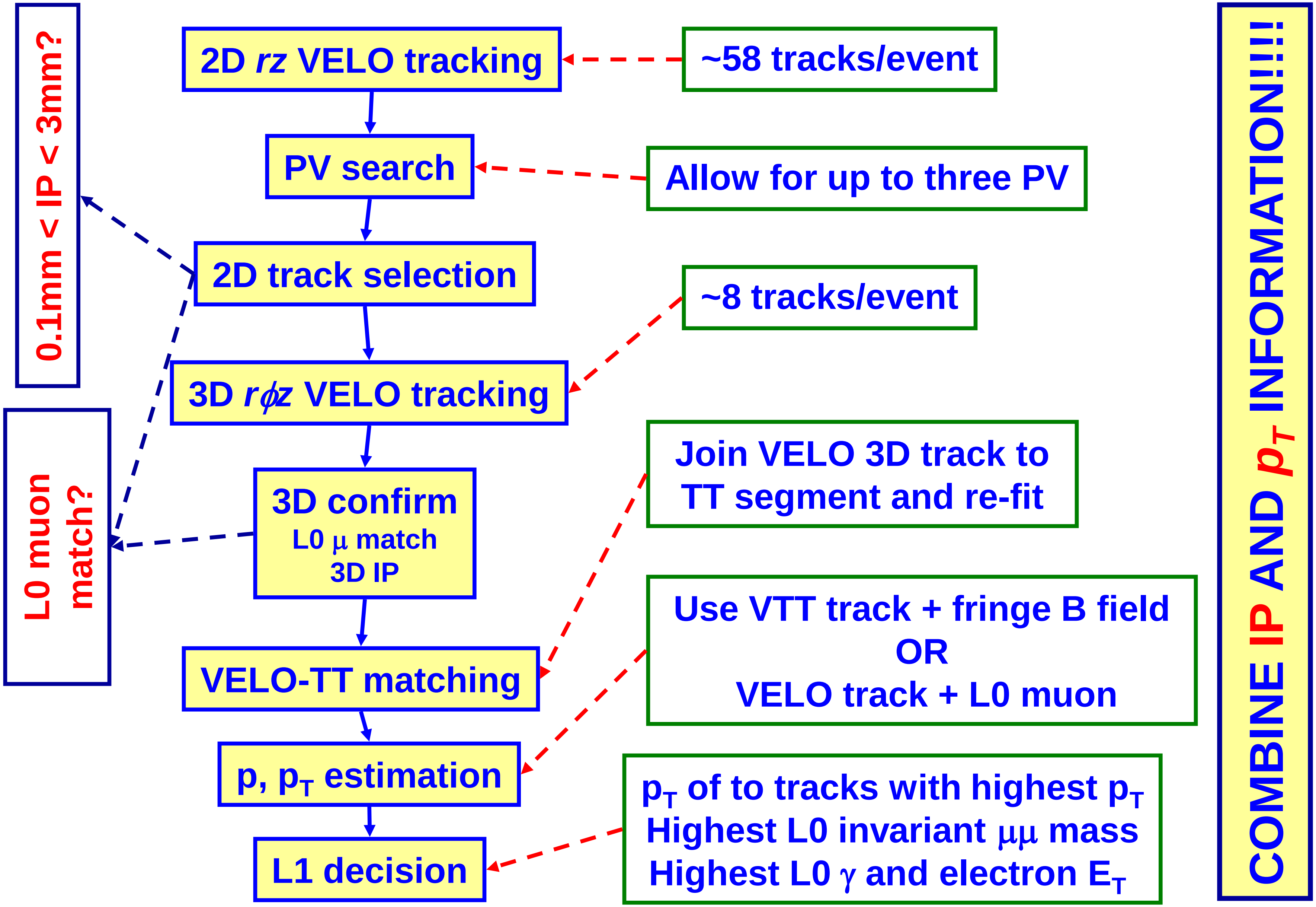
Pass ALL global cuts
AND
at least one E_T threshold

OR

Pass $\Sigma p_T(\mu)$ cut
(2 highest p_T muons)



L1 algorithm in a nutshell



L1 2D VELO tracking / 1

- **rz tracking motivated by speed**
  - Tracks from beam line form straight lines in ***rz***
  - This is the reason VELO has ***rϕ*** geometry

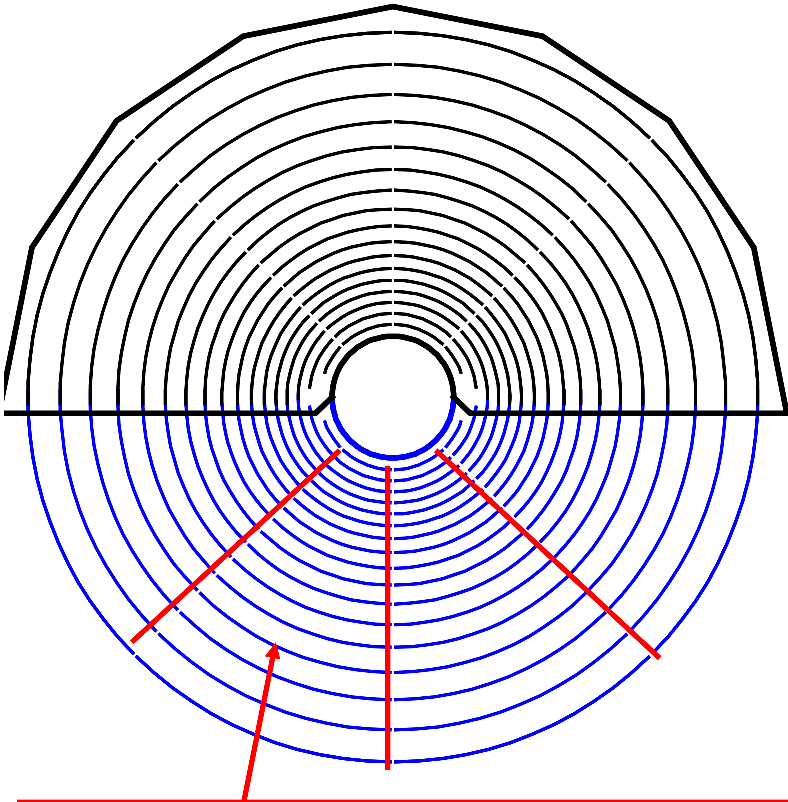
TRIPLET SEARCH
3 z-consecutive hits in up to 4 sensors, all same 45º ϕ sector

