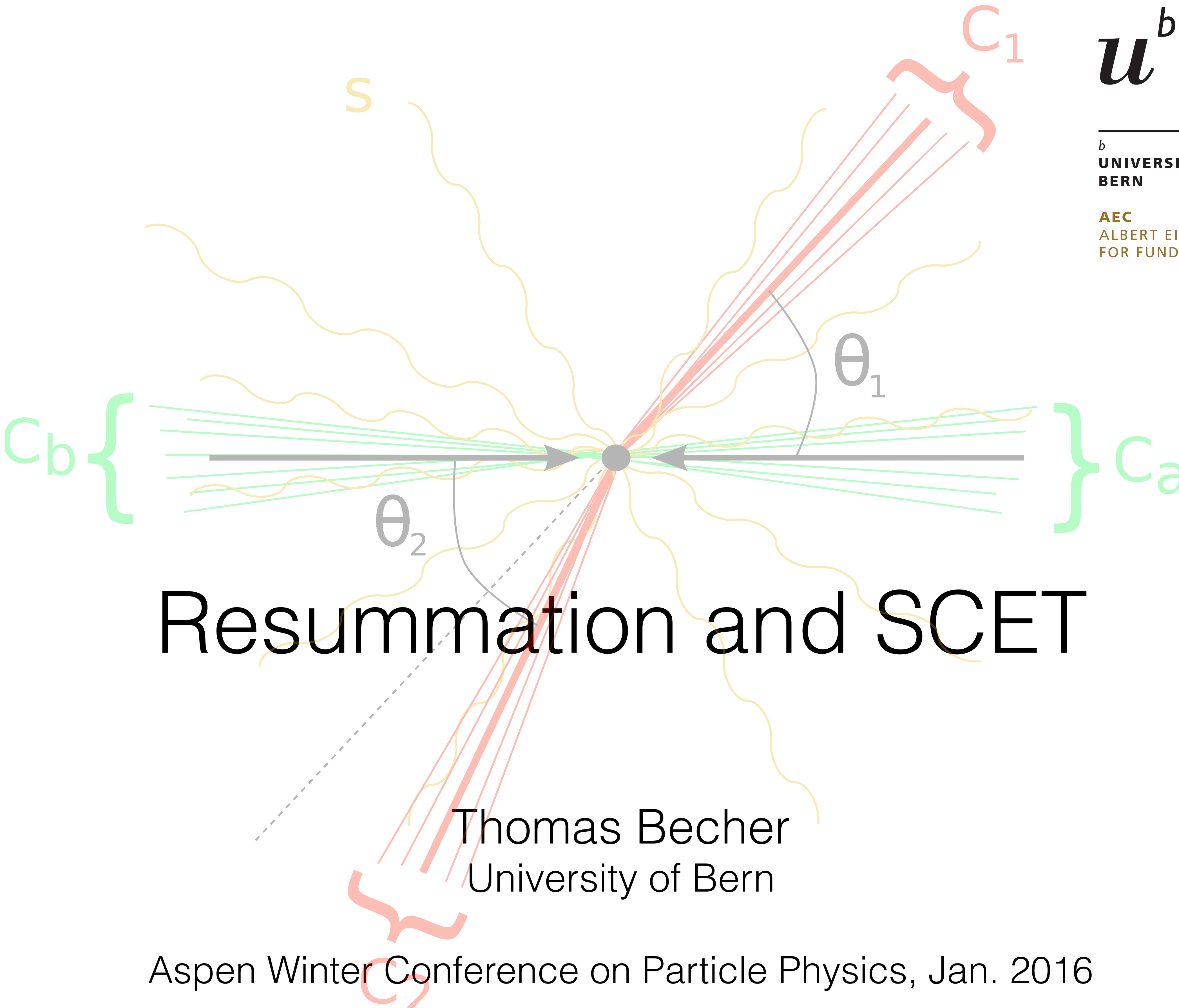

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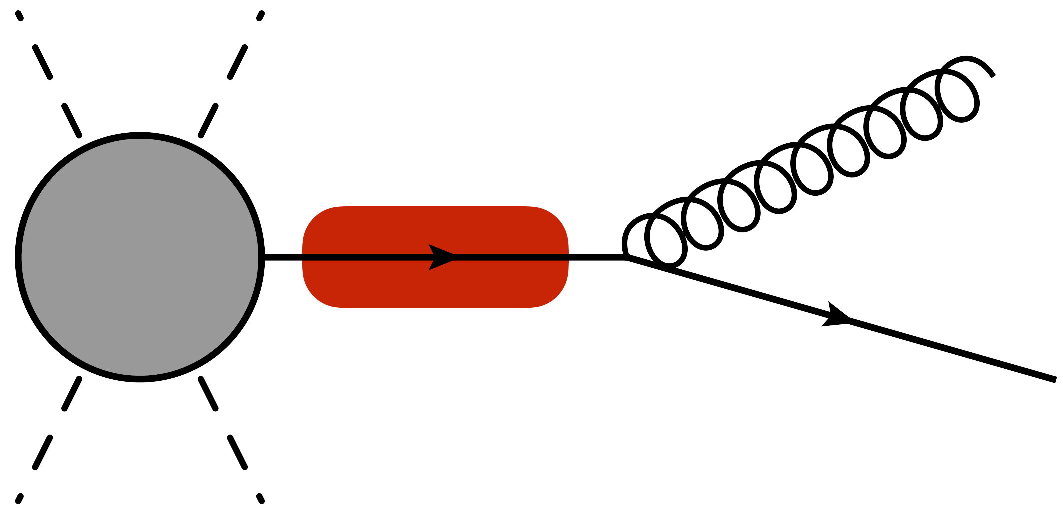
Resummation and SCET

Thomas Becher
University of Bern

Aspen Winter Conference on Particle Physics, Jan. 2016



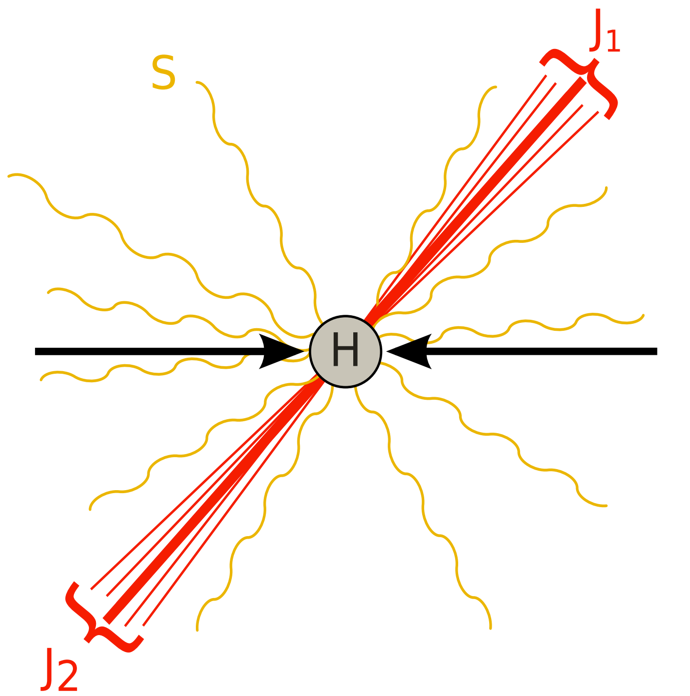
Scattering amplitudes are enhanced for soft and collinear emissions

- Large logarithms in higher orders corrections terms for observables sensitive to such emissions
- Resummation: for some observables, we manage to sum large logarithms to all orders.

Parton showers can resum leading-logarithmic terms, here I will discuss techniques such as Soft-Collinear Effective Theory for resummation to higher accuracy.

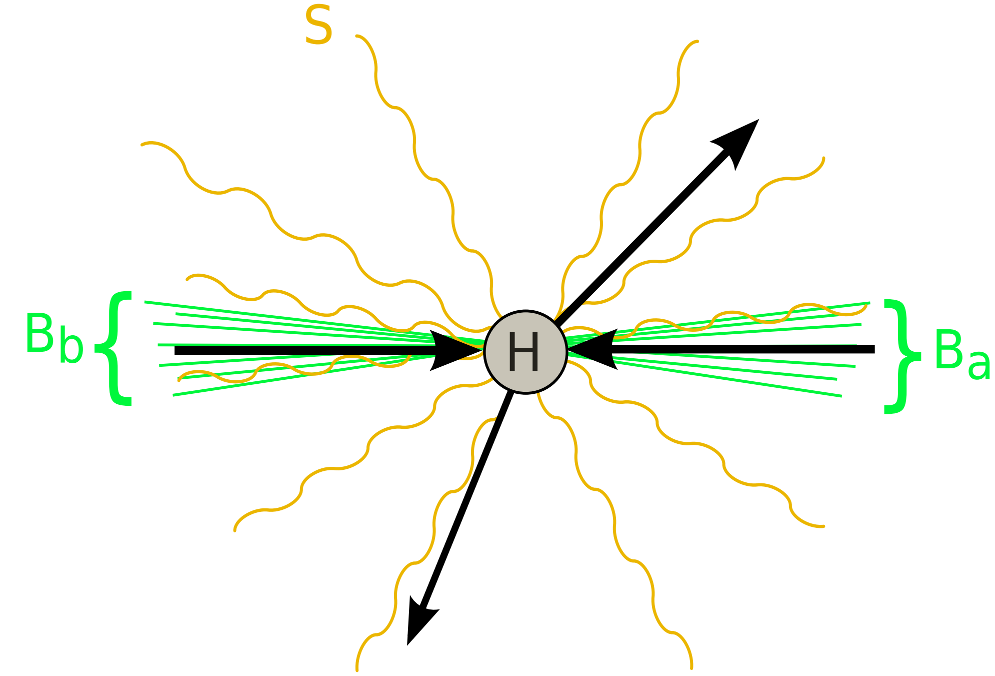
Simple structure of soft and collinear emissions leads to **factorization**. Simplest examples

