Probing the nature of the neutrino: the search for neutrinoless double β-decay with the LUX-ZEPLIN detector

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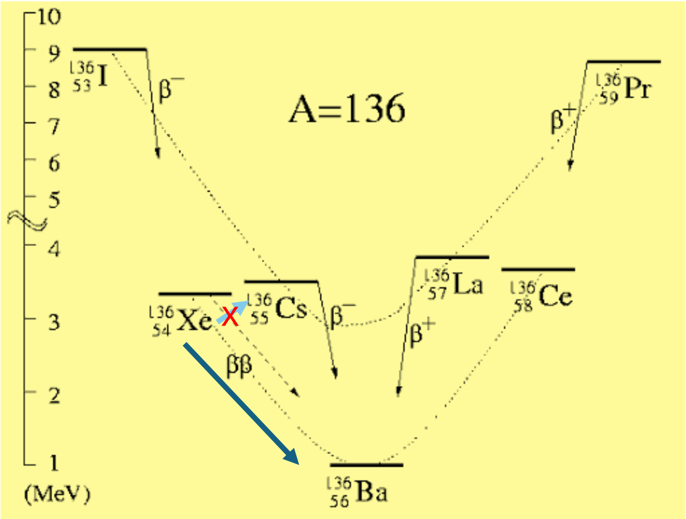
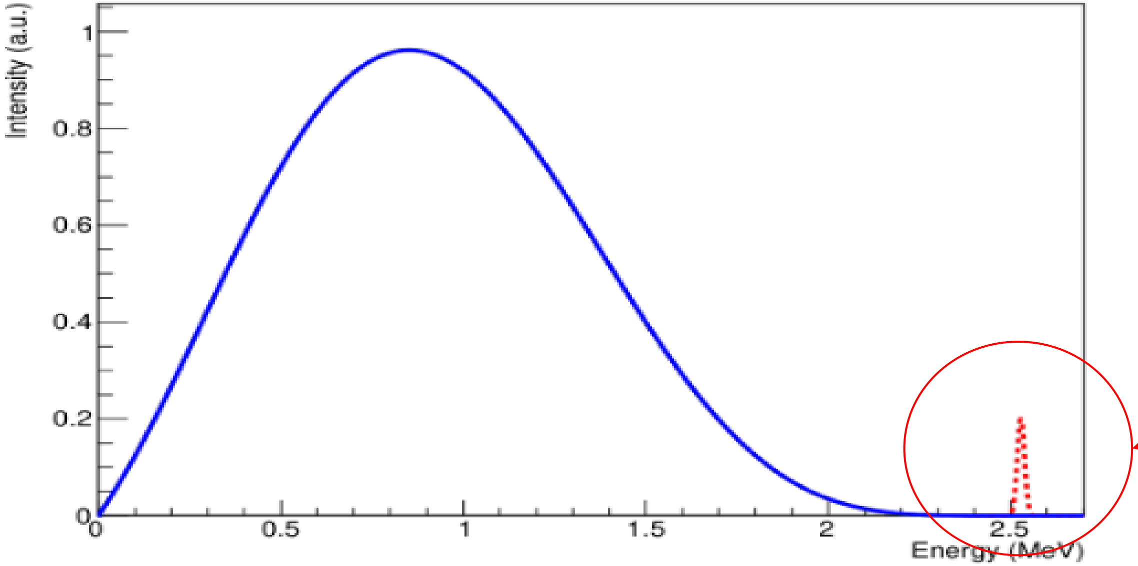
Neutrinoless double β-decay

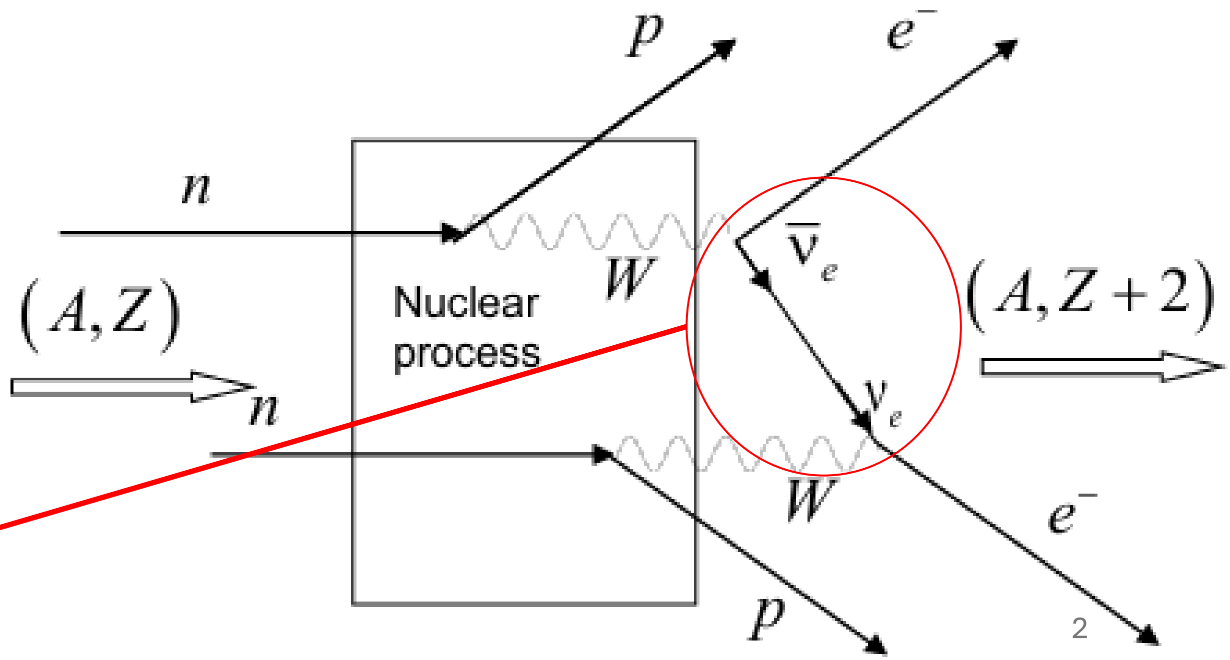


- BSM process where the emitted $\bar{\nu}_e$ at one vertex is absorbed as a ν_e at the 2nd vertex $\Rightarrow \bar{\nu}_e \equiv \nu_e$

