New electron multiple scattering results

(one or two bugs found)

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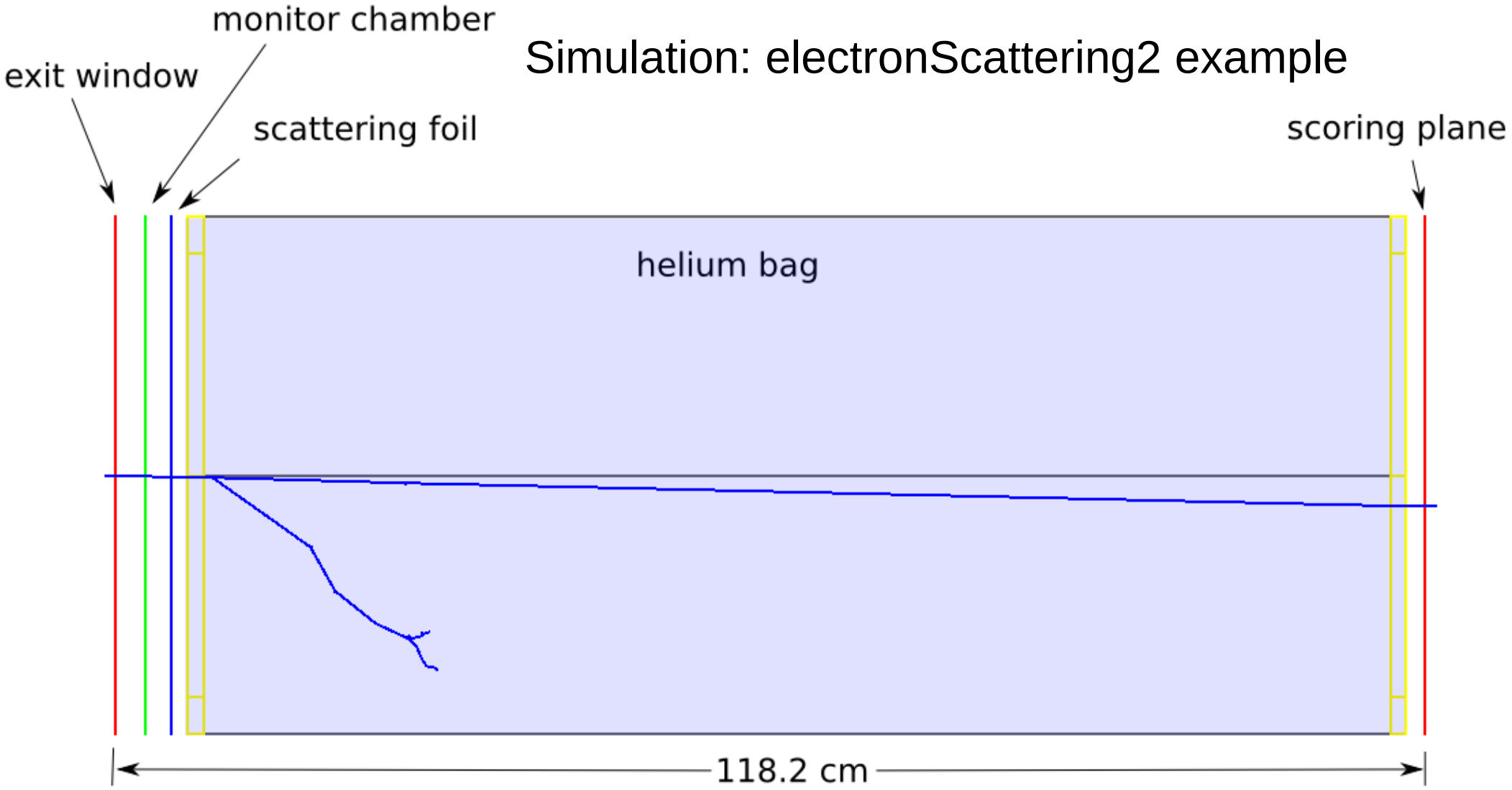
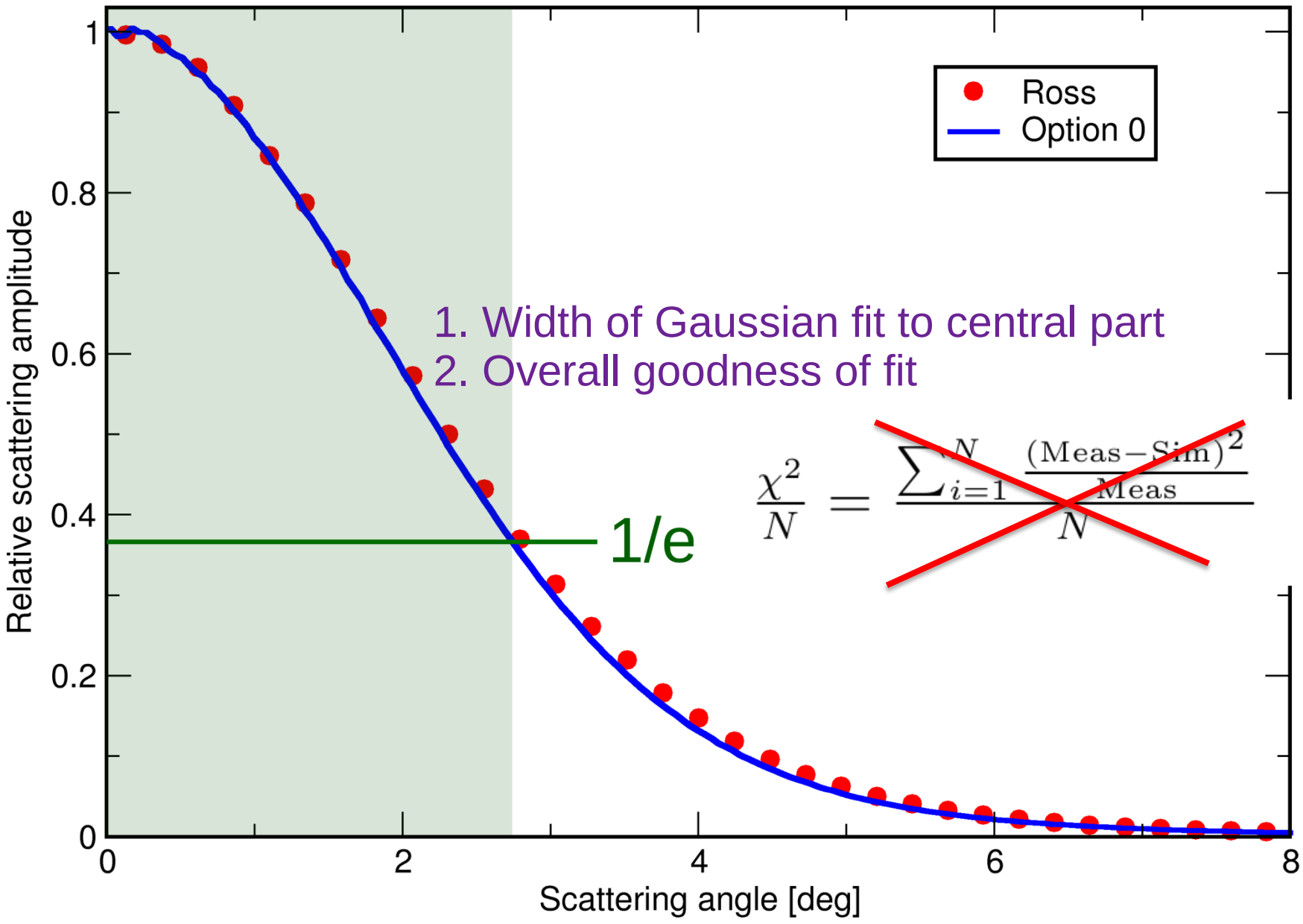
Experiment: Ross et al., Med. Phys. **35**, 4121 (2008)

7 materials, various thickness, 13 and 20 MeV

Simulation: electronScattering2 example




Ross
Option 0
1. Width of Gaussian fit to central part
2. Overall goodness of fit
1/e
$\frac{\chi^2}{N} = \frac{\sum_{i=1}^{N} \frac{(\mathrm{Meas}-\mathrm{Sim})^2}{\mathrm{Meas}}}{N}$
Relative scattering amplitude
Scattering angle [deg]
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8

Improvements:

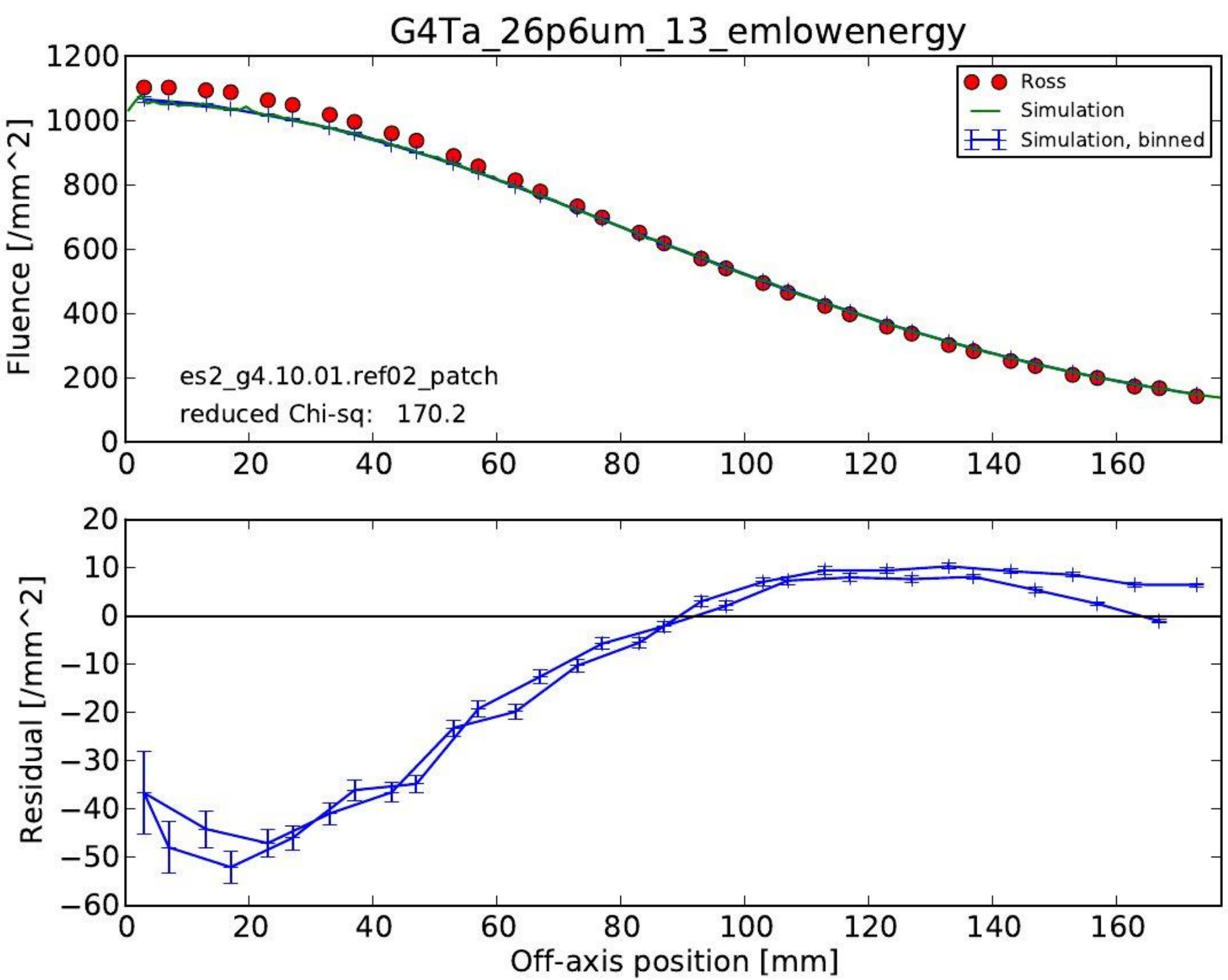
- (latest results) Use physics lists from Geant4 source rather than local
- same # of incident particles for each physics list (previously SS was 10%)
- Include simulation, measurement uncertainties in chi-squared

