

# Kaon experiments: Status and outlook

**Exotic Hadrons and Flavor Physics**

Simons Center for Geometry and Physics

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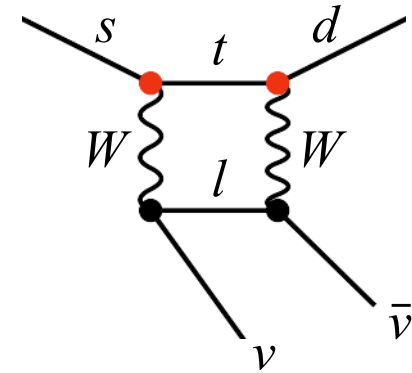
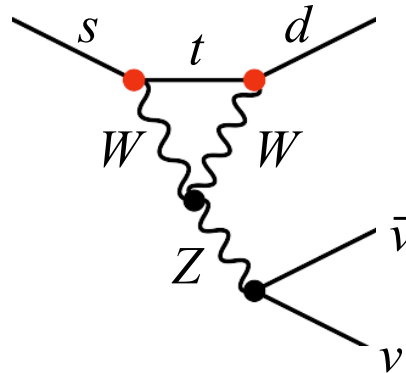
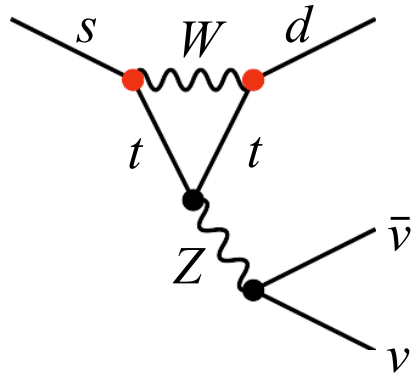
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# $K \rightarrow \pi \nu \bar{\nu}$ in the Standard Model

FCNC processes dominated by Z-penguin and box amplitudes:



**Extremely rare decays with rates very precisely predicted in SM:**

- Hard GIM mechanism + pattern of CKM suppression ( $V_{ts}^* V_{td}$ )
- No long-distance contributions from amplitudes with intermediate photons
- Hadronic matrix element obtained from  $\text{BR}(K_{e3})$  via isospin rotation

## SM predicted rates

Buras et al, JHEP 1511\*

## Experimental status

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

**$\text{BR} = (8.4 \pm 1.0) \times 10^{-11}$**

**$\text{BR} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$**   
Stopped  $K^+$ , 7 events observed  
BNL 787/949, PRD79 (2009)

$K_L \rightarrow \pi^0 \nu \bar{\nu}$

**$\text{BR} = (3.4 \pm 0.6) \times 10^{-11}$**

**$\text{BR} < 2600 \times 10^{-11}$  90%CL**  
KEK 391a, PRD81 (2010)

\* Tree-level determinations of CKM matrix elements

# $K \rightarrow \pi \nu \bar{\nu}$ and the unitarity triangle

Dominant uncertainties for SM BRs are from CKM matrix elements

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[ \frac{|V_{cb}|}{0.0407} \right]^{2.8} \cdot \left[ \frac{\gamma}{73.2^\circ} \right]^{0.74}$$

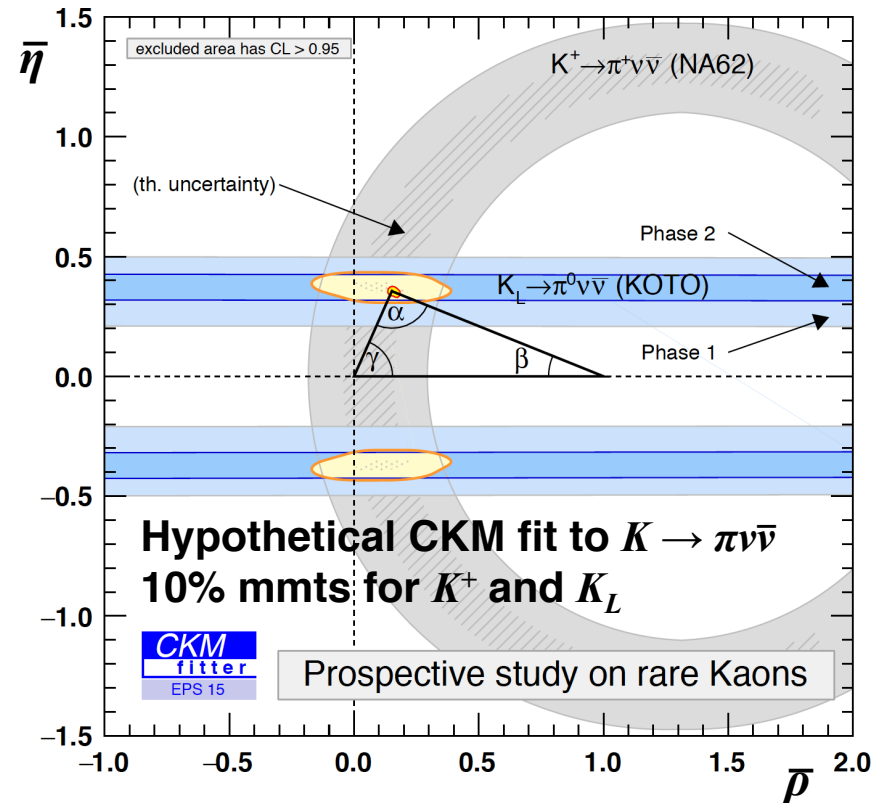
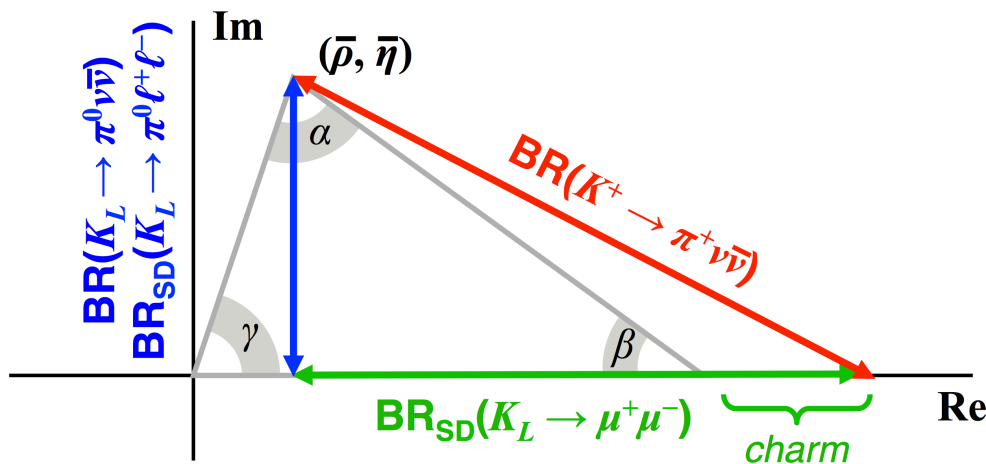
Buras et al.,  
JHEP 1511

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[ \frac{|V_{ub}|}{3.88 \times 10^{-3}} \right]^2 \cdot \left[ \frac{|V_{cb}|}{0.0407} \right]^2 \cdot \left[ \frac{\sin \gamma}{\sin 73.2^\circ} \right]^2$$

Intrinsic theory uncertainties ~ few percent

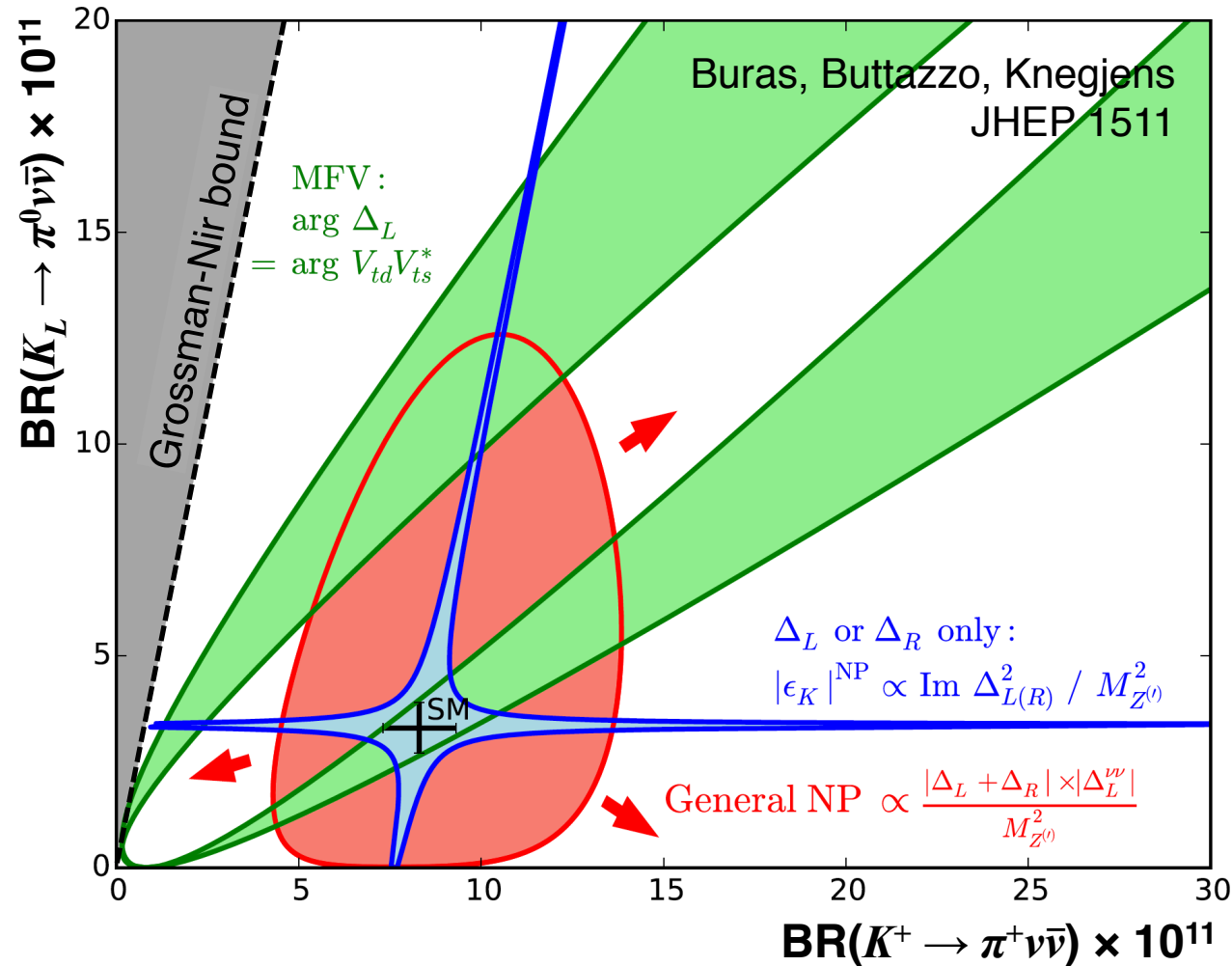
Measuring both  $K^+$  and  $K_L$  BRs can determine the CKM unitarity triangle independently from  $B$  inputs

- Overconstrain CKM matrix  $\rightarrow$  reveal NP?



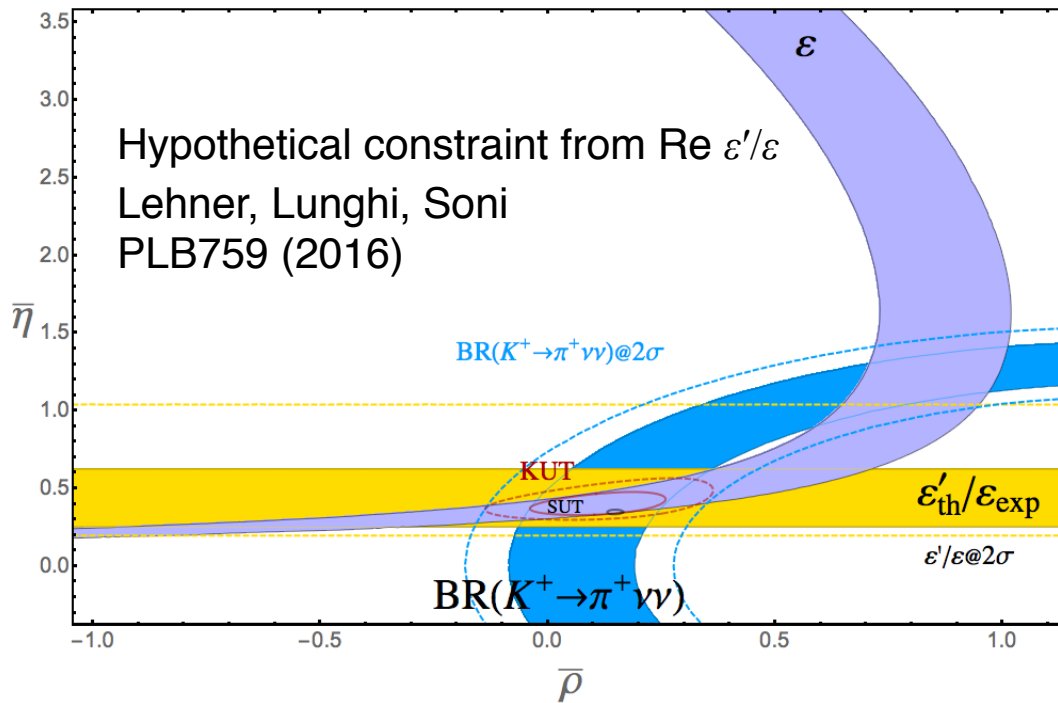
# $K \rightarrow \pi \nu \bar{\nu}$ and new physics

New physics affects BRs differently for  $K^+$  and  $K_L$  channels  
Measurements of both can discriminate among NP scenarios



- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - $Z/Z'$  models with pure LH/RH couplings
  - Littlest Higgs with  $T$  parity
- Models without above constraints
  - Randall-Sundrum

# Re $\varepsilon'/\varepsilon$ vs BR( $K_L \rightarrow \pi^0 \nu \bar{\nu}$ )



**Calculations: Re  $\varepsilon'/\varepsilon \times 10^4$**

**RBC/UKQCD '15**     $1.38 \pm 5.15 \pm 4.59$

**Gisbert & Pich '17**     $15 \pm 7$

**Re  $\varepsilon'/\varepsilon$  constrains UT in same way as BR( $K_L \rightarrow \pi^0 \nu \bar{\nu}$ )**

Scenario assumes:

- Lattice value for Im  $A_0$  in agreement with expt
- $\delta(\text{Im } A_0) = \sim 100\% \rightarrow 18\%$   
 $\rightarrow \delta(\text{Re } \varepsilon'_{\text{th}}/\varepsilon) = 1.6 \times 10^{-4}$
- BR( $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ) = SM value with 10% error

**Measurements: Re  $\varepsilon'/\varepsilon \times 10^4$**

**KTeV**     $19.2 \pm 1.1 \pm 1.8$

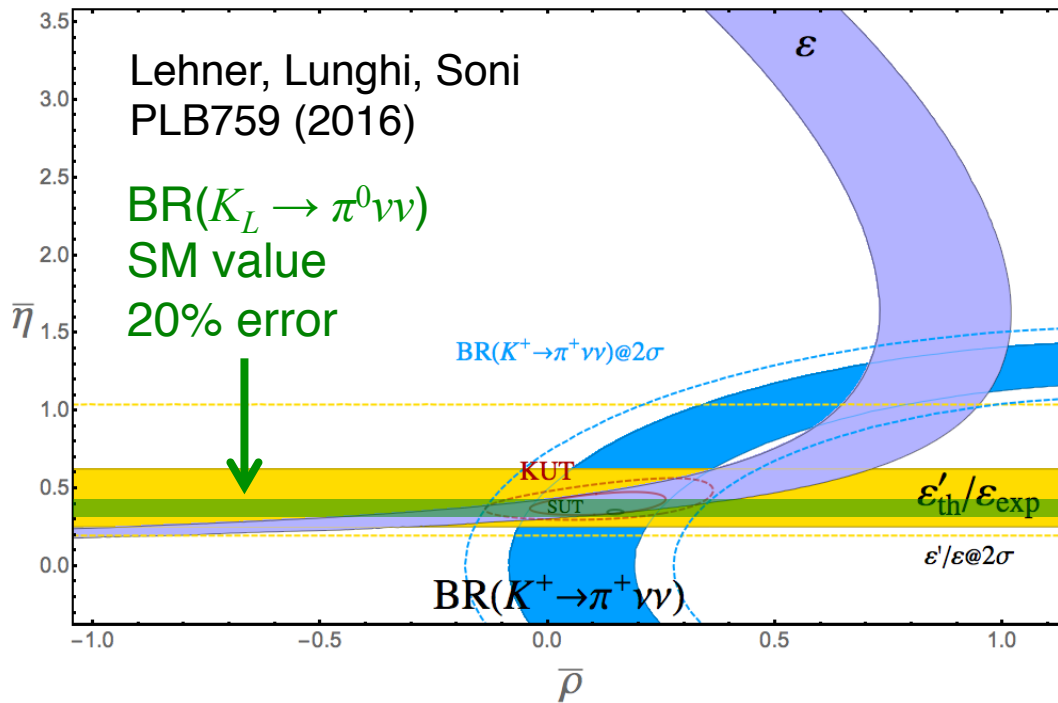
**NA48**     $14.7 \pm 1.7 \pm 1.5$

**PDG fit**     $16.6 \pm 2.3 (S = 1.6)$

RBC/UKQCD value is  $2.1\sigma$  lower than experimental value:

- Claim: Uncertainty  $\sim 10\%$  of experimental value can be reached by  $\sim 2020$
- In progress: Increased statistics, larger volumes, additional lattice spacings

# Re $\varepsilon'/\varepsilon$ vs BR( $K_L \rightarrow \pi^0 \nu \bar{\nu}$ )



**Re  $\varepsilon'/\varepsilon$  constrains UT in same way as BR( $K_L \rightarrow \pi^0 \nu \bar{\nu}$ )**

Scenario assumes:

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**How does progress on Re  $\varepsilon'/\varepsilon$  impact experimental interest in BR( $K_L \rightarrow \pi^0 \nu \bar{\nu}$ )?**

- Measurement of Re  $\varepsilon'/\varepsilon$  is dominated by systematics

$$R = \frac{\text{BR}(K_L \rightarrow \pi^0 \pi^0)}{\text{BR}(K_S \rightarrow \pi^0 \pi^0)} \cdot \frac{\text{BR}(K_S \rightarrow \pi^+ \pi^-)}{\text{BR}(K_L \rightarrow \pi^+ \pi^-)} \approx 1 - 6 \text{ Re } \varepsilon'/\varepsilon$$

- NA48 and KTeV measured  $R$  to 0.1%: Very difficult to improve!

Small gains from statistics and from resolution of  $S=1.6$  in PDG fit

- **$\delta \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \sim 20\%$  gives tighter UT constraint than  $\delta(\text{Re } \varepsilon'/\varepsilon) \sim 1 \times 10^{-4}$**

# $K \rightarrow \pi \nu \bar{\nu}$ and other kaon observables

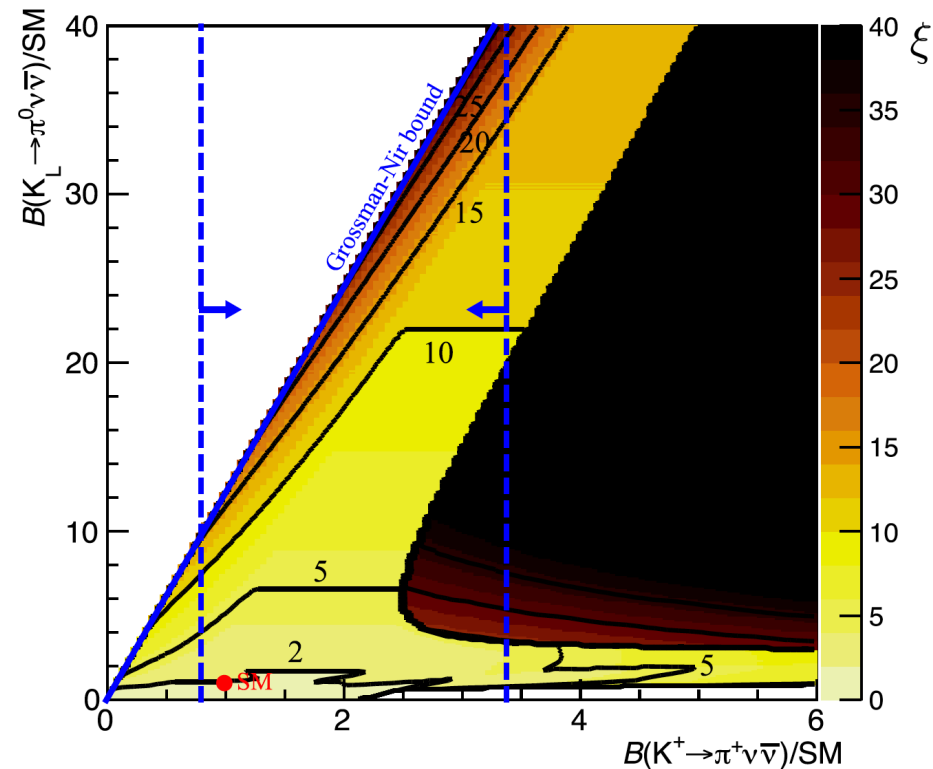
Do constraints from  $\text{Re } \varepsilon'/\varepsilon$ ,  $\varepsilon_K$ ,  $\Delta m_K$ ,  $K_L \rightarrow \mu\mu$  limit size of effects on  $K \rightarrow \pi \nu \bar{\nu}$  BRs?

