Closing remarks:

Nonleptonic Decays of Heavy Mesons

Méril Reboud and Keri Vos

Thanks to Marta for the arrows!

Why now?

- Can finally confront theories with experimental data!
- Thanks to advances in data and form factor inputs!
- This is the time to further study nonleptonic decays!

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- Thanks to advances in data and form factor inputs!
- This is the time to further study nonleptonic decays!
- Challenge: Revise assumptions regarding power countings and "small" effects

Update see also [0909.5229]

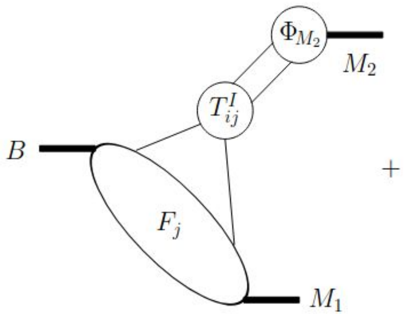
How to handle nonleptonic decays?

1. QCD Factorization [BBNS '99, 00; Beneke Neubert '03]

$$\langle M_1 M_2 | \mathcal{O}_i | \bar{B} \rangle = \sum_j F_j^{B\to M_1}(m_2^2) \int_0^1 du\, T_{ij}^I(u)\, \Phi_{M_2}(u) \; + \; (M_1 \leftrightarrow M_2)$$
$$+ \int_0^1 d\xi du dv\, T_i^{II}(\xi, u, v)\, \Phi_B(\xi)\, \Phi_{M_1}(v)\, \Phi_{M_2}(u)$$

Main limitations:

- LO in Λ_{QCD}/m_b
- α_s corrections?
- Requires knowledge of the form factors and the DA parameters



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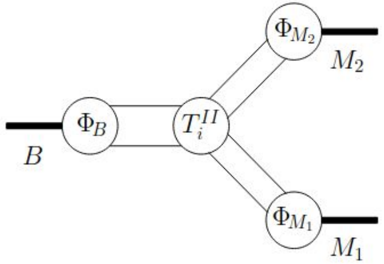
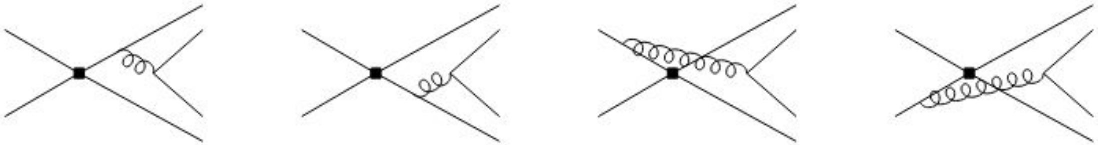


Challenges in QCDF

- Current-current tree operators known at NNLO.
  Only part of the penguins (a_4) known at NNLO, but mixes with chirally enhanced a_6.
- Weak annihilation terms suffer from end-point divergences: currently simply modelled
- Power-suppressed spectator scattering term also divergent and modelled

Challenges in QCDF: weak annihilation

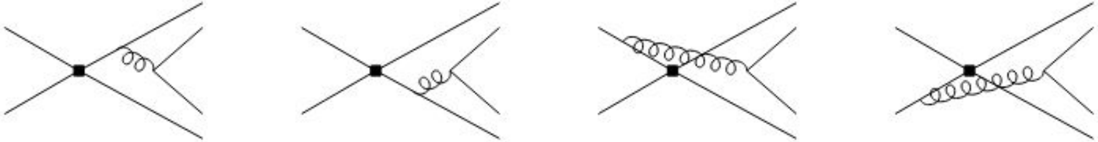


Example: $$A_1^i = \pi\alpha_s \int_0^1 dxdy \left\{ \Phi_{M_2}(x)\, \Phi_{M_1}(y) \left[\frac{1}{y(1-x\bar{y})} + \frac{1}{\bar{x}^2 y} \right] + r_\chi^{M_1} r_\chi^{M_2}\, \Phi_{m_2}(x)\, \Phi_{m_1}(y)\, \frac{2}{\bar{x}y} \right\},$$