$$\frac{\chi^2}{N} = \frac{1}{N}\sum \frac{(meas - sim)^2}{uncertainty^2}$$

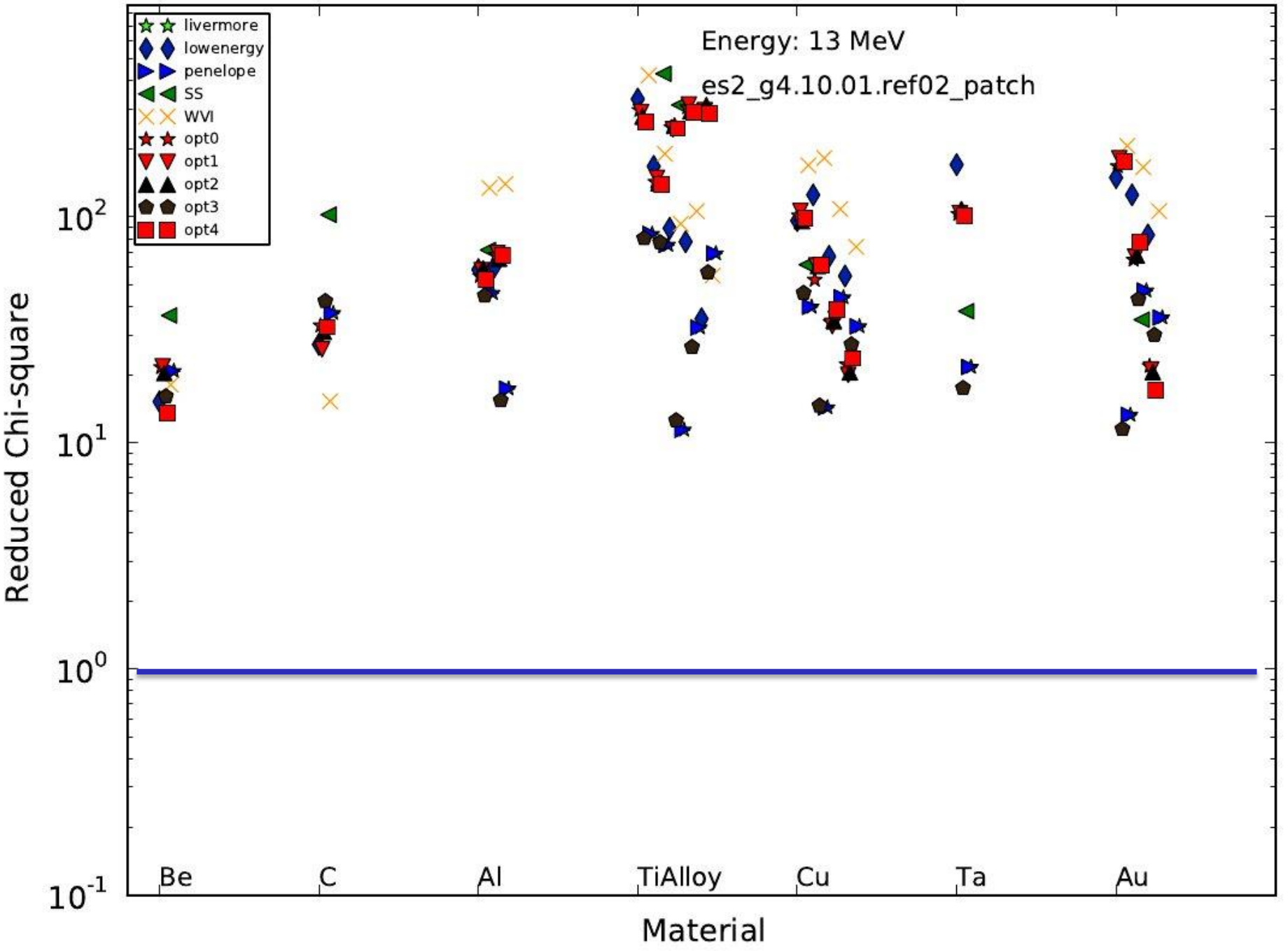
Simulation uncertainty: $\frac{N \pm \sqrt{N}}{Area}$

Measurement uncertainty: 1% in width—what is it for each data point?

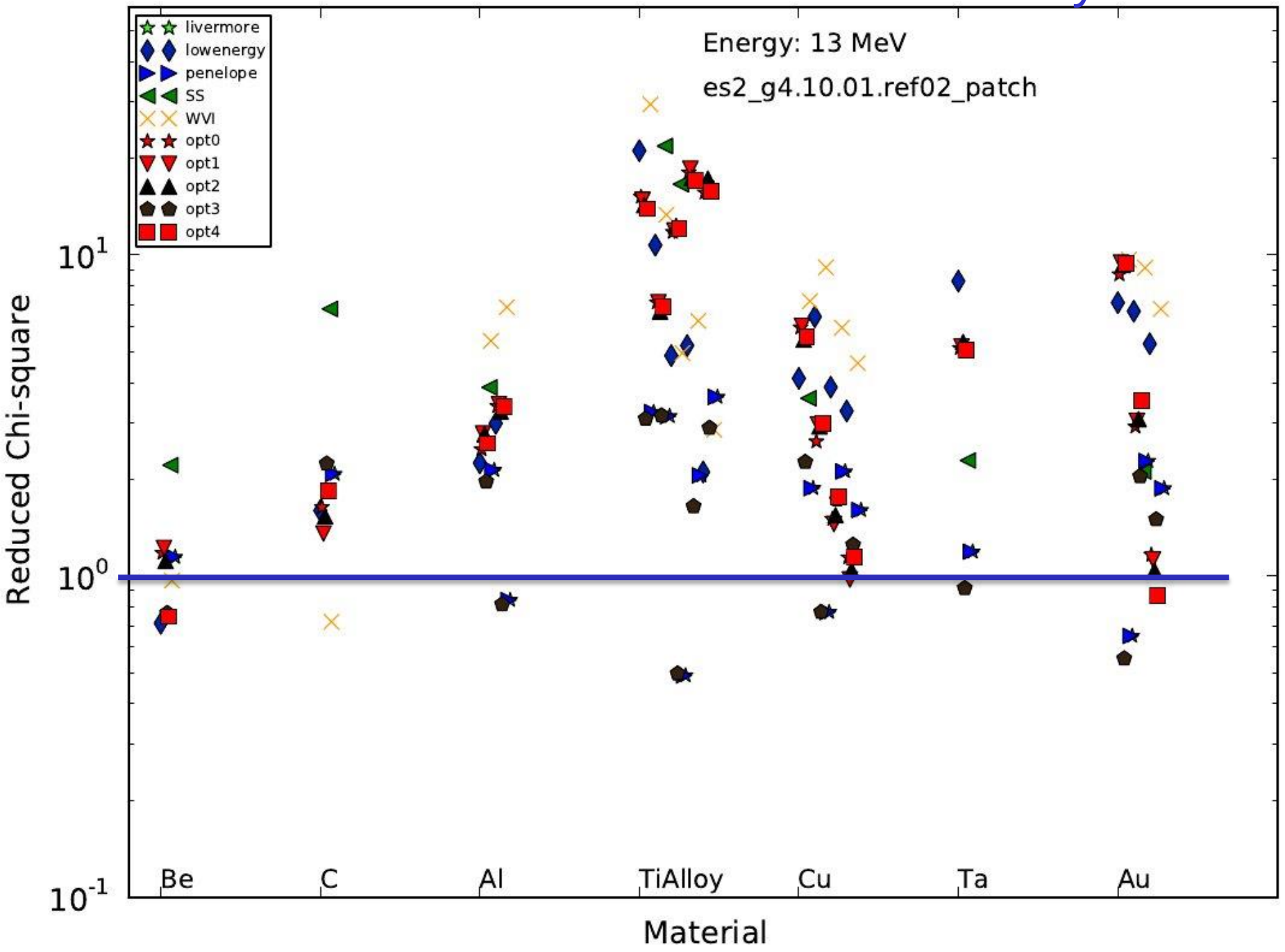
determine empirically


G4Ta_26p6um_13_emlowenergy
Ross
Simulation
Simulation, binned
es2_g4.10.01.ref02_patch
reduced Chi-sq: 170.2
Fluence [/mm^2]
Residual [/mm^2]
Off-axis position [mm]
1200
1000
800
600
400
200
0
20
10
0
−10
−20
−30
−40
−50
−60
0
20
40
60
80
100
120
140
160

