Direction biasing of annihilation and prompt photons in FLUKA

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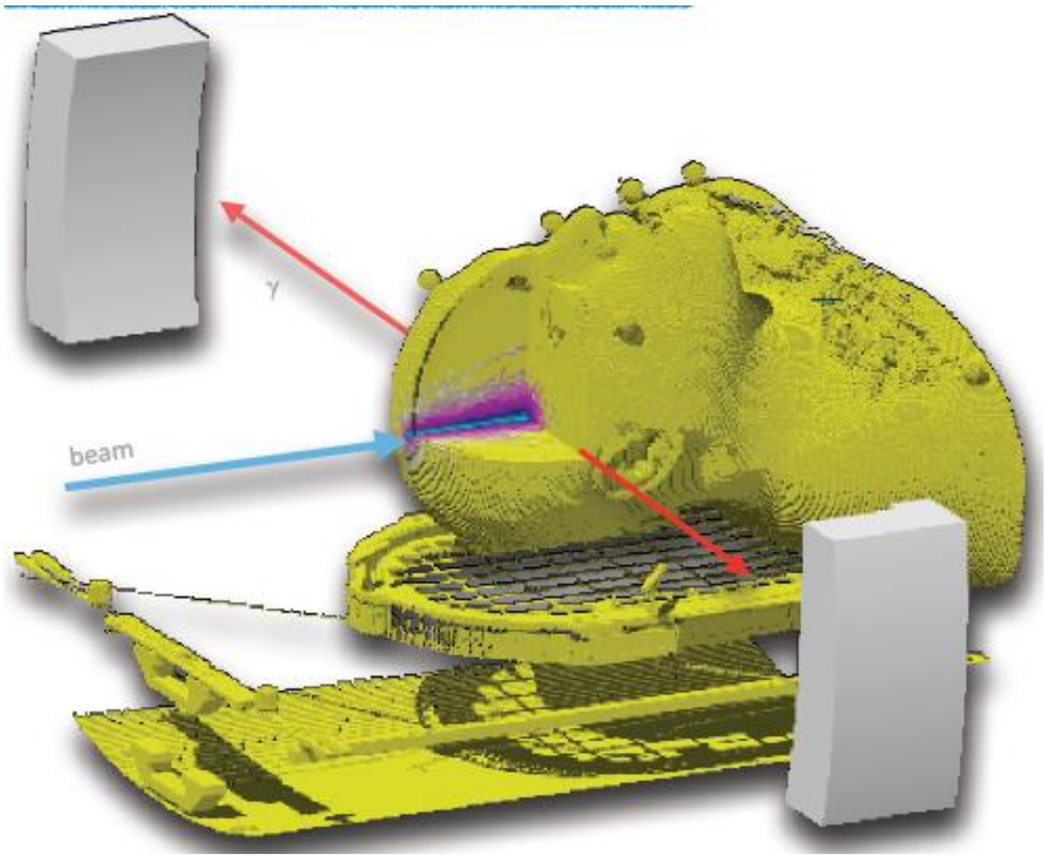
Within the ENVISION FP7 Project:
Development of techniques to speed up the simulation of PET and SPECT for hadrontherapy monitoring



Detectors for monitoring have a limited solid angle in general. Most of simulated physics is wasted outside the detector

How to accelerate FLUKA calculations for PET and prompt photon calculations

- Optimization of **production** and **transport thresholds**
- **Inelastic interaction biasing**
- Further “tuning” as a function of particle energy
- Multiple **“replicas”** of **radioactive decays**
- **Direction biasing** of **annihilation photons**
- Multiple **“replicas”** of final **(gamma) de-excitation**
- **Direction biasing** of **de-excitation photons** *(work in progress)*

Preliminary step to speed up simulations:

Optimization of production and transport thresholds

- No delta ray production (compared to 100 keV)
- Electron production and transport thresholds up to 300 keV from 100 keV (even higher possible, little impact expected)
- Photon threshold 100 keV

