K_LEVER

News and progress on sensitivity

NA62 Italia, 04 May 2020

(Slides from NA62 Future, 17 April 2020)

Matthew Moulson
INFN Frascati

Sensitivity update (from 08 April)

Consolidation of sensitivity analysis for KLEVER CDS:

- Malensek generator for all samples ($\pi^0\nu\nu$, $\pi^0\pi^0$, $\Lambda \to n\pi^0$)
- Decay weights for $\Lambda \to n\pi^0$ to increase effective statistics
- Explore use of efficiency weights
- Fix issue with clustering of hits on MEC: affects $\pi^0\pi^0$ sample
- First attempt at optimization of selection cuts: FV, r_{min}, $p_\perp$, $\theta_{\pi 0}$ and preshower

2020v0 zOptical samples: Malensek K_L and Λ generators

$\boldsymbol{K_L \to \pi^0\nu\nu}$	100M events (scale 3000x)
$\boldsymbol{K_L \to \pi^0\pi^0}$	910G events (scale 1x)
$\boldsymbol{\Lambda \to n\pi^0}$	83.6G events (scale 1/2000)
	836M events weighted (scale tbd)

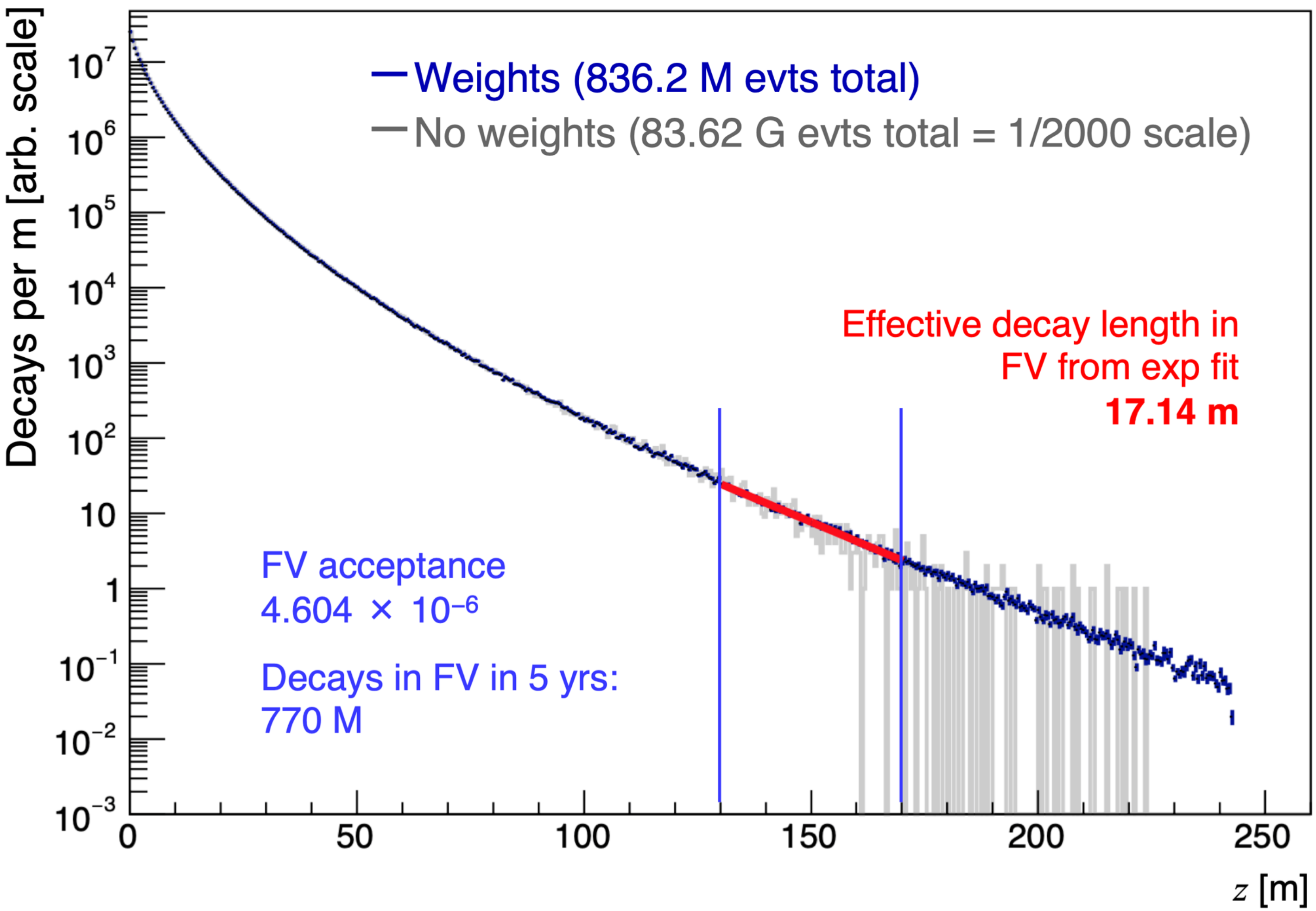
- K_L produced in 5 yrs from Maarten's results: **includes converter losses**
- Does not include losses to random veto

