SCET predictions for the Higgs transverse-momentum distribution and jet-veto cross section

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erc
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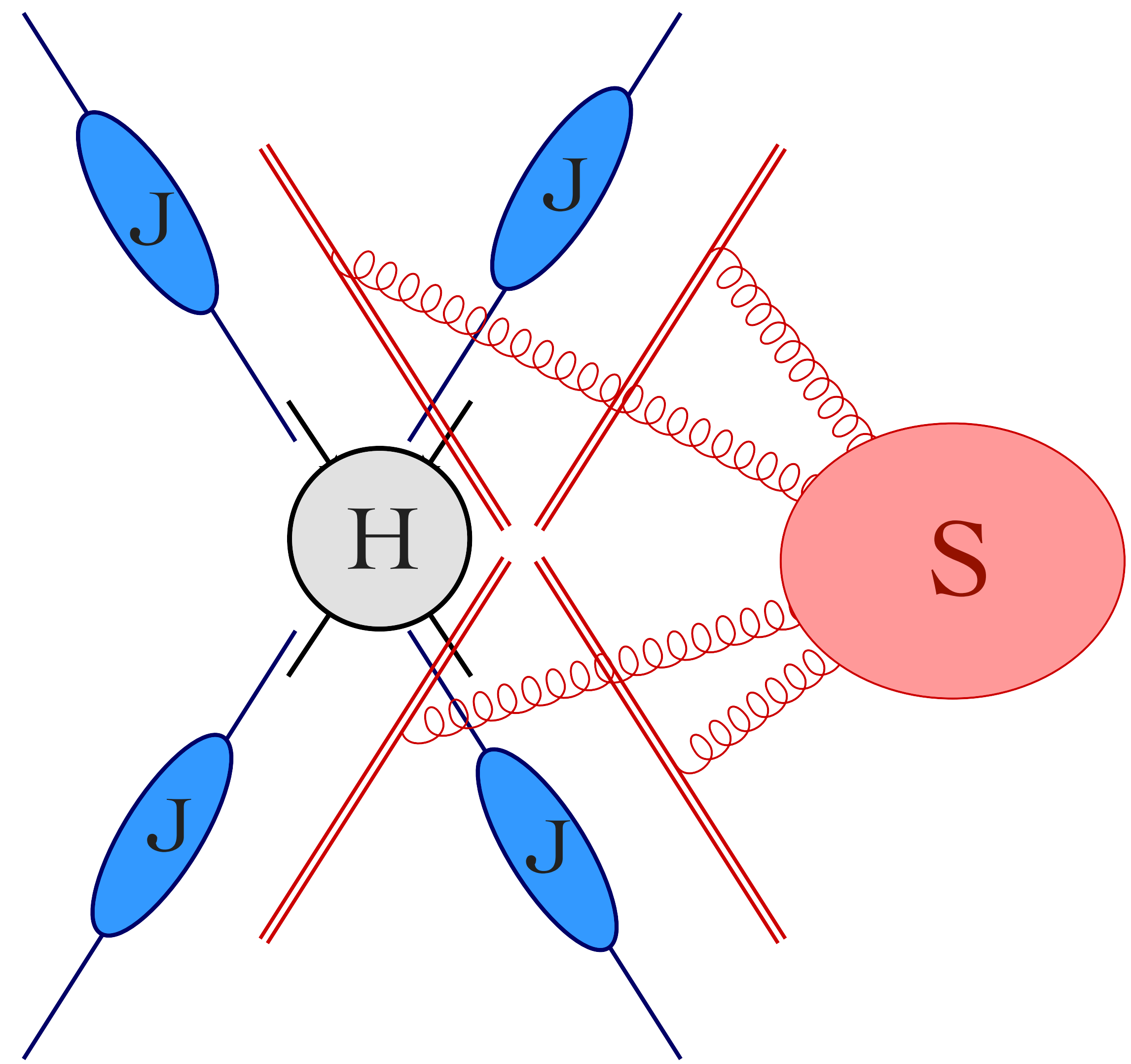
An Effective Field Theory Assault on the
Zeptometer Scale: Exploring the Origins of
Flavor and Electroweak Symmetry Breaking

Introduction

- Hadron-collider processes are prime examples of **multi-scale problems** involving several hierarchical scales
- Due to **light-like nature** of these processes, scale separation cannot be performed using a conventional OPE
- Instead, any field-theory description of these processes 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**

Scale separation in Sudakov problems

Separation of **short-distance** and **long-distance contributions** is subtle:

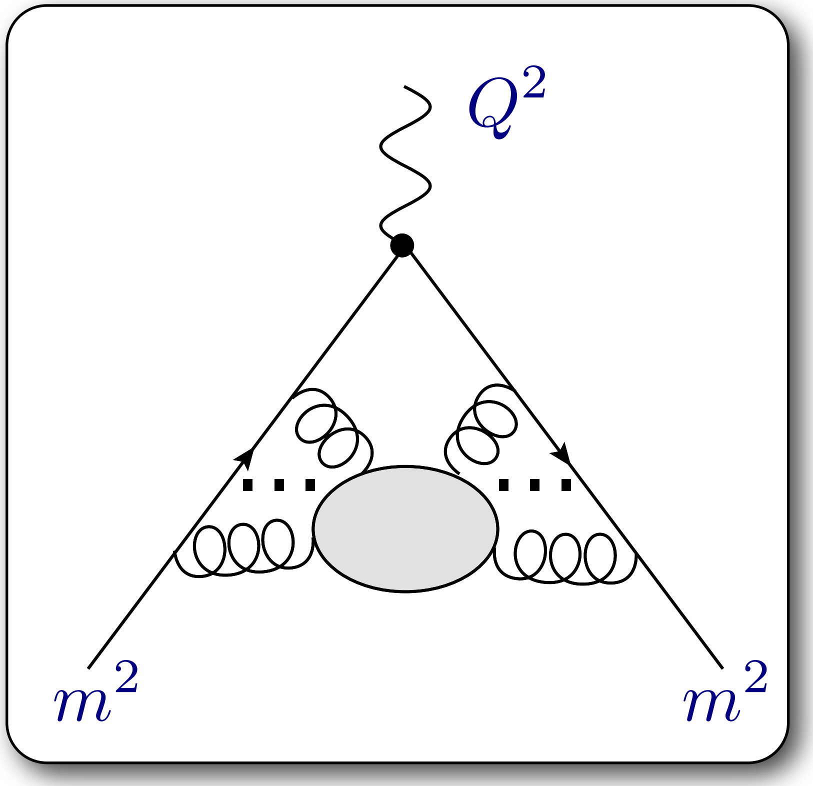
- usually, large logarithms in QFT arise from hierarchy between a long-distance (soft) scale *m* and a short-distance (hard) scale $Q \gg m$:

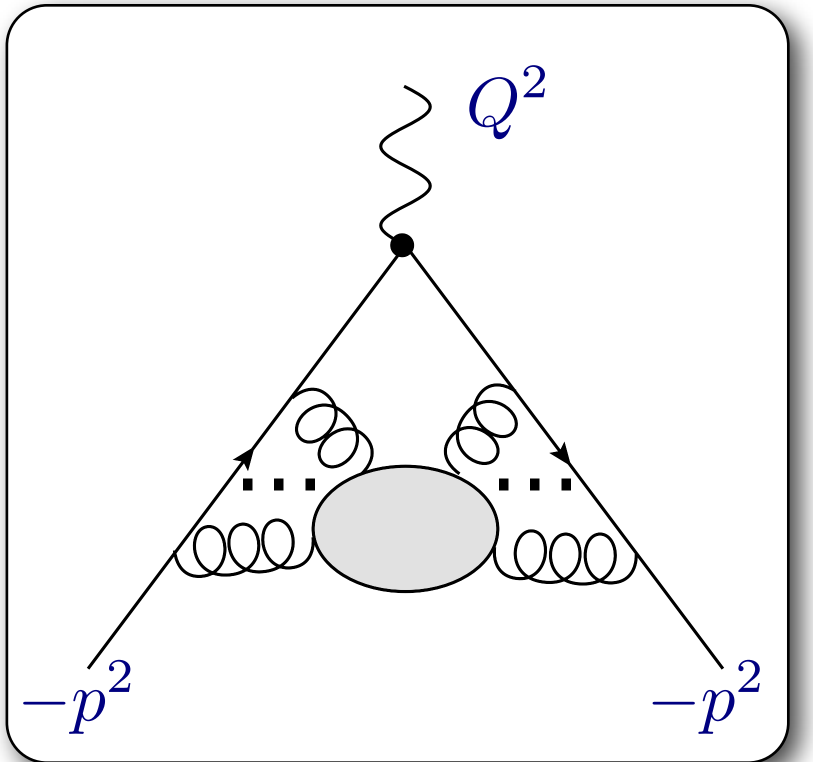
$$\ln \frac{Q^2}{m^2} = \ln \frac{Q^2}{\mu^2} + \ln \frac{\mu^2}{m^2}$$

- in Sudakov problems, dependence on the **hard scale Q** is affected by **long-distance physics**:

$$F(Q)\big|_{\text{on shell}} = 1 - \frac{C_F \alpha_s}{4\pi} \left(\ln^2 \frac{Q^2}{m^2} + \dots \right)$$

$$F(Q)\big|_{\text{off shell}} = 1 - \frac{C_F \alpha_s}{4\pi} \left(2 \ln^2 \frac{Q^2}{-p^2} + \dots \right)$$





Scale separation in Sudakov problems

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

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

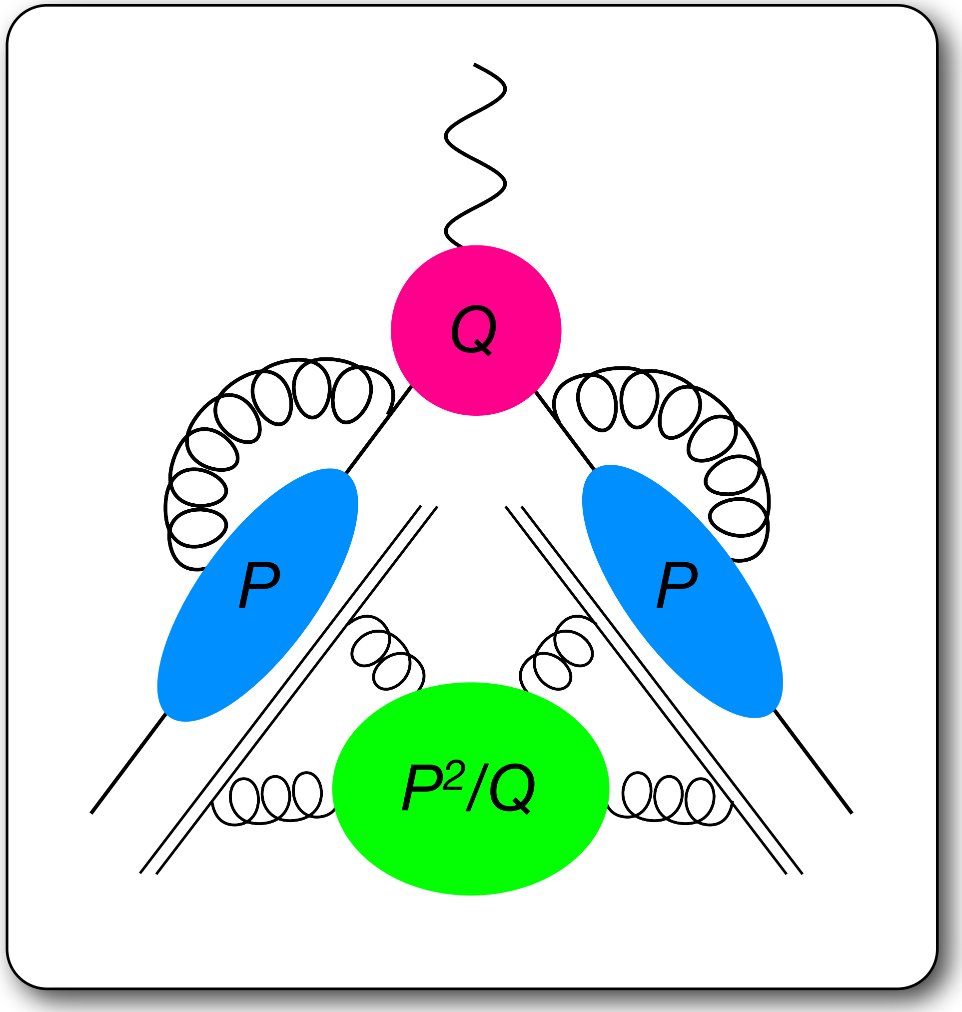
Elegant method for (re-) deriving and using **factorization theorems** in collider and heavy-flavor physics, several times going beyond existing calculations

- in few cases, **new factorization theorems** have been established: **Higgs cross section with a jet veto is an important example!**

SCET-I: Correlated scales

Sudakov problems with scale hierarchy $Q \gg P$ really involve **three correlated scales**:

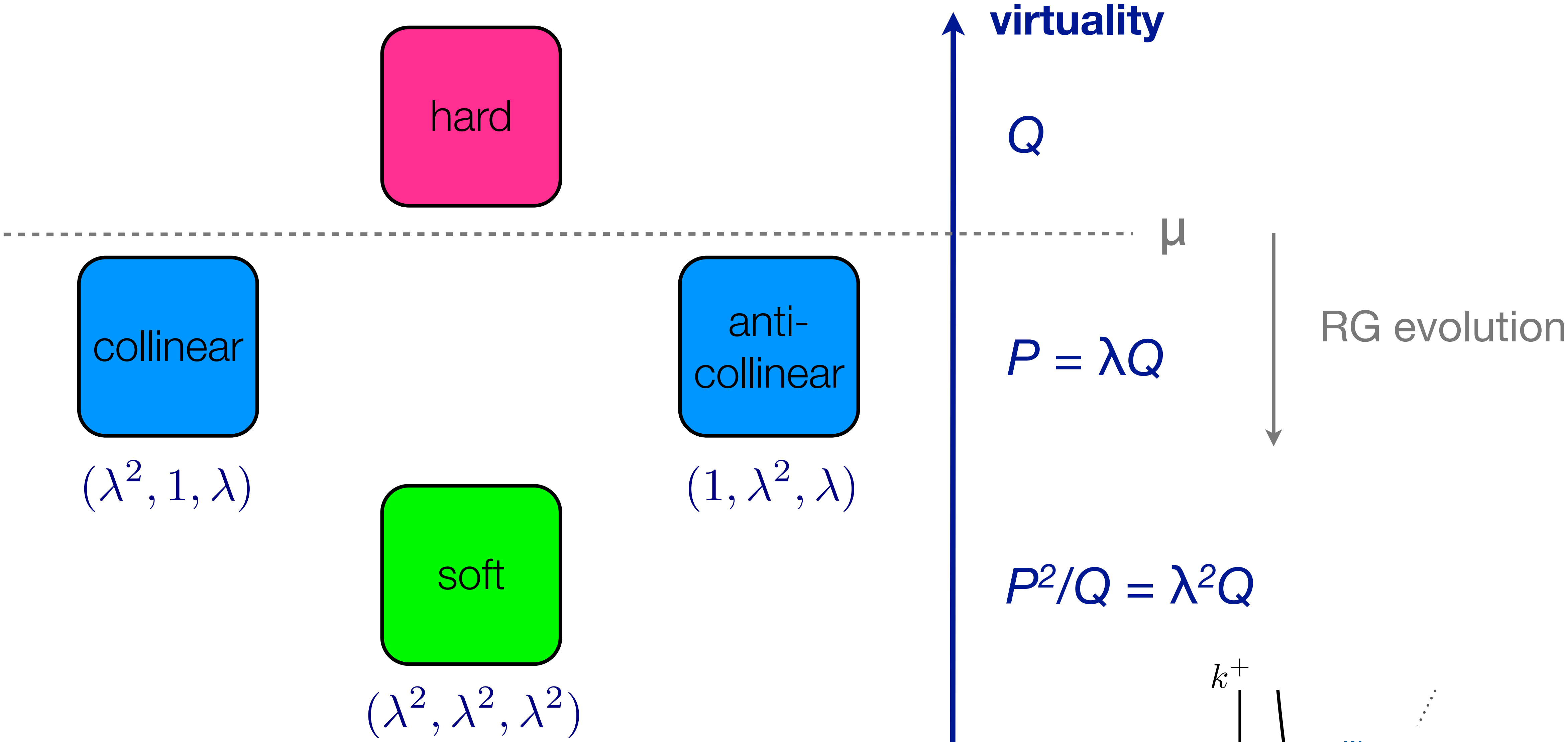
- hard scale Q
- (anti-)collinear scale P
- soft scale P^2/Q

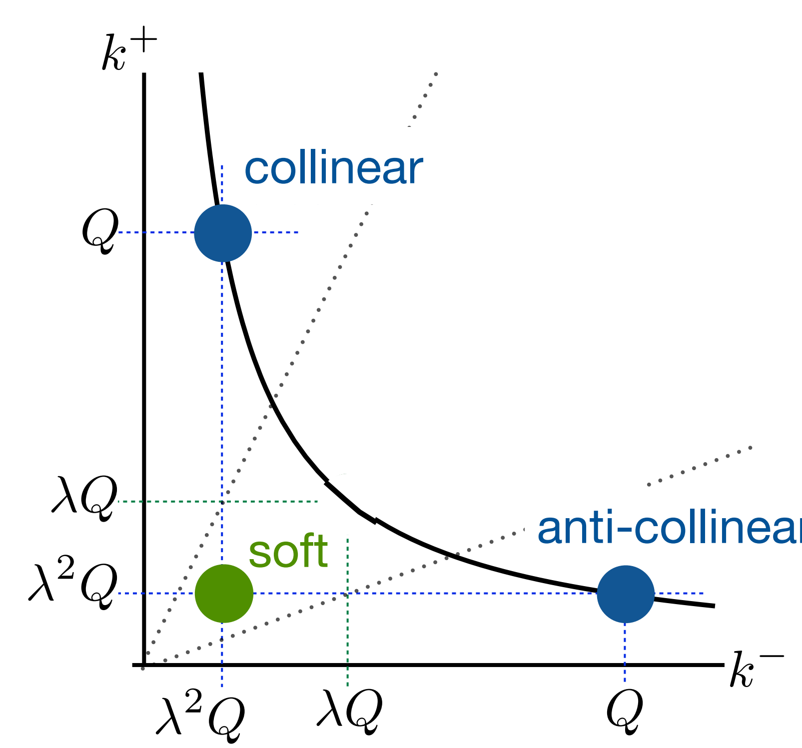


Region analysis of off-shell Sudakov form factor reveals that (with $P^2 = -p^2$):

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

SCET-I: Correlated scales

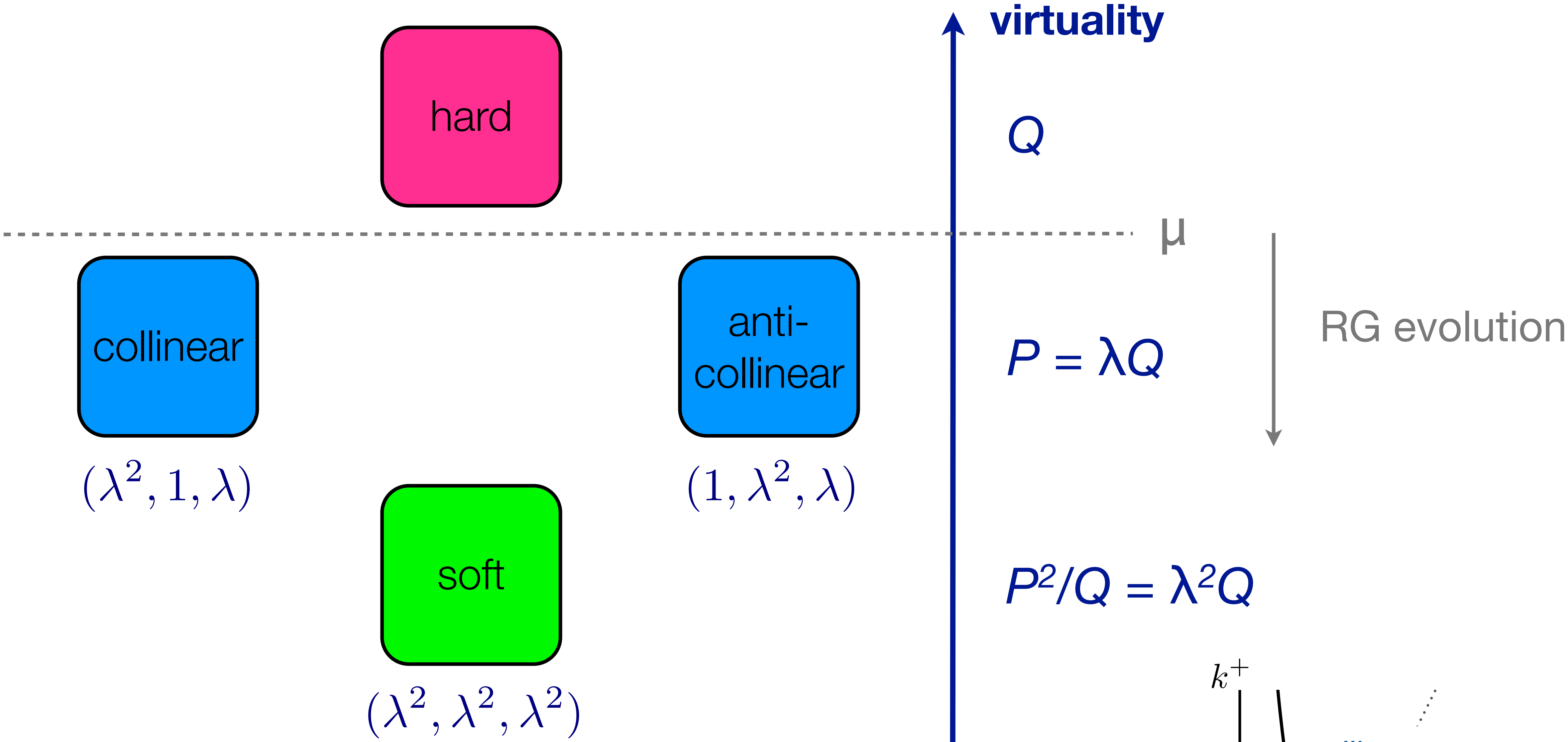


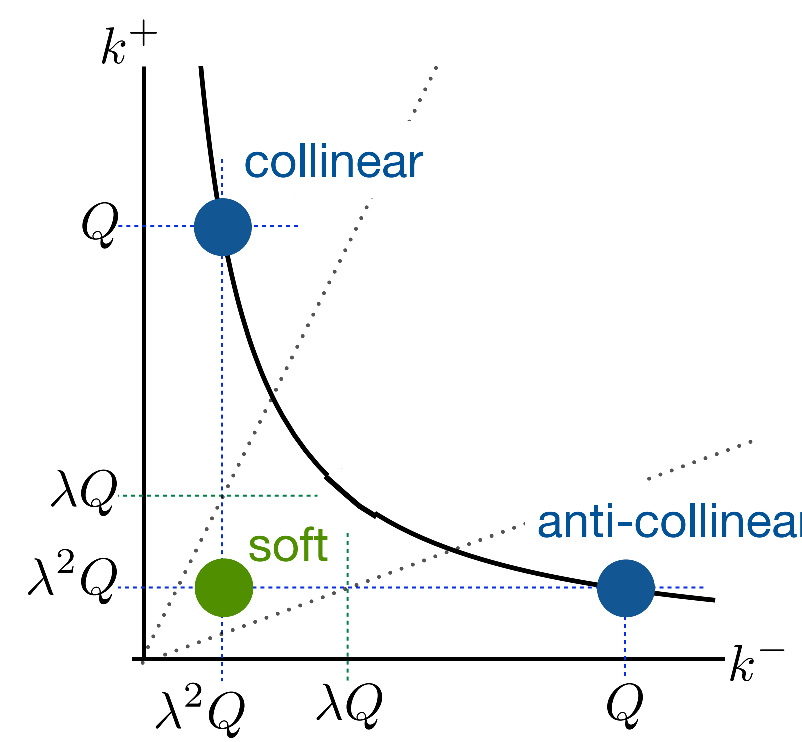


Generic **SCET-I factorization theorem:**

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

SCET-I: Correlated scales





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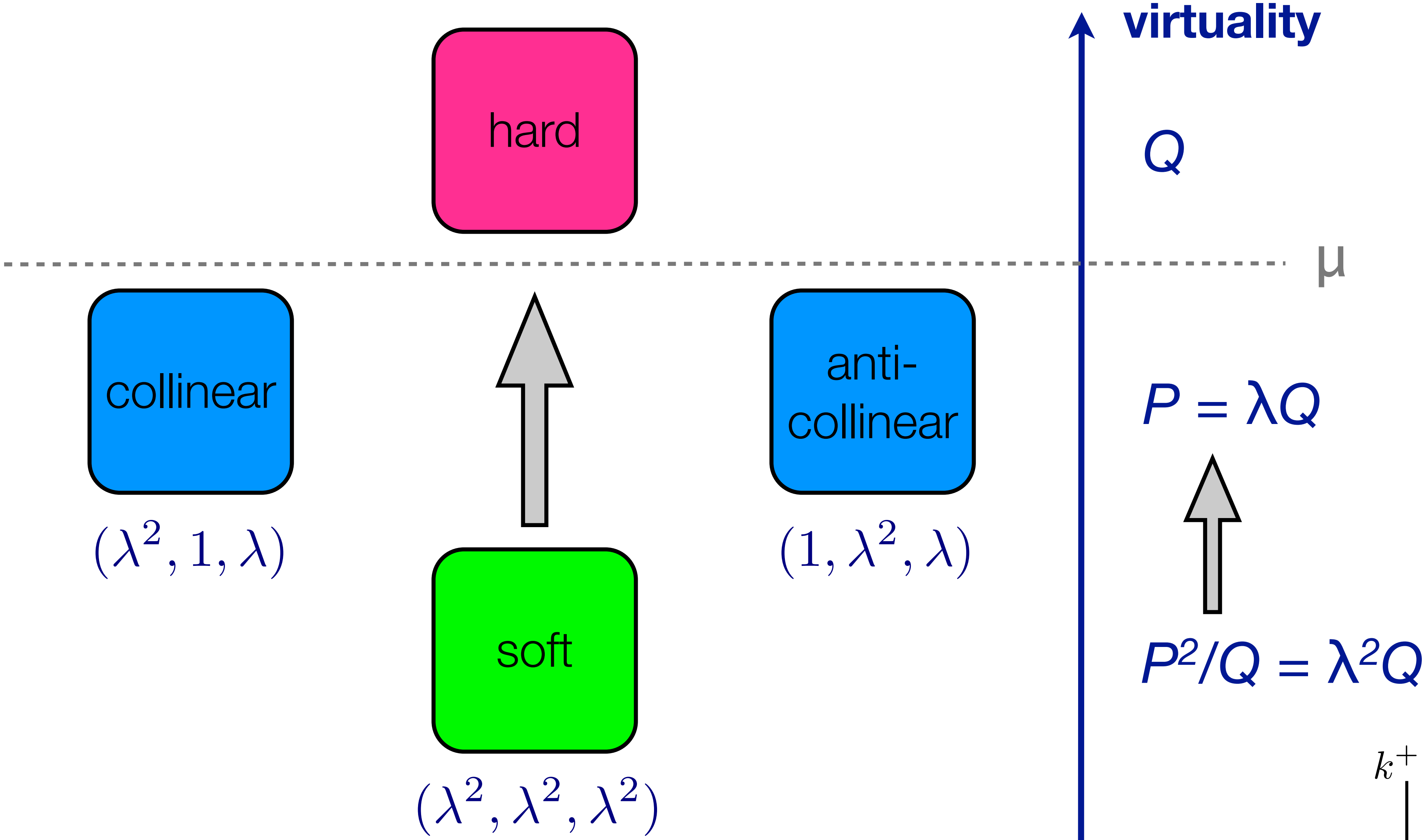
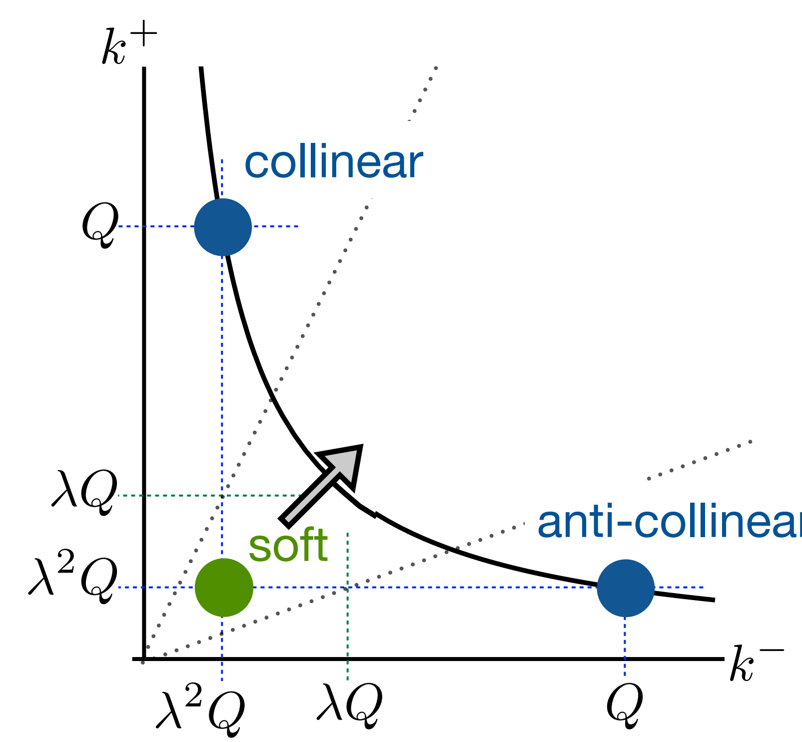
SCET-I: Correlated scales





