




Validation test of Geant4 electron backscattering

T. Basaglia[1], M. C. Han[2], G. Hoff[3], C. H. Kim[3], S. H. Kim[3], M. G. Pia[4], P. Saracco[4]

[1]CERN, [2]Hanyang University, Seoul, Korea, [3]CAPES, Brasilia, Brazil, [4]INFN Genova, Italy

CERN/PH/SFT-Simulation meeting
16 December 2014

Brief summary

Validation Test of Geant4 Simulation of Electron Backscattering

Sung Hun Kim, Maria Grazia Pia, Tullio Basaglia, Min Cheol Han, Gabriela Hoff, Chan Hyeong Kim and Paolo Saracco

Submitted 12/12/2014 to IEEE TNS

to be cited → *Copyright transferred to IEEE*

The background: 2007-2008

2007 IEEE Nuclear Science Symposium Conference Record N36-4

Best Student paper, IEEE NSS 2007

Validation of Geant4 low energy physics models against electron energy deposition and backscattering data

Anton Lechner, *Student Member, IEEE,* Maria Grazia Pia and Manju Sudhakar

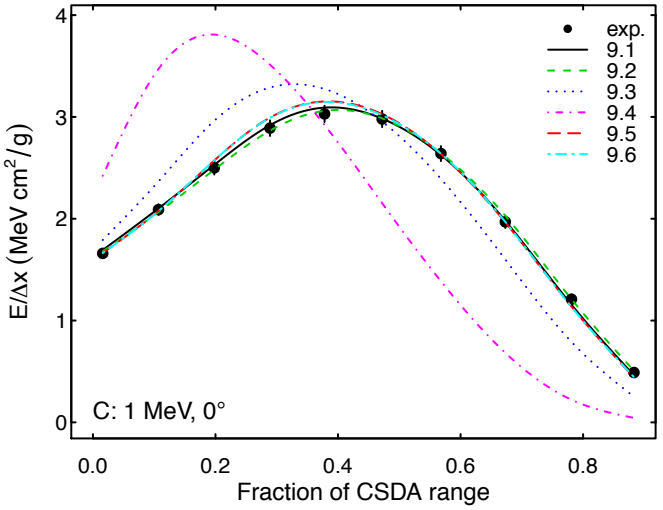
398 TNS, 2009 IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 2, APRIL 2009

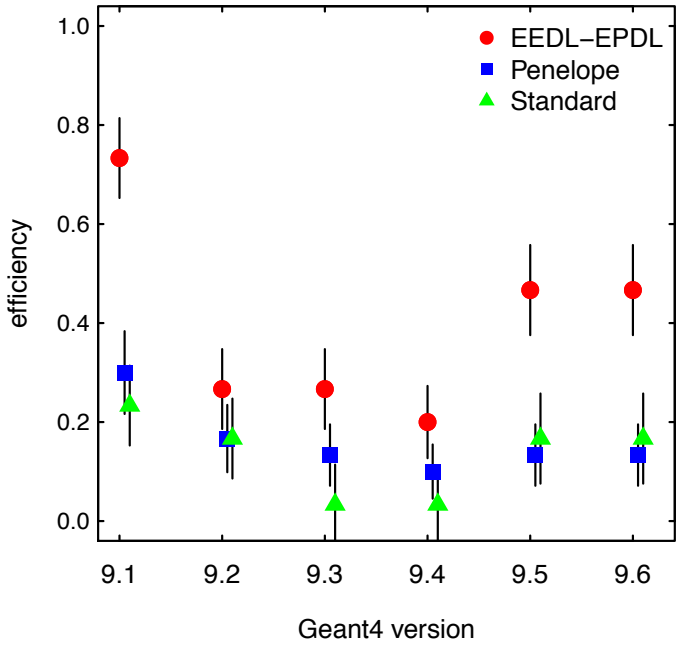
Validation of Geant4 Low Energy Electromagnetic Processes Against Precision Measurements of Electron Energy Deposition

Anton Lechner, Maria Grazia Pia, and Manju Sudhakar

Hint at effects of multiple scattering simulation

The background: 2011-2013





Validation of Geant4 Simulation of Electron Energy Deposition

Matej Batič, Gabriela Hoff, Maria Grazia Pia, Paolo Saracco, and Georg Weidenspointner

Target	Z	E (kev)	angle (degrees)	Geant4 version 9.1	9.2	9.3	9.4	9.5	9.6
Be	4	58	0	0.071	0.014	0.124	0.311	0.149	0.156
Be	4	109	0	0.021	< 0.001	< 0.001	< 0.001	0.015	0.013
Be	4	314	0	0.015	0.764	< 0.001	< 0.001	0.013	0.014
Be	4	521	0	0.092	0.967	< 0.001	< 0.001	0.832	0.793
Be	4	1033	0	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
C	6	1000	0	0.917	0.994	< 0.001	< 0.001	0.290	0.346
Al	13	314	0	0.182	< 0.001	< 0.001	< 0.001	0.004	0.007
Al	13	521	0	0.574	< 0.001	< 0.001	< 0.001	0.091	0.089
Al	13	1033	0	0.484	0.123	< 0.001	< 0.001	< 0.001	< 0.001
Al	13	314	60	0.396	0.596	< 0.001	< 0.001	0.001	0.002
Al	13	521	60	0.137	0.011	0.001	< 0.001	0.056	0.086
Al	13	1033	60	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Fe	26	300	0	0.832	< 0.001	0.351	0.741	0.787	0.742
Fe	26	500	0	0.055	< 0.001	0.314	0.003	0.814	0.808
Fe	26	1000	0	< 0.001	< 0.001	0.169	0.003	< 0.001	< 0.001
Cu	29	300	0	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cu	29	500	0	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Mo	42	100	0	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Mo	42	300	0	0.062	< 0.001	0.001	< 0.001	0.008	0.002
Mo	42	500	0	0.020	< 0.001	< 0.001	0.001	0.128	0.115
Mo	42	1000	0	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Mo	42	300	60	0.023	0.002	0.049	0.043	0.029	0.022
Mo	42	500	60	0.022	< 0.001	0.011	0.006	0.003	0.007
Mo	42	1000	60	0.037	< 0.001	0.010	0.028	0.001	0.002
Ta	73	300	0	0.043	0.511	0.242	0.272	0.364	0.294
Ta	73	500	0	0.025	0.003	< 0.001	< 0.001	0.012	0.019
Ta	73	1000	0	0.030	< 0.001	< 0.001	< 0.001	0.002	0.001
Ta	73	500	60	0.011	0.003	0.040	0.042	0.010	0.007
Ta	73	1000	60	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Ta	73	500	30	0.034	0.005	0.004	0.006	0.020	0.017

Hint at effects of multiple scattering simulation

2014

1st dedicated validation test of Geant4 simulation of electron multiple scattering

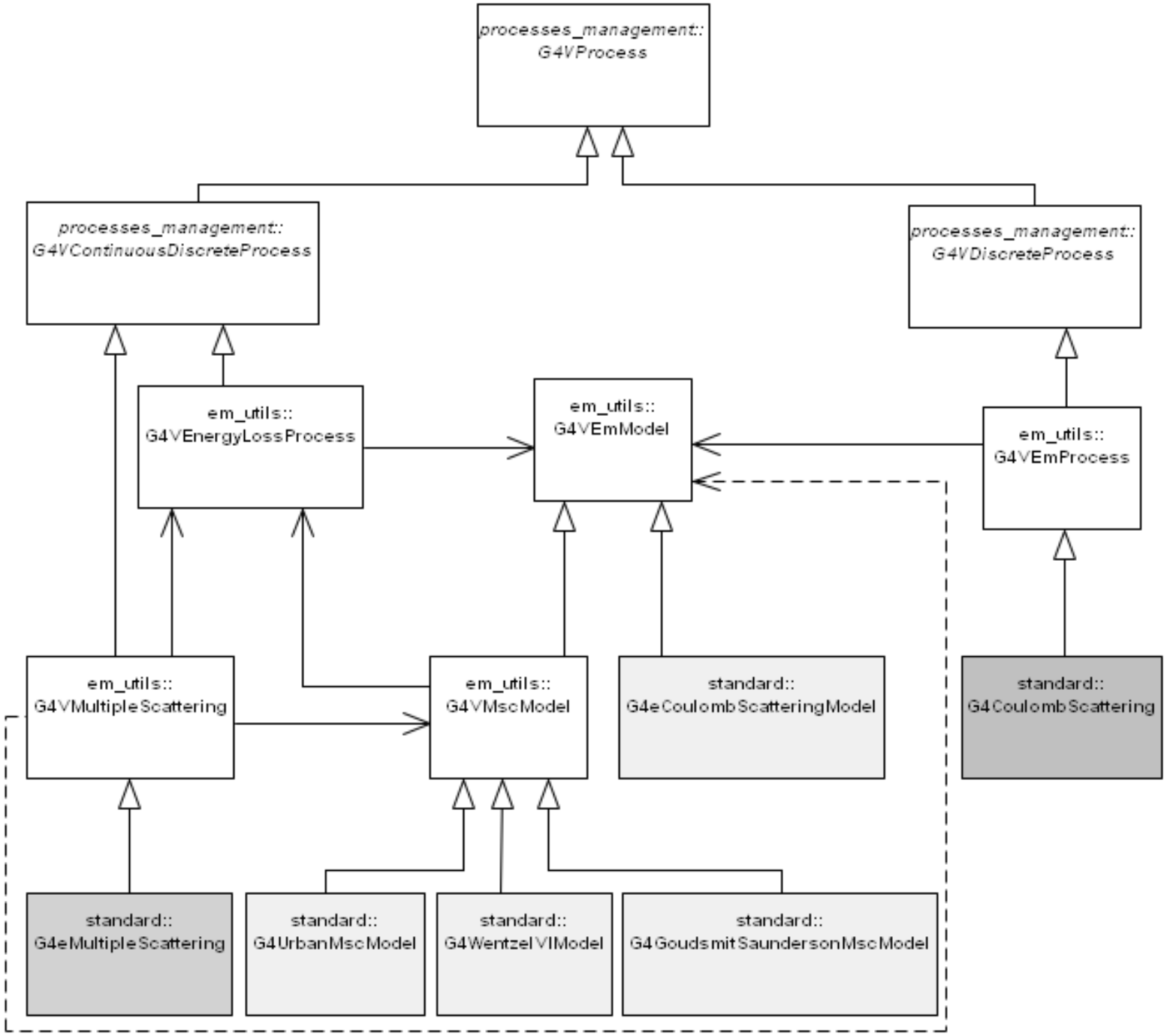
The simplest experimental observable related to electron multiple (single) scattering:
backscattering fraction

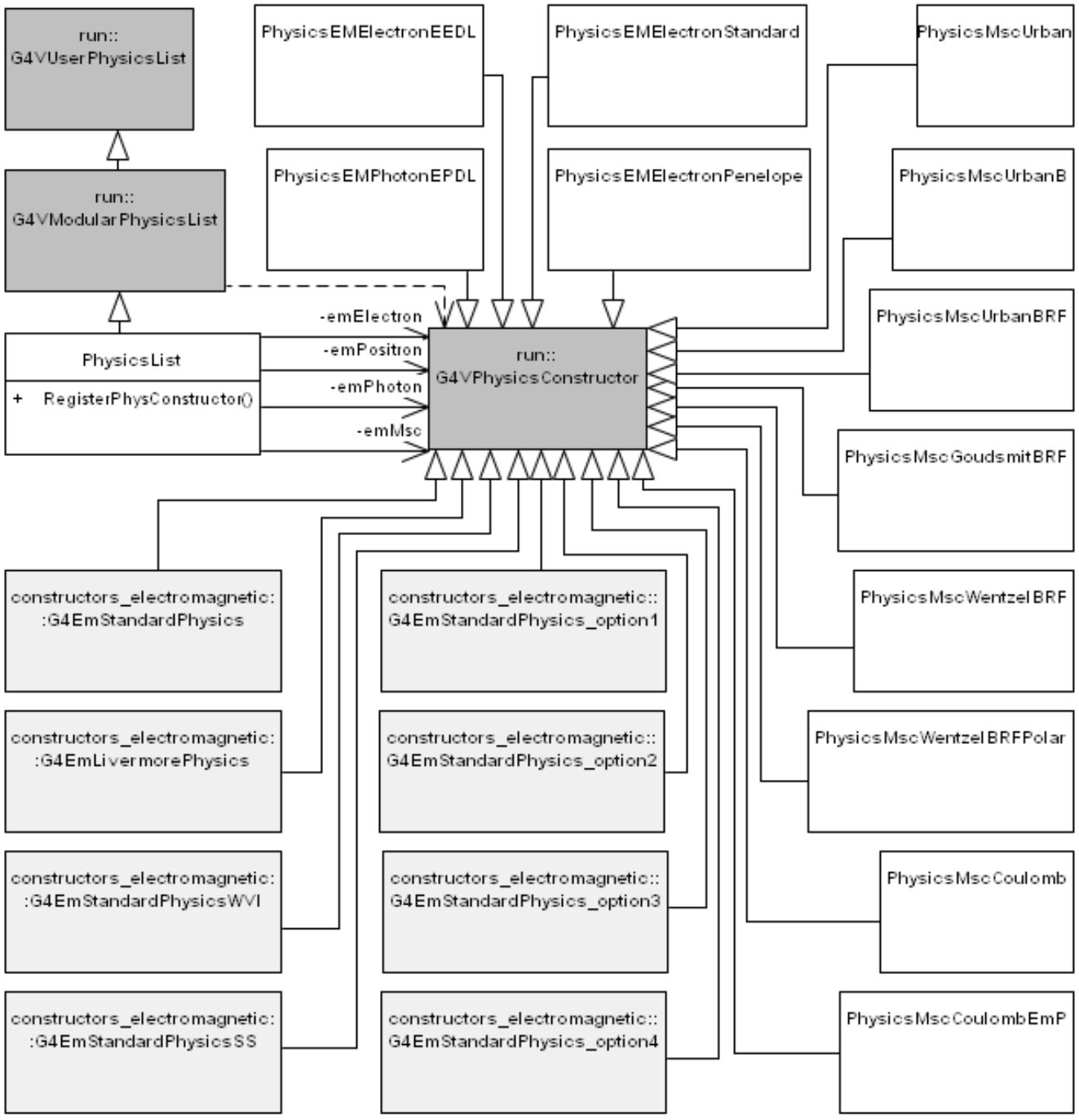
Is there any correlation with the validity of simulated electron energy deposition?