$$e^+e^- \to 2\,\mathrm{jets}$$



$$d\sigma = H \cdot J_1 \otimes J_2 \otimes S$$

$$pp \to \ell_1 \bar{\ell}_2 + 0\,\mathrm{jets}$$



$$d\sigma = H \cdot B_1 \otimes B_2 \otimes S$$

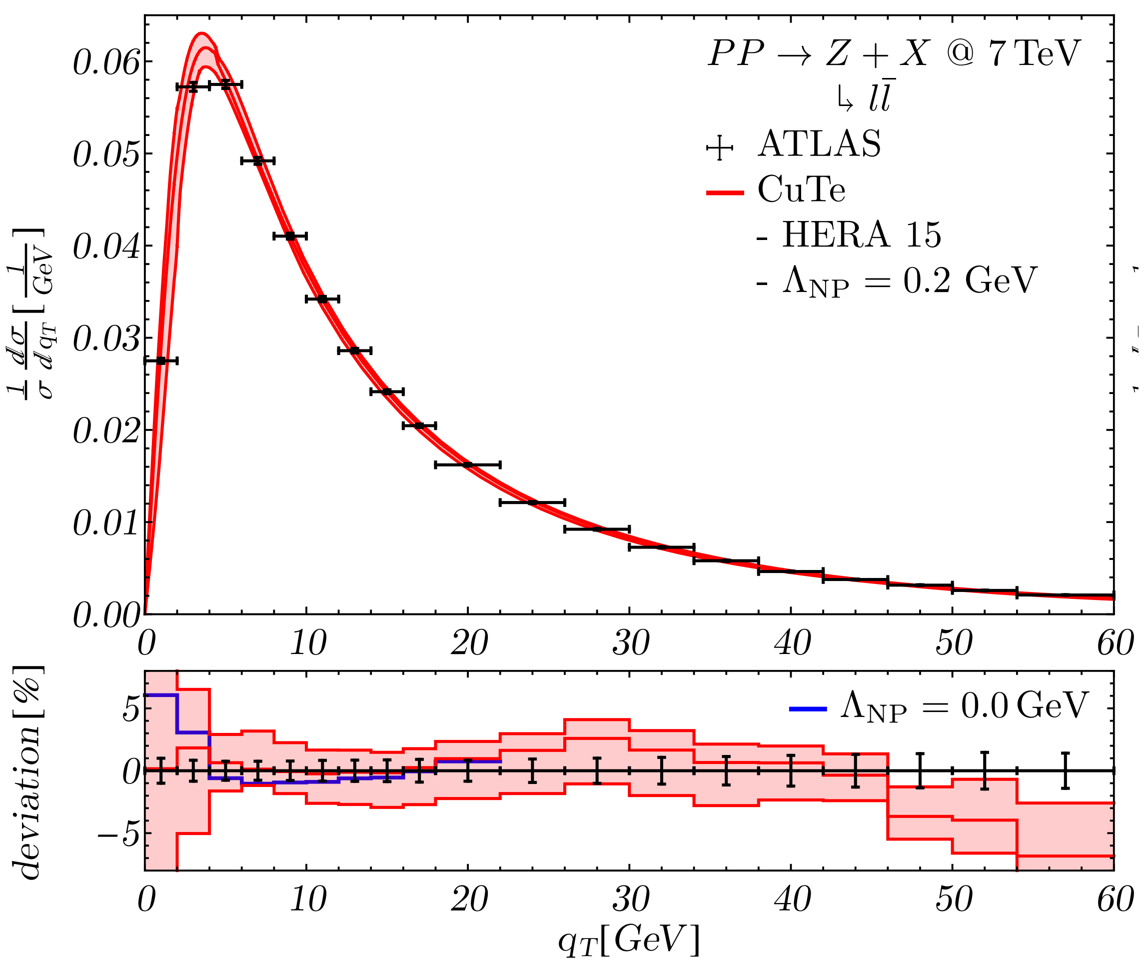
Factorization = scale separation ⇒ Resummation

Overview

- Recent highlights
  - q_T spectra of vector bosons
  - cross sections with a jet veto
  - N-jettiness subtraction
- New developments
  - Automated resummation
  - Resummation for jet processes

Recent highlights

q_T spectrum of Z at N^{3}LL*+N^{2}LO



- Large logarithm $\ln \frac{q_T^2}{M_Z^2}$
- Result from CuTe 2.0 TB Luebbert, Neubert, Wilhelm, to appear.
- Other codes: DYRes Catani, Grazzini et al.; ResBos Balasz, Nadolsky, Yuan et al.; Banfi, Dasgupta, Marzani and Tomlinson

Combining resummation with fixed-order results (“matching”) yields some of the most precise collider physics predictions available.

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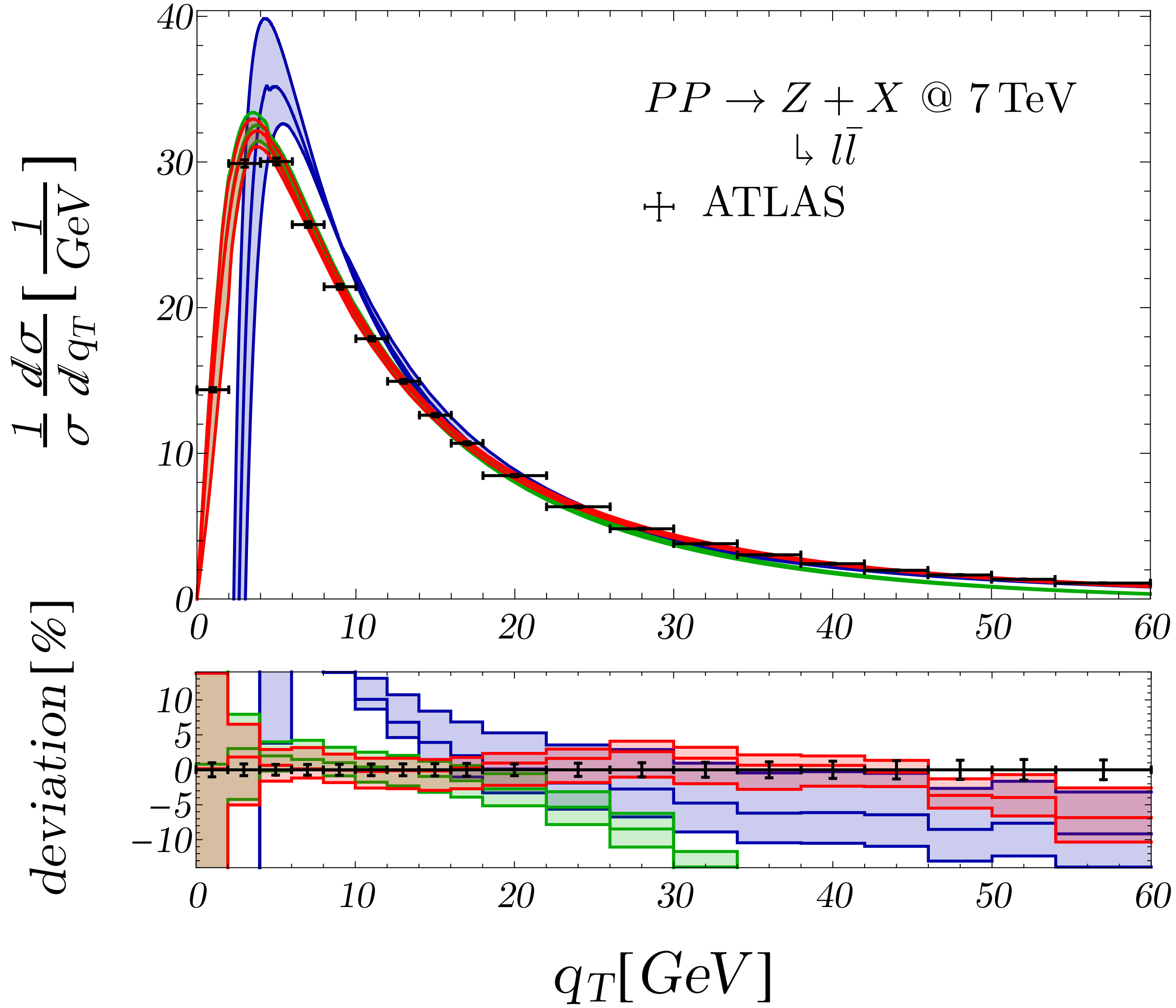
* Two numbers are not known to this accuracy: γ^3_{cusp} and d_3; estimate their effect.

