RECENT ADVANCES IN SOFT-COLLINEAR EFFECTIVE THEORY FOR COLLIDER & FLAVOR PHYSICS

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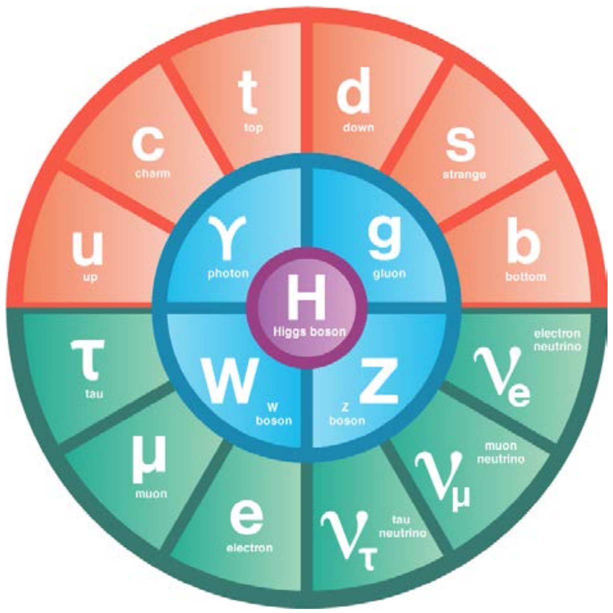
STANDARD MODEL TESTS AND NEW PHYSICS SEARCHES



symmetrymagazine.org

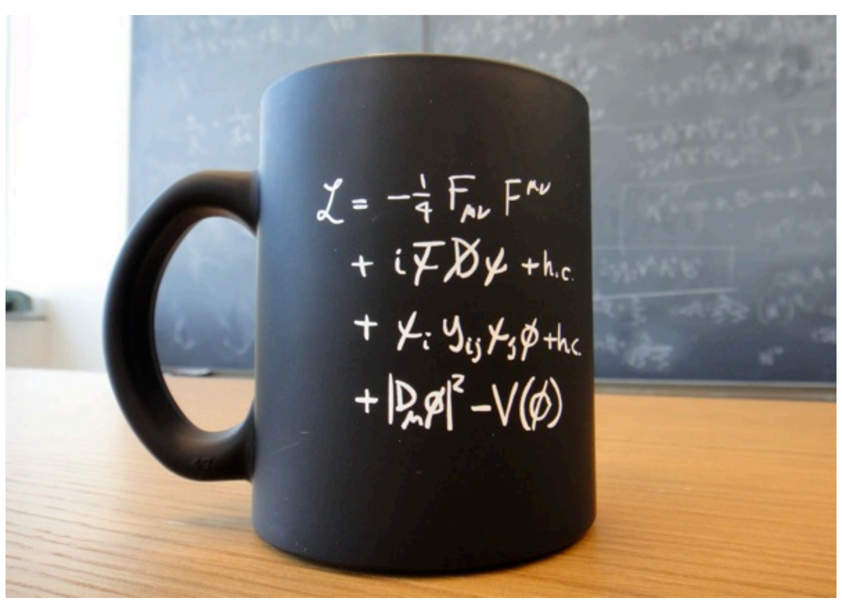


Photo by CERN

Photo by CERN

- Origin of Dark Matter?
- Abundance of matter over antimatter?

OUTLINE

- Factorization at next-to-leading power
  - systematic method for dealing with endpoint-divergent convolution integrals
  - applications to Higgs production in gluon-gluon fusion and rare exclusive *B* decays

Z.L. Liu, MN: JHEP 04 (2020) 033; Z.L. Liu, B. Mecaj, MN, X. Wang: JHEP 01 (2021) 077;
Z.L. Liu, MN, M. Schnubel, X. Wang: arXiv:2212.10477; C. Cornella, M. König, MN: arXiv:2212.14430

- Theory of non-global observables at hadron collider
  - first resummation of "super-leading logarithms"
  - estimates for $gg \to gg$ scattering and outlook

T. Becher, MN, D. Y. Shao: Phys. Rev. Lett. 127 (2021) 212002 & to appear (with M. Stillger)

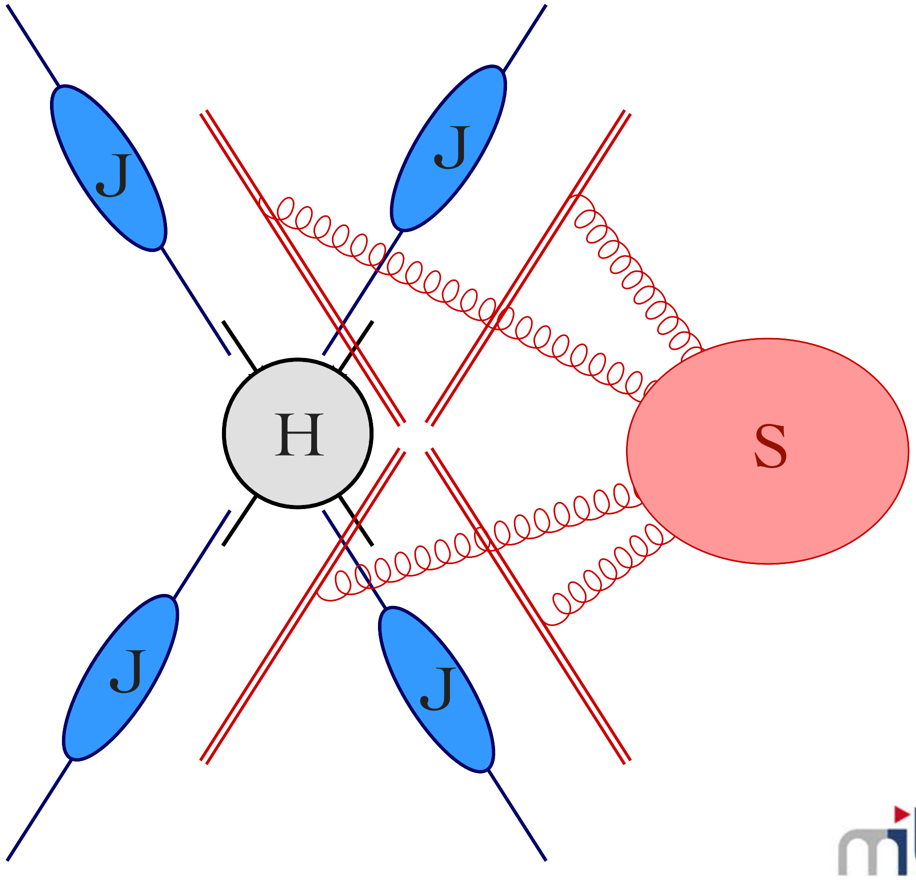
SCALE FACTORIZATION IN HIGH-ENERGY PROCESSES

Factorization of different scales is a fundamental concept of physics:

- LHC cross sections: $\sigma(pp \to X) = \sigma_{\text{parton}}(ab \to X) \otimes$ PDFs
- Basis for separation of perturbative from nonperturbative effects
- Systematic resummation of large logarithmic corrections

Soft-collinear effective theory (SCET) provides a framework for studying scale separation and resummation for processes involving light energetic particles, using powerful EFT tools

[Bauer et al. 2000-2001; Beneke et al. 2002]



SCALE FACTORIZATION IN HIGH-ENERGY PROCESSES

Conventional EFTs provide a series expansion in inverse powers of a large scale Q:

$$\mathcal{L}_{\text{eff}} = \sum_i C_i(Q,\mu)\, O_i(\mu) + \frac{1}{Q} \sum_j C_j^{(1)}(Q,\mu)\, O_j^{(1)}(\mu) + \frac{1}{Q^2} \sum_k C_k^{(2)}(Q,\mu)\, O_k^{(2)}(\mu) + \dots$$

- Examples: $\mathscr{H}_{\text{eff}}^{\text{weak}}$, χPT, HQET, SMEFT, …
- Extension to higher orders is straightforward, even if often tedious

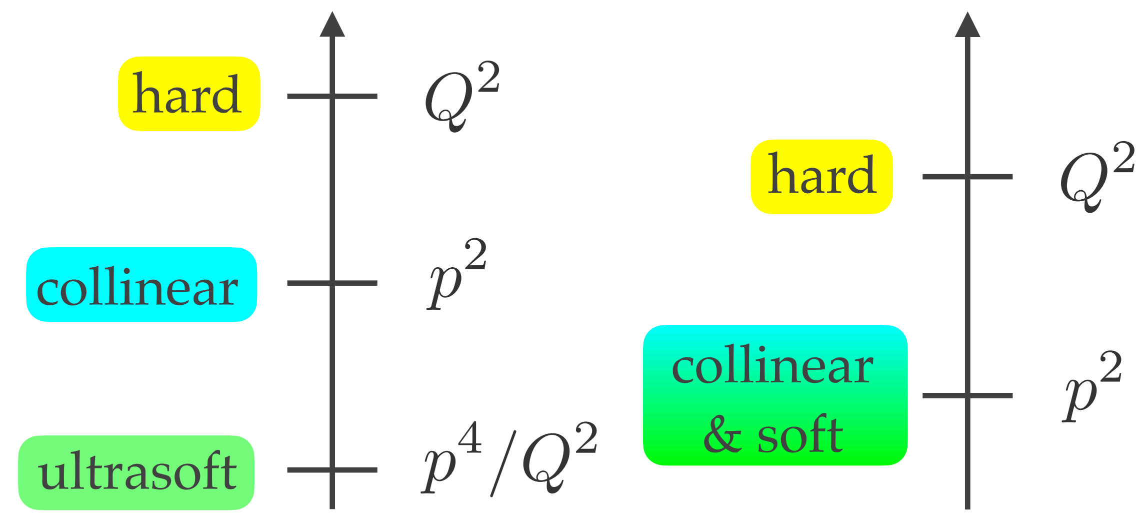
SCET is more complicated in many regards:

- Operators contain **non-local products of fields**, separated by light-like distances
- EFT fields are split up in **momentum modes** (soft, collinear, hard, …)

SCALE FACTORIZATION IN HIGH-ENERGY PROCESSES

Prototypical SCET factorization theorem

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



SCET-1 SCET-2

- **Examples:** threshold resummation and p_T resummation for Drell-Yan and Higgs production, jet vetos, event shapes, jet substructure, non-global and super-leading logarithms, …
- Products/convolutions of component functions, which live at a single characteristic scale

SCALE FACTORIZATION IN HIGH-ENERGY PROCESSES

$$\sigma \sim \boxed{H} \int \boxed{J \otimes J} \otimes \boxed{S}$$

Extension to next-to-leading power?

