# Effective field theory methods for the LHC

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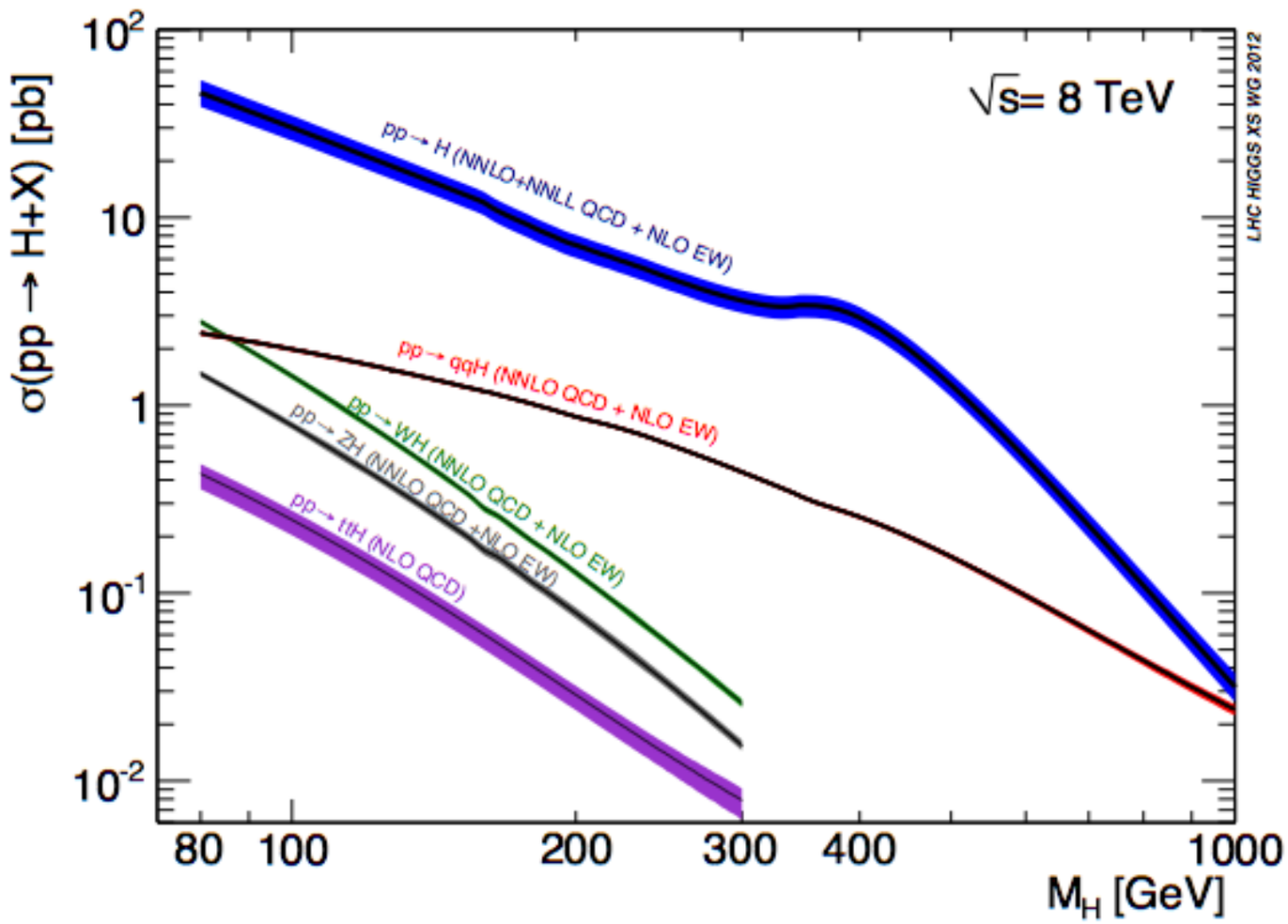
PRISMA **Cluster of Excellence**
Precision Physics, Fundamental Interactions and Structure of Matter

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

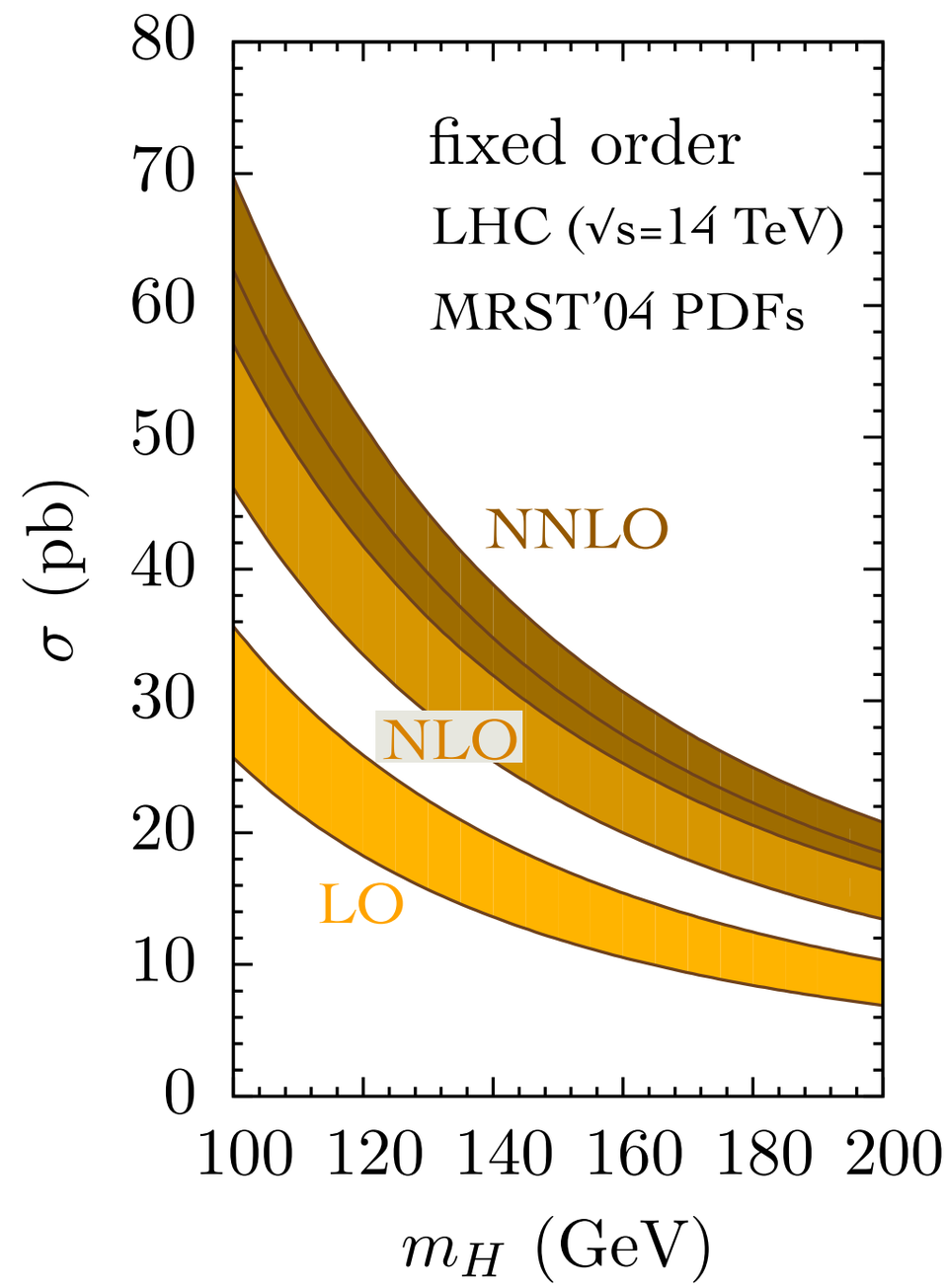
# Puzzle of the inclusive Higgs cross section

The simplest hadron collider process, yet very large corrections ...




Higgs cross sections working group (2012)

→ see talks by S. Dittmaier & R. Boughezal



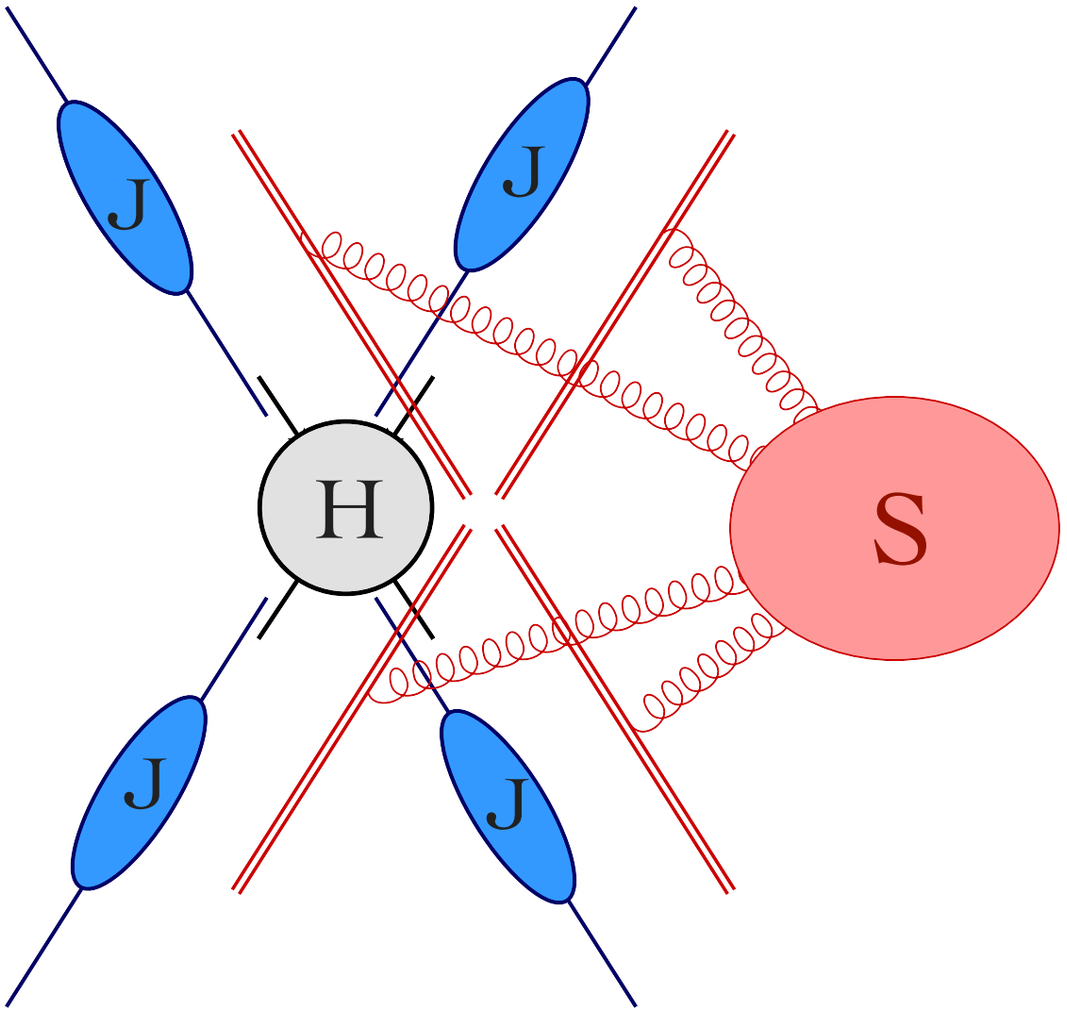

Harlander, Kilgore (2002); Anastasiou, Melnikov (2002); Ravindran, Smith, van Neerven (2003)

# Outline: Production of EW bosons W, Z, H (+ jets)

- Motivation and introduction
- Conventional factorization theorems
- “Anomalous” factorization theorems
- Summary

# Complexities of hadron collider processes

- **Multi-scale problems**, typically involving several hierarchical scales and often complicated kinematics
- Presence of **soft and collinear singularities** leads to large Sudakov double logarithms
- Separation of **short and long-distance contributions** is subtle; cannot be performed using a conventional OPE
- Due to **light-like nature** of these processes, any field-theory description must be intrinsically **non-local**




**QCD factorization theorems:**

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

operators containing **Wilson lines**

# Philosophy of effective field theory

- Separate contributions associated with different mass scales, turning a multi-scale problem into a series of single-scale problems
- Evaluate each contribution at its natural scale, leading to improved perturbative behavior
- Use the renormalization group to evolve contributions to an arbitrary factorization scale, thereby exponentiating (resumming) large corrections

**When this can be done consistently large K-factors do not arise, since no large perturbative corrections are left unexponentiated !**

# Scale separation in collider physics

**Soft-collinear effective theory** (SCET): systematic framework to study collider problems by describing collinear and soft particles by effective quark and gluon fields with well-defined interactions and power counting

Bauer, (Fleming,) Pirjol, Stewart (2000, 2001); Bauer, Fleming, Pirjol, Rothstein, Stewart (2002); Beneke, Chapovsky, Diehl, Feldmann (2002); Becher, MN (2010)

- **factorization** of short- and long-distance contributions follows from structure of $L_{eff}$ (caveat: "collinear anomaly")
- **gauge invariance** implemented at Lagrangian level
- **operator definitions** of jet and soft functions
- **resummation** of Sudakov logarithms is accomplished by solving RG equations

Elegant method for (re-)deriving **factorization theorems** in collider and heavy-flavor physics and **resumming** large perturbative corrections

Often allows for improved control over nonperturbative **long-distance effects**

# Conventional factorization theorems

**Drell-Yan processes near threshold**

- W/Z production — Becher, MN: 0605050 (PRL); + Xu: 0710.0680 (JHEP)
- Higgs production in gluon fusion — Ahrens, Becher, MN, Yang: 0809.4283 (EPJC), 1008.3162 (PLB)
- slepton pair production — Broggio, MN, Vernazza: 1111.6624 (JHEP)

**Pair production of heavy particles**

- top-quark pair production — Ahrens, Ferroglia, MN, Pecjak, Yang: 1003.5827 (JHEP), 1103.0550 (JHEP), 1105.5824 (PLB), 1106.6051 (PRD); Beneke, Falgari, Klein, Schwinn: 1109.1536 (NPB)
- boosted tops — Ferroglia, Pecjak, Yang: 1205.3662 (PRD), 1306.1537 (JHEP); + Marzani: 1310.3836 (JHEP)
- squark and gluino pair production — Broggio, Ferroglia, MN, Vernazza, Yang: 1304.2411 (JHEP), 1312.4540 (JHEP); Beneke *et al.*: 1312.0837

**Threshold production of W/Z/H+jet** — Becher, Lorentzen, Schwartz: 1106.4310 (PRL), 1206.6115 (PRD); Becher, Bell, Lorentzen, Marti: 1309.3245 (JHEP)

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# Conventional factorization theorems

