Perturbative calculations

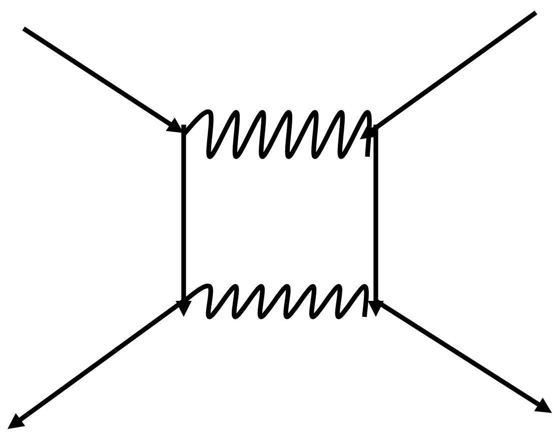
- In principle, all hadronic physics should be calculated by QCD
- In fact, you can always use QCD to calculate any process,

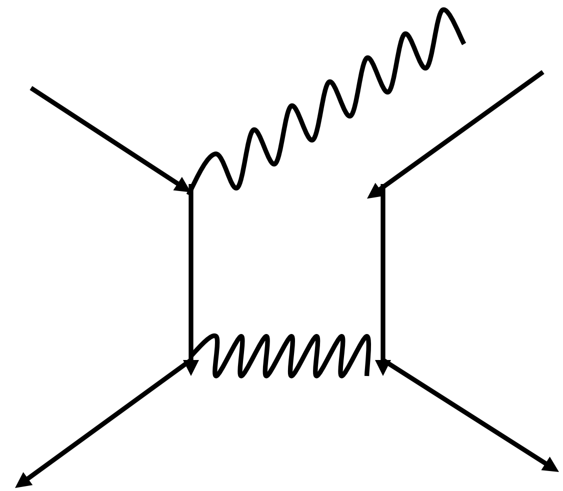
provided you can renormalize the infinities and do all order calculations.

- Perturbation calculation means order by order
- Involving loop diagrams
- Therefore divergences unavoidable

Divergences

- Ultraviolet divergences → renormalization
- Infrared divergences ? **Infrared divergence in virtual corrections should be canceled by real emission**
- In exclusive QCD processes → factorization





Factorization can only be proved in power expansion by operator product expansion. To achieve that, we need a hard scale Q

- In the certain order of 1/Q expansion, the hard dynamics characterized by Q factorize from the soft dynamics
- Hard dynamics is process-dependent, but calculable
- Soft dynamics are universal (process-independent) ⇨ predictive power of factorization theorem
- Usually, factorization holds up to all orders in α_s, but to certain power in 1/Q
- In B decays the hard scale Q is just the b quark mass

QCD-methods based on factorization work well for the leading power of $1/m_b$ expansion

collinear QCD Factorization approach
[Beneke, Buchalla, Neubert, Sachrajda, 99']

Perturbative QCD approach based on k_T factorization
[Keum, Li, Sanda, 00'; Lu, Ukai, Yang, 00']

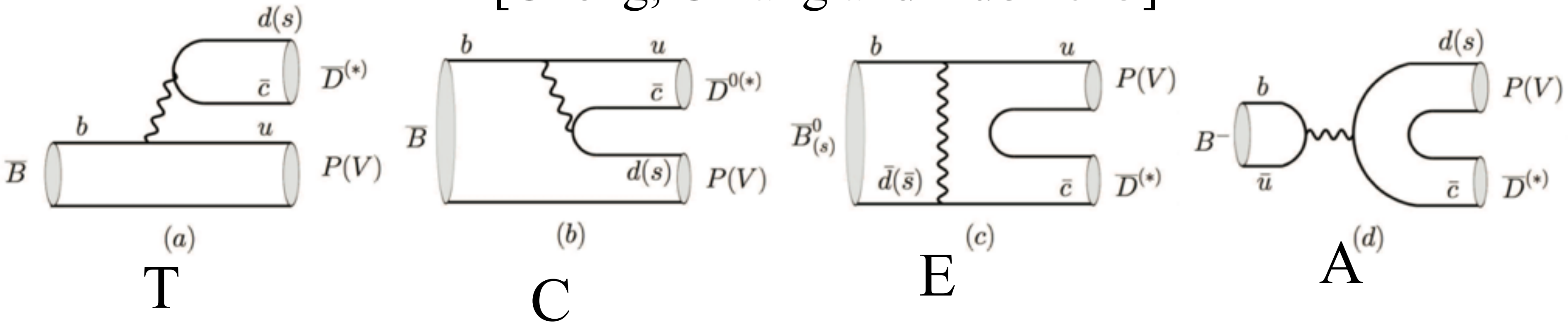
Soft-Collinear Effective Theory
[Bauer, Pirjol, Stewart, 01']

NLO (NNLO) α_s corrections have been done. Unavailable for $1/m_b$ power corrections

- Work well for most of charmless B decays, except for ππ, πK puzzle etc.

