# Higgs Cross Sections from SCET

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Precision Physics, Fundamental Interactions and Structure of Matter

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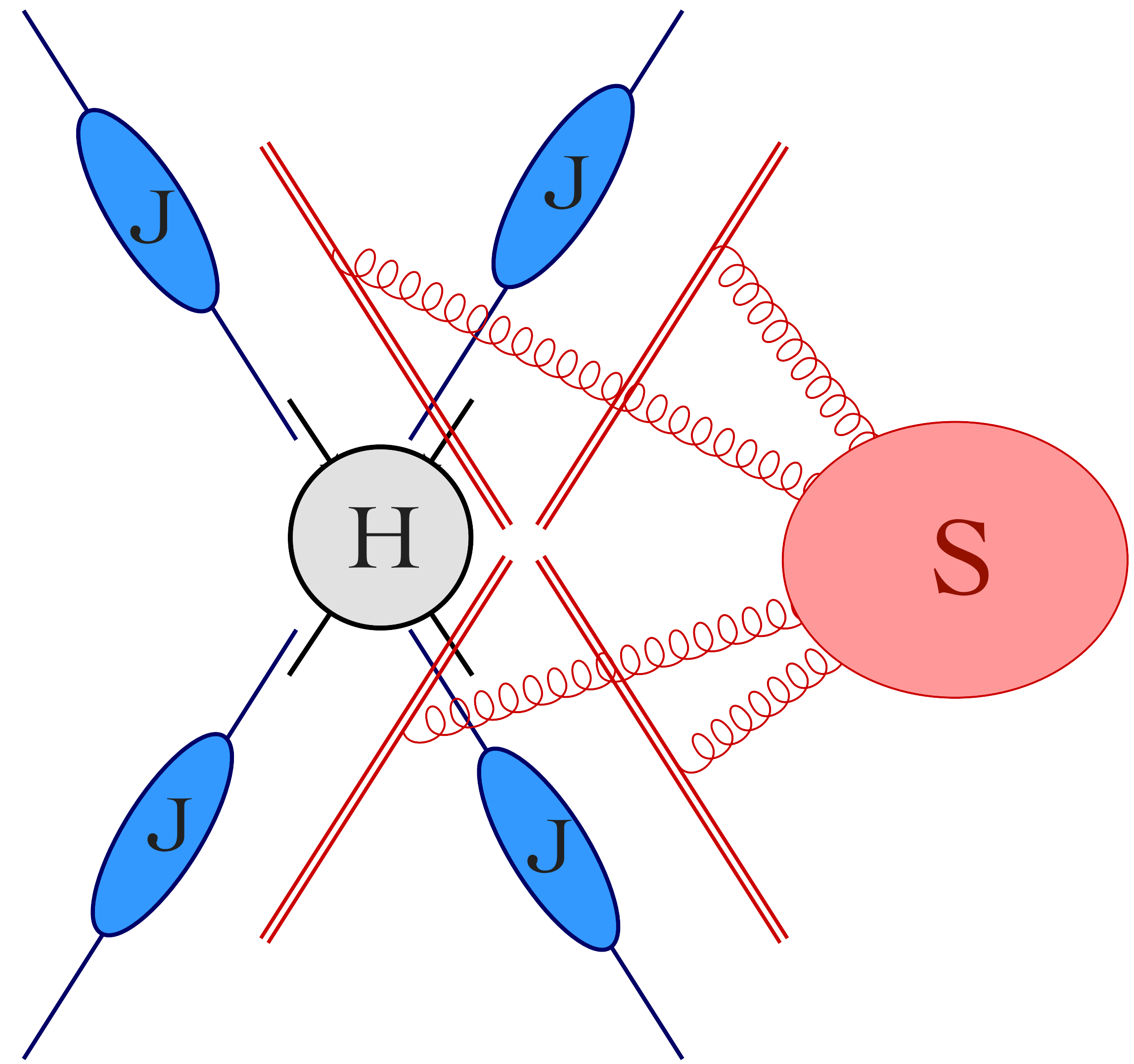
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

*Higgs Identification Workshop*
KITP, Santa Barbara, 12 December 2012

# 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:

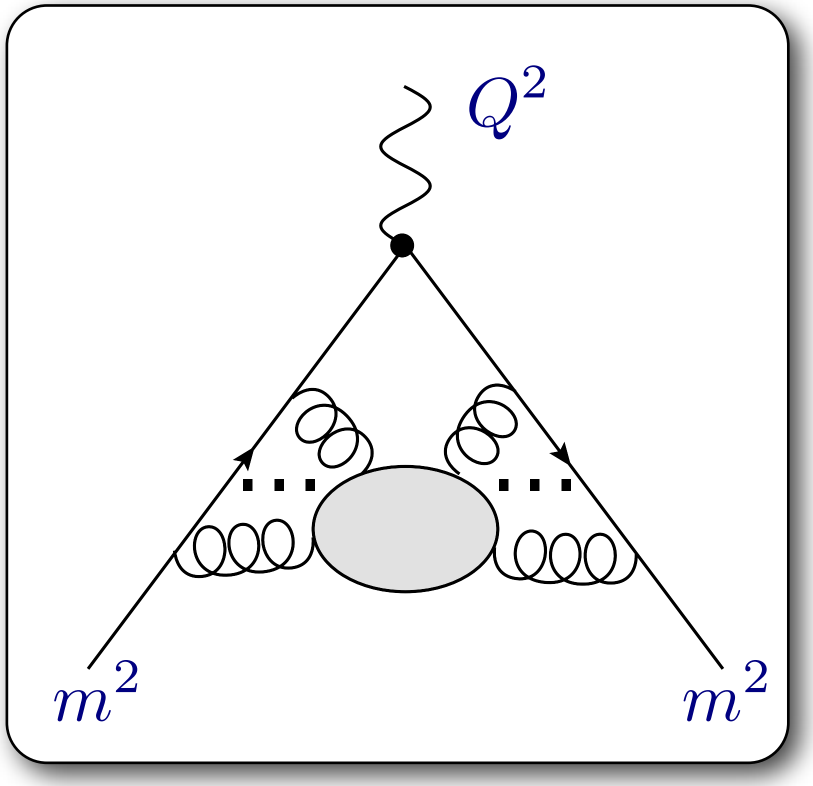
- usually, large logarithms in QFT arise from hierarchy between a long-distance (soft) scale *m* and a short-distance (hard) scale $Q \gg m$:

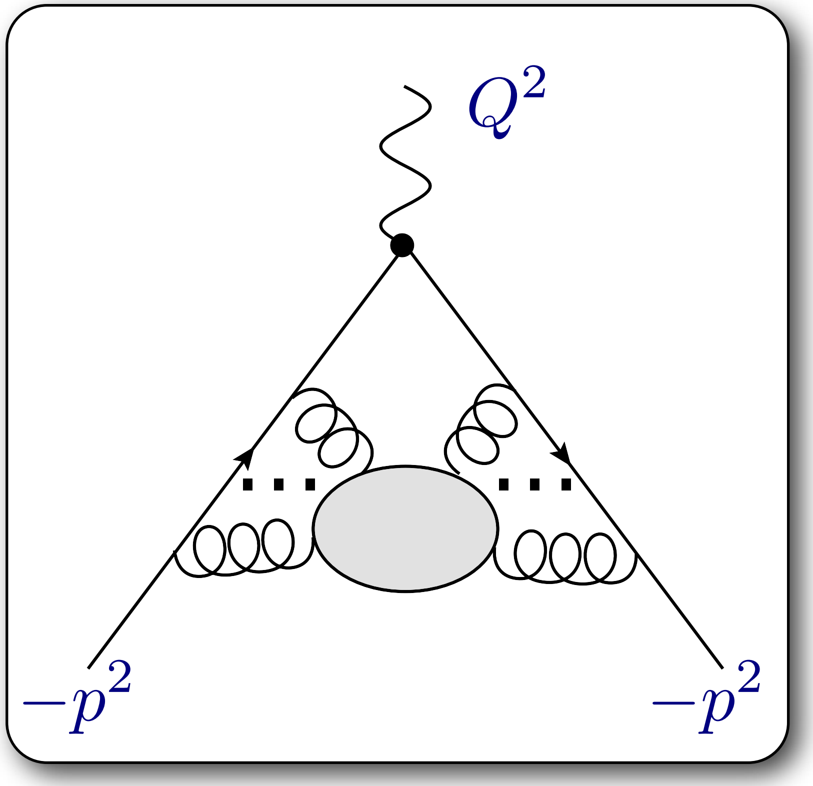
$$\ln\frac{Q^2}{m^2} = \ln\frac{Q^2}{\mu^2} + \ln\frac{\mu^2}{m^2}$$

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

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

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



# 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-distance and long-distance contributions follows from structure of the effective Lagrangian
- **resummation** of Sudakov logarithms is accomplished by solving renormalization-group equations (RGEs)
- elegant method for re-deriving many known results in collider and heavy-flavor physics, several times going beyond existing calculations