Model	Effect	Refs
<b>Vector-like quarks</b>	$K_L$ suppressed, $K^+$ possibly enhanced	Bobeth et al. '16
<b>Leptoquarks</b>	Large effects for both $K_L$ , $K^+$ : possibly ruled out?	Bobeth, Buras '17
<b>Simplified Z</b>	$K_L$ suppressed 30%, $K^+$ enhanced up to 2x	Endo et al. '17
<b>SUSY</b>	$K^+$ and $K_L$ enhanced 10-20% for $\Lambda_{\text{SUSY}} \sim 3 \text{ TeV}$	Kitahara et al. '16

## Endo et al. PLB771 (2017)

General Z scenario with modified couplings,  $\Lambda = 1 \text{ TeV}$

- Because of interference between SM and NP amplitudes, if all constraints satisfied including “discrepancy” in  $\text{Re } \varepsilon'/\varepsilon$ :  
 **$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \sim 0.5 \text{ SM BR}$**
- Particularly in simplified scenarios: LH, RH, LRS
- With moderate tuning (cancellation of interference terms to 10%), large values for  $\text{BR}(K \rightarrow \pi \nu \bar{\nu})$  are possible



# $K \rightarrow \pi \nu \bar{\nu}$ and other flavor observables

**New ideas relating  $K \rightarrow \pi \nu \bar{\nu}$  to  $B$ -sector LFU anomalies:**

$R_K, P_5'$ :  $\mu/e$  LFU in  $B \rightarrow K \ell \ell, B \rightarrow K^* \ell \ell$

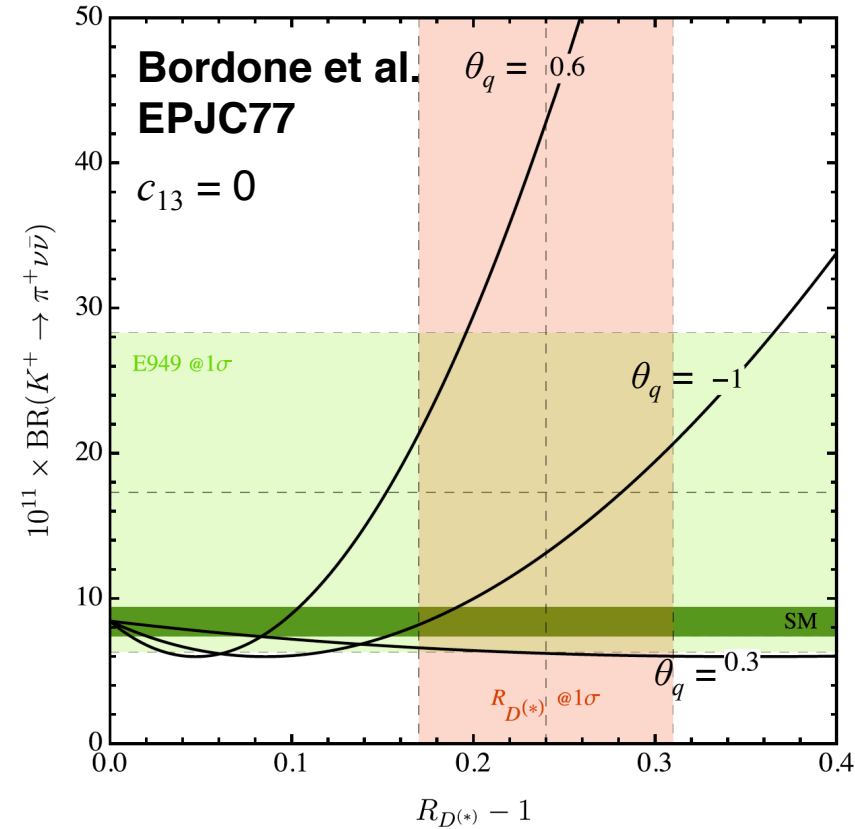
$R_{D^{(*)}}$ :  $\tau/(\mu, e)$  LFU in  $B \rightarrow D^{(*)} \ell \nu$

Coherent explanation from NP coupled predominantly to 3<sup>rd</sup> generation LH quarks and leptons, e.g., mediated by vector leptoquark

- Di Luzio et al. PRD 96 (2017)
- Buttazzo et al. JHEP 1711

EFT studies suggest large effect for  $K \rightarrow \pi \nu \bar{\nu}$

- Bordone et al. EPJC77 (2017)



$$\mathcal{B}(B \rightarrow D^{(*)} \tau \bar{\nu}) = \mathcal{B}(B \rightarrow D^{(*)} \tau \bar{\nu})_{\text{SM}} \left| 1 + R_0 \left( 1 - \theta_q e^{-i\phi_q} \right) \right|^2$$

$$R_0 = \frac{1}{\Lambda^2} \frac{1}{\sqrt{2} G_F}$$

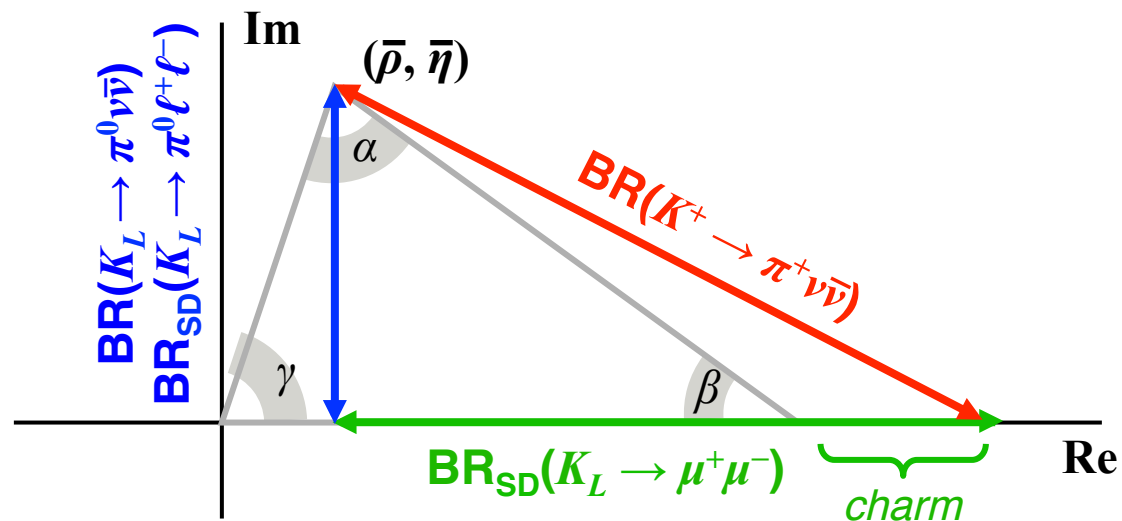
$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = 2\mathcal{B}(K_L \rightarrow \pi^0 \nu_e \bar{\nu}_e)_{\text{SM}} + \mathcal{B}(K_L \rightarrow \pi^0 \nu_\tau \bar{\nu}_\tau)_{\text{SM}} \left| 1 - \frac{R_0 \theta_q^2 (1 - c_{13})}{(\alpha/\pi)(X_t/s_w^2)} \right|^2$$

# Rare kaon decays besides $K \rightarrow \pi \nu \bar{\nu}$

Decay	$\Gamma_{\text{SD}}/\Gamma$	Theory err.*	SM BR $\times 10^{11}$	Exp. BR $\times 10^{11}$
$K_L \rightarrow \mu^+ \mu^-$	10%	30%	$79 \pm 12$ (SD)	$684 \pm 11$
$K_L \rightarrow \pi^0 e^+ e^-$	40%	10%	$35 \pm 10$	$< 28^\dagger$
$K_L \rightarrow \pi^0 \mu^+ \mu^-$	30%	15%	$14 \pm 3$	$< 38^\dagger$
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	90%	4%	$8.4 \pm 1.0$	$17 \pm 11$
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	$> 99\%$	2%	$3.4 \pm 0.6$	$< 2600^\dagger$

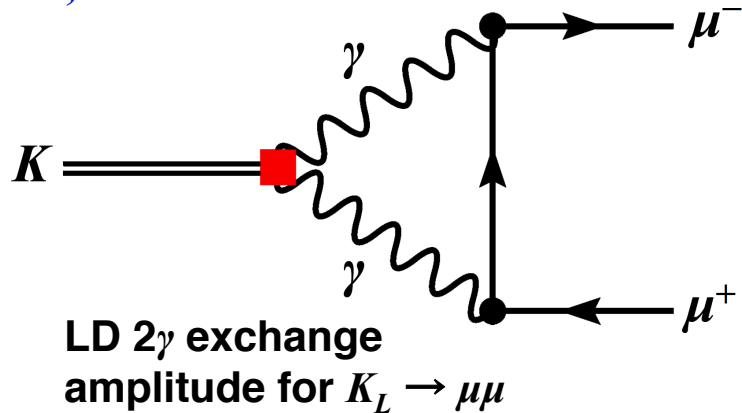
\*Approx. error on LD-subtracted rate excluding parametric contributions     $^\dagger 90\%$  CL

- $K_{L,S} \rightarrow \ell \ell$  and  $K_{L,S} \rightarrow \pi^0 \ell \ell$  modes have larger theoretical uncertainties from LD physics
- Need information for both  $K_L$  and  $K_S$  to separate CPC and CPV amplitudes
- $K_{L,S} \rightarrow \pi^0 \ell^+ \ell^-$  can be used to explore helicity suppression in FCNC decays



# Rare $K_L$ and $K_S$ decays

$$K_{L,S} \rightarrow \mu\mu$$



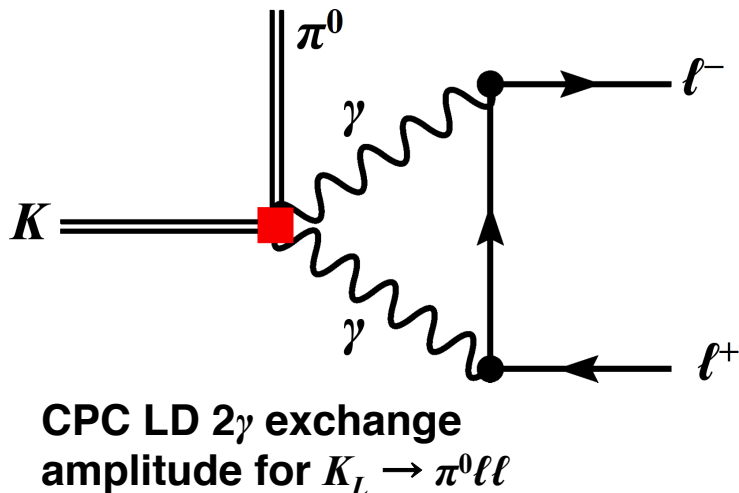
LD amplitude from  $2\gamma$  exchange dominant

$$\text{BR}_{\text{SM}}(K_S \rightarrow \mu^+\mu^-) = (5.2 \pm 1.5) \times 10^{-12}$$

- Significant uncertainty from unknown sign of interference between  $K_L$  and  $K_S$  amplitudes
- Measurement of  $K_S$  BR improves accuracy of theory prediction for  $K_L$  BR
- NP contribution to  $\text{BR}(K_S \rightarrow \mu^+\mu^-)$  could be as high as  $10^{-11}$

See e.g., Chobanova et al., 1711.11030

$$K_{L,S} \rightarrow \pi^0 \ell\ell$$



Theoretical uncertainties from LD physics

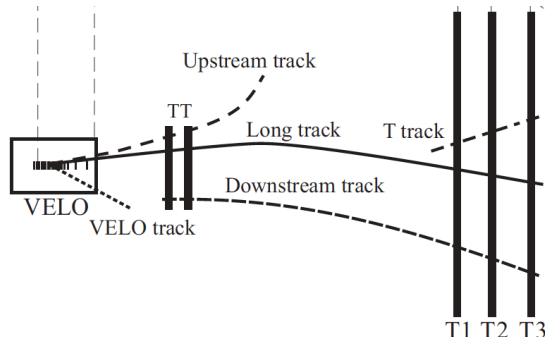
- SD CPV amplitude:  $\gamma/Z$  exchange
- LD CPC amplitude from  $2\gamma$  exchange
- LD indirect CPV amplitude:  $K_L \rightarrow K_S$

Probes helicity suppression in FCNC decays

Can look for LFU violation, like for  $B \rightarrow K\ell\ell$

# Rare $K_S$ decays with LHCb

- $10^{13} K_S/\text{fb}^{-1}$  produced in LHCb acceptance
- Use only “long tracks” to reconstruct  $K_S$   
40% decay in VELO region



- Good  $\mu$  identification and  $\mu\mu$  mass resolution
- Main limitation:  
HW trigger eff = 2.5%

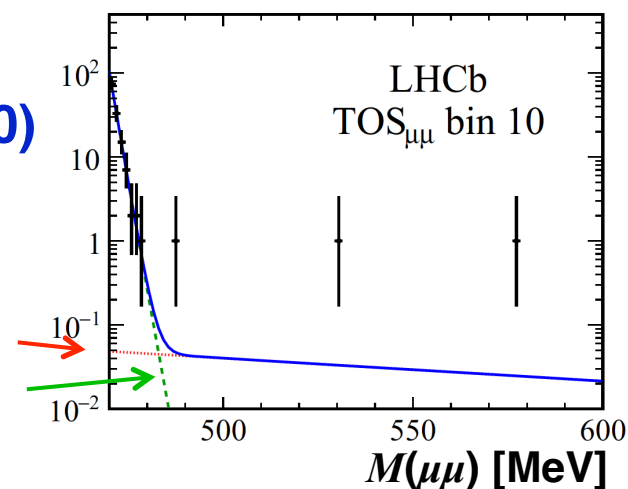
$$K_S \rightarrow \mu\mu$$

$$\text{BR} < 0.8 \times 10^{-9} \text{ (CL90)}$$

3 fb<sup>-1</sup> 2011-12 data  
EPJC 77 (2017)

Combinatorial bkg

$\pi^+\pi^-$  mis-ID



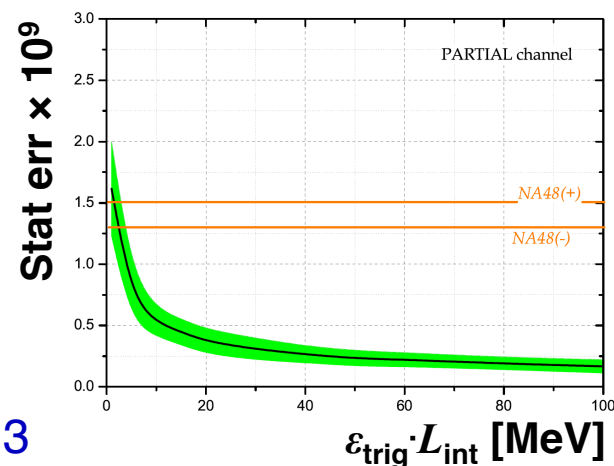
$$K_S \rightarrow \pi^0 \mu\mu$$

LHCb Pub 2016-017

Sensitivity study:

- TIS selection
- $\pi^0$  not required

Improvement on NA48/1  
result is possible in Run 3



NA48/1 PLB599 (2004)

$$\text{BR}(K_S \rightarrow \pi^0 \mu\mu) = (2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$$

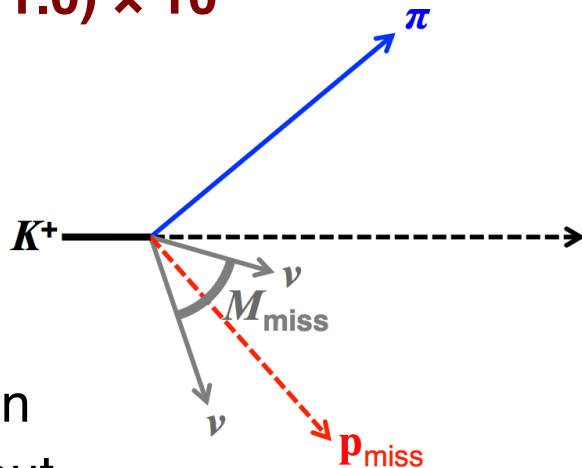
# The NA62 experiment at the CERN SPS



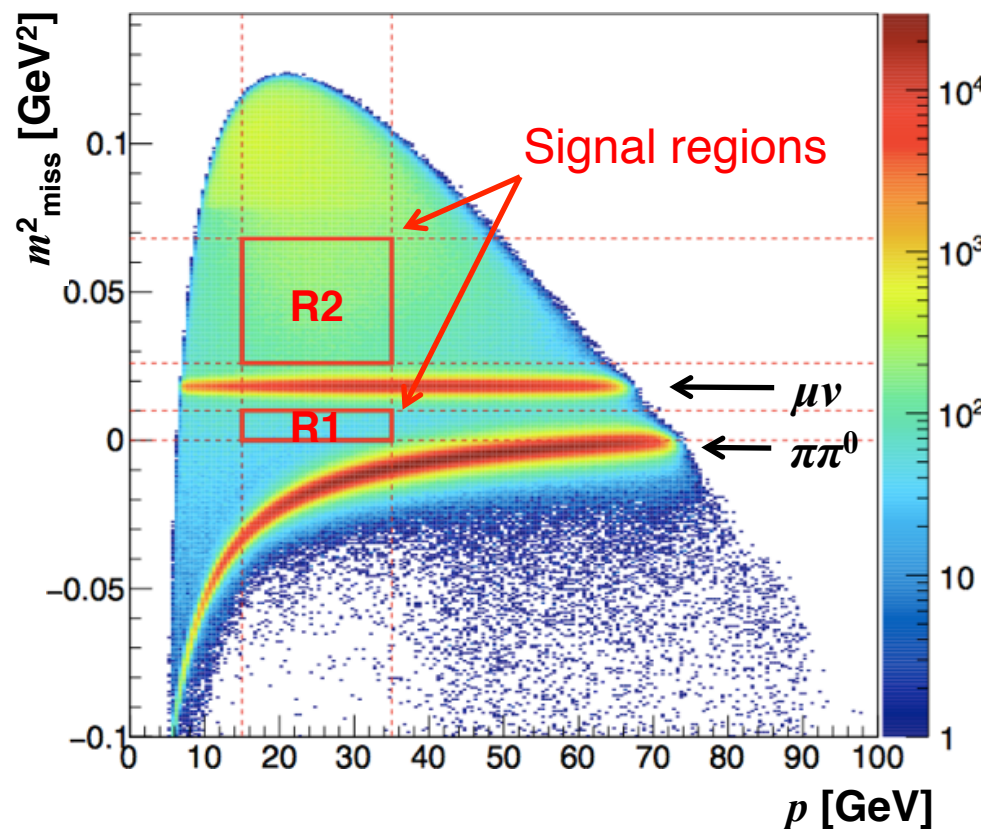
# $K^+ \rightarrow \pi^+ \nu \nu$ with decay in flight