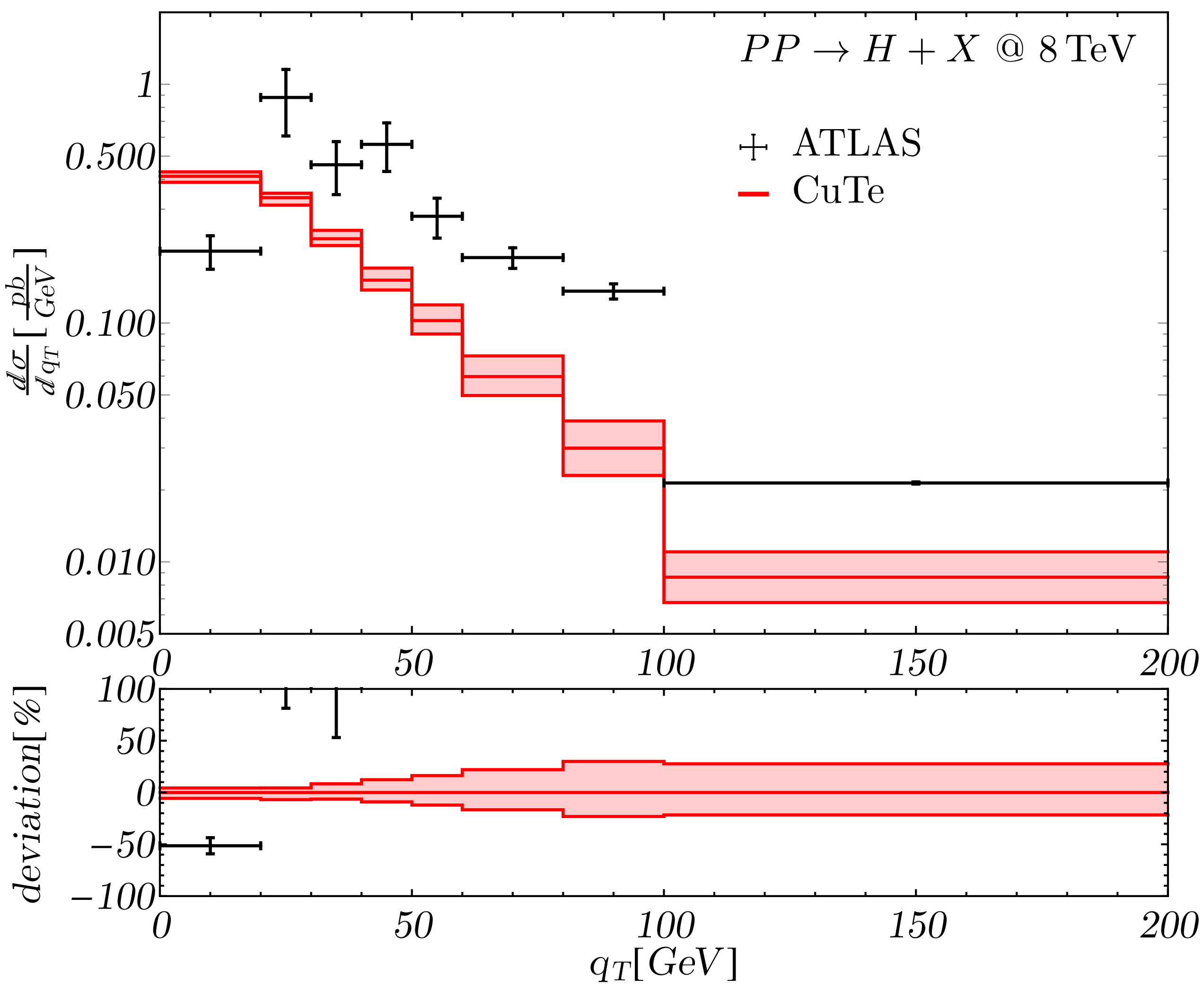
Matching



- **Resummation**: includes logs at low q_T, neglects q_T^2/M_Z^2 at high q_T
- **Fixed order**: good at large q_T, but large logs at small q_T.
- **Matched result**: the best of both worlds.

Important goal: extend higher-log resummation to more and more exclusive observables!

Side remark: Higgs cross section



- Result from CuTe 2.0 TB Luebbert, Neubert, Wilhelm, to appear.
- Other codes: HRes Catani, Grazzini et al.; ResBos Balasz, Nadolsky, Yuan et al. ; Neill, Rothstein, Vaidya '15

- Theory predictions by different groups are consistent
- Can change normalization (i.e. consider spectrum instead of σ) to get better agreement at higher q_T but then have larger disagreement in lowest bin.

Cross sections with a jet veto

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

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

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

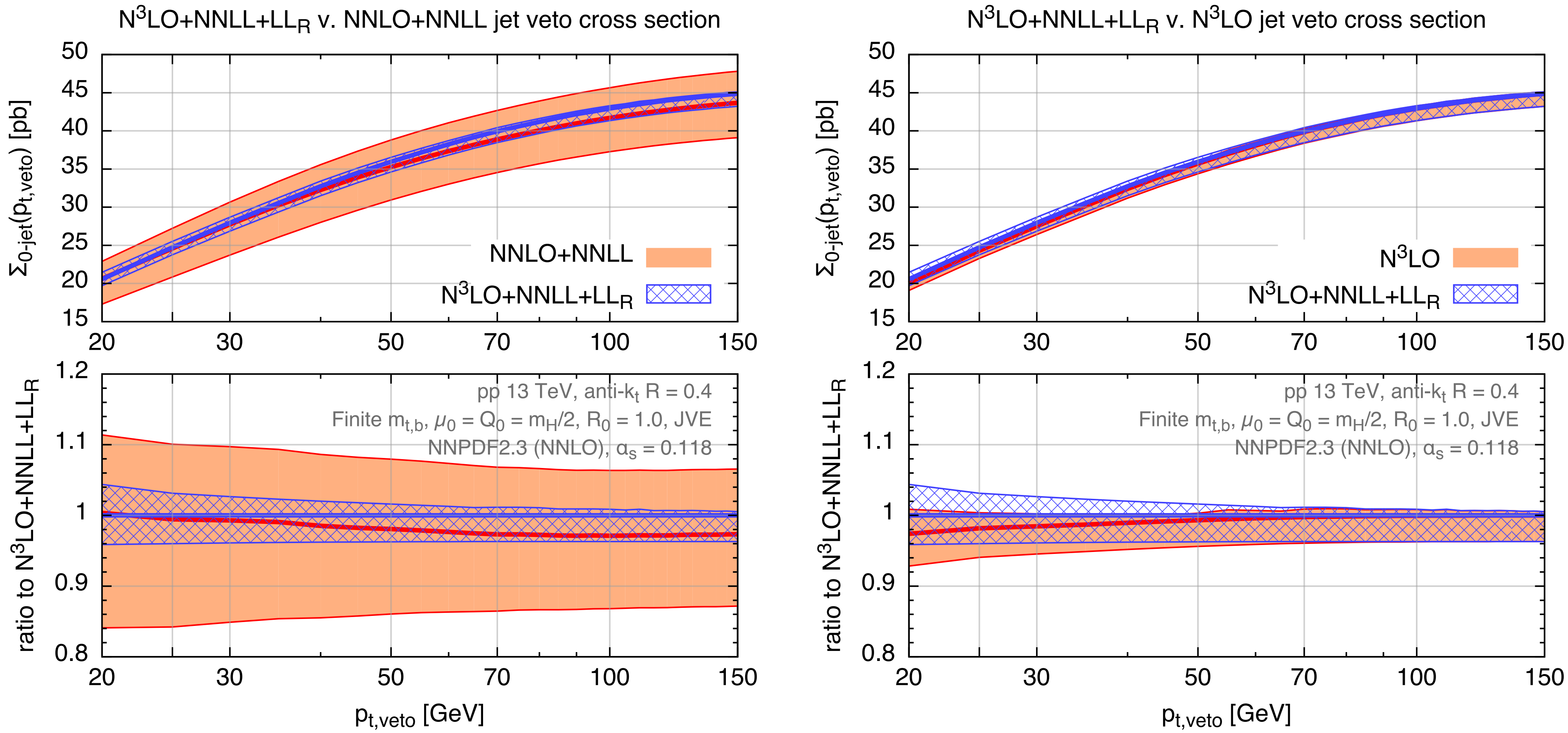
A lot of work on their resummation, both in QCD and SCET:

- 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; Banfi et al. ‘15

- $W^+ W^-$: Jaiswal, Okui ’14; Monni, Zanderighi ’14; TB, Frederix, Neubert, Rothen ’14; Jaiswal, Meade, Ramani ’15

Higgs cross section with a jet veto

Banfi, Caola, Dreyer, Monni, Salam, Zanderighi and Dulat '15



- Includes N^3LO total rate and NNLO H+j results
- LL resummation of logarithms of the jet radius *R*
- quark-mass effects
- Consistent combination with predictions for *H*+1-jet and *H*+2-jet rates.

Soft-collinear fixed-order computations

- Expansion around soft and collinear limit simplifies fixed-order computations
  - Approximate higher-order results
    - soft-gluon resummation
    - N^3LO Higgs cross section was computed as a high-order expansion around soft limit Anastasiou et al. '15
  - Slicing methods at NNLO: use expanded NNLO results near singular limit, NLO computation away from it.
    - q_T subtraction Catani, Grazzini '07
    - *N*-jettiness subtraction, Boughezal, Focke, Liu Petriello '15; Gaunt, Stahlhofen, Tackmann, Walsh '15
- Need fixed-order computations of *H*, *B*, *J*, *S* as inputs!

