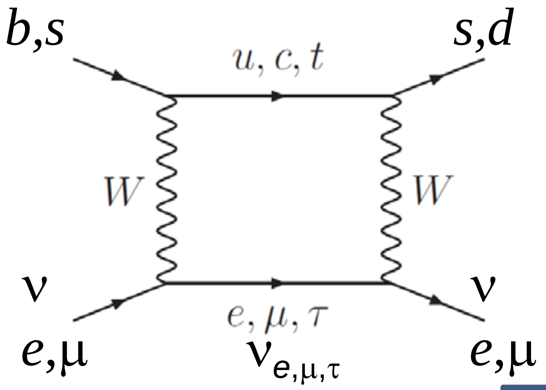
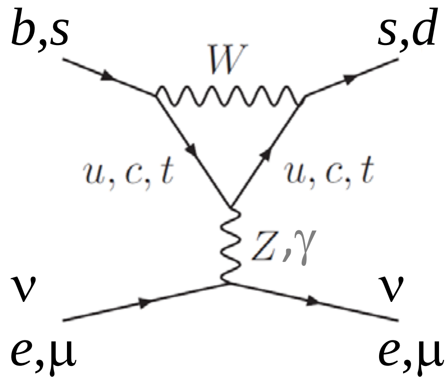
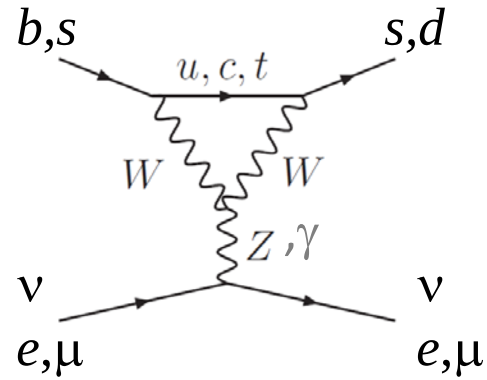
IF21: Describe the increase in sensitivity to new particles in loops as a function of time coming from improved measurements of $b \to s\gamma$, B and $B_s \to \mu\mu$, and related observables. There should be separate estimates for SUSY models, in which flavor-changing effects come from loops, and from models in which the flavor-change comes from a tree-level effective operator.

Flavor Changing Neutral Currents







Responsible for rare decays in Standard Model

e.g.,

$B \to X_s \gamma$

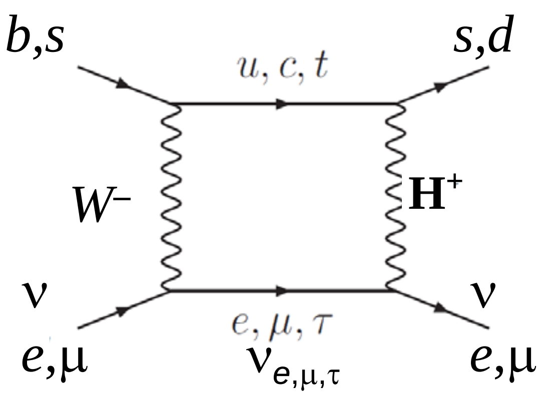
$B \to X_s \ell^+ \ell^- \ (\ell = e \text{ or } \mu)$

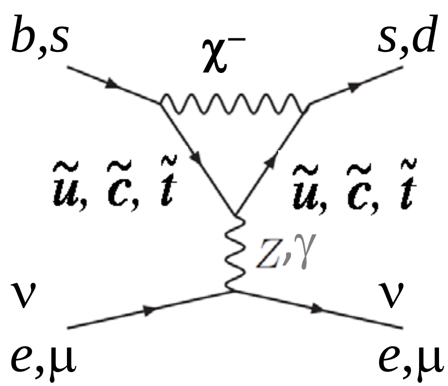
$B_s \to \mu^+ \mu^-$

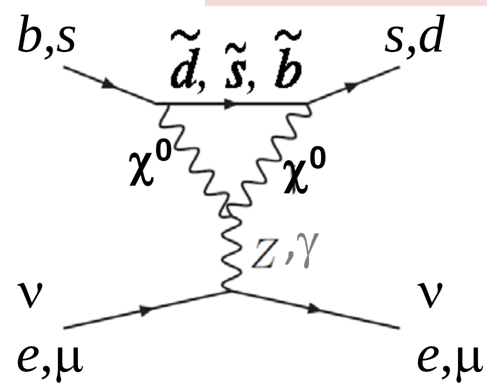
$K_L^0 \to \mu^+ \mu^-$

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

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







Sensitive to new (high-mass) particles in loops.

