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B_s Physics in the Standard Model and in a Scenario with a Single Universal Extra Dimension

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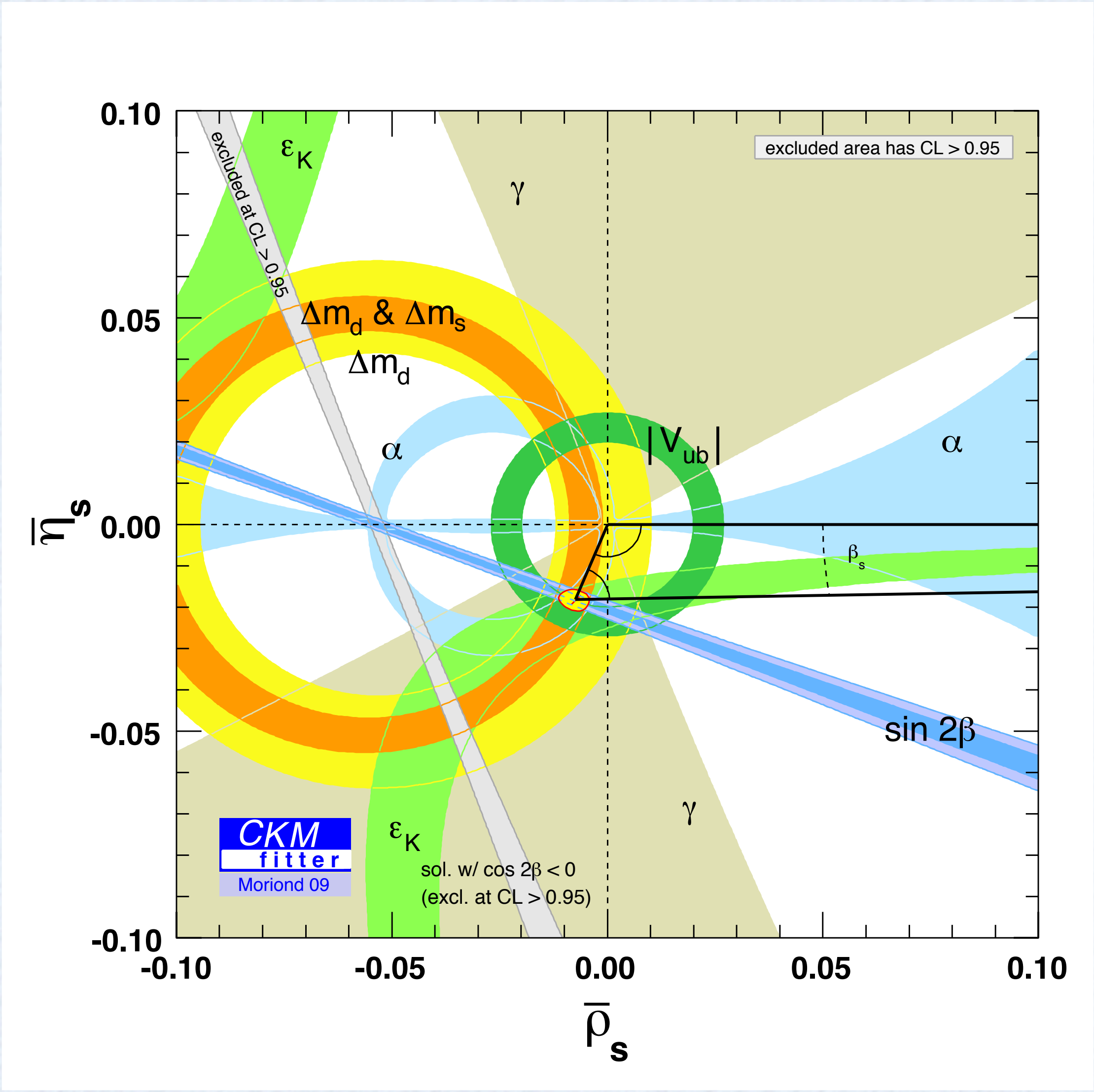
INFN - Istituto Nazionale di Fisica Nucleare

Outline

- Introduction: motivations for B_s phenomenology and extra dimensions
- The ACD Model with a single Universal Extra Dimension
- B_s - $\bar{B}_s$ mixing in the SM and in the ACD Model
- Rare B_s decays to $\eta^{(\prime)}$ final states in the SM and in the ACD Model
- Conclusions

B_s PHENOMENOLOGY

- Completing CKM phenomenology: access to the *bs* Unitarity Triangle



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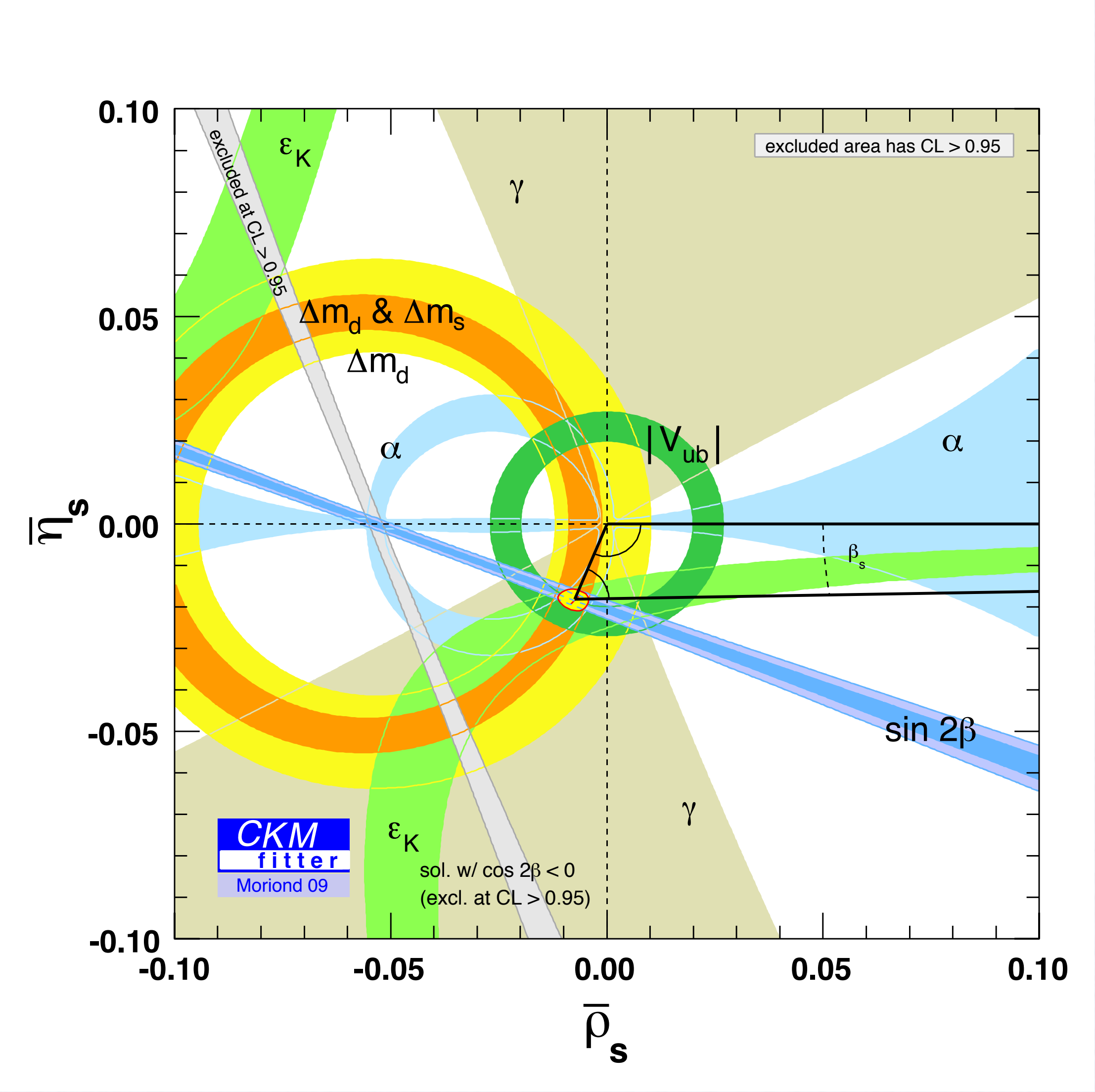

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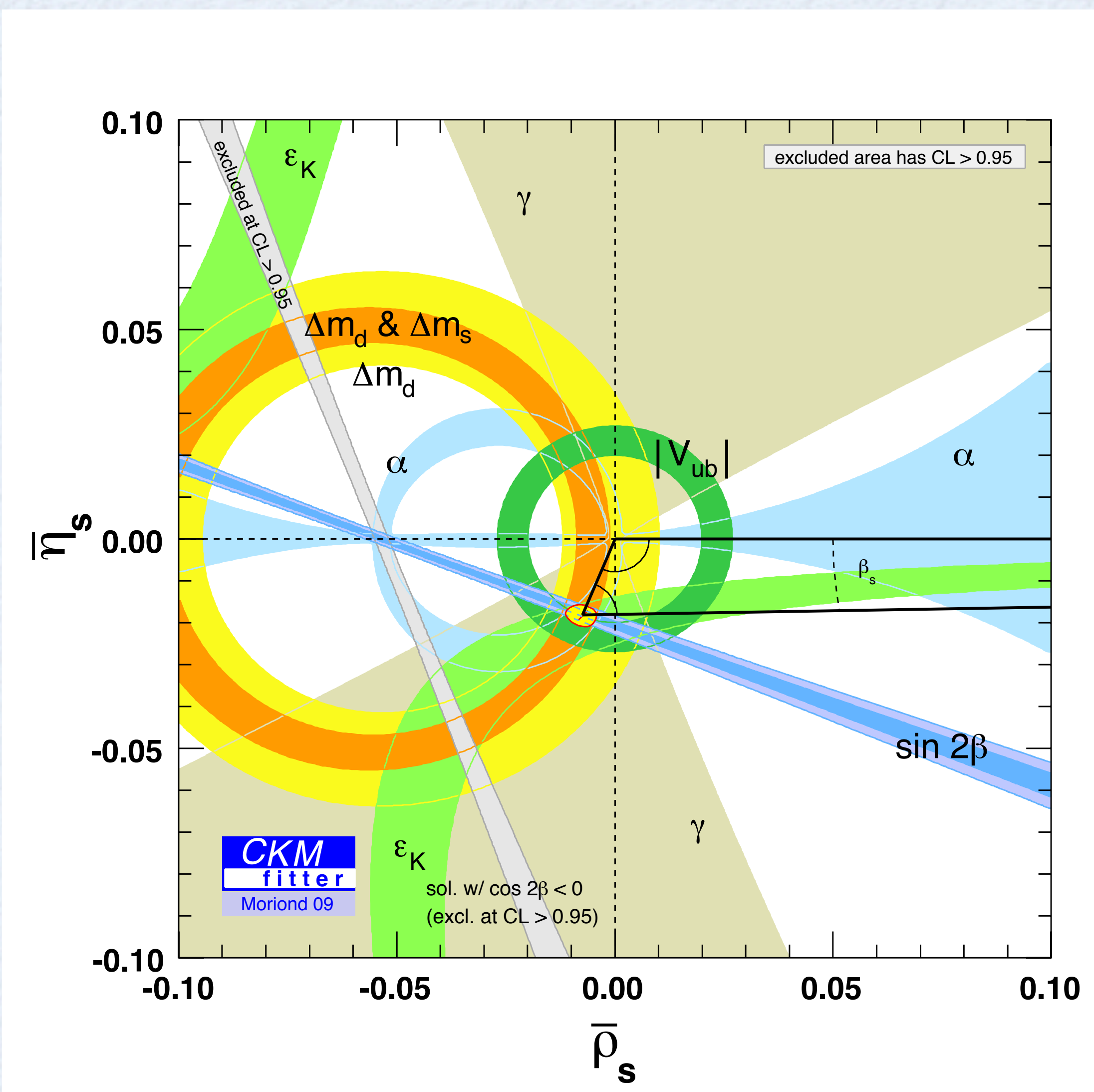

- FCNC $b \leftrightarrow s$ $\longrightarrow$ possibility to test New Physics

- First evidence of New Physics?

UT*fit*, arXiv:0803.0659v1

FIRST EVIDENCE OF NEW PHYSICS IN b ↔ s TRANSITIONS
(**UT***fit* Collaboration)

CKMfitter, Nucl. Phys. Proc. Suppl. **185** (2008)

Although there is a hint of a departure from the Standard Model related to the measurement of the phase ϕ_s, consistently by the CDF and D0 experiments, we do not see evidence (larger than the 3σ threshold) for New Physics, which has to be contrasted with Ref. [8].