- Generically, find **endpoint-divergent convolution integrals**
- Upset scale separation and break factorization
- Failure of dimensional regularization and MS scheme

$\Rightarrow$ **questions usefulness of the entire SCET framework!**

A hard problem! Several groups worldwide have been working on this for years…

[Beneke et al. ; Moult et al.; Stewart et al.; MN et al.; Bell et al.] (2018–2022)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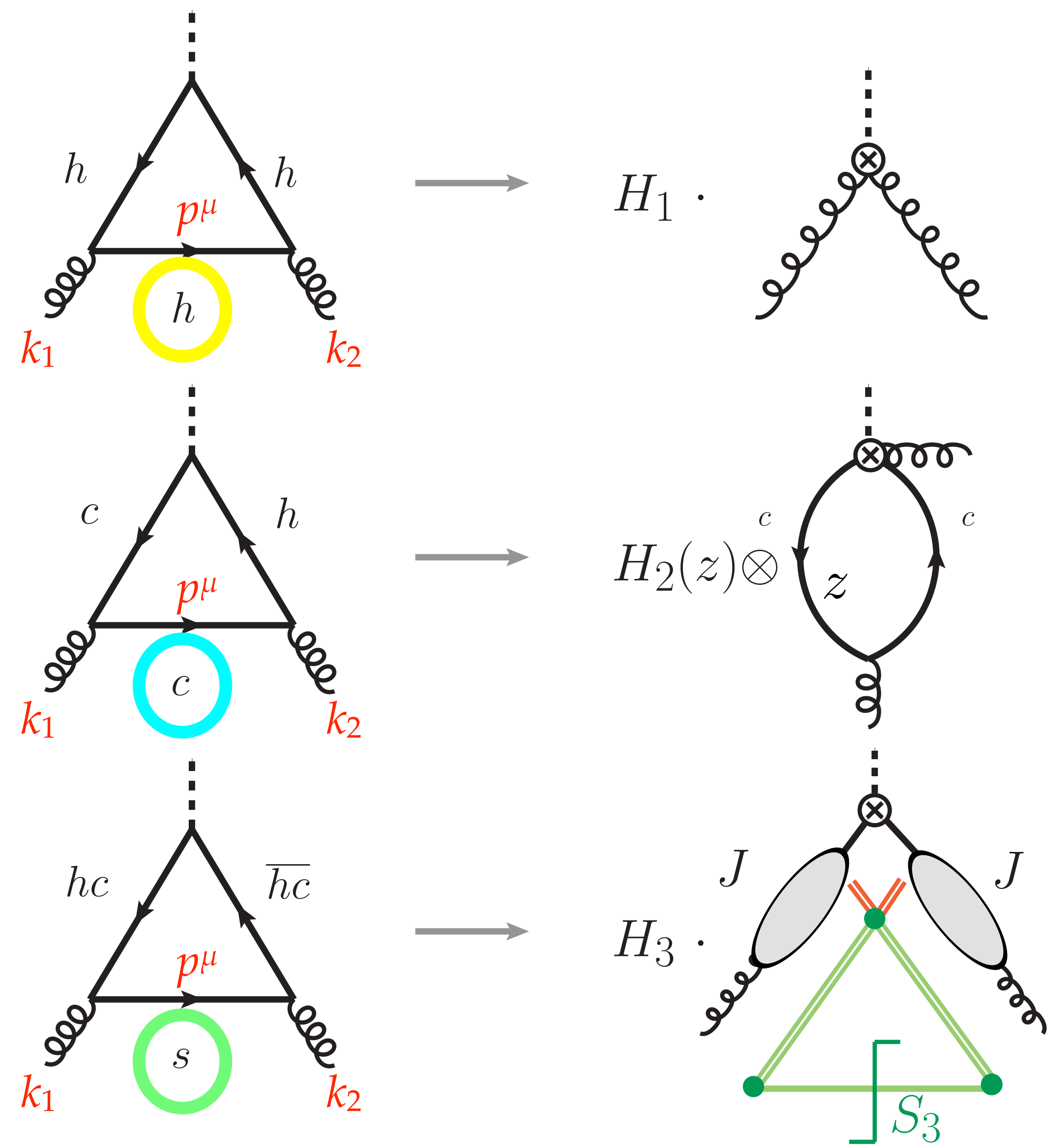
HIGGS PRODUCTION VIA BOTTOM-QUARK LOOPS

Leading momentum regions, each corresponding to a SCET operator:

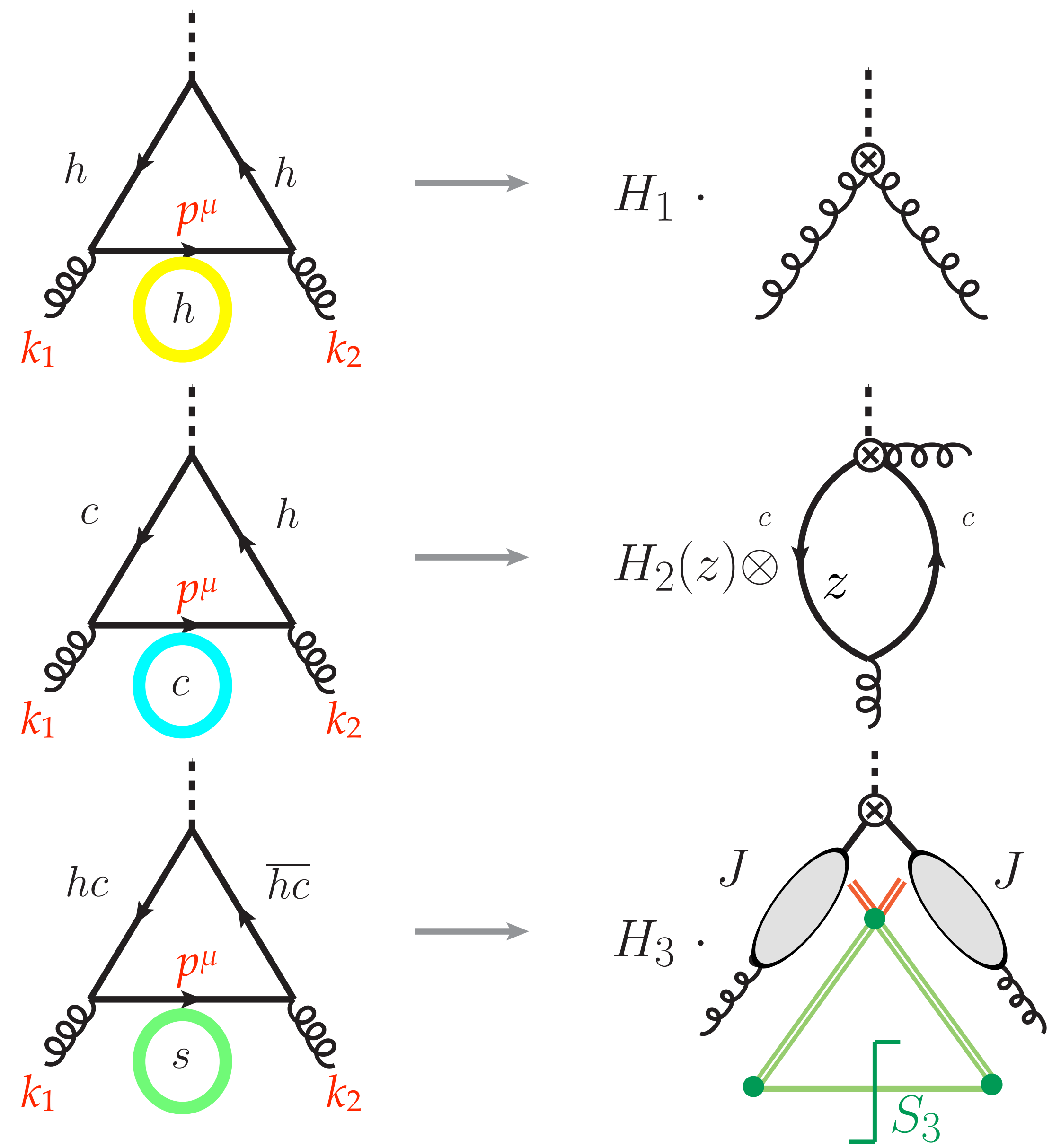
[Liu, MN 2020; Liu, Mecaj, MN, Wang 2021]