→ topics for the QCD session

**Jet substructure**

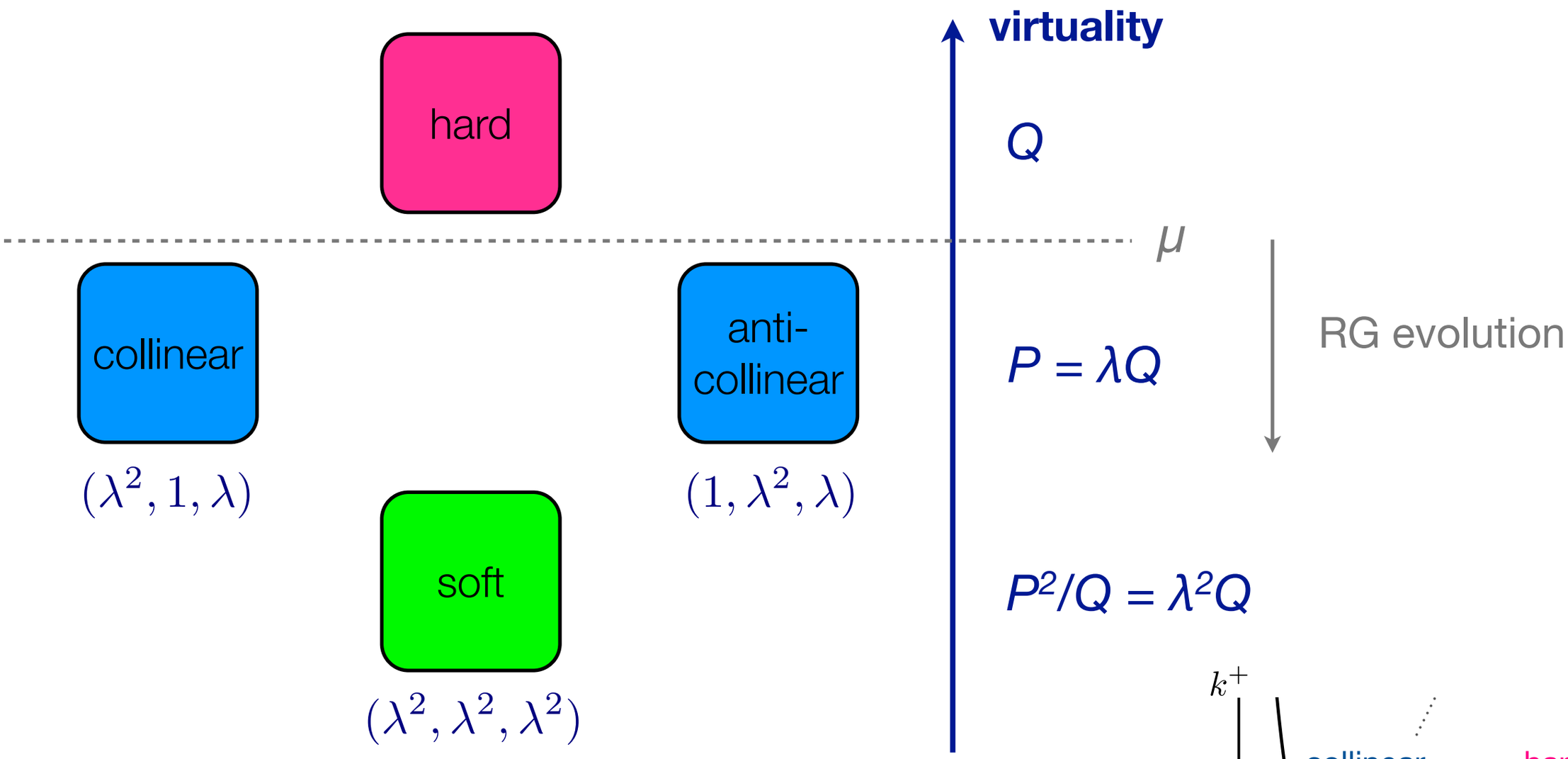
- boosted event shapes — Feige, Schwartz, Stewart, Thaler: 1204.3898 (PRL)
- jet charge — Waalewijn: 1209.3019 (PRD)
- energy correlation functions — Larkoski, Salam, Thaler: 1305.0007 (JHEP)

**Soft radiation at hadron colliders**

- matching fully differential NNLO predictions with parton showers — Alioli, Bauer, Berggren, Tackmann, Walsh, Zuberi: 1311.0286
- factorization analysis of soft hadronic activity underlying primary hard interaction (ISR, multiple parton interactions, underlying event, …) — Stewart, Tackmann, Waalewijn: 1405.6722

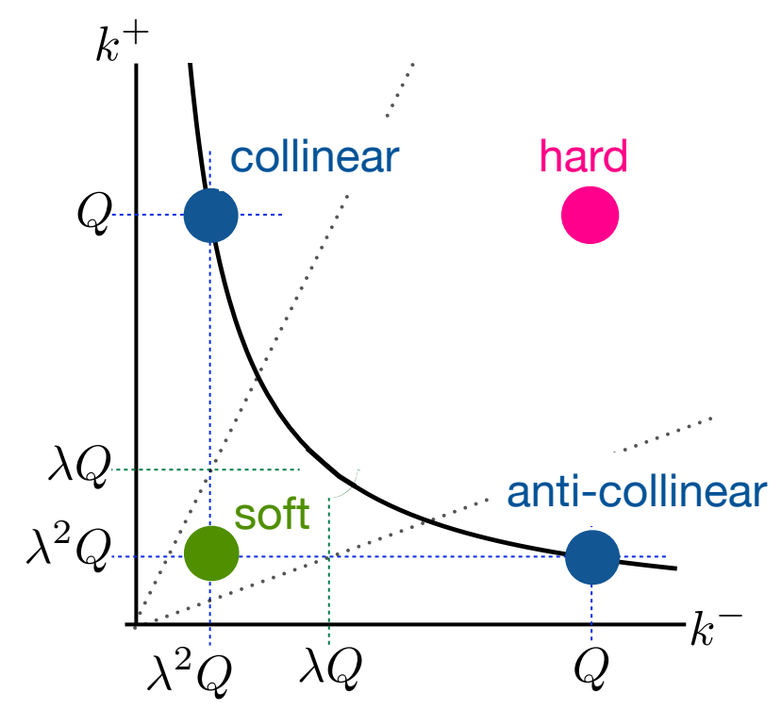
and many more papers …

# Factorization of three correlated scales




Generic **factorization theorem**:

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



# Drell-Yan processes near threshold

In Drell-Yan processes $pp \to V + X \quad (V = \gamma, Z, W, H)$ near the **partonic threshold**, where $z = M_V^2/\hat{s} \to 1$, the collinear functions are standard parton distribution functions (PDFs):

$$d\sigma = H \, \phi \otimes \phi \otimes S$$

Hence large Sudakov logarithms can be resummed by **evolving the hard function *H*** and PDFs to the characteristic soft scale, using the RGE:

$$\mu^2 \frac{d}{d\mu^2} H(Q,\mu) = \left[ C_{q/g} \, \gamma_{\rm cusp}(\alpha_s) \, \ln \frac{|Q^2|}{\mu^2} + 2\gamma_{q/g}(\alpha_s) \right] H(Q,\mu)$$

SCET factorization theorem is **equivalent to standard QCD factorization theorem** by Sterman (1987) and Catani, Trentadue (1989)

Almeida, Ellis, Lee, Sterman, Sung, Walsh (2014)
[cf: Bonvini, Forte, Ghezzi, Ridolfi (2012)]

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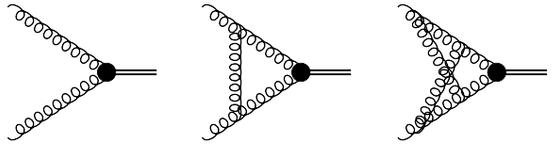
$$d\sigma = H\, \phi \otimes \phi \otimes S$$

SCET resummation approach is equivalent to standard soft-gluon resummation in QCD with **one important twist**:

- hard function for time-like processes $q\bar{q} \to W, Z$ and $gg \to H$ is naturally evaluated at $\mu^2 \sim Q^2 = -m_H^2$

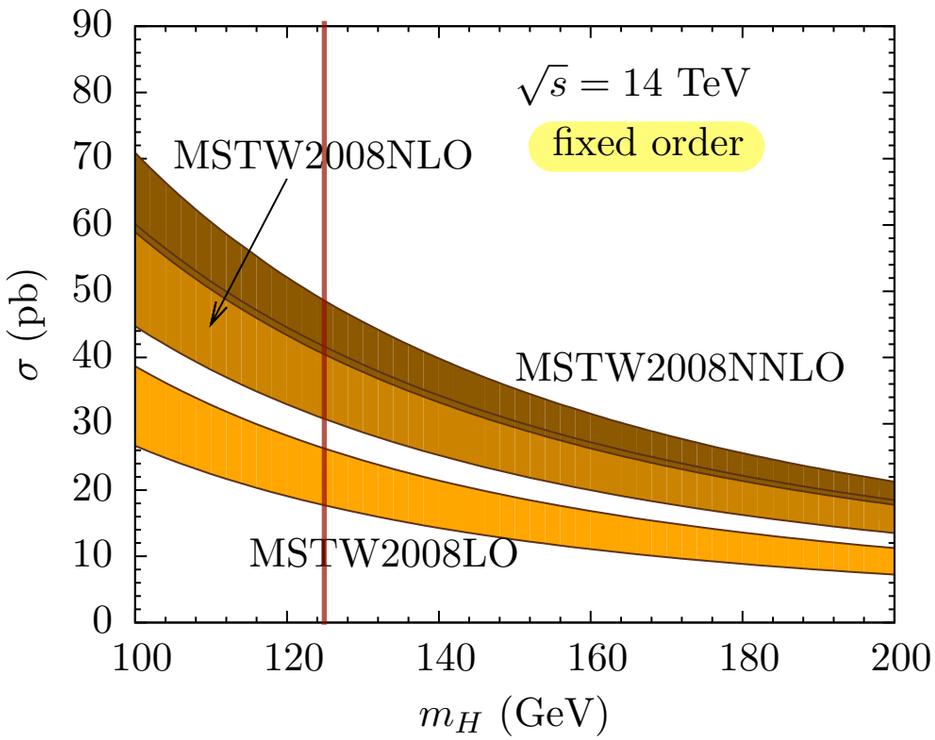


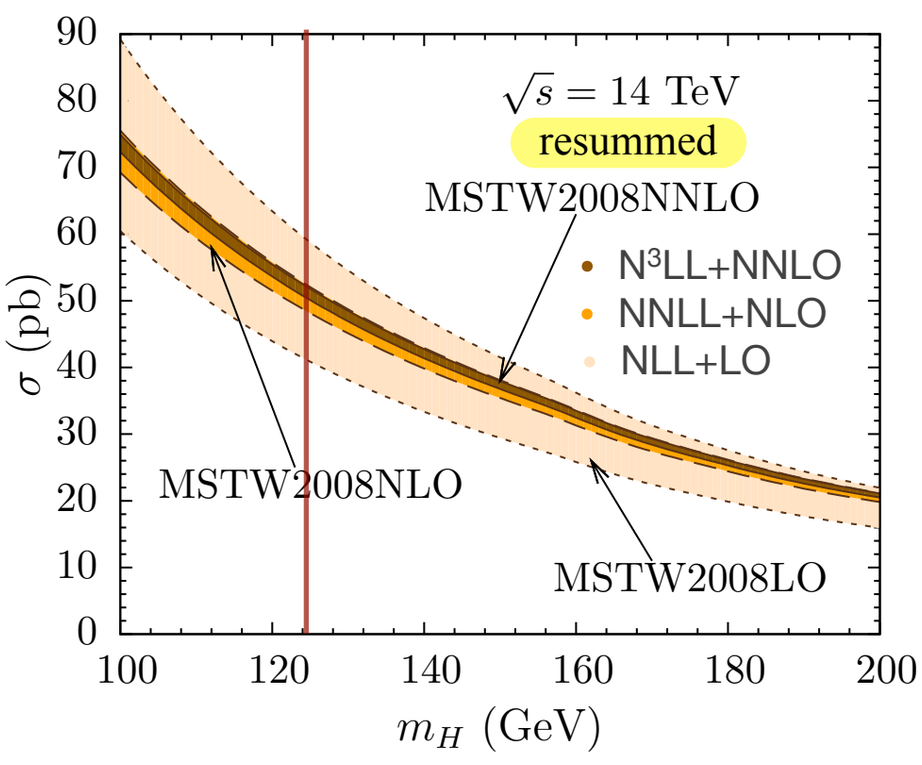
- EFT evolution then **automatically resums** a class of large perturbative corrections $\sim (N_c \alpha_s \pi)^n$ and **significantly improves the convergence** of the perturbative expansion!

Ahrens, Becher, MN, Yang (2008)

# Higgs production in gluon fusion @ N$^3$LL+NNLO

Ahrens, Becher, MN, Yang (2008, 2010)




- perturbative expansion after resummation **converges** very well
- scale uncertainties are **reduced** order by order
- prediction at N$^3$LL+NNLO is about **15% higher** than fixed-order NNLO, accounting for most of the ~16% enhancement expected from preliminary NNNLO calculations → see talk by S. Dittmaier
- remaining uncertainty dominated by **PDFs**:

| $m_H$ [GeV] | LHC (14 TeV) | LHC (14 TeV) | LHC (14 TeV) |
|---|---|---|---|
| 115 | $57.9^{+1.6+4.4}_{-0.3-4.2}$ | $58.8^{+1.7+3.1}_{-0.4-3.5}$ | $60.3^{+1.8+3.9}_{-0.7-3.9}$ |
| 120 | $54.0^{+1.5+4.1}_{-0.3-3.9}$ | $54.7^{+1.6+2.9}_{-0.3-3.2}$ | $56.3^{+1.7+3.7}_{-0.7-3.7}$ |
| 125 | $50.4^{+1.4+3.8}_{-0.3-3.6}$ | $51.1^{+1.4+2.6}_{-0.3-3.0}$ | $52.6^{+1.5+3.4}_{-0.8-3.4}$ |
| 130 | $47.2^{+1.3+3.5}_{-0.3-3.4}$ | $47.8^{+1.3+2.5}_{-0.3-2.7}$ | $49.3^{+1.4+3.2}_{-0.8-3.2}$ |
| 135 | $44.3^{+1.2+3.3}_{-0.3-3.2}$ | $44.8^{+1.2+2.3}_{-0.3-2.5}$ | $46.3^{+1.3+3.0}_{-0.8-3.0}$ |
| | MSTW | CT | NNPDF |

PDF uncertainties

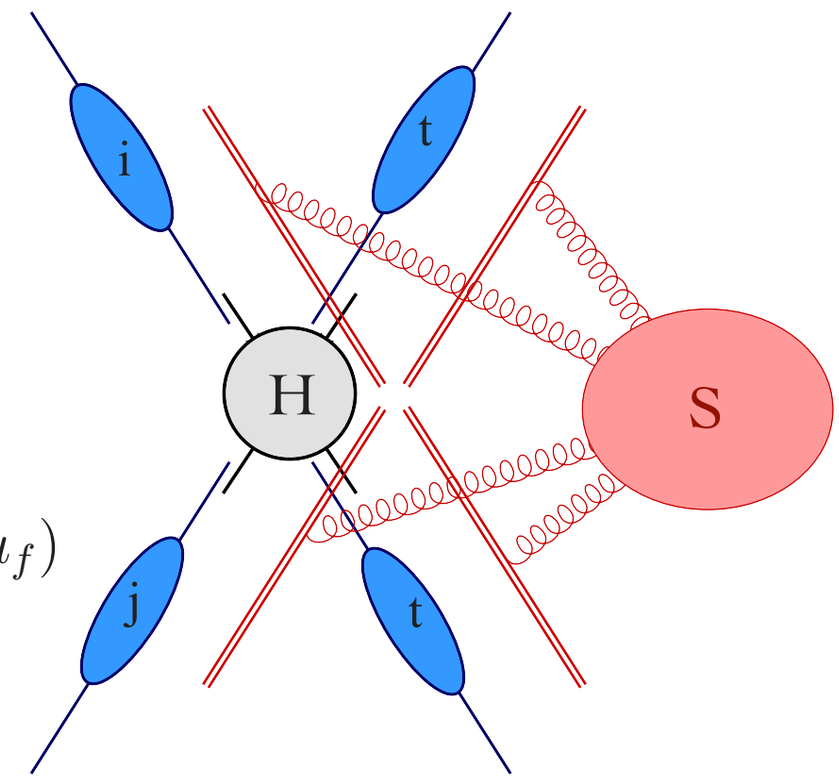
→ public code RGHiggs available at: http://projects.hepforge.org/rghiggs

