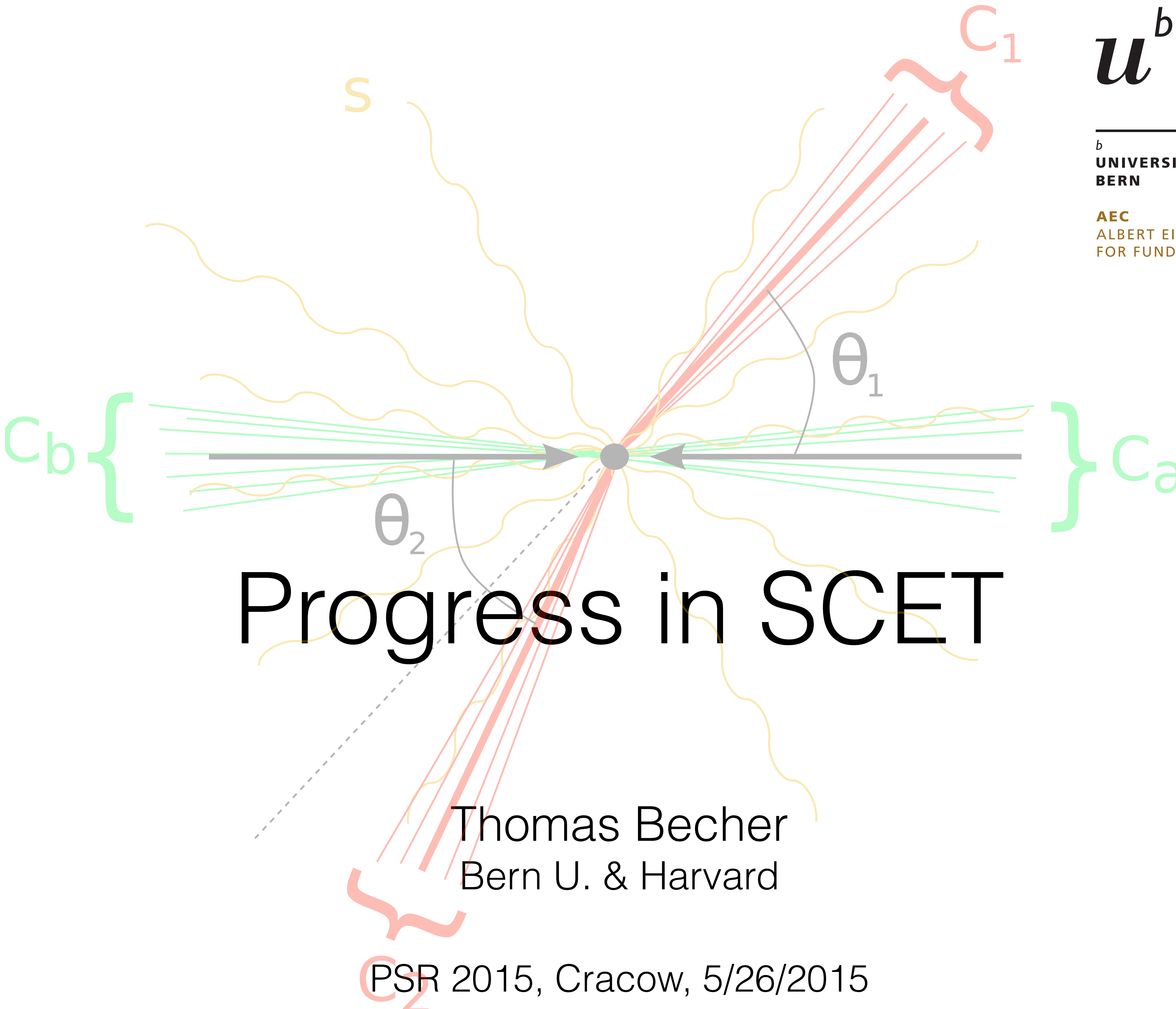
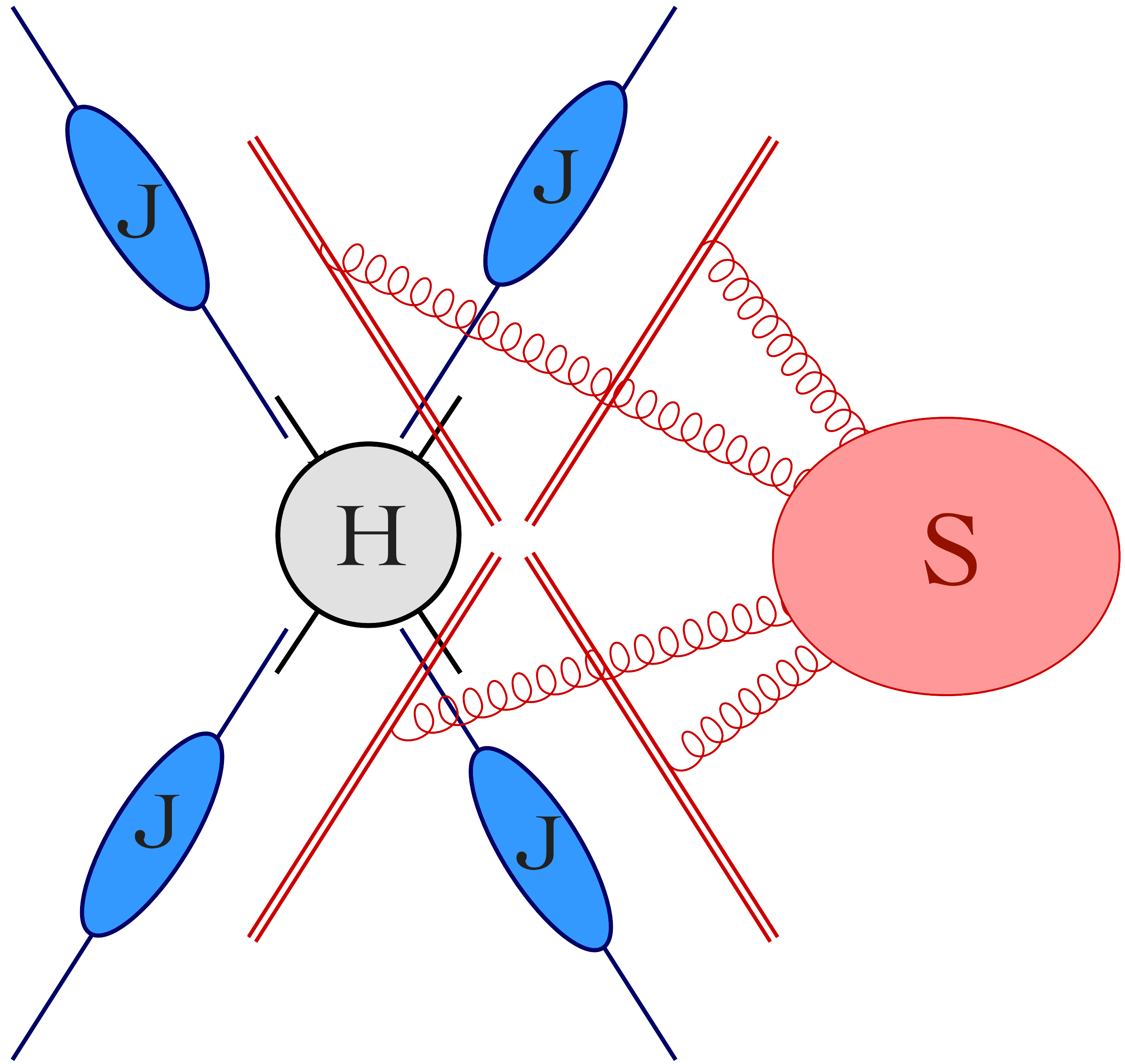


Progress in SCET

Thomas Becher
Bern U. & Harvard

PSR 2015, Cracow, 5/26/2015

UNIVERSITÄT BERN
AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS



Collins, Soper, Sterman, ...

The basis for resummation is soft-collinear factorization, both in SCET and for QCD based resummation techniques.

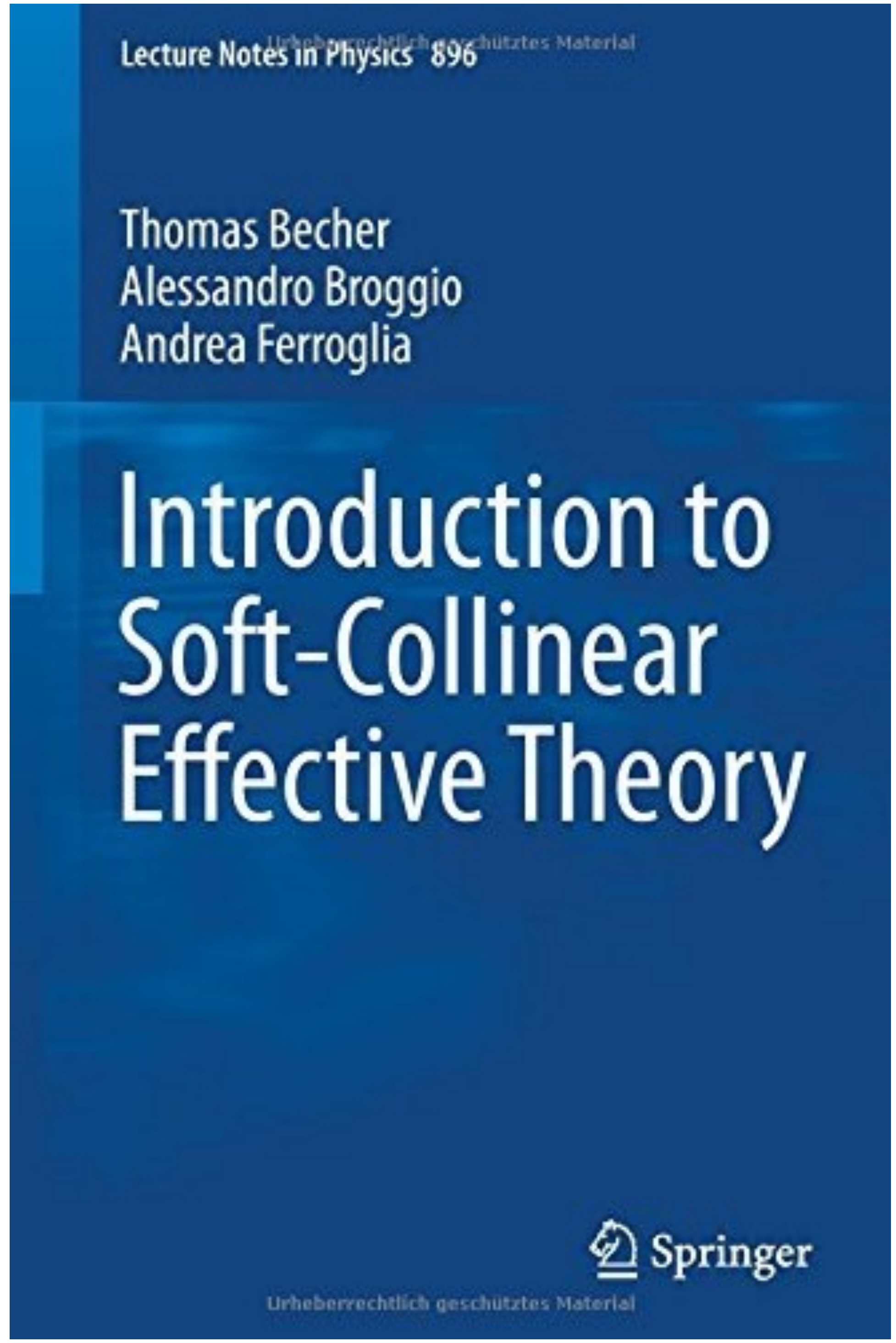
SCET vs. dQCD: Formalism

Effective field theory framework

- Collinear fields, to describe energetic radiation along directions of jets.
- Soft fields for radiation outside jets.
- Hard-scattering corrections are integrated out: **Wilson coefficients** of effective theory operators.

