$K_L EVER$

Update on $\Lambda \to n\pi^0$ background

19 May 2020

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Outline

- Conclusions from last time
- Polarization in $\Lambda \to n\pi^0$ decay
- $p_\perp$ reconstruction systematics
- Weights and normalization
- Next steps
- Possible projects and contributions

Thoughts on $\Lambda \to n\pi^0$ background

New conclusion:

It is imperative to further reduce Λs in FV by several orders of magnitude

Items requiring further study:

- Scattered $\Lambda \to n\pi^0$ may not be confined to beam kinematic region
  - Λs from inelastic events produced much closer to the FV, but will also have much lower energy and can be eliminated with π^0 energy cuts
- There are uncertainties concerning:
  - Λ production rate and momentum spectrum
  - Λ polarization/angular distribution (generator uses isotropic 2-body decay)

Examined in detail as prerequisite to further studies

- Uncertainties in Λ production rate and momentum spectrum can be studied by:
  - Comparison of results with different generators (Geant4 vs FLUKA)
  - Direct sampling of existing results, including results from NA48?
    - My first studies were based on parameterization of Kichimi 1979 data used in NA48 MC

Polarization in $\Lambda \to n\pi^0$ decay

Λs created by unpolarized beam on unpolarized target are *polarized*:

- Discovered in 1976
- Polarization perp. to Λ production plane (required by parity conservation)
- Magnitude increases monotonically from 0 at $p_\perp$ = 0 to 20% at $p_\perp$ ~ 1.6 GeV
- Decreases slowly with A of target species: P(Cu or Pb)/P(Be) = 75%
- Does not depend strongly on longitudinal momentum (?)
- Does not depend strongly on beam momentum up to SPS energies (?)
- Mechanism for polarization not completely understood
  - From interference of at least two different spin-dependent amplitudes
  - In CQM, u and d quarks are in singlet state → spin of Λ = spin of s quark

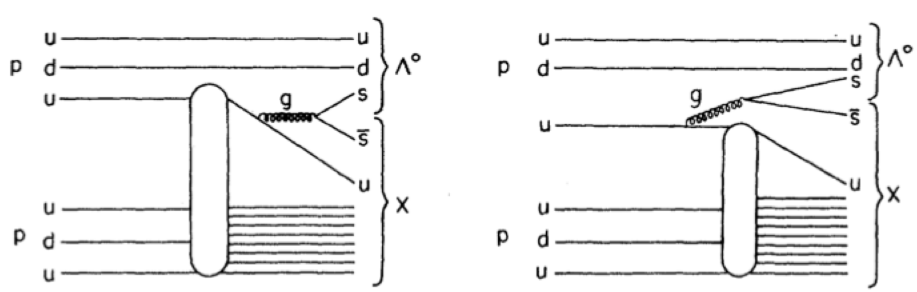


FIG. 4. The gluon bremsstrahlung mechanism discussed in the text.

Heller et al. ’78

Polarization in $\Lambda \to n\pi^0$ decay

In $\Lambda \to n\pi^0$ decay, n is preferentially emitted along Λ polarization axis

$$\frac{dN}{d\cos\theta} \propto 1 + \alpha P \cos\theta$$

$$\hat{\mathbf{P}} = \frac{\mathbf{p}_{\mathrm{beam}} \times \mathbf{p}_{\Lambda}}{\left|\mathbf{p}_{\mathrm{beam}} \times \mathbf{p}_{\Lambda}\right|} \qquad \hat{\mathbf{P}} \cdot \hat{\mathbf{p}}_n^{\mathrm{CM}} = \cos\theta$$

e.g. polarization along x-axis if beam vertically incident

parity conservation in Λ production → no longitudinal polarization

Λ decay asymmetry parameter:
α = 0.692 for $\Lambda \to n\pi^0$

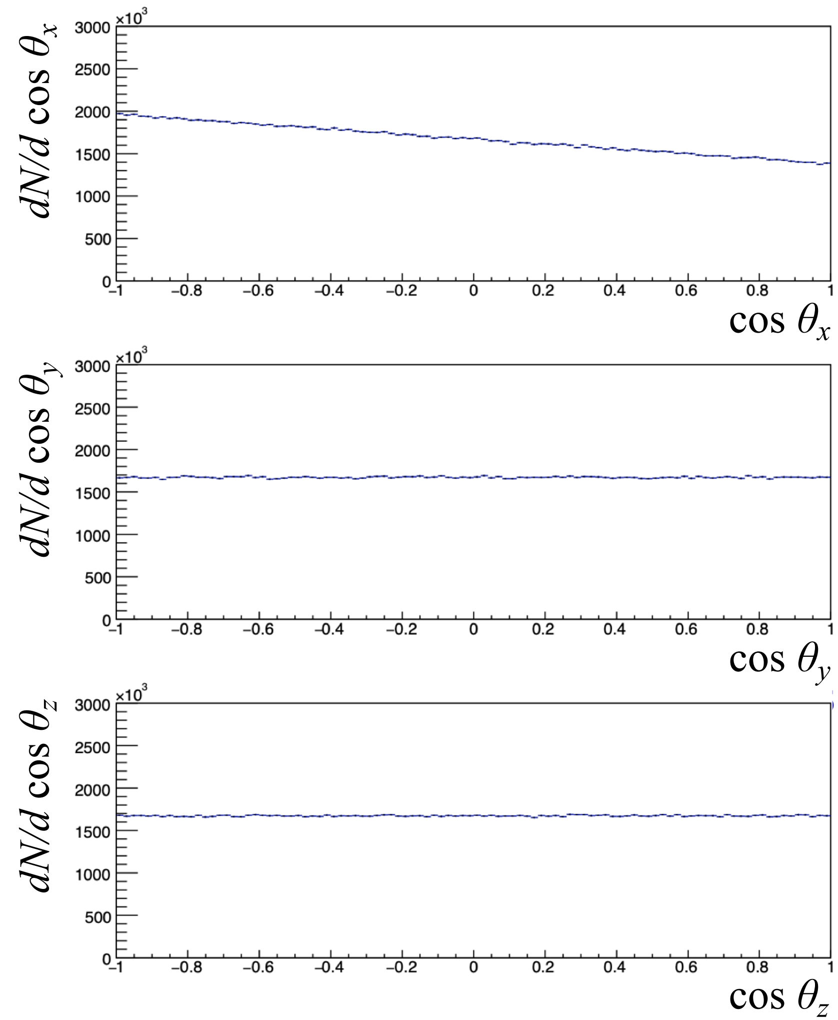
BES-III 2018

For p + Be at 400 GeV

$$P(x_F, p_\perp) = (C_1 x_F + C_2 x_F^3)(1 - e^{C_3 p_\perp^2})$$

Lundberg 1989
Heller 1983

Neutron decay angle in CM for P = –0.25



Polarization in $\Lambda \to n\pi^0$ decay

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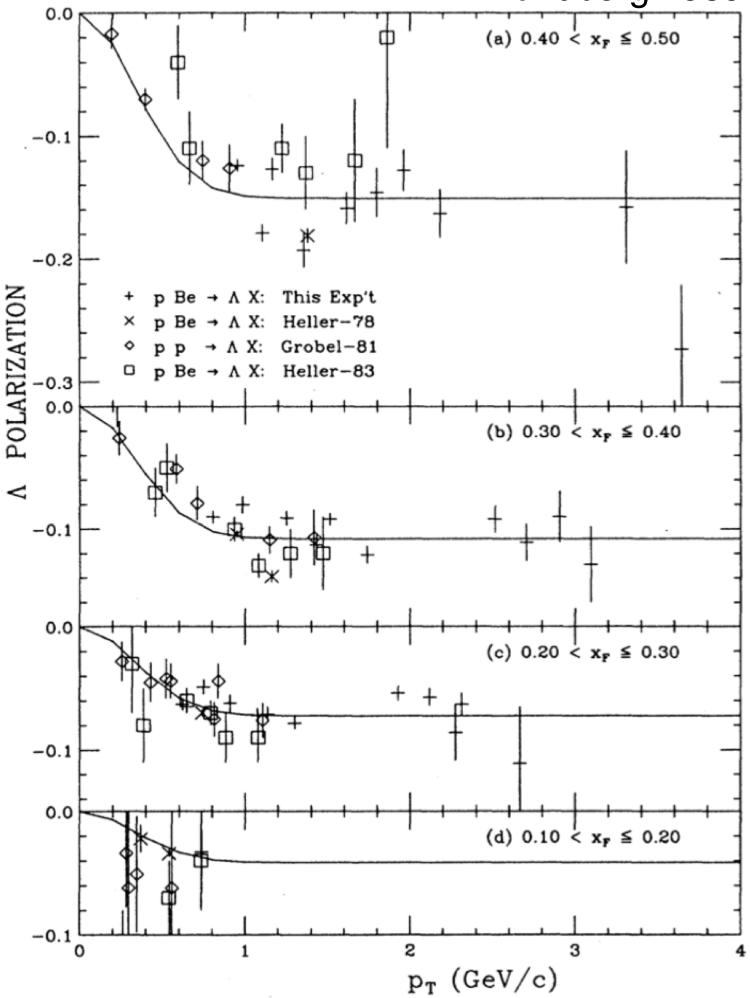
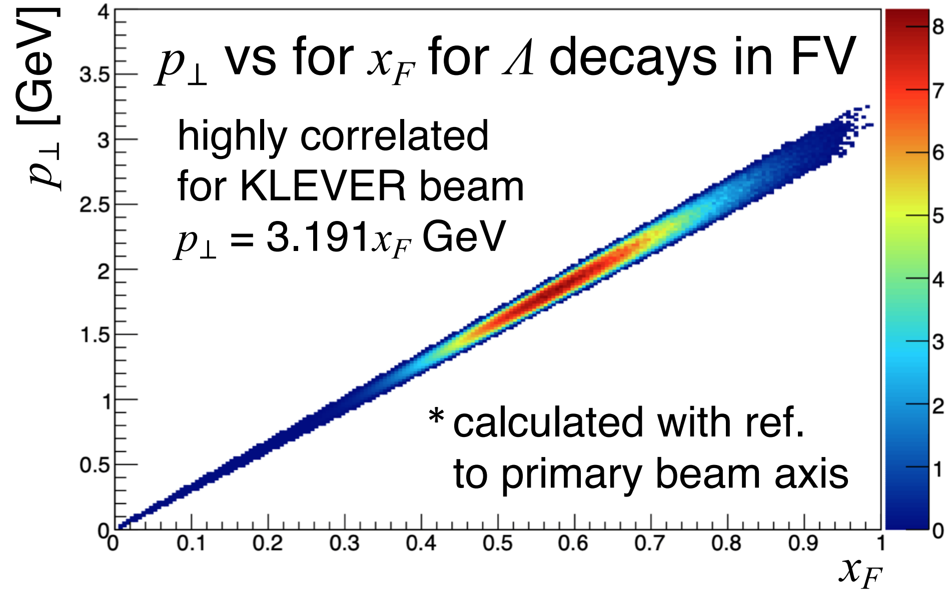
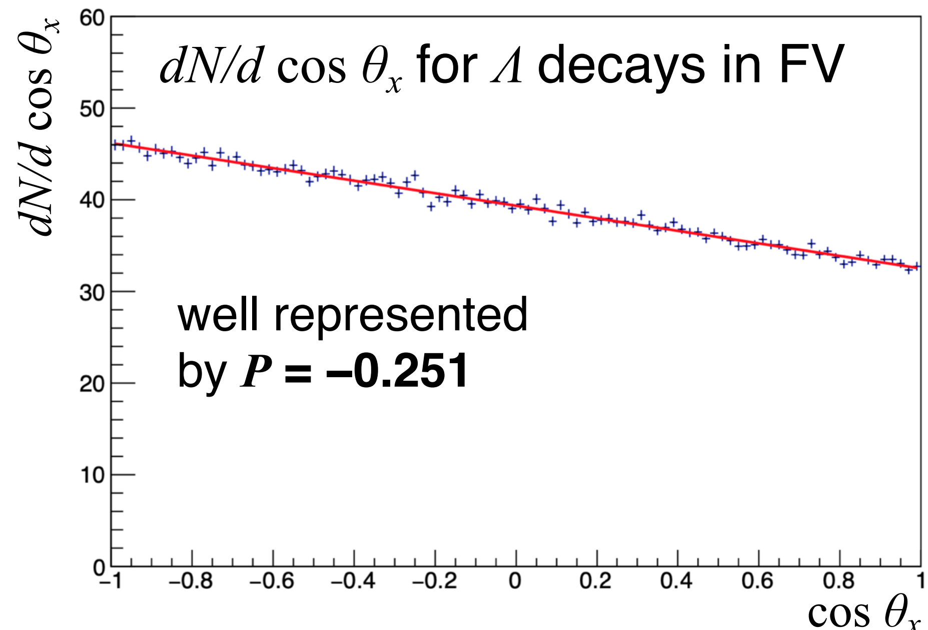
p + Be at 400 GeV

