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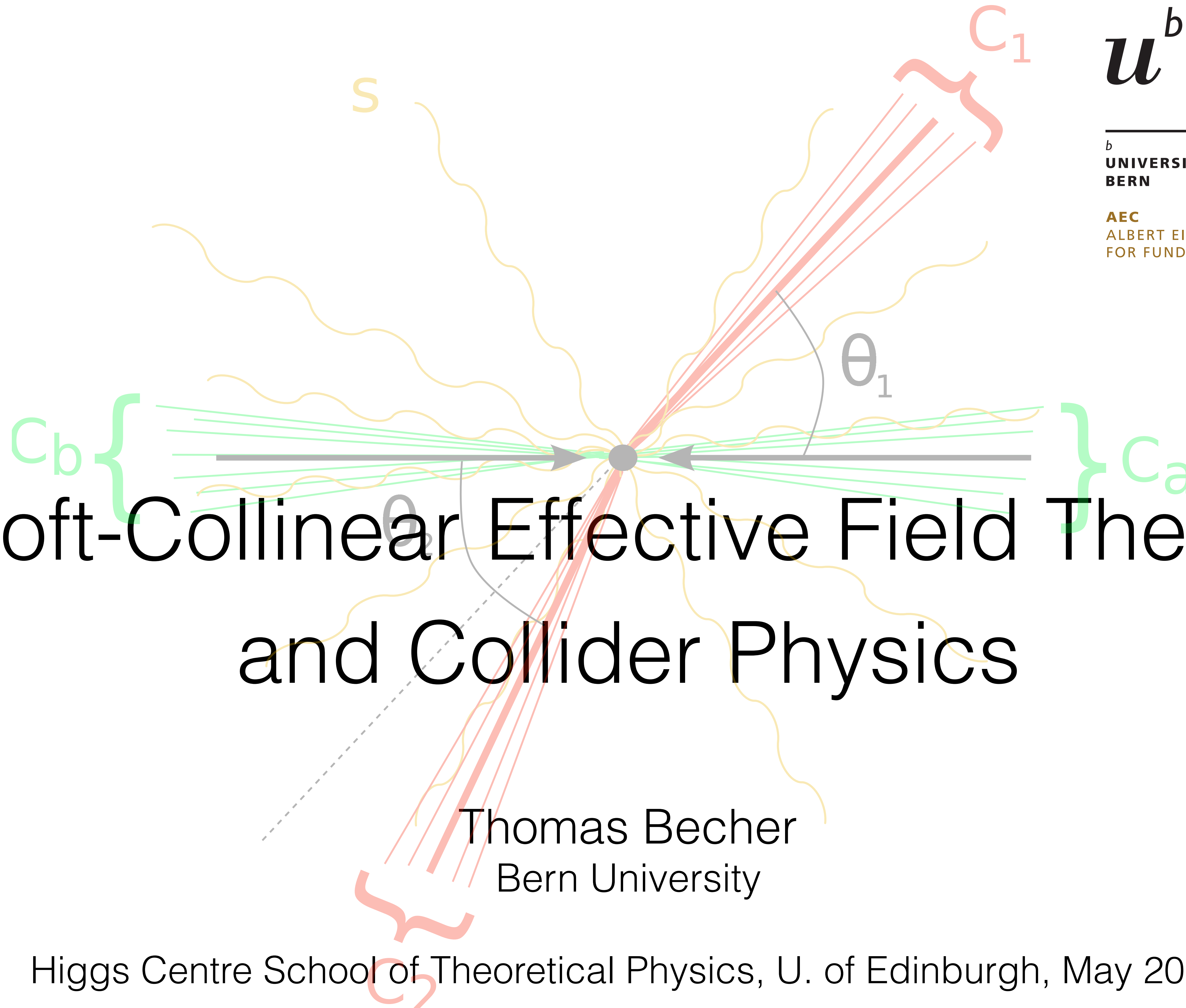