# Pair-production of heavy colored particles

Formula

$$d\sigma = H\,\phi \otimes \phi \otimes S$$

still valid, but hard and soft functions now depend on **several kinematic variables** and are **matrices in color space**




For top-quark pair production near threshold:

$$\frac{d^2\sigma}{dM\,d\cos\theta} = \frac{8\pi\beta_t}{3sM}\sum_{i,j}\int_\tau^1 \frac{dz}{z}\,\mathit{ff}_{ij}(\tau/z,\mu_f)\,C_{ij}(z,M,m_t,\cos\theta,\mu_f)$$

with: → see talks by A. Ferroglia & S. Moch

$$C_{ij}(z,M,m_t,\cos\theta,\mu_f) = \mathrm{Tr}\left[\boldsymbol{H}_{ij}(M,m_t,\cos\theta,\mu_f)\,\boldsymbol{S}_{ij}(\sqrt{\hat{s}}(1-z),m_t,\cos\theta,\mu_f)\right] + \mathcal{O}(1-z)$$

Ahrens, Ferroglia, MN, Pecjak, Yang (2010)

# Pair-production of heavy colored particles

**Anomalous dimensions** needed for threshold resummation are matrices in color space and depend on kinematic variables as well

- for resummation at NNLL order, they are known for an **arbitrary collider process**, involving any number of massless or massive external particles:

$$\begin{aligned}\boldsymbol{\Gamma}(\{\underline{p}\},\{\underline{m}\},\mu) = &\sum_{(i,j)} \frac{\boldsymbol{T}_i\cdot\boldsymbol{T}_j}{2}\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{\mu^2}{-s_{ij}} + \sum_i \gamma^i(\alpha_s) \\ &- \sum_{(I,J)} \frac{\boldsymbol{T}_I\cdot\boldsymbol{T}_J}{2}\,\gamma_{\rm cusp}(\beta_{IJ},\alpha_s) + \sum_I \gamma^I(\alpha_s) + \sum_{I,j} \boldsymbol{T}_I\cdot\boldsymbol{T}_j\,\gamma_{\rm cusp}(\alpha_s)\,\ln\frac{m_I\mu}{-s_{Ij}} \\ &+ \sum_{(I,J,K)} i f^{abc}\,\boldsymbol{T}_I^a\,\boldsymbol{T}_J^b\,\boldsymbol{T}_K^c\,F_1(\beta_{IJ},\beta_{JK},\beta_{KI}) \\ &+ \sum_{(I,J)}\sum_k i f^{abc}\,\boldsymbol{T}_I^a\,\boldsymbol{T}_J^b\,\boldsymbol{T}_k^c\,f_2\Big(\beta_{IJ},\ln\frac{-\sigma_{Jk}\,v_J\cdot p_k}{-\sigma_{Ik}\,v_I\cdot p_k}\Big) + \mathcal{O}(\alpha_s^3)\end{aligned}$$

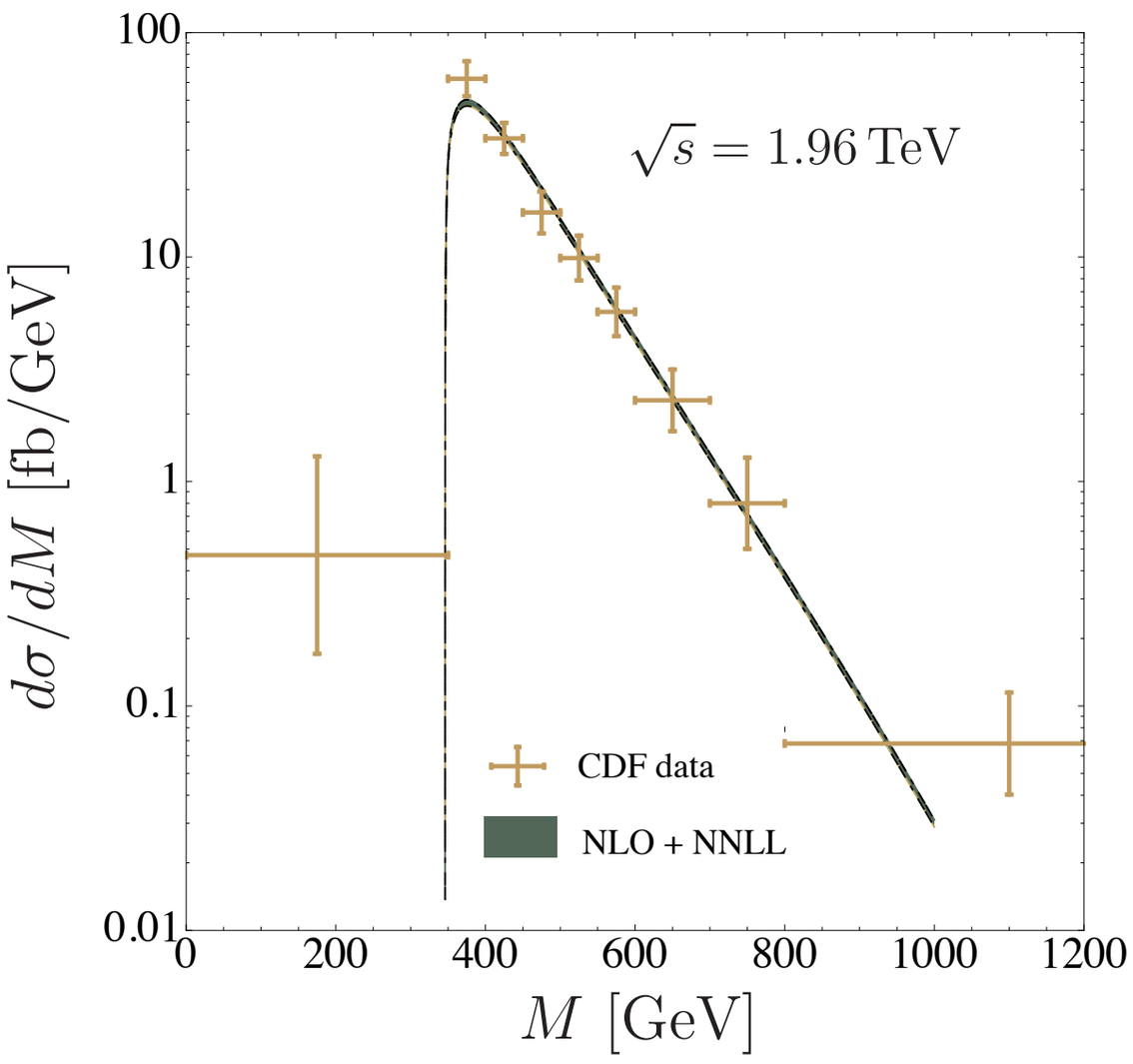
- deep connection to **IR singularities of scattering amplitudes** in non-abelian gauge theories

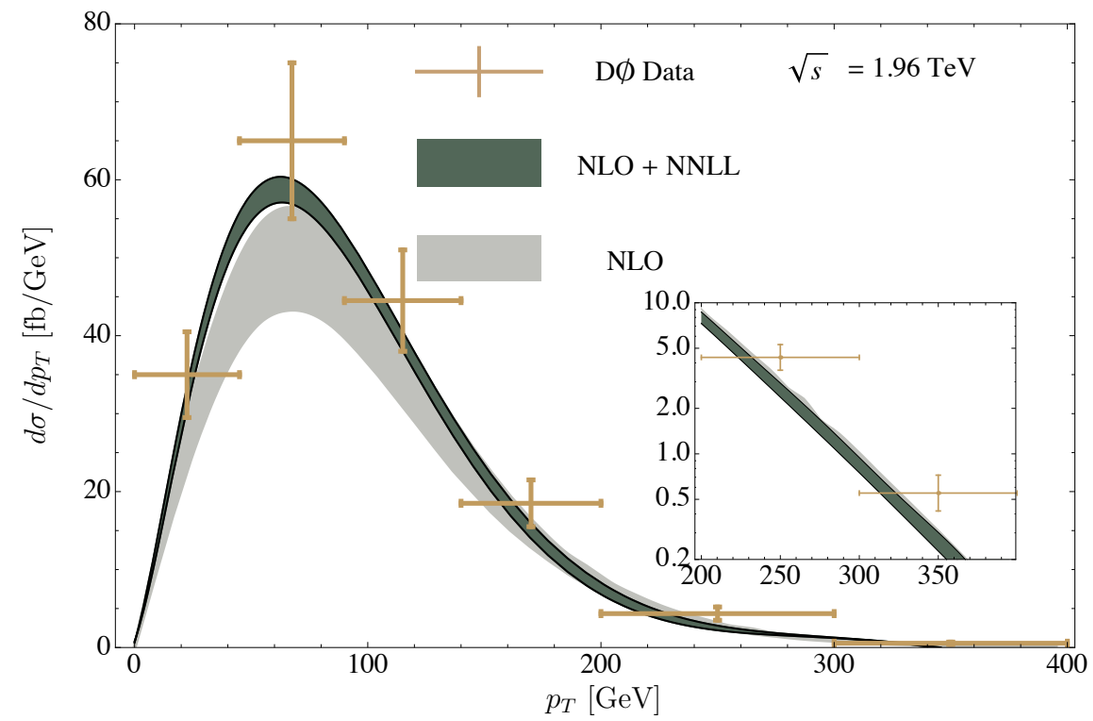
Becher, MN (2009); Gardi, Magnea (2009);
Mitov, Sterman, Sung (2009); Ferroglia, MN, Pecjak, Yang (2009)

# Top-quark pair production @ NNLL+NLO

Ahrens, Ferroglia, MN, Pecjak, Yang (2010)

**Arbitrary differential distributions** (of the top-quark pair and of individual top quarks) can be resummed near threshold:




→ update and comparison with new Tevatron and LHC data in preparation

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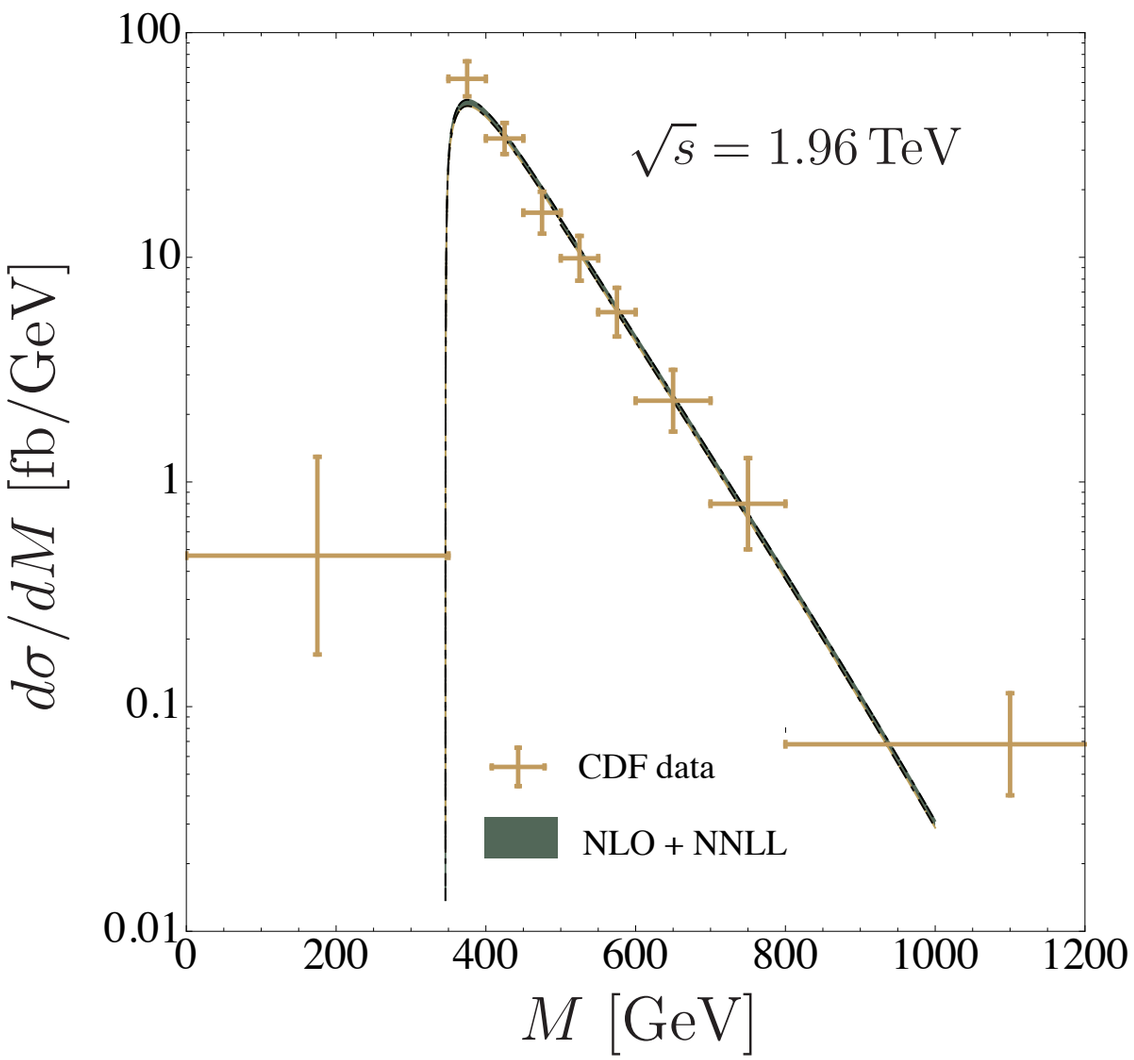


