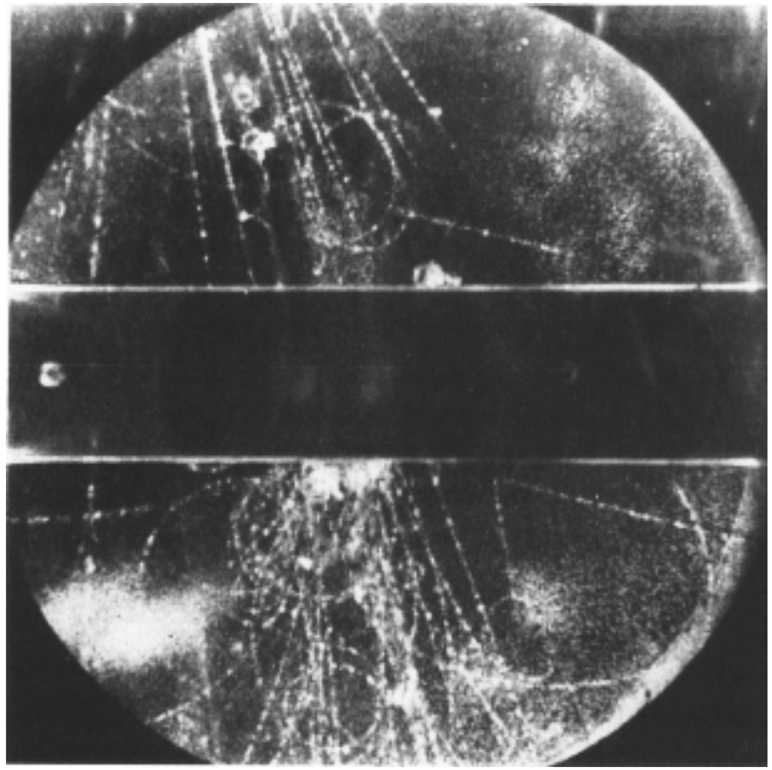
Beauty 2013, 14th International Conference on B-physics at Hadron Machines
Bologna, Italy

The "wrong flavor" -topics on Kaon physics-

Barbara Sciascia - LNF/INFN

Kaon physics, the "wrong" flavor?

Kaon decays have played a key role in the shaping of SM from the discovery of until today: the introduction of strangeness, the parity violation, the quark mixing, the discovery of CP violation, the suppression of FCNC and the GIM mechanism,...



Kaon decays involve an intricate interplay between weak, electromagnetic and strong interactions. A major theoretical challenge has to do with the intrinsically non-perturbative nature of the strong interactions in kaon physics.

Even in the "B physics age", Kaon physics continues to be a good playground to investigate flavor dynamics in constraining physics beyond the SM.

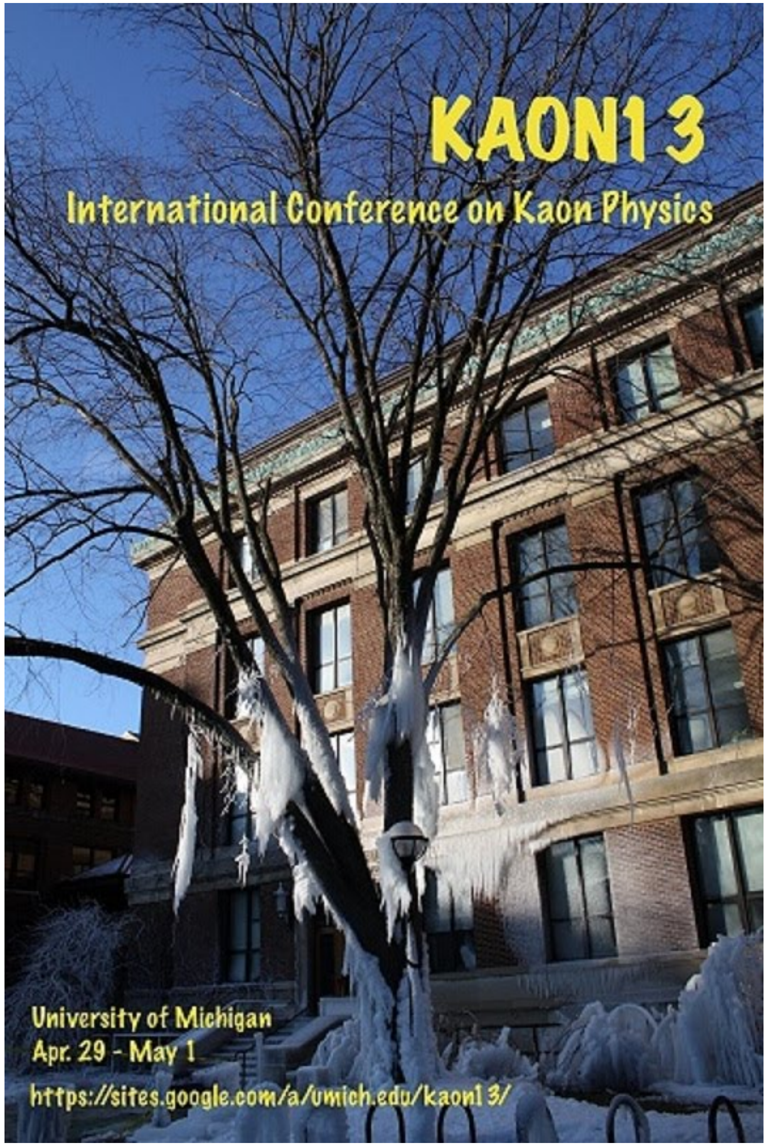
Kaon physics

<u>My outline</u>:
- CP violation and beyond.
- R_K=$K^+e2/K^+\mu2$: KLOE, NA62, T-REK
- $K \to \pi\nu\nu$: NA62, ORKA, K0TO,…
- From WG1 at CKM 2012, mainly Vus.

- A **theoretical** comprehensive survey of K decays allowed in the SM with BF of at least 10^{-11}: V.Cirigliano et al. arXiv:1107.6001v3 [hep-ph].

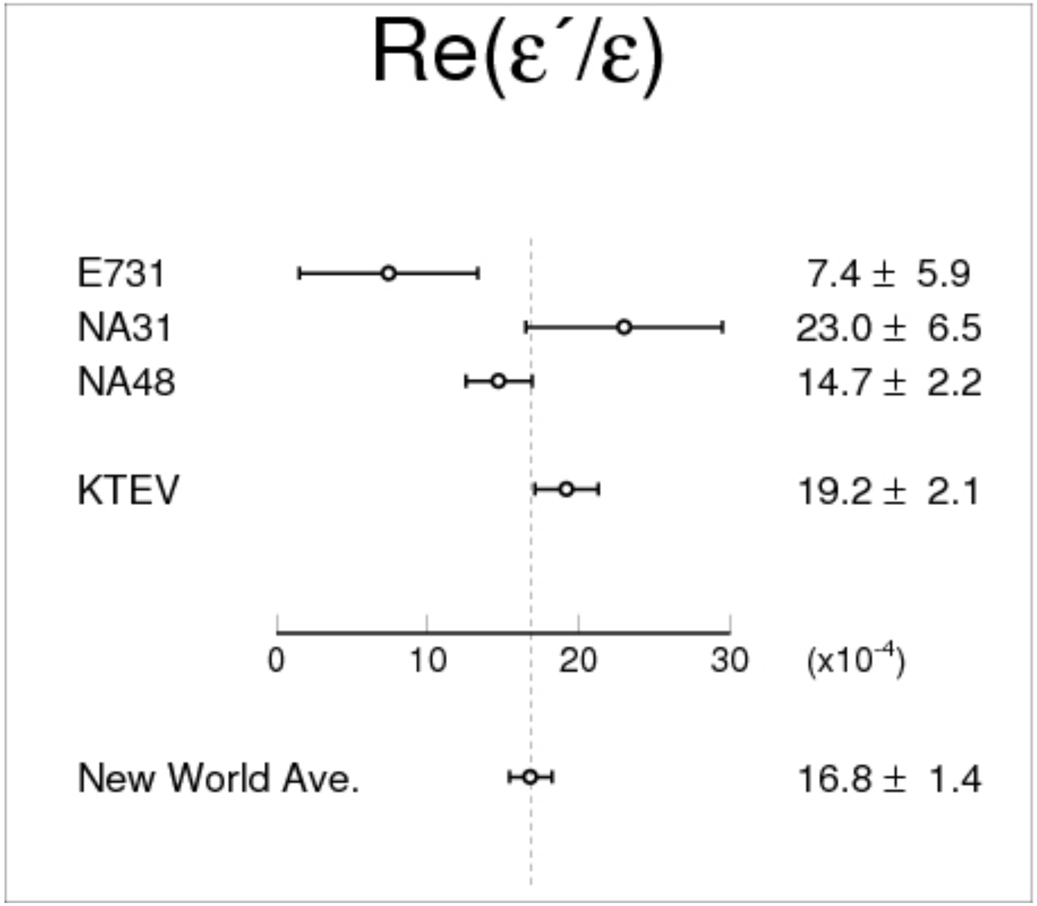
- A **complementary experimental** survey: A. Sergi at PIC2012, arXiv:1303.0629v1 [hep-ex]

… and don't **miss** **next KAON Conference** held in Ann Arbor, Michigan (USA) from April 29-May 1



CP violation

CPV: indirect (or in the mixing, ε) or direct (or in the decay, ε')

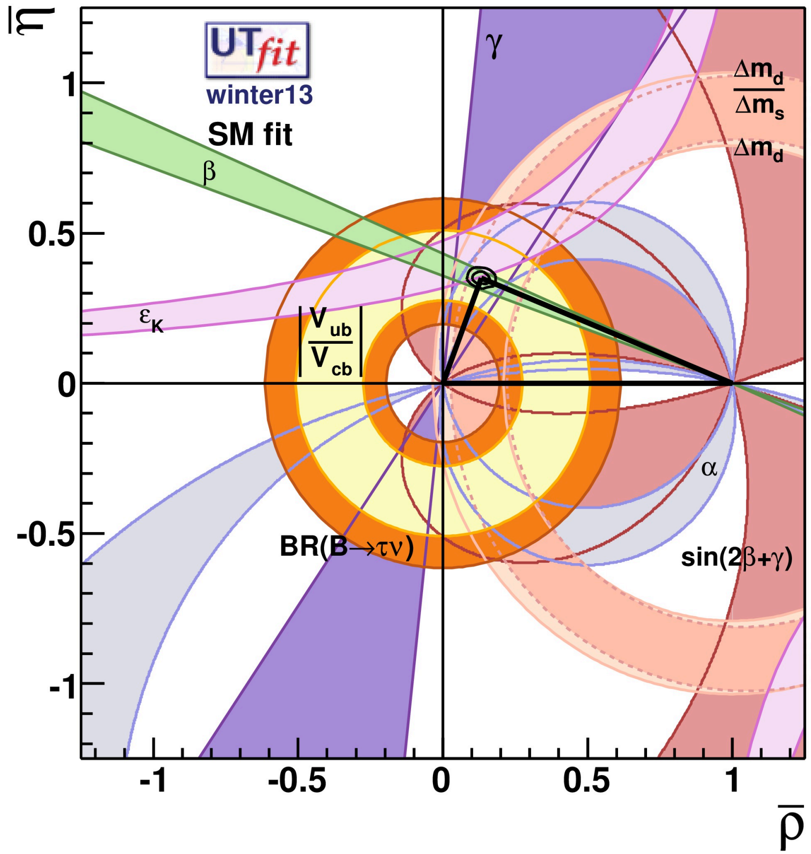


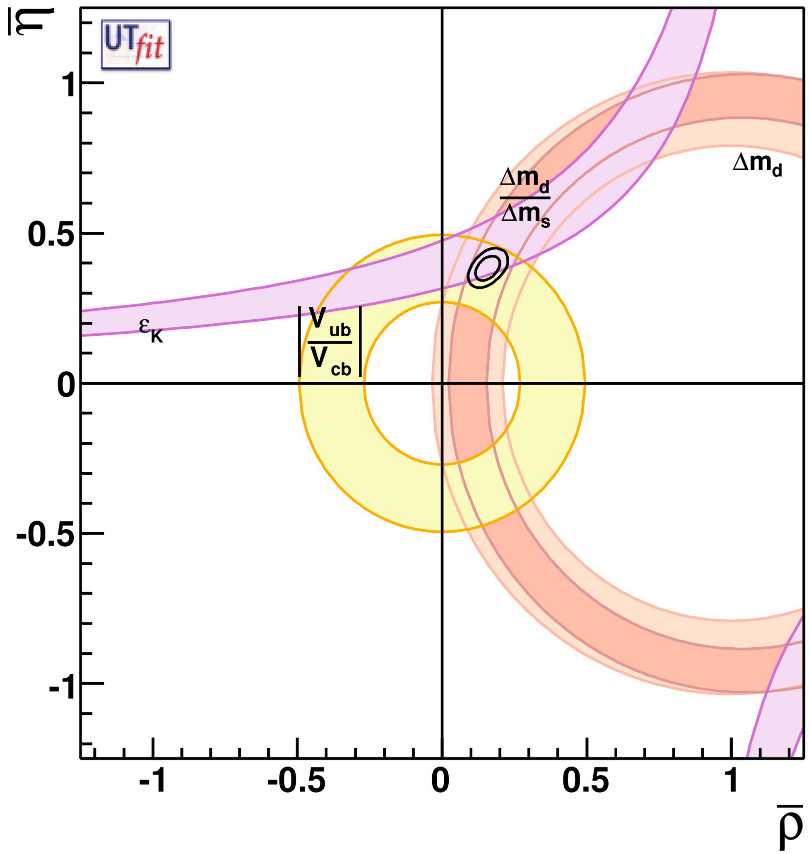
In the SM, all described by the CKM mechanism.

- ε measured since 60s
- ε' /ε have to wait the end of 90s.

CPV legacy from KTeV and NA48 exp: first confirmation of CKM picture, ε' /ε measurement (12% accuracy), ε_K, CPT,…

Reasonably precise data, but not impressive impact on UT. SM: $(1.9\pm0.2)\times10^{-3}$



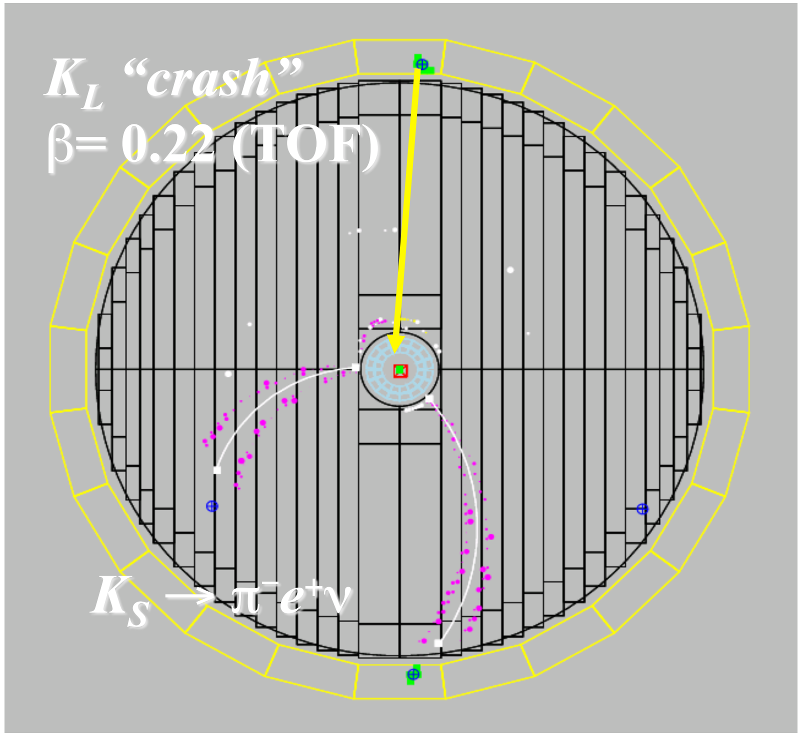


Waiting for Lattice breakthrough (from arxiv:1206.5142[hep-lat] RBC and UKQCD):
"We anticipate that a complete calculation of CP violation in K ππ decay within the SM will be achieved before the fiftieth anniversary of its original discovery."

KLOE experiment at DaΦne

e^+e^- collider, cm energy: **$\sqrt{s} \sim m_\phi$=1019.4 MeV**
Cross section for ϕ production at peak: **$\sigma_\phi \sim$ 3.1 μb**

- KLOE data taking completed (2001/5):
2.5 fb^{-1} integrated at $\sqrt{s}=M(\phi)$.



Now, novel collision scheme: (at least) L ~ ×3. Resume of data taking foreseen for next June 2013

- $K_S K_L$ (K^+K^-) pairs emitted ~back to back, p~110 MeV (~127 MeV)
- Identification of $K_{S,L}$ ($K^{+,-}$) decay (interaction) tags presence of $K_{L,S}$ ($K^{-,+}$)
- Almost pure $K_{S,L}$ and $K^\pm$ beams **of known momentum**.

$K_S \to \pi^0\pi^0\pi^0$ at KLOE

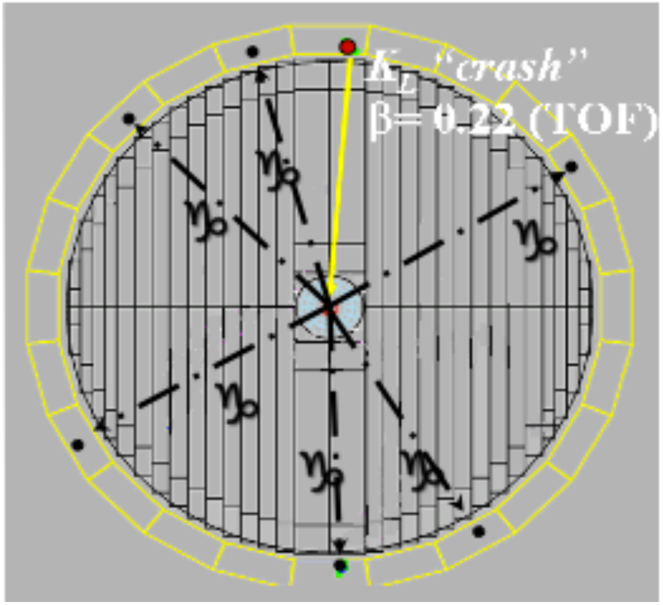
$3\pi^0$ is pure CP=−1 state; observation of $K_S \to 3\pi^0$ is an unambiguous sign of CPV in mixing and/or in decay

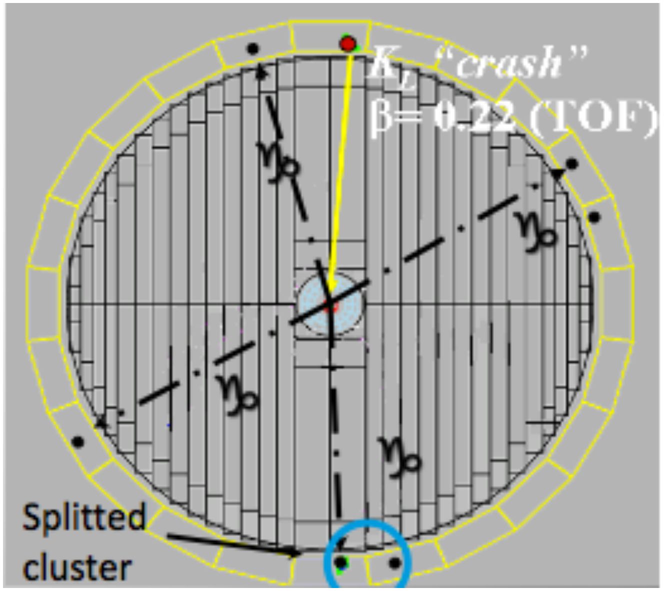
SM: BF($K_S \to \pi^0\pi^0\pi^0$) = **1.9×10^{-9}.**

Existing BF($K_S \to \pi^0\pi^0\pi^0$) measurements:
- SND (direct search) 1999: < **1.4×10^{-5}**
- NA48 (from interference) 2004: < **7.4×10^{-7}**
- KLOE (direct search) 2005: < **1.2×10^{-7}**

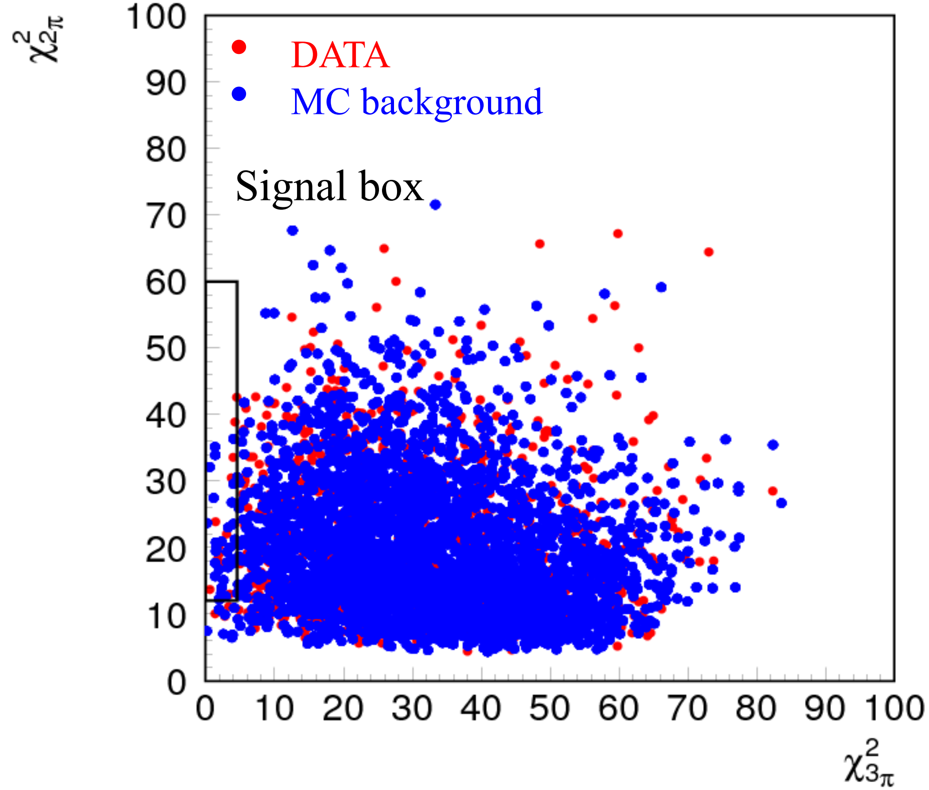
K_L interactions in the calorimeter to tag K_S decay and 6 prompt photons required
Analysis based on photon counting and kinematic fit in the $2\pi^0$ and $3\pi^0$ hypothesis
Dominant background : $K_S \to 2\pi^0$ + 2 fake clusters.

Normalized to $N_{2\pi0}$

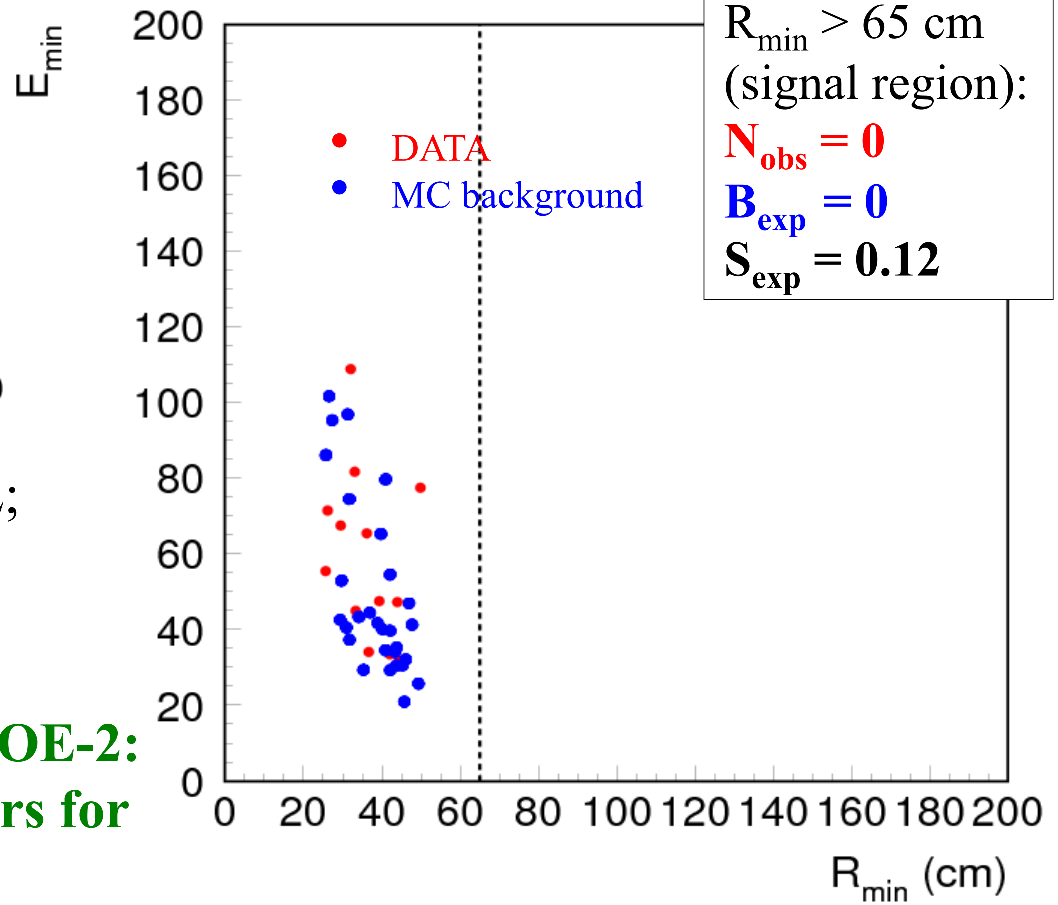




$K_S \rightarrow \pi^0\pi^0\pi^0$ at KLOE



<u>Change wrt the 2005 analysis</u>:
- 2004-2005 data sample: ×4
- improved clustering algorithm.
- hardening K_S tagging algorithm.



