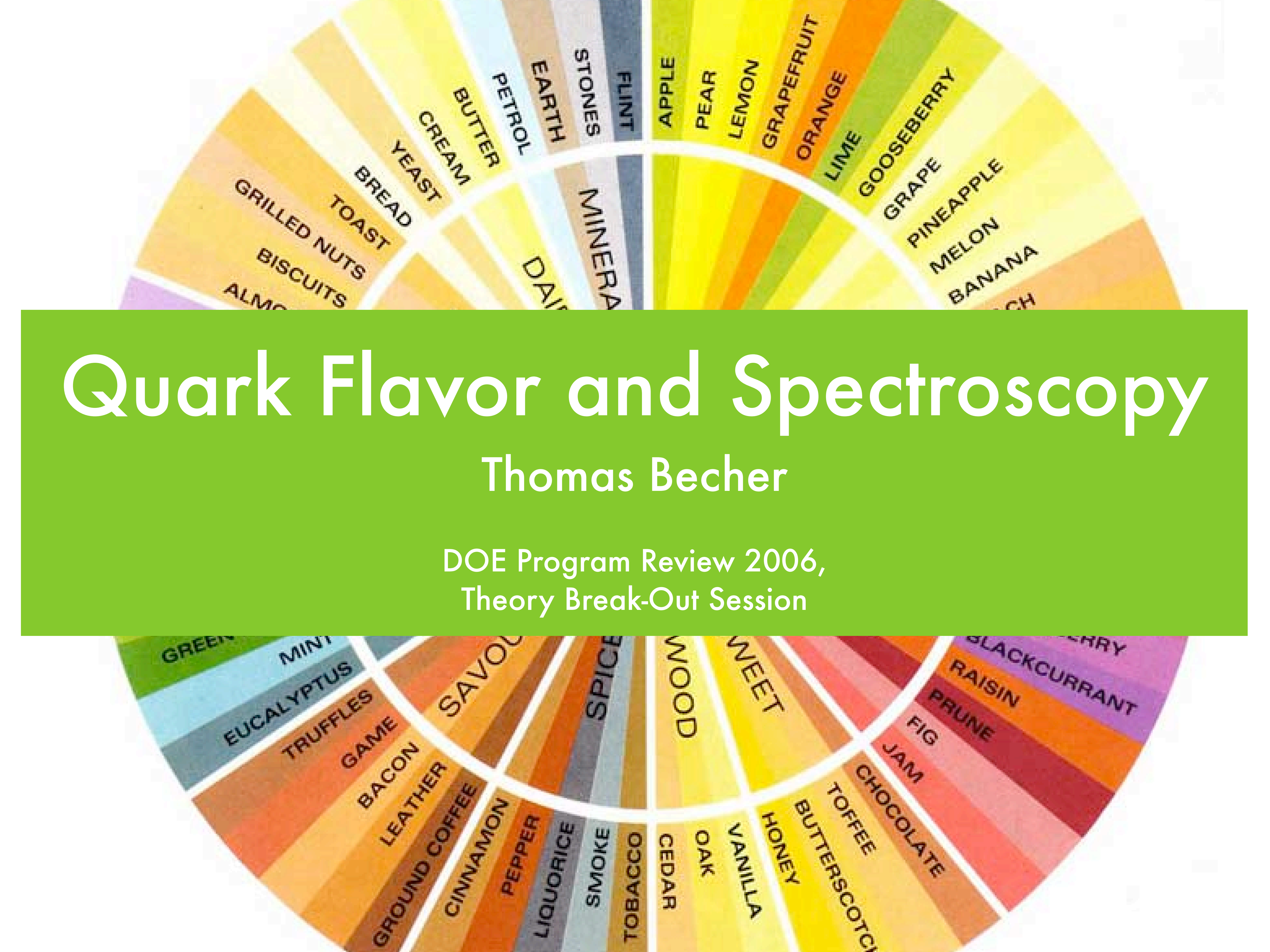


Quark Flavor and Spectroscopy

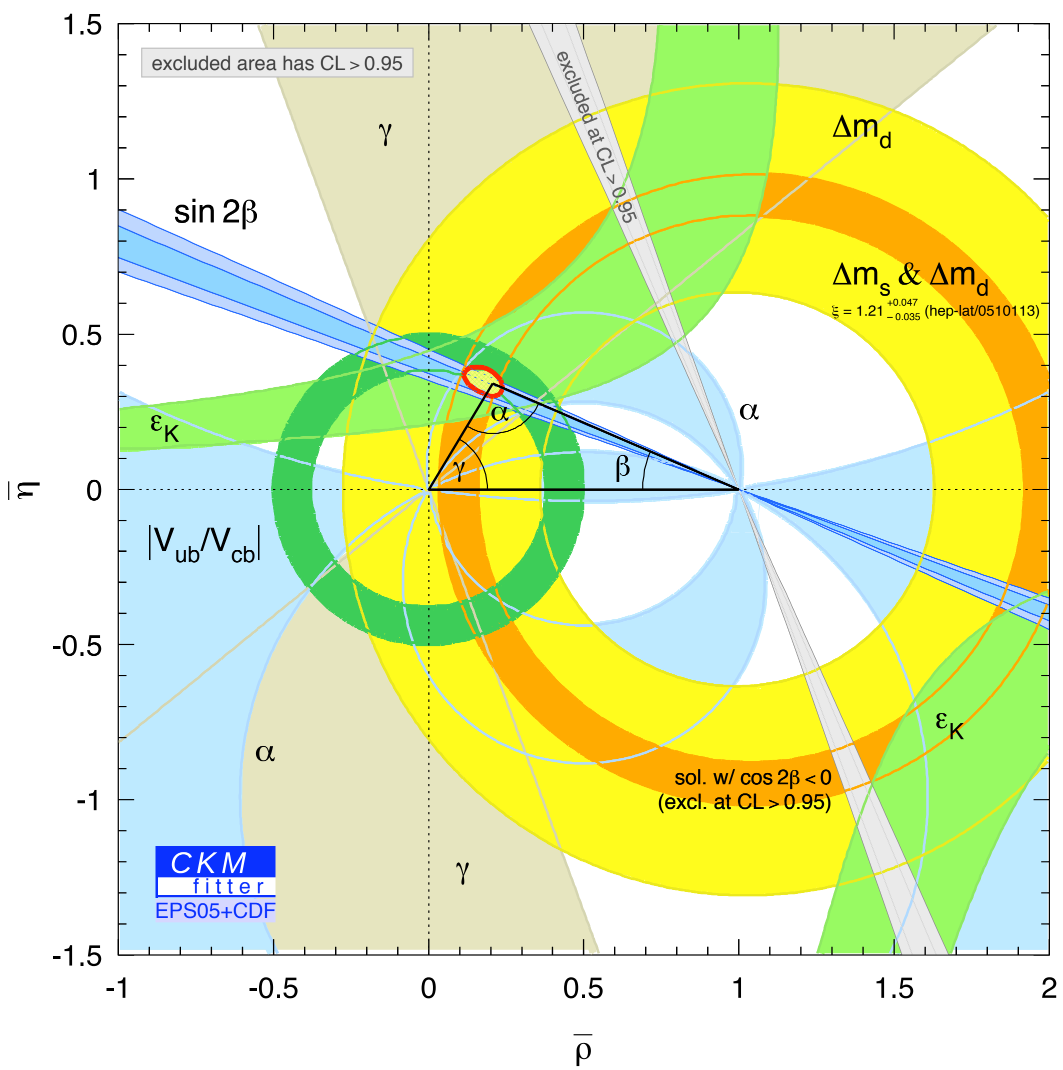
Thomas Becher

DOE Program Review 2006,
Theory Break-Out Session

Overview

- Flavor physics
  - at the Tevatron and at the B-factories
  - in the Fermilab theory group
- Research during the past year