Sung Hun's paper for Korean PhD scholarship application

Strategy

- Compare Geant4 electron backscattering simulated by Geant4 with experimental data
  - Sensitive to electron multiple (single) scattering
- First validation phase: the **simplest scenario**
  - Normal incidence
  - (Semi-)infinite (bulk) targets
  - Examine backscattering fraction
- *Next phases: more complex observables*
  - *backscattered energy, angular distribution*
- Large sample of **experimental data** from the literature
- **Geant4 simulation application** reproducing the experimental scenario as realistically as possible
- **Quantitative: statistical data analysis**


processes_management::
G4VProcess
processes_management::
G4VContinuousDiscreteProcess
processes_management::
G4VDiscreteProcess
em_utils::
G4VEnergyLossProcess
em_utils::
G4VEmModel
em_utils::
G4VEmProcess
em_utils::
G4VMultipleScattering
em_utils::
G4VMscModel
standard::
G4eCoulombScatteringModel
standard::
G4CoulombScattering
standard::
G4eMultipleScattering
standard::
G4UrbanMscModel
standard::
G4WentzelVIModel
standard::
G4GoudsmitSaundersonMscModel



Geant4 electron multiple and single electron scattering **processes**

Urban
Goudsmit-Saunderson
WentzelVI
eCoulombScattering
models

EmStandard
EmLivermore
EmStandard_option1
EmStandard_option2
EmStandard_option3
EmStandard_option4
EmStandard_WVI
EmStandard_SS
PhysicsConstructors

9.1-10.1 *(except 9.5)*
Geant4 versions

Configuration	Description	Process class	Model class	StepLimitType	RangeFactor
Urban	Urban model, user step limit	G4eMultipleScattering	G4UrbanMscModel	default	default
UrbanB	Urban model, user step limit	G4eMultipleScattering	G4UrbanMscModel	DistanceToBoundary	default
UrbanBRF	Urban model	G4eMultipleScattering	G4UrbanMscModel	DistanceToBoundary	0.01
GSBRF	Goudsmit-Saunderson	G4eMultipleScattering	G4GoudsmitSaundersonModel	DistanceToBoundary	0.01
WentzelBRF	WentzelVI model	G4eMultipleScattering	G4WentzelVIModel	DistanceToBoundary	0.01
WentzelBRFP	WentzelVI, angle limit	G4eMultipleScattering	G4WentzelVIModel	DistanceToBoundary	0.01
Coulomb	Single scattering, default	G4CoulombScattering	G4eCoulombScatteringModel	default	default
CoulombP	Single scattering, with angle limit *(10.1)*	G4CoulombScattering	G4eCoulombScatteringModel	default	default
		PhysicsConstructor class			
EmLivermore		G4EmLivermorePhysics		DistanceToBoundary	0.01
EmStd	Predefined	G4EmStandardPhysics		default	default
EmOpt1	electromagnetic	G4EmStandardPhysics_option1		default	default
EmOpt2	physics	G4EmStandardPhysics_option2		default	default
EmOpt3	selections	G4EmStandardPhysics_option3		DistanceToBoundary	default
EmOpt4		G4EmStandardPhysics_option4		DistanceToBoundary *(10.0)* SafetyPlus *(10.1)*	0.01 *(10.0)* 0.02 *(10.1)*
EmSS		G4EmStandardPhysics_SS *(10.1)*		default	default
EmWVI		G4EmStandardPhysics_WVI *(10.1)*		default	default

BRF: with *"distanceToBoundary"* and *"rangeFactor"* options (recommended in "high accuracy" EmPhysicsConstructors)

User step limit (Urban, UrbanB): 1 (10) μm

GS, WentzelVI w/o BRF also analyzed

Geant4 versions

- 9.1p03
- 9.2p04
- 9.3p02
- 9.4p04
- 9.6p03
- 10.0p03
- 10.1
  - Preliminary analysis on 10-01-cand02
  - Production verified on released 10.1
- 9.5 omitted due to quantitatively observed similarity with 9.6 in energy deposition validation

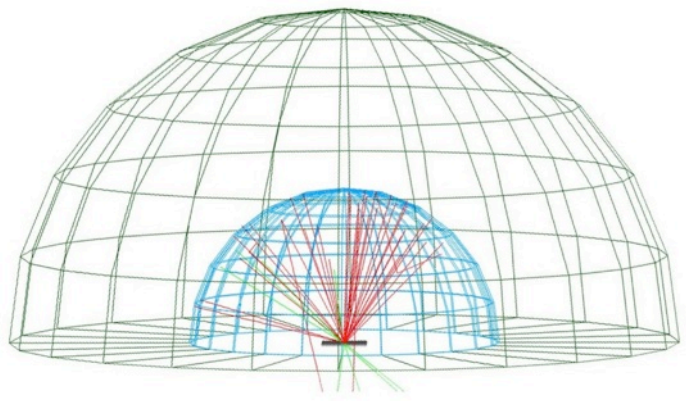
Experimental data

- Collected from the literature: 1947-2008
  - >3000 measurements
  - Z = 4-92
  - Electron energy: 78 eV – 22.2 MeV
- Many experimental papers do not report errors at all
- Many papers only report statistical uncertainties, neglecting sources of systematic errors
- Risk of underestimated experimental errors
  - Uncertainties differ even by an order of magnitude among measurements performed with similar techniques by different groups
- Inconsistencies in the experimental data *(systematics)*
  - Rely on statistical analysis of a large data sample to infer conclusions regarding Geant4 validation

Experimental model

Geant4 application geometry:

- Semi-infinite (infinite) target
- Electron beam, normal incidence, monochromatic
- Sensitive volume: shell in the backward hemisphere,
  energy threshold to exclude counting low energy secondary electrons
- Count events with at least one electron entering the detector
  - May be true backscattered primary electron or secondary electron



Reproduce experimental parameters as documented in the corresponding references

Assumptions based on similar experiments when papers do not document details

Skip details about study of the systematics of the geometry/material model

Physics configuration

When using EM PhysicsConstructors: as is

When using user-defined PhysicsLists

- EEDL-EPDL for electron-photon interactions
  (unless differently specified)
  - Study of systematics with Standard/Penelope electron-photon interactions
  - Photon interactions: negligible *(EPDL validation: published/preliminary)*
- Several multiple/single scattering configurations
  - documented in following slides
- Secondary production threshold: 1 μm (10 μm)

Statistical data analysis

- **Two-sample goodness-of-fit tests**
  - To determine compatibility of simulation and experiment in single test cases
- **Categorical analysis**
  - To quantify whether different models/versions exhibit statistically different compatibility with experiment
  - Beware: **NOT** a comparison of models, but a comparison of their compatibility with experiment, based on the outcome of GoF tests
  - Distinguish analysis of related/unrelated data
- **Correlation analysis:**
  - Backscattering/energy deposition **validation**
  - Correlation measures *(descriptive statistics, no inference)*
  - Tests of significance *(for inference)*
- Use a **variety of tests** and **correlation measures** to **mitigate the risk** of systematic effects in the conclusions
- **Significance level: $\alpha \geq 0.01$**

GoF tests

- Two-sample goodness-of-fit tests based on the EDF *(empirical distribution function)*
  - **Kolmogorov-Smirnov**
  - **Anderson-Darling**
  - **Cramer-von-Mises**
  - **Watson**
- These tests do not involve experimental errors explicitly *(unlike the χ^2 test)*
  - Allow using data from experimental sources that do not report errors
  - **Mitigate the risk** of incorrect conclusions when experimental errors are underestimated
- Use a **variety of tests** based on different test statistic to **mitigate the risk** of biased conclusions
- **Significance level**: **$\alpha \geq 0.01$**
- **Efficiency** = fraction of test cases with **$\alpha \geq 0.01$**

Categorical analysis

Unrelated

- e.g. backscattering simulated with two (nominally) different multiple scattering models
- Fisher exact test
- Barnard test *(Z-pooled statistic)*
- Boschloo test
- Pearson χ^2 *(when appropriate)*

- Contingency tables

	Category A	Category B
Pass	N_{passA}	N_{passB}
Fail	N_{failA}	N_{failB}

Related

- e.g. same multiple scattering model in two Geant4 versions, same model with different parameter settings
- McNemar (exact) test
  - McNemar test with χ^2 approximation when appropriate

- Matched-pair tables

	Category A: Pass	Category A: Fail
Category B: Pass	$N_{pass\ A,\ pass\ B}$	$N_{fail\ A,\ pass\ B}$
Category B: Fail	$N_{pass\ A,\ fail\ B}$	$N_{fail\ A,\ fail\ B}$

Partitioning the data sample

- Experimental sample dominated by low energy measurements
- Analysis over the whole data sample risks to mask the energy dependence of the capabilities of Geant4 models
- Partitioned in 3 intervals + 1
  - 1-20 keV
  - 20-100 keV
  - ≥ 100 keV
  - *(no Geant4 electron scattering model appears capable to deal with E<1 keV)*
- Evaluation of **possible systematic effects**: whole analysis repeated with 4 different options of intervals
  - Slightly different tests statistics, **same general conclusions**

Correlation analysis

Non-parametric measures

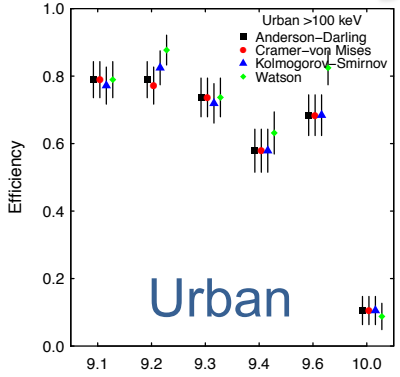
- Spearman ρ
- Kendall τ

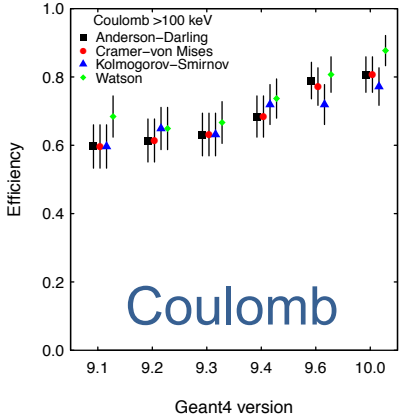
Parametric measures

- Pearson correlation coefficient
  - Normal
  - Limited to linear correlation

Test of significance for inference: Hollander & Wolfe

Efficiency





Consistent results of GoF tests

Use Anderson-Darling results in further analysis

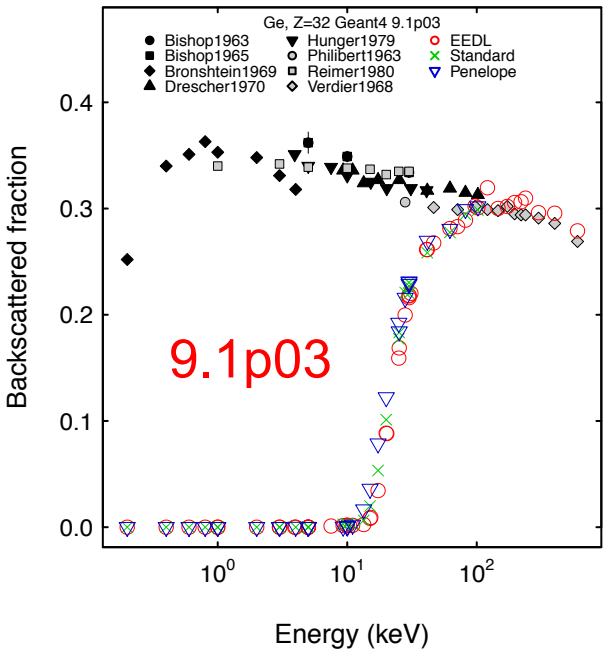
Configuration	Geant4 version	1-20 keV AD	1-20 keV CvM	1-20 keV KS	1-20 keV Watson	20-100 keV AD	20-100 keV CvM	20-100 keV KS	20-100 keV Watson	$>100keV$ AD	$>100keV$ CvM	$>100keV$ KS	$>100keV$ Watson
Urban	9.1	< 0.01	< 0.01	< 0.01	< 0.01	0.10±0.03	0.10±0.03	0.10±0.03	0.10±0.03	0.79±0.05	0.79±0.05	0.77±0.05	0.79±0.05
Urban	9.2	< 0.01	< 0.01	< 0.01	< 0.01	0.03±0.02	0.03±0.02	0.03±0.02	0.03±0.02	0.79±0.05	0.77±0.05	0.82±0.05	0.88±0.04
Urban	9.3	< 0.01	< 0.01	< 0.01	< 0.01	0.09±0.03	0.09±0.03	0.09±0.03	0.09±0.03	0.74±0.06	0.74±0.06	0.72±0.06	0.74±0.06
Urban	9.4	< 0.01	< 0.01	< 0.01	< 0.01	0.10±0.03	0.10±0.03	0.10±0.03	0.10±0.03	0.56±0.06	0.56±0.06	0.56±0.06	0.61±0.06
Urban	9.6	< 0.01	< 0.01	< 0.01	< 0.01	0.17±0.04	0.17±0.04	0.17±0.04	0.17±0.04	0.68±0.06	0.68±0.06	0.68±0.06	0.82±0.05
Urban	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.11±0.04	0.11±0.04	0.11±0.04	0.09±0.04
Urban	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.09±0.04
UrbanB	9.1	< 0.01	< 0.01	< 0.01	< 0.01	0.10±0.02	0.10±0.02	0.10±0.02	0.10±0.02	0.79±0.05	0.79±0.05	0.77±0.05	0.79±0.05
UrbanB	9.2	< 0.01	< 0.01	< 0.01	< 0.01	0.03±0.02	0.03±0.02	0.03±0.02	0.03±0.02	0.79±0.05	0.77±0.05	0.82±0.05	0.88±0.04
UrbanB	9.3	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.11±0.04	0.11±0.04	0.11±0.04	0.11±0.04
UrbanB	9.4	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
UrbanB	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.05±0.03	0.05±0.03	0.05±0.03	0.07±0.04
UrbanB	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
UrbanB	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.09±0.04	0.07±0.04	0.09±0.04	0.11±0.04
UrbanBRF	9.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.05±0.03	0.05±0.03	0.05±0.03	0.07±0.04
UrbanBRF	9.2	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.02±0.02	0.02±0.02	0.02±0.02	0.04±0.03
UrbanBRF	9.3	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
UrbanBRF	9.4	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
UrbanBRF	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
UrbanBRF	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
UrbanBRF	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.09±0.04	0.09±0.04	0.09±0.04	0.09±0.04
Coulomb	9.1	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.16±0.03	0.16±0.03	0.17±0.04	0.18±0.04	0.60±0.06	0.60±0.06	0.60±0.06	0.68±0.06
Coulomb	9.2	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.04±0.02	0.04±0.02	0.04±0.02	0.04±0.02	0.61±0.06	0.61±0.06	0.65±0.06	0.65±0.06
Coulomb	9.3	0.19±0.03	0.18±0.03	0.18±0.03	0.20±0.03	0.08±0.03	0.08±0.03	0.08±0.03	0.09±0.03	0.63±0.06	0.63±0.06	0.63±0.06	0.67±0.06
Coulomb	9.4	0.03±0.02	0.03±0.02	0.04±0.02	0.04±0.02	0.22±0.04	0.21±0.04	0.21±0.04	0.21±0.04	0.68±0.06	0.68±0.06	0.72±0.06	0.74±0.06
Coulomb	9.6	0.48±0.04	0.48±0.04	0.48±0.04	0.46±0.04	0.42±0.05	0.42±0.05	0.42±0.05	0.41±0.05	0.79±0.05	0.77±0.05	0.72±0.06	0.81±0.05
Coulomb	10.0	0.49±0.04	0.49±0.04	0.48±0.04	0.48±0.04	0.40±0.05	0.39±0.05	0.39±0.05	0.38±0.05	0.79±0.05	0.77±0.05	0.79±0.05	0.89±0.04
Coulomb	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.02	< 0.02	< 0.02	< 0.02
CoulombP	10.1	0.47±0.04	0.47±0.04	0.47±0.04	0.46±0.04	0.45±0.05	0.44±0.05	0.44±0.05	0.43±0.05	0.81±0.05	0.81±0.05	0.77±0.05	0.88±0.04
GSBRF	9.3	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.07±0.03	0.07±0.03	0.07±0.03	0.07±0.03
GSBRF	9.4	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.07±0.03	0.07±0.03	0.07±0.03	0.07±0.03
GSBRF	9.6	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.58±0.06	0.58±0.06	0.60±0.06	0.58±0.06
GSBRF	10.0	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.58±0.06	0.56±0.06	0.58±0.06	0.54±0.06
GSBRF	10.1	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.39±0.06	0.40±0.06	0.39±0.06	0.39±0.06
WentzelBRF	9.3	0.18±0.03	0.18±0.03	0.19±0.03	0.20±0.03	0.09±0.03	0.09±0.03	0.09±0.03	0.10±0.03	0.60±0.06	0.60±0.06	0.60±0.06	0.65±0.06
WentzelBRF	9.4	0.02±0.01	0.02±0.01	0.02±0.01	0.04±0.02	0.21±0.04	0.20±0.04	0.20±0.04	0.20±0.04	0.61±0.06	0.60±0.06	0.60±0.06	0.68±0.06
WentzelBRF	9.6	0.46±0.04	0.46±0.04	0.46±0.04	0.46±0.04	0.44±0.05	0.43±0.05	0.43±0.05	0.42±0.05	0.79±0.05	0.77±0.05	0.75±0.06	0.81±0.05
WentzelBRF	10.0	0.49±0.04	0.48±0.04	0.48±0.04	0.49±0.04	0.44±0.05	0.43±0.05	0.43±0.05	0.42±0.05	0.81±0.05	0.79±0.05	0.82±0.05	0.88±0.04
WentzelBRF	10.1	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.42±0.06	0.42±0.06	0.42±0.06	0.46±0.06
WentzelBRFP	9.3	0.02±0.01	0.02±0.01	0.02±0.01	0.03±0.02	0.04±0.02	0.04±0.02	0.04±0.02	0.04±0.02	0.33±0.06	0.33±0.06	0.33±0.06	0.37±0.06
WentzelBRFP	9.4	0.02±0.01	0.02±0.01	0.02±0.01	0.02±0.01	0.03±0.02	0.03±0.02	0.03±0.02	0.03±0.02	0.21±0.05	0.21±0.05	0.21±0.05	0.21±0.05
WentzelBRFP	9.6	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.30±0.05	0.28±0.05	0.30±0.05	0.33±0.05
WentzelBRFP	10.0	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.44±0.06	0.42±0.06	0.44±0.06	0.46±0.06
WentzelBRFP	10.1	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.42±0.06	0.42±0.06	0.42±0.06	0.46±0.06
EmLivermore	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.05±0.03	0.07±0.04	0.07±0.04
EmLivermore	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.05±0.03	0.05±0.03	0.05±0.03	0.05±0.03
EmLivermore	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.09±0.04
EmStd	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.40±0.06	0.40±0.06	0.42±0.06	0.44±0.06
EmStd	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.09±0.04
EmStd	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.05±0.03	0.05±0.03	0.05±0.03	0.05±0.03
EmOpt1	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.33±0.06	0.33±0.06	0.33±0.06	0.35±0.06
EmOpt1	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.39±0.06	0.39±0.06	0.39±0.06	0.40±0.06
EmOpt1	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.14±0.05	0.12±0.05	0.14±0.05	0.18±0.05
EmOpt2	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.32±0.06	0.32±0.06	0.32±0.06	0.35±0.06
EmOpt2	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.37±0.06	0.37±0.06	0.37±0.06	0.40±0.06
EmOpt2	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.16±0.05	0.16±0.05	0.16±0.05	0.19±0.05
EmOpt3	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
EmOpt3	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
EmOpt3	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
EmOpt4	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07±0.04	0.07±0.04	0.07±0.04	0.07±0.04
EmOpt4	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.09±0.04	0.09±0.04	0.09±0.04	0.09±0.04
EmOpt4	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.02	< 0.02	< 0.02	< 0.02
EmWVI	10.1	< 0.01	< 0.01	< 0.01	< 0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.01±0.01	0.40±0.06	0.40±0.06	0.44±0.06	0.46±0.06