➡ Majorana neutrino

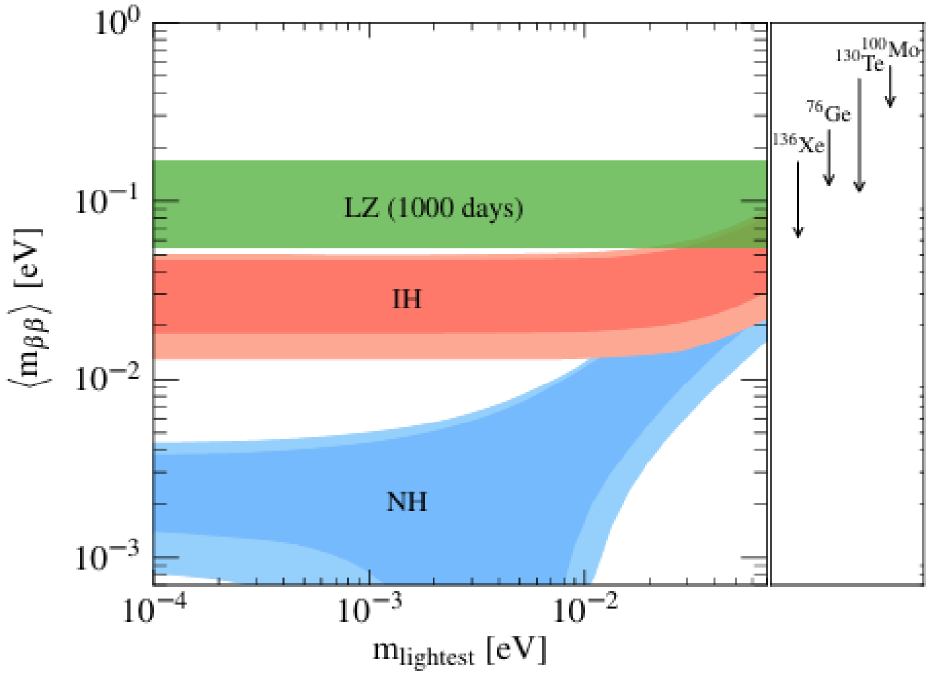
$$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + \cancel{2\bar{\nu}_e}$$



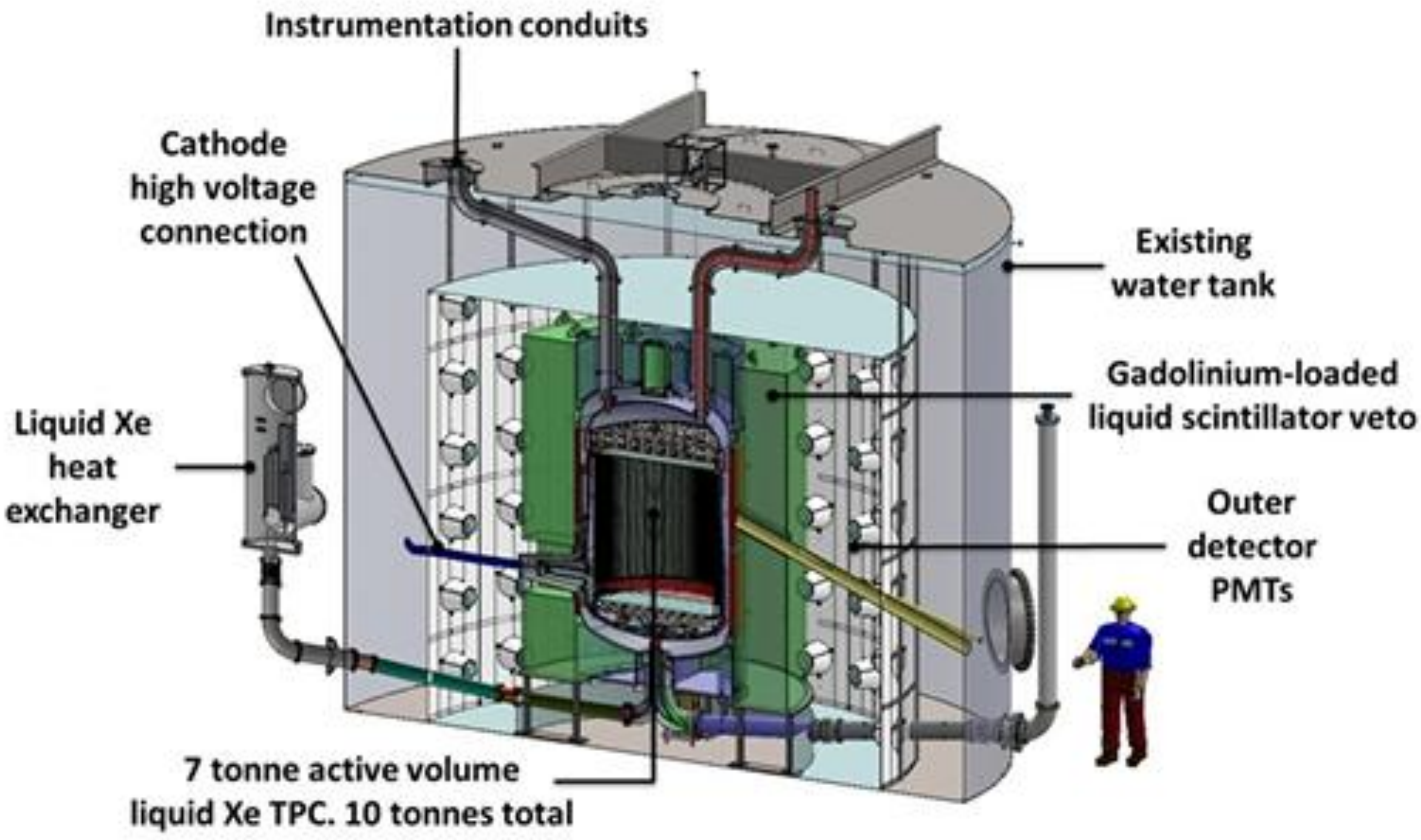


The LUX-ZEPLIN Experiment (LZ)

The LUX-ZEPLIN detector is a dual-phase liquid Xe Time Projection Chamber (TPC)



$$\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2 m_{\nu_i}\right| = \sqrt{\frac{\Gamma_{\beta\beta}^{0\nu}}{G^{0\nu}\left|M^{0\nu}\right|^2}}$$



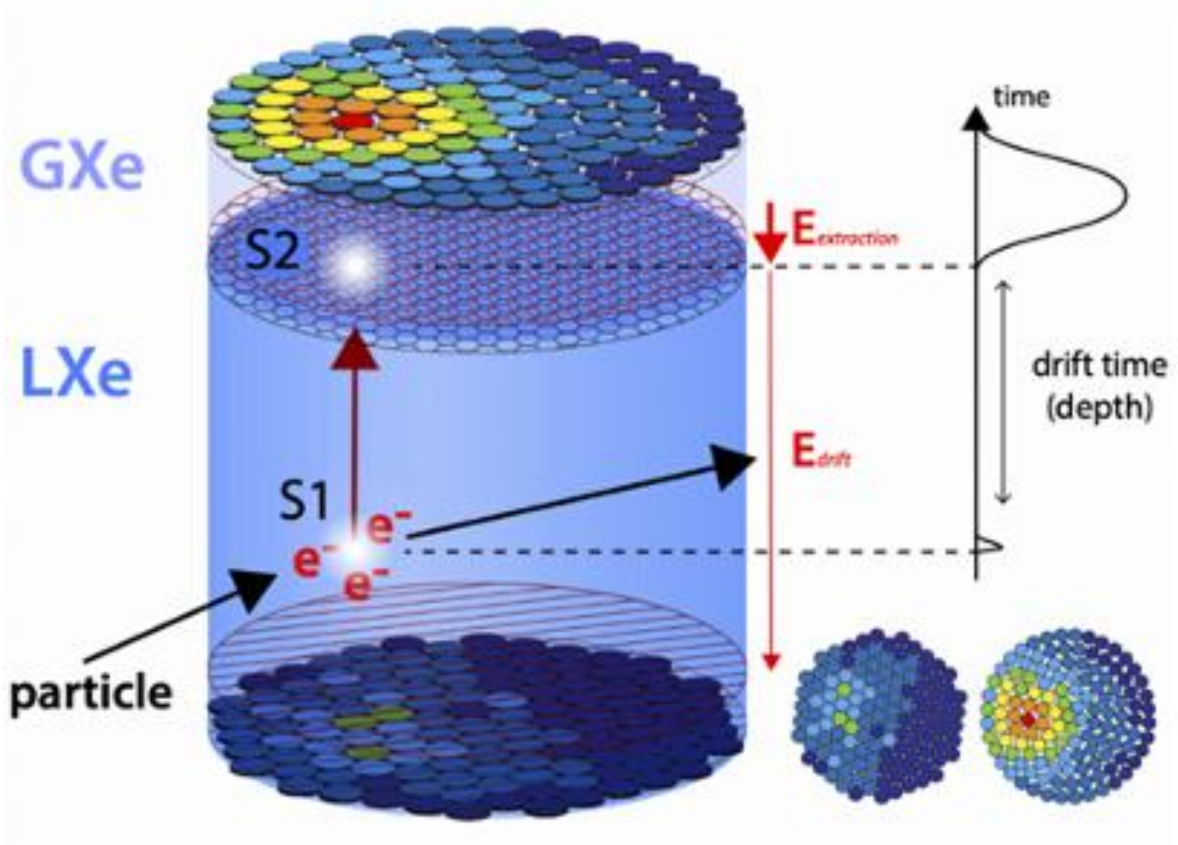
- Main goal is to detect dark matter WIMPs
- Has potential for $0\nu\beta\beta$ with ^{136}Xe (~ 623 kg in LZ)