Model: $$\int_0^1 \frac{dy}{y} \to X_A^{M_1}, \qquad \int_0^1 dy \frac{\ln y}{y} \to -\frac{1}{2}(X_A^{M_1})^2,$$

Consequence: no information on strong phase nor amplitude. Model cannot account for CPV in annihilation modes

Challenges in QCDF: weak annihilation



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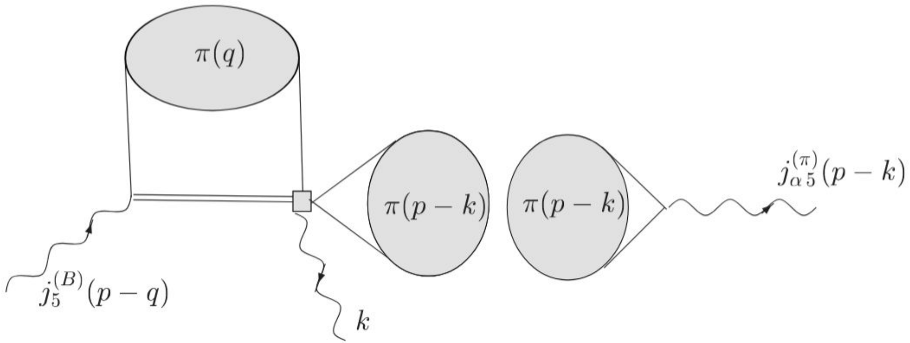
Needed: Measurements!

How to handle nonleptonic decays?

1. QCDF
2. QCD sum rules [Khodjamirian ‘01; Khodjamirian, Mannel, Melcher, Melic ‘05; Lenz, Piscopo, Rusov ‘23]

Main limitations:

- Requires knowledge of the DA parameters
- Not all contribution are easily evaluable



How to handle nonleptonic decays?

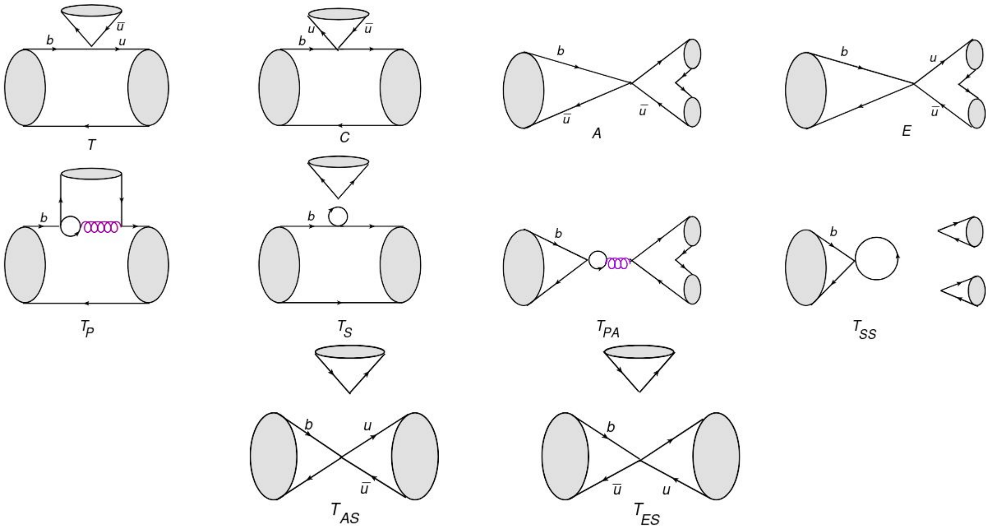
See talk Marta Burgos Marcos

and talk by Gilberto Tetlalmatzi-Xolocotzi

1. QCDF
2. QCD sum rules
3. SU(3) [Zeppenfeld ‘81; Rosner, Gronau, London, Fleischer, …]

Main limitations:

- Bottom-up approach
- Hardly predictive without a lot of data
- SU(3)-breaking corrections?



Can SU(3) describe heavy to light data?