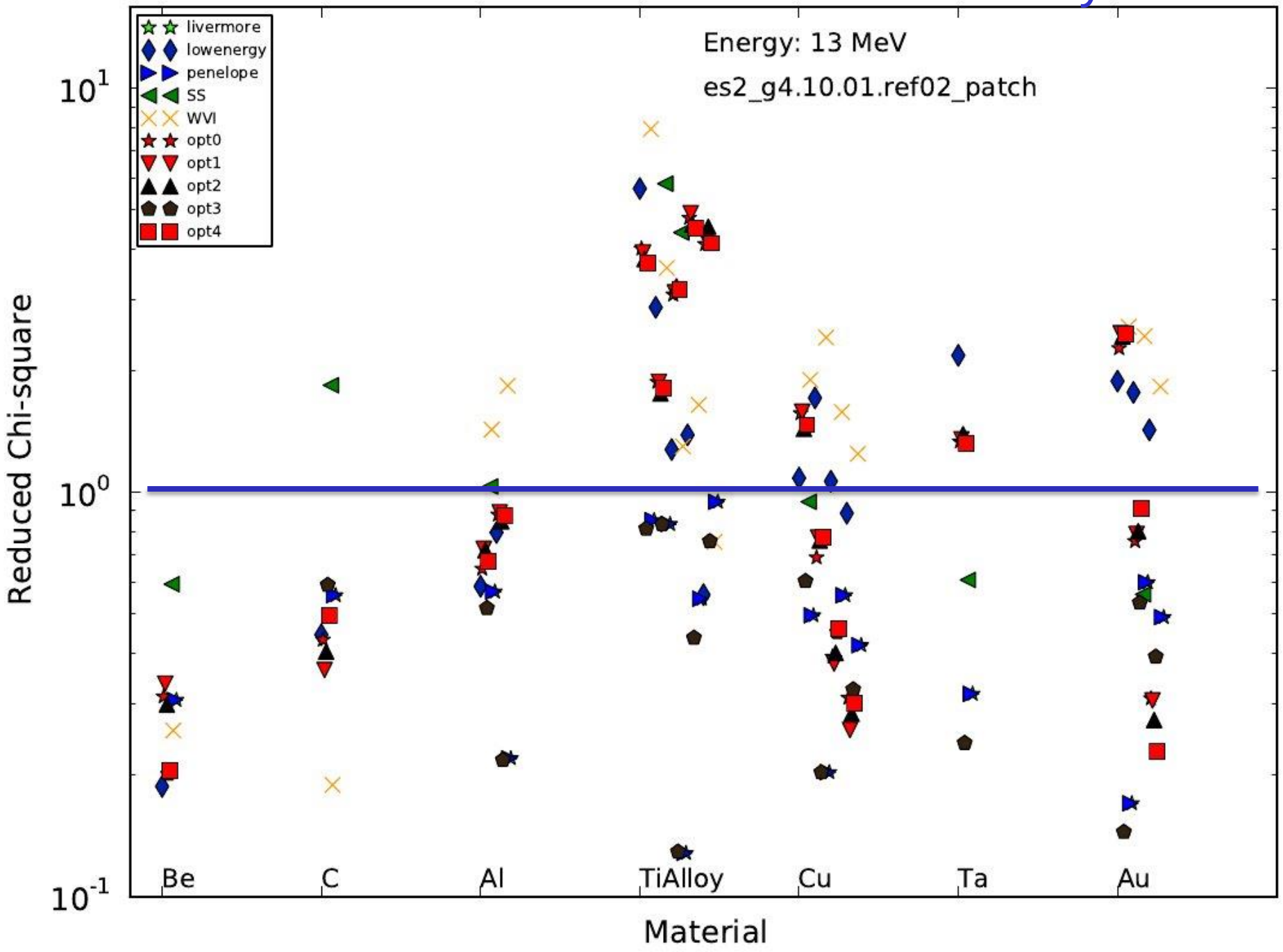
Assume 0% measurement uncertainty



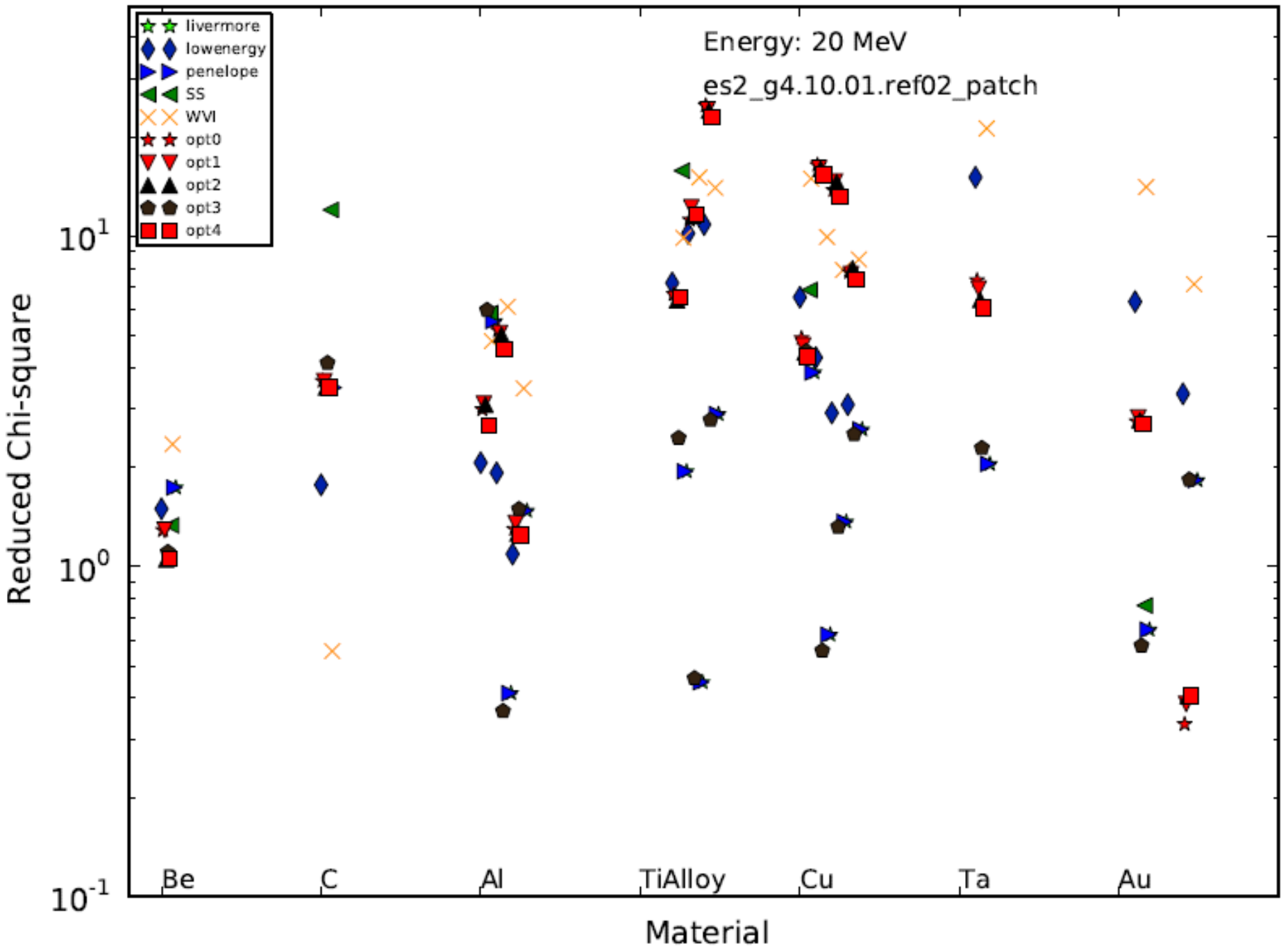
Assume 1% measurement uncertainty



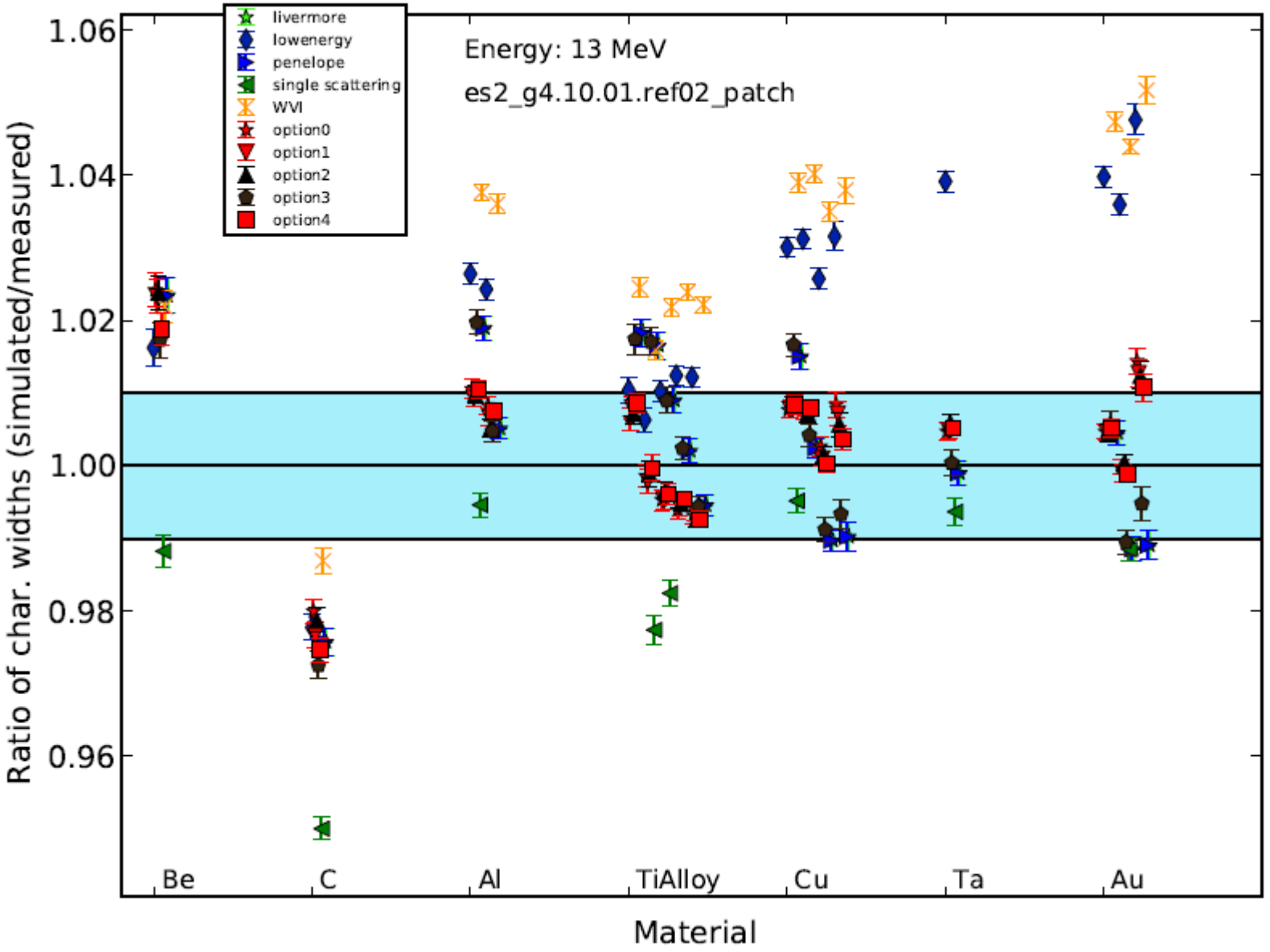
Assume 2% measurement uncertainty



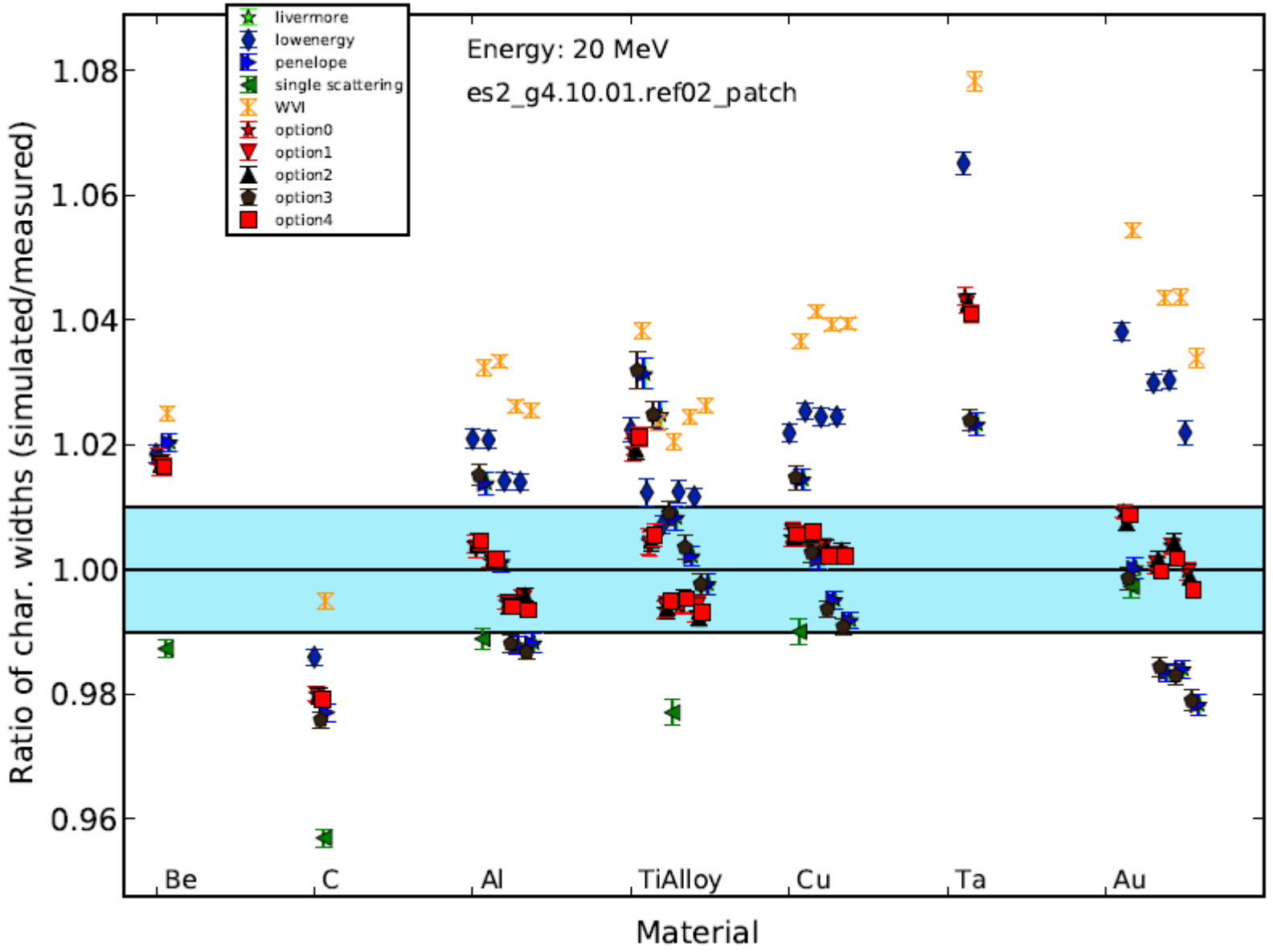
20 MeV


livermore
lowenergy
penelope
SS
WVI
opt0
opt1
opt2
opt3
opt4
Energy: 20 MeV
es2_g4.10.01.ref02_patch
Reduced Chi-square
10^{1}
10^{0}
10^{-1}
Be
C
Al
TiAlloy
Cu
Ta
Au
Material

