Flavor Physics Opportunities of Project-X

R. Tschirhart
Fermilab

Fermilab Lattice QCD Meeting
December 10th , 2007

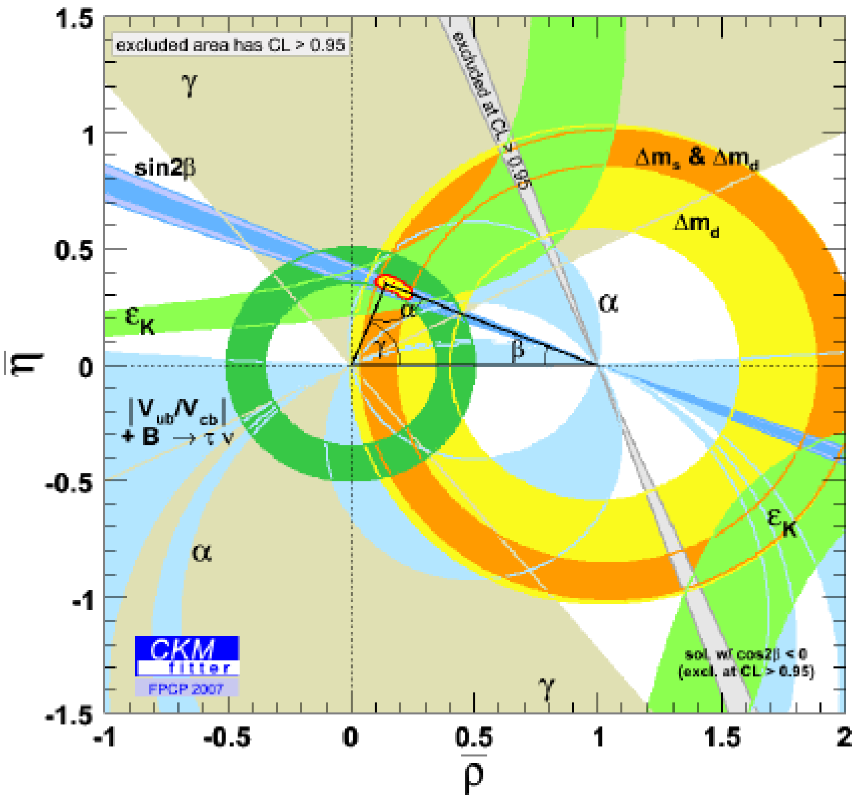
Discussion Today

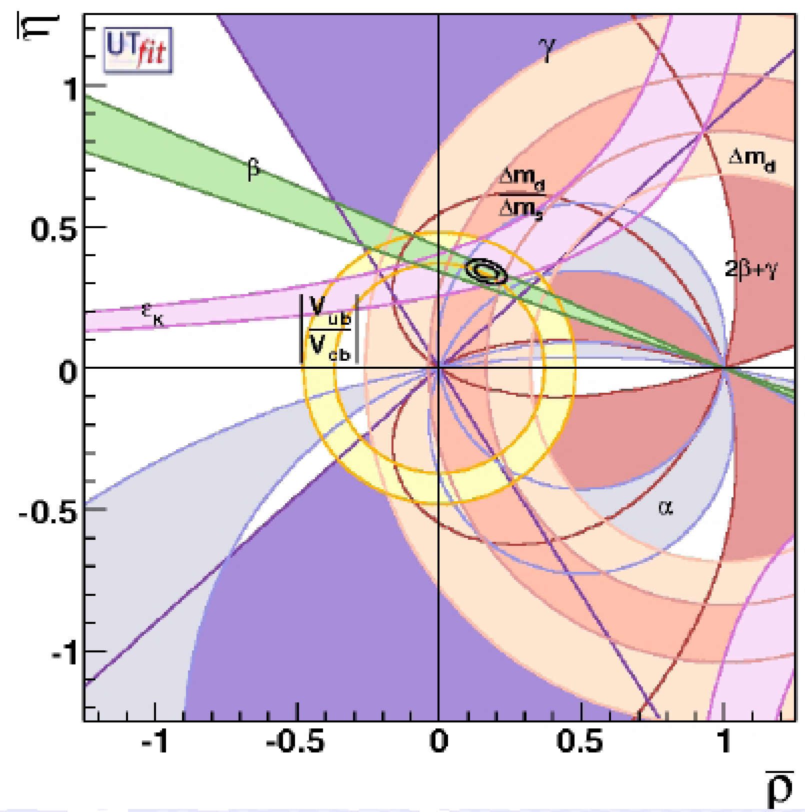
- Quark flavor physics today: Best of times……
- What Project-X can do for flavor physics.
- What you can do for Project-X:
- Next Workshop January 25th/26th 2008.

The main lessons of flavour physics:

I. The SM is very successful in describing quark-flavour mixing

This is quite clear looking at the consistency of the various constraints appearing in CKM fits

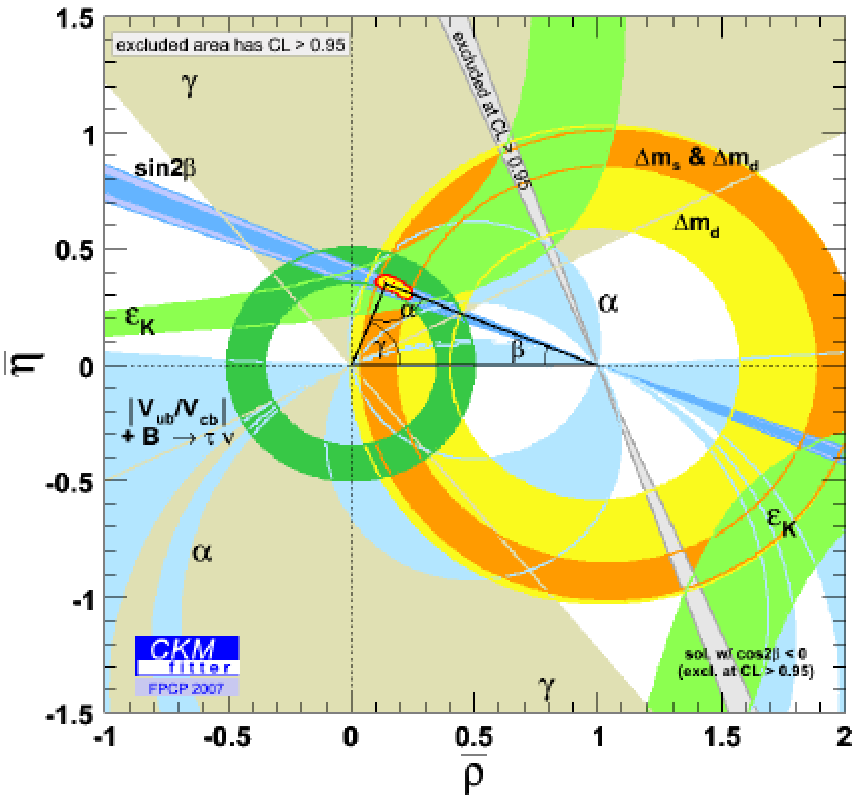




The main lessons of flavour physics:

I. The SM is very successful in describing quark-flavour mixing

...And LQCD applied to kaon physics has played an important role...



ε_K and B_K , establishing explicit CP violation in the (ρ,η) plane.

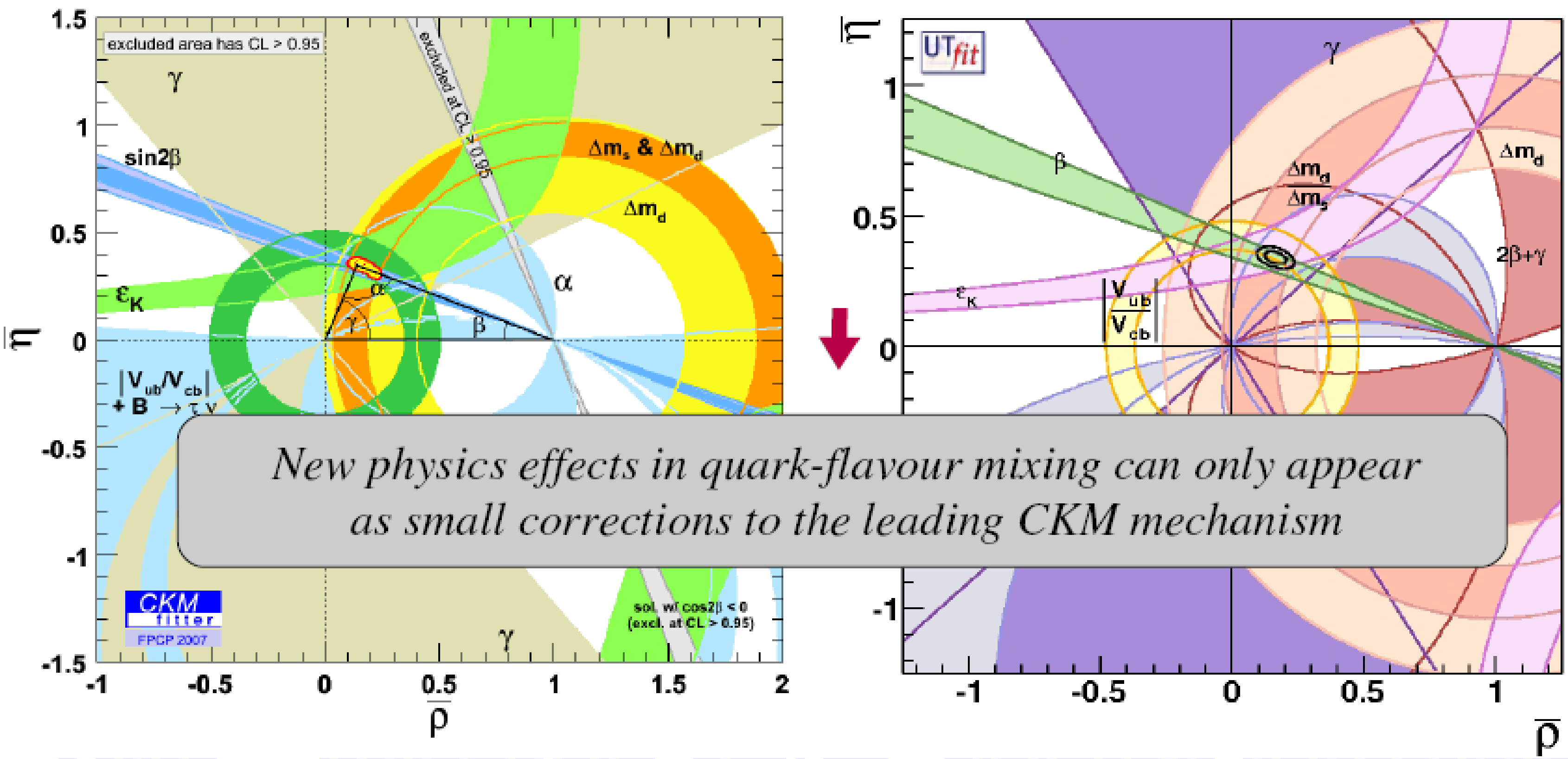
f_K, f_π, unitarity test of first row of the CKM matrix.