Automated resummation

Higher-log resummations (in SCET or in QCD) are usually carried out analytically, on a case-to-case basis. Notable exceptions: CAESAR Banfi, Salam, Zanderighi '04, ARES Banfi, McAslan, Monni, Zanderighi '14

- Inefficient and error prone

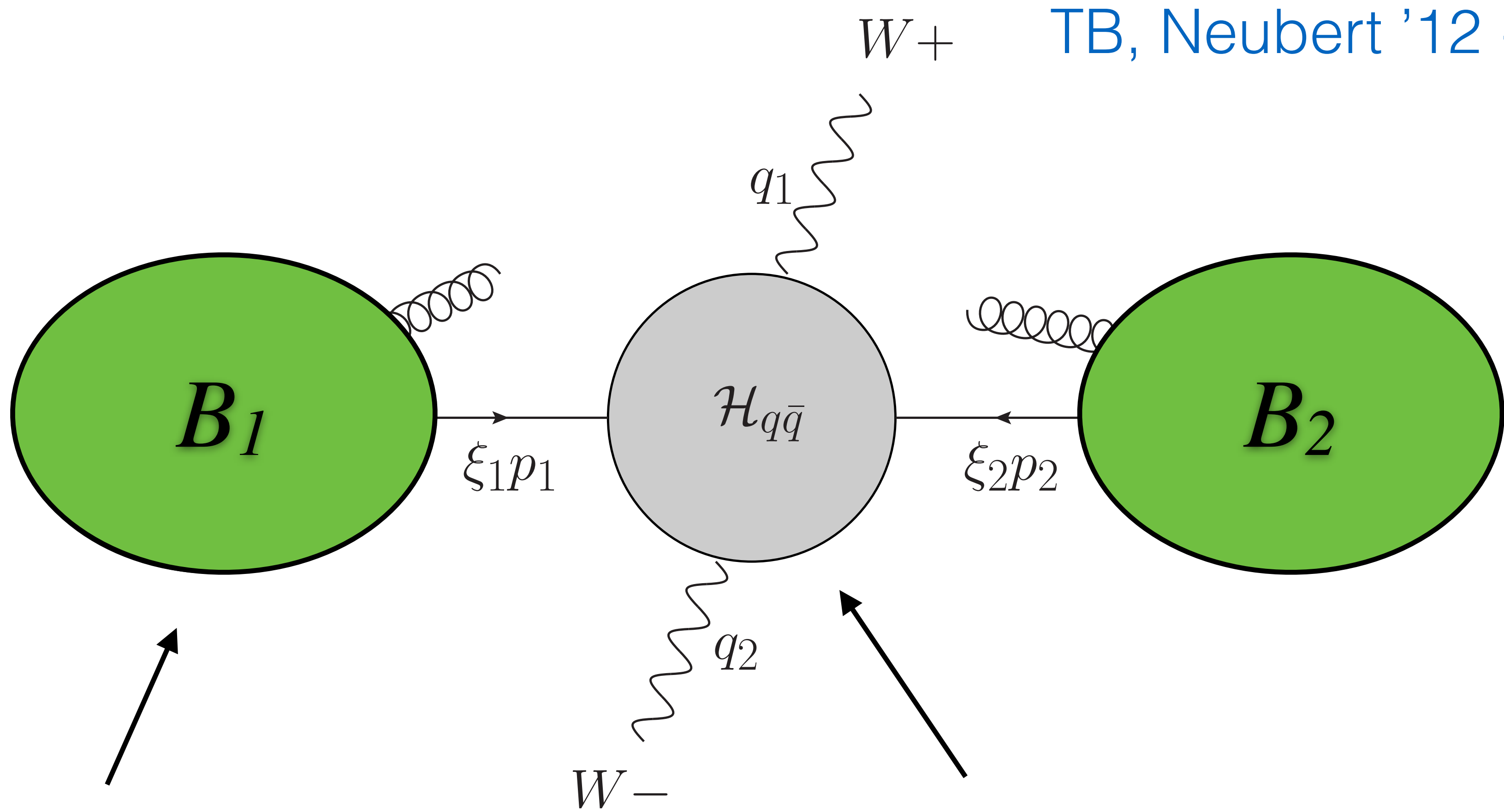
In contrast, LO and NLO computations have been completely automated over the past years. These codes can be used as a basis to perform resummation:

- 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

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

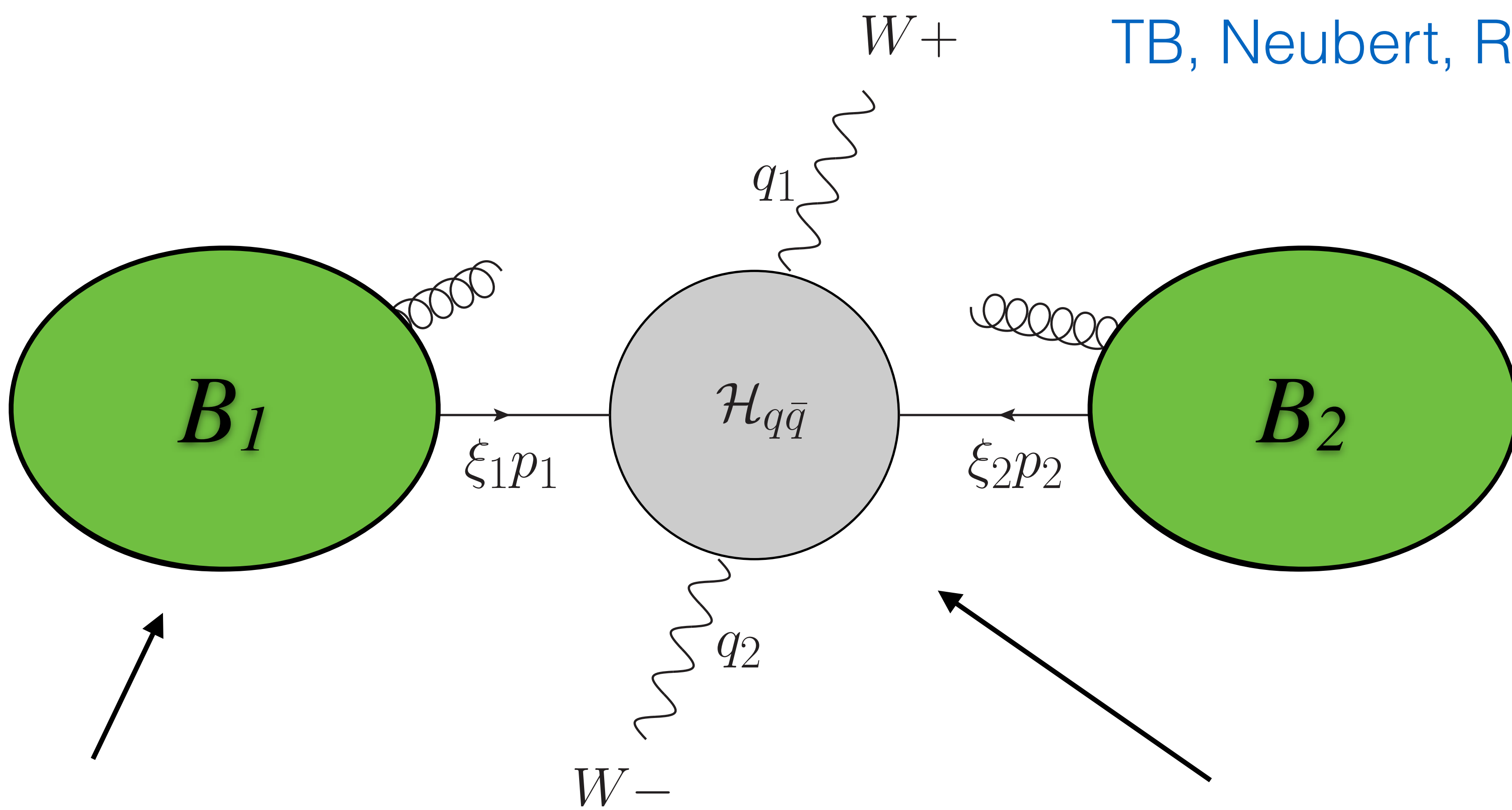
Hard functions $H(Q)$

- virtual corrections, standard QCD loops
- process dependent

Born-level kinematics for small p_T^{veto}

Automated resummation based on MG5_aMC@NLO

TB, Neubert, Rothen, Frederix '14



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

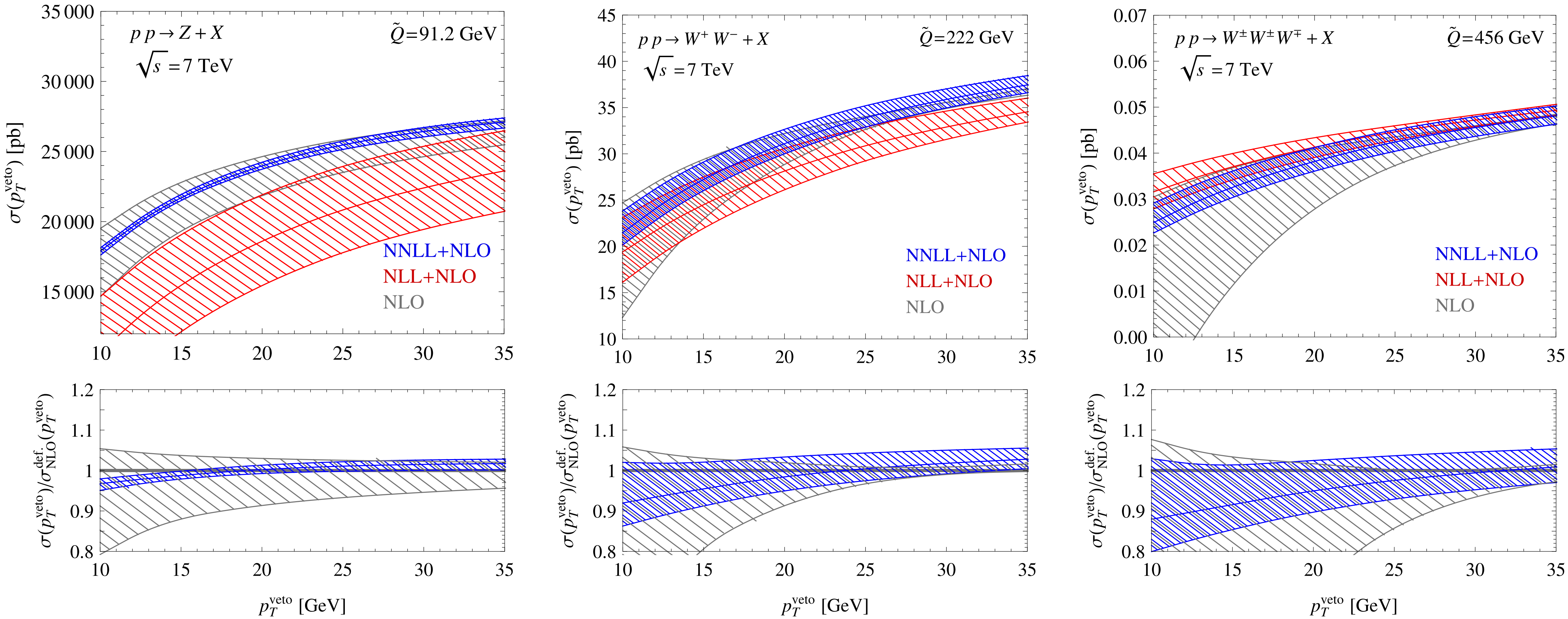
- compute once and for all; tabulate using PDF grids

Hard functions $H(Q)$

- from automated one-loop computation

Reweight Madgraph Born-level events to obtain NNLL resummed cross sections. Use aMC@NLO to compute matching.

Z | W^+W^- | $W^+W^-W^\pm$



- For NLO result we vary $p_T^{\text{veto}}/2 < \mu < 2Q$.
- NNLL+NLO is close to NLO at $\mu = Q$

Automated NNLL+NLO is implemented in Madgraph5_aMC@NLO 2.3 (set `ickkw=-1`)

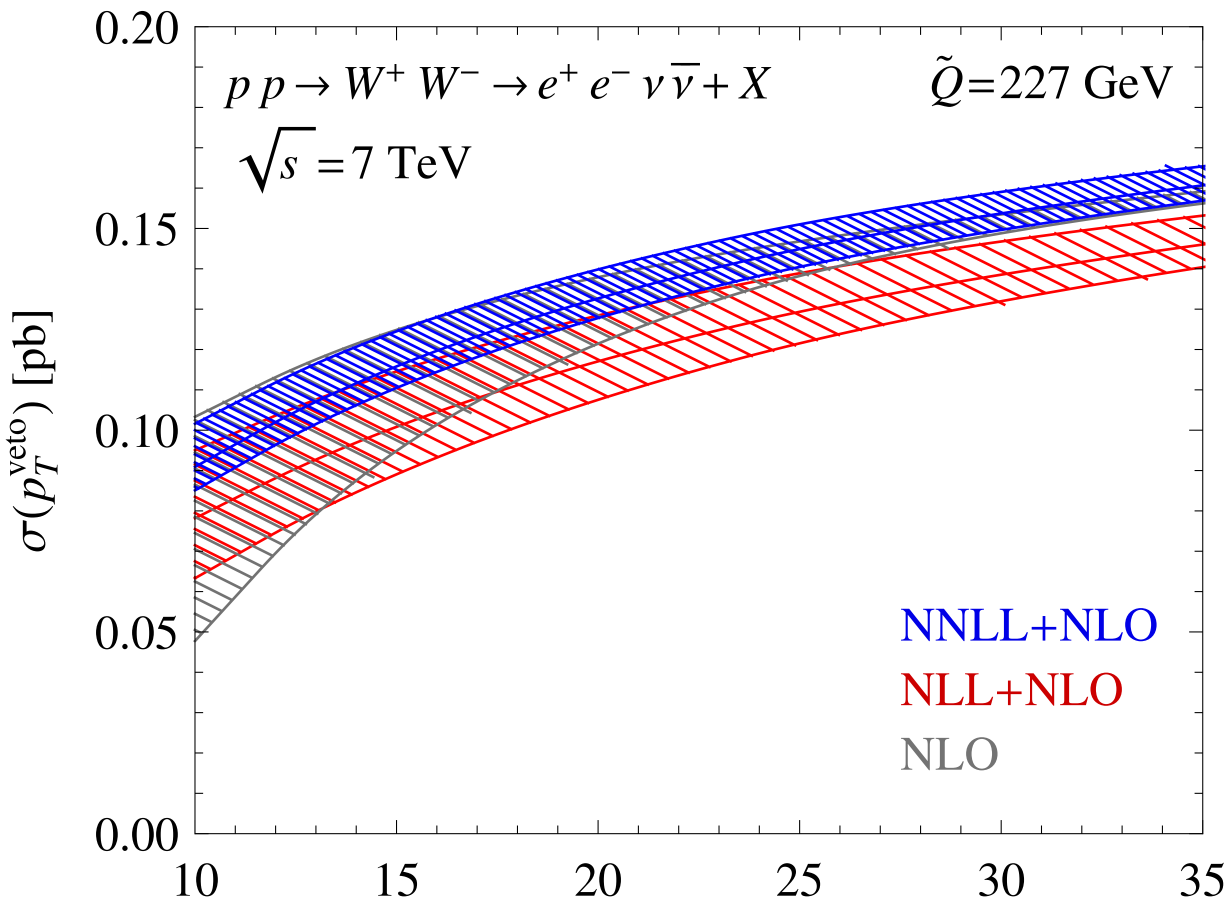
Decays and Cuts

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

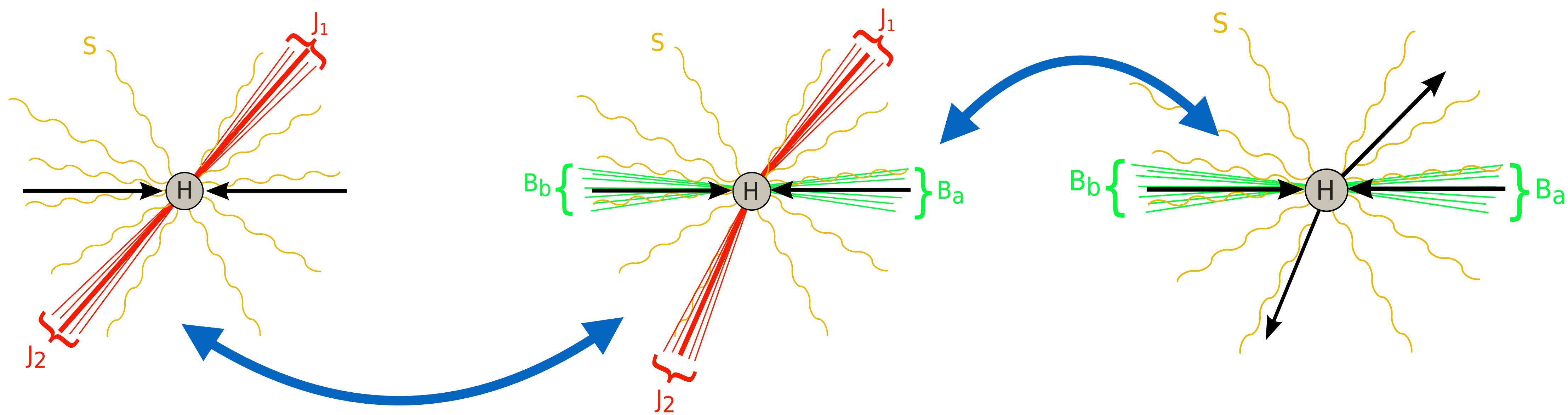


Extension to other observables

Same technique for automated resummation can also be used for more general observables. Complications:

- Nontrivial color structure
  - Hard function at tree level: Farhi, Feige, Freytsis, Schwartz ’15 have modified Madgraph to provide color information. Automated NLL resummation for two-jet observables
  - Soft function: Gerwick, Schumann, Höche, Marzani ‘15 have automated color structure and NLL evolution in Sherpa.
  - Loops: Broggio + GoSam modified GoSam so that it provides color and imaginary part of one-loop amplitudes.
- NNLL needs automated computations of one-loop beam, jet, and soft functions, **two-loop anomalous dimensions**.
- **Restriction to global observables**: only a very limited class of observables (e.g. event shapes) can be resummed.
  - so far no complete higher-log resummations for actual jet cross sections

