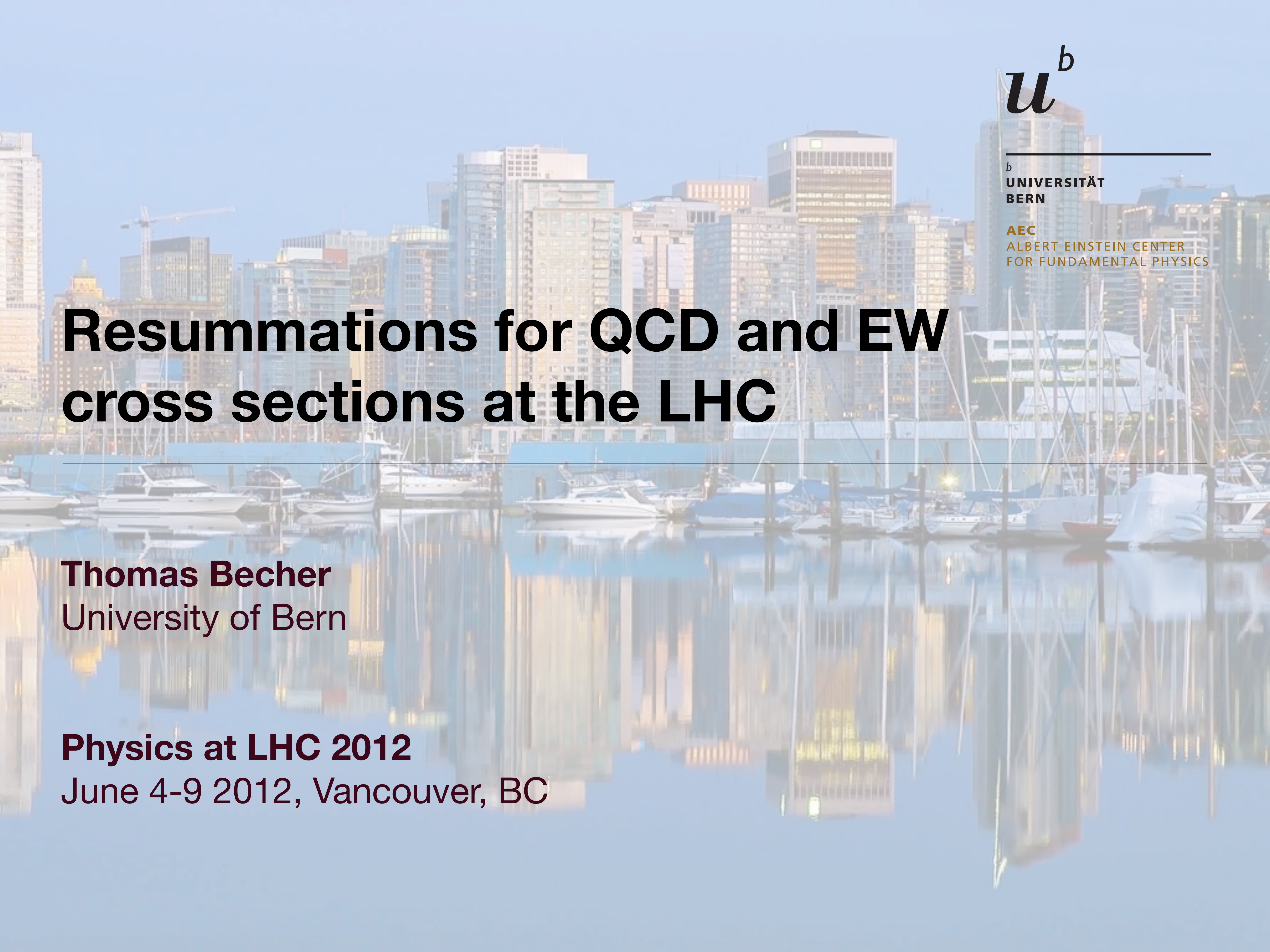

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Resummations for QCD and EW cross sections at the LHC

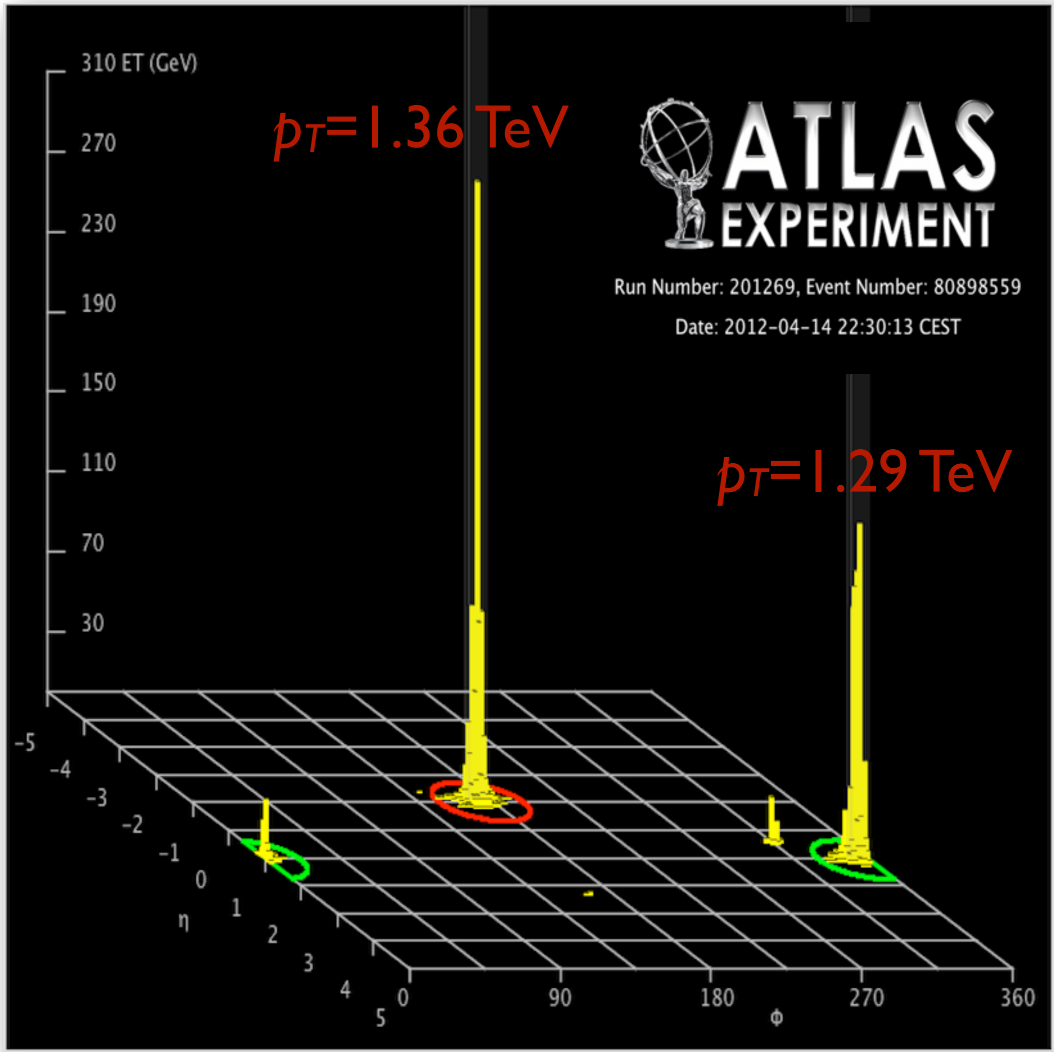
Thomas Becher
University of Bern

Physics at LHC 2012
June 4-9 2012, Vancouver, BC

Hadron Collider Physics

Many different scales in collider processes

- $E_{\mathrm{c.m.}}$
- p_{T} of jets
- Jet masses M_J,
- Energy of soft radiation,
- Hadron masses: m_p



p_T=1.36 TeV

p_T=1.29 TeV

Observables sensitive to several disparate scales cannot be reliably computed in fixed-order perturbation theory.

Resummation

Multi-scale problems involve logarithmically enhanced terms from soft and collinear emissions. Classic example: transverse momentum spectrum of EW boson

$$\begin{aligned}\frac{d\sigma}{dq_T^2} = \frac{1}{q_T^2}\Big[&A_1^{(1)}\alpha_s \ln\frac{M^2}{q_T^2} + \alpha_s A_0^{(1)} + A_3^{(2)}\alpha_s^2 \ln^3\frac{M^2}{q_T^2} + \dots \\ &+ A_{2n-1}^{(n)}\alpha_s^n \ln^{2n-1}\frac{M^2}{q_T^2} + \dots\Big] + \dots\end{aligned}$$

Methods to resum these terms to all orders:

- Parton shower
- Diagrammatic Factorization
- Soft-Collinear Effective Theory

Only leading logs

$\Big\}$ (So far) limited to simple observables

Soft-Collinear Effective Theory

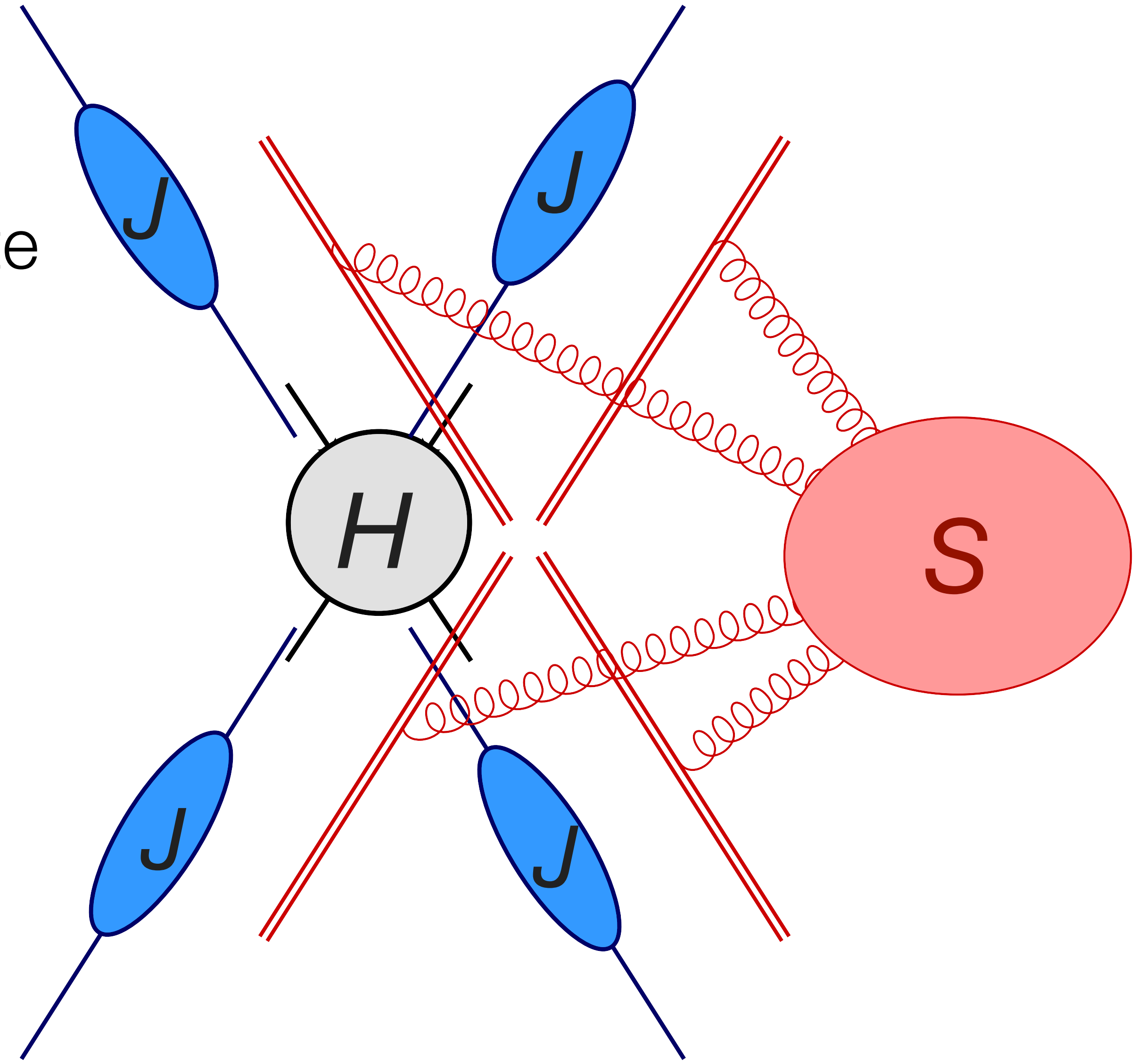
Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke et al. 2002; ...