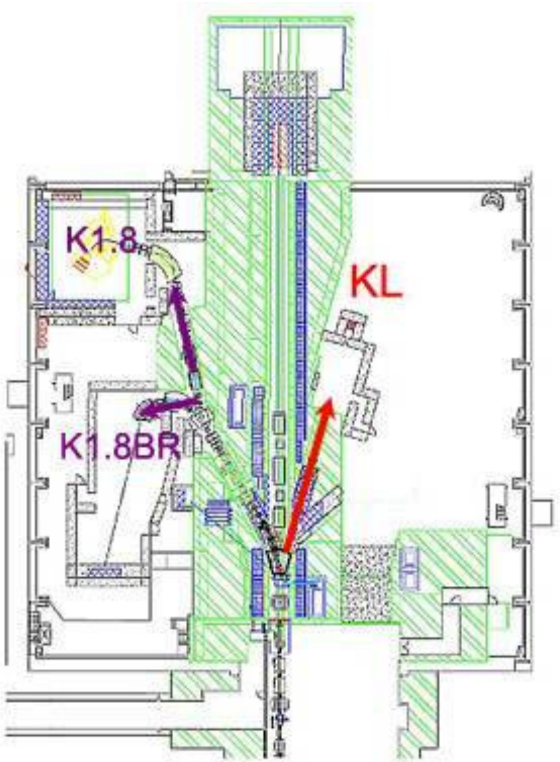
$R_{min} > 65$ cm (signal region):
$N_{obs} = 0$
$B_{exp} = 0$
$S_{exp} = 0.12$

$BF(K_S \rightarrow \pi^0\pi^0\pi^0) < 2.6 \times 10^{-8}$ @90% CL;
$|\eta_{000}| < 0.0088$ @ 90%CL
arXiv: 1301.7623 [hep-ex]

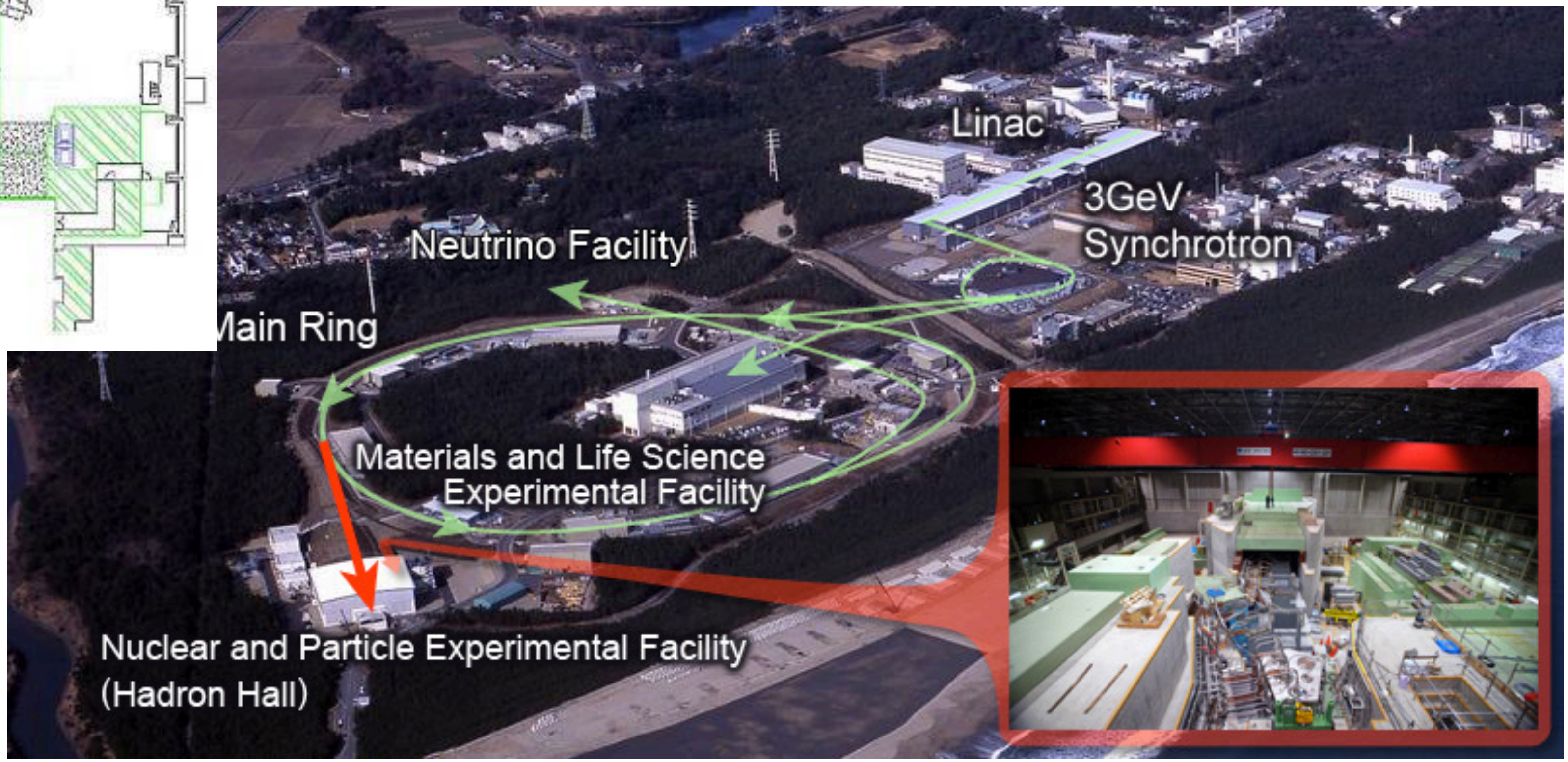
First SM observation feasibility at KLOE-2: new inner tracker, forward calorimeters for better coverage near IP

J-PARC

Japan Proton Accelerator Research Complex: a series of proton accelerators and the experimental facilities that make use of the high-intensity proton beams.



30 GeV/c, 100 kW reached, upgrade to 1 MW
Hadron-Hall: 3 Kaon lines (two separated K+, one K^0)



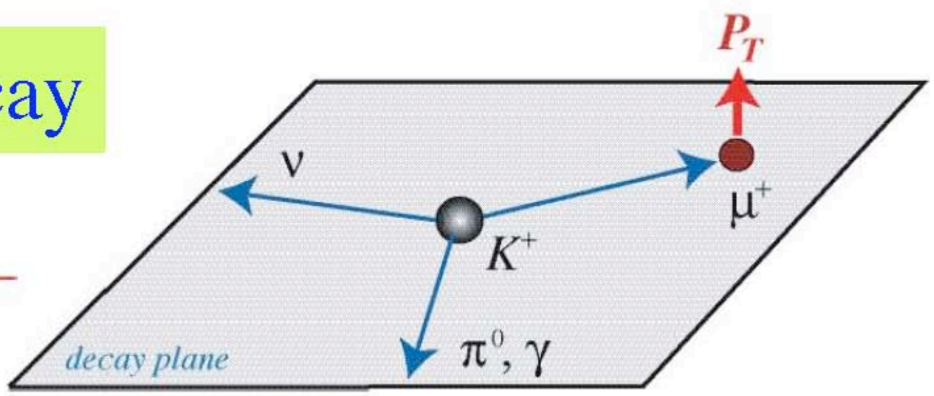
J-PARC, March 2011 earthquake damages

J-PARC, TREK (E06): T violation

Time
Reversal
Experiment with
Kaons

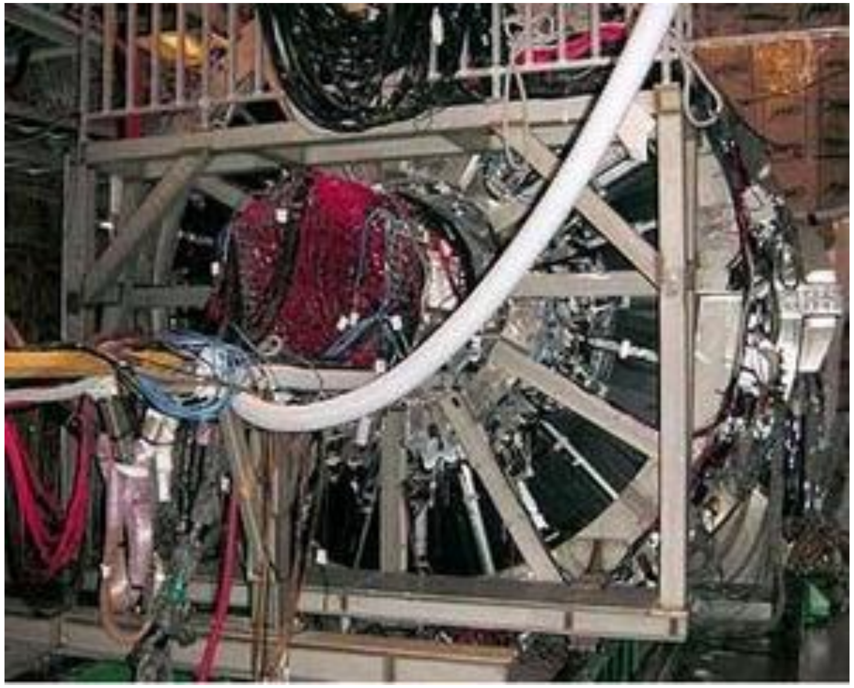
$K^+ \rightarrow \pi^0 \mu^+ \nu$ decay

$$P_T = \frac{\sigma_\mu \cdot (p_{\pi^0,\gamma} \times p_{\mu^+})}{|(p_{\pi^0,\gamma} \times p_{\mu^+})|}$$



- Original proposal by J.J.Sakuray: in $K^+\mu 3$ decay measure the transverse muon polarization: **null at 1st order in SM; higher order loop effects at <10^{-6}**.
- TREK aims at 10^{-4} sensitivity
- Non-zero P_T: T-violation; also an excellent NP probe with many models allowing for sizable P_T.

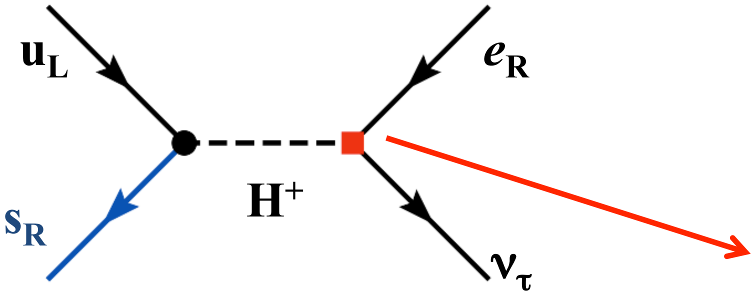
- detector: upgrade of earlier experiment E246 used at the KEK: $P_T=-0.0017(23)_{STAT}(17)_{SYST}$.
- **data taking ~2016**



$R_K = \Gamma(K^{\pm}_{e2})/\Gamma(K^{\pm}_{\mu2})$ as New Physics probe

• SM prediction with 0.04% precision, benefits of cancellation of hadronic uncertainties (no f_K): **R_K=2.477(1)×10^{-5}** [*Cirigliano Rosell arXiv:0707:4464*].

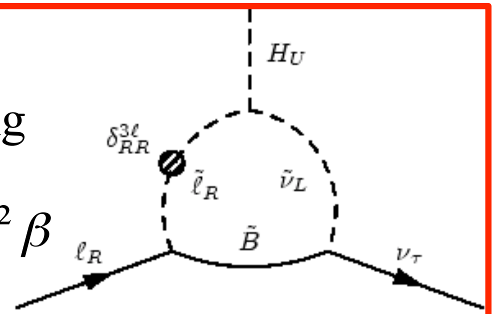
• Helicity suppression can boost NP [*Masiero-Paradisi-Petronzio PRD74(2006)011701*].



$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \approx \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$

LFV from loop generates an effective $eH^+\nu_\tau$ coupling

$$eH^+\nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$



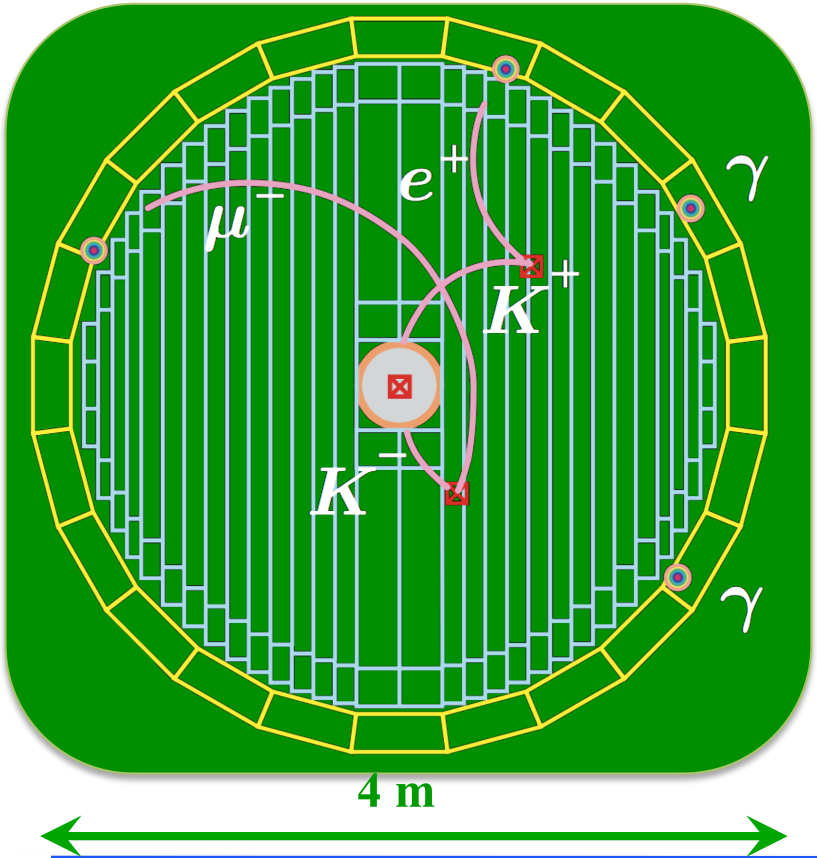
$$R_K^{LFV} \approx R_K^{SM} \left(1 + \frac{m_K^4}{m_H^4} \frac{m_\tau^2}{m_e^2} \left|\Delta_R^{31}\right|^2 \tan^6\beta\right)$$

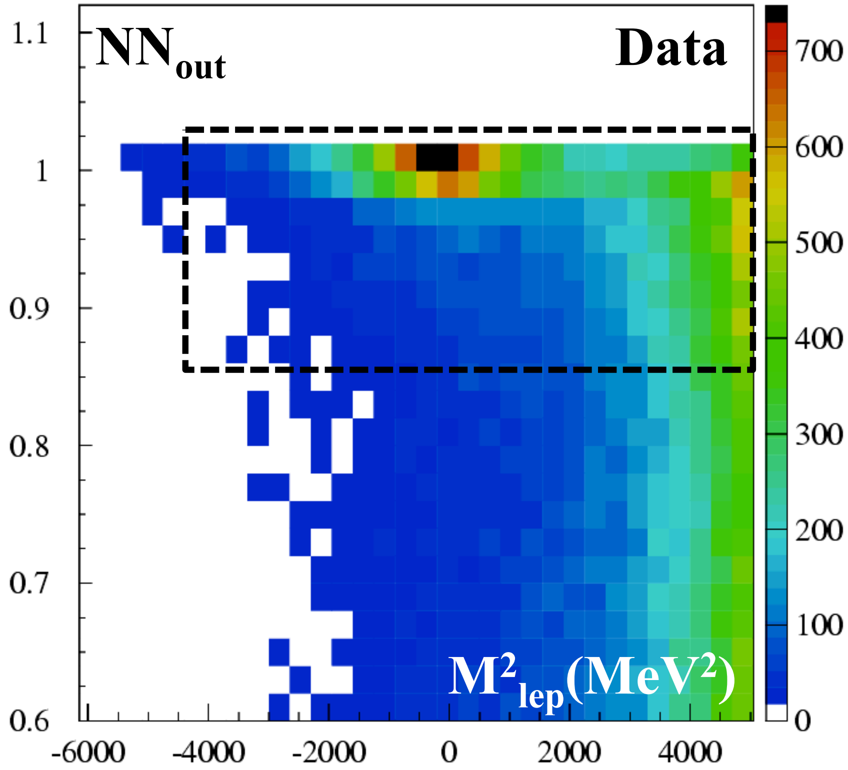
LFV can give **O(1%) deviation from SM (Δ_R^{31}~5×10^{-4}, tanβ ~40, m_H~ 500 GeV)**

• Experimental accuracy on R_K (before KLOE and NA62 results) at 5% level.
• Measurements of R_K can be very interesting, **if error at 1% level or better**.

R_K from KLOE (2009)

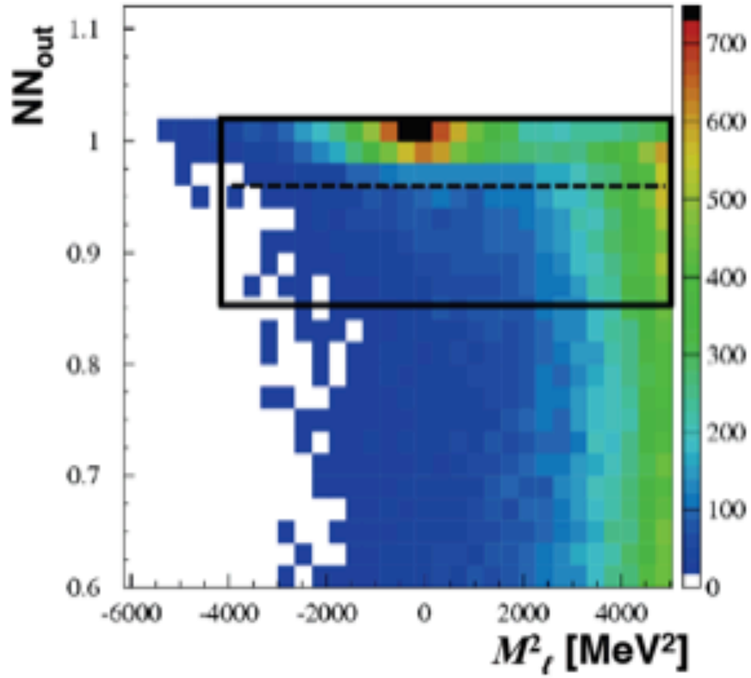
- Data sample (2001–2005): 2.5 fb^{-1}
- 560M $K_{\mu 2}$ decays analyzed
- Identify kink in fiducial volume of DC
- Tight kinematic & track quality cuts

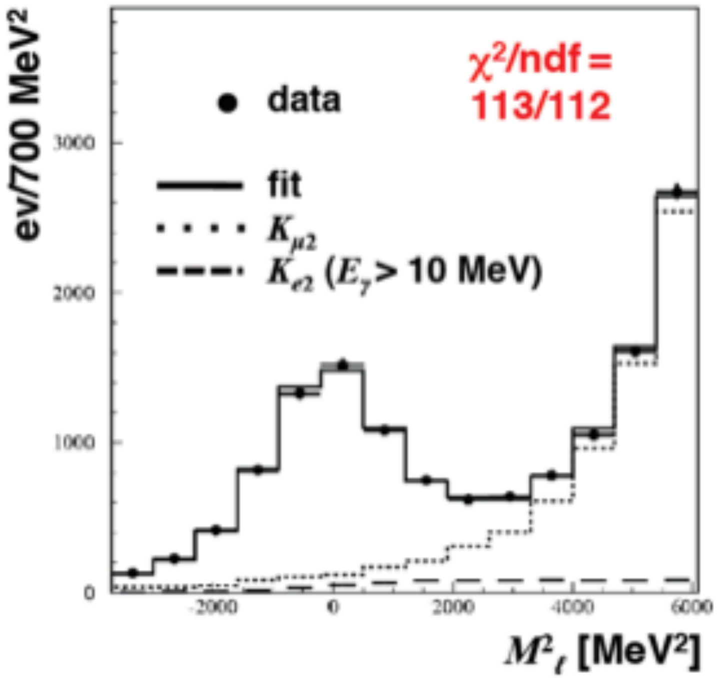




- $M^2_\ell = (E_K - p_{\text{miss}})^2 - p^2_\ell$ with $m_{\text{miss}} = m_\nu$
- Neural network (NN) for e/μ ID in calorimeter: E/p, TOF, shower profile
- Count K_{e2} events via 2-dim likelihood fit in NN$_{out}$ vs. M^2_ℓ

R_K from KLOE (2009)





K^+_{e2} **fit**
M^2_ℓ projection
NN$_{out}$ > 0.96

Obtain
7060 ± 102 K^+_{e2}
6750 ± 101 K^-_{e2}

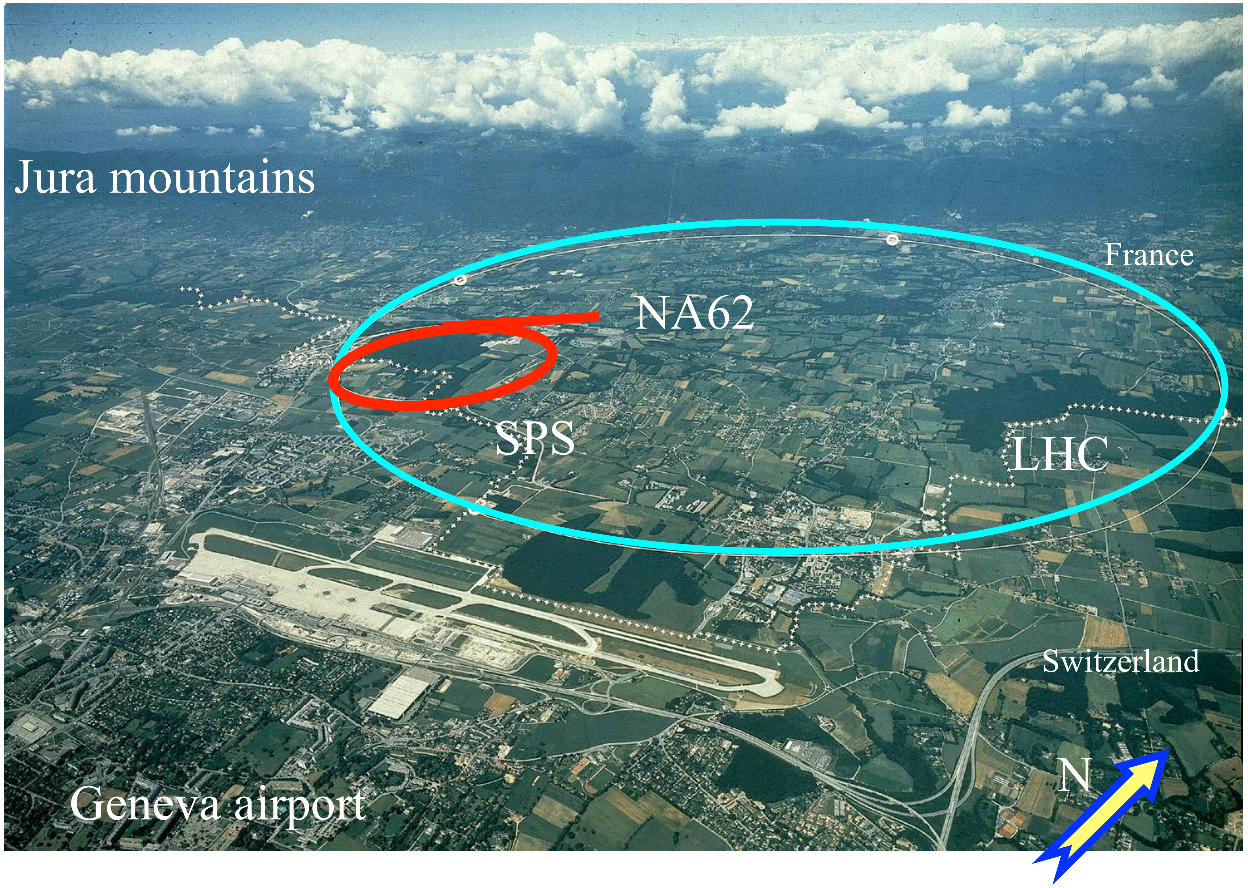
Source of uncertainty	$\delta R_K/R_K$ (%)
Statistical	1.0
$K_{\mu2}$ subtraction	0.3
$K_{e2\gamma}$ (SD+)	0.2
Reconstruction efficiency	0.6
Trigger efficiency	0.4
Total	**1.3**

KLOE
EPJC 64 (2009)

13.8k K_{e2} candidates
16% background

$$R_K = 2.493(25)_{st}(19)_{sy} \times 10^{-5}$$

NA62 experiment at CERN



Kaon Physics @ CERN SPS:

1995-2001: **NA48** ε'/ε
2002: **NA48/1** $K_S \rightarrow l^+l^-$
2003-2004: **NA48/2** CPV $K^\pm$
From 2007: **NA62**

NA62

2007-2008 R_K measurement

2007-2011 R&D for $K^+ \rightarrow \pi^+\nu\nu$
2011-2014 Construction and installation of the new detectors

