University of Zurich - January 7, 2025 Particle Physics from Low to High Energies

Future of Heavy Quark Physics of Heavy Quark Physics - LepageFest Physical Sciences Building - Cornell University America/New_York timezone **The Power of EFTs DANIEL WYLER FEST** University of Zurich — January 7, 2025 **From HQET to SCET and beyond**

Matthias Neubert, Johannes Gutenberg University Mainz

ZPW2025

An oeuvre of enormous breadth and impact

Fermion masses and mixing angles

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

Higgs physics

(incl. d=6 effective

Lagrangian)

Kaon physics and effective chiral Lagrangian

Neutrino physics

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

An oeuvre of enormous breadth and impact

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 thirdgeneration quarks
- ▶ Precise determinations of angles (CP violation)
- ▸ New-physics searches using FCNC processes

states Wyler Fest – January 7, 2025 **In the Notawa (1973)** [Kobayashi, Maskawa (1973)] non-leptonic and pure-leptonic processes.

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):

 \rightarrow $\mathcal{H}_{\rm eff}^{\rm weak}$, HQET, NRQCD, QCDF, SCET ▸ SCET later became a versatile tool for addressing difficult QCD problems eff

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

- ▸ Systematic method to separate shortdistance 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 o perators $Q_i(\mu)$ in all but simplest cases

[Gilman, Wise (1979); Buras et al. (1990s)] C2 1.120 1.120 1.120 1.120 1.120 1.120 1.120 1.120 1.120 1.120 1.120 1.120 1.139 1.139 1.139 1.156 1.1139 1.11
1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.139 1.

operators only in section V , to the inclusion V and \mathcal{N} penculis in section V . Hence, in this section V

EFFECTIVE WEAK HAM

HEAVY QUARK SYMMETRY

- $\sim m_{B^*}^2 m_B^2 \approx 0.49$ GeV² vs. $m_{D^*}^2 m_D^2 \approx 0.55$ GeV² and $\begin{bmatrix} 2 & 2 & 0 & 10 & 0 & 1 \end{bmatrix}$ $\begin{bmatrix} 2 & 0 & 2 & 0 \end{bmatrix}$ $\begin{bmatrix} 2 & 0 & 0 \end{bmatrix}$ $\frac{1}{2}$ in $\frac{m}{B^*} - m_B \approx 0.49$ dev vs. $m_{D^*} - m_D \approx 0.33$ dev
- $\longrightarrow m_{B_s} m_B \approx m_{D_s} m_d \approx 0.10 \text{ GeV}$ analysis considerably by including the first-order power corrections in 1 \sim *m* and in 1 \sim *m* and in 1 \sim *m* as and 1 \sim *m* as well as \sim *m* as well as \sim *m* as well as \sim *m* as \sim *m* as \sim *m* a mate in r_m in r_m in r_m \sim m_{D_s} \sim m_{D_s} \sim m_d \sim 0.1000 σ $r_{\rm m}$ - $m_{\rm p} \approx m_{\rm p} - m_{\rm d} \approx 0.10$ GeV
- $\sim m_B^2$ B_2^* $- m_B^2$ B_1 $\approx m_D^2$ D_2^* $- m_D^2$ D_1 ≈ 0.17 GeV 2 included in a systematic way in Refs. [86,90]. $\mu_{B_2^*} - m_{B_1}^2 \approx m_{D_2^*}^2 - m_{D_1}^2 \approx 0.1 / \text{ GeV}^2$ is due to Luce $\frac{1}{2}$. $m_{\rm B}^2 = m_{\rm B}^2 \approx m_{\rm D}^2 = m_{\rm D}^2 \approx 0.17 \text{ GeV}^2$ \mathbf{D}_2 in \mathbf{D}_1 in \mathbf{D}_2 corrections is due to $\frac{D_s}{2}$. Radiative corrections at least $\frac{D_s}{2}$ $i_1 \cdot m_{B_2^*}^2 - m_{B_1}^2 \approx m_{D_2^*}^2 - m_{D_1}^2 \approx 0.17$ We start by introducing a convenient set of six hadronic form factors *h (w),* which parameterize

