The TB 2008
Energy Scan Puzzle

Zbyněk Drásal, Peter Kodyš and Peter Kvasnička
Institute of Particle and Nucelar Physics,
Charles University, Prague

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Contents

- The E-scan experiment and what was the problem
- The suspicious low energy beams
- Low-energy breakdown of resolution estimators
- Improvements
- Conclusions

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Introduction : Energy Scan at TB 2008

- **Results:**
  - Pions with energies of 120, 100, and 80 GeV obtained by selection with a magnet; lower energy pions obtained using a secondary target
  - Number of tracks per event dramatically reduced at 60 GeV, practically no tracks at 40 and 20 GeV
  - Resolutions dramatically change at 60 GeV

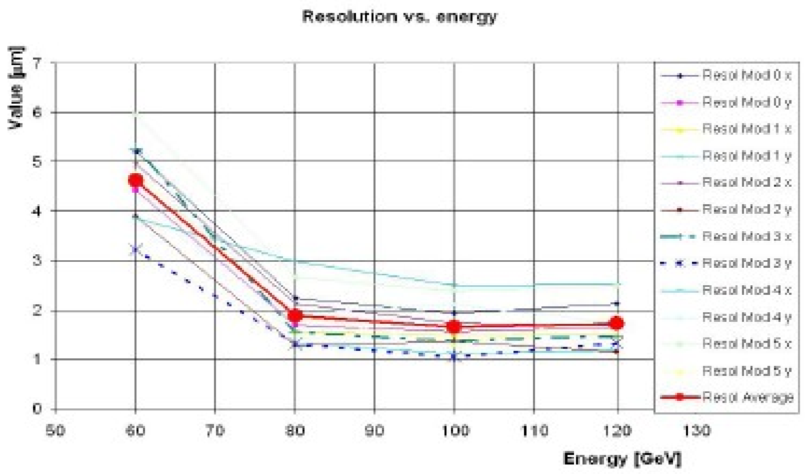

Figure 19.2: Energy scan: Resolutions vs. energy for all modules. The thick line is average of all modules.

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The Suspicious Low Energy Beams

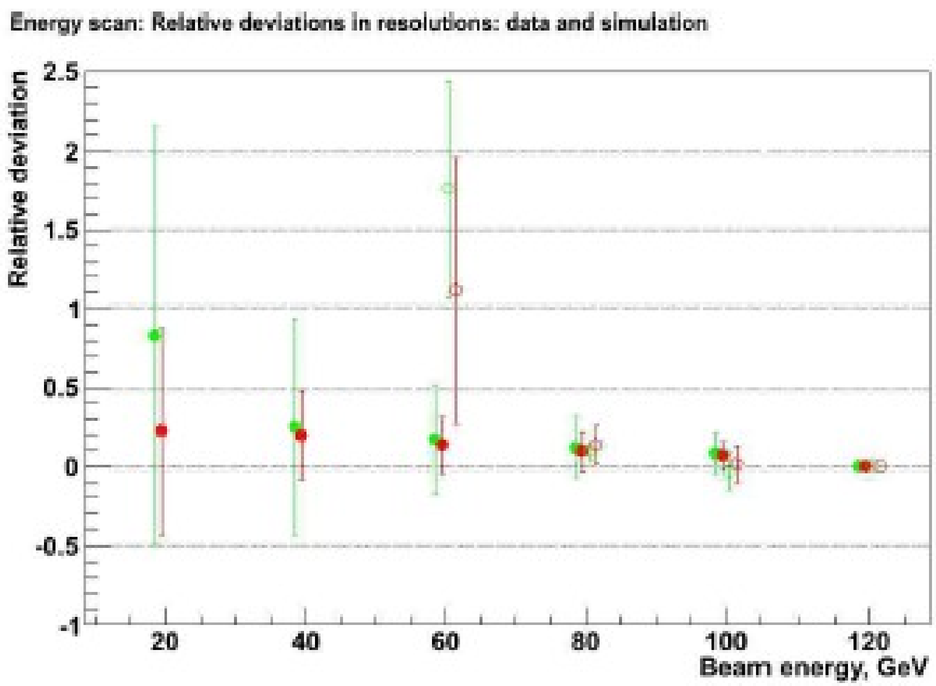

Figure 19.4: Energy scan: Relative deviations of resolutions, comparison of data and simulations. Solid circles are simulations, hollow circles are data; green - "diagonal" estimates, red - ML estimates. Simulation data are the same as shown in Fig. 19.3. The plotted values are $(x_E - x_{true})/x_{true}$ for simulations, and $(x_E - x_{120GeV})/x_{120GeV}$ for data.