Flavor Physics at the Tevatron



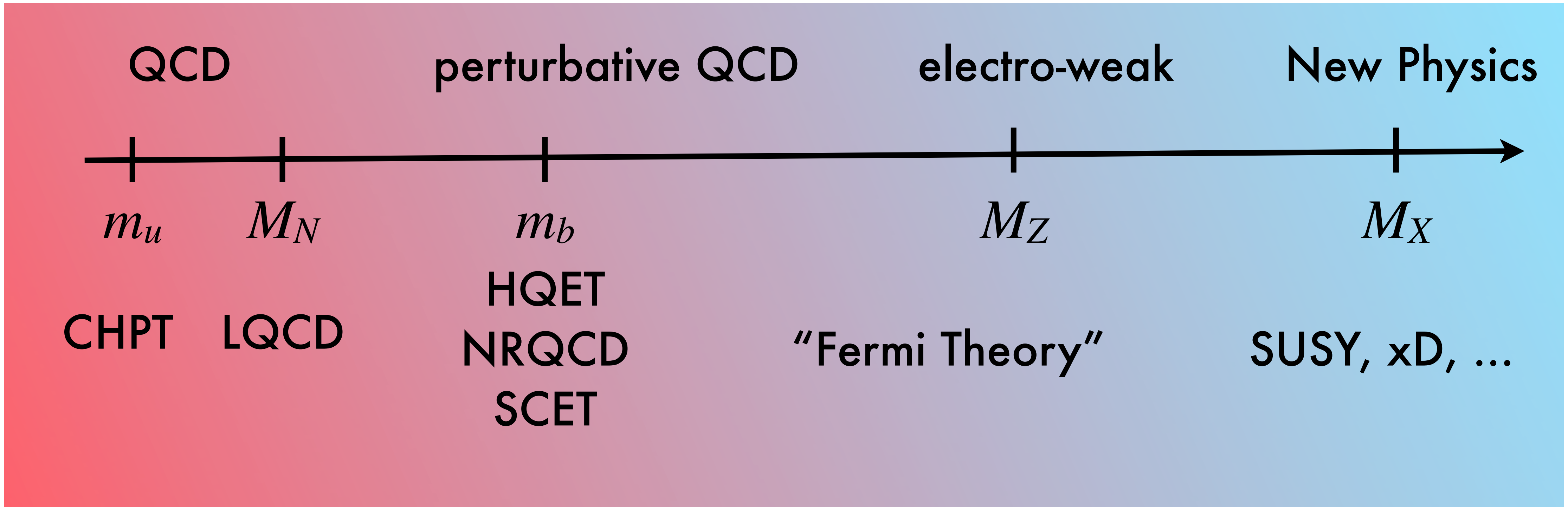
$$\Delta m_s = 17.33^{+0.42}_{-0.21}(\mathrm{stat}) \pm 0.07(\mathrm{sys})$$

- Flavor physics is an important part of the experimental program of CDF and DZero.
- Contrary to *B*-factories, all *b*-hadrons are accesible at hadron collider: B_s, Λ_b , ...

Flavor in the theory group

- Goals
  - Investigate possible new physics effects in flavor changing processes.
  - Separate and calculate QCD effects associated with higher scales. $\rightarrow$ Effective Field Theories
  - Calculate low energy QCD matrix elements. $\rightarrow$ Lattice QCD
  - Contribute to FNAL experimental program.