WHY EXTRA DIMENSIONS?

- Hierarchy problem
  Large ED, Warped ED, ...

- Electroweak simmetry breaking without a Higgs boson
  Orbiforld breaking, Warped ED, Composite Higgs, ...

- Generation of mass and CKM hierarchy, new sources of CP violation
  Warped ED, ...

- Grand Unifications
  Superstrings, Supergravity, Warped ED, ...

- New Dark Matter candidates
  Universal ED, ...

- Black hole production at future colliders as a window on quantum gravity
  Phys. Rev. Lett. **87** (2001), Phys. Rev. **D65** (2002), ...

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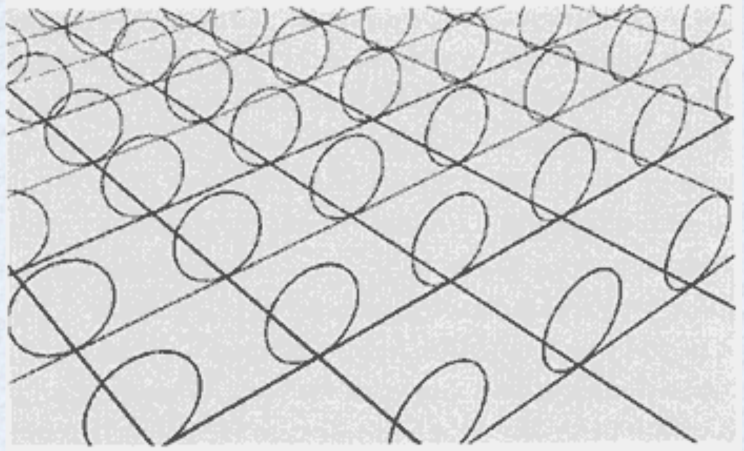
The Model

Assumptions of the model by **A**ppelquist, **C**heng, **D**obrescu, in its version with a single UED:

- there is a unique universal extra dimension
- it is compactified in the orbifold S^1_R/Z_2

Appelquist, Cheng, Dobrescu, Phys. Rev. **D** 64, 035002 (2001)



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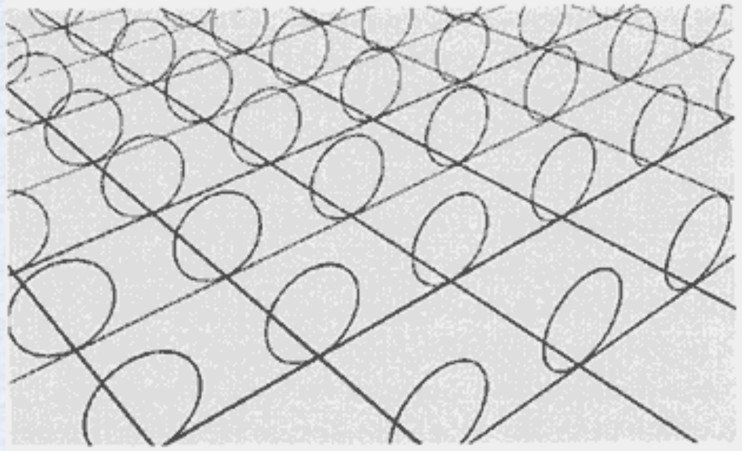

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The form of fields is constrained:

- scalar
$$\begin{cases} \Phi^+(x,y) = \frac{1}{\sqrt{2\pi R}}\phi^+_{(0)}(x) + \frac{1}{\sqrt{\pi R}}\sum_{n=1}^{\infty}\phi^+_{(n)}(x)\cos(m_n y) \\ \Phi^-(x,y) = \frac{1}{\sqrt{\pi R}}\sum_{n=1}^{\infty}\phi^-_{(n)}(x)\sin(m_n y) \end{cases}$$

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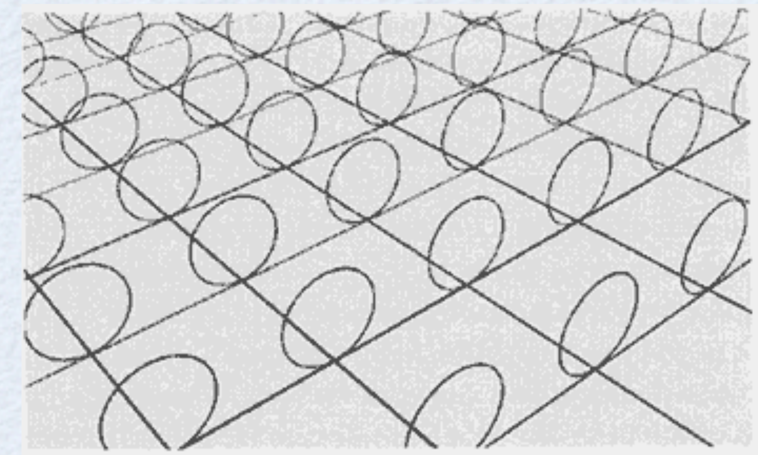

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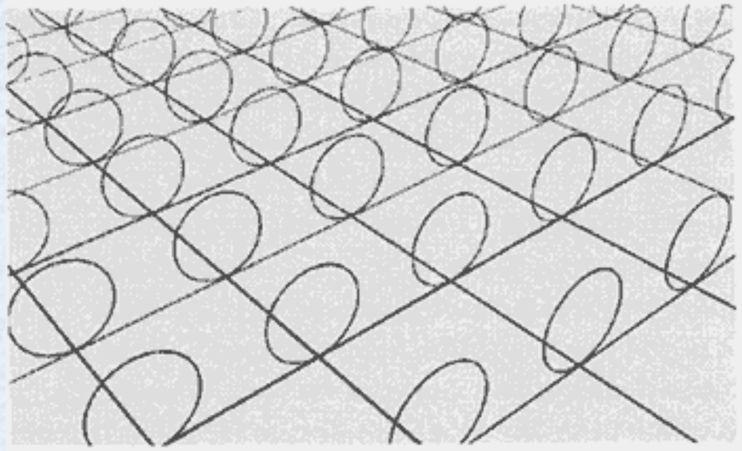

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$$m_n = \frac{n}{R}$$

EXTENSION OF THE STANDARD MODEL

One can introduce a Standard Model-inspired Lagrangian:

$$\mathscr{L}^{5D} = \mathscr{L}_G + \mathscr{L}_H + \mathscr{L}_Y$$

$$\begin{aligned}\mathscr{L}_G = {} & \bar{\mathcal{L}}_\ell \left(i\Gamma_A D^A\right)\mathcal{L}_\ell + \bar{\mathcal{R}}_\ell \left(i\Gamma_A D^A\right)\mathcal{R}_\ell - \frac{1}{4}\mathrm{Tr}\left(W_{MN}W^{MN}\right) - \frac{1}{4}B_{MN}B^{MN} \\ & + \bar{\mathcal{L}}_q \left(i\Gamma_A D^A\right)\mathcal{L}_q + \bar{\mathcal{R}}_u \left(i\Gamma_A D^A\right)\mathcal{R}_u + \bar{\mathcal{R}}_d \left(i\Gamma_A D^A\right)\mathcal{R}_d\end{aligned}$$

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$\downarrow$

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Mixing of Neutral Mesons

Described by a Schrödinger-like equation (justified by the Wigner-Weisskopf approximation):

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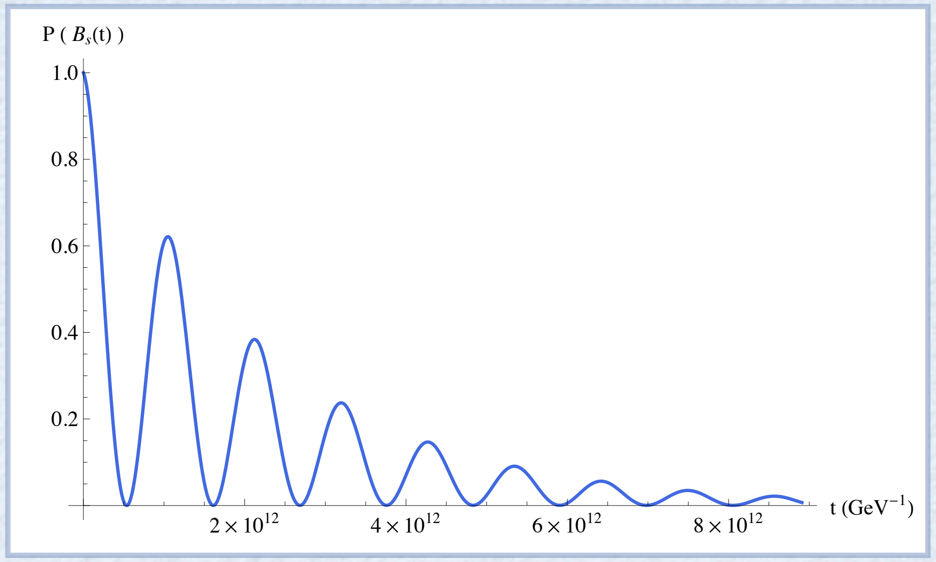

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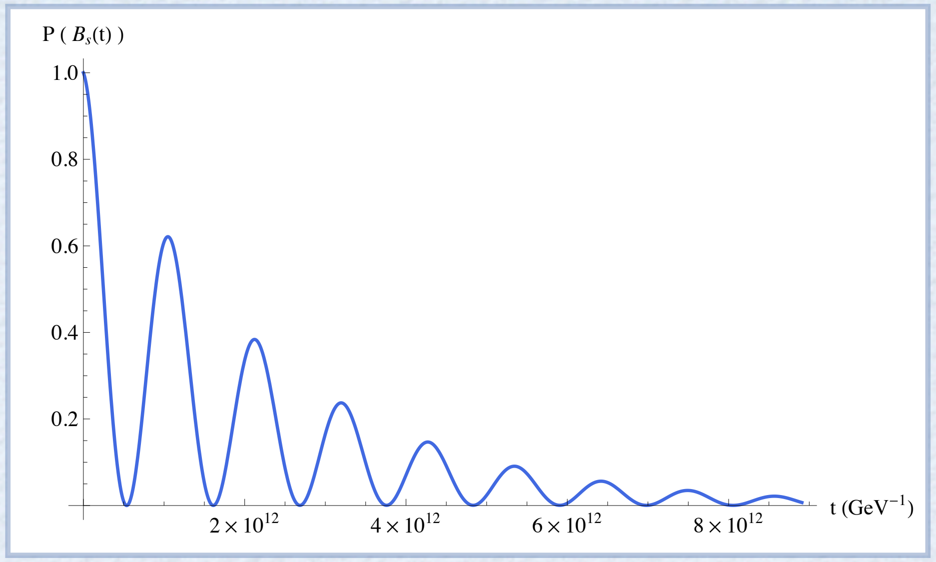

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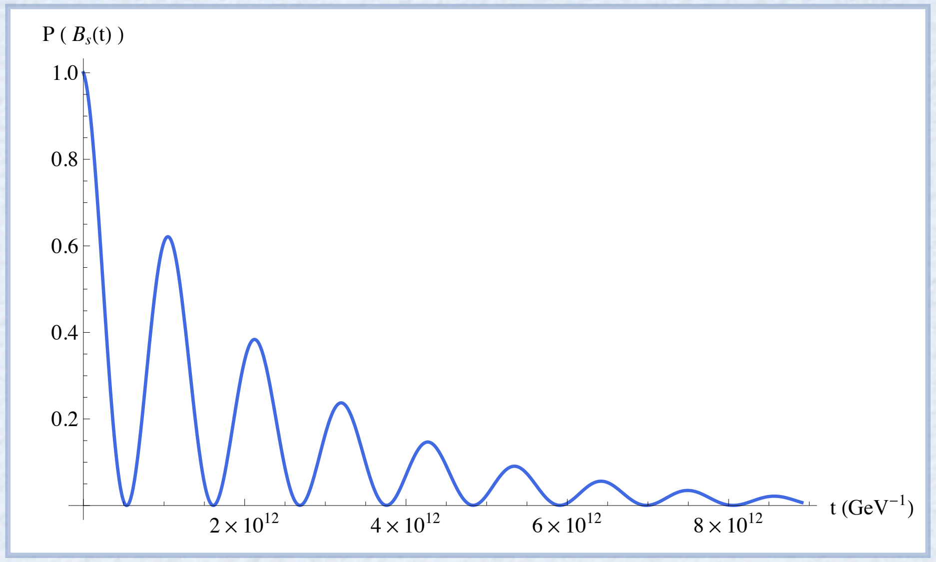