Altmannshofer and Straub, arXiv:1206.0273

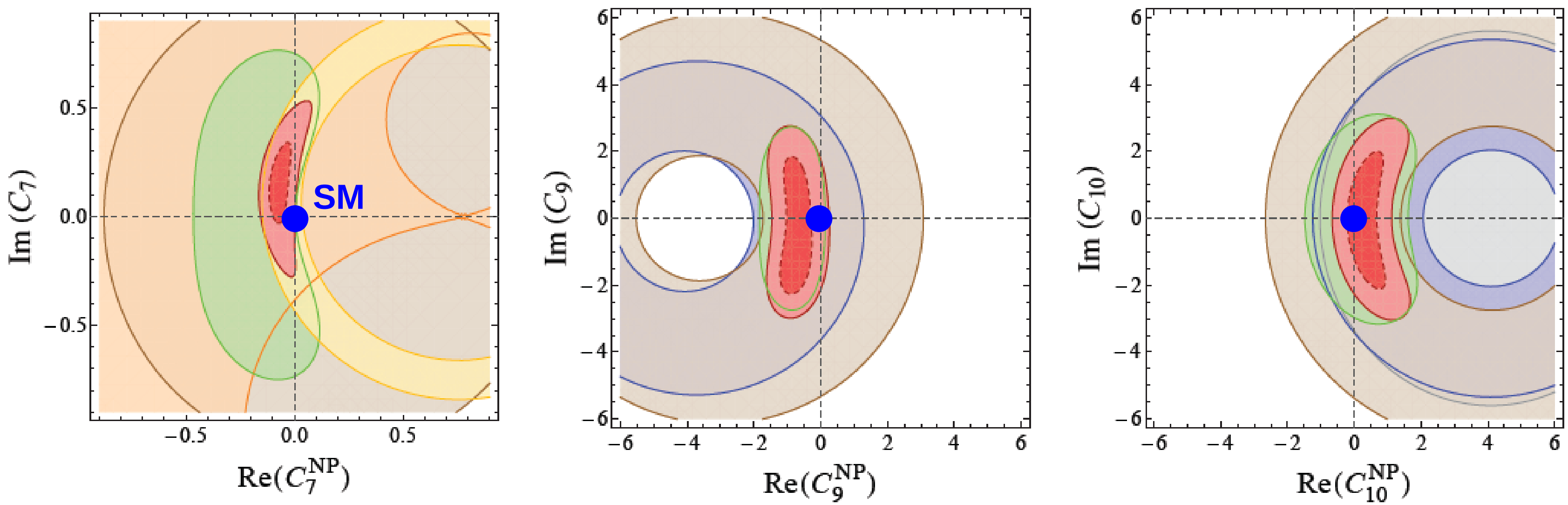
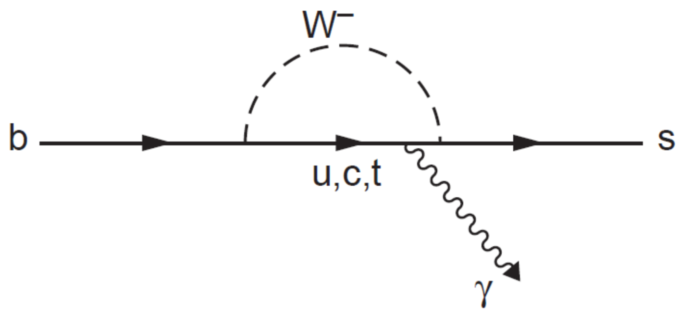


Figure 1: Individual 2σ constraints on the unprimed Wilson coefficients from $B \to X_s \ell^+ \ell^-$ (brown), BR$(B \to X_s \gamma)$ (yellow), $A_{CP}(b \to s\gamma)$ (orange), $B \to K^* \gamma$ (purple), $B \to K^* \mu^+ \mu^-$ (green), $B \to K \mu^+ \mu^-$ (blue) and $B_s \to \mu^+ \mu^-$ (gray) as well as combined 1 and 2σ constraints (red).

Related FCNC observables provide complementary constraints on new physics. As measurements improve, overall consistency of the SM can be tested.