Widths of central part

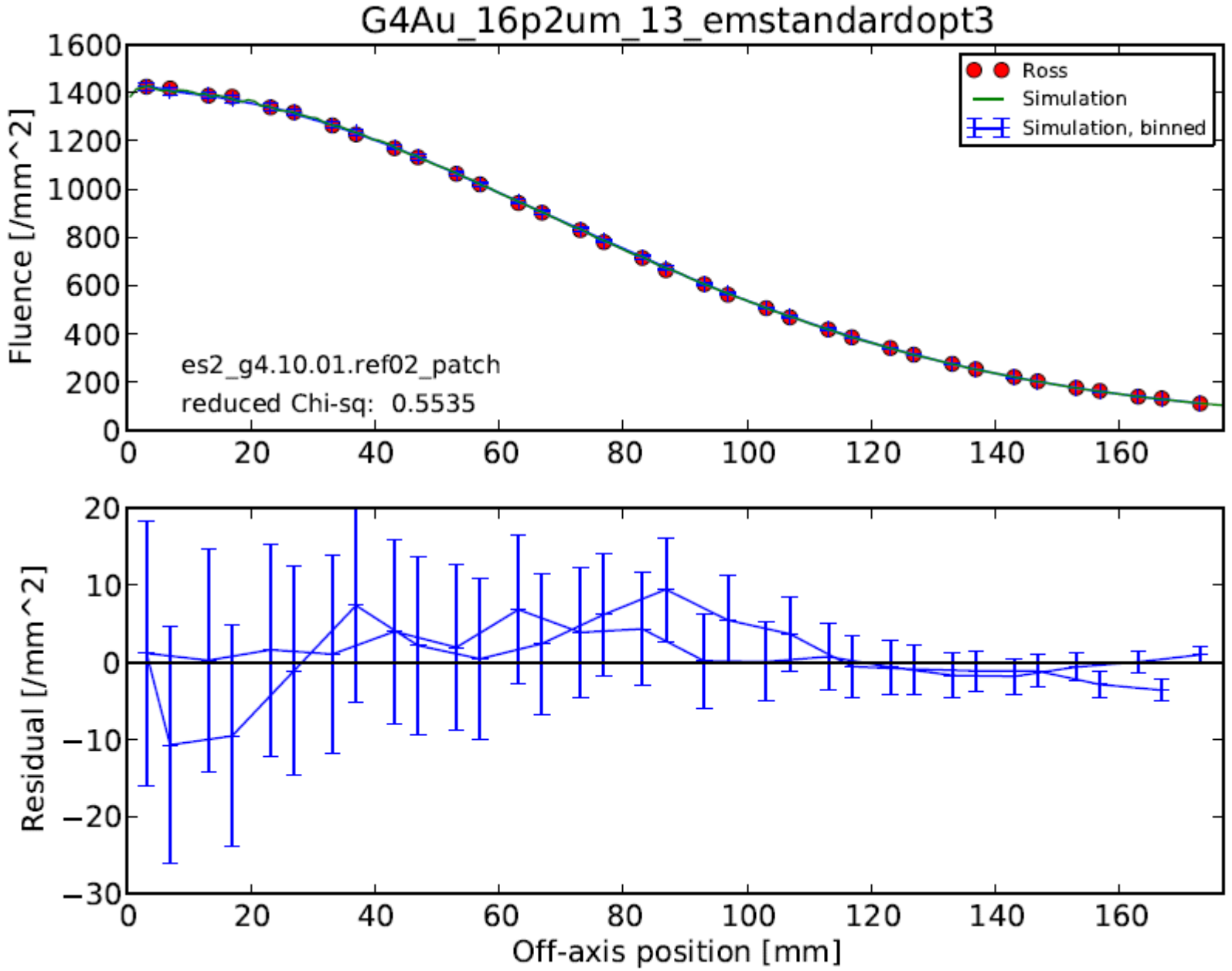


Widths of central part



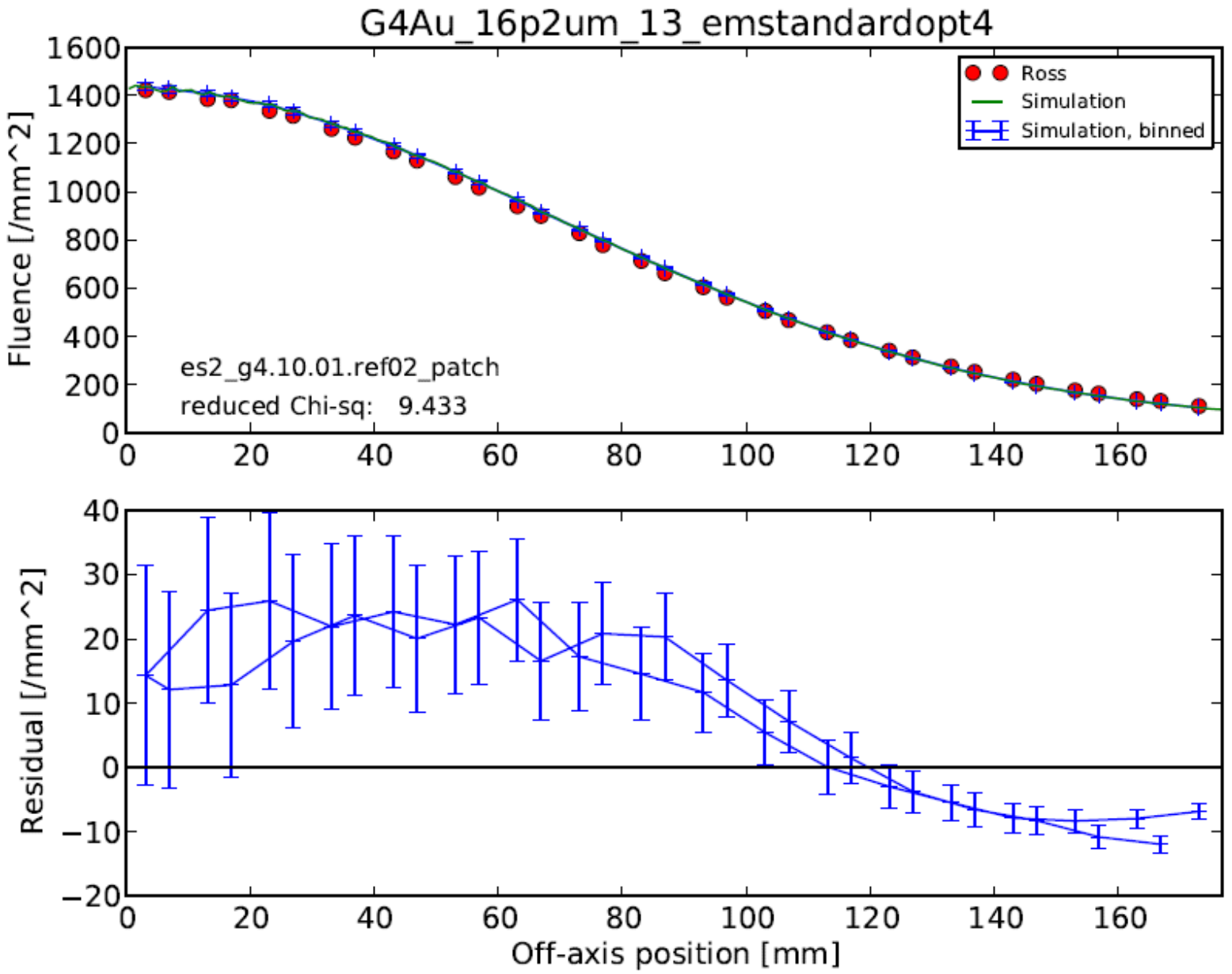
Examples

Width good, chi-sq good



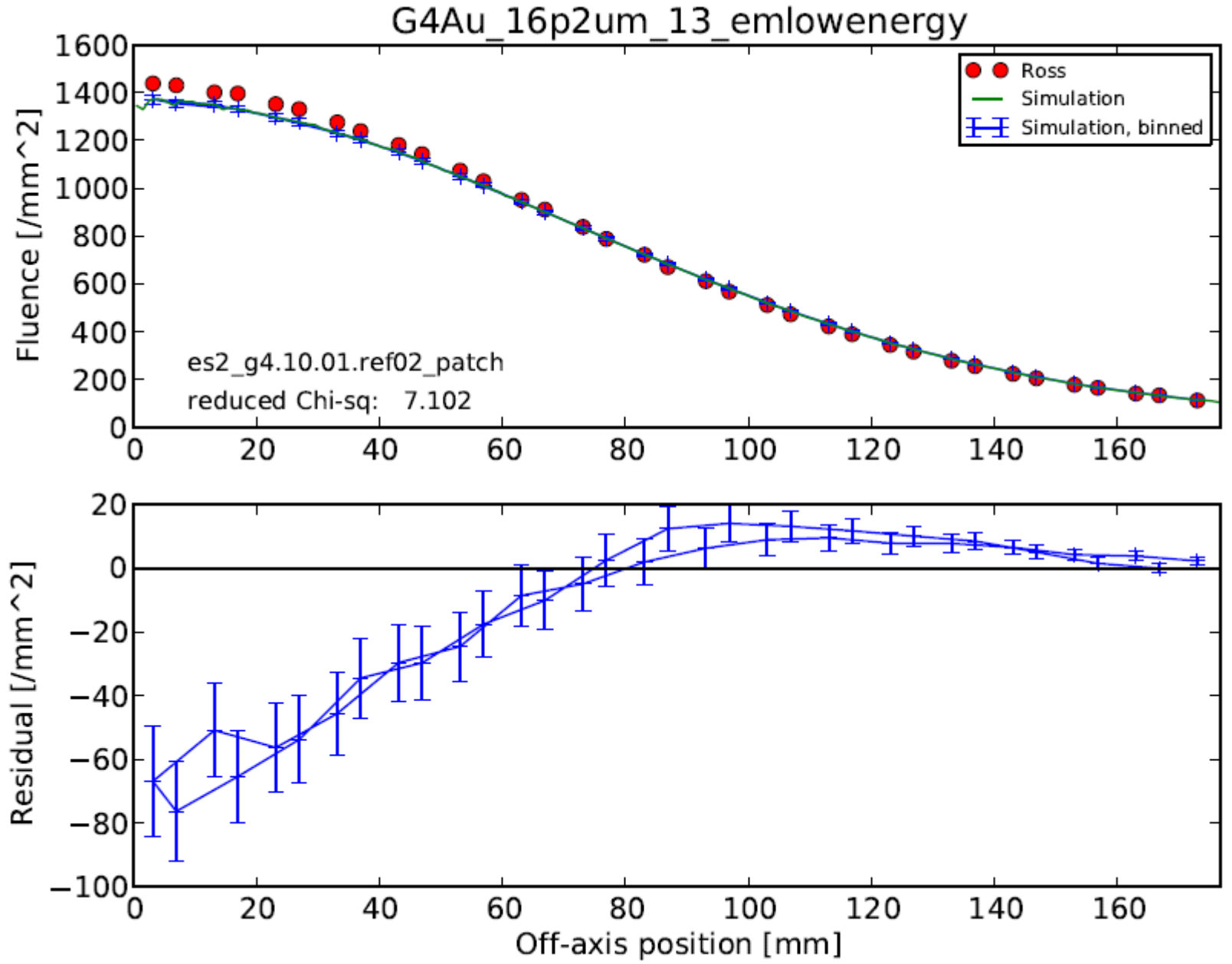
Examples

Width good, chi-sq poor