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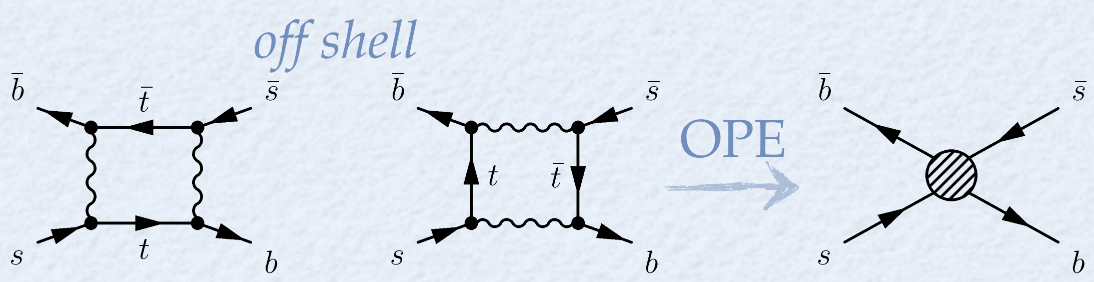

$$M_{12} = \frac{G_F^2}{12\pi^2}\left(V_{tb}V_{ts}^*\right)^2 m_{B_s} m_W^2 S_0(x_t)\hat{\eta}_b f_{B_s}^2 B_{B_s}$$

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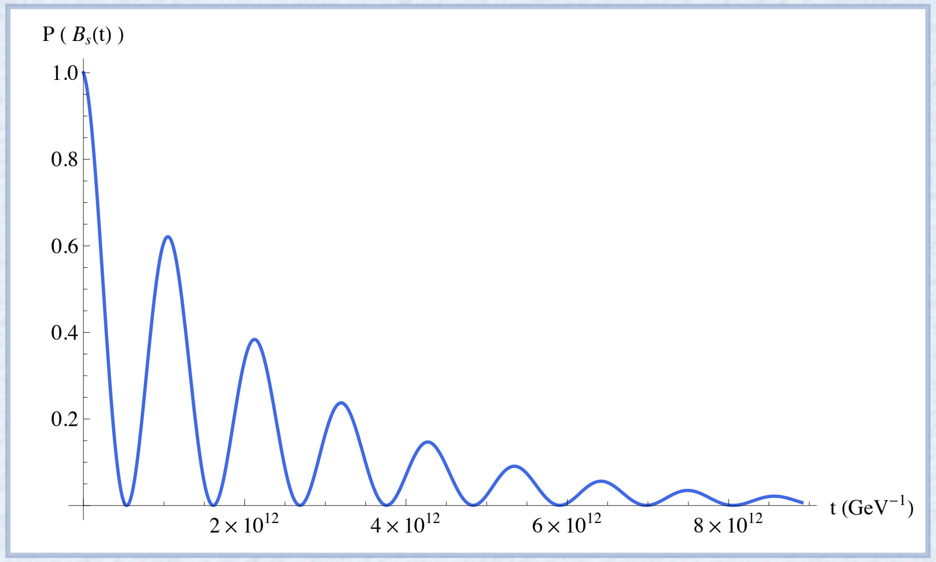

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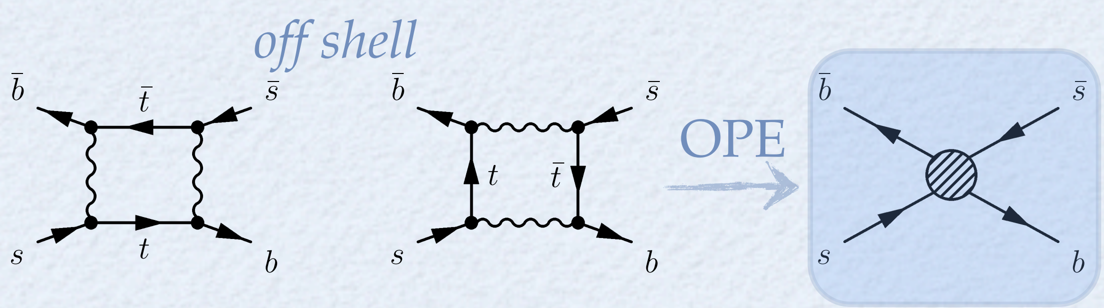

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$$S_0(x_t) = \frac{4x_t - 11x_t^2 + x_t^3}{4(1-x_t)^2} - \frac{3x_t^3 \ln x_t}{2(1-x_t)^3}$$

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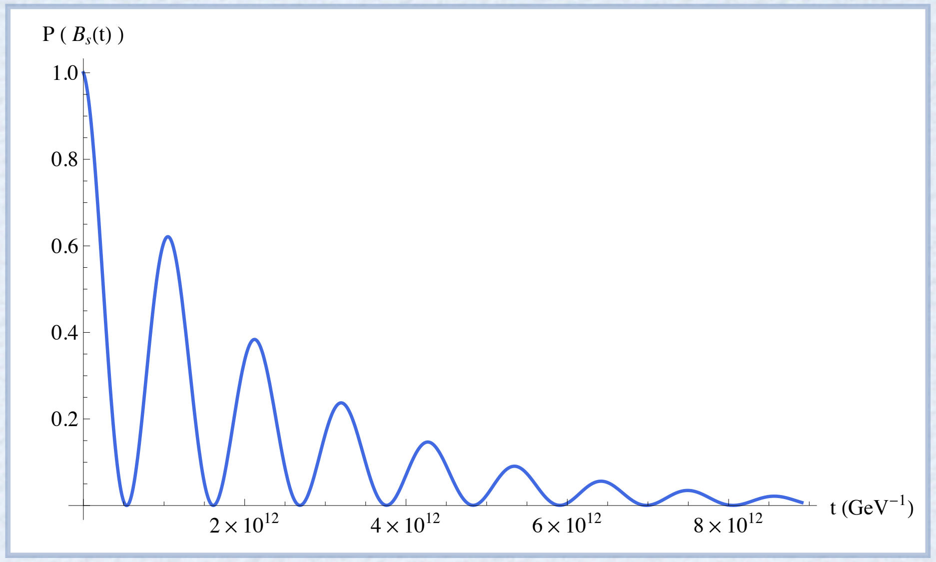

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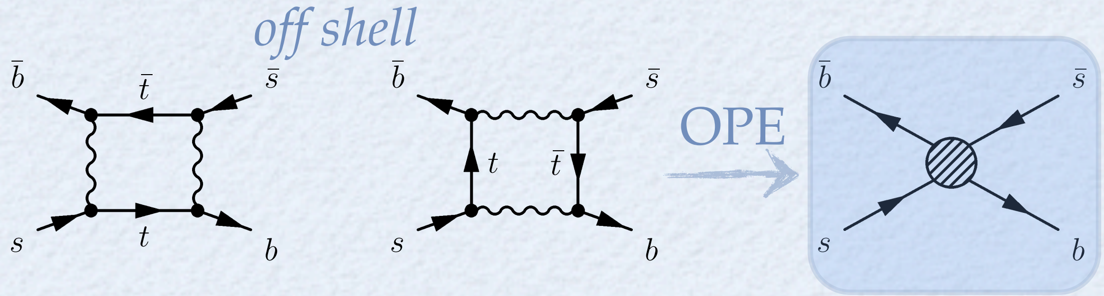

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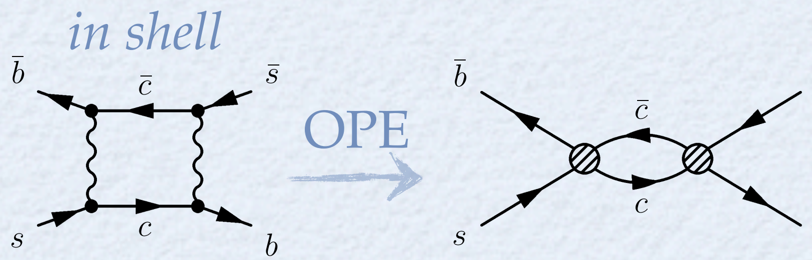

$$\Gamma_{12} \simeq \frac{G_F^2}{6\pi}\left(V_{cb}V_{cs}^*\right)^2 m_b^2 m_{B_s} f_{B_s}^2\left[-\frac{2}{3}B_{B_s}F(\mu) + \frac{5}{12}\frac{m_{B_s}^2}{(m_b+m_s)^2}B_{B_s}^S F_S(\mu)\right]$$

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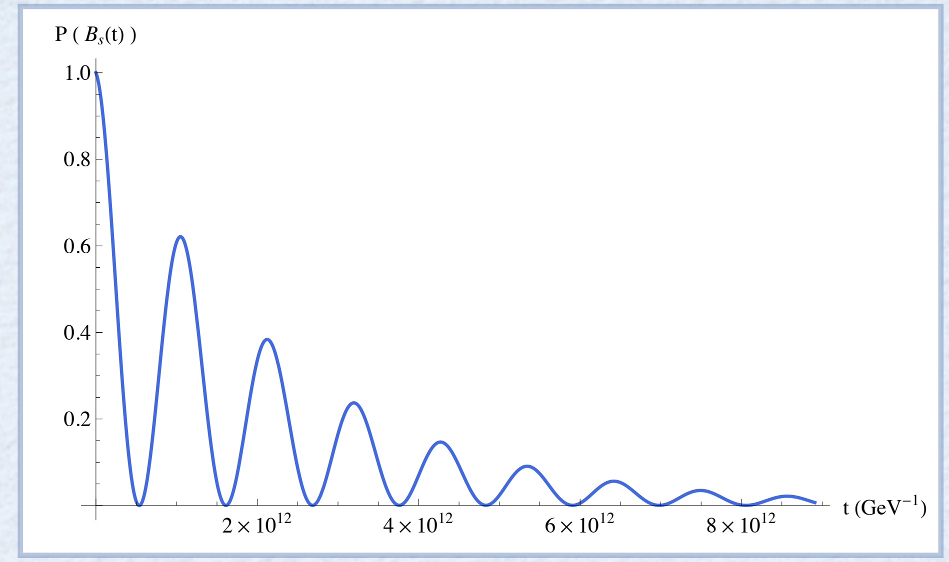

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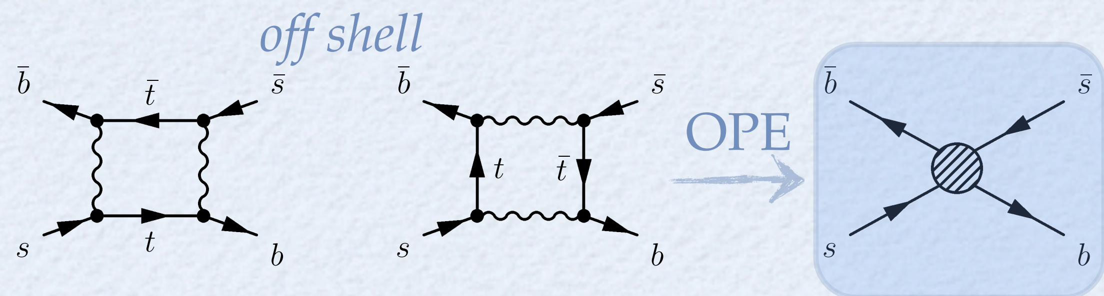

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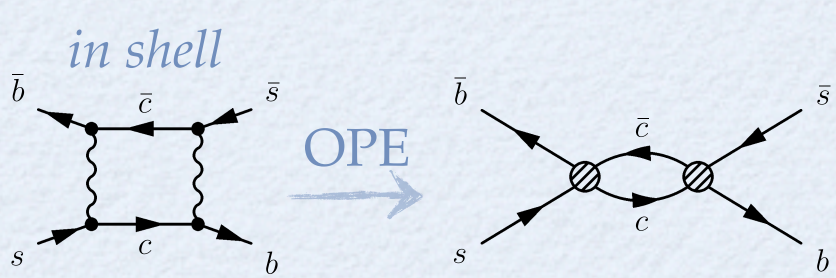

