DSNB Upper Limit Results with New MSG Cut

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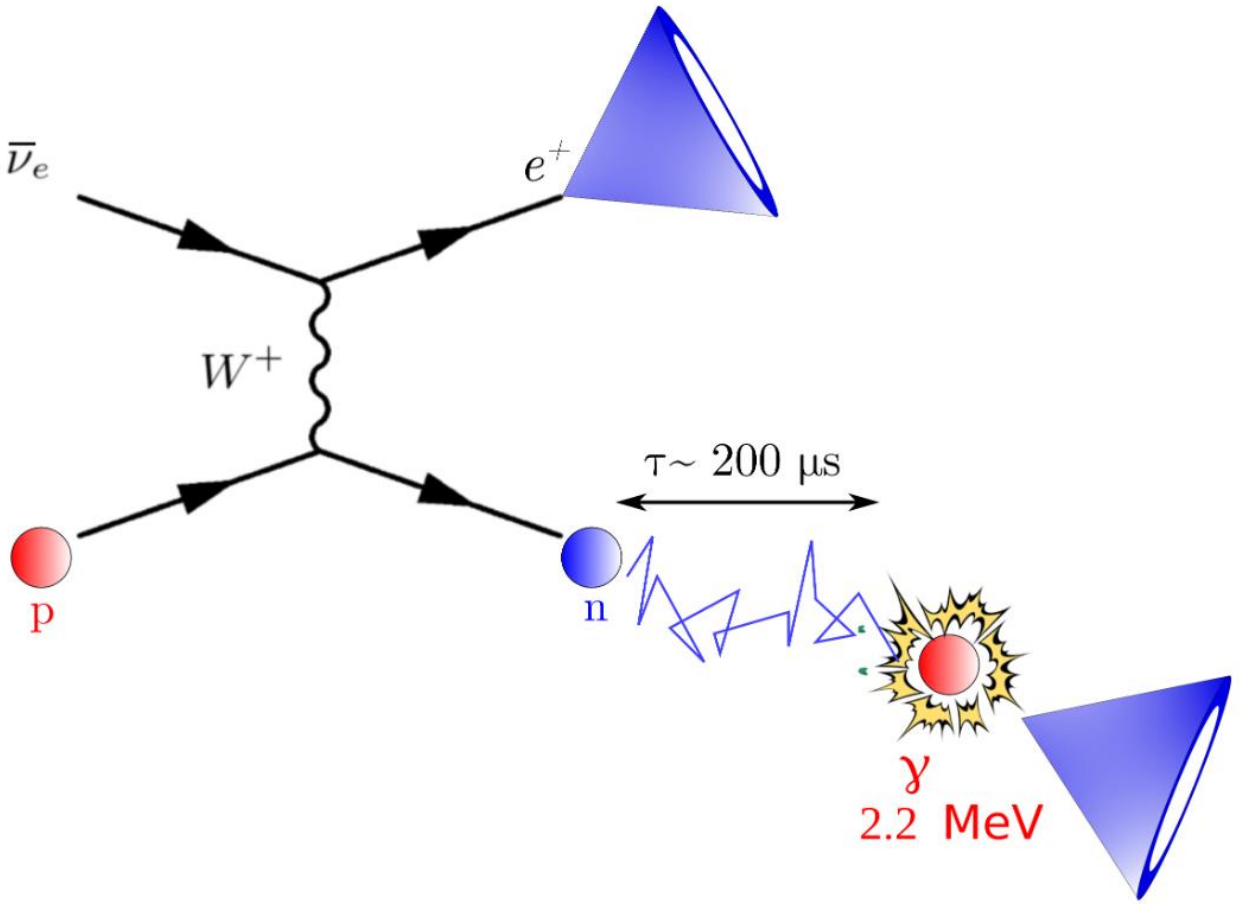
École Polytechnique – IP Paris

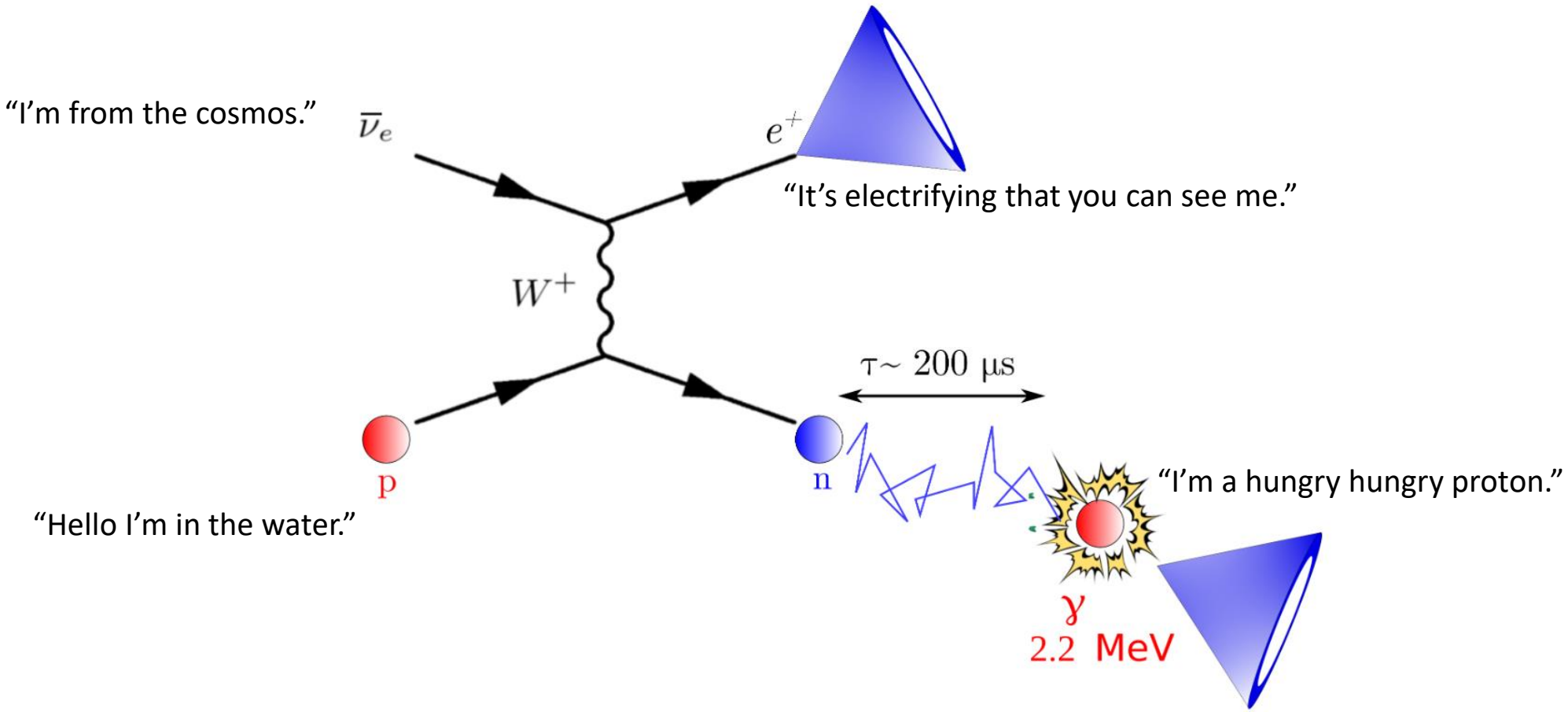
14 Nov 2023

LLR Neutrino Group

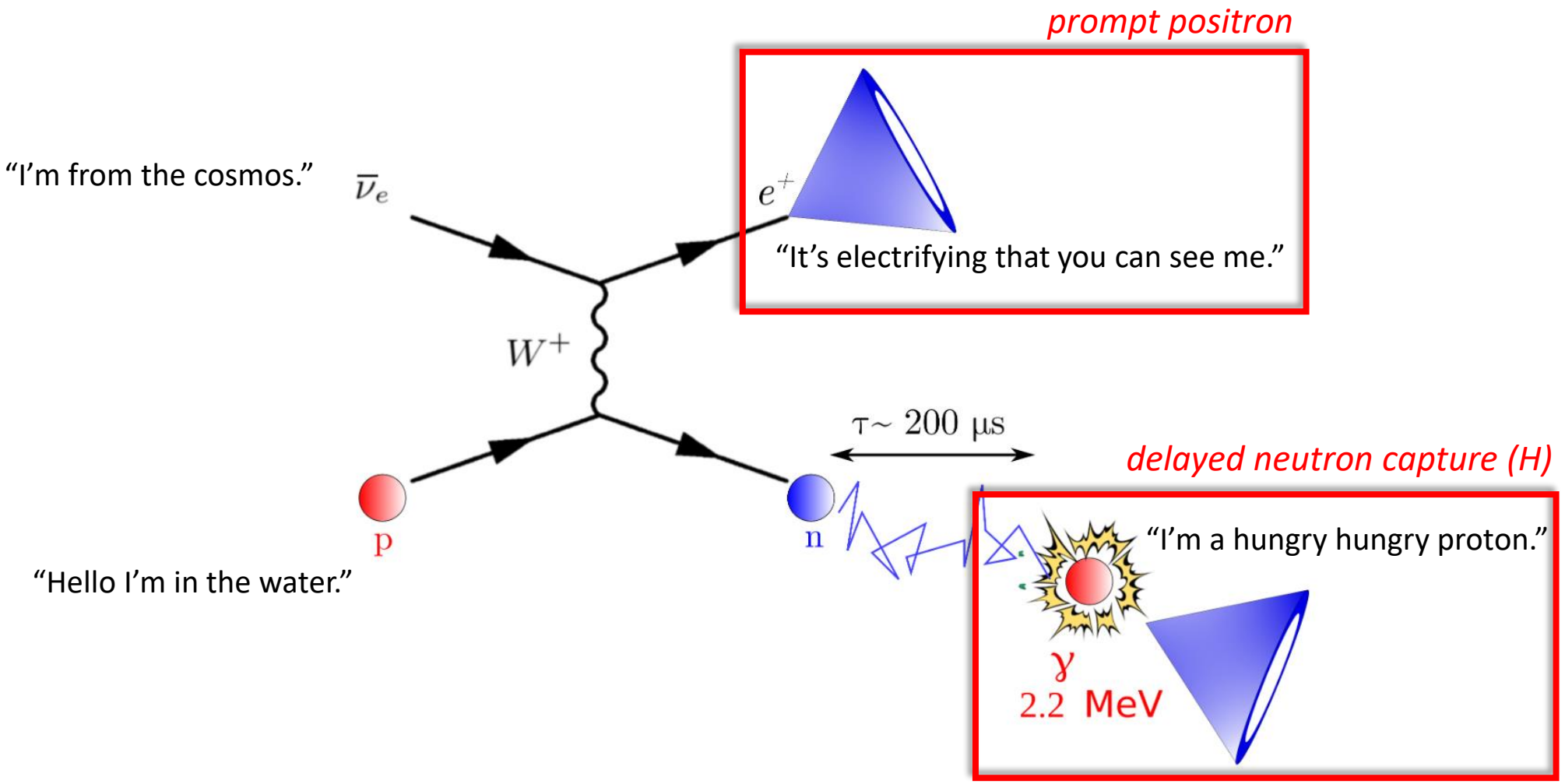
Diffuse Supernova Neutrino Background signal in Super-K



Diffuse Supernova Neutrino Background signal in Super-K



Diffuse Supernova Neutrino Background signal in Super-K



Isolating the IBD events using positron and neutron coincidence

Tagging positron + neutron:

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

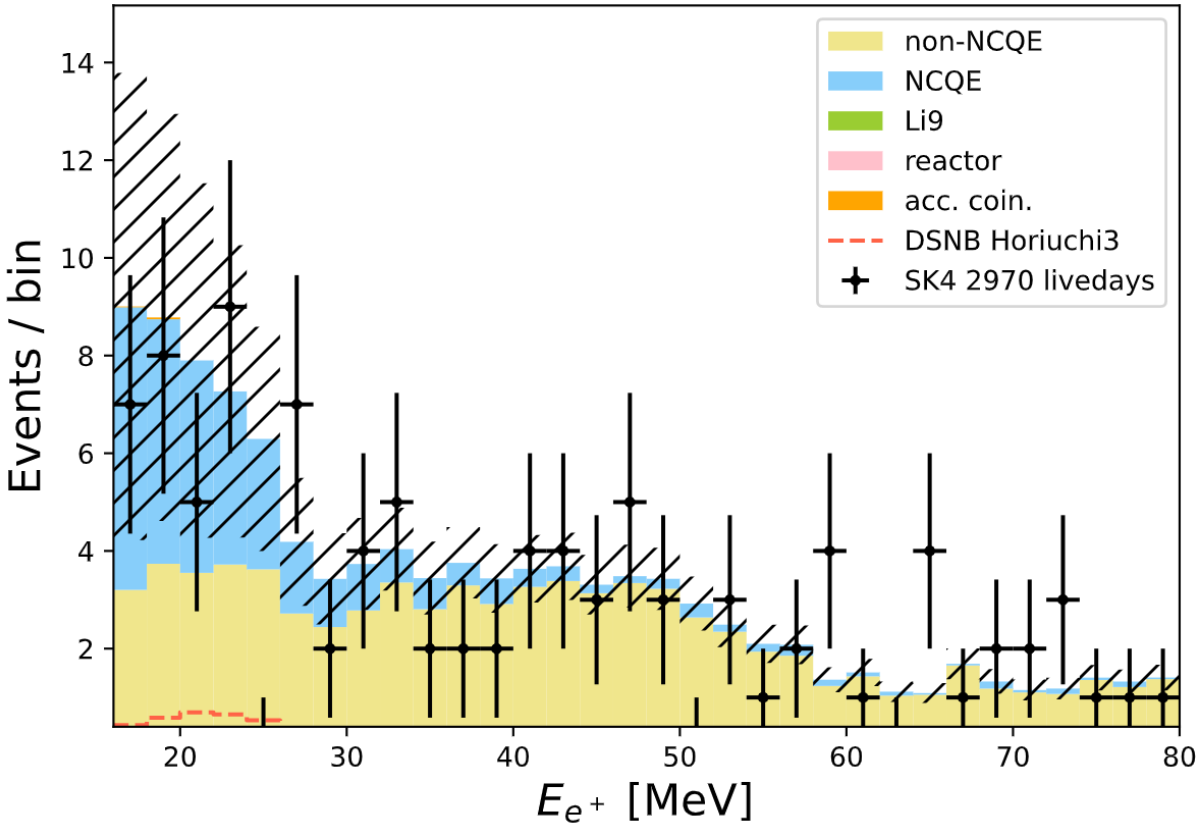
removed
- **Solar neutrinos** are a background at energies up to around 20 MeV (not shown in plot).

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

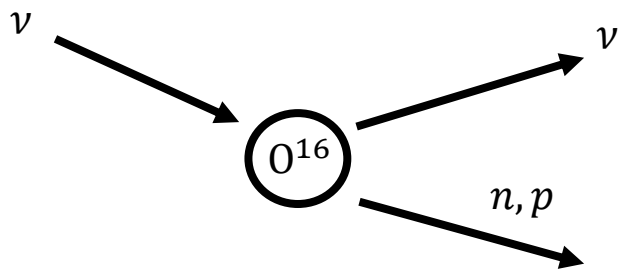
reduced
- **Atmospheric neutrinos** after around 15 MeV produce **charged-current (CC)** interaction backgrounds.

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

prompt positron + *delayed neutron capture (H)*



Neutral-current quasi-elastic (NCQE) atmospheric backgrounds



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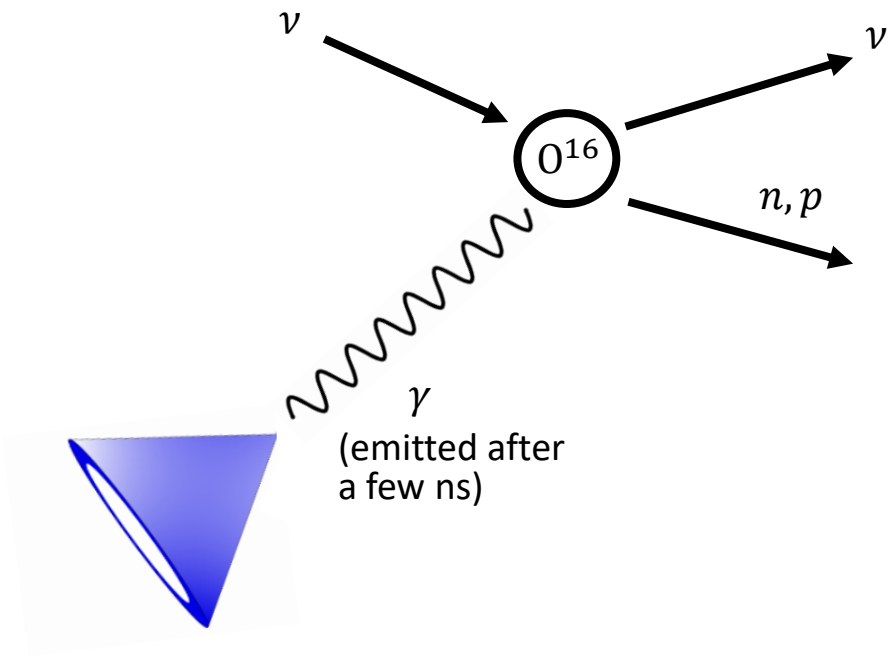

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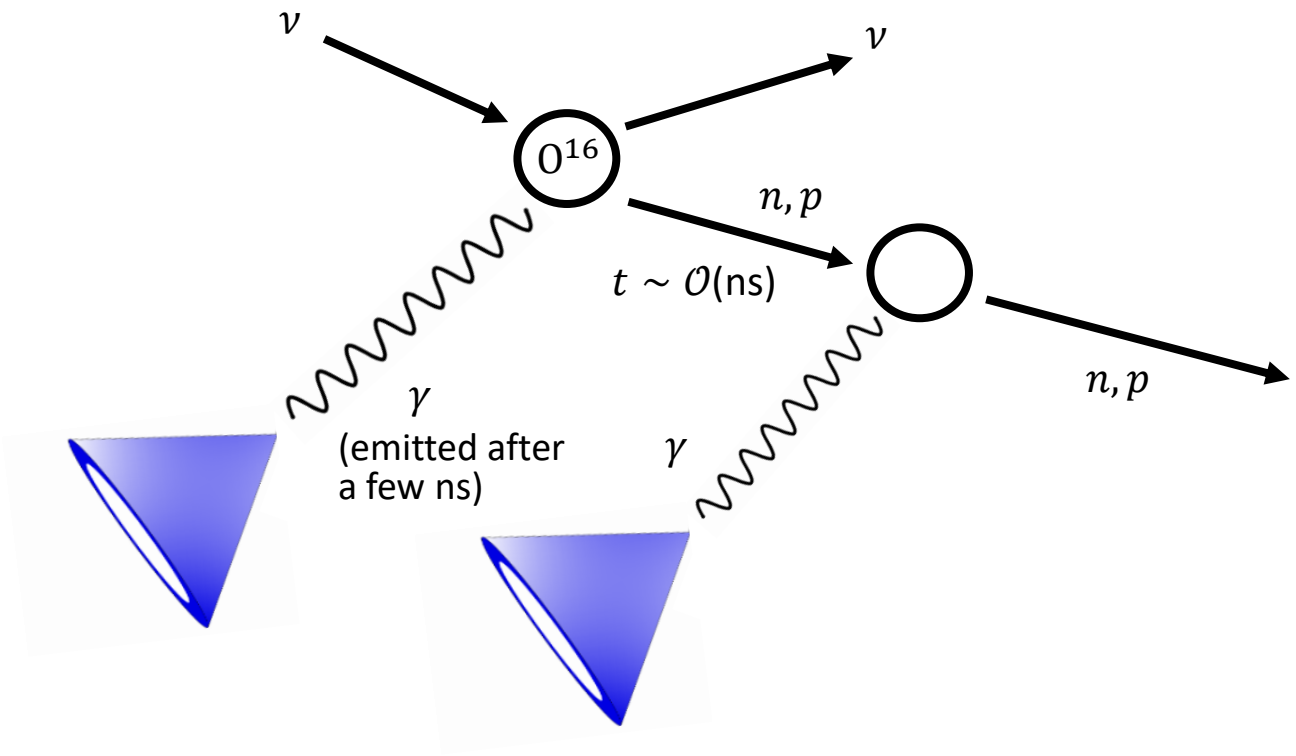

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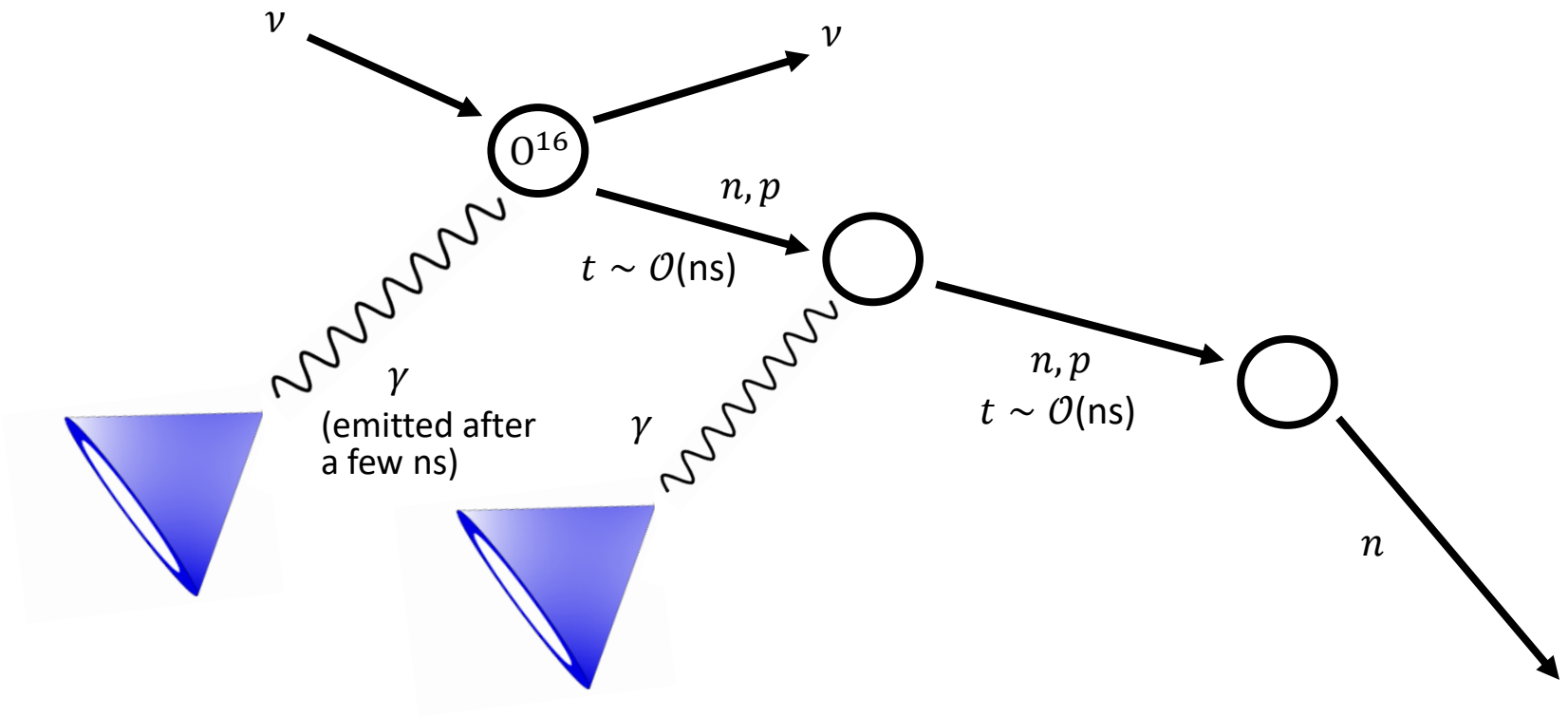

