UNIVERSITY OF BIRMINGHAM

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K_LEVER

An experiment to measure BR($K_L \to \pi^0\nu\nu$) at the CERN SPS

Birmingham. 2018, January 17th

Outline

- Overview of precision physics and rare decays K ⟶ πνν
- BR(K ⟶ πνν) measurement state of the art:
  - NA62 experiment at the CERN SpS for the BR($K^+ \longrightarrow \pi^+\nu\nu$) measurement
  - KOTO Experiment at J-PARC for the BR($K_L \longrightarrow \pi^0\nu\nu$) measurement
- KLEVER project, proposal for a new experiment at the CERN SpS for the BR($K_L \longrightarrow \pi^0\nu\nu$) measurement:
  - Goal, challenges
  - Apparatus
  - Expected sensitivity

Precision physics and rare decays

How can we extend the search for new physics to high effective scales?

Direct search ▶ **Energy** frontier

Create new degrees of freedom in lab.
Explore spectroscopy of new d.o.f.
$\Lambda \sim$ 1-10 TeV

Indirect search ▶ **Intensity** frontier

Evidence of new degrees of freedom as alteration of SM rates
Explore symmetry properties of new d.o.f
$\Lambda \sim$ 1-1000 TeV

A rare decay is useful as a New Physics (NP) probe if:

- Process is (strongly) suppressed in the SM
- Parameter to be measured precisely calculated in SM
- There are specific predictions for NP contributions

What may be studied with rare decays:

- Explicit violations of the SM (e.g., lepton flavor violation)
- Tests of fundamental symmetries such as CP and CPT
- Search for new d.o.f. in the flavor sector, e.g., in FCNC processes
- Strong interaction dynamics at low energy using exclusive processes
- ....

The CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

V is unitary: V†V = 1

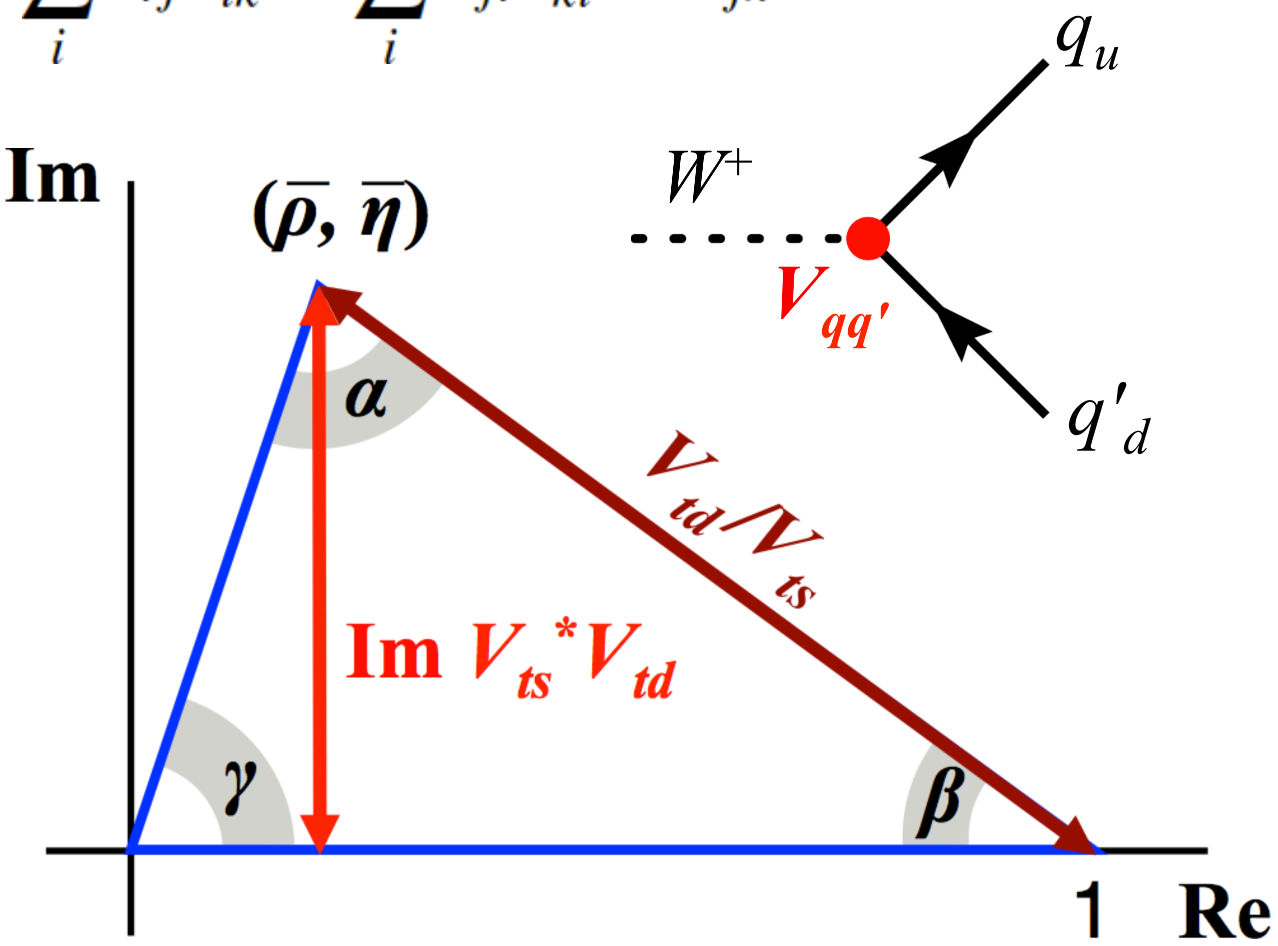
$$\sum_i V_{ij} V_{ik}^* = \sum_i V_{ji} V_{ki}^* = \delta_{jk}$$

B unitary triangle

$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$

K unitary triangle

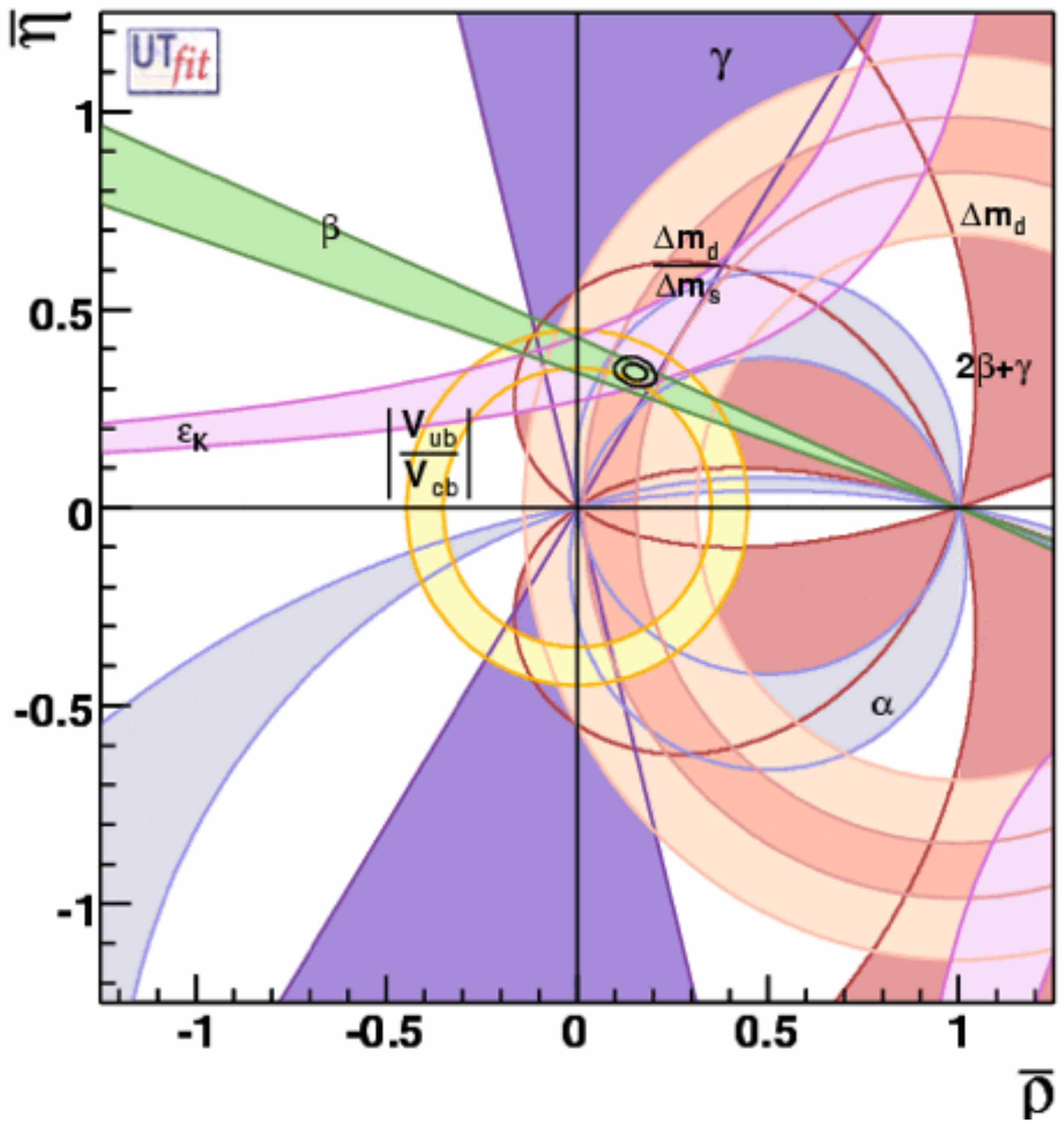
$V_{us} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0$



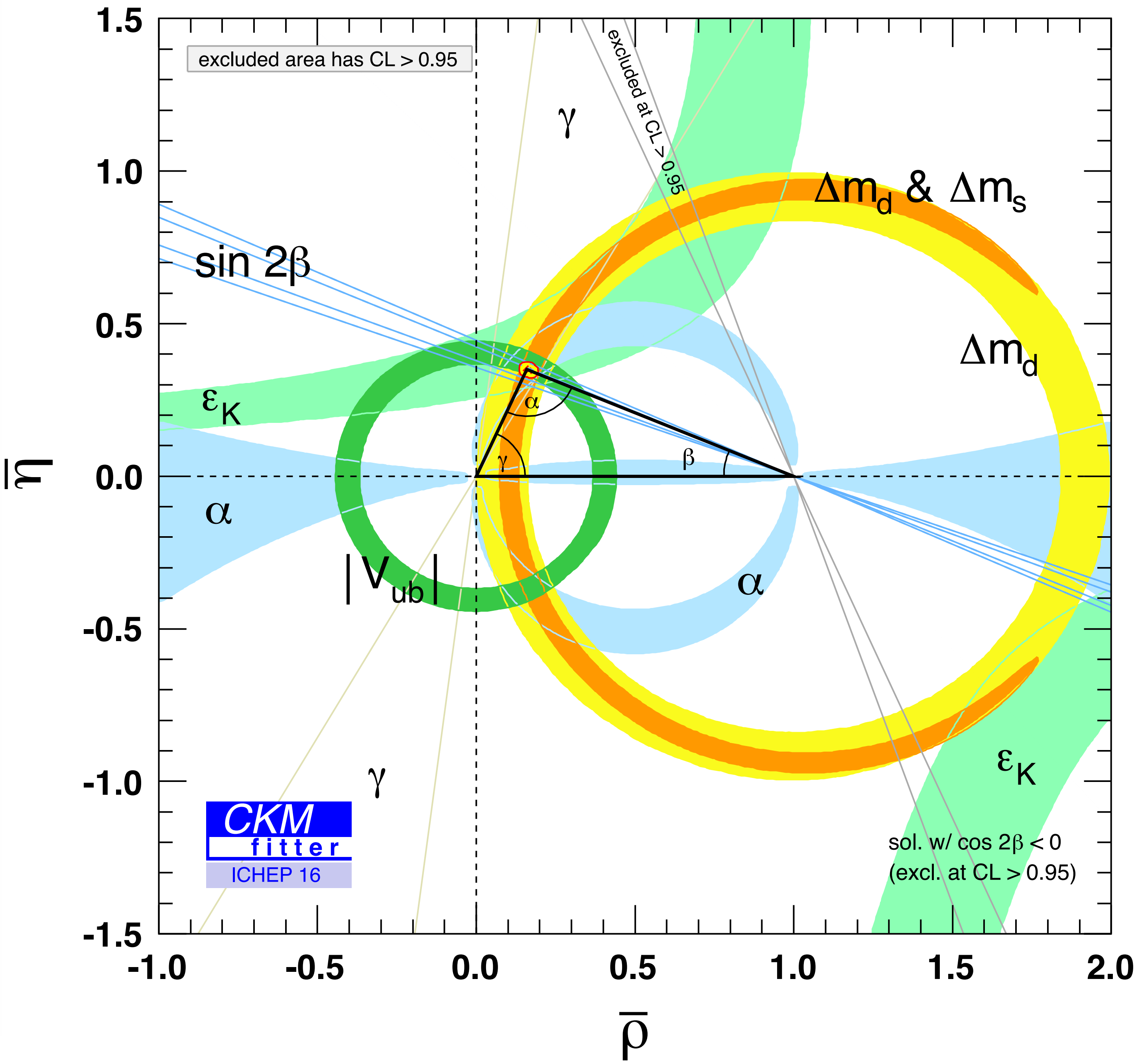
Observable	Measurement
$K^+ \to \pi^+ \nu \bar{\nu}$	$\lvert V_{ts}^* V_{td} \rvert$
$K_L \to \pi^0 \nu \bar{\nu}$	$\mathrm{Im}\, V_{ts}^* V_{td} \propto \eta$
$B_d \to J/\psi K_S$	$\sin 2\beta$
$\frac{\Delta m_{B_d}}{\Delta m_{B_s}} = \frac{B_d - \bar{B}_d}{B_s - \bar{B}_s}$	$\lvert V_{td}/V_{ts} \rvert$

Unitarity triangles: state of the art

www.utfit.org



ckmfitter.in2p3.fr

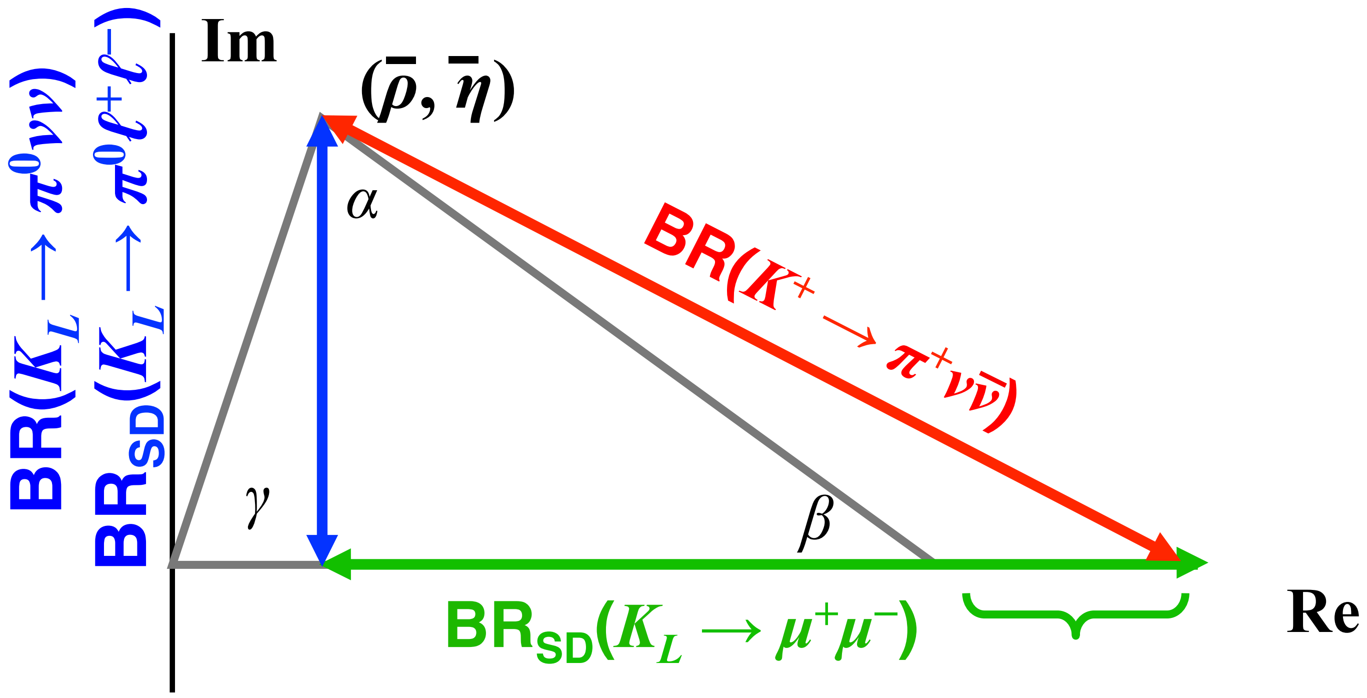


Summer 2016 (ICHEP).

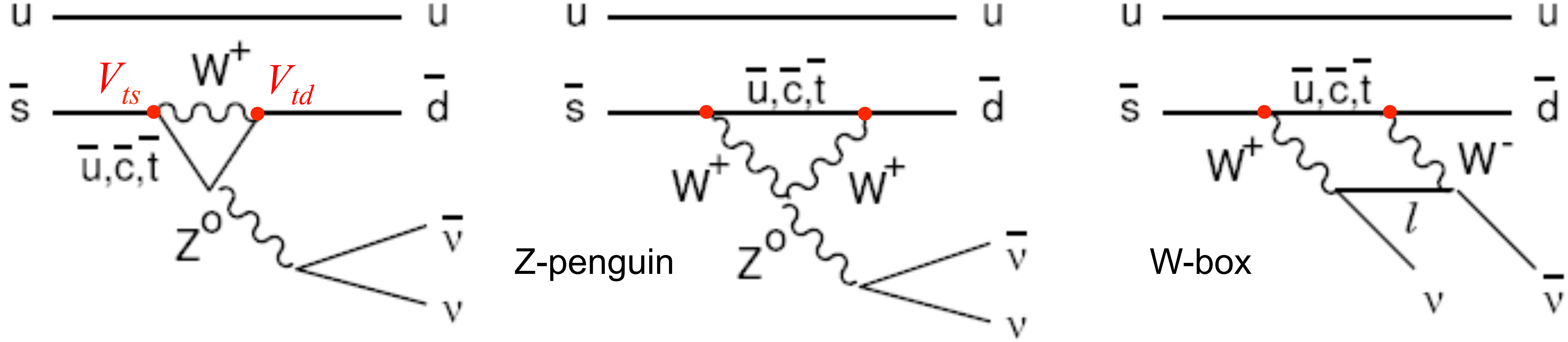
Rare Kaon Decays

Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{-11}	Exp. BR × 10^{-11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	35 ± 10	$< 28^\dagger$
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	14 ± 3	$< 38^\dagger$
$K^+ \to \pi^+ \nu\nu$	90%	4%	7.8 ± 0.8	17 ± 11
$K_L \to \pi^0 \nu\nu$	>99%	2%	2.4 ± 0.4	$< 2600^\dagger$

- FCNC processes
- Dominated by Z-penguin and box diagrams
- Suppressed by GIM mechanism.



$K \to \pi\nu\nu$ in the Standard Model

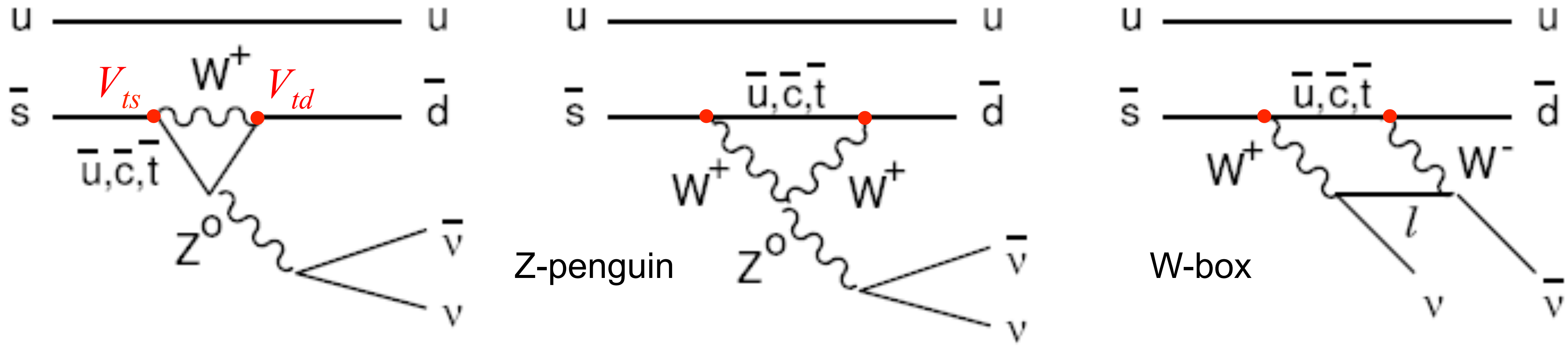


$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

$\lambda = V_{us}$
$\lambda_c = V_{cs}V_{cd}^*$
$\lambda_t = V_{td}V_{ts}^*$
$x_t = m^2_t/m^2_W$

$K \rightarrow \pi\nu\nu$ in the Standard Model



Loop functions favor top contribution

↓

$$\mathrm{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\mathrm{BR}(K_L \rightarrow \pi^0\nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \leftarrow \cancel{CP}$$

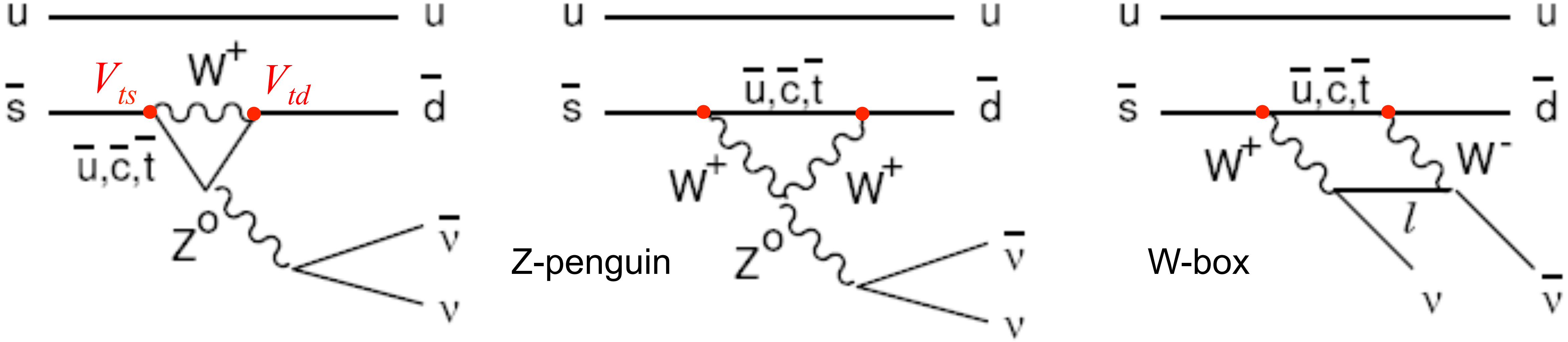
$\lambda = V_{us}$

$\lambda_c = V_{cs}V_{cd}{}^*$

$\lambda_t = V_{td}V_{ts}{}^*$

$x_t = m^2_t/m^2_W$

$K \rightarrow \pi\nu\nu$ in the Standard Model



Hadronic matrix element obtained from BR(K_{e3}) via isospin rotation

Loop functions favor top contribution

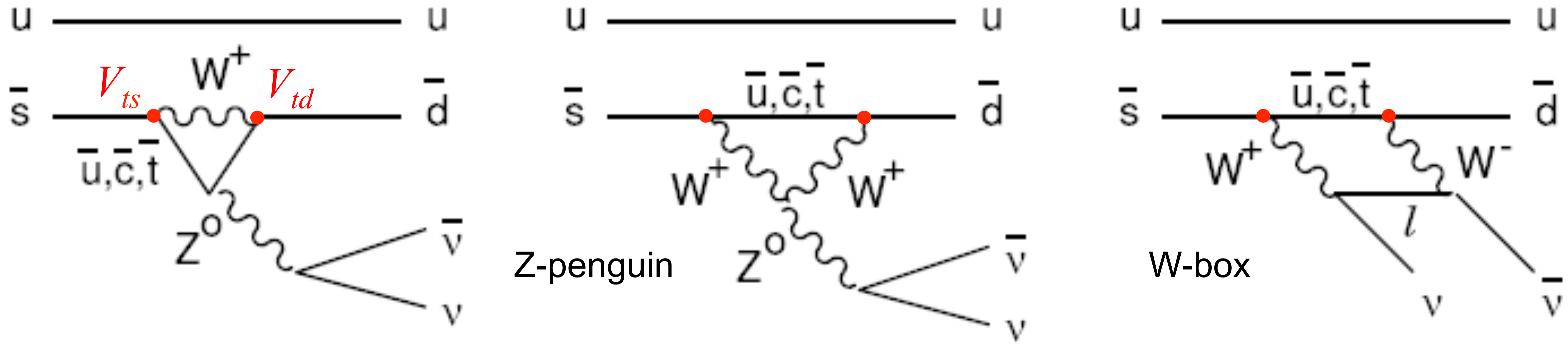
$$\mathrm{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\mathrm{BR}(K_L \rightarrow \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \leftarrow \cancel{CP}$$

$\lambda = V_{us}$
$\lambda_c = V_{cs}V_{cd}^*$
$\lambda_t = V_{td}V_{ts}^*$
$x_t = m_t^2/m_W^2$

$$\kappa_+ = r_{K^+} \frac{3\alpha^2 \mathrm{BR}(K^+ \rightarrow \pi^0 e^+ \nu)}{2\pi^2 \sin^4\theta_W} \lambda^8$$