30 expected signal events

54 expected background from $K_L \to \pi^0\pi^0$

$\Lambda \to n\pi^0$ background: 08 April

Λ fiducial volume acceptance

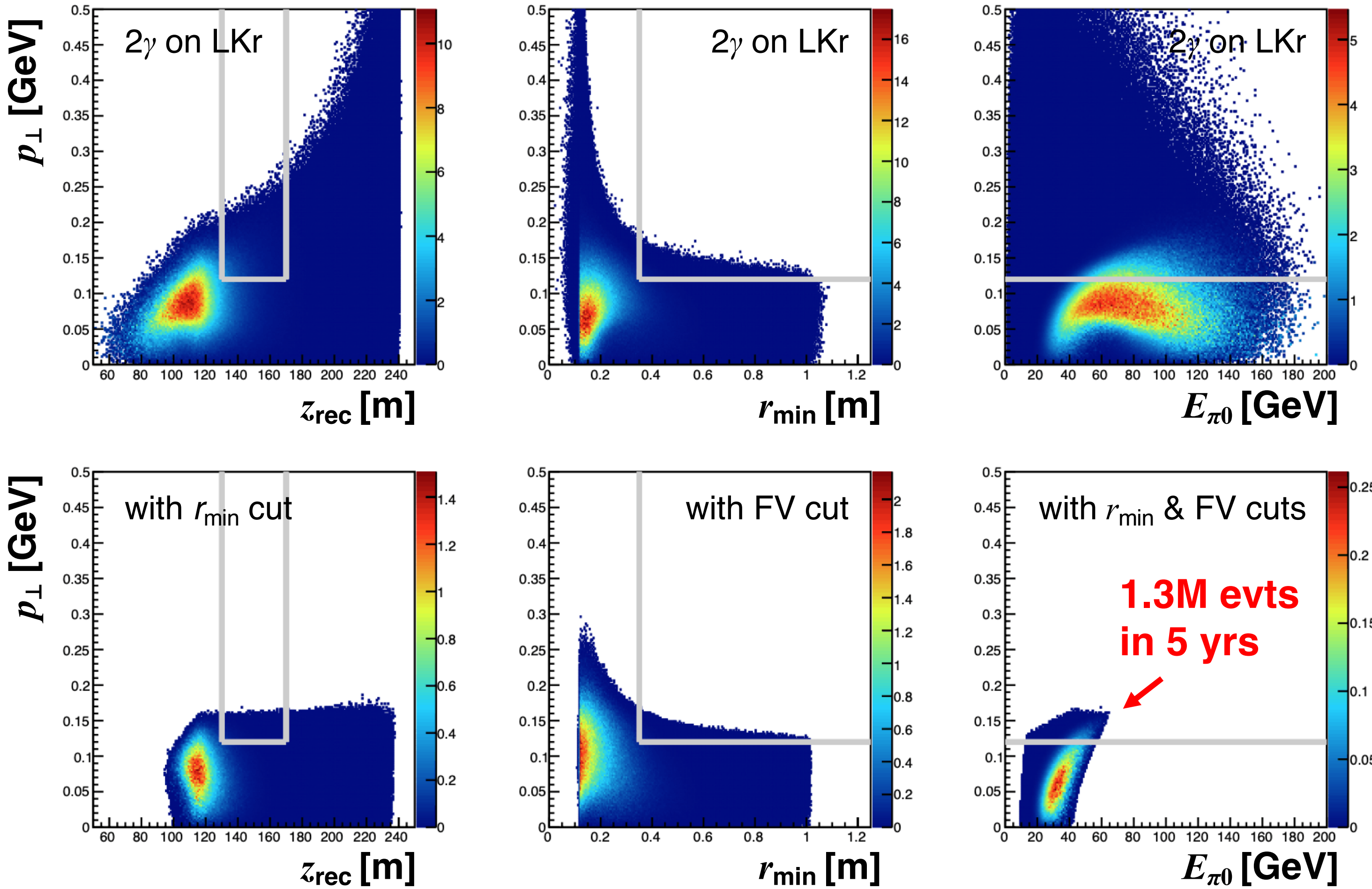


KLEVER: News and progress on sensitivity – M. Moulson – 08 April 2020 6

$\Lambda \to n\pi^0$ background: 08 April

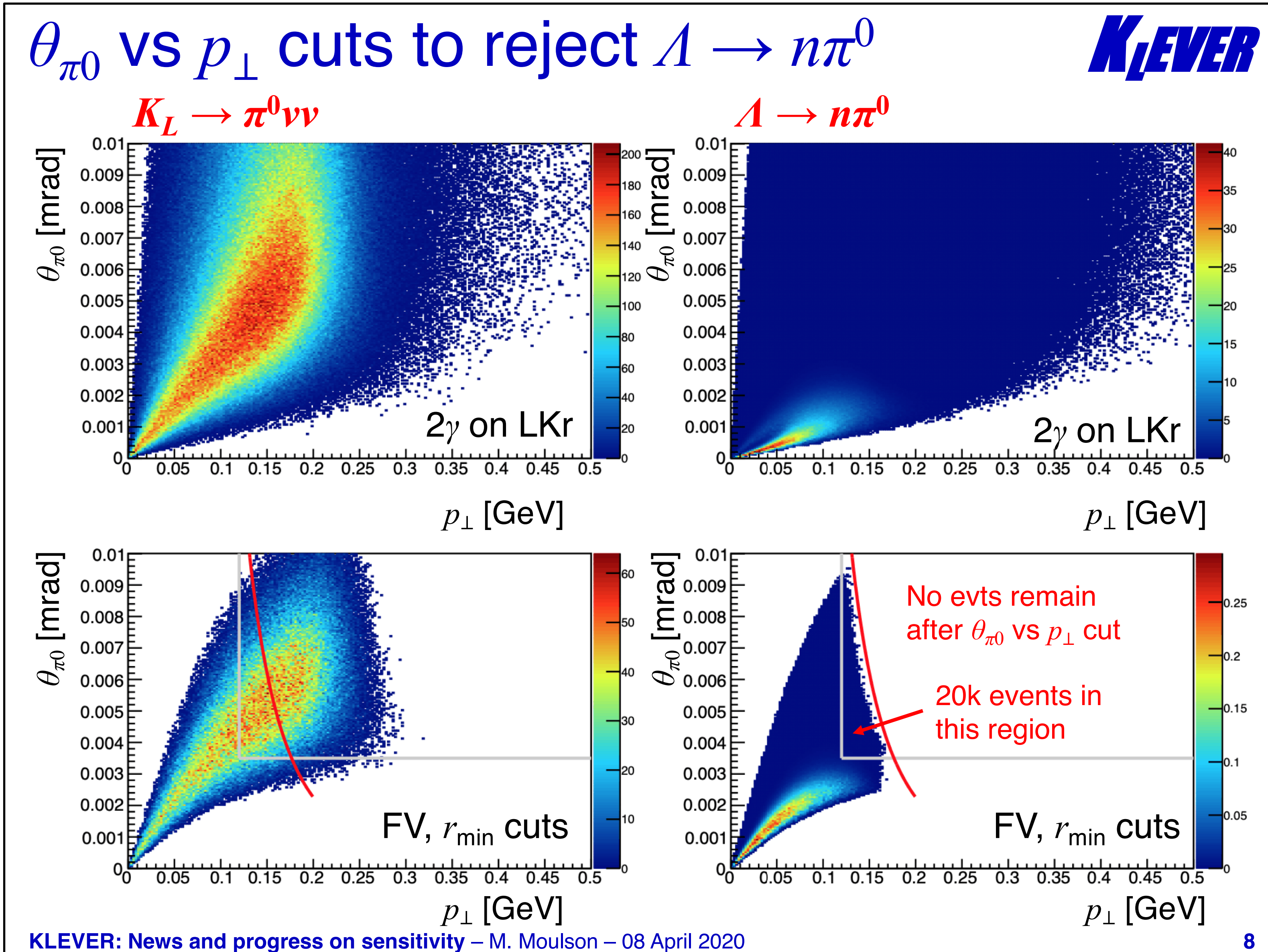
$\Lambda \to n\pi^0$ background

863.2M $\Lambda \to n\pi^0$ with Malensek/FLUKA spectrum, decay weights



$\Lambda \to n\pi^0$ background: 08 April

KLEVER



$\Lambda \rightarrow n\pi^0$ background: 08 April

KLEVER

08 Apr 2020 results with revisions

Stage	Acceptance	Cumulative acceptance	Events in 5 yrs
Produced $\Lambda \rightarrow n\pi^0$	1	1	$1.672 \times 10^{14*}$
Decay in FV	4.713×10^{-6}	4.713×10^{-6}	$7.882 \times 10^{8\dagger}$
2γ on LKr	1.691×10^{-5}	1.691×10^{-5}	$2.828 \times 10^{9\dagger}$
+ Reconst. in FV	0.1362	2.303×10^{-6}	3.852×10^{8}
+ $r_{\mathrm{min}} > 35$ cm	0.05391	1.242×10^{-7}	2.077×10^{7}
+ $p_{\perp} > 120$ MeV	0.06292	7.814×10^{-9}	1.307×10^{6}
+ $\theta_{\pi 0}$ vs $p_{\perp}$ cut	$< 1 \times 10^{-7}$	$< 8 \times 10^{-16}$	$< 0.126^{\ddagger}$ (no events left)

Notes:

* Λ produced in 5 yrs including converter losses (2x)

† FV acceptance 30-40% higher than Apr 2018: histogram sampling?

‡ Recalculated limit for no events in sample: **decreased by 10x**

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

Conclusions from 08 April:

$\Lambda \to n\pi^0$ is distinguishable *in principle*

- $\Lambda \to n\pi^0$ in the beam are confined to a kinematic region that can be excluded preserving substantial $K_L \to \pi^0 \nu\nu$ acceptance
- In worst case, the above can be accomplished by a hard $p_\perp$ cut, so conclusion is not necessarily changed by uncertainties concerning:
  - Λ production rate and momentum spectrum
  - Λ polarization/angular distribution (generator uses isotropic 2-body decay)
    - Preliminary update (04 May): polarization added to generator
    - Doesn't appear to make any significant difference

***In practice* it is highly desirable to further reduce Λs in FV**

- Even for $\Lambda \to n\pi^0$ in the beam, 10^{-7} rejection required from kinematics alone
- 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

$\Lambda \to n\pi^0$ generator problem

On Thursday 9 April (1 day after meeting), I started investigating events with π^0 at high $p_\perp$ and θ.

I quickly found this bug:

```
// Generate momentum of beam KL

  fSource->Generate();
  Double_t p = fSource->GetMomentum();
  fp.SetXYZM(p*sth*cph, p*sth*sph, p*cth, mK0);
```

The last line should be:

```
  fp.SetXYZM(p*sth*cph, p*sth*sph, p*cth, fParentMass);
```

The K^0 mass was being used to calculate the boost vector for the beam particle, used to boost the decay into the lab frame.

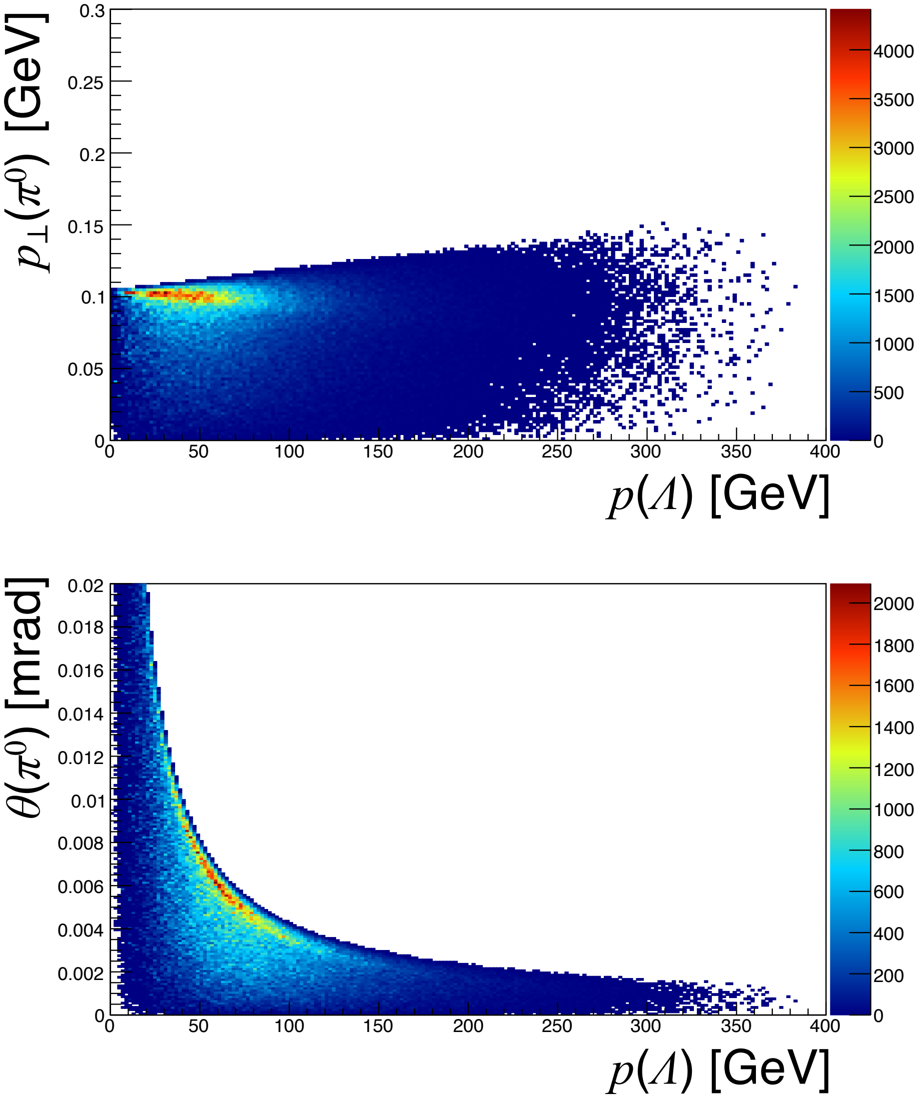
Even for the $\Lambda \to n\pi^0$ generator.