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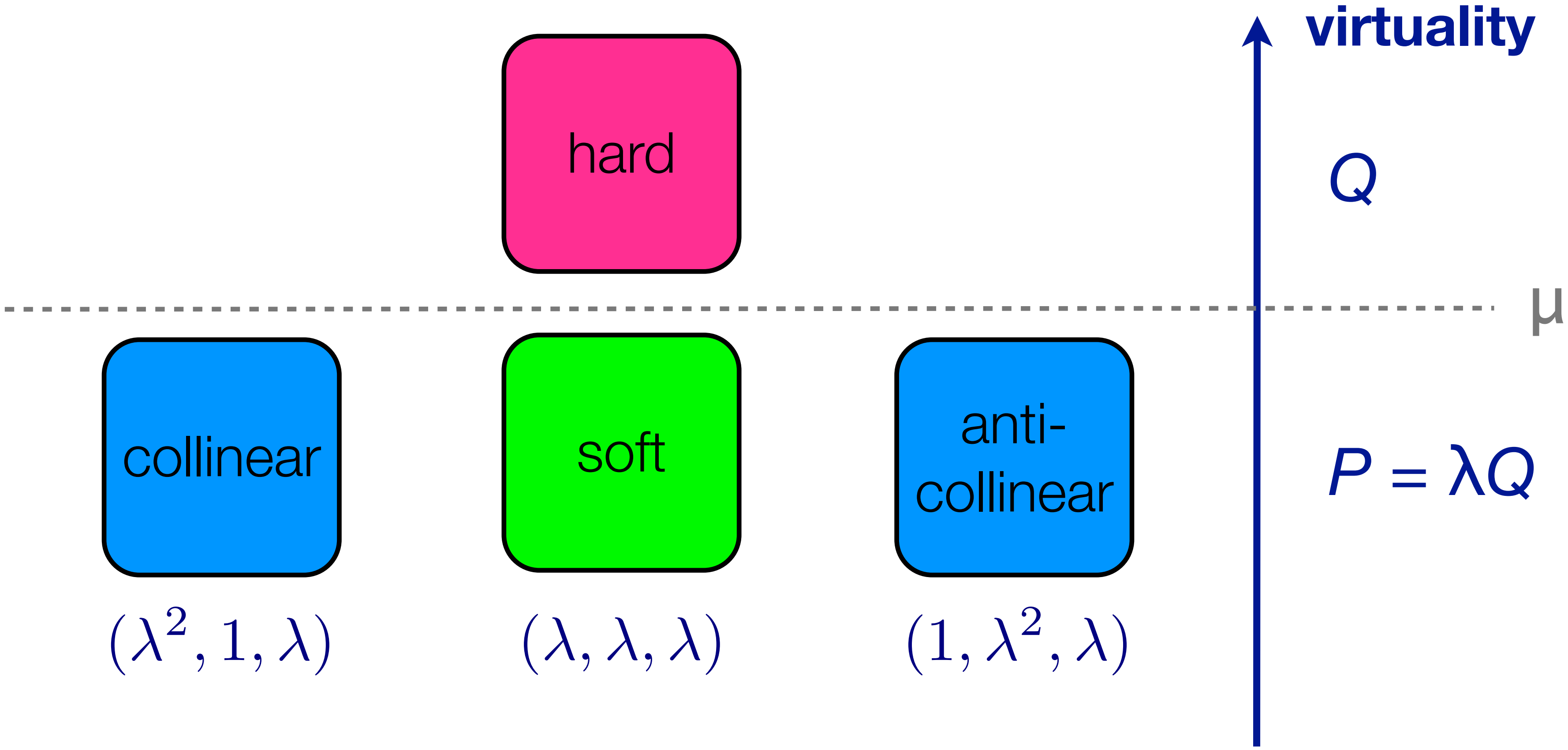
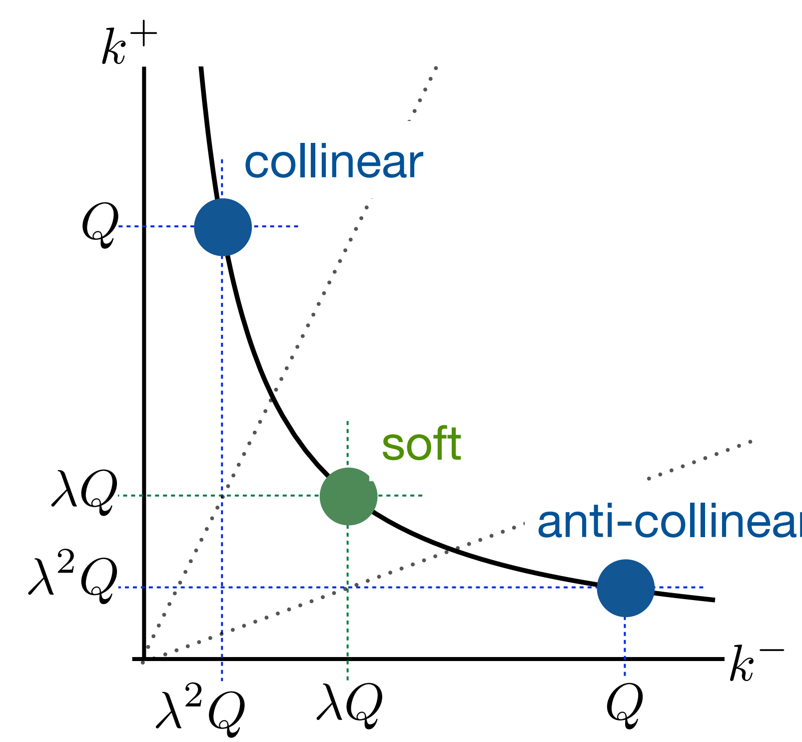
SCET-II: Absence of the third (soft) scale



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

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



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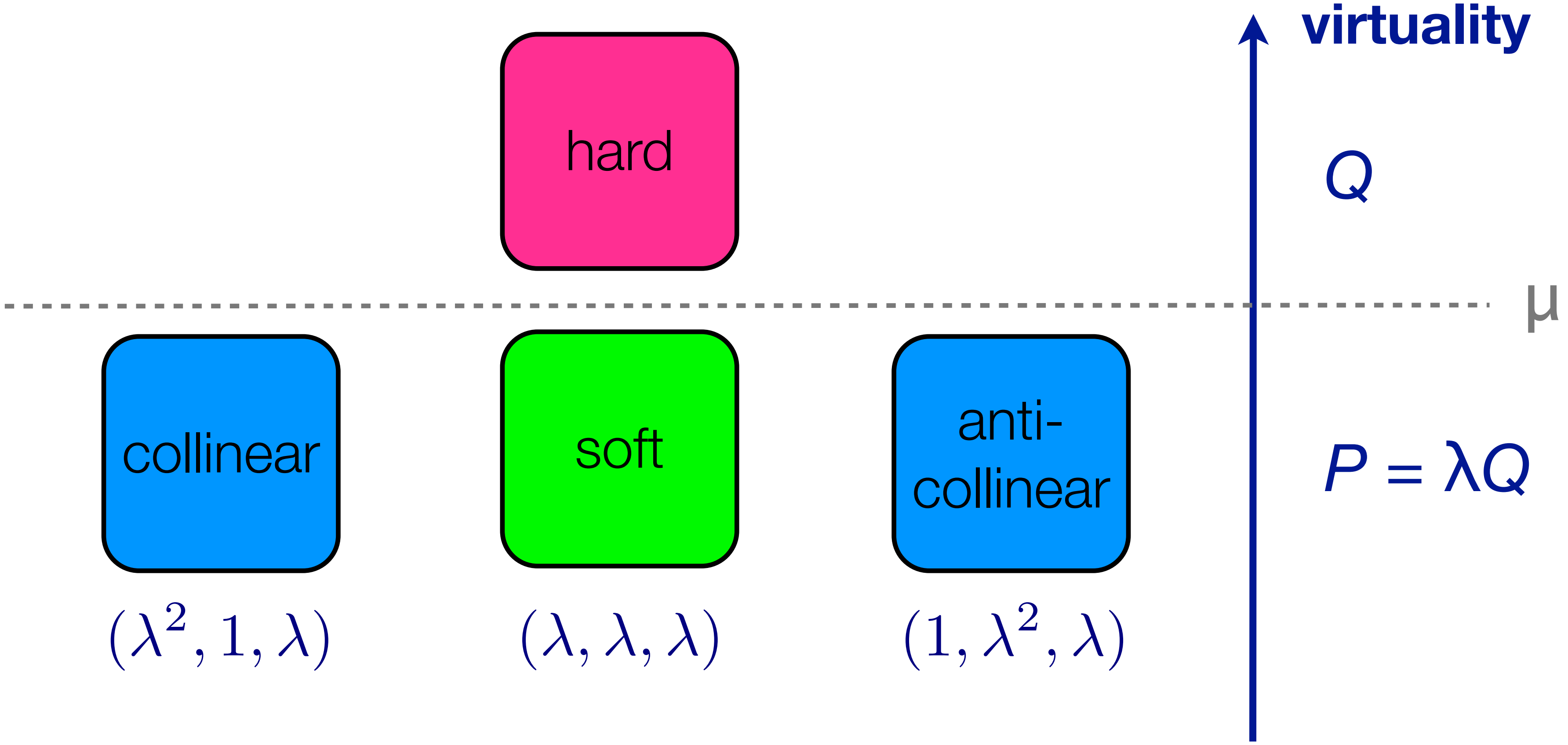

- Problem is cured by an anomaly of the effective theory SCET-II: **collinear factorization anomaly**

Becher, MN: 1007.4005

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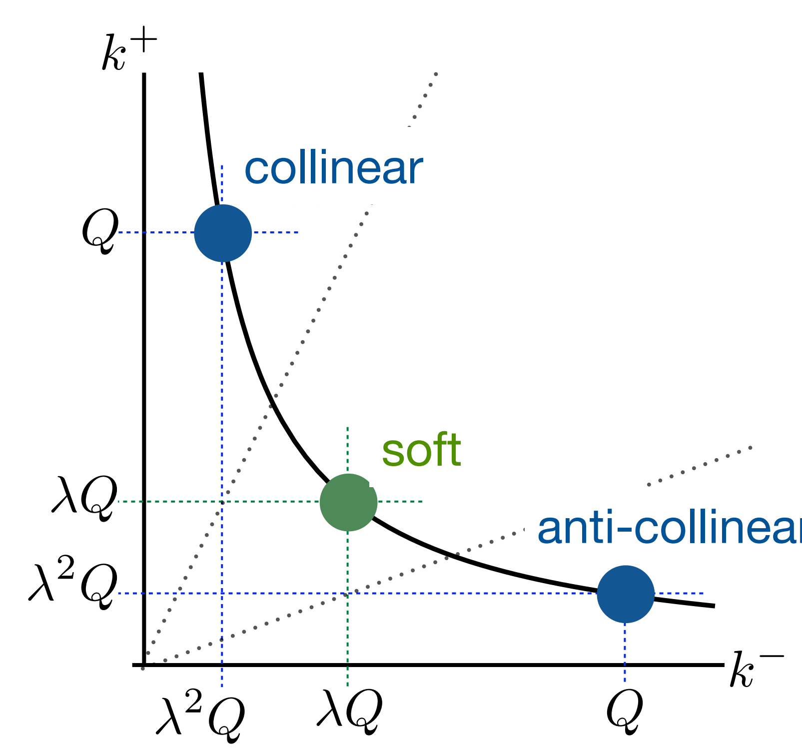

SCET-II: Collinear factorization anomaly

Generic phase-space integrals in SCET-II are **ill-defined** in dimensional regularization and require an **additional regulator**

- integrals such as $\int_0^\infty dk_+/k_+$ can be avoided using an analytic regulator:

$$\int d^Dk\,\delta(k^2)\,\theta(k^0) \to \int d^Dk\,\delta(k^2)\,\theta(k^0)\left(\frac{\nu}{k_+}\right)^\alpha$$

Becher, Bell: 1112.3907

- **poles in 1/α** cancel when one adds the collinear, anti-collinear, and soft contributions, but an anomalous **dependence on the hard scale Q** remains
- a variant of the analytic regularization scheme is the **rapidity regularization scheme** proposed in Chiu, Jain, Neill, Rothstein: 1202.0814

