B decays at hadron colliders

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LBNL

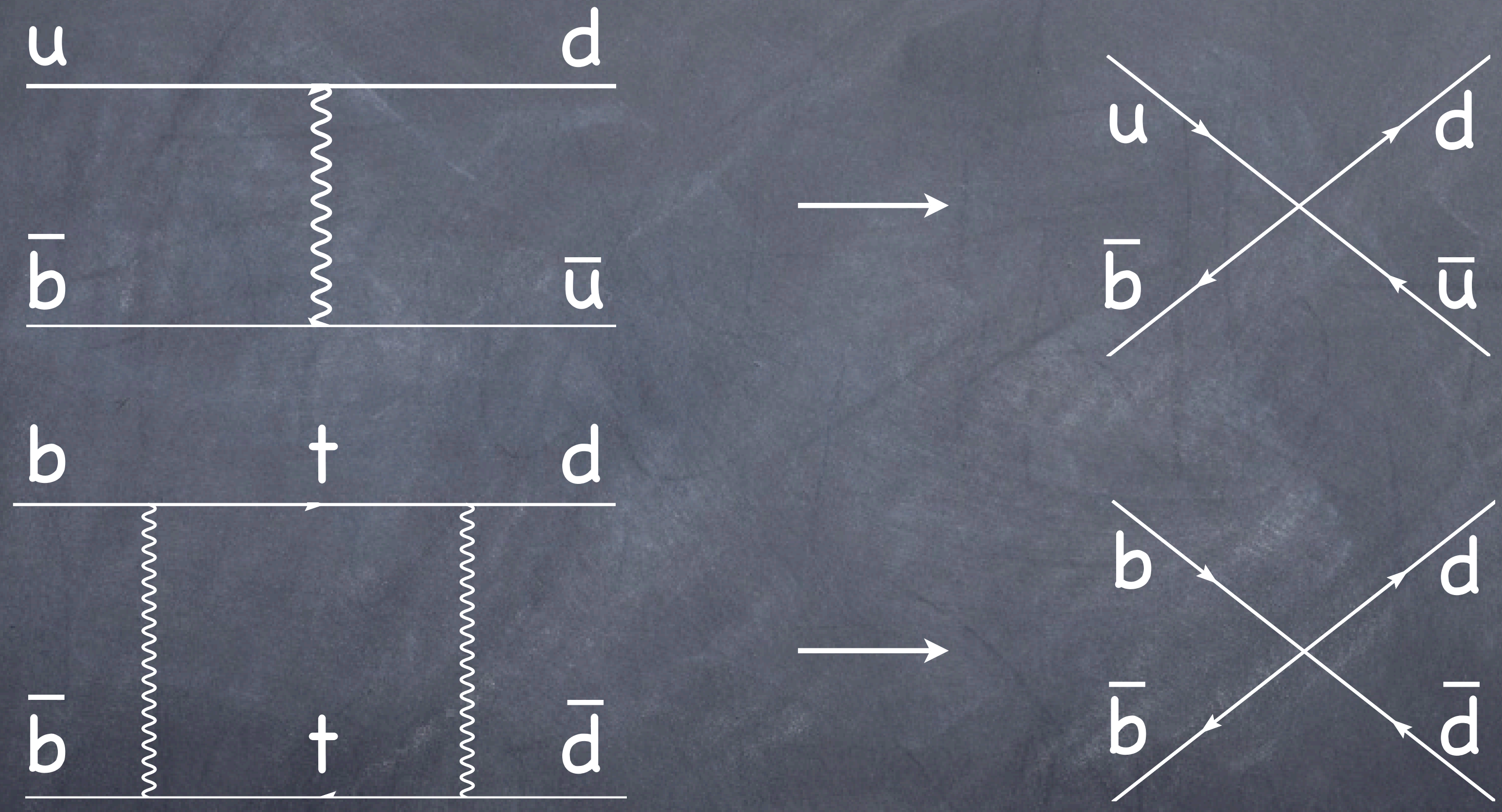
HCP, Durham, 5/24/06

Outline

- Flavor physics in and beyond the standard model
- General parametrization of new sources of flavor violation
- $\Delta B=2$ processes and B_s mixing
- $\Delta B=1$ processes and hadronic matrix elements
- Conclusions

Flavor physics in the SM

Mediated by four quark operators



By dimensional arguments proportional to $1/\Lambda^2_{EW}$

Flavor hierarchies in the SM

Strength of couplings determined by CKM matrix

$$V_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

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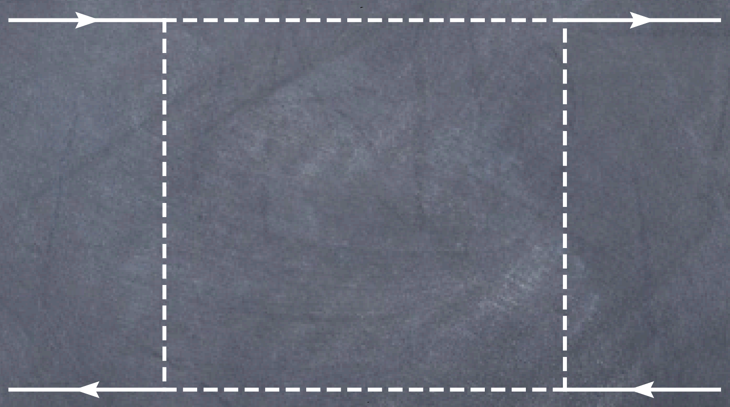
$B_d\, \bar{B}_d$ mixing : $(V_{tb}V_{td})^2/m_W{}^2 = \lambda^6/m_W{}^2$

$B_s\, \bar{B}_s$ mixing : $(V_{tb}V_{ts})^2/m_W{}^2 = \lambda^4/m_W{}^2$

Flavor physics beyond the SM

Hierarchy problem: need additional physics at EW scale to cancel quadratic divergences

Such additional particles can participate in the loops



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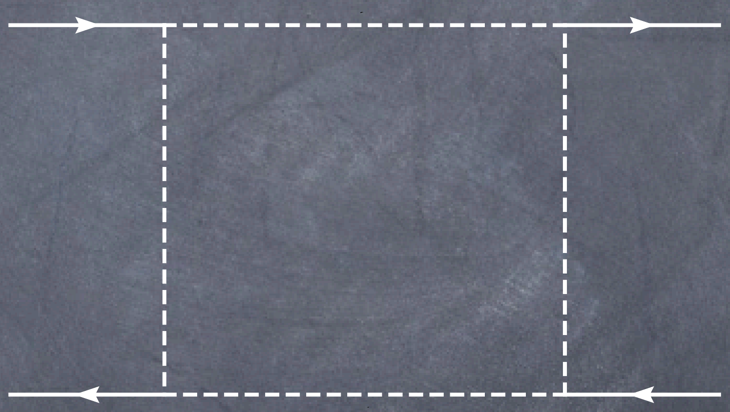

For generic BSM physics contribution ~ $1/\Lambda^2$

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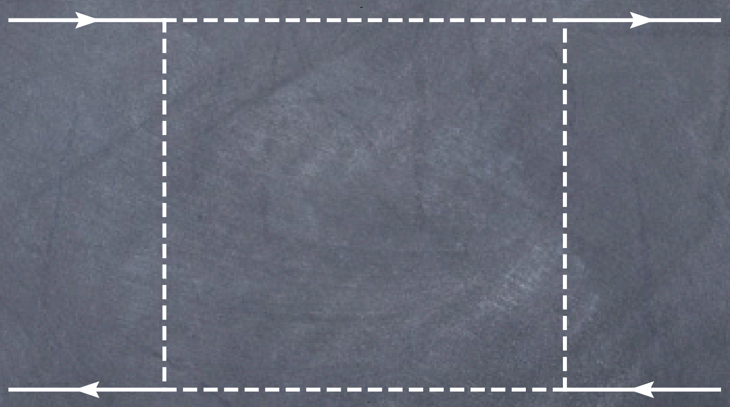

For generic BSM physics contribution ~ $1/\Lambda^2$

If $\Lambda \sim \Lambda_{EW}$ much too large flavor violation

Flavor physics and EWSB

- Most models of BSM physics motivated by hierarchy problem
- Scale of flavor physics much higher that EW scale
- Generic models have way too much flavor mixing
- Special care needed to ensure consistency with flavor physics experiments
- Classify models according to their additional contributions to flavor physics

Minimal Flavor Violation

- All flavor effects have been seen in couplings to first two generations
  - B B mixing from coupling first and third generation
  - K K mixing from first and second generation
- If new physics only affects third generation, no new sources of flavor violation
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Rather few concrete models avalailable

No hope of connecting origin of mass and flavor

Next-to-minimal Flavor Violation

- Allow small deviations from minimal flavor violation
- Flavor mixing scales in same way as CKM matrix
- New sources of flavor violation of comparable to SM contributions
- Many models fall into NMFV class (SUSY alignement, Little Higgs models, RS1 models, ...

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Given the many measurements, how large can new sources of flavor violation be?

