Updates on DSNB analysis and sensitivity from new NCQE reduction

Andrew Santos

Laboratoire Leprince-Ringuet
École Polytechnique – IP Paris

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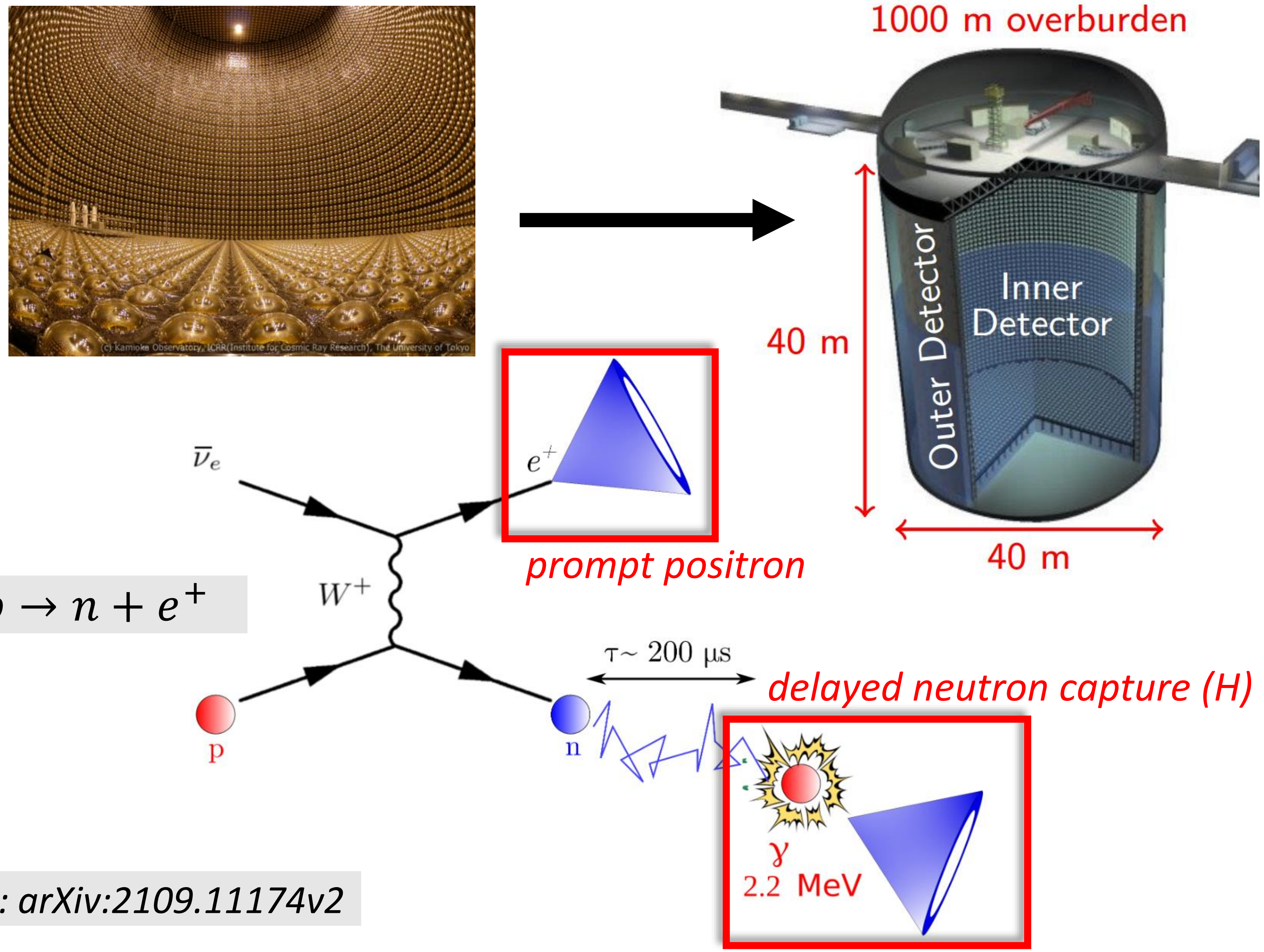
Neutrino Group

Recap: Two-part DSNB signal at Super-Kamiokande



(IBD)

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Source: arXiv:2109.11174v2

- Super-K detector is **water Cherenkov detector** located in Japan under 1000 m of mountain with **50 kton of water**.
- More than **13 000 photomultiplier tubes** line the inner and outer detector walls.
- The **main DSNB detection channel is inverse beta decay** in which an electron anti-neutrino interacts with a proton in the water.

Recap: Remaining backgrounds for the DSNB analysis

Tagging positron + neutron:

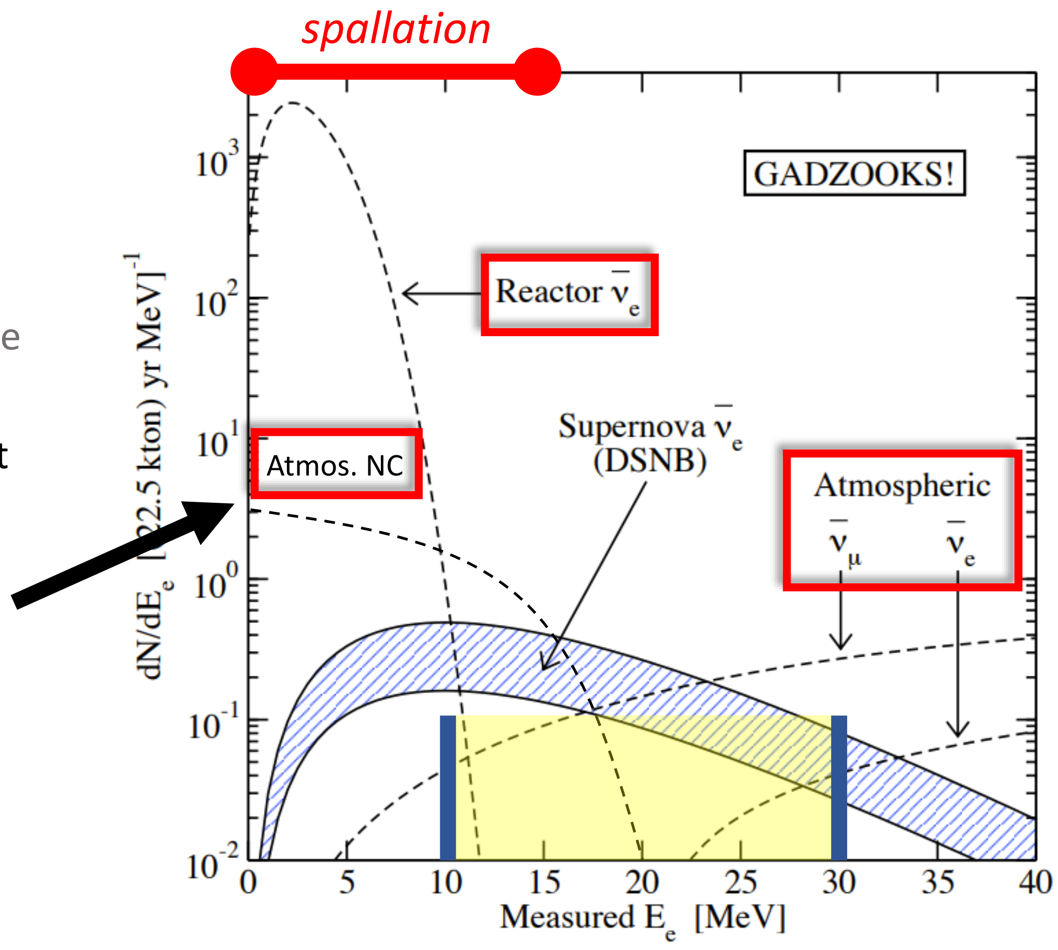
reduced
- The product of cosmic ray interactions form **"spallation" background** at low energy.

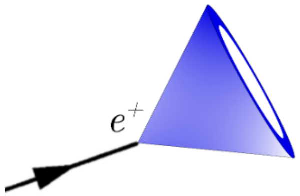
removed
- **Solar neutrinos** are a background at energies up to around 20 MeV (not shown in plot).

reduced
- **Atmospheric neutrinos** after around 15 MeV produce **charged-current (CC)** interaction backgrounds.

irreducible
- **Reactor neutrinos** form an irreducible background at low energy because they produce an IBD signal.

reduced
- **Atmospheric neutral-current (NC)** interactions produce photons **mimicking** the positron and a neutron capture just like the **DSNB signal channel**.





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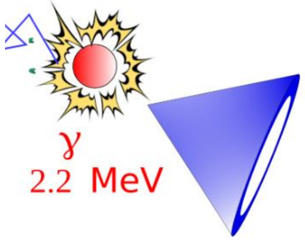
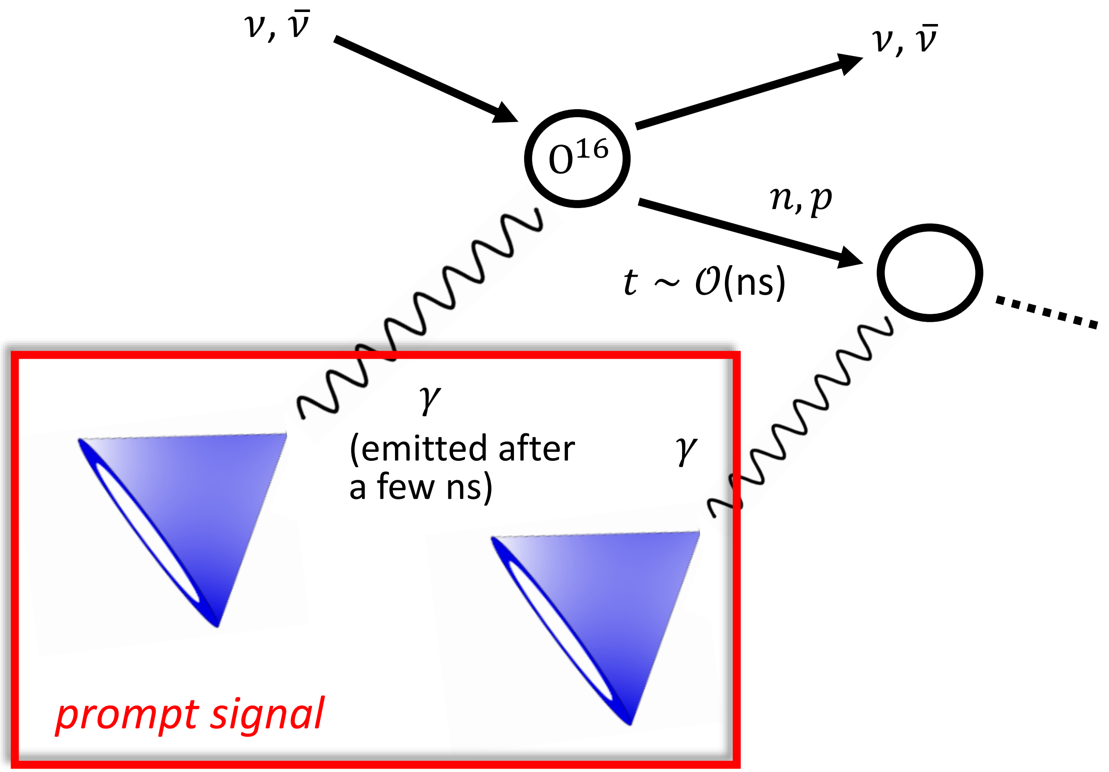