Soft-Collinear Effective Field Theory and Collider Physics

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Tools for QFT computations

Expansion
in the interaction
strength:
perturbation
theory

Expansion in
scale ratios:
Effective Field
Theories

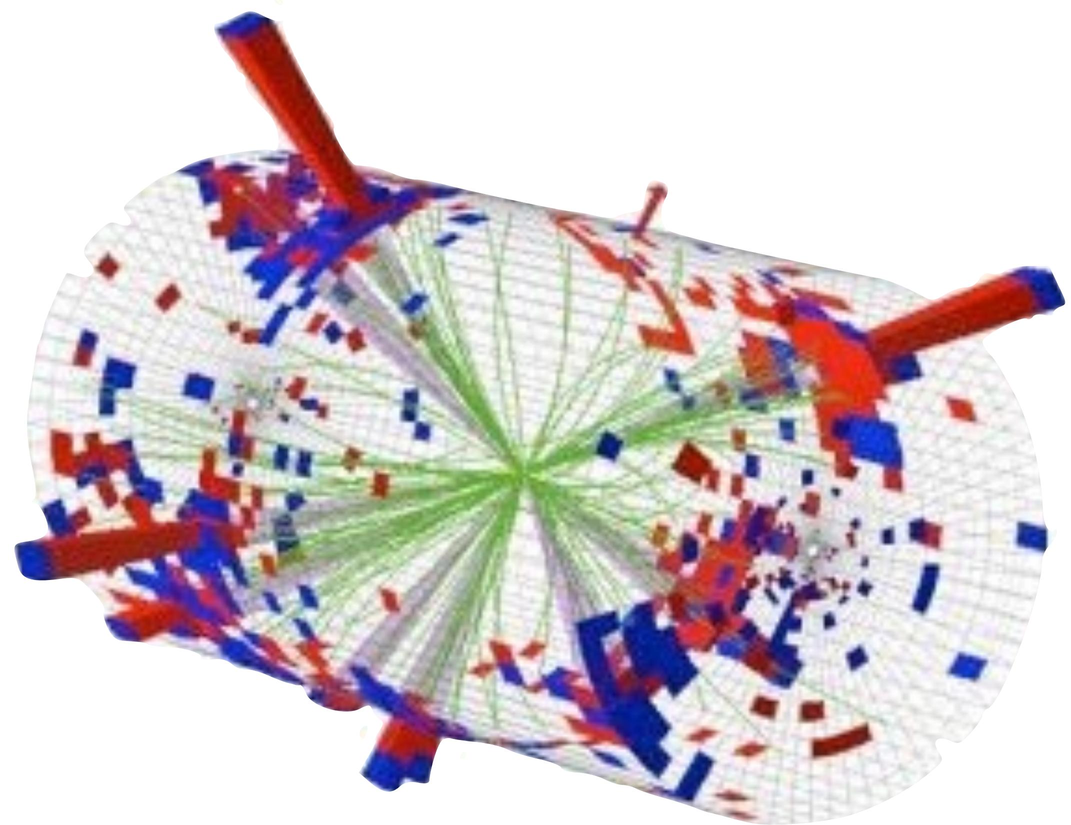
Numerical
methods:
lattice simulations

Toy models:
solvable models
SUSY theories
AdS/CFT

Benefits of EFTs

- Simplification: expansion in scale ratios simplifies computations
- Factorization of physics at different energy scales
  - Dimensional analysis
  - Separate perturbative from non-perturbative physics
  - Perturbation theory works.
    - It cannot be applied in multi-scale problems due to large logarithms.
    - RG improved perturbation theory resums large logarithms.
- Symmetries
  - emergent: heavy-quark symmetry
  - approximate: chiral symmetry
- General framework also for cases where the full theory is not known, or cannot be used for computations

