The High-Intensity Frontier

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La Thuile, March 2, 2004

NEW ISSUES CAN BE INVESTIGATED IN SEVERAL WAYS:

1) At very high energies (LHC and beyond) searches can be made for the production of heavy particles (predicted or unpredicted) and for new phenomena (possibly totally unexpected).

2) At lower energies, searches can be made for very rare processes or for small deviations from expected results (for example, due to small effects caused by unseen heavy particles).

Historically, many fundamental discoveries and measurements have come from accelerators which were not the highest energy machine available at the time:

- weak neutral currents at the CERN PS
- J/ψ at the AGS (Brookhaven)
- limits on the lepton-number conservation
- most of the parameters of CP violation
- etc.

- **Leading the quest for new physics**
  - **direct searches:**
    - **LHC, ILC, CLIC**
  - **indirect evidence:**
    - **Leptons:** neutrino masses and mixings, LFV
    - **Quarks:** K, B hadron decays
    - **CPT** violation searches **, Axion** searches

- **Exploring dynamical issues**
  - **ancillary to the exploration of the fronteer, e.g.:**
    - better PDF's for LHC studies
  - **with no obvious or direct impact on the HE frontier:**
    - hadron spectroscopy
    - polarised/transverse/generalized/... PDFs
    - ...

Beyond the Standard Model: the clue from Hadron studies ...

- **Precision study of hadrons ….**

  deviations in expected behaviour of light and c quarks ➡ evidence for new physics + will elucidate new physics if found elsewhere

  - Rare decays
  - Mixing & CPV

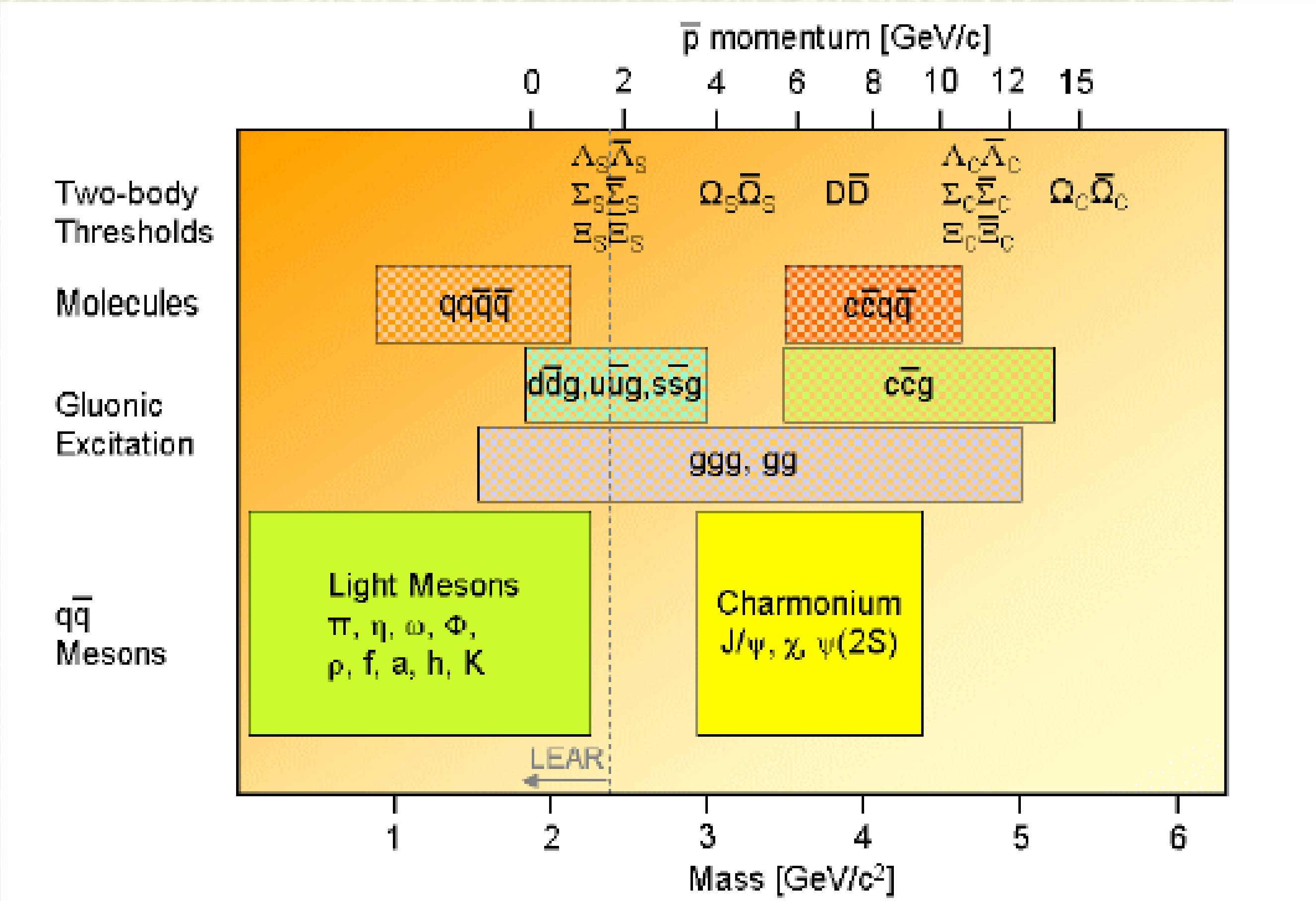
Study of QCD Systems

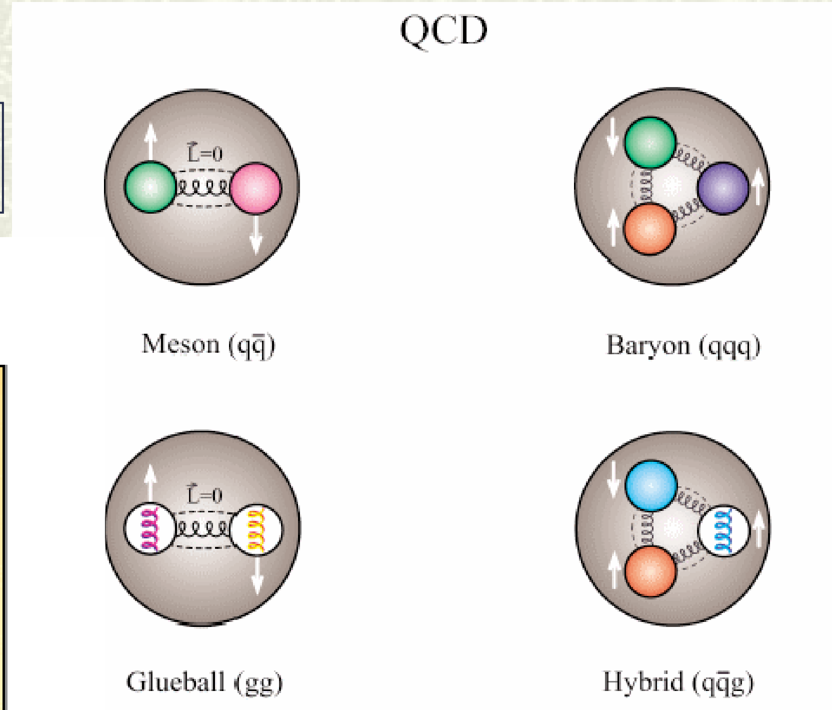
Search for foreseen states, look for exotics (not yet established !!):