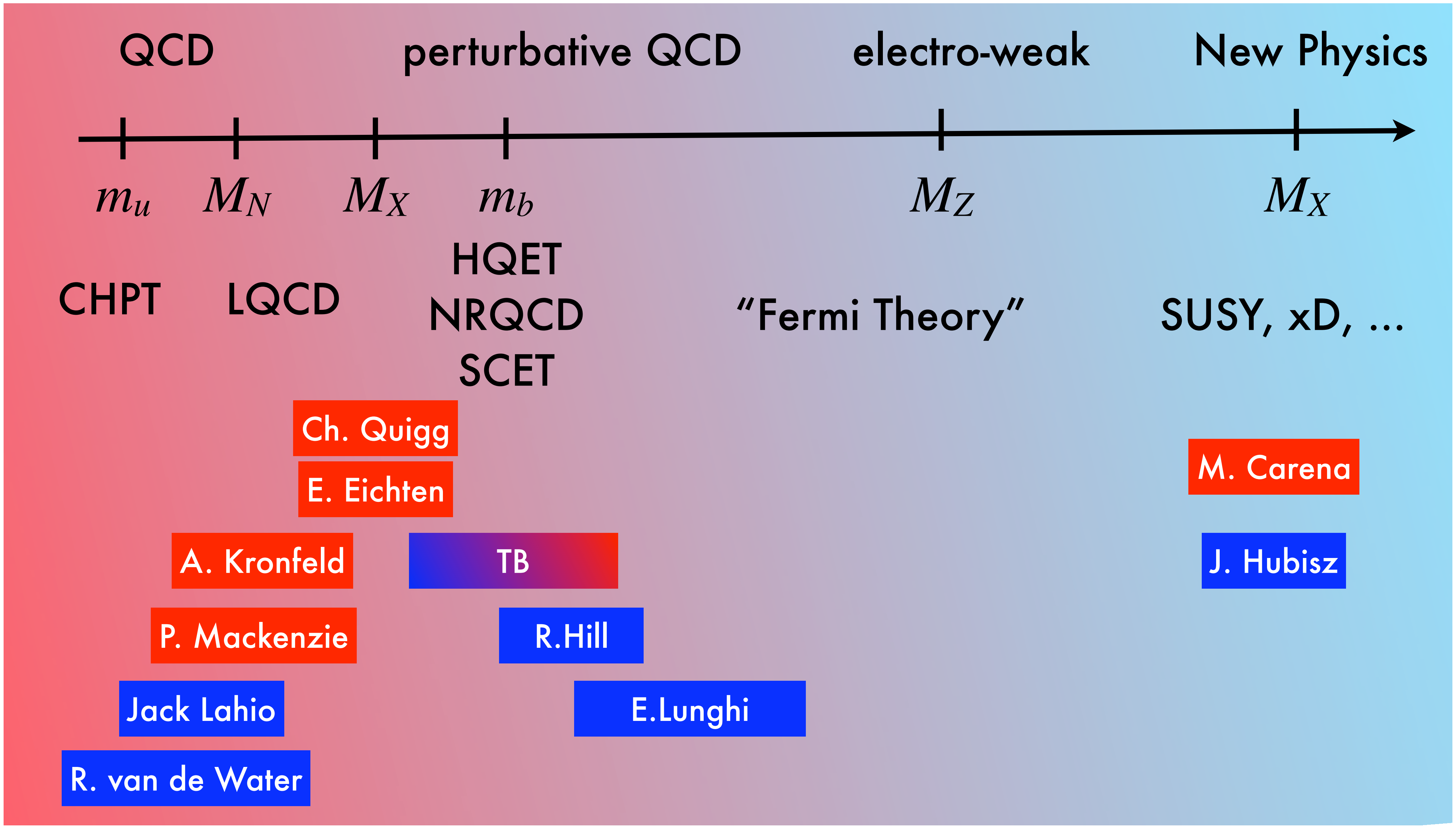
Theoretical aspects of flavor physics



- Many scales, many different tools
- Fermilab theory group covers the entire range
  - Not the case at most universities.
  - FNAL theory group provides expertise on the various aspects relevant to experimentalists from universities.

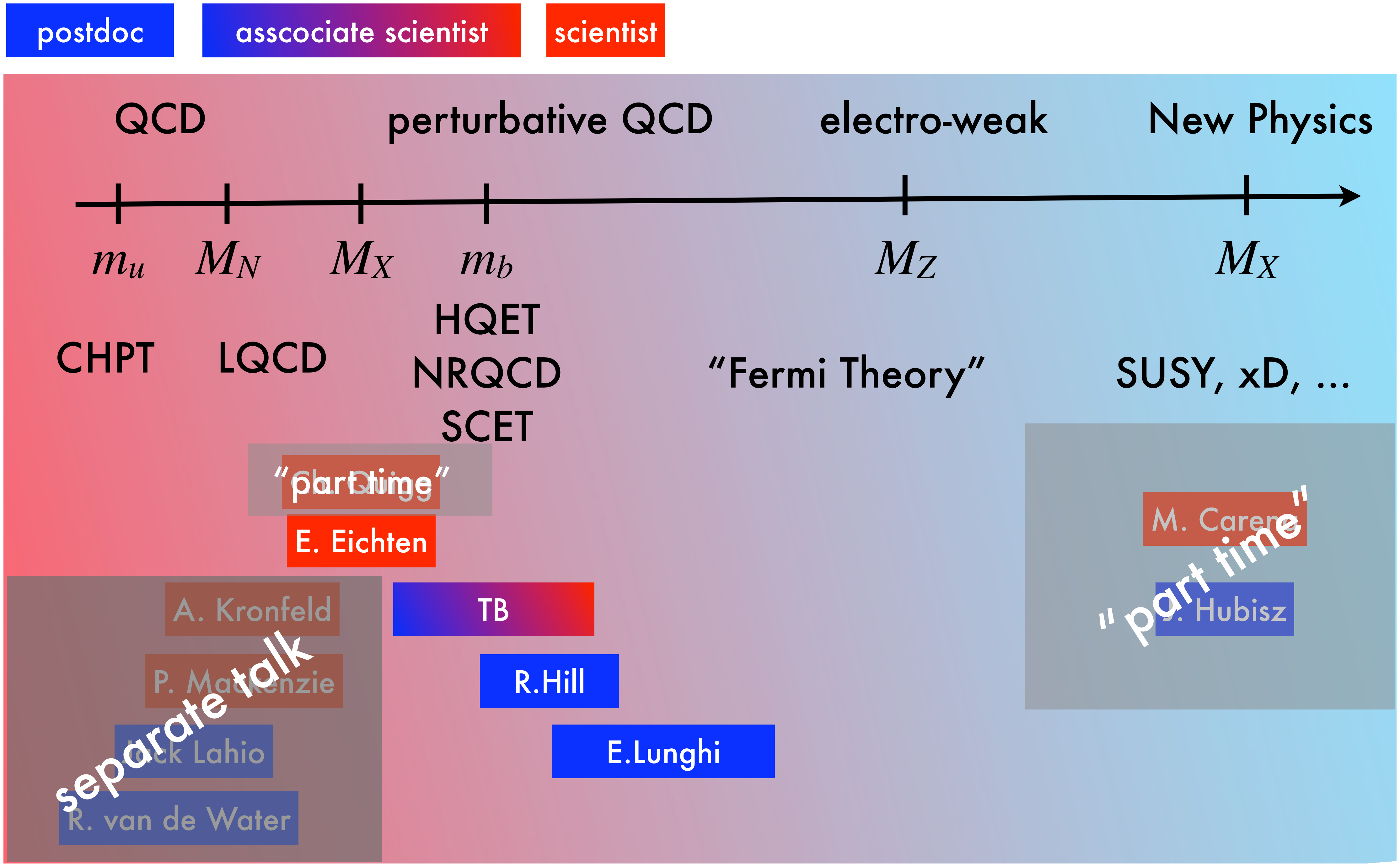
People

postdoc | asscociate scientist | scientist



Note: Positioning at energy *E* means flavor-physics/spectroscopy paper(s) at relevant scale during past year.

Continuum limit



Work in the past year

- New Physics
  - Flavor structure of littlest Higgs with T-parity. *J. Hubisz, hep-ph/0512169*
  - Constraints on B- and Higgs-physics in MSSM at large tanβ. *M. Carena, hep-ph/0603106*
- Old physics
  - Perturbative lattice-to-continuum matching for B_K. *TB, Phys.Rev.D72:074506, 2005*
  - Constraints on form factors entering semi-leptonic decays and extraction of |Vub| from $B\to\pi\ell\nu$. *TB and R. Hill, PLB 633, 2006*
  - New states above charm threshold. *E. Eichten and Ch. Quigg, Phys.Rev.D73:014014, 2006*
  - Electromagnetic logarithms in $B\to X_{s,d}\,\ell^+\ell^-$. *E. Lunghi, hep-ph/0512066*
  - NNLO analysis of photon energy cut effect in $B\to X_{s,d}\,\gamma$. *TB, PLB 633, 739, 2006, and PLB, in press.*
  - Resummation for collider processes with EFT methods. *TB, hep-ph/0605050*