Montreal-Durham

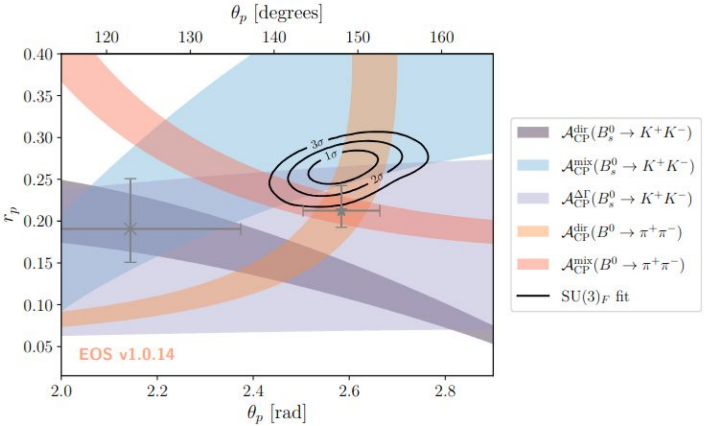
Orsay- Maastricht

Siegen

SU(3)limit: B-> PP described by 19 real parameters : bad fit

include EWP-tree relations (ETR) 16 real parameters: bad fit

But: ETRs + separations in Delta S =0,1: 2x good fit but with weird parameters



Goal?

In progress: add SU(3) breaking!

B-> PV modes

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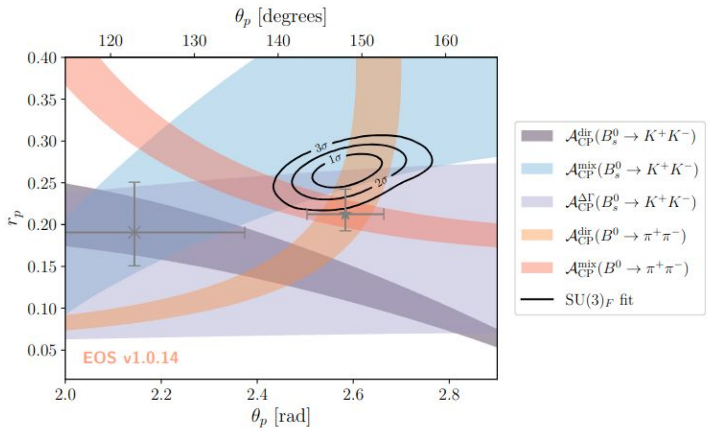


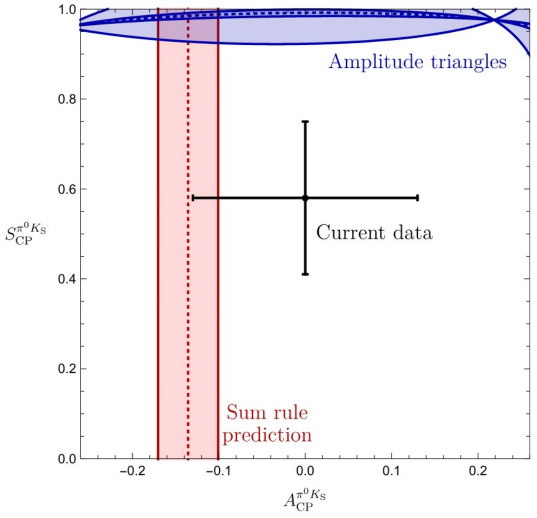
Goal: Identify what data is need?