Implements structure of soft and collinear interactions on the Lagrangian level:

- Soft and collinear fields with definite interactions and power counting.
- Theory contains non-localities associated with large light-like momenta.

Provides efficient formalism to

- (re-)derive factorization theorems
- perform resummations of logarithmically enhanced contributions to all orders



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

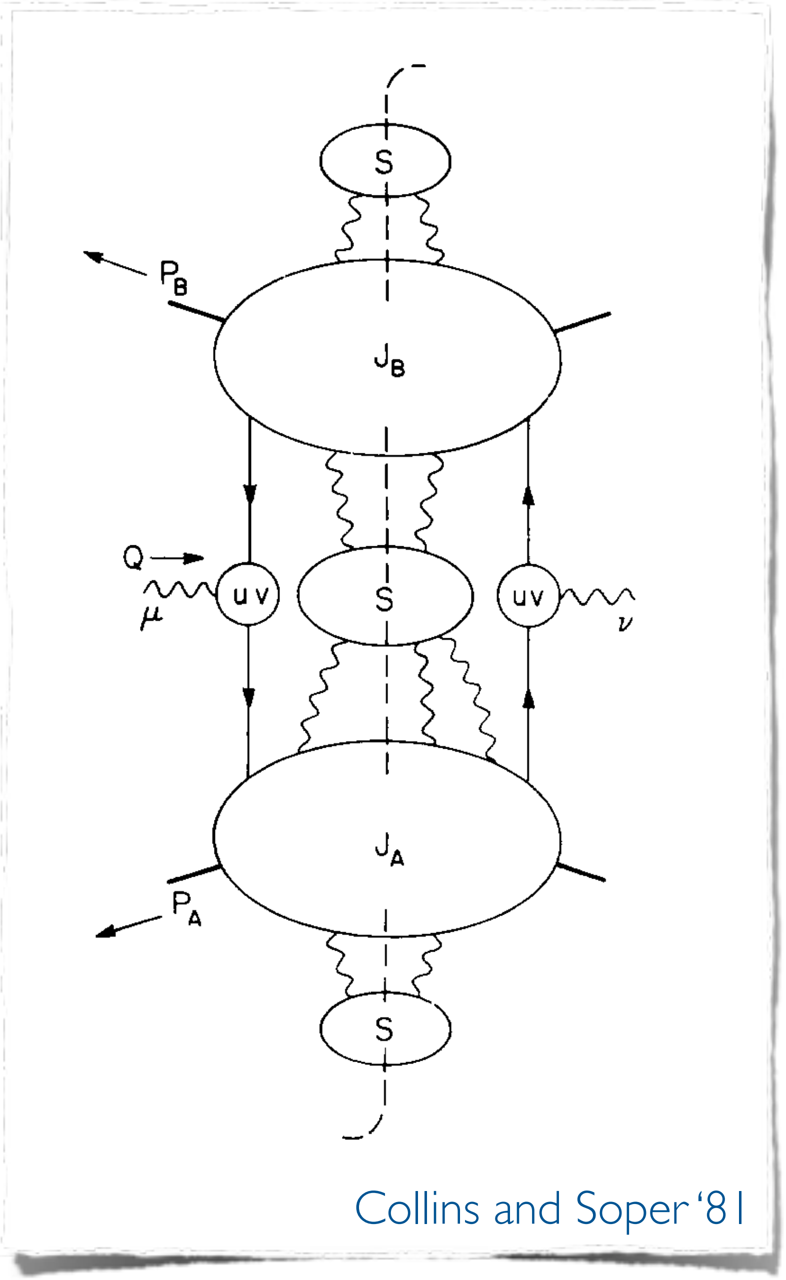
Diagrammatic Factorization

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, ...

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

Some LHC physics papers during the past year

- **Higgs**. q_T spectrum de Florian, Ferrera, Grazzini and Tommasini, 1109.2109, 1203.6321, Wang, Li, Li, Yuan and Li 1205.4311, jet veto Banfi, Salam and Zanderighi 1203.5773, TB and Neubert 1205.3806

- **Top**: total cross section (soft-gluon, Coulomb) Beneke, Falgari, Klein, Piclum and Schwinn 1109.1536, 1205.0988, Cacciari, Czakon, Mangano, Mitov and Nason 1111.5869, Ferroglia, Pecjak and Yang 1205.3662. EW in forward-backward asymmetry Manohar and Trott 1201.3926

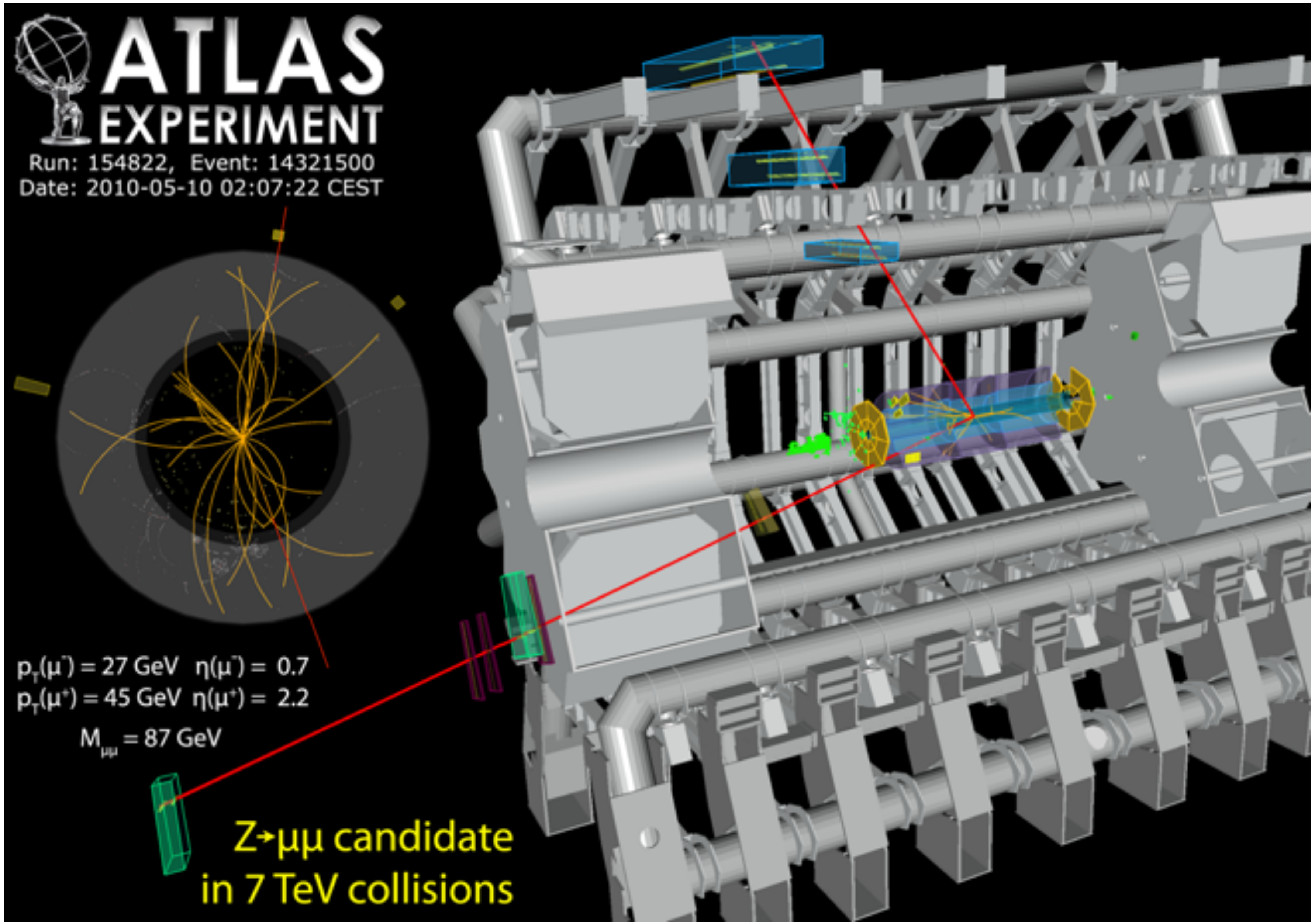
- **W,Z**: large q_T TB, Lorentzen and Schwartz 1106.4310, Kidonakis and Gonsalves 1201.5265, small q_T TB, Neubert and Wilhelm 1109.6027, Garcia-Echevarria, Idilbi and Scimemi 1111.4996, ϕ^* Banfi, Dasgupta, Marzani and Tomlinson 1106.6294, 1110.4009, 1205.4760, SCET vs. traditional Bonvini, Forte and Ridolfi 1009.5691

- **SUSY**: Gluino and squark pair production Beneke, Falgari and Schwinn 1007.5414, Beenakker, Brensing, Kramer, Kulesza, Laenen and Niessen 1110.2446, Falgari, Schwinn and Wever 1202.2260. Slepton pair production Broggio, Neubert and Vernazza 1111.6624,1111.0864

Some theory* papers during the past year

- **infrared structure of n-jet processes**. new constraint from Regge limit Del Duca,Duhr,Gardi, Magnea, White 1108.5947, 1109.3581 anomalous dimension computations in AdS, Chien, Schwartz, Simmons-Duffin and Stewart 1109.6010
- **collinear anomaly**: phase-space regularization of SCET TB and Bell 1112.3907, rapidity renormalization group Chiu, Jain, Neill, Rothstein: 1202.0814
- **jet substructure** : clustering logs Kelley, Walsh and Zuberi 1202.2361,1203.2923,factorization constraints on jet substructure Walsh and Zuberi 1110.5333 subtructure from boosted event shapes Feige, Schwartz, Stewart and Thaler 1204.3898, dijets with small invariant mass Bauer, Tackmann, Walsh and Zuberi
- **fragmentation** inside jet Procura, Waalewin 1111.6605

* i.e. no cross section predictions.



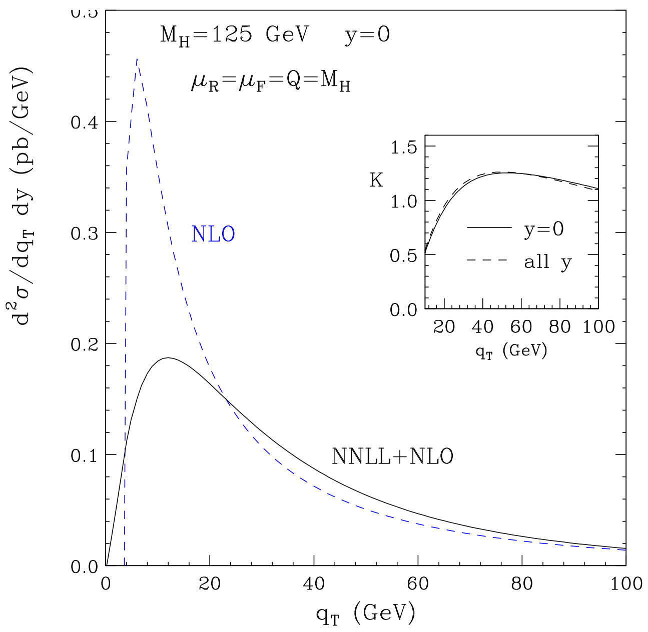
Transverse momentum resummation for *Z*, *W* and Higgs bosons

Drell-Yan production at small q_T

Classical two-scale process for which the resummation of Sudakov logs $\sim \alpha_s^n \ln^{2n}(M/q_T)$. is essential.

