ZPW2025

Particle Physics from Low to High Energies

University of Zurich – January 7, 2025

The Power of EFTs

From HQET to SCET and beyond

Matthias Neubert, Johannes Gutenberg University Mainz

An oeuvre of enormous breadth and impact

Fermion masses and mixing angles

Superalgebras and finite groups

Higgs physics (incl. d=6 effective Lagrangian)

Soft-collinear effective theory

QFT: QCD and EW interactions, anomalies, phase transitions, axions, topological charge …

BSM models: SUSY, little Higgs with T parity, unparticles in astrophysics, axino dark matter …

Charm physics

B-meson physics and CP violation (many directions!)

Lepto-quarks

Kaon physics and effective chiral Lagrangian

SUSY: broken global symmetries, CP violation, radiative fermion masses, flavor physics …

EDMs and dipole moments

Neutrino physics

QCD sum rules

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EDMs and dipole moments

$K^\pm \to \pi^\pm a$ at NLO in χPT and updated bounds on ALP couplings

C. Cornella, A.M. Galda, M. Neubert and D. Wyler, JHEP **06** (2024) 029

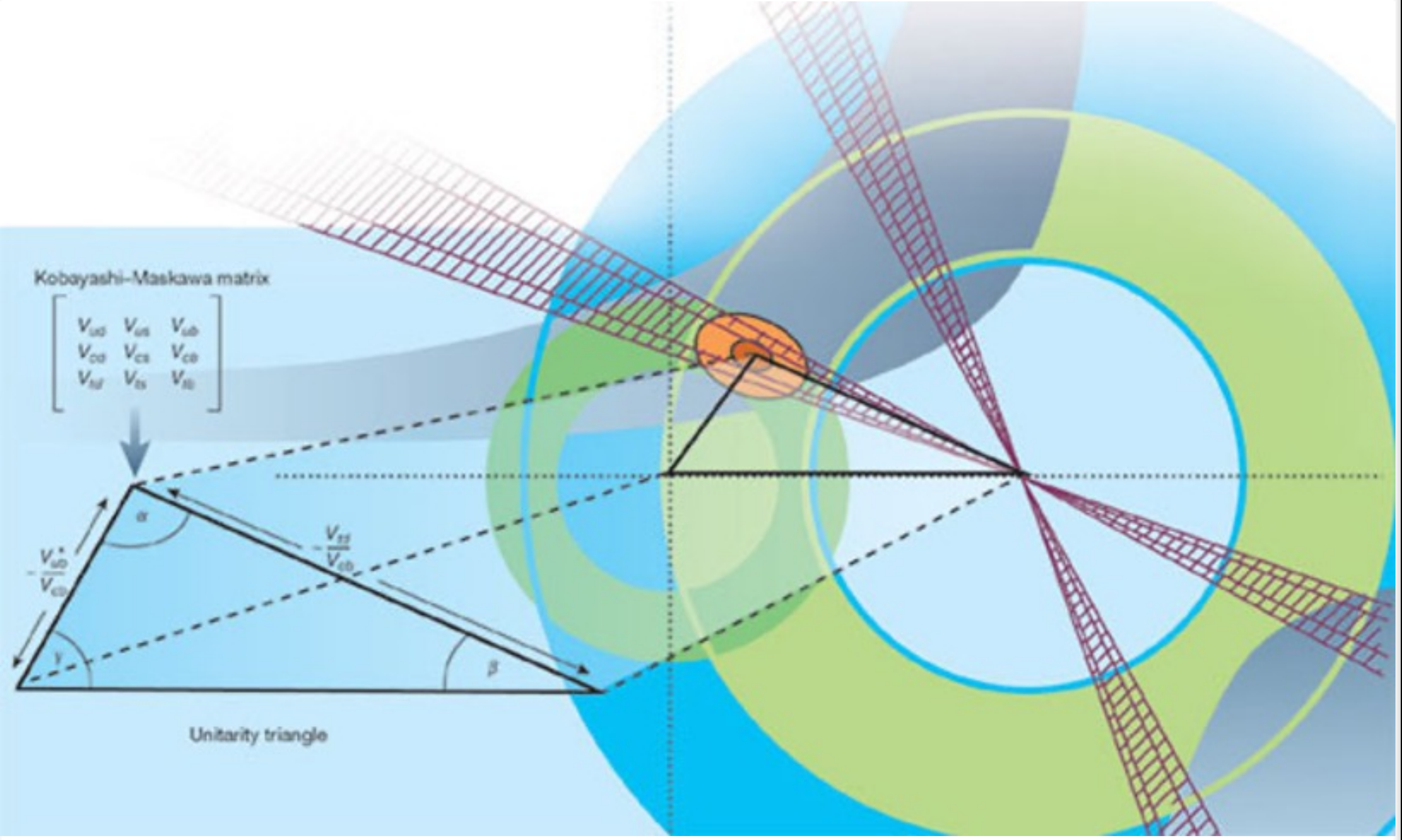
Neutrino physics

QCD sum rules

M. Neubert, "The Flavor of Beauty", Symposium in honor of Prof. Daniel Wyler ("Abschiedskolloquium"), University of Zurich, 8 May 2015

PUSHING THE LUMINOSITY FRONTIER – GOLDEN AGE OF HEAVY-QUARK THEORY

- Tremendous experimental advances:
  - 1. generation: ARGUS & CLEO, LEP expts.
  - 2. generation: BaBar & Belle, LHC*b*, CMS, …
  - 3. generation: Belle II, LHC*b* upgrade, …
- Precise measurement of CKM elements $|V_{cb}|, |V_{ub}|, |V_{td}|, |V_{ts}|$ involving third-generation quarks
- Precise determinations of angles (CP violation)
- New-physics searches using FCNC processes

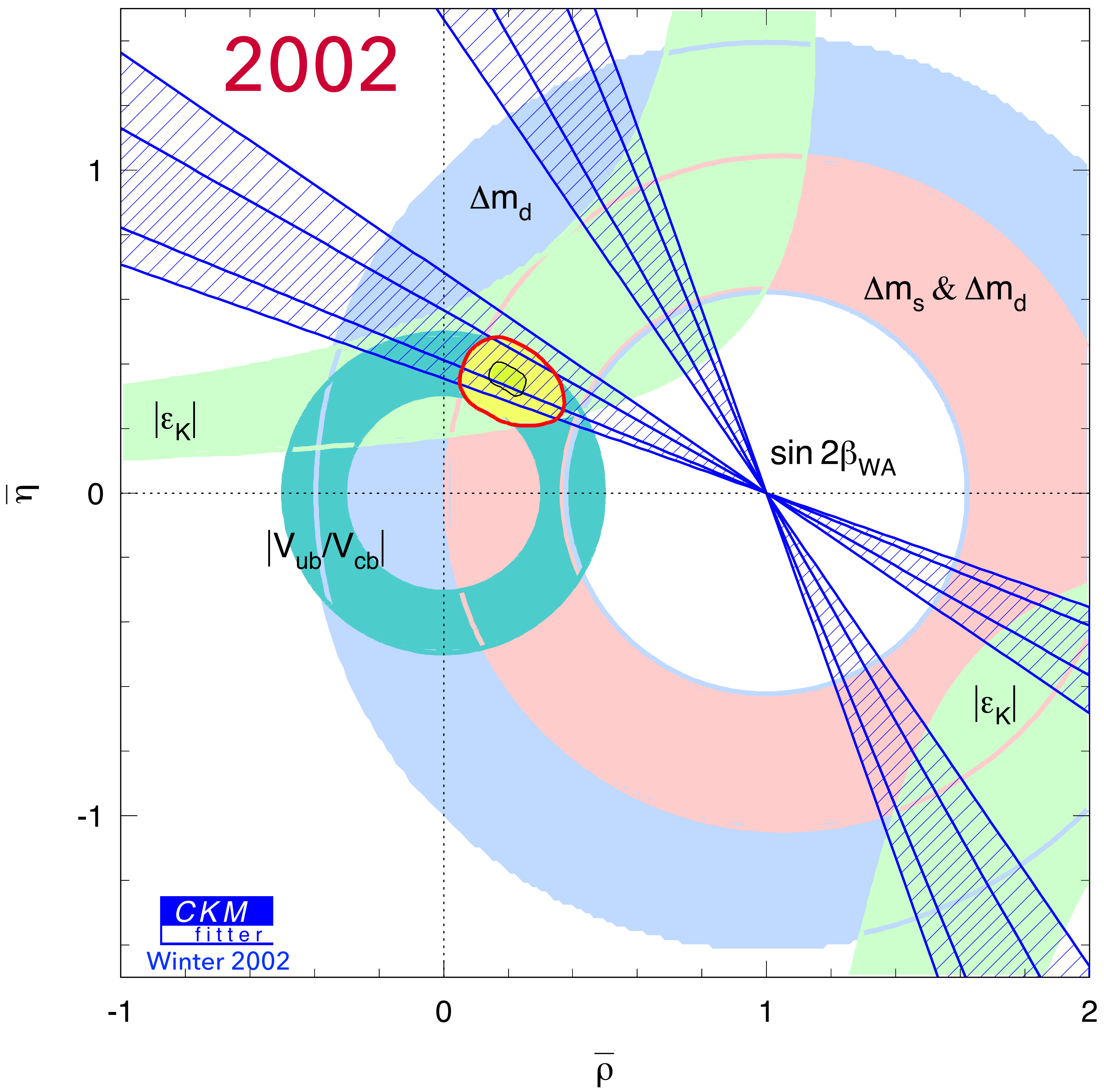


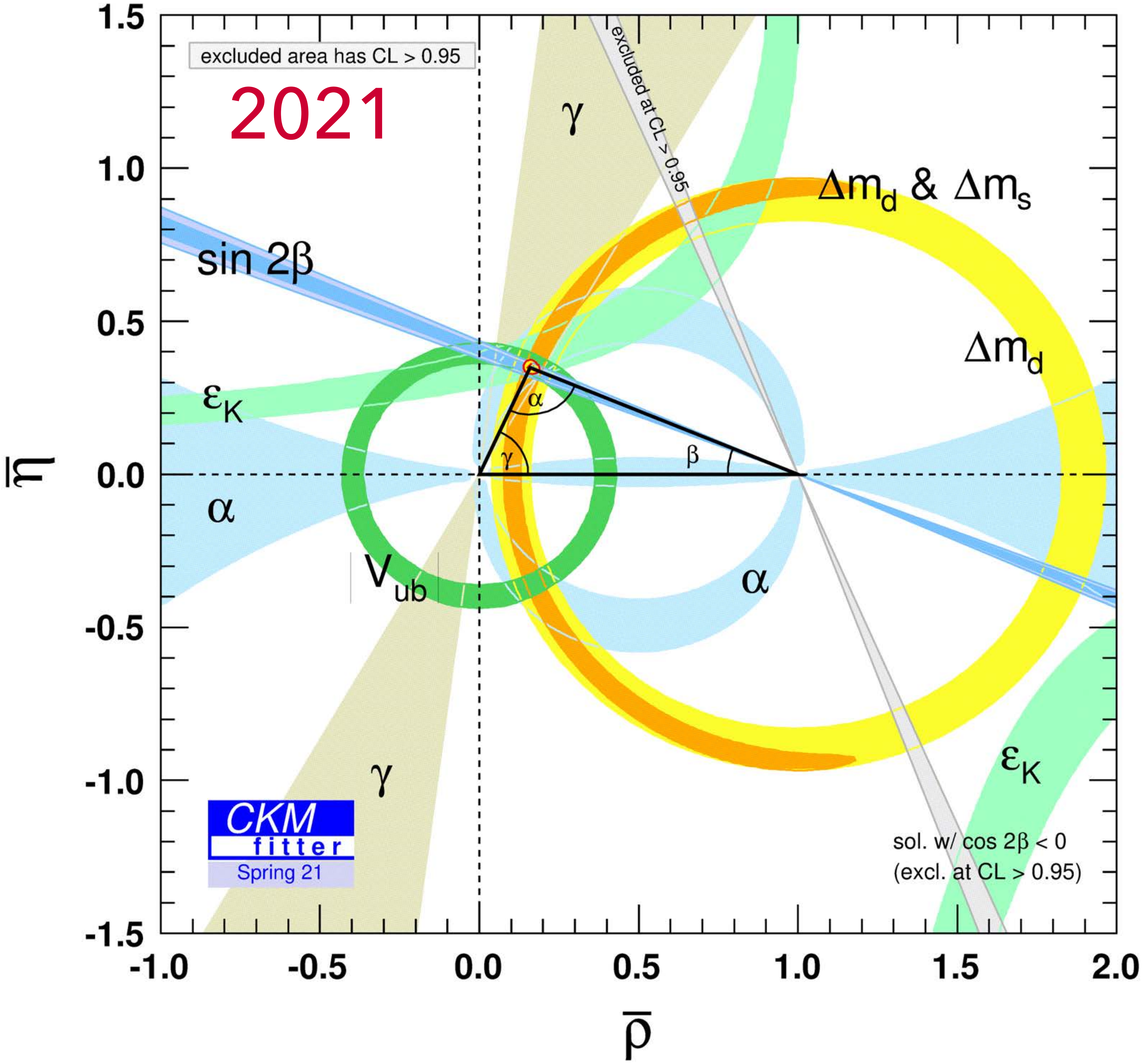
$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \quad (13)$$

Then, we have *CP*-violating effects through the interference among these different current components.

[Kobayashi, Maskawa (1973)]

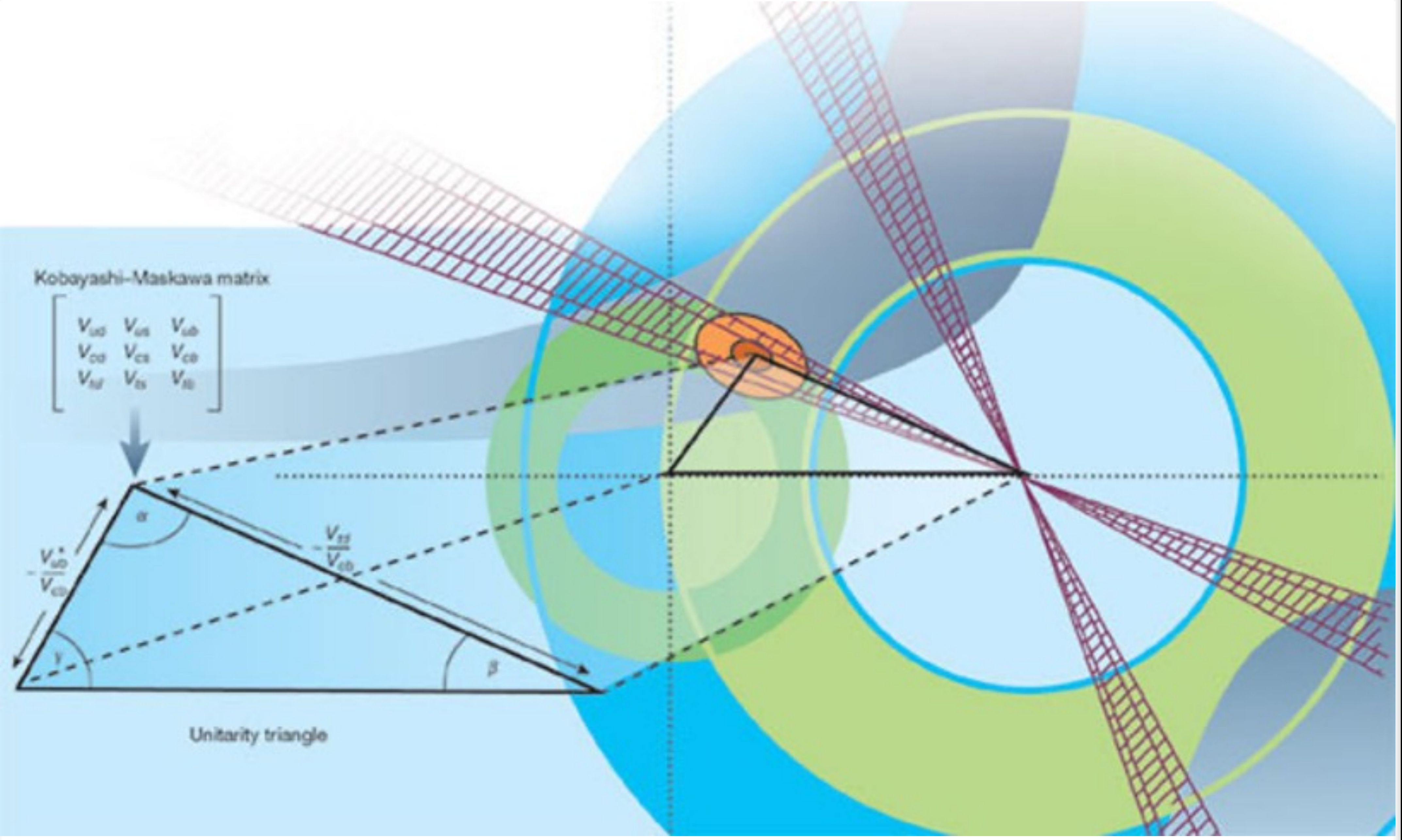
PUSHING THE LUMINOSITY FRONTIER – GOLDEN AGE OF HEAVY-QUARK THEORY





PUSHING THE LUMINOSITY FRONTIER – GOLDEN AGE OF HEAVY-QUARK THEORY

- Matching the incredible precision of the *B*-factories required a revolution in theory
- Concerted effort of theory community was an important consequence
  Breakthrough came from using **effective field theories** (EFTs):
  - $\mathscr{H}_{\text{eff}}^{\text{weak}}$, HQET, NRQCD, QCDF, SCET
- SCET later became a versatile tool for addressing difficult QCD problems