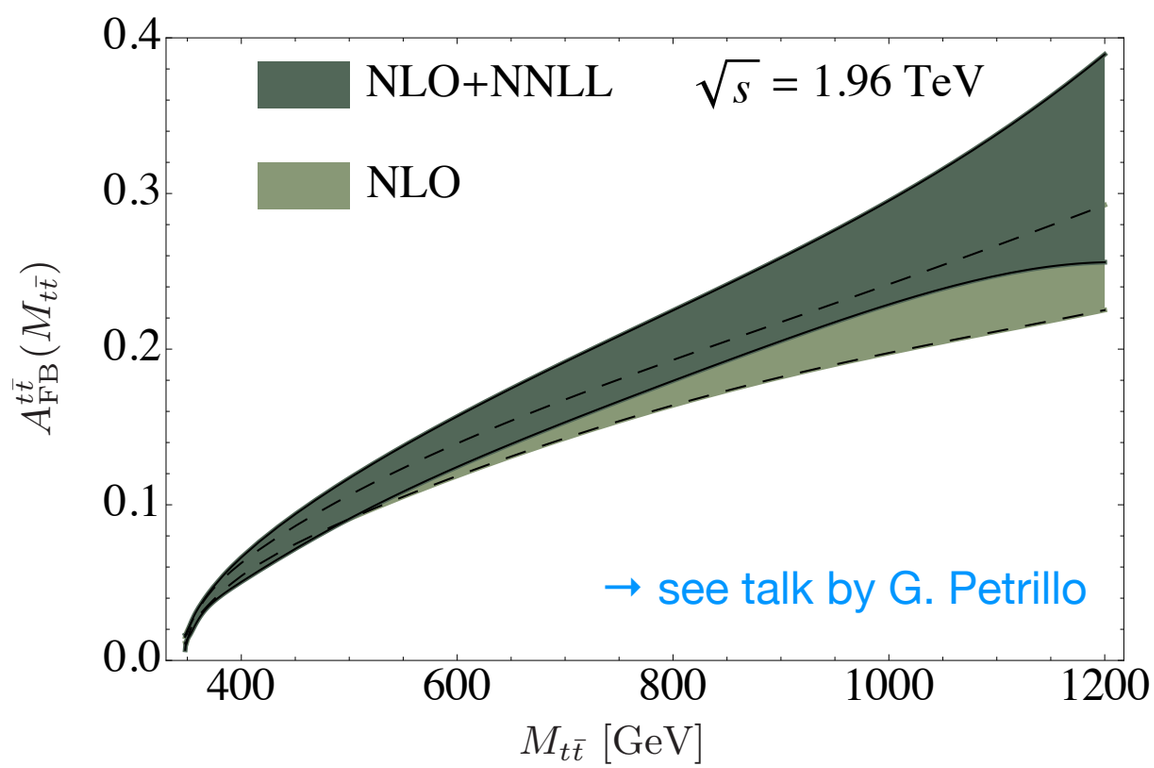


→ see talk by G. Petrillo

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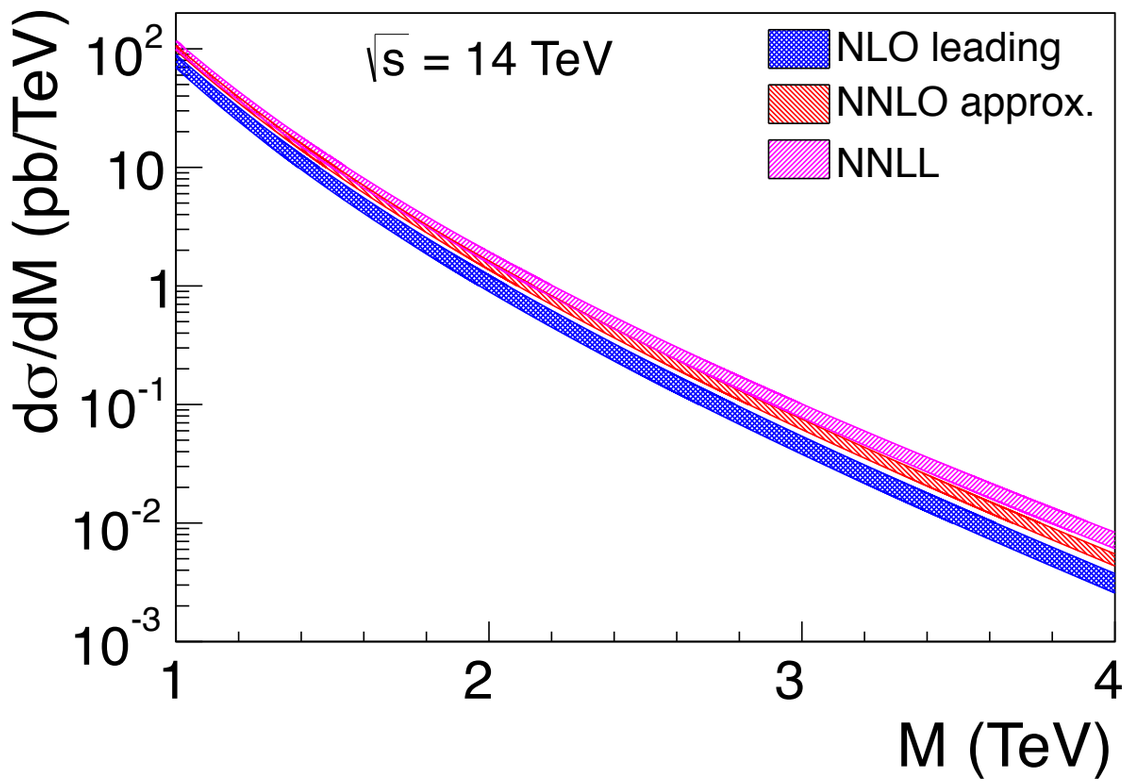
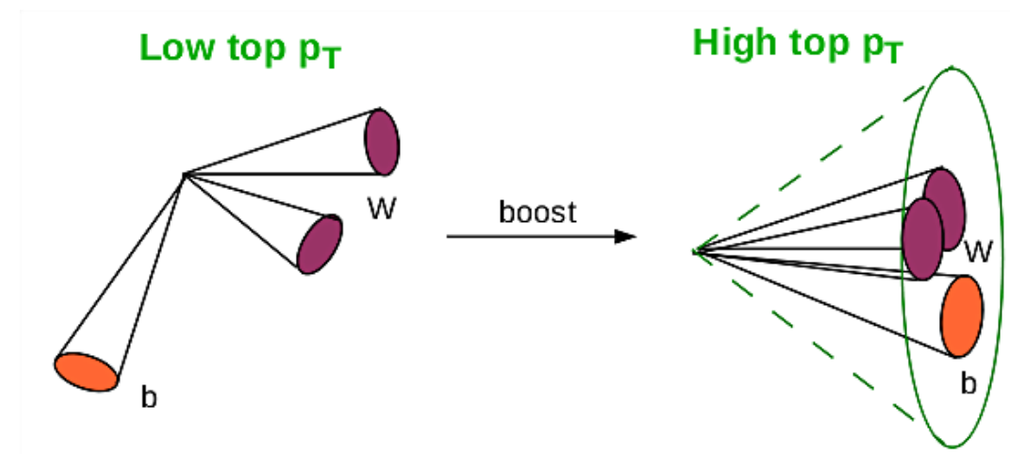
# Top-quark pair production @ NNLL+NLO

**Boosted tops:** for $M \gg 2m_t$ (or $p_t^\perp \gg m_t$) a more complicated factorization theorem was derived, which resums logarithms of $(1-z)$ and $M/m_t$ (or $p_t^\perp/m_t$)




Ferroglia, Pecjak, Yang (2012, 2013); + Marzani (2013)

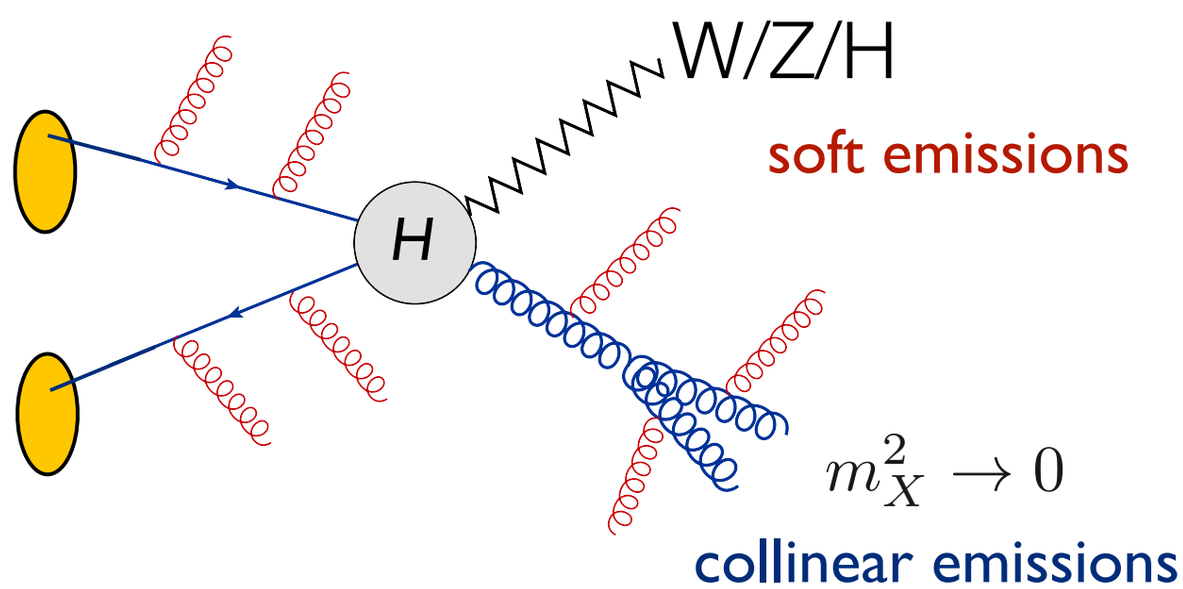
→ see talk by A. Ferroglia

# Threshold production of W/Z/H + jet @ N$^3$LL+NLO

Extended factorization formula

$$d\sigma = H\,\phi \otimes \phi \otimes S \otimes J$$

holds for associated production of a high-$p_T$ boson with a jet, in the limit where the extra radiation is such that $m_X^2 \to 0$




Main features of the prediction:

- first resummation of a **3-jet observable** at N$^3$LL+NLO
- threshold terms expected to give good approximation to exact NNLO result

$$\hat{s}\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{u}\,\mathrm{d}\hat{t}} = \hat{\sigma}_{ab}^{(0)}(\hat{u},\hat{t},\mu)\,\hat{H}_{ab}(\hat{u},\hat{t},\mu)\int \mathrm{d}k\,J_c(m_X^2 - 2E_J k,\mu)\,S_{ab}(k,\mu)$$

Becher, Schwartz (2009); + Lorentzen (2011, 2012)

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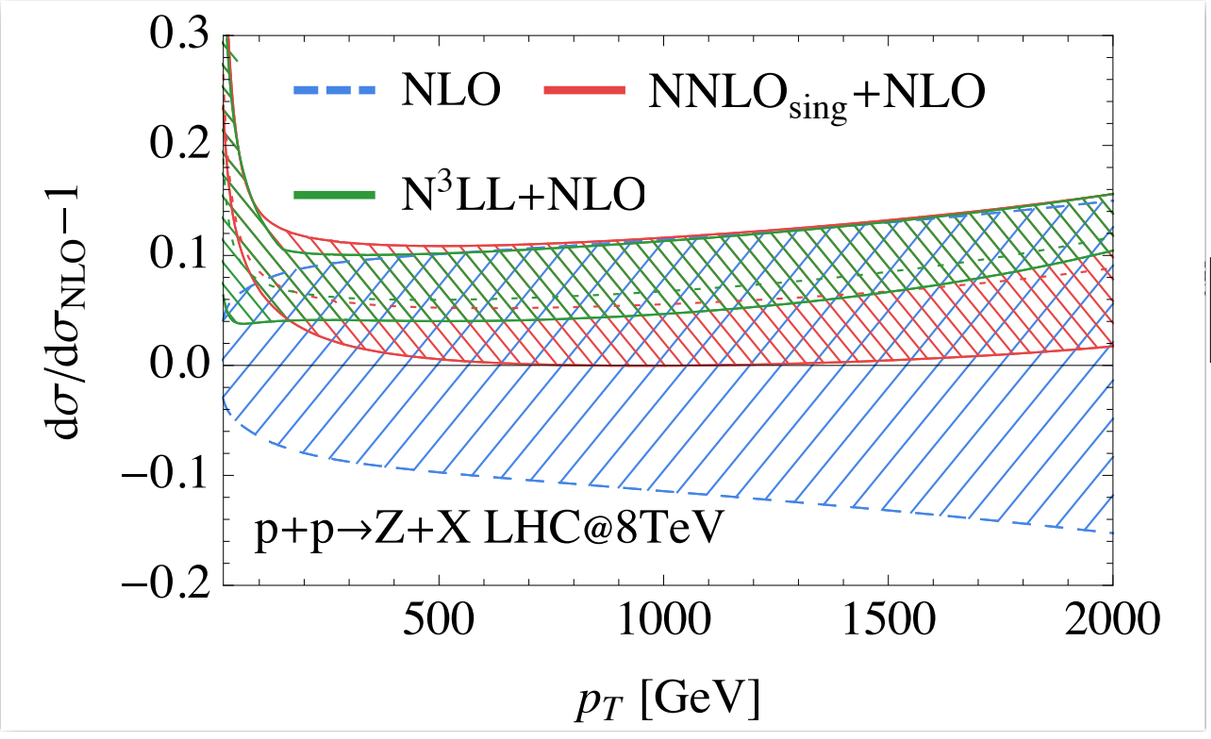
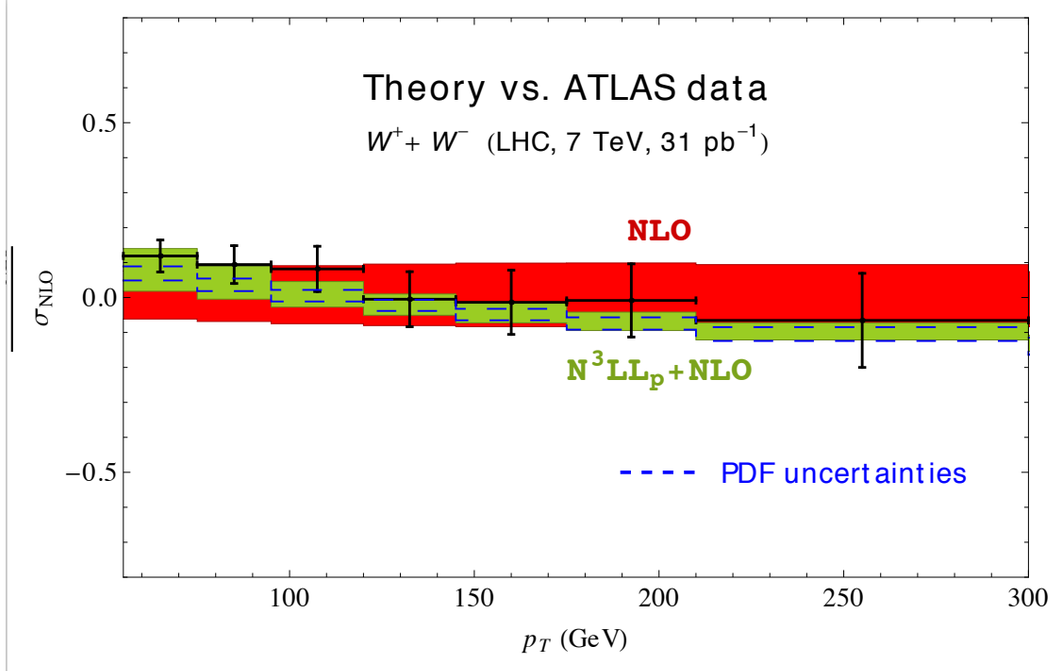



Becher, Bell, Lorentzen, Marti (2013)
Becher @ SCET2014




Becher, Lorentzen, Schwartz (2012)

# “Anomalous” factorization theorems

**Electroweak Sudakov resummation** — Chiu, Golf, Kelley, Manohar: 0712.0396 (PRD)

**Transverse momentum spectra**

- W/Z production — Becher, MN: 1007.4005 (EPJC); + Wilhelm: 1109.6027 (JHEP)
- $x_\perp$-dependent PDFs — Gehrmann, Lübbert, Yang: 1209.0682 (PRL), 1403.6451
- Higgs production — Chiu, Jain, Neill, Rothstein: 1202.0814 (JHEP); Becher, MN, Wilhelm: 1212.2621 (JHEP)
- top-pair production — Li, Li, Shao, Yang, Zhu: 1208.5774 (PRL), 1307.2464 (PRD)