- in few cases, **new factorization theorems** have been derived

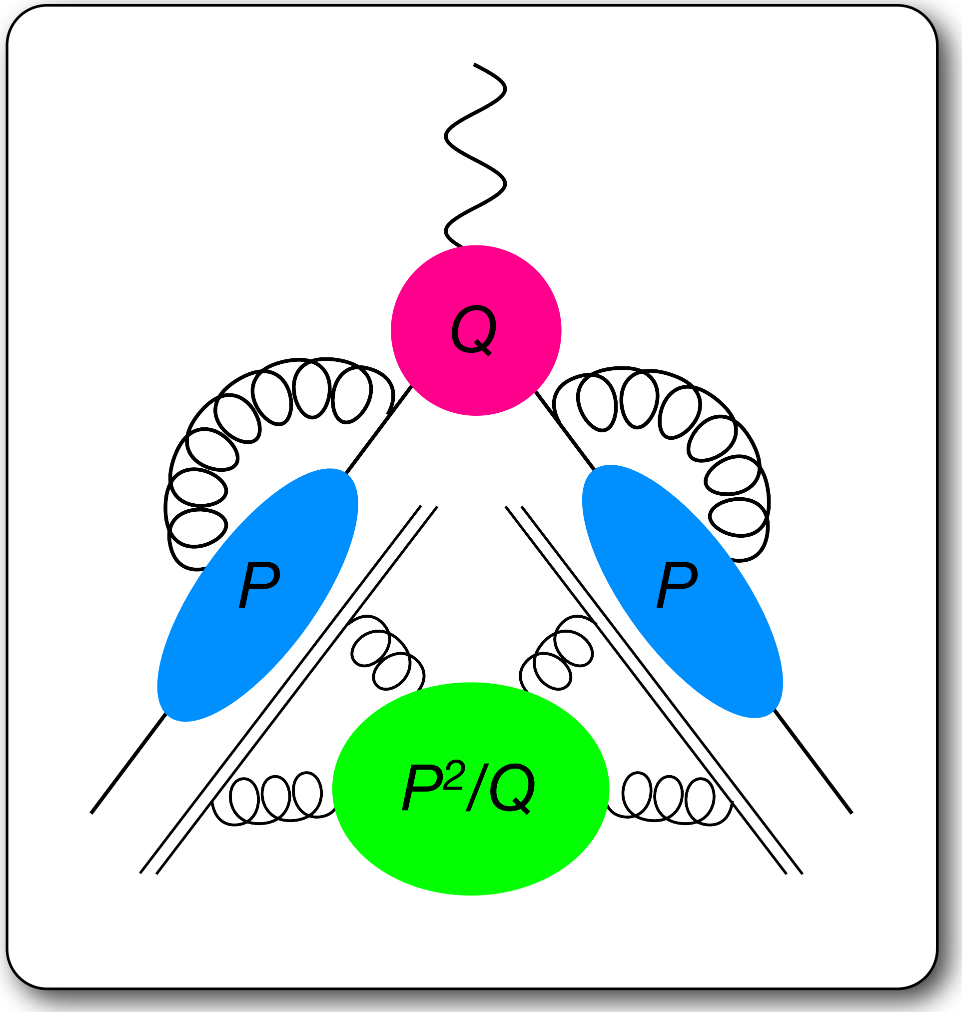
# SCET-I: Correlated scales

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

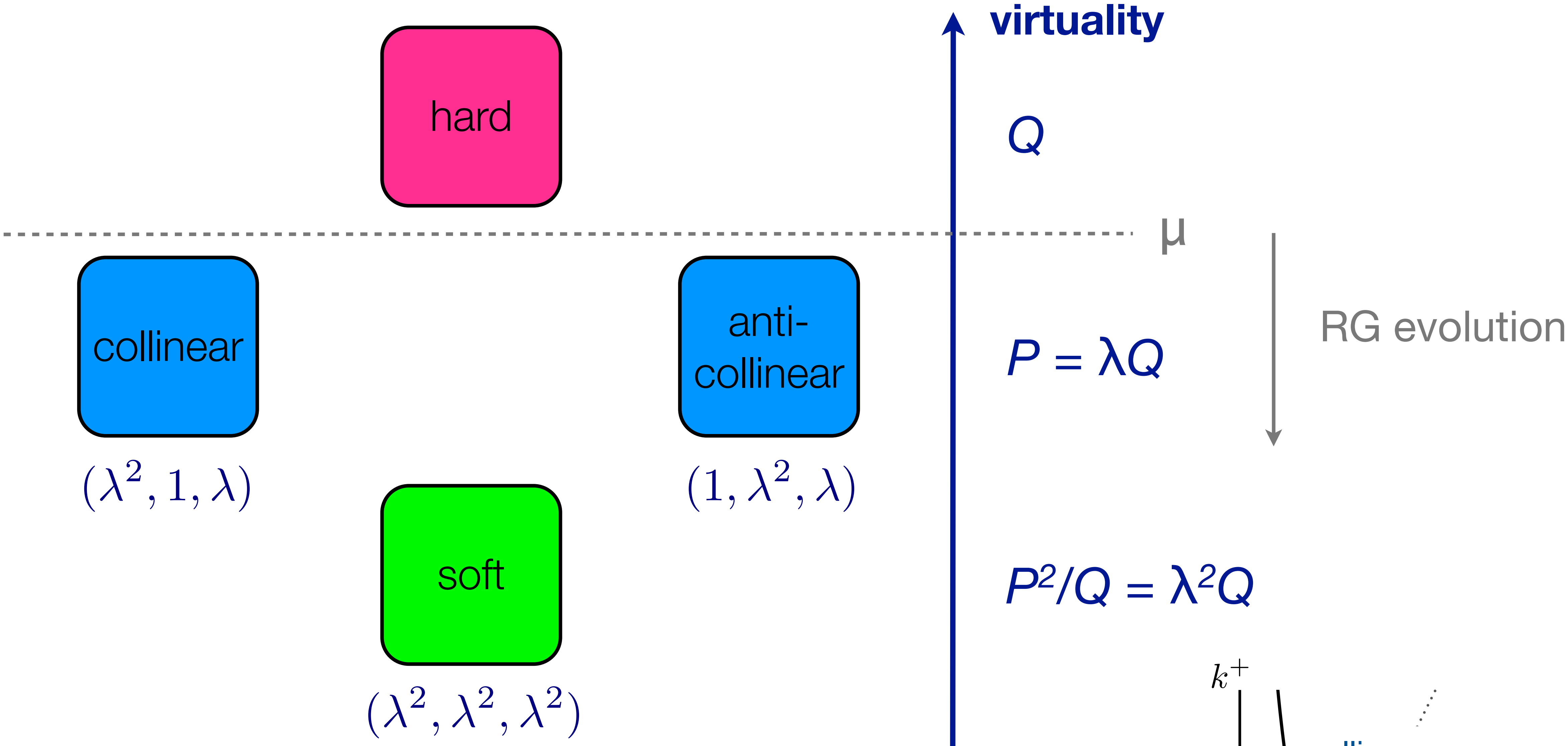
- hard scale $Q$
- (anti-)collinear scale $P$
- soft scale $P^2/Q$

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

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

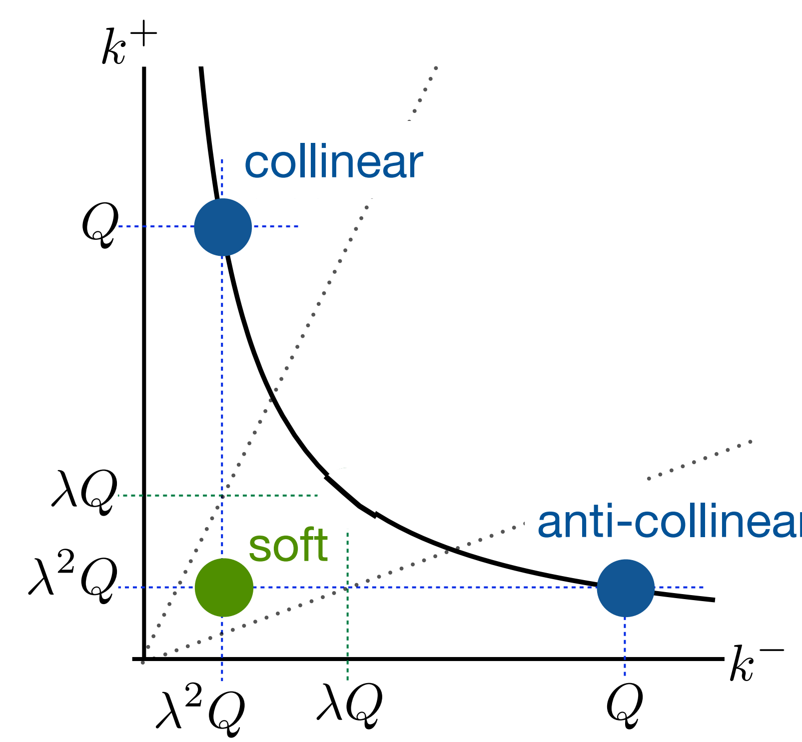


# SCET-I: Correlated scales




Generic **SCET-I factorization theorem:**

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



# SCET-I: Drell-Yan processes near threshold

In Drell-Yan processes $pp \to V + X$ near threshold, the jet functions are standard parton distribution functions (PDFs),

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

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

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

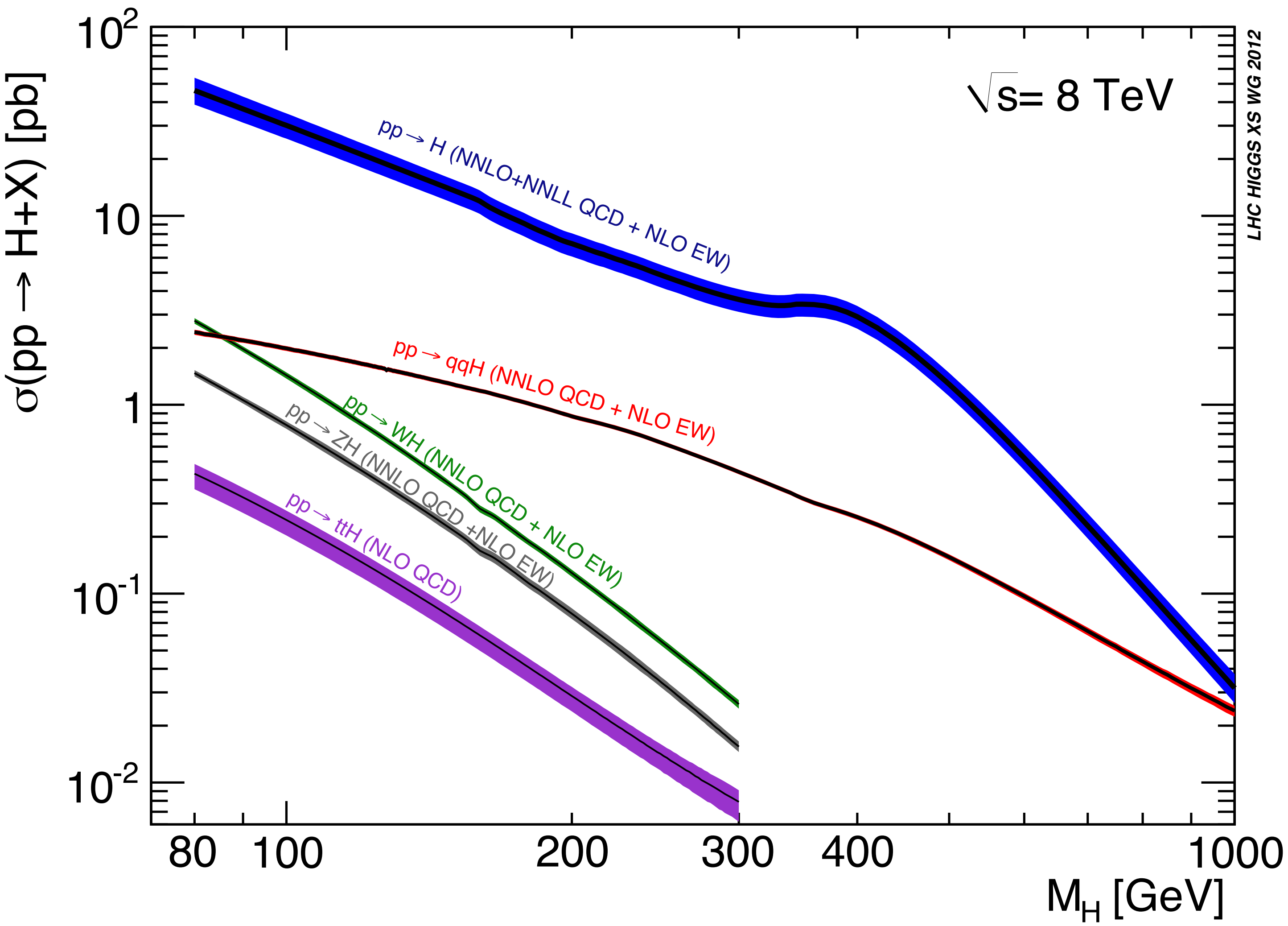
**RG invariance of the cross section** requires that the cusp logarithm must be cancelled by corresponding terms in the RGEs for collinear and soft functions, by virtue of:

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

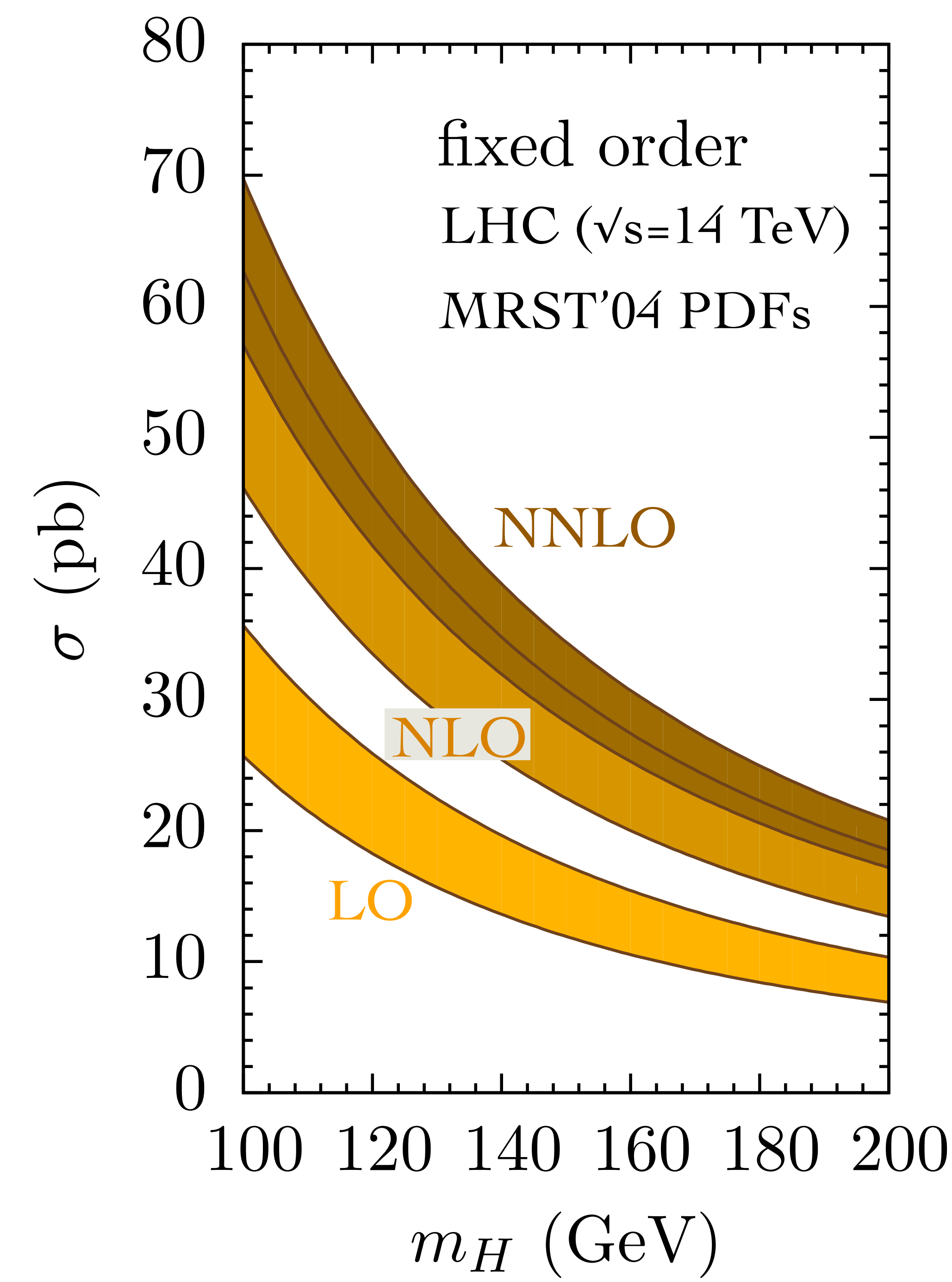
# Application I: Higgs-boson production

# Poor convergence of fixed-order pert. theory

The simplest hadron collider process, yet ...




Higgs cross sections working group (2012)




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

# Apply philosophy of effective field theory

- Separate contributions associated with different 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 renormalization group to evolve contributions to an arbitrary factorization scale, thereby exponentiating (resumming) large corrections

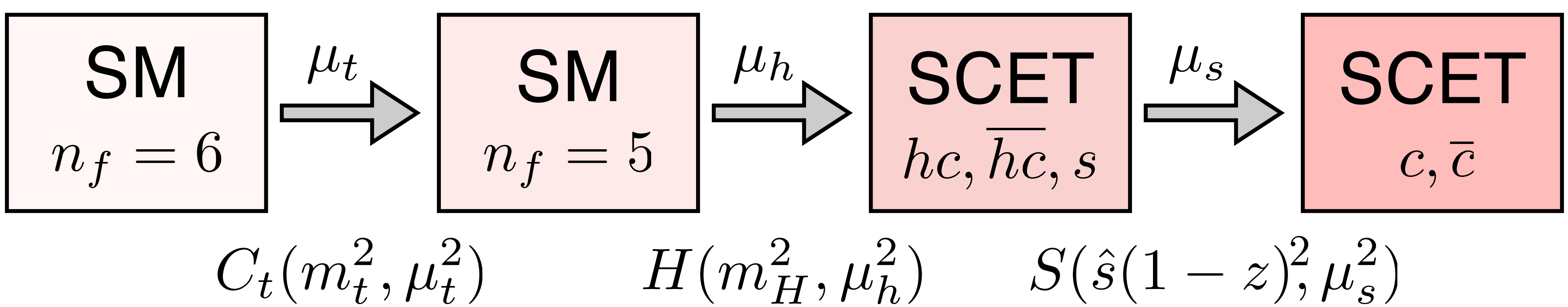
**When this is done consistently, large K-factors should not arise, since no large perturbative corrections should be left unexponentiated !**

# Apply philosophy of effective field theory

- We will analyze the Higgs cross section assuming the scale hierarchy ($z = M_H^2/\hat{s}$)

$$2m_t \gg m_H \sim \sqrt{\hat{s}} \gg \sqrt{\hat{s}}(1-z) \gg \Lambda_{\mathrm{QCD}}$$

- Treating one scale at a time leads to a sequence of effective theories:

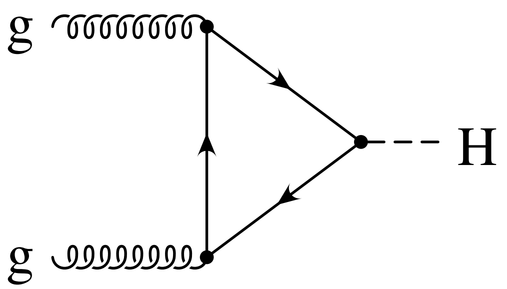



- Effects associated with each scale are absorbed into matching coefficients

# Integrate out heavy modes

1. Integrate out top quark:

$$\mathcal{L}_{\text{eff}} = C_t(m_t^2, \mu)\, \frac{\alpha_s(\mu)}{12\pi}\, \frac{H}{v}\, G^a_{\mu\nu}\, G^{\mu\nu,a}$$




Matching coefficient exhibits good convergence at natural scale choice $\mu \approx m_t$:

$$C_t(m_t^2, \mu) = 1 + \frac{11}{4}\frac{\alpha_s}{\pi} + \left(\frac{\alpha_s}{4\pi}\right)^2 \left[\frac{2777}{18} - 19\ln\frac{m_t^2}{\mu^2} + n_f\left(-\frac{67}{6} - \frac{16}{3}\ln\frac{m_t^2}{\mu^2}\right)\right] + \ldots$$

$$\approx 1 + 0.09 + 0.007 + \ldots \quad \text{for } \mu = m_t$$

Kramer, Laenen, Spira 1996; Chetyrkin, Kniehl, Steinhauser 1997

# Integrate out heavy modes

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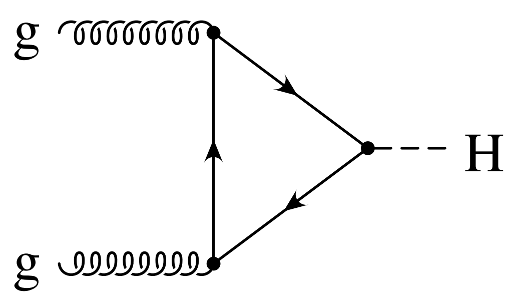
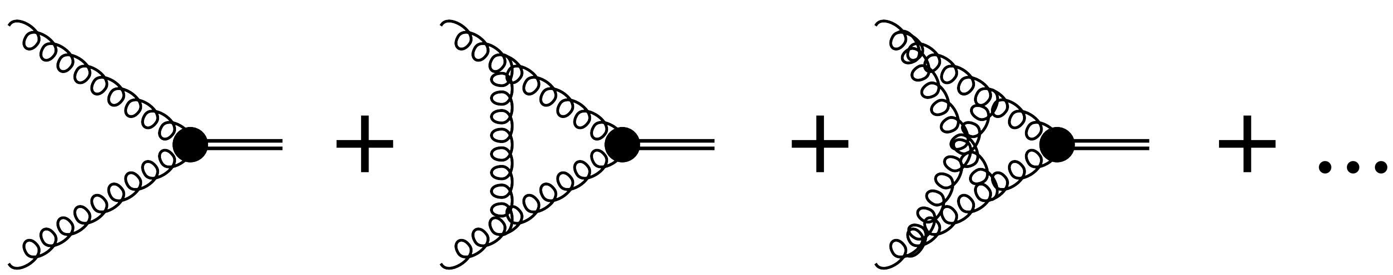


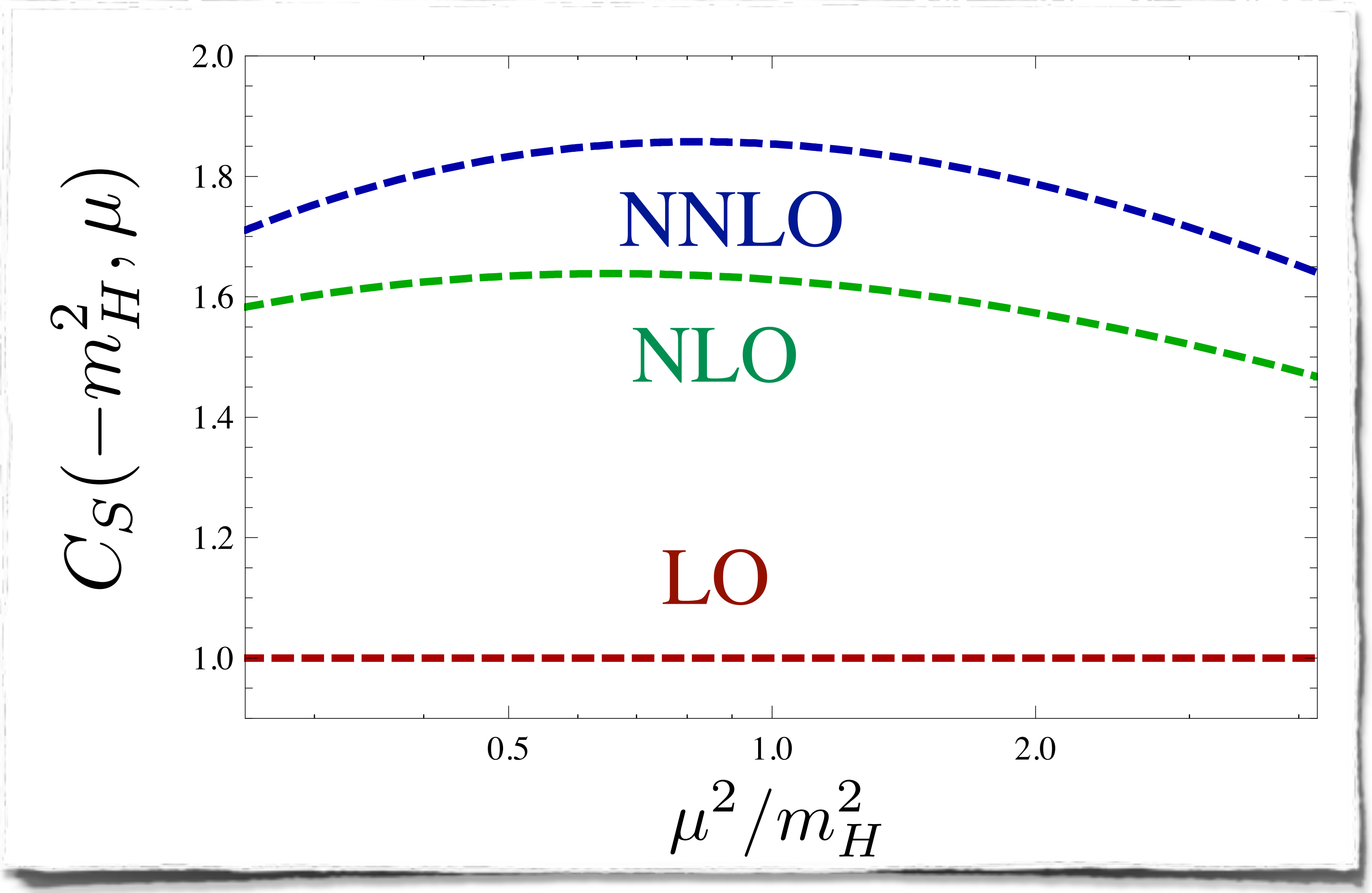

2. Match scalar gluon current onto SCET operator:

$$G^a_{\mu\nu}\,G^{\mu\nu,a} \to -2q^2\,C_S(-q^2-i\epsilon,\mu)\,g^\perp_{\mu\nu}\,\mathcal{A}^{\mu,a}_c\left(S_n^\dagger S_{\bar n}\right)^{ab}\mathcal{A}^{\nu,b}_{\bar c}$$