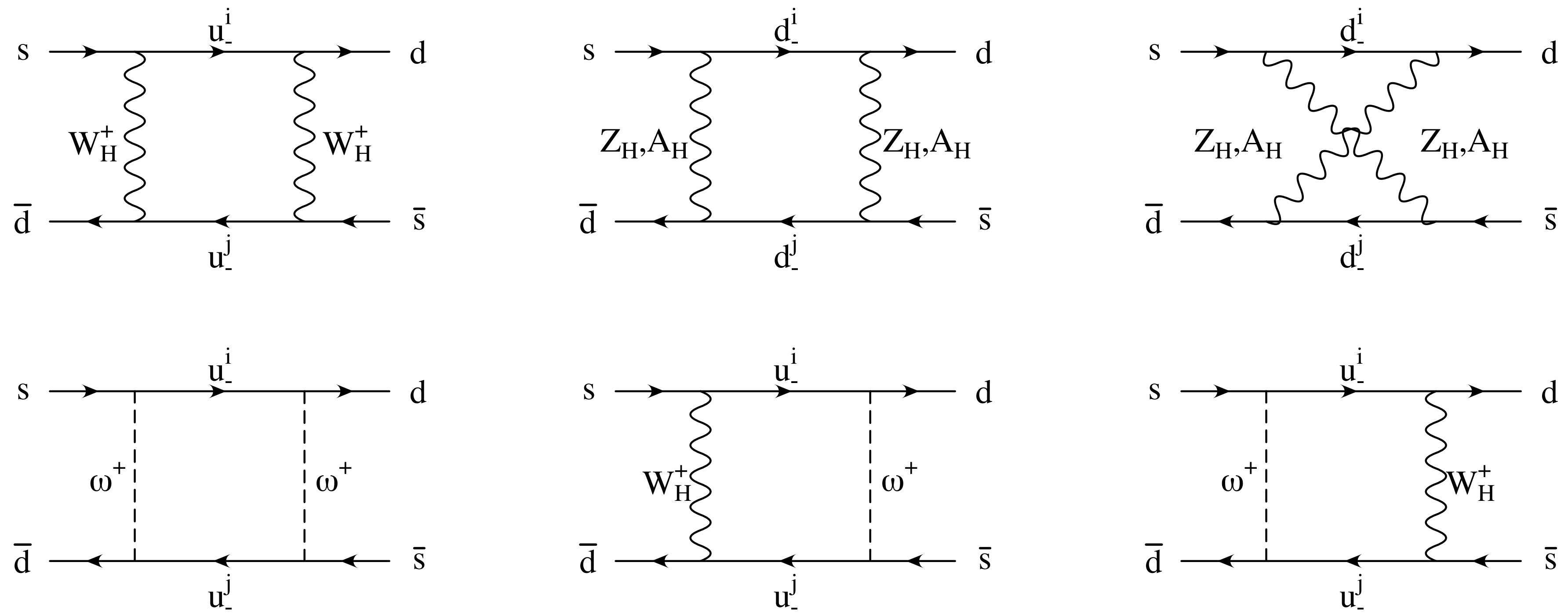
Flavor of a little Higgs with T-parity

J. Hubisz, G. Paz and S. Lee, hep-ph/0512169

- In little Higgs theories same-spin partners of SM particles are introduced to cancel quadratic divergence in Higgs mass to one-loop order.
- T-parity symmetry ensures that heavy partners are only pair-produced. (Otherwise problems with precision EW.)
- →New CKM-type matrices for coupling to T-odd heavy fermions and gauge bosons V_{Hu} and V_{Hd} with $V_{\rm CKM} = (V_{Hu})^\dagger V_{Hd}$.

Flavor of a little Higgs with T-parity

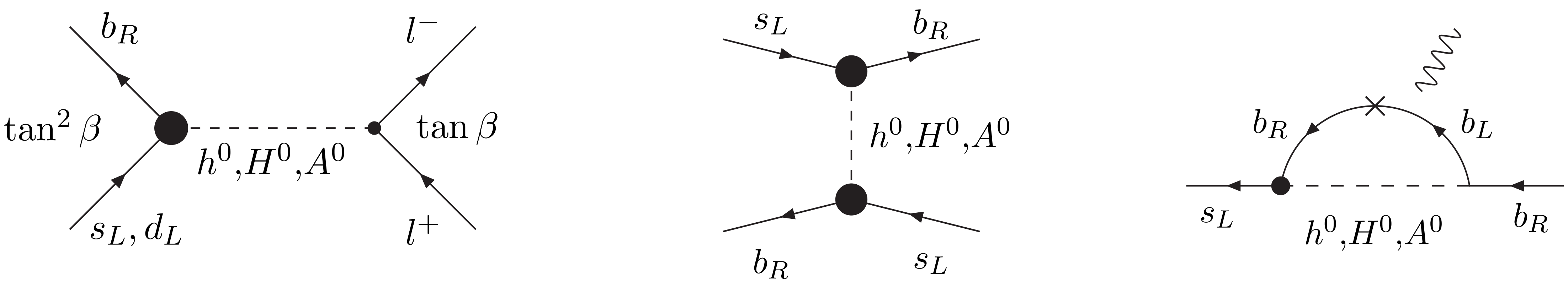
J. Hubisz, G. Paz and S. Lee, hep-ph/0512169



- Jay Hubisz and collaborators study constraints from meson mixing.
  - Strong constraints, but ∃ scenarios consistent with experiment.
- Are now also including constraints from rare decays.

B- and Higgs-physics in MSSM

M.Carena, A.Menon, R.Noriega-Papaqui, A.Szynkman and C.E.M.Wagner, hep-ph/0603106.



$$p\bar{p} \rightarrow H/A \rightarrow \tau^+\tau^-$$

- At large tanβ, correlations between
  - B_s-mixing, $B_s \rightarrow \mu^+\mu^-$, $B_s \rightarrow X_s\,\gamma$
  - and heavy Higgs search $pp \rightarrow H/A \rightarrow \tau^+\tau^-$
- Complementary constraints from B-physics and collider search for H/ A.

B and Higgs Physics at the Tevatron and the LHC:

explore complementary regions of SUSY parameter space

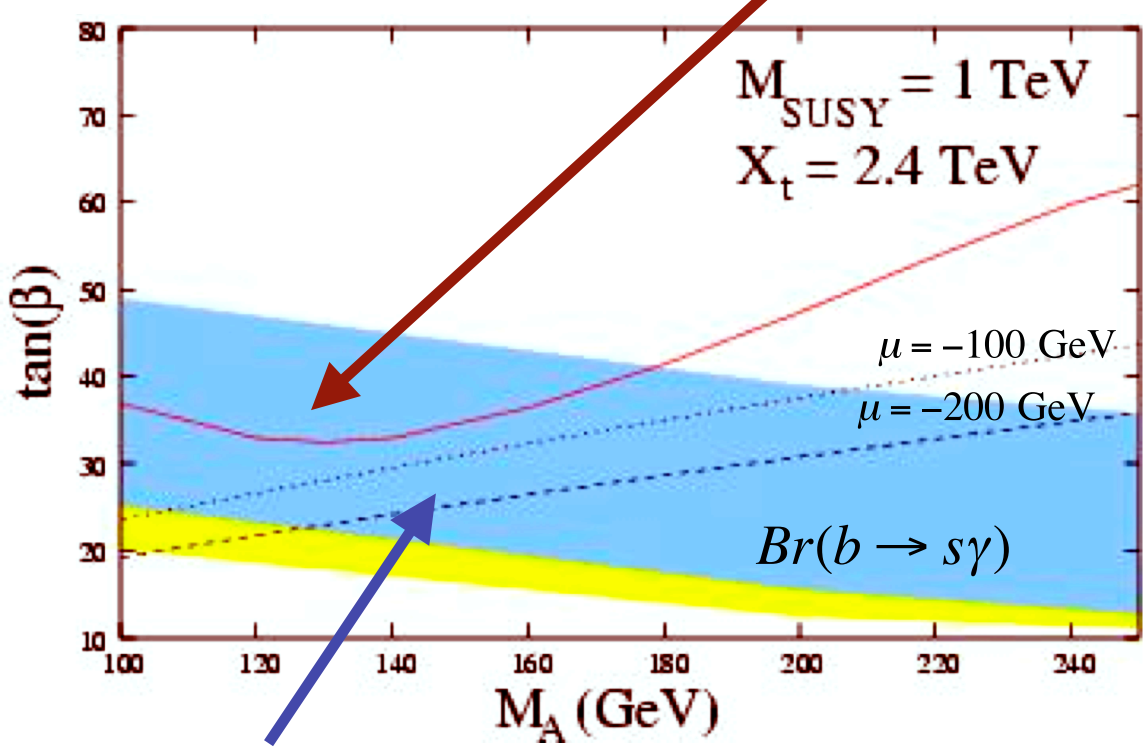
-- MSSM Higgs searches probe large tan β and M_A regions via the inclusive process $p\bar{p} \to H/A \to \tau^+\tau^-$ => only small SUSY model dependence

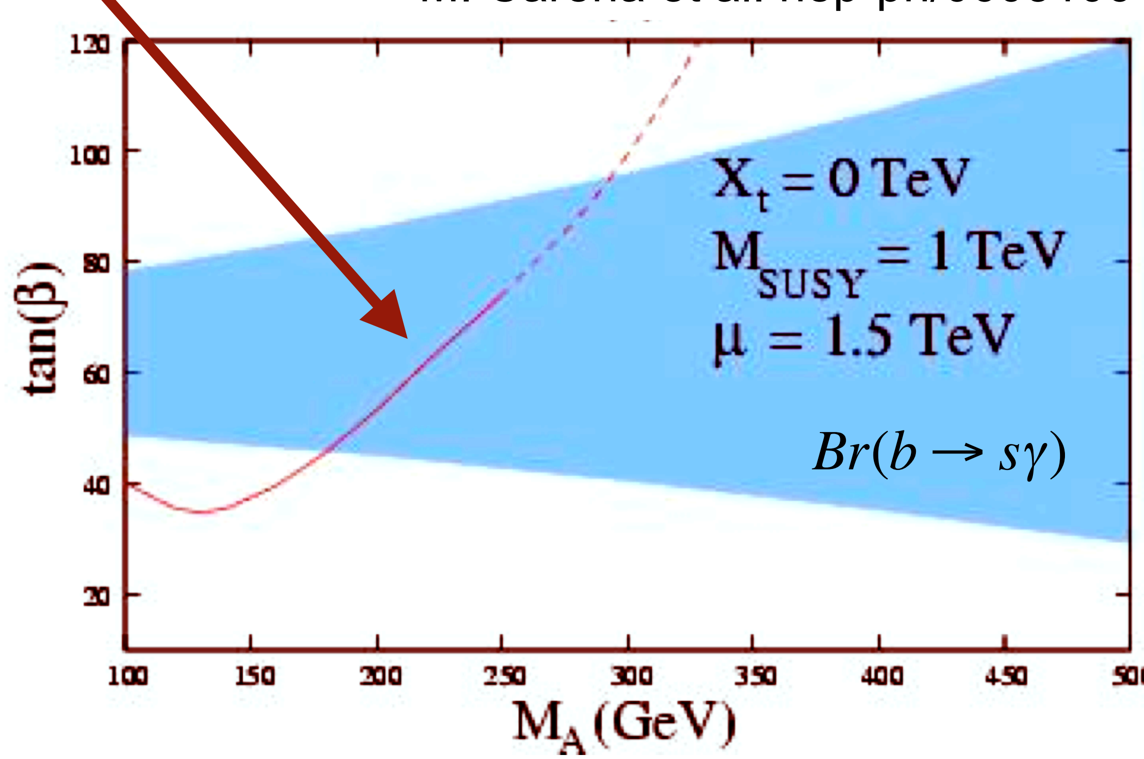
M. Carena et al. hep-ph/0511023

-- Higgs mediated FCNC can enhance the rare decay rate $B_S \to \mu^+\mu^-$ up to levels accessible at the Tevatron => explores efficiently large tan β and M_A region

Tevatron Higgs reach with $1fb^{-1}$

M. Carena et al. hep-ph/0603106





CDF limit : $BR(B_S \to \mu^+\mu^-) < 1 \times 10^{-7}$

- **Enhanced reach at the LHC**

- Bs mixing and $\mathrm{BR}(B_s \to \mu^+\mu^-)$ strongly correlated due to Higgs mediated flavor violating effects