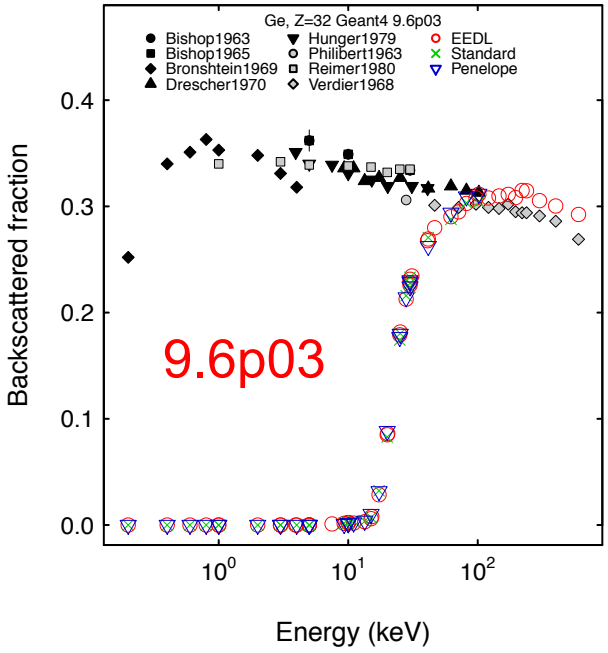
Maria Grazia Pia, INFI

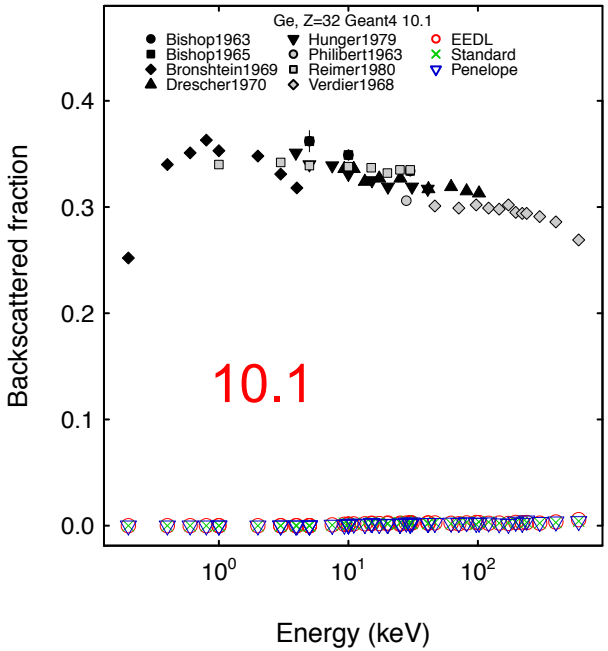
Analysis topics

- Effect of different electron physics modeling
- Urban
- Goudsmit-Saunderson
- Wentzel
- Coulomb (single scattering)
- Predefined electromagnetic constructors
- Correlation with deposited energy validation

Effect of electron-photon interaction modeling







Urban multiple scattering model, with user step limitation

EEDL-EPDL, Standard and Penelope electron models

Limited dependence of the backscattering fraction on the choice of electron-photon models

(backward detected electrons include a small fraction of secondary electrons)

Quantified through categorical analysis

(Fisher exact, Barnard Z-pooled, Boschloo tests, α=0.01)

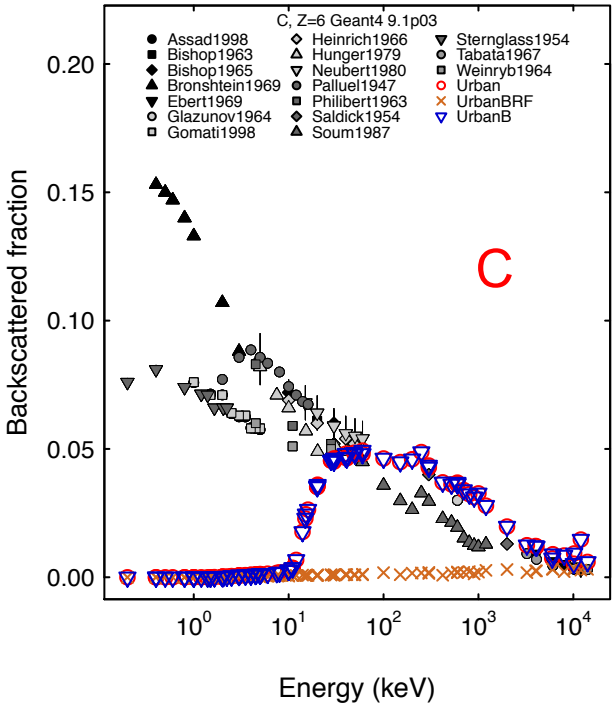
No systematics introduced in further analysis

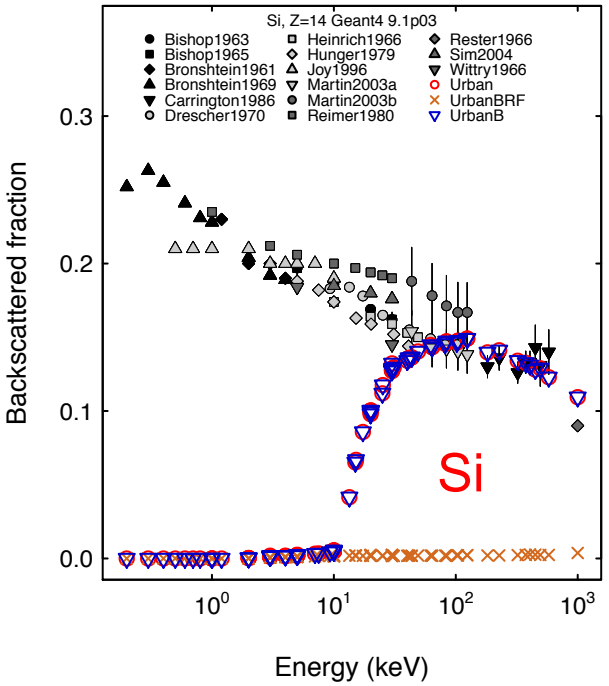
EFFICIENCY FOR THE URBAN MULTIPLE SCATTERING CONFIGURATION WITH DIFFERENT ELECTRON PHYSICS MODELS

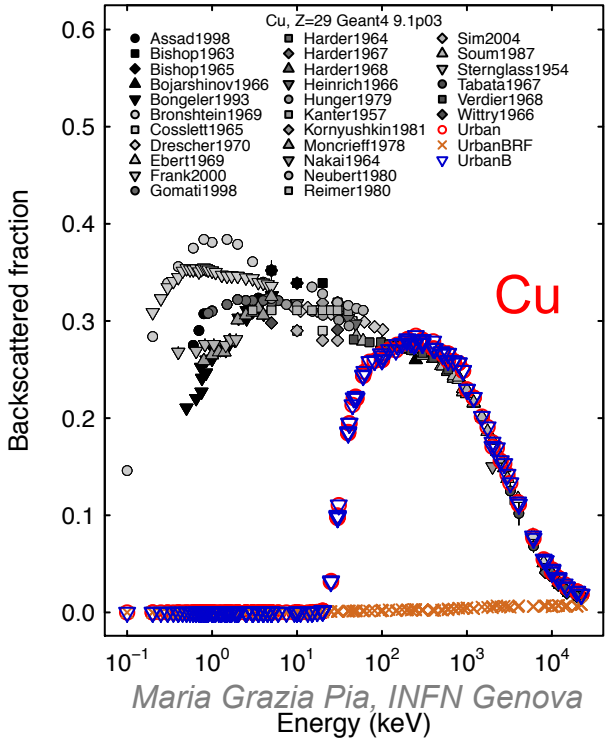
Energy (keV)	Version	EEDL	Standard	Penelope
1-20	9.1	< 0.01	< 0.01	< 0.01
	9.2	< 0.01	< 0.01	< 0.01
	9.3	< 0.01	< 0.01	< 0.01
	9.4	< 0.01	< 0.01	< 0.01
	9.6	< 0.01	< 0.01	< 0.01
	10.0	< 0.01	< 0.01	< 0.01
	10.1	< 0.01	< 0.01	< 0.01
20-100	9.1	0.10±0.03	0.11±0.03	0.07±0.02
	9.2	0.03±0.02	0.06±0.02	0.03±0.02
	9.3	0.09±0.02	0.04±0.02	0.07±0.02
	9.4	0.10±0.03	0.08±0.03	0.09±0.03
	9.6	0.17±0.04	0.15±0.03	0.12±0.03
	10.0	< 0.01	< 0.01	< 0.01
	10.1	< 0.01	< 0.01	< 0.01
>100	9.1	0.79±0.05	0.75±0.06	0.77±0.05
	9.2	0.79±0.05	0.81±0.05	0.74±0.06
	9.3	0.74±0.06	0.65±0.06	0.67±0.06
	9.4	0.58±0.06	0.61±0.06	0.61±0.06
	9.6	0.68±0.06	0.72±0.06	0.68±0.06
	10.0	0.11±0.04	0.09±0.04	0.09±0.04
	10.1	0.07±0.04	0.07±0.04	0.09±0.04