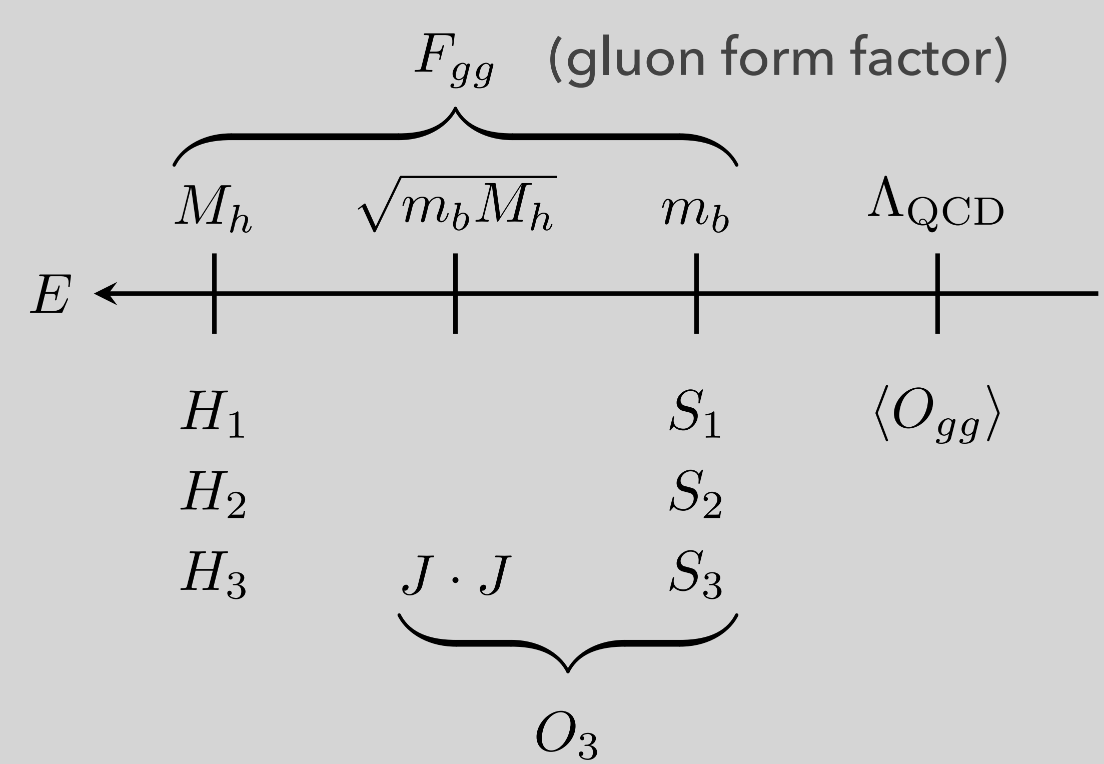
$p^\mu \sim M_h$	hard
$p^\mu \parallel k_1\,, \quad p^2 \sim m_b^2$	n_1-collinear
$p^\mu \sim m_b$	soft

HIGGS PRODUCTION VIA BOTTOM–QUARK LOOPS

Leading momentum regions, each corresponding to a SCET operator:



3-step matching procedure:

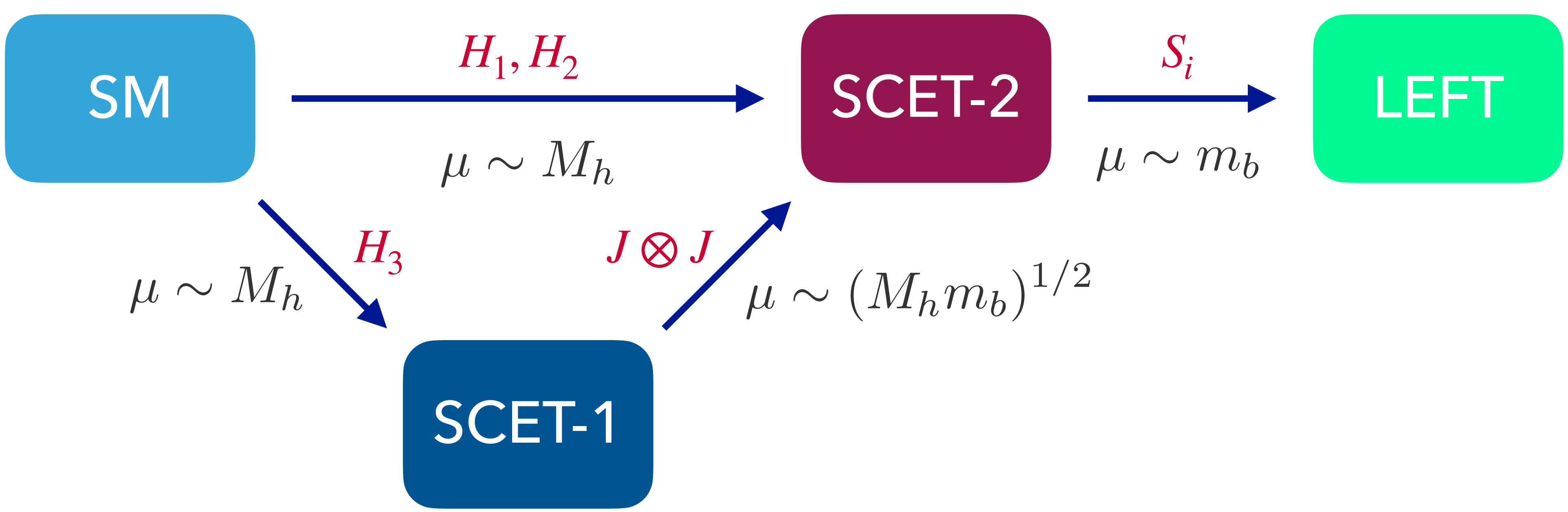


[Liu, MN, Schnubel, Wang 2022]

HIGGS PRODUCTION VIA BOTTOM-QUARK LOOPS

Bare factorization theorem

$$F_{gg}^{(0)} = H_1^{(0)} S_1^{(0)} + 2\int_0^1 \frac{dz}{z}\, H_2^{(0)}(z)\, S_2^{(0)}(z)$$
$$+ H_3^{(0)} \int_0^\infty \frac{d\ell_+}{\ell_+} \int_0^\infty \frac{d\ell_-}{\ell_-}\, J^{(0)}(-M_h \ell_+)\, J^{(0)}(M_h \ell_-)\, S_3^{(0)}(\ell_+ \ell_-)$$



HIGGS PRODUCTION VIA BOTTOM-QUARK LOOPS

Bare factorization theorem

$$F_{gg}^{(0)} = H_1^{(0)} S_1^{(0)} + 2 \int_{\boxed{0}}^1 \frac{dz}{z} \, H_2^{(0)}(z) \, S_2^{(0)}(z) \\ + H_3^{(0)} \int_0^{\boxed{\infty}} \frac{d\ell_+}{\ell_+} \int_0^{\boxed{\infty}} \frac{d\ell_-}{\ell_-} \, J^{(0)}(-M_h \ell_+) \, J^{(0)}(M_h \ell_-) \, S_3^{(0)}(\ell_+ \ell_-)$$

- Convolution integrals in the second and third term are endpoint divergent for $z \to 0$ and $\ell_\pm \to \infty$

HIGGS PRODUCTION VIA BOTTOM-QUARK LOOPS

Refactorization-based subtraction (RBS) scheme

$$F_{gg}^{(0)} = H_1^{(0)} S_1^{(0)} + 2 \int_{\boxed{0}}^1 \frac{dz}{z}\, H_2^{(0)}(z)\, S_2^{(0)}(z)$$
$$+ H_3^{(0)} \int_0^{\boxed{\infty}} \frac{d\ell_+}{\ell_+} \int_0^{\boxed{\infty}} \frac{d\ell_-}{\ell_-}\, J^{(0)}(-M_h \ell_+)\, J^{(0)}(M_h \ell_-)\, S_3^{(0)}(\ell_+ \ell_-)$$

- Exact *D*-dimensional refactorization conditions ensure that the integrands of the second and third terms are identical in the singular regions (to all orders of perturbation theory):

[Liu, MN 2020; also: Beneke et al. 2020]

$$[[H_2^{(0)}(z)]] = -H_3^{(0)}\, J^{(0)}(\underbrace{zM_h^2}_{M_h\ell_-})$$

$$[[S_2^{(0)}(z)]] = -\frac{1}{2} \int_0^\infty \frac{d\ell_+}{\ell_+}\, J^{(0)}(-M_h \ell_+)\, S_3^{(0)}(\overbrace{zM_h}^{\ell_-}\ell_+)$$

HIGGS PRODUCTION VIA BOTTOM-QUARK LOOPS

Renormalized factorization theorem in the RBS scheme

[Liu, MN, Schnubel, Wang 2022]

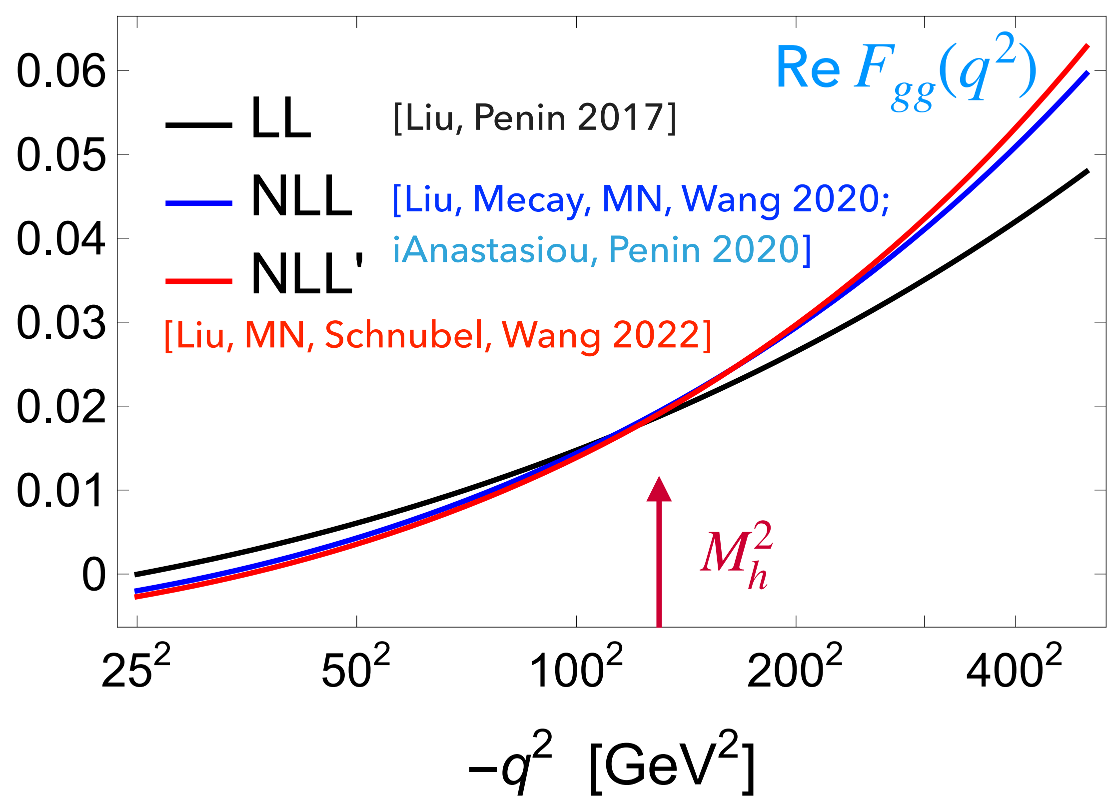
$$F_{gg}(\mu) = \Big[H_1(\mu) - \Delta H_1(\mu)\Big]\, S_1(\mu) + 2\int_0^1 \frac{dz}{z} \Big(H_2(z,\mu)\, S_2(z,\mu) - [[H_2(z,\mu)]]\,[[S_2(z,\mu)]]\Big)$$

