Toward Super-B: QED logs in $B \to X_s \ell\ell$ & uses of $B \to \tau\nu$

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Super-B, Frascati

Dec 3, 2009

OUTLINE

(1) Precision calculations of inclusive $b \to sll$ decays:

- Present status of SM predictions and NP implications
- Electromagnetic corrections: issues and resolution (preliminary)

(2) UT fit without semileptonic decays:

- Present status of the UT fit and hints for NP
- Issues with V_{cb} and V_{ub} from semileptonic decays
- Impact of a determination of $B \to \tau\nu$ with super-B precision

PART I: INCLUSIVE B→SLL

T. Huber, E.L., M. Misiak and D. Wyler, hep-h/0512066
T. Huber, T. Hurth and E.L., arXiv:0712.3009
T. Huber, T. Hurth and E.L., in preparation

[Misiak; Buras, Munz;
Bobeth, Misiak, Urban;
Asatryan, Asatrian, Greub, Walker;
Ghinculov, Hurth, Isidori, Yao;
Bobeth, Gambino, Gorbahn, Haisch;
Huber, Lunghi, Misiak, Wyler]

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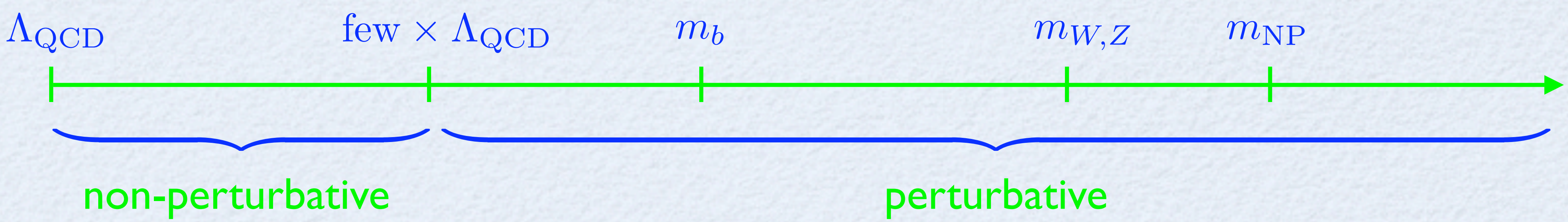
Effective Lagrangian

$$\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{tq}^* \left[\sum_{i=1}^{10} C_i Q_i + \frac{V_{ub}V_{uq}^*}{V_{tb}V_{tq}^*} \sum_{i=1}^{2} C_i (Q_i - Q_i^u) + \underbrace{\sum_{i=3}^{6} C_{iQ} Q_{iQ} + C_b Q_b}_{\text{for QED corrections}} \right]$$



- Magnetic & chromo-magnetic

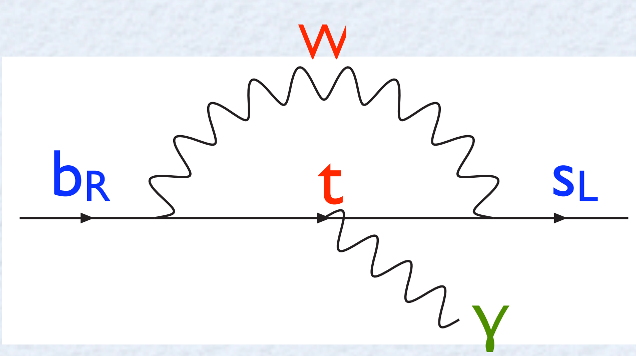
$$Q_7 = \frac{e}{16\pi^2} m_b (\bar{q}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

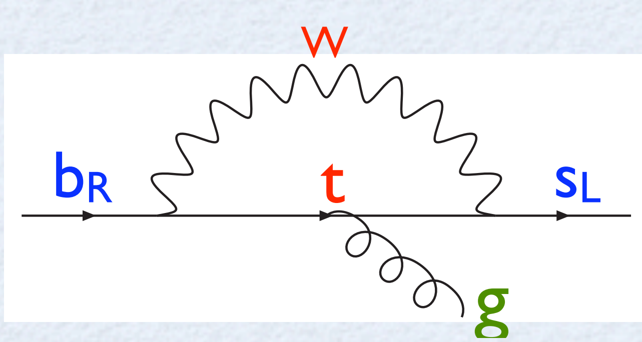
$$Q_8 = \frac{g}{16\pi^2} m_b (\bar{q}_L \sigma^{\mu\nu} T^a b_R) G^a_{\mu\nu}$$

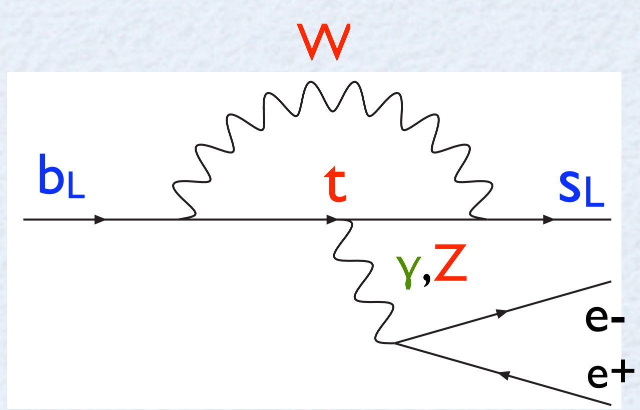
- Semileptonic

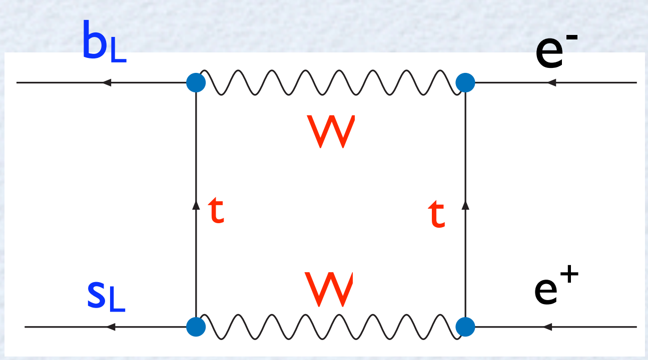
$$Q_9 = (\bar{q}_L \gamma_\mu b_L) \sum (\bar{\ell} \gamma^\mu \ell)$$

$$Q_{10} = (\bar{q}_L \gamma_\mu b_L) \sum (\bar{\ell} \gamma^\mu \gamma_5 \ell)$$









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General Considerations

$$\Gamma\left[\bar{B}\to X_s\ell^+\ell^-\right]=\Gamma\left[\bar{b}\to X_s\ell^+\ell^-\right]+O\left(\frac{\Lambda^2_{QCD}}{m_b^2},\frac{\Lambda^3_{QCD}}{m_b^3},\frac{\Lambda^2_{QCD}}{m_c^2},\dots\right)$$

local OPE, optical theorem
quark-hadron duality

HQET

Phase space cuts introduce sensitivity to new scales, the rate becomes less inclusive and new non-perturbative effects appear

(I) $q^2=(p_{\ell^+}+p_{\ell^-})^2$ cut to remove $B\to X_s(J/\psi,\psi')\to X_s\ell^+\ell^-$ background

(II) $M_{X_s}<[1.8,2]\ \mathrm{GeV}$ cut to remove the double semileptonic $b\to c\ell^-\bar{\nu}\to s\ell^-\ell^+\bar{\nu}\nu$ background

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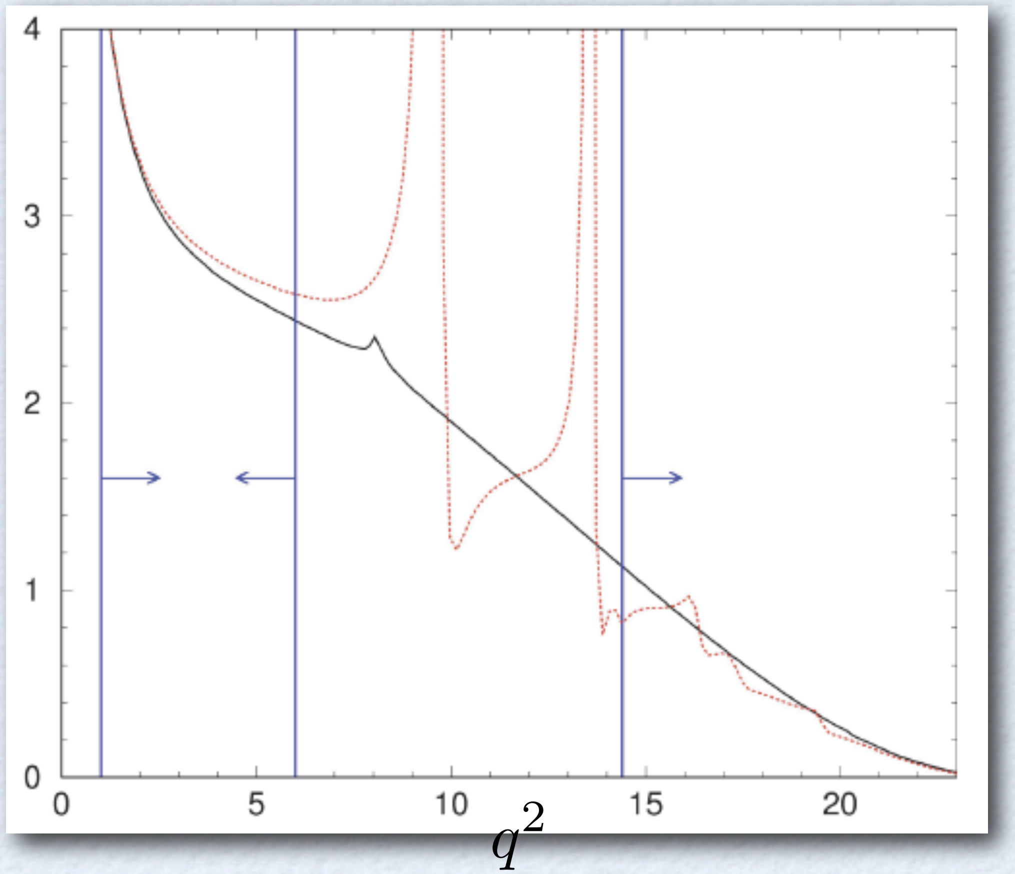
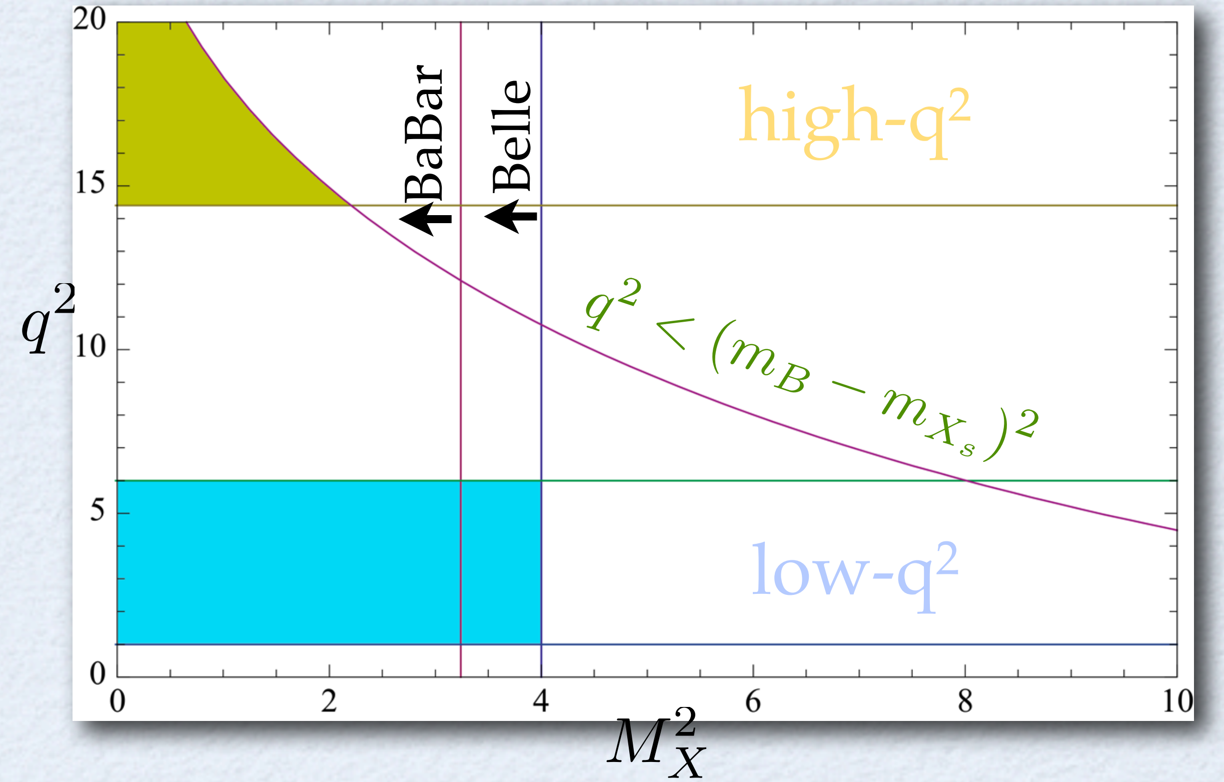
CUTS

- Di-lepton invariant mass:



- low: ***1 GeV² < q² < 6 GeV²***
- high: ***q² > 14.4 GeV²***
- Model resonances with data
- Away from resonances expansion in $1/m_c^2$

- Hadronic invariant mass:



- high-q² region unaffected
- Experiments correct using Fermi motion model
- Leading power SCET suggests cuts are universal (same for b→sll and b→ulν)

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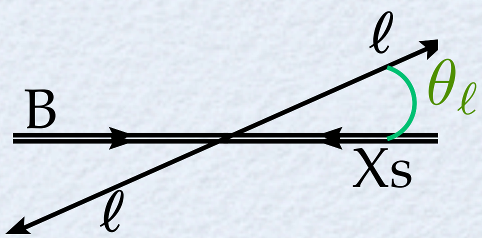
Status in the SM

- Known at NNLO in QCD and NLO in QED
- Double differential rate:

$$\frac{d^2\Gamma}{dq^2 dz} = \frac{3}{8}\left[(1+z^2)H_T(q^2) + 2zH_A(q^2) + 2(1-z^2)H_L(q^2)\right]$$



$$\frac{d\Gamma}{dq^2} = H_T + H_L \qquad \frac{d\mathcal{A}_{FB}}{dq^2} = \frac{3}{4}H_A \qquad z = \cos\theta_\ell$$

$$H_T \propto (1-\hat{s})^2\hat{s}\left[\left(C_9 + \frac{2}{\hat{s}}C_7\right)^2 + C_{10}^2\right]$$

$$H_L \propto (1-\hat{s})^2\left[(C_9 + 2C_7)^2 + C_{10}^2\right]$$

⇒ Independent combinations of WC's

- Standard approach: normalization to the full $B \to X_u \ell \nu$ rate
- At high-q^2 it is convenient to normalize to the $B \to X_u \ell \nu$ rate with the same q2 cut: $\mathcal{R}(s_0) = \int_{s_0}^1 \mathrm{d}\hat{s} \frac{\mathrm{d}\Gamma(\bar{B} \to X_s \ell^+\ell^-)}{\mathrm{d}\hat{s}} / \int_{s_0}^1 \mathrm{d}\hat{s} \frac{\mathrm{d}\Gamma(\bar{B}^0 \to X_u \ell\nu)}{\mathrm{d}\hat{s}}$

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Status in the SM

- SM predictions for the branching ratios:

$\mathcal{B}^{\rm low}_{\mu\mu} = (1.59 \pm 0.14) \times 10^{-6}$ $\mathcal{B}^{\rm high}_{\mu\mu} = (2.4 \pm 0.7) \times 10^{-7}$

$\mathcal{B}^{\rm low}_{ee} = (1.64 \pm 0.14) \times 10^{-6}$ $\mathcal{B}^{\rm high}_{ee} = (2.1 \pm 0.6) \times 10^{-7}$

scale, α_s / m_b, m_t m_b^{-3} parameters, scale

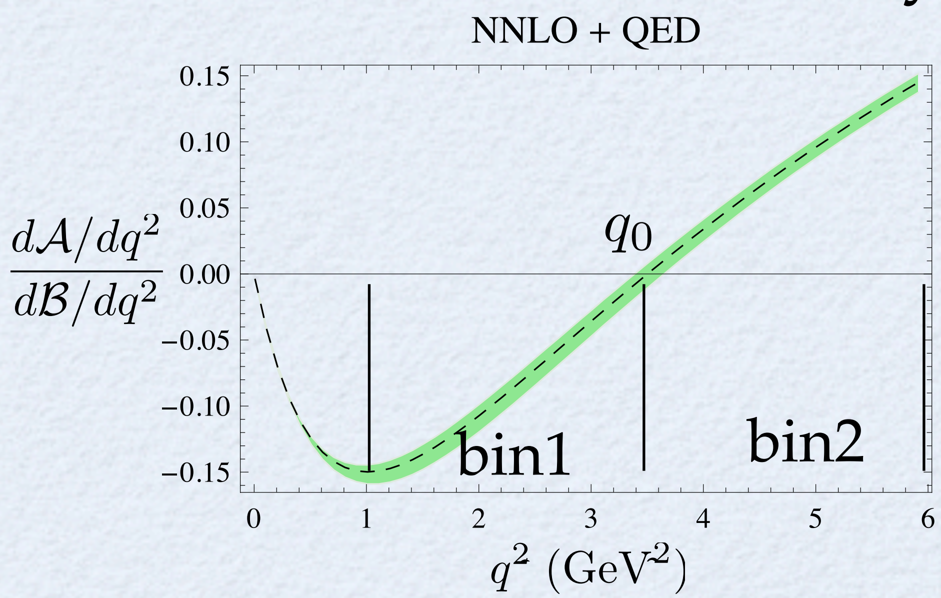
- New normalization: $\mathcal{R}(14.4{\rm GeV}^2)_{\mu\mu} = 2.29 \times 10^{-3}(1 \pm 0.13)$

$\mathcal{R}(14.4{\rm GeV}^2)_{ee} = 1.94 \times 10^{-3}(1 \pm 0.16)$ → V_{ub}

- Experimental world averages:

$(\mathcal{B}^{\rm low}_{\ell\ell})_{\rm exp} = (1.60 \pm 0.51) \times 10^{-6}$ $(\mathcal{B}^{\rm high}_{\ell\ell})_{\rm exp} = (4.4 \pm 1.2) \times 10^{-7}$

- Forward-Backward asymmetry:



$(q_0^2)_{\mu\mu} = (3.50 \pm 0.12)$ GeV^2 $(q_0^2)_{ee} = (3.38 \pm 0.11)$ GeV^2

$(\bar{\mathcal{A}}_{\mu\mu})_{\rm bin1} = [-9.1 \pm 0.9]\%$ $(\bar{\mathcal{A}}_{ee})_{\rm bin1} = [-8.1 \pm 0.9]\%$

