Track reconstruction in the LHC experiments

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Are Strandlie

Gjøvik University College, Norway and
University of Oslo, Norway

- This talk will be an overview of the **track reconstruction strategies and algorithms** in the four LHC experiments
  - will not be able to cover all relevant material in 30 minutes
    - e.g. effects of misalignment treated in other talks
  - have therefore chosen to emphasize
    - algorithms rather than software technicalities
    - main/inner tracking systems and track reconstruction starting from prepared raw data

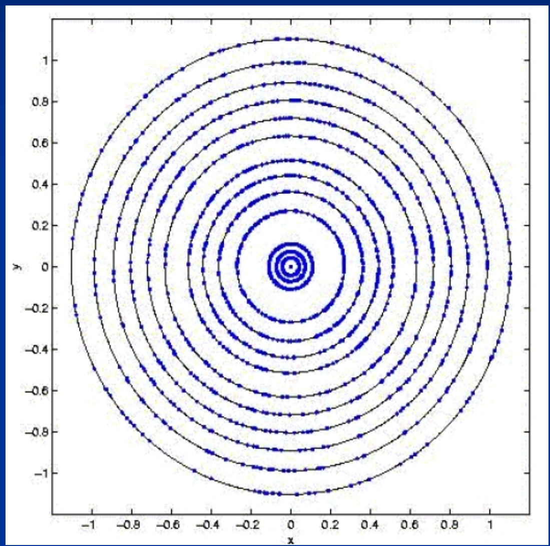
Outline

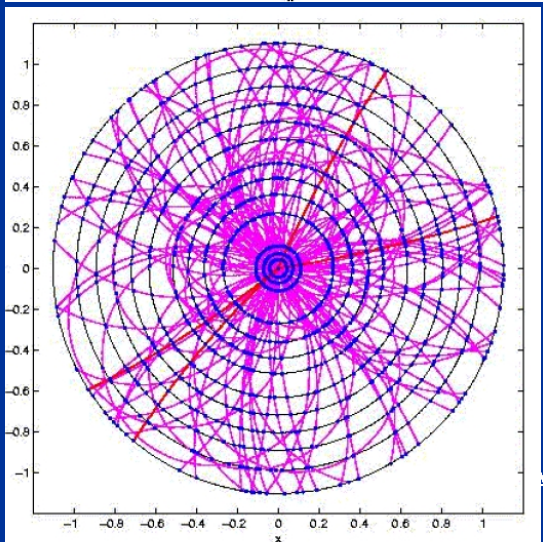
- Introduction
- Overall comparison of tracking strategies
  - similarities
  - differences
- Specific strategies for each experiment
- Examples of (relatively) recent developments
- Conclusions

Introduction

- Track reconstruction is traditionally divided into two separate subtasks:
  - track finding
  - track fitting
- Track finding:
  - division of set of measurements in a tracking detector into subsets
  - each subset contains measurements believed to originate from the same particle
- Track fitting:
  - starts out with the measurements inside one subset as provided by the track finder
  - aims to optimally estimate a set of track parameters from the information from the measurements
  - evaluates the quality and final acceptance of the track candidate

Introduction





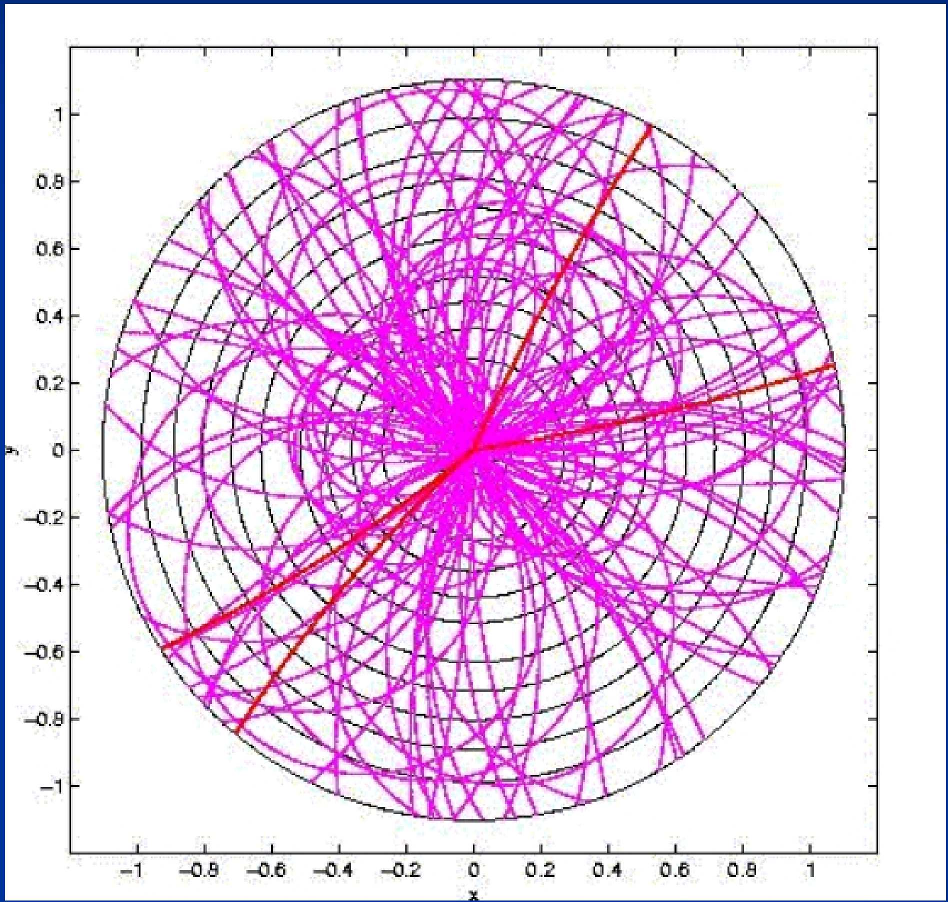
Tracking detector with cylindrical layers

Input to track finding is all or parts of the measurements in the detector at a given instance

A successful track finder identifies a set of potential tracks as indicated in the figure

Measurements along these tracks are given to the track fitter for parameter estimation and final validation of track candidate

Introduction



After the track fit one usually forgets about the measurements and only cares about a compact representation of the tracks

Overall strategies

- All experiments have implemented several tracking strategies
  - seems to be consensus that there is **no single algorithm optimal for all use cases**
  - typically one default approach as well as various alternative approaches, e. g.
    - second-pass track finding
    - track fitting in dense jets
    - special treatment of electrons

Overall strategies

- Overall decomposition in all experiments:
  - Seed generation
  - Local track finding (trajectory building) starting from seed
  - Track fitting
  - Post-processing
    - refitting, ambiguity resolution etc.

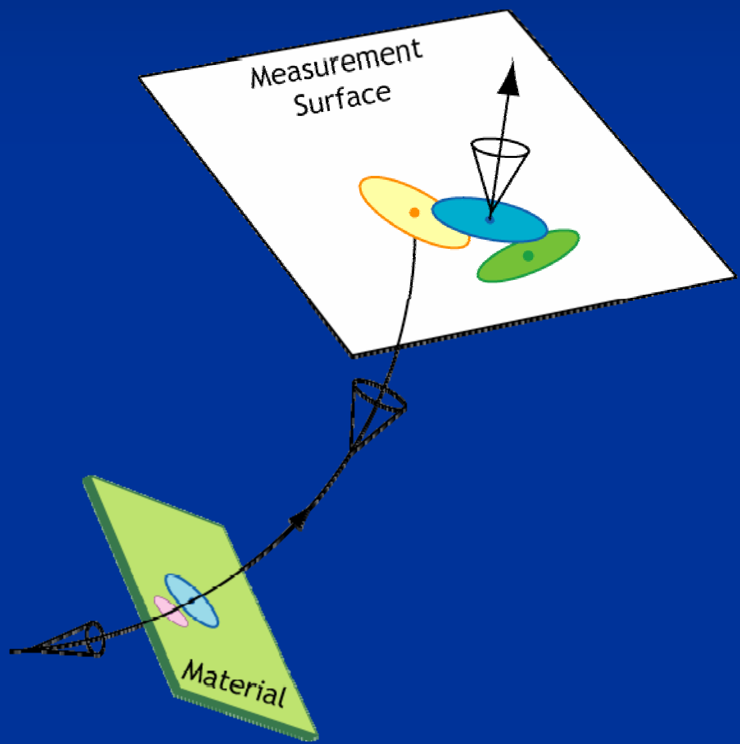
Overall strategies

- Seed generation
  - seed: typically a few measurements (and sometimes a vertex constraint) plus initial track parameters
  - ALICE: outer part of TPC
    - alternative starting in ITS (close to beam)
  - ATLAS: inner part of Inner Detector
    - alternative starting in TRT
  - CMS: inner part of Tracker
    - recent alternative using measurements also at the outside
  - LHCb: seeds in VELO (close to beam)
    - alternative starting in T stations further out

Overall strategies

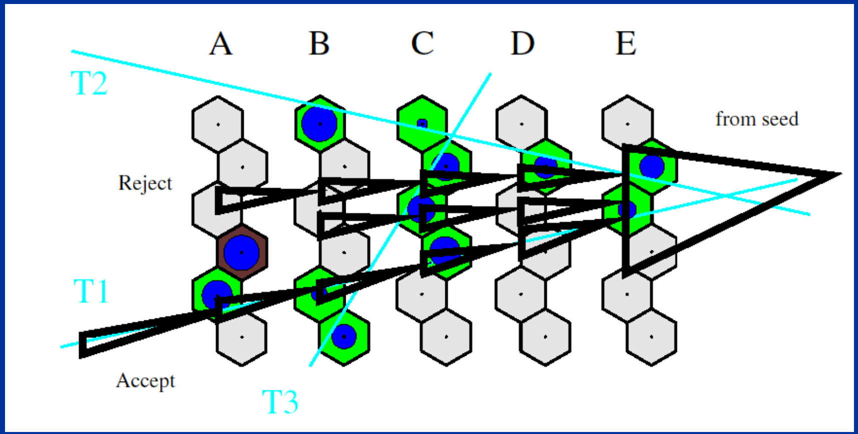
- Local track finding starting from seed
  - global approaches more or less absent, except e. g.
    - ALICE:
      - Hough transform in slices of TPC
      - Hopfield neural network in stand-alone track finding in ITS
    - ATLAS:
      - Hough transform in TRT
    - CMS:
      - Hopfield net tried out and abandoned several years ago
    - none of the above are default
  - common denominator: **combinatorial Kalman filter (CKF)**
    - all experiments except LHCb for default track finding
    - LHCb: histogram of distances from measurements to parameterized trajectory

Overall strategies



- Kalman filter:
  - recursive least-squares estimator, mathematically equivalent to global least-squares fit
  - alternating between propagation and update steps
  - several advantages as compared to global least-squares approach
  - introduced by P. Billoir in 1984 (without realizing it was a Kalman filter) and R. Frühwirth in 1987 (realizing it was a Kalman filter , introducing the Kalman smoother)
  - first implementation in DELPHI experiment at LEP at CERN

Overall strategies



- Due to recursive nature Kalman filter well suited for combined track finding and fitting
- CKF most popular approach (due to Rainer Mankel, NIM A 395 (1997)):
  - build up tree of track candidates starting from seed
  - various quality criteria used to cut branches during recursive procedure
  - keep best candidate in the end

Overall strategies

- Track fitting
  - Kalman filter most common track fitting algorithm in all LHC experiments
  - global fit still used as alternative in ATLAS Inner Detector and as default in ATLAS muon system
  - generalizations of Kalman filter also used in ATLAS and CMS
    - Deterministic Annealing Filter (DAF)
      - high-luminosity TRT track fitting in ATLAS
      - track fitting in dense jets in CMS
    - Gaussian-sum filter (GSF)
      - electron track fitting in both experiments

Overall strategies

- Post-processing:
  - CMS: removing track candidates which have too many measurements in common
    - trajectory cleaning
  - ATLAS: outlier rejection at various stages
  - ALICE+LHCb: second-pass track finding
  - refitting

