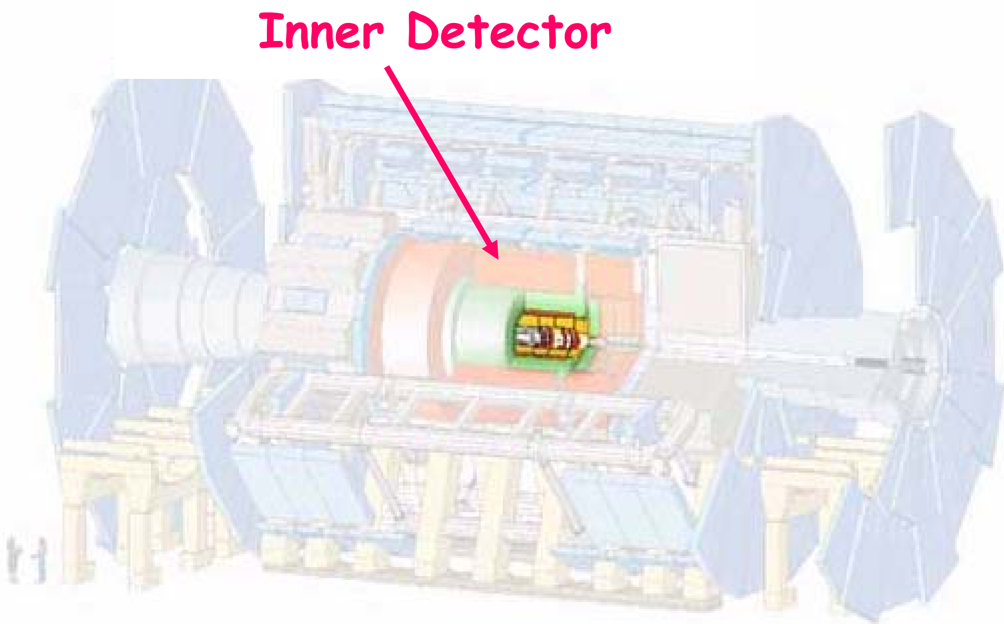
Duke 26 May 2006

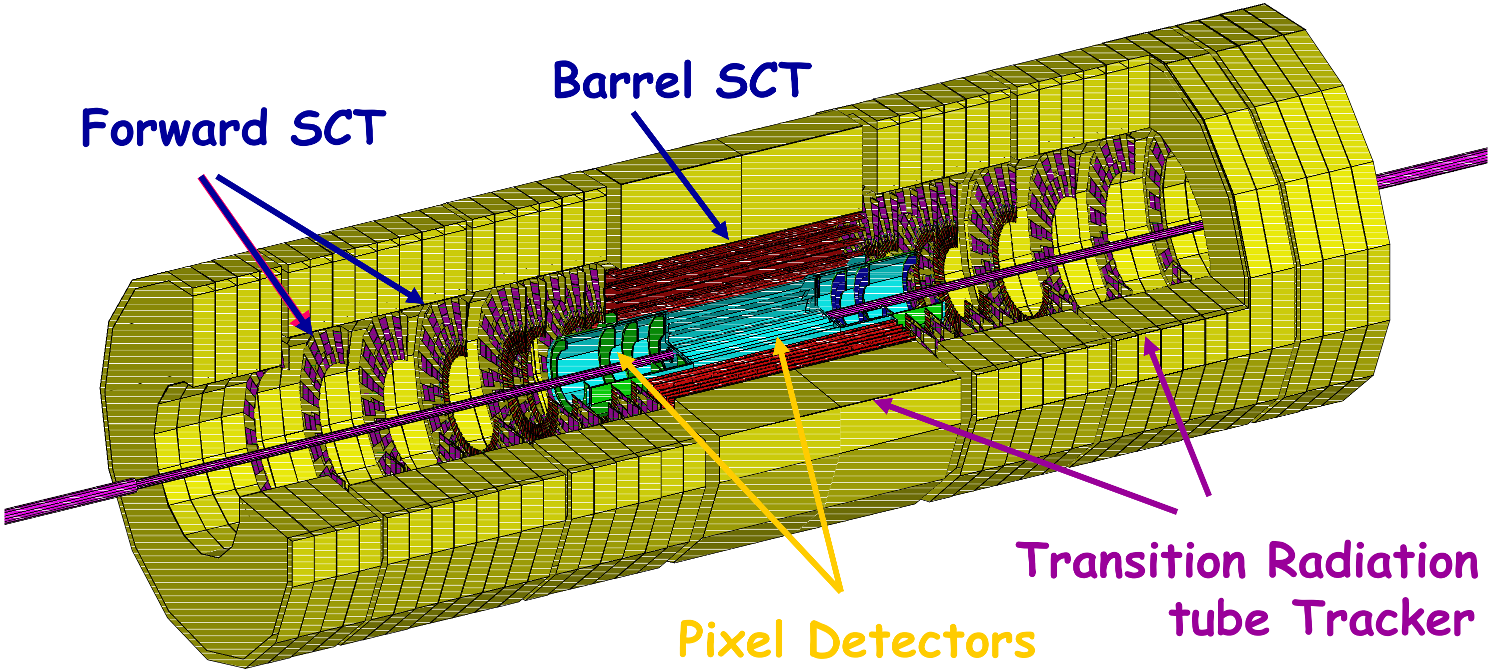
Tracking and vertexing at ATLAS

P.Ferrari (CERN)

The ATLAS Detector



The ATLAS Inner Detector



The Inner Detector

pixel:

Barrel: 3 layers of Silicon detectors (average R=5.05,8.85,12.25 cm).

endcap:3 disks of Silicon pixel detectors.

For some simulation the intermediate layer is not present for historical reasons (2-layer layout)

SCT:

8 layers of semiconductor tracker SCT in the barrel and 9 disks per side in the EndCaps (stereo strip detectors)

TRT:

Several layers of 4 mm straws in the barrel region (arranged in 3 layers of modules). 14 Transition Radiation Tracker wheels in the endcap

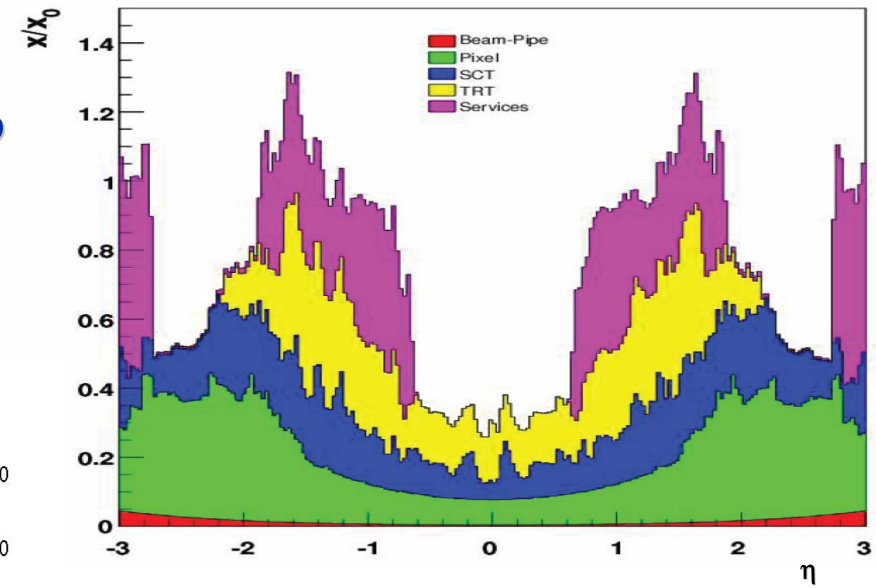
~30 hits per track

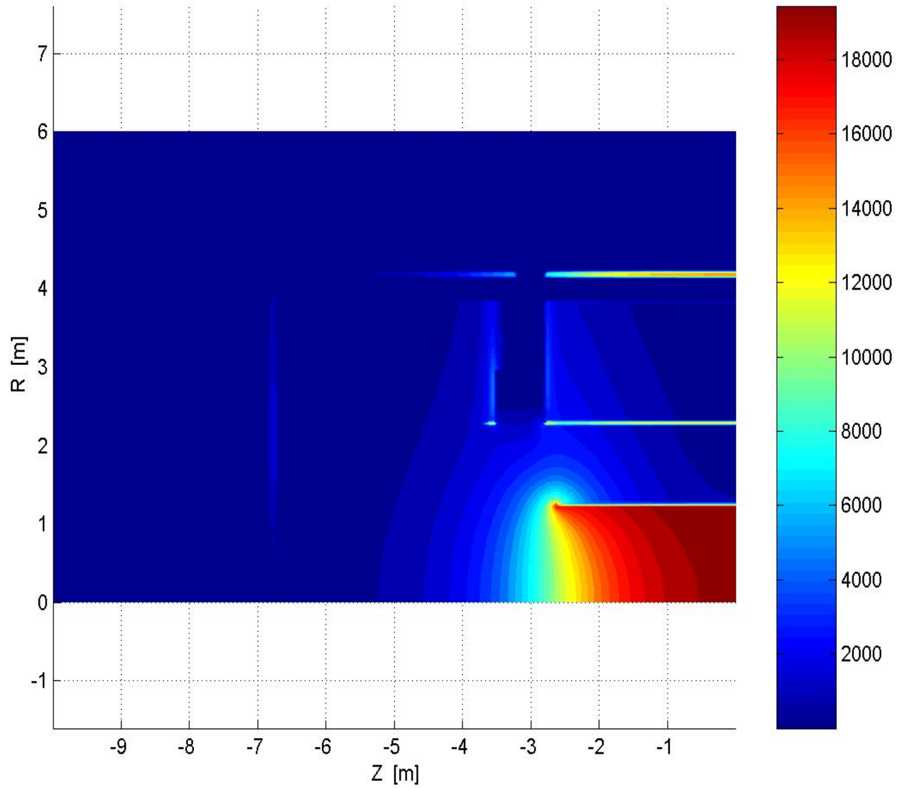
	points	σ ($R\phi$) (μm)	σ (Rz) (μm)
pixel	3	12	60
SCT	4	17	580
TRT	36	170	-

Magnetic field and material knowledge

Knowledge of material in the detector

- To reconstruct tracks one needs to take into account:
  - multiple scattering
  - energy loss in material





The magnetic field ~2T in ID

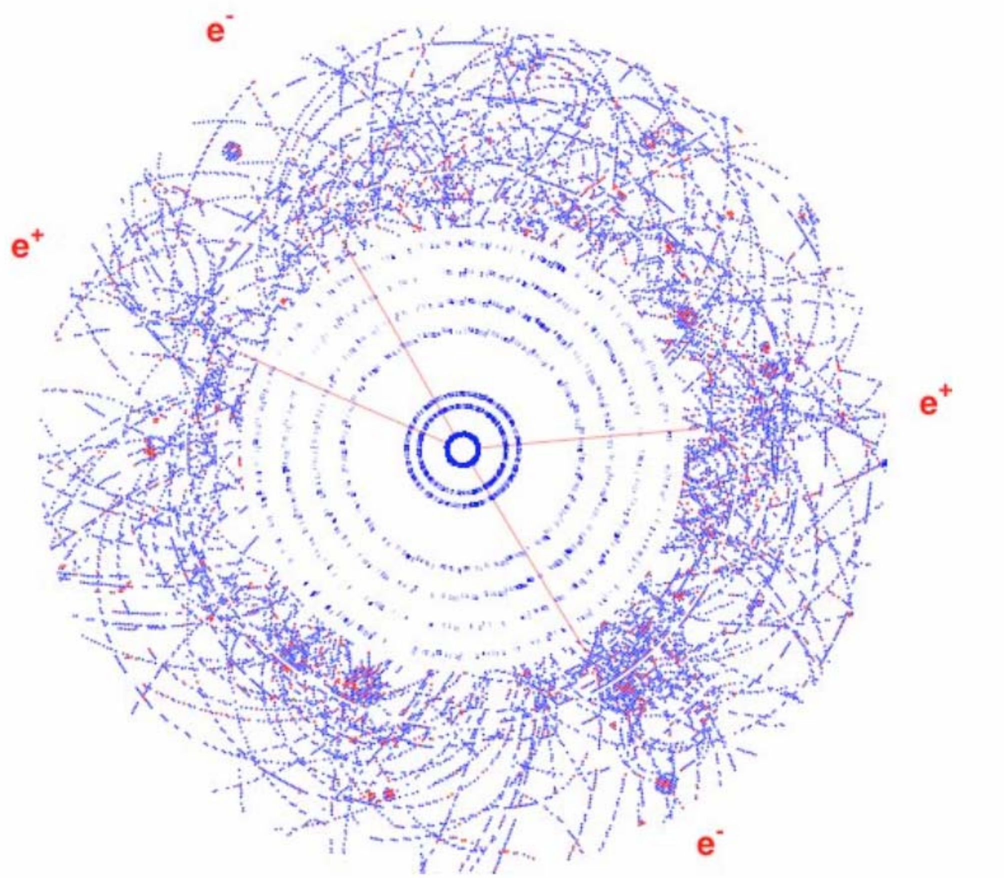
- B= 1T at the end of solenoid
- B= 0.8 T at end of ID
- more complicated tracking algs
- track resolution degradation on μ
  - mainly at high p_T
  - on $1/p_T$ for $|\eta| > 1.5$
  - on d_0 small effect since B field is uniform around Int. Point

Number of tracks per event

	$\mathcal{L}_{int}/y$ (fb^{-1})	$\mathcal{L}$ (cm^2/s)	$\sqrt{s}$ (TeV)	Minimum bias/bco
LHC (low $\mathcal{L}$)	10	2×10^{33}	14	5
LHC (high $\mathcal{L}$)	100	10^{34}	14	25