Advantages

- **Operator definitions** for all ingredients
- Clear scale separation. Resummation by **RG evolution**
- Simpler to exploit gauge invariance at the **Lagrangian** level
- Can include **power corrections** → Chris White's talk



arXiv:1410.1892

SCET vs. dQCD: Scheme choices

Sterman, Zeng ‘13 ; Almeida, Ellis, Lee, Sterman, Sung, Walsh ’14; Bonvini, Forte, Ghezzi and Ridolfi ’12; Bonvini, Forte, Ridolfi and Rottoli ‘14

The two communities use different scheme choices

- dQCD resums integrated cross section, SCET typically the differential one
- dQCD prefers Laplace/moment/position space; SCET momentum space
  - different power corrections due to variable choices
- dQCD modifies logarithms to switch off resummation away from end-point; SCET typically changes RG scales (``profile functions'') to switch it off.

These are not fundamental differences! Interesting to compare results from different schemes.

Hot topics at **SCET 2015** conference at end of March

- **Automation** → talks by Simone Alioli, Zoltan Nagy, Rudi Rahn
- **Event-shapes**, jet-shapes, jet substructure, multi-differential cross sections
- **Glauber gluons** and Regge behavior
- **Non-global logarithms** → talk by Simon Caron-Huot
- Resummation for **power corrections** → talk by Chris White
- Resummation for **heavy particles**: dark matter annihilation, exclusive W and Z decays
- Since then: **NNLO subtraction scheme** using N-jettiness event shape (extension of q_T subtraction) → talk by J. Gaunt

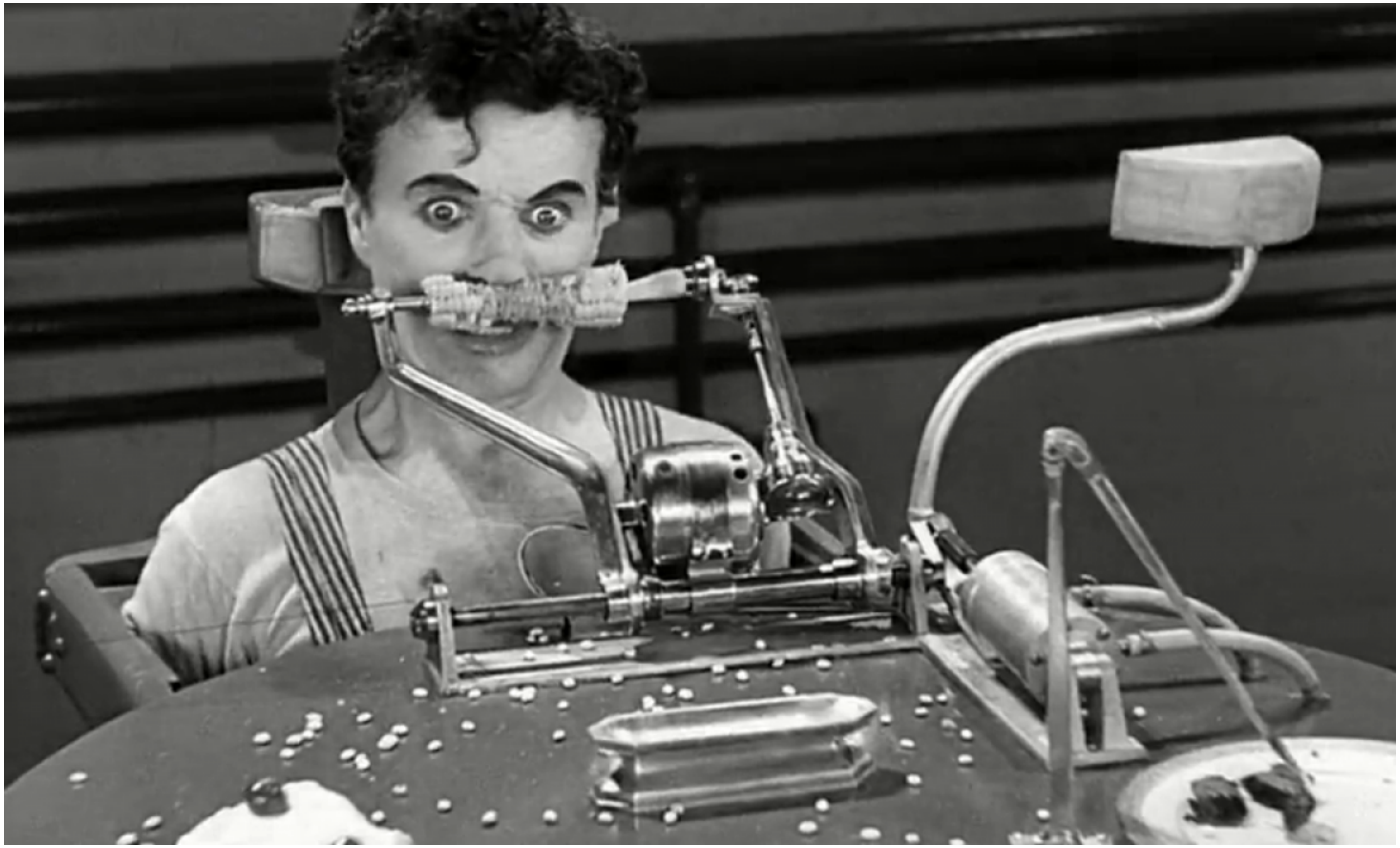
Outline

Will discuss three topics in greater detail

1. Automated NNLL resummation for jet-veto cross sections

2. NNLL resummation for hadron collider dijet event shapes

3. Jet Effective Theory: Towards resummation for cone-jet cross sections



Automated NNLL+NLO resummation for cross sections with a jet veto

TB, Frederix, Neubert, Rothen 1412.8408 (JHEP)

Higher-log resummations (in SCET or in QCD) are usually carried out analytically, on a case-to-case basis. (Notable exception: CAESAR, ARES → Pier Monni's talk)

- Inefficient and error prone

In contrast, LO and NLO computations have been completely automated over the past years. These codes can be used as a basis to perform resummation:

- Large logarithms arise near Born-level kinematics. Can reweight LO events to achieve resummation.

- Can use NLO codes to compute ingredients for the resummation: hard function, jet and soft functions

Cross section with a jet veto

A veto on jets $p_T^{\rm jet} < p_T^{\rm veto} \approx 15 - 30\,{\rm GeV}$ is used to suppress top background, in particular in processes involving W-bosons, e.g. in

$pp \to W^+ W^-$, $pp \to H \to W^+ W^-$, etc.

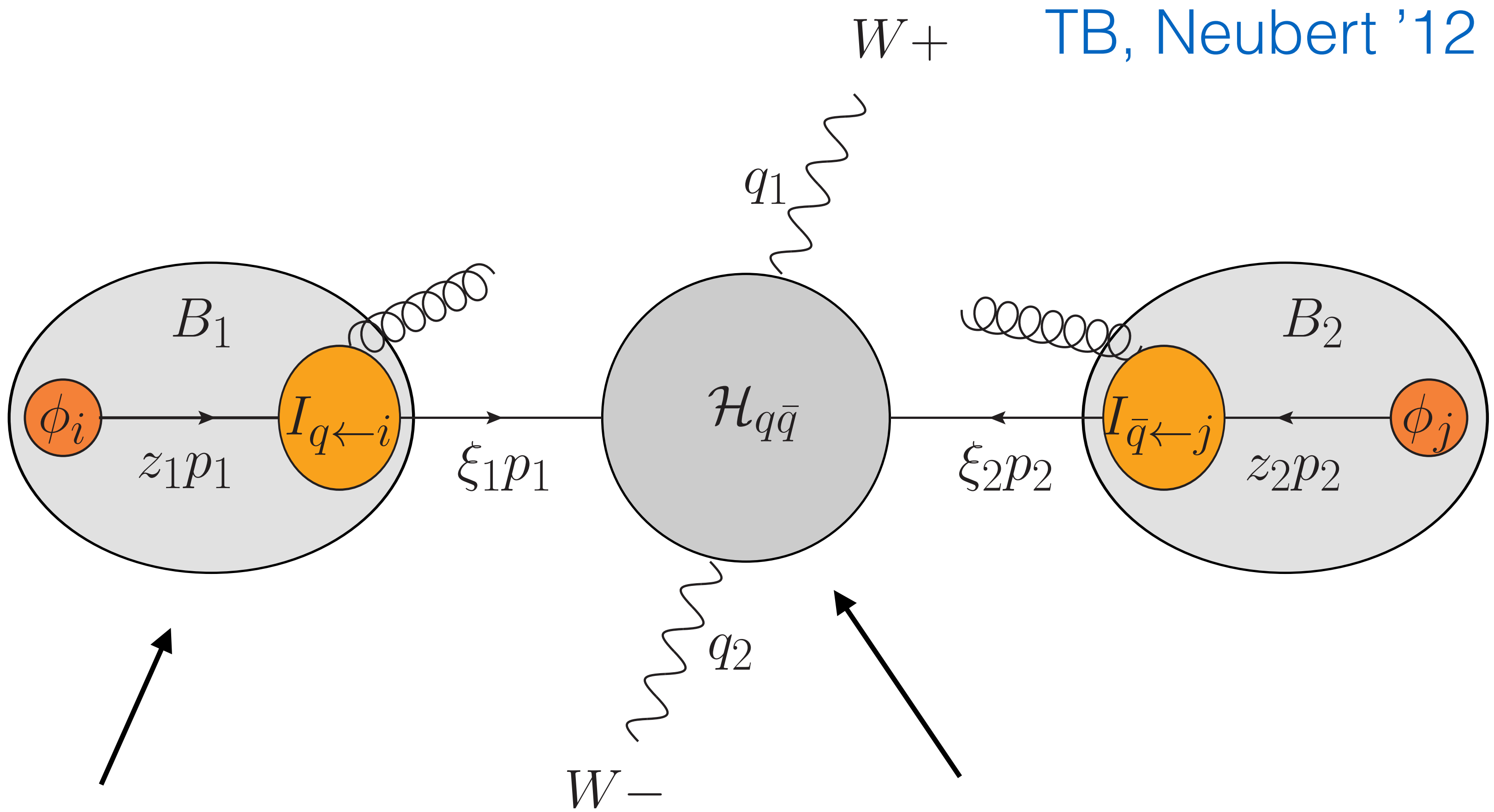
→Large Sudakov logarithms $\alpha_s^n \ln^k \left(\frac{p_T^{\rm veto}}{Q} \right)$

A lot of work on their resummation, both in QCD and SCET:

- Higgs: Banfi, Salam, Zanderighi '12; + Monni '12; TB Neubert '12 + Rothen '13; Tackmann, Walsh, Zuberi '12 + Stewart '13; Liu Petriello '13; + Boughezal, Tackmann and Walsh '14
- $W^+ W^-$: Jaiswal, Okui '14; Monni, Zanerighi '14; TB, Frederix, Neubert, Rothen '14

Factorization theorem for $\sigma(p_T^{veto})$

TB, Neubert '12 + Rothen '13



Beam functions $B(p_T^{veto})$

- real emission with veto. perturbative part ⊗ PDF
- process independent

Hard functions $H(Q)$

- virtual corrections, standard QCD loops
- process independent

Born-level kinematics for small p_T^{veto}

Resummed cross section

Born-level | evolution factors, resummation

$$\frac{d^3\sigma(p_T^{\rm veto})}{dy\,dQ^2\,d\hat{t}} = \sigma_0(Q^2,\hat{t},\mu)\,U_q(Q^2,\mu_h,\mu)\left(\frac{Q}{p_T^{\rm veto}}\right)^{-2F_q(p_T^{\rm veto},\mu)}$$

$$\times\,\mathcal{H}_{q\bar{q}}(Q^2,\hat{t},\mu_h)\,B_q(\xi_1,\mu,p_T^{\rm veto})\,B_{\bar{q}}(\xi_2,\mu,p_T^{\rm veto})$$

hard function | beam functions

"Born-level cross section" x "prefactor $P(p_T^{\rm veto})$"

- Can obtain resummed cross section by reweighting Born-level events with $P(p_T^{\rm veto})$

Automated Resummation using Madgraph5_aMC@NLO

Scheme A: NNLL from reweighting Born events

- Rescale each LO event weight with the ratio to the resummed cross section.
- Beam functions included via modified PDFs
  - Tabulate grid of values, use standard PDF interpolation
- One-loop hard function (only process dependent piece) computed using the MadGraph5_aMC@NLO code
- Additive matching to NLO fixed-order

$$\sigma_{\mathrm{NNLL+NLO}} = \sigma_{\mathrm{NNLL}}(\mu, \mu_h) + \Big(\sigma_{\mathrm{NLO}}(\mu_m) - \sigma_{\mathrm{NNLL}}(\mu_m)\big|_{\text{expanded to NLO}}\Big)$$

Automated Resummation using Madgraph5_aMC@NLO

Scheme B: NNLL+NLO with automated computation of the beam functions and matching corrections

- Define reduced cross section by dividing out hard function and evolution factors

Power-correction

$$d\tilde{\sigma}_{ij}(p_T^{\text{veto}}) = d\sigma_{ij}^0(Q^2, \hat{t}, \mu)\, \bar{B}_i(\xi_1, p_T^{\text{veto}})\, \bar{B}_j(\xi_2, p_T^{\text{veto}}) + \Delta\tilde{\sigma}$$

  - Reduced cross section is free of large log's. Compute it at NLO for $\mu \approx p_T^{\text{veto}}$ by running aMC@NLO in fixed-order mode
  - multiply back evolution factor and hard function

- MadGraph5_aMC@NLO computes *both* hard and beam functions!