→ Light states

→ Heavy states

QCD systems

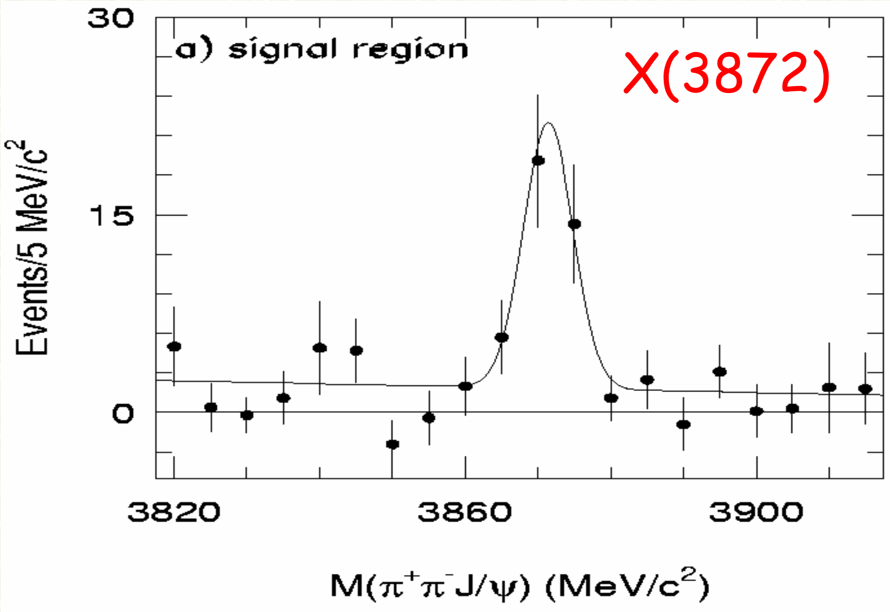




Many different experimental approaches.

The Renaissance of Hadron Spectroscopy

- **Quarkonium**
  - η'_c (Belle, BaBar, CLEO)
  - X(3872) (Belle, CDF, D0, BaBar)
- **Narrow Charmed States**
  - D_{sJ} (BaBar, CLEO, Belle)
  - $D_{sJ}(2632) \rightarrow \eta D_s^+$ (Selex ?)
  - Ξ_{cc} (Selex ?)
- **Pentaquark candidates**
  - $\Theta^+(1540)$
  - $\Xi^{--}(1862)$
  - $\Theta_c^+(3100)$



M = 3872.0 ± 0.6 ± 0.5 MeV
Γ< 2.3 MeV (90 % C.L.)

Statistics is relevant!

Although statistics might be a not sufficient condition, it is certainly necessary!

PS	10^{13} p/sec @ 26 GeV/c
SIS100/300	10^{13} p/sec @29GeV/c
NEW PS	$6x10^{14}$ p/sec @ 30 GeV/c

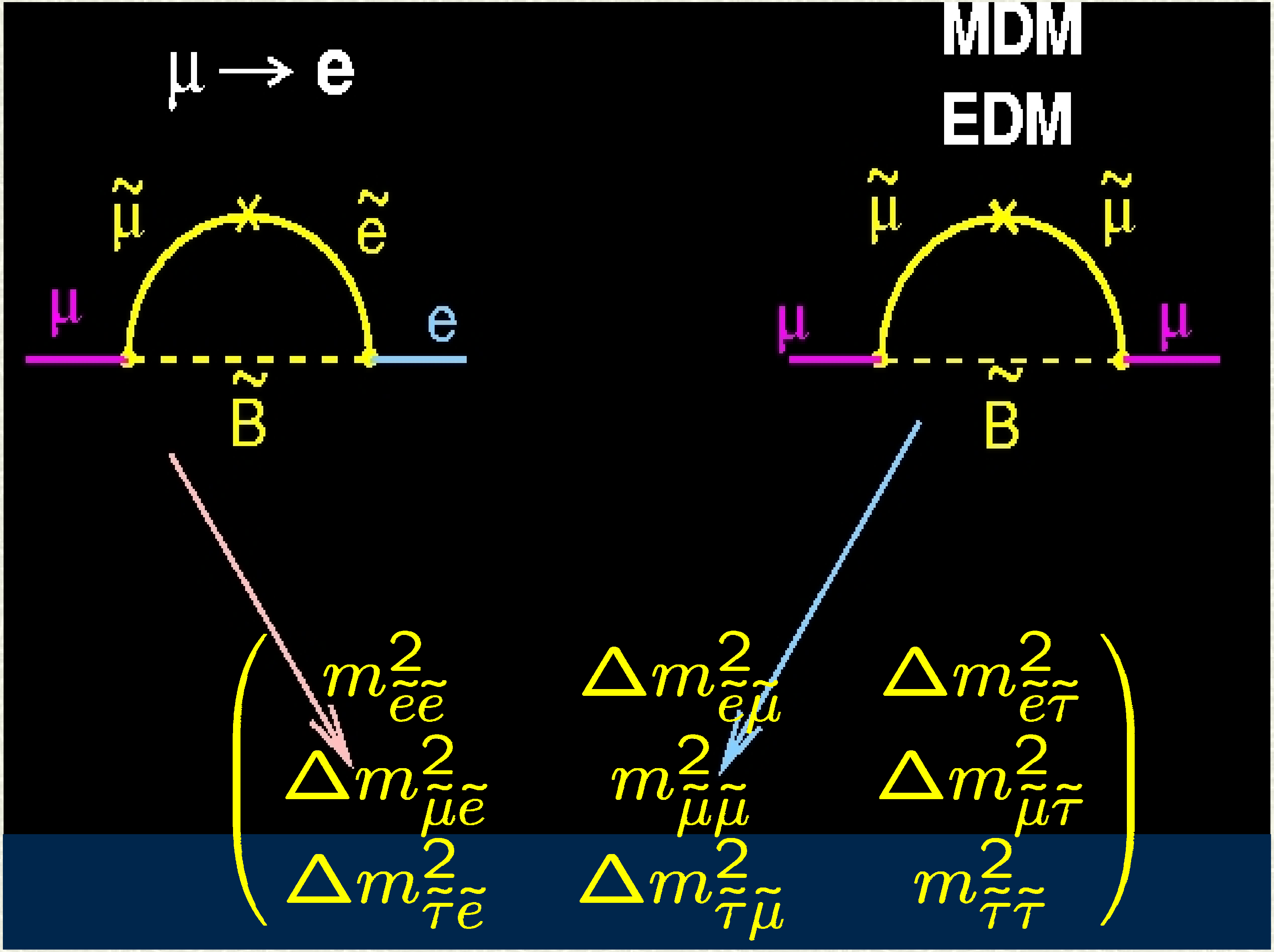
Hadron Physics Summary

- **Strong interaction effects** have important (crucial) impact on **many different measurements** and **New Physics** searches
- Many short/medium term projects already planned
  - GSI-JLab-CLEO-c, LHC-b
- Where will we be in 10 years from now?
- A vast program in the field of hadronic physics will be possible with a **diverse and flexible accelerator complex.**

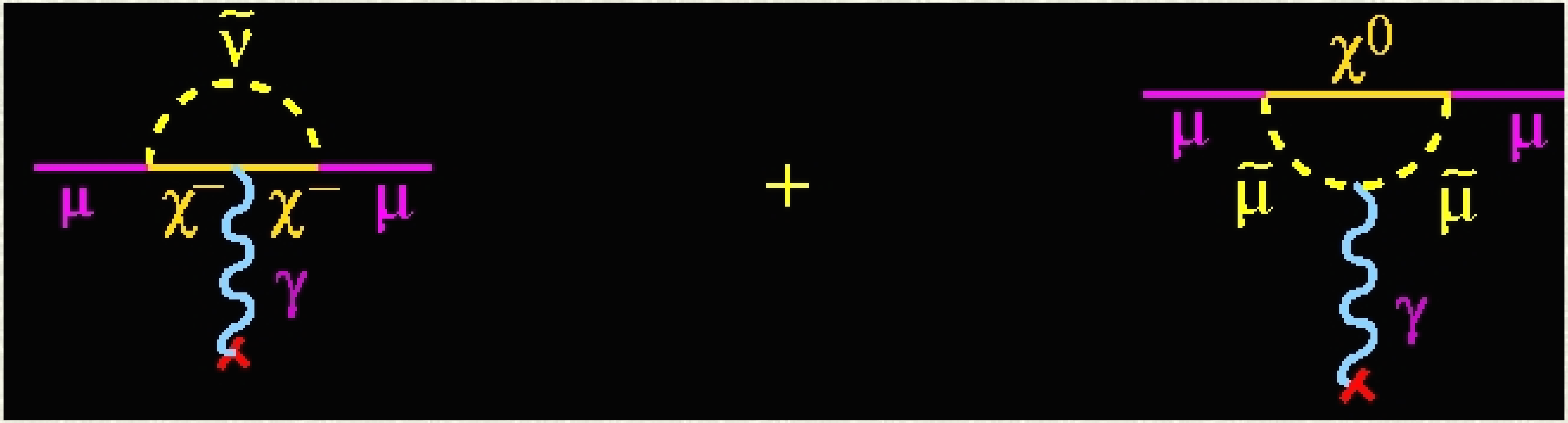
Future Muon Dipole Moment Measurements

- at a high intensity muon source

SUSY connection between D_μ, $\mu \to e$ (LFV)



a_μ is sensitive to **all** virtual particles which couple to the muon, e.g. SUSY



a toy model with equal susy masses gives:

$$a_\mu(\mathrm{SUSY}) \sim 1.3 \ \mathrm{ppm} \quad \tan\beta \left(\frac{100 \ \mathrm{GeV}}{\tilde{m}}\right)^2$$