⇩

On the (proton) test case, an overall FOM gain of a factor (mostly due to the δ suppression)

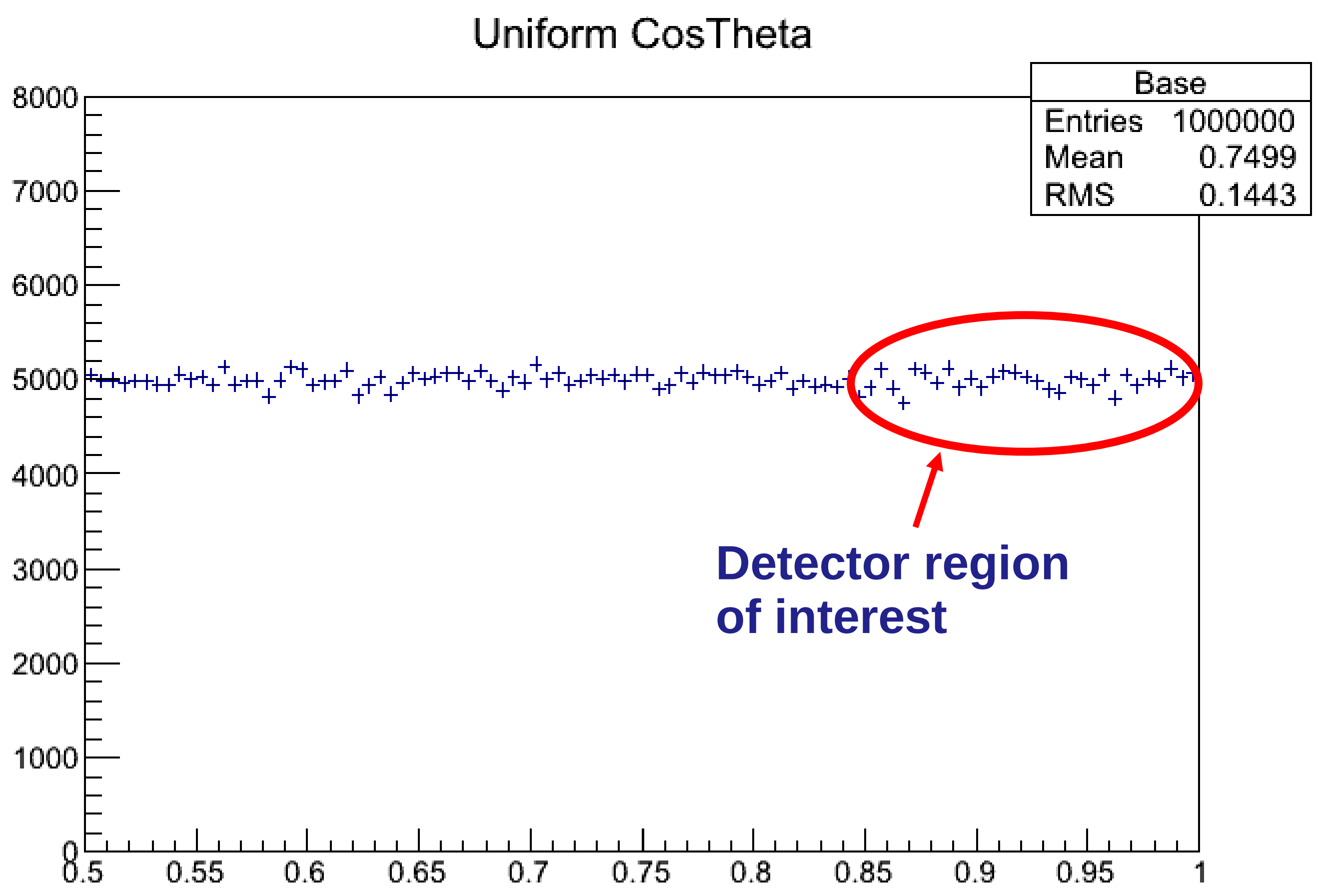
2.1

on both prompt photons and annihilation photons