 \blacksquare Form-factor relations: with $(w = v \cdot v')$: $\langle D(U')|V''|B(U)\rangle = n_+(W)(U+U')^2 + n_-(W)(U \langle D'(v, \epsilon)|v'|B(v)\rangle = i\hbar v(w) \epsilon' - \epsilon_v v_\alpha v_\beta$ $\langle D^{\dagger} \rangle^T$ form $\langle D^*(v', \epsilon) | A^{\mu} | B(v) \rangle = h_{A_1}(w)(w+1) \epsilon^{*\mu}$ $\mathcal{W}_{A_2}(\mathcal{W},\mathcal{V})$ is the velocity transfer of the mesons. The mesons of th $h_{+}(w) = h_{V}(w) - h_{A_1}(w) - h_{A_3}(w) - S(w)$ and Example 2011 Form-factor relations: t relevant meson matrix elements of the flavor-changing vector \vert $\langle D^*(v', \epsilon)|V^{\mu}|B(v)\rangle = ih_V(w)\epsilon$ $Sing$ $\begin{bmatrix} 1 & -1 \cdot \ln_{A_2}(w)v^2 + n_{A_3}(w)v^3 \end{bmatrix}$ m_{Ω} *v* $w = h_{\Omega}(w) - h_{\Omega}(w) - h_{\Omega}(w) - k(u) - k(w)$ and $k(1) = 1$ $n_+(w) = n_v(w) = n_{A_1}(w) = n_{A_3}(w) = g(w)$ and $\zeta(1) = 1$ *h*_a(*w*) = *h*_{A2}(*w*) = 0. and $\frac{1}{\sqrt{D}}$ \leq $\frac{1}{2}$ *(D(v')IV~IB(v))*= *h~(w)(v + V~)~L+ h_(w) (v* — $\sum_{i=1}^{n}$ $\left\{P^{(v)}(v^{\prime},\epsilon)\right\}^{I} = \left\{P(v^{\prime})\right\}^{I} = \left\{P_{A_1}(w)(w+1)\epsilon\right\}^{I}$

- ▸ Hadronic bound states containing a heavy quark obey an approximate **spin-flavor symmetry**
- ▸ Many predictions for spectroscopy of heavy hadrons and *A,U* ⁼ *~#y5b,* [Shuryak (1980)]
- **B** Symmetry relations among $B \to D^{(*)}$ form factors, including symmetry-breaking corrections $\sim \alpha_s(m_Q)$ or Λ_{QCD}/m_Q $h_+(w) = h_v(w) = h_{A_1}(w) = h_{A_3}(w) = \xi(w)$ and $\xi(1) = 1$ [Isgur, Wise (1990)]

Relations between level spacings in bottom and \qquad and the charm systems, e.g.: *M.* α *Charm systems. e.g.:*

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

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

Fig. 1. Extraction of $|V_{cb}|$ and the Isgur–Wise function from $\bar{B}^0 \rightarrow D^{*+} \bar{\mathbb{V}}_{\bar{\mathbb{X}}}$ 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 $v v' = 1$. Its currently best value is indicated as a shaded area on the vertical axis.

MODEL-INDEPENDENT DETERMINATION OF |VCB|

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

 \triangleright Firm theoretical basis for deriving he quark symmetry and its consequence

$$
\begin{array}{ll}\n\text{Eq} & \text{Equation (a)} \\
\text{Eq} & \text{Equation (b)} \\
\text{Eq} & \text{Equation (a)} \\
\text{Eq} & \text{Equation (b)} \\
\text{Eq} & \text{Equation (a)} \\
\text{Eq} & \text{Equation (b)} \\
\text{Eq} & \text{Equation (c)} \\
\text{Eq} & \text{Equation (d)} \\
\text{Eq} & \text{Equation (e)} \\
\text{Eq} & \text{Equation (e)} \\
\text{Eq} & \text{Equation (f)} \\
\text{Eq} & \text{Equation (g)} \\
\text{Eq} & \text{Equation (h)} \\
\text{Eq} & \text{Equation (i) } \\
\text{Equation (i) } & \text{Equation (i) } \\
\
$$

HEAVY QUARK EFFECTIVE THEORY (HQE

THE GRAND CHALLENGE: NON-LEPTONIC DECAYS

▸ Naive factorization approach was semi-successful in describing early data,

- ▸ Georgi: *"Why we can't calculate …"*
- but lacked a firm theoretical foundation

[Georgi: *Weak Interactions and Modern Particle Theory* (1984)]

