PRISMA Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

An Effective Field Theory for Jet Processes

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30 September 2015

Based on: T. Becher, MN, L. Rothen, D.Y. Shao (arXiv:1508:06645)

ERC Advanced Grant (EFT4LHC)
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

Mainz Institute for Theoretical Physics

Factorization and resummation for jet processes

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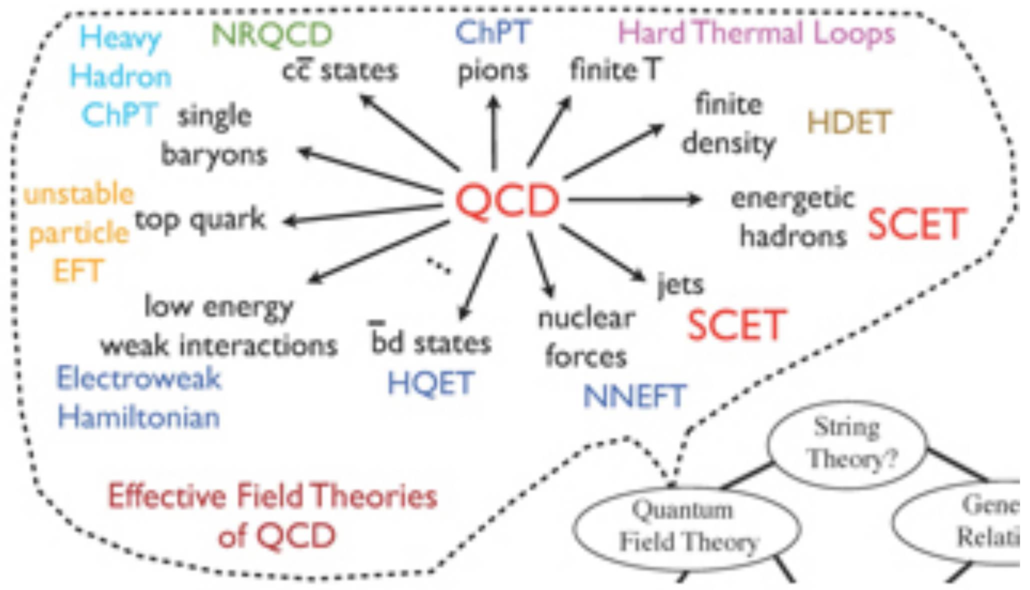
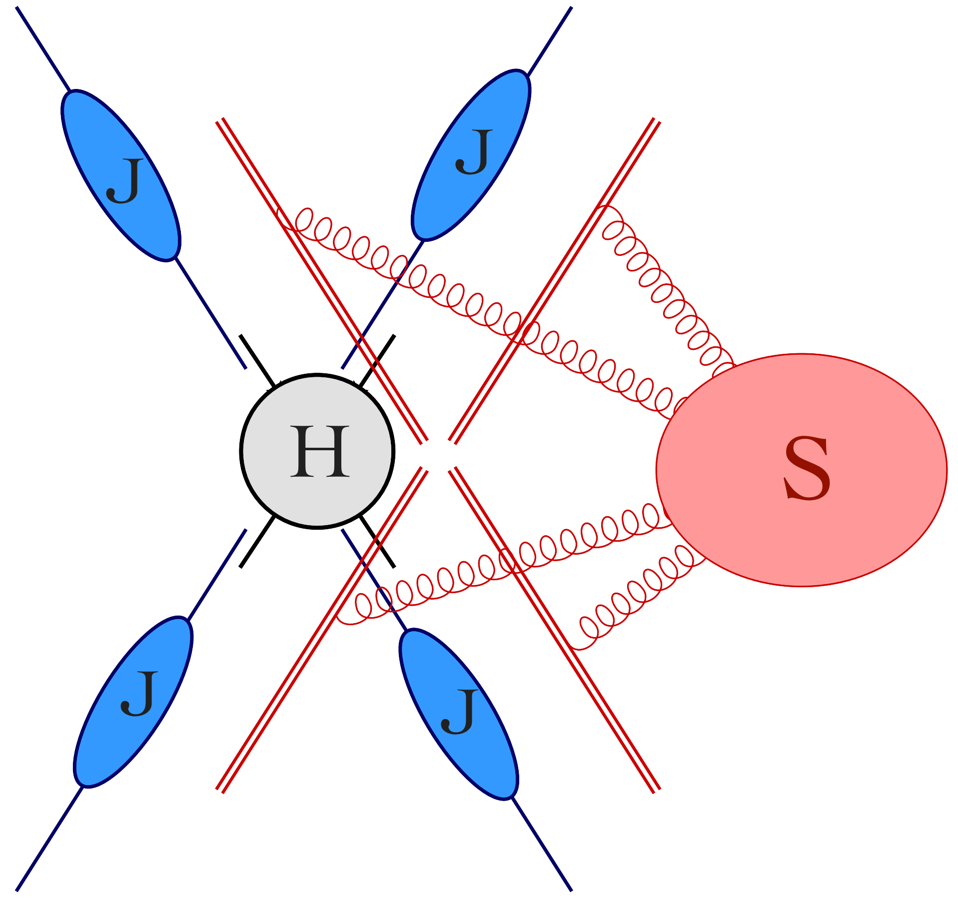
Why go beyond SCET?

Bauer, Fleming, Pirjol, Stewart (2000); Bauer Pirjol, Stewart (2001)
Beneke, Chapovsky, Diehl, Feldmann (2002)

Soft-Collinear Effective Theory is a powerful and versatile tool to study multi-scale processes involving light, energetic particles:

- many successful applications in *B* physics and collider physics
- elegant framework in which to study factorization properties of cross sections and perform resummations of large (Sudakov) logarithms using RG equations
- for sufficiently inclusive processes, cross sections involving energetic particles can be factorized into products (convolutions) of hard functions, jet functions, and soft functions





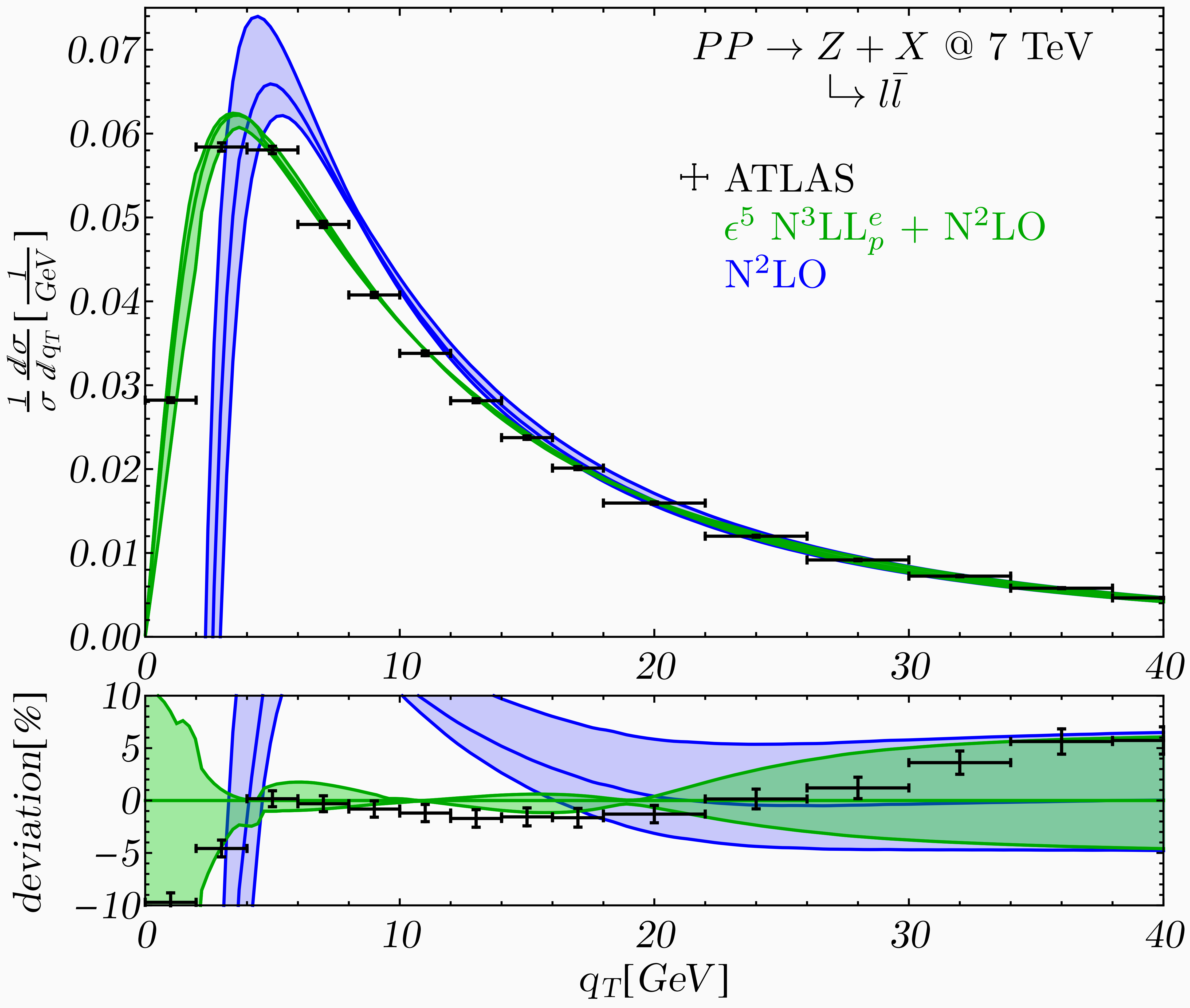
Conventional SCET factorization theorems