## Signal:

$$\text{BR} = (8.4 \pm 1.0) \times 10^{-11}$$



- $K$  track in
- $\pi$  track out
- No other particles in final state
- $M_{\text{miss}}^2 = (p_K - p_\pi)^2$



## Main backgrounds:

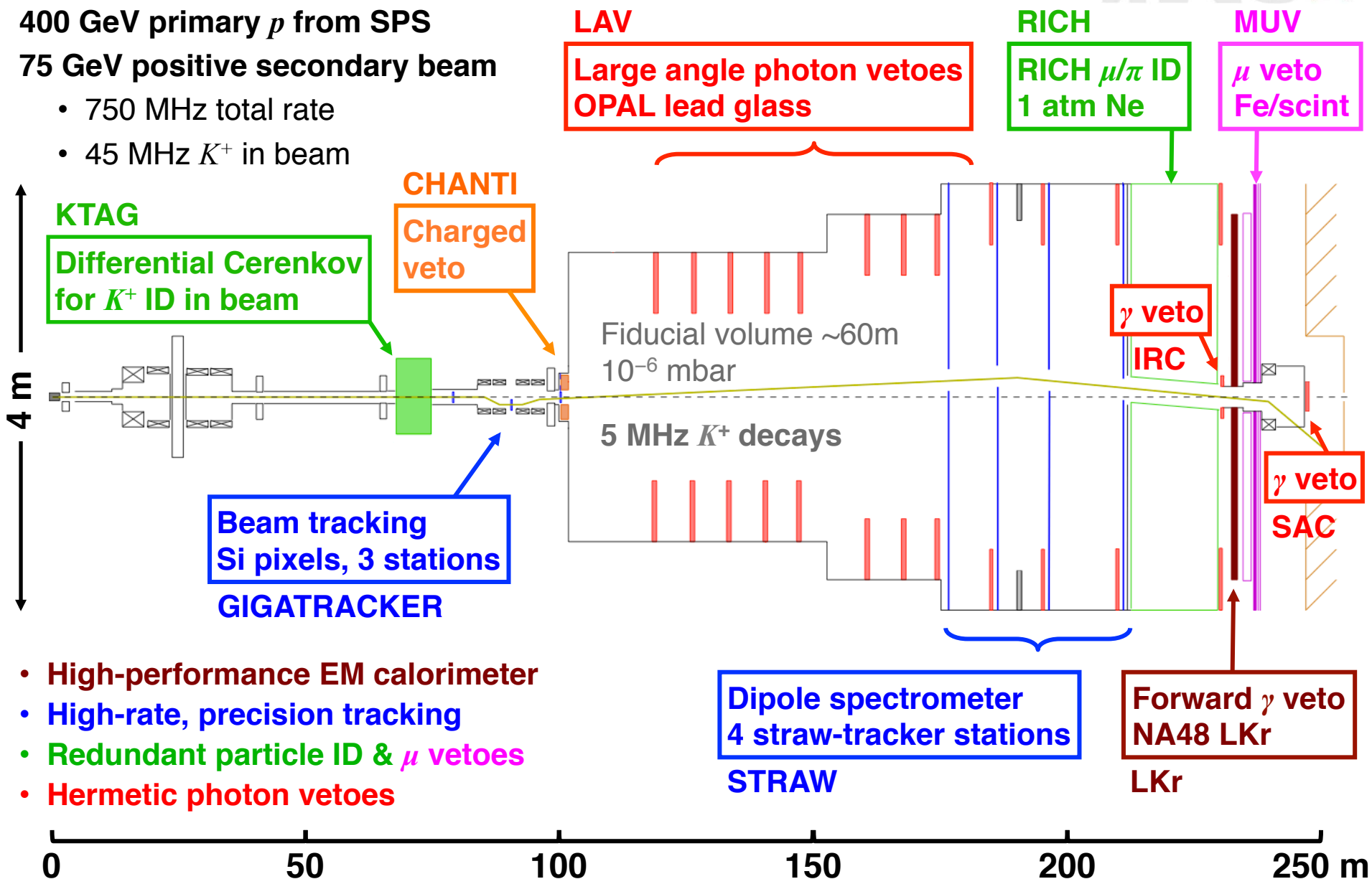
$$K^+ \rightarrow \mu^+ \nu(\gamma) \quad \text{BR} = 63.5\%$$

$$K^+ \rightarrow \pi^+ \pi^0(\gamma) \quad \text{BR} = 20.7\%$$

## Selection criteria:

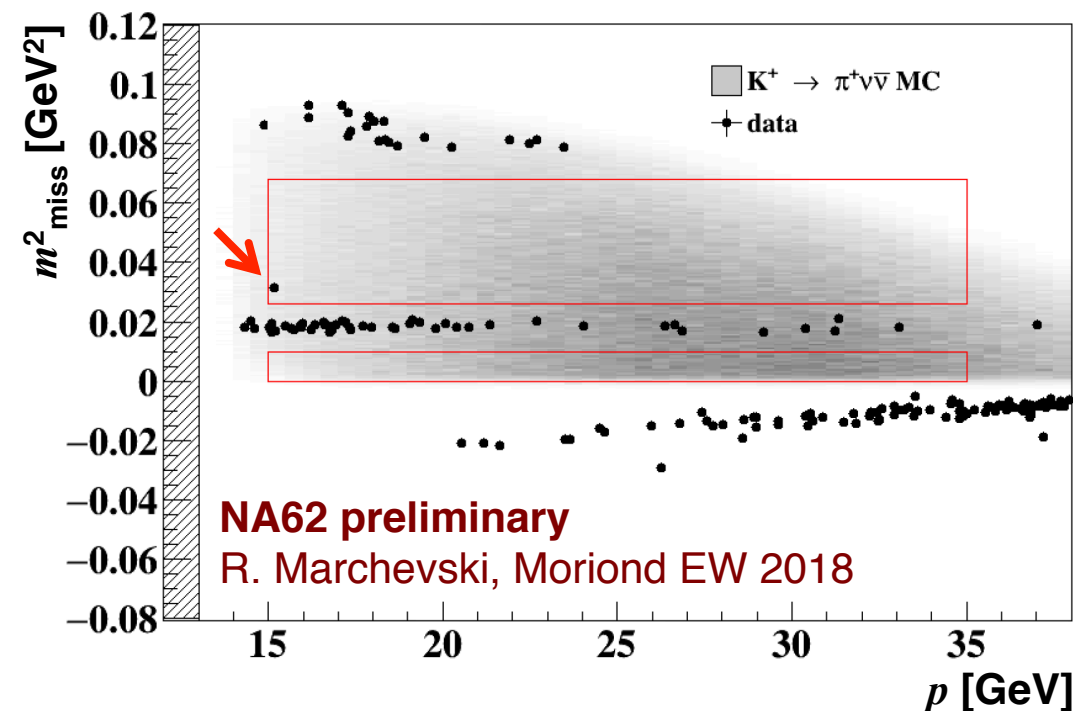
- $K^+$  beam identification
- Single track in final state
- $\pi^+$  identification ( $\epsilon_\mu \sim 1 \times 10^{-8}$ )
- $\gamma$  rejection ( $\epsilon_{\pi^0} \sim 3 \times 10^{-8}$ )

# The NA62 experiment at the SPS



- High-performance EM calorimeter
- High-rate, precision tracking
- Redundant particle ID &  $\mu$  vetoes
- Hermetic photon vetoes

# 2016 results for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



**NA62 preliminary – 2016 data**

$1.2 \times 10^{11}$   $K^+$  decays

**SES =  $(3.15 \pm 0.24) \times 10^{-10}$**

**Expected signal  $0.267 \pm 0.038$**

**Expected background  $0.15 \pm 0.09$**

**1 event observed in R2**

**BR( $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ )**

**$< 14 \times 10^{-10}$  (95%CL)**

**$< 10 \times 10^{-10}$  (90%CL)**

**$= 28^{+44}_{-23} \times 10^{-11}$  (68% CL)**

Background source	Expected events R1 + R2
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (SM)	$0.267 \pm 0.001_{\text{stat}} \pm 0.029_{\text{sys}} \pm 0.032_{\text{ext}}$
$K^+ \rightarrow \pi^+ \pi^0 (\gamma_{\text{IB}})$	$0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{sys}}$
$K^+ \rightarrow \mu^+ \nu (\gamma_{\text{IB}})$	$0.020 \pm 0.003_{\text{stat}} \pm 0.003_{\text{sys}}$
$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$	$0.018^{+0.024}_{-0.017} \text{ stat} \pm 0.009_{\text{sys}}$
$K^+ \rightarrow \pi^+ \pi^- \pi^+$	$0.002 \pm 0.001_{\text{stat}} \pm 0.002_{\text{sys}}$
Upstream background	$0.050 \pm ^{+0.090}_{-0.030}$
<b>Total background</b>	<b><math>0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{sys}}</math></b>

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<b>2014-2015</b>	Pilot/commissioning runs
<b>2016</b>	Commissioning + 1 <sup>st</sup> physics run <b>First result presented in March 2018</b> <b>1 event observed</b> <b><math>\text{BR}(K^+ \rightarrow \pi^+ \nu \nu) &lt; 14 \times 10^{-11}</math> (95%CL)</b>
<b>2017</b>	Physics run (23 weeks) 20x more data than 2016 result Data processing in progress
<b>2018</b>	Physics run (31 weeks, started 9 April)
<b>2019-2020</b>	LS2 (LHC Long Shutdown 2)

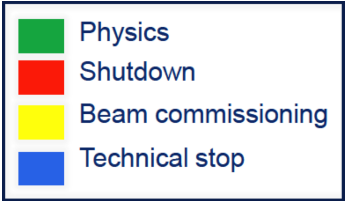
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**By end of 2018 NA62 will reach a sensitivity of 20 SM  $K^+ \rightarrow \pi^+ \nu \nu$  events**

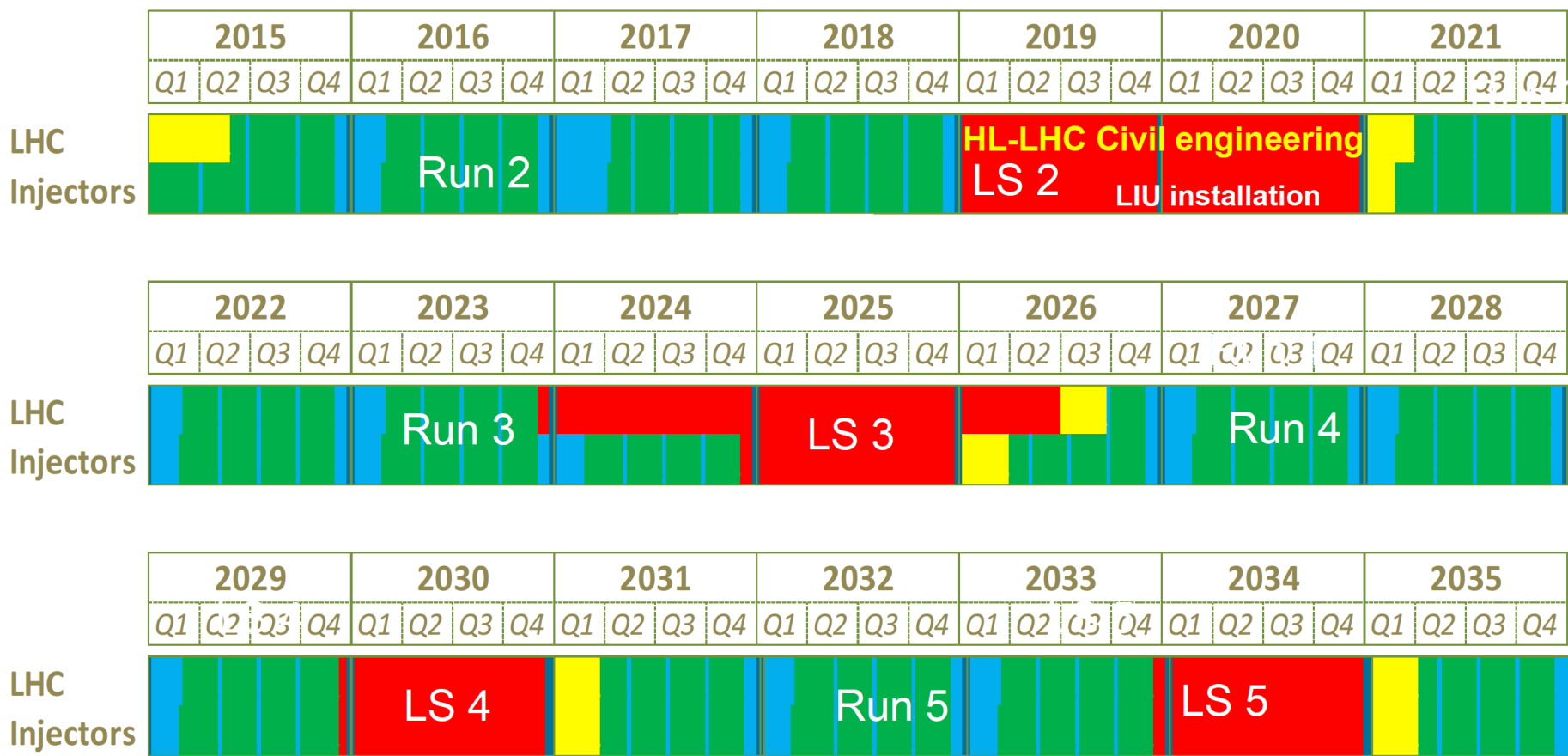
- Input to the European Strategy for Particle Physics
- Solid extrapolation to ultimate sensitivity of NA62 achievable after LS2

# Fixed target runs at the SPS

- 2021 (Run 3): Intention to continue data taking with NA62
  - Measure  $BR(K^+ \rightarrow \pi^+ \nu \nu)$  with ultimate sensitivity
  - Search for hidden particles in beam-dump mode



2026 (Run 4): Turn focus to measurement of  $BR(K_L \rightarrow \pi^0 \nu \nu) \rightarrow K_{L}EVER$



F. Bordry, presentation to HEPAP, Dec 2015

# $K_L \rightarrow \pi^0 \nu \bar{\nu}$ : Experimental issues

**Essential signature:  $2\gamma$  with unbalanced  $p_\perp$  + nothing else!**

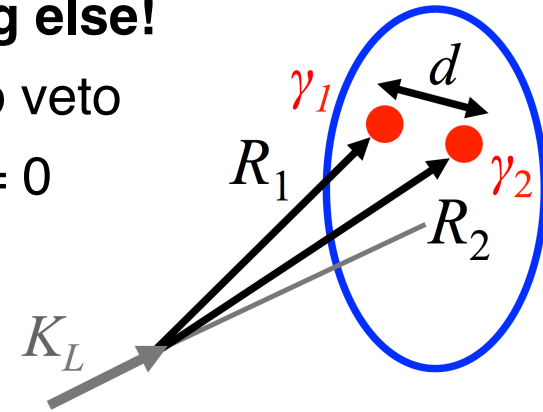
All other  $K_L$  decays have  $\geq 2$  extra  $\gamma$ s or  $\geq 2$  tracks to veto

Exception:  $K_L \rightarrow \gamma\gamma$ , but not a big problem since  $p_\perp = 0$

$K_L$  momentum generally is not known

$M(\gamma\gamma) = m(\pi^0)$  is the only sharp kinematic constraint

Generally used to reconstruct vertex position



$$m_{\pi^0}^2 = 2E_1 E_2 (1 - \cos \theta)$$

$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1 E_2}}{m_{\pi^0}}$$

**Main backgrounds:**

Mode	BR	Methods to suppress/reject
$K_L \rightarrow \pi^0 \pi^0$	$8.64 \times 10^{-4}$	$\gamma$ vetoes, $\pi^0$ vertex, $p_\perp$
$K_L \rightarrow \pi^0 \pi^0 \pi^0$	19.52%	$\gamma$ vetoes, $\pi^0$ vertex, $p_\perp$
$K_L \rightarrow \pi e \nu(\gamma)$	40.55%	Charged particle vetoes, $\pi$ ID, $\gamma$ vetoes
$\Lambda \rightarrow \pi^0 n$		Beamline length, $p_\perp$
$n + \text{gas} \rightarrow X \pi^0$		High vacuum decay region

# $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC



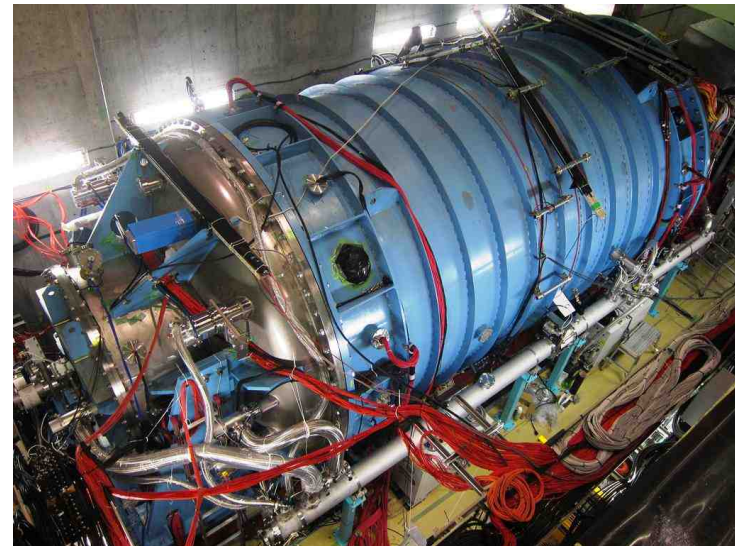
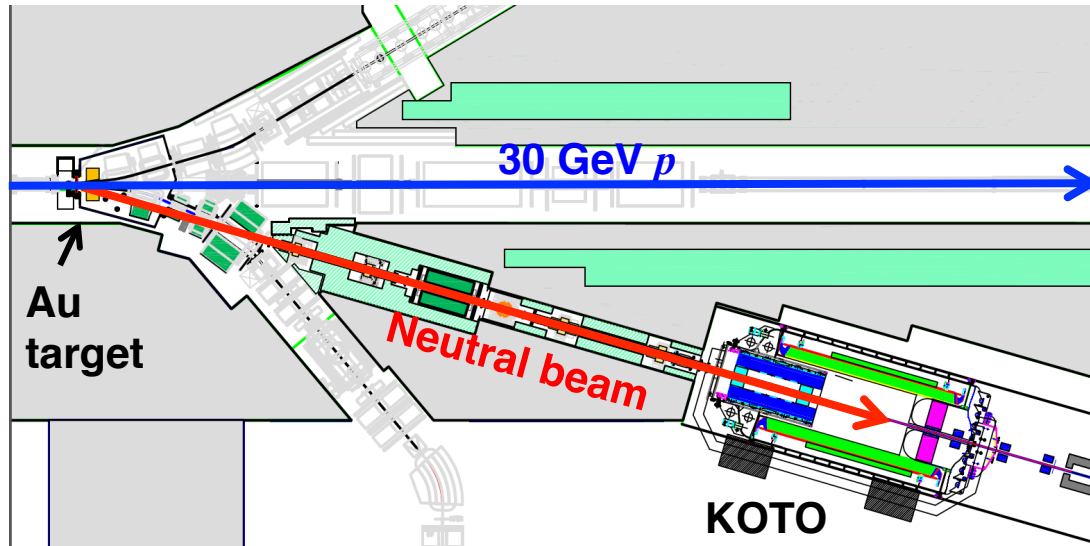
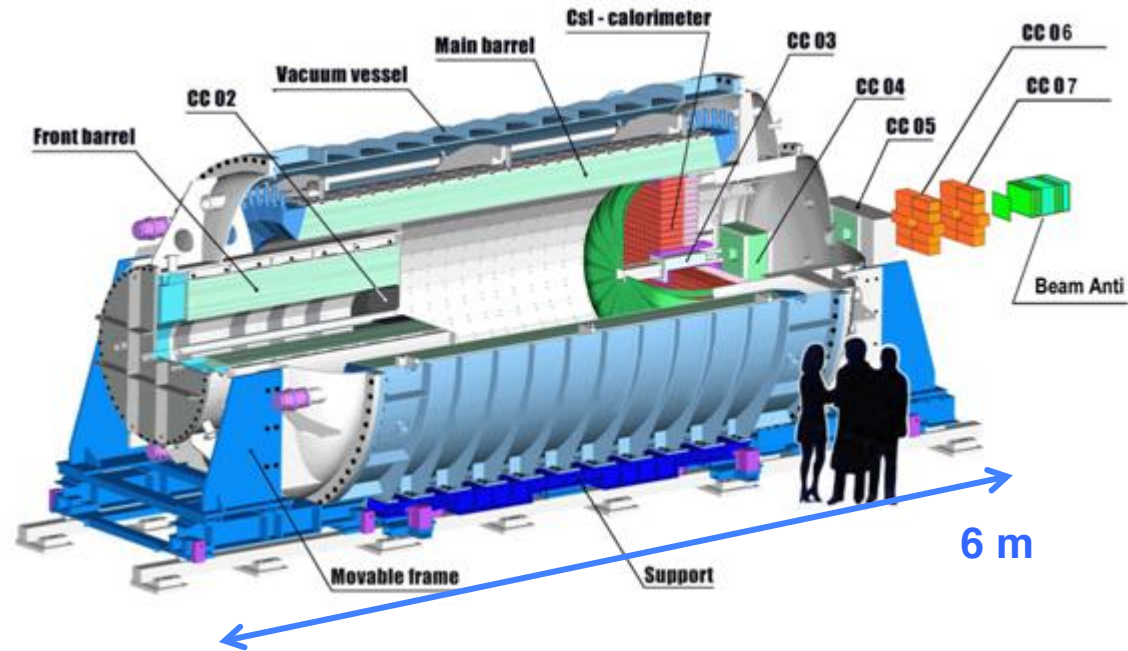
Primary beam: 30 GeV  $p$   
 100 kW =  $1.2 \times 10^{14}$  p/6 s