**time-like** gluon form factor

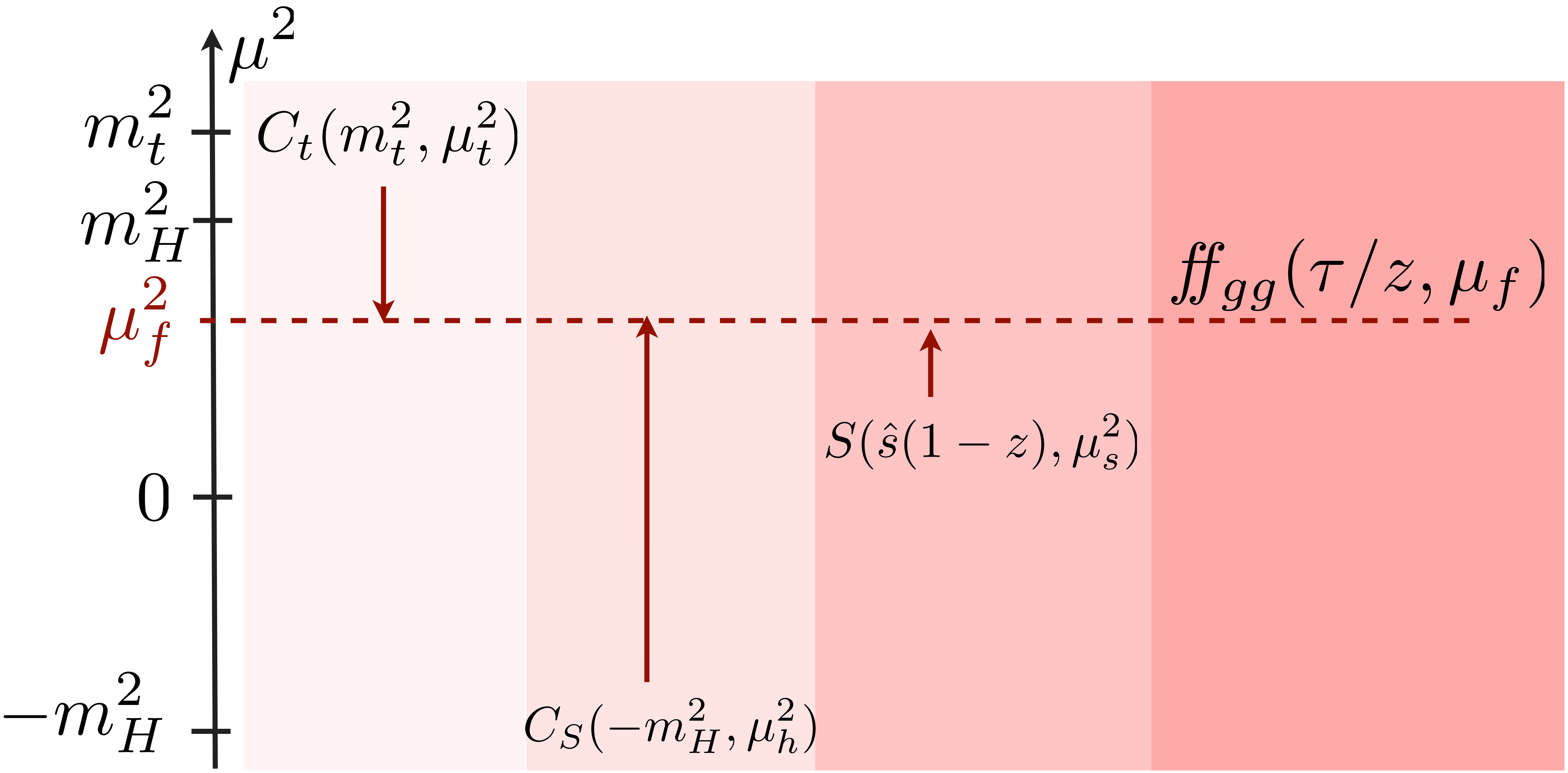
# Poor convergence for space-like scale choice



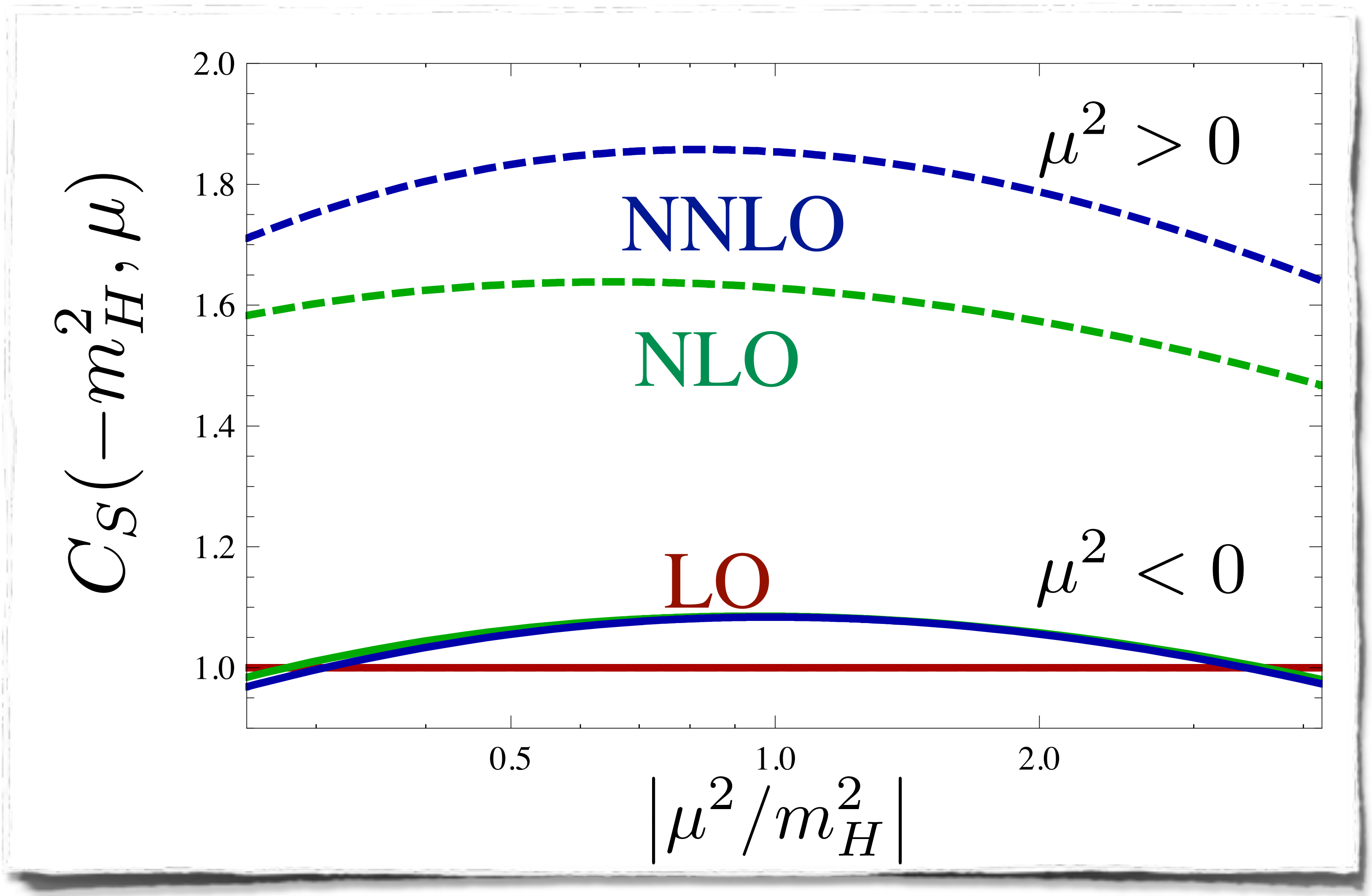

- Matching corrections appear to be huge for any choice of scale !?!
- Explains **huge K-factor** for Higgs production !
- Break-down of EFT approach ?

# Evolve Wilson coefficients to their natural scales

- Evaluate each part at its characteristic scale and evolve to a common scale using RGEs:

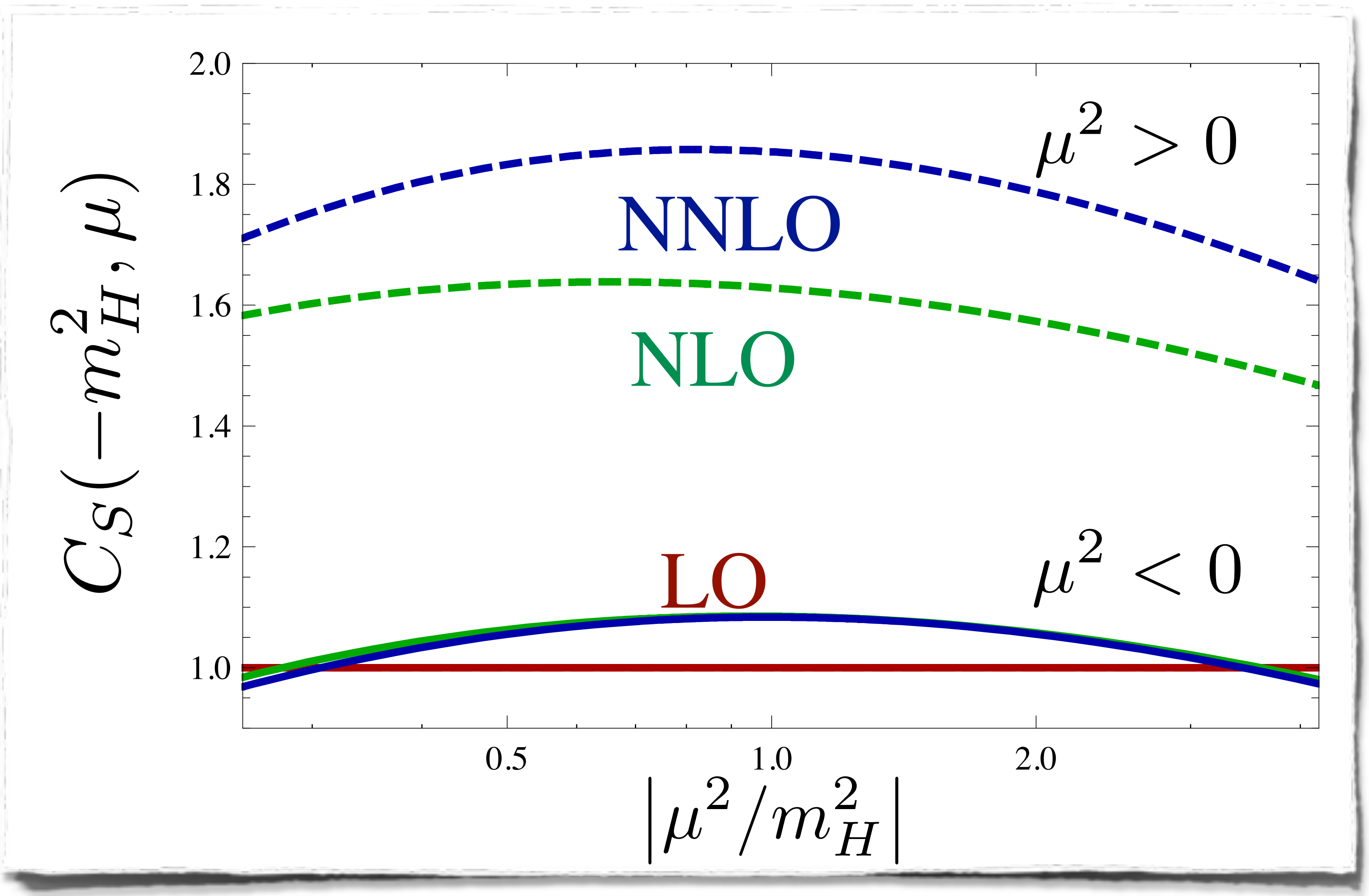


# Good convergence for time-like scale choice

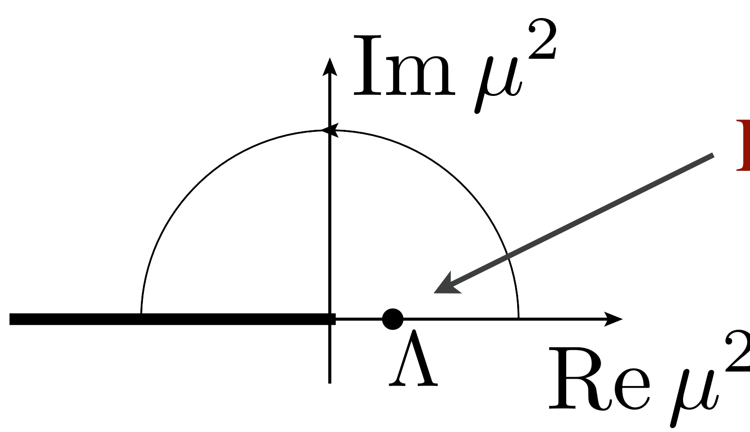



- Much better convergence for $\mu^2 < 0$ (time-like)
- Perform matching in time-like region and use RGE to evolve to any other scale