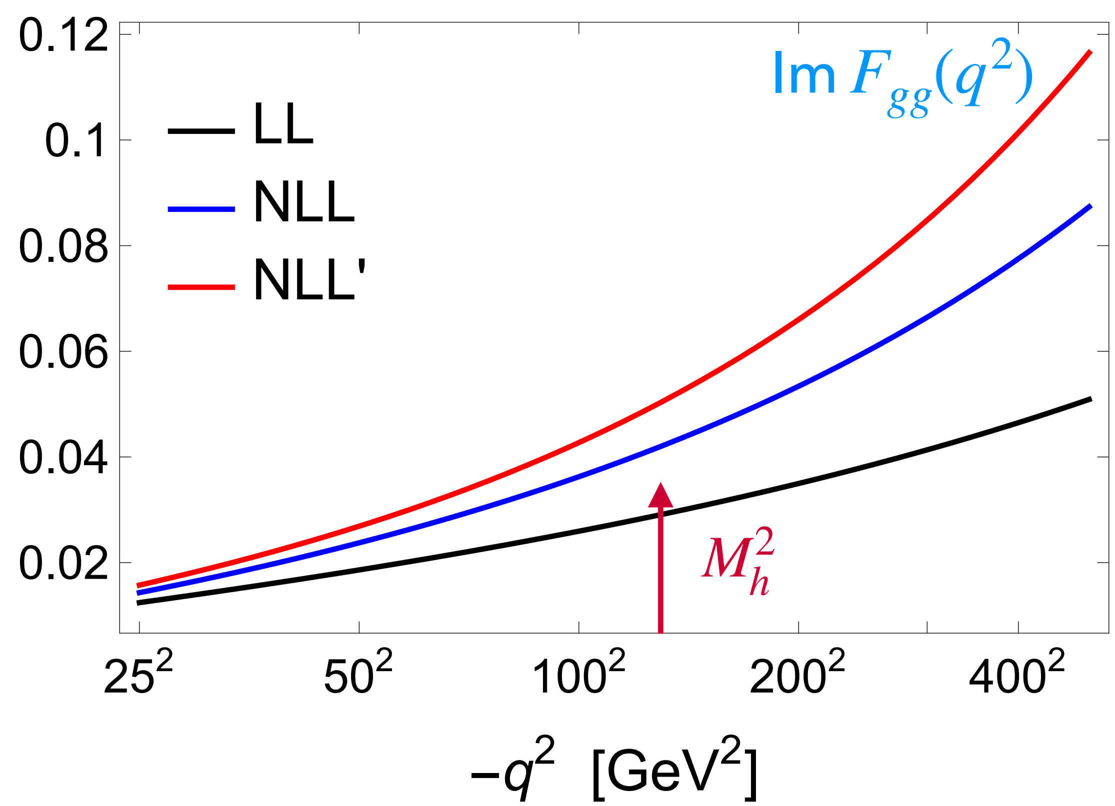
$$+ \lim_{\sigma\to -1} H_3(\mu) \int_0^{\sigma M_h} \frac{d\ell_+}{\ell_+} \int_0^{M_h} \frac{d\ell_-}{\ell_-}\, J(-M_h \ell_+,\mu)\, J(M_h \ell_-,\mu)\, S_3(\ell_+ \ell_-,\mu)$$

- Provides basis for systematic resummations of large double (and single) logarithms $\sim \alpha_s^n \ln^{2n-k}(-M_h^2/m_b^2)$ with $k \geq 0$
- Have succeeded to sum the towers of these logarithms for $k = 0{,}1{,}2$ (NLL′ approximation); result expressed in terms of hypergeometric functions ${}_2F_2$ and Dawson integral $D(z)$

HIGGS PRODUCTION VIA BOTTOM-QUARK LOOPS

Form factor $F_{gg}(q^2)$ in the time-like region:

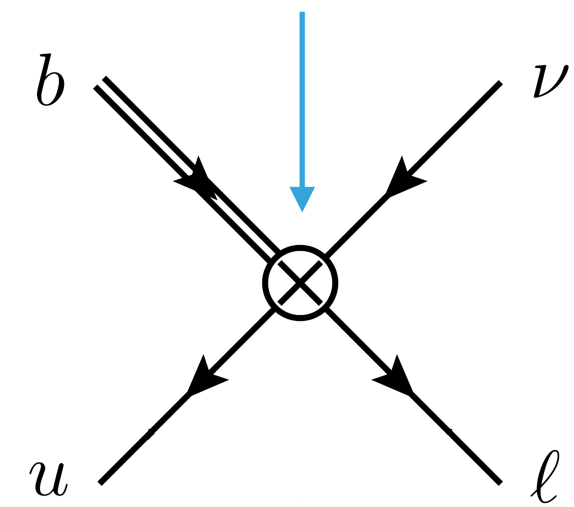




$\Rightarrow$ significant reduction of the perturbative uncertainty of light-quark indices contributions to the gluon-fusion cross section!

QED CORRECTIONS IN LEPTONIC B DECAY

effective 4-fermion interaction from *W*-boson exchange



Decay $B^- \to \ell^- \bar{\nu}_\ell$ is another example of a power-suppressed process, because the amplitude is chirally suppressed by m_ℓ / m_b ; rate ratios for $\ell = e, \mu, \tau$ can provides **tests of lepton universality**

- Effective weak Hamiltonian at $\mu \sim m_b$:

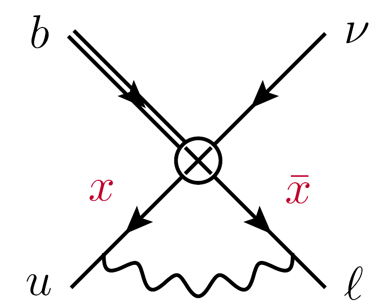
$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} K_{\rm EW}(\mu) V_{ub} \, (\bar{u}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$$

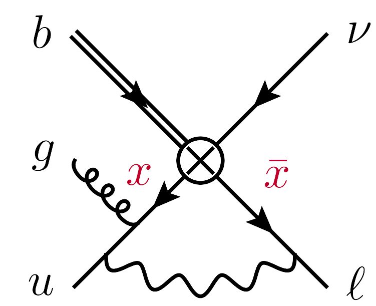
- In QCD, decay amplitude is given in terms of V_{ub} times the *B*-meson decay constant f_B, defined by:

$$\langle 0 | \, \bar{u}\gamma^\mu \gamma_5 \, b \, | B^-(v) \rangle = i m_B f_B \, v^\mu$$

QED CORRECTIONS IN LEPTONIC B DECAY

- Problem becomes interesting when QED corrections are included, because virtual photons can resolve the inner structure of the *B* meson [Cornella, König, MN 2022; also: Beneke, Bobeth, Szafron 2018]





- Quark current $\bar{u}\,\gamma^\mu P_L\,b$ is not gauge invariant under QED; to fix this, one must add a Wilson line accounting for soft photon interactions with the charged lepton: $\bar{u}\,\gamma^\mu P_L\,b\,S_n^{(\ell)\dagger}$ [Beneke, Bobeth, Szafron 2019]
- Two problems:
  - **operator is ill-defined** (IR sensitive anomalous dimension) [Beneke, Böer, Toelstede, Vos 2020]
  - appearance of **endpoint divergences**

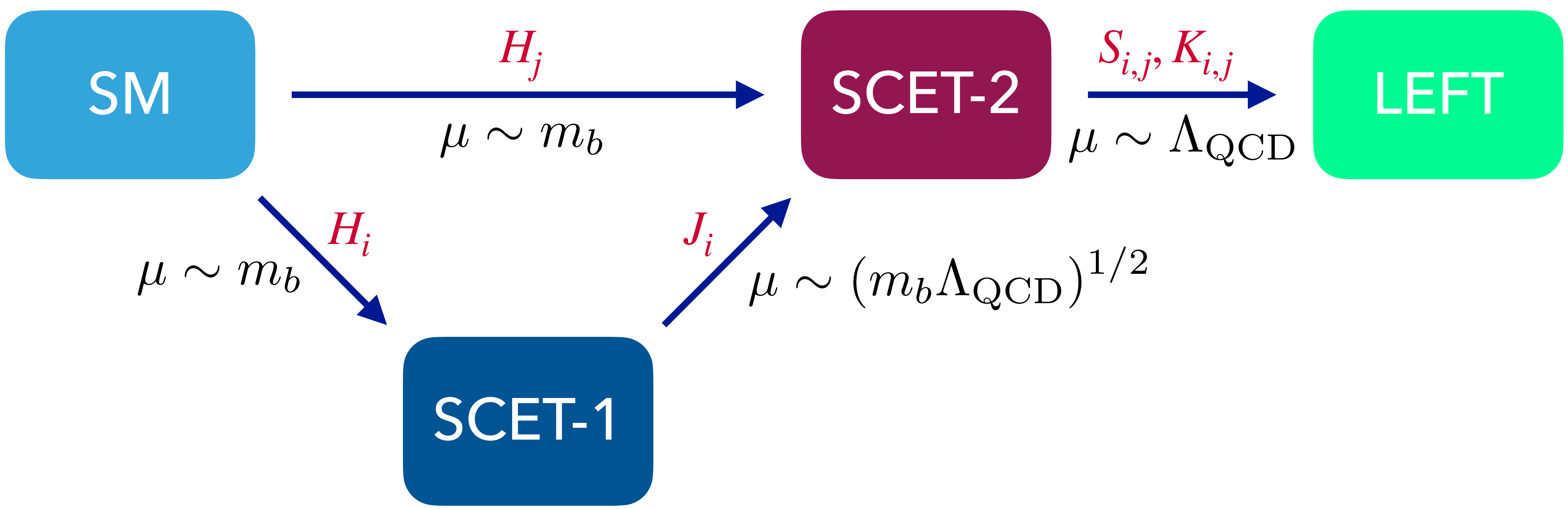
QED CORRECTIONS IN LEPTONIC B DECAY

SCET factorization theorem

B-meson matrix elements of soft quark operators O_i

lepton matrix elements (collinear fields)

$$\mathcal{A}_{B\to\ell\bar{\nu}} = \sum_j H_j S_j K_j + \sum_i H_i \otimes J_i \otimes S_i \otimes K_i$$