If SUSY is discovered at LHC, then (g-2) will give a 20% determination of tan β

Required μ Fluxes

Experiment	N_μ	p_μ(MeV)	$\Delta p_\mu / p_\mu$(%)	sensitivity	I_{off}/I_{on}, δT, ΔT
$\mu^+ \to e^+e^-e^+$	10^{17}	< 30	< 10	BR=10^{-15}	DC beam
$\mu^+ \to e^+\gamma$	10^{17}	< 30	< 10	BR=10^{-15}	DC beam
$\mu^- - e^-$ pulsed	10^{21}	< 80	< 5	BR=10^{-19}	10^{-10}, < 100ns, $> 1\mu$s
$\mu^- - e^-$ continuos	10^{20}	< 80	< 5	BR=10^{-19}	DC beam
μEDM	$10^{16}/P^2$	$300 - 500$	< 5	$10^{-24}\,e\,cm$	pulsed beam
$g-2$	10^{16}	3100	< 2	< 0.1ppm	pulsed beam

momentum range (GeV/c)	length (m)	flux per sec	beam purity
0.4 to 0.8	17.5	K^+ 10^6 K^- $5\cdot10^5$	$\pi/K \gtrsim 1$
0.4 to 0.8	14.5	K^+ $5\cdot10^6$ K^- 2.5×10^6	$\pi/K \gtrsim 1$
0.7 to 1.5	26.5	K^+ $6\cdot10^6$ K^- $3\cdot10^6$	$\pi/K \sim 2$
1.2 to 2.5	32	K^+ 10^7 K^- $5\cdot10^6$	$\pi/K \sim 1$
4 to 13	750	μ^+ $5\cdot10^8$	π/μ 10^{-6}
1 to 6	750	$\bar{p}$ $2\cdot10^6$	10^{-3}
		$\bar{p}$ $3\cdot10^8$	$\pi^-/\bar{p}$ 3
		$\bar{p}$ $2\cdot10^8$	20
2.5 to 7.5	90	K^+ $8\cdot10^7$ K^- $3\cdot10^7$	$\pi/K \sim 3(4)$
K^0_L (0°)	50	K^0_L 10^7	(3.5m C abs) $K^0_L/n \sim 1$

PHYTHIA: E = 30 GeV, I = 80 μA

Summary on muons

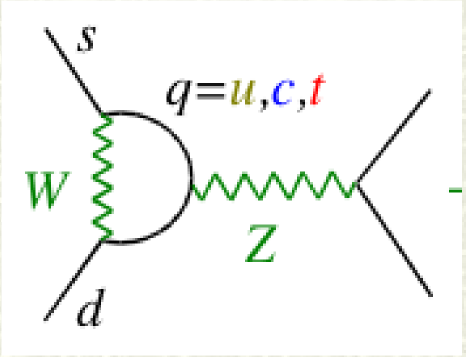
- Both g-2 and μEDM are sensitive to new physics *behind the corner*
- Unique opportunity of studying *phases of mixing matrix* for SUSY particles
- Historically, limits on d_E have been strong tests for new physics models
- μEDM would be the first tight limit on d_E from a second generation particle
- The experiments are hard but, in particular the μEDM, not impossible
- A large muon polarized flux of energy 3GeV (g-2) or 0.5GeV (μEDM) is required

Why study Rare Kaon Decays

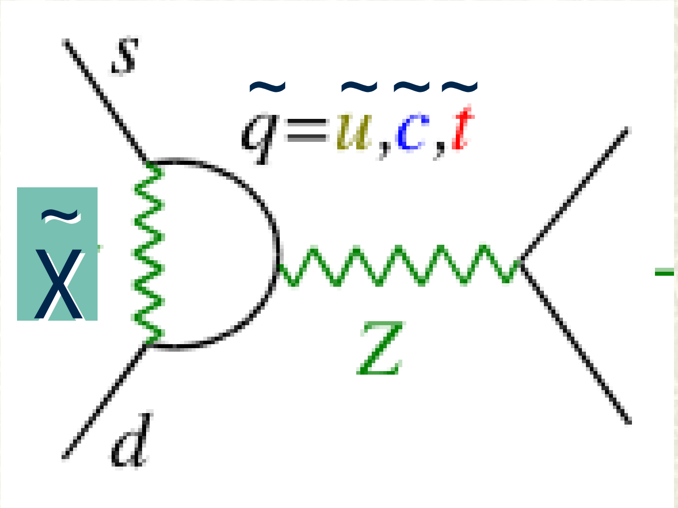
- Search for explicit violation of Standard Model
  - Lepton Flavour Violation
- Probe the flavour sector of the Standard Model
  - FCNC
- Test fundamental symmetries
  - CP,CPT
- Study the strong interactions at low energy
  - Chiral Perturbation Theory, kaon structure

Guiding rationale

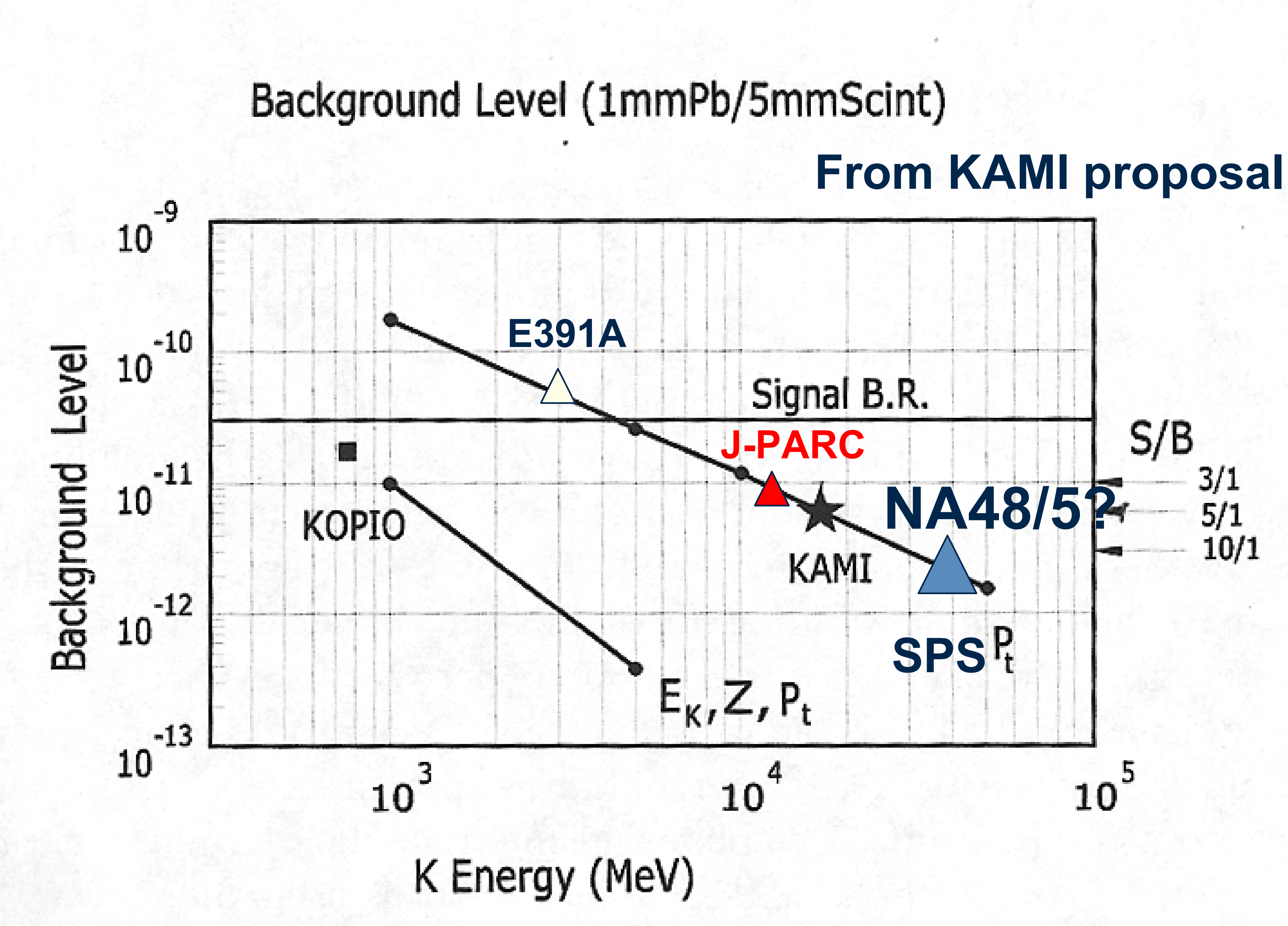
In the SM:



In Supersymmetry:



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



New projects starting/proposed

		Tp/s	MK/s
K_L KOPIO (BNL):	2010+ on track	14	33
K_L (J-PARC):	2008++ (beam line? accidentals?)	60	320
K_L KLOD (Protvino):	2007+	1.1	9
K^+ (CERN):	After R&D, 2009+ (tracking?)	0.2	9
K^+ CKM-2 (FNAL):	Re-design, 2009+ (tracking?, veto?)	2	3(?)
K^+ (J-PARC):	2008+ (improvements?)	23	2.3
K^+ OKA (Protvino)	2005+ ($K \to 3\pi$)	1.1	0.6

Conclusion for K's

Absolutely clear physics case, to be pursued with the strongest determination in a global context of healthy, aggressive and very competent competition

The discovery of Supersymmetry at the LHC will dramatically increase the motivation for searches of new phenomena in flavour physics.

The K physics programme will find a natural complement in the B physics studies at the LHC, and in new Lepton Flavour Violation searches.

The definition of a potential LFV programme and the study of its implications for the accelerator complex should be strongly encouraged and supported

ν

Neutrino oscillations are the most important discovery in HEP in the last 15 years

Most of the parameters are waiting to be measured

δm^2_{12} ✓ SOLARS+KAMLAND $\delta m^2_{12} = (7 +/- 1)\ 10^{-5}\ eV^2$

θ_{12} ✓ SOLARS+KAMLAND $0.2 < \sin^2(\theta_{12}) < 0.5$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} ✓ ATMOSPHERICS $\delta m^2_{23} = (2.0 +/- 0.4)\ 10^{-3}\ eV^2$

θ_{23} ✓ ATMOSPHERICS $0.9 < \sin^2 2(\theta_{23}) < 1$

θ_{13} ☐ CHOOZ LIMIT $\theta_{13} < 14^0$

δ_{CP} ☐

Mass hierarchy ☐

Σm_ν ☐ BETA DECAY END POINT $\Sigma m_\nu < 6.6\ eV$

Dirac/Majorana ☐

Straightforward theoretical interpretation: entries of a 3x3 matrix

Clear criteria driving the experimental design/optimization:

source

$$P(\nu_i \rightarrow \nu_j) = S \times \sin(\Delta m^2 E / L)$$

beam purity, backgrounds

Source power, detector Volume

location

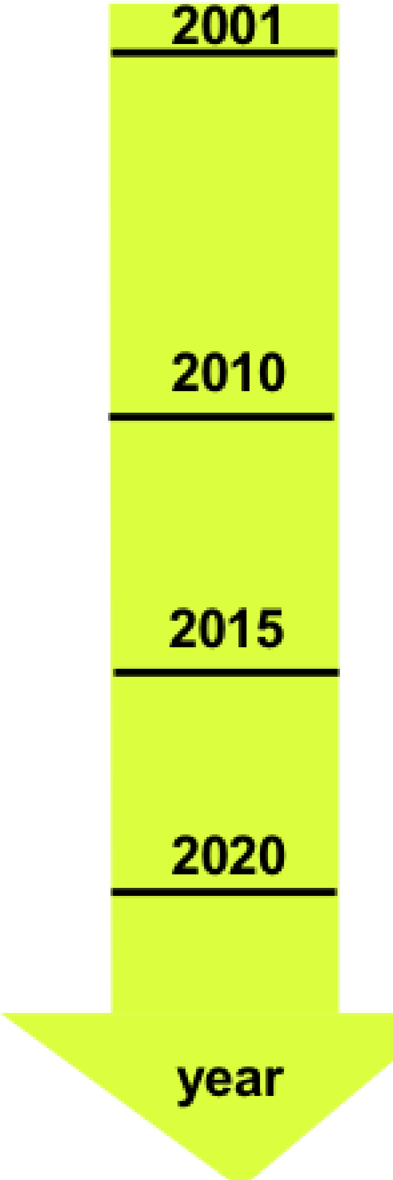
Rather general consensus on the pros and cons of different configurations:

Perhaps too much consensus? K→SK→YK→?K .....

Need to explore new detector concepts? capabilities?

Timescale

At least 4 phases of Long Baseline experiments



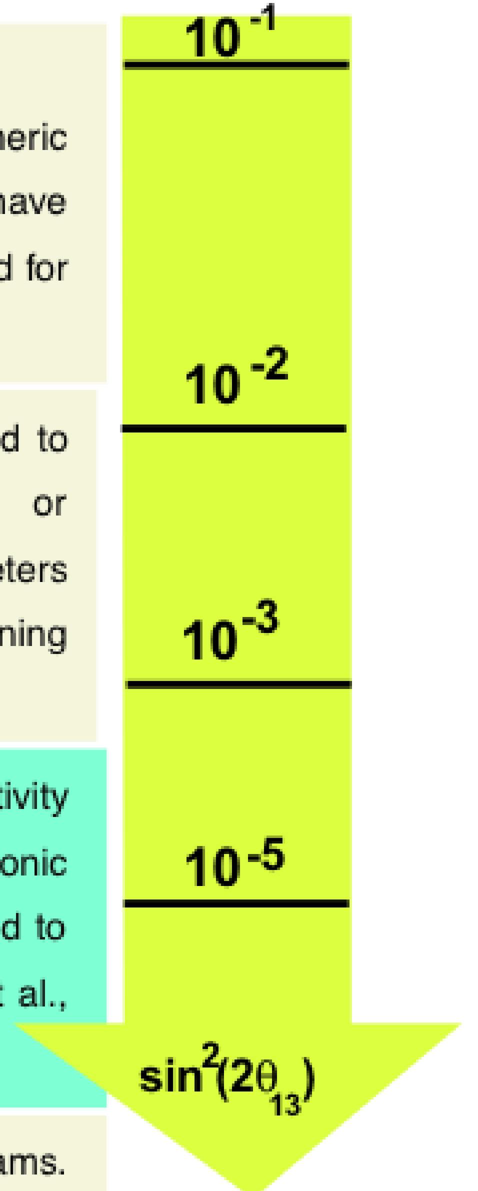
1) 2001-2010. K2K, Opera, Icarus, Minos.

