Modelling and corrections of random & scatter coincidences in J-PET

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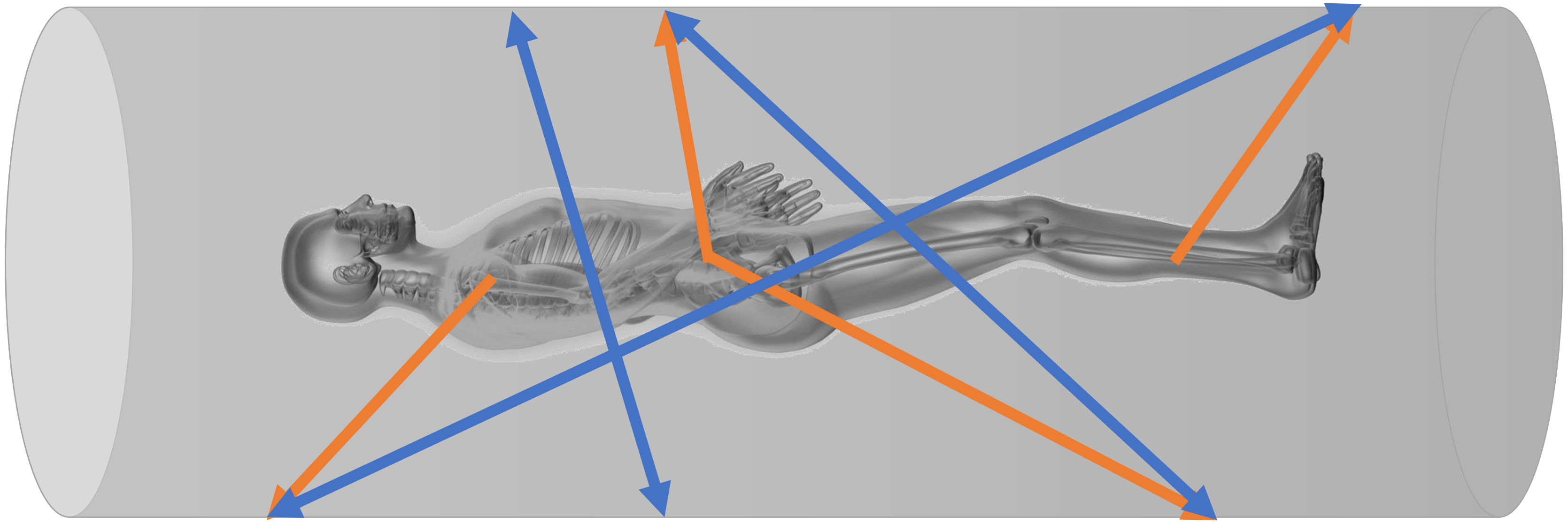
Outline

1. J-PET tomograph
2. Motivation
3. Modelling of random coincidences
4. Scatter estimation

Motivation

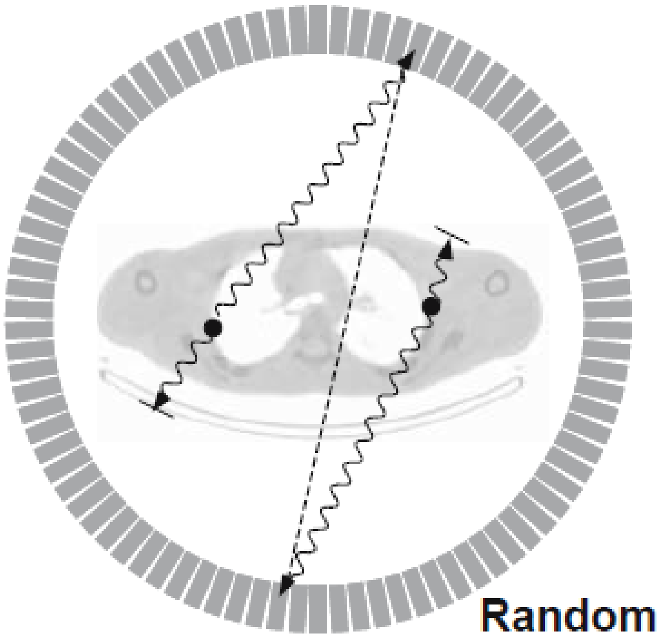
Photons

Lines of respone (LORs)



Random coincidences

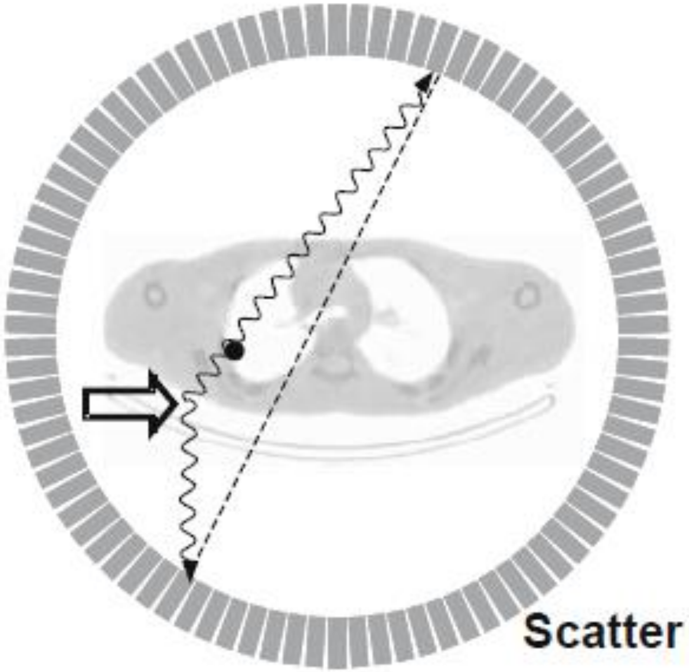
A random coincidence occurs when two nuclei decay at approximately the same time. After annihilation two photons from different annihilations are counted within the same time window and are considered to have come from the same positron.



Bailey, D.L., Townsend, D.W., Valk, P.E., Maisey, M.N. (Eds.), Positron Emission Tomography Basic Sciences, Springer, 2005

Scatter coincidences

Scatter coincidences are true coincidence events from single annihilation points, but where one or both the photons undergo Compton scatter within the imaging FOV before entering the PET detector.