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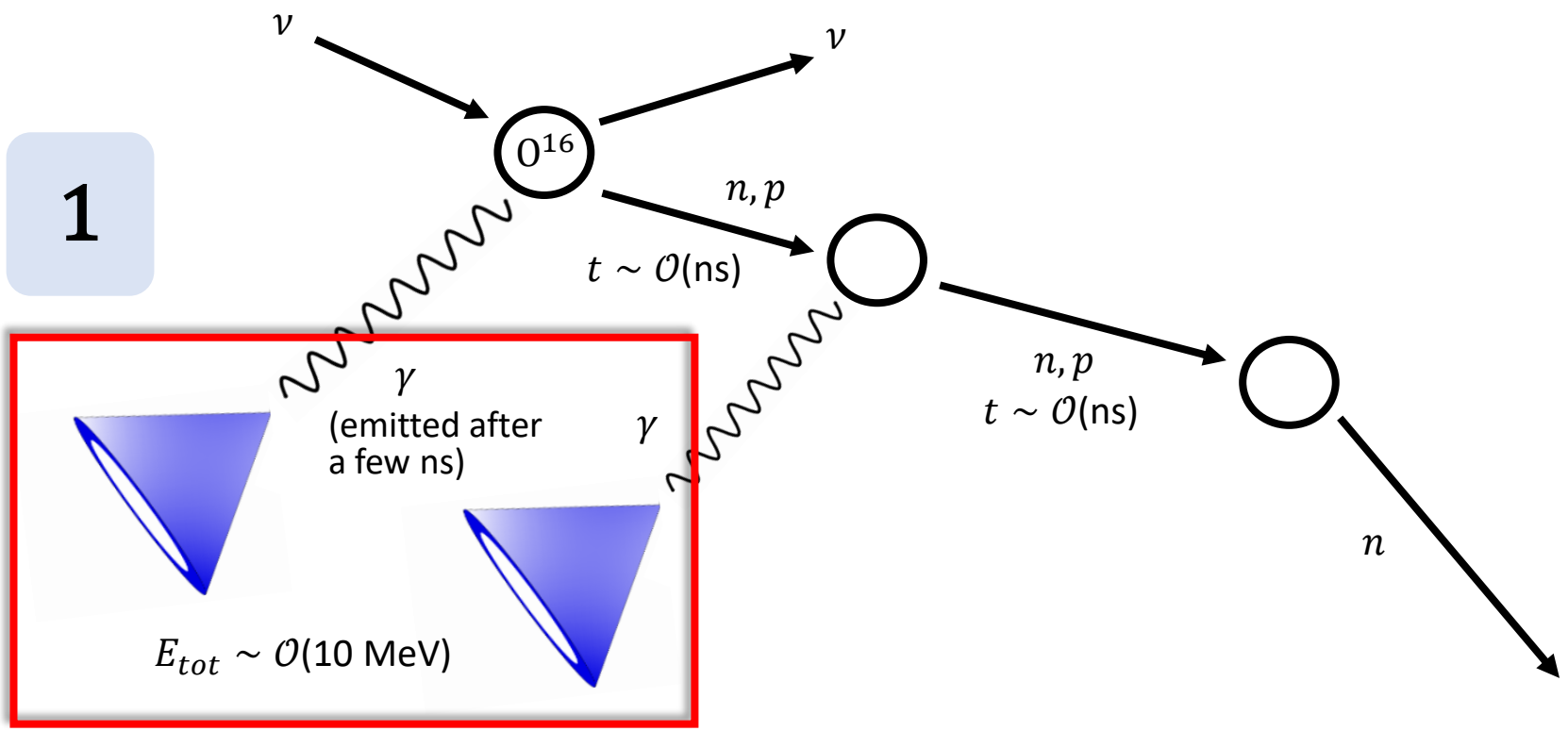
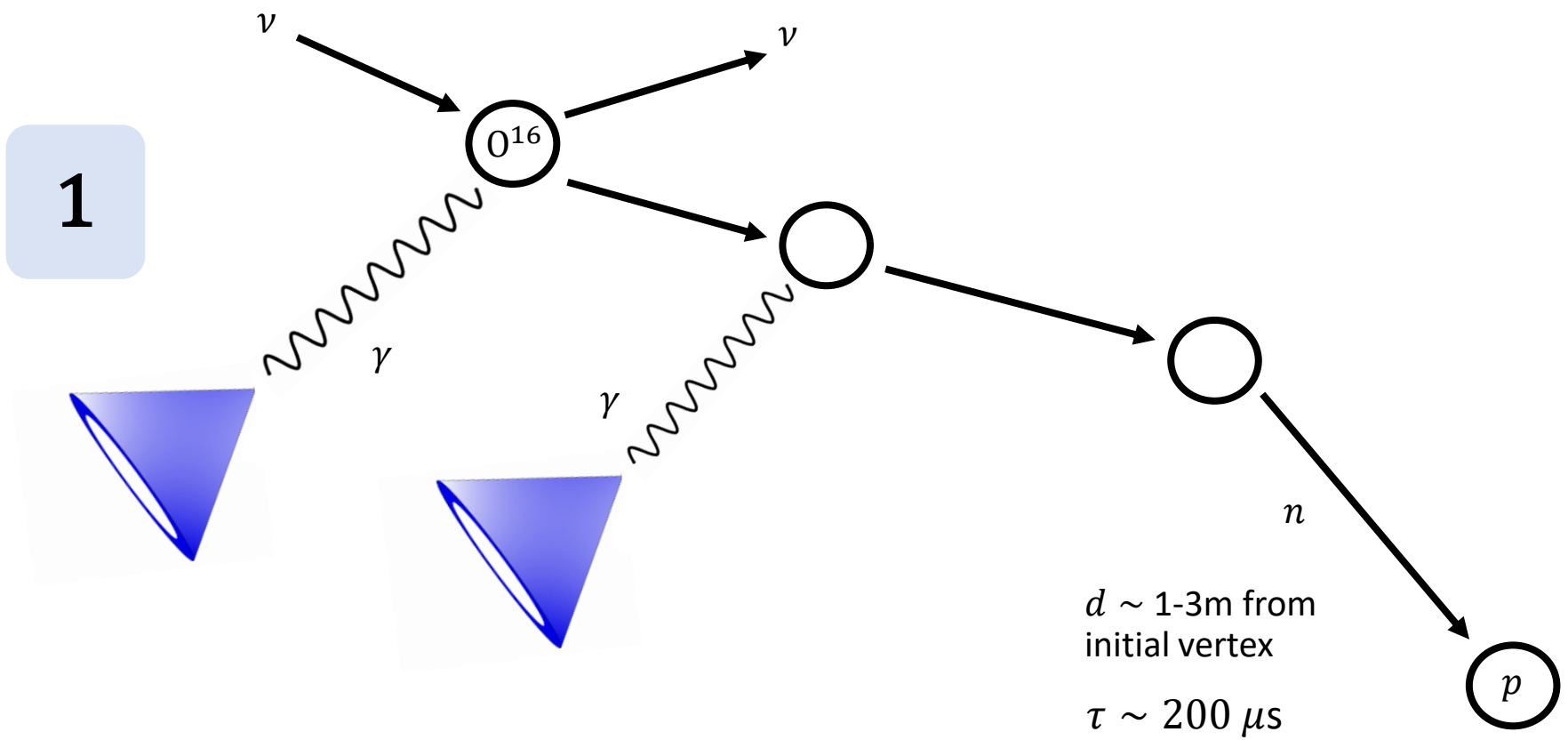


Prompt signal

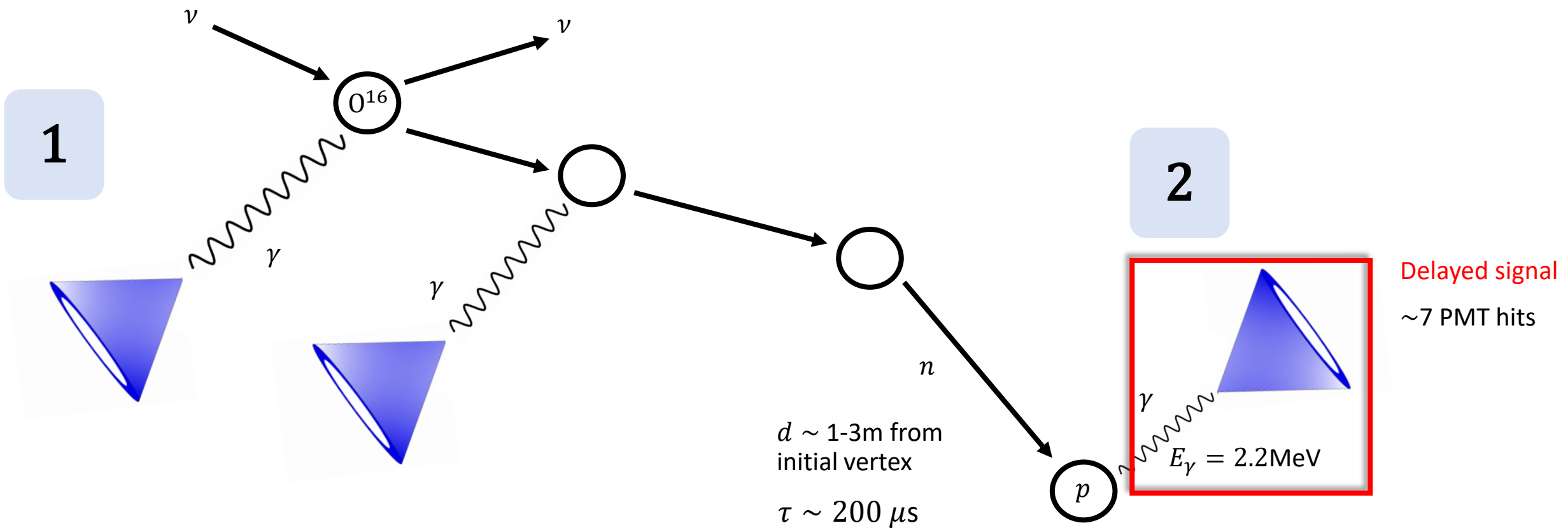
> 58-70 PMT hits

within 200ns t-window

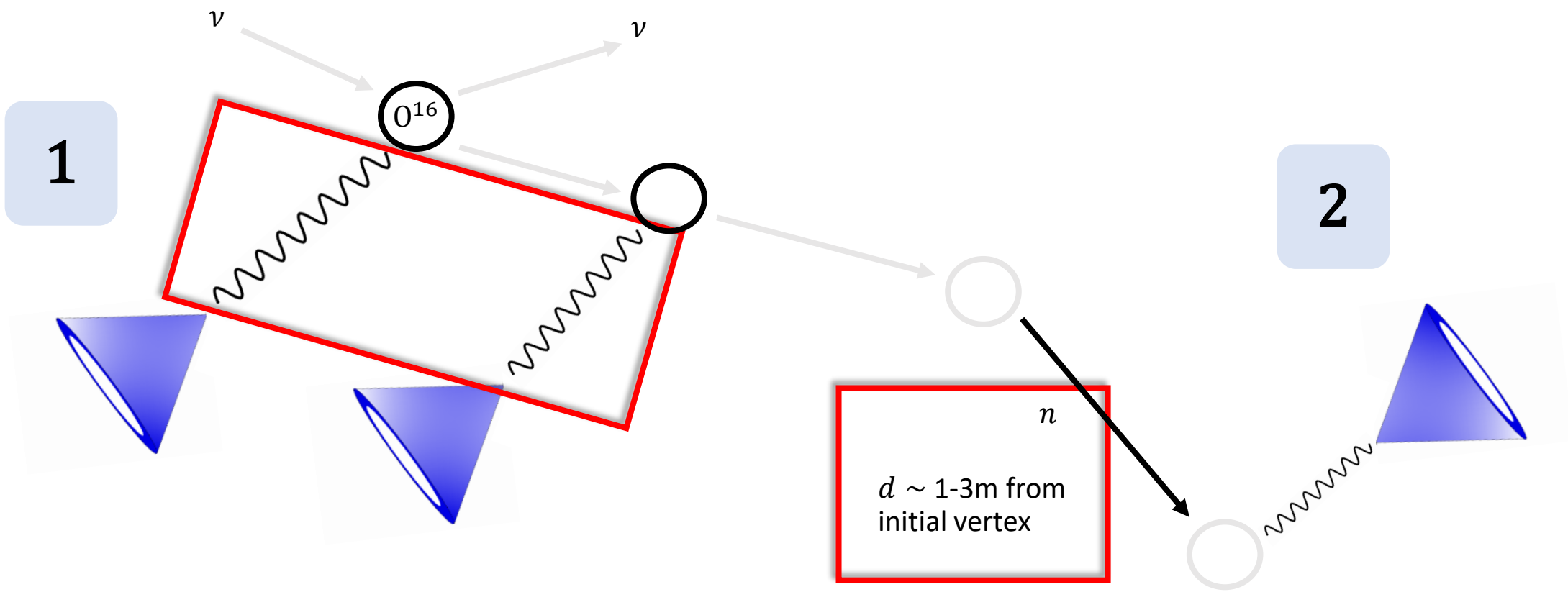
Neutral-current quasi-elastic (NCQE) atmospheric backgrounds



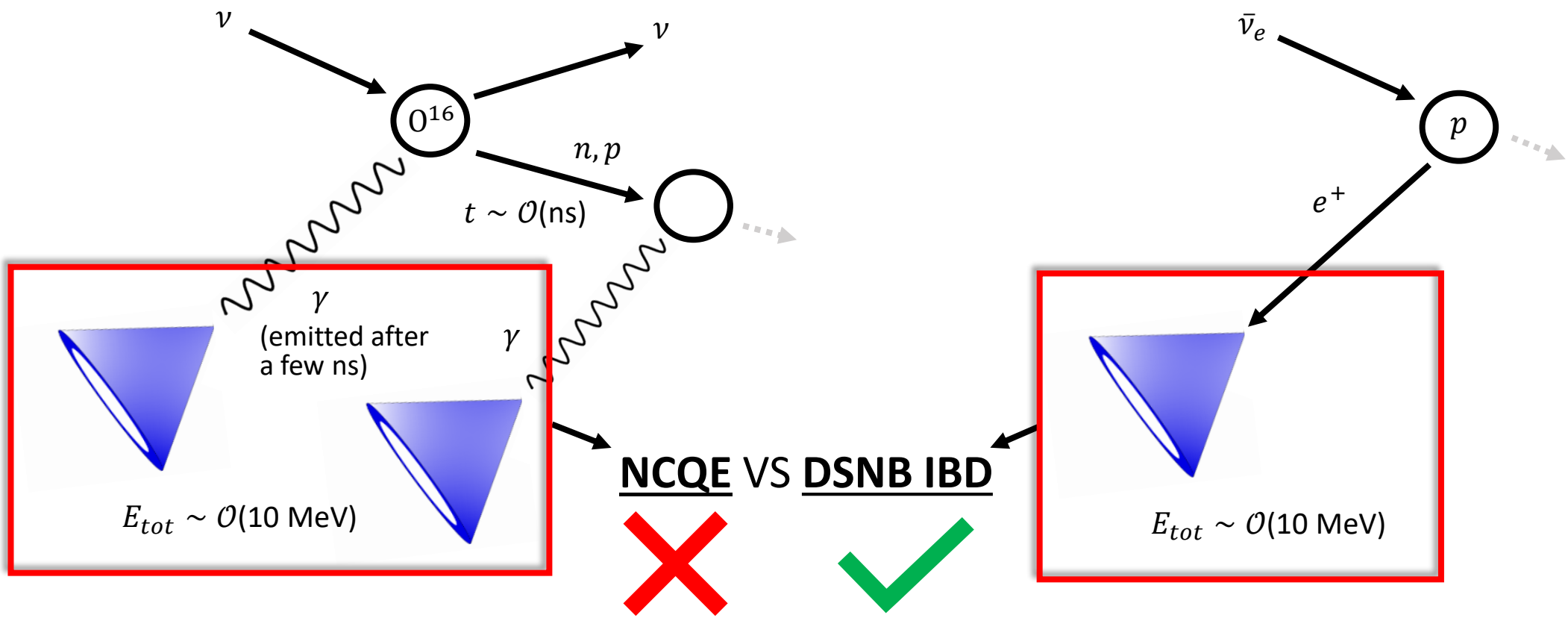
Neutral-current quasi-elastic (NCQE) atmospheric backgrounds



Differences of overall NCQE from DSNB IBD signal



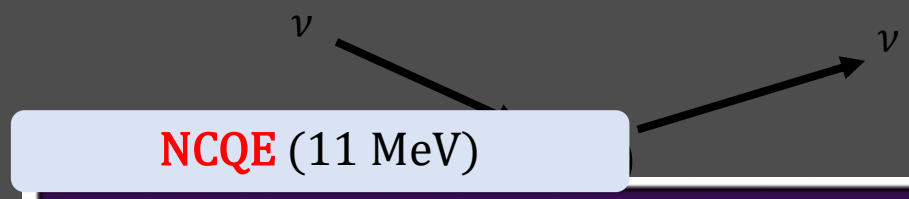
NCQE vs DSNB prompt event topology



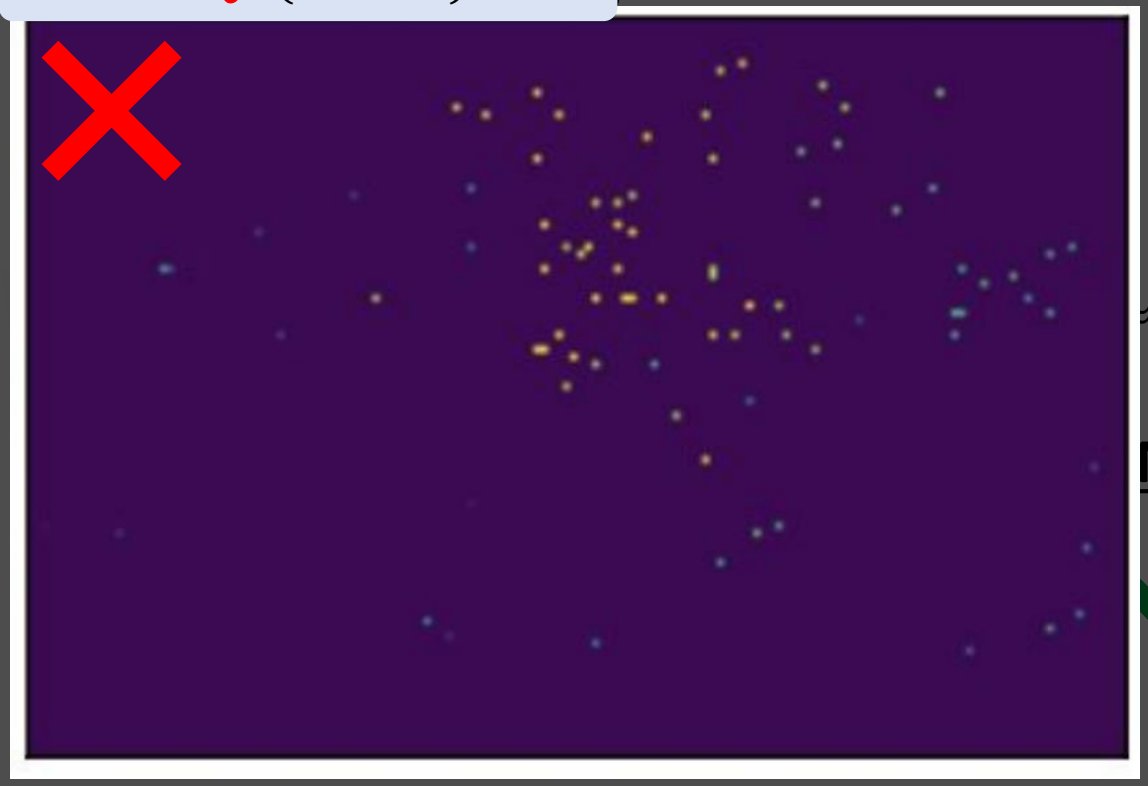
- **Multi-ring** prompt event wrongly reconstructed as one ring!

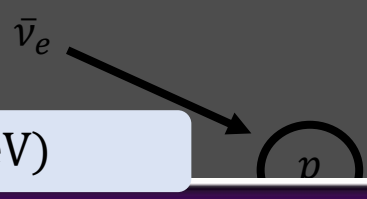
- **One-ring** prompt event correctly reconstructed as one ring!

NCQE vs DSNB prompt event topology

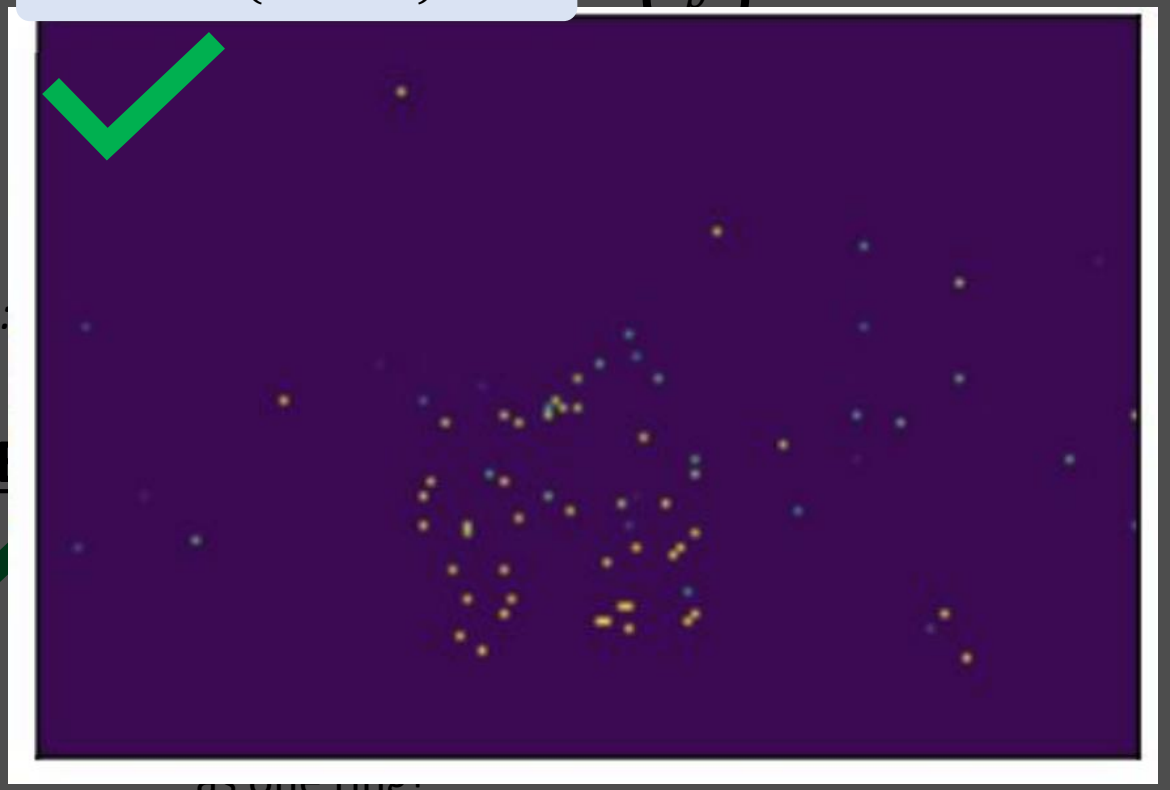


NCQE (11 MeV)



