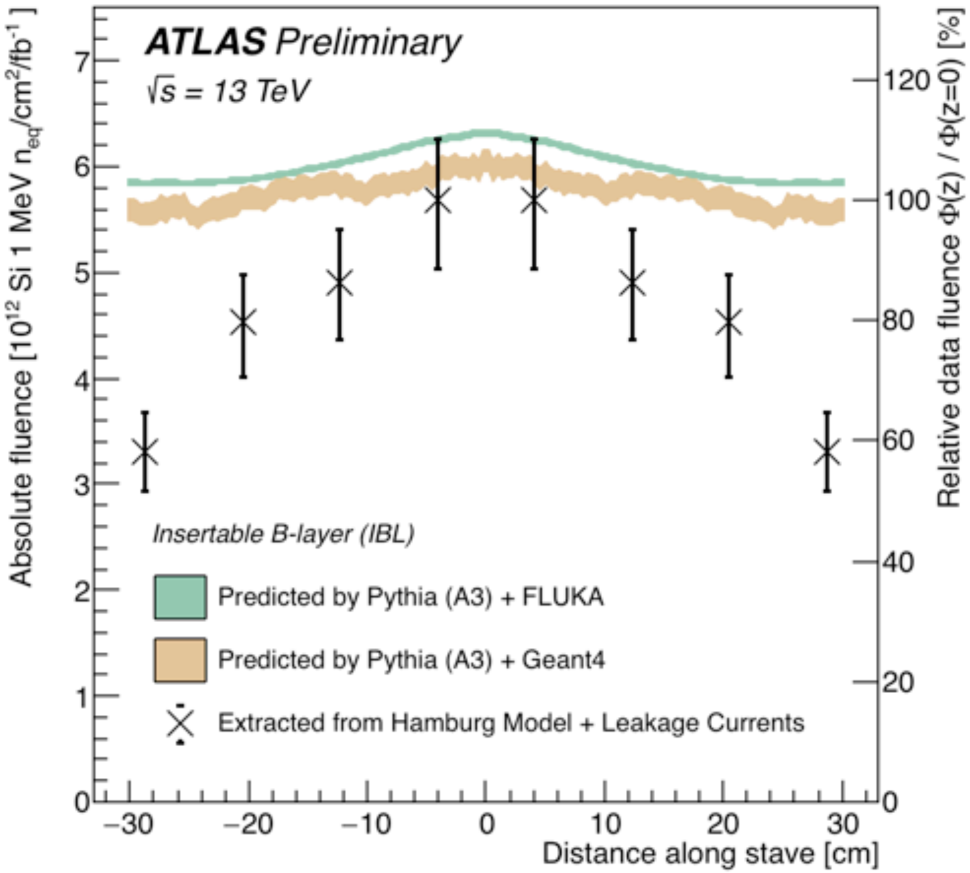
# On the uncertainties of silicon hardness factors

**M. Huhtinen, A. Manousos**

**Disclaimer: This presentation is about (very) old studies & results. It is not my intention to advertise these, but rather to invite anybody using them to exercise appropriate criticism.**

# Introduction

**A year ago, at this same workshop, we saw this plot, which compares predicted damage in ATLAS IBL sensors with measurement:**




**Its interpretation prompted an intense discussion within ATLAS**

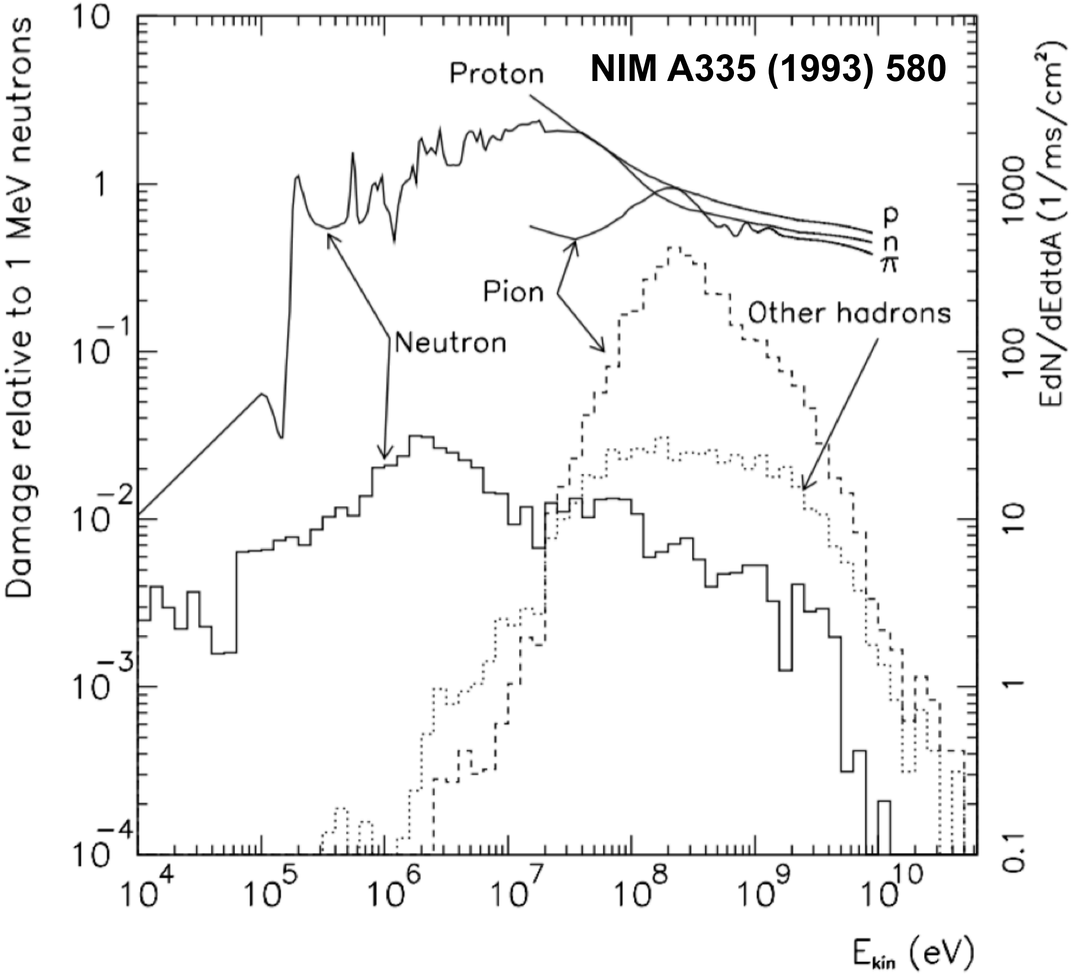
**Looking at it, one is immediately tempted to conclude that simulations agree well at z~0, but overestimate at large z**

**...and then one starts to look for possible reasons of this overestimation**

**While the right approach would be to first re-evaluate the uncertainties**

# The (very) old plot

**In the early 90ies we wanted to alert (with a simple estimate) the community to the fact that pions are likely to be the principal source of damage to LHC tracking detectors**




**→ irradiation campaign at PSI**

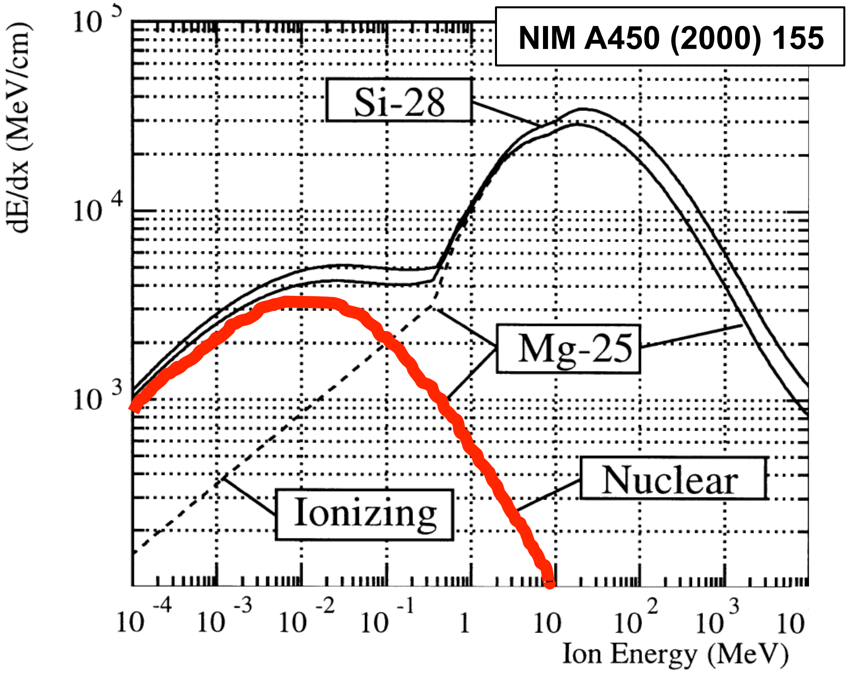
**Result: pions ~ 1 MeV n equivalent**

**Our damage curves were adopted by ROSE / RD50, implemented in FLUKA, etc**

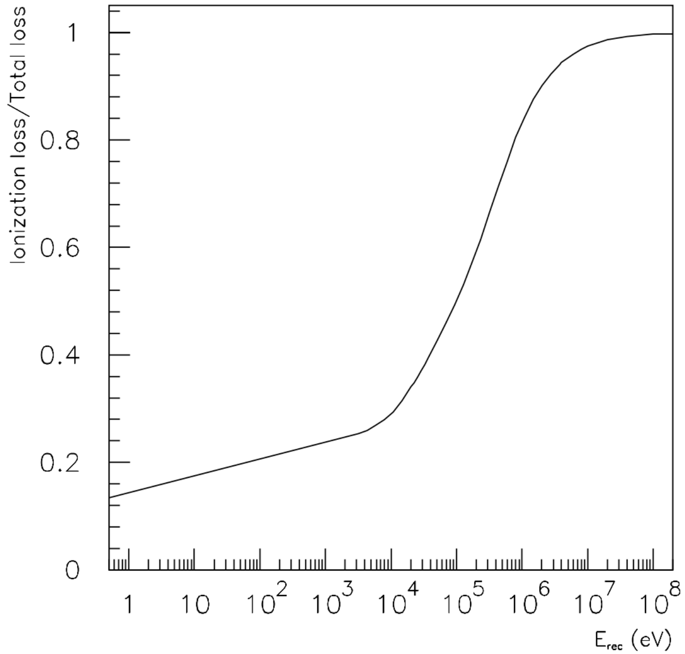
**Everybody uses them since 25 years, so they must be right.**