The Suspicious Low Energy Beams

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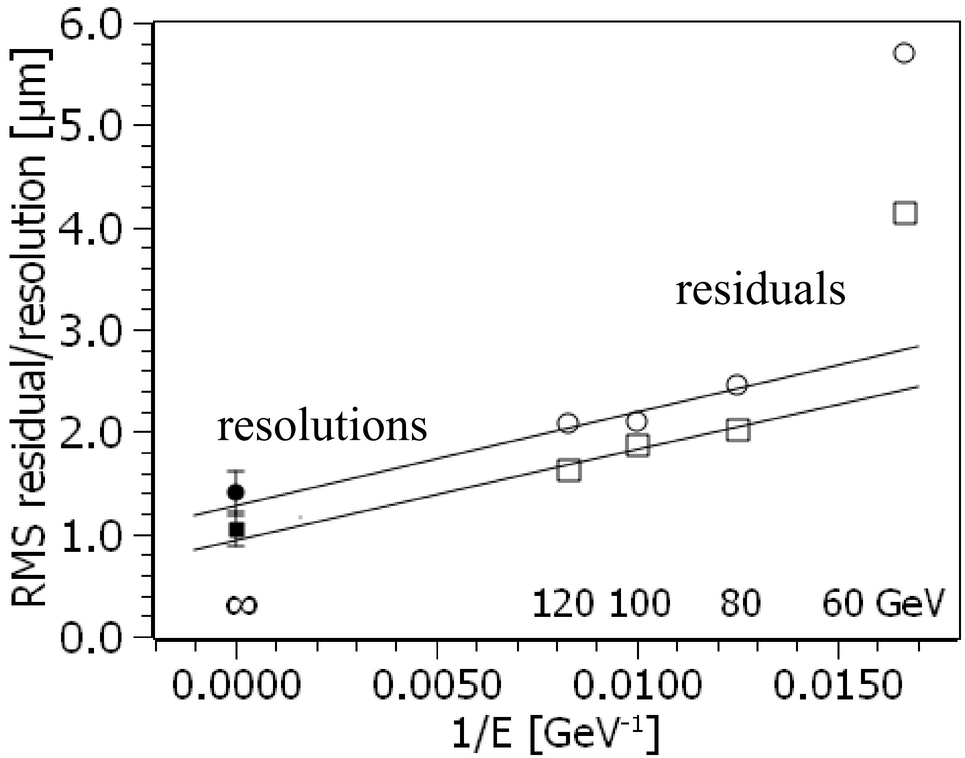

Legend: residuals, hollow; resolutions, solid;
X – circles, Y-rectangles

Residuals vs. 1/E for detector 3

•Calculated resolutions are consistent with residuals extrapolated to E→∞

•The 60 GeV points are obviously wrong (and are not included in the fit)

•The prediction of the fit for E=∞ has large error bars, as it is too far from the data points

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The Suspicious Low Energy Beams

- **What can be wrong:**
  - MC shows that
    - the resolution estimates degrade at low energies, but not so dramatically as seen in the data
    - Alignment is less precise due to larger MS and small data sample, but should not go totally wrong

Conclusion:

1. The low-energy beams must have been different from what we expected

2. If using only 120, 100 and 80 GeV, the error bars on extrapolation to $E \to \infty$ will be too big – there are only 3 points far from $E=\infty$

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Low-Energy Breakdown of Resolution Estimators

- **Resolution estimates are very poor at low energy!**
  - Even worse, the estimates break down at low energies – we often get zeroes or numeric exceptions !

So what's wrong, and can we do better?

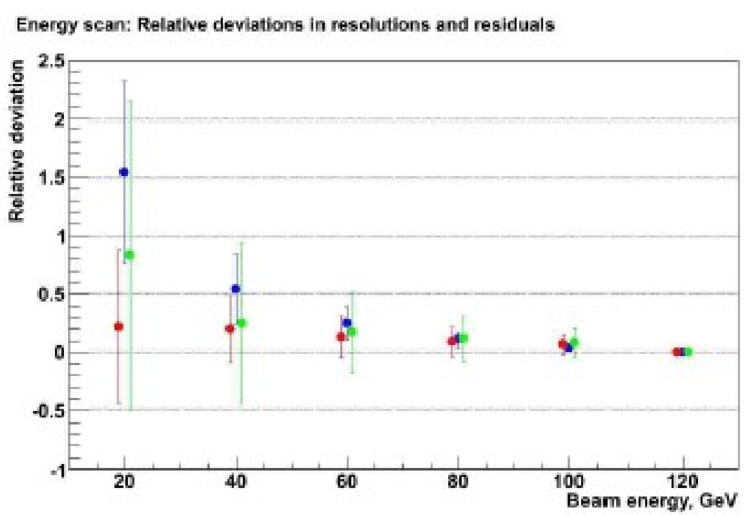

Figure 19.3: Energy scan: Relative deviations of resolutions (green - "diagonal" estimate, red - ML estimate) with energy, as seen in analysis of GEANT4 simulation data. For reference, we also plot residuals (blue). The data for each energy are based on analysis of 100 replicas of a data file containing 10,000 tracks. The plotted values are $(x_E - x_{true})/x_{true}$.