Lundberg 1989



$$P(x_F, p_\perp) = (C_1 x_F + C_2 x_F^3)(1 - e^{C_3 p_\perp^2})$$

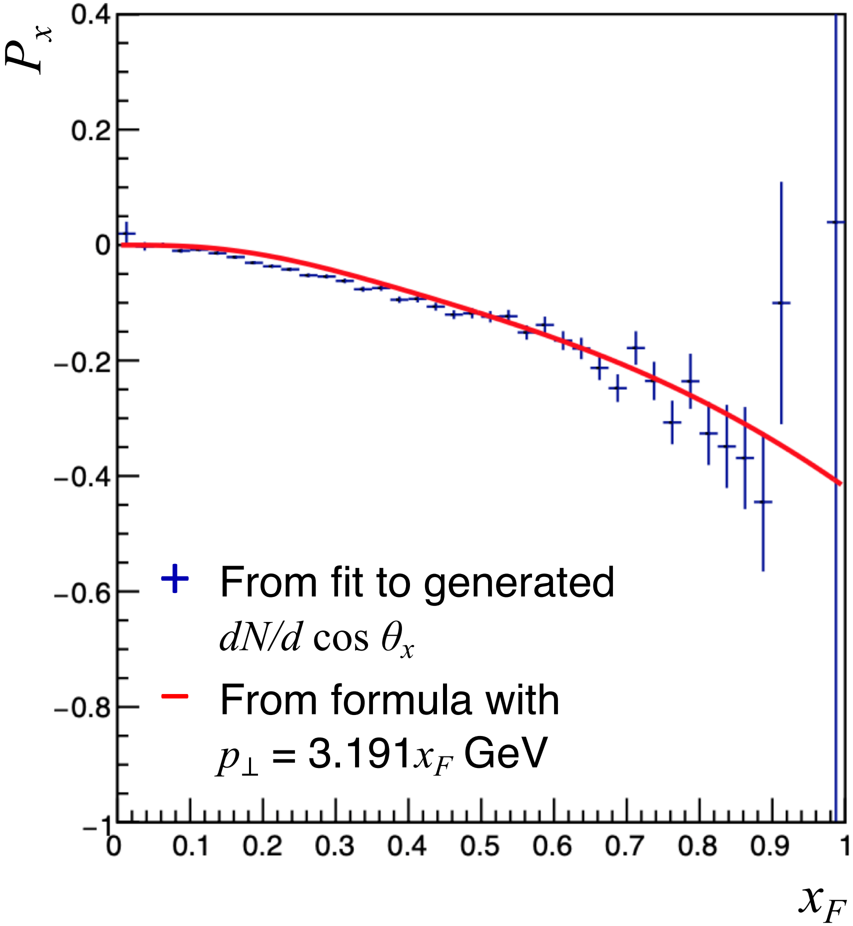




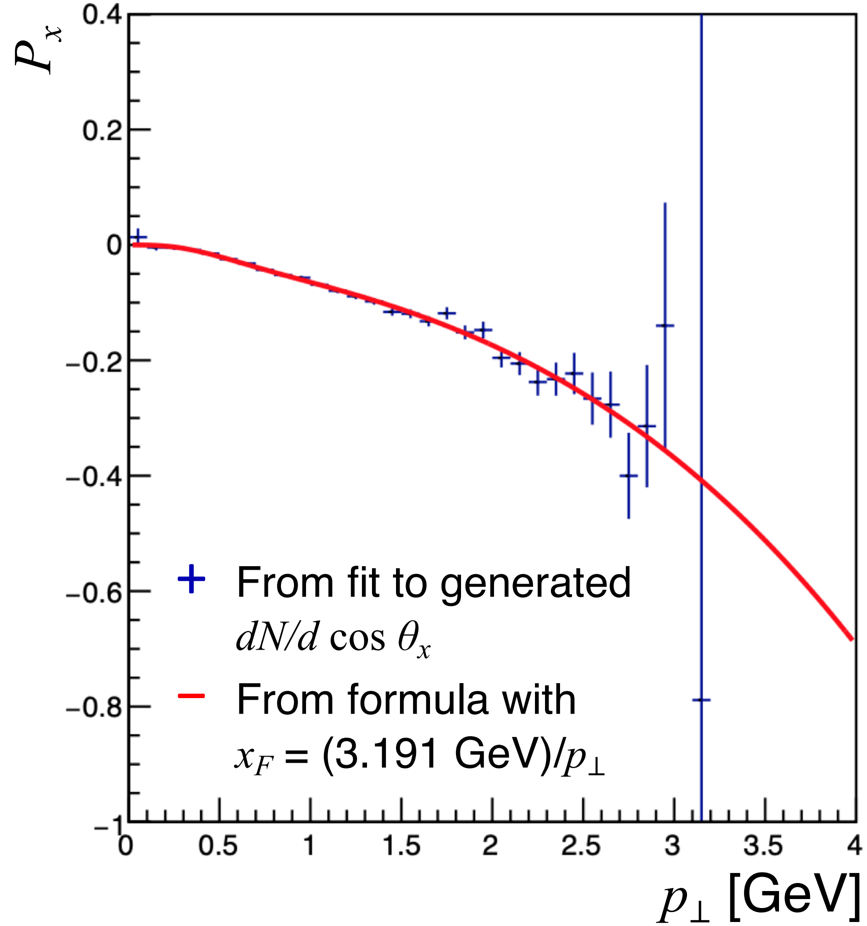
Polarization in $\Lambda \to n\pi^0$ decay

Polarization in zOptical $\Lambda \to n\pi^0$ decay generator

P_x vs x_F



P_x vs $p_\perp$



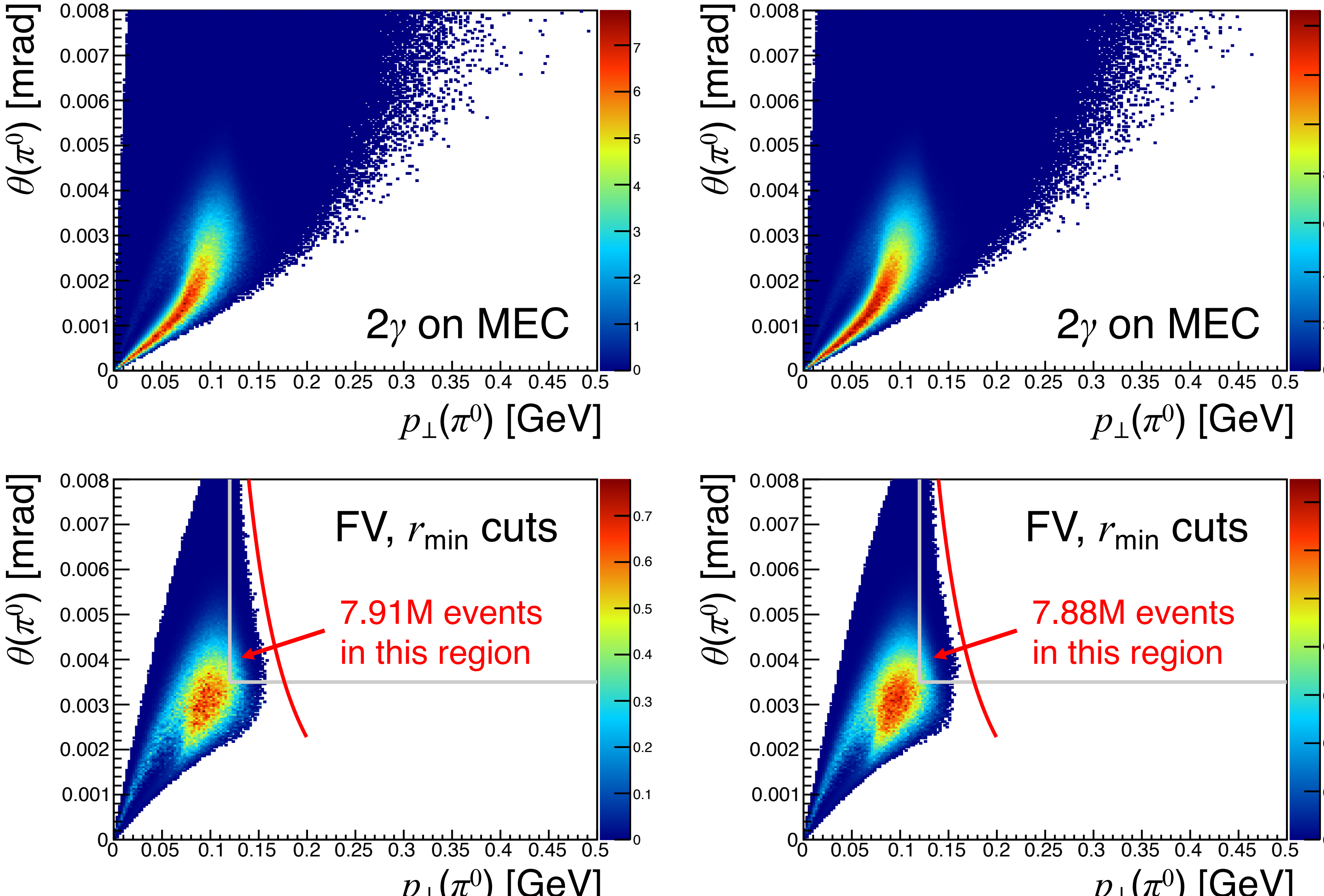
$$P(x_F, p_\perp) = (C_1 x_F + C_2 x_F^3)(1 - e^{C_3 p_\perp^2})$$

$\Lambda \to n\pi^0$: effect of polarization in MC

No polarization

Polarization (Lundberg '89)