**" Why should I doubt them, if nobody else does...? "**

# Nuclear recoils & damage




Only a fraction of the energy loss is non-ionising




In addition, only ~45% of the $E_{NIEL}$ goes into damage (lattice dislocations), the rest is dissipated as heat (phonons).

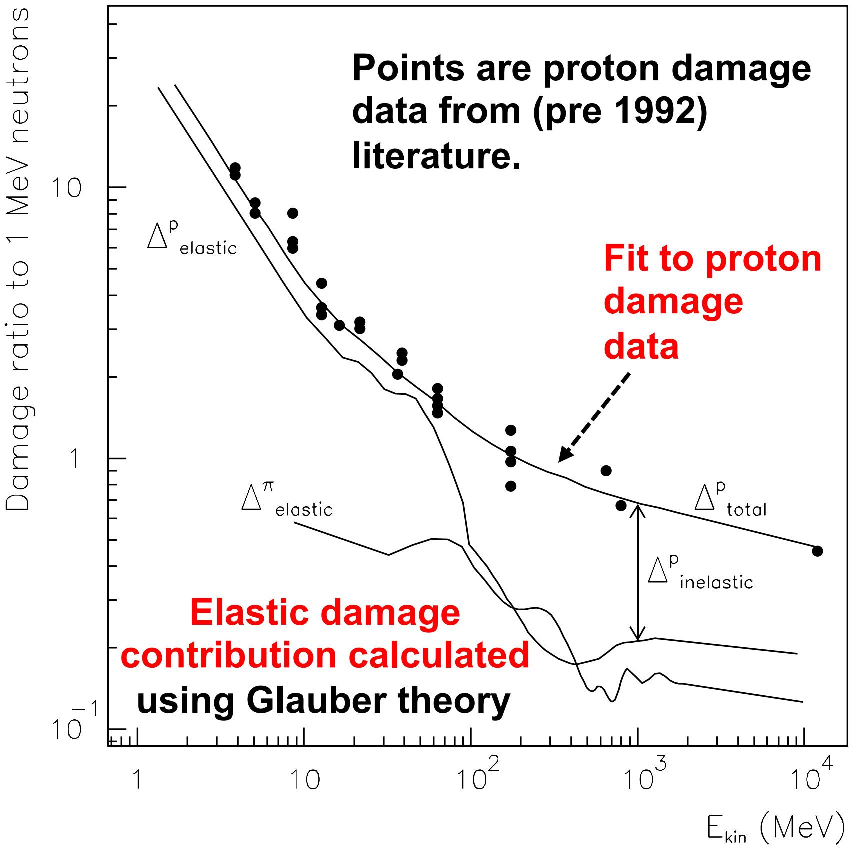
- The number of lattice defect is roughly $0.4\ E_{NIEL}/\ E_D$, where $E_D \sim 25 \pm 5$ eV for Si

In our 1993 study the total $E_{NIEL}$ was used, since the NIEL partitioning largely cancels, as will be discussed later

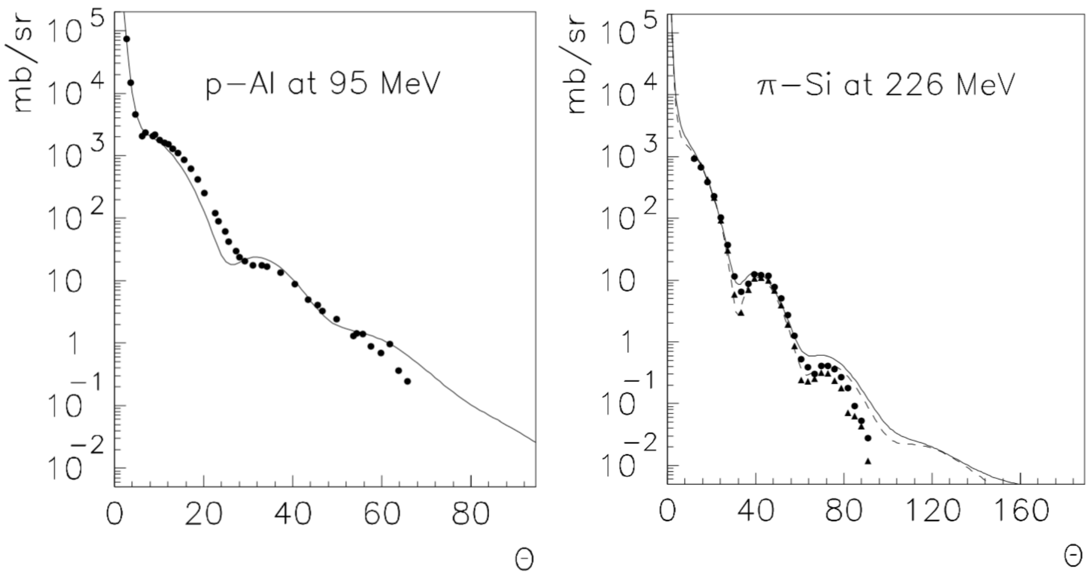
# Origin of that plot (step 2)

**We collected all proton damage ($\alpha$) data we could find in literature and fitted it.**

**Basic assumption: Inelastic p-Si and $\pi$-Si collisions give same damage at same energy. The proton/pion mass difference matters only for elastic scattering.**

