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Trigger selection Software for B-physics in ATLAS

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Outline

- The ATLAS Experiment and ATLAS Trigger System
- B-physics Trigger: requirements and constraints
- Trigger strategy for B-physics
- Algorithms for B-physics selection
  - Fast track reconstruction
  - Fast vertex fitting algorithm
- Conclusion

The ATLAS experiment

Centre of mass energy = 14 TeV

BX rate = 40 MHz,

pp-collision rate = 1 GHz

Luminosity :

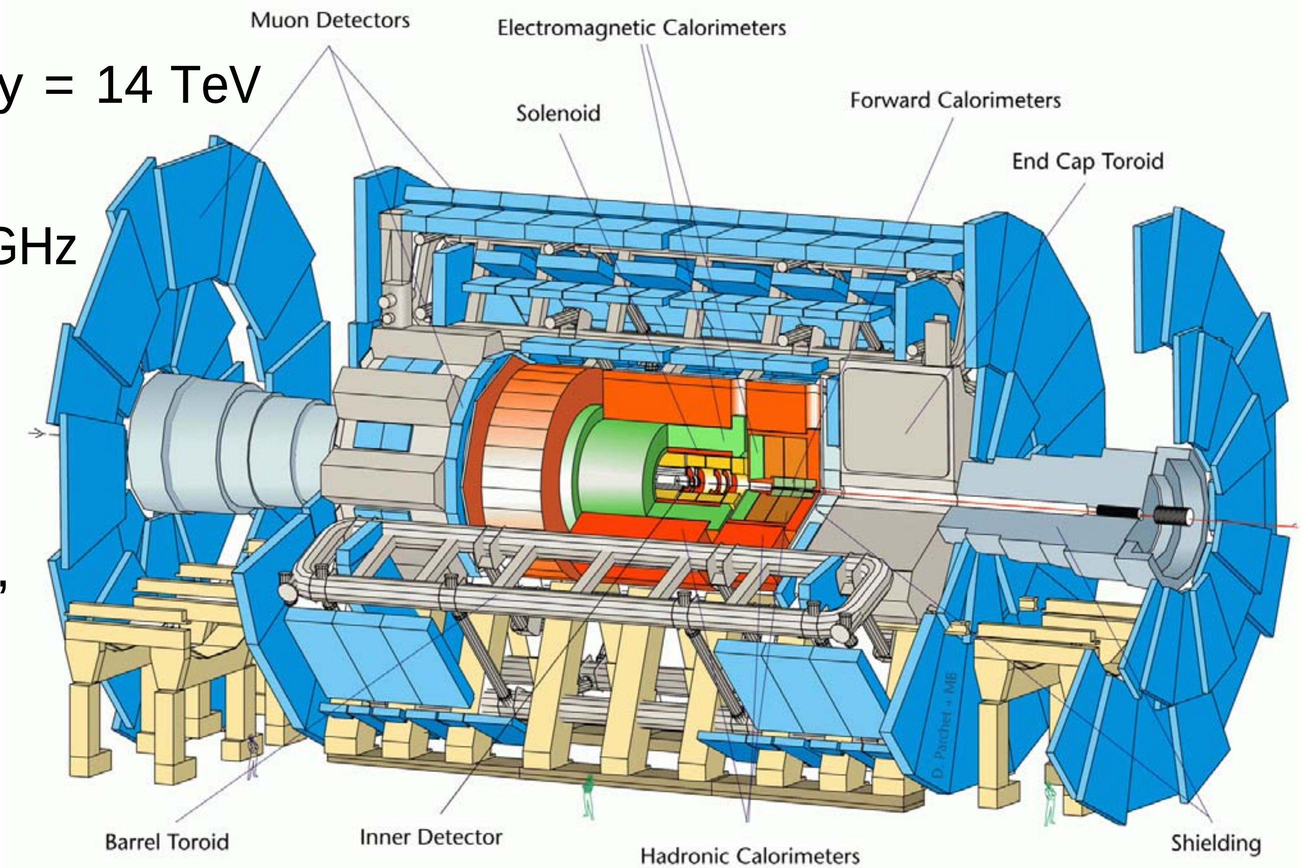
initial: $10^{31} cm^{-2} s^{-1}$

design: $10^{34} cm^{-2} s^{-1}$

7000 Ton Detector,

22m Diameter,

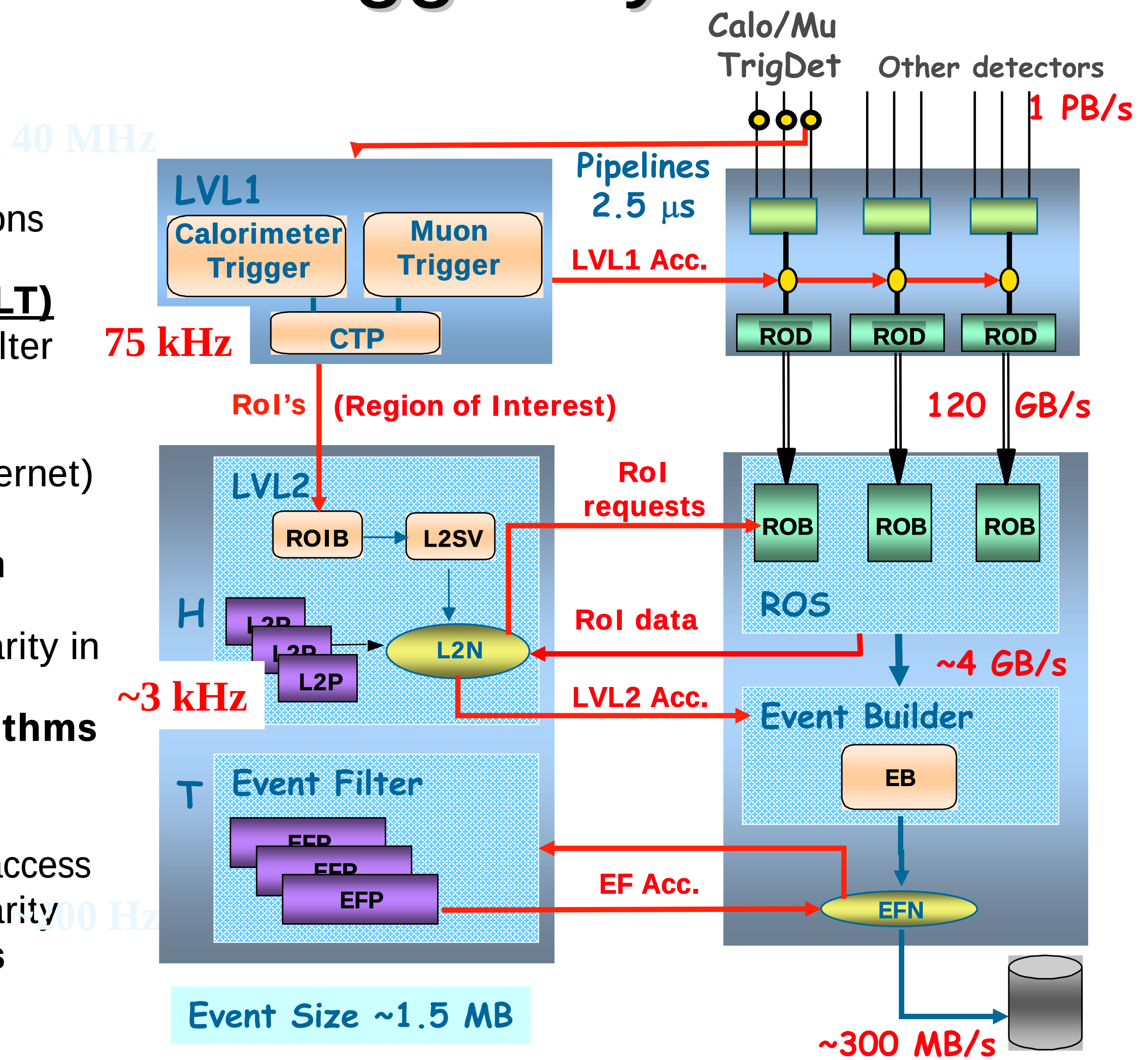
46m Long



- ATLAS detector is a general purpose spectrometer – broad physics program with an emphasis on high-pT physics
- ATLAS features a three-level trigger system (see S.George's talk for more details)

The ATLAS Trigger System

- **Level 1**
  - Hardware based
  - Coarse granularity calorimeter and muons only
- **High Level Trigger (HLT)**
  - Level 2 and Event Filter
  - Software based
  - Mostly commodity hardware (PC + Ethernet)
- **Level 2 (L2)**
  - Data requested from ROBs over network
  - Full detector granularity in RoIs
  - **Special fast algorithms**
- **Event Filter (EF)**
  - **Seeded by L2**
  - Potential full event access
  - Full detector granularity
  - **Offline algorithms**