The distribution of Λ decay position is not affected.

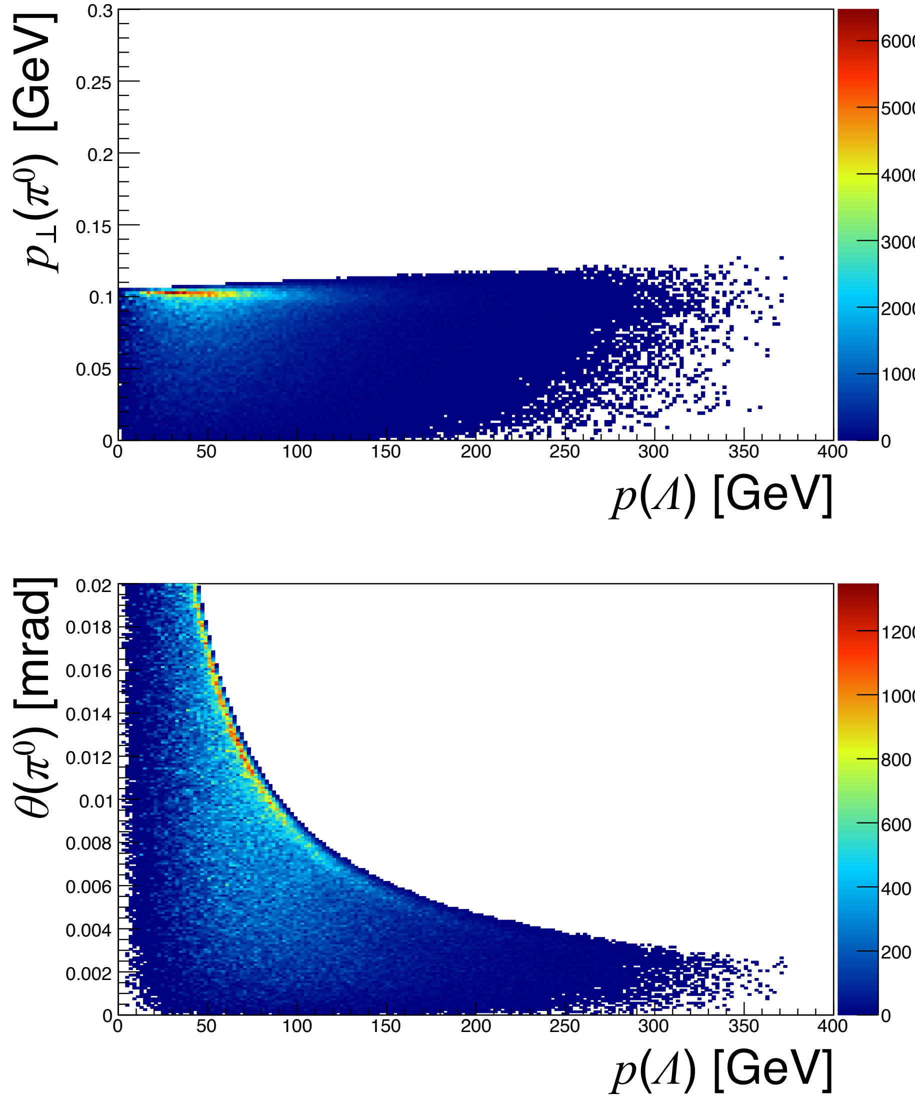
$\Lambda \to n\pi^0$ generator problem

zOptical $\Lambda \to n\pi^0$ decay generator output

Old (bug)



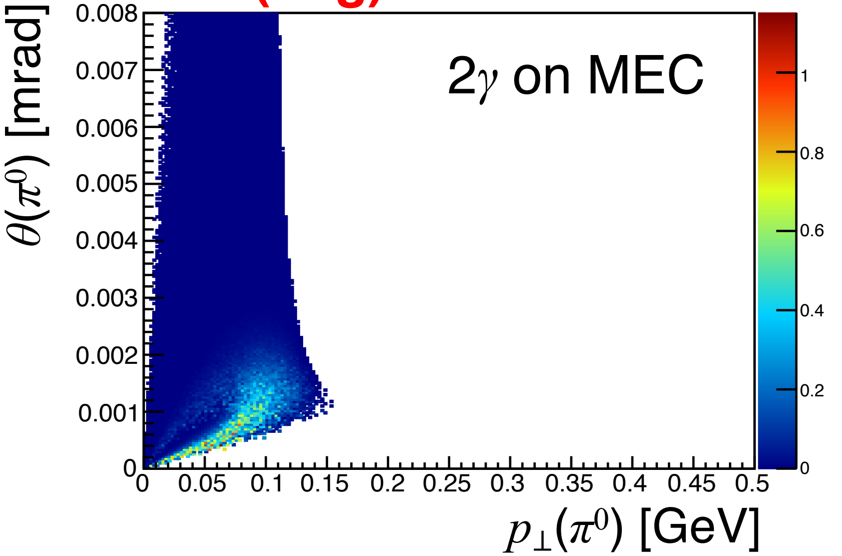
New (bug fixed)



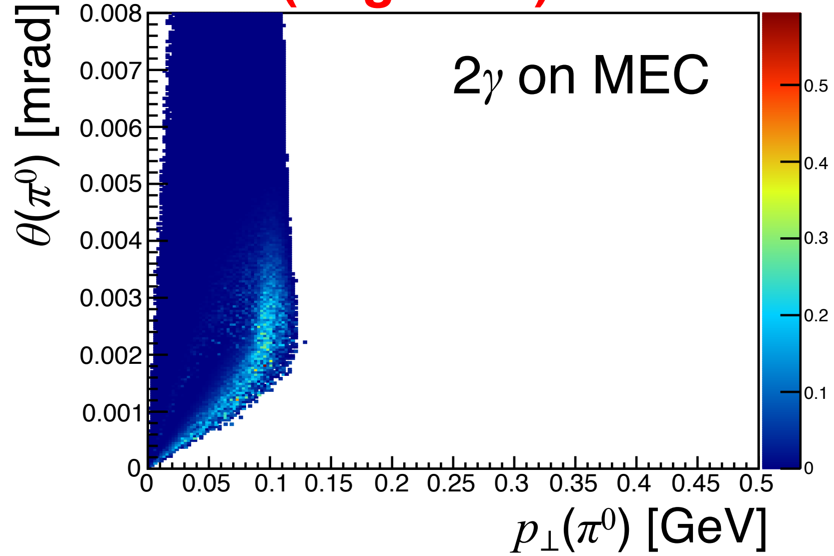
$\Lambda \to n\pi^0$ generator problem

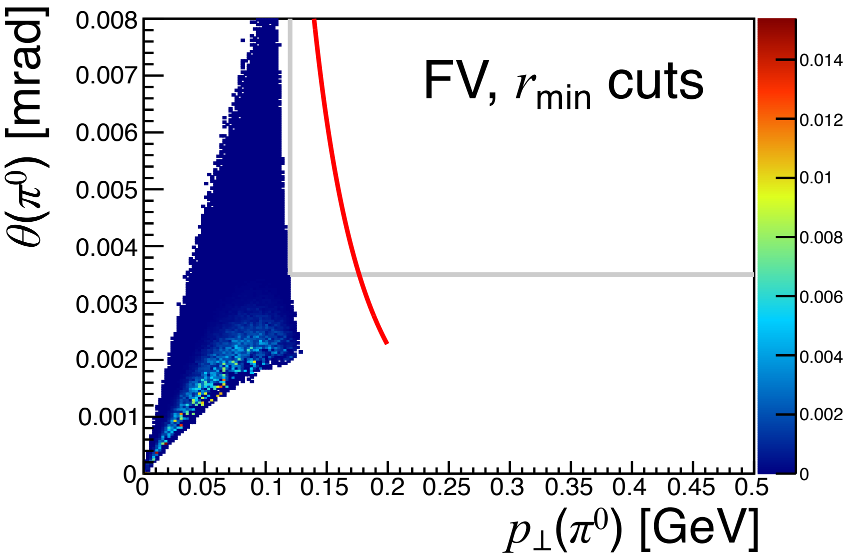
MC true quantities for selected events (for illustration: limited statistics)

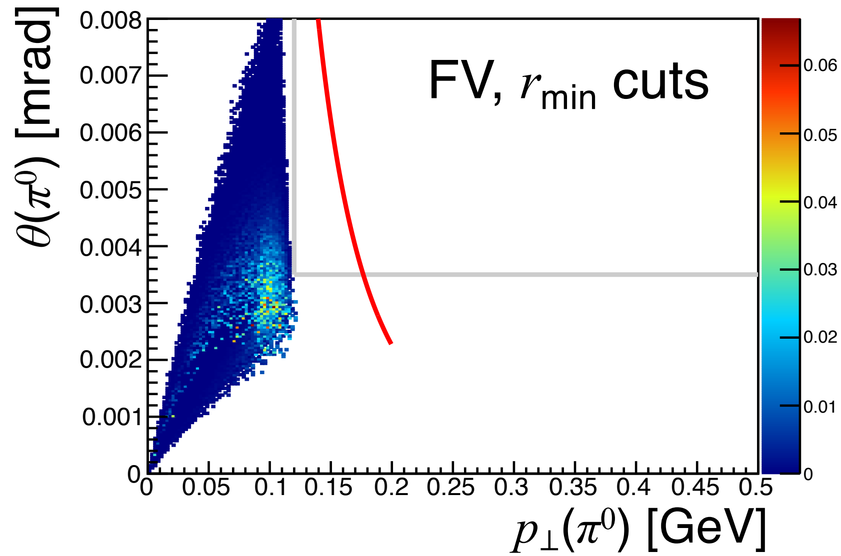
Old (bug)