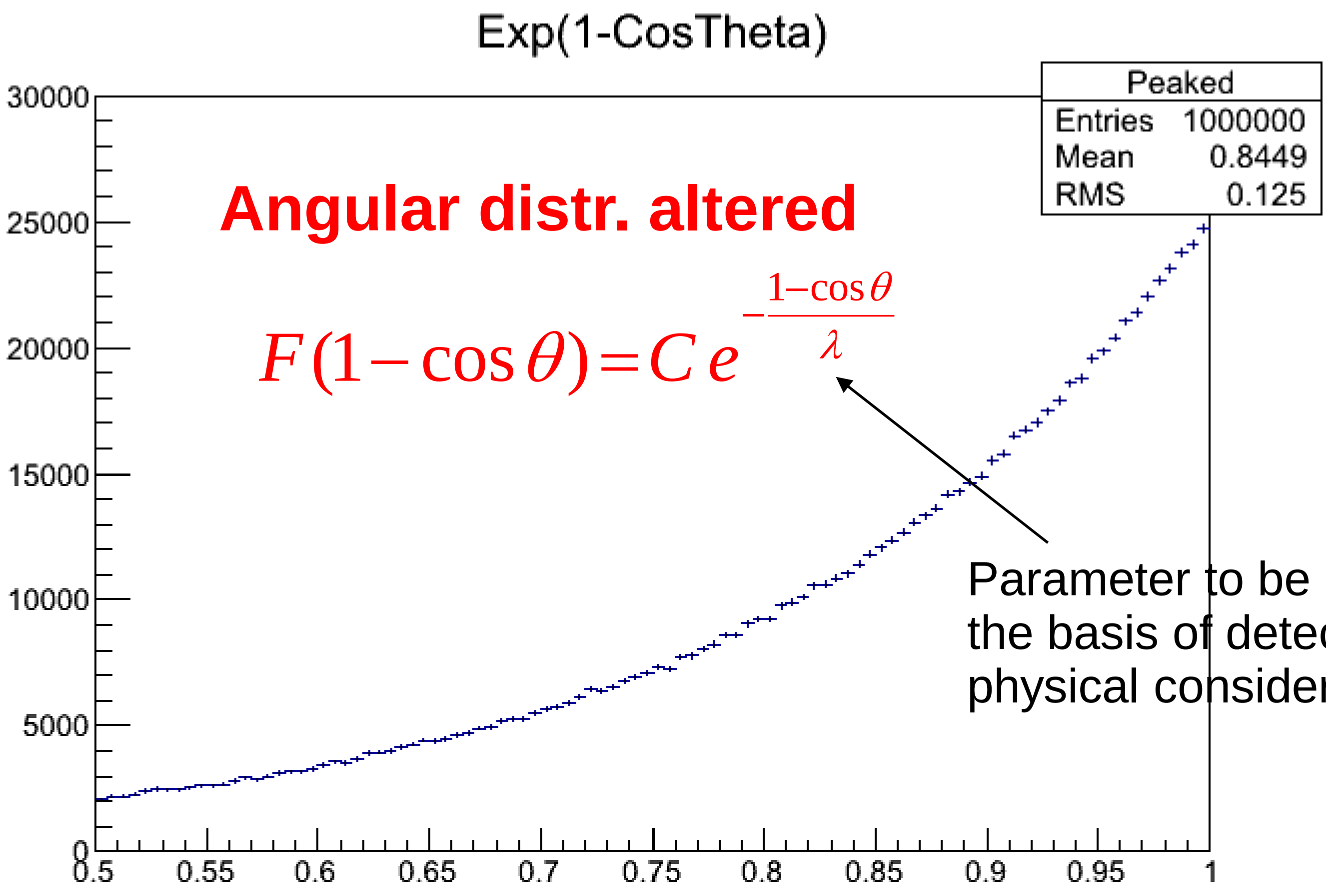
From now on this is the reference case

Pedagogic Example:

a photon is sampled from a uniform Cosθ distribution (as expected)