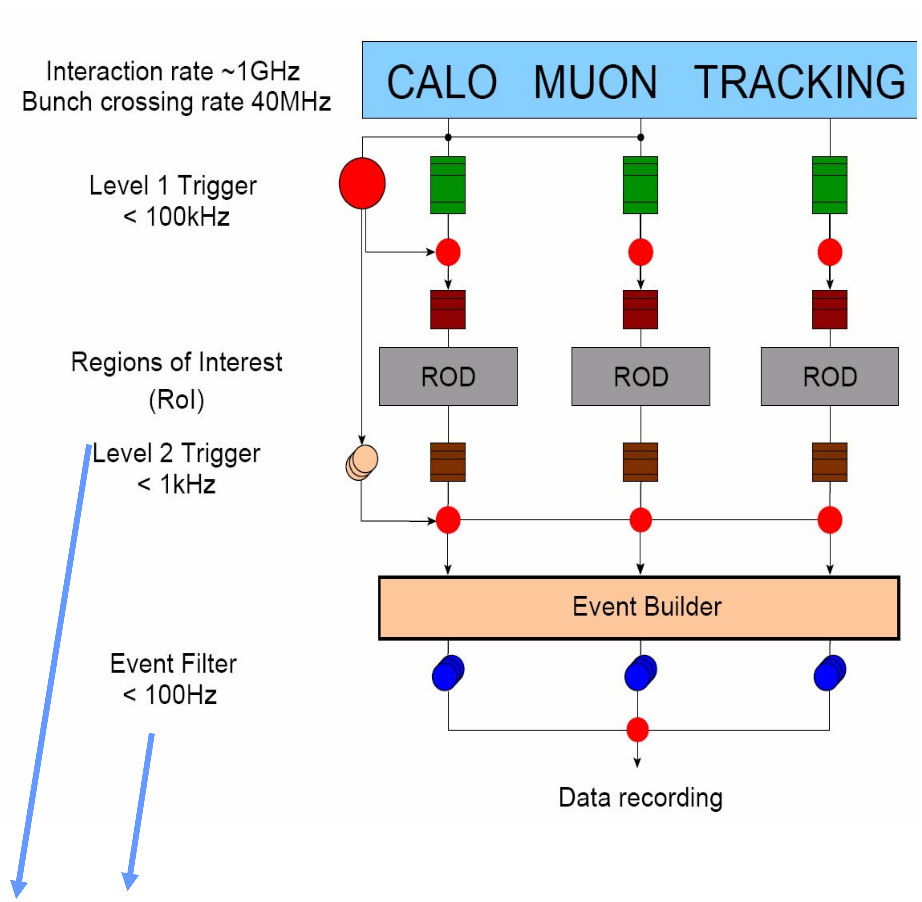
At high luminosity per each bunch crossing (25 ns)

- more than 200 tracks
- about 15-20 vertex candidates



Complex task for tracking and Vertexing because of pile-up. Triggering algorithms have to be fast and robust to avoid to miss rare events

ATLAS trigger



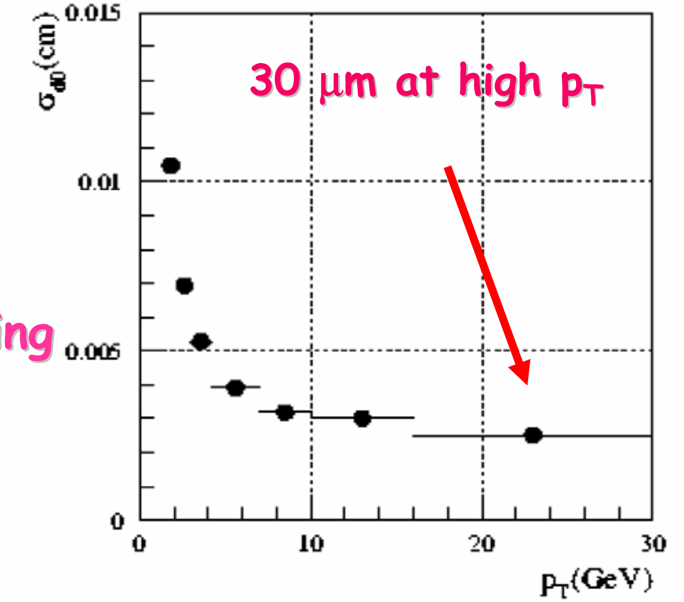
HLT:software triggers

- **LVL1 trigger:**
  - -hardware trigger (2.5μs latency)
  - -calorimeter + muon chambers.
  - -Defines Regions Of Interest (ROI)
- **LVL2:**
  processing in parallel info from ROI, uses ID information (latency 10ms)
- **Event Filter:**
  uses tools similar to "offline" code (thanks to longer latency ~1s)
- **Challenge:**
  have traking and b-tagging at trigger level ⇨ speed!

Tracking algorithm at LVL2

- Tracks seeds formed by fitting with a straight line pairs of space points in pixel B layer and in second logical layer (in a given RoI).
  - Tracks extrapolated back to beam line ⇨ impact parameter (IP)
  - Track retained if IP is small in transverse plane.
- The Z coordinate of the primary vertex = maximum of the histogram filled with the z intersection of the seeds with the beam line.
- Third space point is extracted in modules situated in positions where the hits may lay (LookUpTables). Space points compatible with linear extrapolation of track extend the seed.
- remove ambiguities due to overlapping space points in triplets with extrapolation quality
- Triplets fitted and identified with tracks

- Efficiency for tracks in jets 80-90% depending on luminosity and event topology
- 95% for single electrons.

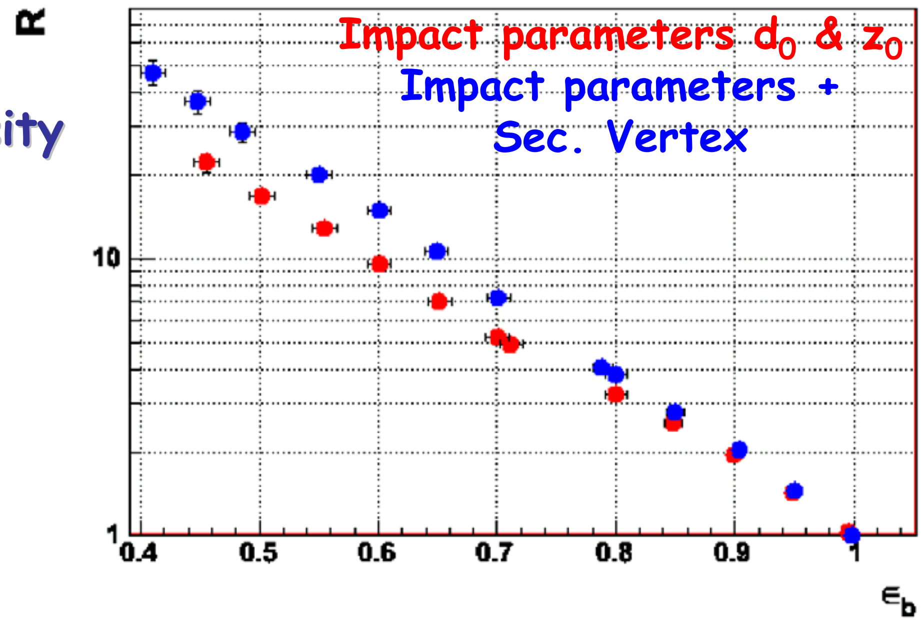


B-tagging at LVL2

- b-jet selection is performed by using impact parameters significance ($S=d_0/\sigma(d_0)$, where $\sigma(d_0)$ dependence from p_T is obtained from simulation)
- Secondary vertex algorithm similar to offline but faster
- b-jet estimator uses likelihood ratio

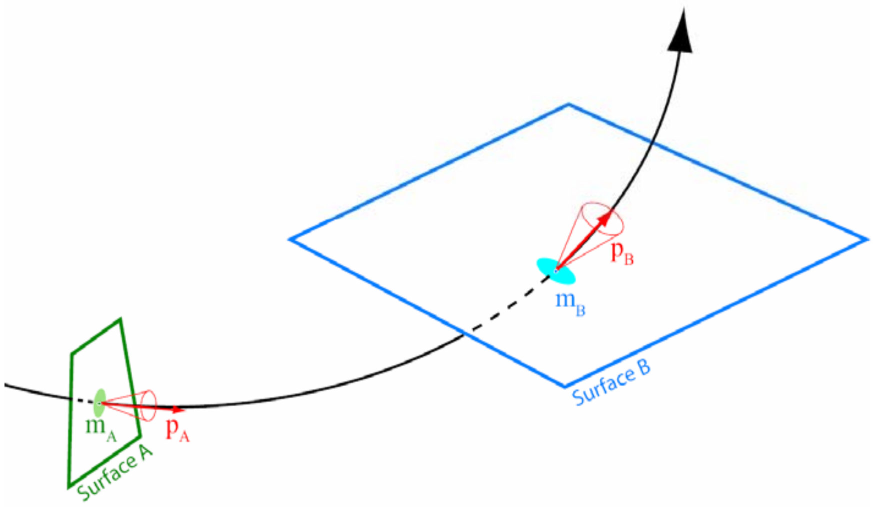
$$W_{jet} = \sum_{i=1}^{N_{tr}} \ln \frac{b(S_i)}{u(S_i)}$$

- WH (m_H=120 GeV/c^2), low luminosity
- Timing: 3 ms per RoI (track rec.) + < 2 ms Sec. Vtx rec.
- R ~ 25 (15) for ε_b=50%(60%)



Track extrapolation ingredients

1. The first step is the geometrical transport of the track parameters and their covariance matrices to a given detector surface



2. The second procedure is the update of the propagated parameters and errors, taking multiple Coulomb scattering and energy loss effects during the propagation process into account.

ATLAS offline tracking algorithms

- **The xKalman algorithm:** finding space points defining primary trajectories in SCT & pixel. Kalman filter associates clusters to tracks.In TRT reconstruct track in a narrow region around the extrapolated trajectory retaining all hits in that region.
  - Kalman fitter= track fitting with Gaussian noise and all measurements and material effects are approximately Gaussian

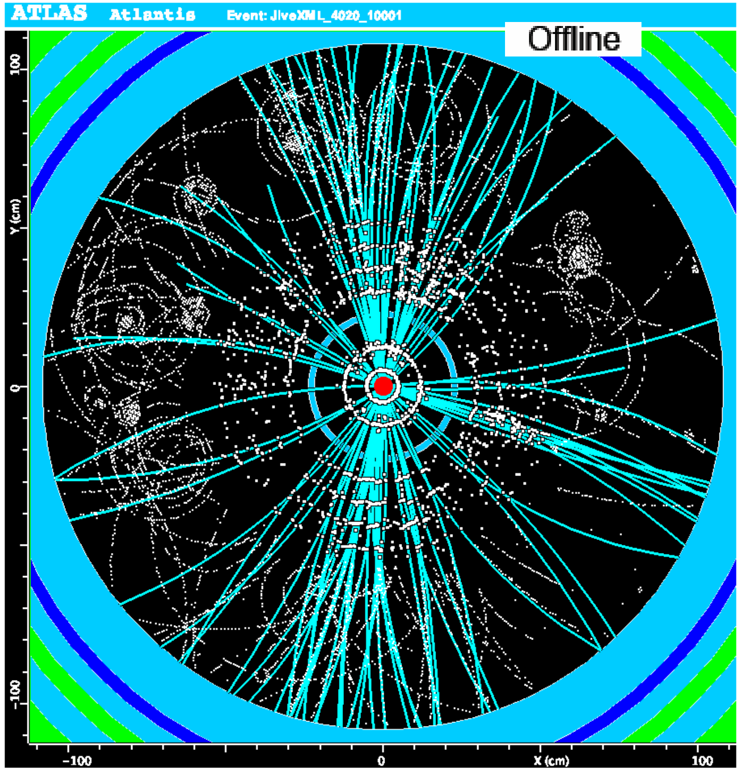
- **The iPatRec algorithm:** form track-candidates using space-point combinatorials subject to criteria on maximum curvature and crude vertex region projectivity.

  Global χ2 fitter used to fit tracks and associate clusters.

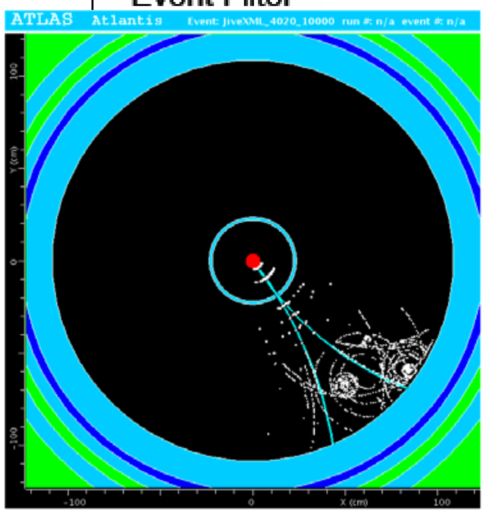
  Only good tracks are retained for extrapolation in TRT, where TRT hits are added.
  - Using global χ^2 fitter = minimises track χ^2 by considering all measurements simultaneously

New Tracking

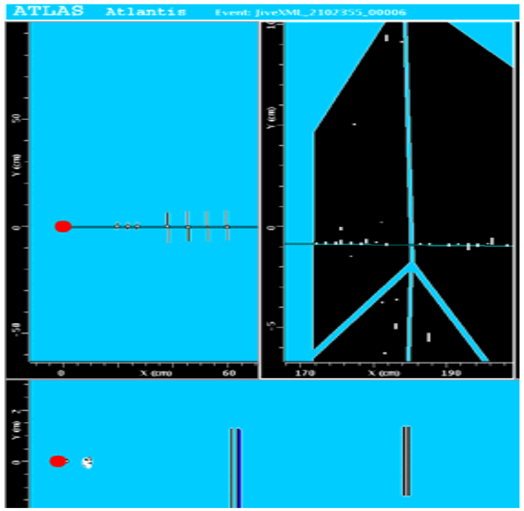
- NewTracking algorithm: Logical reorganization of tracking code. Largely based on xKalman, but in the future it will combine as well some tools from iPatRec ⇨ optimised tracking algorithm.
- Can be used at event filter level, offline and for the Combined testbeam and Cosmics runs.
- Uses better geometry description built from full geomodel ⇨ easy development of new code