**Exclusive production in jet bins**

- Higgs production with jet veto — Banfi, Salam, Zanderighi: 1203.5773 (JHEP); + Monni: 1206.4998 (PRL); Becher, MN: 1205.3806 (JHEP); + Rothen: 1307.0025 (JHEP); Stewart, Tackmann, Walsh, Zuberi: 1307.1808; Alioli, Walsh: 1311.5234 (JHEP)
- Jet veto for off-shell Higgs — Moult, Stewart: 1405.5534
- W/Z/H + jet production — Liu, Petriello: 1210.1906 (PRD), 1303.4405 (PRD)
- SCET and small-x physics (BFKL) — Fleming: 1404.5672; Stewart @ SCET 2014

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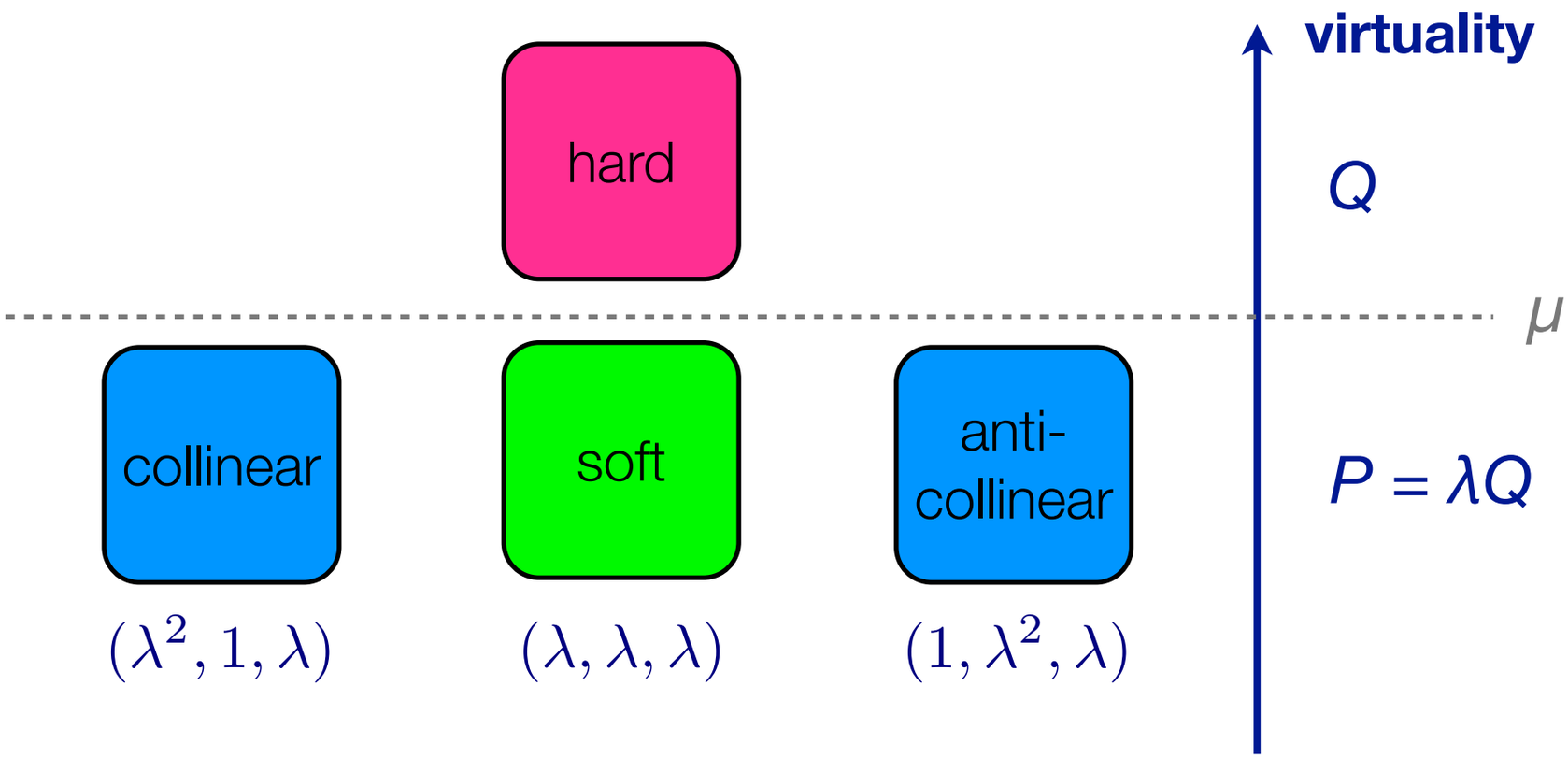
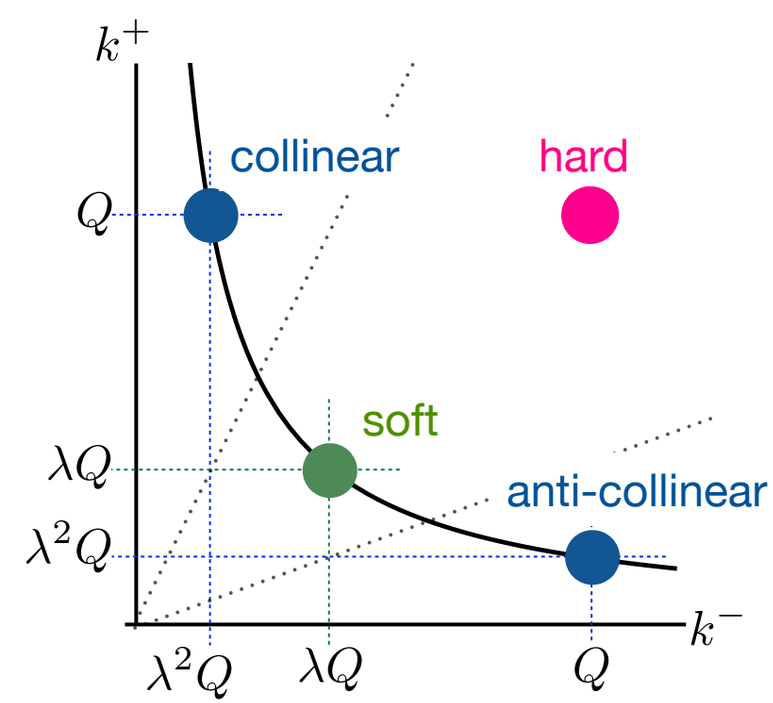
# “Anomalous” factorization of two scales




- For observables sensitive to transverse momentum, standard (ultra-)soft modes do not contribute
- How to factorize?

$$\frac{1}{2}\ln^2\frac{Q^2}{P^2} = \underbrace{\frac{1}{2}\ln^2\frac{Q^2}{\mu^2}}_{\text{hard}} - \underbrace{\frac{1}{2}\ln^2\frac{P^2}{\mu^2}}_{\text{collinear}} + \,?$$



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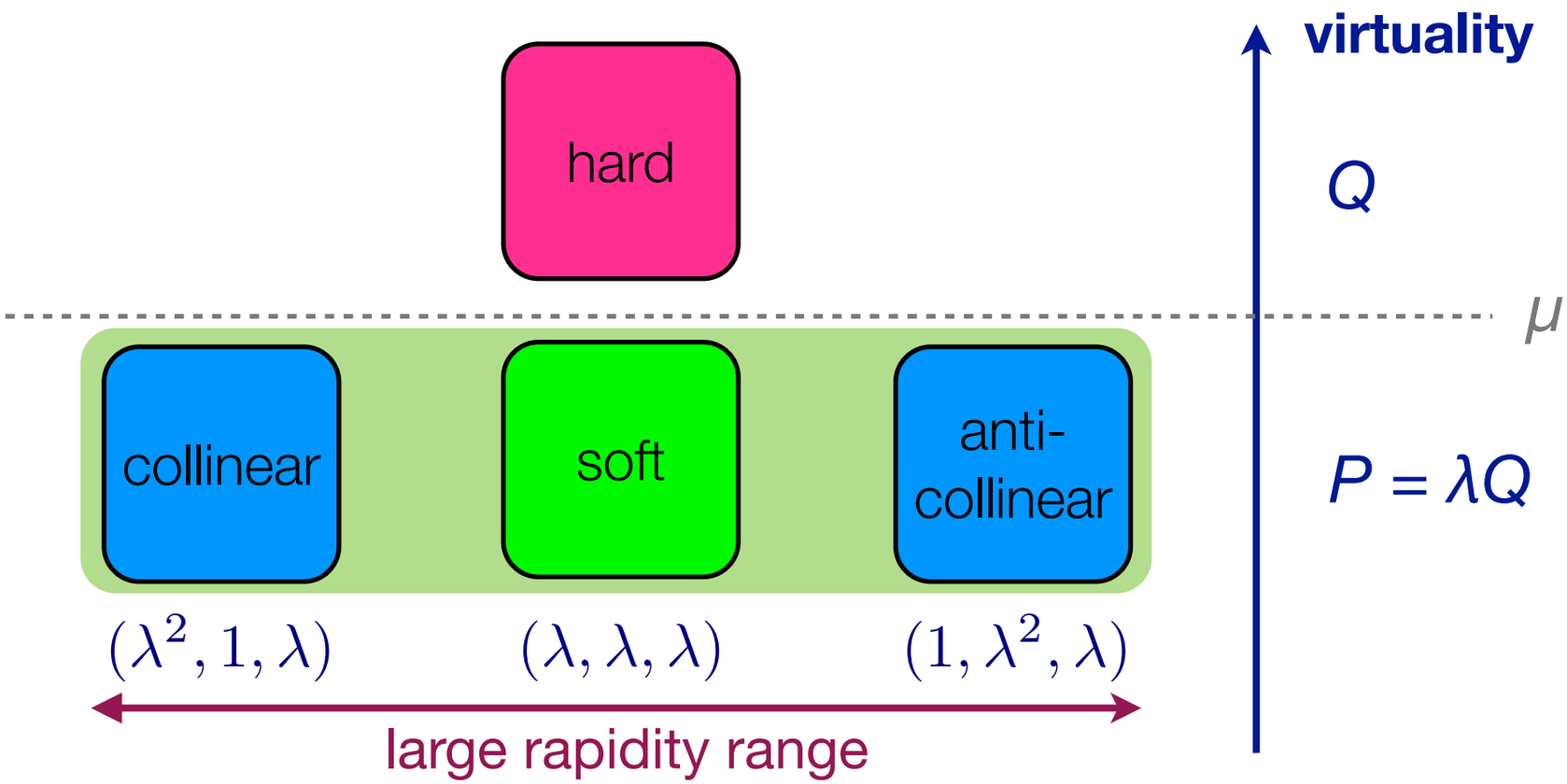
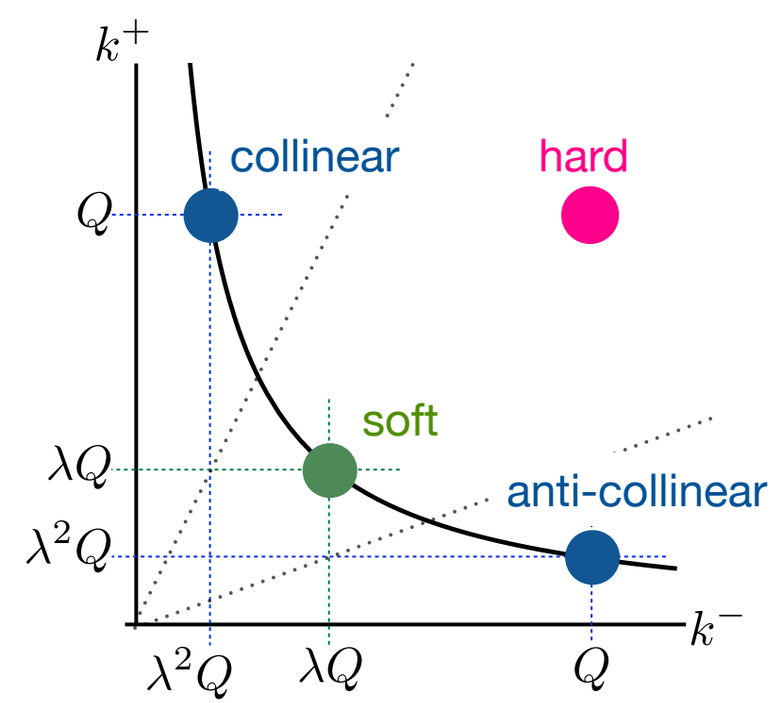



- **Anomaly** of classical SCET Lagrangian provides another source of **large rapidity logarithms**

Becher, MN (2010); Chiu, Jain, Neill, Rothstein (2011, 2012)

$$\frac{1}{2}\ln^2\frac{Q^2}{P^2} = \underbrace{\frac{1}{2}\ln^2\frac{Q^2}{\mu^2}}_{\text{hard}} - \underbrace{\frac{1}{2}\ln^2\frac{P^2}{\mu^2}}_{\text{collinear}} - \underbrace{\ln\frac{P^2}{\mu^2}\ln\frac{Q^2}{P^2}}_{\text{anomalous}}$$



# Transverse momentum spectra of W/Z/h

Transverse momentum distributions in Drell-Yan processes $pp \to V + X$ with V=W/Z/H require resummation of large logarithms

anomalous contribution (pure power in $x_T$ space)

**SCET factorization formula** (with $\xi_{1,2} = e^{\pm y} M/\sqrt{s}$ ):

$$\frac{d^2\sigma}{dq_T^2\, dy} = \sum_{i,j} H_{ij}(-M^2,\mu) \int d^2x_\perp\, e^{-iq_\perp\cdot x_\perp} \left(\frac{x_T^2 M^2}{4e^{-2\gamma_E}}\right)^{-F_{q\bar{q}}(x_T^2,\mu)}$$

$$\times\, B_{i/N_1}(\xi_1, x_T^2, \mu)\, B_{j/N_2}(\xi_2, x_T^2, \mu) + \mathcal{O}\left(\frac{q_T^2}{M^2}\right)$$

Becher, MN (2010)

- **two sources** of large Sudakov logarithms $\sim \alpha_s^n \ln^{2n}(M/q_T)$
- collinear **beam functions** describe the transverse structure of the proton:

Stewart, Tackmann, Waalewijn (2009)

$$B_{i/N}(\xi, x_T^2, \mu) = \sum_j \int_\xi^1 \frac{dz}{z}\, I_{i\leftarrow j}(z, x_T^2, \mu)\, \phi_{j/N}(\xi/z, \mu) + \mathcal{O}(\Lambda_{\rm QCD}^2\, x_T^2)$$

- factorization formula provides **consistent definition of transverse-position dependent PDFs**, which has been checked to 2-loop order!