$\Delta B = 2$ Processes

General Parametrization

$$M_{12} = M_{12}{}^{SM} + M_{12}{}^{BSM}$$

$$= M_{12}{}^{SM} (1 + h\, e^{i\sigma})$$

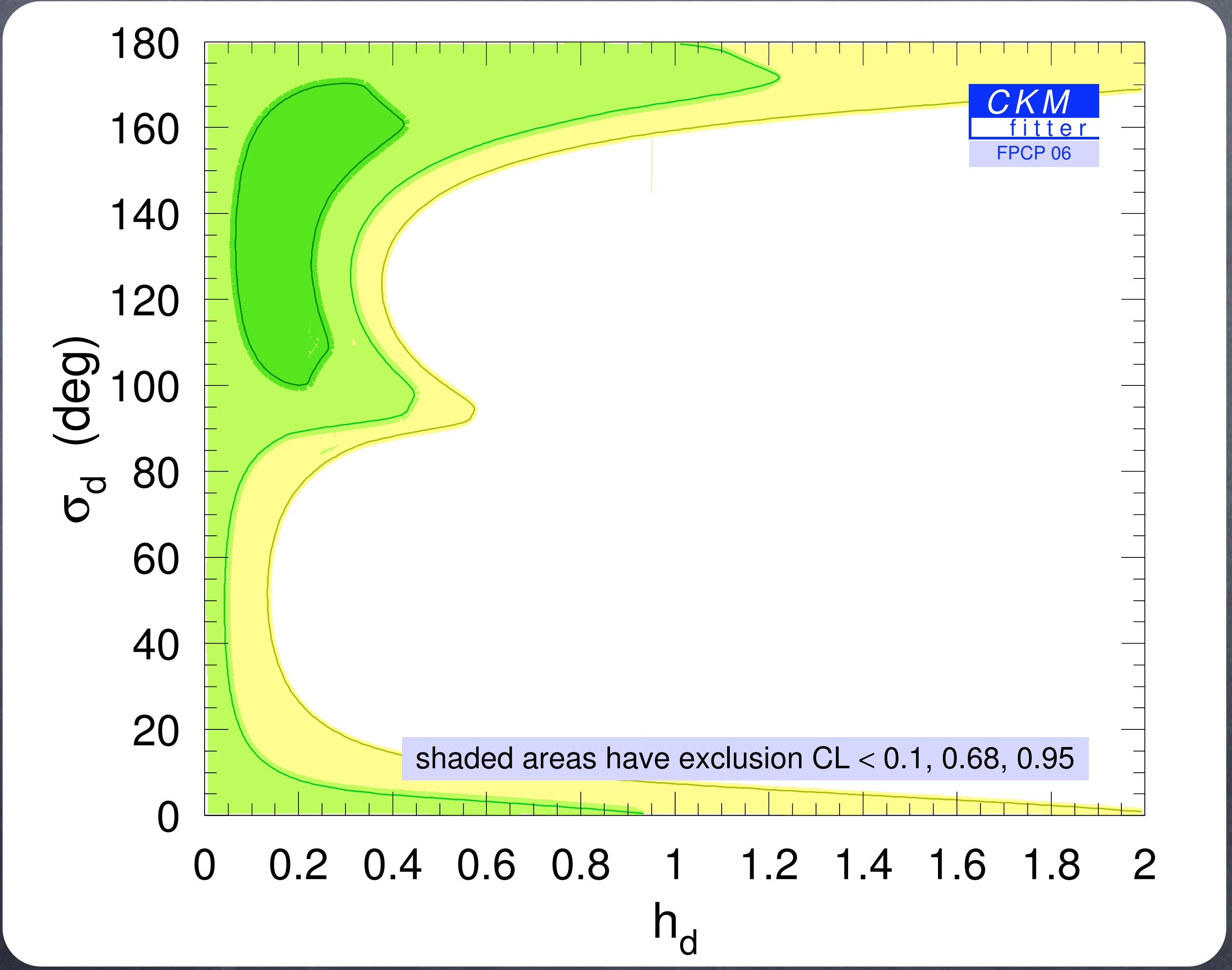
$B_d\, \bar{B}_d$ mixing : $\{h_d, \sigma_d\}$

$B_s\, \bar{B}_s$ mixing : $\{h_s, \sigma_s\}$

Results

Agashe, Papucci, Perez, Pirjol ('05)

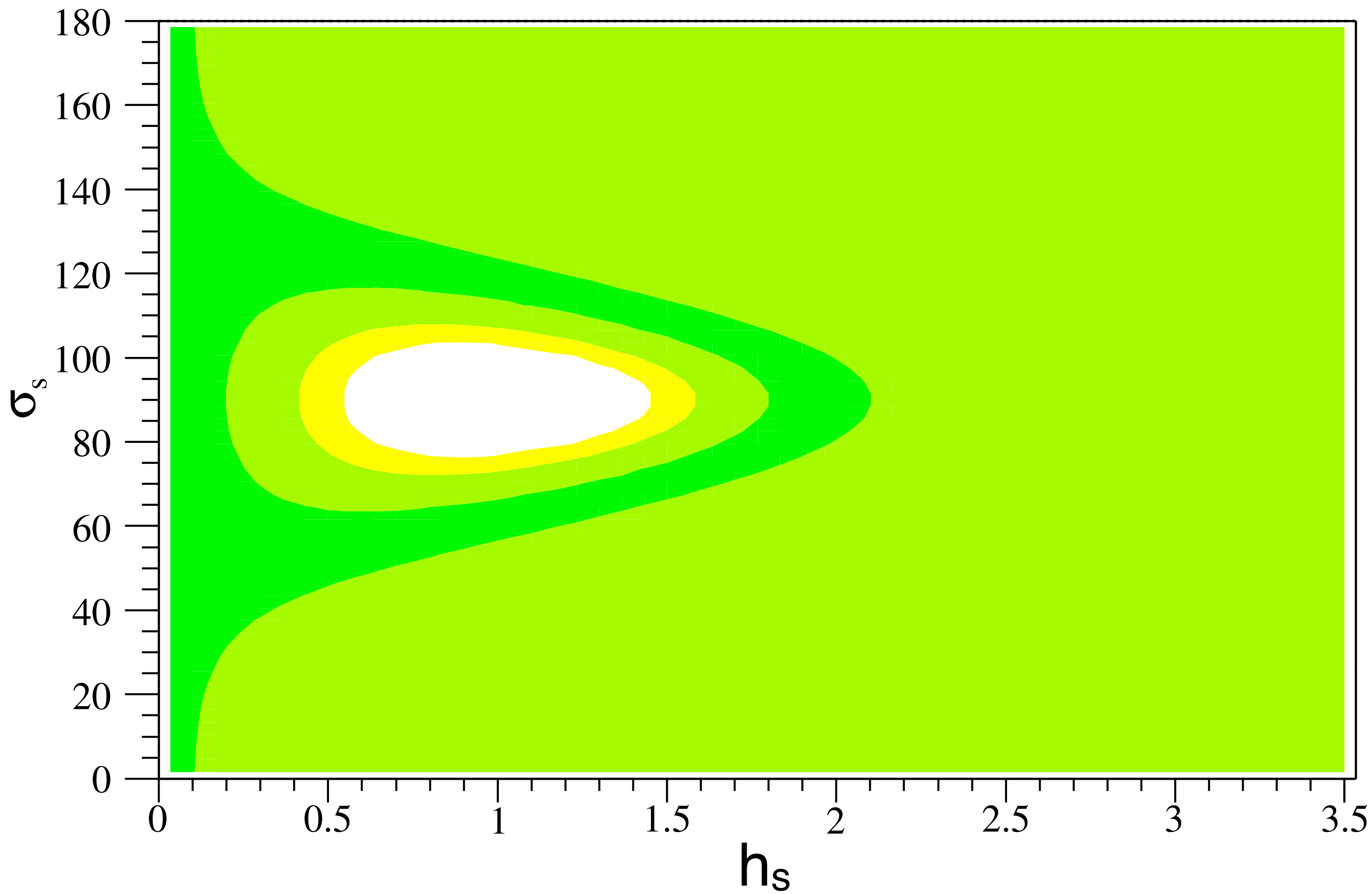
B B mixing



Results

Ligeti, Papucci, Perez ('06)

Constraints without Δm_s



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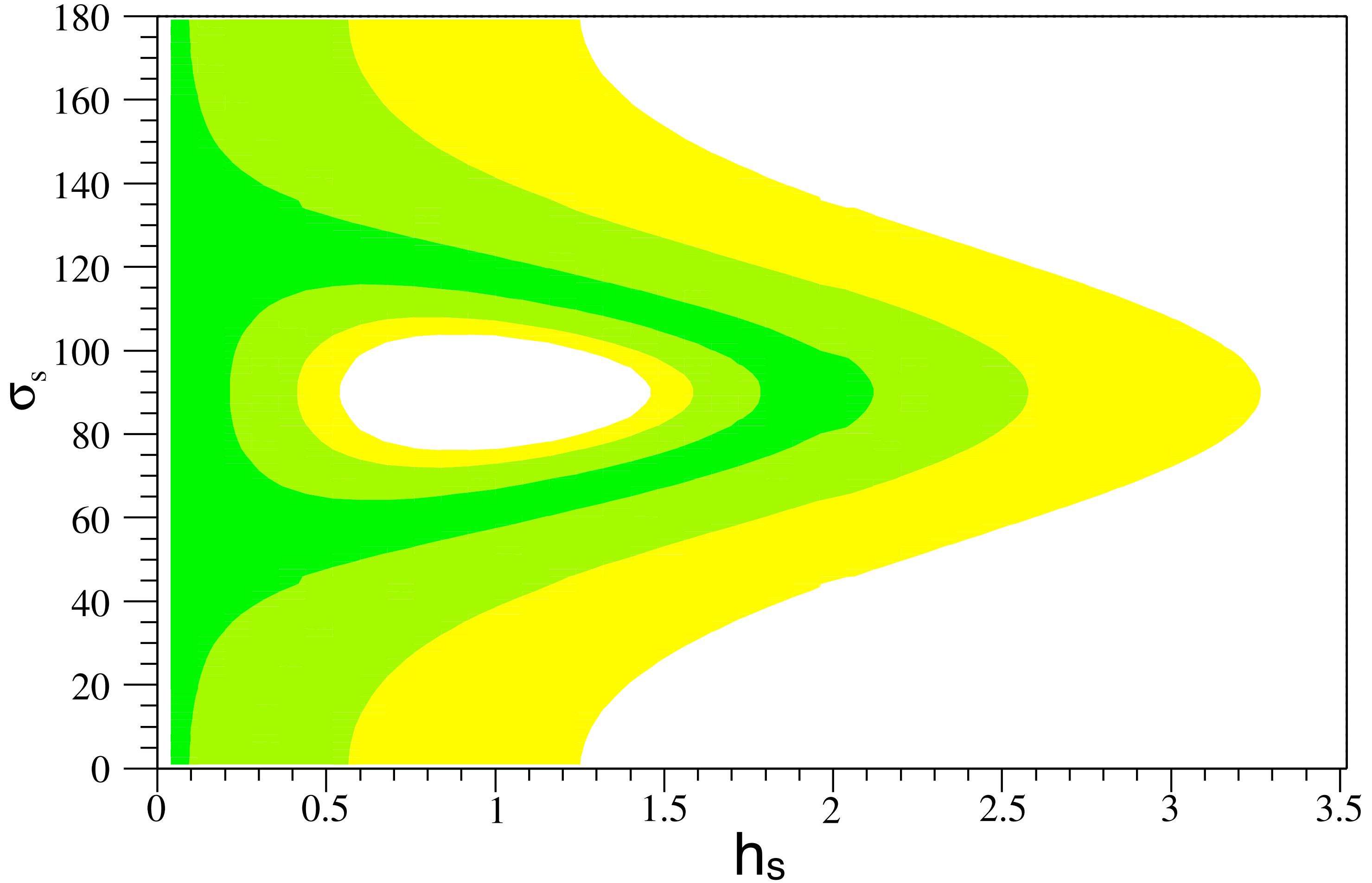