- Both problems have a common solution! [Cornella, König, MN 2022]

QED CORRECTIONS IN LEPTONIC B DECAY

Two most important contributions:

$$\mathcal{A}_{B\to\ell\bar\nu} = -\frac{4G_F}{\sqrt{2}}\,K_{\rm EW}(\mu)\,V_{ub}\,\frac{m_\ell}{m_b}\,K_A(m_\ell)\,\bar u(p_\ell)P_L\,v(p_\nu)$$

$$\cdot\Big[H_A(m_b)\,S_A + \int d\omega \int_0^1 dx\, \underbrace{H_B(m_b,x)}_{\sim\, x^{-n\epsilon}}\, \underbrace{J_B(m_b\omega,x)}_{\sim\, x^{-1-n\epsilon}}\, S_B(\omega)\Big]$$

where (with $\bar n \parallel p_\nu$):

$$O_A = \bar n_\mu\,\bar u_s\gamma^\mu P_L b_v\,S_n^{(\ell)\dagger}$$

$$O_B(\omega) = \int \frac{d\omega}{2\pi}\,e^{i\omega t}\,\bar u_s(tn)\,[tn,0]\,\bar{n}\!\!\!/\,P_L b_v(0)\,S_n^{(\ell)\dagger}(0)$$

quark fields at light like separation

→ *B*-meson light-cone distribution amplitudes

QED CORRECTIONS IN LEPTONIC B DECAY

Subtraction of endpoint divergences in the RBS scheme

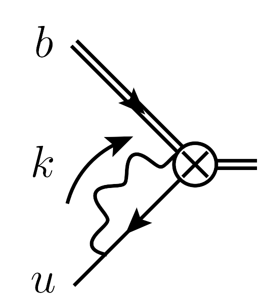
$$
\begin{aligned}
\mathcal{A}_{B\to\ell\bar\nu} &= -\frac{4G_F}{\sqrt{2}}\,K_{\rm EW}\,V_{ub}\,\frac{m_\ell}{m_b}\,K_A(m_\ell)\,\bar u(p_\ell)P_L\,v(p_\nu) \\
&\cdot\Bigg[\Big(H_A(m_b)-\Delta H_A(m_b)\Big)\,S_A^{(m_b)} \\
&\quad+\int d\omega\int_0^1 dx\,\Big[H_B(m_b,x)\,J_B(m_b\omega,x)\;-\;[\![H_B(m_b,x)]\!]\,[\![J_B(m_b\omega,x)]\!]\Big]\,S_B(\omega)\Bigg]
\end{aligned}
$$

[Cornella, König, MN 2022]

with the redefined soft operator:

$$
O_A^{(m_b)} = \bar u_s\,\not{\bar n}P_L\,b_v\,\theta(m_b - i\bar n\cdot D_s)\,S_n^{(\ell)\dagger}
$$

- cuts away high photon momenta
- well-defined anomalous dimension!



with $\bar n\cdot k\le m_b$

QED CORRECTIONS IN LEPTONIC B DECAY

Decay amplitude including virtual QED corrections at $\mathcal{O}(\alpha)$:

$$\mathcal{A}_{B\to\ell\bar{\nu}}^{\text{virtual}} = i\sqrt{2}G_F\,K_{\text{EW}}(\mu)\,V_{ub}\,\frac{m_\ell}{m_b}\sqrt{m_B}\,F(\mu,m_b)\;\bar{u}(p_\ell)P_L\,v(p_\nu)\sum_j \mathcal{M}_j(\mu)$$

with:

$$\begin{aligned}
\mathcal{M}_{2-\text{part.}}(\mu) &= 1+\frac{\alpha}{4\pi}\left\{Q_b^2\left[-\frac{3}{2}\ln\frac{\mu^2}{m_b^2}-2\right]+Q_\ell(Q_\ell-Q_b)\int_0^\infty d\omega\,\phi_-(\omega)\left[2\ln\frac{\mu^2}{m_b\omega}+\frac{\pi^2}{3}+3\right]\right.\\
&\qquad\left.+Q_bQ_\ell\left[2\ln\frac{\mu^2}{m_b^2}-3\ln\frac{\mu^2}{m_\ell^2}-1\right]+Q_\ell^2\,K_\epsilon(m_\ell,\mu)\right\}+\frac{C_F\,\alpha_s(\mu)}{4\pi}\left[-\frac{3}{2}\ln\frac{\mu^2}{m_b^2}-2\right]\\
\mathcal{M}_{3-\text{part.}}(\mu) &= -\frac{\alpha}{\pi}\,Q_\ell(Q_\ell-Q_b)\int_0^\infty d\omega\int_0^\infty d\omega_g\,\phi_{3g}(\omega,\omega_g)\left[\frac{1}{\omega_g}\ln\left(1+\frac{\omega_g}{\omega}\right)-\frac{1}{\omega+\omega_g}\right]
\end{aligned}$$

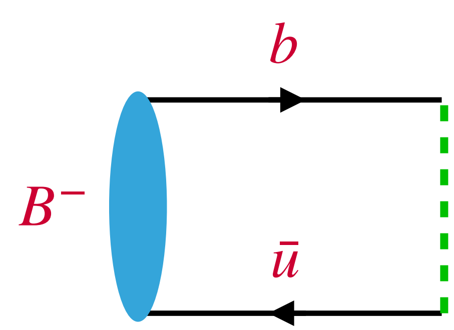
[Cornella, König, MN 2022]

⇒ significant hadronic uncertainties in $\mathcal{O}(\alpha)$ terms!

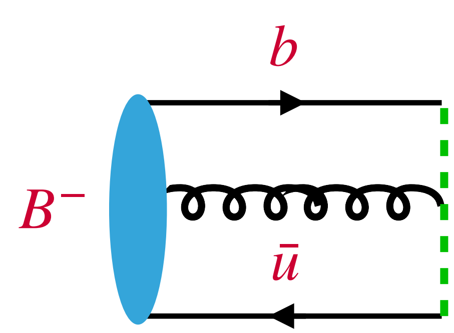
QED CORRECTIONS IN LEPTONIC B DECAY

Non-local hadronic matrix elements:

$$\langle 0|\, O_A^{(m_b)}(\mu)\,|B^-(v)\rangle = -\frac{i\sqrt{m_B}}{2}\, F(\mu, m_b)$$



$\phi_\pm(\omega)$ [Grozin, MN 1996]

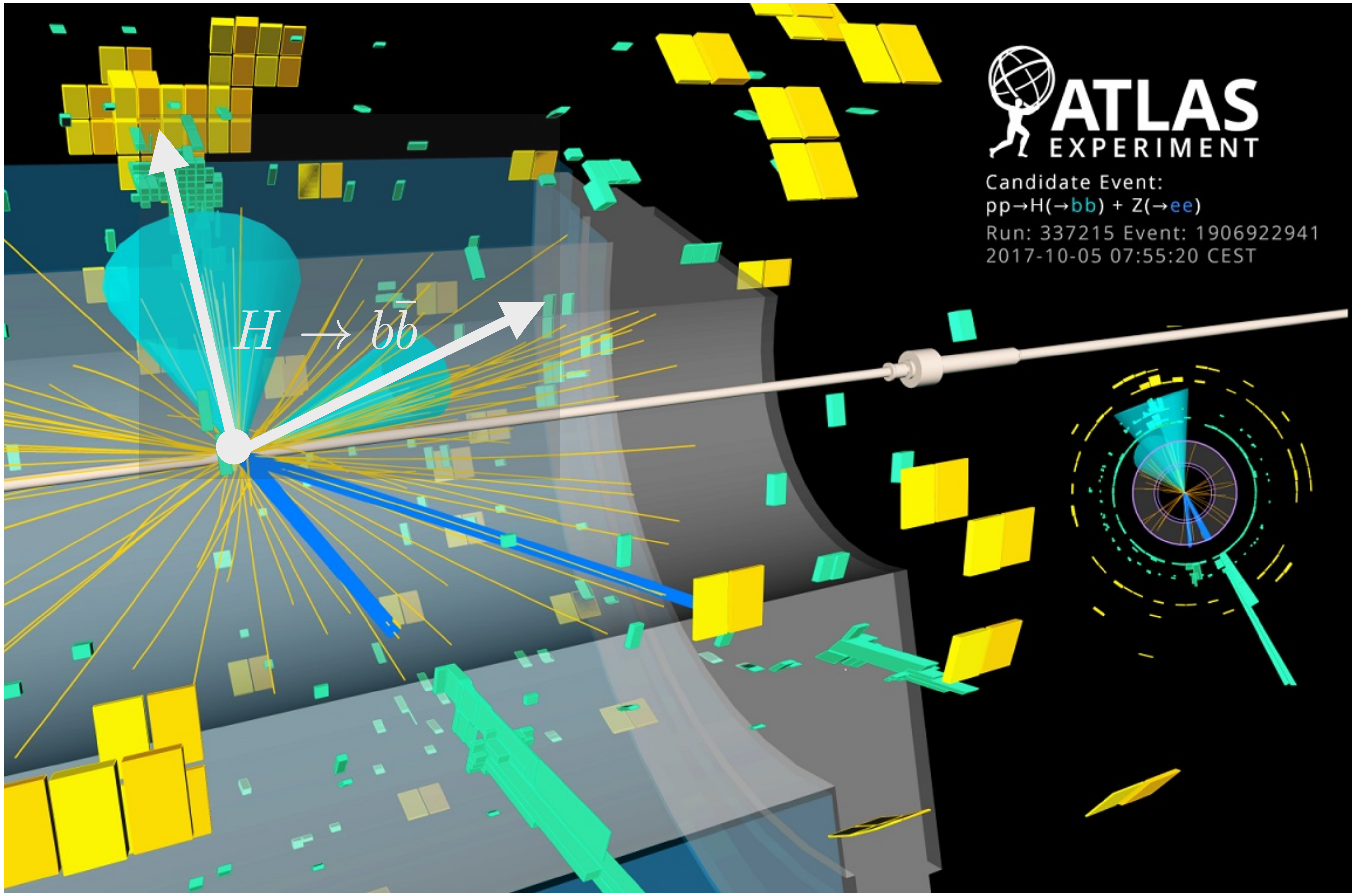


$\phi_{3g}(\omega, \omega_g)$ [Kawamura, Kodaira, Qiao, Tanaka 2001; Braun, Ji, Manashov 2017]