$K \to \pi\nu\nu$ in the Standard Model

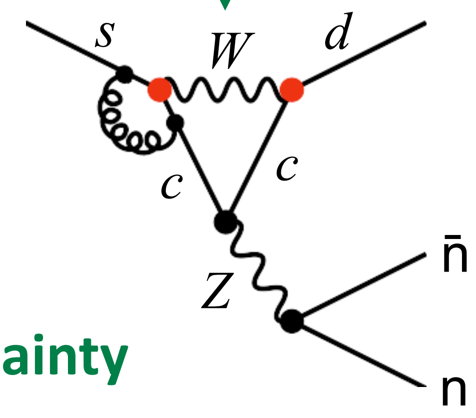


Hadronic matrix element obtained from BR(K_{e3}) via isospin rotation

Loop functions favor top contribution

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5}X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda}P_c(X)\right)^2\right]$$

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2 \quad \leftarrow \cancel{CP}$$



$\lambda = V_{us}$
$\lambda_c = V_{cs}V_{cd}^*$
$\lambda_t = V_{td}V_{ts}^*$
$x_t = m^2_t/m^2_W$

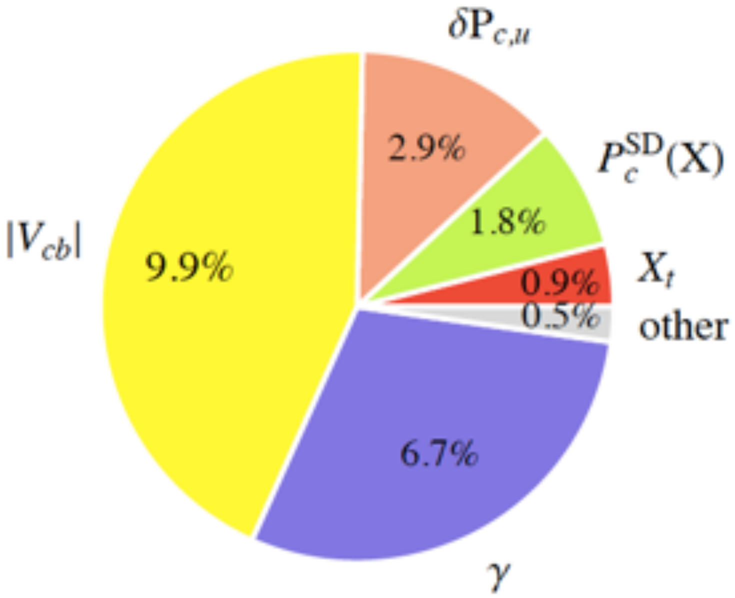
$$\kappa_+ = r_{K^+}\frac{3\alpha^2\,\mathrm{BR}(K^+ \to \pi^0 e^+\nu)}{2\pi^2\sin^4\theta_W}\lambda^8$$

QCD corrections for charm diagrams contribute to uncertainty

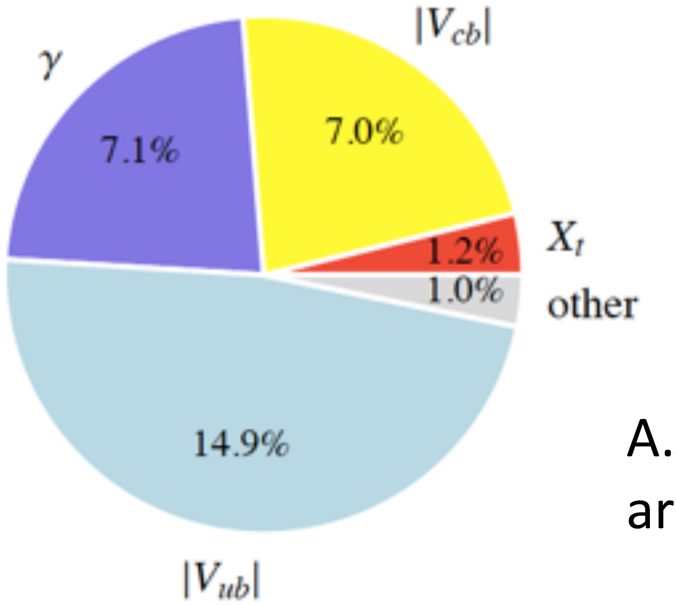
BR($K \to \pi\nu\nu$) and the CKM matrix

Uncertainty on SM predictions for $K \to \pi\nu\nu$ BRs **mostly from V_{CKM}**

BR$_{SM}$ ($K^+ \to \pi^+\nu\nu$) = (8.39 ± 0.95$_{par}$ ± 0.30$_{th}$)×10^{11}



BR$_{SM}$($K_L \to \pi^0\nu\nu$) = (3.36 ± 0.58$_{par}$ ± 0.05$_{th}$) × 10^{11}

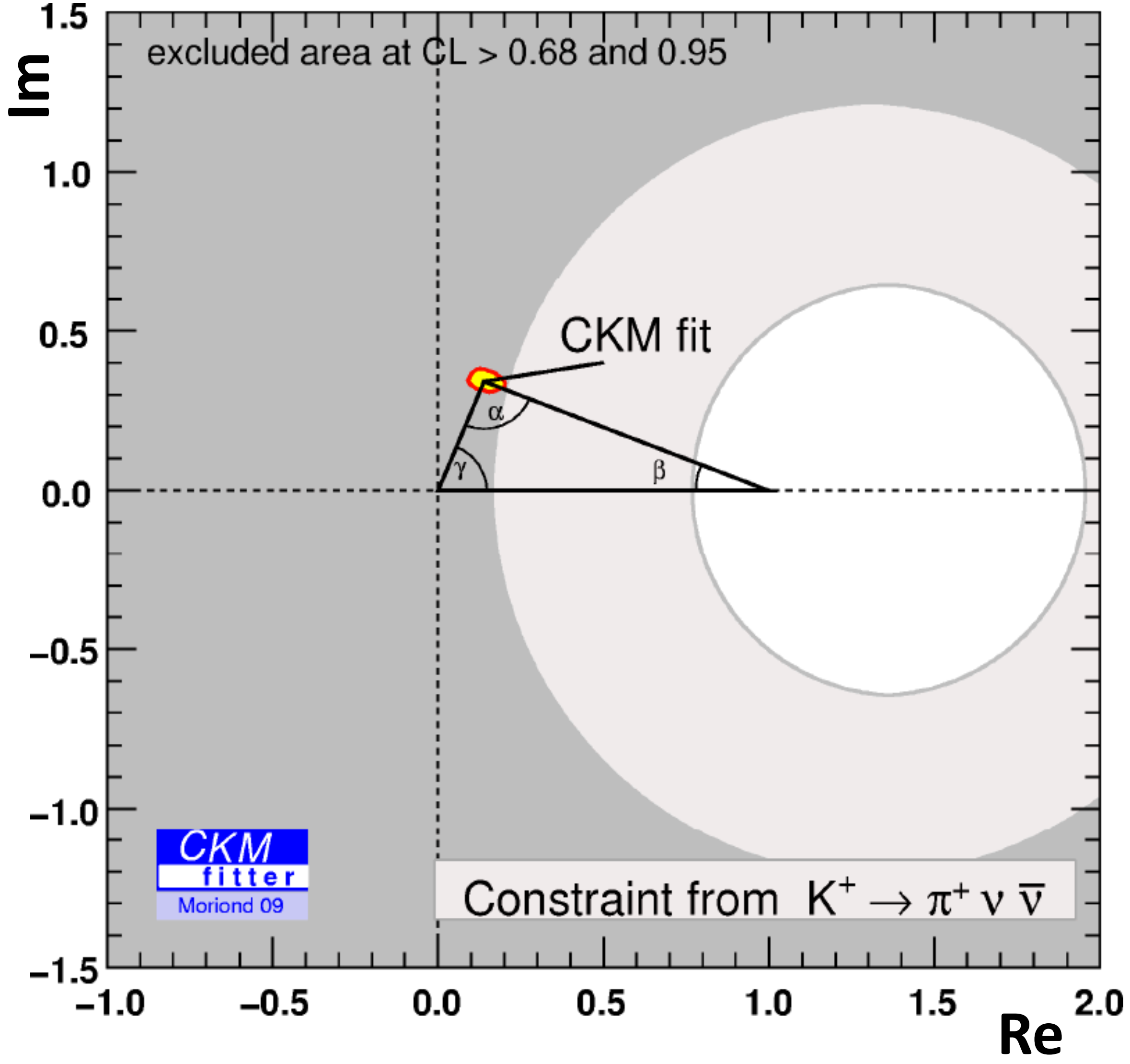


A.J. Buras, et al.
arXiv:1503.02693. 2015

Example of CKM constraints:

- Current experimental value for BR($K^+ \to \pi^+\nu\nu$)

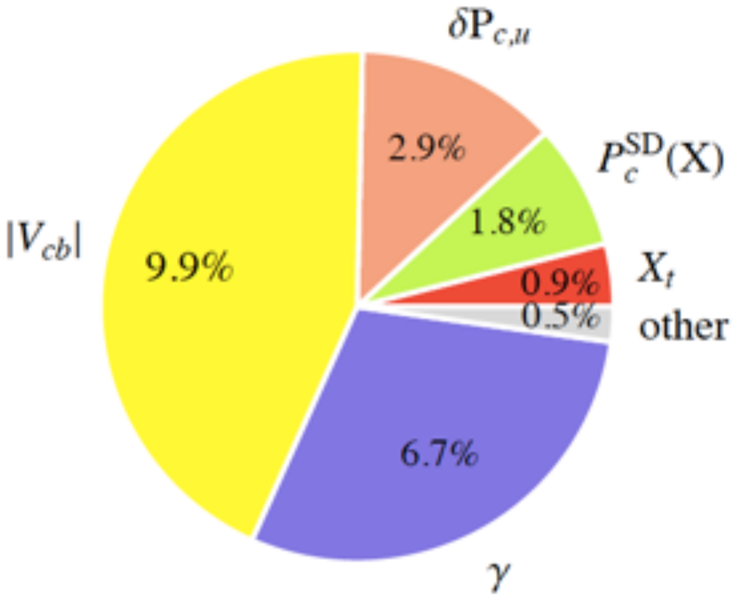
Ocariz, EPS ’09



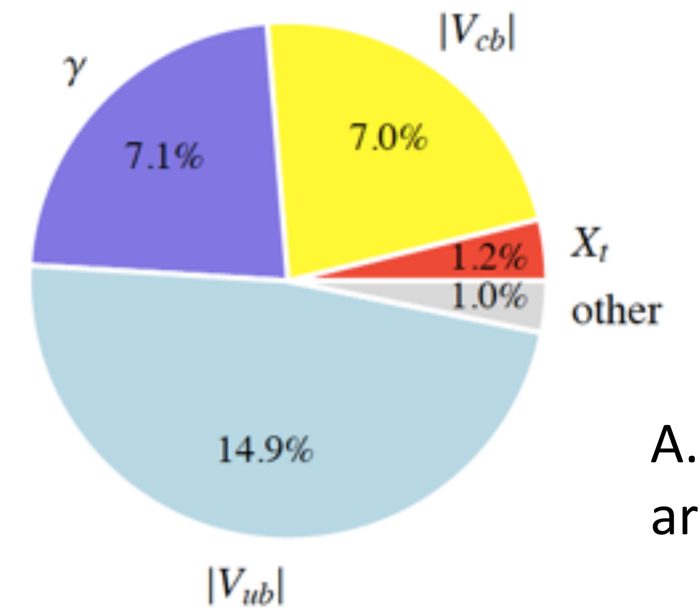
BR($K \to \pi\nu\nu$) and the CKM matrix

Uncertainty on SM predictions for $K \to \pi\nu\nu$ BRs **mostly from V_{CKM}**

$BR_{SM}(K^+ \to \pi^+\nu\nu) = (8.39 \pm 0.95_{par} \pm 0.30_{th})\times10^{11}$



$BR_{SM}(K_L \to \pi^0\nu\nu) = (3.36 \pm 0.58_{par} \pm 0.05_{th}) \times 10^{11}$



A.J. Buras, et al.
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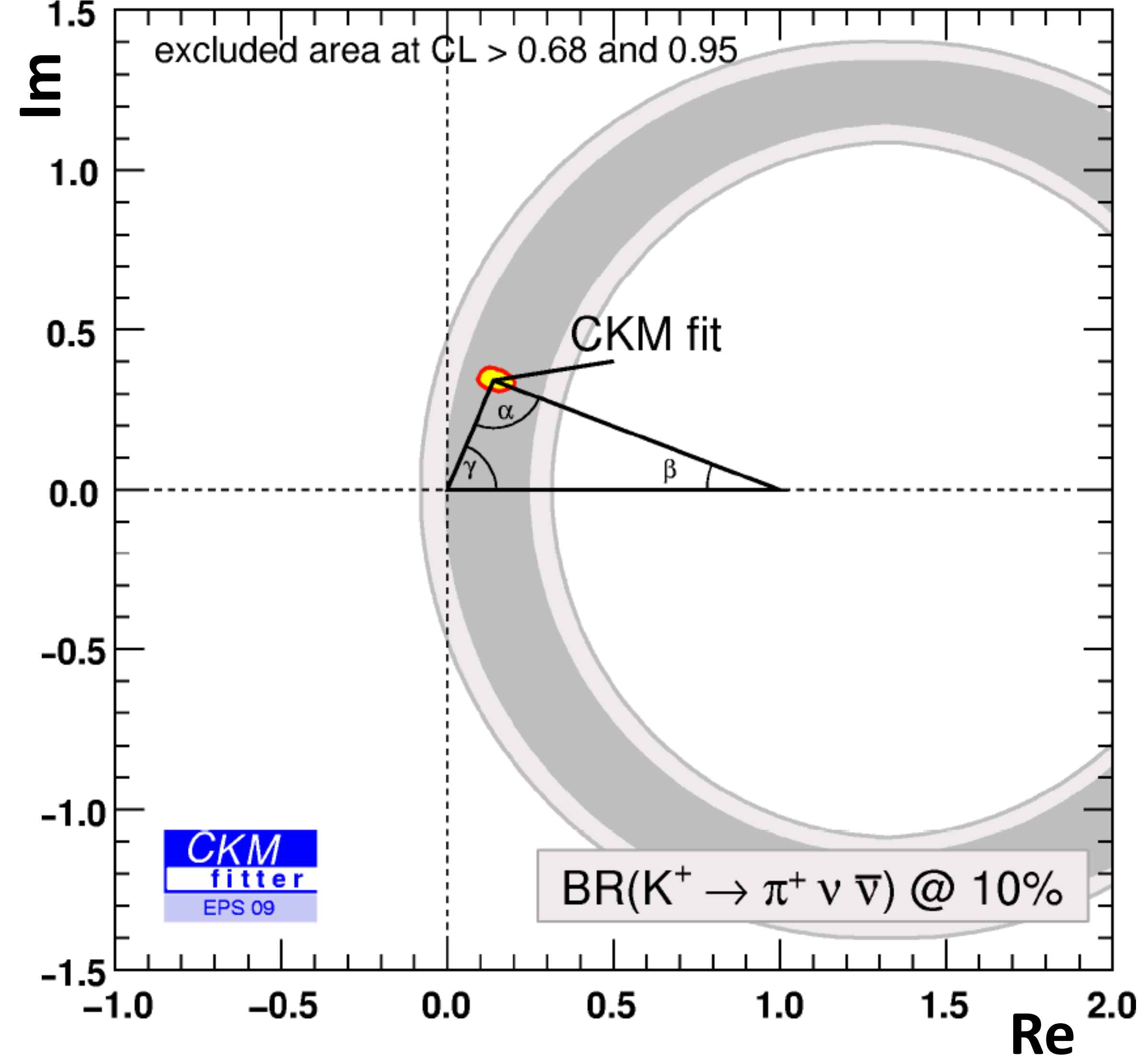
Example of CKM constraints:

- Current experimental value for BR($K^+ \to \pi^+\nu\nu$)
- BR($K^+ \to \pi^+\nu\nu$) to ±10%

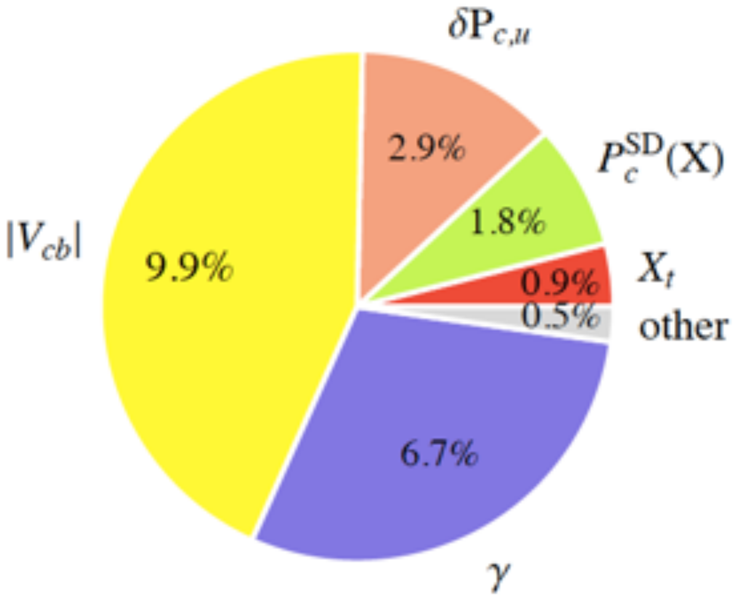
Ocariz, EPS '09



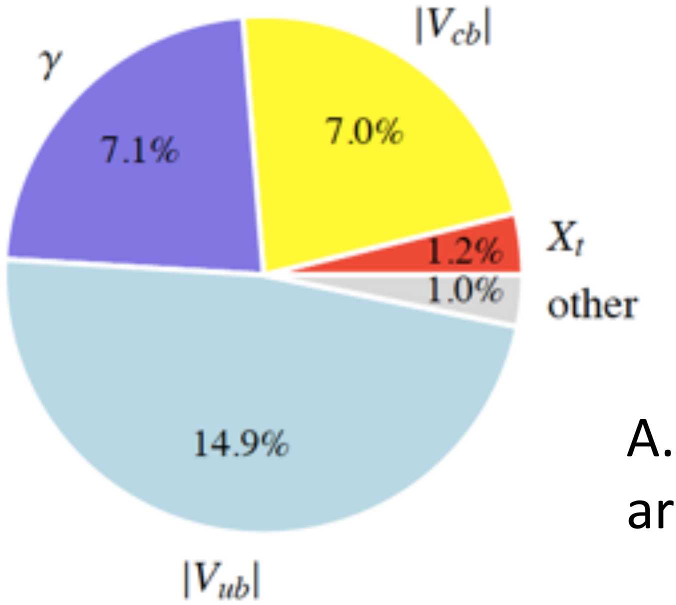
BR($K \to \pi\nu\nu$) and the CKM matrix

Uncertainty on SM predictions for $K \to \pi\nu\nu$ BRs **mostly from V_{CKM}**

BR_{SM} ($K^+ \to \pi^+\nu\nu$) = ($8.39 \pm 0.95_{par} \pm 0.30_{th}$)$\times 10^{11}$



BR_{SM}($K_L \to \pi^0\nu\nu$) = ($3.36 \pm 0.58_{par} \pm 0.05_{th}$) $\times 10^{11}$



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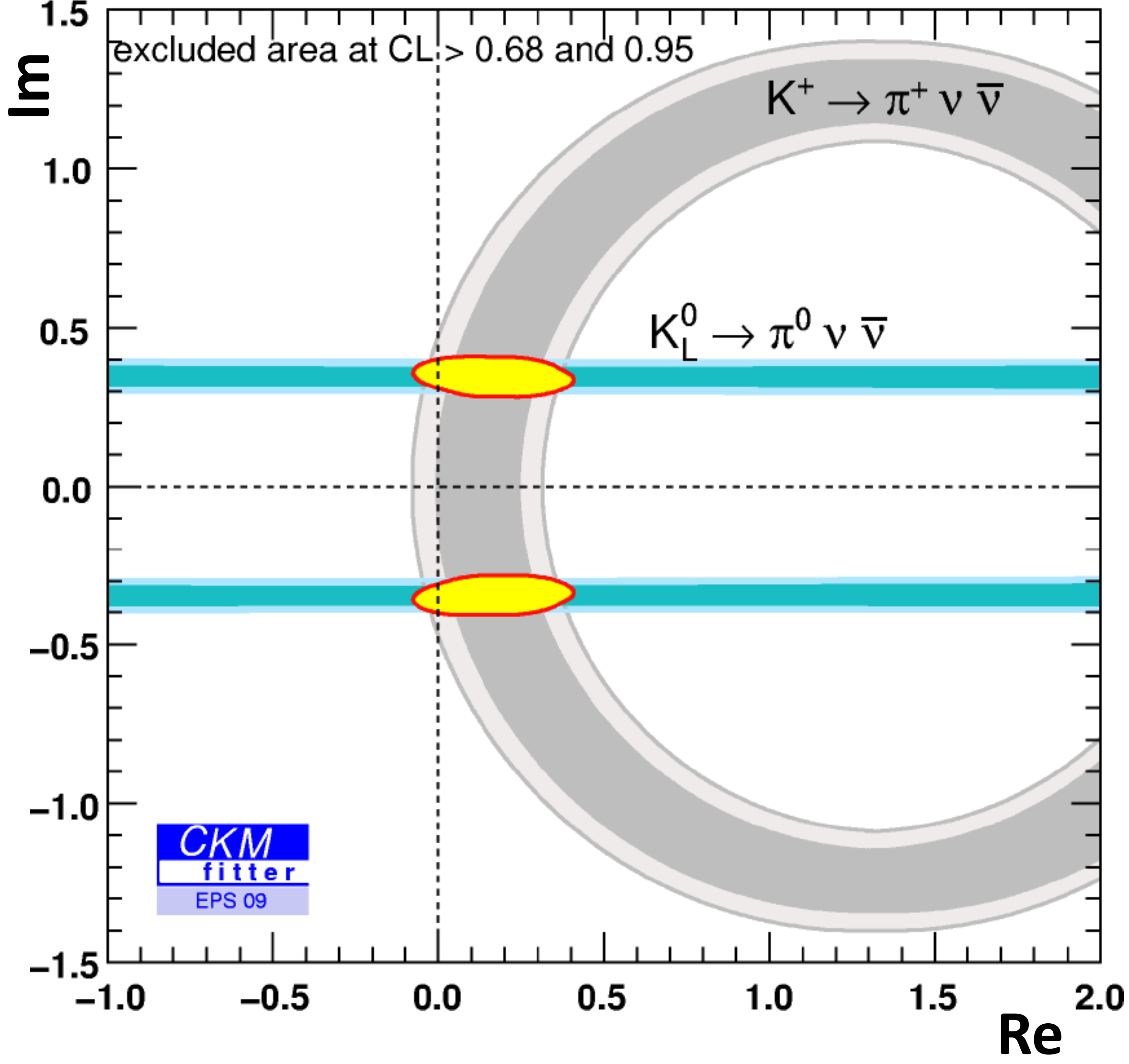
Example of CKM constraints:

- Current experimental value for BR($K^+ \to \pi^+\nu\nu$)
- BR($K^+ \to \pi^+\nu\nu$) to ±10%
- BR($K_L \to \pi^0\nu\nu$) to 15%

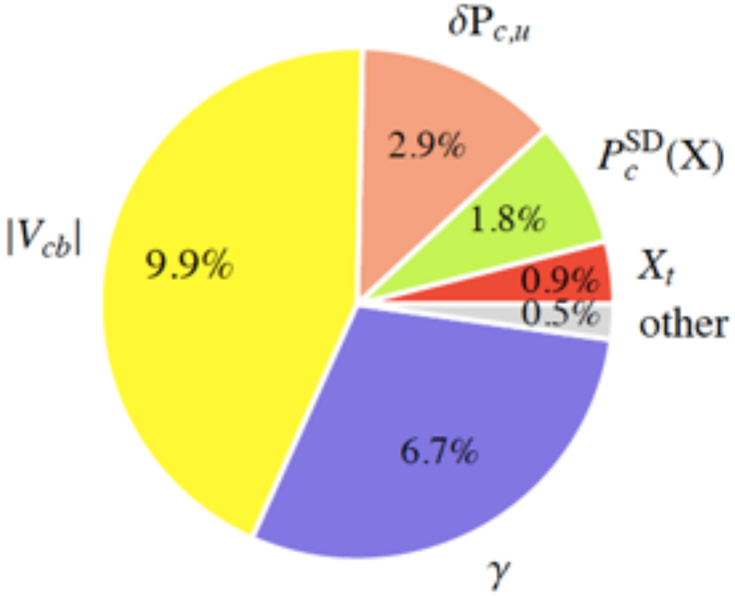
Ocariz, EPS ’09



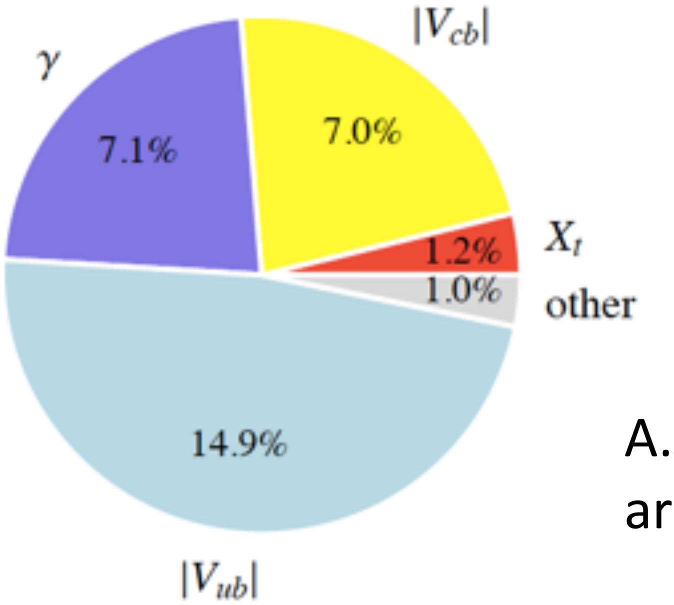
BR($K \to \pi\nu\nu$) and the CKM matrix

Uncertainty on SM predictions for $K \to \pi\nu\nu$ BRs **mostly from V_{CKM}**

$\mathrm{BR_{SM}}\,(K^+ \to \pi^+\nu\nu) = (8.39 \pm 0.95_{\mathrm{par}} \pm 0.30_{\mathrm{th}})\times 10^{11}$