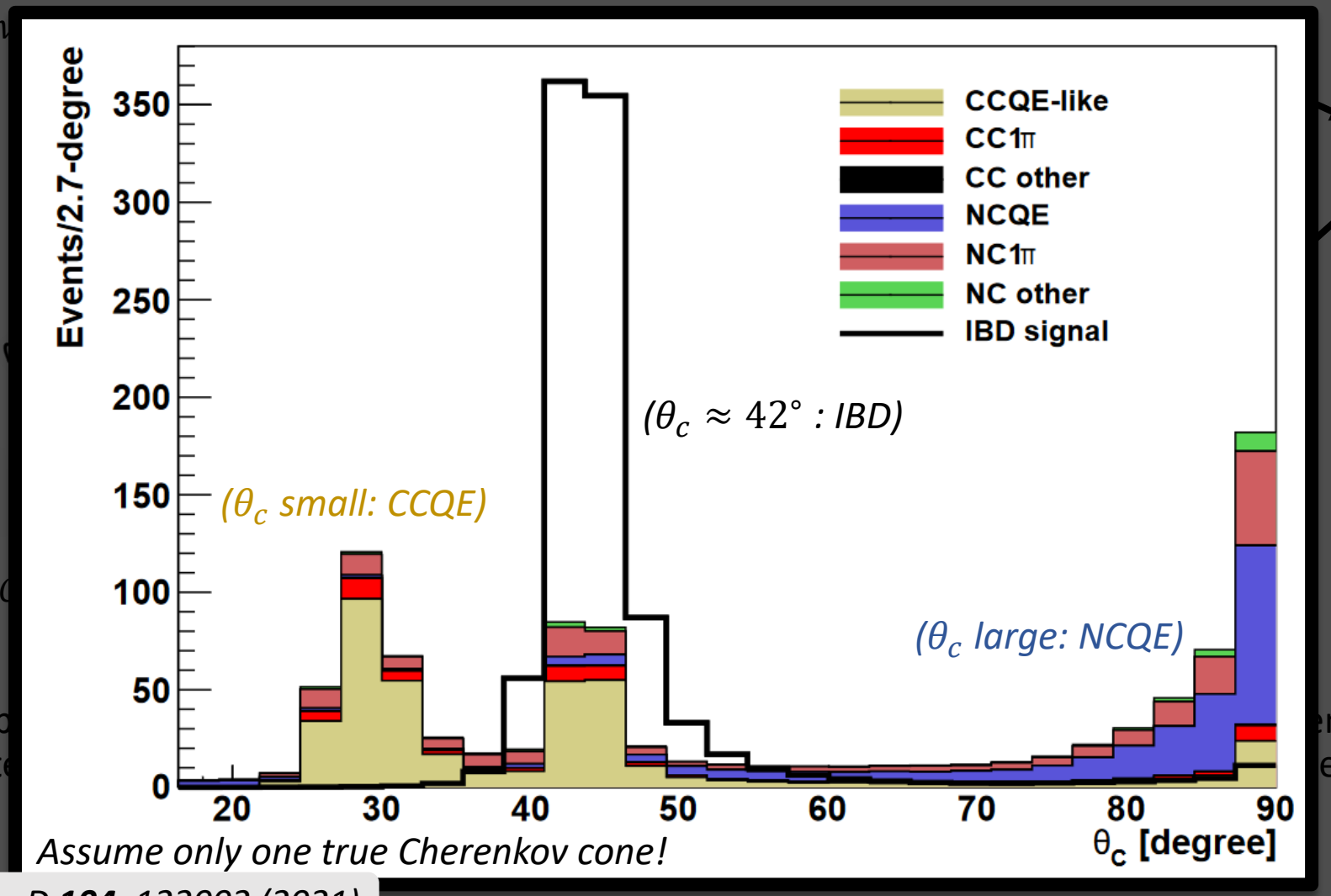


IBD (10 MeV)



Source: S. Fujita

NCQE vs DSNB prompt event topology



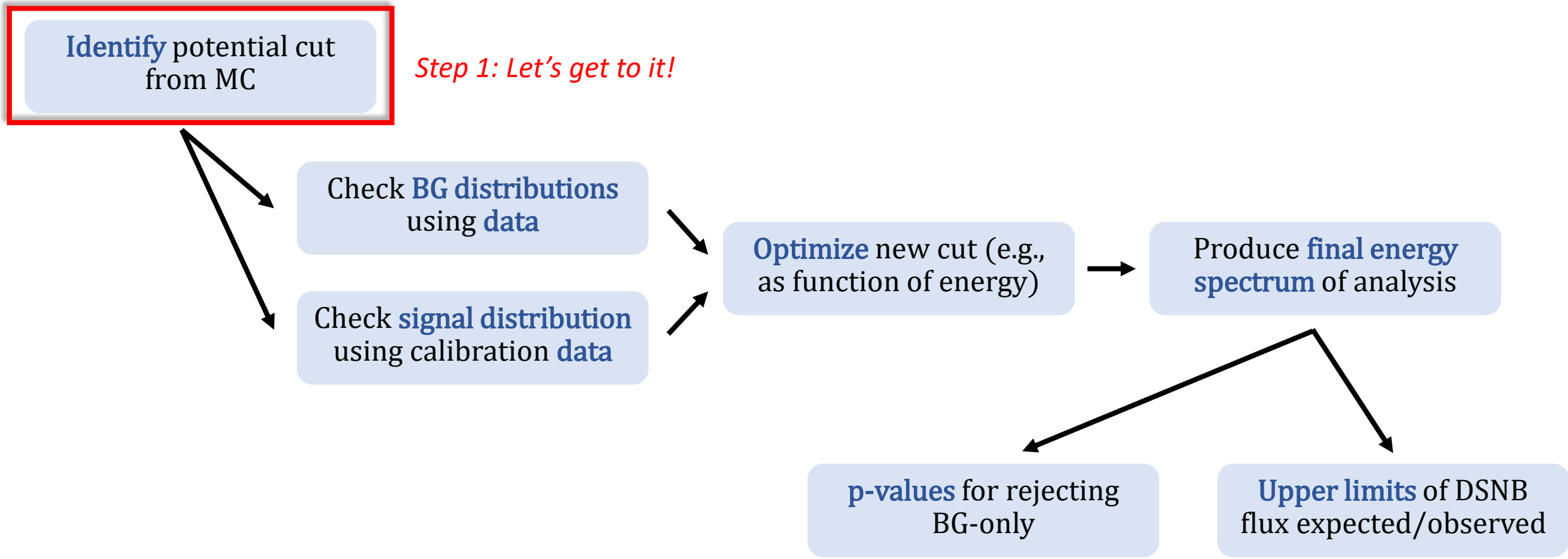
$E_{tot} \sim$ C

- **Multi-ring** p… reconstructe… …nt …ed

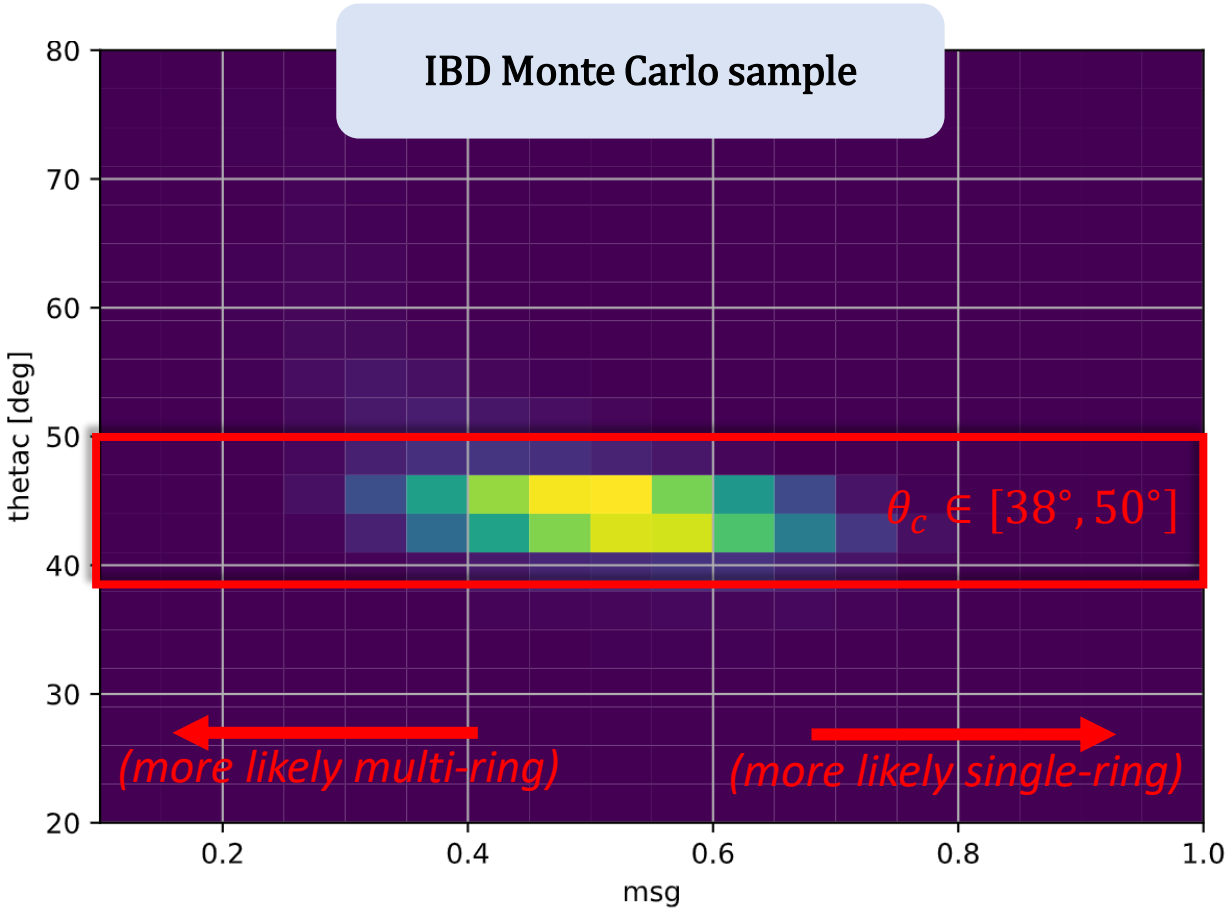
Cherenkov angle (θ_c)

*Source: Phys. Rev. D **104**, 122002 (2021)*

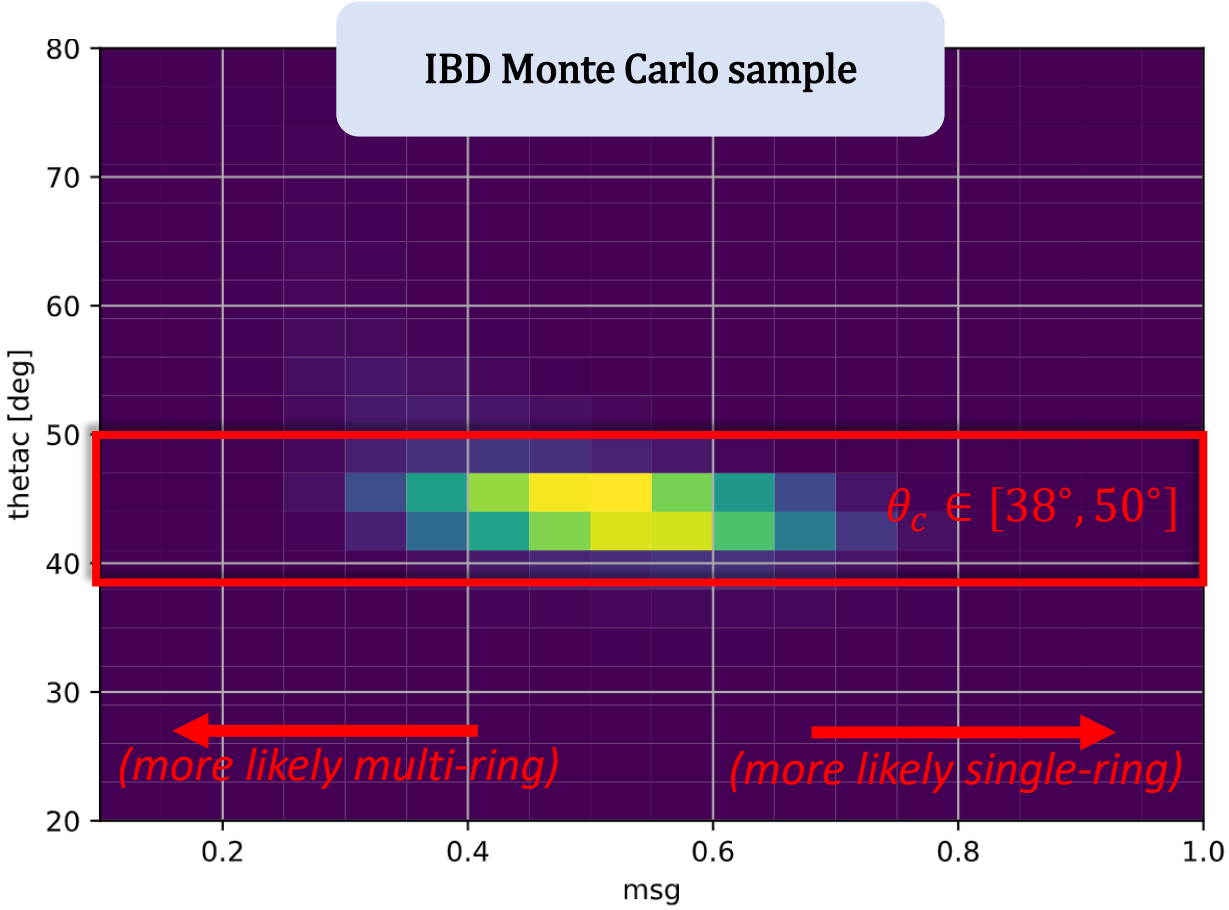
Finding, validating, optimizing, and applying new cut for DSNB

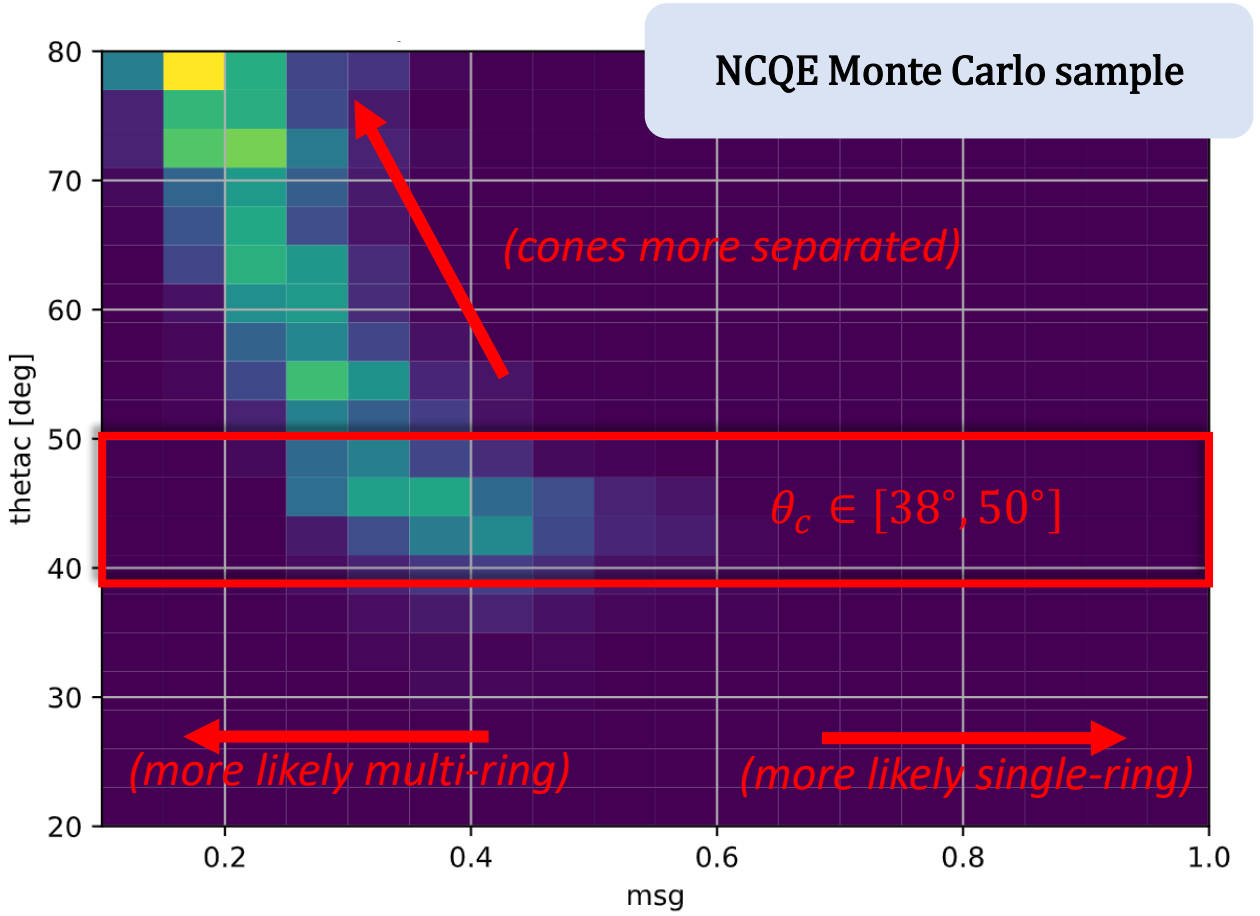


IBD versus NCQE θ_C-MSG Monte Carlo

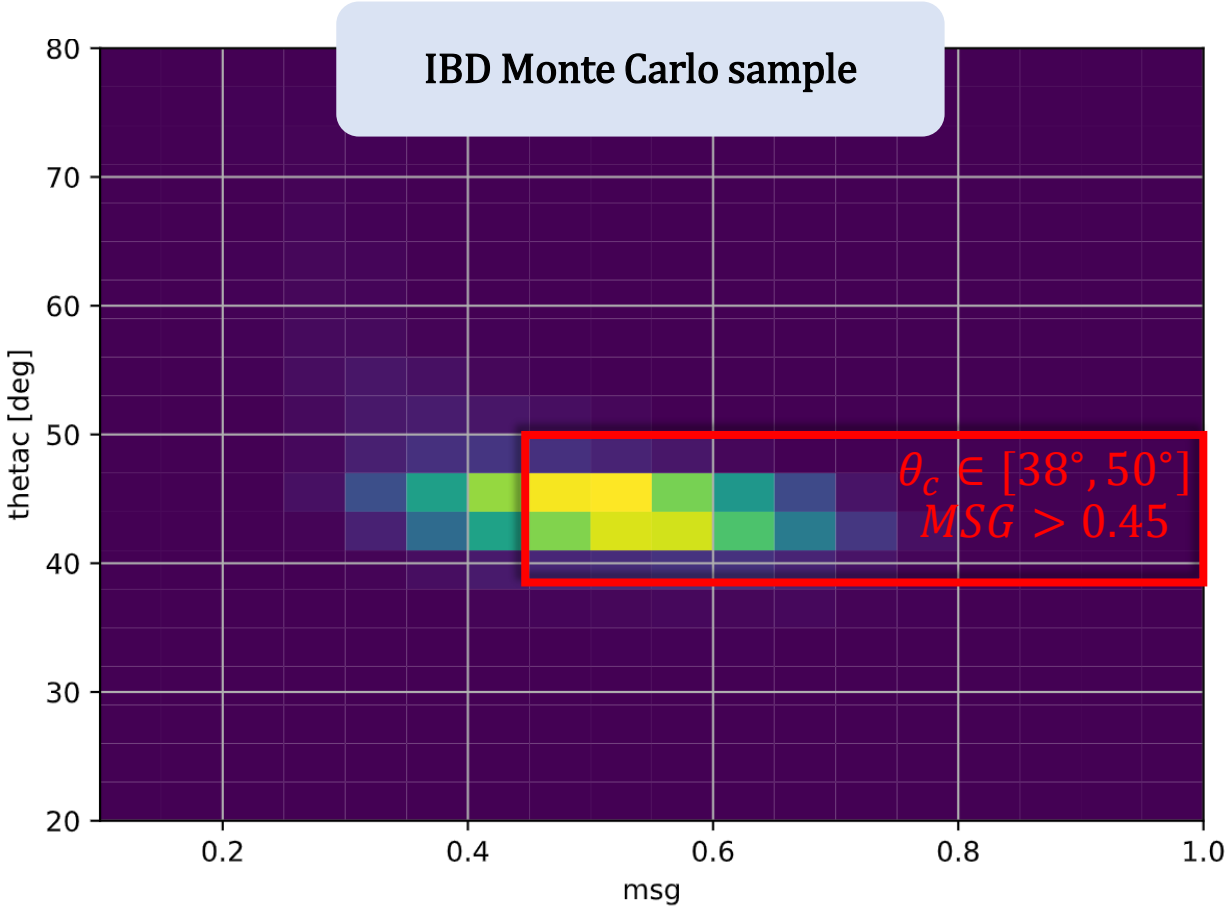


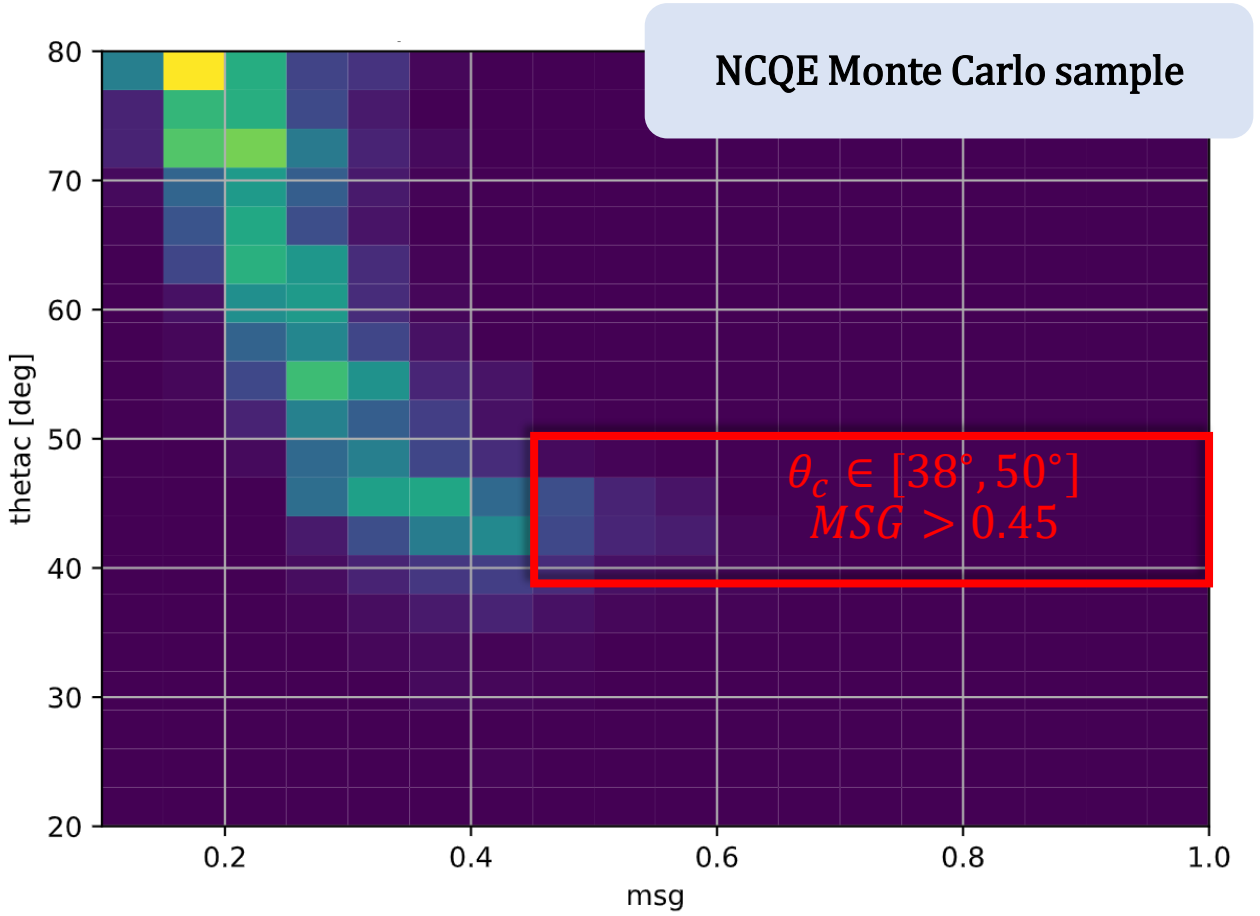
IBD versus NCQE θ_C-MSG Monte Carlo



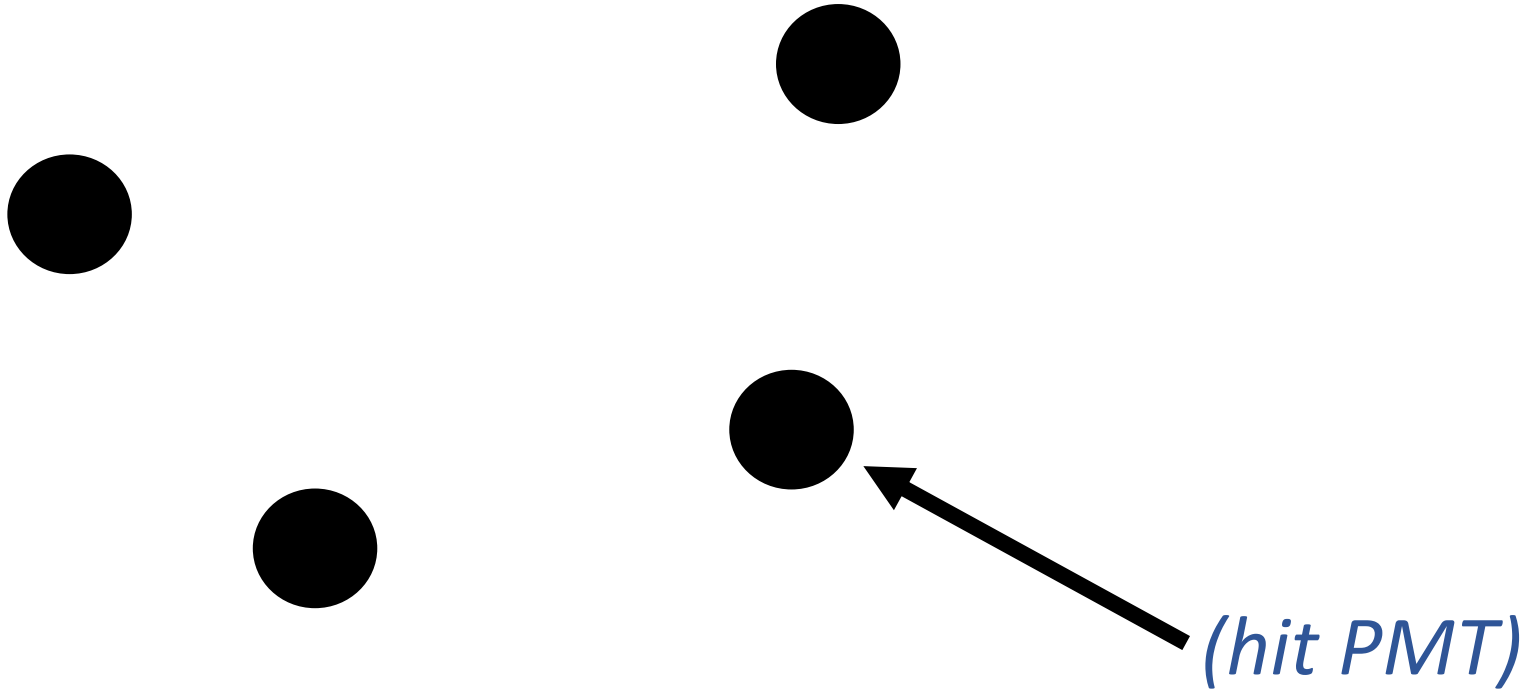


IBD versus NCQE θ_C-MSG (example cut MSG>0.45)