↓

TRIPLET EXTENSION
Search for additional r hits compatible with triplet

↓

GHOST + CLONE KILLING
Overlap region, Shared hits, Number of hits

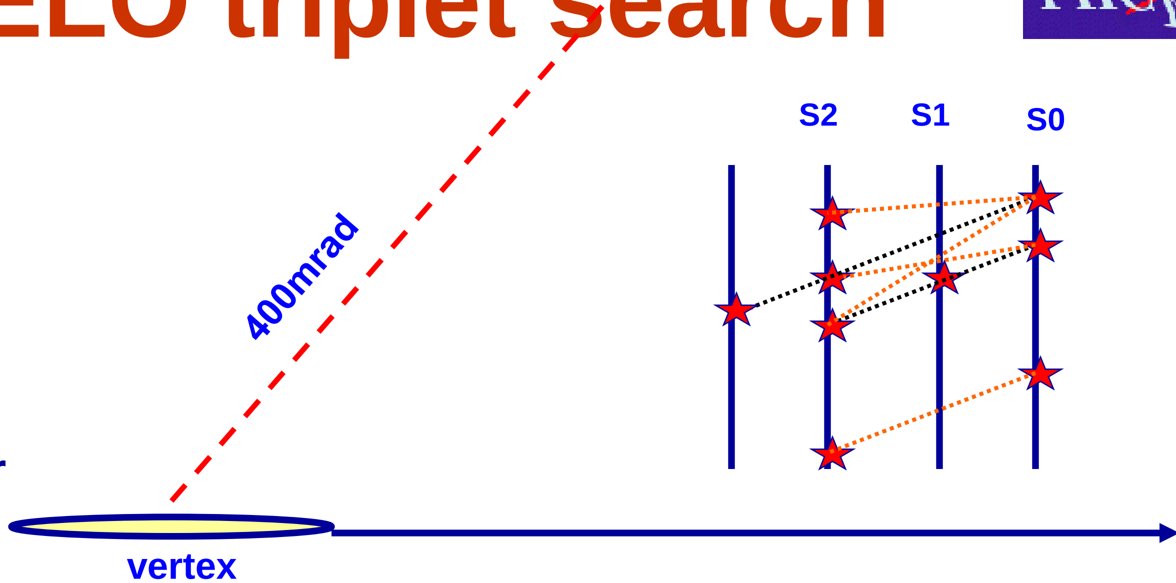


ϕ segmentation 45º for pattern recognition + speed

Reconstruct ~58 tracks/event

L1 2D VELO triplet search

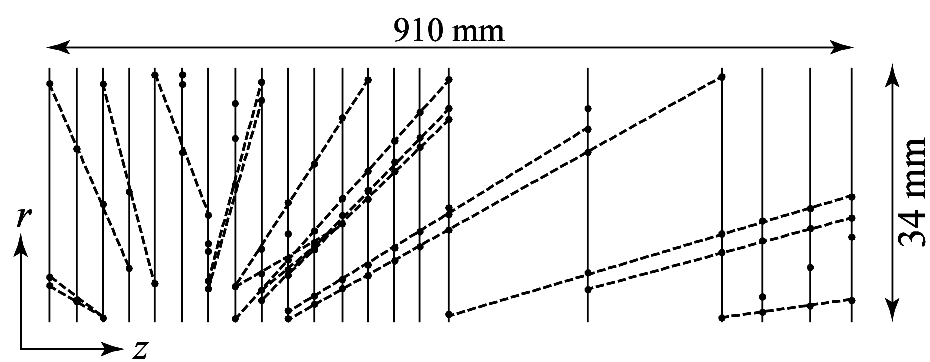
- **Start from hit in most downstream sensor, S0**
- **Loop over hits in S2**
  - Take first hit such that line satisfies angular criteria*
- **Project into S1 and look for closest hit**
  - 0.9*pitch search window
  - If no hit found go to next S2 hit
- **If good triplet found, start again from next S0 hit**
  - Exclude hits in found triplets from search



***compatible with coming from vertex and slope < 400mrad**

BAD (orange dotted line)

GOOD (black dotted line)



ALLOW FOR ONE INEFFICIENT DETECTOR

L1 2D VELO Triplet extension

- **Project *rz* track to next sensor and look for hits in 3.5*pitch window**
  - Allow for off-axis tracks, not straight in rz
  - Flag good hits as used
- **Fit straight line to rz points and continue**
- **After all extensions done**
  - Non-extended triplets discarded and hits flagged as unused
  - All hits in extended tracks flagged as used
  - Go back to triplet search with remaining unused hits, moving towards the interaction point

2D tracking performance:

Efficiency: 98.2%

Ghost rate 6.5%

Reconstruct ~58 2D tracks/event

L1 primary vertex search

Select tracks compatible with PV

Start with 2D tracking *rz* histogram

1. **Fit *rz* PV of ALL sectors**
2. **Reject outliers**
3. **Iterate three times**
4. **Allow up to 3 PV**

Project *rz* tracks to centre of each ϕ sector

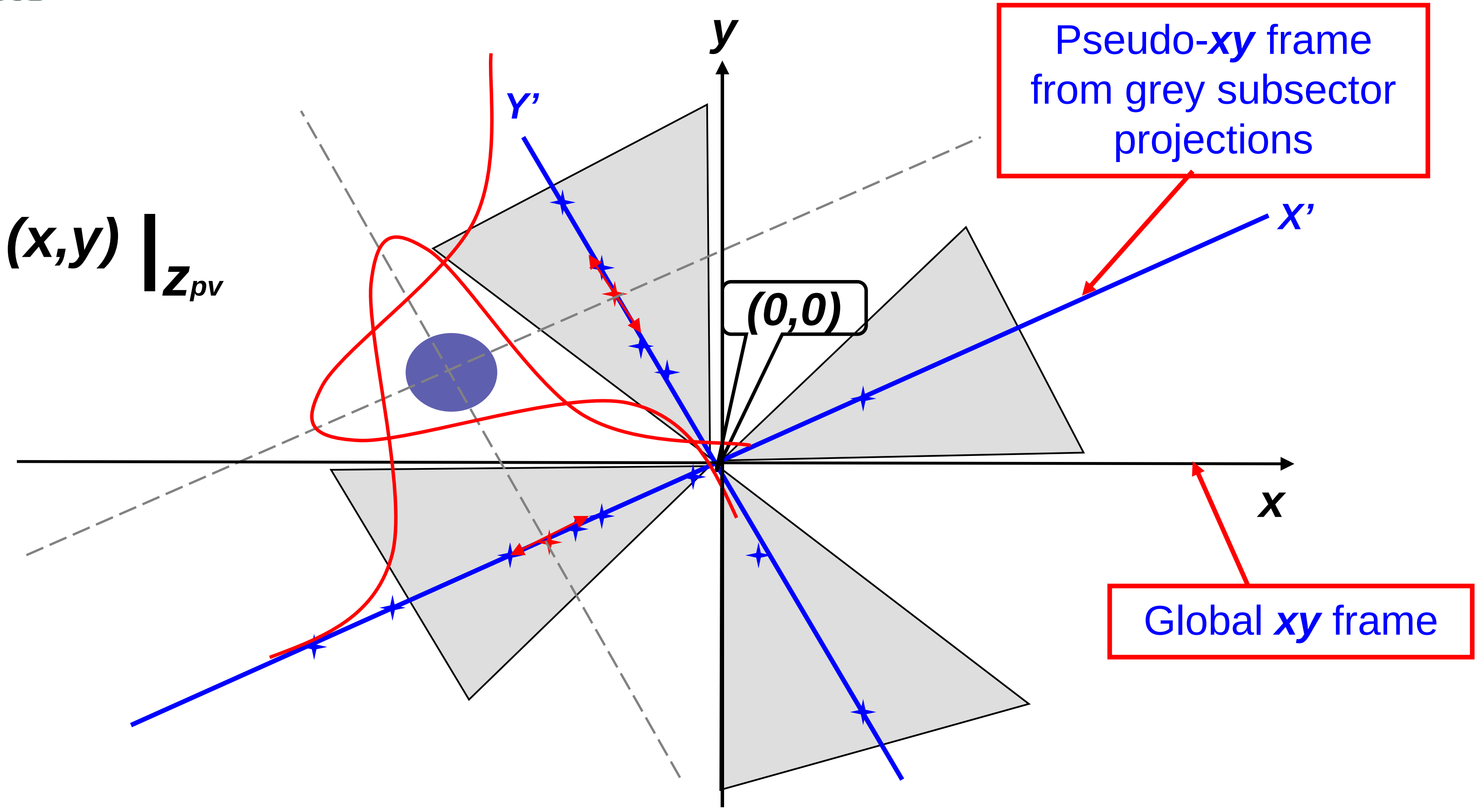
Localise track in average ϕ of sector

Combine tracks from orthogonal ϕ sectors to perform "*xy*" 3D PV fit

Treat individual rz tracks as xz, yz projections of same track in cartesian space

BETTER EXPLAINED WITH THE AID OF A CLEAR DIAGRAM!