Neutral beam (16°)

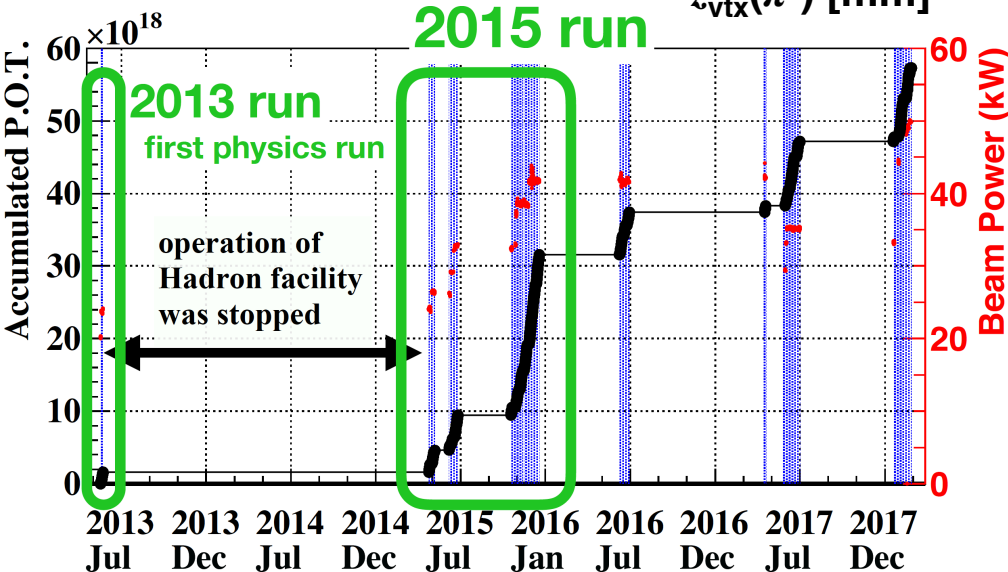
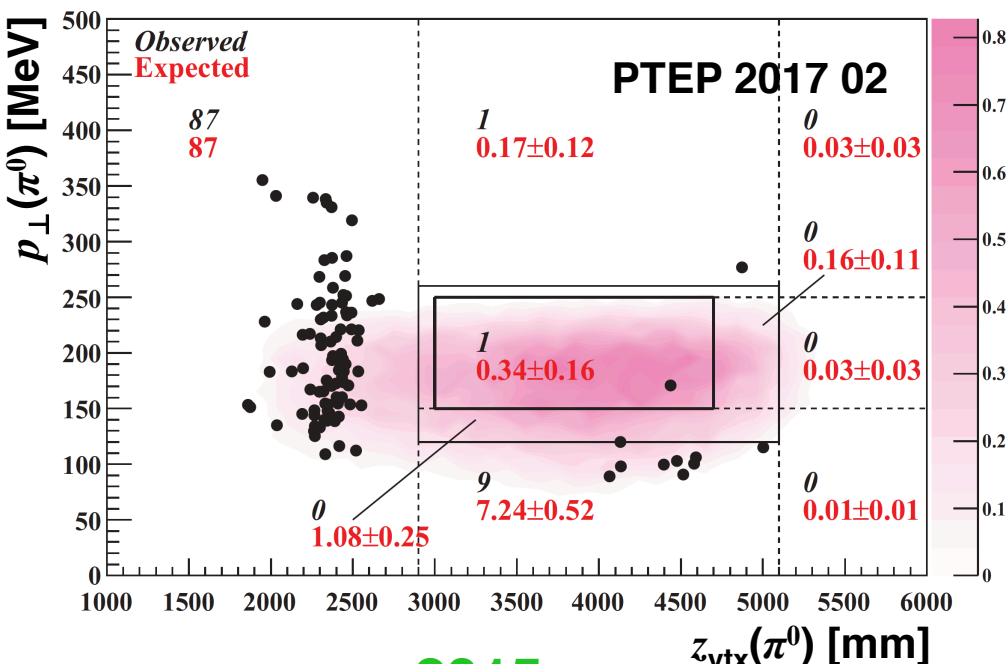
$\langle p(K_L) \rangle = 2.1$  GeV

50% of  $K_L$  have 0.7-2.4 GeV

8  $\mu$ sr “pencil” beam



# $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC



**KOTO is based on KEK-E391a**

E391a result = current exp. value:

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \leq 2.6 \times 10^{-8} \text{ (90\%CL)}$$

**KOTO run history:**

**2013 pilot run (100 hrs)**

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \leq 5.1 \times 10^{-8} \text{ (90\%CL)}$$

**2015 run (result coming soon)**

- 40 kW slow-extracted beam power
- 3e19 pot collected

**2016-2017**

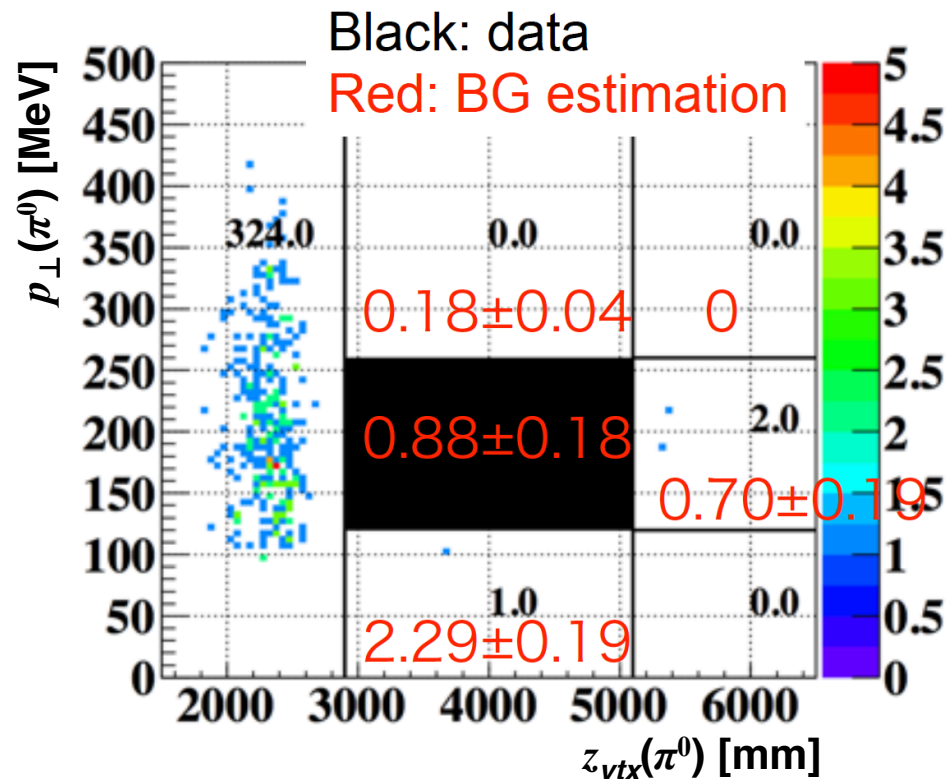
- Beam power increased to **50 kW**
- 3e19 pot collected (6e19 total)
- With all 2015-2017 data, expected sensitivity below Grossman-Nir limit

# Sensitivity from 2015 data



J-PARC PAC, Jan 2018

Background	Expected counts
$K_L \rightarrow 2\pi^0$	$0.07 \pm 0.07$
$K_L \rightarrow \pi^+\pi^-\pi^0$	$0.18 \pm 0.05$
$K_L \rightarrow 3\pi^0$	$0.17 \pm 0.12$
$K_L \rightarrow 2\gamma$	$0.02 \pm 0.02$
Hadron cluster	$0.26 \pm 0.08$
$\pi^0$ from NCC	$0.13 \pm 0.07$
$\eta$ from CV	$0.05 \pm 0.02$
<b>Total</b>	<b><math>0.88 \pm 0.18</math></b>



Preliminary sensitivity, all 2015 data:

**SES =  $1.2 \times 10^{-9}$**

**Expected bkg =  $0.88 \pm 0.18$  events**

**Signal box to be opened summer 2018**

$K_L$  flux from  $K_L \rightarrow 2\pi^0 = 4.62 \times 10^{12}$

$\pi^0\nu\nu$  acceptance from MC:

Decay in FV: 3.8%

Overall acceptance:  $1.8 \times 10^{-4}$

# Upgrades to improve sensitivity



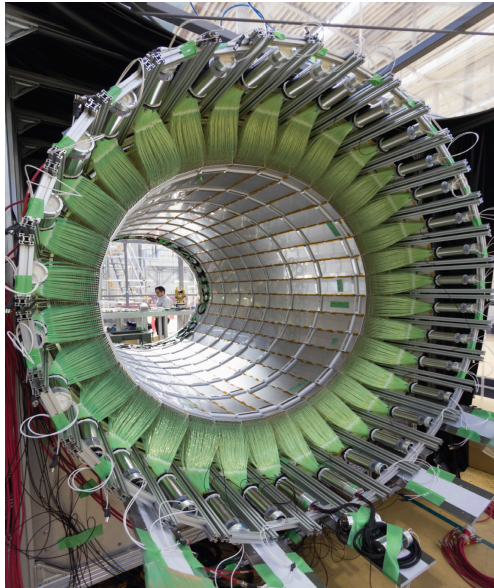
**Signal:** Need  $\sim 40\times$  more flux  $\times$  acceptance for 1 expected SM  $\pi^0\nu\nu$  event

- Beam power expected to increase 50  $\rightarrow$  100 kW gradually by 2021
- 20+ months of additional running planned in 2018-2021

**Background:** Need  $\sim 40\times$  more background rejection for S/B  $\sim 1$

- Continuing program of detector upgrades

## Inner barrel veto

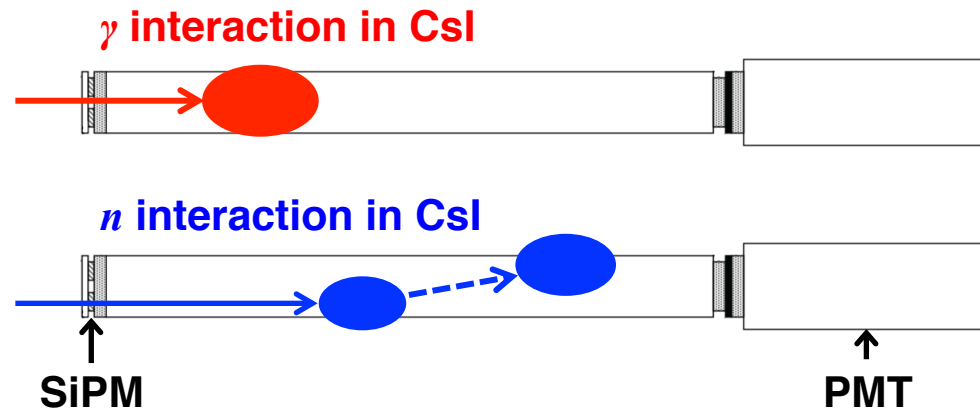


Increase barrel thickness  
 $13.5 + 5 X_0$

3x better rejection for  
 $K_L \rightarrow 2\pi^0$

Installed April 2016

## Dual side readout for CsI modules



Resolve  $\gamma/n$  interaction depth by reading light from front CsI face with SiPM

SiPMs to be installed summer 2018

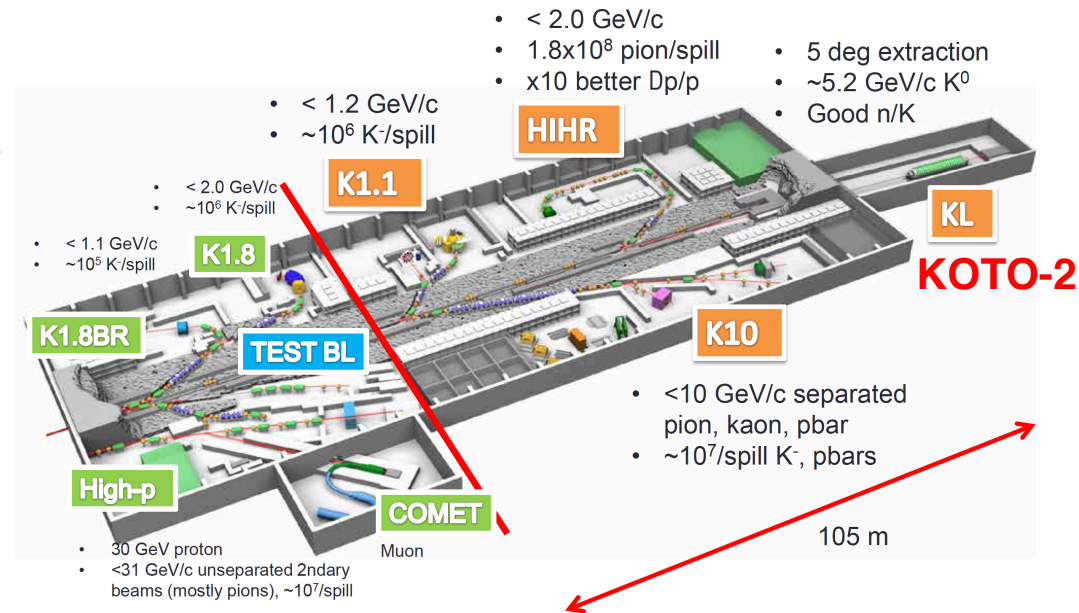
**Expect to reach SM sensitivity by 2021**

# $K_L \rightarrow \pi^0 \nu \bar{\nu}$ : Long-term plans



## KOTO Step-2 upgrade:

- Increase beam power to >100 kW
- New neutral beamline at 5°  
 $\langle p(K_L) \rangle = 5.2 \text{ GeV}$
- Increase FV from 2 m to 11 m  
Complete rebuild of detector
- Requires extension of hadron hall

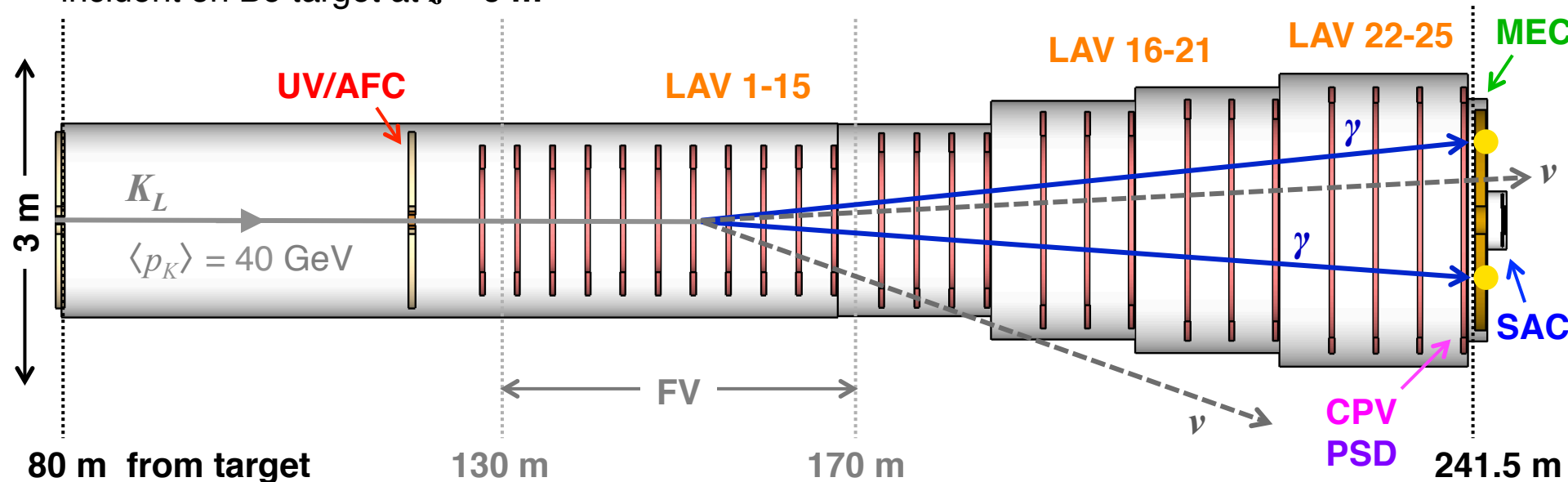


## Strong intention to upgrade to O(100) event sensitivity over long term:

- No official Step 2 proposal yet (plan outlined in 2006 KOTO proposal)
- Scaling KOTO performance for smaller beam angle & larger detector:  
 $\sim 10 \text{ SM evts/year at } 100 \text{ kW beam power?}$
- Exploring possibilities for machine & detector upgrades to further increase sensitivity

# A $K_L \rightarrow \pi^0 \nu \bar{\nu}$ experiment at the SPS?

400-GeV SPS proton beam ( $2 \times 10^{13}$  pot/16.8 s)  
incident on Be target at  $z = 0$  m



## ***K<sub>L</sub>EVER***

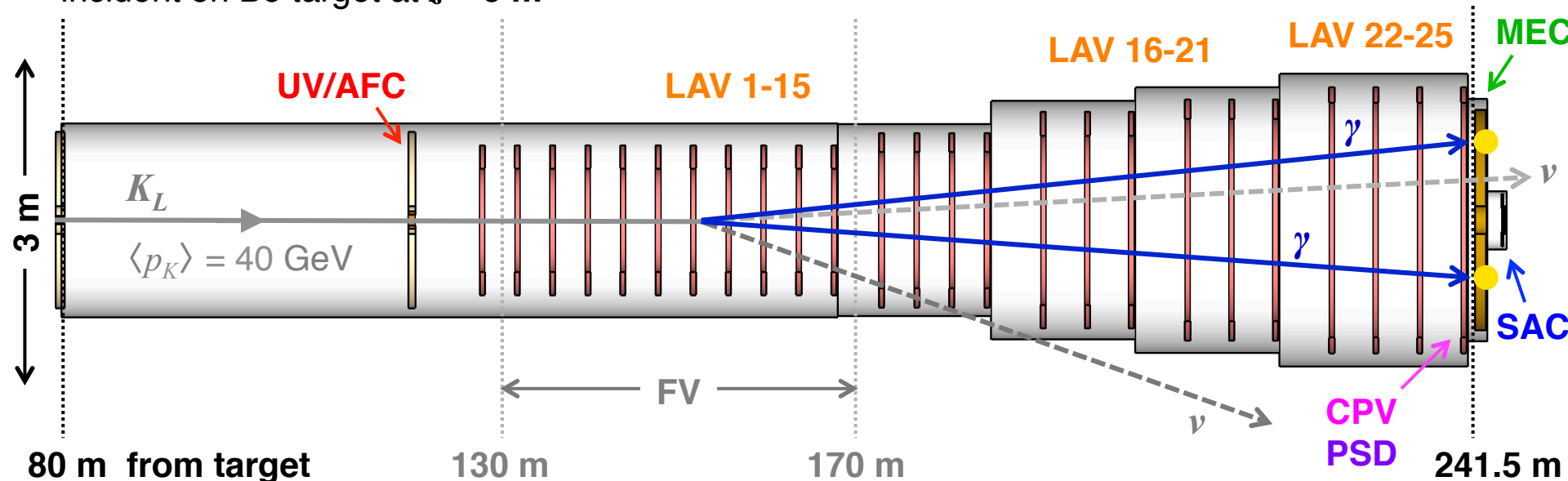
$K_L$  Experiment for  
VEry Rare events