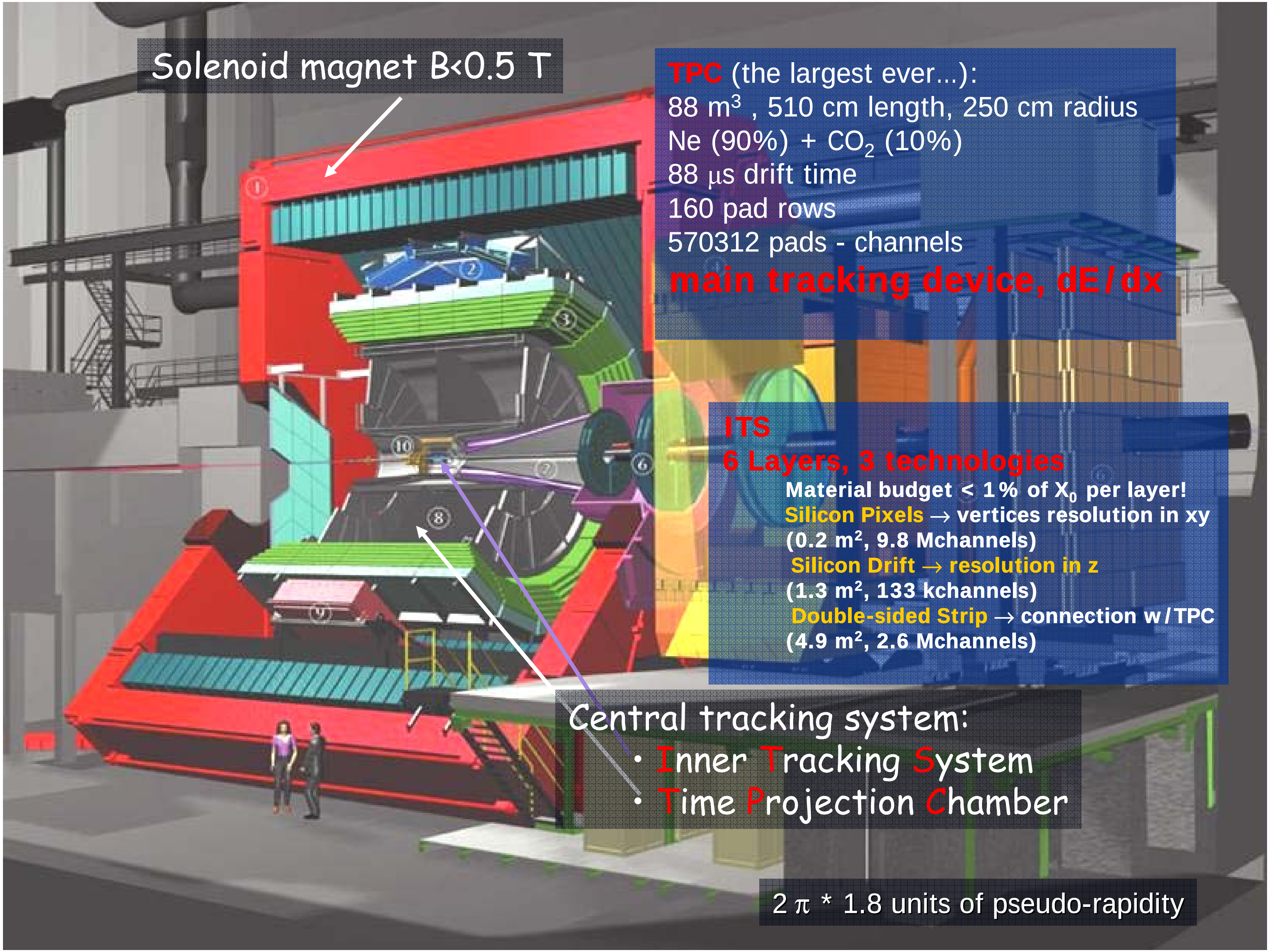
Muon tracking

- In general more material, less well-behaved magnetic fields and longer propagation distances than in main tracking systems
  - need of dedicated propagators
  - potential code re-use if propagator implementations are hidden behind abstract interface
- ALICE+CMS: combinatorial Kalman filter
- ATLAS: local track finding in regions of interest, matching track segments, global track fit
- LHCb: local track finding, momentum estimated by vertex constraint and measured kink through magnetic field

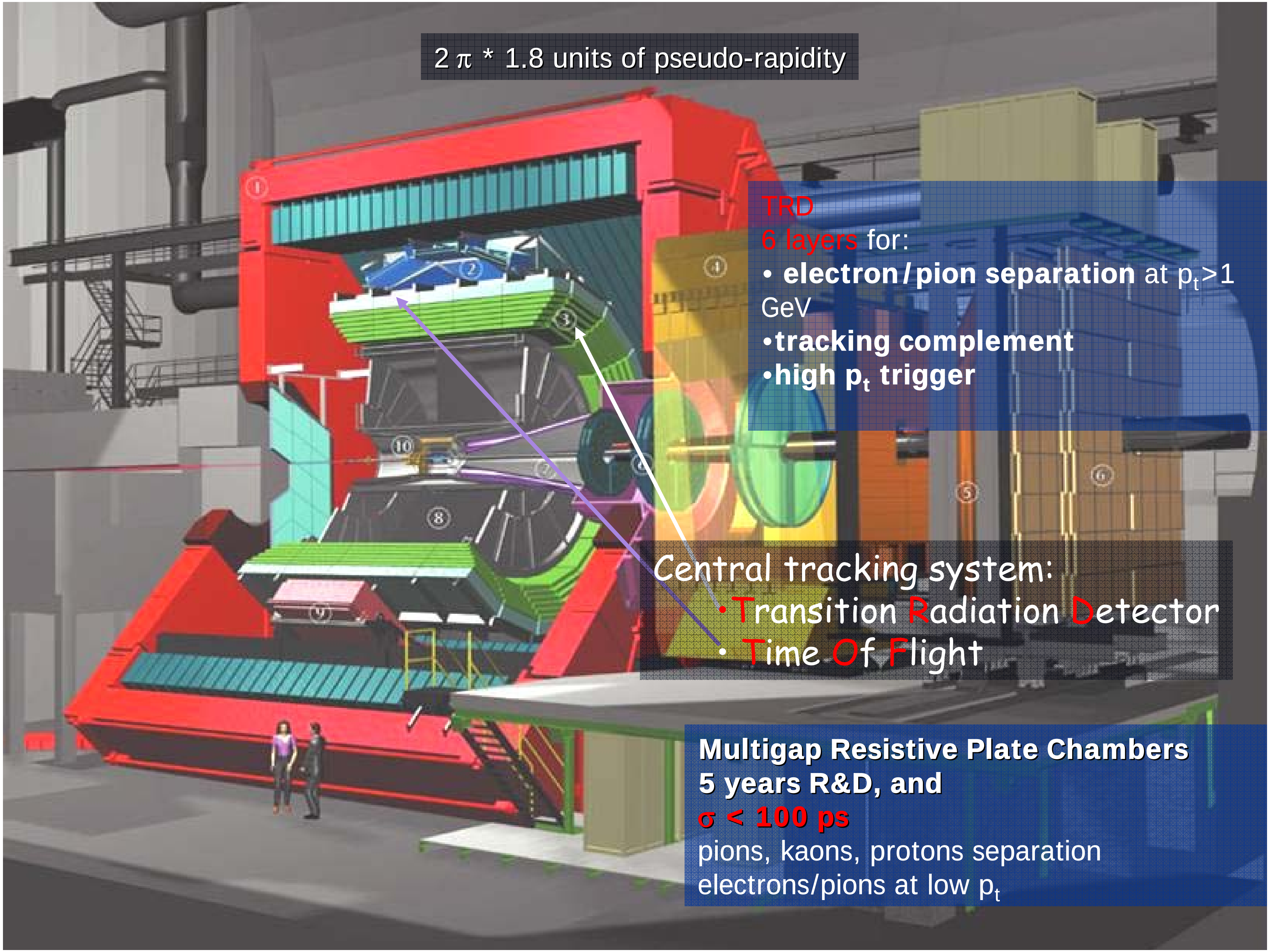
Software

- Main programming language: C++
  - some (very few) pieces of residual F77
  - important part of ATLAS muon reconstruction in F90
- Trend: decomposition of code into components with implementation details hidden behind abstract interfaces
  - different reconstruction algorithms put basic components together in different ways
  - ATLAS+CMS: code sharing muon/inner tracking systems
  - in general the experiments are moving away from monolithic packages