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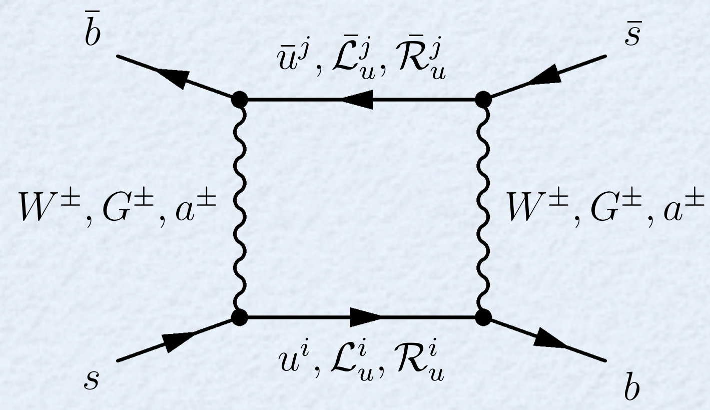
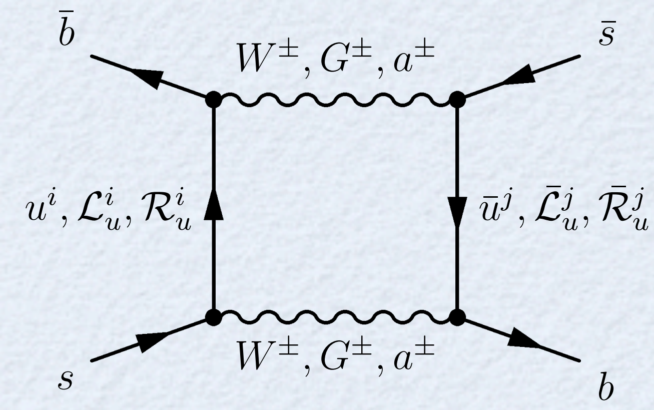
- ϕ: $\quad \phi = \mathrm{Arg}\left(-\frac{M_{12}}{\Gamma_{12}}\right) \simeq 2\,\mathrm{Arg}\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) = 2\beta_s$

PARAMETERS IN THE ACD MODEL

Only M_{12} is modified:





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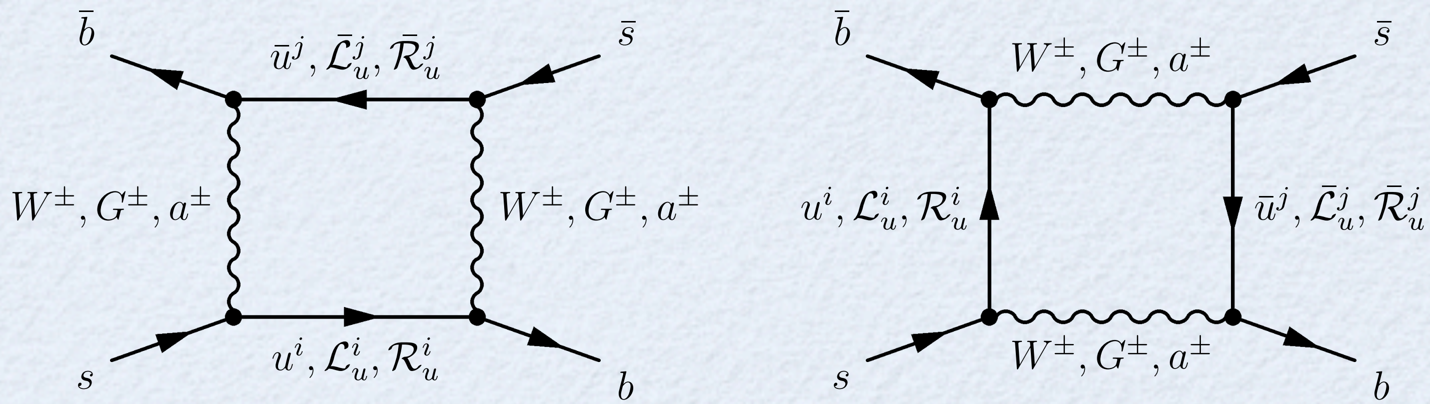

For each n the modified Inami-Lim function is

$$
\begin{aligned}
S_n(x_t, x_n) =& \frac{1}{4(x_t-1)^3 x_t}\Big[6x_n x_t - 5x_t^2 - 12x_n x_t^2 + 15x_t^3 + \\
&+\ 10x_n x_t^3 - 11x_t^4 - 4x_n x_t^4 + x_t^5 - \\
&-\ 2x_n(x_t-1)^3(3x_n + 3x_n x_t - x_t)\ln\frac{x_n}{1+x_n} + \\
&+\ \Big(-6x_n^2 + 2x_n x_t + 12x_n^2 x_t - 6x_n x_t^2 - 2x_t^3 + \\
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Buras *et al.*, Nucl. Phys. **B660**, 225 (2003)

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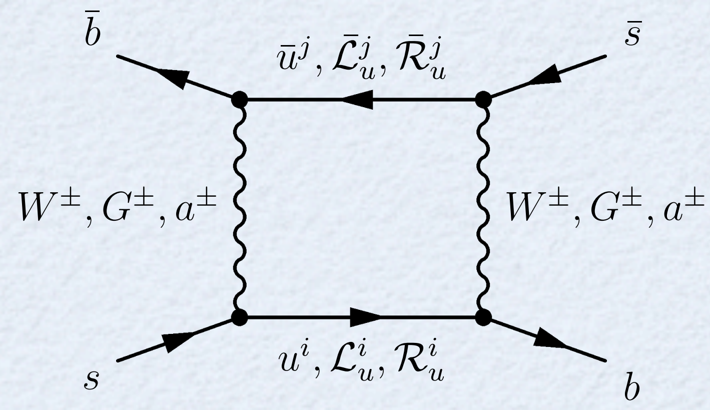

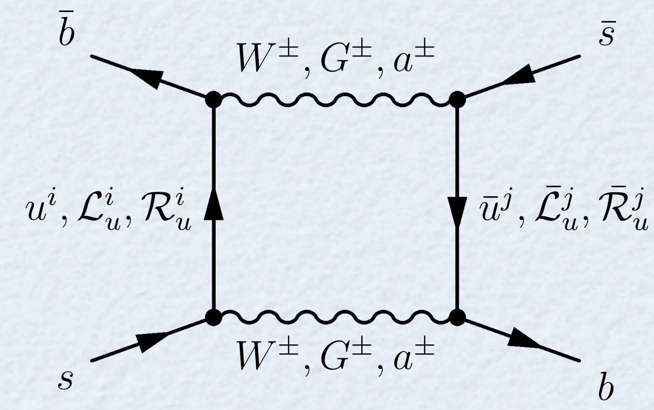

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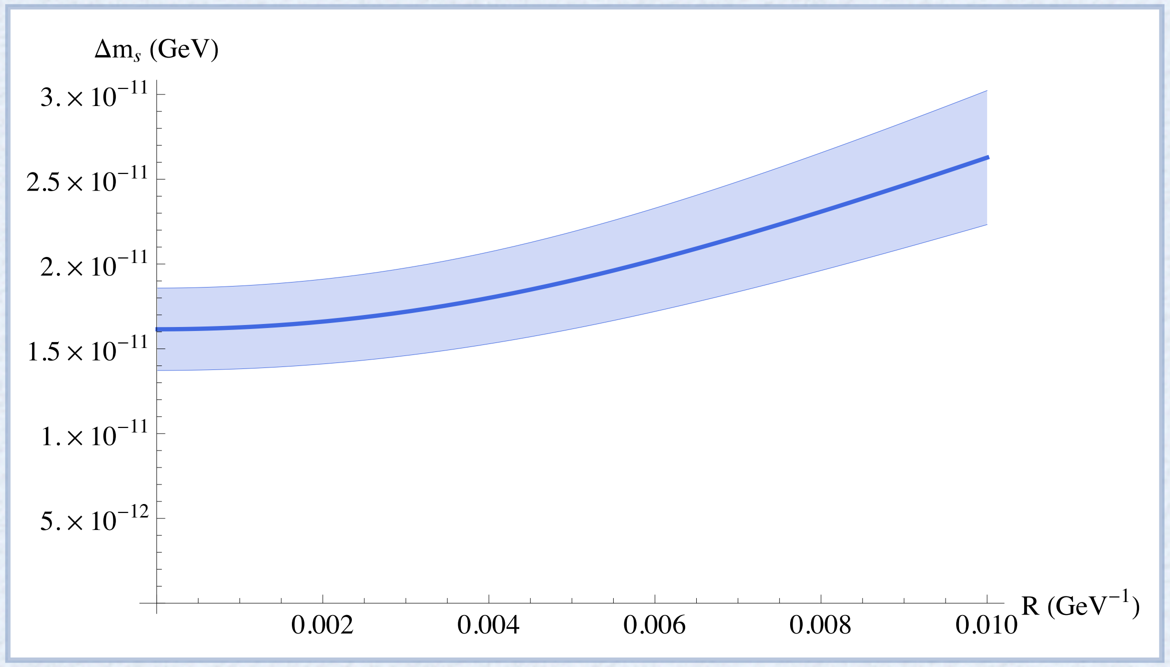
The series converges due to the GIM mechanism:

$$
\begin{aligned}
S(x_t, R) = & \ S_0(x_t) + \sum_{n=1}^{\infty} S_n(x_t, x_n) = \\
= & \ \frac{4x_t - 11x_t^2 + x_t^3}{4(1-x_t)^2} - \frac{3x_t^3 \ln x_t}{2(1-x_t)^3} + \\
& + \frac{1}{4(x_t-1)^3 x_t}\Big[x_t^3(3x_t - 1) J_{-1,m_t}(R) + \\
& + (-1 + 3x_t - 7x_t^2 + x_t^3) J_{0,m_t}(R) + \\
& + (-3 + 6x_t - x_t^3) J_{1,m_t}(R) + x_t(1 - 3x_t) J_{-1,m_W}(R) + \\
& + (4x_t) J_{0,m_W}(R) + x_t(-5 + 3x_t) J_{1,m_W}(R)\Big]
\end{aligned}
$$

DEVIATIONS FROM THE SM

Effects on the observable $\Delta m = 2\, M_{12}$:

$$\boxed{\Delta m(R)} = 2\frac{G_F^2}{12\pi^2}\left(V_{tb}V_{ts}^*\right)^2 m_{B_s} m_W^2 \boxed{S\left(x_t, R\right)}\, \hat{\eta}_b f_{B_s}^2 B_{B_s}$$



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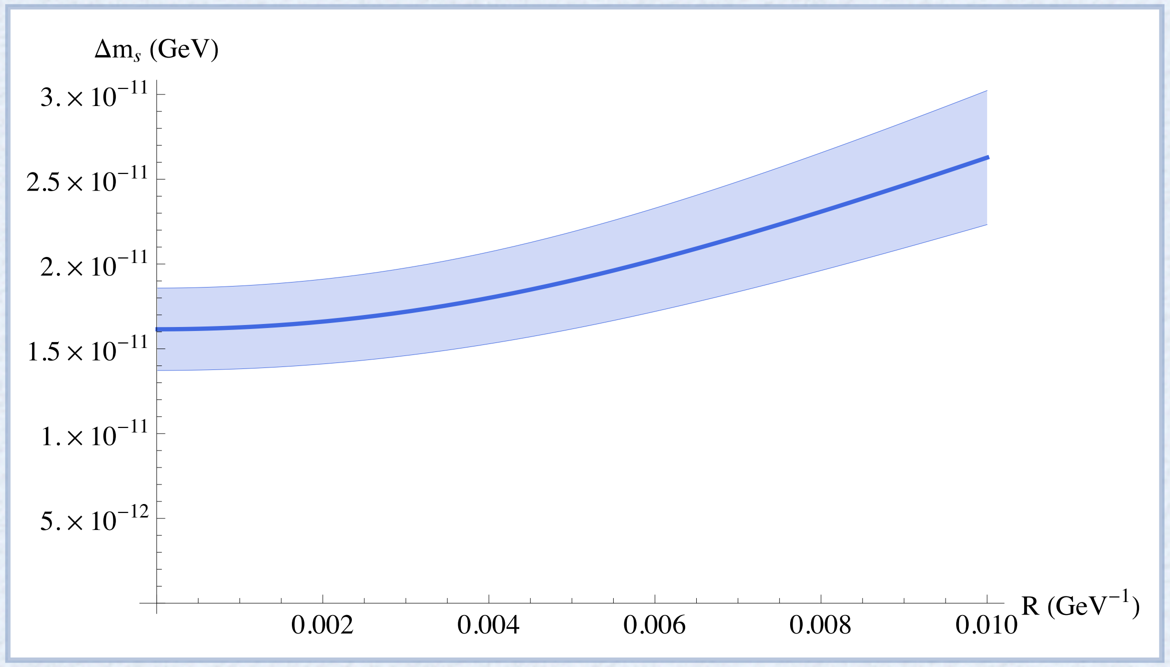