- High-energy experiment: Complementary to KOTO
- Photons from  $K_L$  decays boosted forward
  - Makes photon vetoing easier - veto coverage only out to 100 mrad
- Roughly same vacuum tank layout and fiducial volume as NA62

# A $K_L \rightarrow \pi^0 \nu \bar{\nu}$ experiment at the SPS

***K<sub>L</sub>EVER***

400-GeV SPS proton beam ( $2 \times 10^{13}$  pot/16.8 s)  
incident on Be target at  $z = 0$  m



## Main detector/veto systems:

***K<sub>L</sub>EVER* target sensitivity:**

**5 years starting Run 4**

**60 SM  $K_L \rightarrow \pi^0 \nu \bar{\nu}$**

**$S/B \sim 1$**

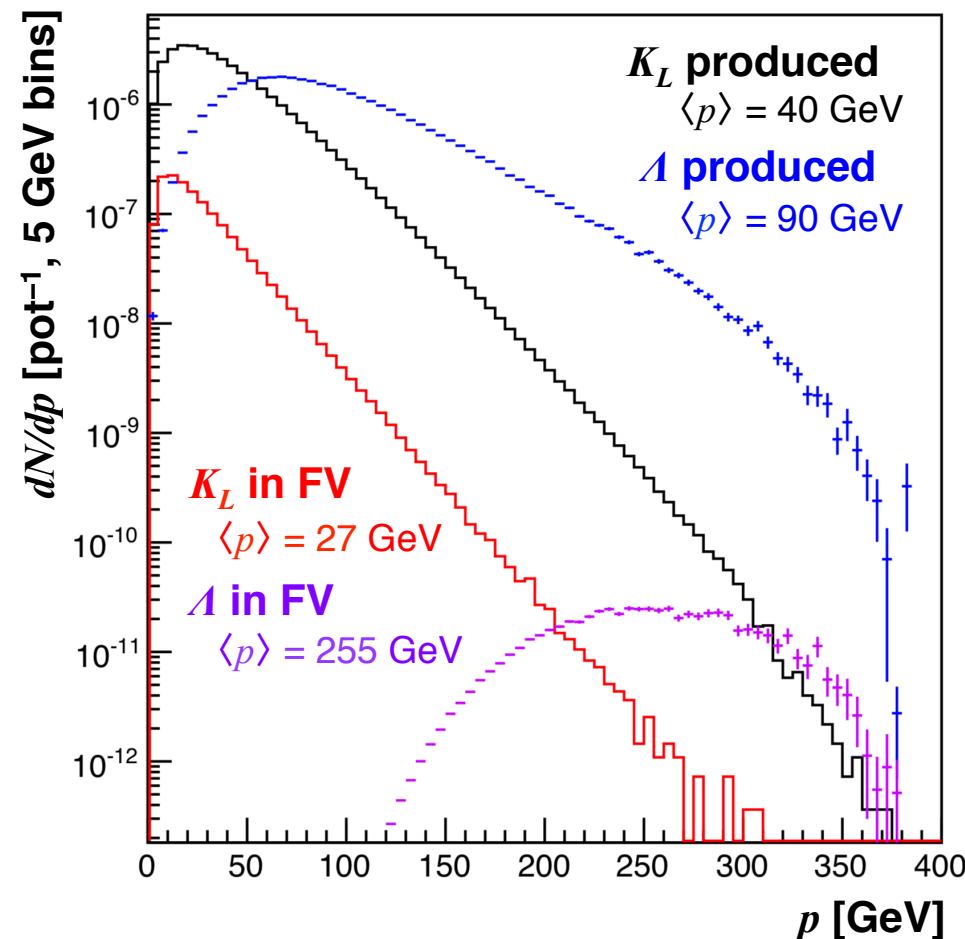
**$\delta BR/BR(\pi^0 \nu \bar{\nu}) \sim 20\%$**

<b>UV/AFC</b>	Upstream veto/Active final collimator
<b>LAV1-25</b>	Large-angle vetoes (25 stations)
<b>MEC</b>	Main electromagnetic calorimeter
<b>SAC</b>	Small-angle vetoes
<b>CPV</b>	Charged particle veto
<b>PSD</b>	Pre-shower detector

# Beam and intensity requirements

## $K_L$ and $\Lambda$ fluxes in beam

FLUKA simulation



$10^{19}$  pot/year (= 100 eff. days)

E.g.:  $2 \times 10^{13}$  ppp/16.8 s

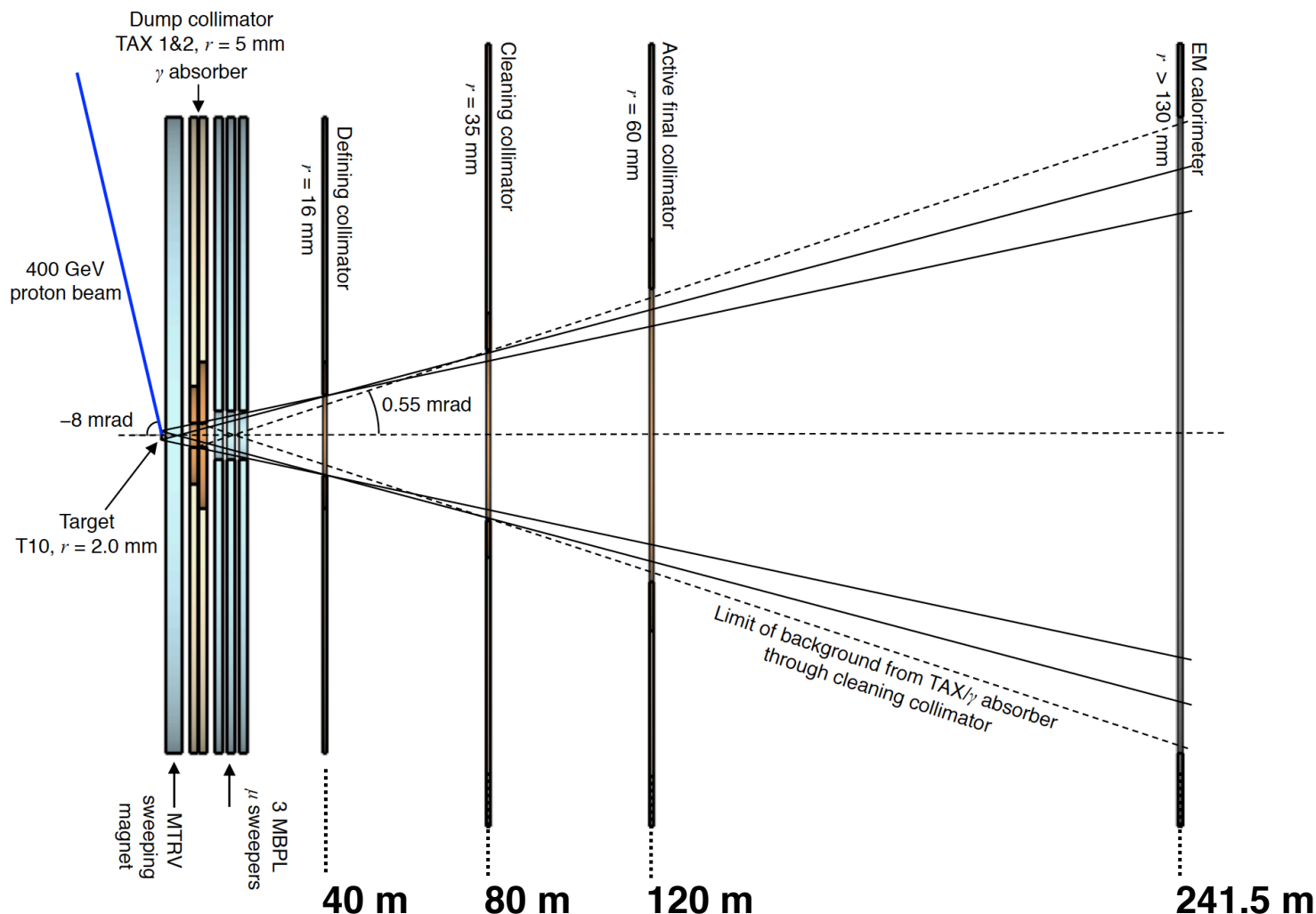
× 5 years



**$60 K_L \rightarrow \pi^0 \nu \nu$  events**

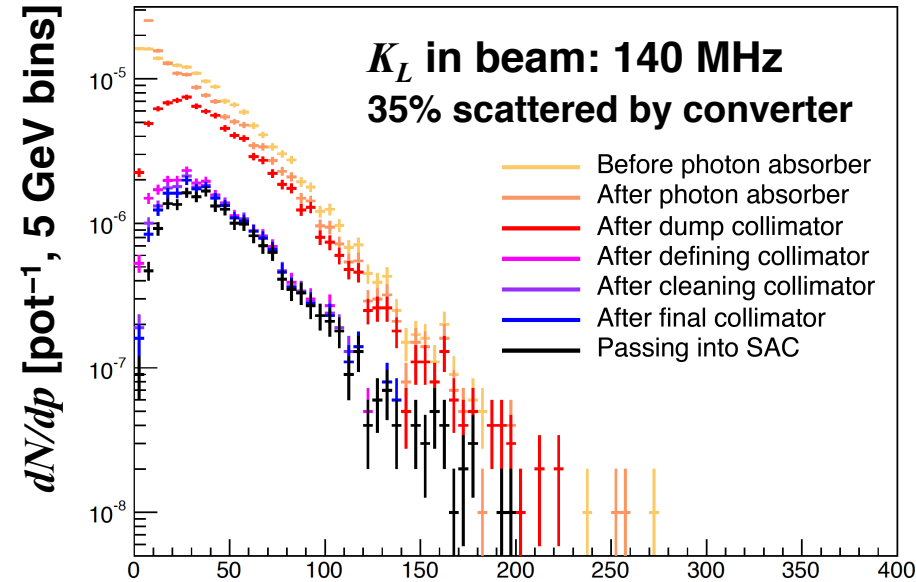
- 400 GeV  $p$  on 400 mm Be target
- Production at  $\theta = 8.0$  mrad:
  - As much  $K_L$  production as possible
  - Low ratio of  $n/K_L$  in beam  $\sim 3$
  - Reduce  $\Lambda$  production and soften momentum spectrum
- Solid angle  $\Delta\theta = 0.4$  mrad
  - Large  $\Delta\theta$  = high  $K_L$  flux
  - Maintain tight beam collimation to improves  $p_{\perp}$  constraint for background rejection
- $2.1 \times 10^{-5} K_L$  in beam/pot
- Probability for decay inside FV  $\sim 2\%$
- Acceptance for  $K_L \rightarrow \pi^0 \nu \nu$  decays occurring in FV  $\sim 10\%$

# Neutral beamline layout



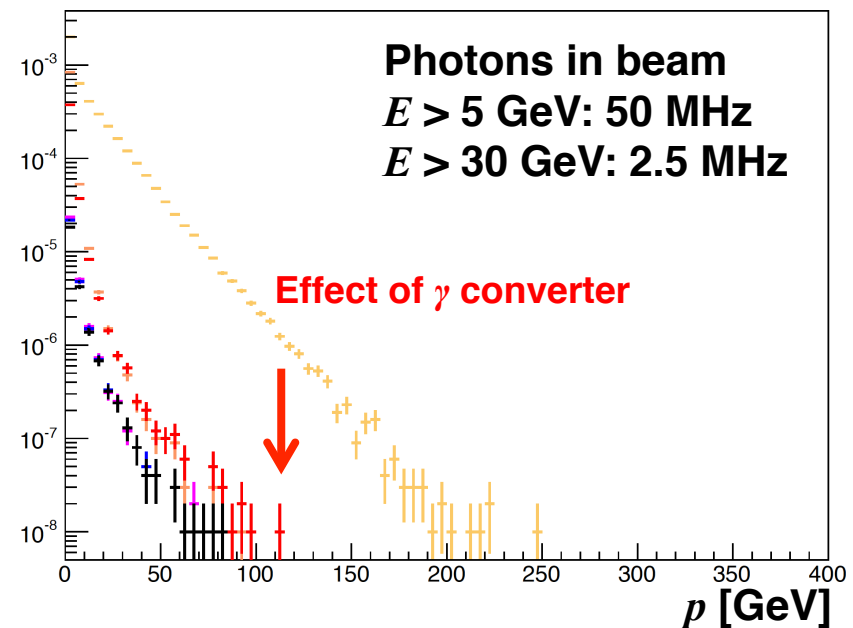
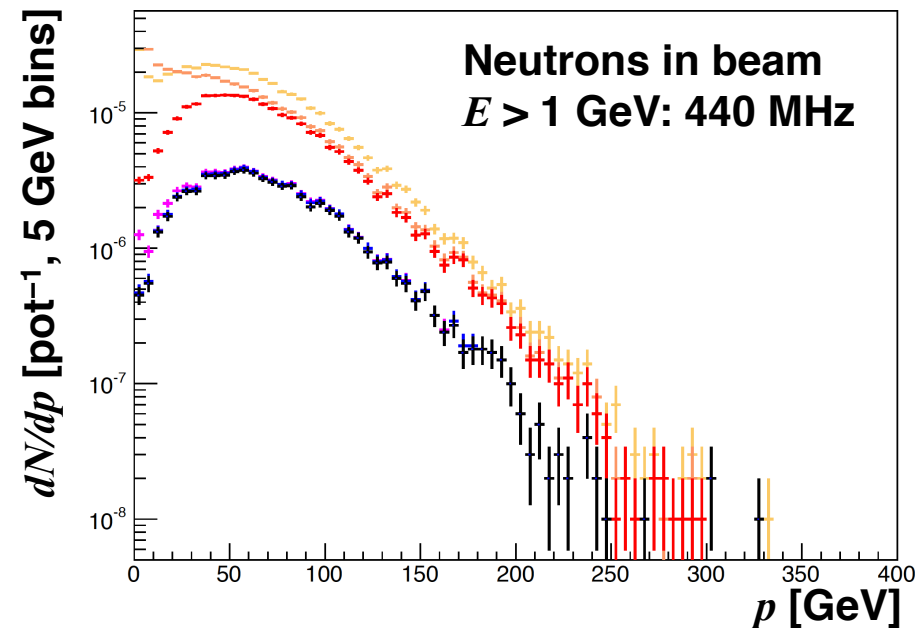
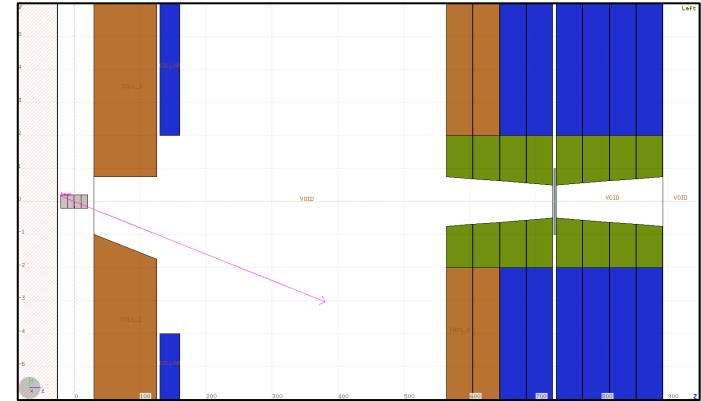
- Compact primary beam sweeping
- Photon absorber in dump collimator
- 4 collimation stages to minimize neutron halo, including beam scattered from absorber
- Active final collimator in LYSO

# Neutral beam simulation



**FLUKA simulation of beamline**  
 32-mm tungsten converter ( $9X_0$ )

Detail of target and dump collimator:



# Shashlyk calorimeter with spy tiles

Main electromagnetic calorimeter (MEC):

Fine-sampling shashlyk based on PANDA  
forward EM calorimeter produced at Protvino

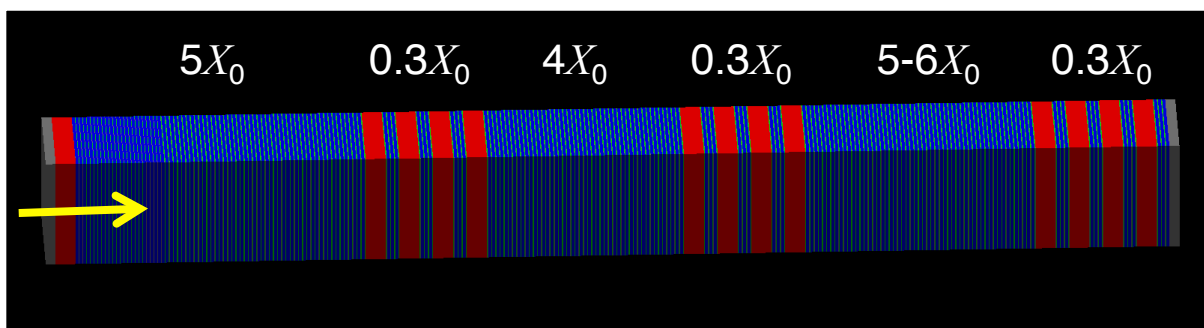
0.275 mm Pb + 1.5 mm scintillator

PANDA/KOPIO prototypes:

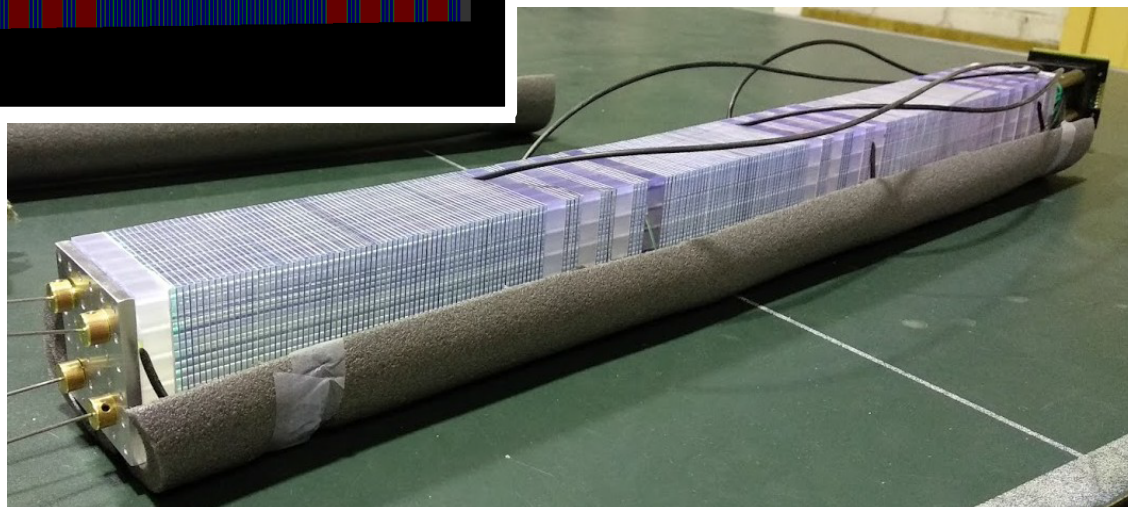
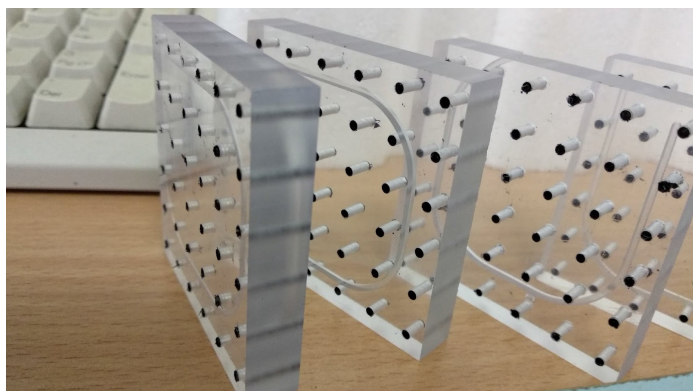
- $\sigma_E/\sqrt{E} \sim 3\% \sqrt{E}$  (GeV)
- $\sigma_t \sim 72 \text{ ps} \sqrt{E}$  (GeV)
- $\sigma_x \sim 13 \text{ mm} \sqrt{E}$  (GeV)