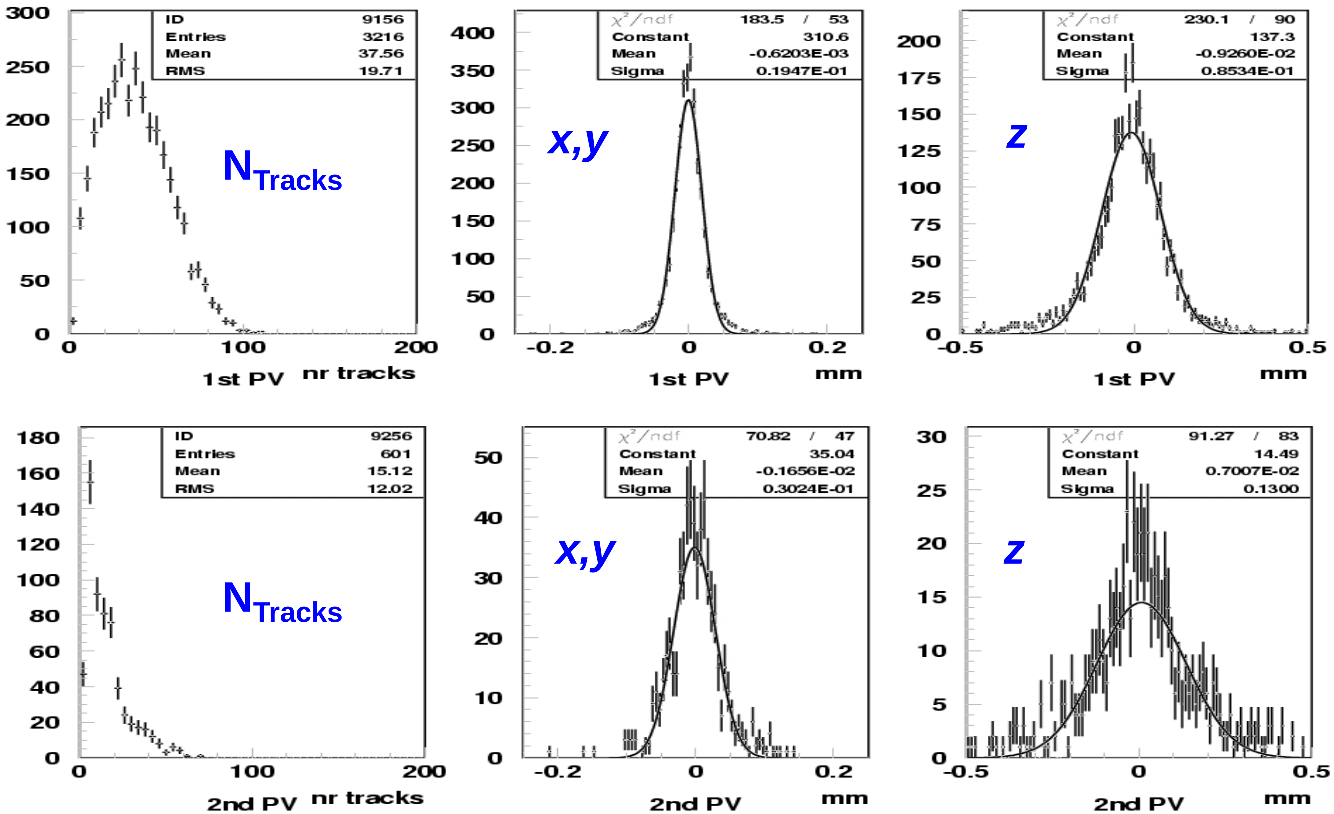
PV search algorithm



Track pairs in perpendicular sub-sectors treated as independent measurements in 2 rotated Cartesian coordinate systems

PV is then constructed as with XYZ geometry

PV performance



1st PV
<tracks> = 38
σ_x, σ_y = 19μm
σ_z = 85μm

2nd PV
<tracks> = 15
σ_x, σ_y = 30μm
σ_z = 130μm

- **With 2D tracks + limited ϕ information**
  - Fast reconstruction: **0.33ms on 1GHz PIII**
  - Good resolution
- **30 to 40 PV 2D tracks/event contain enough info to "saturate" the resolution**
  - Half as many effective 3D tracks
  - At some point the PV resolution does not vary drastically with number of tracks
- **Remember: no momentum information. Errors due to multiple scattering not known.**

2D and 3D VELO track matching to L0 μ

- **2D matching**
  - For selection of 2D tracks to be reconstructed in 3D
  - Compare dr/dz slopes
    - Construct χ^2 using uncertainties in ***rz*** slopes of tracks and L0 objects, ϕ information from VELO sectors, B-field kick
- **3D matching**
  - Rejection of 2D mismatches
  - Improvement of VELO track p_T estimate
    - Construct χ^2 using uncertainties in ***xz*** , ***yz*** slopes of tracks and L0 objects, B-field kick

	χ^2 max	Purity	Efficiency	σ_p/p
2D	16	21.0%	96.5%	37%
3D	16	51.2%	94.7%	6%

VELO 3D tracking algorithm

- **Sort 2D tracks by length and start with longest**
- **Work in 45º sectors independently**
- **Search inwards from sensor furthest from PV**
- **Look for compatible hits in neighbouring ϕ sensor**
  - Calculate r of track in ϕ sensor, check sector, look for hit
  - Build list for each compatible ϕ hit
- **Search in following ϕ sensors**
  - Project 3D lines with ***rz*** from track and ϕ from each hit in list
  - Build new lists for each good ϕ hit found near projection
- **Select best 3D track for given 2D one**
  - Scan through tree of lists, select track with most clusters or best χ^2
- **Mask all hits used and start again with next 2D track**

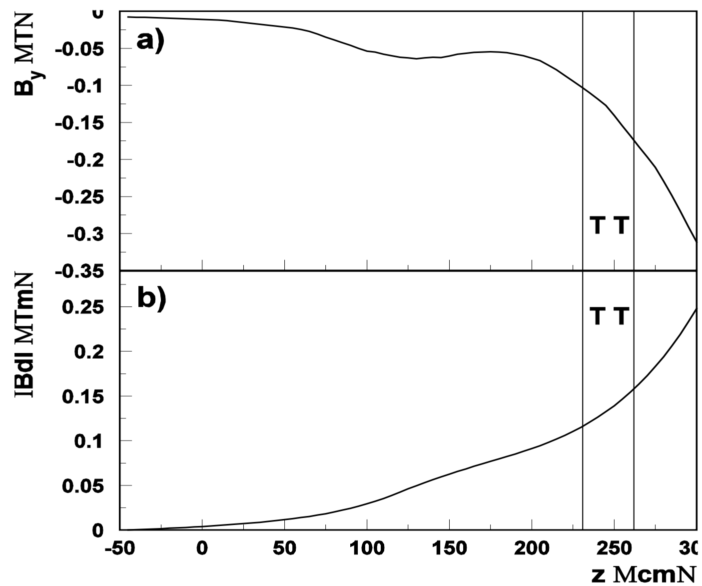
Combined 2D and 3D
Efficiency: 94.8%, 96.4% for B tracks
Ghost rate 5.0%

Reconstruct ~8.5
3D tracks/event

VELO-TT matching

Get an estimate of *p* for good IP tracks!

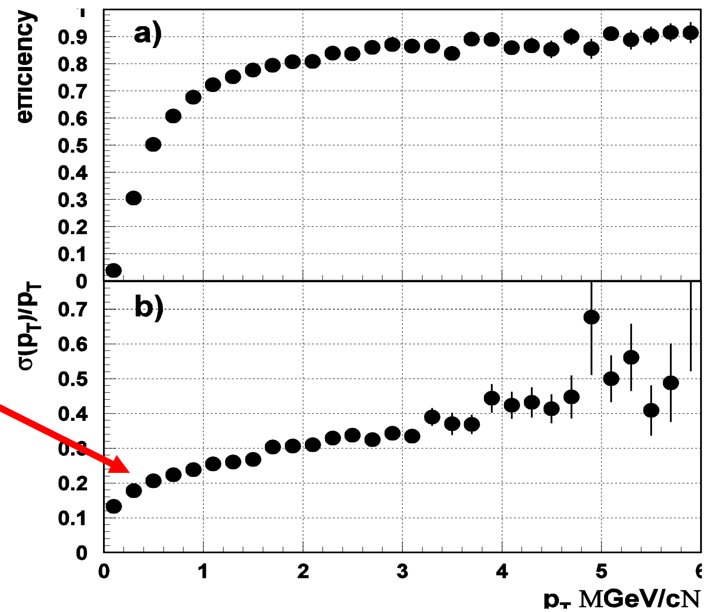
- **Project 3D VELO tracks into TT for pattern recognition**
- **Use as seeds to form TT track segments with 4 or 3 planes**
- **Pick one with best χ^2**
  - χ^2 based on slopes and B field kick
- **Re-fit VELO and TT tracks allowing slopes to vary**
  - Demand both meet at nominal place in centre of fringe field
  - L1 optimised: good purity for high p_T tracks
- **Momentum obtained from re-fitted slopes and integrated bending field**