2012 $K^+ \rightarrow \pi^+\nu\nu$ Technical run

2014 $K^+ \rightarrow \pi^+\nu\nu$ Physics run

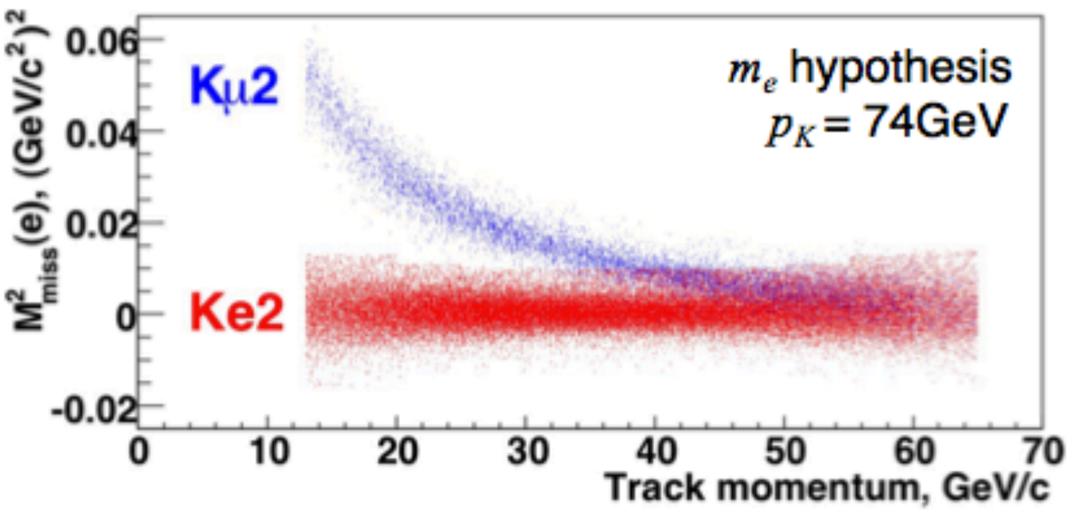
R_K : Ke2 and Kμ2 selection

Kinematic identification

$M^2_{miss} = (p_K - p_\ell)^2$

Use avg $\mathbf{p}_K$ measured with $K_{\pi 3}$

Require $p_K < 30$ GeV

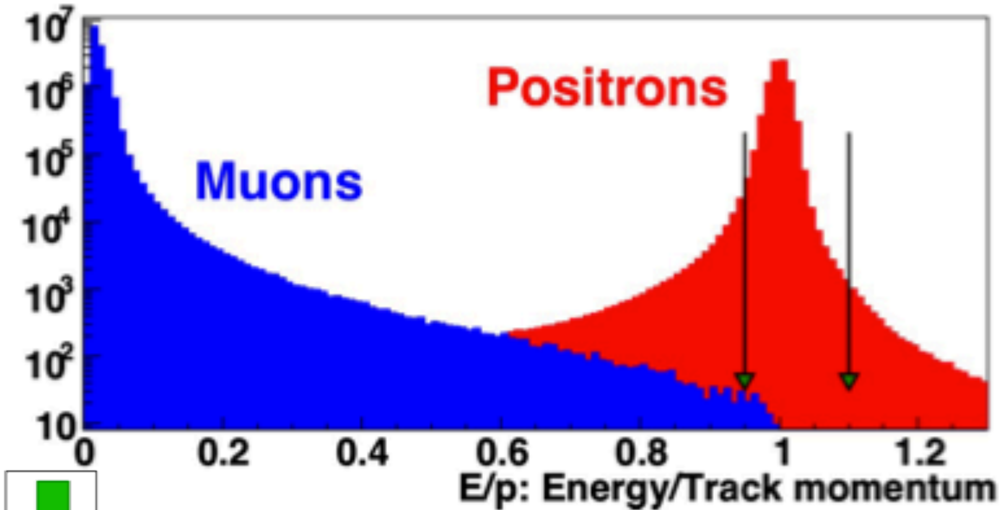


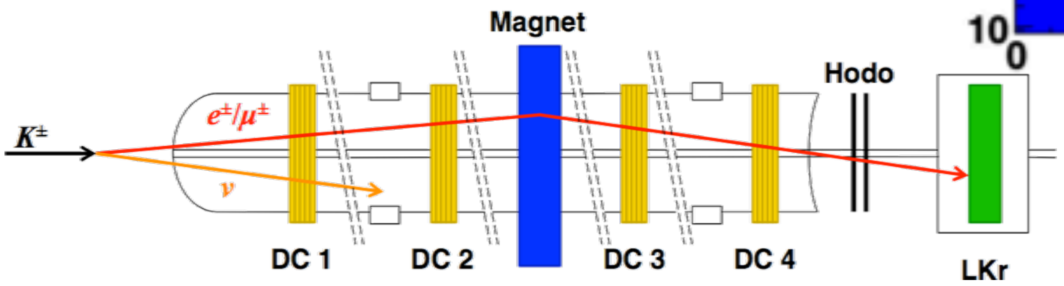
***e*/*μ* discrimination in LKr**

e (0.90 to 0.95) $< E/p <$ 1.10

μ $E/p <$ 0.85 for muons

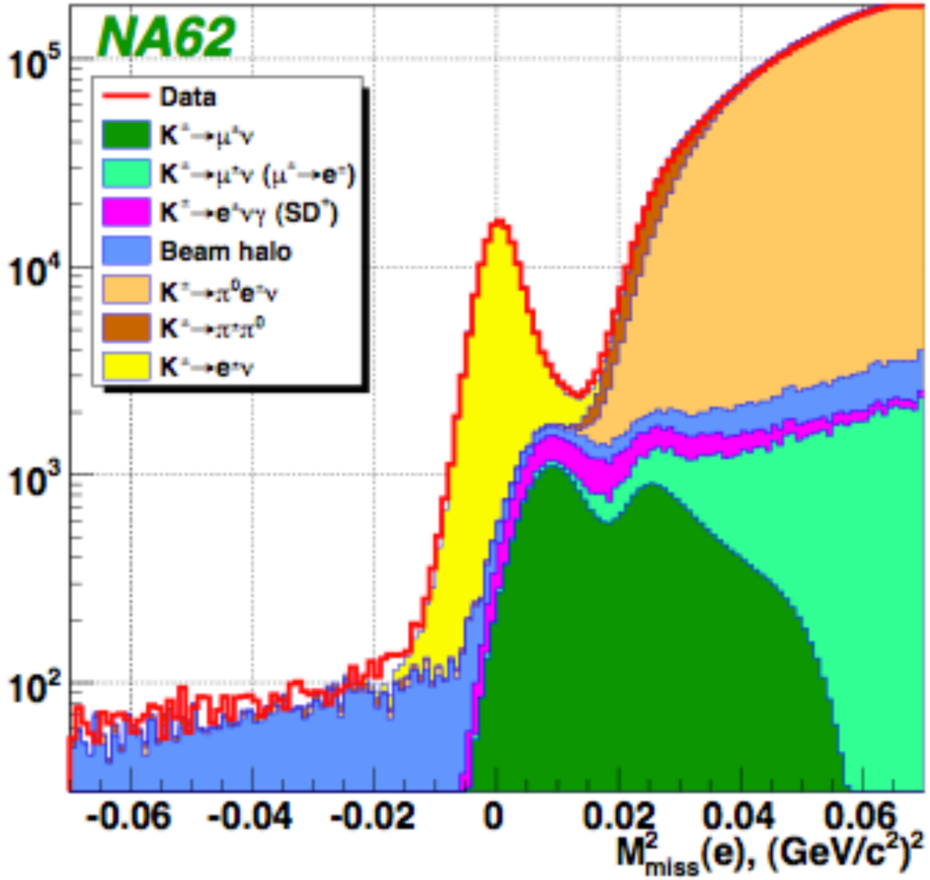
μ suppression ~10^6

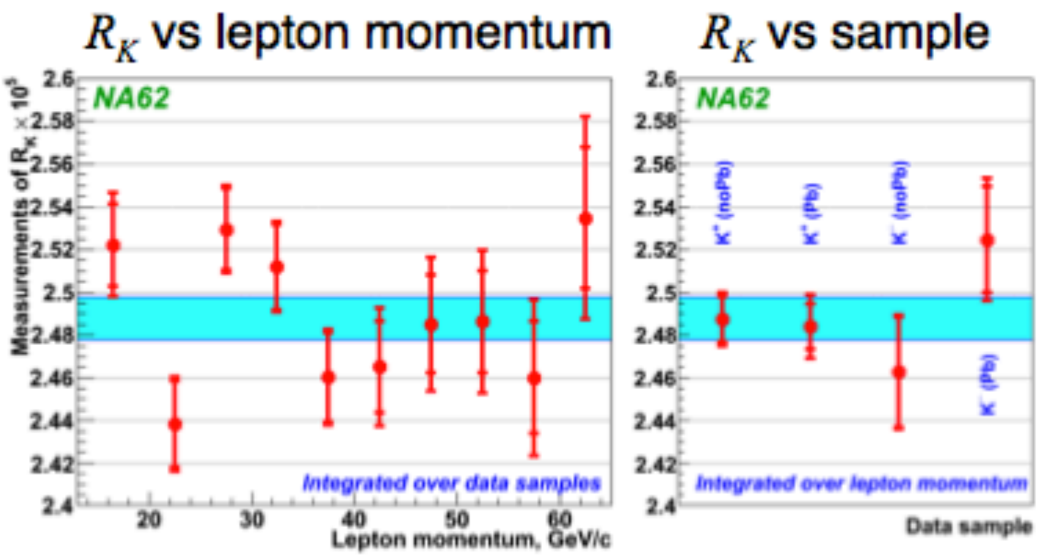




K± beams: P_K = 75 (2) GeV

R_K final result (full 2007 data set)



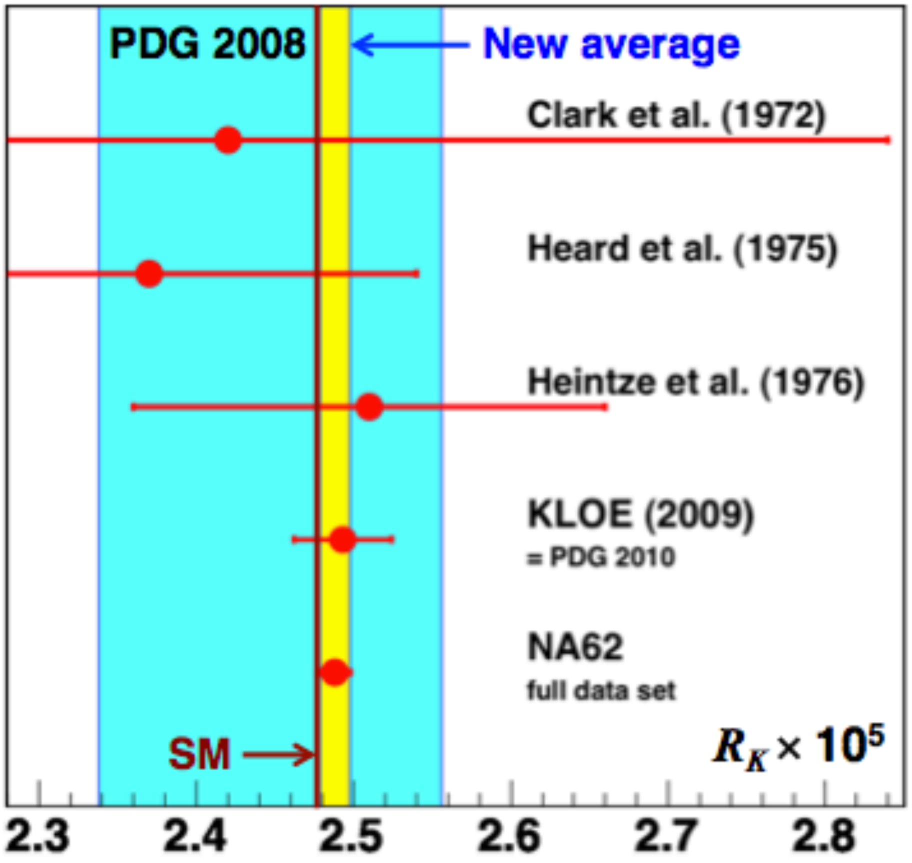


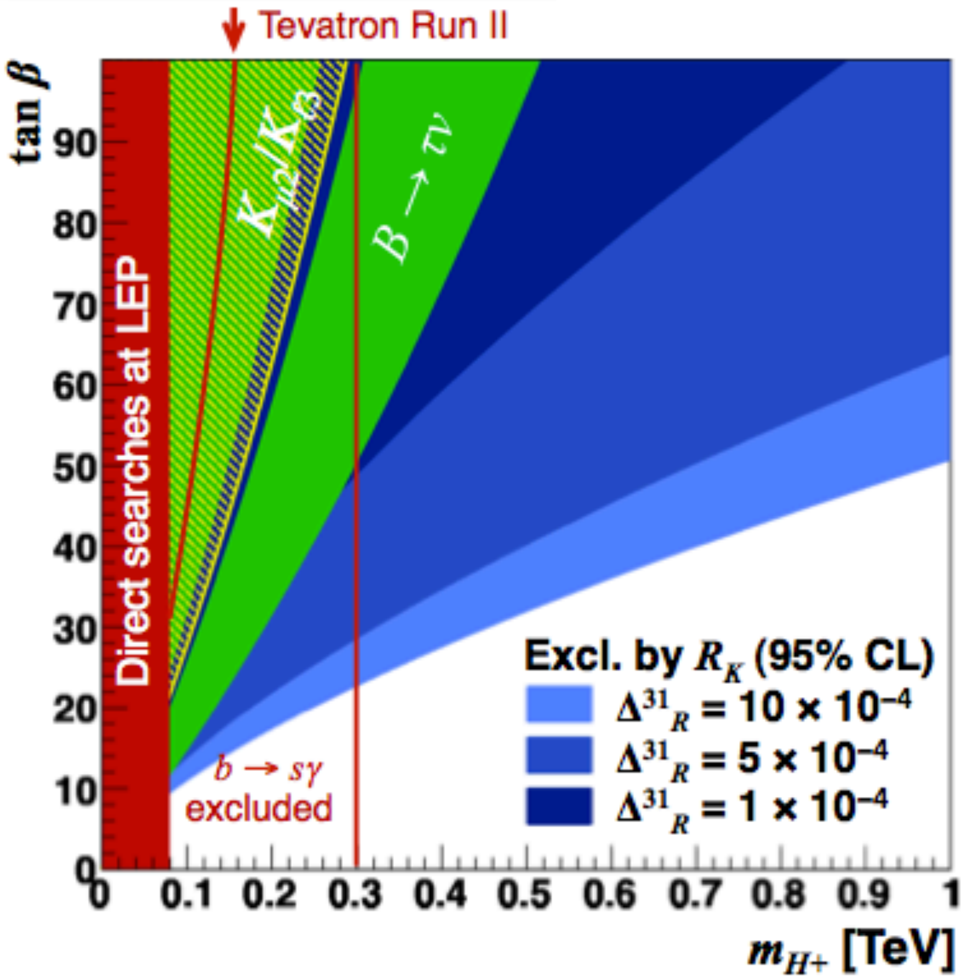
Fit to 40 measurements gives χ^2/ndf=47/39
4 data samples × 10 momentum bins

146k K_{e2} candidates (mainly K^+)
Background: B/(S+B)=(10.95±0.27)%
Electron ID efficiency: (99.28±0.05)%

$R_K = 2.488(7)_{STAT}(7)_{SYST} \times 10^{-5}$;
full data set: **Phys.Lett. B719 (2013) 326-336**
[Includes previous PLB result, 40% 2007 data set]

R_K world average





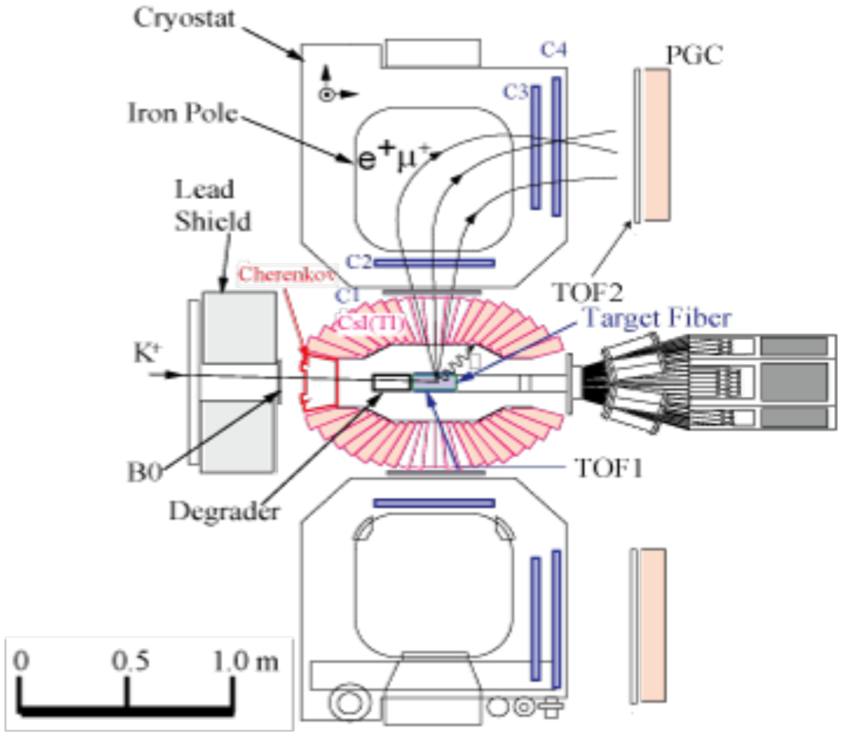
Average	$R_K \times 10^5$	$\delta R_K/R_K$
PDG 2008	2.447±0.109	4.5%
Current	**2.488±0.009**	**0.4%**

MSSM with R parity

$$R_K^{\mathrm{LFV}} \approx R_K^{\mathrm{SM}} \left[1 + \frac{m_K^4}{m_H^4} \frac{m_\tau^2}{m_e^2} |\Delta_R^{31}|^2 \tan^6\beta \right]$$

R_K near future: J-PARC E36 (TREK)

Using a subset of TREK detector and stopped kaons from K1.1BR line, E36 plans to measure R_K; **aims at 2×10^{-3} (stat) and 2×10^{-3} (syst) accuracy**.

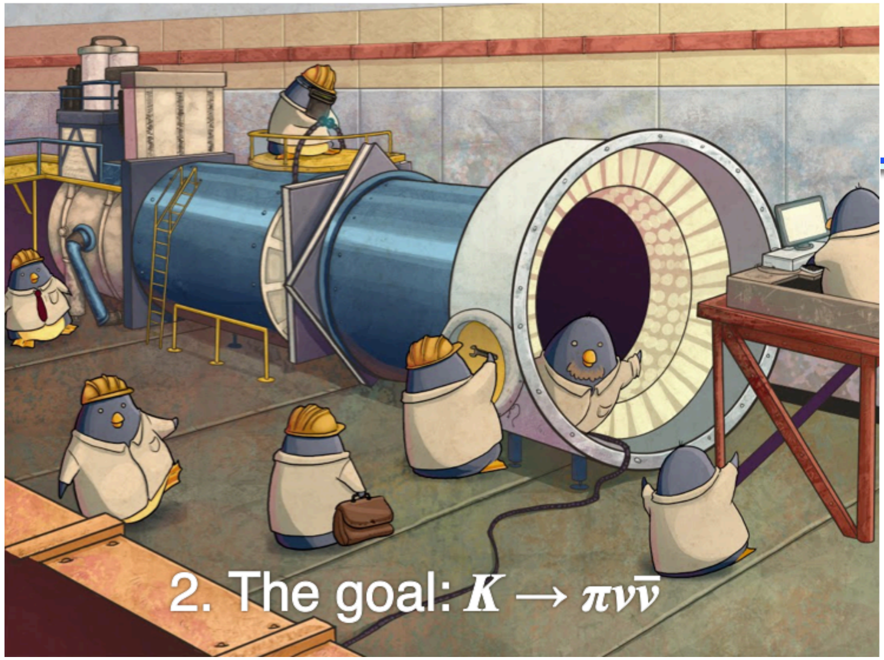


"TREK collaboration remains interested in executing E06 if the accelerator beam power will be growing faster."

	2012	2013	2014	2015
Detector				
Target	Assembl Test	Beam test		
cost		(0 k$)	(0 k$)	0
TOF	Prototype Test	Mass production		
cost (k¥)		5,720	8,374	0
Aerogel C	Prototype Test	Mass production		
cost (k¥)		5,920	4,180	0
PGC	Prototype	Test Preparation		
cost (k¥)		2,890	1,680	0
GEM (C1)	Design	Production	Test	
cost		(250 k$)	(100 k$)	
MWPC (C2–C4)		Repair etc.		
cost (k¥)		7,020	0	0
CsI(Tl) readout	Test	Preparation	FADC productio	
cost (k¥)		1,630	7,200	0
Collimator etc.		Design Producti		
cost (k¥)		0	340	0
Electronics/DAQ	FADC development	Production		
cost (k¥)		10,430	7,380	0
Assembly			Detector assembly	
cost (k¥)		0	3,030	0
Total detector cost in Japan (k¥)		33,610	32,184	running cost
SC spectrometer				
Magnet		Installation		
He cryogenics		Building Installation		
System			Test	
Engineering run			Engineering run	
Experiment			Run	

From "Progress Report of P36, July 2012":
quite aggressive schedule to run E36 in a narrow restricted time window before the start of the COMET beam line installation:
- **final assembly in 2014**
- **run on fall 2014-spring 2015**

K→πνν in the SM



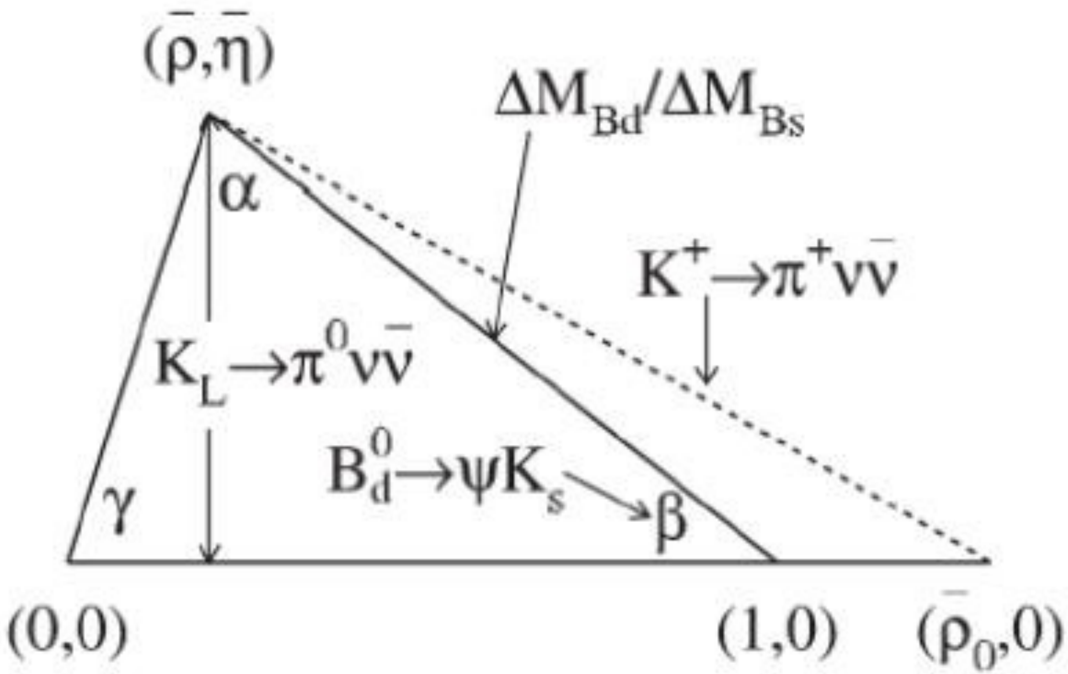
K: theoretical cleanliness unmatched, simple system, few decay channels

Extreme hard-GIM SM-suppressed FCNC decays: room for NP up to 10× SM.

Unique sensitivity to flavor couplings of BSM physics about to be produced at LHC

--- or ---

Sensitivity to extremely high NP scales in the unfortunate case that... (10% measurement of K→πυυ BR can probe 1000 TeV NP scale)



K→πνν and the UT

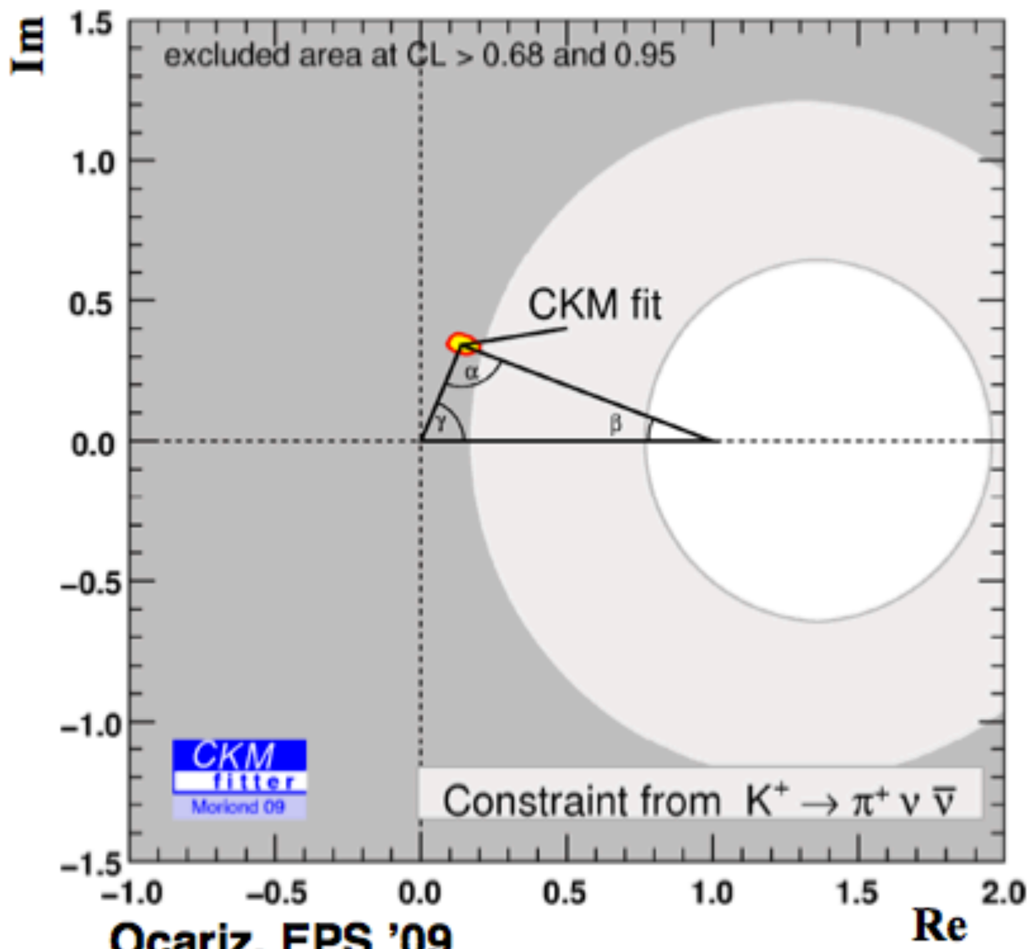
Uncertainty on SM predictions for $K \to \pi\nu\bar{\nu}$ BRs mostly from V_{CKM}

$BR_{SM}(K_L \to \pi^0\nu\bar{\nu}) \times 10^{11}$ $2.43 \pm 0.39_{par} \pm 0.06_{th}$		
V_{cb}	0.31	48%
$\bar{\eta}$	0.22	35%
X_t(QCD)	0.06	9%

$BR_{SM}(K^+ \to \pi^+\nu\bar{\nu}) \times 10^{11}$ $7.81 \pm 0.76_{par} \pm 0.29_{th}$		
V_{cb}	0.69	40%
$\bar{\rho}$	0.26	15%
$\delta P_{c,u}$	0.24	14%
X_t(QCD)	0.12	7%

Brod, Gorbahn, Stamou '11

CKM constraints from:
Current exp. value for BR($K^+ \to \pi^+\nu\bar{\nu}$)



Ocariz, EPS '09

K→πνν and the UT

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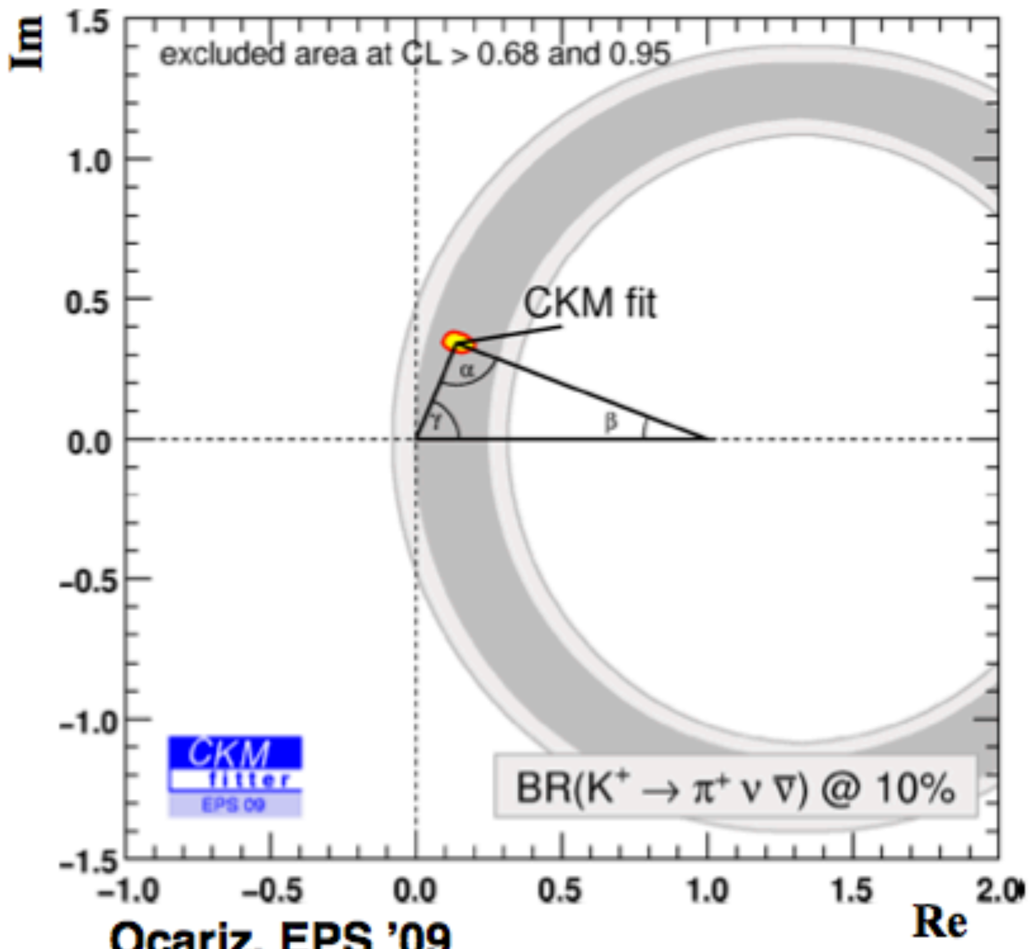
Brod, Gorbahn, Stamou '11