$\mathrm{Re}(\varepsilon'/\varepsilon)$, experimental result consistent with expectations for η, but the theory error is too large now to permit a constraint on the (ρ,η) plane

The main lessons of flavour physics:

I. The SM is very successful in describing quark-flavour mixing

This is quite clear looking at the consistency of the various constraints appearing in CKM fits, and by the absence of significant deviations from the SM in processes such as $B \to X_s \gamma\ (l^+ l^-)$, D-$\bar{D}$ mixing, rare K decays, ...



New physics effects in quark-flavour mixing can only appear as small corrections to the leading CKM mechanism

Case for Minimal Flavor Violation

$$M(B_d\text{-}\overline{B}_d) \sim \frac{(y_t V_{tb}^* V_{td})^2}{16\,\pi^2 M_W^2} + c_{NP}\frac{1}{\Lambda^2}$$

contrbution of the new heavy degrees of freedom

c_{NP}

- ~ 1 — tree/strong + generic flavour → $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ — loop + generic flavour → $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2$ — tree/strong + MFV → $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\,\pi^2)$ — loop + MFV → $\Lambda \gtrsim 0.5$ TeV [K & B]

If you don't think this is an accident of $\Delta F=2$... $\Rightarrow$ MFV

recent analysis: Bona *et al.* '07

G. Isidori, LP-2007

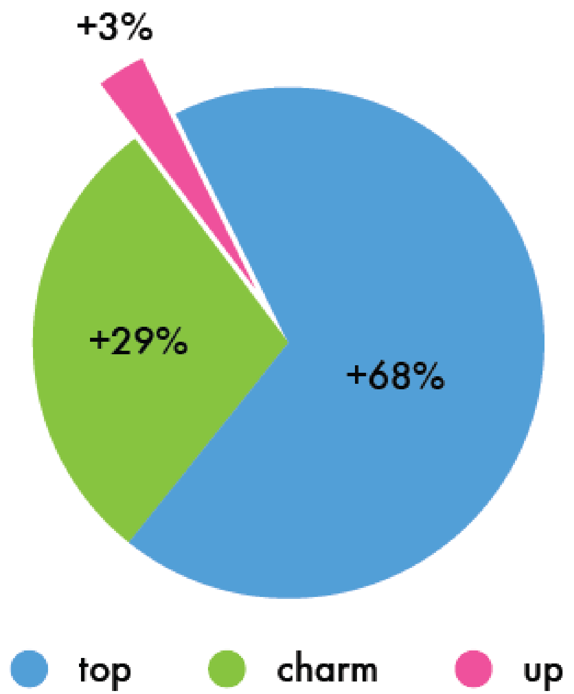
Minimal Flavor Violation limits New Physics enhancements to less than x2 ! High Premium on rock-solid SM predictions

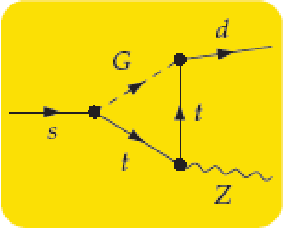
Branching Ratios	MFV (95%)	SM (68%)	SM (95%)	exp
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \times 10^{11}$	< 11.9	8.3 ± 1.2	$[6.1, 10.9]$	$(14.7^{+13.0}_{-8.9})$ [19]
$Br(K_L \to \pi^0 \nu\bar{\nu}) \times 10^{11}$	< 4.59	3.08 ± 0.56	$[2.03, 4.26]$	$< 5.9 \cdot 10^4$ [37]
$Br(K_L \to \mu^+\mu^-)_{SD} \times 10^9$	< 1.36	0.87 ± 0.13	$[0.63, 1.15]$	-
$Br(B \to X_s \nu\bar{\nu}) \times 10^5$	< 5.17	3.66 ± 0.21	$[3.25, 4.09]$	< 64 [38]
$Br(B \to X_d \nu\bar{\nu}) \times 10^6$	< 2.17	1.50 ± 0.19	$[1.12, 1.91]$	-
$Br(B_s \to \mu^+\mu^-) \times 10^9$	< 7.42	3.67 ± 1.01	$[1.91, 5.91]$	$< 2.7 \cdot 10^2$ [39]
$Br(B_d \to \mu^+\mu^-) \times 10^{10}$	< 2.20	1.04 ± 0.34	$[0.47, 1.81]$	$< 1.5 \cdot 10^3$ [39]

Bobeth et, al. Nucl.Phys. B726 (2005) 252-274C, hep-ph/0505110

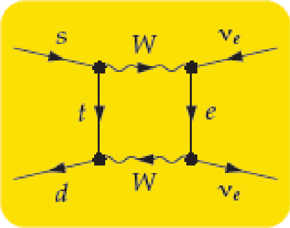
Warm-up: basic facts about $s \to d\nu\bar{\nu}$

$$\mathcal{A}_{\rm SM}(s \to d\nu\bar{\nu}) = \sum_{q=u,c,t} V_{qs}^* V_{qd}\, X_{\rm SM}^q \propto \frac{m_t^2}{M_W^2}(\lambda^5 + i\lambda^5) + \frac{m_c^2}{M_W^2} \ln \frac{m_c}{M_W} \lambda + \frac{\Lambda^2}{M_W^2}\lambda$$





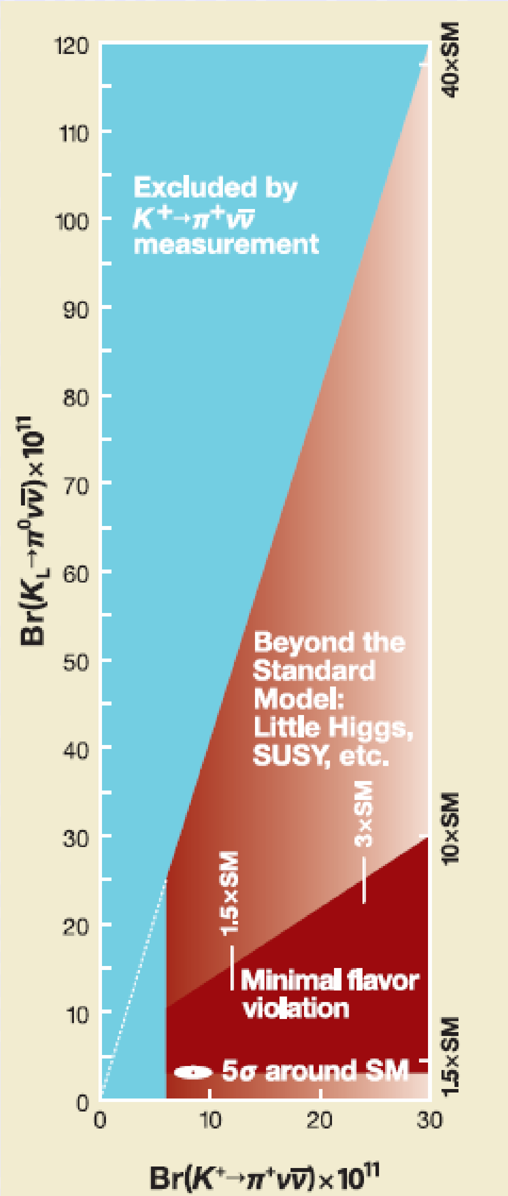
$\propto \frac{m_t^2}{M_W^2}$



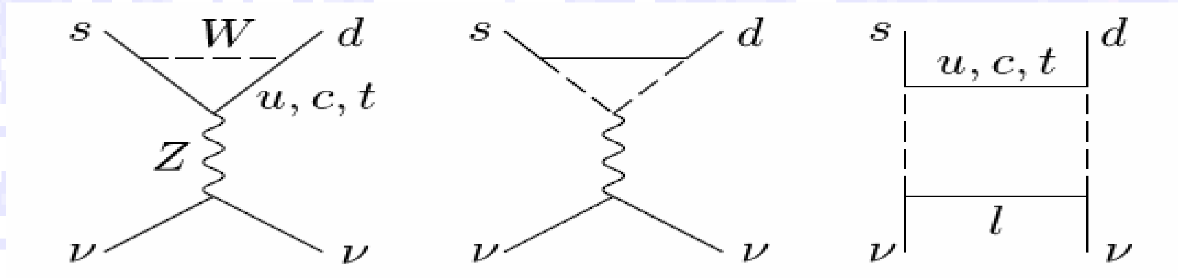
$\propto$ const.

- thus: $s \to d\nu\bar{\nu}$ exceptional tool to discover non-MFV physics where hard GIM is not active

Uli Haisch, Kaon-2007.



$K \to \pi \nu \bar{\nu}$



Standard Model (*Buras*): $\mathrm{Im}\,\lambda_t = \mathrm{Im} V_{ts}^* V_{td} = \eta A^2 \lambda^5$