First achieved in Collins, Soper and Sterman (CSS) '84

Bozzi, Catani, de Florian, Grazzini: 0705.3887



Obtain **factorization theorem based on collinear anomaly.**

TB, Neubert: 1007.4005

$$\frac{d\sigma}{dq_T} \sim H(M) \int d^2x_T\, e^{-iq_T\cdot x_T}\, [I(x_T)\otimes\phi]\, [I(x_T)\otimes\phi]\, (M^2 x_T^2)^{-F_{q\bar{q}}(x_T)}$$

beam functions

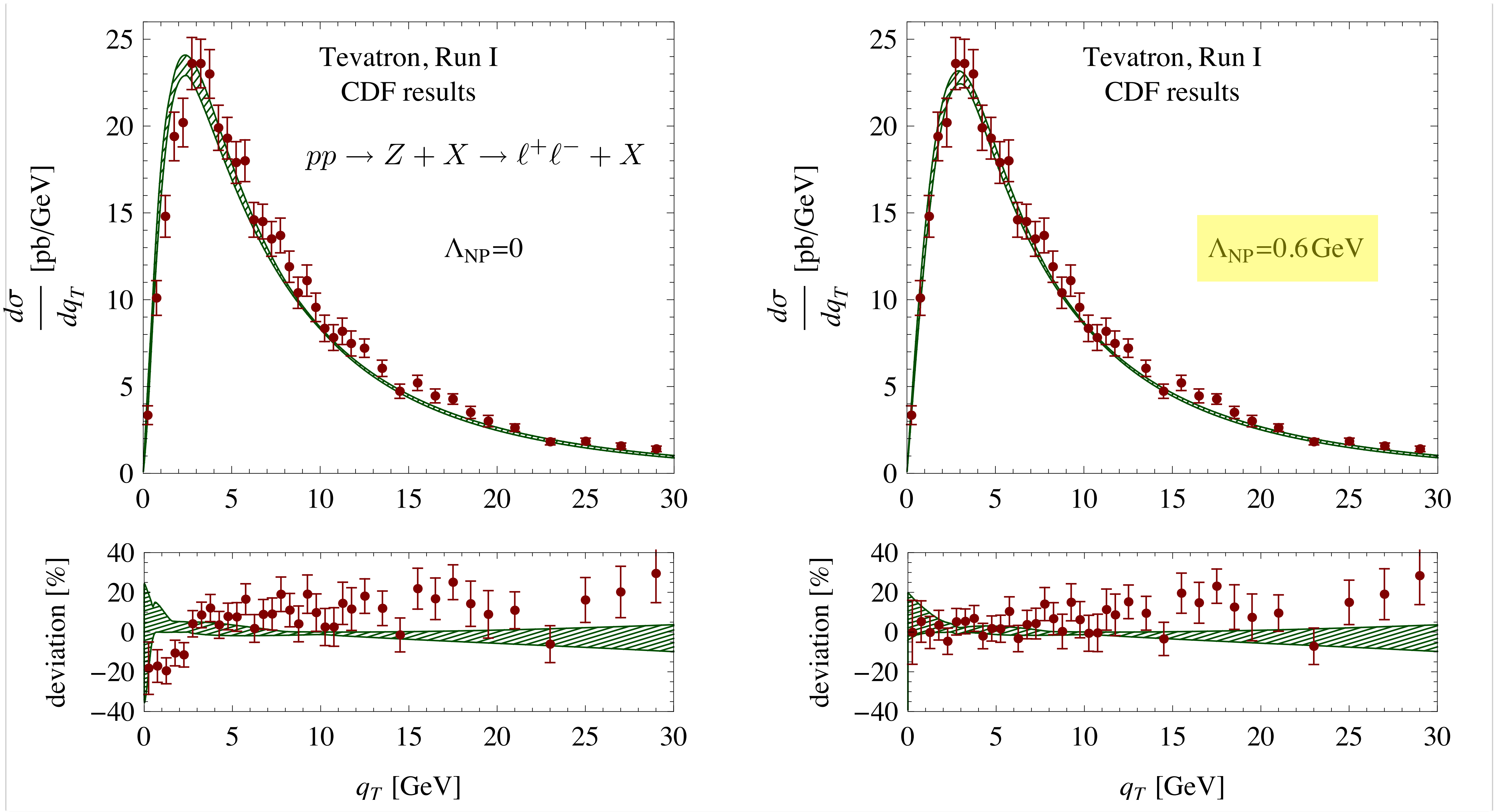
anomalous *M* dependence is a **pure power** in x_T space

Matches onto CSS. Derive three-loop coefficient $A^{(3)}$, last unknown ingredient for NNLL accuracy in CSS formula.

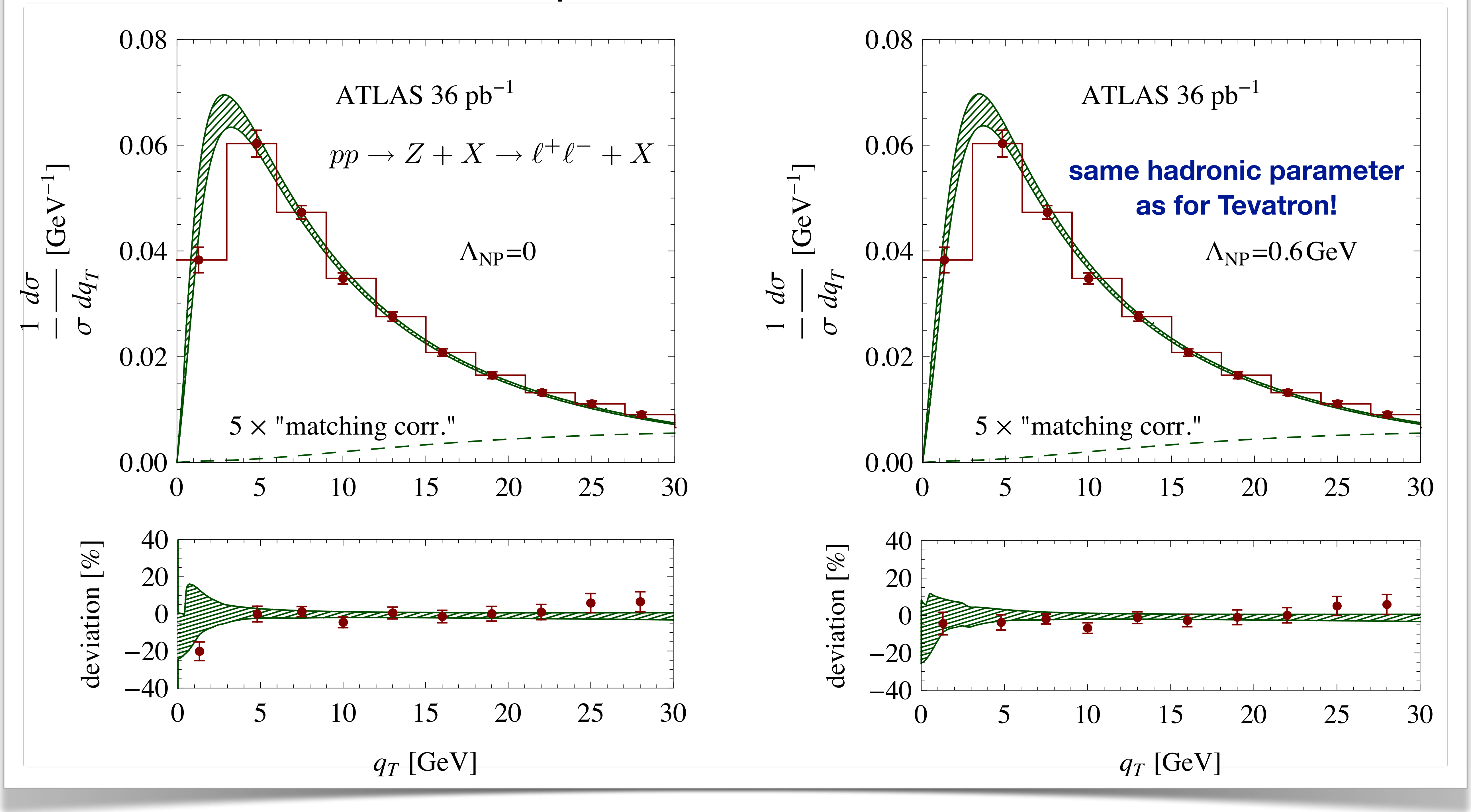
Z-boson production at Tevatron

TB, Neubert, Wilhelm: 1109.6027 (JHEP)

Full NNLL resummation and NLO matching.



Z-boson production at the LHC



More detailed measurements of low q_T region, maybe in terms of a_T and ϕ^* would be interesting. Banfi, Dasgupta, Marzani and Tomlinson 1106.6294, 1110.4009, 1205.4760

Infrared protection at very small q_T

TB, Neubert, Wilhelm: 1109.6027 (JHEP)

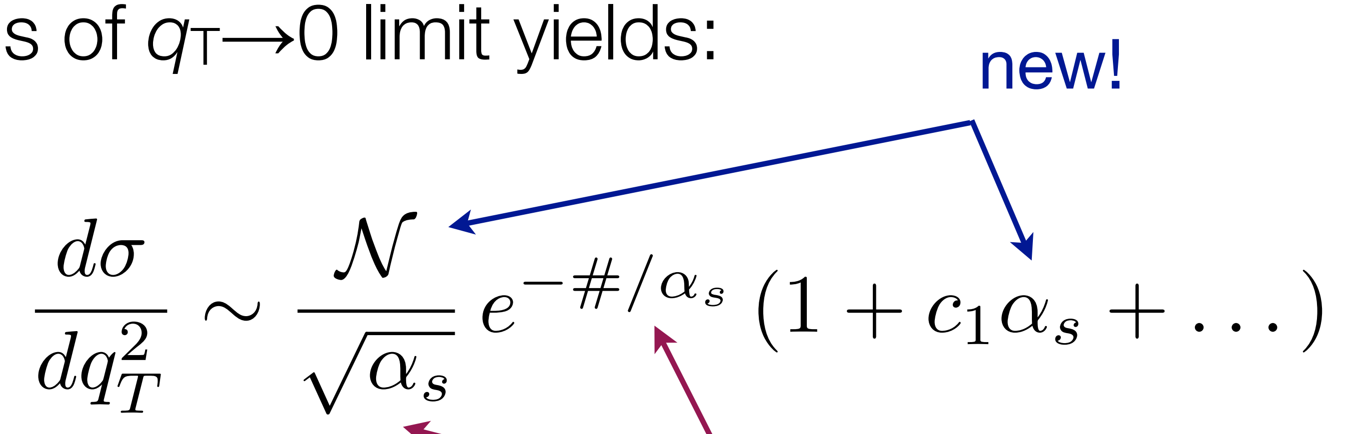
A careful analysis reveals that the spectrum $d\sigma/dq_T$ is short-distance dominated (but genuinely non-perturbative) all the way to $q_T=0$

For very low q_T a **new scale q_*** emerges in the Bessel integral:

$$q_* \approx M \exp\left(-\frac{2\pi}{(4C_{F/A}+\beta_0)\,\alpha_s(M)}\right)$$

Numerically: **q_*=1.9 GeV for Z** production, and **q_*=7.7 GeV for Higgs** production. Controls the size of long-distance hadronic corrections.