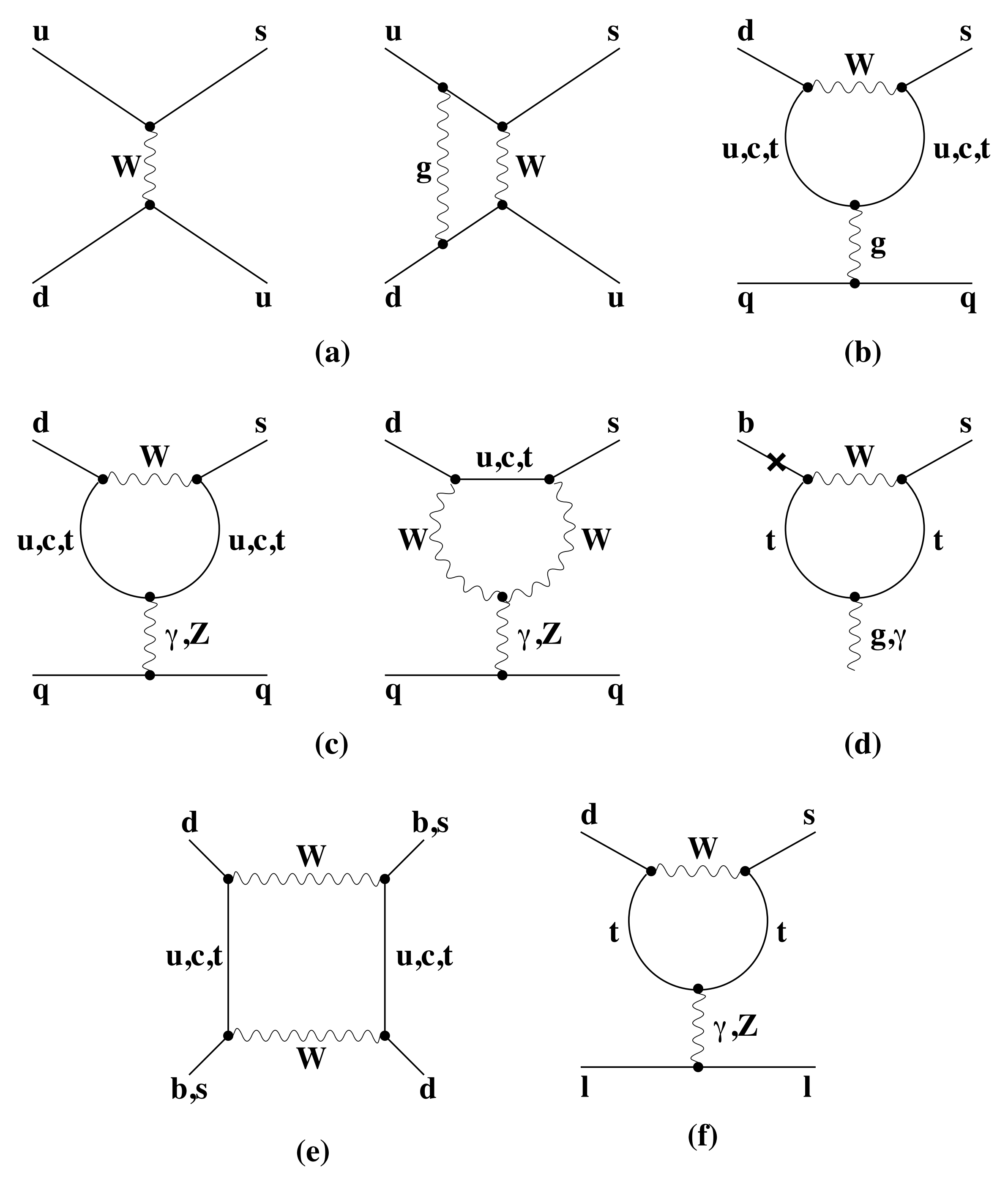


$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have CP-violating effects through the interference among these different current components.

EFFECTIVE WEAK HAMILTONIAN

- Systematic method to separate short-distance effects (weak scale and beyond) from long-distance hadronic dynamics
- Nowadays embedded into SMEFT and its low-energy variant LEFT
- **But:** challenge is to evaluate hadronic matrix elements of the quark-gluon operators $Q_i(\mu)$ in all but simplest cases



$$Q_1^q = (\bar b_i q_j)_{V-A} (\bar q_j d_i)_{V-A}$$
$$Q_2^q = (\bar b q)_{V-A} (\bar q d)_{V-A}$$
$$Q_3 = (\bar b d)_{V-A} \sum_q (\bar q q)_{V-A}$$
$$Q_4 = (\bar b_i d_j)_{V-A} \sum_q (\bar q_j q_i)_{V-A}$$
$$Q_5 = (\bar b d)_{V-A} \sum_q (\bar q q)_{V+A}$$
$$Q_6 = (\bar b_i d_j)_{V-A} \sum_q (\bar q_j q_i)_{V+A}$$
$$Q_7 = \frac{3}{2} (\bar s d)_{V-A} \sum_q e_q (\bar q q)_{V+A}$$
$$Q_8 = \frac{3}{2} (\bar s_i d_j)_{V-A} \sum_q e_q (\bar q_j q_i)_{V+A}$$
$$Q_9 = \frac{3}{2} (\bar s d)_{V-A} \sum_q e_q (\bar q q)_{V-A}$$
$$Q_{10} = \frac{3}{2} (\bar s_i d_j)_{V-A} \sum_q e_q (\bar q_j q_i)_{V-A}$$

$$\mathcal{H}_{\rm eff}(\Delta S = 1) = \frac{G_F}{\sqrt{2}} V_{\rm us}^* V_{\rm ud} \sum_{i=1}^{10} \left(z_i(\mu) + \tau\, y_i(\mu) \right) Q_i(\mu)$$

[Gilman, Wise (1979); Buras et al. (1990s)]

HEAVY QUARK SYMMETRY

- Hadronic bound states containing a heavy quark obey an approximate **spin-flavor symmetry**
- Many predictions for spectroscopy of heavy hadrons [Shuryak (1980)]
- Symmetry relations among $B \to D^{(*)}$ form factors, including symmetry-breaking corrections $\sim \alpha_s(m_Q)$ or $\Lambda_{\rm QCD}/m_Q$ [Isgur, Wise (1990)]

Relations between level spacings in bottom and charm systems, e.g.:

- $m_{B^*}^2 - m_B^2 \approx 0.49\,\text{GeV}^2$ vs. $m_{D^*}^2 - m_D^2 \approx 0.55\,\text{GeV}^2$
- $m_{B_s} - m_B \approx m_{D_s} - m_d \approx 0.10\,\text{GeV}$
- $m_{B_2^*}^2 - m_{B_1}^2 \approx m_{D_2^*}^2 - m_{D_1}^2 \approx 0.17\,\text{GeV}^2$

Form-factor relations:

$$\langle D(v')|V^\mu|B(v)\rangle = h_+(w)\,(v+v')^\mu + h_-(w)\,(v-v')^\mu$$

$$\langle D^*(v',\epsilon)|V^\mu|B(v)\rangle = i h_V(w)\,\epsilon^{\mu\nu\alpha\beta}\epsilon^*_\nu v'_\alpha v_\beta$$

$$\langle D^*(v',\epsilon)|A^\mu|B(v)\rangle = h_{A_1}(w)(w+1)\epsilon^{*\mu} - [h_{A_2}(w)v^\mu + h_{A_3}(w)v'^\mu]\,\epsilon^*\cdot v$$

with ($w = v\cdot v'$):

$$h_+(w) = h_V(w) = h_{A_1}(w) = h_{A_3}(w) = \xi(w) \quad \text{and} \quad \xi(1) = 1$$

$$h_-(w) = h_{A_2}(w) = 0$$

MODEL-INDEPENDENT DETERMINATION OF $|V_{CB}|$

- Extrapolate observed spectrum in $w = v \cdot v'$ to zero recoil:

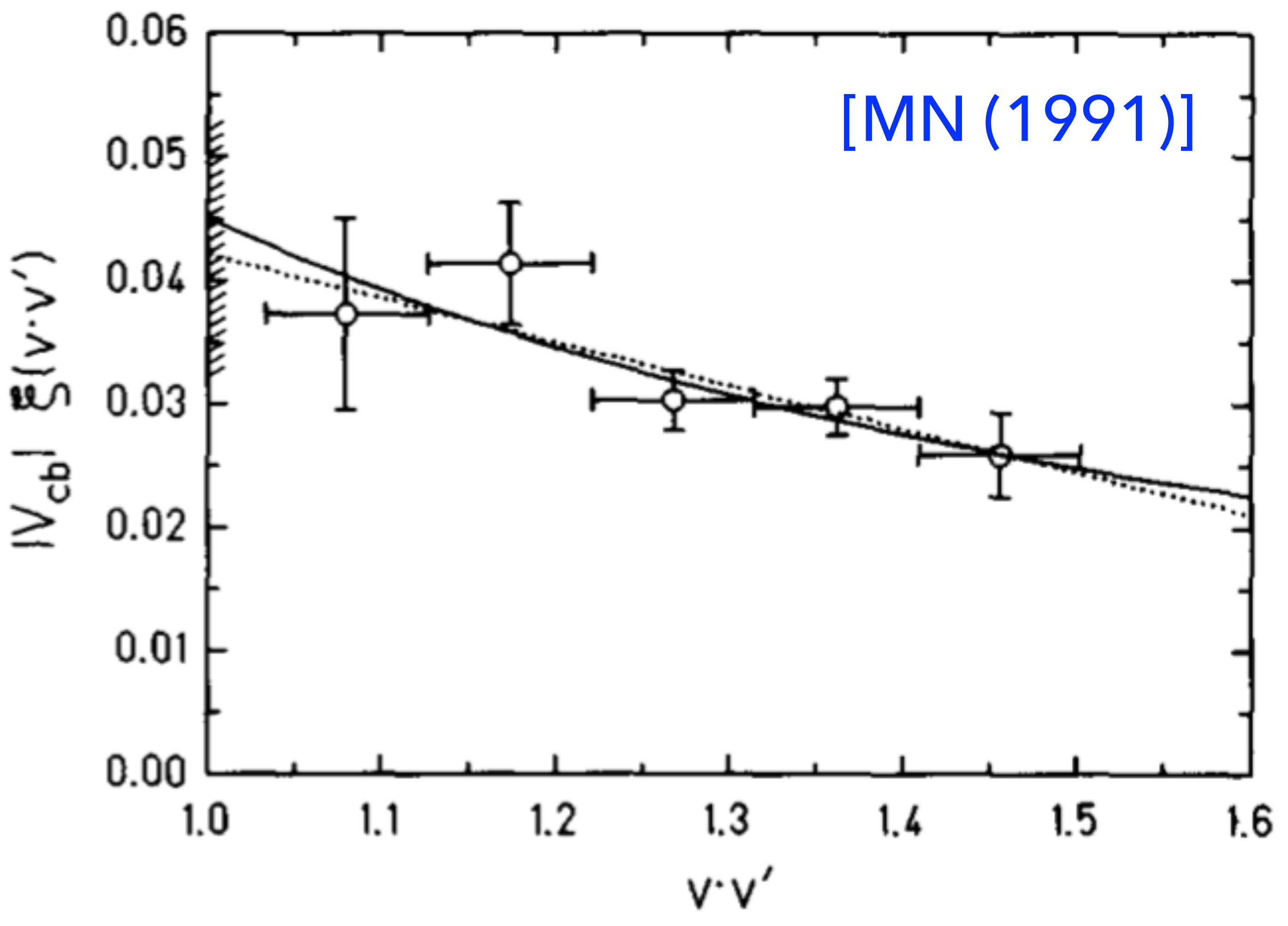
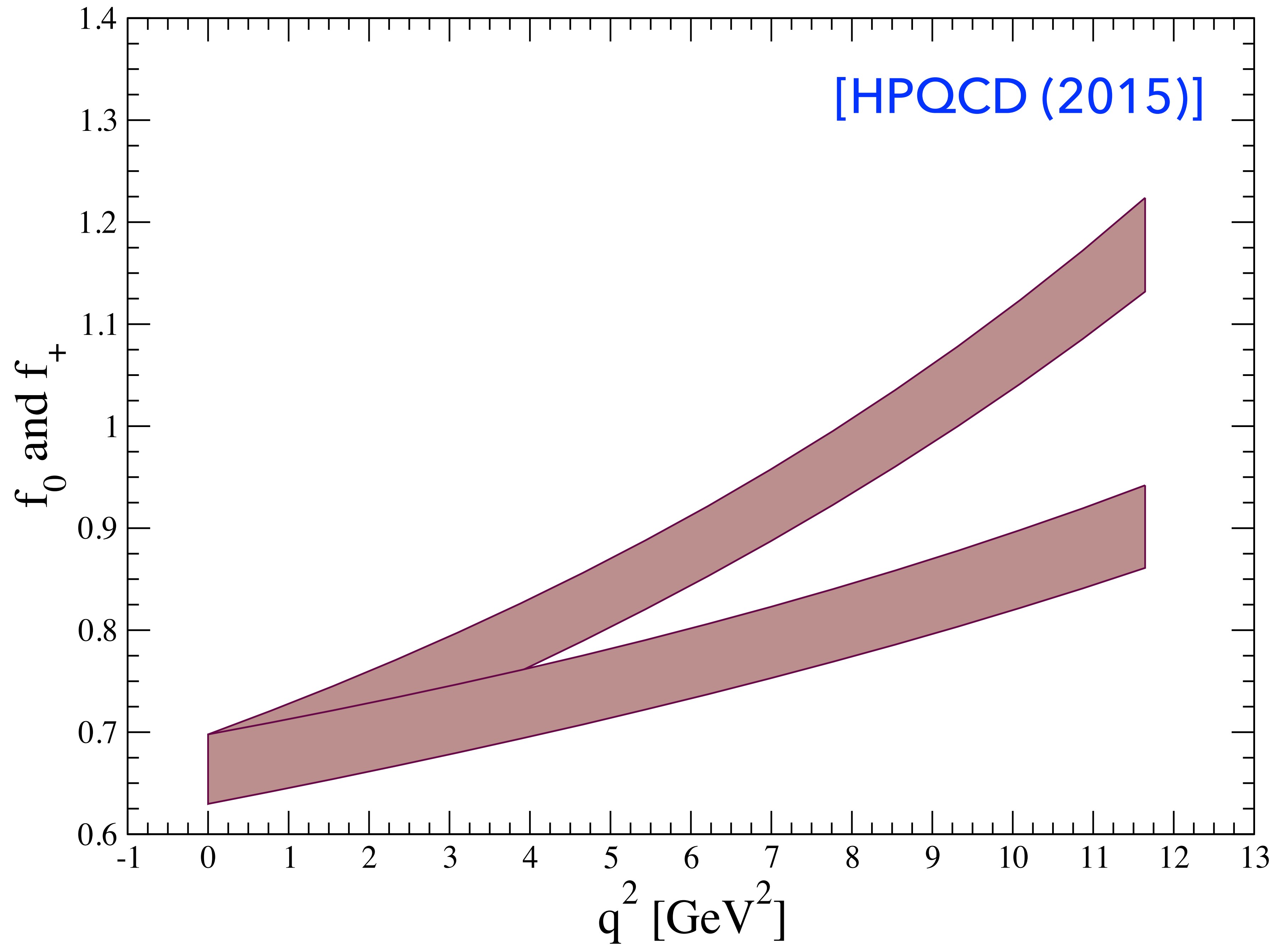


Fig. 1. Extraction of $|V_{cb}|$ and the Isgur–Wise function from $\bar{B}^0 \to D^{*+} \ell \bar{\nu}_\ell$ decays. The data are taken from ref. [16]. $\tau_{B^0} = 1.18$ ps is assumed. $|V_{cb}|$ follows from an extrapolation of the data to $v \cdot v' = 1$. Its currently best value is indicated as a shaded area on the vertical axis.