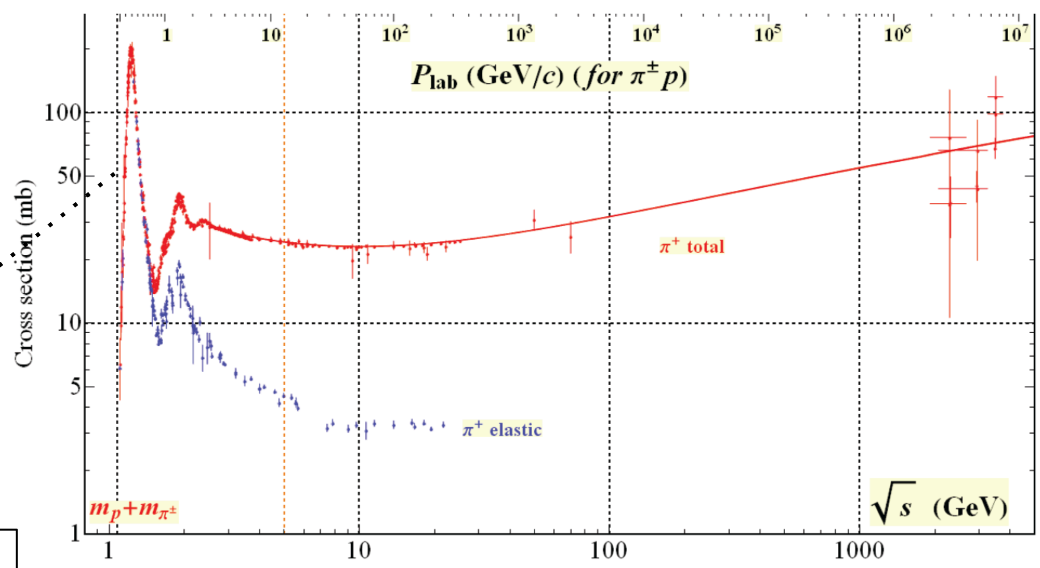



**Used Glauber theory to calculate the scattering cross sections and elastic angular distributions**

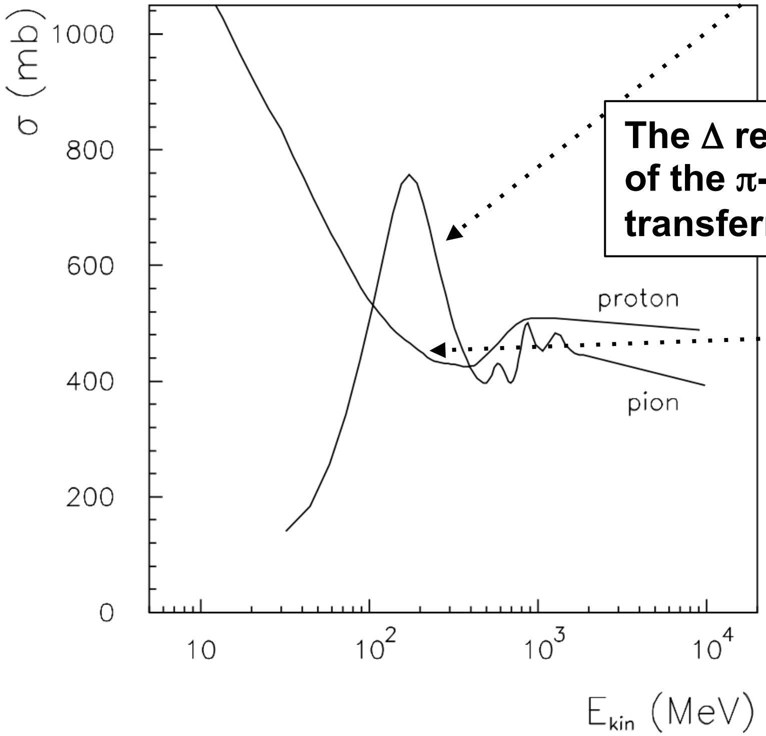


# Inelastic cross sections

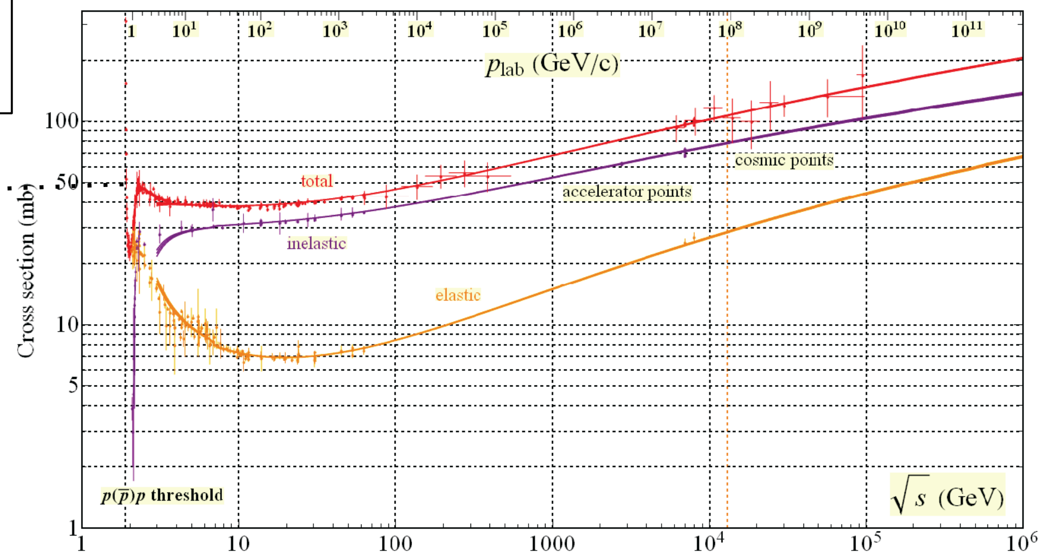
Inelastic p-p and π-p cross sections from PDG. These are the input to the Glauber theory calculations.




The resulting inelastic p-Si and π-Si cross sections




The Δ resonance of the π-p Xsec is transferred to π-Si



# Inelastic recoils

**Here it starts to get vague...**

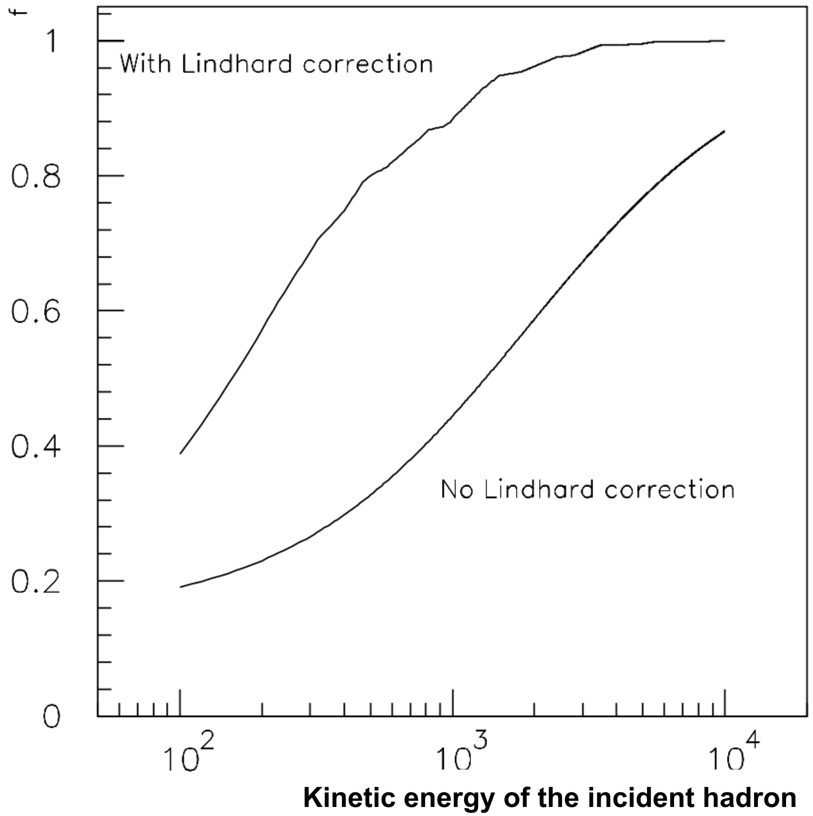
**This is the method to derive the pion damage from the fit to proton damage data:**

$$\Delta_{\pi}^{\text{total}} = \Delta_{\pi}^{\text{elastic}} + f \frac{\sigma_{\pi}^{\text{inelastic}}}{\sigma_{p}^{\text{inelastic}}} \Delta_{p}^{\text{inelastic}}$$

**Where f is derived from the assumption that p and π transfer on average 40% of their momentum to the recoil.**
**f is the ratio of the recoil energies Ep and Eπ at projectile energy E.**

$$f = \frac{E_{\pi}(E)\{1 - F(E_{\pi}(E))\}}{E_{p}(E)\{1 - F(E_{p}(E))\}}$$

**Where F is the Lindhard energy partitioning**




**Thanks to the Lindhard partitioning recoil energy differences are less significant**

# Intermediate summary

**The hardness factor presented in our 1993 paper and adopted by RD50 are**

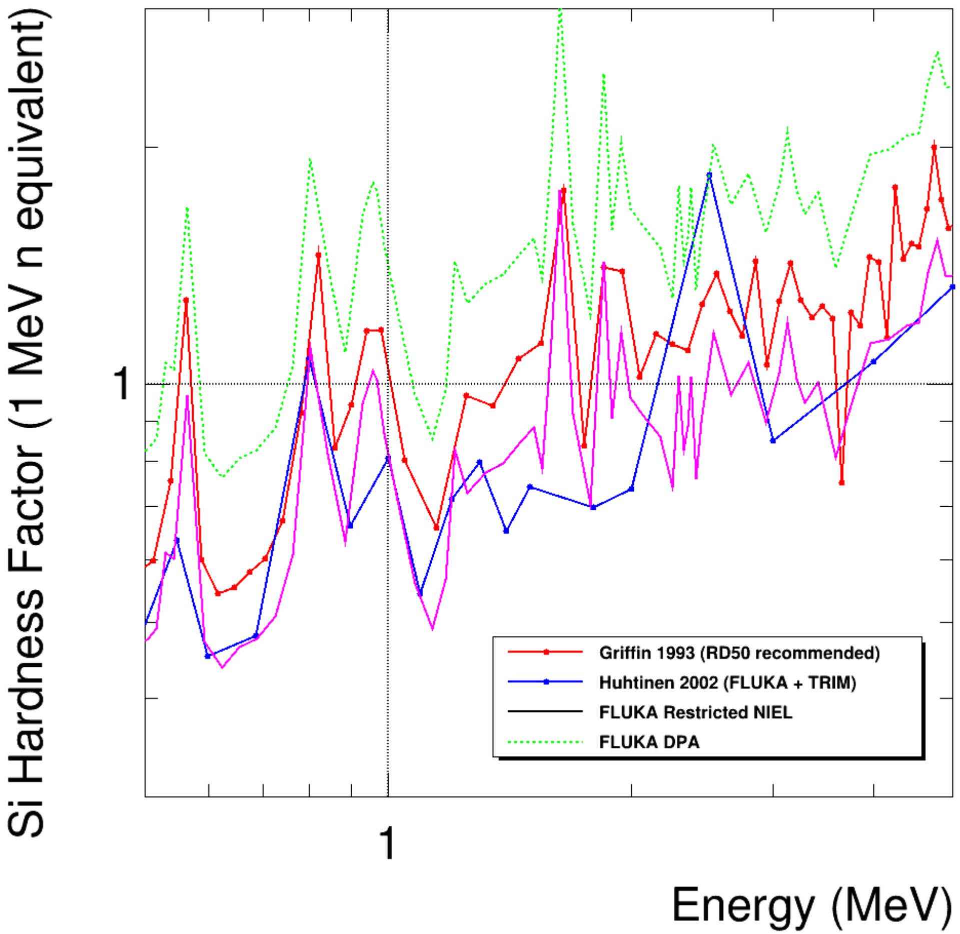
- ✧ **Fits to data (available in 1992) for protons**
- ✧ **Scaling of the proton damage fit with π-Si/p-Si cross sections for the pion damage**