$(\bar{\mathcal{A}}_{\mu\mu})_{\rm bin2} = [7.8 \pm 0.8]\%$ $(\bar{\mathcal{A}}_{ee})_{\rm bin2} = [8.3 \pm 0.6]\%$

dominant uncertainty: scale

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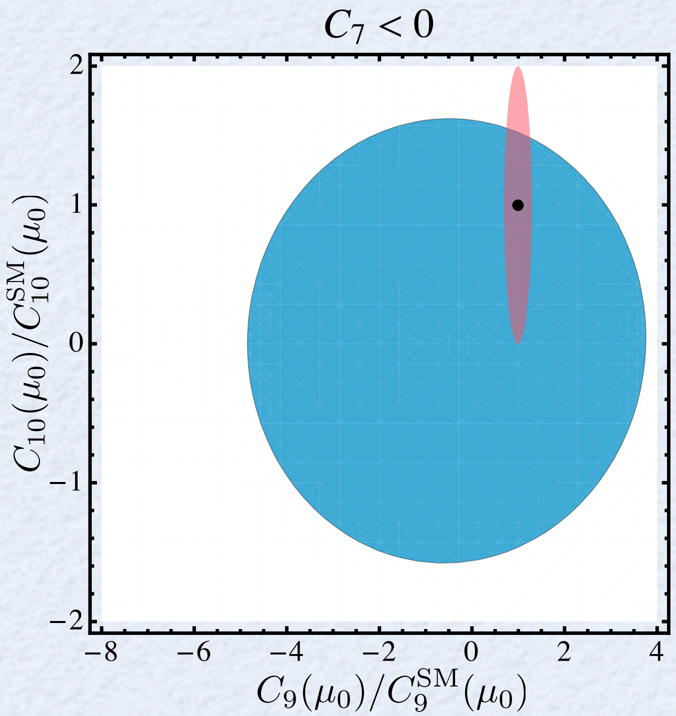
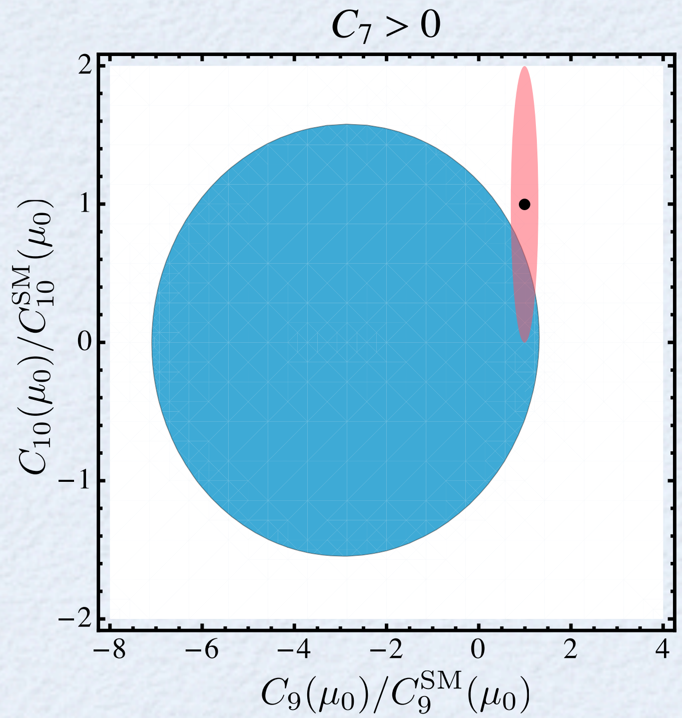
Model Independent NP Reach

- Present bounds:

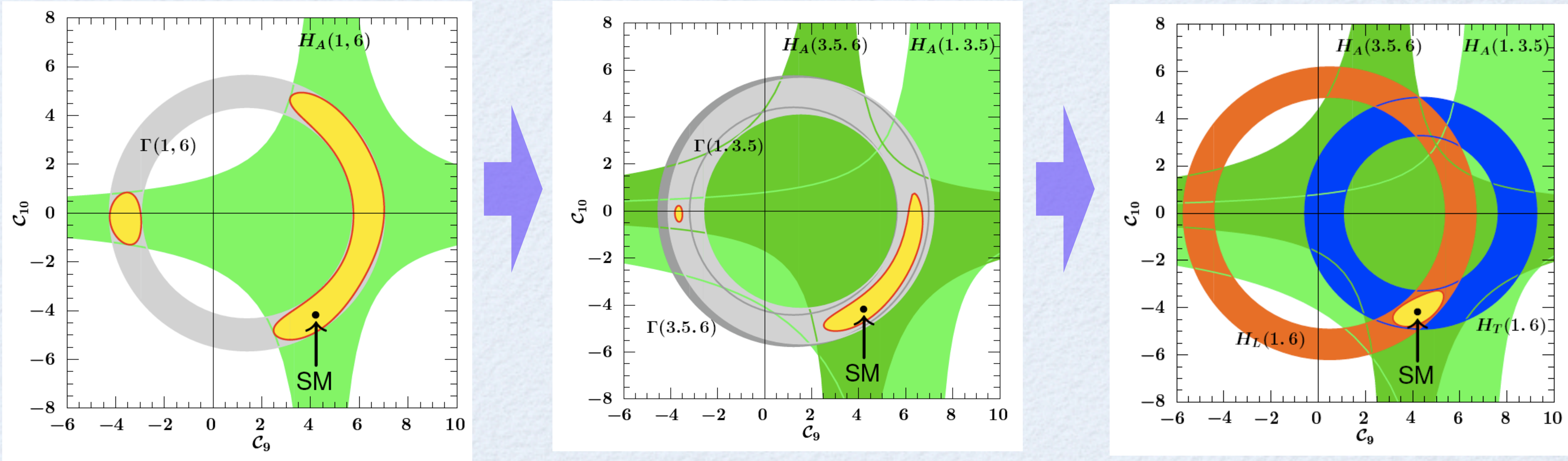




- C_7 constrained by b→sγ
- $C_7 > 0$ excluded in MFV
- pink ellipses are allowed ranges in the most general MSSM ($(\delta_{23}^{d,u})_{LL,RR} \neq 0$)

- Future possibilities (extrapolated to 1 ab^{-1}):

[Lee,Ligeti,Stewart,Tackmann]



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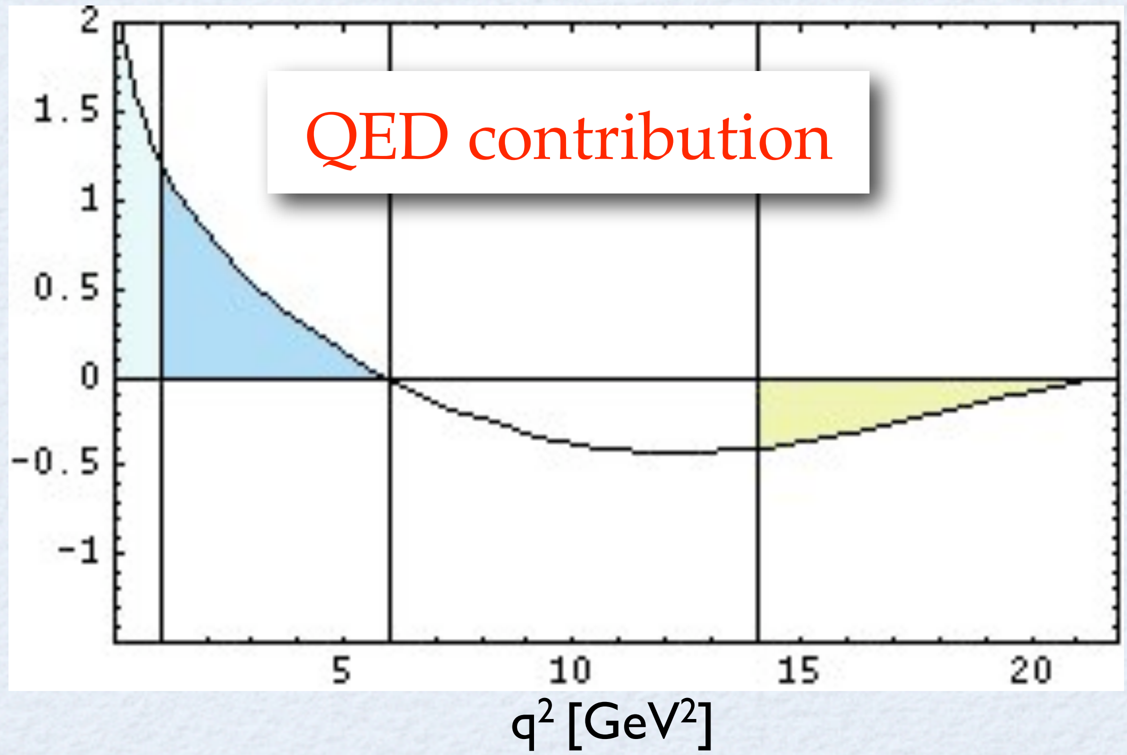
QED Logs: overview

- The *rate is proportional to* $\alpha_{\rm em}^2(\mu^2)$. Without QED corrections the scale μ is undetermined → $\pm 4\%$ uncertainty
- Focus on corrections enhanced by large logarithms:
  - $\alpha_{\rm em} \log(m_W/m_b) \sim \alpha_{\rm em}/\alpha_s$ [WC, RG running] [Bobeth,Gambino,Gorbahn,Haisch]
  - $\alpha_{\rm em} \log(m_\ell/m_b)$ [Matrix Elements]
- The differential rate is not IR safe with respect to photon emission the results in the presence of a physical collinear logarithm, $\log(m_\ell/m_b)$



$$\text{virtual} = \frac{A_{\rm soft+collinear}}{\epsilon^2} + \frac{B_{\rm collinear} + B_{\rm soft}}{\epsilon} + C$$

$$\text{real} = -\frac{A_{\rm soft+collinear}}{\epsilon^2} - \frac{B'_{\rm collinear} + B_{\rm soft}}{\epsilon} + C'$$

$$\int dq^2 \left(B_{\rm collinear} - B'_{\rm collinear}\right) = 0$$

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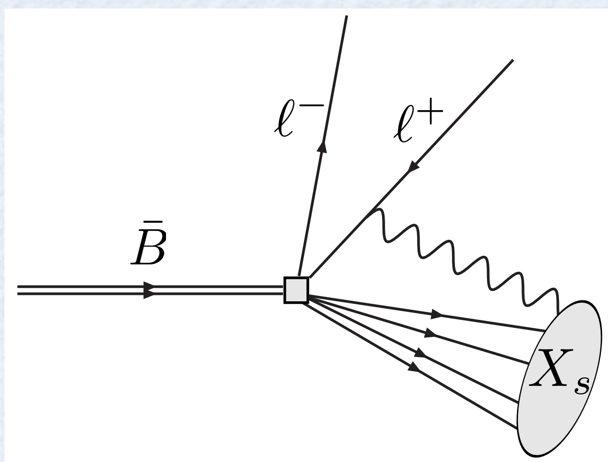
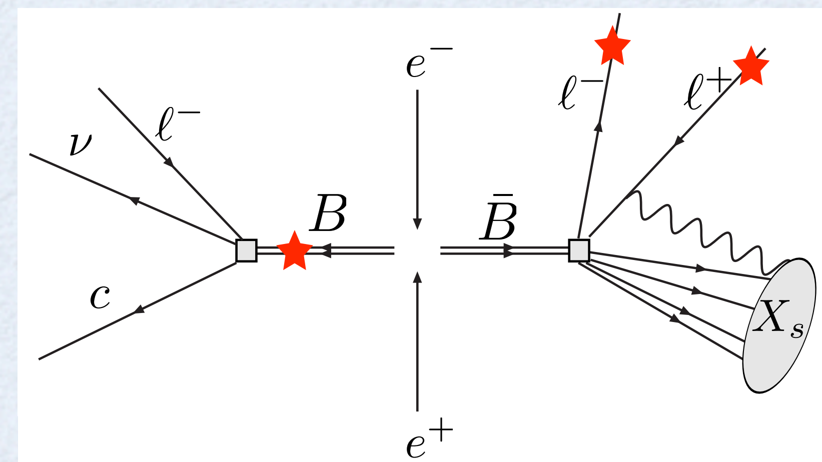
Comparison to Experiments

- *Theory*
  include all bremsstrahlung photons into the X_s system:



- *Experiment (fully inclusive, Super-B only)*
  One B is identified; on the other side only the two leptons are reconstructed:



- *Experiment (Xs system reconstructed as a sum over exclusive states):*
  At BaBar (Belle) photons with energies smaller than 30 (20) MeV are not resolved. Photons emitted inside a small cone (35x50 mrad) around the electrons are identified and included in the event reconstruction. Events with any other photon (E > 30 (20) MeV and outside of the cone) are vetoed.

  Note: at BaBar (Belle) photons inside the cone are (are not) included in the definition of the q^2

- *Measured rates are sensitive to the soft photon cutoff and to the size of the cone*

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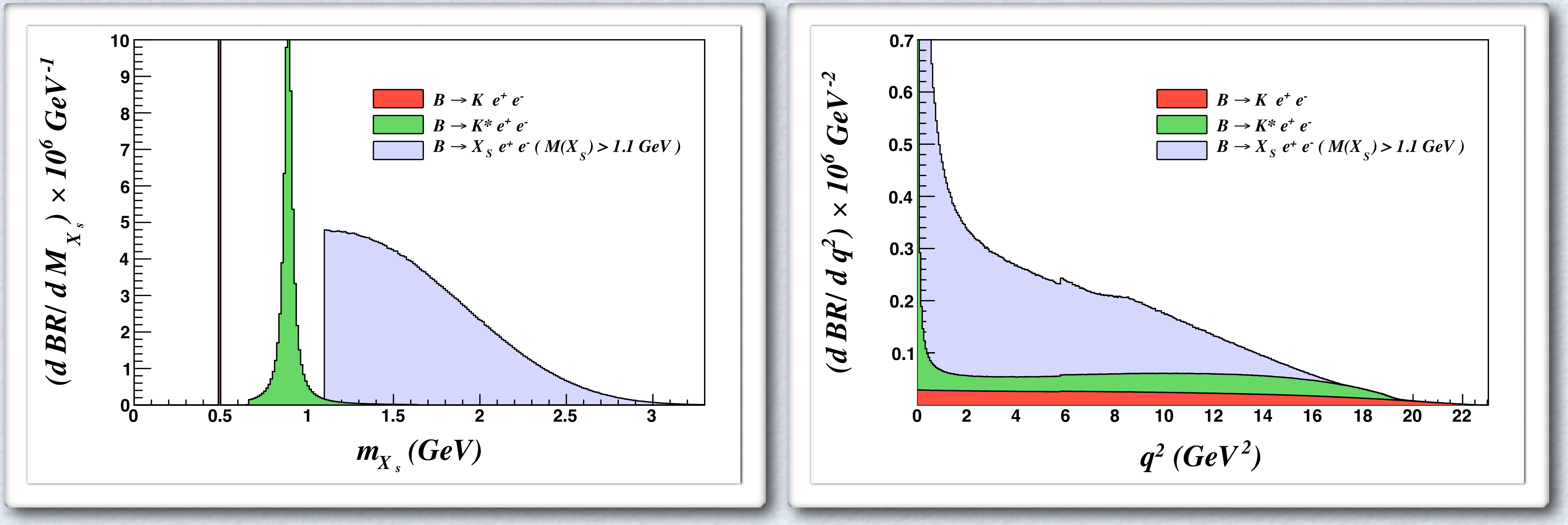
Comparison to experiments

- Use BaBar b→sll MonteCarlo to study the effects of the photon cuts
  [Many thanks to Kevin Flood, Owen Long and Chris Schilling]
- Inclusive b→sll events are obtained combining fully inclusive events with $M_{Xs} > 1.1$ GeV with B->K$^{(*)}$ ll exclusive samples to cover the low M_{Xs} (high q^2 region):



- Spectator effects are described using a Fermi motion model [Ali,Hiller]
- The Xs system is hadronized with JetSet
- Photons are modeled using PHOTOS (hard cut-off for $E_\gamma = 150$ eV)

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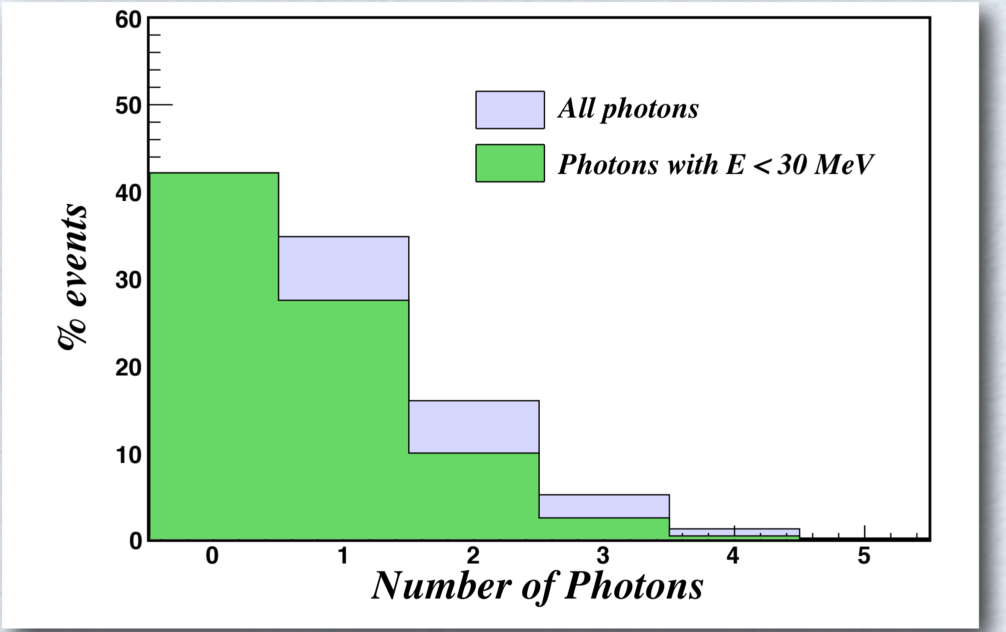
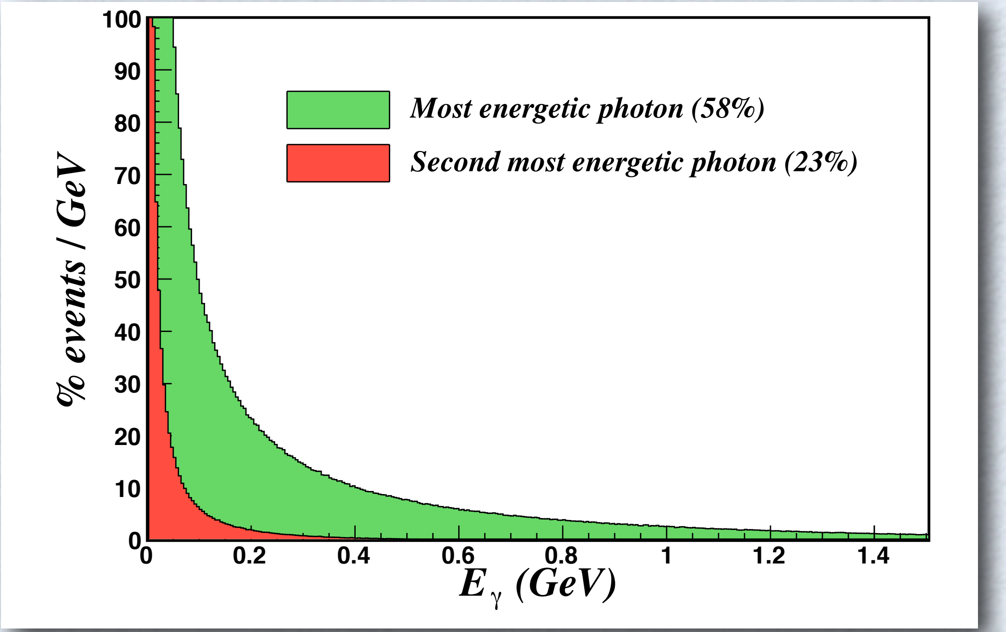
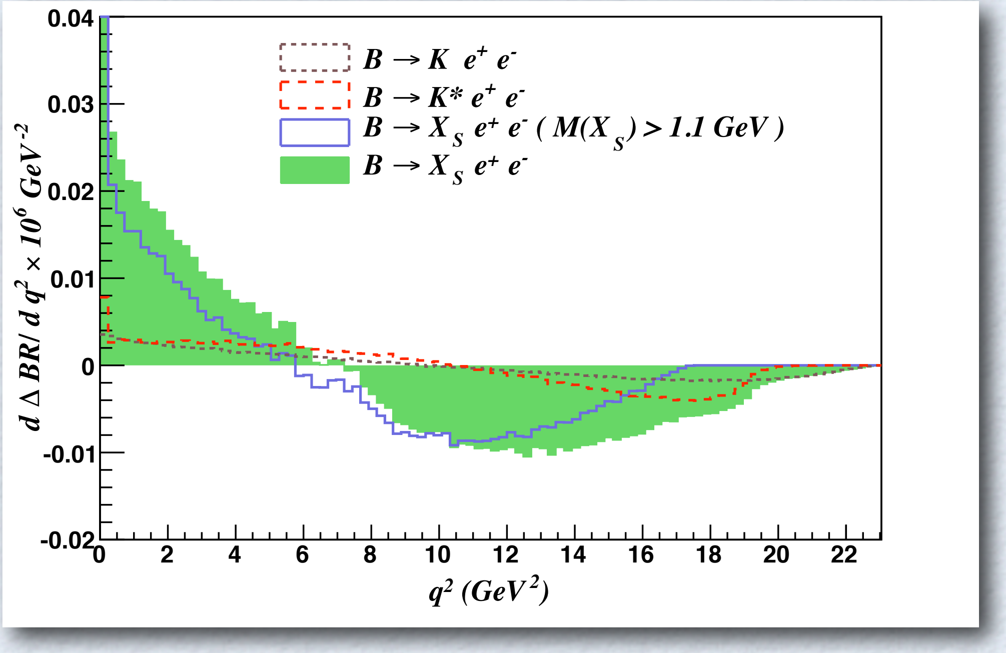
Comparison to Experiments