$\mathrm{BR_{SM}}(K_L \to \pi^0\nu\nu) = (3.36 \pm 0.58_{\mathrm{par}} \pm 0.05_{\mathrm{th}}) \times 10^{11}$



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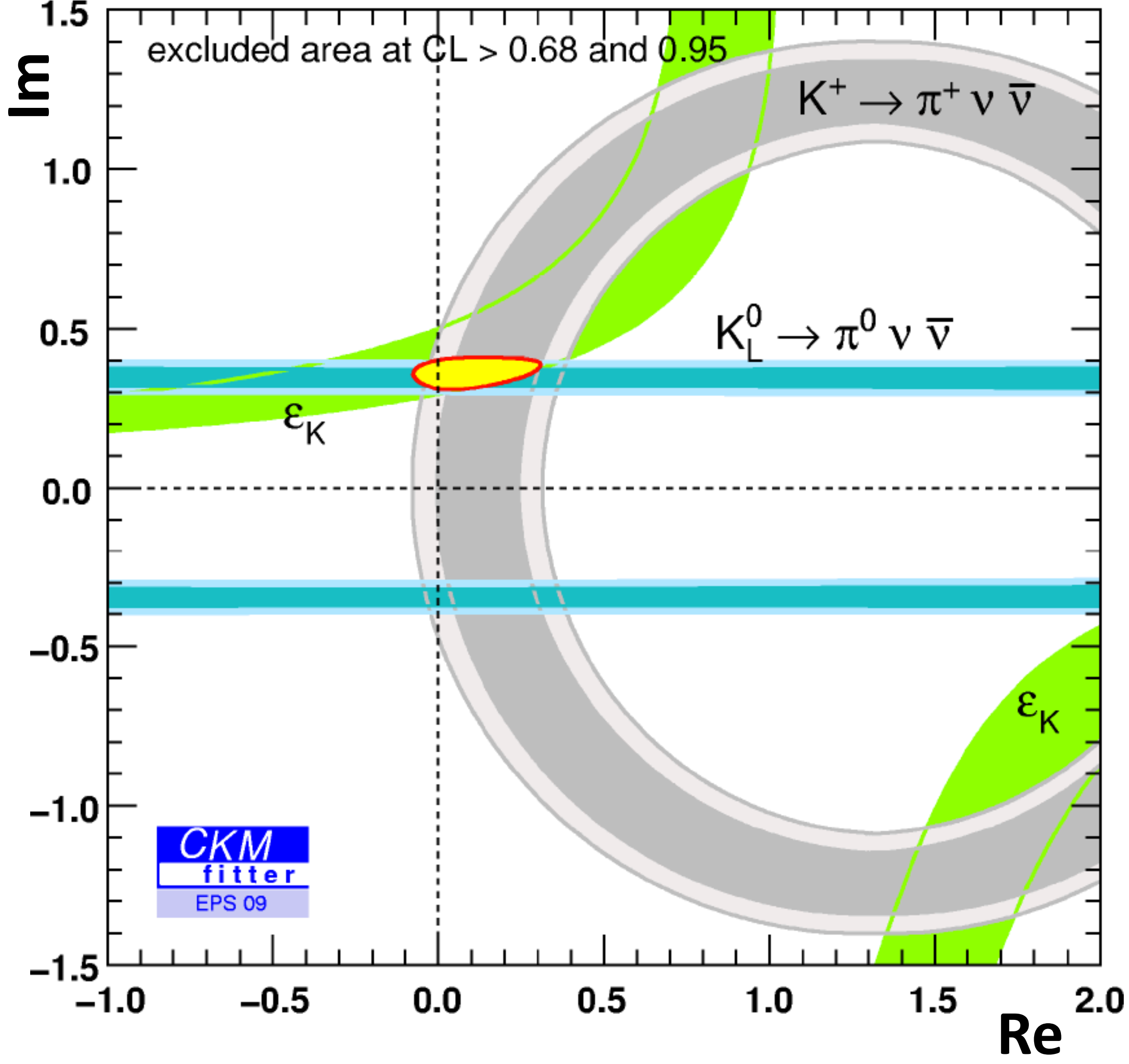
Example of CKM constraints:

- Current experimental value for BR($K^+ \to \pi^+\nu\nu$)
- BR($K^+ \to \pi^+\nu\nu$) to ±10%
- BR($K_L \to \pi^0\nu\nu$) to 15%
- ε_K resolve ambiguities ($K \to \pi\pi\ \cancel{CP}$)

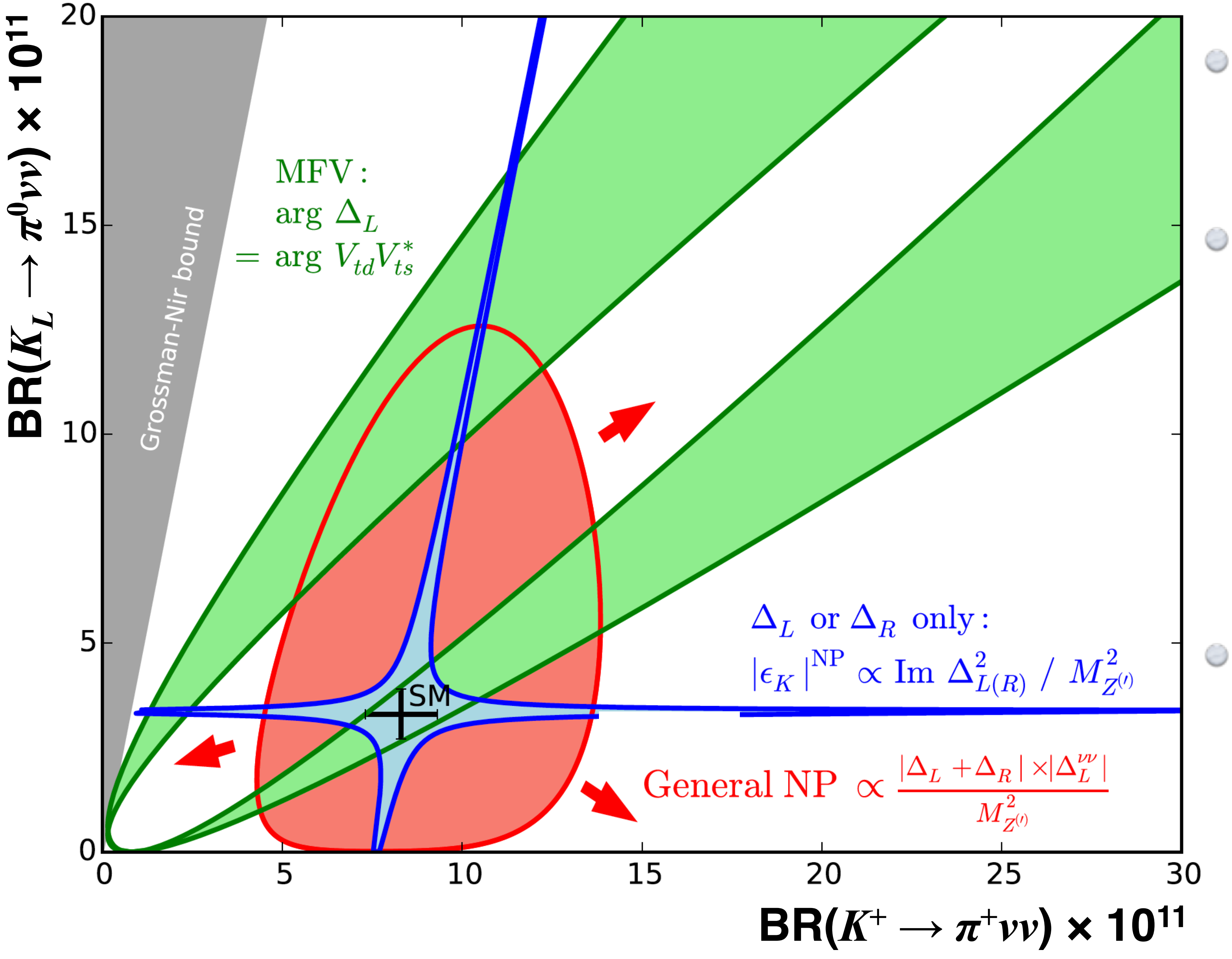
Ocariz, EPS ’09



$K \to \pi\nu\nu$ and new physics

New physics (NP) affects BRs differently for K^+ and K_L channels

Measurements of both could 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**

$K \to \pi\nu\nu$ and new physics

$K \to \pi\nu\nu$ is uniquely sensitive to high mass scales.

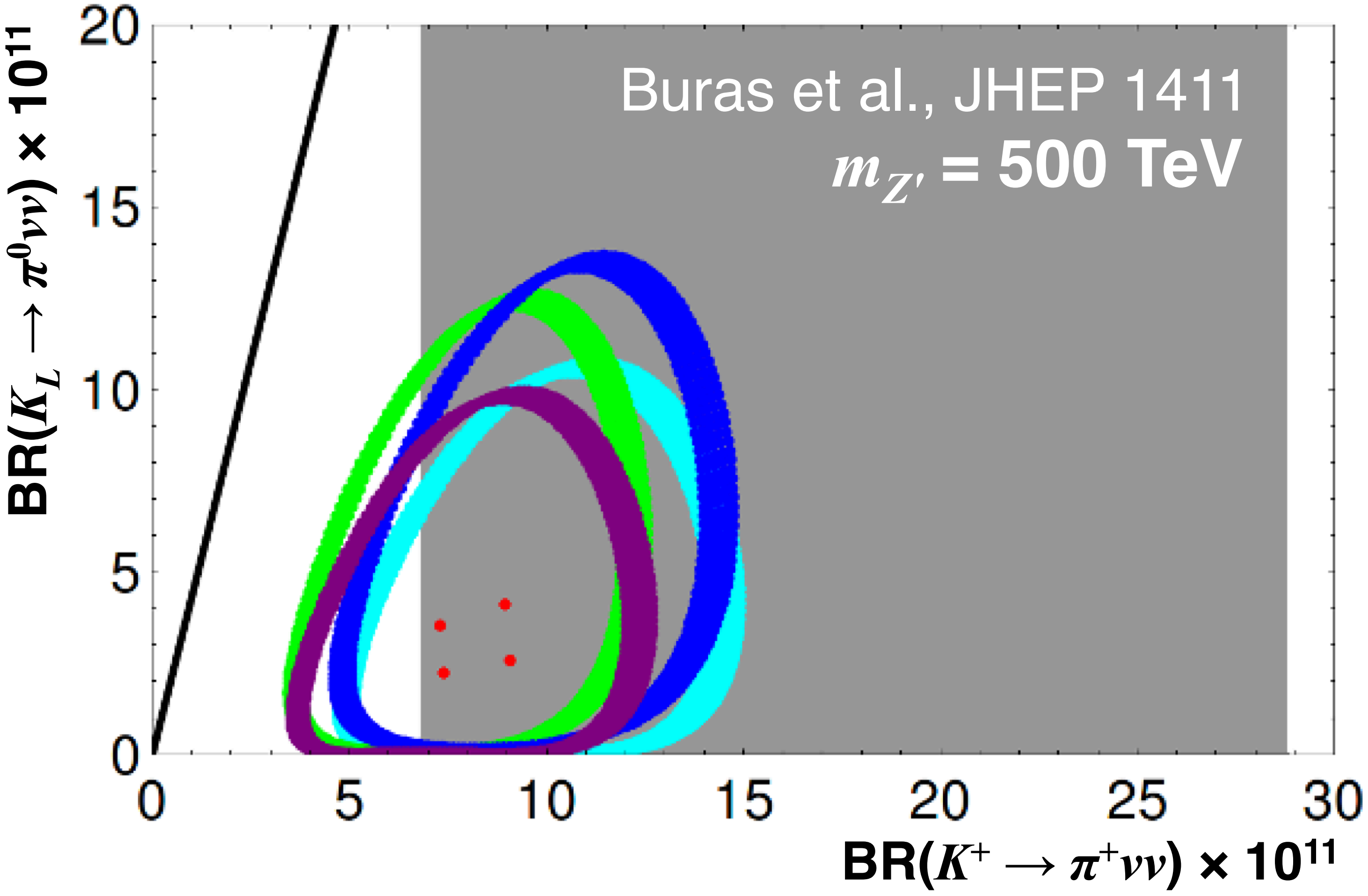
NP may simply occur at a higher mass scale

→ Null results from direct searches at LHC so far….

Indirect probes to explore high mass scales become very interesting!

Es: Tree-level flavor changing Z′ LH+RH couplings

- Some fine-tuning around constraint from ε_K
- K → πνν 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



Experimental measurement

Current theoretical prediction:

BR($K^+ \rightarrow \pi^+ \nu\nu)_{SM}$ = (8.4 ± 1.0) x 10^{-11}

Experimental status:

$BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$

Only measurement obtained by **E787** and **E949** at BNL with **stopped kaon decays (7 events)**

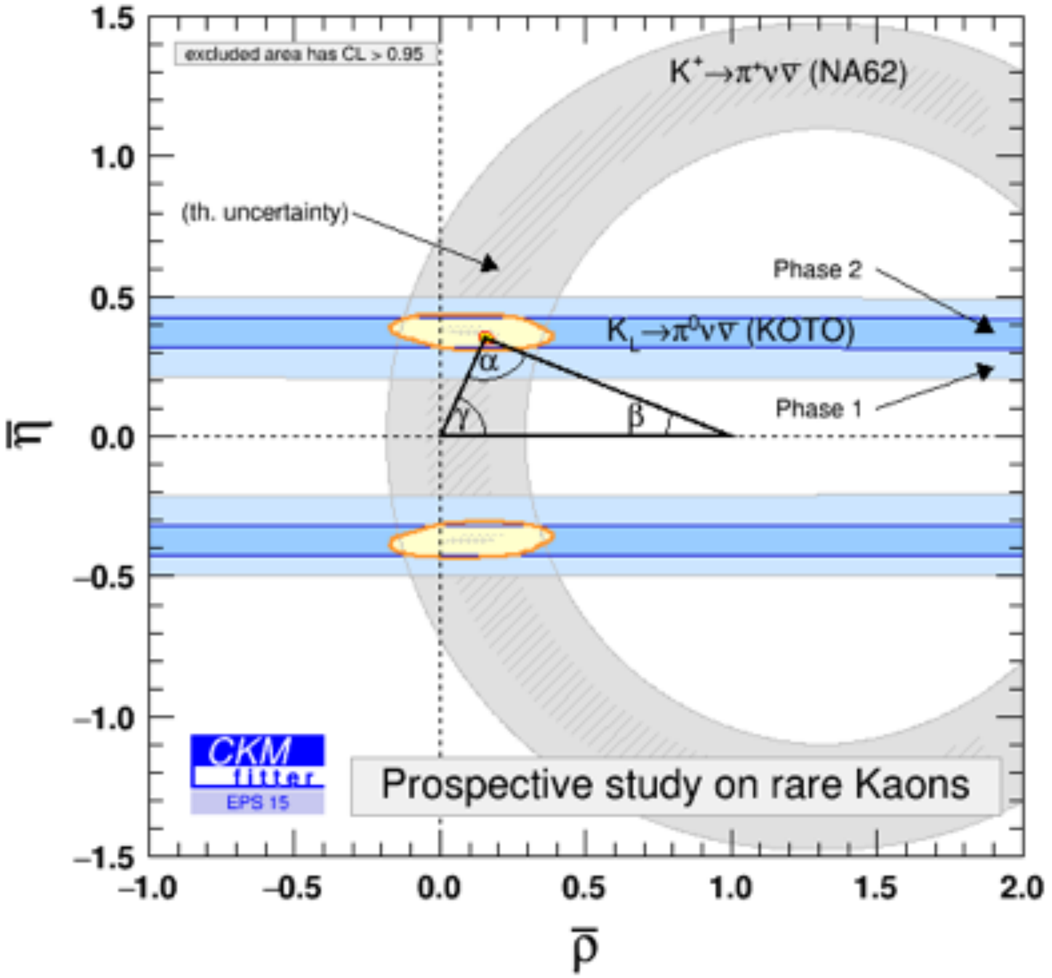
BR($K_L \rightarrow \pi^0 \nu\nu)_{SM}$ = (3.4 ± 0.6) x 10^{-11}

Neutral decay $K_L \rightarrow \pi^0 \nu\nu$ has never been measured

Gap between theoretical precision and large experimental error motivates a **strong experimental effort**. Significant new constraints can be obtained.

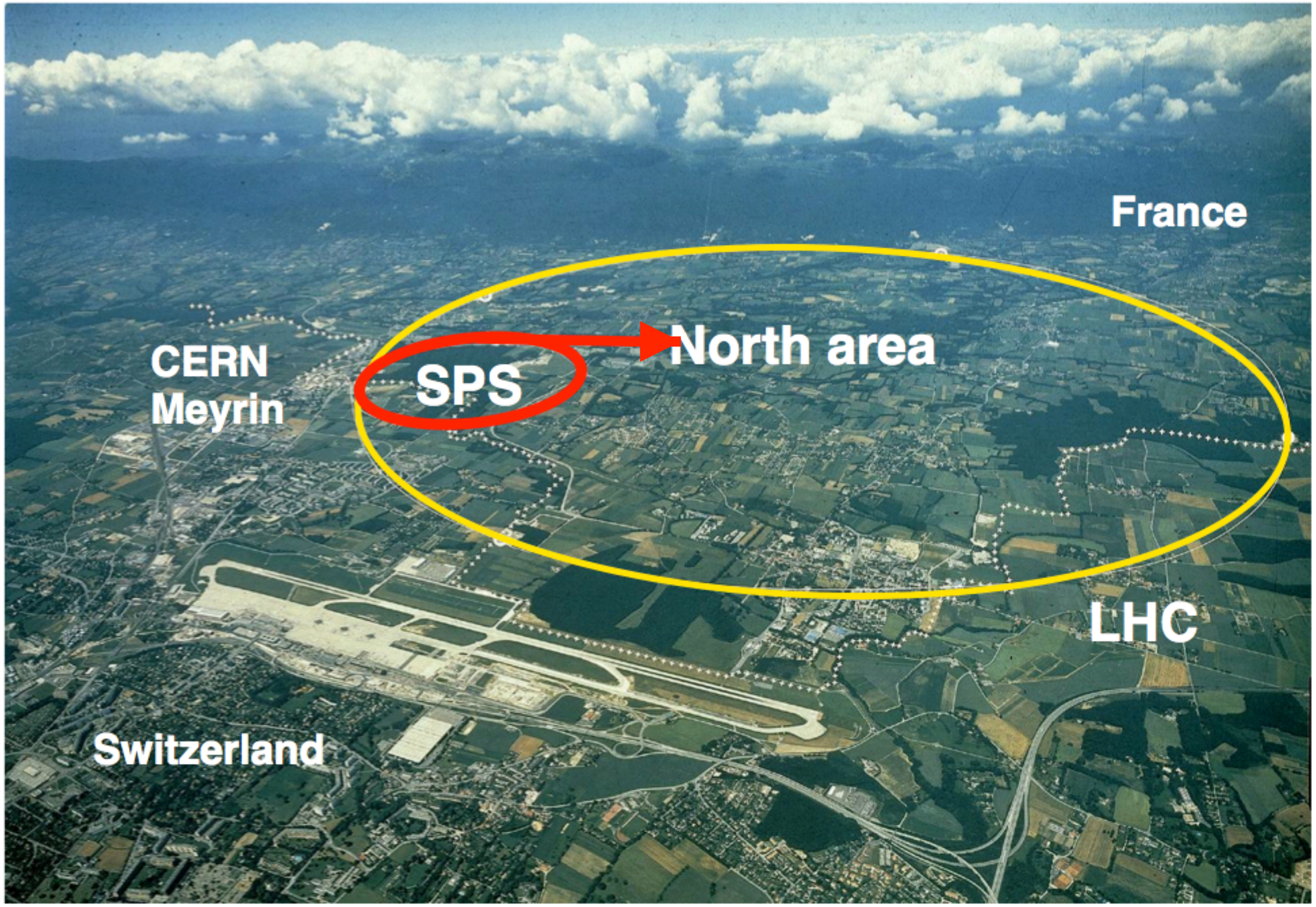
NA62 experiment at CERN SpS is now running with the aim to measure BR($K^+ \rightarrow \pi^+ \nu\nu$)

KOTO experiment at J-PARC is now running with the aim to measure BR($K_L \rightarrow \pi^0 \nu\nu$)



NA62 at CERN SPS

The **CERN-SPS secondary beam line** already used for the NA48 experiment can deliver the required K^+ intensity



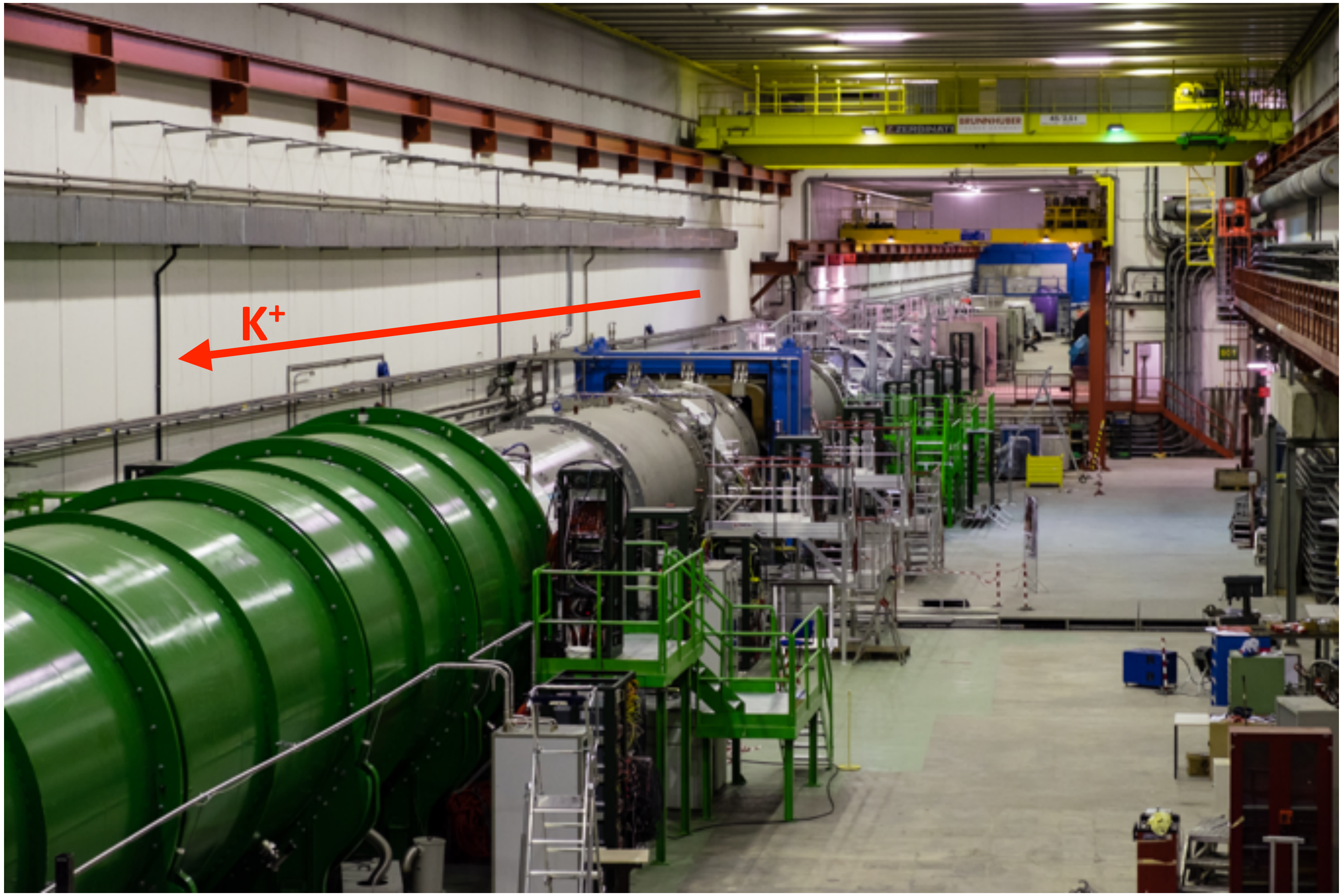
NA62 is housed in the **CERN North Area**. The SpS extraction line is providing a secondary charged hadron beam 50 times more intense than in the past, with only 30% more SPS protons on target.

400 GeV/c p impinge on a Be target and produce a secondary charged beam: **6%** are **K^+** (mixed with π and p). Signal acceptance considerations drive the choice of a **75 GeV/c K^+**

NA62 Experiment site

NA62 Apparatus

270 m long downstream of the beryllium target.
Useful K^+ decays are detected in a **65 m long fiducial volume**.



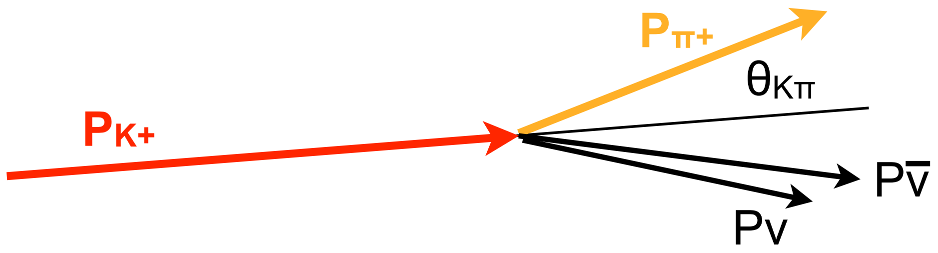
Approximately cylindrical shape around the beam axis for the main detectors.
Diameter varies from 20 to 400 cm.

Each detector sends ~ 10 MHz of raw input data to the Level 0 trigger (FPGA) that selects 1 MHz of events. L1 and L2 triggers (software) guarantee a maximum of 10 kHz of acquisition rate.