Jet physics at the LHC

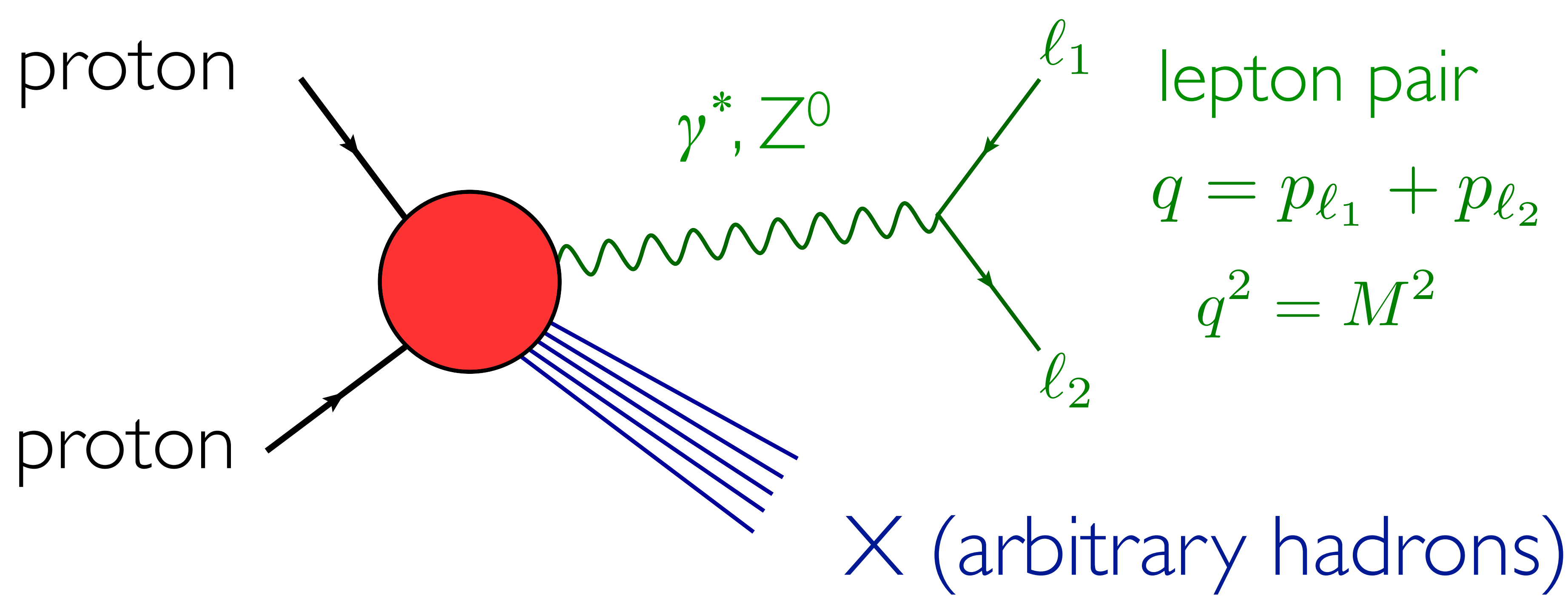


Many scale hierarchies!

$$\sqrt{s} \gg p^T_{\rm Jet} \gg M_{\rm Jet} \gg E_{\rm out} \gg m_{\rm proton} \sim \Lambda_{\rm QCD}$$

→ Soft-Collinear Effective Theory (SCET)

Example: Drell-Yan process



The total DY cross section involves physics associated with two scales

- hard scales $q^2 = M^2$, …
- low-energy scale $\Lambda_{QCD} \sim 1$ GeV (hadronic bound state effects)

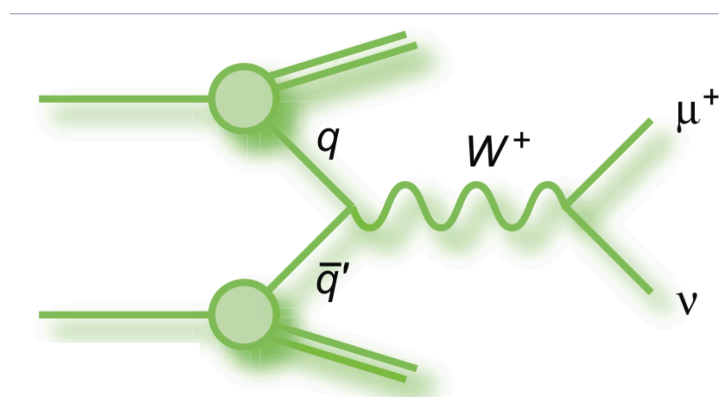
Cross section factorizes into parton distribution functions (PDFs) convoluted with partonic amplitudes