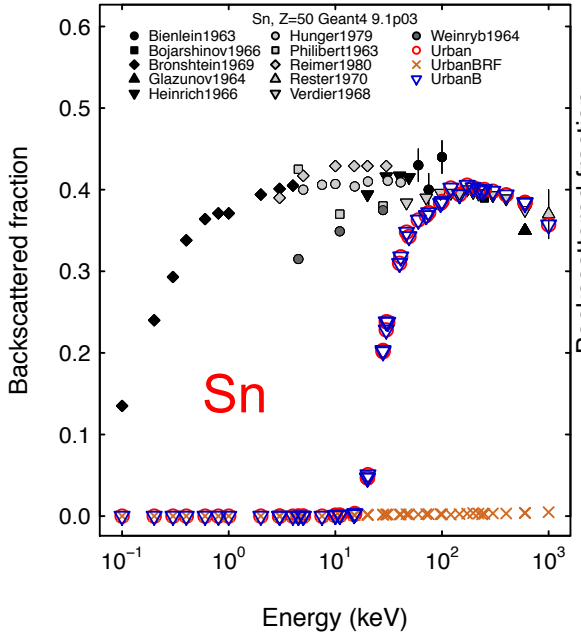
Urban model, Geant4 9.1p03

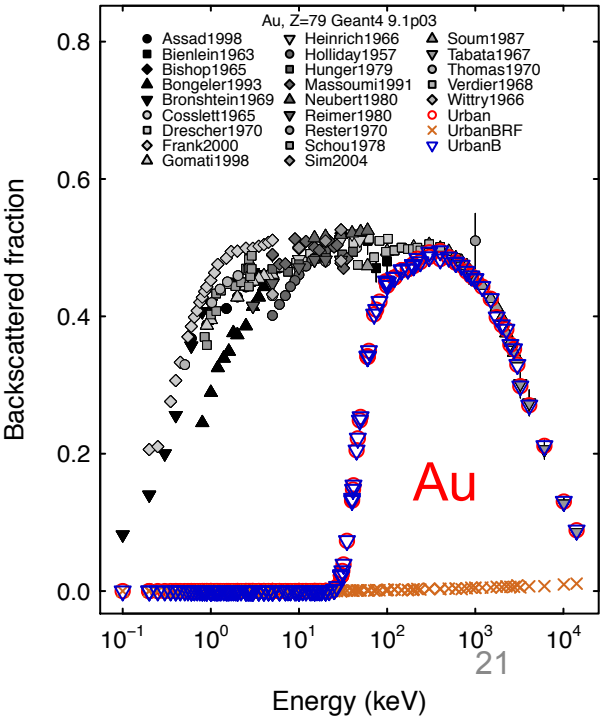
Urban
UrbanB
UrbanBRF





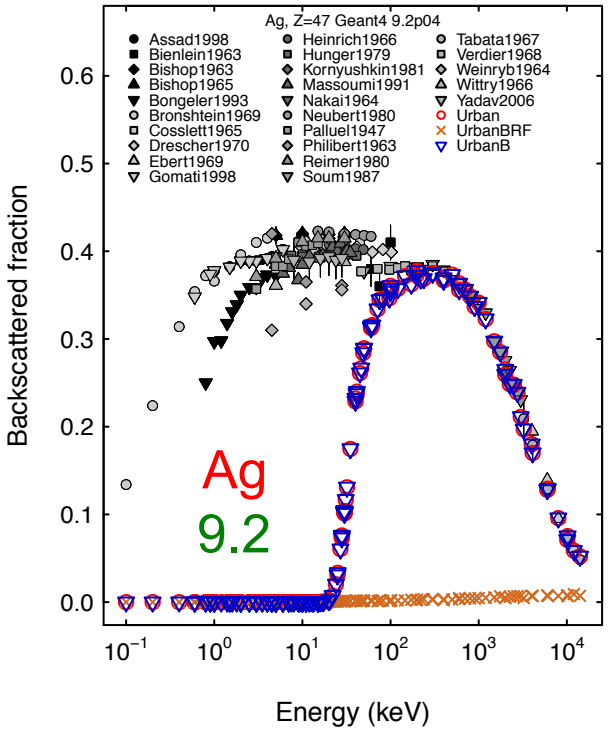


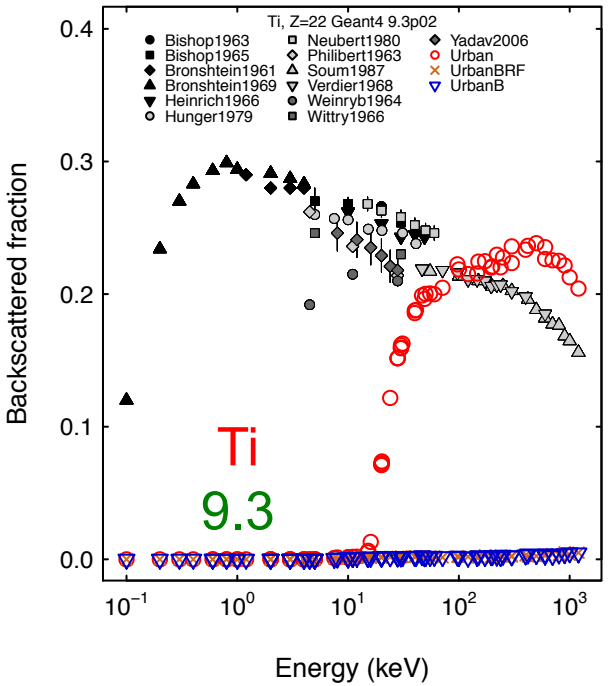


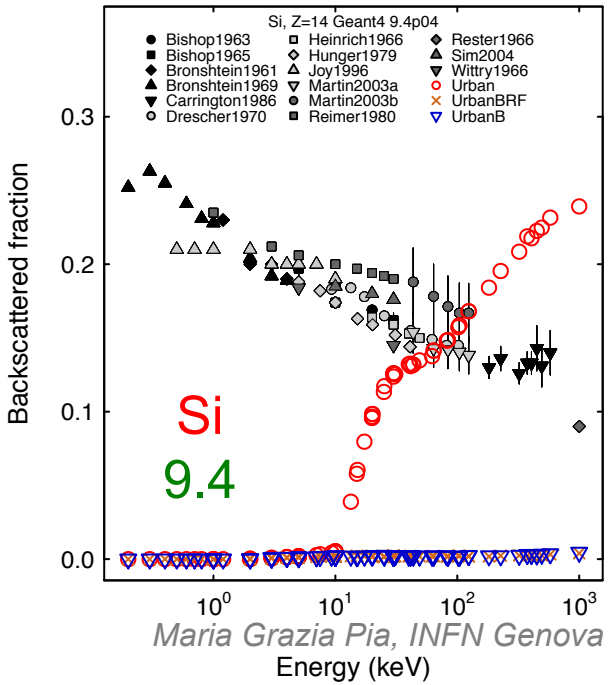


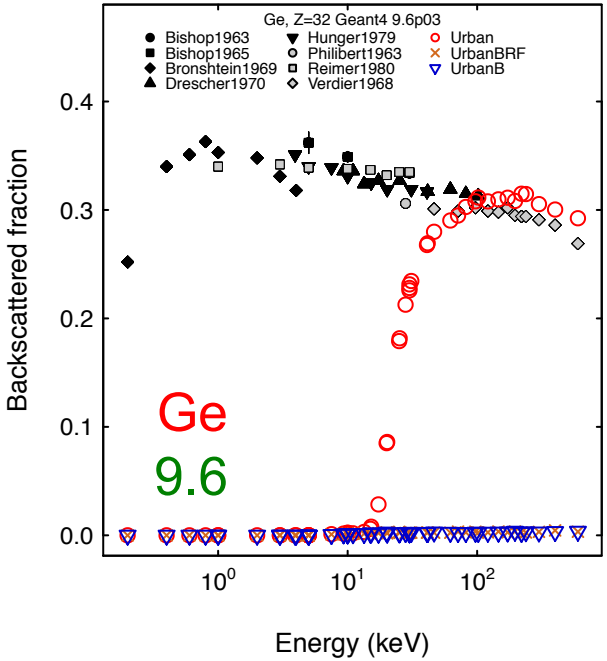
Urban model, Geant4 9.2p04 9.3p02 9.4p04 9.6p03 10.0p03

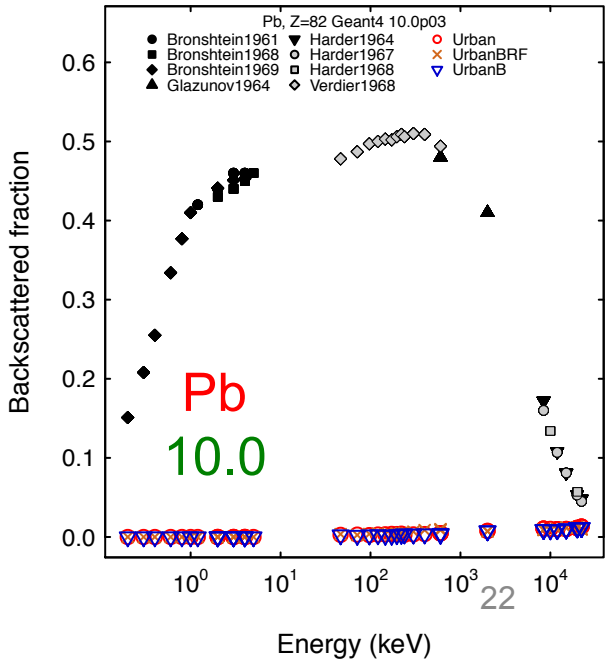
Urban
UrbanB
UrbanBRF





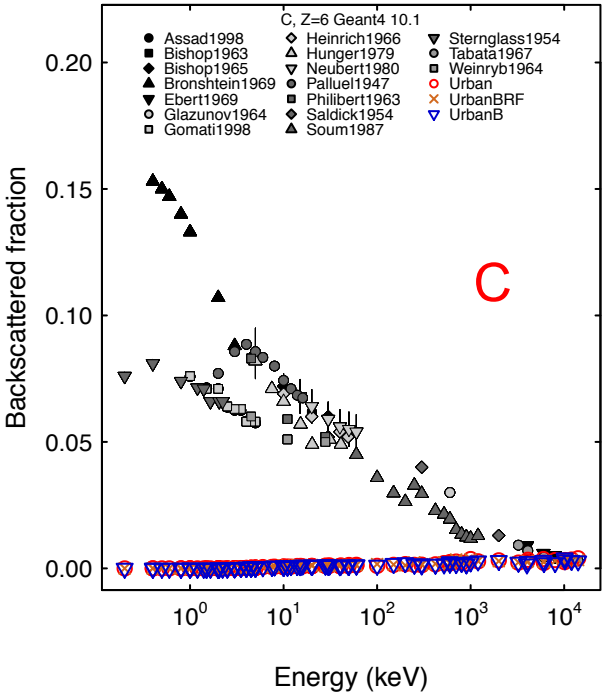


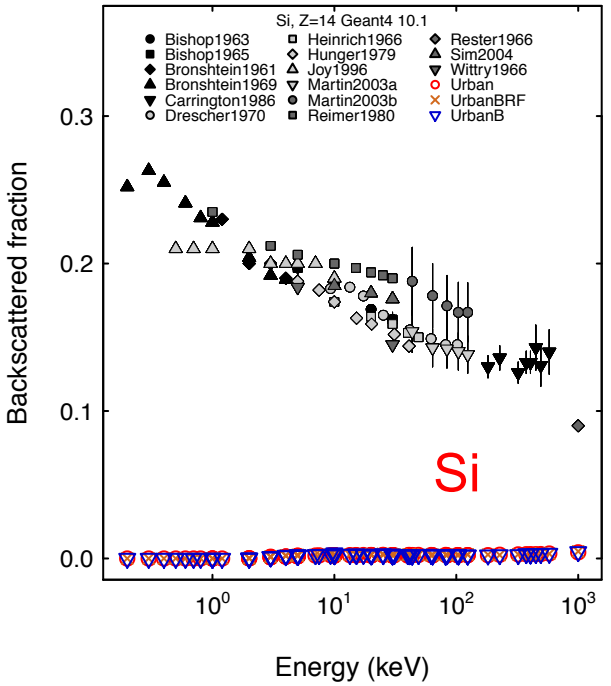


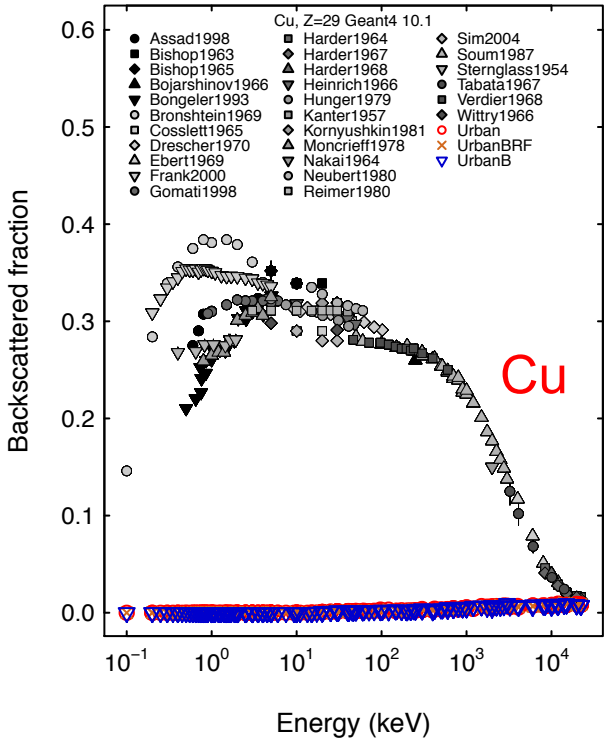


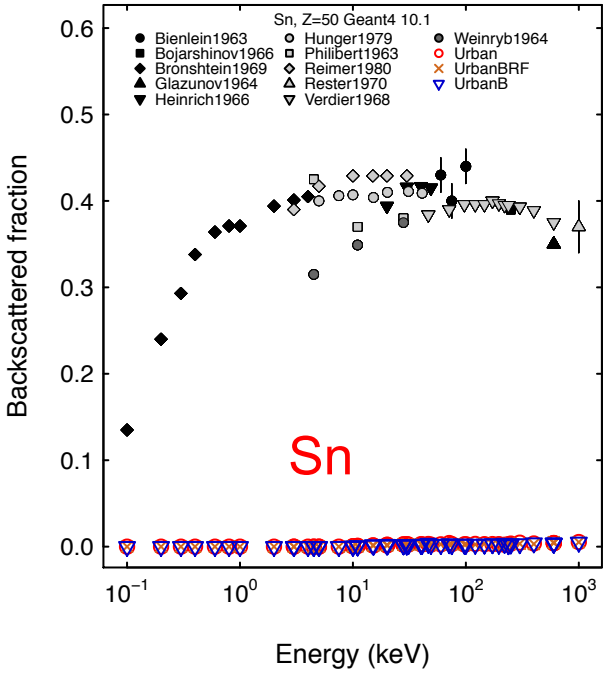
Urban model, Geant4 10.1

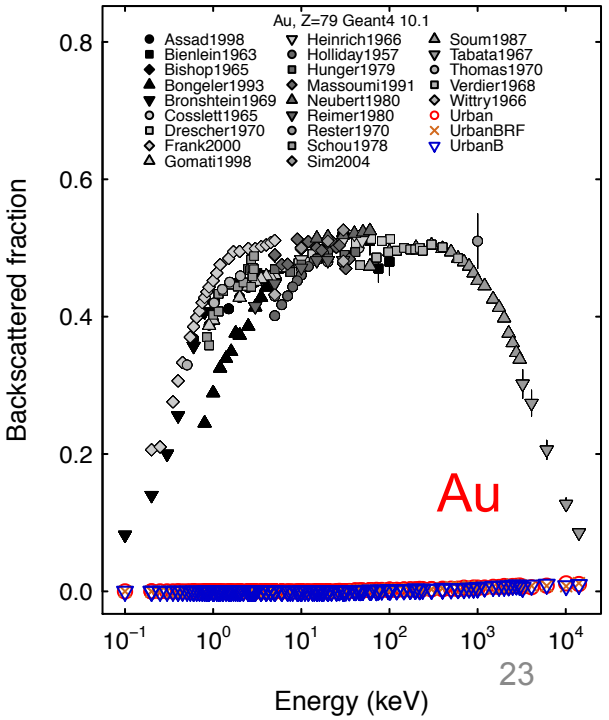
Urban
UrbanB
UrbanBRF



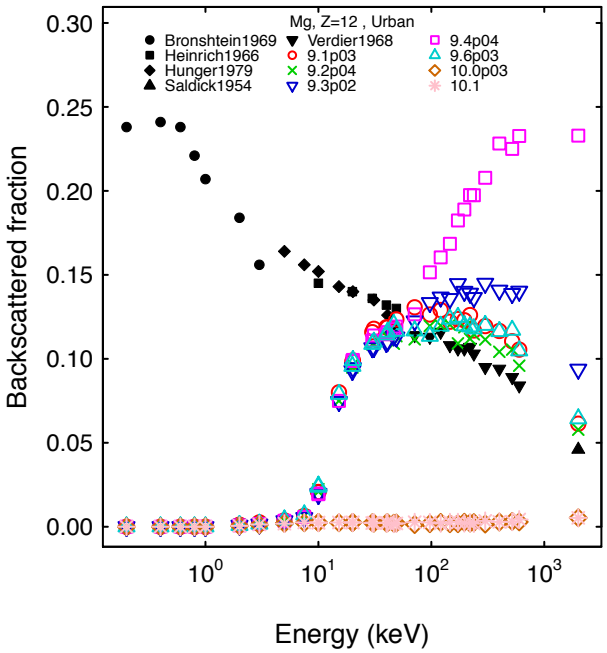


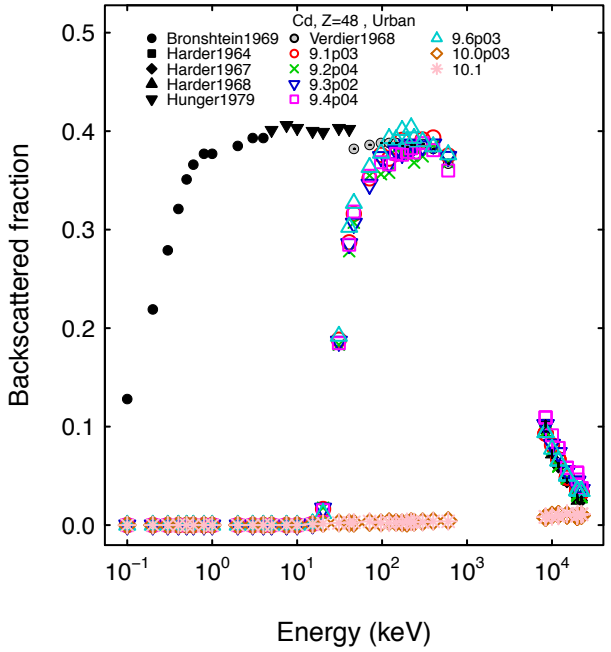






Urban model: 9.1-10.1





9.1p02 9.2p04 9.3p02 9.4p04 9.6p03 10.0p03 10.1

Urban model

P-VALUES RESULTING FROM THE COMPARISON OF COMPATIBILITY WITH EXPERIMENT BETWEEN SIMULATIONS USING URBAN MULTIPLE SCATTERING IN GEANT4 9.1 AND SIMULATIONS USING OTHER UNRELATED CONFIGURATIONS IN VERSIONS 9.6, 10.0 AND 10.1, CONCERNING ELECTRON ENERGY ABOVE 100 KEV

Geant4 Version	Physics Configuration	Fisher Test	Pearson χ^2 Test	Barnard Test	Boschloo Test
9.6	Coulomb	1	1	1	1
	GSBRF	0.026	0.016	0.019	0.19
	WentzelBRF	1	1	1	1
	WentzelBRFP	<0.0001	<0.0001	<0.0001	<0.0001
	EmLivermore	<0.0001		<0.0001	<0.0001
	EmStd	<0.0001	<0.0001	<0.0001	<0.0001
	EmOpt1	<0.0001	<0.0001	<0.0001	<0.0001
	EmOpt2	<0.0001	<0.0001	<0.0001	<0.0001
	EmOpt3	<0.0001		<0.0001	<0.0001
	EmOpt4	<0.0001		<0.0001	<0.0001
10.0	Coulomb	1	0.815	0.889	1
	GSBRF	0.026	0.016	0.019	0.19
	WentzelBRF	1	0.815	0.889	1
	WentzelBRFP	<0.0001		<0.0001	<0.0001
	EmLivermore	<0.0001		<0.0001	<0.0001
	EmStd	<0.0001	<0.0001	<0.0001	<0.0001
	EmOpt1	<0.0001	<0.0001	<0.0001	<0.0001
	EmOpt2	<0.0001	<0.0001	<0.0001	<0.0001
	EmOpt3	<0.0001		<0.0001	<0.0001
	EmOpt4	<0.0001	<0.0001	<0.0001	<0.0001
10.1	Coulomb	<0.0001		<0.0001	<0.0001
	CoulombP	1	1	1	1
	GSBRF	<0.0001	<0.0001	<0.0001	<0.0001
	WentzelBRF	<0.0001	<0.0001	<0.0001	<0.0001
	WentzelBRFP	0.0001		0.0001	0.0001
	EmLivermore	0.0001		0.0001	0.0001
	EmStd	<0.0001		<0.0001	<0.0001
	EmOpt1	<0.0001	<0.0001	<0.0001	<0.0001
	EmOpt2	<0.0001	<0.0001	<0.0001	<0.0001
	EmOpt3	<0.0001		<0.0001	<0.0001
	EmOpt4	<0.0001		<0.0001	<0.0001
	EmWVI	<0.0001		<0.0001	<0.0001

