INCL in Geant4

(INCL = IntraNuclear Cascade of Liège)

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Measuring neutrino interactions for next-generation oscillation experiments

23 October 2024 – ECT* - Trento

Next ν-oscillation experiments → ν energy more precise than ever!

→ What nuclear reaction models can do?

→ Which models?

→ Role of Geant4?

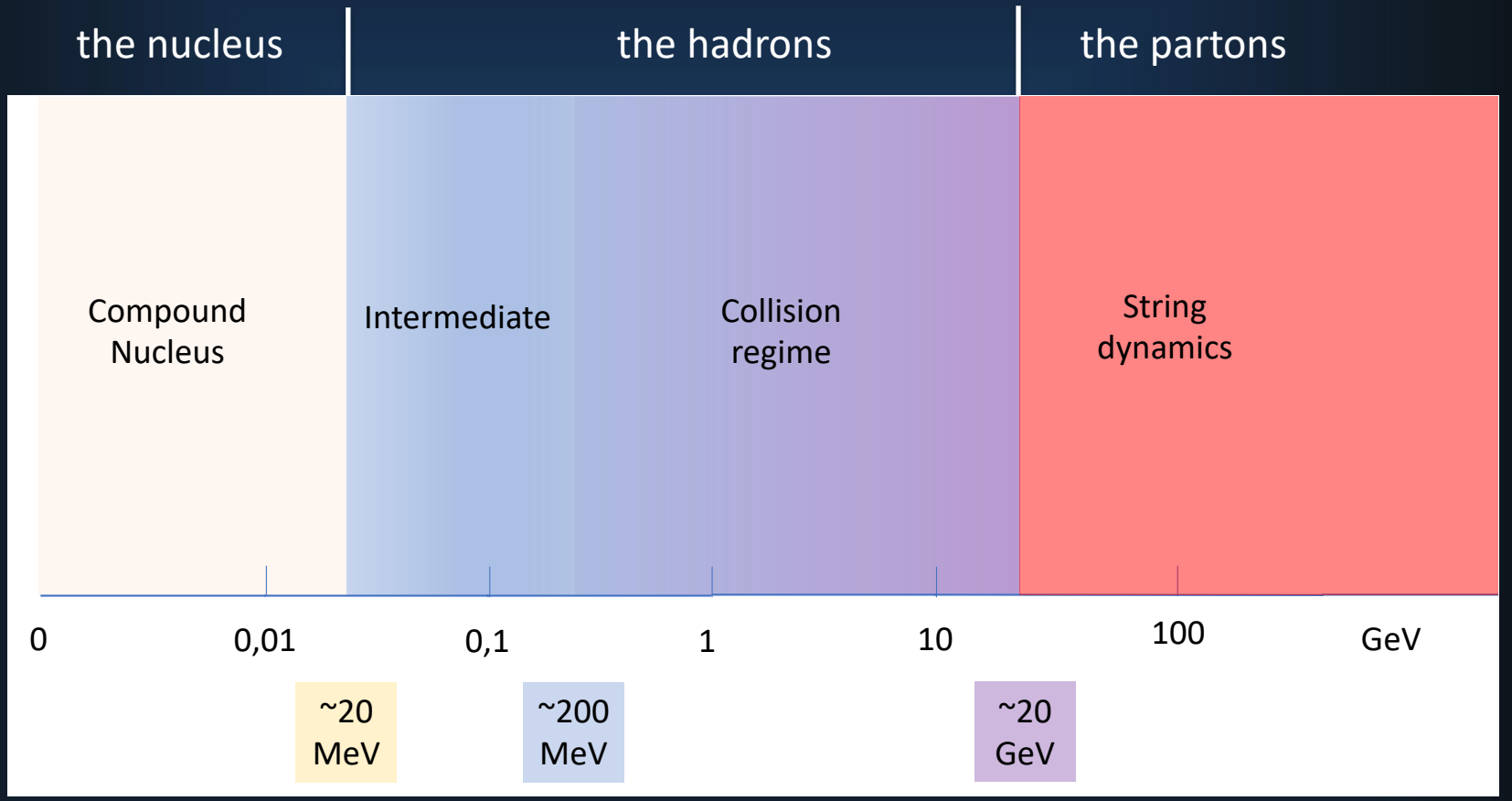
→ The beginning of an answer (…I hope)
from a non-expert neutrino physicist