Detection Principle with liquid noble gas TPC

1. The energy deposit inside the detector produces a prompt scintillation light (S1) from atomic excitation and free electrons from ionisation
2. The e^- drift upward under the effect of an applied electric field until they reach the liquid surface
3. The e^- are extracted into a high-field gas region, creating an electroluminescence signal (S2)

⇨ The time difference between the S1 and S2 pulses gives the depth of the interaction

⇨ The S2 signal on the surface array is used to reconstruct the XY-position of the interaction

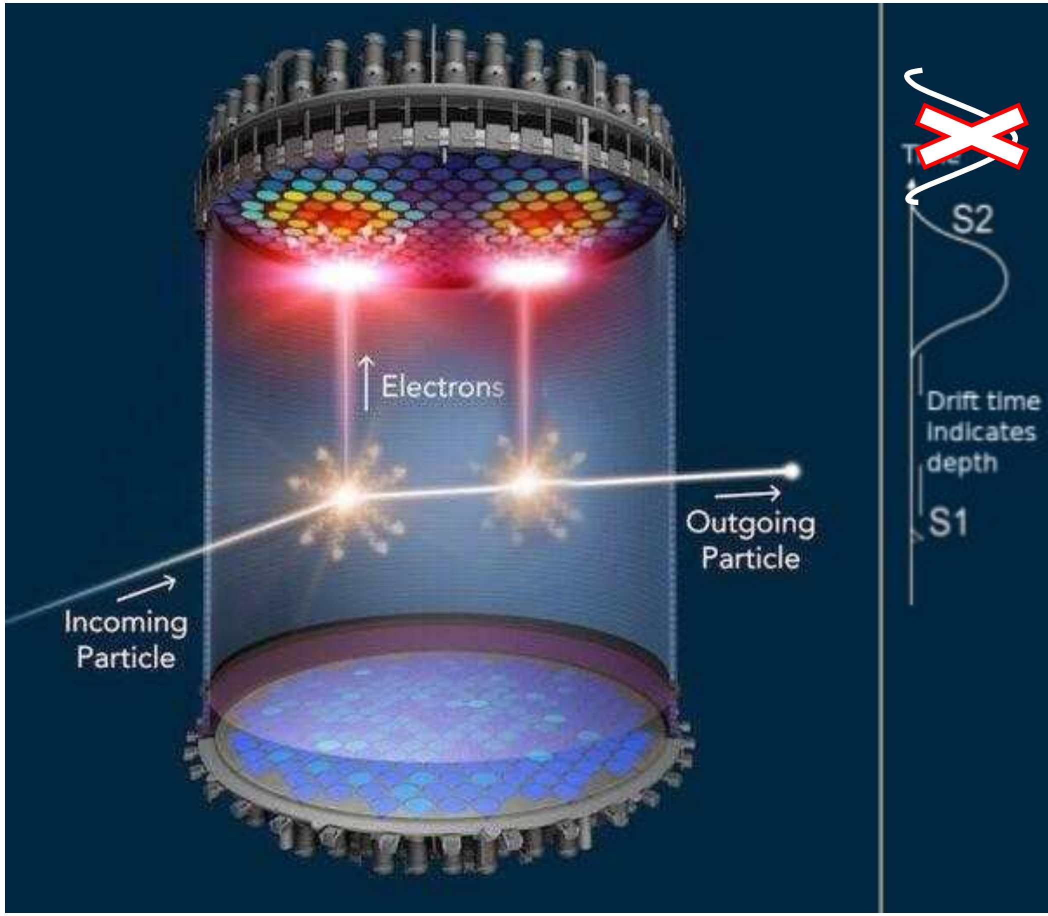


Single Scatters vs Multiple Scatters

- The $0\nu\beta\beta$ signal is expected to be a single scatter (SS) event because we consider it as a point-like source
- Background of γ-rays instead is very likely to produce multiple scatter (MS) events
  - If the MS occur at different depths, they have ≠ drift times and lead to two S2 pulses

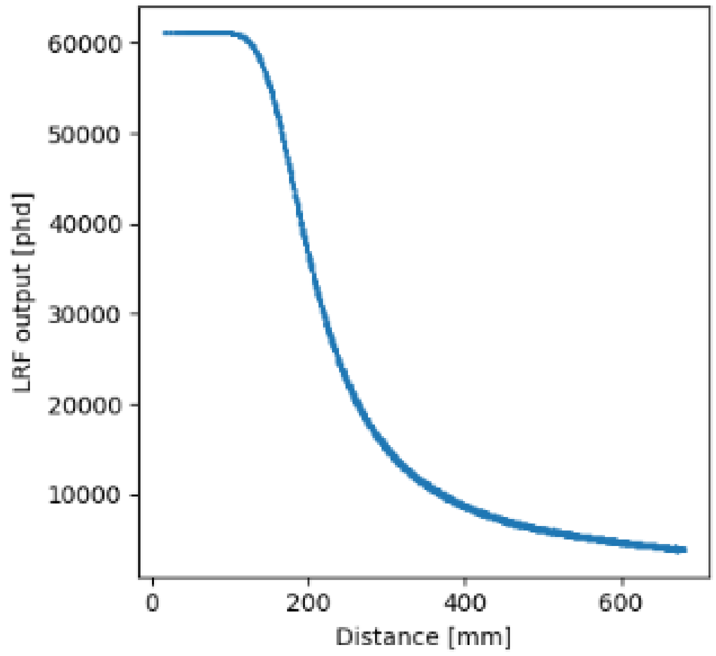
  ⟶ Easier to reject
  - But if they occur at a similar depth, there is only one S2 pulse!
    - But it carries information of a MS, so we'd expect a worse reconstruction…