CKM constraints from:
$BR(K^+ \to \pi^+\nu\bar{\nu})$ to ±10%



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$K \to \pi\nu\nu$ and the UT

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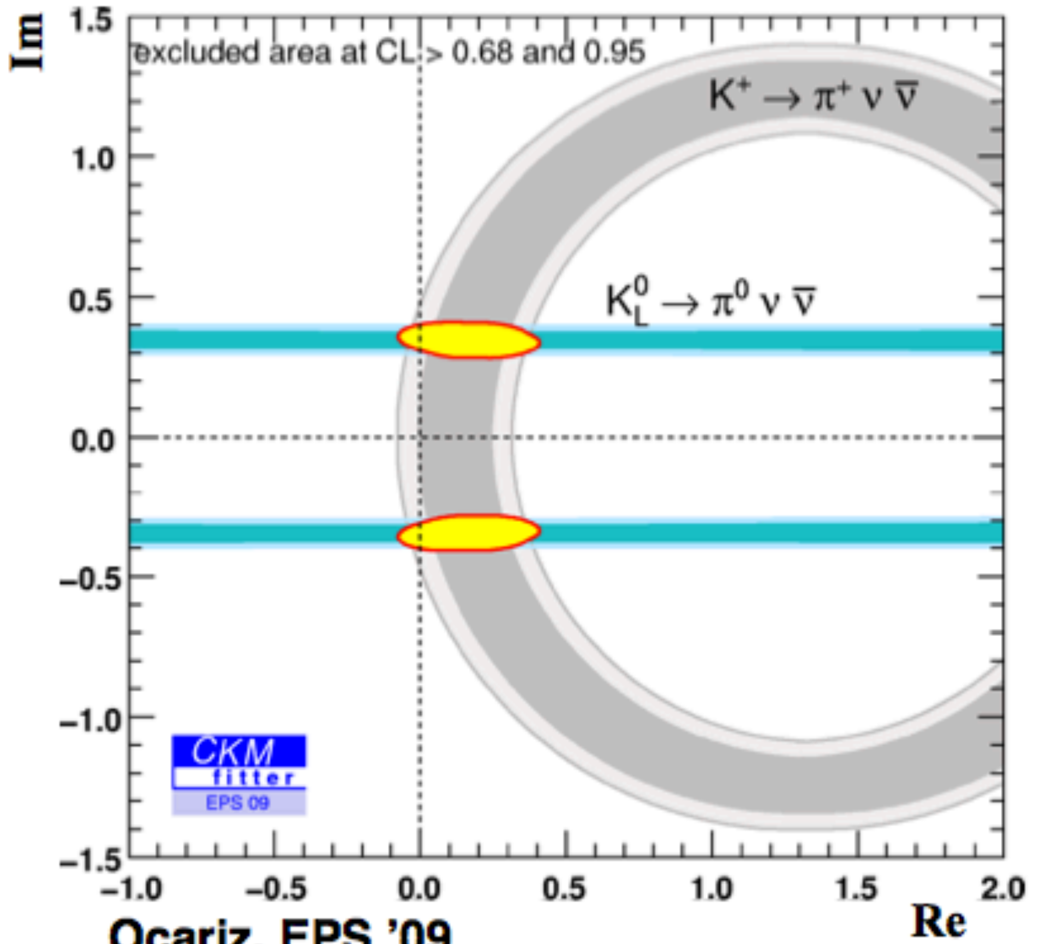
Brod, Gorbahn, Stamou '11

CKM constraints from:

$BR(K^+ \to \pi^+\nu\bar{\nu})$ to ±10%

$BR(K_L \to \pi^0\nu\bar{\nu})$ to 15%



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$K \to \pi\nu\nu$ and the UT

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

$BR_{SM}(K_L \to \pi^0\nu\bar{\nu}) \times 10^{11}$ $2.43 \pm 0.39_{par} \pm 0.06_{th}$		
V_{cb}	0.31	48%
$\bar{\eta}$	0.22	35%
X_t(QCD)	0.06	9%

$BR_{SM}(K^+ \to \pi^+\nu\bar{\nu}) \times 10^{11}$ $7.81 \pm 0.76_{par} \pm 0.29_{th}$		
V_{cb}	0.69	40%
$\bar{\rho}$	0.26	15%
$\delta P_{c,u}$	0.24	14%
X_t(QCD)	0.12	7%

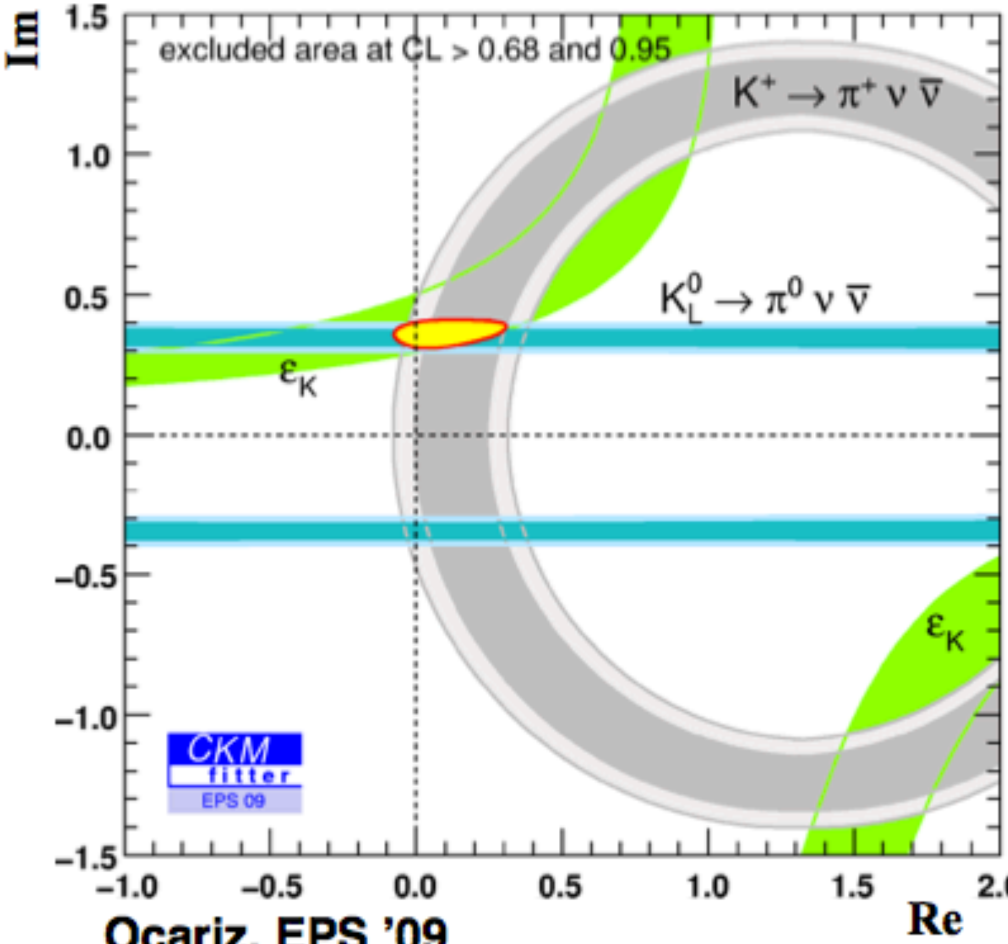
Brod, Gorbahn, Stamou '11

CKM constraints from:

$BR(K^+ \to \pi^+\nu\bar{\nu})$ to ±10%

$BR(K_L \to \pi^0\nu\bar{\nu})$ to 15%

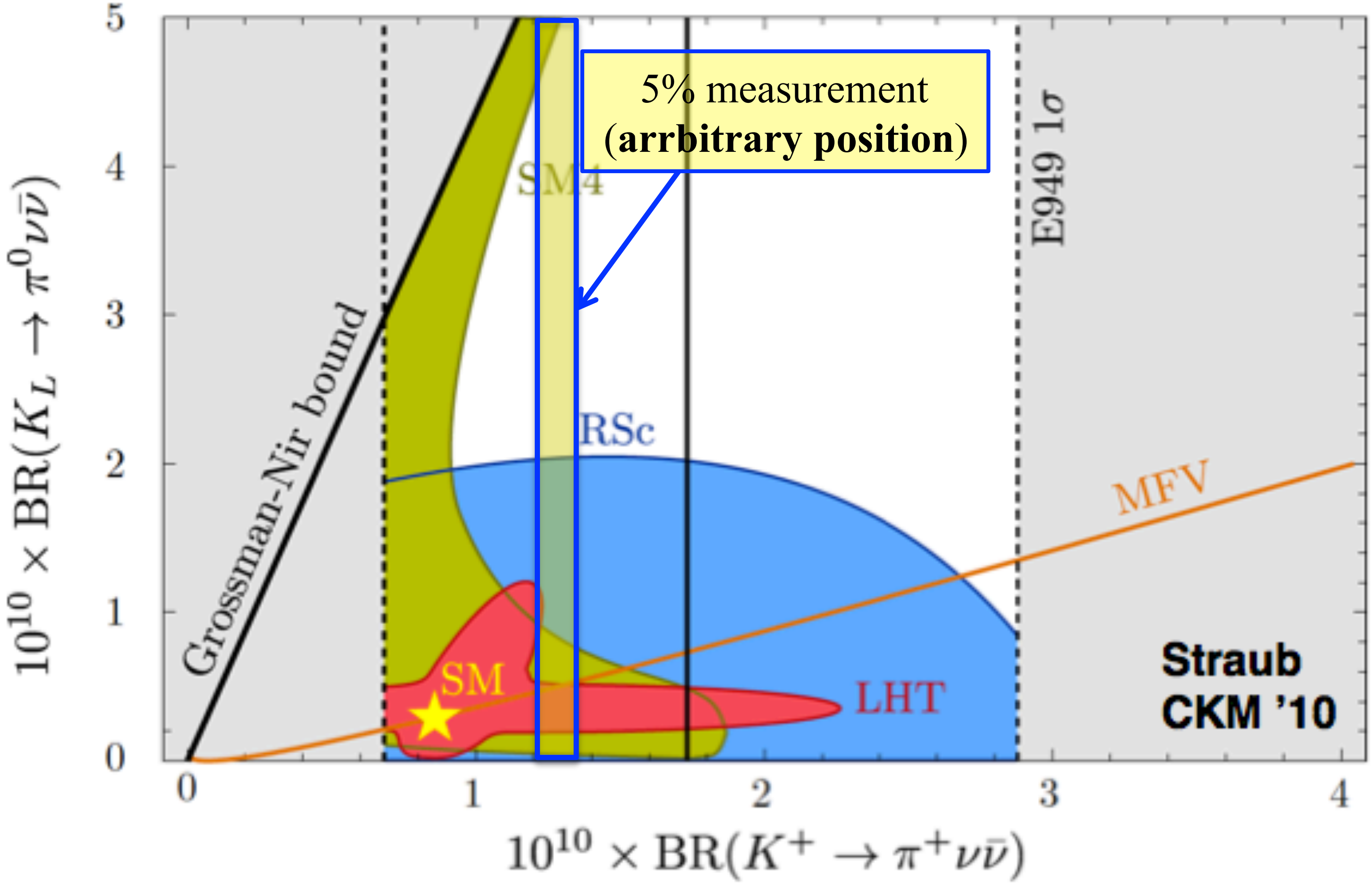
ε_K to resolve ambiguities



Ocariz, EPS '09

K→πνν and New Physics

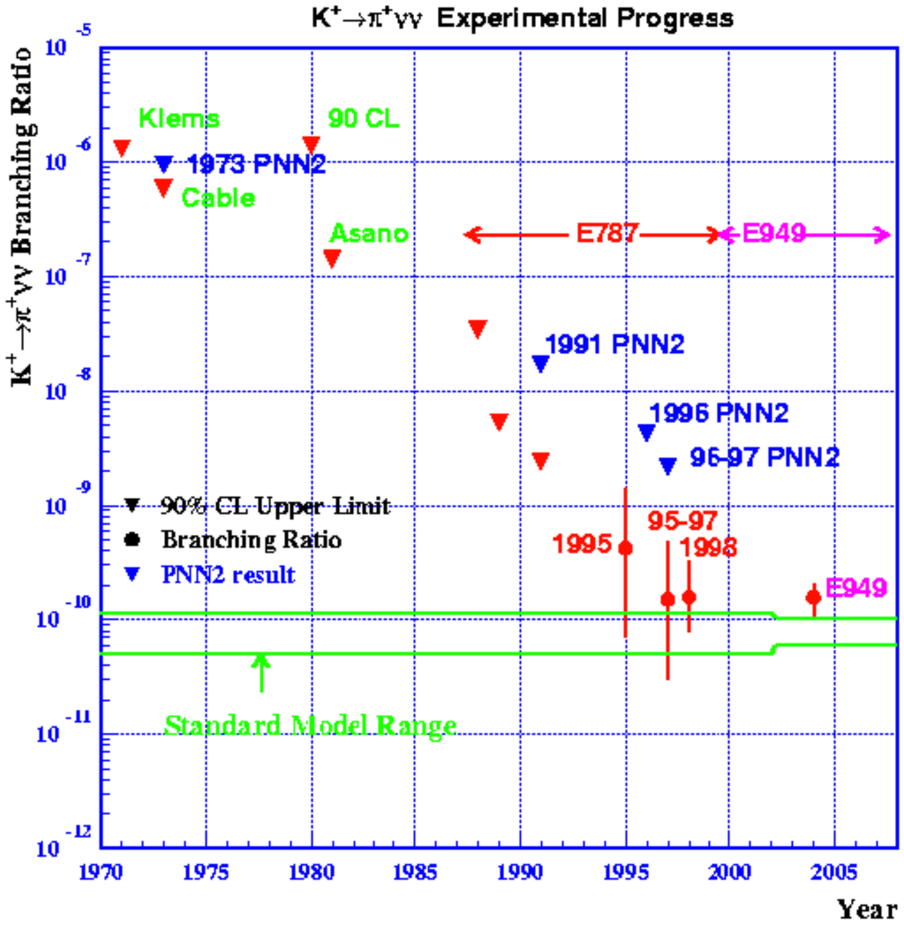
New physics affect BRs differently for different channels
Multiple measurements can discriminate among NP scenarios

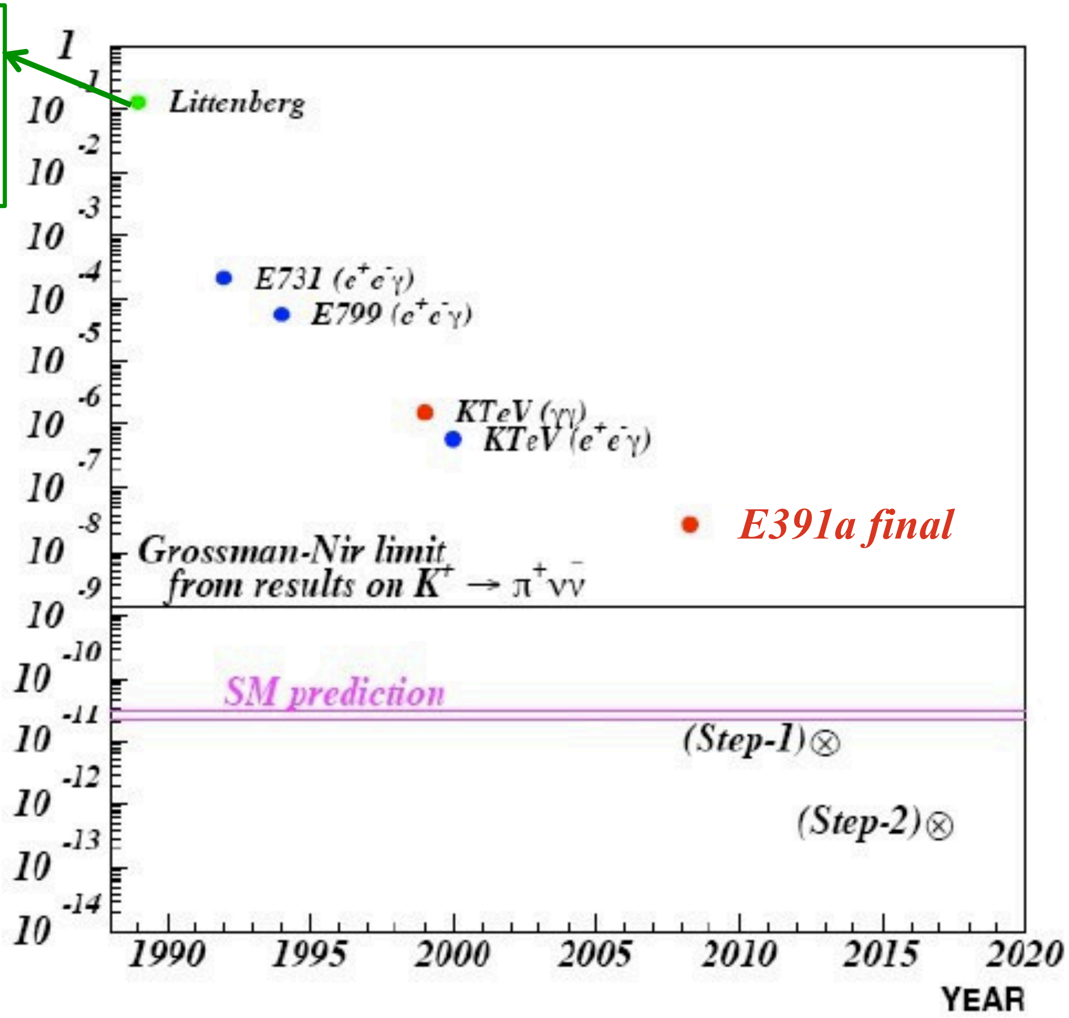


SM4: SM with 4^{th} generation (Buras et al. '10) **LHT:** Littlest Higgs with T parity (Blanke '10)
RSc: Custodial Randall-Sundrup (Blanke '09) **MFV:** Minimal flavor violation (Hurth et al. '09)

K→πνν: the long quest

"The best it can be said is that so far nobody demonstrated conclusively that the measurement is impossible".

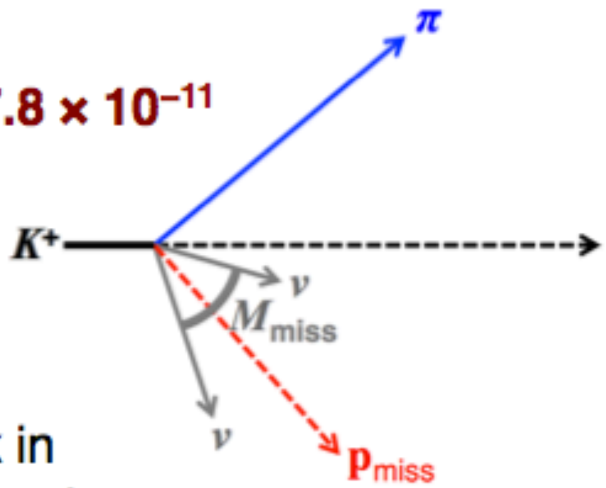




Two players in the near future: NA62 and (probably) ORKA

$K^+ \to \pi\nu\nu$: signal and background

Signal:
$BR_{SM} \sim 7.8 \times 10^{-11}$



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

NA62 goal:
Measure BR to 10% → **100 signal events**
S/B ~ 10

10^{13} *K* decays with:
- Acceptance ~10%
- Background rejection ~10^{12}
- Background known to ~10%

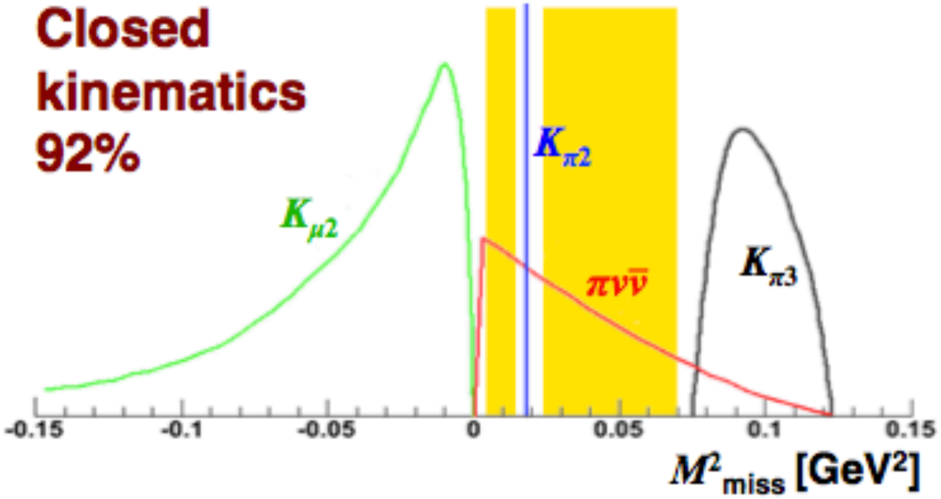
Decay backgrounds

Mode	BR
$\mu^+\nu(\gamma)$	63.5%
$\pi^+\pi^0(\gamma)$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$	5.1%
$\pi^0\mu^+\nu$	3.3%
$\pi^+\pi^- e^+\nu$	4.1×10^{-5}
$\pi^0\pi^0 e^+\nu$	2.2×10^{-5}
$\pi^+\pi^-\mu^+\nu$	1.4×10^{-5}
$e^+\nu(\gamma)$	1.5×10^{-5}

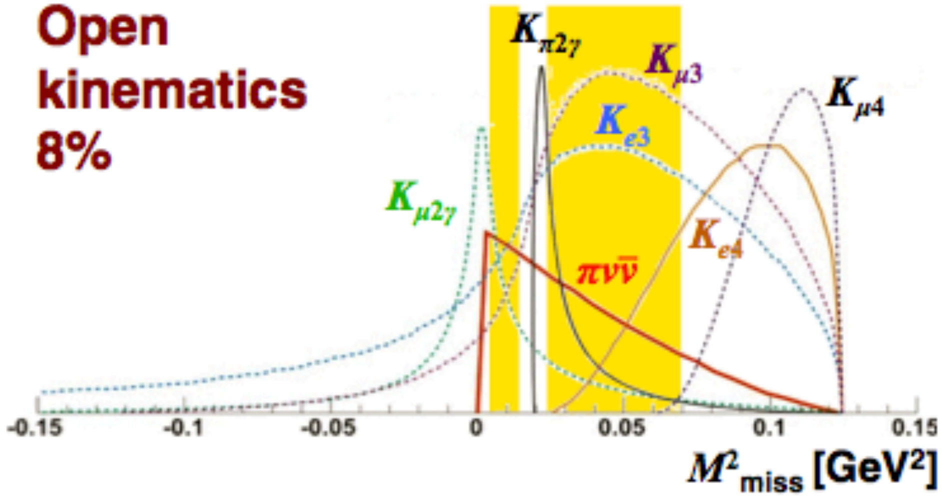
Other backgrounds
- Beam-gas (DIF)
- Charge exchange (K_{stop})

$K^+ \to \pi\nu\nu$: background rejection

Closed kinematics 92%



Open kinematics 8%



m^2_{miss} = 0 or m_π^2 to reject $\mu\nu$, $\pi\pi^0$ ➡ 2 fiducial regions in m^2_{miss}

- High resolution m^2_{miss} reconstruction
- Precise measurement of p_K and p_π
- Minimize multiple scattering

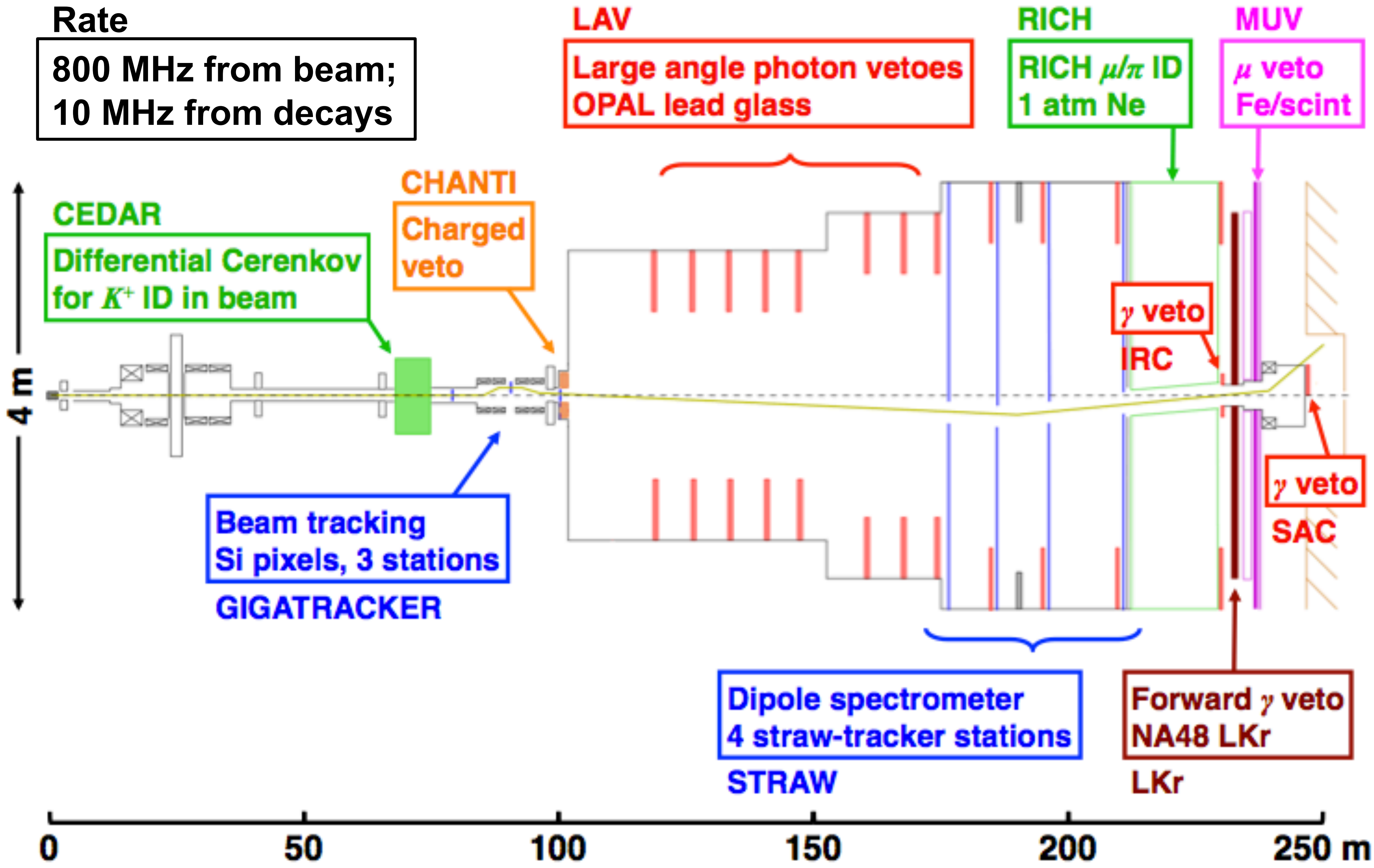
High-rate beam tracker
Low-mass spectrometer in vacuum

Rejection relies on PID and vetoes

- Veto detectors for π^0 rejection
- K^+ identification in hadron beam
- Detectors for π/μ separation

Hermetic γ vetoes
Non-destructive beam ID
Secondary particle ID
Muon vetoes

The experimental setup at the SPS



Installation and startup

- Installation of complete detectors started in early 2012
- "Dry run" Aug 2012 to read out installed detectors for the first time
- Technical run Nov-Dec 2012 to take data with 60% of detectors installed
- No beam in 2013 – finish installation of remaining detectors
- 2 years of physics running starting 2014, depending on SPS (LHC)

ORKA: the golden kaon experiment

- ORKA will apply the method and techniques that were demonstrated in BNL E878/E949.
  - ORKA does not assume (or require) better background rejection than E949 achieved.
- ORKA will use existing facilities at Fermilab.
  - Main Injector slow extracted beam to produce kaons.
  - Existing infrastructure (e.g., B0 hall).
  - Existing superconducting magnet (from CDF).
- ORKA will be a modern detector based on the E949 concept.
  - E787 was built in the mid-1980's; E949 was an upgrade in late 1990's.
- ORKA will observe about 1000 $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events in a few years of running (~200 events/yr at SM BF).