Plan

- Generalities on nuclear interactions around MeV-GeV (with light projectiles)
- Geant4 (which models)
- INCL ⟷ Neutrino
- INCL in (some) details

MeV-GeV Interactions

4 main interaction domains can be considered where the projectile see



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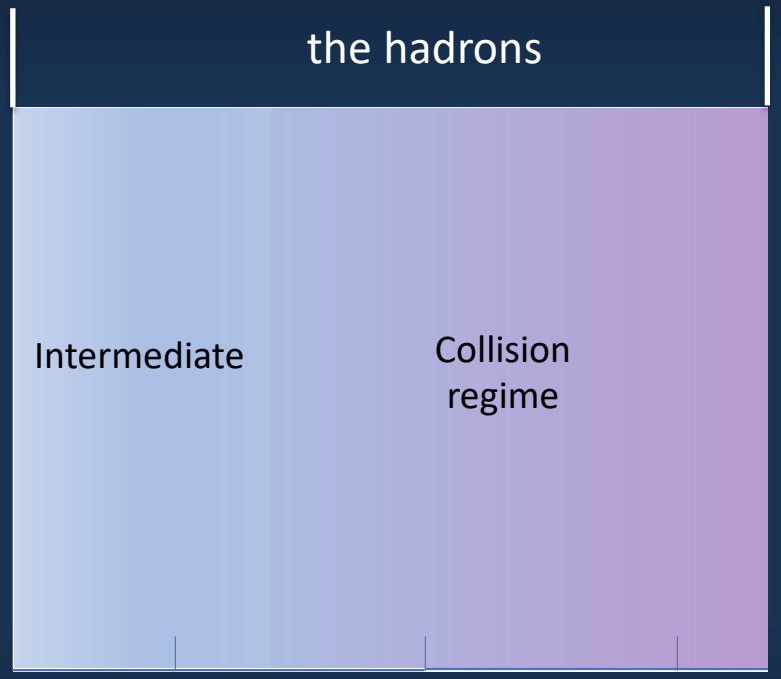

Two possibilities or ways of simulating this domain:

- two phases: precompound + INC
- INC alone

} depends on the INC « ingredients »

MeV-GeV Interactions

Modeling

Numerous nucleons interacting → Schrödinger equation → assumptions needed

→ BUU/VUU equation (transport equation with a collision term)

1 + 2 → 3 + 4

$$\frac{\partial f_1}{\partial t} + \vec{v}.\vec{\nabla}_r f_1 - \vec{\nabla}_r U.\vec{\nabla}_p f_1 = -\int \frac{d^3\vec{p}_2 d^3\vec{p}_3 d^3\vec{p}_4}{(2\pi)^6} \quad \sigma v_{12} \quad \delta^3(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4)$$
$$[f_1 f_2 (1 - f_3)(1 - f_4) - f_3 f_4 (1 - f_1)(1 - f_2)]$$

f_i: density distributions
σv_{12}: collision term
U: potential

Monte-Carlo method

2 ways

BUU – QMD models	Examples of differences	INC models
Potential calculated (Heavy ion collisions)		Potential = *constant* (Light particle projectile)
Slow (NOT convenient in particle transport code)		Fast (convenient in particle transport code)