Factorization into hard, jet and soft functions

$$d\sigma \sim H(\{s_{ij}\},\mu) \prod_i J_i(M_i^2,\mu) \otimes S(\{\Lambda_{ij}^2\},\mu)$$

operators containing **Wilson lines**

- soft-gluon (threshold) resummation in Drell-Yan production, Z-boson production, Higgs production, top-quark pair production etc. (jet functions = PDFs)
- p_T resummation for transverse-momentum distributions of Z and Higgs bosons (jet functions = beam functions = TMDPDFs)
- jet-veto cross sections
- inclusive jet observables such as jettiness



Becher, Lübbert, MN, Wilhelm (in preparation)

Cone-jet processes

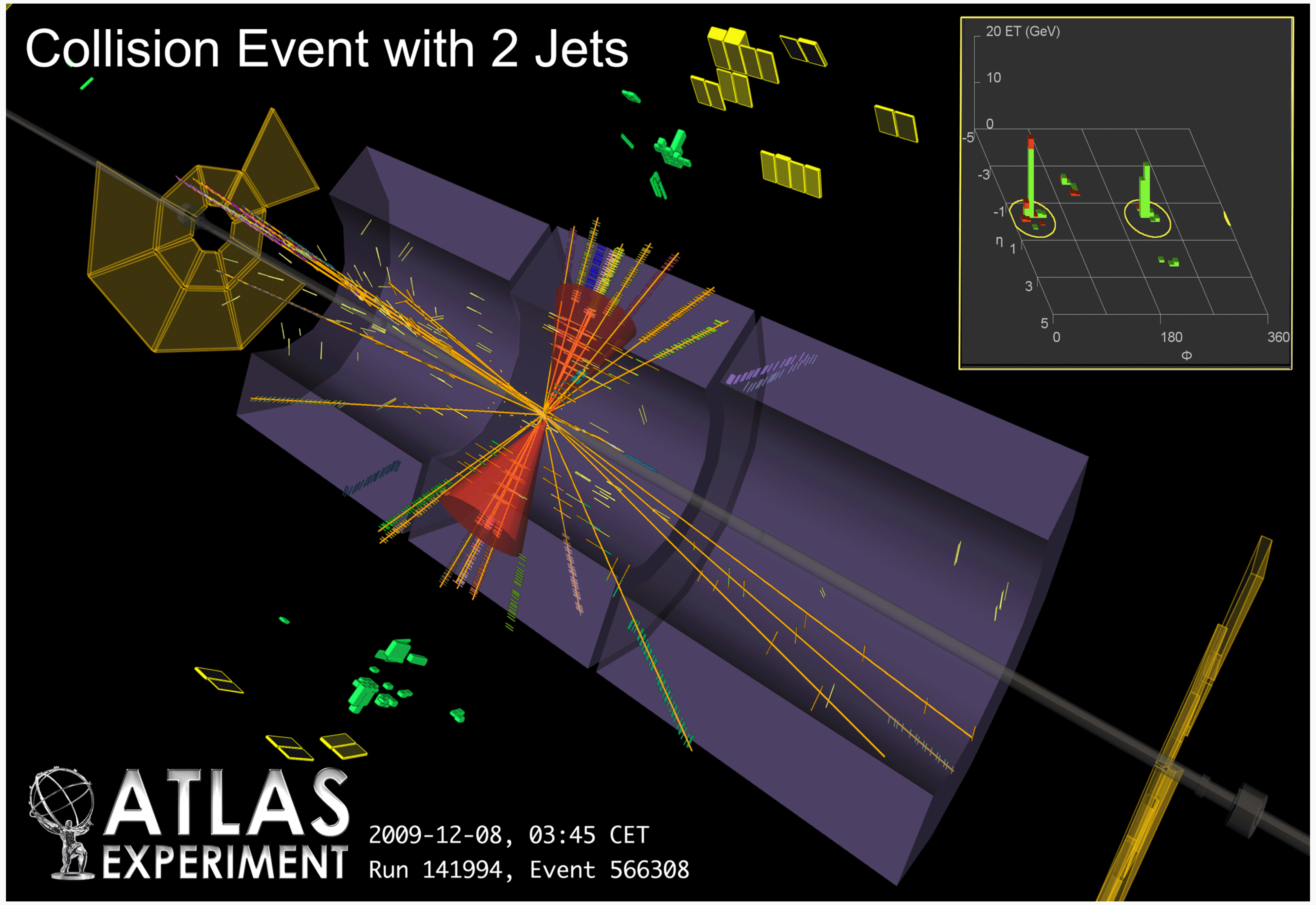
Such a simple formula **does not work for jet cross sections** defined using a standard cone (or hemisphere) algorithm

Previous SCET studies of hemisphere soft functions have found results containing large logarithms, i.e. depending on more than one scale

Kelley, Schwartz, Schabinger, Zhu (2011)
Hornig, Lee, Stewart, Walsh, Zuberi (2011)
von Manteuffel, Schabinger, Zhu (2013)

Recently, an approximate (but not systematic) resummation scheme based on the resummation of observables with *n* soft subjects was proposed

Larkoski, Moult, Neill [arXiv:1501.04596]



This finding shows that the effective theory is incomplete and misses some essential physics!

Non-global logarithms

Non-global logarithms (NGLs) arise whenever soft radiation is not distributed evenly in the final state of a collider process Dasgupta, Salam (2001)

The resummation of NGLs has thus far only be accomplished at leading-logarithmic order (LLO):

- large-N_c limit: BMS integral equation allows for a numerical solution using Monte Carlo techniques Banfi, Marchesini, Smye (2002)
- generalizations to finite N_c have been studied Weigert (2003) Hatta, Ueda (2013)

We have constructed the generalization of SCET needed to deal with NGLs

For the first time, we have proposed an **all-order factorization formula for cone-jet cross sections** (general approach applicable to many processes)

Our approach recasts the problem of **resumming NGLs in the language of RG equations**, which in principle allows for a solution at NLLO and beyond

Recently, Simon Caron-Huot has proposed a functional evolution equation for the resummation of NGLs beyond LO in the color density-matrix approach. His resummation approach may be equivalent to ours (difficult to show), but it does not (yet) provide a factorization formula for cross sections sensitive to NGLs

Caron-Huot [arXiv:1501.03754]