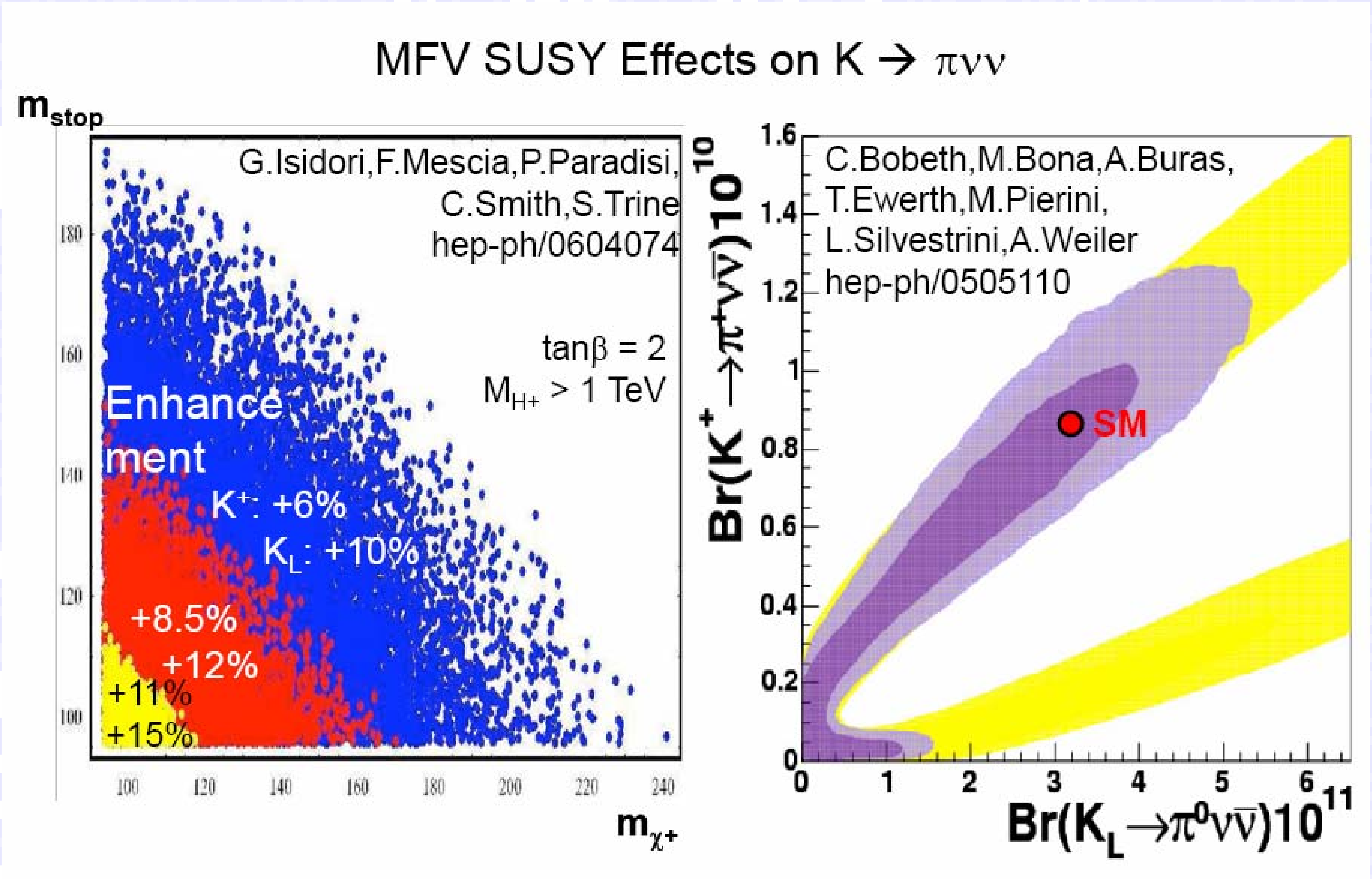
$$B(K_L^0 \to \pi^0 \nu \bar{\nu}) = 1.8 x 10^{-10} \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

$$\approx 4.1 x 10^{-10} A^4 \eta^2 = 3.0 \pm 0.6 x 10^{-11}$$

$$B(K^+ \to \pi^+ \nu \bar{\nu}) \approx 1.0 x 10^{-10} A^4 \left[\eta^2 + (\rho_0 - \rho)^2 \right] = 7.8 \pm 1.2 x 10^{-11}$$

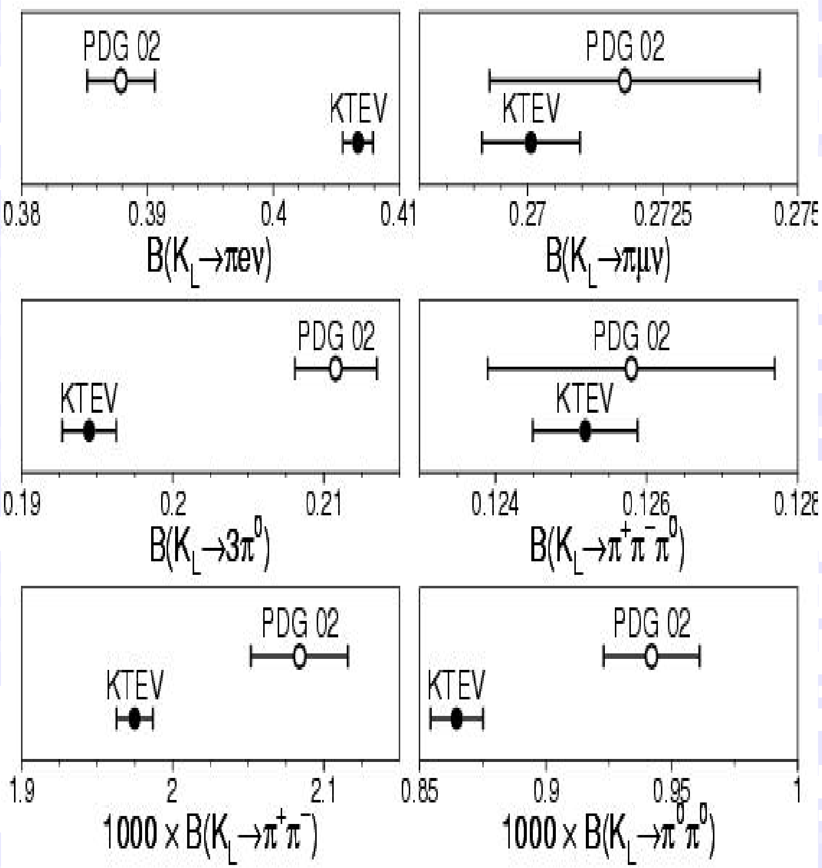
Theoretical error <2% for neutral, <4% charged modes which motivates 1000-event experiments---conceivable with Project-X!

SUSY MFV Effects.



What's Needed? Not just V_{cb}! Extraordinary Claims will require an Extraordinary Basis. Consider the Vus saga…

Circa 2004



Wrong scale can fake new physics!

Interpreting a precision measurement of $K_L \to \pi\nu\bar{\nu}$ requires:

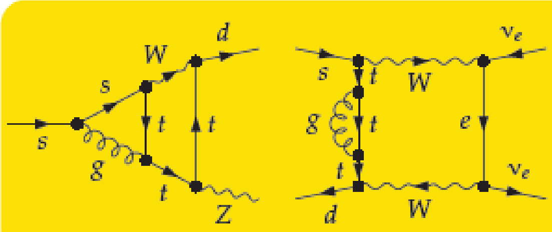
- Sub-percent **control** of $|V_{cb}|$.
- Sub-percent **control** of experiment scale.
- Sub-percent **control** of (ρ,η).
- Sub-percent **control** of charm quark contributions.
- A broad self-consistency check of the CKM framework ranging from radiative corrections to unitarity.
- Only then can we claim a foundation for percent level challenges to the SM.

SM prediction of $K_L \to \pi^0 \nu\bar{\nu}$

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left[\frac{\mathrm{Im}(V_{ts}^* V_{td})}{\lambda^5} X \right]^2 = (2.54 \pm 0.35) \times 10^{-11}$$

$$\kappa_L = (2.229 \pm 0.017) \times 10^{-10} \left(\frac{\lambda}{0.225} \right)^8 \; *$$

$$X = 1.456 \pm 0.017_{m_t} \pm 0.013_{\mu_t} \overset{?}{\pm} 0.015_{\mathrm{EW}}^{\ddagger}$$



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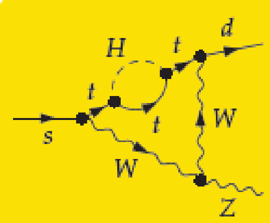
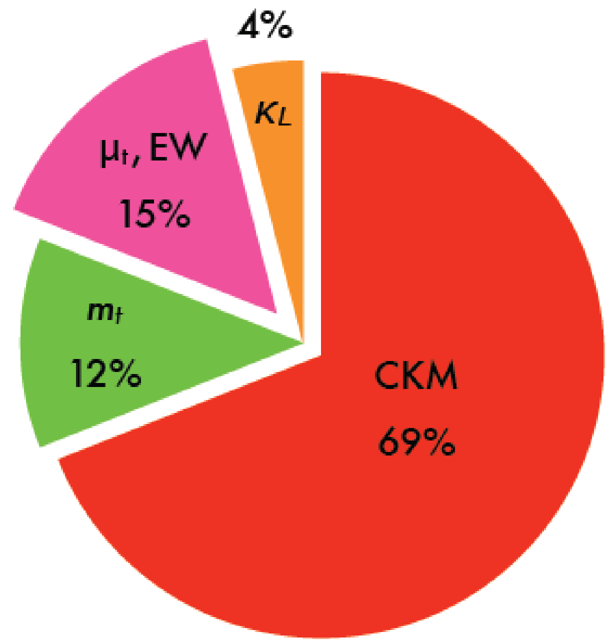




*Mescia & Smith '07 †Misiak & Urban '99, Buchalla & Buras '99 ‡Buchalla & Buras '97

Uli Haisch, Kaon-2007.

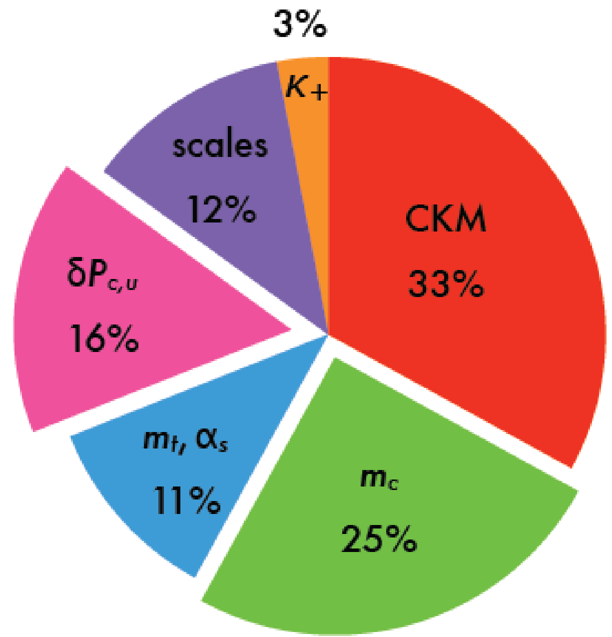
SM prediction(s) of $K^+ \to \pi^+ \nu\bar{\nu}$

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)) = \{7.96 \pm 0.86, 7.90 \pm 0.67, 7.46 \pm 0.91\} \times 10^{-11}$$

$m_c(m_c) = (1.30 \pm 0.05)$ GeV

$m_c(m_c) = (1.286 \pm 0.013)$ GeV *

$m_c(m_c) = (1.224 \pm 0.017 \pm 0.054)$ GeV †



*Kühn et al. '07 †Hoang & Manohar '05

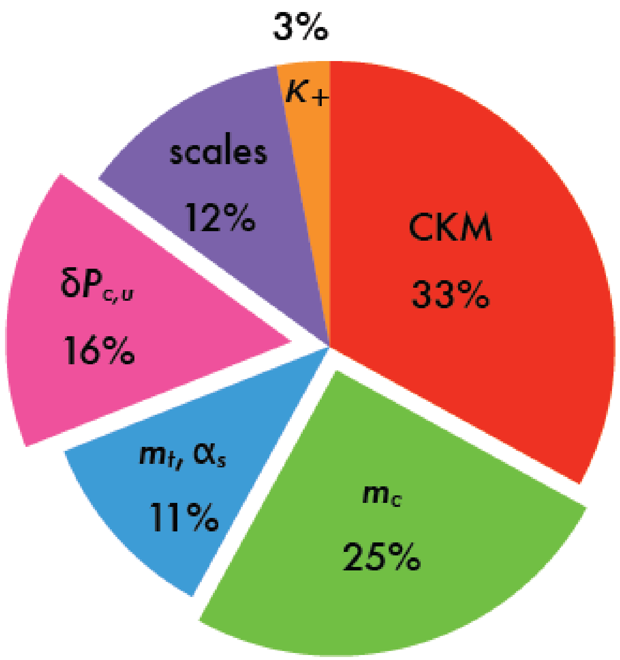
Uli Haisch, Kaon-2007.