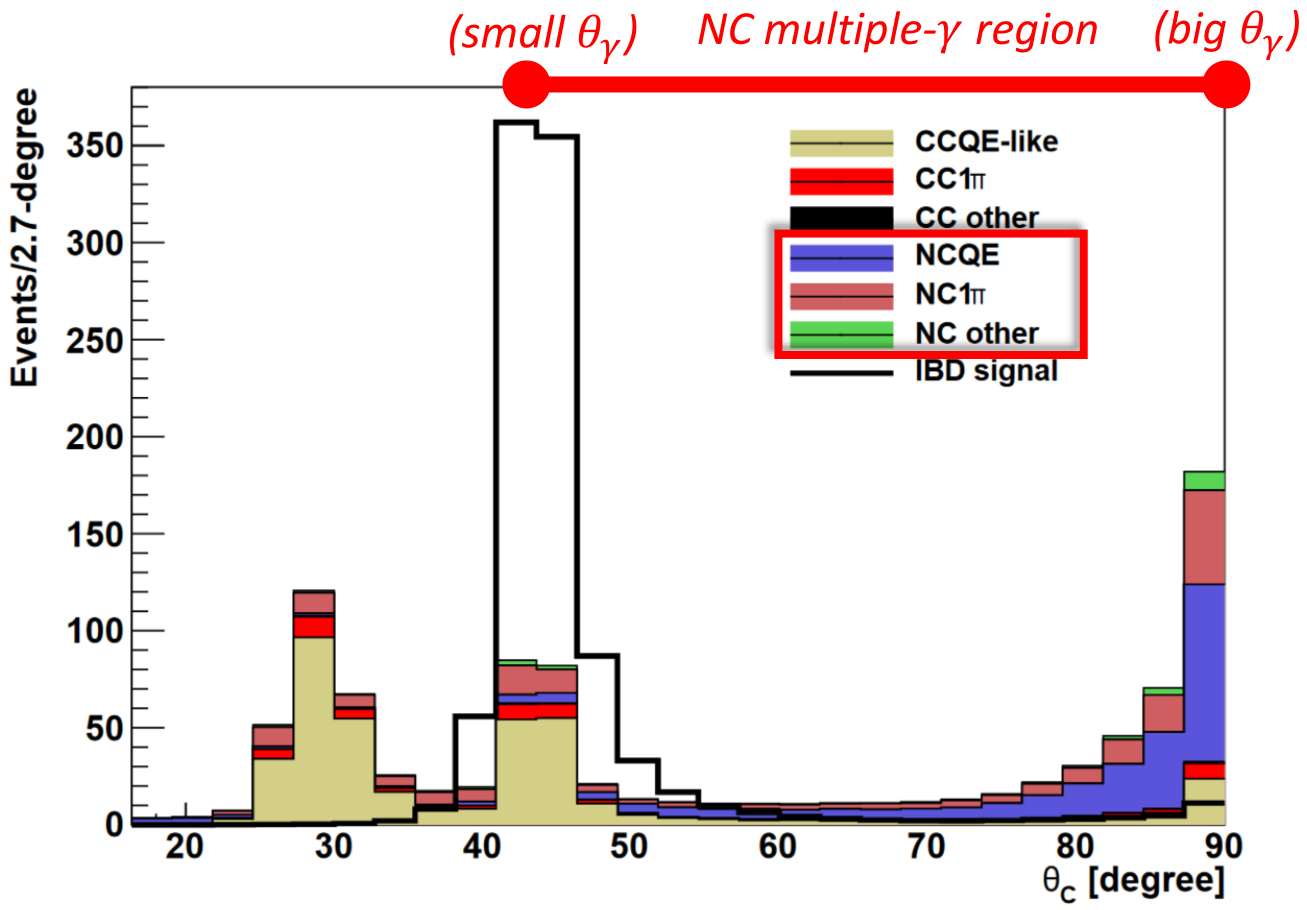
prompt positron

delayed neutron capture (H)

*Source: Beacom (2010), Ann. Rev. Nucl. Part. Sci., **60**, p. 439-462*

Reconstructing NCQE events with two Cherenkov rings (prompt)





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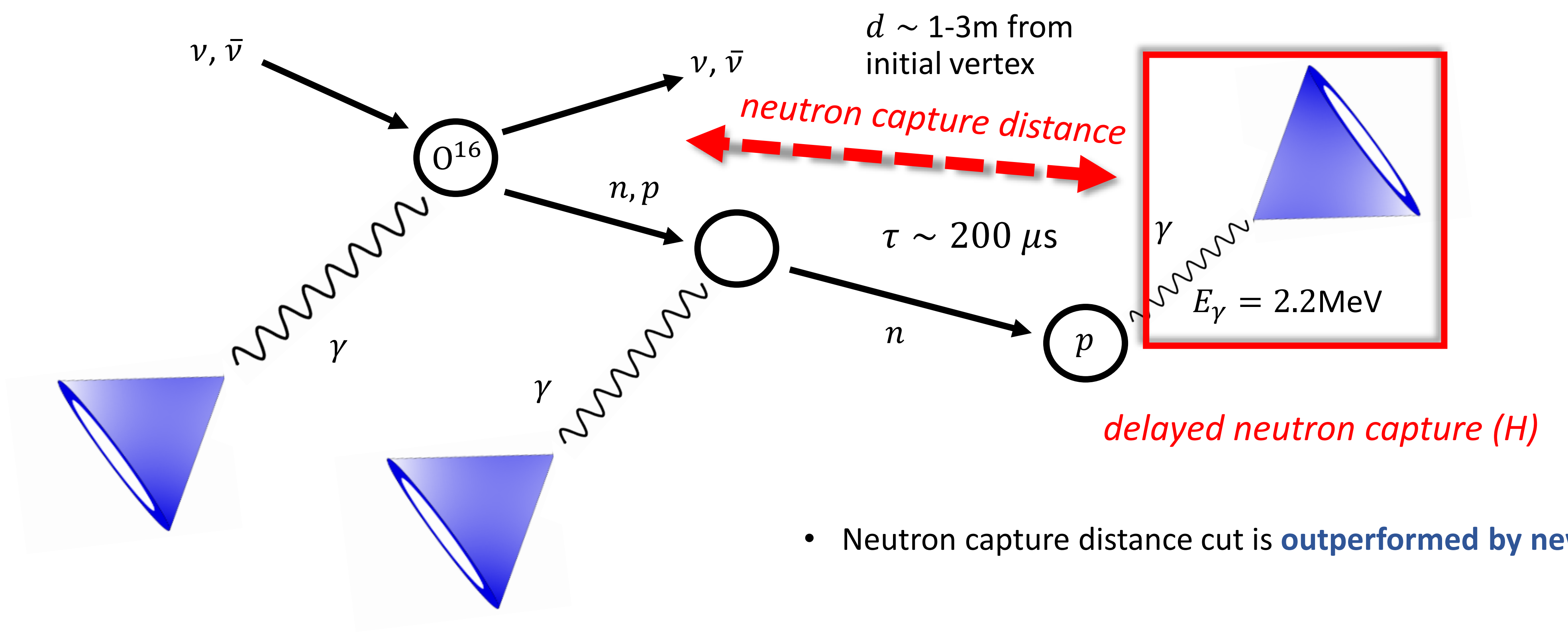
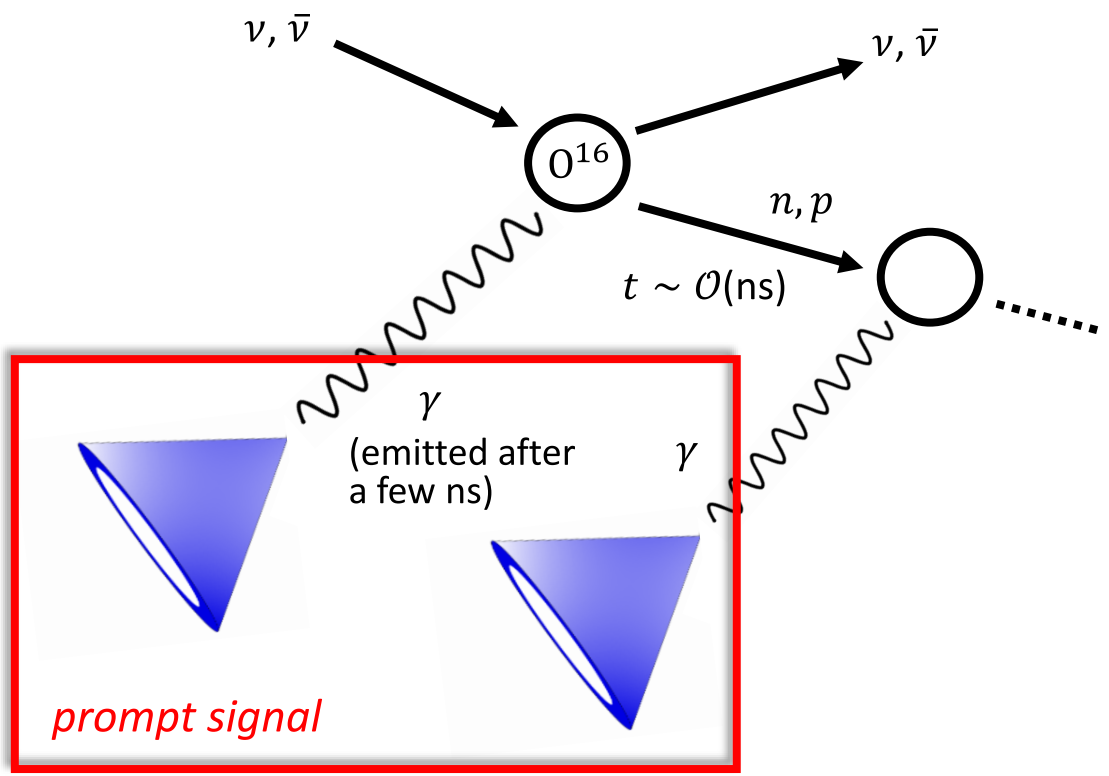
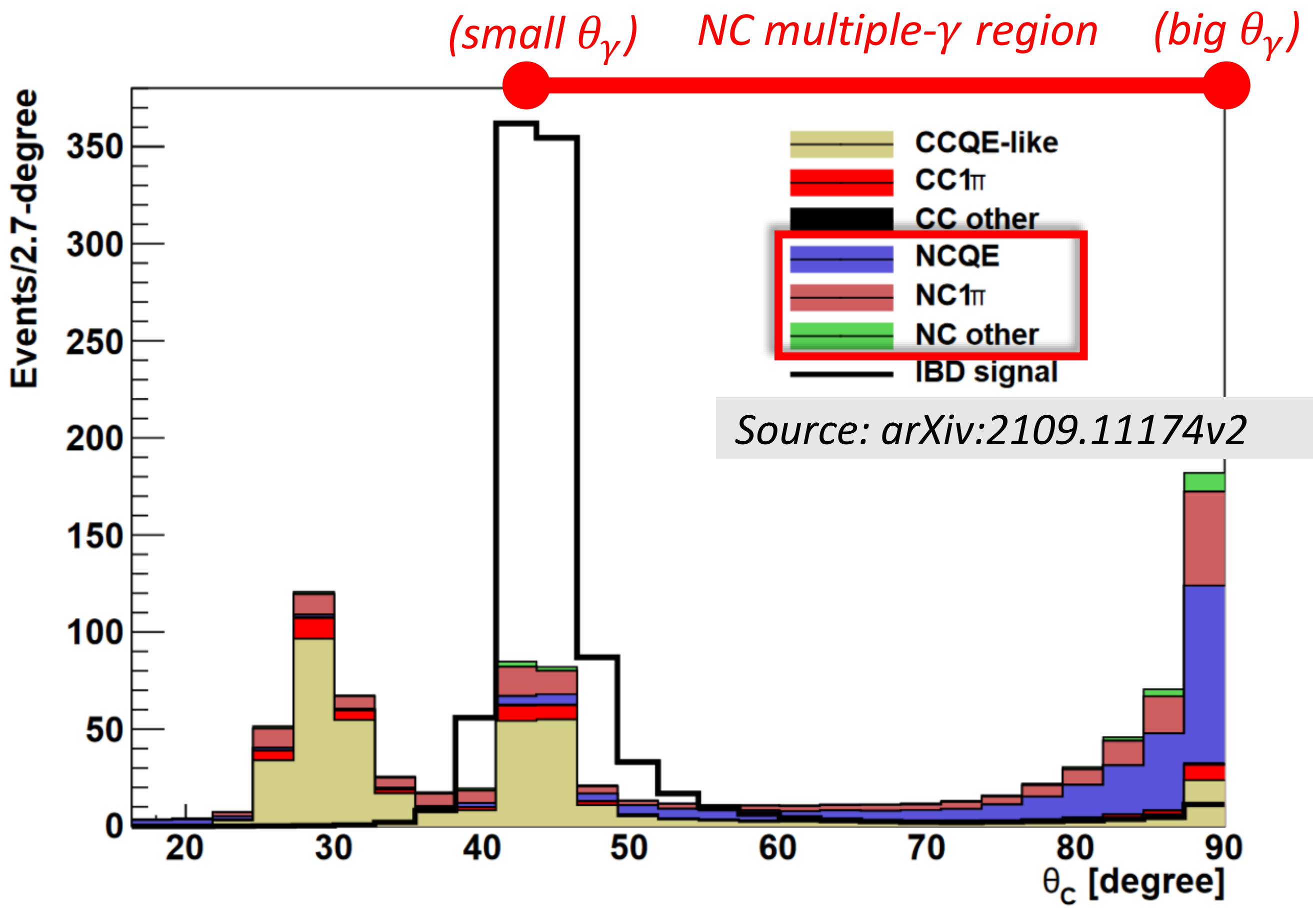
Reconstructing NCQE events with two Cherenkov rings (delayed)