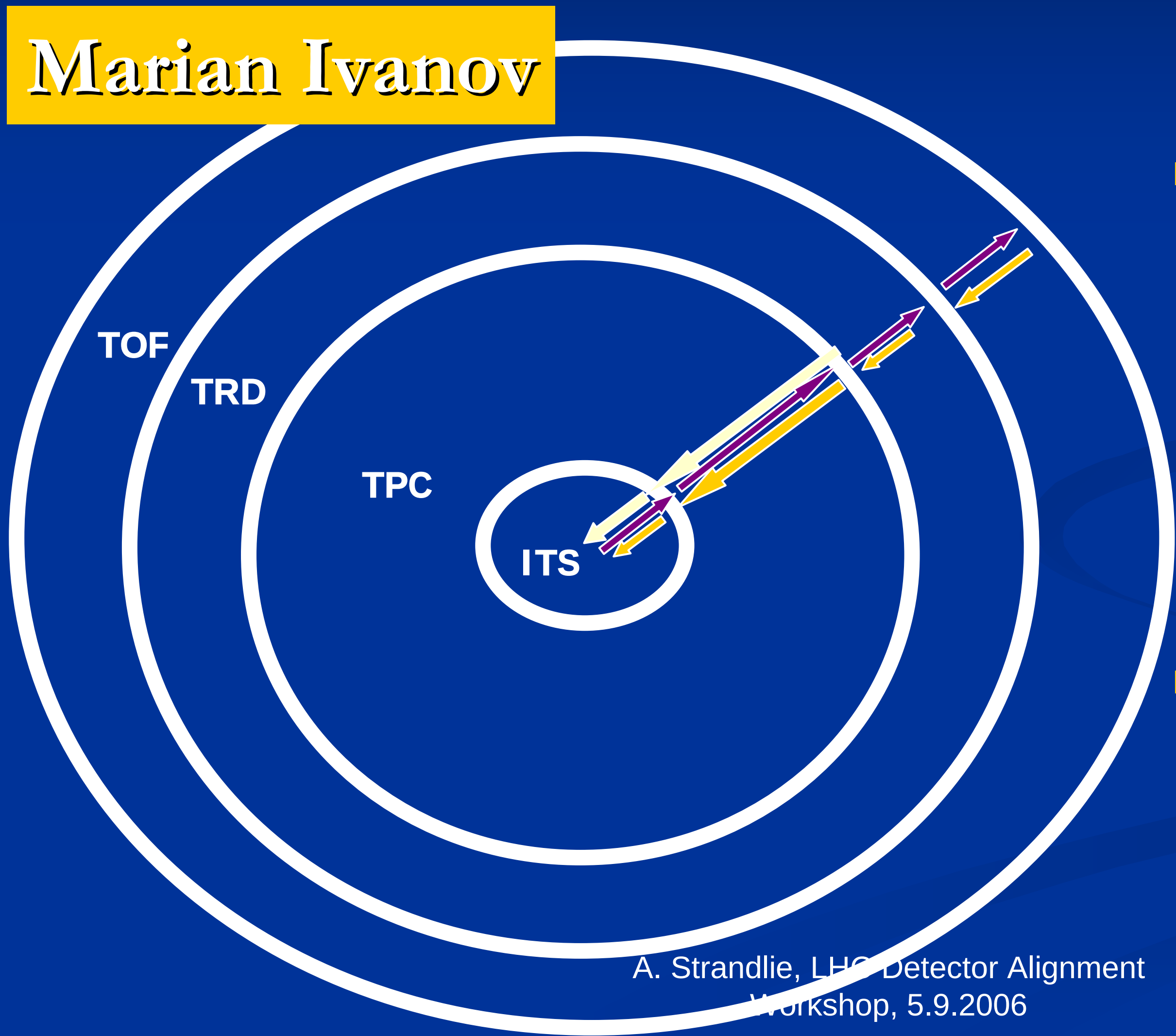
ALICE



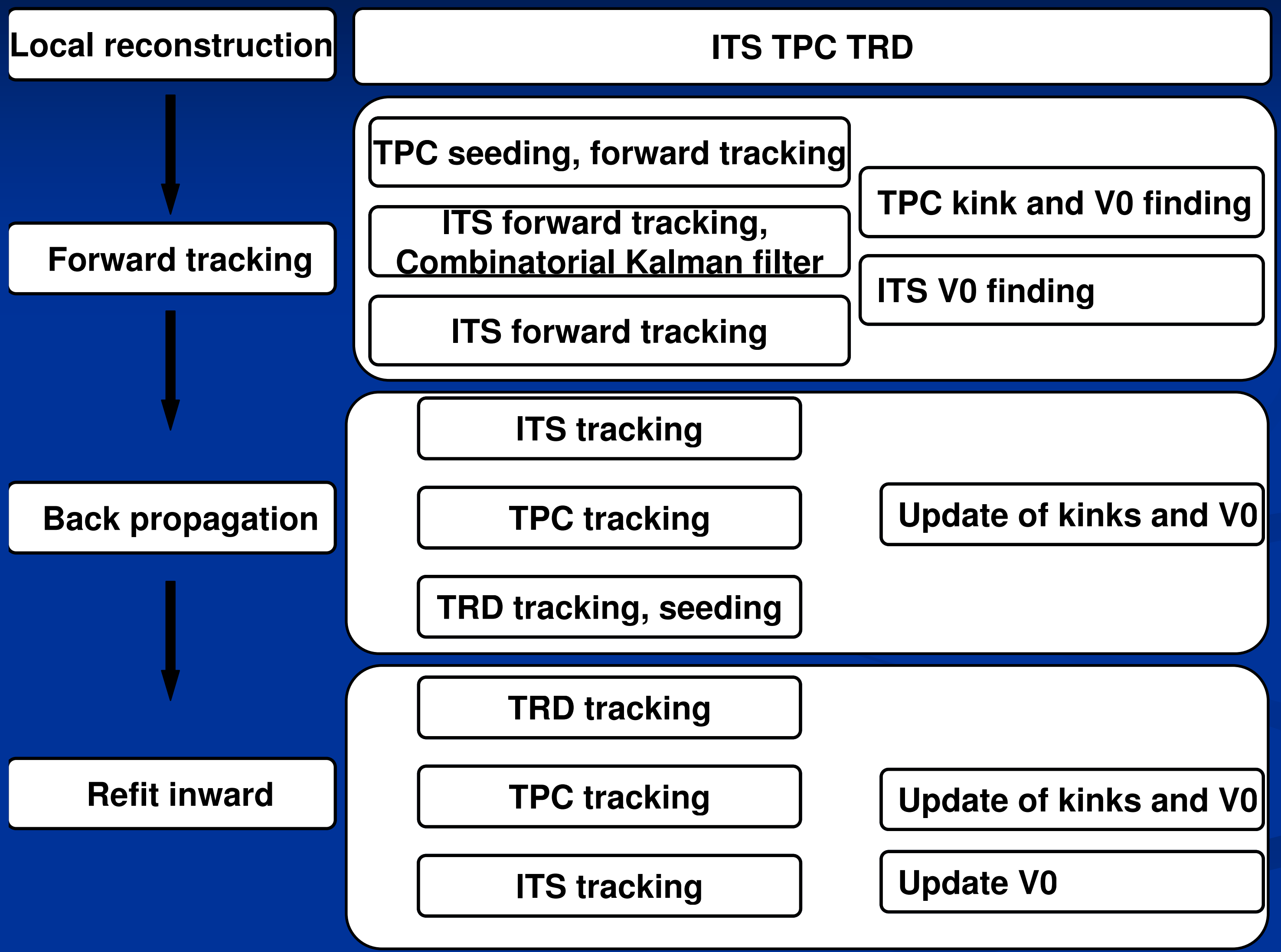
Solenoid magnet B<0.5 T
TPC (the largest ever...):
88 m^3 , 510 cm length, 250 cm radius
Ne (90%) + CO_2 (10%)
88 μs drift time
160 pad rows
570312 pads - channels
main tracking device, dE/dx
ITS
6 Layers, 3 technologies
Material budget < 1% of X_0 per layer!
Silicon Pixels → vertices resolution in xy
(0.2 m^2, 9.8 Mchannels)
Silicon Drift → resolution in z
(1.3 m^2, 133 kchannels)
Double-sided Strip → connection w/TPC
(4.9 m^2, 2.6 Mchannels)
Central tracking system:
• Inner Tracking System
• Time Projection Chamber
2 π * 1.8 units of pseudo-rapidity


2 π * 1.8 units of pseudo-rapidity
TRD
6 layers for:
• electron / pion separation at p_t>1 GeV
•tracking complement
•high p_t trigger
Central tracking system:
• Transition Radiation Detector
• Time Of Flight
Multigap Resistive Plate Chambers
5 years R&D, and
σ < 100 ps
pions, kaons, protons separation
electrons/pions at low p_t

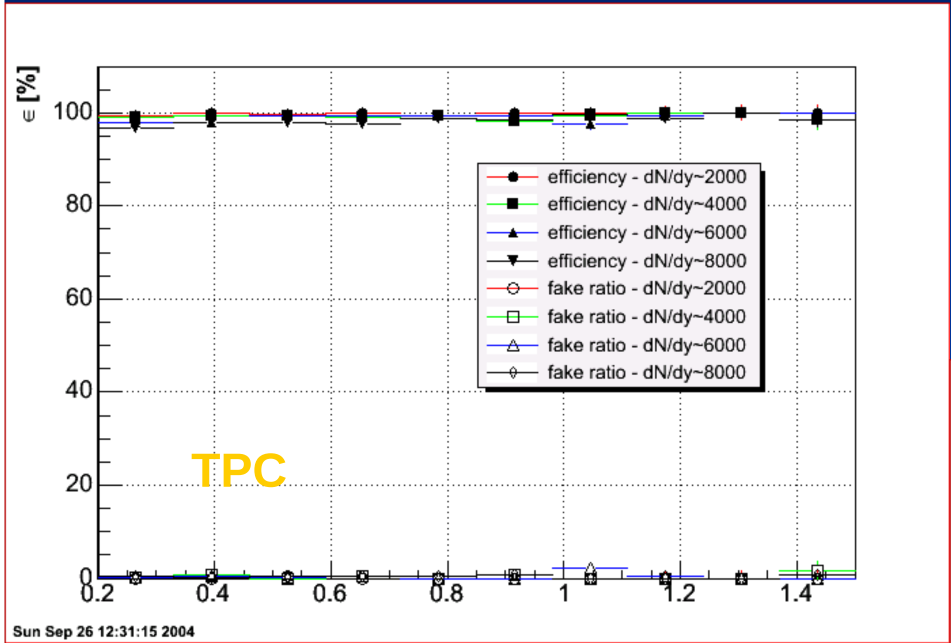
Tracking strategy – Primary tracks



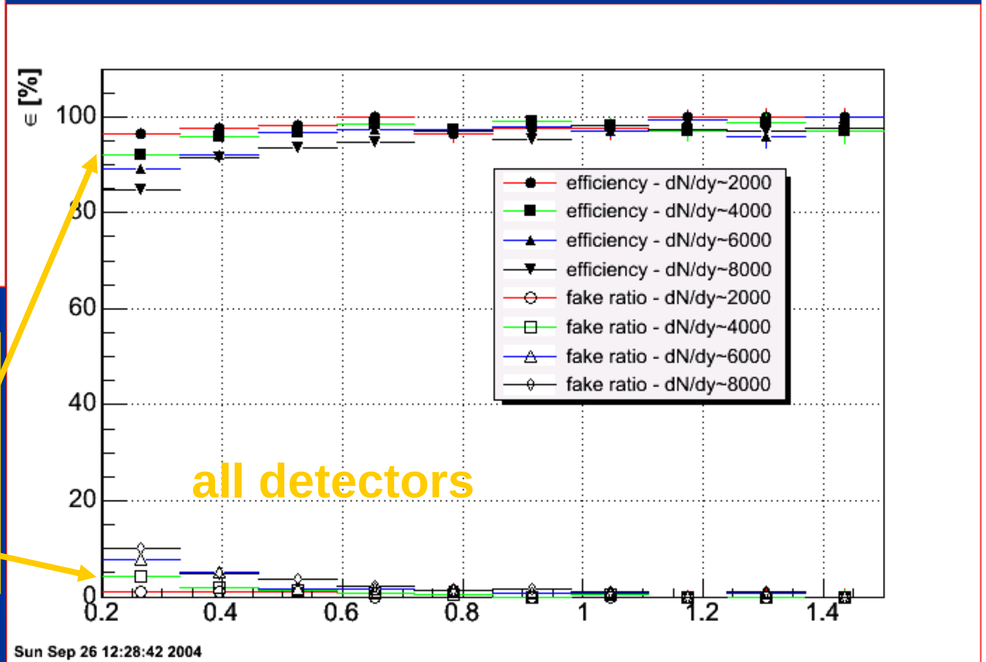
- Iterative process
  - Forward propagation towards to the vertex – TPC-ITS
  - Back propagation –ITS-TPC-TRD-TOF
  - Refit inward TOF-TRD-TPC-ITS
- Continuous seeding – track segment finding in all detectors


Local reconstruction
ITS TPC TRD
Forward tracking
TPC seeding, forward tracking
ITS forward tracking, Combinatorial Kalman filter
ITS forward tracking
TPC kink and V0 finding
ITS V0 finding
Back propagation
ITS tracking
TPC tracking
TRD tracking, seeding
Update of kinks and V0
Refit inward
TRD tracking
TPC tracking
ITS tracking
Update of kinks and V0
Update V0

Tracking efficiency



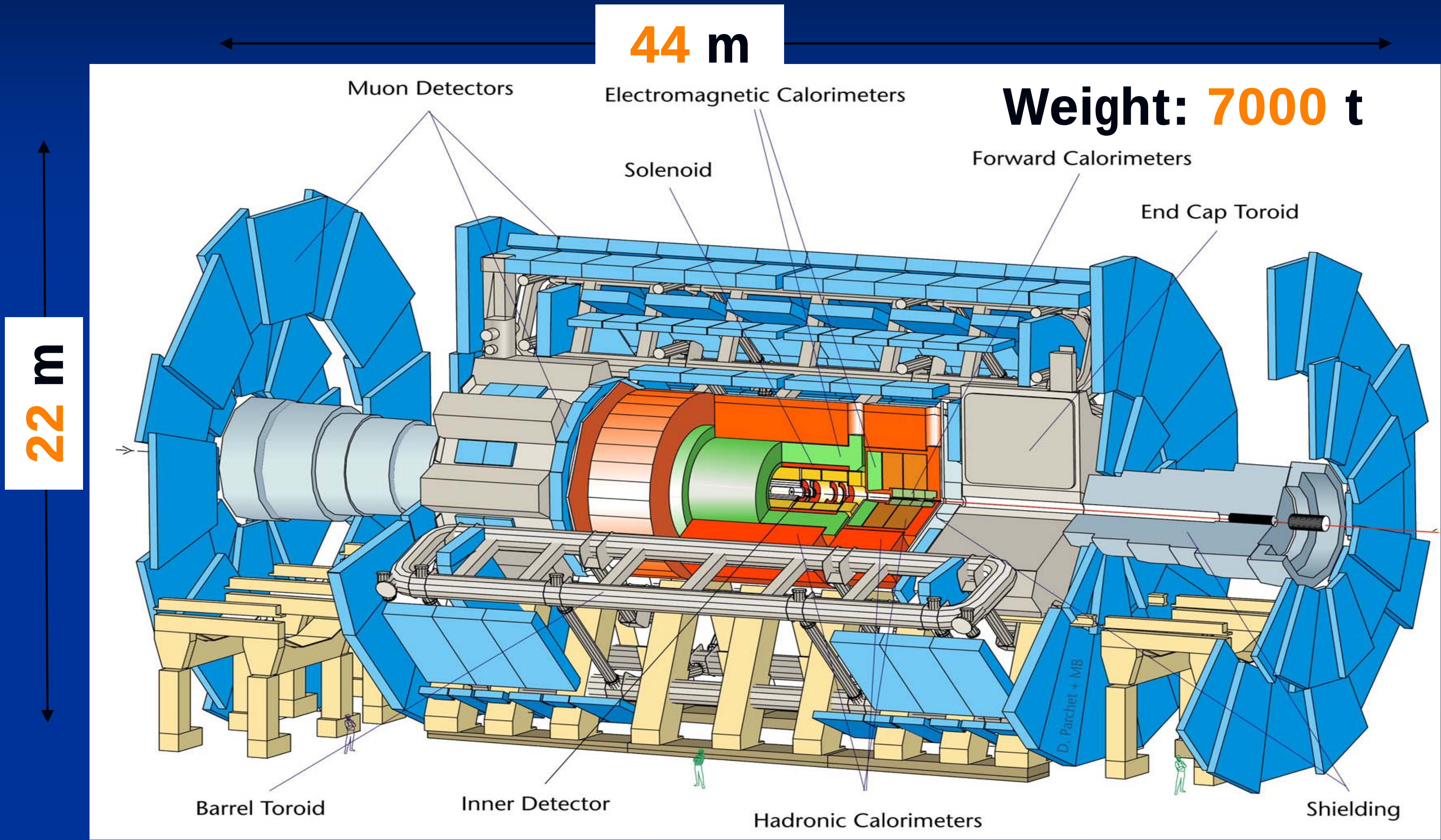
Challenge in high-particle density environment



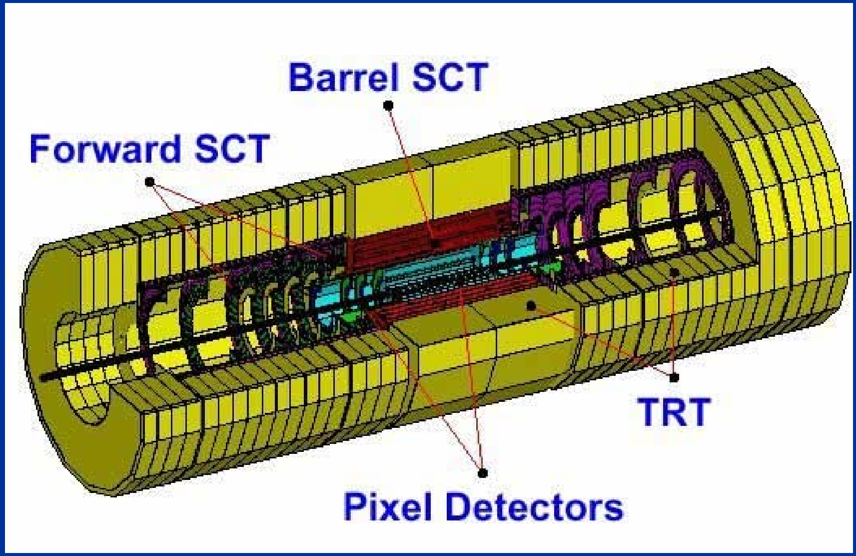
For realistic particle densities
dN/dy = 2000 – 4000
combined efficiency well above 90%
and fake track probability below 5%