Probability of pointing to the detector region is artificially enhanced (biased) towards the detector region



Angular distr. altered

$$F(1-\cos\theta) = C\, e^{-\frac{1-\cos\theta}{\lambda}}$$

Parameter to be optimized on the basis of detector size and physical considerations

h->Fill(cost)

True physics is restored by **assigning a weight** to the particles

$$Weight(\cos\theta) = \frac{\int e^{-\frac{1-\cos\theta}{\lambda}}}{e^{-\frac{1-\cos\theta}{\lambda}}}$$

Math. base: Importance Sampling

Problem: optimizing the calculation of the integral of function f(x)

$$I = \int_a^b f(x)\,dx$$

A new function p(x) having poting values and normalized in [a,b] can be properly chosen:

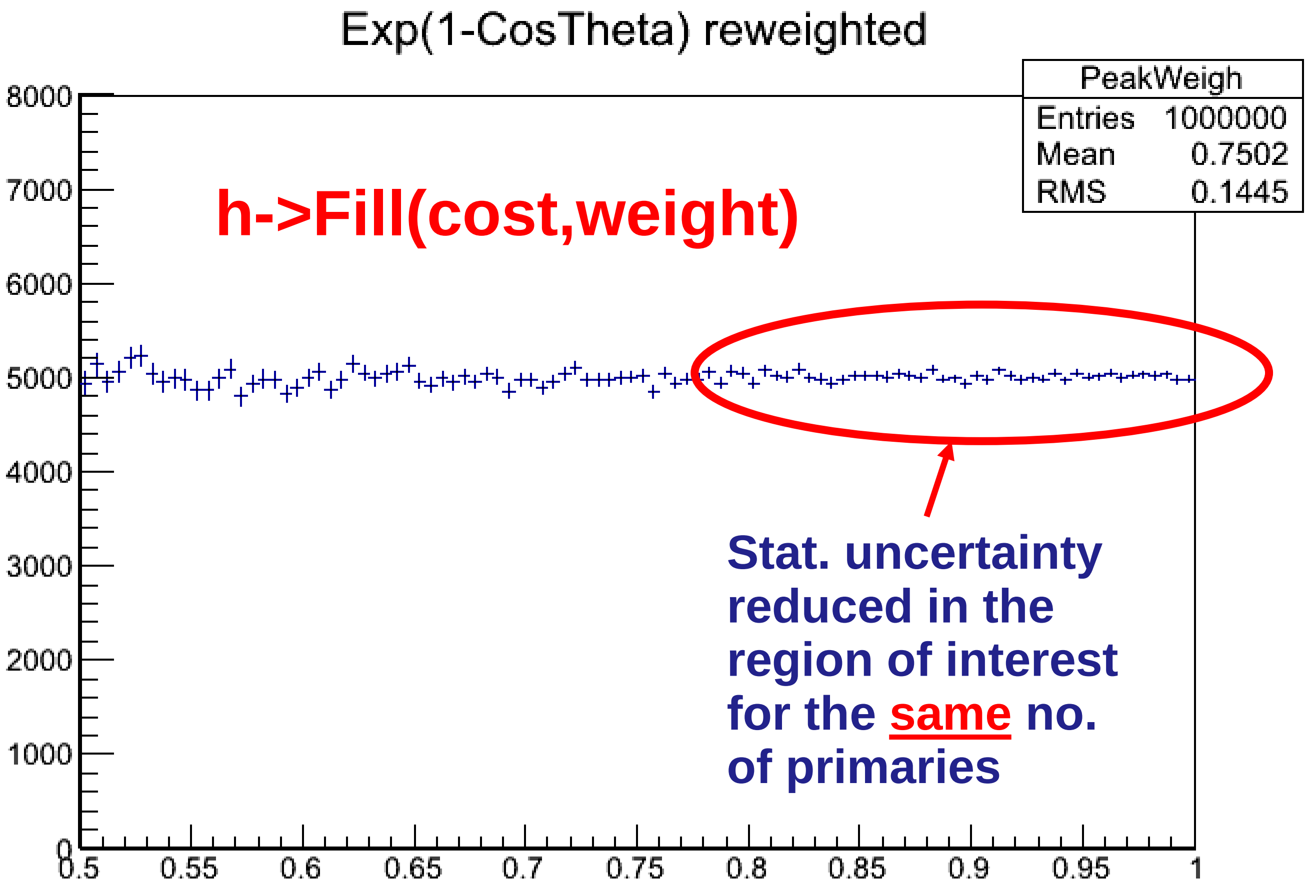
$$\int_a^b p(x)\,dx = 1$$