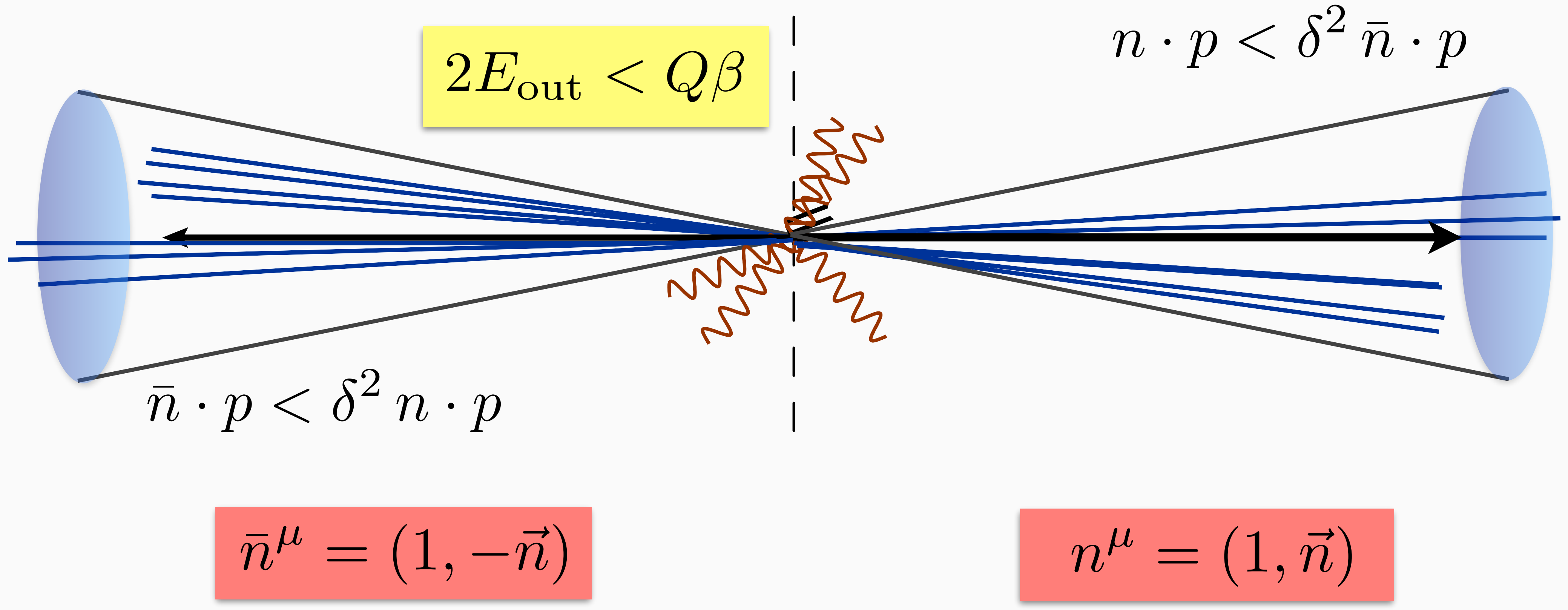
Jet production in e

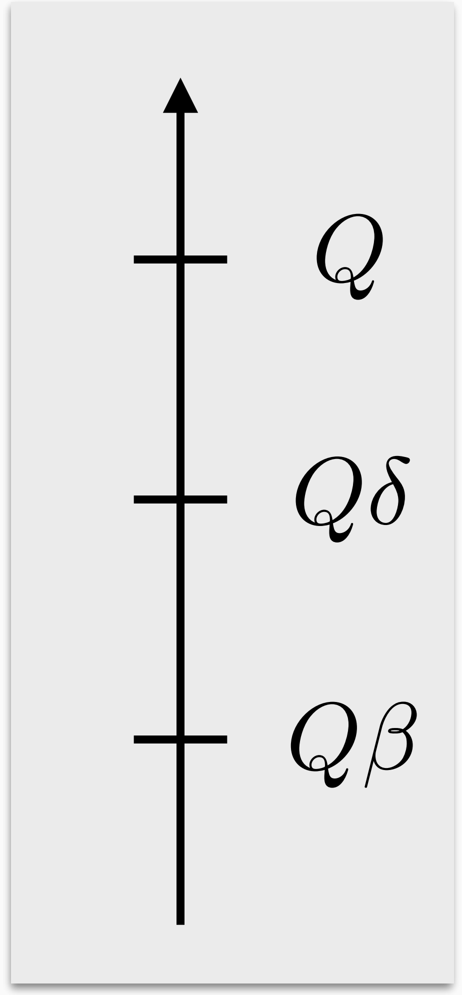
Consider $e^+e^- \to$ 2 jets at $\sqrt{s}$=Q (jet axis=thrust axis $\vec{n}$)

- after hard virtual corrections have been integrated out, the process involves (anti-)collinear particles contained inside the jets and soft particles emitted outside the jet cones
- naively one expects:

$$\sigma = H(Q)\, J(Q\delta) \otimes J(Q\delta) \otimes S(Q\beta)$$

- NGLs arise because the energy of soft emissions outside the cones is limited, while soft radiation inside the cones in unconstrained





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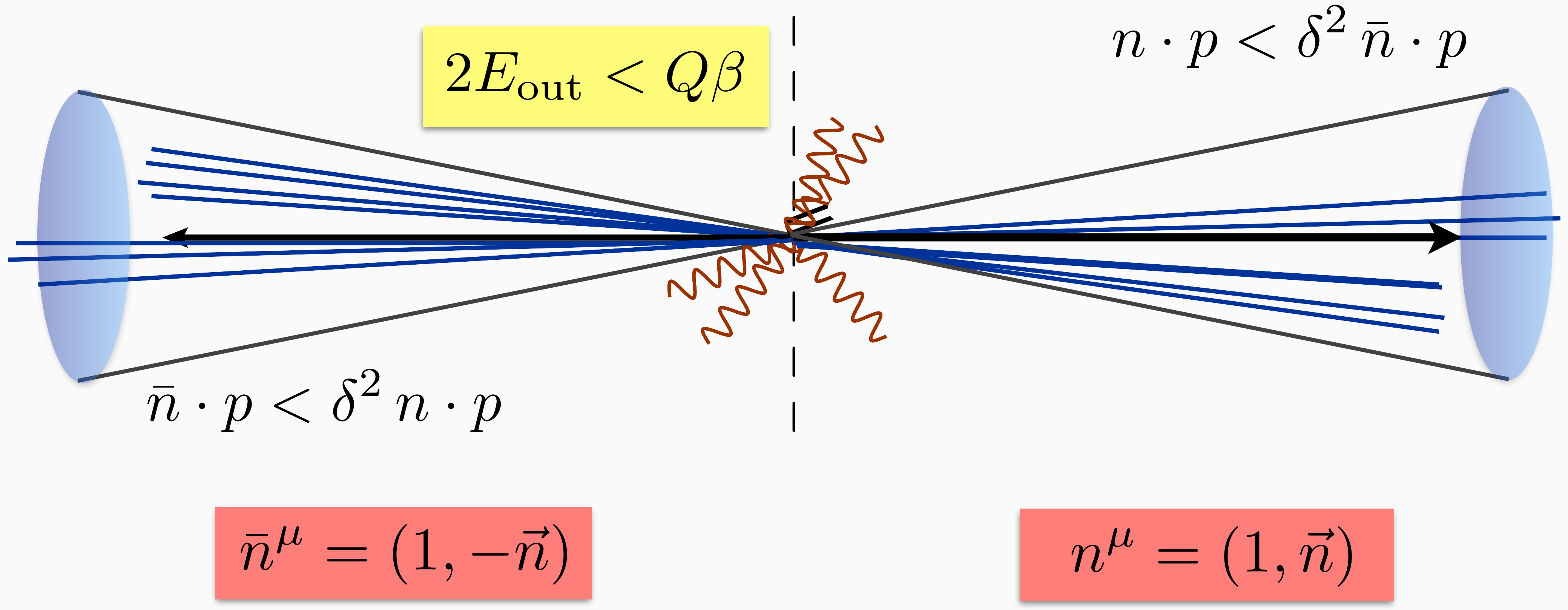


- naively one expects:

$$\sigma = H(Q)\,J(Q\delta)\otimes J(Q\delta)\otimes S(Q\beta)$$

- previous SCET work for jet cross sections has failed to resum NGLs and hence does not provide a complete factorization beyond one-loop order:

$$\Delta\sigma_h = \frac{\alpha_s C_F}{4\pi}\,\sigma_0\left(\frac{\mu}{Q}\right)^{2\epsilon}\left(-\frac{4}{\epsilon^2}-\frac{6}{\epsilon}-16+\frac{7\pi^2}{3}\right)$$

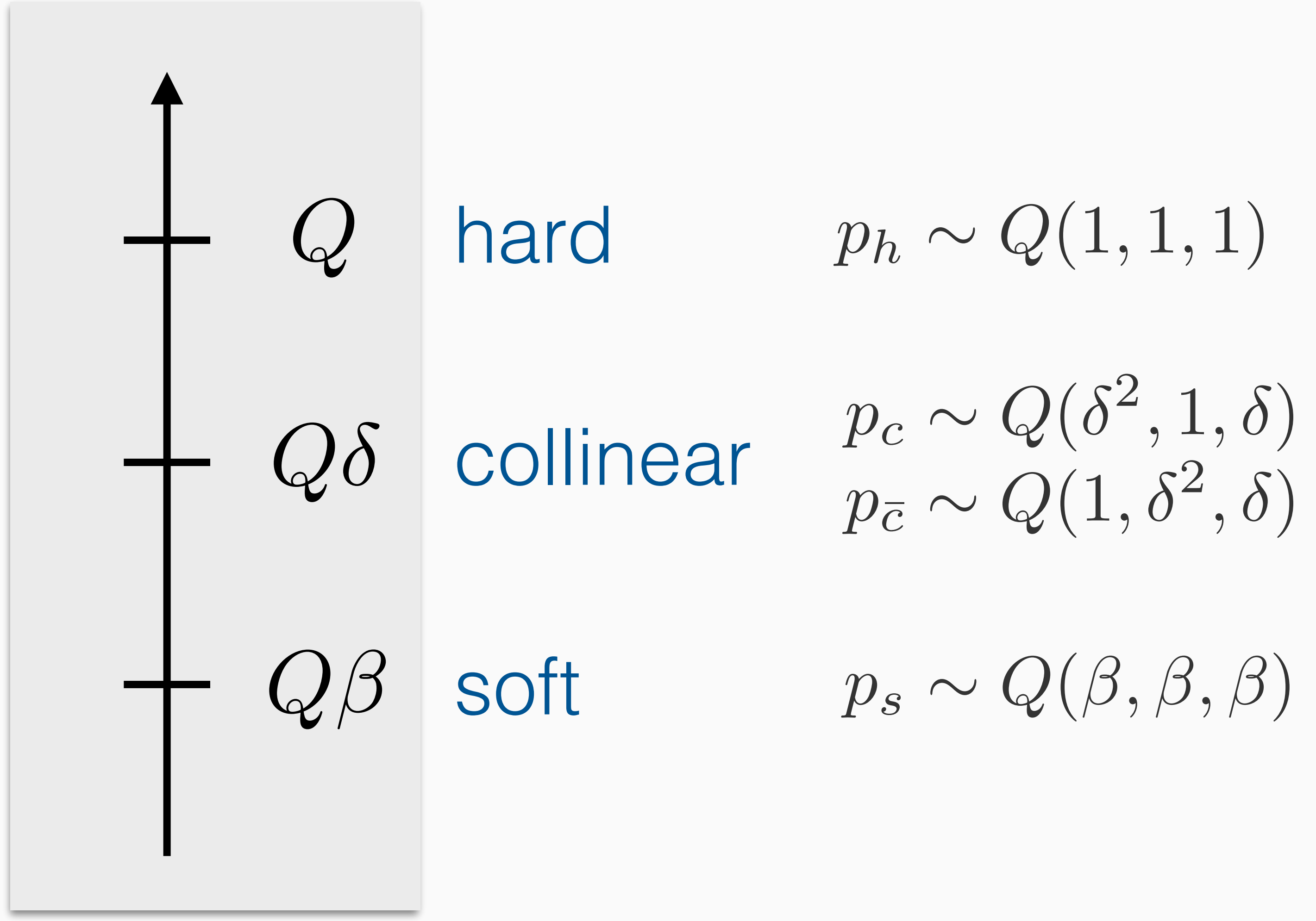
$$\Delta\sigma_{c+\bar{c}} = \frac{\alpha_s C_F}{4\pi}\,\sigma_0\left(\frac{\mu}{Q\delta}\right)^{2\epsilon}\left(\frac{4}{\epsilon^2}+\frac{6}{\epsilon}+16-\frac{5\pi^2}{3}+c_0\right)$$