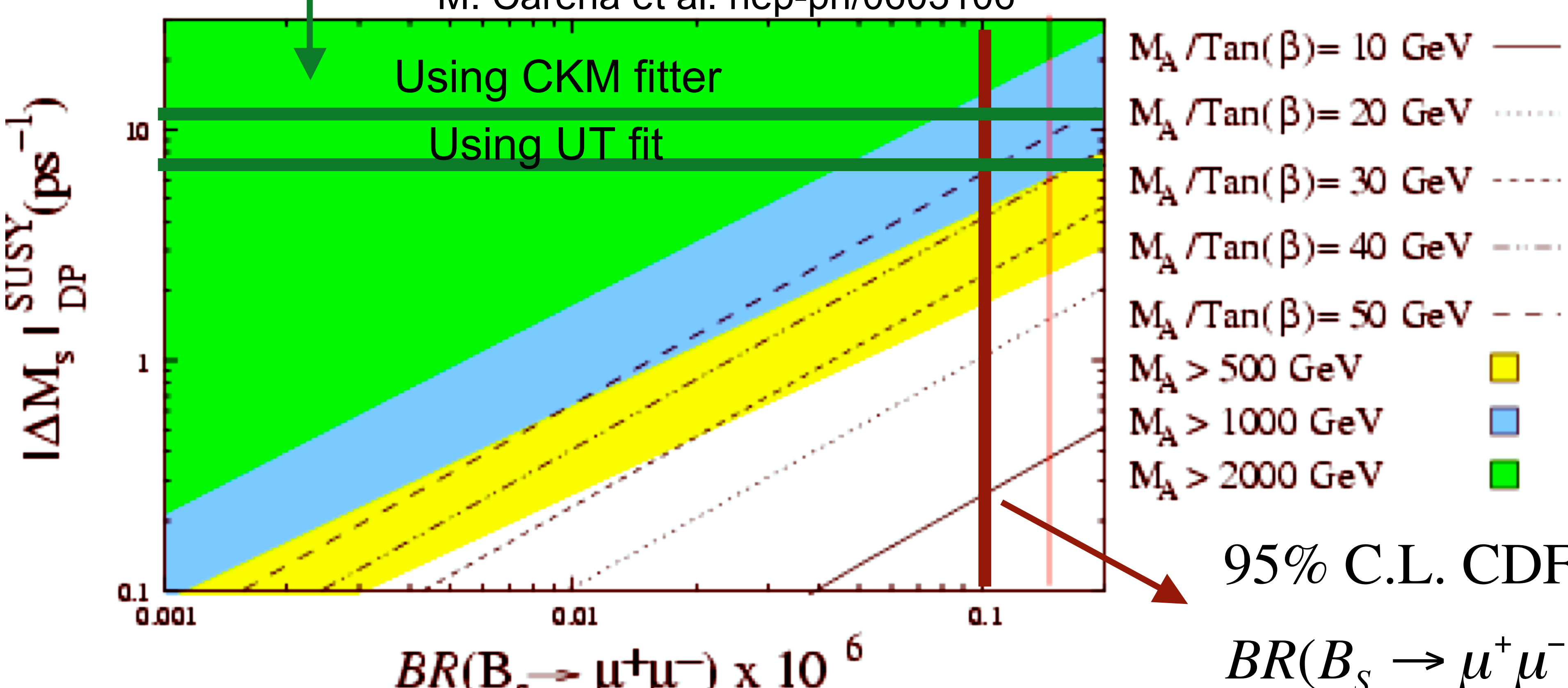
$$BR(B_s \to \mu^+\mu^-)^{MSSM} \propto |V_{ts}^* V_{tb}|^2 \left(\tan\beta^6 / m_{A/H}^4\right)$$

$$\Delta M_s^{MSSM} \propto |V_{ts}^* V_{tb}|^2 \left(\tan\beta^4 / m_{A/H}^2\right)$$

Upper bound on new physics contribution based on CDF measurement:

$$\Delta M_s^{CDF} = 17.34^{+0.49}_{-0.20}$$

M. Carena et al. hep-ph/0603106



95% C.L. CDF limit :

$$BR(B_S \to \mu^+\mu^-) < 1 \times 10^{-7}$$

- $\tan\beta$ enhanced contributions to ΔM_s strongly constrained by $B_S \to \mu^+\mu^-$

New states above charm threshold

E.J.Eichten, K.Lane and C.Quigg, PRD 73 (2006) 014014

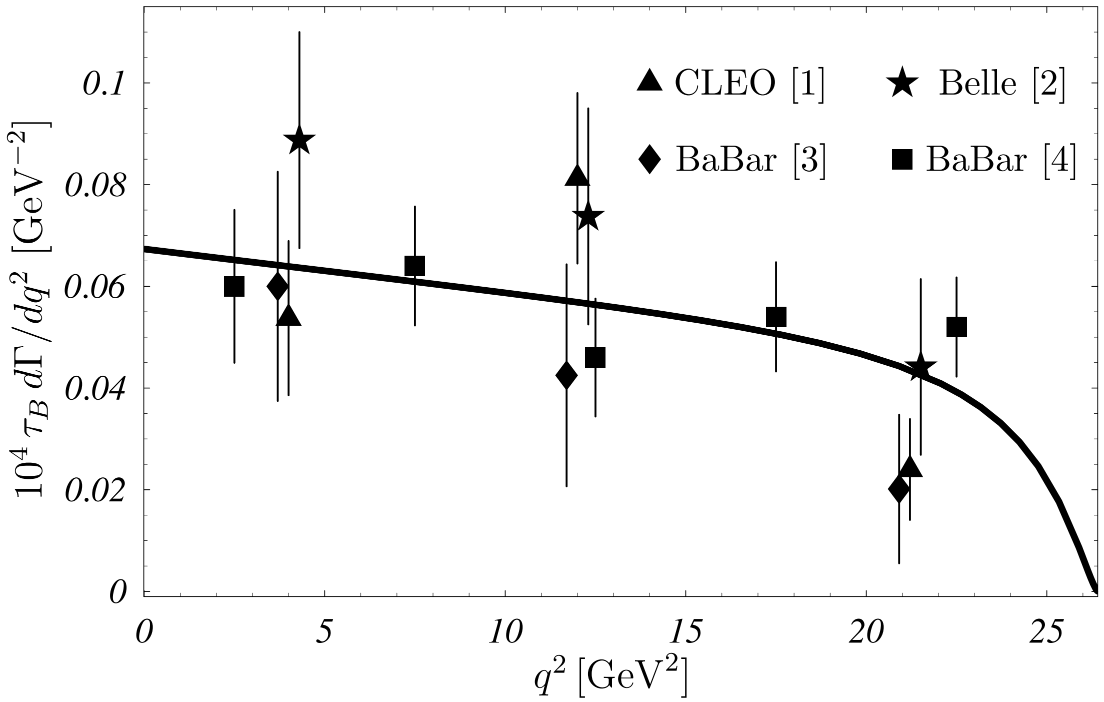
- Many new charm states observed in last three years.
- States near threshold: X(3872), Z(3934), Y(3940), Y(3943), Y(4260), ...
  - Very difficult to analyze with LQCD
  - ELQ use Cornell Coupled-Channel Model to study effect of light-quark pairs.

X, Y, Z 's Status Table

Observed	State	JPC	$(\bar{c}c)$	Alternative
Many	X(3872)	1++	χ_{c1}' ✓	D D* Molecule
Belle	Z (3934)	2++	χ_{c2}' ✓✓✓	
Belle	Y (3940)	JP+	?	?
Belle	X (3943)	0-+	η_c'' ✓✓	
Babar	Y (4260)	1--	2^3D_1 ✗	Hybrid

Semileptonic form factor shape

TB, R. Hill, PLB633:61-69,2006



$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |\vec{p}_\pi|^3 |V_{ub}|^2 |F_+(q^2)|^2$$

- CLEO, BABAR and Belle have measurements of partial $B \to \pi \ell \nu$ decay rates.
- Fermilab and HPQCD have unquenched lattice results in the large q^2-region.
- Both used simple pole parameterizations for form factor shape. Systematic uncertainty from form factor shape?