- Neutron capture distance cut is **outperformed by new prompt cuts**…!

Remaining IBD/NC separation in MSG/Lclear after prompt cuts

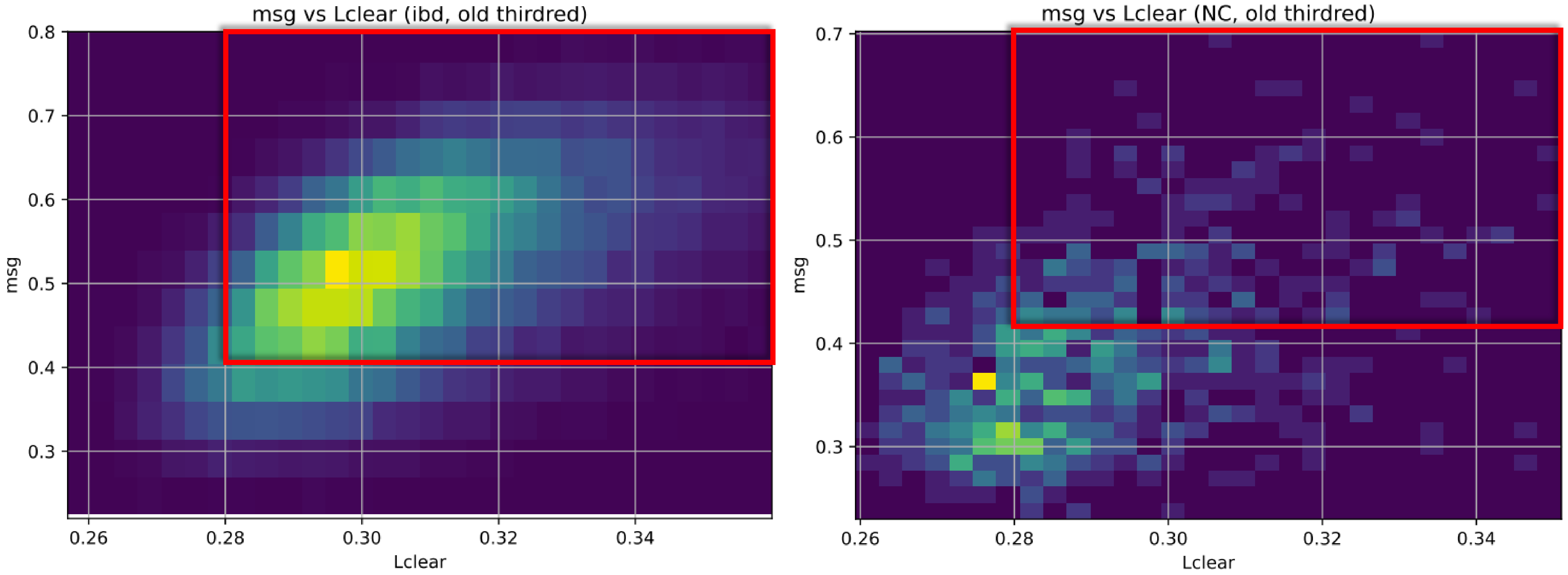




Source: arXiv:2109.11174v2

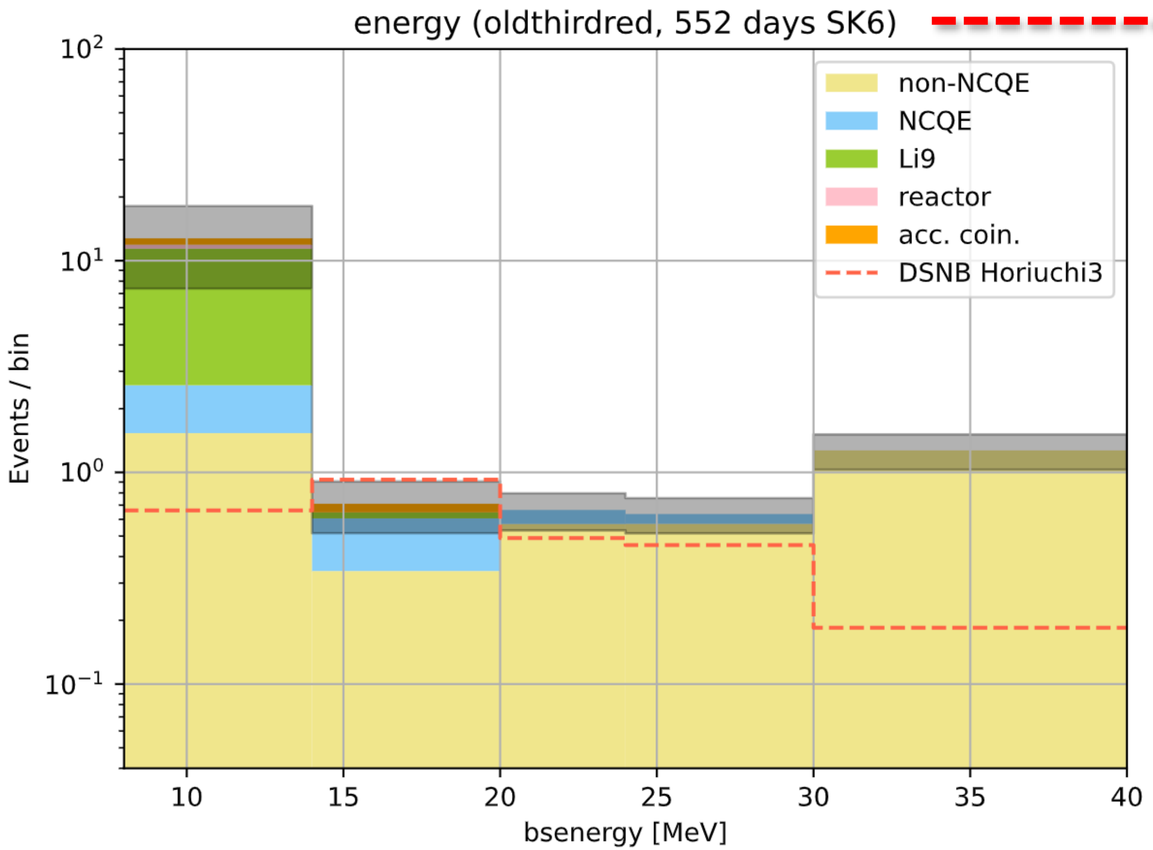
- **Multiple scattering goodness (MSG)** $\in [0,1]$ is closer to 0 when it is possible to reconstruct more than one ring.
- **Ring clearness (Lclear)** $\in [0,1]$ is closer to 1 when most hit triplets in a ring reconstruct the same Cherenkov angle.

