Modelling and impact of random coincidences in Total-Body J-PET scanner

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on behalf of the J-PET Collaboration

Applications of radiation detection techniques in fundamental physics, food control, medicine and biology

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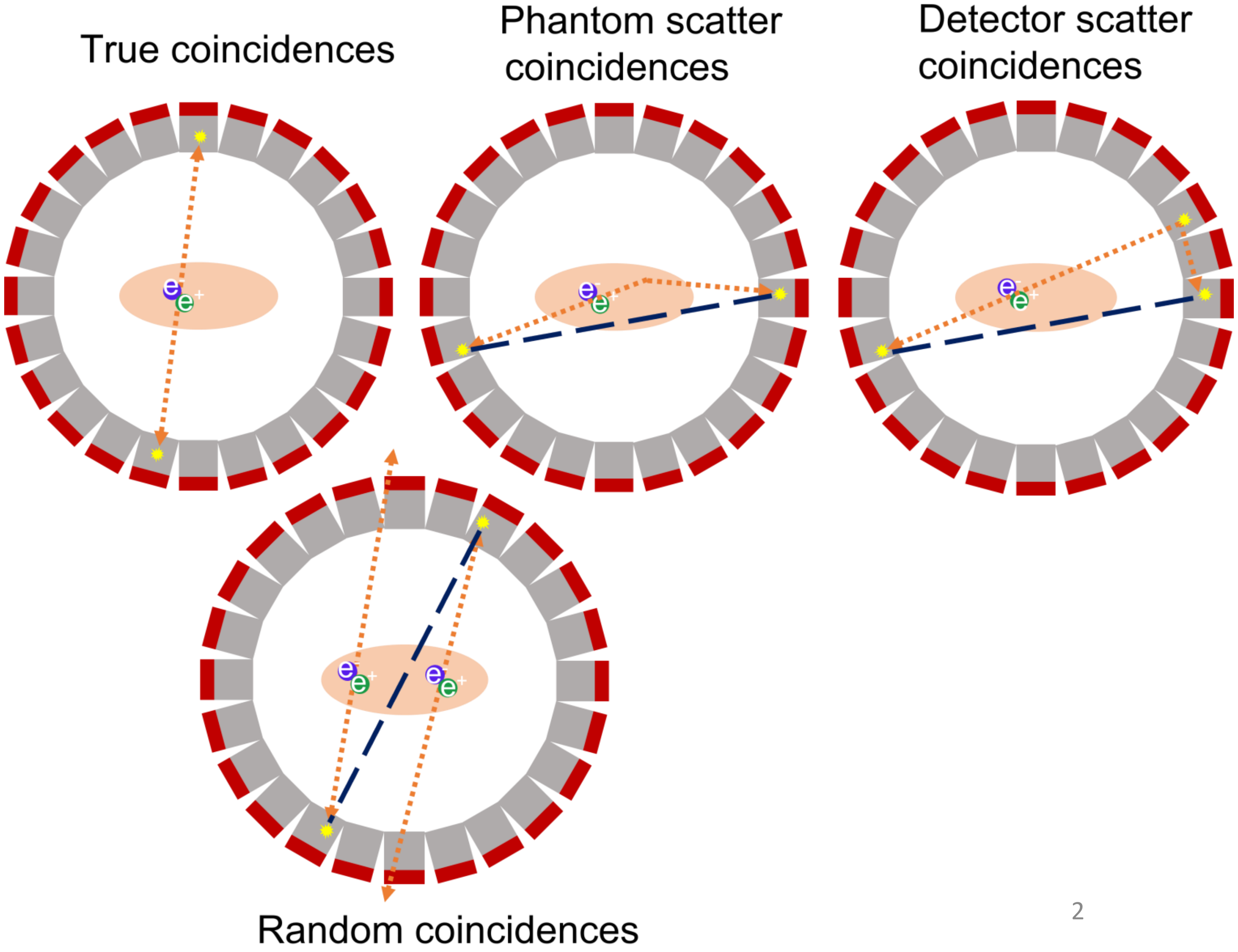
Coincidences in PET tomography

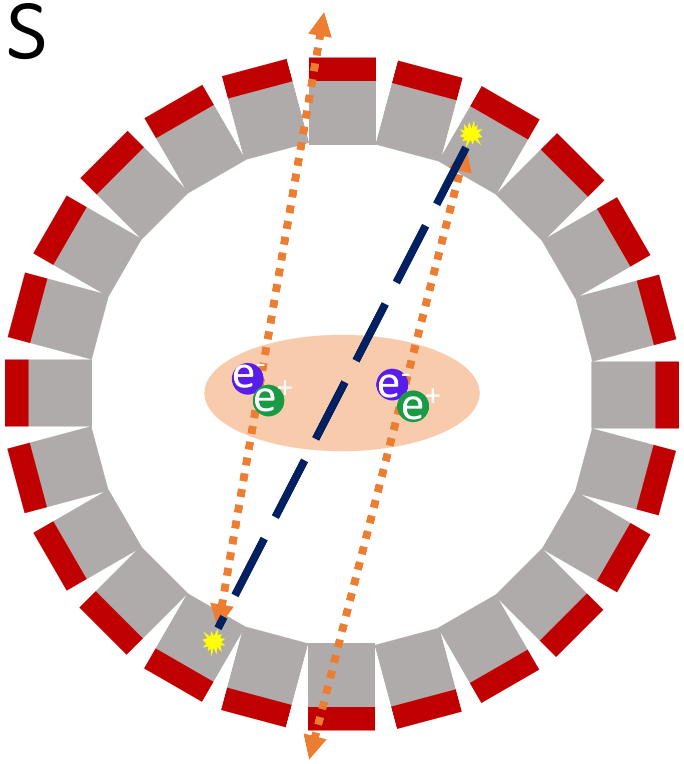
- Coincidence in PET – detection of 2 interactions in the scintillators in a given time window