with:

$$\sqrt{m_B}\, f_B^{\mathrm{QCD}} = \left[1 - C_F\,\frac{\alpha_s(m_b)}{2\pi}\right] F(m_b, m_b)\Big|_{\alpha\to 0}$$

THEORY OF JET PROCESSES AT LHC



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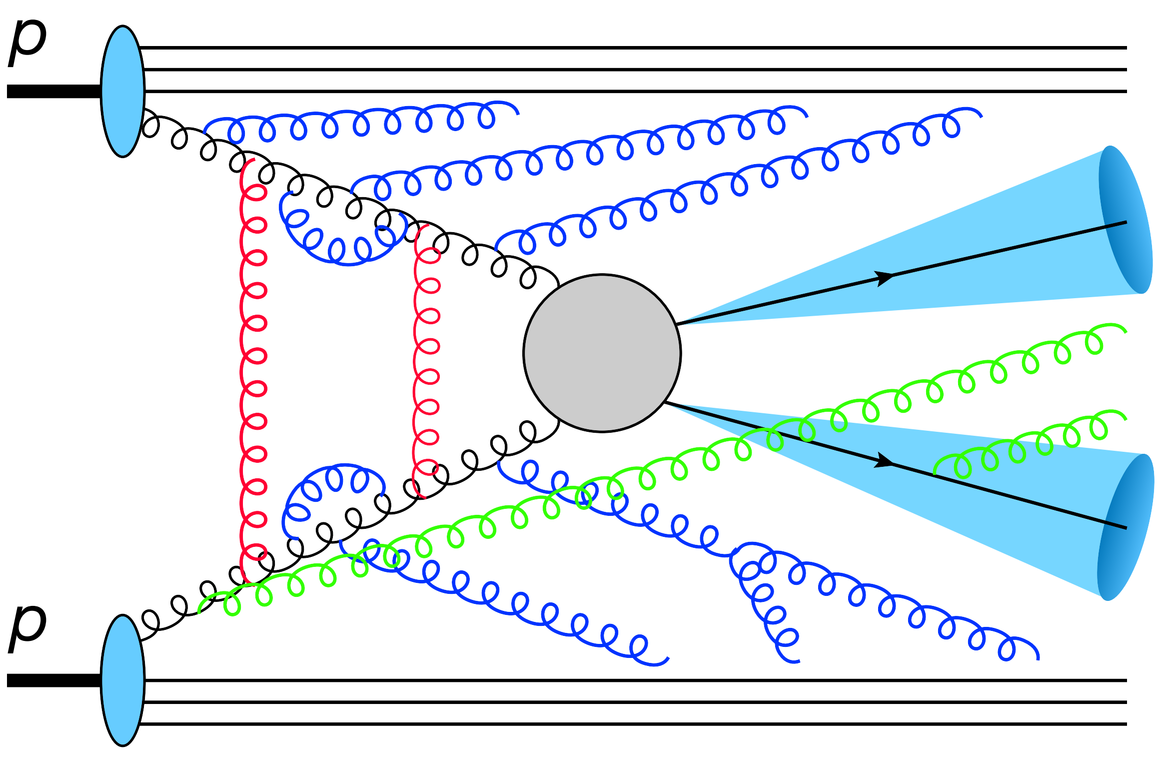
THEORY OF JET PROCESSES AT LHC



red: Coulomb gluons

blue: gluons emitted along beams

green: soft gluons between jets

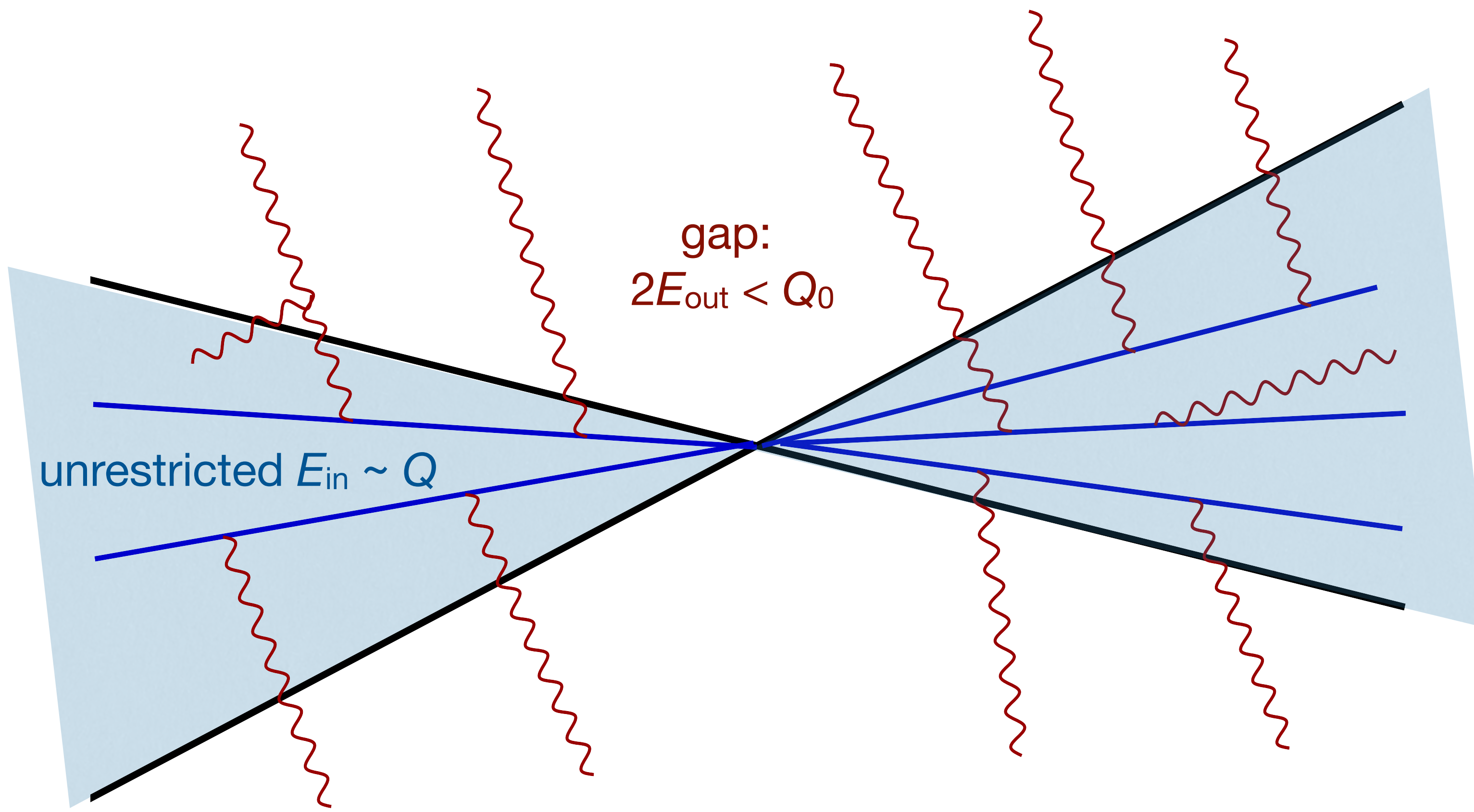
[Forshaw, Kyrieleis, Seymour 2006]

Loss of color coherence from initial-state Coulomb interactions

- Breakdown of factorization?
- Phenomenological consequences?

Need for a complete theory of quantum interference effects in jet processes!