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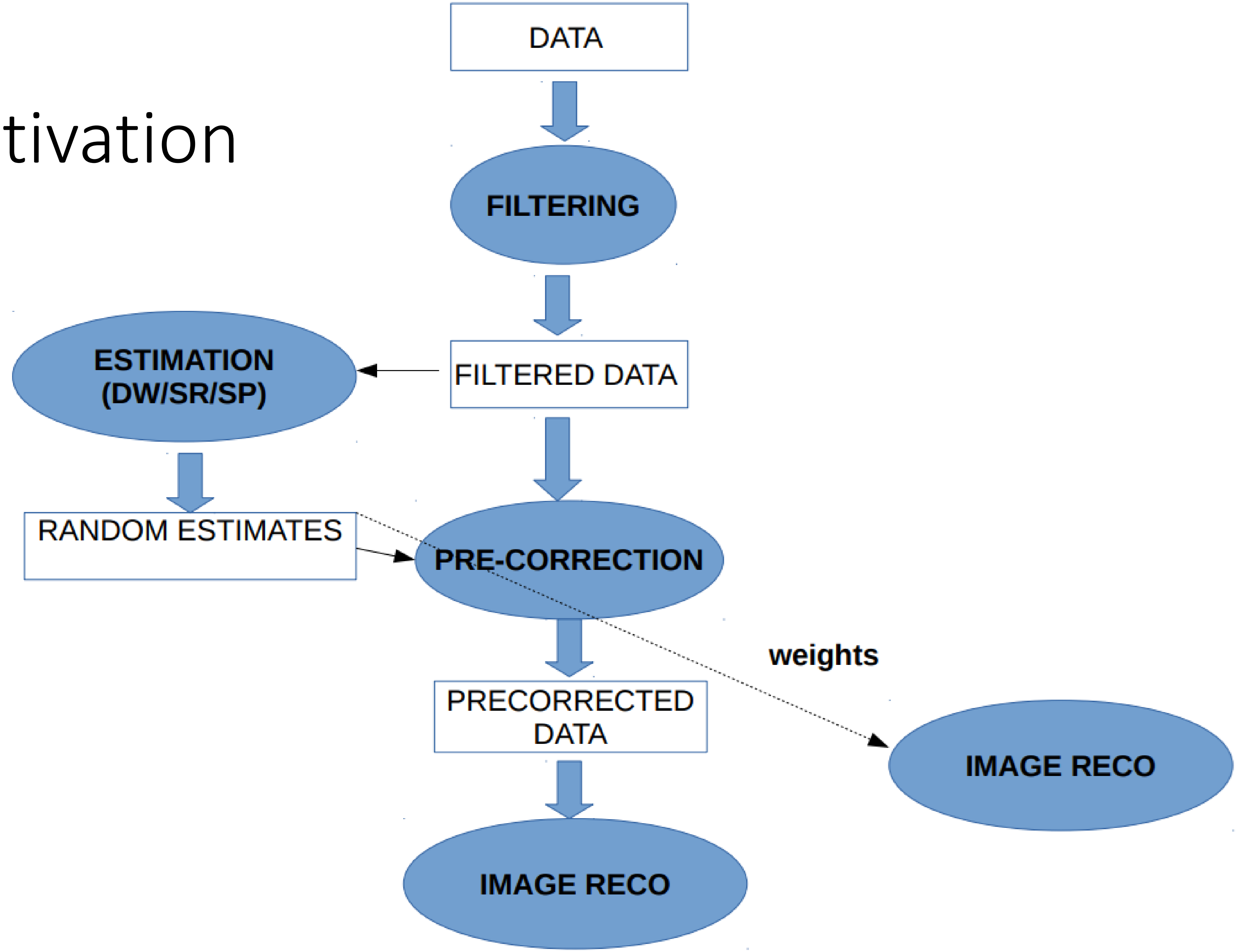
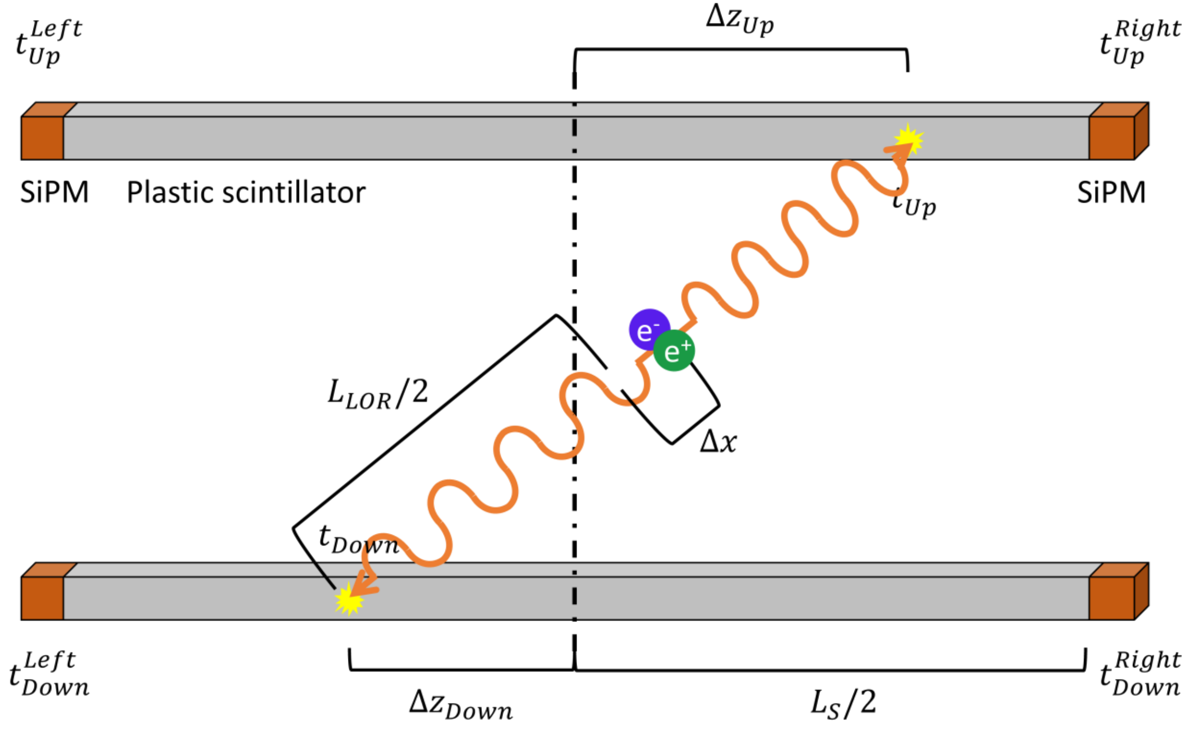
Motivation


DATA
FILTERING
ESTIMATION
(DW/SR/SP)
FILTERED DATA
RANDOM ESTIMATES
PRE-CORRECTION
weights
PRECORRECTED
DATA
IMAGE RECO
IMAGE RECO

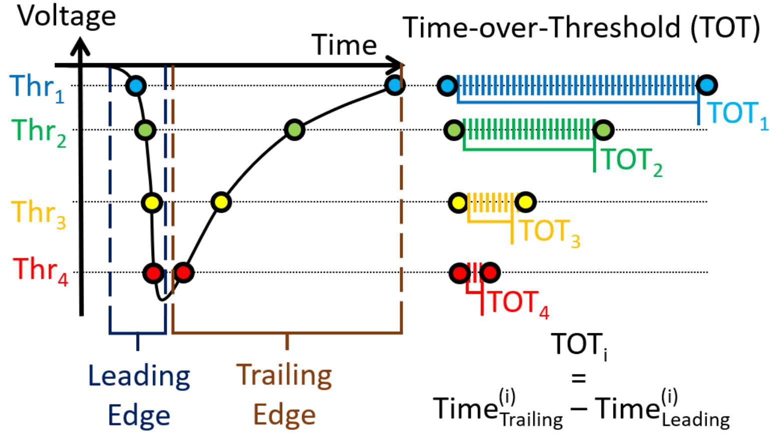
J-PET tomography

- Jagiellonian PET (J-PET)
- Detection based on Compton effect in long plastic scintillators
- Energy estimated as a Time-over-Threshold value
- Both energy and position of the hit reconstructed based on the measured times (resolution ~350 ps in FWHM*)
- Trigerless acquisition
- **Saving all interactions**



$$\Delta z_{Up/Down} = \frac{\left(t_{Up/Down}^{Left} - t_{Up/Down}^{Right}\right) v_S}{2} \qquad t_{Up/Down} = \frac{t_{Up/Down}^{Left} + t_{Up/Down}^{Right}}{2}$$

$$\Delta x = \frac{\left(t_{Up} - t_{Down}\right) v}{2}$$



http://koza.if.uj.edu.pl/pet/

*K. Dulski et al., NIM A 1008 (2021) 165452

Modular J-PET tomograph

Modules

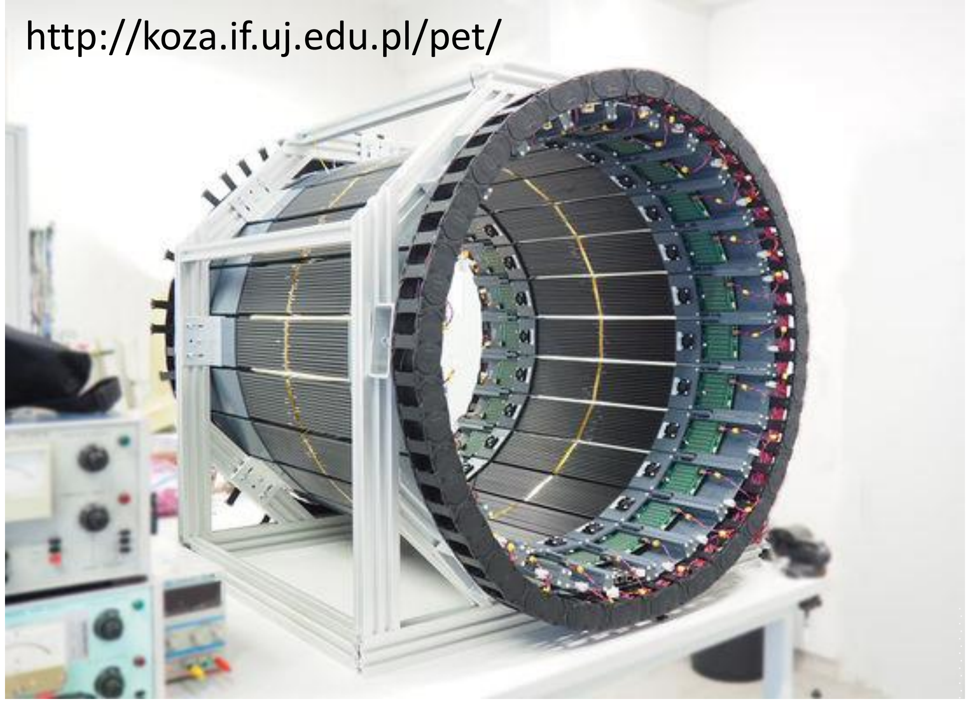
- 24
- Electronic read-out on both sides

Scintillators

- 13 per module
- 6 mm × 24 mm (radial) × 500 mm (axial)

„Crystals”

- (Simulation) Scintillators divided into pseudo-crystals – 2.5 mm in axial direction



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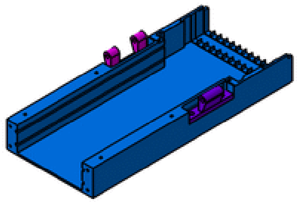


Random coincidences estimation

Random coincidences estimation methods:

- Singles Rate (SR)

This method uses the singles count rates of two detectors to infer the randoms rate in the corresponding LOR

$$R_{i,j}^{SR} = 2\tau R_i R_j$$

where R_i is a single events rate in detector i and τ is the time window

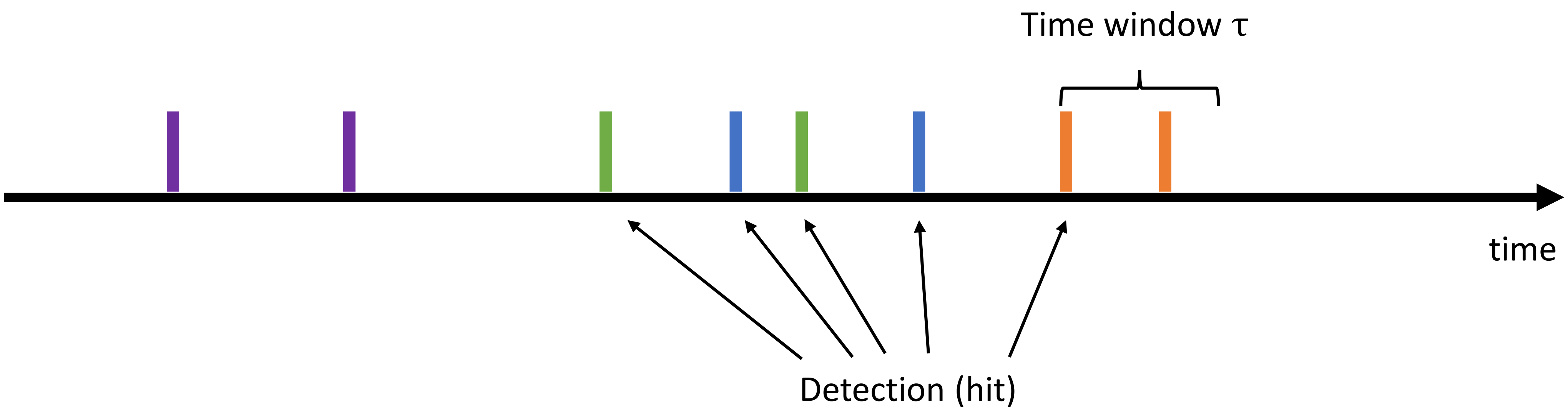
PLoS One. 2016 Sep 7;11(9):e0162096. doi: 10.1371/journal.pone.0162096. PMID: 27603143; PMCID: PMC5014417.