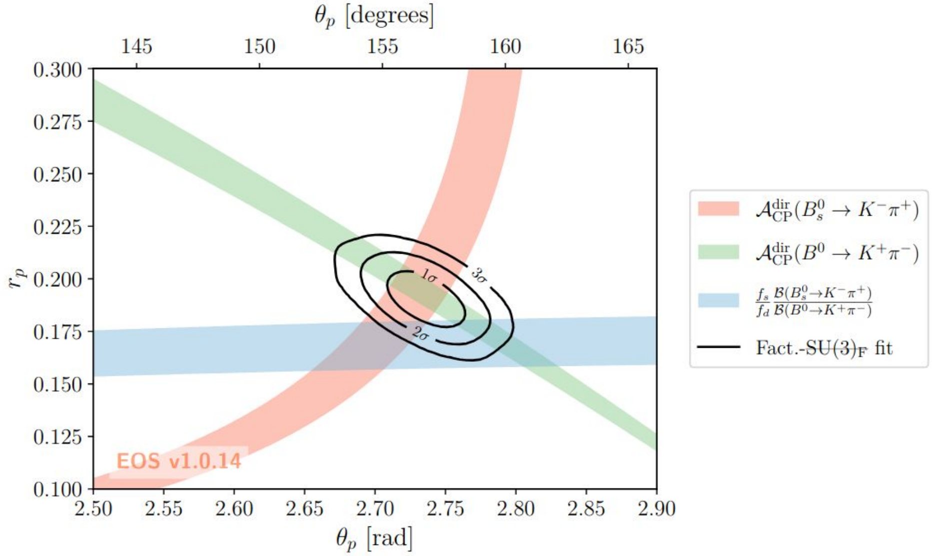
In progress: add SU(3) breaking!
B-> PV modes

Anomalies in nonleptonic B decays

See talk David London

1. Heavy to light
   - "Kπ puzzle": Data can be fitted, but relative sizes of contributions don't agree with QCDF





Anomalies in nonleptonic B decays

See talk David London

1. Heavy to light
   - "Kπ puzzle"
   - CP asymmetries, Kπ sum rule [Gronau '05; Gronau, Rosner '06]

$$\Delta_{\rm SR} = -\mathcal{A}_{\rm CP}^{\rm dir}(B^+ \to \pi^0 K^+)\frac{2\mathcal{B}(B^+ \to \pi^0 K^+)}{\mathcal{B}(B_d^0 \to \pi^- K^+)}\frac{\tau_{B^0}}{\tau_{B^+}} - \mathcal{A}_{\rm CP}^{\rm dir}(B_d^0 \to \pi^0 K^0)\frac{2\mathcal{B}(B_d^0 \to \pi^0 K^0)}{\mathcal{B}(B_d^0 \to \pi^- K^+)}$$
$$+ \mathcal{A}_{\rm CP}^{\rm dir}(B_d^0 \to \pi^- K^+) + \mathcal{A}_{\rm CP}^{\rm dir}(B^+ \to \pi^+ K^0)\frac{\mathcal{B}(B^+ \to \pi^+ K^0)}{\mathcal{B}(B_d^0 \to \pi^- K^+)}\frac{\tau_{B^0}}{\tau_{B^+}}\,, \qquad (5.18)$$

$$\Delta_{\rm SR}^{\rm exp.} = 0.12 \pm 0.08 \qquad\qquad \Delta_{\rm SR}^{\rm QCDF} \sim 1\%$$

→ exactly zero due to B → πK $SU(2)_I$ EWP-tree relations [Bhattacharya, Bouchard, Jean, London, Ray '25]

See talk Bhubanjyoti Bhattacharya

Anomalies in nonleptonic B decays

See talk Suman Kumbhakar

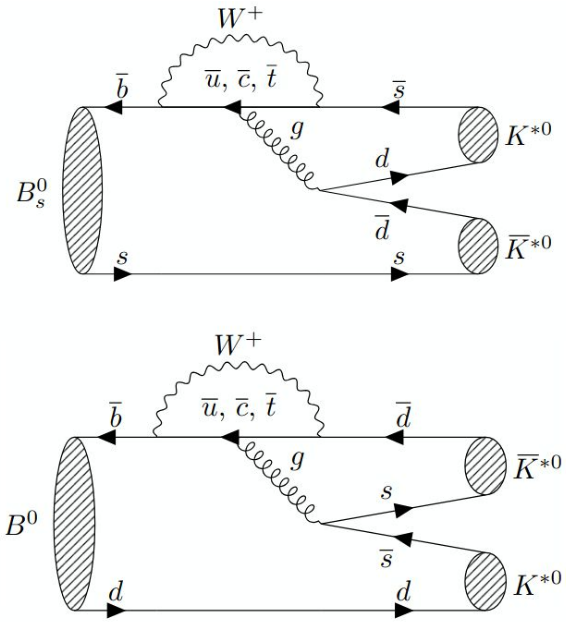
1. Heavy to light
   - “Kπ puzzle”
   - CP asymmetries, Kπ sum rule
   - Unexpected tensions in longitudinal fractions