* 2x more statistics



$\Lambda \to n\pi^0$ with polarization

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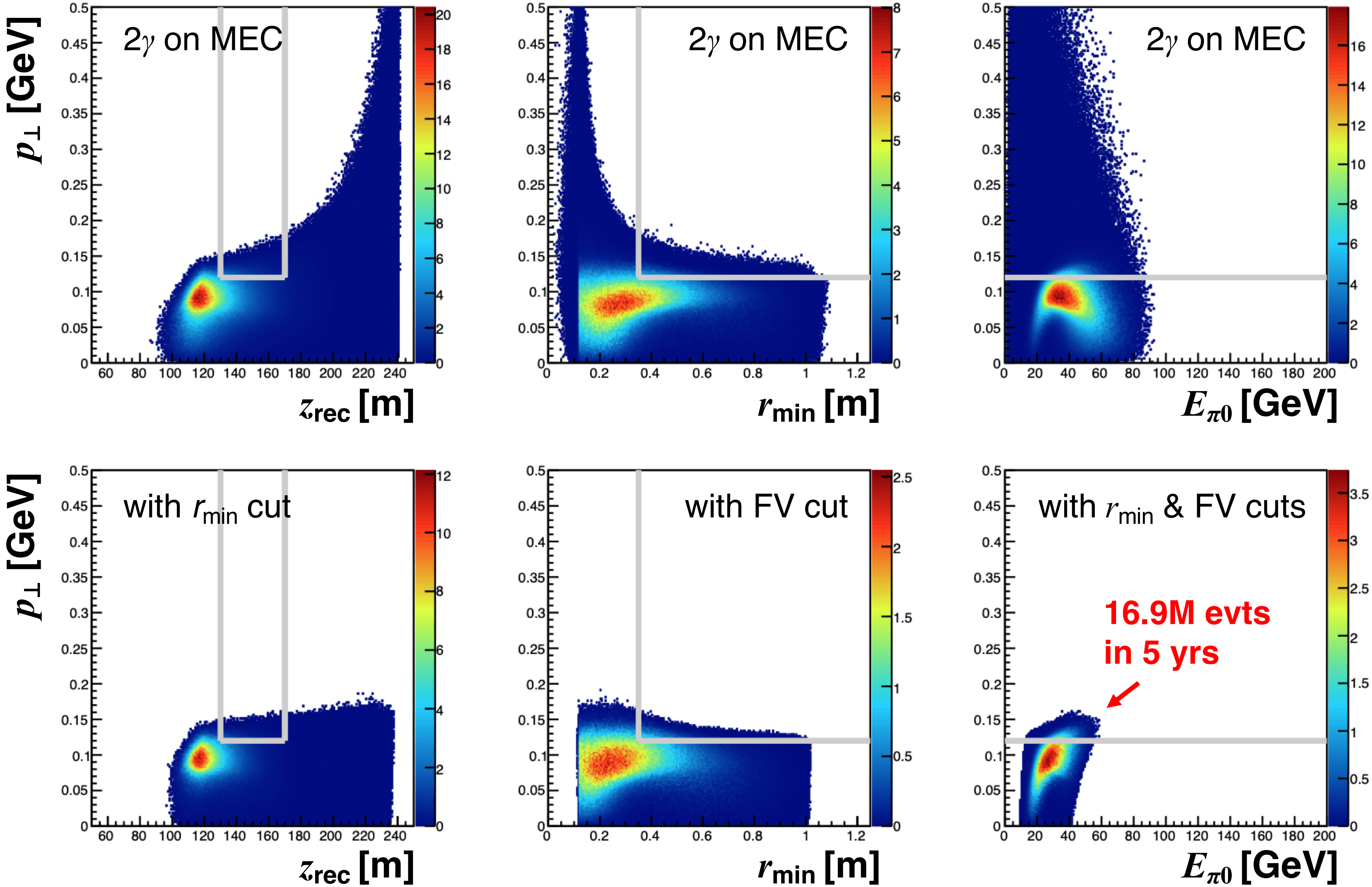
1.672G $\Lambda \to n\pi^0$ with Malensek/FLUKA spectrum, decay weights



$\Lambda \to n\pi^0$ with polarization

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Stage	Acceptance	Change	Events in 5 yrs	Change
Produced $\Lambda \to n\pi^0$	1		1.672×10^{14}	
Decay in FV	4.709×10^{-6}	1.003	7.875×10^{8}	1.003
2γ on LKr	7.866×10^{-6}	0.997	1.316×10^{9}	0.997
+ Reconst. in FV	0.3262	1.006	4.292×10^{8}	1.003
+ $r_{\text{min}} > 35$ cm	0.3399	1.007	1.459×10^{8}	1.011
+ $p_\perp > 120$ MeV	0.1162	0.998	1.694×10^{7}	1.009
+ $\theta_{\pi0} > 3.5$ mrad	0.4650	0.987	7.879×10^{6}	0.996
+ $\theta_{\pi0}$ vs $p_\perp$ cut	$< 4.27 \times 10^{-5}$	**1.18***	< 336 (no events left)	**1.17***

Notes:

- Generation at 2x statistics of previous sample (raw scale = 1:100000)
- Little change with respect to generation without polarization (2020v3 vs v1)
- To what extent is the decay angle distribution maintained through event selection stages?

$\Lambda \to n\pi^0$ with polarization

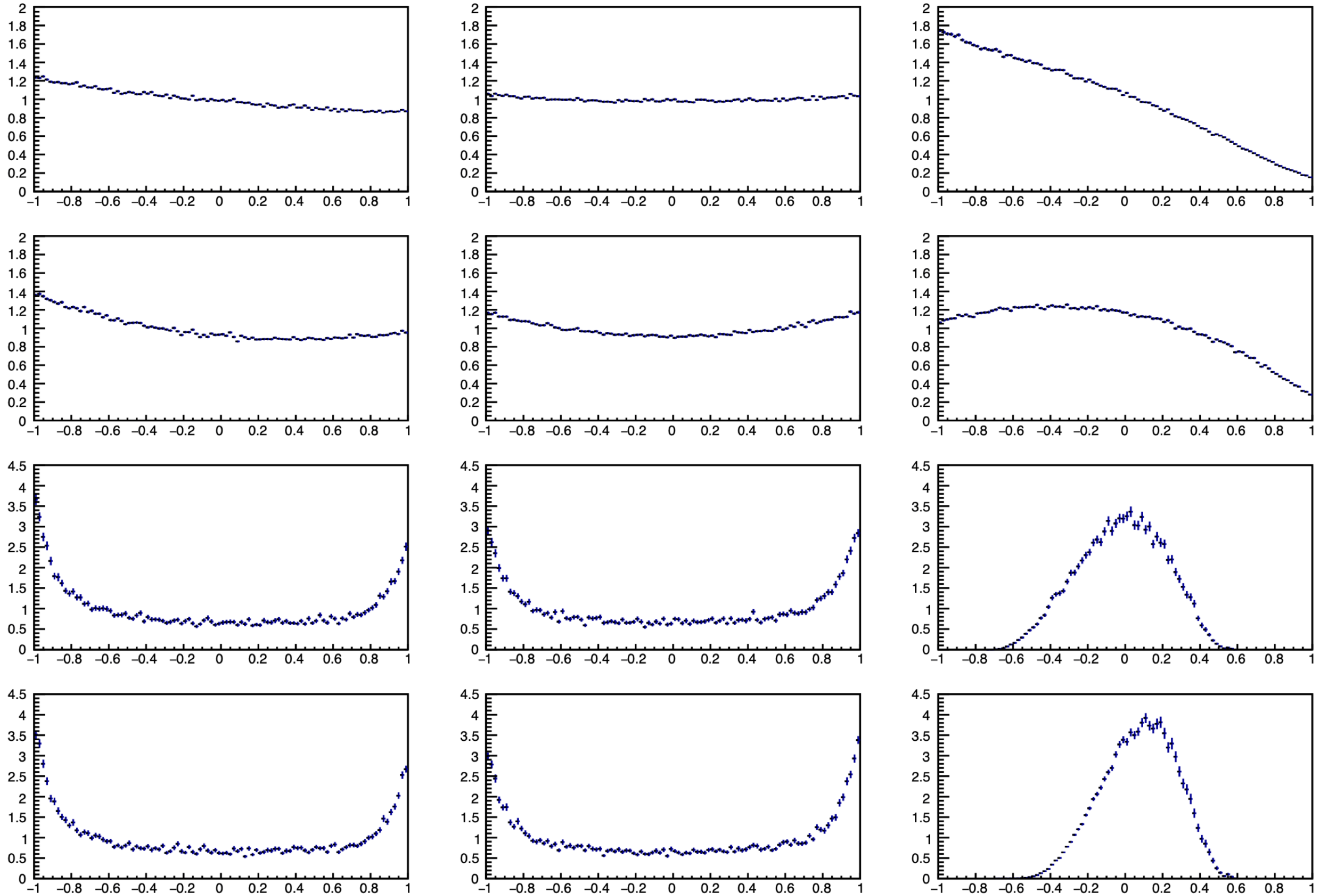
$dN/d\cos\theta_x$ | $dN/d\cos\theta_y$ | $dN/d\cos\theta_z$

2γ on MEC

+ FV cut

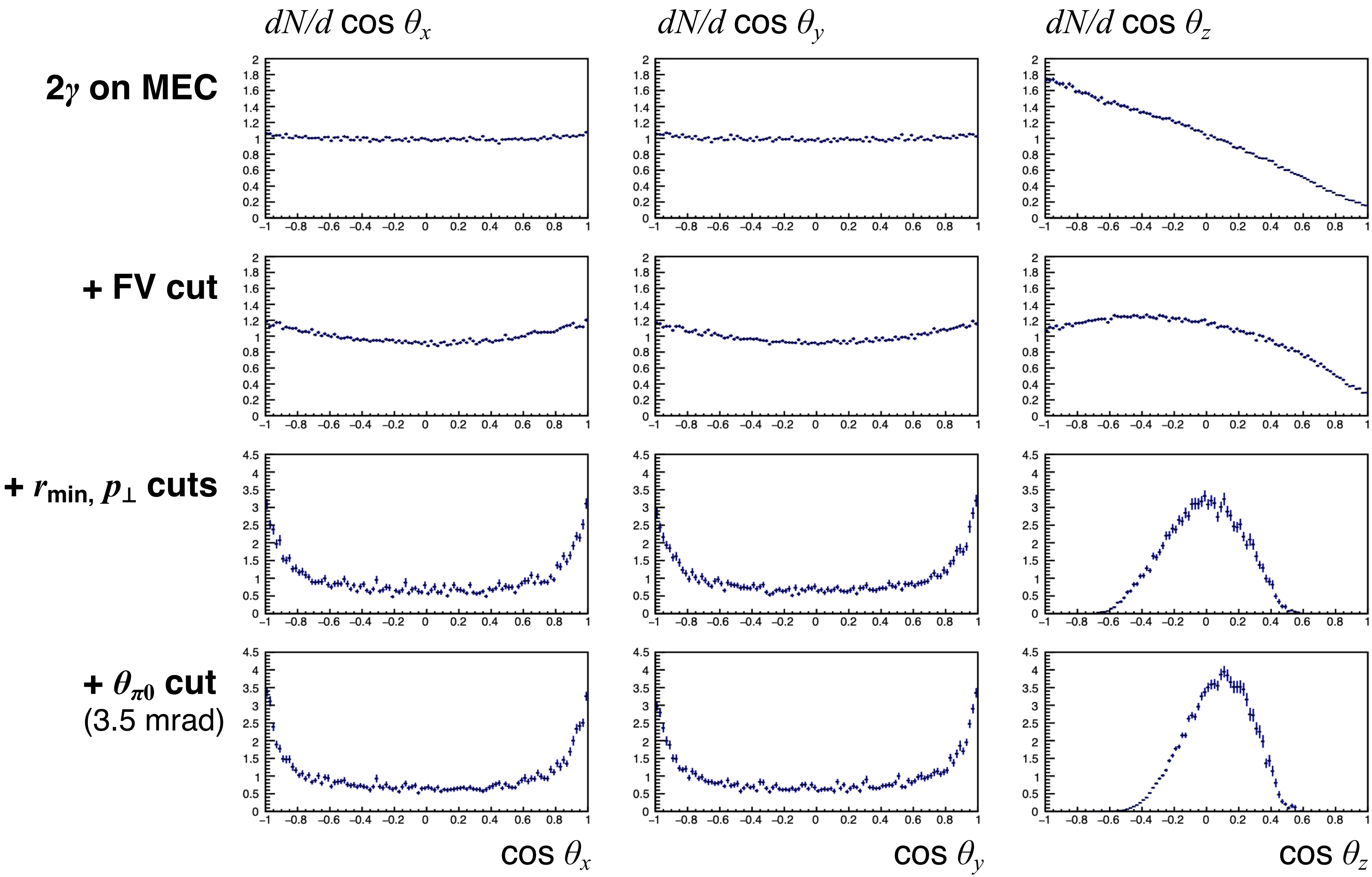
+ r_{min}, $p_\perp$ cuts

+ $\theta_{\pi 0}$ cut
(3.5 mrad)