⇨ Goal: study MS rejection capacity with XY-position reconstruction



XY-position Reconstruction in LZ

- XY position reconstruction of events is achieved by Mercury algorithm from analysing the hit patterns of the S2 light measured by the top array PMTs
  - Light Response Functions (LRFs)

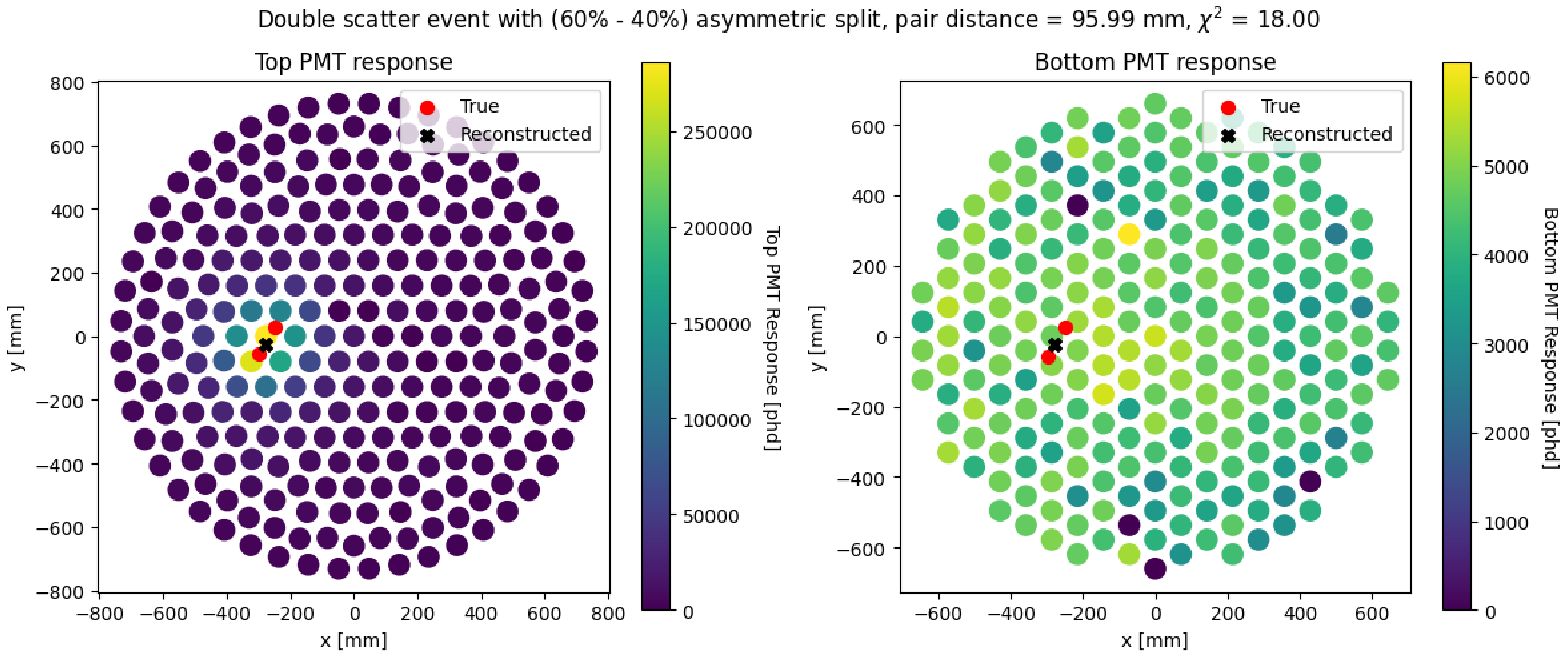


- The χ^2 test statistic quantifies the quality of the reconstruction compared to the single scatter model hypothesis

Greater values of χ^2 mean less agreement between observed data and hypothesis of a single scatter

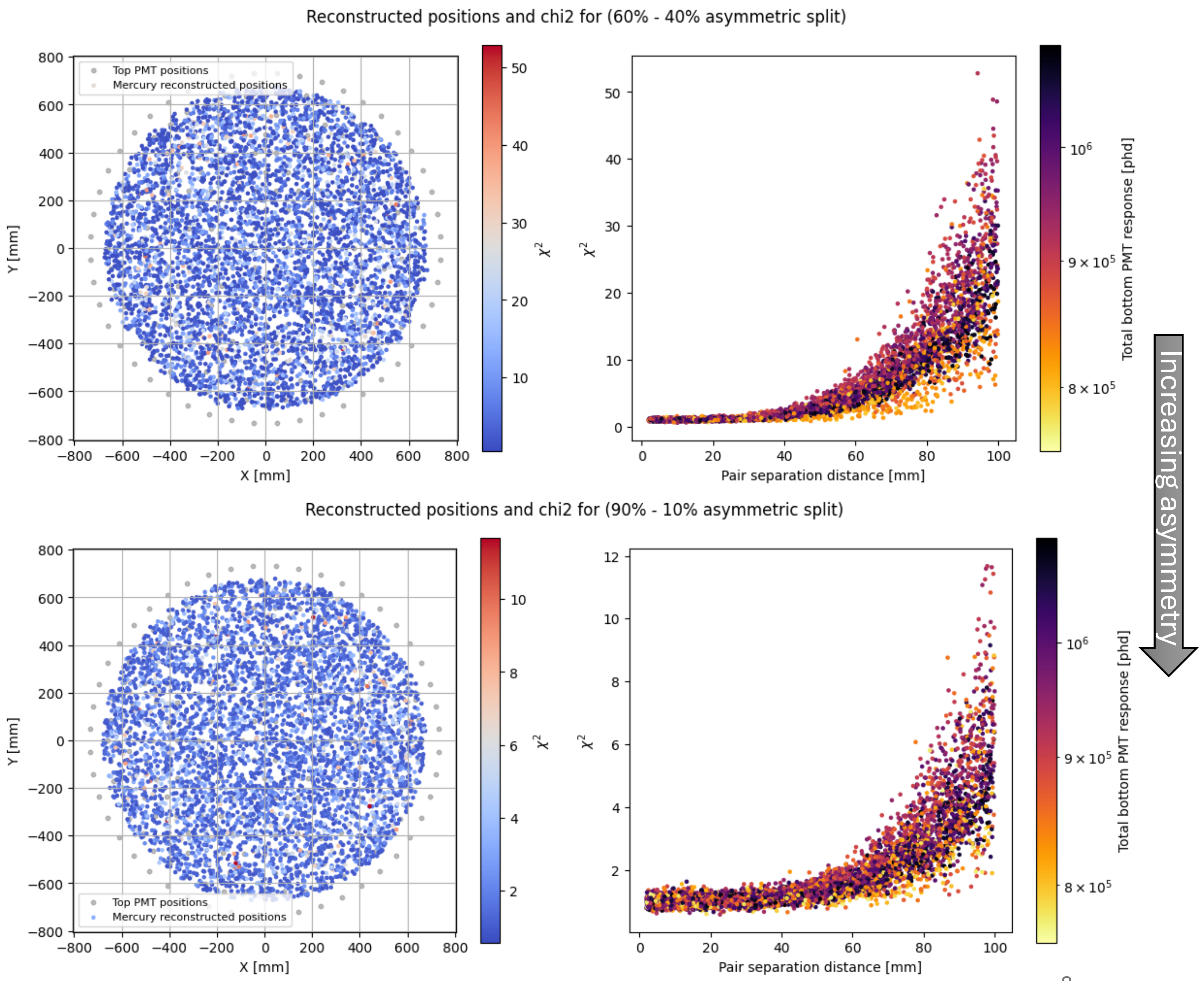
Generating Double Scatters

- Model-driven approach: Generated fake double scatters by varying the position, pair separation distance, and asymmetry, using the Mercury LRFs to simulate the S2 light patterns and reconstruct the position & computing the (reduced) χ^2