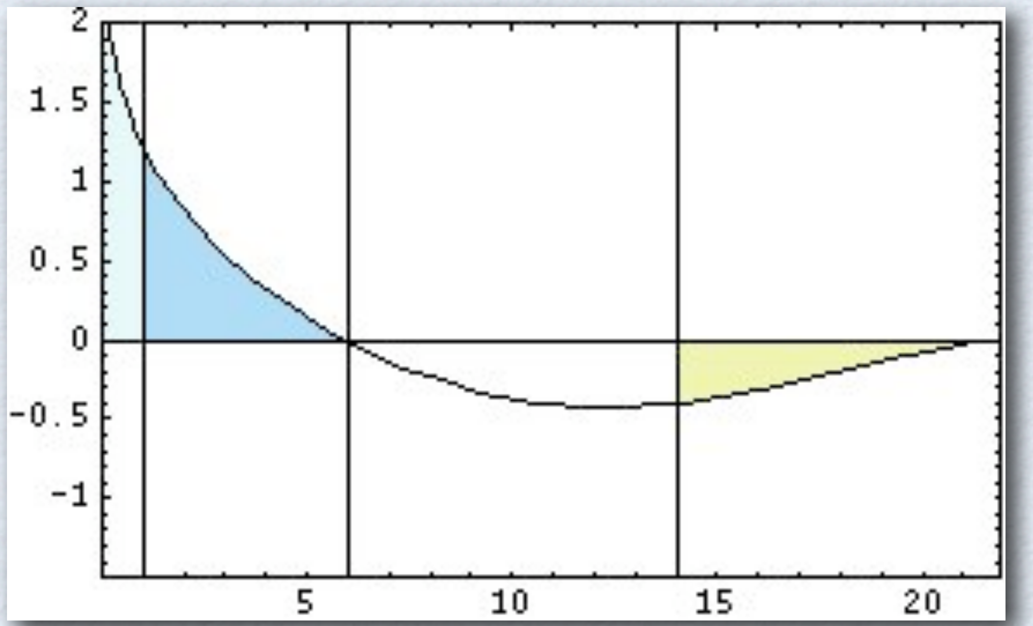
- PHOTOS generates photons with large multiplicity. Most of the energy is carried by a single photon:





- Comparison between event sets generated with and without PHOTOS yields:





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Numerical Results

- Impact of real photon emission on integrated observables (in bracket the analytical result - without charmonium effects):

	$\mu\mu$	ee
low q^2	+1.5% (+2.0%)	+3.6% (+5.2%)
high q^2	-4.4% (-6.8%)	-12.9% (-17.6%)

  - Good agreement taking into account that the MC sample contains events with multiple photon emissions
  - Inclusion of the leading photon into the q^2 leads to integration over IR safe regions of the phase space and log-enhanced QED corrections vanish

- The weights of the K and K* samples relatively to the Xs ($M_{Xs} > 1.1$ GeV) one have to be supplemented externally (not built in the MC). We find:

$$X_K^{ee} = (8 \pm 2)\% \qquad X_K^{\mu\mu} = (11 \pm 2)\%$$

$$X_{K^*}^{ee} = (15 \pm 3)\% \qquad X_{K^*}^{\mu\mu} = (25 \pm 4)\%$$

$$X_{X_s(M_{X_s}>1.1\text{GeV})}^{\ell\ell} = 100\% - X_K^{\ell\ell} - X_{K^*}^{\ell\ell}$$

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INTERPRETATION

- Fully inclusive (analytical) vs sum over exclusive (BaBar/Belle):

	low($\mu\mu$)	low(ee)	high($\mu\mu$)	high(ee)
Fully inclusive	1.59 x 10^{-6}	1.64 x 10^{-6}	2.4 x 10^{-7}	2.1 x 10^{-7}
BaBar	-(7.5±0.2)%	-(13.5±0.2)%	-(5.2±0.1)%	-(0.7±0.3)%
Belle	-(8.4±0.2)%	-(13.4±0.2)%	-(6.2±0.1)%	-(8.1±0.1)%

¡ !

- We have checked that inclusion of the second most energetic photon in the cone does not affect the above results
- Effect induced by the soft photon cut (30/20 MeV for BaBar/Belle)
- Order of magnitude of the effect agrees with Sudakov double log:

$$\sigma_{\rm measured} \simeq \sigma_0 \left(1 - \frac{\alpha_{\rm em}}{\pi} \log\frac{m_b^2}{m_\ell^2} \log\frac{m_b^2}{E_{\rm cut}^2}\right) \Rightarrow \sigma_0 \left|\exp\left[-\frac{\alpha_{\rm em}}{2\pi} \log\frac{m_b^2}{m_\ell^2} \log\frac{m_b^2}{E_{\rm cut}^2}\right]\right|^2$$

- The MC sample contains events with up to 12 photons: Sudakov resummation is effectively implemented

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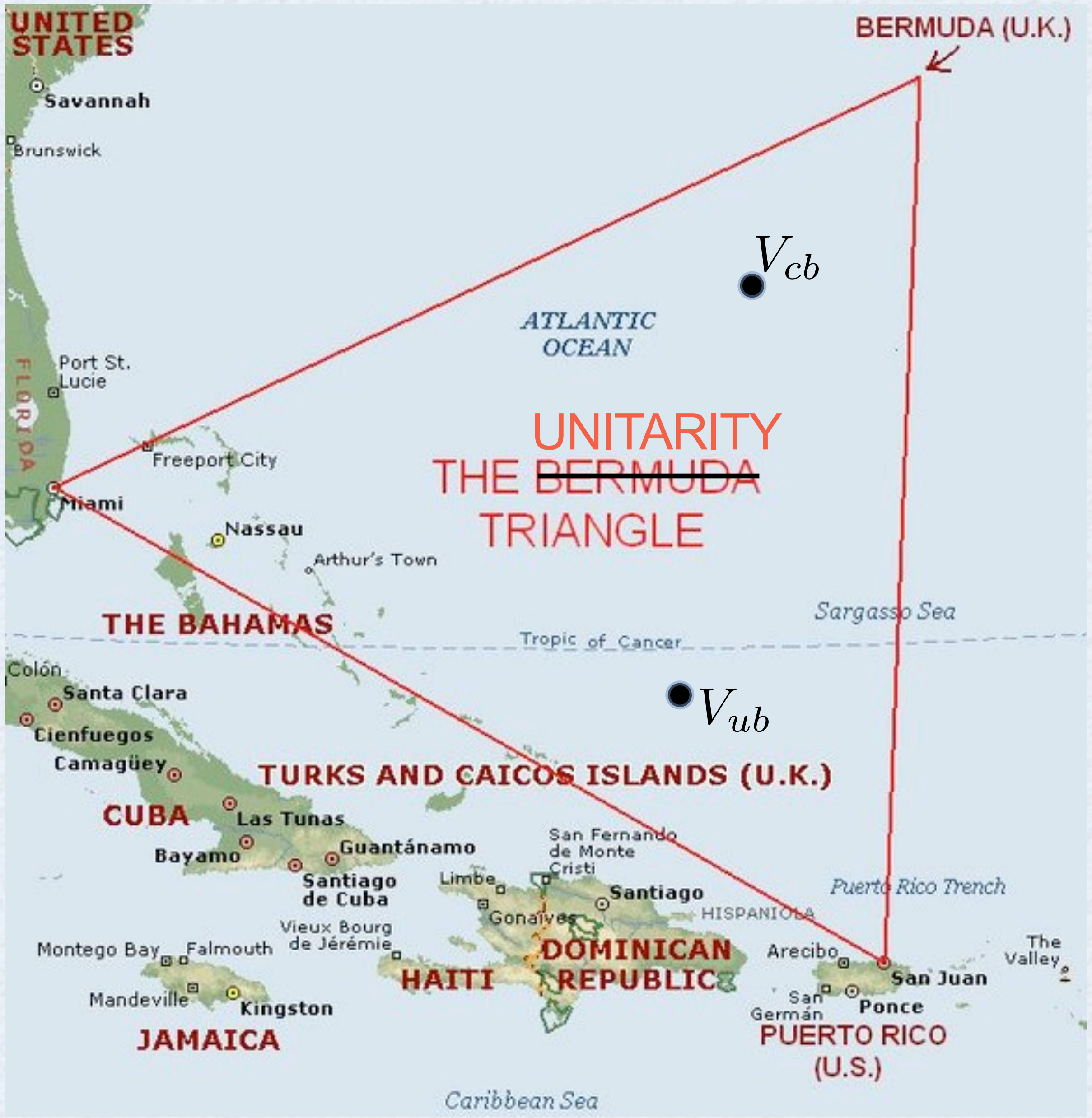
Alternative Selection

- Previous results obtained using the following cuts:
  - $\mu^+\mu^-$ final state → $E_\gamma < 30$ MeV
  - e^+e^- final state → $E_\gamma < 30$ MeV or γ_1 in a (35,50) mrad cone around $e^\pm$
- Alternative possibility:
  - Construct $m_{ES} = \sqrt{E_{beam}^2 - \vec{P}_B^2}$ and $\Delta E = E_B - E_{beam}$ for each event
  - Impose $m_{ES} > 5.2$ GeV and $|\Delta E| < 100$ MeV
  - Note that $p_B = (E_B, \vec{P}_B)$ is the reconstructed B meson momentum in the colliding electrons COM frame
    - $\mu^+\mu^-$ final state → $p_B = p_{X_s} + p_{\mu^+} + p_{\mu^-}$
    - e^+e^- final state → $p_B = p_{X_s} + p_{e^+} + p_{e^-} + p_\gamma$ ← $E_\gamma > 30$ MeV & in the cone

	$\text{low}(\mu\mu)$	$\text{low}(ee)$	$\text{high}(\mu\mu)$	$\text{high}(ee)$
Fully inclusive	1.59×10^{-6}	1.64×10^{-6}	2.4×10^{-7}	2.1×10^{-7}
BaBar (alternative)	-(5.5±0.2)%	-(10.4±0.2)%	-(2.7±0.1)%	-(2.8±0.3)%
Belle (alternative)	-(5.5±0.2)%	-(8.9±0.2)%	-(2.7±0.1)%	-(3.5±0.1)%

PART 2:
UT WITHOUT SEMILEPTONIC DECAYS



E.L. and A. Soni, arXiv:0903.5059
J. Laiho, E.L., R. van de Water, arXiv:0910.2928
E.L. and A. Soni, arXiv:0912.0002

Pay tribute to:
UTfit
CKMfitter
Buras, Guadagnoli
...

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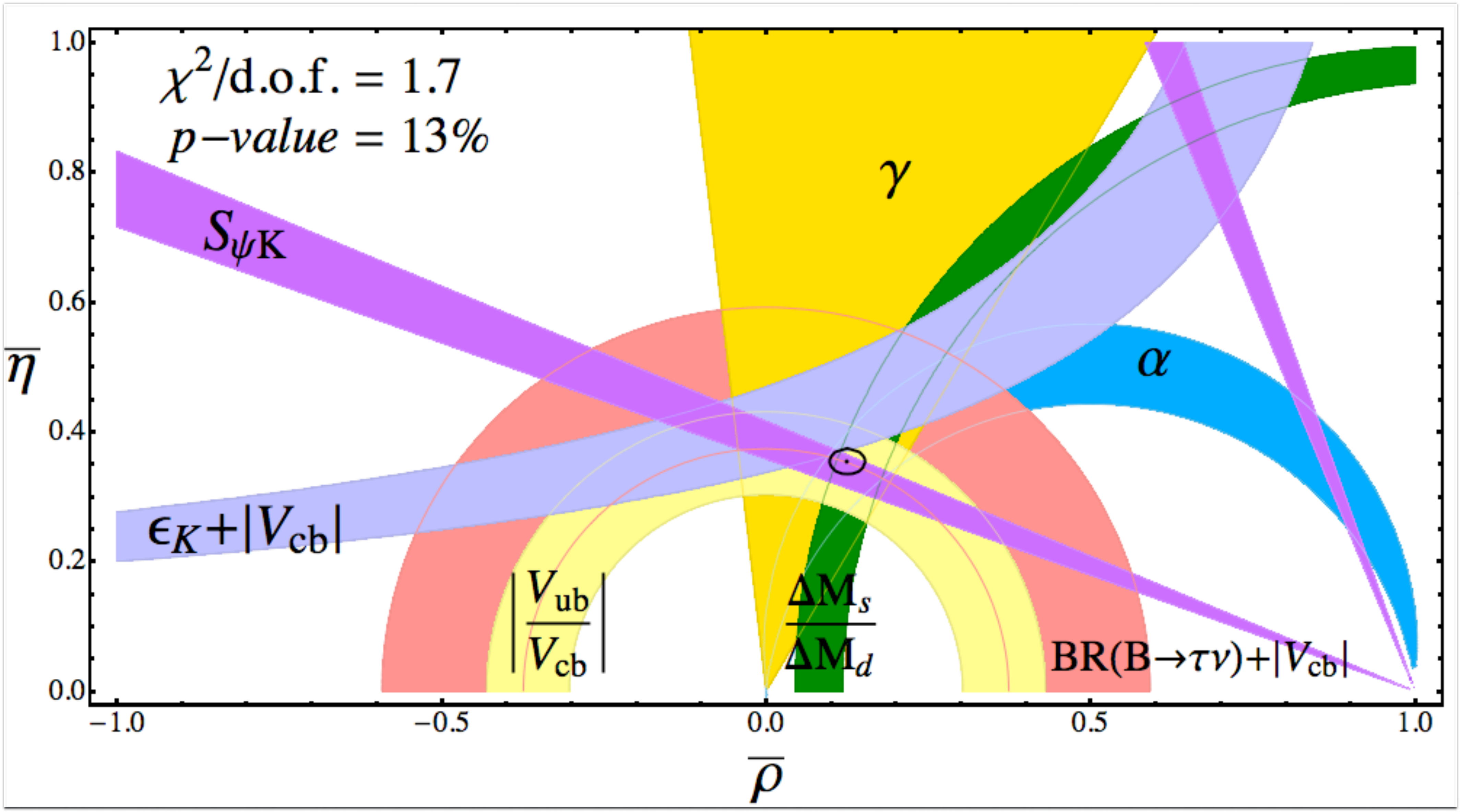
UNITARITY TRIANGLE

- Present status of the Unitarity Triangle fit:



- Note the ubiquitous use of $|V_{cb}|$ for the individual constraints

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Status of V_{xb}

- Presently we have discrepancies at the (1-2)σ level between exclusive and inclusive determinations of $|V_{cb}|$ and $|V_{ub}|$

- $b \to c$:

$$|V_{cb}|_{\rm excl} = (38.6 \pm 1.2) \times 10^{-3}$$

$$|V_{cb}|_{\rm incl} = (41.31 \pm 0.76) \times 10^{-3}$$

  - Error on exclusive V_{cb} from D^* data rescaled to take into account bad experimental χ^2
  - Inclusive calculation quite mature (NNLO and α_s/m_b^2 not in fit yet)
  - Issues with violation of quark-hadron duality (D and D^* represent 70% of the spectrum)

- $b \to u$:

$$|V_{ub}|_{\rm excl} = (34.2 \pm 0.37) \times 10^{-4}$$

$$|V_{ub}|_{\rm incl} = (40.3 \pm 1.5^{+2.0}_{-2.5}) \times 10^{-4}$$

  - Inclusive calculation is sensitive to non-local effects (Shape function)
  - New NNLO corrections seem to push the $|V_{ub}|$ to higher central values (!)