This is similarr to the plot shown previously, but there are now residuals instead of data points.
The plot shows that as residuals increase towards low energies, also their variability increases.
But primarily, it shows that resolution esitmates DEGRADE SERIOUSLY

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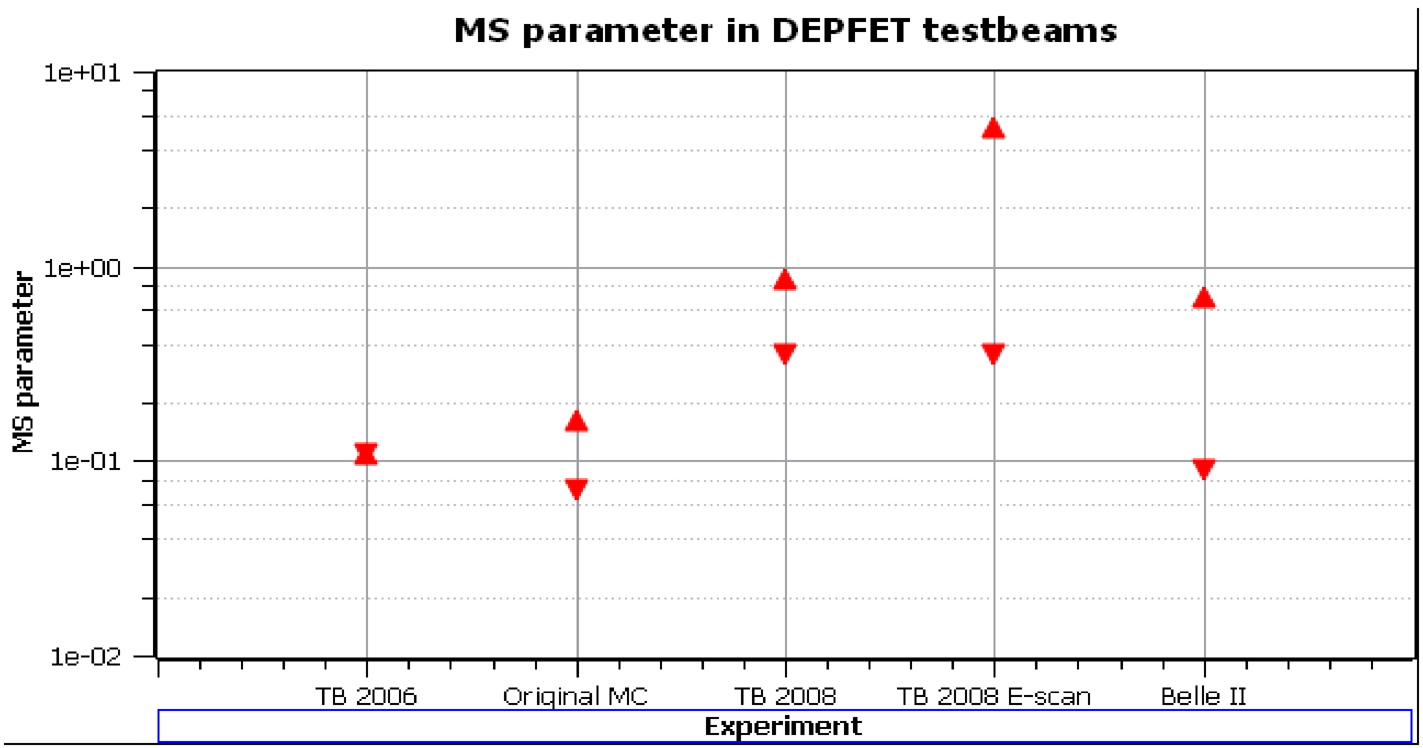
Low-Energy Breakdown of Resolution Estimators

- **Why didn't we see before?**
  - Scattering parameter: Multiple scattering relative to detector resolution:

MS parameter = (sigma MS) * (distance between detectors) / (detector resolution)



Belle II: 0,5 – 4 GeV, resolution 10 µm, distance 1 cm

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Low-Energy Breakdown of Resolution Estimators

- **With energy scan, we are in quite extreme range.**
  - BUT WE CAN DO BETTER !!!

Ways to go:

1. Improve representation of multiple scattering for better estimates and better MC simulations

2. Improve resolution estimates:

- use all available data

- protect against overfitting

Improvement: MS representation

- **To estimate resolutions, we have to somehow subtract or deconvolve multiple scattering from residuals.**
  - So far, we lived with Gaussian approximation to MS distribution and with Moliere/Highland formula. For high scattering regimes, we need something better,
  - We cannot treat the long tails with cuts – MS deviations sum together, so we would need too restrictive cuts! (meaning more than 2 sigma!!!)
- **We also rely on an appropriate modeling of MS by MC – specifically, by GEANT.**
  - But this is not default!!!