Implications

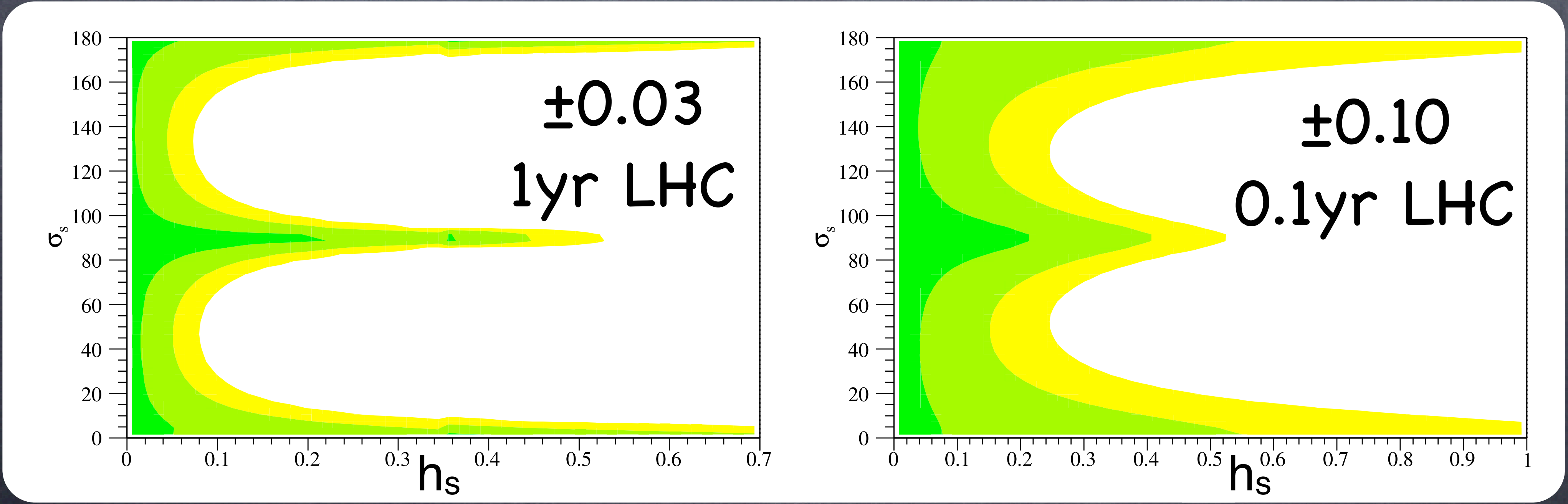
- Recent observation of B_s mixing is in agreement with SM expectations
- This does not give strong constraints on possible contributions from BSM physics
- BSM contributions can be as large as SM contributions

Need LHC to add addtional information to constrain BSM contributions

Add information from LHC

Ligeti, Papucci, Perez ('06)

- Time dependent CP asymmetry in $B_s \to \psi\Phi$
- Analogous to $\sin(2\beta)$ (just as clean)
- Prediction $\sin(2\beta_s) = 0.0365 \pm 0.0020$

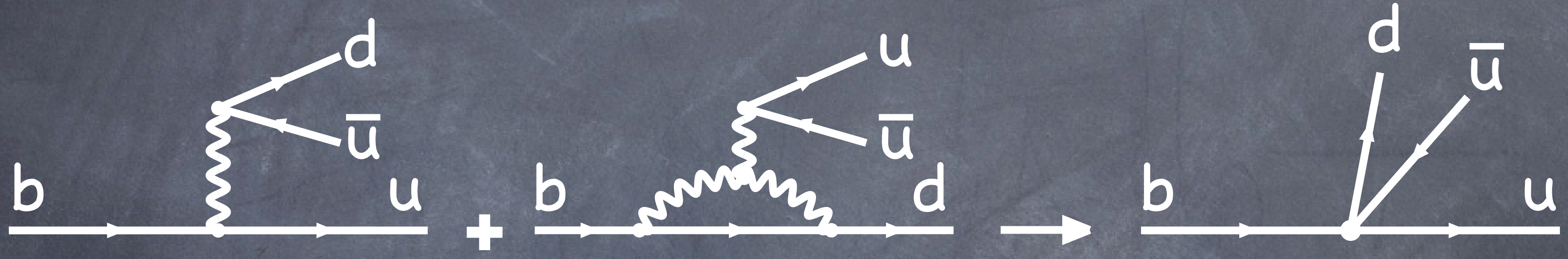


This could be one of the first signals at LHC

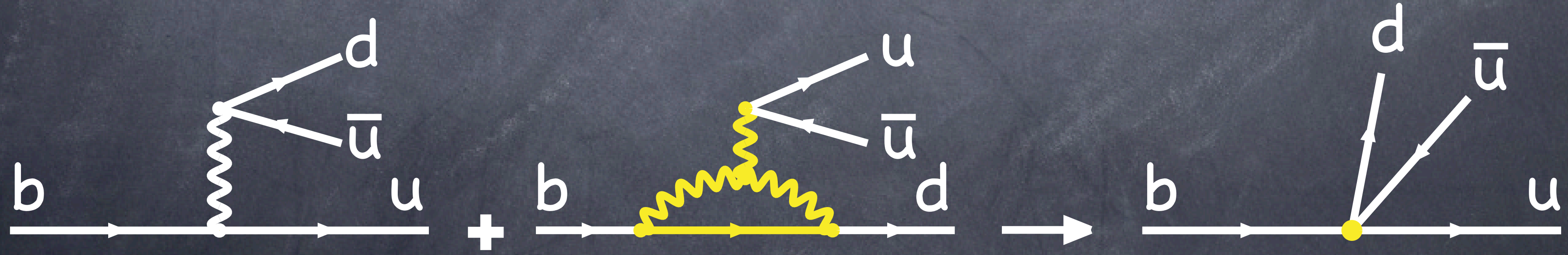
$\Delta B = 1$ Processes

Direct CP violation

In SM both tree and loop contributions possible



BSM physics can modify loop contributions



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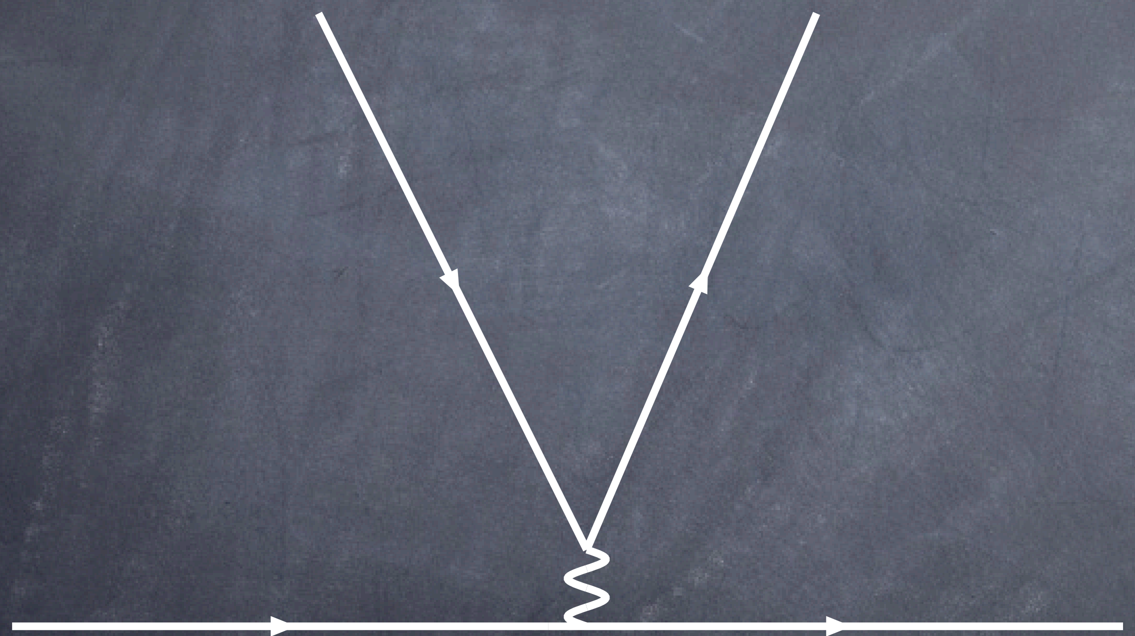

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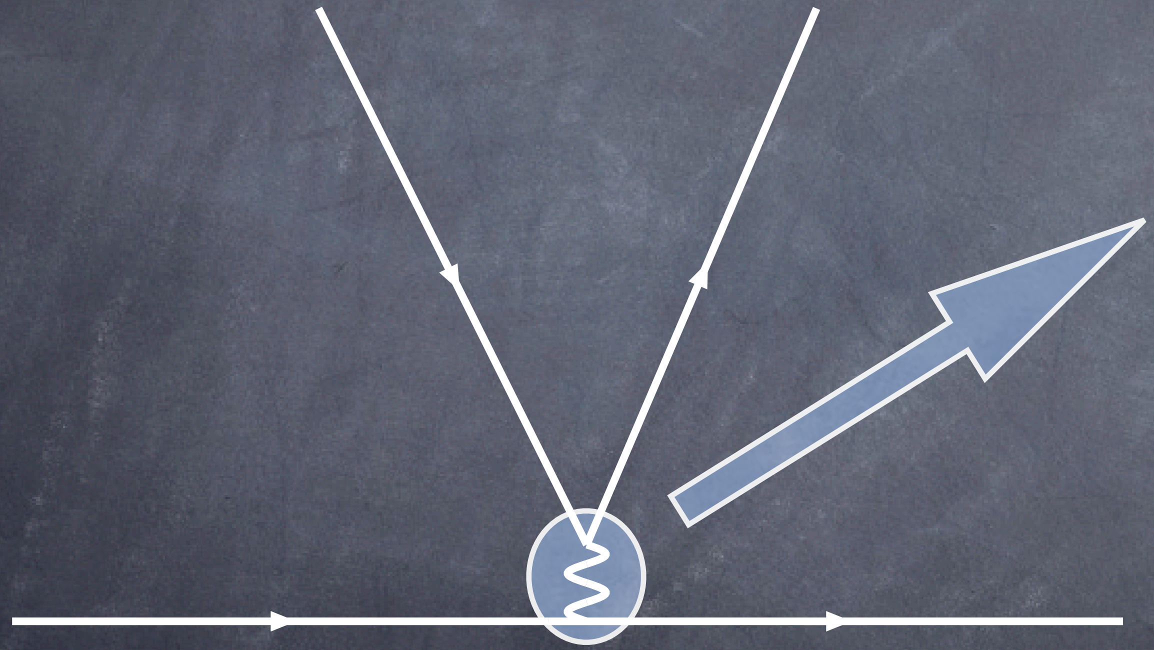