# Good convergence for time-like scale choice



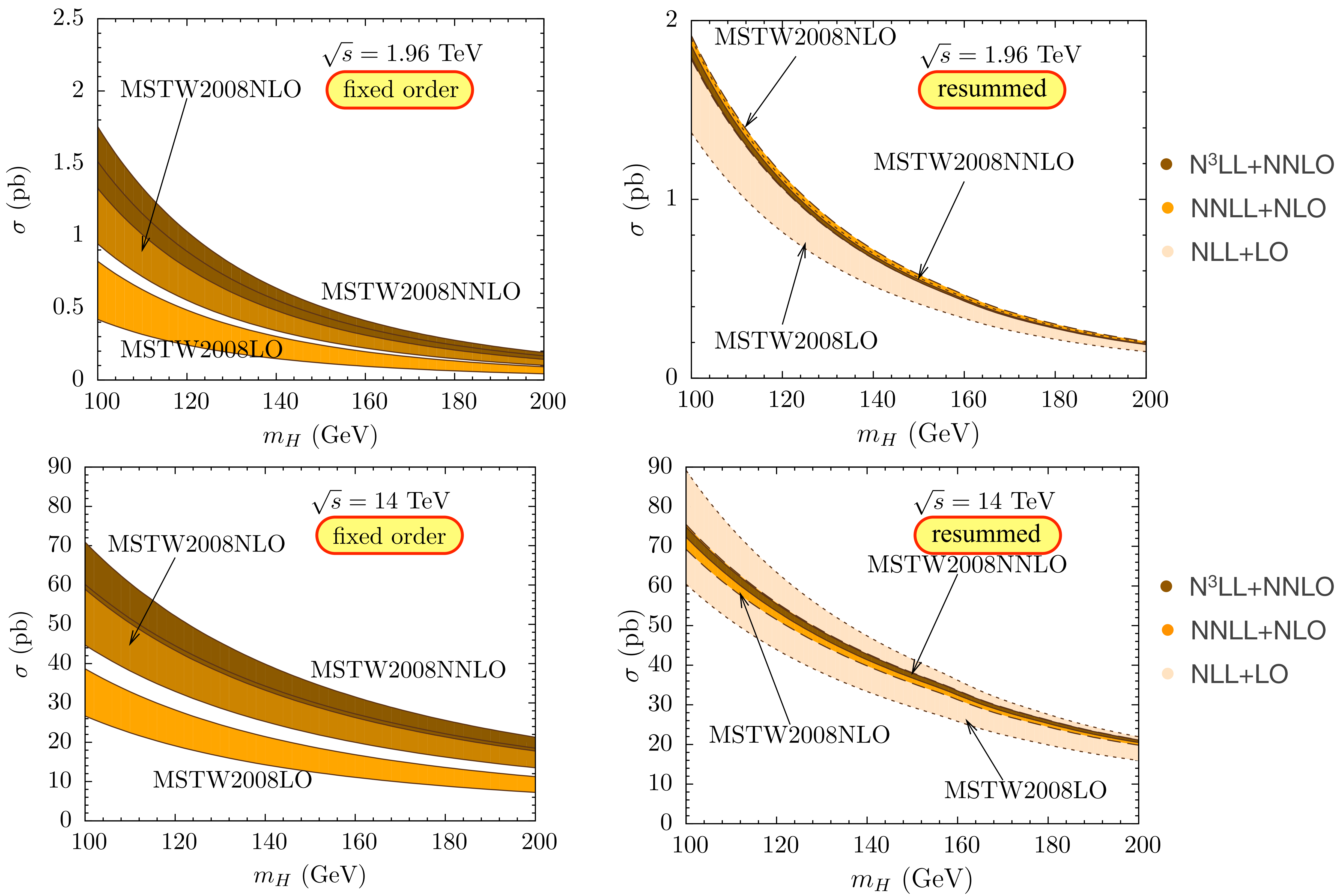

$$\alpha_s(\mu^2) \sim \frac{1}{\ln(\mu^2/\Lambda^2)}$$




$$\alpha_s\left[-(120\,\mathrm{GeV})^2 + i\epsilon\right] \approx 0.108 - 0.025i \qquad \alpha_s\left[(120\,\mathrm{GeV})^2\right] \approx 0.114$$

# Higgs production in gluon-gluon fusion

Ahrens, Becher, MN, Yang: 0809.4283 (EPJC), 1008.3162 (PLB)



# Higgs production in gluon-gluon fusion

Ahrens, Becher, MN, Yang: 0809.4283 (EPJC), 1008.3162 (PLB)

- Resummation at **N$^3$LL order**, matched to NNLO fixed-order theory
- SCET analysis automatically resums an important class of large perturbative corrections related to the **time-like nature** of the fusion process
- Electroweak radiative corrections are included, and results are available for all modern PDF sets
- **Most precise predictions available**

## MSTW 2008 PDFs

| $m_H$ [GeV] | Tevatron | LHC (7 TeV) | LHC (10 TeV) | LHC (14 TeV) |
|---|---|---|---|---|
| 115 | $1.215^{+0.031+0.141}_{-0.007-0.135}$ | $18.19^{+0.53+1.46}_{-0.14-1.39}$ | $33.7^{+1.0+2.6}_{-0.2-2.5}$ | $57.9^{+1.6+4.4}_{-0.3-4.2}$ |
| 120 | $1.073^{+0.026+0.126}_{-0.006-0.121}$ | $16.73^{+0.48+1.34}_{-0.13-1.28}$ | $31.2^{+0.9+2.4}_{-0.2-2.3}$ | $54.0^{+1.5+4.1}_{-0.3-3.9}$ |
| 125 | $0.950^{+0.022+0.113}_{-0.005-0.108}$ | $15.43^{+0.44+1.23}_{-0.12-1.18}$ | $29.0^{+0.8+2.2}_{-0.2-2.1}$ | $50.4^{+1.4+3.8}_{-0.3-3.6}$ |
| 130 | $0.844^{+0.019+0.102}_{-0.004-0.098}$ | $14.27^{+0.40+1.14}_{-0.11-1.09}$ | $27.0^{+0.7+2.1}_{-0.2-2.0}$ | $47.2^{+1.3+3.5}_{-0.3-3.4}$ |

## CT10 PDFs

| $m_H$ [GeV] | Tevatron | LHC (7 TeV) | LHC (10 TeV) | LHC (14 TeV) |
|---|---|---|---|---|
| 115 | $1.215^{+0.031+0.105}_{-0.007-0.095}$ | $18.34^{+0.54+0.95}_{-0.14-1.00}$ | $34.1^{+1.0+1.8}_{-0.2-1.9}$ | $58.8^{+1.7+3.1}_{-0.4-3.5}$ |
| 120 | $1.073^{+0.026+0.096}_{-0.005-0.087}$ | $16.86^{+0.49+0.87}_{-0.13-0.91}$ | $31.5^{+0.9+1.6}_{-0.2-1.8}$ | $54.7^{+1.6+2.9}_{-0.3-3.2}$ |
| 125 | $0.950^{+0.022+0.088}_{-0.005-0.079}$ | $15.54^{+0.45+0.80}_{-0.12-0.83}$ | $29.3^{+0.8+1.5}_{-0.2-1.6}$ | $51.1^{+1.4+2.6}_{-0.3-3.0}$ |
| 130 | $0.845^{+0.019+0.081}_{-0.004-0.072}$ | $14.36^{+0.41+0.74}_{-0.11-0.76}$ | $27.2^{+0.8+1.4}_{-0.2-1.5}$ | $47.8^{+1.3+2.5}_{-0.3-2.7}$ |