Improvement: MS representation

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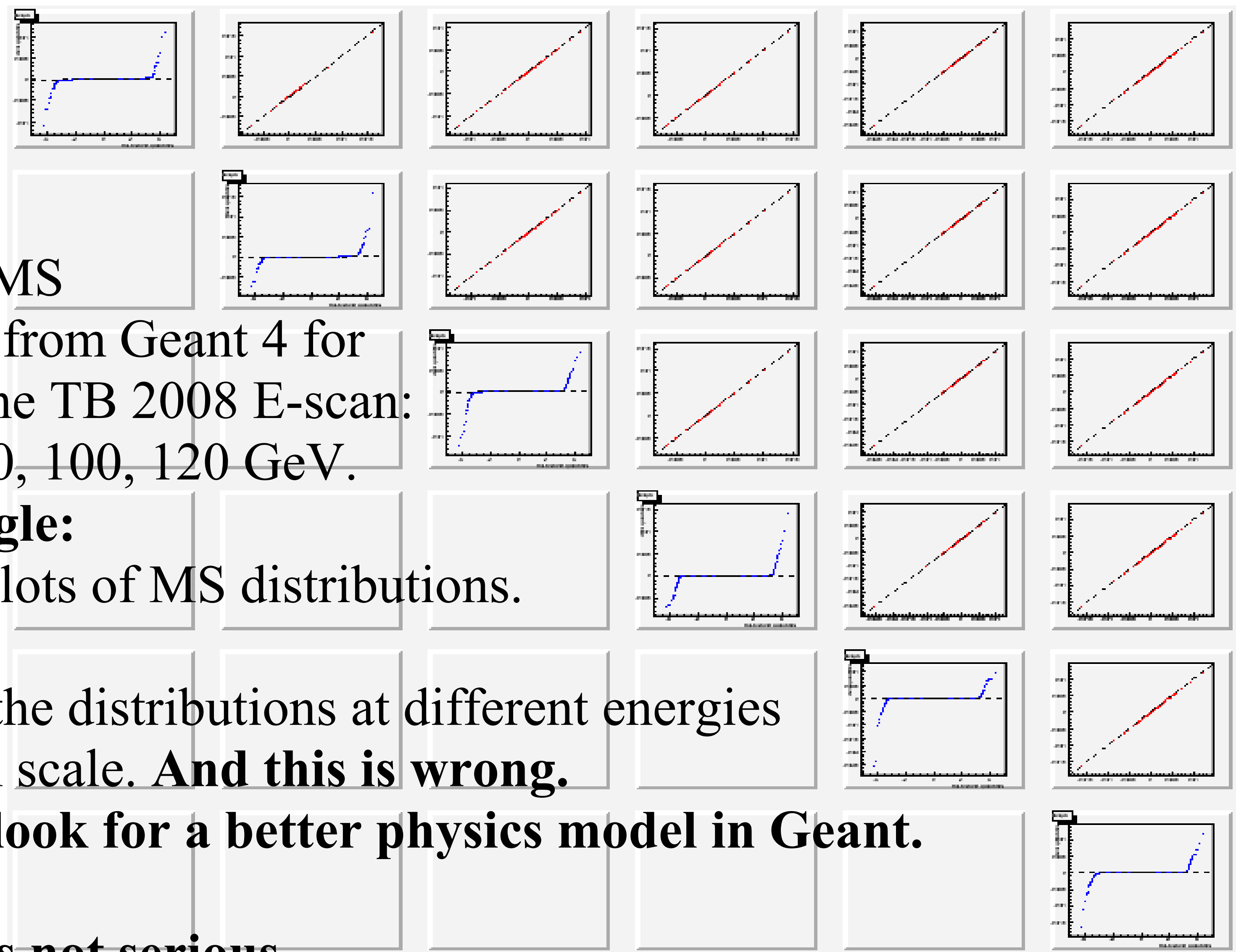

Diagonal:
QQ plots of MS distributions from Geant 4 for energies of the TB 2008 E-scan: 20, 40, 60, 80, 100, 120 GeV.
Upper triangle:
mutual QQ plots of MS distributions.

Apparently, the distributions at different energies differ only in scale. **And this is wrong.**
We have to look for a better physics model in Geant.

Anyway, it is not serious.

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Improvement: MS representation

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  - So far, we lived with Gaussian approximation to MS distribution and with Moliere/Highland formula. For high scattering regimes, we need something better,
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Moliere (98%) ~ $0{,}0136 / p\, (d/X_0)^{1/2}(1+0{,}038 \ln(d/X_0))$

Total (100%) ~ $0{,}015 / p\, (d/X_0)^{1/($

- **We also rely on an appropriate modeling of MS by MC – specifically, by GEANT.**

  - But this is not default!!!