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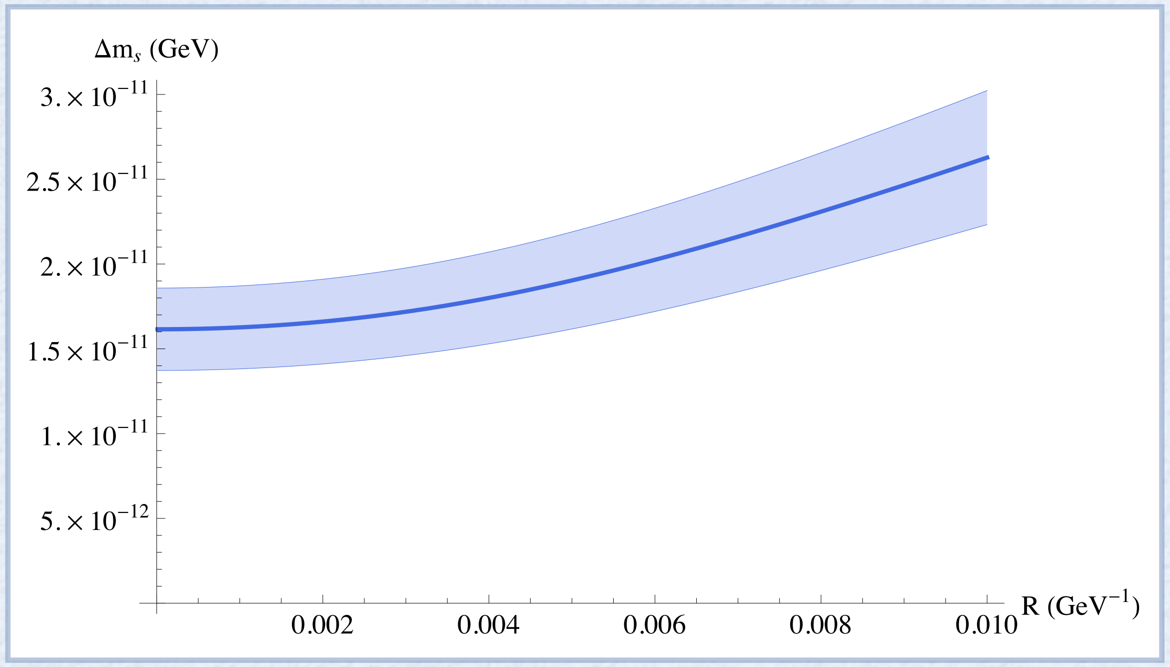

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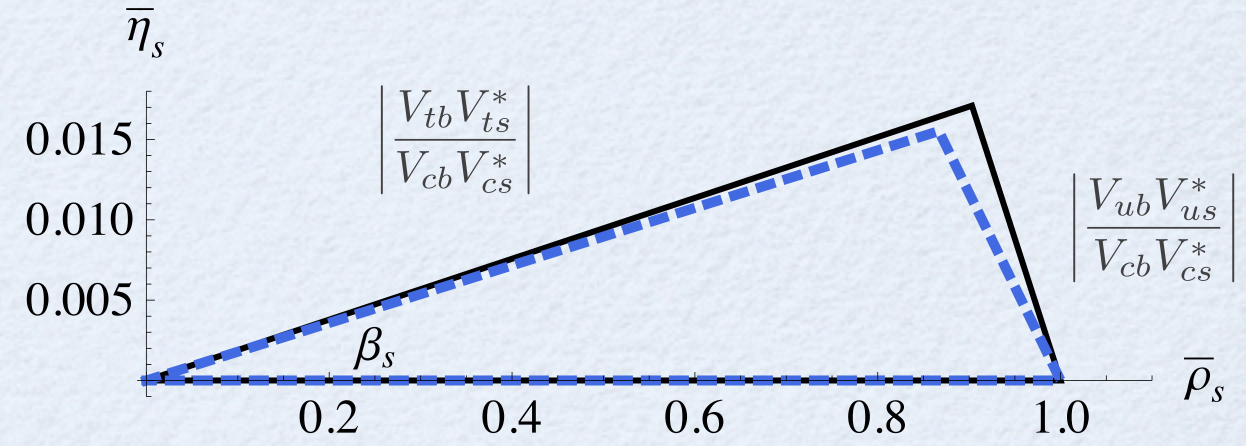
But the elements of the CKM matrix are extracted from experimental datas:

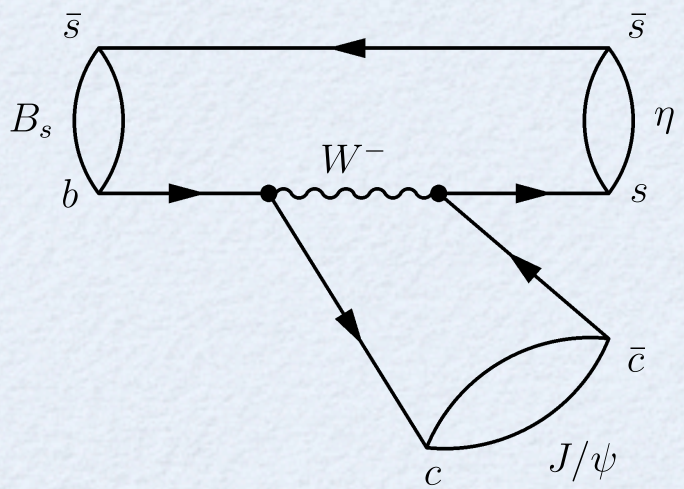
$$\Delta m^{\rm EXP} = 2\frac{G_F^2}{12\pi^2}\boxed{\left(V_{tb}V_{ts}^*\right)}^2 m_{B_s} m_W^2 \boxed{S(x_t, R)}\hat{\eta}_b f_{B_s}^2 B_{B_s}$$

$$\downarrow$$

$$V_{ts} \equiv V_{ts}(R) = |V_{ts}(R)| \exp\left[\beta_s(R)\right]$$



Signatures in $B_s \to \eta^{(\prime)} \, J/\psi$



Naive factorization

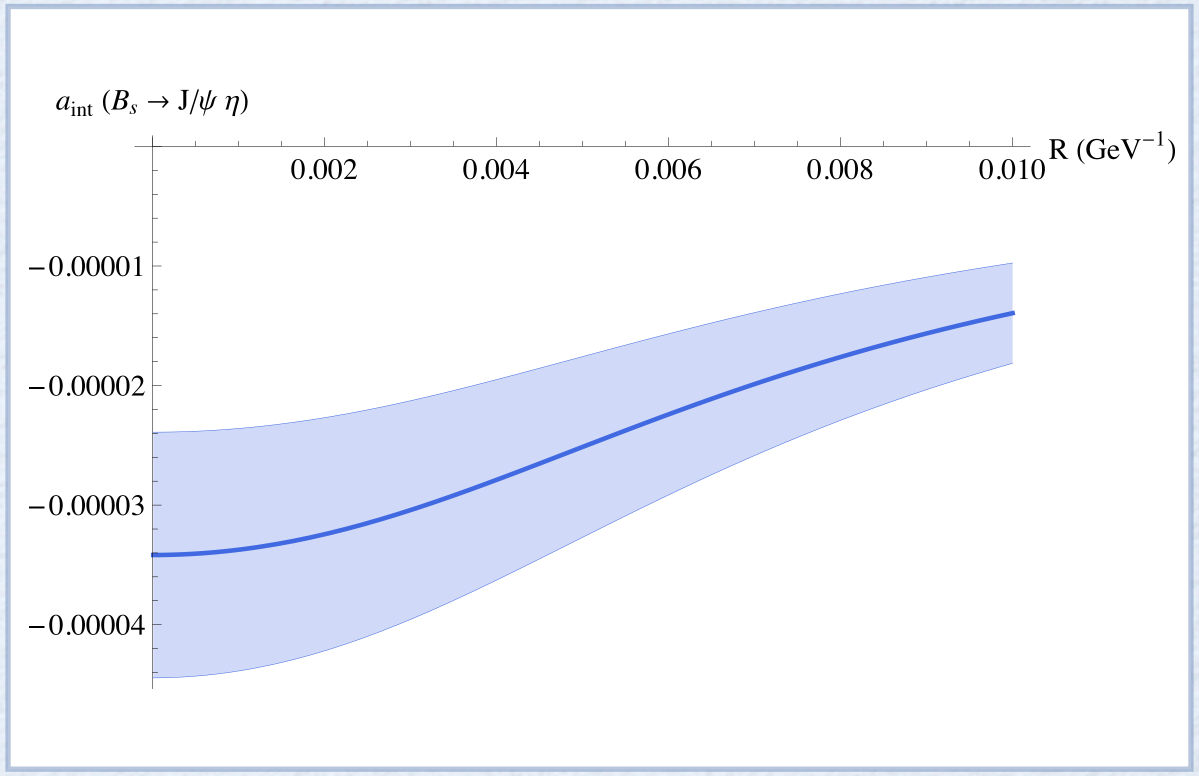
$$\langle \eta \; J/\psi | \left(\bar{s}_L \gamma^\mu b_L\right) \left(\bar{c}_L \gamma_\mu c_L\right) | B_s \rangle \simeq \langle \eta | \left(\bar{s}_L \gamma^\mu b_L\right) | B_s \rangle \, \langle J/\psi | \left(\bar{c}_L \gamma_\mu c_L\right) | 0 \rangle$$

Amplitude not modified in the ACD Model:

$$\Gamma\left(B_s \to \eta^{(\prime)} J/\psi\right) = \frac{G_F^2 |V_{cb} V_{cs}^*|^2}{8\pi m_{B_s}^3} \left(C_1 + \frac{C_2}{N_c}\right)^2 |f_{J/\psi}|^2 \left(F_1(m_{J/\psi}^2)\right)^2 \lambda^{3/2}\left(m_{B_s}^2, m_\eta^2, m_{J\psi}^2\right)$$

Integrated asymmetry

$$a_f = \frac{\int_0^\infty dt \; \left[\Gamma\left(\bar{B}_s(t) \to f\right) - \Gamma\left(B_s(t) \to f\right)\right]}{\int_0^\infty dt \; \left[\Gamma\left(\bar{B}_s(t) \to f\right) + \Gamma\left(B_s(t) \to f\right)\right]} =$$
$$= \frac{1}{4} \frac{1 + [\Delta\Gamma]^2}{1 + [\Delta m(R)]^2} \frac{\sin\phi}{1 - \cos\phi}$$



EFFECTIVE HAMILTONIAN

$$B_s \to \eta^{(\prime)} \quad \longrightarrow \quad \text{FCNC} \quad b \leftrightarrow s$$

Operator **P**roduct **E**xpansion: $H_{OPE} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$

Wilson coefficients — Local operators

$$O_1 = (\bar{c}_{L\alpha}\gamma^\mu b_{L\beta})\,(\bar{s}_{L\beta}\gamma_\mu c_{L\alpha})$$
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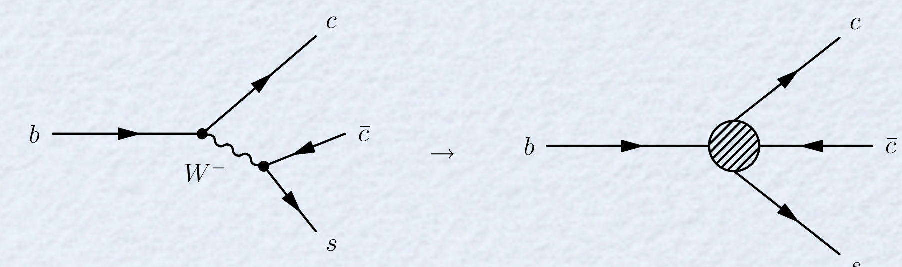

$$O_3 = (\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\left[(\bar{u}_{L\beta}\gamma_\mu u_{L\beta}) + \ldots + (\bar{b}_{L\beta}\gamma_\mu b_{L\beta})\right]$$
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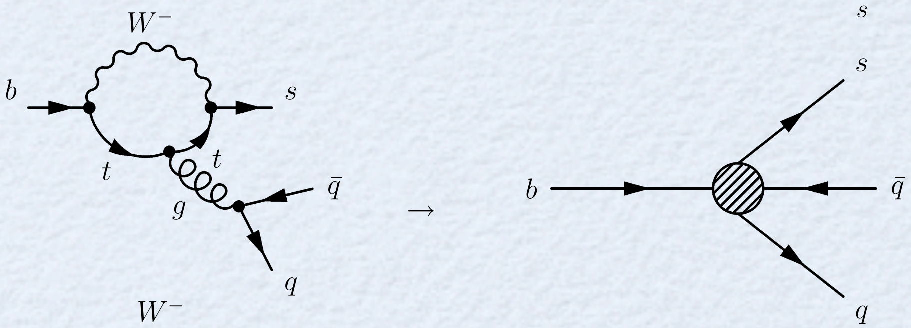
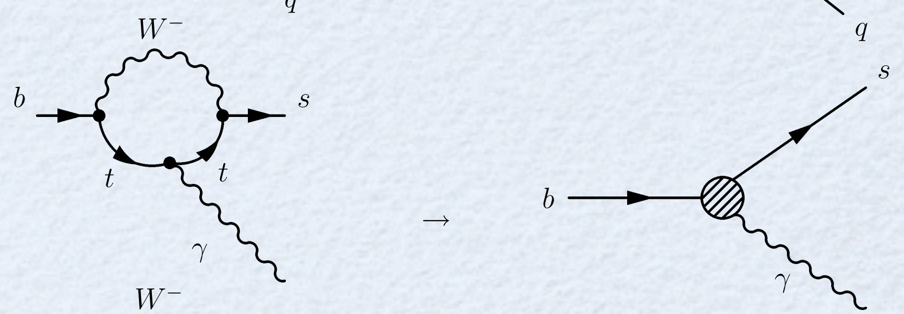