SM prediction of $K^+ \to \pi^+ \nu\bar{\nu}$: upshot

- theoretical progress in $K^+ \to \pi^+ \nu\bar{\nu}$ closely related to precision determination of charm mass

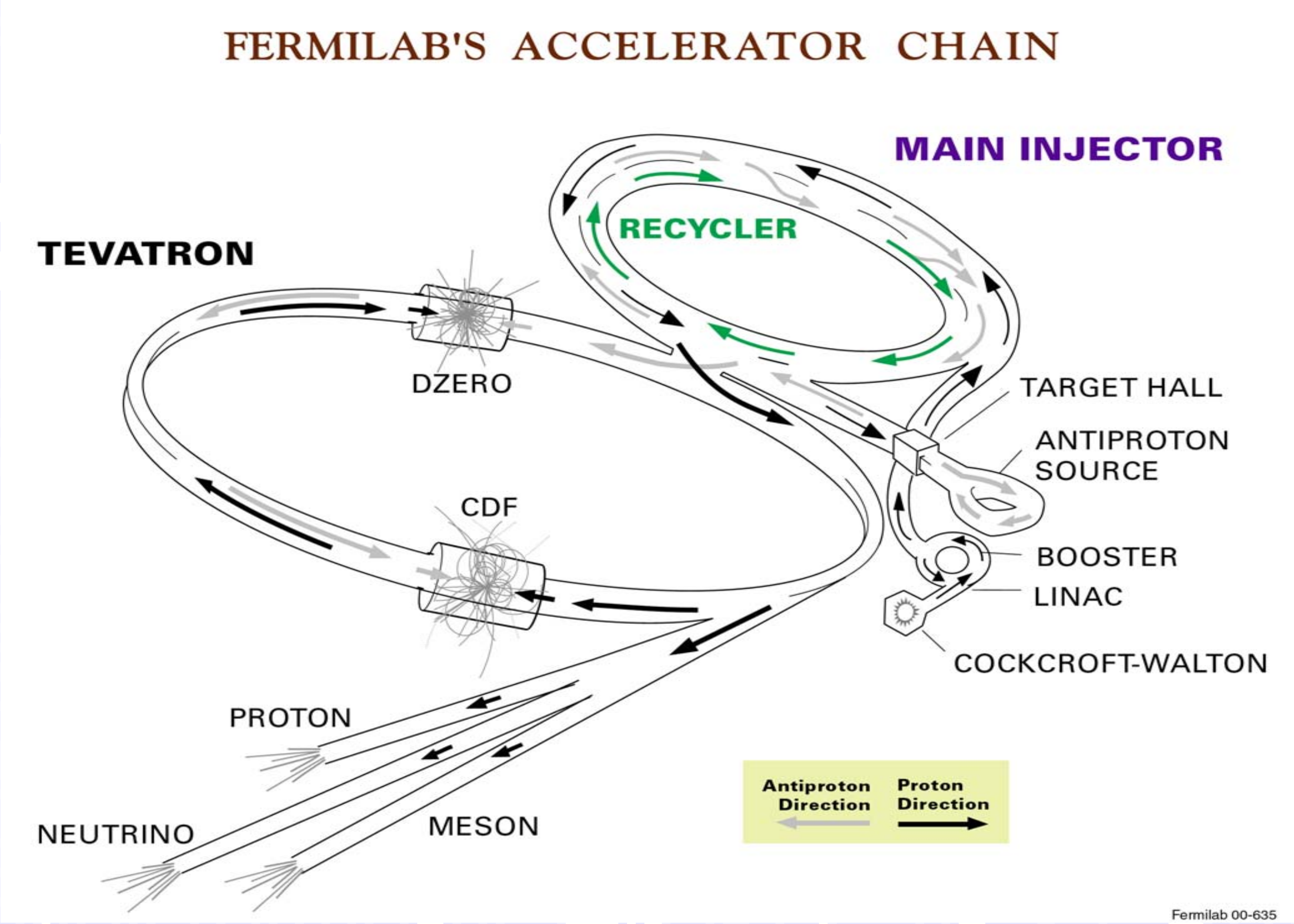
- better knowledge of long-distance effects desirable

- $K^+ \to \pi^+ \nu\bar{\nu}$ new field of interesting physical applications for lattice community



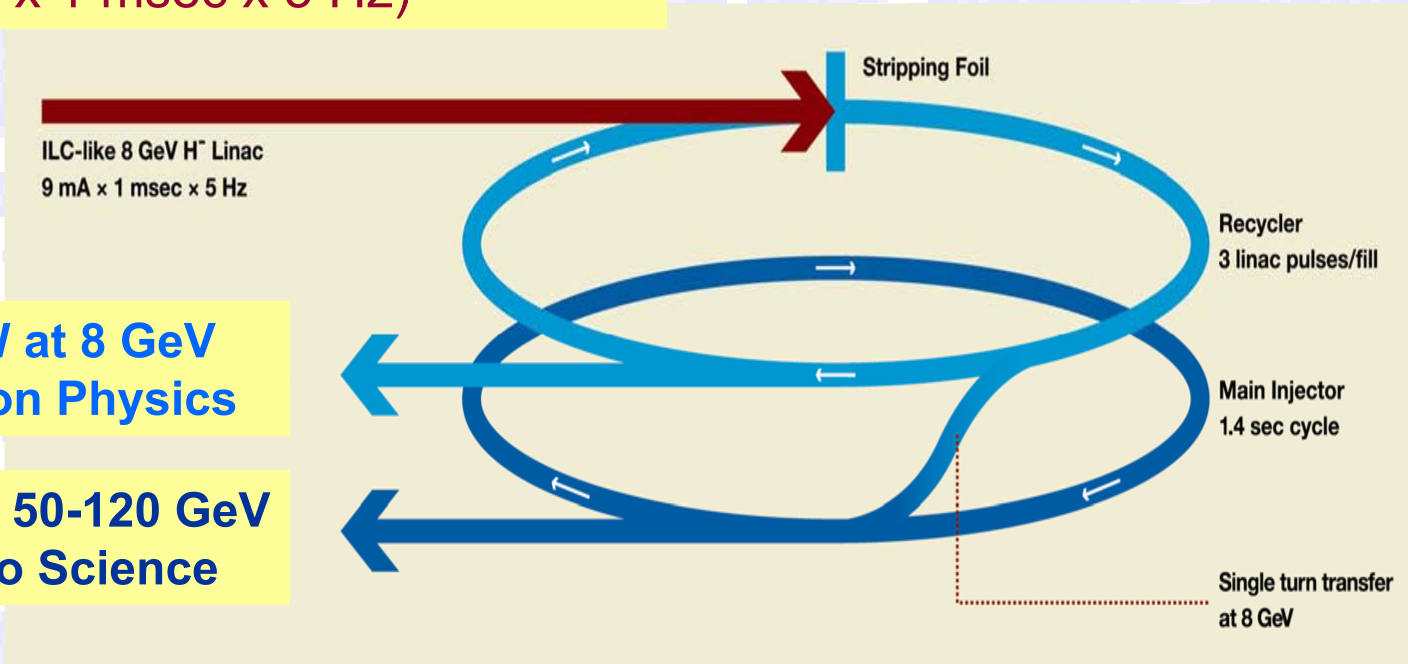
Uli Haisch, Kaon-2007.

Fermilab Accelerator Complex Today



Project X: What is it?

8 GeV H^- Linac with ILC Beam Parameters
(9 mA x 1 msec x 5 Hz)



100-200 kW at 8 GeV for Precision Physics

>2.0 MW at 50-120 GeV for Neutrino Science

Project X Linac:

ILC-like (0.6 – ~1.0 GeV)

ILC-identical (~1 – 8 GeV)

Vehicle for National & International Collaboration

Conceptual flavor experiments that were discussed in the Fermilab Steering Group process

- Mounting a Super-B experiment in the Tevatron collider complex.
- A next generation 8 GeV pbar/gas-jet experiment for a high sensitivity charm experiment.
- **Next-generation Kaon decay experiments starting with 10^{-12} SES/year then reaching 10^{-13} SES/year with Project-X.**
- A high sensitivity muon-to-electron conversion experiment (ala the former MECO experiment at BNL)

Project-X: A blow-torch of protons...all the time!

Per year

Facility	Duty Factor	Clock hours	Beam hours	Projected # of $K \rightarrow \pi\nu\bar{\nu}$
☆ CERN-SPS (450 GeV)	30%	1420	405	40 (charged)
Booster Stretcher (8GeV, 16kW)	90%	5550	5000	50 (charged)
Tevatron-Stretcher (120 GeV)	90%	5550	5000	200 (charged)
ProjectX Stretcher (8GeV, 200kW)	90%	5550	5000	300 (charged)
☆ JPARC-I (30 GeV)	21%	2780	580	~1 (neutral)
BNL AGS (24 GeV)	50%	1200	600	20 (neutral)
JPARC-II (30 GeV)	21%	2780	580	30 (neutral)
Booster Stretcher (8GeV, 16kW)	90%	5550	5000	50 (neutral)
ProjectX Stretcher (8GeV, 200kW)	90%	5550	5000	300 (neutral)