New (bug fixed)



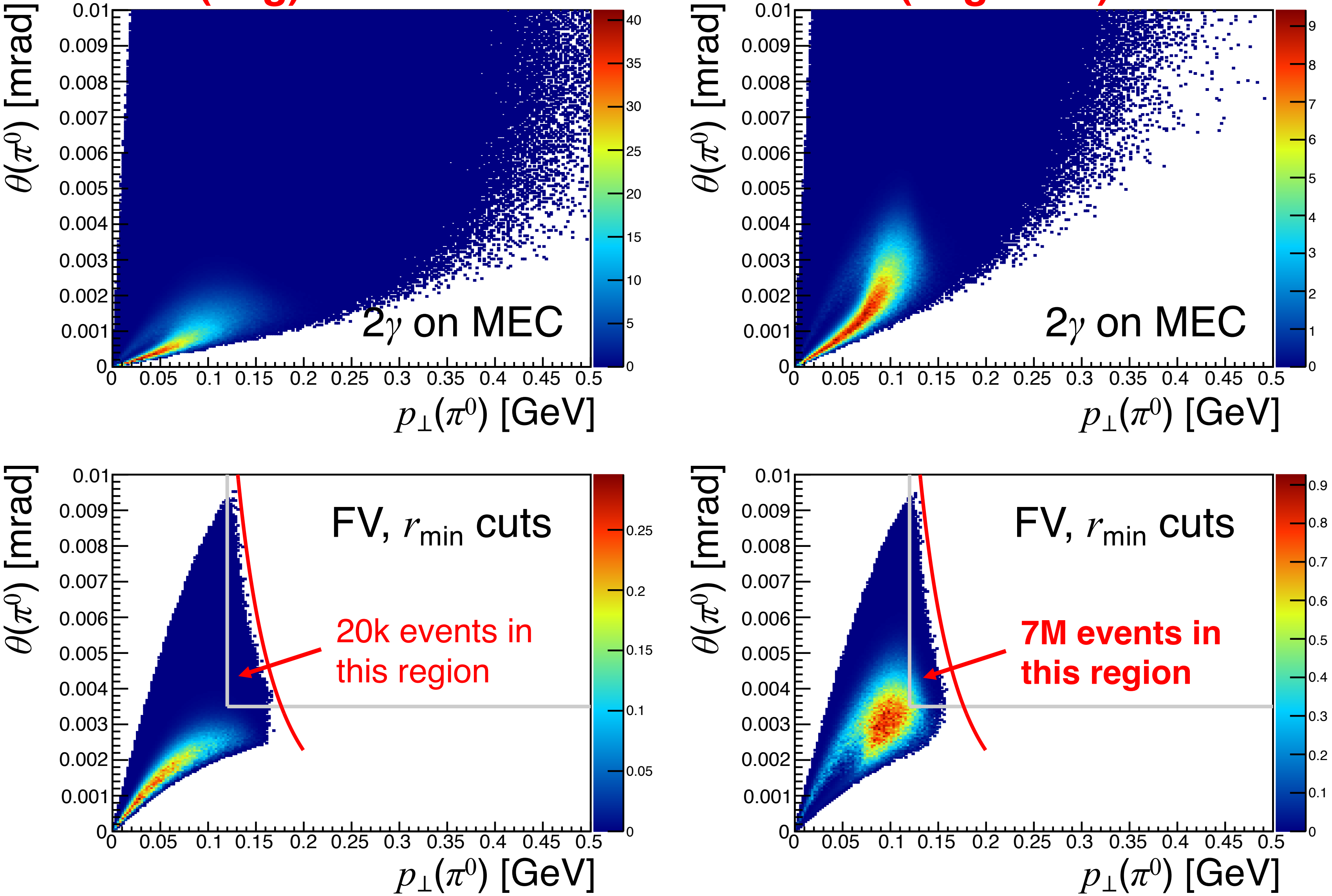




$\Lambda \to n\pi^0$ generator problem

863.2M $\Lambda \to n\pi^0$ with Malensek spectrum, decay weights, as reconstructed

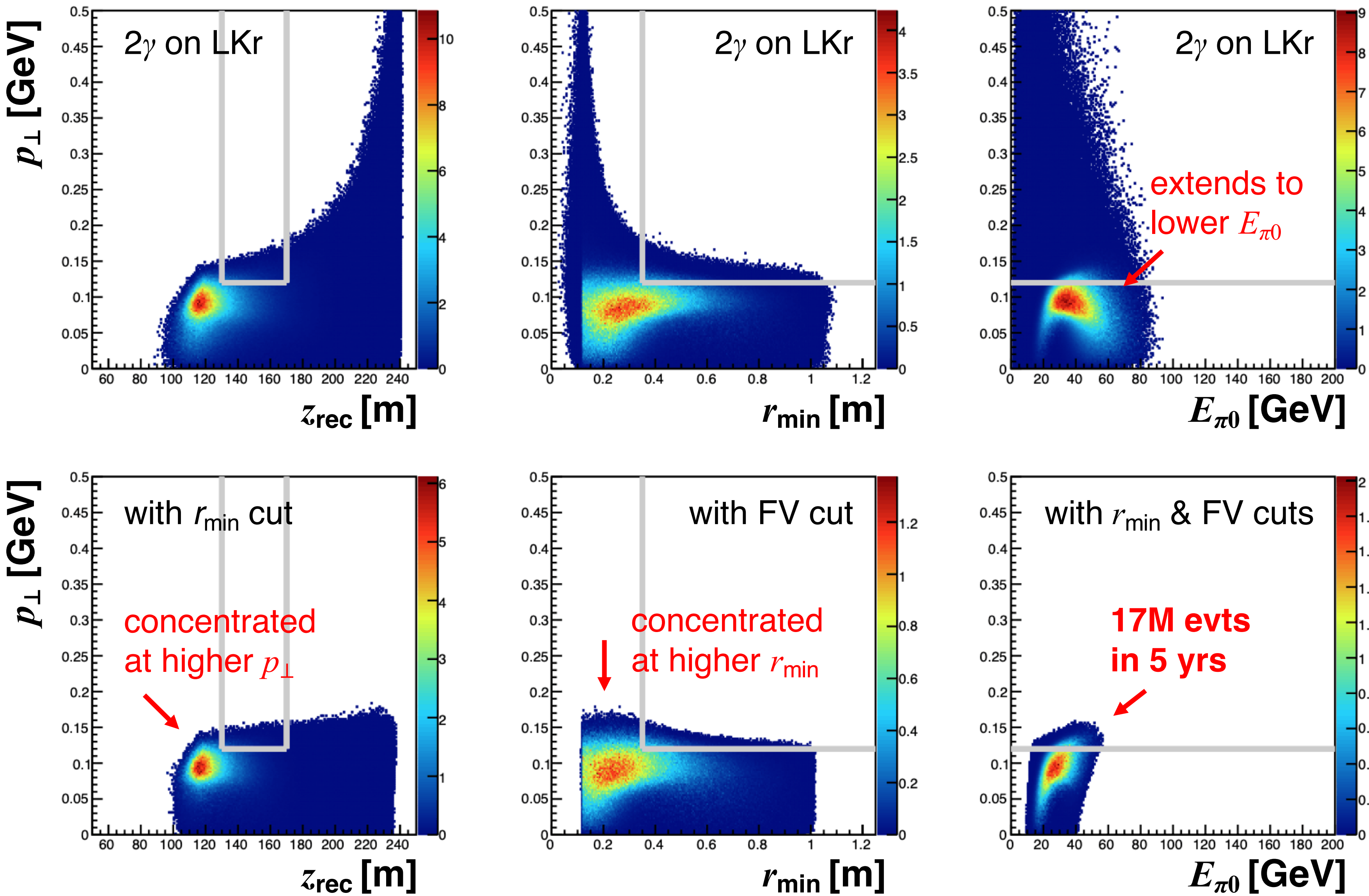
Old (bug) **New (bug fixed)**



$\Lambda \to n\pi^0$ updated background

KLEVER

863.2M $\Lambda \to n\pi^0$ with Malensek/FLUKA spectrum, decay weights



$\Lambda \to n\pi^0$ updated background

KLEVER

Stage	Acceptance	Change	Events in 5 yrs	Change
Produced $\Lambda \to n\pi^0$	1		1.672×10^{14}	
Decay in FV	4.693×10^{-6}	1.0	7.848×10^{8}	1.0
2γ on LKr	7.891×10^{-6}	0.5	1.320×10^{9}	0.5
+ Reconst. in FV	0.3241	2.4	4.278×10^{8}	1.2
+ $r_{\mathrm{min}} > 35$ cm	0.3374	6	1.443×10^{8}	7
+ $p_\perp > 120$ MeV	0.1164	1.9	1.679×10^{7}	13
+ $\theta_{\pi 0}$ vs $p_\perp$ cut	$< 3.3 \times 10^{-5}$	**?**	< 560 (no events left)	**?**