Optimized to confirm the SuperK evidence of oscillation of atmospheric neutrinos through ν_μ disappearance or ν_τ appearance. They will have limited potential in measuring oscillation parameters. Not optimized for ν_e appearance (θ_{13} discovery).

2) 2009-2015. T2K (approved), Noνa, Double Chooz. Optimized to measure θ_{13} (Chooz $\times$ 20) through ν_e appearance or ν_e disappearance. Precision measure of the atmospheric parameters (1 % level). Tiny discovery potential for CP phase δ, even combining their results.

3) 2015 - 2025. SuperBeams and/or Beta Beams. Improved sensitivity on θ_{13} (Chooz $\times$ 200). They will have discovery potential for leptonic CP violation and mass hierarchy for $\theta_{13} \geq 1^\circ$. In any case needed to remove any degeneracy from Nufact results (see P. Hernandez et al., hep-ph/0207080)

4) Ultimate facility: Neutrino Factories or high energy Beta Beams. Ultimate sensitivity on the CP phase δ, θ_{13} , mass hierarchy.



ν beams parameters

Main parameters for present and future long base-line neutrino oscillation experiments at accelerators with conventional ν_μ beams.

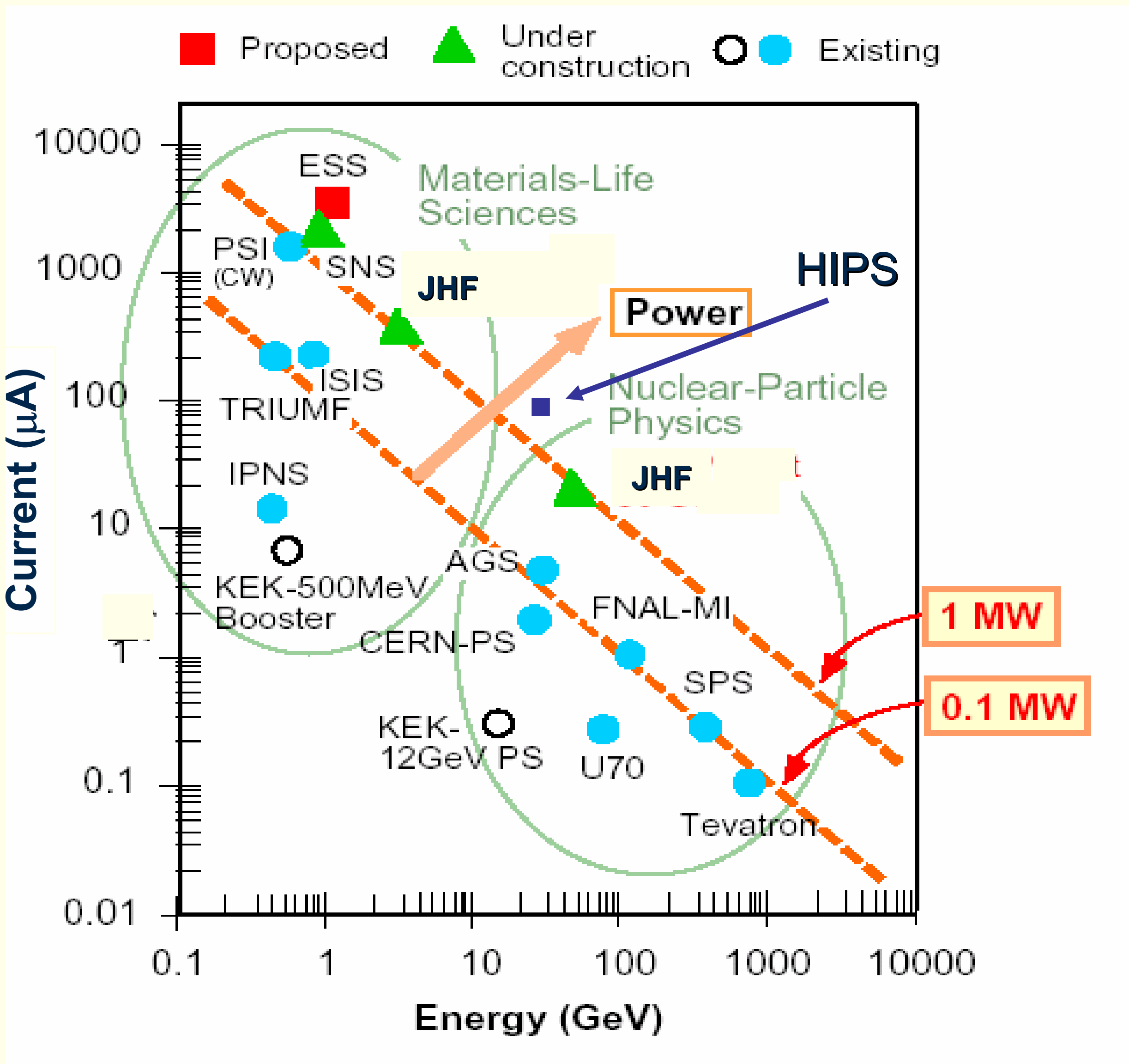
Neutrino facility	Proton momentum (GeV/c)	L (km)	$E_\nu (GeV)$	p.o.t./year (10^{19})
KEK PS	12	250	1.5	2
FNAL NUMI	120	735	3	36
CERN CNGS	400	732	17.4	4.5
CERN SPL	2.2	130	0.27	10000
JHF-OA	50	295	0.76	100
NUMI-OA	120	820	2.0	40

Current and planned facilities

	E_p (GeV)	Power (MW)	Beam	$\langle E_n \rangle$ (GeV)	L (km)	M_{det} (kt)	n_mCC (/yr)	n_e @peak
K2K	12	0.005	WB	1.3	250	22.5	~50	~1%
MINOS(LE)	120	0.4	WB	3.5	730	5.4	~2,500	1.2%
CNGS	400	0.3	WB	18	732	~2	~5,000	0.8%
T2K-I	50	0.75	OA	0.7	295	22.5	~3,000	0.2%
NOnA	120	0.4	OA	~2	810?	50	~4,600	0.3%
C2GT	400	0.3	OA	0.8	~1200	1,000?	~5,000	0.2%
T2K-II	50	4	OA	0.7	295	~500	~360,000	0.2%
NOnA+PD	120	2	OA	~2	810?	50?	~23,000	0.3%
BNL-Hs	28	1	WB/OA	~1	2540	~500	~13,000	
SPL-Frejus	2.2	4	WB	0.32	130	~500	~18,000	0.4%
FeHo	8/120	"4"	WB/OA	1~3	1290	~500	~50,000	

From: Takashi Kobayashi, Paris 2004

High Intensity Machines



Long term: preliminary comparison

	INTEREST FOR			
	LHC upgrade	Neutrino physics beyond CNGS	Radioactive ion beams (EURISOL)	Others **
SPL * (>2 GeV – 50 Hz)	Valuable	Very interesting for super-beam + beta-beam	Ideal	Spare flux ⇒ possibility to serve more users
RCS (30 GeV – 8 Hz)	Valuable	Very interesting for neutrino factory	No	Valuable
New PS (30 GeV)	Valuable	No	No	Valuable
New LHC injector (1 TeV)	Very interesting for doubling the LHC energy	No	No	Potential interest for kaon physics

* Comparison should also be made with an RCS of similar characteristics.

** Input expected from the present workshop !

MARGINALIA

- Sociology of particle physics should not be neglected.
- Higher Energy machines will host fewer experiments:
    - personal satisfaction of physicists
    - difficulties in incorporating new and innovative ideas
    - difficulties for proper training of graduate students

A HIPS will host a large number of experiments, each with a “moderate” number of experimenters. Some risky innovative experiments will be possible. Graduate students will be able to grasp all aspects of an experiment.

QCD and strong interactions

- Strong interaction studies will play a crucial role: QCD is ubiquitous in high energy physics!