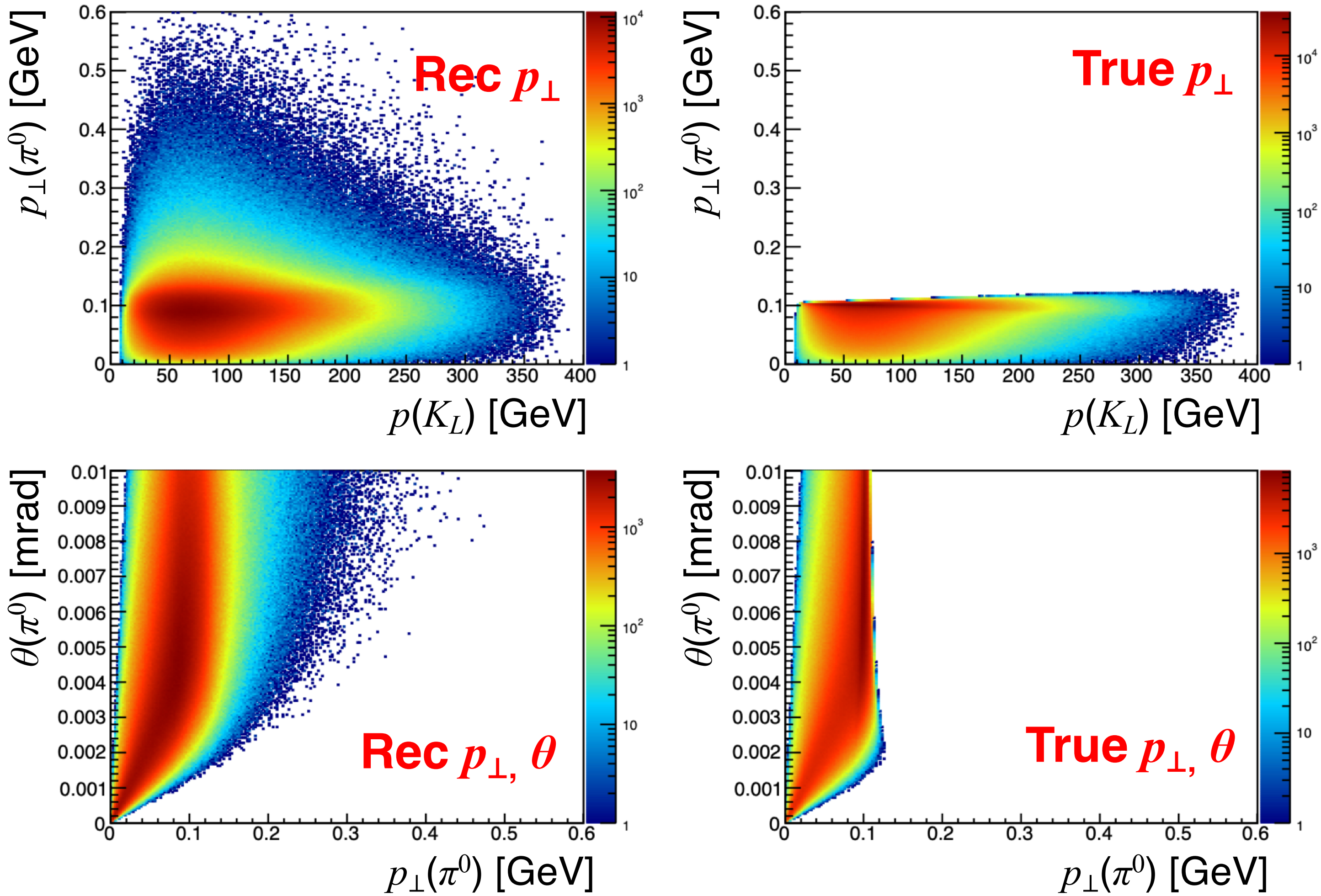
$\cos\theta_x$ | $\cos\theta_y$ | $\cos\theta_z$

$\Lambda \to n\pi^0$ without polarization



$p_\perp$ reconstruction systematics

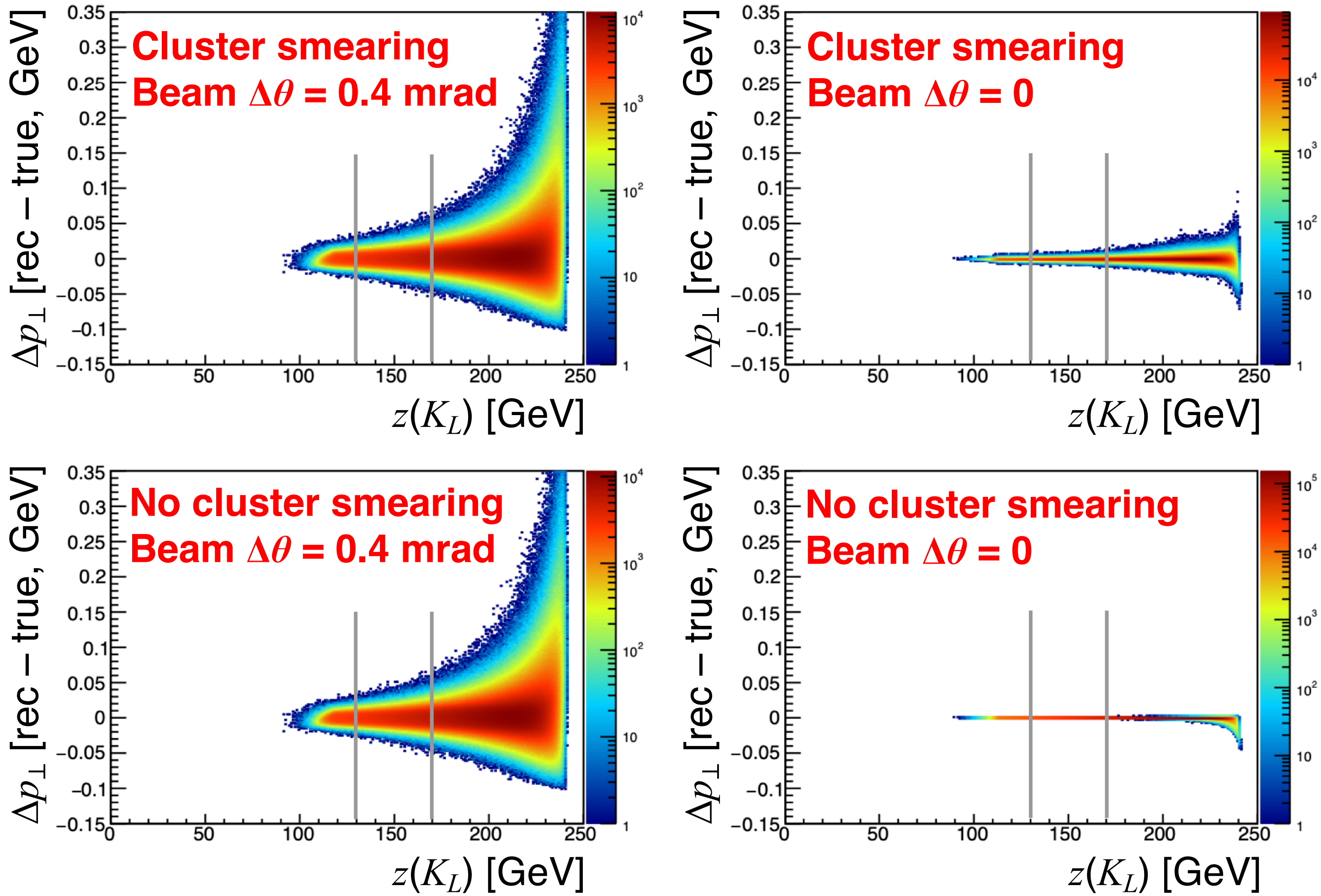
$\Lambda \to n\pi^0$ with 2γ on MEC, **no weights** – log scale



- Jacobian peak in $p_\perp(\pi^0)$ smeared towards lower values → also reconstructed $\theta(\pi^0)$
- What gives rise to long tail towards unphysically high $p_\perp$?

$p_\perp$ reconstruction systematics

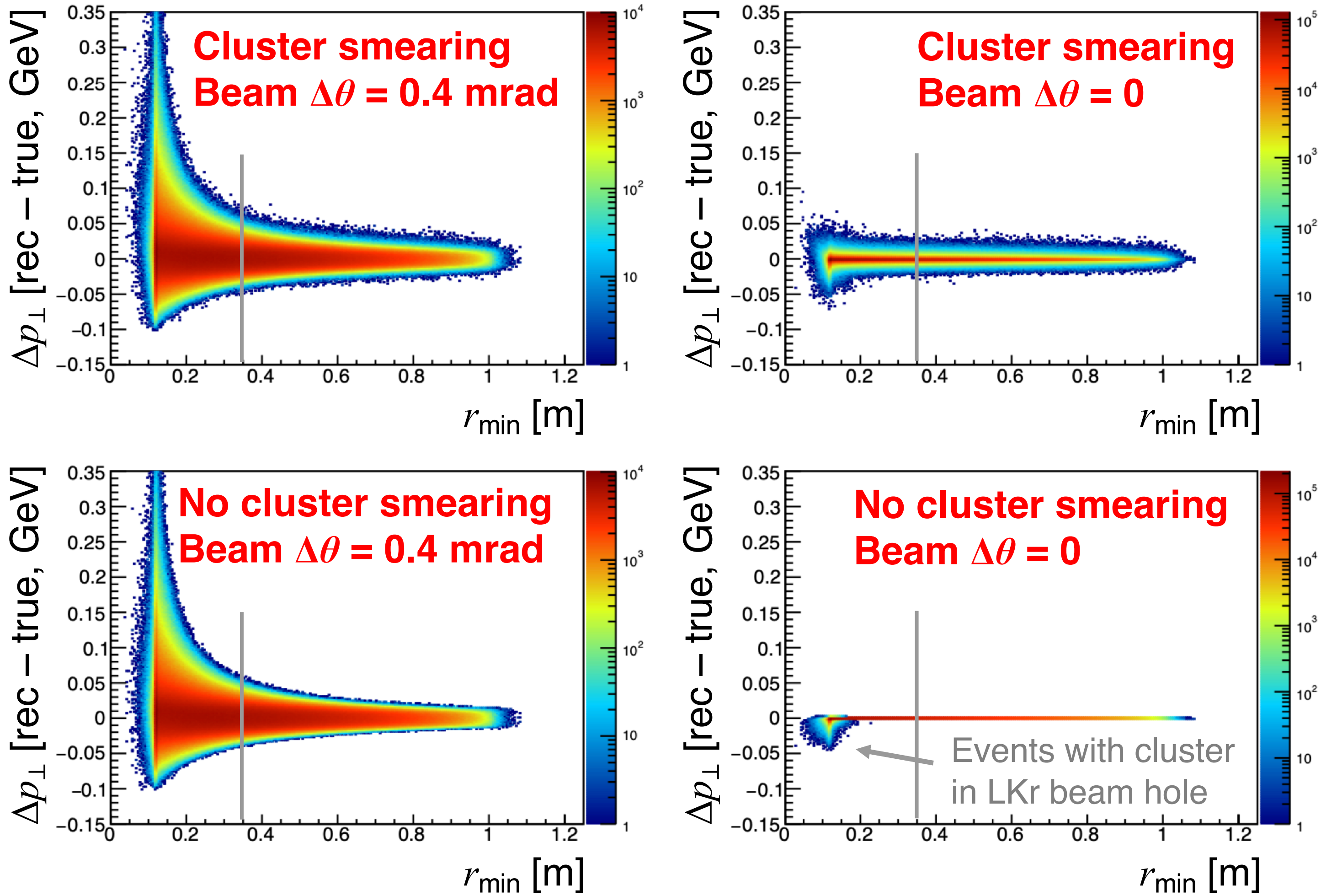
$\Lambda \to n\pi^0$ with 2γ on MEC, **no weights** – log scale



- High-$p_\perp$ tail comes from downstream decays, close to MEC
- Calorimeter energy, position resolution unimportant compared to beam divergence
  - But beam $p_\perp$ mainly given to neutron: true $p_\perp(\pi^0)$ maximum ~120 MeV