**New for KLEVER: Longitudinal shower information from spy tiles**

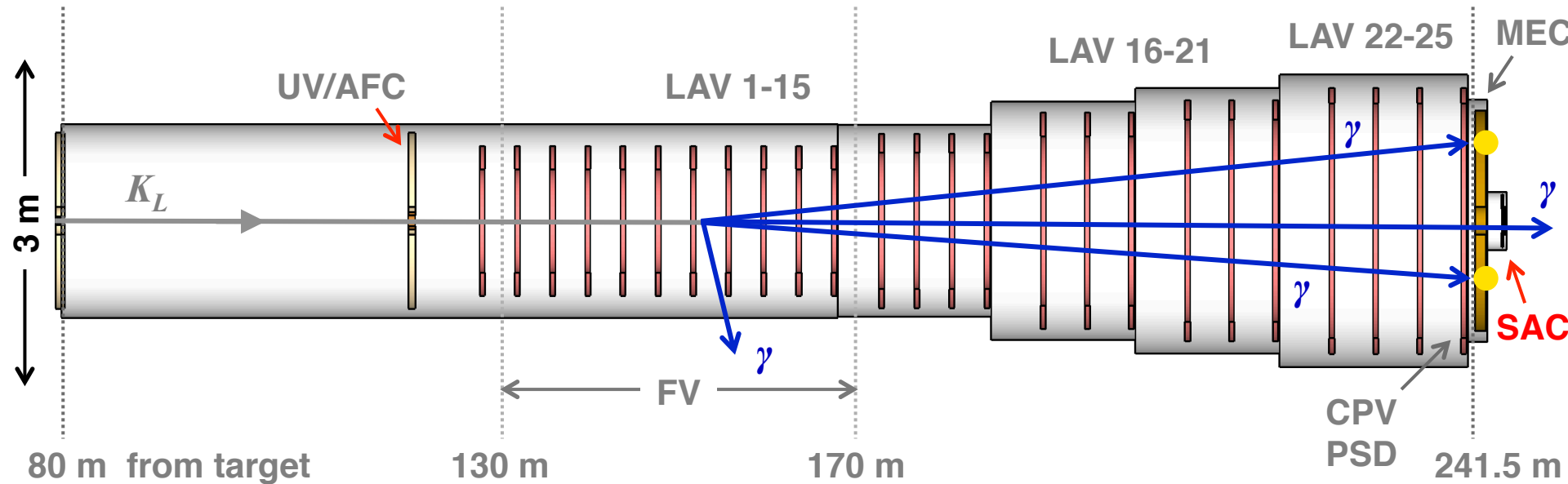
- PID information: identification of  $\mu$ ,  $\pi$ ,  $n$  interactions
- Shower depth information: improved time resolution for EM showers



**1<sup>st</sup> prototype assembled  
and tested at Protvino  
OKA beamline, April 2018**



# Small-angle photon veto



## Small-angle photon veto systems (IRC, SAC)

- Reject high-energy  $\gamma$ s from  $K_L \rightarrow \pi^0\pi^0$  escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

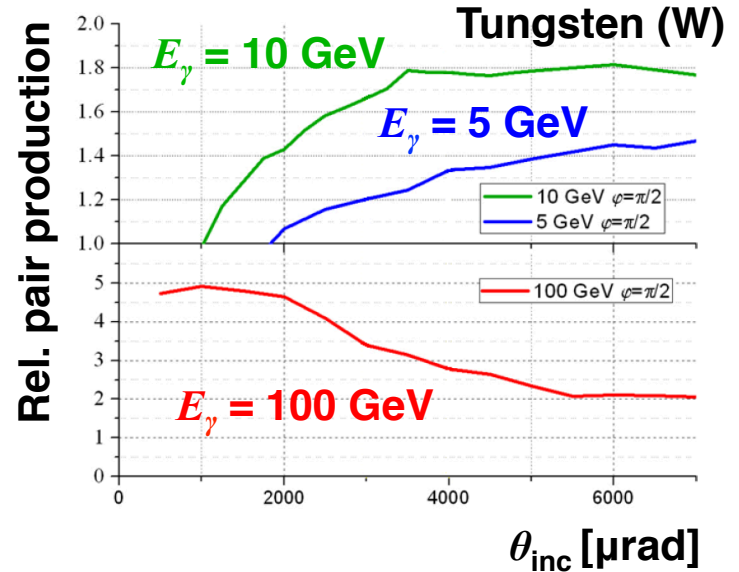
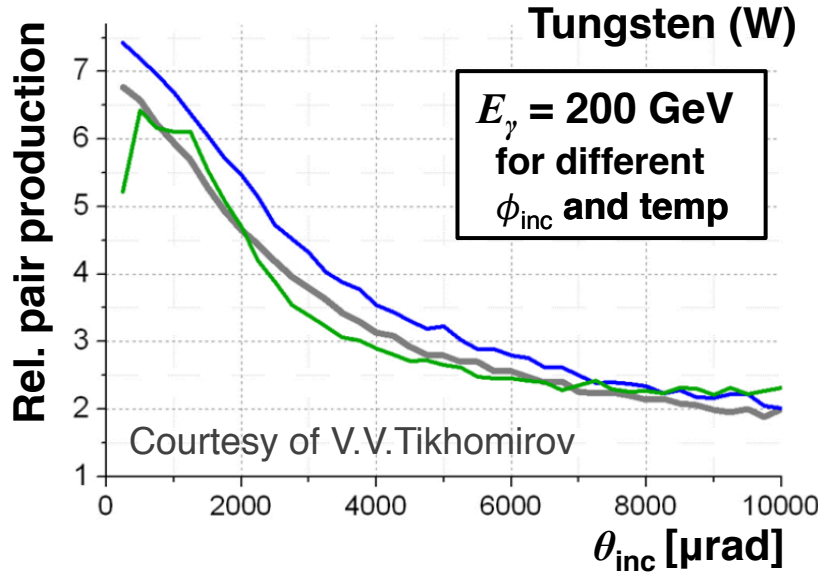
Beam comp.	Rate (MHz)	Req. $1 - \varepsilon$
$\gamma, E > 5 \text{ GeV}$	<b>50</b>	<b><math>10^{-2}</math></b>
$\gamma, E > 30 \text{ GeV}$	<b>2.5</b>	<b><math>10^{-4}</math></b>
$n$	<b>430</b>	<b>—</b>

## Baseline solution:

- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber

# Efficient $\gamma$ conversion with crystals

Coherent effects in crystals enhance pair-conversion probability



Use coherent effects to obtain a converter with large effective  $\lambda_{\text{int}}/X_0$ :

**1. Beam photon converter in dump collimator**

Effective at converting beam  $\gamma$ s while relatively transparent to  $K_L$

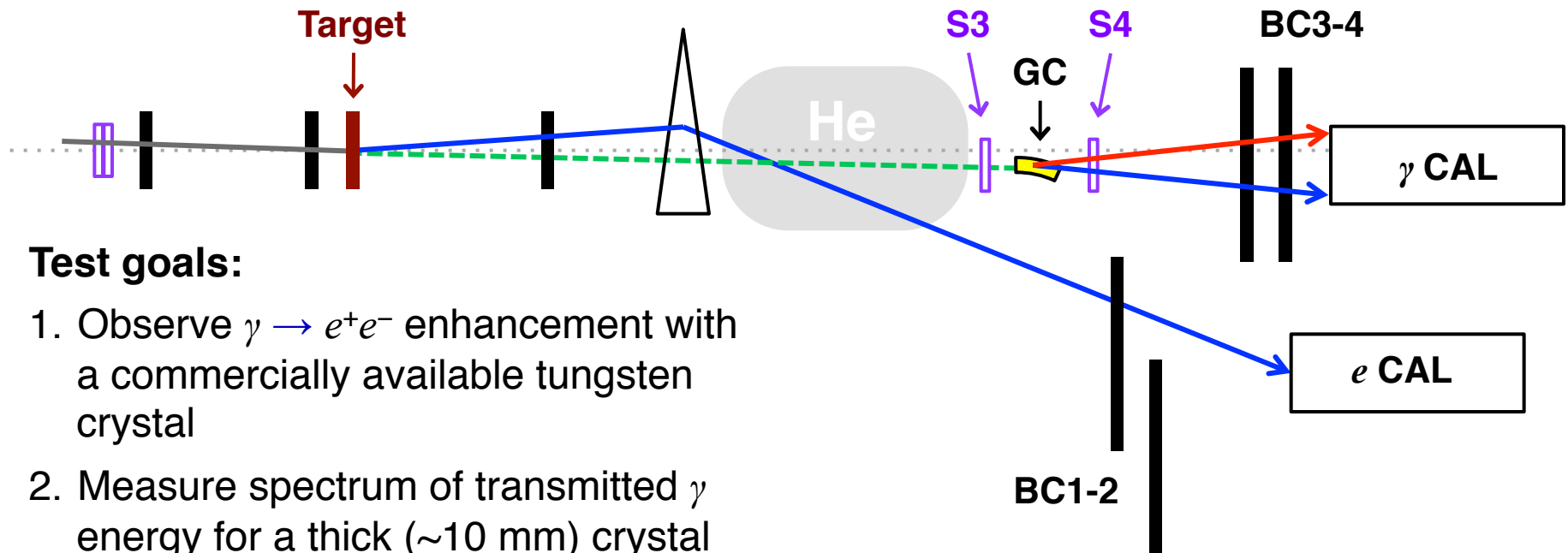
**2. Absorber material for small-angle calorimeter (SAC)**

Must be insensitive as possible to high flux of beam neutrons while efficiently vetoing high-energy  $\gamma$ s from  $K_L$  decays

# Beam test of $\gamma \rightarrow e^+e^-$ in crystals

**AXIAL group is collaborating with KLEVER on test beam measurement of pair-production enhancement in crystals**

**Tagged photon test beam setup:**



**Test goals:**

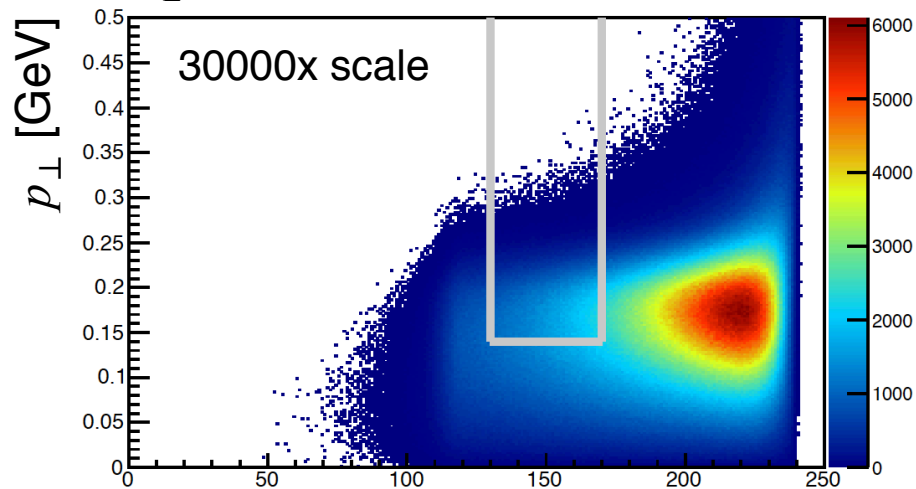
1. Observe  $\gamma \rightarrow e^+e^-$  enhancement with a commercially available tungsten crystal
2. Measure spectrum of transmitted  $\gamma$  energy for a thick ( $\sim 10$  mm) crystal
3. Measure pair conversion vs.  $E_\gamma$ ,  $\theta_{\text{inc}}$  for  $5 < E_\gamma < 150$  GeV
4. Obtain information to assist MC development for beam photon converter and SAC

- **Nearly all detectors and DAQ system available for use from AXIAL**
- **1 week of beam H2 beam time in August 2018**

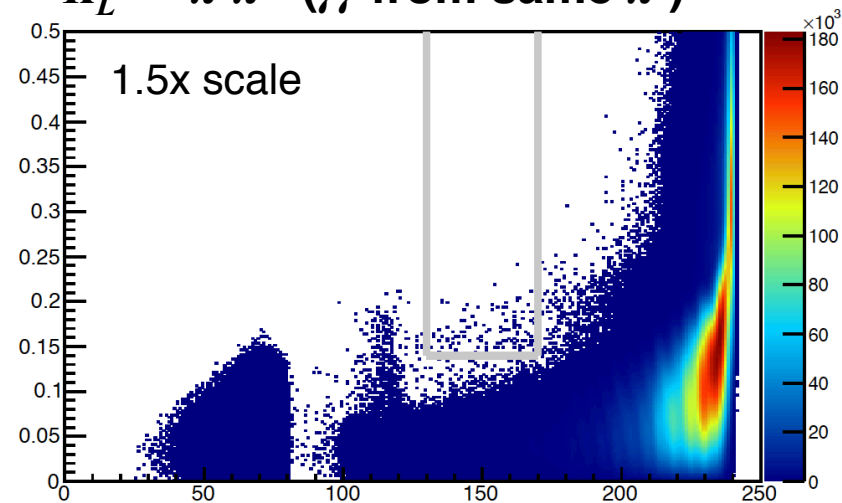
# Basic signal selection

No hits in UV, AFC, LAV, SAC + fiducial volume (FV) and  $p_{\perp}$  cuts

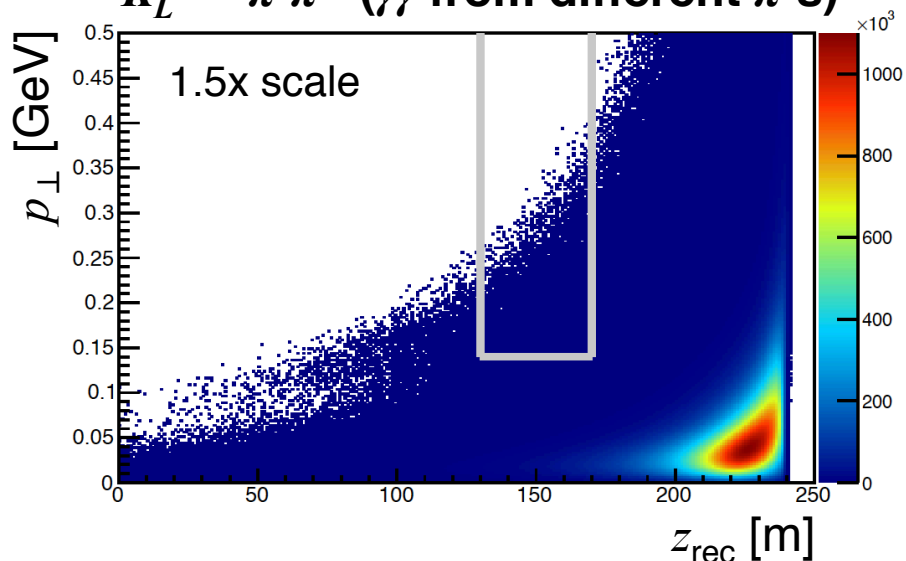
$K_L \rightarrow \pi^0 \nu \nu$



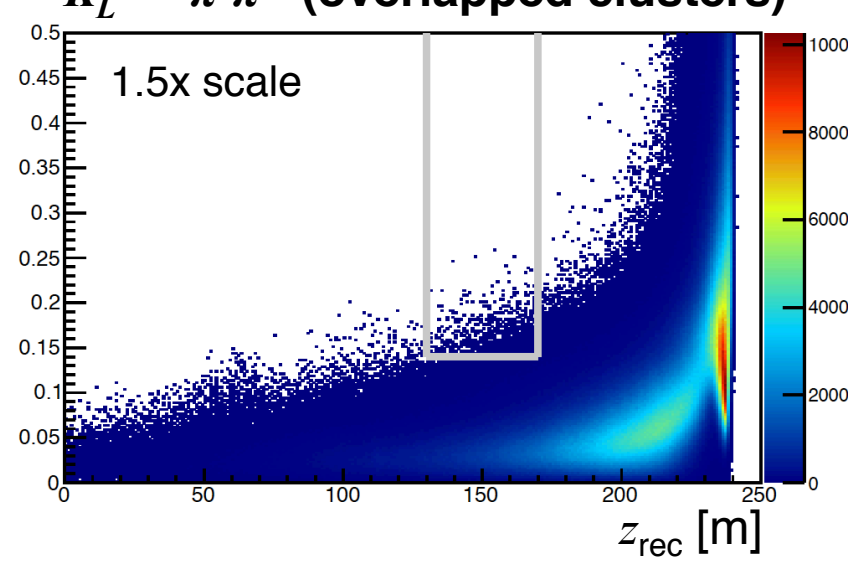
$K_L \rightarrow \pi^0 \pi^0$  ( $\gamma\gamma$  from same  $\pi^0$ )



$K_L \rightarrow \pi^0 \pi^0$  ( $\gamma\gamma$  from different  $\pi^0$ s)



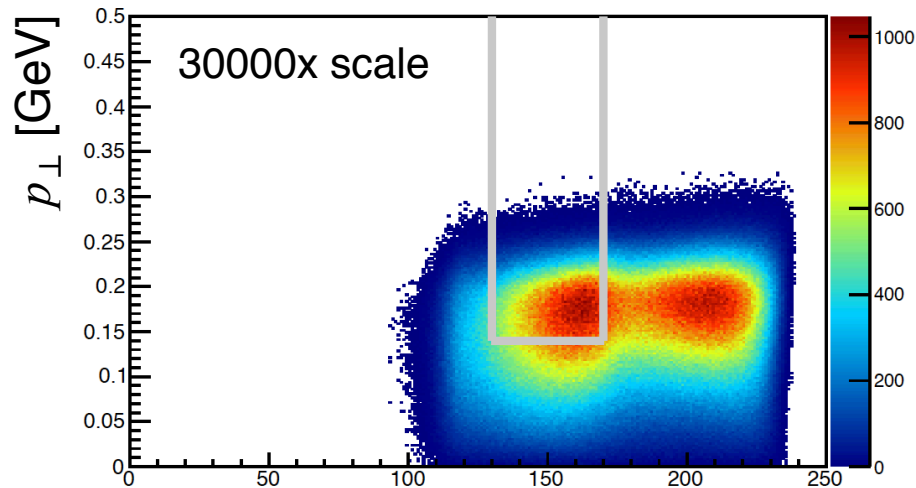
$K_L \rightarrow \pi^0 \pi^0$  (overlapped clusters)



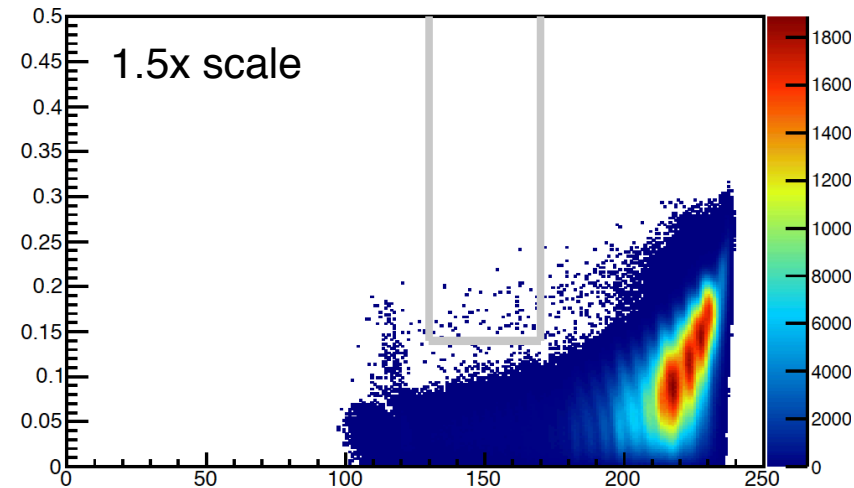
# Additional background rejection

Cluster radius  $r_{\text{MEC}} > 35$  cm – Require  $z_{\text{PSD}}$  in FV if PSD hit available