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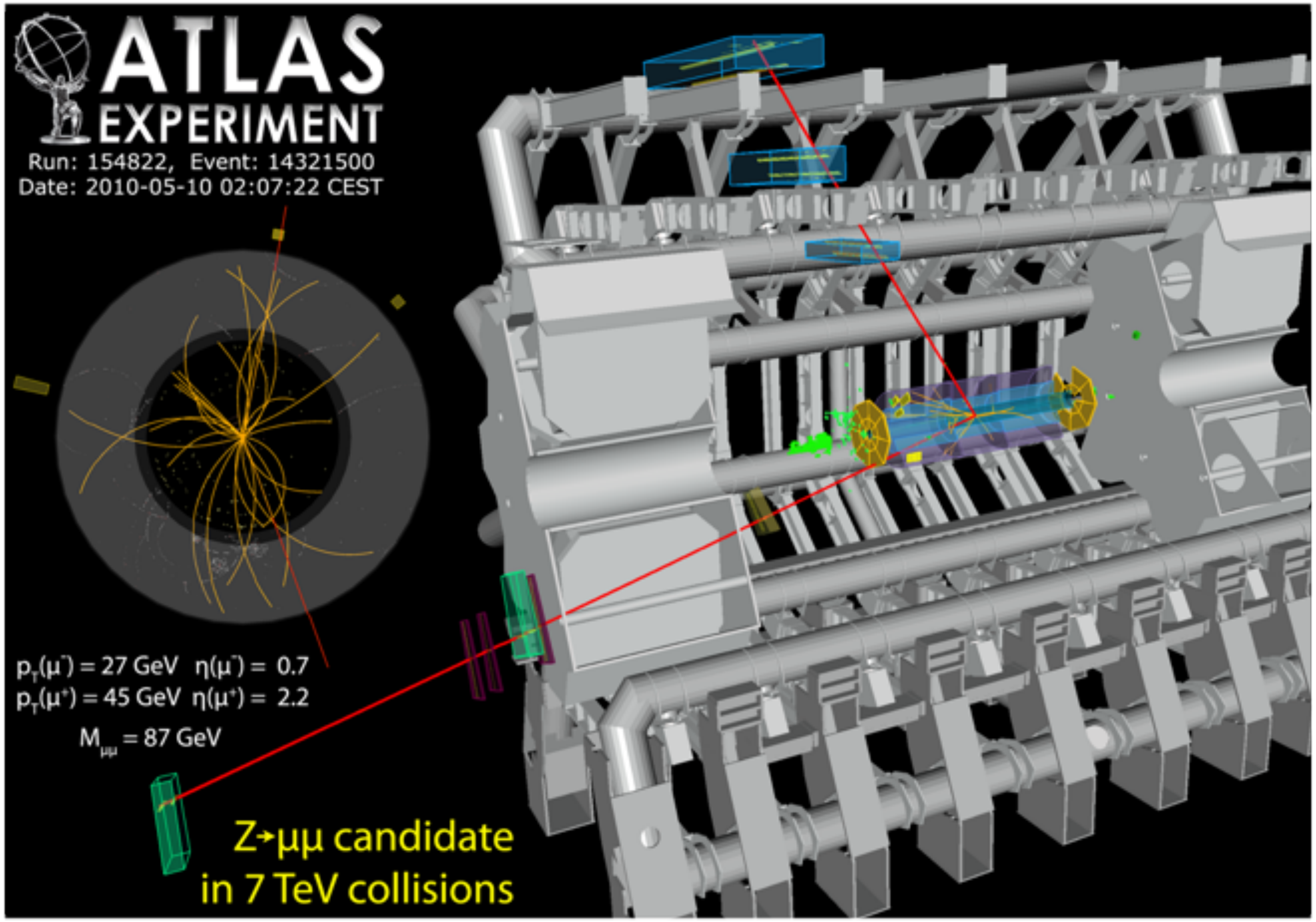
In SCET-II, this phenomenon can be interpreted as an anomaly: the **breaking of a classical symmetry** of the effective Lagrangian by **quantum effects**

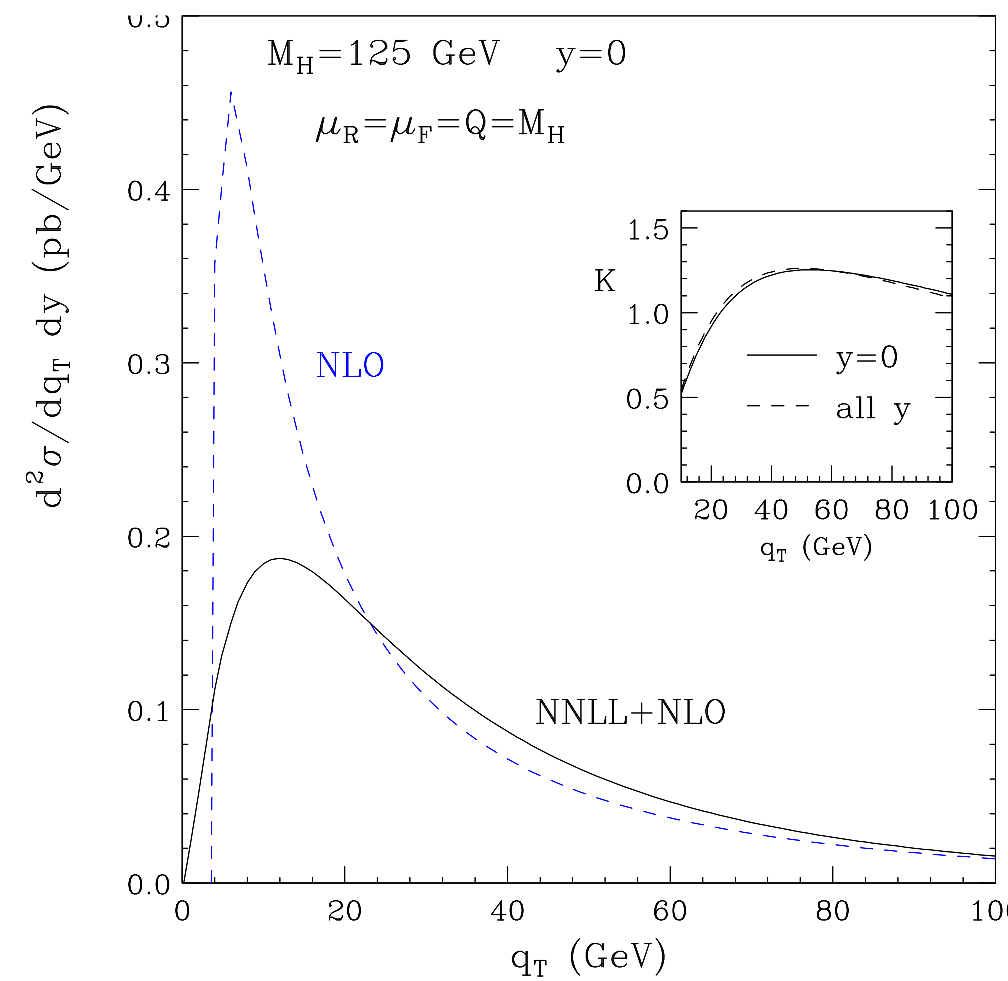
- as a result, the **functional dependence on Q** is highly constrained and can be derived from simple **differential equations** w.r.t. regulator



Application I: Transverse-momentum resummation for Z and Higgs production

Drell-Yan production at small q_T

Bozzi, Catani, de Florian, Grazzini: 0705.3887



Drell-Yan production of Z, W or Higgs bosons at small transverse momentum ($q_T \ll M$) is a classical two-scale process, for which the resummation of Sudakov logs $\sim \alpha_s^n \ln^{2n}(M/q_T)$ is essential

- no reasonable fixed-order perturbative approximation can be obtained, even if $q_T \gg \Lambda_{\rm QCD}$

Factorization theorem obtained using the collinear anomaly: Becher, MN: 1007.4005

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

beam functions
Stewart, Tackmann, Waalewijn: 0910.0467

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

Drell-Yan production at small q_T

In full detail:

$$\frac{d^3\sigma}{dM^2\, dq_T^2\, dy} = \frac{4\pi\alpha^2}{3N_c M^2 s} \sum_q e_q^2 \sum_{i=q,g} \sum_{j=\bar{q},g} \int_{\xi_1}^1 \frac{dz_1}{z_1} \int_{\xi_2}^1 \frac{dz_2}{z_2}$$

$$\times \Big[C_{q\bar{q}\to ij}(z_1, z_2, q_T^2, M^2, \mu)\, \phi_{i/N_1}(\xi_1/z_1, \mu)\, \phi_{j/N_2}(\xi_2/z_2, \mu) + (q, i \leftrightarrow \bar{q}, j) \Big]$$

with:

$$C_{q\bar{q}\to ij}(z_1, z_2, q_T^2, M^2, \mu) = \left|C_V(-M^2, \mu)\right|^2 \frac{1}{4\pi} \int d^2x_\perp\, e^{-iq_\perp \cdot x_\perp} \left(\frac{x_T^2 M^2}{4e^{-2\gamma_E}}\right)^{-F_{q\bar{q}}(x_T^2, \mu)}$$

$$\times\, I_{q\leftarrow i}(z_1, x_T^2, \mu)\, I_{\bar{q}\leftarrow j}(z_2, x_T^2, \mu)$$

Result can be matched onto the standard **CSS resummation formula** (Collins, Soper, Sterman 1984)

Using the anomaly equations, we have derived the **last missing ingredient** (the three-loop coefficient A_3) required for resummation at NNLL order

Infrared protection at very small q_T

Becher, MN, Wilhelm: 1109.6027

A careful analysis reveals that the spectrum $d\sigma/dq_T$ is **short-distance dominated** (but genuinely non-perturbative) all the way down to zero transverse momentum

The appropriate choice of μ eliminating large logarithms from the Fourier integral is:

$$\mu \sim \max\big(q_T, q_*\big) \qquad \text{with:} \quad q_* \approx M \exp\left(-\frac{2\pi}{(4C_{F/A}+\beta_0)\,\alpha_s(M)}\right)$$

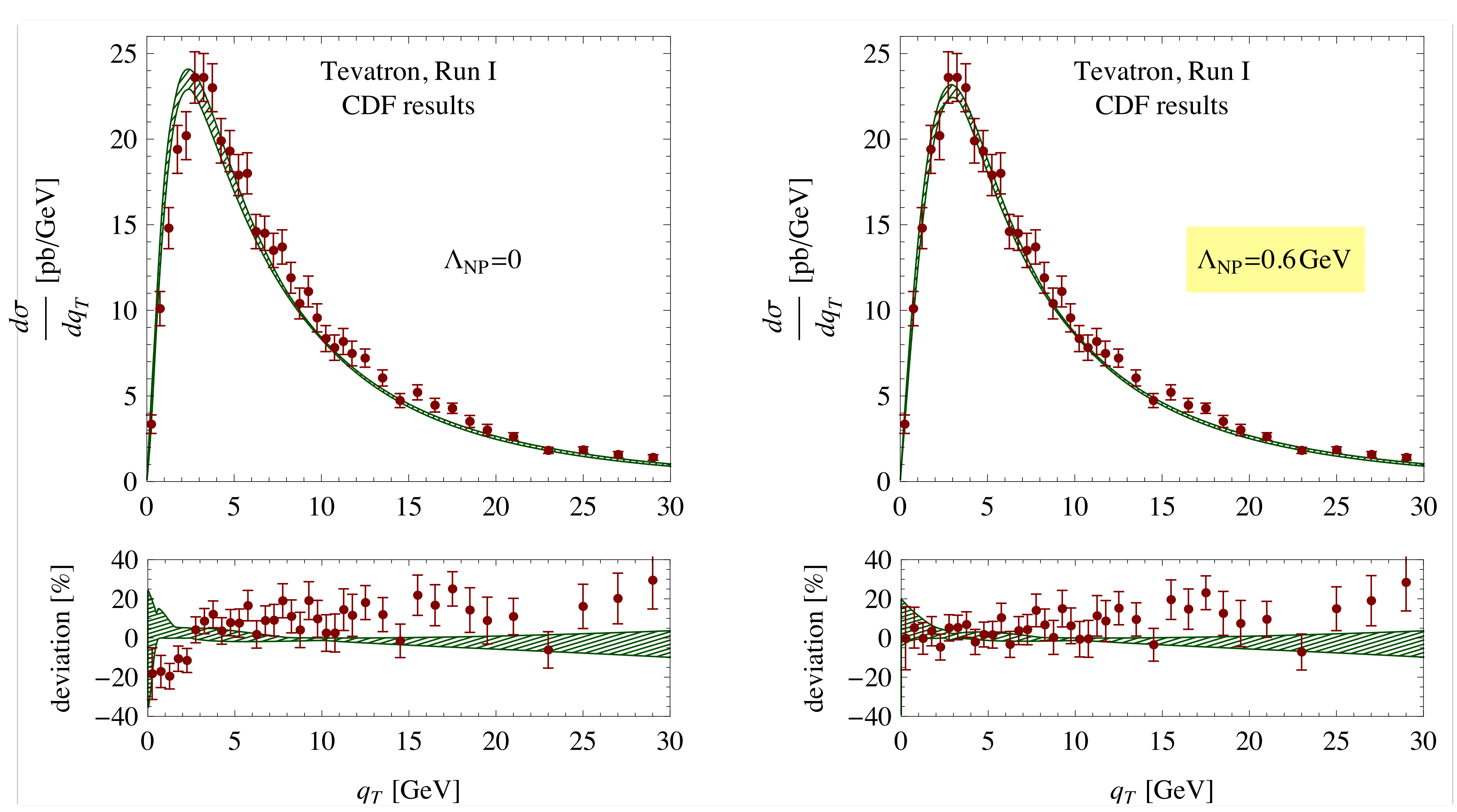
➡ yields **1.9 GeV** for Z production, and **7.7 GeV** for Higgs production

Scale q_* controls the size of **long-distance hadronic corrections**, which can be noticable for Z production but are very small for Higgs production

Z-boson production at Tevatron

Becher, MN, Wilhelm: 1109.6027

- First complete calculation of Z-boson and Higgs production at NNLL+NLO
- Extension to NNLL+NNLO is technically possible (work in progress)