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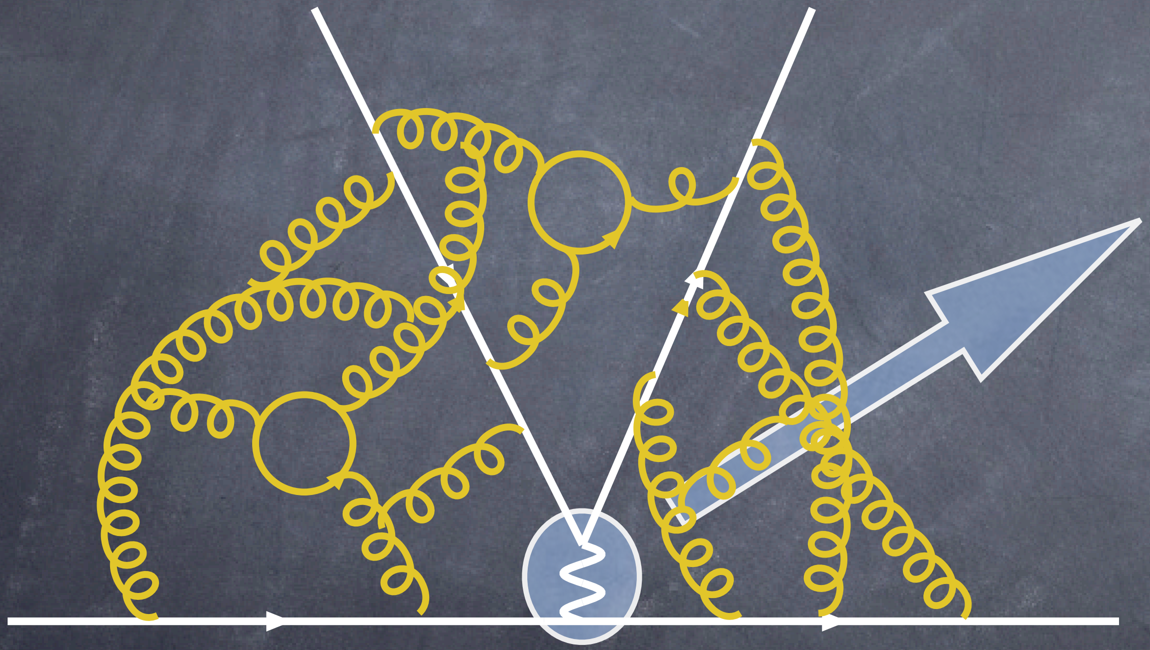

Weak interaction effect we are after

Non-perturbative effects from QCD

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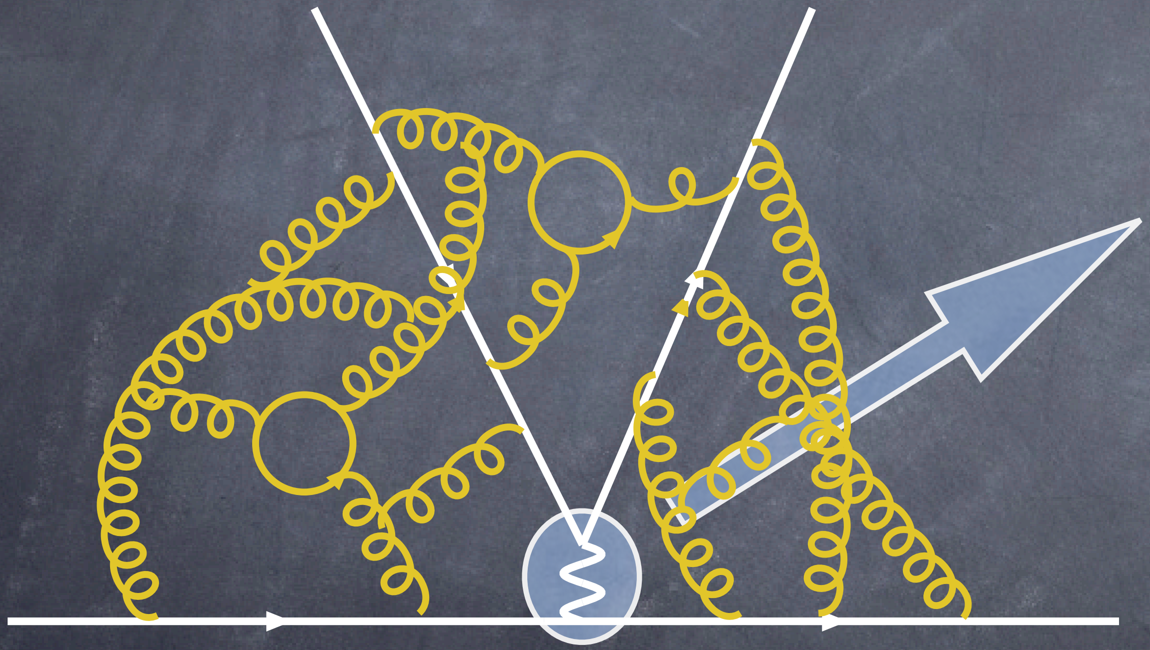


Weak interaction effect we are after

Non-perturbative effects from QCD

Crucial to understand long distance physics to extract weak flavor physics from these decays

Effective Field Theories

- Separate short distance from long distance effects
- Short distance physics is calculable perturbatively
- Long distance physics simplifies in limit $\Lambda_{QCD}/Q \to 0$
- Long distance physics is independent of the details of effects at short distances
- Measure the long distance effects in one process and use results in other processes

Kinematics

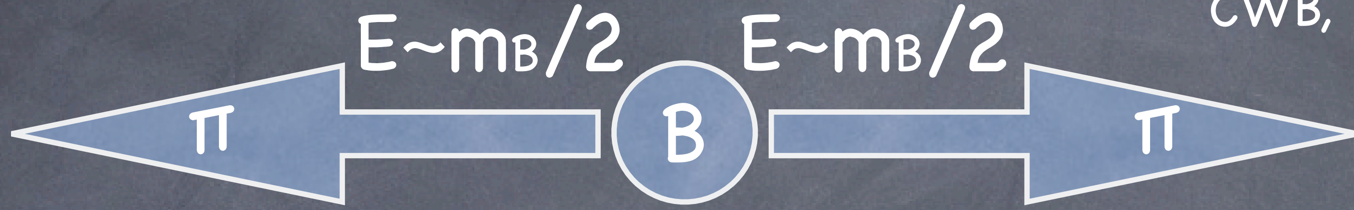
Typical size of hadrons ~$1/\Lambda_{QCD}$

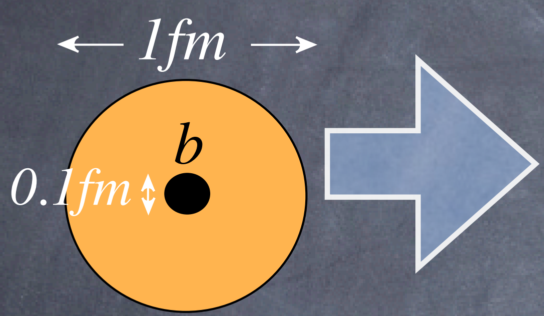
$E \gg \Lambda_{QCD}$

Soft Collinear Effective Theory

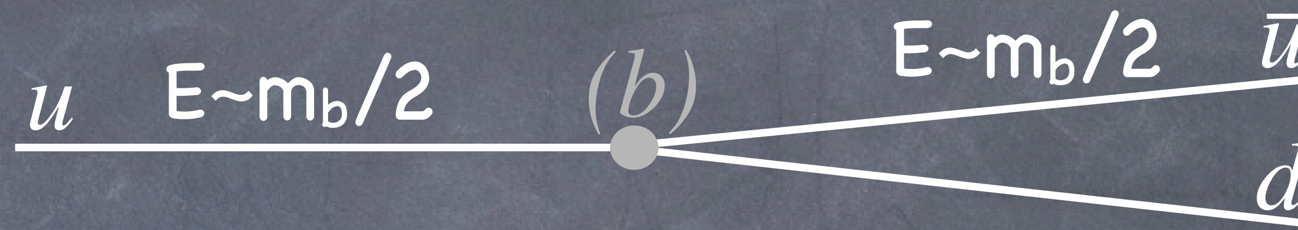
SCET in pictures

CWB, Pirjol, Rothstein, Stewart ('03)