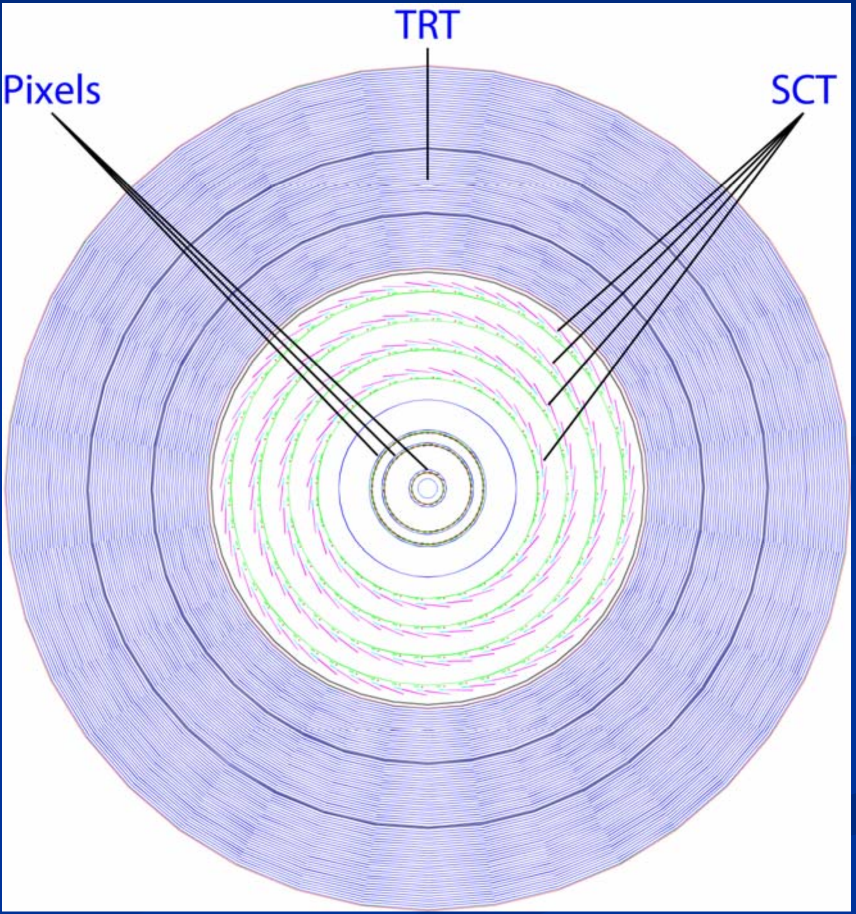
ATLAS

The ATLAS Detector



ATLAS Inner Detector

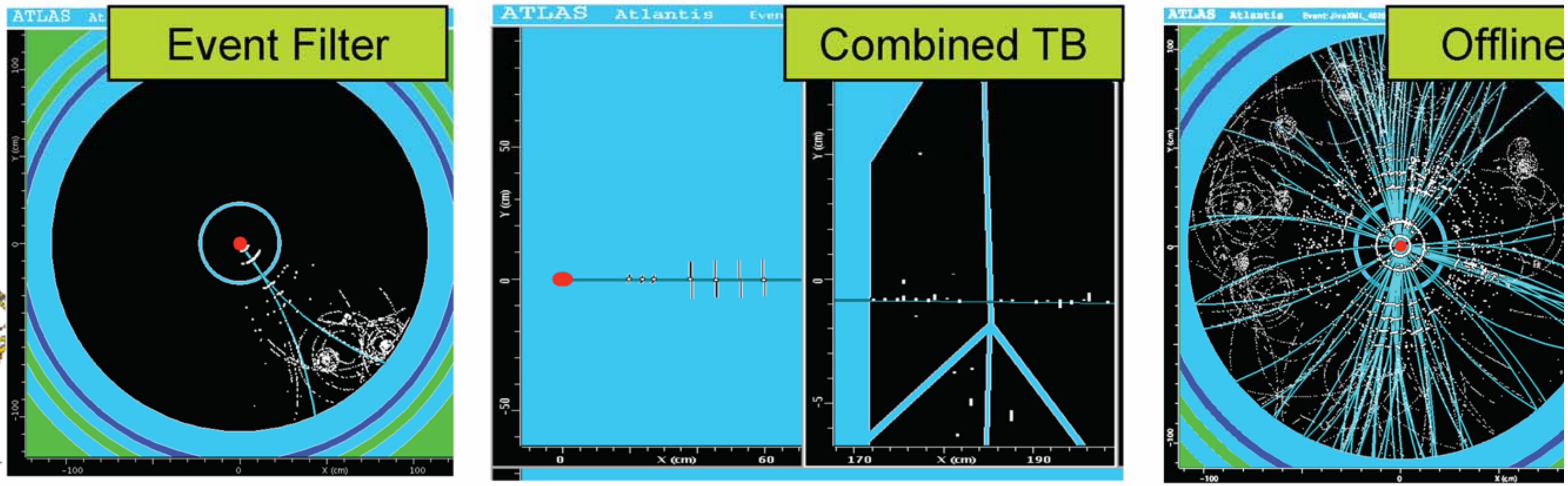




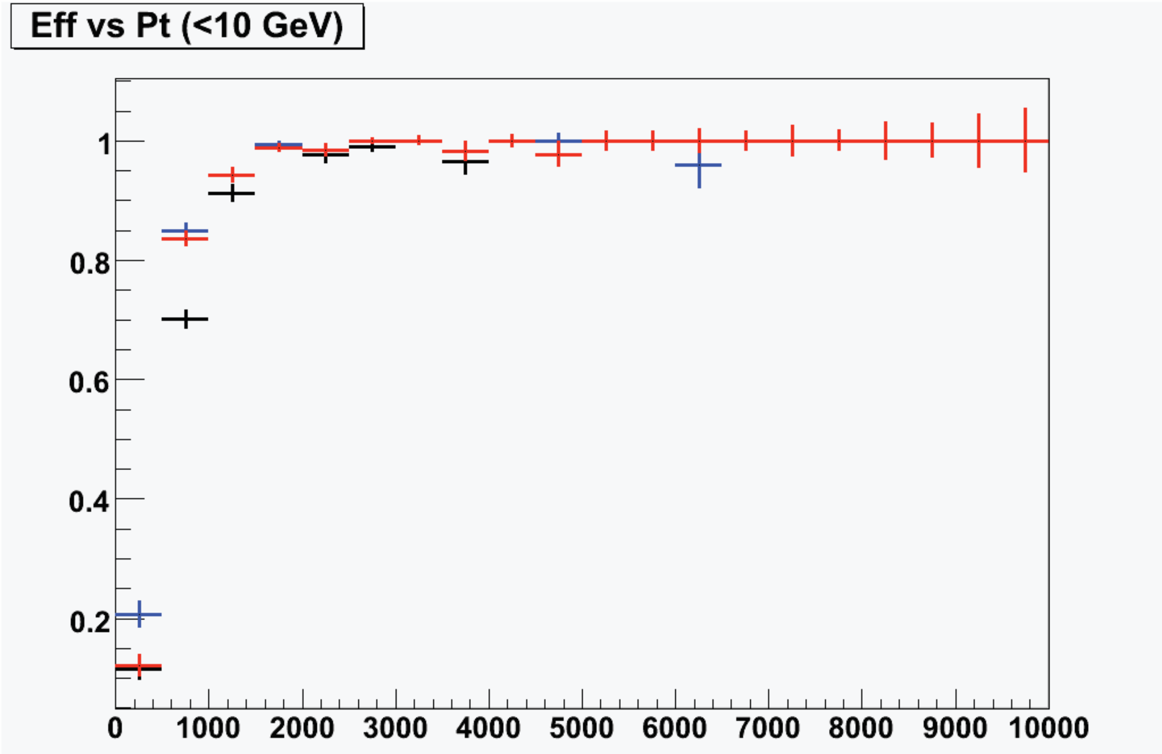
New Tracking Algorithm Sequence (current)

- Inside-out track search, starting from Pixel+SCT spacepoints
  - track search and extension migrated from xKalman
- First strategy consists of 4 algorithms:
  1. SiSPSeededTrackFinder - track candidate finding in Pixel and SCT
  2. InDetAmbiguitySolver - select good track candidates, full track fit, resolve ambiguities
  3. TRT_TrackExtension - extend resolved tracks into TRT
  4. InDetExtensionProcessor - refit of extensions and replace original
- Covers 3 use-cases

Wolfgang Liebig



New ID Tracking on ttbar Events (2)



- tuning of silicon pattern recognition in past release
- validation inside runtime-testing framework
  - one out of several validation schemes
  - now intensified before release 12.0
- newTracking performance competitive with iPatrec