For pT > 1GeV:

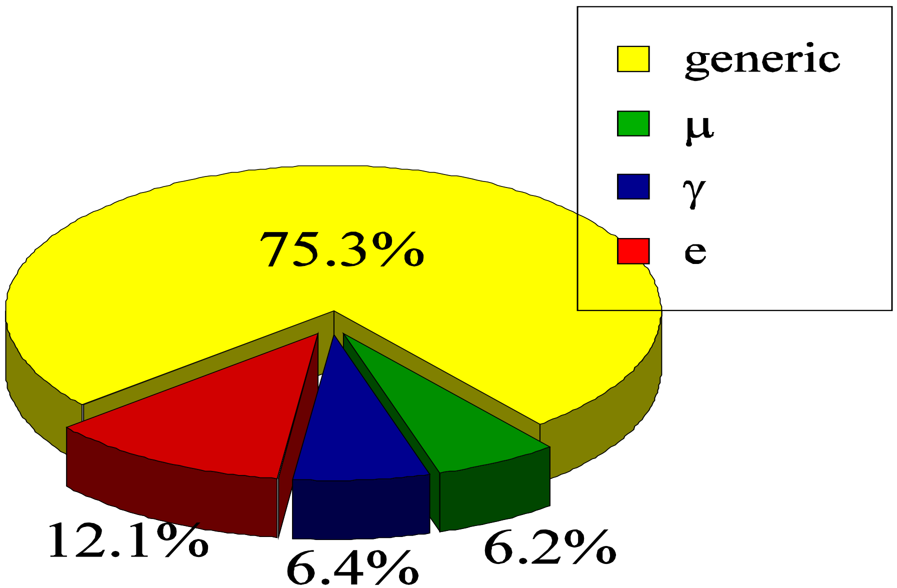
79% efficiency
98.7% purity
$\sigma(p_T)$ ~ 20-30%

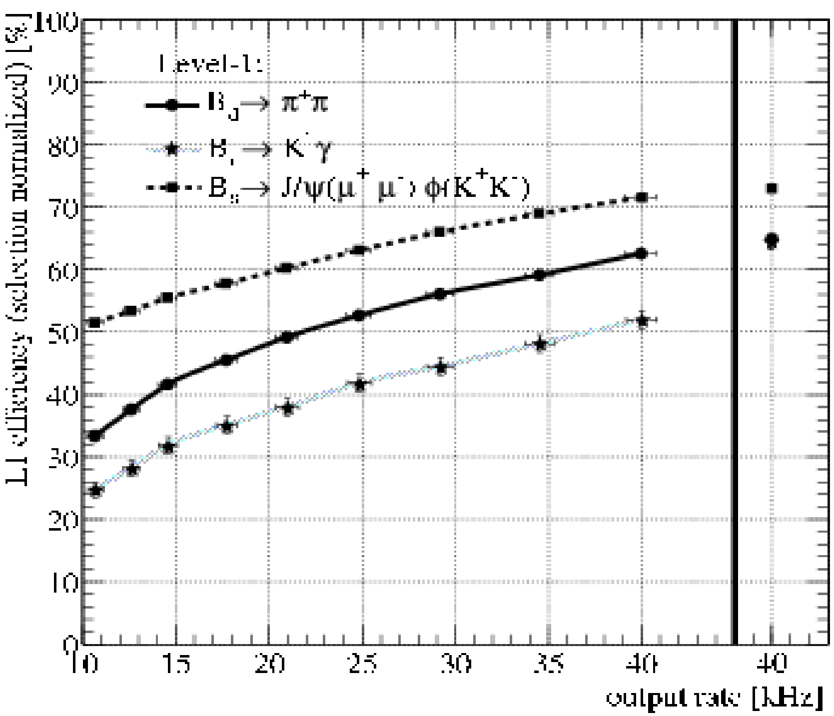
Good p_T resolution at low p_T means we are unlikely to mistake low p_T tracks for high p_T ones



L1 decision

- **Use $\Sigma \ln(p_T)$ of 2 tracks with highest p_T and 0.15mm < 3D IP < 3mm**
- **Information highest di-muon invariant mass, highst E_T γ and electron above 3GeV**
  - Give weight to specific decay modes
- **tuned for retention of 4% of minimum bias L0 triggers (**40kHz L1 output rate**)**





L1 timing

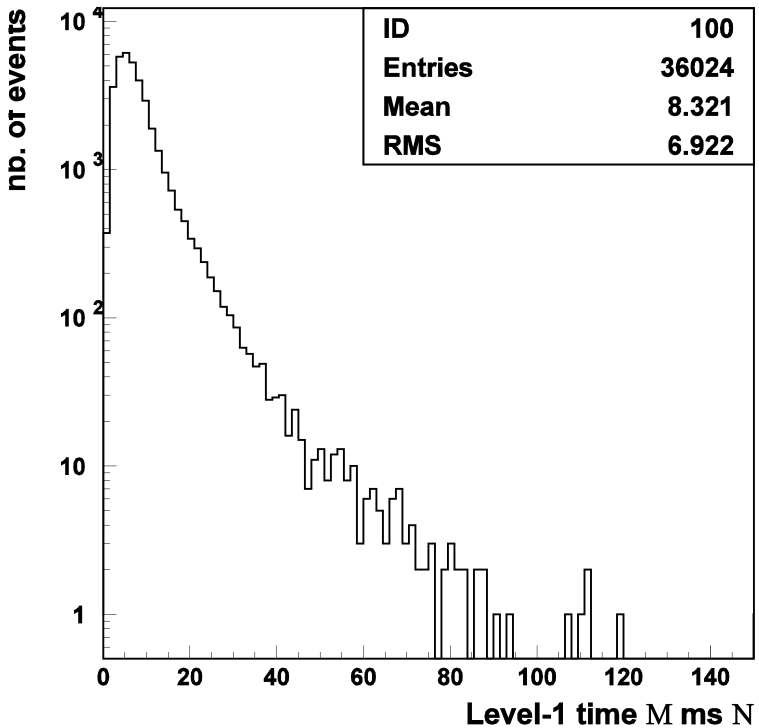
- **Timing of L1 algorithms crucial**
  - Balance between quality of reconstructed information available to make L1 decision and complexity of L1 algorithm process
  - But algorithms can be slow for reasons other than complexity
- **Separate L1 s/w algorithm implementations benchmarked in search for inefficiencies**
  - Technical changes
    - Information caching
    - Look-up tables
    - Static memory allocation where necessary

Remember: L1 trigger implementation in off-line style S/W environment. In general quality and conceptual speed of algorithms was of essence. Actual fine tuning of timing performance wrt technical s/w implementation details comes after validation… still, gains in speed can allow changes in conceptual approach…

L1 Timing performance

L1 phase	Time [ms 1GHz PIII]
VELO initialisation	0.46
2D tracking	0.82
PV search/fit	0.33
2D track selection	0.21
3D tracking	1.1
L0 3D track matching	0.01
VELO-TT matching	1.49
3D track preparation	0.16
L1 variables calculation	0.04
Decision	0.02
Total	4.64

- Time measured between start and stop of each algorithm
- Minimise number of calculations needed to reject event
- Granularity 1μs
- Time for min. bias L0 accepted events



L1 algorithms can provide fast efficient background rejection and signal retention with reasonably complex reconstruction in 1ms (2007)

Conclusions

- **The three-level LHCb trigger reduces rate from 40MHz (10MHz visible) to 200Hz**
- **L0*L1 efficiency between 20% and 70%**
- **L1 efficiency between 60% and 80%**
- **Within tight time and CPU budget**
- **System is highly flexible and scalable, allowing to change retained event composition at all three levels**
  - Possibility of adjusting thresholds in L0
  - Possibility of adjusting logic in L1
  - Possibility of bringing other detectors into L1
    - At a cost! More network, but same CPU power
  - Possibility of doing pretty much anything in HLT, except using RICH information… so far at least
- **L1 performs high quality reconstruction within 1ms time budget**