New cut: “multiple scattering goodness” (MSG)



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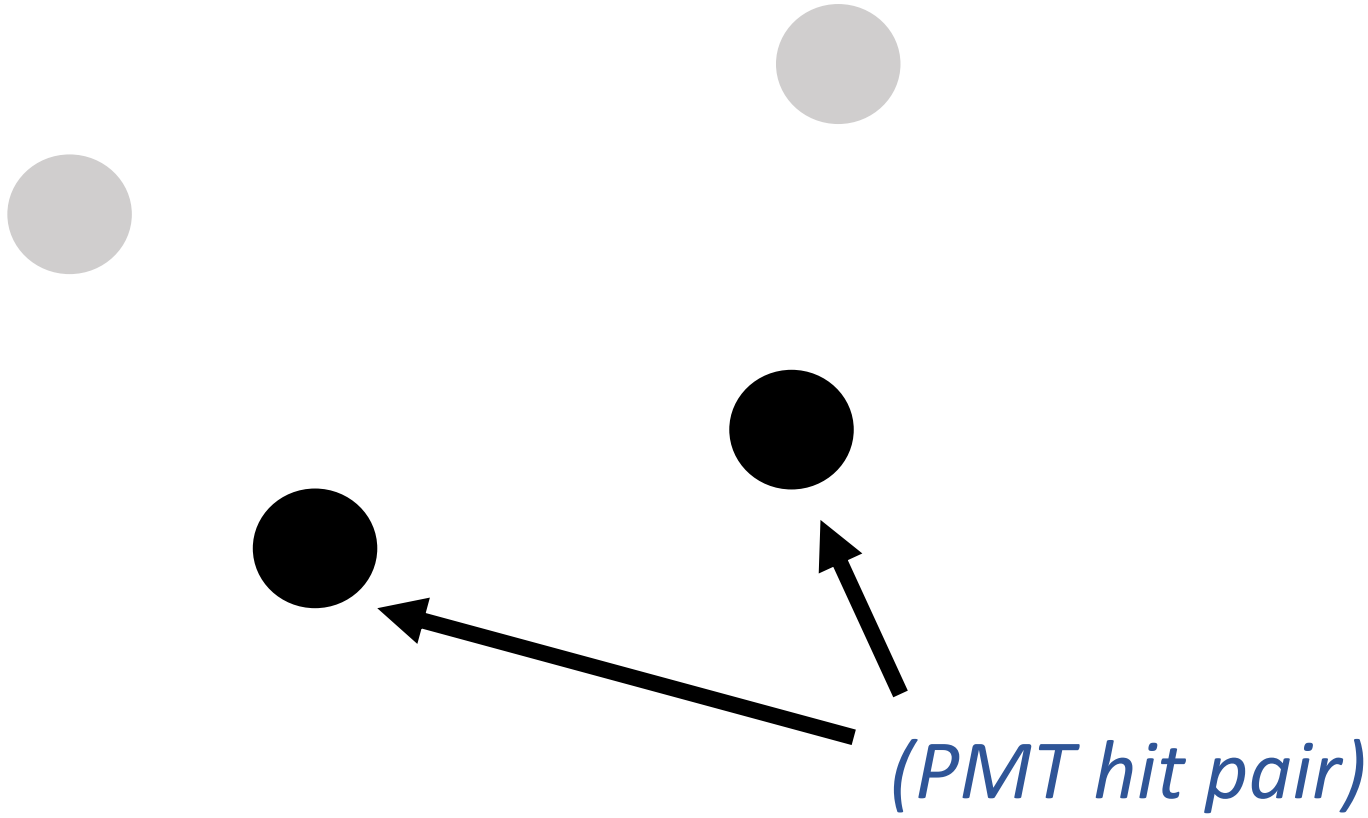

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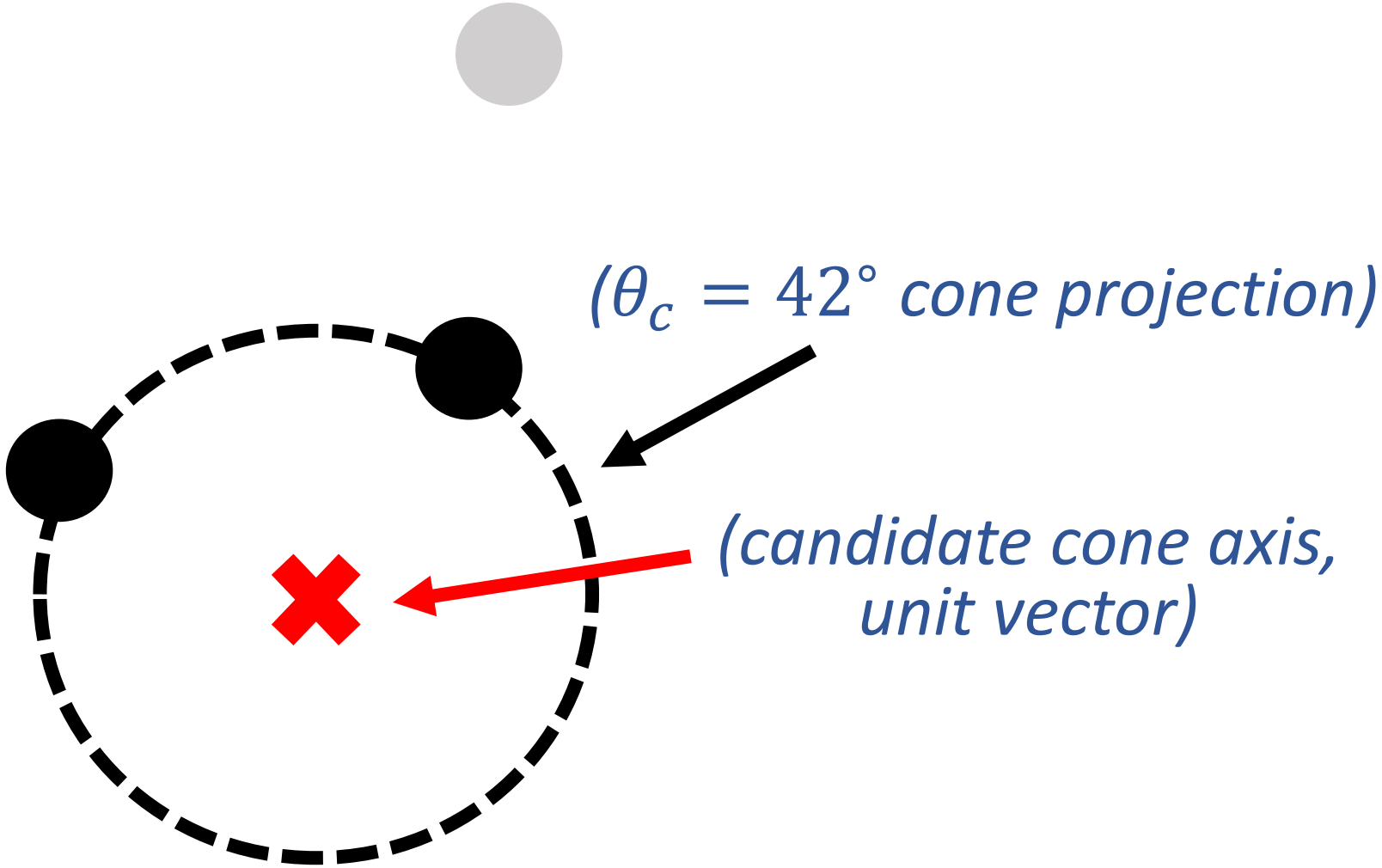

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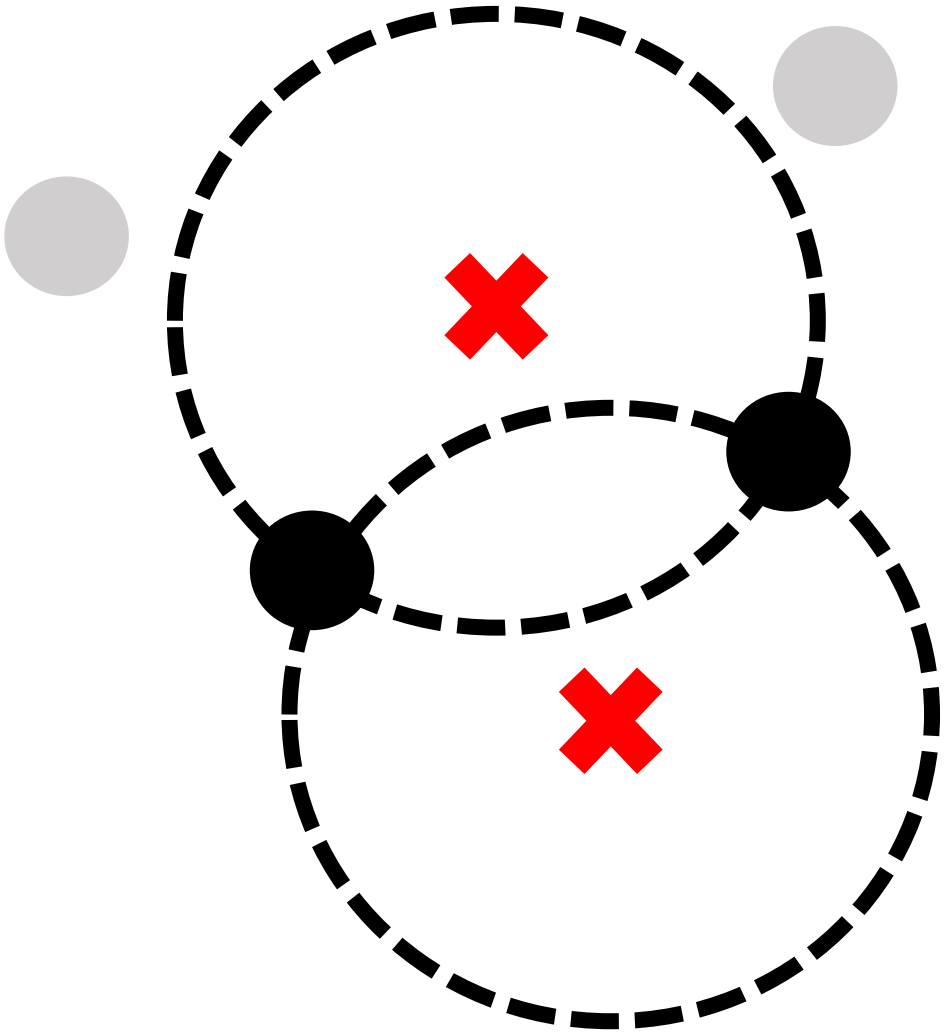

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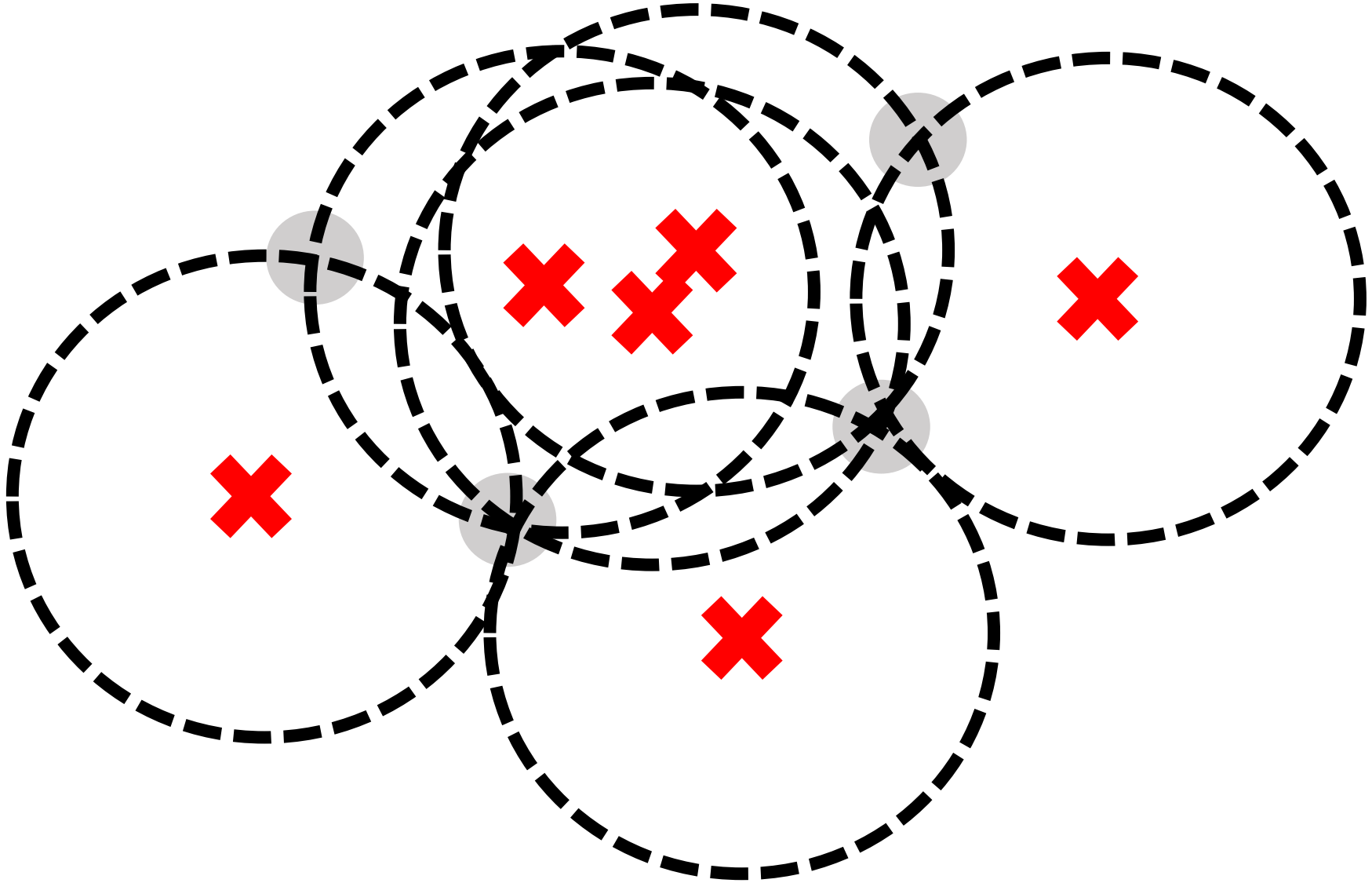

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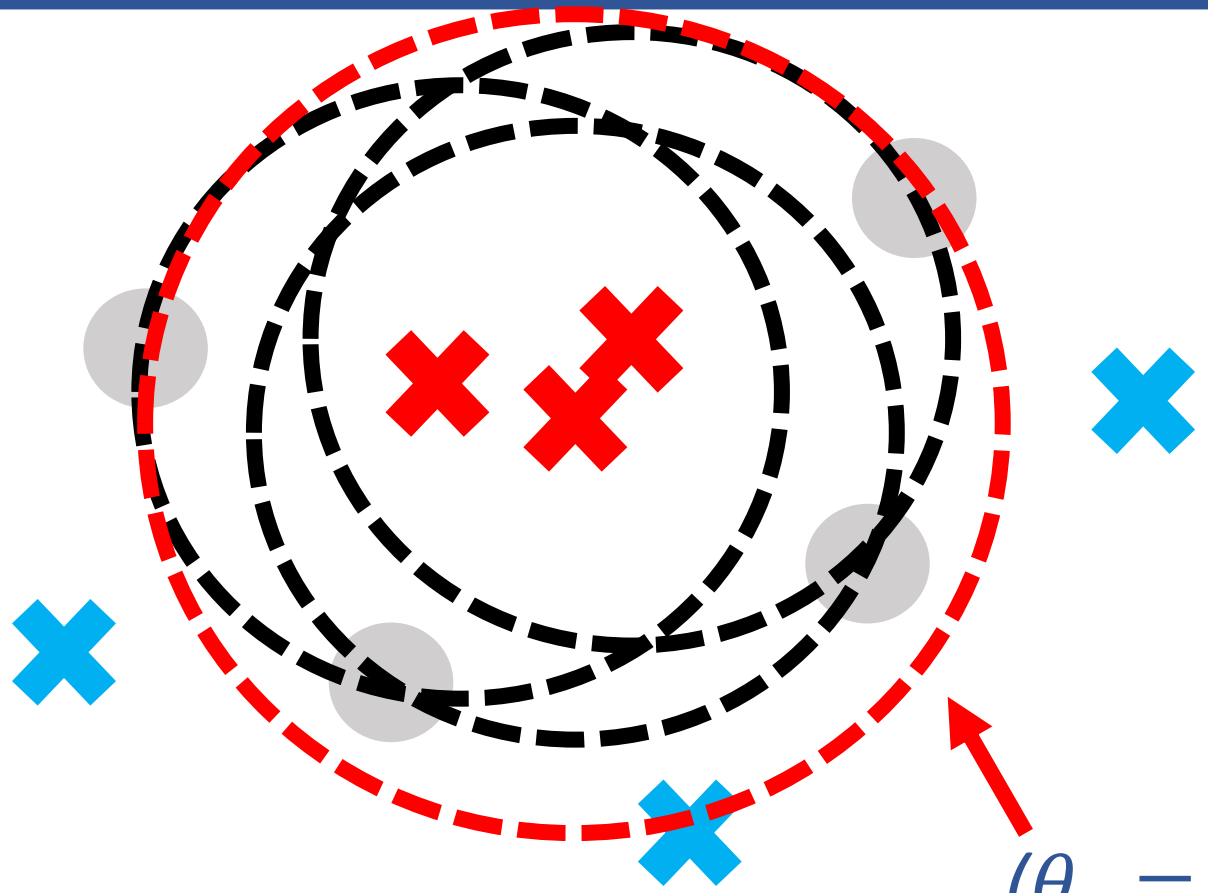
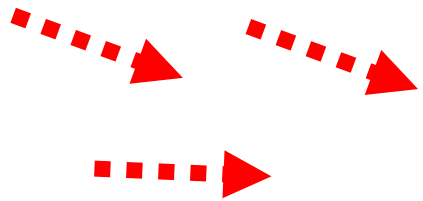
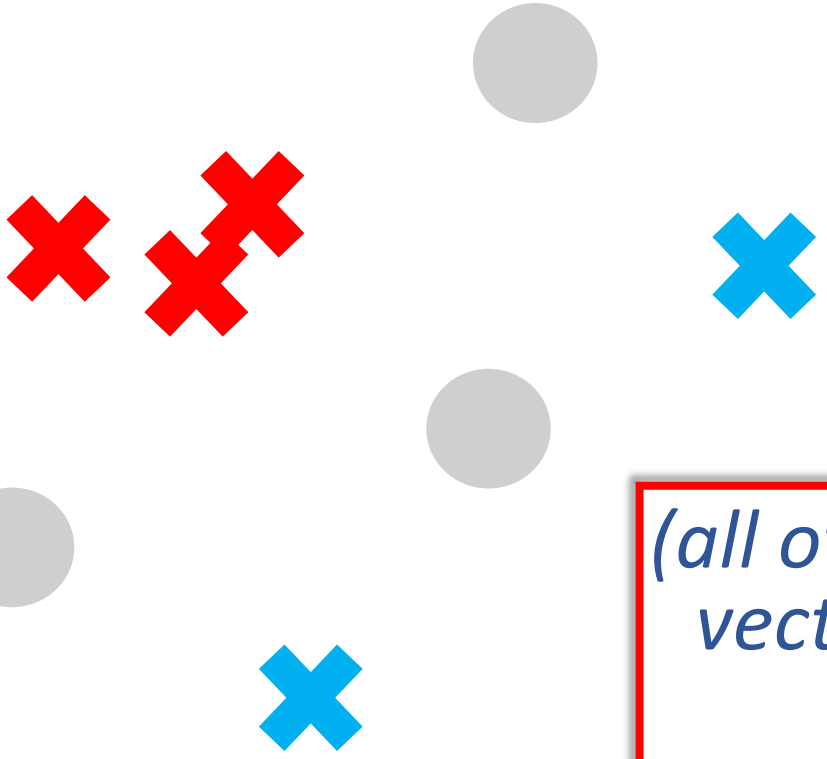


($\theta_c = 50°$ cone projection to define biggest cluster)

New cut: “multiple scattering goodness” (MSG)

(candidate unit vectors in cluster)

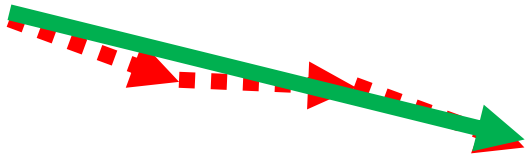


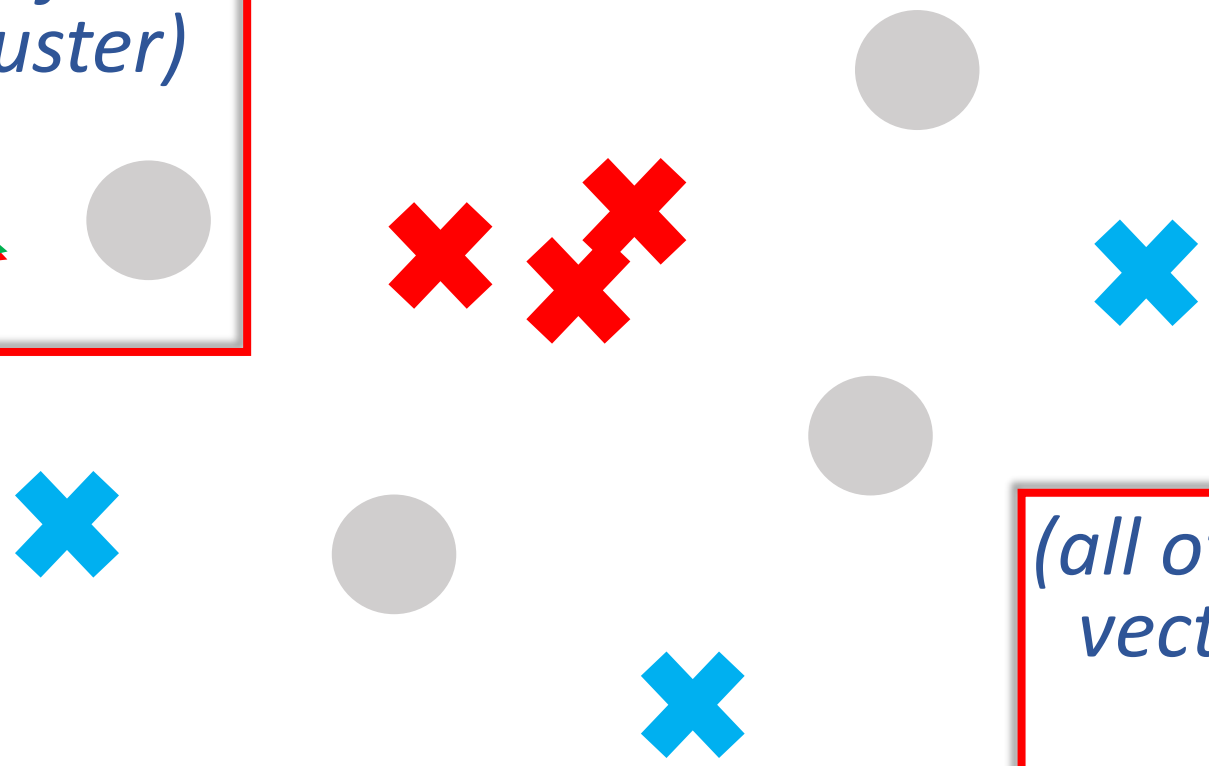


(all other candidate unit vectors not in cluster)