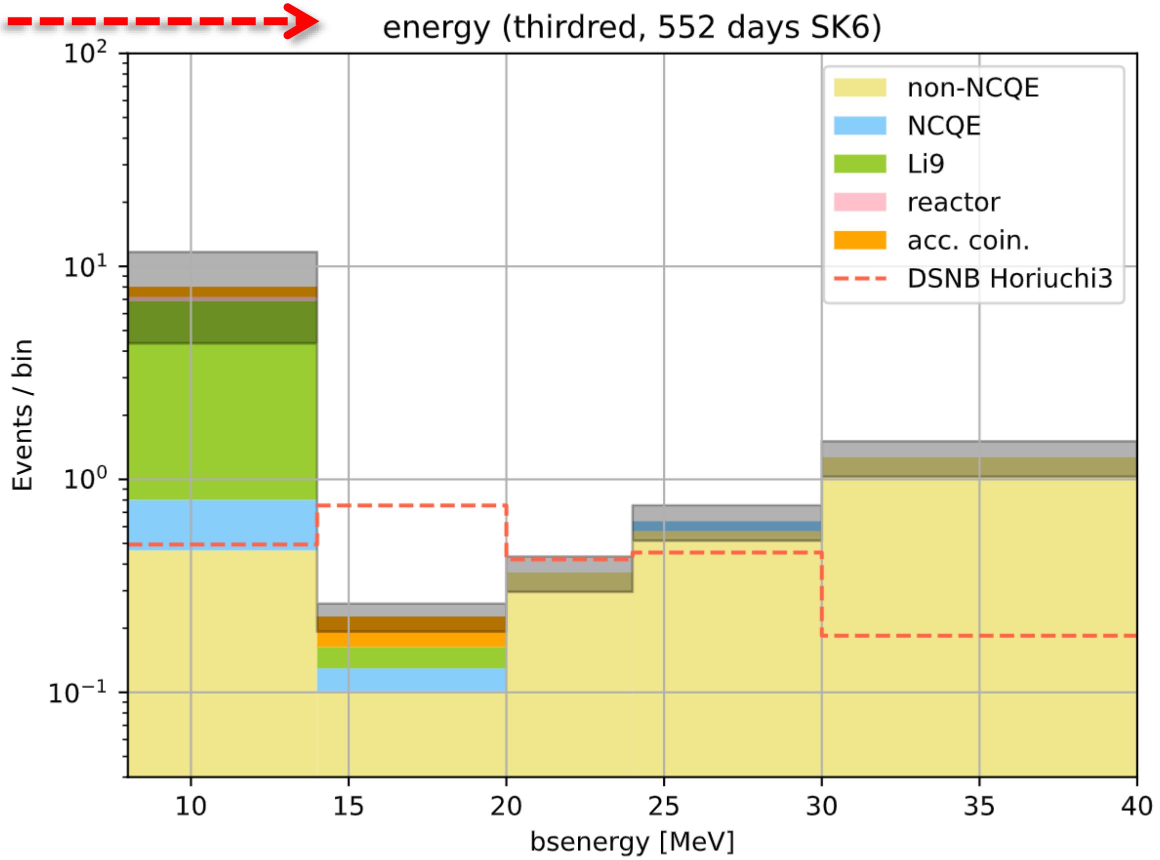
Remaining IBD/NC separation in MSG/Lclear after prompt cuts



- **Multiple scattering goodness (MSG)** $\in [0,1]$ is closer to 0 when it is possible to reconstruct more than one ring.
- **Ring clearness (Lclear)** $\in [0,1]$ is closer to 1 when most hit triplets in a ring reconstruct the same Cherenkov angle.
- Box cut shown gives $\epsilon_{IBD} = 0.84$ and $\boldsymbol{\epsilon_{NC} = 0.29}$.

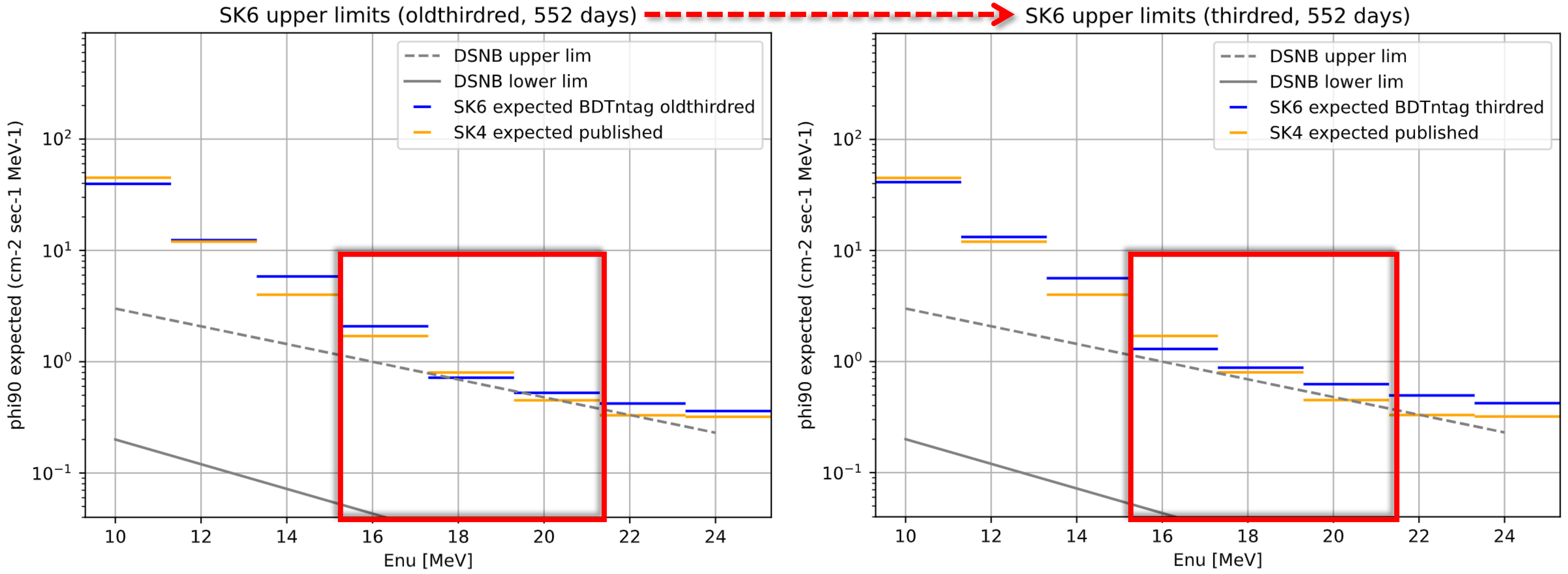
SK6 bsenergy spectrum (552.2days, old vs new prompt cuts)





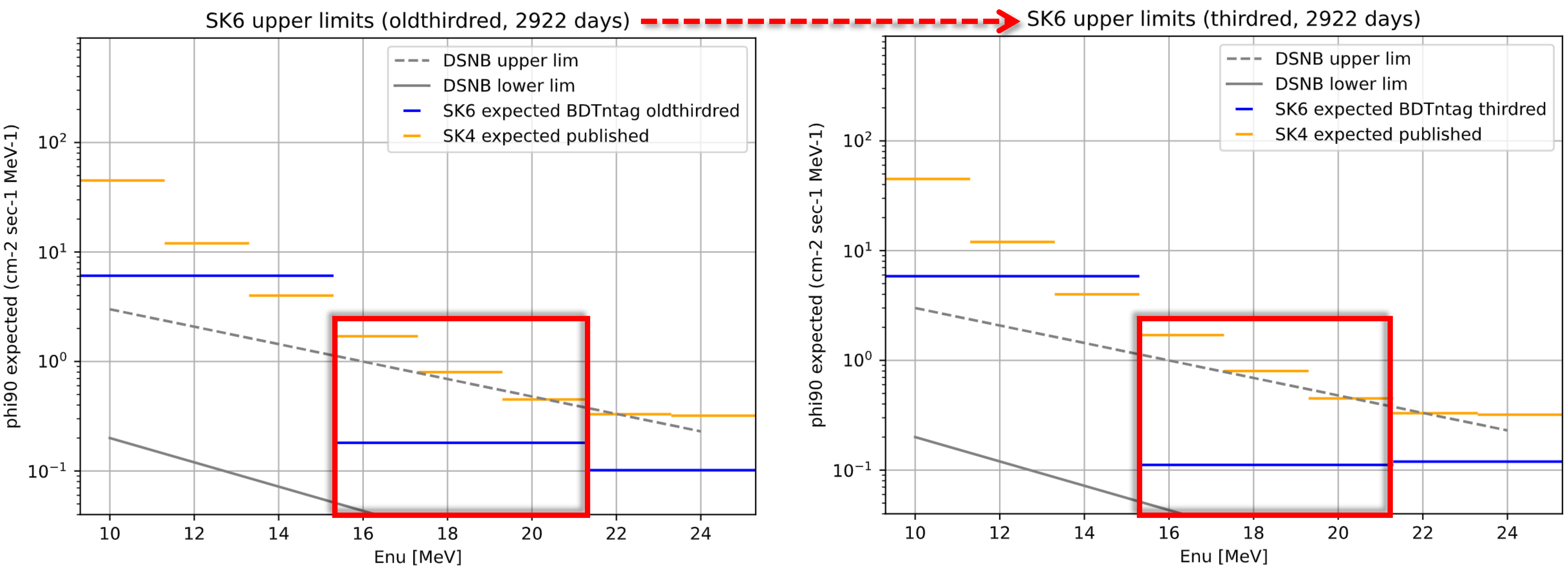
- The new MSG/Lclear cut **especially affects NCQE-dominant bin** of [14, 20] MeV.

SK6 upper limits (552.2days, old vs new prompt cuts)



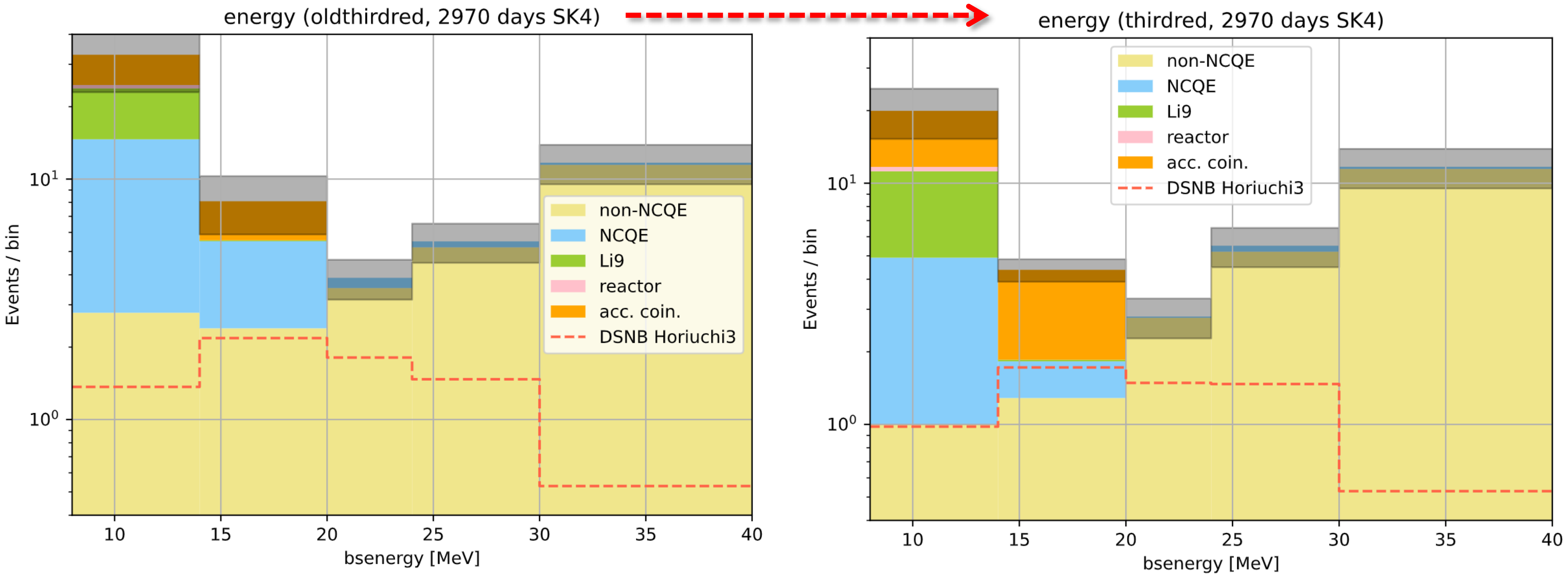
- **For SK6 livetime only**, the MSG/Lclear cut **does not improve upper limits** because of low event count.