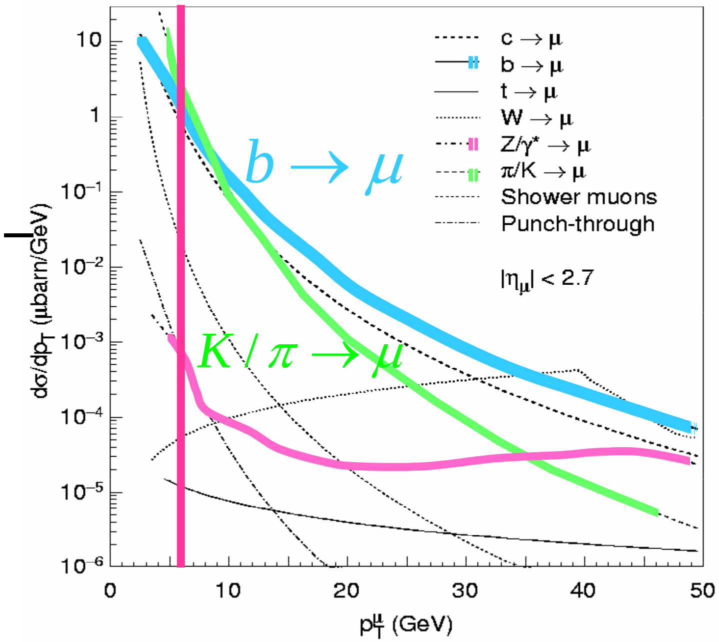
Triggering B-physics events

- ATLAS has a well defined B-physics program which includes:
  - CP violation in $B_d^0 \to J/\psi K_S^0$ and $B_s^0 \to J/\psi \phi$
  - B_s^0 oscillations using $B_s^0 \to D_s \pi$ and $B_s^0 \to D_s a_1$ channels
  - rare B-decays, e.g. $B_{d,s}^0 \to \mu^+ \mu^- (X)$, $B_s^0 \to \phi\gamma$, $B_d^0 \to K^* \gamma$
- Trigger resources are finite – only 5-10 % of total resources are allocated for B-physics
- A highly selective trigger with exclusive or semi-inclusive decay reconstruction is required
  - must reject non-B background
  - must select B-decays of specific interest (B-background rejection)
- Trigger strategy must be flexible enough to adapt to increasing luminosity during LHC running

B-physics Trigger: LVL1

- LVL1 muon trigger:
  - $Br(b \to \mu) \sim 10\%$, a clean signature already at LVL1 + flavor tagging; main background is from $K/\pi \to \mu$ decays – to be removed by LVL2 trigger
  - muon pT threshold:
    - 4 GeV for initial running
    - rising to 6-8 GeV as luminosity rises
  - single and di-muon triggers:
    - at design luminosity only di-muon trigger will be used

Cross-section



p_T of muons from different processes

- Using additional LVL1 Regions-of-Interests at low lumi:
  - Jet LVL1 RoI for hadronic decays, e.g. $B_s^0 \to D_s \pi$
  - electromagnetic (EM) LVL1 RoIs for radiative decays, e.g. $B_s^0 \to \phi\gamma$ or channels with $J/\psi \to e^+e^-$

B-physics Trigger: HLT

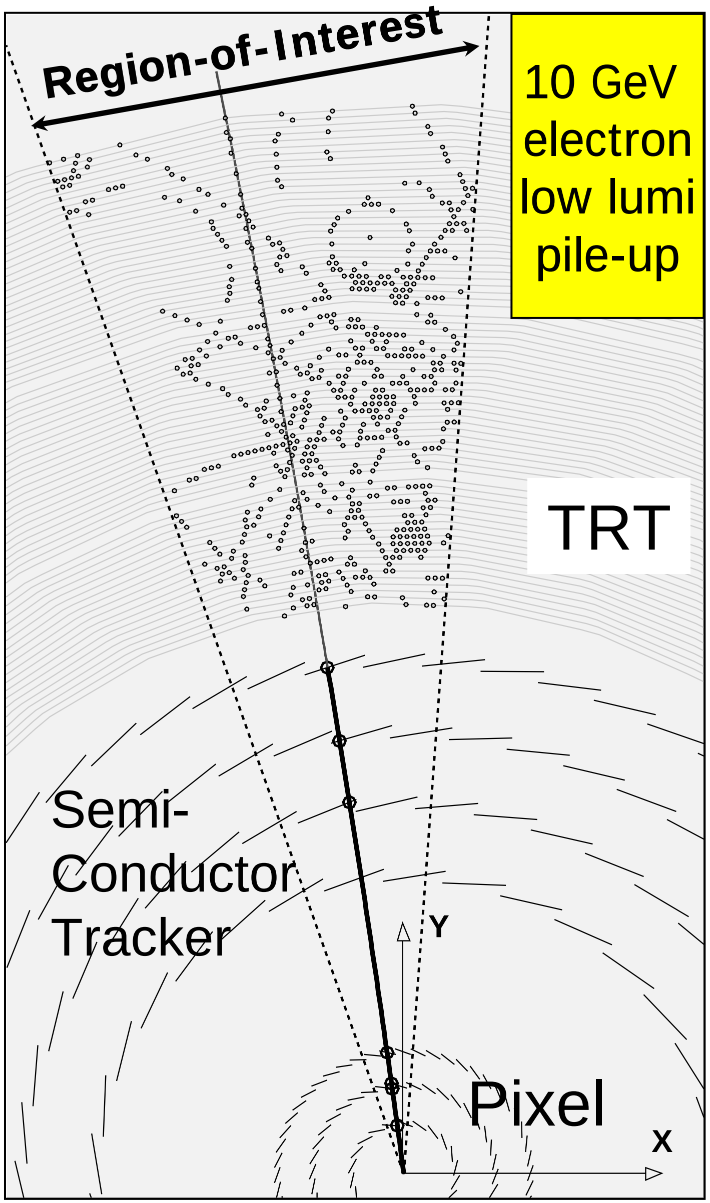
1. Confirmation of LVL1 muon(s)
   1. Fast LVL2 tracking of muon candidate in LVL1 muon RoI
   2. Tracking in Inner Detector using muon RoI
   3. Track parameter matching (spatial and p_T) of ID and Muon segments – to suppress $K/\pi \rightarrow \mu$ background and fake tracks
2. LVL2 reconstruction of the other B-decay products in Inner Detector using:
   1. enlarged RoI around LVL1 muon (e.g. $J/\psi \rightarrow \mu^+\mu^-$)
   2. additional (EM, Jet) RoIs from LVL1
   3. full detector (“FullScan”) – option for initial luminosity
3. Track selection, combinatorial search for decay vertices, vertex fitting, cuts on inv. mass and fit quality
4. Track reconstruction is repeated and event selection is refined by the Event Filter algorithms