requires a non-trivial zero-bin subtraction

$$\Delta\sigma_s = \frac{\alpha_s C_F}{4\pi}\,\sigma_0\left(\frac{\mu}{Q\beta}\right)^{2\epsilon}\left(\frac{8}{\epsilon}\ln\delta - 8\ln^2\delta - \frac{2\pi^2}{3}\right)$$

😢

Cheung, Luke, Zuberi (2009)



Need for a new mode

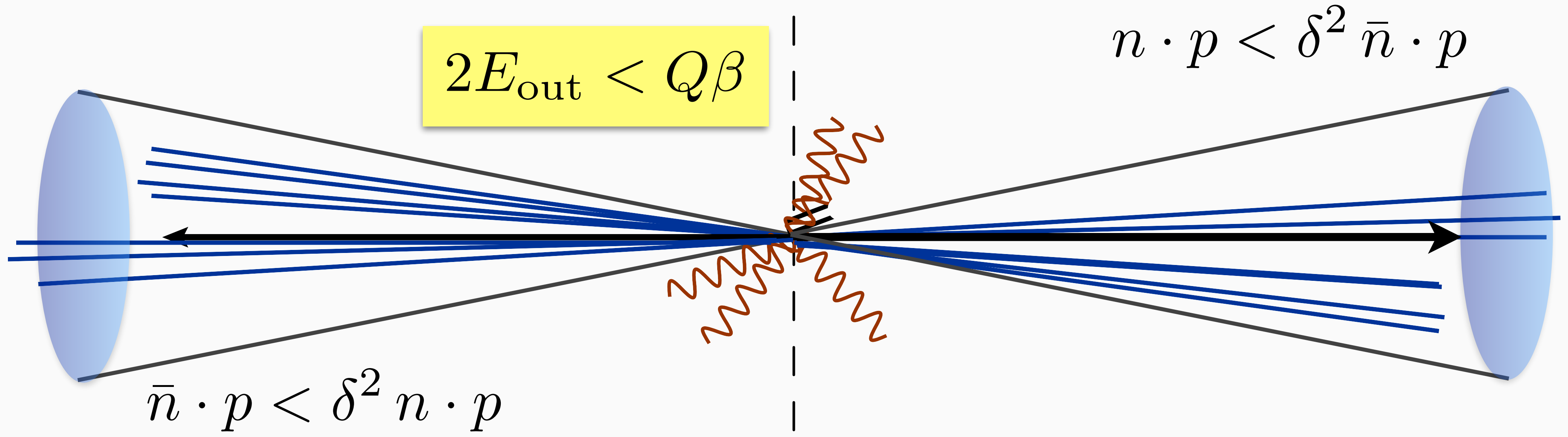
Relevance of the soft-collinear scale for cone-jet processes

Jet production in e

A consistent EFT must be based on a systematic expansion in the small parameters β and δ everywhere, including the phase-space constraints

- then no zero-bin subtractions are required
- collinear particles have small angle and large energy
  $\rightarrow$ always inside the jet cones
- soft particles have small energy and large angle
  $\rightarrow$ always outside the jet cones
- relevance of a new, soft-collinear ("coft") scale $Q\delta\beta$

Associated particles have **small angle and small energy** and give rise to leading contributions to the cross section!



$\bar{n}^\mu = (1, -\vec{n})$ $\qquad$ $n^\mu = (1, \vec{n})$

Q	hard	$p_h \sim Q(1,1,1)$
$Q\delta$	collinear	$p_c \sim Q(\delta^2,1,\delta)$ $p_{\bar{c}} \sim Q(1,\delta^2,\delta)$
$Q\beta$	soft	$p_s \sim Q(\beta,\beta,\beta)$
$Q\delta\beta$	soft-collinear ("coft")	$p_{sc} \sim Q\beta(\delta^2,1,\delta)$ $p_{\overline{sc}} \sim Q\beta(1,\delta^2,\delta)$

Jet production in e

Complete scale separation:

$$\Delta\sigma_h = \frac{\alpha_s C_F}{4\pi}\,\sigma_0 \left(\frac{\mu}{Q}\right)^{2\epsilon} \left(-\frac{4}{\epsilon^2} - \frac{6}{\epsilon} - 16 + \frac{7\pi^2}{3}\right)$$

$$\Delta\sigma_{c+\bar{c}} = \frac{\alpha_s C_F}{4\pi}\,\sigma_0 \left(\frac{\mu}{Q\delta}\right)^{2\epsilon} \left(\frac{4}{\epsilon^2} + \frac{6}{\epsilon} + 16 - \frac{5\pi^2}{3} + c_0\right)$$

$$\Delta\sigma_s = \frac{\alpha_s C_F}{4\pi}\,\sigma_0 \left(\frac{\mu}{Q\beta}\right)^{2\epsilon} \left(\frac{4}{\epsilon^2} - \pi^2\right)$$

$$\Delta\sigma_{sc+\overline{sc}} = \frac{\alpha_s C_F}{4\pi}\,\sigma_0 \left(\frac{\mu}{Q\delta\beta}\right)^{2\epsilon} \left(-\frac{4}{\epsilon^2} + \frac{\pi^2}{3}\right)$$

$$\Delta\sigma^{\text{tot}} = \frac{\alpha_s C_F}{4\pi}\,\sigma_0 \left(-16\ln\delta\ln\beta - 12\ln\delta + c_0\right)$$

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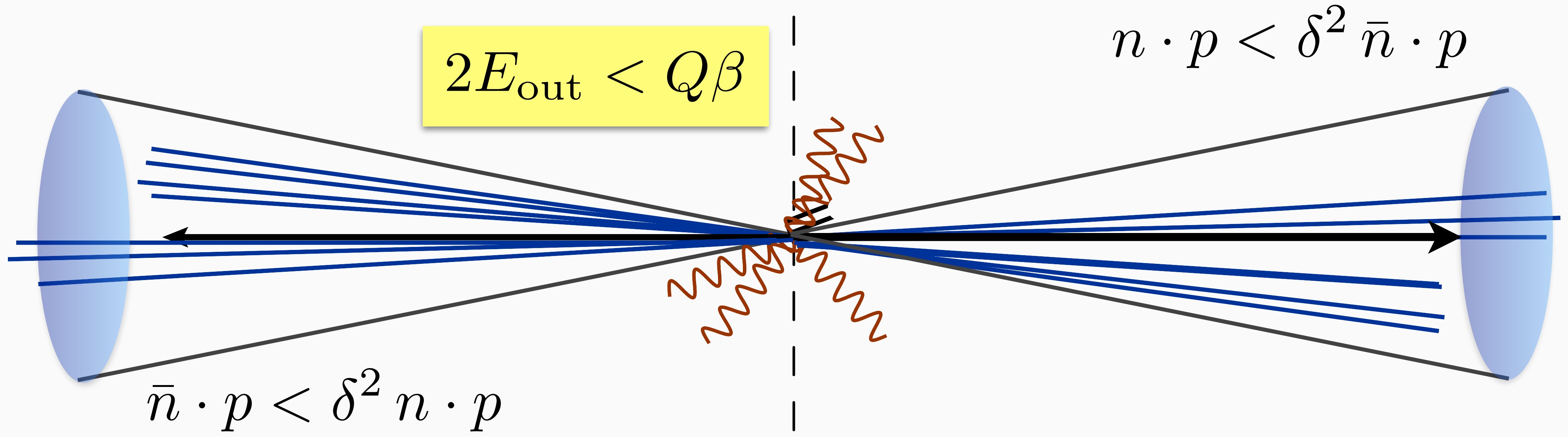