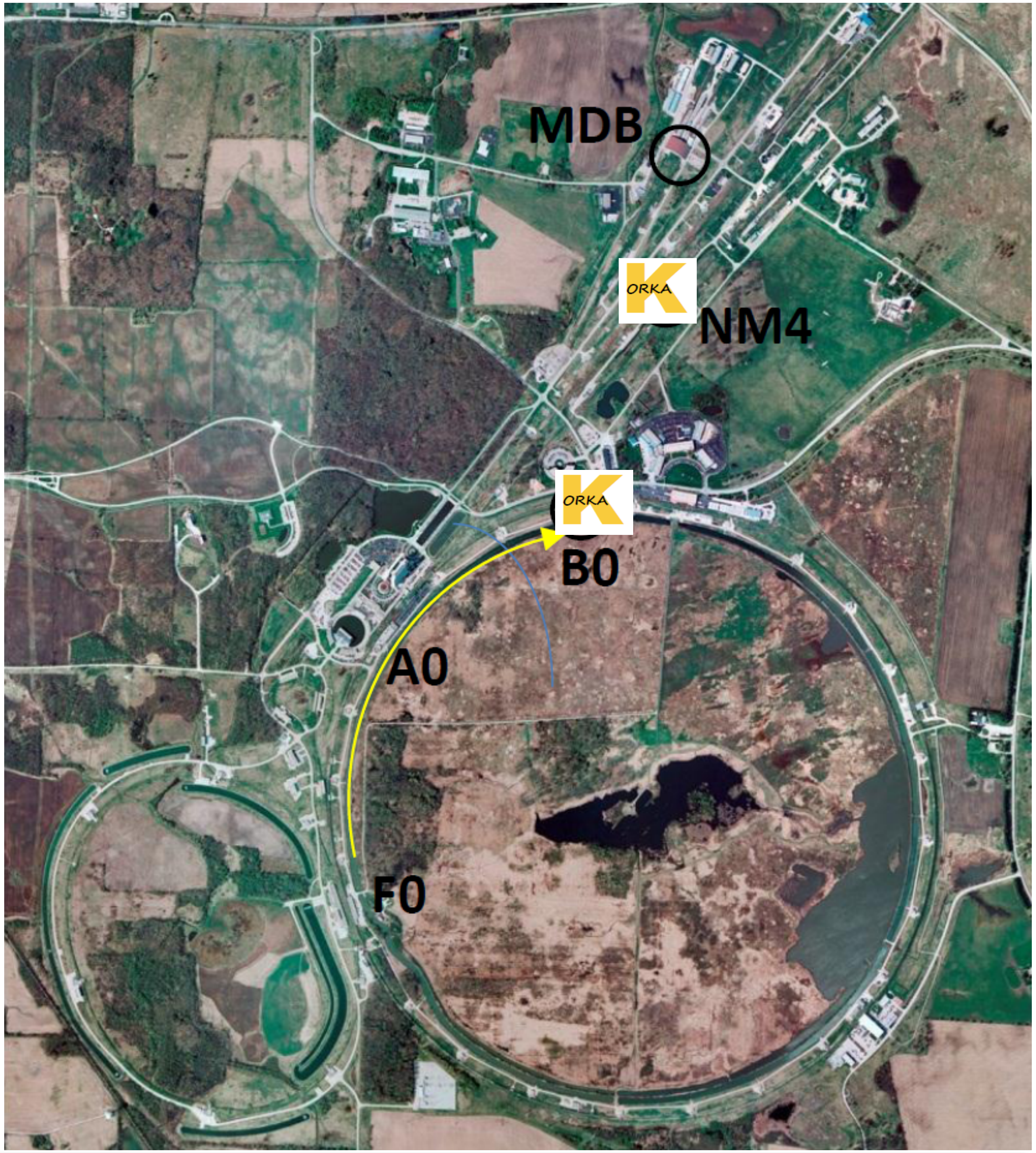
ORKA: sites considered

- **KTeV/Sea-Quest Hall:**

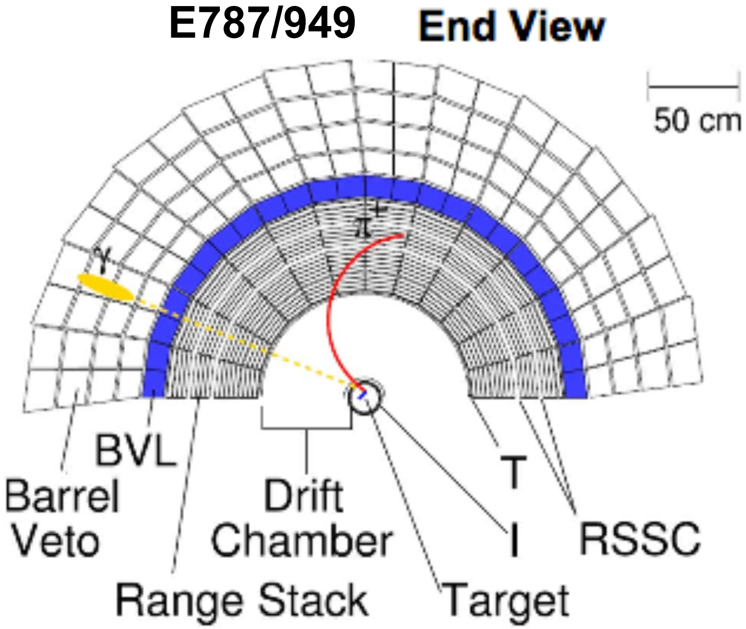
Existing beam transport but not Rad hard; small hall, no magnet and no cryo, existing and possible future Drell-Yan program.

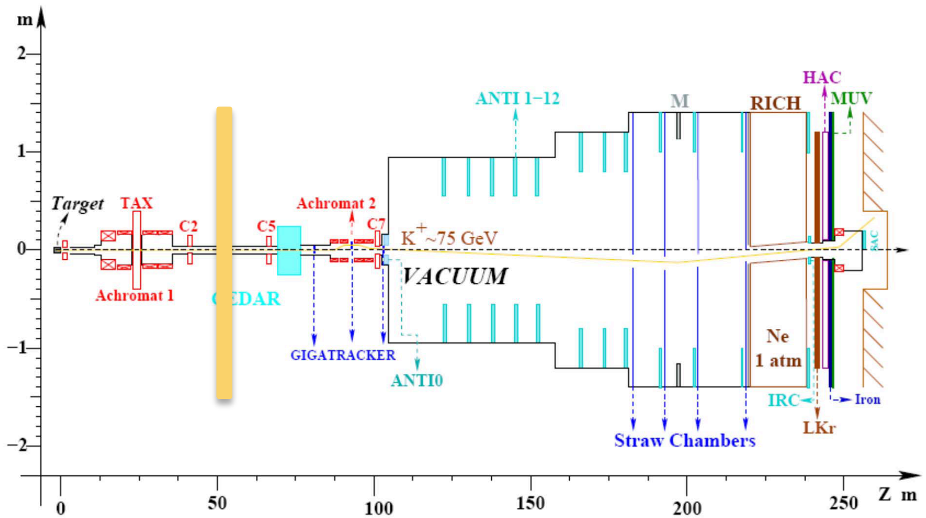
- **CDF(B0) collision hall:**

Existing tunnels and hall, Rad hard transport; adequate hall, magnet and cryo, A0->B0 beam-line required.

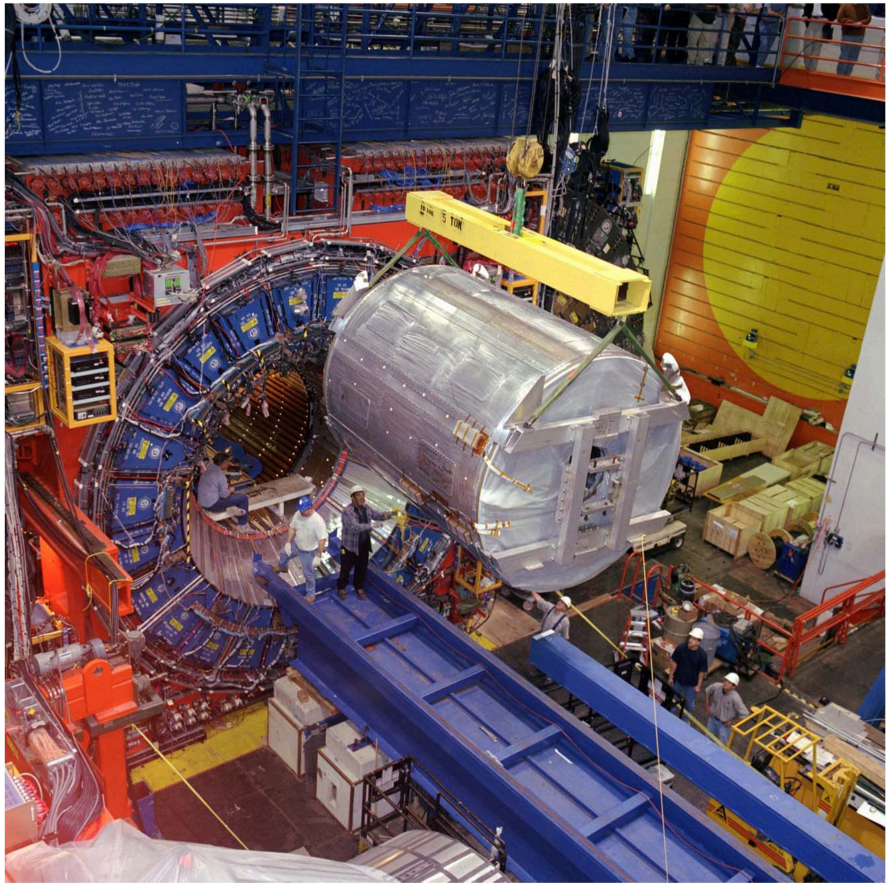


"the detector"





The entire ORKA detector (P966 FNAL proposal) will fit within the CDF tracking volume; also, a "tiny section" of NA62.



ORKA: status and timeline

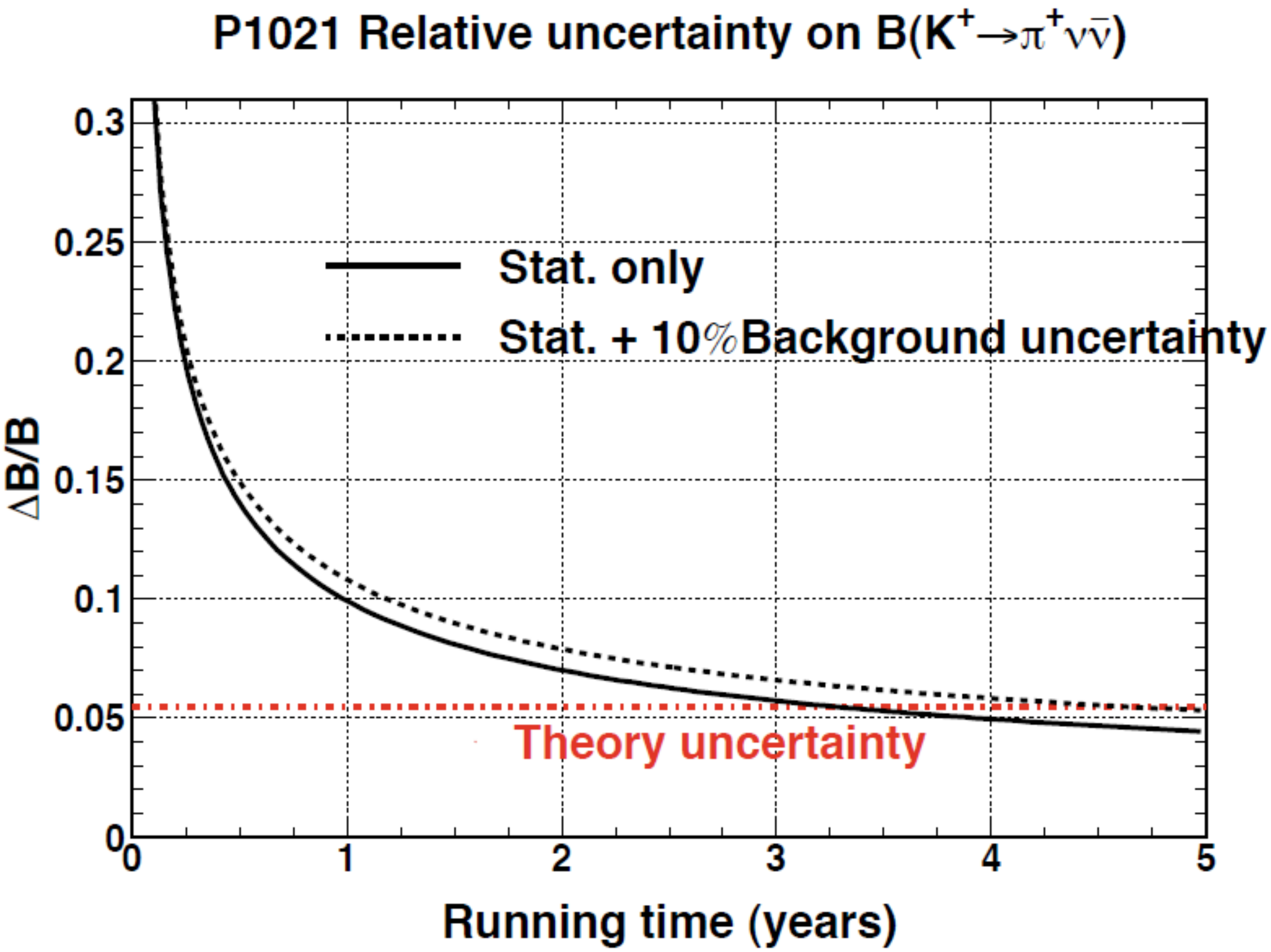
- ORKA (P-1021) received Stage 1 approval from Fermilab in December 2011.
- DOE is cogitating on the issue of "Mission Need" (aka CD-0).

Milestone/Activity	Time Period
Stage One Approval	Winter 2012
DOE Approval of Mission Need (CD-0)	Fall 2012
Beam/Detector Design	2012–2013
Approve Cost Range (CD-1)	early 2013
Baseline Review/CD-2	End of 2013
Start Construction (CD-3)	Spring 2014
Begin Installation	mid-2015
First Beam/Beam Tests	End of 2015
Complete Installation	Mid-2016
First Data (Start Operations/CD-4)	End of 2016

- ORKA could have data in 2017.

J.Ritchie at CKM2012

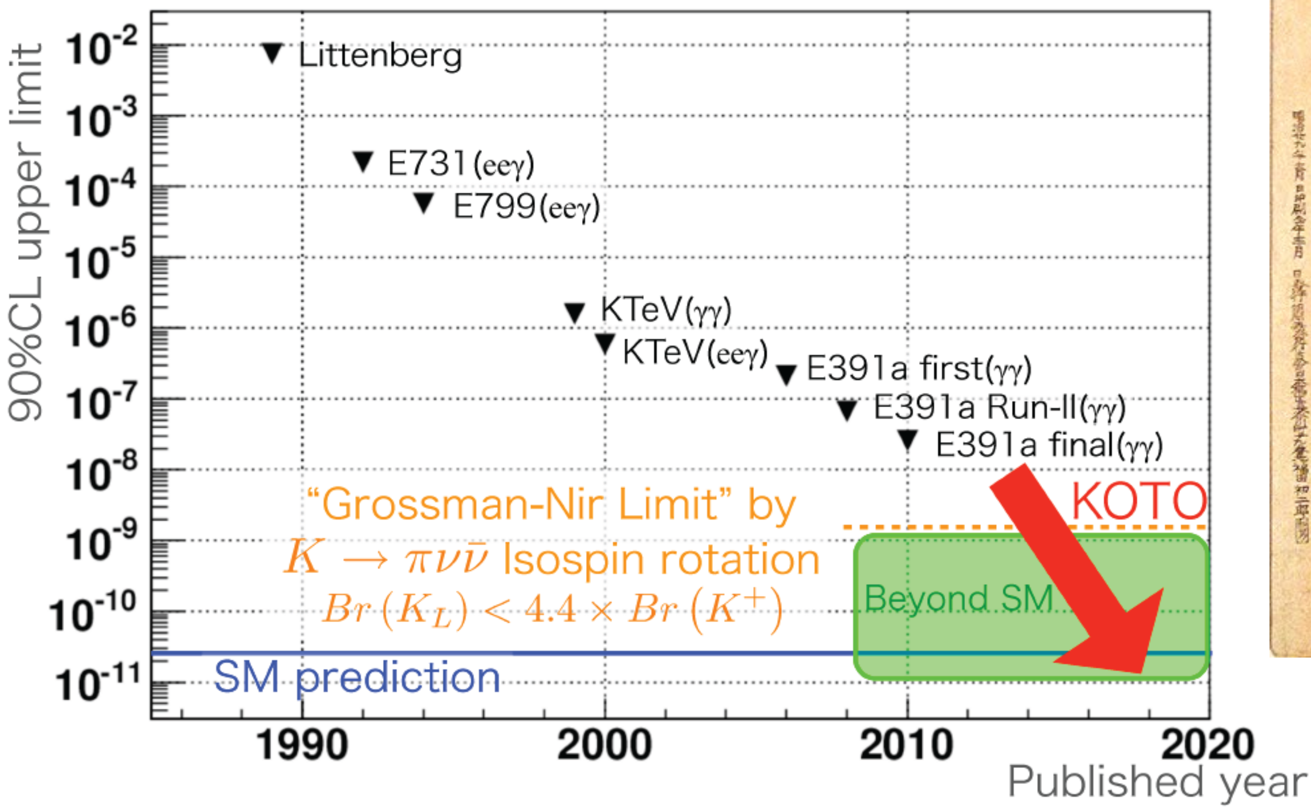
ORKA: sensitivity

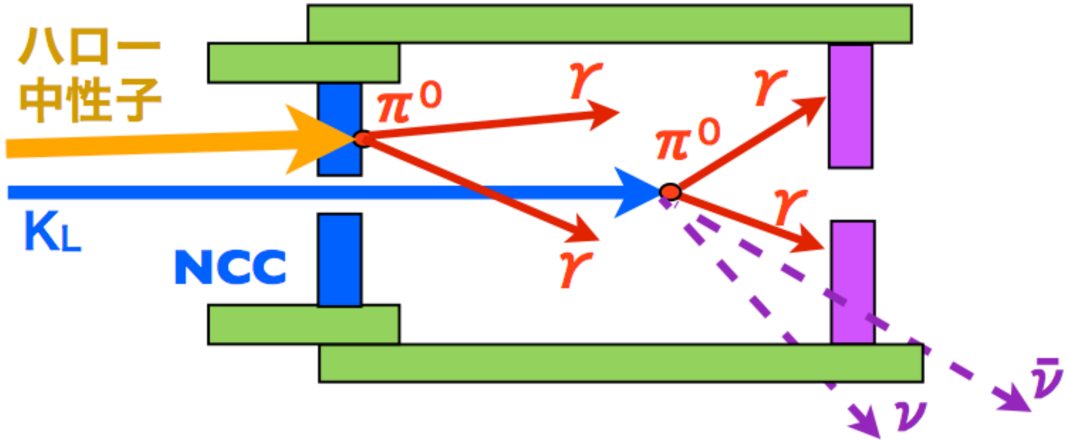


Data taking in 2017 and first results in 2020
Reduce the experimental error to the size of the theory uncertainty.

$K_L \rightarrow \pi^0 \nu\nu$: "Nothing in, nothing out"

The K0TO at J-PARC experiment (E14) aims to capture 100 events at SM branching ratio for a 5% measurement, using the 30 GeV beamline



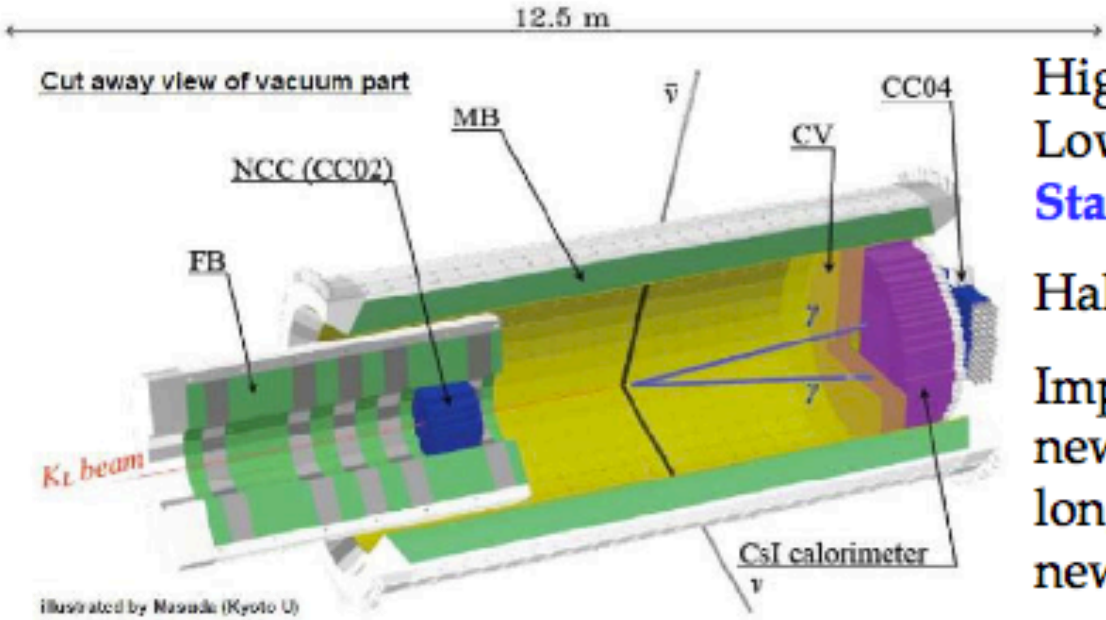


High acceptance detector plus a small hole to allow **the "pencil" K_L beam** to pass.
Cover the decay region with hermetic and very low inefficiency photon veto counters.
Detectors in high vacuum to minimize dead materials.

Selection: require events to have only 2 photons with π^0 invariant mass and large $p_T(\pi^0)$ (corresponding to the momentum carried by the neutrinos).
Project back from the photon hit positions towards the beam line to determine the K_L position in the decay region.
Eliminate, eliminate, and eliminate backgrounds and unwanted events.

All methods were developed for E391a, and will be extended.

K0TO



Higher beam intensity, acceptance
Lower DC, yield (angle):
Statistics: 3000 x E391a

Halo **n/K: 240x E391a**: new beam line

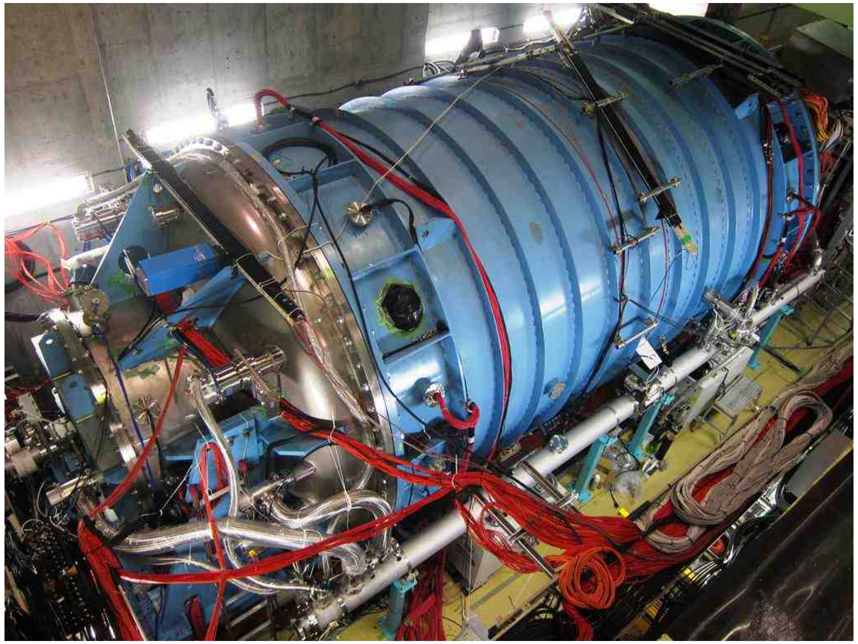
Improved **background** control:
new EM calorimeter (> granularity, longer), new backside charged veto, new beam-hole γ veto (25x Pb/aerogel)

Step 1: SES = **2.7 SM events** (3 Snowmass years) with **2.2 background**

Step 2 upgrade: **100 SM events**
(dedicated, smaller targeting angle beam line, larger detector)

66 people, 16 institutions (Japan, Korea, USA, Russia, Taiwan)
Stage 2 approval, beam line commissioned, in preparation

K0TO: physics run!



From the K0TO web-page: the only kaon experiment which is taking data ~NOW! Approaching the G-N limit?