Fast Tracking Algorithms

- LVL2 features
  - Fast pattern recognition in silicon detectors (Pixel and SCT) and Kalman filter-based track fit
  - track following algorithm and stand-alone pattern recognition for Transition Radiation Tracker (TRT)
  - algorithms are optimized for B-physics events to be efficient for low-pT (~1GeV) tracks: $D_s \to \phi(KK)\pi$

Track (pT>1.5 GeV)	π	K
tracking efficiency	93 %	94 %

- Event Filter
  - essentially EF runs offline algorithms adapted for running inside RoIs – for details see A.Salzburger's talk (#192)



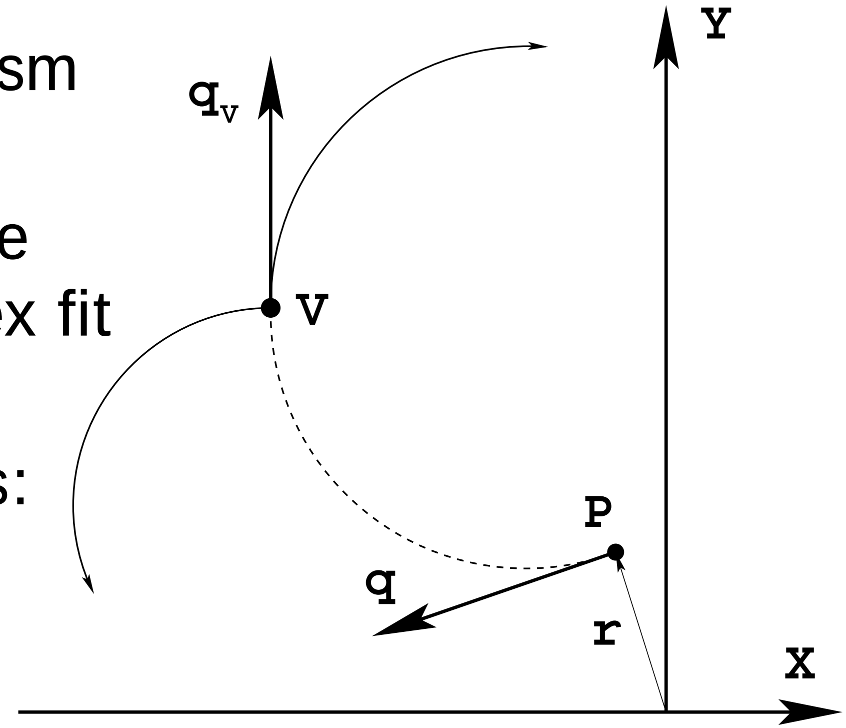
Fast Vertex fitter for B-Trigger

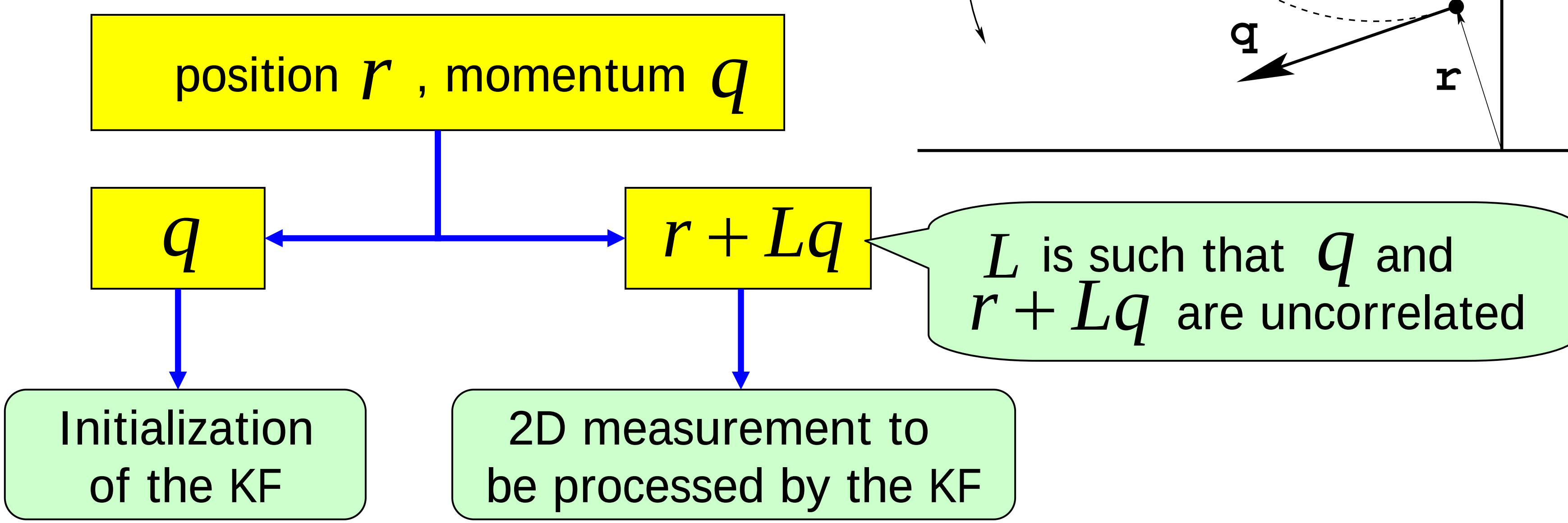
- Vertex reconstruction is essential for selection of many interesting B-physics channels
- LVL2 track reconstruction imposes certain constraints:
  - track parameters are estimated at perigee points – points of the closest approach to z-axis (parallel to the magnetic field)
  - errors are represented by covariance matrices
- Algorithms proposed in literature (Billoir, Fruewirth et al.) require weight matrices (inverse covariance)
- We have developed a fast vertex fitting algorithm which
  - features a Kalman filter with reduced-size measurement model
  - can use track covariances directly, without time-consuming matrix inversion

Main ideas of the algorithm

(see backup slides for mathematical details)

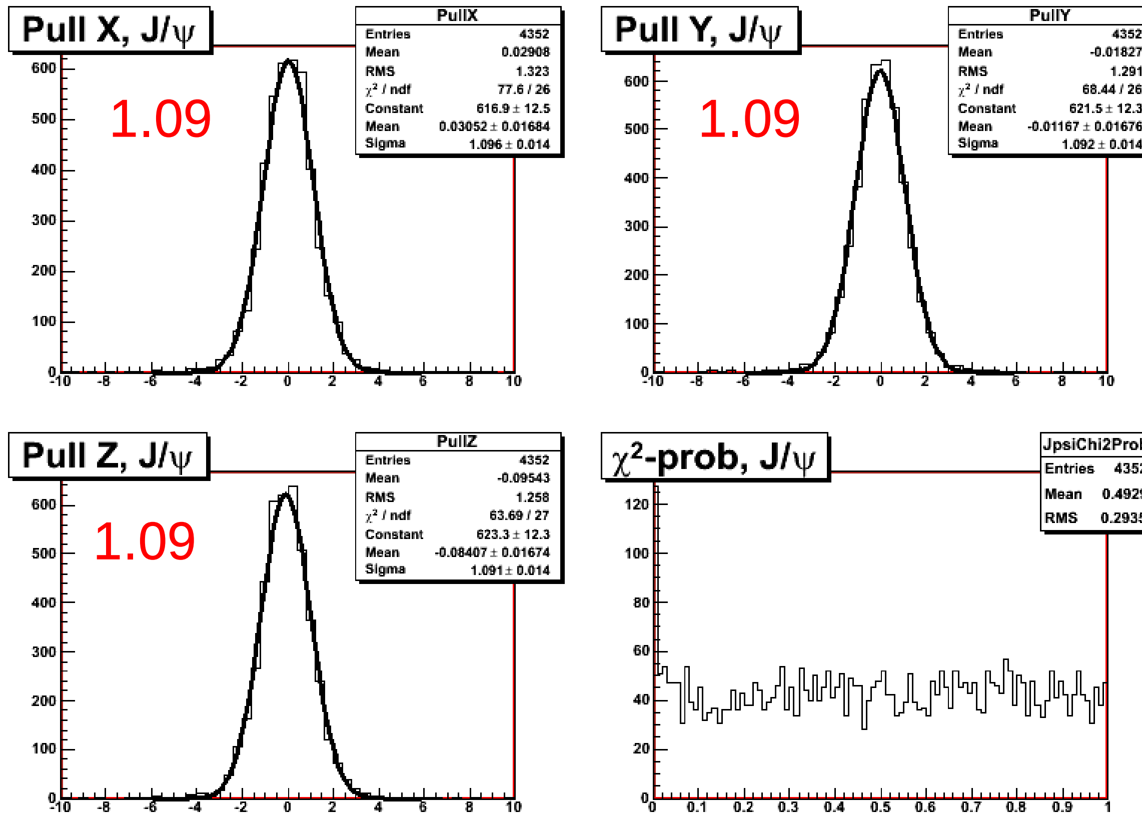
1. Using the “gain-matrix” formalism of a Kalman filter (KF)
2. Using track momenta at perigee (rather than at vertex) as vertex fit parameters
3. Decoupling of track parameters:





Algorithm validation

- The algorithm has been validated on $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$
- The results show
  - good fit quality:
    - vertex pulls close to 1
    - flat χ^2-probability
  - CPU time < 1% of available LVL2 budget

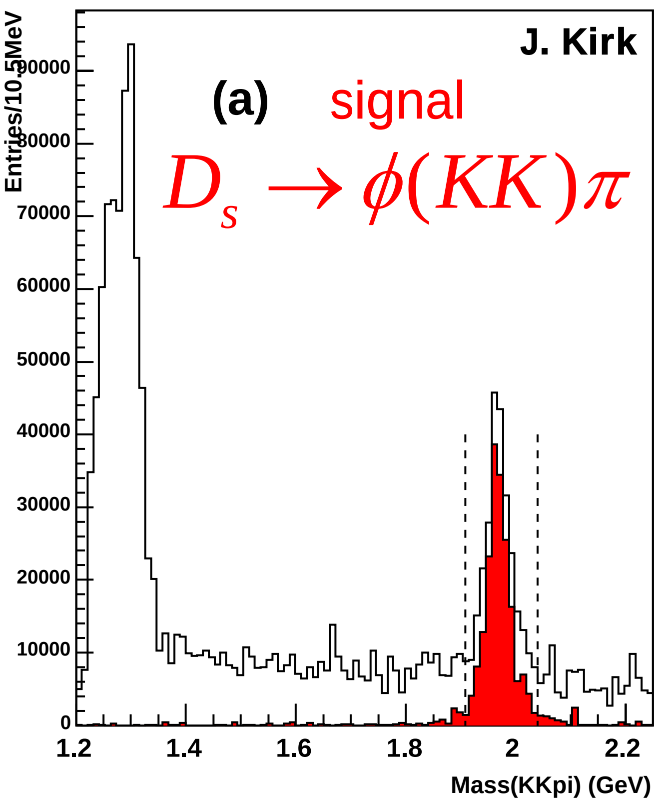


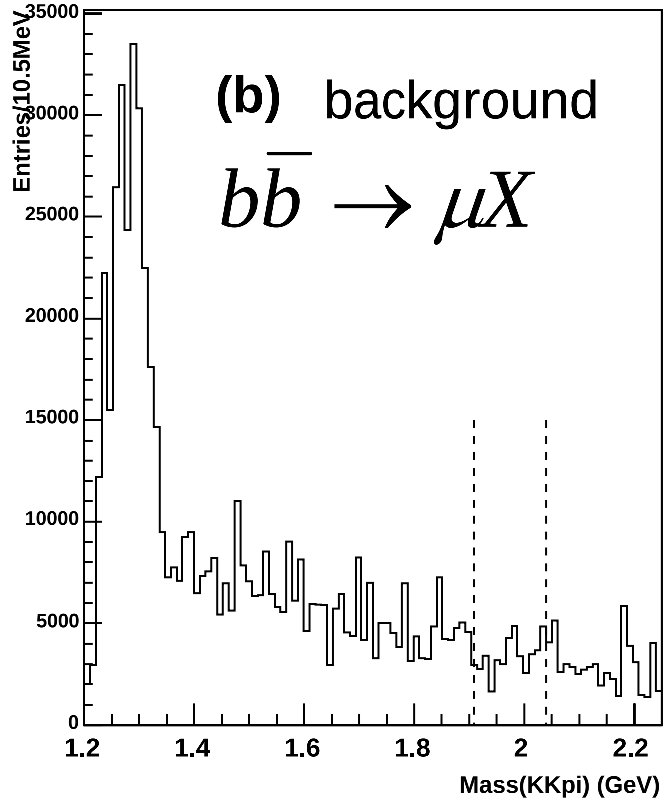
CPU time measured on a 2.4 GHz Xeon CPU :