CMS

Thomas Speer

The CMS Experiment

13x6 m Solenoid: 4 Tesla Field

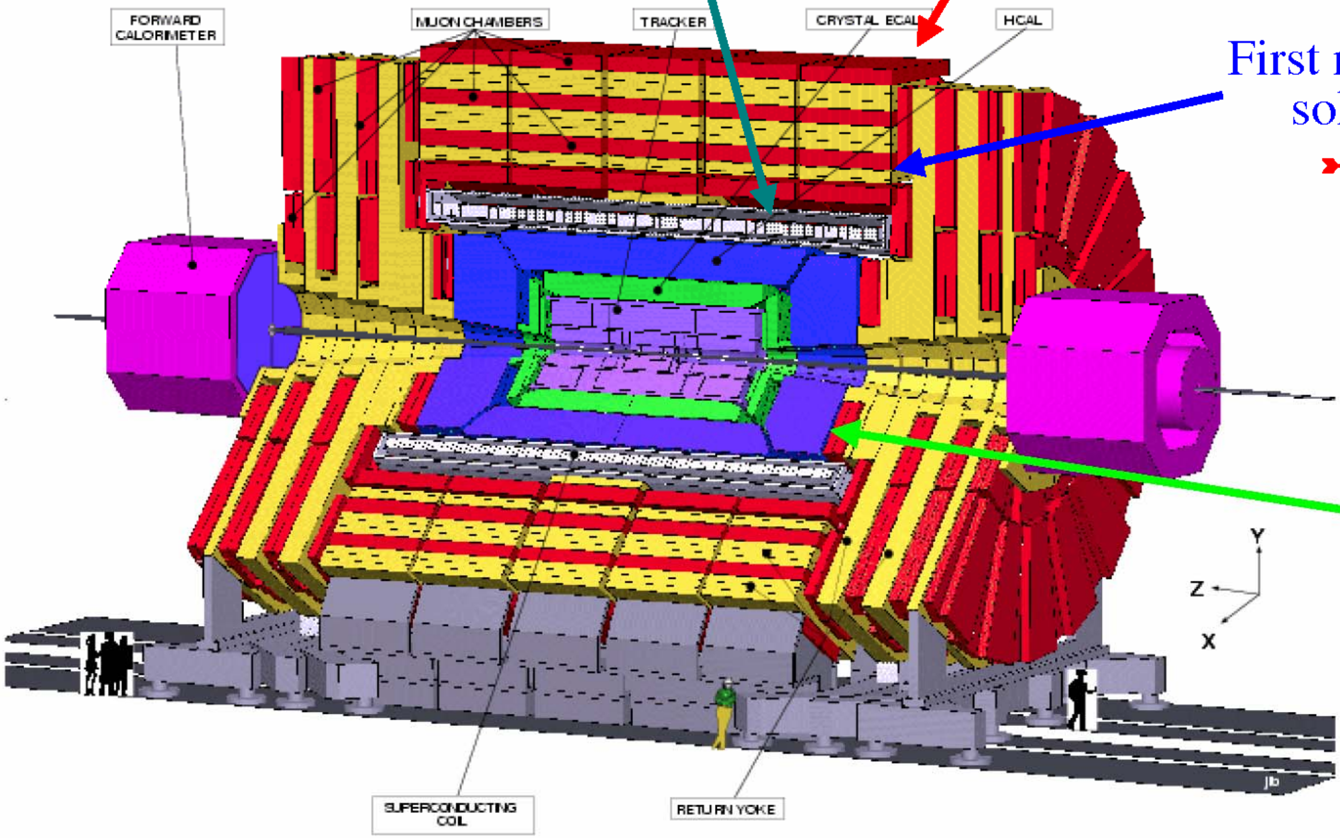
- Tracking up to $\eta \sim 2.5$

Muon system in return yoke

First muon chamber just after solenoid

- extend lever arm for p_T measurement

ECAL & HCAL inside solenoid



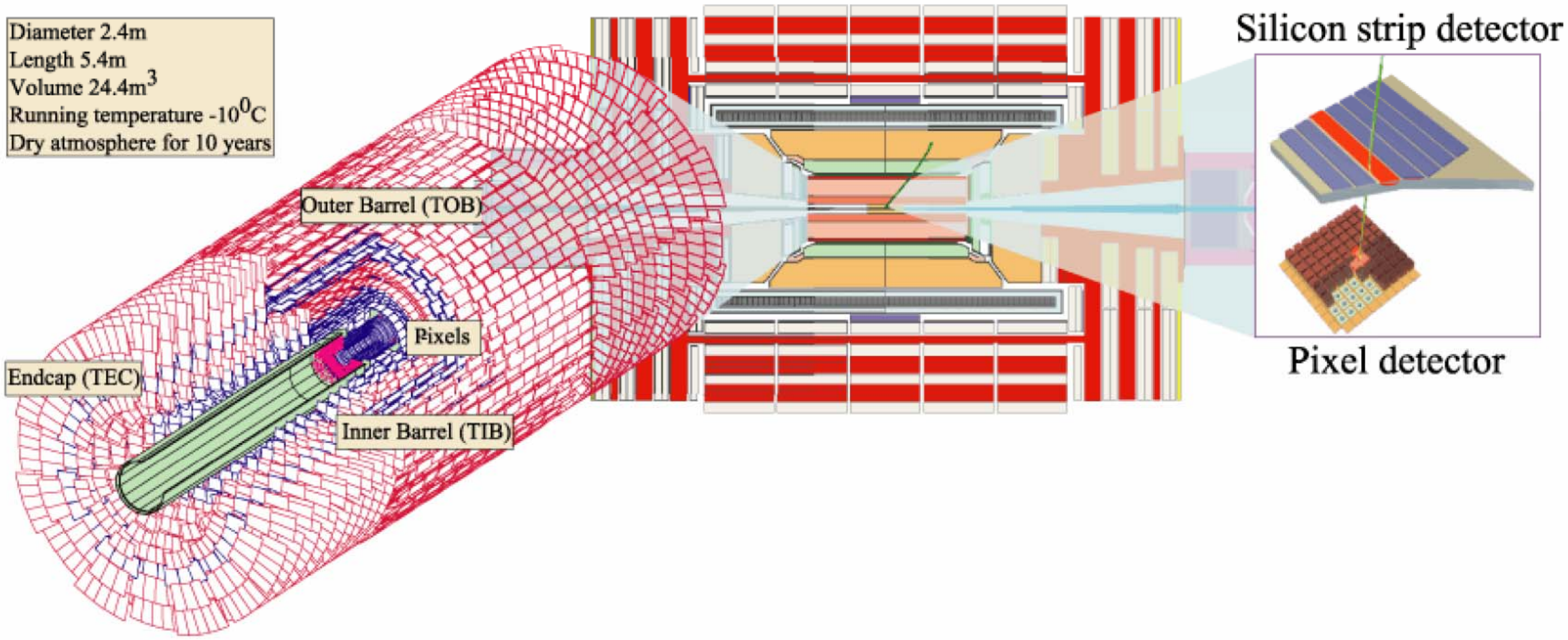
- 22m Long, 15m Diameter, 14'000 Ton Detector

The CMS Tracker

➣ CMS has chosen an all-silicon configuration

Rely on "few" measurement layers, each able to provide robust (clean) and precise coordinate determination:

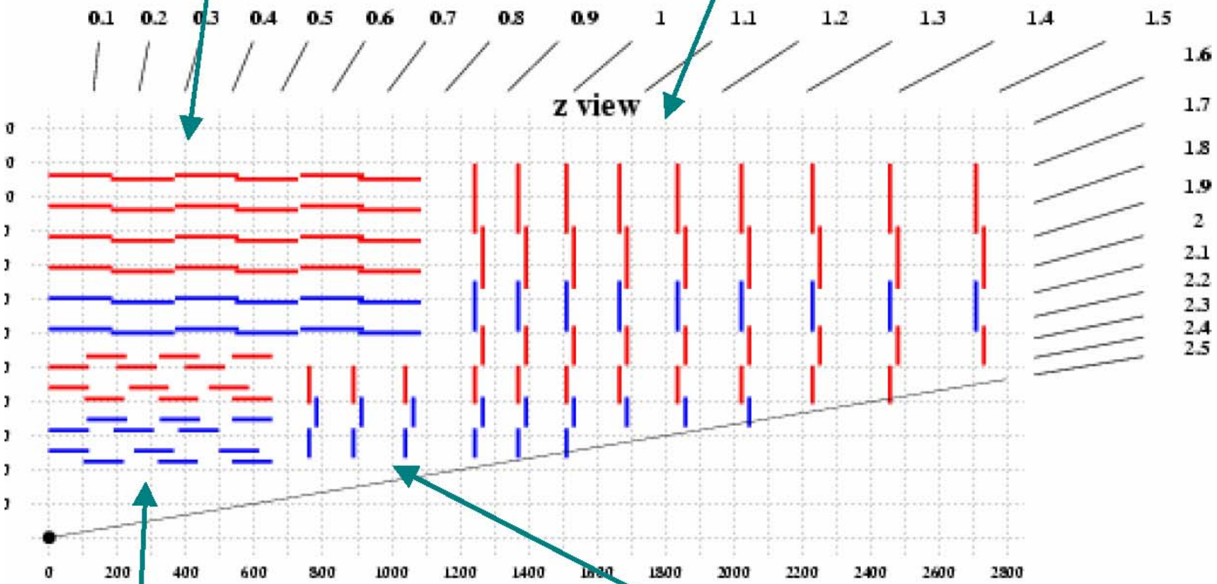
- Pixel detector: 2 - 3 points
- Silicon Strip Tracker: 10 - 14 points

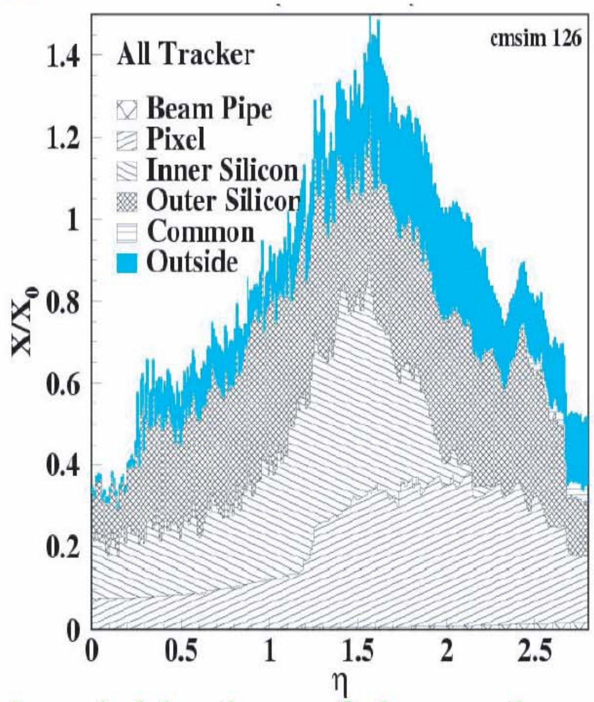


The CMS Silicon Strip Tracker

)uter Barrel (TOB): 6 layers
- Thick (500 μm) sensors
- Long Strips

Endcap (TEC): 9 disks pairs
- r<60cm: Thin sensors
- r>60cm: Thick sensors





Material budget of the tracker

Inner Disks (TID): 3 disks pairs
- Thin sensors

nner Barrel (TIB): 4 layers
- Thin (320 μm)sensors
- Short Strips

blue: double-sided detectors
red: single-sided detectors

The Combinatorial Kalman Filter

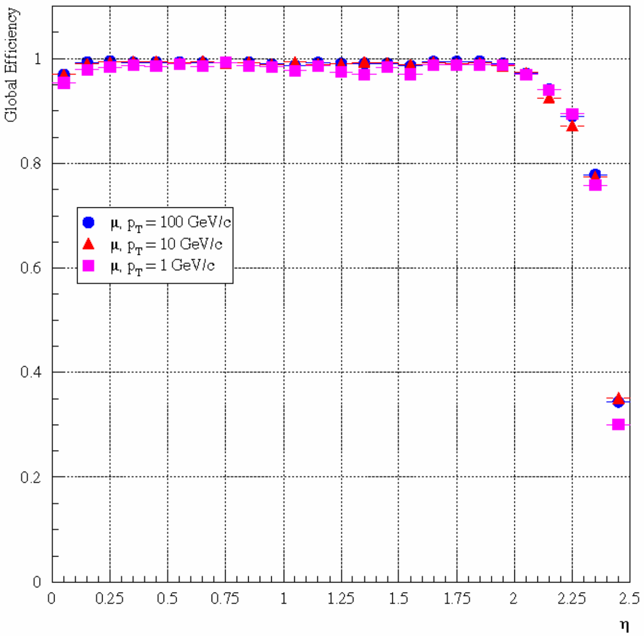
Track reconstruction is decomposed in 4 modular, independent, components:

- Generation of *seeds*
- Trajectory Building: construction of trajectories for a given seed
  - ➢ Trajectories are extrapolated from layer to next layer, accounting for multiple scattering and energy loss
  - ➢ On the new layer, new trajectories are constructed, with updated parameters (and errors) for each compatible hit in the layer.
  - ➢ All trajectories are grown to the next layer in parallel to avoid bias.
  - ➢ The number of trajectories to grow is limited according to their χ^2 and the number of missing hits.
- Trajectory Cleaning: hit assignment ambiguity resolution
- Trajectory Smoothing: final fit of trajectories
  - ➢ Obtain optimal estimates at every measurement point along the track.
  - ➢ In addition to providing tracks accurate at both ends this procedure provides more accurate rejection of outliers

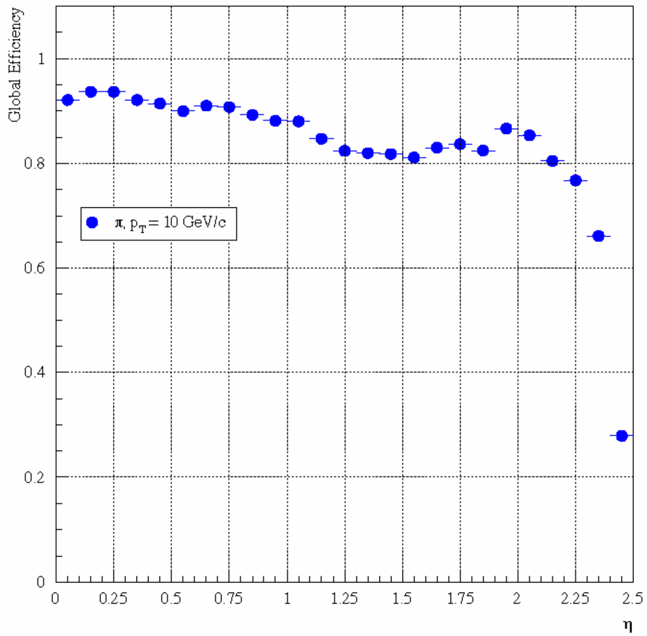
The Combinatorial Kalman Filter

Track reconstruction efficiency for single tracks:

muons, p_T = 1, 10, 100 GeV/c



pions, p_T = 10 GeV/c

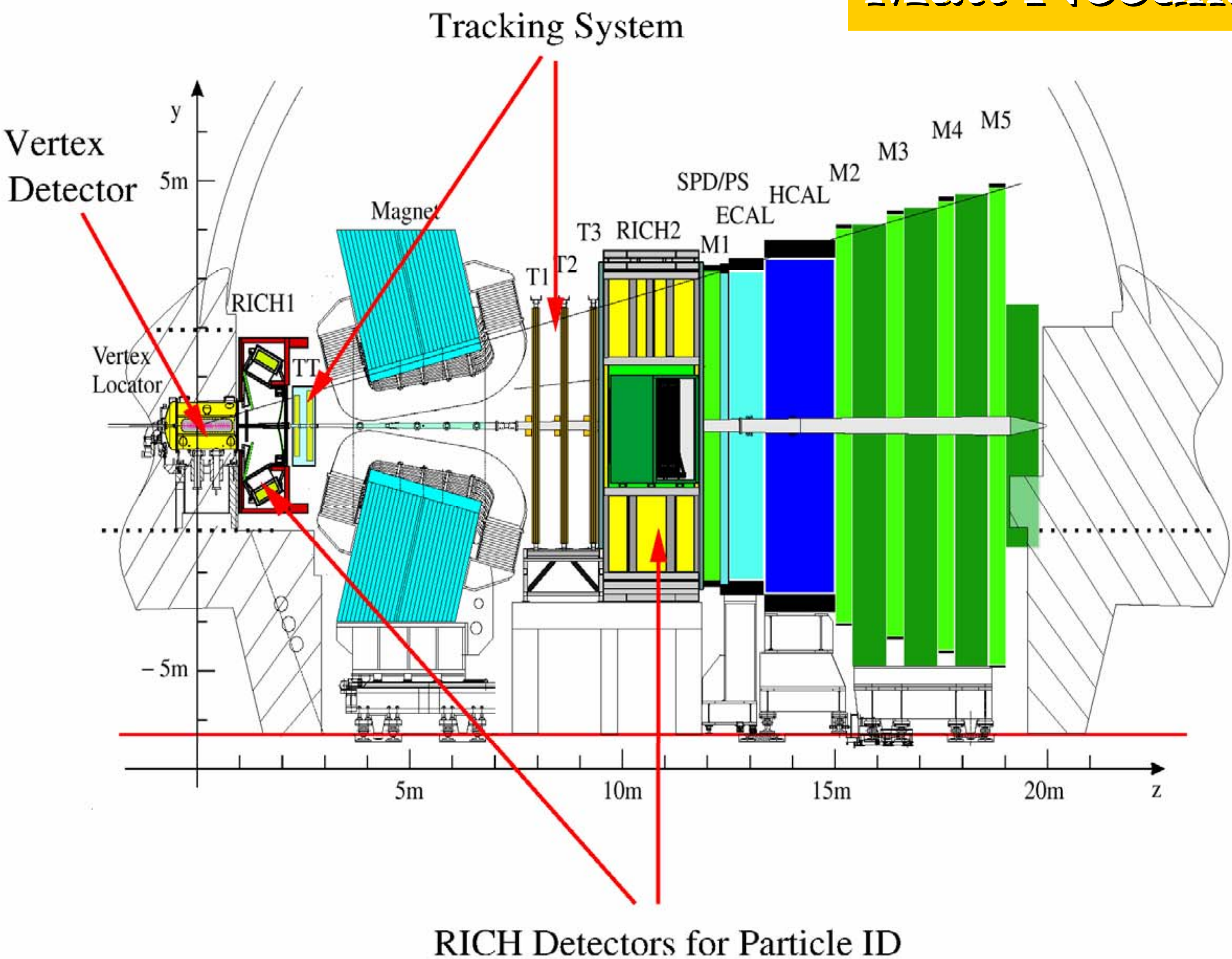


For pions: lower efficiency due to nuclear interactions in the tracker

LHCb

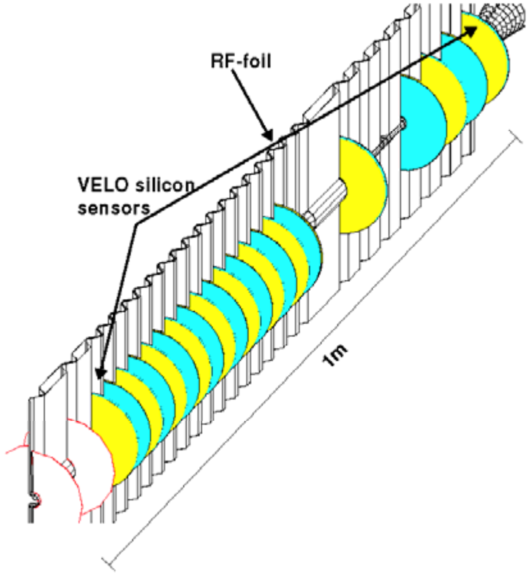
The LHCb Detector

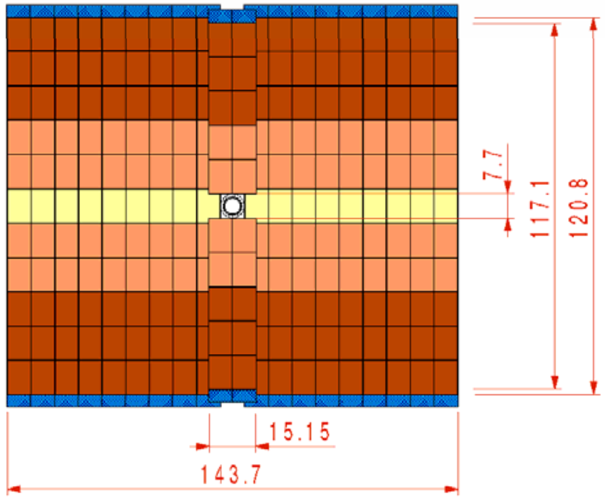
Matt Needham

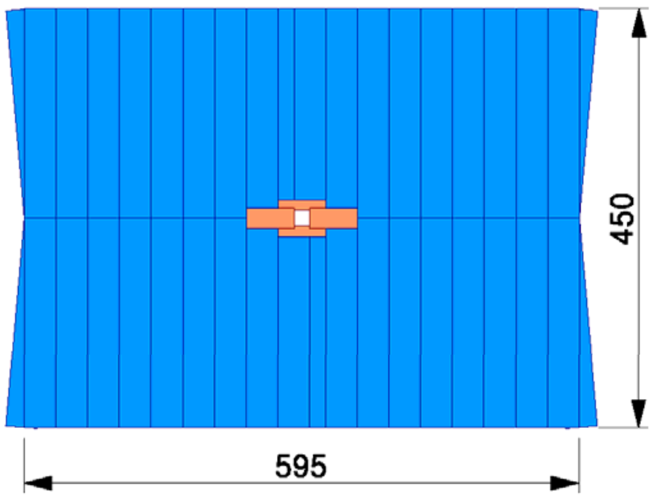


The LHCb tracking system

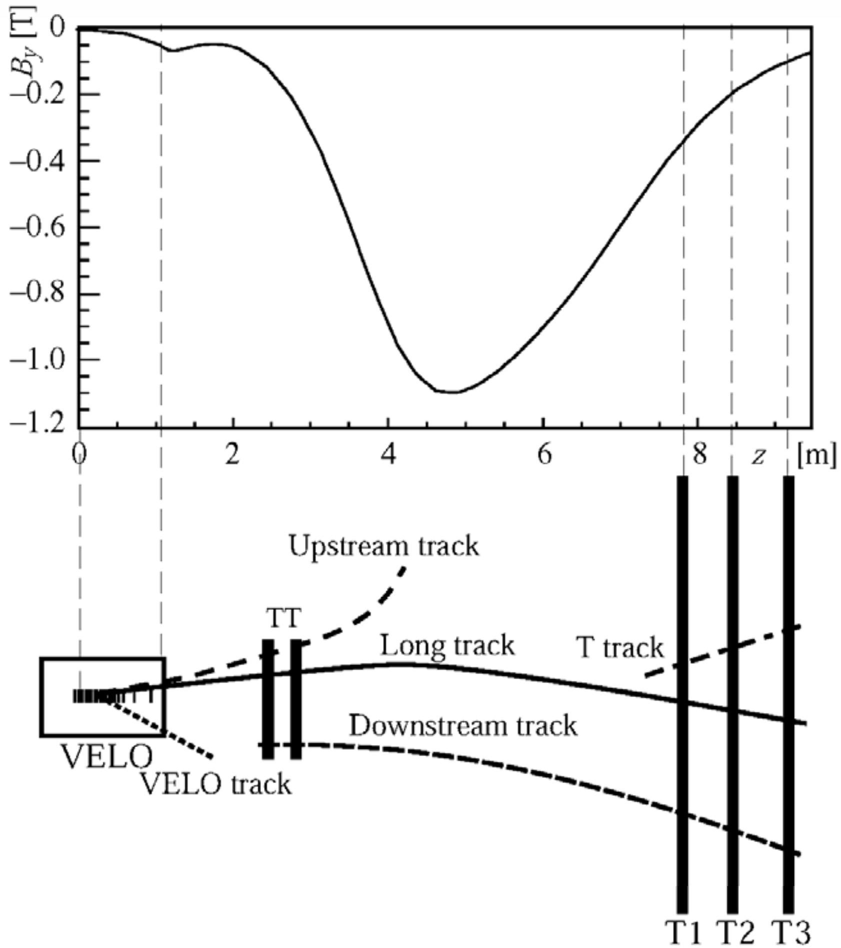
- Vertex Locator: 21 stations with r-ϕ geometry
- Large area Silicon Microstrip detector (TT)
- 4 Tm magnet
- 3 T stations
  - Inner part Silicon
  - Outer part 5 mm diameter straw tubes







Tracking: Strategy



Multi-pass track finding strategy ⇒ combined many track types, many algorithms....

Find long tracks ⇒ most important for physics

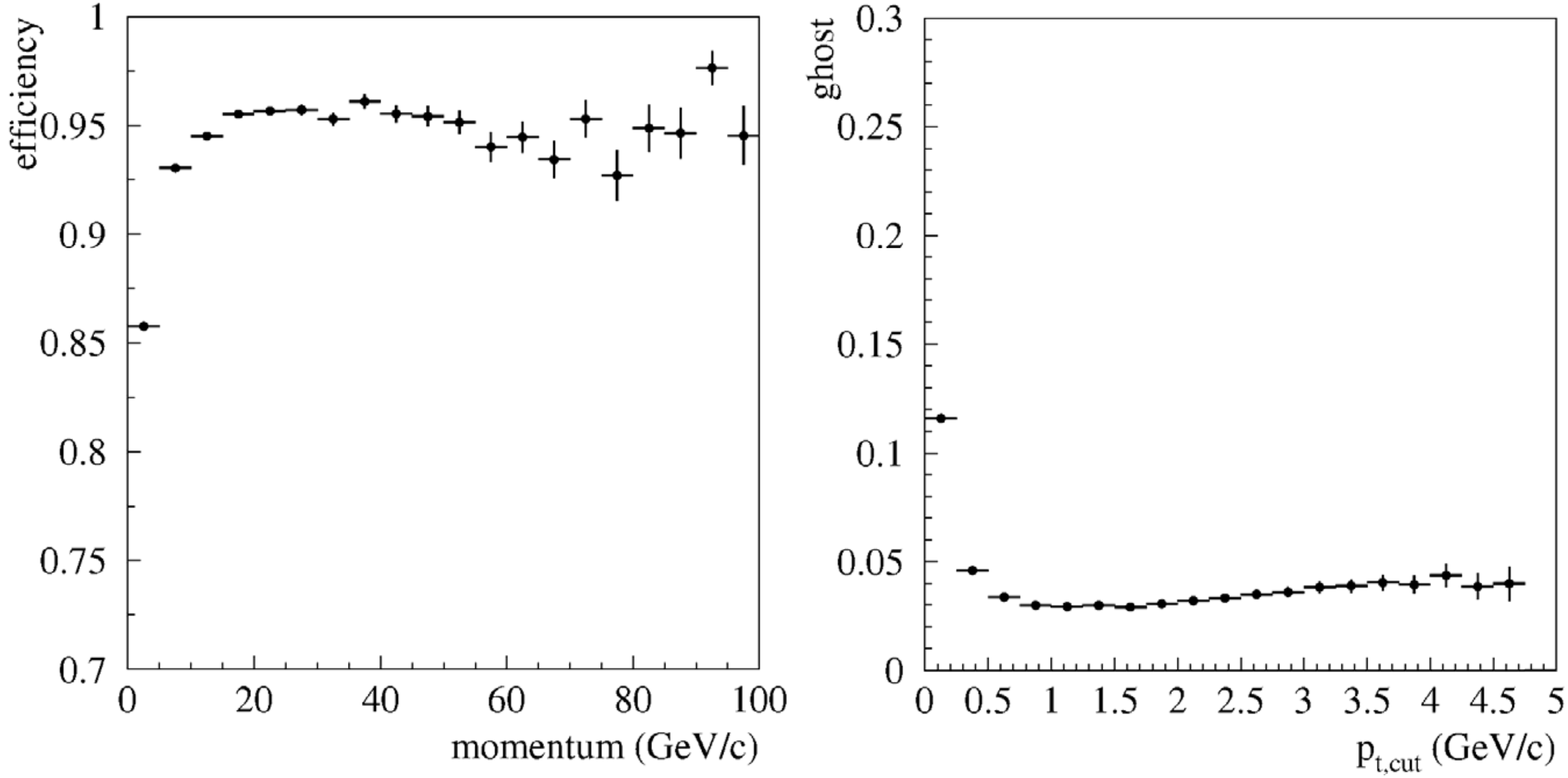
- Velo track finding
- Extend Velo tracks to T stations using optical method (Forward tracking)
- Clean used hits: T station seeding
- Match Velo tracks and Seeds

Look for other useful tracks

- Clean hits and look for tracks with hits in TT (K_s candidates)
- Upstream track search (low momentum tracks)

Track fit and clone killing

Long Tracking: Performance



- Efficiency for long tracks 0.9
- B decay products 0.95 (higher p)
- Ghost rate 0.06 pt $>$ 0.5 GeV
- Ghosts mainly at low pt