Z-boson production at LHC

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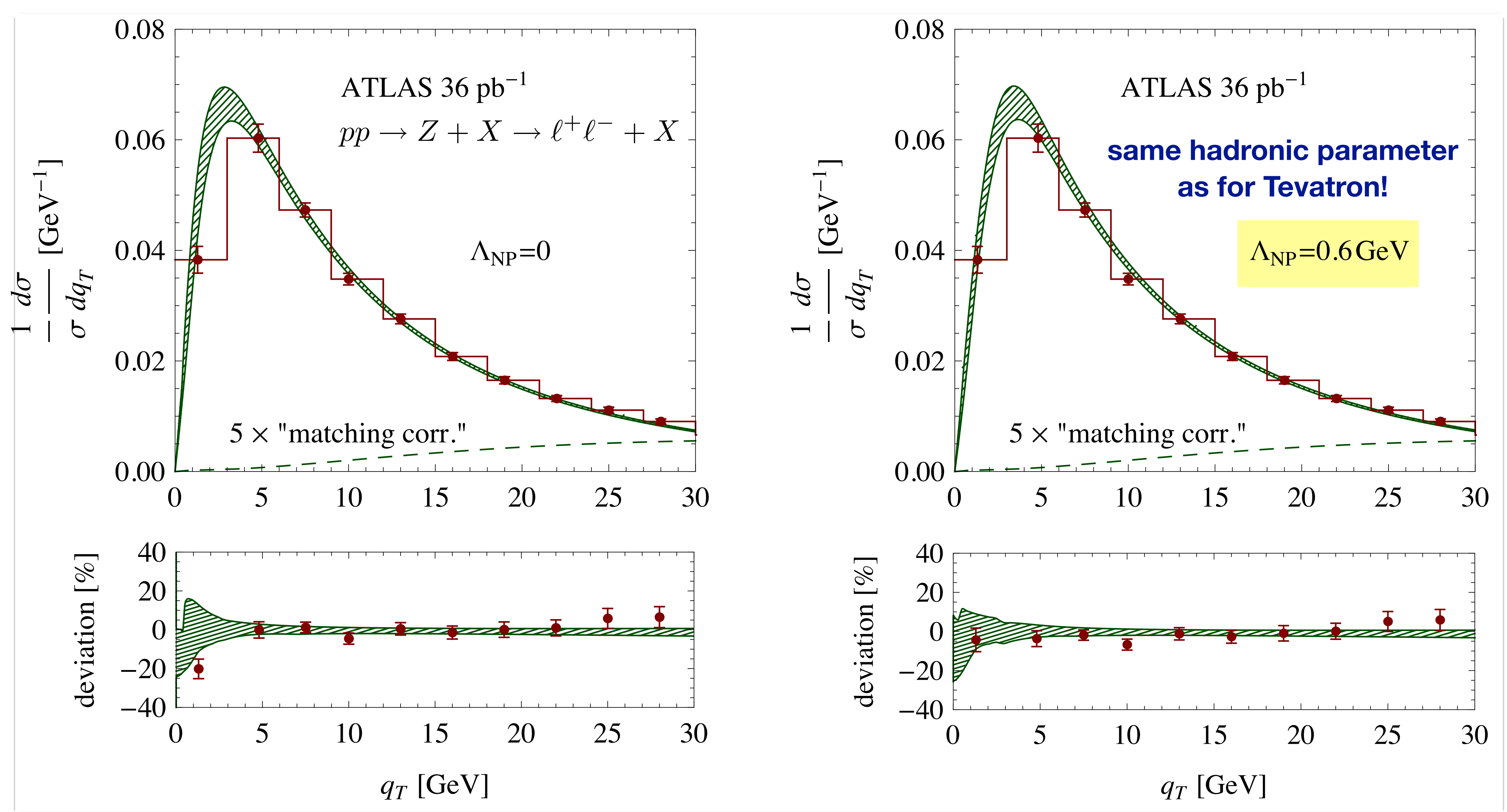
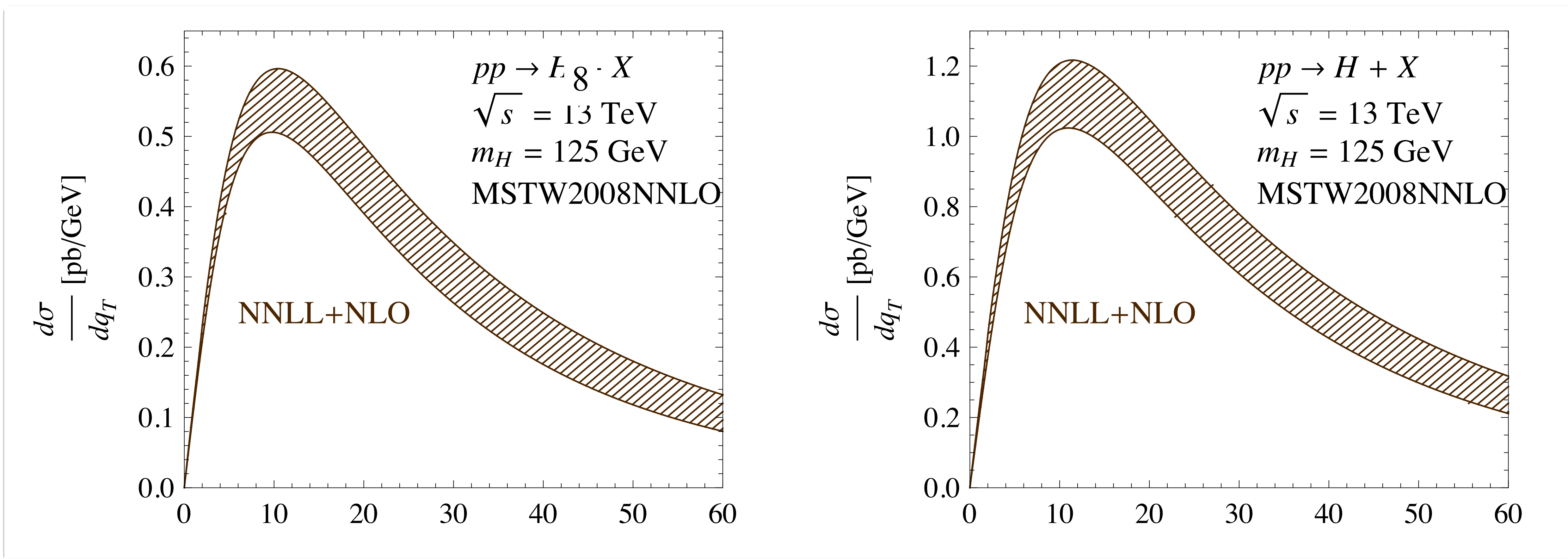


Higgs-boson production at LHC

Becher, MN, Wilhelm: 1212.2621

- Higgs q_T spectrum is predicted using same formalism, only that long-distance hadronic corrections are much smaller in this case
- Eagerly awaiting data ...



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

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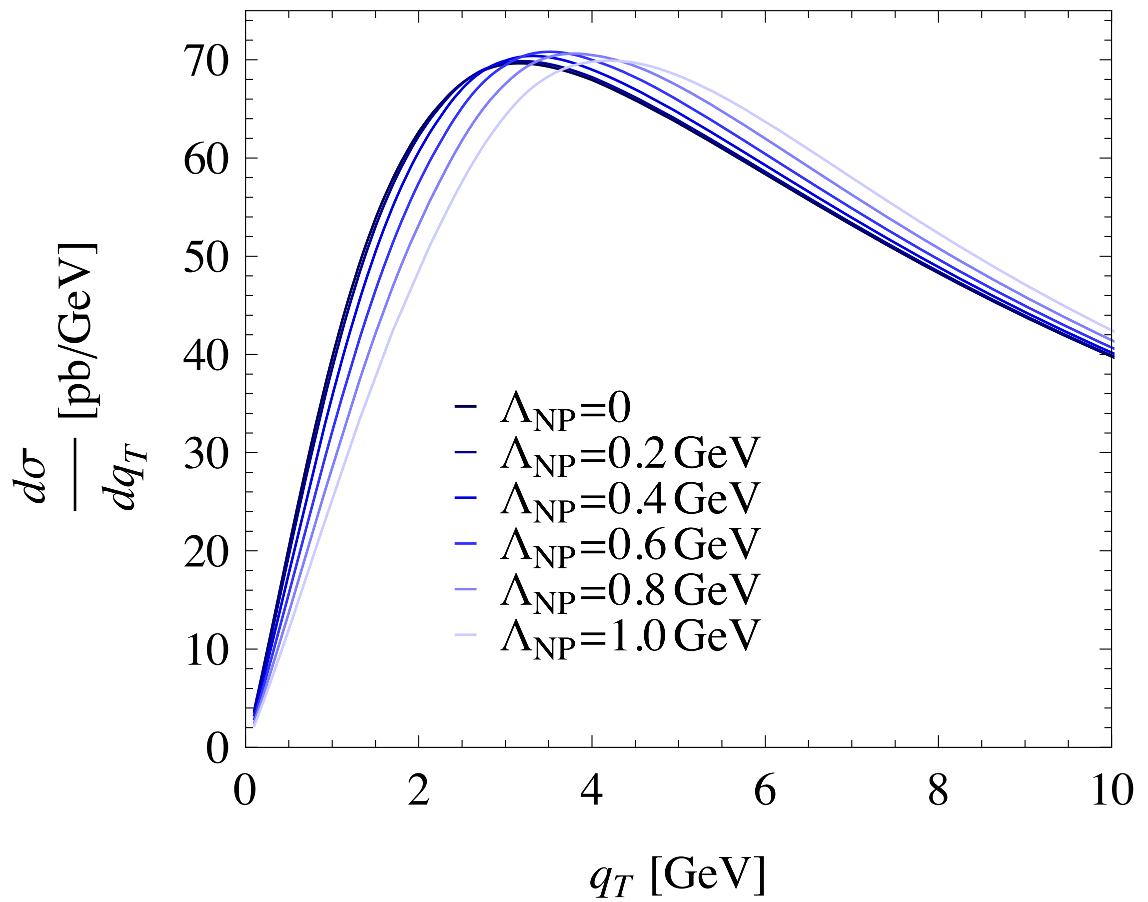
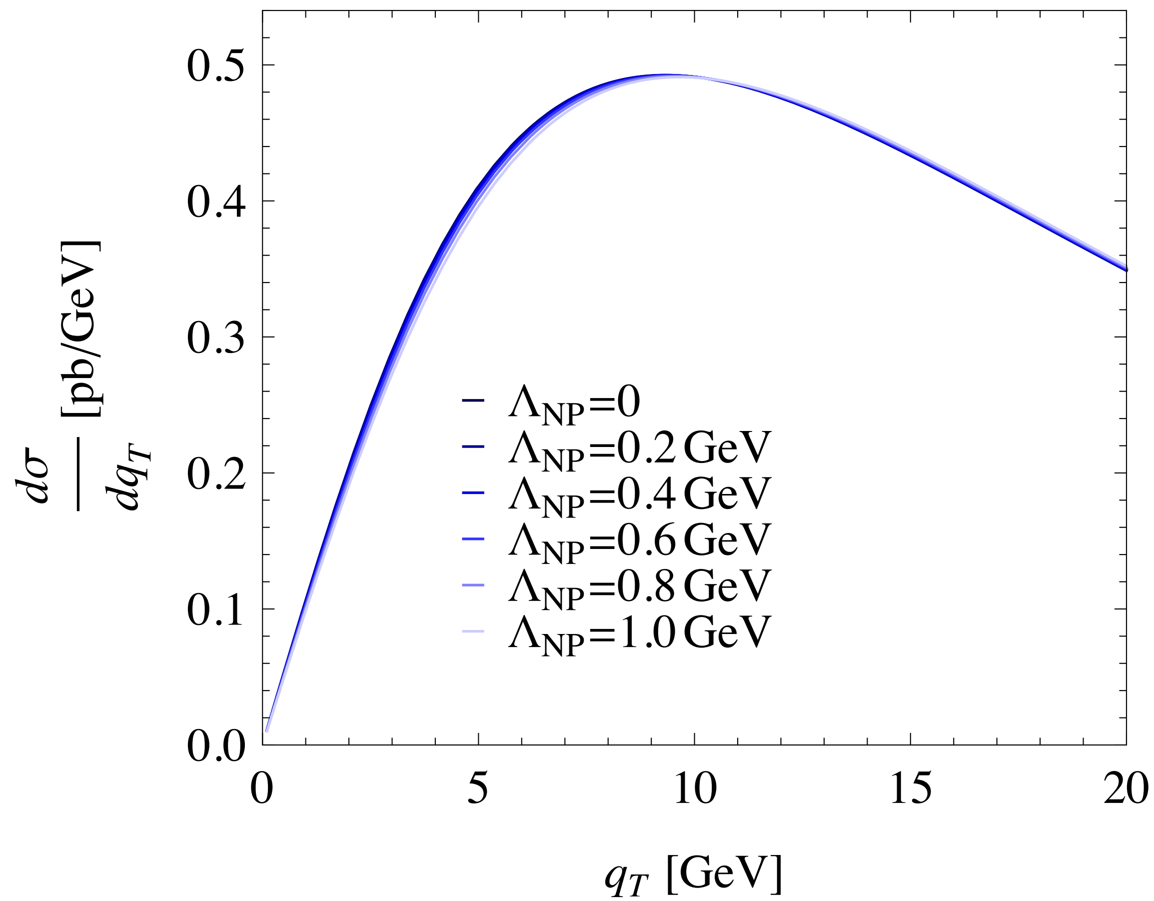


hadronic corrections: Z-boson case



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Application II:
Higgs production with a jet veto

Higgs production with a jet veto

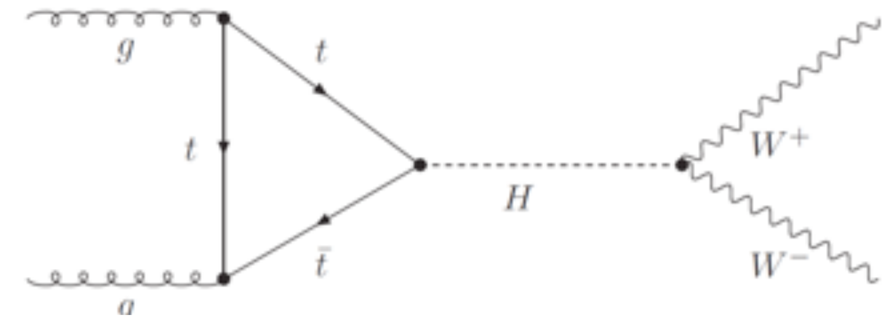
Searches for Higgs boson require stringent cuts to suppress background events

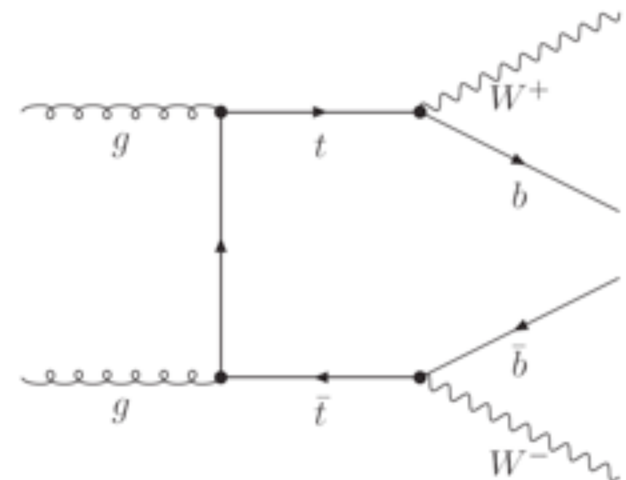
Since backgrounds are very different when the Higgs is produced in association with jets, the searches are performed in **jet bins**