Tracks/vertex	2	4
CPU time, ms	0.20	0.36

An example: LVL2 $D_s \to \phi\pi$ selection

- LVL2 track reconstruction in a Jet RoI
- Combinatorial search for $\phi(K^+K^-)$, 3σ-cut on ϕ mass
- Combinatorial search for π, 3σ-cut on $KK\pi$ mass





Trigger Rate at

$L = 10^{33} cm^{-2} s^{-1}$

Step	Rate
LVL1 single μ	20 kHz
LVL2 μ confirm	5 kHz
LVL2 $D_s \to \phi\pi$	200 Hz

- A similar selection at the EF will give a further factor 10 rate reduction

Conclusion

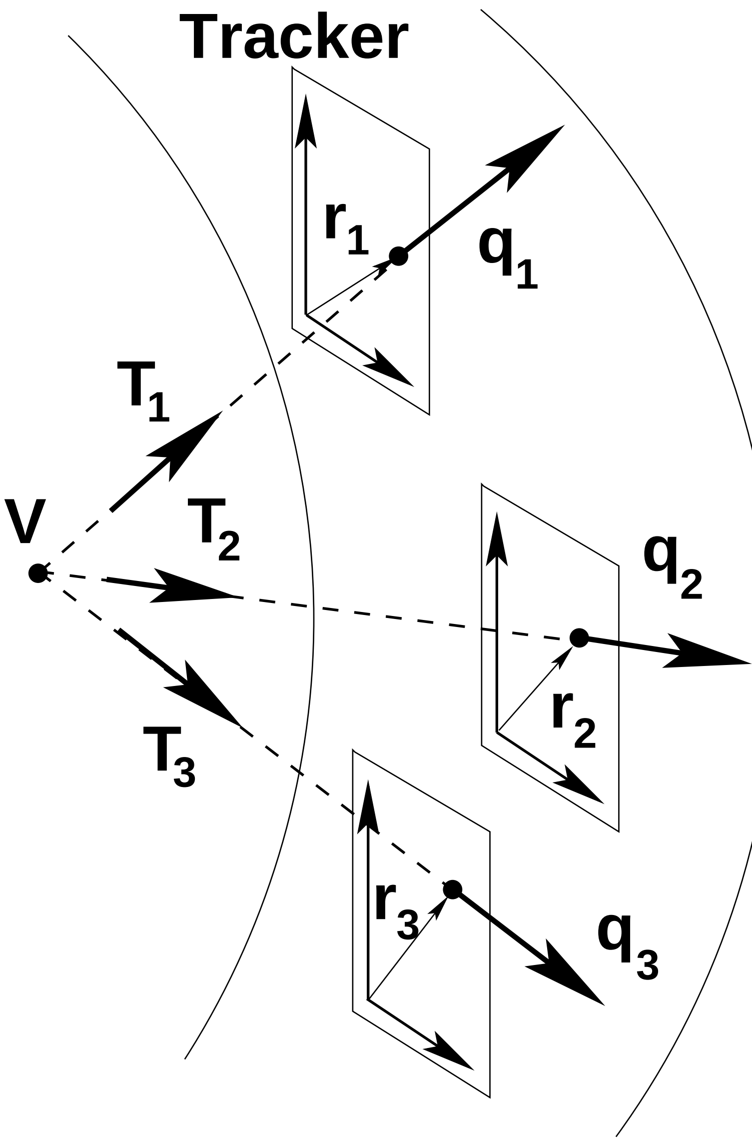
- ATLAS has a well-defined B-physics trigger strategy adapted to the currently planned LHC luminosity schedule
- Event-selection software for B-physics trigger has been developed and validated using simulated data
- Looking forward to testing it on real data ...

Backup Slides

Time constraints on HLT Algorithms

- LVL2 timing requirement
  - Need to absorb up to 75 kHz LVL1 rate (upgradeable to 100 kHz)
    - Processing of a new event is initiated every 10 μs
  - ~500 1U slots allocated to the LVL2 farm
    - Current baseline: 500 quad-core dual CPU (>=2 GHz), one event per core
      - $\Rightarrow$ ~40 ms average processing time per event (includes data access & processing time)
- EF timing requirement
  - Need to absorb up to ~3 kHz LVL2 rate
    - Processing of a new event is initiated every ~300 μs
  - ~1800 1U slots for the EF farm
    - Current baseline: 1800 quad-core dual CPU (>=2 GHz), one EF process per core
      - ~4s average processing time per event (includes data access & processing time)
- Aggregate processing power of current baseline HLT farms is consistent with assumption in TDR based on 8 GHz single core dual CPU
- Relative allocation of LVL2 & EF processors is configurable