Dedicated analysis of $q_T \to 0$ limit yields:



new!

$$\frac{d\sigma}{dq_T^2} \sim \frac{\mathcal{N}}{\sqrt{\alpha_s}}\, e^{-\#/\alpha_s}\,(1+c_1\alpha_s+\dots)$$

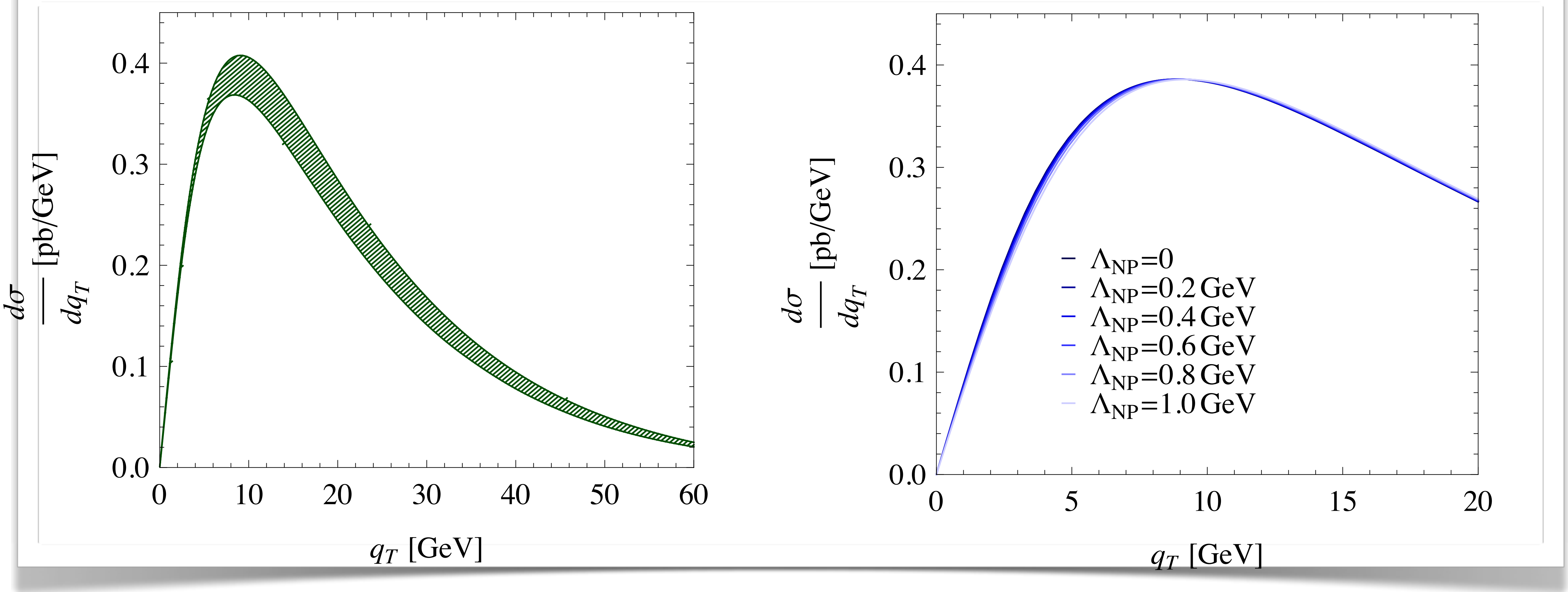
Parisi, Petronzio 1979;
Collins, Soper, Sterman 1985; Ellis, Veseli 1998

- Essential singularity at α_s=0 !

Higgs-boson q_T spectrum at LHC

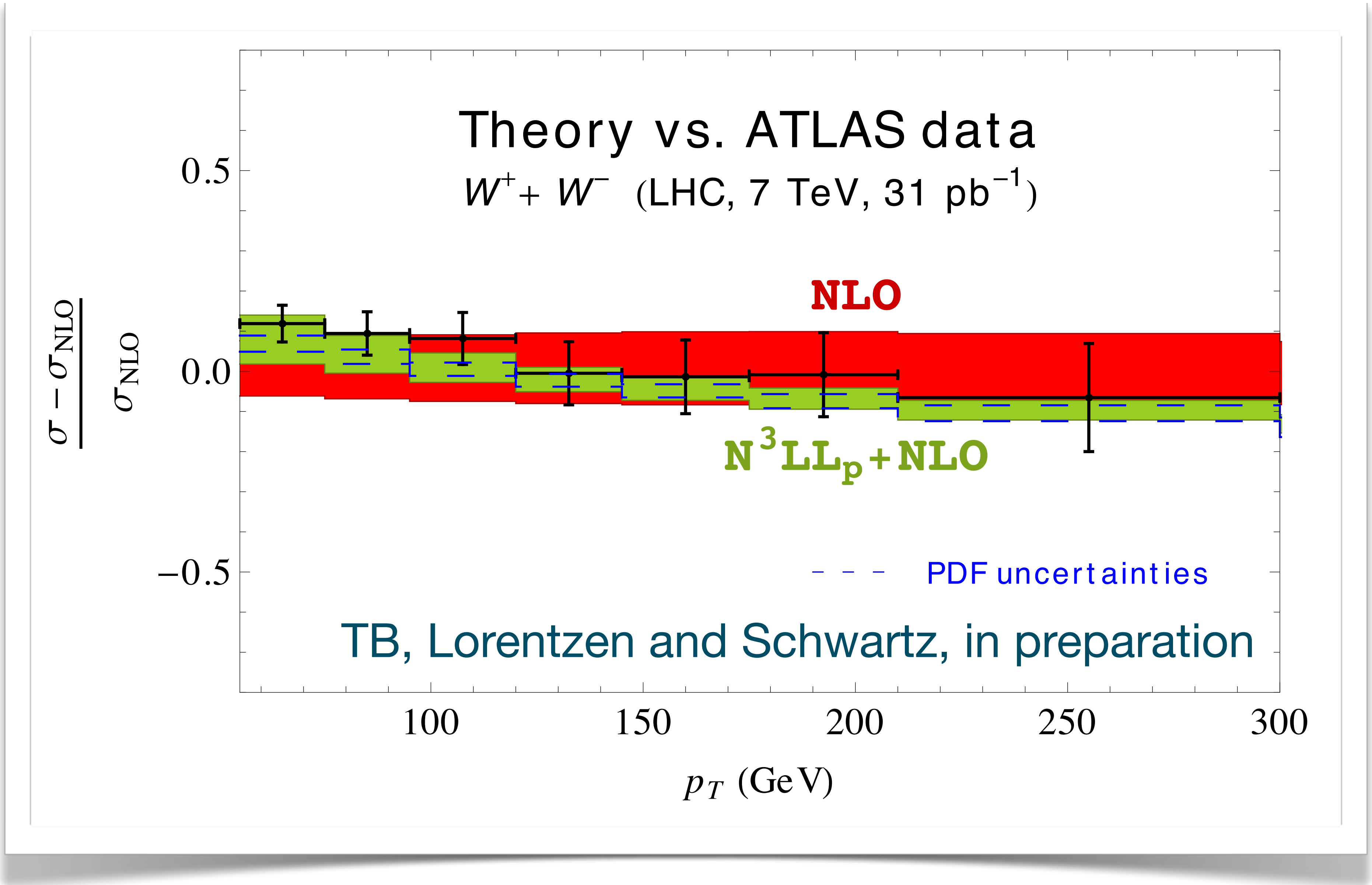
Similar accuracy, but long-distance hadronic corrections are much smaller in this case.

TB, Neubert, Wilhelm: in preparation



New NNLL+NNLO codes: **`HqT`**, **`HRes`** de Florian, Ferrera, Grazzini and Tommasini, 1109.2109, 1203.6321 **`ResBos`** update Wang, Li, Li, Yuan and Li 1205.4311

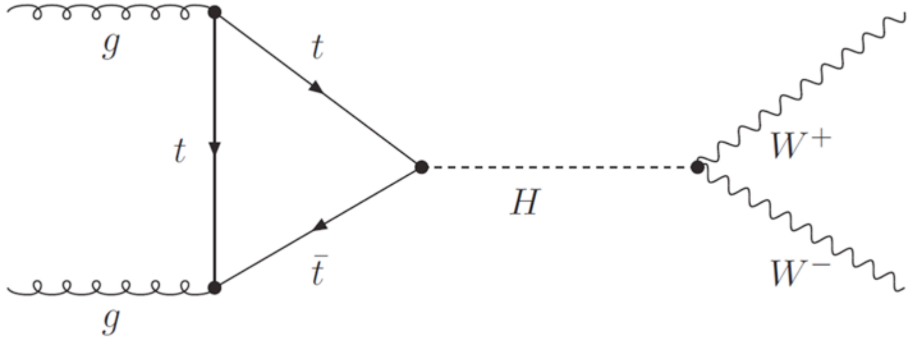
Large transverse momentum q_T

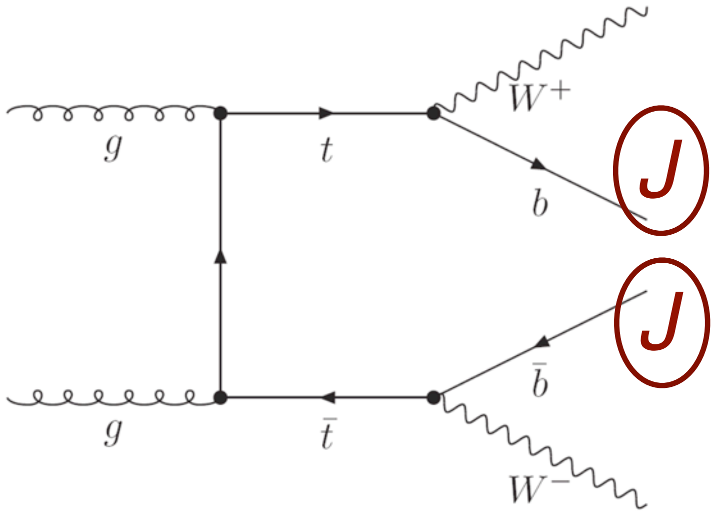


NNLL predictions TB, Lorentzen and Schwartz 1106.4310, Kidonakis and Gonsalves 1201.5265. All ingredients for N^3LL have now been determined: Two loop Soft function TB, Bell, Marti 1201.5572.

Resummation for Higgs production with a jet veto

Higgs production

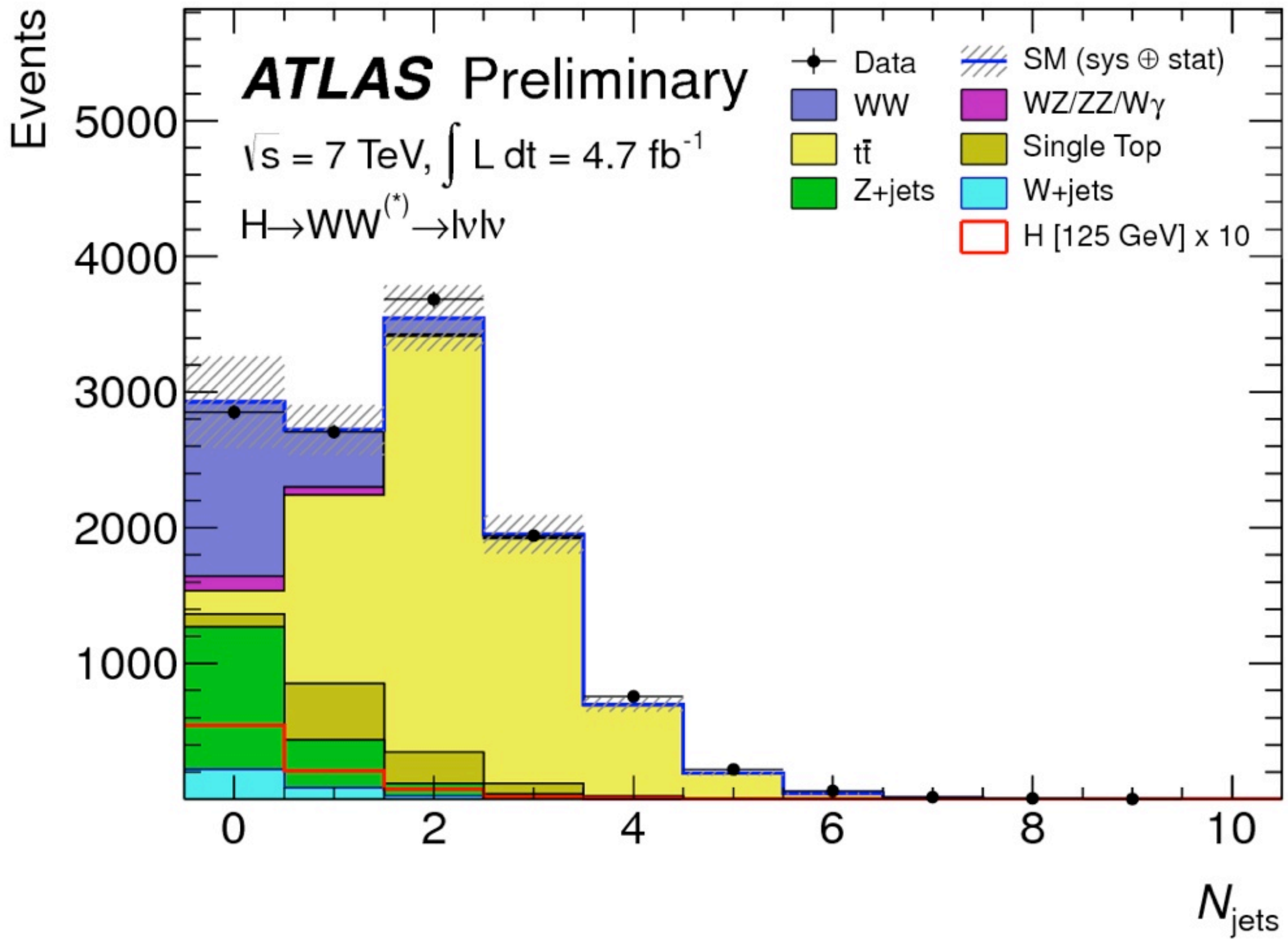




Need stringent cuts in order to isolate the small Higgs signal from the background.