☆ **Moving toward full approval.**

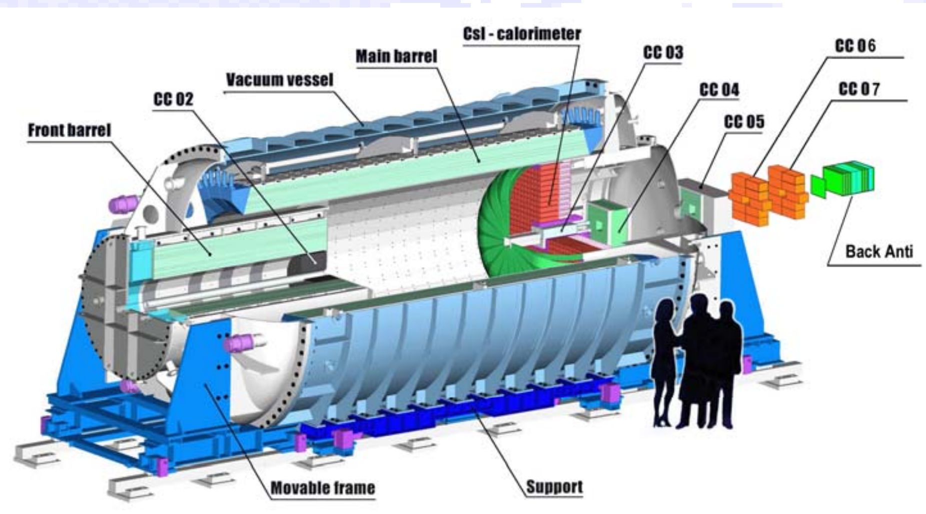
J-PARC - Neutrino:Kaon = 50%:50%

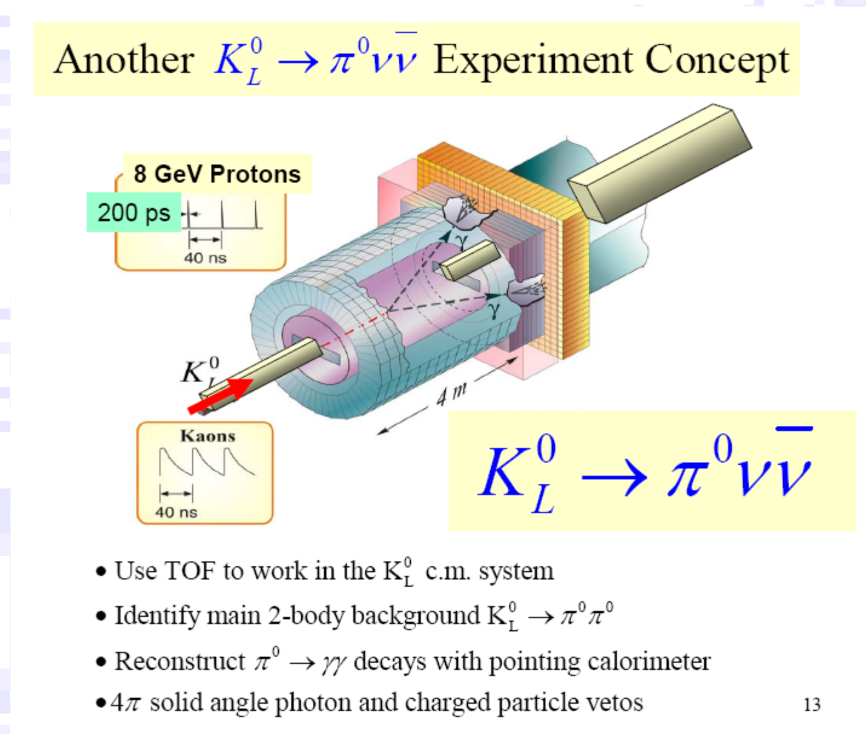
$K_L \to \pi^0 \nu\nu$ Experimental Challenge: "Nothing-in nothing out"

•JPARC approach emphasizes high acceptance for the two decay photons while vetoing everything else:

A hermetic "bottle" approach.

•The original KOPIO concept measures the kaon momentum and photon direction…Good! But costs detector acceptance and requires a large beam to compensate. Project-X Flux can get back to small kaon beam!





Lattice QCD can and should advance many other avenues of kaon physics accessible to Project-X…

- Direct CP violation in the $K^0 \to \pi\pi$, $K^0 \to \pi\pi\gamma$, $K^0 \to \pi\pi\gamma^*$ systems.
  $Re(\varepsilon'_{\pi\pi}/\varepsilon_{\pi\pi})$, and $Re(\varepsilon'_{\pi\pi\gamma}/\varepsilon_{\pi\pi\gamma})$

- V_{us} extraction. (f_π, f_K), see Andreas' following talk.

- Extracting the short-distance amplitudes of $K_L \to \pi^0 ee$, $K_L \to \pi^0 \mu\mu$ and $K_L \to \mu\mu$. This requires better, less model dependent understanding of the $K_L \to \gamma^*\gamma^*$ amplitude and radiative daughters.

- Precision control of the $[K^+ \to e\nu(\gamma)/ K^+ \to \mu\nu(\gamma)]$ ratio which is sensitive to BSM enhancements which can be as large as 2% (SUSY).

What you can do for Project-X...

- Build the foundation for interpreting 1% measurements! We are not there yet. This REQUIRES a broad program in quark flavor physics. Controlling $|V_{cb}|$ and the effective charm quark mass to the sub-percent level is probably the most important, but this is not a singular quest.

- Control of systematics is the game at the sub-percent level. Explore construction of observables that minimize systematics (e.g. $K_L \rightarrow \pi^0 \nu\nu / K^+ \rightarrow \pi^+ \nu\nu$ which nulls $|V_{cb}|$ dependence).

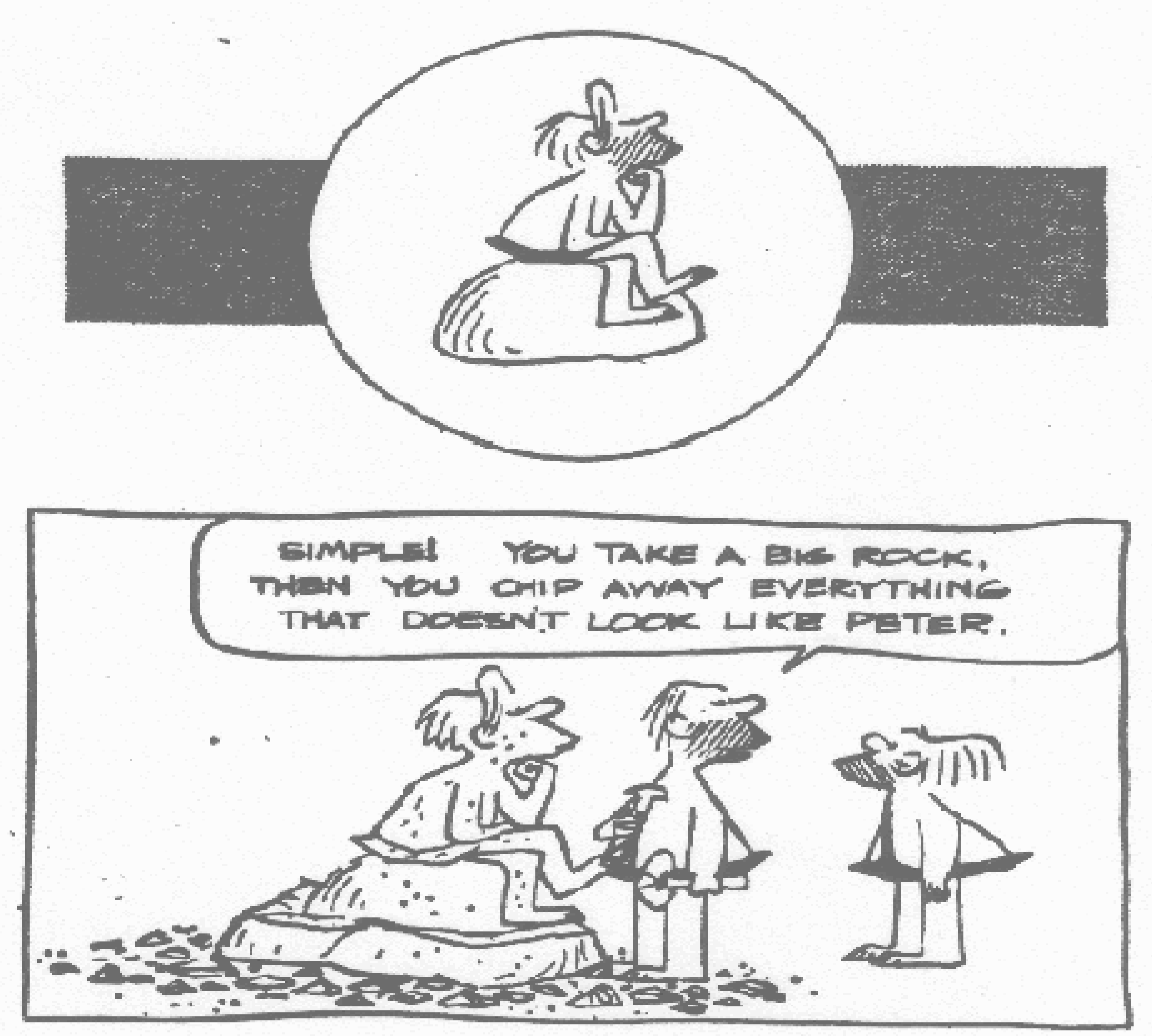
- Can we realize, perhaps working in the context of Chiral Perturbation Theory, a comprehensive "kaon calculator" to take on $Re(\varepsilon'_{\pi\pi}/\varepsilon_{\pi\pi})$, radiative decays, etc.

- Come to the next workshop ! (January 25th & 26th 2008)

Spare Slides

The Secret of Rare Decay Experiments

"BC", thanks to Doug Bryman.


SIMPLE! YOU TAKE A BIG ROCK, THEN YOU CHIP AWAY EVERYTHING THAT DOESN'T LOOK LIKE PETER.

“BC”

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

Background suppression factor needed: 10^{10}

Primary Backgrounds

Mode	Branching Ratio
$K_L^0 \rightarrow \pi^0 \pi^0$	$0.93 \ x \ 10^{-3}$
$K_L^0 \rightarrow \pi^- e^+ \nu \gamma$	$0.36 \ x \ 10^{-2}$
$K_L^0 \rightarrow \pi^+ \pi^- \pi^0$	0.1255
$K_L^0 \rightarrow \pi^0 \pi^0 \pi^0$	0.2105
Others	

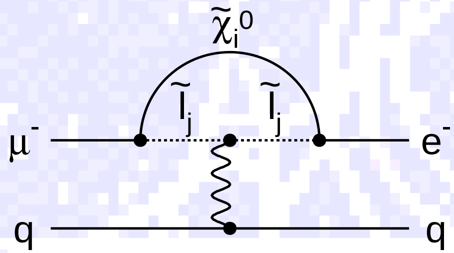
Challenge to Experimenters

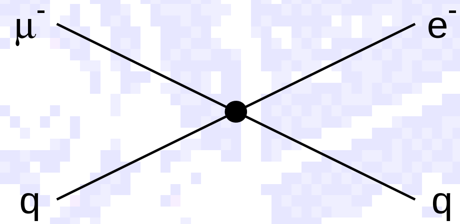
- $B(K_L \to \pi^0 \nu \bar{\nu}) \sim 3 \times 10^{-11}$;
  need huge flux of kaons -> high rates
- Weak Kinematic signature (2 particles missing)
- Backgrounds with π^0 up to 10^{10} times larger
- Veto inefficiency on extra particles must be $\leq 10^{-4}$
- Neutrons dominate the beam
  - ✓make π^0 off residual gas – require high vacuum
  - ✓halo must be very small
  - ✓hermeticity requires photon veto in the beam
- Need convincing measurement of background

Rare muon decays in Project-X: $\mu^- N \rightarrow e^- N$ Sensitivity to New Physics