- Direct calculation of the $B \to Dl\nu$ form factors (HPQCD):



HEAVY QUARK EFFECTIVE THEORY (HQET)

[Eichten, Hill (1990); Georgi (1990)]

- Firm theoretical basis for deriving heavy-quark symmetry and its consequences

$$\mathcal{L}_{\text{HQET}} = \bar{h}_v\, iv\cdot D\, h_v + \mathcal{O}\!\left(\frac{1}{m_Q}\right)$$
$$+\frac{1}{2m_Q}\left[\bar{h}_v\,(iD)^2\,h_v + \frac{g_s}{2}\,\bar{h}_v\,\sigma_{\mu\nu}G^{\mu\nu}h_v\right] + \dots$$

THE GRAND CHALLENGE: NON-LEPTONIC DECAYS

- Georgi: *"Why we can't calculate …"* [Georgi: *Weak Interactions and Modern Particle Theory* (1984)]
- Naive factorization approach was semi-successful in describing early data, but lacked a firm theoretical foundation [Bauer, Stech, Wirbel (1986)]

THE GRAND CHALLENGE: NON-LEPTONIC DECAYS

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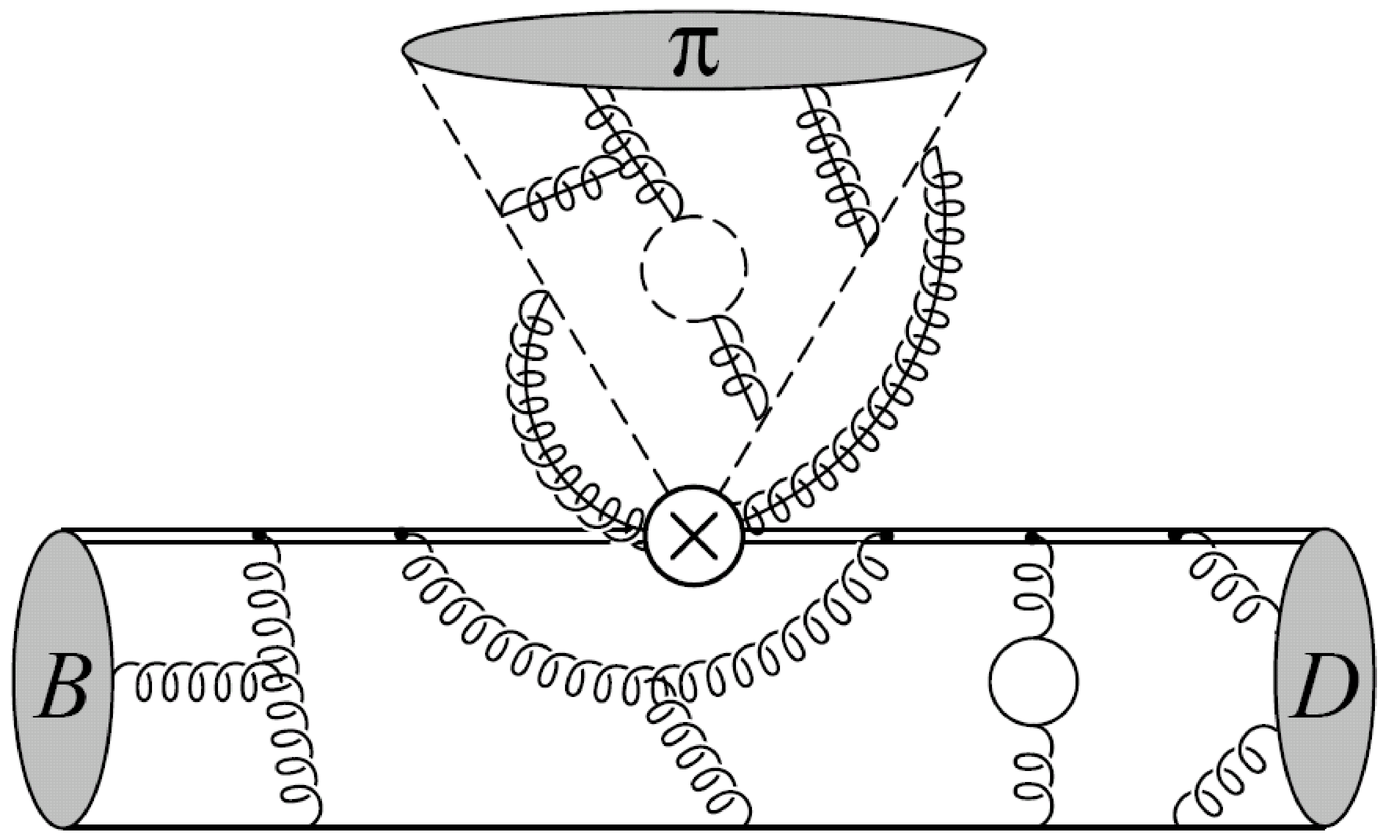
- Naive factorization approach was semi-successful in describing early data, but lacked a firm theoretical foundation [Bauer, Stech, Wirbel (1986)]
- **QCD factorization approach (BBNS):**
  - First model-independent calculation of $B \to M_1 M_2$ decay amplitudes from first principles (including strong- and weak-interaction phases) in heavy-quark limit

[Beneke, Buchalla, MN, Sachrajda (1999–2001)]

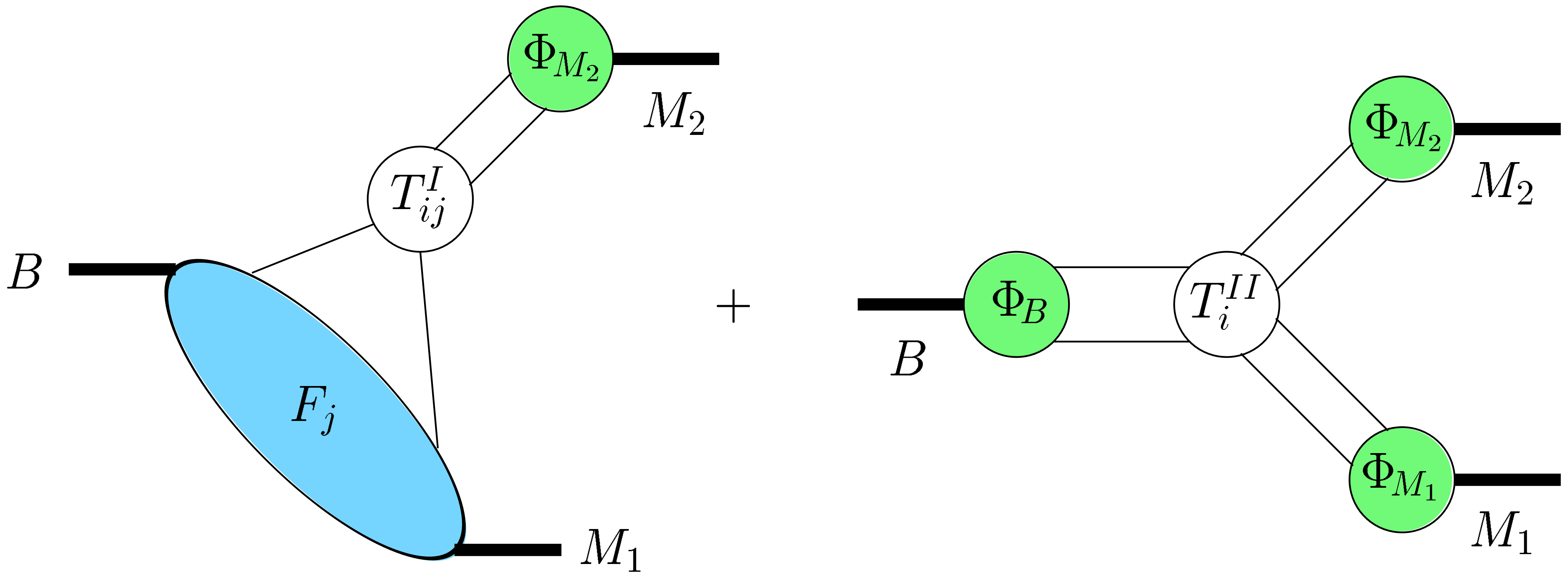


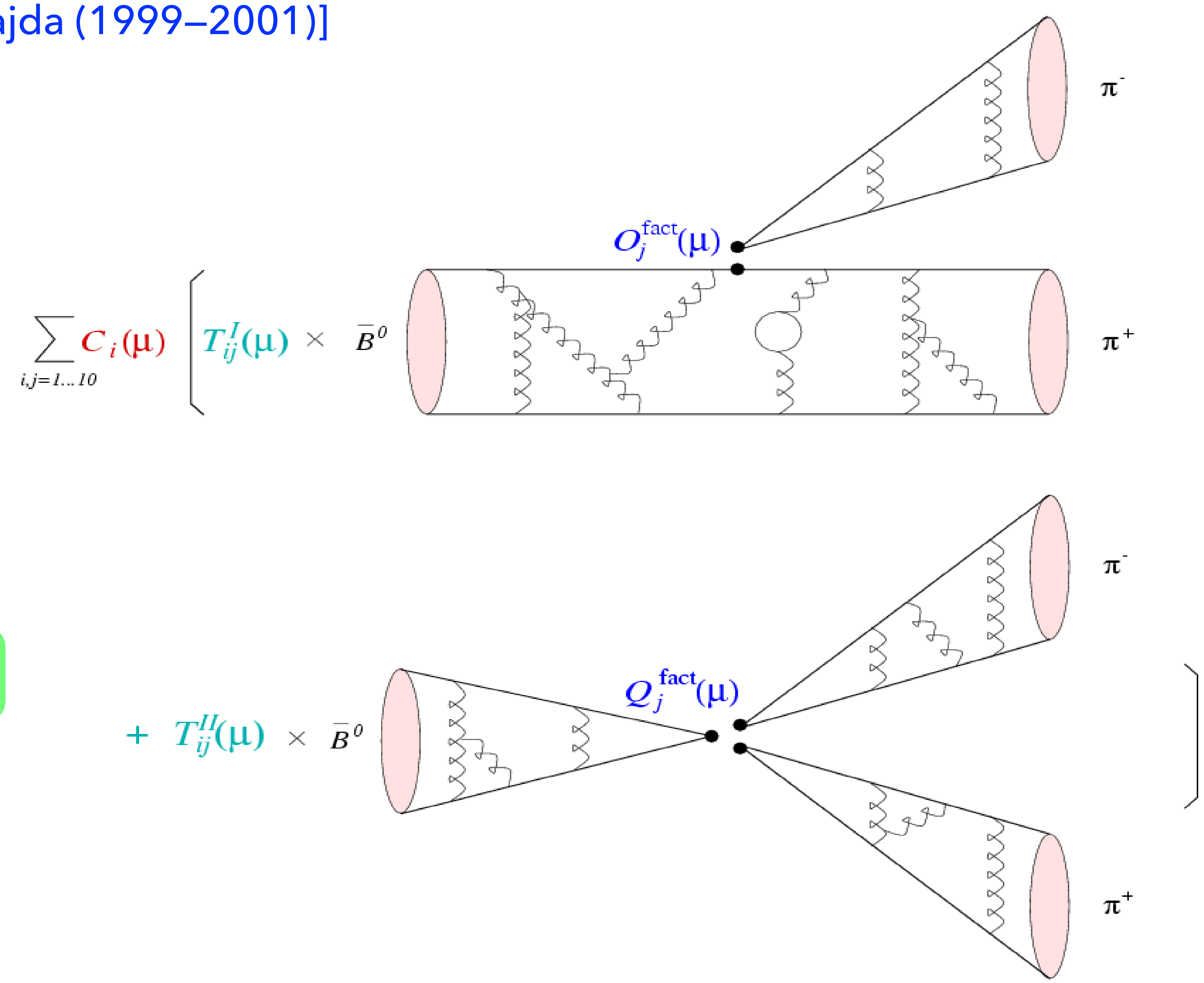
Factorization proof at two-loop order based on method of regions, see pp. 48-79 in BBNS (2000)

QCD FACTORIZATION IN NONLEPTONIC B DECAYS INTO LIGHT MESONS

QCD factorization theorem:

[Beneke, Buchalla, MN, Sachrajda (1999–2001)]





$$\langle \pi K | Q_i | B \rangle = F_0^{B\to\pi}\, T^{\rm I}_{K,i} * f_K \Phi_K + F_0^{B\to K}\, T^{\rm I}_{\pi,i} * f_\pi \Phi_\pi + T^{\rm II}_i * f_B \Phi_B * f_K \Phi_K * f_\pi \Phi_\pi$$
$$+\mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