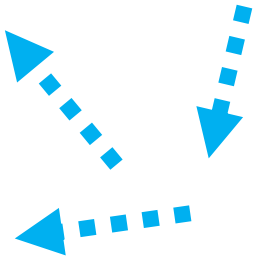
New cut: “multiple scattering goodness” (MSG)

(vector sum of candidates in cluster)





(all other candidate unit vectors not in cluster)



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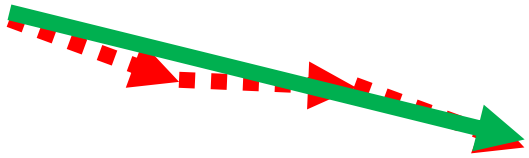

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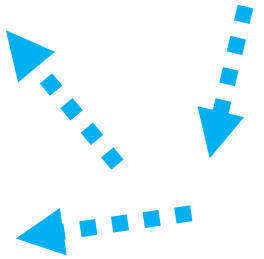
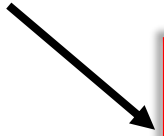


($MSG \in [0,1]$)

$$MSG = \frac{\text{length of } (\rightarrow)}{\#\text{ of } (\dashrightarrow + \dashrightarrow)}$$

Finding, validating, optimizing, and applying new cut for DSNB

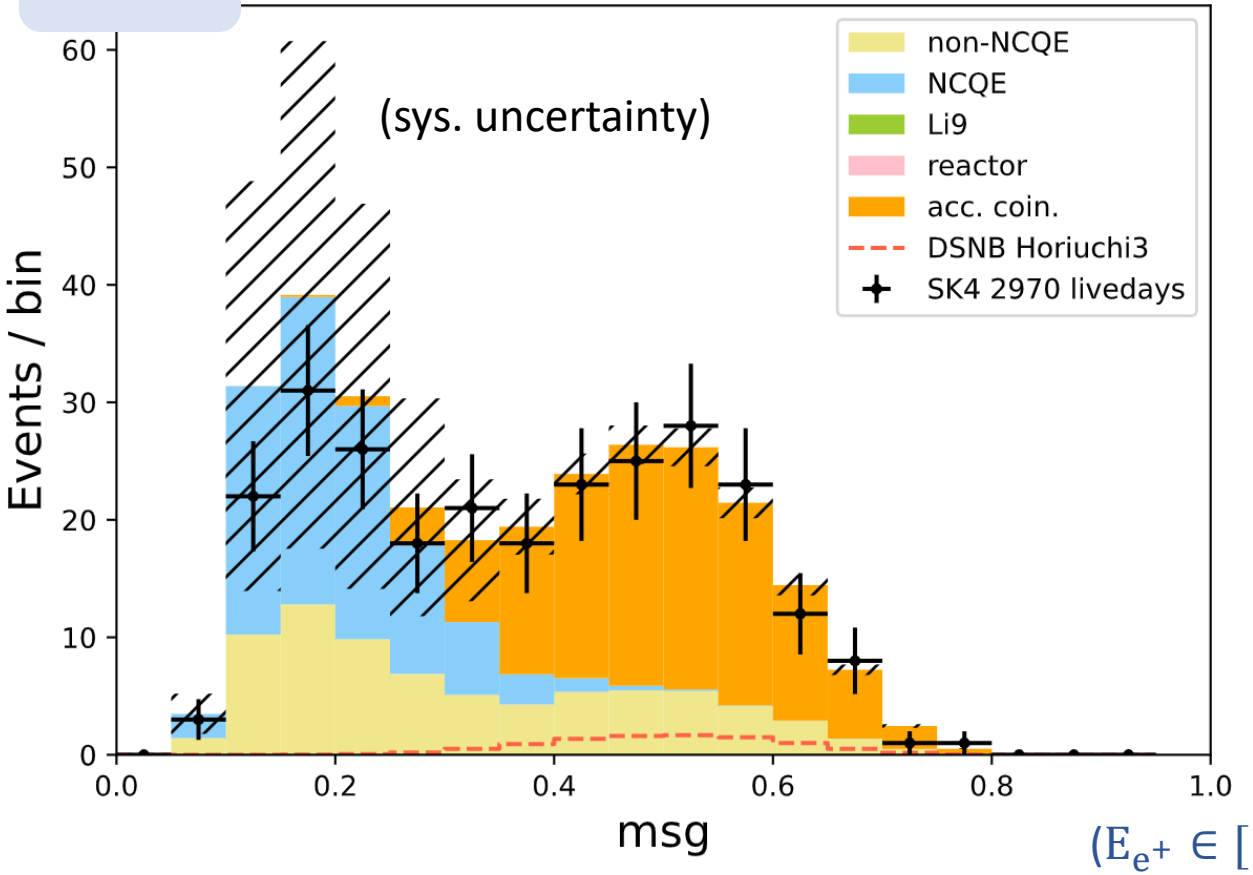
Identify potential cut from MC



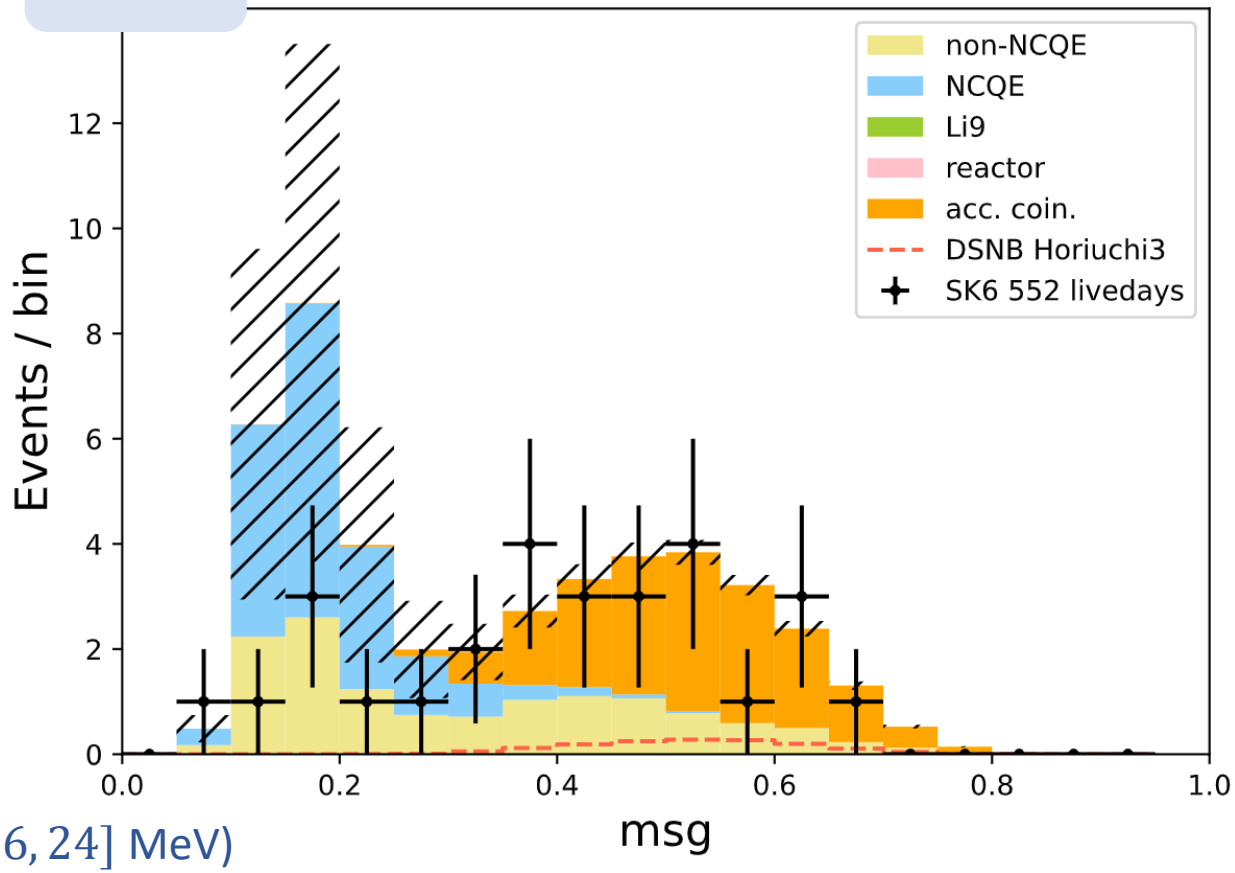
Check BG distributions using data

MSG distribution (MC-vs-data comparison)

SK4



SK6

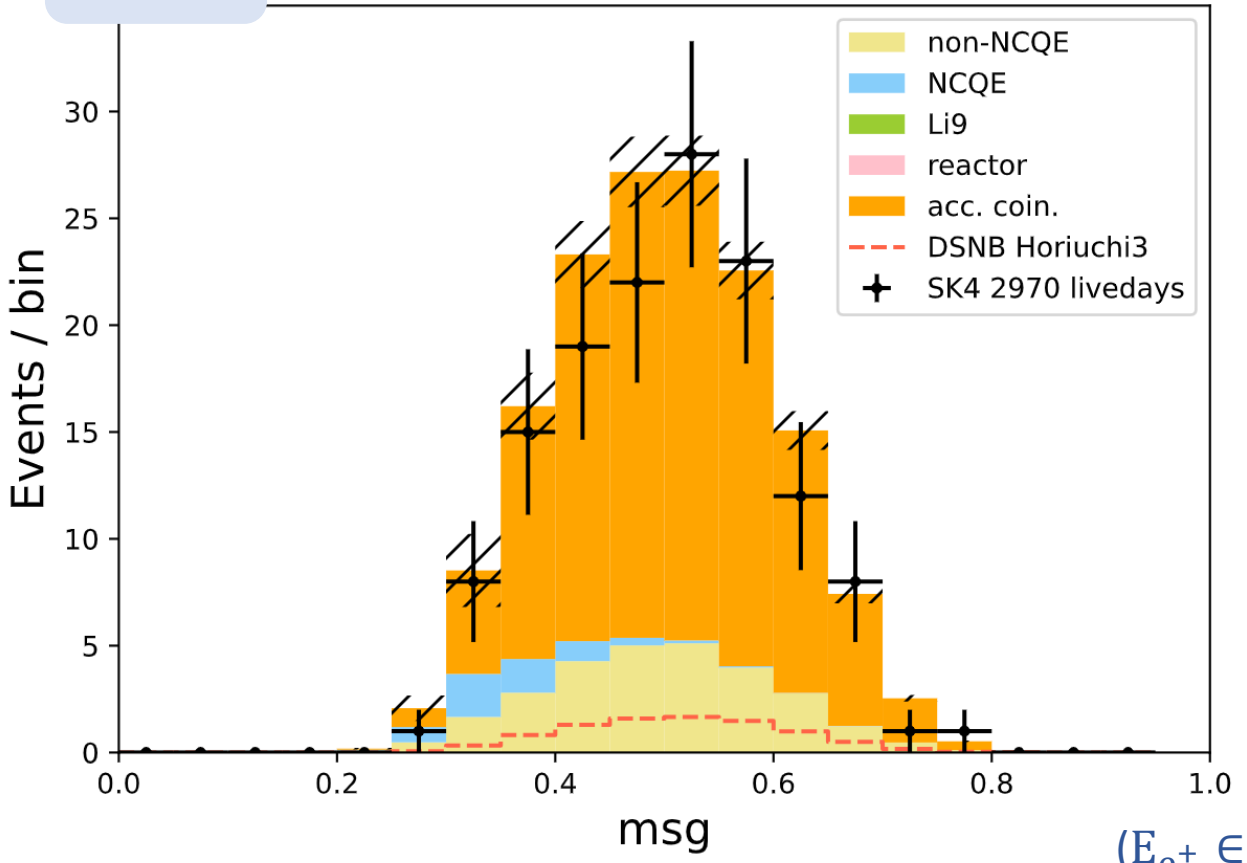


($E_{e^+} \in [16, 24]$ MeV)

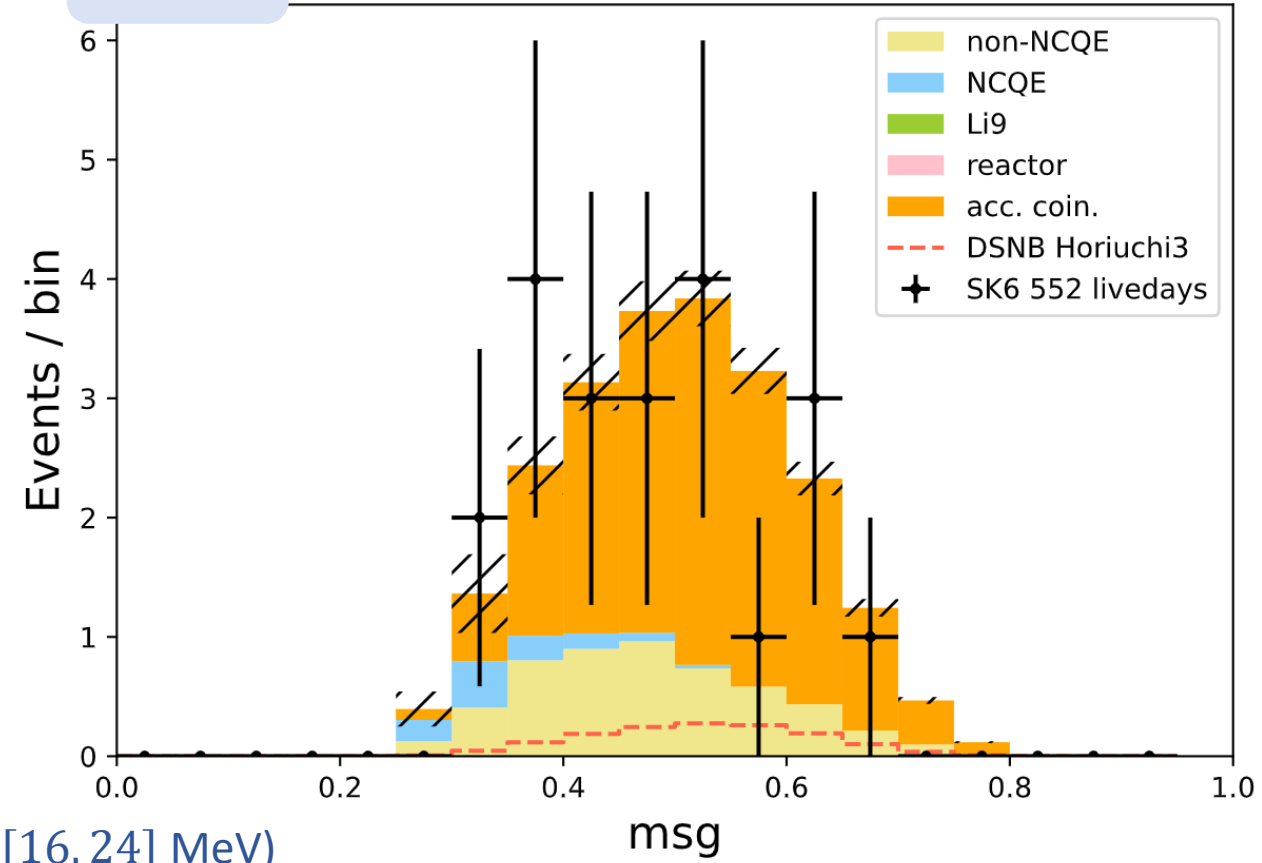
No neutron tagged, no θ_c cut

MSG distribution (MC-vs-data comparison)

SK4



SK6



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No neutron tagged, θ_c cut

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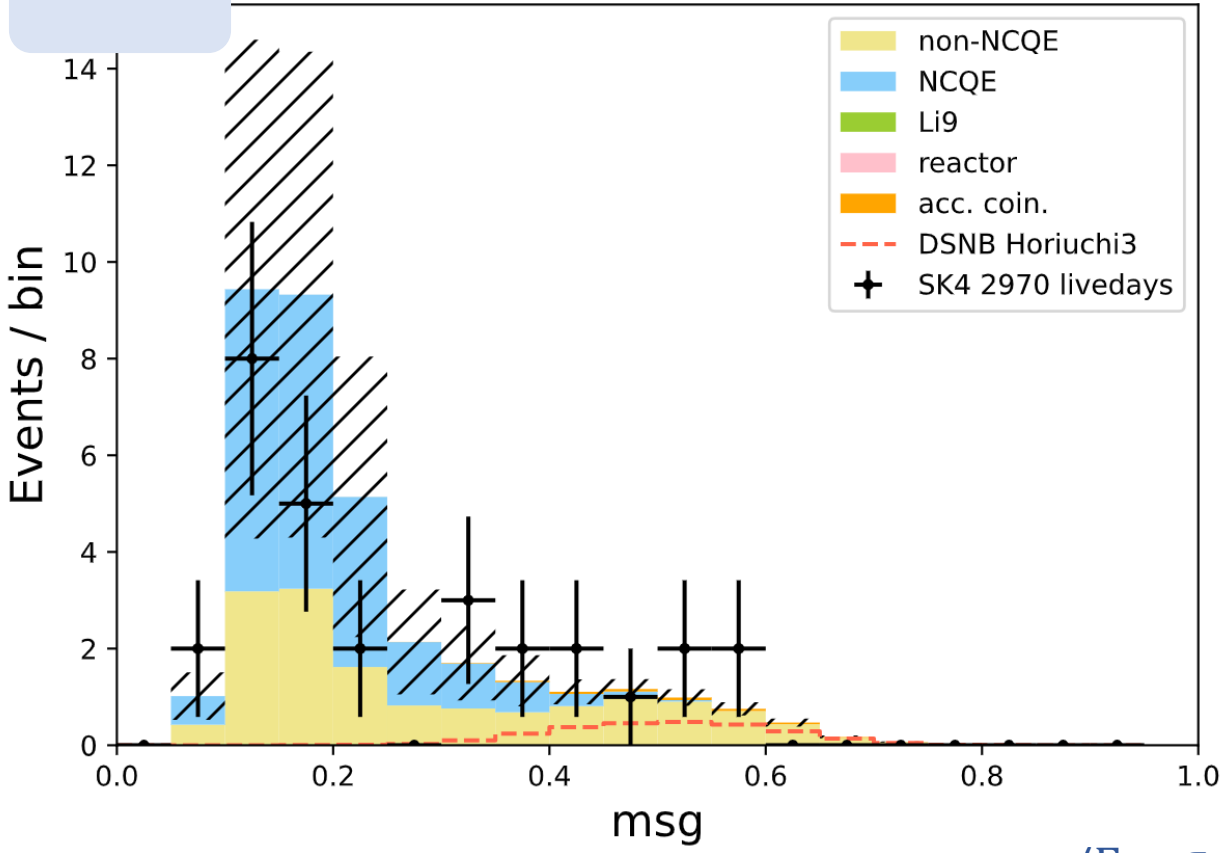
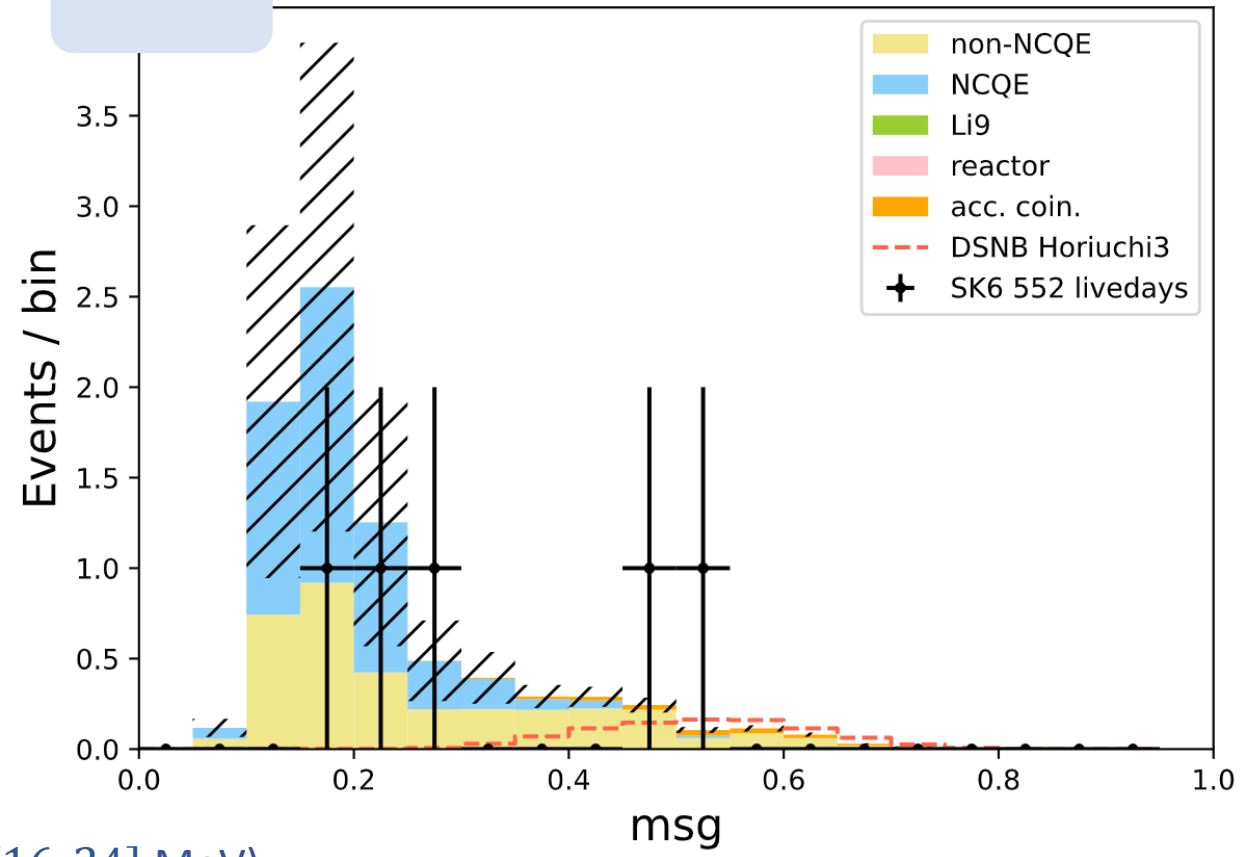