$p_\perp$ reconstruction systematics

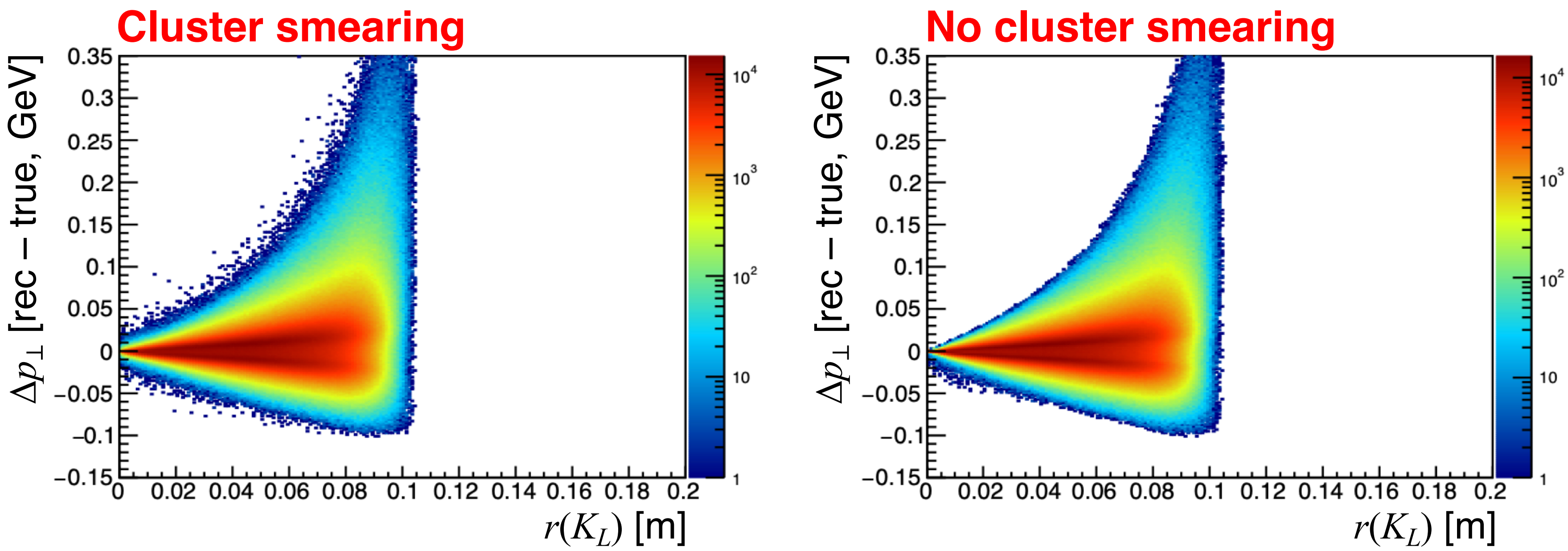
$\Lambda \to n\pi^0$ with 2γ on MEC, **no weights** – log scale



- Like FV cut, $r_{\min}$ cut cleans up $p_\perp$ reconstruction (but FV cut does most of the work)
- $r_{\min}$ cut not very helpful for Λ rejection: can be retuned for K_L rejection

$p_\perp$ reconstruction systematics

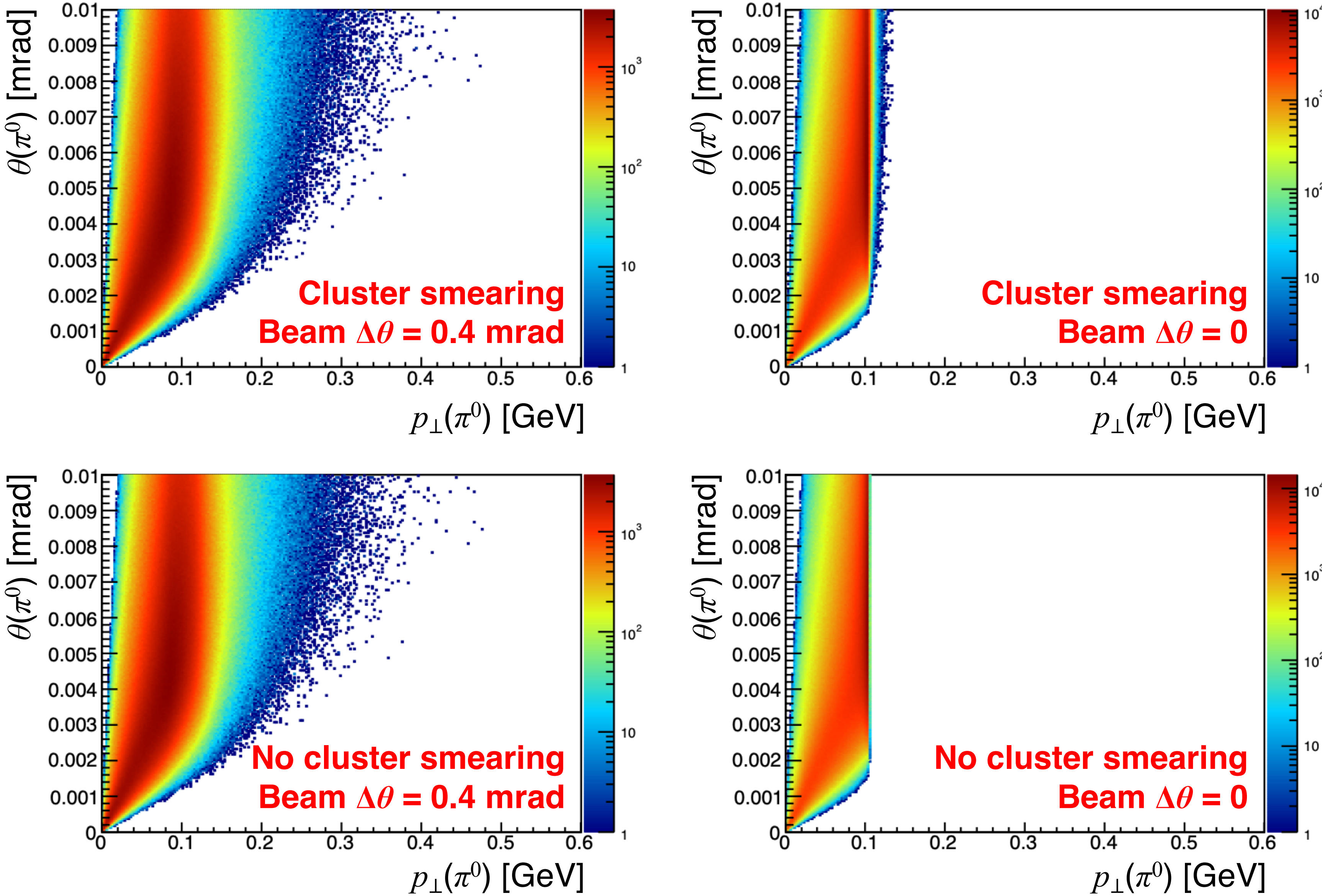
$\Lambda \to n\pi^0$ with 2γ on MEC, **no weights** – log scale



- Most of the high-$p_\perp$ tail is from the size of the beam spot at a given z
  - π^0 reconstruction assumes decay is on axis!
- $p_\perp$ reconstruction depends on beam opening angle more than MEC performance
  - In principle beam opening angle is fixed by size of collimators
- Best strategy to improve $p_\perp$ reconstruction is to reduce beam opening angle