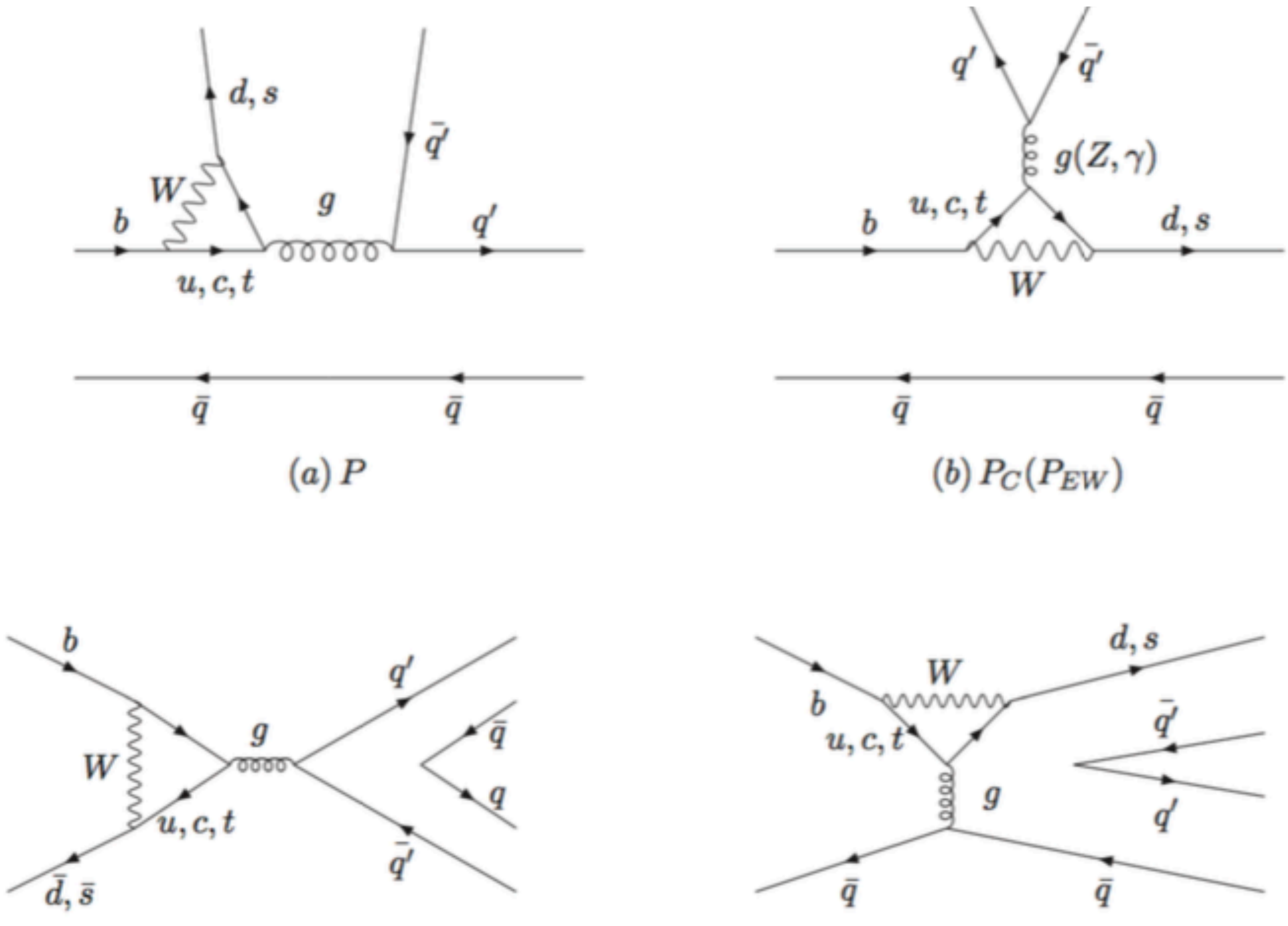
Topological diagrammatic approach

[Cheng, Chiang and Kuo 2015]



- Distinct by weak interaction and flavor flows with all strong interaction encoded, including non-perturbative ones. Model-independent
- Based on flavor SU(3) symmetry. Amplitudes with strong phases extracted from data. SU(3) breaking was lost.
- *PP*, *VP* and *PV* fitted separately, 13+19 = 32 parameters. Less predictive. Improved by FAT