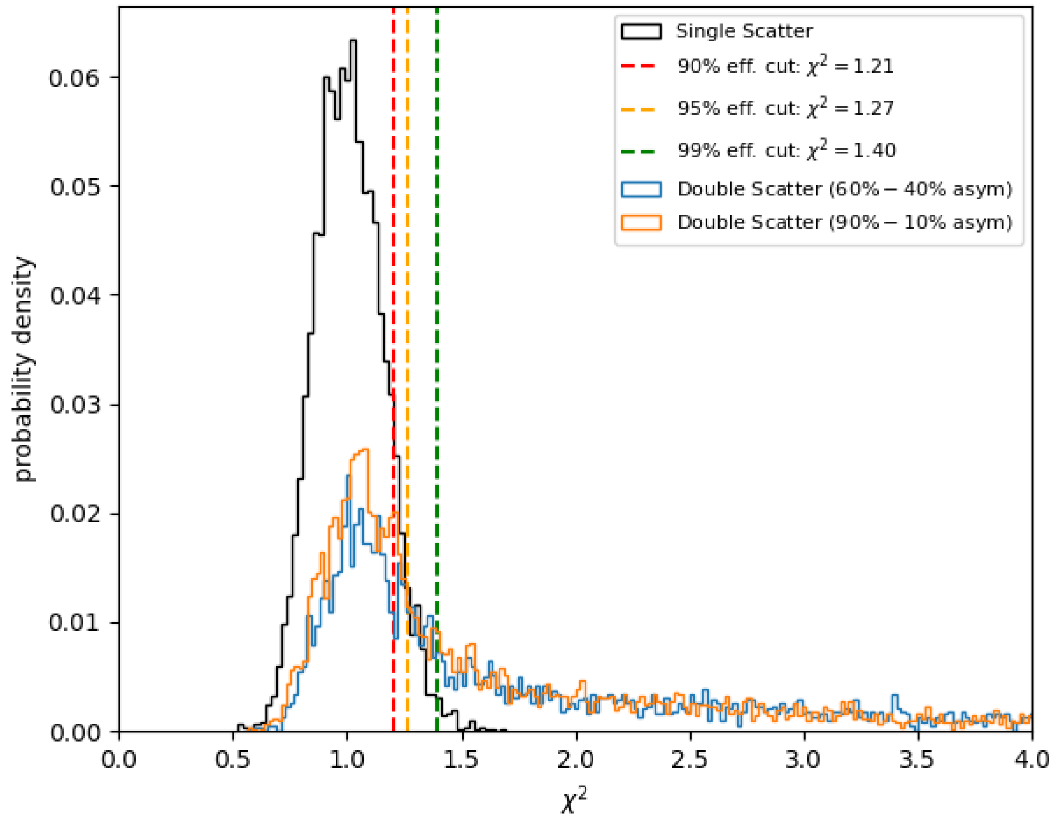
Reconstructed positions and χ^2

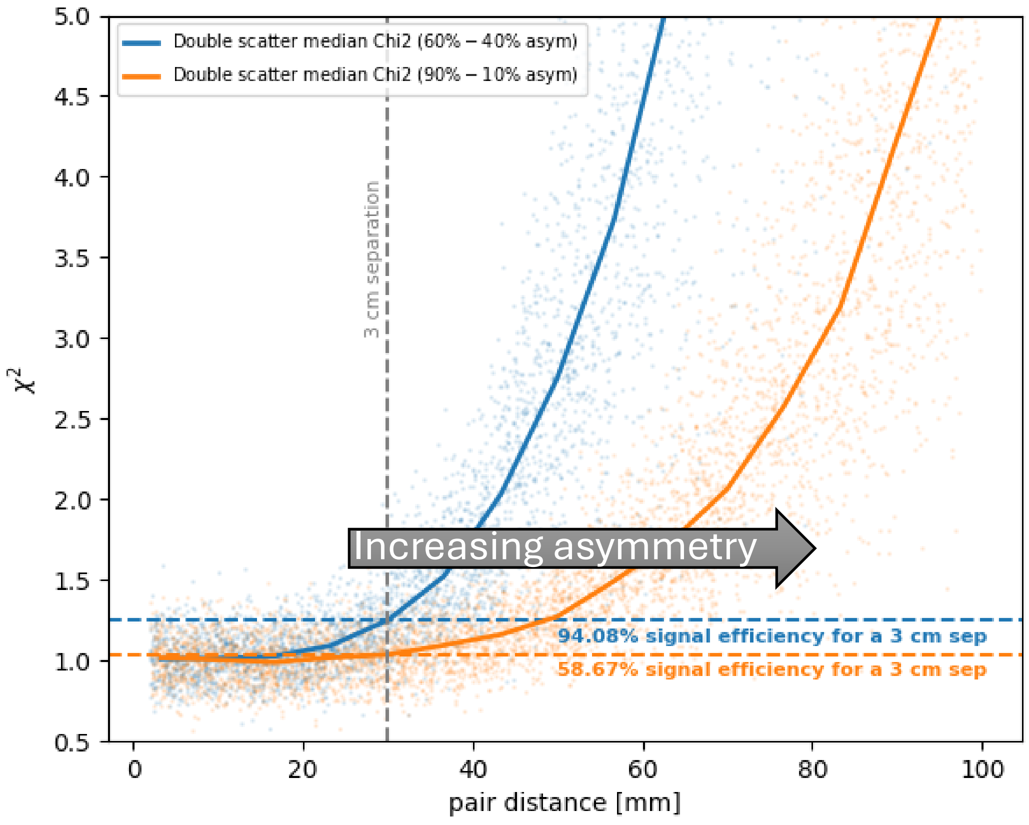
- The XY-position of the double scatters doesn't impact the χ^2
- However, the pair separation distance is a leading factor in the χ^2 dependency