Gehrmann, Lübbert, Yang (2012, 2014)

# Transverse momentum spectra of W/Z/h

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SCET factorization theorem is **equivalent to standard QCD factorization theorem** by Collins, Soper, Sterman (1984), however:

- could derive **last missing ingredient** (coefficient $A_3$) needed for NNLL resummation from a 2-loop calculation (anomaly equation) Becher, MN (2010)
- obtain **model-independent prediction** for the leading, **logarithmically enhanced long-distance correction** to the spectrum:

$$F_{ij}(x_T^2) \to F_{ij}(x_T^2) + \Lambda_{NP}^2 x_T^2$$

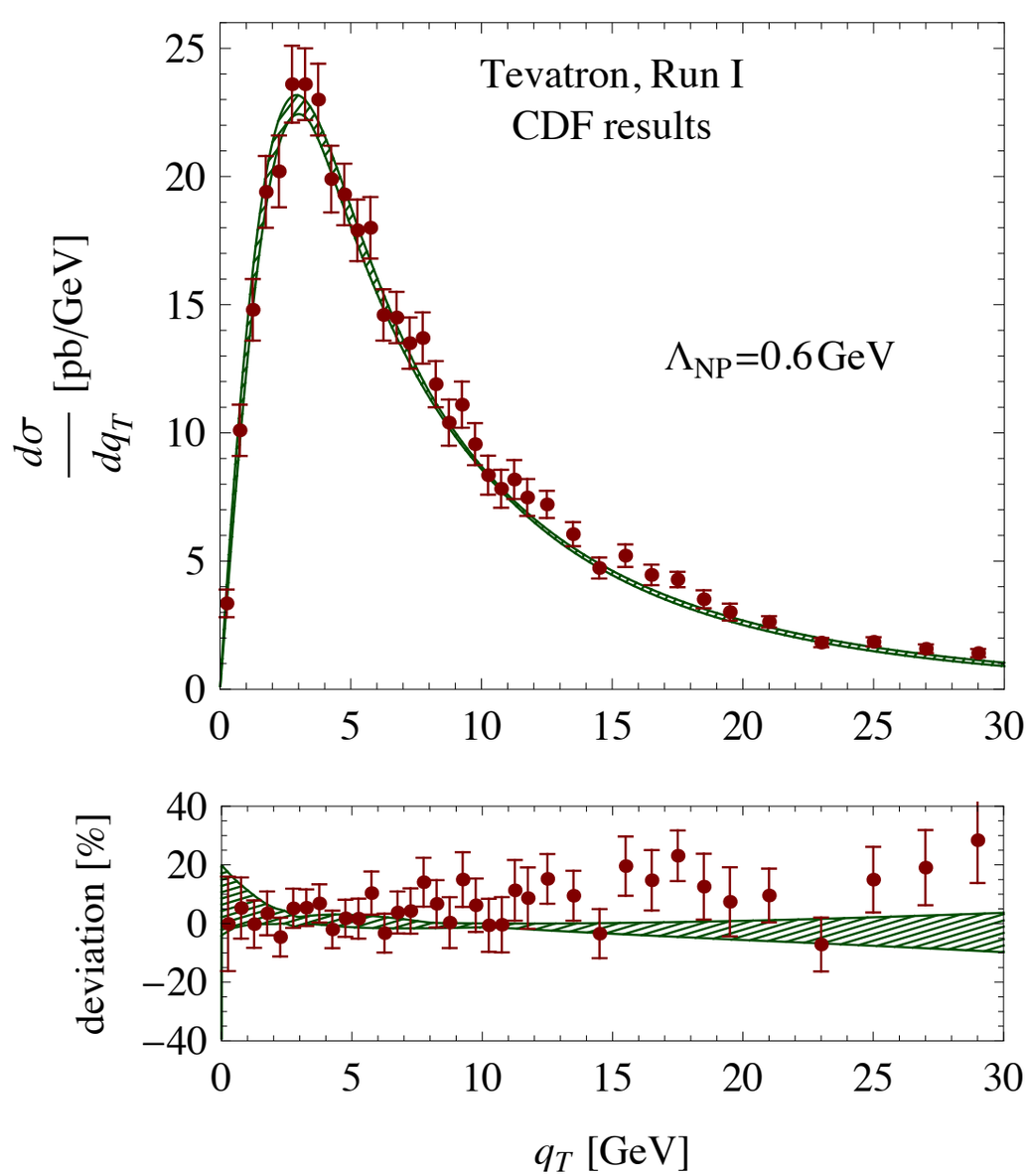
Becher, Bell (2013)

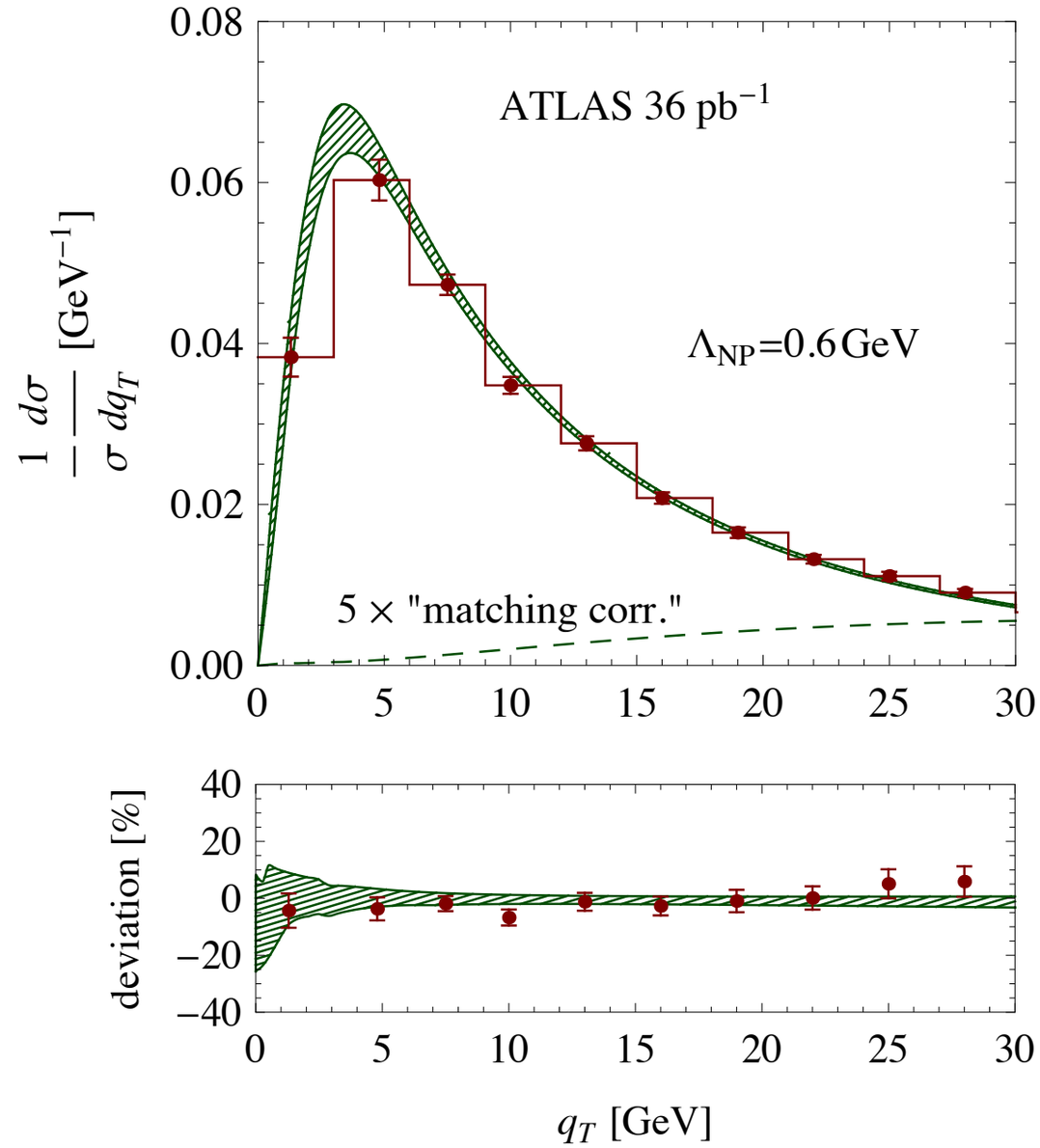
where universal parameter $\Lambda_{NP}^2$ only depends on the color representation

# Z-boson production @ NNLL+NLO

Becher, MN, Wilhelm (2011)

First complete calculation of Z-boson production at this order:



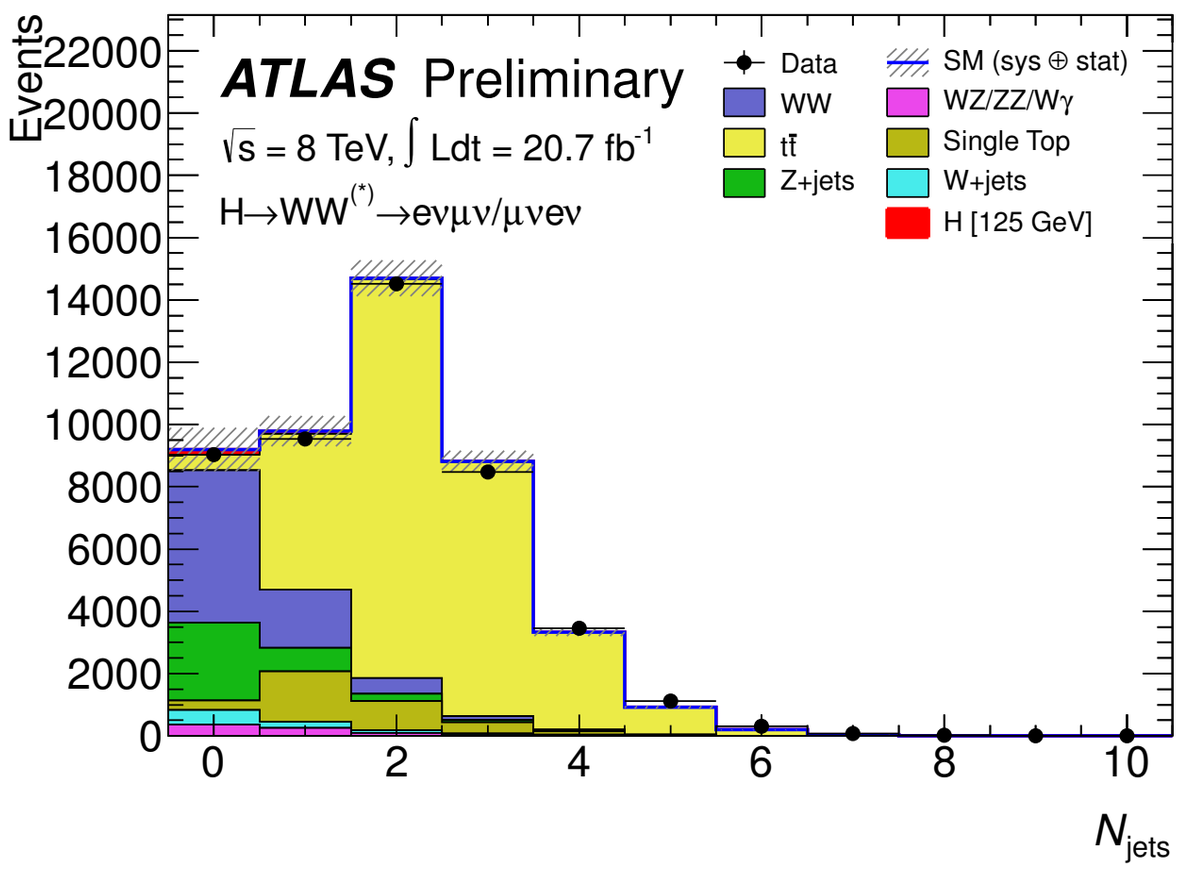

→ upgrade to NNLL+NNLO and improved treatment of long-distance corrections is possible (work in progress)

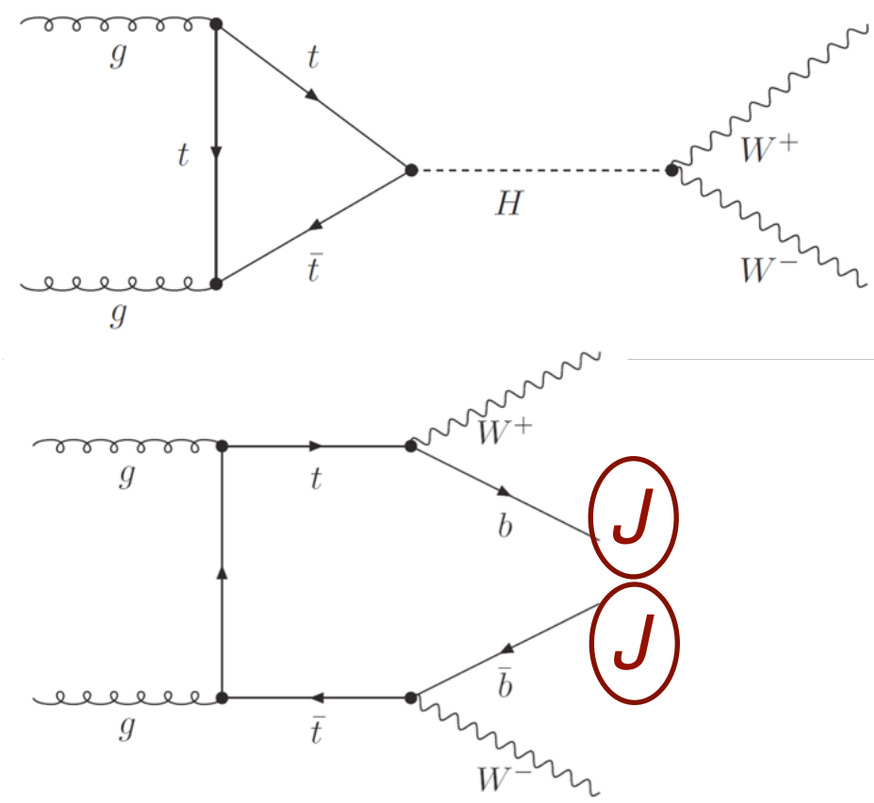
→ public code CuTe available at: http://cute.hepforge.org

# Higgs production with jet veto

Higgs search in $h \to WW^*$ channel is done in **jet bins**, since background is very different if Higgs is produced in association with jets

Need precise cross-section predictions for Higgs + *n* jets, in particular for *n*=0 bin (jet veto), where $p_T^{\rm jet} < p_T^{\rm veto} \sim 20 - 30\,{\rm GeV}$