Unrelated modeling options

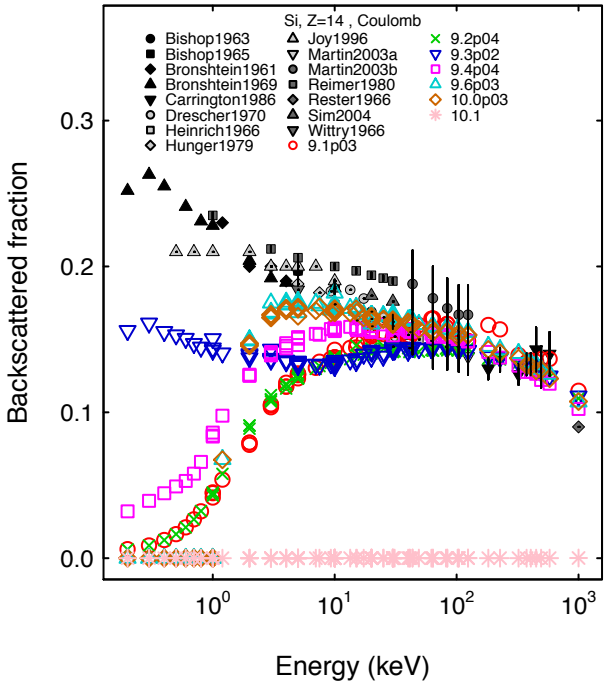
Related modeling options

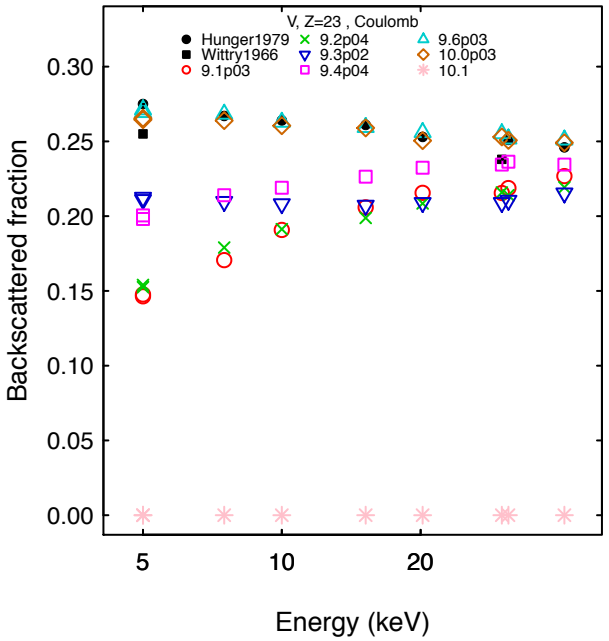
P-VALUES OF MCNEMAR EXACT TEST COMPARING THE COMPATIBILITY WITH EXPERIMENT OF THE URBAN CONFIGURATION IN GEANT4 9.1 WITH LATER GEANT4 VERSIONS AND WITH VARIANTS OF THE URBAN CONFIGURATION

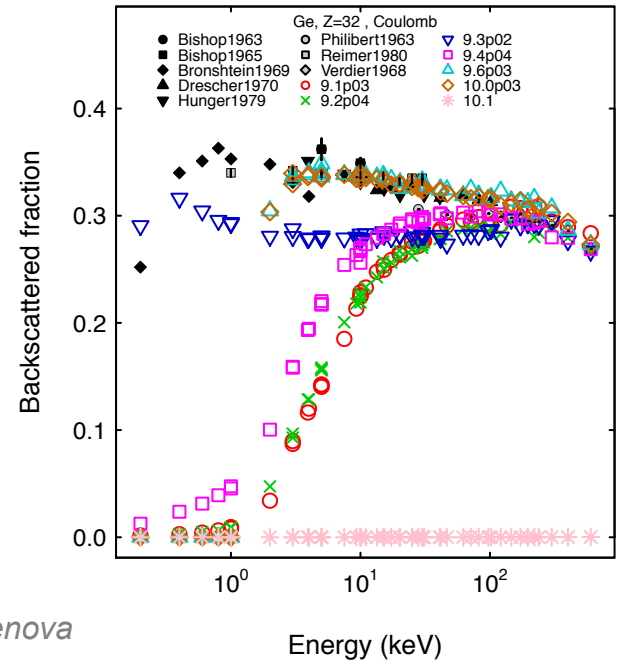
Geant4 Version	Configuration		
	Urban	UrbanB	UrbanBRF
9.1		1.000	<0.001
9.2	1.000	1.000	<0.001
9.3	0.453	<0.001	<0.001
9.4	0.002	<0.001	<0.001
9.6	0.070	<0.001	<0.001
10.0	<0.001	<0.001	<0.001
10.1	<0.001	<0.001	<0.001

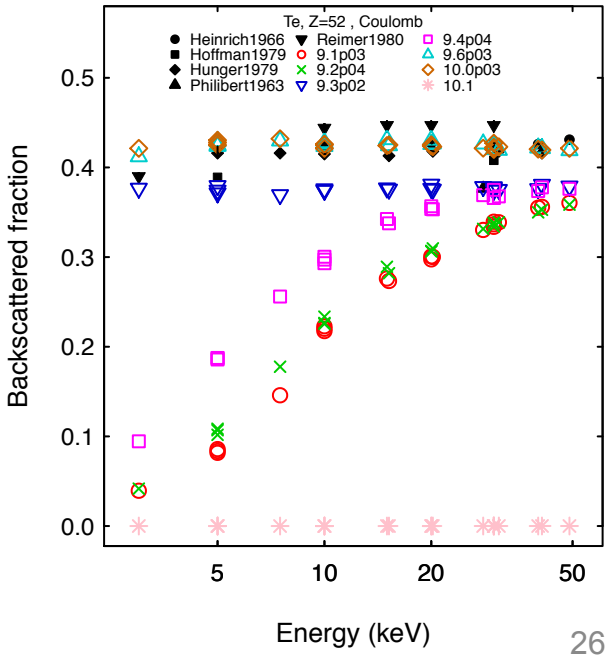
Coulomb scattering

9.1p02
9.2p04
9.3p02
9.4p04
9.6p03
10.0p03
10.1









Coulomb scattering

P-VALUES OF MCNEMAR EXACT TEST COMPARING THE COMPATIBILITY WITH EXPERIMENT OF THE COULOMB CONFIGURATION IN GEANT4 10.0 AND IN OTHER GEANT4 VERSIONS

Version	1-20 keV	20-100 keV	≥100 keV
9.1	< 0.001	< 0.001	< 0.001
9.2	< 0.001	< 0.001	< 0.001
9.3	< 0.001	< 0.001	< 0.001
9.4	< 0.001	0.008	< 0.001
9.6	0.625	0.754	0.625
10.1	< 0.001	< 0.001	< 0.001

Semantic change of Coulomb scattering constructor

Comparable efficiency restored in 10.1 by manually setting "θ limit=0." in the new EmParameters singleton

Coulomb	9.1	0.01±0.01	0.16±0.03	0.60±0.06
Coulomb	9.2	0.01±0.01	0.04±0.02	0.61±0.06
Coulomb	9.3	0.19±0.03	0.08±0.03	0.63±0.06
Coulomb	9.4	0.03±0.02	0.22±0.04	0.68±0.06
Coulomb	9.6	0.48±0.04	0.42±0.05	0.79±0.05
Coulomb	10.0	0.49±0.04	0.40±0.05	0.79±0.05
Coulomb	10.1	< 0.01	< 0.01	< 0.02
CoulombP	10.1	0.47±0.04	0.45±0.05	0.81±0.05

EmStandardPhysics_SS equivalent to CoulombP

P-VALUES RESULTING FROM THE COMPARISON OF COMPATIBILITY WITH EXPERIMENT BETWEEN THE SINGLE COULOMB SCATTERING CONFIGURATION IN GEANT4 10.0 AND OTHER UNRELATED CONFIGURATIONS IN VERSIONS 9.6, 10.0 AND 10.1

Energy (kev)	Geant4 Version	Model	Fischer Test	Pearson χ^2 Test	Barnard Test	Boschloo Test
1-20	9.6	Urban	< 0.001		< 0.001	< 0.001
		GSBRF	< 0.001		< 0.001	< 0.001
		WentzelBRF	0.716	0.627	0.683	0.666
	10.0	Urban	< 0.001		< 0.001	< 0.001
		GSBRF	< 0.001		< 0.001	< 0.001
		WentzelBRF	1	0.903	0.951	1
	10.1	Urban	< 0.001		< 0.001	< 0.001
		GSBRF	< 0.001		< 0.001	< 0.001
		WentzelBRF	< 0.001		< 0.001	< 0.001
20-100	9.6	Urban	< 0.001	< 0.001	< 0.001	< 0.001
		GSBRF	< 0.001		< 0.001	< 0.001
		WentzelBRF	0.685	0.588	0.682	0.624
	10.0	Urban	< 0.001		< 0.001	< 0.001
		GSBRF	< 0.001		< 0.001	< 0.001
		WentzelBRF	0.685	0.588	0.682	0.624
	10.1	Urban	< 0.001		< 0.001	< 0.001
		GSBRF	< 0.001		< 0.001	< 0.001
		WentzelBRF	< 0.001		< 0.001	< 0.001
>100	9.6	Urban	0.196	0.132	0.144	0.160
		GSBRF	0.014	0.008	0.009	0.009
		WentzelBRF	1	0.815	0.889	1
		WentzelBRFP	< 0.001	< 0.001	< 0.001	< 0.001
		EmLivermore	< 0.001		< 0.001	< 0.001
		EmStd	< 0.001	< 0.001	< 0.001	< 0.001
		EmOpt1	< 0.001	< 0.001	< 0.001	< 0.001
		EmOpt2	< 0.001	< 0.001	< 0.001	< 0.001
		EmOpt3	< 0.001		< 0.001	< 0.001
		EmOpt4	< 0.001		< 0.001	< 0.001
	10.0	Urban	< 0.001	< 0.001	< 0.001	< 0.001
		GSBRF	0.014	0.008	0.009	0.009
		WentzelBRF	1	1	1	1
		WentzelBRFP	< 0.001	< 0.001	< 0.001	< 0.001
		EmLivermore	< 0.001		< 0.001	< 0.001
		EmStd	< 0.001		< 0.001	< 0.001
		EmOpt1	< 0.001	< 0.001	< 0.001	< 0.001
		EmOpt2	< 0.001	< 0.001	< 0.001	< 0.001
		EmOpt3	< 0.001		< 0.001	< 0.001
		EmOpt4	< 0.001	< 0.001	< 0.001	< 0.001
	10.1	Urban	< 0.001		< 0.001	< 0.001
		GSBRF	< 0.001	< 0.001	< 0.001	< 0.001
		WentzelBRF	< 0.001	< 0.001	< 0.001	< 0.001
		WentzelBRFP	< 0.001	< 0.001	< 0.001	< 0.001
		EmLivermore	< 0.001		< 0.001	< 0.001
		EmStd	< 0.001		< 0.001	< 0.001
		EmOpt1	< 0.001	< 0.001	< 0.001	< 0.001
		EmOpt2	< 0.001	< 0.001	< 0.001	< 0.001
		EmOpt3	< 0.001		< 0.001	< 0.001
		EmOpt4	< 0.001		< 0.001	< 0.001
		EmWVI	< 0.001	< 0.001	< 0.001	< 0.001