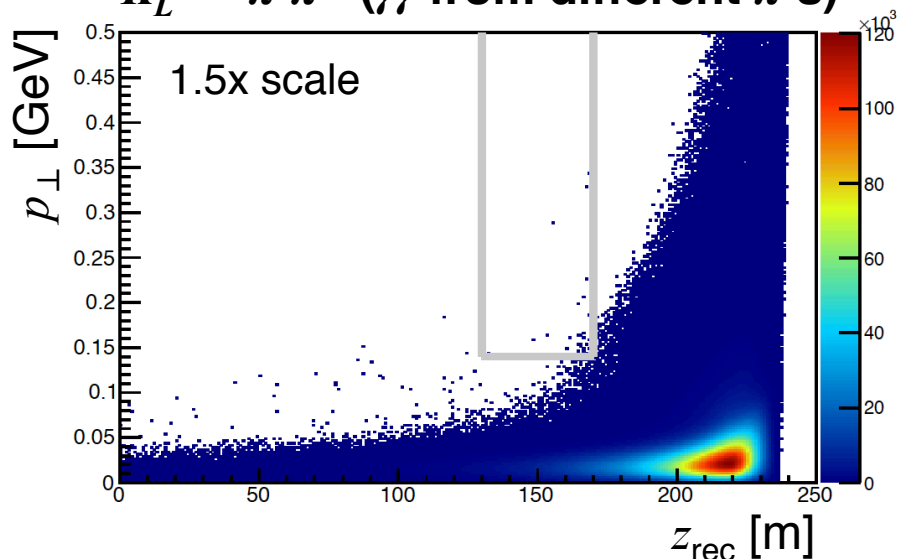
$K_L \rightarrow \pi^0 \nu \nu$



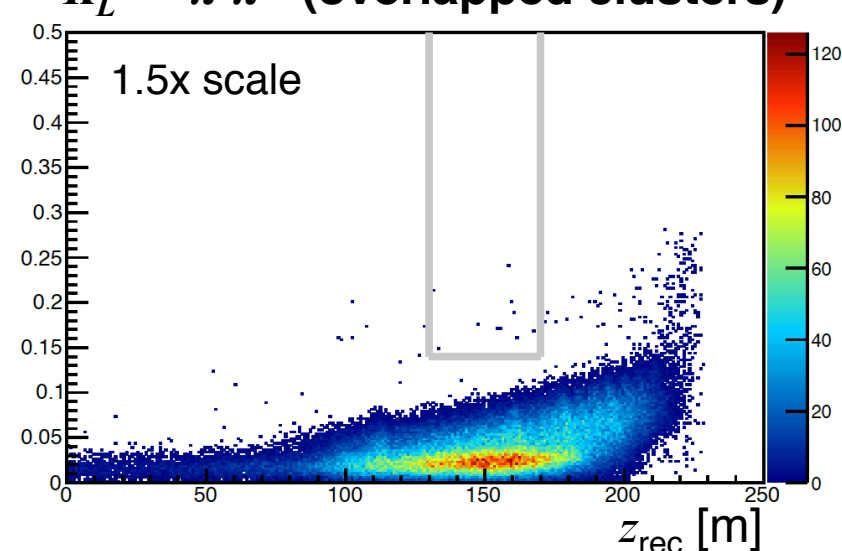
$K_L \rightarrow \pi^0 \pi^0$  ( $\gamma\gamma$  from same  $\pi^0$ )



$K_L \rightarrow \pi^0 \pi^0$  ( $\gamma\gamma$  from different  $\pi^0$ s)



$K_L \rightarrow \pi^0 \pi^0$  (overlapped clusters)



## Project timeline – target dates:

- |                  |  |
|------------------|--|
| <b>2017-2018</b> | <b>Project consolidation and proposal</b> <ul style="list-style-type: none"><li>• Beam test of crystal pair enhancement</li><li>• Consolidate design</li></ul> |
| <b>2019-2021</b> | <b>Detector R&amp;D</b>  |
| <b>2021-2025</b> | <b>Detector construction</b> <ul style="list-style-type: none"><li>• Possible K12 beam test if compatible with NA62</li></ul>                                  |
| <b>2024-2026</b> | <b>Installation during LS3</b>   |
| <b>2026-</b>     | <b>Data taking beginning Run 4</b>   |
- **KLEVER is actively seeking new collaborators!**
  - KLEVER is represented in the CERN Physics Beyond Colliders study
  - An Expression of Interest to the CERN SPSC is in preparation and will also be submitted as input to the European Strategy for Particle Physics

# Summary and outlook

**LHCb has demonstrated unprecedented sensitivity for rare  $K_S$  decays**

**$K \rightarrow \pi \nu \nu$  is a uniquely sensitive indirect probe for high mass scales**

- Need precision measurements of both  $K^+$  and  $K_L$  decays

**NA62 will improve on current knowledge of  $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$  in short term, ultimately reaching  $\sim 100$  event sensitivity**

**KOTO will reach SM sensitivity to  $\text{BR}(K_L \rightarrow \pi^0 \nu \nu)$  by 2021**

**Preliminary design studies indicate that an experiment to measure  $\text{BR}(K_L \rightarrow \pi^0 \nu \nu)$  can be performed at the SPS in Run 4 (2026-2029)**

- Many issues still to be addressed!
- Expected sensitivity:  $\sim 60$  SM events with  $S/B \sim 1$
- KLEVER is preparing Expression of Interest to CERN SPSC and will provide input to European Strategy for Particle Physics

# Additional information

**Exotic Hadrons and Flavor Physics**  
Simons Center for Geometry and Physics  
Stony Brook NY, 1 June 2018

Matthew Moulson  
INFN Frascati

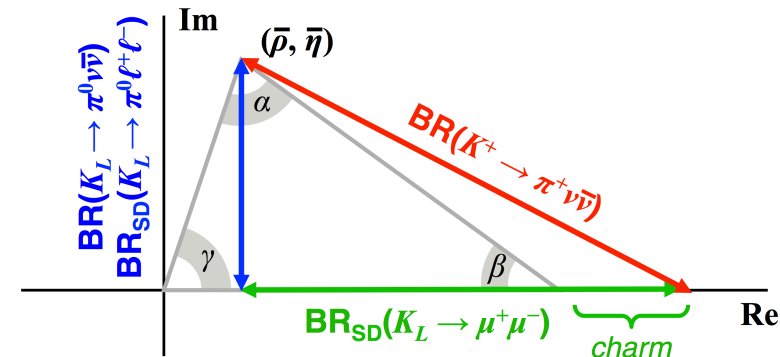
[moulson@Inf.infn.it](mailto:moulson@Inf.infn.it)



$$K_L \rightarrow \pi^0 \ell^+ \ell^-$$

$$K_L \rightarrow \pi^0 \ell^+ \ell^- \text{ vs } K \rightarrow \pi \nu \nu:$$

- Somewhat larger theoretical uncertainties from long-distance physics
  - SD CPV amplitude:  $\gamma/Z$  exchange
  - LD CPC amplitude from  $2\gamma$  exchange
  - LD indirect CPV amplitude:  $K_L \rightarrow K_S$
- $K_L \rightarrow \pi^0 \ell^+ \ell^-$  can be used to explore helicity suppression in FCNC decays



$K_L \rightarrow \pi^0 \ell^+ \ell^-$  CPV amplitude  
constrains UT in same way  
as  $\text{BR}(K_L \rightarrow \pi^0 \nu \nu)$

**Main background:**  $K_L \rightarrow \ell^+ \ell^- \gamma \gamma$

- Like  $K_L \rightarrow \ell^+ \ell^- \gamma$  with hard bremsstrahlung

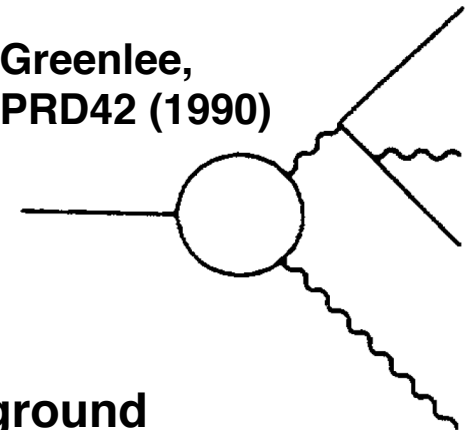
$$\text{BR}(K_L \rightarrow e^+ e^- \gamma \gamma) = (6.0 \pm 0.3) \times 10^{-7}$$

$$\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma \gamma) = 10^{+8}_{-6} \times 10^{-9}$$

$$E_\gamma^* > 5 \text{ MeV}$$

$$m_{\gamma\gamma} > 1 \text{ MeV}$$

Greenlee,  
PRD42 (1990)



$K_L \rightarrow \pi^0 e^+ e^-$  channel is plagued by  $K_L \rightarrow e^+ e^- \gamma \gamma$  background  
– Small acceptance because of tight cuts on Dalitz plot

$K_L \rightarrow \pi^0 \mu^+ \mu^-$  channel may be more tractable

# $K \rightarrow \pi \nu \bar{\nu}$ and new physics

**General agreement of flavor observables with SM  $\rightarrow$  invocation of MFV**

- Long before recent flavor results from LHC

**But NP may simply occur at a higher mass scale**

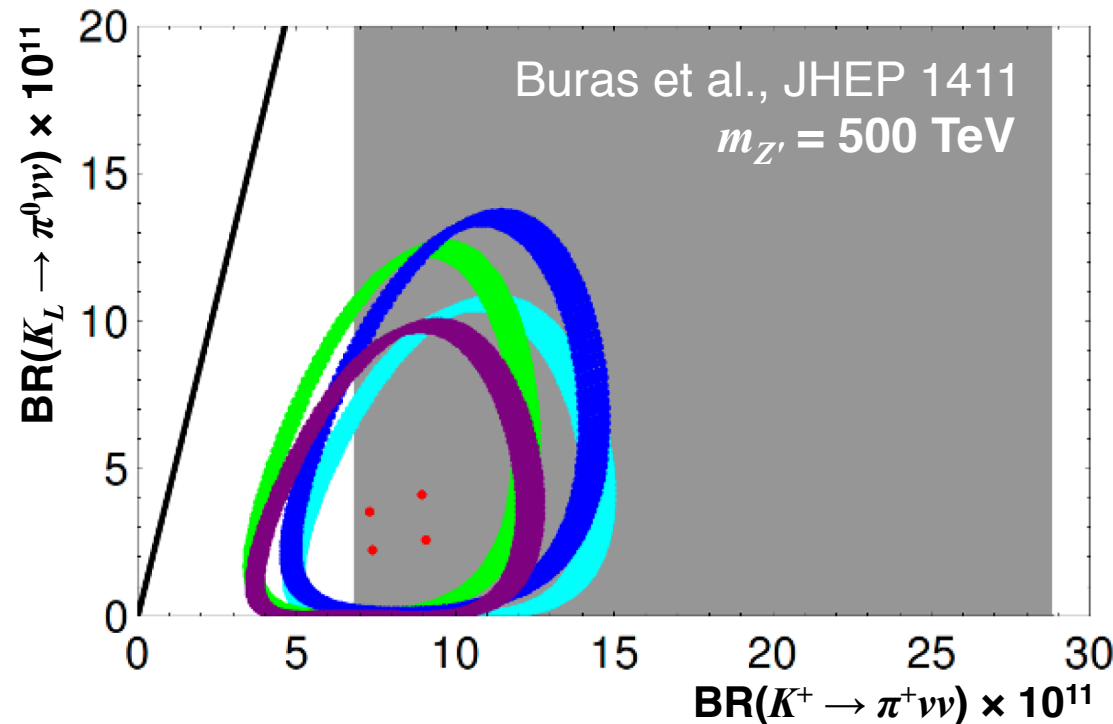
- Null results from direct searches at LHC so far

**Indirect probes to explore high mass scales become very interesting!**

**$K \rightarrow \pi \nu \bar{\nu}$  is uniquely sensitive to high mass scales**

**Tree-level flavor changing  $Z'$   
LH+RH couplings**

- Some fine-tuning around constraint from  $\varepsilon_K$
- $K \rightarrow \pi \nu \bar{\nu}$  sensitive to mass scales up to 2000 TeV
  - Up to tens of TeV even if LH couplings only
- Order of magnitude higher than for  $B$  decays



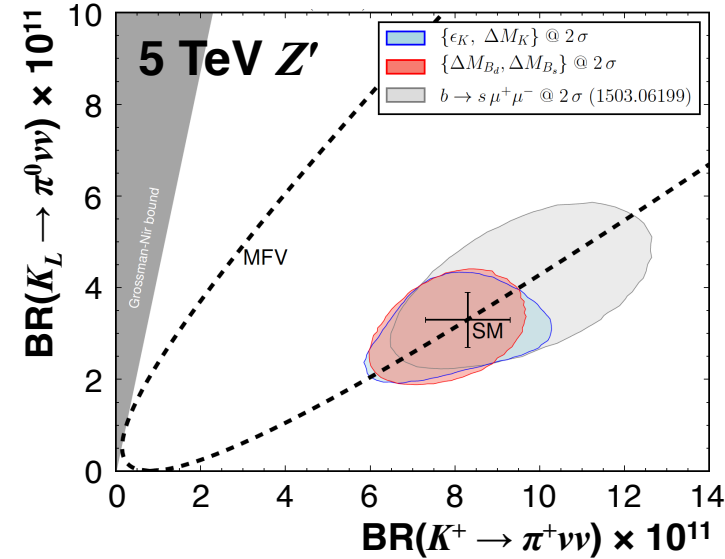
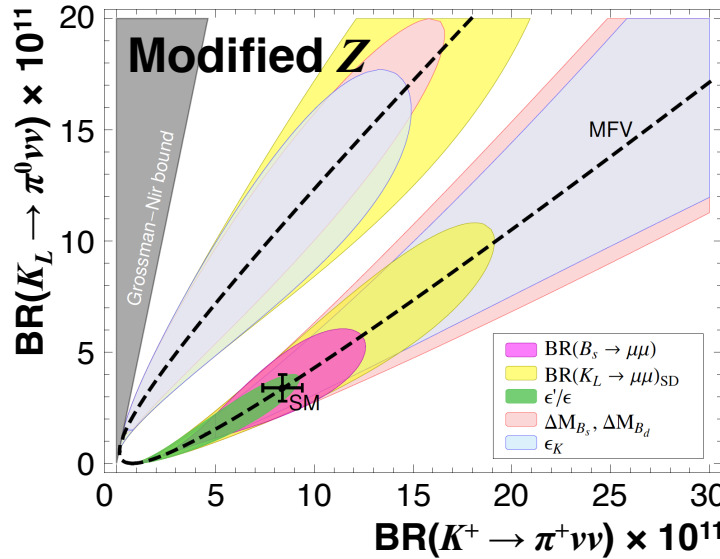
# $K \rightarrow \pi \nu \bar{\nu}$ and other flavor observables

Simplified  $Z, Z'$  model used as paradigm

Buras, Buttazzo, Kneijens, JHEP 1511

## CMFV hypothesis:

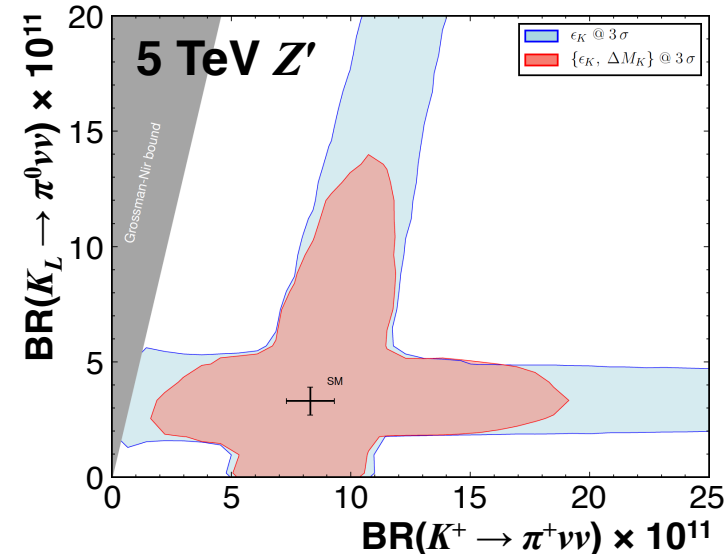
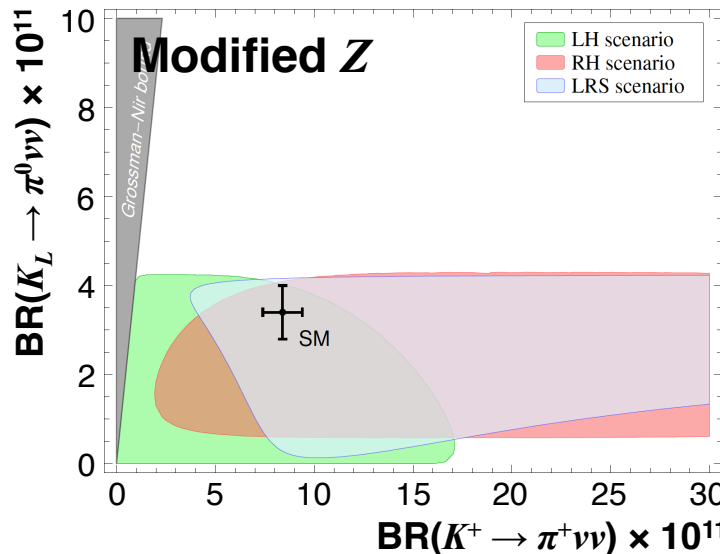
Constraints from  $B$  and  $K$  observables



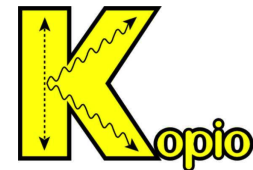
## LH and RH couplings allowed:

Constraints from  $K$  observables:

- $\epsilon_K, \Delta M_K$
- $\epsilon'/\epsilon, K \rightarrow \mu\mu$  (for modified  $Z$ )



# Extra constraints for $K_L \rightarrow \pi^0 \nu \bar{\nu}$



## KOPIO

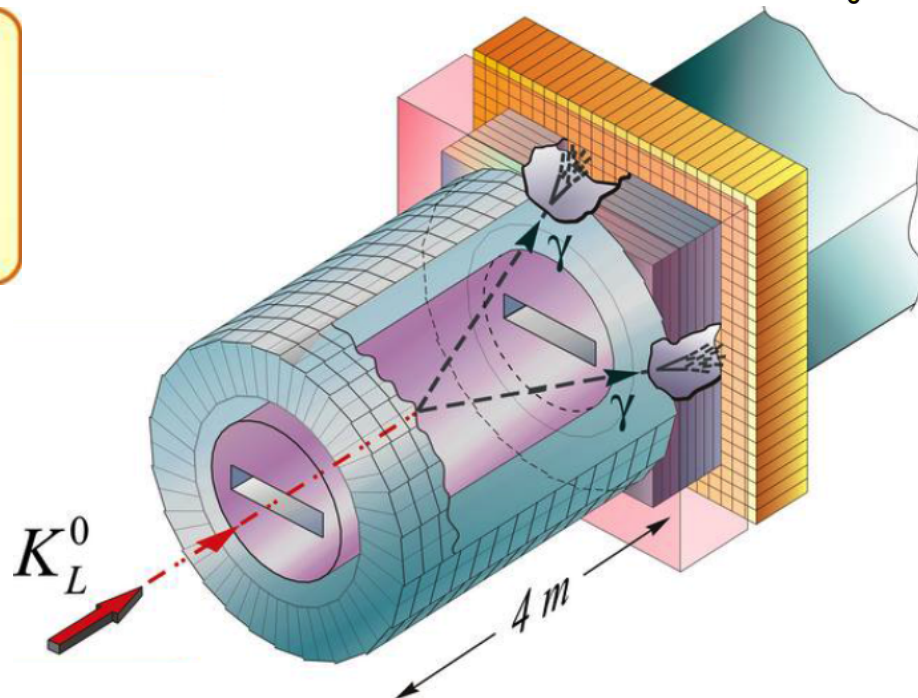
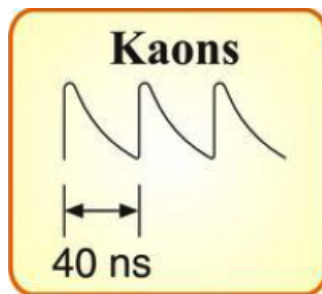
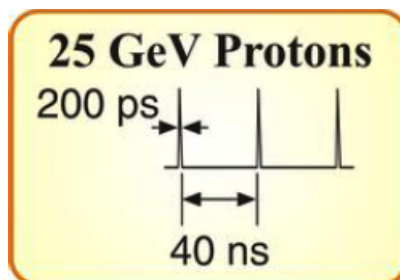
Brookhaven AGS  
Cancelled 2005

**Primary: 26 GeV  $p$**   
 $10^{14} p/7.2 \text{ s}$

**Neutral beam ( $43^\circ$ )**

$\langle p(K_L) \rangle = 0.9 \text{ GeV}$

50% of  $K_L$  have  
0.5-1.2 GeV



## Microbunched beam from AGS:

200 ps every 40 ns,  $10^{-3}$  extinction

## Flat beam to increase $K_L$ flux

Solid angle  $360 \mu\text{sr} = 1 \text{ m}$  wide!