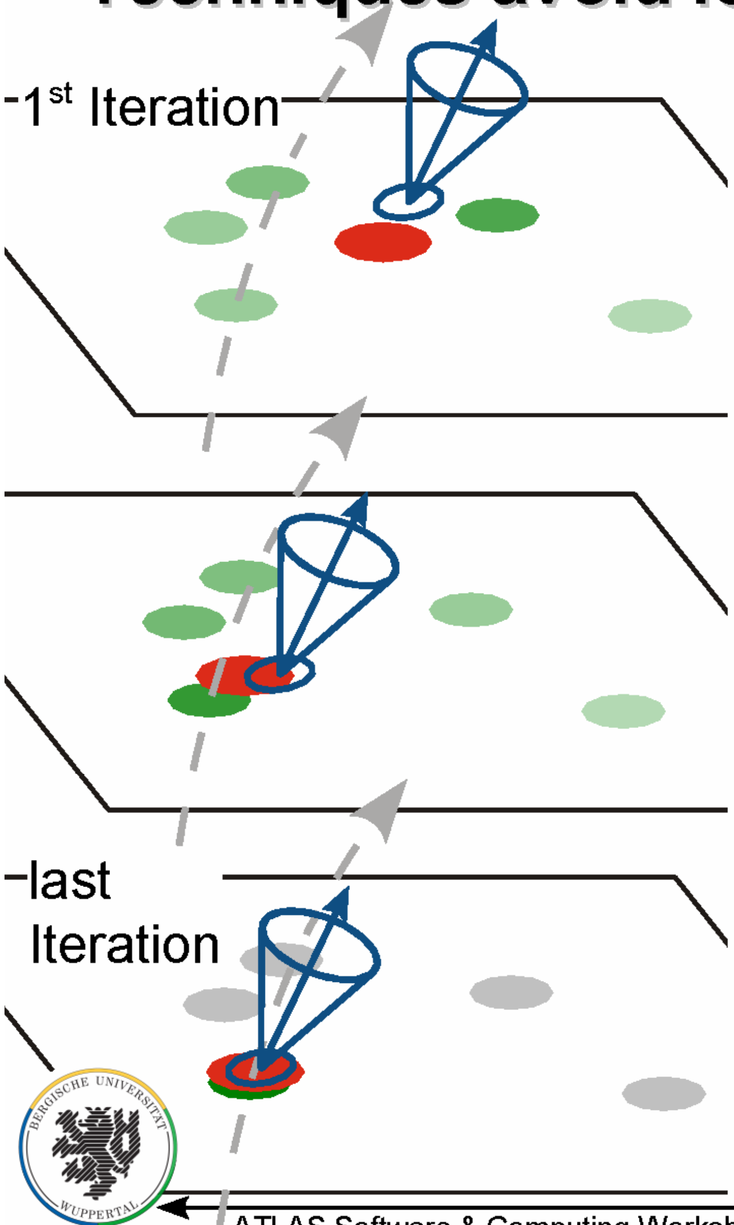
Tracking beyond the Kalman filter

Deterministic Annealing Filter

Gaussian-sum filter

ATLAS + CMS

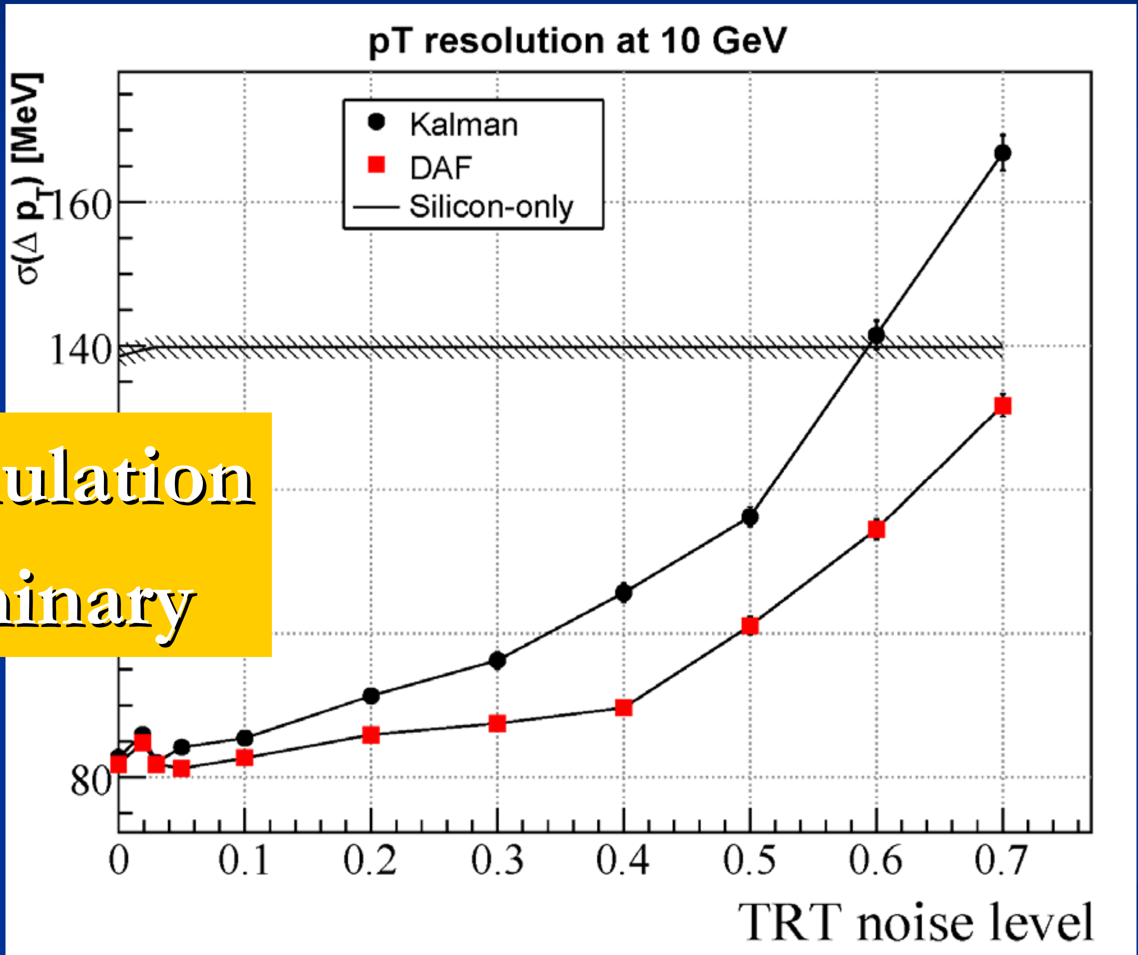
DAF in a nutshell: "Deterministic Annealing"- Techniques avoid local minima



- "thermodynamical approach"
- probabilities changed in iterative procedure; complete Kalman-Process is redone in every Iteration
- High "temperature" at first includes even measurements further away from first track prediction
- assignment probabilities are frozen out
- freezing out up to "hard" assignments equivalent to χ^2-Cuts in KF – but not the best solution! Stop at temperature > 0 (fuzzy-assignment)