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Removing V_{xB}

- $|V_{ub}|$ not essential to the fit (main effect is to favor NP in ε_K rather than in B_d mixing)

- $|V_{cb}|$ seems essential to ε_K, $B\to\tau\nu$ and ΔM_{Bs}:

$$\Delta M_{B_s} = \chi_s\, f_{B_s}^2 \hat{B}_{B_s} A^2 \lambda^4$$

$$|\varepsilon_K| = 2\chi_\varepsilon \hat{B}_K \kappa_\varepsilon\, \eta\lambda^6 \Big(A^4\lambda^4(\rho-1)\eta_2 S_0(x_t) + A^2 \big(\eta_3 S_0(x_c,x_t) - \eta_1 S_0(x_c)\big)\Big)$$

$$\mathrm{BR}(B\to\tau\nu) = \chi_\tau f_B^2 A^2 \lambda^6(\rho^2+\eta^2)$$

- The interplay of these constraints allows to drop V_{cb}, while still constraining new physics in K mixing:

$$|\varepsilon_K| \propto \hat{B}_K\, (f_{B_s}\hat{B}_s^{1/2})^{-4}\, f(\rho,\eta)$$
$$|\varepsilon_K| \propto \hat{B}_K\, \mathrm{BR}(B\to\tau\nu)^2\, f_B^{-4}\, g(\rho,\eta)$$

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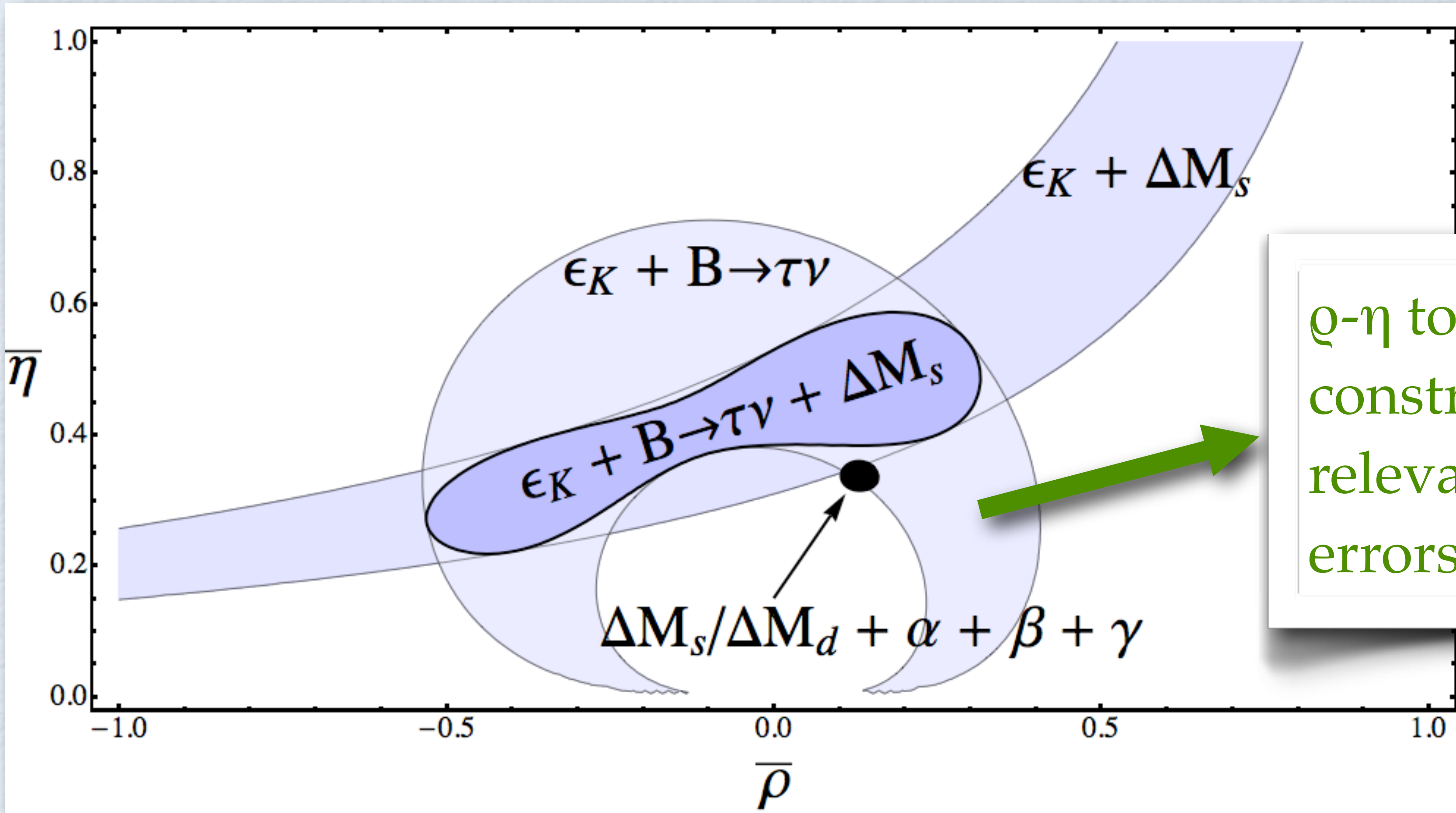
Removing V_{xb}



ϱ-η topology of the constraint makes it relevant despite large errors on B→τν

X :	$\hat{B}_K$	$\lvert V_{cb}\rvert$	$f_{B_s}\hat{B}_s^{1/2}$	$\mathrm{BR}(B\to\tau\nu)$	f_B
δX :	4%	2.5%	5%	26%	5%
$\delta\varepsilon_K$:	4%	10%	20%	52%	20%

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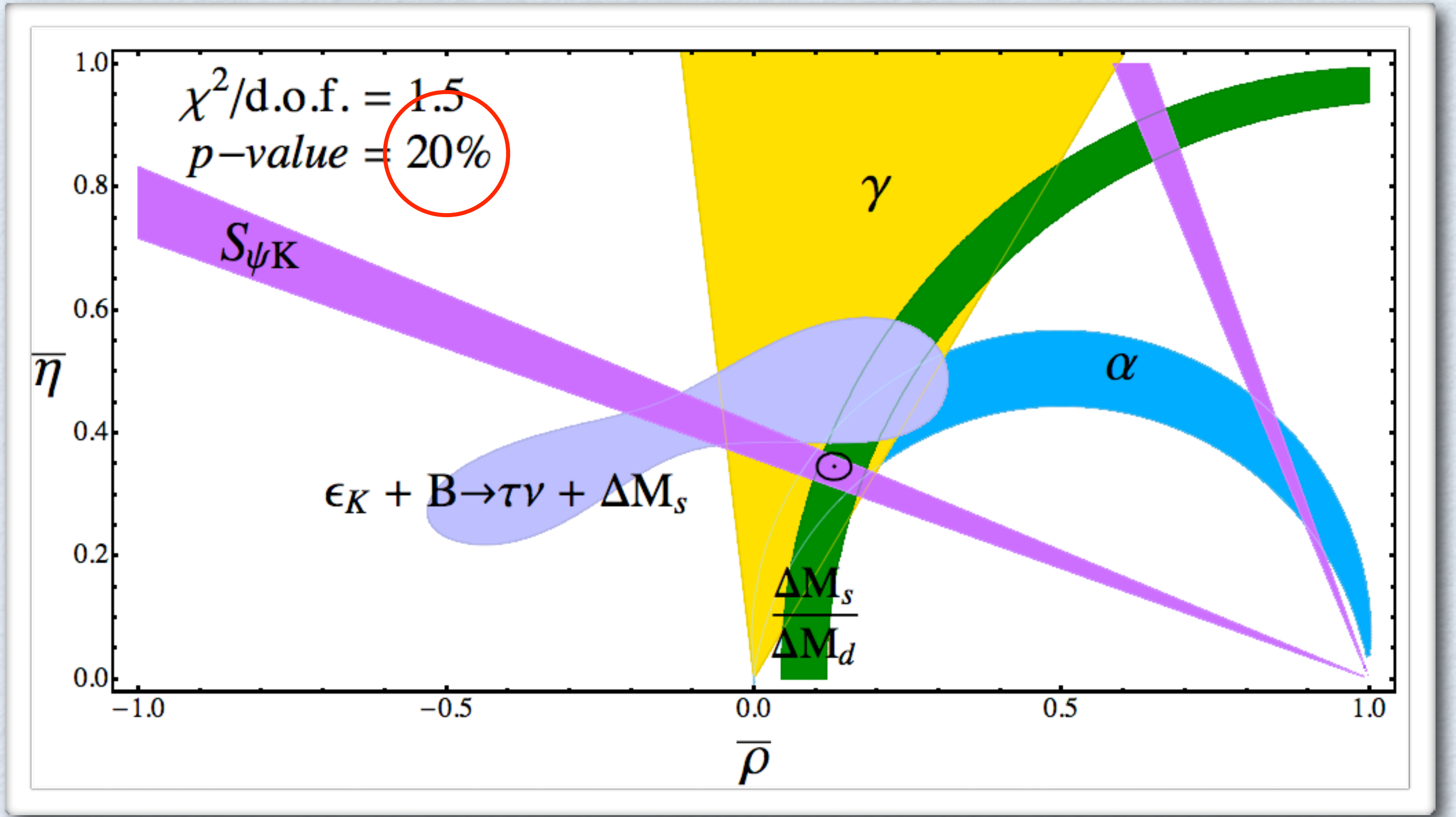
Fit w/out semileptonic decays



$$
\begin{aligned}
|\varepsilon_K^{\rm NP}| &= C_\varepsilon \; |\varepsilon_K^{\rm SM}| \\
M_{12}^{d,\rm NP} &= e^{i\theta_d} \; M_{12}^{d,\rm SM} \\
{\rm BR}(B\to\tau\nu)^{\rm NP} &= r_H \; {\rm BR}(B\to\tau\nu)^{\rm SM}
\end{aligned}
$$

$$
\begin{aligned}
C_\varepsilon^{{\rm no}V_{qb}} &= 1.30 \pm 0.23 &&\Rightarrow (1.3\sigma, p = 40\%) \\
\theta_d^{{\rm no}V_{qb}} &= -(8.9 \pm 4.2)^{\rm o} &&\Rightarrow (2.1\sigma, p = 89\%) \\
r_H^{{\rm no}V_{qb}} &= 1.7 \pm 0.5 &&\Rightarrow (1.4\sigma, p = 43\%)
\end{aligned}
$$

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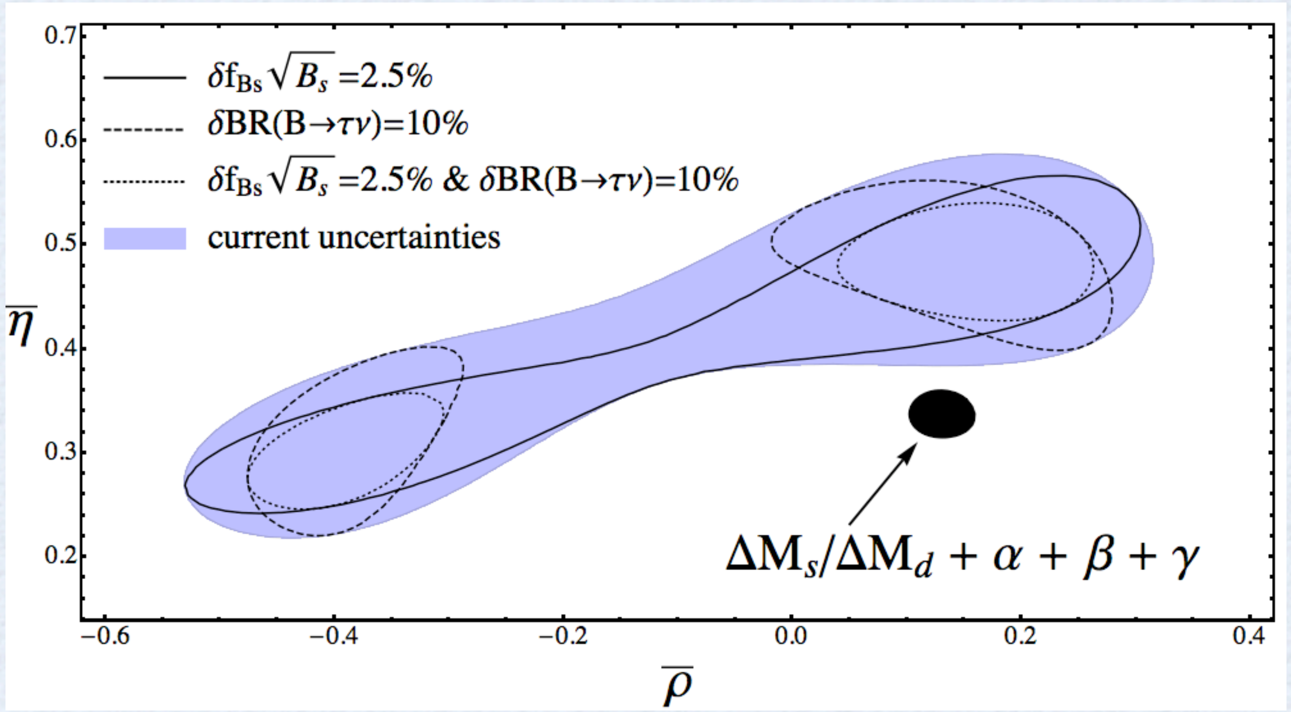
SuperB expectations

$\delta_\tau = \delta\mathrm{BR}(B \to \tau\nu)$ $\delta_s = \delta(f_{B_s}\sqrt{B_s})$

δ_τ	δ_s	p_{SM}	$\theta_d \pm \delta\theta_d$	p_{θ_d}	$\theta_d/\delta\theta_d$
*26%	*5%	20%	$-(8.9 \pm 4.2)^\circ$	89%	2.1σ
*26%	2.5%	3.5%	$-(9.6 \pm 3.5)^\circ$	88%	2.7σ
*26%	1%	0.1%	$-(10.1 \pm 2.9)^\circ$	87%	3.4σ
10%	*5%	1%	$-(8.8 \pm 2.7)^\circ$	89%	3.3σ
3%	*5%	0.04%	$-(8.8 \pm 2.2)^\circ$	89%	4.0σ
10%	2.5%	0.1%	$-(9.2 \pm 2.5)^\circ$	88%	3.7σ
10%	1%	0.004%	$-(9.6 \pm 2.2)^\circ$	86%	4.4σ
3%	2.5%	0.004%	$-(9.1 \pm 2.1)^\circ$	88%	4.4σ
3%	1%	0.0001%	$-(9.4 \pm 1.9)^\circ$	86%	5.0σ



- Even modest improvements on B→τν have tremendous impact on the UT fit (10 ab^{-1} → 10%; 50 ab^{-1} →3%)
- Interplay with reduced errors on B_s mixing can produce a 5σ effect
- Fit is completely clean

Conclusions

(1) Inclusive b→sll decays

- Calculations are approaching the "end-of-the-road"
- Electromagnetic corrections: effect of BaBar & Belle treatment of soft and collinear photons *seems* to have very large impact (7-13%)
- QED effects on H_T and H_L ($\Gamma = H_T + H_L$) are at the top of the TODO list

(2) UT fit without semileptonic decays

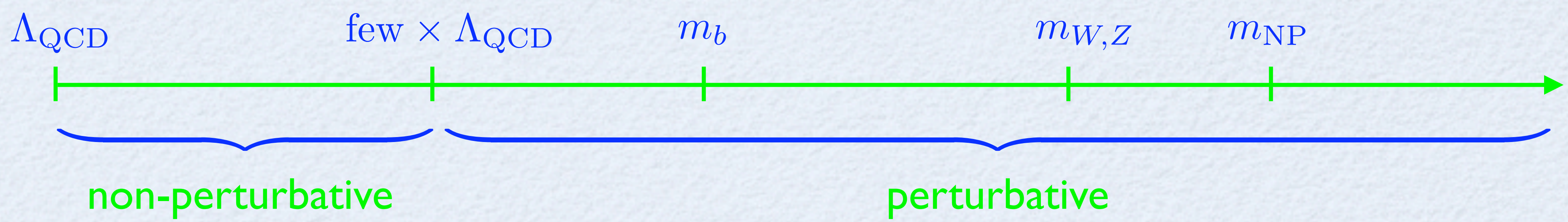
- As long as V_{xb} determinations remain problematic, removing semileptonic decays allows to cast the UT fit as a clean & high-precision tool to identify new physics
- Super-B level precision on $B \to \tau\nu$ coupled with improvements on the lattice determination of $f_{B_s} \hat{B}_s^{1/2}$ can test the SM at the 5σ level

Backup Slides

①

Effective Lagrangian

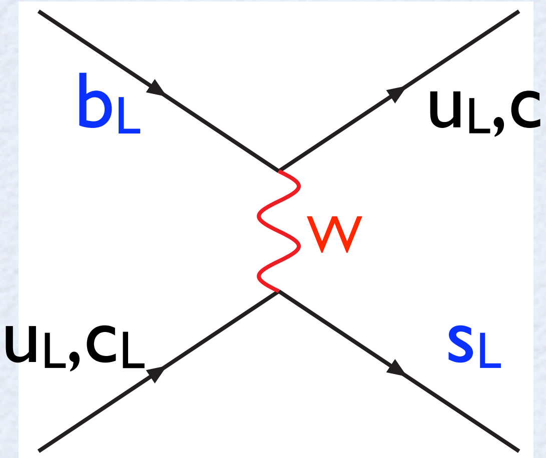
$$\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{tq}^* \left[\sum_{i=1}^{10} C_i Q_i + \frac{V_{ub}V_{uq}^*}{V_{tb}V_{tq}^*} \sum_{i=1}^{2} C_i (Q_i - Q_i^u) + \underbrace{\sum_{i=3}^{6} C_{iQ} Q_{iQ} + C_b Q_b}_{\text{for QED corrections}} \right]$$

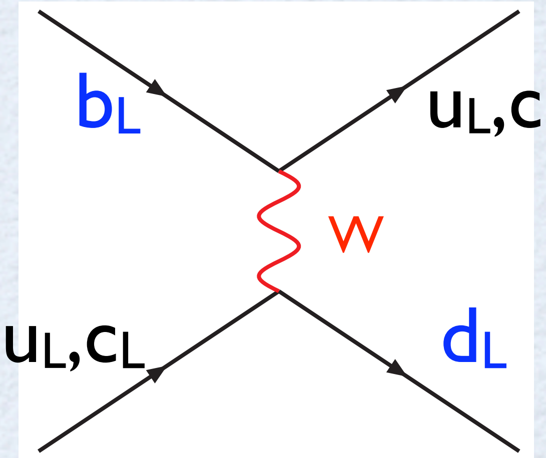


- Current-current:

$$Q_1 = (\bar{q}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L)$$
$$Q_2 = (\bar{q}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

$$Q_1^u = (\bar{q}_L \gamma_\mu T^a u_L)(\bar{u}_L \gamma^\mu T^a b_L)$$
$$Q_2^u = (\bar{q}_L \gamma_\mu u_L)(\bar{u}_L \gamma^\mu b_L)$$



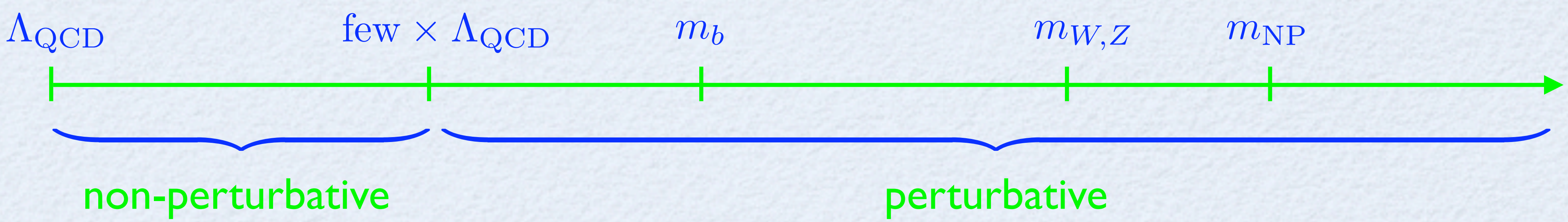


$$\left| \frac{C_2}{C_9} \frac{V_{ub}V_{us}}{V_{tb}V_{ts}} \right| \sim 0.5\ \%$$

$$\left| \frac{C_2}{C_9} \frac{V_{ub}V_{ud}}{V_{tb}V_{td}} \right| \sim -10\ \%$$

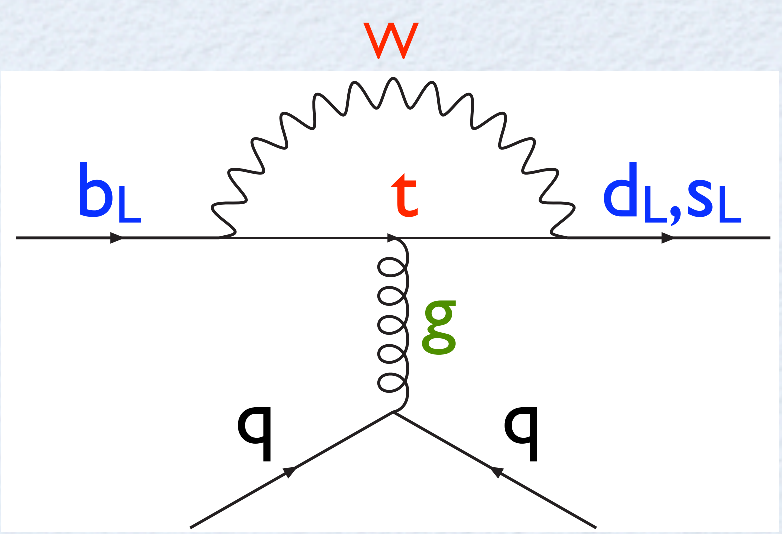
Effective Lagrangian

$$\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \left[\sum_{i=1}^{10} C_i Q_i + \frac{V_{ub} V_{uq}^*}{V_{tb} V_{tq}^*} \sum_{i=1}^{2} C_i (Q_i - Q_i^u) + \underbrace{\sum_{i=3}^{6} C_{iQ} Q_{iQ} + C_b Q_b}_{\text{for QED corrections}} \right]$$