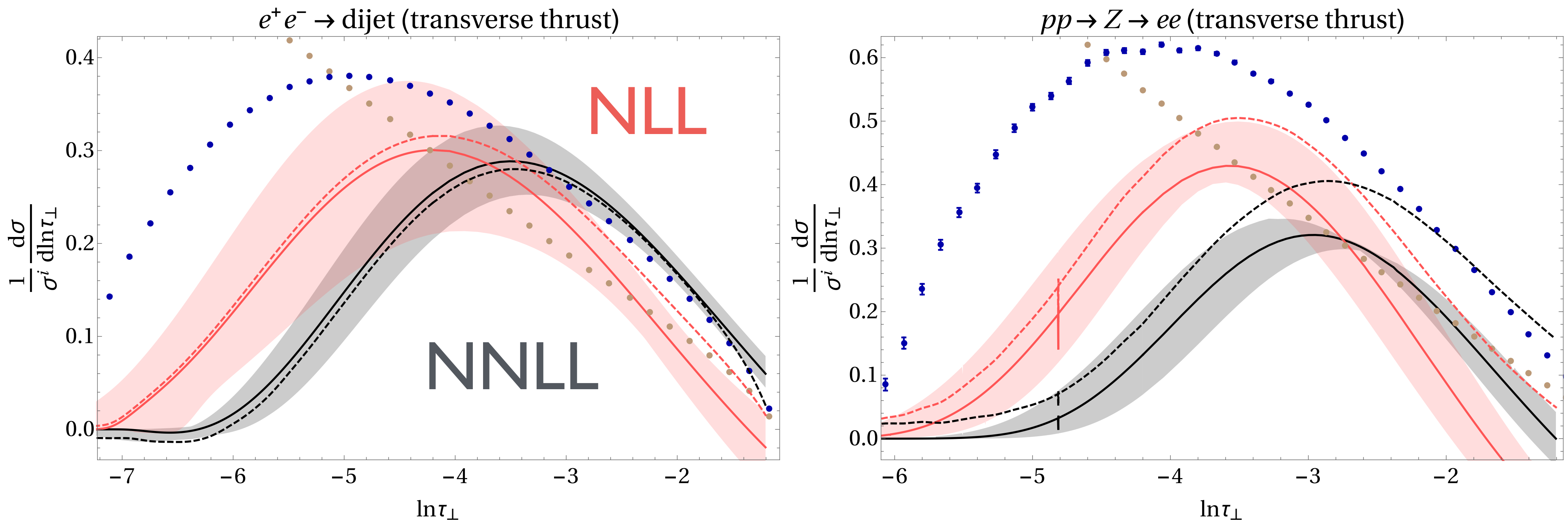
Two-loop anomalous dimensions: universality



TB, Garcia i Tormo, Piclum ‘15

- RG invariance, universality and known result for hard-function anomalous dimensions fixes all two-loop ingredients up to two numbers.

- These can be obtained numerically with small effort from two-jet soft function or e^+e^- fixed-order codes. Automation of NNLO 2-jet soft function Bell, Rahn and Talbert ’15.



TB, Garcia i Tormo, Piclum '15

Using this procedure, we have recently extracted all ingredients for transverse thrust

$$T_\perp := \max_{\vec{n}_\perp} \frac{\sum_m |\vec{p}_{m\perp} \cdot \vec{n}_\perp|}{\sum_m |\vec{p}_{m\perp}|}$$

at NNLL. Numerical implementation for $pp \to Z+j$ and $pp \to 2j$ under way.

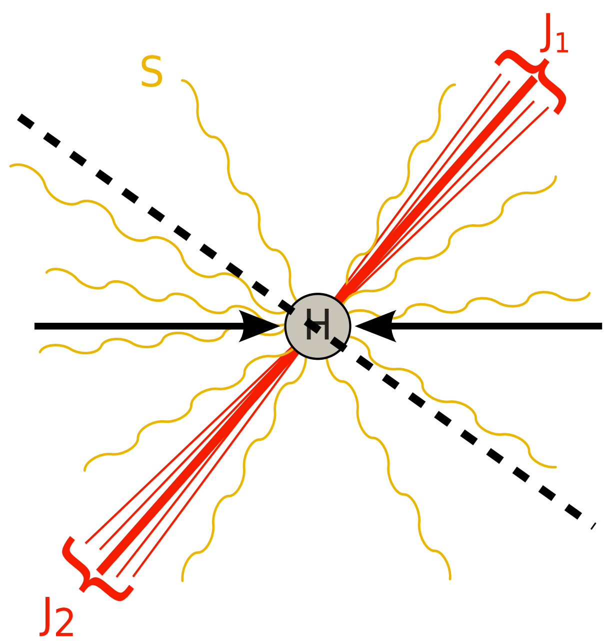
From SCET to Jet Effective Theory

resummation for jet processes

TB, Neubert, Rothen, Shao, arXiv:1508.06645

Non-global logarithms

Dasgupta, Salam '01



$$\frac{d\sigma}{dM} \overset{?}{=} H \cdot J_1 \otimes J_2 \otimes S$$

Consider hemisphere jet masses M_1 and M_2 in $e^+e^- \rightarrow 2$ jets. Factorization and resummation works for

$$M_h = \max(M_1,\ M_2)$$

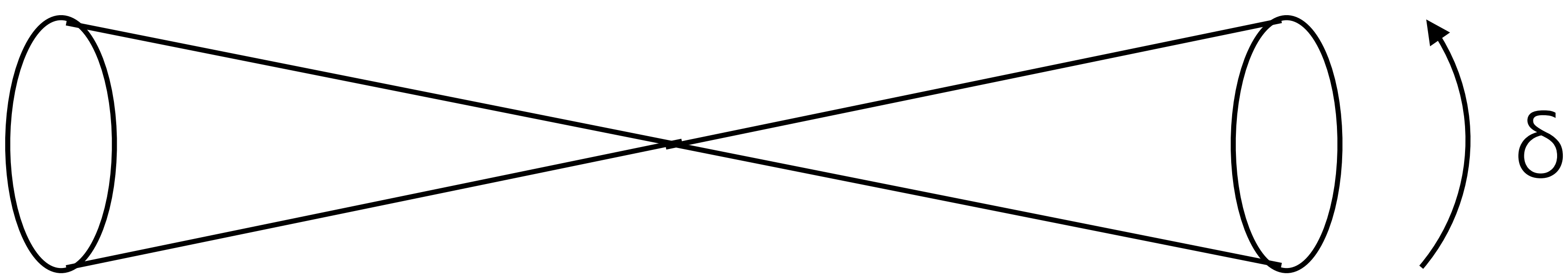
but fails for the non-global observables

$$M = M_1$$

Nonglobal, because they only probe one hemisphere.

Cone-jet cross sections

Jet cross sections are an important example of non-global observables. Consider, for example narrow cone jets (Sterman-Weinberg jets ‘77)



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

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

Non-global because the cross section does not change under emissions inside the jets.

Complicated pattern of logarithms not captured by H J_1 J_2 S (no exponentiation!).

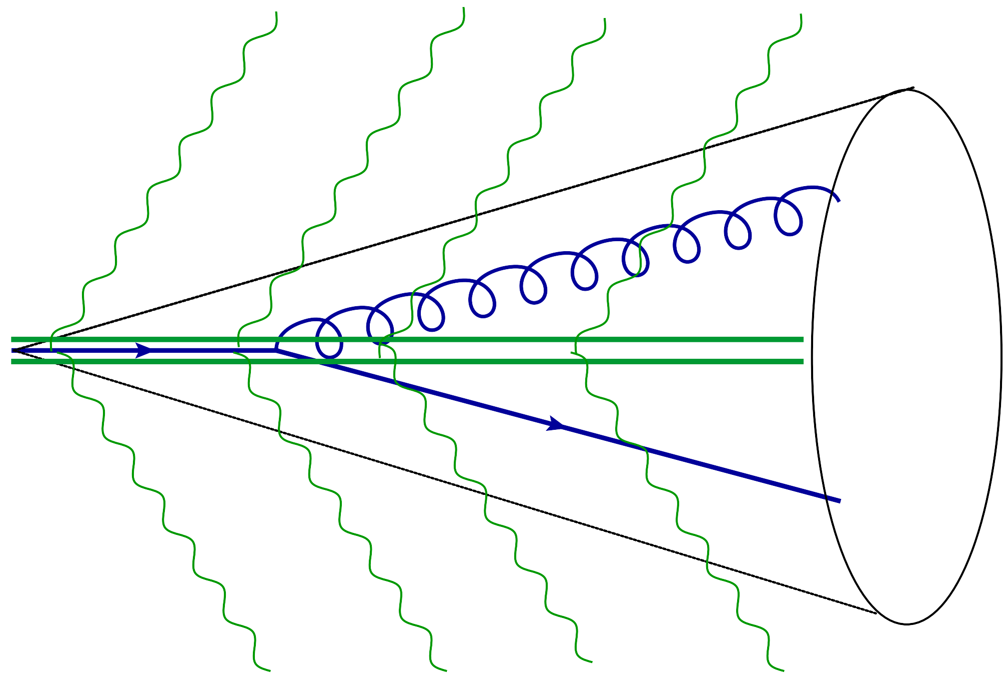
Non-global logarithms

A lot of work on these types of logarithms

- Equations for resummation of leading logs, at large N_c Banfi, Marchesini, Smye '02 (BMS equation), and beyond Weigert '03, Hatta, Ueda '13 + Hagiwara '15; Caron-Huot '15.
- Fixed-order results: 2 loops 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 up to 5 loops by solving BMS equation Schwartz, Zhu '14, 5 loops and arbitrary N_c Delenda, Khelifa-Kerfa '15
- Approximate resummation of such logs, based on resummation for observables with *n* soft subjets. Larkoski, Moult and Neill '15

A systematic factorization of non-global observables was missing.