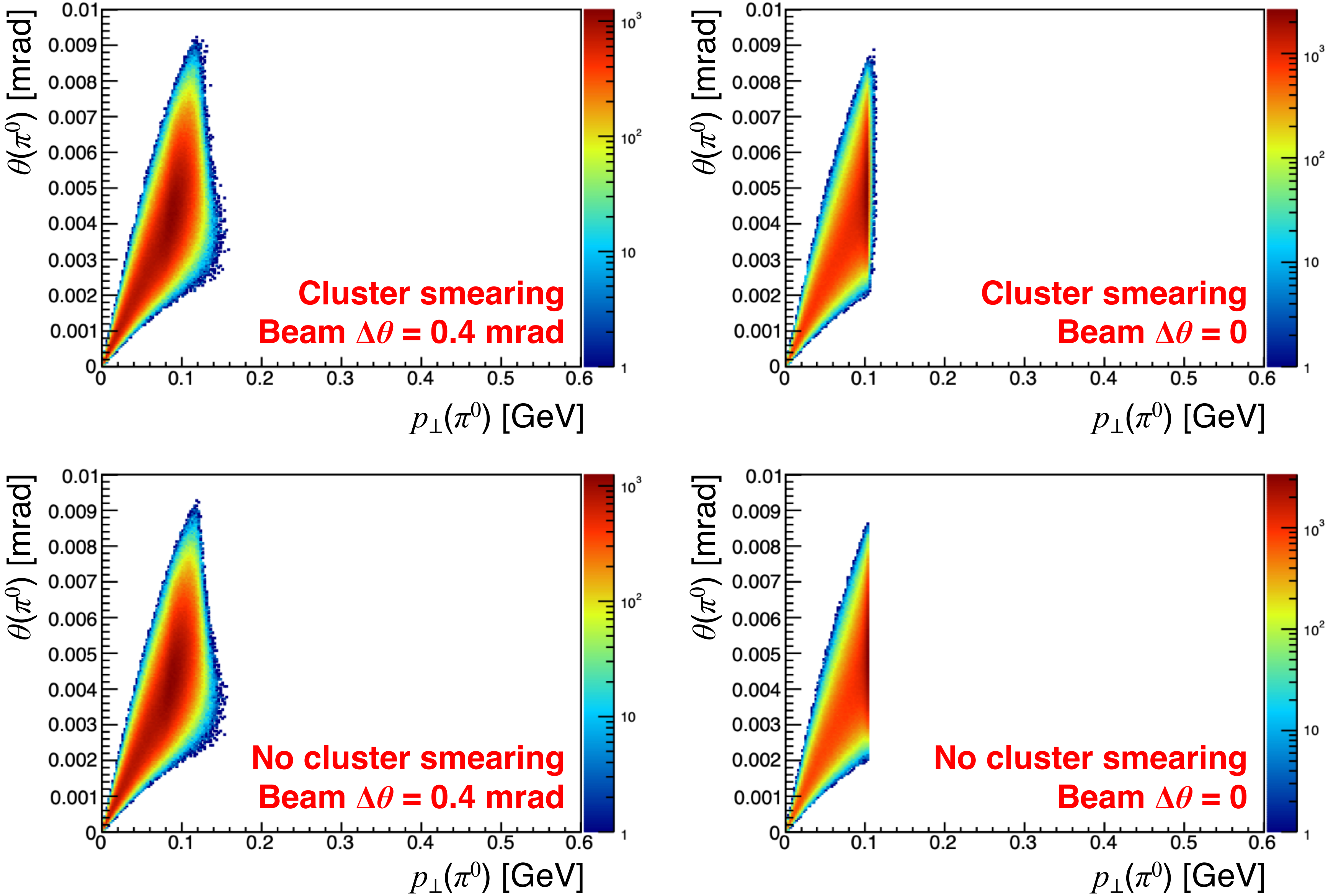
$p_\perp$ reconstruction systematics

$\Lambda \to n\pi^0$ with 2γ on MEC, **no weights** – log scale



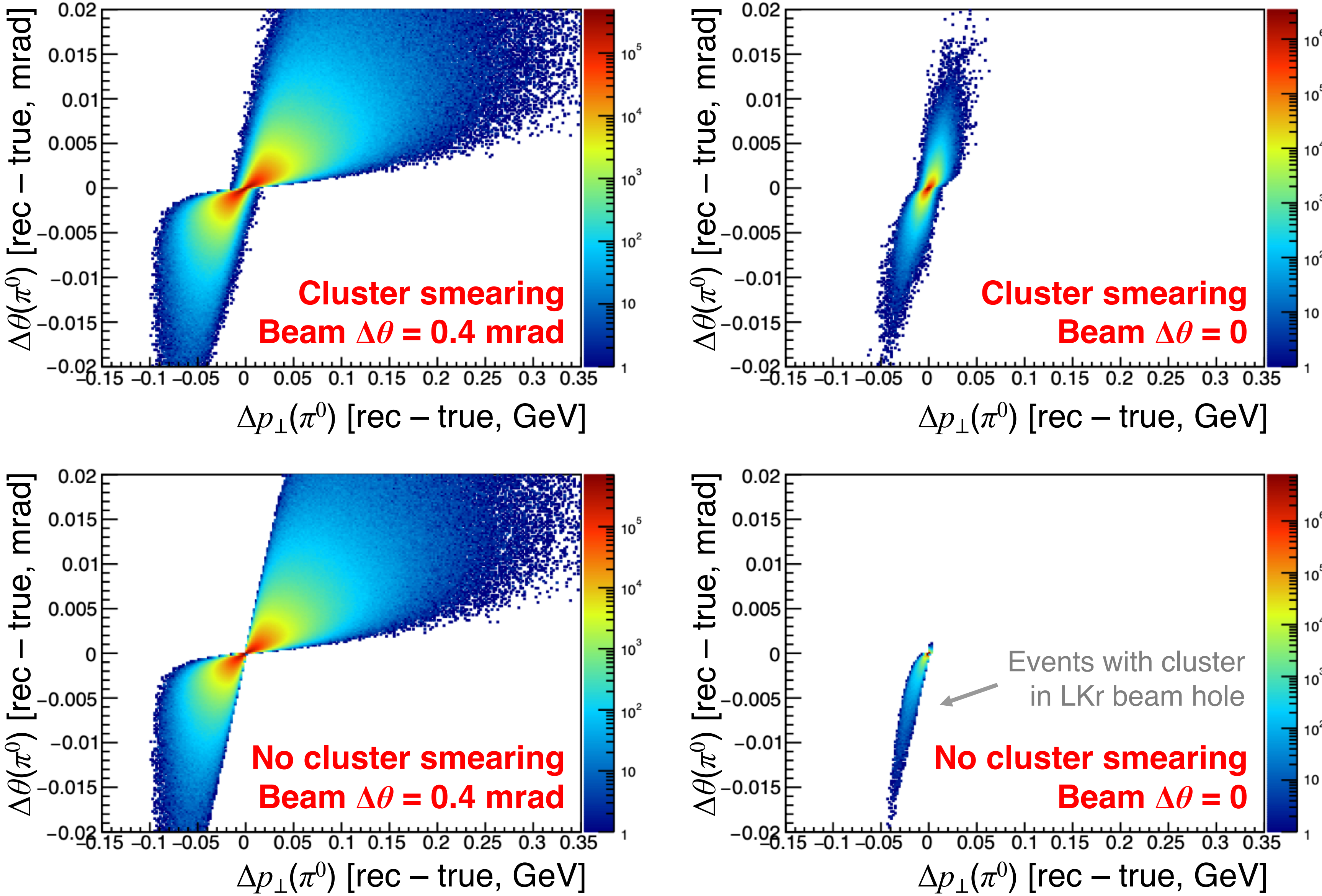
$p_\perp$ reconstruction systematics

$\Lambda \to n\pi^0$ with 2γ on MEC + FV and r_{min} cuts, **no weights** – log scale



$p_\perp$ reconstruction systematics

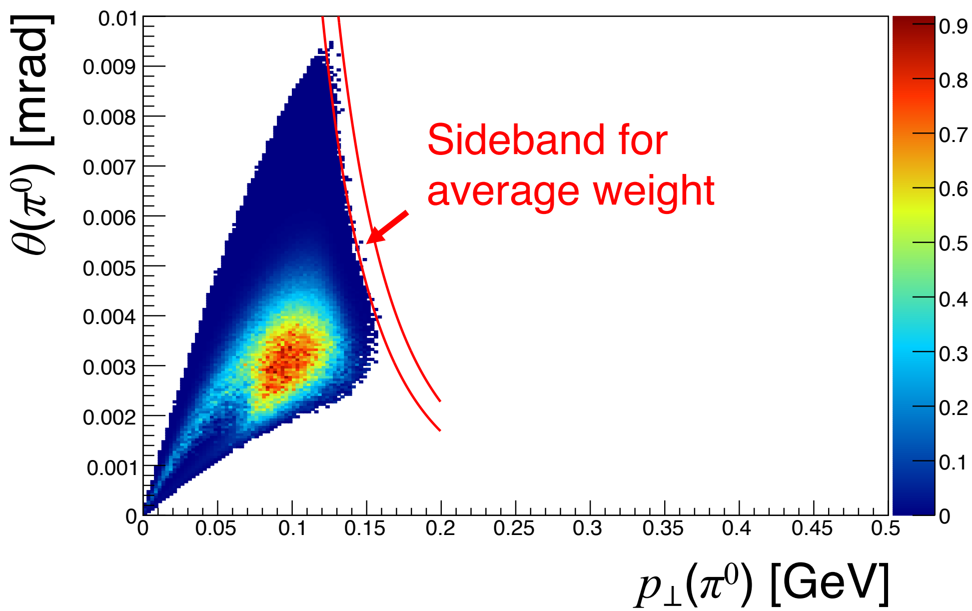
$\Lambda \to n\pi^0$ with 2γ on MEC, **no weights** – log scale



Weights and normalization

Weighting scheme for decay distribution:

- Uniform z distribution for $0 < z < 250$ m ($\Delta z = 250$ m)
- Events weighted by $W = \Delta z/\lambda \times \exp(-z/\lambda)$, with $\lambda = pc\tau_\Lambda/m_\Lambda$
- Generation scale known
- Number of observed events from sum of weights
- Effective scale from errors on sum of weights
- What is the effective scale when zero counts observed?



- Calculate average weight for events in sideband
- Quote 90%CL by assigning this weight to 2.30 evts

	Old	New
n_{side}	397	10
$\langle W \rangle$	2.7×10^{-7}	1.3×10^{-3}

Why does $\langle W \rangle$ increase so much? Implies higher decay probability?

Weights and normalization

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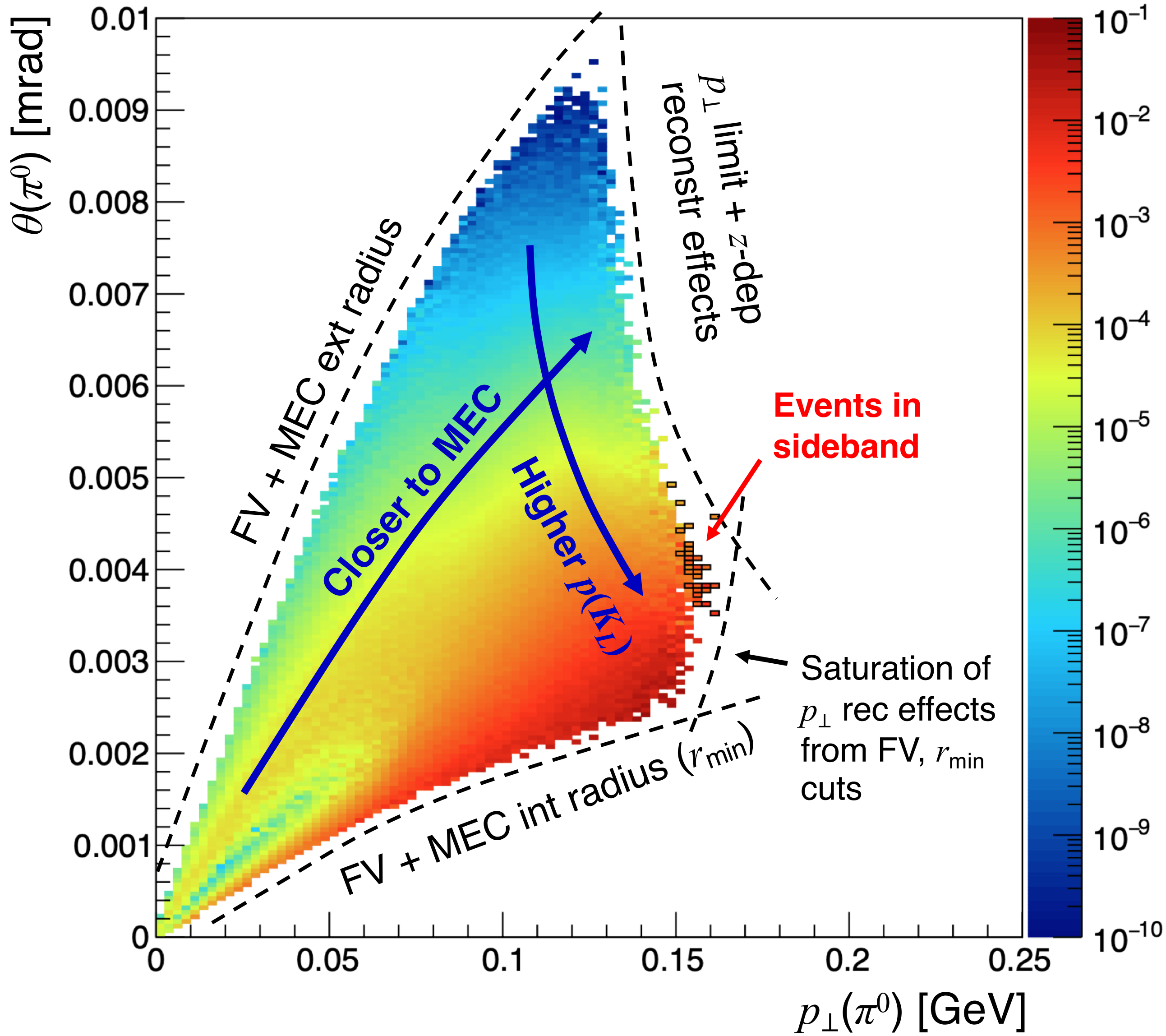
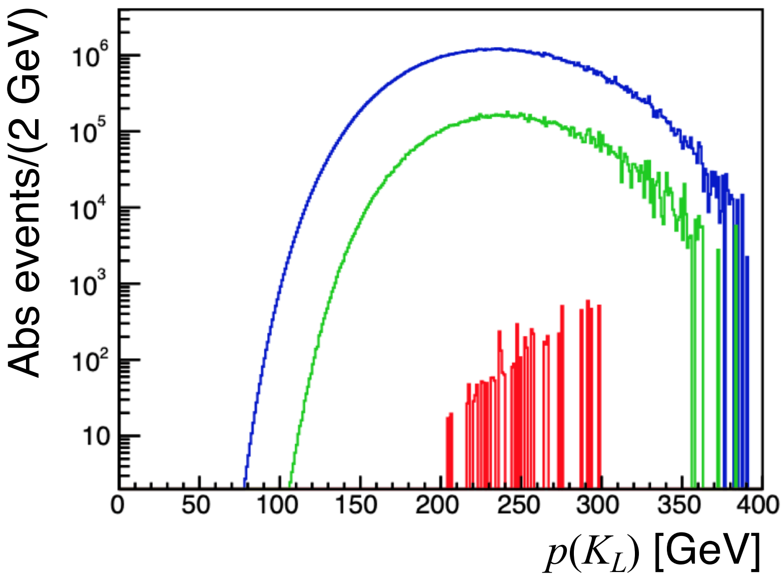
Decay weights for $\Lambda \to n\pi^0$ with 2γ on MEC + FV and r_{min} cuts



- Boundaries in $(p_\perp, \theta)$ plane are from FV cuts and int/ext calorimeter radii
- Angular acceptance increases with z
- $p_\perp$ misreconstruction effects are largest in downstream region
  - Background in high-$p_\perp$ selection will come from this region
- At given z, decay weight increases with Λ momentum
  - These events will dominate weight if any enter into sample