[Bauer, Stech, Wirbel (1986)]

THE GRAND CHALLENGE: NON-LEPTONIC DECAYS

▸ Naive factorization approach was semi-successful in describing early data,

[Georgi: *Weak Interactions and Modern Particle Theory* (1984)]

- ▸ Georgi: *"Why we can't calculate …"*
- but lacked a firm theoretical foundation
- ▸ **QCD factorization approach (BBNS):**
	- ▸ First model-independent calculation of $B \to M_1 M_2$ decay amplitudes from first principles (including strong- and weakinteraction 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)

[Bauer, Stech, Wirbel (1986)]

QCD FACTORIZATION IN NONLEPTONIC B DECAYS INTO LIGHT MESONS

QCD factorization theorem:

$$
\langle \pi K | Q_i | B \rangle = F_0^{B \to \pi} T_{K,i}^{\text{I}} * f_K \Phi_K + F_0^{B \to K} T_{\pi,i}^{\text{I}} * f_\pi \Phi_\pi + T_i^{\text{II}} * f_B \Phi_B
$$

$$
+ \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right)
$$

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

QCD FACTORIZATION IN NONLEPTONIC B DECAYS INTO LIGHT MESONS

QCD factorization theorem:

$$
\langle \pi K | Q_i | B \rangle = F_0^{B \to \pi} T_{K,i}^{\text{I}} * f_K \Phi_K + F_0^{B \to K} T_{\pi,i}^{\text{I}} * f_\pi \Phi_\pi + T_i^{\text{II}} * f_B \Phi_B * f_K \Phi_K * f_\pi \Phi_\pi
$$
\nspecific for B-r

\ncontributes at

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

-
- $i\ast f_K\Phi_K\ast f_\pi\Phi_\pi$
- $\sqrt{\Phi_{M_2}}$ **the factoric matrix here** importance of **non-local hadronic matrix elements**, in particular light-cone distribution amplitudes (LCDAs), to account for hadronic dynamics
	- Spec *m^b* $\mathbf{r} = \mathbf{r} \mathbf{r}$ ▸ 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

Daniel Wyler Fest – January 7, 2025

- \blacktriangleright ln 2001, fact that $\mathsf{Im}(V_{td}) \neq 0$ had been \overline{R} and $\overline{B}-\overline{B}$ and $\overline{B}-\overline{B}$ mixing and first measurements of sin 2*β* **CPN b** 2004 analysis: $\bar{\rho} = 0.15 \pm 0.08$, $\bar{\eta} = 0.36 \pm 0.09$ 2004 analysis: $\bar{\rho} = 0.15 \pm 0.08$, $\bar{\eta} = 0.36 \pm 0.09$ $\gamma = (67 \pm 15)^\circ, \quad \beta = (24 \pm 2)^\circ$
- **▶ Fact that** $Im(V_{ub}) \neq 0$ **has been established by** *studying rare hadronic decays* $B \to πK, ππ$ *in* QCD factorization [BBNS (2001), here updated to 2004 data]
- ▸ **KM relation confirmed;** most stringent test of KM mechanism at the time

 $F_{\rm{min}}$ $\gamma = (65.5^{+1.3}_{-1.2})^{\circ}, \quad \beta = (22.42^{+0.64}_{-0.37})^{\circ}$ 2021 values: $\bar{\rho} = 0.157^{+0.009}_{-0.005}$, $\bar{\eta} = 0.347^{+0.012}_{-0.005}$

ensitive B decays using $[{\rm CKMfitter\,global\,fit, spring\,2021}]$

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

- ▸ Measuring time-dependent CP asymmetries $\sin B \to \pi\pi$ and $B \to \pi\rho$ decays one obtains an internally consistent determination of *γ*
- ▸ 2003 analysis found: *γ* = (62 ± 8) ∘
- ▸ 2021 value: $\gamma = (65.5^{+1.3}_{-1.2})$ $^{+1.5}_{-1.2})$ **o**

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

↪ **Gronau—Wyler method**

and ences 6- \sim 0.000 \pm $\frac{1}{\sqrt{2}}$ separately for the triangles of these separately for each of these separately for the these separately for the these separately for the theorem in t

Daniel Wyler processes and comparing the respective and comparing the respective angles Γ

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

Received 27 May 1991 **State can be identified by its CP-even** by its CP-even by its CP- Nc processes of the weak phase and the we