χ^2 Distributions and Efficiency Levels

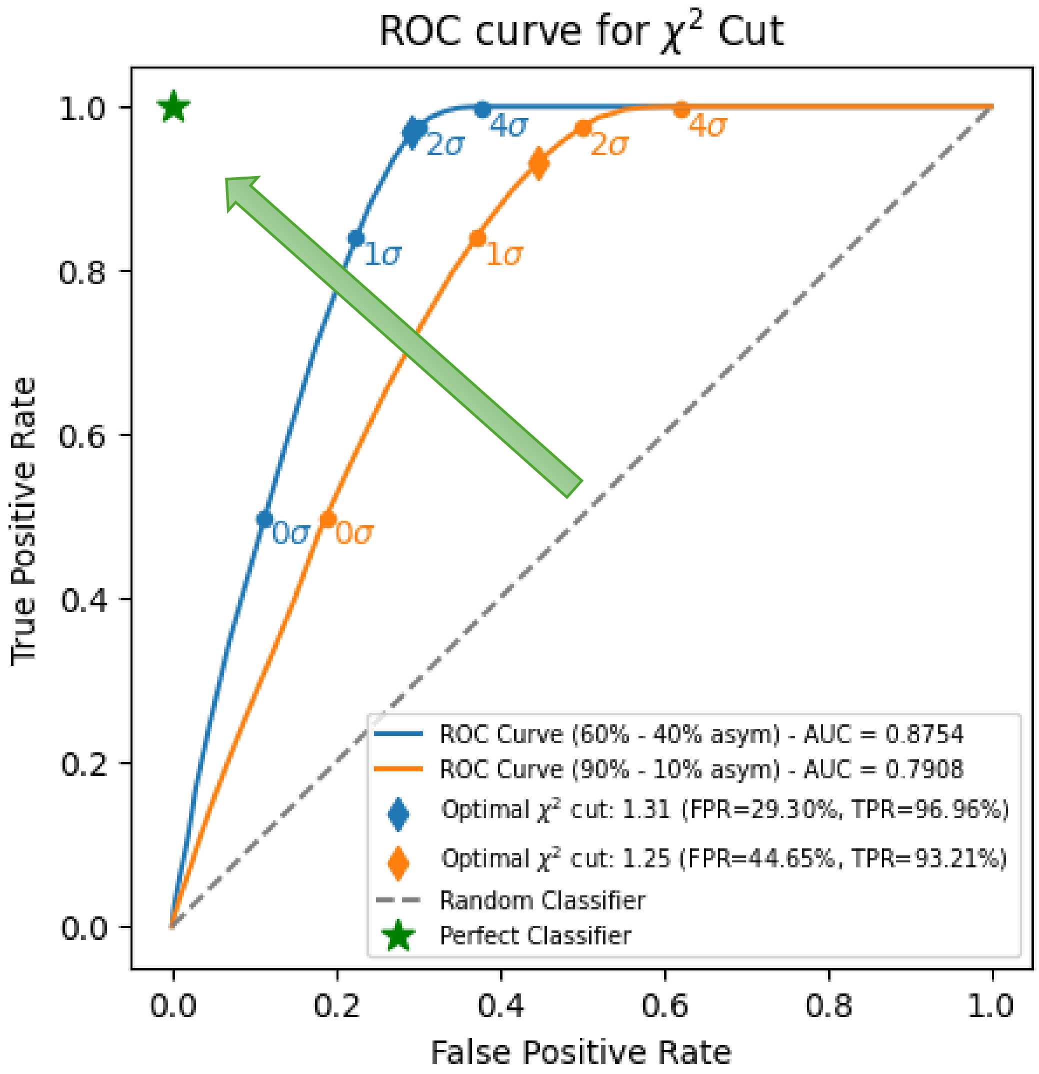
- Signal efficiency = fraction of single scatters below cut
- Contamination = fraction of double scatters below cut





Distance between PMT centers ~ 5cm

ROC Curve



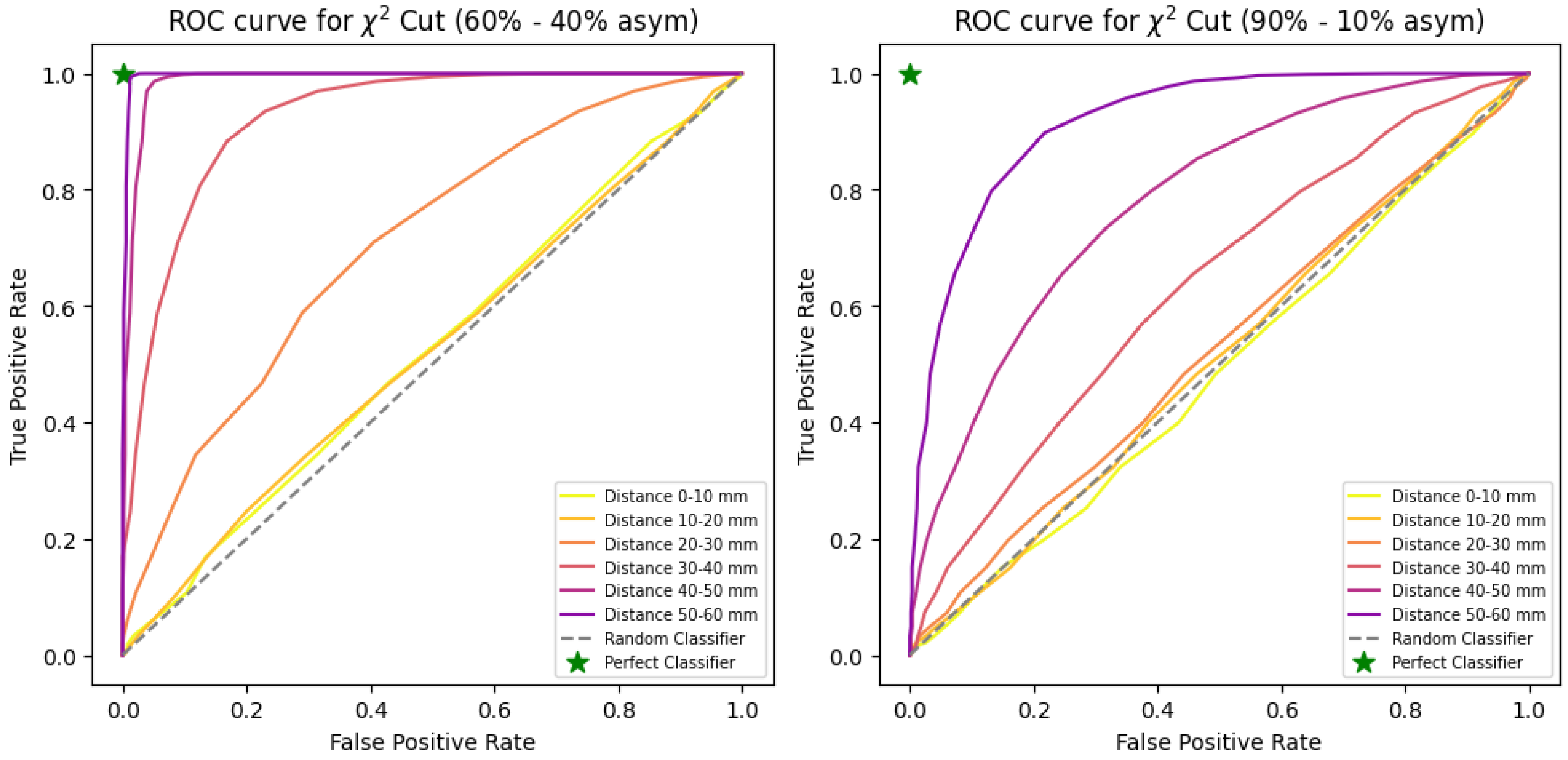
- FPR ~ Multiple Scatter Contamination
- TPR ~ Single Scatter Efficiency