$b \to s\gamma$



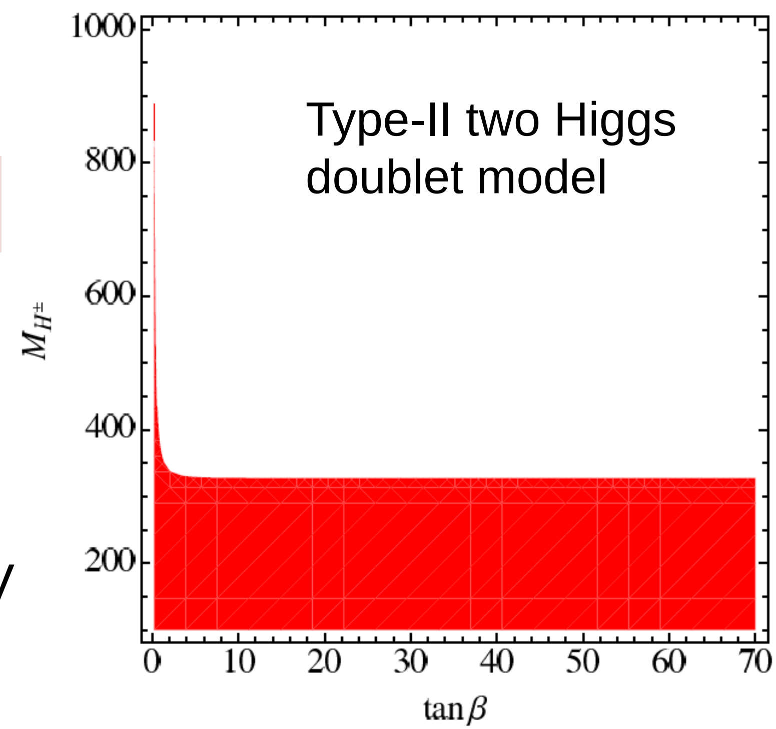
$$E_\gamma^* \cong \frac{m_b^2 - m_s^2}{2m_b} \approx \frac{m_b}{2}$$

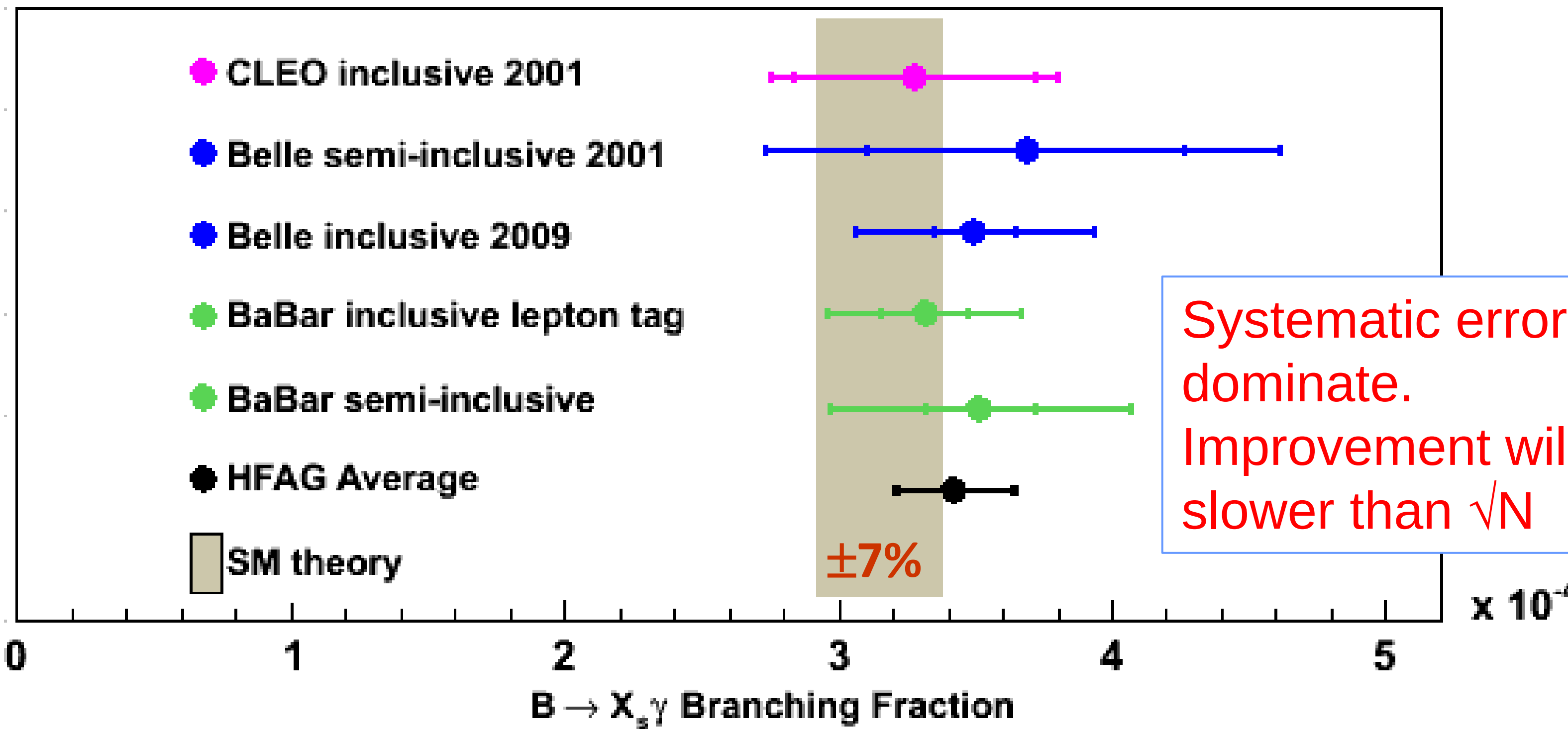
- Heavy-quark hadron duality $\Rightarrow$ $B(B \to X_s\gamma) \cong B(b \to s\gamma)$
- Theoretically clean prediction in the Standard Model
  - Next-to-next-leading order (NNLO) calculation (E_γ > 1.6 GeV)

$$B(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

Misiak et al., PRL 98, 022002(2007)