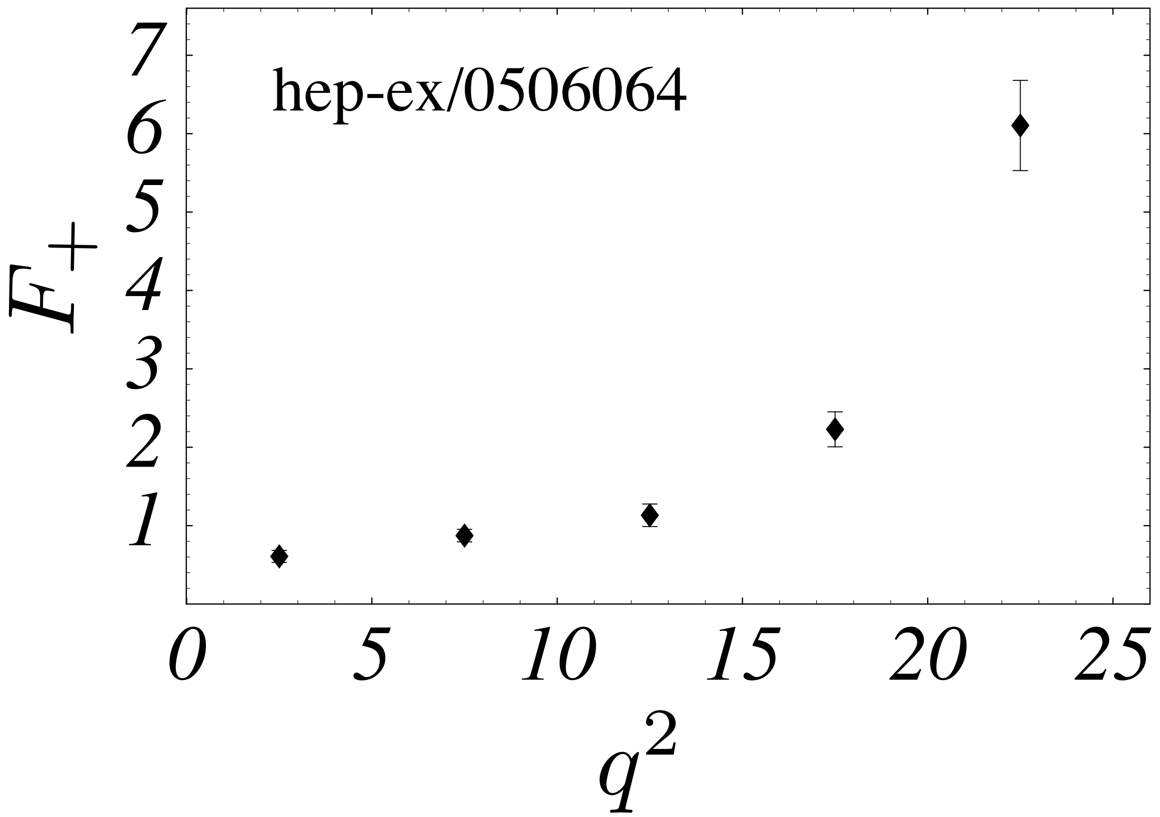
Constraints on form factor shape

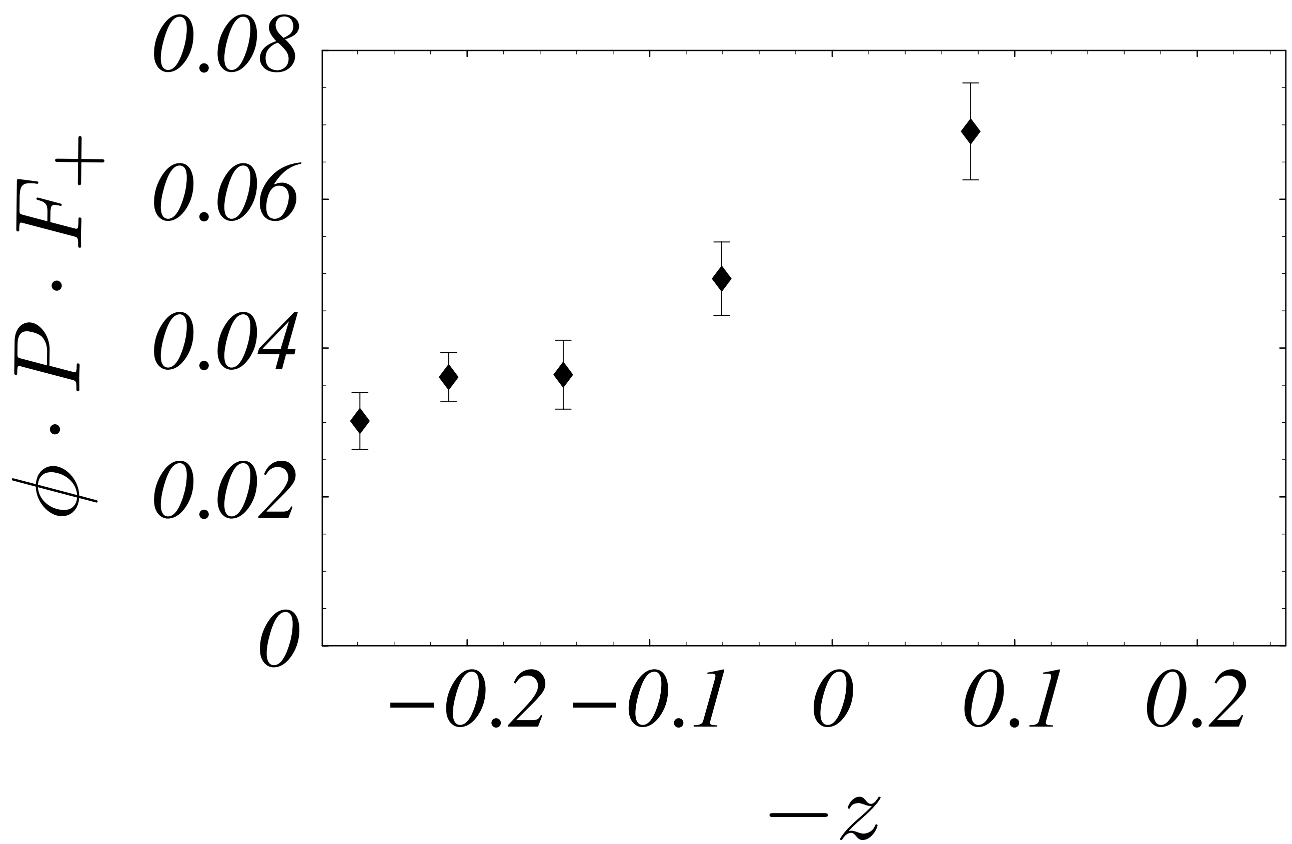
TB, R.J. Hill, PLB633:61-69, 2006

$$F_+(q^2) = \frac{1}{P(q^2)\phi(q^2)} \sum_{k=0}^{\infty} a_k \left[z(q^2)\right]^k \qquad A = \sum_{k=0}^{\infty} a_k^2$$

- Constrained series parameterizations
  - Map $q^2 \to z(q^2)$. Improved convergence of series $|z|_{\rm max} \approx 0.5$.
  - Bound $A < 1$ from unitarity.
  - Much stronger bound $A \sim \left(\frac{\Lambda}{m_b}\right)^3$ from heavy-quark power counting.