Sebastian Fleischmann

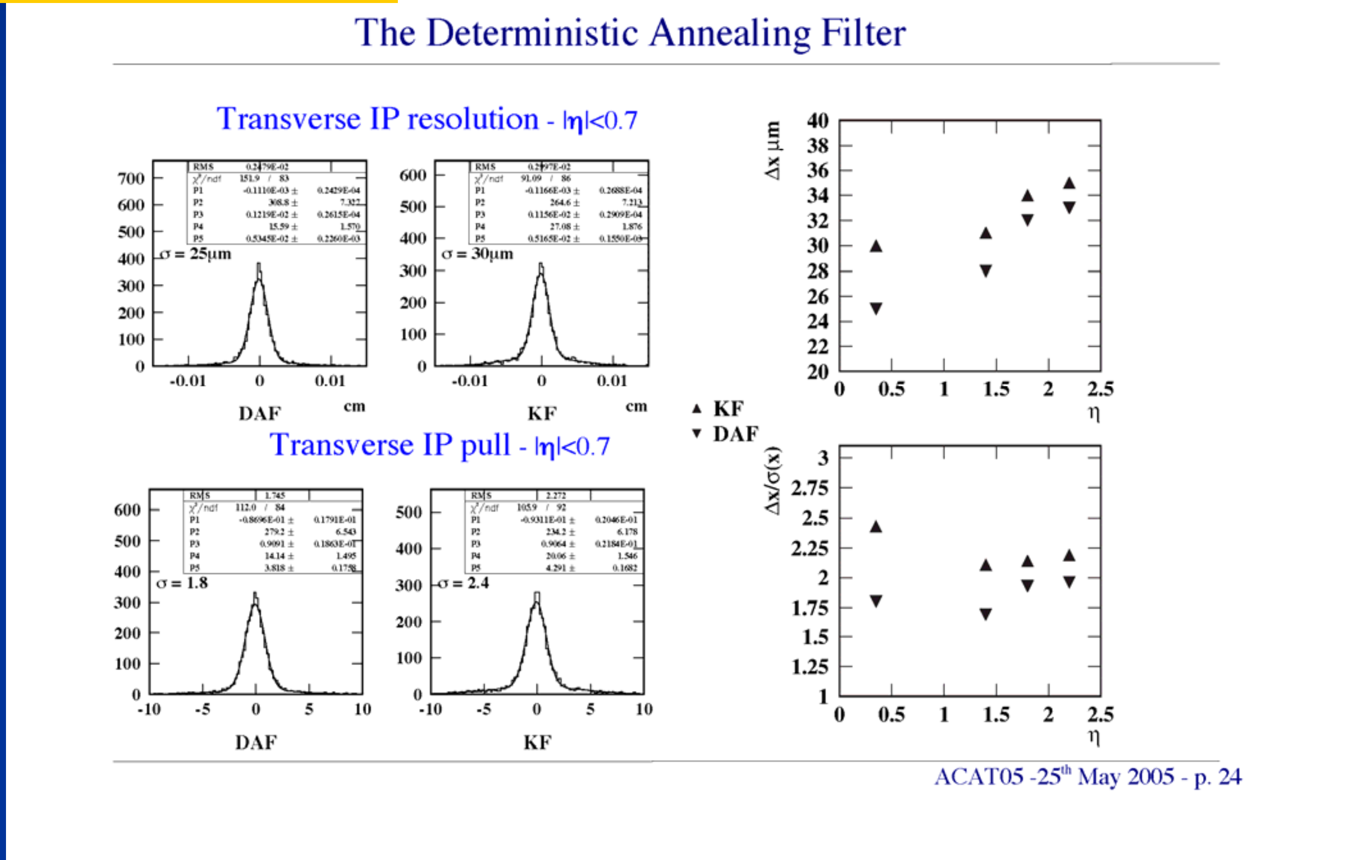
ATLAS: resolution as function of noise



fast simulation preliminary

CMS: tracks in high-pt b-jets

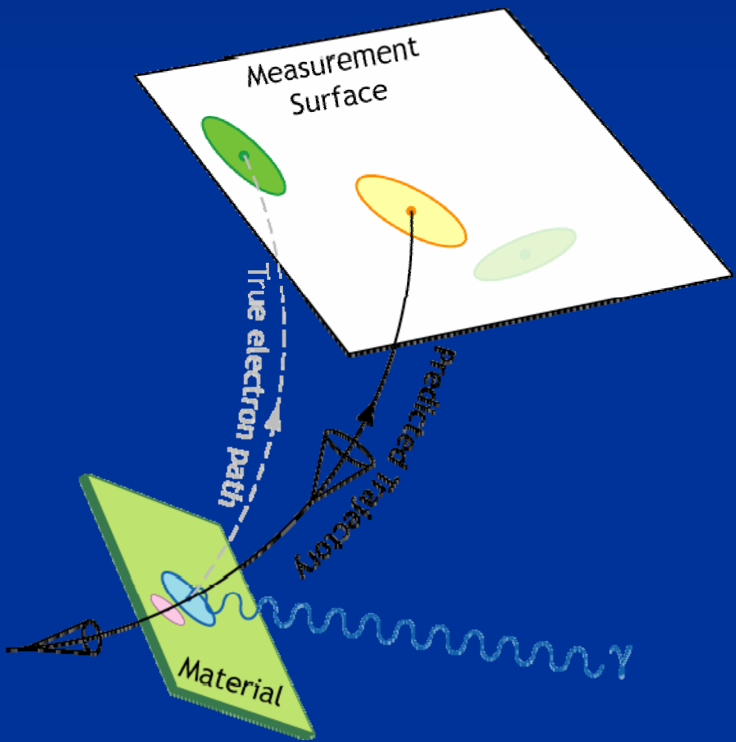
Matthias Winkler



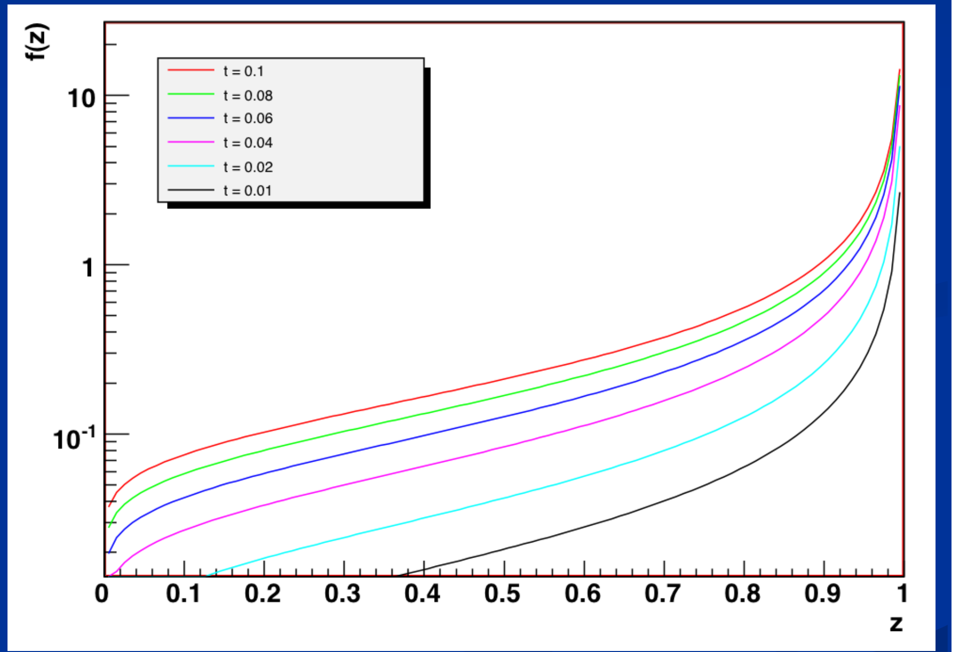
Electrons

Tom Atkinson

Electrons lose energy mostly by Bremsstrahlung

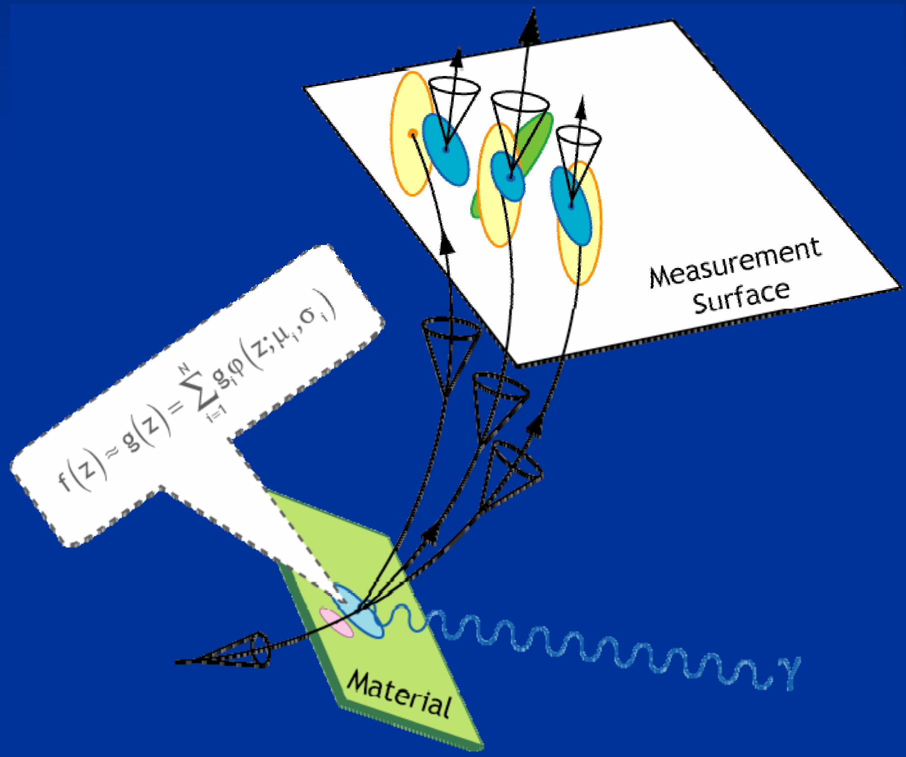


Bethe-Heitler Distribution PDF



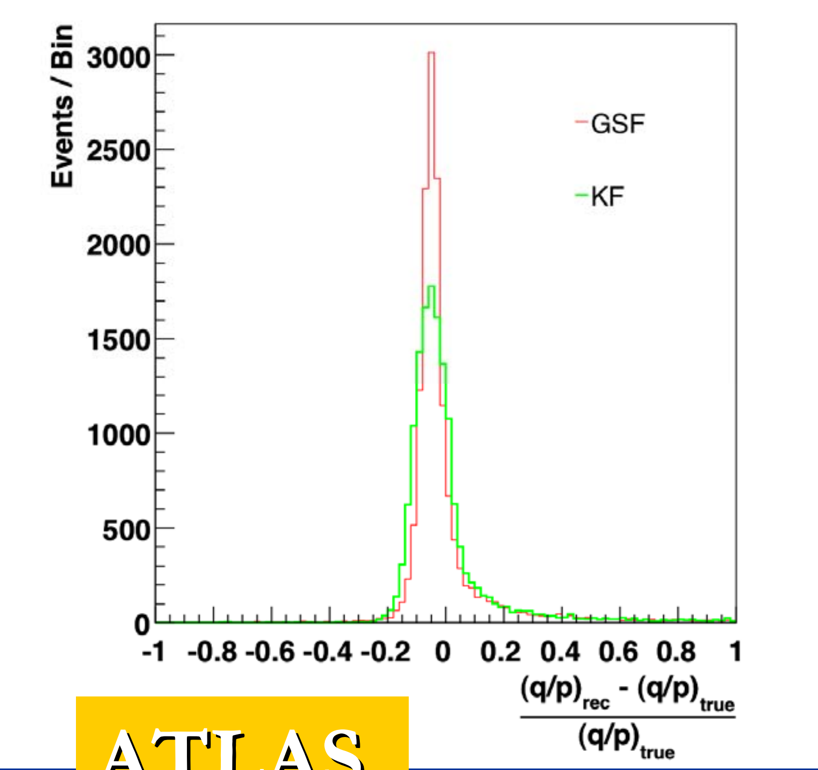
$$z = \frac{\text{final Energy}}{\text{initial Energy}}$$

Gaussian-Sum Filter

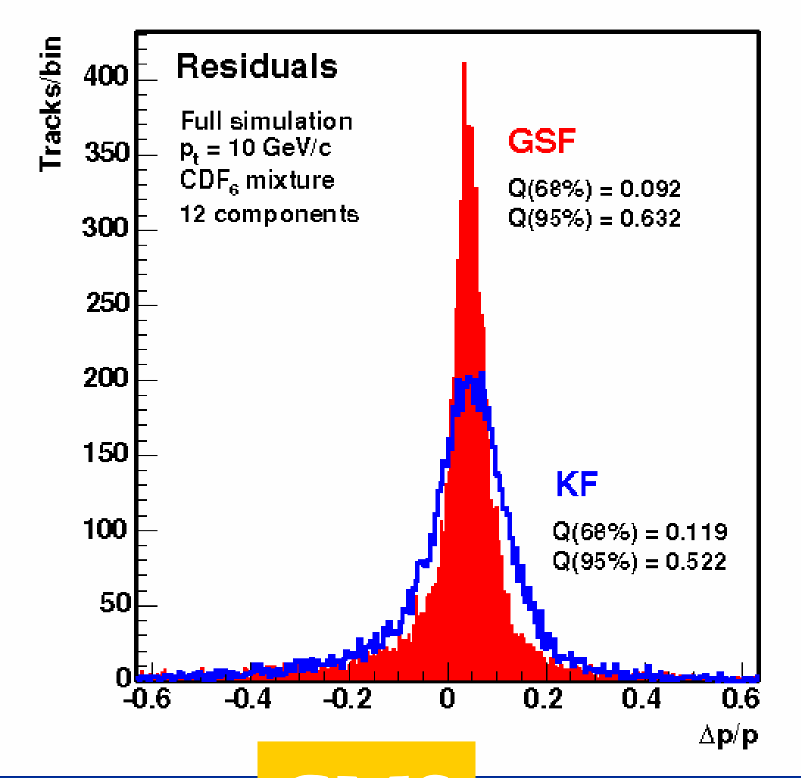


- GSF resembles several Kalman filters running in parallel
- Different components correspond to various degrees of hardness of bremsstrahlung radiation
- Measurements used to a posteriori determine which component is correct

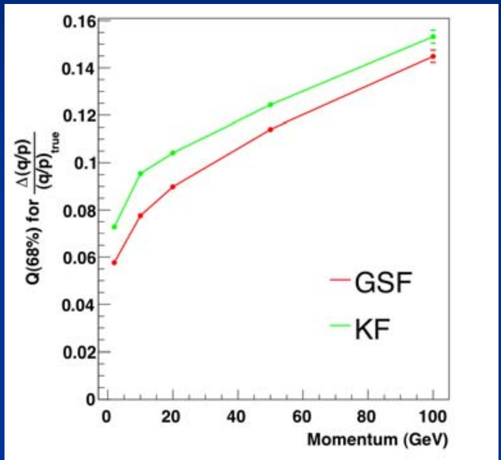
Momentum residuals



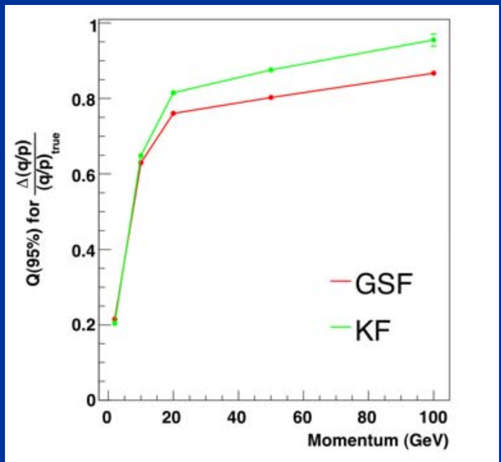
ATLAS



CMS



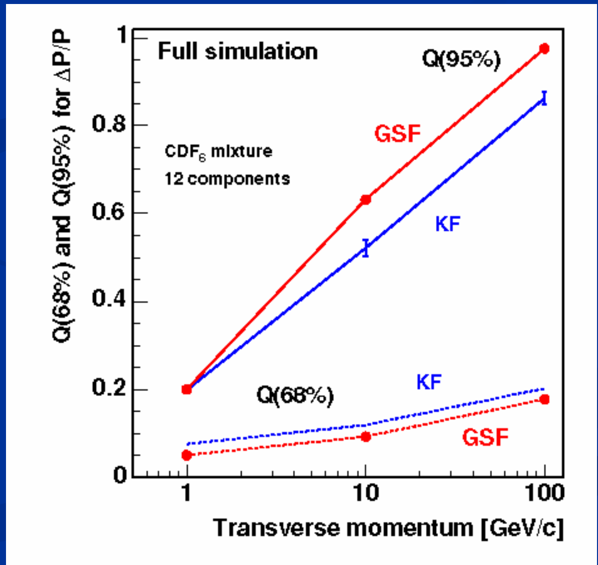
Effective 1σ resolution vs. true momentum



Effective 2σ resolution vs. true momentum

ATLAS

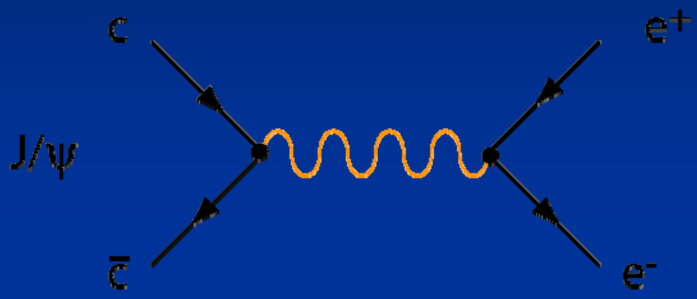
Effective 1σ and 2σ resolution vs. true momentum



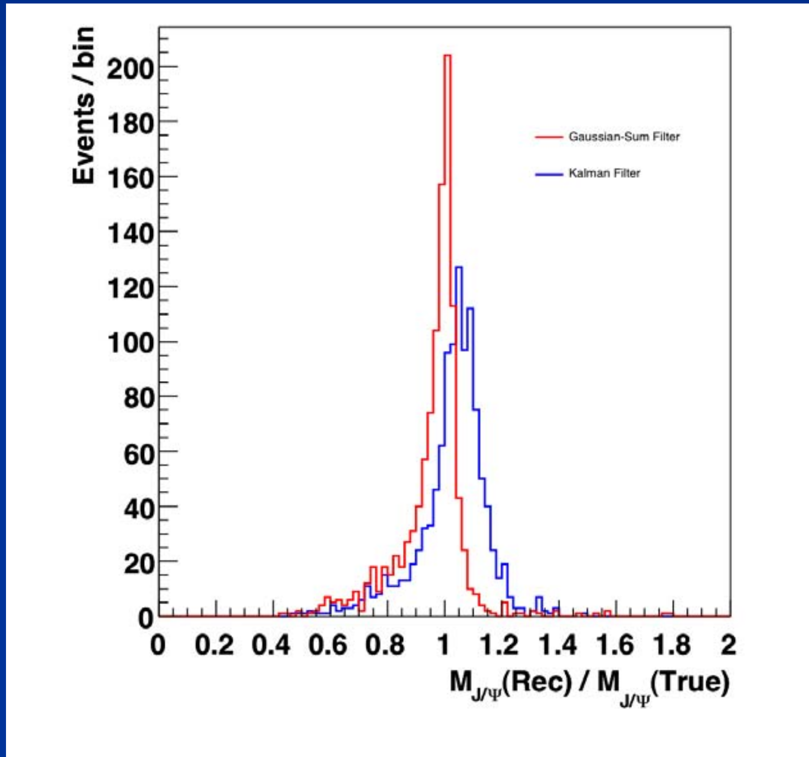
CMS

J/ψ reconstruction

ATLAS



Reconstructed invariant mass e^+e^-



$m_{J/\Psi}$ = 3096.9GeV

Full width Γ = 91.0KeV

Invariant mass: $m_0^2 = E^2 - |\vec{p}|^2$

Invariant mass from GSF

Invariant mass from KF

Conclusions

- I have given an overview of current tracking strategies in the LHC experiments
  - transverse view
  - longitudinal view
- Many commonalities but also differences
  - detectors are different
  - manpower situation is different
- Significant changes since beginning of LEP era:
  - early LEP: dominated by global least-squares techniques, Kalman filter was new and exotic
  - early LHC: dominated by Kalman filter, some new developments are starting to appear in ATLAS and CMS

Acknowledgments

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  - Jochen Schiek
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  - Tom Atkinson
  - Sebastian Fleischmann
  - Wolfgang Liebig
  - Matthias Winkler