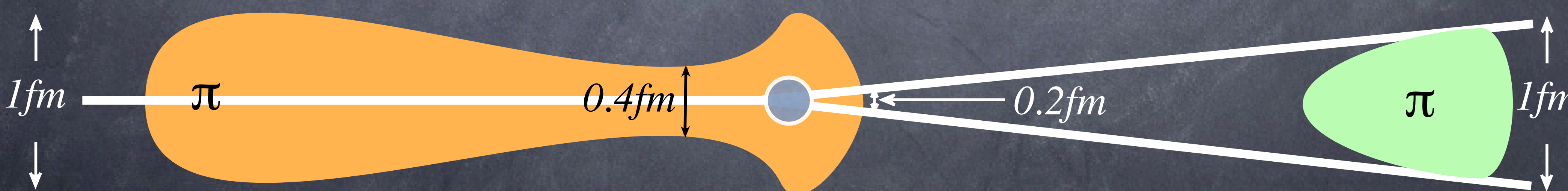




Heavy b quark almost at rest in B meson



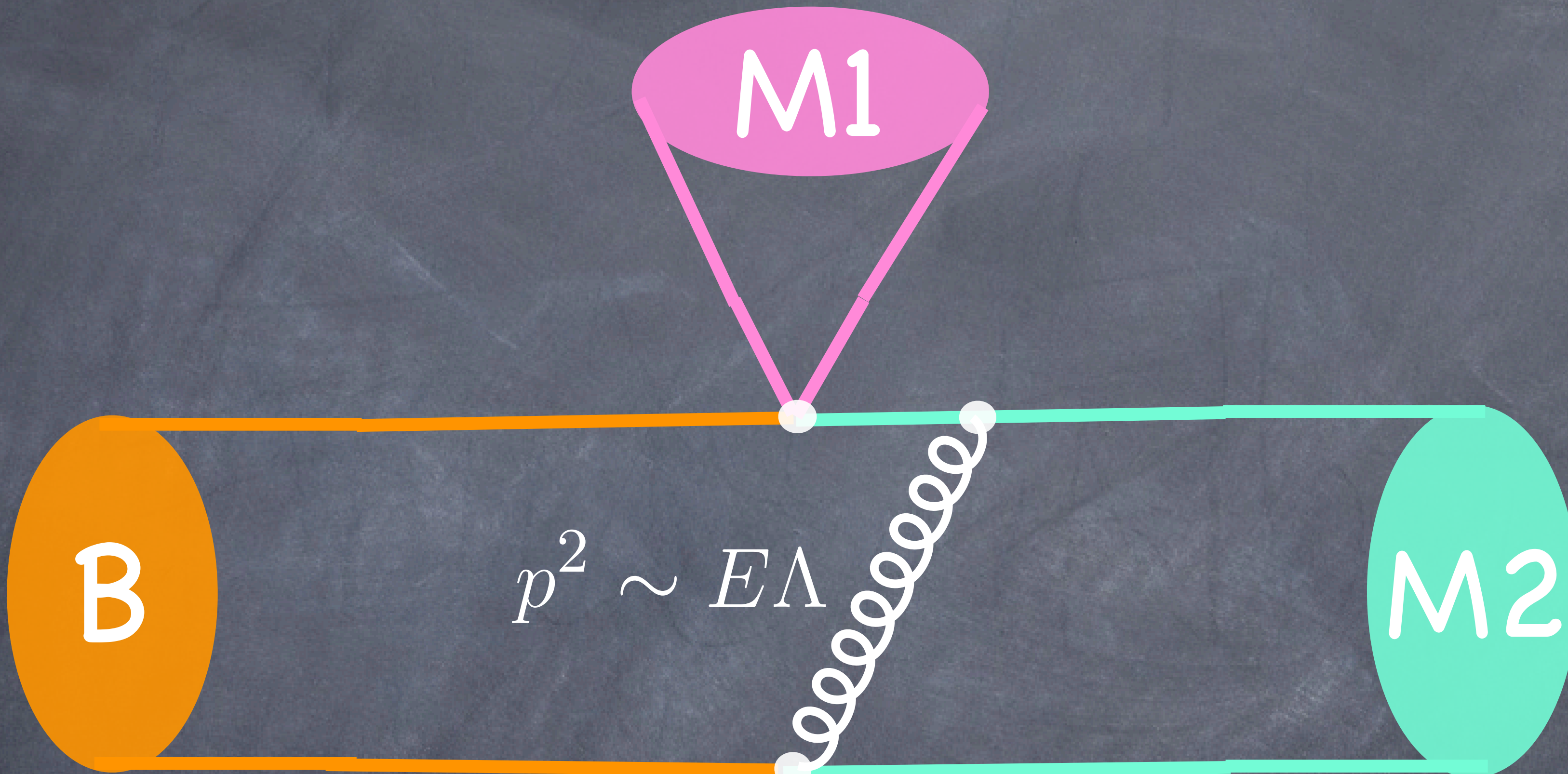
b quark decays into three light quarks, two in the same direction, one in opposing direction



energetic quark requires spectator of the B meson to form pion. Factorization more subtle

two quarks are very close until far from B meson. Thus no coupling between B and pion

The factorization formula



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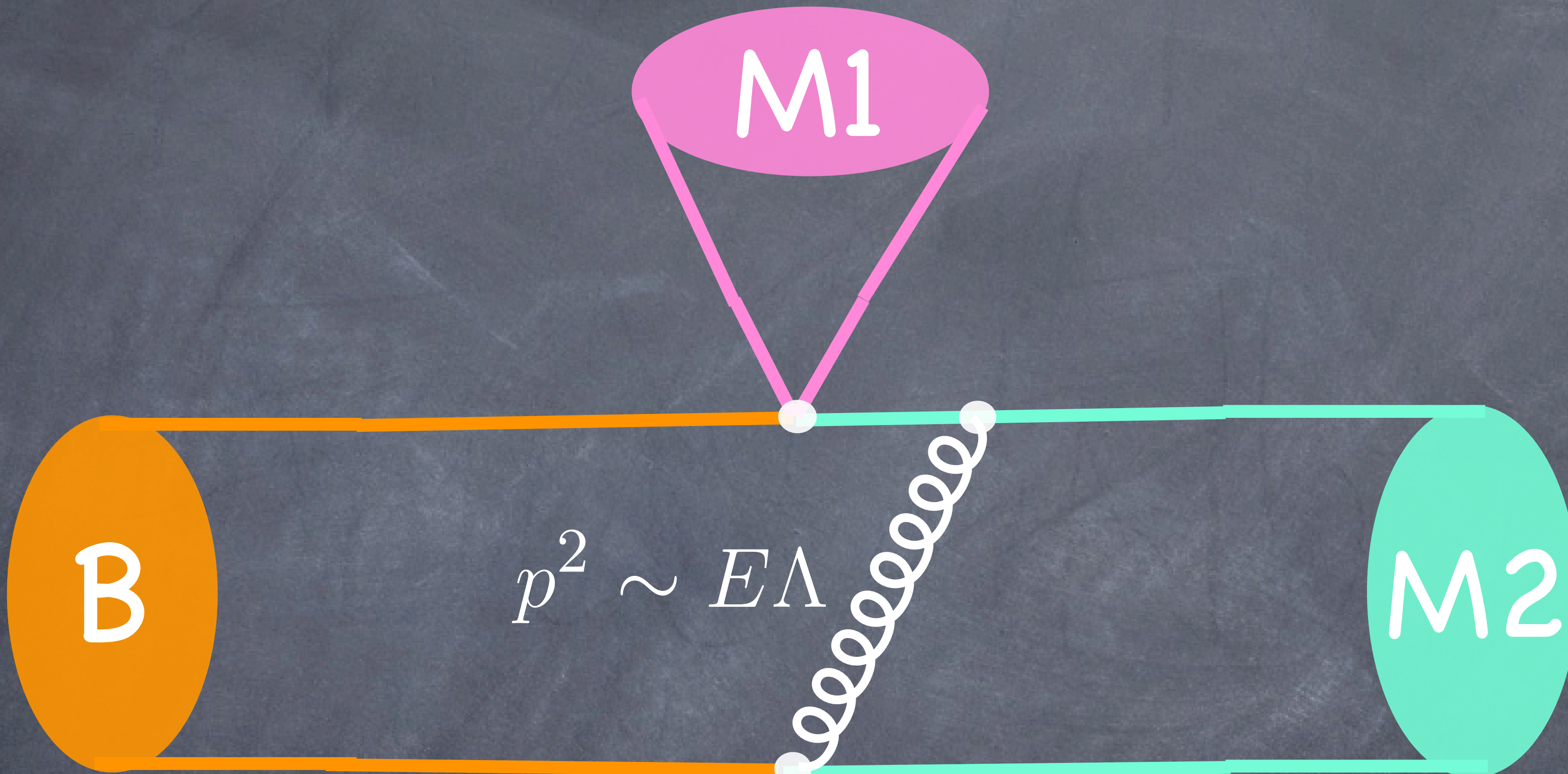

$$A = N\left\{ f_\pi \int du\, dz\, T_{1J}(u,z)\zeta_J^{B\pi}(z)\phi^\pi(u) + \zeta^{B\pi} f_\pi \int du\, T_{1\zeta}(u)\phi^\pi(u) \right\} + \lambda_c^{(f)} A_{c\bar{c}}^{\pi\pi}$$

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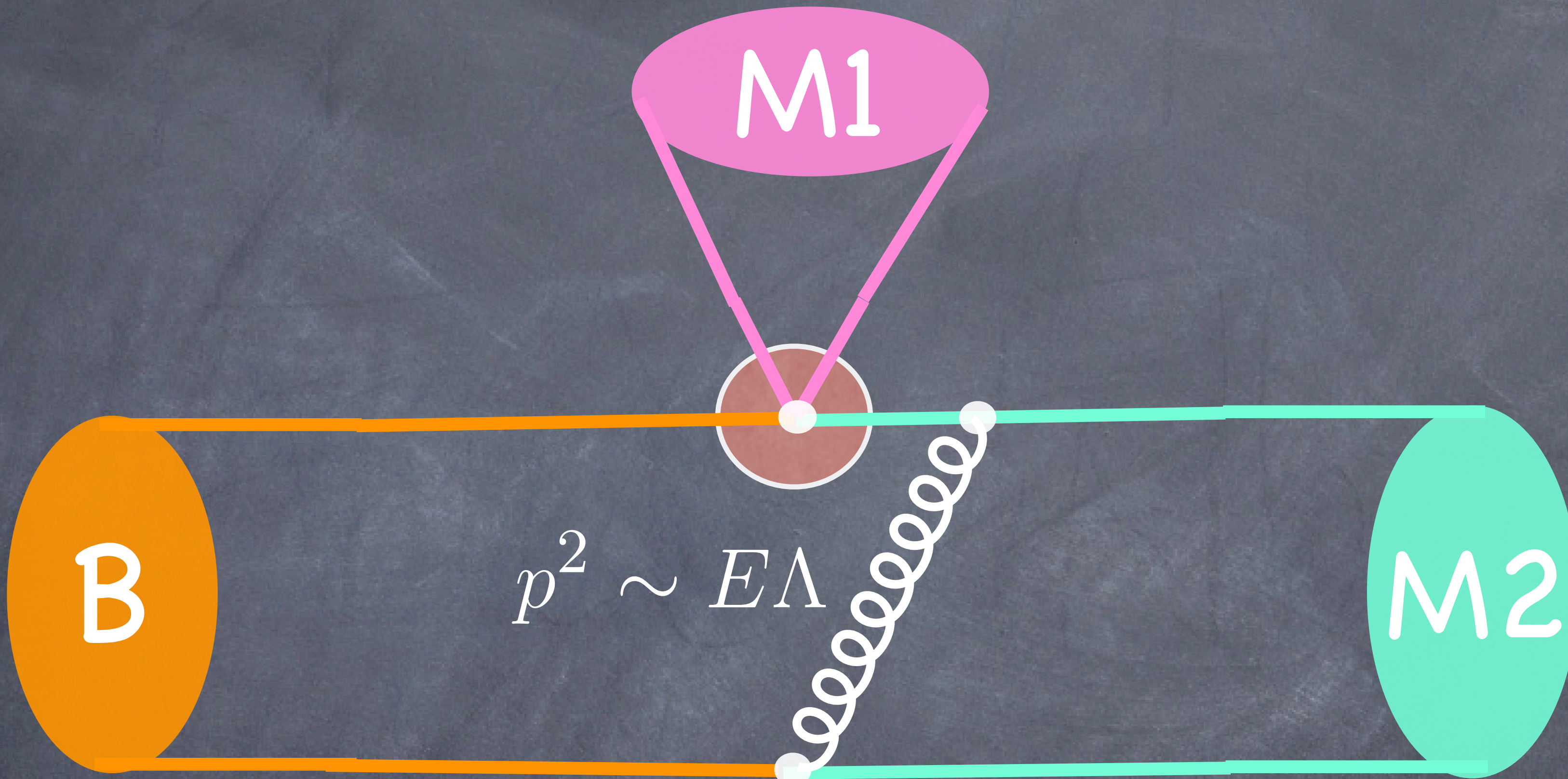