What's New

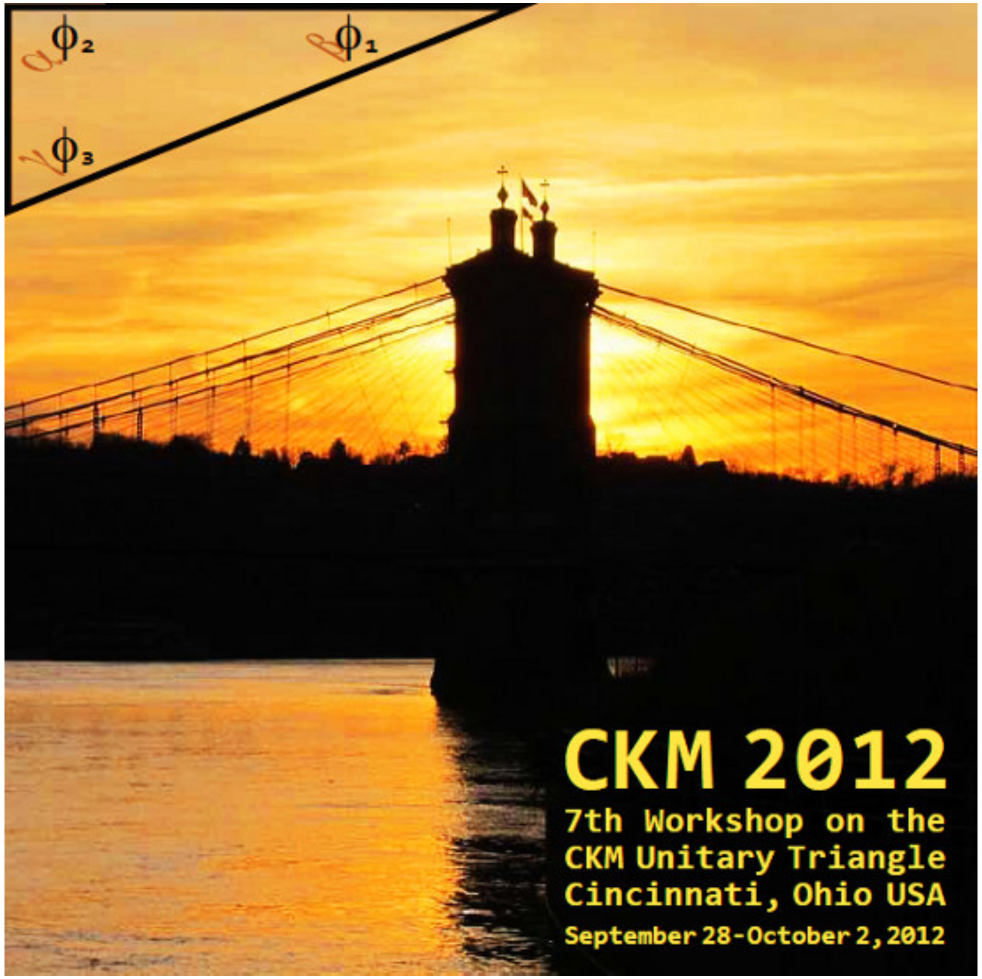
- [March./07/2013] Started the March run.
- [Jan./07/2013-Jan./16/2013] Engineering run in vacuum.
- [Dec./14/2012-Dec./26/2012] Engineering run in air.

From CKM 2012: nothing new?

Unitarity from first row: $|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\mathrm{CKM}}(\epsilon_i)$
(most precise test of CKM unitarity)

CKM 2010:
Δ=−0.0001(6)

CKM 2012:
Δ=+0.0001(6)



(*) Calepino = an old and tiring reading volume

*Calepino** for the 1st row

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta_q)$$

Fermi constant

$$|V_{ud}|^2 = \frac{K}{\mathcal{F}t G_F^2 M_F^2 (1+\Delta_R^V)}$$

Superallowed Fermi transitions

$$|V_{ud}|^2 = \frac{K_{1/2}}{\mathcal{F}t(1+\rho f_A / f_V)}$$

Mirror decays

$$\tau_n^{-1} = \frac{G_F^2}{2\pi^3} m_l^5 |V_{ud}|^2 (1+3\lambda^2) f(1+RC)$$

Neutron lifetime

Semileptonic decays

$$\Gamma_{Kl3} = \frac{G_F^2 M_K^5}{192\pi^3} C_K S_{EW} |V_{us} f_+(0)|^2 I_{Kl} \left\{1+\delta_{EM}^{Kl}+\delta_{SU(2)}^{K\pi}\right\}$$

Leptonic decays

$$\frac{\Gamma_{Kl2(\gamma)}}{\Gamma_{\pi l2(\gamma)}} = \frac{|V_{us}|^2}{|V_{ud}|^2}\frac{f_K^2}{f_\pi^2}\frac{(1-m_l^2/M_{K^\pm}^2)^2}{(1-m_l^2/M_{\pi^\pm}^2)^2}\left\{1+\delta_{EM}+\delta_{SU(2)}\right\}$$

τ hadrons decays

$$|V_{us}| = \frac{R_{\tau,S}}{R_{\tau,NS}/|V_{ud}|^2 - \delta R_\tau}, \quad R = \frac{\Gamma(\tau\to\nu_\tau + \text{hadrons})}{\Gamma(\tau\to\nu_\tau e\bar{\nu}_e)}, \quad \delta R = \frac{R_{\tau,NS}}{|V_{ud}|^2} - \frac{R_{\tau,S}}{|V_{us}|^2}$$

Vus: a bit of history

→ **2002** (2004 PDG)	**Old $K_{\ell 3}$ data give $1 - \|V_{ud}\|^2 - \|V_{us}\|^2 = 0.0035(15)$** A 2.3σ hint of unitarity violation?
2003	**BNL 865 measures BR($K^+ \to \pi^0 e^+ \nu$) = 5.13(10)%** Value for V_{us} consistent with unitarity
2004-present	**Many new measurements from KTeV, ISTRA+, KLOE, NA48** • **BRs, lifetimes, form-factor slopes** • **Much higher statistics** than older measurements • Importance of **radiative corrections** • Proper reporting of **correlations** between measurements
2008-beyond	**Much progress on hadronic constants from lattice QCD** **Value of V_{us} used in precision tests of the Standard Model**

Experiment, theory, and evaluation

V_{us} from $K_{\ell 3}$ & $K_{\ell 2}$:
- ~100 measurements of ~10 experimental parameters
- ~20 lattice evaluations of 2 hadronic matrix elements
- Radiative and SU(2)-breaking corrections, ChPT results, etc.

FlaviA net Kaon WG
2006-2010 (EU 6FP)
http://www.lnf.infn.it/wg/vus

Experimental averages, fits, etc
Selection of results (lattice, ChPT, experiments)
Evaluation, discussion and intepretation
Final report: EPJC 69 (2010) 399

Corresponding efforts to synthesize results from lattice QCD (beyond V_{us})

FLAG
http://itpwiki.unibe.ch/flag
Active since 2008 (Europe)

FlaviaNet Lattice Averaging Group
LECs, quark masses, Vus
EPJC 69 (2010) 399

LLVdW
www.latticeaverages.org
Active since 2009 (USA)

Includes hadronic constants for B physics, CKM fits, etc.
PRD 81 (2010) 034503

FLAG-2
Active since May 2012
Europe + USA + Japan
Participation by all major lattice collaborations
Expanded physics scope

Modern Vus inputs

Experiment	Measurement	Year
BNL865	BR($K^+ \to \pi^0{}_D e^+ \nu$)/BR($K^+ \to \pi^0{}_D X^+$)	2003
KTeV	$\tau(K_S)$	2003
	BR(K_{Le3}), BR($K_{L\mu3}$), $\lambda_+(K_{Le3})$, $\lambda_{+,0}(K_{L\mu3})$	2004
ISTRA+	$\lambda_+(K^-{}_{e3})$, $\lambda_{+,0}(K^-{}_{e3})$	2004
KLOE	$\tau(K_L)$	2005
	BR(K_{Le3}), BR($K_{L\mu3}$), BR(K_{Se3}), $\lambda_+(K_{Le3})$	2006
	$\lambda_{+,0}(K_{L\mu3})$	2007
	$\tau(K^\pm)$, BR(K_{Le3}), BR($K_{L\mu3}$)	2008
NA48	$\tau(K_S)$	2002
	BR(K_{Le3}/2 tracks), $\lambda_+(K_{Le3})$	2004
	BR(K_{Se3}/K_{Le3}), $\lambda_{+,0}(K_{L\mu3})$	2007
NA48/2	BR($K^+{}_{e3}/\pi^+\pi^0$), BR($K+{}_{\mu3}/\pi^+\pi^0$)	2007

Input data of the 2010 FlaviaNET final report

Update: K_S lifetime

FlaviaNet WG — τ_S = 89.59(6) ps

KLOE
EPJC 71 (2011)

τ_S = 89.562(29)(43) ps

- 2×10^7 $K_S \rightarrow \pi^+\pi^-$ decays from 0.4 fb^{-1} '04 data
- Tight track quality cuts & geometric fit
- $\sigma(L_K) \sim$ 0.22-0.27 λ_S (1.3-1.6 mm)
  Measured for 180 bins in (θ_K, ϕ_K)

KTeV
PRD 83 (2011)

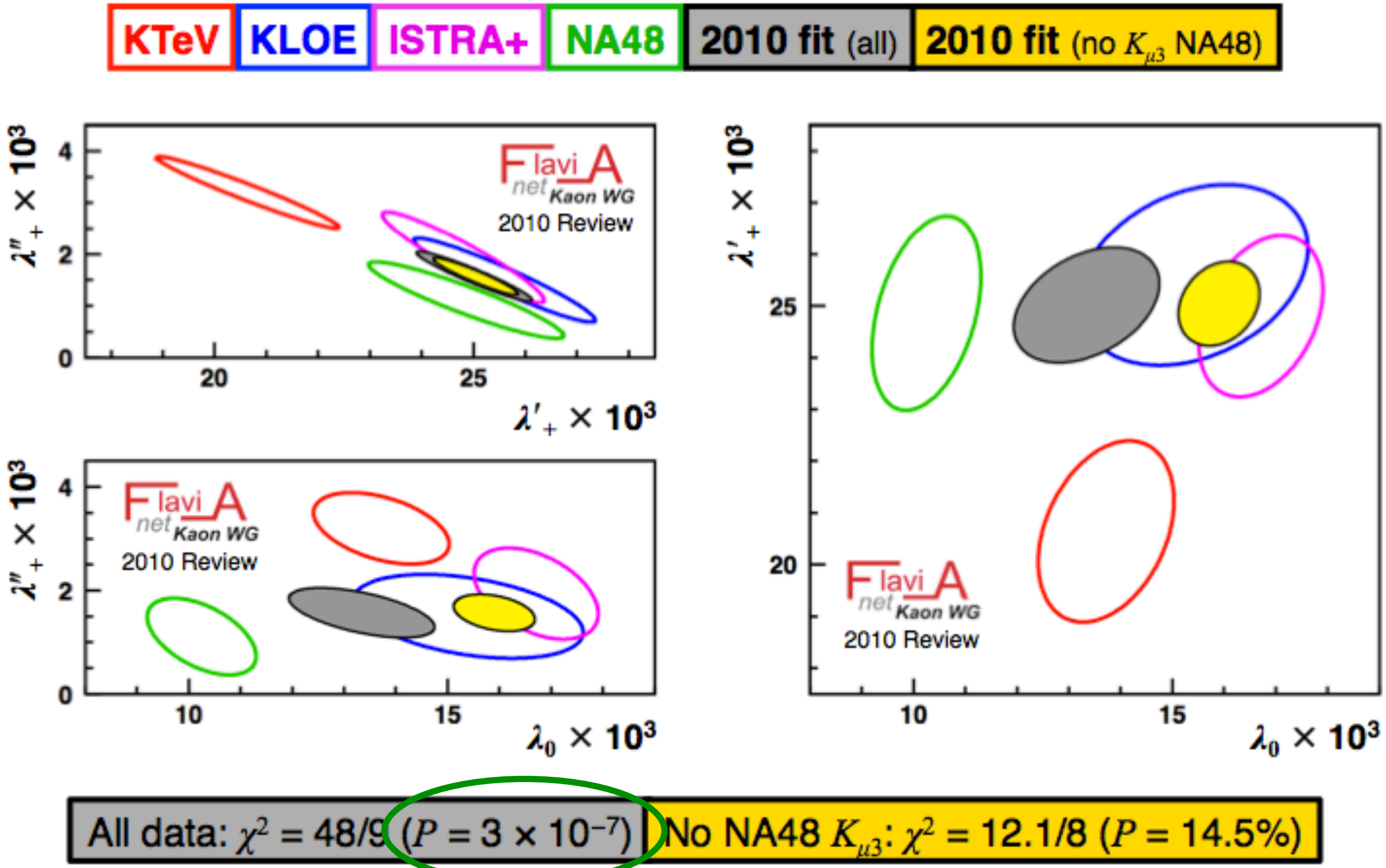
τ_S = 89.589(42)(56) ps
Re ε'/ε = $(21.10 \pm 3.43) \times 10^{-6}$

- New analysis of Re ε'/ε with improved Monte Carlo
- From fit to z_{vertex} distribution for regenerator beam without assuming CPT
- Result for Re ε'/ε averaged with NA48 '02 and used to constrain BR($K_L \rightarrow \pi^0\pi^0$)/BR($K_L \rightarrow \pi^+\pi^-$) in K_L fit

FlaviaNet WG — τ_S = 89.58(4) ps

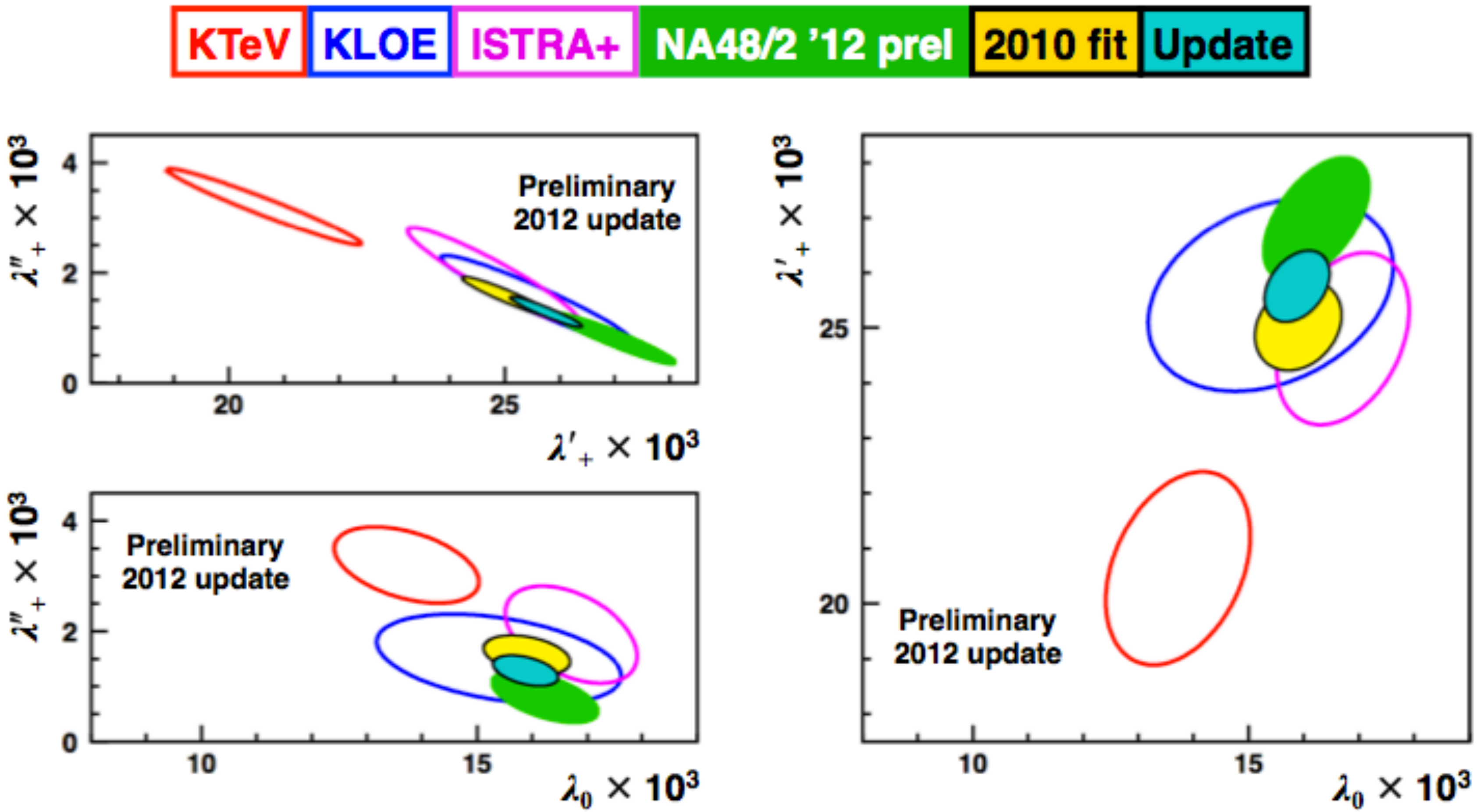
New NA48/2 FF: solve tension in data set

Fits to $K_{e3} + K_{\mu 3}$ form-factor slopes: 2010



New NA48/2 FF: solve tension in data set

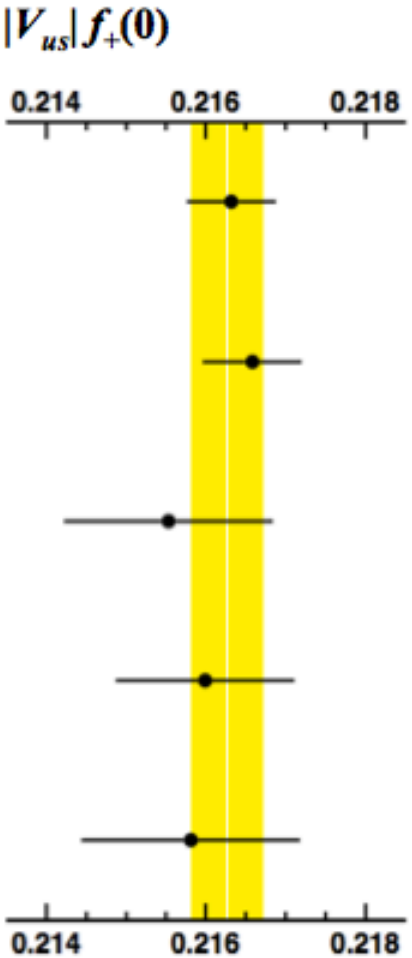
Fits to $K_{e3} + K_{\mu3}$ form-factor slopes: Update



2010: $\chi^2 = 12.1/8$ ($P = 14.5\%$) | Update: $\chi^2 = 14.3/11$ ($P = 22.0\%$)

Vus from K semileptonic decays: CKM 2010

$|V_{us}| f_+(0)$ from world data: 2010

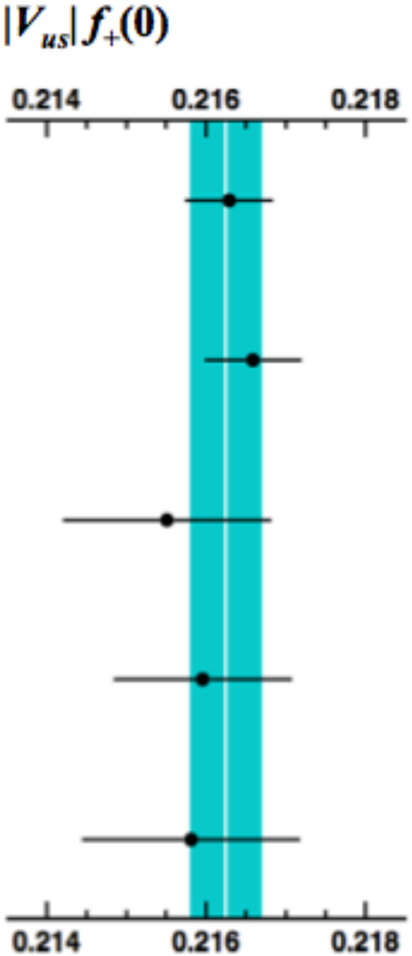


	$|V_{us}| f_+(0)$	% err	Approx. contrib. to % err from: BR	τ	Δ	Int
$K_L e3$	0.2163(6)	0.26	0.09	0.20	0.11	0.06
$K_L \mu 3$	0.2166(6)	0.29	0.15	0.18	0.11	0.08
$K_S e3$	0.2155(13)	0.61	0.60	0.03	0.11	0.06
$K^\pm e3$	0.2160(11)	0.52	0.31	0.09	0.40	0.06
$K^\pm \mu 3$	0.2158(14)	0.63	0.47	0.08	0.39	0.08

Average: $|V_{us}| f_+(0) = 0.2163(5)$ $\chi^2/\text{ndf} = 0.77/4\ (94\%)$

2012: new τ_S (KLOE, KTeV) and FF (NA48)

$|V_{us}| f_+(0)$ from world data: Update



		% err	Approx. contrib. to % err from: BR	τ	Δ	Int
$K_L e3$	0.2163(5)	0.26	0.09	0.20	0.11	0.05
$K_L \mu 3$	0.2166(6)	0.28	0.15	0.18	0.11	0.06
$K_S e3$	0.2155(13)	0.61	0.60	0.02	0.11	0.05
$K^{\pm} e3$	0.2160(11)	0.52	0.31	0.09	0.41	0.04
$K^{\pm} \mu 3$	0.2158(13)	0.63	0.47	0.08	0.41	0.06

Average: $|V_{us}| f_+(0) = 0.2163(5)$ $\chi^2/\text{ndf} = 0.84/4$ (93%)

Accuracy of SU(2)-breaking correction

$$\Delta^{SU(2)} \equiv \frac{f_+(0)^{K^+\pi^0}}{f_+(0)^{K^0\pi^-}} - 1$$

Strong isospin breaking

Quark mass differences, η-π^0 mixing in $K^+\pi^0$ channel

$$= \frac{3}{4}\left(\frac{m_d^2 - m_u^2}{m_s^2 - \hat{m}^2}\right)\left[\frac{m_K^2}{m_\pi^2} + \frac{\chi_{p^4}}{2}\left(1 + \frac{m_s}{\hat{m}}\right)\right]$$

= **+2.9(4)%** Kastner & Neufeld '08, used to calculate $|V_{us}|\,f_+(0)$
Quark mass ratio from Ananthanaryan & Moussalam '04

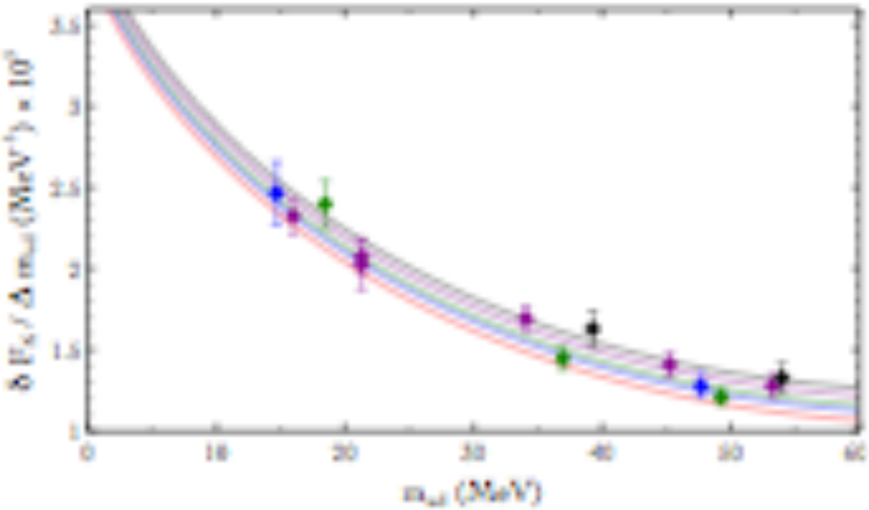
Equality of V_{us} values from $K^\pm$ and K^0 data would require $\Delta^{SU(2)}$ = 2.73(41)%

Uncertainty on $\Delta^{SU(2)}$ a major contributor to uncertainties for determination of V_{us} for $K^\pm$ decays

Observed value of $\Delta^{SU(2)}$ can be related to quark-mass ratios

Isospin corrections from lattice

- At present one of the dominant (theoretical) source of error in K+l3
- Soon needed also for Kl2/πl2: the error on $f_K/f_\pi \sim 0.5\%$, comparable with the SU(2) correction value.
- More accurate calculation needed: non-perturbative method, LQCD
- **new collaboration (RM123) set up on purpose**; new general method (calculate $O(m_d-m_u)$ effects $O((m_d-m_u)^2)$ negligible, to be applied to many observables) first results obtained look very promising.
- reasonably consistent with χPT calculations
- calculation for f+(0) is on going (more involved, many diagrams)



$\left[\frac{F_{K^+}/F_{\pi^+}}{F_K/F_\pi} - 1\right]^{QCD}$, -0.0039(3)(2): LQCD

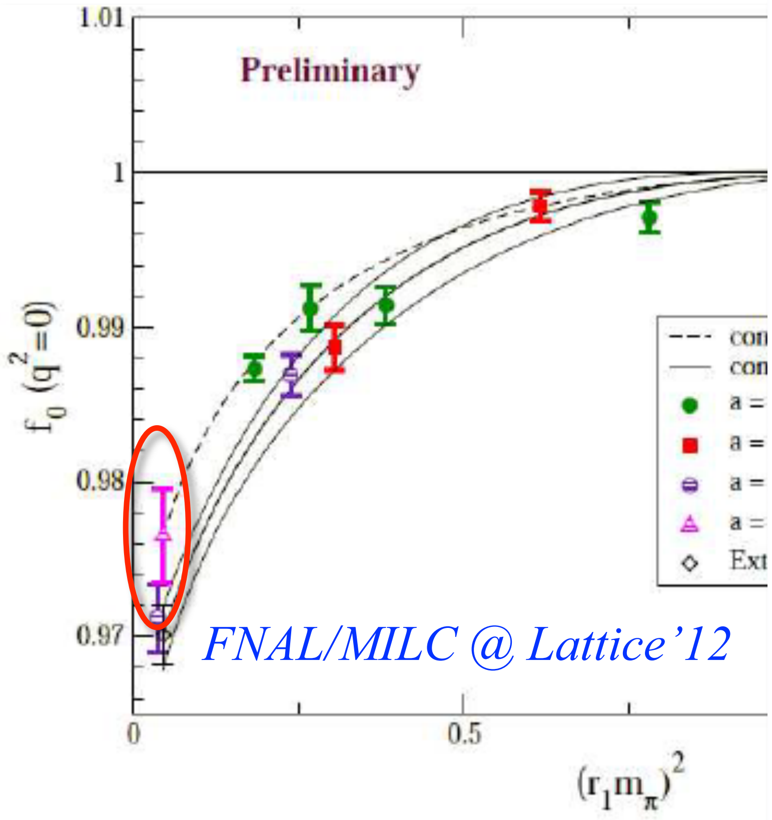
$\varepsilon_\gamma = 0$ -0.0032(3): LQCD, $\varepsilon_\gamma=0$