$$\frac{d^4\sigma}{dq^4} = \int_0^1 dx_1 \int_0^1 dx_2\, f_i(x_1,\mu)\, f_i(x_2,\mu)\, \frac{d^4\hat{\sigma}_{ij}(x_1,x_2,\mu)}{d^4q} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}^2}{q^2}\right)$$

PDFs

low-energy part

non-perturbative
universal



partonic cross section
$i + j \rightarrow l^+ l^- + X$

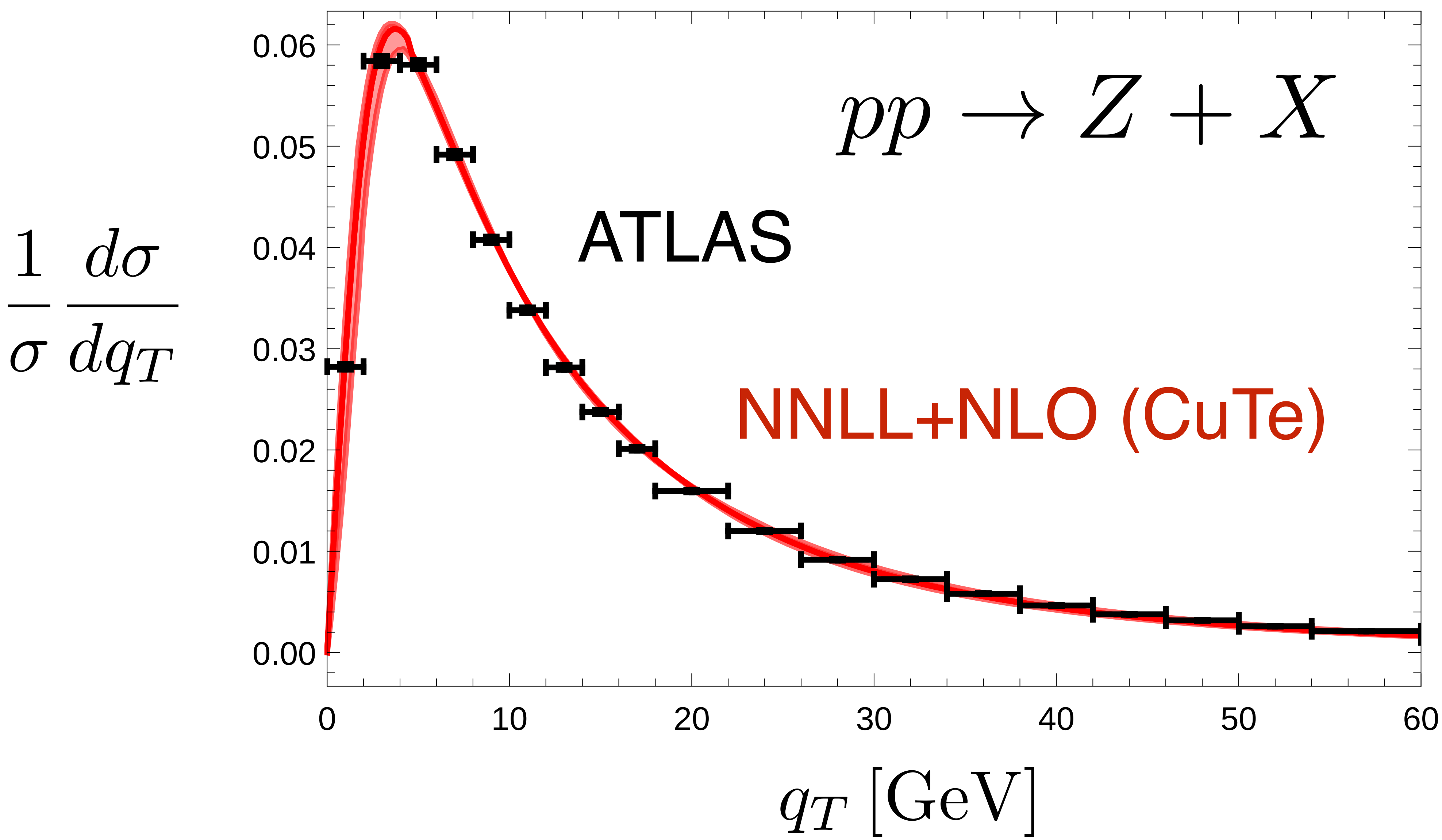
high-energy part

perturbatively calculable

Can be obtained from an analysis within SCET.