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Jet production in e

Expected factorization formula:

This analysis suggests a factorization theorem of the form:

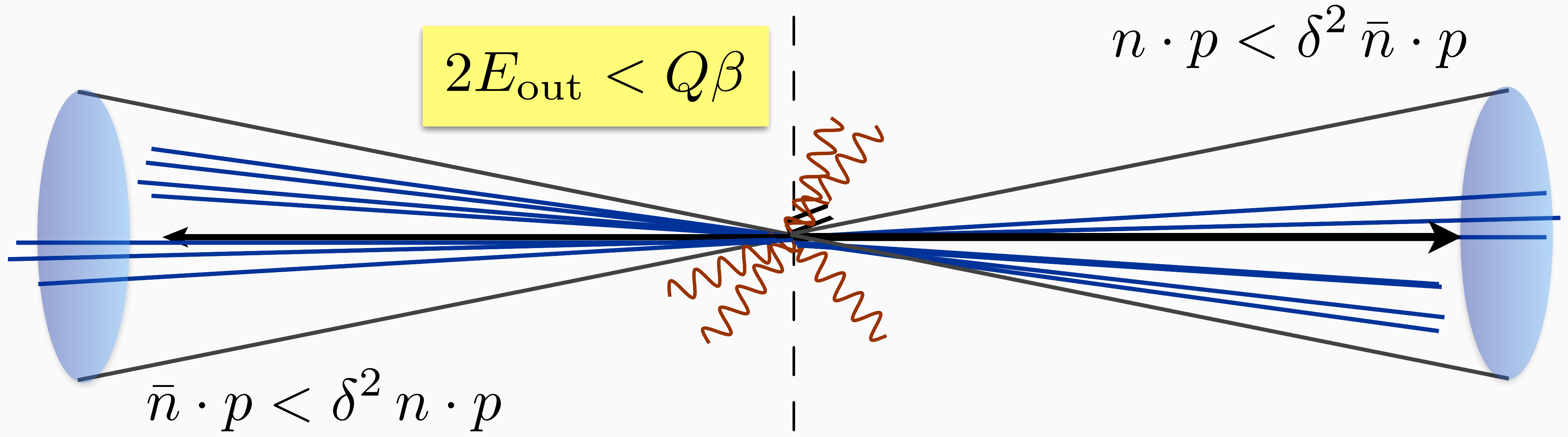
$$\sigma = H(Q)\,[J(Q\delta)\otimes U(Q\delta\beta)]^2 \otimes S(Q\beta)$$

- have shown explicitly that this works to two loops

$$\frac{\sigma(\beta)}{\sigma_0} = 1 + \frac{\alpha_s}{2\pi}\,A(\beta,\delta) + \left(\frac{\alpha_s}{2\pi}\right)^2 B(\beta,\delta) + \dots$$

$$\begin{aligned}
B(\beta,\delta) = C_F^2 \Bigg[& \left(32\ln^2\beta + 48\ln\beta + 18 - \frac{16\pi^2}{3}\right)\ln^2\delta + \left(-2 + 10\zeta_3 - 12\ln^2 2 + 4\ln 2\right)\ln\beta \\
& + \left((8 - 48\ln 2)\ln\beta + \frac{9}{2} + 2\pi^2 - 24\zeta_3 - 36\ln 2\right)\ln\delta + c_2^F\Bigg] \\
+ C_F C_A \Bigg[& \left(\frac{44\ln\beta}{3} + 11\right)\ln^2\delta - \frac{2\pi^2}{3}\ln^2\beta + \left(\frac{8}{3} - \frac{31\pi^2}{18} - 4\zeta_3 - 6\ln^2 2 - 4\ln 2\right)\ln\beta \\
& + \left(\frac{44\ln^2\beta}{3} + \left(-\frac{268}{9} + \frac{4\pi^2}{3}\right)\ln\beta - \frac{57}{2} + 12\zeta_3 - 22\ln 2\right)\ln\delta + c_2^A\Bigg] \\
+ C_F T_F n_f \Bigg[& \left(-\frac{16\ln\beta}{3} - 4\right)\ln^2\delta + \left(-\frac{16}{3}\ln^2\beta + \frac{80\ln\beta}{9} + 10 + 8\ln 2\right)\ln\delta + \left(-\frac{4}{3} + \frac{4\pi^2}{9}\right)\ln\beta + c_2^f\Bigg]
\end{aligned}$$

→ have performed detailed comparisons with EVENT2



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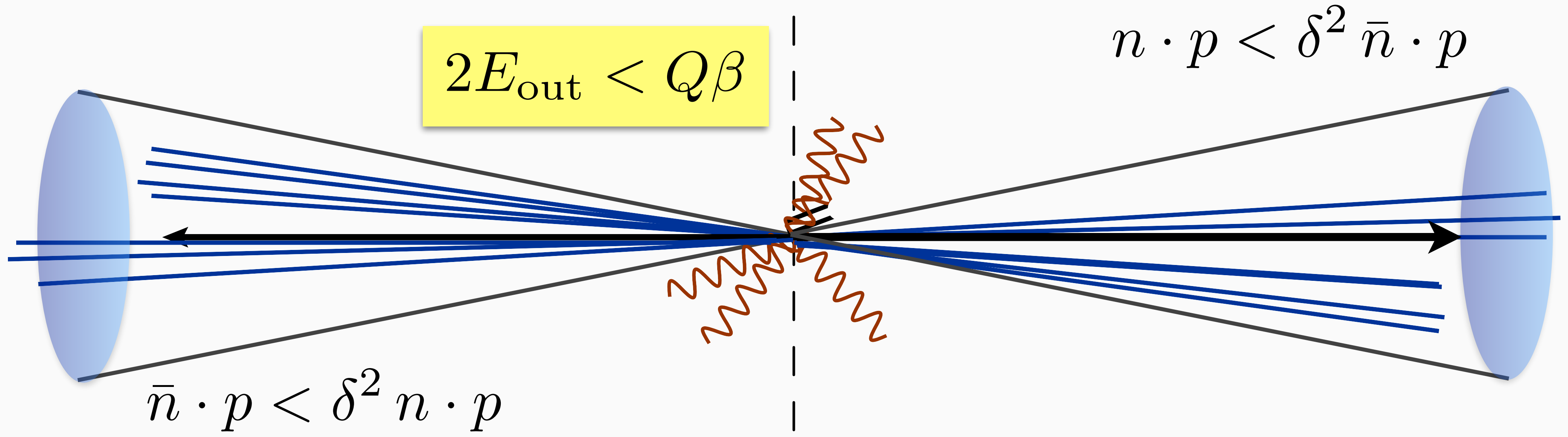
Jet production in e

Expected factorization formula:

This analysis suggests a factorization theorem of the form:

$$\sigma = H(Q)\,[J(Q\delta) \otimes U(Q\delta\beta)]^2 \otimes S(Q\beta)$$

- have shown explicitly that this works to two loops
- however, we find a **highly non-trivial interplay** of jet and coft functions beyond one-loop order



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Factorization theorem

Subtleties of coft-collinear factorization

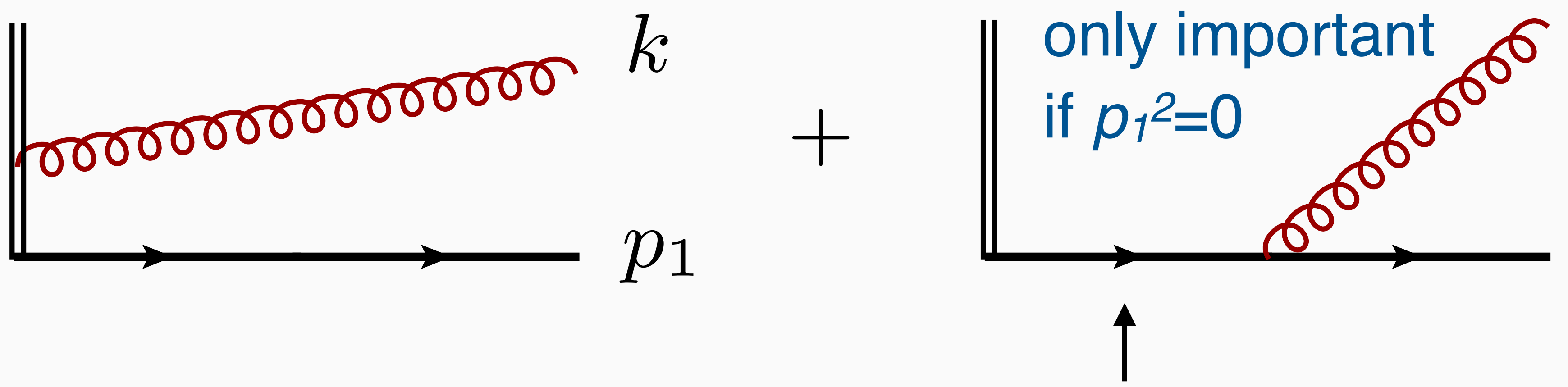
Interactions of coft gluon with collinear fields

Soft-collinear gluons can interact with collinear fields in two ways:

- split-up $A_c \to A_c + A_{sc}$ yields $W_c \to W_c\, U(\bar{n})$ with:

$$U(\bar{n}) = \mathbf{P} \exp\left[i g_s \int_{-\infty}^{0} dt\, \bar{n} \cdot A_{sc}(t\bar{n}) \right]$$

- in addition, coft gluons can couple to **on-shell external collinear particles**; e.g. for a (gauge-invariant) quark field $\chi_c = W_c^\dagger \xi_c$:



$$\frac{(\not{p}_1 + \not{k})\gamma^\mu}{p_1^2 + 2k \cdot p_1 + k^2} \to \frac{n_1^\mu}{n_1 \cdot k}$$

Squaring the amplitude gives

$$|\mathcal{M}|^2 = 2C_F g_s^2 \frac{n_1 \cdot \bar{n}}{(n_1 \cdot k)\,(\bar{n} \cdot k)}\,,$$

which is the matrix element for the emission from two Wilson lines

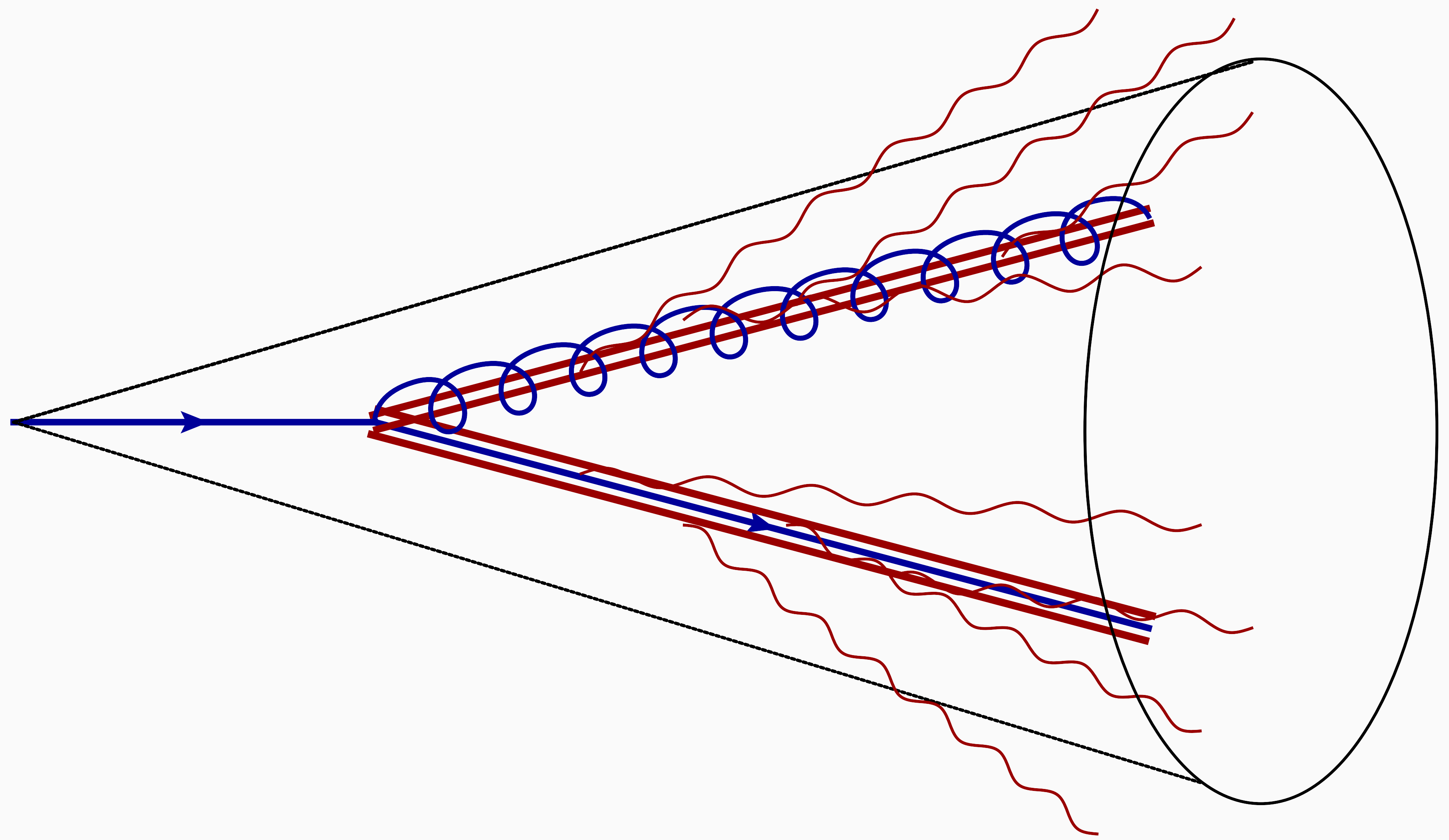
For a final state consisting of m collinear particles, the coft emissions are described by the matrix element of the operator

$$\boldsymbol{U}_0(\bar{n})\, \boldsymbol{U}_1(n_1)\, \dots\, \boldsymbol{U}_m(n_m) |\mathcal{M}_m(p_0; \{\underline{p}\})\rangle$$

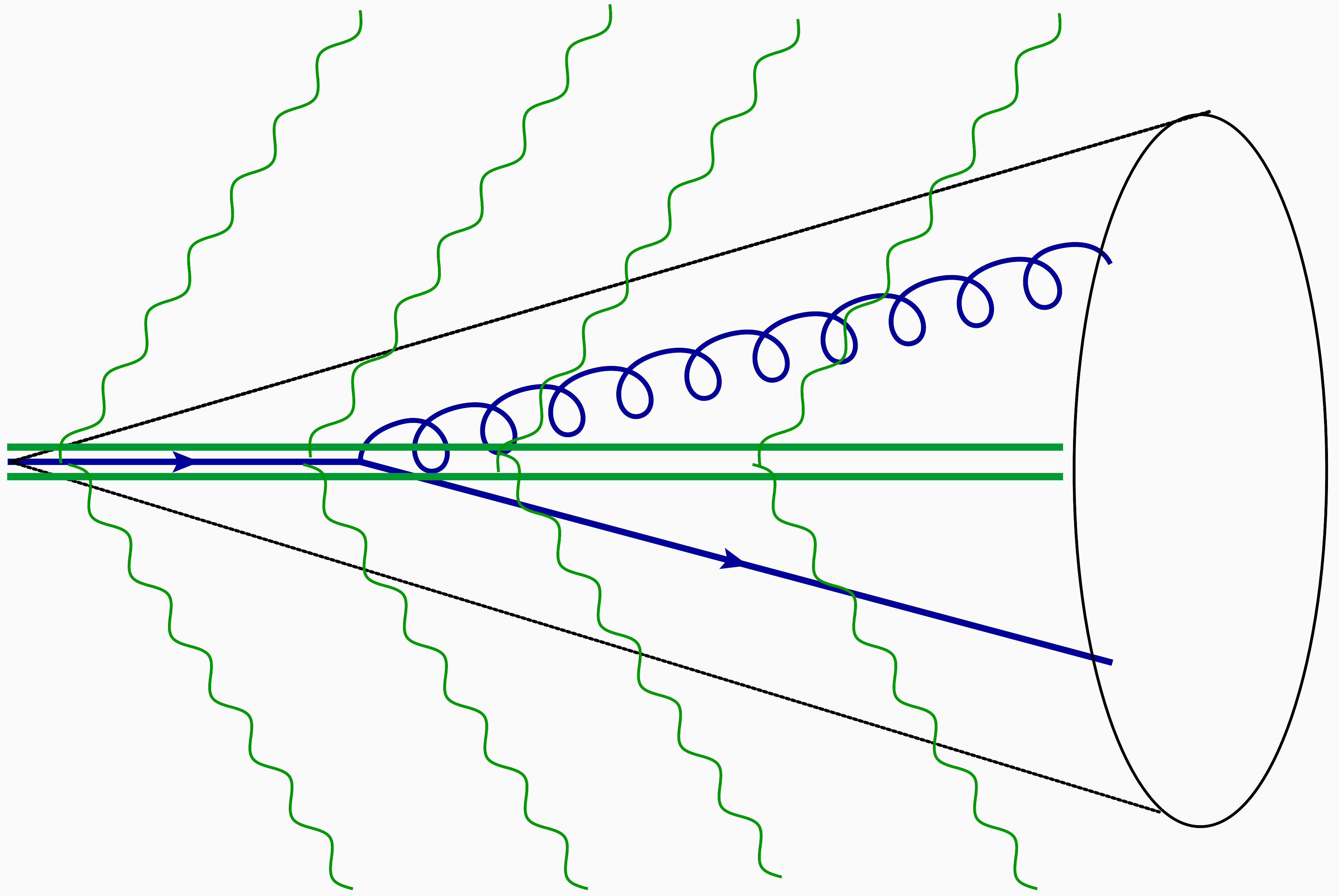
where $\{n_i\}$ are the light-like directions of the collinear particles