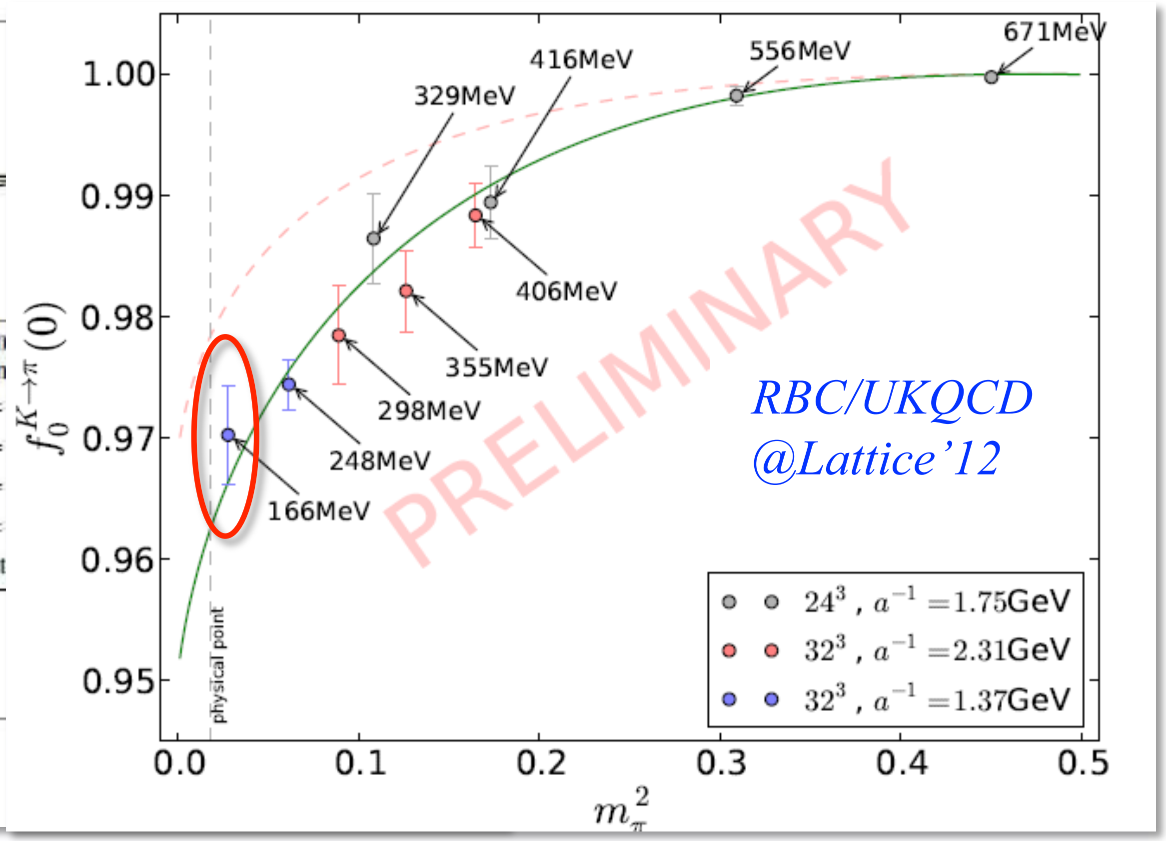
to be compared with

$\left[\frac{F_{K^+}/F_{\pi^+}}{F_K/F_\pi} - 1\right]^{\chi pt} = -$ -0.0022(6): χPT

K semileptonic decays: lattice

$$\Gamma_{Kl3} = \frac{G_F^2 M_K^5}{192\pi^3} C_K S_{EW} \left| V_{us} f_+(0) \right|^2 I_{Kl} \left\{ 1 + \delta_{EM}^{Kl} + \delta_{SU(2)}^{K\pi} \right\}$$





simulation around physical m_{ud} eliminate the error due chiral extrapolation

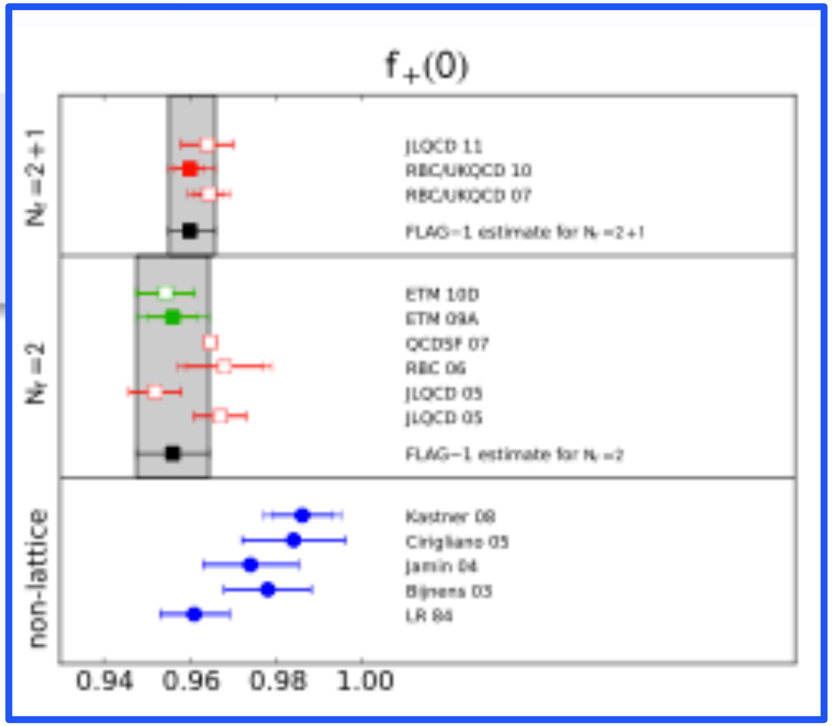
K semileptonic decays: lattice

Error budget

typical result RBC+UKQCD Phys. Rev. Lett. 2008:

$$f_+^{K\pi}(0) = 0.9644(33)^{stat}(34)^{q^2,\chi}(14)^a$$

$$|V_{us}^{K_{l3}}| = 0.2242 \quad \begin{matrix} (5)^{\Gamma} & (8)^{stat} & (8)^{q^2,\chi} & (3)^a \\ (0.2\%)^{\Gamma} & (0.3\%)^{stat} & (0.4\%)^{q^2,\chi} & (0.1)^a\% \end{matrix}$$



Dominant systematic errors removed:
- q^2-interpolation (twisted boundary condition)
- chiral extrapolation at the physical point

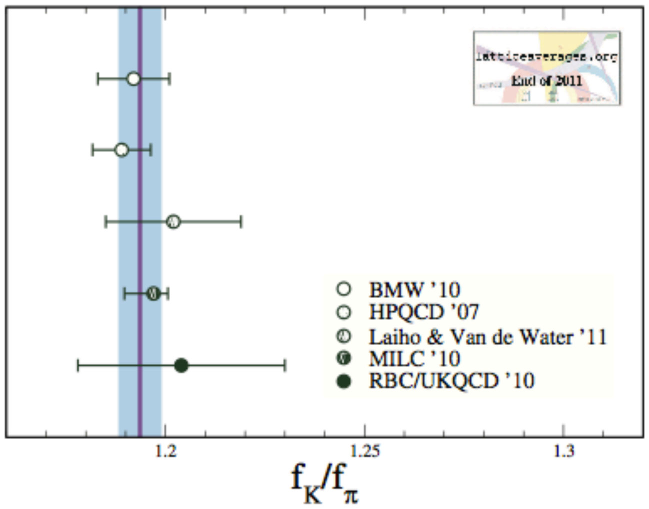
QCD-part in most simulation **statistical limited** ("good point": can be improved!)
A lot of work [ETM, JLQCD, MILC, and RBC.UKQCD] improves previous results: hopefully soon published!

FLAG-2 review is coming.

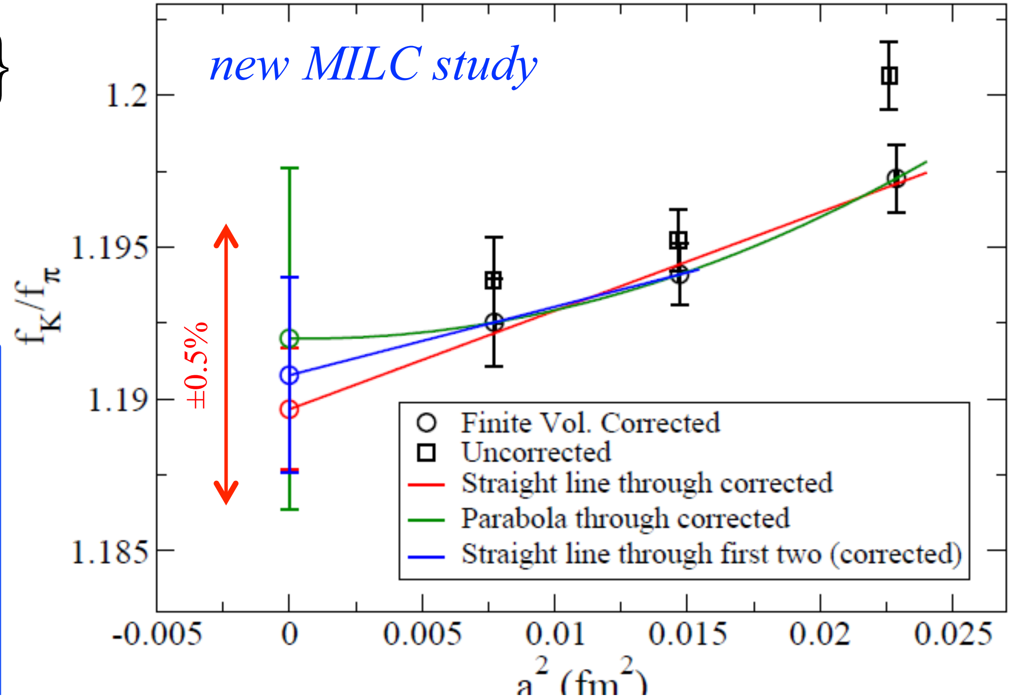
Leptonic decays

$$\frac{\Gamma_{Kl2(\gamma)}}{\Gamma_{\pi l2(\gamma)}} = \frac{|V_{us}|^2}{|V_{ud}|^2}\,\frac{f_K^2}{f_\pi^2}\,\frac{(1-m_l^2/M_{K^\pm}^2)^2}{(1-m_l^2/M_{\pi^\pm}^2)^2}\left\{1+\delta_{EM}+\delta_{SU(2)}\right\}$$

f_K/f_π



BMW, MILC, and HPQCD dominate the 2+1 flavor world average $f_K/f_\pi = 1.1936(53)$.



Longer term

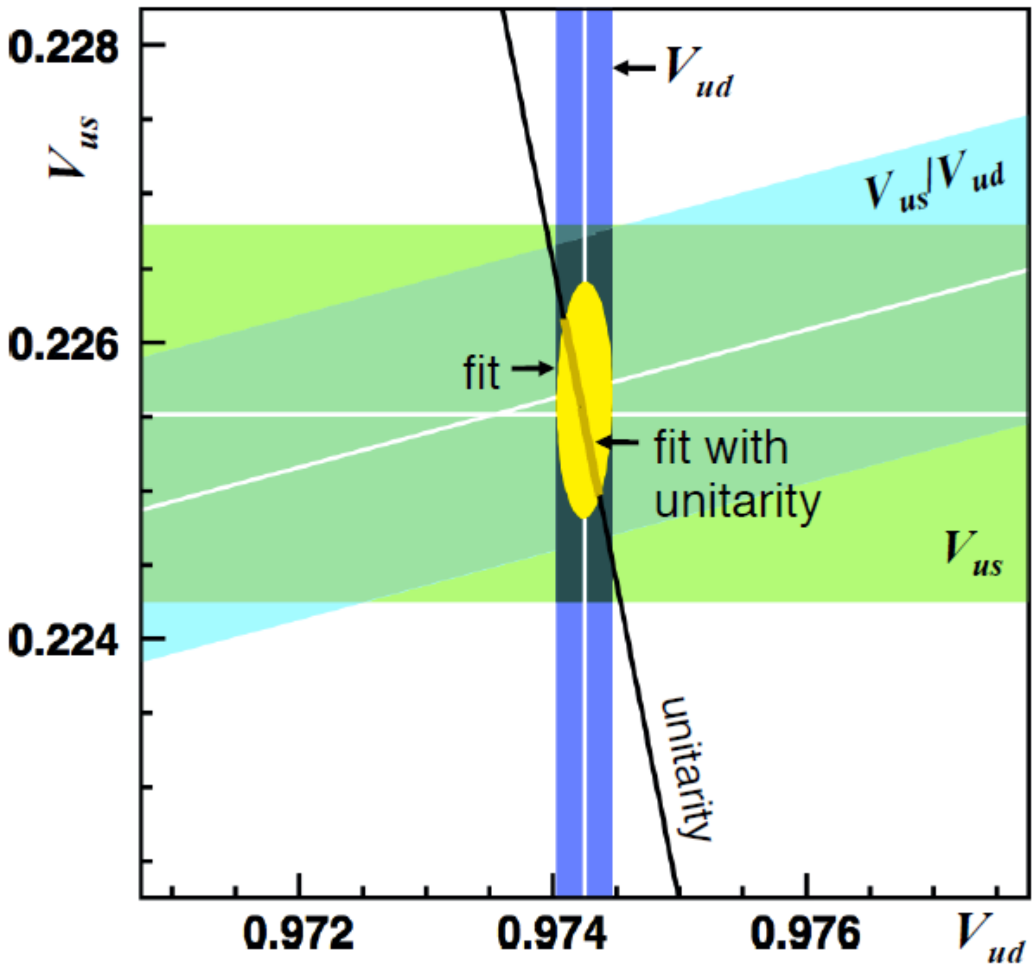
Current error on world average is 0.44%.

New MILC result will have error ~ 0.25%.

Better statistics and a finer lattice spacing should help reduce this even further.

Unitarity test

Use $f_+(0) = 0.959(5)$ and $f_K/f_\pi = 1.193(5)$
Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$



$|V_{ud}| = 0.97425(22)$ $0^+ \to 0^+$
$|V_{us}| = 0.2255(13)$ K_{l3}
$|V_{us}|/|V_{ud}| = 0.2317(11)$ K_{l2} / π_{l2}

Fit results, no constraint

$V_{ud} = 0.97425(22)$
$V_{us} = 0.2256(8)$
$\chi^2/\text{ndf} = 0.03/1$ (86%)
$\Delta_{CKM} = +0.0001(6)$

$(4)_{|Vud|}(4)_{|Vus|}$

Fit results, unitarity constraint

$V_{ud} = 0.97423(14)$
$V_{us} = 0.2255(6)$
$\chi^2/\text{ndf} = 0.05/2$ (97%)

New Physics implications of Δ_{CKM}

Model independent effective-theory approach

Cirigliano, González-Alonso, Jenkins, 2010

Effective Lagrangian for $\mu \sim 1$ GeV with general set of dim-6 operators giving rise to (semi)leptonic transitions

$$\mathcal{L}^{\text{eff}}_{d^j \to u^i \ell \bar{\nu}} = \mathcal{L}^{\text{eff,SM}}_{d^j \to u^i \ell \bar{\nu}} + \frac{v^2}{\Lambda^2} \mathcal{L}^{\text{eff,NP}}_{d^j \to u^i \ell \bar{\nu}}$$

Consider the **flavor-blind** limit (or similar: minimal flavor violation, etc.)
New physics appears as a small difference between G_{CKM} and G_μ

From comparison of operators for $d \to ul\nu$ and $\mu \to e\nu\nu$

$$\Delta_{\text{CKM}} = 4(-\hat{\alpha}^{(3)}_{\varphi\ell} + \hat{\alpha}^{(3)}_{\varphi q} - \hat{\alpha}^{(3)}_{\ell q} + \hat{\alpha}^{(3)}_{\ell\ell}) = \frac{G_{\text{CKM}}}{G_\mu} - 1$$

Strong constraints from precision EW data — Weak constraint from LEP-II $e^+e^- \to qq$

EW fit: $\Delta_{\text{CKM}} = (-4.7 \pm 2.9) \times 10^{-3}$

Exp. V_{ud}, V_{us}: $\Delta_{\text{CKM}} = (-0.1 \pm 0.6) \times 10^{-3}$ ⇒ **$\Lambda^{\text{eff}}_{\text{NP}} > 11$ TeV (90% CL)**

From 2010 FlaviaNet analysis. Now $\Delta_{\text{CKM}} = (+0.1 \pm 0.6) \times 10^{-3}$

Summary and conclusions

All measurements are currently in agreement with the SM.
Kaons: results complementary to LHC.
"ecological" experiments: deep re-use of previous detectors

Results from the upcoming $K \to \pi\nu\nu$ NA62 and K0TO experiments (hoping ORKA will join too) will probe deeply the flavor structure of the SM.

After 67 years of honorable service to physics, kaons are active as ever in offering new ways to explore the mysteries of the flavor sector, and to answer "Who ordered that?".

As in any review talk, plots, ideas, slides, numbers, information,… stolen here and there.
Special thanks to: V. Cirigliano, S. Giovannella, M. Hasinoff, T.K. Komatsubara, M. Moulson, J. Ritchie, G. Ruggiero, M. Sozzi, R. Tshirhart, and WG1 CKM2012 speakers.

Additional information

The “wrong” flavor?

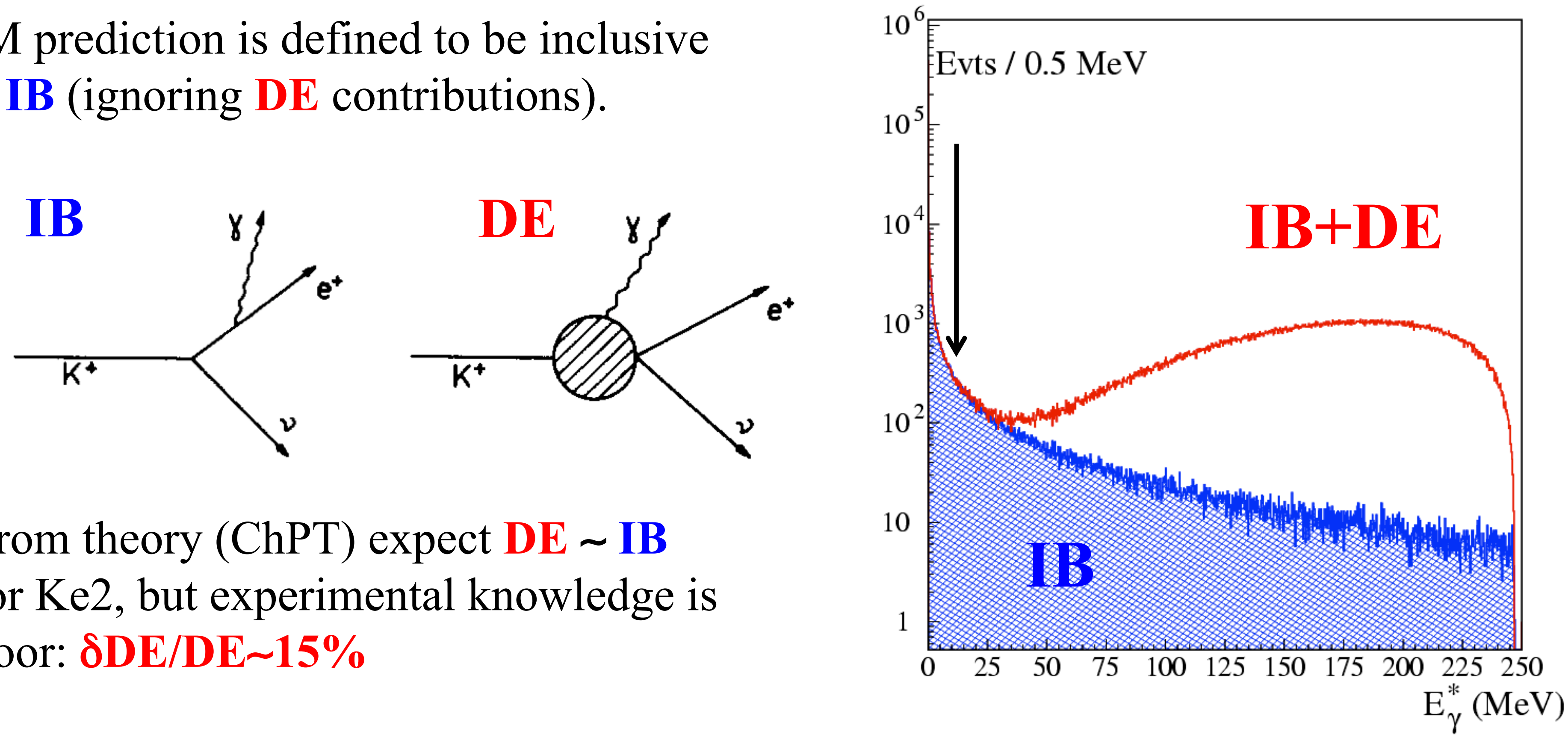
Sorry, I could not resist!

“The Flashpoint Kaon Under Siege was added to Star Wars: The Old Republic with Patch 1.1 and it’s **one of the hardest in the game. It’s intended for players who are at least a level 50**. It takes place on a Spaceshuttle where an infection broke out, which turned everyone into a creature that resembles a zombie.”

Read more at http://www.swtorstrategies.com/2013/01/flashpoint-guides-kaon-under-siege.html#hOGHugoejv7GG1bC.99

Ke2(γ): signal definition

SM prediction is defined to be inclusive of **IB** (ignoring **DE** contributions).



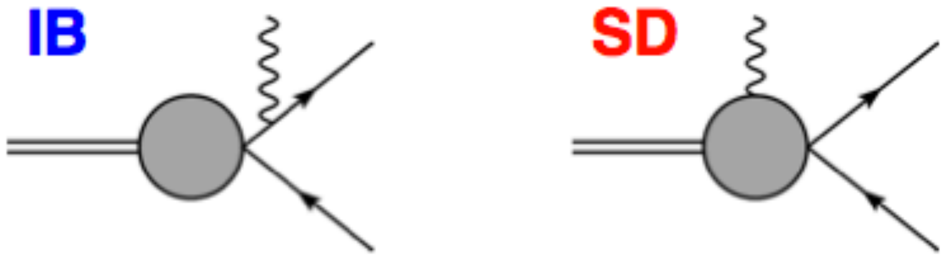
From theory (ChPT) expect **DE ~ IB** for Ke2, but experimental knowledge is poor: **δDE/DE~15%**

- **Define as "signal" events with E_γ<10 MeV**.
- Evaluating **IB** spectrum (O(α)+resummation of leading logs) obtain a 0.0625(5) correction for the IB tail.
- Under 10 MeV, the **DE** contribution is expected to be negligible.

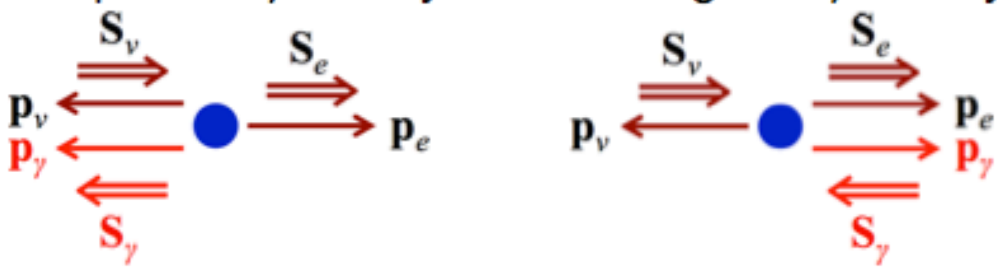
Ke2γ (not only R_K background)

SM prediction is for $\Gamma(K \to \ell\nu(\gamma_{IB}))$

R_K includes IB and excludes SD



SD⁺: positive γ helicity   **SD⁻**: negative γ helicity



KLOE $\dfrac{\Gamma_{SD+}(K_{e2\gamma})}{\Gamma(K_{\mu2(\gamma)})} = 1.484(66)_{st}(16)_{sy} \times 10^{-5}$

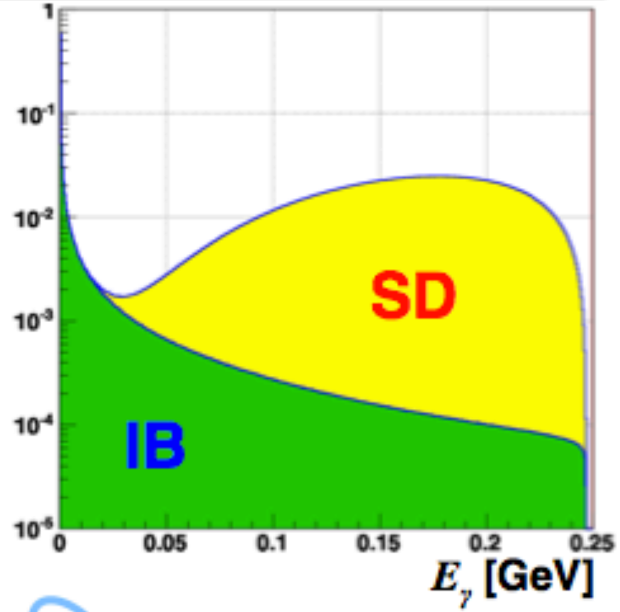
$E_\gamma > 10$ MeV, $\cos\theta_{e\gamma} < 0.9$, $p_e > 200$ MeV

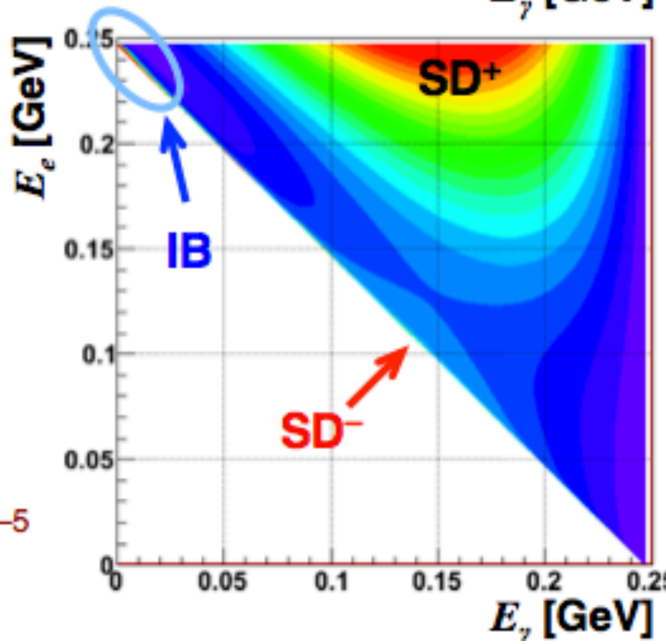
Fit E_γ spectrum for $O(p^4)$ ChPT form factors