We demonstrate a possible determination of the weak phase γ from the CP asymmetry in B⁺ \rightarrow D₁₍₂₎ X⁺, where D₁₍₂₎ is a CPeven (odd) state and X^{\dagger} is any hadronic state with the flavor of a K^{\dagger} . To obtain the phase one needs separate measurements of the rates $\Gamma(B^+ \to D^0_{1(2)} X^{\pm})$ and of the equal rates $\Gamma(B^{\pm} \to D^0 X^{\pm}) = \Gamma(B^{\pm} \to \bar{D}^0 X^{\mp})$. Certain ambiguities are discussed and reso- $\frac{1}{2}$ lutions are proposed. en (odd) state and X^+ is any nadrome state with the havor of a K^+ . e rates $I(\mathbf{B} \to D_{1(2)}^{\vee} \mathbf{X}^{\perp})$ and of the equal rates $I(\mathbf{B}^{\perp} \to D^{\vee} \mathbf{X}^{\perp}) = I(\mathbf{B}^{\perp} \to D^{\vee} \mathbf{X}^{\perp})$. Certain ambiguities are discussed and reso-
ions are proposed

On determining a weak phase from charged B decay asymmetries tistics considerably. Also, one makes the following

Michael Gronau

Technion – Israel Institute of Technology, Haifa 32000, Israel

$$
\sqrt{2} A(B^+ \rightarrow D_1^0 K^+)
$$
\n
$$
= |A| \exp(i\gamma) \exp(i\delta) + |\bar{A}| \exp(i\delta),
$$
\n
$$
= |A| \exp(-i\gamma) \exp(i\delta) + |\bar{A}| \exp(i\delta),
$$
\n
$$
= |A| \exp(-i\gamma) \exp(i\delta) + |\bar{A}| \exp(i\delta).
$$
\n
$$
= |A| \exp(-i\gamma) \exp(i\delta) + |\bar{A}| \exp(i\delta).
$$
\n
$$
= A(B^- \rightarrow \bar{D}^0 K^-) + A(B^- \rightarrow D^0 K^-).
$$

GRONAU-WYLER METHODE Physics Letters B 265 (1991) 172-176 [Gronau Wyler (1991)] $A(B^* - D^0 K^*)$ $\frac{2y}{2}$ $\sqrt{A(B^2 + \bar{D}^0 K^-)}$ \sim $A(B^* + \overline{D}^{\circ}K^*)$ = $A(B^* + D^{\circ}K^-)\$ \sim \sim $A(B^* + \overline{D}^{\circ}K^*)$ \sim . \sim \sim \sim \sim \sim \sim \sim \sim $\sqrt{2} A (B^* - D^0_s K^*)$ \sim $\lambda^{A (B^* - D^0 K^*)}$ $\times [2|A_1^-|^2 - (|A|-|A|)^2]$ ^{1/2} II_MVI LD MLIL The procedure for obtaining $\mathcal{L}(\mathcal{N})$ is straightforward. $A(B^* + D^0 K^*)$ cesses, two pairs of which are equal, determine the second termine that the second termine the second termine the $\sqrt{2} A(B^* + D_1^0 K^*)$ $\sqrt{2} A(B^- + D_1^0 K^*)$ in fig. is defined as \sim in the two triangles are formed, \sim $A(B^-+0^{\circ}K^-)$ $\sqrt{2}$ - $\sqrt{2}$ \leftarrow and $S \sim \text{A(B - D'K)}$ and A(B - D'K) tained from each other by interchanging \mathcal{N} interchanging y and \mathcal{N} This ambiguity follows from the symmetry of the symmetry of the rela-symmetry of the rela-symmetry of the relalatter interchange. There is also a sign ambiguity for all \mathcal{L}_{max} $\mathcal{L}_{\mathcal{A}}$ y, since each of the two triangles may be reflected in through its basis $\mathcal{L}^{\mathcal{A}}$ is basis. The four solutions for sin $\mathcal{L}^{\mathcal{A}}$ are given $\mathcal{L}^{\mathcal{A}}$ **1** $\sin \gamma = \frac{1}{4! \cdot 4 \cdot 4!}$ (\pm {[(|A| + |A|)² - 2|A₁' |²] $\pm\{[(\vert A\vert+\vert\bar{A}\vert)^2-2\vert A_1^{\,-}\vert^2]\}$ \times [2|A⁺|²-(|A|-|Ā|)²]}^{1/2}), [Gronau, Wyler (1991)]