- Automatically includes multiplicative matching to NLO

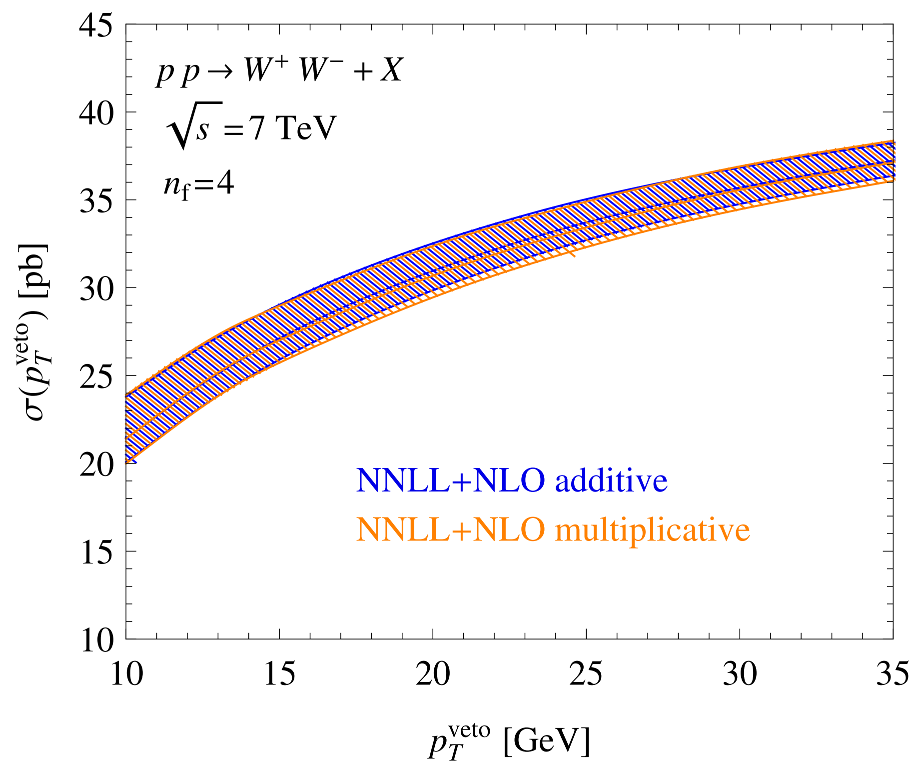
Comparison

Scheme A

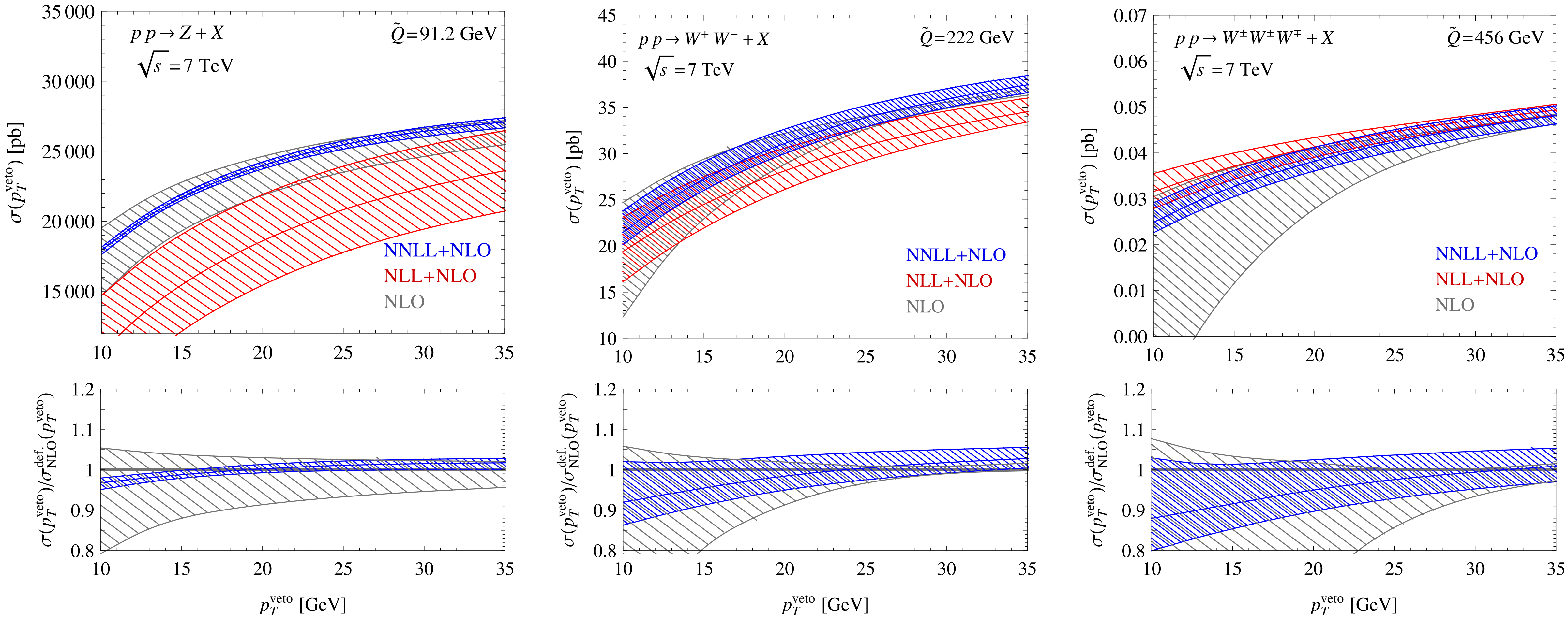
- Is easily extended to higher accuracy
- Can be applied to other processes
- Flexible, since it works with events (up to the NLO matching!)

Scheme B

- Resummation and NLO matching in one run
- Beam functions on the fly



Both will be included in version 2.3 of Madgraph5_aMC@NLO



- For NLO result we vary $p_T^{veto}/2 < \mu < 2Q$.
- NNLL+NLO is close to NLO at $\mu = Q$
- Matching corrections are small, grow linearly to 3% at p_T^{veto}=80 GeV. Can neglect matching at low p_T^{veto}.

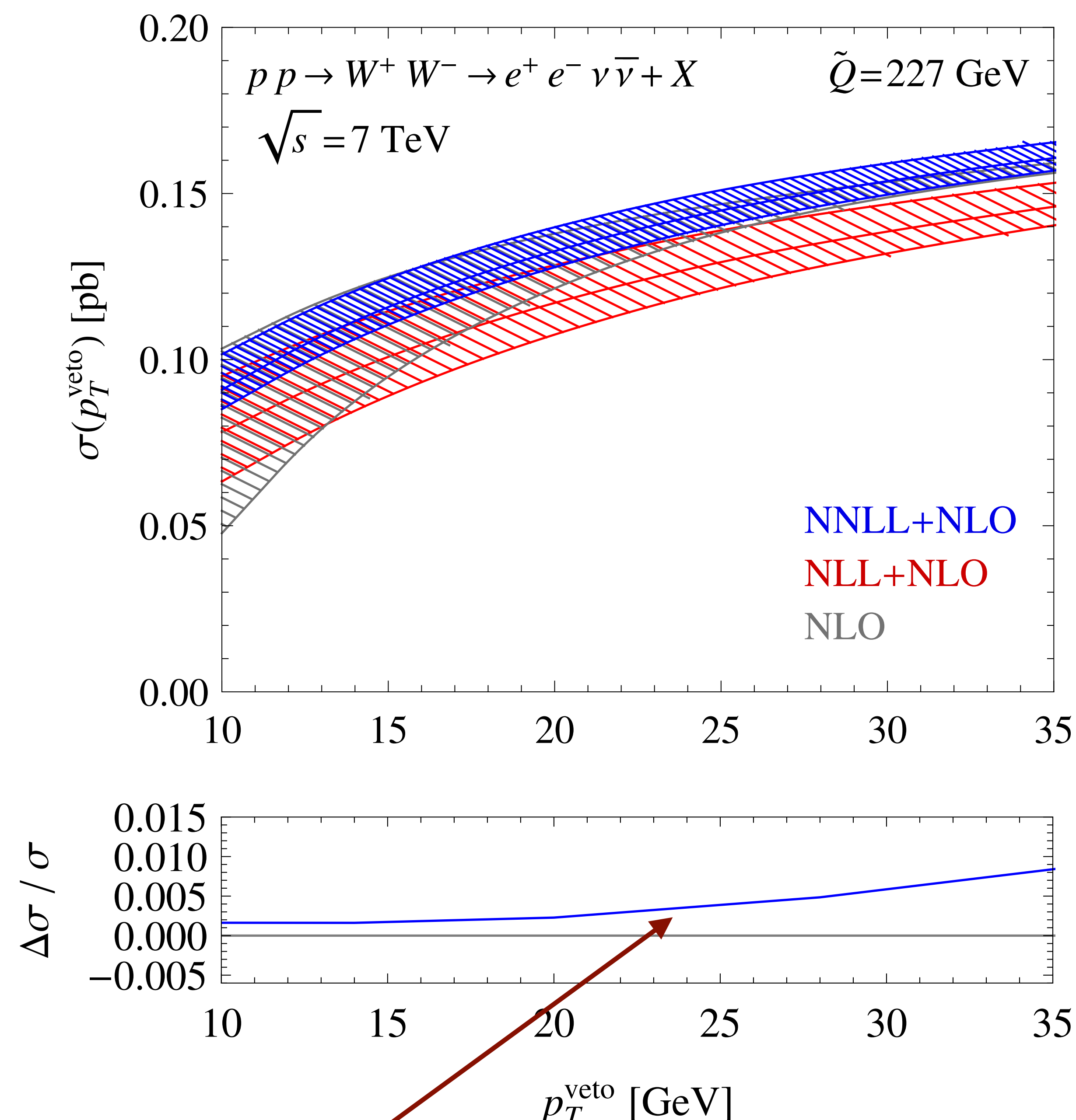
Decays and Cuts

Important advantage:

Straightforward to include the decay of the vector bosons and cuts on the final state leptons.