- QCD penguins:

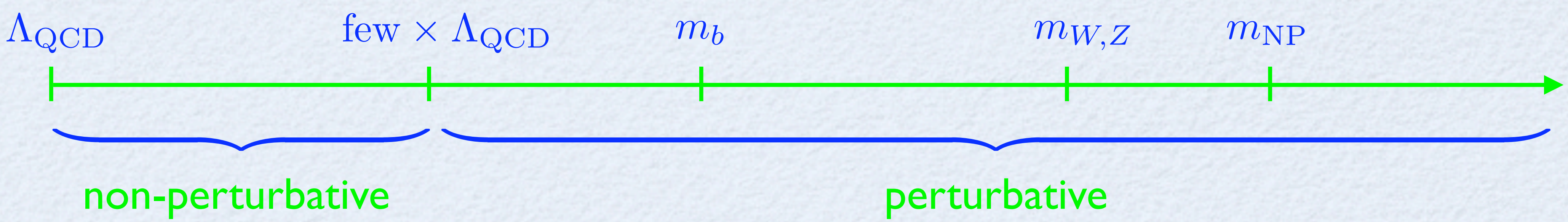
$$\begin{aligned}
Q_3 &= (\bar{q}_L \gamma_\mu b_L) \sum (\bar{q} \gamma^\mu q) \\
Q_4 &= (\bar{q}_L \gamma_\mu T^a b_L) \sum (\bar{q} \gamma^\mu T^a q) \\
Q_5 &= (\bar{q}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} b_L) \sum (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} q) \\
Q_6 &= (\bar{q}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} T^a b_L) \sum (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} T^a q)
\end{aligned}$$



①

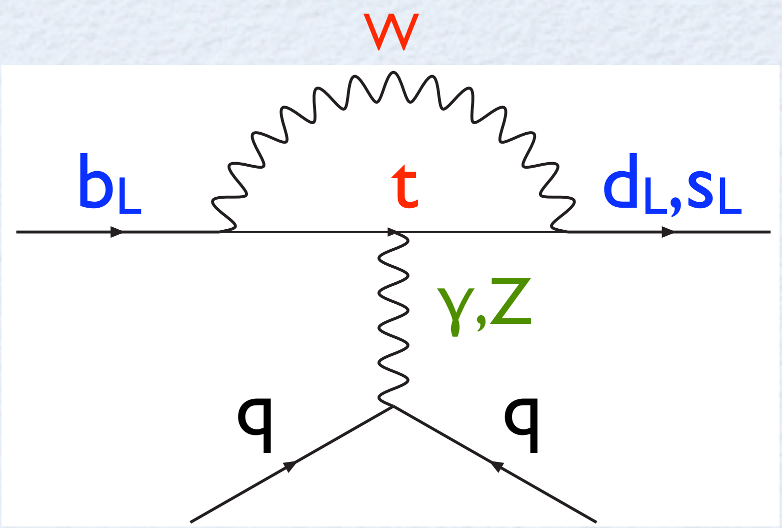
EFFECTIVE LAGRANGIAN

$$\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \left[\sum_{i=1}^{10} C_i Q_i + \frac{V_{ub} V_{uq}^*}{V_{tb} V_{tq}^*} \sum_{i=1}^{2} C_i (Q_i - Q_i^u) + \underbrace{\sum_{i=3}^{6} C_{iQ} Q_{iQ} + C_b Q_b}_{\text{for QED corrections}} \right]$$



- EW penguins:

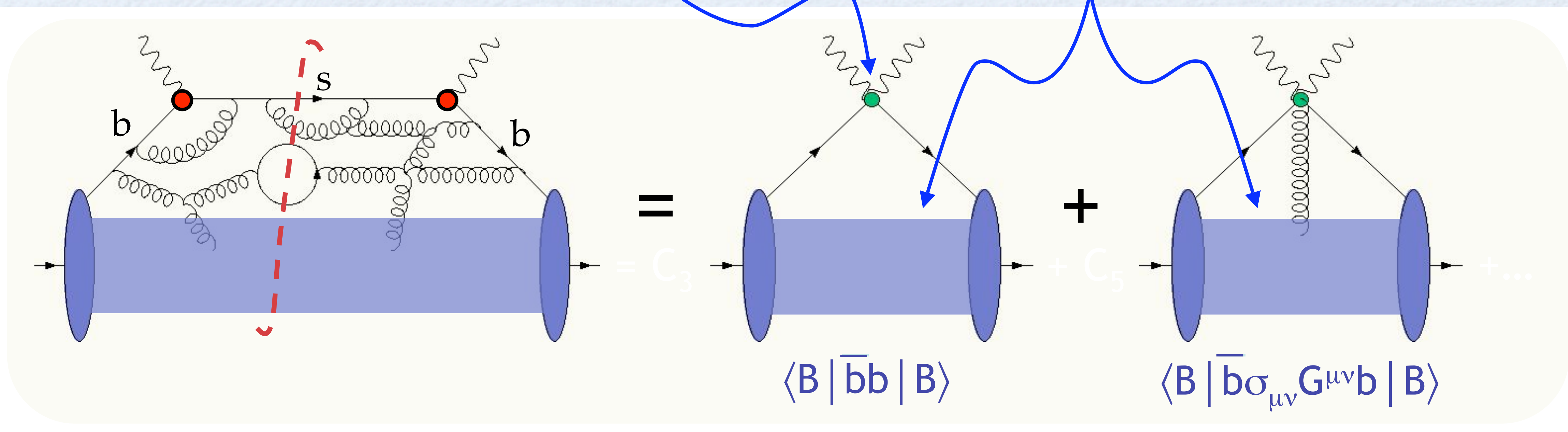
$$\begin{aligned}
Q_{3Q} &= (\bar{q}_L \gamma_\mu b_L) \sum Q_q (\bar{q} \gamma^\mu q) \\
Q_{4Q} &= (\bar{q}_L \gamma_\mu T^a b_L) \sum Q_q (\bar{q} \gamma^\mu T^a q) \\
Q_{5Q} &= (\bar{q}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} b_L) \sum Q_q (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} q) \\
Q_{6Q} &= (\bar{q}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} T^a b_L) \sum Q_q (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} T^a q)
\end{aligned}$$

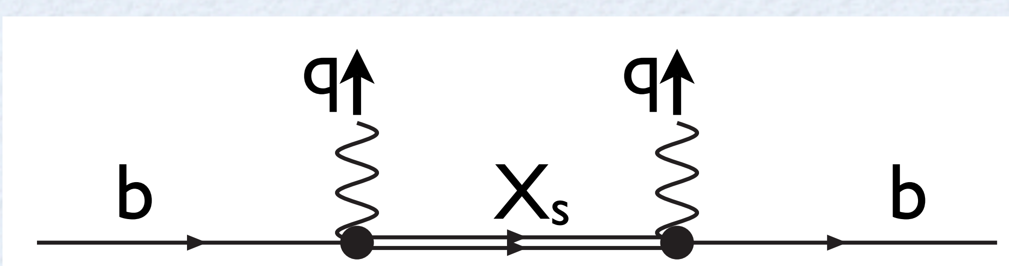


①

Power corrections

$$\Gamma\left[\bar{B}\to X_s\ell^+\ell^-\right]=\Gamma\left[\bar{b}\to X_s\ell^+\ell^-\right]+O\left(\frac{\Lambda_{QCD}^2}{m_b^2},\frac{\Lambda_{QCD}^3}{m_b^3},\frac{\Lambda_{QCD}^2}{m_c^2},\ldots\right)$$





$$\begin{aligned} p_{X_s}^2 &= (p_b-q)^2=m_b^2+q^2-2m_bq_0 \\ &< m_b^2+q^2-2m_b\sqrt{q^2}=\left(m_b-\sqrt{q^2}\right)^2 \end{aligned}$$

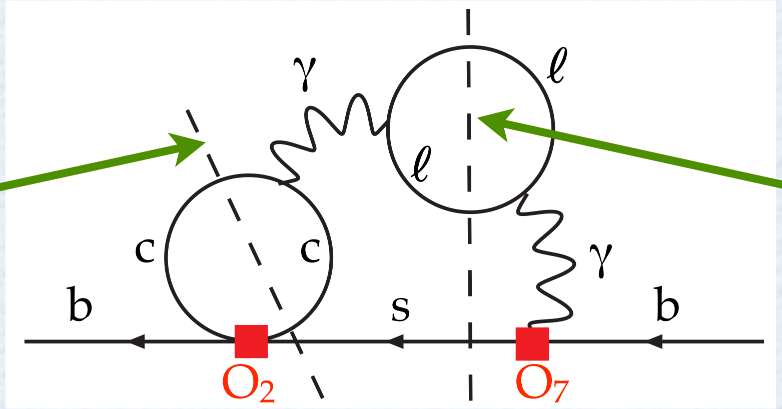
OPE is an expansion in $\Lambda_{QCD}/(m_b-\sqrt{q^2})$ and breaks down at $q^2\sim m_b^2$

①

Q^2 cuts

- Quark-hadron duality breaks down when the rate is dominated by charmonium resonances:

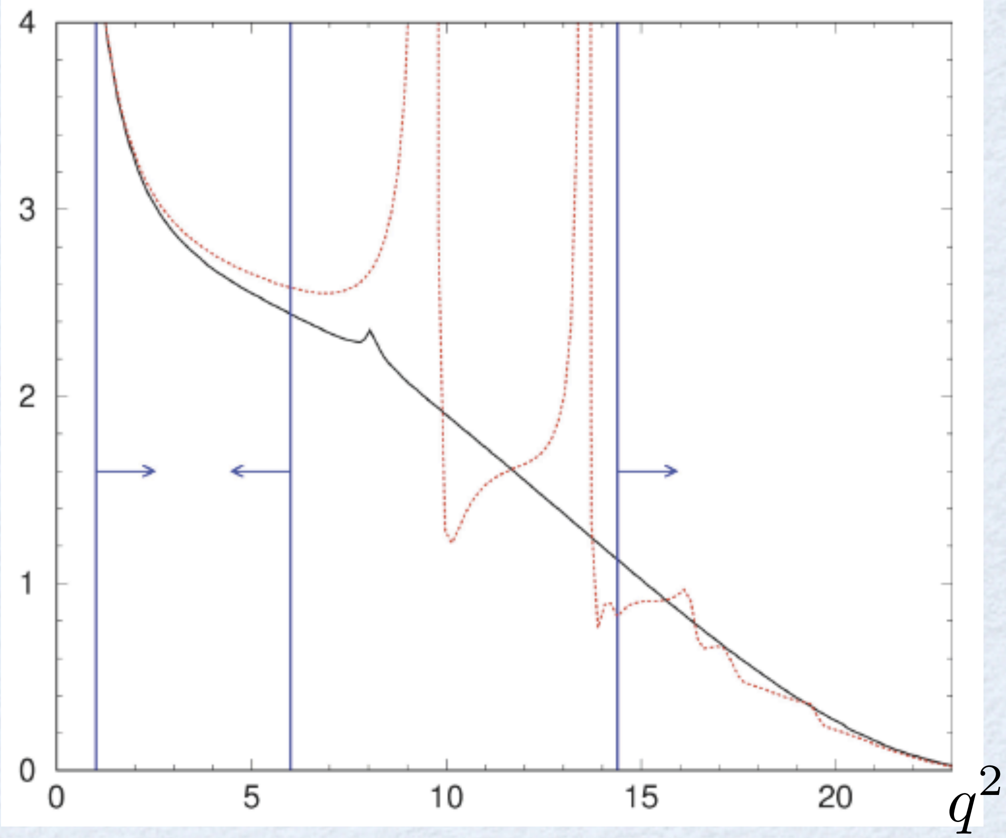
$b \to c\bar{c}s$



$b \to s\ell^+\ell^-$

- Three regions:
  - $0.04\ \mathrm{GeV}^2 < q^2 < 1\ \mathrm{GeV}^2$
  - ***$1\ \mathrm{GeV}^2 < q^2 < 6\ \mathrm{GeV}^2$***
  - ***$q^2 > 14.4\ \mathrm{GeV}^2$***

  dominated by the photon pole ($b \to s\gamma$)



- Resonances model using data:
  - ★ Krüger-Sehgal (e+e- data)
  - ★ Simple Breit-Wigner
- Away from resonances expansion in $1/m_c^2$ is performed

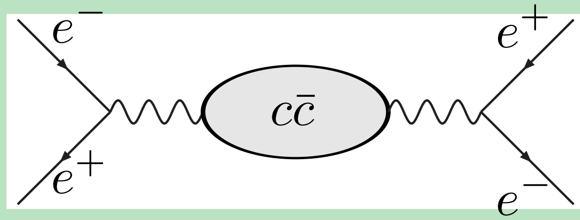
①

Q^2 cuts

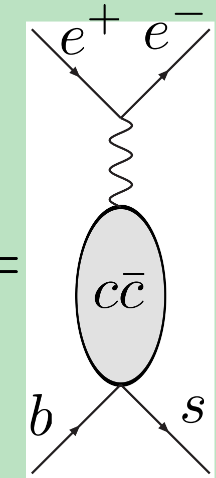
- Kruger-Sehgal mechanism:

$$R_{\rm had}^{c\bar c} = \frac{\sigma(e^+e^- \to c\bar c \text{ hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$=$$

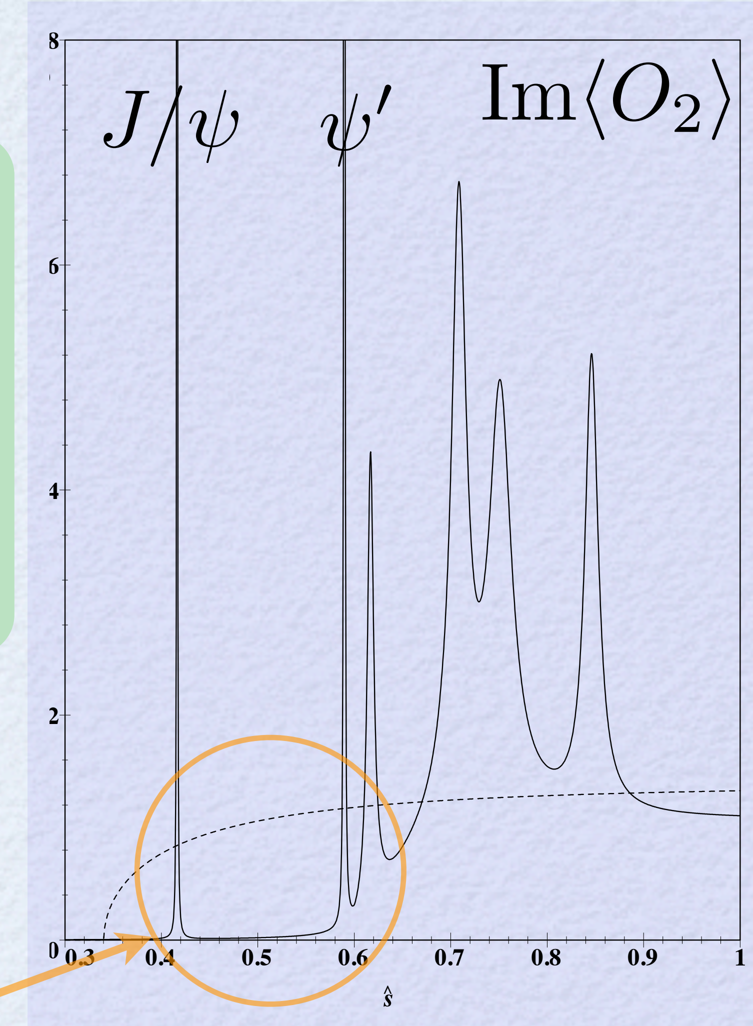


$$\langle O_2 \rangle =$$



$$\mathrm{Im}\langle O_2\rangle \to \langle O_9\rangle_{\rm tree}\left(\frac{\pi}{3} R_{\rm had}^{c\bar c}(\hat s)\right)$$

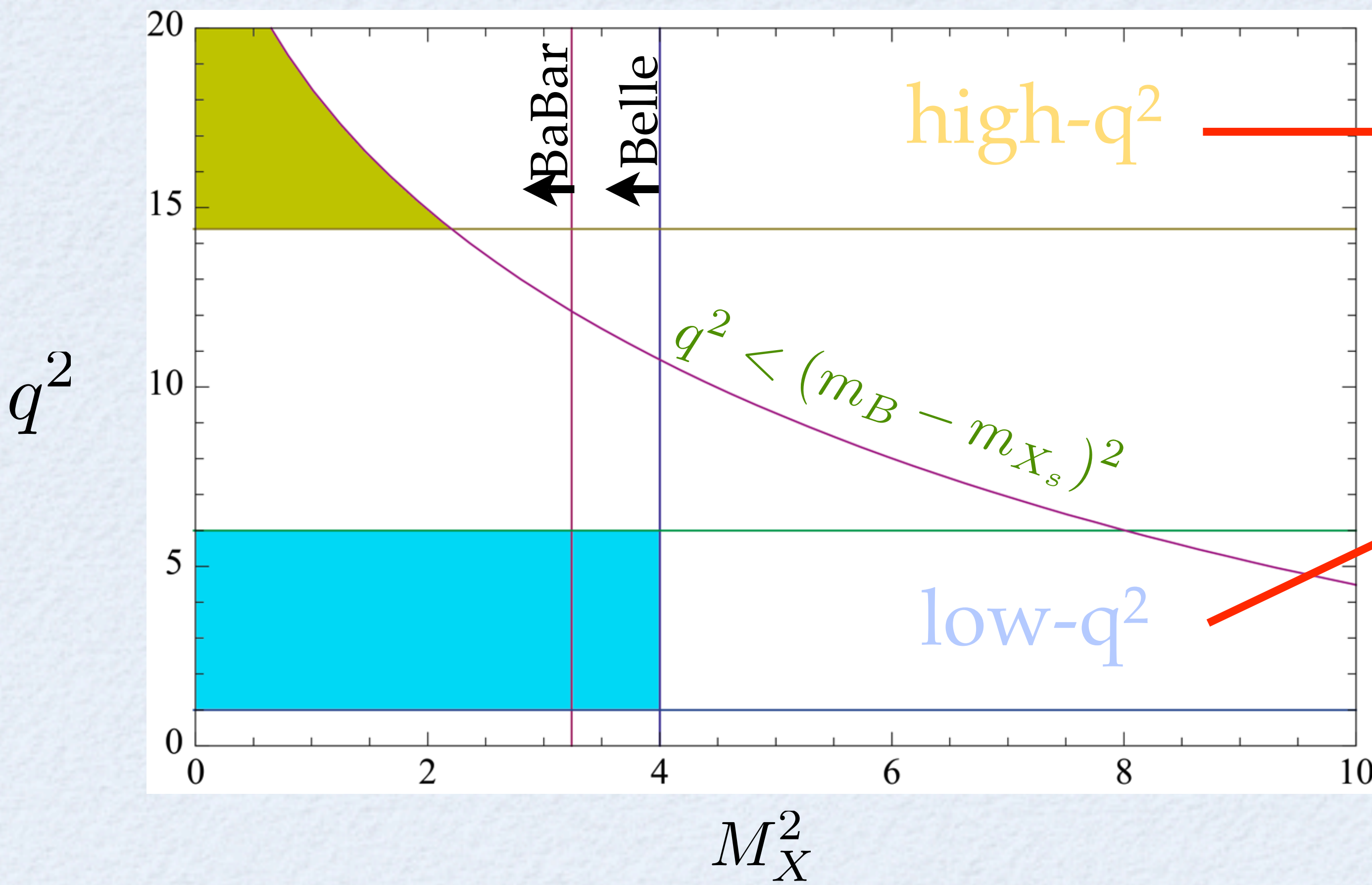
$$\mathrm{Re}\langle O_2\rangle \to \langle O_9\rangle_{\rm tree}\left(-\frac{8}{9}\log m_c/m_b - \frac{4}{9} + \frac{\hat s}{3} P\int_{4\hat m_D^2}^{\infty} \frac{R_{\rm had}^{c\bar c}(\hat s')}{\hat s'(\hat s' - \hat s)} d\hat s'\right)$$