- AUC (Area Under Curve) quantifies how good is the discrimination between signal and background:
  - Larger asymmetry
    ⇨ smaller AUC
    ⇨ worse discriminatory power

- Pair separation at optimal threshold:
  - 3.10 cm (FPR = 29%, TPR = 96%)
  - 4.86 cm (FPR = 44%, TPR = 93%)

ROC curves for several pair separations

- Larger asymmetry ⇨ higher multiple scatter contamination
- Closer pairs ⇨ higher multiple scatter contamination



Conclusions

- It is possible to discriminate multiple scatters in XY
- For low asymmetry, we could reject double scatters with ~ 3 cm separation with:
  - > 95% signal efficiency
  - ~ 30% contamination
- Idealised case with ideal double scatters in 2D
  - It would require a full simulation of γ-rays interactions in the detector volume to reach a better physical interpretation
  - This preliminary study shows it would be possible
- Another possible approach involves using real SS events from data for the S2 and create artificial double scatters, but the model-driven approach provided better control of the variables and events
  - For future studies with more data
- Even though discrimination power in XY (~ cm) is not amazing compared to discrimination in vertical separation (~ mm), any amount of rejected background is important for 0νββ searches to increase the sensitivity

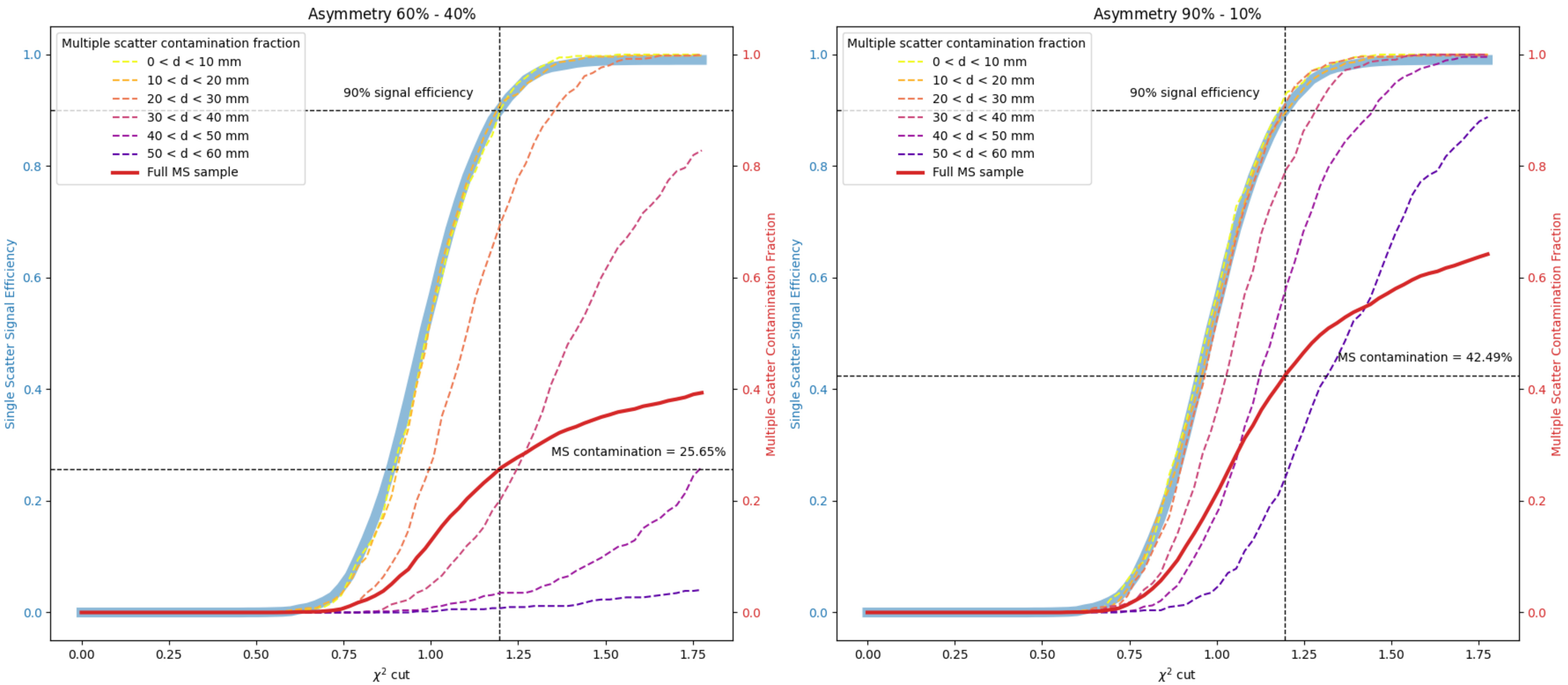
Thank you for your attention!

Denis Yusufov

Backup

Signal Efficiency vs Multiple Scatter Contamination

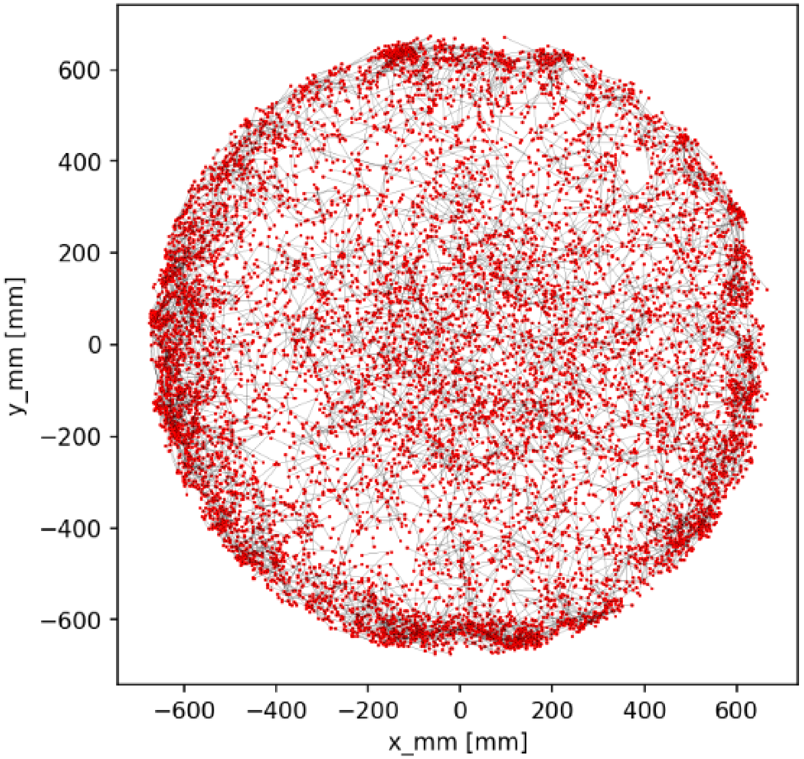
- Larger asymmetry ⇨ higher multiple scatter contamination
- Closer pairs ⇨ higher multiple scatter contamination