- Line of response (LOR) – line connecting 2 detected interactions



Random (accidental) coincidences

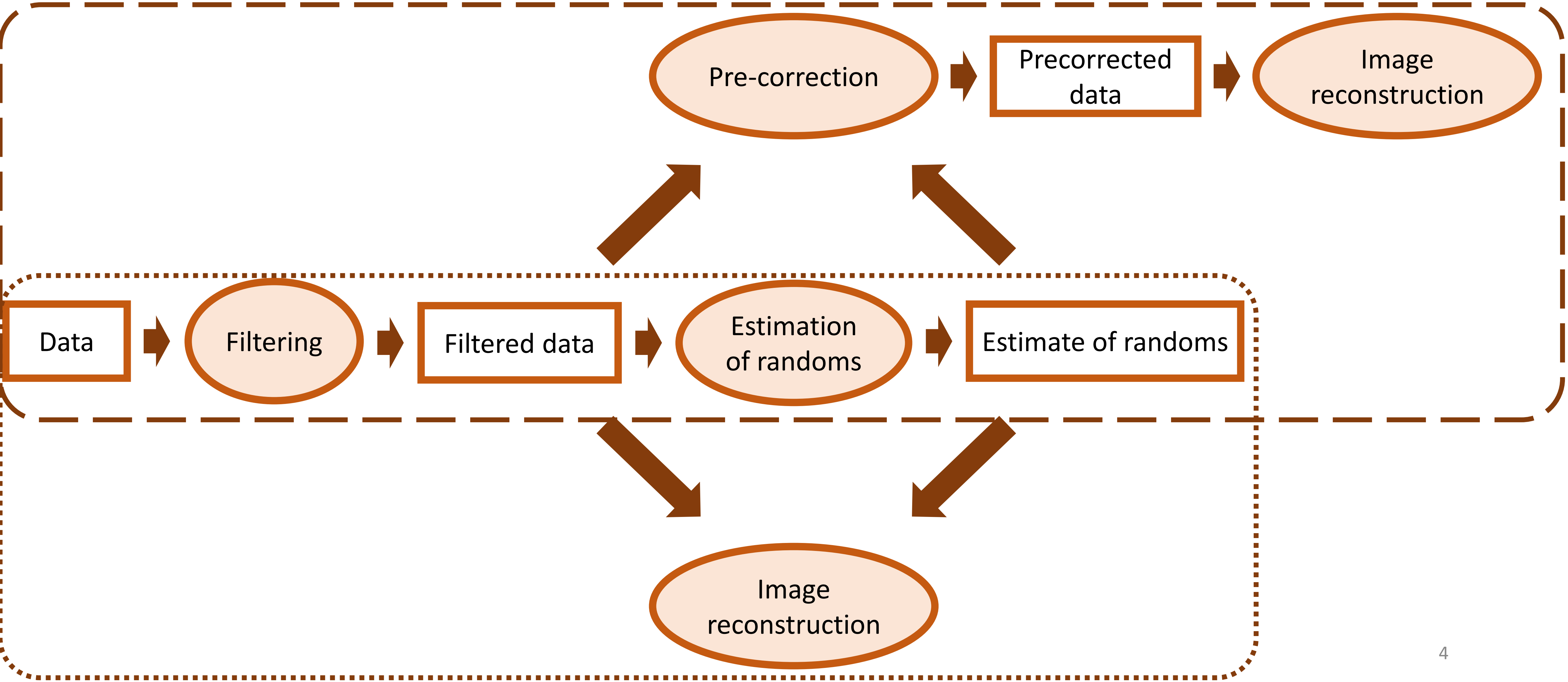
A random coincidence occurs when two nuclei decay at approximately the same time. After annihilation two photons from different annihilations are counted within the same time window and are considered to have come from the same positron



Random coincidence

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

Correction for random coincidences (randoms)



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

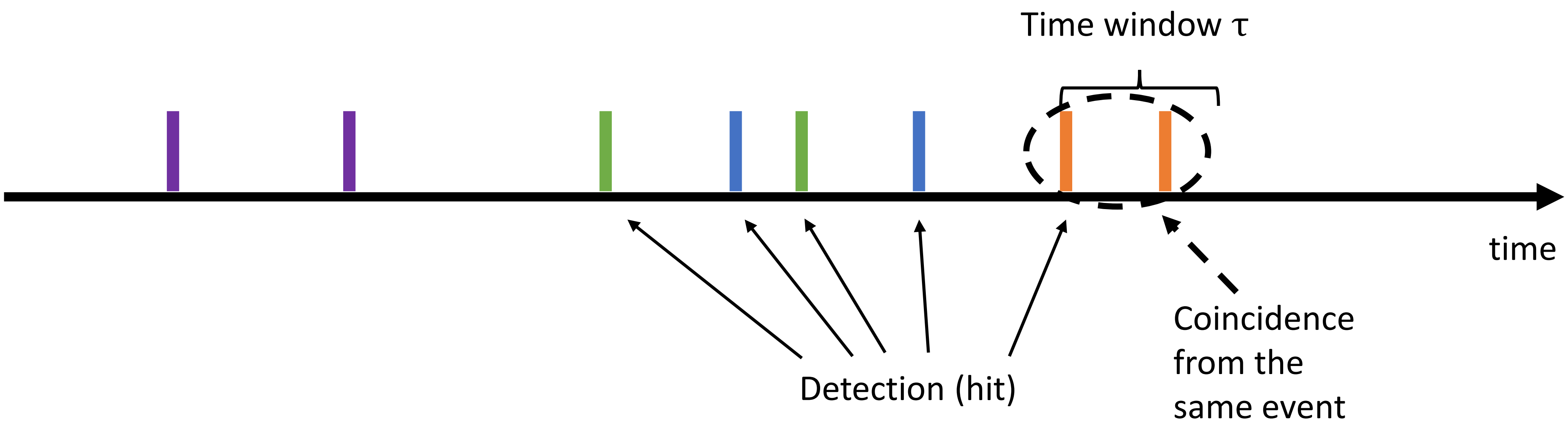
PLoS One. 2016 Sep 7;11(9):e0162096. doi: 10.1371/journal.pone.0162096. PMID: 27603143; PMCID: PMC5014417.

Random coincidences estimation

Random coincidences estimation methods:

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

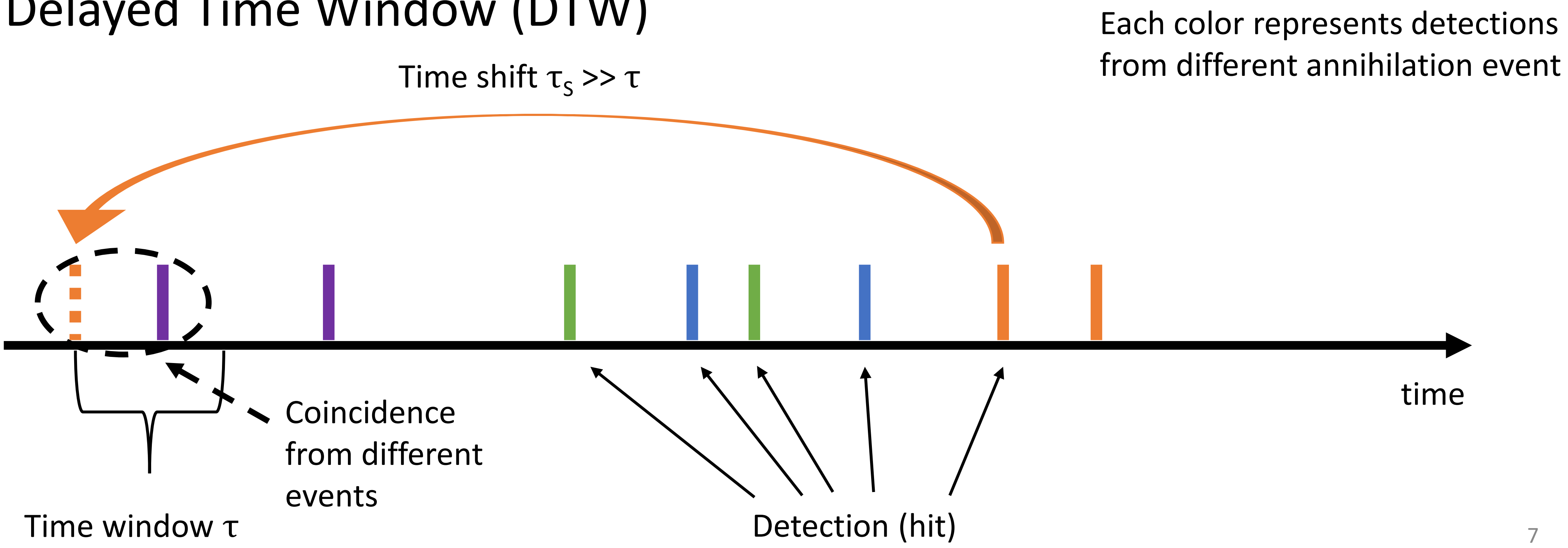
Each color represents detections from different annihilation event



Random coincidences estimation

Random coincidences estimation methods:

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



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.