E.g. cuts by ATLAS in e^+e^- channel

1. lepton $p_T > 20\,\mathrm{GeV}$
2. leading lepton $p_T > 25\,\mathrm{GeV}$
3. lepton pseudorapidity $\eta_e < 1.37$ or $1.52 < \eta_e < 2.47$
4. $m_{e^+e^-} > 15\,\mathrm{GeV}$ and $|m_{e^+e^-} - m_Z| > 15\,\mathrm{GeV}$

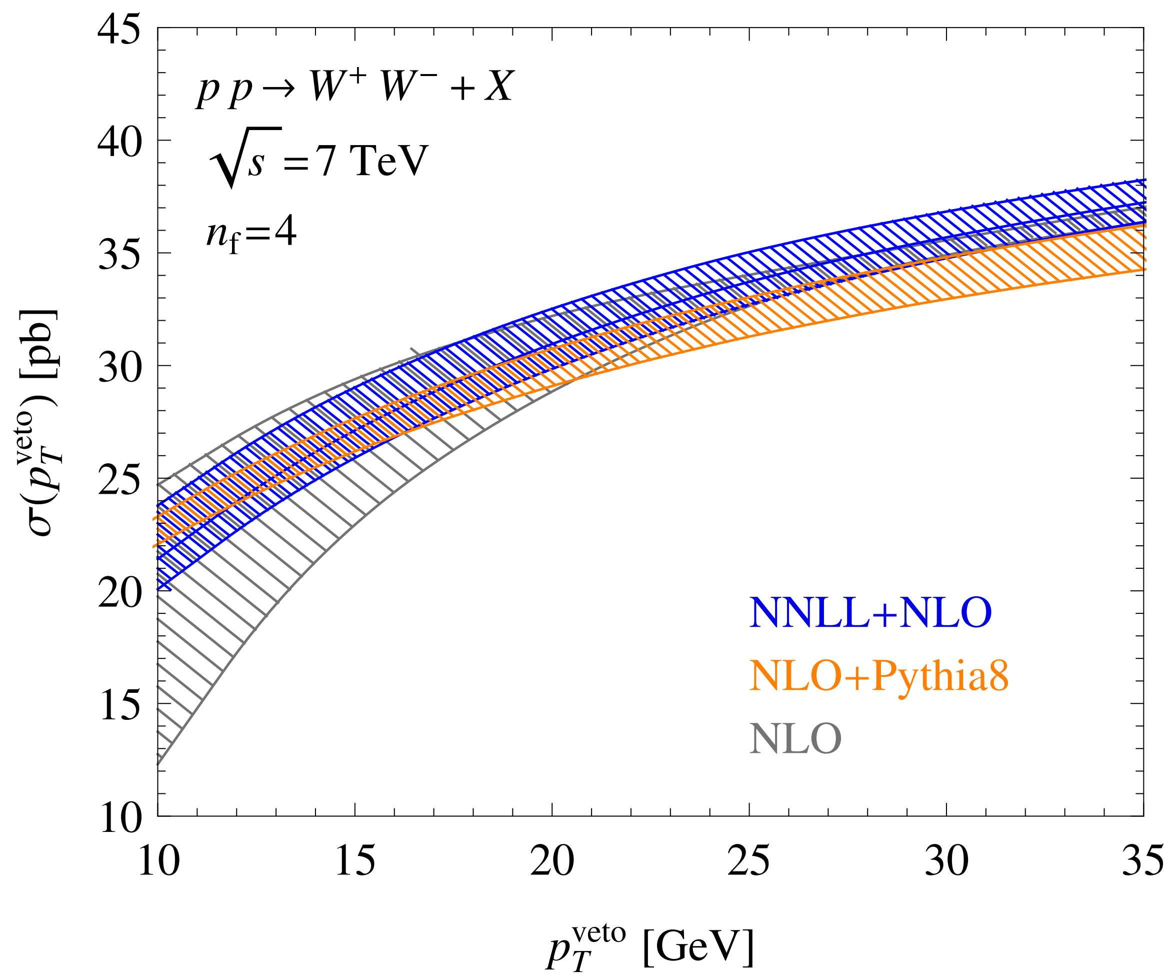


matching corrections remain small!

Comparison to matched PS

Observation: At higher values of p_T^{veto} the matched parton shower leads to lower results.

Unitarity of the shower, leads to compensation of changes at low transverse momentum.



Matched parton shower underestimates the jet-veto cross section

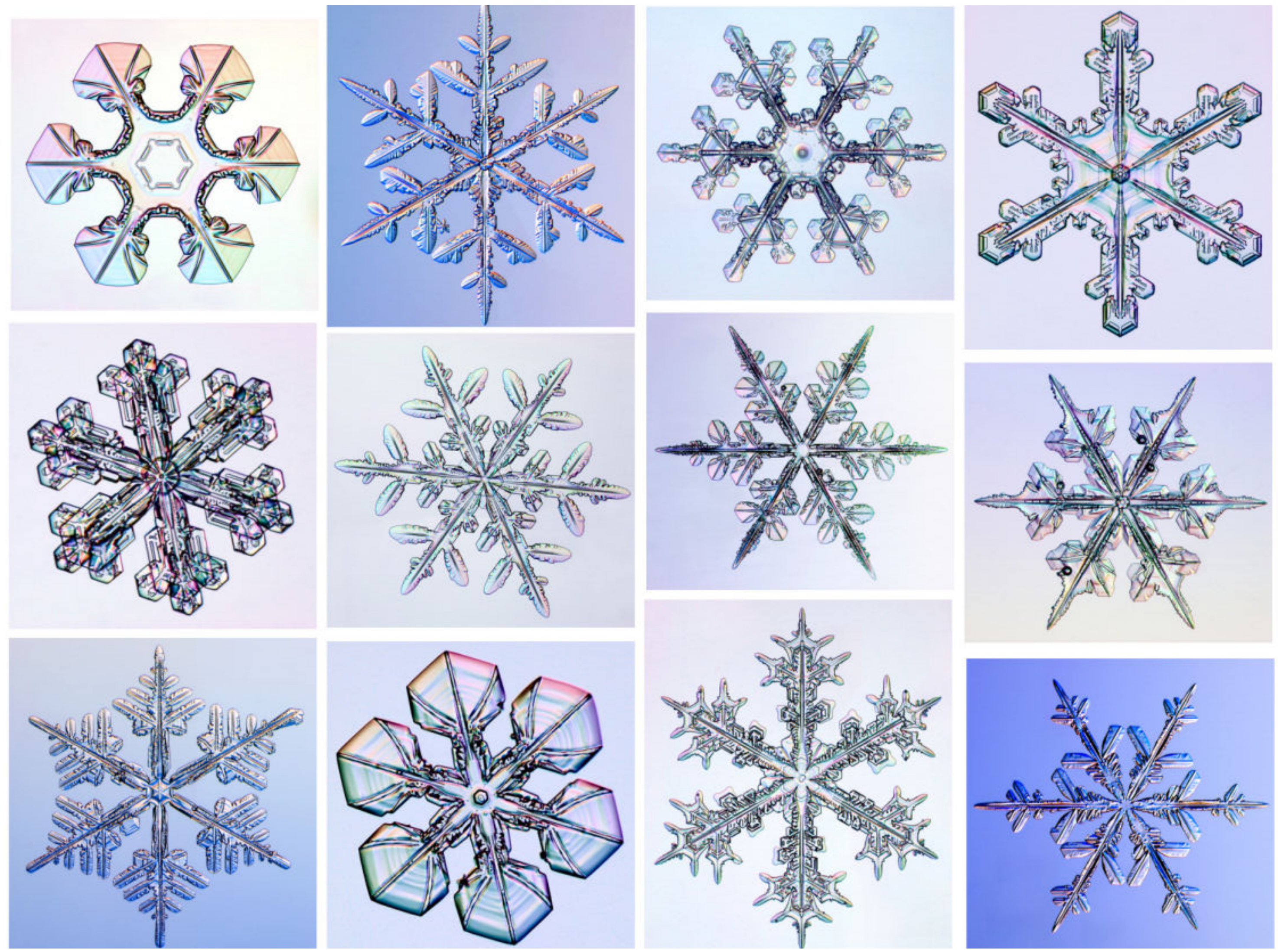
- In line with conclusions of Monni, Zanderighi ‘14

Extension to other observables

Since Sudakov logarithms always arise near Born-level kinematics, the same technique for automated resummation can also be used for more general observables.

Complications:

- Nontrivial color structure of the hard function. Need color information and imaginary part of amplitudes. Modified GoSam (Broggio + GoSam) can provide this information.
- NNLL needs automated computations of one-loop beam, jet, and soft functions, two-loop anomalous dimensions. →Rudi Rahn's talk
- Restriction to global observables



NNLL resummation for dijet event shapes at hadron colliders

TB, Xavier Garcia Tormo 1502.04136 (JHEP)
and ongoing + Jan Piclum

Resummation for LHC processes

Many higher-log results for e^+e^- but, only for a handful of NNLL predictions for *differential* cross sections for hadron colliders

- Z/W/H transverse momentum spectra
- Z/W/H/WW/… cross sections with jet-veto
- Beam thrust
- 1-jettiness in *H* and *W* production

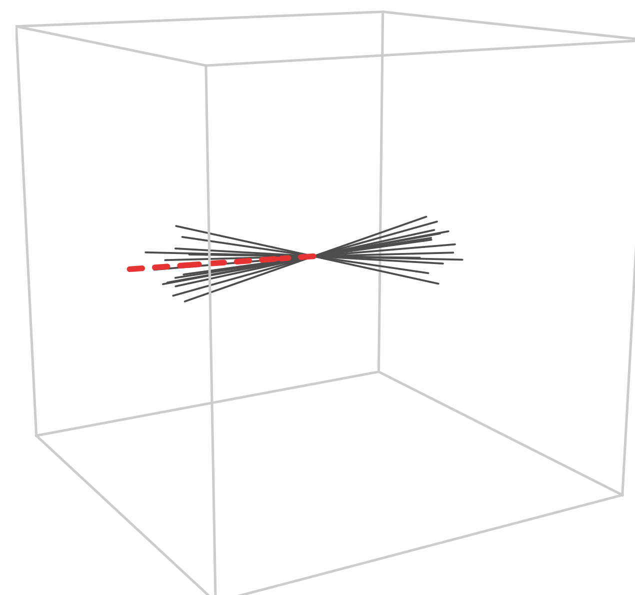
Not a single dijet observable! (Some threshold results.)

Chien, Kelley, Schwartz, Zhu ’10-‘12

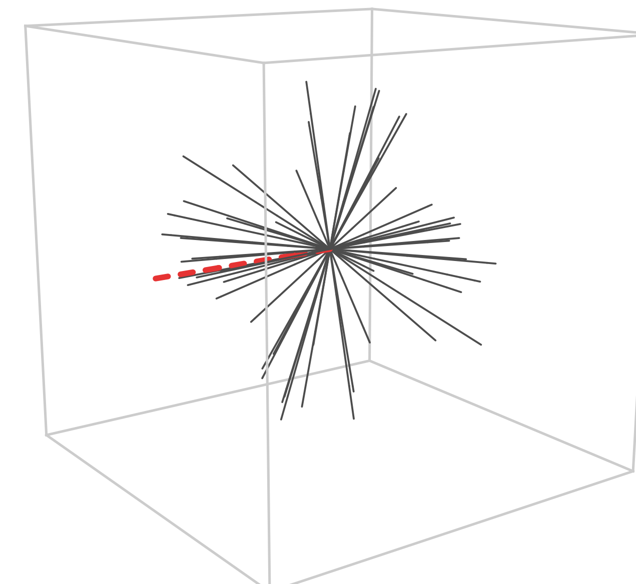
Canonical e^+e^- event shape: thrust

$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$

$$\tau = 1 - T$$



$\tau \approx 0$



$\tau \approx 1/2$

Precise measurement at LEP, theoretical predictions at N^3LL+NNLO TB, Schwartz '08.

