Electron track reconstruction in the ATLAS experiment

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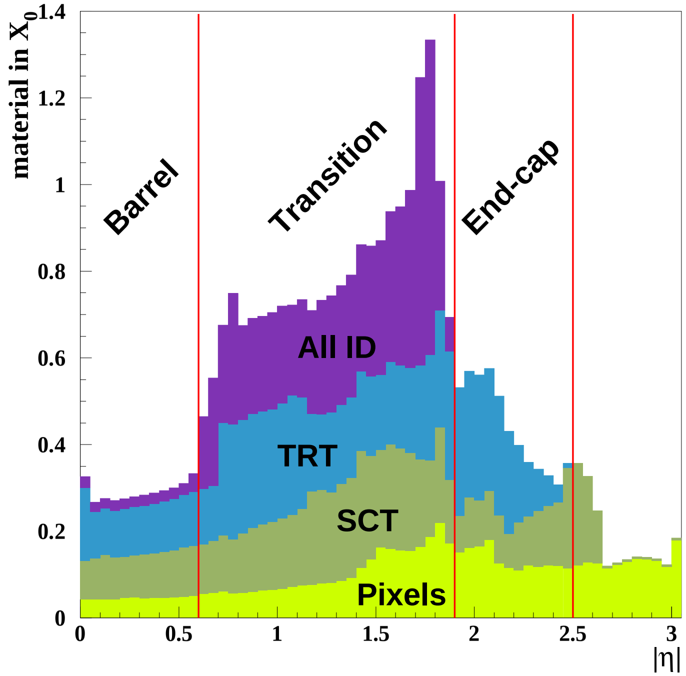
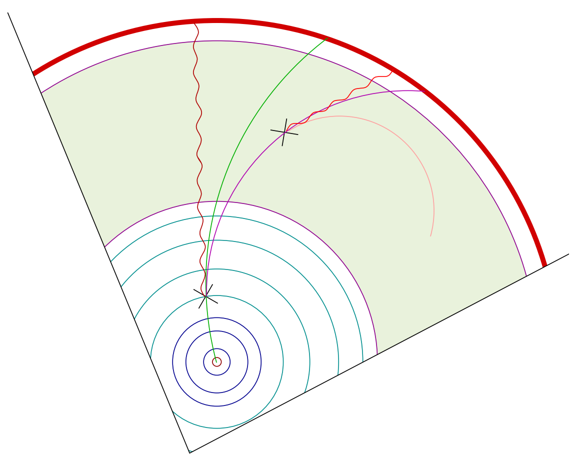
- **Electron reconstruction:** situation in the ATLAS detector
  detailed analysis of bremsstrahlung effects
  construction of a pessimistic electron reconstruction algorithm
  performance analysis: single particles, pion rejection, electrons in jets & pile-up
- **Applications of the algorithm:** benchmarking against simulated physics processes
  $\mathrm{B}^0 \to \mathrm{J}/\Psi \to ee$
  $\mathrm{Z} \to ee$
  $\mathrm{H} \to \mathrm{ZZ}^{(\star)} \to 4e$

TDR detector layout used for simulations
realistic magnetic field

Problem statement: large amount of material ⇒ bremsstrahlung effects dominate reconstruction





1. p_T **resolution** deteriorated with traversed material
   improves with more measurements & track length
2. **Reconstruction/Identification efficiency**
   cuts required to retain resolution and suppress fakes
   requiring a full-length track is too restrictive
3. **ECAL/ID matching** for identification
   disastrous early bremsstrahlung ⇒ position matching sufficient

Fraction of e's that lost more that 10% of their energy:

η bins	$0 - 0.6$	$0.6 - 1.9$	$1.9 - 2.45$	weighted sum
pixels	0.11	≈ 0.22	0.35	0.22
SCT	0.32	≈ 0.58	0.45	0.49
TRT	0.52	≈ 0.75	0.70	0.68

p_T **deterioration:** fraction of electrons out of 10% cut on $p_T^{\rm true}$

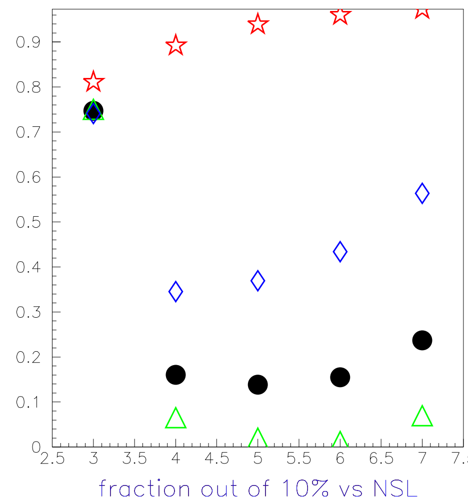
△ **Less** than 10% loss by the end of the SCT