Illustration: BaBar 5-bin data





- Current experiments (and lattice) measure intersect and slope, but cannot yet resolve curvature.
- No longer need for model parameterizations.
- R. Hill in contact with KTeV, CLEO-C, Babar and Belle experimentalists, to convince them to abandon model parameterizations.

$B \to X_s \gamma$

- Important probe of FCNCs. Experimental matches theoretical uncertainty.
- Large effort underway to evaluate rate to NNLO.
  - Weak Hamiltonian to NNLO. Two- (and three-loop) matching, three- (and four-loop) anomalous dimensions.
  - Two- (and three-loop) matrix elements of operators in H_{eff}.
- Experiments do not measure total rate.
  - Take experimental cut $E_\gamma > E_0 = 1.8\text{GeV}$ into account!

$B \to X_s \gamma$

TB, M.Neubert, PLB633:739-747,2006 and PLB in Press

$$\Gamma(B \to X_s\gamma)|_{E_\gamma > E_0 = 1.8\text{GeV}} = H \cdot J \otimes S$$

- Three relevant scales
  - Hard scale $m_b \sim 5\text{GeV}$ → H
  - Jet-scale $M_X \sim (m_b\,\Delta)^{1/2} \sim 2\text{GeV}$ → J
  - Soft scale $\Delta = m_b - 2E_0 \sim 1\text{GeV}$ → S
- All three scales perturbative.
- Have evaluated both soft- and jet-function to two loops.
- Using RG evolution in Soft-Collinear Effective Theory, we have resummed perturbative logs of scale ratios to NNLO.

Threshold resummation in momentum space

TB, M.Neubert, hep-ph/0605050

- Apply EFT methods to collider processes.
- Traditionally, resummation for hard processes is performed in moment space.
  - Landau poles (in Sudakov exponent and Mellin inversion)
  - Mellin inversion only numerically
- Solving RG equations in SCET, we have obtained resummed expressions directly in momentum space.
  - Transparent physical interpretation, no Landau poles, simple analytic expressions for resummed rates.
  - Reproduce moment space expressions order by order

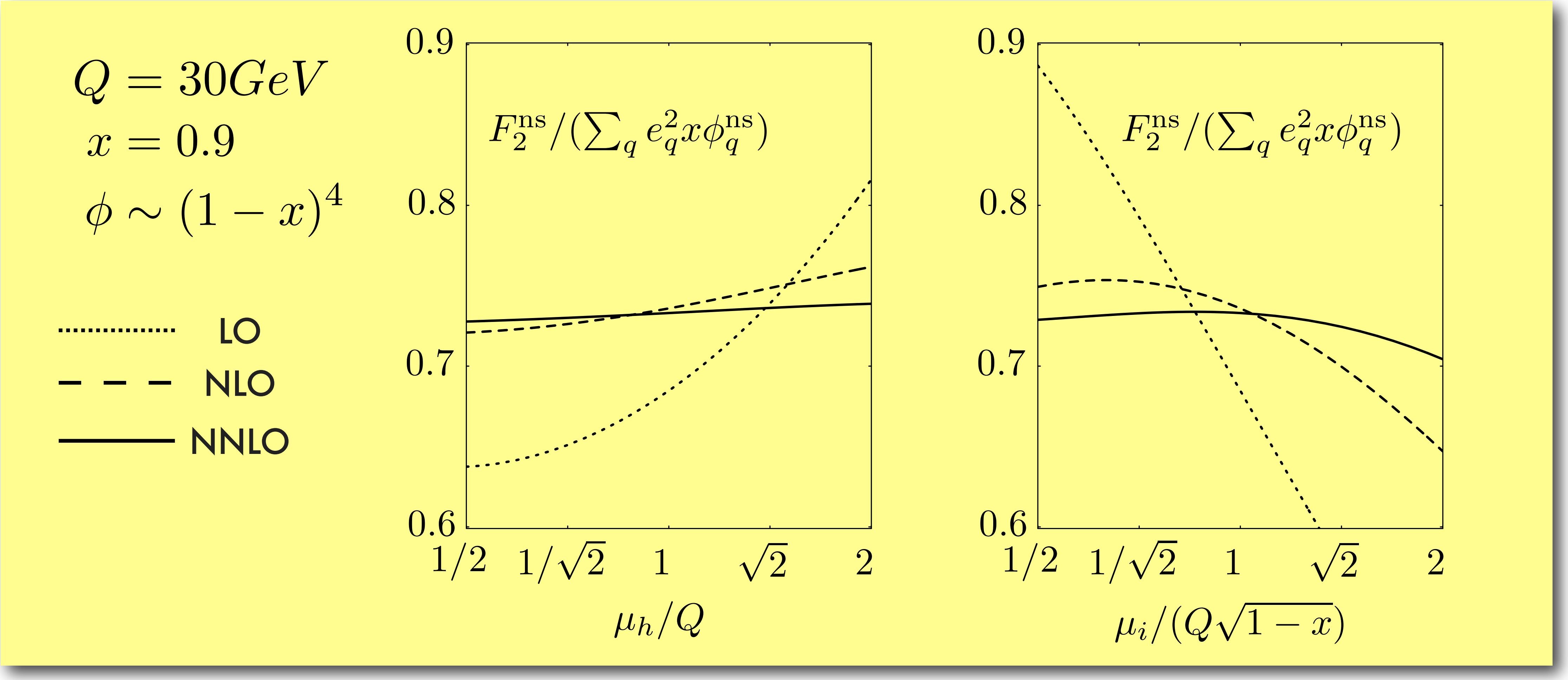
RG evolution of the jet-function

$$\frac{dJ(p^2,\mu)}{d\ln\mu} = -\left[2\Gamma_{\rm cusp}(\alpha_s)\,\ln\frac{p^2}{\mu^2} + 2\gamma^J(\alpha_s)\right] J(p^2,\mu) - 2\Gamma_{\rm cusp}(\alpha_s)\int_0^{p^2} dp'^2\,\frac{J(p'^2,\mu)-J(p^2,\mu)}{p^2-p'^2}$$

$$J(p^2,\mu) = \exp\left[-4S(\mu_i,\mu) + 2a_{\gamma^J}(\mu_i,\mu)\right] \times \widetilde{j}(\partial_\eta,\mu_i)\,\frac{e^{-\gamma_E\eta}}{\Gamma(\eta)}\,\frac{1}{p^2}\left(\frac{p^2}{\mu_i^2}\right)^\eta,$$

- Associated jet-function $\widetilde{j}$ is Laplace transform of $J(p^2,\mu_{\rm i})$.

DIS: $F_2^{\rm ns}(x)|_{x\to 1} = H \cdot J \otimes \phi_{q/N}$.



- Two-step evolution
  - $H(\mu_h) \times U_1(\mu_h, \mu_i) \times J(\mu_i) \otimes U_2(\mu_i, \mu_f) \otimes \phi(\mu_f)$

    match $\rightarrow$ **run** $\rightarrow$ **match** $\rightarrow$ **run**