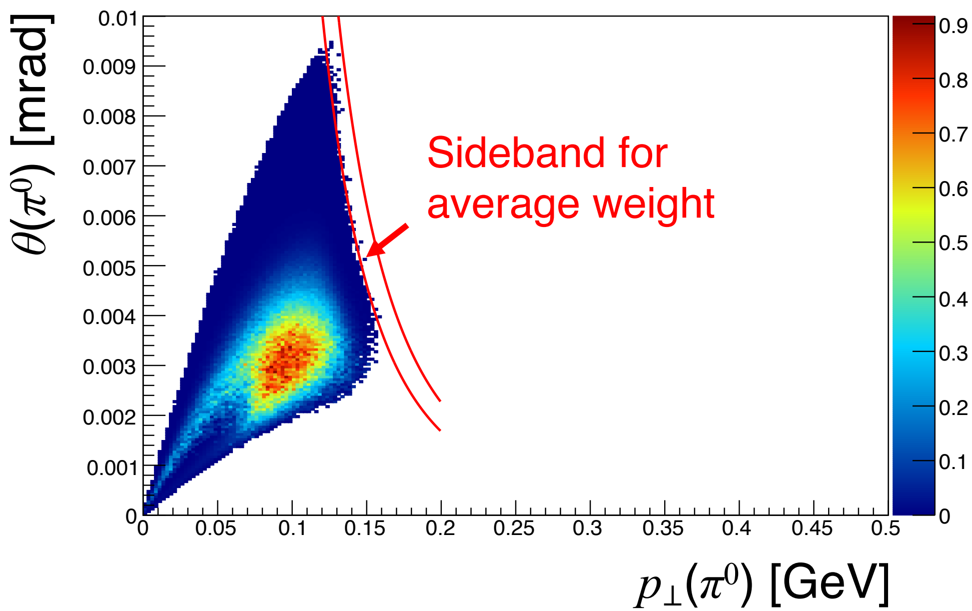
Notes:

- Order of magnitude more rejection required from $p_\perp$ and $\theta_{\pi 0}$ cuts: $10^{-7} \to 10^{-8}$
- Event concentration much closer to cut boundary in $p_\perp$ and $\theta_{\pi 0}$
- Still no events survive selection
- Limit is 4400x higher (0.126 → 560 events)! Why?

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?

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 (preliminary result: not significant?)
- 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

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

Longer beam line: λ_{eff} ~ 16 m

- Adding 30 m from target to start of FV gives ~7x reduction

Reduce beam energy:

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

Increase targeting angle further:

- Reduces Λ flux and softens momentum spectrum: fewer Λ in FV
- Will reduce K_L flux and soften K_L spectrum

Tighten beam collimation:

- E.g. 0.4 → 0.35 mrad: more kinematic margin
- Will reduce K_L flux

Extend large-angle veto coverage: moved FV further downstream

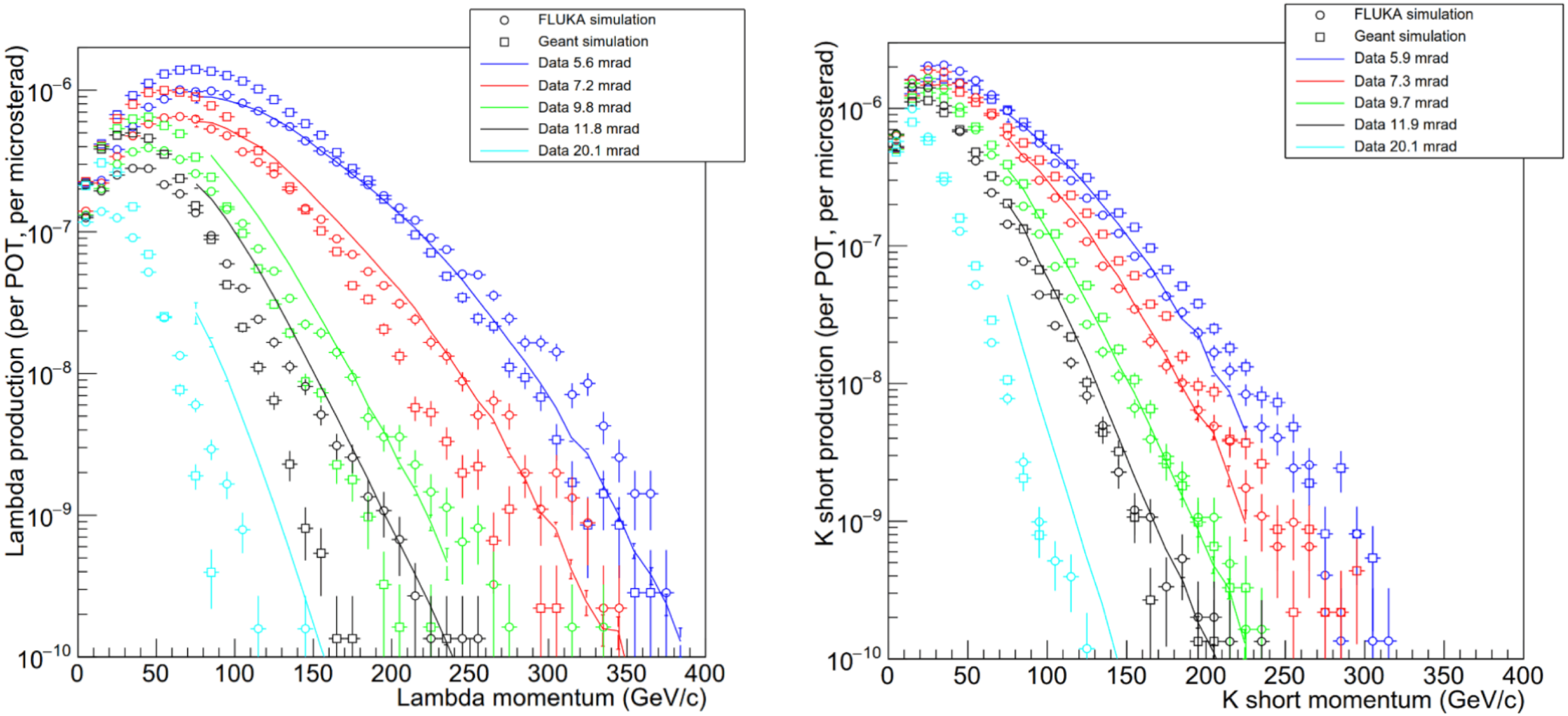
- Be careful: $p_\perp$ reconstruction blows up near calorimeter

Try to reject very high energy neutrons with SAC: dedicated hadronic module

- A large fraction of beam neutrons would veto → stringent timing requirements or increased random veto rate

Targeting angle considerations

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



Could try to increase production angle to 10, 12 or even 20 mrad

- Move from 2.4 → 8 mrad decreased Λ in FV by 370x
  - Increases FV acceptance: K_L in FV decreased only ~2x
- K_L momentum will be significantly reduced: changes to LAV coverage
- Complications for beam targeting scheme, need wider target

New reference sensitivity analysis

Conservative scheme: try to push down S/B and examine how robust background rejection is, esp. for $K_L \to \pi^0\pi^0$

Require at least 1 hit from PSD: z_{PSD} < 170 m ($z_{\mathrm{max\ FV}}$)

- Adds redundancy for rejection of odd pairs, reduces rejection factor required from calorimeter
- Very loose cut, perhaps possible to improve

Increase $p_\perp$ cut from 120 MeV to 160 MeV

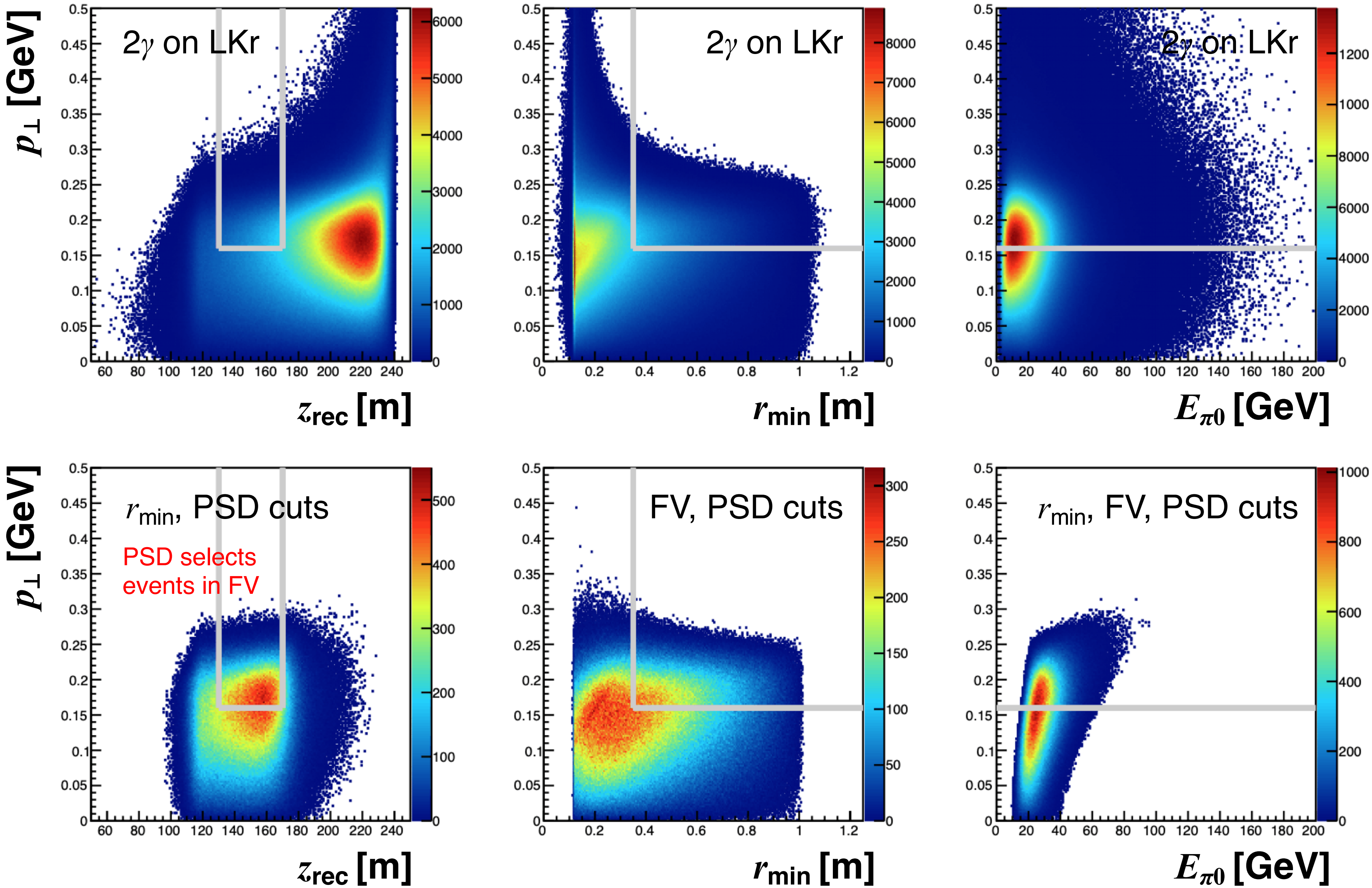
- Instead of $\theta_{\pi0}$-dependent cut: Simpler analysis scheme for $K_L \to \pi^0\pi^0$
- Sufficient to nominally reject $\Lambda \to n\pi^0$, in the same sense as before