NA62 Use KLOE SD⁺ form factor to obtain

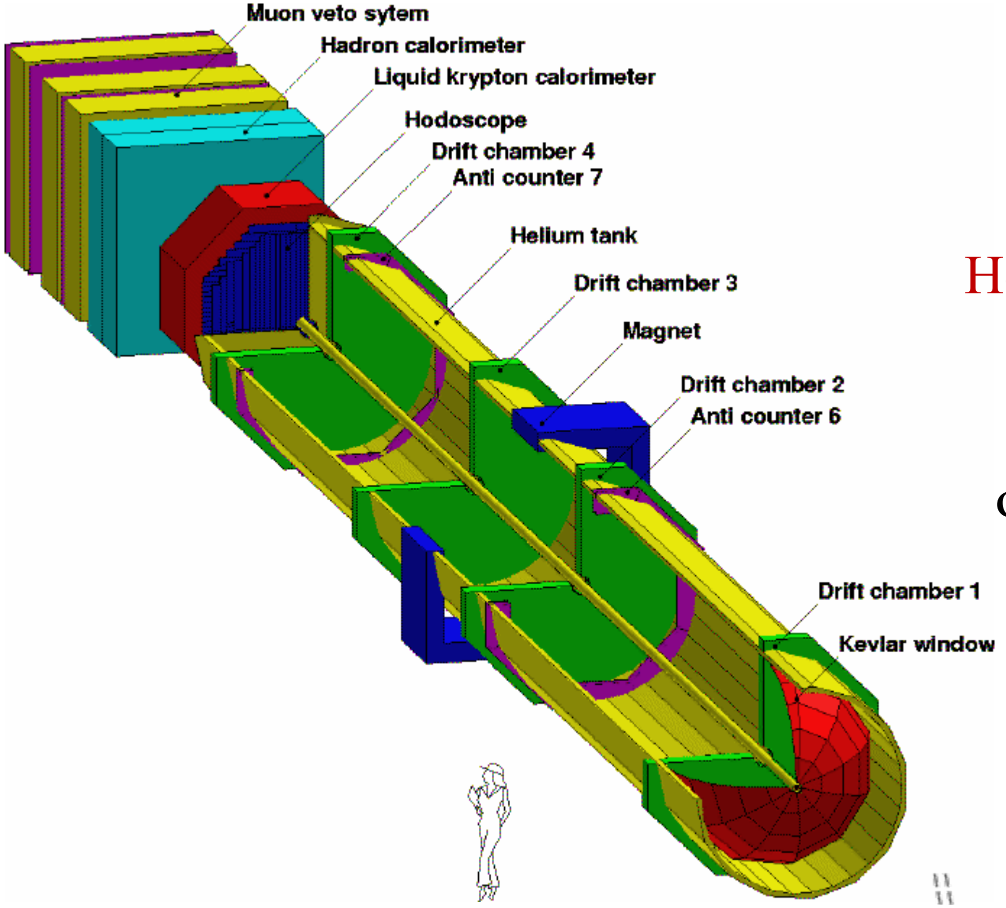
BR(SD⁺, full phase space) = $(1.37 \pm 0.06) \times 10^{-5}$

Result: $B/(S+B) = (2.60 \pm 0.11)\%$





NA62 layout for R_K



Main Detectors (NA48):

Magnetic Spectrometer:

$\sigma(P)/P = 0.48\% \oplus 0.009\, P(GeV/c)\%$

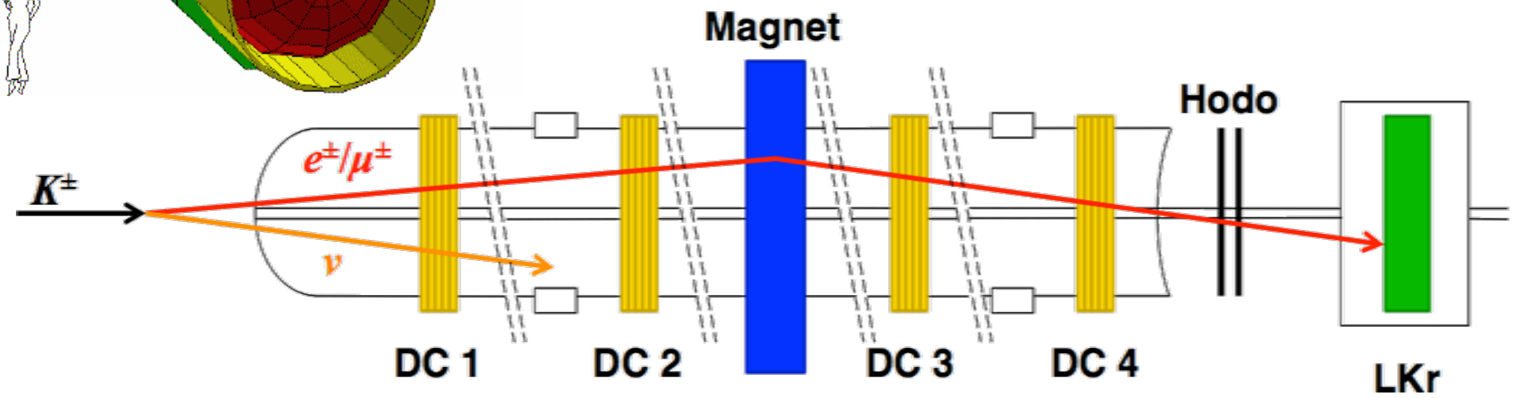
Hodoscope: Fast trigger for charged particles and timing for the event ($\sigma(t) = 200$ ps)

Liquid Kripton e.m. calorimeter (LKr):

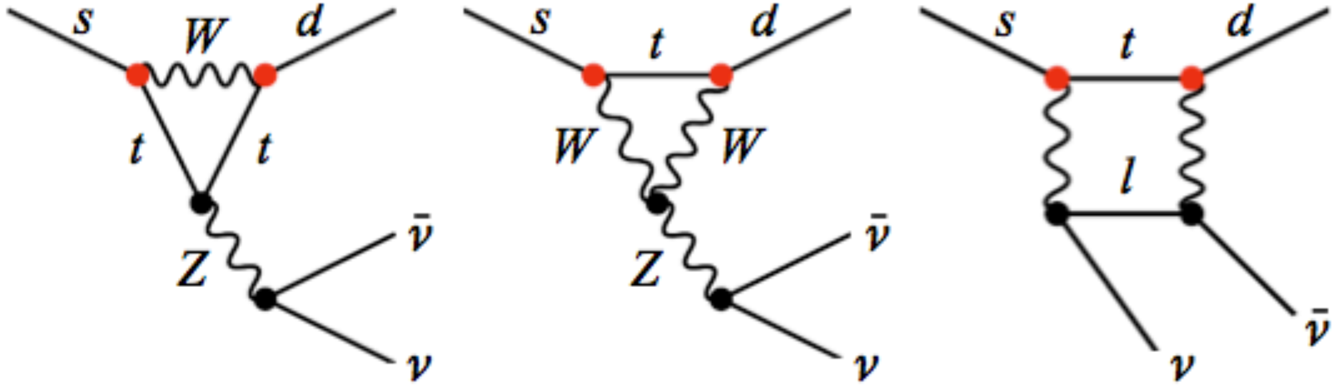
$\sigma(E)/E = 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%$ (GeV)

$K^{\pm}$ beams:

$P_K = 75 \pm 2$ GeV/c



K→πνν in the SM



$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$
$$x_q \equiv m_q^2 / m_W^2$$

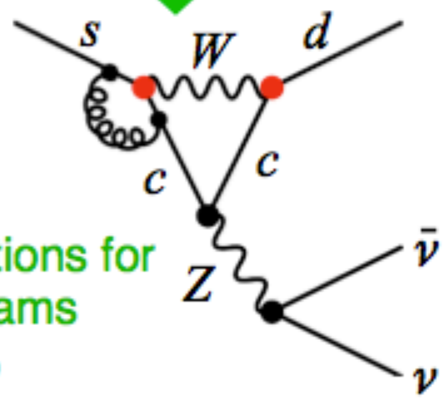
Loop functions favor top contribution

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

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 \leftarrow \not{C}\not{P}$$

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

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



QCD corrections for charm diagrams contribute to uncertainty

$K^+ \rightarrow \pi\nu\nu$: sensitivity

Acceptance = 14.4%
Decay rate in fiducial volume = 4.8×10^{12}/yr

➡ **55 signal events/yr**

Background mode	Expected B/S
$K^+ \rightarrow \pi^+\pi^0$	4.3%
$K^+ \rightarrow \pi^+\pi^0$	~2%
$K^+ \rightarrow \mu^+\nu$	2.2%
$K^+ \rightarrow \mu^+\nu$	~0.7%
$K^+ \rightarrow \pi^+\pi^- e^+\nu$	<3%
Other $K^+ \rightarrow$ 3 tracks	<1.5%
$K^+_{e3}, K^+_{\mu3}$	negligible
Total	**13.5%**

NA62 will measure $K^+ \rightarrow \pi\nu\nu$ to 10%

Vus: CKM unitarity, gauge universality

Standard-model coupling of quarks and leptons to W:

$$\frac{g}{\sqrt{2}} W^+_\alpha \left(\overline{\mathbf{U}}_L \mathbf{V}_{\rm CKM} \gamma^\alpha \mathbf{D}_L + \overline{e}_L \gamma^\alpha \nu_{e\,L} + \overline{\mu}_L \gamma^\alpha \nu_{\mu\,L} + \overline{\tau}_L \gamma^\alpha \nu_{\tau\,L} \right) \;+\; \text{h.c.}$$

↑ *Single gauge coupling*

↑ *Unitary matrix*

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

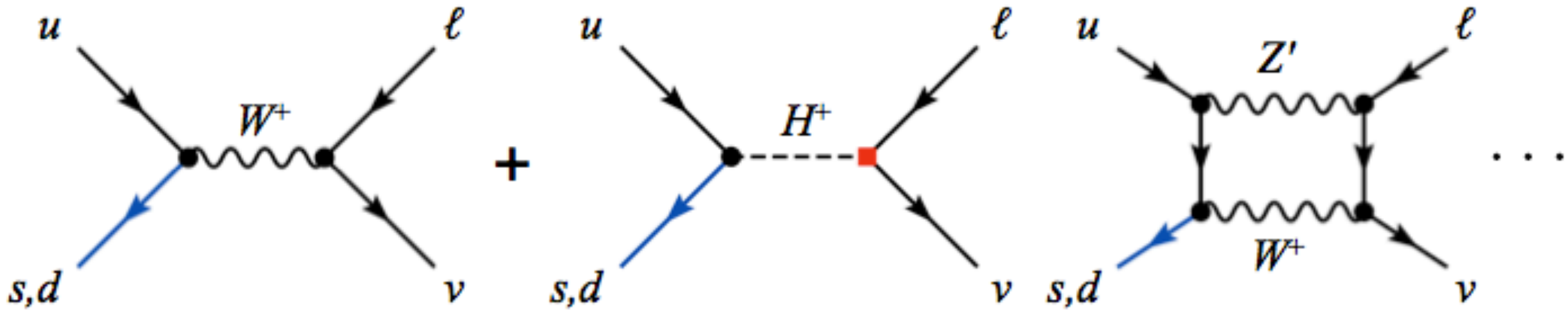
($|V_{ub}|^2 \approx 2\times10^{-5}$)

Most precise test of CKM unitarity

Universality: Is G_F from μ decay equal to G_F from π, K, nuclear β decay?

$$G_\mu^2 = (g_\mu g_e)^2/M_W^4 \quad \stackrel{?}{=} \quad G_{\rm CKM}^2 = (g_q g_\ell)^2 \left(|V_{ud}|^2 + |V_{us}|^2\right)/M_W^4$$

Physics beyond the Standard Model can break gauge universality:



Kl3 form-factor parameterization

Parameterizations based on systematic expansions

Taylor expansion:

$$\tilde{f}_{+,0}(t) = 1 + \lambda_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right)$$

$$\tilde{f}_{+,0}(t) = 1 + \lambda'_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right) + \lambda''_{+,0}\left(\frac{t}{m_{\pi^+}^2}\right)^2$$

Notes:

Many parameters: λ_+', λ_+'', λ_0', λ_0''

Large correlations, unstable fits

Parameterizations incorporating physical constraints

Pole dominance: $\tilde{f}_{+,0}(t) = \frac{M_{V,S}^2}{M_{V,S}^2 - t}$

Notes:

What does M_S correspond to?

Dispersion relations:

$$\tilde{f}_+(t) = \exp\left[\frac{t}{m_\pi^2}(\Lambda_+ - H(t))\right]$$

$$\tilde{f}_0(t) = \exp\left[\frac{t}{m_K^2 - m_\pi^2}(\ln C - G(t))\right]$$

Notes:

Allows tests of ChPT & low-energy dynamics

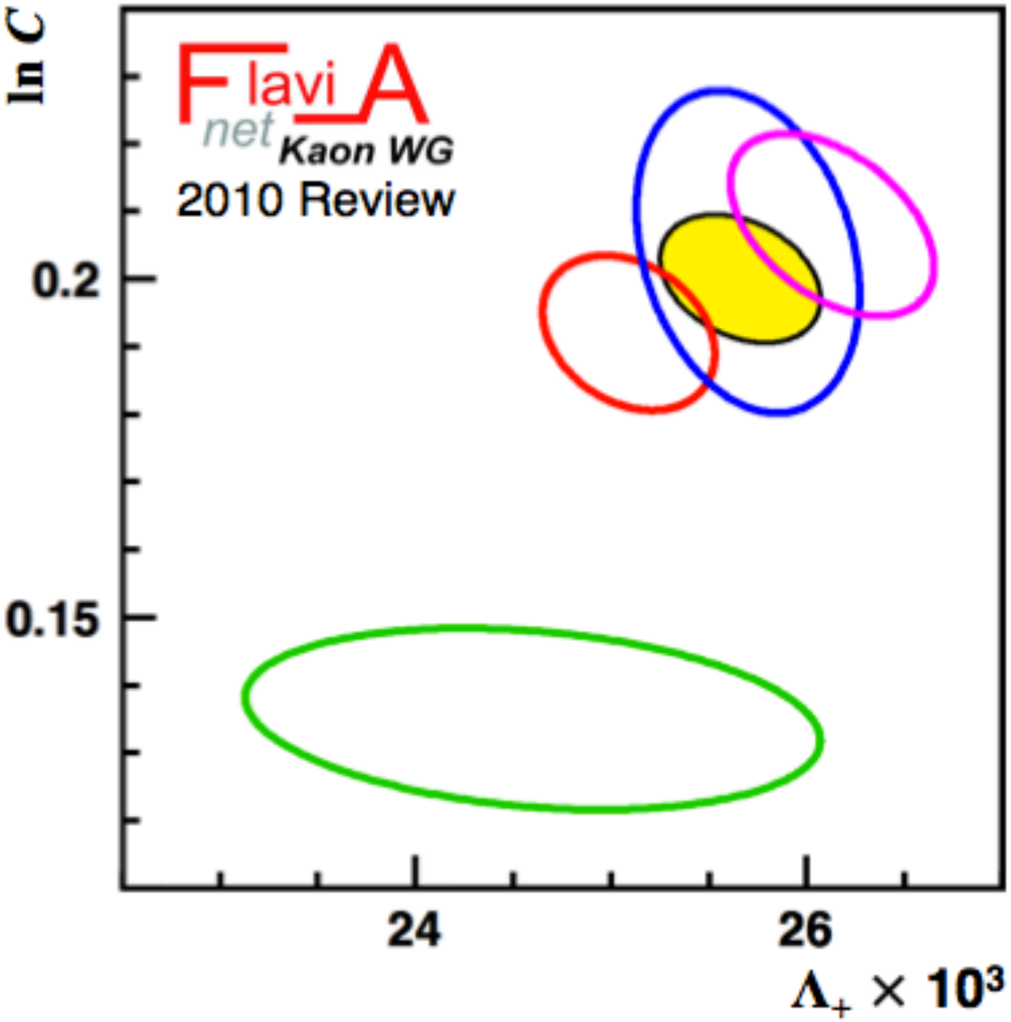
$H(t)$, $G(t)$ evaluated from $K\pi$ scattering data and given as polynomials

Bernard et al., PRD 80 (2009)

Dispersive parameterization for Kl3 FF

$K_{e3} + K_{\mu 3}$ averages from KTeV KLOE ISTRA+ NA48 2010 fit

For NA48, only K_{e3} data included in 2010 fit



$\Lambda_+ \times 10^3$	=	**25.61 ± 0.41**
$\ln C$	=	**0.2004(91)**
$\rho(\Lambda_+, \ln C)$	=	−0.328
χ^2/ndf	=	5.6/5 (34%)

Integrals

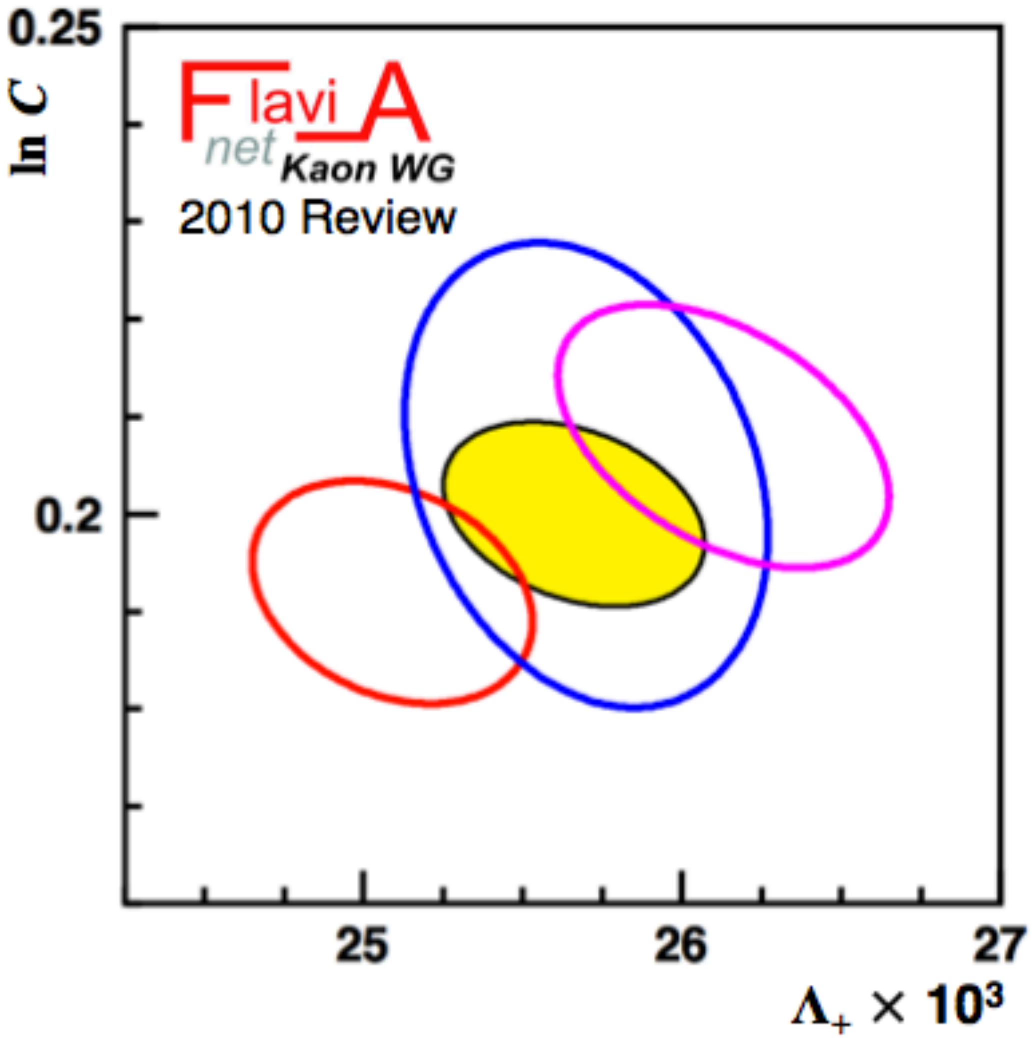
Mode	Quad-lin	Disp
$K^0{}_{e3}$	0.15457(20)	**0.15476(18)**
$K^+{}_{e3}$	0.15894(21)	**0.15922(18)**
$K^0{}_{\mu 3}$	0.10266(20)	**0.10253(16)**
$K^+{}_{\mu 3}$	0.10564(20)	**0.10559(17)**

Maximum change 0.2% if same data used as for quad-lin fits

Dispersive parameterization for Kl3 FF

$K_{e3} + K_{\mu3}$ averages from KTeV | KLOE | ISTRA+ | NA48 | 2010 fit

For NA48, only K_{e3} data included in 2010 fit



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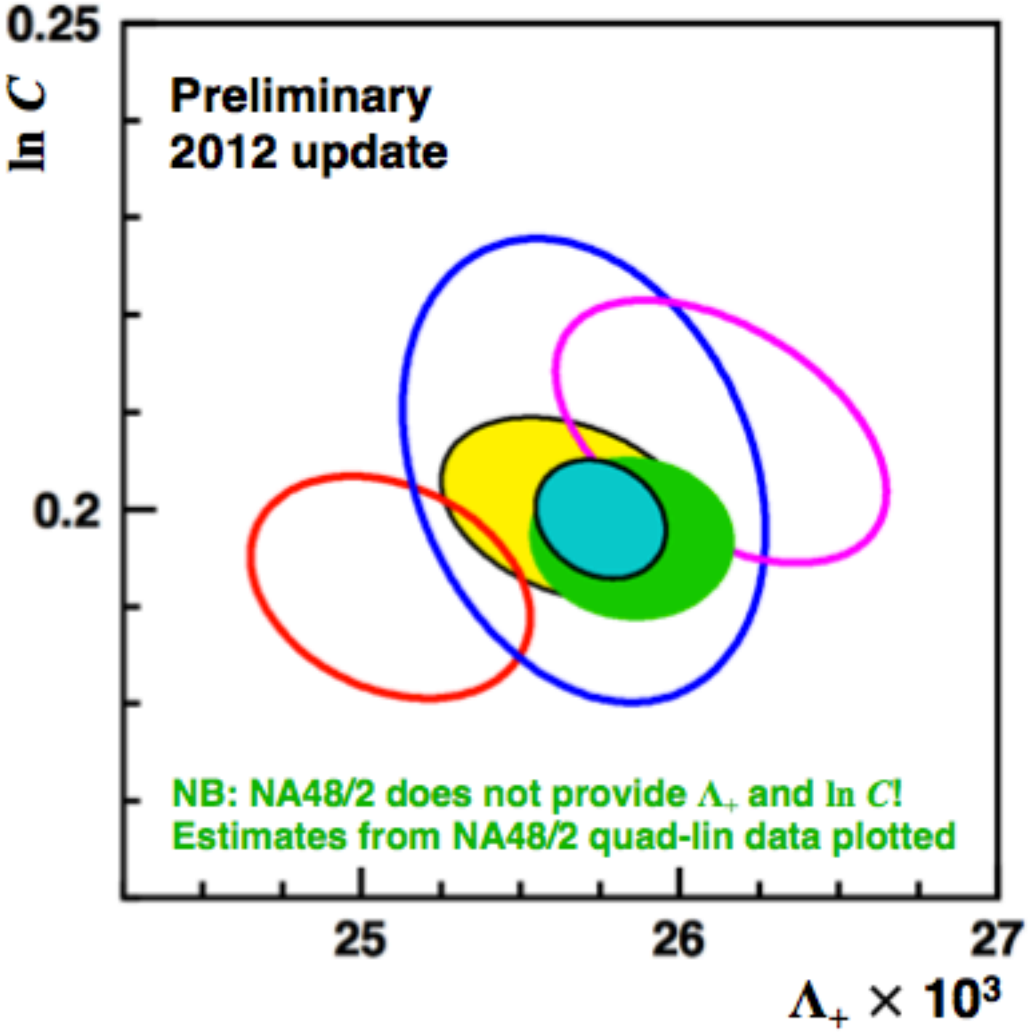
Dispersive parameterization for Kl3 FF

$K_{\ell 3}$ avgs from KTeV | KLOE | ISTRA+ | NA48/2 '12 prel | 2010 fit | Update

For NA48, only K_{e3} data included in fits



$$\Lambda_+ \times 10^3 = 25.75 \pm 0.36$$
$$\ln C = 0.1985(70)$$
$$\rho(\Lambda_+, \ln C) = -0.202$$
$$\chi^2/\text{ndf} = 5.9/7\ (55\%)$$

Integrals

Mode	Update	2010
$K^0{}_{e3}$	**0.15481(14)**	0.15476(18)
$K^+{}_{e3}$	**0.15927(14)**	0.15922(18)
$K^0{}_{\mu 3}$	**0.10253(13)**	0.10253(16)
$K^+{}_{\mu 3}$	**0.10558(14)**	0.10559(17)

Only tiny changes in central values

Implications from BSM physics

- 1st row unitarity tests probe a variety of BSM effects

$$\frac{1-|V_{uD}|^2}{1-|U_{\mu N}|^2} \cdot \frac{1}{1+BR^{\mu}_{\text{exotic}}} \cdot \frac{[G_F^{(\beta)}]^2}{[G_F^{(\mu)}]^2} = 1 + \Delta_{CKM}$$

Heavy fermion mixing

$$|V_{uD}| \leq 0.03$$
$$|U_{\mu N}| \leq 0.03$$

95% C.L.

Marciano 2008

Exotic muon decays

$$BR^{\mu}_{\text{exotic}} < 0.001$$

95% C.L.

Stronger than direct limits

$$BR(\mu^+ \to e^+ \bar{\nu}_e \nu_\mu) < 0.012$$

Marciano 2008

New interactions

- Can arise from heavy or light (and weakly coupled) new physics

- Focus here on the case of UV extensions of the Standard Model

EFT test

BSM operators modify (V-A)(V-A) coupling

$$\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[(1 + \delta_{RC} + \epsilon_L) \ \bar{e}\gamma_\mu (1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu (1-\gamma_5) d$$

BSM operators induce different interactions

$$+ \ \epsilon_R \ \bar{e}\gamma_\mu (1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu (1+\gamma_5) d$$

$$+ \ \epsilon_S \ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u} d$$

$$- \ \epsilon_P \ \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

$$+ \ \epsilon_T \ \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5) d \Big] + \text{h.c.}$$

BSM operators also modify Fermi constant from μ decays: $G_\mu = G_F^{(0)}(1-\varepsilon_L^{(\mu)})$

What we learn from Δ_{CKM}

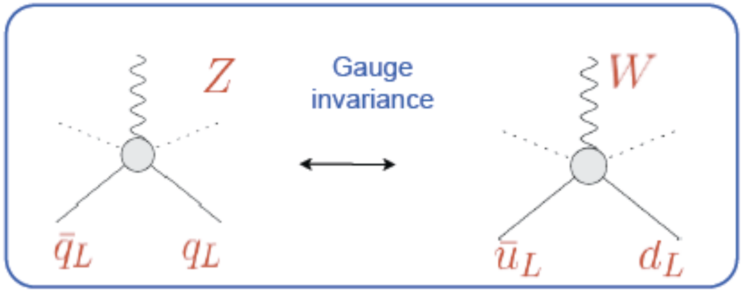
$\Delta_{CKM} = 2(\varepsilon_L - \varepsilon_L^{(\mu)})$ under $U(3)^5$ flavor symmetry

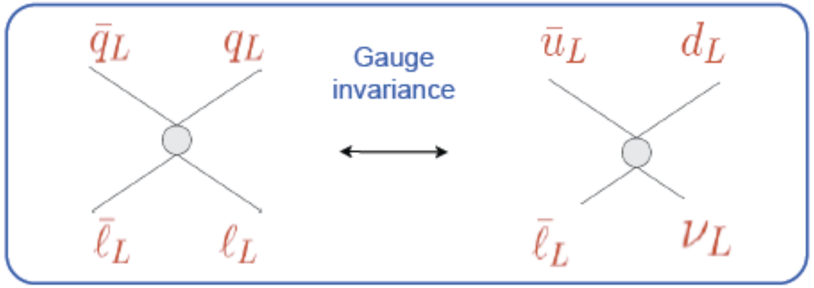
BSM operators also affects precision EW measurements

$$\epsilon_L = \epsilon_L^{(v)} + \epsilon_L^{(c)}$$

$|\epsilon_L|_{\text{vertex}} < 5 \times 10^{-4}$

$|\epsilon_L|_{4-\text{fermi}} < 4 \times 10^{-3}$





- Already strong constraints from Z-pole
- CKM is at the same level

- Constraints from σ_{had} at LEP would allow Δ_{CKM} ~0.01 !!
- CKM "wins" by factor of ~ 10

many other cases are also discussed (w/o $U(3)^5$; 2HDM, …)