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)
- 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:

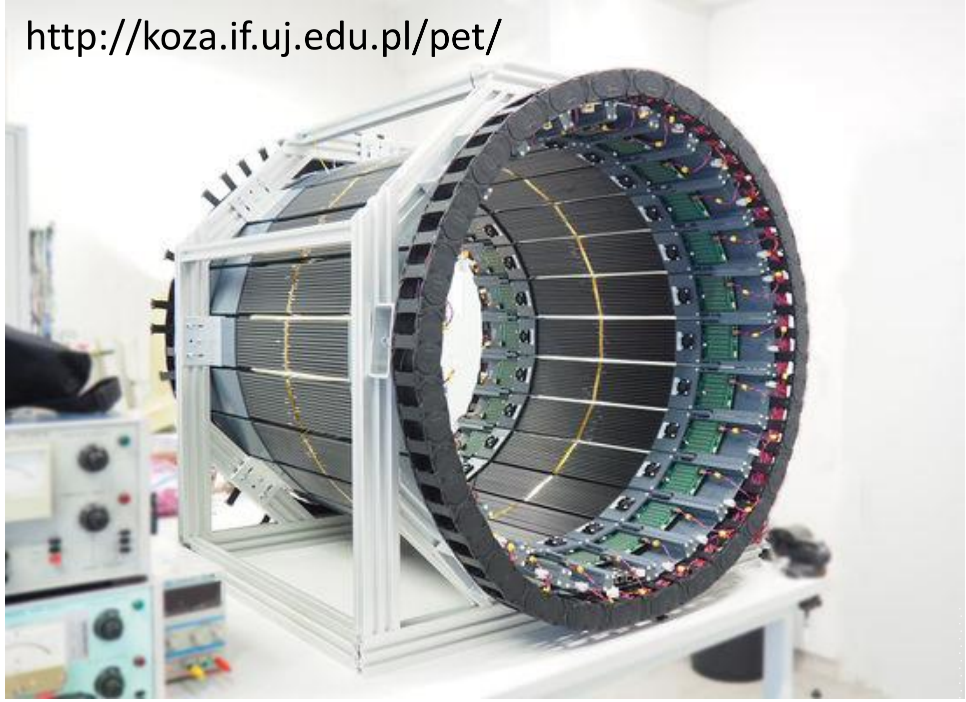
$$2\tau\lambda^2 - \lambda + S - P\ e^{(\lambda+S)\tau} = 0$$

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

Simulation software

- Geant4 Application for Tomographic Emission (GATE)
- Version 9.0
- Opensource software
- Allows for generation of radioactive source decays and investigation of interactions of their products, together with simulation of the PET scanners and their responses

Modular J-PET tomograph



Modules

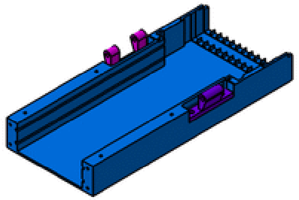
- 24
- Electronic read-out on both sides

Scintillators

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

„Crystals”

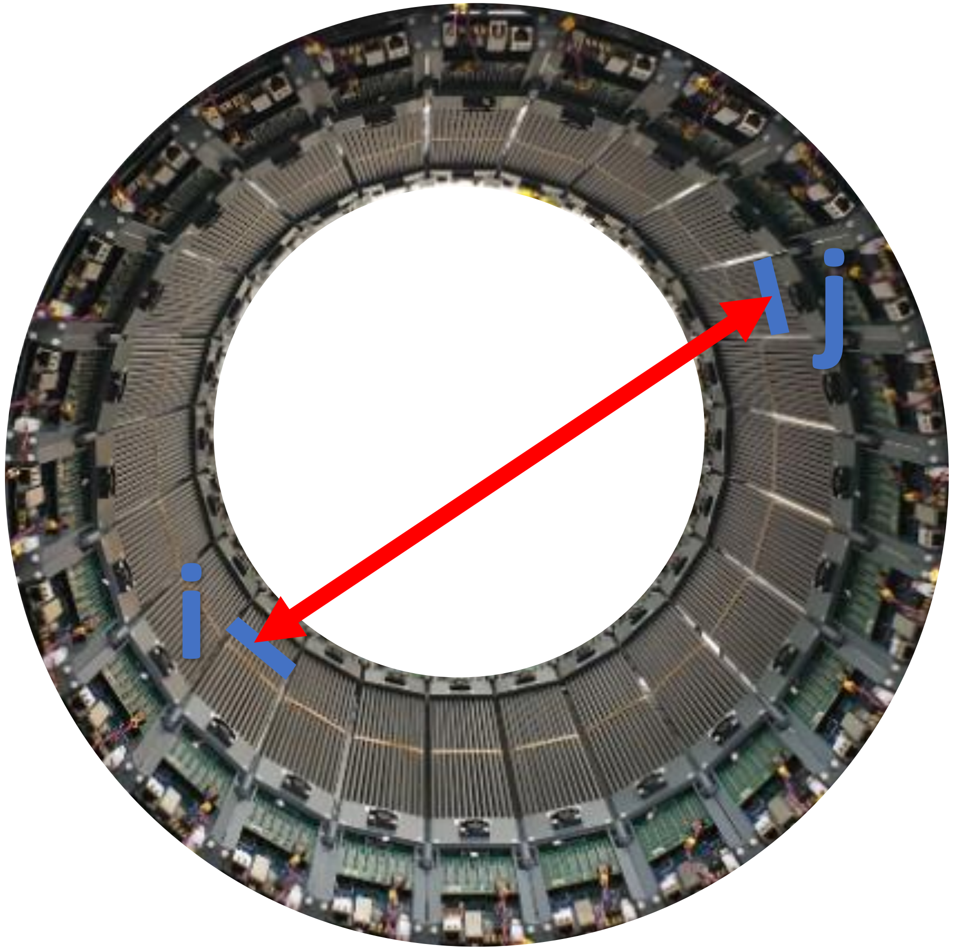
- (Simulation) Scintillators divided into pseudo-crystals – 2.5 mm in axial direction



Modular J-PET tomograph

- 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*



„Figures of merit”

- Total number (in whole PET scanner) of estimated coincidences
- Distribution of random coincidences per LOR projection connecting detectors *i* and *j*
- Impact of random coincidences per LOR projection connecting detectors *i* and *j* represented as probability that given LOR is coming form true coincidence