  Once new particles are discovered at LHC, it will be mandatory to explore parameters, mixing patterns, i.e , **we need an unprecedented ability to interpret the strong interaction structure of final states**

  Synergy: Kaon system, Heavy Flavour, Hadron spectroscopy

- Many intellectual puzzles still open in QCD!
  - Confinement, chiral symmetry breaking, vacumm structure (glueballs etc) light particle classifications, multi-quark states...

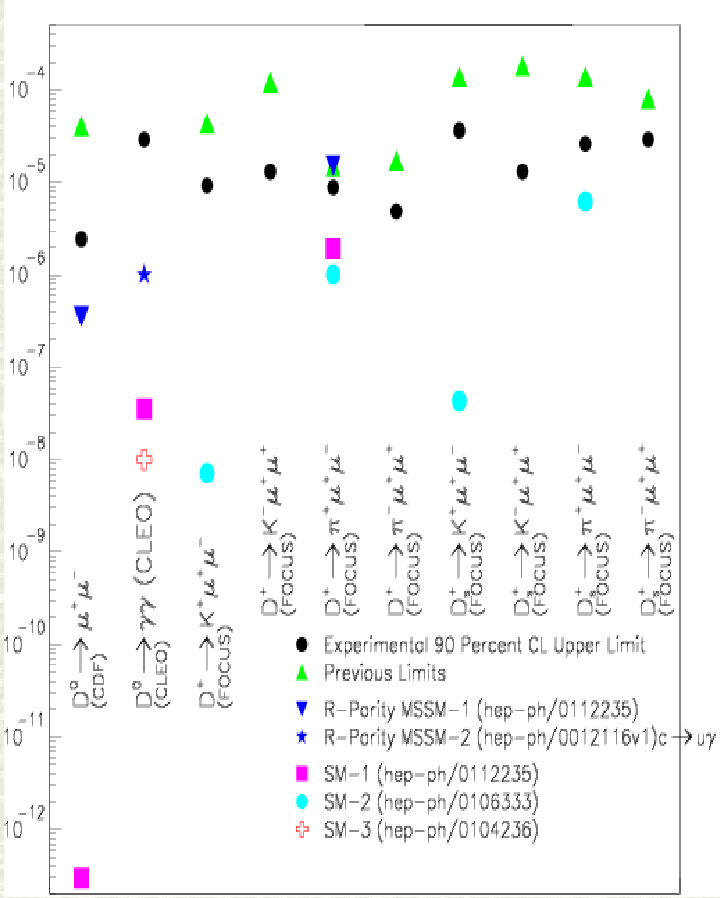
Rare and forbidden decays

Motivation: lepton number violation study
investigation of long range effects and SM extension

$$D^+, D_s^+ \rightarrow h^\pm \mu^\mp \mu^+$$

$$(h = \pi, K)$$

Approaching theoretical predictions for some of the modes but still far for the majority



Present EDM Limits

Particle	*Present EDM limit* (e-cm)	*SM value* (e-cm)
n	6.3×10^{-26}	10^{-31}
e^{-}	$\sim 1.6 \times 10^{-27}$	10^{-38}
μ	$< 10^{-18}$ (CERN) $\sim 10^{-19}$ * (E821)	10^{-35}
future μ exp	10^{-24} to 10^{-25}	

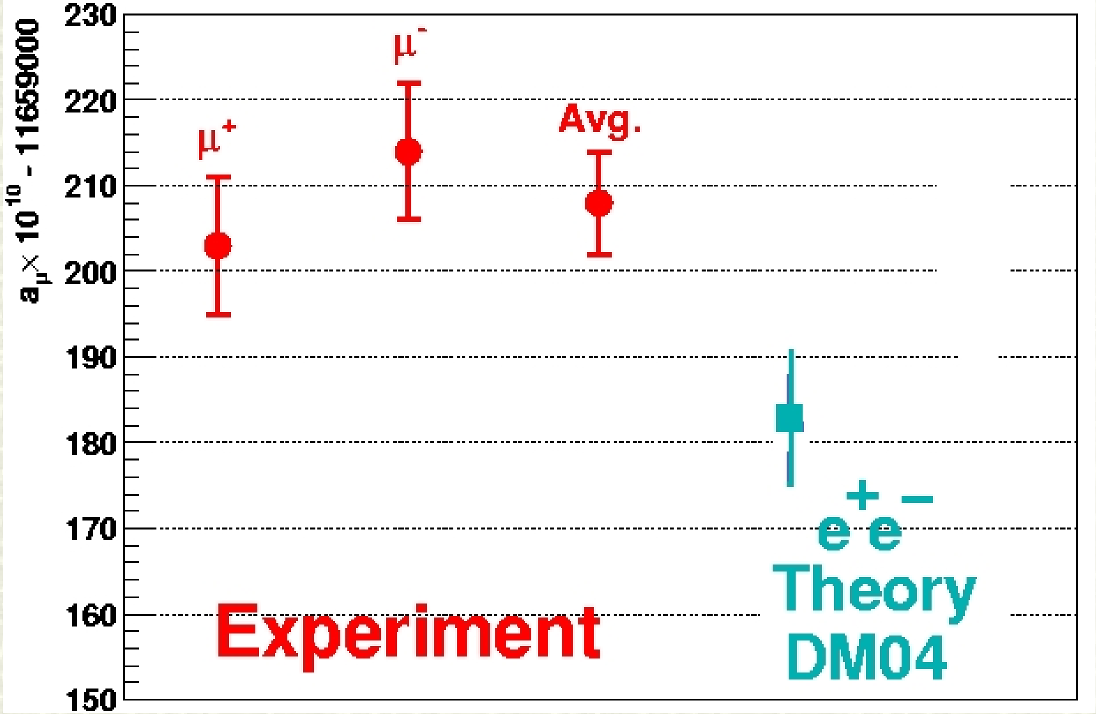
*projected

Unlike the EDM, a_μ is well measured.

$$a_{\mu^-} = 11\,659\,214(8)(3) \times 10^{-10} \quad (\pm 0.7\,\text{ppm})$$

$$a_{\mu^+}(\text{exp}) = 11\,659\,203(8) \times 10^{-10} \quad (\pm 0.7\text{ppm})$$

Comparing with e^+e^- - data shows a discrepancy with the standard model of 2.4σ



the combined value is

$$a_\mu(\text{exp}) = 11\,659\,208(6) \times 10^{-10} \quad (\pm 0.5\,ppm)$$

$$K^+ \to \pi^+ \nu \bar{\nu} \qquad K^0_L \to \pi^0 \nu \bar{\nu}$$

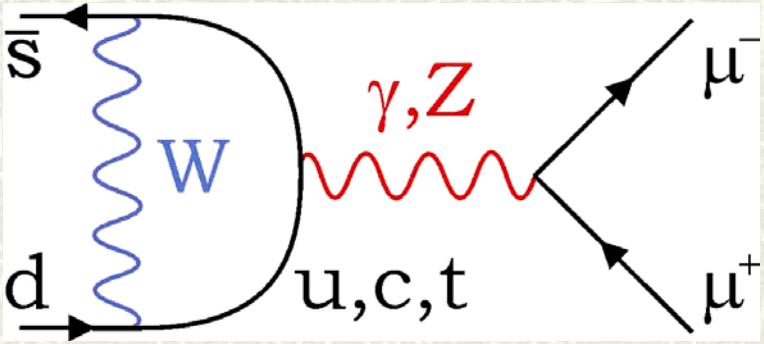
$$K^0_L \to \pi^0 e^+ e^- \qquad K^0_L \to \pi^0 \mu^+ \mu^-$$

A measurement of the 4 decay modes is a crucial element in the exploration of the new physics discovered at the LHC.