- PDFs are operator matrix elements in SCET
- Partonic cross sections are Wilson coefficients of the operators

q_T spectrum of Z-bosons



For $q_T \ll M$ the *partonic* cross section contains two widely separated scales.

Sudakov logarithms

The integrated cross section

$$\Sigma(q_T) = \int_0^{q_T} dq'_T \frac{1}{\sigma}\frac{d\sigma}{dq'_T}$$

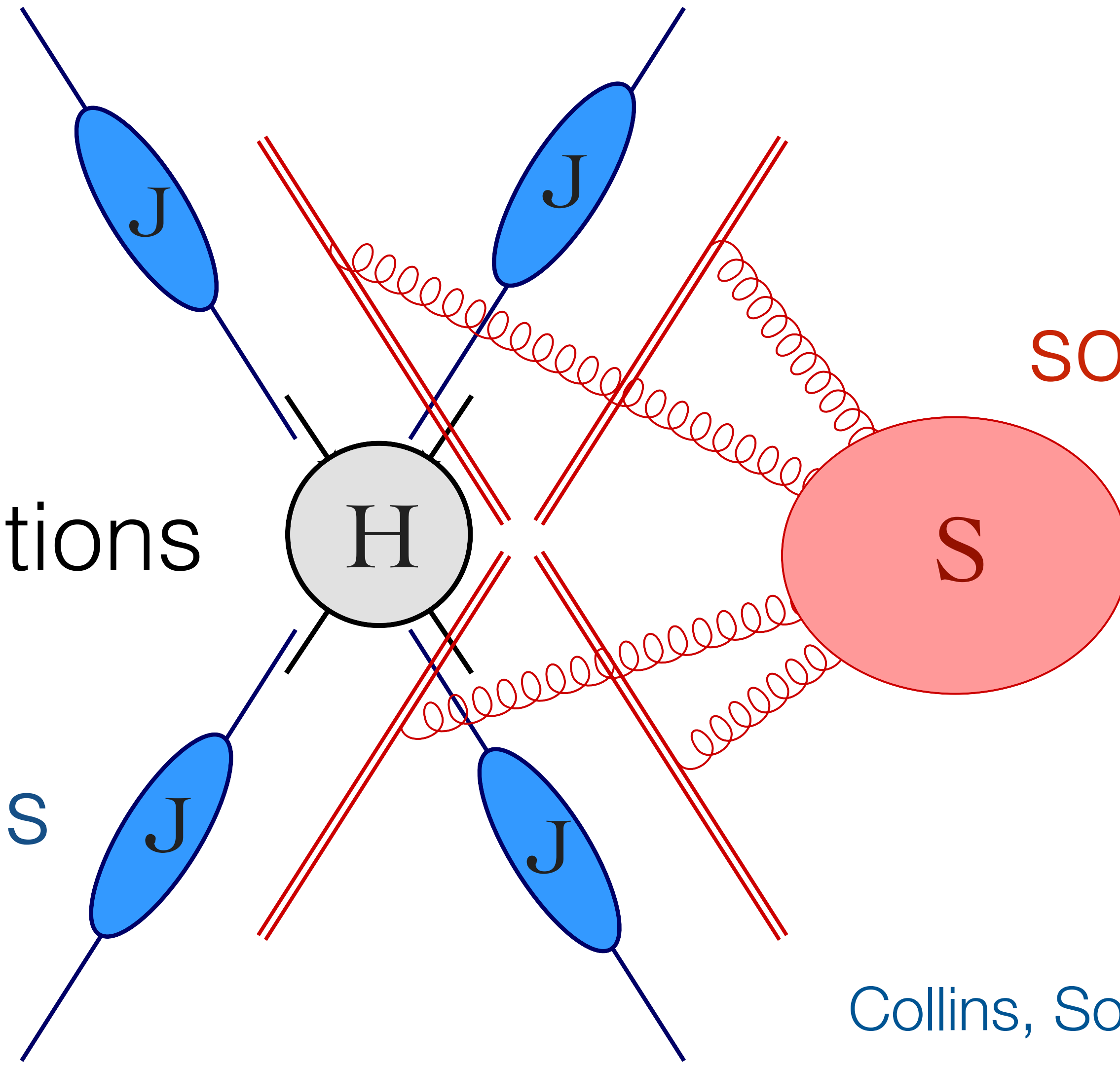
has for low q_T an expansion of the form ($L = \ln \frac{q_T^2}{M^2}$)