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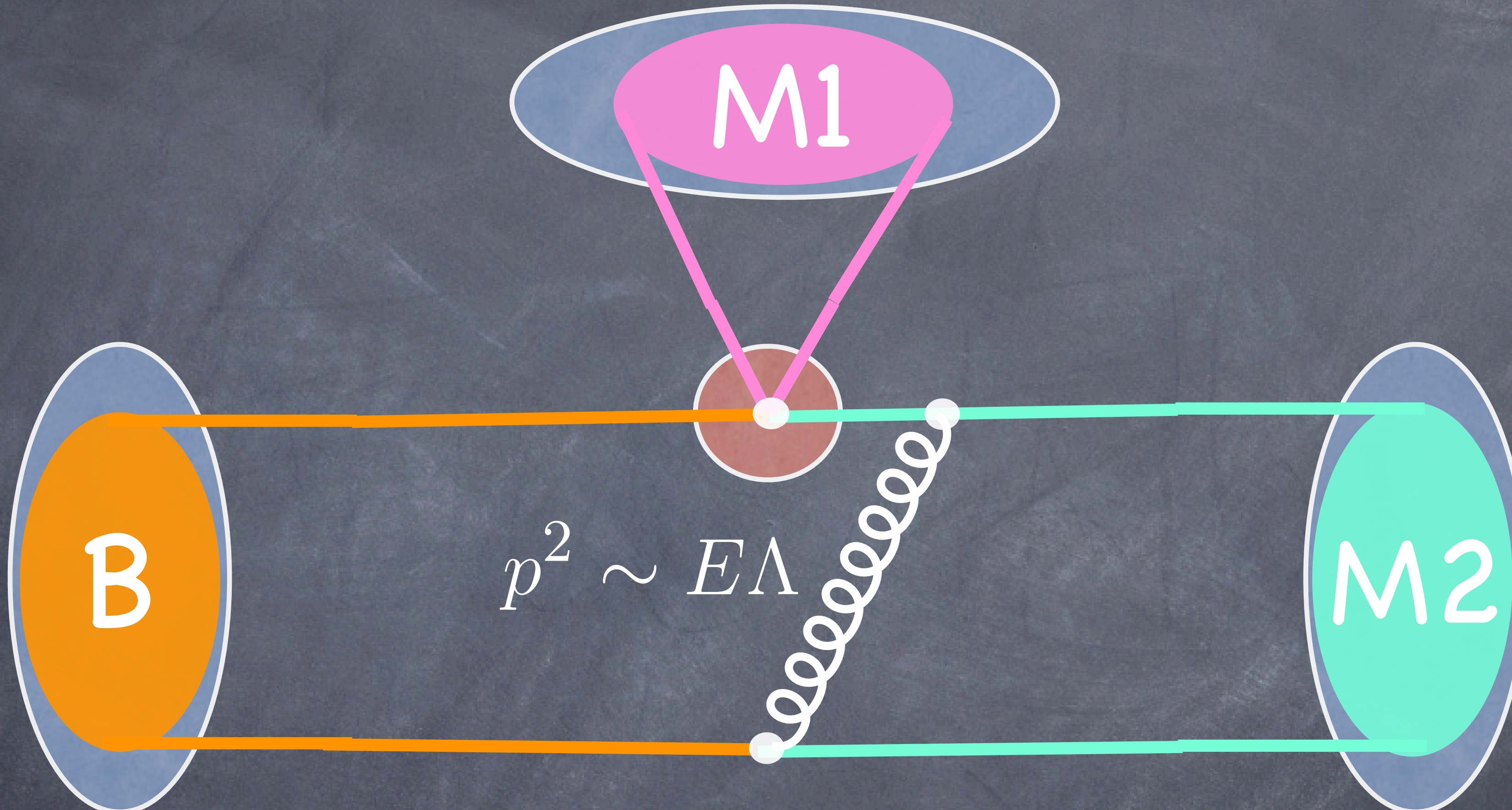

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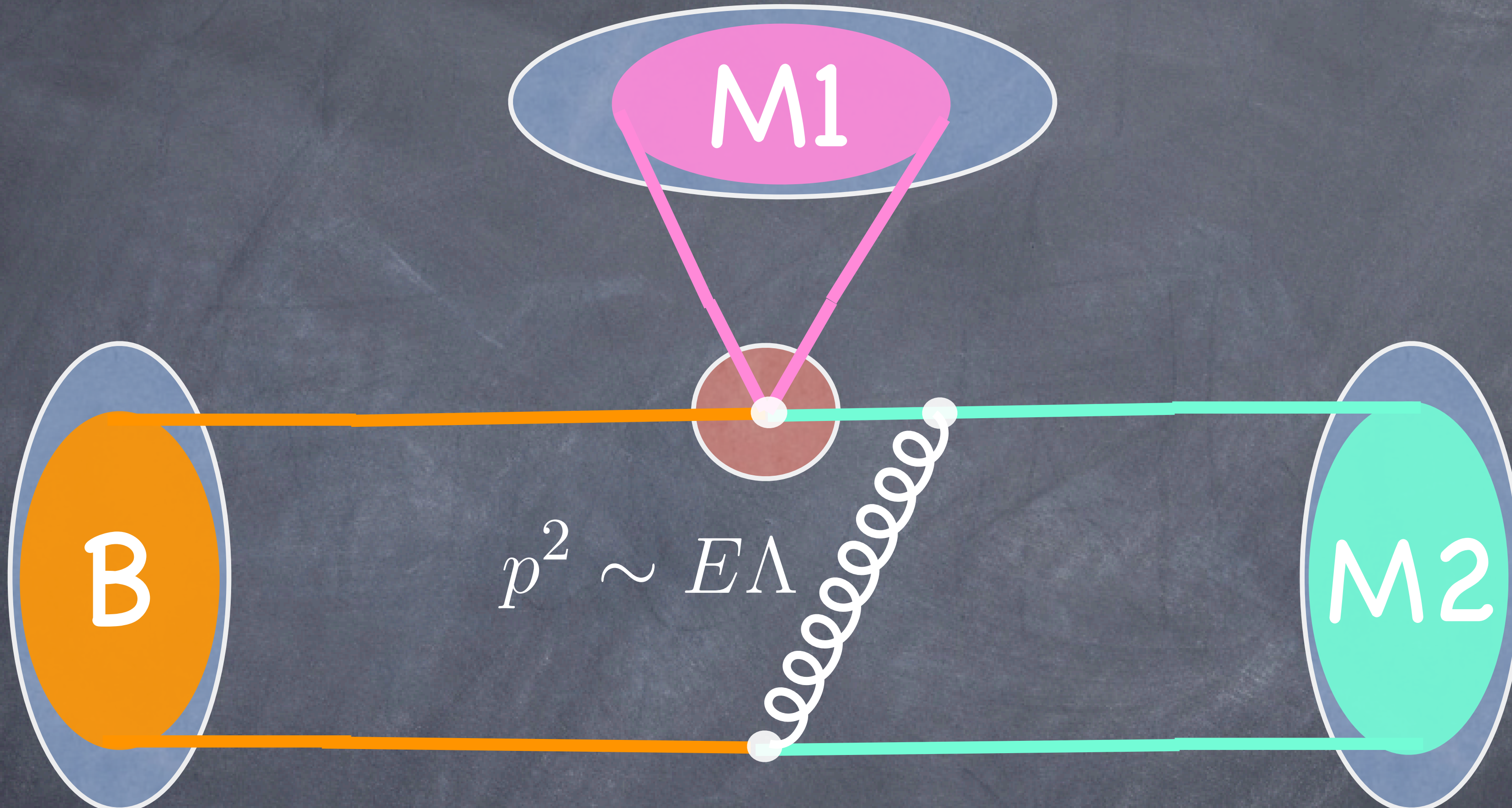