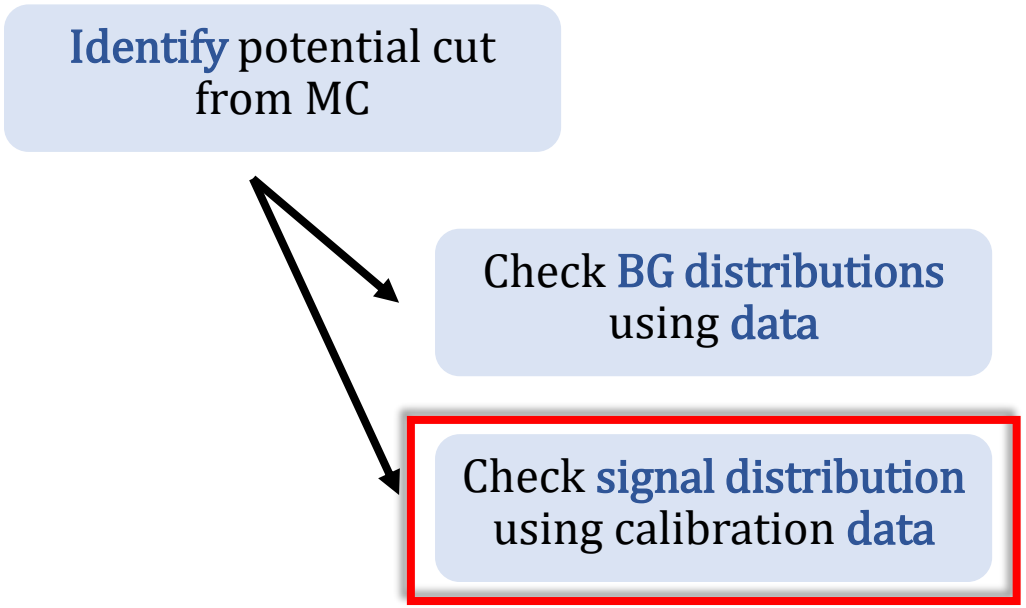
SK6



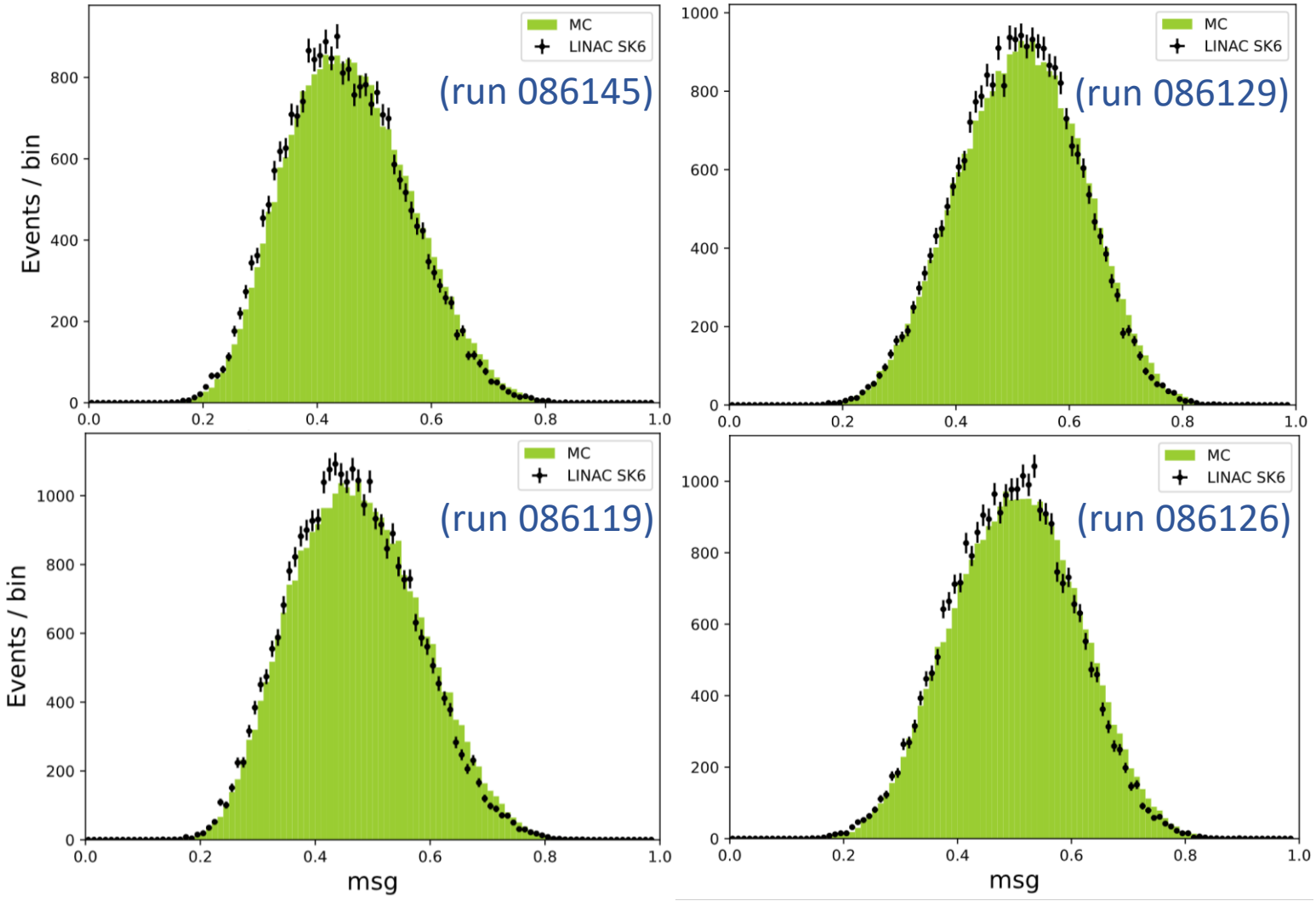
$(E_{e^+} \in [16, 24]$ MeV)

Neutron tagged, no θ_c cut

Finding, validating, optimizing, and applying new cut for DSNB



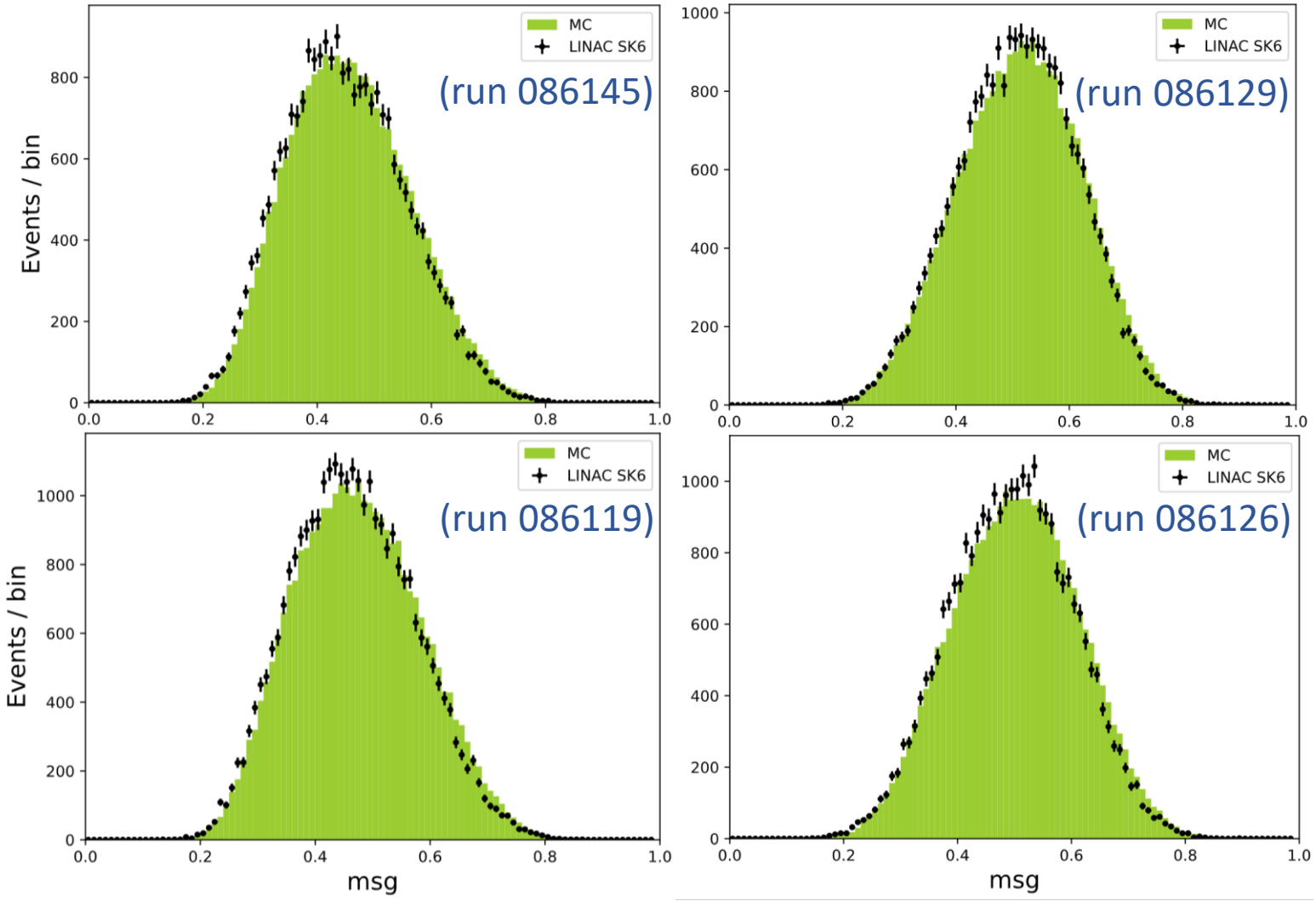
LINAC validation for MSG distributions in SK6



LINAC Run	$\langle MSG \rangle$ (data-MC)	$\sqrt{Var(MSG)}$ (data-MC)
086145 (~6 MeV)	-2.0%	-1.6%
086119 (~9 MeV)	-1.8%	-2.9%
086126 (~13 MeV)	-1.6%	-2.7%
086129 (~17 MeV)	-0.93%	-2.9%

- SK6 LINAC **MSG data/MC discrepancies** are on the order of **percent to sub-percent.**

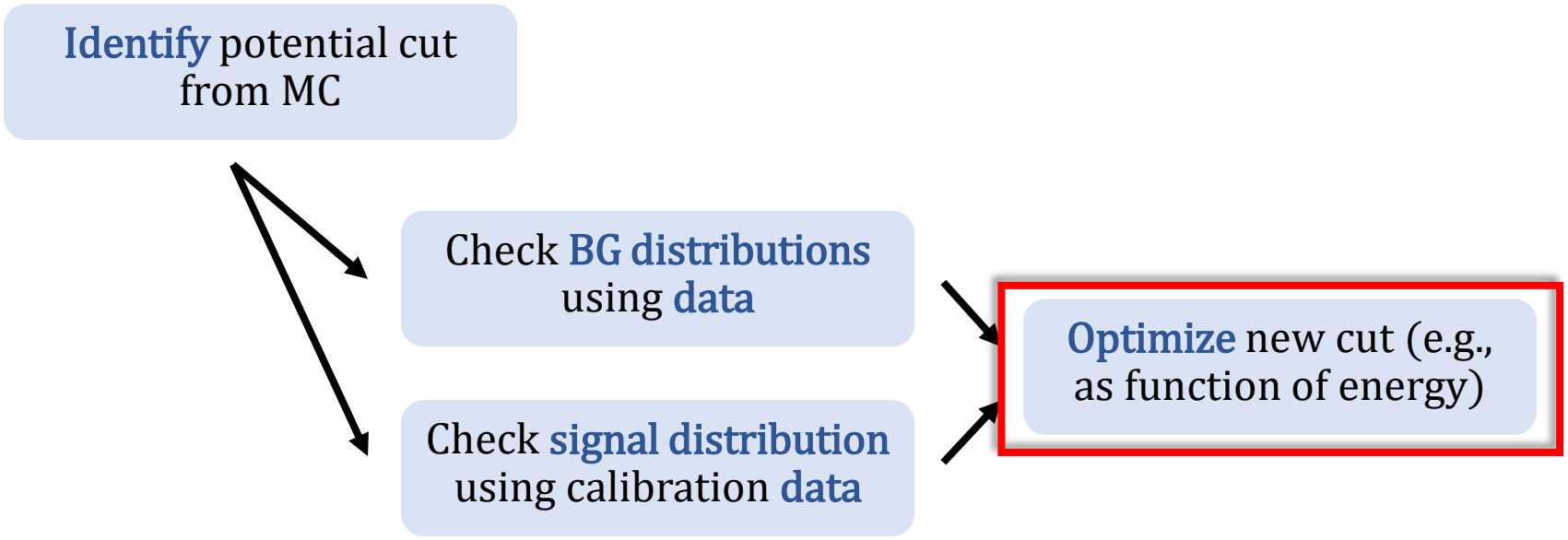
LINAC validation for MSG distributions in SK6



LINAC Run	ϵ_{data}, ϵ_{MC} (MSG>0.45)	$\frac{\epsilon_{data} - \epsilon_{MC}}{\epsilon_{data}}$
086145 (~6 MeV)	0.474, 0.506	-6.8%
086119 (~9 MeV)	0.541, 0.568	-5.0%
086126 (~13 MeV)	0.657, 0.676	-2.9%
086129 (~17 MeV)	0.705, 0.713	-1.1%

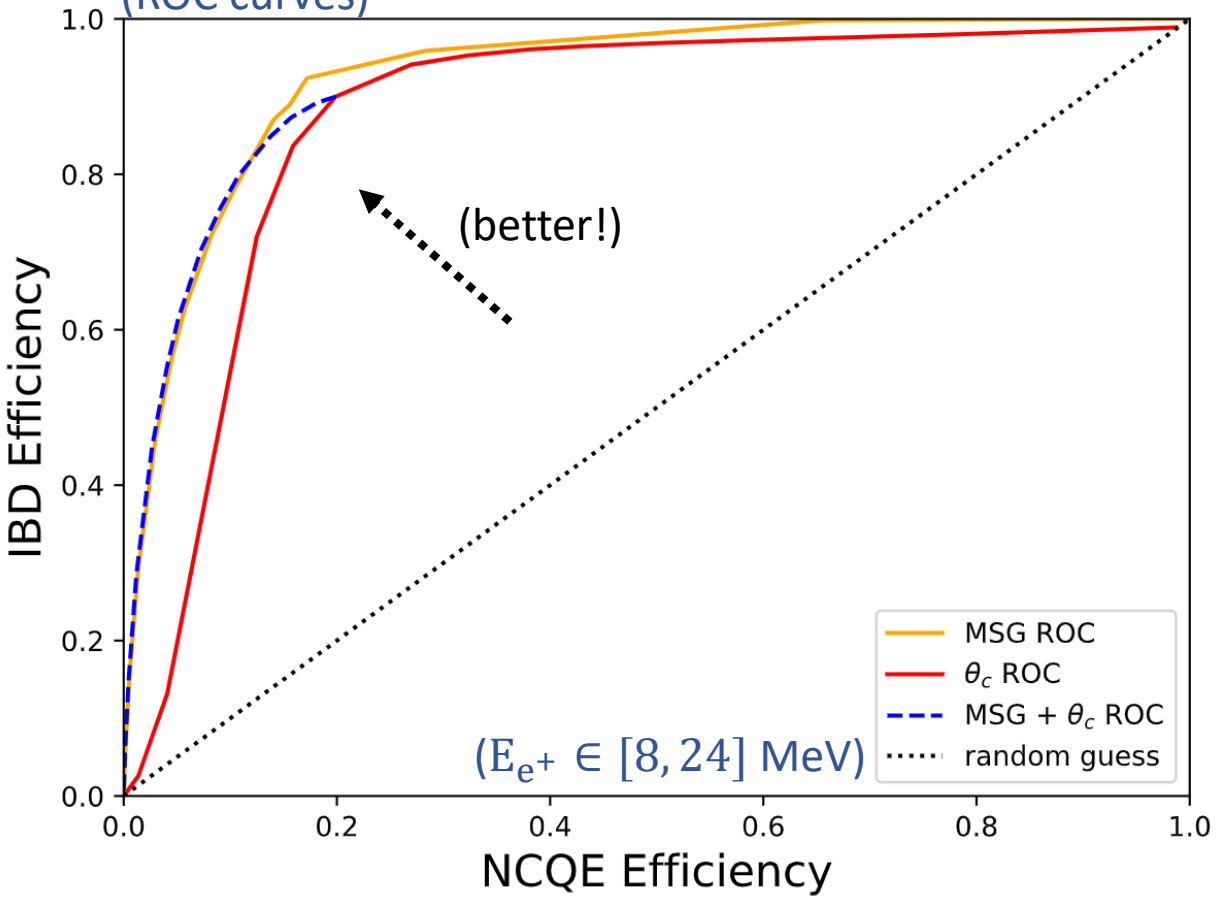
- **SK6 IBD cut efficiencies** have a **systematic uncertainty** of **a few percent**.

Finding, validating, optimizing, and applying new cut for DSNB



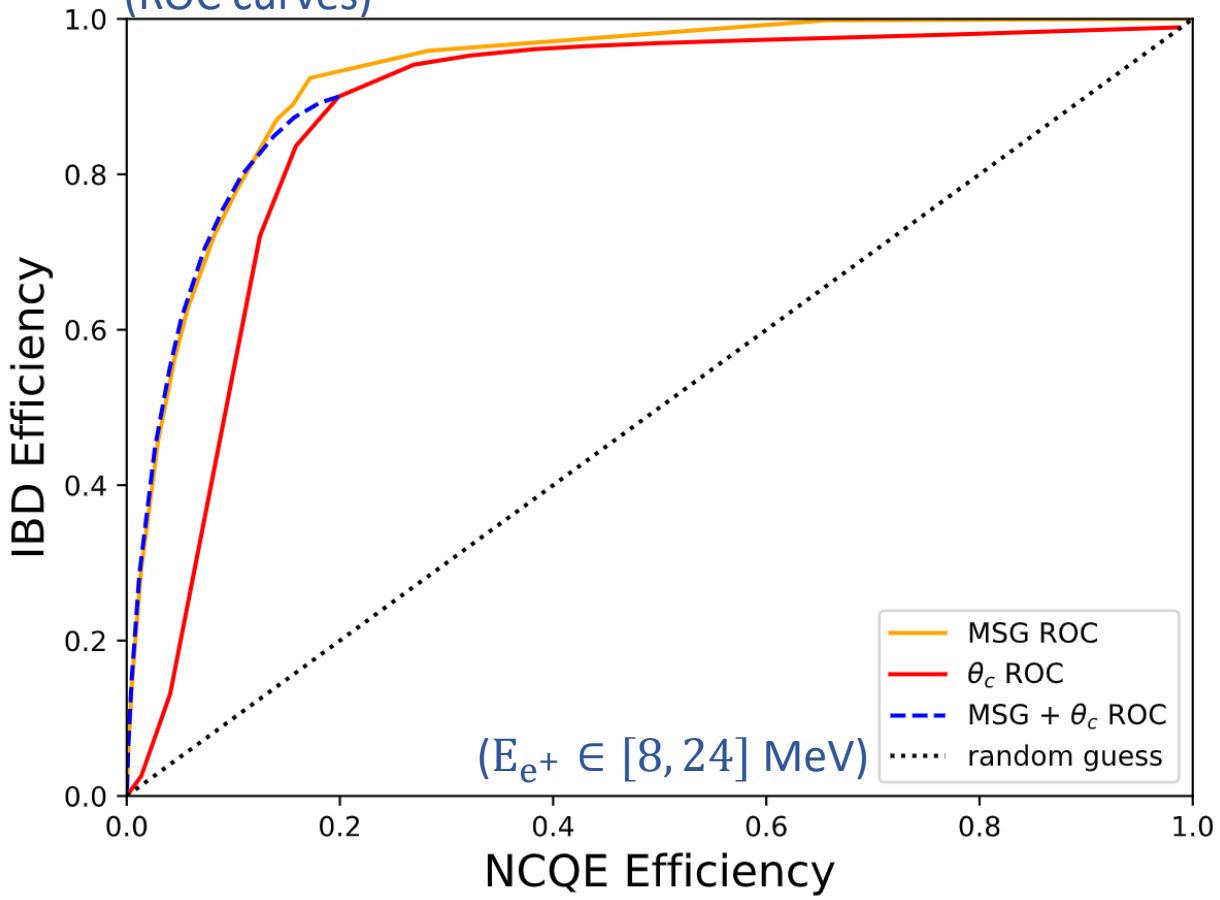
SK6 signal efficiencies after MSG cut optimization

(ROC curves)



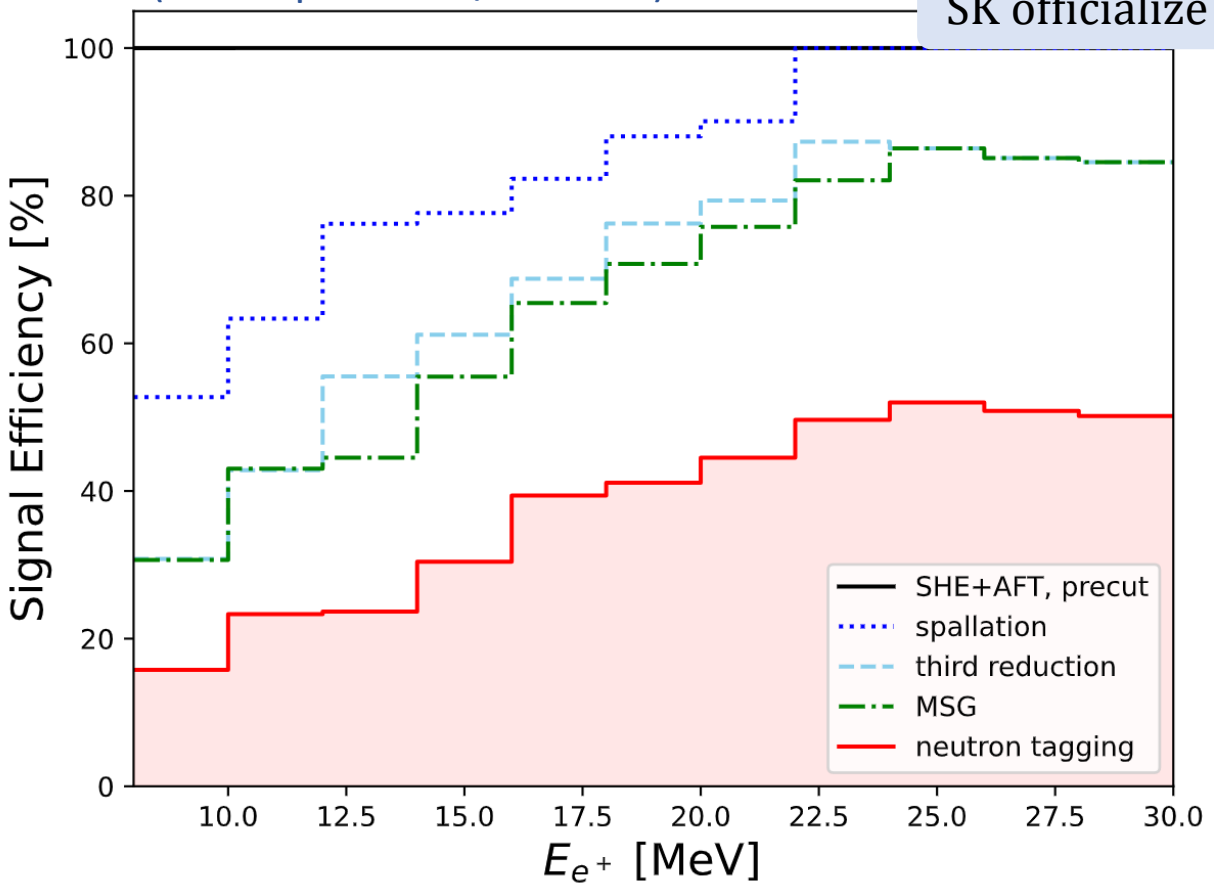
SK6 signal efficiencies after MSG cut optimization

(ROC curves)