● all events

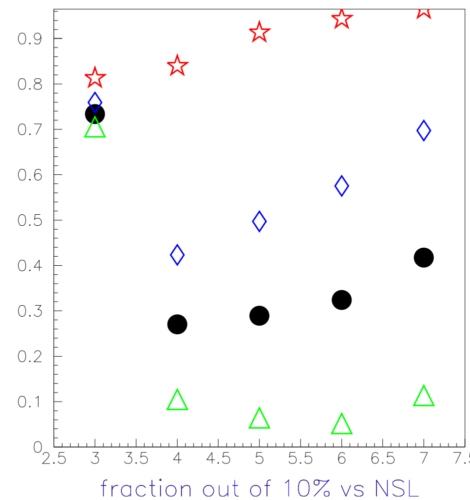
☆ **More** than 10% loss by the end of the pixels catastrophic events → ID measurement doomed new measurements should deteriorate p_T

◇ **More** than 10% loss by the end of the SCT excluding ☆: a good p_T measurement should be possible

$0 \le \eta \le 0.6$:



$0.6 < \eta \le 1.9$:



ECAL measurements:

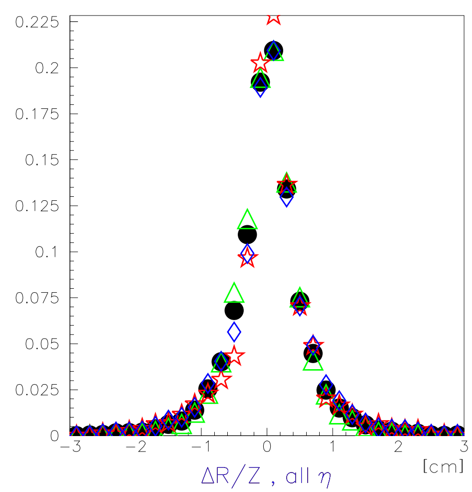
3×7 window for clustering

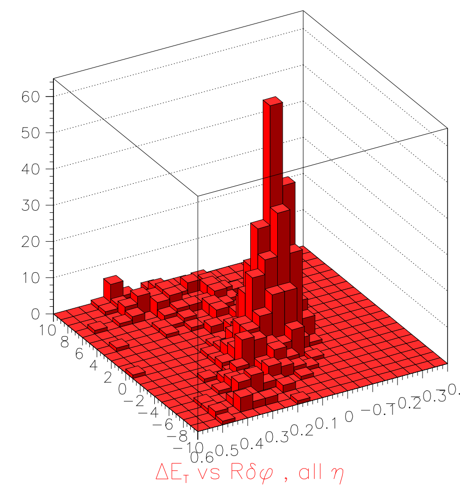
ECAL efficiency: 41.9% ($1.5\,\rm GeV$), 74.6% ($2\,\rm GeV$), 94.4% ($3\,\rm GeV$) and 98.6% ($5\,\rm GeV$)

η measurement not influenced

φ and E_T measurements correlated

for $E_T > 10\,\rm GeV$ ECAL measurement is almost independent of bremsstrahlung





	% bremmed energy	Barrel	Transition	Endcap
Primary	≥ 90	0.26	0.12	0.21
	≥ 80	0.47	0.27	0.38
	≥ 70	0.62	0.42	0.53
Primary + Secondary	≥ 90	0.69	0.40	0.56
	≥ 80	0.87	0.67	0.79
	≥ 70	0.95	0.84	0.91

Case	Barrel	Transition	End-cap
1	0.716	0.496	0.477
2	0.122	0.122	0.116
3	0.066	0.080	0.190
4	0.096	0.302	0.217

Bremsstrahlung scenarios: considering reconstruction till the end of the SCT

1. **Negligible amount of bremsstrahlung (55% of events):**
   below 10% energy loss by the end of the SCT
   these events can be handled with the usual fitting procedure
2. **Single measurable bremsstrahlung photon emission (12%):**
   above 10% energy loss by the end of the SCT;
   the primary photon originates from the SCT & takes $> 80\%$ of all the emitted energy
   ID bremsstrahlung recovery can be applied (i.e., allowing for a single kink on a track)
3. **Early hard bremsstrahlung photon emission (10%):**
   as above with the hardest bremsstrahlung occurring within the pixels
   can be reconstructed with a poorer p_T resolution
4. **Two (or more) hard bremsstrahlung photon emissions (23%)**, early ones not excluded
   recuperation of these events is questionable as it depends on several factors

`ieElRec`**:** algorithm for electron identification and reconstruction

Design decisions:

1. **Second stage reconstruction:** inputs are lists of tracks in the ID $\oplus$ EM clusters
2. **Accept also partial tracks:** track searching package doesn't have to perform the brem-fit
   `iPatRec` modified to follow this convention
3. **Track's head:** used for track parameter determination
   select the track segment best matching to the seeding EM cluster
4. **Track's tail:** fake suppression & TRT association
   there is NOT enough information to fully reconstruct most of the bremsstrahlung occurrences

Goals:

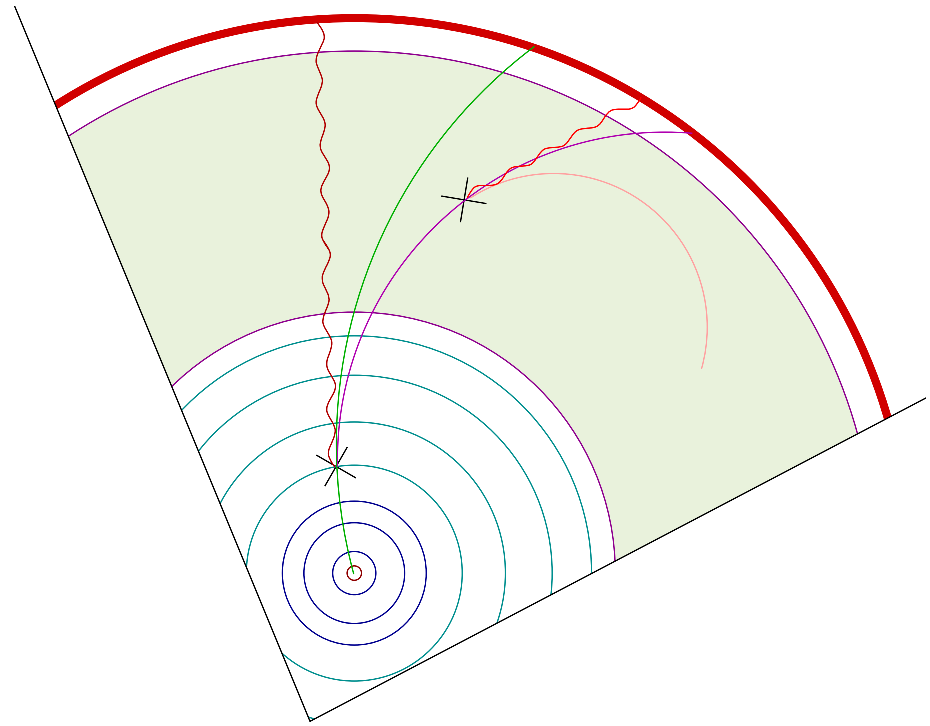
1. **Electron identification:** a prerequisite; photon and pion separation $\oplus$ identification in jets
2. **Bremsstrahlung tagging:** attempt to estimate the amount and location of a hard bremsstrahlung
   linked with electron identification as quantities used can become corrupted
3. **An improvement of p_T resolution:** important at energies below $20\,\mathrm{GeV}$ (where the tracker precision is better)
   enables a better ECAL calibration.
4. **Improvement of perigee parameters:** allows for smaller errors in reconstruction of decaying particles
   no improvement of longitudinal parameters expected

Modifications of `iPatRec`**:**

truncated tracks (failed TRT extrapolation)

secondary tracks (failed vertex association)

TRT extrapolation for secondary tracks
mid-SCT bremsstrahlung



Selection algorithm:

Project ID track (or track segment) to ECAL

Normalize differences by using look-up tables extracted from simulated data (p_T: $1.5\,\mathrm{GeV} \nearrow 60\,\mathrm{GeV}$)

$\boldsymbol{\delta\eta} \sim \eta^E - \eta^{\mathrm{iPat}}$ $\Rightarrow$ Gaussian

$\boldsymbol{\delta\varphi} \sim -\mathrm{sgn}(\mathrm{e})(\varphi^{\mathrm{E}} - \varphi^{\mathrm{iPat}})$
$\boldsymbol{\delta p} \sim E_T^E - |p_T^{\mathrm{iPat}}|$ $\Rightarrow$ brem tails, correlated

For extraction of track parameters select track segment best realizing the ID/ECAL matching

Pion rejection: ~ 30 achieved by requiring a good ID/ECAL matching
TR information
longitudinal profile of the EM shower

Good match (M1): $|\delta p| < 3 \ \wedge \ |\delta\varphi| < 3$

[$\sim 80\%$ at low p_T, 86% for $p_T > 10\,\mathrm{GeV}$]

tighter cuts can be used to obtain a *cleaner* sample

Imprecise ECAL (M2): $-3 < \delta p < 1 \ \wedge \ -10 < \delta\varphi < -3$

[3% at $p_T = 3\,\mathrm{GeV}$]

relevant for $p_T \leq 10\,\mathrm{GeV}$

selects tails of the ECAL measurement

Poor ID (M3): $\delta p > 1 \ \wedge \ \delta\varphi < 3$

[$\sim 10\%$ for $p_T > 10\,\mathrm{GeV}$]

early hard bremsstrahlung; p_T underestimated

Poor ECAL (M4): $\delta p < -3$

[10% at $p_T = 10\,\mathrm{GeV}$]