Event Filter



Combined TB

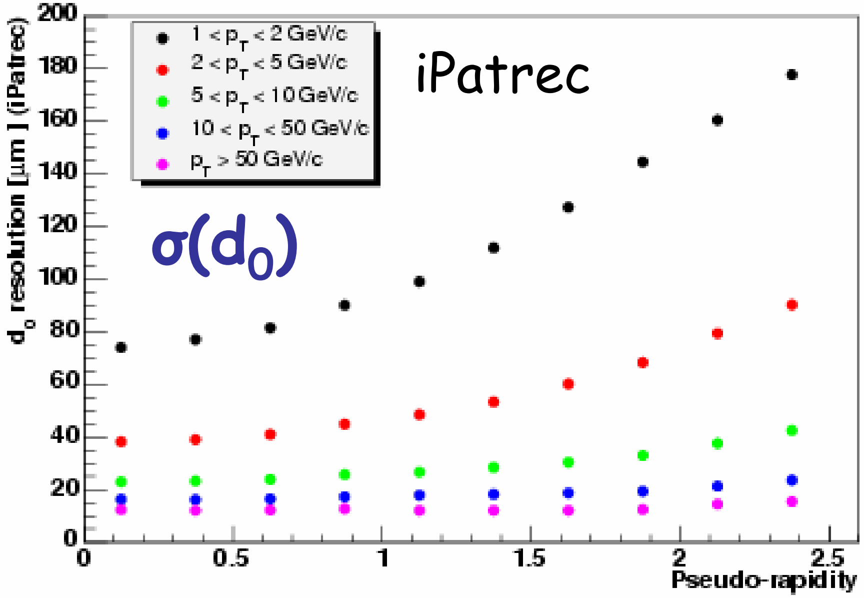


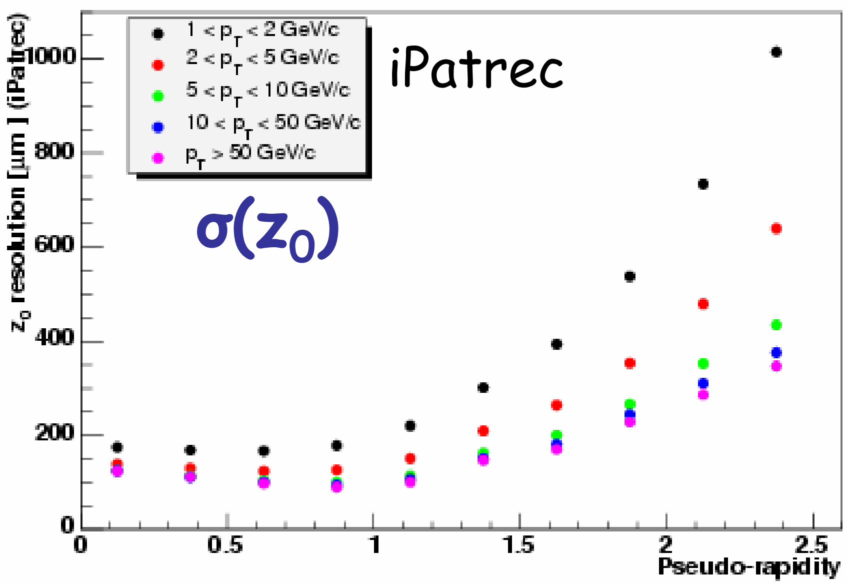
Comparison of results

- Using $t\bar{t}$ events

	xkalman	iPatRec	newTracking
Multiplicity (P>1 GeV)	16.69	17.06	16.88
Barrel Track eff/ fake rate	99%/0.6%	99%/0.7	96%/2.5%
Transition eff/ fake rate	98%/0.6%	98%/0.5%	96%/3.6%
Forward eff/ fake rate	98%/0.3%	99%/1.3%	95%/2.7%

- WH(400 GeV/c²) W(→μν)H(→uu)

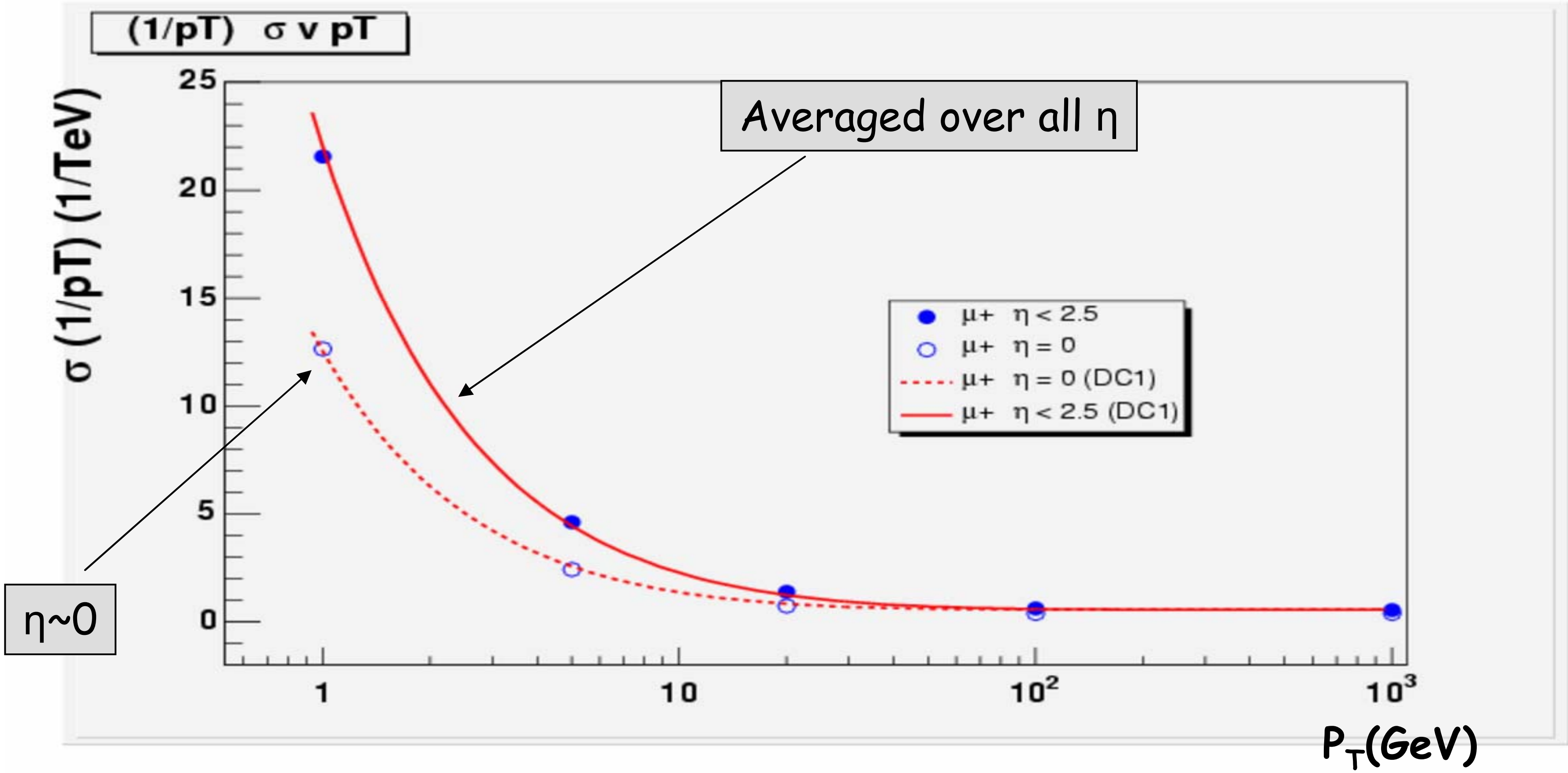




Momentum Resolution vs P_T

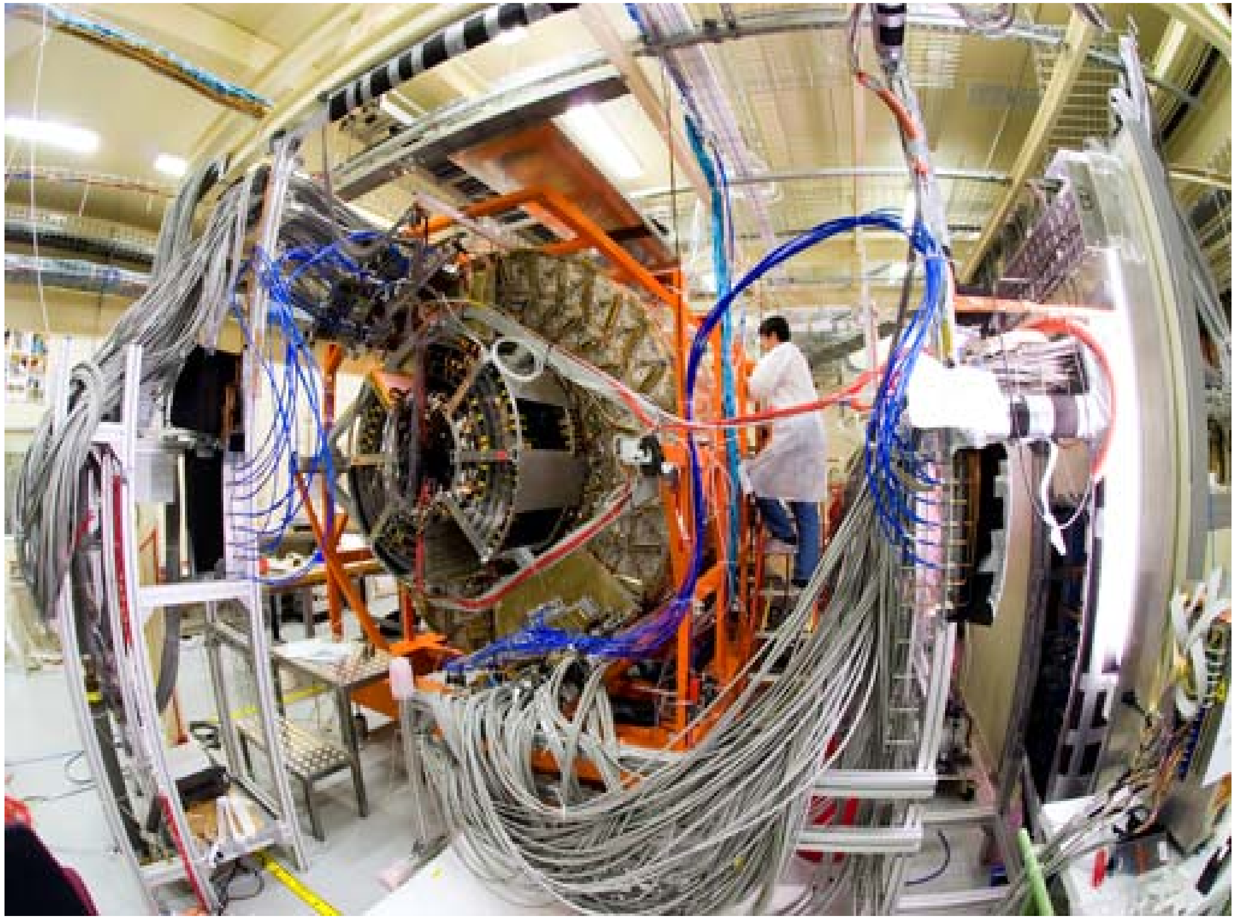
Single μ± (DC1 / 2 pixel layer layout p_T = 1, 5, 20,100, 1000 GeV/c)

Resolutions obtained here using iPatRec (xKalman gives same results)



Cosmics with SCT & TRT

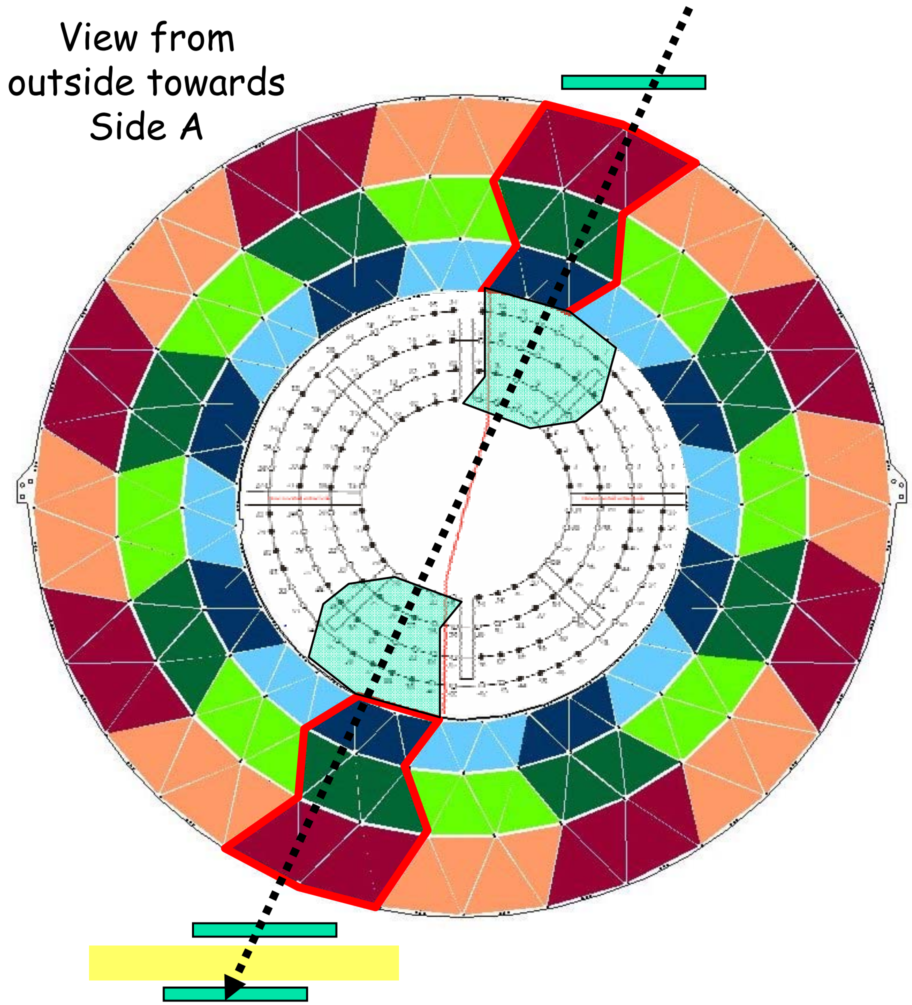
- the SCT & TRT barrel are integrated on the surface
- We are having cosmics data taking since the 9th of May



- We expect to collect 300K of cosmics until mid of June
- remember that we have still a non-aligned detector.