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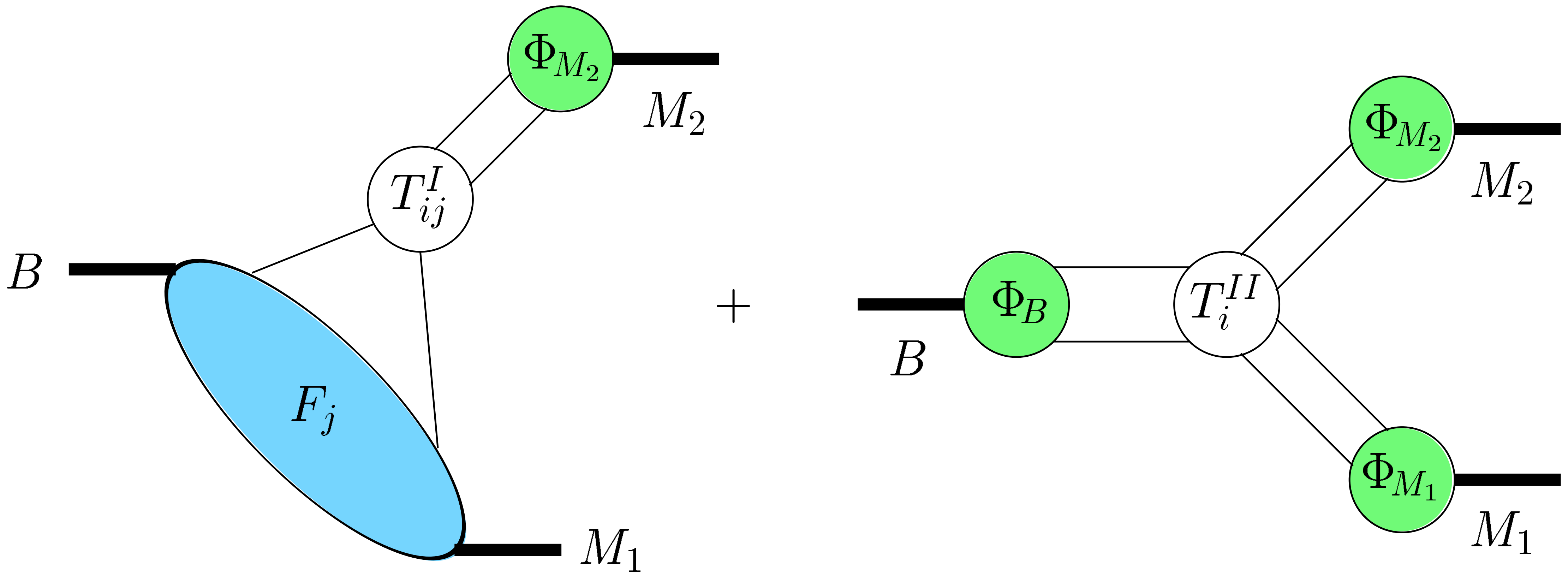
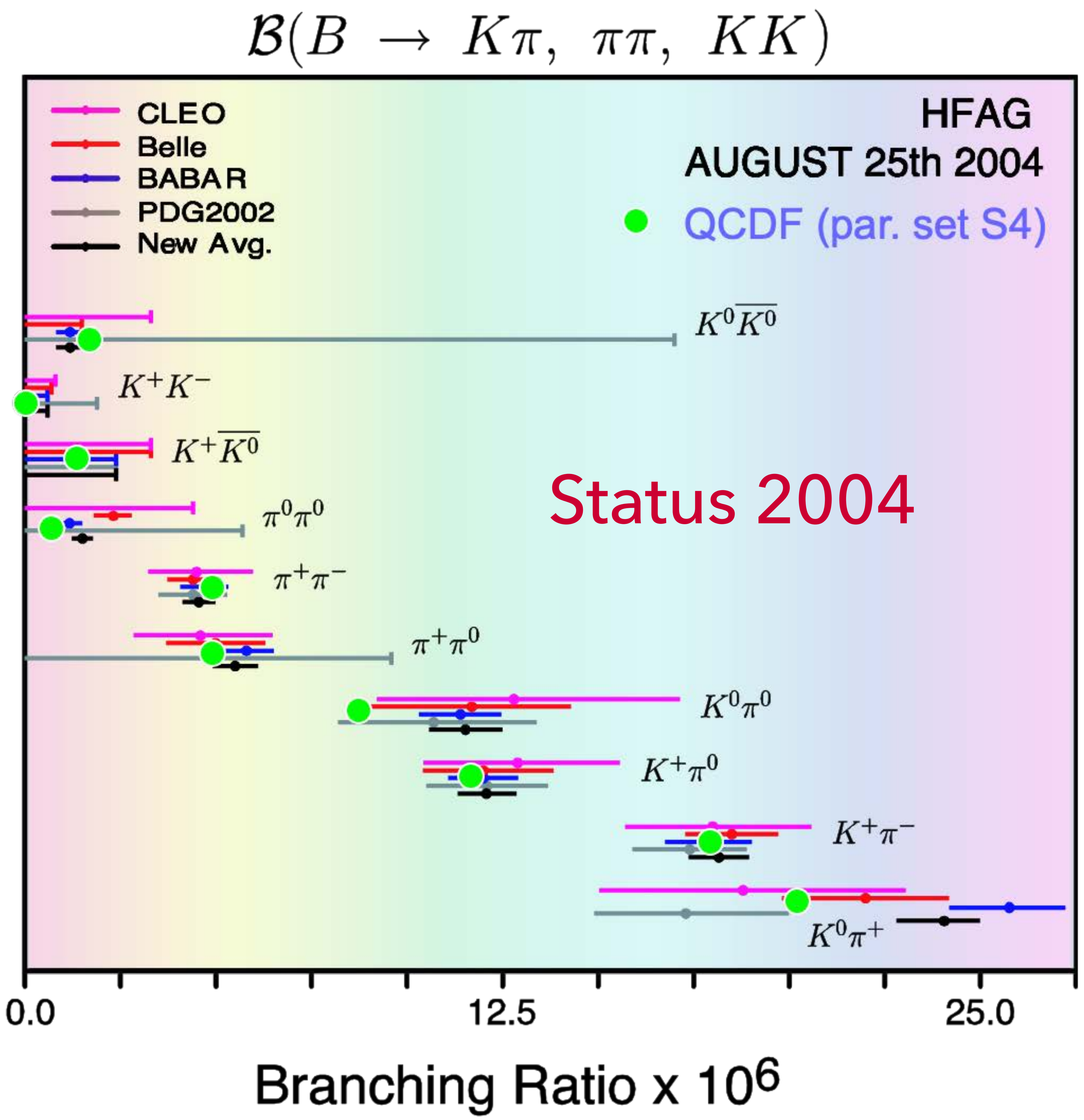
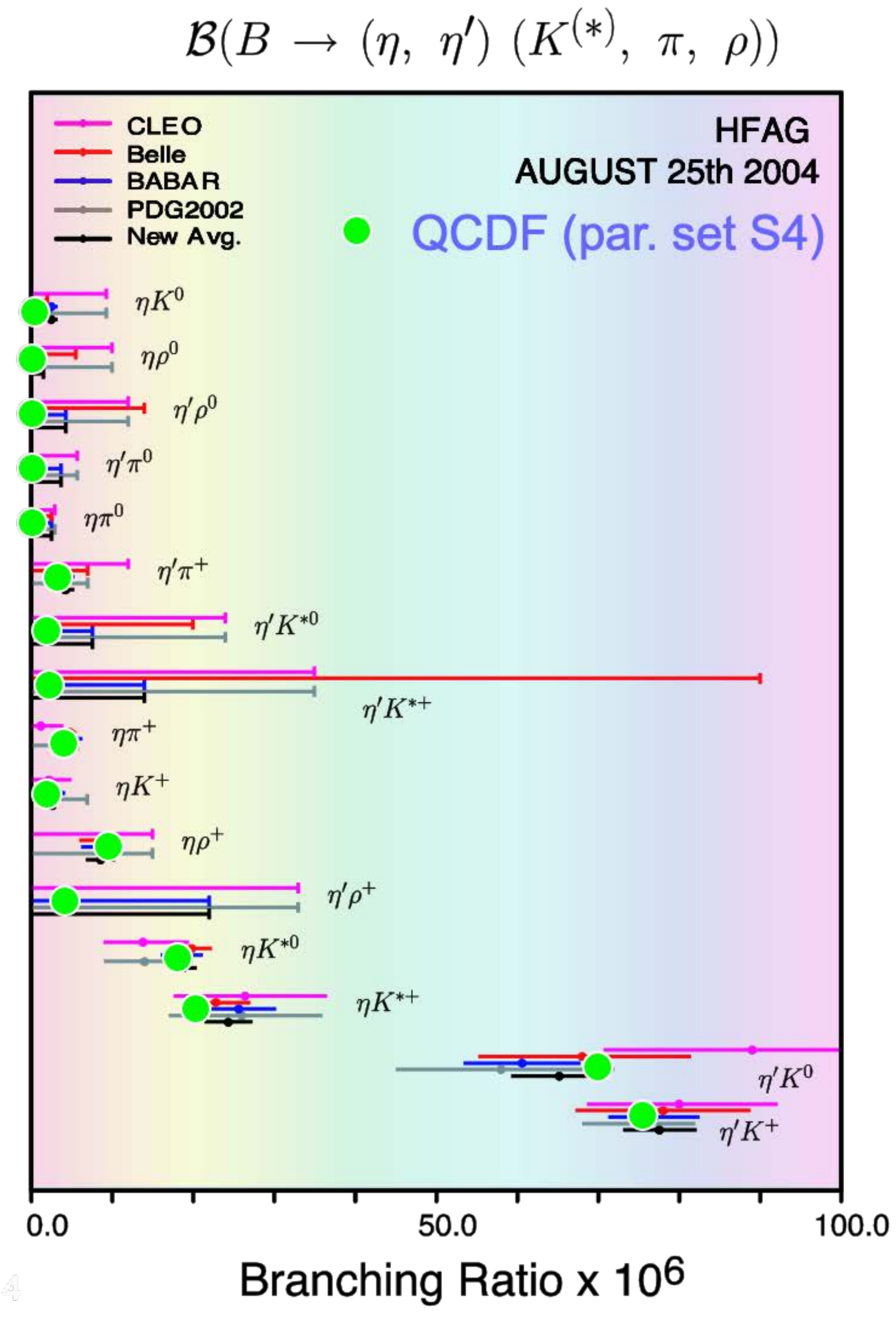


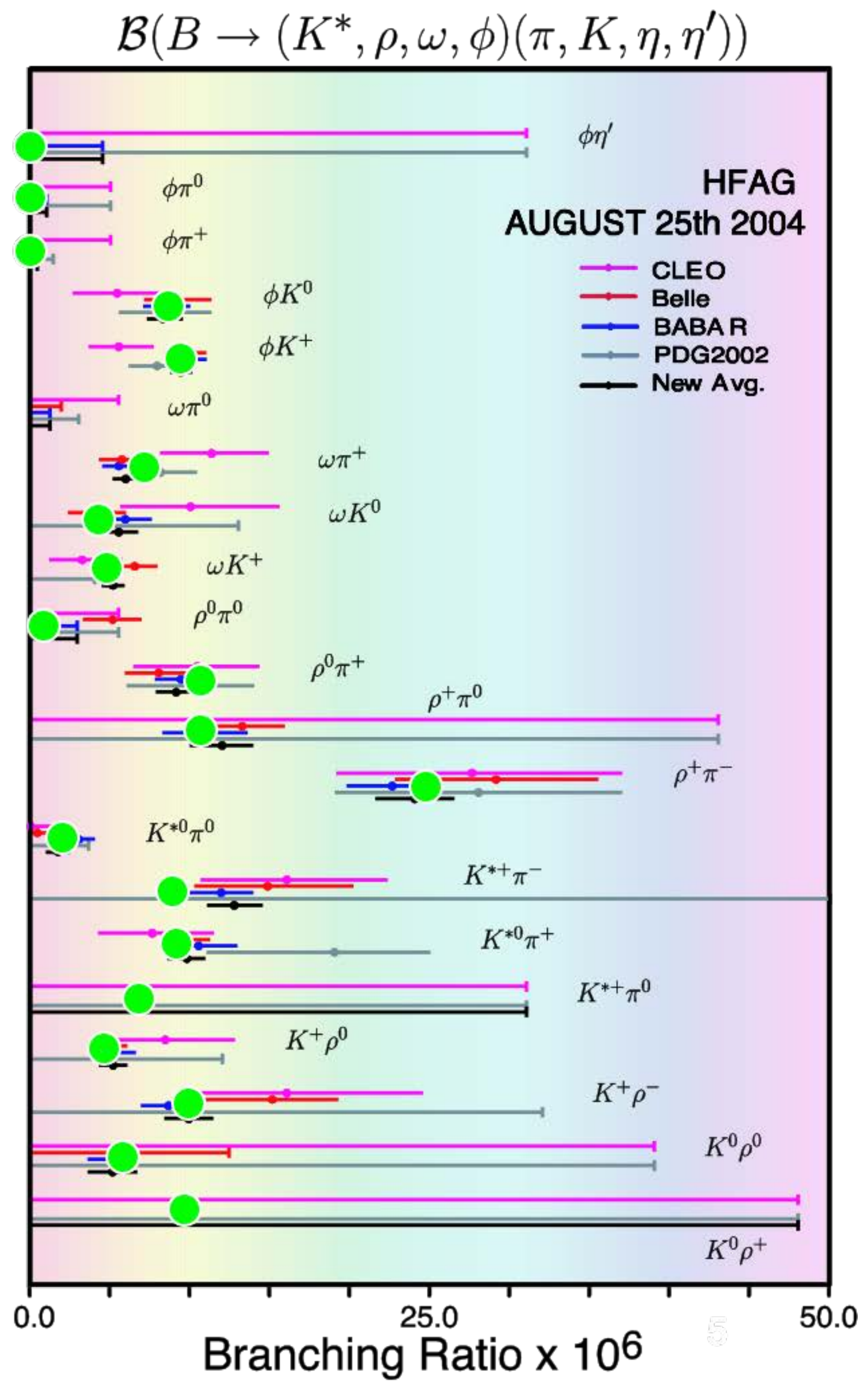
$$\langle \pi K | Q_i | B \rangle = F_0^{B\to\pi}\, T^{\rm I}_{K,i} * f_K \Phi_K + F_0^{B\to K}\, T^{\rm I}_{\pi,i} * f_\pi \Phi_\pi + T^{\rm II}_i * f_B \Phi_B * f_K \Phi_K * f_\pi \Phi_\pi + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

- Importance of **non-local hadronic matrix elements**, in particular light-cone distribution amplitudes (LCDAs), to account for hadronic dynamics
- Second term corresponds to Brodsky-Lepage (1980), while the first term is specific for *B*-meson decays and contributes at the same order in $\Lambda_{\rm QCD}/m_b$

QCD FACTORIZATION IN NONLEPTONIC B DECAYS INTO LIGHT MESONS







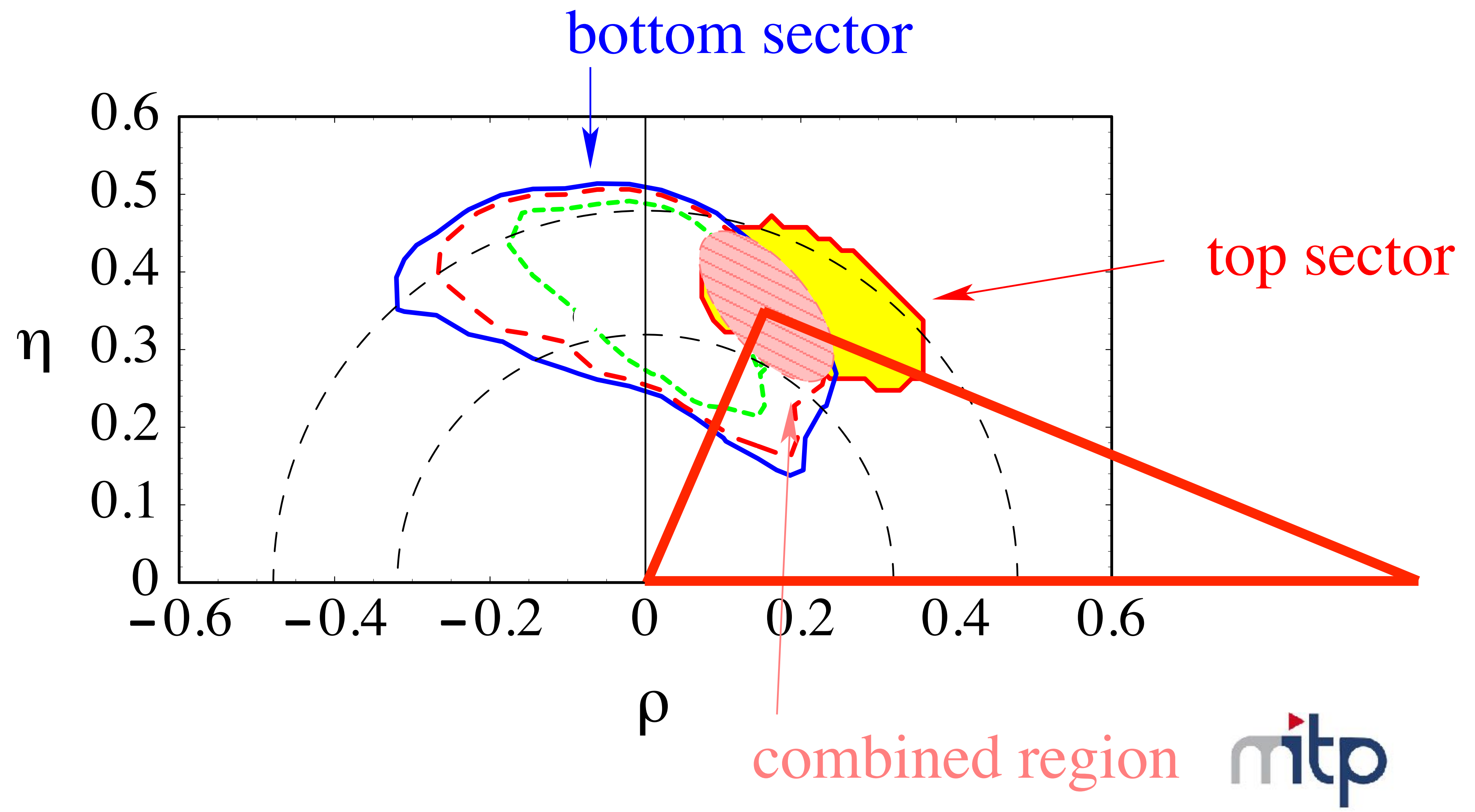
[Beneke, MN (2003)]