MeV-GeV Interactions

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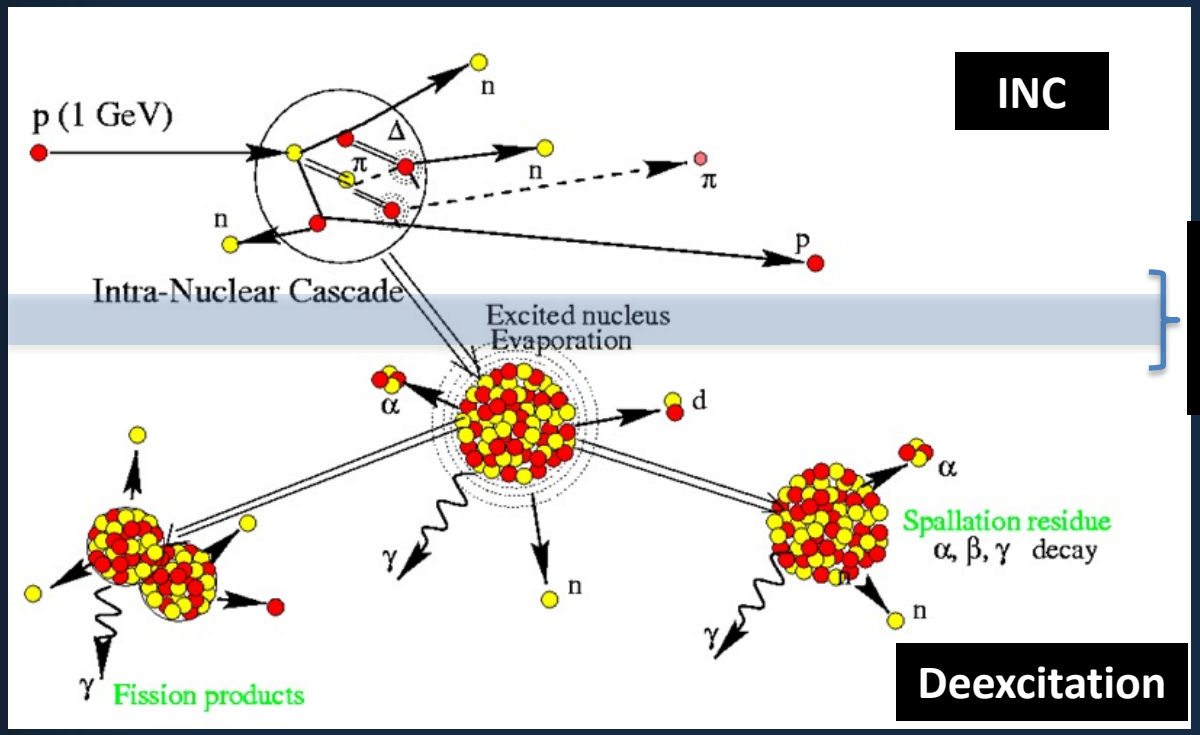
Examples of differences

Geant4 - INCL...