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

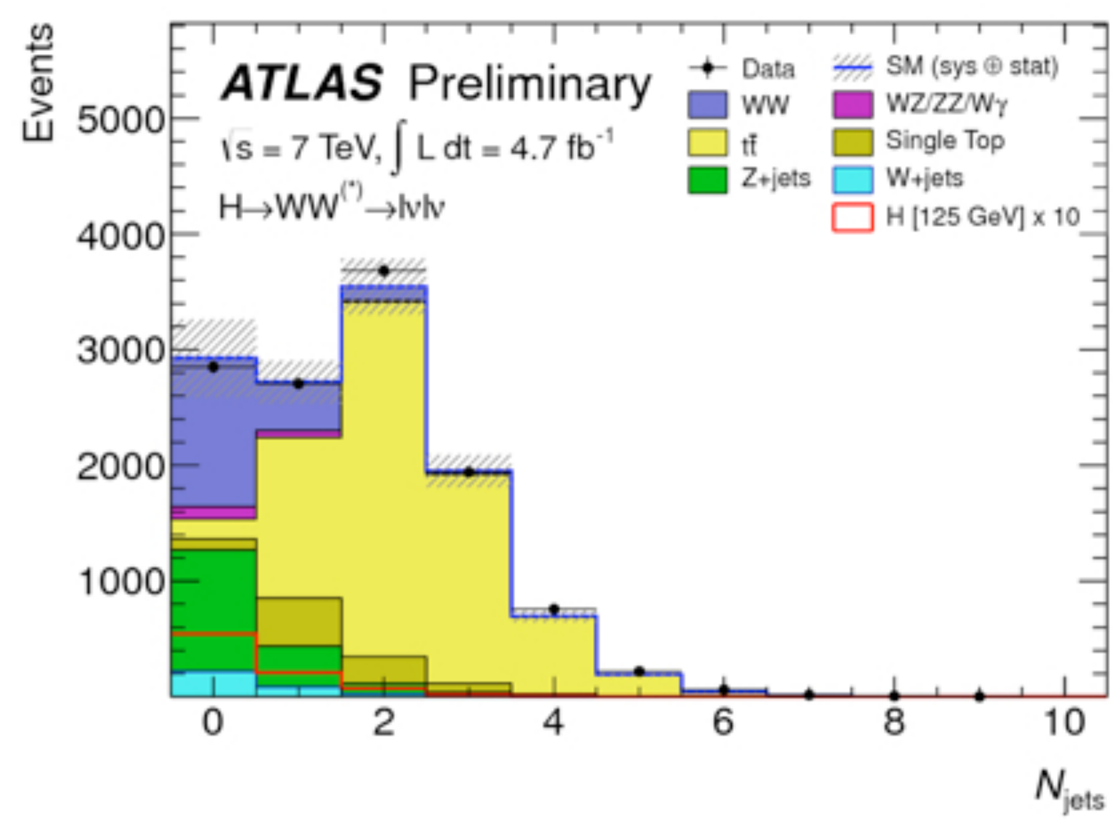
$$p_T^{\text{jet}} < p_T^{\text{veto}} \approx 15 - 30\,\text{GeV}$$

Until very recently, no resummed results for the cross section defined with a jet veto were available beyond LL order (parton shower)





jets



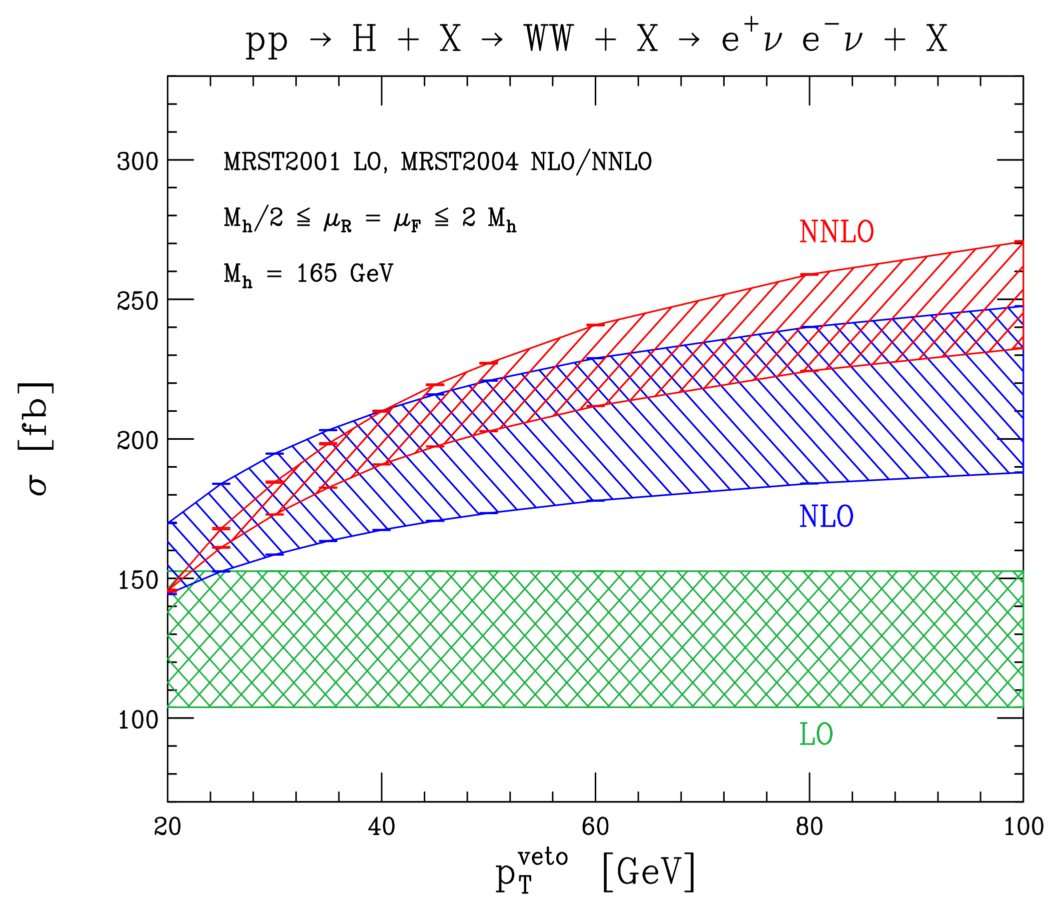
Higgs production with a jet veto

Fixed-order predictions naively suggest that the cut rate has smaller uncertainties than the total cross section

Effect is due to an **accidental cancellation** of large corrections from two sources:

- large **positive** corrections to total cross sections from analytic continuation of scalar form factor to time-like region
  Ahrens, Becher, MN, Yang (2008)
- large **negative** corrections from Sudakov logarithms $\alpha_s^n \ln^{2n}(m_H/p_T^{\text{veto}})$

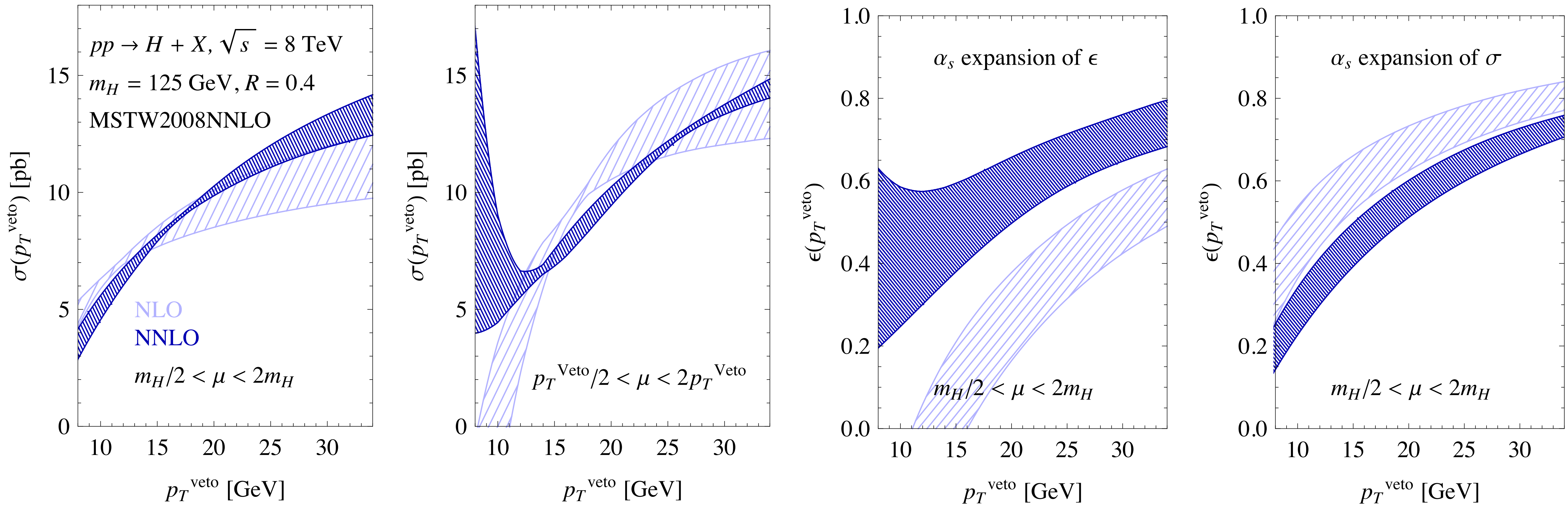
True perturbative uncertainty is most likely significantly larger
Stewart, Tackmann, Waalewijn (2010)
Stewart, Tackmann (2011)



Anastasiou, Dissertori, Stöckli (2007)

Higgs production with a jet veto

Updated fixed-order predictions for different schemes and scale choices:



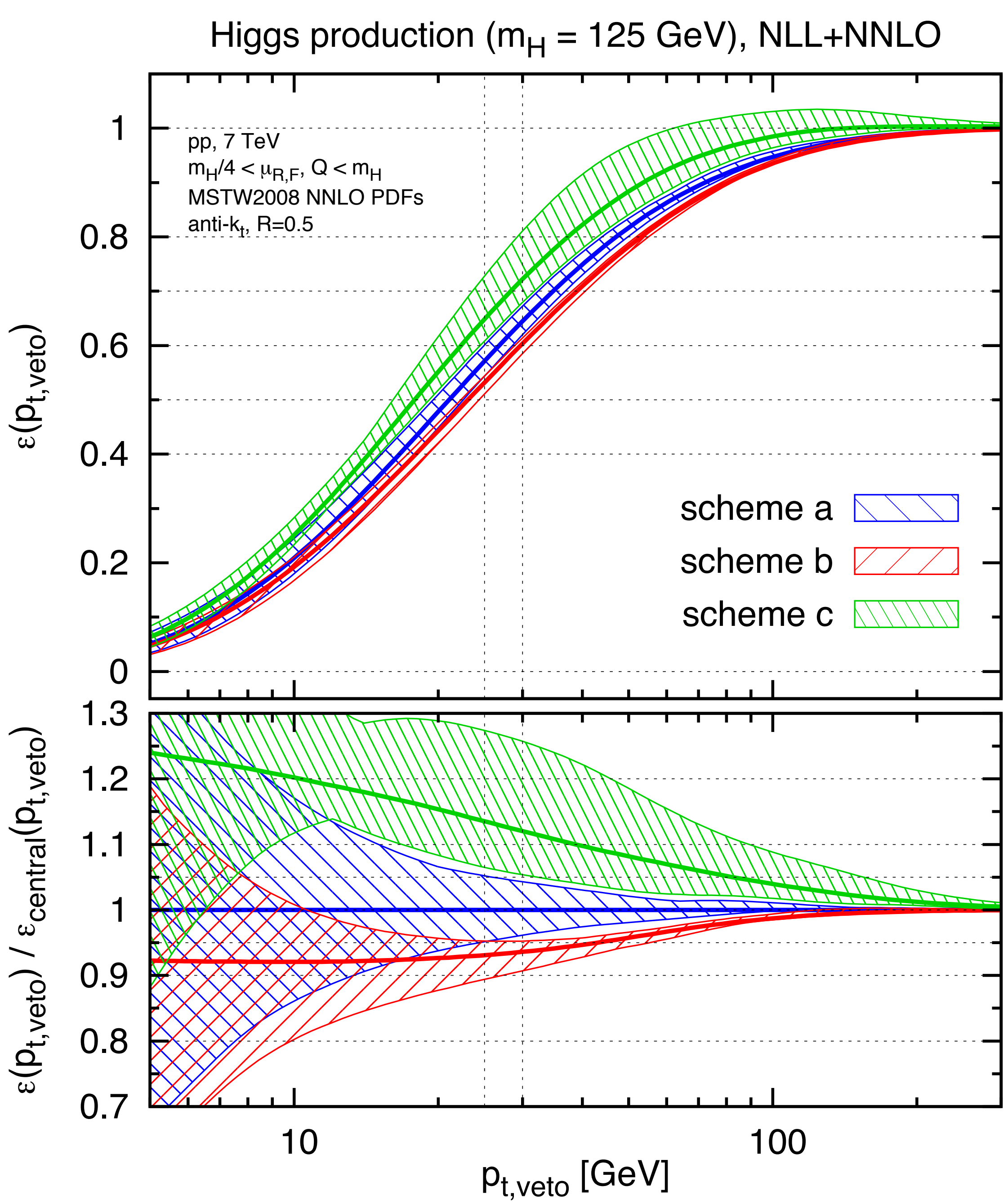
⇒ bands do not reflect true uncertainties!

Resummation at NLL order

Recently, it has been shown that the jet veto can be resummed at **NLL order** using the numerical resummation code **CAESAR**

Banfi, Salam, Zanderighi: 1203.5773

- NLL+NNLO calculation still suffers from significant perturbative uncertainties and scheme dependences; hence calculate **cut efficiency** instead of cross section



Resummation at NNLL order and beyond

Recently, it has been shown that the jet veto can be resummed at **NLL order** using the numerical resummation code **CAESAR**

Banfi, Salam, Zanderighi: 1203.5773

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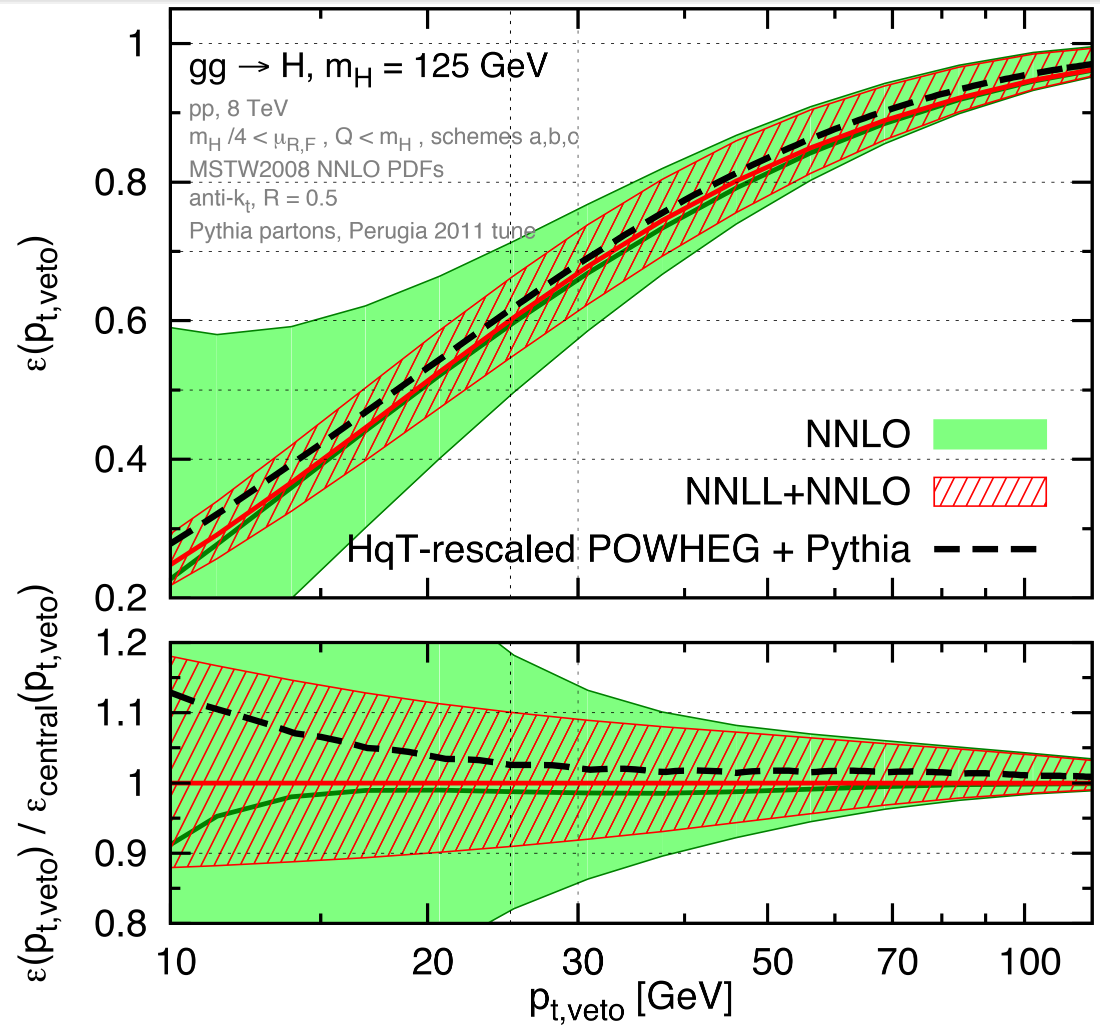


Soon after, the resummation was extended to **NNLL order** (matched to NNLO)

Banfi, Monni, Salam, Zanderighi: 1206.4998

- uncertainties are significantly reduced

Meanwhile, we have shown that the jet-veto cross factorizes to all orders and can be resummed using SCET !