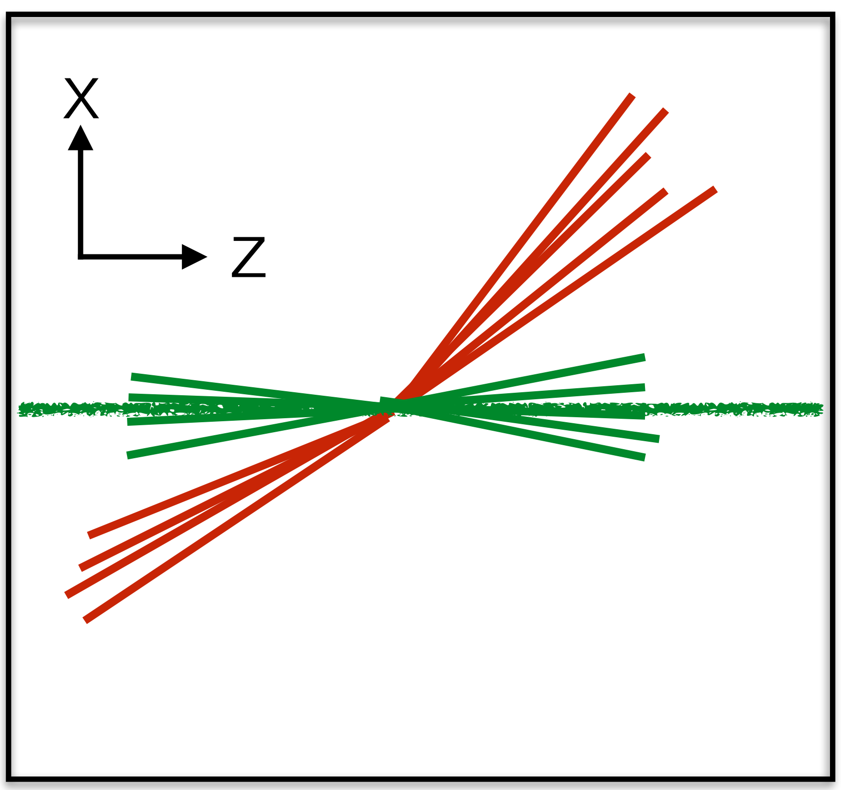
$$\alpha_s(m_Z) = 0.1135 \pm (0.0002)_{\text{expt}} \pm (0.0005)_{\text{hadr}} \pm (0.0009)_{\text{pert}}$$

Abbate, Fickinger, Hoang, Mateu and Stewart '10

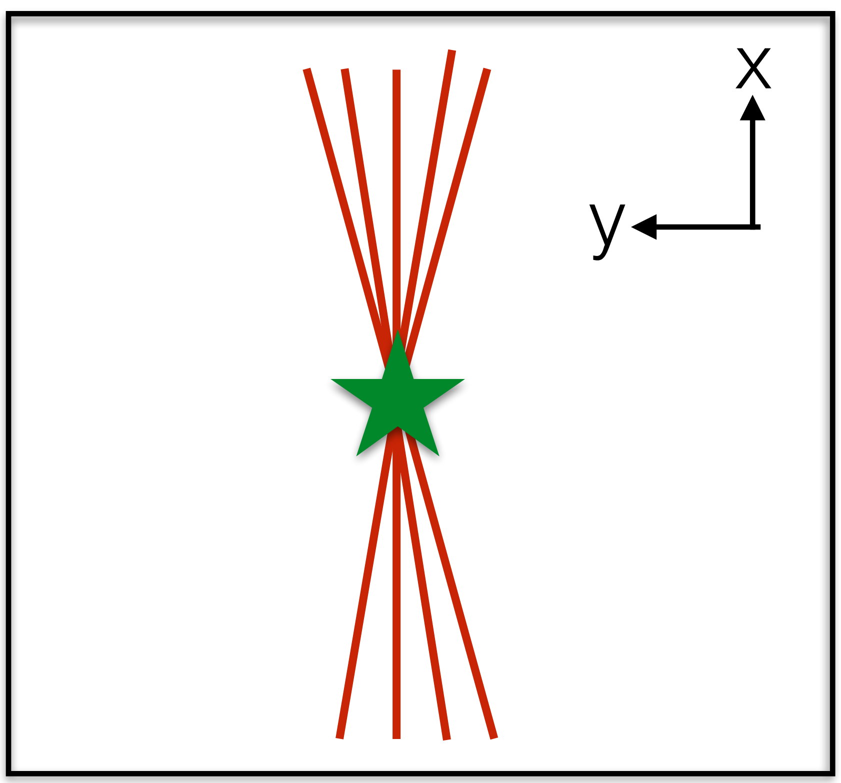
Hadron collider event shapes

- Each event has two jets down the beam pipe, no detector close to the beam.
- Natural to define event shapes in the transverse plane. (Alternative: *N*-jettiness Stewart, Tackmann, Waalewijn '10. Groups particles using multiple reference vectors.)

side view



transverse plane



Hadron collider event shapes

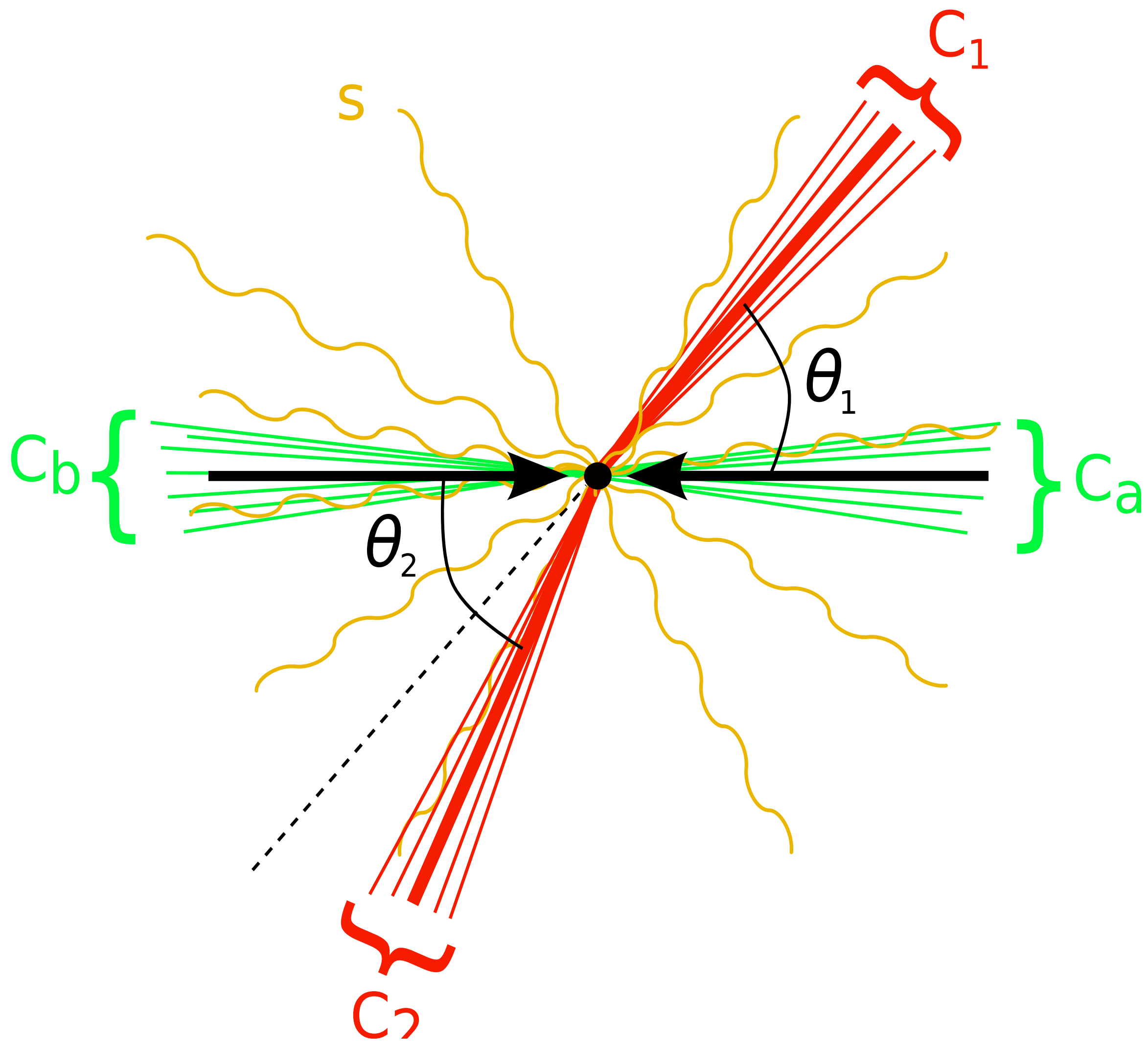
- Going into the transverse plane, basically any e^+e^- event shape can be turned into a hadron collider event shape.

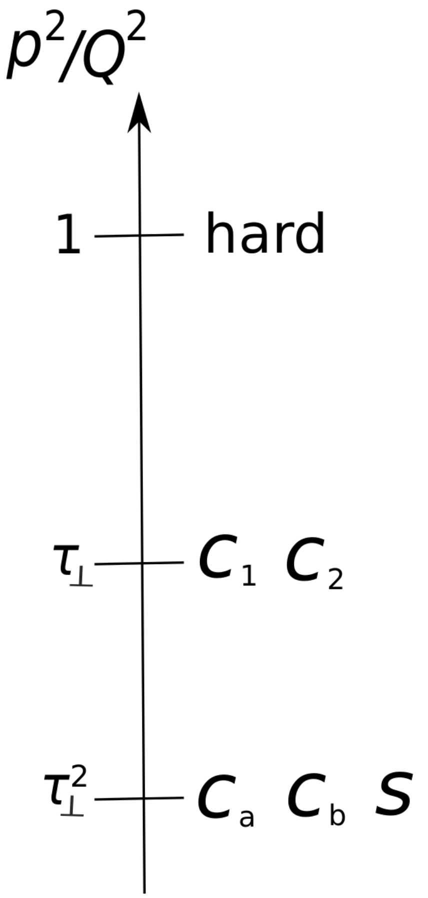
- Large class of such observables was computed at NLL +NLO using automated CAESAR framework. Banfi, Salam, Zanderighi ’04, ’10

  - Ongoing work to extend this to NNLL (“ARES”), first results for e^+e^- Banfi, McAslan, Monni and Zanderighi ‘14

- Transverse thrust has been measured both at the Tevatron and the LHC

- Have analyzed transverse thrust in SCET, as a first step towards a more general understanding of this class of event shapes.





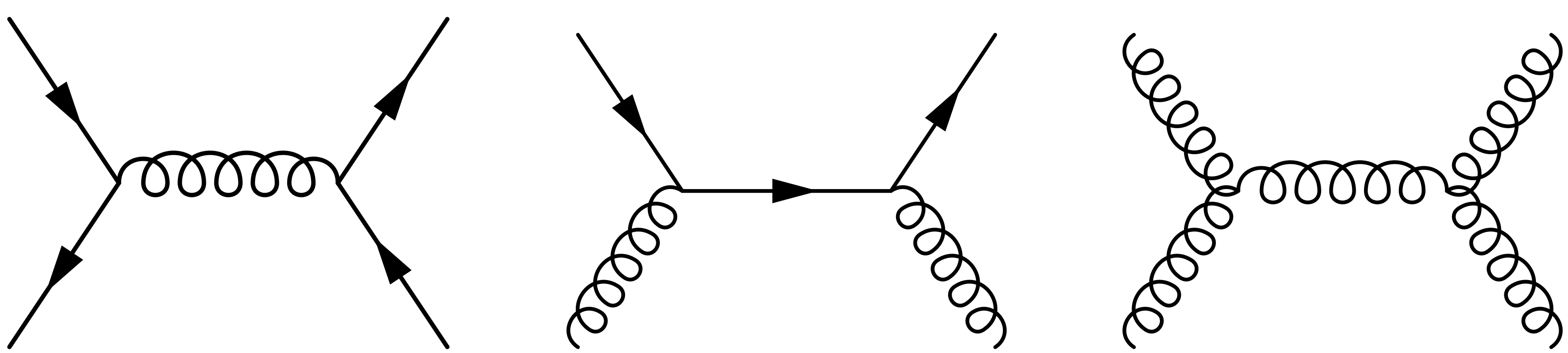
Factorization involves several interesting aspects

- Collinear fields with different virtuality: $\text{SCET}_{\text{I+II}}$
- Nontrivial color structure of hard and soft function
- Collinear anomaly (with color structure!)