$$O_7 = \frac{e}{16\pi^2} m_b\,(\bar{s}_{L\alpha}\sigma^{\mu\nu} b_{R\alpha})\,F_{\mu\nu}$$
$$O_8 = \frac{g_s}{16\pi^2} m_b \left[\bar{s}_{L\alpha}\sigma^{\mu\nu}\,(\lambda^a/2)_{\alpha\beta}\, b_{R\beta}\right] G^a_{\mu\nu}$$



$$O_9 = \frac{e^2}{16\pi^2}\,(\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\,\ell\gamma_\mu\bar{\ell}$$
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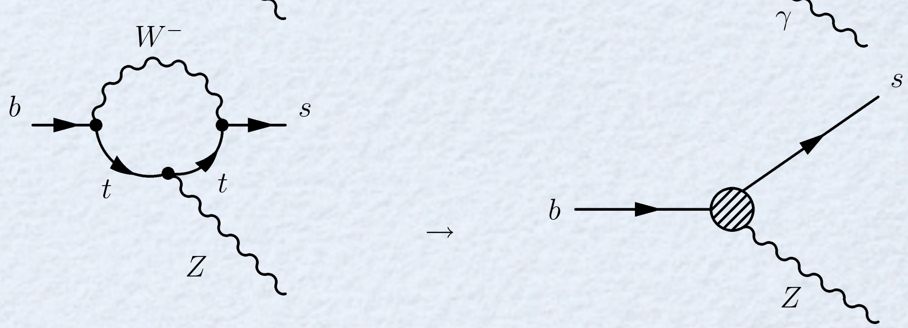

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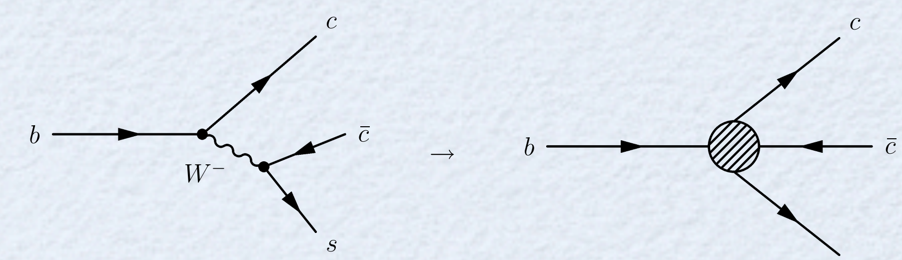

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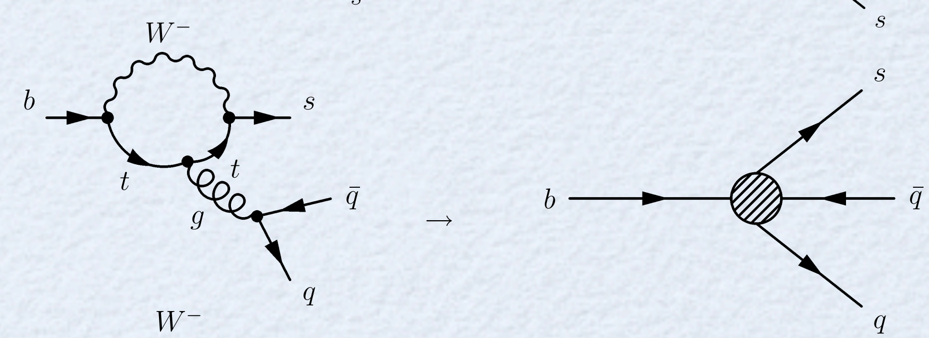

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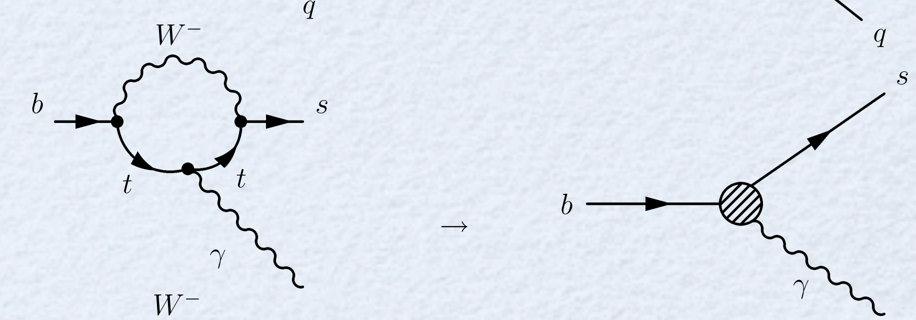
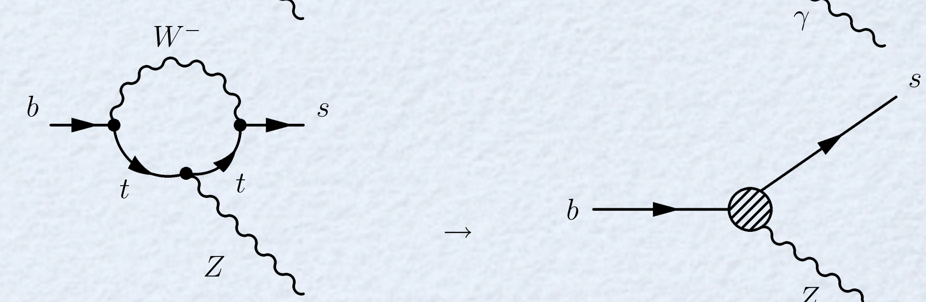
$$O_8 = \frac{g_s}{16\pi^2} m_b \left[\bar{s}_{L\alpha}\sigma^{\mu\nu}\,(\lambda^a/2)_{\alpha\beta}\, b_{R\beta}\right] G^a_{\mu\nu}$$



$$\boxed{O_9 = \frac{e^2}{16\pi^2}\,(\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\,\ell\gamma_\mu\bar{\ell}}$$
$$\boxed{O_{10} = \frac{e^2}{16\pi^2}\,(\bar{s}_{L\alpha}\gamma^\mu b_{L\alpha})\,\ell\gamma_\mu\bar{\ell}}$$



Wilson Coefficients in the ACD Model

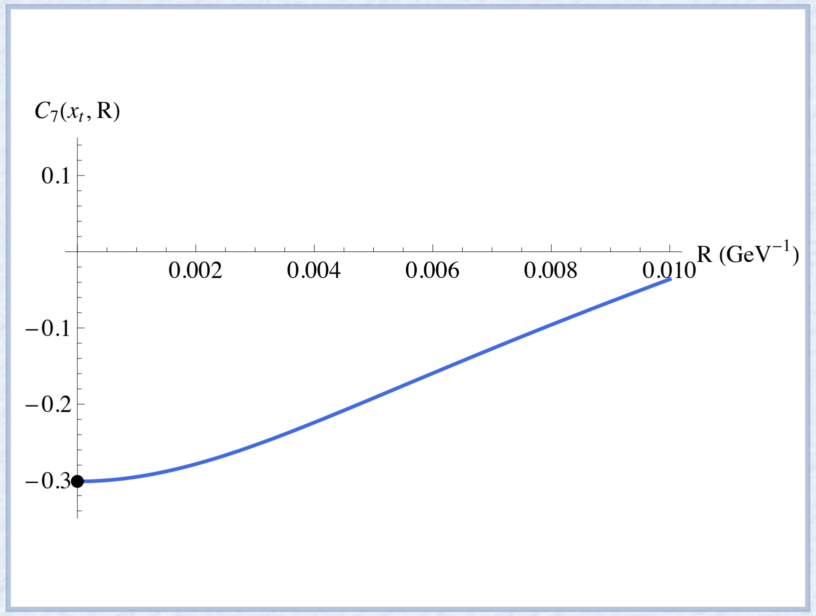
The considered Wilson coefficients are modified in the ACD Model.

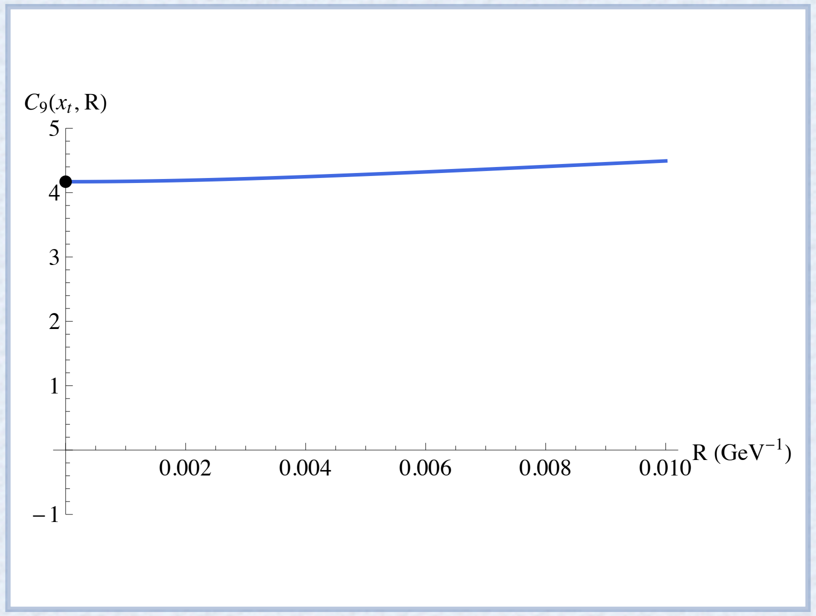
WILSON COEFFICIENTS IN THE ACD MODEL

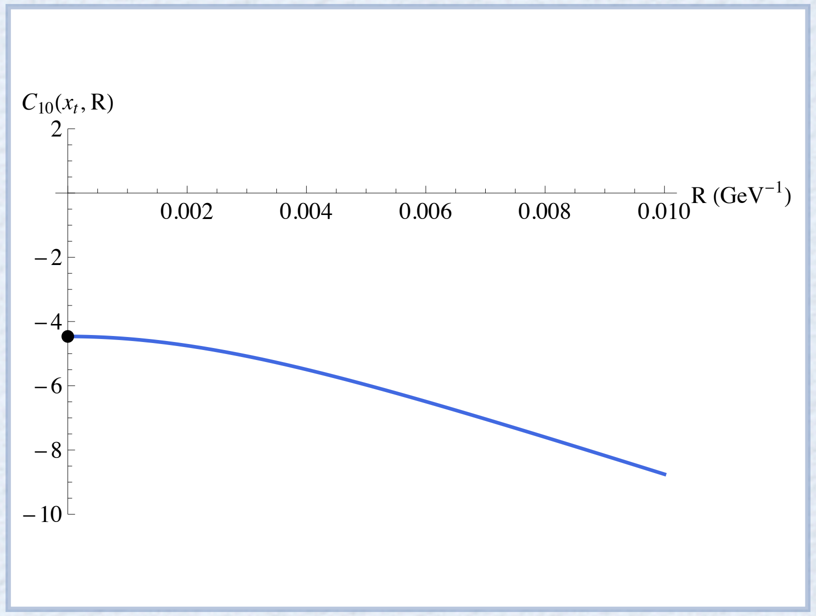
The considered Wilson coefficients are modified in the ACD Model.