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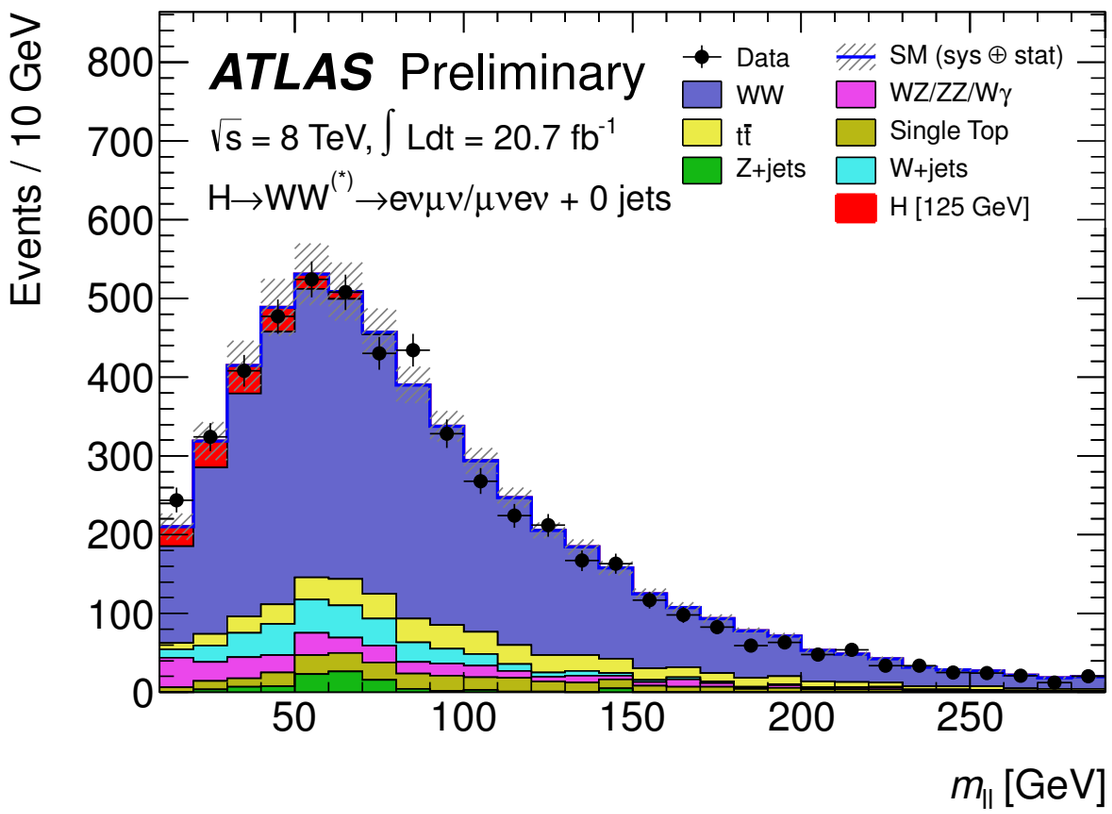
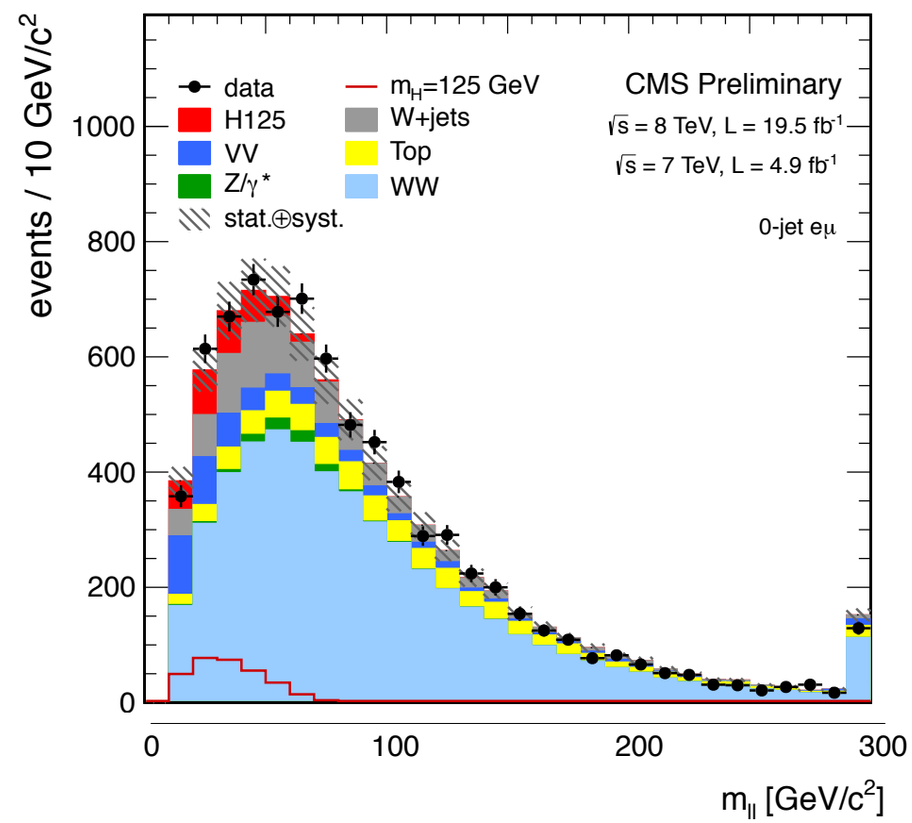


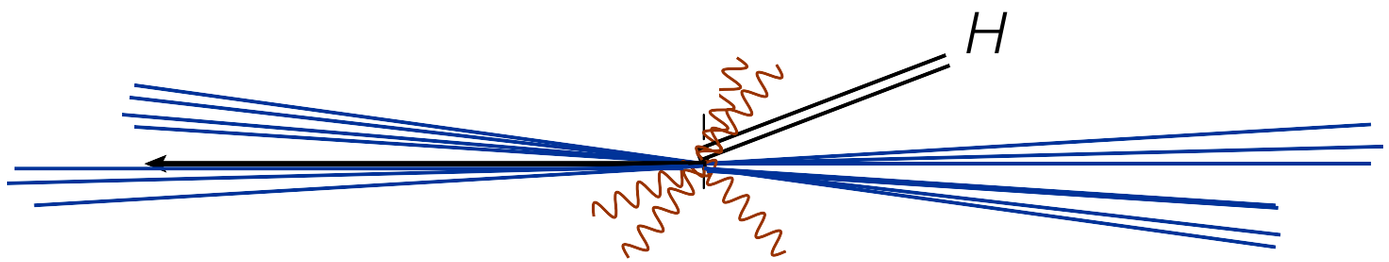



# Higgs production with jet veto

**SCET factorization theorem** for jet-veto cross section, valid for $R = \mathcal{O}(1)$:

$$\frac{d\sigma(p_T^{\rm veto})}{dy} = H(-m_H^2,\mu) \left(\frac{m_H}{p_T^{\rm veto}}\right)^{-2F_{gg}(p_T^{\rm veto},R,\mu)} B_{g/p}(\xi_1, p_T^{\rm veto}, R, \mu)\, B_{g/p}(\xi_2, p_T^{\rm veto}, R, \mu)$$

Becher, MN (2012); + Rothen (2013)

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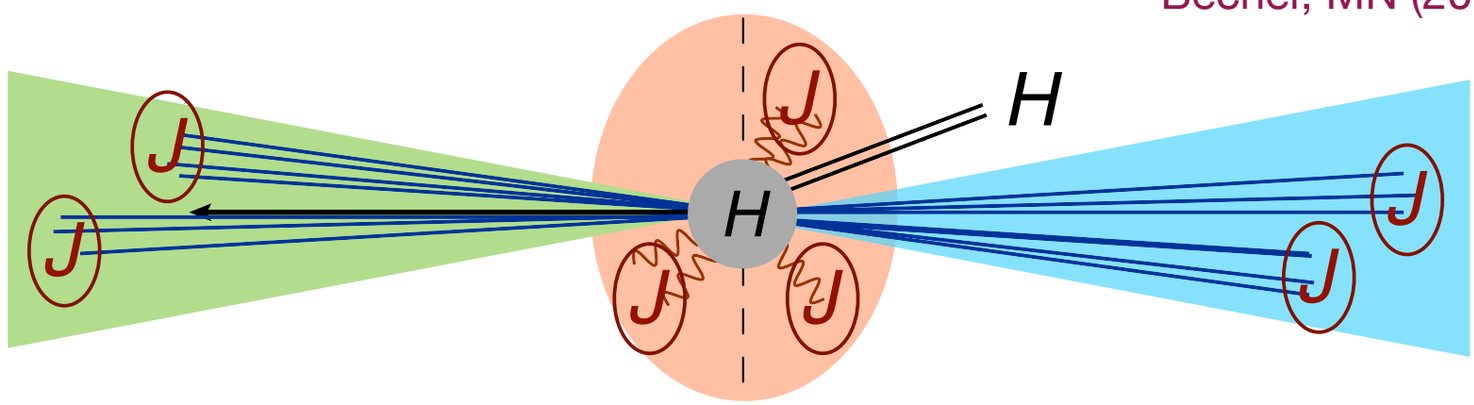
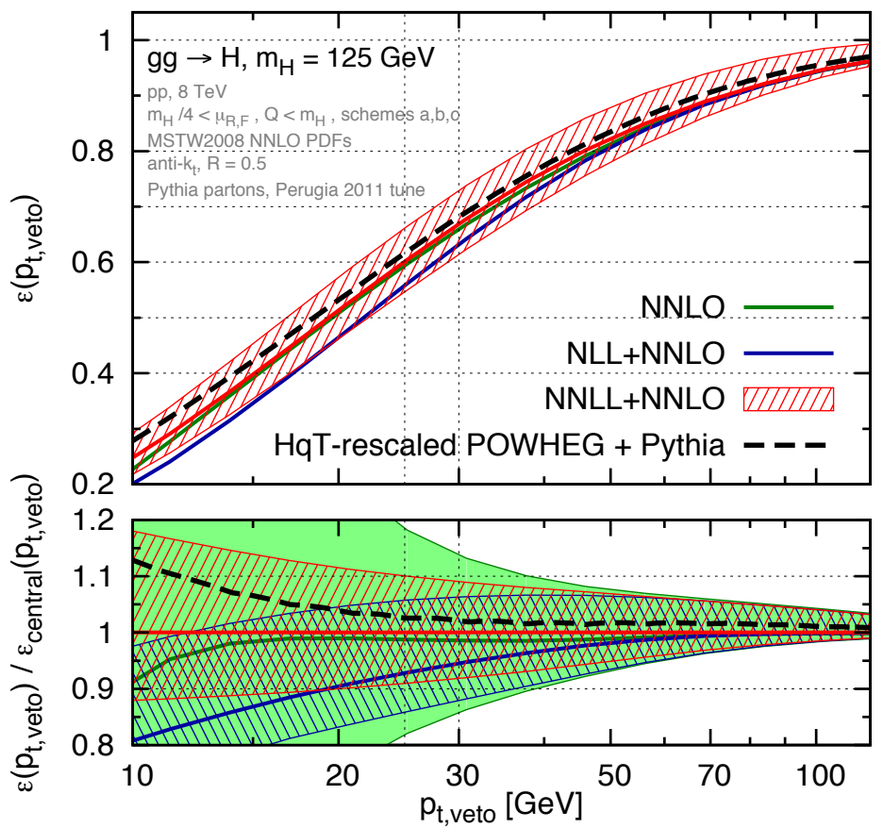



- sequential jet recombination algorithms ($k_T$, anti-$k_T$, C/A) **clusters soft and collinear radiation separately**, as long as *R* is not parametrically large
- results in **simple factorization formula**
- anomalous exponent and beam functions depend on jet radius *R*

Banfi, Monni, Salam, Zanderighi (2012)

# Higgs jet-veto cross section @ $N^3LL_p$+NNLO

Accurate predictions with similar accuracy available from different groups:

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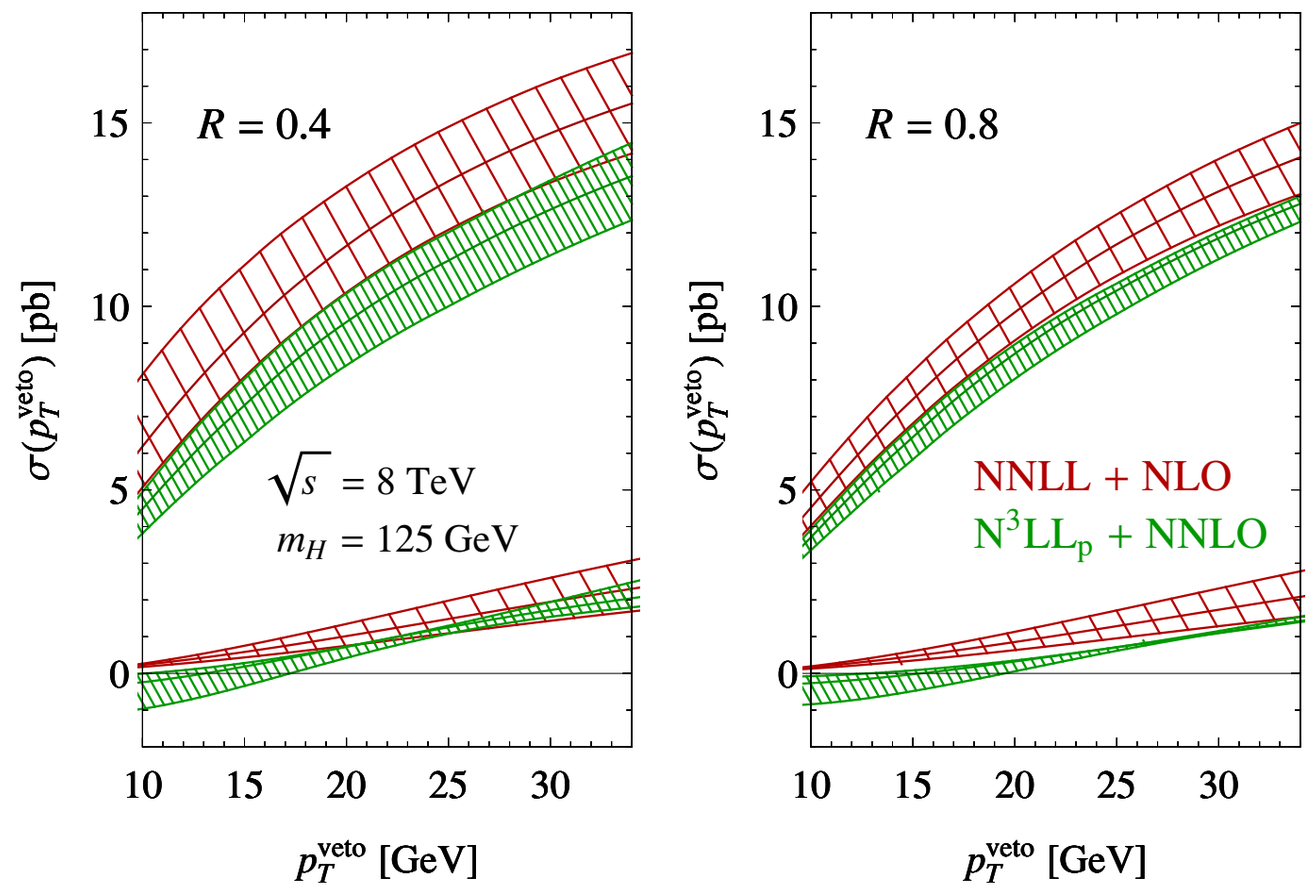


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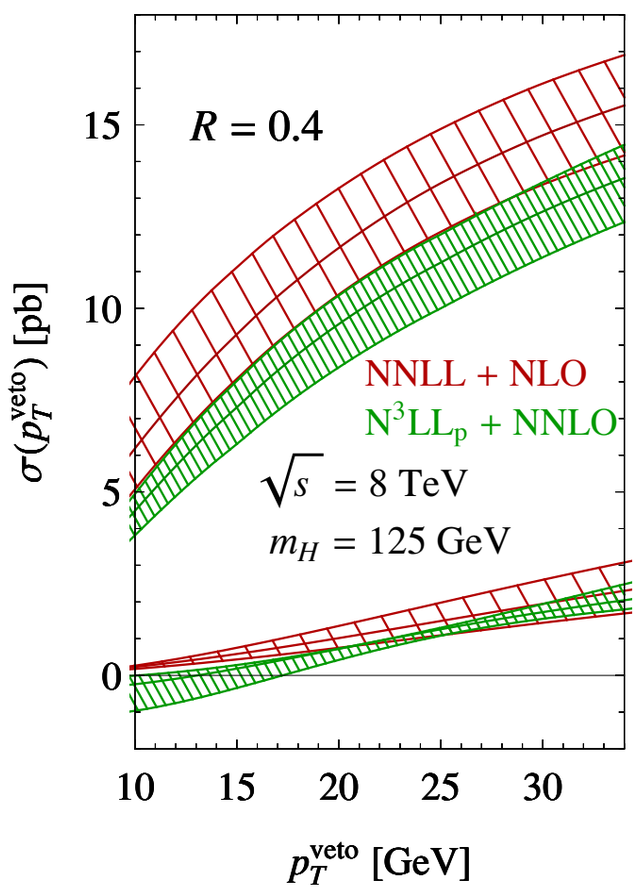