The alignment precision is given by the module placement precision on the barrel

Cosmics data taking



SCT:

- Read 504 modules grouped in a sector at the top and another one at the bottom

- The bottom sector is not fully cabled up will be ready the the 22nd of May

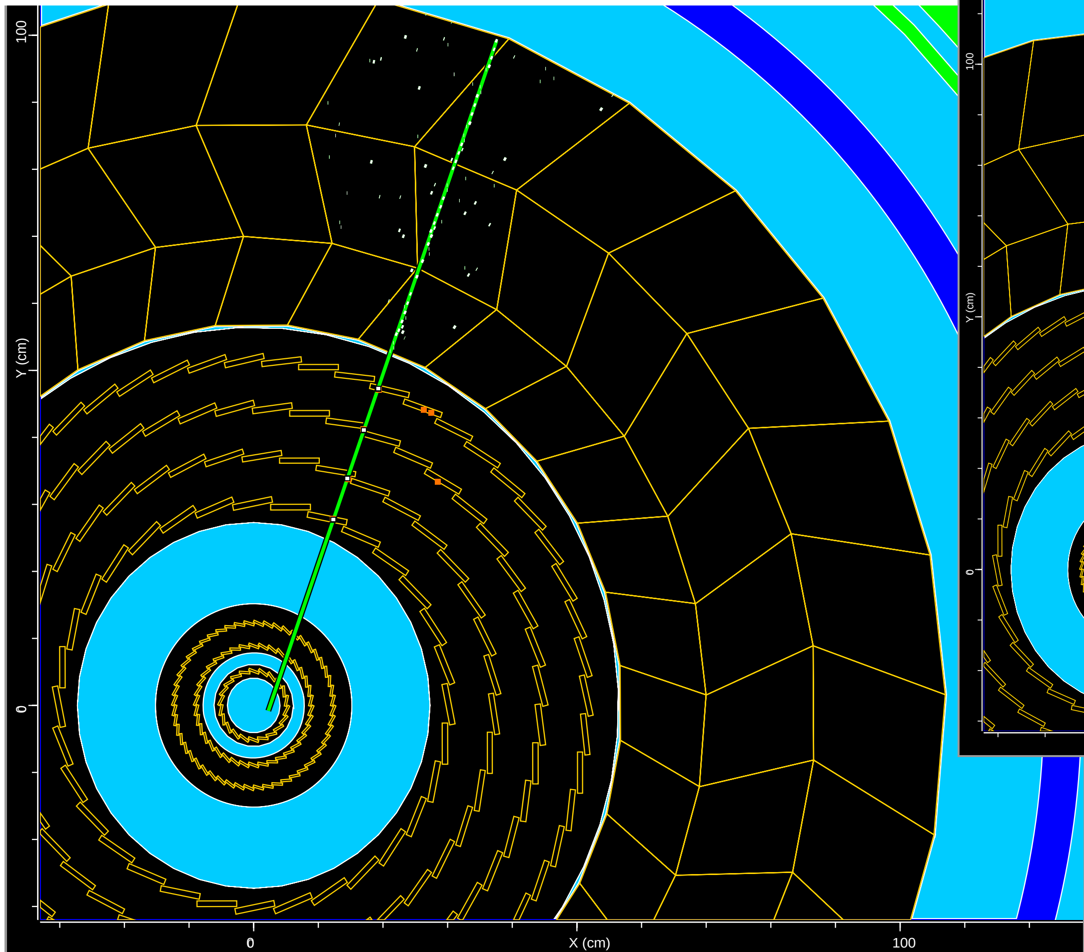
TRT:

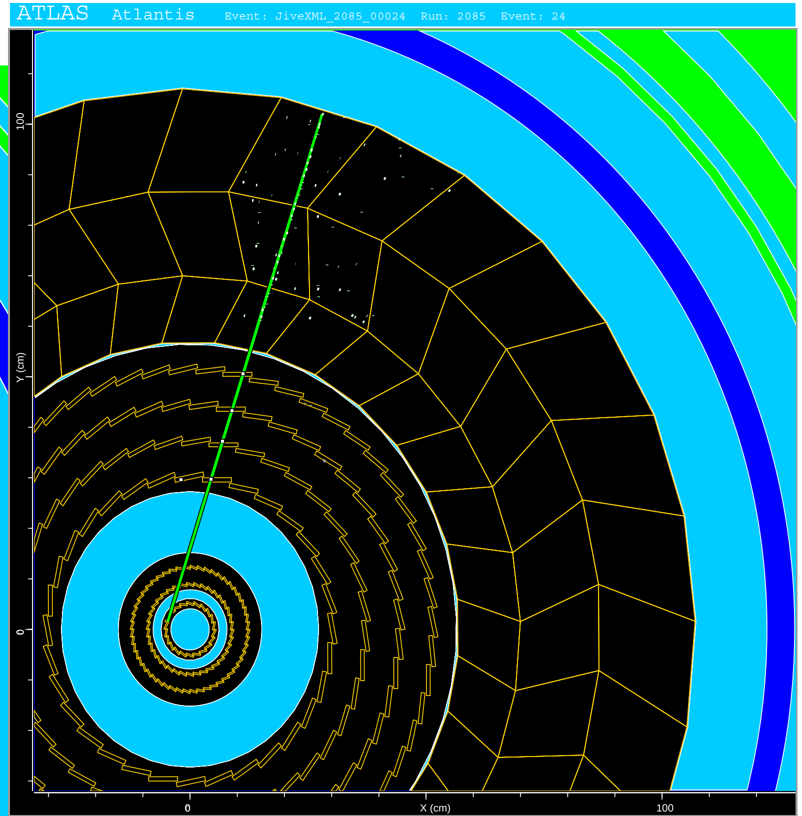
- Read 2 sectors in top +2 sectors in bottom

Cosmics with SCT & TRT

- First Cosmics tracks in top sector

We aim to use the cosmics to do a first exercise on the alignment



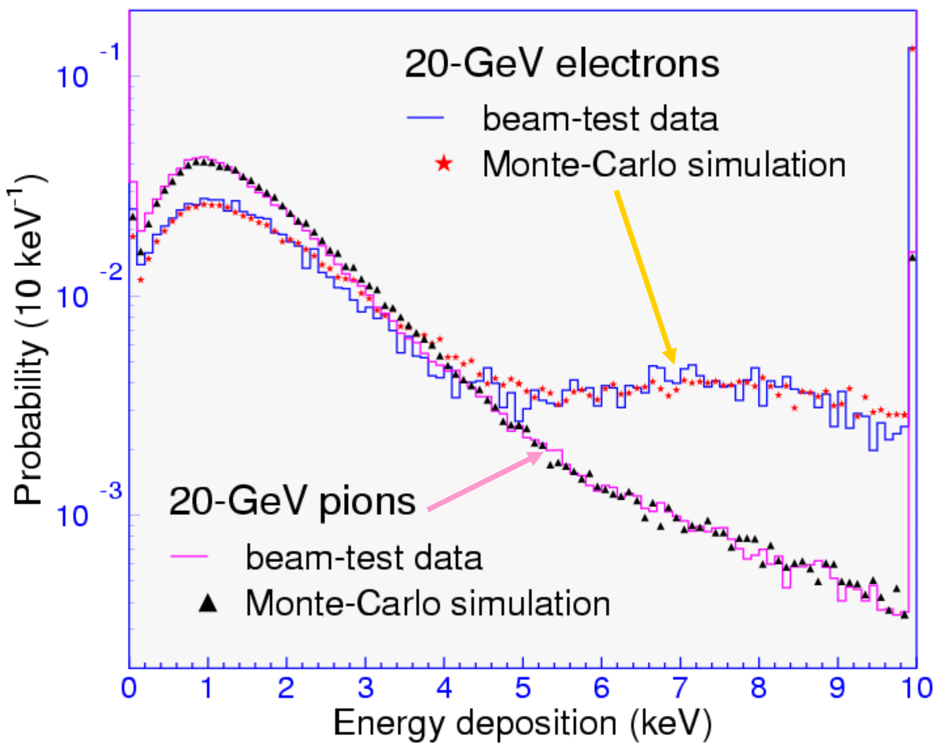


Present alignment == module positioning precision

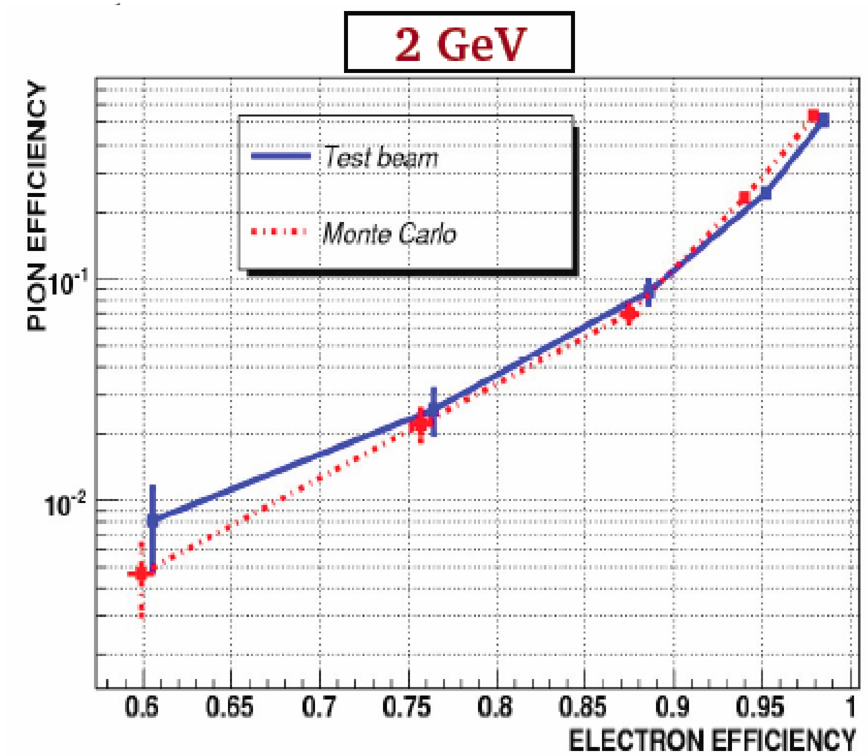
e/π separation using the TRT

Electron identification using large energy depositions due to transition radiation (X-rays) when they traverse radiators between TRT straws

Results from TB 2002 @20 GeV



Results from CTB2004



Typical TR photon energy depositions in TRT ~ 8-10 keV
pions deposit ~ 2 keV

Primary vertex reconstruction

- Large multiplicity of tracks (several hundreds as we have seen)
  ⇨ vertex reconstruction must be fast

- Input needed consists of 3D trajectory & error matrix of tracks. Quality requirements on track are applied

- Approximate primary vertex position in Z: sliding window of 0.7 cm is moved along all interaction region. The window with largest number of tracks weighted with p_T is chosen.

  The <z> is the mean obtained by all the tracks in that window

- Tracks belonging to primary vertex are taken away and the procedure is iterated to get other (pile-up) vertices.

Primary vertex reconstruction cont'd

- All tracks at ± 5mm in z and ± 1mm in transverse plane are accepted as coming from primary vertex

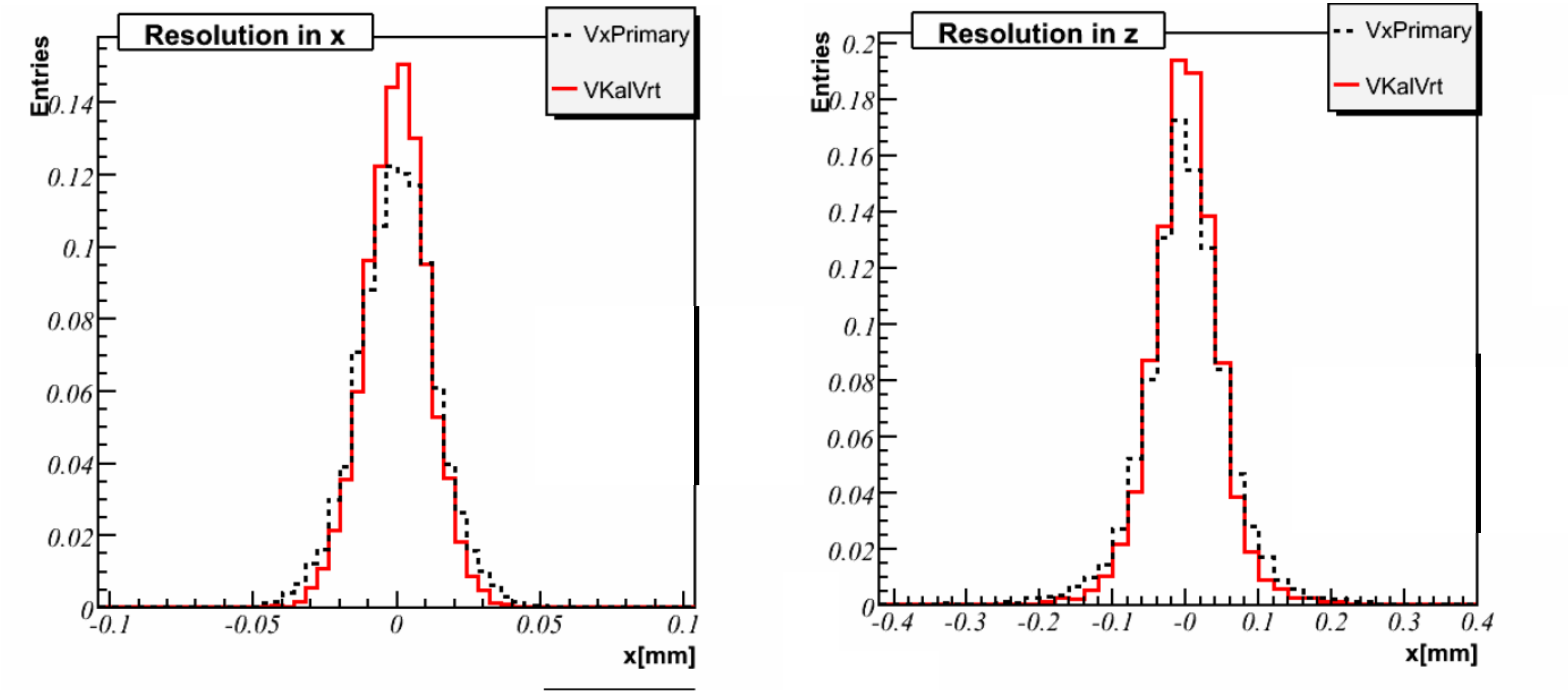
- At this point the vertex fitting is performed using a Billoir method: if the χ^2 is too high, the tracks that give too high χ^2 are rejected and everything is recalculated (outliers are removed)