Vertex Fitting Problem



- It's assumed that **n** reconstructed tracks originate from a common point – a vertex **V**
- Given estimated track parameters **m** :
  - track positions **r** and
  - track momenta **q**

  vertex fit estimates a fit parameter vector **X** – vertex position **R** and track momenta **T**
- For each track, **m** and **X** are related by the measurement equation:

$$m_k = h(R, T_k) + \varepsilon_k$$

Track reconstruction errors $\mathrm{cov}(\varepsilon_k) = V_k$

- Usually, track momenta *at vertex* are used as fit parameters **T**

Measurement model reduction

- Alternatively, track momenta *at measurement surface* **q** can be used as the fit parameters: **T** = **q**
- Such choice of fit parameters reduces a size of non-trivial part of the measurement equation:

track position

2-dim

$$m_k = \begin{pmatrix} m_k^r \\ m_k^q \end{pmatrix} = \begin{pmatrix} h(R, q_k) \\ q_k \end{pmatrix} + \begin{pmatrix} \varepsilon_k^r \\ \varepsilon_k^q \end{pmatrix}$$

track momentum

- Let the vertex fit be done by a Kalman filter. Let's split m_k into m_k^r and m_k^q, and treat
  - m_k^q as a *prior estimate* $\hat{q}_k^0$ of the momentum q_k and
  - V_k^{qq} block of track covariance V_k as initial covariance of $\hat{q}_k^0$

Decorrelating transformation

- The Kalman Filter (KF) equations need modifying as, in general, errors of track position and track momentum are *correlated* – i.e. $< \varepsilon_k^q, \varepsilon_k^r >= V_k^{rq} \neq 0$
- The following change of variables solves this problem:

$$\begin{pmatrix} r \\ q \end{pmatrix} \to \begin{pmatrix} r + Lq \\ q \end{pmatrix}$$

where matrix L is such that $\varepsilon_k^r + L\varepsilon_k^q$ and ε_k^q are uncorrelated

- As can be easily verified $L = -V_k^{rq}\left(V_k^{qq}\right)^{-1}$
- Applying this decorrelating transformation we obtain modified equations of the Kalman filter
- These equations describe how vertex fit parameters are updated if a new ($k+1$-th) track is added to a vertex already fitted with k tracks

Fast Vertex Fitting Algorithm

- Update of the vertex fit parameters

$$\hat{X}_{k+1} = \begin{pmatrix} \hat{X}_k \\ m^q_{k+1} \end{pmatrix} + K_{k+1} d_{k+1}$$

- Kalman gain matrix

$$K_{k+1} = M_{k+1} S^{-1}_{k+1}$$

- Residual (2-dim)

$$d_{k+1} = m^r_{k+1} - h\left(\hat{R}_k, m^q_{k+1}\right)$$

- Residual covariance $S_{k+1} = A_{k+1} C_k A^T_{k+1} + V^{rr}_{k+1} - B_{k+1} V^{qr}_{k+1} -$

$$- V^{rq}_{k+1} B^T_{k+1} + B_{k+1} V^{qq}_{k+1} B^T_{k+1}$$

$$M_{k+1} = \begin{pmatrix} C_k A^T_{k+1} \\ E_k A^T_{k+1} \\ V^{qq}_{k+1} B^T_{k+1} - V^{qr}_{k+1} \end{pmatrix}$$

- Covariance matrix of the vertex fit parameters

$$\mathrm{cov}\left(X_k\right) = \hat{\Gamma}_k = \begin{pmatrix} C_k & E^T_k \\ E_k & D_k \end{pmatrix}$$

Fast Vertex Fitting Algorithm

- Linearization:

$$A_{k+1} = \left.\frac{\partial h(R,q)}{\partial R}\right|_{\hat{R}_k, m_{k+1}^q} \qquad B_{k+1} = \left.\frac{\partial h(R,q)}{\partial q}\right|_{\hat{R}_k, m_{k+1}^q}$$

- Update of the covariance matrix

$$\hat{\Gamma}_{k+1} = \begin{pmatrix} \hat{\Gamma}_k & 0 \\ 0 & V_{k+1}^{qq} \end{pmatrix} - K_{k+1} M_{k+1}$$

- χ^2 contribution (with 2 DOF) $\Delta\chi_{k+1}^2 = d_{k+1}^T S_{k+1}^{-1} d_{k+1}$

- Computational advantages of the algorithm:
  - Track covariance (blocks of) is used directly in the fit
  - The only matrices to invert are 2x2 $S_k, k = 1, \ldots, n$
  - After processing the last track the full fit covariance $\hat{\Gamma}_n$ is available immediately, i.e. no smoother needed