- Measured BF vs SM theory gives constraint on new physics models. E.g., charged Higgs mass > 330 GeV





Systematic errors dominate. Improvement will be slower than √N

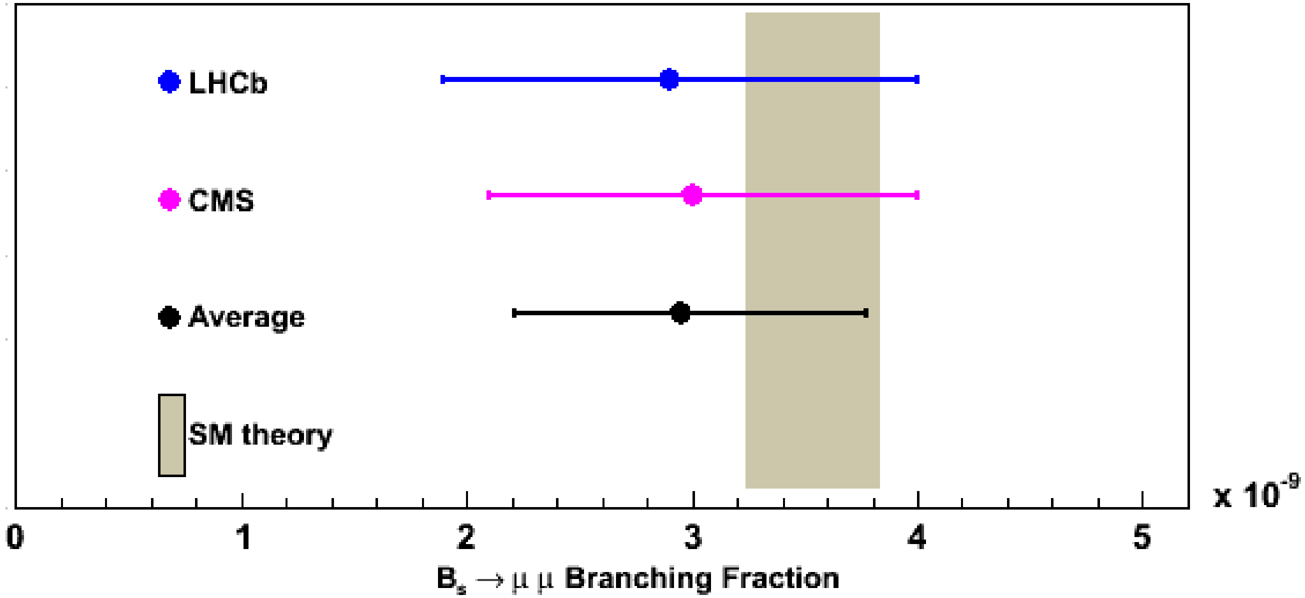
- The branching fraction provides a useful constraint on models, but future improvements will not be substantial.
- CP-violation observables hold promise for the future.
  - ➢ Direct CP violation (inclusive)
  - ➢ Direct CP violation (charged vs neutral modes)
  - ➢ Time-dependent CP-violation in $B^0 \to K^{*0} \gamma$