- There are two different implementation of this method which are basically using the same strategy:
  - VxPrimary
  - VKalVrt

Primary vertex with IPatRec

WH→μνbb events m_H=120 GeV/c^2

	x[μm]	z[μm]
VxPrimary	12.6 ± 0.1	50.0 ± 0.5
VKalVrt	10.8 ± 0.1	42.7 ± 0.4



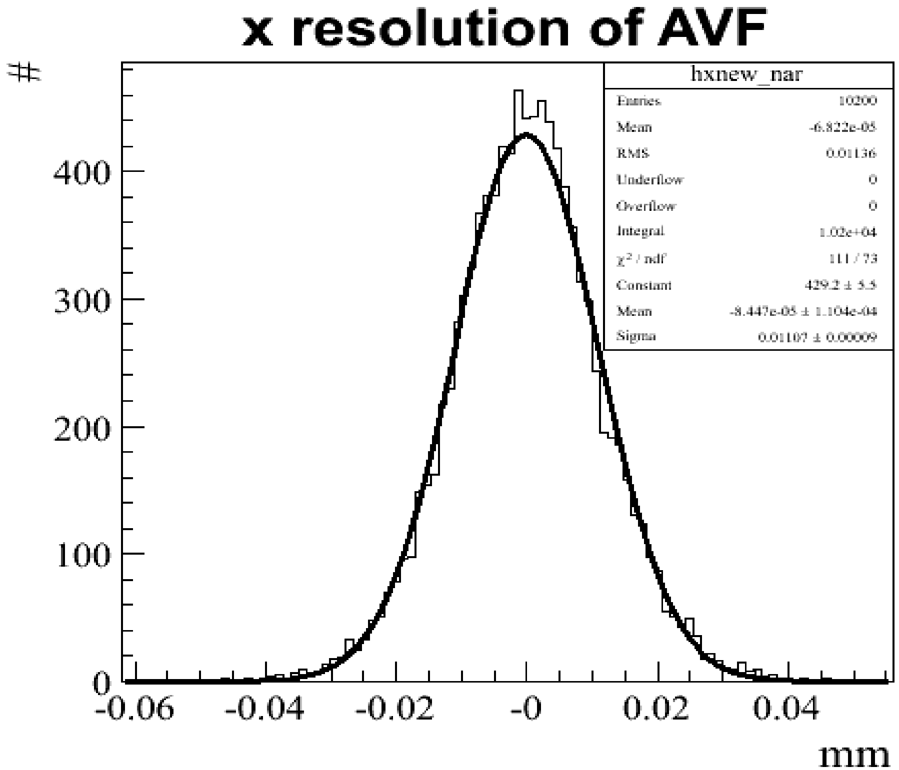
New Adaptive Vertex Fitter

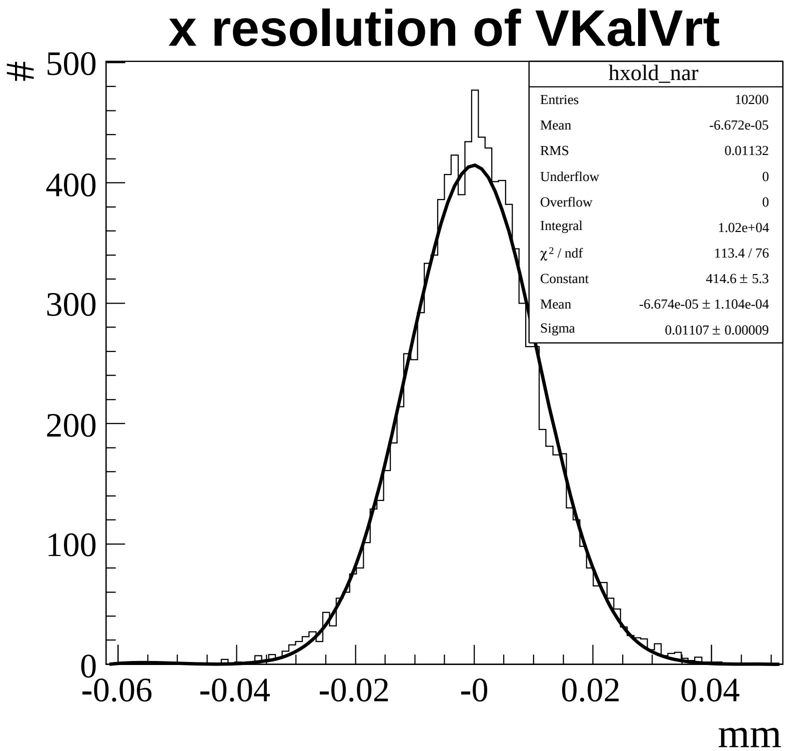
The "Adaptive Vertex Fitter" solves the problem of outlier tracks that spoil the fit, not by discarding them, but by down-weighting them.

Minimises instead than residuals, weighted sum of squared residuals (weight depending on χ^2)

(10000 events of WH(120) with H->bb)

	x (μm)	z (μm)
AVF	11.07±0.09	46.76±0.05
VKalVrt	11.07±0.09	45.43±0.05





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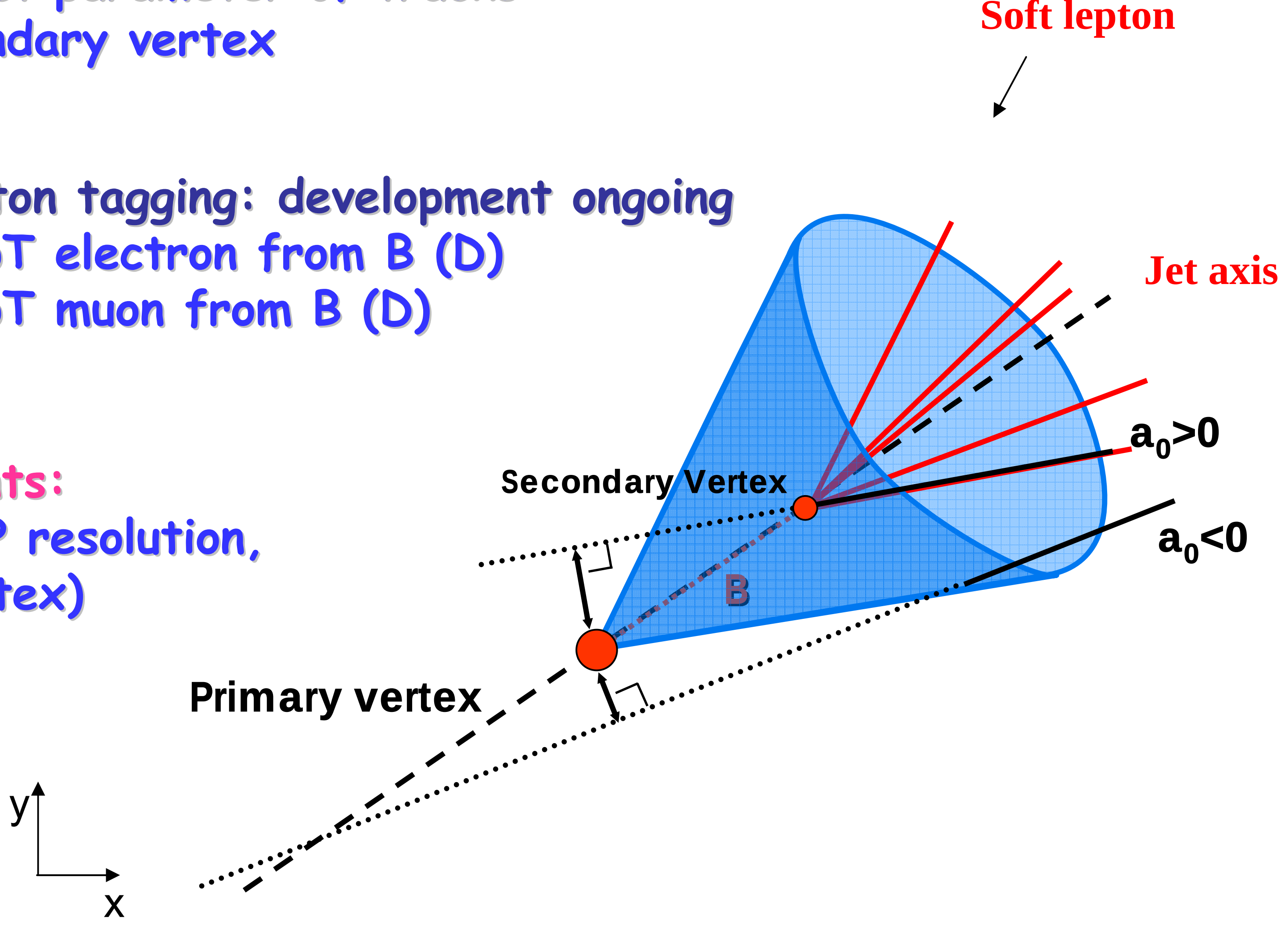
B-Tagging methods

1. Based on lifetime of b-hadrons jets, high multiplicity of b-jets
   - Impact parameter of tracks
   - Secondary vertex

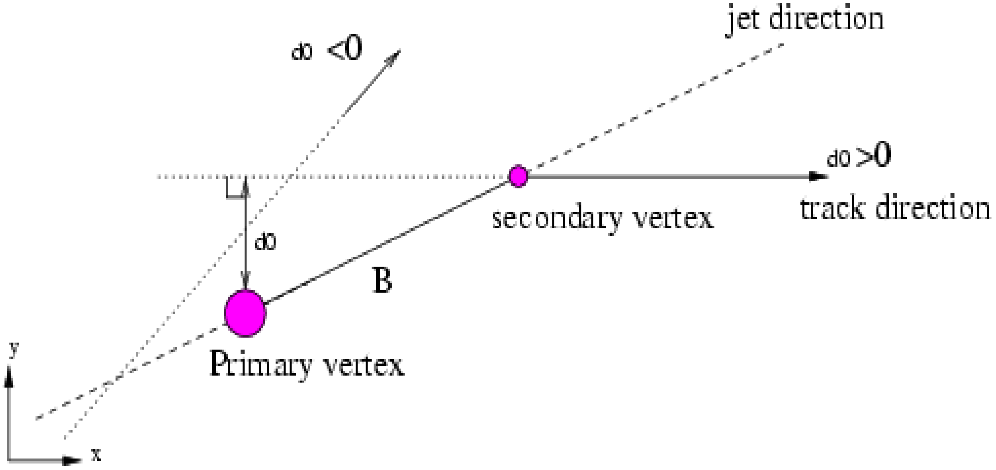
2. Soft-lepton tagging: development ongoing
   - Low pT electron from B (D)
   - Low pT muon from B (D)

Key ingredients:

- tracking (IP resolution, PrimaryVertex)
- jets (axis)

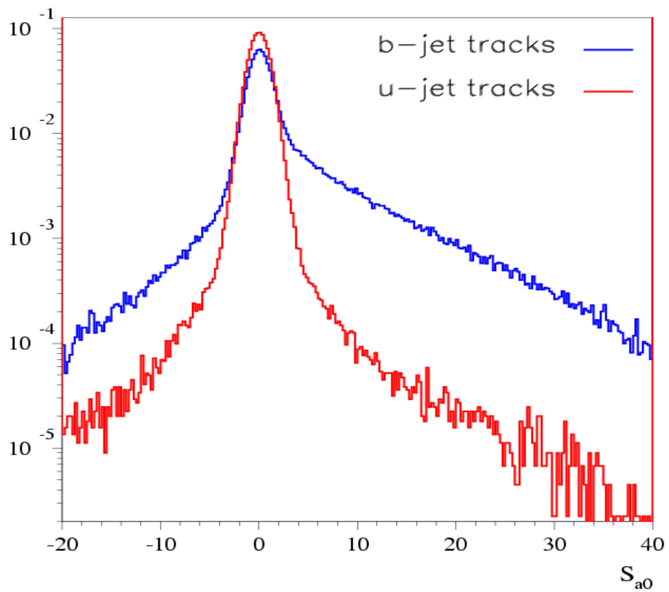


IP in transverse plane

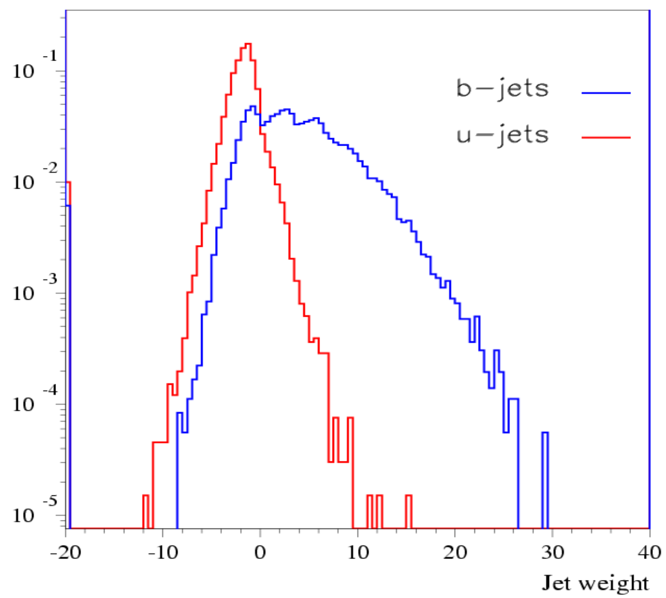


- Use normalised $S = d_0/\sigma_{d_0}$ for each track
- compare it to predefined calibration p.d.f. for the b and light q hypothesis: get probabilities b(S) and u(S)