Aknowledgements

Many thanks in particular to the following :

Mariusz Witek
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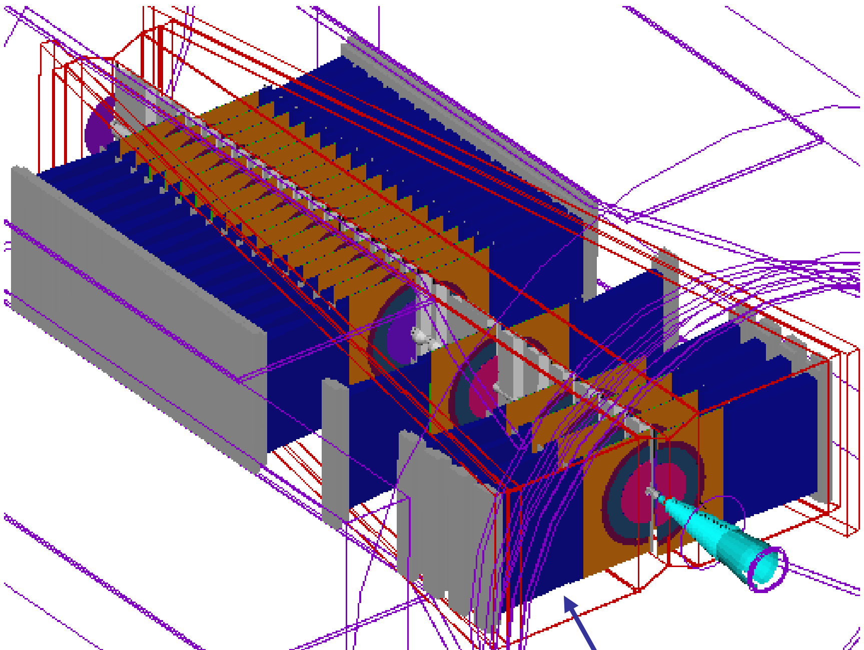
Olivier Callot
Thomas Schietinger

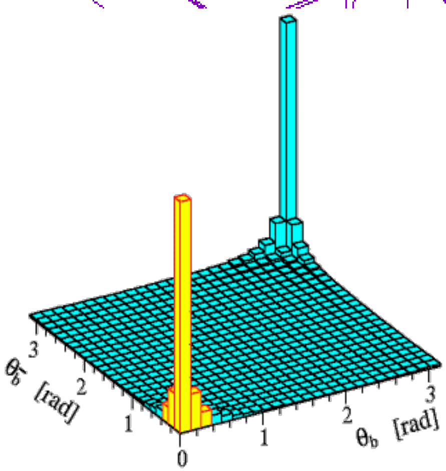
BACKUP SLIDES

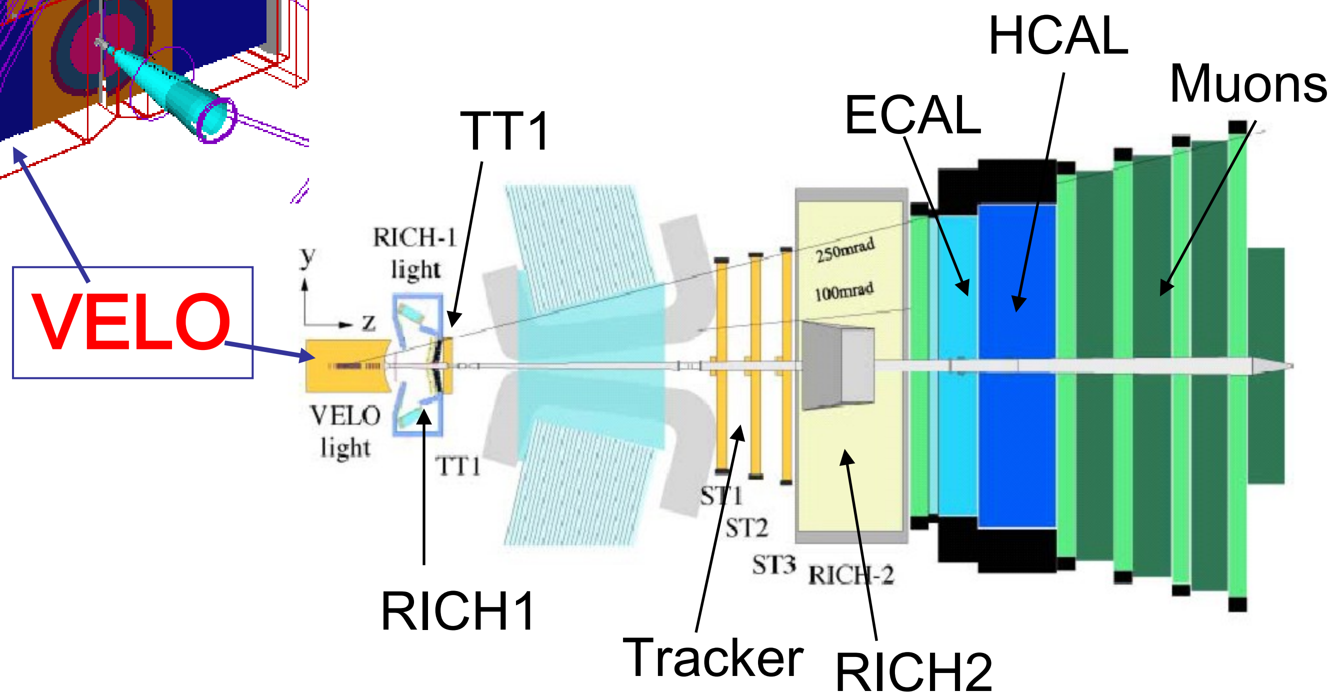
The LHCb experiment

- **A dedicated B-physics CP violation experiment**
  - Good primary, secondary vertex resolution
  - Good particle ID

A small angle forward spectrometer with excellent PV and IP resolution







LHCb Trigger Overview

- **L0**
  - Reduce rate from ~10MHz visible interactions to 1MHz accept rate to L1
  - Use global varialbes
    - Charged track multiplicity
    - Number of interactions
    - Hadronic E_T to reject empty events
  - Use B signatures
    - Large E_T lepton, hadron or γ
  - Latency 4μs (2μs for data processing)
- **L1**
  - Maximum accept rate ~40kHz
  - High p_T, E_T
  - Impact parameter information
  - Electron, hadron E_T, di-muon invariant mass
- **HLT**
  - Accept rate ~200Hz, use CPU power not used by L1
  - High P_T, E_T
  - Displaced vertex
  - B candidate invariant mass

Shall concentrate on these. Emphasis on tracking/vertexing

Close to offline quality data
No RICH PID
Use of full LHCb tracking system
Large S/W commonality with L1 algorithms