In the following:

- K_L produced in 5 yrs from Maarten's results: **includes converter losses**
- Does not include losses to random veto
- Not too much room for further optimization because $\Lambda \to n\pi^0$ fixes $p_\perp$ cuts

Signal acceptance

1G $K_L \to \pi^0 \nu\nu$ with Malensek/FLUKA spectrum



Signal acceptance

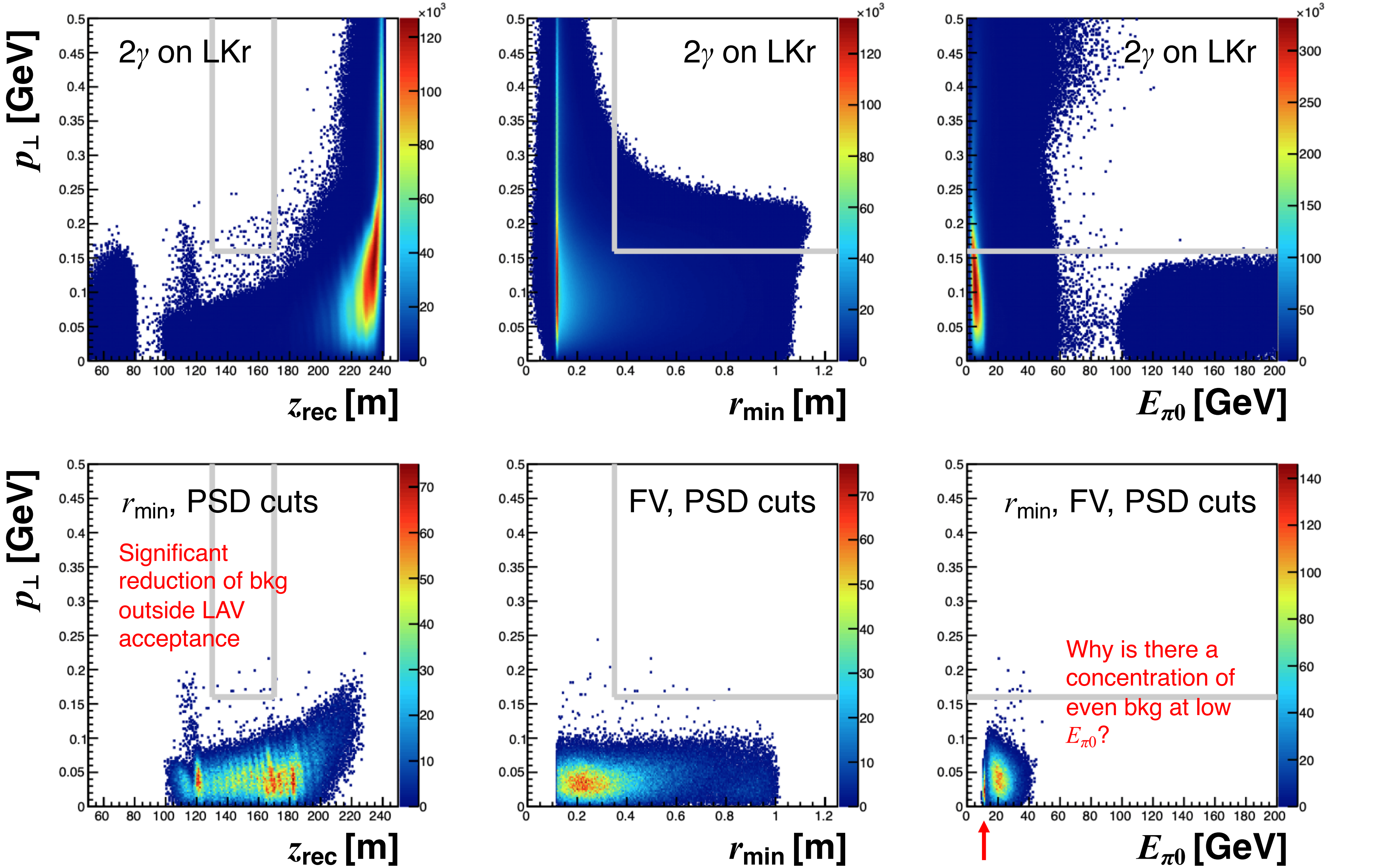
Stage	Acceptance	Cumulative acceptance	Events in 5 yrs
Prod. $K_L \to \pi^0 \nu\nu$	1	1	**35819**
Decay in FV	4.040%	4.040%	**1448**
2γ on LKr	2.228%	2.228%	**798**
+ Reconst. in FV	0.1693	3.771×10^{-3}	**135**
+ $r_{\text{min}} > 35$ cm	0.5483	2.068×10^{-3}	**74**
+ $z_{\text{PSD}} < 170$ m	0.4660	0.964×10^{-3}	**35**
+ $p_\perp > 160$ MeV	0.4293	0.414×10^{-3}	**15**

Notes:

- PSD efficiency of 0.47 is essentially prob of at least 1 conversion in 0.5 X_0
- Hard $p_\perp$ cut (ε = 0.43) substitutes $\theta_{\pi 0}$- $p_\perp$ cut and has about same efficiency
- Decrease from 30 to 15 events essentially from added PSD requirement