SK6->HK upper limits (8 yrs SK6 effective when scaling ntag)



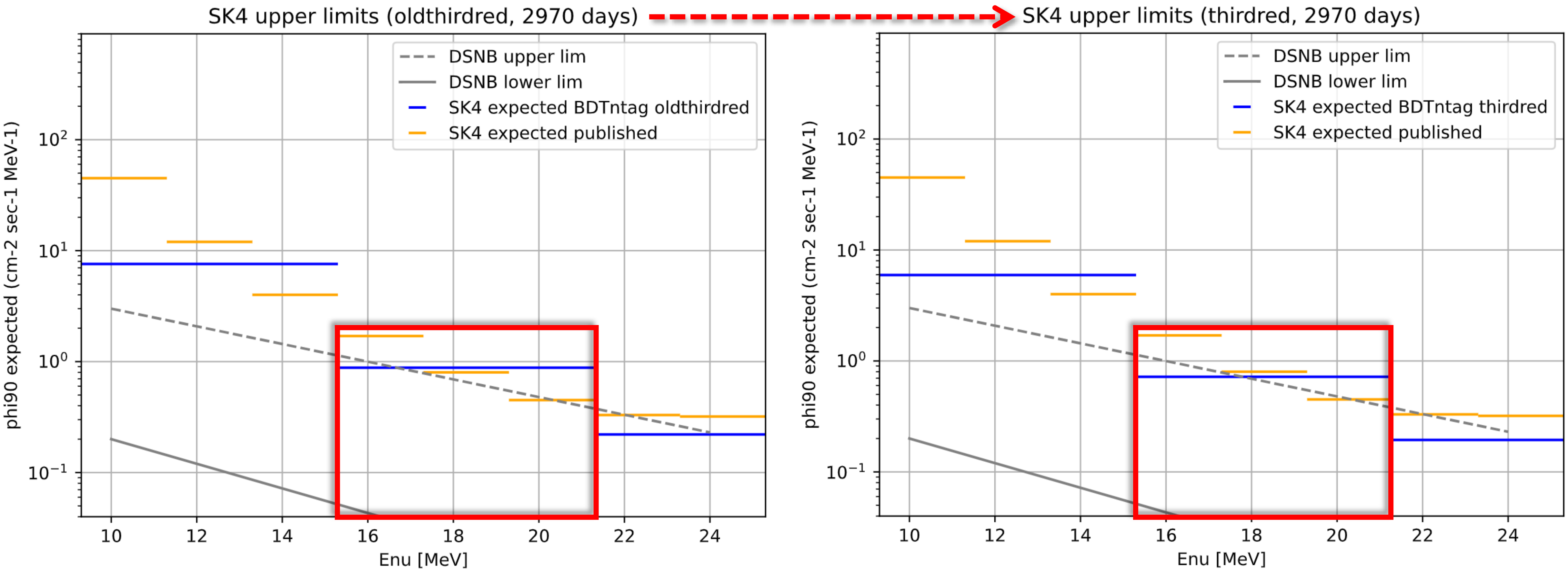
- **For SK6->HK**, sensitivity in [15.3, 21.3] MeV Enu is improved by **reducing the 90% limit by 40%**.

SK4 bsenergy spectrum (2970days, old vs new prompt cuts)



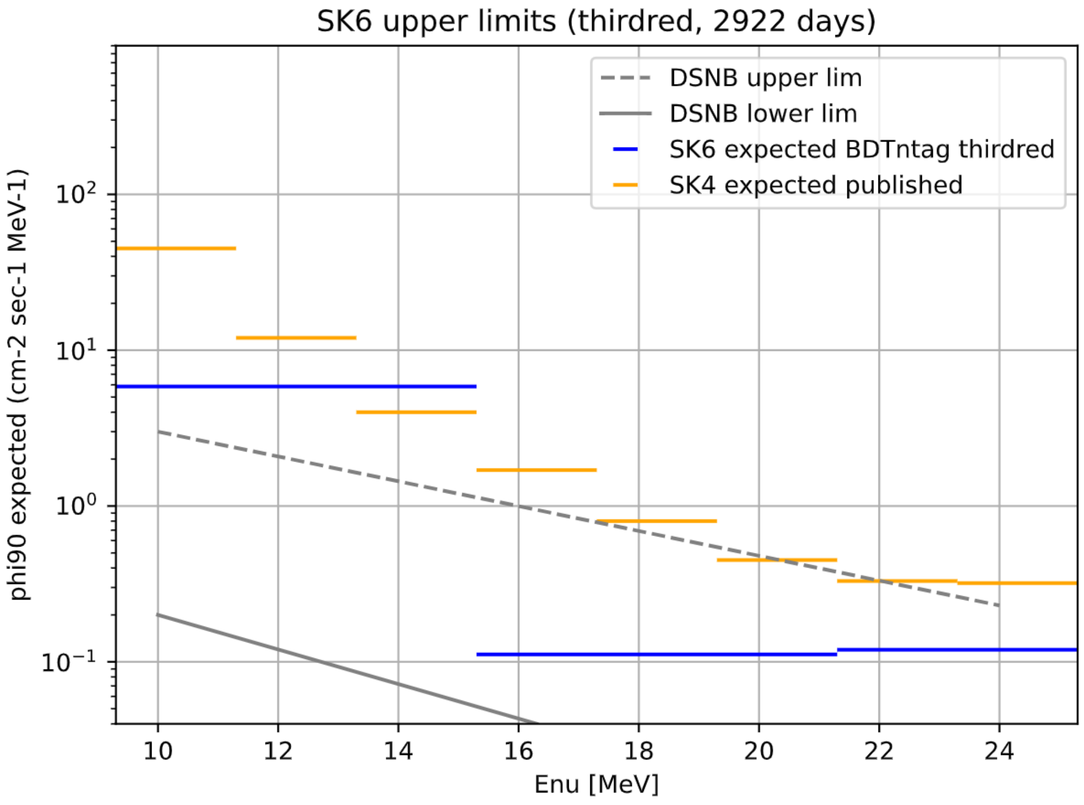
- For SK4, **NCQE reduction is evident below 20 MeV** bsenergy but we have more accidental coincidences.

SK4 upper limits (2970days, old vs new prompt cuts)



- **For SK4**, sensitivity in [15.3, 21.3] MeV Enu is improved by **reducing the 90% limit by 20%**.

Summary of this update and next steps



Takeaways

- Adding MSG/Lclear cuts **reduces initial NCQE to few percent** level.
- **Upper limits** for SK4 are **reduced by 20%**.
- **Upper limits** for SK6->HK are **reduced by 40%**.
- **Data processed** for SK4, SK6 **with these cuts**.

Some next steps

- Complete **combined sensitivity** predictions for **SK4+SK6->HK** in upper limits.
- **Validate sideband regions** looking for residual spallation and other potential issues using processed data.
- **Cross-check** with SK4 binned/spectral results, SK6 Harada-san analysis, and SK6 Alberto/Antoine spectral results.

Backup

Multiple scattering goodness (MSG) in SK analyses

Source: arXiv:1606.07538v1

4. Multiple scattering goodness (MSG)

Even at the low energies of the recoil electrons from ^{8}B solar neutrino-electron scattering, the PMT hit pattern from the Cherenkov cone reflects the amount of multiple Coulomb scattering recoil electrons experience. Very low-energy electrons will incur such scattering more than higher energy electrons and thus have a more isotropic PMT hit pattern. Radioactive background events, such as ^{214}Bi beta decays, generally have less energy than ^{8}B recoil electrons. Radioactive background events with γ emission will be more isotropic still. The "goodness" of a directional fit characterizes this hit pattern anisotropy: it is constructed by first projecting 42° cones from the vertex position, centered around each PMT that was hit within a 20 ns time window (after time of flight subtraction). Pairs of such cones are then used to define "event direction candidates", which are vectors along the intersection lines of the two cones. Only cone pairs which intersect twice are used to define event direction candidates. Fig. 5 shows a schematic view of how the event direction candidates are found. The gray points represent hit PMTs, which will roughly be found around the Cherenkov "ring", the projection of the cone onto the inner detector wall shown by the gray circle. As seen in the figure, for pairs of PMTs with positions located near the Cherenkov ring, one of the intersection lines shown by the black crosses will fall close to the best fit direction vector shown as the black point on the inner detector wall which this vector passes through. Clusters of these event direction candidates are then found by associating other event direction candidates which are within 50° of a "central event direction" seeded by the candidates themselves. Once an event direction candidate has been associated to a cluster, it then will not seed another cluster. The event direction candidate vectors of a cluster are added together to adjust the central event direction. Several iterations of this adjustment with subsequent cluster reassignment will center the clusters and maximize the magnitude of the vector sum. The vector sum with the largest magnitude is kept as the "goodness direction". The multiple scattering goodness (MSG) is then defined by the ratio of this magnitude and the number of event direction candidates within the 20 ns time window. Electrons undergoing more multiple Coulomb scattering will have a lower MSG value than those undergoing less. The filled squares (error bars) and solid (dotted) lines of Fig. 6 compare the LINAC data and MC MSG distributions for 4.38 MeV (8.16 MeV) electrons. As expected, higher energy electrons have a larger mean MSG since they undergo less multiple Coulomb scattering.

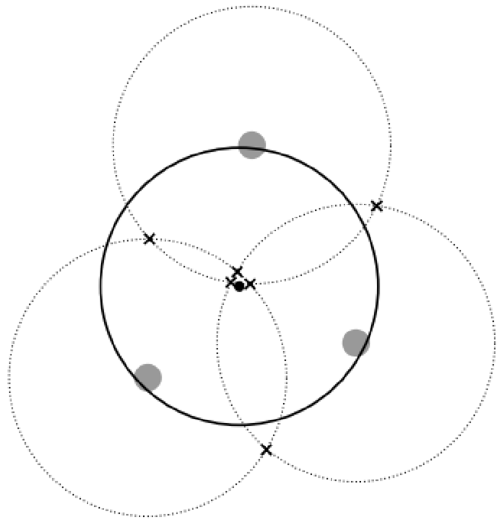


FIG. 5: Schematic view of the event direction candidates used to calculate the multiple scattering goodness. The gray points represent PMT hits and the dotted circles surrounding them are the projections of the 42° cones centered around each hit. The black crosses give the intersection points of the cones. The vectors from the event vertex position to these intersection points are taken as event direction candidates. The black dot shows the event best fit direction and the black solid circle is the projection of its Cherenkov cone onto the inner detector wall. The intersections will cluster around the event direction.