- Alternatively use a Breit-Wigner ansatz to parametrize $\langle O_2 \rangle$
- The two approaches agree well above and below the resonances but not in between
- The impact in the low q^2 region is +1.8%, in the high q^2 region is -10%

X_s CUT

- MX cuts required to suppress the $b \to c\, l^- \nu \to s\, l^- l^+ \nu\, \nu$ background



unaffected

parton level at LO:

$M_{Xs} = m_s$

bremsstrahlung:

$m_s < M_{Xs} < m_b$

non-perturbative effects:

phase space ($M_B - m_b = \Lambda$)

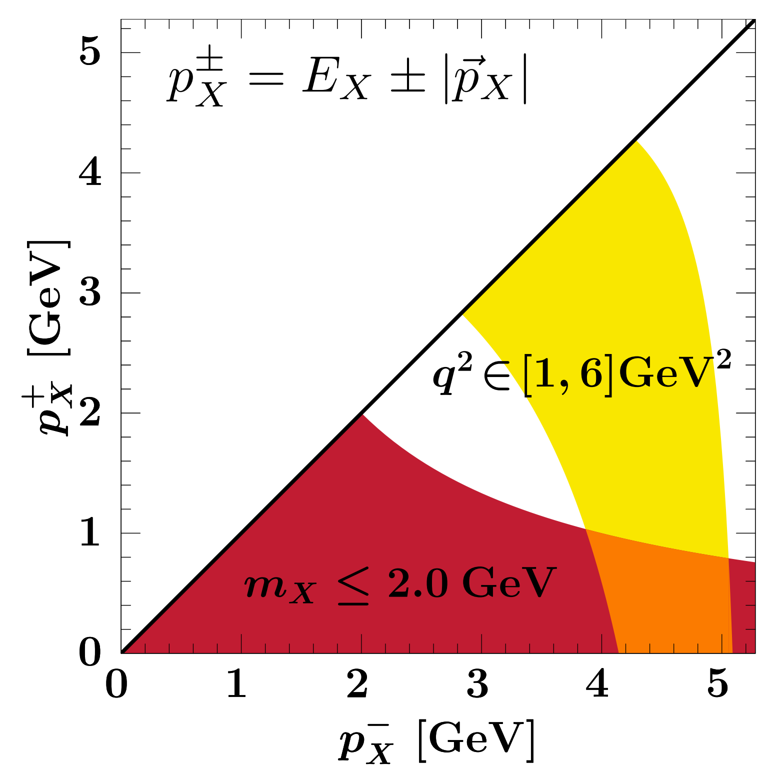
Fermi motion [Ali, Hiller]

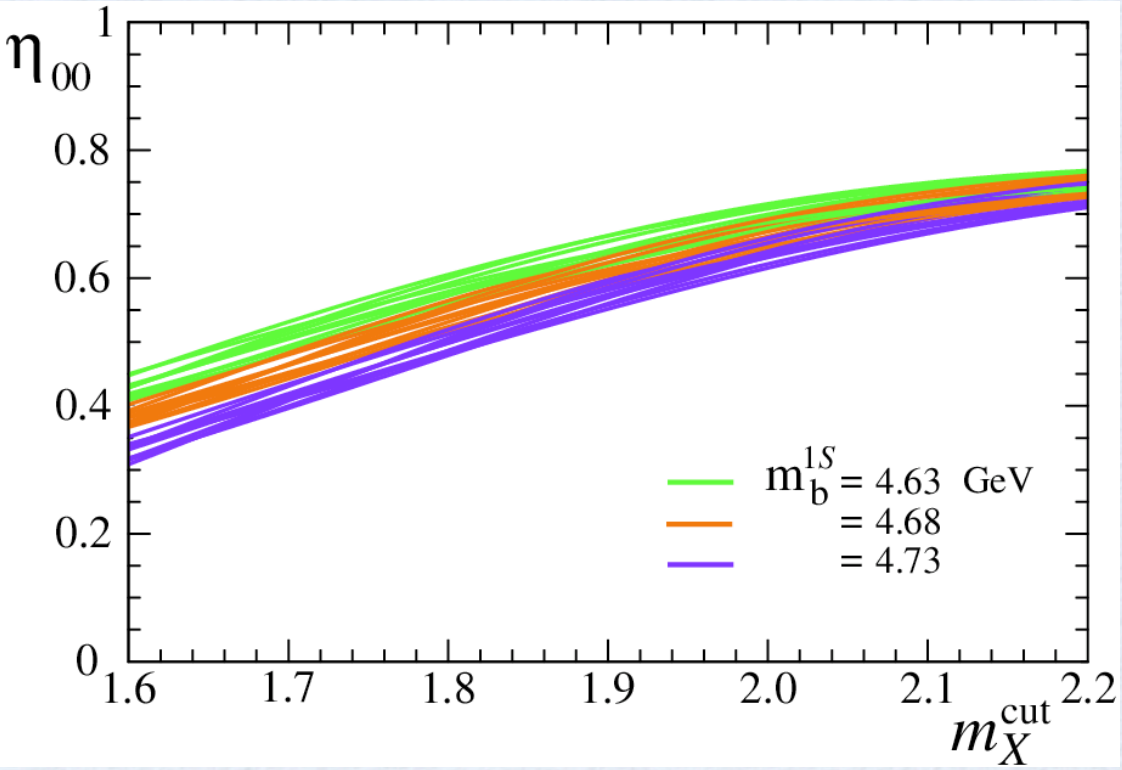
- Correction factor added in experimental results
- Framework: Fermi motion, SCET

①

X_s cut

- New idea: use SCET to describe the X_s system





$$p_X^+ \ll p_X^- \Longrightarrow m_X^2 \ll E_X^2$$

X_S is a hard-collinear mode:

$$\Lambda^2 \ll p_{X_s}^2 \sim \Lambda m_b \ll m_b^2$$

$$\eta_{ij} = \frac{\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2 \int_0^{m_X^{cut}} dm_X^2 \frac{d\Gamma_{ij}}{dq^2\, dm_X^2}}{\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2 \frac{d\Gamma_{ij}}{dq^2}}$$

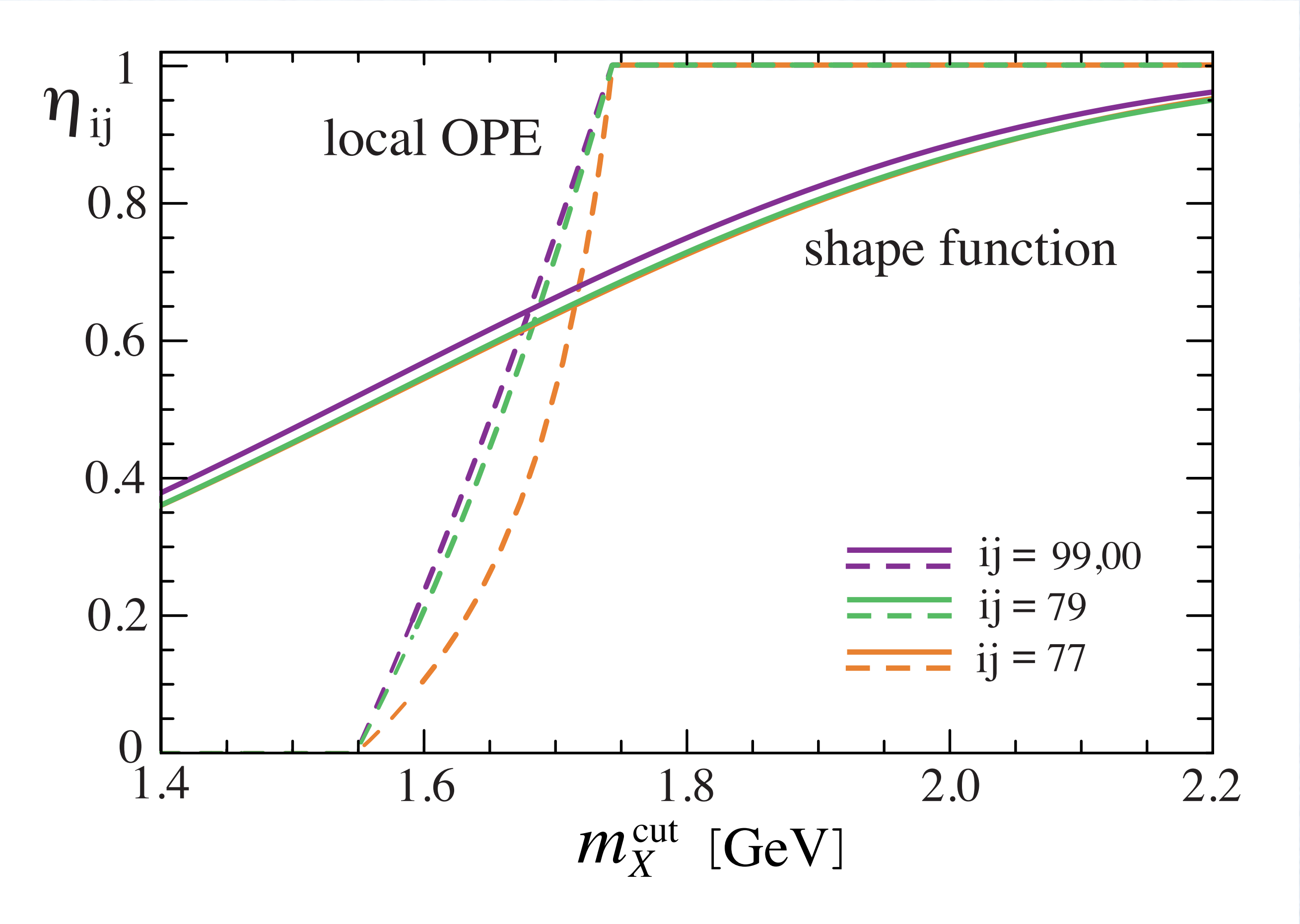
ij: C_9^2 and C_{10}^2, C_7C_9, C_7^2

- The effect seems very large (power corrections?)

①

X_s cut

- At leading power and at order α_s, these corrections are a universal multiplicative factor:



- Reduce non-perturbative effects by considering: [Lee, Ligeti, Stewart, Tackmann]

$\Gamma^{cut}(B \to X_s \ell^+ \ell^-)/\Gamma^{cut}(B \to X_u \ell \bar{\nu})$ *[same M_X cut]*

①

INPUTS FOR B→SLL

$\alpha_s(M_z) = 0.1189 \pm 0.0010$ [40]	$m_e = 0.51099892$ MeV
$\alpha_e(M_z) = 1/127.918$	$m_\mu = 105.658369$ MeV
$s_W^2 \equiv \sin^2\theta_W = 0.2312$	$m_\tau = 1.77699$ GeV
$\lvert V_{ts}V_{tb}/V_{cb}\rvert^2 = 0.962 \pm 0.002$ [41]	$m_c(m_c) = (1.224 \pm 0.017 \pm 0.054)$ GeV [42]
$\lvert V_{ts}V_{tb}/V_{ub}\rvert^2 = (1.28 \pm 0.12) \times 10^2$ [41]	$m_b^{1S} = (4.68 \pm 0.03)$ GeV [31]
$BR(B \to X_c e\bar{\nu})_{\rm exp} = 0.1061 \pm 0.0017$ [43]	$m_{t,{\rm pole}} = (170.9 \pm 1.8)$ GeV [44]
$M_Z = 91.1876$ GeV	$m_B = 5.2794$ GeV
$M_W = 80.426$ GeV	$C = 0.58 \pm 0.01$ [31] $= \left\lvert \frac{V_{ub}}{V_{cb}} \right\rvert^2 \frac{\Gamma(\bar{B} \to X_c e\bar{\nu})}{\Gamma(\bar{B} \to X_u e\bar{\nu})}$
$\lambda_2^{\rm eff} = (0.12 \pm 0.02)$ GeV^2	$\rho_1 = (0.06 \pm 0.06)$ GeV^3 [31]
$\lambda_1^{\rm eff} = (-0.243 \pm 0.055)$ GeV^2 [42]	$f_u^0 + f_s = (0 \pm 0.2)$ GeV^3 [24]
$f_u^0 - f_s = (0 \pm 0.04)$ GeV^3 [24]	$f_u^\pm = (0 \pm 0.4)$ GeV^3 [24]

①

BRANCHING RATIO

- Theory [Huber,Lunghi,Misiak,Wyler; Huber,Hurth,Lunghi]:

LOW

$$\mathcal{B}^{\rm low}_{\mu\mu} = \Big[1.59 \pm 0.08_{\rm scale} \pm 0.06_{m_t} \pm 0.024_{C,m_c} \pm 0.015_{m_b} \pm 0.02_{\alpha_s(M_Z)}$$
$$\pm 0.015_{\rm CKM} \pm 0.026_{{\rm BR}_{sl}} \pm 0.08_{\alpha_s/m_b}\Big] \times 10^{-6} = (1.59 \pm 0.14) \times 10^{-6}$$

$$\mathcal{B}^{\rm low}_{ee} = (1.64 \pm 0.14) \times 10^{-6}$$

HIGH

$$\mathcal{B}^{\rm high}_{\mu\mu} = 2.40 \times 10^{-7}\Big(1 + \left[{}^{+0.01}_{-0.02}\right]_{\mu_0} + \left[{}^{+0.14}_{-0.06}\right]_{\mu_b} \pm 0.02_{m_t} + \left[{}^{+0.006}_{-0.003}\right]_{C,m_c} \pm 0.05_{m_b}$$
$$+ \left[{}^{+0.0002}_{-0.001}\right]_{\alpha_s} \pm 0.002_{\rm CKM} \pm 0.02_{{\rm BR}_{sl}} \pm 0.05_{\lambda_2} \pm 0.19_{\rho_1} \pm 0.14_{f_s} \pm 0.02_{f_u} \pm 0.05_{\alpha_s/m_b}\Big)$$
$$= (2.40 \pm 0.7) \times 10^{-7}$$

$$\mathcal{B}^{\rm high}_{ee} = (2.1 \pm 0.6) \times 10^{-7}$$

Breakdown of the OPE results in large power corrections over which we have a poor control

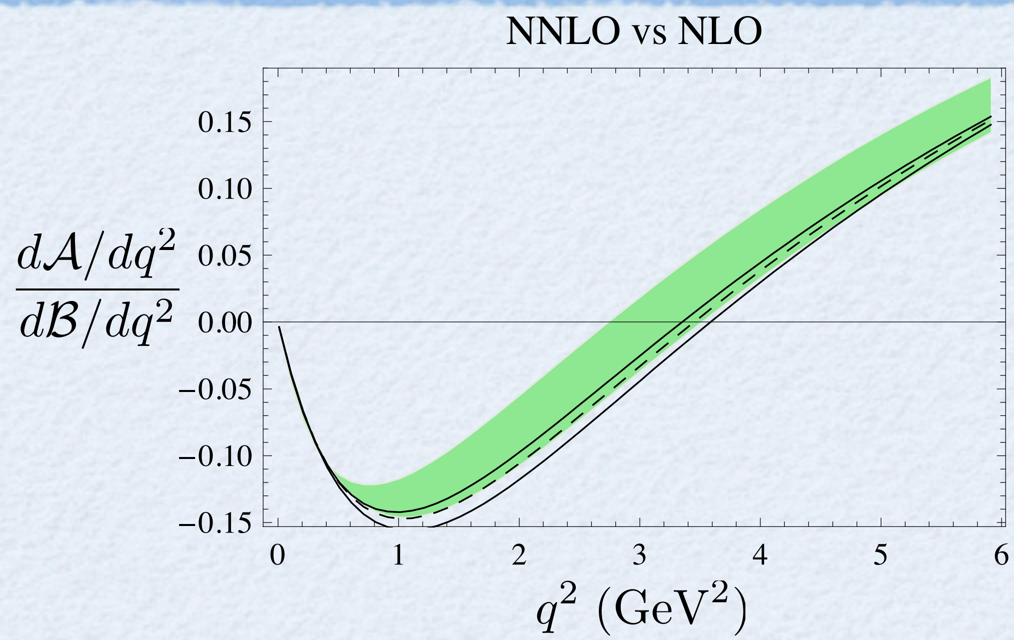
- Experiment [BaBar and Belle]:

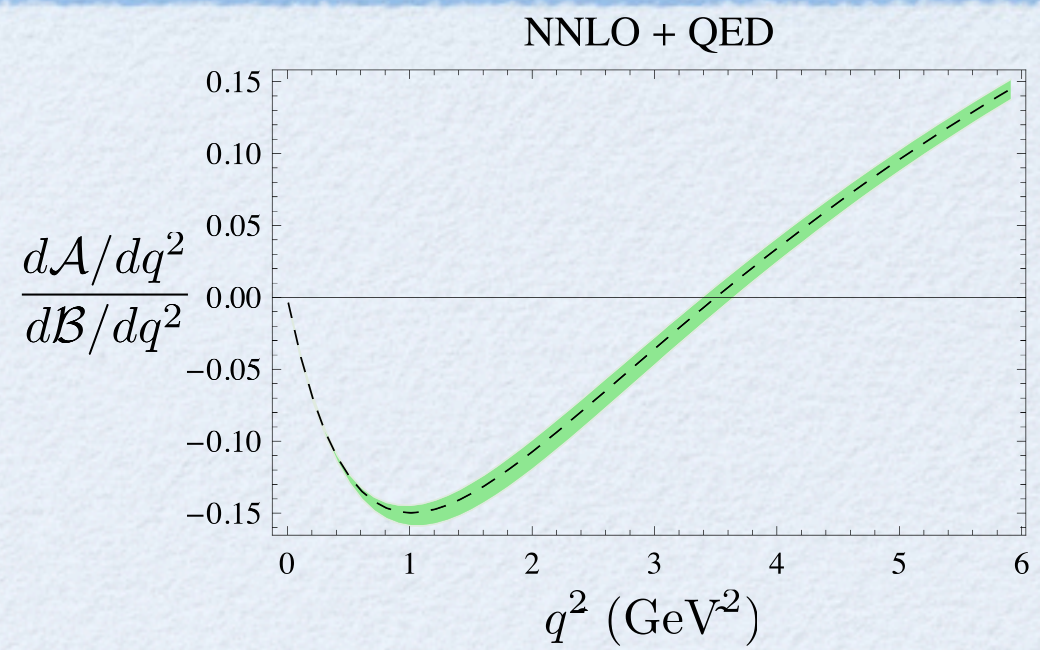
$$\mathcal{B}^{\rm low}_{\ell\ell} = (1.60 \pm 0.51) \times 10^{-6}$$
$$\mathcal{B}^{\rm high}_{\ell\ell} = (4.4 \pm 1.2) \times 10^{-7}$$