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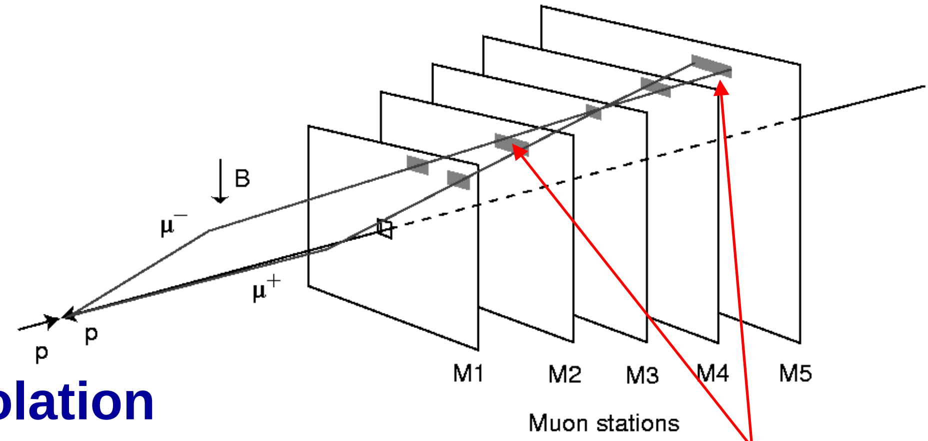
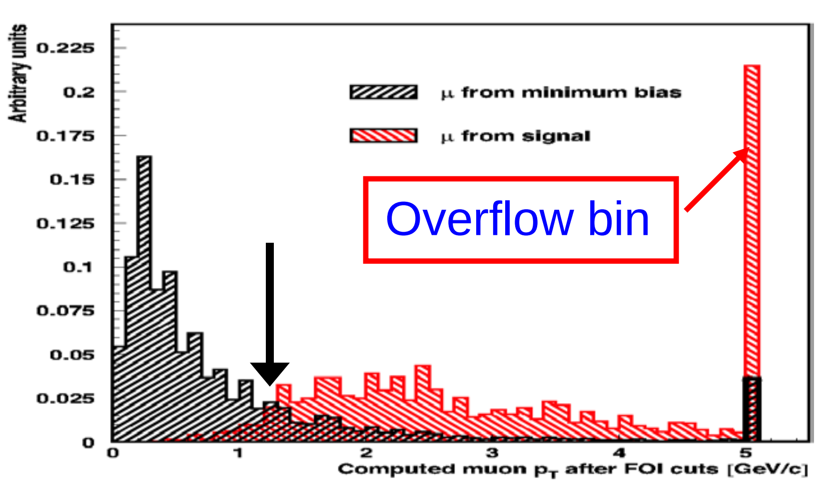
L0 high p_T μ,

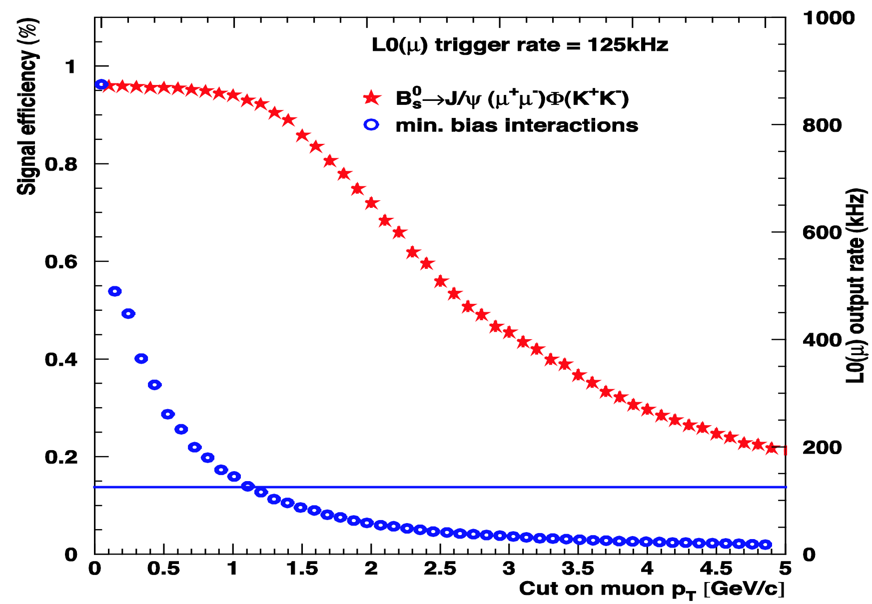
- Use M3 hits as seeds
- Look in FOI in M2, M4, M5 along extrapolation to (0,0,0)
- Assume single B-kick at given *z*
- Pick hit in M2 FOI closest to extrapolation
- Extrap M3, M2 to M1. Pick closest M1 hit
- p_T determined from M1, M2 and lookup tables



FOI size depends on station, background level, required min bias retention level

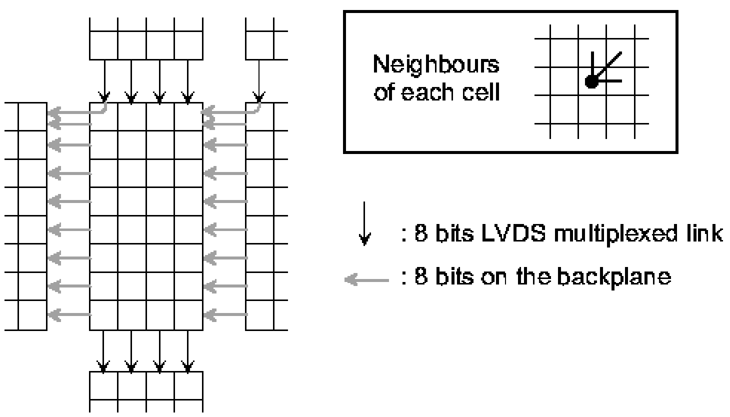
Resolution ~ 20% for μ from b quark decays

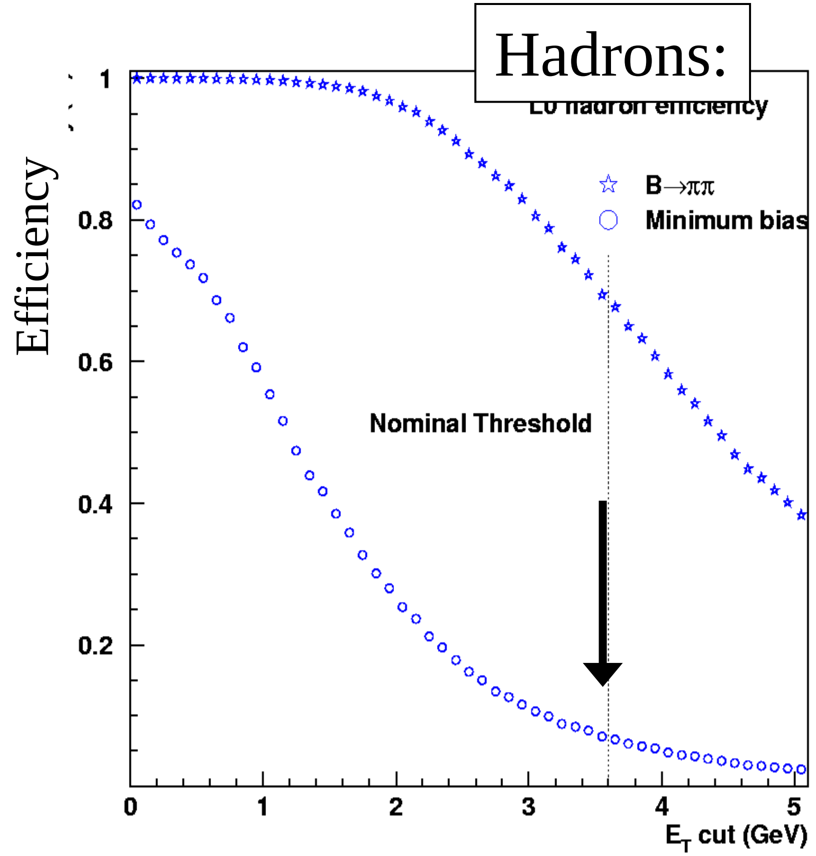




L0 high E_T e, γ and h

- **SPD: e/γ separation**
- **PreShower: 2.5 X0 pb. Identify EM particles**
- **ECAL: shaslik, EM shower energy**
- **HCAL: Fe scintillator tiles, hadronic shower energy**





L0 Decision Unit (L0DU)

Information for L0DU:

- **Calorimeters:**
  - E_T of all candidates (hadron, electron, γ, etc.)
  - ΣE_T (to avoid no collision + μ from LHC bg)
  - SPD hit multiplicity
- **Muon trigger:**
  - 4×2 largest P_T muons
- **Pile-up detector:**
  - z and number of tracks in 1st and 2nd vertex
  - total hit multiplicity

L0DU performs simple arithmetic, with adjustable thresholds, downscaling, etc.