NA62 Goal

Design criteria: **kaon intensity, signal acceptance, background suppression**

Kaons with high momentum.
Decay in flight technique.
Signal signature: **K^+ track** + **π^+ track**



Backgrounds

Decay	BR	Main Rejection Tools
$K^+ \to \mu^+\nu_\mu(\gamma)$	63%	μ-ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi-track + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e-ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$	3%	μ-ID + γ-veto

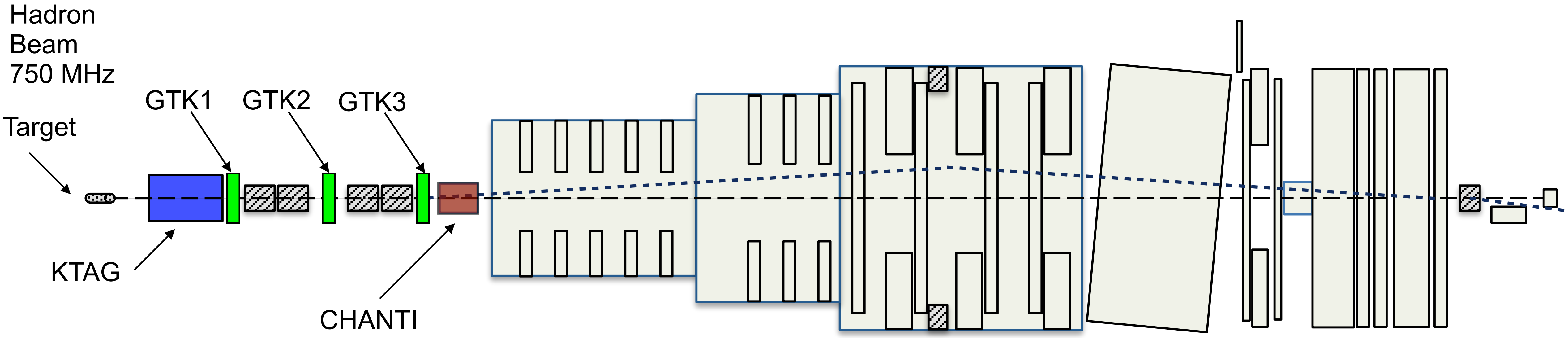
Basic ingredients:

- O(100 ps) Timing between sub-detectors
- O(10^4) Background suppression from kinematics
- O(10^7) μ-suppression ($K^+ \to \mu^+\nu$)
- O(10^7) γ-suppression
  (from $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$)

BR($K^+ \to \pi^+\nu\nu$) with 10% accuracy: O(100) SM events + control of systematics at % level

Assuming 10% signal acceptance and a BR($K^+ \to \pi^+\nu\nu$) ~10^{-10} at least **10^{13} K^+ decays are required**

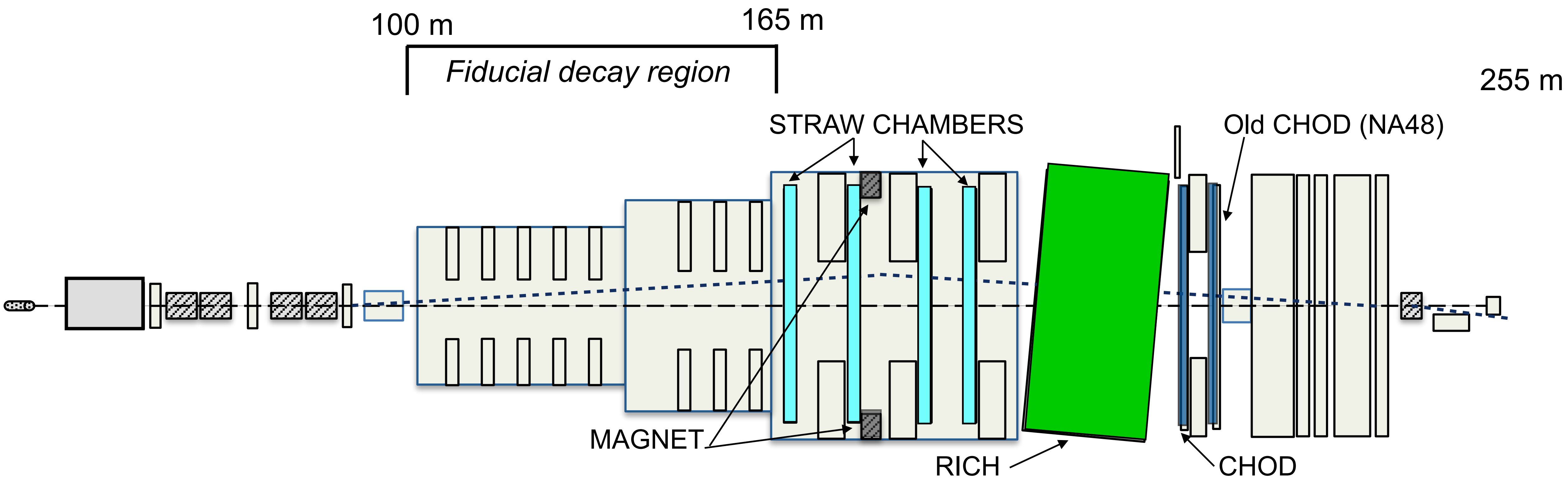
NA62: Beam ID & Traking



Beam ID & Tracking

KTAG:	Differential Čerenkov counter blind to all particles but kaons of appropriate momentum
GTK:	GigaTracKer Spectrometer for K^+ momentum and timing measurement
CHANTI:	Charged particle veto to reduce the background induced by inelastic interactions

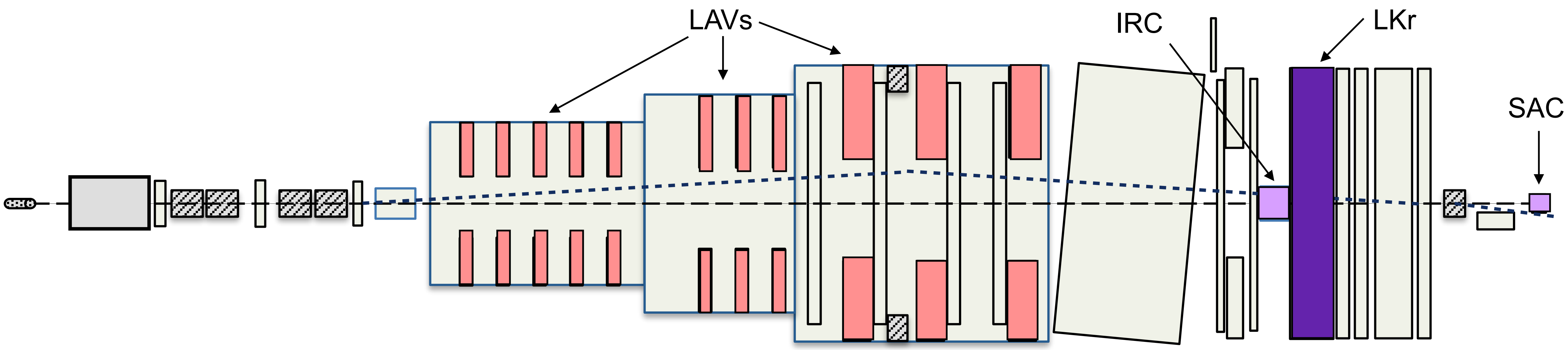
NA62: Secondary ID & Tracking



Secondary particle ID & Tracking

STRAW:	Spectrometer with STRAW tubes for secondary particle momentum measurement
CHOD:	Charged Hodoscope of plastic scintillator to provide fast signal of the beam
RICH:	Ring Imaging Cherenkov detector for the secondary particle identification

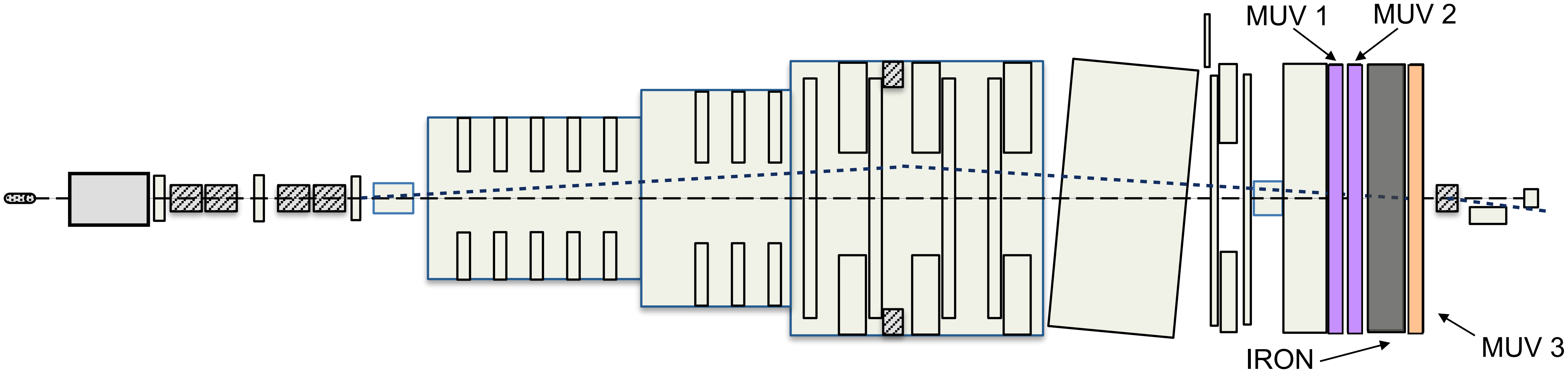
NA62: Photon Veto System



Photon Veto

LAV:	Large Angle Veto. 12 stations to veto γ with angles $8.5 < \theta < 50$ mrad
IRC/SAC:	Inner Ring Calorimeter and Small Angle Calorimeter. To veto γ with angles <1 mrad
LKr:	NA48 LKr Calorimeter: to veto γ with angles $1 < \theta < 8.5$ mrad and for PID.

NA62: Muon Veto System



Beam ID & Tracking

MUV3: Efficient fast Muon Veto used in the hardware trigger level.

MUV1/2: Hadronic calorimeters for the μ/π separation

NA62 Timescale

2014	Pilot Run
2015	Commissioning Run
2016	Commissioning + Physics Run → SM sensitivity reached O(10^{-10}).
2017	Physics Run → Improve on the present state of the art.
2018	> 6 months of data taking expected…

Assuming that the 2018 run is as successful as the 2017 one,
by the end of 2018 NA62 should have collected
between 20 and 30 PNN events at the SM sensitivity

- For the spring 2018 the results from the full 2016 statistics will be presented
- Processing of the 2017 data has started

2019-2020 LS2 (Long shutdown 2)

Fixed target runs at the SPS

2021 **Run 3**: To fulfill the original goal of about O(100) SM events the hypothesis to continue NA62 data taking after LS2 is under consideration, together with a dump-mode data taking for dark sector studies.

2026 **Run 4:** Once **$K^+\to\pi^+\nu\nu$** has been measured to 10%, try to measure **$K_L\to\pi^0\nu\nu$** $\Longrightarrow$ KLEVER experiment

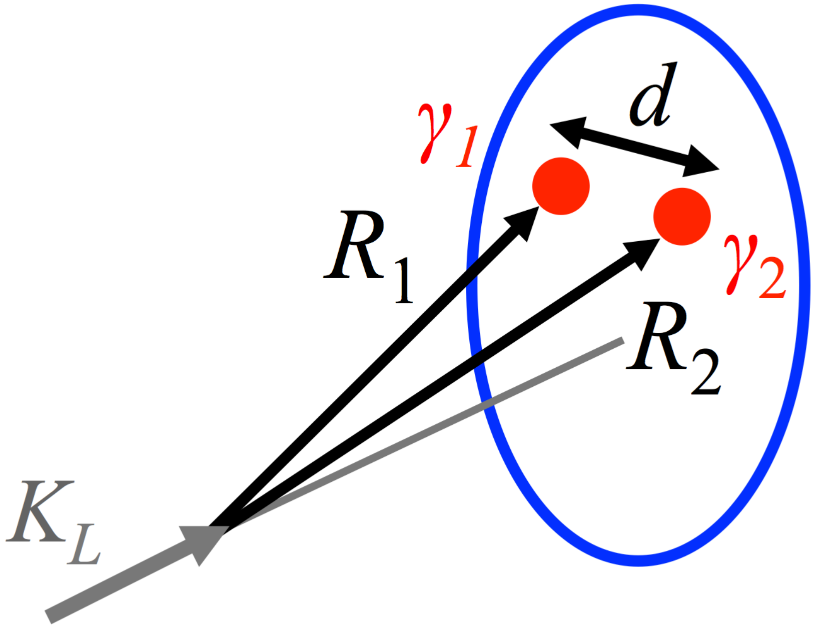
🟩 Physics
🟥 Shutdown
🟨 Beam commissioning
🟦 Technical stop

$K_L \to \pi^0 \nu\nu$: Experimental issues

With neutral beam there is no information on K_L momentum

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

- All other K_L decays have ≥ 2 extra γs or ≥ 2 tracks to veto
- Exception: $K_L \to \gamma\gamma$, but not a big problem since $p_\perp = 0$



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

- Used to reconstruct vertex position

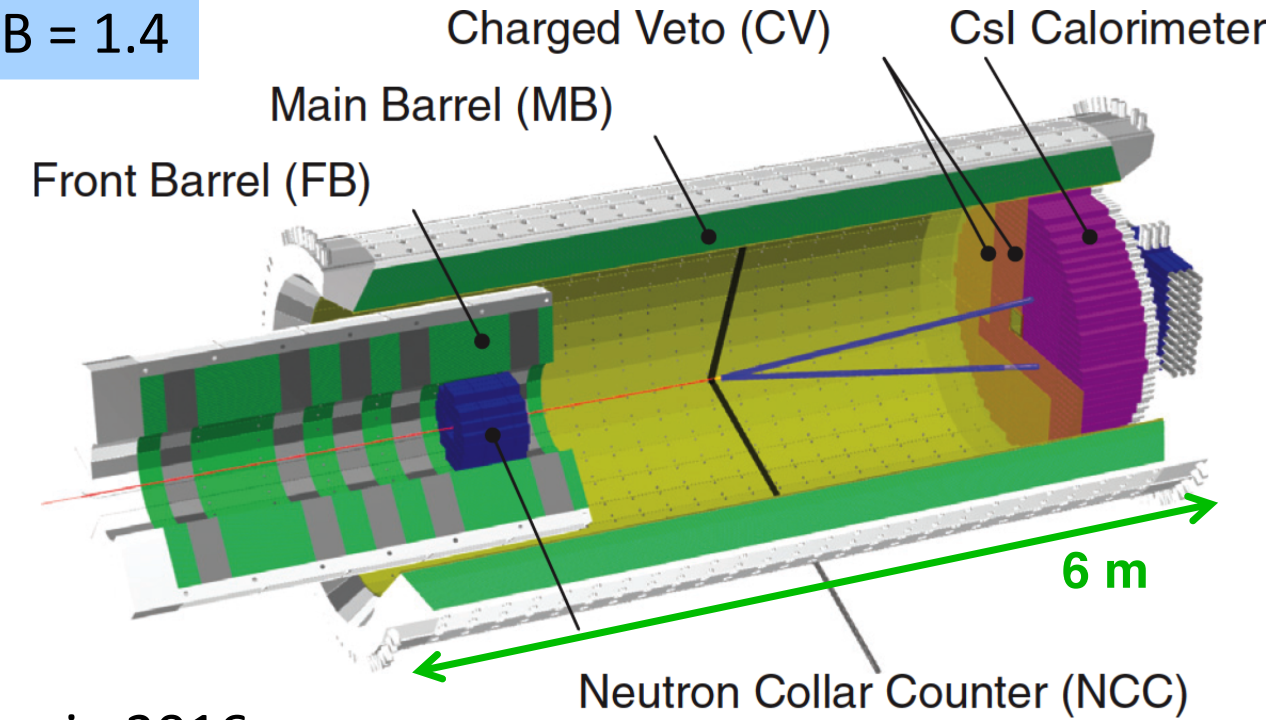
$$m_{\pi^0}^2 = 2E_1E_2\,(1-\cos\theta) \qquad R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1E_2}}{m_{\pi^0}}$$

Main backgrounds

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

KOTO: $K_L \to \pi^0 \nu\nu$ at J-PARC

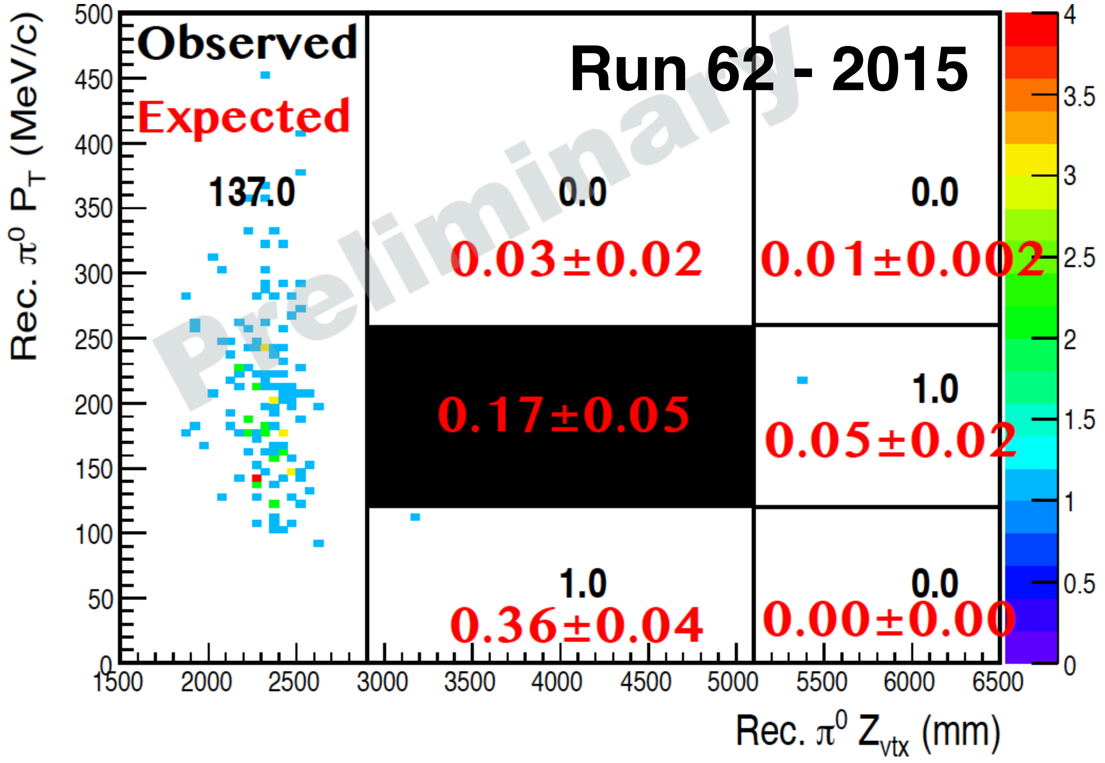
Proposal: in 3 yr SES 8×10^{-12} (3.5 SM evts). S/B = 1.4



Primary beam:
30 GeV/p
Design: 2×10^{14} p/3.3 s = 300 kW
Neutral beam (16°):
〈p(KL)〉 = 2.1 GeV
50% of K_L have 0.7-2.4 GeV

Current status:

- Reached 42 kW of slow-extracted beam power in 2016



Preliminary results: 10% of 2015 data

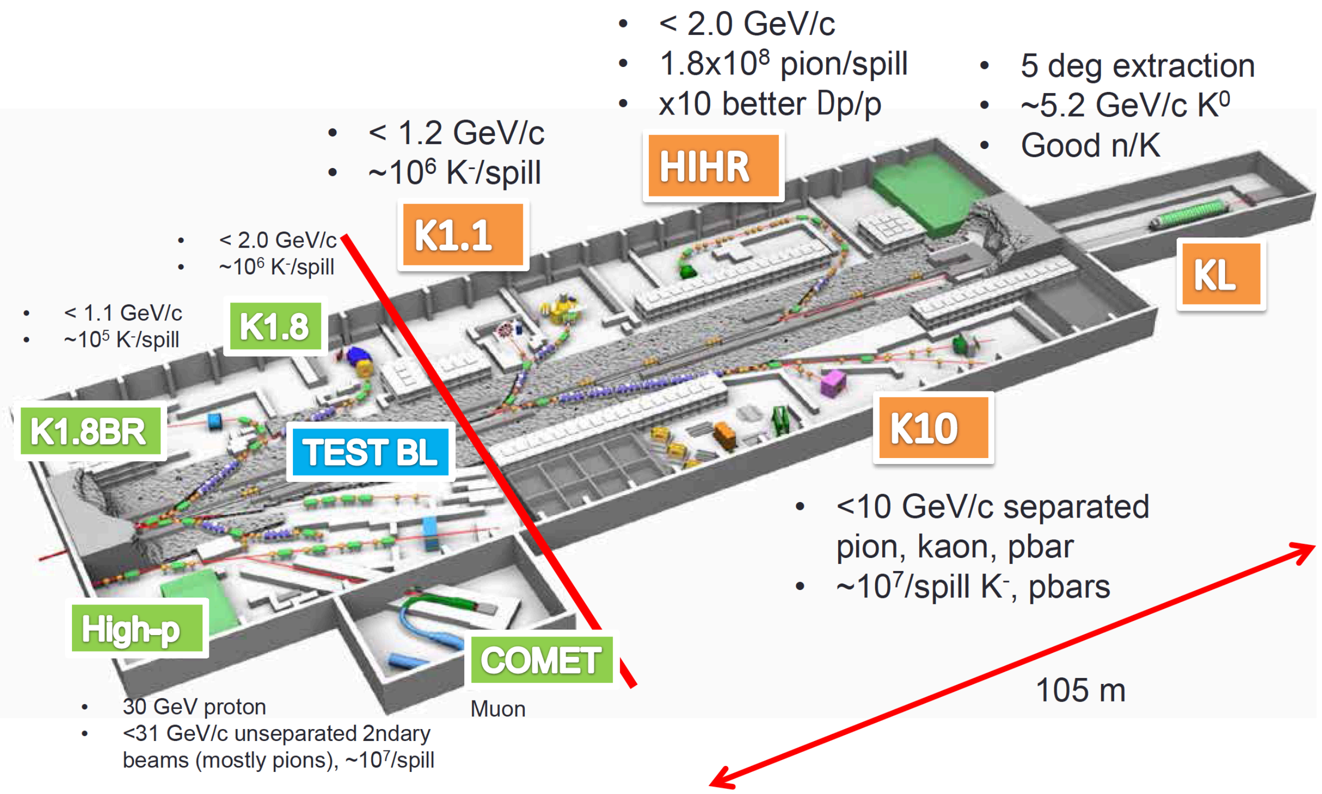
- SES = 5.9×10^{-9}
- Expected background = 0.17 events
- Background estimate under study, signal box not yet unblinded

Beam power will gradually increase to 100 kW by 2018

KOTO: $K_L \rightarrow \pi^0 \nu\nu$ at J-PARC

KOTO Step-2 upgrade:

- Increase beam power to >100 kW
- New neutral beamline at 5°
- 〈p(KL)〉 = 5.2 GeV
- Increase FV from 2 m to 11 m
- Complete rebuild of detector
- Requires extension of hadron hall



HIHR:
- < 2.0 GeV/c
- 1.8x10^8 pion/spill
- x10 better Dp/p

KL:
- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K

K1.1:
- < 1.2 GeV/c
- ~10^6 K^-/spill

K1.8:
- < 2.0 GeV/c
- ~10^6 K^-/spill

K1.8BR:
- < 1.1 GeV/c
- ~10^5 K^-/spill

K10:
- <10 GeV/c separated pion, kaon, pbar
- ~10^7/spill K^-, pbars

High-p:
- 30 GeV proton
- <31 GeV/c unseparated 2ndary beams (mostly pions), ~10^7/spill

COMET: Muon

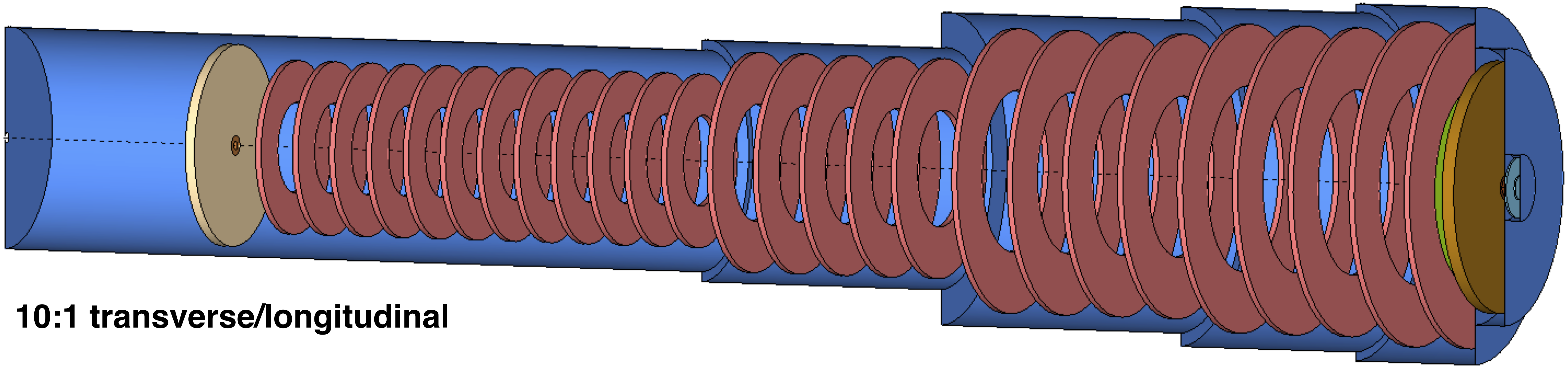
Long-term future: Strong intention to upgrade to ~100 event sensitivity

- No official Step 2 proposal yet (plan outlined in 2006 KOTO proposal)
- Scaling from original estimates: ~10 SM evts/yr per 100 kW beam power
- Exploring machine & detector upgrade possibilities to increase sensitivity
- Indicative timescale: data taking starting 2025?

A $K_L \rightarrow \pi^0 \nu\nu$ experiment at the SPS?

KLEVER

KL Experiment for **VE**ry **R**are events



10:1 transverse/longitudinal

Interesting features

- High-energy experiment: complementary approach 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
- Possible to re-use LKr calorimeter, NA62 experimental infrastructure?