## Preradiator in front of calorimeter

Reconstruct angle of incidence for  $\gamma$ s

**Sensitivity: 180 SM evts in  $\sim 4 \text{ yr}$**

## Advantages:

- $p(K_L)$  from time of flight
- Vertex position from preradiator
- Redundant constraints

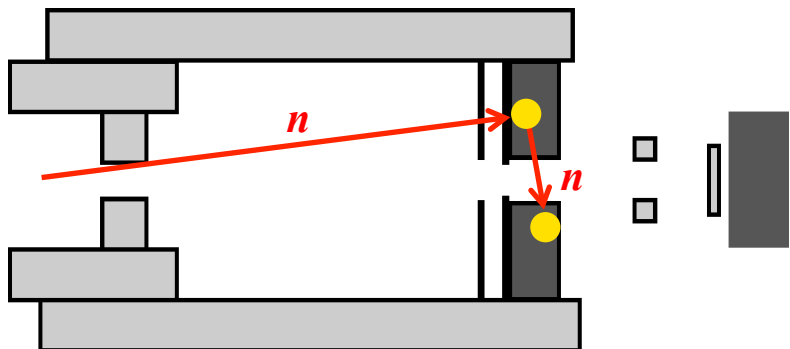
## Disadvantages:

- Difficult to veto low-energy  $\gamma$ s
- Much lower  $K_L$  flux at high angle

# Background rejection

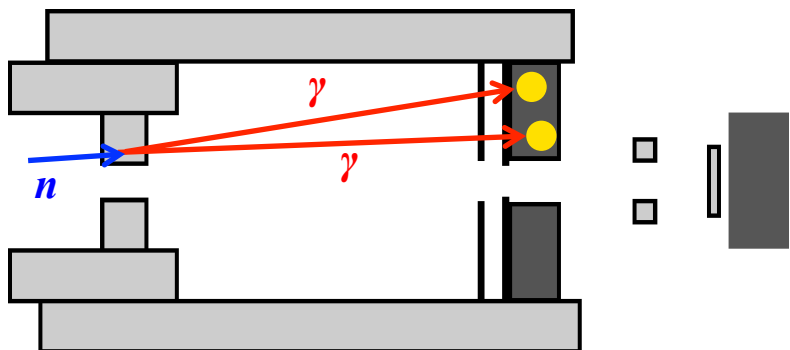
Lessons from 2013 run help to reject backgrounds other than  $K_L \rightarrow \pi^0\pi^0$

## 1. Hadron clusters on Csl



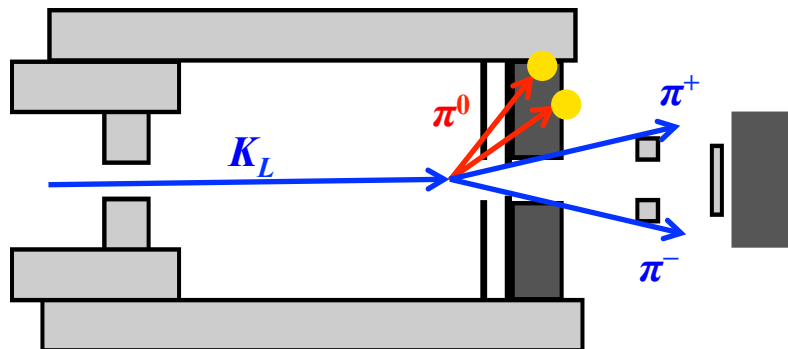
- Control sample with Al plate in beam
- Cluster and pulse shape analysis

## 3. $n \rightarrow X\pi^0$ on collar (NCC)



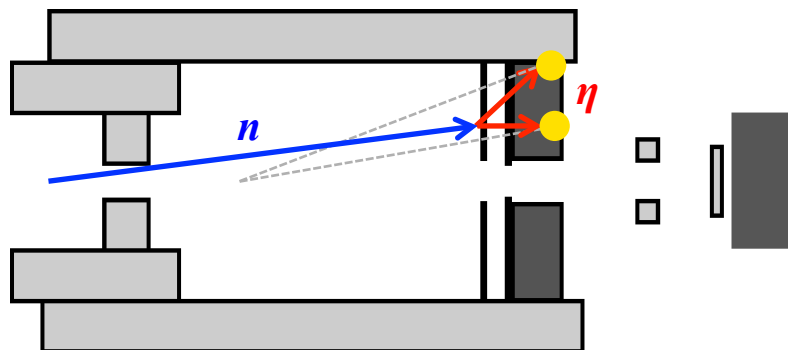
- Beam profile monitor for better alignment
- Thinner vacuum window

## 2. $K_L \rightarrow \pi^+\pi^-\pi^0$ with $\pi^+\pi^-$ escape



- New charged-particle vetoes lining beam exit

## 4. $n \rightarrow X\eta$ on charged veto (CV)



- Cluster shape (angle of incidence)

# High-intensity neutral beam issues

$10^{19}$  pot/yr  $\times$  5 years  $\rightarrow 2 \times 10^{13}$  ppp/16.8s = 6 $\times$  increase relative to NA62

Feasibility/cost study a primary goal of our involvement in Conventional Beam WG

## Preliminary analysis of critical issues by Secondary Beams & Areas group

Issue	Approach
Extraction losses	Good results on ZS losses and spill quality from SPS Losses & Activation WG (SLAWG) Slow extraction workshop, 9-11 November: <a href="https://indico.cern.ch/event/639766/">https://indico.cern.ch/event/639766/</a>
Beam loss on T4	Vertical by-pass to increase transmission to T10
Equipment protection	Possibly use SIS interlock to stop extraction during P0Survey reaction time
Ventilation in ECN3	Need to understand better current safety margin May need comprehensive ventilation system upgrade
ECN3 beam dump	Significantly improved for NA62 Need to understand better current safety margin
Background fluxes	Detailed simulations getting started

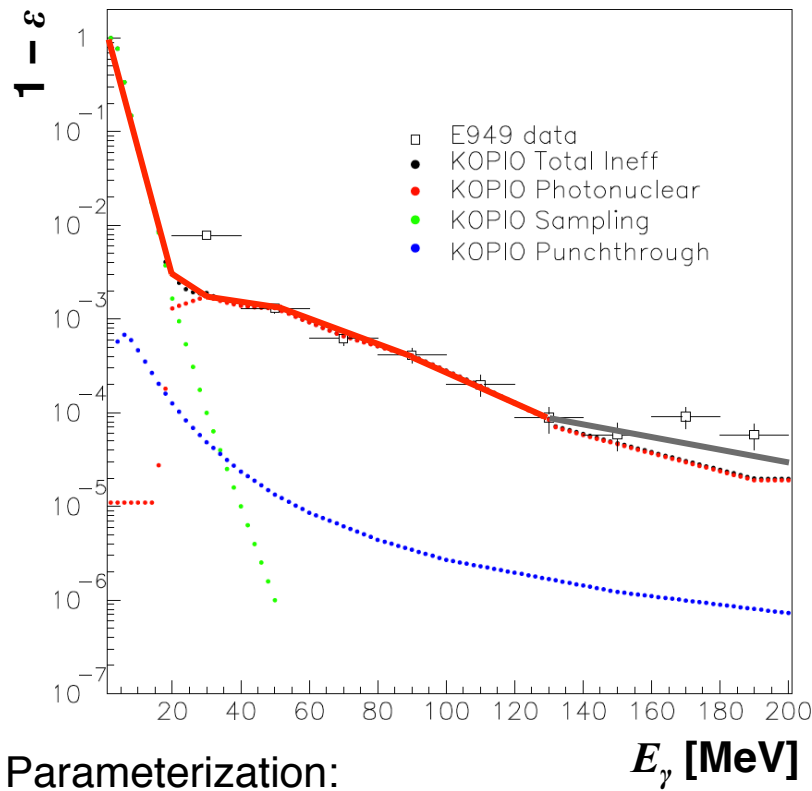
# Large-angle photon vetoes

25 new LAV detectors providing hermetic coverage out to 100 mrad  
Need good detection efficiency at low energy ( $1 - \varepsilon \sim 0.5\%$  at 20 MeV)

**Baseline technology: CKM VVS**  
Scintillating tile with WLS readout



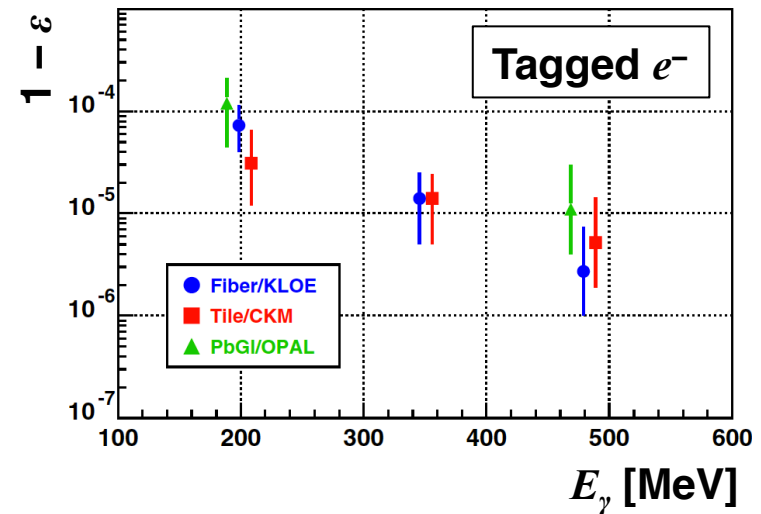
Good efficiency assumptions based on  
E949 and CKM VVS experience



1-129 MeV: KOPIO (E949 barrel)  
203-483 MeV: CKM VVS

**E949 barrel veto efficiencies**  
Same construction as CKM

**Tests for NA62 at Frascati BTF**



**Tests at JLAB for CKM:**

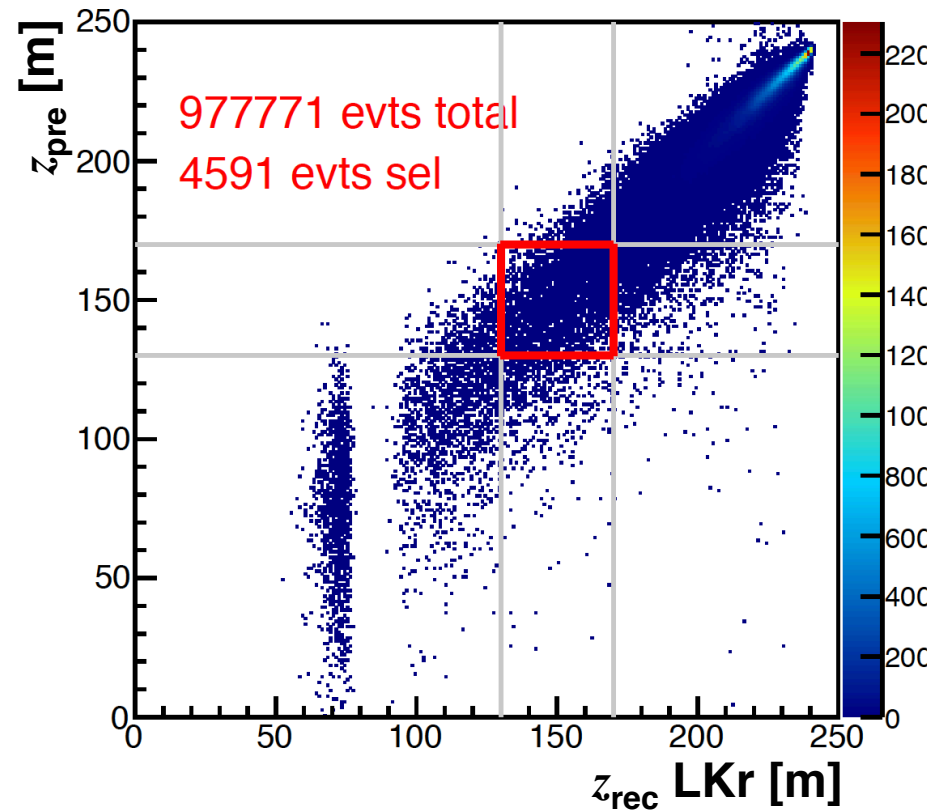
- $1 - \varepsilon \sim 3 \times 10^{-6}$  at 1200 MeV

# Preshower background rejection

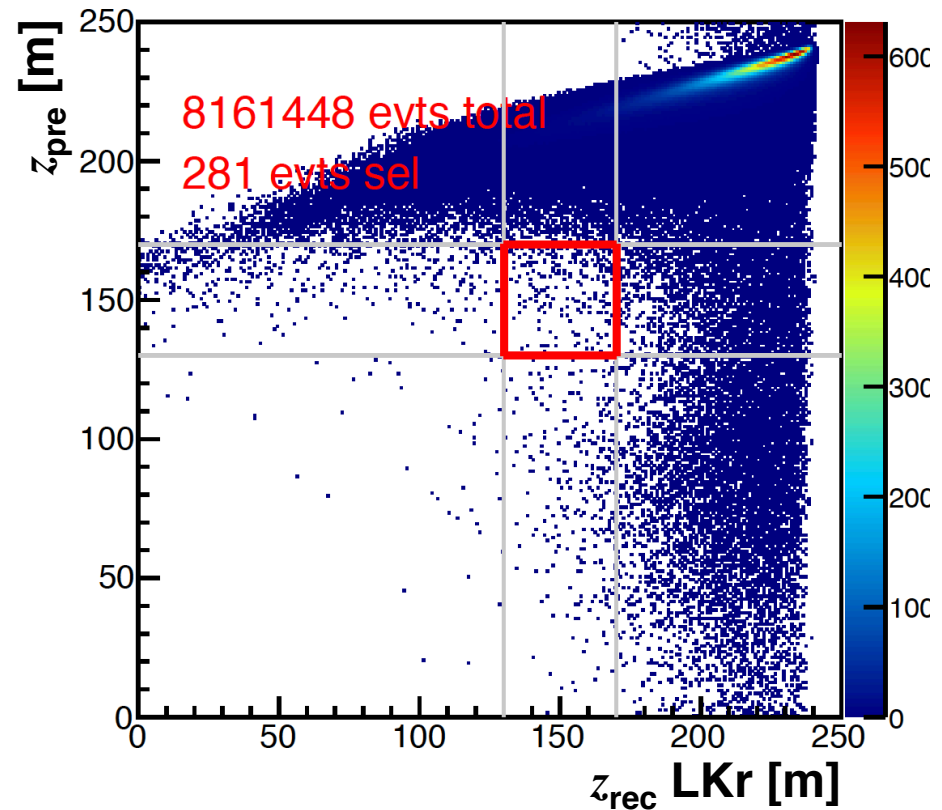
**Preshower vertex  $z_{\text{pre}}$  vs. LKr vertex  $z_{\text{rec}}$**   
 $z_{\text{rec}}$  reconstructed by imposing  $M(\gamma\gamma) = m_{\pi^0}$

- $K_L \rightarrow \pi^0\pi^0$ , 1 year equivalent
- No cuts on FV,  $p_{\perp}$ ,  $r_{\text{min}}$

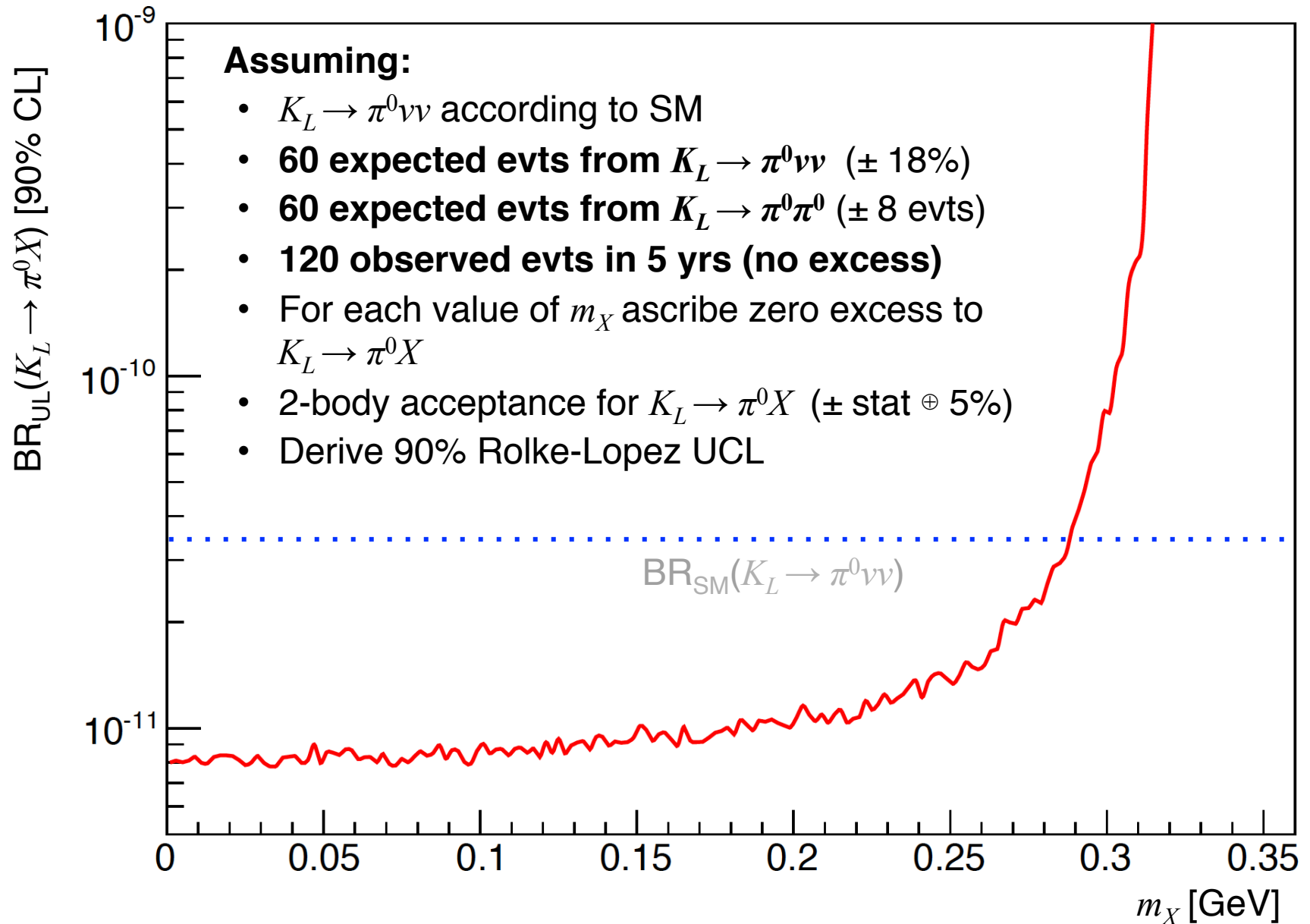
**Even pairs** (2  $\gamma$  from same  $\pi^0$ )  
1  $\gamma$  converts in preshower



**Odd pairs** (2  $\gamma$ s from different  $\pi^0$ )  
1  $\gamma$  converts in preshower



# Limits on $K_L \rightarrow \pi^0 X$ from $K_L \rightarrow \pi^0 \nu \bar{\nu}$



# Limits on dark photon from $K_L \rightarrow \pi^0 \nu \bar{\nu}$ ***K<sub>L</sub>EVER***

Interpret  $X$  as dark photon and obtain limits in  $\varepsilon^2$  vs.  $m_X$  plane

As per Davoudiasl, Lee, Marciano 2014 (analysis giving E787/E949 limits)