Most important (and delicate...) is a jet veto:

$$p_T^{\text{Jet}} < p_T^{\text{Veto}} \sim \text{15-30 GeV}$$

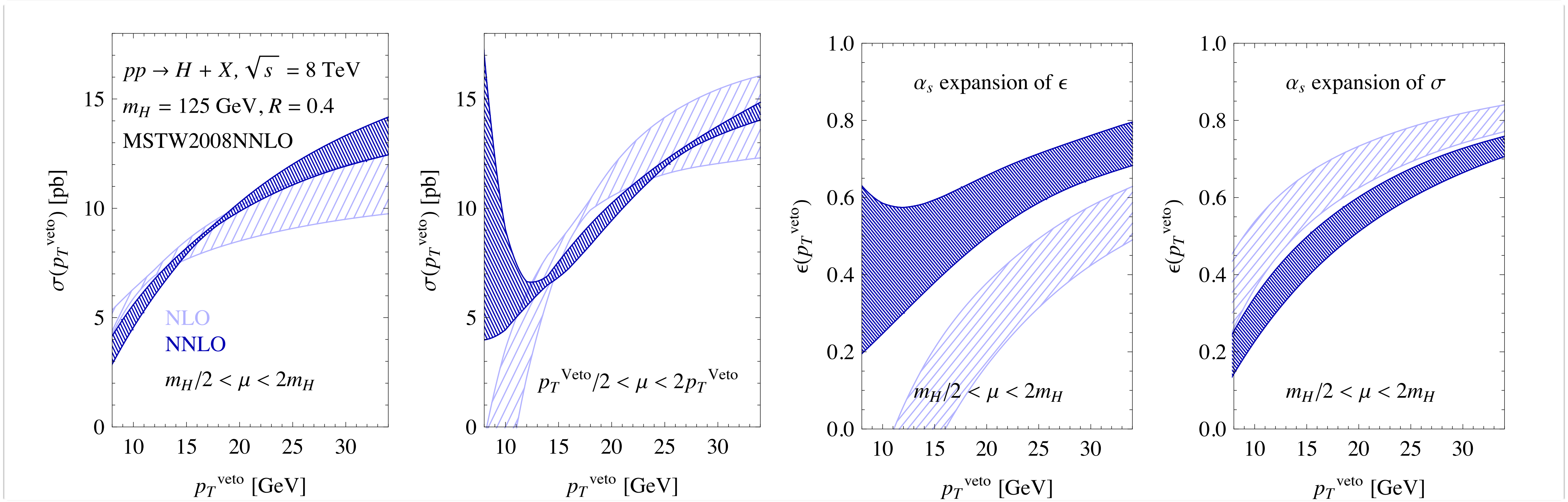


Search is done in jet bins, since background is very different when Higgs is produced in association with jets.

Need precise predictions for $H + n$ jets, in particular for the 0-jet bin, i.e. the cross section with a jet veto.

Fixed order results for $\sigma(p_T^{\text{veto}})$

NNLO codes: FEHIP Anastasiou, Melnikov and Petriello, HNNLO Grazzini



- Schemes: $\mu = m_H$ or $\mu = p_T^{\text{veto}}$? σ or efficiency $\varepsilon = \sigma^{\text{veto}}/\sigma^{\text{tot}}$? Expansion schme for ε ?

- Large ambiguities due to **two sources of large corrections**

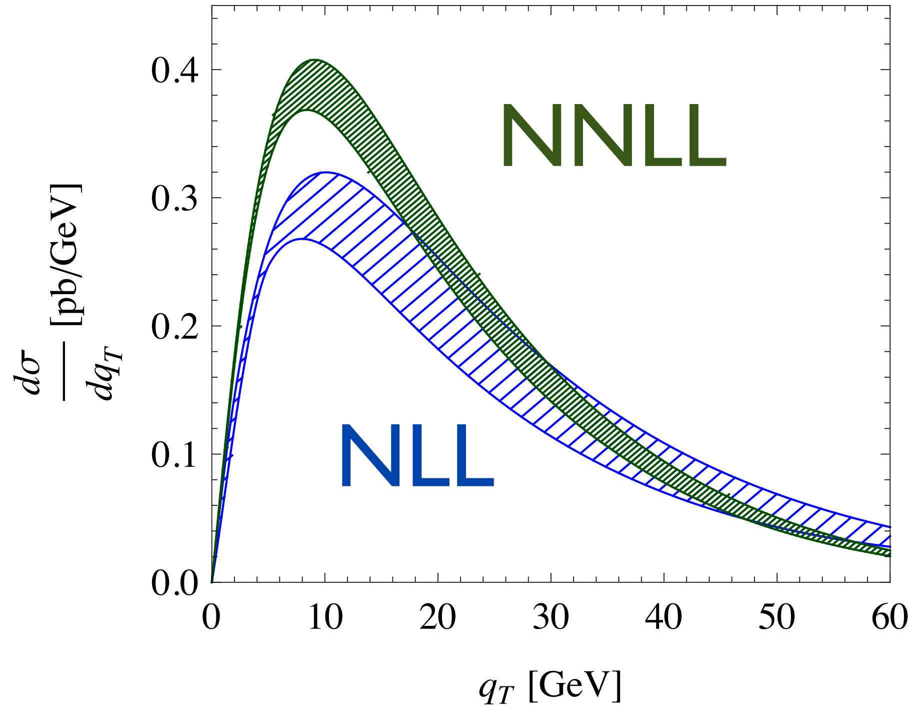
1. time-like gluon form factor in both σ^{tot} and σ^{veto}
2. Sudakov logs $\alpha_s^n \ln^m(p_T^{\text{veto}}/m_H)$ in σ^{veto}

Resummation

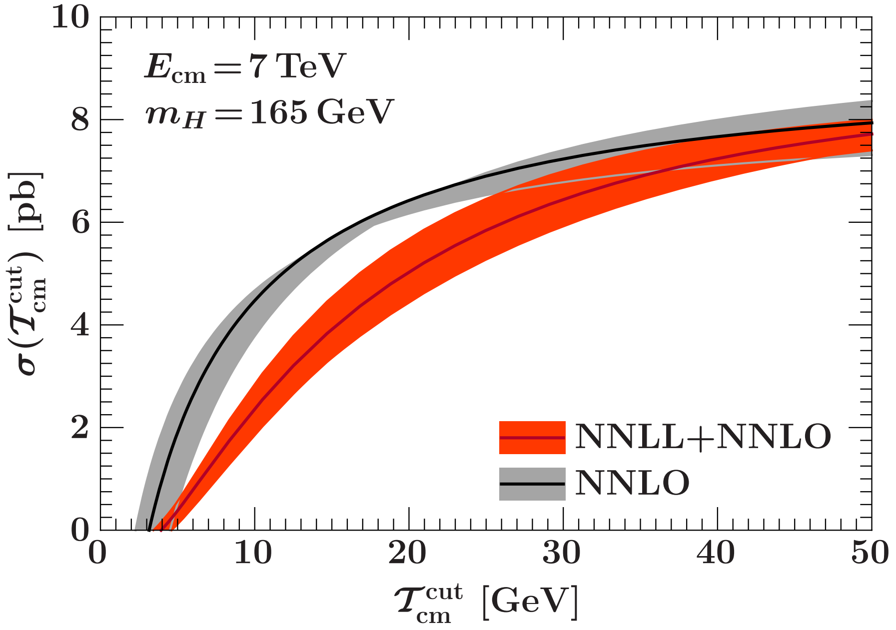
Until very recently, no resummed results for the rate with a jet veto were available, except LL resummation with parton shower.

NNLL resummation for related quantities (used to reweigh parton showers)

- Higgs q_T spectrum, Bozzi, Catani, de Florian, Grazzini ’03. In SCET: TB, Neubert, Wilhelm, in prep.
- Beam Thrust. Stewart, Tackmann, Waalewijn ’10
  - Use event shape instead of jet-veto to suppress additional jets. Looks difficult experimentally.



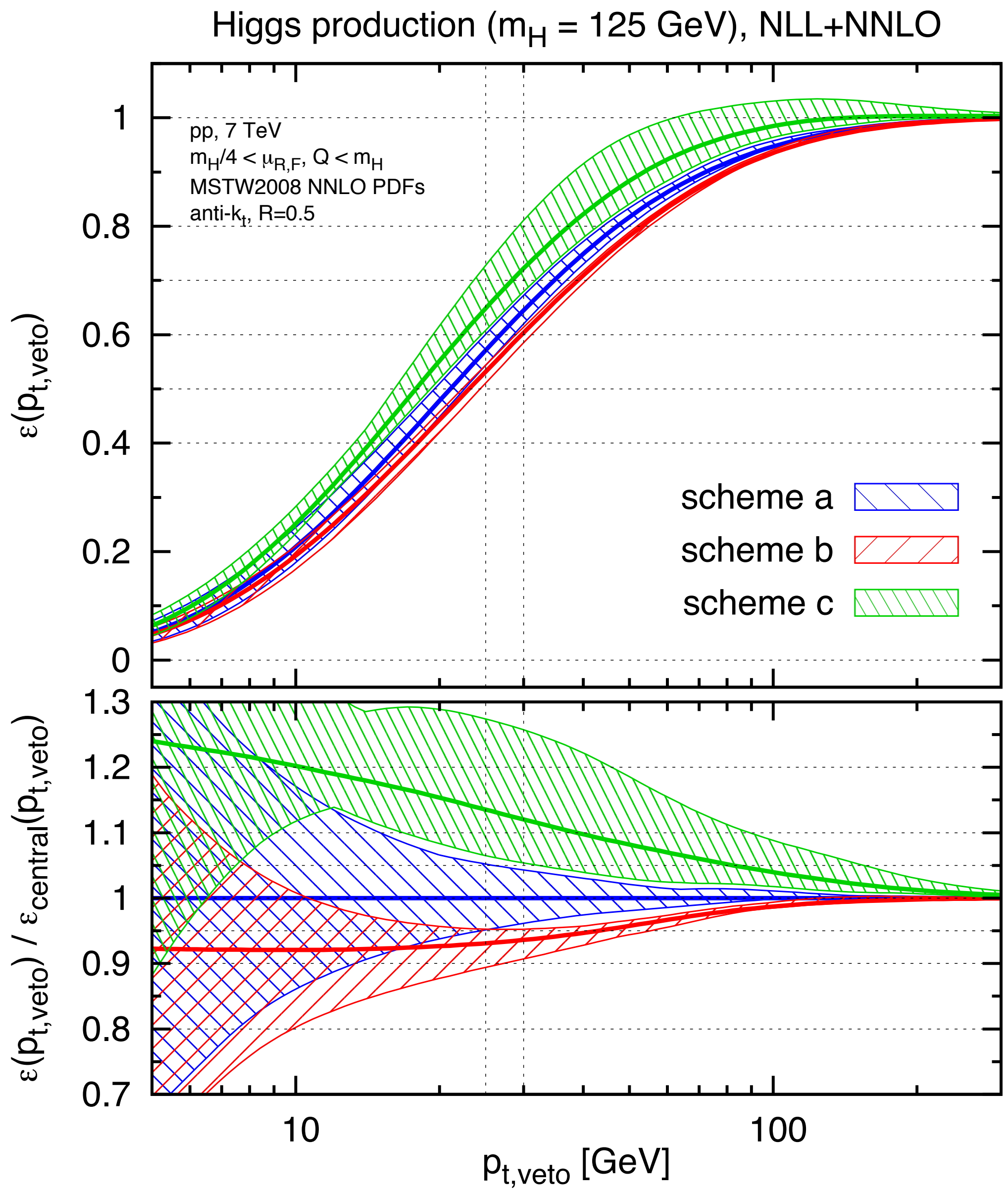
Higgs p_T



Beam thrust

Matched NLL+NNLO

Banfi, Salam, Zanderighi, 1203.5773



Based on numerical resummation code CAESAR

Three different matching schemes

Compute efficiency **ε**, instead of cross section.

Perform detailed comparison with event generators.