**Let's now compare various hardness factor curves:**

# 1 MeV neutron equivalent

**About the most unfortunate choice one can make !**

**Probably it was historically motivated by good availability of neutron facilities**



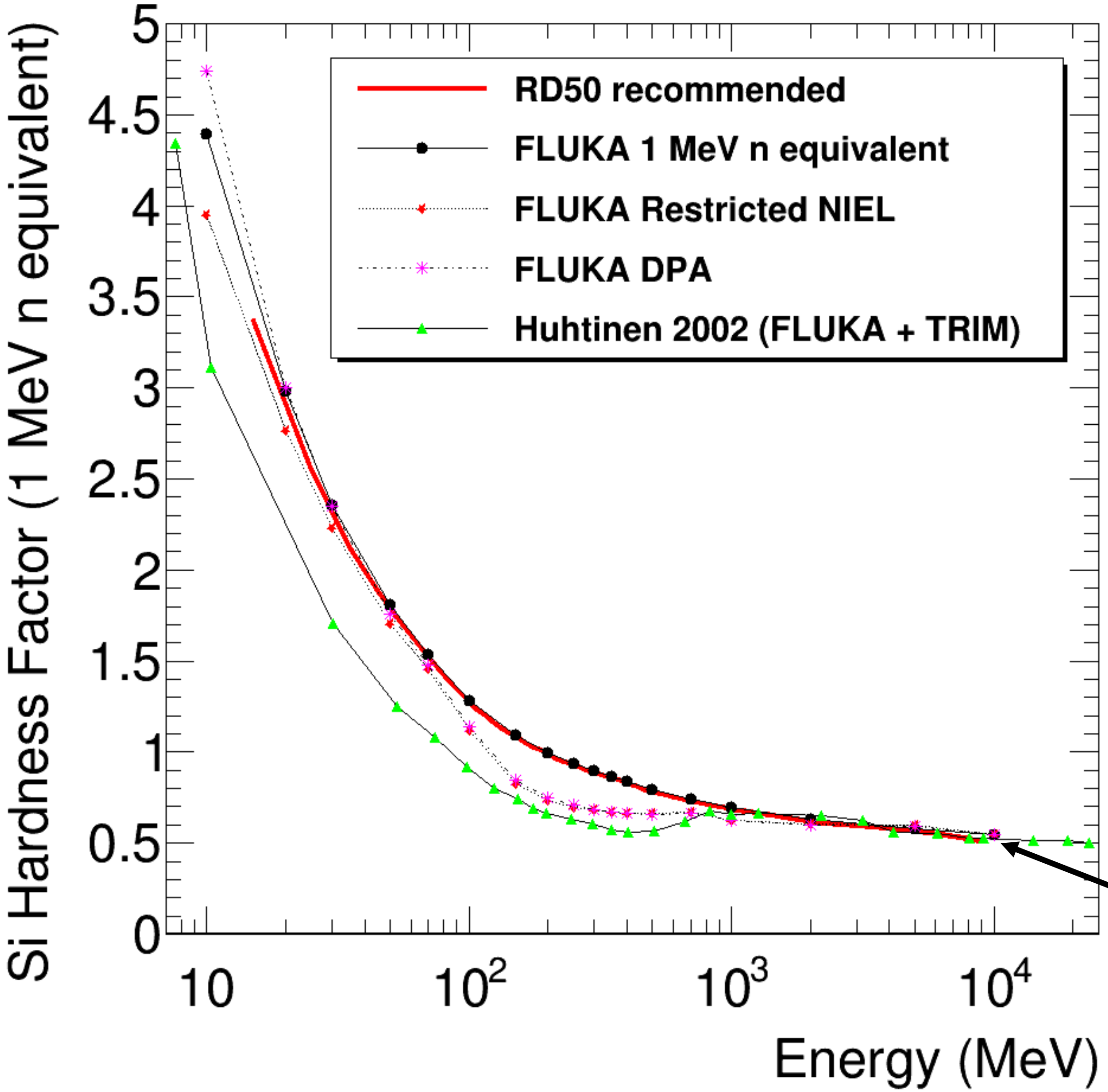

**Problems:**

- **The n-Si cross section varies by factor ~2 in the vicinity of 1 MeV**
- **Neutron spectra (esp at reactors) are broad**

**To determine the 1 MeV n equivalent in a neutron irradiation one must:**

- **Know exactly the shape of the neutron spectrum used → uncertainties**
- **Fold it with these rapidly varying damage function → more uncertainties**
- **Which are based on some assumed value of $E_D$ → further uncertainty**

# Proton hardness factors




**FLUKA restricted NIEL and DPA are mutually consistent, but lower than the data-fit between 100 MeV and 1 GeV**

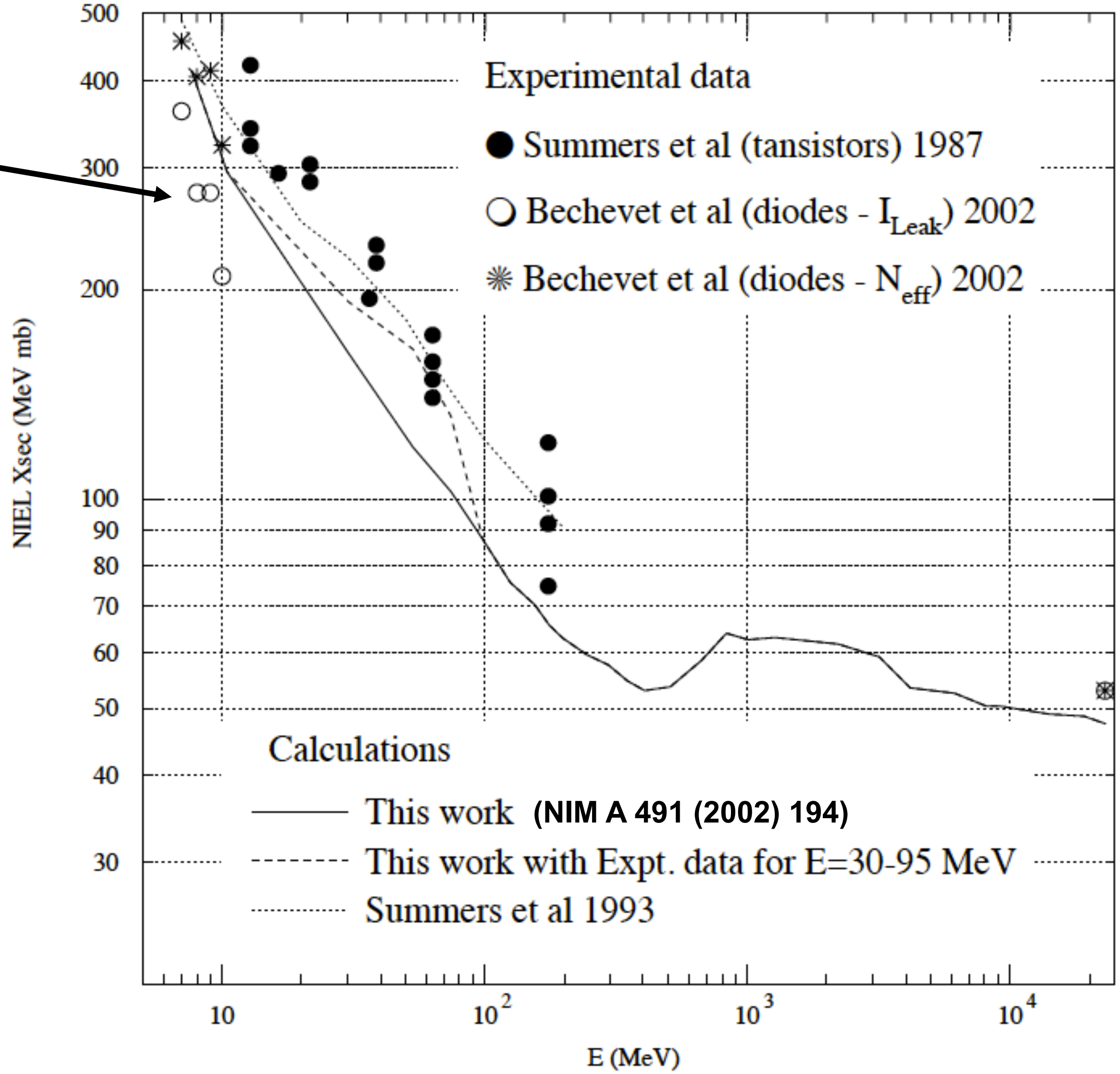
**My 2002 FLUKA+TRIM calculation appears too low for $E_p$ < 1 GeV. However....**

**All new FLUKA results (not 2002) matched together at 10 GeV and this is transferred to other particle types and energies.**