relevant for $p_T \lesssim 30\,\mathrm{GeV}$

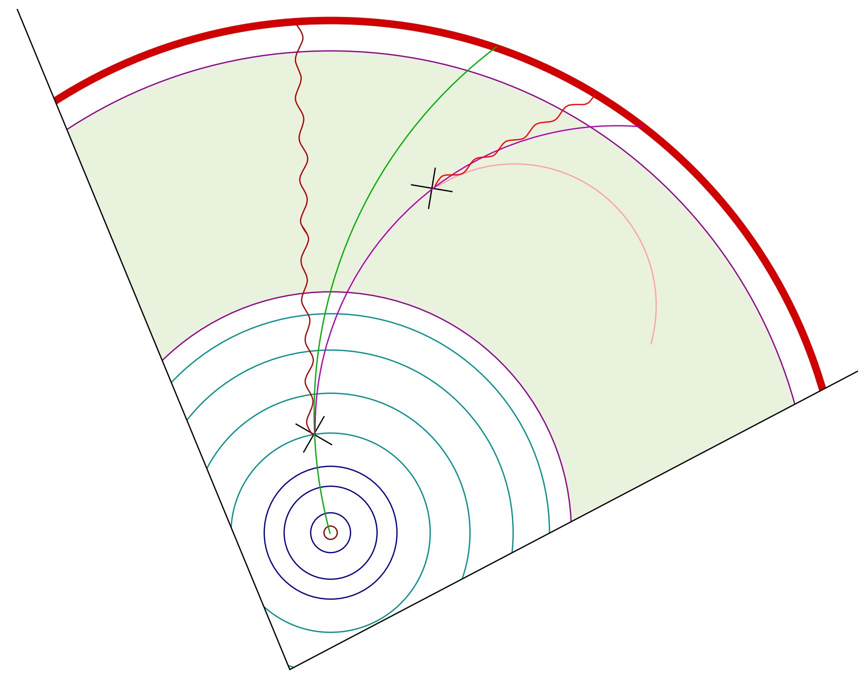
hard bremsstrahlung after a good p_T measurement

Unknown (M0): all cuts failed

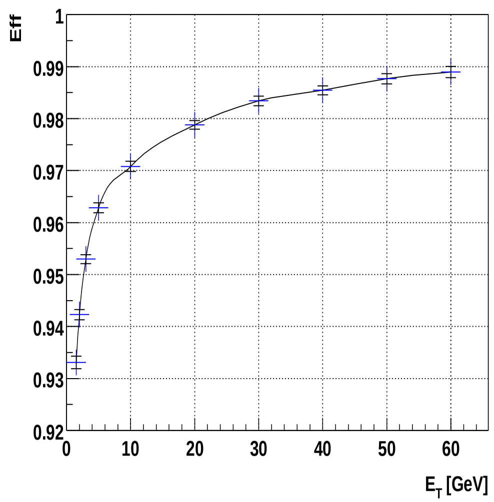
[3% at $p_T = 2\,\mathrm{GeV}$]

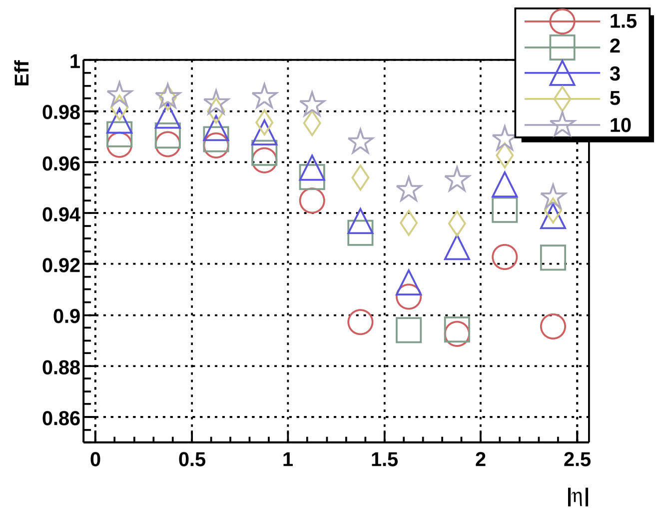
relevant for $p_T \lesssim 20\,\mathrm{GeV}$

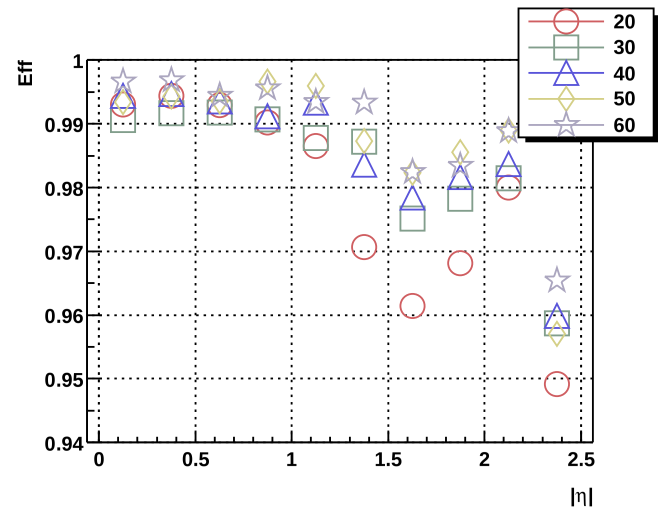
occurs due to multiple scattering



Efficiency as a function of p_T and η:

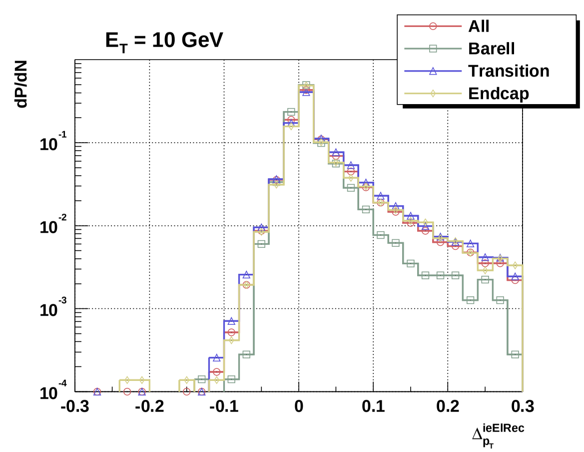


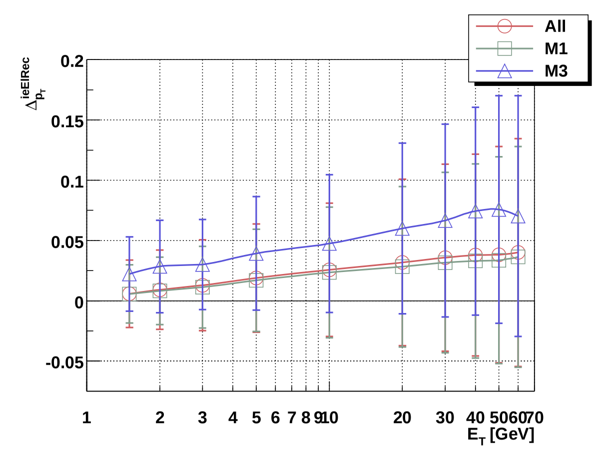




Improvement of the p_T measurement:

$$\Delta_{p_T}^{\texttt{ieElRec}} = \frac{|p_T^{\mathrm{true}} - p_T^{\texttt{iPatRec}}| - |p_T^{\mathrm{true}} - p_T^{\texttt{ieElRec}}|}{|p_T^{\mathrm{true}}|}$$

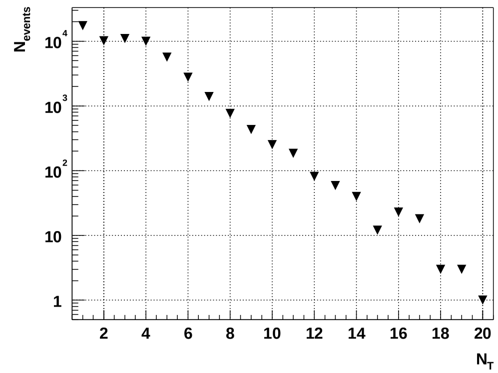


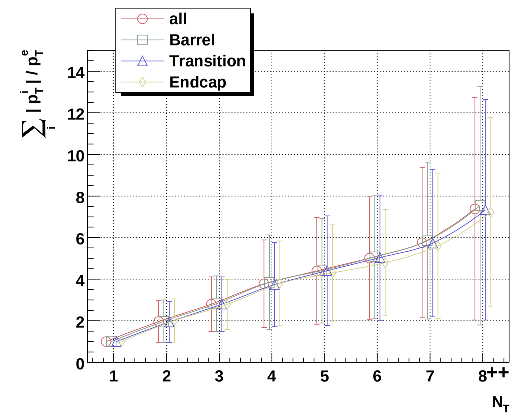


transverse impact parameter resolution likewise improved

Electrons in jets: studied on $B^0 \to J/\Psi \to ee$ sample: $p_T > 2\,\mathrm{GeV}$, $|\eta| < 2.5$; $\sim 63\,000$ events

Different track multiplicities (up to 8) available
multiplicity: charged particles ($p_T > 1\,\mathrm{GeV}$)
contained within HCAL cluster ($\pm 2 \times$ rms)