Simulations conditions

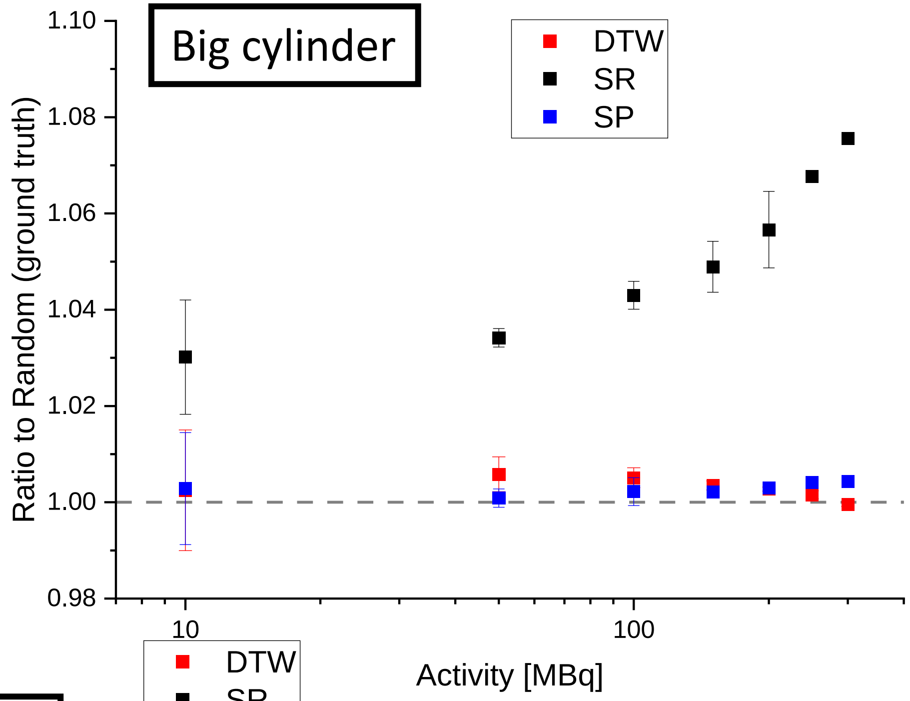
NEMA IEC Phantom
https://gammagurus.com/products/pet-phantom-nema-2012-iec-2008
Access: 09.05.2023

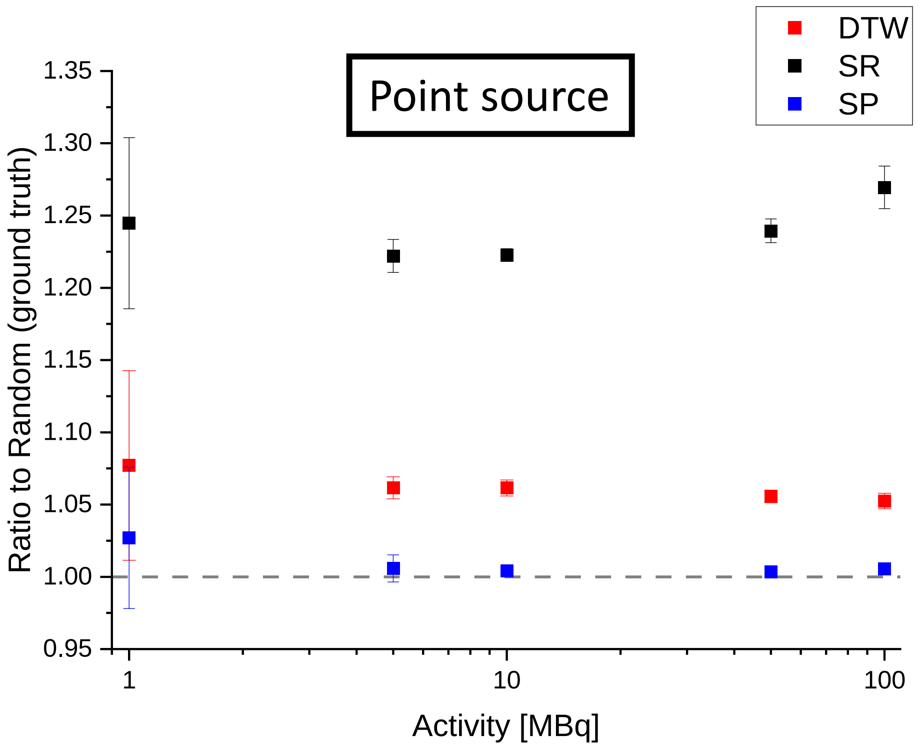
- Phantoms / Sources (back-to-back):
  - Point source in tomograph's center
  - Small water-filled cylinder (radius=15 cm, length=22 cm -> ~NEMA IEC)
  - Big water-filled cylinder (radius=10.555 cm, length=168 cm -> BMI=22.6*)
  - NEMA IEC
- Coincidence time window: 3 ns
- Minimum difference of 1 module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

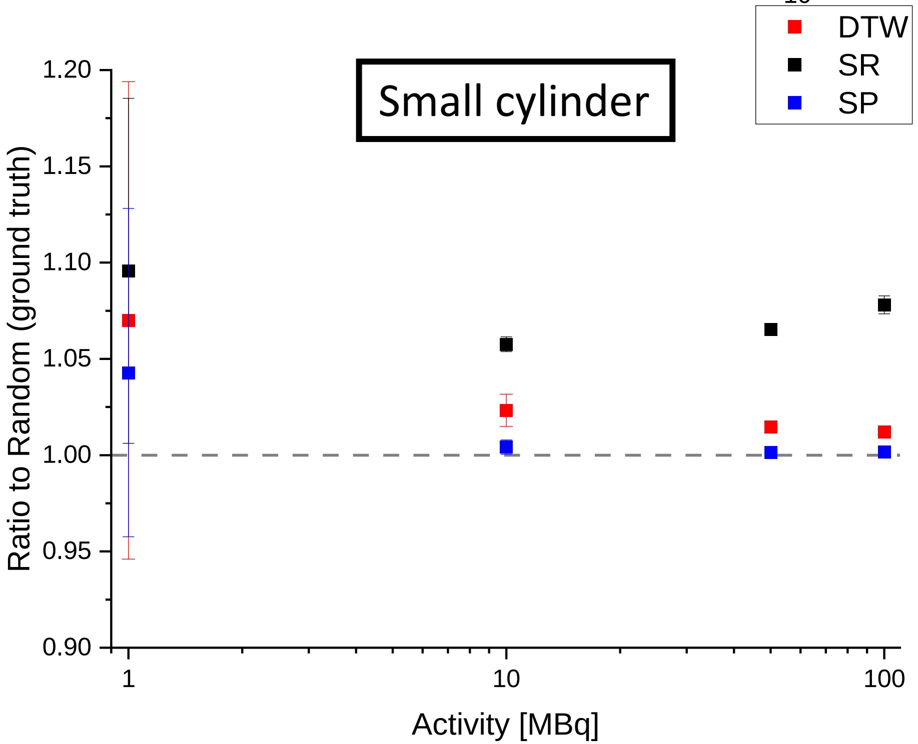
*Z Med Phys. 2021 Aug;31(3):305-315. doi: 10.1016/j.zemedi.2021.01.006. Epub 2021 Feb 13. PMID: 33593642.