High-intensity neutral beam issues

Assumptions

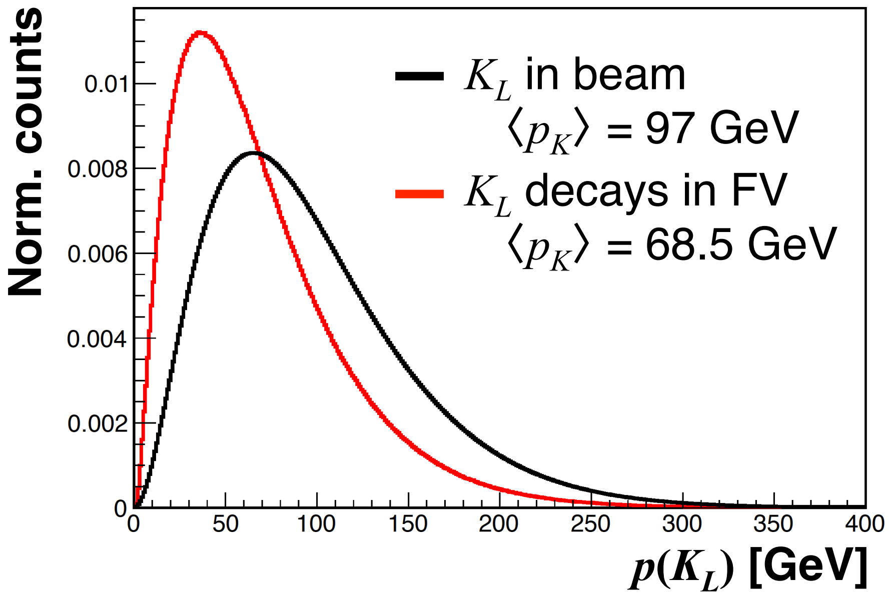
- BR($K_L \to \pi^0 \nu\nu$) = 3.4×10^{-11}
- Acceptance for decays occurring in FV ~ 10%

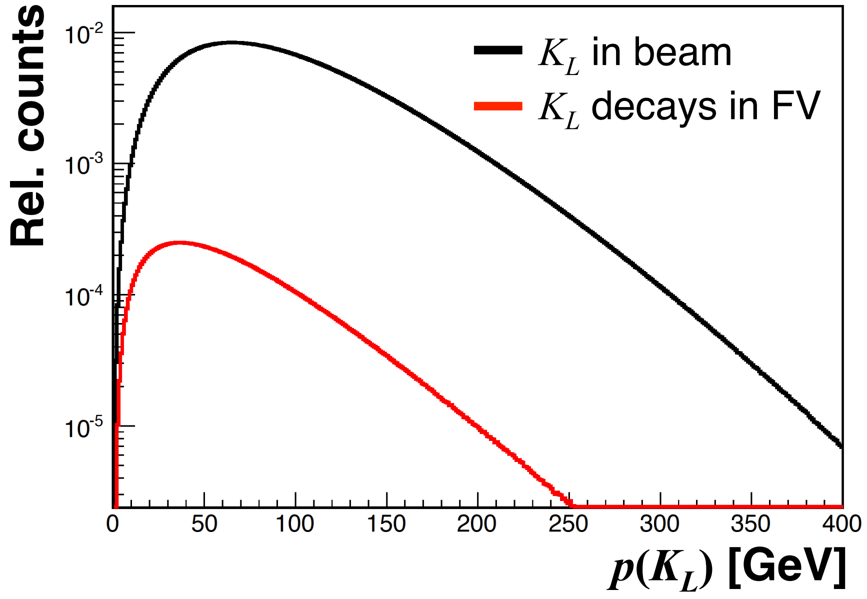
3×10^{13} K_L decays in FV for 100 signal evts

Beam parameters

- 400 GeV p on 400 mm Be target
- Production at 2.4 mrad to optimize (K_L in FV)/n

2.8×10^{-5} K_L in beam/pot





Probability for decay inside FV ~ 2%

Required total proton flux = 5×10^{19} pot.
10^{19} pot/year (= 100 eff. days) E.g.: 2×10^{13} ppp/16.8 s

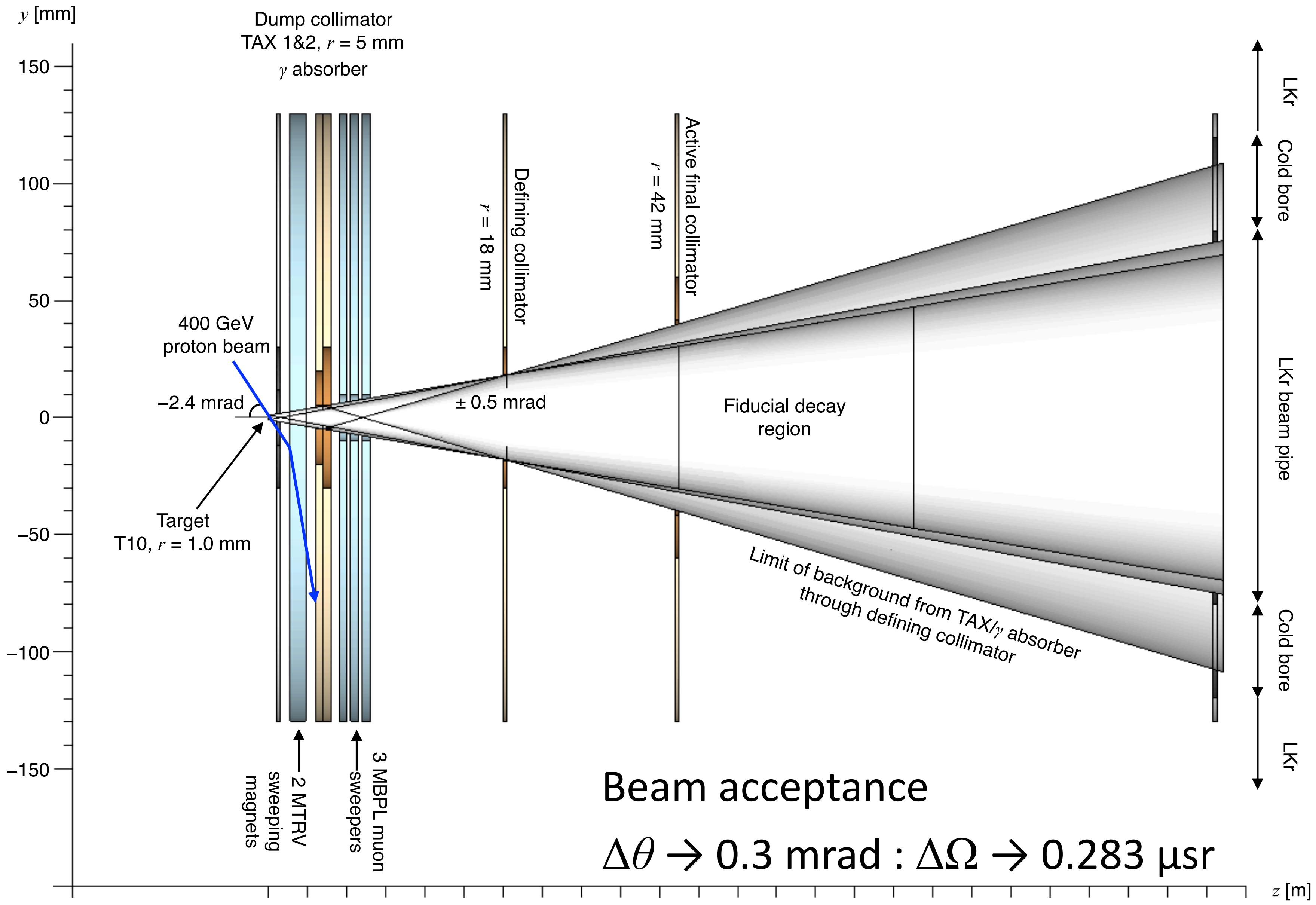
6× increase relative to NA62, 2×10^{13} ppp not currently available on North Area targets

Target area and transfer lines would require upgrades:

- Minimization of consequences of beam loss
- Additional shielding against continuous small losses
- Study issues of equipment survival, e.g., TAX motors
- Ventilation, zone segmentation, etc.

Beamline layout for intensity upgrade

- Tight neutral beam collimation
- Longer K_L lifetime ($\tau_L/\tau_+ \sim 5$)



Beam acceptance

$\Delta\theta \rightarrow 0.3$ mrad : $\Delta\Omega \rightarrow 0.283$ μsr

Detailed solutions & meaningful cost estimates will require serious study by the CERN Accelerator & Technology Sector

- **Dump collimator TAX1/2:**

$r = 5$ mm at $z = 15$ m
  - 2 vertical sweeping magnets upstream of TAX
  - 3 horizontal muon sweeping magnets downstream of TAX.
- **Defining collimator:**

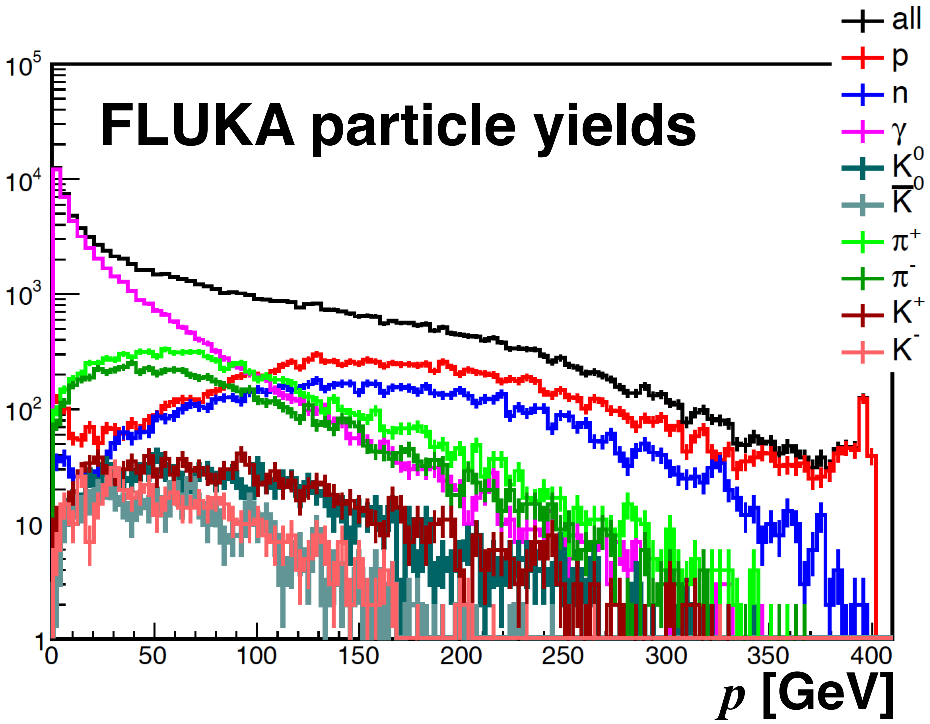
$r = 42$ mm at $z = 60$ m
- **Active Final Collimator**

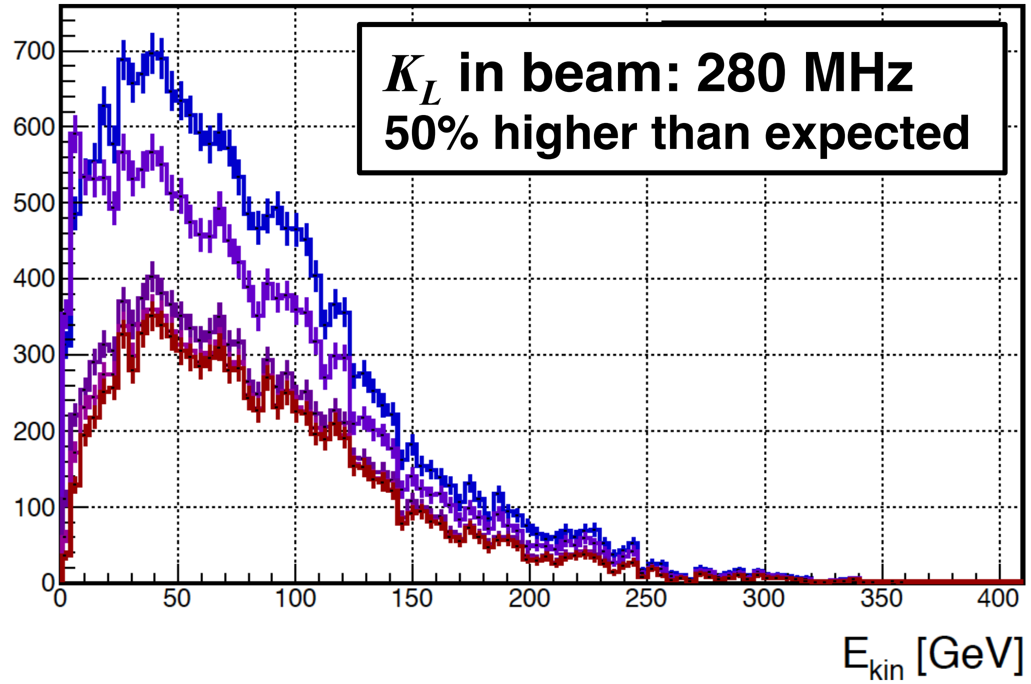
z = 105 m to remove upstream decay products
  - Regenerated K_S reduced to 10^{-4} between defining and final collimators
  - Final collimator is also an active detector to veto upstream decays

Beam simulation and flux estimates

Fluka target simulation

- 400 GeV p + Be, 2.4 mrad
- Obtain p vs. θ distributions



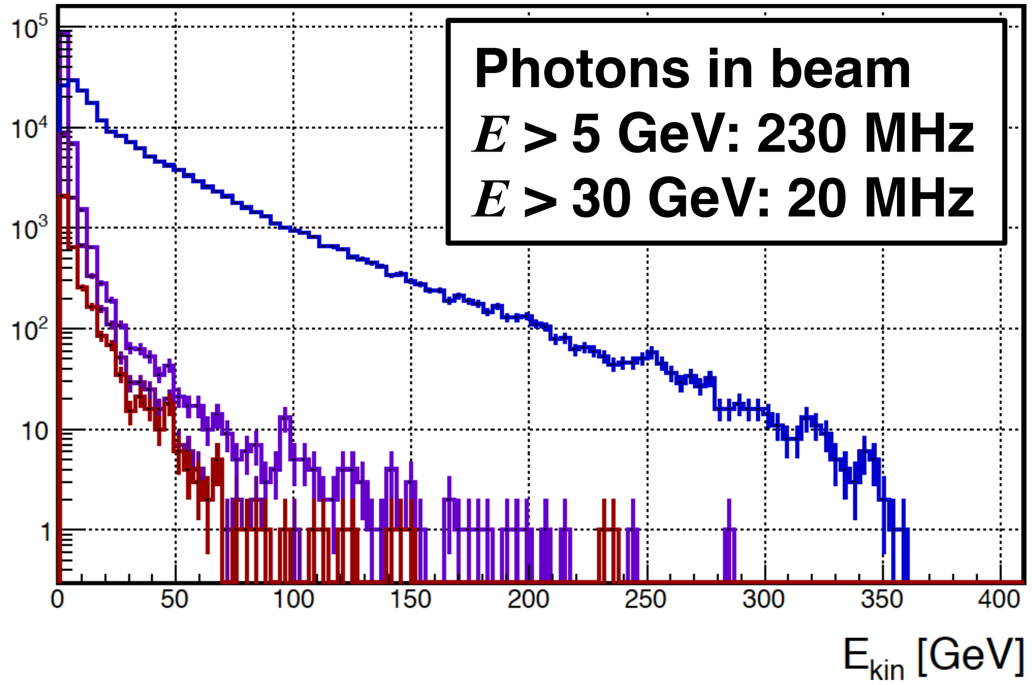


K_L in beam: 280 MHz
50% higher than expected

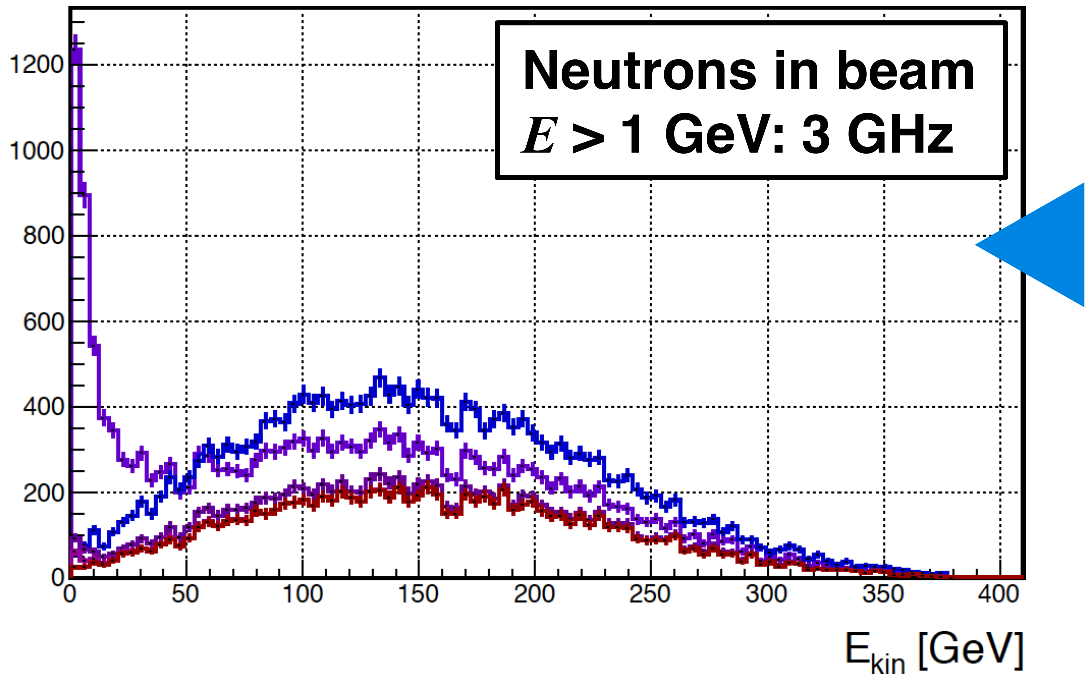
gen
After absorber
After dump collimator
After defining collimator
After final collimator

Geant4 beamline simulation

- 30-mm Ir photon converter
- 3-collimator layout



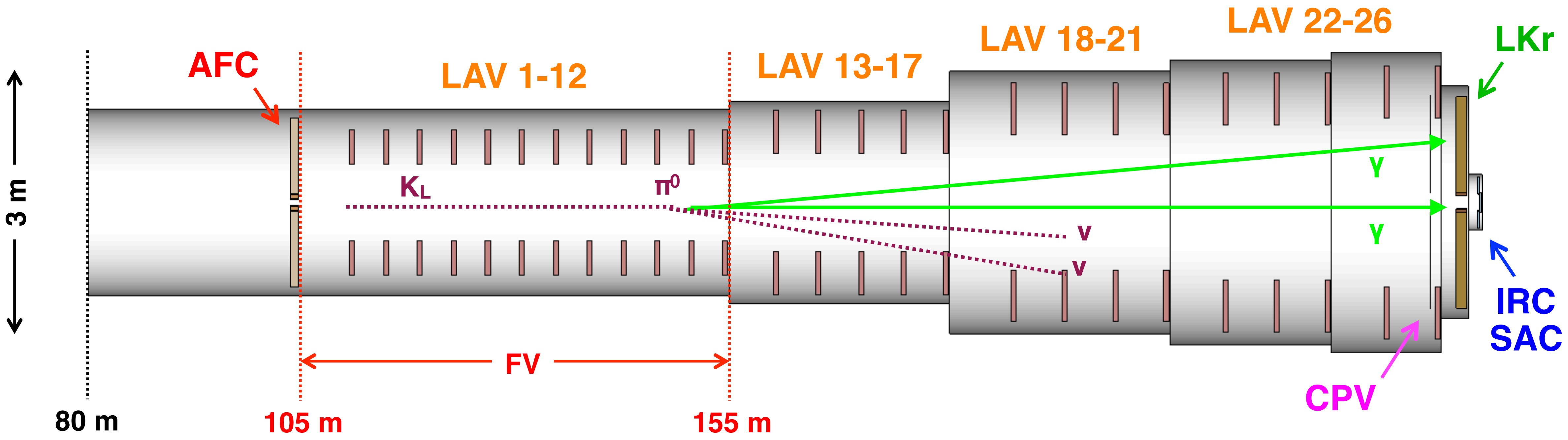
Photons in beam
E > 5 GeV: 230 MHz
E > 30 GeV: 20 MHz



Neutrons in beam
E > 1 GeV: 3 GHz

KLEVER Detector layout for $K_L \to \pi^0 \nu\nu$

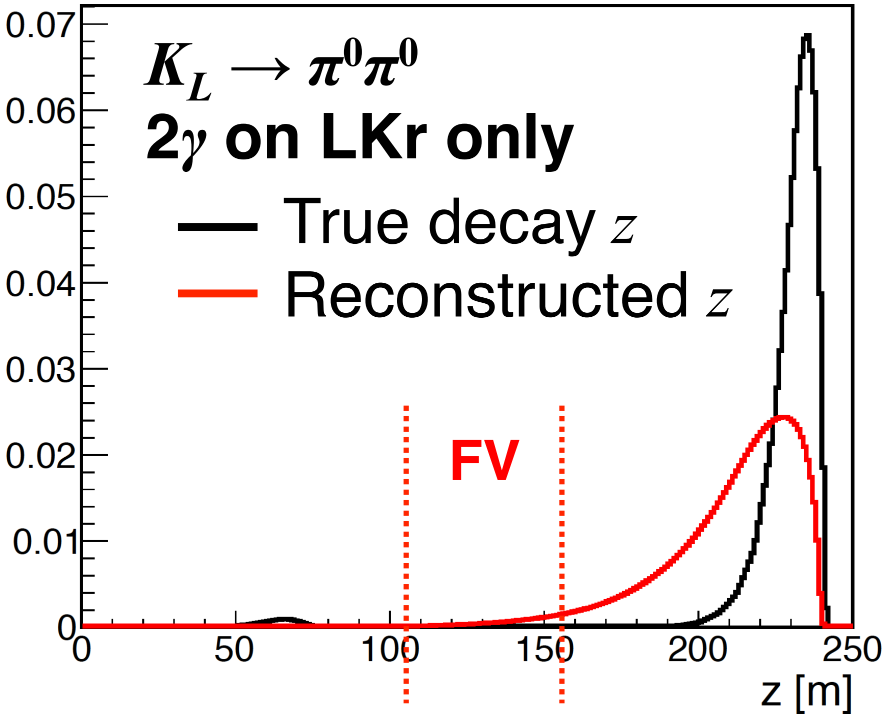
Vacuum tank layout and FV similar to NA62



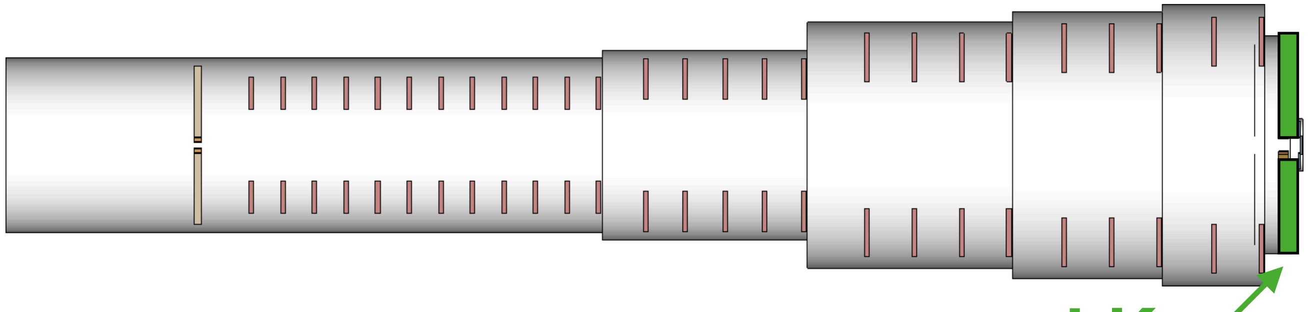
90-m distance from FV to LKr significantly helps background rejection

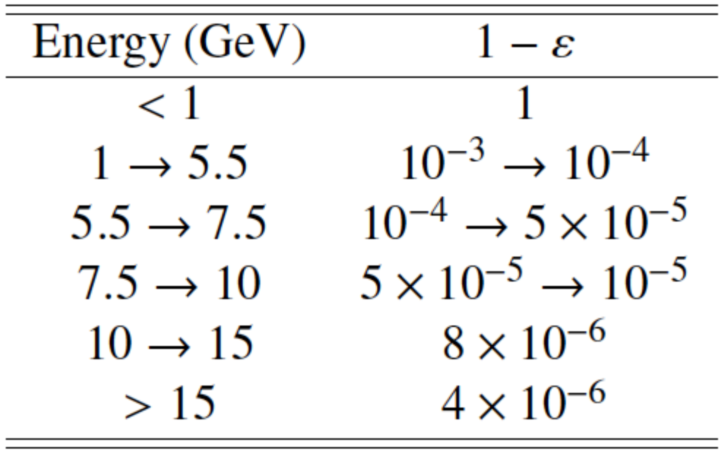
- Most $K_L \to \pi^0\pi^0$ decays with lost photons occur just upstream of the LKr
- "π^0s" from mispaired γs are mainly reconstructed downstream of FV

Signal selection: 2 γ in the LKr + nothing!