Random coincidences estimation

Random coincidences estimation methods:

- Singles Rate (SR)
- Delayed Time Window (DTW)

Each color represents detections from different annihilation event



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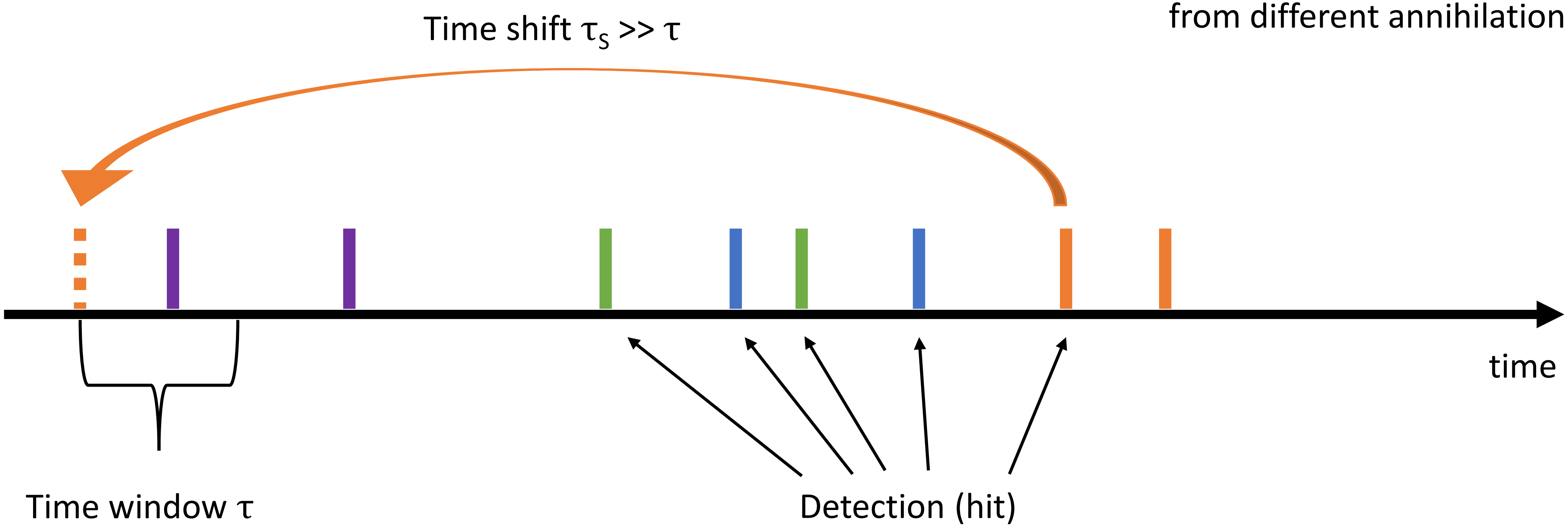

Random coincidences estimation

Random coincidences estimation methods:

- Singles Rate (SR)
- Delayed Time Window (DTW)
- Singles-Prompts (SP)

Extention to the conventional SR approach by exploiting the information contained in the singles and prompts rates. Uses only measurable data and provides the correct value for the randoms rate in one step (i.e. avoiding iterations) even for high count rate scenarios.

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Random coincidences estimation

Random coincidences estimation methods:

- Singles Rate (SR)
- Delayed Time Window (DTW)
- Singles-Prompts (SP)

$$R_{ij}^{SP} = \frac{2\tau e^{-(\lambda+S)\tau}}{(1-2\lambda\tau)^2}(S_i - e^{(\lambda+S)\tau}\ P_i)(S_j - e^{(\lambda+S)\tau}\ P_j)$$

where $S = \sum_i S_i$ is the rate of singles measured by the scanner as a whole, $P_i = \sum_j P_{ij}$ is the prompts rate in detector i and $P = \sum_i P_i$ is twice the prompts rate detected by the scanner; λ corresponds to the solution of the equation:

$$2\tau\lambda^2 - \lambda + S - P\ e^{(\lambda+S)\tau} = 0$$

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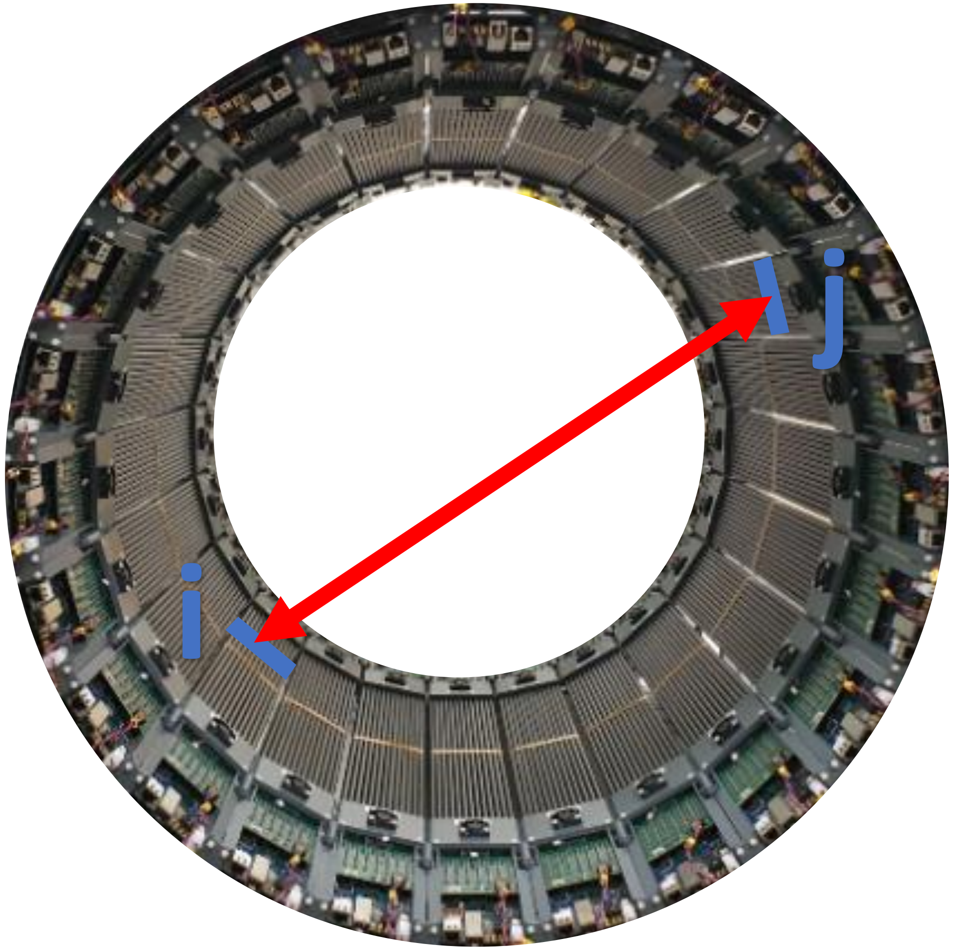
Random coincidences in Modular J-PET

- Division of tomograph to small detectors to obtain discrete numer of LOR projections
- In transverse plane -> 24 modules
- In axial coordinate -> 50 × 10 mm sections
- In total 1200 detectors

- $R_{i,j}$ – rate of coincidences per LOR projection connecting detectors *i* and *j*