SCET result

TB, Neubert, 1205.3806

All-order factorization theorem for cross section

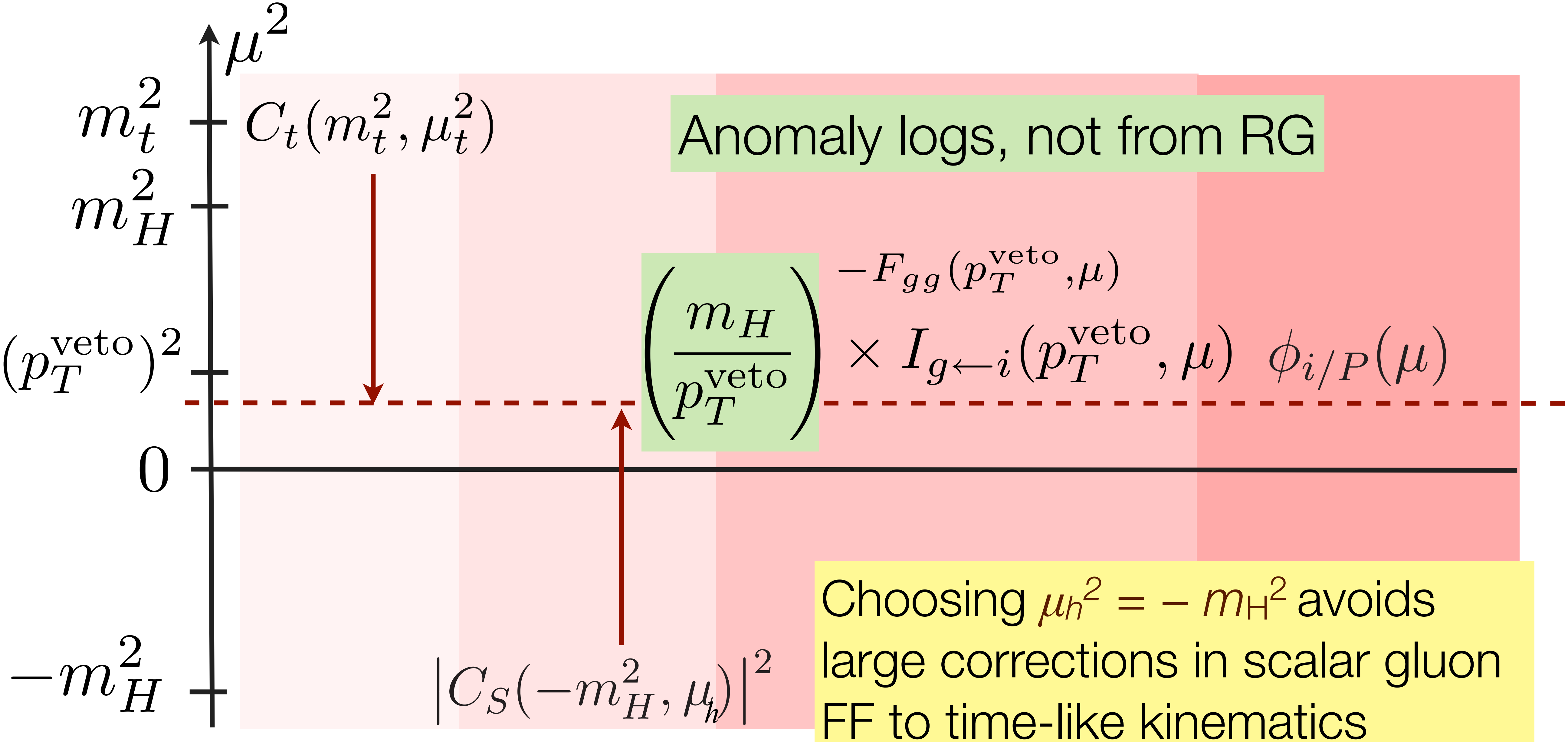
top-loop   scalar form factor   collinear anomaly

$$\frac{d\sigma(p_T^{\text{veto}})}{dy} = \sigma_0(\mu)\, C_t^2(m_t^2,\mu)\, \big|C_S(-m_H^2,\mu)\big|^2 \boxed{\left(\frac{m_H}{p_T^{\text{veto}}}\right)^{-2F_{gg}(p_T^{\text{veto}},\mu)}}$$
$$\times \sum_{i,j} I_{g\leftarrow i}(p_T^{\text{veto}},\mu) \otimes \phi_{i/P}(\mu)\;\; I_{g\leftarrow j}(p_T^{\text{veto}},\mu) \otimes \phi_{j/P}(\mu)$$

collinear beam function   PDF   anti-collinear beam function   PDF

- Suffers from collinear anomaly.
- Soft and collinear radiation gets independently clustered, up to power suppressed corrections.

Resummation by RG evolution



Anomaly logs, not from RG

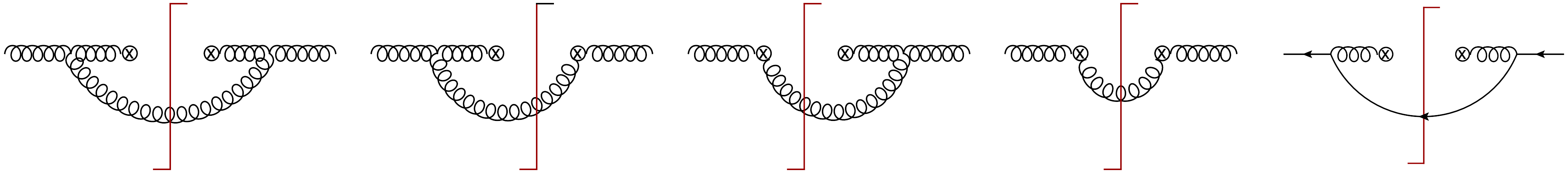
$$\left(\frac{m_H}{p_T^{\text{veto}}}\right)^{-F_{gg}(p_T^{\text{veto}},\mu)} \times I_{g\leftarrow i}(p_T^{\text{veto}}, \mu) \;\; \phi_{i/P}(\mu)$$

Choosing $\mu_h^2 = -m_H^2$ avoids large corrections in scalar gluon FF to time-like kinematics

Ahrens, TB, Neubert, Yang ’08

Ingredients for NNLL

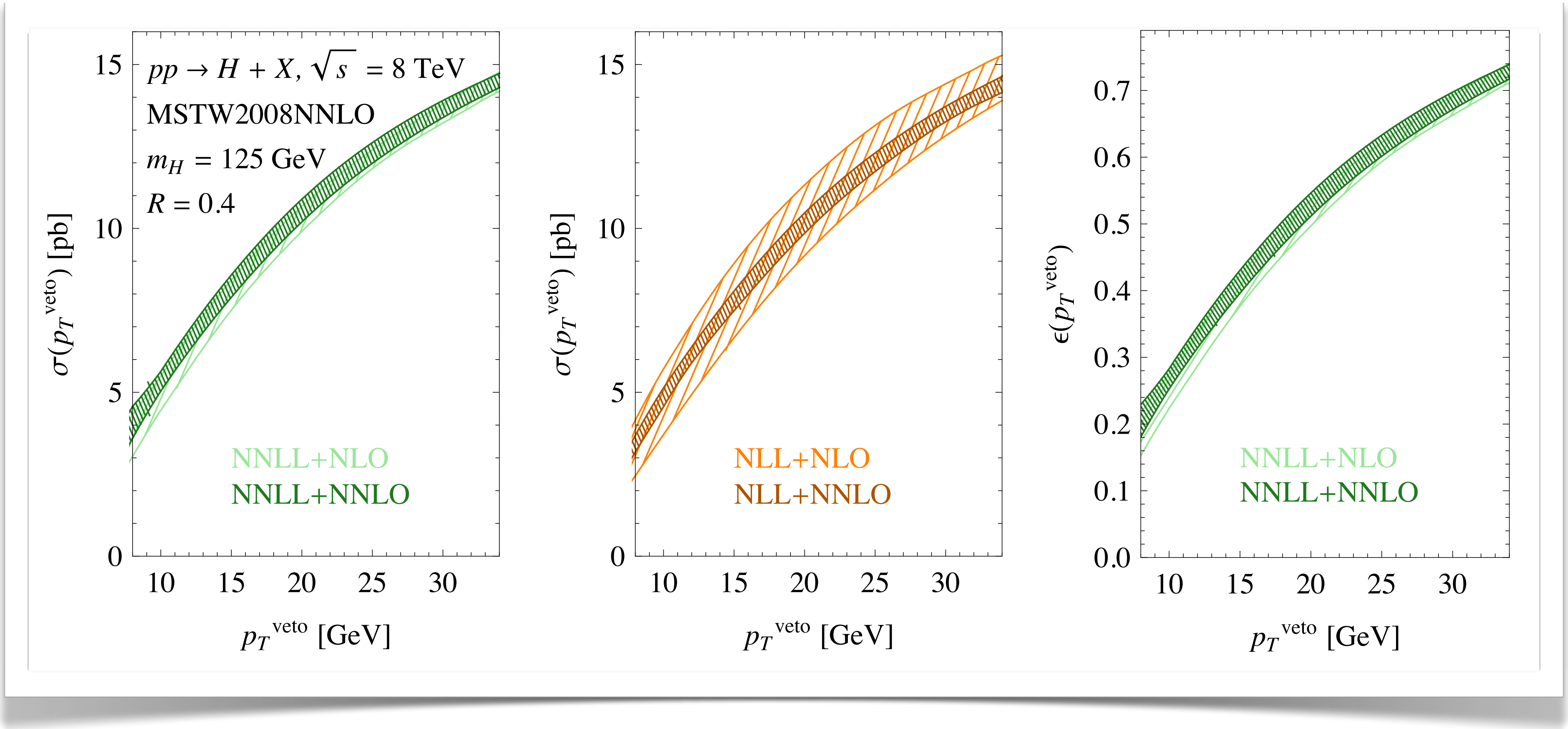
- Hard functions C_t and C_S are known.
- One-loop beam functions $I_{g\leftarrow i}\,(p_T^{\text{veto}},\mu)$.



- Two-loop anomaly $F_{gg}\,(p_T^{\text{veto}},\mu)$. Infer it from
  - result for F_{gg} in q_T resummation TB, Neubert '09
  - R dependent part of NNLL result computed in Banfi, Salam, Zanderighi '1203.5773

Result for cross section

TB, Neubert, 1205.3806



- Band from varying scales μ_t, μ_h and μ_f by a factor 2 around their default values.
- To simplify the fixed-order matching, the full N^{3}LL hard function is used, even for NLL result.

Numerical results for σ and ϵ

p_T^{veto}	$\sigma(p_T^{\text{veto}})$ [pb]	$\epsilon(p_T^{\text{veto}})$
10	$4.97^{+0.59+0.19}_{-0.01-0.22}$	$0.253^{+0.030}_{-0.001}$
15	$7.83^{+0.62+0.34}_{-0.05-0.35}$	$0.399^{+0.032}_{-0.002}$
20	$10.13^{+0.61+0.48}_{-0.08-0.49}$	$0.515^{+0.031}_{-0.004}$
25	$11.88^{+0.55+0.61}_{-0.07-0.61}$	$0.605^{+0.028}_{-0.003}$
30	$13.23^{+0.48+0.71}_{-0.03-0.70}$	$0.673^{+0.024}_{-0.002}$
∞	$19.66^{+0.55+1.54}_{-0.15-1.48}$	1

scale unc.

scale unc.

PDF unc.