Suitability of NA62 LKr calorimeter

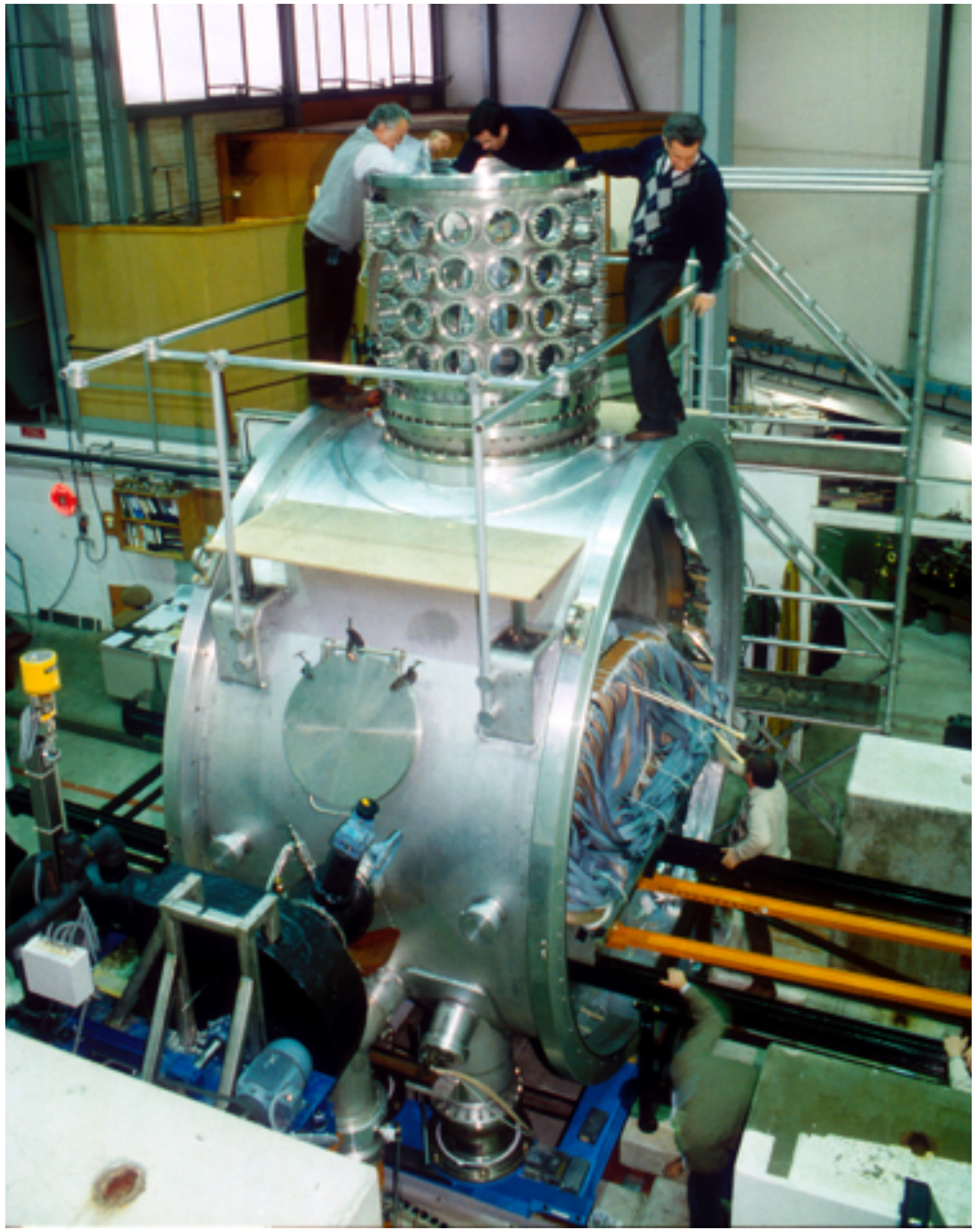




Energy (GeV)	$1-\varepsilon$
< 1	1
$1 \to 5.5$	$10^{-3} \to 10^{-4}$
$5.5 \to 7.5$	$10^{-4} \to 5 \times 10^{-5}$
$7.5 \to 10$	$5 \times 10^{-5} \to 10^{-5}$
$10 \to 15$	8×10^{-6}
> 15	4×10^{-6}

Explore possibilities to improve time resolution with faster readout:

- Signal π^0 candidates all have $E\gamma\gamma > 20$ GeV:
  $\sigma_t = 2.5\ \text{ns}/\sqrt{E}\ (\text{GeV}) \rightarrow 500$ ps or better
- Needs improvements
- Simulating readout upgrades to estimate effect on time resolution: Shorter shaping time, faster FADCs

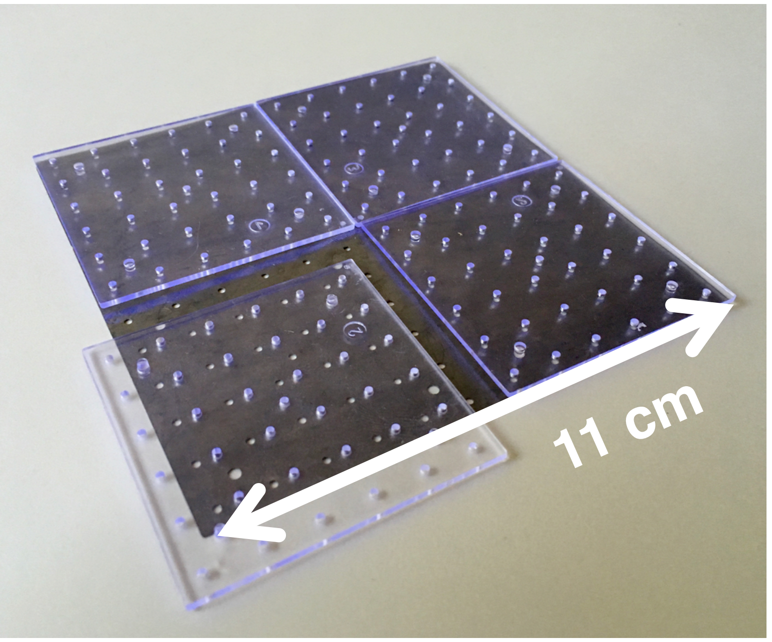


NA48 LKr Installation. 1996

Evaluate long-term reliability of LKr (2018 → 2030):

- Identify support systems needing replacement or upgrade
- Catalog of dead cells, prospects for repair

Alternative: longitudinally-segmented Shashlik



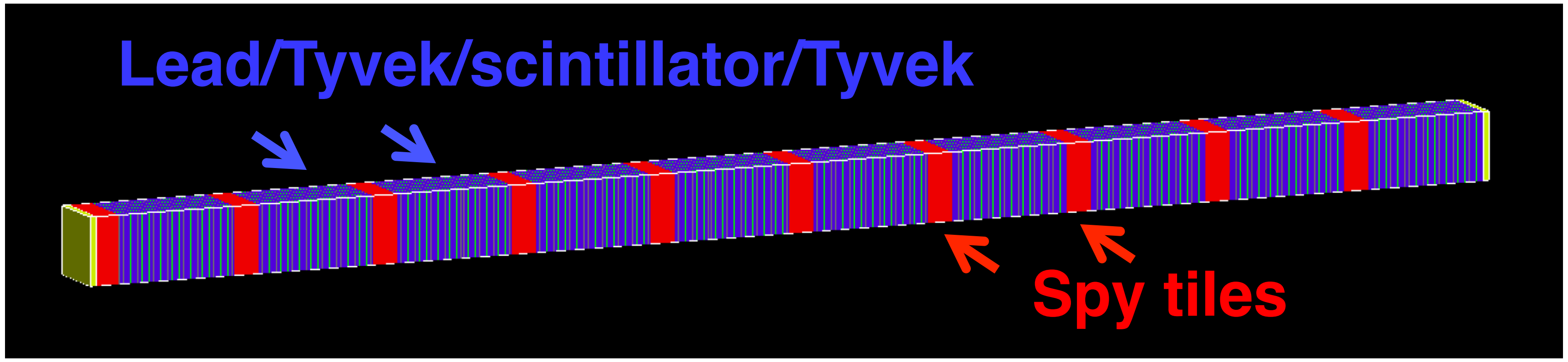
Based on PANDA forward EM calorimeter produced at Protvino

Fine-sampling shashlik:
0.275 mm Pb + 1.5 mm scintillator

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

→ PANDA prototypes

Thicker spy scintillators tiles (5-20 mm) with independent WLS fiber readout to reconstruct the direction of incoming particle

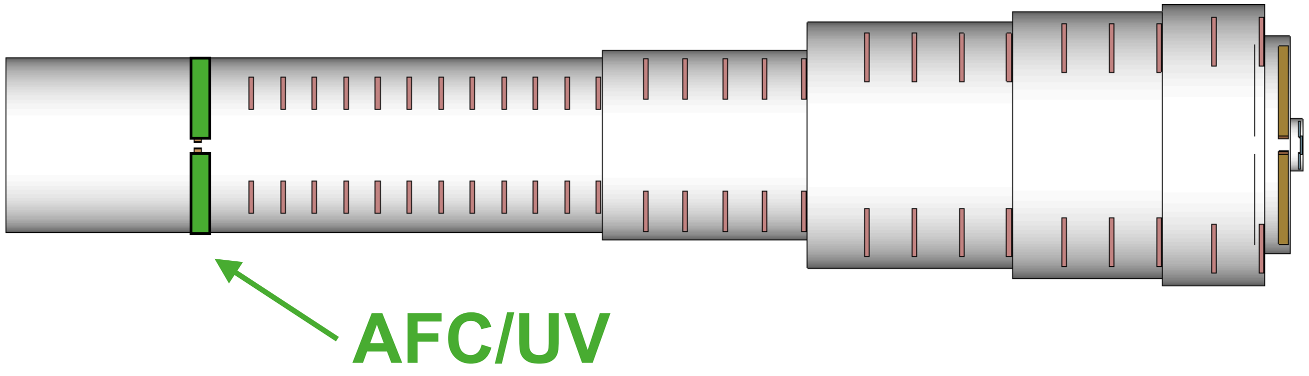


example of shashlik module (500 layers) with 10 extra tiles.

Longitudinal shower information from spy tiles

- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers

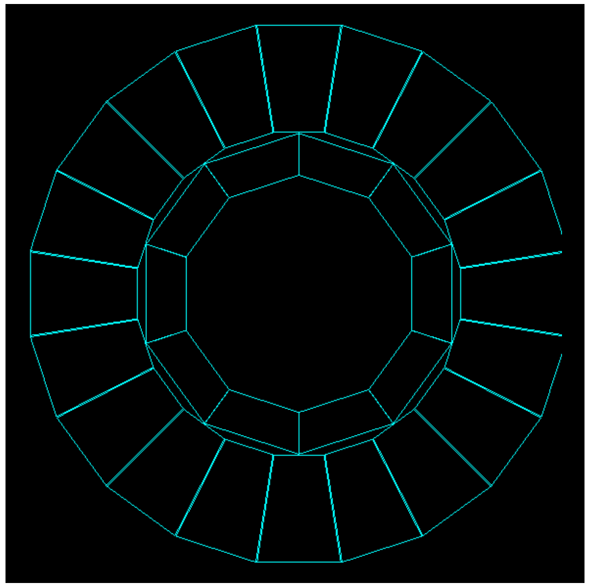
Vetoes for upstream K_L decays



AFC: Active Final Collimator
Rejects $K_L \to \pi^0\pi^0$ from upstream of final collimator
($80 \text{ m} < z < 105 \text{ m}$, 25 m of vacuum)

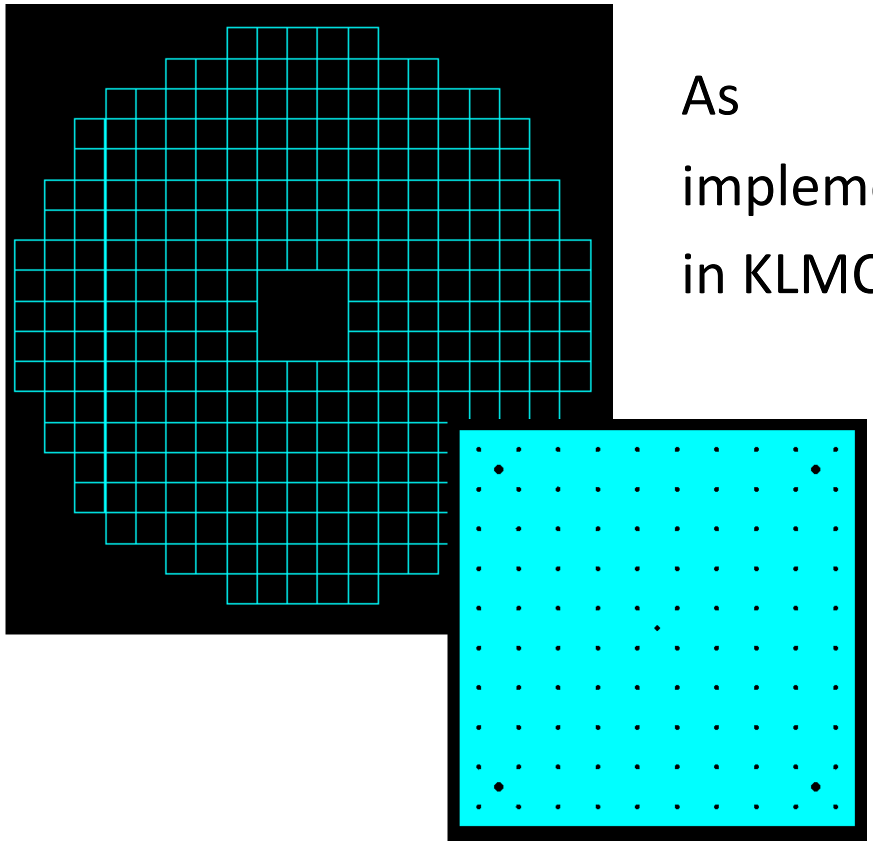
Upstream veto (UV):

- 10 cm < r < 1 m:
- Shashlyk calorimeter modules à la PANDA



Active Final Collimator

- 4.2 < r < 10 cm
- LYSO collar counter
- 80 cm long
- Internal collimating surfaces



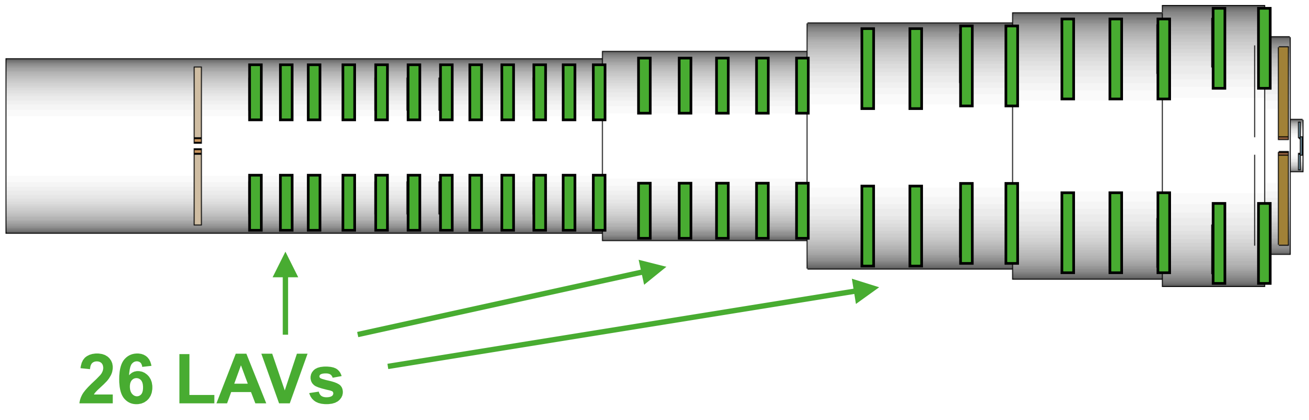
As implemented in KLMC

Intercepts halo particles from scattering on defining collimator or γ absorber

Active detector ⟶ better rejection for π^0 from n interactions

Residual background from upstream
$K_L \to \pi^0\pi^0$: 15 events/5 years

Large-angle photon vetoes



26 new large-angle photon veto stations (LAV)

- 5 sizes, sensitive radius 0.9 to 1.6 m, at intervals of 4 to 6 m
- Hermetic coverage out to 100 mrad for E_γ down to ~100 MeV

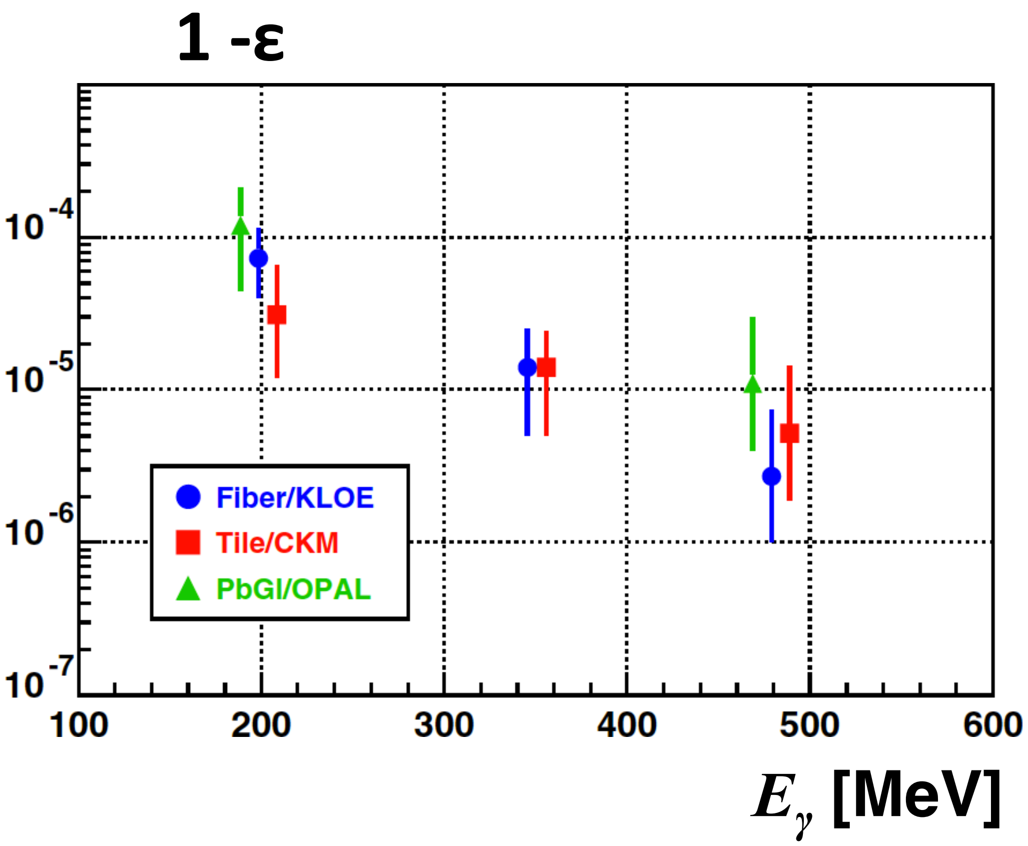
Baseline technology:

- 1 mm Lead + 5 mm scintillator tile detector
- Based on design of Vacuum Veto System detectors planned for the CKM experiment at Fermilab
- Assumed efficiency based on E949 and CKM VVS experience

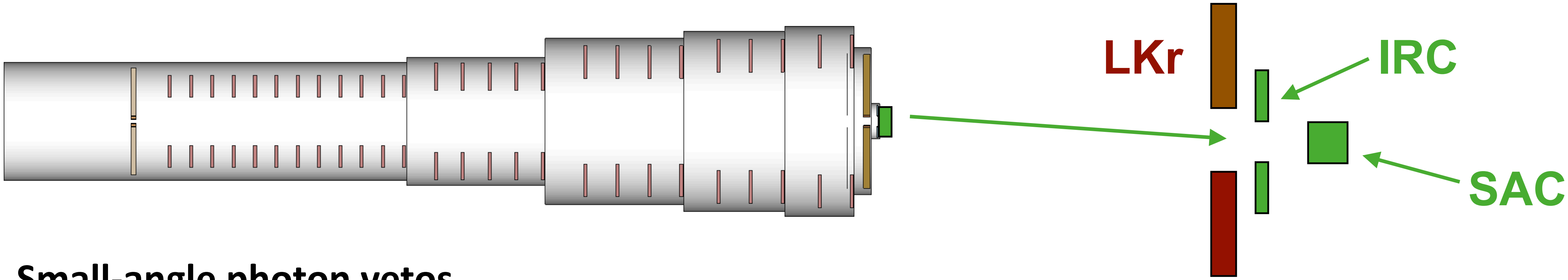
The efficiency of the CKM VVS prototype was measured in 2007 (NA62 hypothesis) using the tagged electron beam of Frascati Beam-Test Facility

Efficiency at low energy from simulations performed by E949 and KOPIO, validated with E949 data (E949 photon vetoes had same basic structure as the CKM VVS)

1-ε = 2.5 x 10^{-6} for Eγ > 2.5 GeV



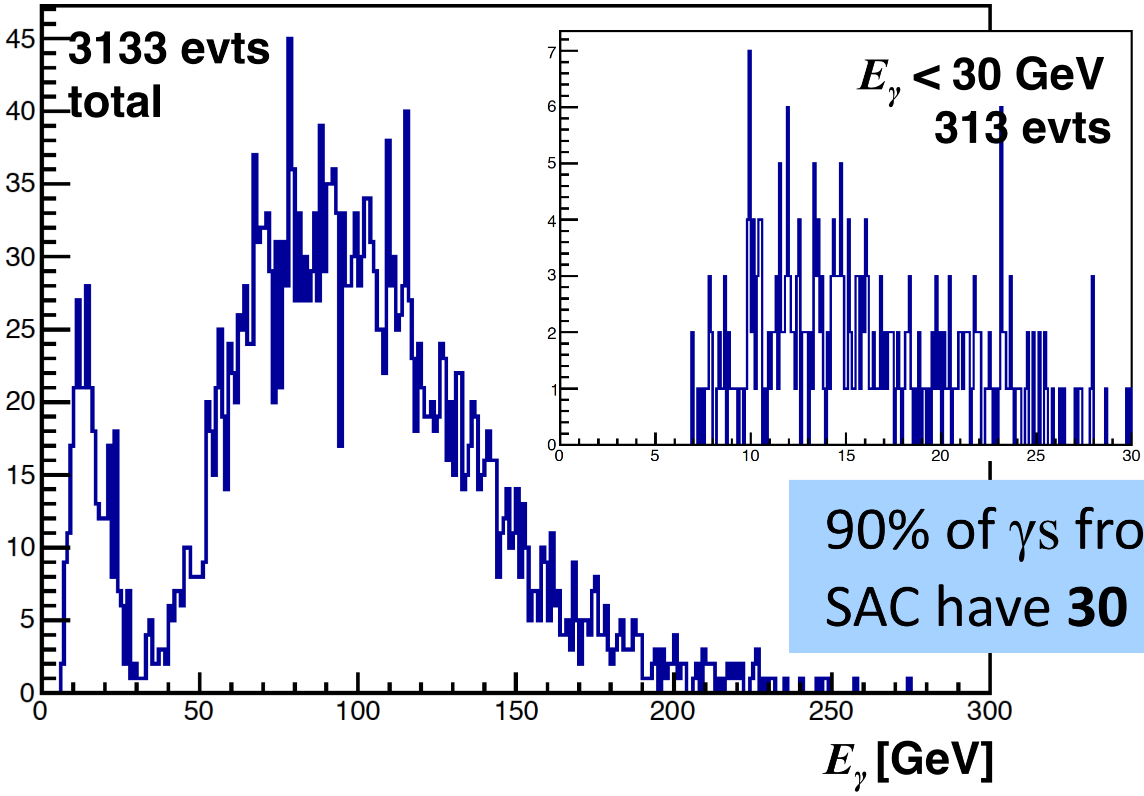
Small-angle photon vetoes



Small-angle photon vetos
must reject high-energy γs escaping through the LKr Calorimeter bore

- **SAC**: angular coverage out to 0.4 mrad, completely occludes the beam.
- **IRC**: for γs from downstream decays at slightly larger angles, it does not see the beam directly

Both detectors: veto photons with very high energy



$K_L \to \pi^0\pi^0$ photons on SAC

- Exactly 2 γs on LKr
- No γs on LAV or IRC
- Cuts on Z_{FV}, $r_{min(LKr)}$, $p_\perp$

90% of γs from $K_L \to \pi^0\pi^0$ on SAC have **30 < E_γ < 250 GeV**

SAC required inefficiency:

Energy (GeV)	$1-\varepsilon$
< 5	1
$5 \to 30$	10^{-2}
> 30	10^{-4}

IRC required inefficiency:

Energy (GeV)	$1-\varepsilon$
< 5	1
$5 \to 25$	10^{-3}
> 25	10^{-4}

Small-angle photon vetoes

Baseline technology: Tungsten/silicon-pad sampling calorimeter with crystal metal absorber

SAC must be largely insensitive to the neutral beam:

3 GHz of neutrons and 700 MHz of photons (only 21 MHz with E > 30 GeV, 97% < 30 GeV)

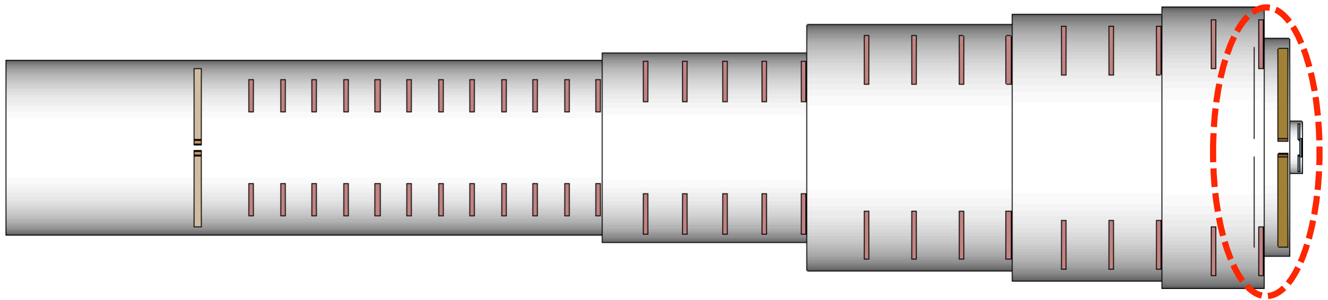
The design of this detector is one of the most challenging aspects of the experiment

Design criteria:

- Ratio λ_{int}/X_0 as large as possible (largely transparent to the neutrons)
- Excellent time resolution: σ_t < 300 ps.
  To reduce accidental veto rate by coincidence with LKr.
- Moderate energy resolution: < 10%/√E (GeV) for γs to allow threshold adjustment
- 2D transverse segmentation with a granularity sufficient to keep the single-channel rate below a few MHz
- longitudinal segmentation for γ/n discrimination by shower profile analysis
- Extremely good radiation tolerance

IRC same technology but with higher sampling fraction

Charged particle Veto



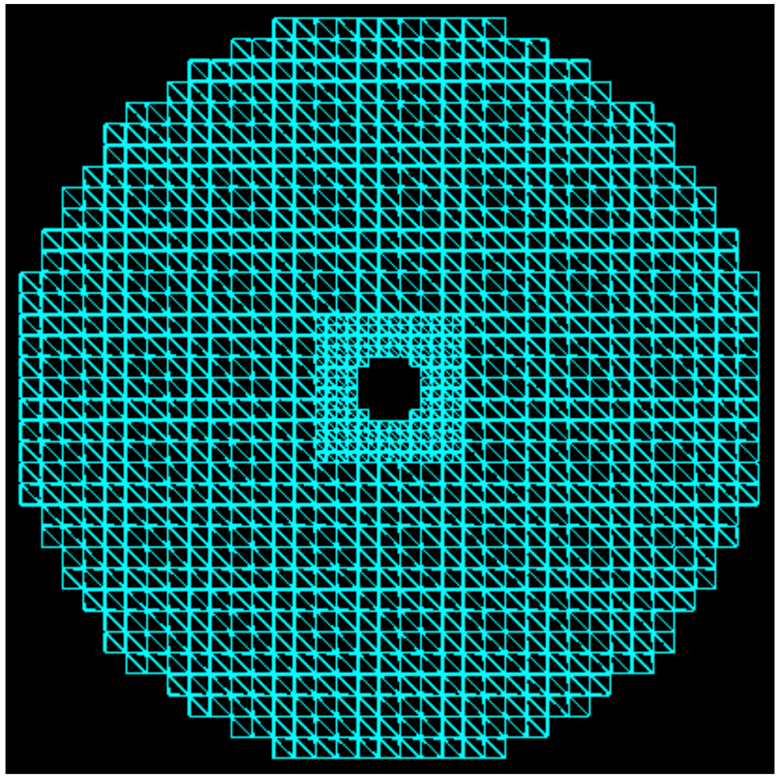
Secondary charged particle clusters in LKr calorimeter can be reconstructed as fake π^0

K_{e3} most dangerous mode:

- Large BR
- $e^{\pm}$ create electromagnetic shower easy to mistake for γ in LKr.