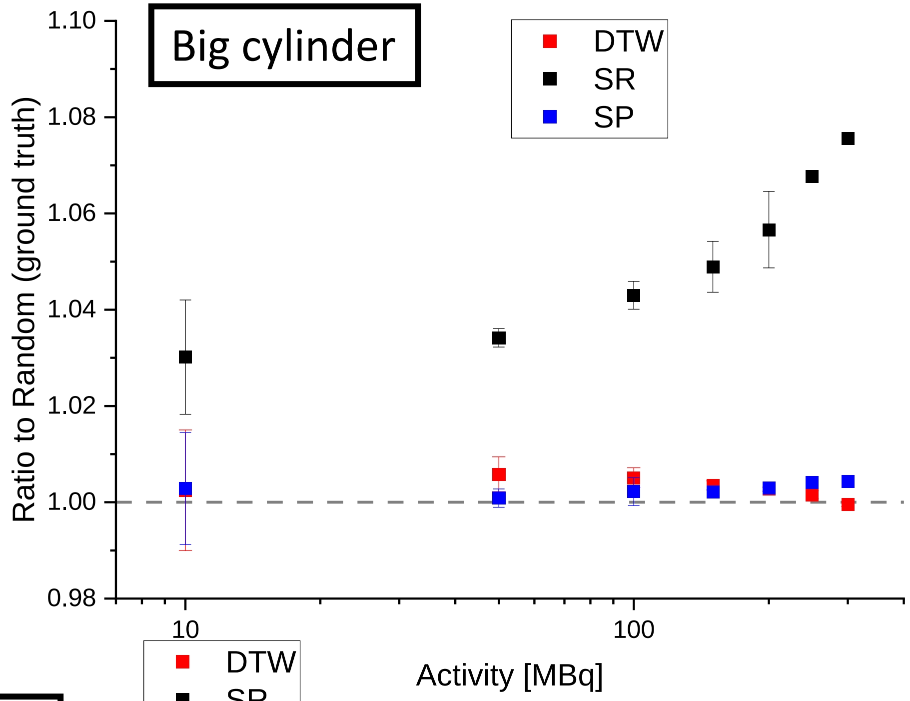


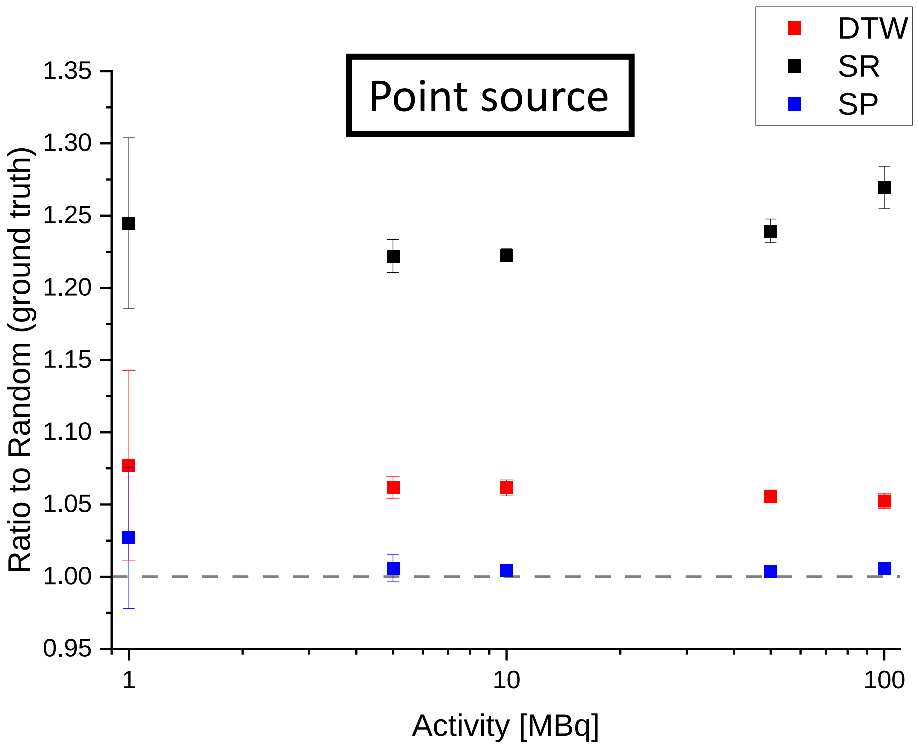
Simulations conditions

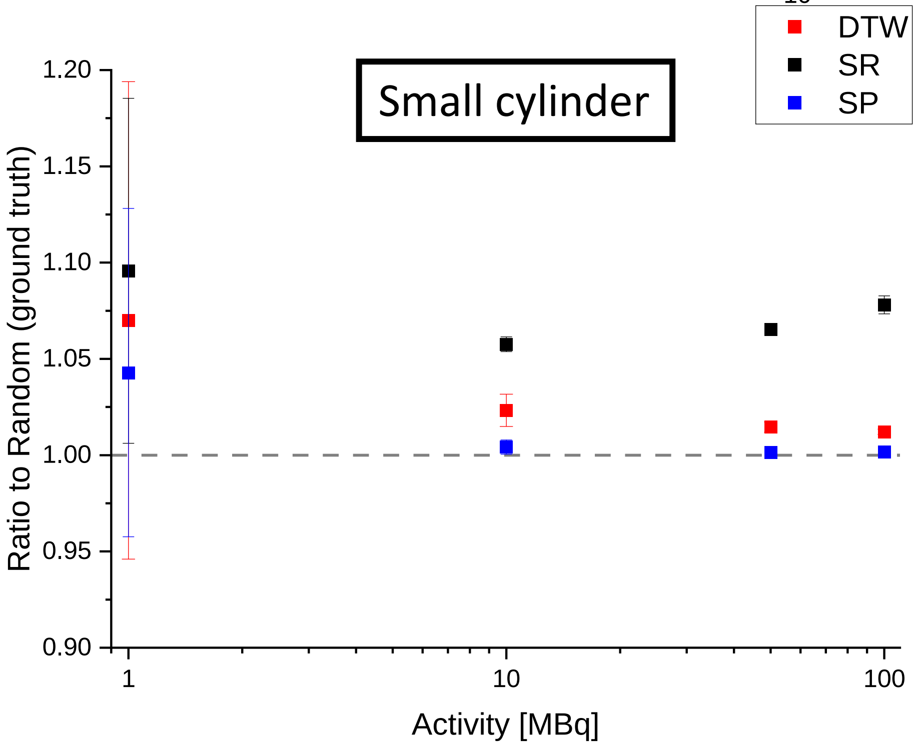
- Phantoms / Sources (back-to-back):
  - Point source in tomograph's center
  - Small water-filled cylinder (radius=15 cm, length=22 cm -> ~NEMA IEC)
  - Big water-filled cylinder (radius=10.555 cm, length=168 cm -> BMI=22.6*)
  - NEMA IEC
- Coincidence time window: 3 ns
- Minimum difference of 1 module for coincidence creation

*Z Med Phys. 2021 Aug;31(3):305-315. doi: 10.1016/j.zemedi.2021.01.006. Epub 2021 Feb 13. PMID: 33593642.

Total random coincidences estimates



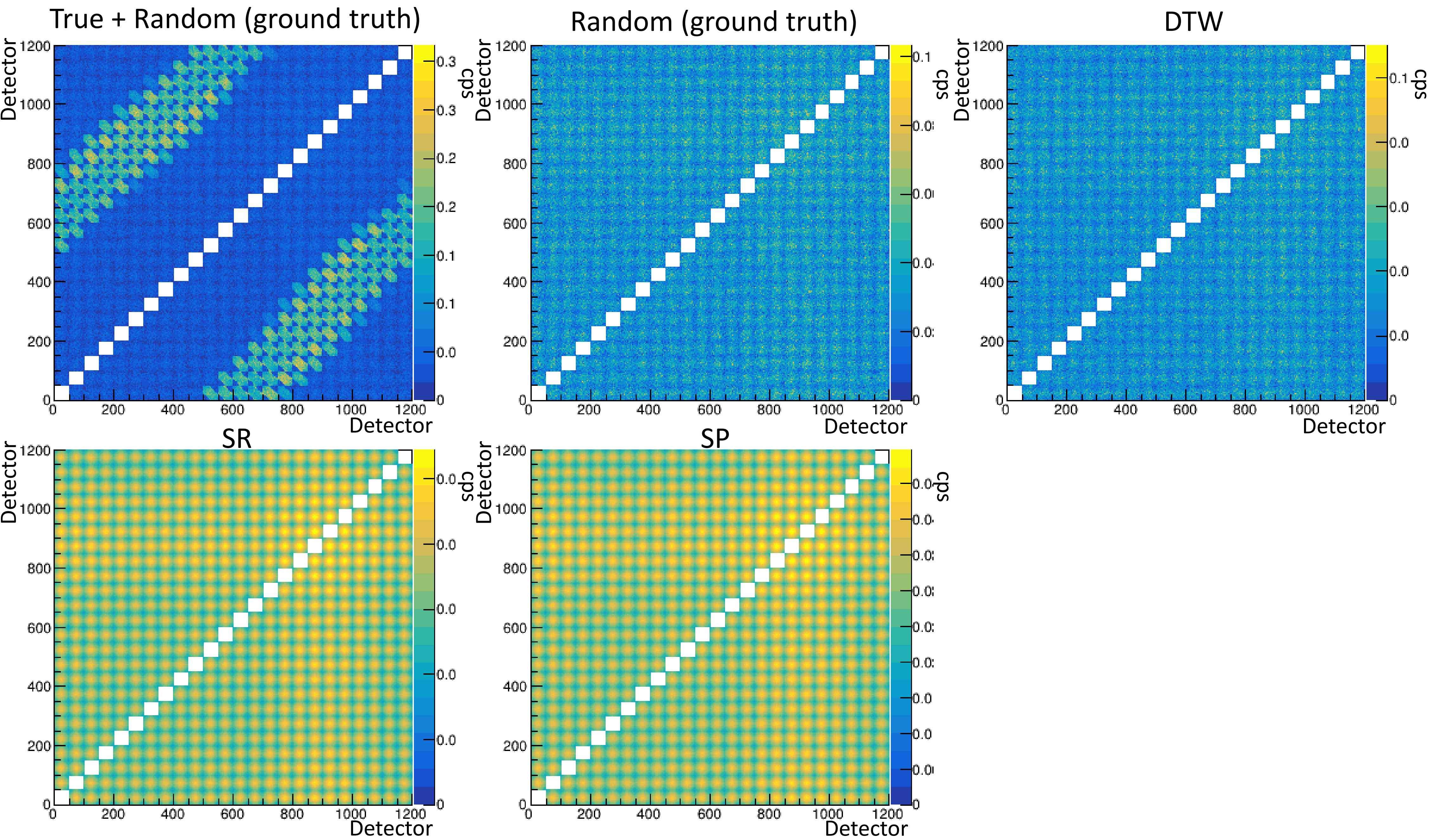




NEMA IEC

DTW / Random (ground truth)	1.0151(16)
SR / Random (ground truth)	1.0745(12)
SP / Random (ground truth)	1.0014(12)