$$\Sigma(q_T) = 1 + \alpha_s \left(c_2 L^2 + c_1 L + c_0\right) + \alpha_s^2 \left(c_4 L^4 + c_3 L^3 + \ldots\right) + \alpha_s^3 \left(c_6 L^6 + \ldots\right) + \ldots$$

leading logarithms, next-to-leading logarithms, …

For large $L \sim 1/\alpha_s$ the standard perturbative expansion breaks down: need to (re)sum the large logs to all orders!

Soft-collinear factorization



Basis for factorization and higher-log resummation.

Soft-Collinear Effective Theory

Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke, Diehl et al. 2002; ...

Implements interplay between soft and collinear into effective field theory

Hard } **high-energy**

Collinear
Soft } **low-energy part**

Correspondingly, EFT for such processes has two low-energy modes:

collinear fields describing the energetic partons propagating in each direction of large energy, and

soft fields which mediate long range interactions among them.

Diagrammatic Factorization

The simple structure of soft and collinear emissions forms the basis of the classic factorization proofs, which were obtained by analyzing Feynman diagrams.

Collins, Soper, Sterman 80's ...

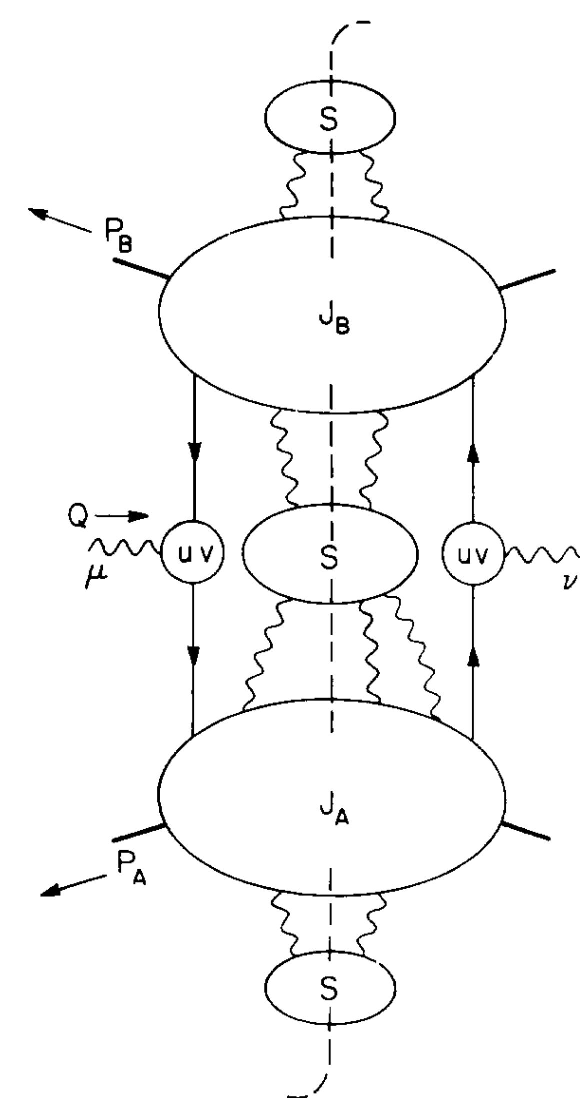
Advantages of the the SCET approach:

Simpler to exploit gauge invariance on the Lagrangian level

Operator definitions for the soft and collinear contributions

Resummation with renormalization group

Can include power corrections



Collins and Soper '81

Outline of the course

- Invitation: EFTs for soft photons
    - $\gamma\gamma$ scattering at low energy ("Euler-Heisenberg Theory")
    - Soft photons in electron scattering (YFS '61, "HQET")
- The method of regions
    - a simple example
    - Scalar Sudakov form factor
- Scalar SCET
    - factorization for the scalar Sudakov form factor in d=6

Outline [...]

- Generalization to QCD
  - Sudakov form factor in QCD
  - Resummation by RG evolution
- An application, e.g.
  - Drell-Yan process near partonic threshold
  - Factorization for DIS or DY
  - Factorization constraints on infrared divergences in n-point amplitudes
  - Factorization and resummation for cone-jet processes (1508.06645,1605.02737 with Neubert, Rothen and Shao).

Literature

A few selected original references are:

Original SCET papers (using the label formalism):

- C.W. Bauer, S. Fleming, D. Pirjol and I.W. Stewart, *An effective field theory for collinear and soft gluons: Heavy to light decays,* PRD 63, 114020 (2001) [hep-ph/0011336]
- C.W. Bauer, S. Fleming, D. Pirjol and I.W. Stewart, *Soft-Collinear Factorization in Effective Field Theory*, PRD 65, 054022 (2002) [hep-ph/0109045]

SCET in position space:

- M. Beneke, A.P. Chapovsky, M. Diehl and T. Feldmann,``Soft-collinear effective theory and heavy-to-light currents beyond leading power,'' Nucl. Phys. B643, 431 (2002) [arXiv:hep-ph/0206152]

Literature for sample collider physics applications:

Factorization analysis for DIS, Drell-Yan and other processes

- C.W. Bauer, S. Fleming, D. Pirjol, I.Z. Rothstein and I.W. Stewart, *Hard scattering factorization from effective field theory*, PRD 66, 014017 (2002) [hep-ph/0202088].

Threshold resummation in momentum space using RG evolution, threshold resummation for Drell-Yan