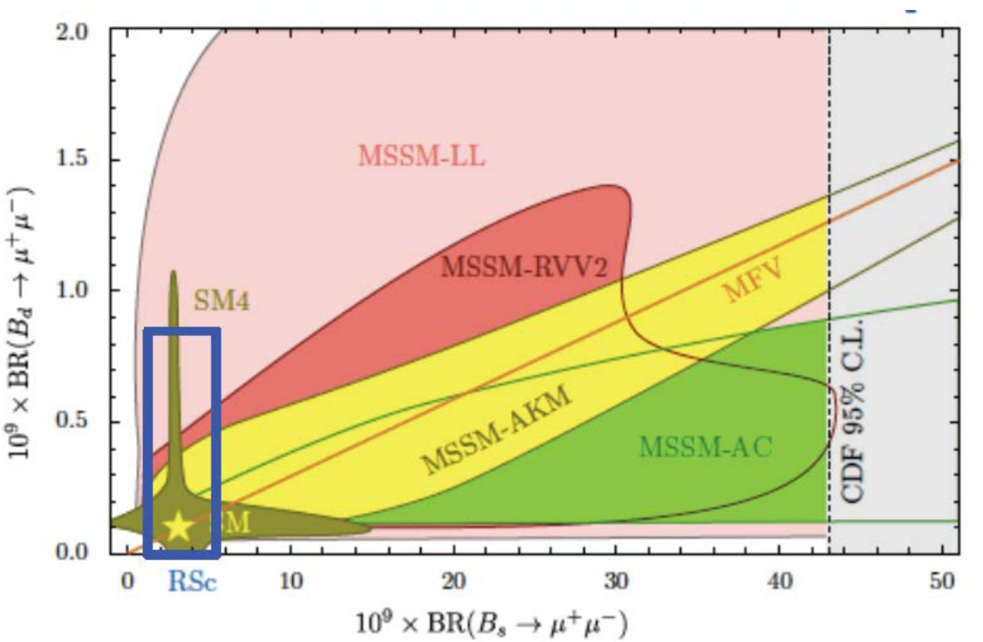
Projections for SuperKEKB/Belle II

Observable	SM theory	Current measurement (early 2013)	Belle II ($50\,\mathrm{ab}^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.03
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.02
α from $B \to \pi\pi,\ \rho\rho$		$\pm 5.4°$	$\pm 1.5°$
γ from $B \to DK$		$\pm 11°$	$\pm 1.5°$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.03
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.15
$A_{\rm CP}(B \to X_{s+d}\,\gamma)$	< 0.005	0.06 ± 0.06	± 0.02
$A^d_{\rm SL}$	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 0.05 \times 10^{-4}$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\pm 0.2 \times 10^{-7}$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 0.13 \times 10^{-4}$
$\mathcal{B}(B \to X_s \ell^+\ell^-)$	1.6×10^{-6}	$(3.66 \pm 0.77) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$\mathcal{B}(B \to K\nu\bar{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 1.0 \times 10^{-6}$
$A_{\rm FB}(B \to K^*\ell^+\ell^-)_{q^2<4.3\,\mathrm{GeV}^2}$	-0.09	0.27 ± 0.14	± 0.04
$A_{\rm FB}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing	0.16	0.029	0.008
$\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ ($q^2 > 16\,\mathrm{GeV}^2$)	$9\% \to 2\%$	11%	2.1%

50 ab^{-1} is projected by 2023 if the current schedule holds.