p(x) can be used to redefine the Integral I (change of variable

$$I = \int_a^b \frac{f(x)}{p(x)} \left(p(x)\,dx \right)$$

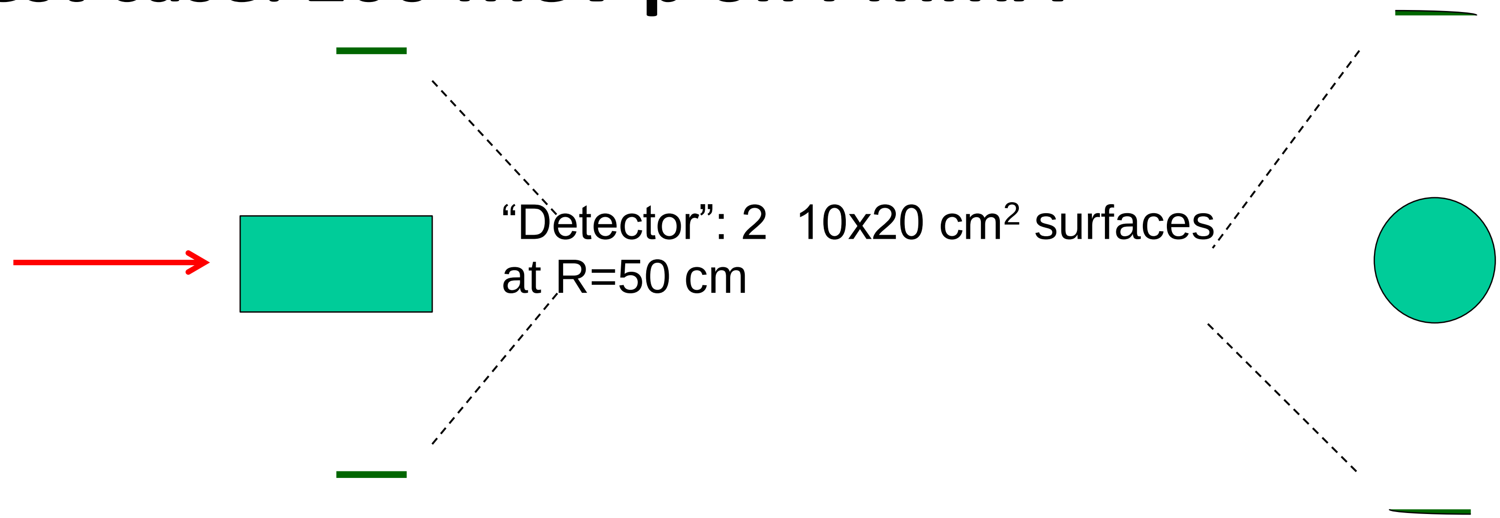
New estimate of the integral by sampling f(x) in points x_i chosen according to p(x)

$$I = \frac{1}{N} \sum_{i=1}^{N} \frac{f(x_i)}{p(x_i)}$$



Exp(1-CosTheta) reweighted
PeakWeigh
Entries 1000000
Mean 0.7502
RMS 0.1445
h->Fill(cost,weight)
Stat. uncertainty reduced in the region of interest for the same no. of primaries
8000
7000
6000
5000
4000
3000
2000
1000
0
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1

Test case: 200 MeV p on PMMA



Observables:

- Prompt photons (> 1 MeV) in the detector area
- Annihilation photons (from β^+ decays) in the detector area