CONFIRMATION OF KM RELATION BETWEEN IM(V_{UB}) AND IM(V_{TB})

- In 2001, fact that $\text{Im}(V_{td}) \neq 0$ had been established by studies of $K - \bar{K}$ and $B - \bar{B}$ mixing and first measurements of $\sin 2\beta$
- Fact that $\text{Im}(V_{ub}) \neq 0$ has been established by studying rare hadronic decays $B \to \pi K, \pi\pi$ in QCD factorization [BBNS (2001), here updated to 2004 data]
- **KM relation confirmed;** most stringent test of KM mechanism at the time

2004 analysis: $\bar{\rho} = 0.15 \pm 0.08, \ \bar{\eta} = 0.36 \pm 0.09$
$\gamma = (67 \pm 15)^\circ, \quad \beta = (24 \pm 2)^\circ$

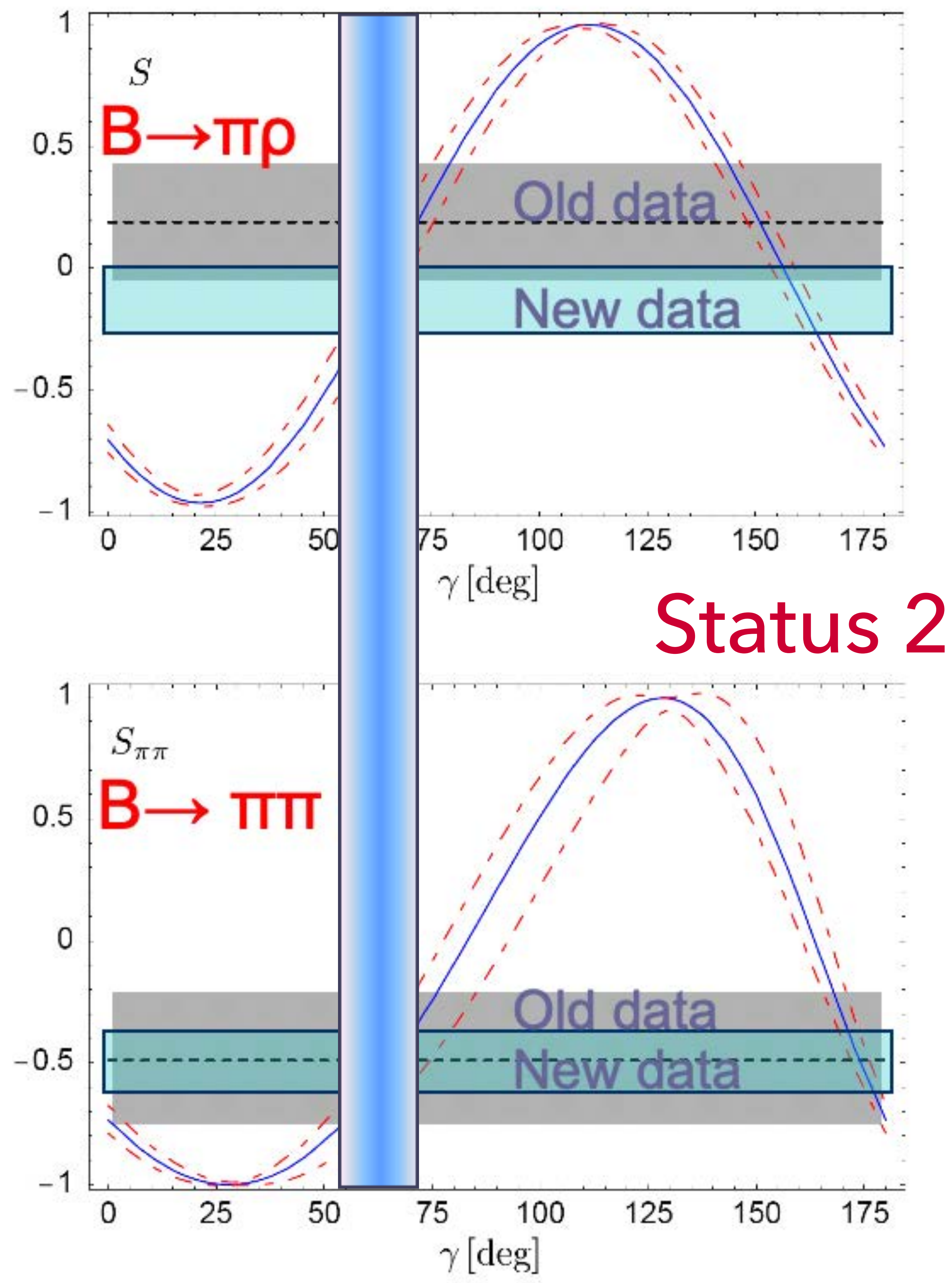
2021 values: $\bar{\rho} = 0.157^{+0.009}_{-0.005}, \ \bar{\eta} = 0.347^{+0.012}_{-0.005}$
$\gamma = (65.5^{+1.3}_{-1.2})^\circ, \quad \beta = (22.42^{+0.64}_{-0.37})^\circ$
[CKMfitter global fit, spring 2021]



CONFIRMATION OF KM RELATION BETWEEN IM(V_{UB}) AND IM(V_{TB})

- Measuring time-dependent CP asymmetries in $B \to \pi\pi$ and $B \to \pi\rho$ decays one obtains an internally consistent determination of γ
- 2003 analysis found: $\gamma = (62 \pm 8)^\circ$
- 2021 value: $\gamma = (65.5^{+1.3}_{-1.2})^\circ$

$\hookrightarrow$ Gronau–Wyler method

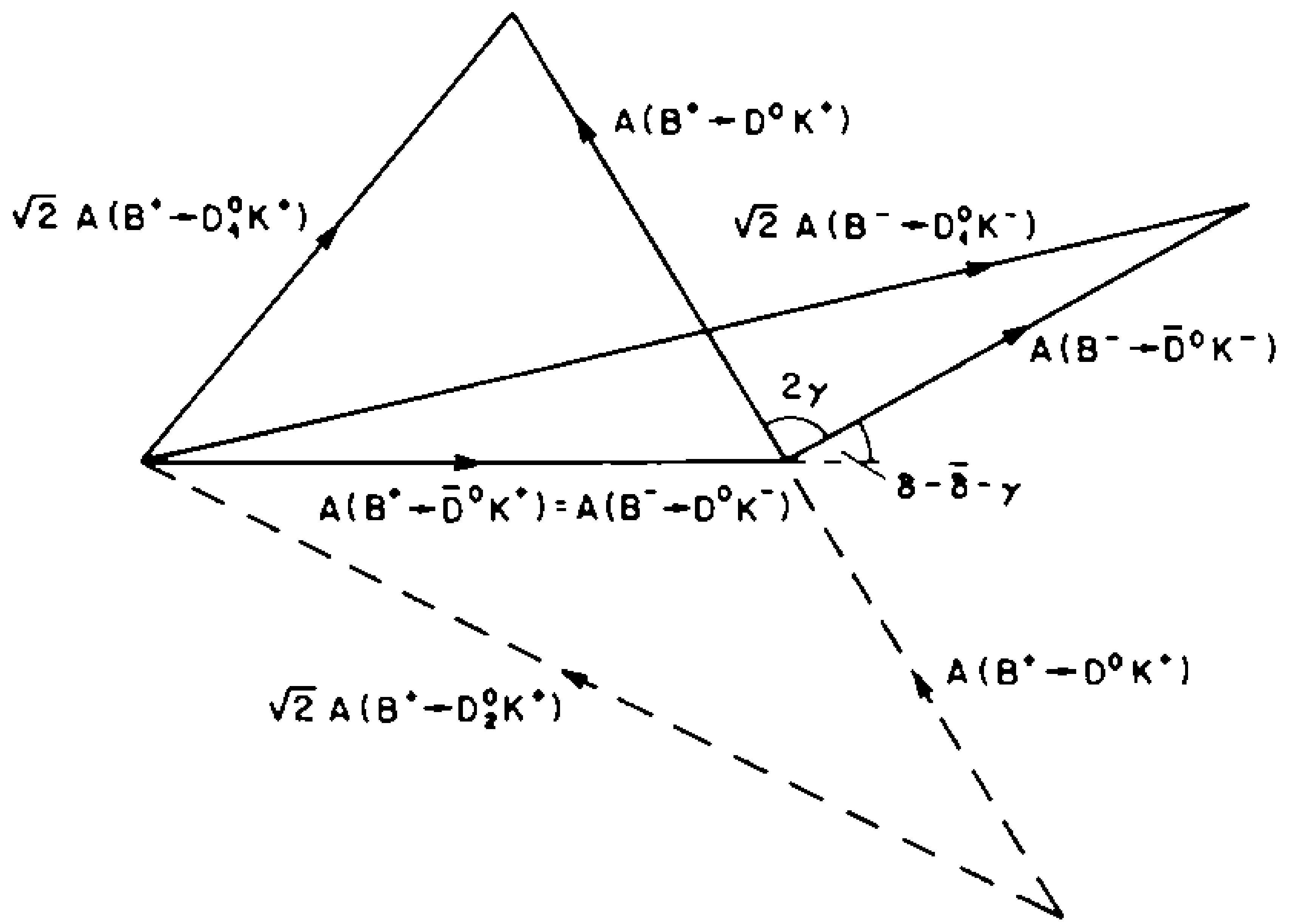


Status 2003

[Beneke, MN (2003)]

GRONAU-WYLER METHODE

[Gronau, Wyler (1991)]



$$\sin\gamma=\frac{1}{4|A\bar{A}|}\left(\pm\{[(|A|+|\bar{A}|)^2-2|A_1^+|^2]\times[2|A_1^-|^2-(|A|-|\bar{A}|)^2]\}^{1/2}\pm\{[(|A|+|\bar{A}|)^2-2|A_1^-|^2]\times[2|A_1^+|^2-(|A|-|\bar{A}|)^2]\}^{1/2}\right),$$

Physics Letters B 265 (1991) 172–176
North-Holland

A pioneering paper!
(1141 citations)

PHYSICS LETTERS B

On determining a weak phase from charged B decay asymmetries

Michael Gronau
Technion – Israel Institute of Technology, Haifa 32000, Israel

and

Daniel Wyler
Institute for Theoretical Physics, University of Zurich, Schönberggasse 9, CH-8001 Zurich, Switzerland

Received 27 May 1991

We demonstrate a possible determination of the weak phase γ from the CP asymmetry in $B^+\to D^0_{1(2)}X^-$, where $D^0_{1(2)}$ is a CP-even (odd) state and X^+ is any hadronic state with the flavor of a $K^\pm$. To obtain the phase one needs separate measurements of the rates $\Gamma(B^+\to D^0_{1(2)}X^+)$ and of the equal rates $\Gamma(B^\pm\to D^0X^\pm)=\Gamma(B^+\to\bar{D}^0X^\mp)$. Certain ambiguities are discussed and resolutions are proposed.

$$\sqrt{2}\,A(B^+\to D^0_1K^+)=|A|\exp(i\gamma)\exp(i\delta)+|\bar{A}|\exp(i\bar{\delta}),$$
$$\sqrt{2}\,A(B^-\to D^0_1K^-)=|A|\exp(-i\gamma)\exp(i\delta)+|\bar{A}|\exp(i\bar{\delta}).$$

$$\sqrt{2}\,A(B^+\to D^0_1K^+)=A(B^+\to D^0K^+)+A(B^+\to\bar{D}^0K^+),$$
$$\sqrt{2}\,A(B^-\to D^0_1K^-)=A(B^-\to\bar{D}^0K^-)+A(B^-\to D^0K^-).$$

LIMITATIONS OF QCD FACTORIZATION

- Lots of predictive power, but uncertainties due to hadronic input quantities: form factors, decay constants, and LCDAs (reducible to some extent)
- **Power corrections in** Λ_{QCD}/m_b do not (naively) factorize due to **endpoint divergences** ($\Rightarrow$ different meanings of "factorization")
- In some cases, power-suppressed effects can be enhanced by large Wilson coefficients (e.g. "color-suppressed" decay modes)
- To make progress, one needed an EFT implementation of QCD factorization

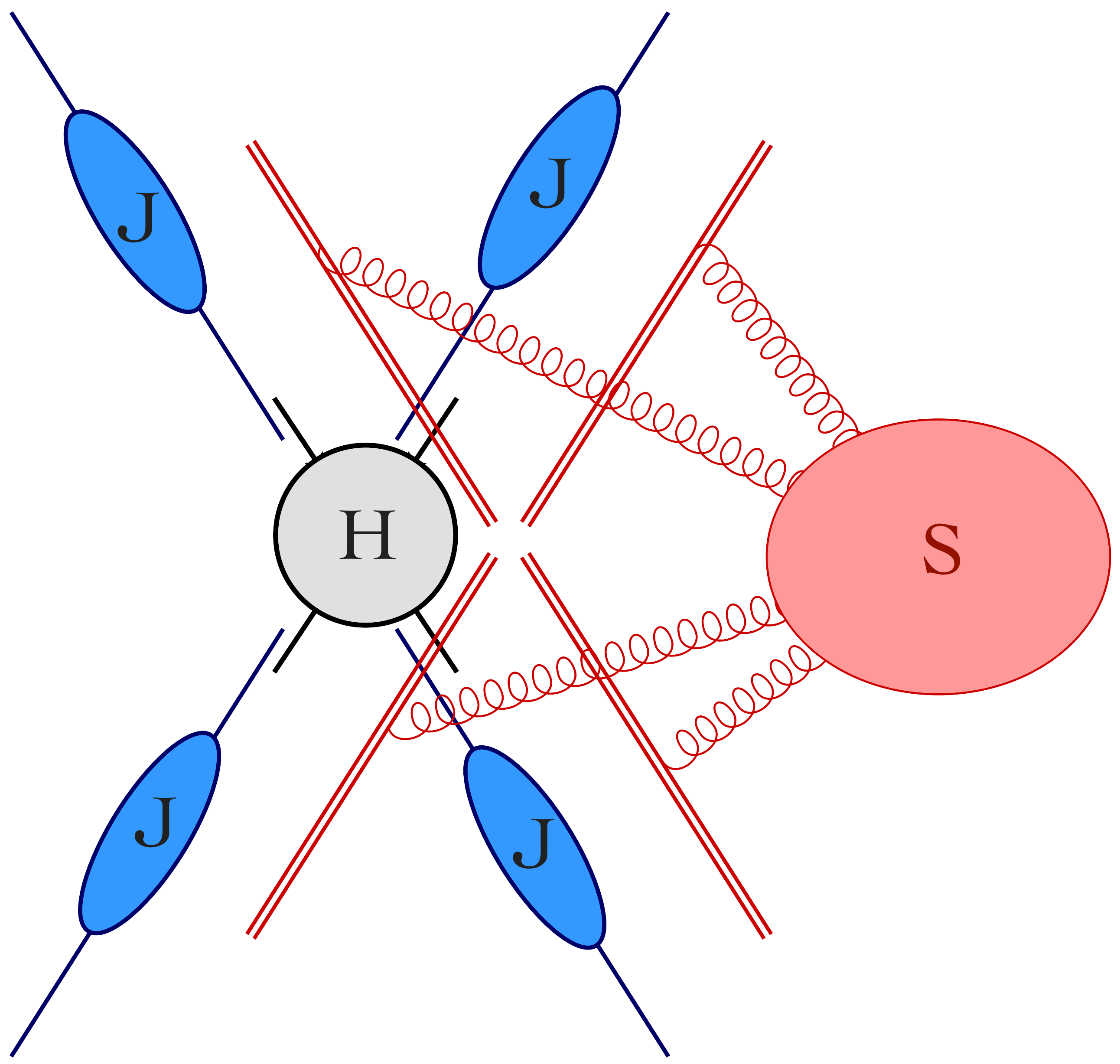
SOFT-COLLINEAR EFFECTIVE THEORY (SCET)