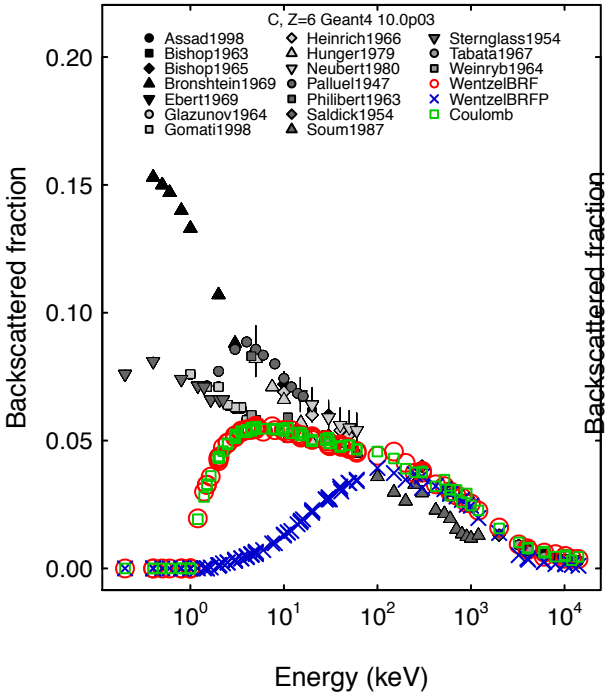
WentzelVI

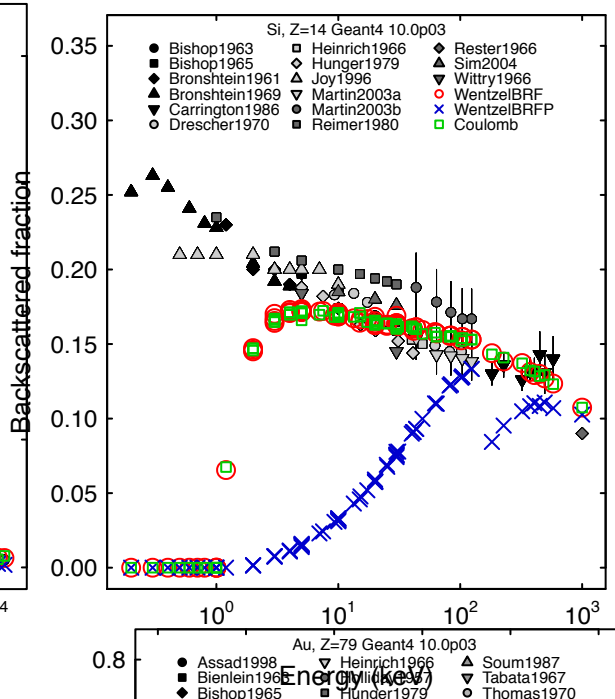
10.0p03

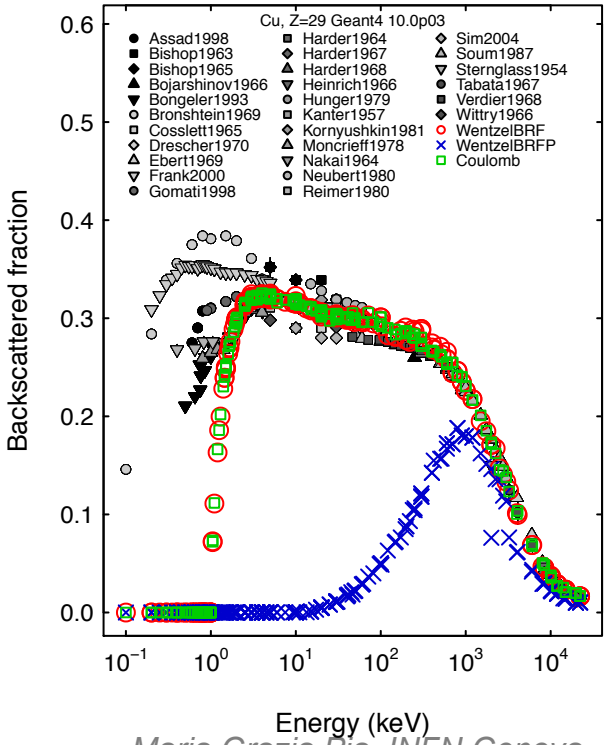
WentzelBRF

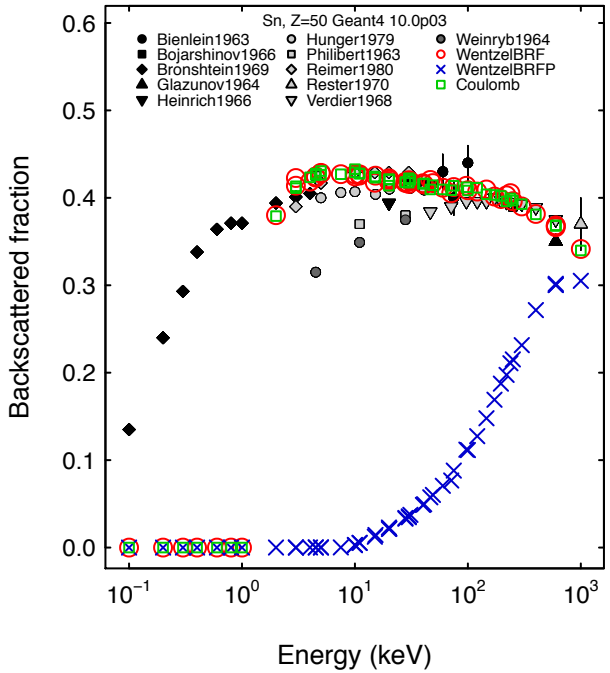
WentzelBRFP

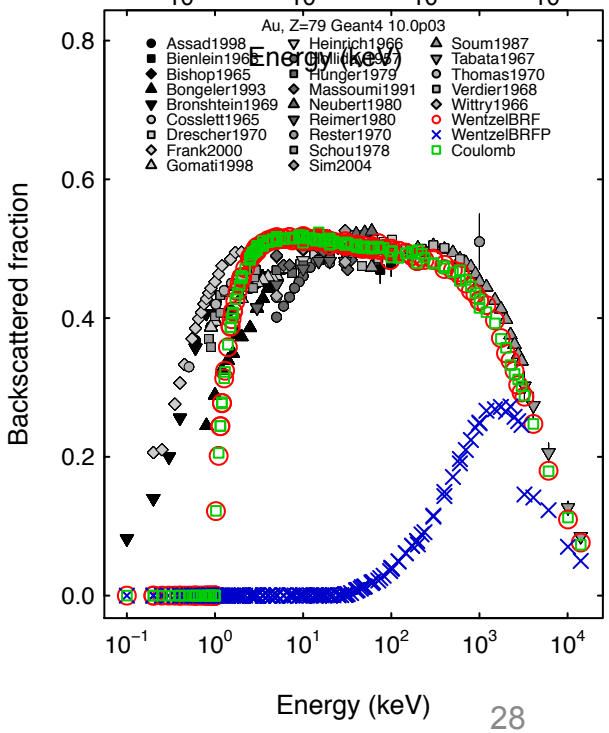
Coulomb











WentzelVI

10.1

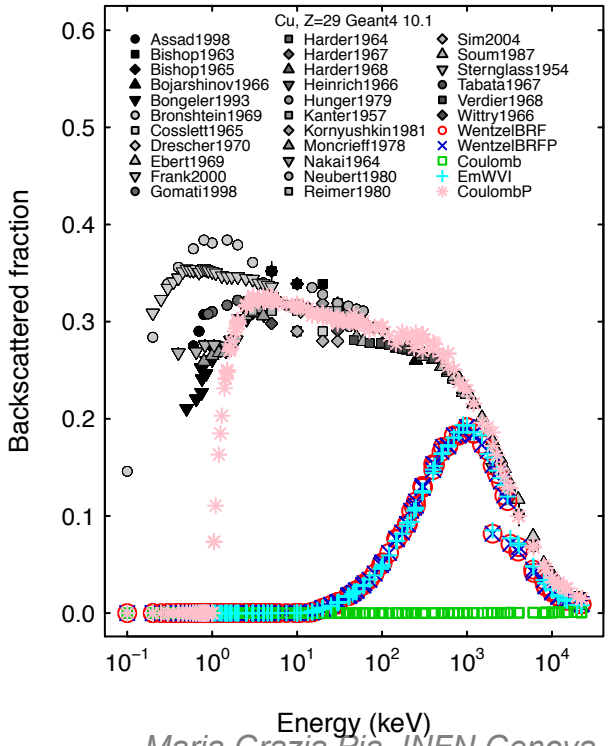
WentzelBRF

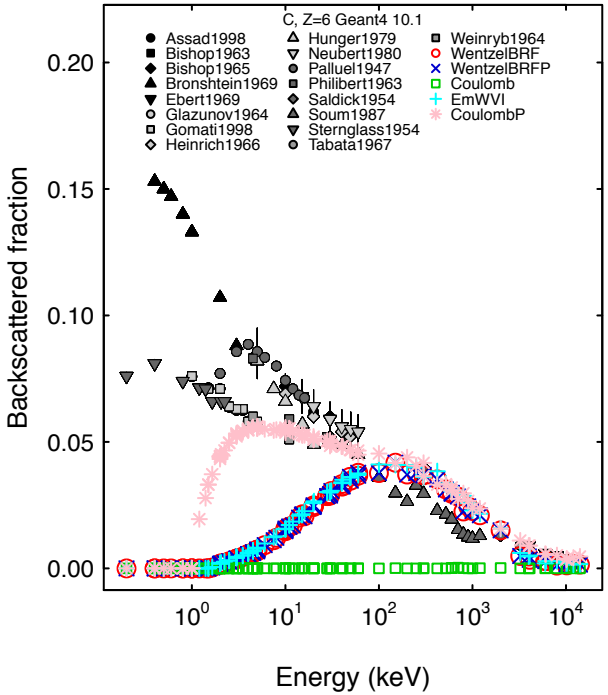
WentzelBRFP

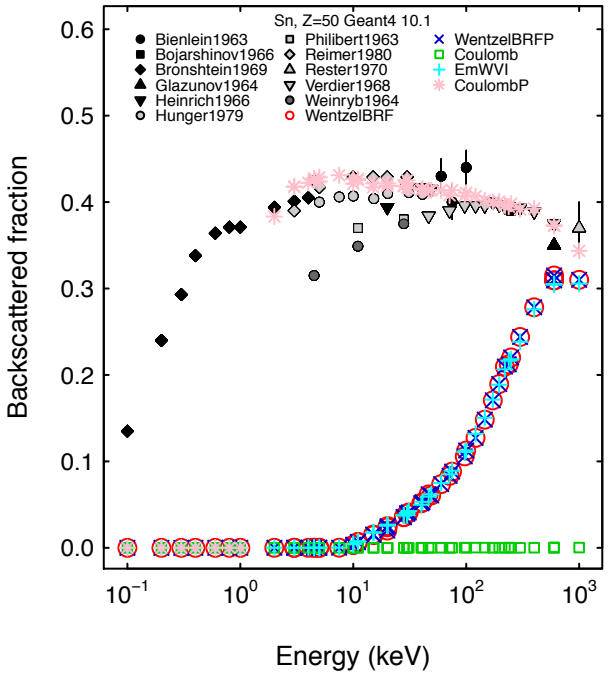
Coulomb

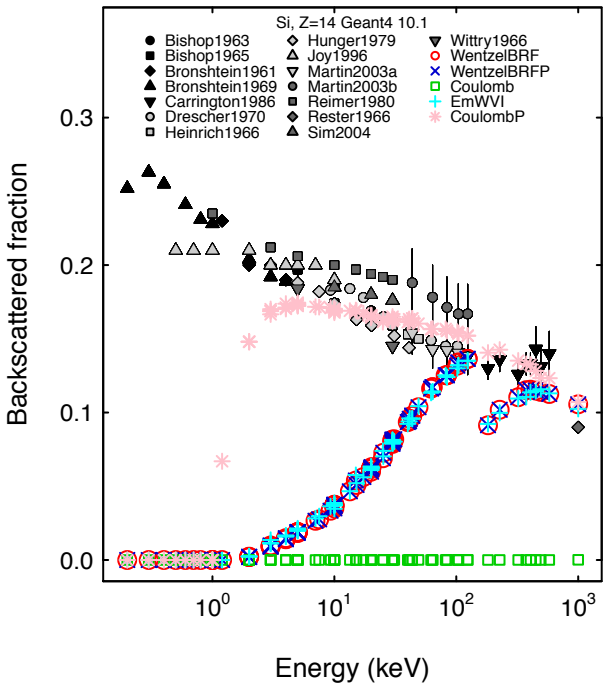
CoulombP

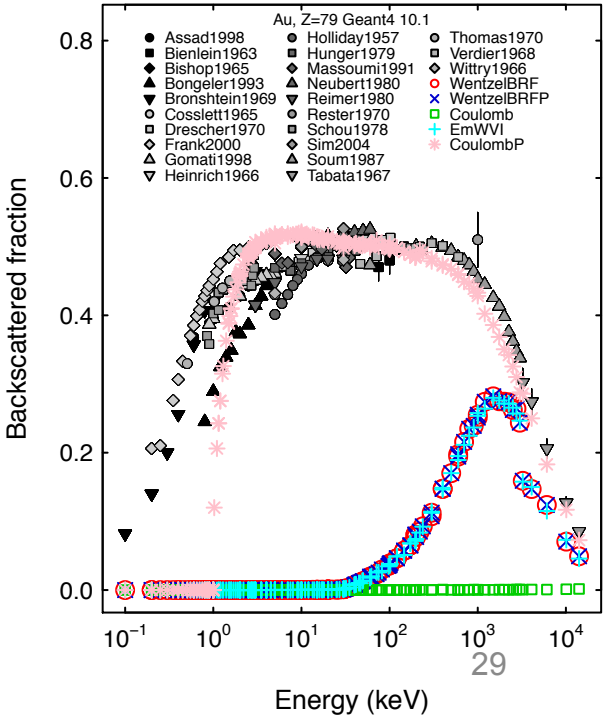
EmWVI









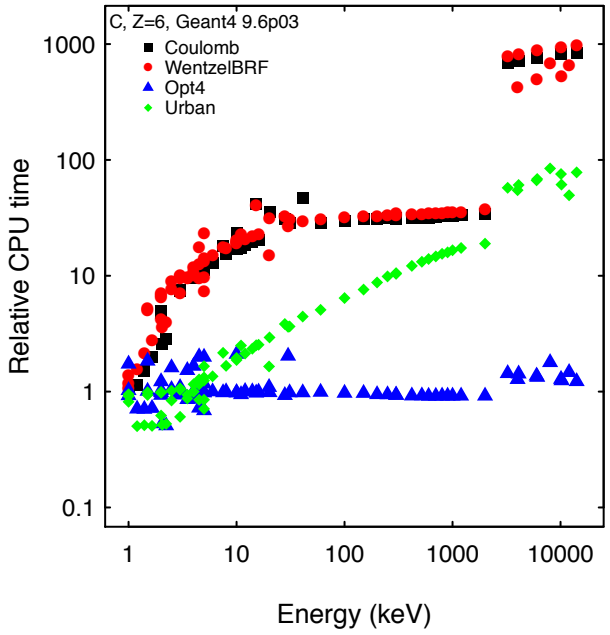


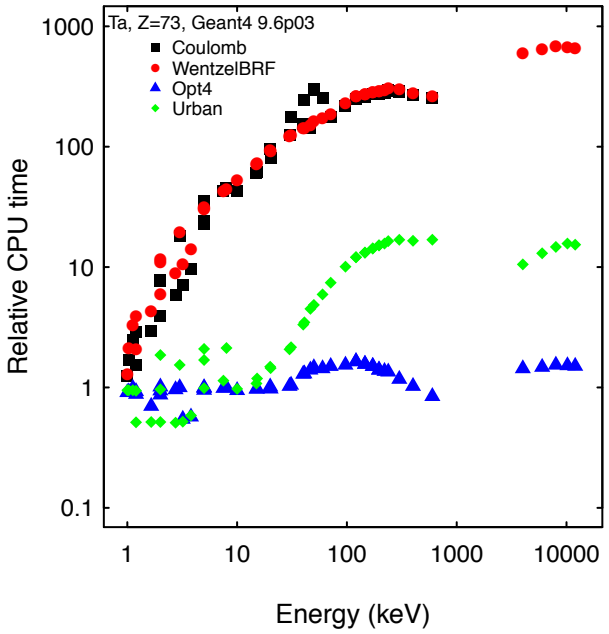
WentzelVI Statistical Analysis

- WentzelBRF and WentzelBRFP
  - H_0 (equivalence) rejected in 9.6, 10.0
  - H_0 not rejected in 10.1
- WentzelBRF and Coulomb(P)
  - H_0 not rejected in 9.6 and 10.0
  - Rejected in 10.1
- WentzelBRF and EmWVI
  - H_0 not rejected in 10.1

Computational performance

Qualitative by-product of validation test





The accuracy of single Coulomb scattering in 9.6 and 10.0 has a CPU cost

Where?

```
void G4EmLivermorePhysics::ConstructProcess()
{
```

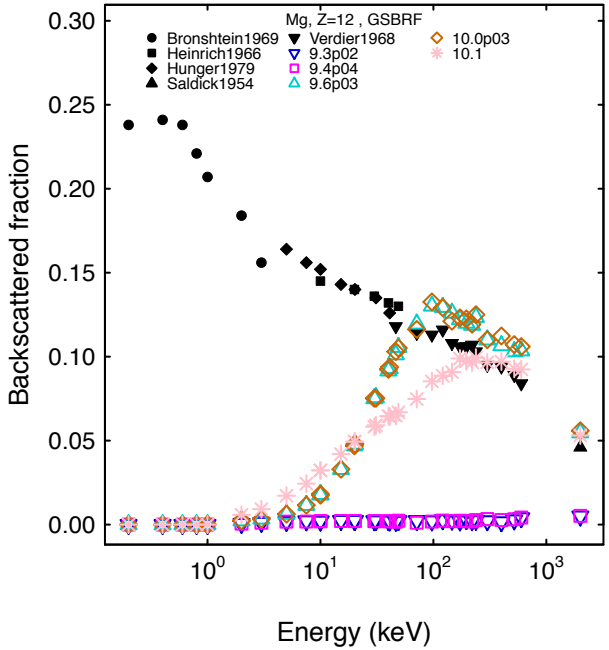
```
  // high energy limit for e+- scattering models
  G4double highEnergyLimit = 100*MeV;
```

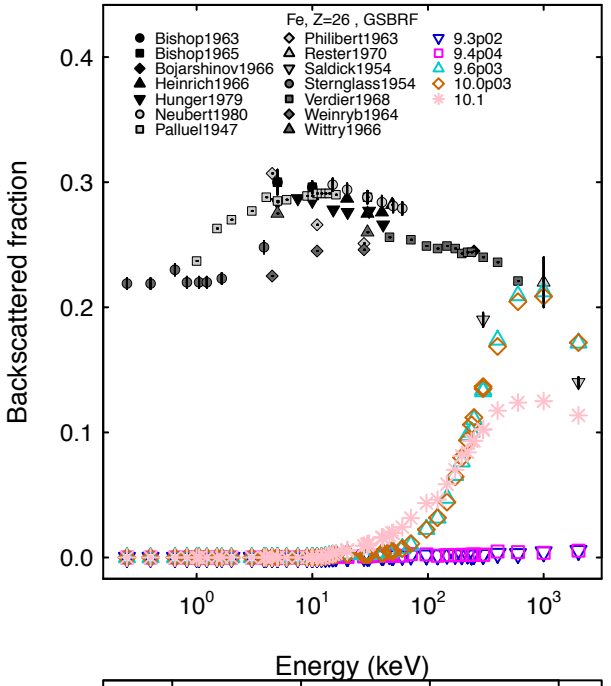
```
  } else if (particleName == "e-") {

    // multiple scattering
    G4eMultipleScattering* msc = new G4eMultipleScattering;
    msc->SetStepLimitType(fUseDistanceToBoundary);
    G4UrbanMscModel* msc1 = new G4UrbanMscModel();
    G4WentzelVIModel* msc2 = new G4WentzelVIModel();
    msc1->SetHighEnergyLimit(highEnergyLimit);
    msc2->SetLowEnergyLimit(highEnergyLimit);
    msc->SetRangeFactor(0.01);
    msc->AddEmModel(0, msc1);
    msc->AddEmModel(0, msc2);

    G4eCoulombScatteringModel* ssm = new G4eCoulombScatteringModel();
    G4CoulombScattering* ss = new G4CoulombScattering();
    ss->SetEmModel(ssm, 1);
    ss->SetMinKinEnergy(highEnergyLimit);
    ssm->SetLowEnergyLimit(highEnergyLimit);
    ssm->SetActivationLowEnergyLimit(highEnergyLimit);
```