$B_{s,d} \to \mu\mu$ Updated at EPS 2013 by LHCb, CMS first result





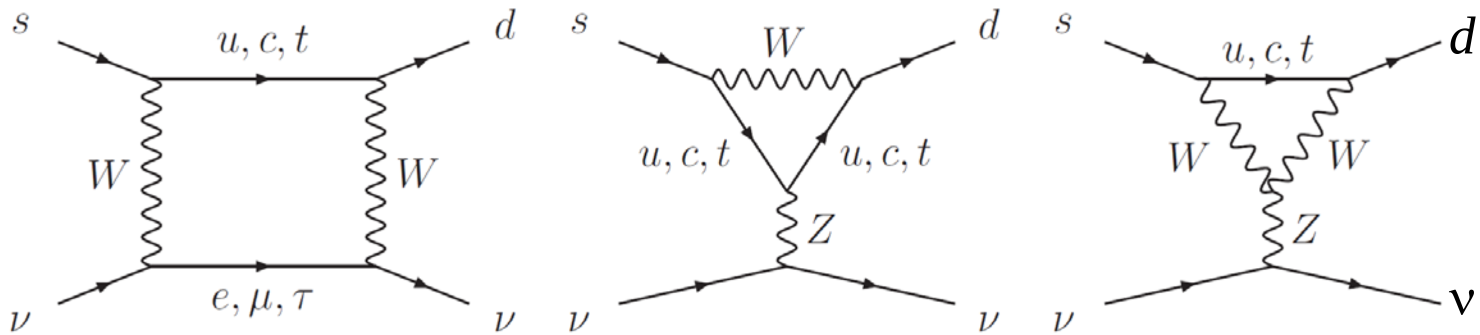
Projections for LHCb

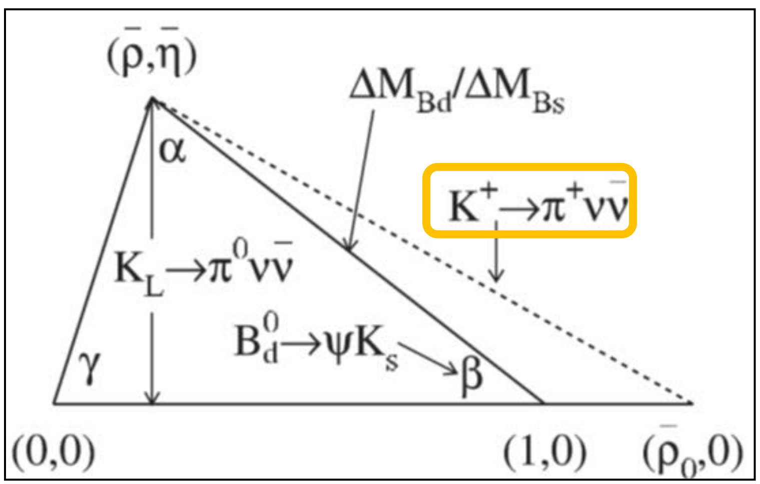
Observable	SM theory uncertainty	Precision as of 2013	LHCb (6.5 fb^{-1})	LHCb Upgrade (50 fb^{-1})
$2\beta_s(B_s \to J/\psi\phi)$	~ 0.003	0.09	0.025	0.008
$\gamma(B \to D^{(*)}K^{(*)})$	$< 1°$	8°	4°	0.9°
$\gamma(B_s \to D_s K)$	$< 1°$	—	$\sim 11°$	2°
$\beta(B^0 \to J/\psi K^0_S)$	small	0.8°	0.6°	0.2°
$2\beta_s^{\rm eff}(B_s \to \phi\phi)$	0.02	1.6	0.17	0.03
$2\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$	< 0.02	—	0.13	0.02
$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	0.2%	—	0.09	0.02
$2\beta^{\rm eff}(B^0 \to \phi K^0_S)$	0.02	0.17	0.30	0.05
$A^s_{\rm SL}$	0.03×10^{-3}	6×10^{-3}	1×10^{-3}	0.25×10^{-3}
$\mathcal{B}(B_s \to \mu^+\mu^-)$	8%	42%	15%	5%
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-)$	5%	—	~100%	~35%
$A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$ zero crossing	7%	18%	6%	2%

50 fb^{-1} is projected by 2030 if the current schedule holds.

$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

$K \to \pi\nu\bar{\nu}$ decays are among the most precisely calculated FCNC decays.





- A single effective operator $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$
- Dominated by top quark (charm significant, but controlled)
- Hadronic matrix element shared with $K \to \pi e \nu$
- Largest uncertainty from CKM elements (which will improve)

$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (7.8 \pm 0.8) \times 10^{-11}$$

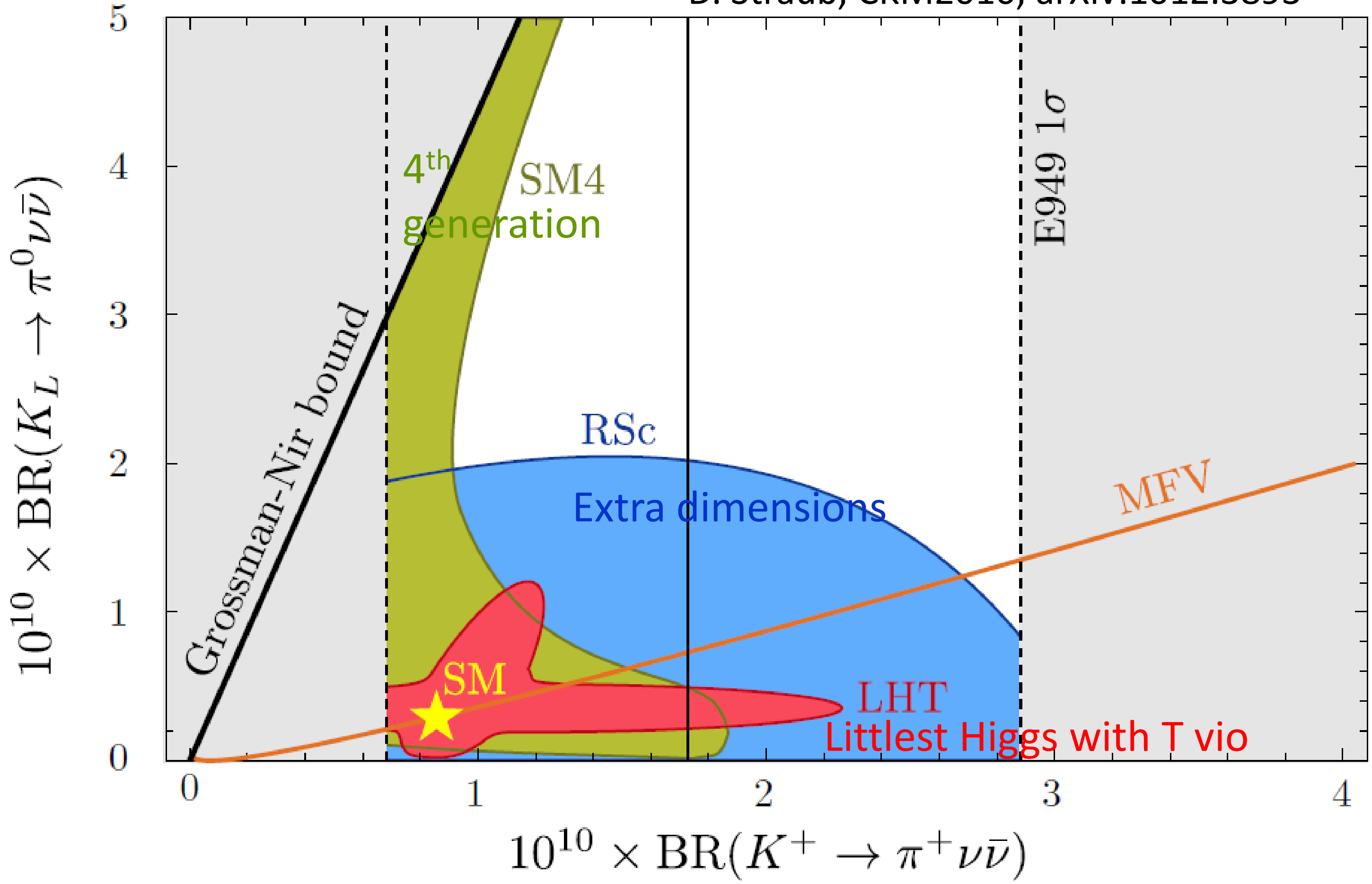
Brod, Gorbahn, and Stamou, PR D **83**, 034030(2011)