Figure Of Merit (FOM):

- $1/[\sigma^2 T_{CPU}]$ for both observables (a factor ***x*** larger FOM $\rightarrow$ a factor ***x*** less CPU required for the same statistics)
- …evaluated with runs with equal T_{CPU} for an easy estimation

Direction biasing of annihilation photons:

- Natural isotropic distribution altered so that the first photon preferentially **points to the detector(s)** (note please ***preferentially*** and ***not always***, in order not to bias the results, particularly Compton related backgrounds)
- Weights corrected accordingly
- Pros:
  - Many more annihilation photons reach the detectors
  - Minimal CPU penalty (negligible)
- Cons:
  - Ineffective when the detector covers a large fraction of the solid angle (for a 4π detector there is obviously no advantage) $\rightarrow$ ideally suited for online PET

In practice:

FLUKA users can activate the call to a user routine: **udcdrl.f** in order to implement direction biasing

Commands in the input file:

```
LAM-BIAS        1.                  POSITRON  POSITRON        DCDRBIAS
LAM-BIAS                               0.                       DCY-DIRE
```

In the udcdrl routine the user must code the sampling of direction cosines for a new direction from the current coordinates of the generated photon to a random point toward (one of) the dector(s) and give $1/\lambda$

Additional useful biasing:
Inelastic interaction biasing

- "Physical" interaction length reduced by a user chosen factor (weights adjusted accordingly)
- Pros:
  - More interactions (ideally at least one per primary proton/ion)
  - $\rightarrow$ more prompt photons and residual nuclei produced
- Cons:
  - Ineffective when CPU time is dominated by inelastic interaction time (eg for ions above 100 MeV in FLUKA), obviously no gain in those conditions

In the proton example presented, the adopted inelastic length reduction factor is 10

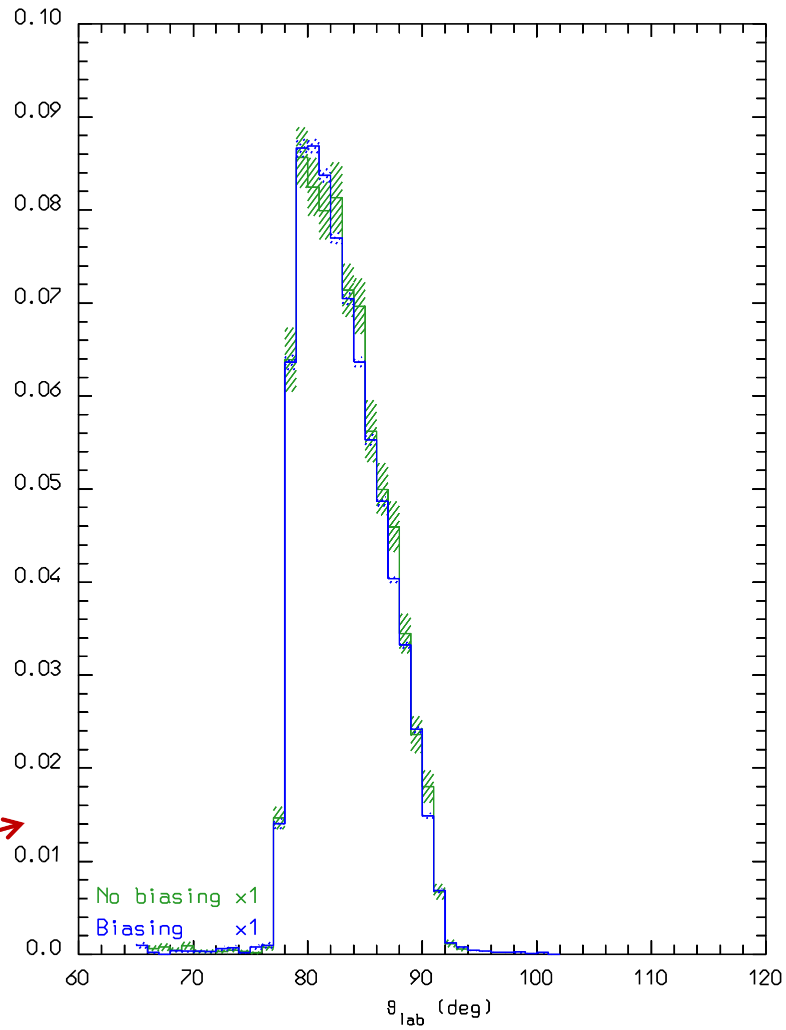
A new special feature for ions: in. int. biasing applied only below 100 MeV/n where BME is used (and it is very fast) $\rightarrow$ gains in the Bragg peak region (mostly for prompt photons) with little CPU penalty. ***Still in evaluation***