- sum over all tracks ➔ jet btag weight



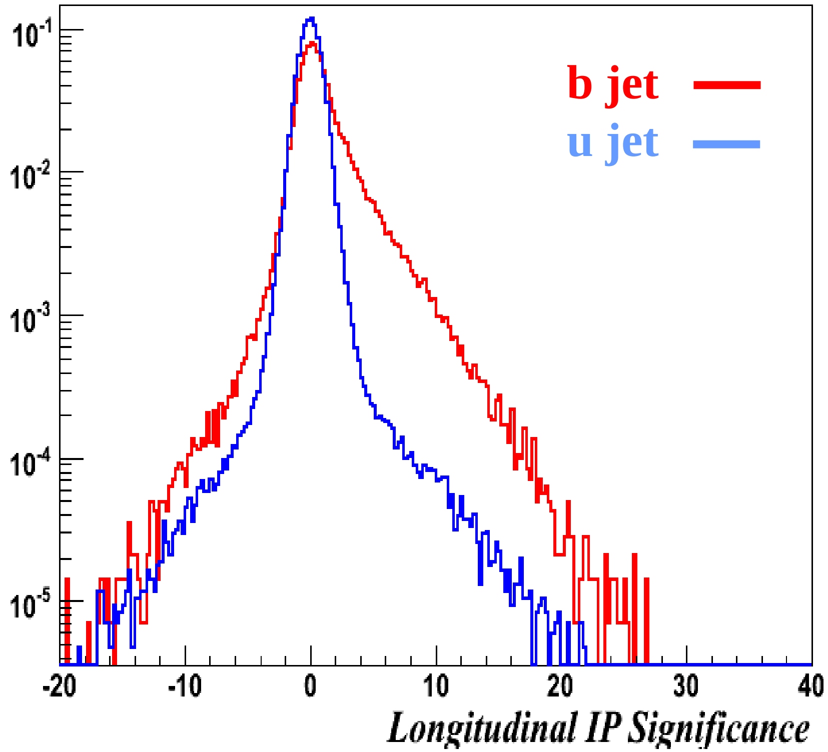
$$W_{jet} = \sum_{i=1}^{N_{tr}} \ln \frac{b(S_i)}{u(S_i)}$$



3D Impact Parameter

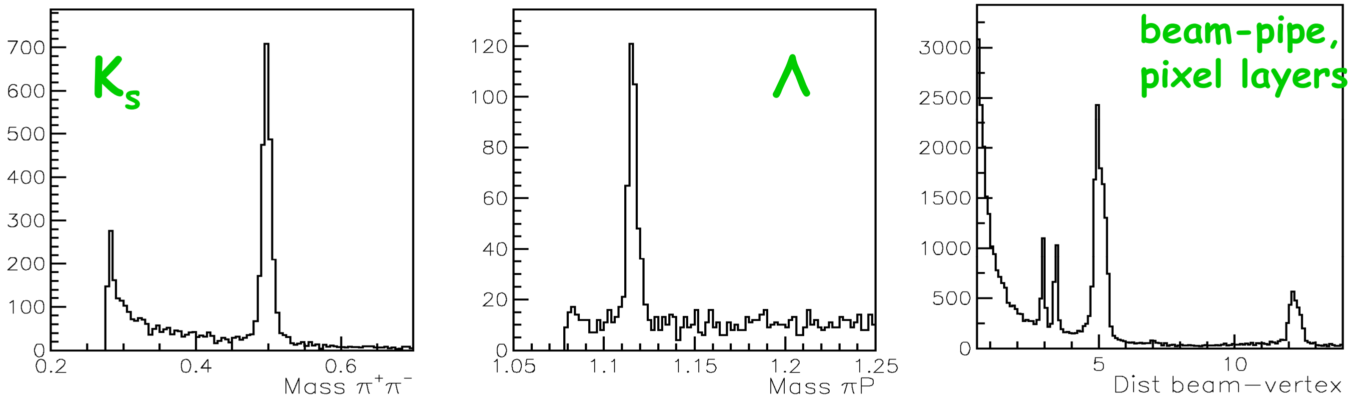
- Improvement can be obtained by combining the longitudinal and the transverse significance.

$$W = P_b(S_{d_0}, S_{z_0}) / P_u(S_{d_0}, S_{z_0})$$



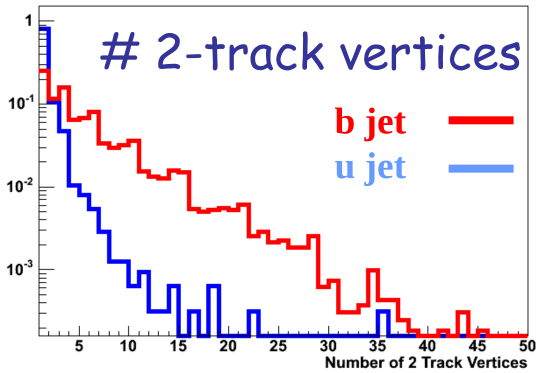
Secondary vertex search

1. Track selection with quality cut:
   (Typically pT > 1 GeV/c, |η| < 2.5; |d0| < 1 mm, |z0| < 1.5 mm; NPixB > 0, NPix > 1, NSi > 6)
2. Search for good 2-track vertices in jet
3. At this point one can remove V0s, identified interaction with material,…



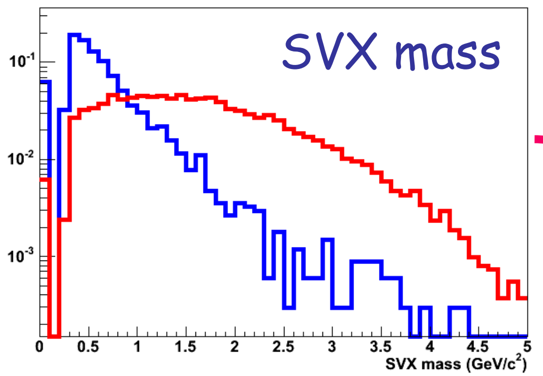
4. Common (inclusive) vertex for remaining tracks

Final jet tagging weight

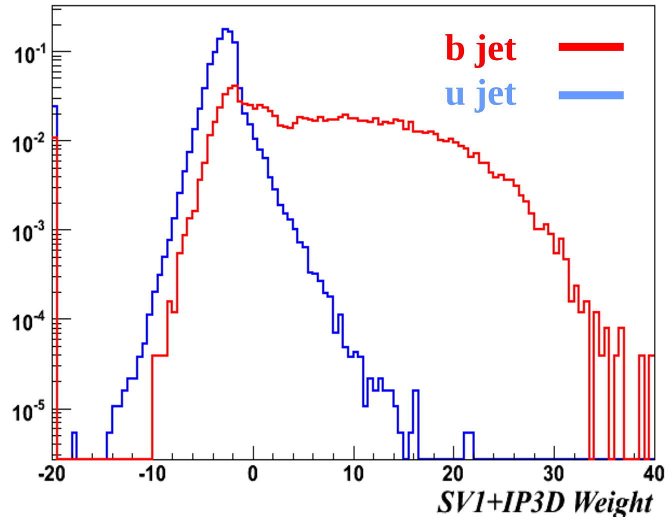


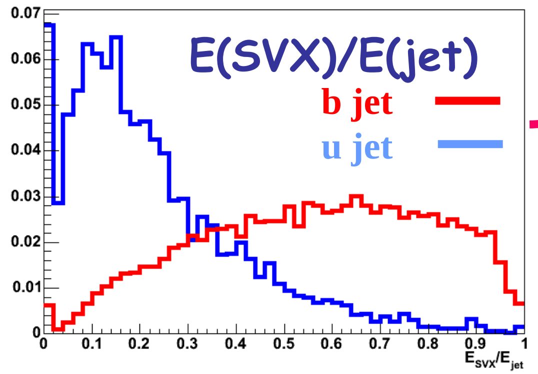
1D variable

Input variables have to be independent from flight distance



+ IP3D





1 2D variable

Taggers available

	1st stream	2nd stream
IP (long. impact)		Lifetime1D
(trans. impact)	IP2D	Lifetime2D
	IP3D	Lifetime3D
Inclusive Secondary Vertex	SV1	SecVtxBU
	SV2	SecVtxTD
Pre-defined combination	VKalVrt= "weight": IP3D + SV1	lhSig= Lifetime1D+ Lifetime2D +SecVtxBU

Different taggers are used as cross-check since they are almost identical wrt discriminating variables:

Lifetime2D ~ IP2D
Lifetime3D ~ IP3D

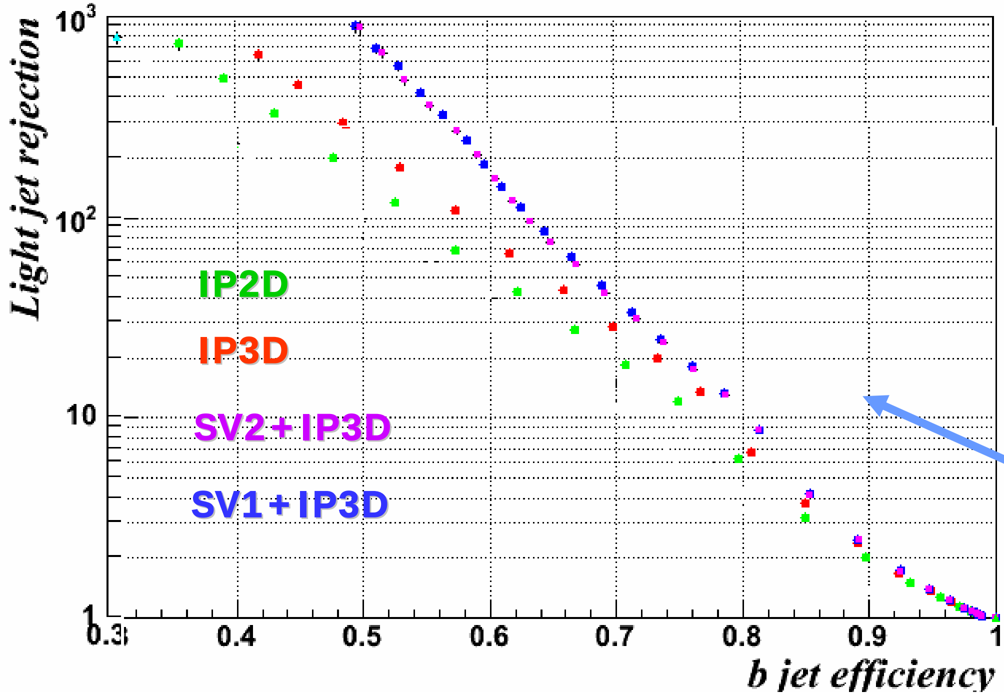
Slight differences:

- refined track selection in IPxD,
- one 2D vs one 1D pdf for IP3D vs Lifetime3D

Performances

Labelling of jets: label a jet as a b-jet if there is a b-quark within $\Delta R<0.3$.
efficiency ε_b : (# b jets)/(#jets labelled as b with $p_T>15$ GeV/c, $|\eta|<2.5$)
light-jet rejection: $R_u = 1 / \varepsilon_u$

Overlapping jets and purification: Overlaps in jets → mislabelling
Jet isolation very dependent on the type of events and physics processes (gluon jets) + jet algorithm



Purification to factorize it from pure b-tagging issues

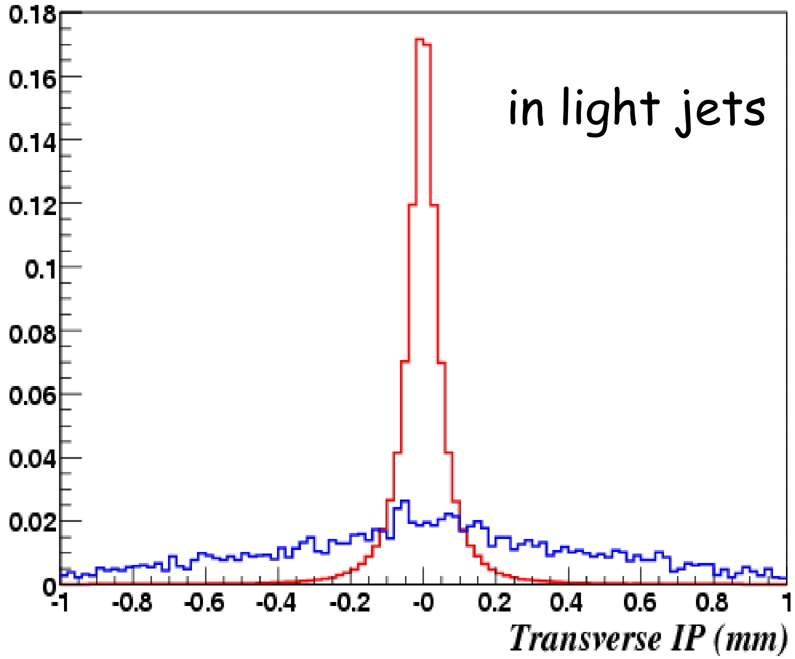
do not consider lights jets when there is a b/c/quark/hadron within $\Delta R<0.8$

Using WH events m_H = 120 GeV/c^2
2 layer-layout, xKalman tracks,
Cone 0.4 jets

Shared hits and bad tracks

b-tagging is obviously very demanding for track quality. One might try to 'clean them up'

1) Tracks in jet may share some hits, resulting in lower quality tracks: special treatment, by either rejecting them, or using dedicated calibrations. Fraction in b-jets:
   - tt events 3.5%
   - WH events (400 GeV) 8.5%



2) Tracks may originate from V0 or interaction with material.
They usually have "more lifetime" → reject them (*bad tracks*)
Fraction of V0 tracks in b-jets:
- tt 1.2%
- WH(400 GeV) 3.6%

B-tagging performance

B-tagging performance using different primary vertex finders.

- WH>uuμν, m_H = 120 GeV/c xKalman
- Geometry for this study: Final Layout for pixels (3 layers/disks)

Physics performance limited by gluon splitting

	IP2D		IP3D		IP3D+SV1	
efficiency	50%	60%	50%	60%	50%	60%
Rej:just tagger VKalVrt	135±9	55 ±2	214 ±18	75 ±4	609 ±86	157 ±11
Rej:just tagger AVF	130 ±9	52 ±2	205 ±17	73 ±4	612 ±87	147 ±10
Rej:bad tracks + VkalVrt	206±17	69 ±3	339 ±35	101 ±6	815 ±134	192 ±15
Rej:bad tracks + AVF	199 ±16	66 ±3	327 ±34	98 ±6	794 ±129	164 ±12

b-tagging in ttbar events

- 190 K tt ttbar, cone $\Delta R=0.4$, iPatrec tracks
- 60k ttH (m_H=120 GeV) cone $\Delta R=0.4$, iPatrec tracks (2-layer layout)

	R_u (ε_b=60%)	R_u (ε_b=50%)
ttbar SV1+IP3D	259 ±7.8	858±42.9
ttbar SV1+IP3D + shared hits	326 ±9.8	1133 ±56.6
ttbar events SV1+IP3D + shared hits + bad tracks	375 ±11.2	1326 ±66.3
ttH events lhSig	313 ±9.4	1392 ±56.6

Conclusions

- There has been a lot of work/improvement on tracking and vertexing in the past year(s).