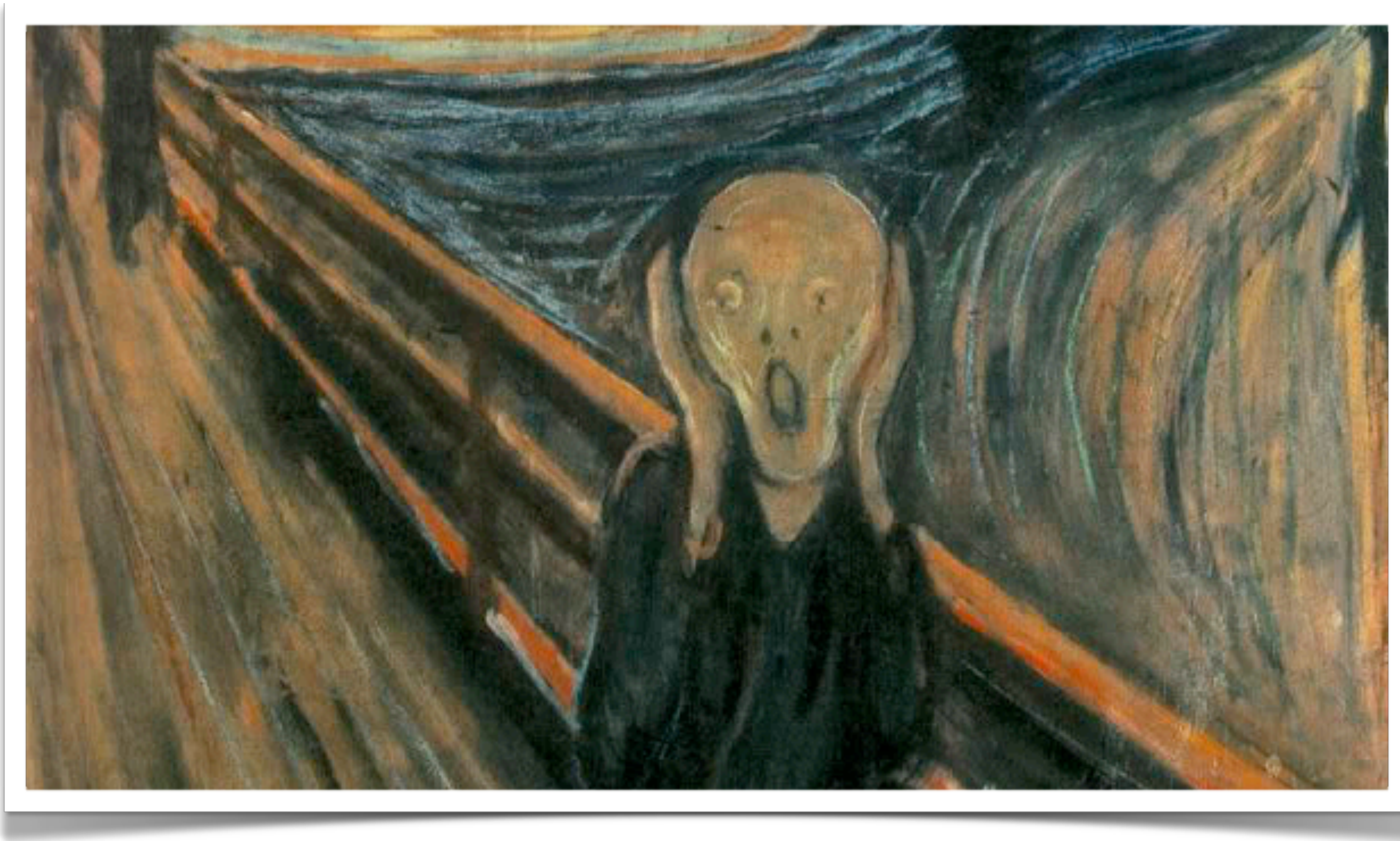
## NNPDF2.0 PDFs

| $m_H$ [GeV] | Tevatron | LHC (7 TeV) | LHC (10 TeV) | LHC (14 TeV) |
|---|---|---|---|---|
| 115 | $1.341^{+0.037+0.143}_{-0.018-0.143}$ | $19.35^{+0.60+1.36}_{-0.29-1.36}$ | $35.4^{+1.1+2.4}_{-0.5-2.4}$ | $60.3^{+1.8+3.9}_{-0.7-3.9}$ |
| 120 | $1.184^{+0.032+0.129}_{-0.016-0.129}$ | $17.82^{+0.54+1.25}_{-0.29-1.25}$ | $32.8^{+1.0+2.2}_{-0.5-2.2}$ | $56.3^{+1.7+3.7}_{-0.7-3.7}$ |
| 125 | $1.049^{+0.027+0.116}_{-0.014-0.116}$ | $16.45^{+0.50+1.15}_{-0.28-1.15}$ | $30.5^{+0.9+2.0}_{-0.5-2.0}$ | $52.6^{+1.5+3.4}_{-0.8-3.4}$ |
| 130 | $0.932^{+0.023+0.105}_{-0.013-0.105}$ | $15.23^{+0.45+1.07}_{-0.28-1.07}$ | $28.5^{+0.8+1.9}_{-0.5-1.9}$ | $49.3^{+1.4+3.2}_{-0.8-3.2}$ |

scale uncertainty

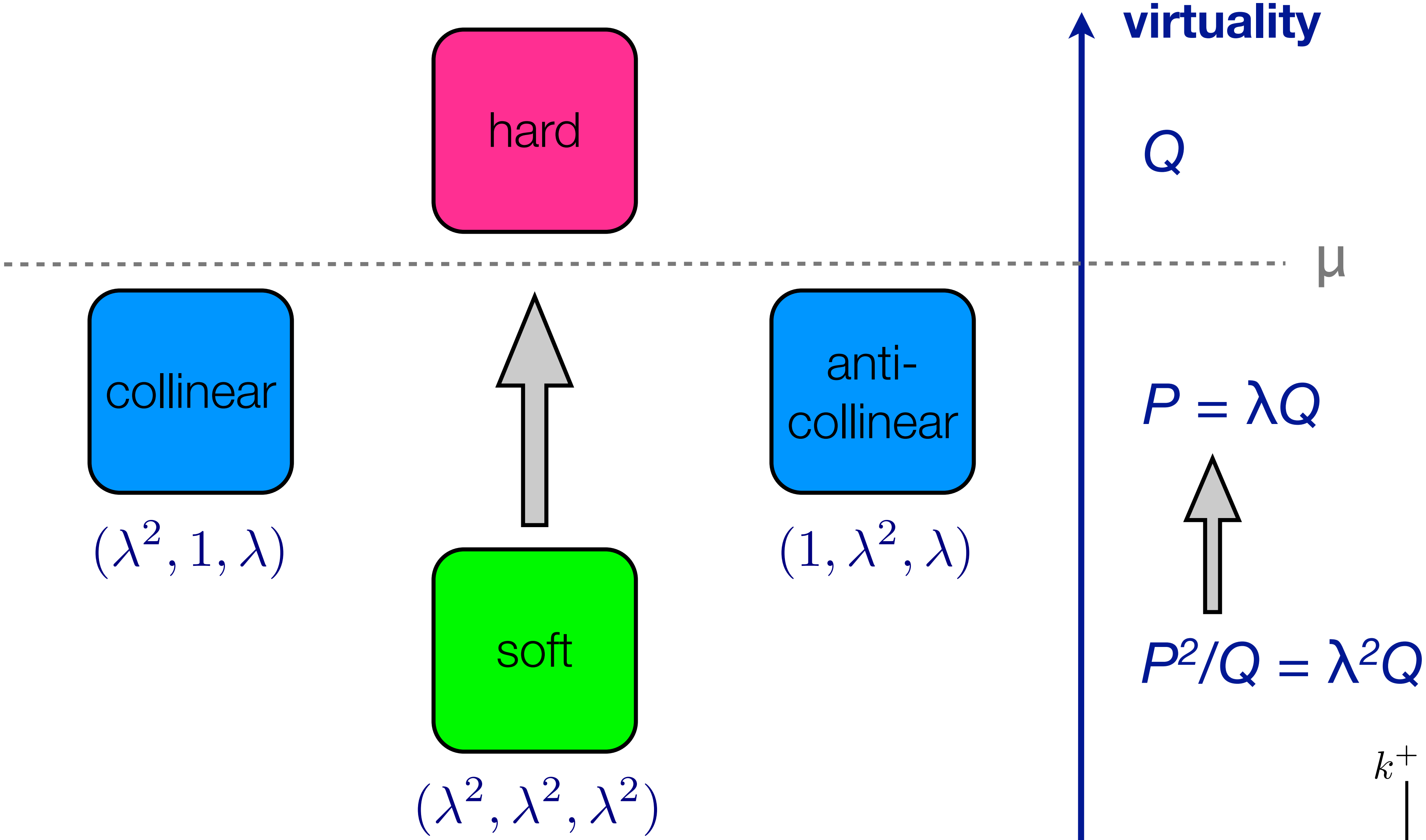
PDF & $\alpha_s$ uncertainty

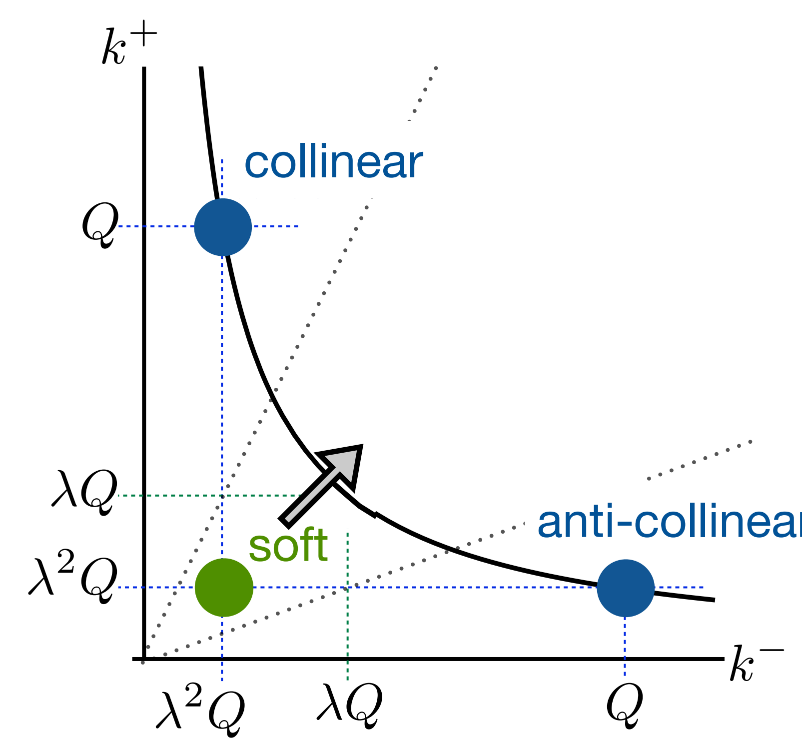
→ public code RGHiggs available at: http://projects.hepforge.org/rghiggs