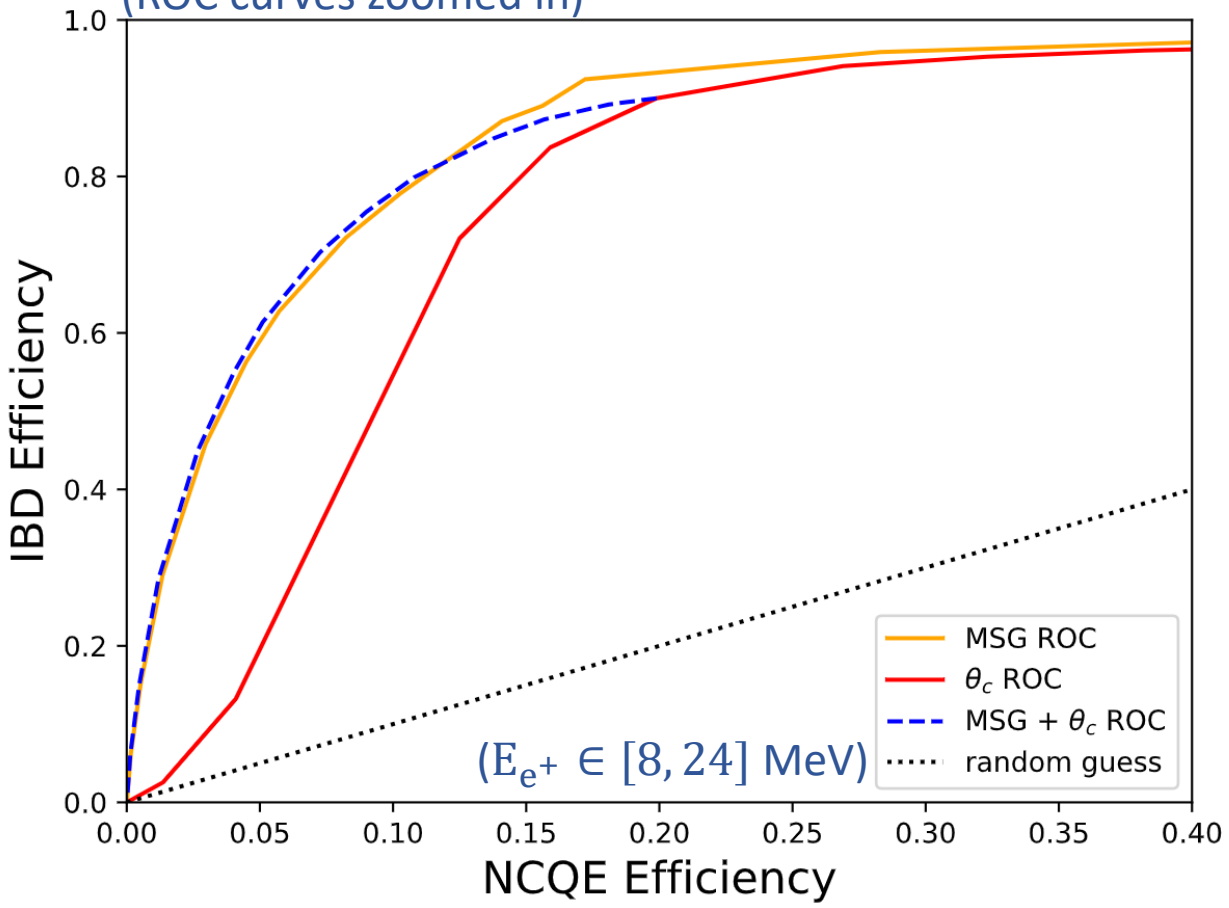
(MSG optimize $S/\sqrt{S+B}$)

SK officialize



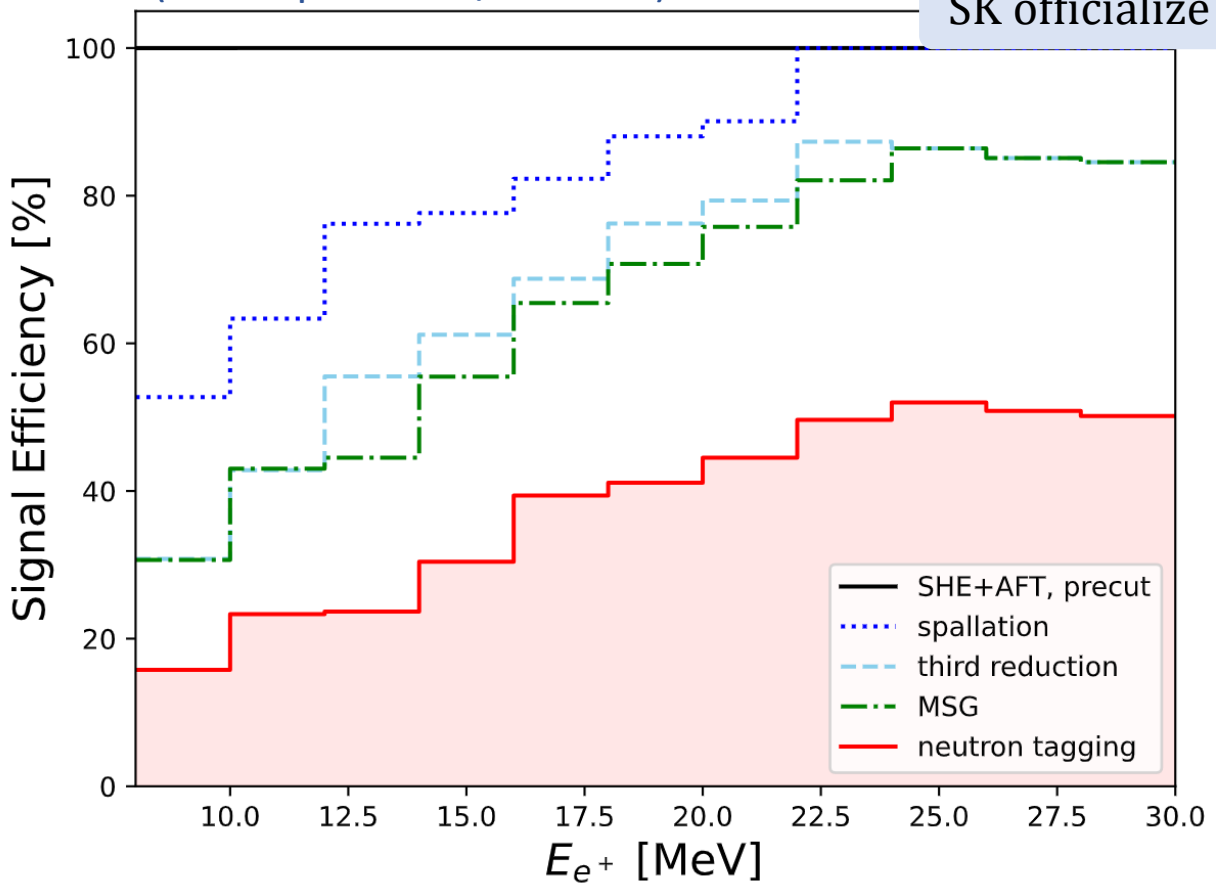
SK6 signal efficiencies after MSG cut optimization

(ROC curves zoomed in)



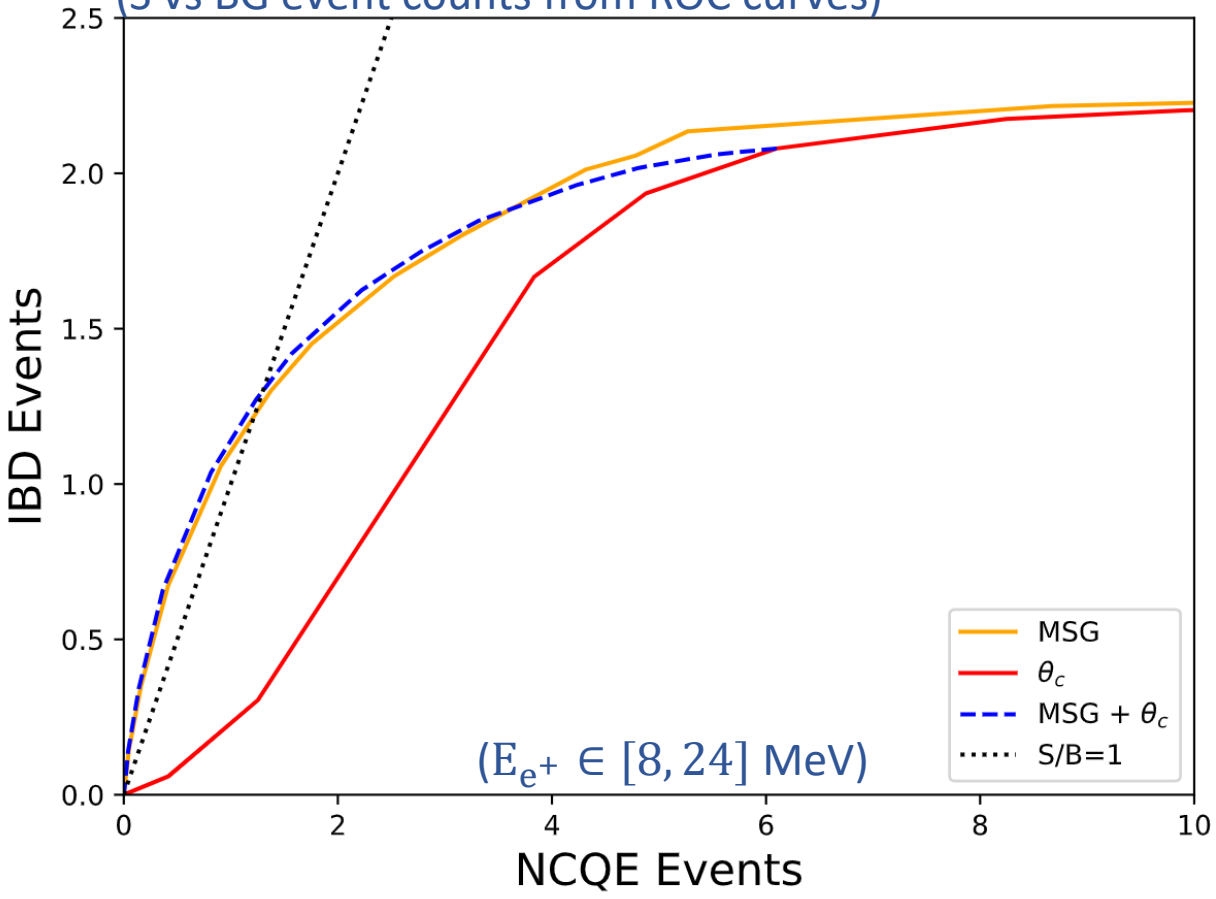
(MSG optimize $S/\sqrt{S+B}$)

SK officialize



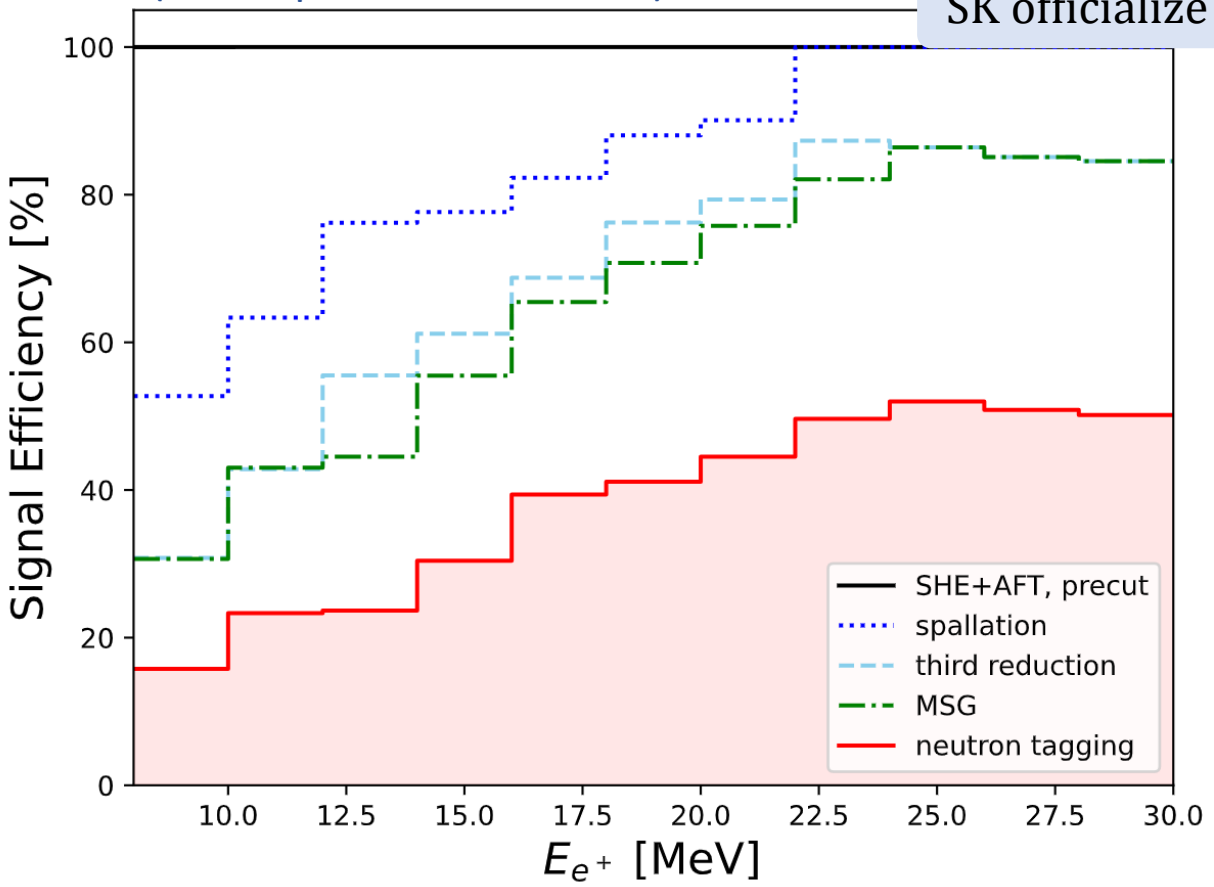
SK6 signal efficiencies after MSG cut optimization

(S vs BG event counts from ROC curves)

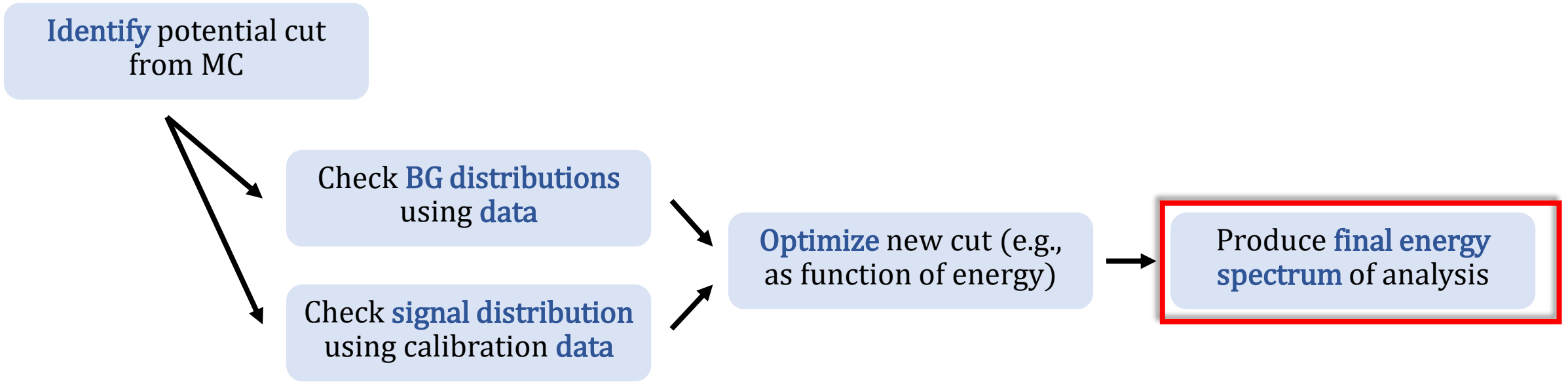


(MSG optimize $S/\sqrt{S+B}$)

SK officialize



Finding, validating, optimizing, and applying new cut for DSNB

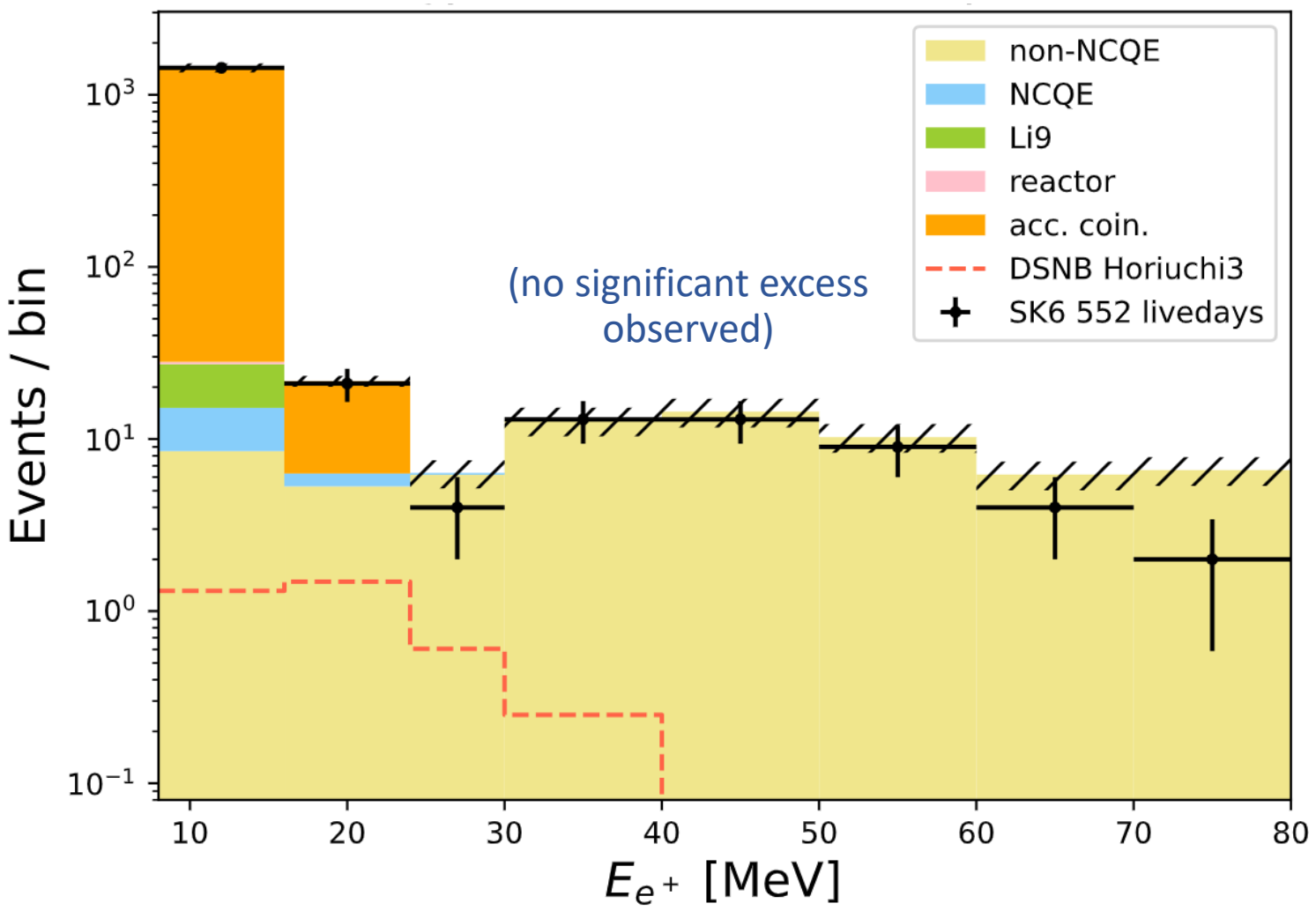


Recap: Energy spectrum (552.2 days SK6)

$\theta_c \in [38^\circ, 50^\circ]$

BDT neutron tagging

E_{e^+} [MeV]	p-value (BG-only)
[8, 16]	0.50
[16, 24]	0.53
[24, 30]	0.85
[30, 40]	0.50
[40, 50]	0.64
[50, 60]	0.66
[60, 70]	0.84
[70, 80]	0.98

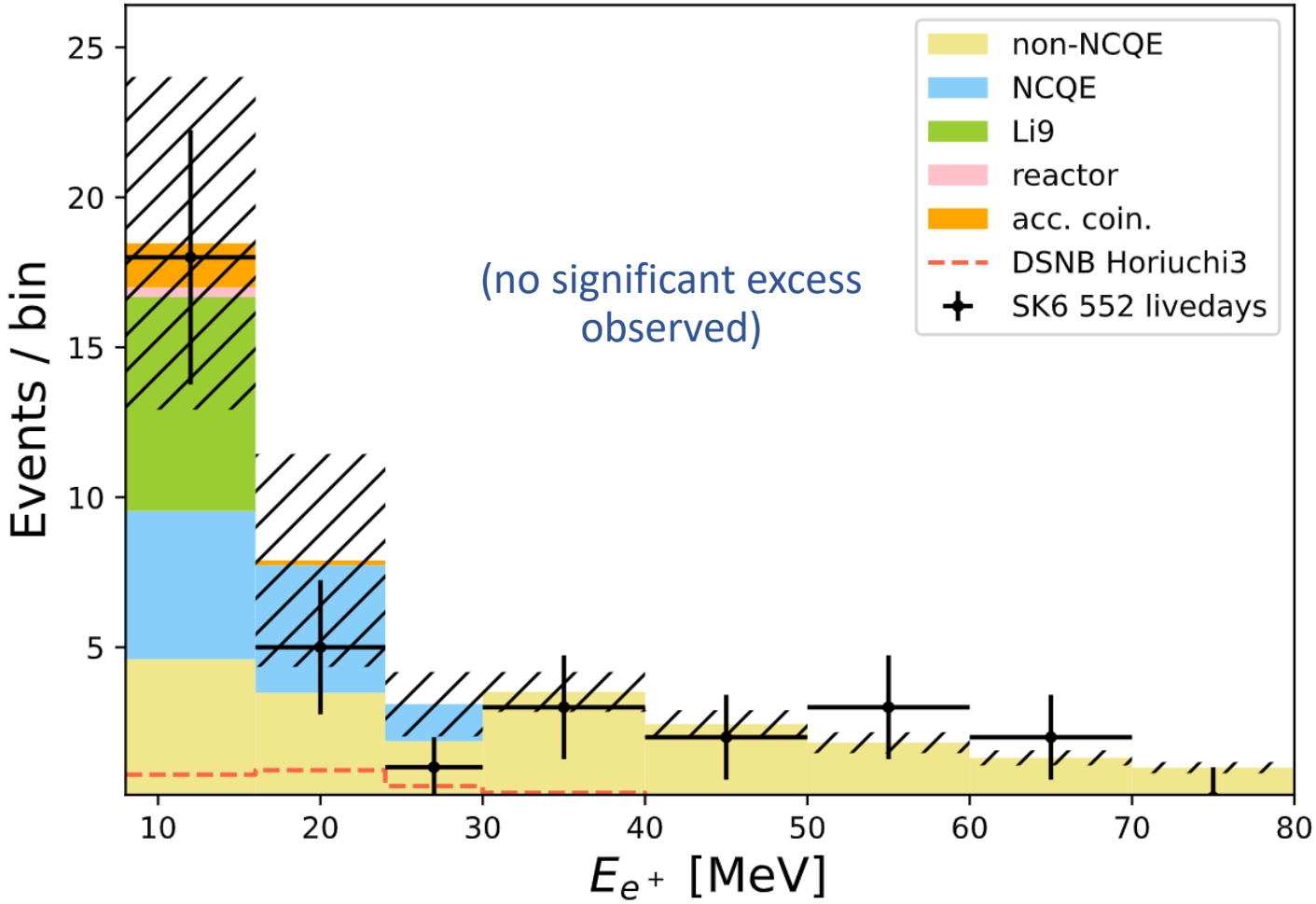


Recap: Energy spectrum (552.2 days SK6)

$\theta_c \in [38^\circ, 50^\circ]$

BDT neutron tagging

E_{e^+} [MeV]	p-value (BG-only)
[8, 16]	0.53
[16, 24]	0.76
[24, 30]	0.92
[30, 40]	0.66
[40, 50]	0.69
[50, 60]	0.27
[60, 70]	0.37
[70, 80]	1.0