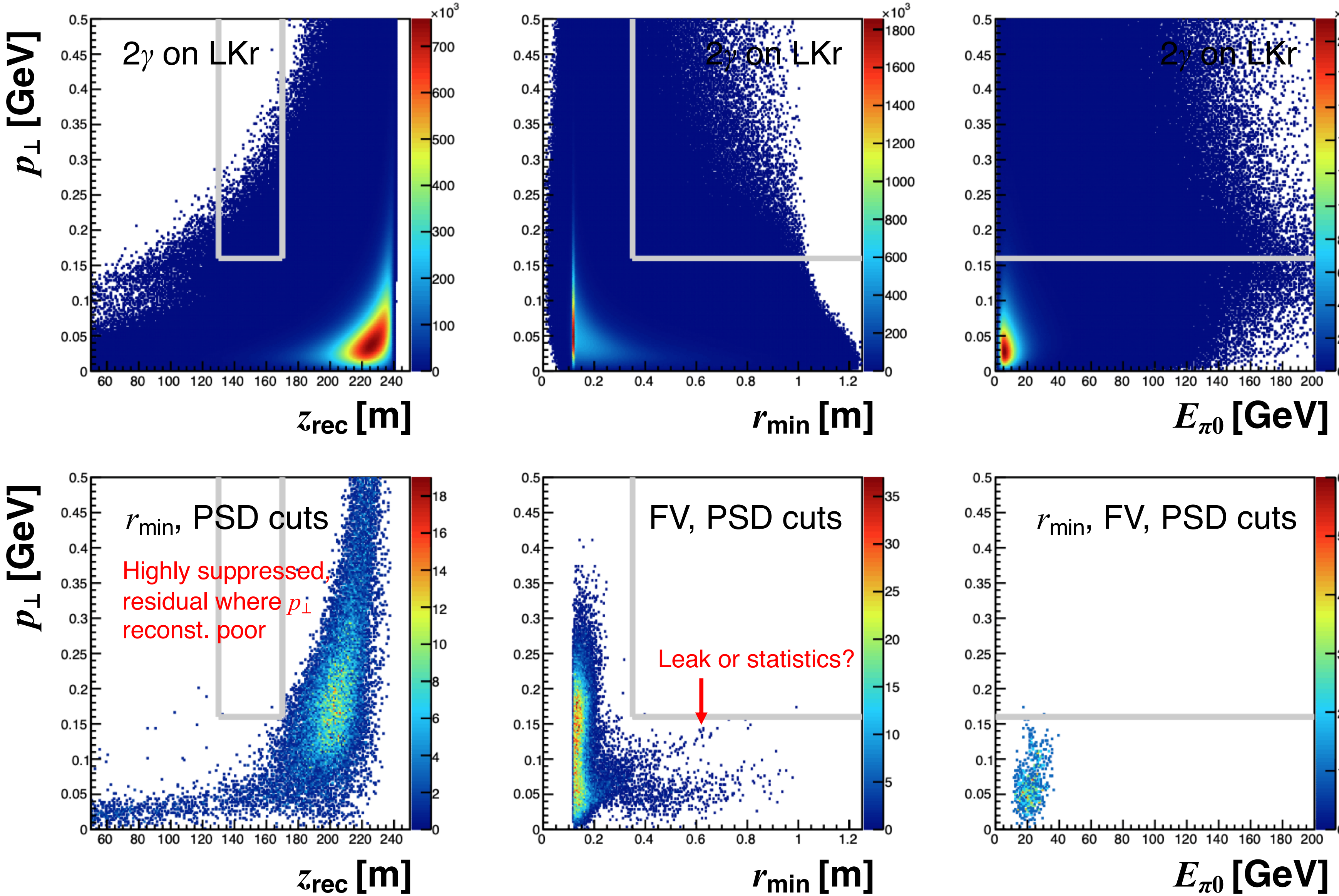
$K_L \to \pi^0\pi^0$ even background

910G $K_L \to \pi^0\pi^0$ with Malensek/FLUKA spectrum, no weights



$K_L \to \pi^0\pi^0$ odd background

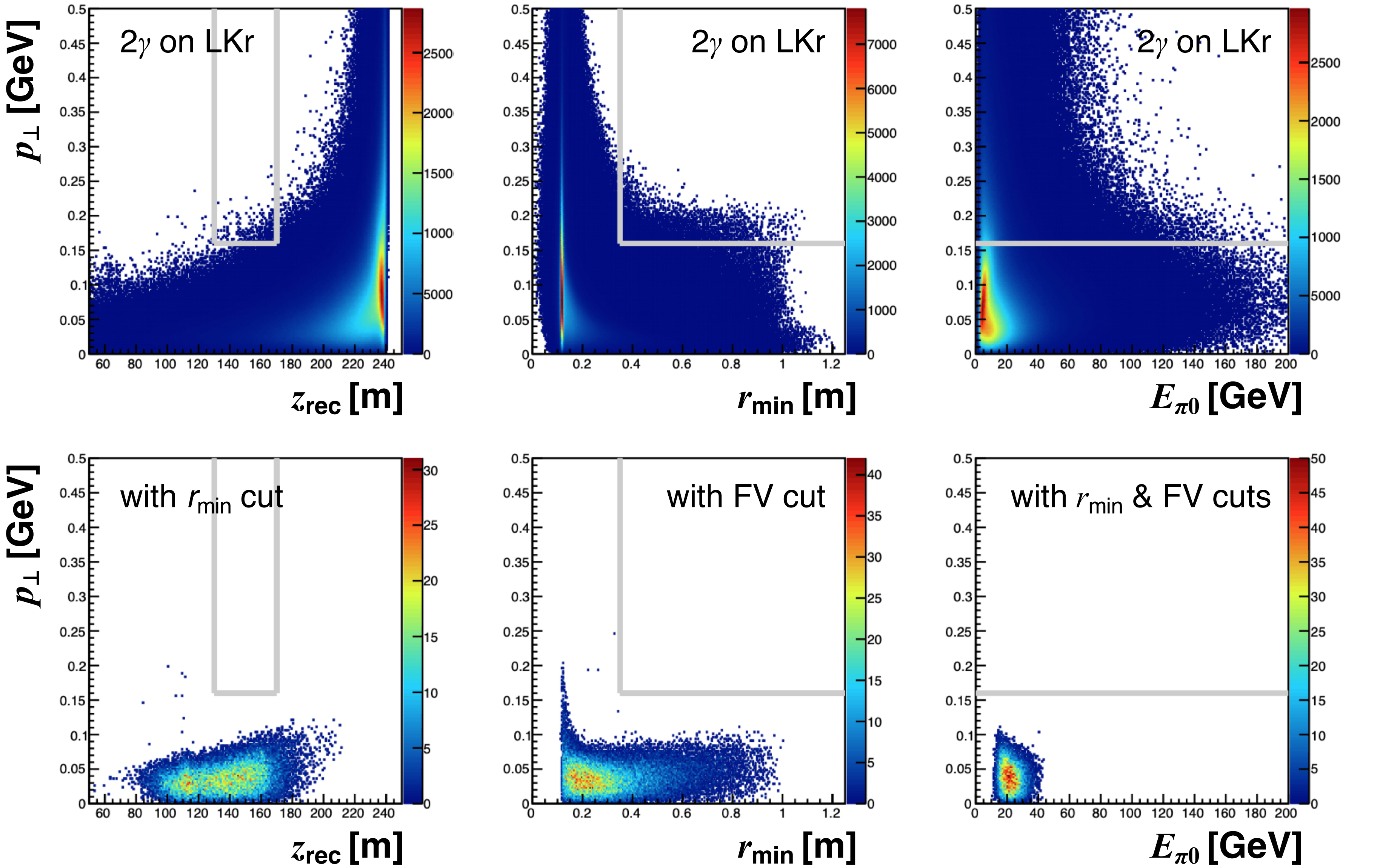
910G $K_L \to \pi^0\pi^0$ with Malensek/FLUKA spectrum, no weights



$K_L \to \pi^0\pi^0$ fused background

KLEVER

910G $K_L \to \pi^0\pi^0$ with Malensek/FLUKA spectrum, no weights



$K_L \to \pi^0\pi^0$ background summary

Stage	Events in 5 yrs			
	Even	Odd	Fused	Total
Prod. $K_L \to \pi^0\pi^0$	**910.224 × 10^9**			
Decay in FV	4.040% = 3677M			
2γ on LKr	151.5M	686.2M	24.4M	**862.1M**
+ Reconst. in FV	193k	9714k	743k	**10.65M**
+ $r_{\text{min}} > 35$ cm	81k	4611k	119k	**4.811M**
+ $z_{\text{PSD}} < 170$ m	35.1k	668	12.3k	**48.0k**
+ $p_\perp > 160$ MeV	11	2	0	**13**

Requiring 1 PSD hit leads to less stringent rejection factor needed from kinematics ($\sim 3 \times 10^{-4}$ overall)

Particularly effective for odd pairs

New reference sensitivity analysis

	08 Apr + bug fix	Conservative
$K_L \to \pi^0 \nu\nu$	30	15
$K_L \to \pi^0 \pi^0$	54	13
$\Lambda \to n\pi^0$	< 560 (no evts)	< 1670 (no evts)

Observations:

S/B **from** $K_L \to \pi^0\pi^0$ **now above 1**

Expected number of signal events decreased by 50%

Almost all loss of signal from requiring 1 hit on PSD

- Can study whether a slightly thicker converter can be used with PSD

Some room for optimization

- Looser $p_\perp$ cut possible if not for $\Lambda \to n\pi^0$
- Tuning r_{min} (or replacing with MVA cut on topological variables)
- Other items needed for standard sensitivity analysis:
  - Optimize layout for IRC and SAC
  - Rebalance efficiency specifications for vetoes

Ongoing projects

General simulation: KLMC

- Goal to restart work on KLMC to make it fully useable
- Summer student (K. Richardson), in coordination with other summer students

Preshower:

- Summer student (D. Hunt, Birmingham) to simulate basic design → KLMC

SAC:

- Test beam analysis: M. Soldani, L. Bandiera
  - Paper on coherent interactions in thick tungsten crystal in progress
- COMPACToR Cerenkov calorimeter: L. Bandiera, StG application
- AIDAnova participation, with L. Bandiera and M. Raggi (PADME)
  - 10 kE for participation in tests of advanced crystals for Cerenkov calorimetry (PWO, PbF2?)
- Summer student (Phil?) to simulate basic design, γ/n response
  - Useful for APEIRON: algorithms for online γ/n separation to run in SAC front end (test case)

Main calorimeter (shashlyk):

- BTF tests of romashka prototype, with S. Kholodenko: on hold till 2021?
- Summer student (J. Conragan) to simulate basic design → KLMC

Conclusions

ESPP input, arXiv:1901.03099

An effort is underway to develop a comprehensive simulation and use it to validate the results obtained so far. Of particular note, backgrounds from radiative K_L decays, cascading hyperon decays, and beam-gas interactions remain to be studied, and the neutral-beam halo from our more detailed FLUKA simulations needs to be incorporated into the simulation of the experiment. While mitigation of potential background contributions from one or more of these sources might ultimately require specific modifications to the experimental setup, we expect this task to be straightforward in comparison to the primary challenges from $K_L \to \pi^0\pi^0$ and $\Lambda \to n\pi^0$.