 13

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

A pioneering paper! A pursus can be processed and **A** for D °) in the form (1141 citations)

 $x \in \mathbb{R}^{n \times n}$ and $x \in \mathbb{R}^{n \times n}$, $x \in \mathbb{R}^{n \times n}$

PHYSICS LETTERS B

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 $\Lambda_{\rm QCD}/m_b$ do not (naively) factorize due to endpoint divergences (⇒ 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) *in*¯ *· ^D iD*/ ‹ ²⁷² As a next step, one separates the large and residual momentum components by decomposing the collinear momentum into a residual momentum into a residual momentum, *p*
[Bayer (Elemina) Piriel Stewart (2001): Beneke Chanevski, Diehl, Feldmann (2002)]

▸ Firm theoretical basis for deriving QCD factorization theorems in heavy-quark

▸ Scale separation and resummation accomplished using powerful EFT tools 2866 small momentum components is to derive the Lagrangian of SCET in position space \sim 56 . In this case \sim \blacktriangleright 3 care separation and resummation accompilshed using

Matthias Neubert - 15

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

- and collider physics for processes involving light energetic particles **Example 275 Depart Conservatives and** *DCD* factorization the Here the label momentum in Scenes and the label operator conserved, one operation in Section 276 and 2
- ▸ Collinear effective Lagrangian: Note that at leading order in power counting *ⁱD^µ* ²⁷⁸ *ⁿ* does not contain the soft gluon field. This leads **279 Collinear effective**

eikonal interaction, can be removed by the field redefinition $\xi_n \to S_n \xi_n^{(0)}$ ²⁸¹ latter term gives rise to the only interaction between a collinear quark and soft gluons at leading 282 **elkonal interaction, can be removed by**
The electron interactions between soft and collinear particles.

▶ Soft-collinear factorization at Lagrangian level \sim Soft collinear factorization at Lagrangian level 8 Soit-coilinear iactorization at Lagrangian lever large and the separation of the separation of the separation o

² *^Ân*(*x*)*.* (16.12) Lfinal1

Daniel Wyler Fest – January 7, 2025 2025 Matthias Neubert – 15 September 19

$$
\mathcal{L}_n = \bar{\xi}_n(x) \left[in \cdot D_n + gn \cdot A_s + i \mathcal{D}_n^{\perp} \frac{1}{i \bar{n} \cdot \mathcal{D}_n} i \mathcal{D}_n^{\perp} \right] \frac{\vec{\eta}}{2} \xi_n(x) + \dots
$$

H

J J

 $J \sqrt{J}$

 $\xi_n(x) + \ldots$

S

SCET PROOF OF QCD FACTORIZATION FOR *B* → *K***γ* **DECAY**

[Becher, Hill, MN (2005)]

Two-step matching procedure $QCD \rightarrow SCET-1 \rightarrow SCET-2$:

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

PROTOTYPICAL SCET FACTORIZATION THEOREM

▸ Extension to next-to-leading power is a hard problem, due to **endpoint-divergent**

- **convolution integrals**
- for dealing with this problem

▸ **Refactorization-based subtraction** (RBS) scheme provides a consistent framework [Liu, MN (2019, 2020); Liu, Mecaj, MN, Wang (2021); Liu, MN, Schnubel, Wang (2022)]

[Beneke et al. ; Moult et al.; Stewart et al.; Bell et al. (2018—2022)]

ZPW2025 Particle Physics from Low to High Energies

Matthias Neubert — 18 Daniel Wyler Fest — January 7, 2025

GAP-BETWEEN-JETS OBSERVABLES

CERN Document Server, ATLAS-PHOTO-2018-022-6

Matthias Neubert — 19 Daniel Wyler Fest — January 7, 2025

Perturbative expansion includes "super-leading" logarithms: $\sigma \sim \sigma_{\rm Born} \times \left\{ 1 + \alpha_s L + \alpha_s^2 L^2 + \alpha_s^3 \right\}$ $\frac{3}{s}L^{3} + \alpha_{s}^{4}$ $\overbrace{\hspace{15em}}$