PRELIMINARY

Total random coincidences estimates





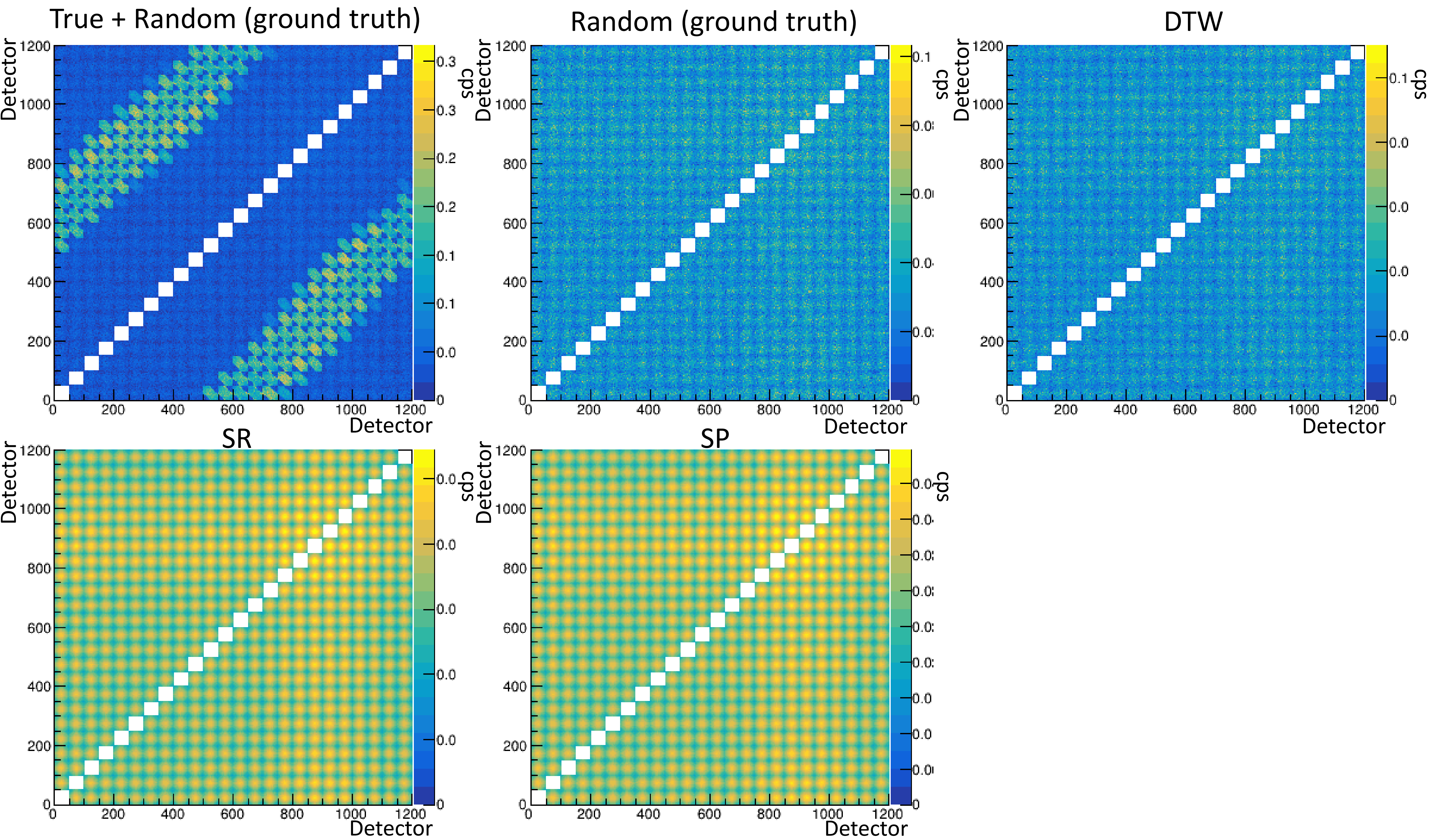


NEMA IEC

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

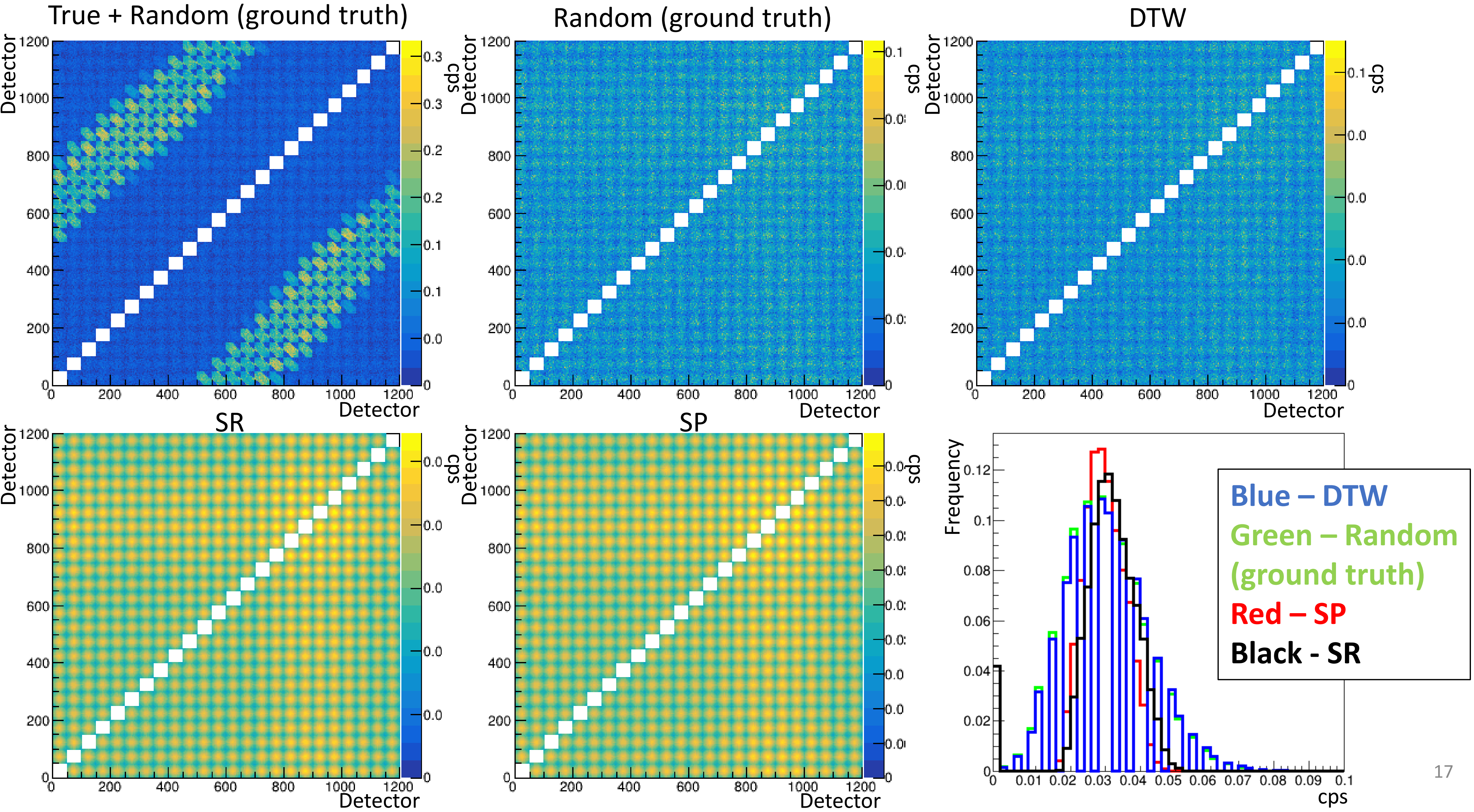
Distribution of random coincidences

PRELIMINARY



Distribution of random coincidences

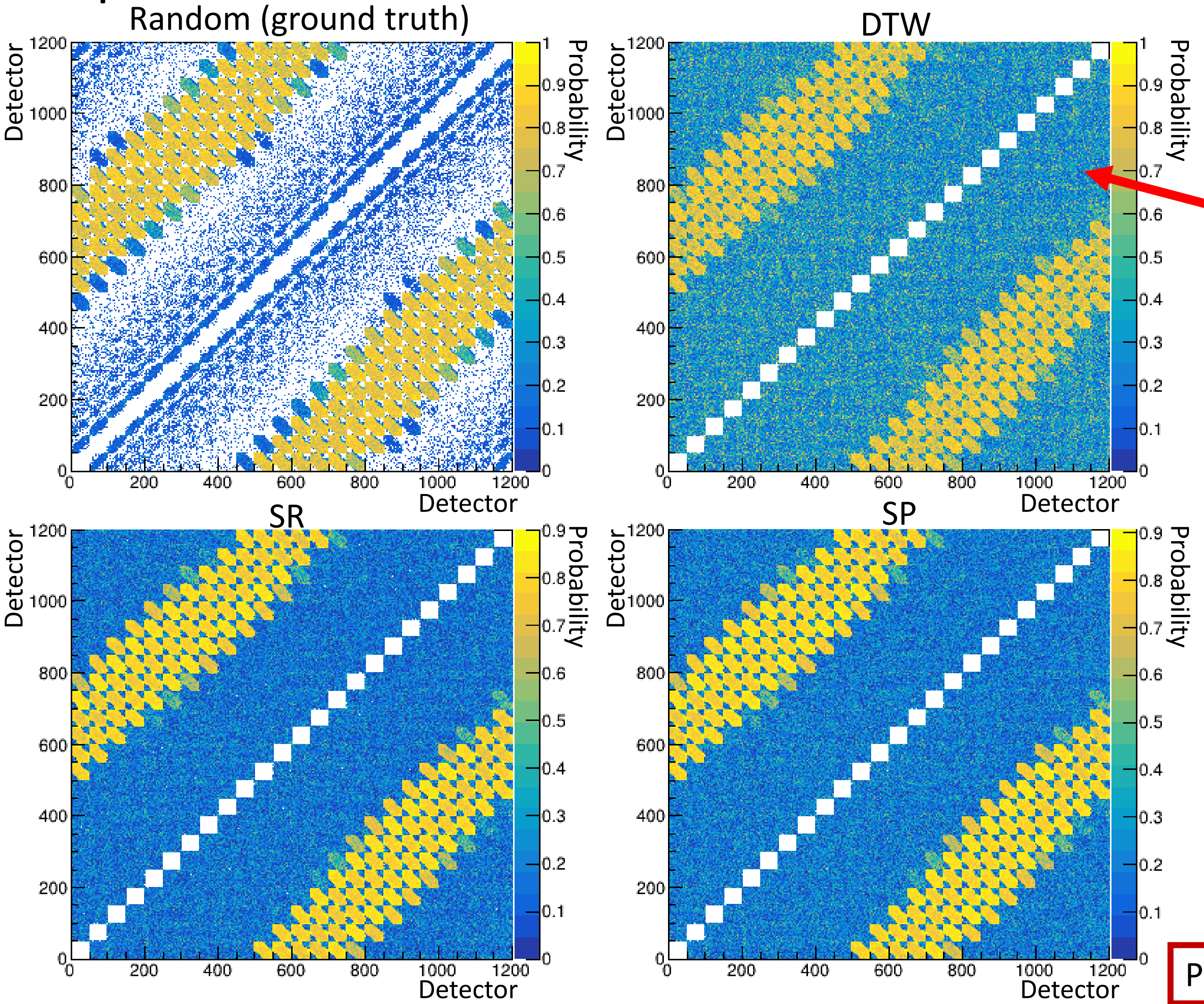