Proton example:

- Inelastic int. biasing + annih. γ's direction biasing
- FOM gain on "detected" prompt γ's (expected minimal while waiting for prompt γ's direc. biasing): **1.5 (3.1*)**
- FOM gain on "detected" annih. γ's: **9.9 (21*)**

* Wrt the non-optimized threshold case

Angular distribution (wrt the beam direction) of the annihilation photons reaching the detectors, for the no biasing and the biasing cases, for the same total CPU time. The huge improvement in statistics is readily observable



In the proton example presented, the adopted angular spread parameter is ~12°

Direction biasing of prompt photons:

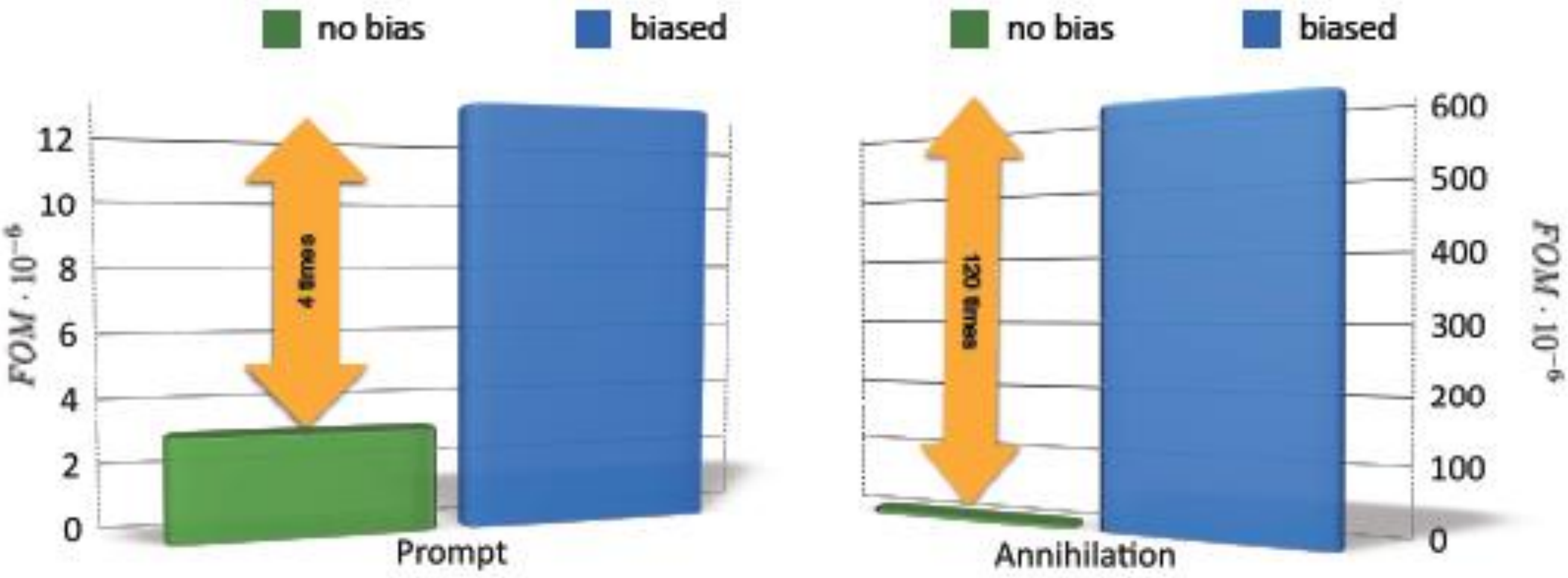
- Natural distribution altered so that the one of the de-excitation photons preferentially **points to the detector(s)** (note please ***preferentially*** and ***not always***, in order not to bias the results, particularly Compton related backgrounds)
- Weights corrected accordingly
- Pros:
  - Many more prompt photons reach the detectors
  - Minimal CPU penalty (negligible)
- Cons:
  - Ineffective when the detector covers a large fraction of the solid angle (for a 4π detector there is obviously no advantage)
  - Complex to implement because of
    - ✓ Lorentz boost of the recoiling exciting nucleus + possibly another boost if the fragment is a projectile-like one
    - ✓ Non-isotropic original distribution (dependning on the emission multi-polarity)