Soft factorization



Large-angle soft radiation only sees total charge. Identical to radiation of a single particle flying in the jet direction.

- Emissions have the same structure as the ones of a classical source (with the total charge of the jet) moving along the jet direction: Wilson line along jet direction.

- This simple factorization is a cornerstone of standard factorization theorems.

Soft emission from a jet

Consider the emission of single soft a gluon from energetic particles with momenta p_i inside a narrow jet:

$$\sum_i Q_i \frac{p_i \cdot \varepsilon}{p_i \cdot k} = Q_{\text{tot}} \frac{n \cdot \varepsilon}{n \cdot k} + \ldots$$

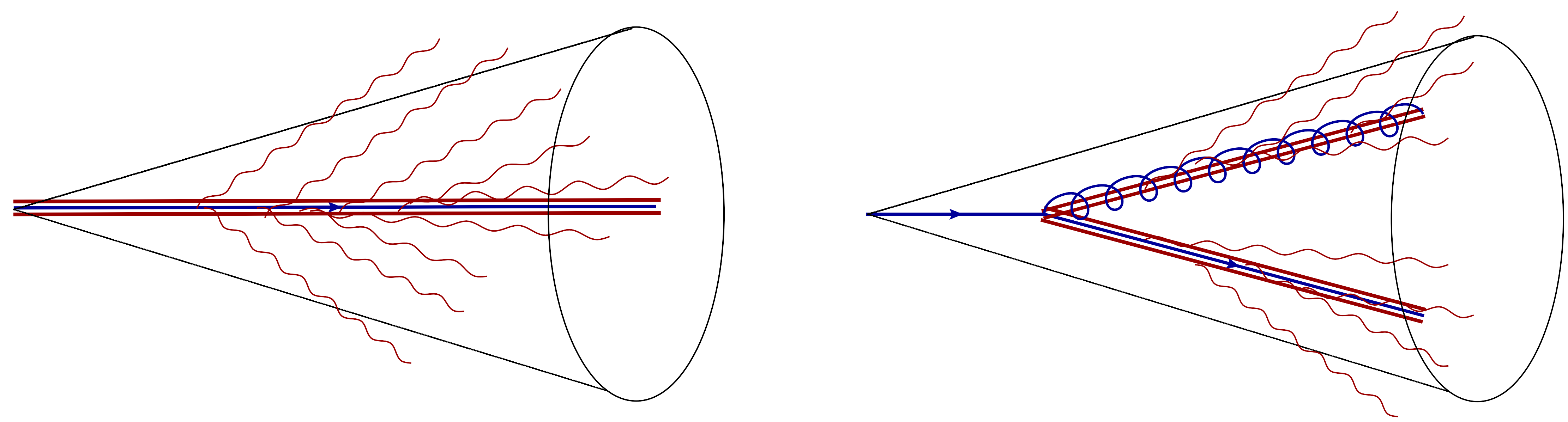
Approximation: $p_i^\mu \approx E_i \, n^\mu$

This approximation breaks down when the soft emission has a small angle, i.e. when $k^\mu \approx \omega \, n^\mu$!

Small region of phase space, but gives a leading contribution to jet rates!

Coft factorization

TB, Neubert, Rothen, Shao, 1508.06645



For cone-jet processes with narrow cones, small angle soft radiation becomes relevant

- collinear *and* soft ("coft")
- resolves individual collinear partons: operators with multiple Wilson lines

Momentum modes for jet processes

TB, Neubert, Rothen, Shao, 1508.06645; Chien, Hornig and Lee 1509.04287

	Region	Energy	Angle	Inv. Mass
standard SCET	Hard	Q	1	Q
	Collinear	Q	δ	$Q\delta$
	Soft	βQ	1	βQ
new	Coft	βQ	δ	$\beta\delta Q$

Full jet cross section is recovered after adding the contributions from all regions ("method of regions")

- Additional coft mode has **very low characteristic scale $\beta\delta Q$**! Jets are less perturbative than they seem!
- Effective field theory has additional "coft" degree of freedom.

Checks at one and two loops

hard	$\Delta\sigma_h = \frac{\alpha_s C_F}{4\pi}\sigma_0 \left(\frac{\mu}{Q}\right)^{2\epsilon}\left(-\frac{4}{\epsilon^2} - \frac{6}{\epsilon} + \frac{7\pi^2}{3} - 16\right)$
collinear	$\Delta\sigma_{c+\bar{c}} = \frac{\alpha_s C_F}{4\pi}\sigma_0 \left(\frac{\mu}{Q\delta}\right)^{2\epsilon}\left(\frac{4}{\epsilon^2} + \frac{6}{\epsilon} + c_0\right)$
soft	$\Delta\sigma_s = \frac{\alpha_s C_F}{4\pi}\sigma_0 \left(\frac{\mu}{Q\beta}\right)^{2\epsilon}\left(\frac{4}{\epsilon^2} - \pi^2\right)$
coft	$\Delta\sigma_{t+\bar{t}} = \frac{\alpha_s C_F}{4\pi}\sigma_0 \left(\frac{\mu}{Q\delta\beta}\right)^{2\epsilon}\left(-\frac{4}{\epsilon^2} + \frac{\pi^2}{3}\right),$

$$\Delta\sigma^{\text{tot}} = \frac{\alpha_s C_F}{4\pi}\sigma_0 \left(-16\ln\delta\ln\beta + 12\ln\delta + c_0 + \frac{5\pi^2}{3} - 16\right)$$

Constant c_0 depends on definition of jet axis:

$c_0 = -3\pi^2 + 26$ (Sterman-Weinberg)

$c_0 = -5\pi^2/3 + 14 + 12\ln 2$ (thrust axis)

Have repeated the same check at two-loop order and checked against numerical result from Event 2 generator

Factorization for two-jet cross section

TB, Neubert, Rothen, Shao, arXiv:1508.06645

Laplace space

$\tau \leftrightarrow \beta$

color trace

integration over angles

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

Coft functions with m Wilson lines

Soft function

Hard function

Jet functions with m partons at fixed direction

First all-order factorization theorem for non-global observable. Achieves full scale separation!

Resummation by RG evolution

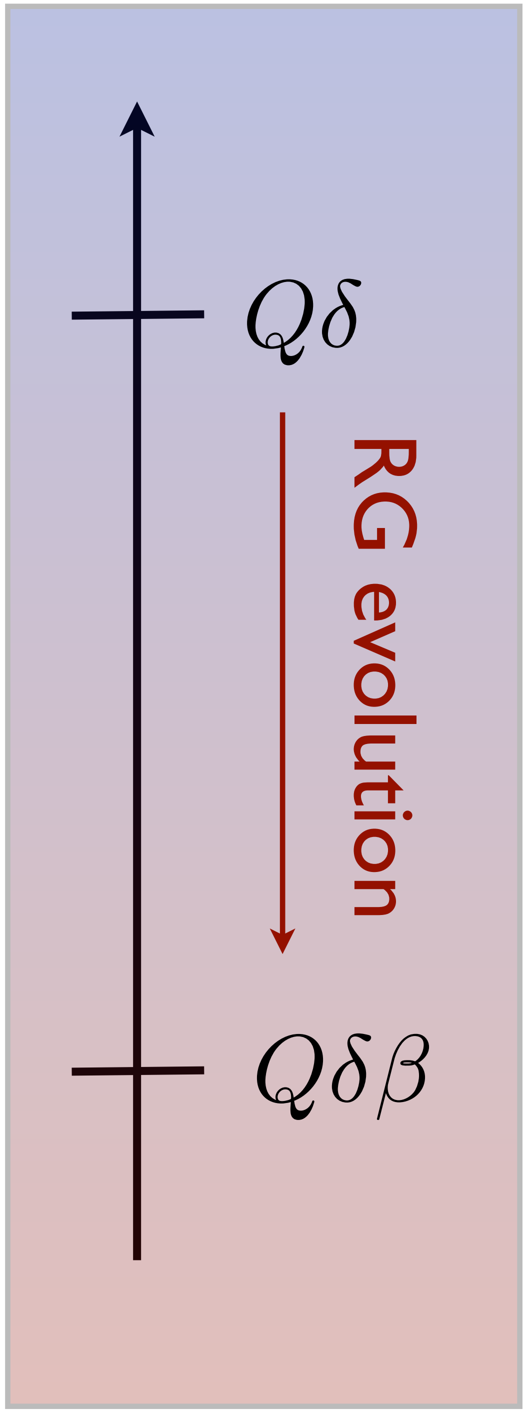
Wilson coefficients fulfill renormalization group (RG) equations, e.g.

$$\frac{d}{d\ln\mu}\mathcal{J}_m(Q\delta,\mu) = \sum_k \mathcal{J}_k(Q\delta,\mu)\,\boldsymbol{\Gamma}^J_{km}$$

1. Compute $\mathcal{J}_m$ at a their characteristic high scale $\mu_h \sim Q\delta$

2. Evolve $\mathcal{J}_m$ to the scale of low energy physics $\mu_l \sim Q\delta\beta$

Avoids large logarithms $\alpha_s{}^n \ln^n(\beta)$ of scale ratios which can spoil convergence of perturbation theory.