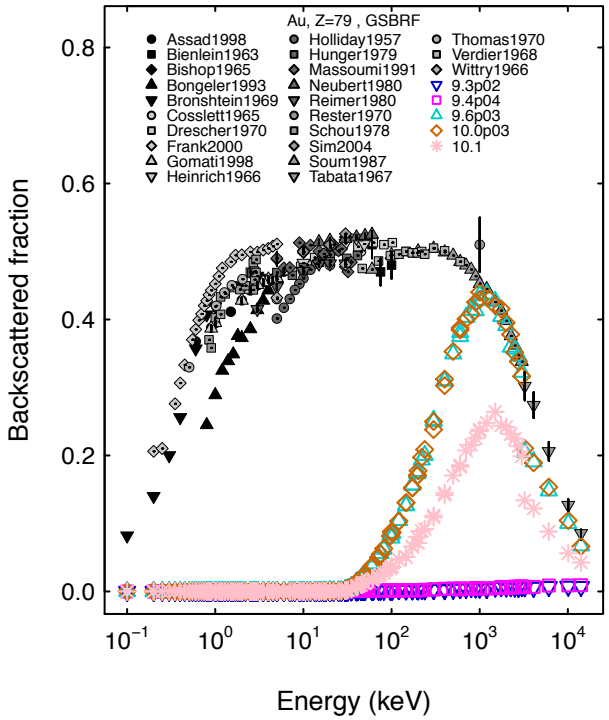
Goudsmit Saunderson

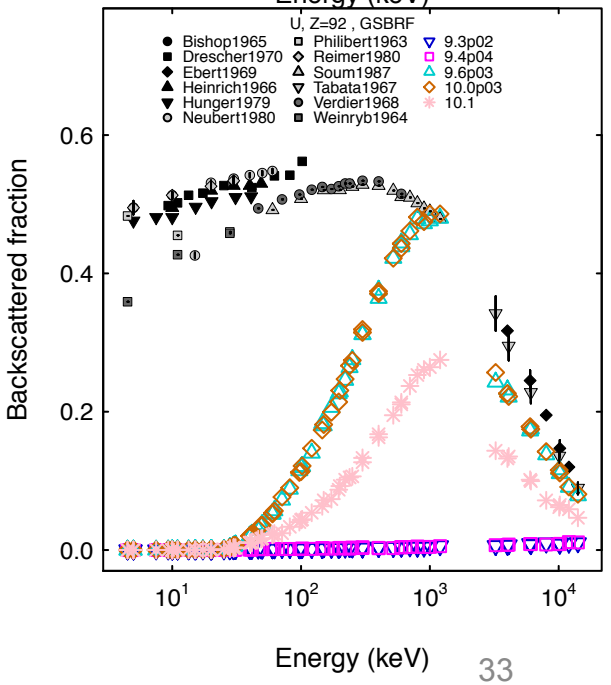
9.1p02
9.2p04
9.3p02
9.4p04
9.6p03
10.0p03
10.1

Geant4 10.0
E>100 keV
p-value = 0.019
(Urban 9.1)
p-value = 0.009
(Coulomb 10.0)









From Geant4 Application Developer Guide:

- **"It is recommended to use physics constructor classes provided with reference physics lists**
- **Default** EM physics (**G4EmStandardPhysics**)
- Optional EM physics providing **fast but less acurate** electron transport due to "Simple" method of step limitation by multiple scattering, reduced step limitation by ionisation process and enabled "ApplyCuts" option; use UrbanMscModel for multiple scattering of electrons and positrons (**G4EmStandardPhysics_option1**)
- **Experimental** EM physics with disabled "ApplyCuts" option (**G4EmStandardPhysics_option2**)
- EM physics for simulation with **high accuracy** due to "UseDistanceToBoundary" multiple scattering step limitation, reduced *finalRange* parameter of stepping function optimized per particle type, alternative model G4KleinNishinaModel for Compton scattering, Rayleigh scattering, and G4IonParameterisedLossModel for ion ionisation (**G4EmStandardPhysics_option3**)
- Combination of **best EM models** for simulation with **high accuracy** includes "UseDistanceToBoundary" multiple scattering step limitation, reduced *finalRange* parameter of stepping function optimized per particle type, low-energy sub-library models G4LivermorePhotoElectricModel, G4LowEPComptonModel below 20 MeV, G4PenelopeGammaConversionModel below 1 GeV, G4PenelopeIonisationModel below 100 keV, and G4IonParameterisedLossModel for ion ionisation (**G4EmStandardPhysics_option4**)
- Models based on **Livermore** data bases for electrons and gamma (**G4EmLivermorePhysics**)"

EM PhysicsConstructors

Progress in NUCLEAR SCIENCE and TECHNOLOGY, Vol. 2, pp.898-903 (2011)

REVIEW

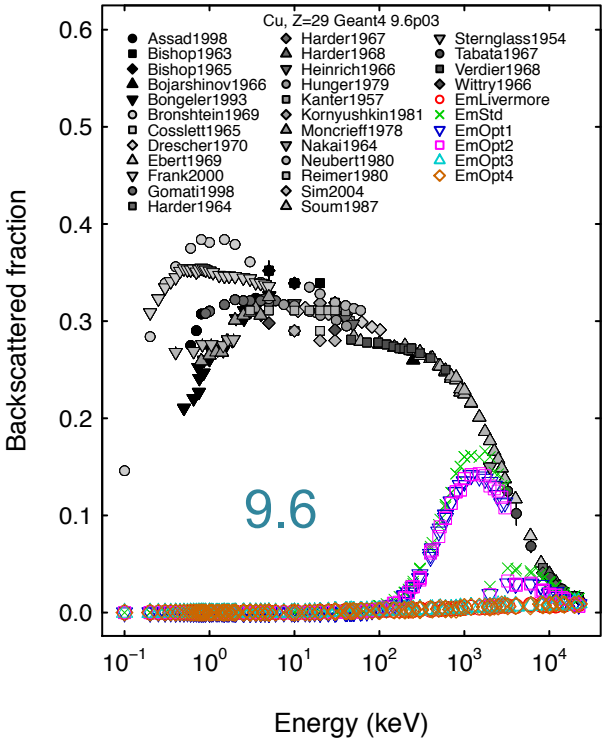
Recent Improvements in Geant4 Electromagnetic Physics Models and Interfaces

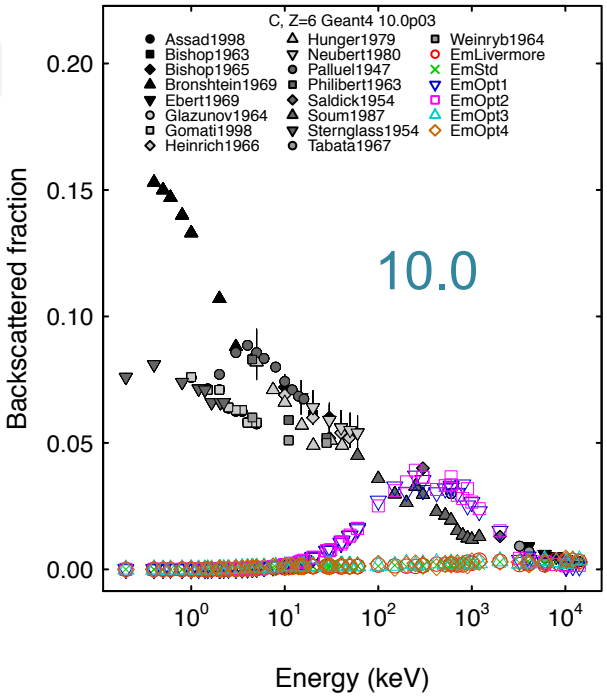
Vladimir IVANCHENKO[1,2,3*], John APOSTOLAKIS[1], Alexander BAGULYA[4], Haifa Ben ABDELOUAHED[5], Rachel BLACK[6], Alexey BOGDANOV[7], Helmut BURKHARD[1], Stéphane CHAUVIE[8], Pablo CIRRONE[9], Giacomo CUTTONE[9], Gerardo DEPAOLA[10], Francesco Di ROSA[9], Sabine ELLES[11], Ziad FRANCIS[12], Vladimir GRICHINE[4], Peter GUMPLINGER[13], Paul GUEYE[6], Sebastien INCERTI[14], Anton IVANCHENKO[14], Jean JACQUEMIER[11], Anton LECHNER[1,15], Francesco LONGO[16], Omrane KADRI[5], Nicolas KARAKATSANIS[17], Mathieu KARAMITROS[14], Rostislav KOKOULIN[7], Hisaya KURASHIGE[18], Michel MAIRE[11,19], Alfonso MANTERO[20], Barbara MASCIALINO[21], Jakub MOSCICKI[1], Luciano PANDOLA[22], Joseph PERL[23], Ivan PETROVIC[9], Aleksandra RISTIC-FIRA[9], Francesco ROMANO[9], Giorgio RUSSO[9], Giovanni SANTIN[24], Andreas SCHAELICKE[25], Toshiyuki TOSHITO[26], Hoang TRAN[14], Laszlo URBAN[19], Tomohiro YAMASHITA[27] and Christina ZACHARATOU[28]

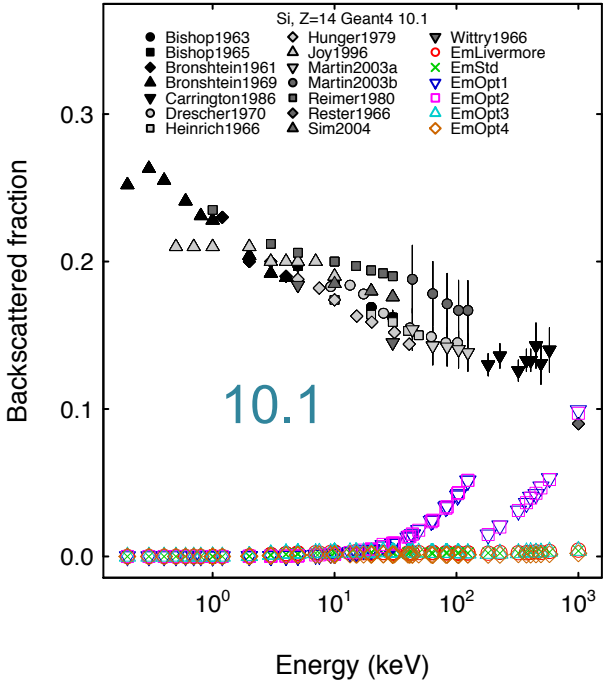
The main advantage of using these physics constructors is the fact that they are intensively validated, so these components of Physics Lists are more reliable and the accuracy of results are better predicted.

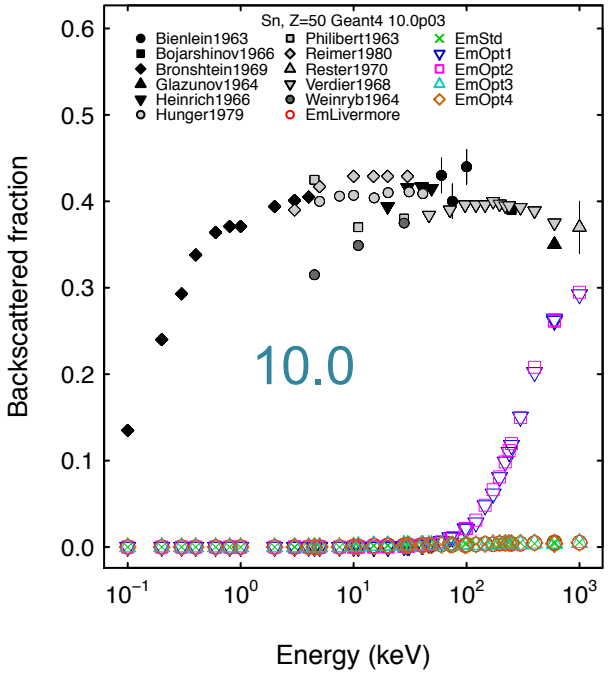
Recommended EM PhysicsConstructors

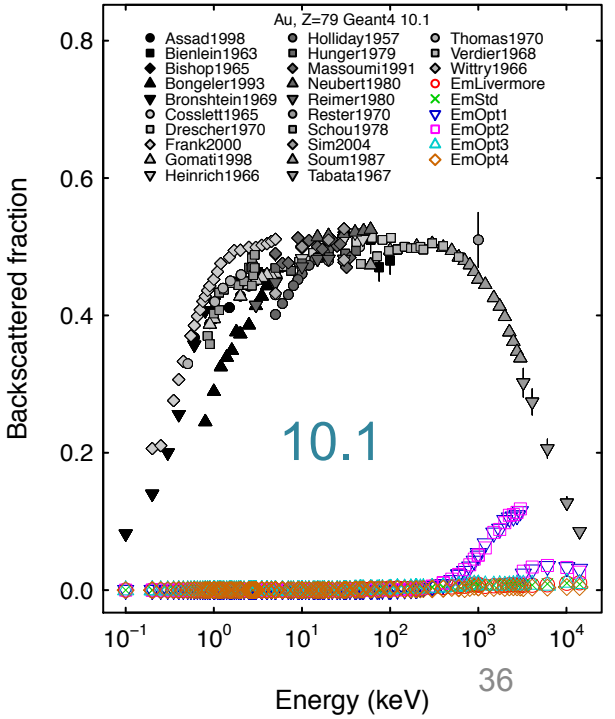
EmLivermore
EmStd
EmOpt1
EmOpt2
EmOpt3
EmOpt4











Efficiency (GoF)

Configuration	Geant4 version	1-20 keV				20-100 keV				$> 100keV$			
		AD	CvM	KS	Watson	AD	CvM	KS	Watson	AD	CvM	KS	Watson
EmLivermore	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07 ± 0.04	0.05 ± 0.03	0.07 ± 0.04	0.07 ± 0.04
EmLivermore	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
EmLivermore	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04	0.09 ± 0.04
EmStd	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.40 ± 0.06	0.40 ± 0.06	0.42 ± 0.06	0.44 ± 0.06
EmStd	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04	0.09 ± 0.04
EmStd	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03	0.05 ± 0.03
EmOpt1	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.33 ± 0.06	0.33 ± 0.06	0.33 ± 0.06	0.35 ± 0.06
EmOpt1	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.39 ± 0.06	0.39 ± 0.06	0.39 ± 0.06	0.40 ± 0.06
EmOpt1	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.14 ± 0.05	0.12 ± 0.05	0.14 ± 0.05	0.18 ± 0.05
EmOpt2	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.32 ± 0.06	0.32 ± 0.06	0.32 ± 0.06	0.35 ± 0.06
EmOpt2	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.37 ± 0.06	0.37 ± 0.06	0.37 ± 0.06	0.40 ± 0.06
EmOpt2	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.16 ± 0.05	0.16 ± 0.05	0.16 ± 0.05	0.19 ± 0.05
EmOpt3	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04
EmOpt3	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04
EmOpt3	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04
EmOpt4	9.6	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04	0.07 ± 0.04
EmOpt4	10.0	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.09 ± 0.04	0.09 ± 0.04	0.09 ± 0.04	0.09 ± 0.04
EmOpt4	10.1	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.02	< 0.02	< 0.02	< 0.02
EmWVI	10.1	< 0.01	< 0.01	< 0.01	< 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.40 ± 0.06	0.40 ± 0.06	0.44 ± 0.06	0.46 ± 0.06

H_0: simulation distribution and experimental data derive from same parent distribution

"High accuracy" options are less accurate than "fast, low accuracy" options

"Livermore" PhysicsConstructor intended for low energy simulation fails to produce simulation results consistent with low energy experimental data

"Fast, low accuracy" EmOpt1-2 produce equivalent efficiency in 10.0 as EmStd in 10.0 and EmWVI in 10.1

Validation…

Geant4 electromagnetic physics: improving simulation performance and accuracy

V. N. Ivanchenko[1,2,3*], S. Incerti[4], J. Allison[3], A. Bagulya[5], J. M. C. Brown[6], C. Champion[4], S. Elles[7], Z. Francis[8], V. Grichine[5], A. Ivantchenko[1,3], J. Jacquemier[7], M. Karamitros[4], M. Maire[3,7], A. Mantero[9], J. P. Marques[10,11], L. Pandola[12], M. Raine[13], M. A. Reis[10,14], G. Santin[15], D. Sawkey[16], A. Schaelicke[17], M. Schenk[18], A. Taborda[10,14], L. Urban[3] and T. Yamashita[19]

V. Multiple and single scattering

The validation was performed using the EM testing suite[36)] which has been significantly extended for multiple and single scattering models[29), 30)]. For electrons, multiple scattering models were tested by comparing simulations to electron scattering benchmark measurements[37)]. The code used for the simulations is the *electronScattering2* extended example[38)], available in the Geant4 distribution. Scattering from various thicknesses of 7 different materials with atomic numbers ranging from 4 to 79, for incident electron energies of 13 and 20 MeV, was simulated. The width of the central portion of the scattering peak was compared to measured values. This width was determined by a Gaussian fit to the part of the curve above 1/e of the peak height. These widths obtained from simulation, divided by the measured widths, are shown in Fig.5 for the standard EM Physics List *standard_option4* (Opt4). For 30 out of 35 points, widths are within 2% of the experimental value (the experimental uncertainty was 1%), with the worst disagreement of 3.5% for carbon.