MeV-GeV Interactions

INC + (preequilibrium) + De-excitation



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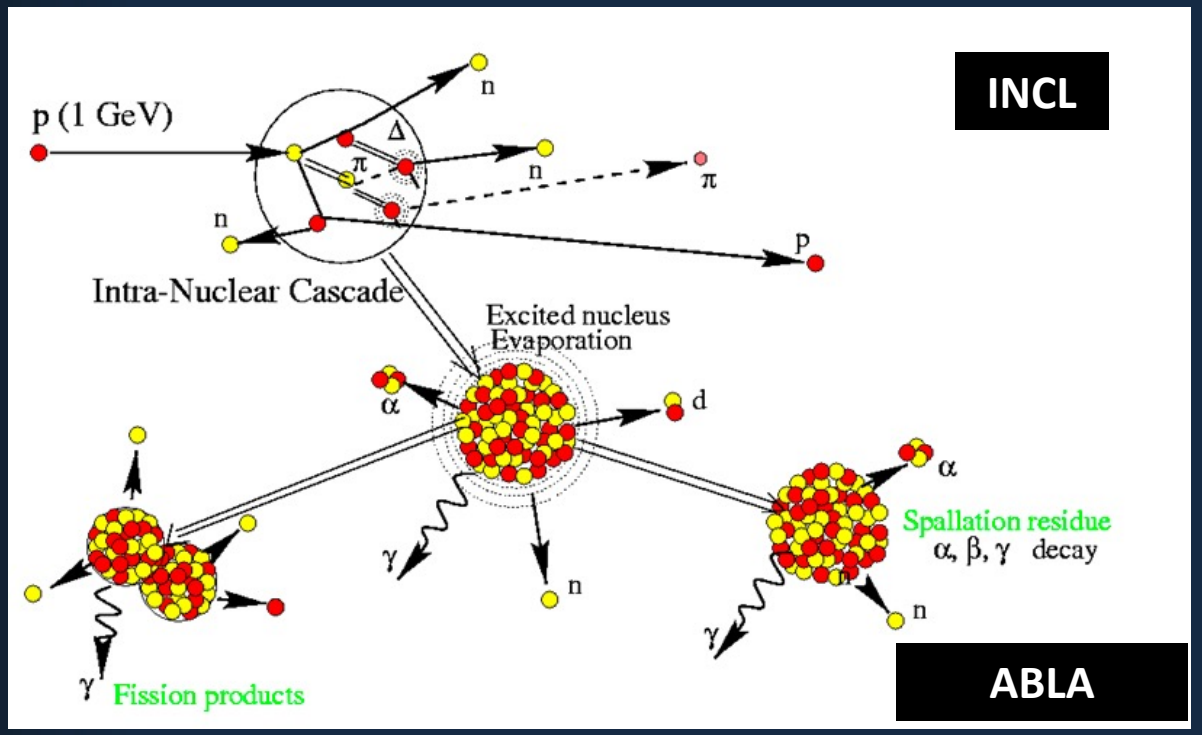

Geant4

Three INC models

	Bertini (BERT)	Binary light Ion Cascade (BIC)	INCL (INCLXX)
projectile	$p, n, \pi^+, \pi^-, K^+, K-, K_L, K_S, \Lambda, \Sigma^+, \Sigma^-, \Sigma^0, \Xi^-, \Xi^0, \Omega^-$	n, p, nucleus	p, n, π^+, π^-,($\pi^0, K^+, K^-, K^0, \Lambda, \Sigma^+, \Sigma^-, \Sigma^0$,) pbar
Energy	0 – 6 GeV	0 – 6 GeV	0 – 20 GeV
Precompound	Its own	The one from Geant4	No
De-excitation	Its own	The one from Geant4	ABLA (Geant4's also)

Often used within Physics Lists (examples)

- FTFP_BERT_HP (BIC used for nucleus-nucleus interaction)
- FTFP_INCLXX_HP
- QGSP_BIC_HP (BERT used for π, K, strange hadrons)
- …

Geant4

None of them deal with the neutrino!
However...

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But
see talk of V. Grichine

INCL and the Neutrinos

Increasing precision of the experiments

↳ Better/refined results in ν-Nucleus interactions

↳ Need to use models known to treat well Final State Interaction (FSI)

see A. Ershova talk

The recent history of « INCL and neutrinos »

	2019	2020-2023	2024	2024	2024
Who	**GENIE**	A. Ershova (Thesis **CEA**)	Antoine L.T. (Internship **CEA**)	**GENIE**	**NEUT**
Link/Goal	Contact	ν-oscillation exp. INCL to treat FSI	CCQE in INCL	New contact	Contact
Work	Implementing INCL	**NuWro** ν-N INCL FSI	It works. Some points to be understood	Implementation OK? Used within Geant4	Implementing INCL