Collinear factorization anomaly

# SCET-I: Correlated scales

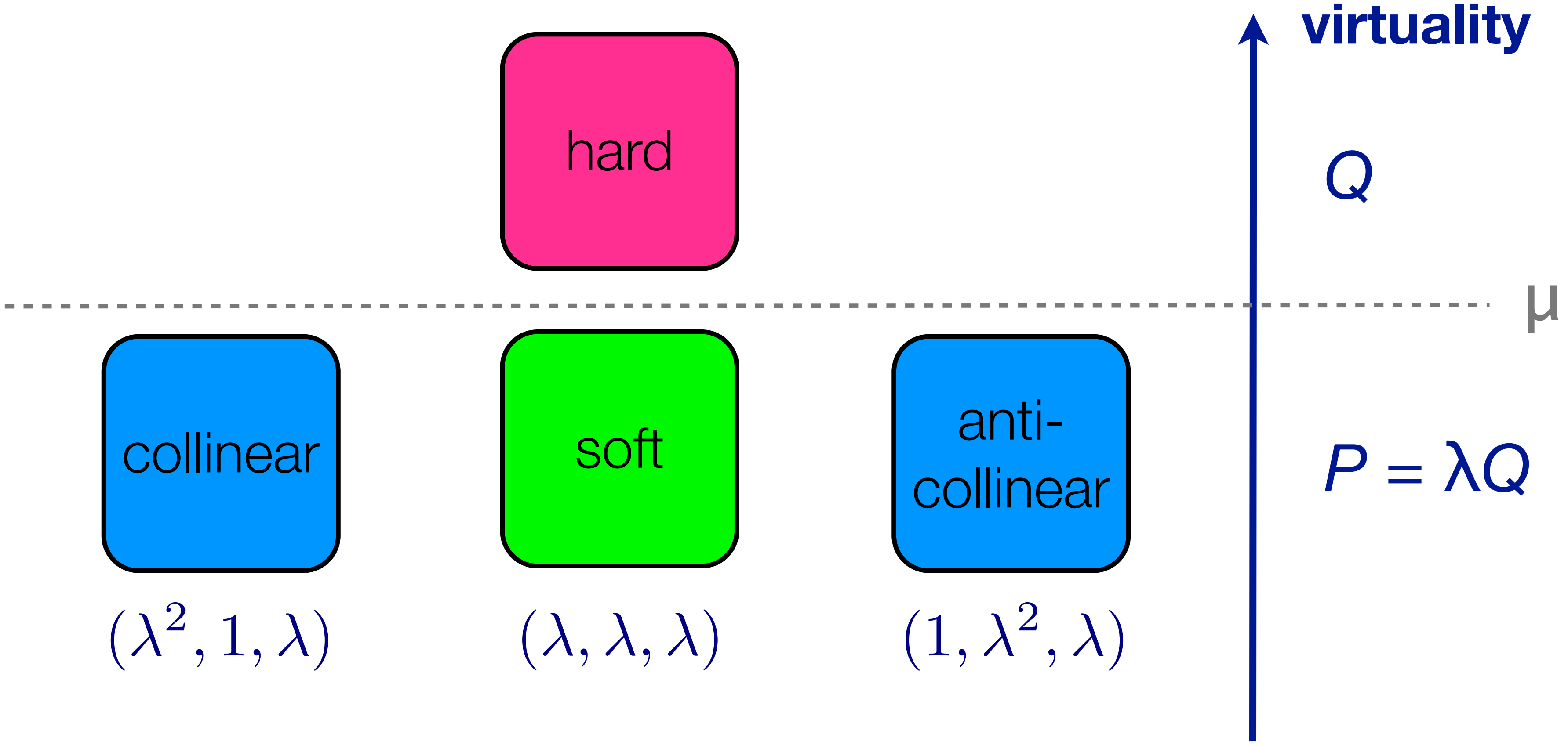



Generic **SCET-I factorization theorem:**

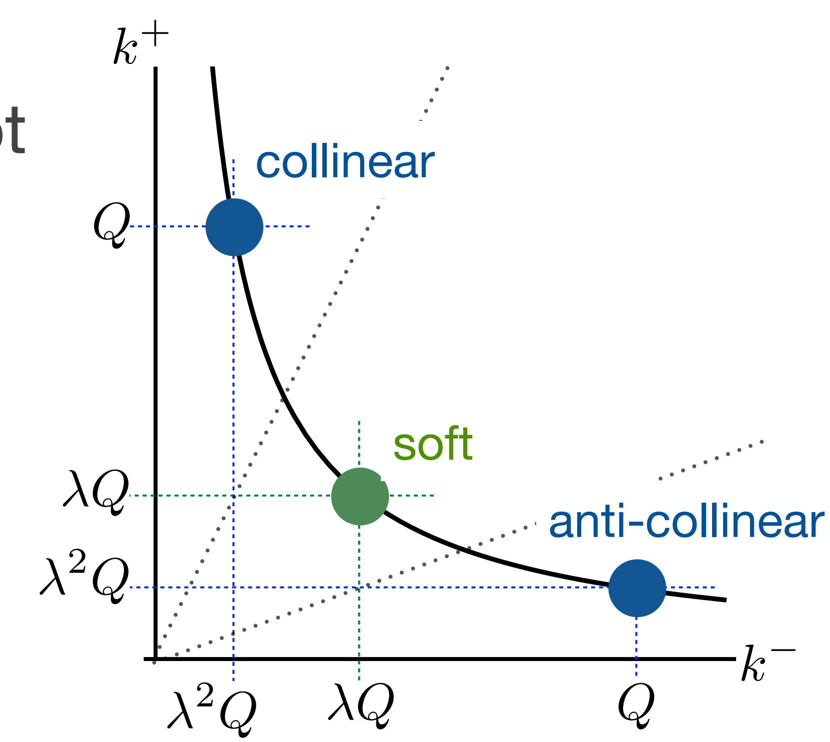
$$d\sigma = H\, J \otimes J \otimes S$$

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




- Naively violates RG invariance, since collinear and soft particles have same virtuality; hence one cannot generate $\ln(Q/\mu)$ from their anomalous dimensions

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



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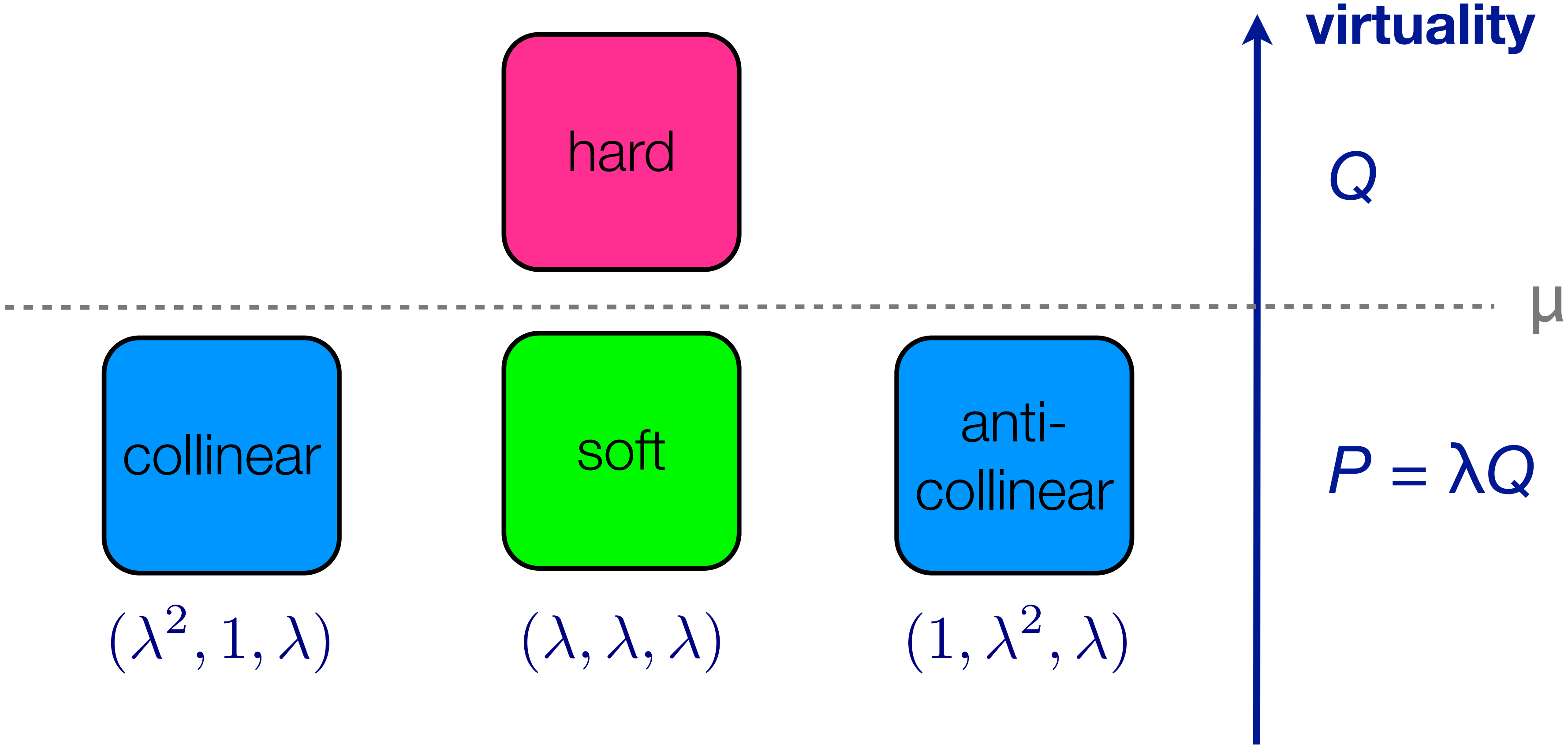
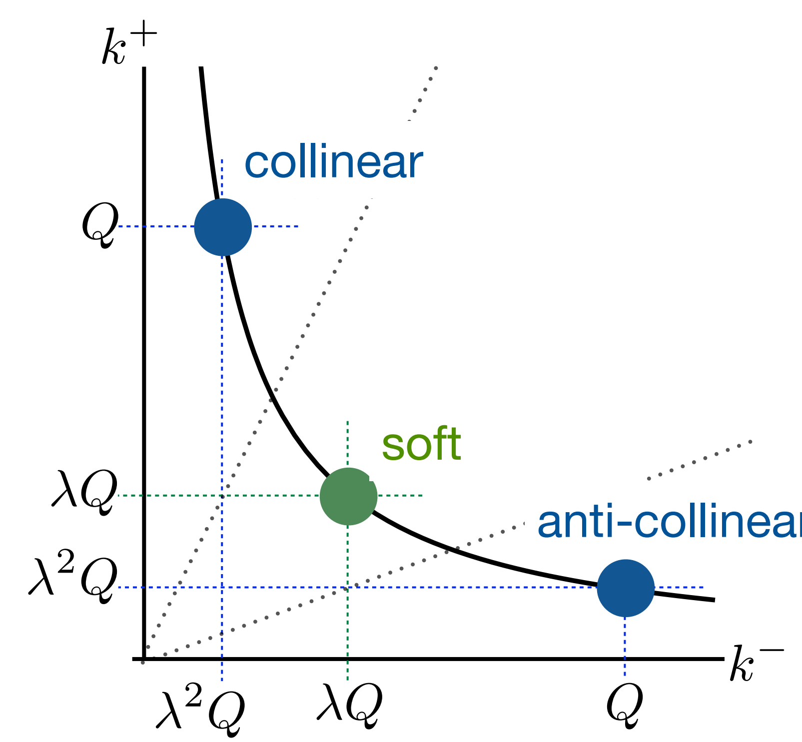



- Problem is cured by an anomaly of the effective theory SCET-II: **collinear factorization anomaly**

Becher, MN: 1007.4005 (EPJC)

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



# SCET-II: Collinear factorization anomaly

Generic (anti-)collinear loop 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 defined using analytic regulators, e.g.:

$$\frac{1}{k_+} \to \frac{\nu^{2\alpha}\, p_-}{(k_+\, p_-)^{1+\alpha}}$$

for an all-order analytic regularization scheme, see:
Becher, Bell: 1112.3907

- **poles in 1/$\alpha$** cancel when one adds the collinear and anti-collinear 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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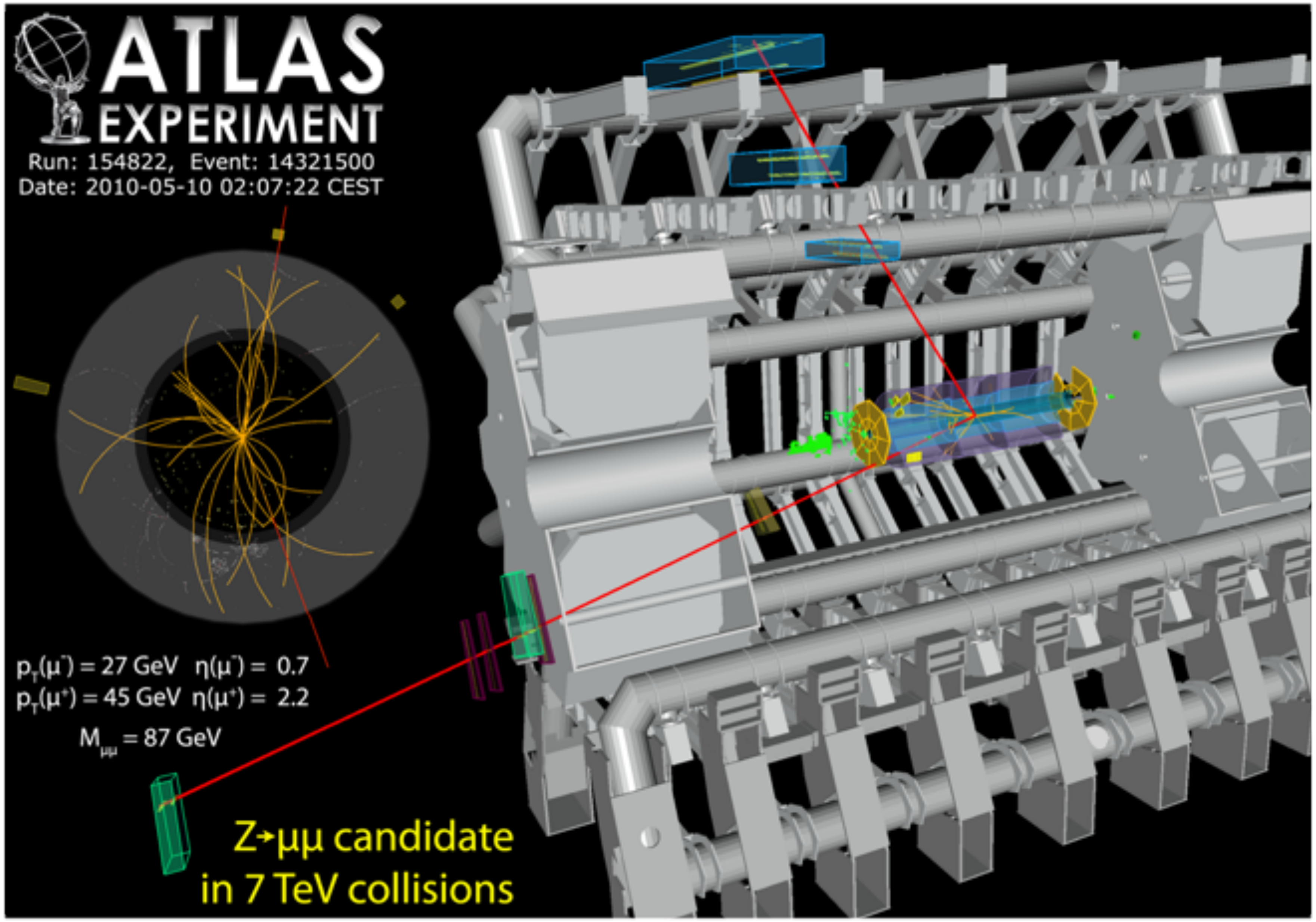
In SCET-II, this phenomenon can be interpreted as an anomaly: the **breaking of a classical symmetry** of the effective Lagrangian by **quantum effects**