•Variables used to find a B-meson signature

Typical thresholds (GeV):

- Electron ~ 2.6
- Photon ~ 3
- Hadron ~ 3.5
- ΣE_T ~ 5
- Muon ~ 1.2

•Global variables used to enrich the triggered sample with "clean" events and avoid triggers due to *e.g.* large combinatorics

L0 decision

Global variable	Cut
Tracks in 2nd vertex	3
Pile-up veto multiplicity	112
SPD multiplicity	280
ΣE_T	5 GeV

E_T threshold	Value/GeV	M.B. rate/kHz
hadron	3.6	705
electron	2.8	103
photon	2.6	126
π^0 local	4.5	110
π^0 global	4.0	145
Muon	1.1	110
$\Sigma p_T(\mu)$	1.3	145

Global variable cuts. Reject events that are busy, empty or having multiple interactions

Thresholds for different L0 inputs after combined optimisation

Pass all global cuts
AND
at least one E_T threshold

OR

Pass $\Sigma p_T(\mu)$ cut
(two highest p_T muons)

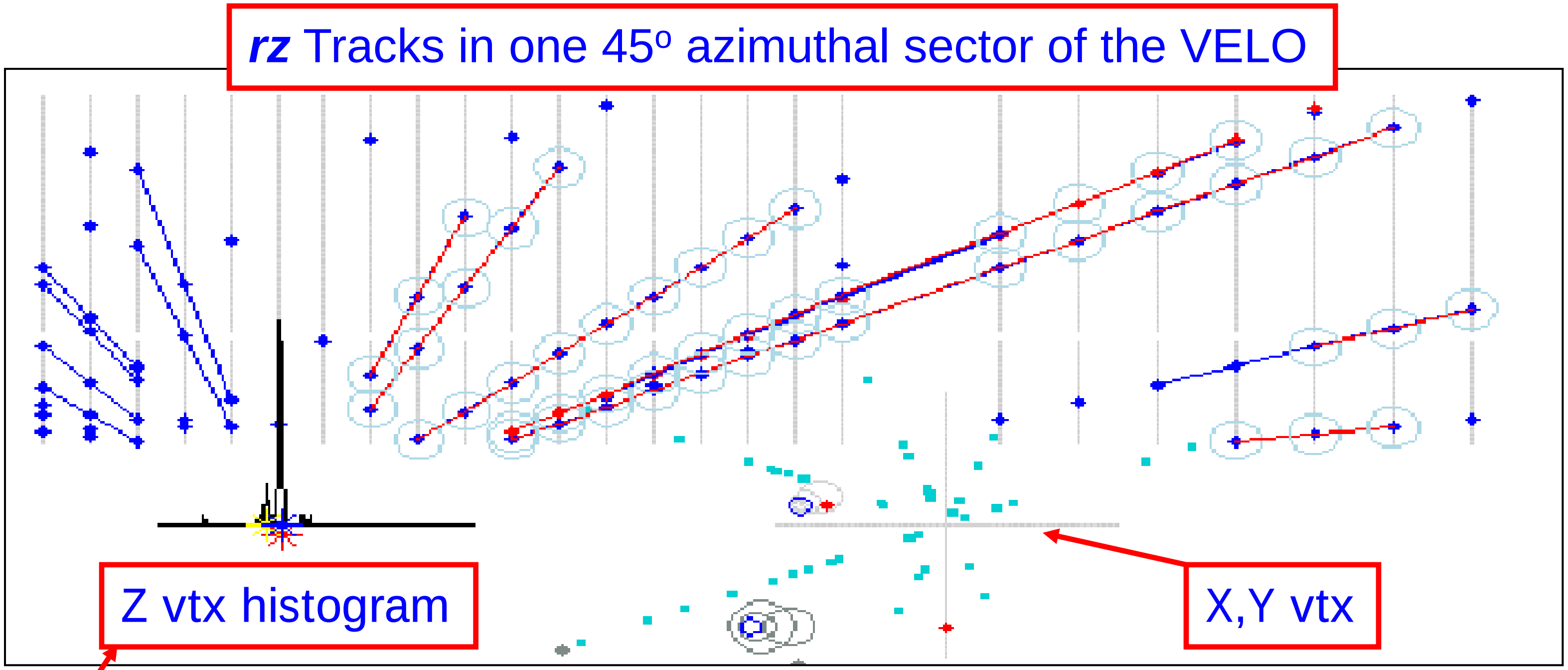
L1 in two nutshells/1

- **Reconstruct 2D VELO tracks (rϕ) ~58/event**
- **Select 2D tracks for 3D reconstruction**
  - Search for PV ⇨select if **0.1 < 2D IP < 3mm**
  - Match 2D tracks to L0μ track segments ⇨ select if good match
- **3D track reconstruction**
- **Match 3D tracks to L0 objects – confirmation**
  - Get estimate of track **p** and $\mathbf{p_T}$
- **Match 3D matched VELO tracks to TT track segments**
  - Make so-called VTT tracks
  - Get first estimate of track **p** and $\mathbf{p_T}$

L1 in two nutshells /2

- **Successfully reconstructed VTT 3D or Velo-L0μ tracks used for decision**
- **Use two highest p_T tracks**
  - P_T of tracks as discriminator
- **Combine with global variables**
  - Highest L0 invariant di-muon mass
  - Highest L0 photon E_T if > 3GeV
  - Highest L0 electron E_T if >3GeV

L1 2D VELO tracking



Event display showing 2D tracks, Z vertex histogram and XY PV

- **Histogram 2D z coord in preparation for PV search**
- **Efficiency 97% for p > 1 GeV (get newest numbers!)**
- **Purity 92% (get newest numbers!!!)**

2D VELO track matching to L0 objects

- **Compare dr/dz slopes**
  - Account for x-kick from B field for L0 object ***dr/dz*** and ϕ uncertainty
  - Use azimuthal information
    - 2D tracks constrained to 45º
  - Construct χ^2 using uncertainties in ***dr/dz*** of tracks and L0 objects, and ϕ
    - Ignore 2D track *dr/dz* uncertainty: small c.f. L0
    - Track ϕ uncertainty $45^o * 12^{-2}$
- **Cut on χ^2 values to select matchings**

	χ^2 max	Purity	Efficiency	σ_p/p
Muons	**16**	**21.0%**	**96.5%**	**37%**
Electrons	**4**	**11.7%**	**98.4%**	**36%**
Hadrons	**4**	**16.2%**	**98.7%**	**37%**

p_T: 3D VELO track matching to L0 μ

- **In practice, only use L0 muon objects**
- **Construct χ^2 from *xz*, *yz* slopes of 3D track and L0 object**
  - Ignore 3D track errors as negligible compared to L0 object slope errors
- **Use μ track segment + VELO track and B kick to get accurate estimate of p_T**
- **Performance:**