These statements are as true now as they were in Dec 2018

Apart from a couple of specific items (e.g. beam gas), until now, KLEVER sensitivity estimates have not evolved much since mid 2018

Experience with $\Lambda \to n\pi^0$ demonstrates that we cannot submit a proposal until sensitivity results are cross checked, ideally with a comprehensive simulation (KLMC)

Highest priority right now: $\Lambda \to n\pi^0$ background mitigation

KLEVER

Additional information

17 April 2020

Matthew Moulson
INFN Frascati

Signal acceptance (08 Apr)

Stage	Acceptance	Cumulative acceptance	Events in 5 yrs
Prod. $K_L \to \pi^0 \nu\nu$	1	1	**35819**
Decay in FV	4.041%	4.041%	**1447**
2γ on LKr	2.228%	2.228%	**798**
+ Reconst. in FV	0.1691	3.769×10^{-3}	**135**
+ $r_{\text{min}} > 35$ cm	0.5476	2.064×10^{-3}	**74**
+ $p_\perp > 120$ MeV	0.6765	1.396×10^{-3}	**50**
+ $\theta_{\pi 0}$ vs $p_\perp$ cut	0.6769	0.945×10^{-3}	**34**
+ Preshower in FV	0.8758	0.828×10^{-3}	**30**

Notes:

- K_L produced in 5 yrs from Maarten's results: **includes converter losses**
- Does not include losses to random veto
- Not too much room for further optimization because $\Lambda \to n\pi^0$ fixes $p_\perp$ cuts

$K_L \to \pi^0\pi^0$ background (08 Apr)

KLEVER

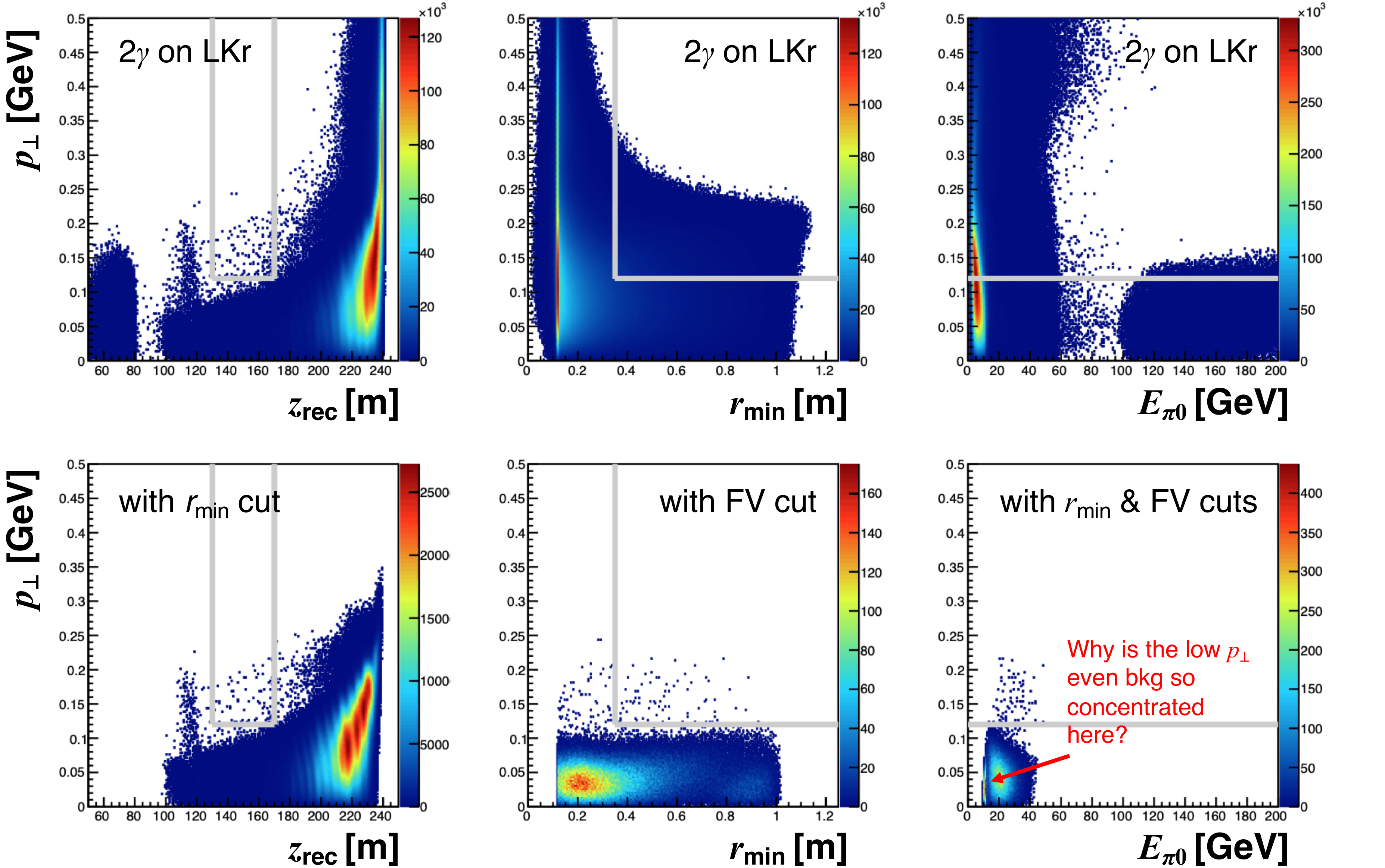
Stage	Events in 5 yrs			
	Even	Odd	Fused	Total
Prod. $K_L \to \pi^0\pi^0$	**91.022 × 10^9**			
Decay in FV	4.039% = 3677M			
2γ on LKr	151.5M	686.2M	24.4M	**862.1M**
+ Reconst. in FV	193k	9714k	743k	**10.65M**
+ $r_{\text{min}} > 35$ cm	81k	4611k	119k	**4.811M**
+ $p_\perp > 120$ MeV	80	109	7	**196**
+ $\theta_{\pi 0}$ vs $p_\perp$ cut	35	29	4	**68**
+ Preshower in FV	30	20	4	**54**

Notes:

- K_L produced in 5 yrs from Maarten's results: **includes converter losses**
- $\theta_{\pi 0}$ vs $p_\perp$ cut (basically a hard $p_\perp$ cut) important for $K_L \to \pi^0\pi^0$ reduction
- Not too much room for further optimization because $\Lambda \to n\pi^0$ fixes $p_\perp$ cuts

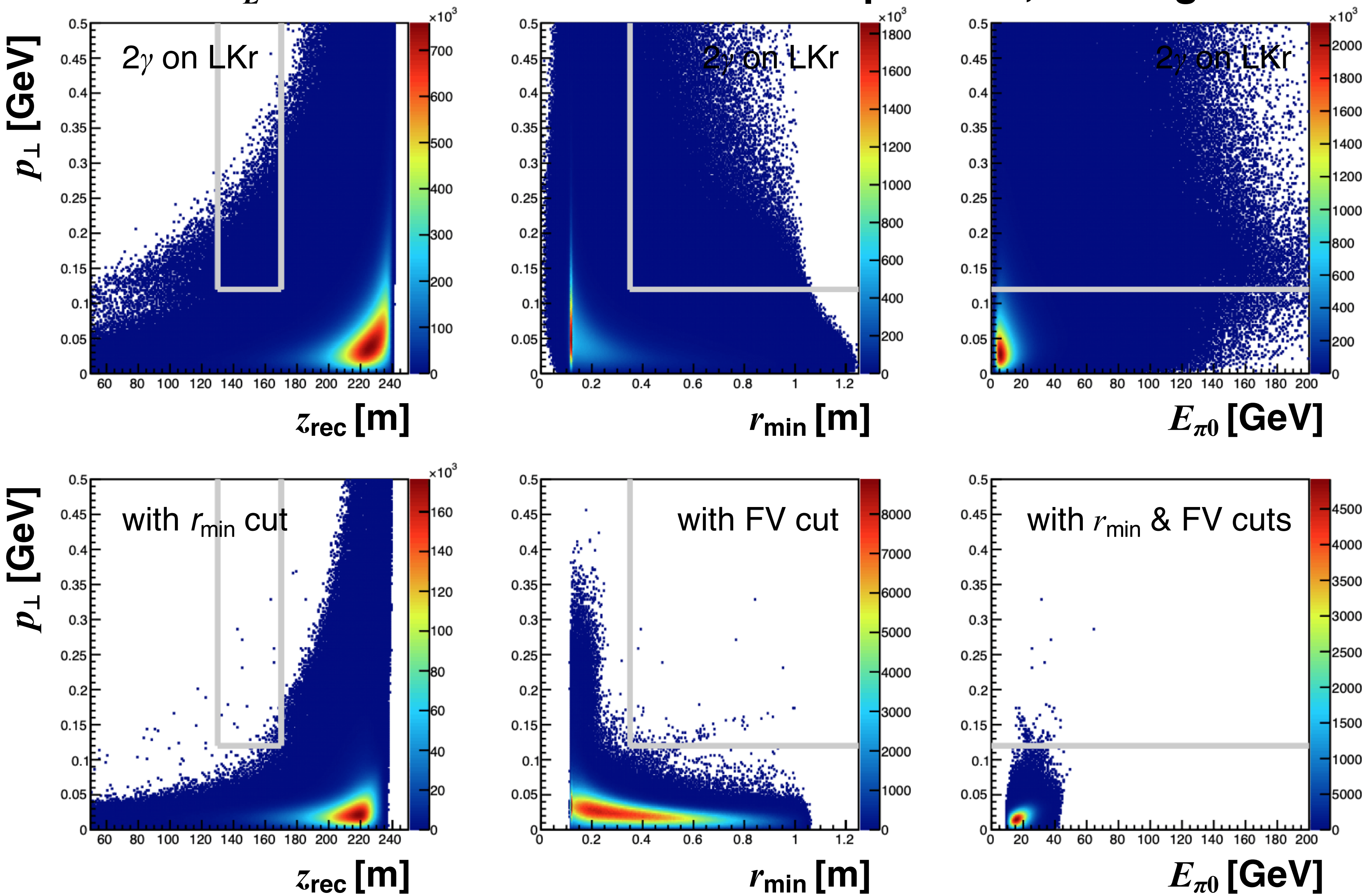
$K_L \to \pi^0\pi^0$ even background (08 Apr)

91.2G $K_L \to \pi^0\pi^0$ with Malensek/FLUKA spectrum, no weights



$K_L \to \pi^0\pi^0$ odd background (08 Apr)

91.2G $K_L \to \pi^0\pi^0$ with Malensek/FLUKA spectrum, no weights



$K_L \to \pi^0\pi^0$ fused background (08 Apr)

KLEVER

91.2G $K_L \to \pi^0\pi^0$ with Malensek/FLUKA spectrum, no weights