Improvement: Resolution Estimates

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We calculate detector resolutions from the covariance matrix of fit residuals. Each fit residual is a linear combination of detector measurement errors and multiple scattering deflections. Therefore, residual covariance is a linear combination of measurement error covariance and multiple scattering covariance:

$$cov(\hat{u}^c) \equiv \left\langle (u^c - \hat{u}^c)(u^c - \hat{u}^c)^T \right\rangle = H(G\Sigma^2 G^T + \Delta^2)H \qquad 1)$$

where:

u are local hit coordinates

H is a projector to the residual space. If the track is fitted with a line, $u = F\beta$, with F the factor matrix and β the vector of line intercepts and slopes, then H$= I - F(F^T F)^{-1} F^T$

G describes the geometry of multiple scattering. In the simplest case, $G_{ij} = (z_j - z_i)_+$ with z_i being the z coordinate of the i-th detector

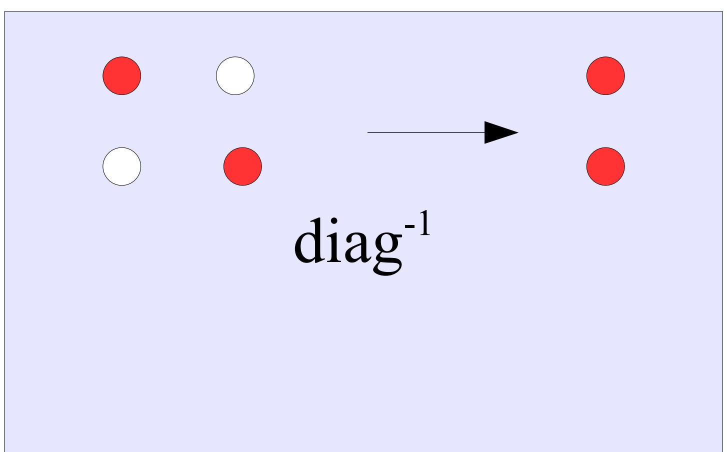
Σ and Δ are diagonal matrices of multiple scattering deflections and squared detector resolutions

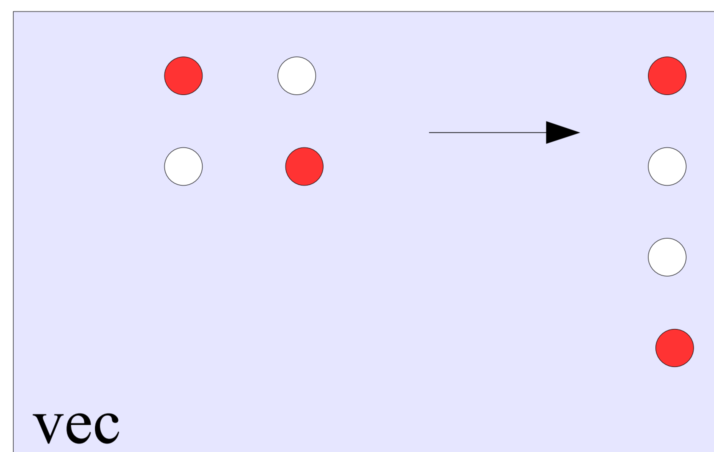
Improvement: Resolution Estimates

$$cov\left(\hat{\mathbf{u}}^c\right) \equiv \left\langle \left(\mathbf{u}^c - \hat{\mathbf{u}}^c\right)\left(\mathbf{u}^c - \hat{\mathbf{u}}^c\right)^T \right\rangle = \mathbf{H}\left(\mathbf{G}\boldsymbol{\Sigma}^2\mathbf{G}^T + \boldsymbol{\Delta}^2\right)\mathbf{H}$$

(This is the same formula as on the previous slide.)

- The multiple scattering distribution is known, so we can express detector resolutions in terms of residual correlations and RMS multiple scattering deflections.
- To do this, **we vectorize the equation** (take *diag*$^{-1}$ or *vec*) and treat it as a linear regression problem.





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Improvement: Resolution Estimates

- **To not go into maths, we did two things:**
  - Use correlation of residual correlations (4th order moments) in calculation of resolutions
    - Due to different distances between detectors, the residuals contain different proportion of MS.
    - There is very little effect at high energies, where the proportion of MS is low, but is a dramatic improvement at low energies.
    - The correlation-correlation matrix is estimated from the data using a reasonable cut on residuals. Otherwise, the calculation is model- (in particular, MS-model-) independent.

Improvement: Resolution Estimates

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- (the second thing of the two)
  - **Protect against overfitting:** At high MS, a good estimator should give up providing estimates of individual resolutions and give some generalized value for all detectors.
    - The „conservative“ estimator giving only one resolution for all detectors is more biased, but has less variance than the full resolution estimator.
    - Thus, we can improve the full resolution estimator by mixing it with the conservative estimator, with the mixing coefficient being chosen to minimize overall variance of the mixture estimator.
    - This has only minor effect at high energies, where the full resolution estimator dominates.

Improvement: Resolution Estimates

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- **Outlook**
  - The resolution estimate is becoming more ad-hoc. This is a price to pay when one want precise estimates.
  - A maximum-likelihood procedure would be preferable, but it is not straightforward how to implement things like prevention against overfitting and conditioning on covariates.
  - On the other hand, implementation of correct MS distribution is straightforward, as well as implementation of any cuts on residuals. However, we don't actually know the distribution of detector measurement errors; we only know that for serious reasons it will not be gaussian!
  - So this is for further thinking.