Distribution of random coincidences



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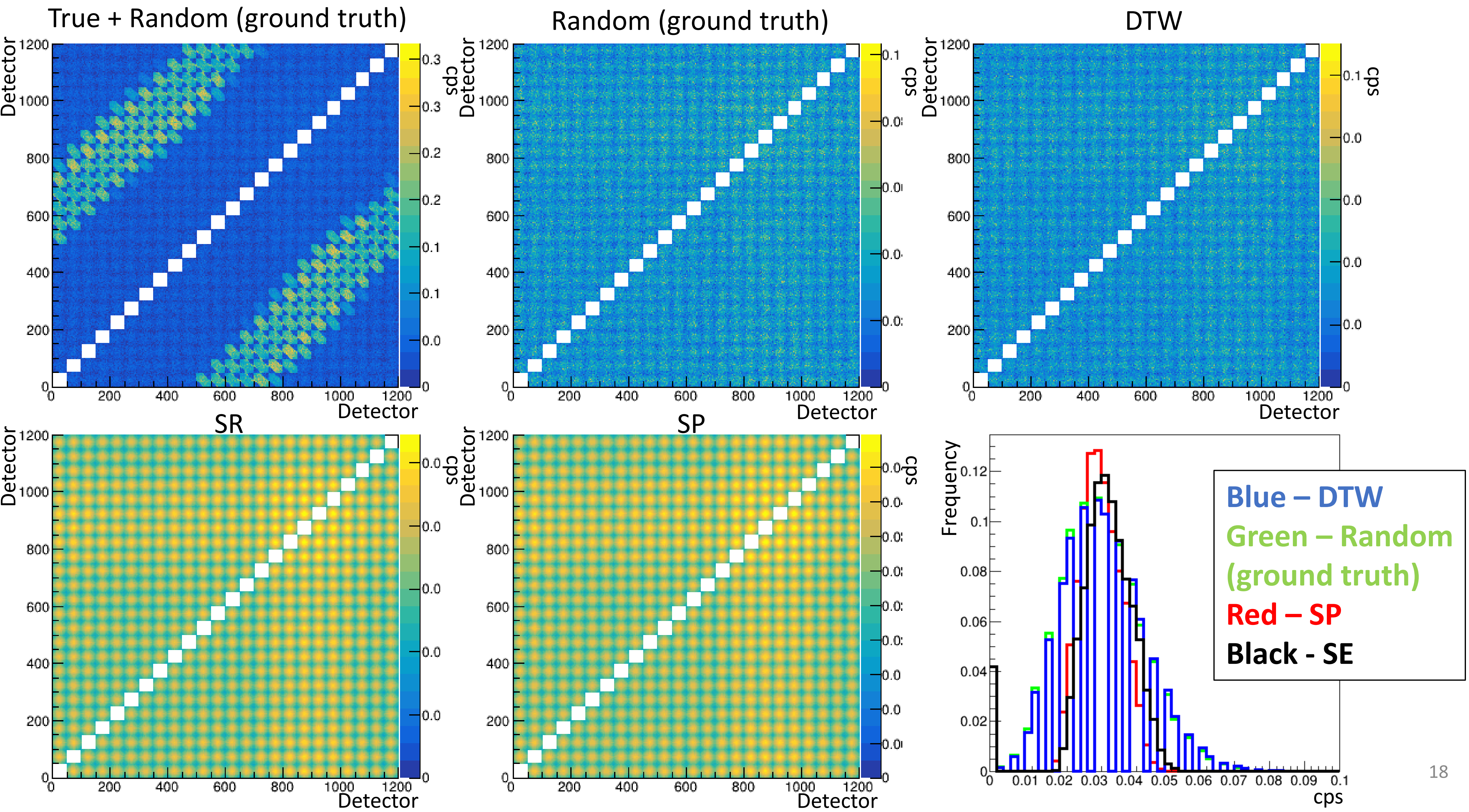
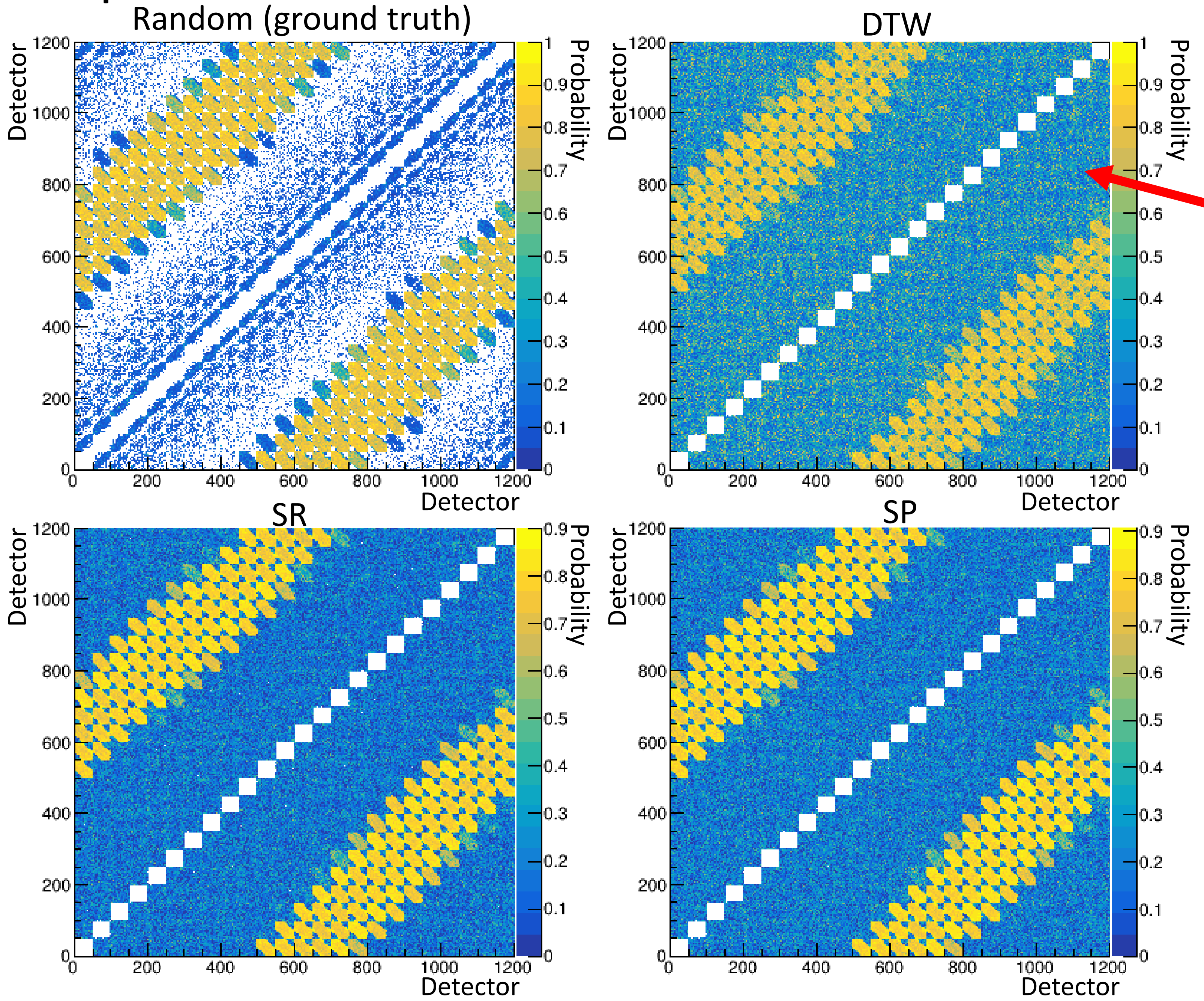
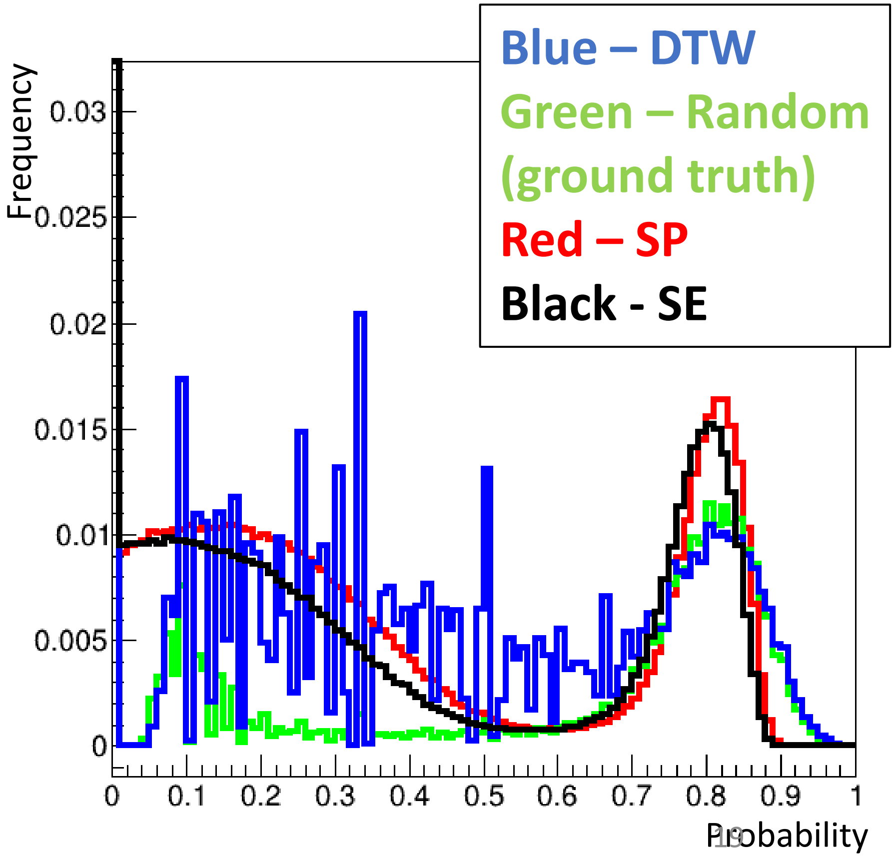