Calculations are similar to the previous ones:

$$F(x_t) \to F'(x_t, R) = F(x_t) + \sum_{n=1}^{\infty} F_n(x_t, x_n)$$







Buras *et al.*, Nucl. Phys. **B678**, 455 (2004)

FORM FACTORS

Used to parametrize hadronic matrix elements of currents:

$$\langle \eta(p_\eta)|\,\bar{s}\gamma_\mu b\,|B_s(p_{B_s})\rangle = \left[(p_{B_s}+p_\eta)_\mu - \frac{m_{B_s}^2 - m_\eta^2}{q^2} q_\mu\right] F_1^\eta(q^2) - \left[\frac{m_{B_s}^2 - m_\eta^2}{q^2} q_\mu\right] F_0^\eta(q^2)$$

$$\langle \eta(p_\eta)|\,\bar{s} i\sigma_{\mu\nu} q^\nu b\,|B_s(p_{B_s})\rangle = \left[(p_{B_s}+p_\eta)_\mu\, q^2 - \left(m_{B_s}^2 - m_\eta^2\right) q_\mu\right] \frac{F_T^\eta(q^2)}{m_{B_s}+m_\eta}$$

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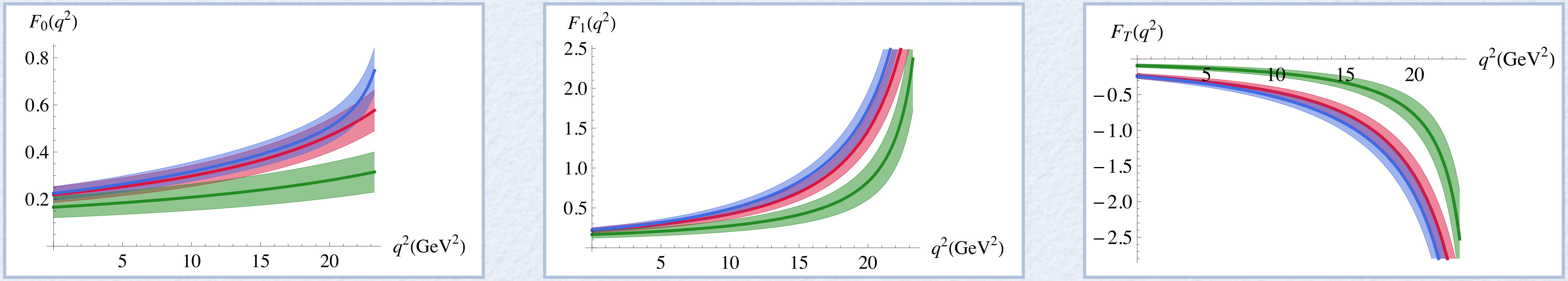
- Set I: Three-Point Function QCD Sum Rules
- Set II: Light-Cone Sum Rules
- Set III: Soft-Collinear Effective Theory QCD Sum Rules

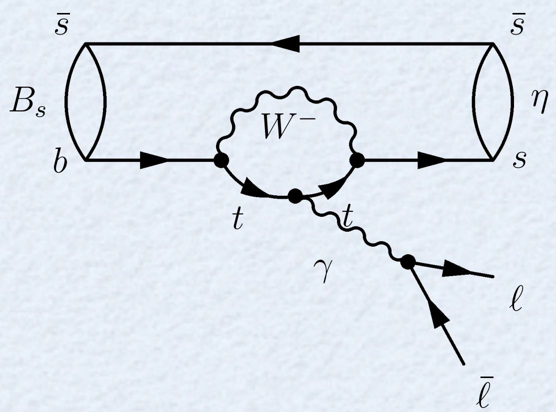
Results for the considered transition are not available $\longrightarrow$ we use

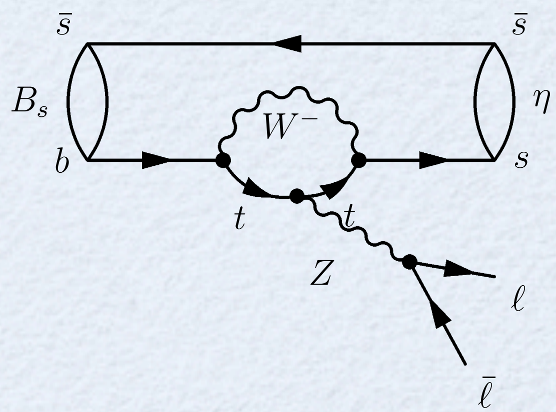
$$F^{B_s\to\eta}(q^2) = -F^{B\to K}(q^2)\sin\theta$$



RARE B_s DECAYS TO η FINAL STATES

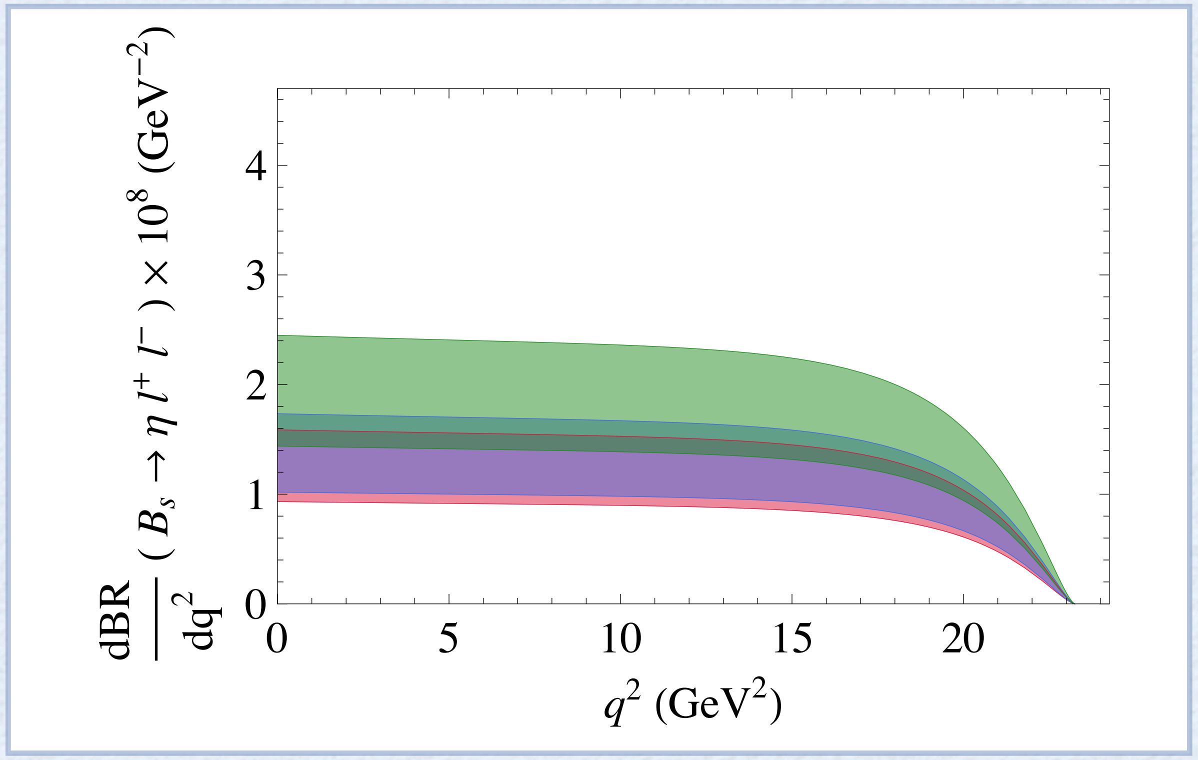
$B_s \to \eta^{(\prime)} e^+ e^-$ AND $B_s \to \eta^{(\prime)} \mu^+ \mu^-$

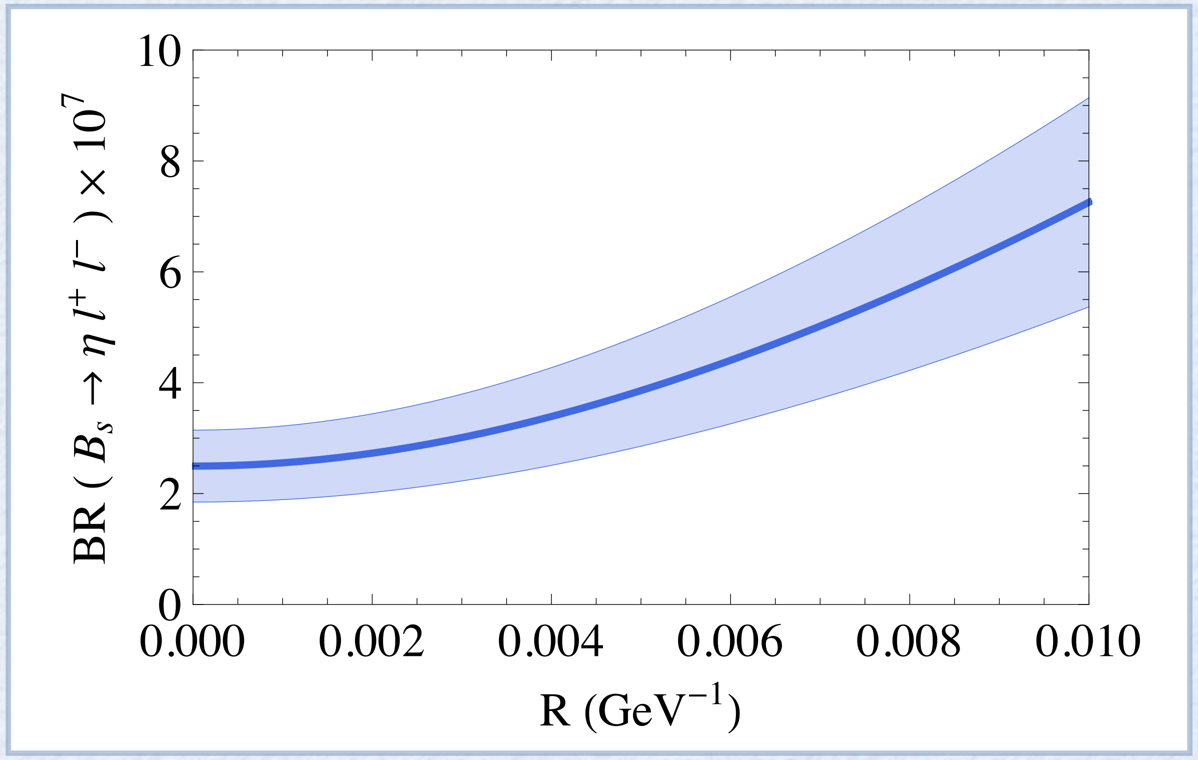




Neglecting the leptons masses:

$$\frac{d\Gamma}{dq^2}\left(B_s \to \eta \ell^+ \ell^-\right) = \frac{G_F^2 \left|V_{tb} V_{ts}^*\right|^2 \alpha^2}{1536 \pi^5 m_{B_s}^3} \left\{ \left| -\frac{2 C_7 m_b}{m_{B_s} + m_\eta} F_T(q^2) + C_9 F_1(q^2) \right|^2 + \left| C_{10} F_1(q^2) \right|^2 \right\} \lambda^{3/2}\left(m_{B_s}^2, m_\eta^2, q^2\right)$$