Becher, MN: 1205.3806

Inclusive jet clustering algorithm

Distance measure:

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

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

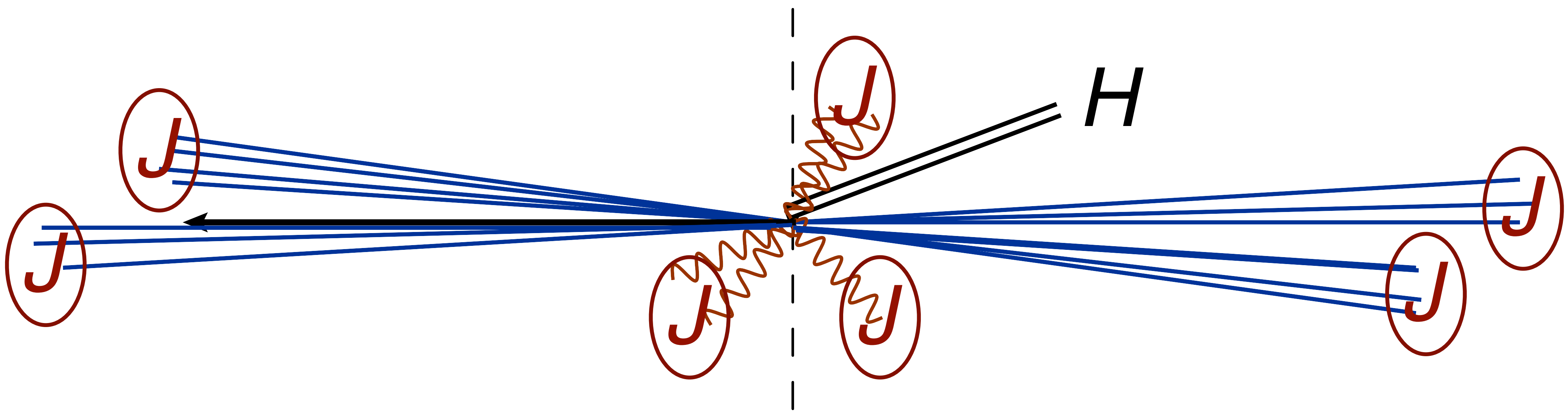
n=1: k_T
n=0: C/A
n=-1: anti-k_T

Find the smallest of all d_{ij}, d_{iB}. If it is a d_{ij}, combine particles *i* and *j* into one particle. If it is a d_{iB}, call particle *i* a jet and remove it from the list. Repeat until all particles are clustered in jets

Since two **different SCET modes have a large rapidity gap**, the jet algorithm clusters soft particles with soft ones and collinear particles with collinear ones, except in corners of phase space (power-suppressed effects)

→ **jet veto can be applied separately in each sector of SCET**
(simple factorization theorem)

All-order factorization theorem



Based on SCET analysis, propose first **all-order factorization formula** for the cross section with a jet veto with **R=O(1)**:

anomalous m_H dependence is a **pure power** in p_T space

$$\frac{d\sigma(p_T^{\rm veto})}{dy} = \sigma_0(\mu)\, C_t^2(m_t^2,\mu)\, \big|C_S(-m_H^2,\mu)\big|^2 \left(\frac{m_H}{p_T^{\rm veto}}\right)^{-2F_{gg}(p_T^{\rm veto},\mu)}$$
$$\times \sum_{i,j} \int_{\xi_1}^1 \frac{dz_1}{z_1} \int_{\xi_2}^1 \frac{dz_2}{z_2}\, I_{g\leftarrow i}(z_1,p_T^{\rm veto},\mu)\, I_{g\leftarrow j}(z_2,p_T^{\rm veto},\mu)\, \phi_{i/P}(\xi_1/z_1,\mu)\, \phi_{j/P}(\xi_2/z_2,\mu)$$

Becher, MN: 1205.3806

Note close structural similarity with q_T resummation formula!

All-order factorization theorem

Ingredients required for **resummation at NNLL order**:

- C_t and C_S at two-loop order in RG-improved perturbation theory (known to three loops)
- one-loop collinear kernel functions:

$$I_{g\leftarrow i}(z, p_T^{\text{veto}}, \mu) = \delta(1-z)\,\delta_{gi}\left[1 + a_s\left(\Gamma_0^A\,\frac{L_\perp^2}{4} - \gamma_0^g\,L_\perp\right)\right] + a_s\left[-\mathcal{P}_{g\leftarrow i}^{(1)}(z)\,\frac{L_\perp}{2} + \mathcal{R}_{g\leftarrow i}(z)\right]$$

$$\mathcal{R}_{g\leftarrow g}(z) = -C_A\,\frac{\pi^2}{6}\,\delta(1-z)\,, \qquad \mathcal{R}_{g\leftarrow q}(z) = 2C_F z$$

$$\boxed{L_\perp = 2\ln\frac{\mu}{p_T^{\text{veto}}}}$$

- two-loop anomaly coefficient:

$$F_{gg}(p_T^{\text{veto}}, \mu) = a_s\left(\Gamma_0^A\,L_\perp + d_1^{\text{veto}}\right) + a_s^2\left(\Gamma_0^A\beta_0\,\frac{L_\perp^2}{2} + \Gamma_1^A\,L_\perp + d_2^{\text{veto}}\right)$$

Becher, MN: 1205.3806

vanishes!

only dependence on **jet radius parameter R** at NNLL order

All-order factorization theorem

Determination of anomaly coefficient d_2^{veto}:

- matching our formula with NNLL result of BMSZ yields: Banfi, Monni, Salam, Zanderighi: 1206.4998

$$d_2^{\text{veto}} = d_2^g - 32 C_A f(R)$$

from: Becher, MN: 1007.4005

with:

$$f(R) = -(1.0963\, C_A + 0.1768\, T_F n_f) \ln R + (0.6072\, C_A - 0.0308\, T_F n_f) - (0.5585\, C_A - 0.0221\, T_F n_f)\, R^2 + (0.0399\, C_A - 0.0004\, T_F n_f)\, R^4 + \dots$$

- originally we had an extra constant term in the above relation, which appeared because we had incorrectly assumed that the BMSZ formula still holds in the limit $R \to \infty$

We have now re-derived the expression for d_2^{veto} from a **two-loop calculation in SCET**, finding complete agreement with the BMSZ formula !

Thomas Becher, MN, Lorena Rothen (to appear)

Matching to fixed-order results

Study two different matching schemes:

- perform matching in naive way (scheme A)
- factor out hard function *H* times anomaly term (scheme B)

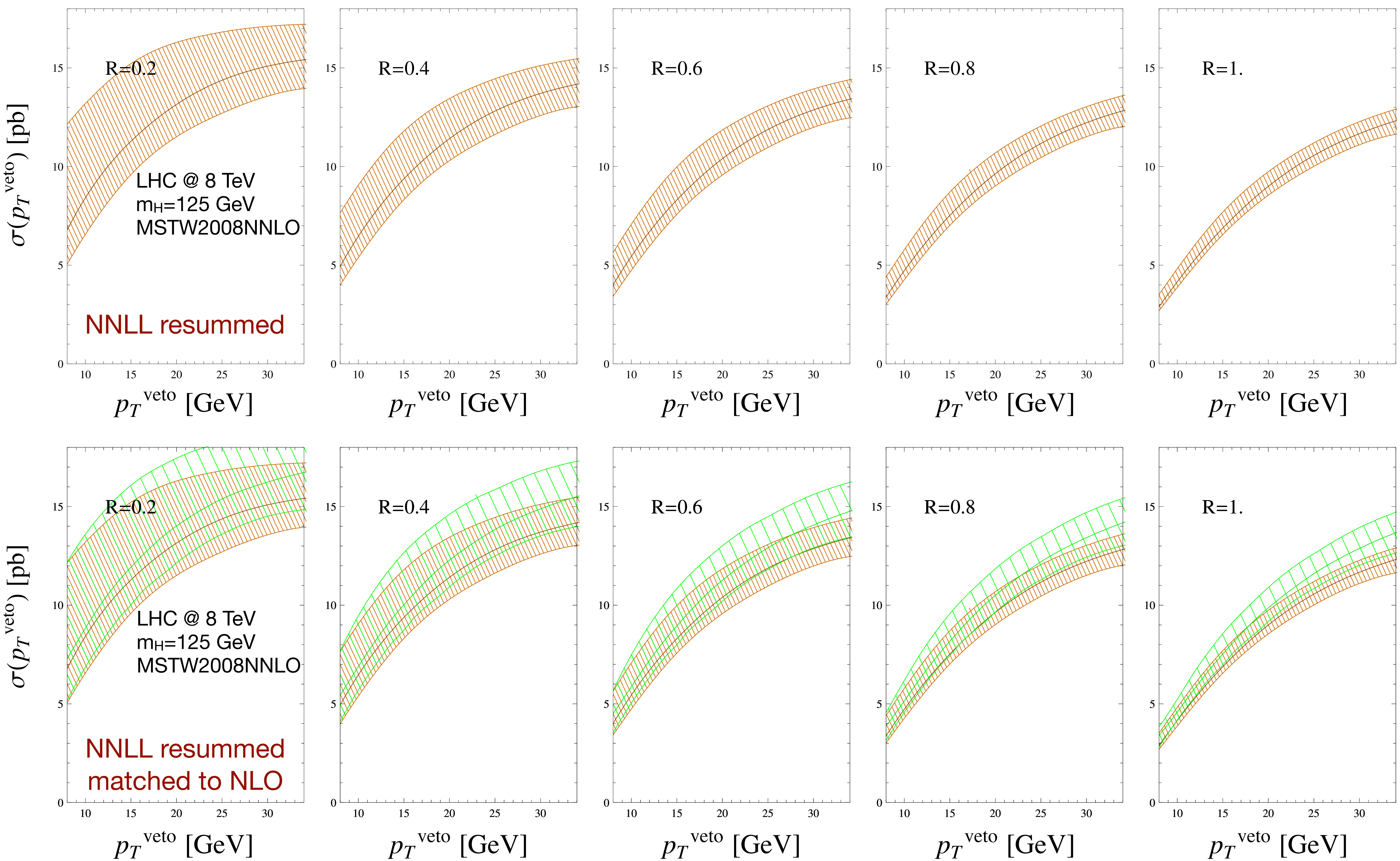
Since the hard function *H* contains the large corrections affecting the total cross section (time-like scalar form factor), scheme B is better motivated than scheme A

$$\sigma(p_T^{\text{veto}}) \sim H(m_H) \left[I(p_T^{\text{veto}}) \otimes \phi\right] \left[I(p_T^{\text{veto}}) \otimes \phi\right] \left(\frac{m_H^2}{(p_T^{\text{veto}})^2}\right)^{-F_{gg}^{\text{veto}}(p_T^{\text{veto}})}$$