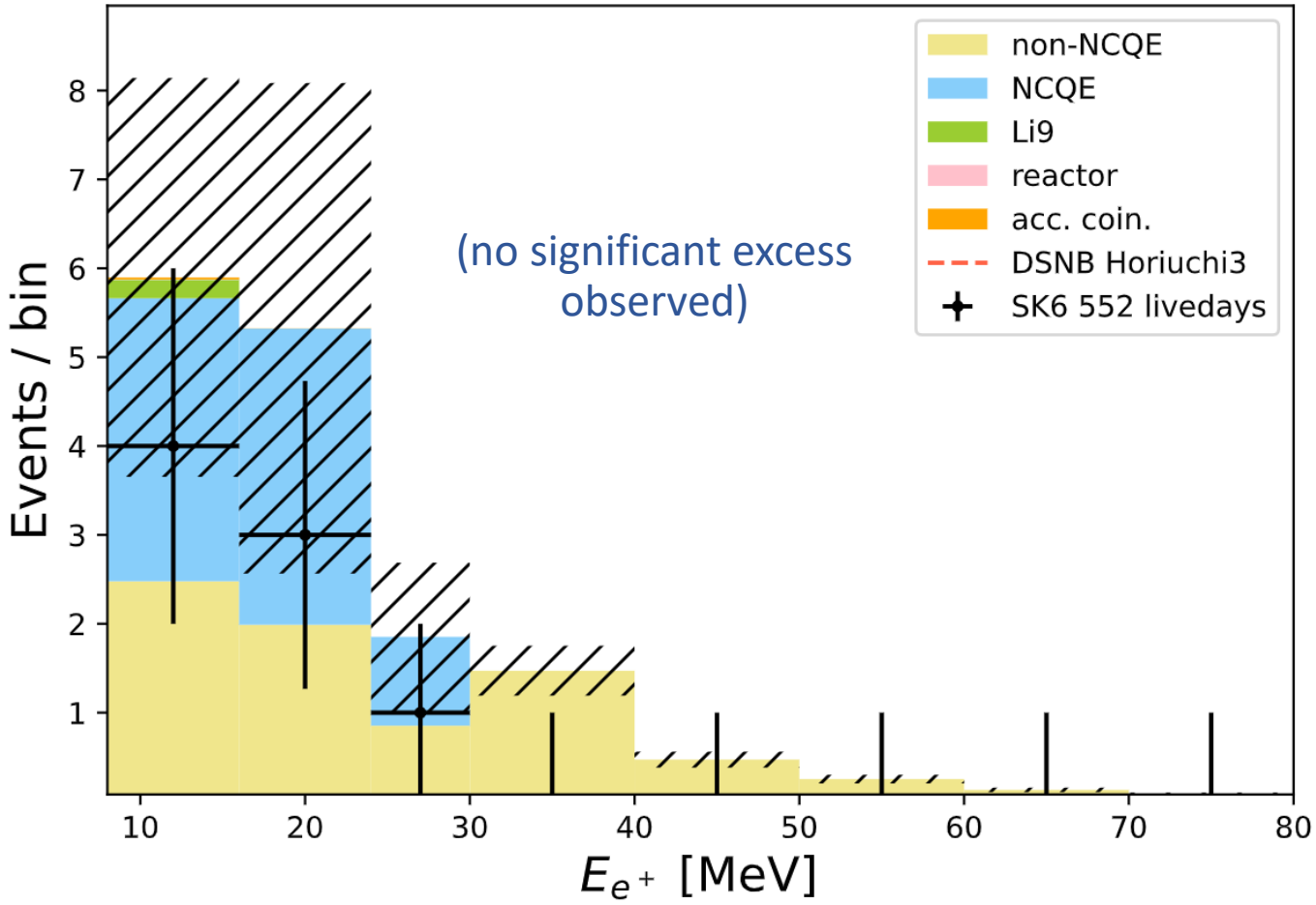


Recap: Energy spectrum (552.2 days SK6)

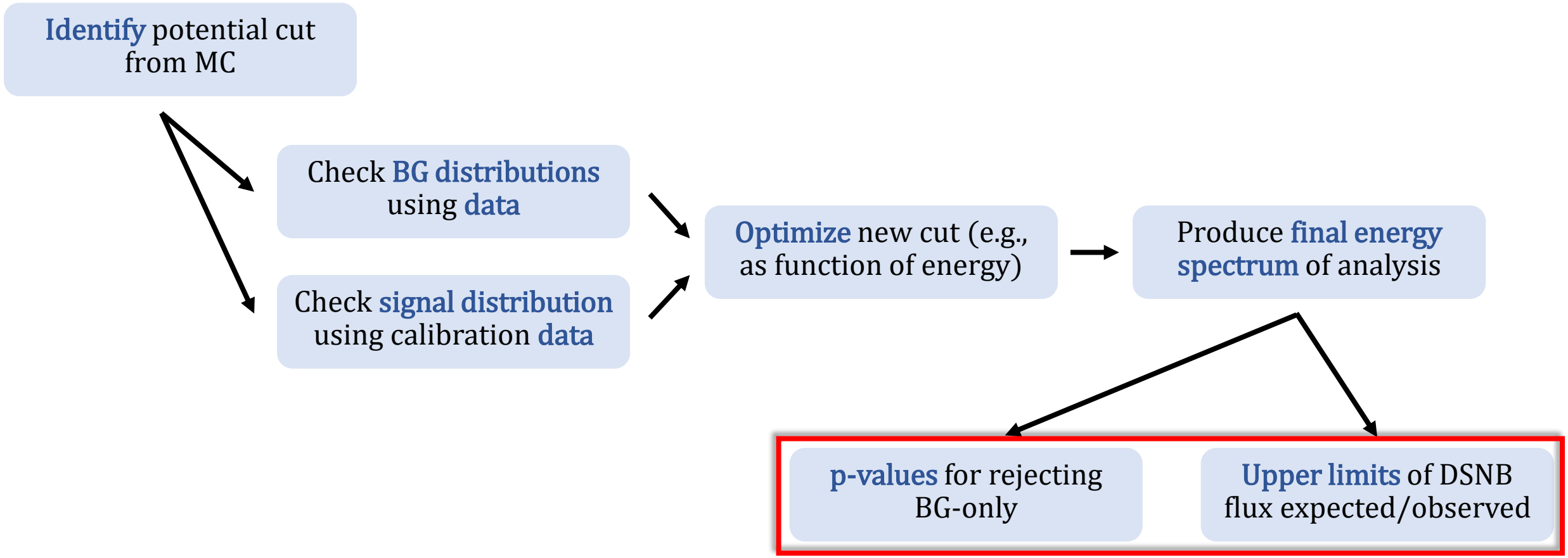
✓ $\theta_c \in [78^\circ, 90^\circ]$

✓ BDT neutron tagging

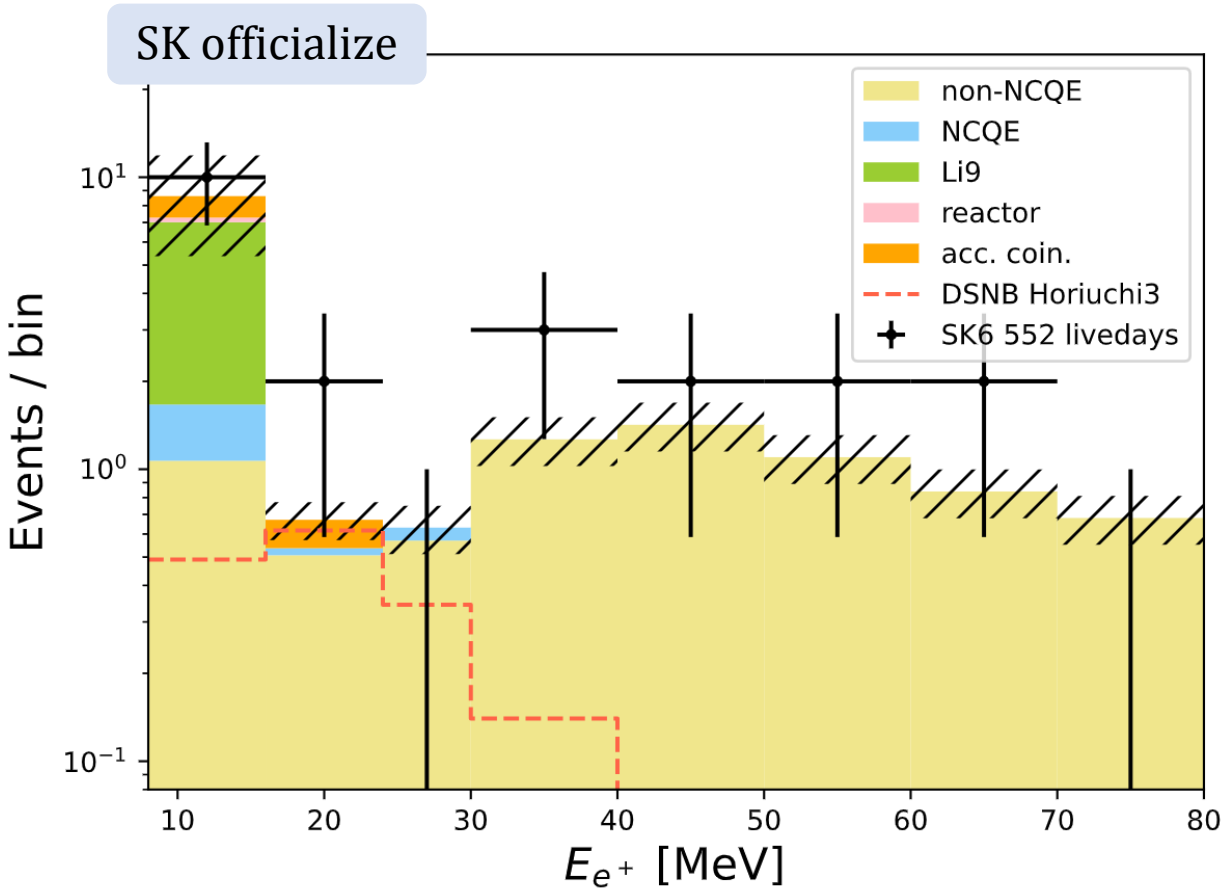
E_{e^+} [MeV]	p-value (BG-only)
[8, 16]	0.75
[16, 24]	0.77
[24, 30]	0.78
[30, 40]	1.0
[40, 50]	1.0
[50, 60]	1.0
[60, 70]	1.0
[70, 80]	1.0



Finding, validating, optimizing, and applying new cut for DSNB



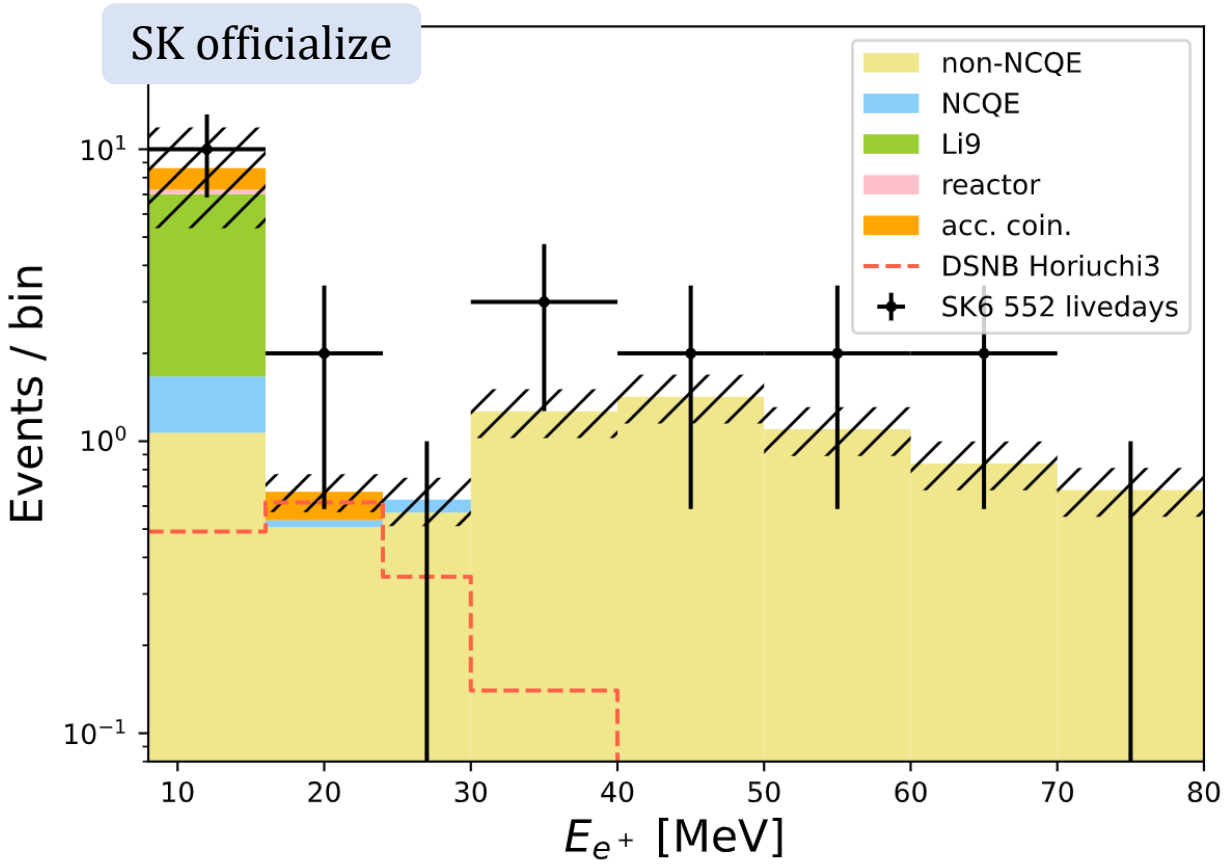
Results: SK6 final energy spectrum and p-values

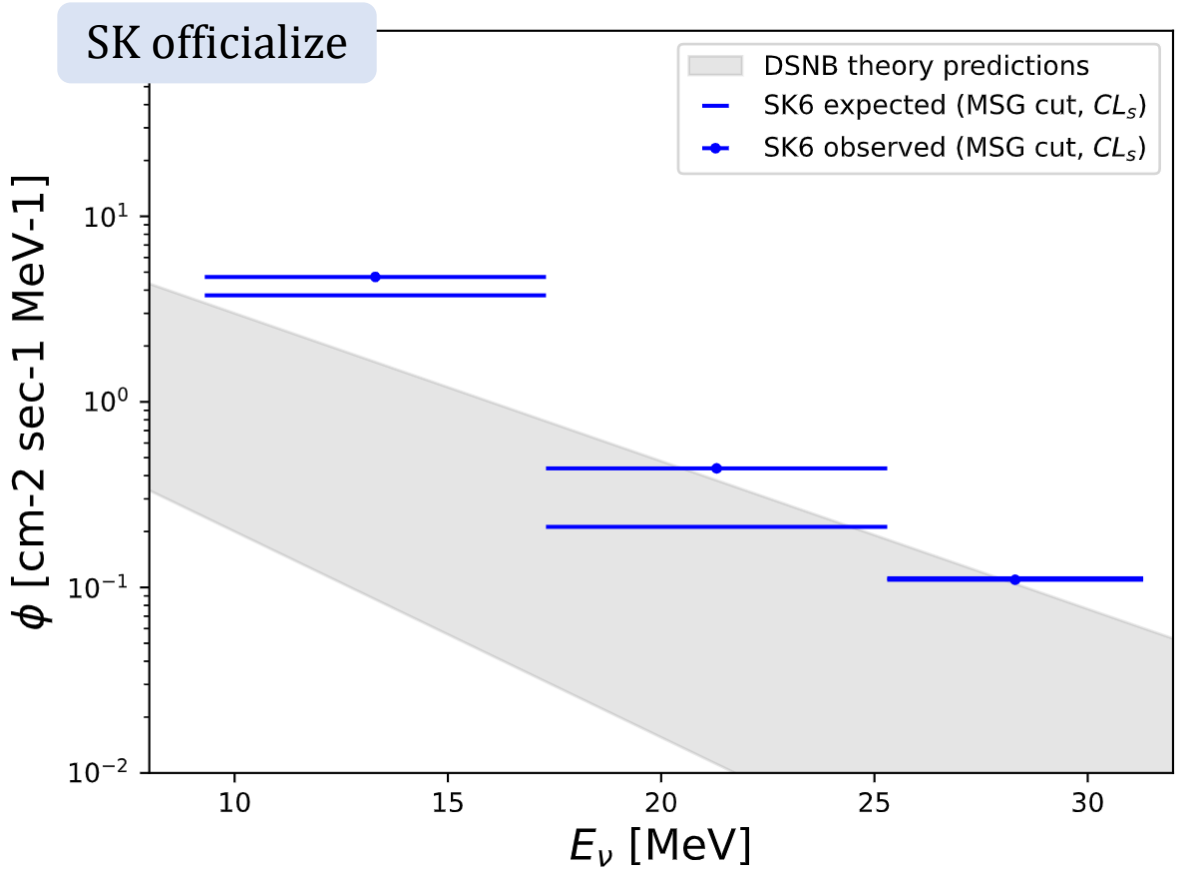


E_{e^+} [MeV]	p-value (BG-only)
[8, 16]	0.39
[16, 24]	0.15
[24, 30]	1.0
[30, 40]	0.14
[40, 50]	0.41
[50, 60]	0.30
[60, 70]	0.21
[70, 80]	1.0

- We see **no significant excess** anywhere.

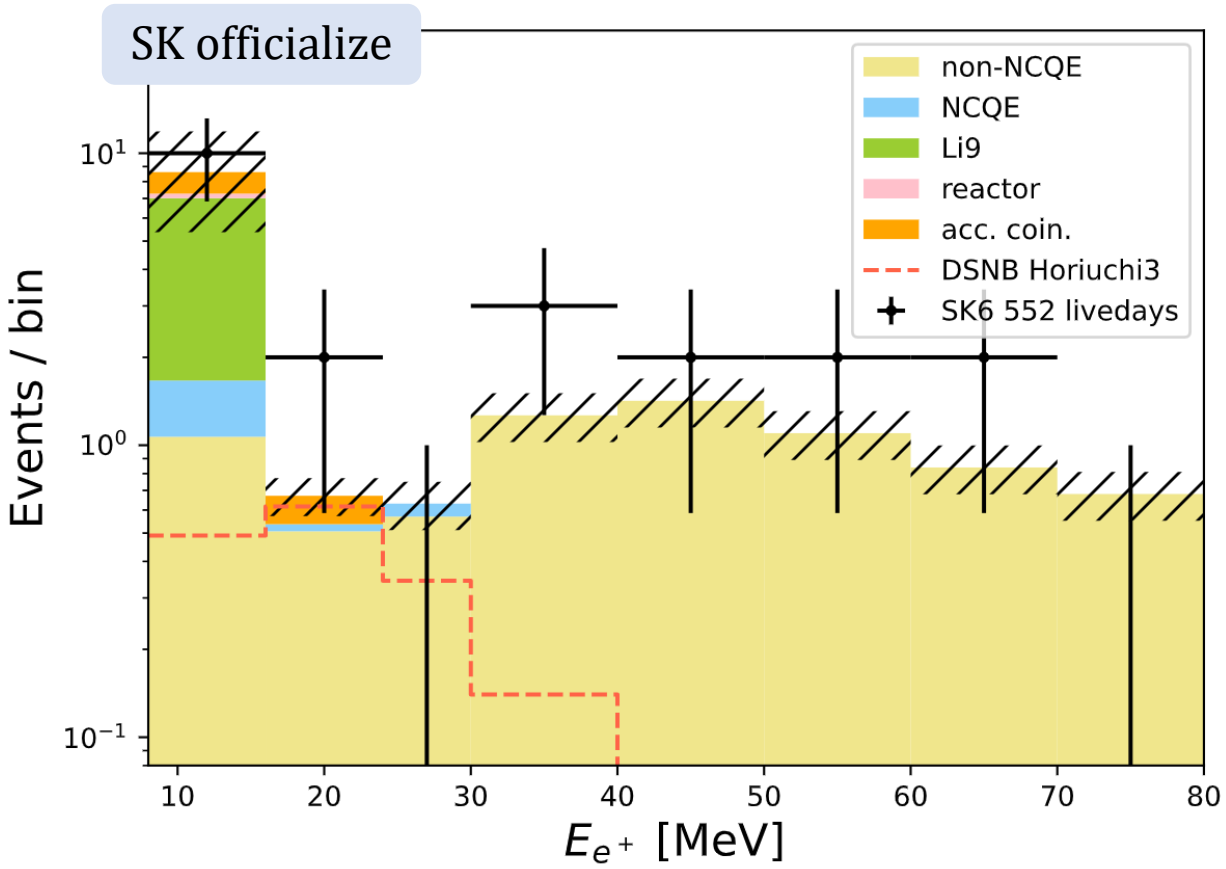
Results: SK6 final energy spectrum and upper limits

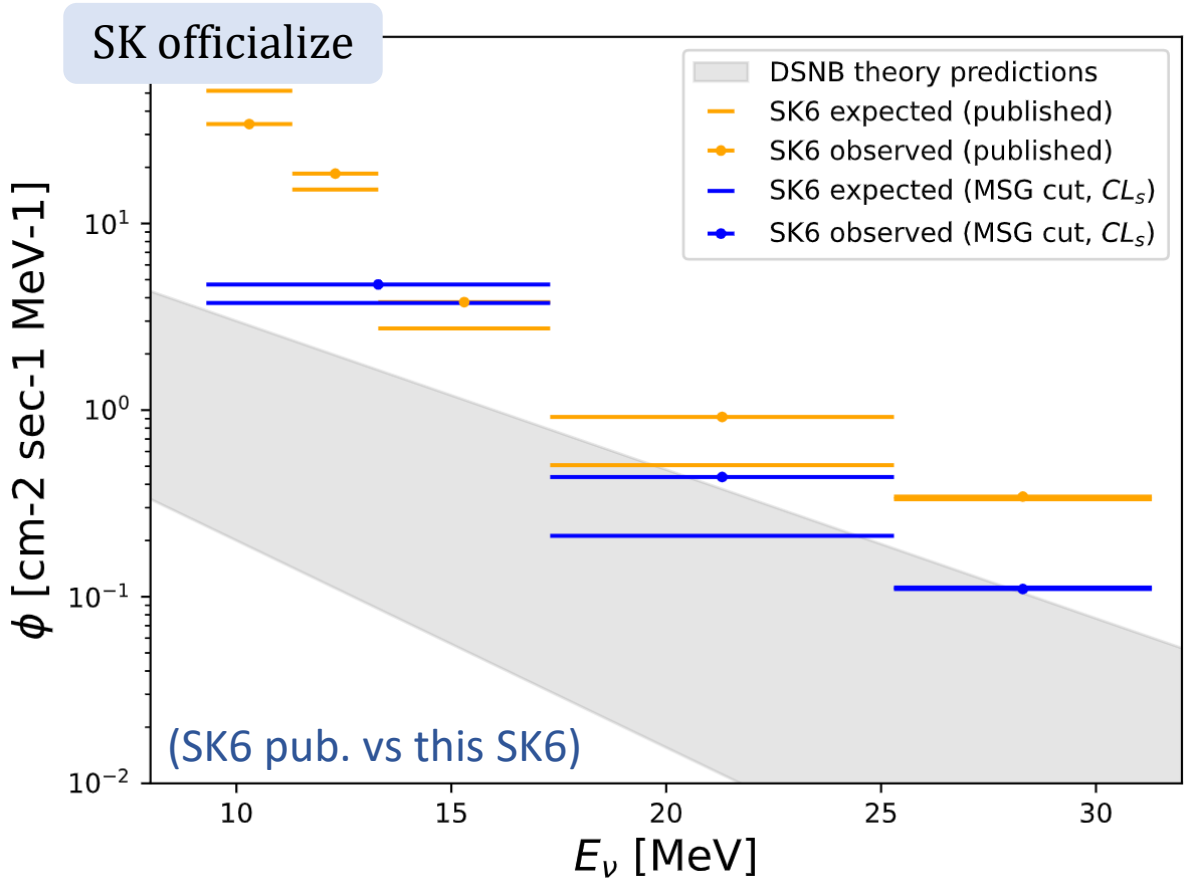




- The **SK6 expected limit** with neutron tagging BDT and MSG cut is **within the upper bound of theory predictions**.

Results: SK6 final energy spectrum and upper limits





- These **results for the SK6** period **lower the expected limit by ~60%** compared to the last published results (new MSG cut plus BDT neutron tagging).

Summary of MSG cut study and DSNB analysis results

Tasks and status

- **MSG sensitivity study** on SK4/SK6 MC only for new cut preparation (SK CM Summer 2023)
- MSG **data/MC LINAC comparison** SK6 and **systematics** study
- MSG **data/MC BG comparison** SK6
- MSG **cut optimization** by "significance" in bins of 2-MeV for SK6 DSNB **p-value/upper limits** (today!)
- **Apply MSG cut** for the upcoming DSNB analysis including SK-VII! (up next)

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