Supersymmetry

Predictions at 10^{-15}



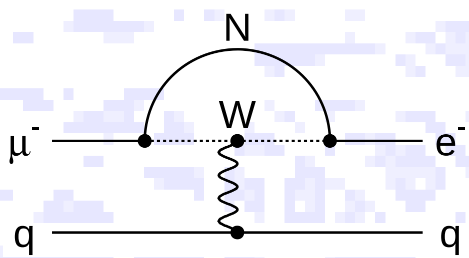


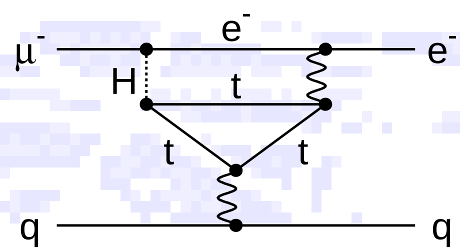
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2 = 8 \times 10^{-13}$



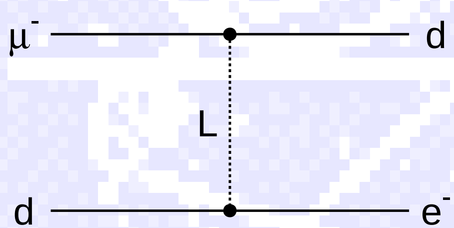


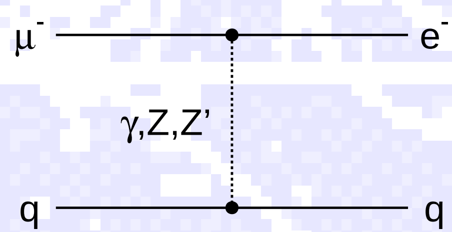
Second Higgs doublet

$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L = 3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/c^2





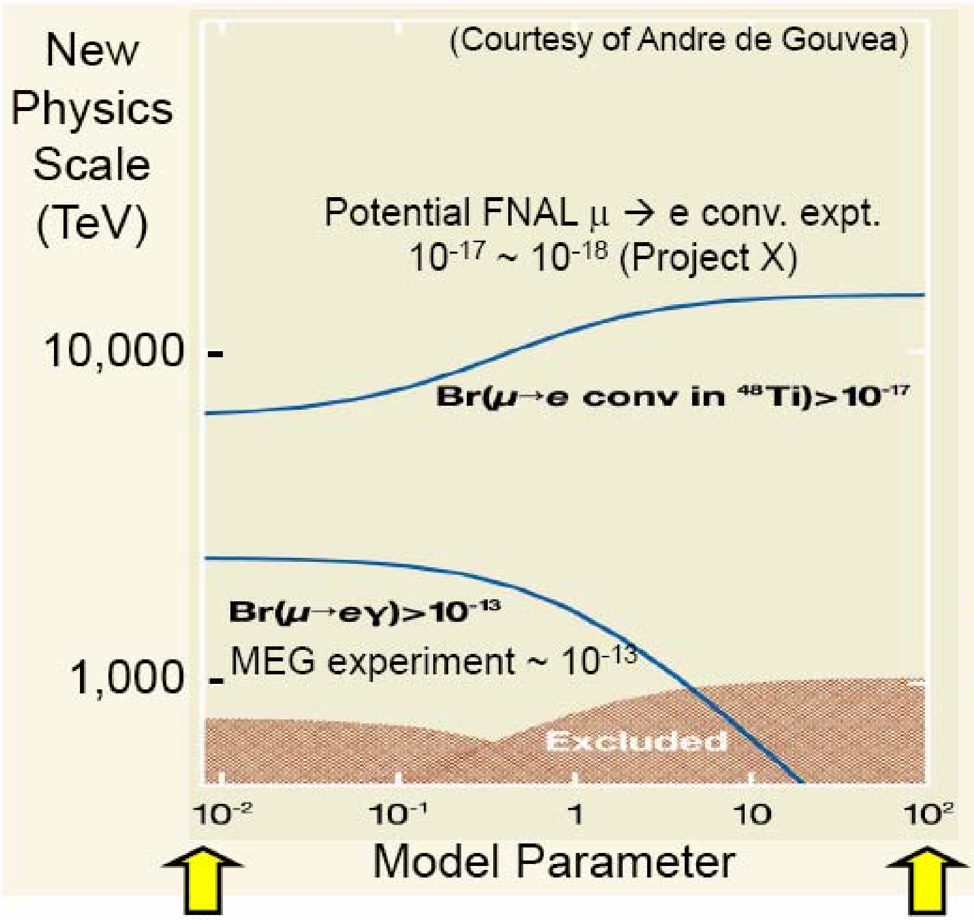
Heavy Z', Anomalous Z coupling

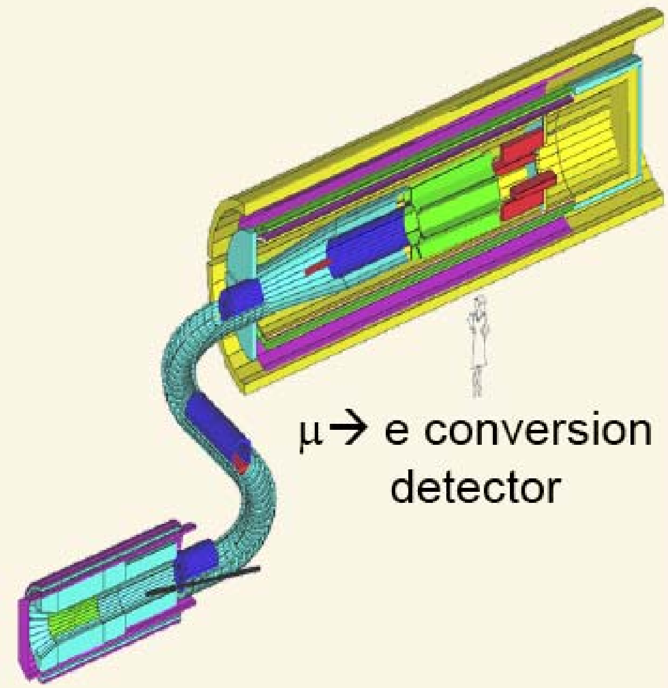
$M_{Z'} = 3000$ TeV/c^2

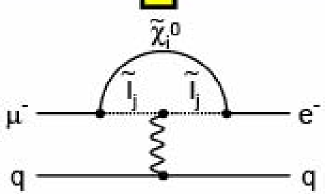
$B(Z \rightarrow \mu e) < 10^{-17}$

After W. Marciano

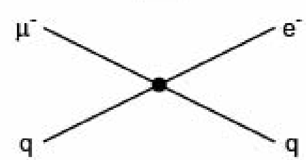
μ → e Conversion







SUSY



Compositeness

Muon-to-Electron Conversion

Rare muon processes provide the deepest CLFV probes.

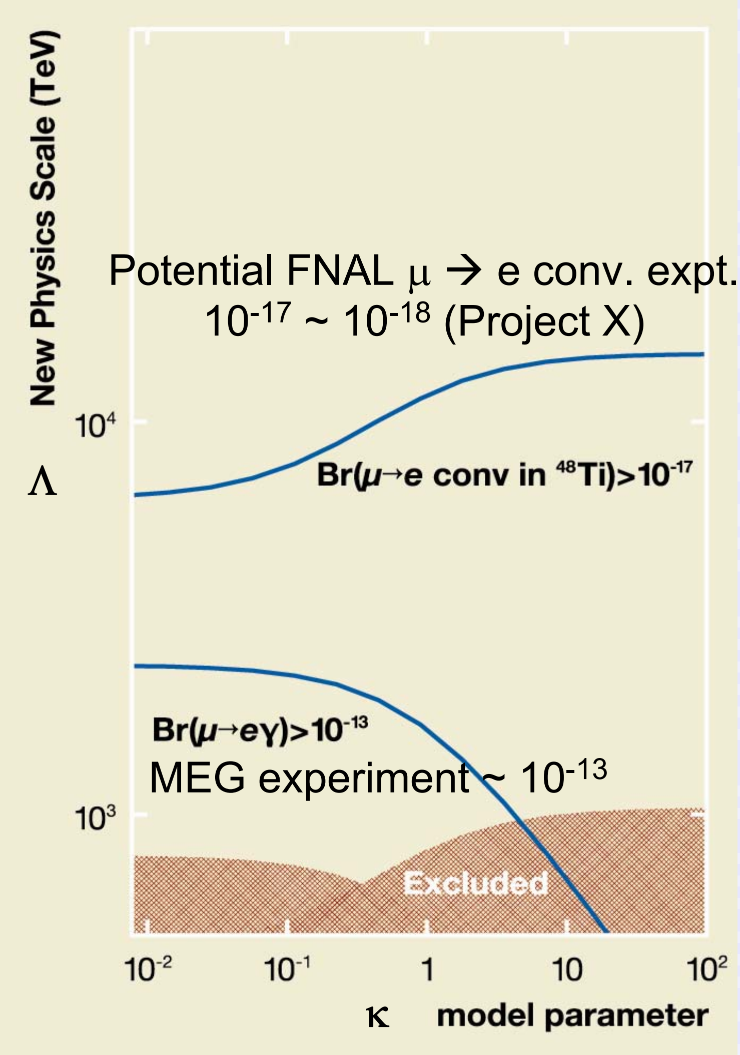
$\mu \rightarrow e$ conversion:

Estimating the new physics expectations for different CLFV processes in a model independent way.

CLFV effective Lagrangian:

$$\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

Λ sets the scale of new physics.
κ interpolates between models.