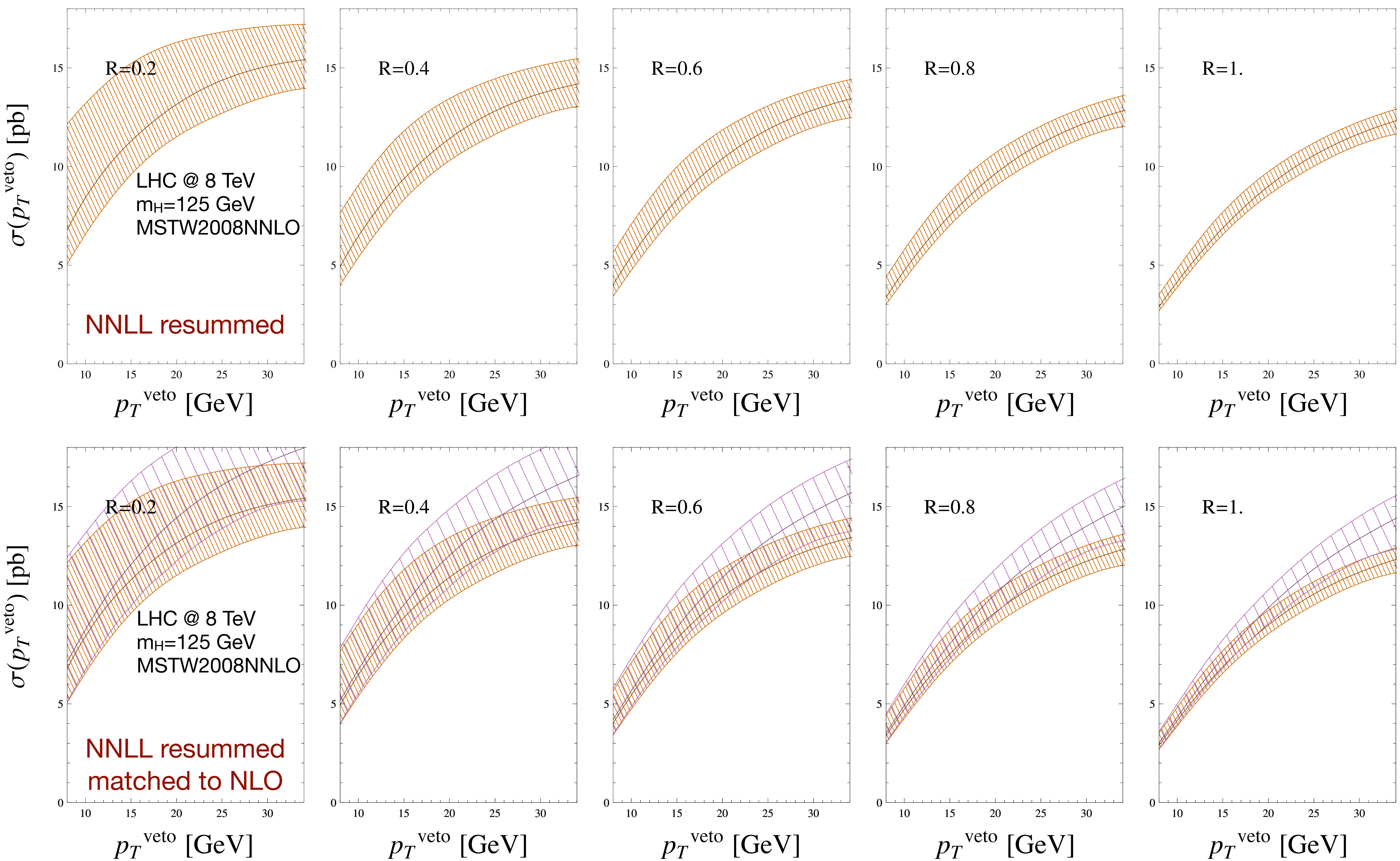
Caveat: numerical results are preliminary

Thomas Becher, MN, Lorena Rothen (to appear)

NNLL+NLO results (scheme A)



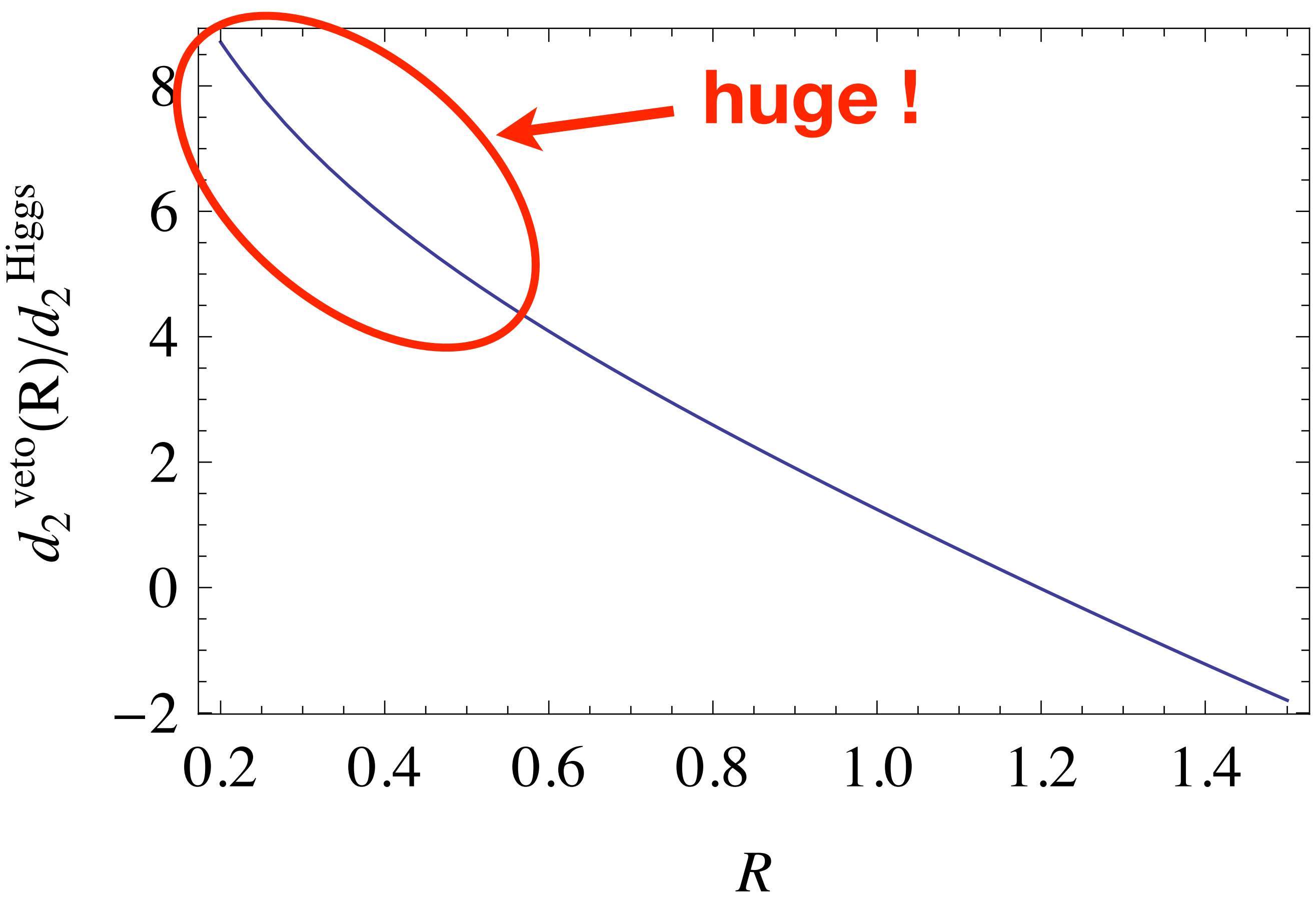
NNLL+NLO results (scheme B)



NNLL+NLO results

General observations:

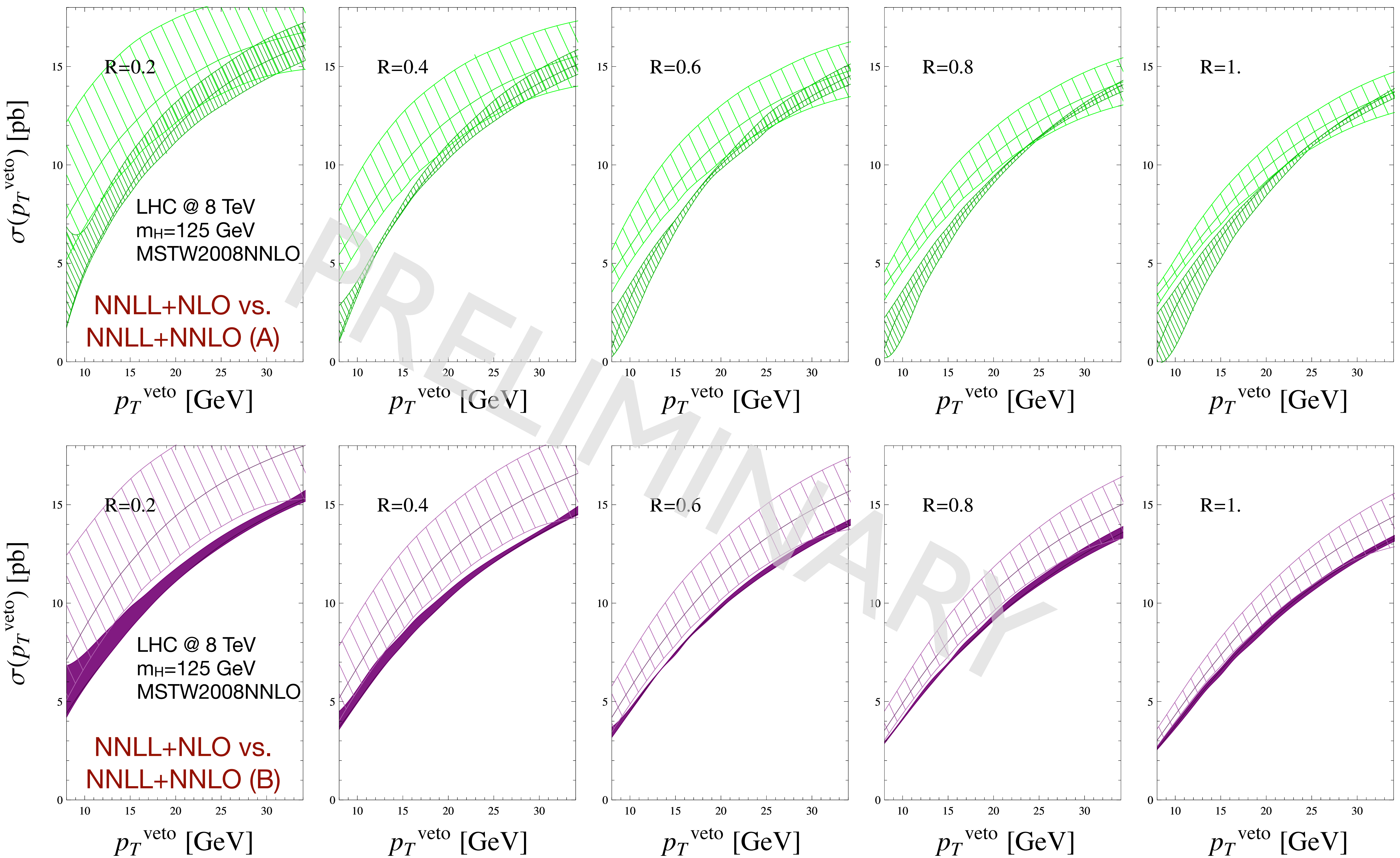
- matching corrections $\sim(p_T^{veto}/m_H)^2$ small for low p_T^{veto} values and increase for larger ones
- scale variations under control for not too small jet radii (R>0.6)
- larger scale dependence for smaller radii results from strong R-dependence of the two-loop anomaly coefficient d_2^{veto}
- in this region, **clustering logarithms** $\sim\alpha_s^{n+1} \ln^n R$ should be resummed



To further reduce the scale variations at small R, one should extend the analysis to **NNNLL+NNLO** order (in progress)

- study NNLO matching as one important part of such an analysis

NNLL+NNLO results

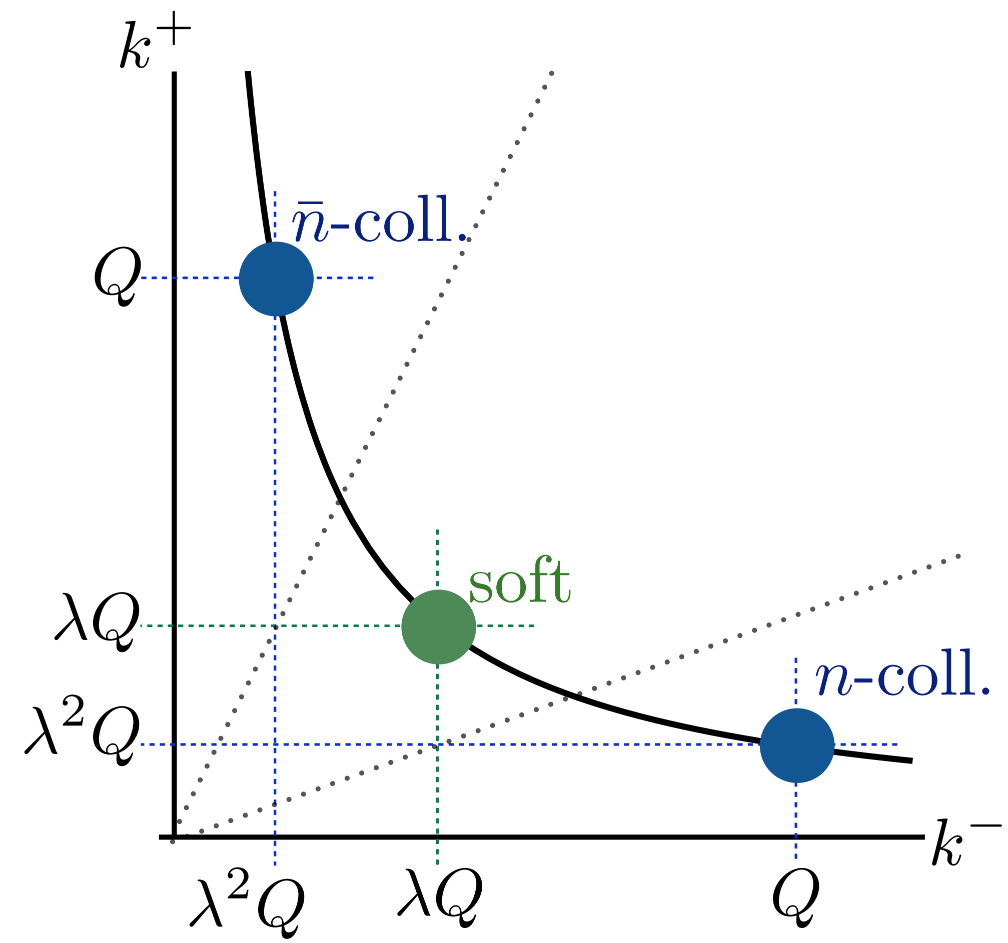


Comparison to other work

- NNLL formula of Banfi, Monni, Salam, Zanderighi: 1206.4998 is fully consistent with our all-order factorization theorem; both general structure and explicit computations of ingredients agree
- Tackmann, Walsh, Zuberi: 1206.4312 (TWZ) use a different formalism ("rapidity renormalization group") but obtain the same factorization formula
- however, they argued that the factorization formula is of little use, since it only holds at **parametrically small $R \ll 1$**, where clustering logs must be resummed
- TWZ claim that **soft-collinear mixing terms** spoil factorization starting at NNLL order (later modified to "beyond NNLL order")

Soft-collinear mixing terms ?

- In dimensional regularization, soft and collinear contributions are integrated over full phase space
- Avoid double counting by **multi-pole expanding** the integrands, or by performing **“zero-bin” subtractions** of overlap contributions



We find that soft-collinear mixing contributions obtained without performing the multi-pole expansion **precisely cancel** against these zero-bin subtraction terms !

Have confirmed this by explicit two-loop calculations

Conclusions

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

Many applications exist for Drell-Yan processes (production of Z, W, H bosons) and top-quark pair production

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

Collinear anomaly is an important ingredient to factorization analyses for observables sensitive to transverse momenta

Have developed a consistent framework for q_T resummation and jet-veto cross sections for pp→(colorless bosons)+0 jets