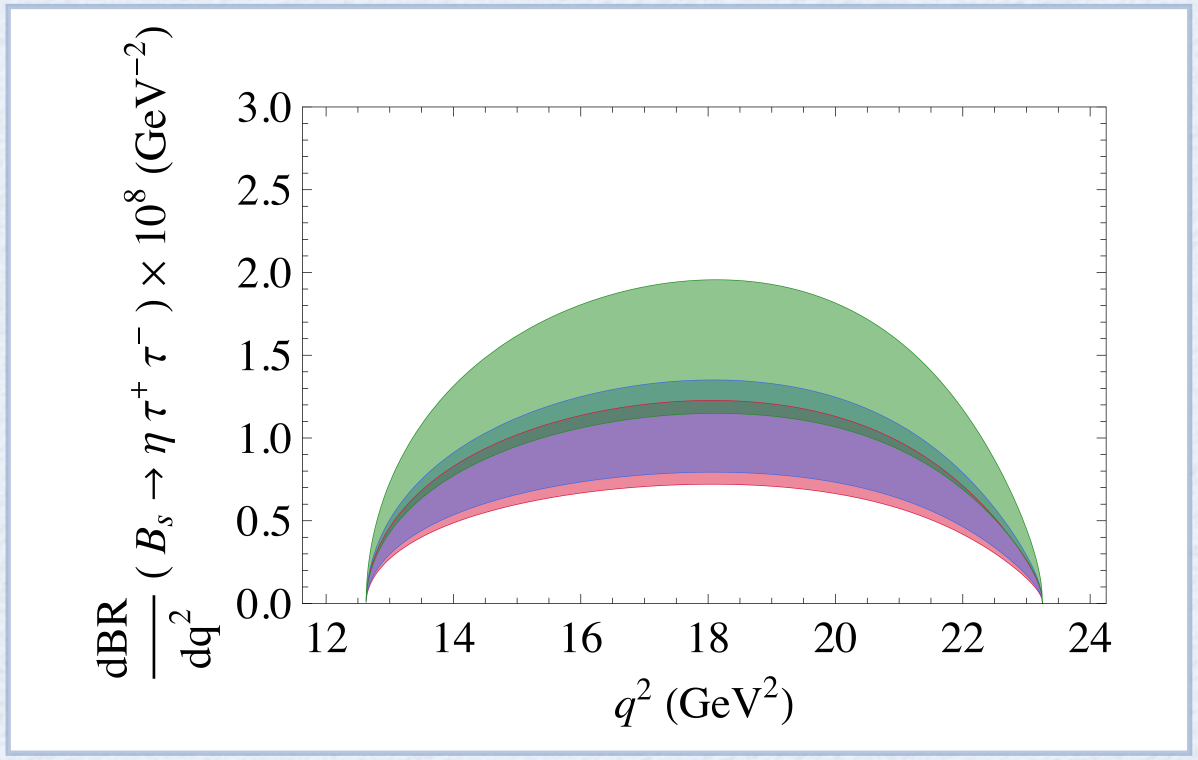
$B_s \to \eta^{(\prime)}\tau^+\tau^-$

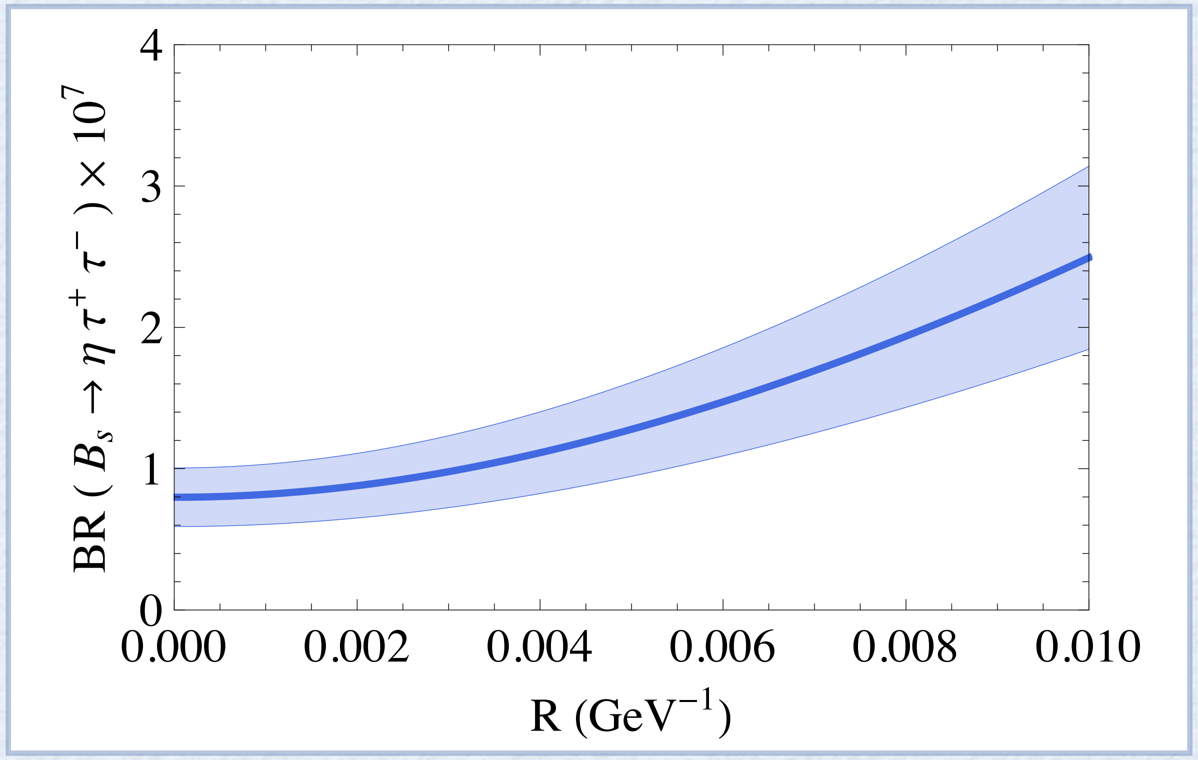
τ masses cannot be neglected:

$$\frac{d\Gamma}{dq^2}\left(B_s \to \eta^{(\prime)}\tau^+\tau^-\right) = \frac{G_F^2|V_{tb}V_{ts}^*|^2\alpha^2}{2^9\pi^5}\frac{\lambda^{1/2}(m_{B_s}^2, m_\eta^2, q^2)}{m_{B_s}^3}\sqrt{1-\frac{4m_\tau^2}{q^2}}\frac{1}{3q^2}p(q^2)$$

$$p(q^2) = 6m_\tau^2(m_{B_s}^2 - m_\eta^2)^2|b(q^2)|^2 + \lambda(m_{B_s}^2, m_\eta^2, q^2)\left[(2m_\tau^2 + sq^2)|c(q^2)|^2 - (4m_\tau^2 - q^2)|a(q^2)|^2\right]$$

$$a(q^2) = C_{10}F_1(q^2) \qquad b(q^2) = C_{10}F_0(q^2) \qquad c(q^2) = C_9F_1(q^2) - 2(m_b + m_q^2)C_7\frac{F_T(q^2)}{m_{B_s}+m_\eta}$$



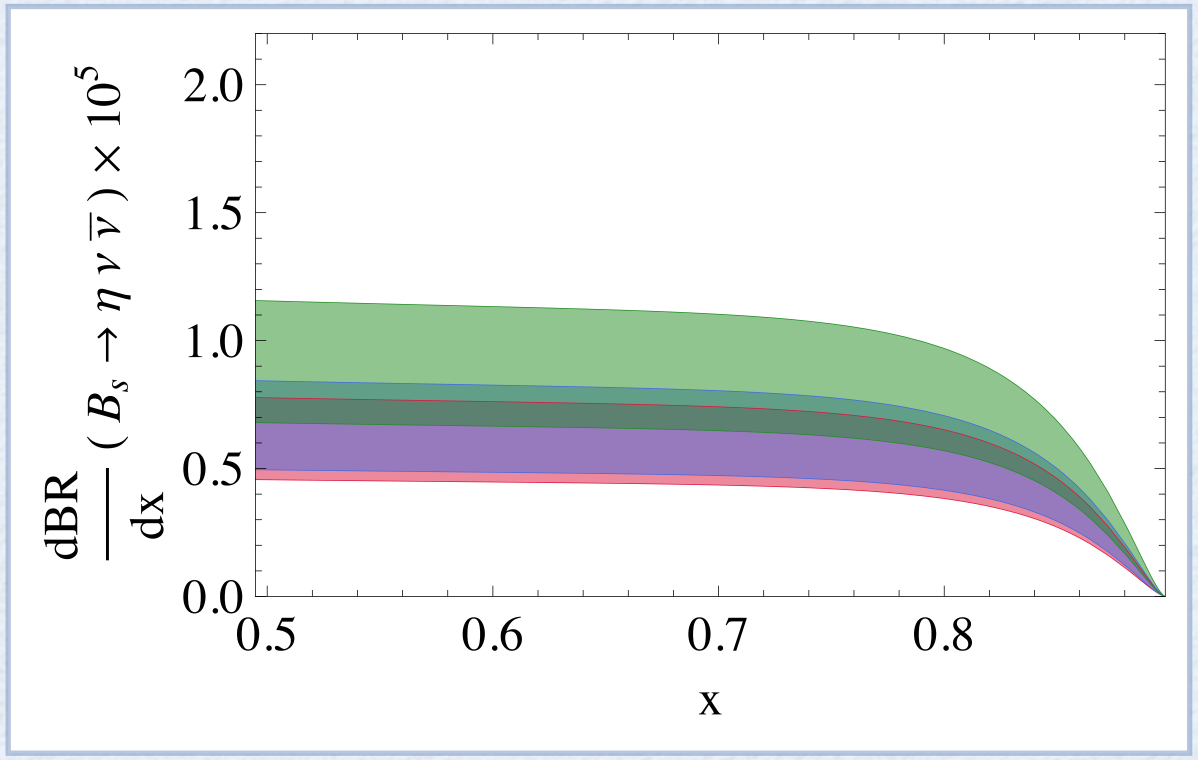


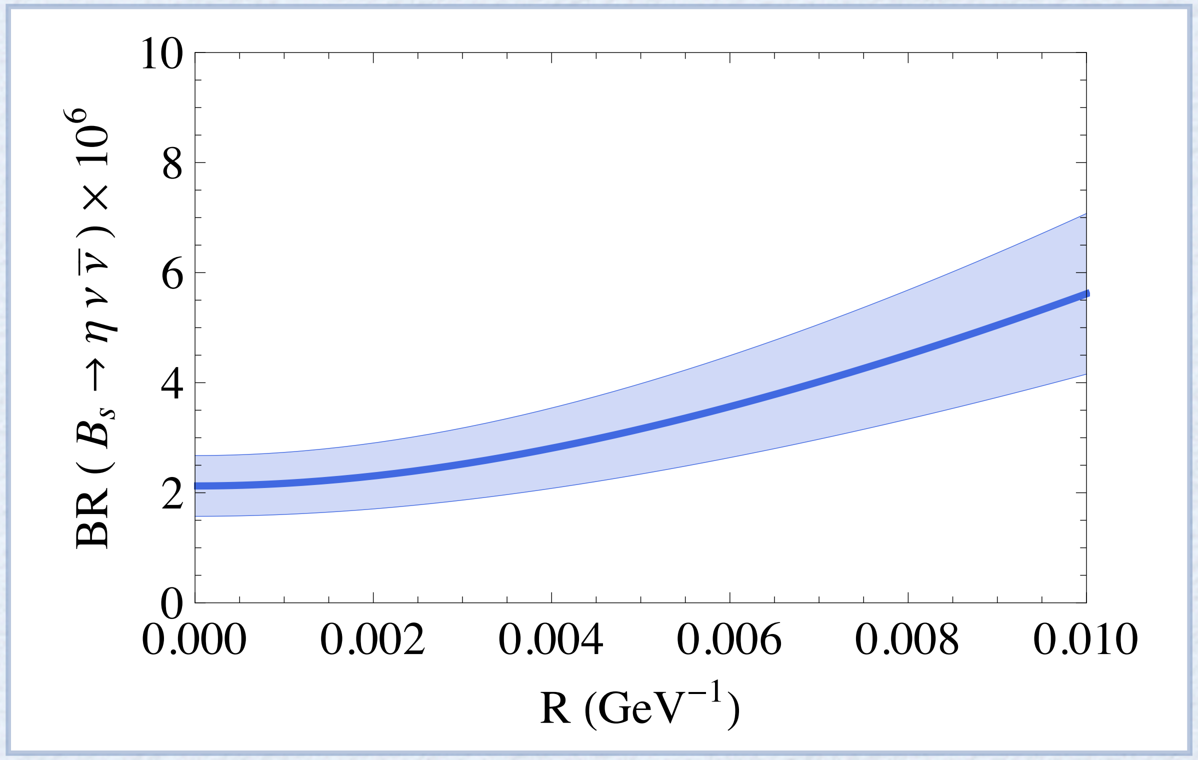
$B_s \to \eta^{(\prime)} \nu \bar{\nu}$

It is convenient to consider the missing energy:

$$\frac{d\Gamma}{dx}\left(B_s \to \eta^{(\prime)} \bar{\nu}\nu\right) = \frac{\left(|c_L|^2 + |c_R|^2\right) \left|F_1(q^2)\right|^2}{16\pi^3 m_{B_s}} \lambda^{3/2}\left(m_{B_s}^2, m_\eta^2, q^2\right)$$

$$x = \frac{E_{\text{miss}}}{m_{B_s}}$$





Conclusions

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- We have seen that the mass difference Δm_s is larger in the ACD Model, and it can be detected through the study of asymmetries in decay channels that are not affected by other effects of the model, such as $B_s \to \eta^{(\prime)} J/\psi$. Moreover, this can also modify the extraction of the *bs* Unitarity Triangle.

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- We have found that the larger the compactification radius is, the larger the branching ratios of some rare decays to η and η' final states are predicted to be, but the detection of deviations could be difficult due to the considerable error of non-perturbative form factors.

References

- M. V. Carlucci, P. Colangelo and F. De Fazio

  Rare B_s decays to η and η' final states

  Phys Rev. D **80**, 055023 (2009)

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A work about another (very different) model with extra dimensions:

- M. V. Carlucci, F. Giannuzzi, G. Nardulli, M. Pellicoro and S. Stramaglia

  AdS/QCD quark-antiquark potential, meson spectrum and tetraquarks

  Eur. Phys. J. C **57**, 569-578 (2008)

Thanks