Examples

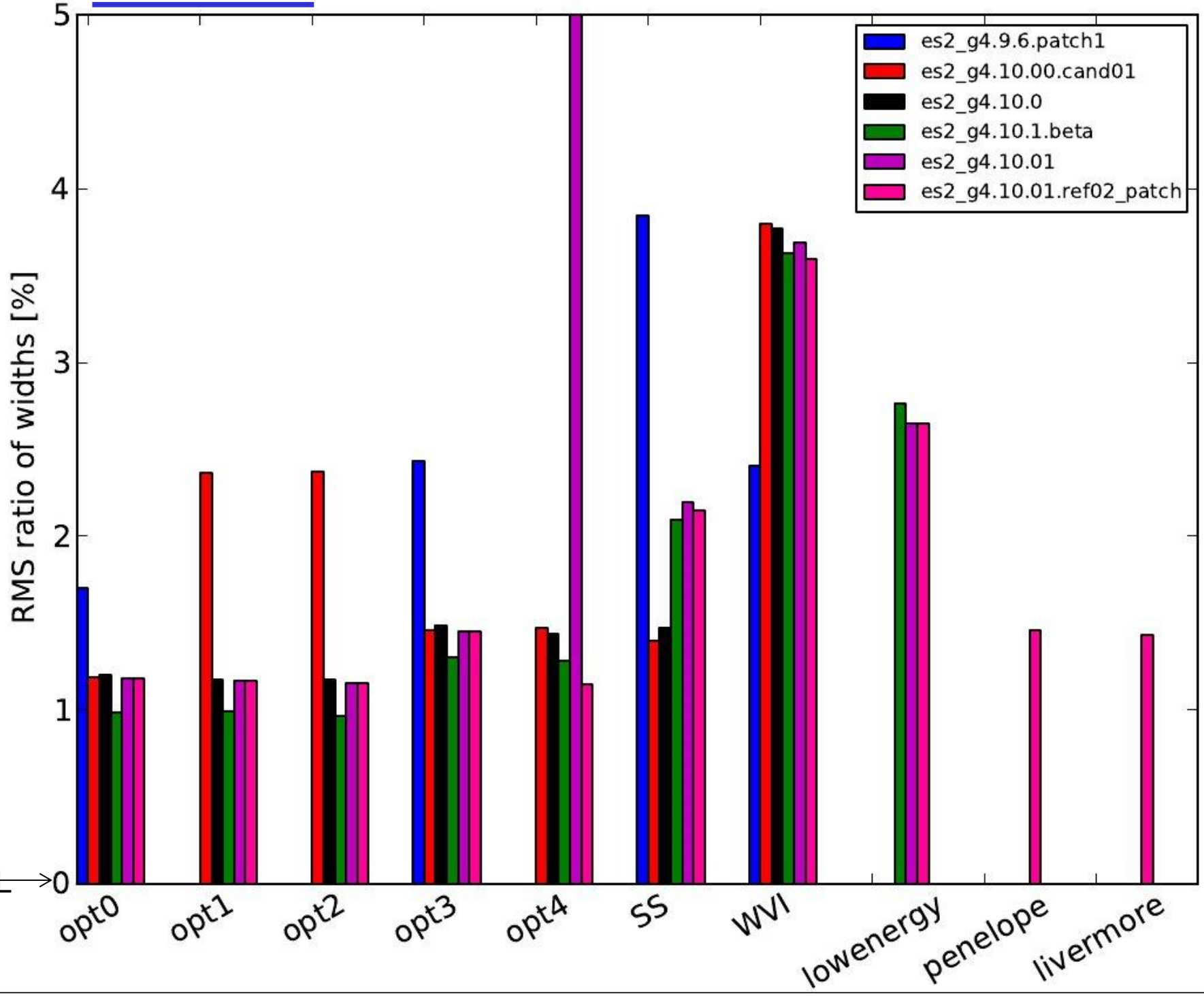
Width poor, chi-sq poor



Summarize results

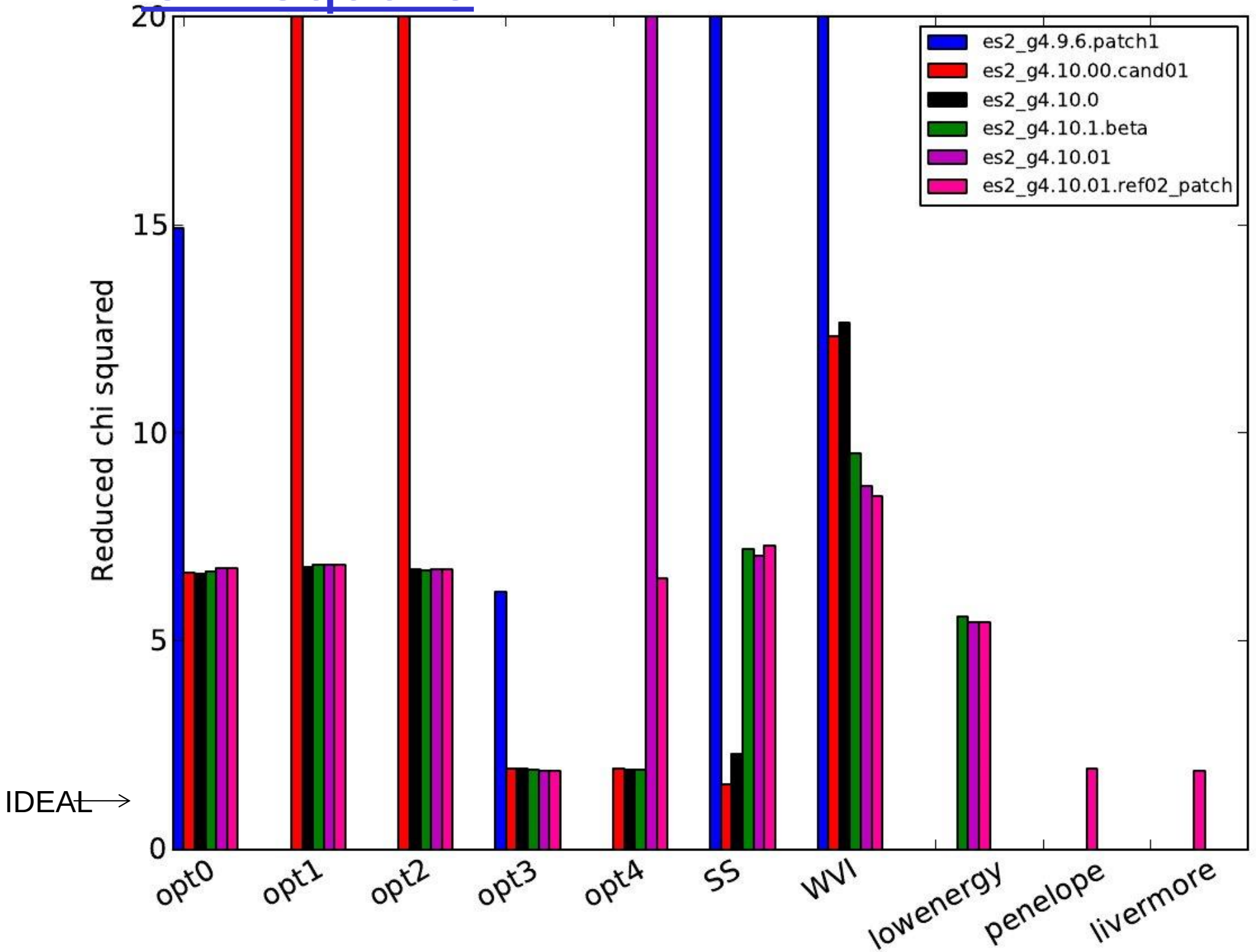
- Calculate average chi-square
- Root-mean-square (ratio of widths – 1)
  - Express as %
- Function of Geant4 version