Factorization theorem

$$d\sigma \sim H_{IJ}\mathcal{S}_{JI} \otimes J_1 \otimes J_2 \otimes \mathcal{B}_a \otimes \mathcal{B}_b$$

- Beam functions $\mathcal{B}_a$, $\mathcal{B}_b$ describe initial state radiation.
- Different partonic channels



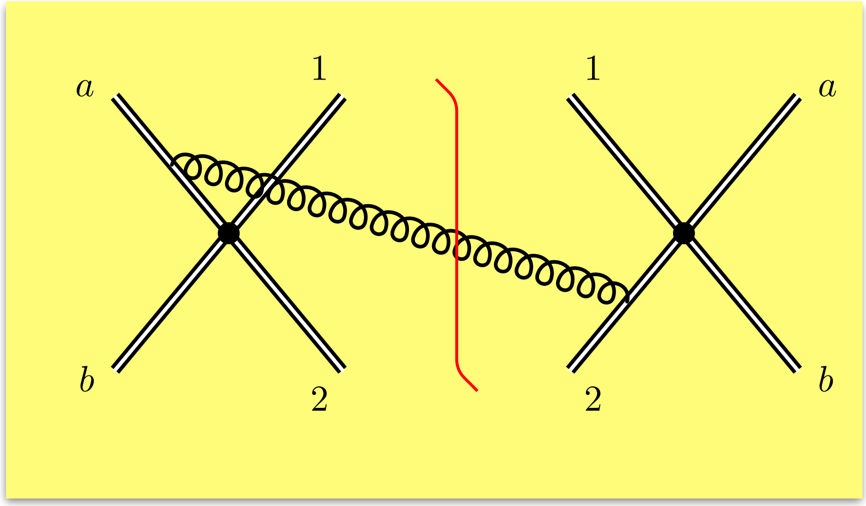
- nontrivial color structure in hard function H_{IJ} and soft functions S_{IJ}.

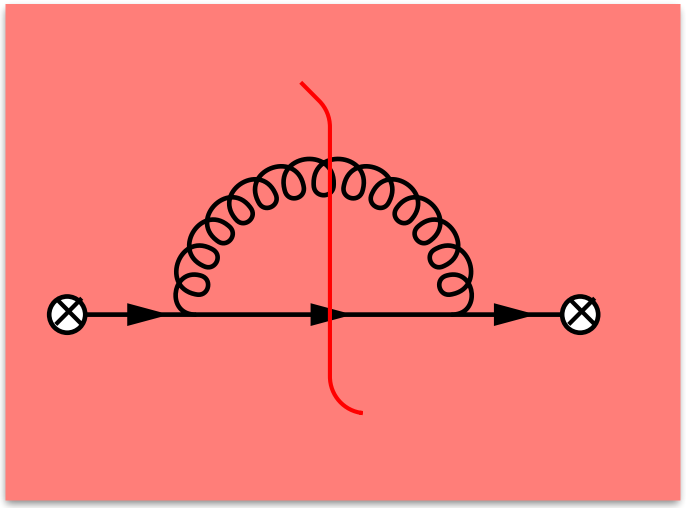
NNLL Resummation

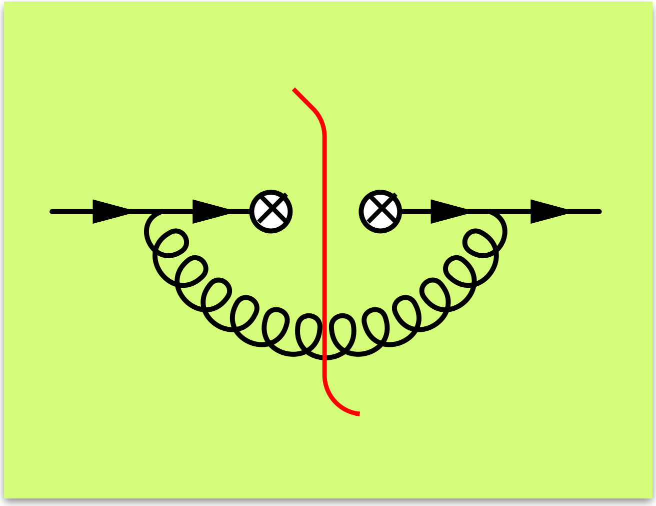
Need

- One-loop **hard**, **jet**, **soft**, **beam** functions
- Two-loop anomalous dimensions for all these objects
- The two-loop anomaly exponent

Computed all one-loop ingredients in 1502.04136







At first sight, many two-loop computations seem necessary to achieve NNLL, but using

- RG invariance and universality
  - same jet functions in $p\,p$ and e^+e^- collisions
  - same beam func. in $pp \to 2$ jets and $pp \to e^+e^-$
- known results for two-loop hard anomalous dimensions Becher, Neubert '09, Casimir scaling of soft function

it turns out, everything is known except anomaly exponent $F_\perp$ and jet anomalous dimension γ_{Jq} !

- Have determined both of these ingredients numerically. TB, Garcia-Tormo, Piclum, to appear.

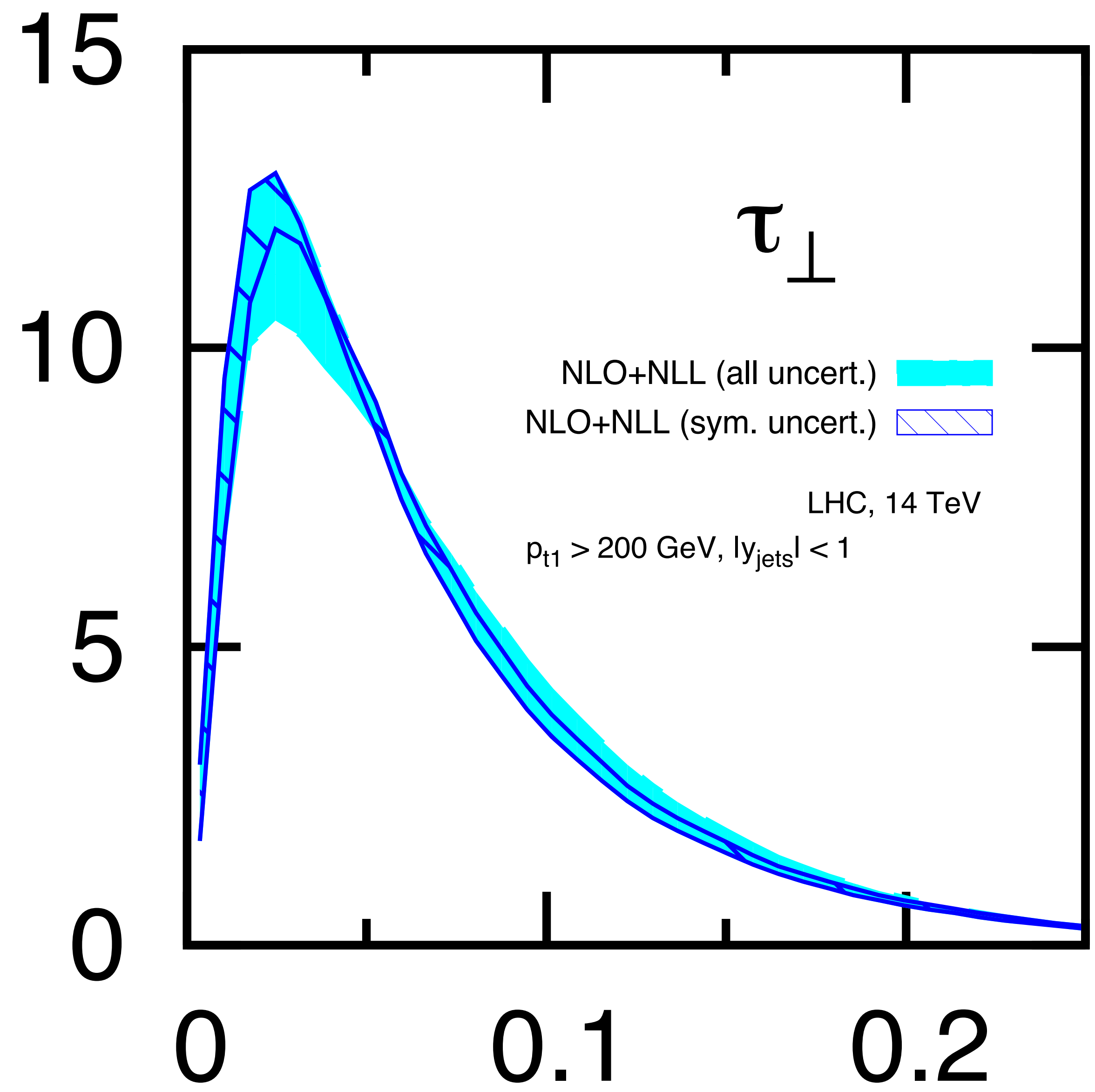
NNLL

We now have *all* ingredients for full NNLL resummation. Implementation is work in progress

- Have coded up two-loop hard function matrices for the different channels Broggio, Ferroglia, Pecjak and Zhang 1409.5294, including RG evolution.
- Have beam function interpolations in PDF format, one-loop soft functions
- Find large perturbative corrections to jet, beam and soft functions and to their anomalous dimensions! This will translate into large corrections at NNLL.

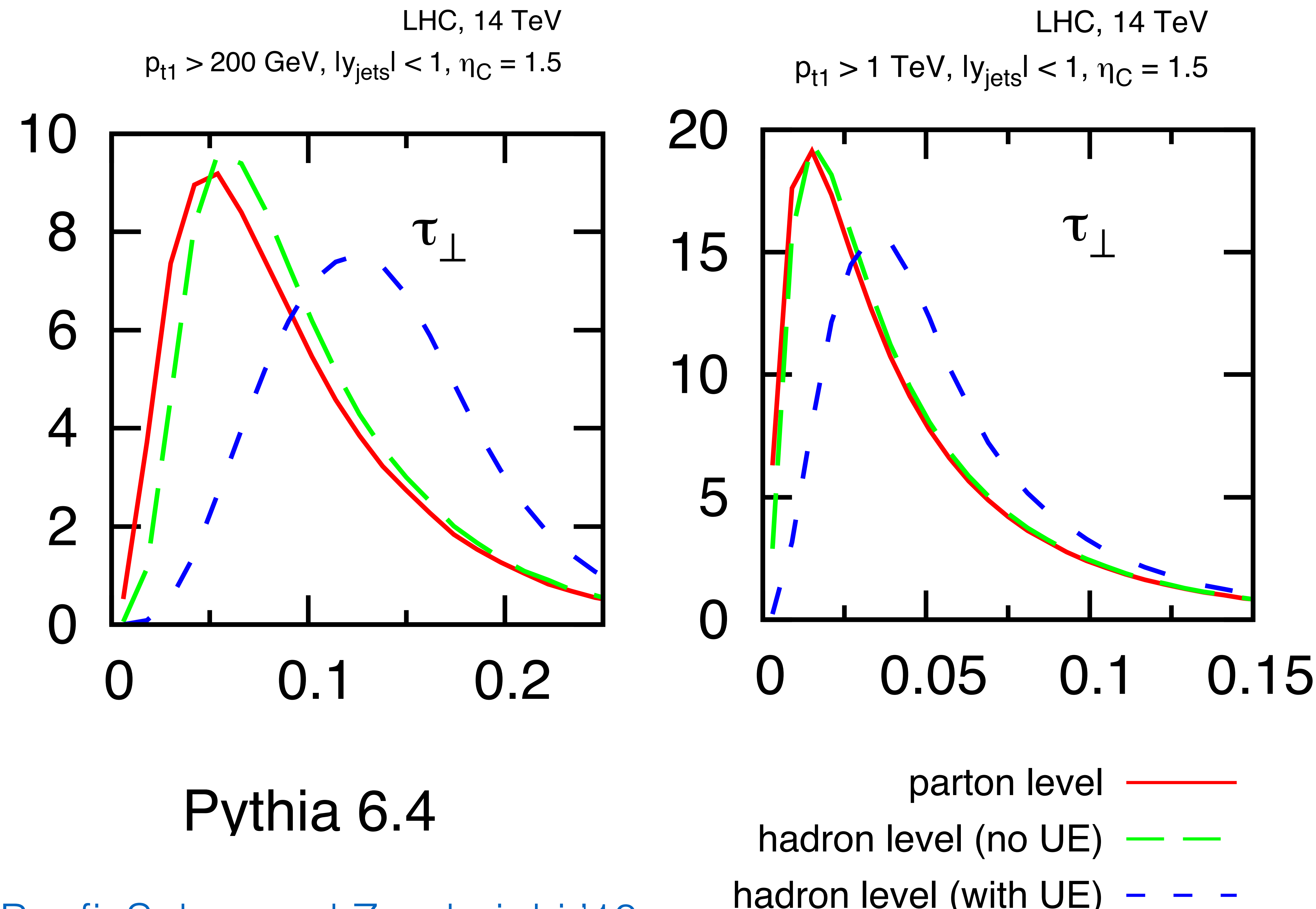
NLL+NLO from CAESAR

Banfi, Salam and Zanderighi '10



NNLL correction will be relatively large, but the basic shape stays the same.