Interactions of coft gluon with collinear fields

Coft particles are emitted at small angle and low energy, so they can **resolve the directions and color charges of individual collinear particles**:

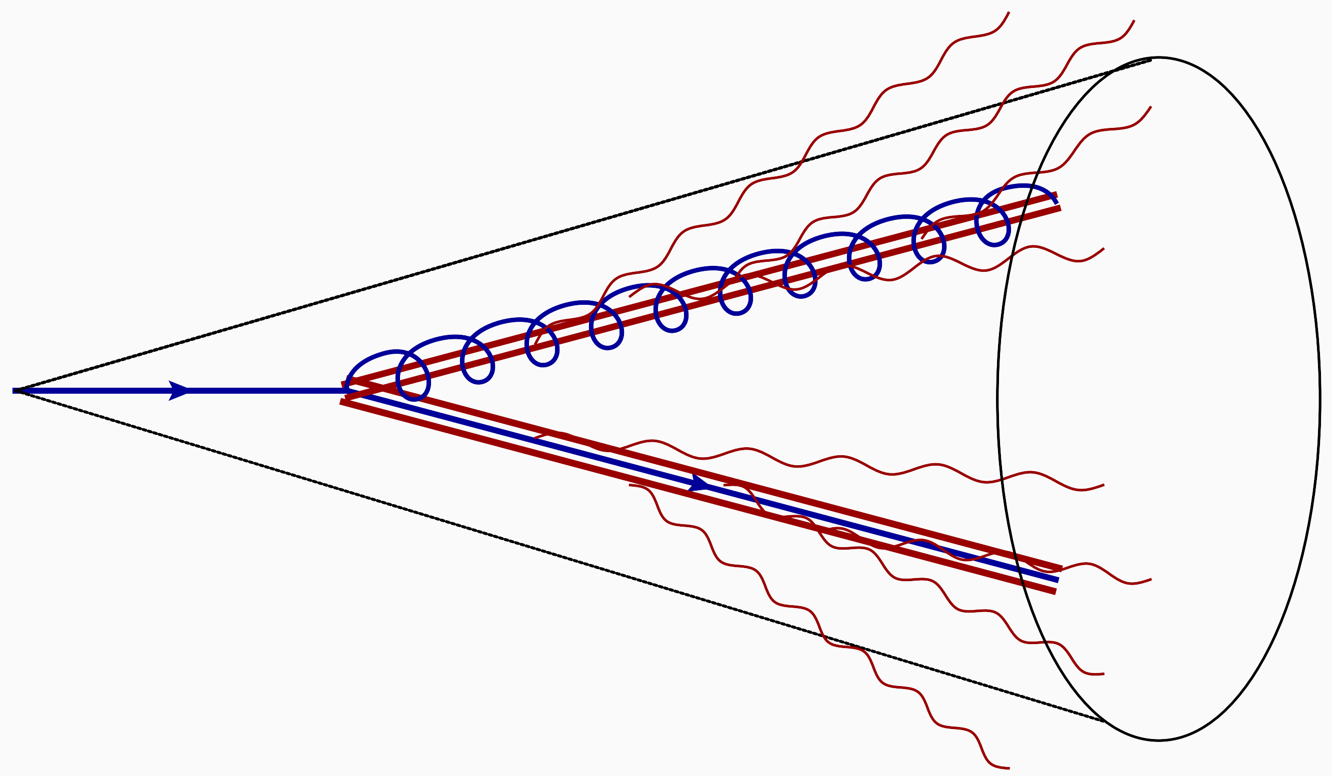


This is different from standard soft emissions, which only resolves the overall direction and color charge of a jet:



Interactions of coft gluon with collinear fields

One must then square this operator and integrate over phase space (including the directions $\{n_i\}$ of the collinear particles) to obtain the cross section



Factorized cross section:

$$\widetilde{\sigma}(\tau) = \sigma_0\, H(Q)\, \widetilde{S}(Q\tau) \left[\sum_{m=1}^{\infty} \Big\langle \underbrace{\mathcal{J}_m(Q\delta)}_{\text{jet function}} \otimes \underbrace{\widetilde{\mathcal{U}}_m(Q\delta\tau)}_{\text{coft function}} \Big\rangle \right]^2$$

integration over directions n_i of collinear particles

Operator definitions of the coft and jet functions:

$$\mathcal{U}_m(Q\delta\beta) = \sum_{X_t} \langle 0| \boldsymbol{U}_0^\dagger(\bar{n})\, \boldsymbol{U}_1^\dagger(n_1) \dots \boldsymbol{U}_m^\dagger(n_m) |X_t\rangle \langle X_t| \boldsymbol{U}_0(\bar{n}) \dots \boldsymbol{U}_m(n_m)|0\rangle \times \delta(Q\beta - \bar{n}\cdot p_{X_{sc}^{\rm out}})$$

$$\frac{\bar{n}\!\!\!/}{2}\, \mathcal{J}_m(Q\delta) = \sum_{\text{spins}} \int d\Pi_m |\mathcal{M}_m(p_0;\{\underline{p}\})\rangle \langle \mathcal{M}_m(p_0;\{\underline{p}\})| \times 2\,(2\pi)^{d-1} \delta(Q - \bar{n}\cdot p_{X_c})\, \delta^{d-2}(p_{X_c}^\perp) \prod_i \theta(\delta^2 \bar{n}\cdot p_c^i - n\cdot p_c^i)$$

fixed directions

Laplace-transformed cross section:

$$\widetilde{\sigma}(\tau) = \int_0^\infty d\beta\, e^{-\beta/(\tau e^{\gamma_E})}\, \frac{d\sigma}{d\beta}$$

Renormalization and resummation

Subtraction of UV divergences and RG-based resummation of NGLs

Our approach

Once all scales are factorized, large logarithms can be resummed by solving RG evolution equations to connect one scale to another

In this sense NGLs are as global as any other large logarithms

The resummation of NGLs has so far only been achieved at LLO using numerical Monte Carlo techniques; our goal is to understand their resummation using the language of the renormalization group

UV subtractions for jet and coft functions

Structure of bare jet functions:

$$\mathcal{J}_1^{\text{bare}} = 1$$

$$\mathcal{J}_2^{\text{bare}} = \frac{\alpha_s C_F}{4\pi} \left(\frac{\mu}{Q\delta}\right)^{2\epsilon} \left[\frac{1}{\epsilon^2}\,\delta(\sqrt{\theta_1})\,\delta(\sqrt{\theta_2}) + \frac{1}{\epsilon}\,k(\theta_1,\theta_2) + h(\theta_1,\theta_2)\right]$$

$$\mathcal{J}_3^{\text{bare}} = \left(\frac{\alpha_s}{4\pi}\right)^2 \left(\frac{\mu}{Q\delta}\right)^{4\epsilon} \left[\frac{1}{\epsilon^4}\,[\#] + \dots\right]$$

This requires a matrix of Z-factors with **triangular structure** (with $m\geq k$):

$$\boldsymbol{\mathcal{J}}_m(Q\delta,\epsilon) = \boldsymbol{\mathcal{J}}_k(Q\delta,\mu)\,\boldsymbol{Z}^J_{km}(Q\delta,\epsilon,\mu)$$

with:

$$Z^J \sim \begin{pmatrix} 1 & \alpha_s & \alpha_s^2 & \cdots \\ 0 & 1 & \alpha_s & \cdots \\ 0 & 0 & 1 & \cdots \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$

Scale invariance of the physical cross section then implies that the coft functions must be renormalized by the matrix (with $k\geq m$):

$$\widetilde{\boldsymbol{\mathcal{U}}}_m(Q\delta\tau,\mu) = \boldsymbol{Z}^U_{mk}(Q\delta\tau,\epsilon,\mu)\,\hat{\otimes}\,\widetilde{\boldsymbol{\mathcal{U}}}_k(Q\delta\tau,\epsilon)$$

integration over unresolved directions

with:

$$\boldsymbol{Z}^U(Q\delta\tau,\epsilon,\mu) \equiv Z_H^{1/2}(Q,\epsilon,\mu)\,Z_S^{1/2}(Q\tau,\epsilon,\mu)\,\boldsymbol{Z}^J(Q\delta,\epsilon,\mu)$$

Non-trivial features:

- Sudakov logarithms in Z_H, Z_S and $\boldsymbol{Z}^J$ must conspire to give logarithms of the coft scale $Q\delta\tau$, modulo terms that vanish when projected onto $\widetilde{\mathcal{U}}_k$
- higher-multiplicity coft functions enter the renormalization of lower-multiplicity ones, e.g.:

$$\widetilde{\boldsymbol{\mathcal{U}}}_1(\mu) = \boldsymbol{Z}^U_{11}\,\widetilde{\boldsymbol{\mathcal{U}}}_1(\epsilon) + \boldsymbol{Z}^U_{12}\,\hat{\otimes}\,\widetilde{\boldsymbol{\mathcal{U}}}_2(\epsilon) + \boldsymbol{Z}^U_{13}\,\hat{\otimes}\,\mathbf{1} + \mathcal{O}(\alpha_s^3)$$