Acceptance $\pi^0\nu\nu/K_{e3}$ = 30

Need 10^{-9} suppression

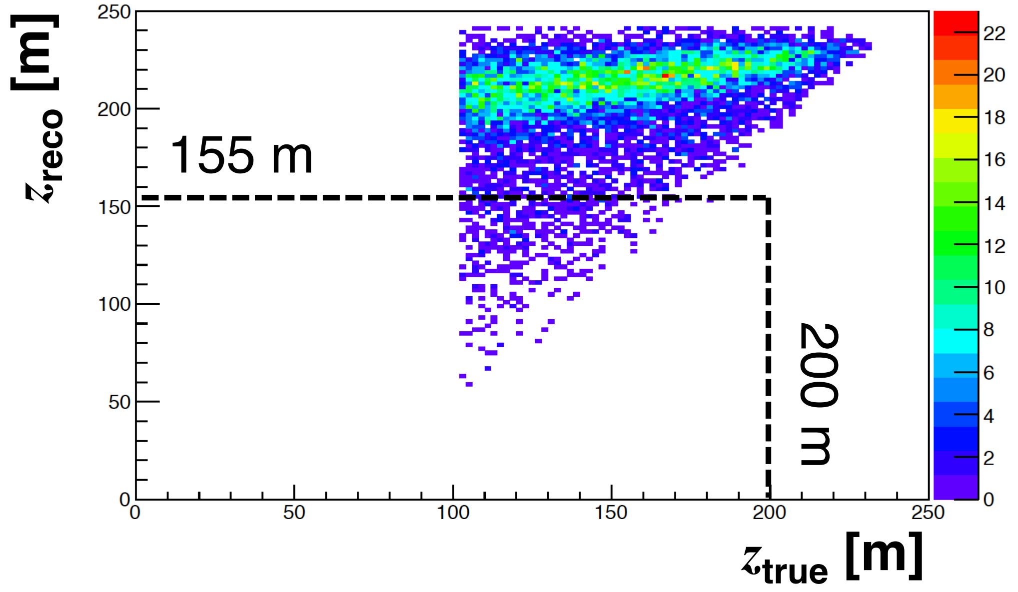


Baseline technology:

- 2 thin plastic-scintillator arrays, 5 mm thick (2 X_0) supported on carbon fiber membrane,
  3 m upstream the LKr calorimeter
- 1 thin plastic-scintillator arrays, 1 cm thick,
  3 m downstream the LKr calorimeter to help identify π and μ
- Cracks staggered between planes

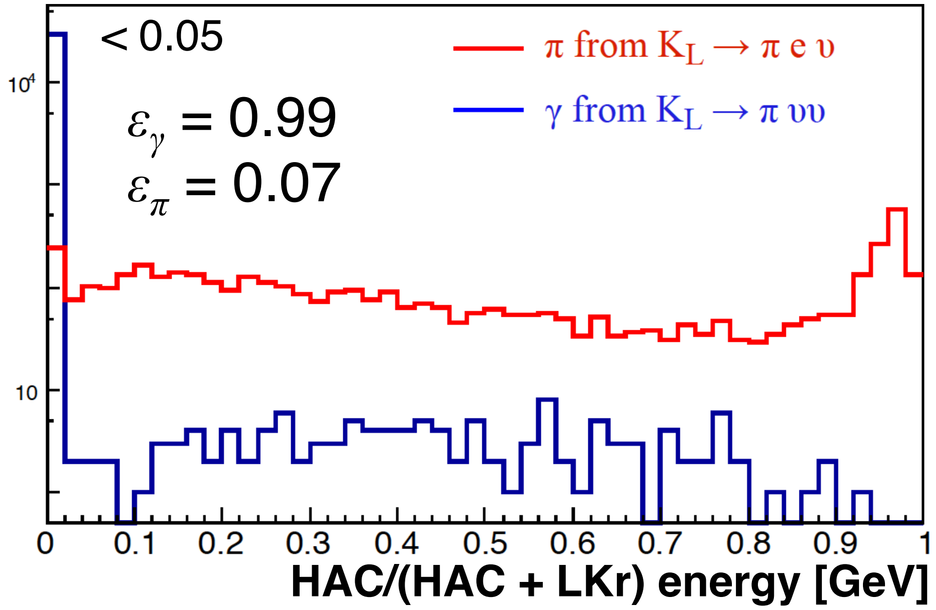
Charged particle rejection

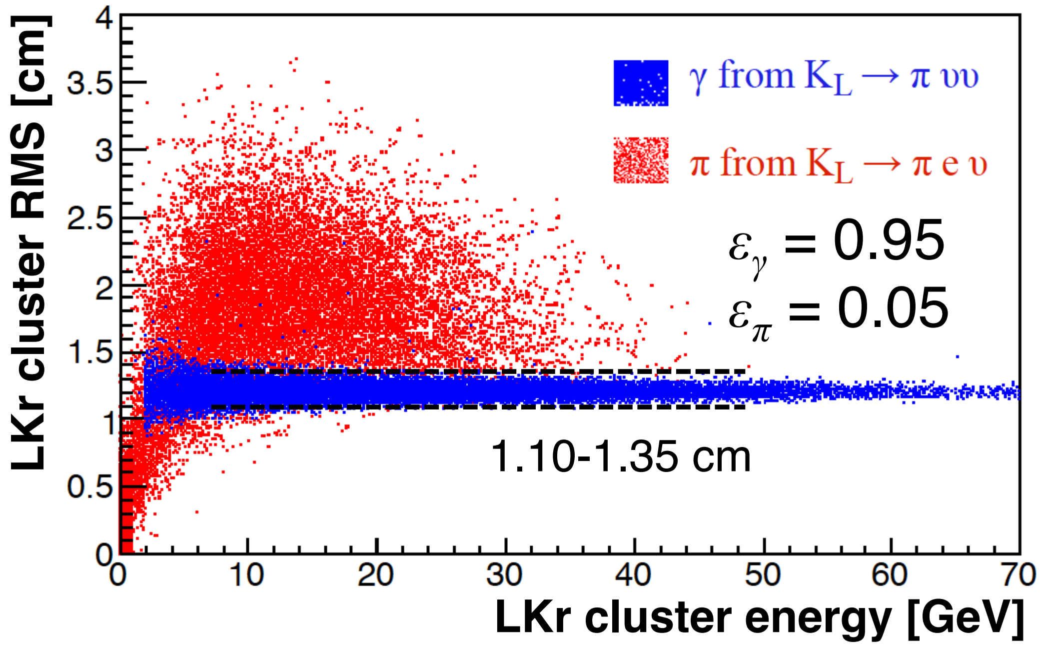
$K_L \to \pi^\pm e^\mp \boldsymbol{\nu}$ can emulate the signal when both $\pi^\pm$ and $e^\mp$ deposits energy in the LKr



Geant4 simulation:

- Fake π^0 vertex are reconstructed always downstream of the true K_L decay point ($\pi^\pm$ deposits only a fraction of its energy).
- Decays in FV all occur at least 50 m upstream of the LKr: **all within the acceptance of the CPV**





HAC/(HAC+LKr) < 0.05 eliminates 93% of π preserving 99% of γ

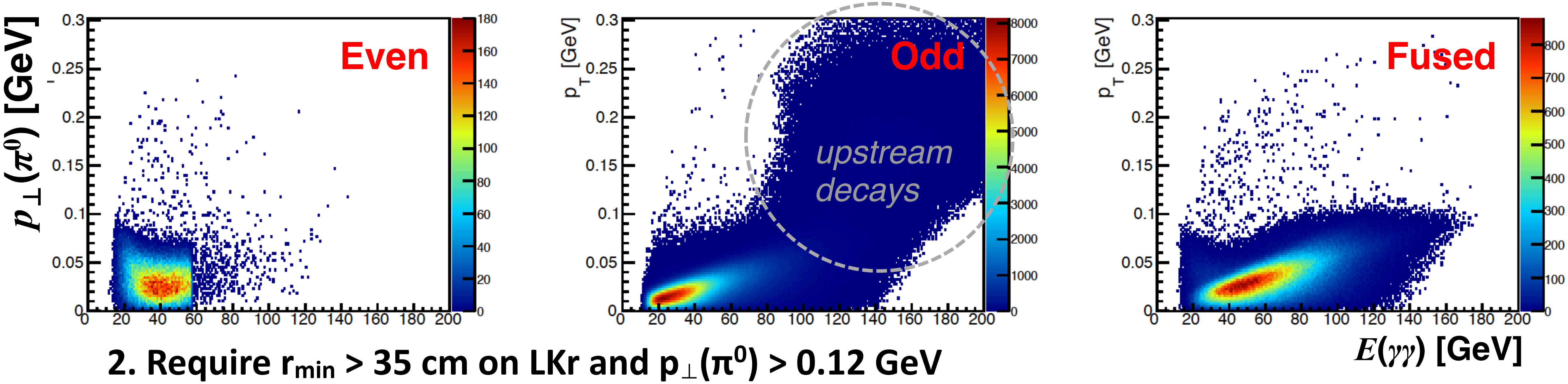
Transverse cluster spread between 1.10 cm and 1.35 cm selects 95% of γ and eliminates 95% of π

$K_L \rightarrow \pi^0\pi^0$ rejection

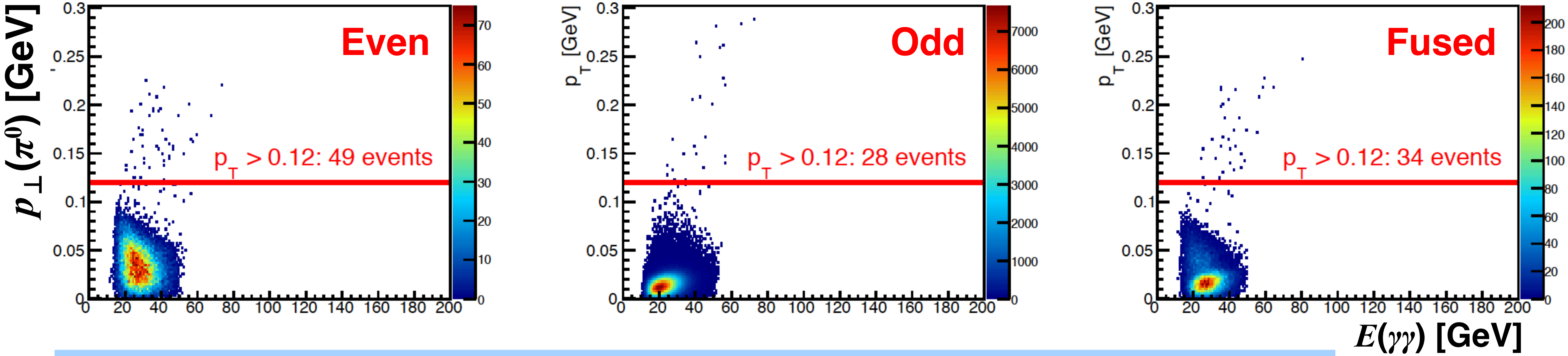
$K_L \rightarrow \pi^0\pi^0$ simulated with fast MC (5 yr equivalent statistics)

- Accept events with 2 γs in LKr and no hits in UV/AFC, LAV, IRC/SAC
- Distinguish between even/odd pairs and events with fused clusters

1. Require $z_{rec}(m_{\gamma\gamma} = m_{\pi 0})$ in fiducial volume (105 m < z < 155 m)



2. Require r_{min} > 35 cm on LKr and $p_\perp(\pi^0)$ > 0.12 GeV



22 $\pi^0\pi^0$ evts/year (about 50% with 1γ with 100 < θ < 400 mrad, E < 50 MeV)

$K_L \to \pi^0 \nu\nu$ acceptance

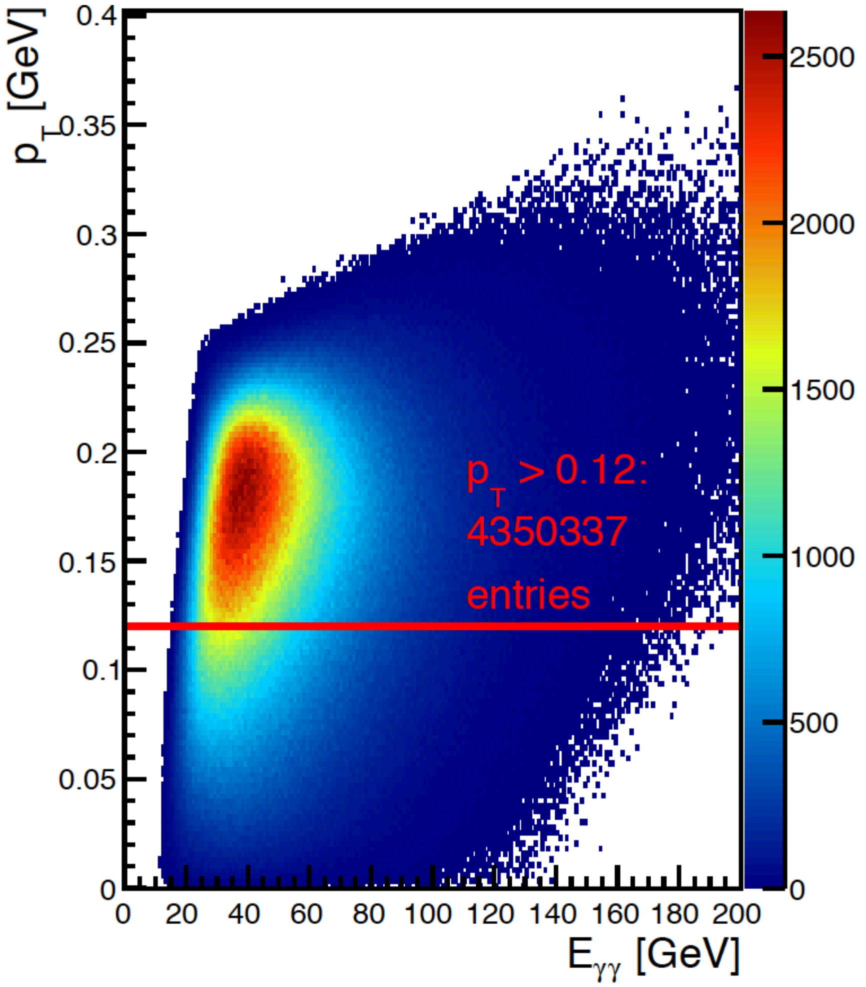
With:

- 10^{19} pot/year
- 2.8×10^{-5} K_L/pot
- BR = 3.4×10^{-11}
- $\varepsilon_{\text{total}}$ = 0.20%

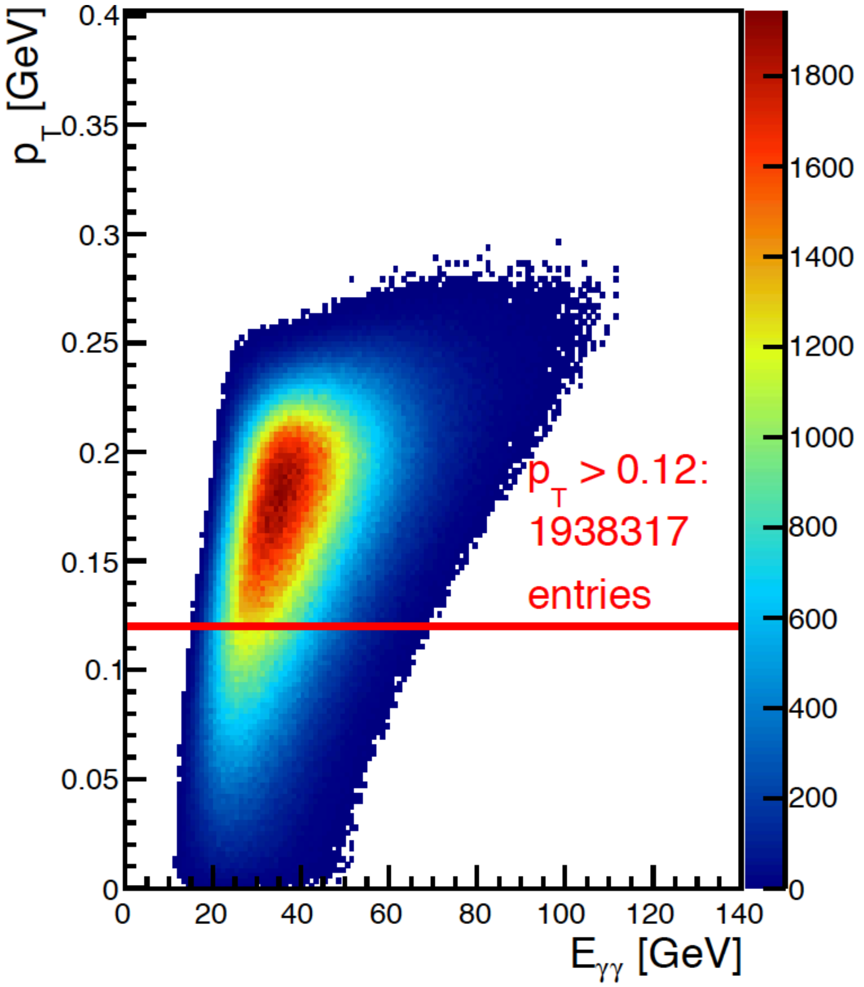
Cut stage	**Cut eff.**	**Cuml. eff.**
$K_L \to \pi^0 \nu\nu$ evts with 2γ on LKr	2.0%	2.0%
$z_{\text{rec}}(m_{\gamma\gamma} = m_{\pi 0})$ in FV	31%	0.62%
$r_{\text{min}} > 35$ cm on LKr	42%	0.26%
$p_\perp(\pi^0) > 0.12$ GeV	78%	0.20%

π^0 in $\pi^0\nu\nu$ has large E_{kin}

$z_{\text{rec}}(m_{\gamma\gamma} = m_{\pi 0})$ in FV



r_{min} and $p_\perp$ cuts



19.4 π^0 $\nu\nu$ evts/year

excluding transmission
losses from γ converter

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

Channel	Simulated statistics	Events found	Expected in 5 yrs*
$K_L \rightarrow \pi^0 \nu\nu$	100k yr	1.94M	**97**
$K_L \rightarrow \pi^0 \pi^0$	5 yr	111	**111**
$K_L \rightarrow \pi^0 \pi^0 \pi^0$ All bkg evts from cluster fusion Upstream decays not yet included	1 yr	3	**15**
$K_L \rightarrow \gamma\gamma$ $p_\perp$ cut very effective	3 yr	0	**0**
$K_L \rightarrow$ **charged**	**thought to be reducible**		

*Must subtract 35% for K_L losses in dump γ converter

~ 60 SM $K_L \rightarrow \pi^0 \nu\nu$ in 5 years with S/B ~ 1

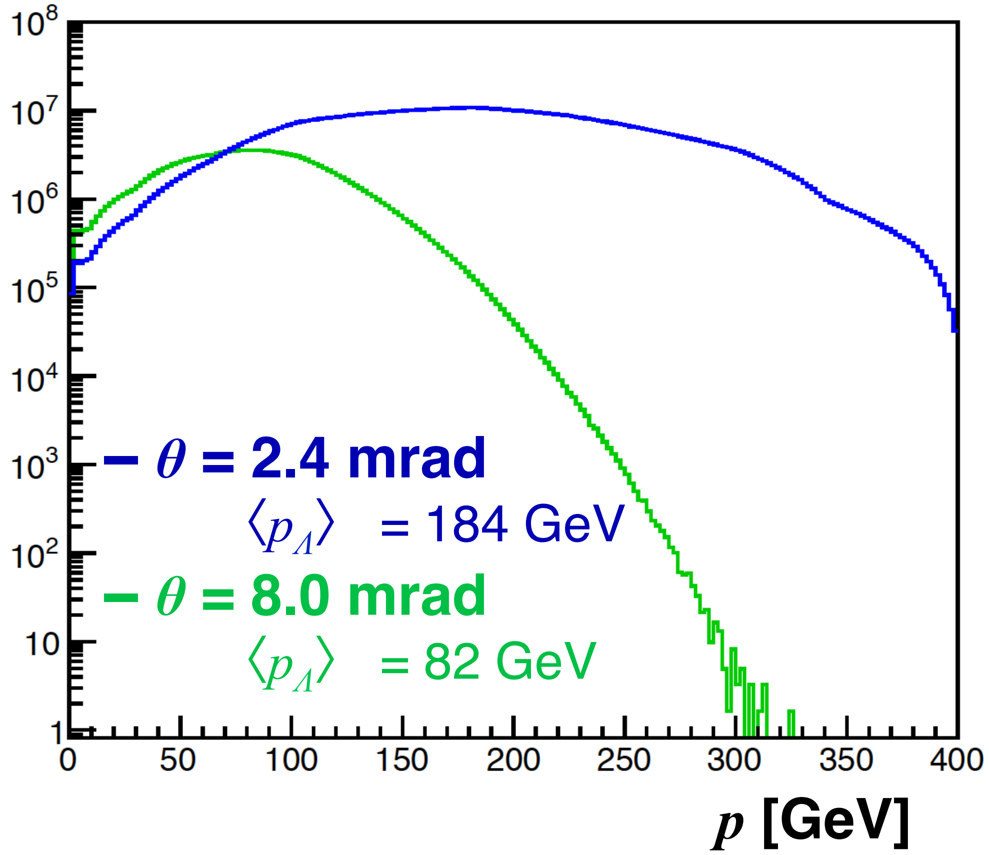
Background study incomplete!