①

Low-Q^2: FBA

[Huber,Hurth,Lunghi]





$$(q_0^2)_{\mu\mu} = \left[3.50 \pm 0.10_{\rm scale} \pm 0.002_{m_t} \pm 0.04_{m_c,C} \pm 0.05_{m_b} \pm 0.03_{\alpha_s(M_Z)} \pm 0.001_{\lambda_1} \pm 0.01_{\lambda_2}\right] {\rm GeV}^2$$

$$= (3.50 \pm 0.12)\,{\rm GeV}^2$$

$$(q_0^2)_{ee} = (3.38 \pm 0.11)\,{\rm GeV}^2$$

- Integrated observables:

Bin 1 ($q^2 \in [1, 3.5]{\rm GeV}^2$)	Bin 2 ($q^2 \in [3.5, 6]{\rm GeV}^2$)	low − q^2 ($q^2 \in [1, 6]{\rm GeV}^2$)
$(\bar{\mathcal{A}}_{\mu\mu})_{\rm bin1} = [-9.1 \pm 0.9]\%$	$(\bar{\mathcal{A}}_{\mu\mu})_{\rm bin2} = [7.8 \pm 0.8]\%$	$(\bar{\mathcal{A}}_{\mu\mu})_{\rm low} = [-1.5 \pm 0.9]\%$
$(\bar{\mathcal{A}}_{ee})_{\rm bin1} = [-8.1 \pm 0.9]\%$	$(\bar{\mathcal{A}}_{\mu\mu})_{\rm bin2} = [8.3 \pm 0.6]\%$	$(\bar{\mathcal{A}}_{\mu\mu})_{\rm low} = [-0.9 \pm 0.9]\%$

①

High-Q^2: Reducing the errors

- New idea: normalize the decay width to the semileptonic B→X_ulν rate with the ***same dilepton invariant mass cut:***

$$\mathcal{R}(s_0) = \frac{\int_{\hat{s}_0}^{1} d\hat{s}\, \frac{d\Gamma(\bar{B} \to X_s \ell^+ \ell^-)}{d\hat{s}}}{\int_{\hat{s}_0}^{1} d\hat{s}\, \frac{d\Gamma(\bar{B}^0 \to X_u \ell \nu)}{d\hat{s}}}$$

[Ligeti,Tackmann]

- ***Impact of non-perturbative*** $1/m_b^2$ ***and*** $1/m_b^3$ ***power corrections drastically reduced***

- In the high-q^2 region we find:

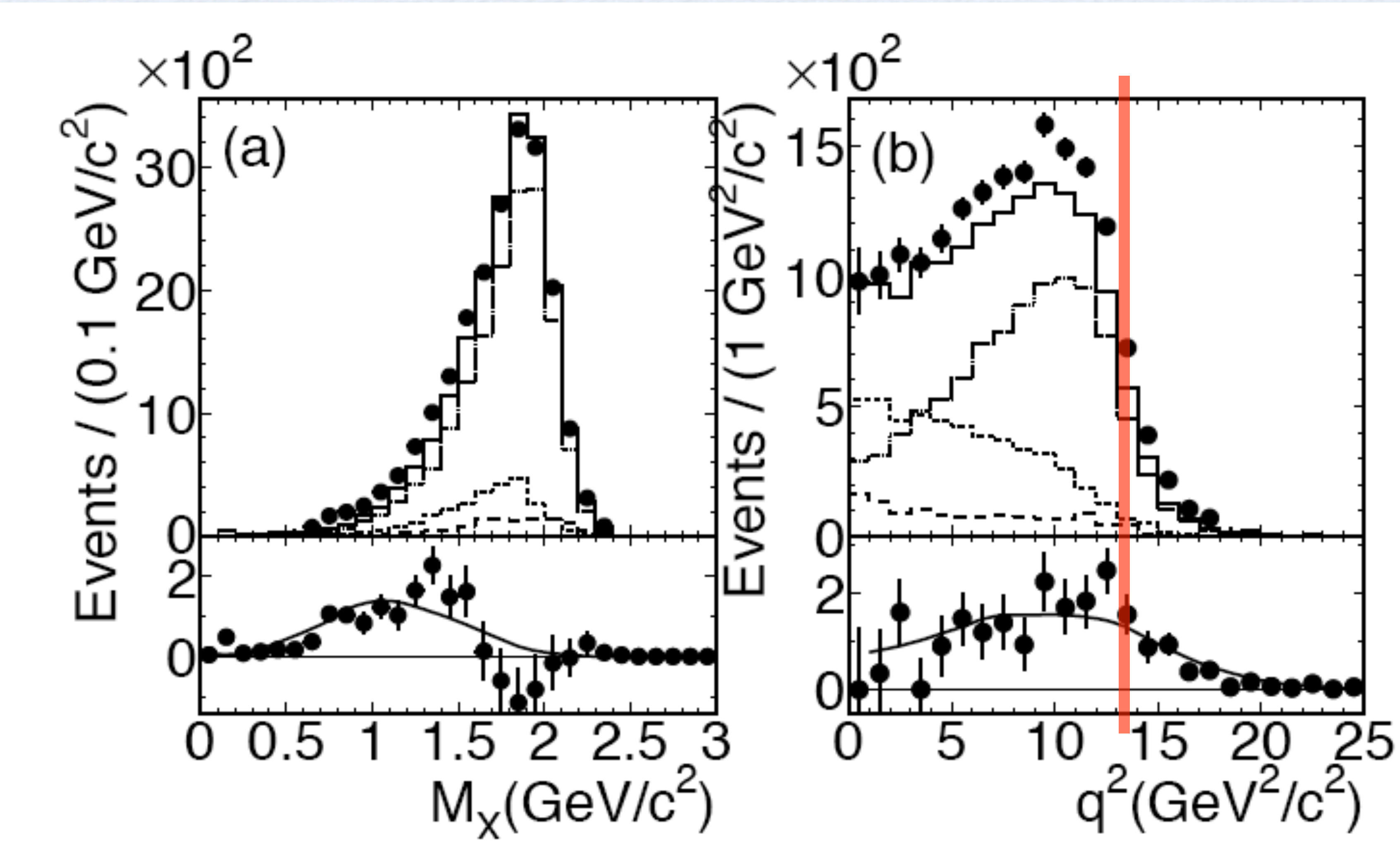
$$\begin{aligned}\mathcal{R}(14.4\mathrm{GeV}^2) &= 2.29 \times 10^{-3}\Big(1 \pm 0.04_{\mathrm{scale}} \pm 0.02_{m_t} \pm 0.01_{C,m_c} \pm 0.006_{m_b} \pm 0.005_{\alpha_s} \pm 0.09_{\mathrm{CKM}} \\ &\quad \pm 0.003_{\lambda_2} \pm 0.05_{\rho_1} \pm 0.03_{f_u^0+f_s} \pm 0.05_{f_u^0-f_s}\Big) \\ &= 2.29 \times 10^{-3}(1 \pm 0.13)\end{aligned}$$

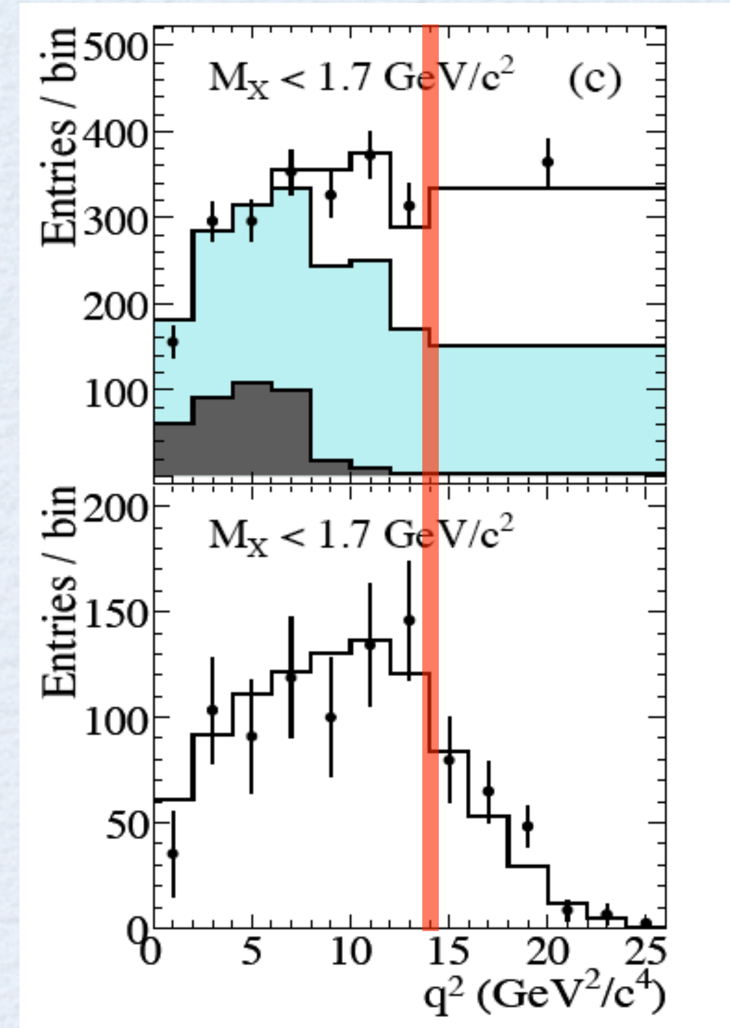
[Huber,Hurth,Lunghi]

- ***The largest source of uncertainty is V_{ub}***

①

HIGH-Q^2: REDUCING THE ERRORS





[Belle, 87 fb^{-1}, hep-ex/0311048]

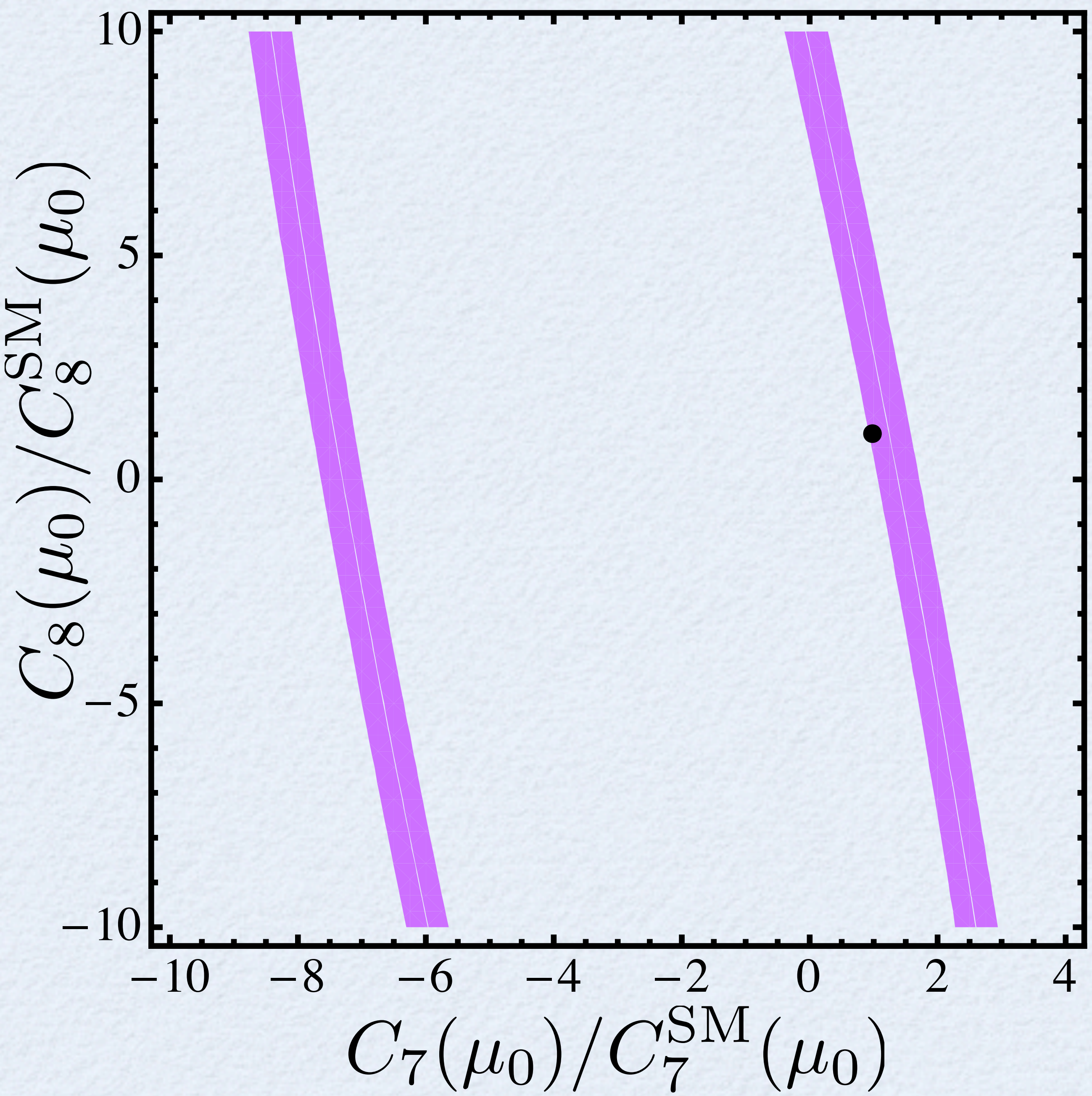
[BaBar, 383 m Υ, arXiv:0708.3702]

- Experiments already positioned to measure $B \to X_u l\nu$ with a q^2 cut
- Separation of B^0 and B^+ is important to control WA contributions

①

Model Independent Analysis

- Use $B \to X_s \gamma$ to constrain C_7 and C_8:



Theory:

$$\mathcal{B}(\bar{B} \to X_s \gamma)_{\mathrm{SM}} = (3.15 \pm 0.23) \times 10^{-4}$$

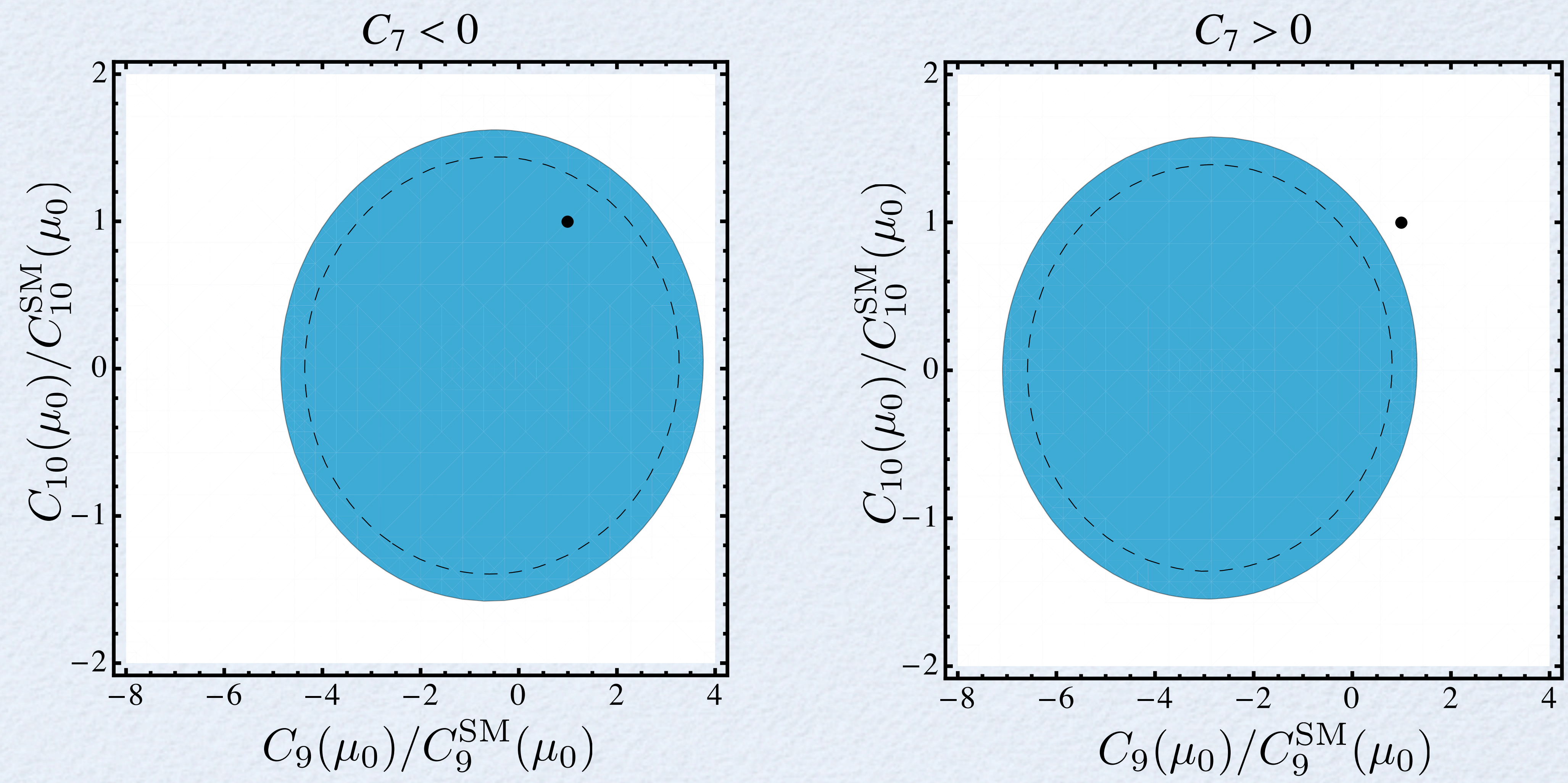
Experiment:

$$\mathcal{B}(\bar{B} \to X_s \gamma)_{\mathrm{exp}} = (3.52 \pm 0.25) \times 10^{-4}$$