RG evolution and resummation

All-order resummation of NGLs is accomplished by the formal expression:

$$\sum_m \mathcal{J}_m(Q\delta,\mu) \otimes \widetilde{\mathcal{U}}_m(Q\delta\tau,\mu)$$

$$\to \sum_{k,m} \mathcal{J}_k(Q\delta,Q\delta) \otimes \mathrm{U}_{km}(Q\delta,Q\delta\tau)\,\hat{\otimes}\,\widetilde{\mathcal{U}}_m(Q\delta\tau,Q\delta\tau)$$

with:

$$\mathbf{U}(\mu_c,\mu_{sc}) = \mathbf{P}_{\hat{\otimes}} \exp\left[\int_{\alpha_s(\mu_{sc})}^{\alpha_s(\mu_c)} d\alpha\, \frac{\mathbf{\Gamma^U}(\alpha)}{\beta(\alpha)}\right]$$

The anomalous dimension matrix $\mathbf{\Gamma^U}$ follows from $\boldsymbol{Z}^U$

At LLO, we only need the tree-level expressions

$$\mathcal{J}_1 = 1\,, \quad \mathcal{J}_{m\neq 1} = 0\,, \quad \widetilde{\mathcal{U}}_m = 1$$

$$\sum_m \mathcal{J}_m(Q\delta,\mu) \otimes \widetilde{\mathcal{U}}_m(Q\delta\tau,\mu) \to \sum_m U_{1m}(Q\delta,Q\delta\tau)$$

along with the **one-loop anomalous dimension** matrix:

$$\mathbf{\Gamma}_1^{\mathbf{U}} \sim \begin{pmatrix} \alpha_s & \alpha_s & 0 & \cdots \\ 0 & \alpha_s & \alpha_s & \cdots \\ 0 & 0 & \alpha_s & \cdots \\ 0 & 0 & 0 & \ddots \end{pmatrix} = \begin{pmatrix} \mathbf{V}_1 & \mathbf{R}_1 & 0 & \cdots \\ 0 & \mathbf{V}_2 & \mathbf{R}_2 & \cdots \\ 0 & 0 & \mathbf{V}_3 & \cdots \\ 0 & 0 & 0 & \ddots \end{pmatrix}$$

Taking higher powers of this matrix generates progressive , more complicated color factors and angular integrals

RG evolution and resummation

Taking higher powers of this matrix generates progressively more complicated color factors and angular integrals:

$$\begin{aligned}
\alpha_s &: \boldsymbol{R}_1 + \boldsymbol{V}_1 \\
\alpha_s^2 &: \boldsymbol{R}_1(\boldsymbol{R}_2 + \boldsymbol{V}_2) + \boldsymbol{V}_1(\boldsymbol{R}_1 + \boldsymbol{V}_1) \\
\alpha_s^3 &: \boldsymbol{R}_1\big[\boldsymbol{R}_2(\boldsymbol{R}_3 + \boldsymbol{V}_3) + \boldsymbol{V}_2(\boldsymbol{R}_2 + \boldsymbol{V}_2)\big] + \boldsymbol{V}_1\big[\boldsymbol{R}_1(\boldsymbol{R}_2 + \boldsymbol{V}_2) + \boldsymbol{V}_1(\boldsymbol{R}_1 + \boldsymbol{V}_1)\big]
\end{aligned}$$

reminiscent of a parton shower

We have analyzed the case of wide-angle jets ($\delta \sim 1$) in detail (simpler, since no Sudakov double logarithms)

We find that in the large-N_c limit the first three terms in the expansion of the evolution matrix **U** agree with the corresponding expansion of the BMS equation, as performed recently in Schwartz, Zhu (2014) and Khelifa-Kerfa, Delenda [arXiv:1501.00475] → a strong cross-check!

Outlook

Our formalism provides for the first time:

- a **complete factorization theorem** for cone-jet cross sections
- a resummation of non-global logs using **RG equations**
- extension beyond the leading logarithmic order is in principle straightforward, if tedious …

Thank you!

ERC Advanced Grant (EFT4LHC)
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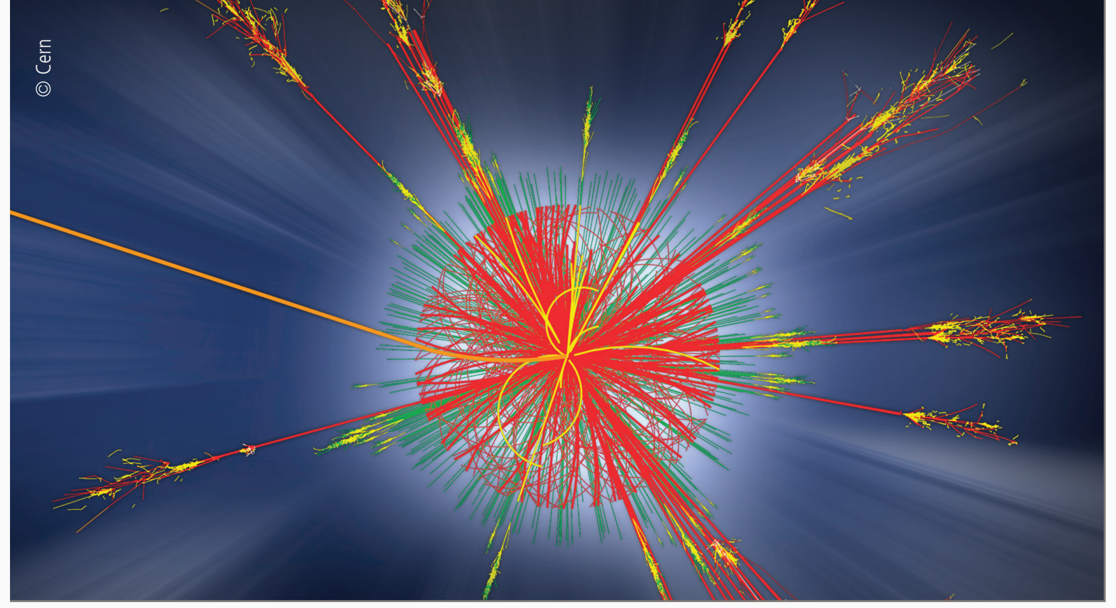

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SCIENTIFIC PROGRAMS

NA62 Kaon Physics Handbook
Augusto Ceccucci **CERN**, Giancarlo D'Ambrosio **INFN Naples**
Ulrich Haisch **Univ. Oxford**, Rainer Wanke **JGU**
January 11-22, 2016

Composite Dynamics: from Lattice to LHC Run II
Giacomo Cacciapaglia **IPN Lyon**
Francesco Sannino **CP³ Origins**, Thomas Flacke **KAIST**
April 4-15, 2016

Dark Matter in the Milky Way
Fabio Iocco **ICTP-SAIFR & IFT-UNESP, São Paulo**
Arianna Di Cintio **DARK, Univ. Copenhagen**
Miguel Pato **Univ. Stockholm**
Christoph Weniger **Univ. Amsterdam**
May 2-13, 2016

Neutron Skins of Nuclei
Charles Horowitz **Indiana Univ.**
Jorge Piekarewicz **Florida State Univ.**
Concettina Sfienti, Marc Vanderhaeghen **JGU**
May 17-27, 2016

Exploring the Energy Ladder of the Universe
Pasquale Di Bari, Steve King **Univ. Southampton**
Qaisar Shafi **Univ. Delaware**
May 30-June 10, 2016

Flavor and Electroweak Symmetry Breaking
Giulia Ricciardi **Univ. Naples Federico II**
Tobias Hurth, Matthias Neubert **JGU**
June 13-24, 2016, Capri, Italy

Understanding the First Results from LHC Run II
Tilman Plehn **Univ. Heidelberg**
Graham Kribs **Univ. Oregon**
Shufang Su **Univ. Arizona**
Tim Tait **UC Irvine**
June 27-July 22, 2016

Effective Field Theories as Discovery Tools
Wolfgang Altmannshofer **Perimeter Inst.**
Yang Bai **Univ. Wisconsin Madison**
Monika Blanke **KIT Karlsruhe**
Felix Yu, Jose Zurita **JGU**
August 22-September 9, 2016

MITP SUMMER SCHOOL

New Physics on Trial at LHC Run II
Joachim Brod, Maikel De Vries
Anna Kaminska, Felix Yu
Matthias Neubert **JGU**
July 25-August 5, 2016

TOPICAL WORKSHOPS

Determination of the Fundamental Parameters in QCD
Irinel Caprini **IFIN-HH Bucharest**
Konstantyn Chetyrkin **INR Moskau**
Cesareo A. Dominguez **Univ. Cape Town**
Antonio Pich **Univ. Valencia**, Hubert Spiesberger **JGU**
March 7-12, 2016

Relativistic Hydrodynamics: Theory and Modern Applications
Francesco Becattini **Florence Univ.**
Dmitri Kharzeev **Stony Brook Univ. & BNL**
Dirk H. Rischke **Goethe Univ. Frankfurt**
Dam Thanh Son **Univ. Chicago**
Mikhail Stephanov **Univ. Illinois, Chicago**
October 10-14, 2016

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