- Tracking algorithms are available at LVL2, Event filter, offline, for cosmic running, combined testbeam etc..

- Different parallel software developments for the tracking and vertexing algorithms have been produced, giving comparable results

- We are already reconstructing cosmic events with the SCT and TRT barrels

- We are looking forward to the commissioning of all those tools with the final detector.

Back-up

Tracking the basics:

1. Pattern recognition: finding hits in SCT and pixel and then make a fast fit to extrapolate tracks to TRT to find TRT hits. At any stage the effect of the magnetic field is taken into account

2. Track fitting: uses the list of hits that the pattern recognition associates to a track, and fits the track. It needs as input the track parameters at the perigee (point of closest approach to the z axis for the track). There are 5 parameters: f0,q0,d0, z0 and q/p. The track fit can correct for energy loss and multiple scattering for each scattering plane.

3. Residuals: difference between the track prediction and the hit

4. Track parameters pulls: a measure of the reliability of the track fit are the pull distributions (rec-tru)/(error on rec) for the 5 track parameters.

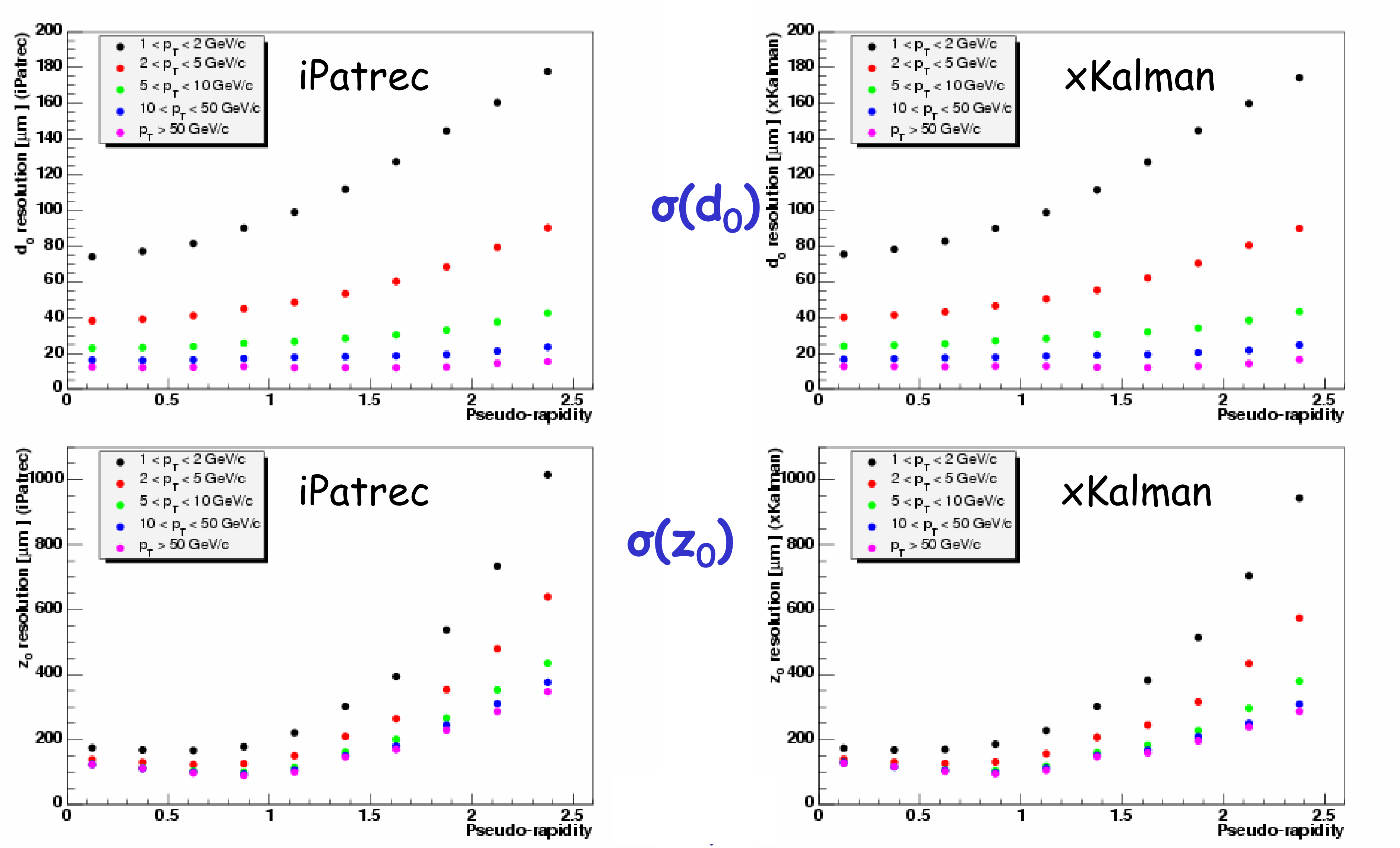
Comparison of results

- Using 100 $t\bar{t}$ events

	xkalman	iPatRec	newTracking
Multiplicity (P>1 GeV)	16.69	17.06	16.88
Barrel Track eff/ fake rate	99%/0.6%	99%/0.7%	96%/2.5%
Transition Track eff/ fake rate	98%/0.6%	98%/0.5%	96%/3.6%
ForwardTrack eff/ fake rate	98%/0.3%	99%/1.3%	95%/2.7%
Barrel # hits Pixel/SCT/TRT	2.9/8.1/28.1	2.9/8.0/27.5	2.9/7.9/28.9
Transition # hits Pixel/SCT/TRT	3.0/8.2/25.8	3.0/8.0/25.7	2.9/7.8/26.4
Forward # hits Pixel/SCT/TRT	3.3/8.8/15.2	3.2/8.5/15.2	3.2/8.4/15.6

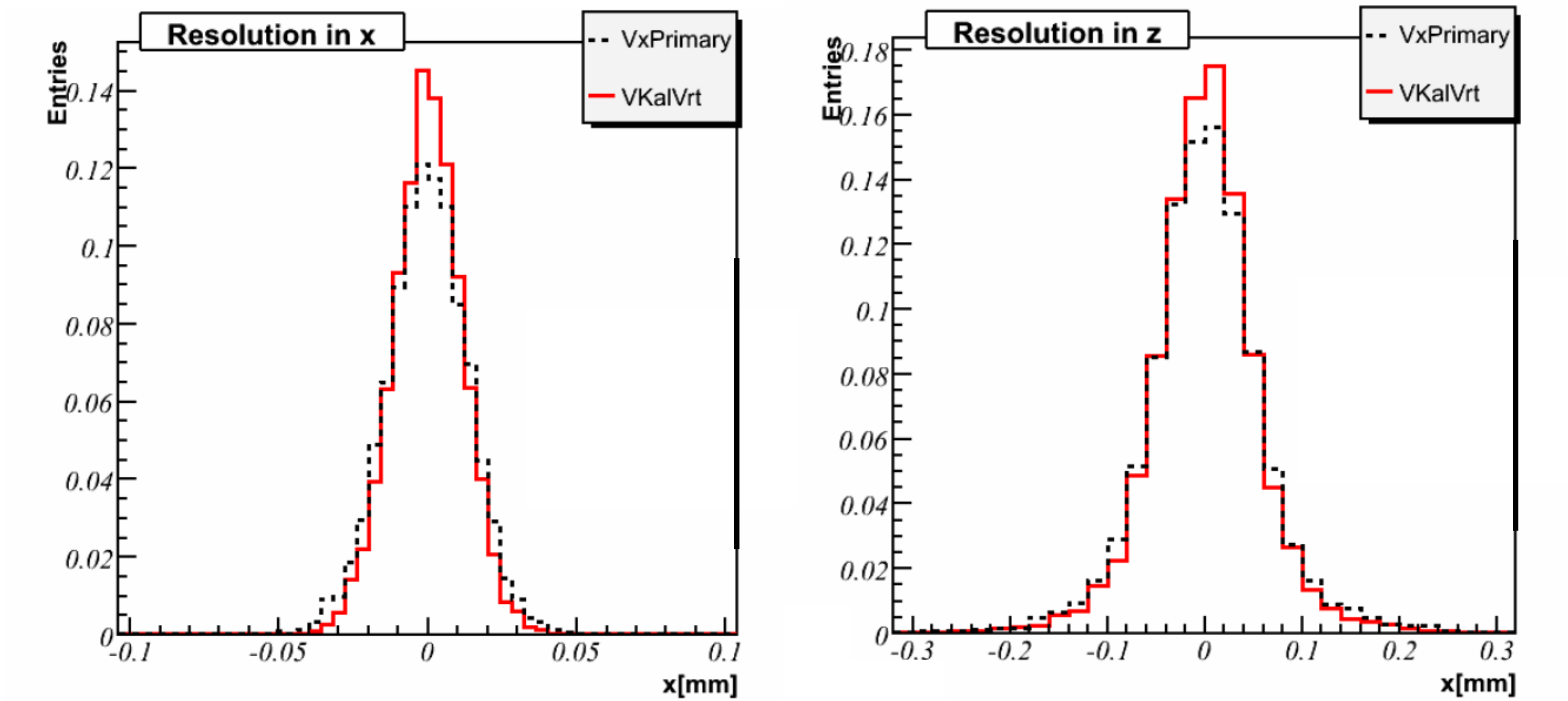
Impact parameter resolutions

WH(400 GeV/c^2) W(→μν)H(→uu)



Primary vertex with xKalman

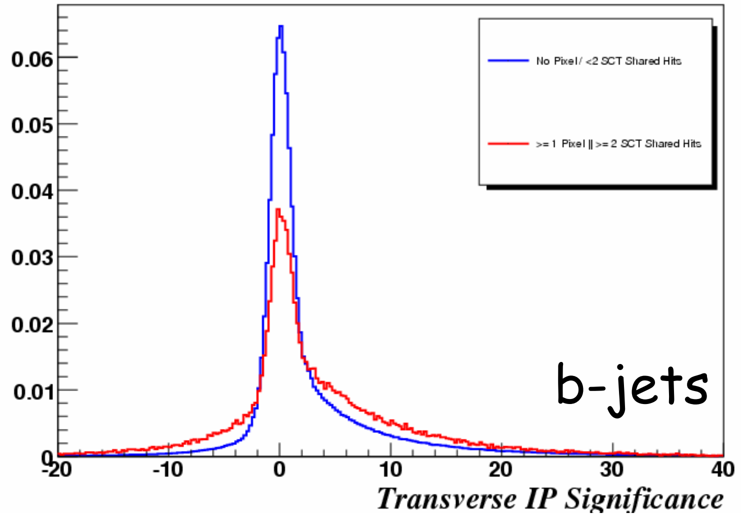
	x[μm]	z[μm]
VxPrimary	13.0 ± 0.2	51.4 ± 0.6
VKalVrt	11.4 ± 0.1	47.4 ± 0.5

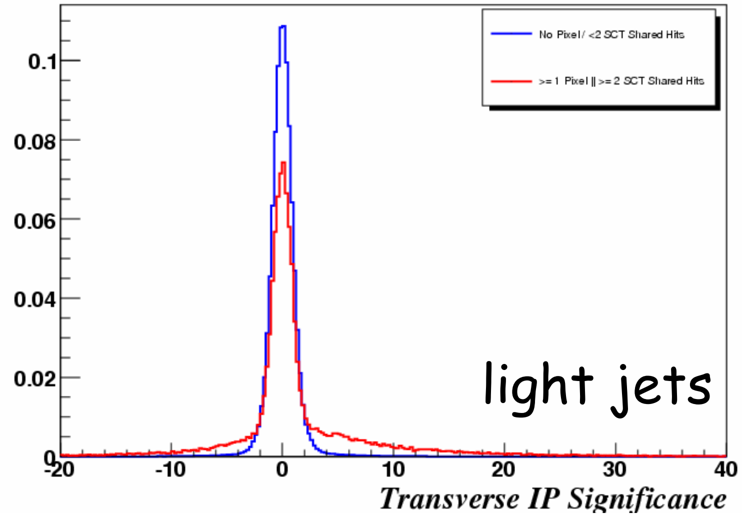


Shared hits: IP distributions

Typical criteria:

- "Good" track: no shared pixel AND < 2 shared SCT hits
- "Shared" track: the rest





Rome samples	Fraction of tracks with shared hits	
	b-jets	light jets
WH(400 GeV)	8.5%	4.4%
ttH, ttbb, tt(jj)	3.5%	1.4%

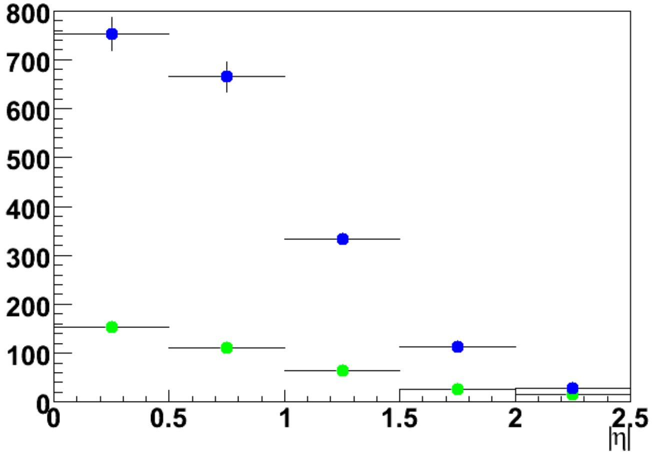
Performances: ttH vs ttjj

Complicated/busy events due to overlaps and mislabellings.