# Low Energy proton damage

**There is at least some data that supports a lower damage at very low proton energies**

**(By now there probably is much more data – this is 2002 status)**



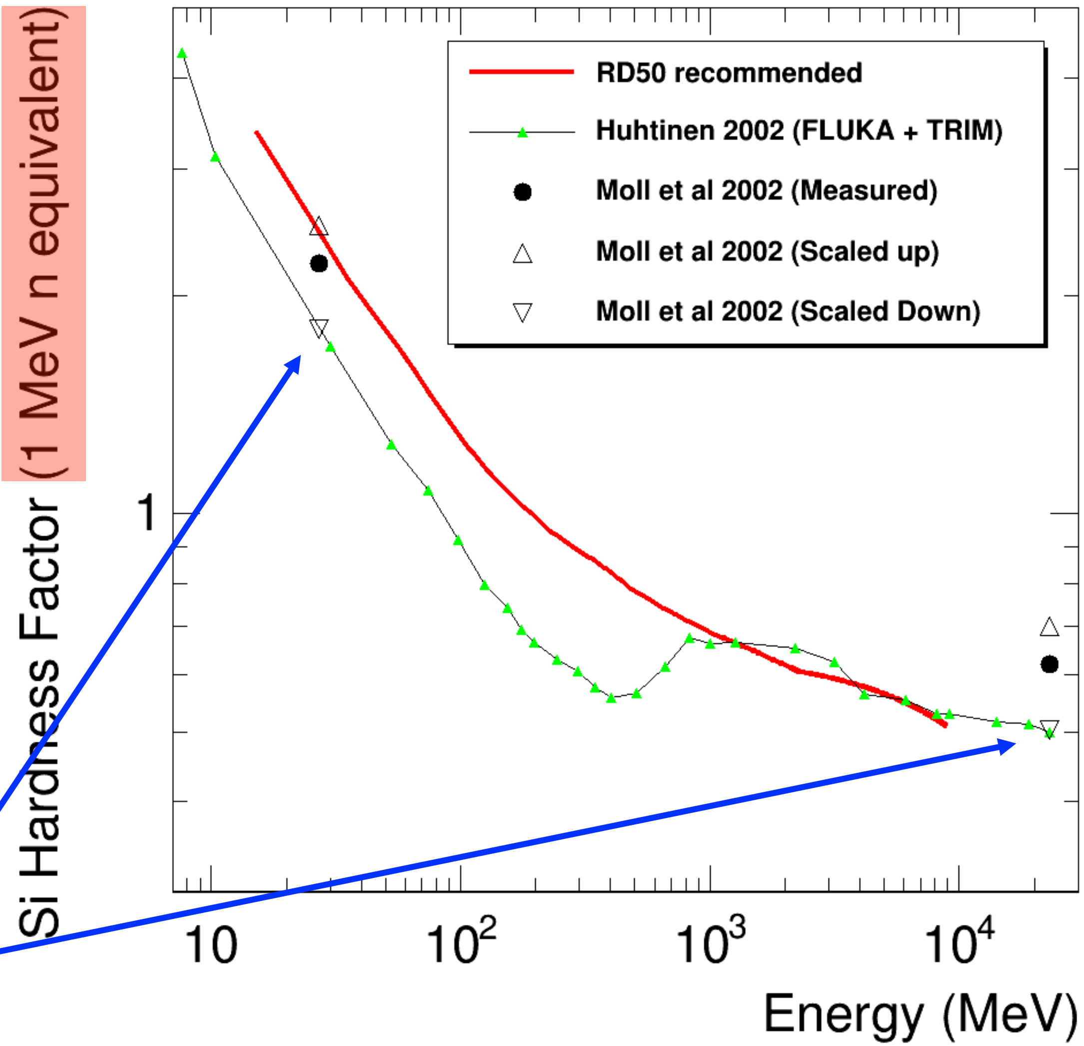
# Proton damage consistency

Recall, that the 1 MeV neutron equivalent is uncertain in itself. This means that **THE ABSOLUTE SCALE IS UNCERTAIN**

I took from NIM B 186 (2002) 100 proton damage data points at 27 MeV and 23 GeV.

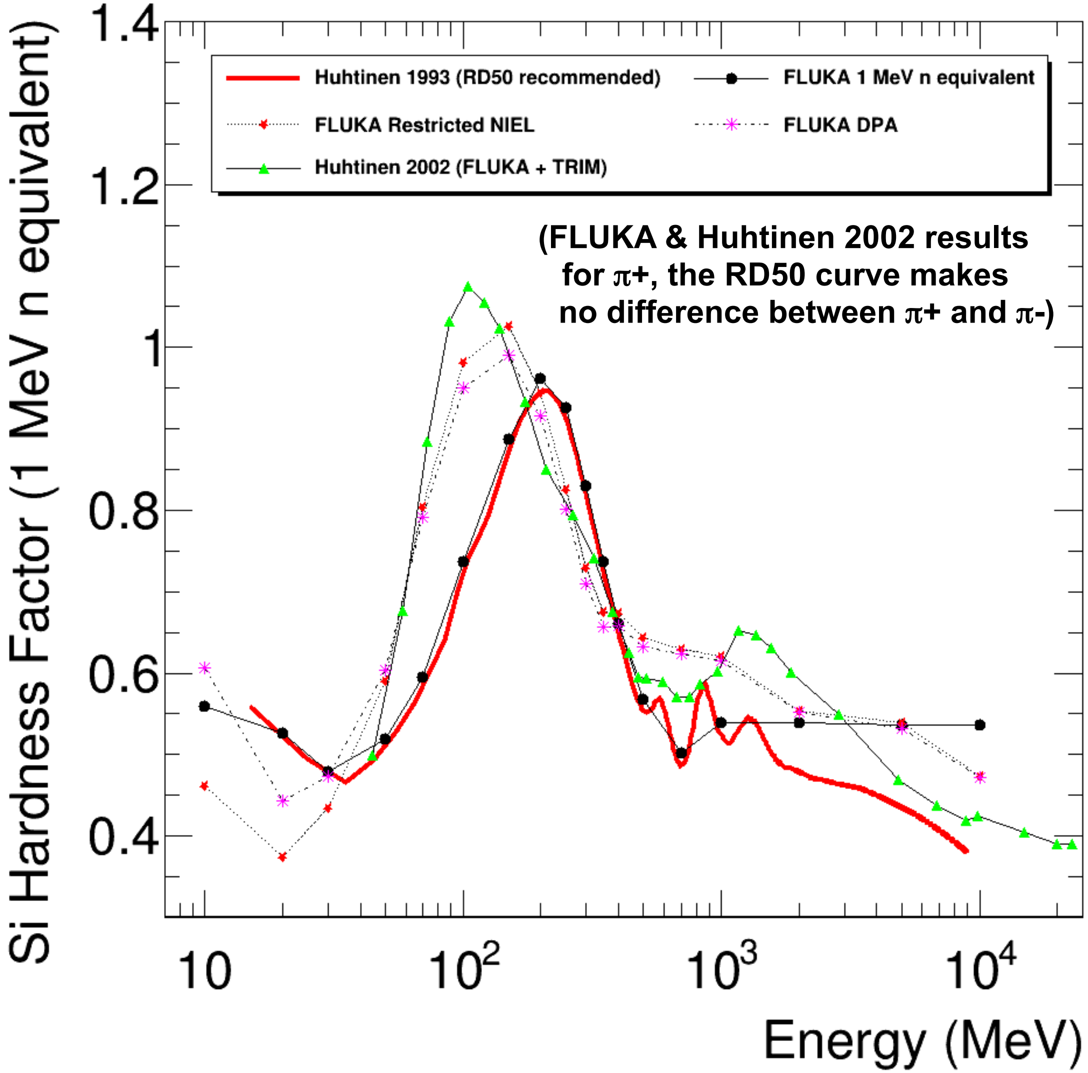
- The solid black circles normalise to a "1 MeV neutron equivalent" (as in the paper)
- The open 'up' triangles are scaled to the RD50 curve at 27 MeV
- The open 'down' triangles to my 2002 FLUKA+TRIM simulation

**The last show best consistency between 27 MeV and 23 GeV**



# Pion damage

(Fluka restricted NIEL and DPA normalisation by matching 10 GeV proton damage)