Impact of random coincidences

$$\frac{\text{(True + Random (ground truth)} - \text{Random Estimation)}}{\text{True + Random (ground truth)}}$$

For each pixel in projection matrices



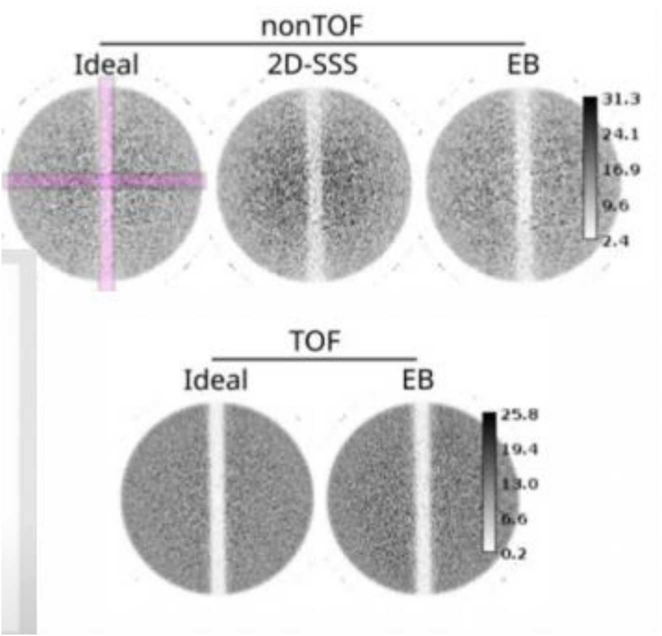


Future plans

- Utilization of DTW estimation method for random coincidences correction
- First trials with statistical subtraction methods – pre-correction
- Test of other correction methods – direct image reconstruction
- Test on real data from Modular J-PET
- Shift to Total-Body J-PET tomograph

SCATTER CORRECTION METHODS

1. Tail fitting
2. Single(Double) Scatter Simulation
3. Monte Carlo Simulations
4. Deep Learning Approaches
5. Energy Based Scatter Simulation



Efthimiou N. et al. PMB (2022)

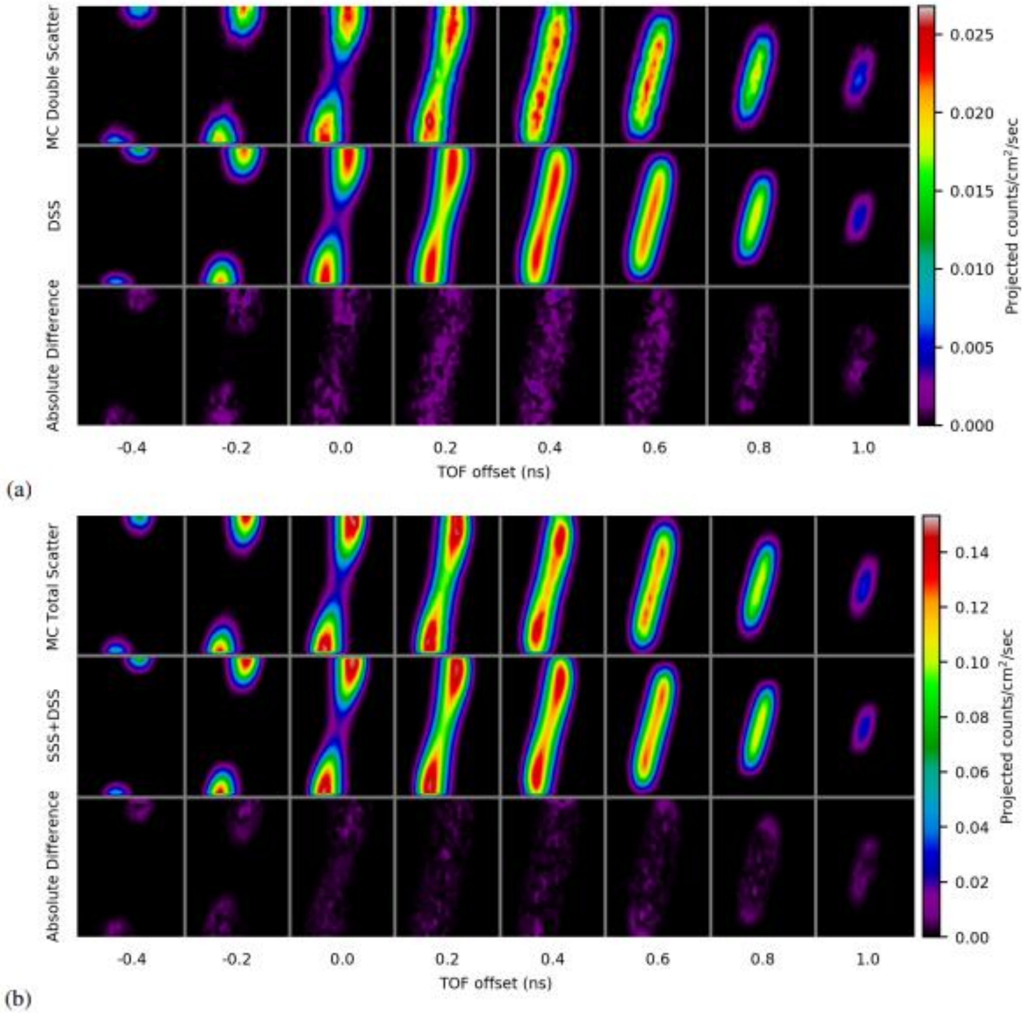


Fig. 7. Results for the test phantom of Fig. 3: (a) TOF double scatter sinograms. (b) MC total scatter versus SSS+DSS TOF sinograms. In each sinogram, radial bin position varies horizontally and projection angle varies vertically.

Watson C. et al. IEEE TRPMS (2022)

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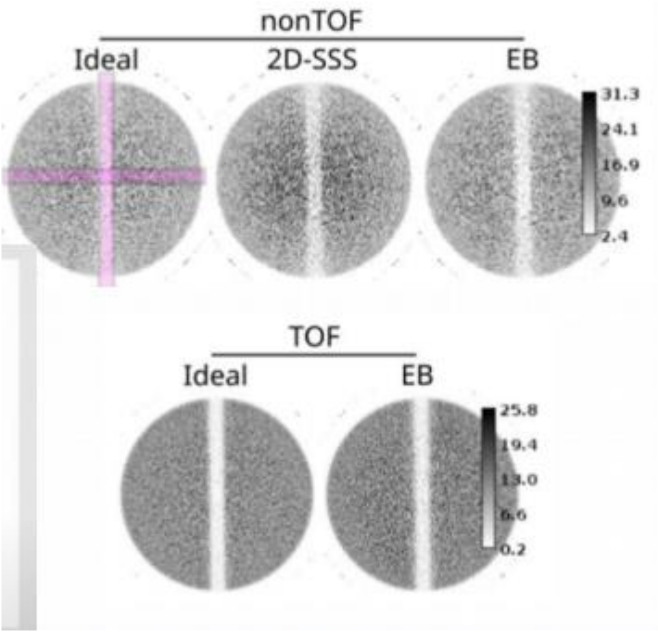