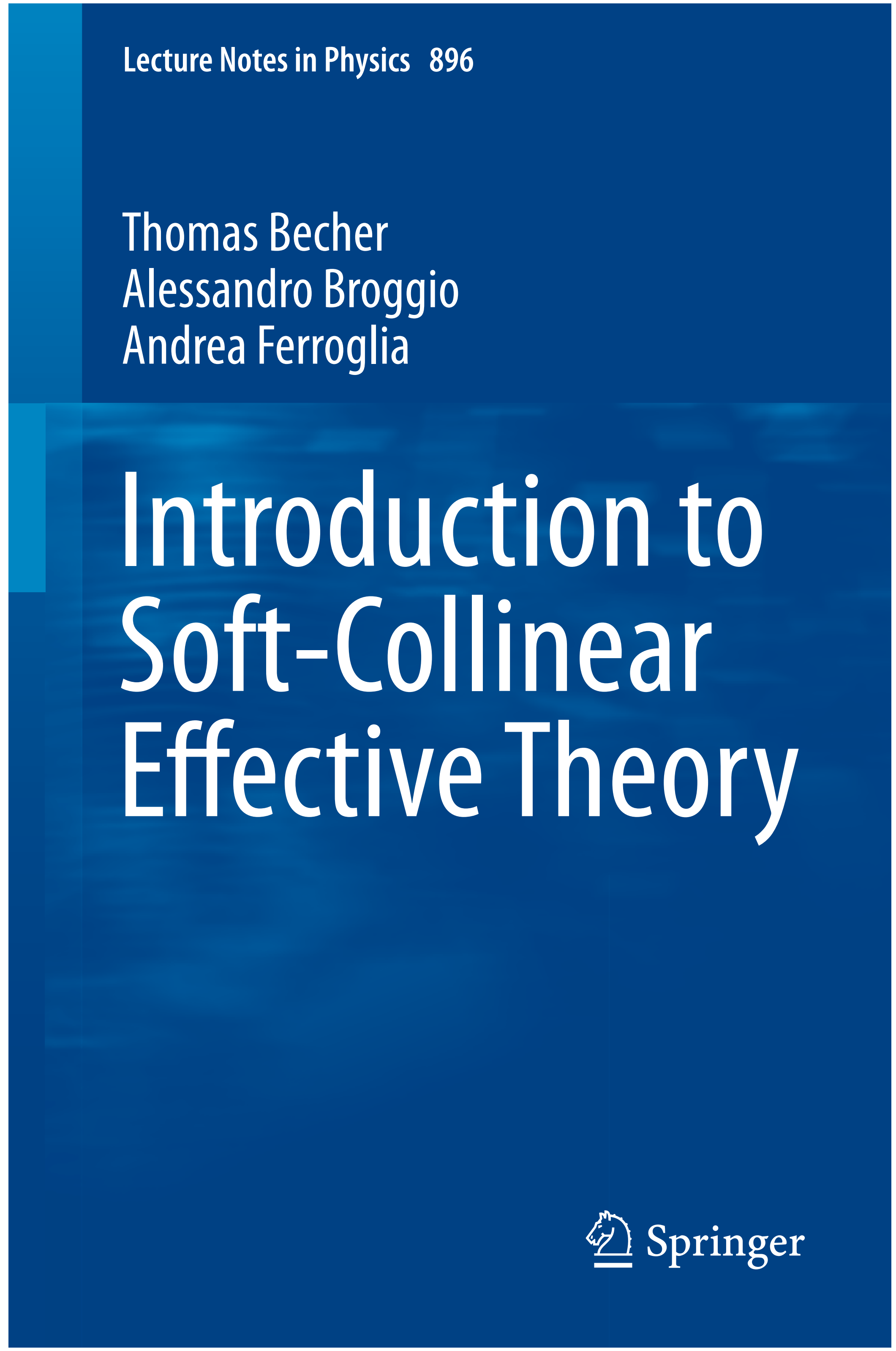
- TB and M. Neubert, *Threshold resummation in momentum space from effective field theory*, PRL 97, 082001 (2006), [hep-ph/0605050]
- TB, M. Neubert and G. Xu, Dynamical Threshold Enhancement and Resummation in Drell-Yan Production,'' JHEP 0807, 030 (2008) [0710.0680]

EFT analysis of the IR structure of gauge theory amplitudes

- TB and M. Neubert, *Infrared singularities of scattering amplitudes in perturbative QCD*, PRL 102, 162001 (2009) [0901.0722]; *On the Structure of Infrared Singularities of Gauge-Theory Amplitudes*, JHEP 0906, 081 (2009) [0903.1126]; *Infrared singularities of QCD amplitudes with massive partons*, PRD 79, 125004 (2009) [0904.1021]

Factorization for cone-jet processes

- TB, M. Neubert, L. Rothen and D.Y. Shao, *An effective field theory for jet processes,* PRL 116 (2016) [1508.06645]*, Factorization and Resummation for Jet Processes 1605.02737*



arXiv:1410.1892

Will follow this book for parts of the lecture, in particular for the construction of the EFT.

The book also contains a chapter with a review of the many application of SCET

- Heavy-particle decays
    - B-physics, top physics, unstable particle EFT, dark matter
- Collider physics
    - Event shapes, jets, threshold resummation, transverse momentum resummation, electroweak Sudakov resummation
- Others: Heavy-ion collisions, soft-collinear gravity, …

and a guide to the associated literature.