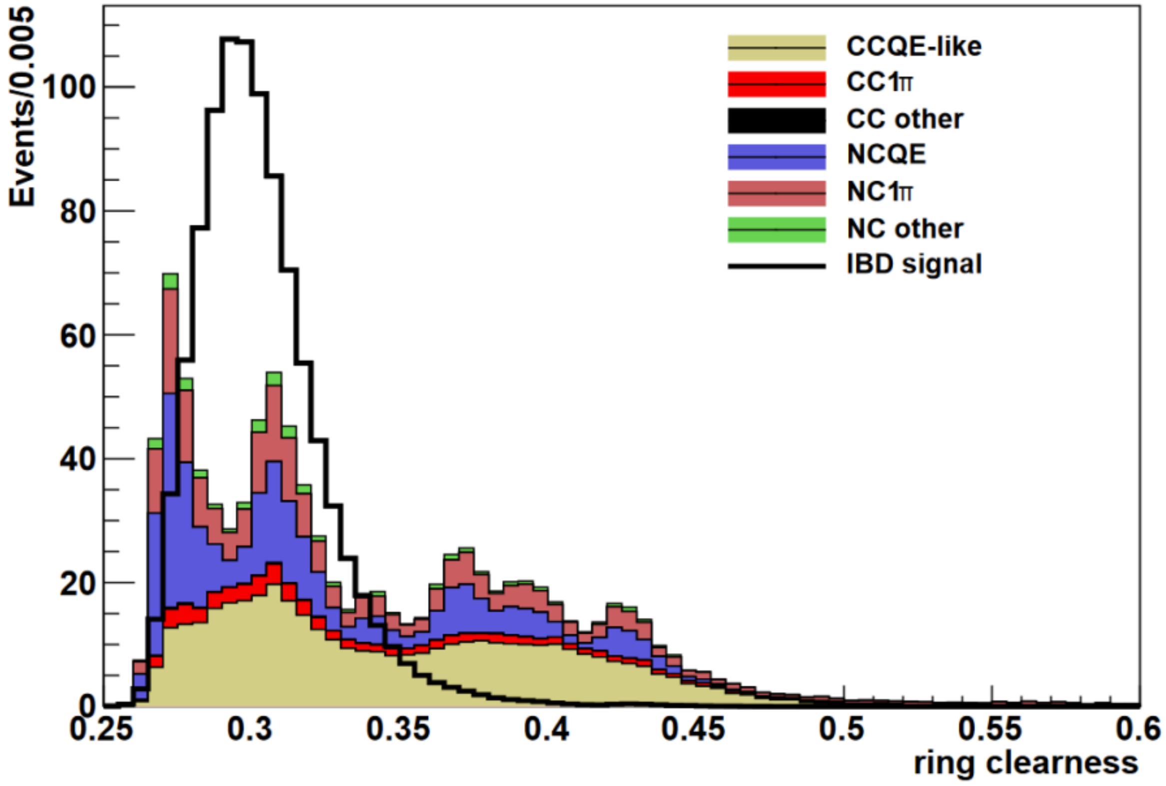
Ring clearness or "pi-like" variable (L_{clear})

4. Ring clearness

Electrons and positrons do not follow a straight trajectory in SK due to scattering and bremsstrahlung, which leads to fuzzy Cherenkov rings. Pions, on the other hand, lead to well-delineated ring patterns. In order to characterize this property we consider a 15-ns time-of-flight subtracted window around the main activity peak and compute the opening angles of the cones formed by the directions of all possible 3-hit combinations. We then identify the peak of this opening angle distribution θ_0 and estimate the "clearness" of the ring by computing:

$$L_{\mathtt{clear}} = \frac{N_{\mathtt{triplets}}(\theta_0 \pm 3^\circ)}{N_{\mathtt{triplets}}(\theta_0 \pm 10^\circ)}. \qquad (4)$$

The $L_{\mathtt{clear}}$ distributions from the atmospheric and IBD Monte-Carlo simulations are shown in Fig. 13. Events with lower $L_{\mathtt{clear}}$ have fuzzier rings. For the analyses presented here we require $L_{\mathtt{clear}} < 0.36$.



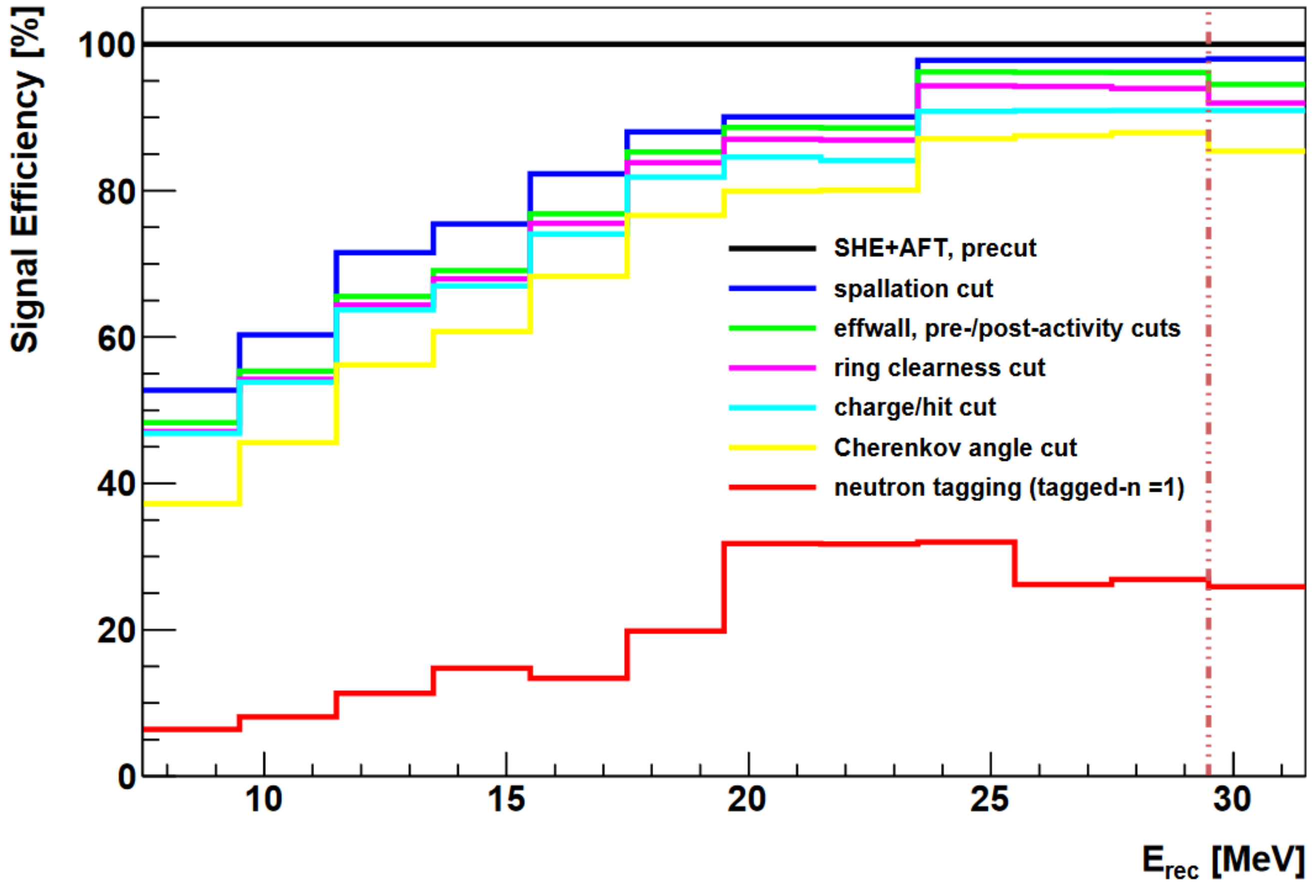
Source: arXiv:2109.11174v2

DSNB first (data quality) and third (prompt) reduction cuts

SK-IV Analysis

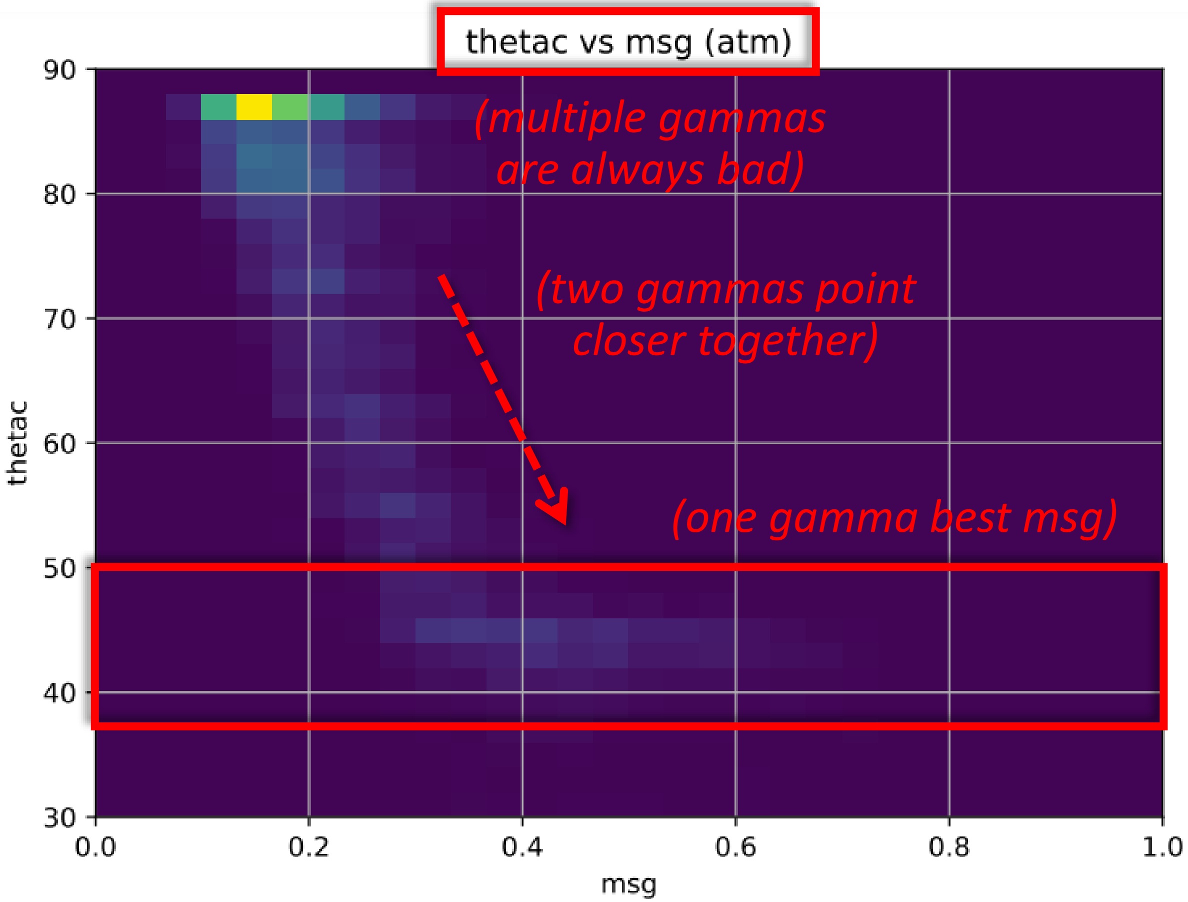
- bsgood > 0.5
- dwall > 200cm
- ovaq > 0.2