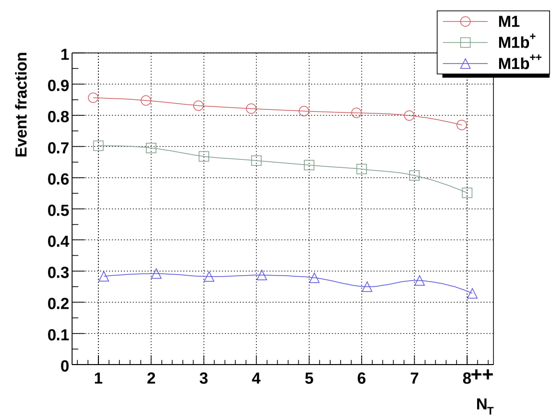


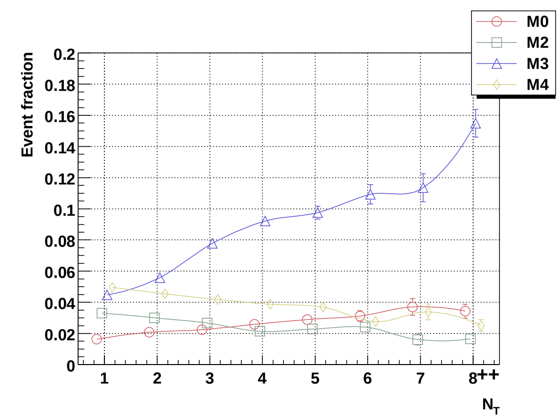
No drop in the `ieElRec` efficiency observed

Migration between ID/ECAL match types:

↗ **M3** ($\sim 10\%$), **M0** ($\sim 2\%$)

↘ **M1** ($\sim 8\%$), **M4** ($\sim 2.5\%$), **M2** ($\sim 1.5\%$)





No degradation of ID performance ⇒ ECAL pollution

Additional energy from jet produces new EM clusters for $E_T < 4\,\mathrm{GeV}$

→ most of the resurrected clusters give poor matches

→ some previously good matches are spoiled

Effects of pile-up: high luminosity $\rightarrow \sim 23$ soft hadronic interactions per bunch crossing

7.5 charged (0.64 for a $p_T > 1\,\mathrm{GeV}$ cut) $\oplus$ 9 neutral particles (90% photons, mean $E_T = 235\,\mathrm{MeV}$) per unit η per event

problem for sub-detectors with long signal collection times: TRT ($\sim 60\,\mathrm{ns}$ + poor granularity), ECAL ($\lesssim 500\,\mathrm{ns}$)

ECAL efficiency: increased for $p_T < 5\,\mathrm{GeV}$

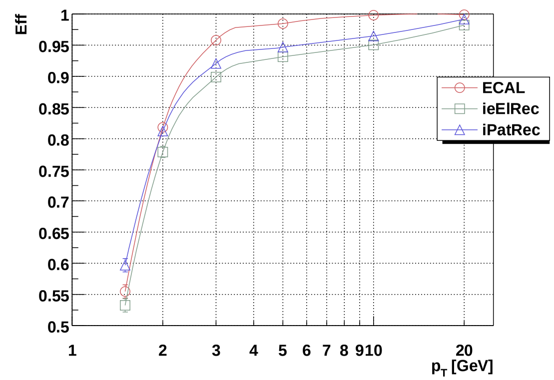
32% at $1.5\,\mathrm{GeV}$, 10% at $2\,\mathrm{GeV}$, $\sim 1\%$ at $3\,\mathrm{GeV}$

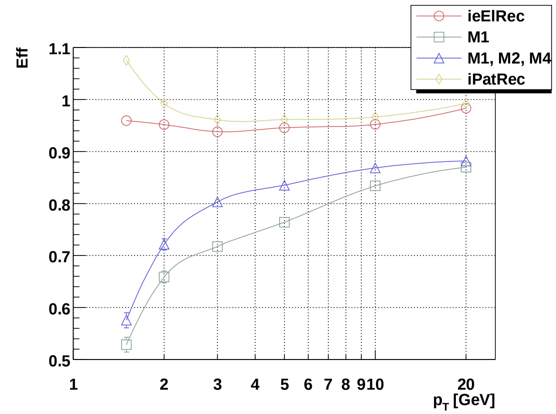
Relative to the ECAL: `iPatRec` too efficient

road $\Delta\varphi \times \eta = 45° \times 0.1$ around ECAL used

All things considered: M1 efficiency drops

5% $p_T \leq 5\,\mathrm{GeV}$, $\sim 2\%$ at $p_T = 10\,\mathrm{GeV}$



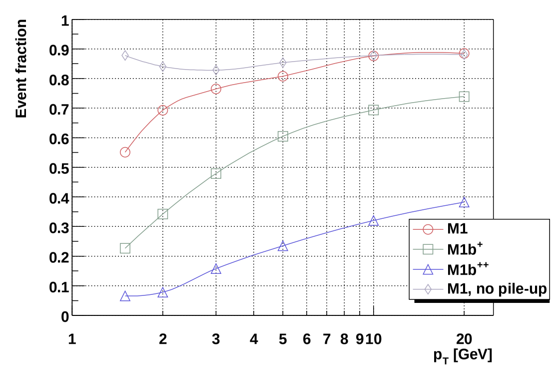


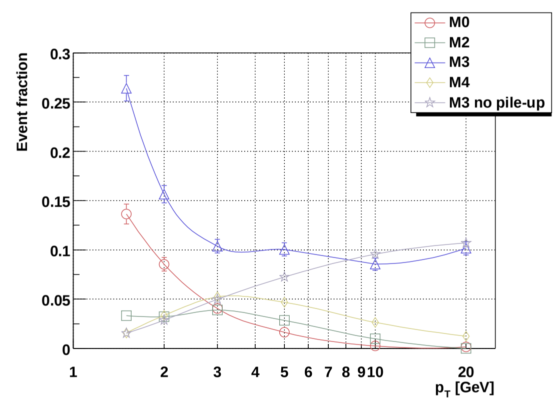
Newly reconstructed EM clusters $\oplus$ lost from **M1**:

M0: uncorrelated track / EM cluster

M3: poor ID measurement (signifies early brem)

additional deposition of energy in the vicinity of the *true* EM cluster





Distributions of E_T/E_T^{true} for different match types support the statements

Additional noise due to pile-up $\sim 100\,\mathrm{MeV}$

$B^0 \to J/\Psi \to ee$: physics $\sin 2\beta$, ECAL calibration; generation cuts: $p_T > 2\,\mathrm{GeV}$, $|\eta| < 2.5$; $\sim 30\,000$ events

Reconstruction efficiency studied as a function of $m_{J/\Psi}$ cut and *pion ambiguity*

40% ↗ to 78%; 65% for a 10% $m_{J/\Psi}$ cut and a reasonable A_π

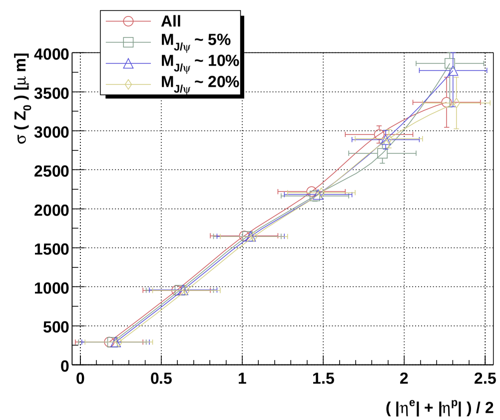
All secondary vertex parameters were studied

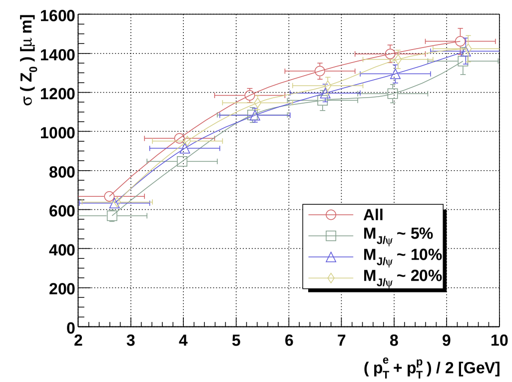
e.g., $\mathbf{Z_0}$ resolution → z-coordinate of the vertex

$\sigma(Z_0) \approx 1.2\,\mathrm{mm}$ compare to $\sigma(z) = 55.6\,\mathrm{mm}$

linear degradation with avg η

a factor 2 decrease over the p_T range

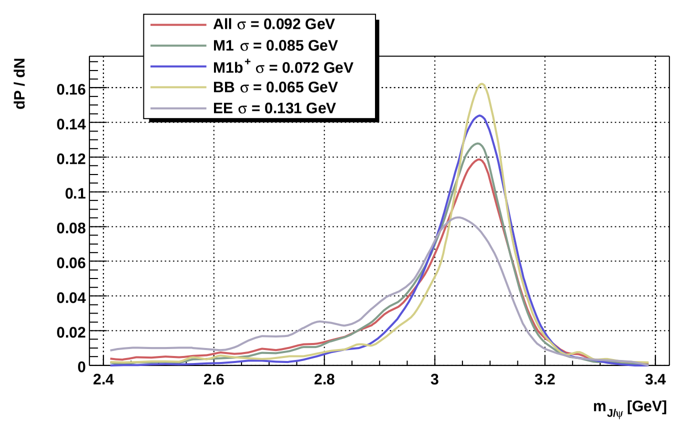


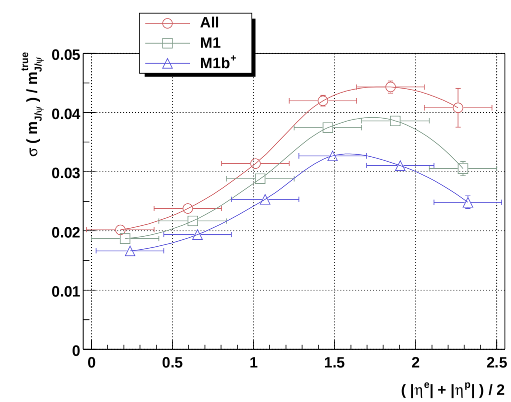


$\mathbf{m_{J/\Psi}}$ reconstruction:

barrel .vs. end-cap & **All** .vs. **M1**

avg $|\eta|$ dependence of $m_{J/\Psi}$ resolution





Compared to the TDR results: $m_{J/\Psi}$ resolution improved by 25% ⊕ tail content reduced by a factor of 2