- Remains clean in New Physics models

ORKA

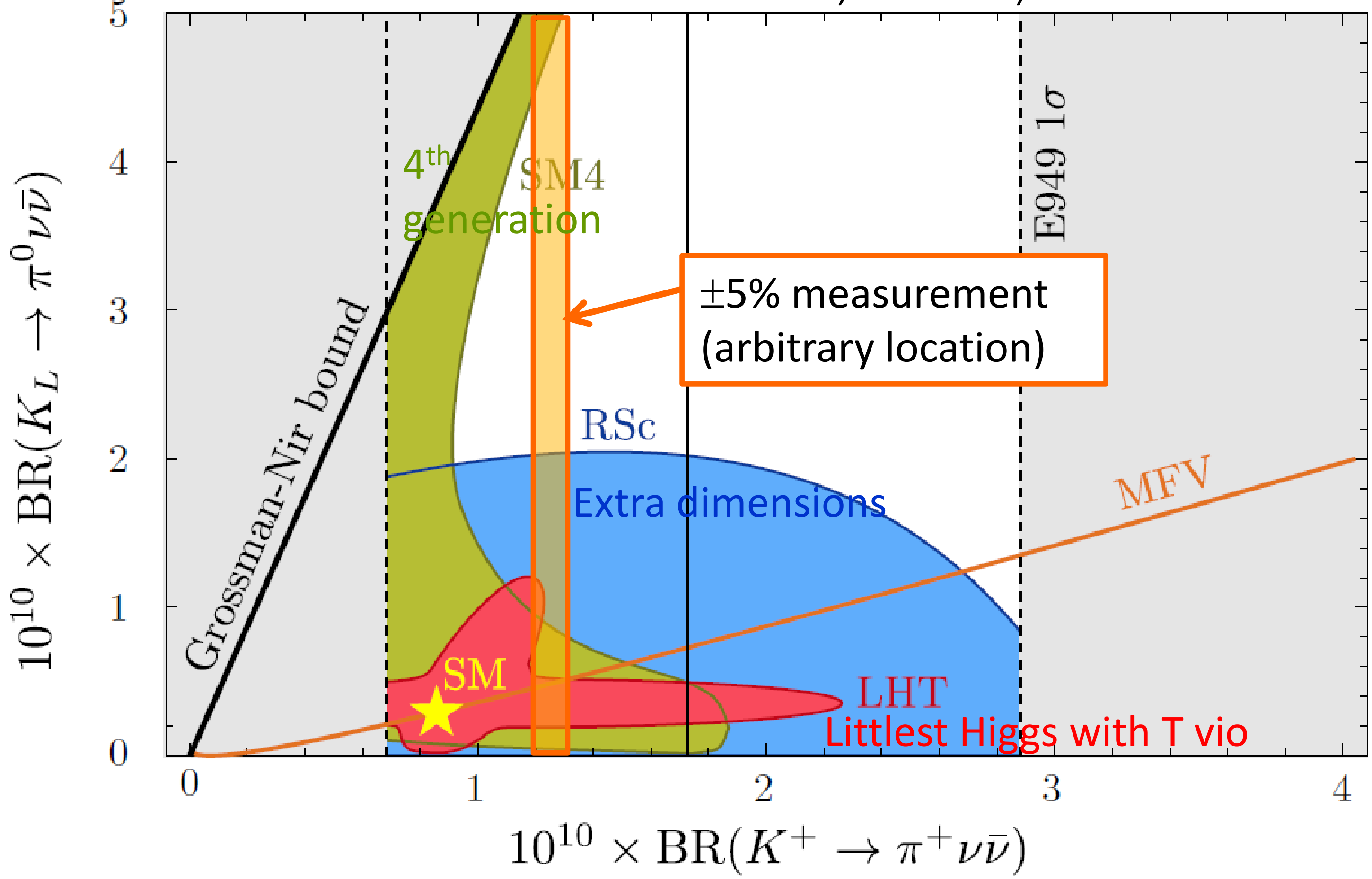
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is sensitive to New Physics