LARGE LOGARITHMS IN JET PROCESSES

$$
L^2 + \alpha_s^3 L^3 + \alpha_s^4 L^5 + \alpha_s^5 L^7 + \dots \}
$$

formally larger than *O*(1)

[Forshaw, Kyrieleis, Seymour (2006)] state-of-the-art

Really, a double-logarithmic series starting at 3-loop order: $\sigma \sim \sigma_{\rm Born} \times \left\{ 1 + \alpha_s L + \alpha_s^2 L^2 + \left(\alpha_s \pi^2 \right) \right\}$ $\sqrt{2}$ α_s^2

LARGE LOGARITHMS IN JET PROCESSES

$$
L^{2} + (\alpha_{s}\pi^{2})\left[\alpha_{s}^{2}L^{3} + \alpha_{s}^{3}L^{5} + \dots\right]
$$

\n
$$
\left(\Im \mathbf{m} L\right)^{2}
$$
 [Forshaw, Kyrieleis, Seymour (2006)]
\nler Fest - January 7, 2025

BREAKING OF COLOR COHERENCE

(time-like splitting):

▸ **Then collinear factorization holds:**

that the relevant color traces are of the form *k* \overline{a}

BREAKING OF COLOR COHERENCE

*Q*⁰ $\mathbf{t} = \mathbf{t} + \mathbf$ *Q*⁰ *k ††p^c* \overline{a}

(space-like splitting), since both sides receive different phase factors: *k*

GAP-BETWEEN-JETS OBSERVABLES factorization proof for the Drell-Yan process. have been measured at the LHC \sim 28.2 and are examered long ago [5, 6, 11], but an all-order understanding of two disparate scales. For small *Q*⁰ ⌧ *Q*, one can dereads [12, 13, 29]

SCET factorization theorem for *M-*jet production at the LHC ing e \sim 12–14]. The contracts is now known for arbitrary processes \sim r M-jet pro **prod decision de la decembre 1976**

ated veto scale *Q*0. Such gap-between-jets observables

[Becher, MN, Shao (2021); + Stillger (2023)] high scale $[Becher, MN, Shao (2021);
+ Stillaer (2023)]$ at four-loop order, and the preservation of PDF factor-loop order, and the preservation of PDF factor*ls*

ples of non-global hadron-collider of non-global hadron-collider observables involving involving involving inv
Involving involving involving involving involving involving involving involving involving involving involving

- rapics
logs can be **resummed using RGEs**
der understanding of super-leading RGEs **m** 3 and 3 ▸ large logs can be **resummed using RGEs**
- logs can be **resummed using RGEs**
d<mark>er understanding</mark> of super-leading
thms for arbitrary processes **Ler understanding** of super-leading

thms for arbitrary processes are the Born-Level Hard functions and the Born-level hard functions and we use the set of logarithms for arbitrary processes ▸ **all-order understanding** of super-leading

$$
\sigma(Q_0) = \sum_{m=m_0}^{\infty} \int d\xi_1 d\xi_2 \langle \mathcal{H}_m(\{\underline{\mathbf{r}}_m\})
$$

GAP-BETWEEN-JETS OBSERVABLES

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

Figure 2: SLL contribution to the $pp \rightarrow 2$ jets cross section at the LHC as a function of the veto scale Q_0 , for a center-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ 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 . The black curve shows the central result obtained in RG-improved perturbation theory.
The perturbative upcertainties indicated by the vellow bands are obtained from the

STRUCTURE OF THE FACTORIZATION THEOREM ? from the jets, the state-of-the-art is NNLO, see e.g. [17]. Despite these advances, for non-global observables we are still lacking and understanding and understanding logarithmically enhanced corrections of the leading logarithmically enhanced corrections of the leading logarithmically enhanced corrections of the leadi

 $\sigma \sim \sum H_{\infty} \otimes \mathcal{W}^{\text{pert}} \otimes f_{\text{tot}} \otimes f_{\text{tot}}$ $\sum_{i=1}^{n}$ in a proton-proton m $\sigma \stackrel{\mathbf{\cdot}}{\sim} \sum$ *m* $\mathcal{H}_m \otimes \mathcal{W}_m^{\mathrm{pert}} \otimes f_{a/p} \otimes f_{b/p}$

STRUCTURE OF THE FACTORIZATION THEOREM ?

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 \mathcal{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