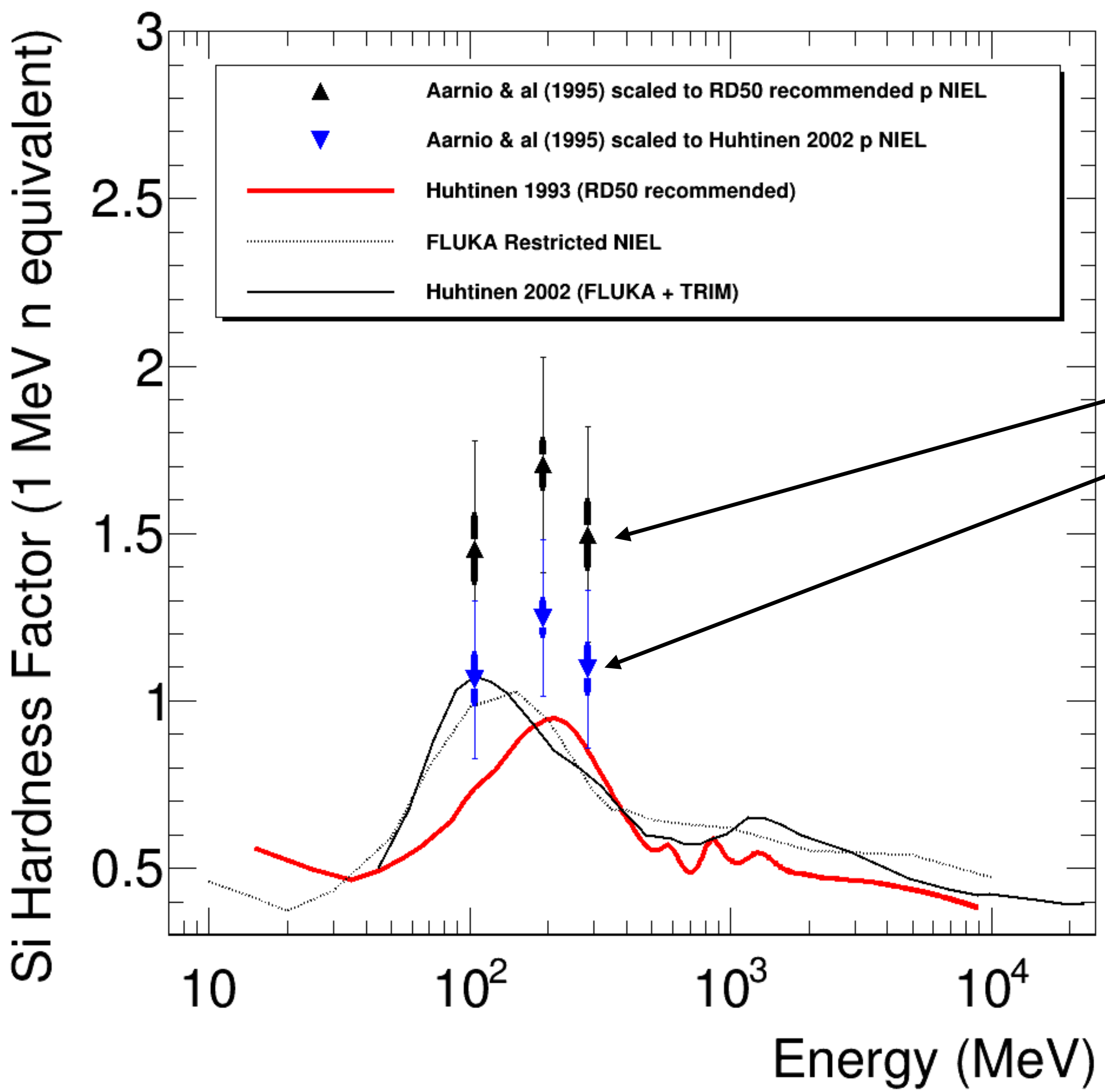

**Significant discrepancies:**

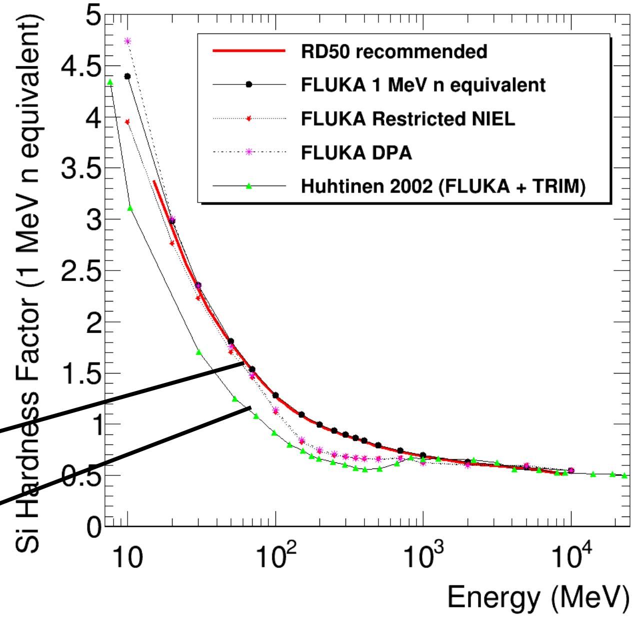
- FLUKA 1 MeV n equivalent constant at E > 1 GeV (no hardness factors implemented)
- NIEL simulations (FLUKA & my 2002) about 20 % higher than RD50 curve at E>500 MeV
- Peak in NIEL simulations shifts towards lower energy wrt RD50 curve and is higher

**Differences typically 20-30 %, depending on pion energy**

# Pion damage vs data (1)

**The pion measurement is compared with 75 MeV proton damage**



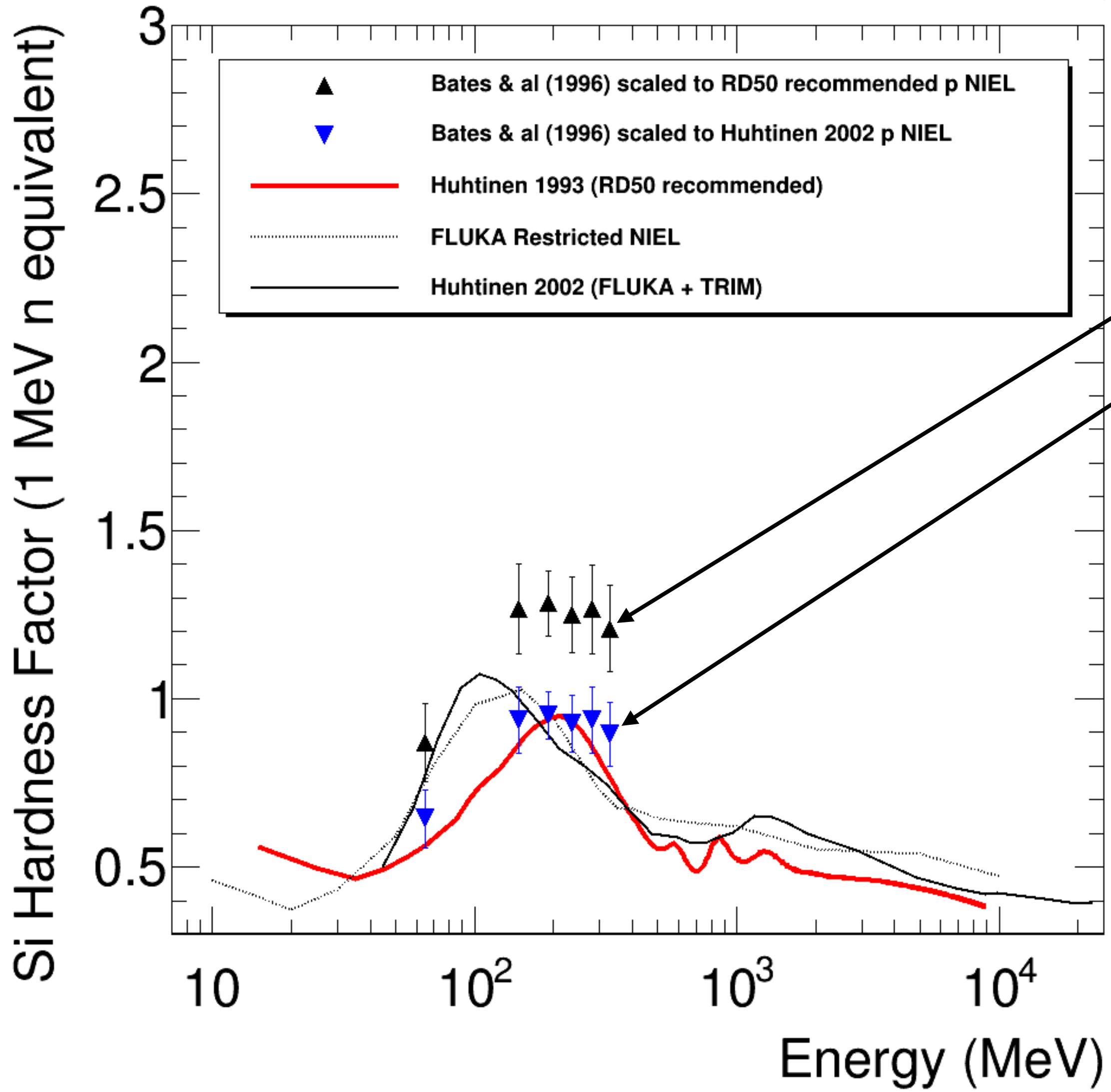



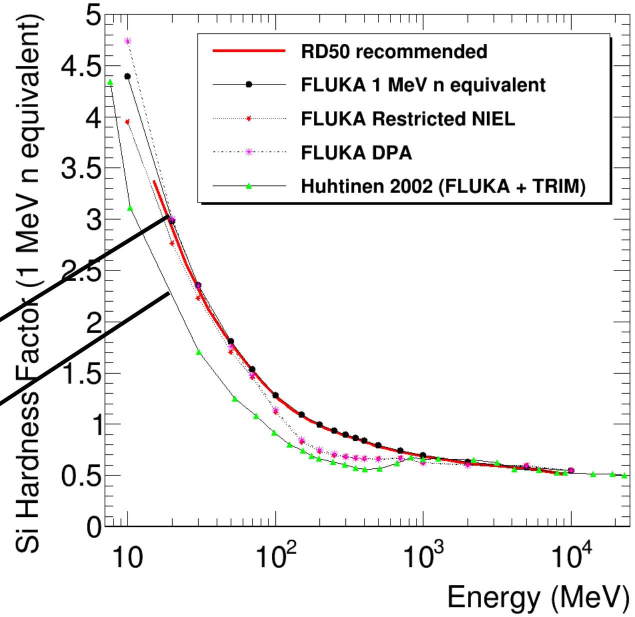

- **Better agreement if the proton damage is matched to my 2002 simulations... (but still higher than estimates)**
- **The data (shape) support a peak at slightly lower E than the RD50 curve, but is not conclusive on best model.**