Expected gain of the same order as the one for annihilation photons ($\rightarrow$ quite substantial)

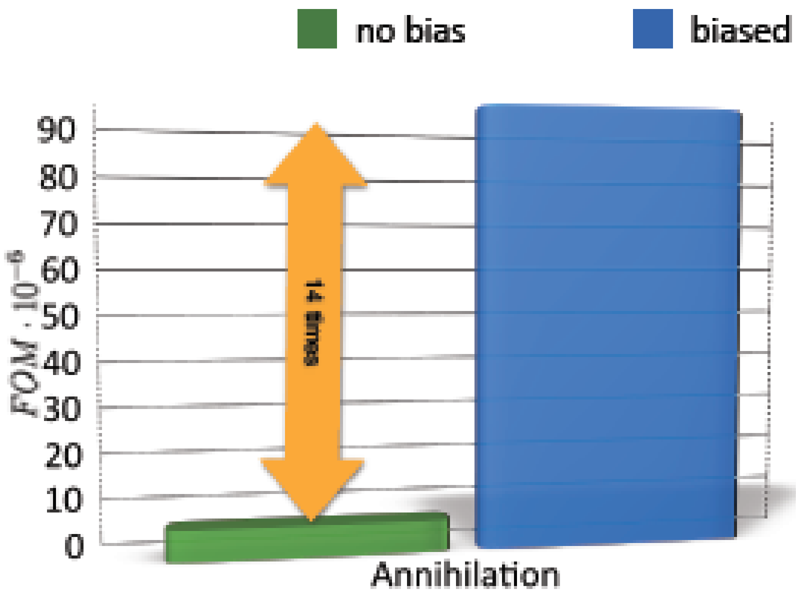
“Replicas” of final de-excitation:

- **Last stage of interaction** (γ de-excitation), **replicated** several times for the same excited fragments
- Weights corrected accordingly
- Pros:
  - Better statistics about prompt photons, with many more produced and tracked
  - Minimal CPU penalty (negligible): the de-excitation step is very fast wrt the rest of the interaction
- Cons:)
  - Technically complex to implement because of the structure of the code
- Maybe the same could be applied to the evaporation stage as well $\rightarrow$ generating several residual nuclei per interaction
- Pros
  - Better statistics about residual nuclei (in particular β^+ emitters)

Expected gains somewhat uncertain, likely a factor of a few



		FOM	speed gain
Prompt	no bias	3.12 E-06	**4**
	biased	1.31 E-05	
Annihilation	no bias	5.10 E-6	**120**
	biased	6.10 E-4	



		FOM	speed gain
Annihilation	no bias	6.7 E-6	14
	biased	9.5 E-5	

For heavy ions increasing the probability of interactionon could not provide great improvements (because the nuclear interaction between two nuclei is very time consuming) but we preliminarily tried to apply the same work also to carbon ions

Despite of the fact that the biasing is optmized for proton beam still there is a gain also for the Annihilation photons produced by Carbon ions by a factor 14, mostly due to the direction biasing.