Results for:

LHC @ 8 TeV

m_H=125 GeV

MSTW2008 PDFs

(anti)-k_T with R=0.4

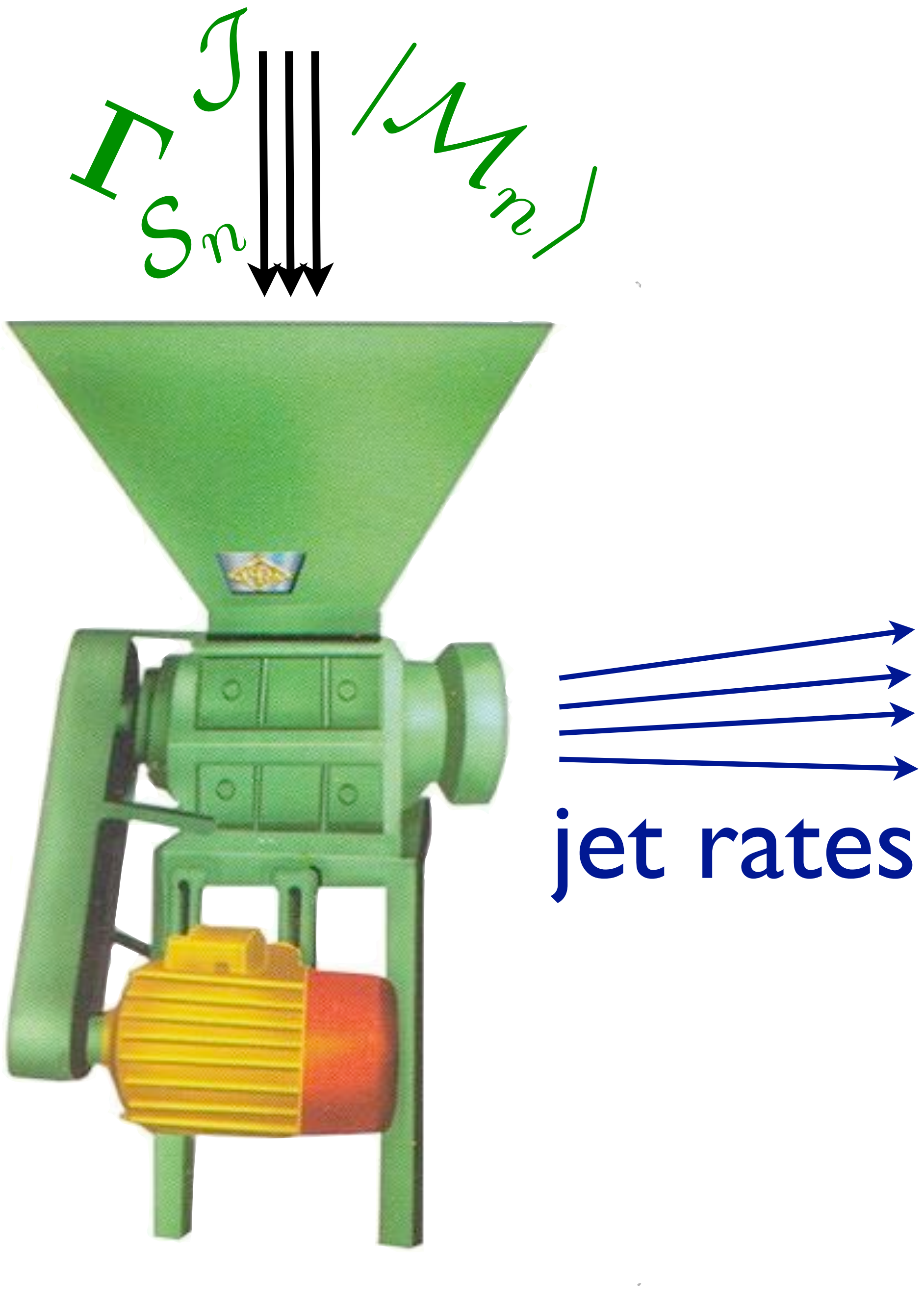
- PDF uncertainties on ϵ are small.
- Total cross section computed with `RGHiggs` Ahrens, TB, Neubert, Yang ’10

Outlook: resummation for n-jet processes

Goal: NLO+NNLL resummation

- Necessary ingredients:
    - **Hard functions**: from fixed-order results for on-shell amplitudes; new unitarity methods allow calculation of NLO amplitudes with many legs (→ match with NNLL resummation)
    - **Jet functions:** from imaginary parts of two-point functions; needed at one-loop order (depend on cuts, jet definitions)
    - **Soft functions:** from matrix elements of Wilson-line operators; one-loop calculations comparatively simple
- Then resum logarithms using RG evolution eqns.

Ultimate goal: Automatization



- in the longer term, this will hopefully lead to automated higher-log resummations for jet rates
- goes beyond parton showers, which are only accurate at LL even after matching
- predicts jet cross sections, not partonic cross sections!

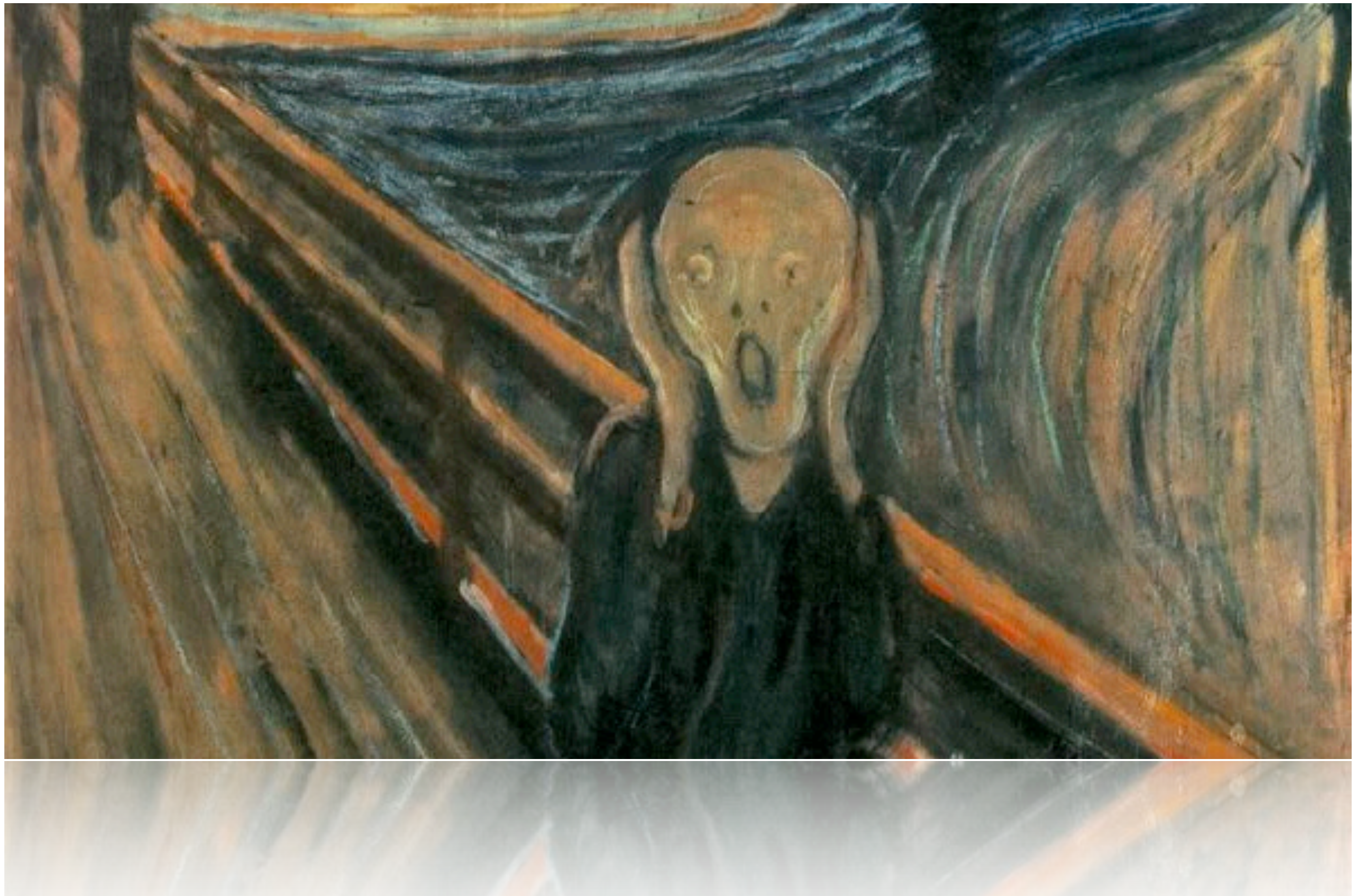
Resummations for *n*-jet processes

- **The good**: hard anomalous dimensions for NNLL resummations of arbitrary n-jet processes known. TB, Neubert '09
- **the bad**: many observables suffer from non-global logarithms in soft functions
  - several explicit computations of such logs, but so far no way to resum them. Kelley et al. '11, Hornig et al. '11
- **and the ugly**: phase-space constraints from traditional jet algorithms induce complicated clustering algorithms at each order. Kelley, Walsh, Zuberi '12
  - will likely need to switch to simpler observables, such as *n*-jettiness Stewart, Tackmann, Waalewijn '10 to reach higher-log accuracy.

Summary

- New higher-log resummed results for a wide variety of LHC processes
  - Many of the recent predictions are obtained using effective field theory methods.
- NNLL resummation for Higgs cross section in the presence of a jet veto.
  - Precise prediction in which all large higher-order corrections are under control.
- Goal is to extend methods to a wider range of observables, in particular to multi-jet cross sections and jet substructure studies.

Extra slides



The collinear anomaly

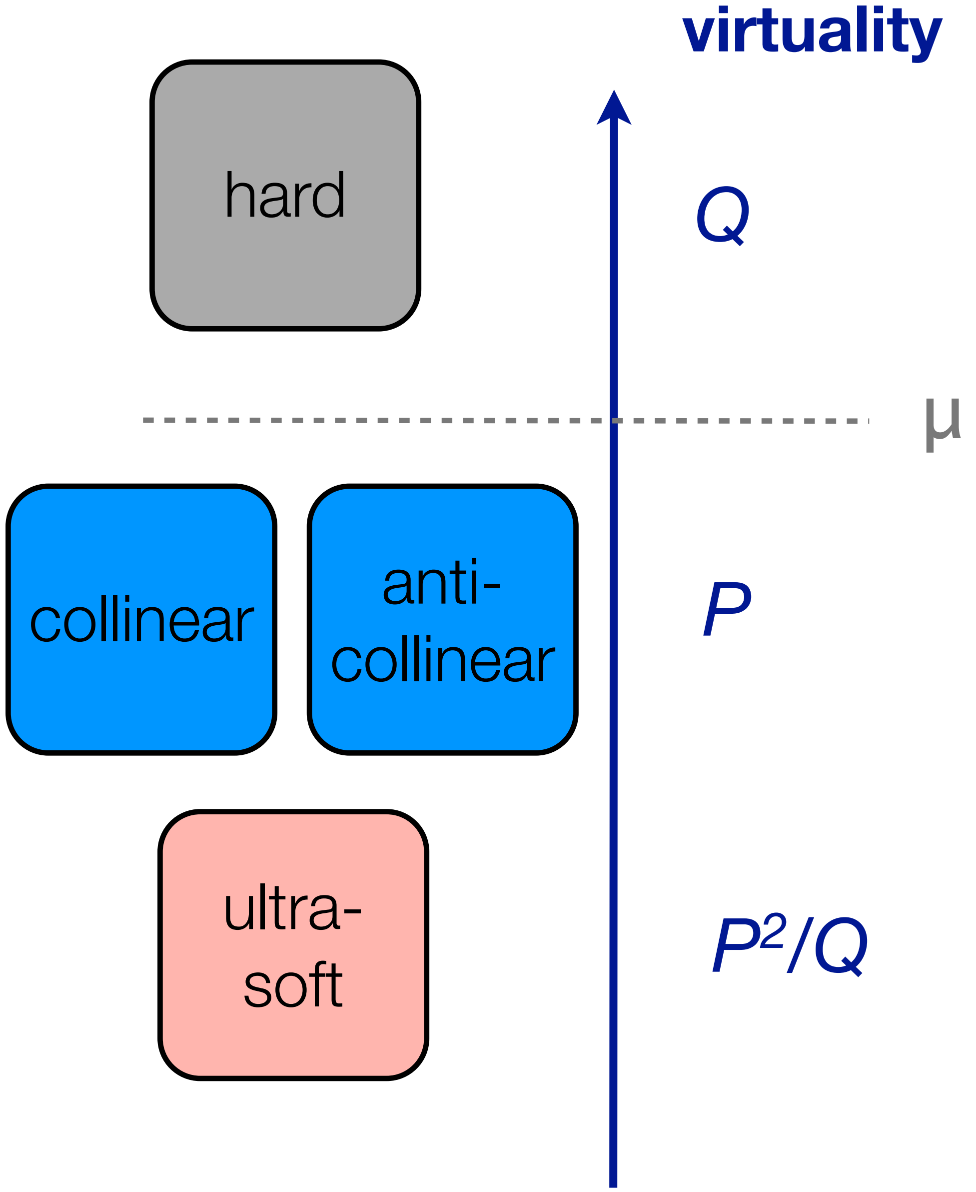
Standard factorization (SCET$_{\mathrm{I}}$)