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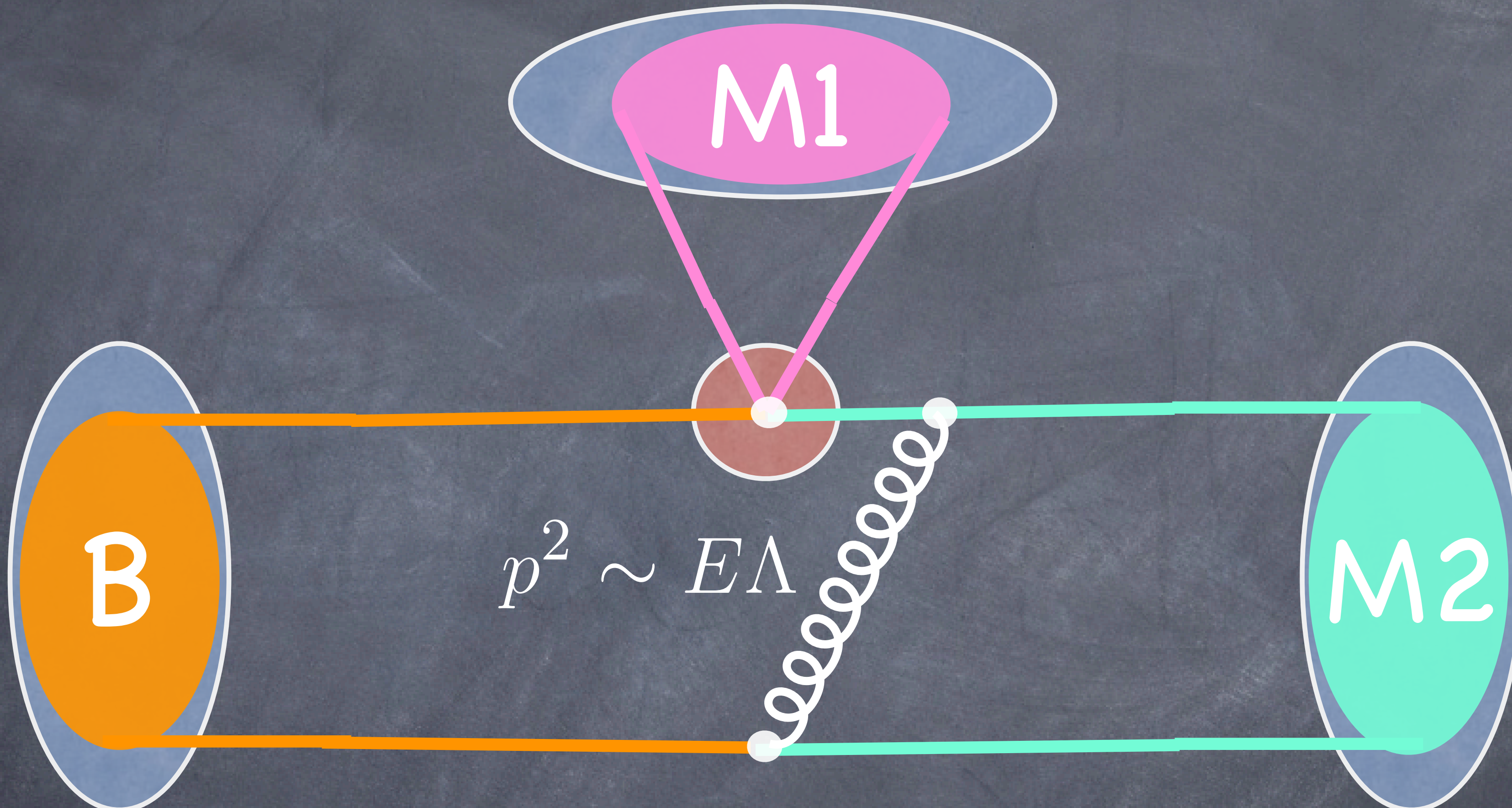

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Parameter counting

Number of hadronic parameters

<table>
<tr><th></th><th>no expns</th><th>SU(2)</th><th>SU(3)</th><th>SCET +SU(2)</th><th>SCET +SU(3)</th></tr>
<tr><td>ππ</td><td>11</td><td>7/5</td><td rowspan="2">15/13</td><td>4</td><td rowspan="3">4</td></tr>
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Implications of small phases

Sum rules for B→Kπ

Lipkin, Gronau, Rosner, Buras et al, Beneke et al

Define Observables

$$R_1 = \frac{2\mathrm{Br}(B^- \to \pi^0 K^-)}{\mathrm{Br}(B^- \to \pi^- \bar{K}^0)} - 1$$
$$= 0.004 \pm 0.086$$

$$R_2 = \frac{\mathrm{Br}(\bar{B}^0 \to \pi^- K^+)\tau_{B^-}}{\mathrm{Br}(B^- \to \pi^- \bar{K}^0)\tau_{B^0}} - 1$$
$$= -0.157 \pm 0.055$$

$$R_3 = \frac{2\mathrm{Br}(\bar{B}^0 \to \pi^0 \bar{K}^0)\tau_{B^-}}{\mathrm{Br}(\bar{B}^0 \to \pi^- \bar{K}^0)\tau_{B^0}} - 1$$
$$= 0.026 \pm 0.105$$

$$\Delta_1 = (1 + R_1)A_{\mathrm{CP}}(\pi^0 K^-)$$
$$= 0.040 \pm 0.040$$

$$\Delta_2 = (1 + R_2)A_{\mathrm{CP}}(\pi^- K^+)$$
$$= -0.097 \pm 0.016$$

$$\Delta_3 = (1 + R_3)A_{\mathrm{CP}}(\pi^0 \bar{K}^0)$$
$$= -0.021 \pm 0.133$$

$$\Delta_4 = A_{\mathrm{CP}}(\pi^- \bar{K}^0)$$
$$= -0.02 \pm 0.04$$

Combinations vanish to LO in $\epsilon \sim |\lambda_u/\lambda_c|$, P_{EW}/P

$R_1 - R_2 + R_3 = O(\epsilon^2)$

$\Delta_1 - \Delta_2 + \Delta_3 - \Delta_4 = O(\epsilon^2)$

Predictions for the R_i and Δ_i

CWB, Rothstein, Stewart ('05)

Experimental Results:

$R_1+R_2-R_3=0.19\pm0.15$

$\Delta_1-\Delta_2+\Delta_3-\Delta_4= 0.14\pm0.15$

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SCET Prediction:

(modest assumptions about hadronic parameters)

$$R_1+R_2-R_3=O(\epsilon^2)=0.028\pm0.021$$

$$\Delta_1-\Delta_2+\Delta_3-\Delta_4\sim\epsilon^2\sin(\varphi_i-\varphi_j) = 0\pm0.013$$

Predictions for the R_i and Δ_i

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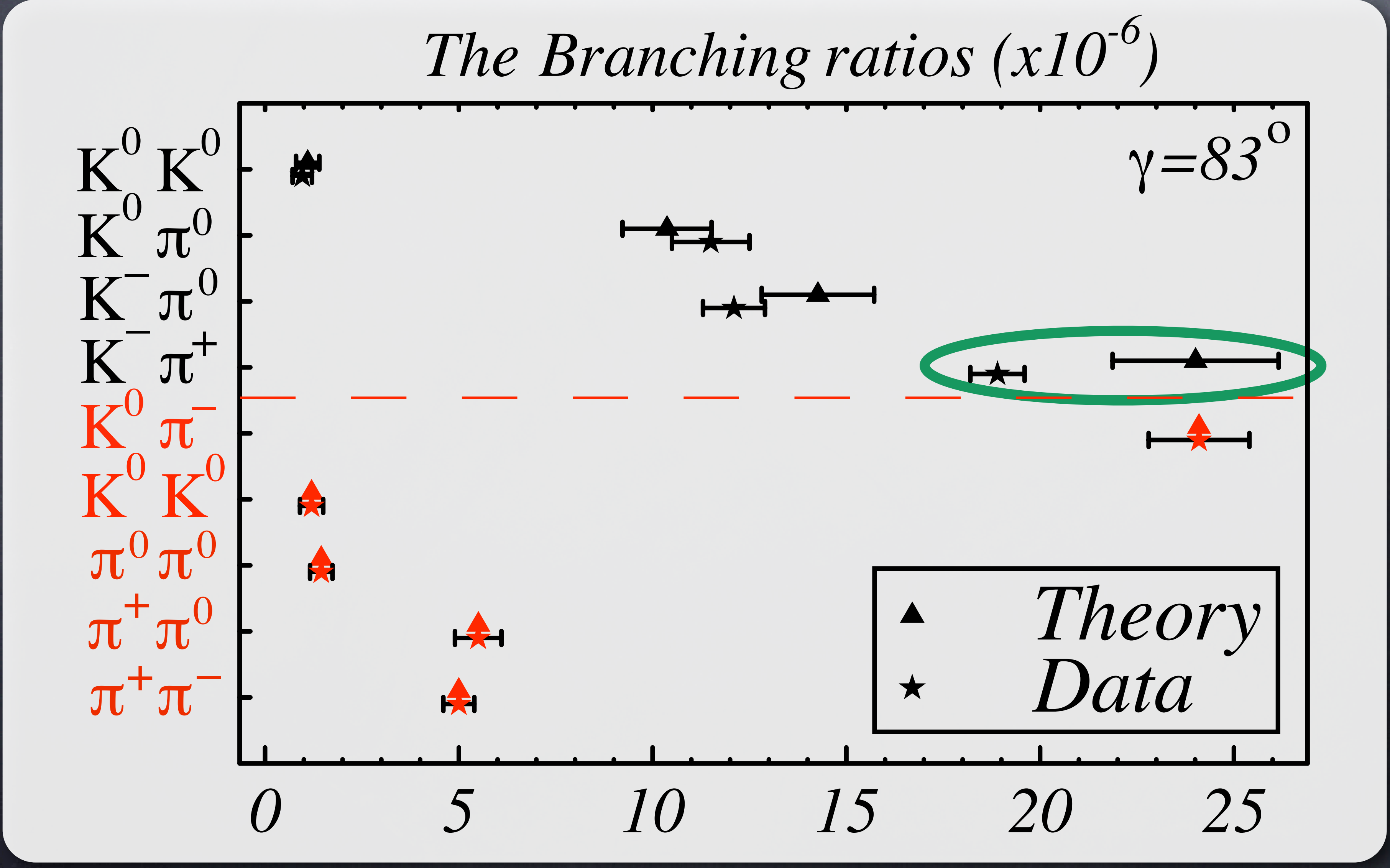
Pretty firm predictions