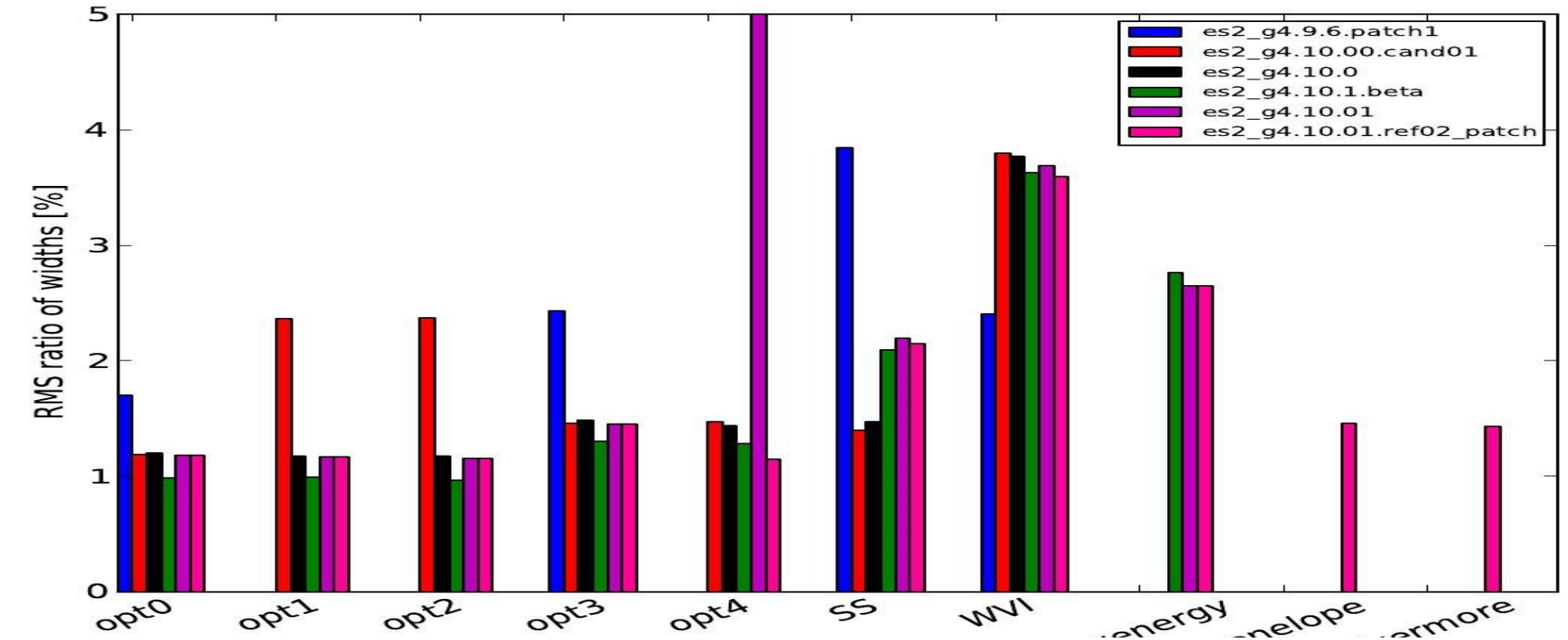
Widths

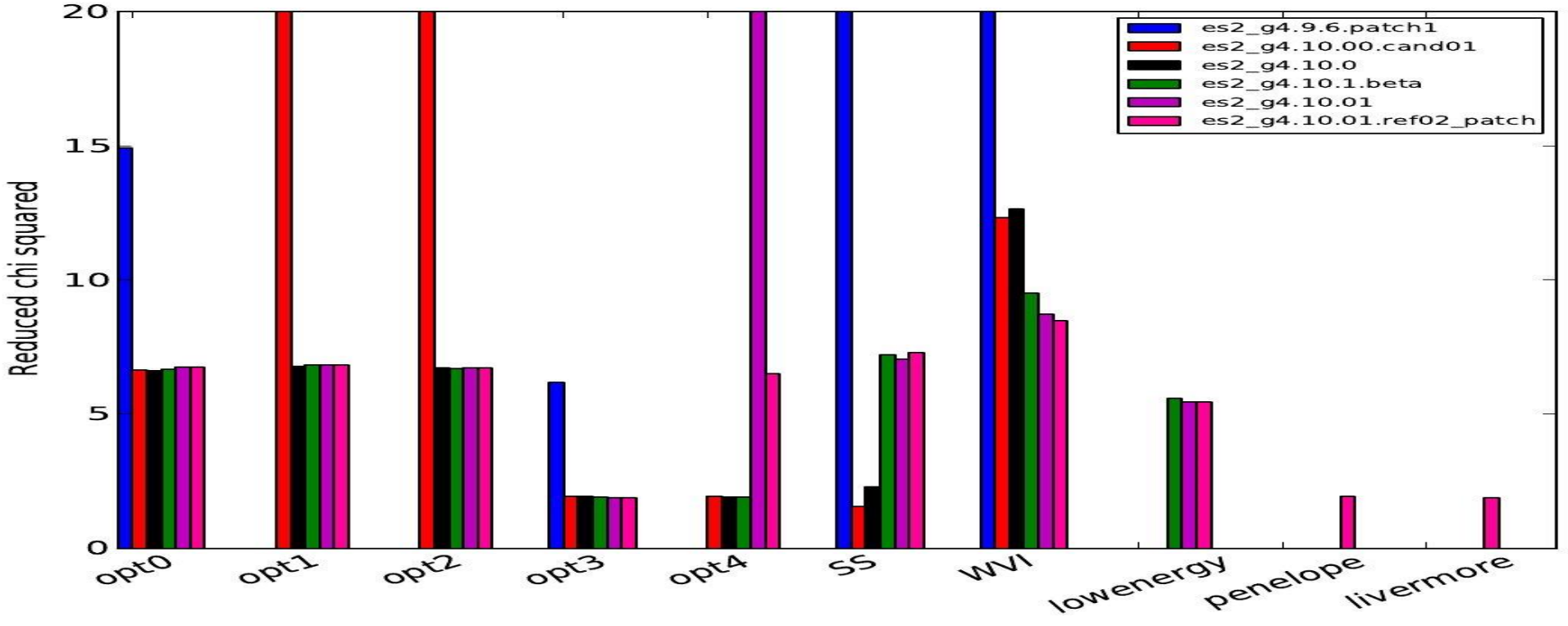


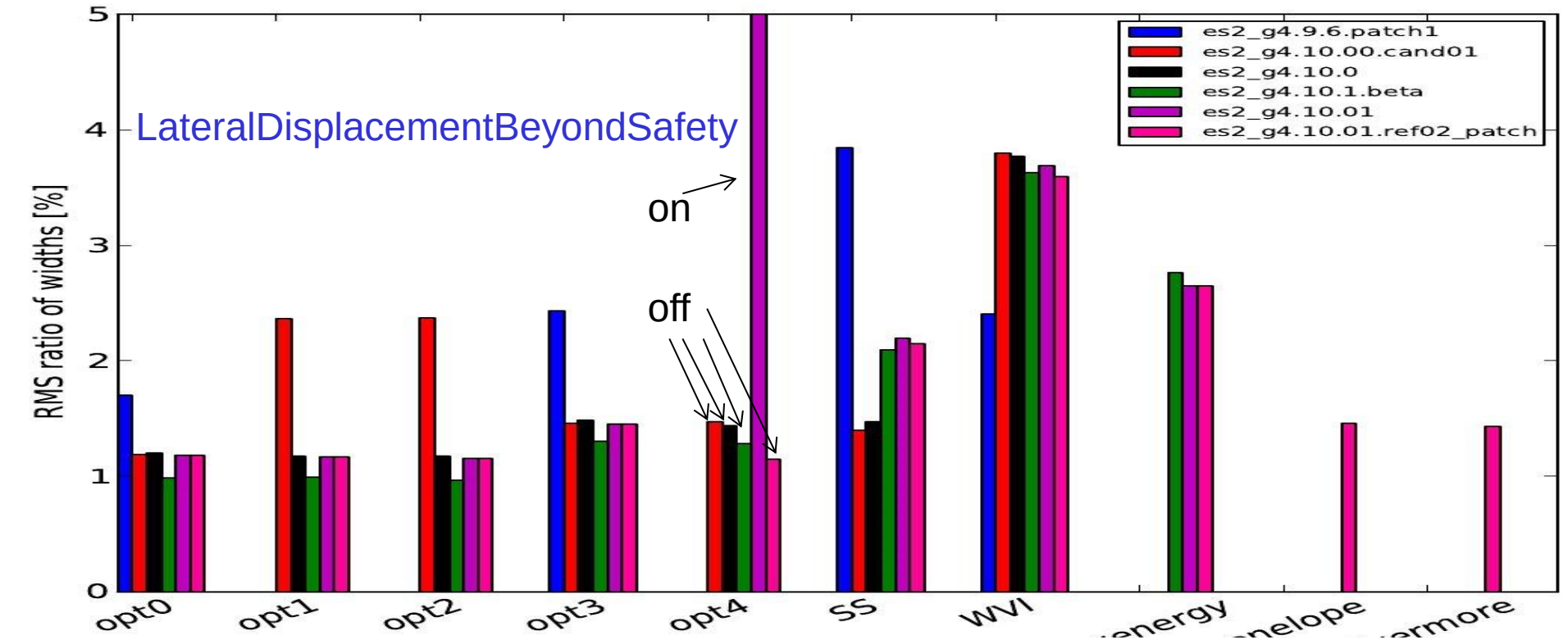
IDEAL →

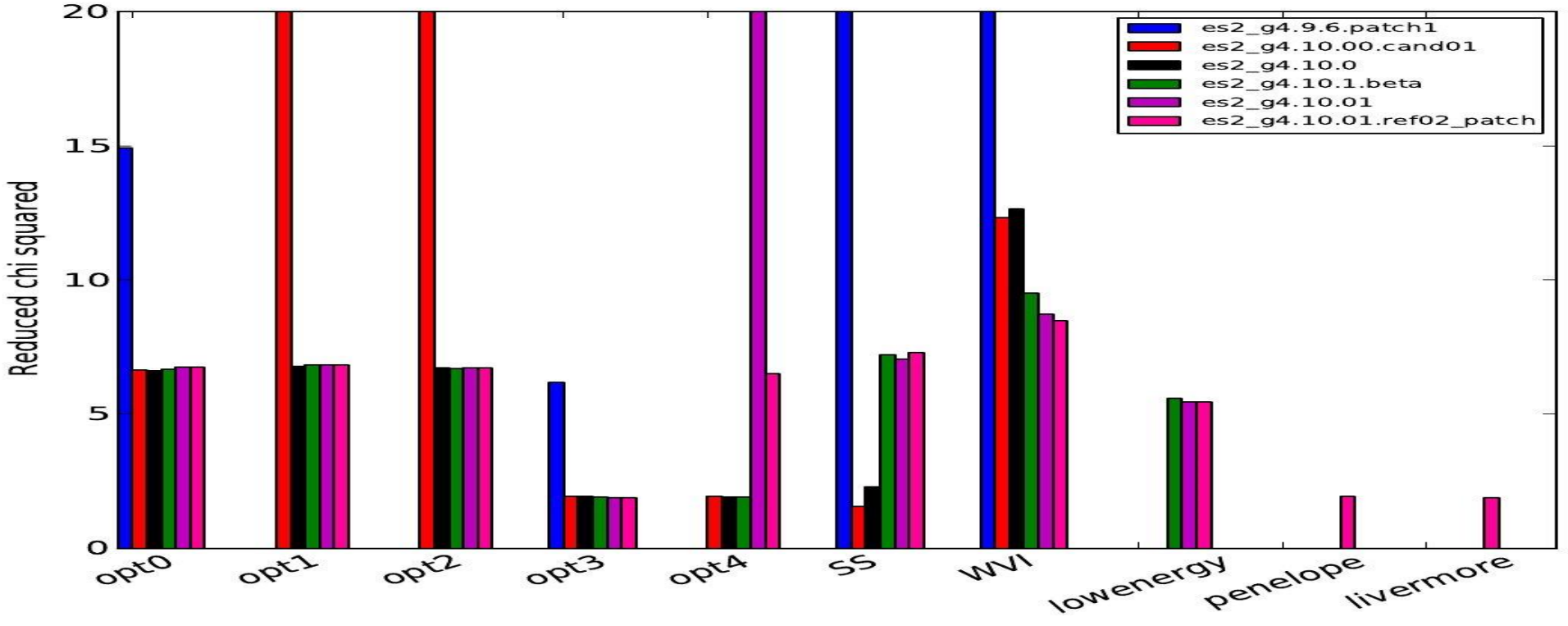
Chi-square

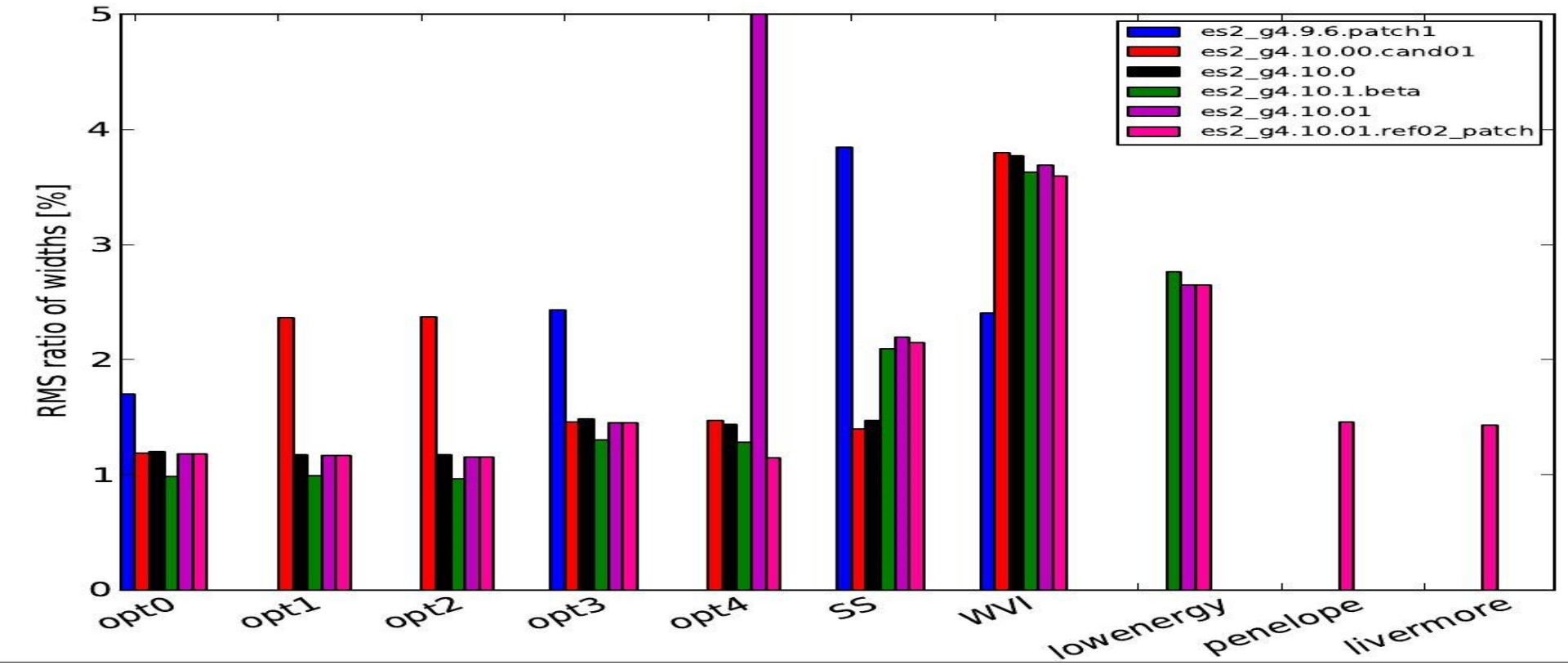

Reduced chi squared
20
15
10
5
0
IDEAL
es2_g4.9.6.patch1
es2_g4.10.00.cand01
es2_g4.10.0
es2_g4.10.1.beta
es2_g4.10.01
es2_g4.10.01.ref02_patch
opt0
opt1
opt2
opt3
opt4
SS
WVI
lowenergy
penelope
livermore

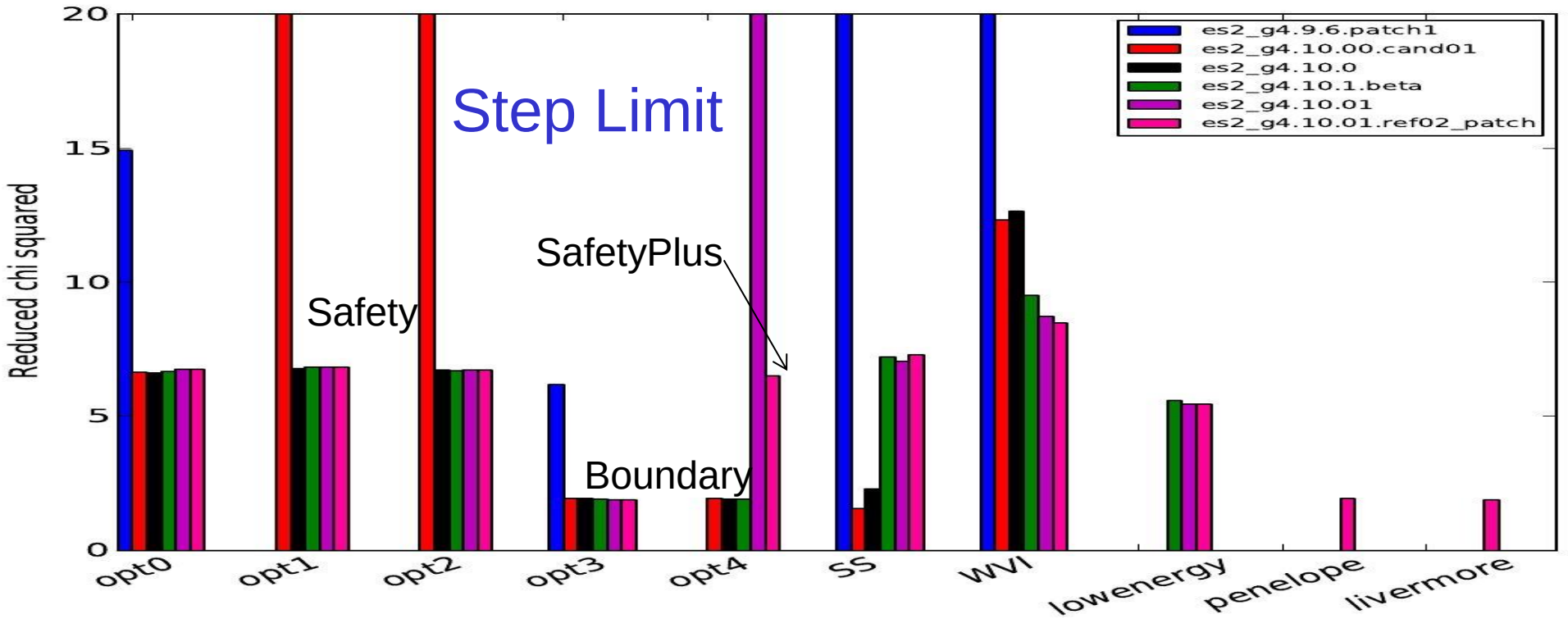

RMS ratio of widths [%]
0
1
2
3
4
5
opt0
opt1
opt2
opt3
opt4
SS
WVI
lowenergy
penelope
livermore
es2_g4.9.6.patch1
es2_g4.10.00.cand01
es2_g4.10.0
es2_g4.10.1.beta
es2_g4.10.01
es2_g4.10.01.ref02_patch


Reduced chi squared
0
5
10
15
20
opt0
opt1
opt2
opt3
opt4
SS
WVI
lowenergy
penelope
livermore
es2_g4.9.6.patch1
es2_g4.10.00.cand01
es2_g4.10.0
es2_g4.10.1.beta
es2_g4.10.01
es2_g4.10.01.ref02_patch


LateralDisplacementBeyondSafety
on
off
RMS ratio of widths [%]
0
1
2
3
4
5
opt0
opt1
opt2
opt3
opt4
SS
WVI
lowenergy
penelope
livermore
es2_g4.9.6.patch1
es2_g4.10.00.cand01
es2_g4.10.0
es2_g4.10.1.beta
es2_g4.10.01
es2_g4.10.01.ref02_patch