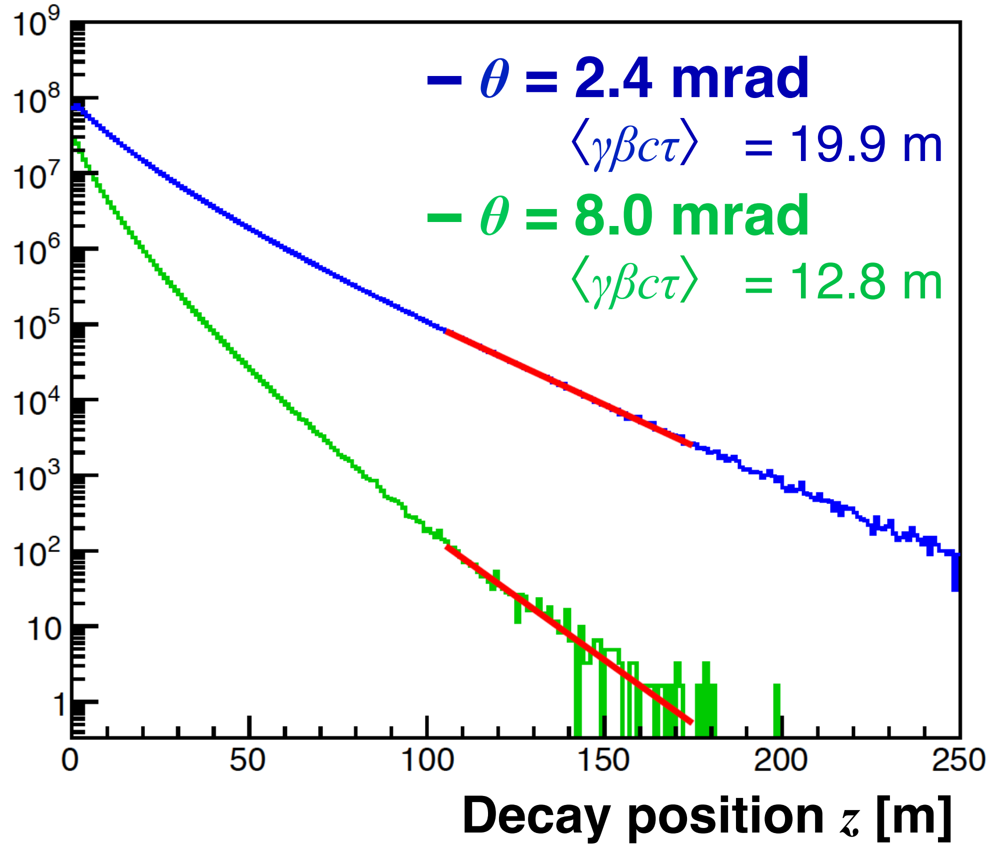
- π^0 from interactions of halo neutrons on residual gas, detector materials
- Radiative K_L decays, **K_S/hyperon decays**

Background from $\Lambda \to n\pi^0$

$\Lambda \to n\pi^0$ (BR = 35.8%) can mimic signal decay

- Λ and K produced in similar numbers: O(10^{15}) Λ in beam in 5 years
- Small but significant fraction of Λ decay in fiducial volume
  - $c\tau_\Lambda$ = 7.89 cm, but Λ is forward produced: hard momentum spectrum
- $p_\perp$ cut of the analysis selection is partially effective: $p^*(\Lambda \to n\pi^0)$ = 105 MeV





Move from θ = 2.4 → **8 mrad** production angle looks promising:
decrease Λ flux in beam and soften Λ momentum spectrum

Neutral beamline layout (8.0 mrad)

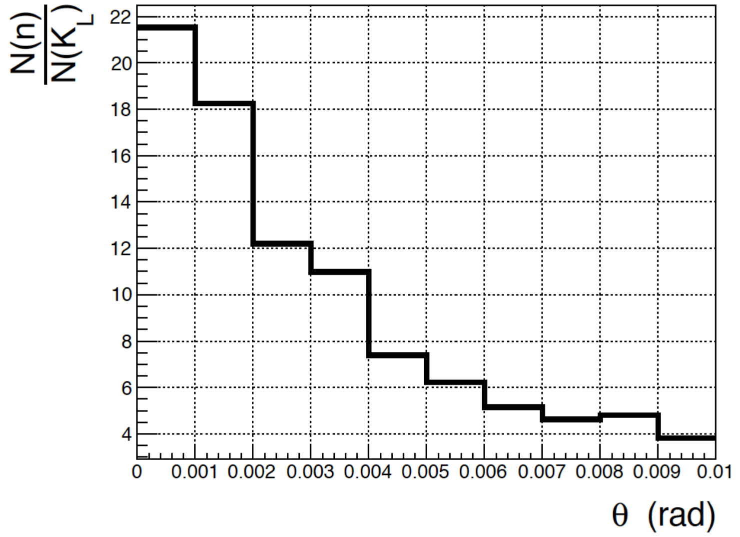
Changing production angle θ = 2.4 → 8.0 mrad:

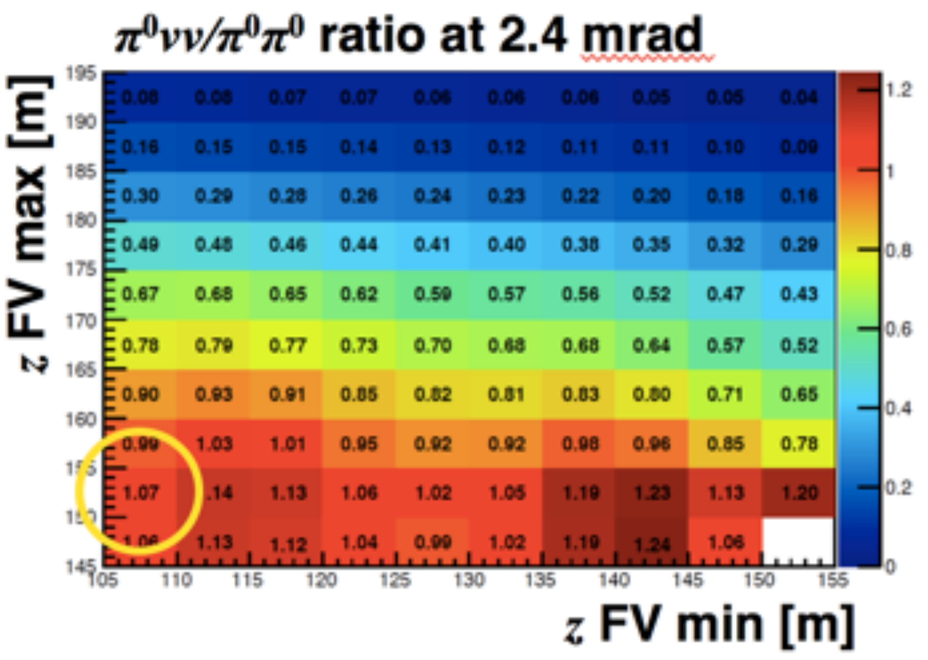
- 3x decrease in K_L decays in fiducial volume

Advantages to moving to larger angle:

- Neutron flux decreased by factor ~7
- Much less demanding rates on SAC

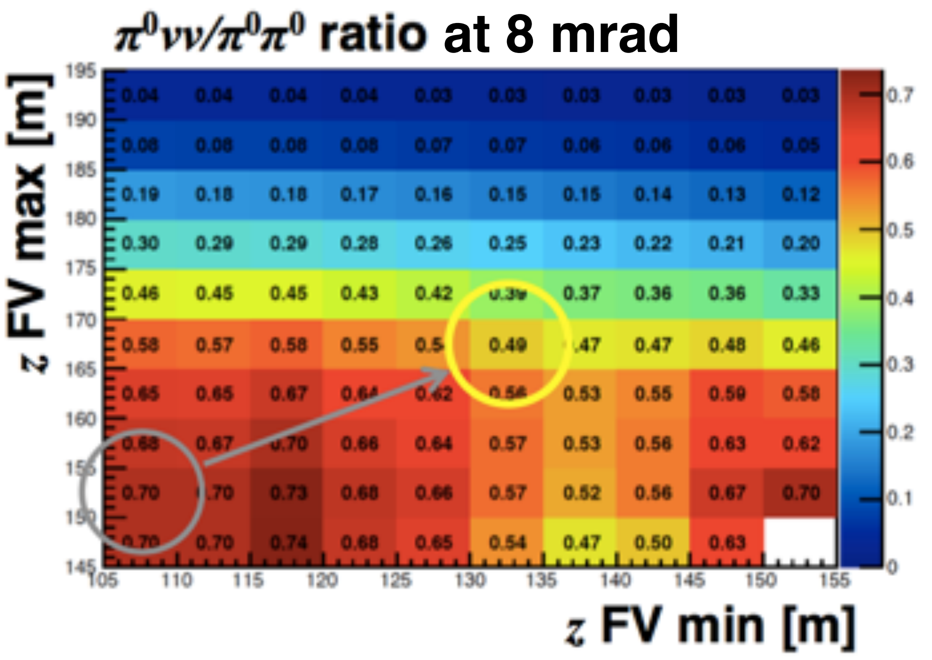
Possible to use thinner absorber in beam?





$\pi^0\nu\nu/\pi^0\pi^0$ ratio at 2.4 mrad

0.08	0.08	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.04
0.16	0.15	0.15	0.14	0.13	0.12	0.11	0.11	0.10	0.09
0.30	0.29	0.28	0.26	0.24	0.23	0.22	0.20	0.18	0.16
0.49	0.48	0.46	0.44	0.41	0.40	0.38	0.35	0.32	0.29
0.67	0.68	0.65	0.62	0.59	0.57	0.56	0.52	0.47	0.43
0.78	0.79	0.77	0.73	0.70	0.68	0.68	0.64	0.57	0.52
0.90	0.93	0.91	0.85	0.82	0.81	0.83	0.80	0.71	0.65
0.99	1.03	1.01	0.95	0.92	0.92	0.98	0.96	0.85	0.78
1.07	.14	1.13	1.06	1.02	1.05	1.19	1.23	1.13	1.20
1.06	1.13	1.12	1.04	0.99	1.02	1.19	1.24	1.06	



$\pi^0\nu\nu/\pi^0\pi^0$ ratio at 8 mrad

0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
0.08	0.08	0.08	0.08	0.07	0.07	0.06	0.06	0.06	0.05
0.19	0.18	0.18	0.17	0.16	0.15	0.15	0.14	0.13	0.12
0.30	0.29	0.29	0.28	0.26	0.25	0.23	0.22	0.21	0.20
0.46	0.45	0.45	0.43	0.42	0.39	0.37	0.36	0.36	0.33
0.58	0.57	0.58	0.55	0.5	0.49	.47	0.47	0.48	0.46
0.65	0.65	0.67	0.64	0.62	0.56	0.53	0.55	0.59	0.58
0.68	0.67	0.70	0.66	0.64	0.57	0.53	0.56	0.63	0.62
0.70	.70	0.73	0.68	0.66	0.57	0.52	0.56	0.67	0.70
0.70	0.70	0.74	0.68	0.65	0.54	0.47	0.50	0.63	

To reject more Λs:

- **Move FV downstream by 25 m**: no additional loss of K_L
- S/B ratio from K_L → $\pi^0\pi^0$ decreased by factor 2

Next steps:

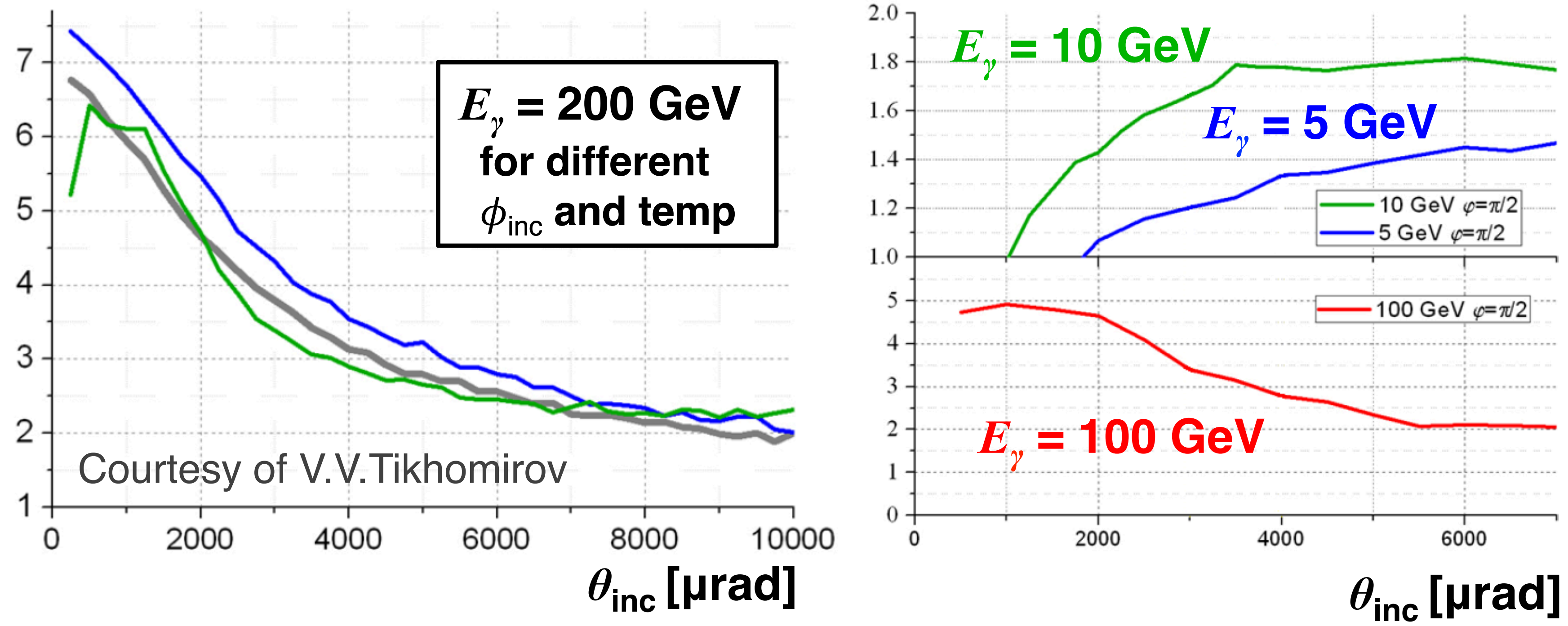
- Finish optimization studies
- Better quantify Λ rejection from p⊥ cut
- New 8.0 mrad beamline design with increased solid angle

Photon Conversion with crystals

The coherent interaction of high-energy photons with a crystal lattice can enhance the probability of pair production: same photon efficiency with **less thickness**

The effect is observed for certain incident angles (depending on the photon energy)

Rel. pair production in Tungsten (W):



2 potential uses in KLEVER for a converter with large effective λ_{int}/X_0:

Beam photon converter in dump collimator

- Effective at converting beam γ while relatively transparent to K_L

Absorber material for small-angle calorimeter (SAC)

- Must be insensitive as possible to ~GHz of beam neutrons while efficiently vetoing high-energy photons from K_L decays

Beam test of $\gamma \longrightarrow e^{+}e^{-}$ in crystals

A test with high-energy tagged photon beam is foreseen in collaboration with the member of the AXIAL experiment (group with experience with coherent phenomena in crystals)

At the CERN SpS tagged photon beam of energy up to ~150 GeV can be produced: **H4 beamline**

1 week of beam requested in 2018

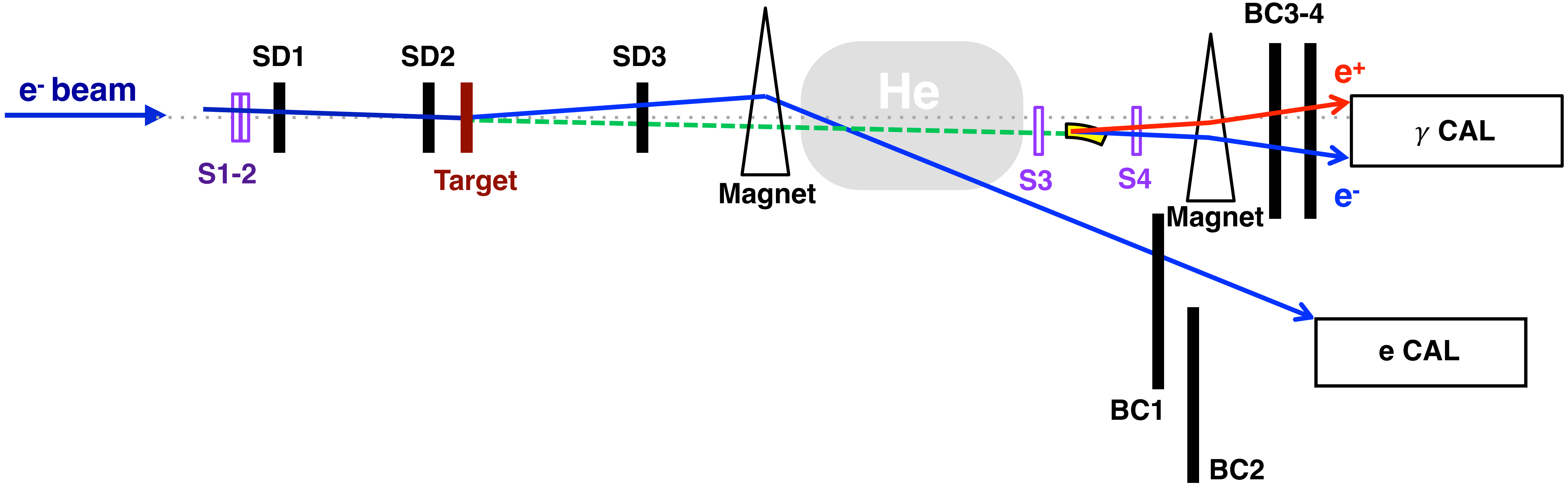
Test measurements:

- $\gamma \rightarrow$ e+e− enhancement with a commercially available tungsten crystal
- Pair-conversion probability as a function of angle of incidence for different energies (spanning $5 < E_{\gamma} < 150$ GeV)
- Spectrum of transmitted γ energy for a thick (~10 mm) crystal

July 2017 AXIAL data taking at H4 (CERN)

Setup for test beam

Tagged photon beam setup for test beam is an evolution of the AXIAL setup (nearly all detectors and DAQ system available for use from AXIAL)



Test goal: direct study about the utility of using crystals converter to reduce the photon flux in the neutral beam and to be transparent to neutrons in the small angle calorimeter. Measurements would allow to introduce into Geant4 detailed simulation of coherent effects in crystal

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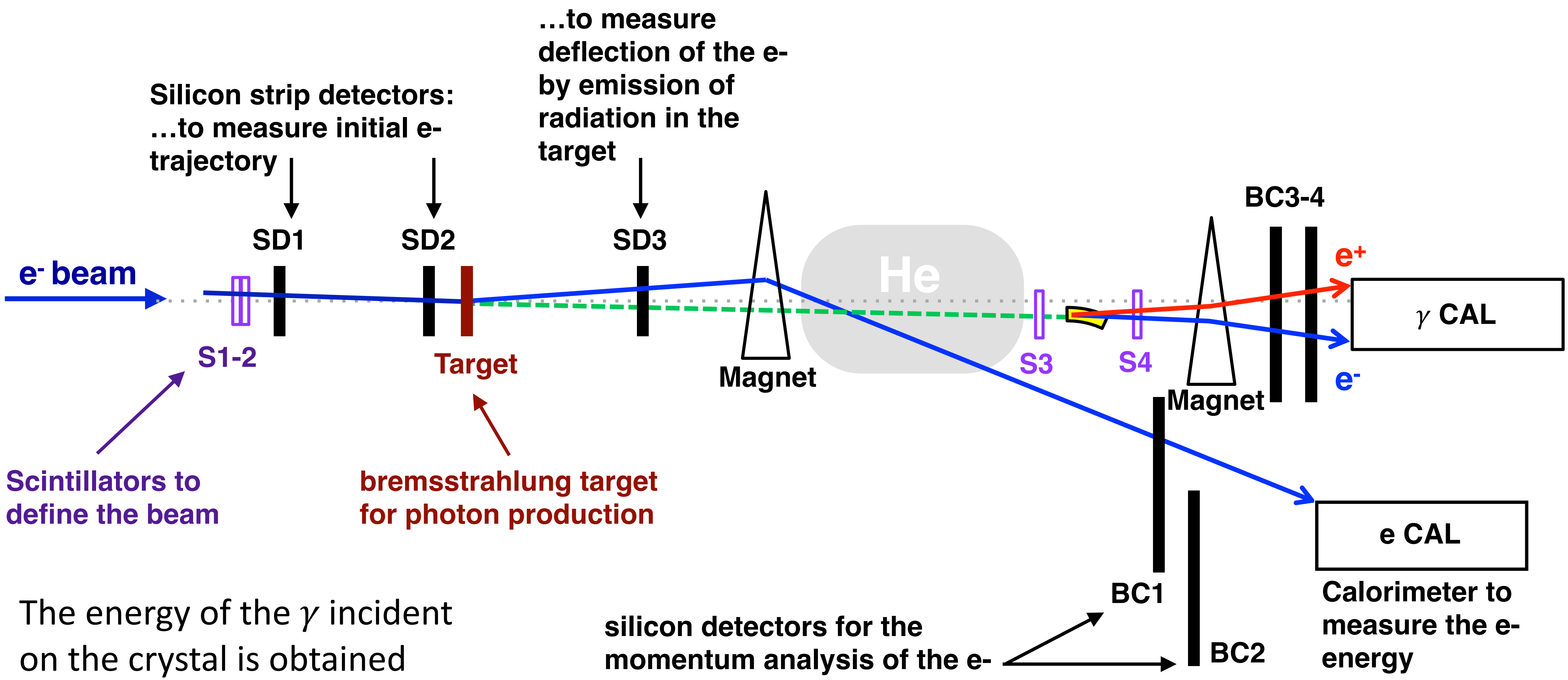

Silicon strip detectors: …to measure initial e- trajectory

…to measure deflection of the e- by emission of radiation in the target

e^- beam

SD1

SD2

SD3

S1-2

Target

Magnet

He

S3

S4

Magnet

BC3-4

e^+

γ CAL

e^-

Scintillators to define the beam

bremsstrahlung target for photon production

BC1

BC2

e CAL

silicon detectors for the momentum analysis of the e-

Calorimeter to measure the e- energy

The energy of the γ incident on the crystal is obtained from kinematics

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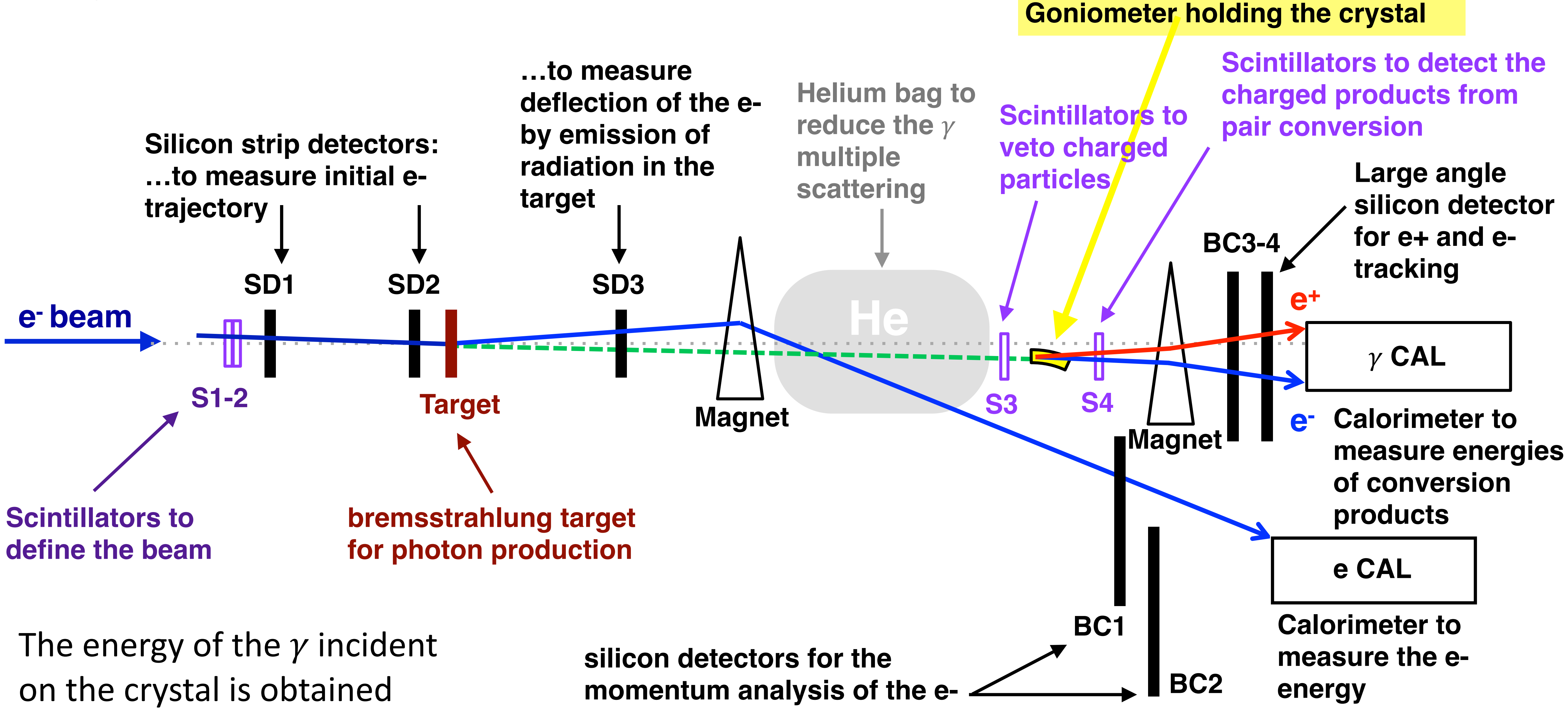

Goniometer holding the crystal

Silicon strip detectors:
…to measure initial e- trajectory

…to measure deflection of the e- by emission of radiation in the target

Helium bag to reduce the γ multiple scattering

Scintillators to veto charged particles

Scintillators to detect the charged products from pair conversion

Large angle silicon detector for e+ and e- tracking

Calorimeter to measure energies of conversion products

Scintillators to define the beam

bremsstrahlung target for photon production

silicon detectors for the momentum analysis of the e-

Calorimeter to measure the e- energy

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Additional ideas to pursue

Preliminary idea investigation

Add a tracking system for charged particle?

- Possible expansion of physics program ($K_L \longrightarrow \pi^0\ell^+\ell^-$, LFV, etc.)
- Final-state reconstruction for LKr efficiency estimation & systematic control
- Potential complications for $K_L \rightarrow \pi^0 \nu\nu$
  - Simulate impact of material budget on photon veto efficiency
  - Evaluate impact of magnet on photon veto coverage
- Non-destructive muon tracking downstream of LKr?

Add a preshower detector in front of LKr?

- Place γ converter in front of tracking planes, measure impact angle
- Require at least 1 conversion for signal events → cost in signal?
- Same complications as for adding tracking

Status and timeline

Project timeline – target dates:

2017-2018 **Project consolidation and proposal**

- Beam test of crystal pair enhancement
- Consolidate the design

2019-2021 **Detector R&D**

2021-2025 **Detector construction**

- Possible neutral beam test if compatible with NA62

2024-2026 **Installation during LS3**

2026- **Data taking beginning Run 4**

Vast majority of institutes participating in NA62 have expressed interest in KLEVER. We are actively seeking new collaborators.

KLEVER is being discussed in the CERN Physics Beyond Colliders working groups and an expression of interest will be prepared for the CERN SPSC to be submitted as input to the European Strategy for Particle Physics

Conclusion

- Flavor will play an important role in identifying new physics, even if NP is found at the LHC
  - $K \longrightarrow \pi\nu\nu$ is a uniquely sensitive indirect probe for high mass scales
  - Need precision measurements of both K^+ and K_L decays
- Preliminary design studies indicate that an experiment to measure BR($K_L \longrightarrow \pi^0\nu\nu$) can be performed at the SPS in Run 4 (2026-2029)
  - Many issues still to be addressed!
  - Expected sensitivity: ~ 60 SM events with S/B ~ 1
  - Comparable in precision to KOTO Step 2, with complementary technique (high vs. low energy) and different systematics
- $K_L \longrightarrow \pi^0\nu\nu$ is a difficult measurement
  - 2 efforts are justified to ensure precision measurement of the BR!