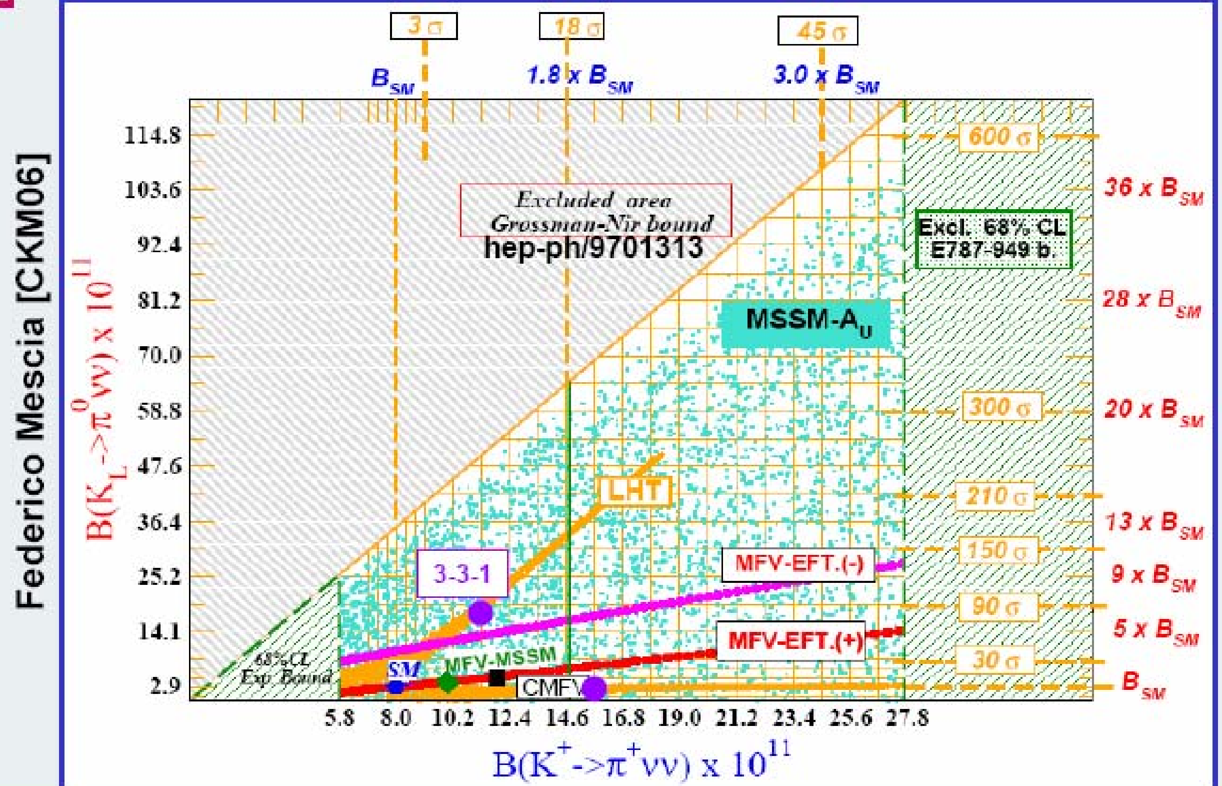


(Courtesy of Andre de Gouvea)

Conclusive Messages

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

Rare K decays are excellent probes of NP, for their theoretical cleanness and strong suppression within the SM



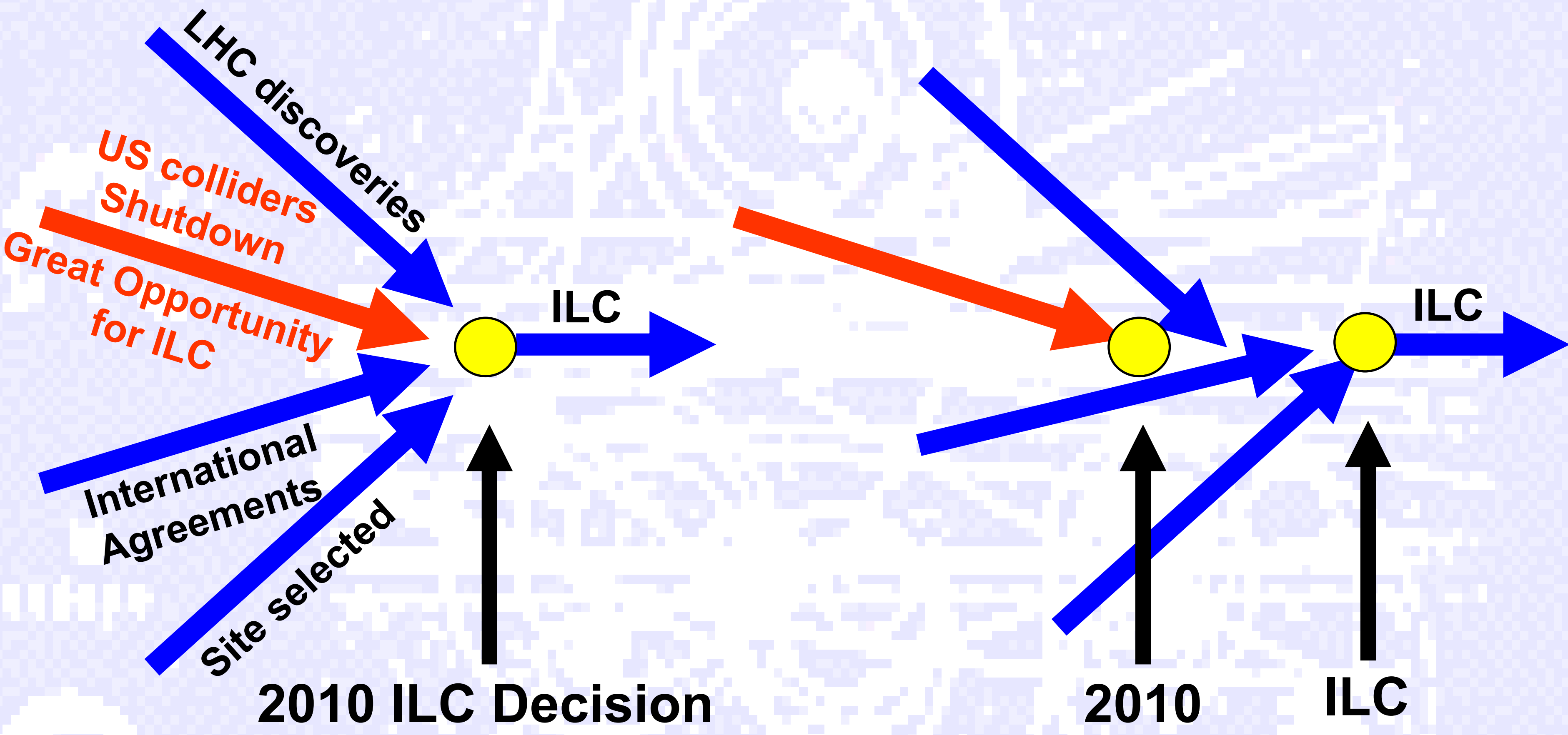
- Large NP signals could be seen in rare K decays (without large effects in B-systems)
- In particular, in MSSM or LHT, K_L can be enhanced by an order of magnitude
- Specific correlations could help in discriminating NP models

DOE Undersecretary for Science (Ray Orbach) Remarks, Feb 2007.

- In his remarks to HEPAP following the release of the ILC Reference Design Report, Undersecretary Orbach requested a dialog with the HEP community:

"In making our plans for the future, it is important to be conservative and to learn from our experiences. ***Even assuming a positive decision to build an ILC, the schedules will almost certainly be lengthier than the optimistic projections.*** *Completing the R&D and engineering design, negotiating an international structure, selecting a site, obtaining firm financial commitments, and building the machine could take us well into the mid-2020s, if not later. Within this context, I would like to re-engage HEPAP in discussion of the future of particle physics. If the ILC were not to turn on until the middle or end of the 2020s,* ***what are the right investment choices to ensure the vitality and continuity of the field*** *during the next two to three decades and to maximize the potential for major discovery during that period?"*

ILC Decision Timelines



EPP2010 & P5 Assumption

ILC RDR with Cost Estimate in Feb. 2007

Possible ILC Decision Timelines

But what about the ILC at Fermilab Today?

- The ILC is Fermilab's highest priority for the future…both the R&D and bidding for the host lab. The FY-2008 US budget has ~$80M for the ILC and SCRF development, which is more than double the previous FY-2007 budget. Resources continue to grow for ILC R&D, and in many cases at the expense of other well motivated initiatives.
- Recognition that TODAY a fast construction start determined from a technically driven schedule is not likely. In hindsight this is not very surprising, but disappointing to many.
- Pier Oddone commissioned a Steering Group led by Young-Kee Kim which developed the strategy of Project-X to maintain a vigorous investment in ILC accelerator R&D while presenting the opportunity of a compelling near-term accelerator-based Fermilab physics program after Run-II

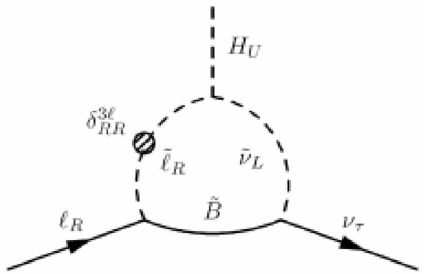
$K_{e2}/K_{\mu 2}$ — Restrictions on New Physics

Limit on LFV in $H^{\pm}$ coupling:

(Masiero, Paradisi, Petronzio, PRD 74, 2006)

LFV Yukawa coupling:

$$l H^{\pm} \nu_\tau \rightarrow \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_{13} \tan^2 \beta$$

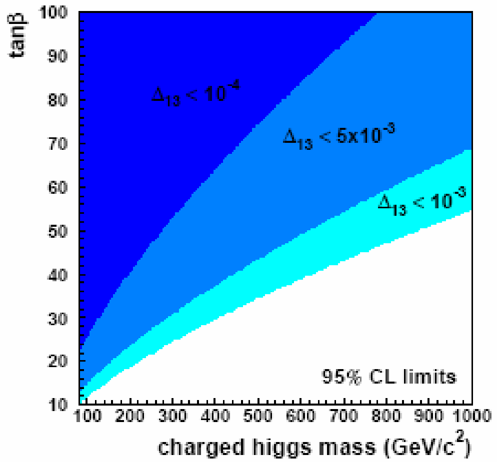


Lepton-flavour violating term: Δ_{13}

(should be $\lesssim 10^{-3}$ from EW theory, but $\neq 0$)

Limit on LFV in K_{e2} converts to limit on $\Delta_{13} = \Delta_{13}(M_{H^\pm}, \tan\beta)$:

$$R_K^{LFV} \approx R_K^{SM} \left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4} \right) \left(\frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6 \beta \right]$$



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$K_{e2}/K_{\mu 2}$ — Comparison with $B \to \tau\nu_\tau$

$B^\pm \to \tau^\pm\nu_\tau$ Decays:

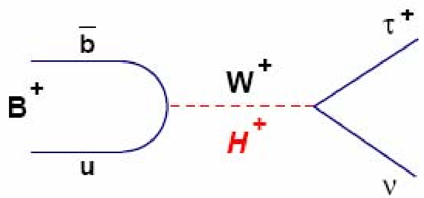
- Also in $B^\pm \to \tau^\pm\nu_\tau$: Possible transition via $H^\pm$, sensitivity to $M_{H^\pm}$, $\tan\beta$.
- No LFV required $\Longrightarrow$ No Δ_{13} term
- Dependency on $M_{H^\pm}$, $\tan\beta$: (Isidori, Paradisi, PLB 639, 2006)

$$\frac{Br_{SUSY}}{Br_{SM}} = \left[1 - \left(\frac{m_B^2}{M_{H^\pm}^2}\right)\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right]^2$$

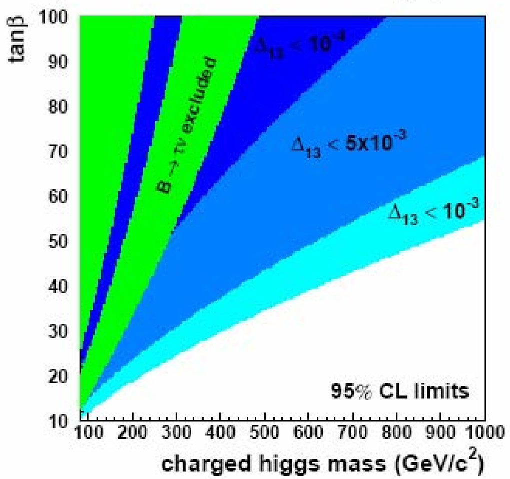
$(\epsilon_0 \sim 0.01)$

For non-tiny Δ_{13}:

Sensitivity to $H^\pm$ in $K_{e2}/K_{\mu 2}$ better than in $B \to \tau\nu_\tau$!