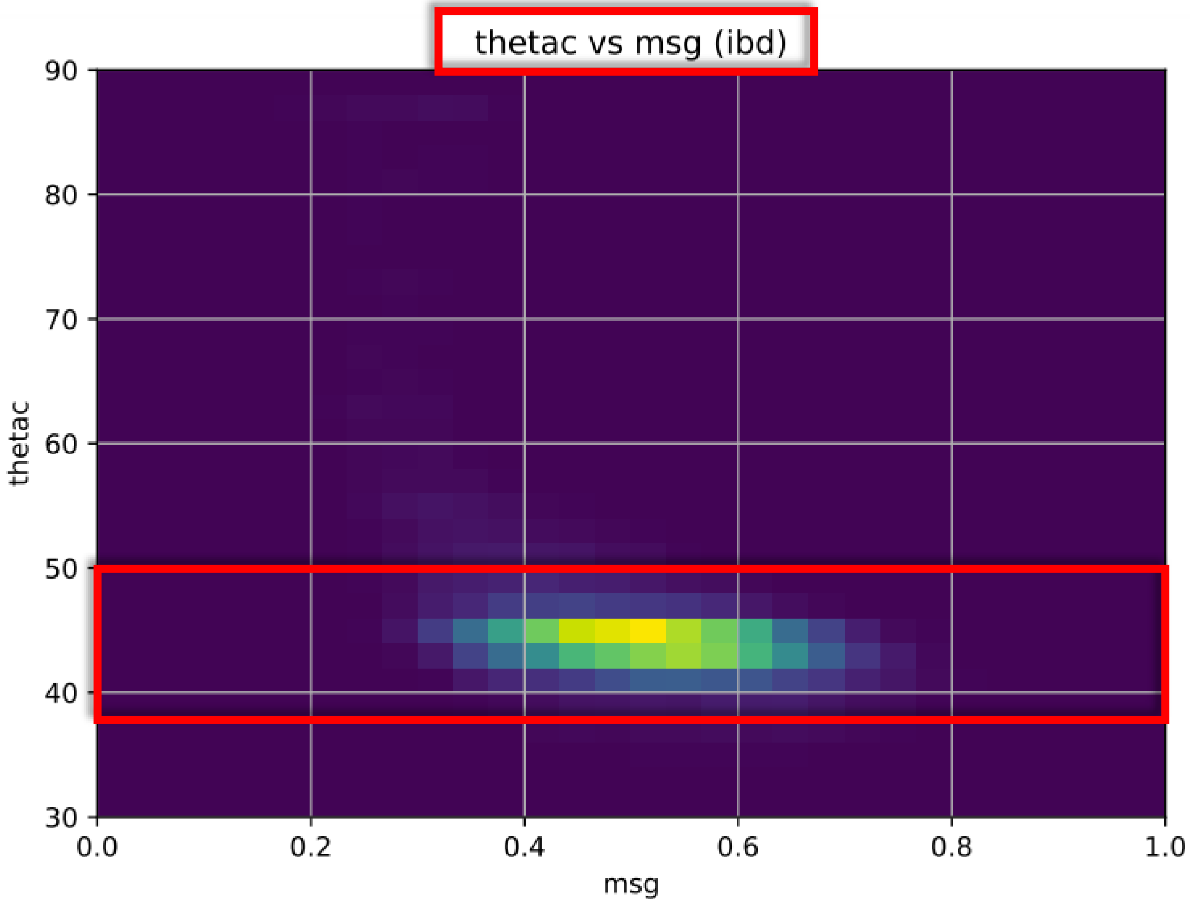
- q50/n50 < 2
- Lclear < 0.36
- maxpre < 12
- effwall > max{300cm, 500-50(Erec[MeV]-16)}
- nmue = 0
- $\theta_c \in [38°, 50°]$



Source: arXiv:2109.11174v2

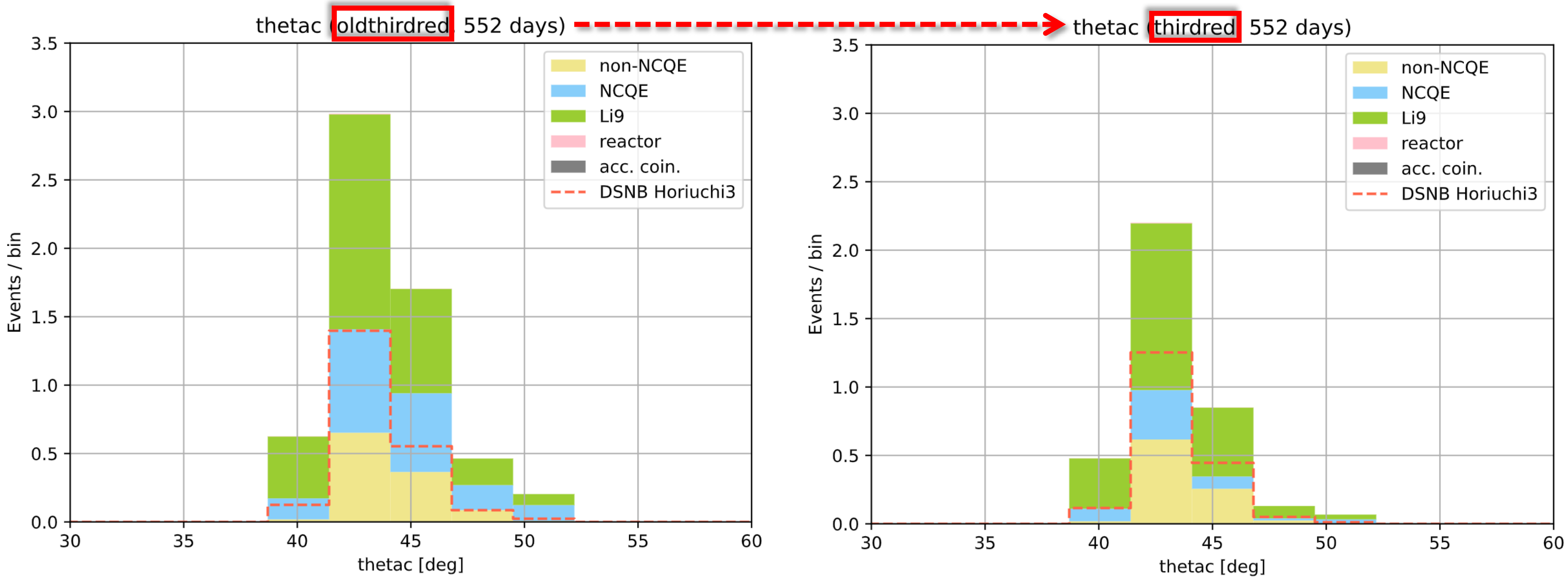
SK6 θ_c vs MSG results (10-30 MeV prompt)





- As the **angle between two gammas decreases**, **msg gets better** because it appears to be one ring forming the prompt event.
- Use new MSG/Lclear cut to target multiple gammas within θ_c signal region $[38°, 50°]$.

SK6 MSG-Lclear cut effect on θ_c distribution [10-30] MeV



- The hypothesis was that MSG/Lclear cuts could target **NCQE events that have two rings but are reconstructed in the region $[38°, 50°]$**.
- Here, we indeed see that the **new cuts** especially remove the **NCQE events different from $42°$ more** than for IBD

Recap: Comparison of MSG/Lclear cuts to CNN NCQE removal

threshold value	DSNB signal efficiency	NCQE background residual
0.500	0.980	0.041
0.965	0.962	0.020

Table 2: Network performance for events with energies between 12-30 MeV in the test sample. The energy region 12-30 MeV is populated by $\sim$ 14,000 events and contains 56% DSNB and 44% NCQE events due to the underlying nature of the energy distribution. Both the DSNB signal efficiency and the NCQE background residual depend on the threshold value chosen for classification.

Source: arXiv:2104.13426v3

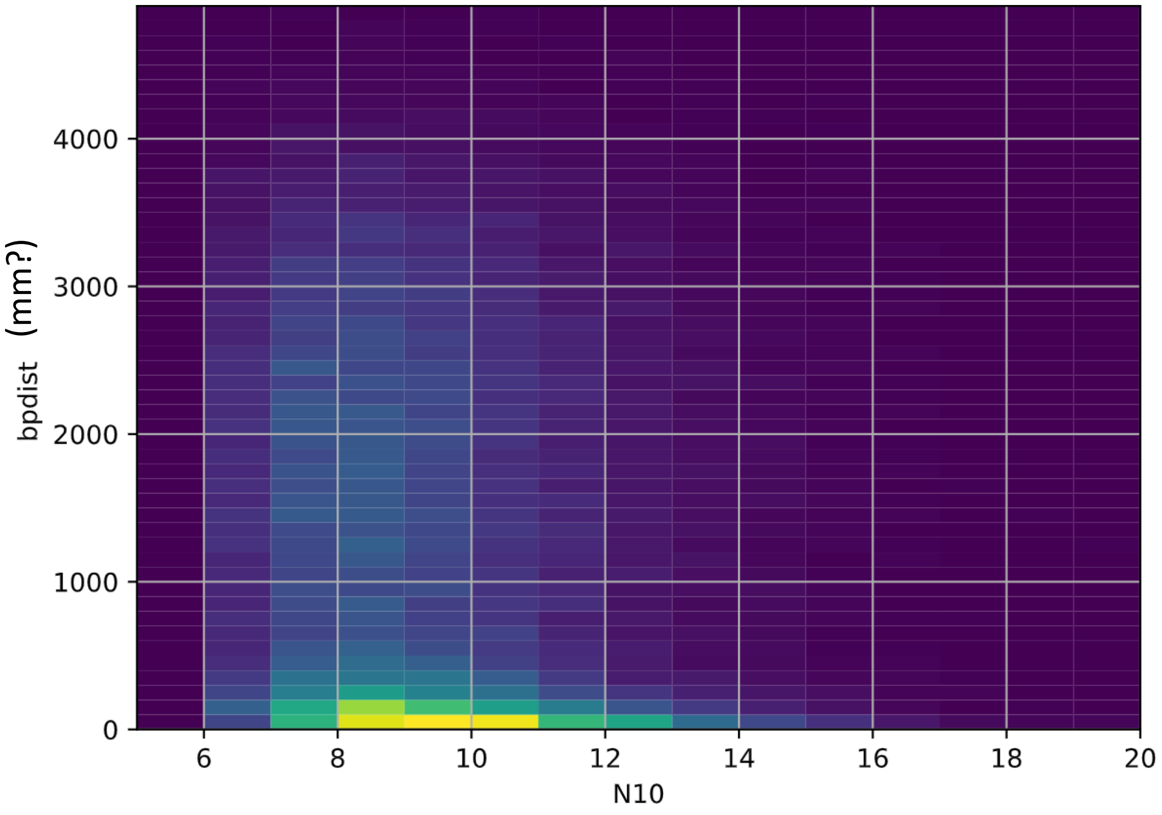
<u>This work</u>

- Add msg > 0.41, L_{clear} > 0.28
- $\epsilon' = \epsilon(oldthirdred)\epsilon(new)$
- $\epsilon'_{IBD} \approx (0.8)(0.85) = 0.7$
- $\epsilon'_{NCQE} \approx (0.1)(0.3) = 0.03$