[Bauer, (Fleming,) Pirjol, Stewart (2001); Beneke, Chapovski, Diehl, Feldmann (2002)]

- Firm theoretical basis for deriving QCD factorization theorems in heavy-quark and collider physics for processes involving light energetic particles
- Collinear effective Lagrangian:

$$\mathcal{L}_n = \bar{\xi}_n(x) \left[in\cdot D_n + gn\cdot A_s + i\not{\mathcal{D}}_n^\perp \frac{1}{i\bar{n}\cdot\mathcal{D}_n} i\not{\mathcal{D}}_n^\perp \right] \frac{\not{\bar{n}}}{2} \xi_n(x) + \dots$$

eikonal interaction, can be removed by the field redefinition $\xi_n \to S_n \xi_n^{(0)}$

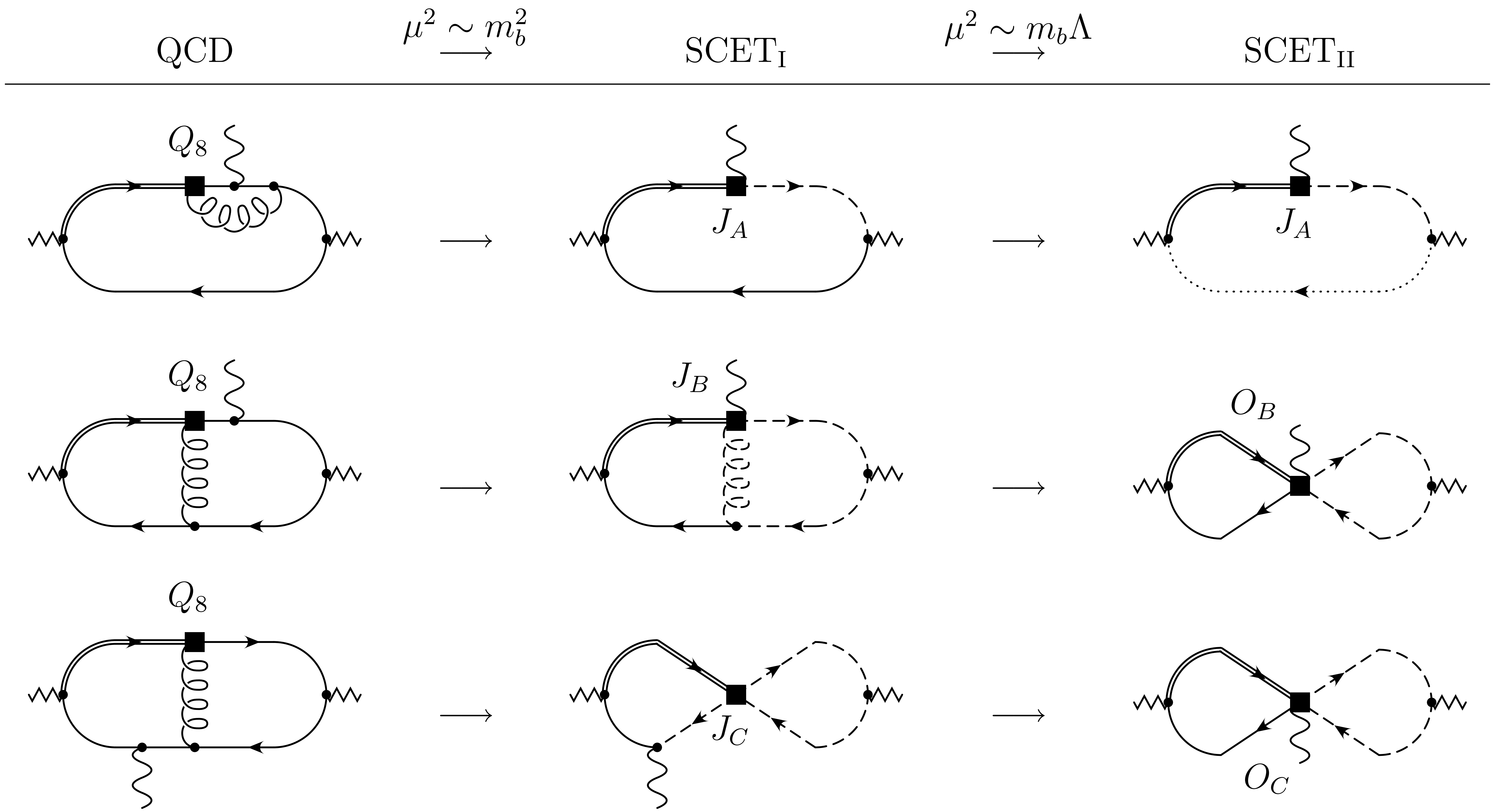


- Soft-collinear factorization at Lagrangian level
- Scale separation and resummation accomplished using powerful EFT tools

SCET PROOF OF QCD FACTORIZATION FOR $B \to K^*\gamma$ DECAY

[Becher, Hill, MN (2005)]

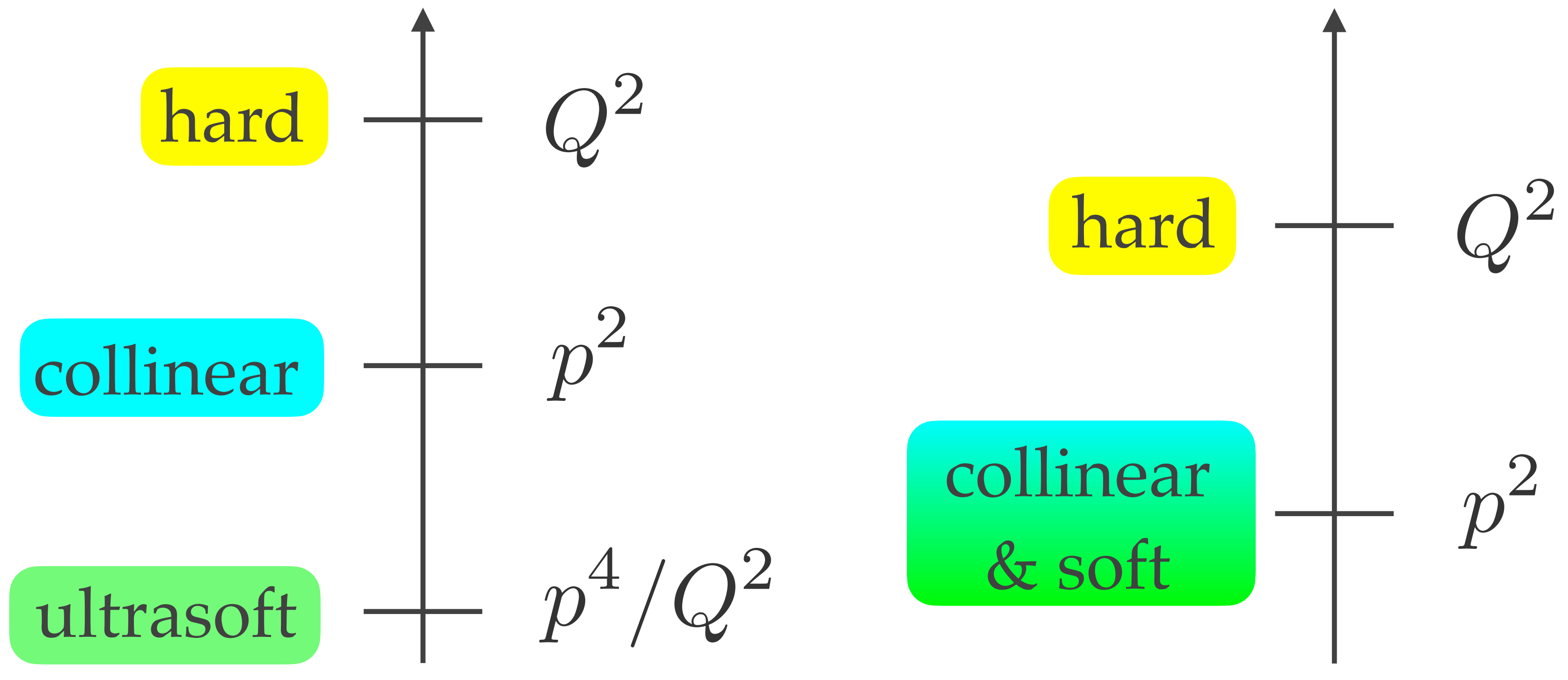
Two-step matching procedure QCD → SCET-1 → SCET-2:



PROTOTYPICAL SCET FACTORIZATION THEOREM

Product/convolution of component functions each depending on a single scale:

$$\sigma \sim \underbrace{H}_{\text{hard}} \int \underbrace{J \otimes J}_{\text{collinear}} \otimes \underbrace{S}_{\text{soft}}$$



SCET-1 SCET-2

- Extension to next-to-leading power is a hard problem, due to **endpoint-divergent convolution integrals** [Beneke et al. ; Moult et al.; Stewart et al.; Bell et al. (2018–2022)]
- **Refactorization-based subtraction** (RBS) scheme provides a consistent framework for dealing with this problem [Liu, MN (2019, 2020); Liu, Mecaj, MN, Wang (2021); Liu, MN, Schnubel, Wang (2022)]

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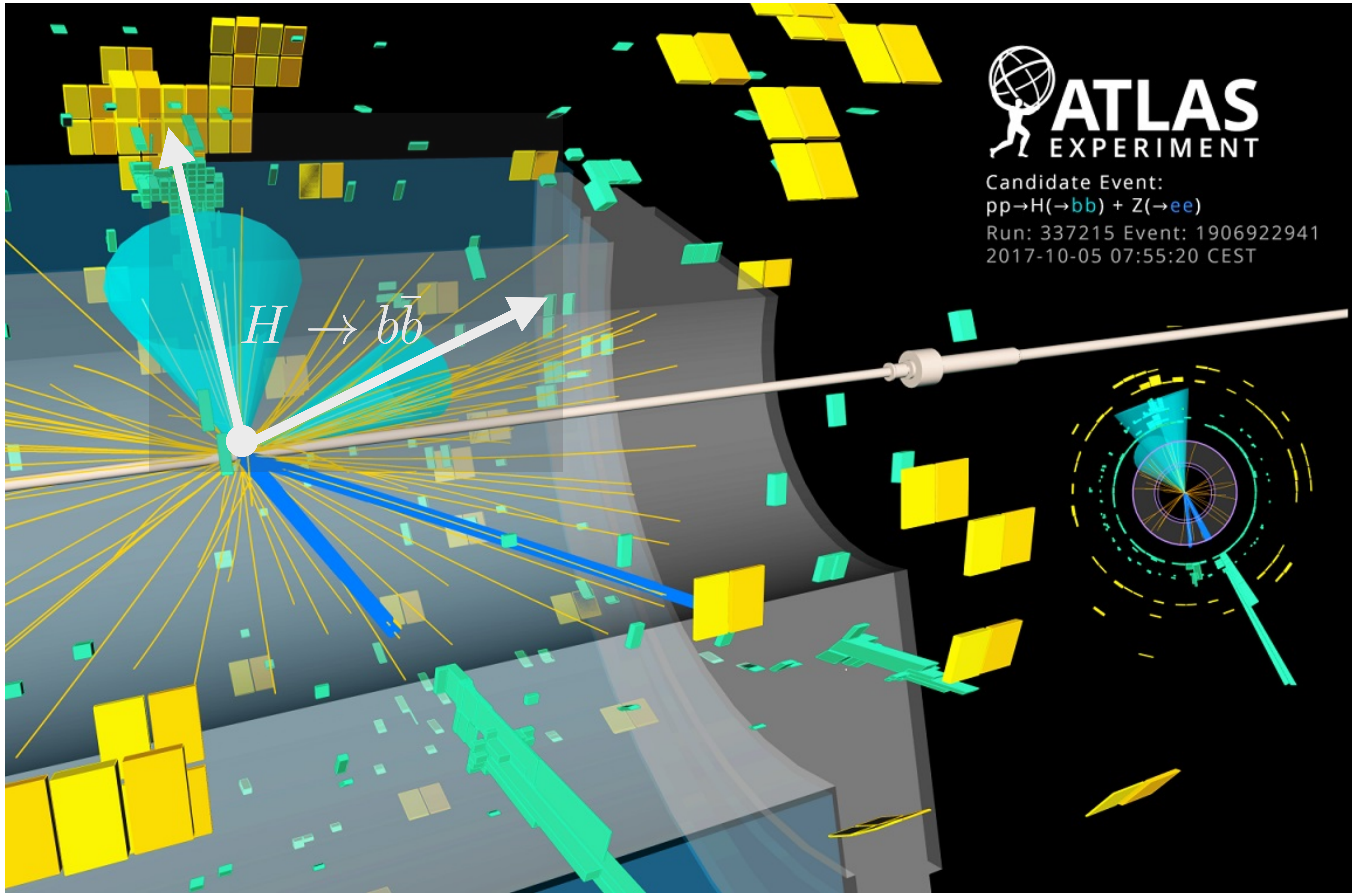
Particle Physics from Low to High Energies

GAP-BETWEEN-JETS OBSERVABLES



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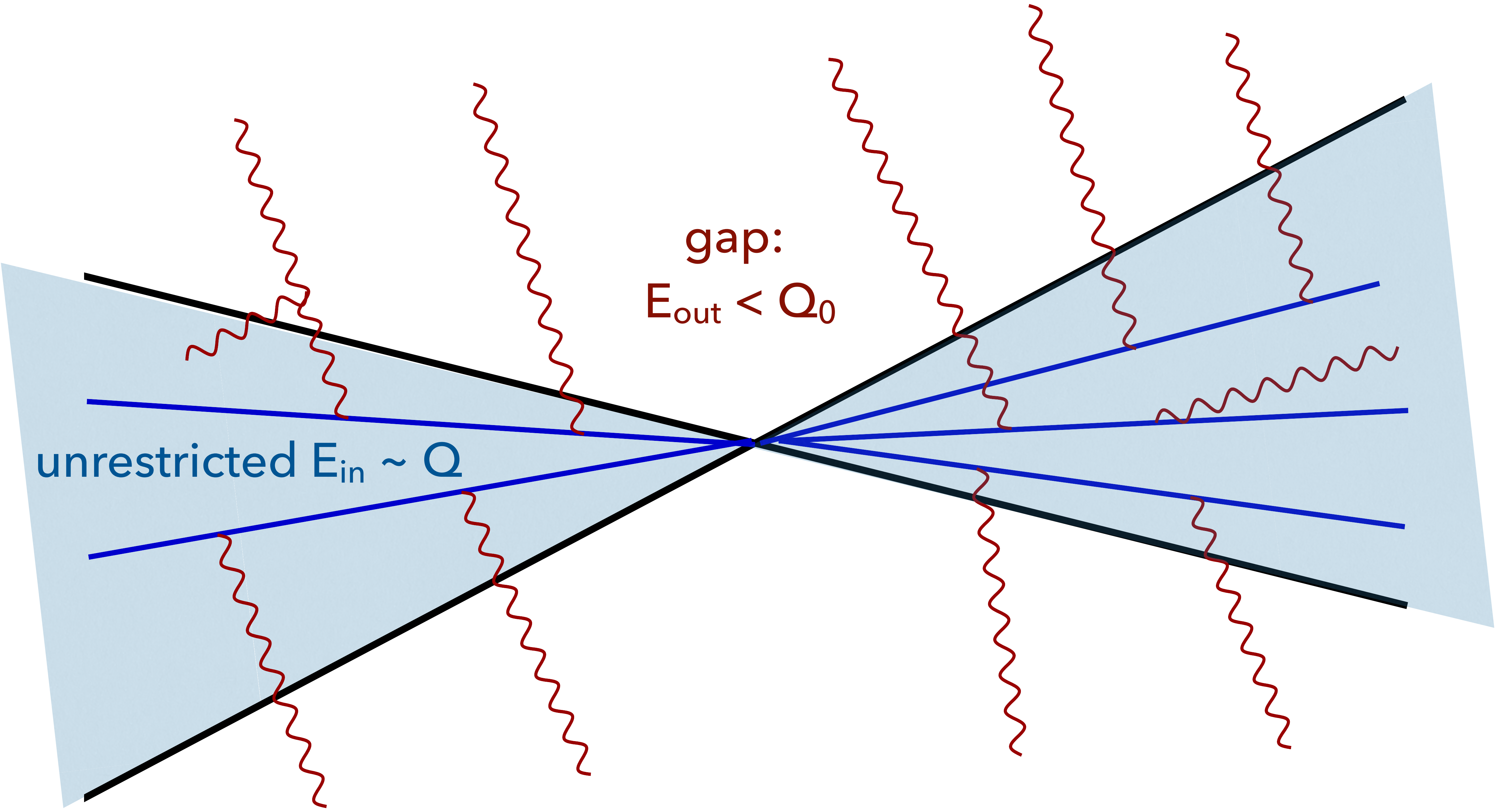
LARGE LOGARITHMS IN JET PROCESSES