$Br(B \to \tau\nu) = (1.42 \pm 0.44) \cdot 10^{-4}$
(current BaBar/Belle average)



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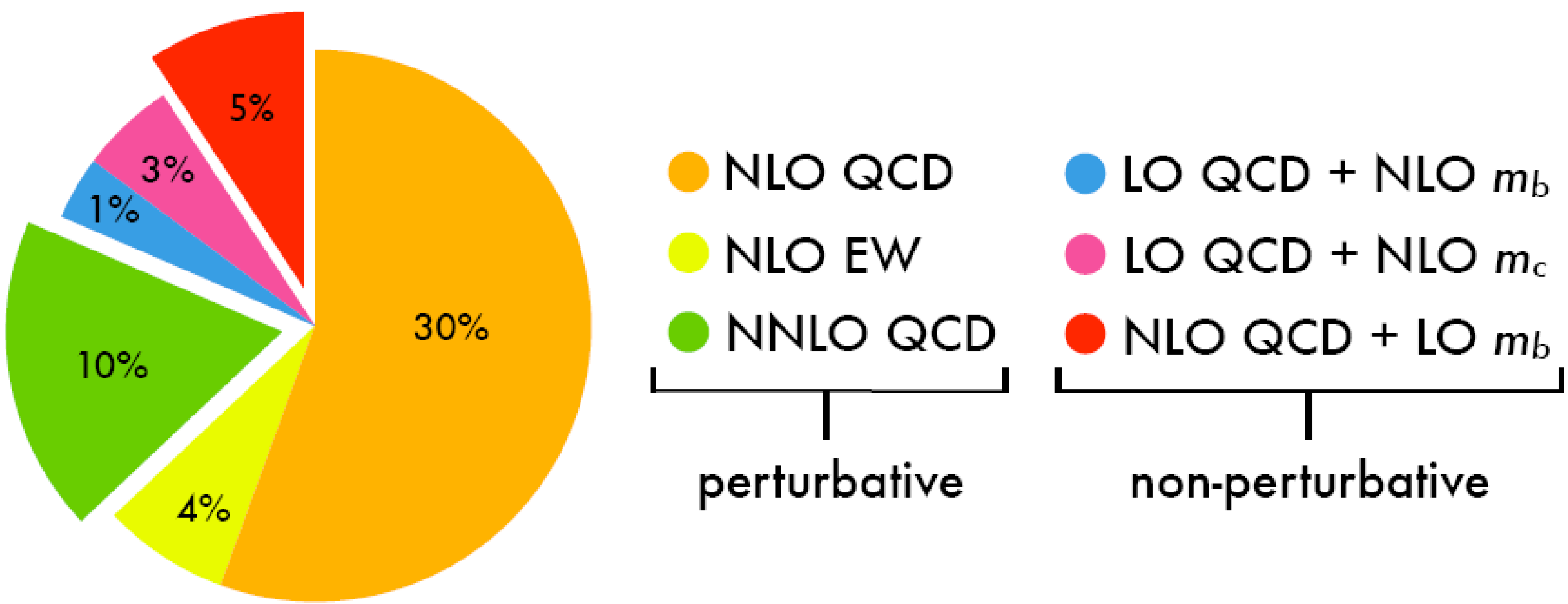
Corrections to $\bar{B} \to X_s \gamma$ beyond LO in SM

$$\mathcal{B}(\bar{B} \to X_s \gamma)^{E_\gamma > 1.6 \text{ GeV}}_{\text{SM}} = \mathcal{B}(\bar{B} \to X_c e \bar{\nu}) \left[\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to c e \bar{\nu})} \right]_{\text{LO}} f\left(\frac{\alpha_s(M_W)}{\alpha_s(m_b)} \right)$$

$$\times \left\{ 1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha) + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left(\frac{\Lambda^2}{m_b^2}\right) + \mathcal{O}\left(\frac{\Lambda^2}{m_c^2}\right) + \mathcal{O}\left(\alpha_s \frac{\Lambda}{m_b}\right) \right\}$$



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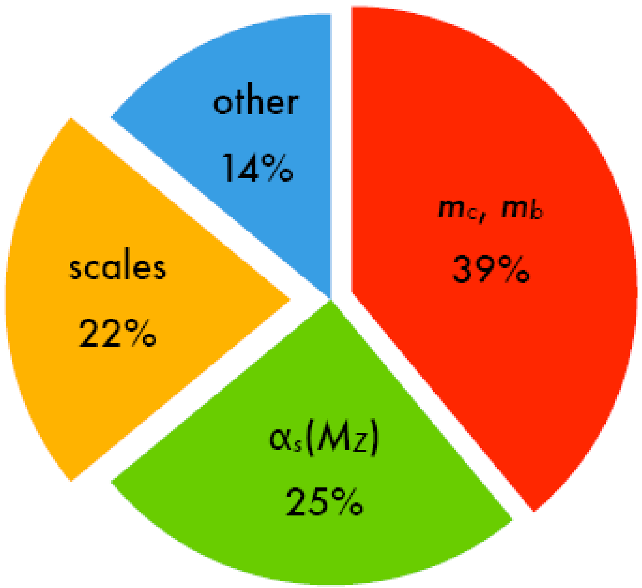
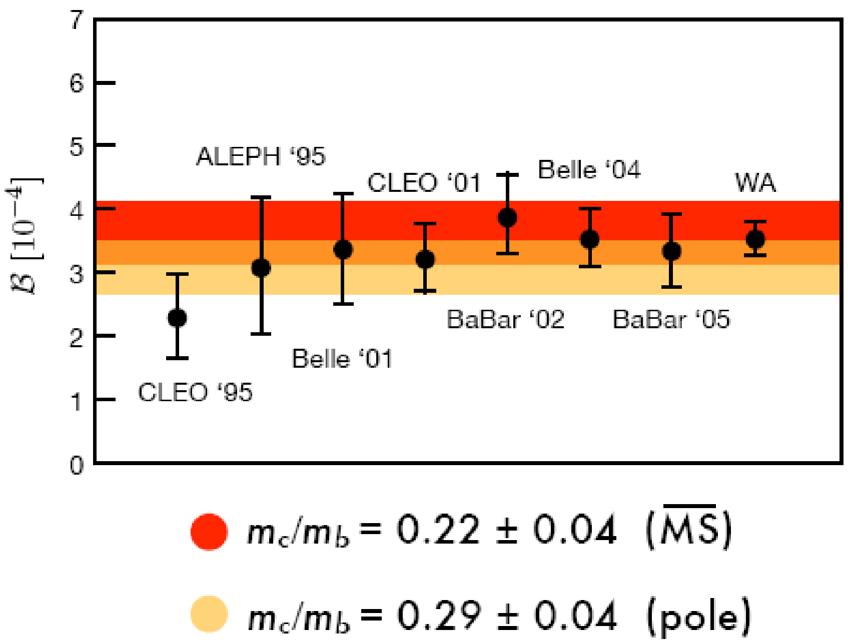
Error budget of $\bar{B} \to X_s \gamma$ at NLO in SM

$$\mathcal{B}_{\rm exp}^{E_\gamma > 1.6 \text{ GeV}} = (3.55 \pm 0.24 \,{}^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$$ *

$$\mathcal{B}_{\rm NLO}^{E_\gamma > 1.6 \text{ GeV}} = (3.33 \pm 0.29) \times 10^{-4}, \; m_c/m_b = 0.26$$





*HFAG '06

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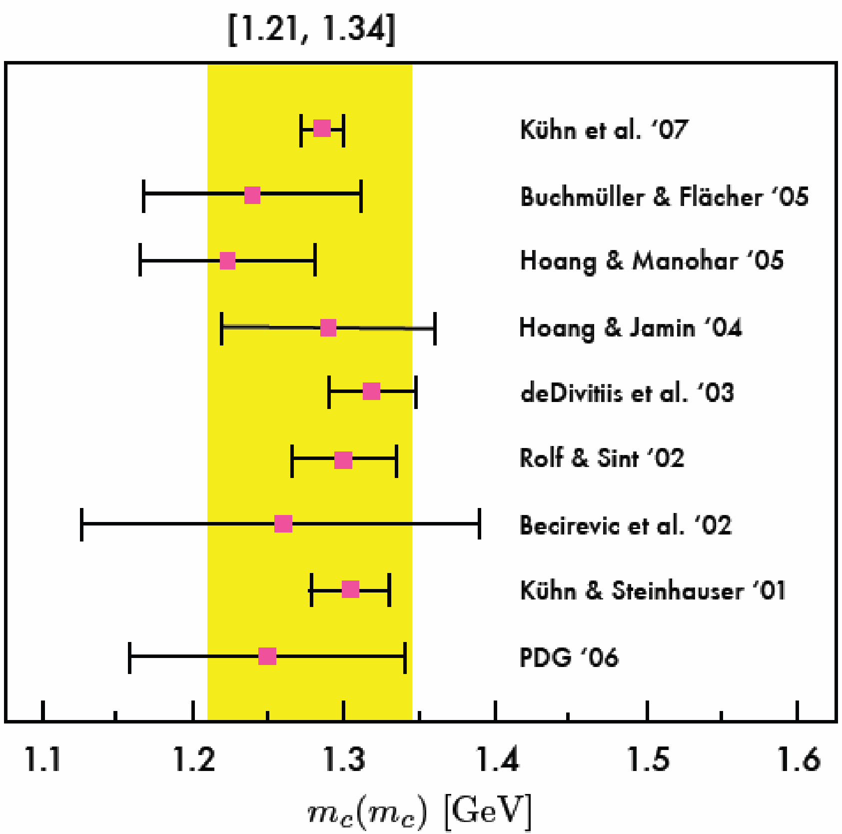
Recent determinations of charm mass



$m_c(m_c)$ [GeV]	method
1.286 ± 0.013	low-momentum sum rules, N^3LO
1.24 ± 0.07	fit to B-decay distribution, $\alpha_s^2\beta_0$
1.224 ± 0.017 ± 0.054	fit to B-decay data, $\alpha_s^2\beta_0$
1.29 ± 0.07	NNLO moments
1.319 ± 0.028	lattice, quenched
1.301 ± 0.034	lattice, quenched
1.26 ± 0.04 ± 0.12	lattice, quenched
1.304 ± 0.027	low-momentum sum rules, NNLO
1.25 ± 0.09	PDG 2006

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