THEORY OF JET PROCESSES AT LHC



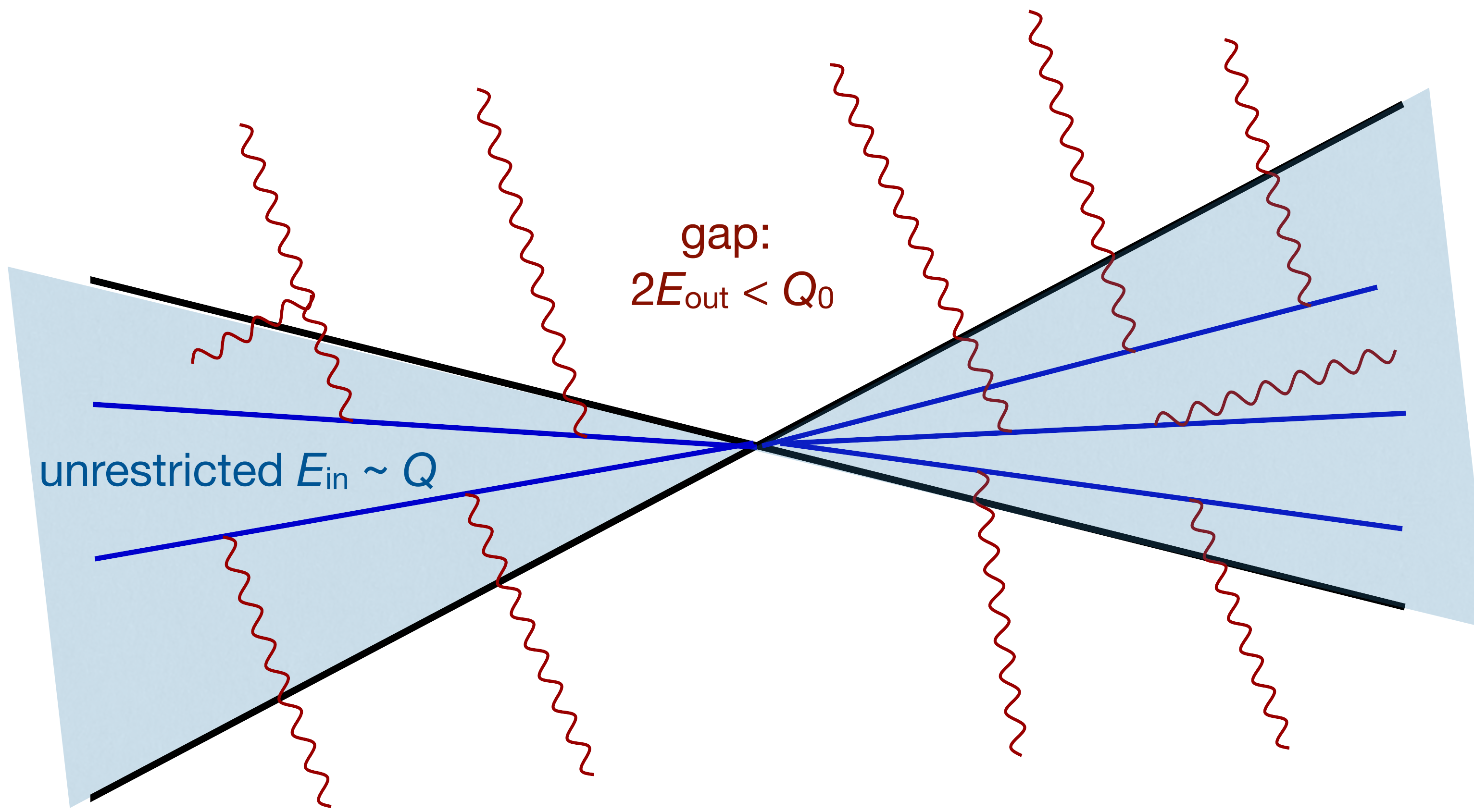
$$L = \ln(Q/Q_0) \gg 1$$

Perturbative expansion:

$$\sigma \sim \sigma_{\mathrm{Born}} \times \left\{ 1 + \alpha_s L + \alpha_s^2 L^2 \right\}$$

state-of-the-art: 2-loop order

THEORY OF JET PROCESSES AT LHC



$$L = \ln(Q/Q_0) \gg 1$$

Perturbative expansion including "superleading" logarithms:

$$\sigma \sim \sigma_{\text{Born}} \times \{1 + \alpha_s L + \alpha_s^2 L^2 + \alpha_s^3 L^3 + \underbrace{\alpha_s^4 L^5 + \alpha_s^5 L^7 + \ldots}_{\sim (\alpha_s L)^3 (\alpha_s L^2)^n}\}$$

state-of-the-art: 2-loop order

$\sim (\alpha_s L)^3 (\alpha_s L^2)^n$: **formally larger than $O(1)$**

[Forshaw, Kyrieleis, Seymour 2006]

THEORY OF JET PROCESSES AT LHC

Novel factorization theorem

$$\sigma_{2\to M}(Q,Q_0)=\sum_{a,b=q,\bar{q},g}\int dx_1 dx_2 \sum_{m=2+M}^{\infty}\Big\langle \boldsymbol{\mathcal{H}}_m^{ab}(\{\underline{n}\},Q,\mu)\otimes \boldsymbol{\mathcal{W}}_m^{ab}(\{\underline{n}\},Q_0,x_1,x_2,\mu)\Big\rangle$$

[Becher, MN, Shao 2021]

high scale

low scale

Renormalization-group equation:

$$\mu\frac{d}{d\mu}\boldsymbol{\mathcal{H}}_l^{ab}(\{\underline{n}\},Q,\mu)=-\sum_{m\le l}\boldsymbol{\mathcal{H}}_m^{ab}(\{\underline{n}\},Q,\mu)\,\boldsymbol{\Gamma}_{ml}^H(\{\underline{n}\},Q,\mu)$$

operator in color space and in the infinite space of parton multiplicities

$\Rightarrow$ new perspective to think about non-global observables

RESUMMATION OF SUPERLEADING LOGARITHMS

All-order summation of large logarithmic corrections, including the superleading logarithms!

⇒ **Example:** Summation of superleading logarithms for $qq \to qq$ scattering in color-singlet channel:

$$\sigma_{\rm SLL} = -\sigma_{\rm Born} \boxed{\frac{16\alpha_s L}{81\pi}\,\Delta Y} \left(3\alpha_s L\right)^2 {}_2F_2\Big(1,1;2,\frac{5}{2};-w\Big) \sim \left(\alpha_s L\right)^3 \sum_{n\ge 0} c_n \left(\alpha_s L^2\right)^n$$