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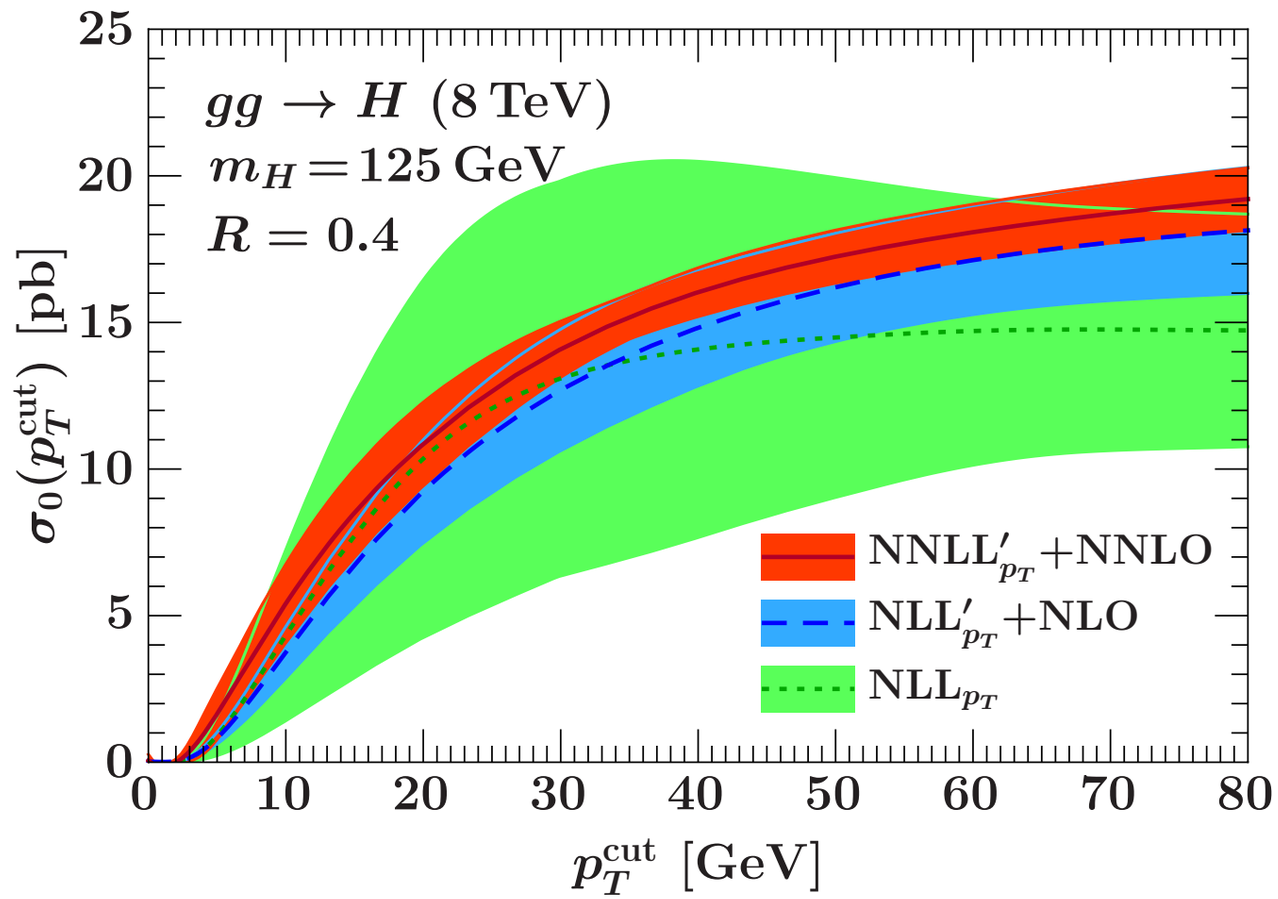


Stewart, Tackmann, Walsh, Zuberi (2013)

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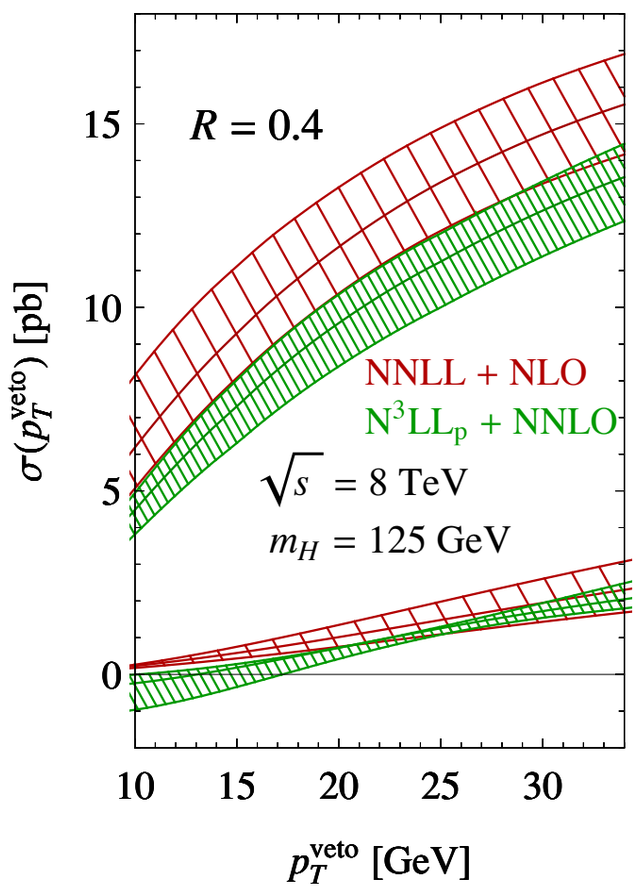


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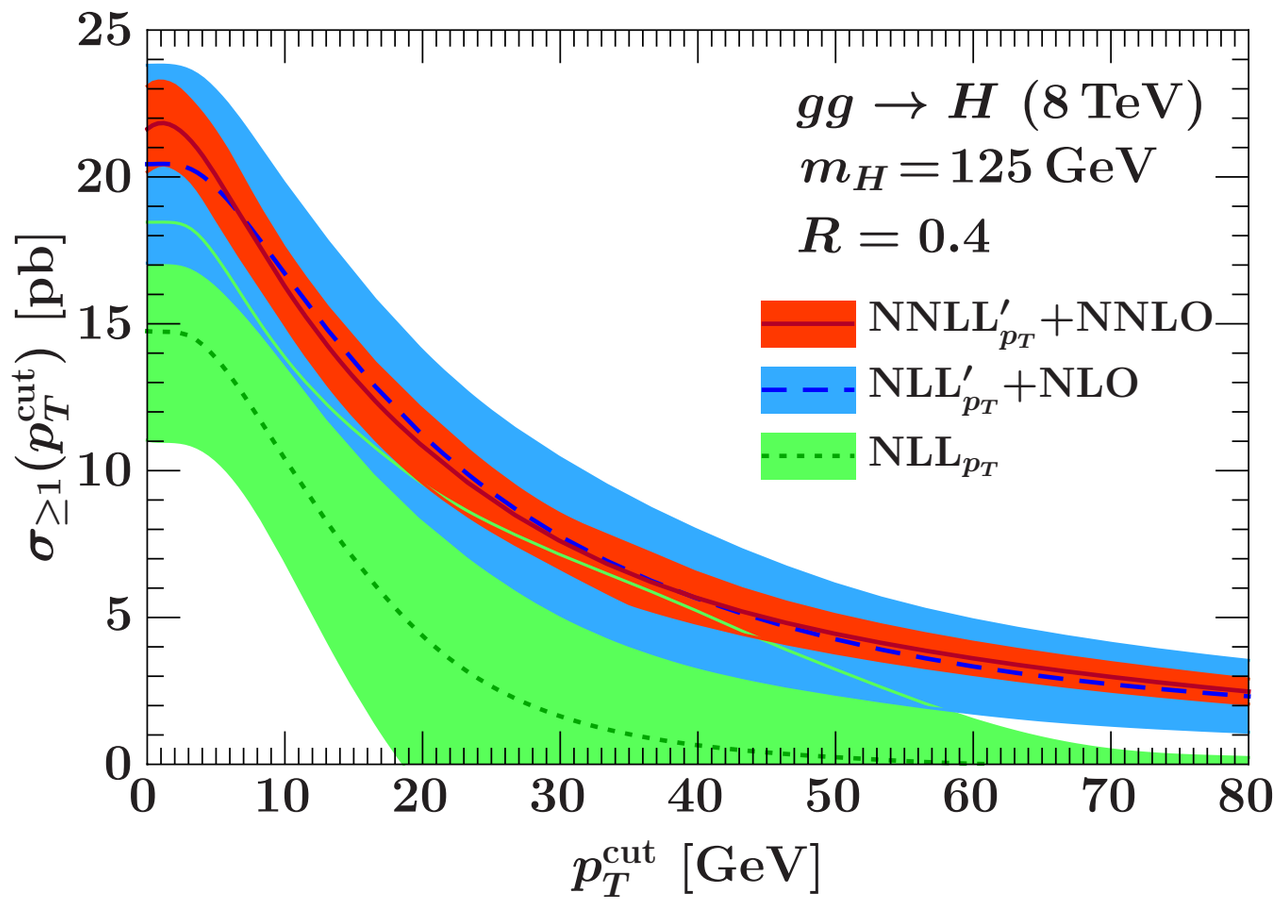



Stewart, Tackmann, Walsh, Zuberi (2013)

- subtracting the jet-veto cross section from the total inclusive cross section one obtains the cross section for Higgs + (≥1 jet) production

[see also: Boughezal, Liu, Petriello, Tackmann, Walsh (2013)]

# Exclusive Higgs + jet production @ NLL'+NLO

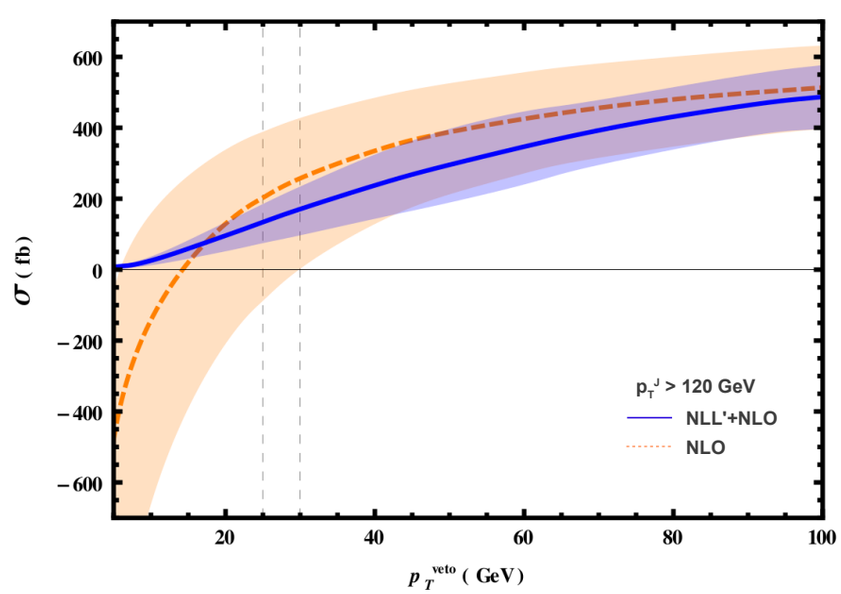
**SCET factorization theorem** for H+1-jet cross section valid to NLL' accuracy:

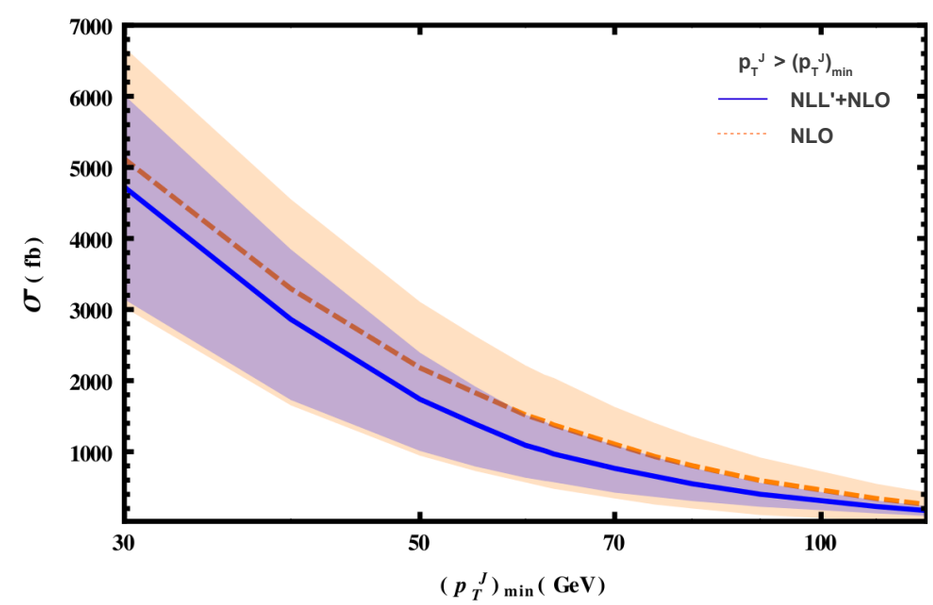
$$\mathrm{d}\sigma_{\mathrm{NLL}'} = \mathrm{d}\Phi_H \mathrm{d}\Phi_J \, \mathcal{F}(\Phi_H, \Phi_J) \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b \frac{1}{2\hat{s}} (2\pi)^4 \delta^4 (q_a + q_b - q_J - q_H)$$
$$\times \bar{\sum_{\mathrm{spin}}} \bar{\sum_{\mathrm{color}}} \mathrm{Tr}(H \cdot S) \, \mathcal{I}_{a,i_a j_a} \otimes f_{j_a}(x_a) \, \mathcal{I}_{b,i_b j_b} \otimes f_{j_b}(x_b) J_J(R)$$

Liu, Petriello: (2013)

- derivation of factorization formula **far more non-trivial**
- formula no longer holds in higher orders, where **non-global logarithms** arise and should be resummed

Dasgupta, Salam (2001, 2002); Banfi, Marchesini, Smye (2002); Kelley, Schwartz, Schabinger, Zhu (2011); Schwartz, Zhu (2014); Hornig, Lee, Stewart, Walsh, Zuberi (2011)



# Conclusions

SCET provides efficient tools for addressing difficult collider-physics problems: factorization and resummation

Many applications exist for Drell-Yan processes (production of Z, W, H, sleptons) and (s)top-quark pair production, both in threshold limit and for transverse momentum spectra

Jet observables (so far W/Z/H + *n* jets with *n*=0,1) are currently being considered by several goups

In some cases, SCET methods have pushed the limits of what has been accomplished using traditional techniques