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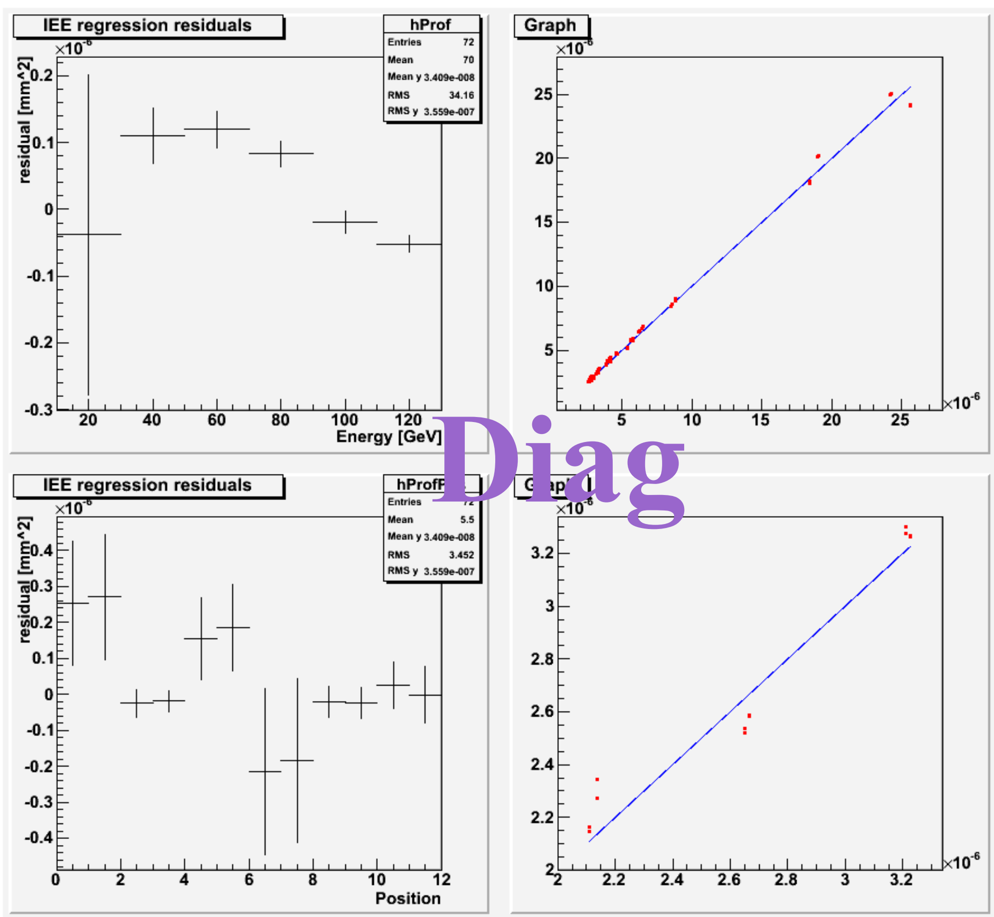
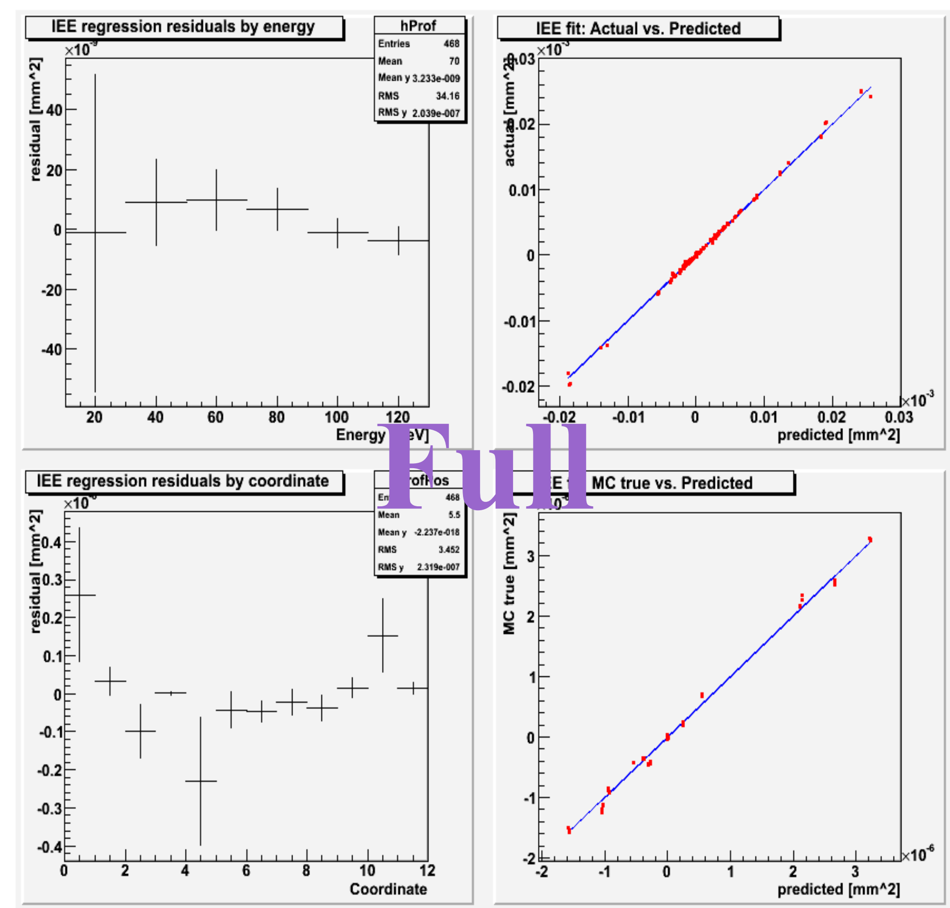
Improvement: Some results