**(Uncertainties dominated by the proton α measurement ('scale'). Thicker bars show the uncertainty of the pion α )**

# Pion damage vs data (2)

**The pion measurement is compared with 27 MeV proton damage**

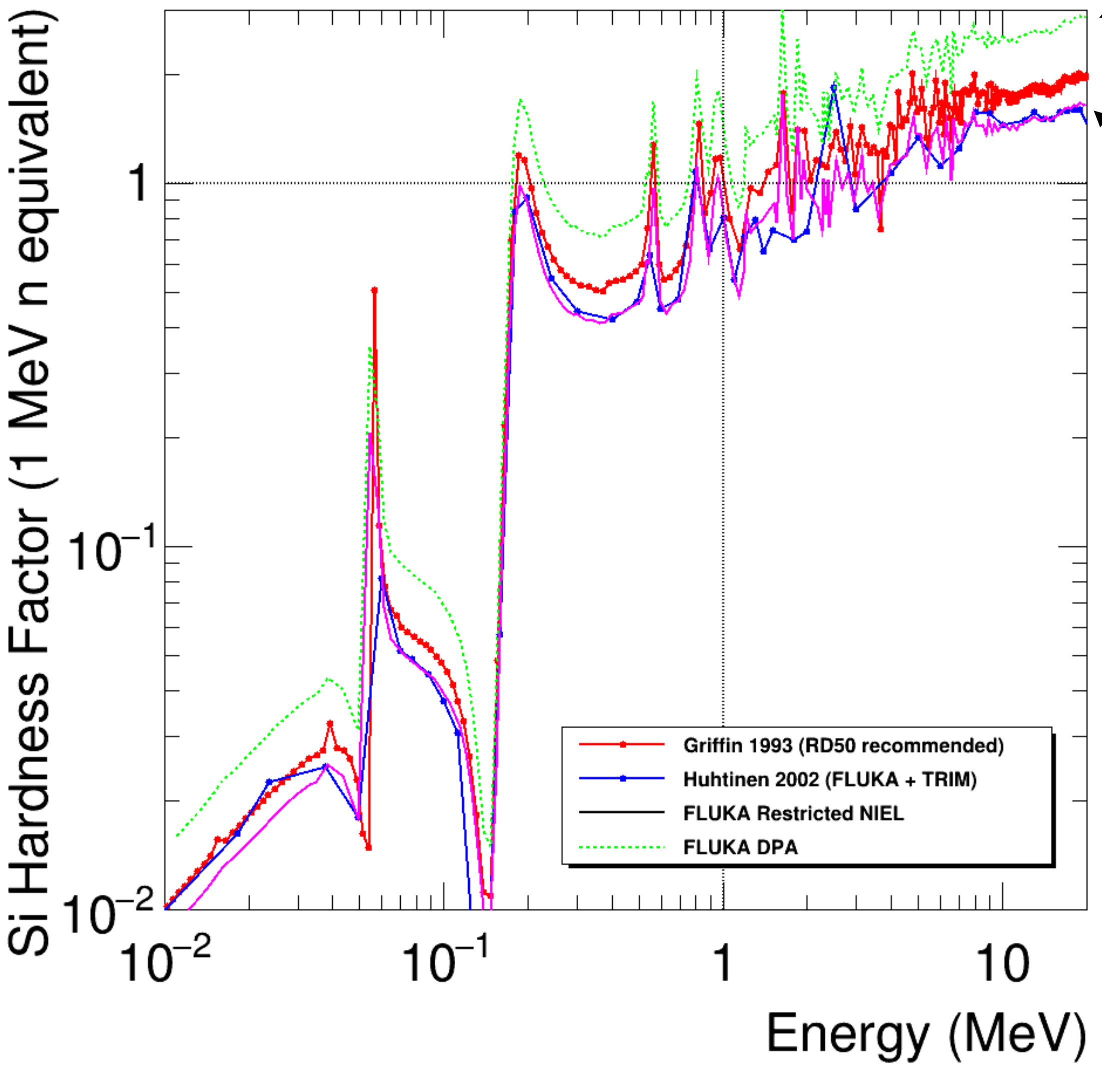



- ✧ **Better agreement if the proton damage is matched to my 2002 simulations...**
- ✧ **There is no clear peak shape and the data are not conclusive about the best damage model**

# Neutron damage comparison

(Fluka restricted NIEL and DPA normalisation by matching 10 GeV proton damage)




- ✧ The FLUKA DPA estimate is a factor 1.7 (almost constant !) above the FLUKA restricted NIEL (→ DON'T USE FLUKA DPA !)
- ✧ Somewhat surprisingly the FLUKA restricted NIEL agrees almost perfectly with my 2002 FLUKA+TRIM simulation
- ✧ The 1 MeV neutron equivalent of FLUKA (not shown) follows the red curve (no surprise since that curve is built in...)

**A 5 eV change of assumed $E_{thres}$ would shift any of these curves by ~20%**

# Summary (...but not yet the conclusions)

The absolute scale on any hardness factor referred to 1 MeV neutron equivalent has a non-negligible uncertainty (> ~ 20 %).

- The neutron damage functions themselves are uncertain (depend on $E_D$ assumed for their evaluation)
- Neutron spectra are difficult to unfold accurately

The proton damage functions used by RD50 seem to have some problems also (low energy not consistent with 23 GeV when compared with data)

I know of only 2 pion damage measurements and these are totally insufficient to test or constrain the pion hardness factors.

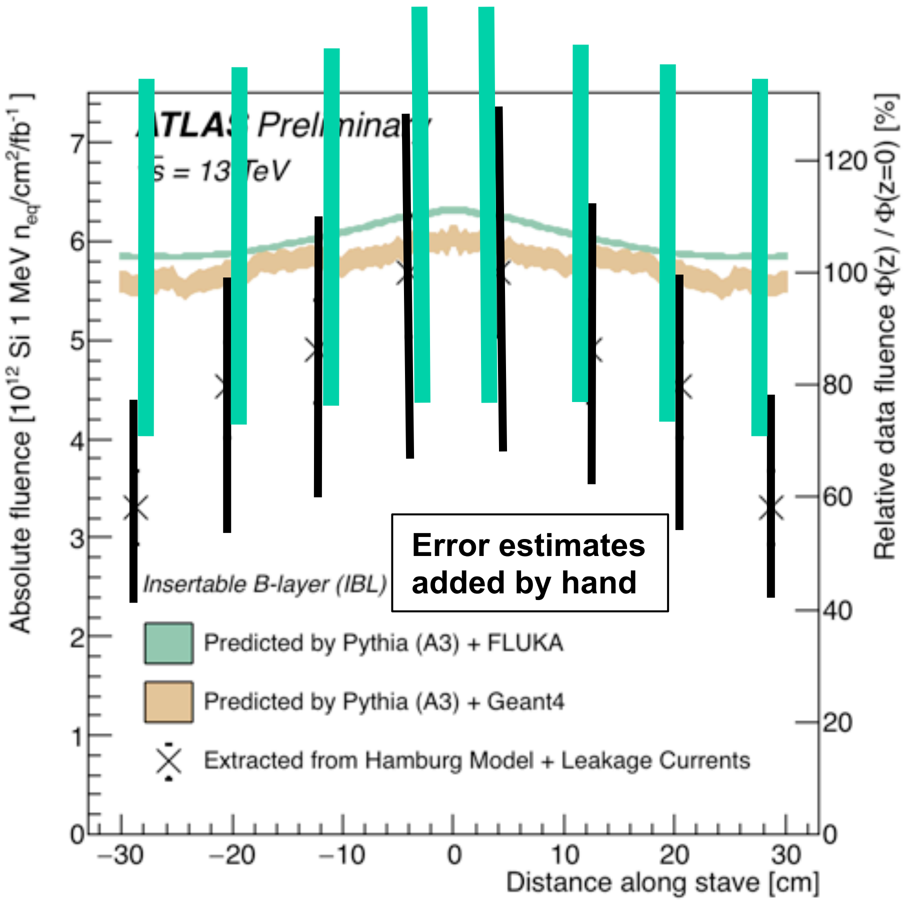
- Neither pion data set really agrees with any of the damage curves
- Data are available only for a narrow energy range (due to available beams)
- Different pion damage estimates differ by up to 30 %

# IBL damage with uncertainties

**Now, let's look again at the ATLAS IBL damage prediction vs data plot:**

**Both simulations use the RD50 damage constants.**

- ✧ **about 60% of the damage is due to pions**
- ✧ **these pion damage constants have ~30%, mostly correlated, uncertainty**
- ✧ **Kaon damage (~15%) is pure guess**