Accuracies at the level of 10% would already provide precious quantitative information

$K^0_L \to \pi^0 e^+ e^-$ and $K^0_L \to \pi^0 \mu^+ \mu^-$

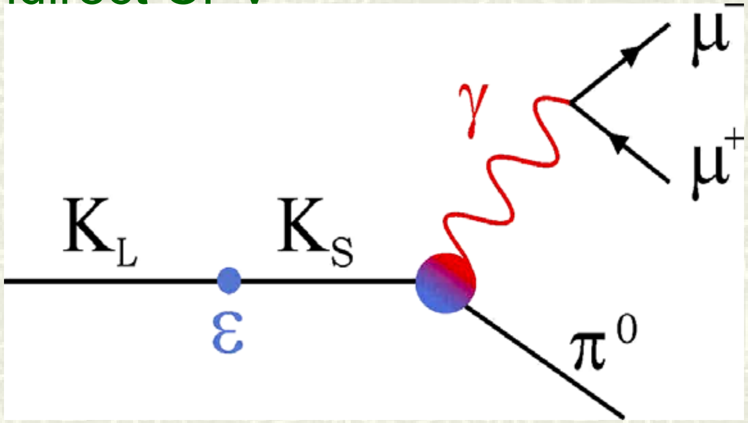
Study Direct CP-Violation

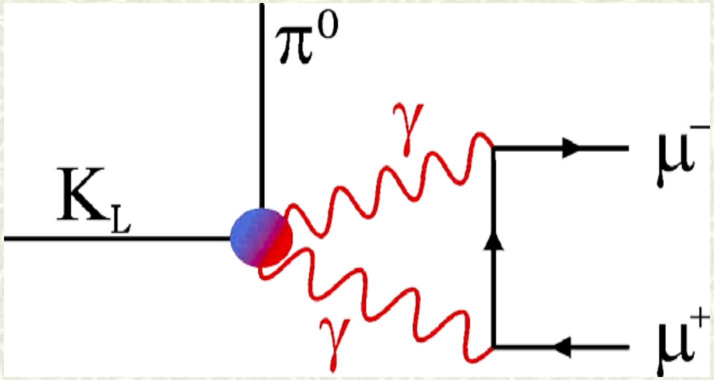


Direct CPV

- Indirect CP-Violating Contribution has been measured (NA48/1, see next slide)
- Constructive Interference (theory)
- CP-Conserving Contributions are negligible

Indirect CPV





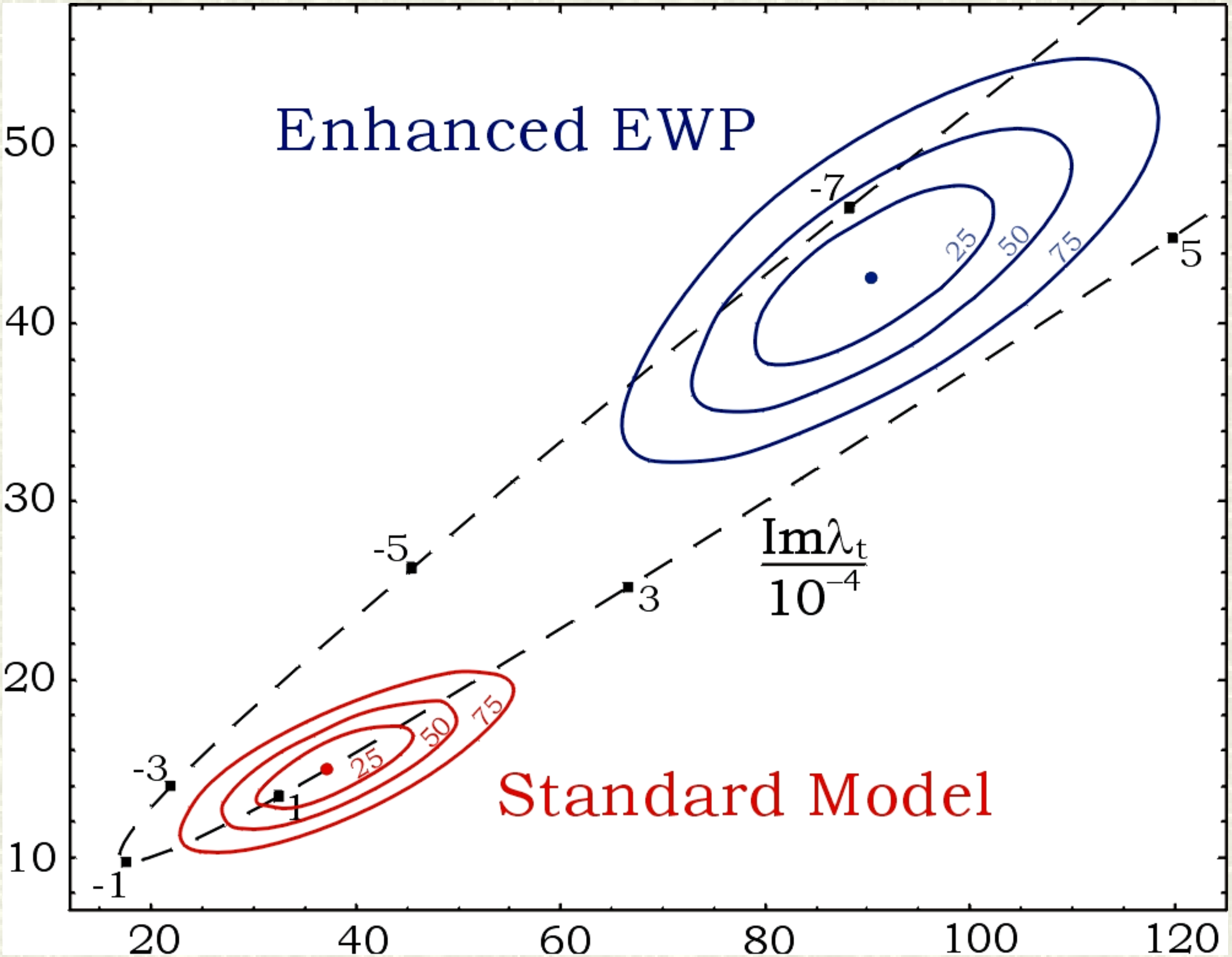
CPC

0^{++}, 2^{++}

$K^0_L \to \pi^0 ee\ (\mu\mu)$: Sensitivity to New Physics

Isidori, Unterdorfer,Smith:

$Br(K_L \to \pi^0 \mu^+ \mu^-)\quad (\times 10^{-12})$



$Br(K_L \to \pi^0 e^+ e^-)\quad (\times 10^{-12})$

Fleisher et al:

Ratios of B → Kπ modes could be explained by enhanced electroweak penguins

and enhance the BR's:

$$B^{NP}_{e^+e^-} = 9.0^{+1.6}_{-1.6} \times 10^{-11}$$

$$B^{NP}_{\mu^+\mu^-} = 4.3^{+0.7}_{-0.7} \times 10^{-11}$$

* A. J. Buras, R. Fleischer, S. Recksiegel, F. Schwab, hep-ph/0402112

$K^0_L \rightarrow \pi^0 \nu \nu$

- **Purely theoretical error ~2%: SM 3 10^{-11}**
  - Purely CP-Violating (Littenberg, 1989)
  - Totally dominated from t-quark
  - Computed to NLO in QCD (Buchalla, Buras, 1999)
  - No long distance contribution SM~3 × 10^{-11}

- **Experimentally: 2/3 invisible final state !!**
- **Best limit from KTeV using $\pi^0 \rightarrow ee\gamma$ decay**

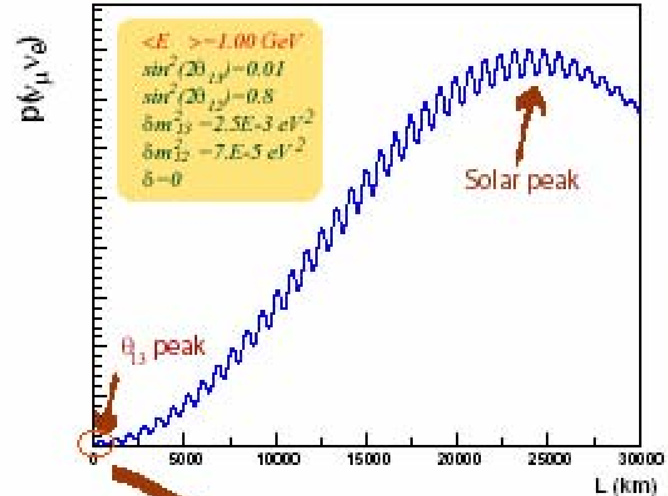
$BR(K^0 \rightarrow \pi^0 \nu\nu) < 5.9 \times 10^{-7}$ 90% CL