Three correlated scales

- Hard scale Q
- Collinear Scale P
- Soft scale P^2/Q

Soft matrix element depends in large scale Q

$$d\sigma = H \cdot J \otimes J \otimes S$$



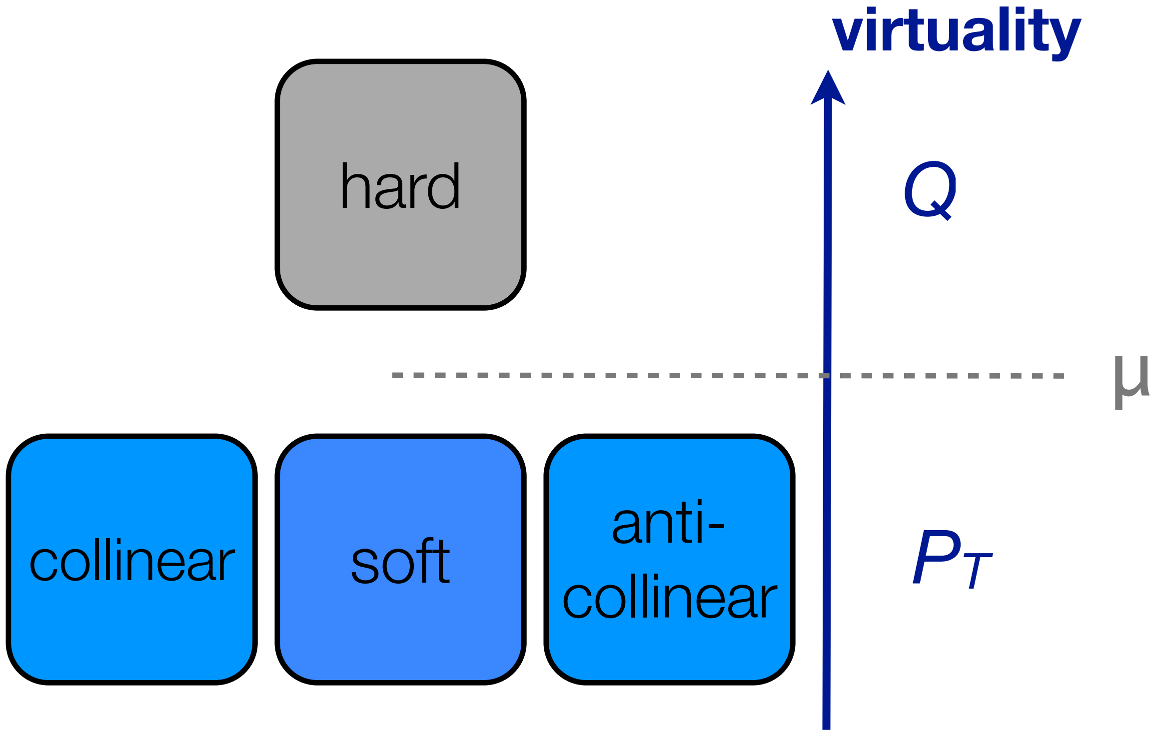
$$\ln^2\frac{Q^2}{P^2} = \underbrace{\frac{1}{2}\ln^2\frac{Q^2}{\mu^2}}_{\text{hard}} - \underbrace{\ln^2\frac{P^2}{\mu^2}}_{\text{collinear}} + \frac{1}{2}\underbrace{\ln^2\frac{P^4/Q^2}{\mu^2}}_{\text{(ultra-)soft}}$$

Sudakov double logarithm

Anomalous factorization (SCET$_{\text{II}}$)

Standard (ultra-)soft modes do not contribute to observables sensitive transverse momentum.

$$P_T^{\text{ultra-soft}} \sim P_T^2/Q \ll P_T$$



Puzzle: The cross section can only be μ independent, if also the low-energy part is Q dependent.

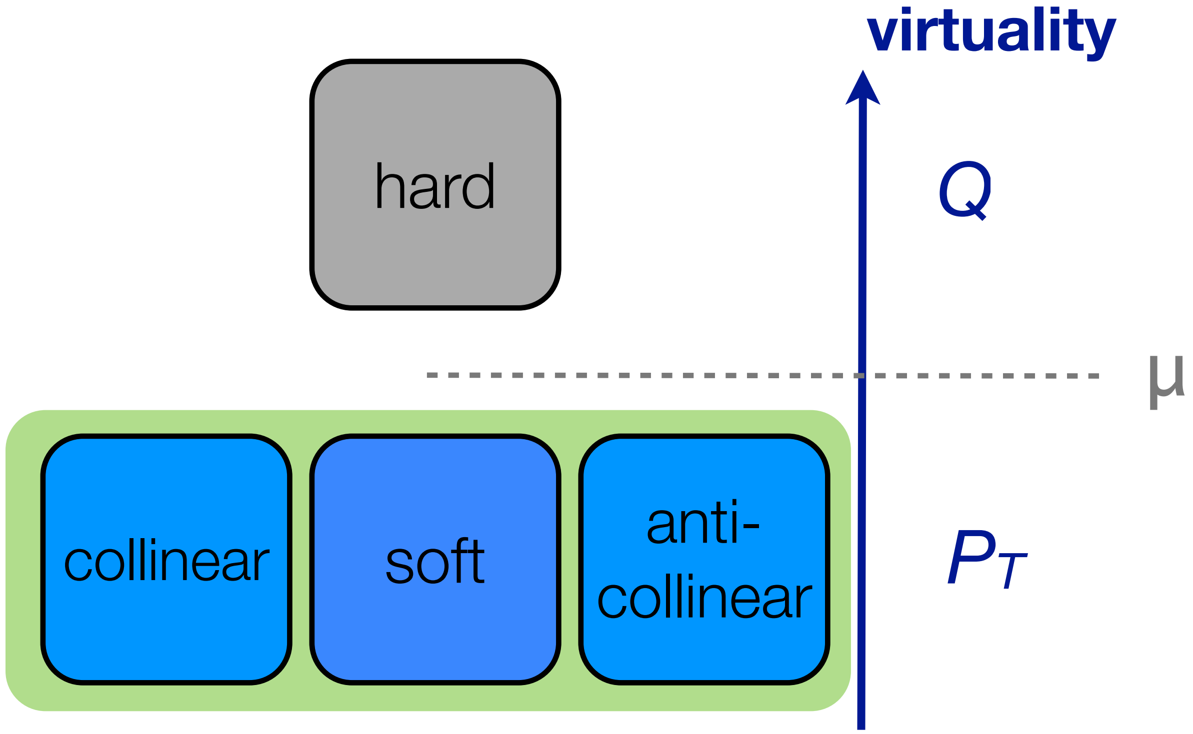
$$\ln^2 \frac{Q^2}{P_T^2} = \ln^2 \frac{Q^2}{\mu^2} - \ln^2 \frac{P_T^2}{\mu^2} + ?$$

Unregularized light-cone singularities in SCET diagrams.

Anomalous factorization (SCET$_{\rm II}$)

Standard (ultra-)soft modes do not contribute to observables sensitive transverse momentum.

$$P_T^{\rm ultra-soft} \sim P_T^2/Q \ll P_T$$



Resolution: Q dependence arises from a collinear factorization anomaly in the effective theory

TB, Neubert: 1007.4005 (EPJC)

$$\ln^2 \frac{Q^2}{P_T^2} = \ln^2 \frac{Q^2}{\mu^2} - \ln^2 \frac{P_T^2}{\mu^2} - 2\ln \frac{P_T^2}{\mu^2} \boxed{\ln \frac{Q^2}{P_T^2}}$$

collinear anomaly

Analytic phase-space regularization

TB, Bell 1112.3907

EFT phase-space integrals suffer from rapidity divergences not regularized dimensionally. Can be regularized analytically with the prescription

$$\int d^d k \;\delta(k^2)\,\theta(k^0) \quad \Rightarrow \quad \int d^d k \left(\frac{\nu_+}{k_+}\right)^{\alpha} \delta(k^2)\,\theta(k^0)$$

Since the amplitudes themselves do not need additional regularization,

- gauge invariance is maintained
- structure of the effective is unchanged

Divergences in α cancel when the contributions from the different sectors of SCET are combined, but anomalous *Q*-dependence remains.

- Consistency conditions yield all-order form of *Q*-dependence

Alternative formalism “Rapidity renormalization group” based on analytic regularization of Wilson lines Chiu, Jain, Neill, Rothstein: 1202.0814.

Jet clustering of soft and collinear modes

Inclusive jet algorithms

Distance measure

$$d_{ij} = \min(p_{Ti}^n, p_{Tj}^n)\,\frac{\sqrt{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}}{R}\,,$$

$$d_{iB} = p_{Ti}^n\,,$$

n=1: k_T
n=0: C/A
n=-1: anti-k_T

1. Find minimum of all d_{ij}, d_{iB}

2a. If d_{ij} is mimimum, combine *i* and *j*,

2b. If d_{iB} is minimum, then *i* is considered a jet and removed from the list.

Repeat until all particles are in jets.

SCET modes $(p_+, p_-, p_\perp)$.

$$p_c^\mu \sim m_H(\lambda^2, 1, \lambda) \qquad p_{\bar{c}}^\mu \sim m_H(1, \lambda^2, \lambda)$$

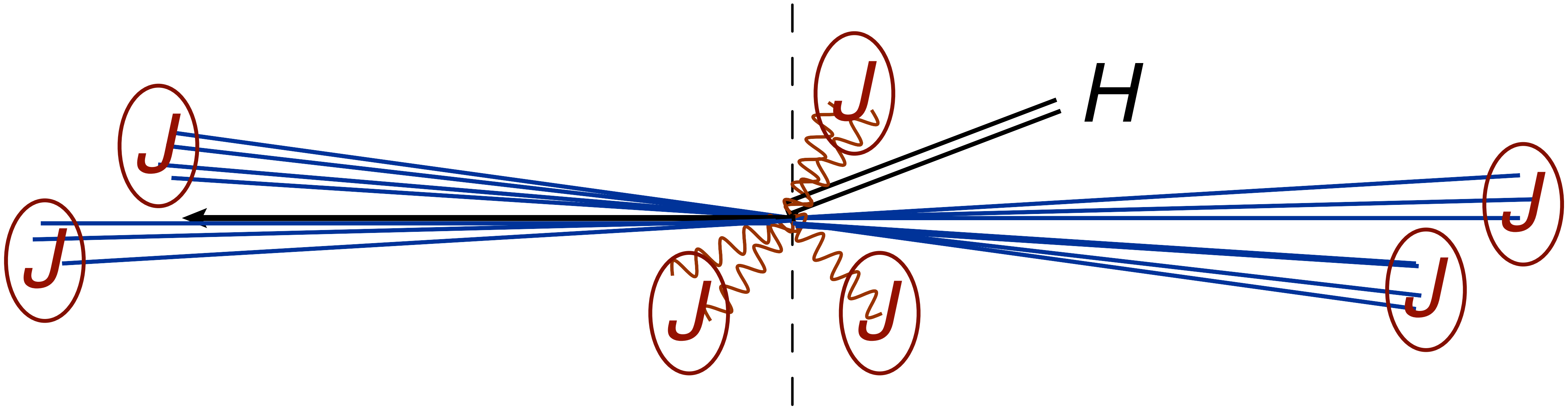
$$p_s^\mu \sim m_H(\lambda, \lambda, \lambda) \qquad \lambda \sim p_T^{\text{veto}}/m_H\,,$$

Transverse momenta scale the same, but large rapidity differences among different modes:

$$y = \frac{1}{2}\ln\frac{p_+}{p_-} \qquad (\Delta y)^2 \sim (\ln\lambda)^2$$

Since $d_{ij} \sim \Delta y_{\mathrm{ij}}$ jet algorithm will not combine different modes, except in corners of phase space.

Jet clustering



- As long as $R < \ln(m_H/p_T) \approx 1.5$, the algorithm will cluster soft and collinear radiation separately.
  - Only power suppressed corrections from soft partons with large rapidity, or collinear partons with small energy.
- Jet veto translates into veto in each individual sector.