PRELIMINARY



Impact of random coincidences

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

For each pixel in projection matrices



PRELIMINARY

Impact of random coincidences

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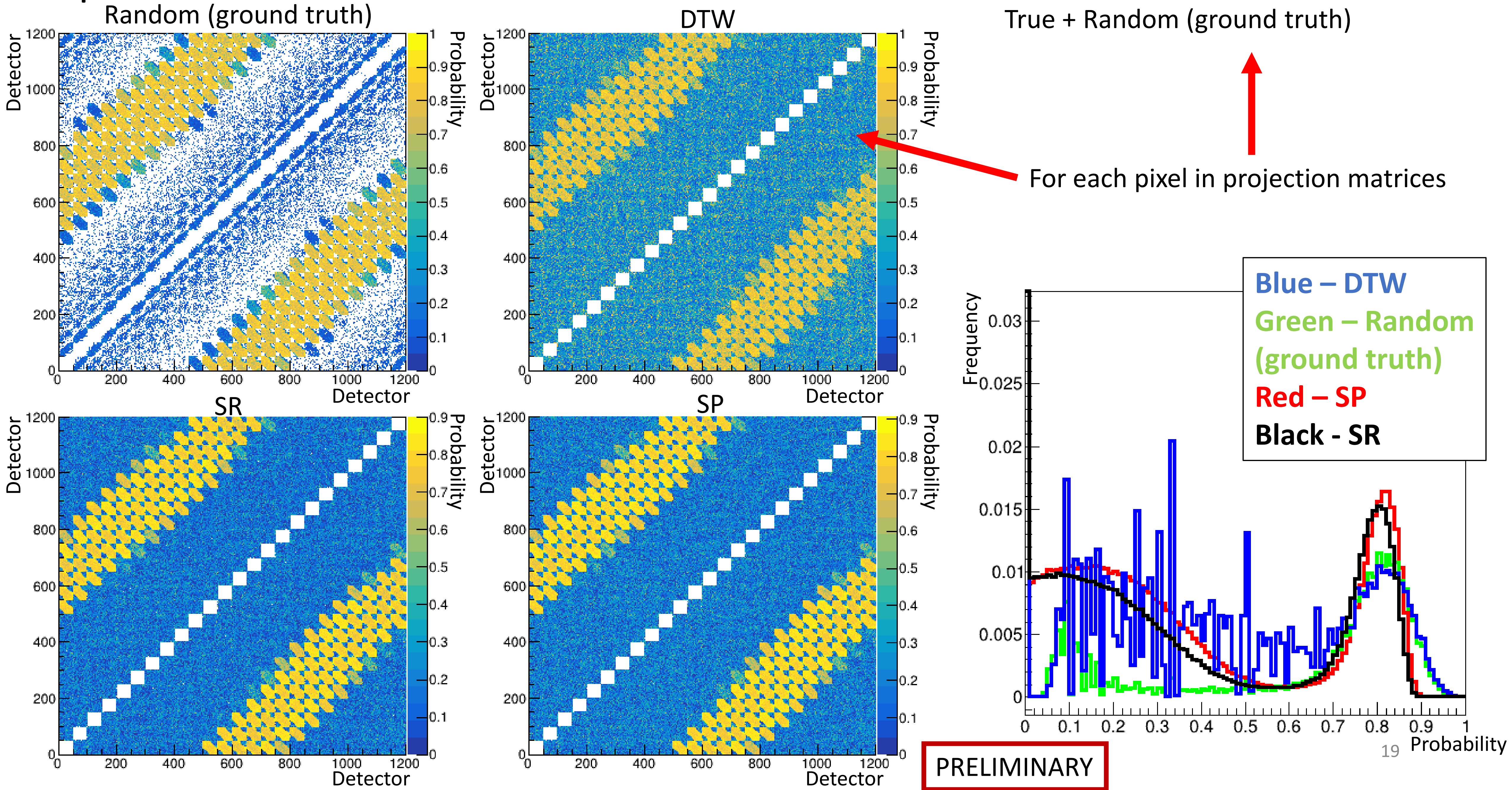
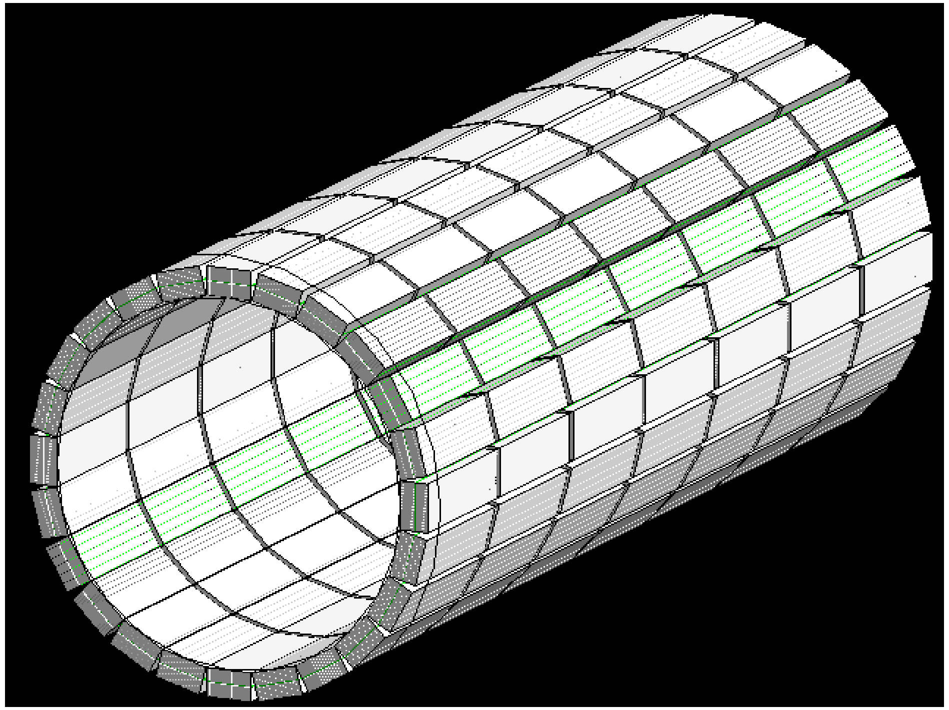