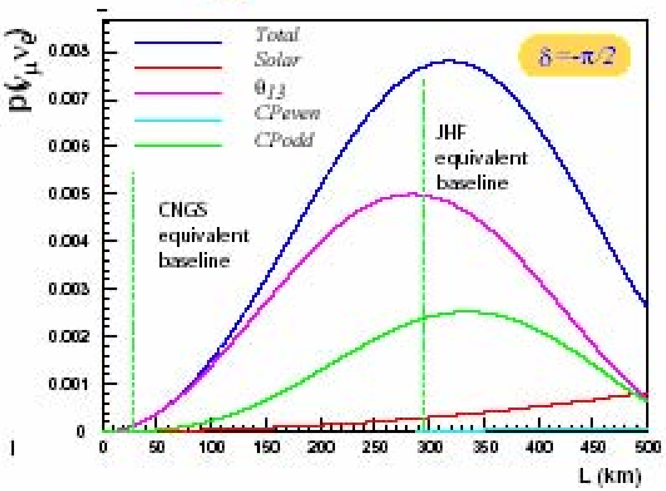
Still far from the model independent limit:

$BR(K^0 \rightarrow \pi^0 \nu\nu) < 4.4 \times BR(K^+ \rightarrow \pi^+ \nu\nu) \sim 1.4 \times 10^{-9}$

Grossman & Nir, PL B407 (1997)

Sub leading $\nu_\mu - \nu_e$ oscillations





$p(\nu_\mu \rightarrow \nu_e)$ developed at the first order of matter effects

$$p(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13}\text{ driven}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \text{ CPeven}$$

$$- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\} \sin\frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$- 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1 - 2s_{13}^2) \qquad \text{matter effect (CP odd)}$$

where $a = \pm 2\sqrt{2} G_F n_e E_\nu = 7.6 \cdot 10^{-5} \rho[g/cm^3] E_\nu[GeV] \quad [eV^2]$

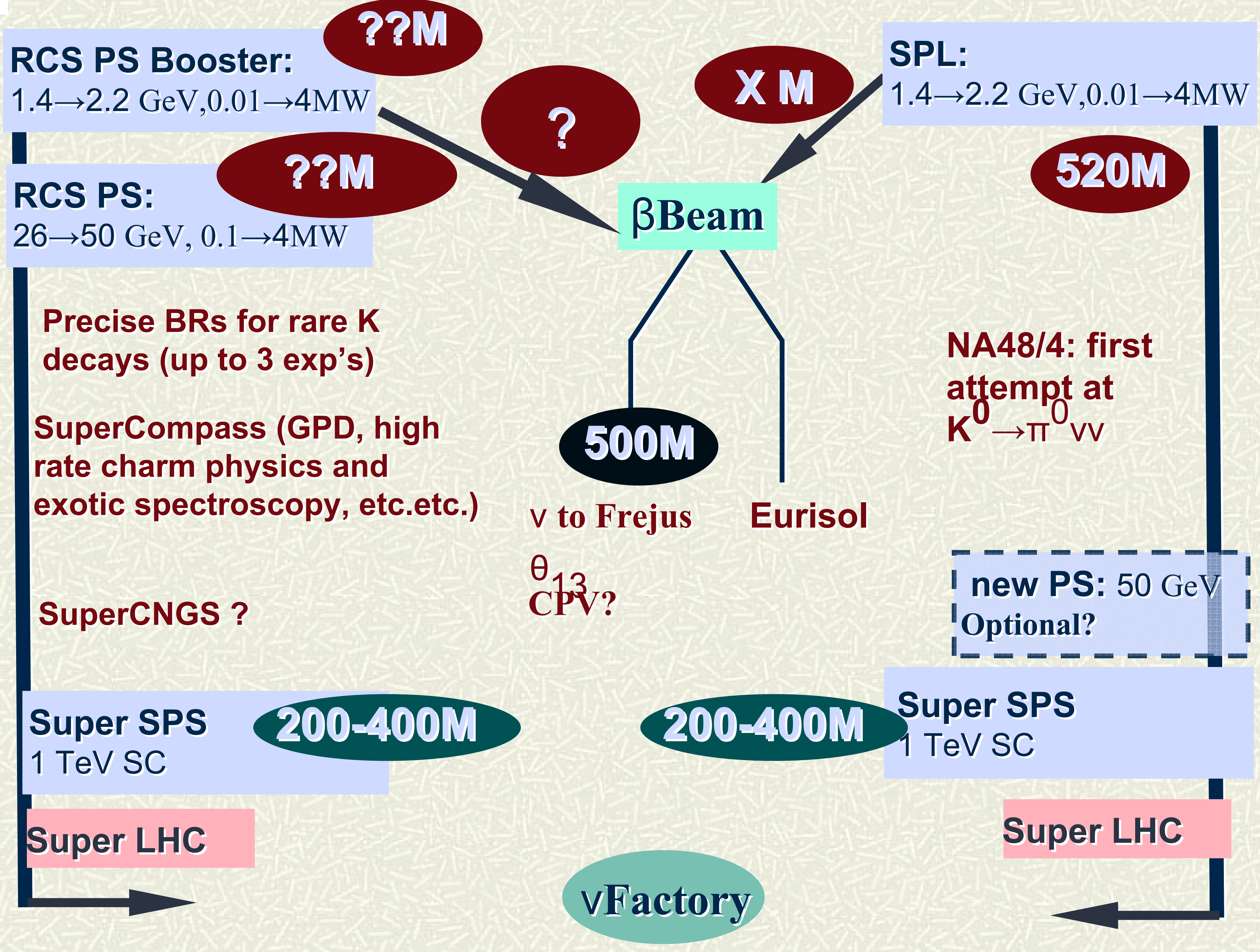
Sensitivity to θ_{13}

The expected 90% C.L. sensitivity on θ_{13} measurements for the long-baseline experiments for $\Delta m^2_{23} \sim 2.5 \cdot 10^{-3}$ eV ($\delta = 0$).

Experiment	fid mass (Kt)	θ_{13}
MINOS	5.0	7.1^0
ICARUS + OPERA	$2.4 + 1.8$	5^0
ICARUS - L.E.$\times$1.5	2.4	3.5^0
β-Beam	440	0.8^0
CERN SPL	440	1.2^0
T2K	22.5	2.3^0
NOνA	50	1.8^0
Neutrino Factory	40	$< 0.1^0$

Machines comparison

		T2K	J-Park 2	PS+++	SPL	βB
power p-driver	(MW)	0.75	4	4	4	0.4
p-beam energy	(GeV)	50	50	20	2.2	1-2.2
E_{ν_μ}	(GeV)	0.7	0.7	1.6	0.27	0.3
L	(Km)	295	295	732	130	130
Off-Axis		2^0	2^0	-	-	-
ν_μ CC/Kt/year		100	500	450	45	38
ν_e CC/ν_μ CC	%	0.4	0.4	1.2 - no opt.	0.7	0



RCS PS Booster:
1.4→2.2 GeV,0.01→4MW
??M
?
X M
SPL:
1.4→2.2 GeV,0.01→4MW
??M
RCS PS:
26→50 GeV, 0.1→4MW
βBeam
520M
Precise BRs for rare K decays (up to 3 exp's)
NA48/4: first attempt at $K^0 \to \pi^0 \nu\nu$
SuperCompass (GPD, high rate charm physics and exotic spectroscopy, etc.etc.)
500M
ν to Frejus
Eurisol
θ_{13}
CPV?
new PS: 50 GeV
Optional?
SuperCNGS ?
Super SPS
1 TeV SC
200-400M
200-400M
Super SPS
1 TeV SC
Super LHC
Super LHC
νFactory