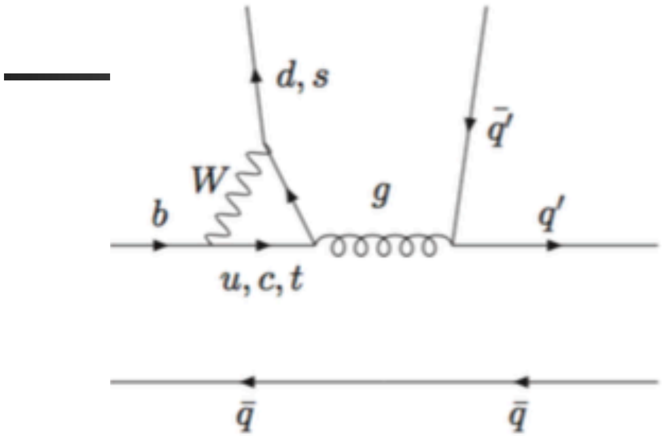
We also have four penguin type diagrams for charmless B decays

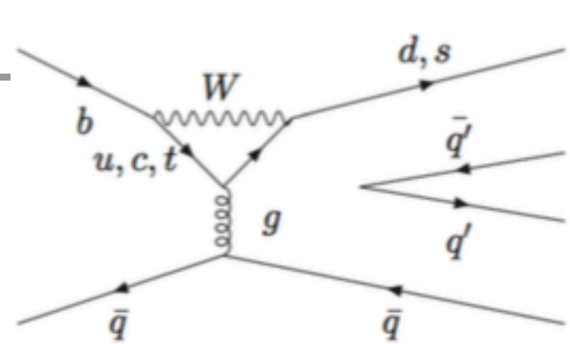


(a) P (b) $P_C(P_{EW})$ (c) P_E (d) P_A

However, this P is similar with penguin annihilation diagram P_A.

The difference is only at QCD not EW





(d) P_A

$$P^{PP} = -i\frac{G_F}{\sqrt{2}}V_{tb}V^*_{tq'}[a_4(\mu) + \chi^P e^{i\phi^P} r_\chi] f_{p_2}(m_B^2 - m_{p_1}^2)F_0^{BP_1}(m_{p_2}^2),$$

$$P^{PV} = -\sqrt{2}G_F V_{tb}V^*_{tq'}a_4(\mu) f_V m_V F_1^{B-P} m_V^2(\varepsilon_V^* \cdot p_B),$$

$$P^{VP} = -\sqrt{2}G_F V_{tb}V^*_{tq'}[a_4(\mu) - \chi^P e^{i\phi^P} r_\chi] f_P m_V A_0^{B-V}(m_P^2)(\varepsilon_V^* \cdot p_B).$$

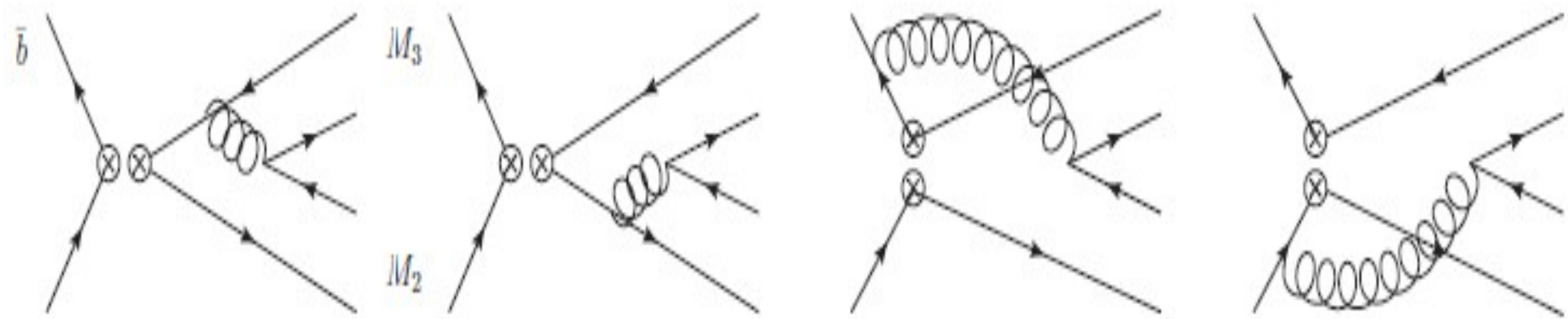
They always come together for any decay channels. No way to be fitted from experiments

Charming Penguin and Annihilation penguin play the same role in phenomenology

For the charming penguin, an additional scale m_c is involved

- $1/m_c$, m_c/m_b expansion is needed
- QCDF and PQCD work well at only the leading order of these power expansion
- SCET (BPRS) parameterize this contribution, since factorization breaks down at the next-to -leading power correction.
- The main source of strong phase needed for direct CP violation, comes from here in BPRS