D. Straub, CKM2010, arXiv:1012.3893



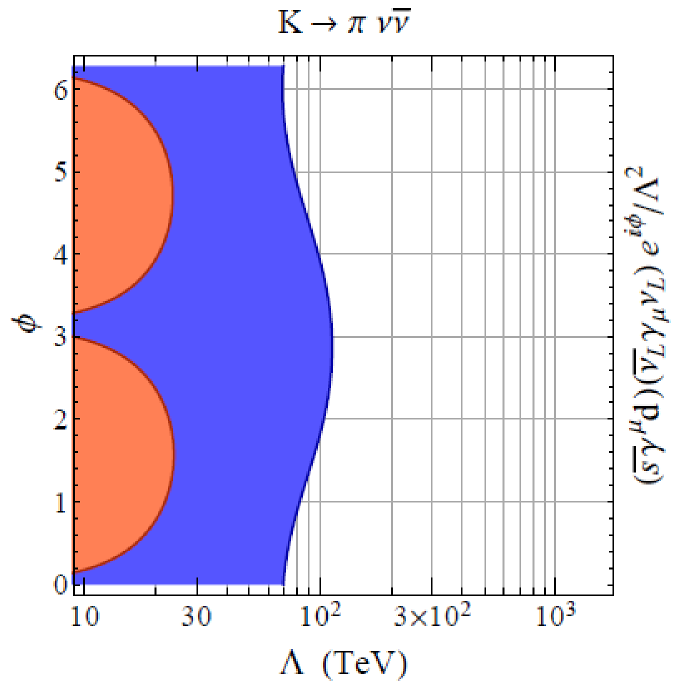
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is sensitive to New Physics

D. Straub, CKM2010, arXiv:1012.3893

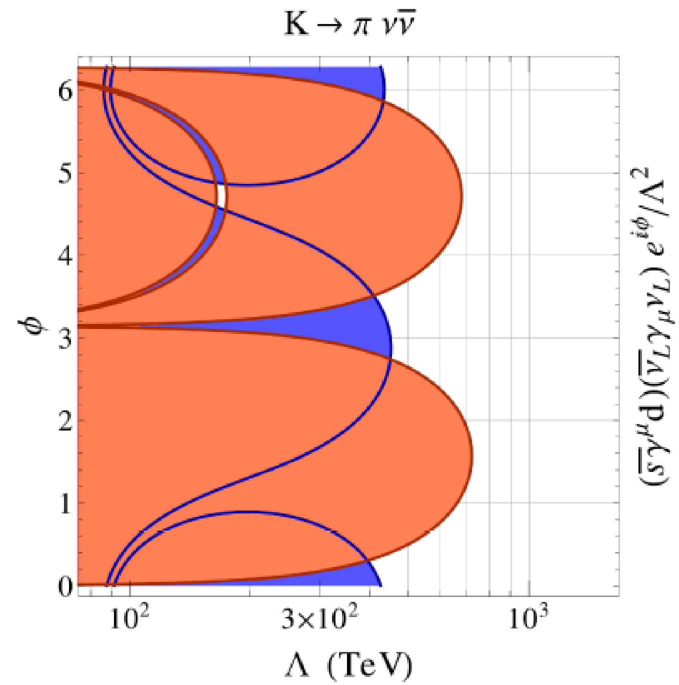


$$(\bar{s}\gamma^{\mu}d)(\bar{\nu}_L\gamma_{\mu}\nu_L)\, e^{i\phi}/\Lambda^2$$

current situation



assuming 5% measurements of both modes



- $K^+ \to \pi^+\nu\bar{\nu}$ already constrains scales of $\sim$ 100 TeV
- $K_L \to \pi^0\nu\bar{\nu}$ bound still above the Grossman-Nir bound $\to$ no additional constraint

- $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ give complementary information
- scales of order 700 TeV are probed

Slide from Wolfgang Altmannshofer's talk, Argonne IF workshop (April)

Summary

- Flavor changing neutral current processes will continue to be incisive probes for new physics for the foreseeable future.
  - Some observables have theoretically clean SM predictions.
  - Some of these processes are sensitive to new physics at mass scales up to several hundred of TeV.
  - Experiments should push these measurements to their logical endpoint, where the experimental errors are no larger than the theory uncertainty.
  - It is important to make (and combine) measurements of related processes to fully exploit the reach for new physics.