Purification done by factorising these effects to disentagle them from b-tagging

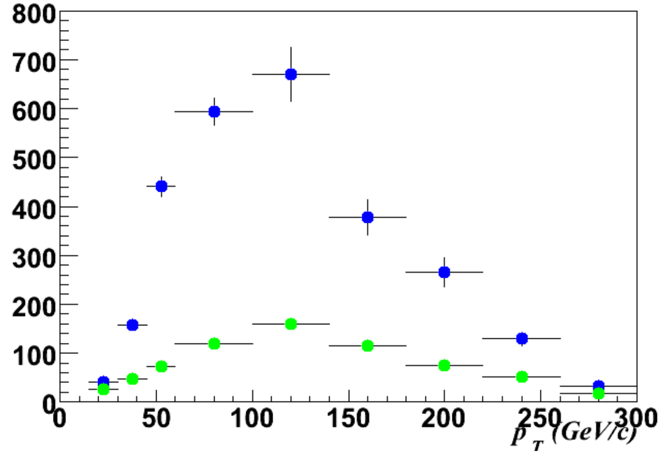
- b-jets: ttH Pythia (samples 4867, 4868)
- u-jets: tt(jj) MC@NLO
- cone $\Delta R=0.4$, iPatrec tracks
- Statistics: 75k b-jets, 1.2M u-jets

	R @ ε_b 50%	R@ ε_b 60%	R@ ε_b 70%
IP2D	218 ± 3	66 ± 1	23
SV1+IP3D	882 ± 24	297 ± 5	59



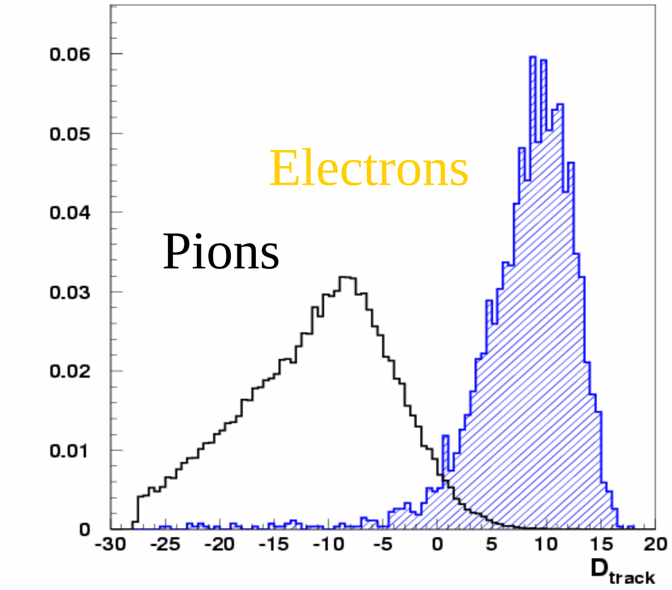
as a function of $|\eta|$ and p_T

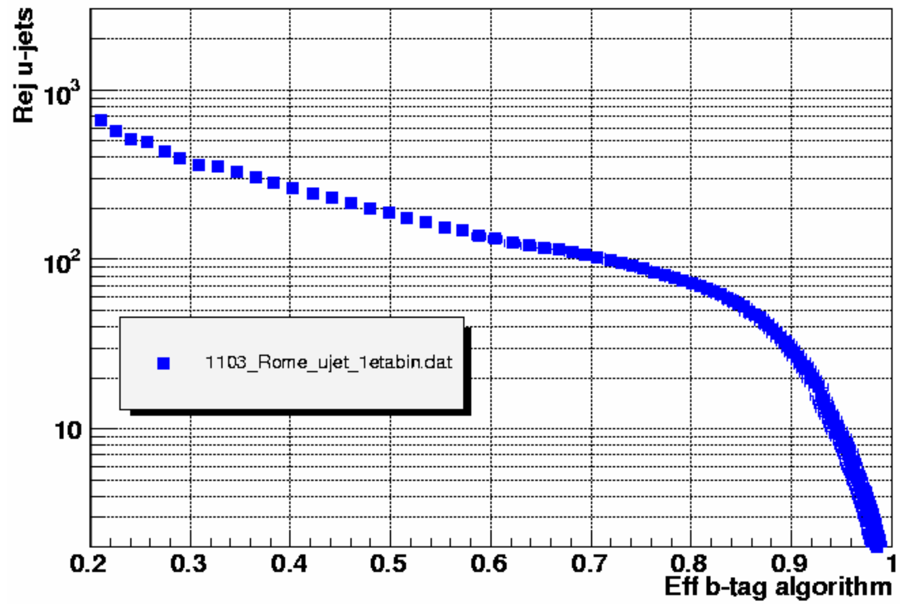
@ 60% efficiency



Soft Electron Tagging

use Soft Electron identification variables to build a probability for each track in a jet ⇒ the track with the highest probability is the "electron candidate"





⇒ light jet rejection vs algorithm efficiency :

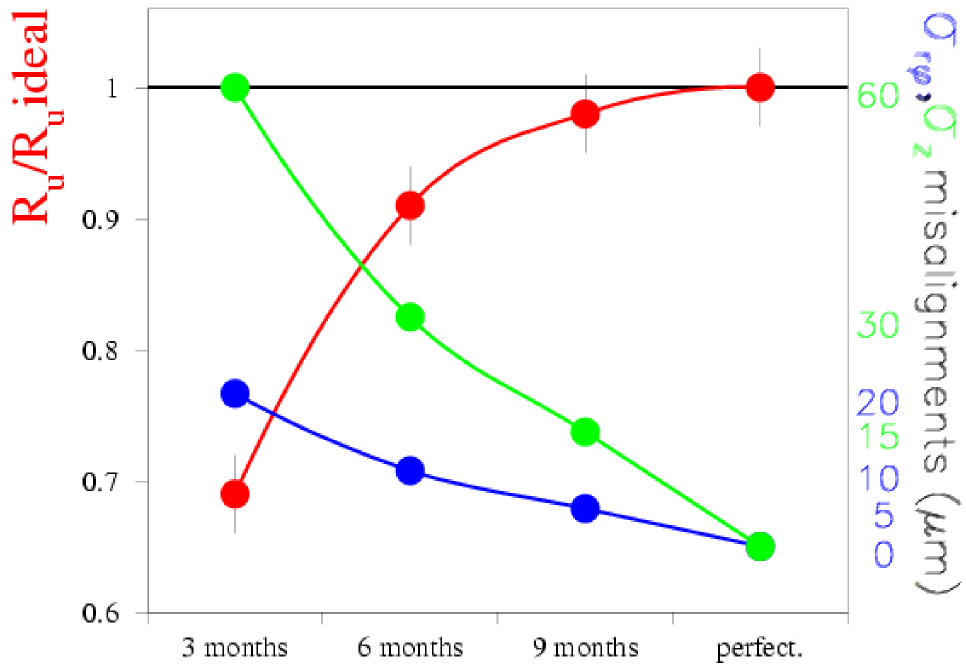
@ 60% algorithm efficiency
(i.e. 0.6*BR(b→eX) ~7.8% b-jet efficiency)

R_u = 134 (WH m_H=120 GeV events)

Impact of (mis)alignment

Random misalignments:

IP3D tagger , ttH events, realistic conditions



⇒ will redo the exercise with misaligned detectors from simulation (more realistic than random misalignments)

Influence of alignment (II)

- ✓ Use CDF experience :

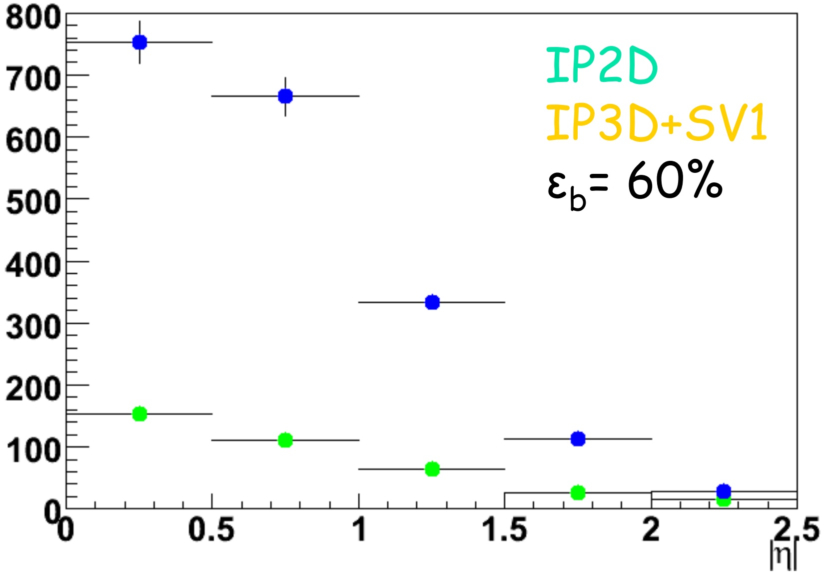
  Map CDF commissioning misalignments from CDF run II to ATLAS and propagate to b-tagging performances

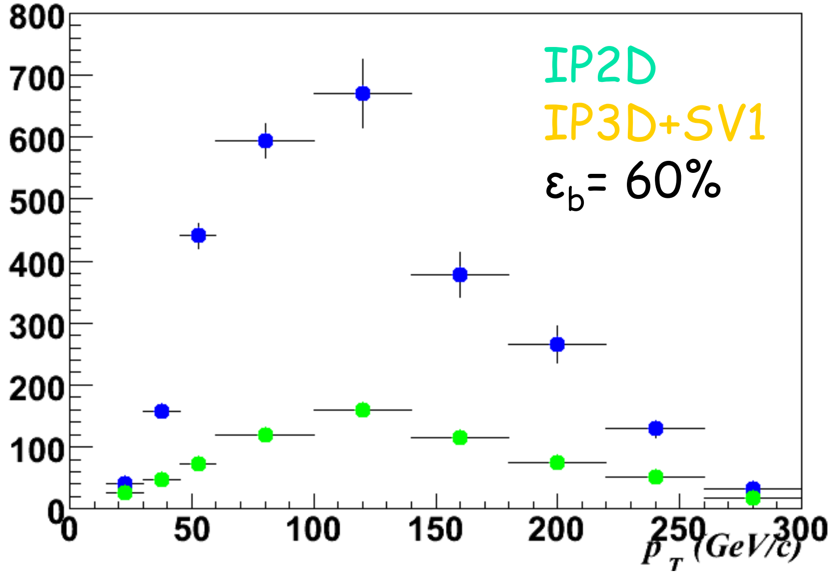
		2D algorithm		*3D algorithm*	
		Perfect	Misaligned	Perfect	Misaligned
$R_u(\epsilon_b)$	$\epsilon_b = 50\%$	155 ± 8	138 ± 6	348 ± 22	316 ± 19
	$\epsilon_b = 60\%$	47.1 ± 1.1	43.6 ± 1.0	89.0 ± 3.4	81.7 ± 2.7
$\frac{R_u^{\text{Misaligned}}}{R_u^{\text{Perfect}}}$	$\epsilon_b = 50\%$	0.89		0.91	
	$\epsilon_b = 60\%$	0.92		0.92	

$\Rightarrow$ ~ 10% loss

Performances versus jet pT, η

Non-uniform performances: tagging b-jets can bias kinematics





How to improve bad regions ?:

- large pseudo-rapidity (|η|>2): z-anolog clusters, matter descrip, interaction in disks
- low pT (<50 GeV) [bbh,...]: better matter description
- high pT (>200 GeV) [Susy, little Higgs,...]: tracks w/o hit in b-layer, ambiguities

➔ A bit more subtle, being investigated now

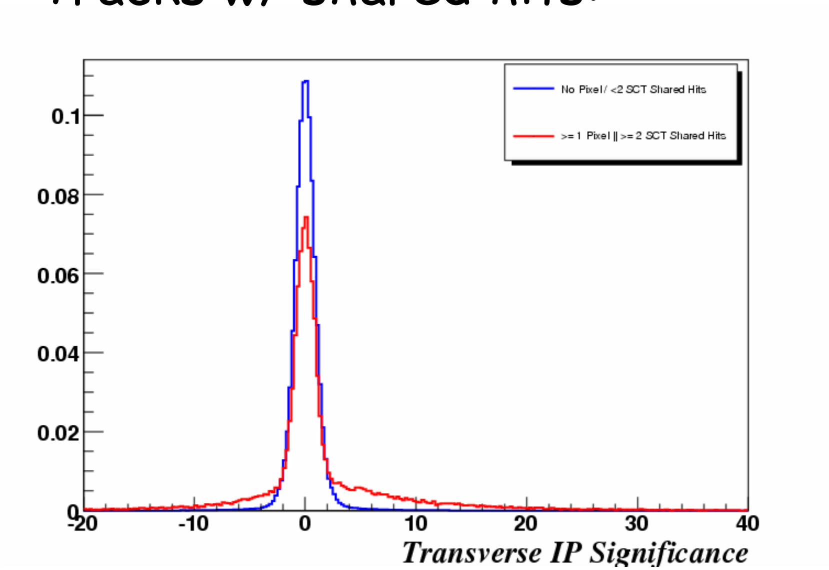
Track Classification

LV, JBdV (CPPM)

Define track quality categories to:

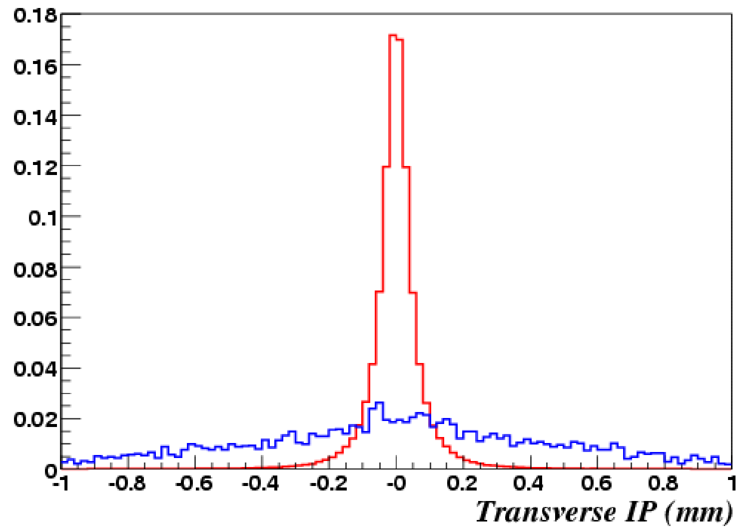
- reject/use dedicated calib for tracks w/ shared hits (≥1 Pix || ≥2 Sct)
- reject tracks from V0 or interactions with material

Tracks w/ shared hits:



Samples	Fraction of shared tracks in b-jets
tt	3.5%
WH(400 GeV)	8.5%

Tracks from V0, interactions:



Samples	Fraction of tracks from V0 in b-jets
tt	1.2%
WH(400 GeV)	3.6%