The annihilation type diagrams are important to the source of strong phases in QCDF and PQCD



- **However, these diagrams have endpoint singularity, not perturbatively calculable in QCDF, but calculable in PQCD.**
- **These divergences are not physical, can only be treated in QCDF as free parameters, which makes CP asymmetry not predictable:**

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

Comparison of the fitted contributions with QCDF results

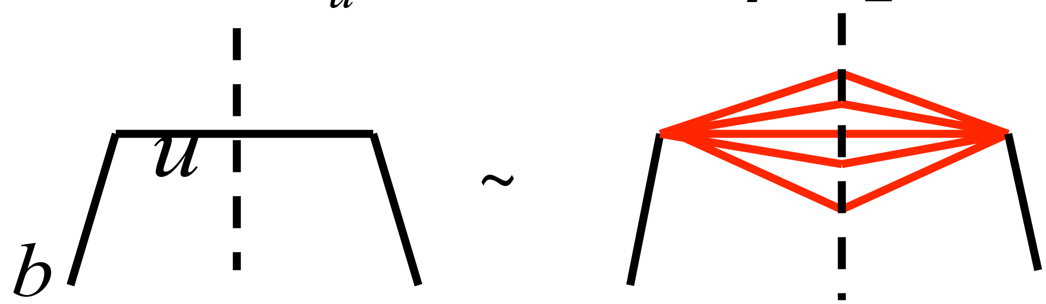
Table 1 The amplitudes and strong phases of topological diagrams in the FAT corresponding to contributions in the QCDF. The topology A and P_E are neglected in the FAT. The electroweak penguin contributions of $\alpha_4^{\rm EW}$, $\beta_3^{\rm EW}$ and $\beta_4^{\rm EW}$ in the QCDF are also neglected in the FAT

Diagram	T	C	P_C	P(PP)	P_{EW}	E	A	P_A(PV)	P_E
FAT	a_1	$\chi^{C^{(\prime)}} e^{i\phi^{C^{(\prime)}}}$	$\chi^{P_C^{(\prime)}} e^{i\phi^{P_C^{(\prime)}}}$	$a_4(\mu) + \chi^P e^{i\phi^P} r_\chi$	$a_9(\mu)$	$\chi^E e^{i\phi^E}$	–	$-i\chi^{P_A} e^{i\phi^{P_A}}$	–
	–	$0.48e^{-1.58i}$	$0.048e^{1.56i}$	$-0.12e^{-0.24i}$	-0.009	$0.057e^{2.71i}$		$0.0059e^{-0.006i}$	
QCDF	α_1	α_2	α_3	α_4	$\alpha_3^{\rm EW}$	β_1	β_2	β_3	β_4
	–	$0.22e^{-0.53i}$	$0.011e^{2.23i}$	$-0.089e^{0.11i}$	$-0.009e^{0.04i}$	0.025	-0.011	-0.008	-0.003

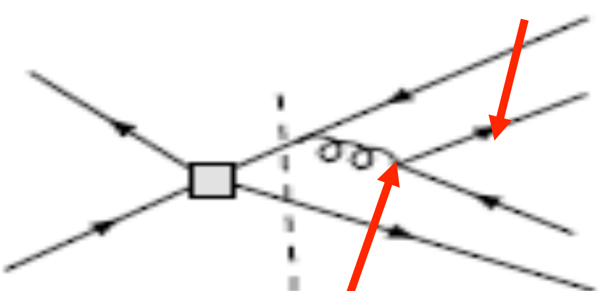
With more and more precise data, power corrections are urgently needed

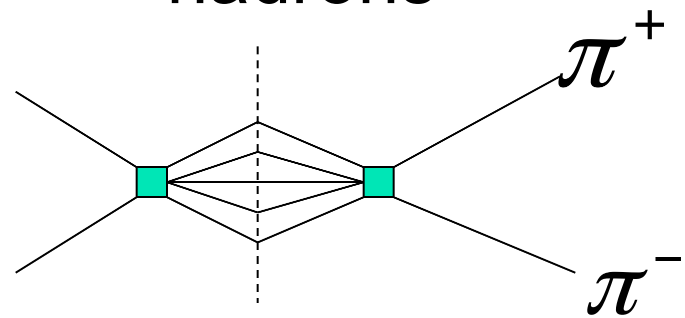
Inclusive Decay and B meson annihilation decay

$B \to X_u l\nu$ $\qquad$ π, ρ, p, n



Cut quark diagram ~ Sum over final-state hadrons





Large strong phase

Thanks