NLL resummation

Need tree-level matrix elements

$$\boldsymbol{\mathcal{U}}_m = \mathbf{1} + \mathcal{O}(\alpha_s) \;\; ; \;\; \boldsymbol{\mathcal{J}}_1 = \mathbf{1} \;, \quad \boldsymbol{\mathcal{J}}_m \sim \alpha_s^{m-1}$$

and one-loop anomalous dimensions

$$\boldsymbol{\Gamma}^J = \frac{\alpha_s}{4\pi} \begin{pmatrix} \boldsymbol{V}_2 & \boldsymbol{R}_2 & 0 & 0 & \dots \\ 0 & \boldsymbol{V}_3 & \boldsymbol{R}_3 & 0 & \dots \\ 0 & 0 & \boldsymbol{V}_4 & \boldsymbol{R}_4 & \dots \\ 0 & 0 & 0 & \boldsymbol{V}_5 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix},$$

Challenging to solve!

- Order-by-order structure similar to parton shower.
- Reproduces BMS equation in large N_C limit
- Close connection to functional RG by Caron-Huot '15

Summary

- Resummed computations for collider processes can provide very precise predictions, but are only available for few observables.
- A lot of recent progress to extend higher-log resummation to more observables
  - Automated resummations
  - Factorization for non-global observables
- Other hot topics, not covered in my talk
  - Role of Glauber gluons? Factorization in their presence? Gaunt '14; Zeng '15; Rothstein, Stewart '?
  - Factorization and resummation for power corrections. Bonocore, Laenen, Magnea, Vernazza and White '14 + Melville '14; Larkoski '14, + Neill and Stewart '14, Kolodrubetz, Moult and Stewart '15

Extra slides

PDF choice in q_T spectra

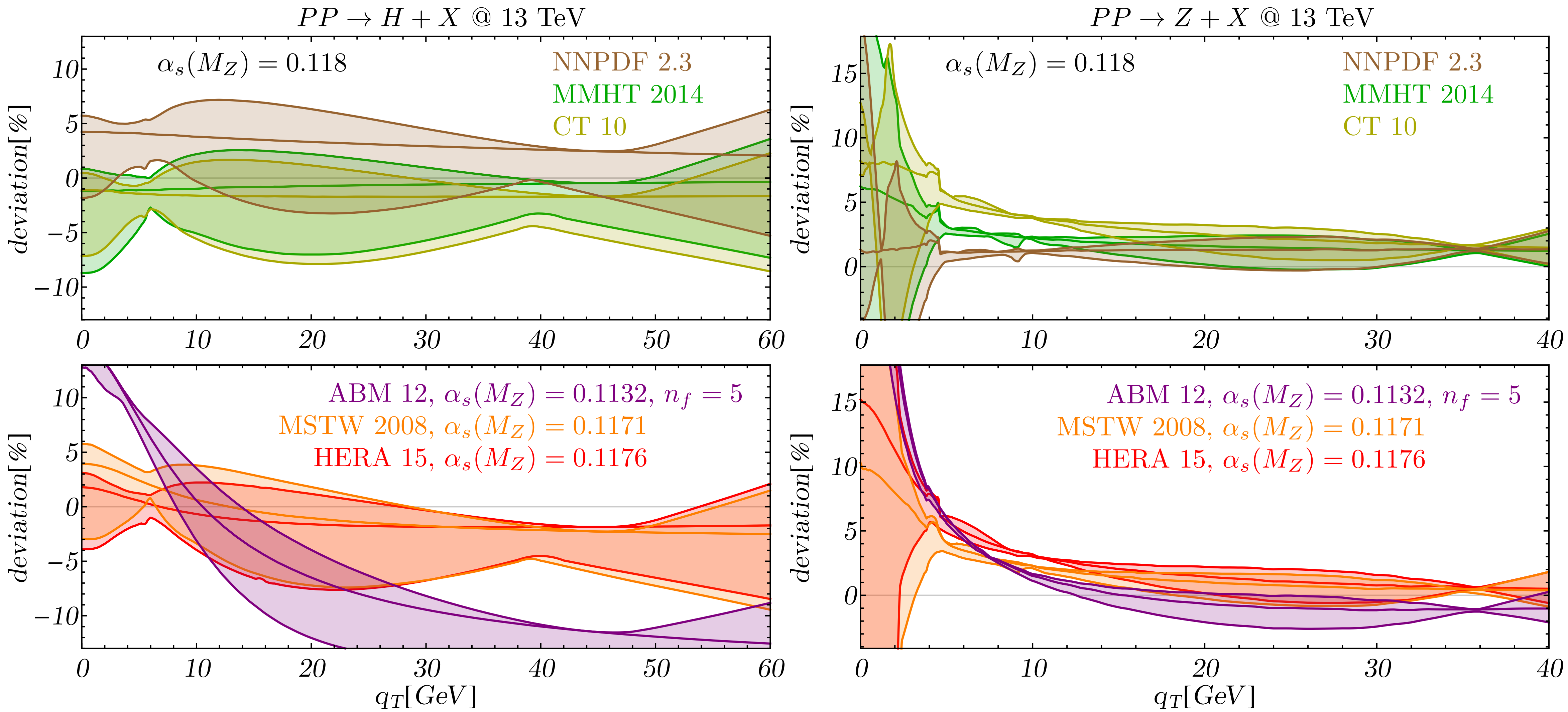
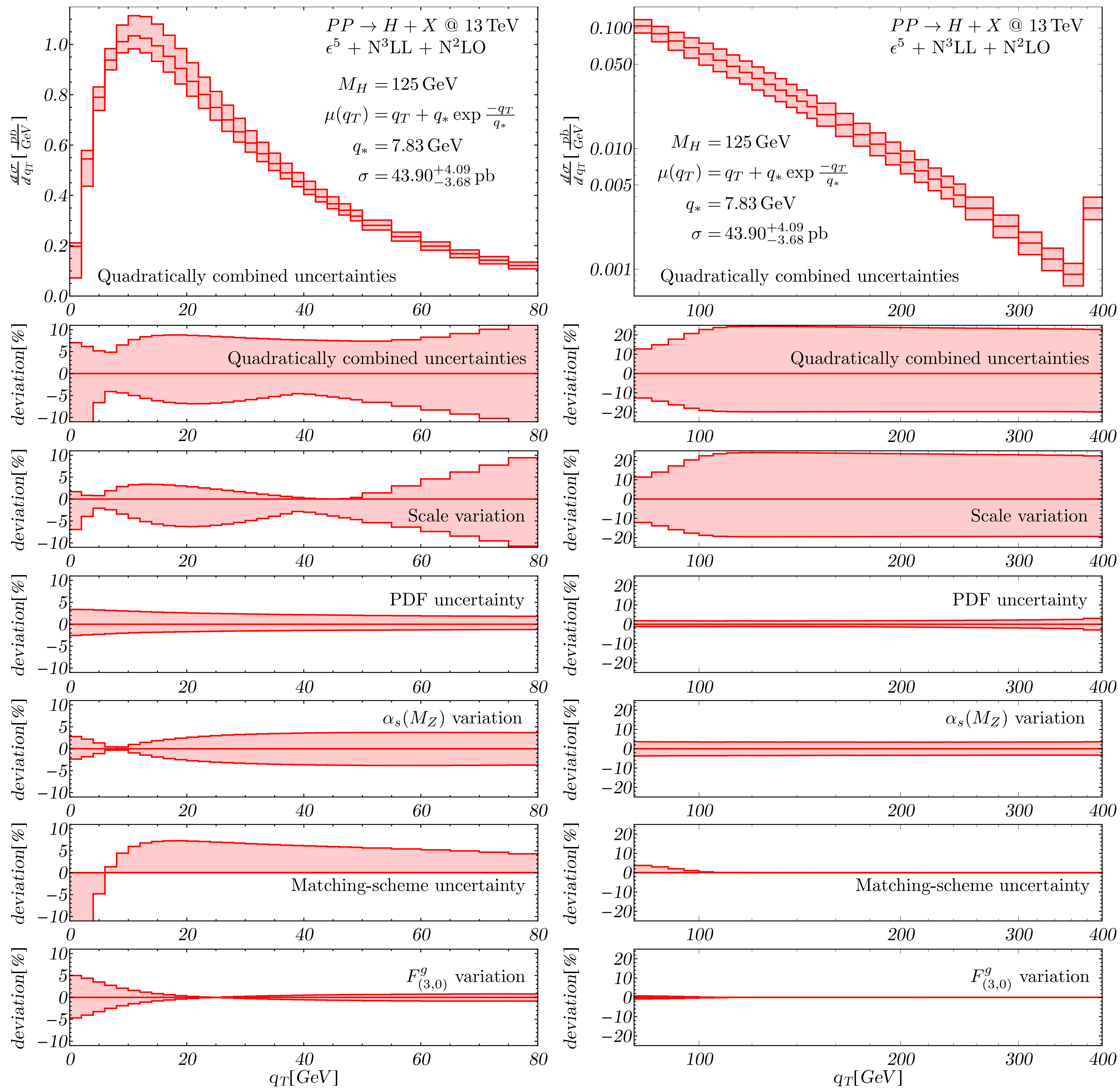


Figure 14: Comparison of different N^{2}LO PDF-sets to NNPDF 3.0, using similar (top) and different (bottom) α_s values and flavour-schemes (ABM 12). Deviation w.r.t. NNPDF 3.0 with $\alpha_s(M_Z) = 0.118$.

Higgs q_T: individual uncertainties



p_T Higgs: comparison