Reduced chi squared
0
5
10
15
20
opt0
opt1
opt2
opt3
opt4
SS
WVI
lowenergy
penelope
livermore
es2_g4.9.6.patch1
es2_g4.10.00.cand01
es2_g4.10.0
es2_g4.10.1.beta
es2_g4.10.01
es2_g4.10.01.ref02_patch


RMS ratio of widths [%]
0
1
2
3
4
5
es2_g4.9.6.patch1
es2_g4.10.00.cand01
es2_g4.10.0
es2_g4.10.1.beta
es2_g4.10.01
es2_g4.10.01.ref02_patch
opt0
opt1
opt2
opt3
opt4
SS
WVI
lowenergy
penelope
livermore


Reduced chi squared
0
5
10
15
20
Step Limit
Safety
SafetyPlus
Boundary
es2_g4.9.6.patch1
es2_g4.10.00.cand01
es2_g4.10.0
es2_g4.10.1.beta
es2_g4.10.01
es2_g4.10.01.ref02_patch
opt0
opt1
opt2
opt3
opt4
SS
WVI
lowenergy
penelope
livermore

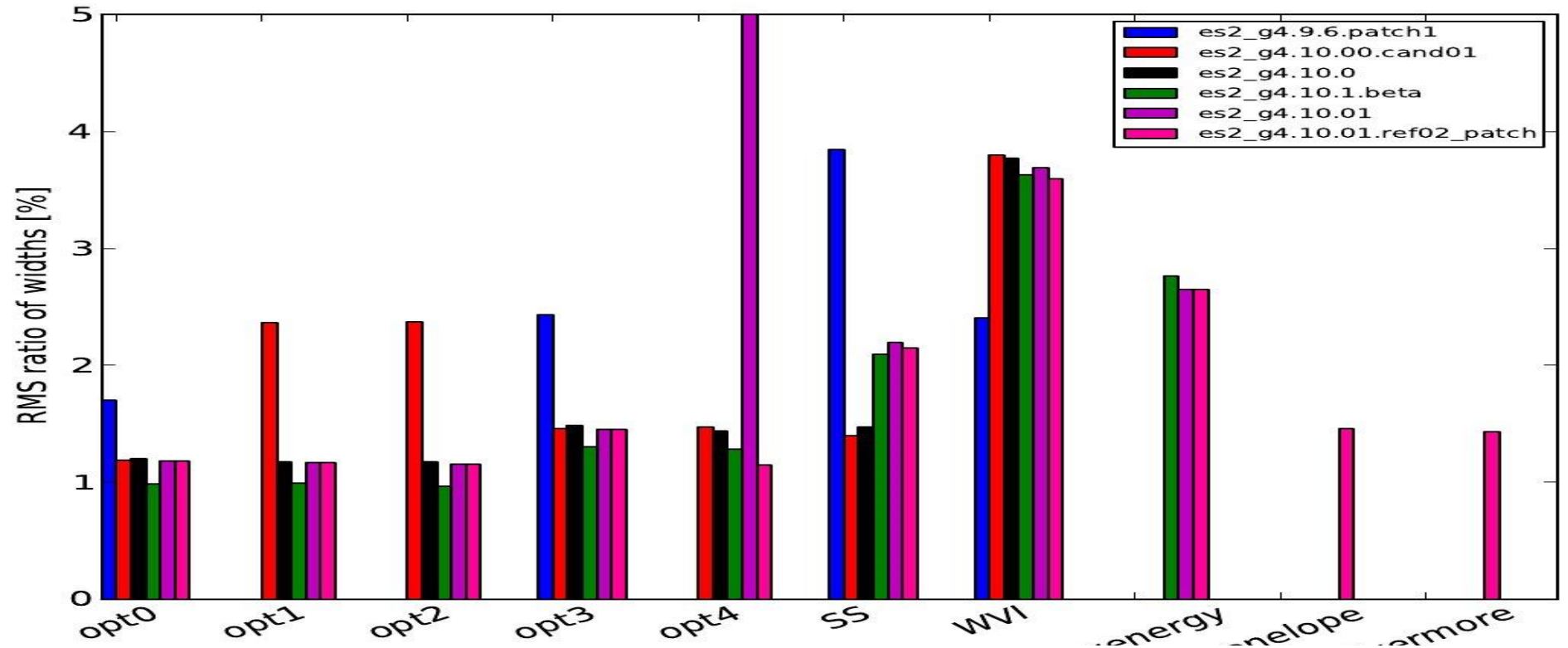
TestEm5, 10 MeV e- through 10 um Cu

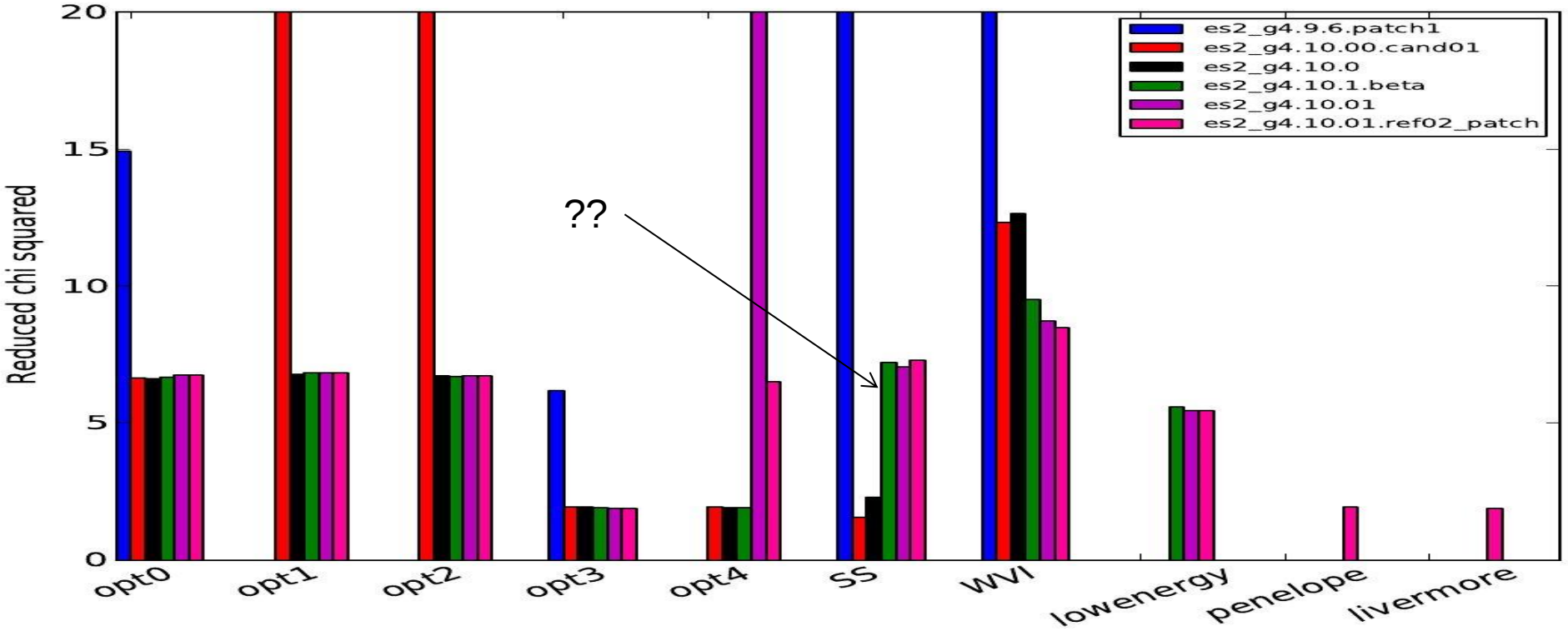
Distance to boundary: msc limits step; strict near boundary

```
*********************************************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 1,   Parent ID = 0
*********************************************************************************************************

Step#      X          Y          Z         KineE    dEStep    StepLeng  TrakLeng    Volume     Process
    0   -7.5 um       0 fm       0 fm     10 MeV     0 eV       0 fm       0 fm      World   initStep
    1     -5 um       0 fm       0 fm     10 MeV7.57e-23 eV    2.5 um     2.5 um      World   Transportation
    2  -4.99 um       0 fm       0 fm     10 MeV     0 eV    8.11 nm    2.51 um   Absorber          msc
    3   -1.6 um    87.2 nm  -1.17 nm   9.99 MeV  6.65 keV    3.4 um    5.91 um   Absorber          msc
    4   2.44 um     -24 nm     180 nm   9.99 MeV  7.67 keV  4.04 um    9.95 um   Absorber          msc
    5   4.99 um   -97.4 nm     108 nm   9.98 MeV  4.33 keV  2.56 um    12.5 um   Absorber          msc
    6      5 um   -97.6 nm     108 nm   9.98 MeV     0 eV   8.11 nm    12.5 um   Absorber          msc
    7      5 um   -97.6 nm     108 nm   9.98 MeV  3.53 eV   2.25 nm    12.5 um   Absorber   Transportation
    8    7.5 um    -163 nm    -4.2 nm   9.98 MeV7.58e-23 eV    2.5 um     15 um      World   OutOfWorld
```

SafetyPlus: msc doesn't limit step in absorber.

```
*********************************************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 1,   Parent ID = 0
*********************************************************************************************************

Step#      X          Y          Z         KineE    dEStep    StepLeng  TrakLeng    Volume     Process
    0   -7.5 um       0 fm       0 fm     10 MeV     0 eV       0 fm       0 fm      World   initStep
    1   -7.5 um       0 fm       0 fm     10 MeV     0 eV       0 fm       0 fm      World          msc
    2     -5 um       0 fm       0 fm     10 MeV7.57e-23 eV    2.5 um     2.5 um      World   Transportation
    3      5 um       0 fm       0 fm   9.99 MeV    12 keV    10 um    12.5 um   Absorber   Transportation
    4    7.5 um     201 nm    24.5 nm   9.99 MeV7.59e-23 eV   2.51 um     15 um      World   OutOfWorld
 Run terminated.
```


RMS ratio of widths [%]
0
1
2
3
4
5
opt0
opt1
opt2
opt3
opt4
SS
WVI
es2_g4.9.6.patch1
es2_g4.10.00.cand01
es2_g4.10.0
es2_g4.10.1.beta
es2_g4.10.01
es2_g4.10.01.ref02_patch


Reduced chi squared
0
5
10
15
20
??
opt0
opt1
opt2
opt3
opt4
SS
WVI
lowenergy
penelope
livermore
es2_g4.9.6.patch1
es2_g4.10.00.cand01
es2_g4.10.0
es2_g4.10.1.beta
es2_g4.10.01
es2_g4.10.01.ref02_patch

Conclusions:

Rigorous test of scattering algorithms!

Good calculation of chi-square to test tails

Two metrics per physics list per Geant4 version

Should use boundary-limited step size for option 4