$\Lambda \to n\pi^0$ events by selection stage



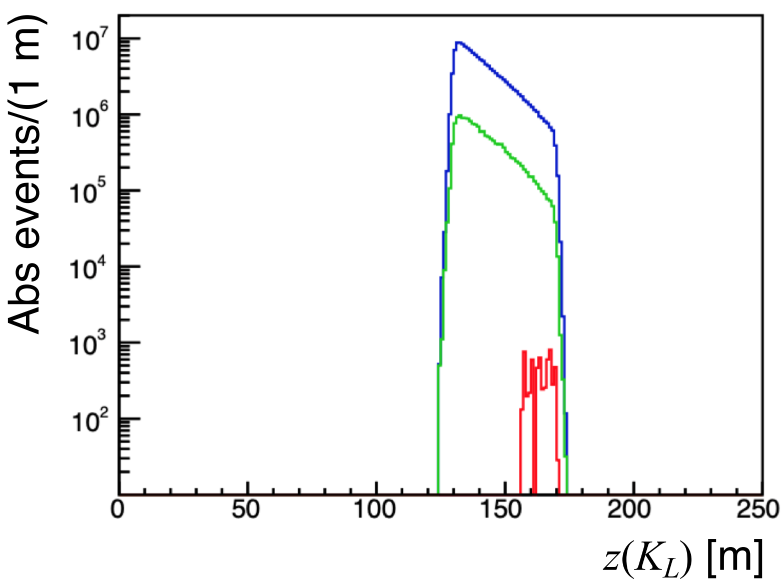
– 130 m < z < 170 m, r_{min} > 35 cm

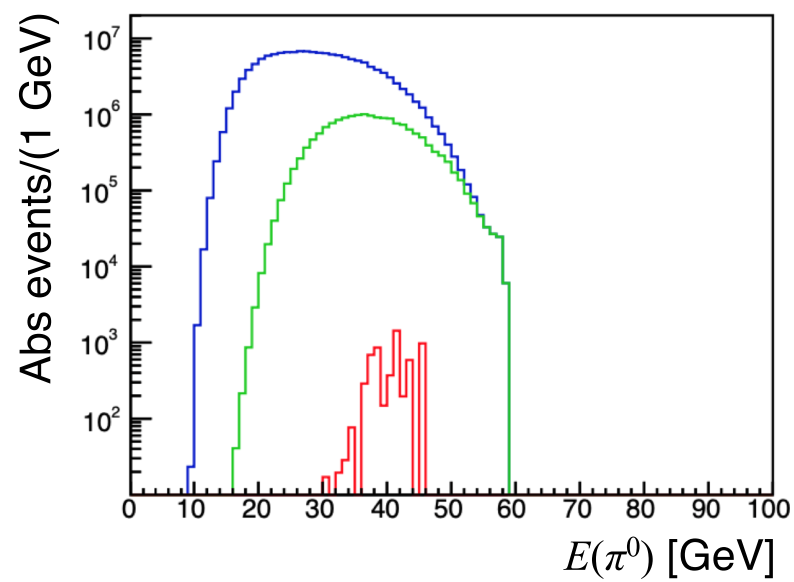
– FV and r_{min} cuts, $p_\perp$ > 120 MeV

– Events in ($p_\perp$, θ) sideband

Events passing all cuts:

- K_L momentum > 200 GeV
- Downstream edge of FV: z > 150 m
- Well reconstructed: $E(\pi^0) \sim 40$ GeV





Measures to reduce $\Lambda \to n\pi^0$

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Move FV further downstream?

Not likely to help by itself with current layout:

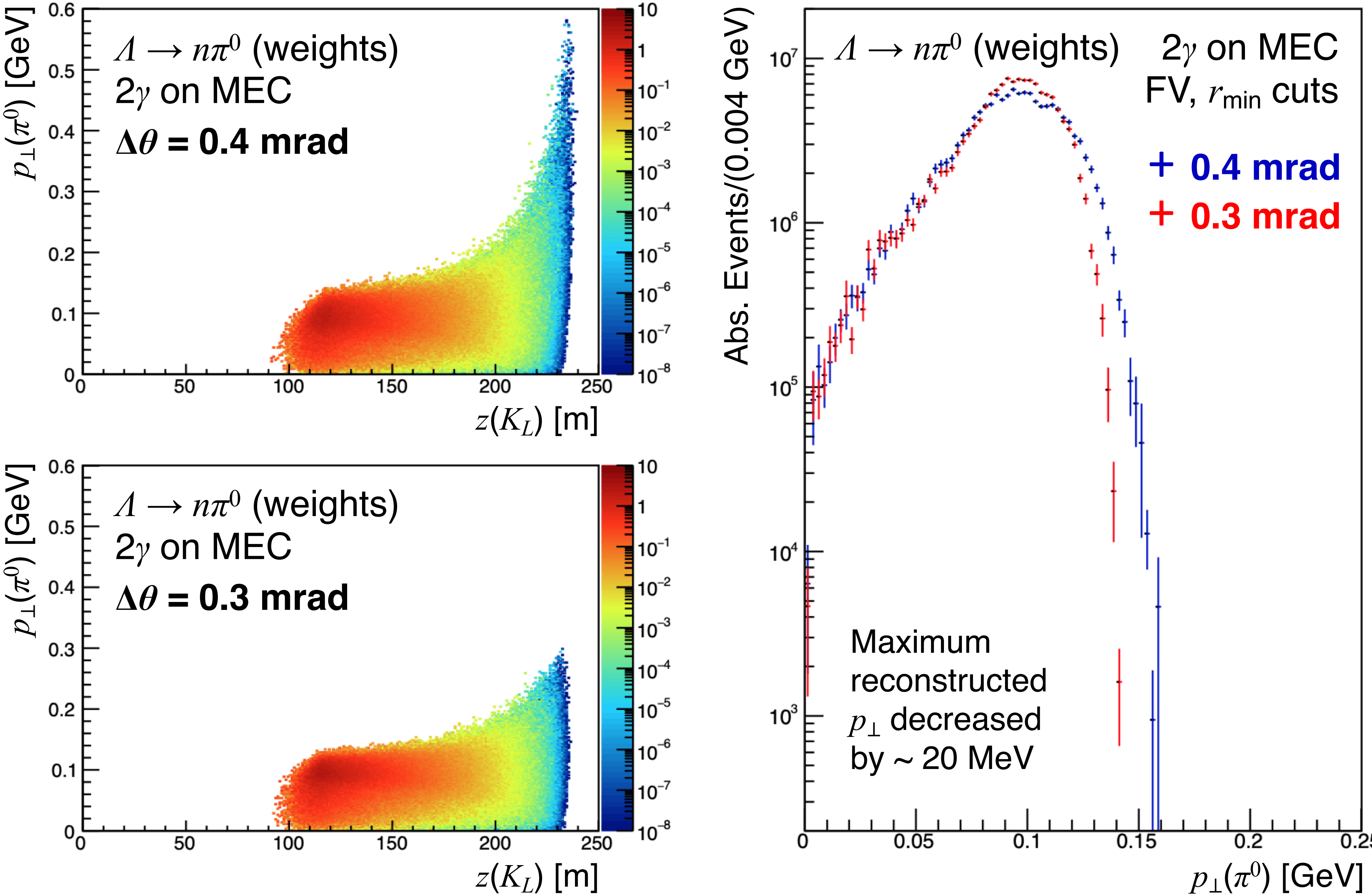
- λ_{eff} ~ 16 m near downstream end of FV
- $p_\perp$ reconstruction blows up near calorimeter
- Need to extend LAV coverage to handle odd pairs from $K_L \to \pi^0\pi^0$
- Maybe possible (or even necessary) if beam angle increased

Tighten beam collimation?

Potentially helpful but needs study:

- Main effect of beam opening angle spread is via quality of constraint in transverse plane for π^0 reconstruction (beam spot size)
  - Contribution of $p_\perp$(beam) to $p_\perp(\pi^0)$ is minor
- Substantial reduction of beam solid angle (e.g. 0.4 → 0.3 mrad) could help to eliminate residual $\Lambda \to n\pi^0$ and will definitely improve rejection for $K_L \to \pi^0\pi^0$
- Will reduce K_L flux (e.g. $0.3^2/0.4^2 = 0.56$)
- More intelligent use of PSD/higher angular resolution in calorimeter?

Effect on $p_\perp$: $\Delta\theta = 0.4$ vs 0.3 mrad



Measures to reduce $\Lambda \to n\pi^0$

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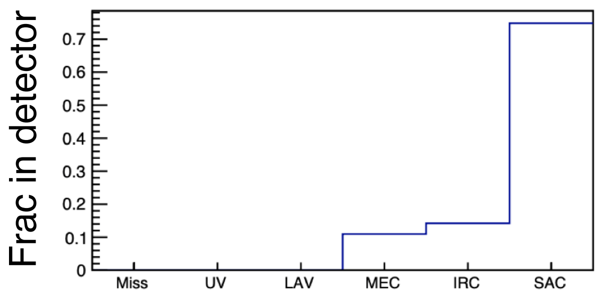
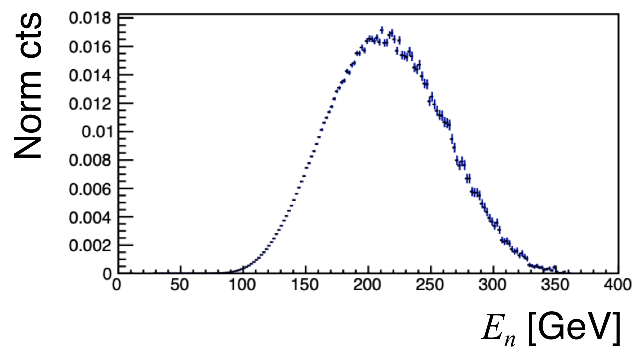
Reject neutrons from $\Lambda \to n\pi^0$ with dedicated hadronic SAC module?

Maybe not impossible:

- Would need to reject e.g. 90% of neutrons from $\Lambda \to n\pi^0$
- Many beam neutrons would veto → stringent timing requirements