$Z^0 \to ee$: basis of stand-alone ECAL calibration;

generation cuts: $|\eta| < 2.5$ and $p_T > 5\,\mathrm{GeV}$; 30 000 events

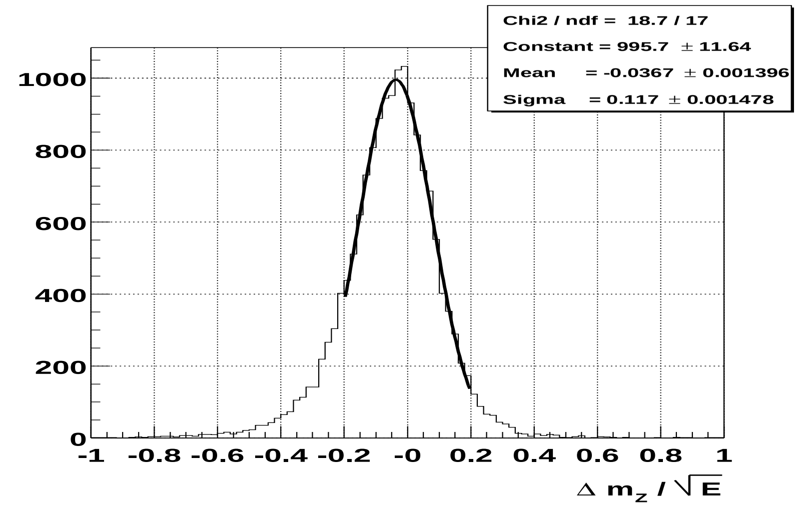
ID provides: vertex parameters

- tags events with a hard FSR or early bremsstrahlung

Z^0 vertex parameters studied

Comparison with the TDR:

- realistic magnetic field
- resolutions comparable **but** tail content reduced



$H \to ZZ^{(\star)} \to 4e$:

generation cuts: $|\eta| < 2.5$ and $p_T > 5\,\mathrm{GeV}$; 10 000 events for each of m_H=130, 150, 180, 200 GeV

For low m_H ID can contribute to $m_{Z^\star}$ reconstruction

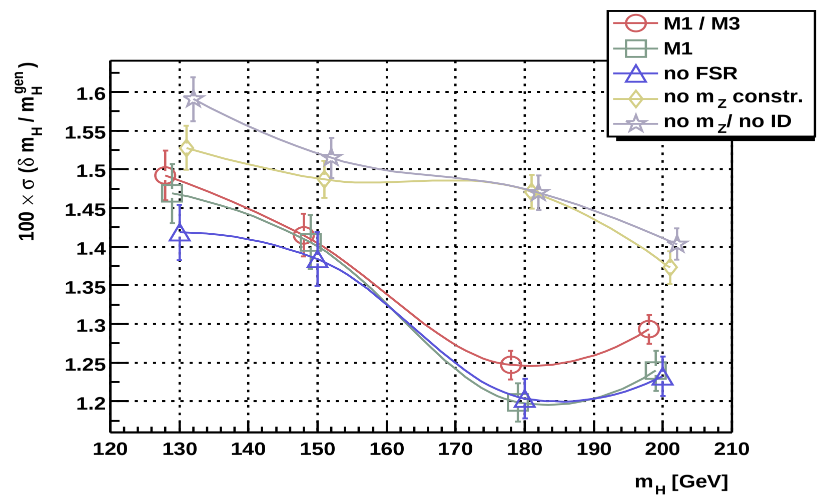
Study of z_0 and a_0 of individual e's

- background rejection ($Z^0 b\bar{b}$ and $t\bar{t} \to b\bar{b}W^+W^-$)

Z^0–$Z^{0(\star)}$ opening angle

m_H reconstruction:

- effects of FSR, early bremsstrahlung and m_{Z^0} constraint
- resolutions comparable to TDR; efficiency can be improved



Conclusions:

usage of an appropriate algorithm results in 5% increase of electron reconstruction efficiency
- almost insensitive to high-luminosity pile-up and the presence of jets
- all but the hardest bremsstrahlung occurrences can be tagged
  - $\rightarrow$ for $p_T \gtrsim 20\,\mathrm{GeV}$ also recuperated using the ECAL measurement

Pixel detectors and inner SCT layers crucial to a reliable electron reconstruction and identification
- every effort should be made to keep these layers operational

Physics analysis:

Increase of efficiency: $\sim 4\%$ per electron

Better tagging of events with a hard FSR or an early bremsstrahlung

Improvement of p_T measurement and transverse track parameters
- improves physical parameters (e.g., invariant mass resolution)
- better background rejection and/or b-tagging

Future:

Compare/update to the new detector layout $\Rightarrow$ expect $\sim 50\%$ increase of irrecoverable early bremsstrahlung

Follow `iPatRec`'s migration into Athena

Publish a scientific note covering all aspects of electron reconstruction
- single electron efficiencies & resolutions
- resolutions of secondary vertex quantities