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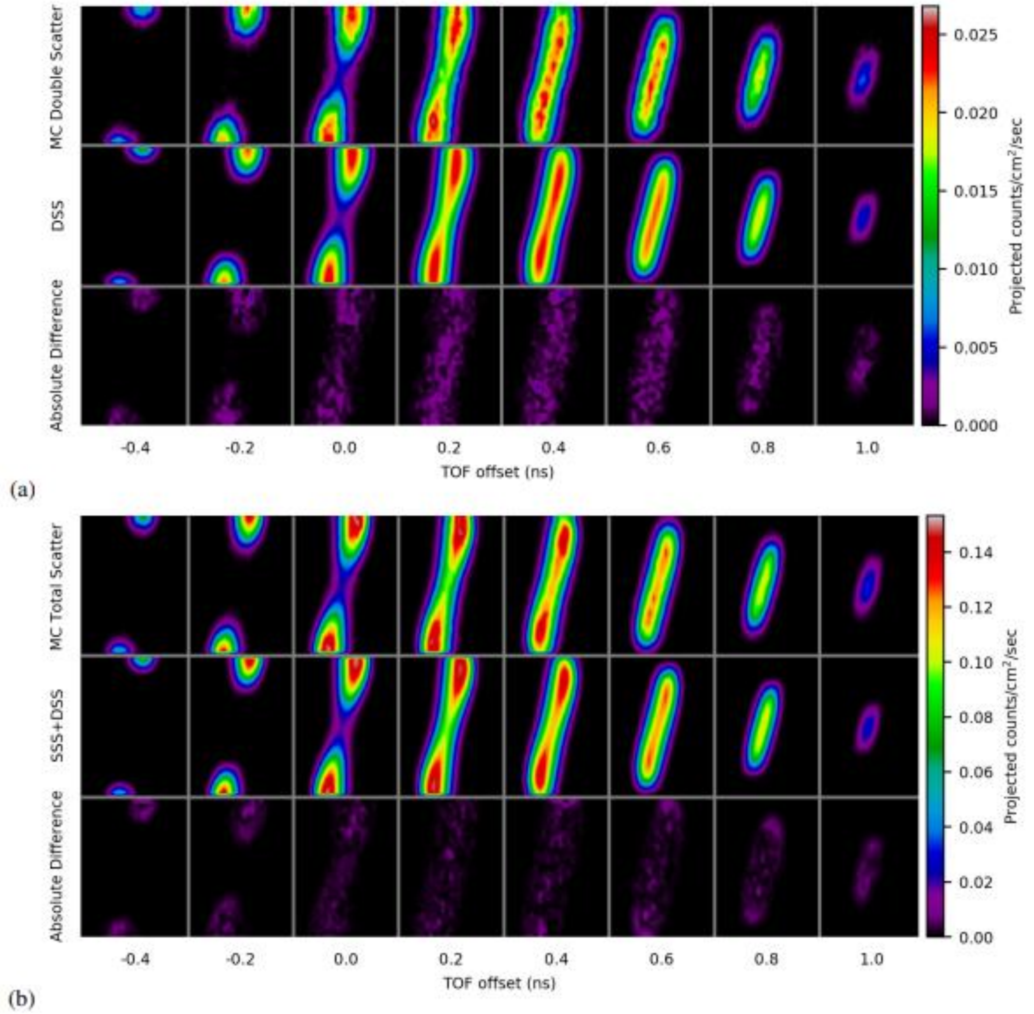

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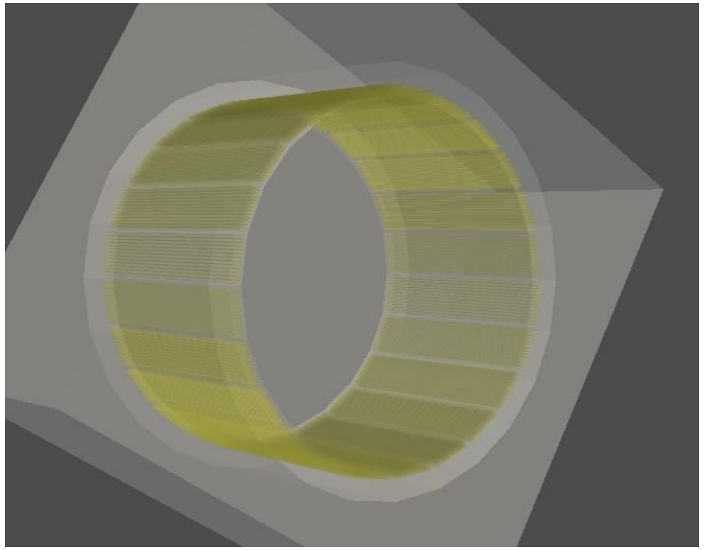
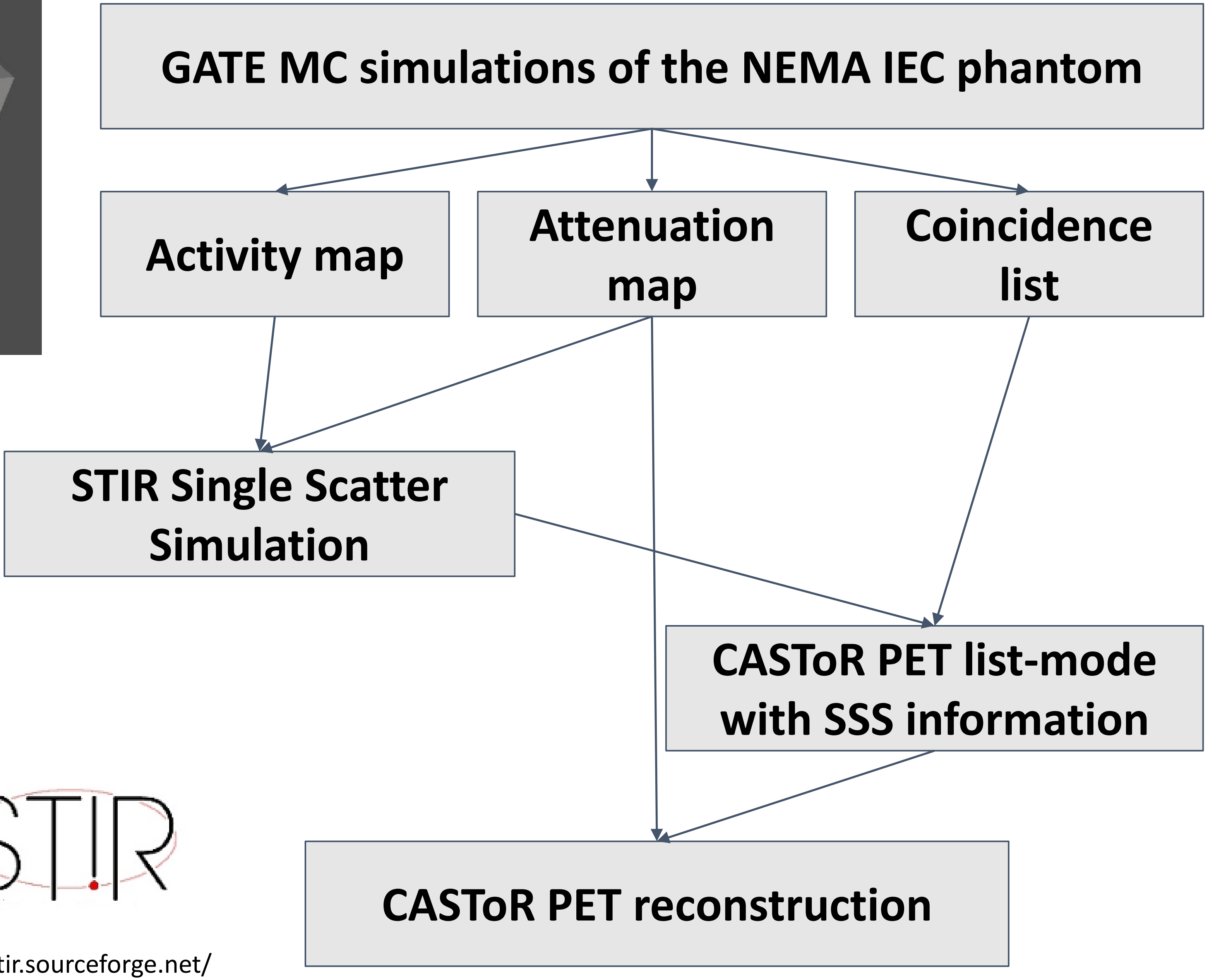
SIMPLIFIED SCATTER CORRECTION WORKFLOW