$\Lambda \to n\pi^0$ decay (weights), 2γ on MEC





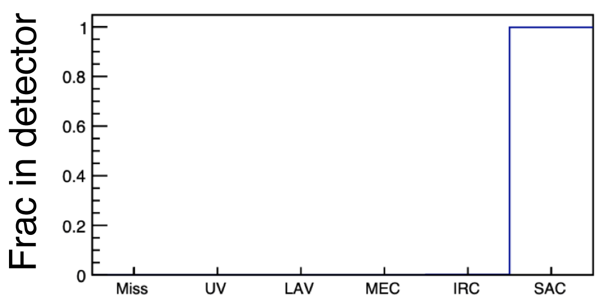
ε (in SAC) = 0.7480

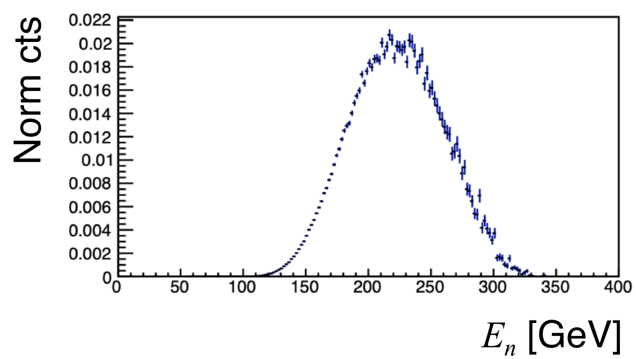
ε (> 100 GeV) = 0.9988

ε (> 150 GeV) = 0.9262

ε (> 200 GeV) = 0.6183

$\Lambda \to n\pi^0$ decay (weights), 2γ on MEC + FV, r_{min} cuts





ε (in SAC) = 0.9998

ε (> 100 GeV) = 1.0000

ε (> 150 GeV) = 0.9803

ε (> 200 GeV) = 0.7705

150 GeV hadronic energy threshold sufficient for 90% neutron efficiency

Measures to reduce $\Lambda \to n\pi^0$

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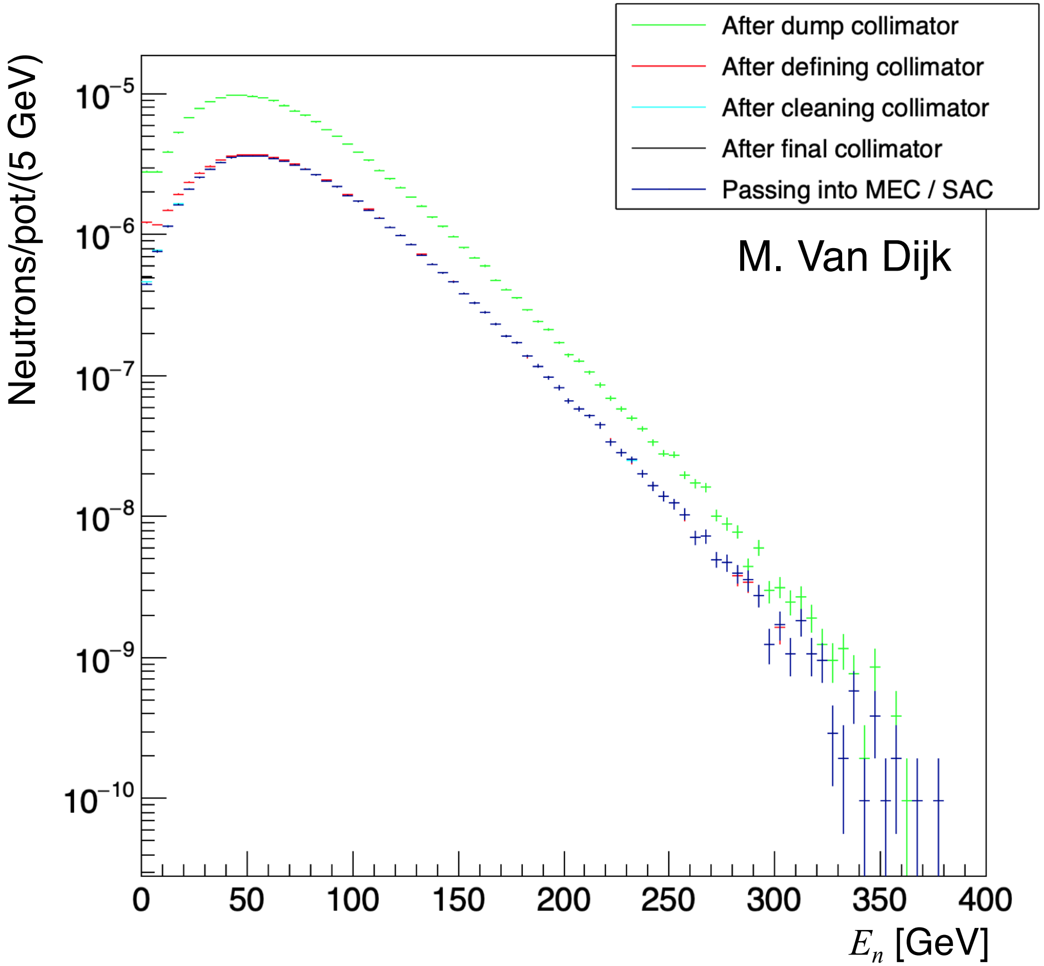
Reject neutrons from $\Lambda \to n\pi^0$ with dedicated hadronic SAC module?

Maybe not impossible:

- Would need to reject e.g. 90% of neutrons from $\Lambda \to n\pi^0$
- Many beam neutrons would veto → stringent timing requirements



n in beam = 1109 MHz

n in SAC = 423 MHz

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n (> 100 GeV) = 82 MHz

n (> 150 GeV) = 16.3 MHz

n (> 200 GeV) = 2.84 MHz

~90% rejection efficiency for $\Lambda \to n\pi^0$ can be obtained with hadronic SAC module:

- E_n > 150 GeV threshold
- ~20 MHz additional veto rate
- Current veto rate ~ 140 MHz

Measures to reduce $\Lambda \to n\pi^0$

Longer beam line?

Small increase not likely to help significantly

- λ_{eff} ~ 16 m: Adding 30 m from target to start of FV gives ~7x reduction
- About 10 m of space remaining in hall in current layout

Reduce beam energy?

Likely effective, requires study

- 400 → 300 GeV = 7.5 → 10 decay lengths in beamline: ~12x reduction
- Need to reoptimize production angle
- Will reduce K_L flux
- Requires negotiation with other NA users

Measures to reduce $\Lambda \to n\pi^0$

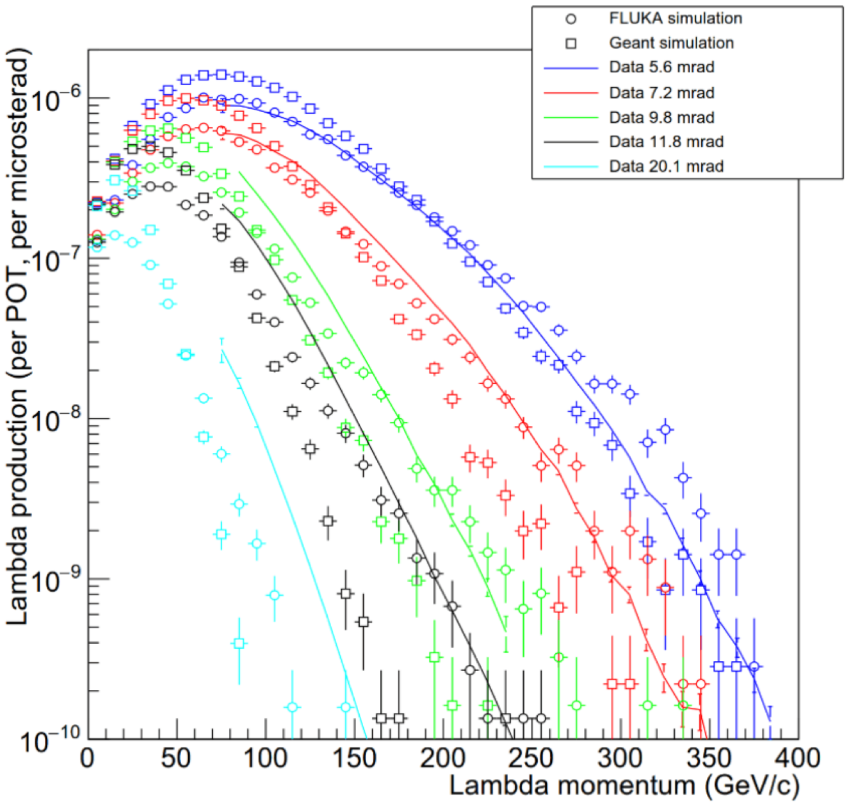
Increase targeting angle?

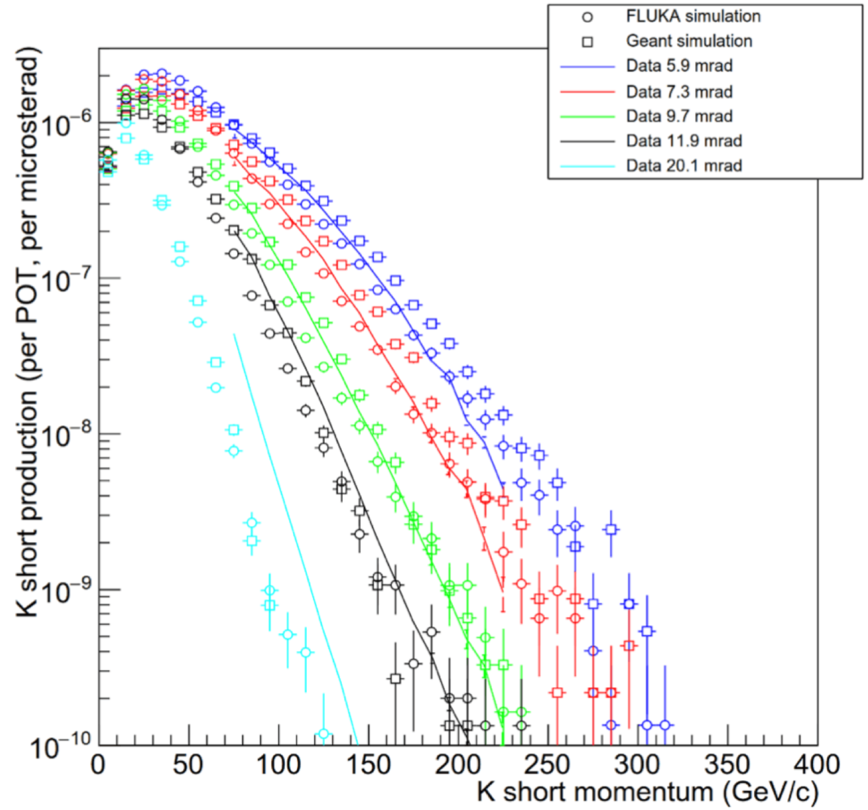
Likely effective, requires study

- Reduces Λ flux and softens momentum spectrum: fewer Λ in FV
- Will reduce K_L flux and soften K_L spectrum
  - If K_L momentum reduced too much may need to make changes to layout (e.g., extend LAV coverage)
- Will require new target design
  - Larger transverse dimensions larger target image
  - High-Z target: substantially more complicated, more surrounding material
- Feasibility of large angles (e.g. 20 mrad) needs to be studied from standpoint of primary beam steering

Targeting angle considerations

M. Van Dijk, CERN-ACC-NOTE 2018-0066





Could try to increase production angle to 12, 16 or even 20 mrad

- FLUKA and Geant spectra already parameterized by Maarten
  - Malensek reasonable up to 12 mrad; overestimates Λ production at 20 mrad
- Move from 2.4 → 8 mrad decreased Λ in FV by 370x
- Increases FV acceptance: K_L in FV decreased only ~2x after reoptimization

Beam angle change: Current status

Reviewing K_L and Λ yields vs production angle:

- Obtained from Maarten root files with FLUKA and Geant4 spectra + all fit results and code
- Need to integrate spectra beyond 16 mrad
- Would like to explore fit systematics in high momentum tails at larger angles

First samples for angle scan produced:

- Scan 8 to 24 mrad in 4 mrad steps
- 167M/step $\Lambda \to n\pi^0$ with decay weights (1/10 of usual statistics)
- 100M/step $K_L \to \pi^0\nu\nu$
- Focus first on signal acceptance and Λ rejection:
  - Substantial layout changes may be needed
  - $K_L \to \pi^0\pi^0$ is time-consuming to generate

Beam angle change: Next steps

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Reoptimization needed when production angle changes:

- Fiducial volume (moves downstream with increasing angle)
- Beam opening angle (decreases, as per above)
- LAV coverage (extends further in polar angle, less boost)
- Energy threshold on MEC for signal events (decreases, lower π^0 energy)
- Efficiency requirements (maybe)
- Analysis cuts (try to increase acceptance)

Systematic exploration of parameter space vs rapid identification of a possible solution

- What if the best solution also requires a slight reduction of the beam energy (e.g. to 350 GeV)?

Need to modify and re-run Maarten's FLUKA beamline simulations after converging on new beam angle and layout modifications

Ongoing projects

1. **Angle change and reoptimization of experiment**
2. **Beamline optimization and simulation (FLUKA)**
   - **Re-run beamline simulation, esp. flux and rate estimates**
3. **KLMC**
   - **Summer student program**
     - Goal to restart work on KLMC to make it fully useable
     - Framework etc.: K. Richardson (USA), in coordination with other students
     - Preshower: D. Hunt (Birmingham) to simulate basic design
     - MEC/Shashlyk: J. Conragan (USA) to simulate basic design
     - SAC: D. Soldi (volunteer), interested for APEIRON: algorithms for online γ/n separation to run in SAC front end (test case)
   - **Longer term**
     - Need to systematically validate and extend studies done so far:
       - Scattered Λ and cascading hyperon decays
       - Neutron halo
       - Decays to charged particles, including radiative decays

Deadlines

FPCP 2020: 12 June

- Cristina L. has a 30 min talk on future kaon experiments after NA62 & KOTO
  - I am not comfortable with a KLEVER 8 mrad hard sell at this point
  - A few slides with the caveat that we are considering a change to the beam angle to further decrease the Λ background?

Snowmass

- EoI (2 pages) due 31 August: Need a firm idea of KLEVER feasibility at new angle and changes needed to layout
- Paper due 31 July 2021: White-paper level of detail?

CERN Seminar

- Postponed to September: not yet scheduled. Ideally would have enough detail about the new layout for a seminar-level presentation

White paper with NA62?