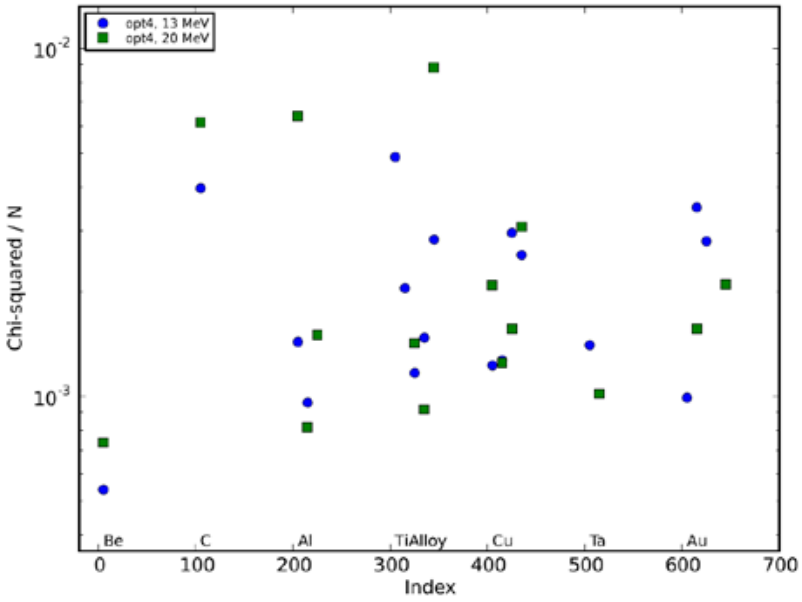
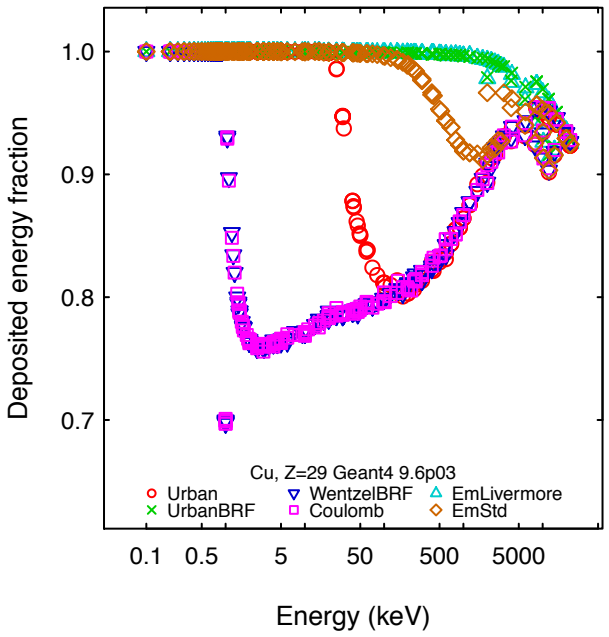


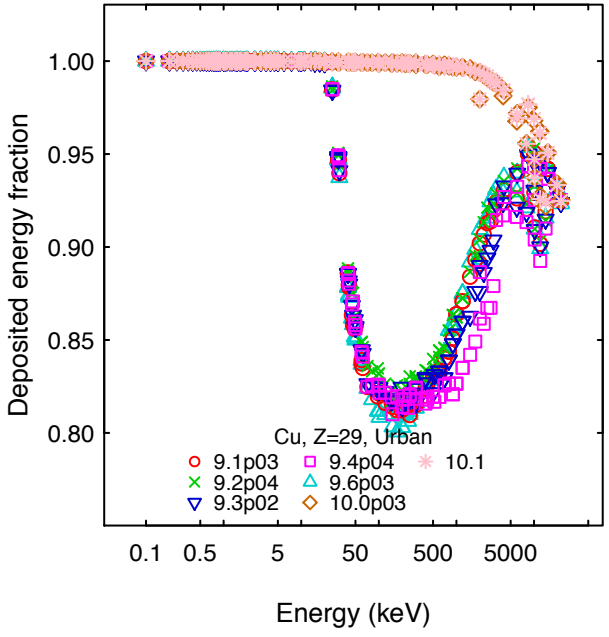
Figure 6: The value χ^2/N, used to compare the goodness of the simulation over the full range of measured scattering angles.

Uncertainties appear severely overestimated!

99% CI for 17 dof: 6.4 – 33.4

Backscattering affects the energy deposited in the target



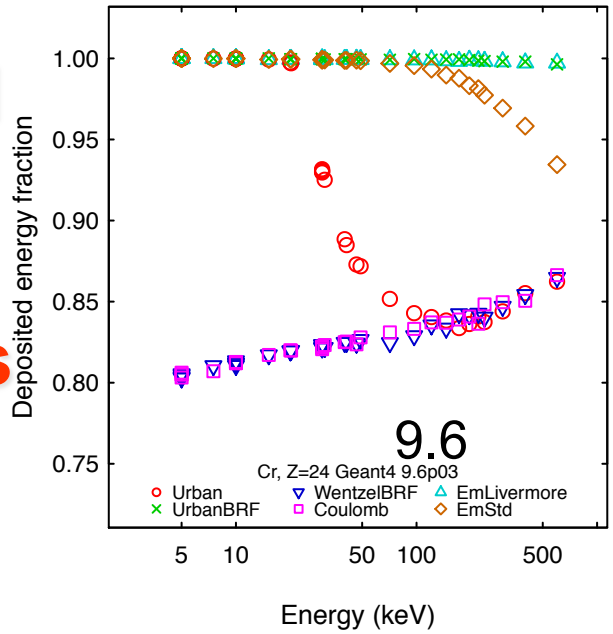


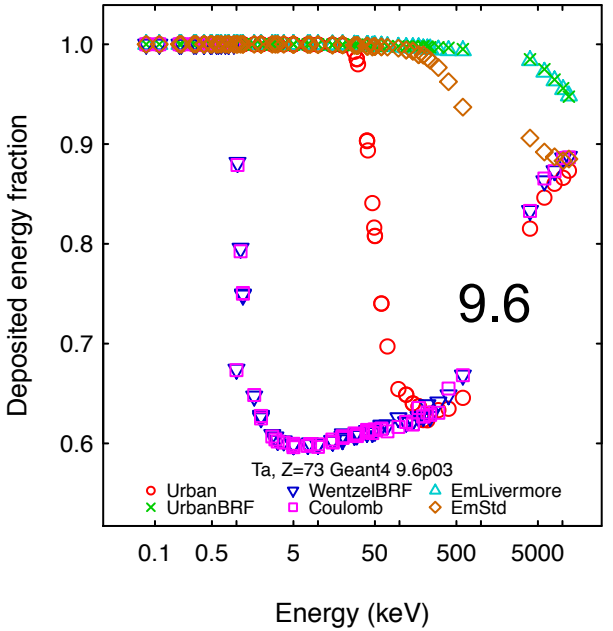
Fraction of electron energy deposited in a copper target with different multiple scattering models as in **Geant4 9.6**

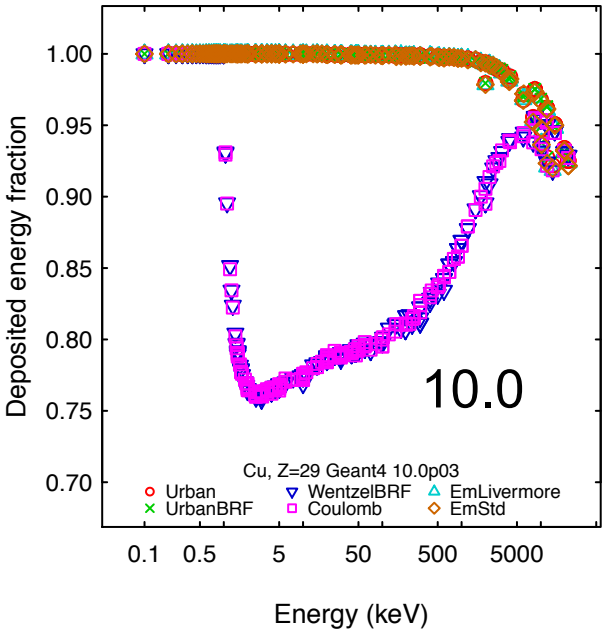
Fraction of electron energy deposited in a copper target with **Urban** multiple scattering model in **Geant4 9.1 – 10.1**

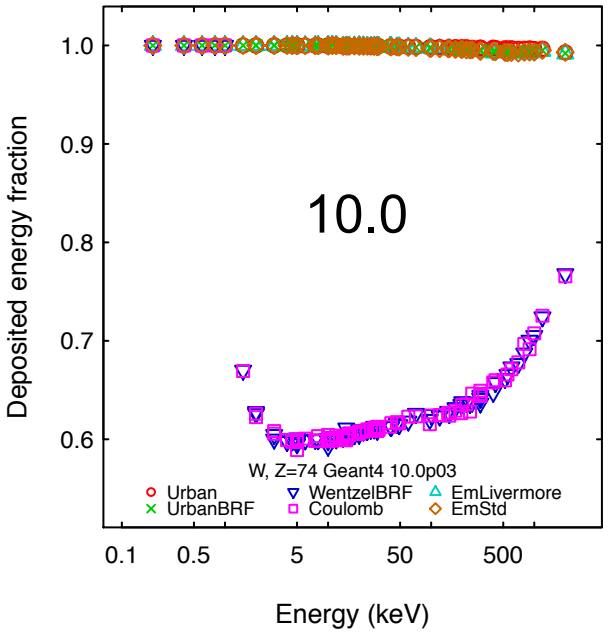
M. Batic, G. Hoff, M. G. Pia, P. Saracco, G. Weidenspointner, Validation of Geant4 simulation of electron energy deposition, *IEEE Trans. Nucl. Sci.*, vol. 60, no. 4, pp. 2934-2957, 2013

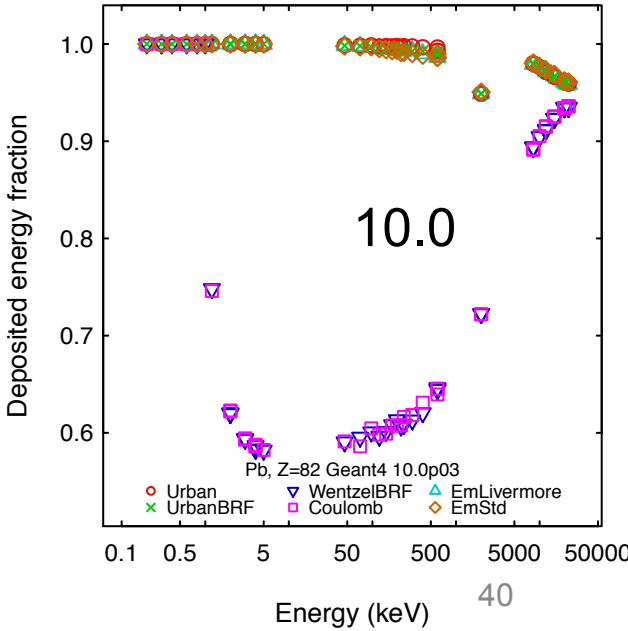
Energy deposited in the target with different scattering models



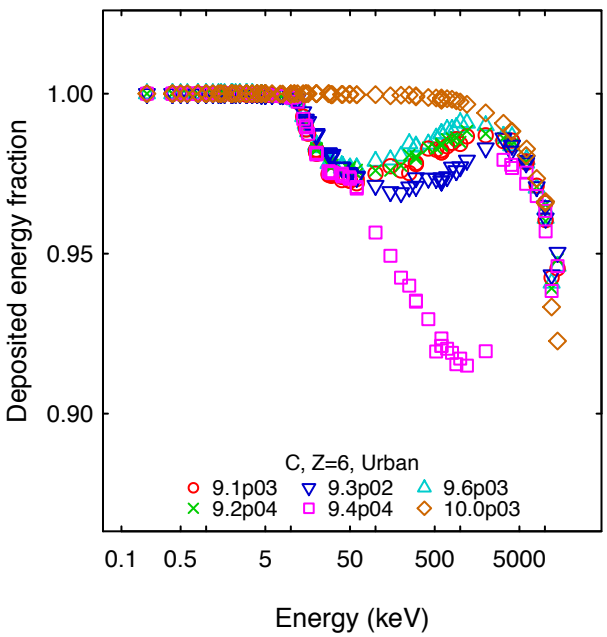


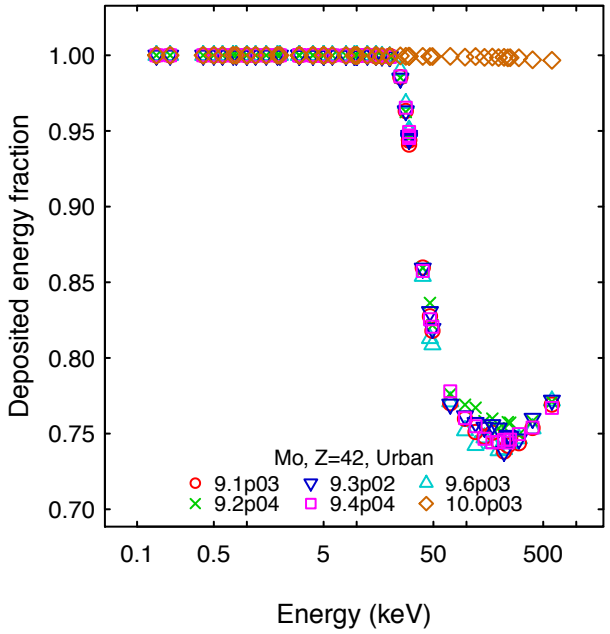






Energy deposited in the target with the same multiple scattering configuration in different Geant4 versions





Urban model

Correlation with validation of energy deposition

Backscattering validation limited to the same energy range as energy deposition validation

Bulk target configuration

H_0: there is no correlation (measure=0)
H_1: there is positive correlation (1-tailed tests)

CORRELATION BETWEEN EFFICIENCY AT SIMULATING BACKSCATTERING COEFFICIENT AND ENERGY DEPOSITION COMPATIBLE WITH EXPERIMENT OVER GEANT4 VERSIONS 9.1 TO 9.6

Correlation	Measure	p-value
Kendall τ	1	0.008
Spearman ρ	1	0.008
Pearson correlation coefficient	0.992	0.0005

Conclusion

Houston, we have a problem.

The problem is not electron backscattering…