…Bertini also in GENIE

↳ Discussions to get a common interface to use INCL for neutrino physics

INCL

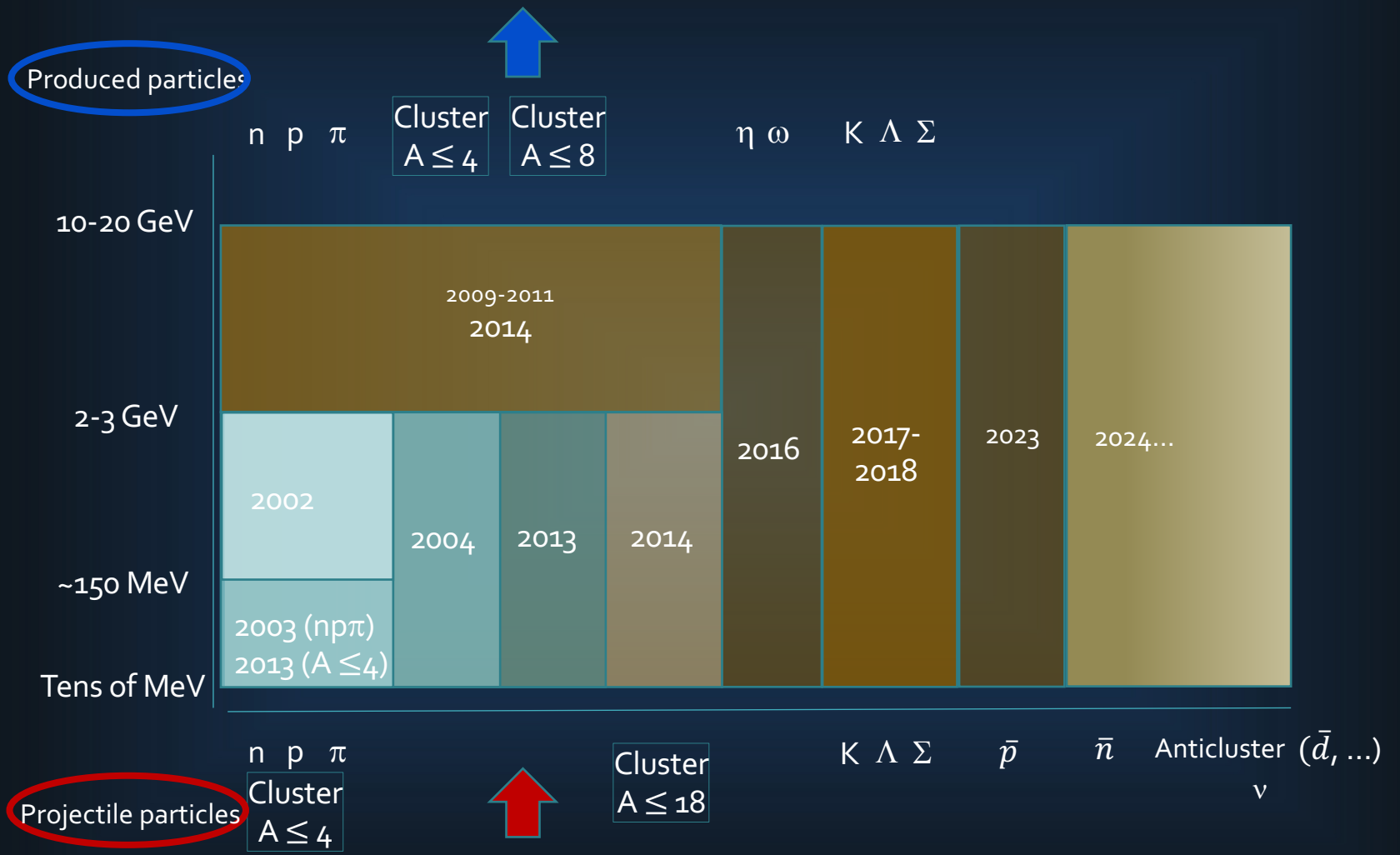
Basic principles

- Four (common) main hypotheses
  - Numerous scatterings → Interferences cancel out
  - Good enough definition of position and momentum → Classical trajectories
  - scattered wave → asymptotic value before next collision → Classical treatment of scattering
  - time of interaction << time between collisions → Binary collision

- Main ingredients
  - Nucleus = nucleons with position-momentum (correlated) and potential
  - Cascade
    - Next collision (driven by cross sections)
    - Final products (driven by cross sections, but not only)
    - Pauli Blocking
    - Ad-hoc models (ex.: cluster production)
  - …Competing with reflection/emission (border) and decays (Δ, Σ^0, ω)
  - Stopping time (based on the thermalization of the remnant nucleus)

INCL

Chronology of development



INCL

Applications

- To study interaction mechanisms — Stand-alone version X exp. data
  - particle spectra
  - residual production (A, Z, (Z,A) distributions, versus energy)
  - cluster production

- Implementation in Transport codes
  - MCNPX — INCL4.2 - Fortran
  - PHITS — INCL4.6 - Fortran
  - **Geant4** — **Latest versions – C++**

- *Macroscopic* applications
  - Neutron sources
  - ADS
  - Facility design
  - Hadrontherapy
  - Meteorites (also std-alone version…)

INCL

Benchmarks

- *External* users → Which models? What's the reliability?