①

Model Independent Analysis

- Use C_7 and C_8 from $B \to X_s\gamma$ to constrain C_9 and C_{10}

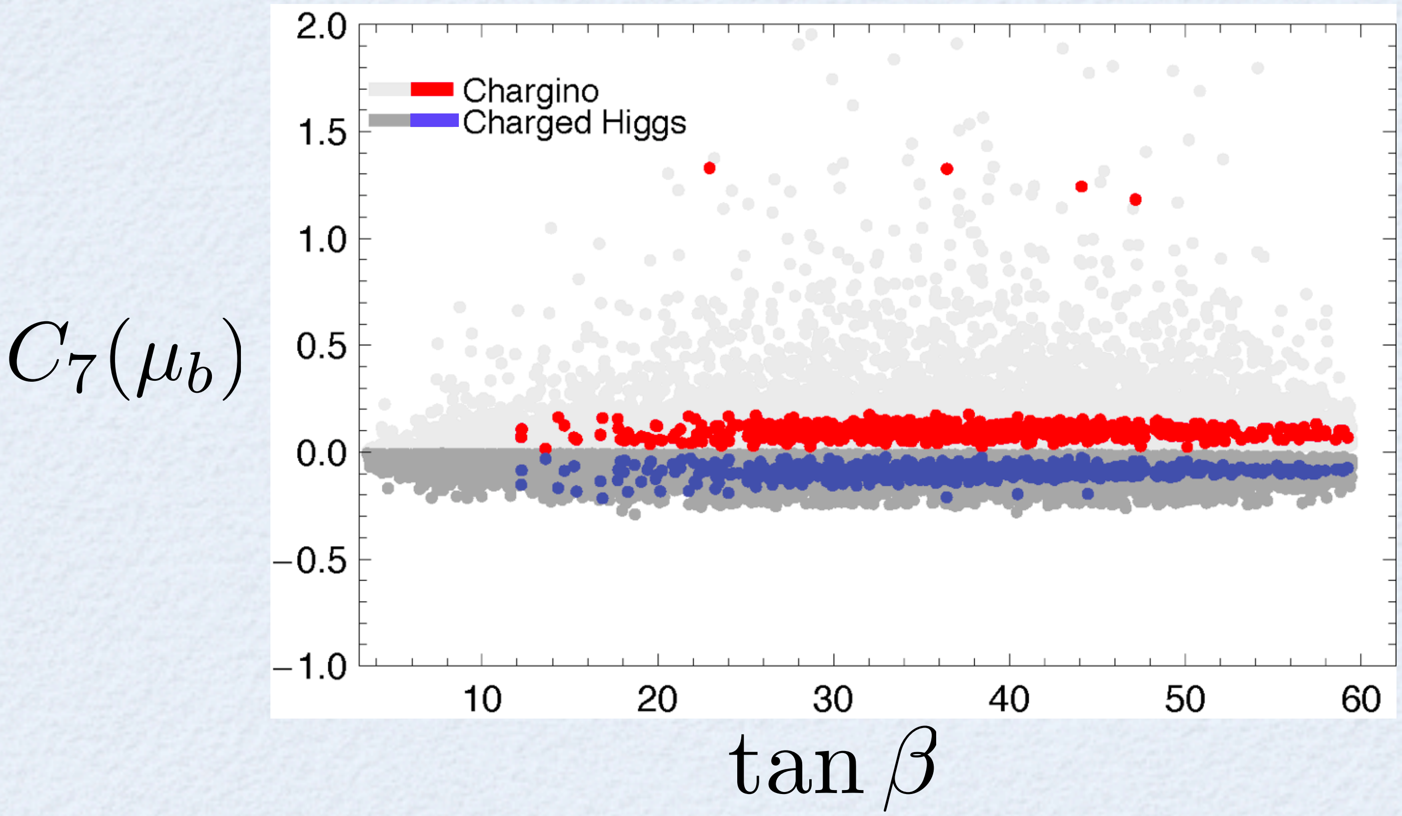


- $C_7 > 0$ requires sizable contributions to C_9 and C_{10}
- Reversing the sign of C_7 we obtain $\mathcal{B}(\bar{B} \to X_s \ell^+ \ell^-) = (3.11 \pm 0.22) \times 10^{-6}$ hence the SM sign is favored at the 2.7σ level
  [Gambino,Haisch,Misiak]

①

MFV SUSY

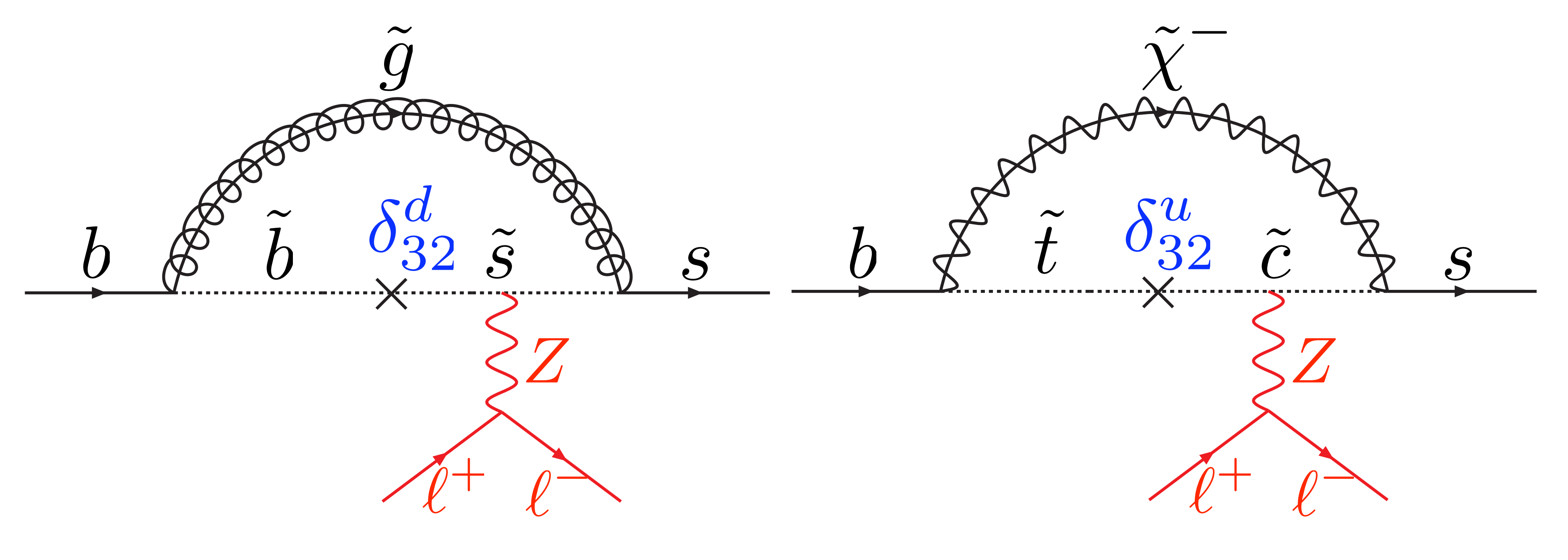
- Computing aid: *Spheno* for the RGE of the MSSM and *MicrOMEGAs* for the relic dark matter density
- Effects on C9 and C10 are tiny: $\left|C_{9,10}(\mu_0)/C_{9,10}^{\rm SM}(\mu_0)\right| < 0.1$
- b→sγ shapes the surviving parameter space:



①

SUSY: MIA Analysis

- In the most general MSSM, gluino and chargino diagrams can lead to huge contributions to the semileptonic operators:

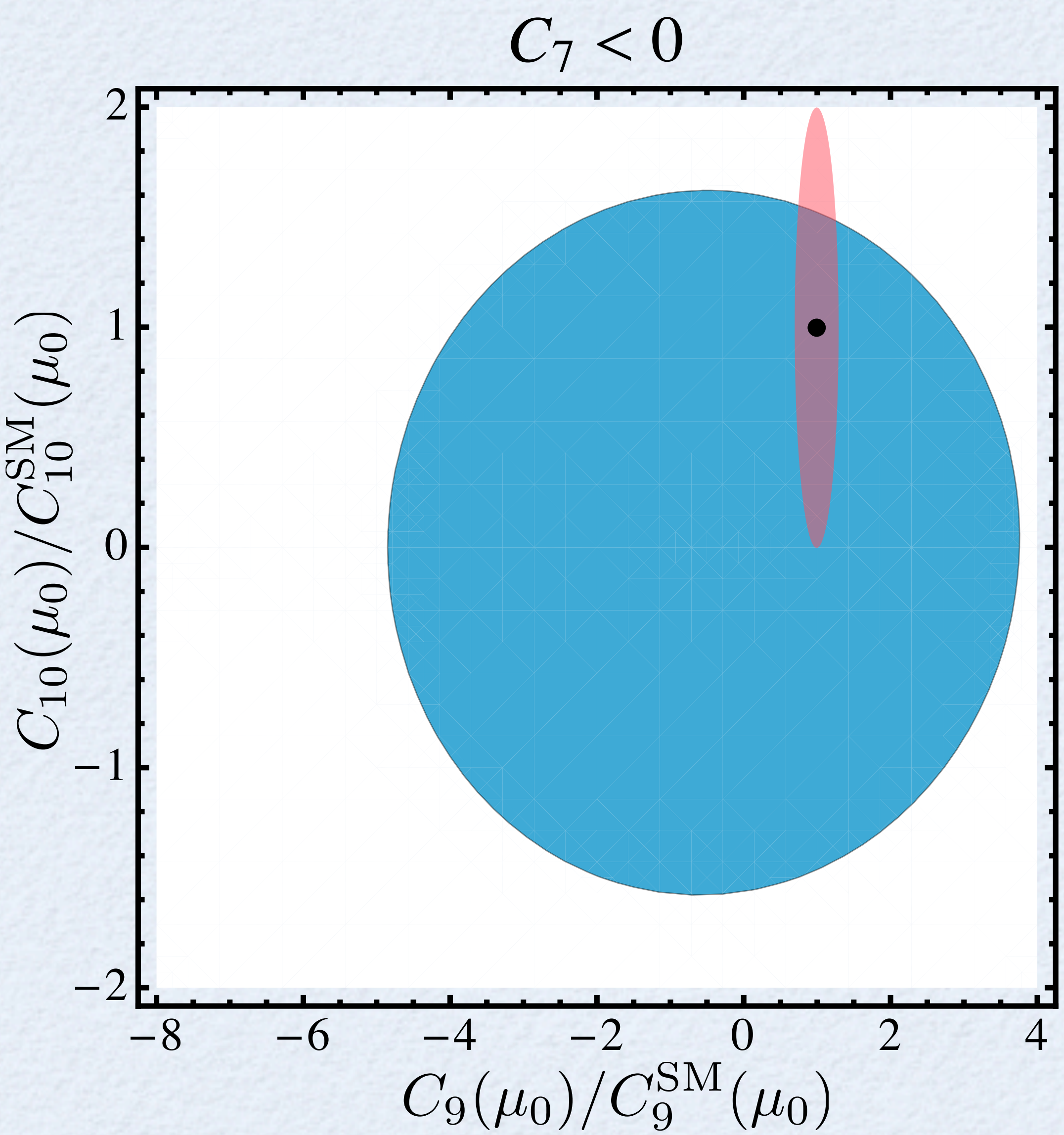


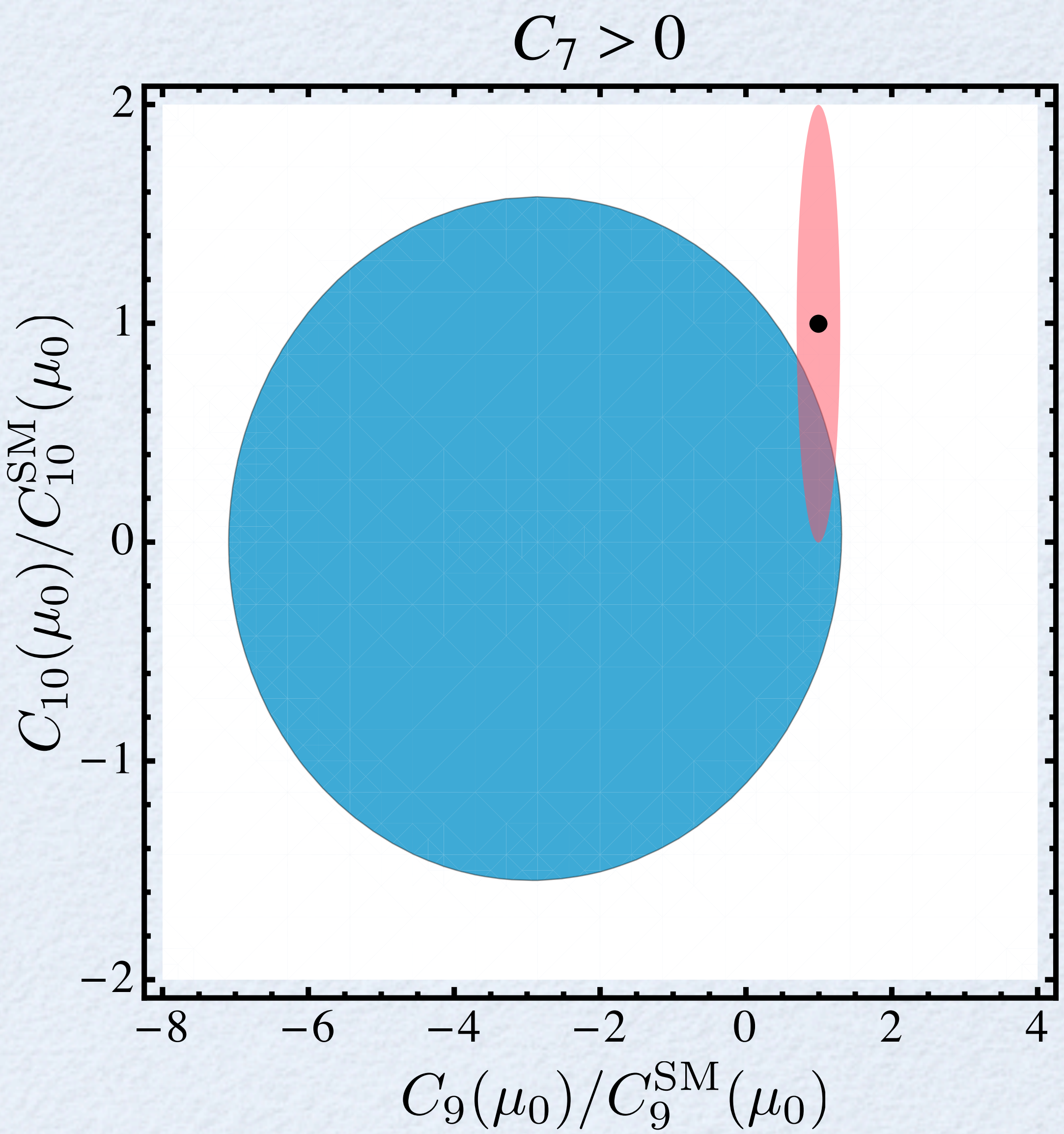
$$0.7 < C_9(\mu_0)/C_9^{\rm SM}(\mu_0) < 1.3$$

$$0 < C_{10}(\mu_0)/C_{10}^{\rm SM}(\mu_0) < 2$$

①

SUSY: MIA ANALYSIS





- The $C_7 > 0$ scenario is viable (with some degree of fine tuning)
- More than one mass insertion present at the same time

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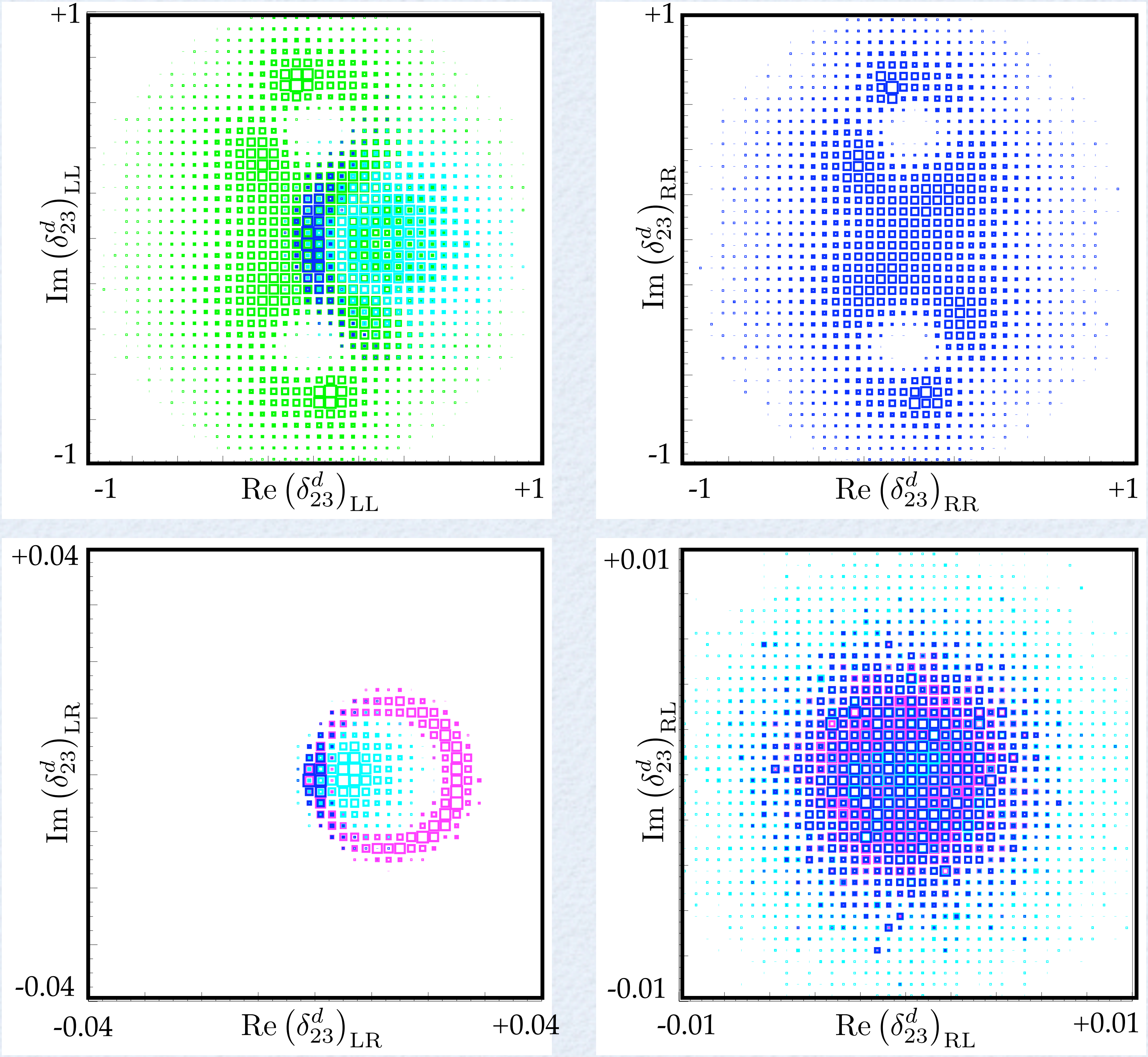
SUSY: MIA analysis

- Constraints on (23) mass insertions in the down sector
  [Ciuchini,Silvestrini]



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INPUTS TO THE UT FIT

$\lvert V_{cb}\rvert_{\text{excl}} = (38.6 \pm 1.2)10^{-3}$	$\eta_1 = 1.51 \pm 0.24$
$\lvert V_{cb}\rvert_{\text{incl}} = (41.31 \pm 0.76)10^{-3}$	$\eta_2 = 0.5765 \pm 0.0065$
$\lvert V_{cb}\rvert_{\text{incl+excl}} = (40.3 \pm 1.0)10^{-3}$	$\eta_3 = 0.47 \pm 0.04$
$\lvert V_{ub}\rvert_{\text{excl}} = (3.42 \pm 0.37)10^{-3}$	$\eta_B = 0.551 \pm 0.007$
$\lvert V_{ub}\rvert_{\text{incl}} = (4.03 \pm 0.15^{+0.20}_{-0.25})10^{-3}$	$\xi = 1.243 \pm 0.028$
$\Delta m_{B_d} = (0.507 \pm 0.005)\ \text{ps}^{-1}$	$\alpha = (89.5 \pm 4.3)^{\text{o}}$
$\Delta m_{B_s} = (17.77 \pm 0.12)\ \text{ps}^{-1}$	$S_{\psi K_S} = 0.672 \pm 0.024$
$\varepsilon_K = (2.229 \pm 0.012) \times 10^{-3}$	$\gamma = (78 \pm 12)^{\text{o}}$
$m_c(m_c) = (1.268 \pm 0.009)\ \text{GeV}$	$\widehat{B}_K = 0.725 \pm 0.026$
$m_{t,pole} = (172.4 \pm 1.2)\ \text{GeV}$	$\kappa_\varepsilon = 0.92 \pm 0.01$
$f_K = (155.8 \pm 1.7)\ \text{MeV}$	$f_B = (192.8 \pm 9.9)\ \text{MeV}$
$f_{B_s}\sqrt{\widehat{B}_s} = (275 \pm 13)\ \text{MeV}$	$\lambda = 0.2255 \pm 0.0007$
$\text{BR}(B \to \tau\nu) = (1.43 \pm 0.37)10^{-4}$ [17]	