$$\left[\frac{f_L(B_d \to K^{*0}\overline{K^{*0}})}{f_L(B_s \to K^{*0}\overline{K^{*0}})}\right]_{\text{QCDF}} = 1.09^{+0.19}_{-0.08}$$

$$\left[\frac{f_L(B_d \to K^{*0}\overline{K^{*0}})}{f_L(B_s \to K^{*0}\overline{K^{*0}})}\right]_{\text{Exp}} = 3.08 \pm 0.55$$

$\Longrightarrow$ Tension at the level of $\sim 3.5\sigma$

$\Longrightarrow$ Polarisation puzzle in $B_{s,d} \to K^{*0}\overline{K^{*0}}$



Anomalies in Heavy to heavy decays

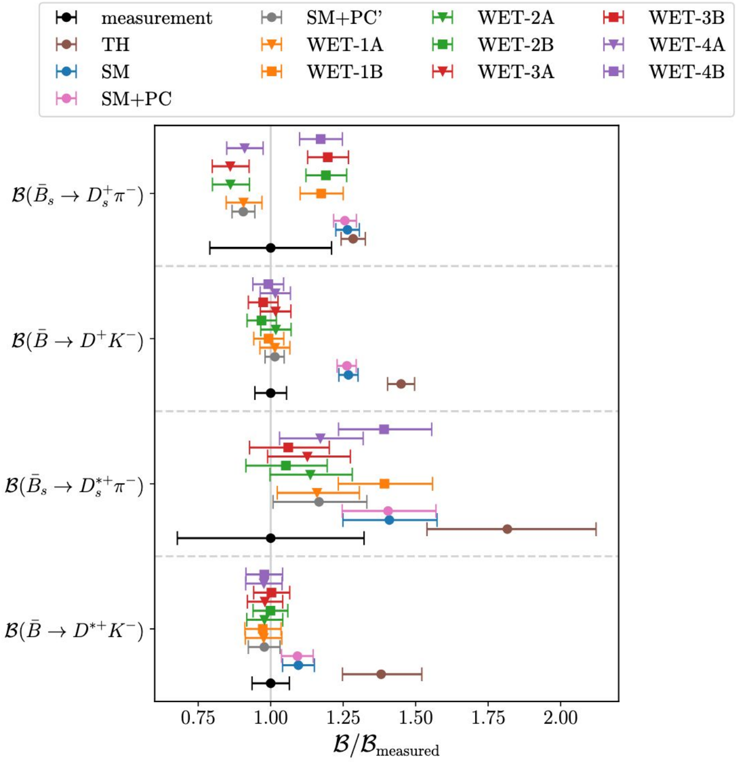
Pure tree decays. Large differences with QCDF at LO

Could this be BSM?

- WET + lifetimes!
- Difficult with specific BSM models

See talk Stefan Meiser

See talk Matthew Kirk



News from La Thuile

NEW Moriond: ΔCP asymmetry in $B_s \rightarrow D_s\pi$ 2603.10860 See talk by Dr. Gooding

$$\langle A^s_{\text{untagged}}\rangle \left(D_s^- \pi^+\right) = (-1.4 \pm 5.9 \pm 1.1) \times 10^{-3}.$$

- Strongly consistent with 0 → *no sign of a direct CP violating contribution from NP*

NEW Moriond: First Belle II CPV measurement for $B_0 \rightarrow \pi_0\pi_0$

$$\boxed{\begin{aligned} S_{00} &= 0.61^{+0.75}_{-0.79}\,(\text{stat}) \pm 0.11\,(\text{syst}), \\ C_{00} &= 0.05 \pm 0.28\,(\text{stat}) \pm 0.07\,(\text{syst}). \end{aligned}}$$

What about Charm?