Modular J-PET geometry build with Opengate during the hackaton



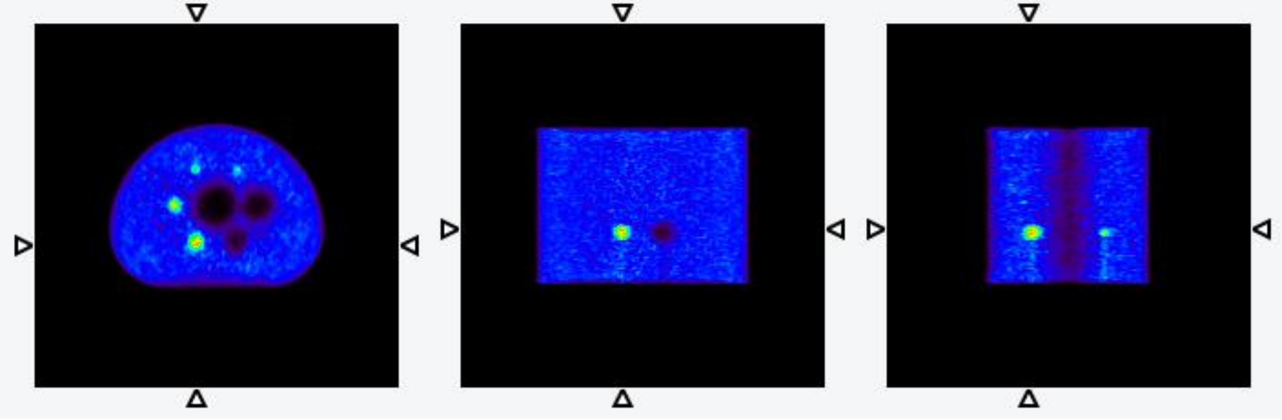
https://gate.uca.fr/#/admin

https://castor-project.org/

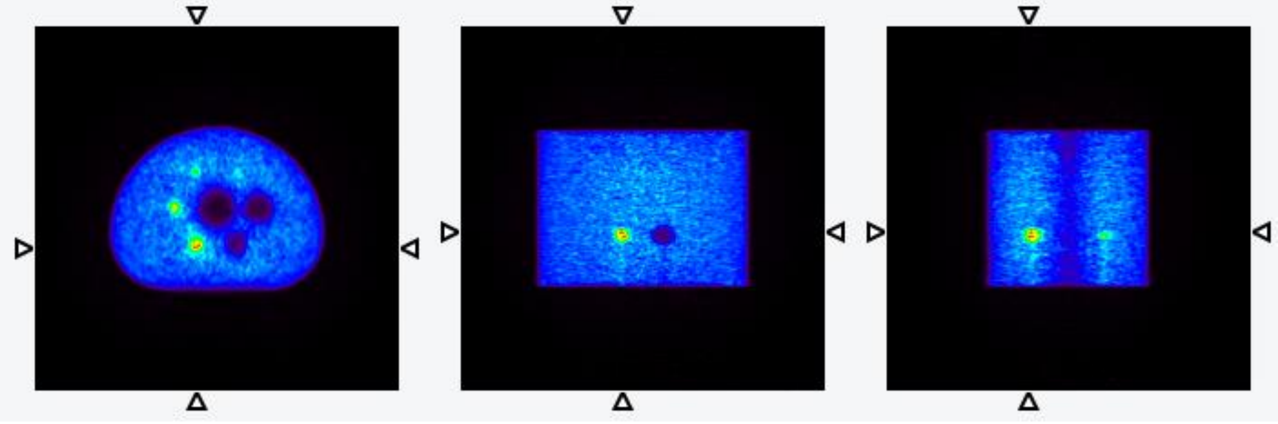
https://stir.sourceforge.net/

PRELIMINARY RESULTS

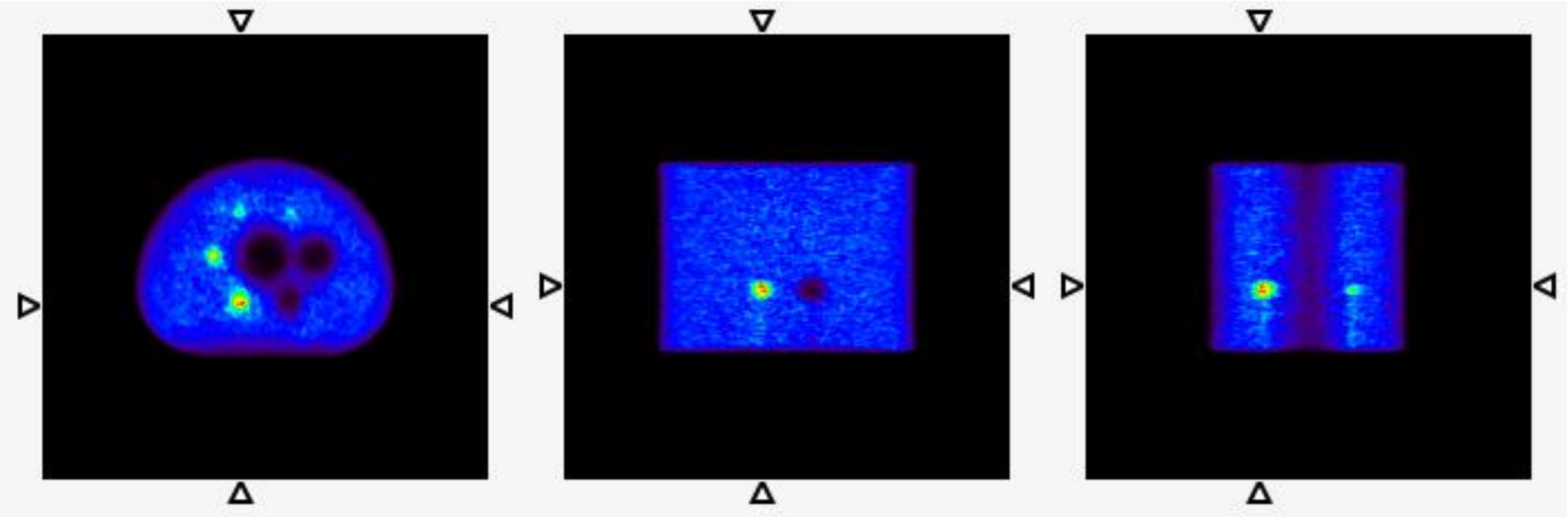
TRUE COINCIDENCES



TRUE + SCATTER COINCIDENCES



TRUE + SCATTER COINCIDENCES WITH SINGLE SCATTER SIMULATION CORRECTIONS



PRELIMINARY RESULTS

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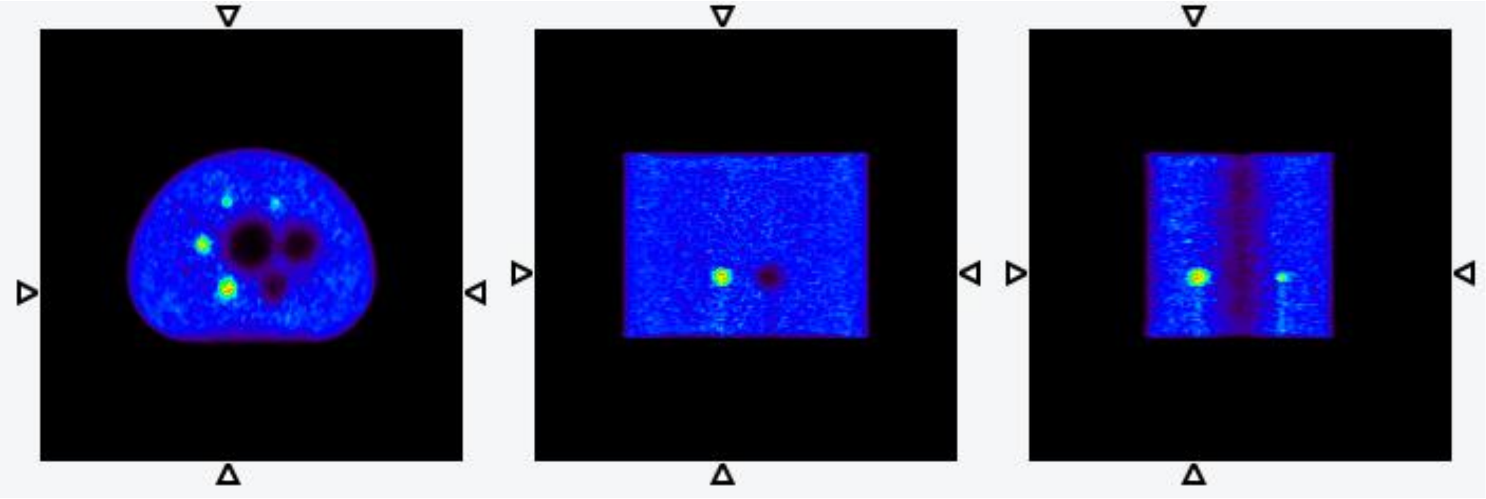

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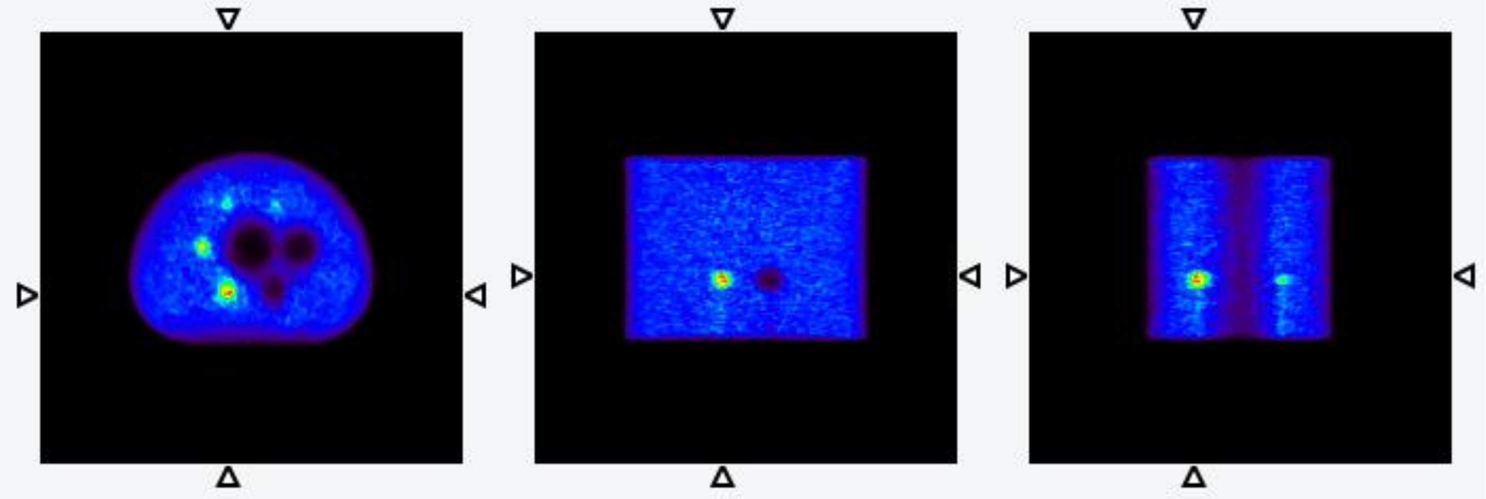

Ongoing works:

1. Understanding and neglecting the effect of underestimation of the activity at the boundary
2. Modelling properly the detector efficiency in the SSS model implemented in STiR
3. Validation of the procedure for the TB J-PET scanners for both NEMA IEC and XCAT phantom
4. Waiting for STiR to implement ToF support for SSS