  → Specific benchmarks (application oriented)

- Much rarer

  General benchmarks (all ref. in J.-C. David, Eur. Phys. J. A (2015) 51: 68)
  - NEA 90's
  - IAEA 2008-2010

- But, how to analyse the benchmark?
  - Plots — Shapes — Developers
  - Figure of merits — Right values — Users

- The main question: Are we able to know the error and uncertainties of our calculations?

  → It could be…

INCL

Errors – Uncertainties
Optimization

A project (NuRBS: Nuclear Reaction model improvement with Bayesian Statistics)

has been funded (2024->2027) – CEA & Bern U. (and IAEA+Coruña U.)

Goals:

- Building tools for biasing and parameter optimisation
- Applying them to INCL and ABLA for several cases

Conclusions

- INCL's interest in neutrinos
    - Recognized model in its field (FSI)
    - Available in Geant4
    - Still maintained
    - … and improved
    - Uncertainties under study
- Interface for multi-input use (ex.: ν-nucleon vertex) → Discussions (manpower…)

Thanks for your attention!

BACKUP

Bias (Error) estimate

- bayesian theorem
- information = exp. data

Method

- y1 = bias
- y2 = exp. data – calculations
-

$$\rho(\mathbf{y}_1|\mathbf{y}_2) \propto \rho(\mathbf{y}_2|\mathbf{y}_1)\rho(\mathbf{y}_1)$$

(ρ = probability distribution)

- each distribution = gaussian

$$\mathcal{N}(\mathbf{y}|\boldsymbol{\mu}, K) = \frac{1}{\sqrt{(2\pi)^N detK}} exp\Big(-\frac{1}{2}(\mathbf{y}-\boldsymbol{\mu})^T K_{11}^{-1}(\mathbf{y}-\boldsymbol{\mu})\Big)$$

- We obtain the new distribution for $\rho(\mathbf{y}_1|\mathbf{y}_2)$ (bias knowing exp. data)

$$\boldsymbol{\mu}_1^{new} = \boldsymbol{\mu}_1 + K_{21}^T K_{22}^{-1}(\mathbf{y}_2 - \boldsymbol{\mu}_2) = K_{21}^T K_{22}^{-1}\mathbf{y}_2$$
$$K_{11}^{new} = K_{11} - K_{21}^T K_{22}^{-1} K_{21}$$

- where K_{ab} have to be estimated
  - form?
  - Hyperparameters from marginal likelihood maximization

$$K_{ab} = (\kappa(x_i, x_j)); \text{ avec } \kappa(x_i, x_j) = \delta^2 exp\Big(-\frac{(x_i - x_j)^2}{2\lambda^2}\Big)$$

GLS = Generalized Least Square

Parameter optimisation
GLS

GLS gives the new values of the parameters and related covariance matrices

$$\vec{p}_{op} = \vec{p}_{ref} + \Sigma_p J_p^T (\Sigma_e + J_p \Sigma_p J_p^T)^{-1} (\vec{\sigma}_{exp} - \mathcal{M}(\vec{p}_{ref}))$$

reference

link between parameter and model

weight of the information

information

Calculation ($\mathcal{M}$) is supposed to be linear…
Not the case for models like INCL, but

1- almost linear close to the value (of the parameter)
2- process by iterations

Hypothesis reasonable to get the optimized value, BUT not for determining the uncertainties!

To estimate uncertainties, we use however a similar method where we broke the linear hypothesis during the process.