PRELIMINARY

Total-Body J-PET tomograph



Rings

- 7
- Total axial field of view: 243 cm

Modules

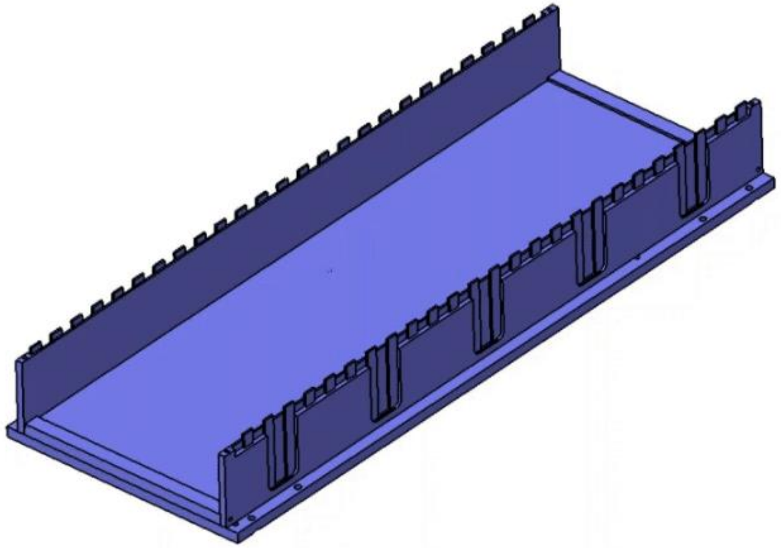
- 24
- Electronic read-out on both sides

Layers

- 2 layers of scintillators
- 1 layer of wavelength shifters

„Crystals"

- (Simulation) Scintillators divided into pseudo-crystals – 3.0 mm in axial direction



Total-Body J-PET tomograph

- Division of tomograph to small detectors to obtain discrete numer of LOR projections
- In transverse plane -> 24 modules
- In axial coordinate -> 243 × 10 mm sections
- In total 5832 detectors

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

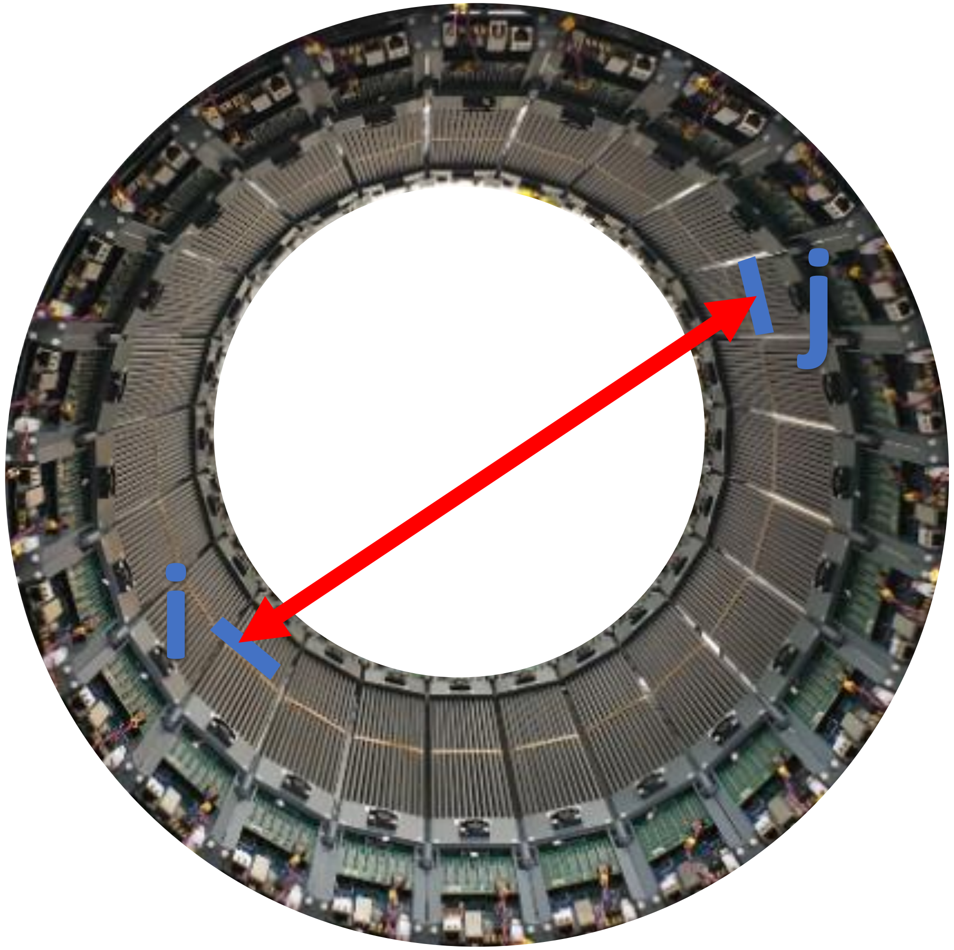


*Figure presents Modular J-PET NOT Total-Body J-PET

Simulations condition

NEMA IEC Phantom
https://gammagurus.com/products/pet-phantom-nema-2012-iec-2008
Access: 09.05.2023