Need better data to check these predictions

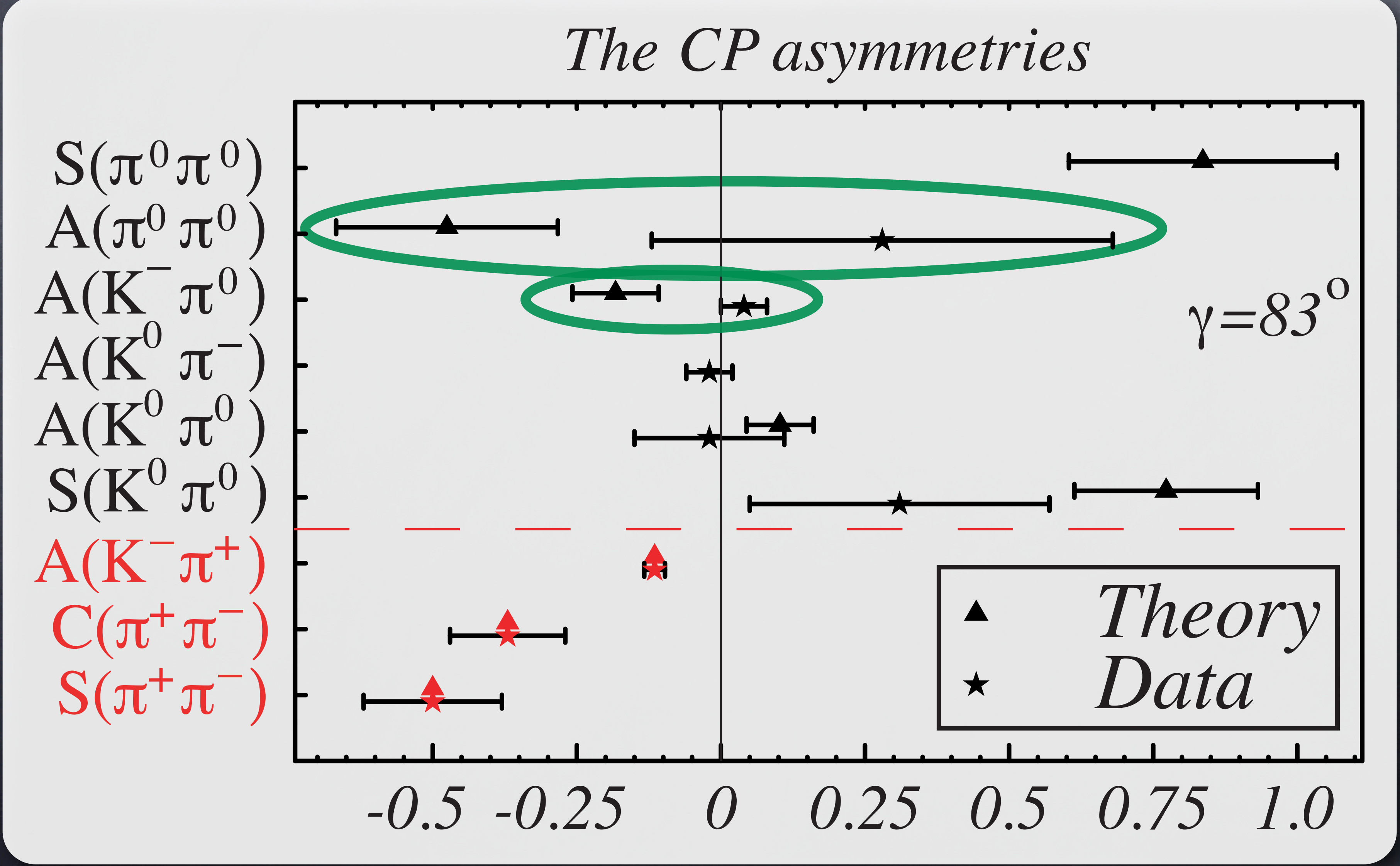
The B→PP predictions

Branching ratios



The B→PP predictions

CP asymmetries



Predictions for B_s decays

Williamson, Zupan ('06)

Mode	Exp	Theory I	Theory II
$\bar{B}_s^0 \to \pi^- K^+$	$< 2.2 f_d/f_s{}^a$	$4.9 \pm 1.2 \pm 1.3 \pm 0.3$	
	$-$	$0.20 \pm 0.17 \pm 0.19 \pm 0.05$	
$\bar{B}_s^0 \to \pi^0 K^0$	$-$	$0.76 \pm 0.26 \pm 0.27 \pm 0.17$	
	$-$	$-0.58 \pm 0.39 \pm 0.39 \pm 0.13$	
$\bar{B}_s^0 \to \eta K^0$	$-$	$0.80 \pm 0.48 \pm 0.29 \pm 0.18$	$0.59 \pm 0.34 \pm 0.24 \pm 0.15$
	$-$	$-0.56 \pm 0.46 \pm 0.14 \pm 0.06$	$0.61 \pm 0.59 \pm 0.12 \pm 0.08$
$\bar{B}_s^0 \to \eta' K^0$	$-$	$4.5 \pm 1.5 \pm 0.4 \pm 0.5$	$3.9 \pm 1.3 \pm 0.5 \pm 0.4$
	$-$	$-0.14 \pm 0.07 \pm 0.16 \pm 0.02$	$0.37 \pm 0.08 \pm 0.14 \pm 0.04$
$\bar{B}_s^0 \to K^- K^+$	$(9.5 \pm 2.0) f_d/f_s{}^a$	$18.2 \pm 6.7 \pm 1.1 \pm 0.5$	
	$-$	$-0.06 \pm 0.05 \pm 0.06 \pm 0.02$	
$\bar{B}_s^0 \to K^0 \bar{K}^0$	$-$	$17.7 \pm 6.6 \pm 0.5 \pm 0.6$	
	$-$	< 0.1	
$\bar{B}_s^0 \to \eta \pi^0$	$-$	$0.014 \pm 0.004 \pm 0.005 \pm 0.004$	$0.016 \pm 0.007 \pm 0.005 \pm 0.006$
	$-$	$-$	$-$
$\bar{B}_s^0 \to \eta' \pi^0$	$-$	$0.006 \pm 0.003 \pm 0.002^{+0.064}_{-0.006}$	$0.038 \pm 0.013 \pm 0.016^{+0.260}_{-0.036}$
	$-$	$-$	$-$
$\bar{B}_s^0 \to \eta\eta$	$-$	$7.1 \pm 6.4 \pm 0.2 \pm 0.8$	$6.4 \pm 6.3 \pm 0.1 \pm 0.7$
	$-$	$0.079 \pm 0.049 \pm 0.027 \pm 0.015$	$-0.011 \pm 0.050 \pm 0.039 \pm 0.010$
$\bar{B}_s^0 \to \eta\eta'$	$-$	$24.0 \pm 13.6 \pm 1.4 \pm 2.7$	$23.8 \pm 13.2 \pm 1.6 \pm 2.9$
	$-$	$0.0004 \pm 0.0014 \pm 0.0039 \pm 0.0043$	$0.023 \pm 0.009 \pm 0.008 \pm 0.076$
$\bar{B}_s^0 \to \eta'\eta'$	$-$	$44.3 \pm 19.7 \pm 2.3 \pm 17.1$	$49.4 \pm 20.6 \pm 8.4 \pm 16.2$
	$-$	$0.009 \pm 0.004 \pm 0.006 \pm 0.019$	$-0.037 \pm 0.010 \pm 0.012 \pm 0.056$

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Williamson, Zupan ('06)

Mode	Exp	Theory I	Theory II
$\bar{B}_s^0 \to K_S \pi^0$	–	$-0.16 \pm 0.41 \pm 0.33 \pm 0.17$	
	–	$0.80 \pm 0.27 \pm 0.25 \pm 0.11$	
$\bar{B}_s^0 \to K_S \eta$	–	$0.82 \pm 0.32 \pm 0.11 \pm 0.04$	$0.63 \pm 0.61 \pm 0.16 \pm 0.08$
	–	$0.07 \pm 0.56 \pm 0.17 \pm 0.05$	$0.49 \pm 0.68 \pm 0.21 \pm 0.03$
$\bar{B}_s^0 \to K_S \eta'$	–	$0.38 \pm 0.08 \pm 0.10 \pm 0.04$	$0.24 \pm 0.09 \pm 0.15 \pm 0.05$
	–	$-0.92 \pm 0.04 \pm 0.04 \pm 0.02$	$-0.90 \pm 0.05 \pm 0.05 \pm 0.03$
$\bar{B}_s^0 \to K^- K^+$	–	$0.19 \pm 0.04 \pm 0.04 \pm 0.01$	
	–	$1-(0.021 \pm 0.008 \pm 0.007 \pm 0.002)$	
$\bar{B}_s^0 \to \pi^0 \eta$	–	$0.45 \pm 0.14 \pm 0.42 \pm 0.30$	$0.38 \pm 0.20 \pm 0.42 \pm 0.37$
	–	$-0.89 \pm 0.07 \pm 0.21 \pm 0.15$	$-0.92 \pm 0.08 \pm 0.17 \pm 0.15$
$\bar{B}_s^0 \to \eta\eta$	–	$-0.026 \pm 0.040 \pm 0.030 \pm 0.014$	$-0.077 \pm 0.061 \pm 0.022 \pm 0.026$
	–	$1-(0.0035 \pm 0.0041 \pm 0.0019 \pm 0.0015)$	$1-(0.0030 \pm 0.0048 \pm 0.0017 \pm 0.0021)$
$\bar{B}_s^0 \to \eta\eta'$	–	$0.041 \pm 0.004 \pm 0.002 \pm 0.051$	$0.015 \pm 0.010 \pm 0.008 \pm 0.069$
	–	$1-(0.0008 \pm 0.0002 \pm 0.0001 \pm 0.0021)$	$1-(0.0004 \pm 0.0003 \pm 0.0003 \pm 0.0007)$
$\bar{B}_s^0 \to \eta'\eta'$	–	$0.049 \pm 0.005 \pm 0.005 \pm 0.031$	$0.051 \pm 0.009 \pm 0.017 \pm 0.039$
	–	$1-(0.0012 \pm 0.0003 \pm 0.0002 \pm 0.0017)$	$1-(0.0020 \pm 0.0007 \pm 0.0009 \pm 0.0041)$

Conclusions

- Recent years have seen enormous advances in our understanding of B physics
- All experimental results have confirmed the SM picture of flavor and CP violation
- Given current uncertainties, still considerable room for BSM contributions to flavor and CP violation
- LHC will help tremendously to constrain new physics in B_sB_s mixing
- Recent new advances in theoretical understanding allows better relation of data to underlying physics