Underlying event

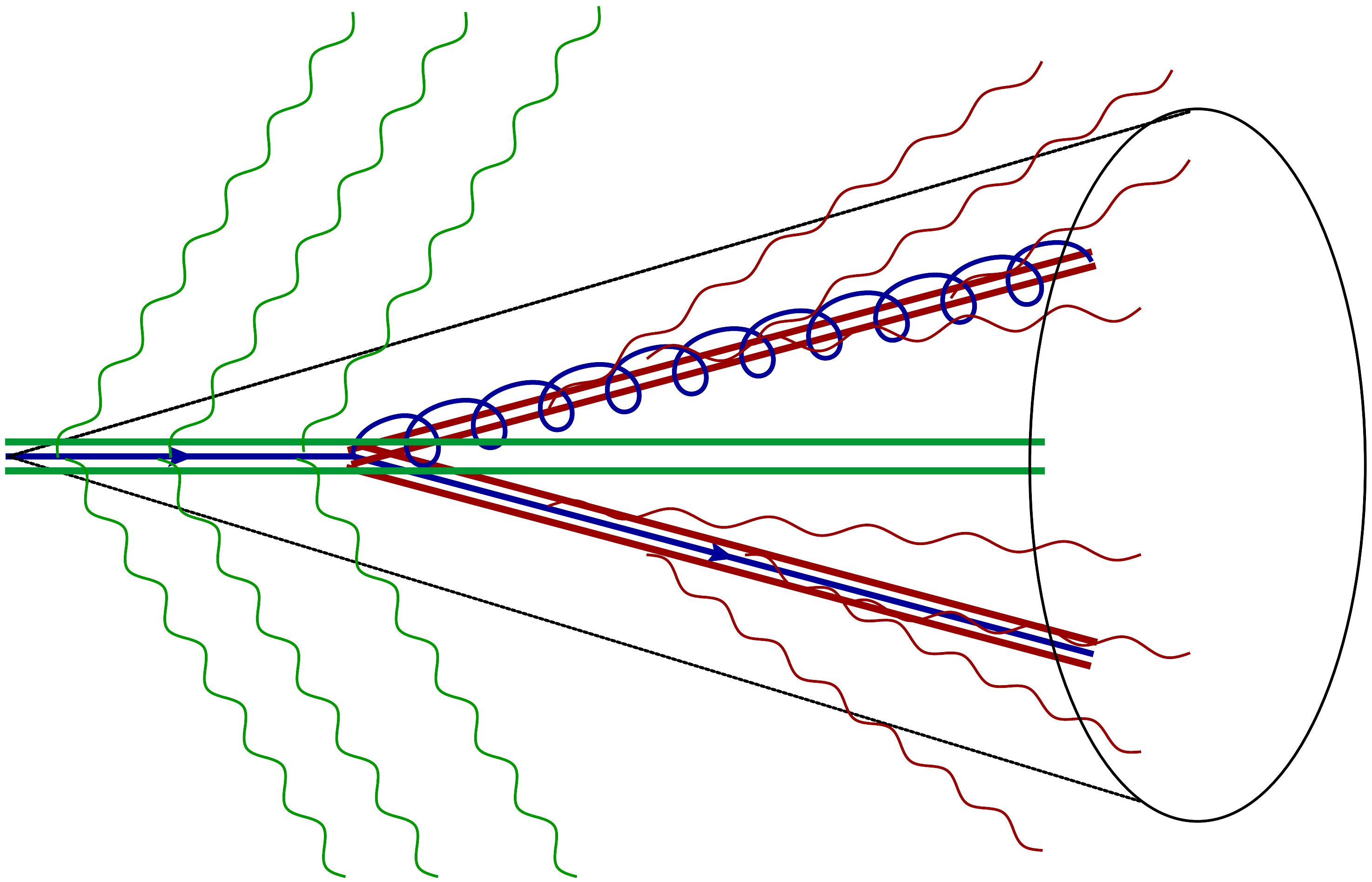


Pythia 6.4

from Banfi, Salam and Zanderighi '10

Glauber Gluons?

- From a theoretical perspective, UE modeling is quite unsatisfactory
    - True MPI is power suppressed!
    - Shouldn't we be able to model-independently describe O(1) effects in infrared safe observables?
- Glauber gluons [$p^\mu \sim(\lambda^n, \lambda^m, \lambda)$, $m+n>2$] could be the source of remnant interactions
    - Shown to be absent in DY Collins, Soper, Sterman, but could contribute to transverse thrust Gaunt '15
    - Implementation in SCET is under way. Donoghue, Kamal El-Menoufi, Ovanesyan; Fleming; Rothstein and Stewart



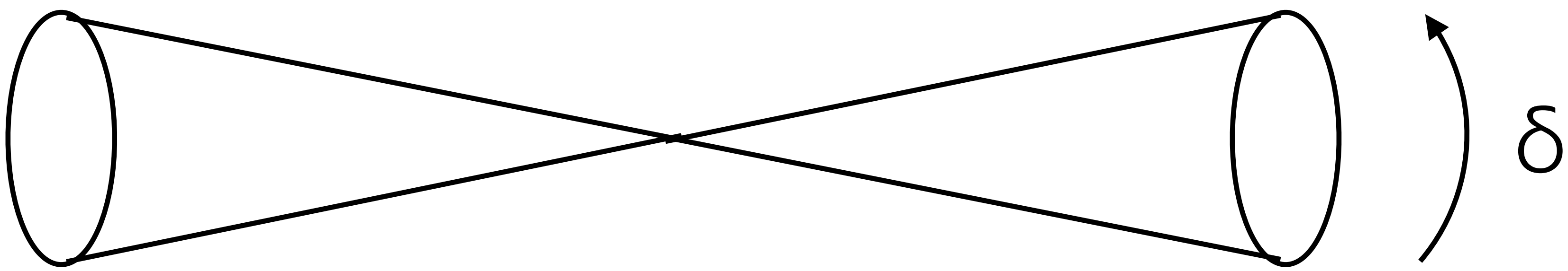
From SCET to

Jet Effective Theory

TB, Rothen, Shao, work in progress

Jet cross section in SCET

Cross sections for narrow cone jets (e.g. Sterman-Weinberg)



$$\beta = \frac{E_{\mathrm{in}}}{E_{\mathrm{out}}}$$

contains large logarithms ln(δ) and ln(β).

Can compute such cross sections using standard SCET, but this does not translate into a resummation of all large logarithms:

- Non-global logarithms: soft function contains multiple scales and therefore large logarithms, independent of μ.

Non-global logarithms in SCET

A number fixed-order computations for hemisphere soft functions

- Two-loop result for $S(\omega_L,\omega_R)$. Kelley, Schwartz, Schabinger and Zhu ’11; Hornig, Lee, Stewart, Walsh and Zuberi ’11; Kelley; with jet-cone Kelley, Schwartz, Schabinger and Zhu ‘11; von Manteuffel, Schabinger and Zhu ‘13

- Leading non-global log terms in $S(\omega_L,\omega_R)$ up to 5 loops by solving BMS. Schwartz, Zhu ‘14

Recently, interesting framework for approximate resummation of such logs, based on resummation for observables with *n* soft subjets was proposed. Larkoski, Moult and Neill ‘15

- Seems to work numerically well in the considered example, but systematics of expansion in subjets unclear. Expansion parameter?

A systematic factorization of non-global observables is missing.

Cheung, Luke and Zuberi '09 have computed one-loop jet cross sections using SCET.

Result for the soft function for Sterman-Weinberg

$$\frac{1}{\sigma_0}\sigma^s_{\mathrm{SW}} = \frac{\alpha_s C_F}{2\pi}\left(\frac{4}{\epsilon}\ln\delta - 4\ln^2\delta + 8\ln\delta\ln\frac{\mu}{\beta Q} - \frac{\pi^2}{3}\right)$$

multiple scales!

they use SCET with the following scaling:

$$\begin{aligned} & \qquad\qquad\quad (\; p_+ \;,\; p_- \;,\; p_\perp \;) \\ \text{collinear:}\quad & p_c \sim Q\,(\;1\;,\;\delta^2\;,\;\delta\;) \\ \text{soft:}\quad & p_s \sim Q\,(\;\beta\;,\;\beta\;,\;\beta\;) \end{aligned}$$

The proper effective theory should completely separate the physics at different scales.

To achieve homogeneous scaling one must systematically expand away power suppressed contributions, also in the phase-space constraints: strategy of regions

As a result of the expansion

- Collinear fields are always inside the jet (they have generically large energies).

$$\theta(\beta Q - 2E_c) \;\longrightarrow\; \theta(-2E_c) = 0$$

- Soft fields are always outside jet (they have generically large angle).

Coft mode

To reproduce QCD when performing the expansion, we need additional region

$$(\, p_+ \, , \, p_- \, , \, p_\perp \,)$$

$$\text{coft:} \quad p_t \sim \beta Q \, (\; 1 \; , \; \delta^2 \; , \; \delta \;)$$

This momentum mode is simultaneously collinear and soft

- Describes soft small angle radiation.
- Characteristic scale $\beta\delta Q$, much lower than soft scale!
- Can be be emitted both inside and outside of the jet.

Factorization of the soft function

The soft function for cone jets factorizes as

$$S_{\text{full}}(Q\beta, \delta, \mu) = \int_0^\beta d\beta' S_{DY}(Q\beta - Q\beta', \mu)\, U(Q\delta\beta', \mu)$$

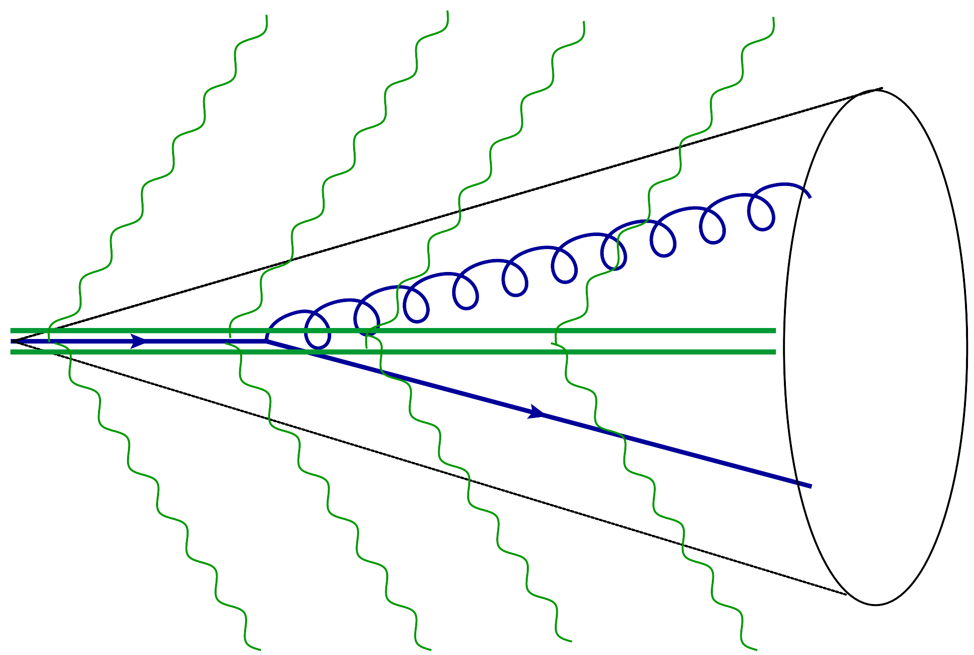
soft contribution (same as in DY)

coft contribution

- Verified this explicitly at the 2-loop level. Two-loop S_{full} can be derived from results for the thrust cone-jet soft function. Manteuffel, Schabinger and Zhu ‘13

- Can resum large logs in S_{full} using RG.