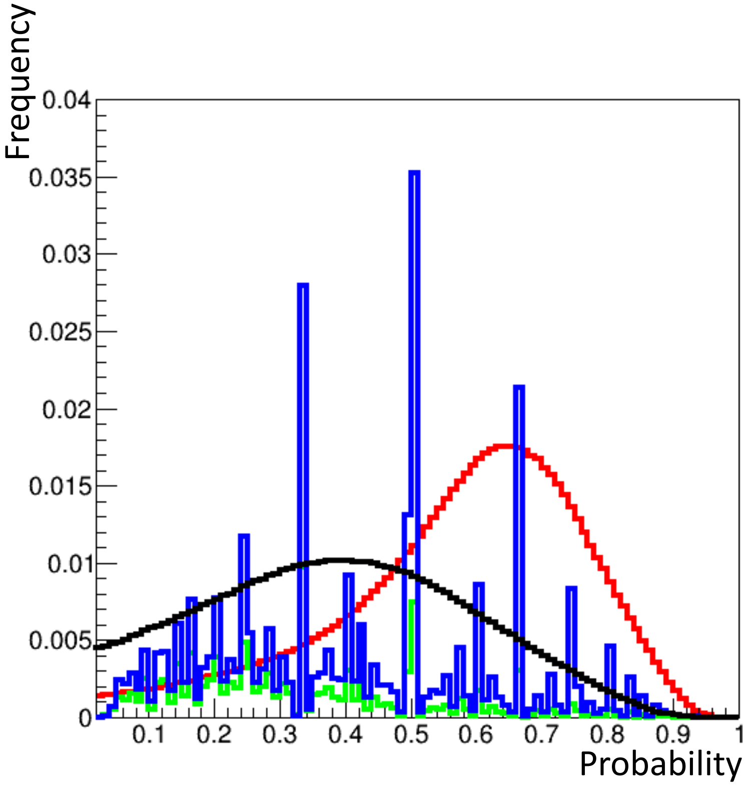
- Phantoms / Sources (back-to-back):
  - 5 × NEMA IEC in axial direction
- Coincidence time window: 3 ns
- Minimum difference of 1 module for coincidence creation

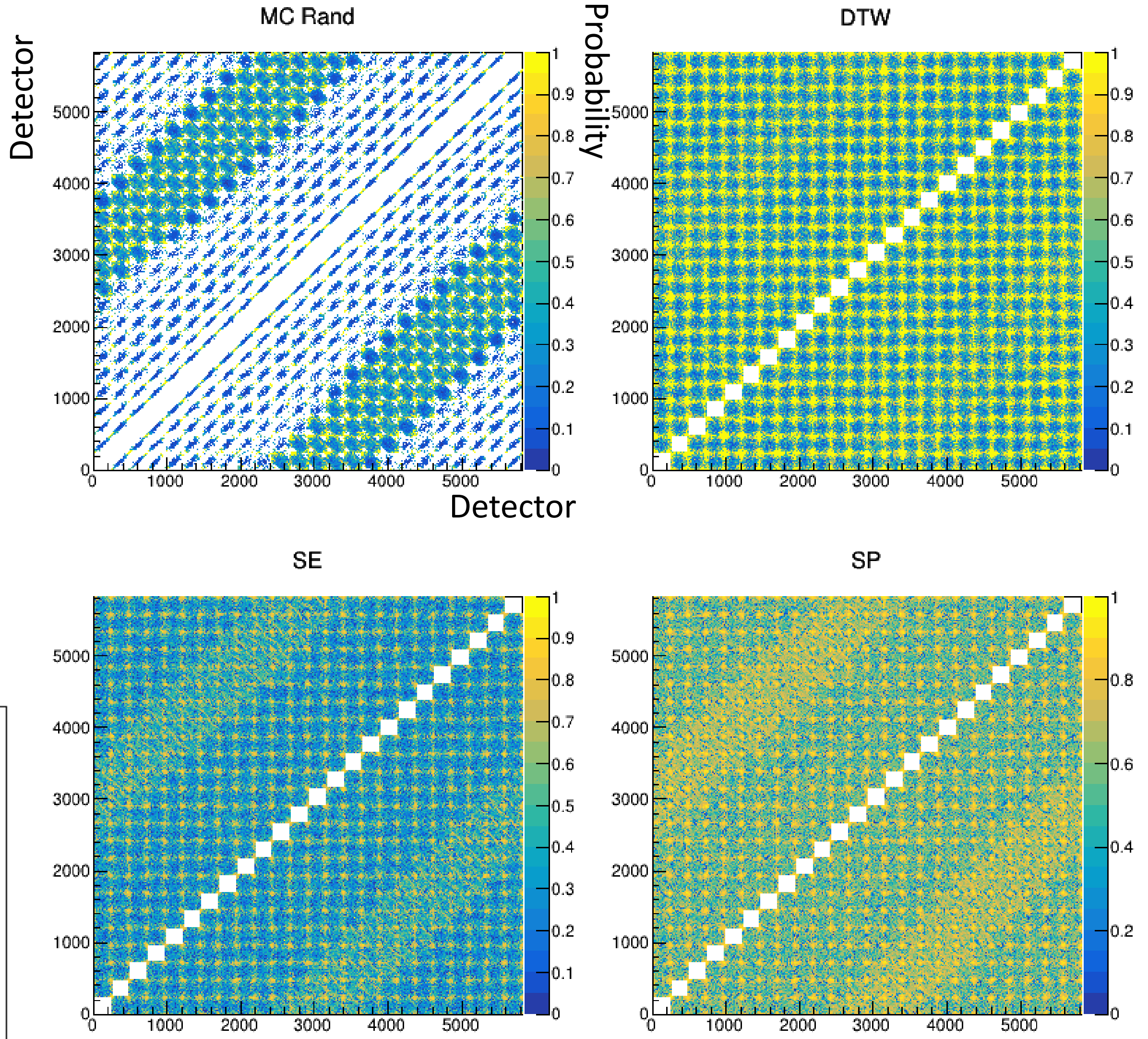
Preliminary results

Total random coincidences estimates

DTW / Random (ground truth)	1.0254
SR / Random (ground truth)	1.5550
SP / Random (ground truth)	0.8997

Impact of random coincidences





Blue – DTW
Green – Random (ground truth)
Red – SP
Black - SR

Summary

- Singles-Prompts method provides much better estimation of total random coincidences than Singles Rates method and better than Delayed Time Window method
- Delayed Time Window is the only method providing correct distribution of random coincidences within the J-PET tomographs
- Utilization of DTW estimation while hard to achieve in standard PET systems is relatively easy in case of J-PET scanners due to its trigerless acquisition which saves all interactions
- Delayed Time Window seems to be an optimal choice for J-PET tomographs based on simulation. Nevertheless, its relatively low statistics can pose a challenge in real data

Acknowledgements

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Thank you for your attention