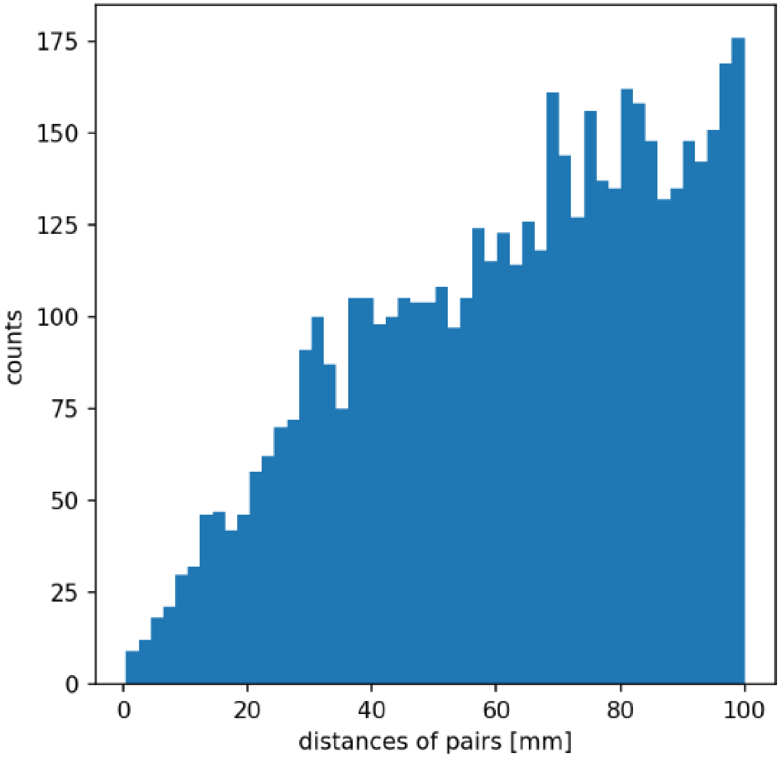


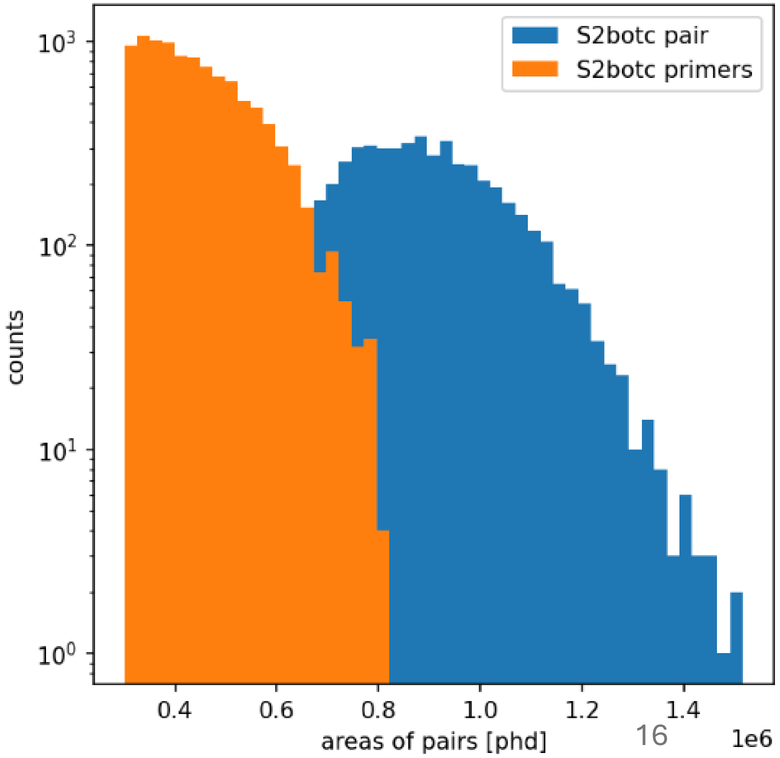
Data-driven approach

- Artificial double scatters produced by “chop-stitching” real SS events from SR3 data
- Draw-backs:
  - Data non uniformly distributed on the XY-plane
  - More statistics for larger pair distances

  ⇨ Need more uniformity
- Less control of the desired variables and events







Neutrino ordering and mass hierarchy

With the evidence that neutrinos have masses (≠ Standard Model), there is an indication that neutrinoless double β-decay could be possible

- What we know so far:

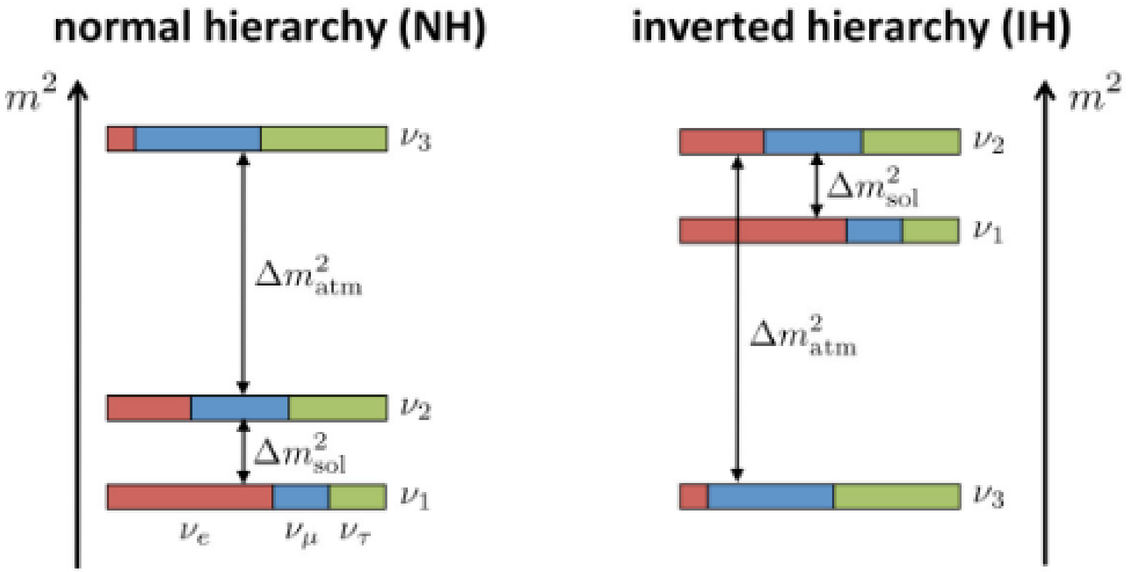
$$\Delta m^2_{21} \sim 8 \times 10^{-5}\,\mathrm{eV}^2$$

$$|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2$$

$$\sum_{\nu} m_{\nu} < 0.12\,\mathrm{eV}$$

- 0vββ decay rate provides:

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| = \sqrt{\frac{\Gamma_{\beta\beta}^{0\nu}}{G^{0\nu} |M^{0\nu\,2}|}}$$



Background in $0\nu\beta\beta$ searches with LZ

- ROI for $0\nu\beta\beta$ is E ~ 2.458 MeV
- γ-lines from radioactive isotopes in detector components and cavern walls:
  - $^{232}Tl \longrightarrow ^{208}Tl$ (E ~ 2.615 MeV)
  - $^{238}U \longrightarrow ^{214}Bi$ (E ~ 2.447 MeV)
- Internal $^{222}Rn \longrightarrow ^{214}Bi$
- ^{136}Xe $2\nu\beta\beta$ (steady decrease)
- ^{137}Xe production (E ~ 4.173 MeV)
- ^{8}B solar neutrino elastic scattering (CEvNS)