Reconstruction of MC energy scan, 10000 tracks per energy (20 to 120 GeV). All resolutions set to 2 μm. Right: deviations of extrapolated correlations from presets; left: Linearity of the model and comparison with theoretical covariance matrix.





Improvement: Some results

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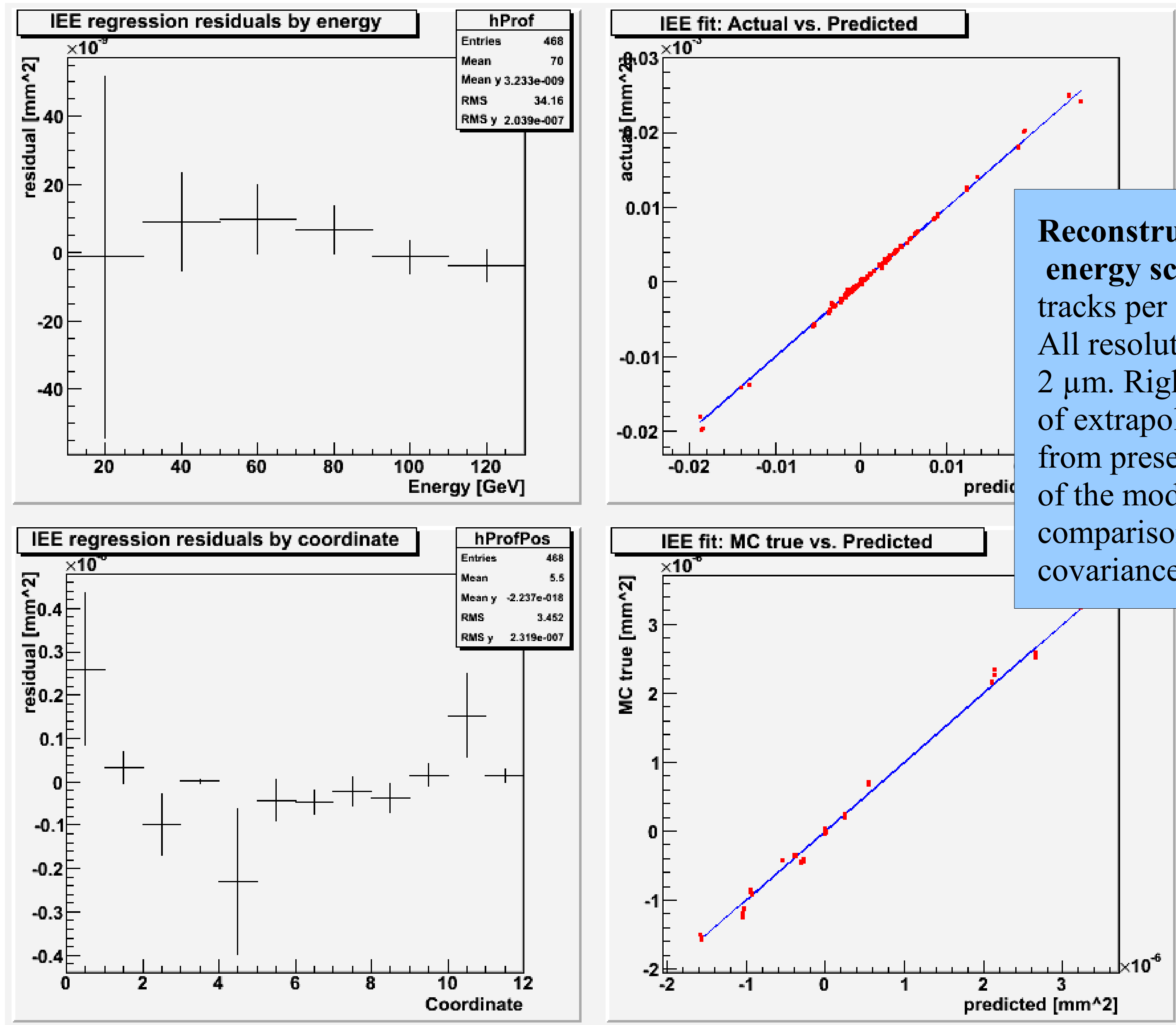
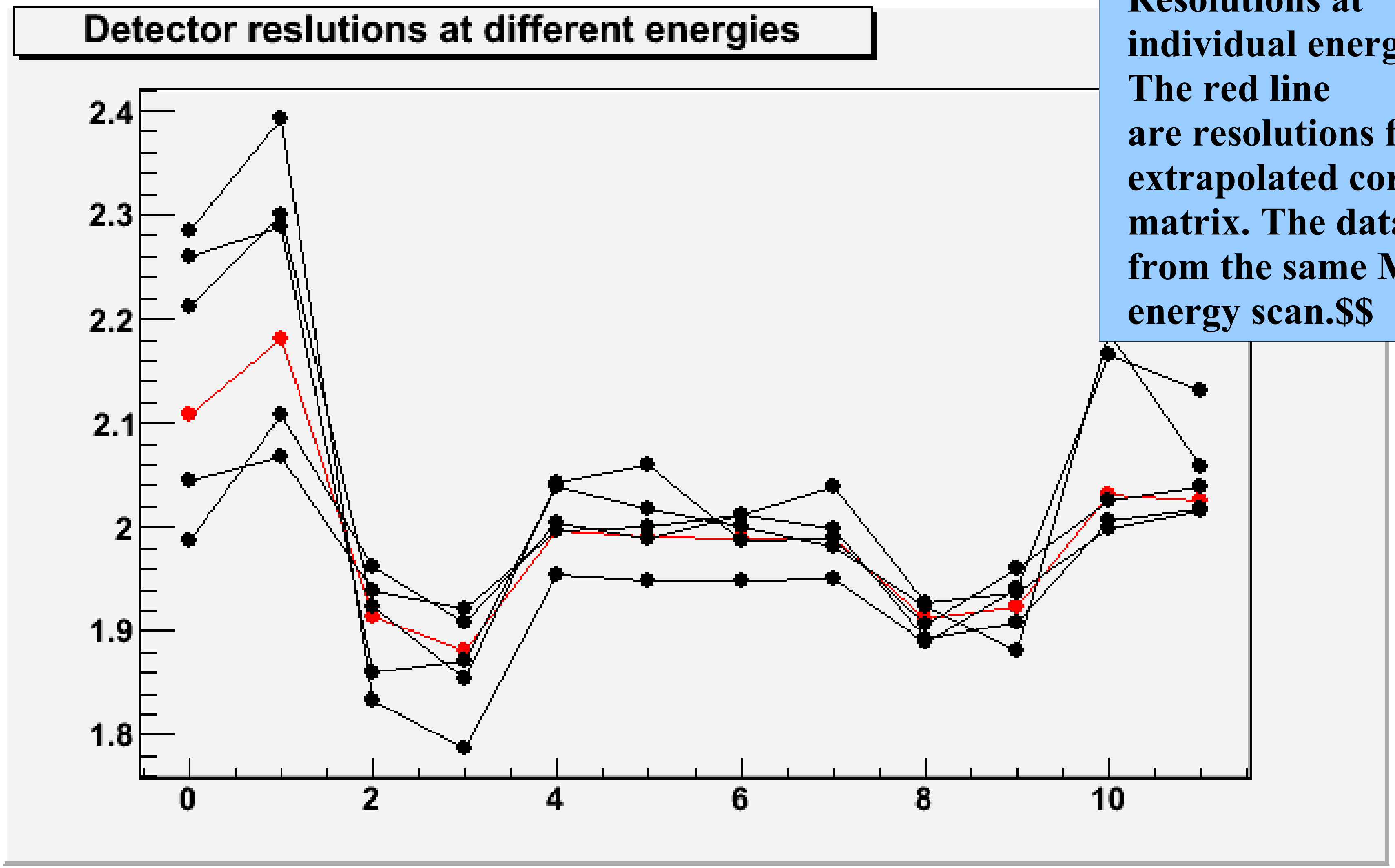


Reconstruction of MC energy scan, 10000 tracks per energy. All resolutions set to 2 μm. Right: deviations of extrapolated correlations from presets; left: Linearity of the model and comparison with theoretical covariance matrix.

Improvement: Some results



Resolutions at individual energies. The red line are resolutions from extrapolated correl. matrix. The data are from the same MC energy scan.$$

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Conclusion

- **TB 2008 data on E-scan**
  - Data for 60 GeV and below apparently not usable
  - Other data are consistent, but there are only 3 energies, too little for a meaningful comparison of extrapolated and „direct" resolutions.

Degradation of resolution estimates in high-MS regimes

- Resolution estimates can be substantially improved by proper adjsutment of the estimators.
- MS has to be modelled carefully and simulations checked for correctness of physics.

Thanks for your attention.