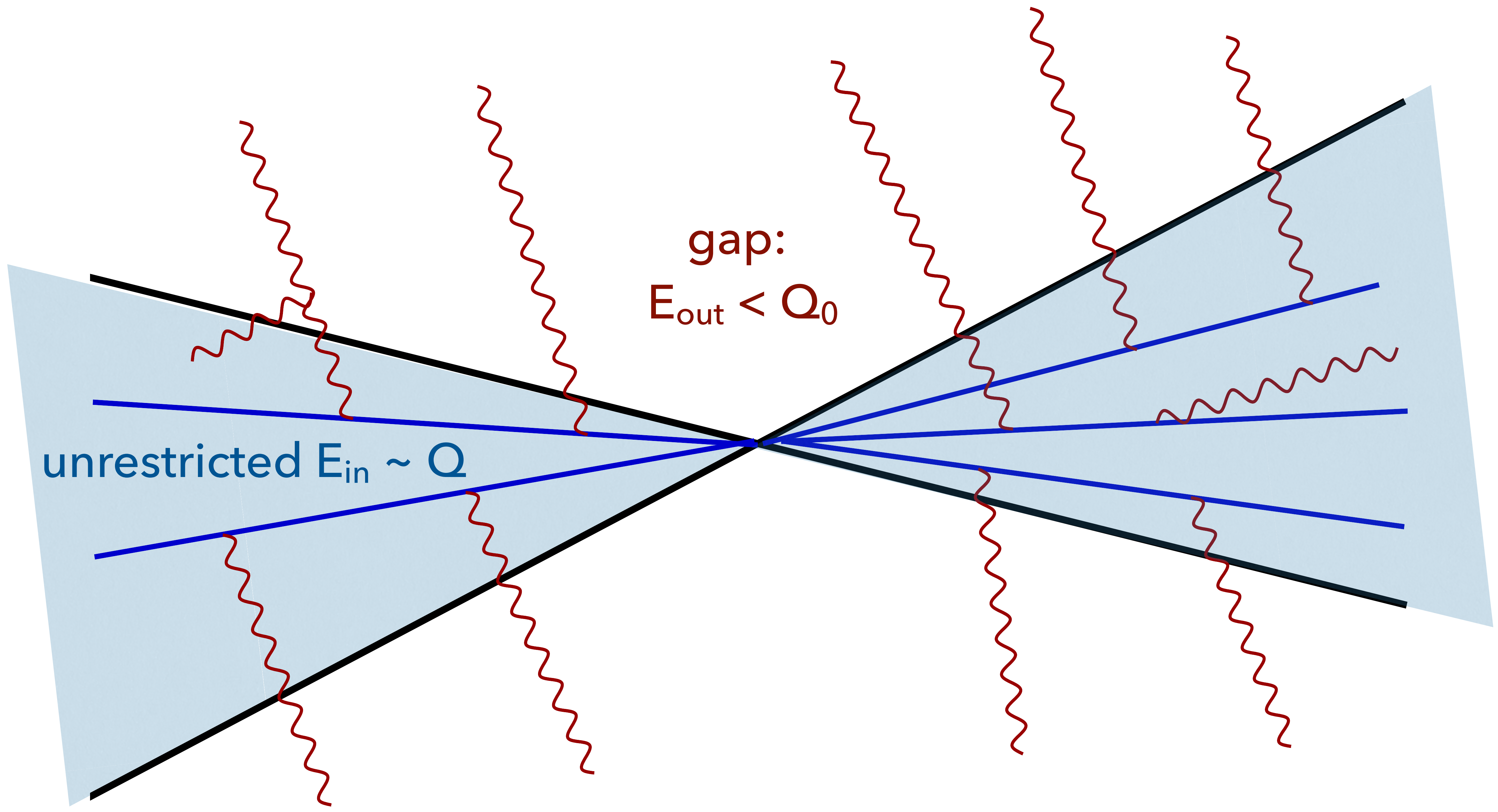
Perturbative expansion includes "super-leading" logarithms:

$$\sigma \sim \sigma_{\text{Born}} \times \{1 + \alpha_s L + \alpha_s^2 L^2 + \alpha_s^3 L^3 + \underbrace{\alpha_s^4 L^5 + \alpha_s^5 L^7}_{\text{formally larger than } O(1)} + \dots\}$$

state-of-the-art

[Forshaw, Kyrieleis, Seymour (2006)]

LARGE LOGARITHMS IN JET PROCESSES



Really, a double-logarithmic series starting at 3-loop order:

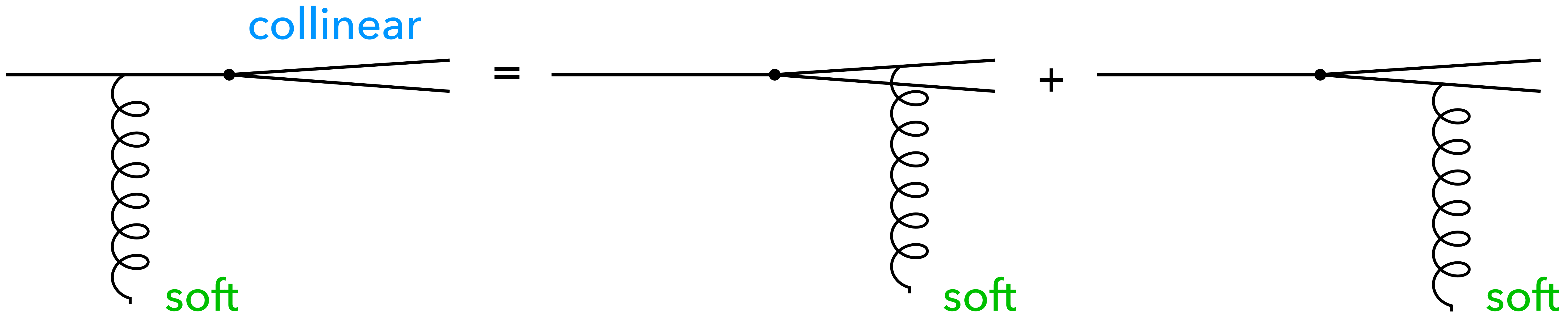
$$\sigma \sim \sigma_{\rm Born} \times \left\{1 + \alpha_s L + \alpha_s^2 L^2 + (\alpha_s \pi^2)\left[\underbrace{\alpha_s^2 L^3 + \alpha_s^3 L^5 + \dots}_{\text{formally larger than } O(1)}\right]\right\}$$

$(\Im\mathrm{m}\, L)^2$

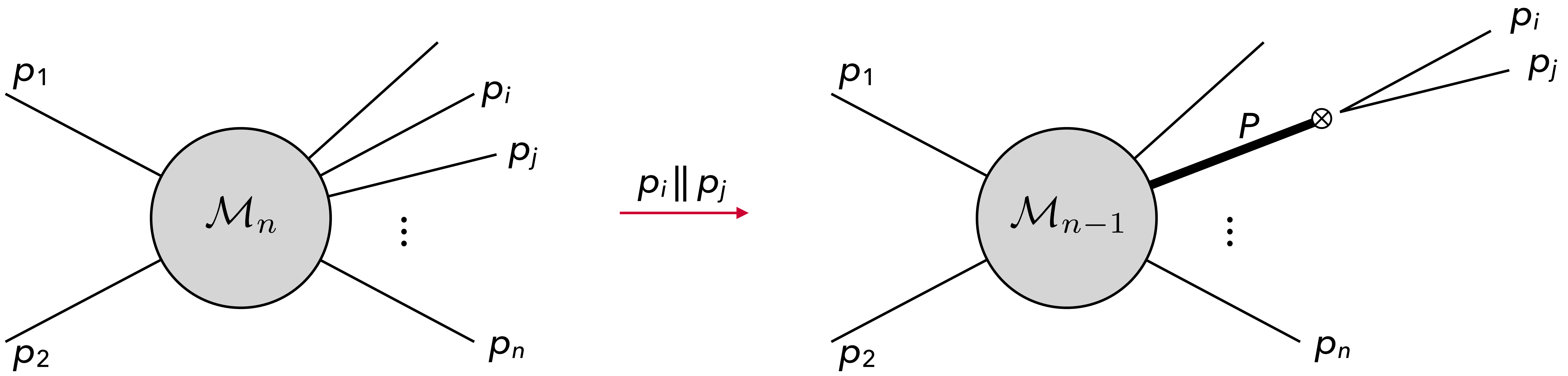
[Forshaw, Kyrieleis, Seymour (2006)]

BREAKING OF COLOR COHERENCE

- **Color coherence holds** if all three particles are incoming or outgoing (time-like splitting):

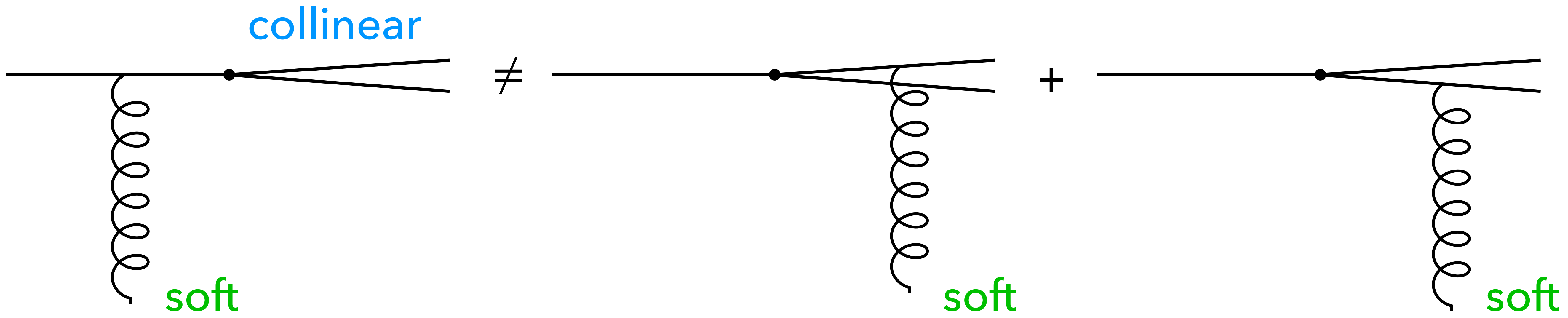


- **Then collinear factorization holds:**



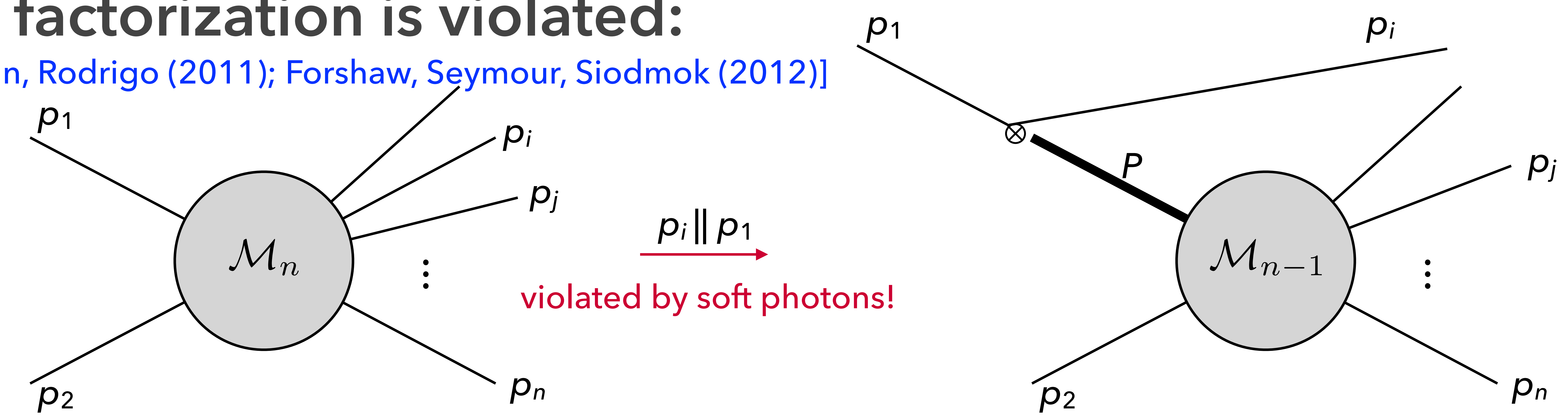
BREAKING OF COLOR COHERENCE

- **Color coherence is broken** if not all particles are incoming/outgoing (space-like splitting), since both sides receive different phase factors:



- **Collinear factorization is violated:**

[Catani, de Florian, Rodrigo (2011); Forshaw, Seymour, Siodmok (2012)]