**The measured leakage current is translated to 1 MeV n Eq. Φ using an α measured in some neutron spectrum, folded with the (RD50) neutron damage curve**

- ✧ **these also have ~30%, fully correlated, uncertainty**

→ **the comparison suggests a difference in z-dependence, but it is inconclusive if the center is underestimated or the large-z region overestimated, or both**

# Conclusions

**The RD50 damage curves have been used since >20 years and seem to have become 'truth' without uncertainties**

**THIS IS A CAPITAL MISTAKE**

**They might be the only available, but that does not mean that they would be good enough**

- **The pion damage curves, which I presented 25 years ago, were intended only to initiate pion beam tests. They did their job - and that should have been it.**
  - **They were never intended to be used for damage estimates (due to the severe approximations made in their derivation).**
- **The "1 MeV neutron equivalent" itself introduces a >~20% scale uncertainty**

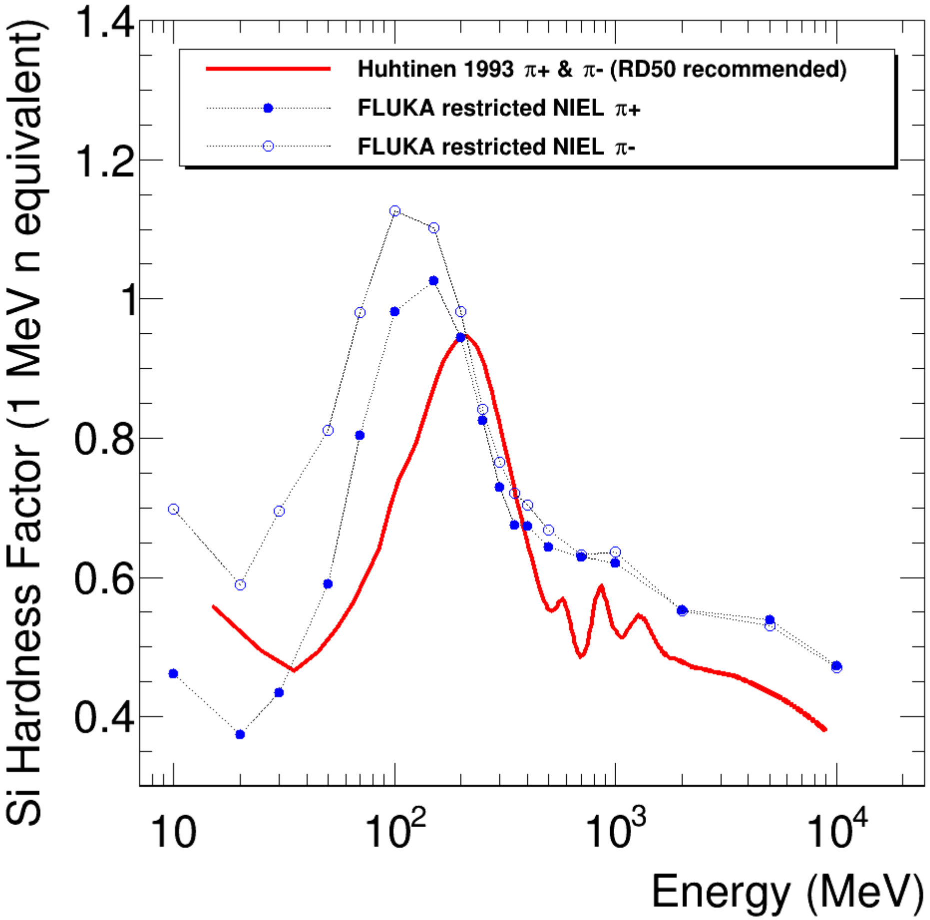
**However, the (1 MeV neutron) scale uncertainty cancels when comparing two materials in the same beam or the same device with different particles or energies.**

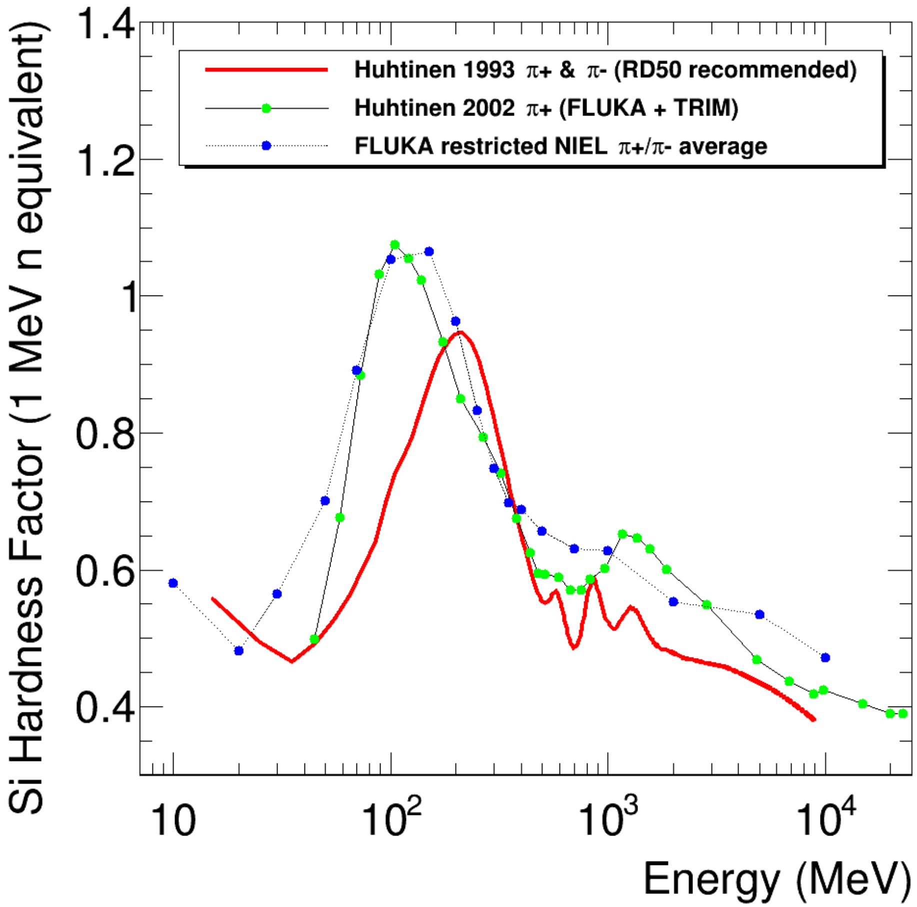
**BUT:** **When comparing simulations (e.g. FLUKA) with data (e.g. leakage current measured in LHC detectors) about 30% uncertainty should be assigned to both, the hardness factors (used in simulation) and the absolute scale (transfer of a measured $\alpha$ to 1 MeV neutron equivalent fluence)**

# Backup

# π+ vs π- hardness factors

- FLUKA indicates significant difference below ~200 MeV (expected du to π- absorption)
- Our 1993 work was a 'high-E approximation' where no difference should appear
- In 2002 I considered only π+. Strangely it agrees best with the FLUKA π+π- average...



# References (used for this presentation)

Huhtinen, Aarnio, NIM A335 (1993) 580

Huhtinen, Aarnio, Report HU-SEFT R 1993-02 (long version of above)

- ✧ The original derivation of the pion damage curves

Aarnio & al, NIM A360 (1995) 521

Bates & al, NIM A379 (1996) 116

- ✧ Pion damage irradiation results

Moll & al, NIM A186 (2002) 100

- ✧ Fig 9 used to normalise the 'Bates & al' pion results to 27 MeV proton damage

Huhtinen, NIM A491 (2002) 194

- ✧ Hardness factor calculation using FLUKA combined with TRIM

# Damage factor extraction form FLUKA

**Since the FLUKA code is not publicly available, we do not know the detailed implementation of the damage estimators.**

- **The curves attributed to FLUKA in this talk are obtained by simulating a pencil beam for each particle type and energy through 300 μm of Si.**
- **For each case 4 sets of 1E6 particles were simulated and it was checked that statistical variation and secondary particle production were negligible.**
- **The scored quantities were:**
  - **(1) 1 MeV neutron equivalent fluence (this, presumably, is just fluence folding of the RD50 damage constants)**
  - **(2) Restricted NIEL**
  - **(3) DPA (Displacements Per Atom)**
- **For the plots (2) and (3) have been normalised by matching them to (1) for 10 GeV protons and transferring this scale to all particle types and energies.**

# The 2002 FLUKA + TRIM calculations

**They are explained in NIM A491 (2002) 194, here just a short summary:**

- ✧ **FLUKA (older 'Helsinki' version) was augmented by a nuclear fragmentation model and used to simulate production of nuclear recoils from inelastic scattering.**
- ✧ **Proton and pion elastic scattering was sampled using Glauber theory (as in our 1993 work)**
- ✧ **Recoils from neutron interactions below 20 MeV were sampled directly from from the angular and energy distributions available in ENDF/B-VI data (processed with NJOY)**
- ✧ **The original TRIM code (Ziegler & al) was modified to simulate the complete atomic cascade down to the dislocation threshold and used to transport the recoils produced by FLUKA (or the elastic Galuber model or neutron interactions)**
- ✧ **The energy going into phonons & dislocations was accounted for during the (modified) TRIM transport**