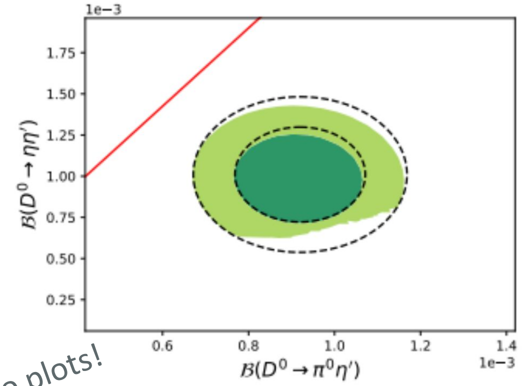
See talks Dr. Bolognani and Margarita Gavrilova

Similar to beauty? SU(3) tests, QCDF?, sumrules!

The prime candidates!

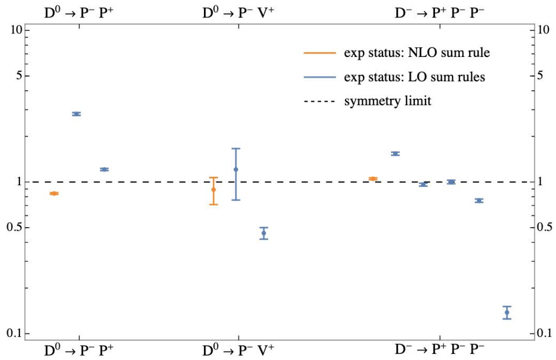
One sumrule to rule them all!

$$\frac{\text{sum of CF and DCS CKM-free rates}}{\text{sum of SCS CKM-free rates}} = 1 + \mathcal{O}(\varepsilon^2)$$



Avocado plots!

$$\left|\frac{\mathcal{A}_{\cancel{\mathrm{SU(3)}}}(D \to P\eta')}{\mathcal{A}_{\mathrm{SU(3)-lim}}(D \to P\eta')}\right| \leq \varepsilon$$



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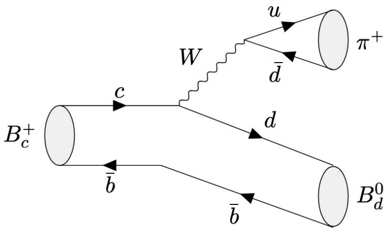
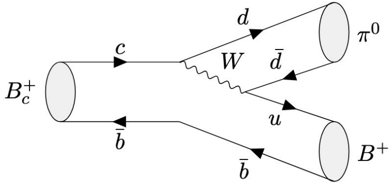
Charmed Beauty Mesons





- Both the b and the c quark can decay
- Small production fraction at LHC, but huge branching ratios.
  Offers option to search for charm CP violation in a Beauty system
- Data is starting to come in.

Next workshop?

Search for $B_c^{\mp} \to K_s K^{\mp}$ [2512.09288]; $B_c \to B_s \pi$ [2210.12000]

What is next?

- Exploit data to improve QCDF? Weak annihilation? FSI?

See talk Davide Lancierini

See Montreal Group

- What about three-body decays or four-body (B-> VV)? Clear next step to go beyond narrow-width approximation: requires form factors, rescattering, resonance understanding

- Charm data is streaming in. How do we treat the charm? Is it really a heavy quark?

What about Lattice?

Getting a handle on form factors and LCDA crucial for theory confrontation

Obtain full matrix element on the lattice?

Progress in charm!

See talk Felix Erben [CKM2025]

Conclusions

hadronic D decays

- Exploratory $D \to K\pi$ study at the $SU(3)_F$ symmetric point
- Finite-volume spectrum shows the expected pattern
- Current technical focus:
  - Computation of challenging 3-point functions
  - Non-perturbative renormalization of the 4-quark operators

What about data?

➡ Naive theory wishlist: update the old modes and measure the new ones!

➡ More realistically: many things to come!

See talk Davide Lancierini

- Updated theory models? (resonances, simulation, …)
- How to optimally publish and interpret the data?
- Ultimate goal? $SU(3)_F$? QCD? BSM?

See talk Alexandre Jean

See talk Matthew Kirk