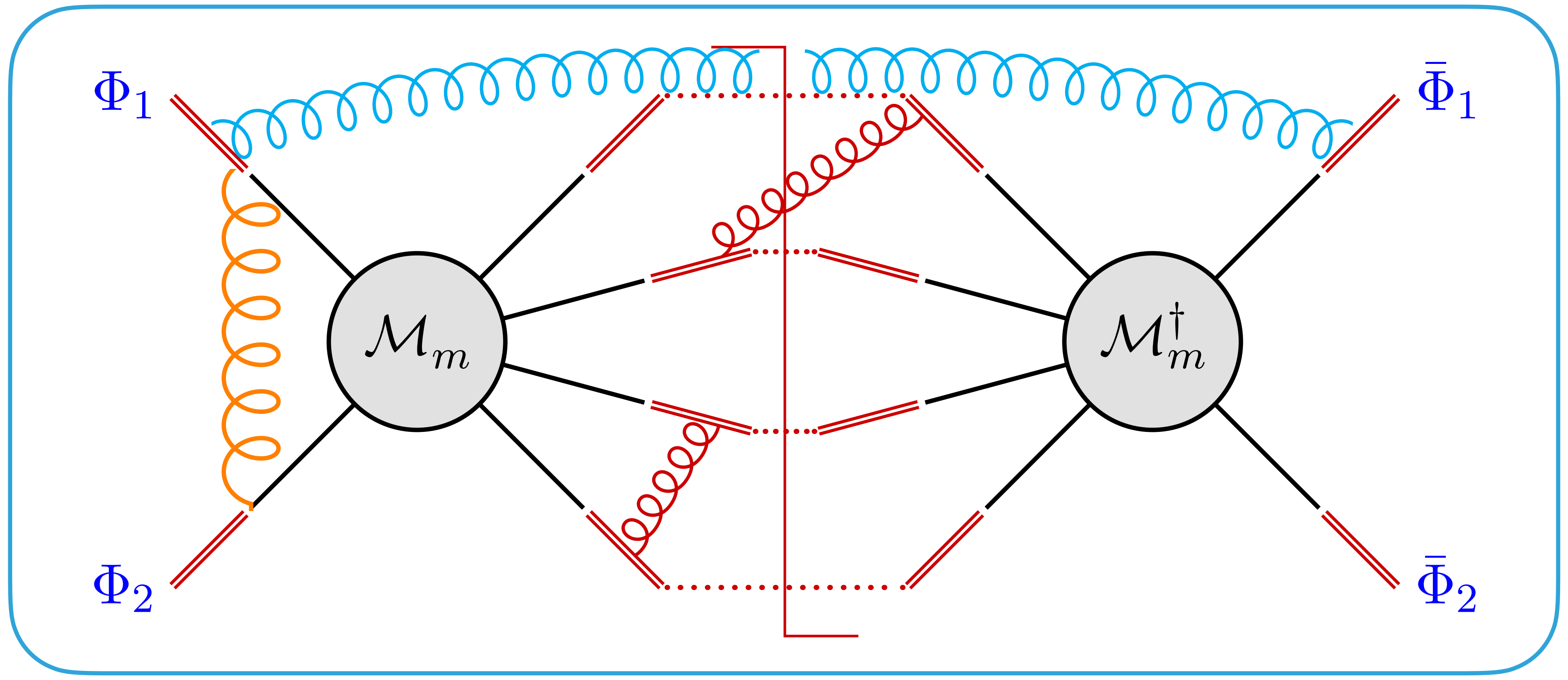


GAP-BETWEEN-JETS OBSERVABLES

SCET factorization theorem for *M*-jet production at the LHC

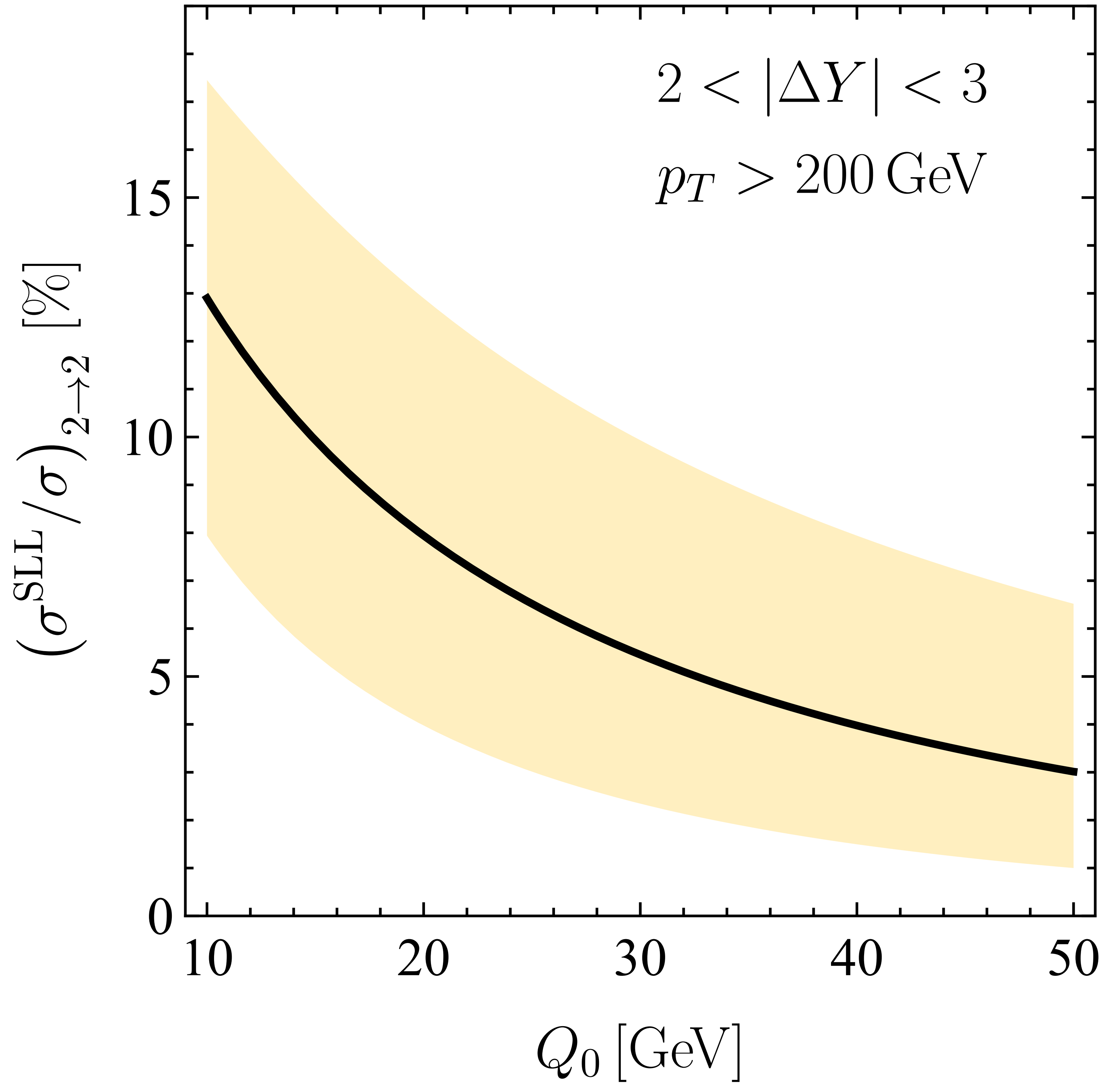
$$\sigma(Q_0) = \sum_{m=m_0}^{\infty} \int d\xi_1 d\xi_2 \, \langle \underbrace{\boldsymbol{\mathcal{H}}_m(\{\underline{n}\}, Q, \xi_1, \xi_2, \mu)}_{\text{high scale}} \otimes \underbrace{\boldsymbol{\mathcal{W}}_m(\{\underline{n}\}, Q_0, \xi_1, \xi_2, \mu)}_{\text{low scales } Q_0 \text{ and } \Lambda_{\text{QCD}}} \rangle$$

[Becher, MN, Shao (2021);
+ Stillger (2023)]



- **new perspective** to think about non-global observables
- large logs can be **resummed using RGEs**
- **all-order understanding** of super-leading logarithms for arbitrary processes

GAP-BETWEEN-JETS OBSERVABLES



[Becher, Martinelli, MN, Schwienbacher (2024)]

Figure 2: SLL contribution to the $pp \to 2$ jets cross section at the LHC as a function of the veto scale Q_0, for a center-of-mass energy $\sqrt{s} = 13\,\mathrm{TeV}$ and jet radius $R = 0.6$. The black curve shows the central result obtained in RG-improved perturbation theory. The perturbative uncertainties indicated by the yellow bands are obtained from the variation of the soft scale μ_s by a factor 2 about its default value Q_0.

STRUCTURE OF THE FACTORIZATION THEOREM ?

hard scale $Q \sim \sqrt{\hat{s}}$ — $\mathcal{H}_m$

double-logarithmic evolution (super-leading logs) & non-DGLAP collinear evolution

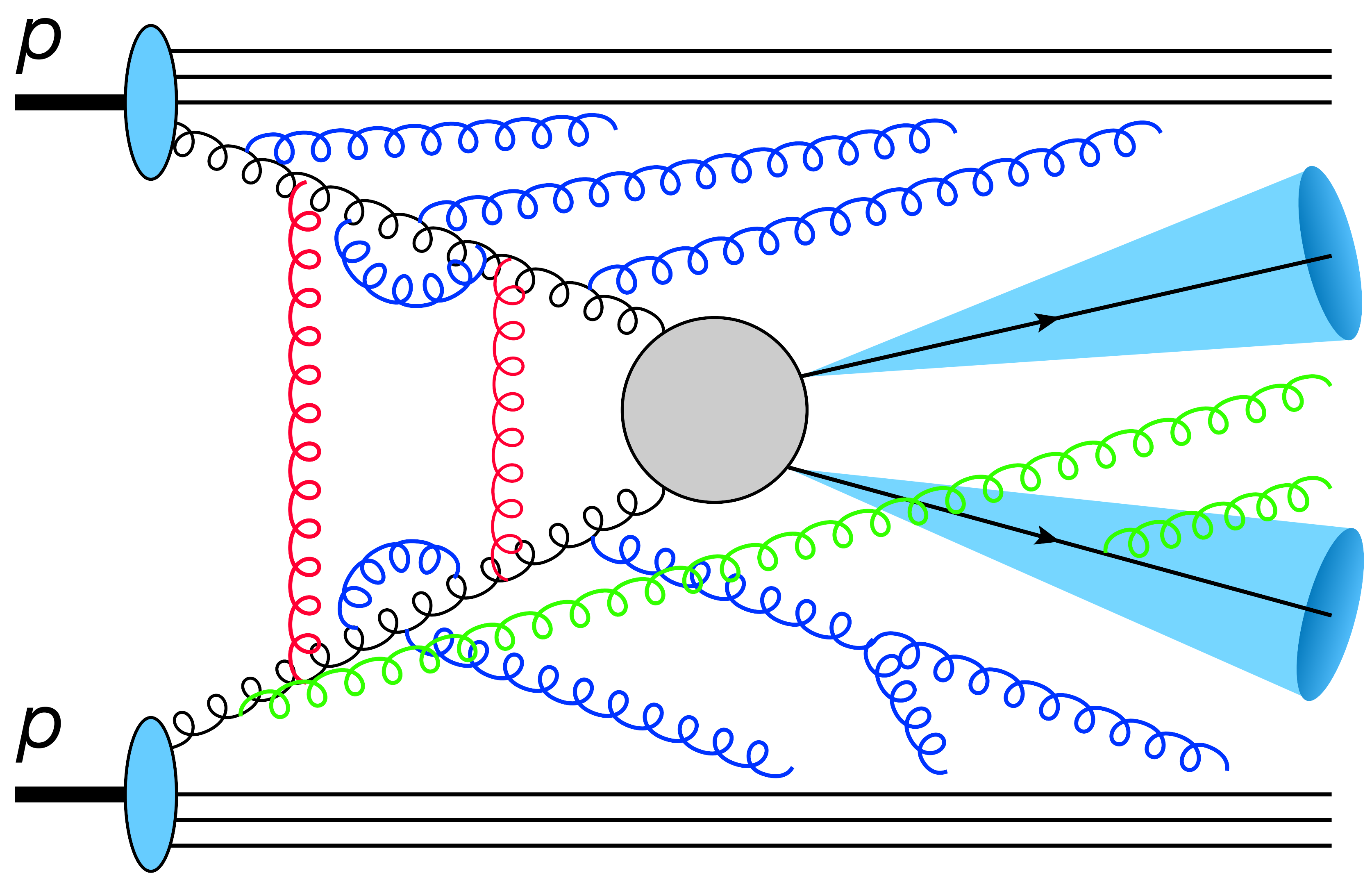
jet-veto scale Q_0 — $\mathcal{W}_m^{\text{pert}}$

single-logarithmic PDF evolution

OR: *double-logarithmic evolution and breaking of PDF factorization?*

hadronic scale Λ_{QCD} — $f_{a/p}(\xi_1)\, f_{b/p}(\xi_2)$

OR: *something more complicated, e.g. a combined two-proton distribution?*



$$\sigma \overset{?}{\sim} \sum_m \mathcal{H}_m \otimes \mathcal{W}_m^{\text{pert}} \otimes f_{a/p} \otimes f_{b/p}$$

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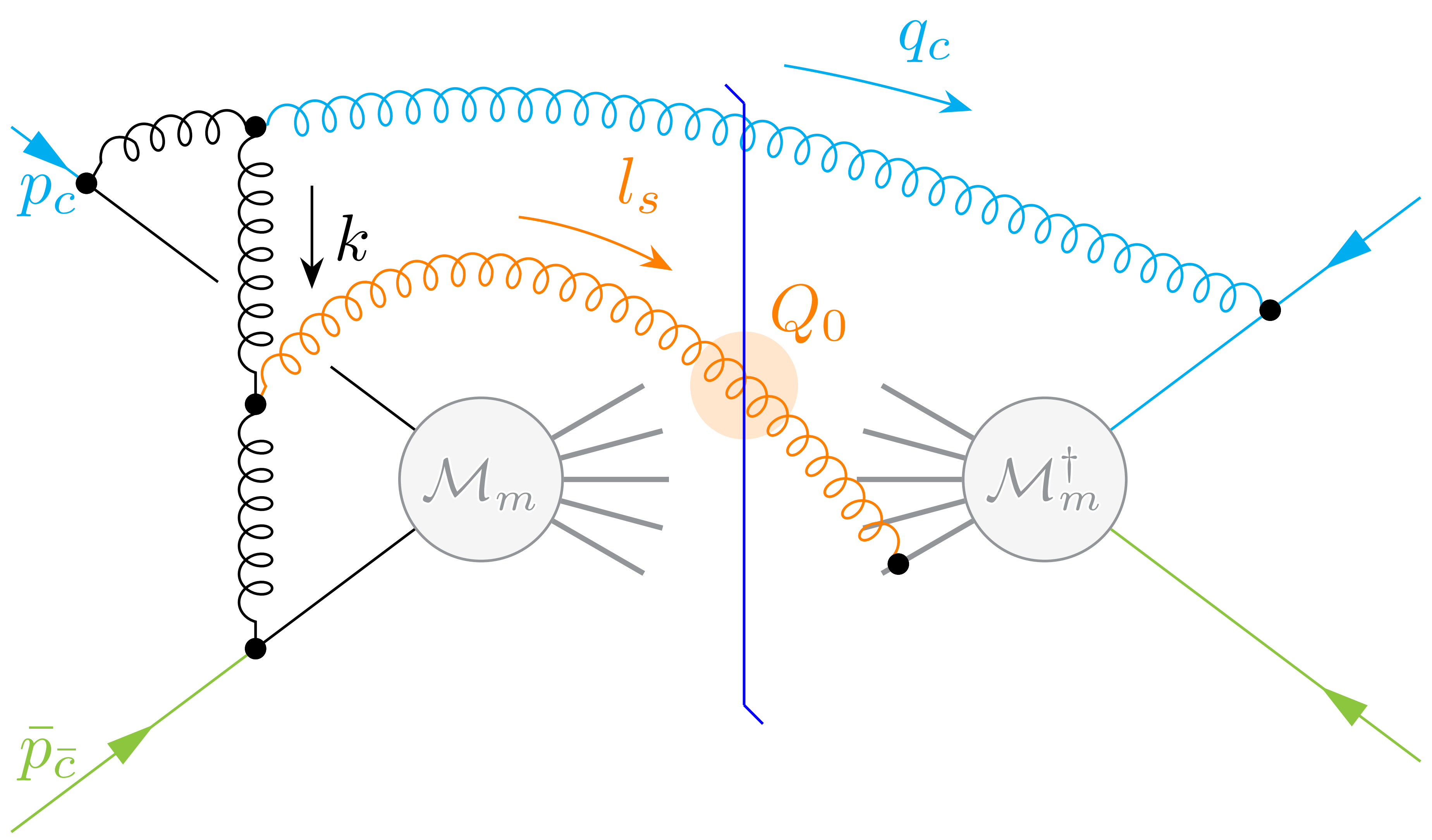

$$\sigma \overset{\checkmark}{\sim} \sum_m \mathcal{H}_m \otimes \mathcal{W}_m^{\text{pert}} \otimes f_{a/p} \otimes f_{b/p}$$

[Becher, Hager, Jaskiewicz, MN, Schwienbacher (2024)]

NEW INSIGHTS

- We have uncovered a new mechanism that reconciles the breaking of collinear factorization with unbroken PDF factorization
- In an interplay of space-like collinear splittings and soft emissions, perturbative Glauber gluons restore the factorization of the cross section by converting double-logarithmic into single-logarithmic evolution below the veto scale Q_0 (shown explicitly up to 3-loop order) [Becher, Hager, Jaskiewicz, MN, Schwienbacher (2024)]
- In the future, it will be important to understand the all-order structure of these effects, paving the way for a proof of PDF factorization for a much wider class of observables!


Thank you for your friendship, Daniel