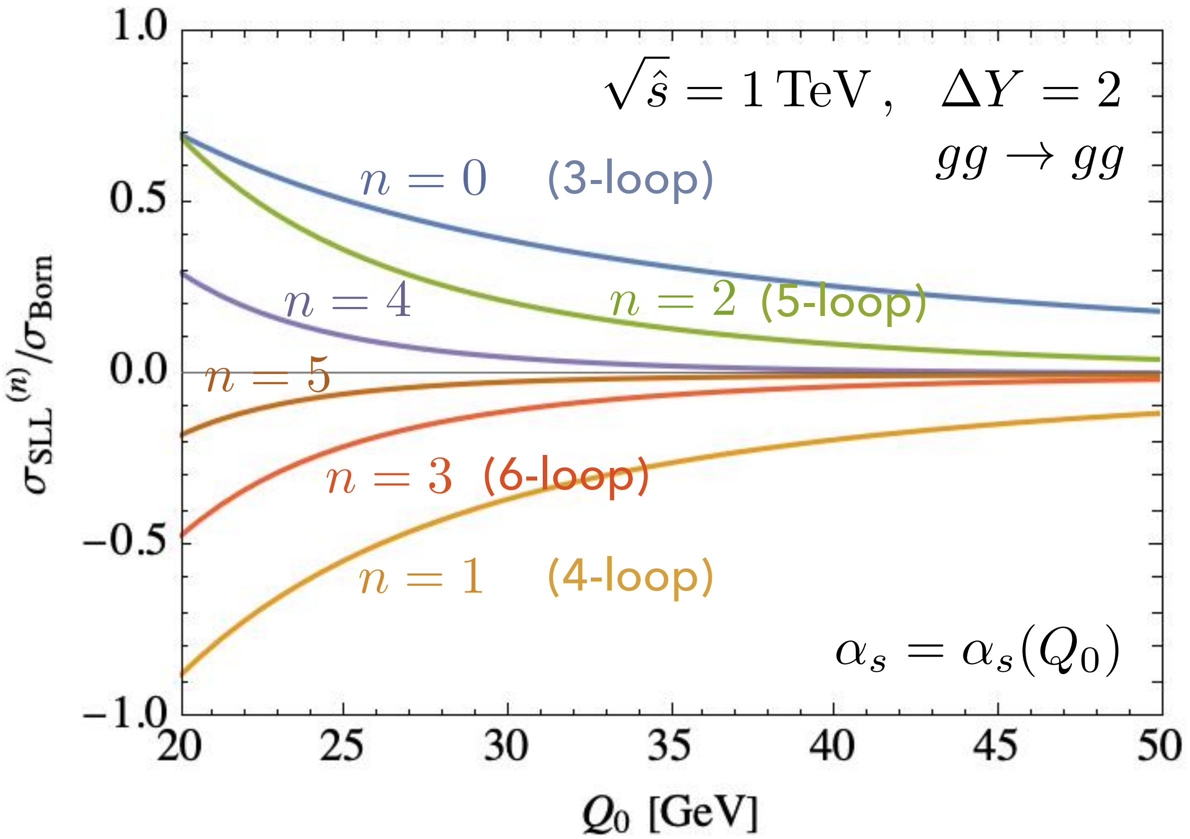
1-loop factor

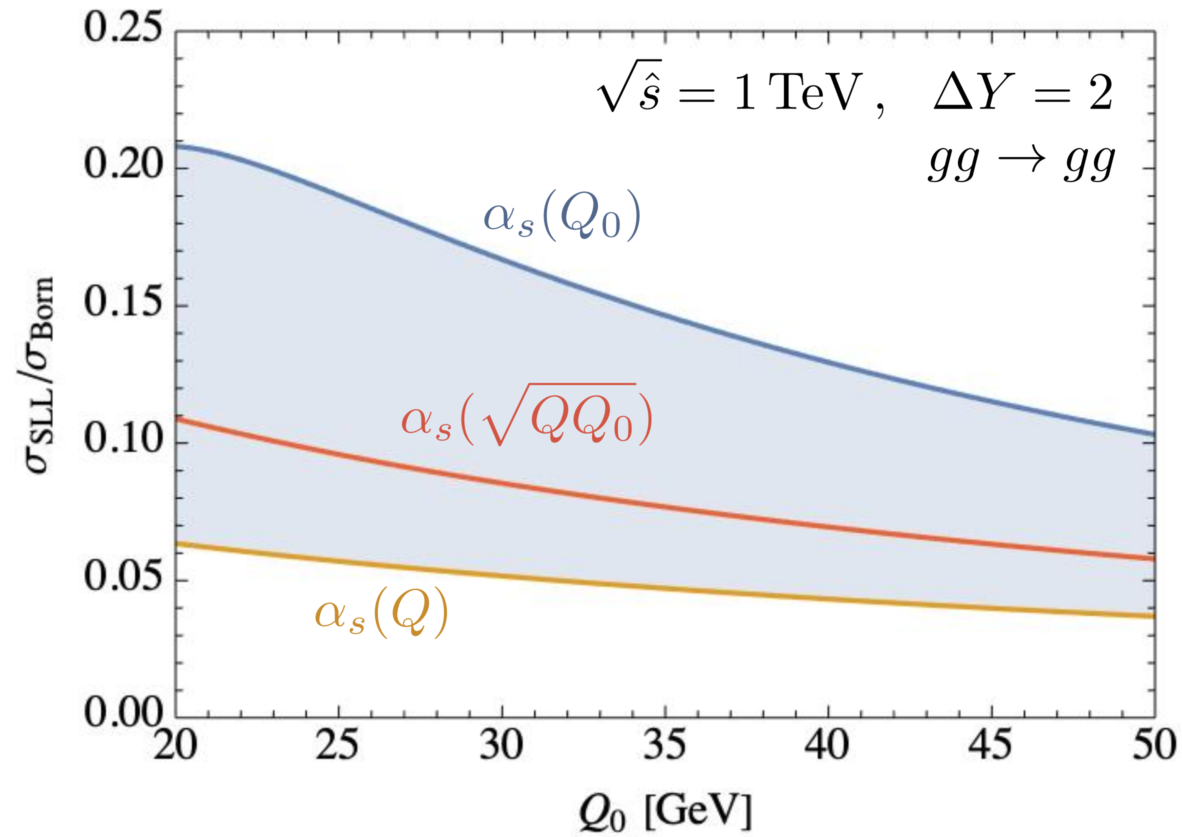
$$w = \frac{3\alpha_s}{\pi} L^2$$

[Becher, MN, Shao 2021]

RESUMMATION OF SUPERLEADING LOGARITHMS

Phenomenological impact in forward gluon-gluon scattering:





$\Rightarrow$ necessary to include eight terms (≤ 10 loops) to obtain reliable results; resummation formalism is essential!

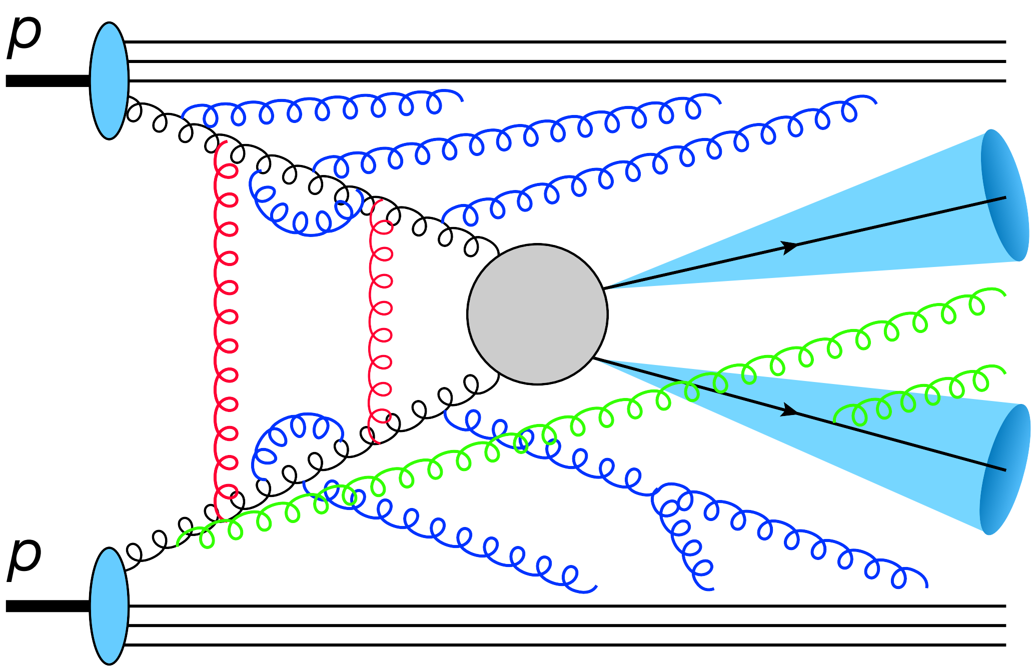
EXPLORING UNCHARTERED TERRITORY

Important open questions

- Do the strong cancellations persist when subleading terms are included? How large is the remaining scale ambiguity?

- Can factorization violations be understood in a quantitative way? Can a more general notion of factorization be established?

- What are the implications for LHC phenomenology? Benchmark processes: $pp \to 2\,\text{jets}$, $pp \to H/V + \text{jets}$, $pp \to \text{jet} + \not{E}_T$, $pp \to$ new particles, …



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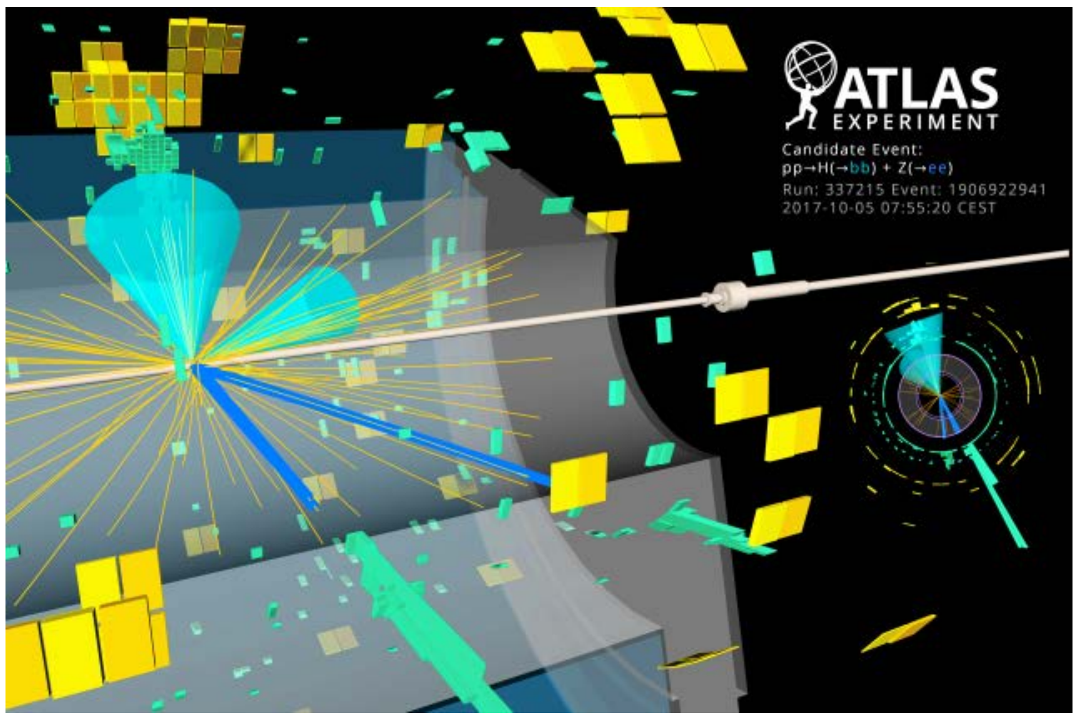
REACHING THE NEXT LEVEL OF PRECISION



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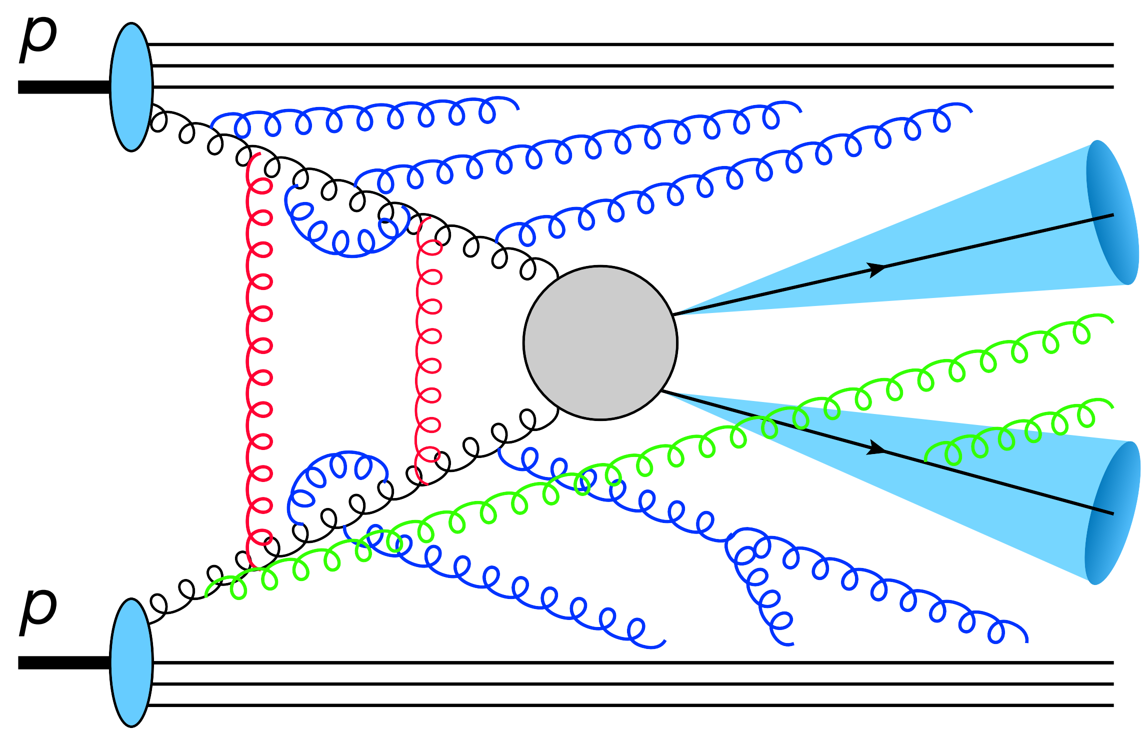

⇒ High-precision probes of known and unknown phenomena at the energy frontier!