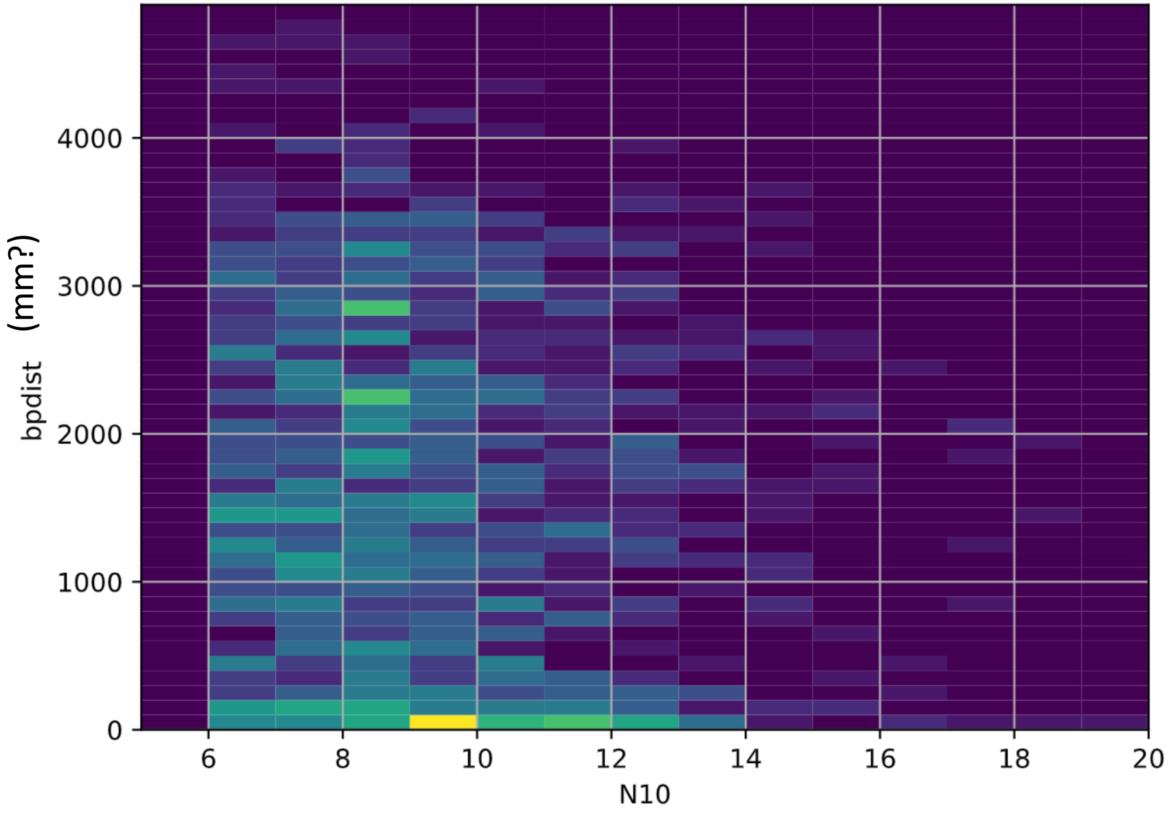
- The **MSG/Lclear cuts reduce** the initial NCQE background to the **few percent level**.
- The proposed **CNN could keep more IBD signal** at the same final NCQE level.
- Cross-checking with those working on CNN will be interesting.

SK4 bpdist vs N10 results BDT ntag (10-30 MeV bsenergy)

(IBD)

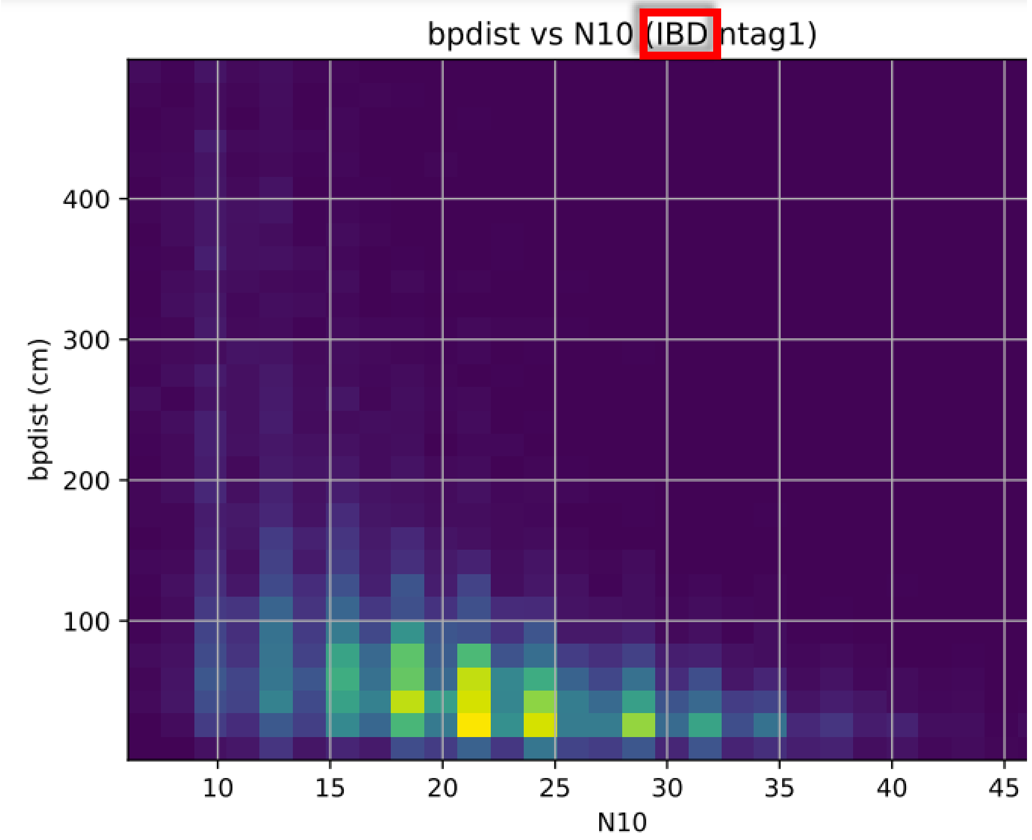


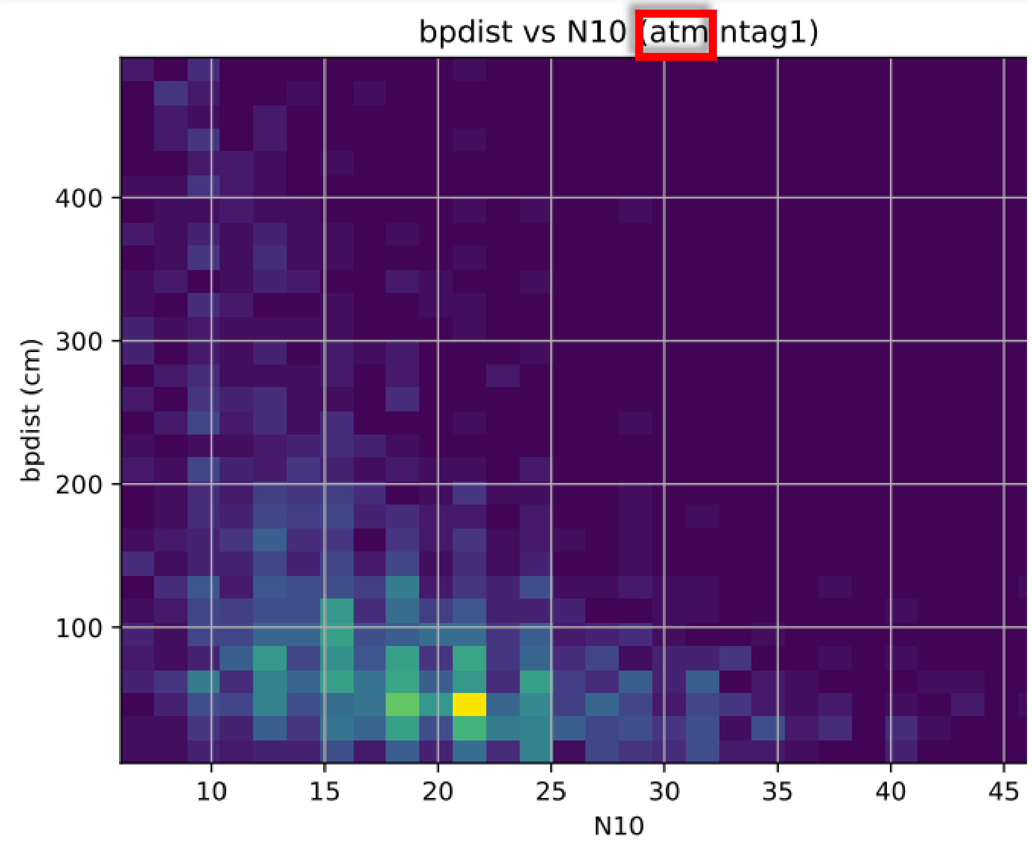
(atm)



- ϵ_{NCQE}(SK4, ntag=1)/ϵ_{IBD}(SK4, ntag=1) = **0.8**, ϵ_{NCQE}(SK6, ntag=1)/ϵ_{IBD}(SK6, ntag=1) = **0.4**.
- In the **SK4 era**, it is **difficult to see any use for the neutron capture distance (bpdist)** because no sensitivity to IBD/NCQE ncapture distance (order 10-100cm)

SK6 bpdist vs N10 results BDT ntag (10-30 MeV bsenergy)





- ϵ_{NCQE}(SK4, ntag=1)/ϵ_{IBD}(SK4, ntag=1) = **0.8**, ϵ_{NCQE}(SK6, ntag=1)/ϵ_{IBD}(SK6, ntag=1) = **0.4**.
- The **ntagging BDT in the Gd era** is sensitive to the NCQE ncapture distances with increased N10.
- Then, **not surprising the BDT disfavors NCQE** over IBD in the Gd era.