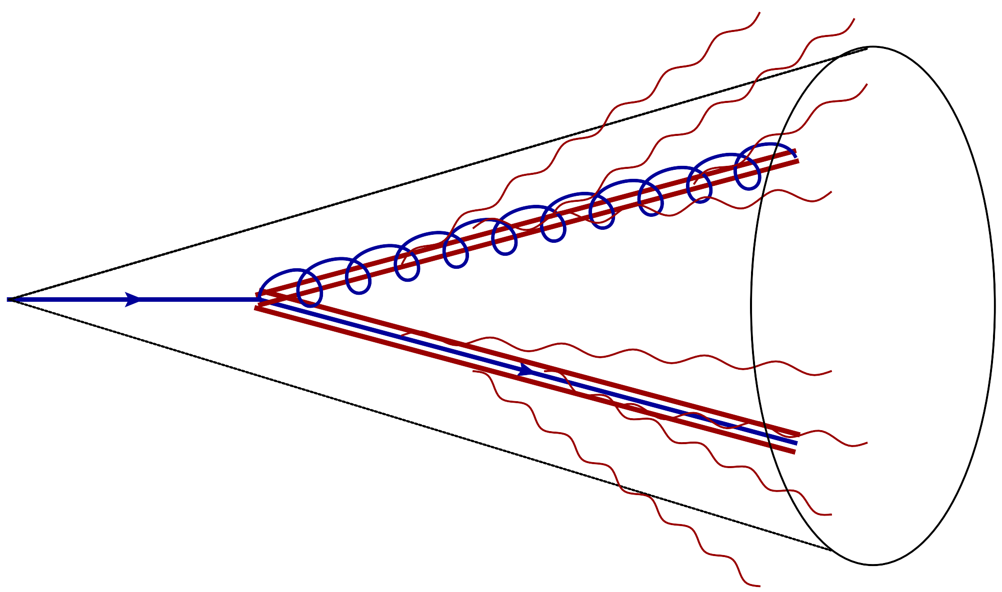
Soft-collinear factorization



Large angle soft radiation sees total charge of collinear radiation inside jet.

- Soft emissions described by single Wilson line.

Coft-collinear factorization



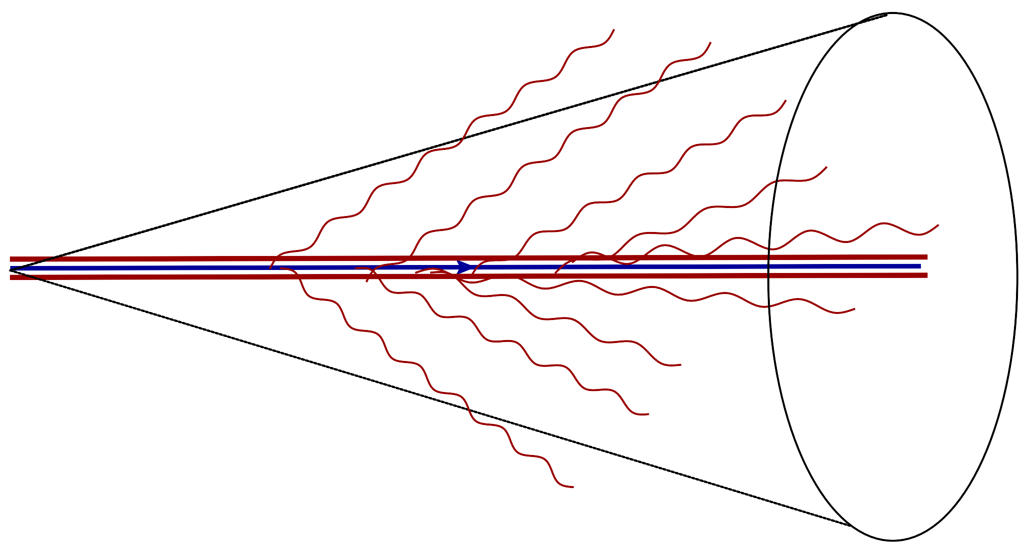
Small angle coft radiation resolves individual collinear particles.

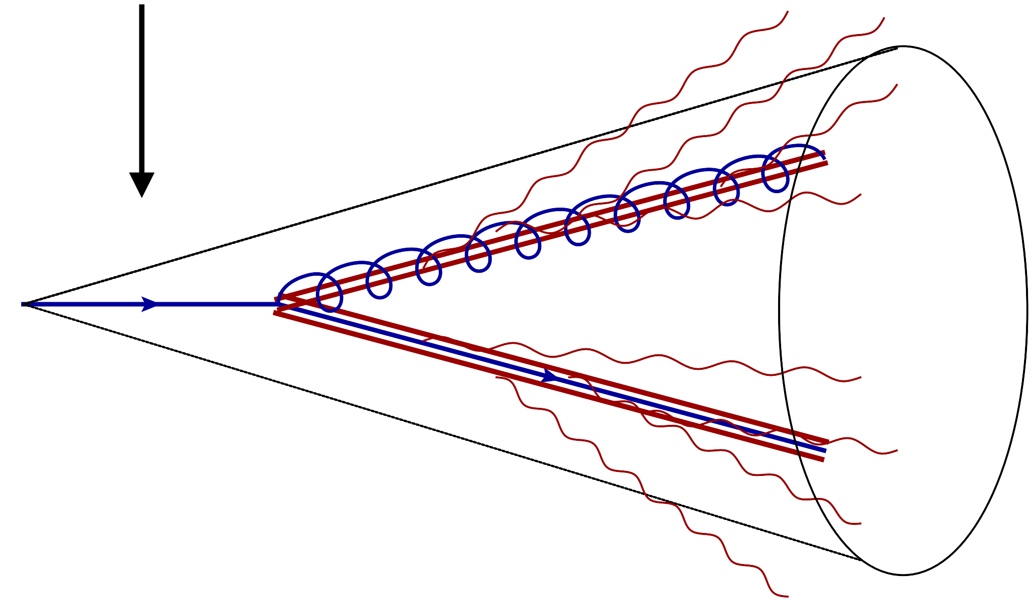
- Coft Wilson line for each final state collinear particle!
- Multi-Wilson-line structure of operators

Verified by expanding $\gamma^* \to \bar{q}qgg$ amplitude in all regions.

Coft operator structure

collinear splitting
amplitude





$$O(n_1) = U^\dagger(\bar{n};0)\,U(n_1;0)$$

$$O^B(n_1,n_2) = U^\dagger(\bar{n};0)t^A\,U(n_1;0)\,U^{AB}(n_2;0)$$

Wilson line along quark

Wilson line along other jet

adjoint Wilson line
along gluon

n_i are light-like reference vectors along collinear partons

Operator matrix elements

Coft matrix element for collinear *qg* final state

$$\mathcal{A}(\delta\beta Q, \Theta_{12}) = \sum_{X_{\rm coft}} \mathcal{M}_{\rm coft}(\{p_i\}) \langle 0|O^{\dagger A}_{ab}|X_{\rm coft}\rangle\langle X_{\rm coft}|O^A_{ba}|0\rangle$$

phase-space constraints

$$O^A = U^\dagger(\bar{n};0)t^A\, U(n_1;0)\, U^{AB}(n_2;0)$$

$$\Theta_{12} = \frac{n\cdot\bar{n}}{\delta^2}\frac{n_1\cdot n_2}{(n_1\cdot\bar{n})(n_2\cdot\bar{n})}$$

interesting similiarities to
color density matrix
by Simon Caron-Huot

gets convolved with collinear matrix element:

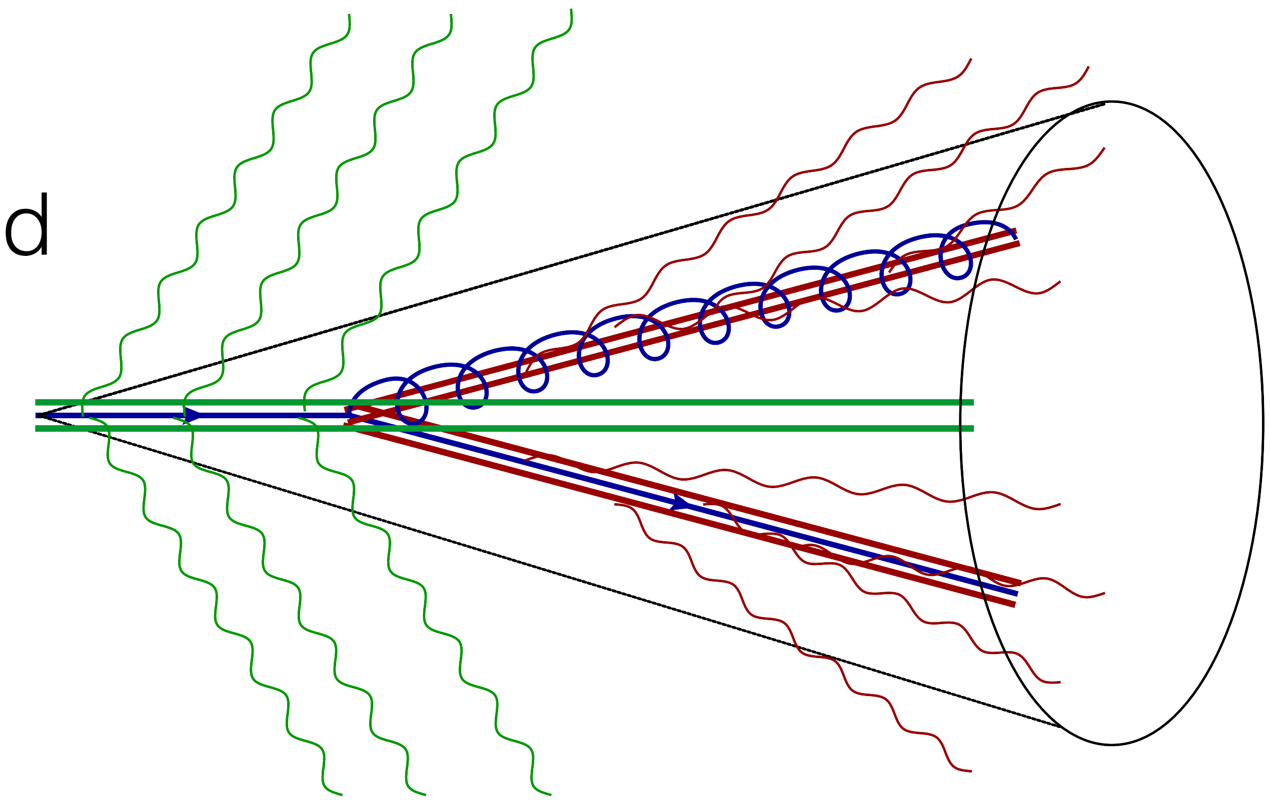
$$\int d\Theta_{12}\, J(Q\delta, \Theta_{12})\, \mathcal{A}(\delta\beta Q, \Theta_{12})$$

collinear matrix element
integral over splitting function

Jet Effective Theory

Understand

- the relevant scales and degrees of freedom
- the (complicated!) structure of the operators



Important first step, but does not immediately translate into resummation. Next steps

- Finish two-loop cross checks by computing coft-collinear matrix element.
- Study renormalization and RG evolution in the effective theory!

Summary

- Automated NNLL resummation for jet-veto cross sections
    - First example of an automated SCET resummation
    - Other observables can be resummed using the same technique
- NNLL resummation for transverse thrust
    - Interesting factorization theorem: SCET_{I}+SCET_{II}, rapidity divergences with nontrivial color structure, …
    - Role of Glauber gluons? UE?
- Jet Effective Theory
    - New ‘coft' mode to describe soft small angle radiation
    - Coft radiation resolves individual collinear final-state particles: leads to multi-Wilson-line structure of coft operators