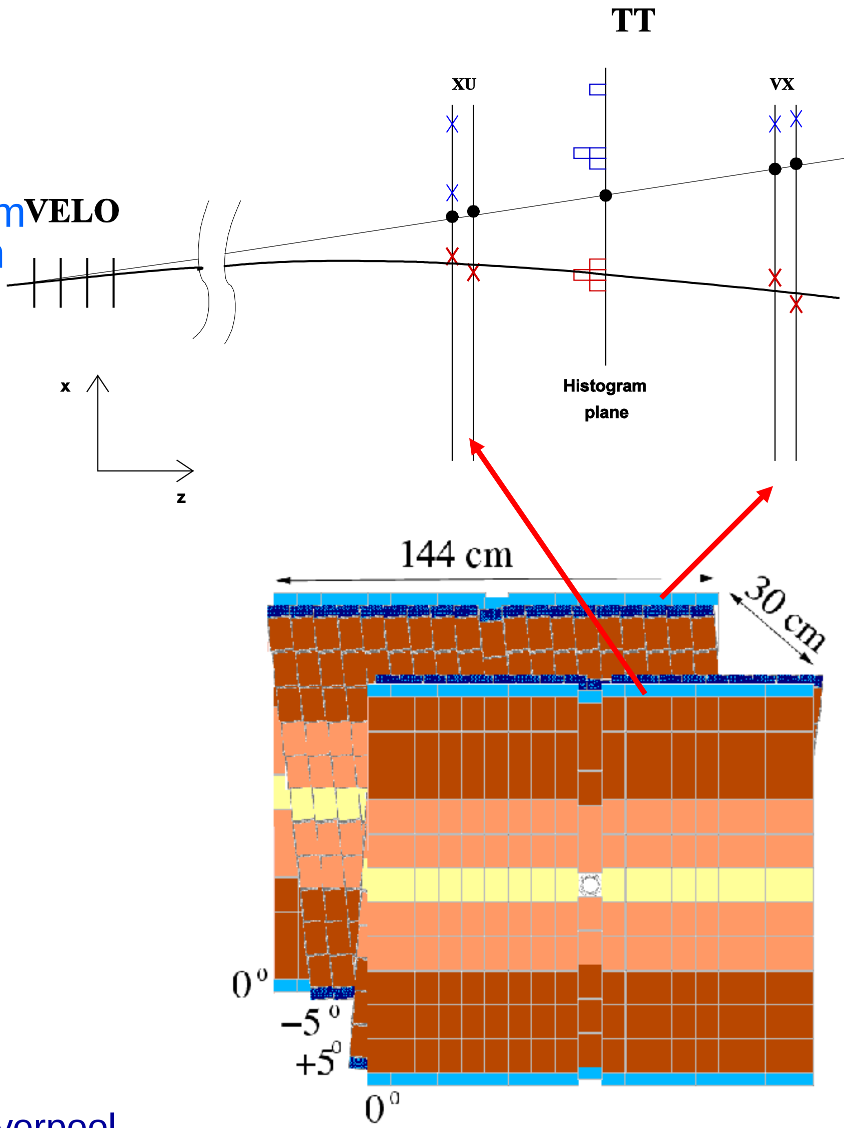
p_T ~ 4%

	χ^2 max	Purity	Efficiency	σ_p/p
Muons	16	51.2%	94.7%	6%
Electrons	4	32.9%	95.8%	12%
Hadrons	4	26.9%	92.8%	15%

p_T: VELO 3D track matching to TT

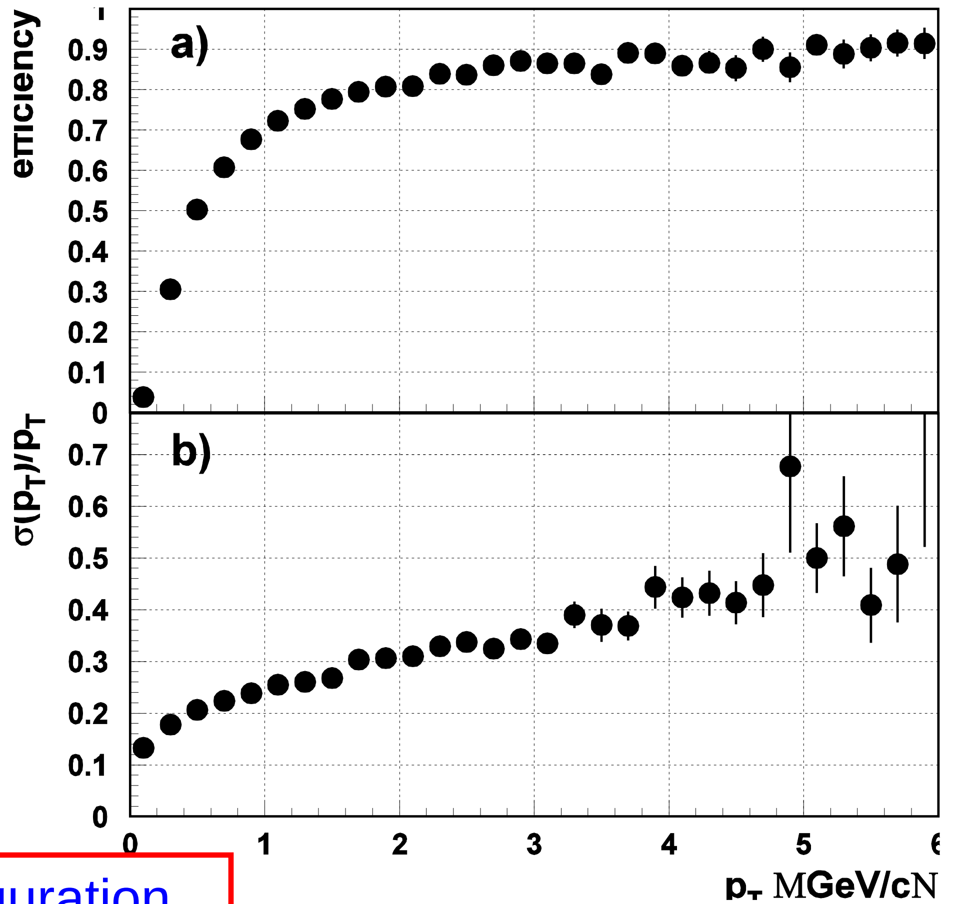
- **Project VELO tracks into TT**
  - Straight line fit
  - Point errors
    - Detector resolution + 3GeV for MS
    - Propagate downstream errors to upstream points to give most weight to last point on track
- **Use as seeds to form TT track segments with 4 or 3 planes**
  - Fit straight line parametrised in xz, yz
  - x slope parametrised in terms of B field
  - Choose candidate with lowest χ^2
- **Re-fit VELO and TT tracks allowing slopes to vary**
  - Demand both meet at nominal place in centre of magnet
- **Momentum obtained from re-fitted slopes and integrated bending field**

p_T ~ 30%



VELO-TT matching

- **Matching tuned to optimise L1 performance:**
  - need good purity for high $\mathbf{p_T}$ tracks!
  - χ^2 for matching favours high **p**
    - **p** dependent
    - ***r*** dependent (multiplicity)
  - For $\mathbf{p_T}$ > 1 GeV
    - 79% efficiency
    - 98.7% purity
  - σ_{pT} ~ 20-30% for $\mathbf{p_T}$ > 1GeV



But this is all software, the trigger configuration For the VELO-TT matching can be changed for optimisation according to other criteria. Eg higher efficiency in HLT…

VELO-TT matching efficiency and p_T significance

L1 decision / 1

- **Use 2 tracks with**
  - highest p_T
  - 0.15mm < 3D IP < 3mm

~6.5/event

- **Construct discriminant:**
  - Δ = distance to cut in $\Sigma \ln(p_T)$ space
- **Construct other "bonus" discriminators β from**
  - Highest di-muon invariant mass $\mathbf{m}_{\mu\mu}$
    - $J/\psi \Rightarrow \mu^+\mu^-$ or $B \Rightarrow \mu^+\mu^-(X)$
    - Variable $\beta_{\mu\mu}$ dominates if $\mathbf{m}_{\mu\mu}$ within 500MeV of **J/ψ** or **B** mass, otherwise linear with $\mathbf{m}_{\mu\mu}$
  - Highest γ $\mathbf{E_T}$ above 3 GeV from L0 $\mathbf{E}_{T\gamma max}$
    - $B \Rightarrow K^*\gamma$
    - Variable β_γ linear with $\mathbf{E}_{T\gamma max}$ from 3 GeV
  - Highest electron $\mathbf{E_T}$ above 3 GeV from L0 $\mathbf{E}_{Temax}$
    - $J/\psi \Rightarrow e^+e^-$
    - Variable β_γ linear with $\mathbf{E}_{Temax}$ from 3 GeV

Some words about HLT

- **Reject events not compatible with interesting b decay**
- **Confirm L1 decision**
  - Add T1-T3 information to improve ***p*** resolution of VELO-TT
  - Fast execution, reduces rate from 40 kHz to 20 kHz

σ(p)/p from ~20-30% to 0.6%

- **Full pattern recognition + limited PID**
  - Better VELO cluster resolution
  - Use full LHCb tracking system – close to offline quality
  - Identify electrons, muons (RICH PID to CPU demanding)
- **Exlusive selection**
  - Very flexible, offline-like algorithms, relaxed cuts
- **Assuming 1ms per L1 event, have ~10ms per event in HLT (2007 CPU)**