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

**Many applications:** EW Sudakov, $q_T$ resummation, jet broadening, jet veto, ...



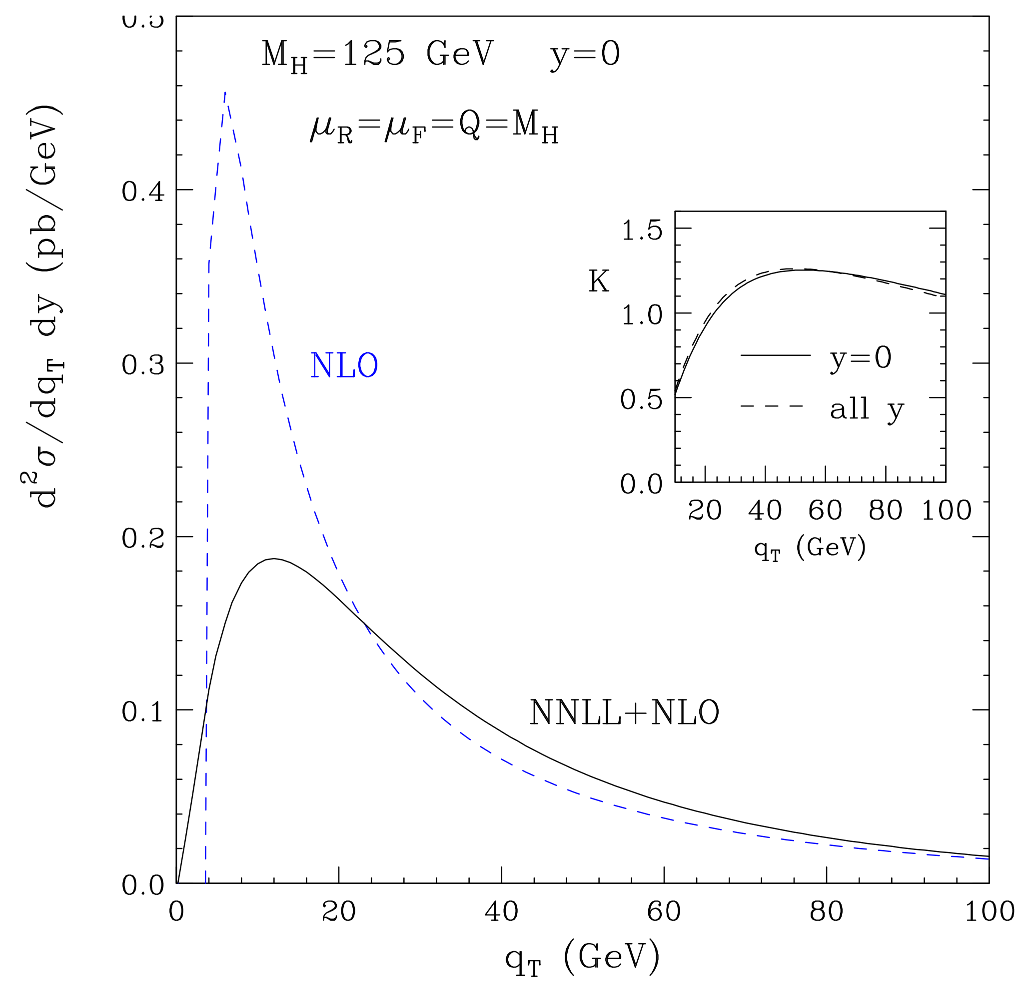

# Application II: Transverse-momentum resummation for Z and Higgs production

# Drell-Yan production at small $q_T$

Bozzi, Catani, de Florian, Grazzini: 0705.3887 (NPB)

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 (EPJC)

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

beam functions
Stewart, Tackmann, Waalewijn: 0910.0467 (PRD)

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

# Infrared protection at very small $q_T$

Becher, MN, 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 down to zero transverse momentum

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

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

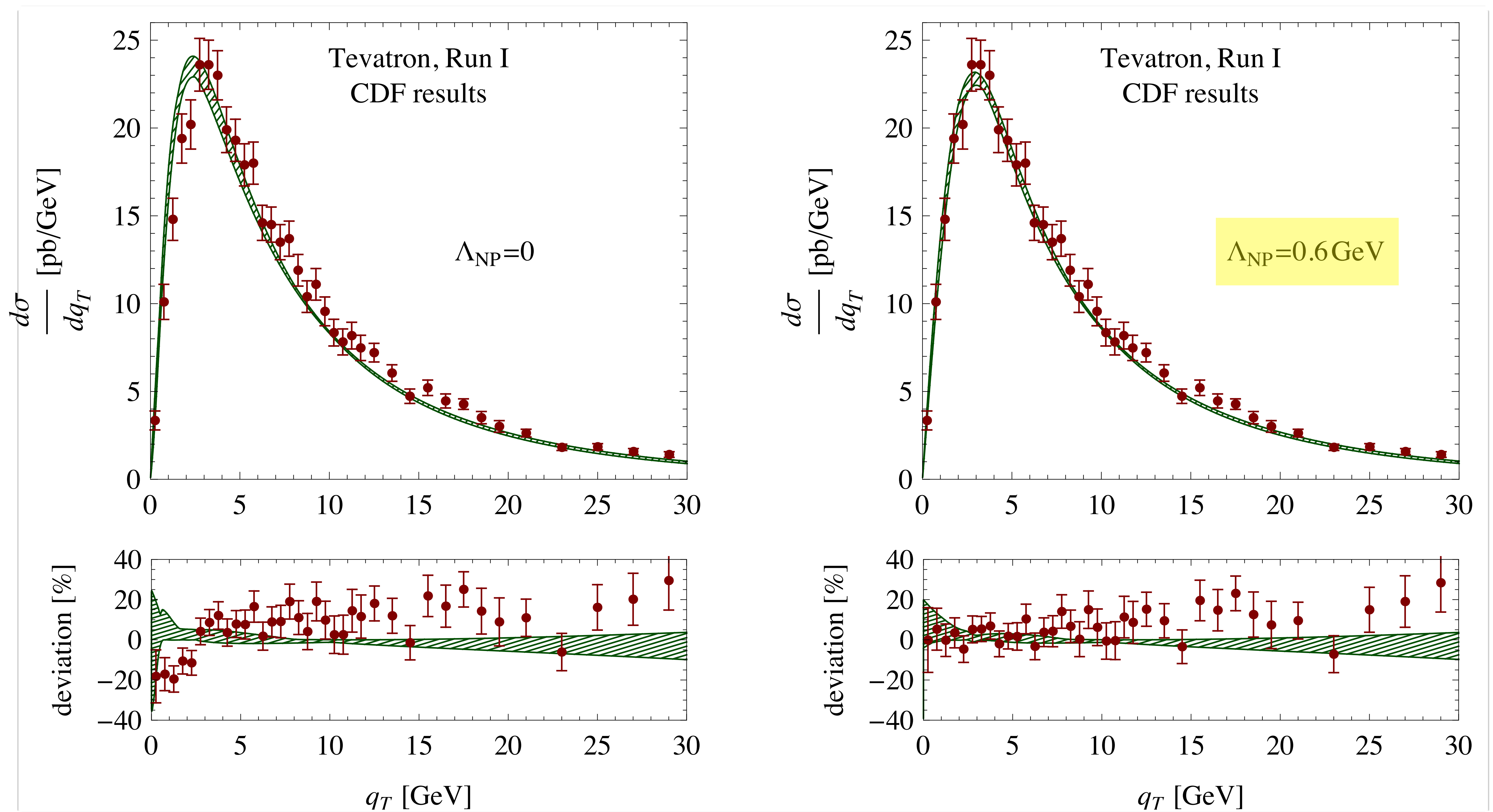
➡ yields **1.9 GeV** for Z production, and **7.7 GeV** for Higgs production

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 (JHEP)

- First **complete** calculation of Z-boson and Higgs production at NNLL+NLO
- Extension to N³LL+NNLO is technically possible (work in progress)



# Z-boson production at LHC

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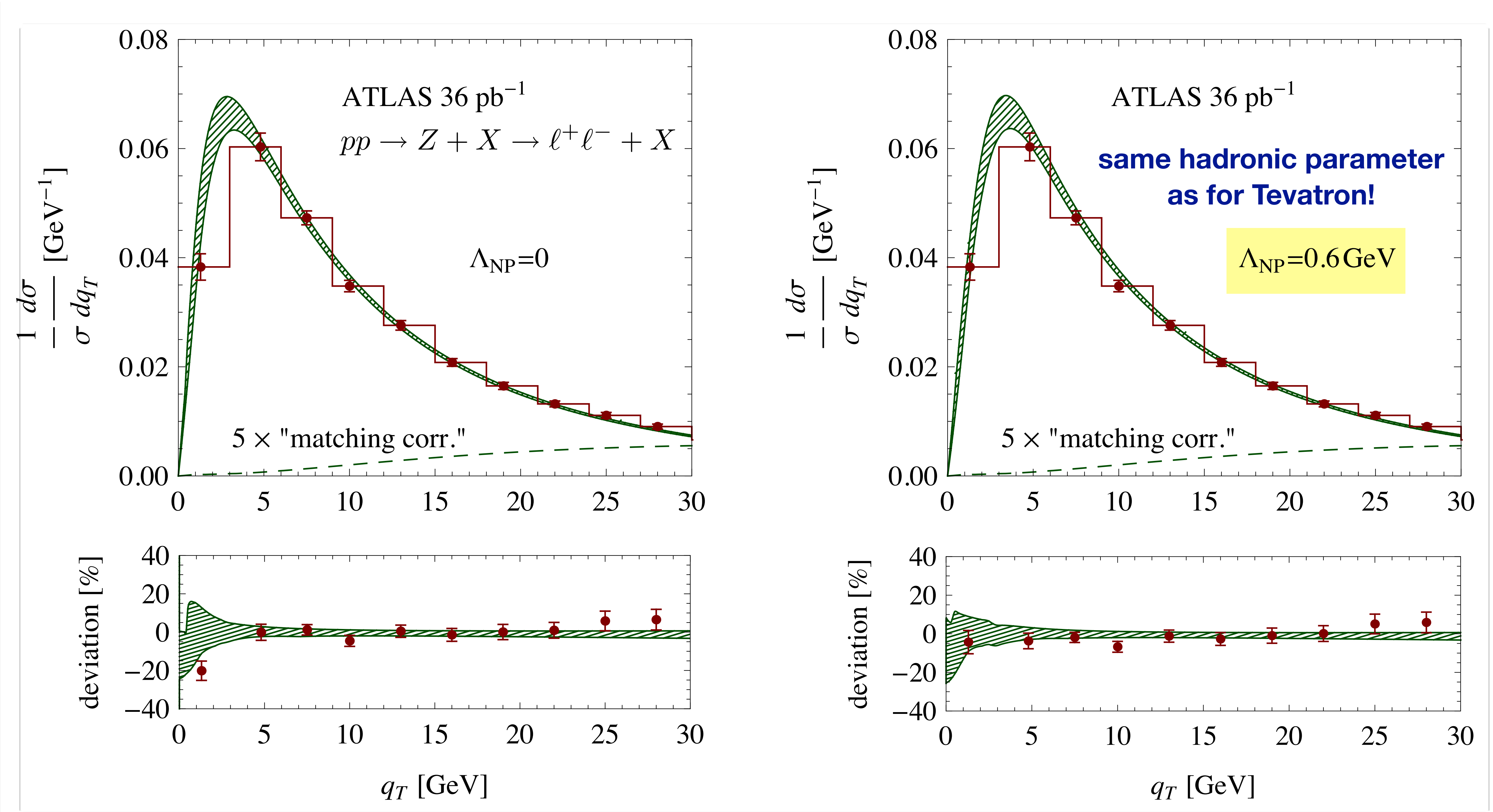
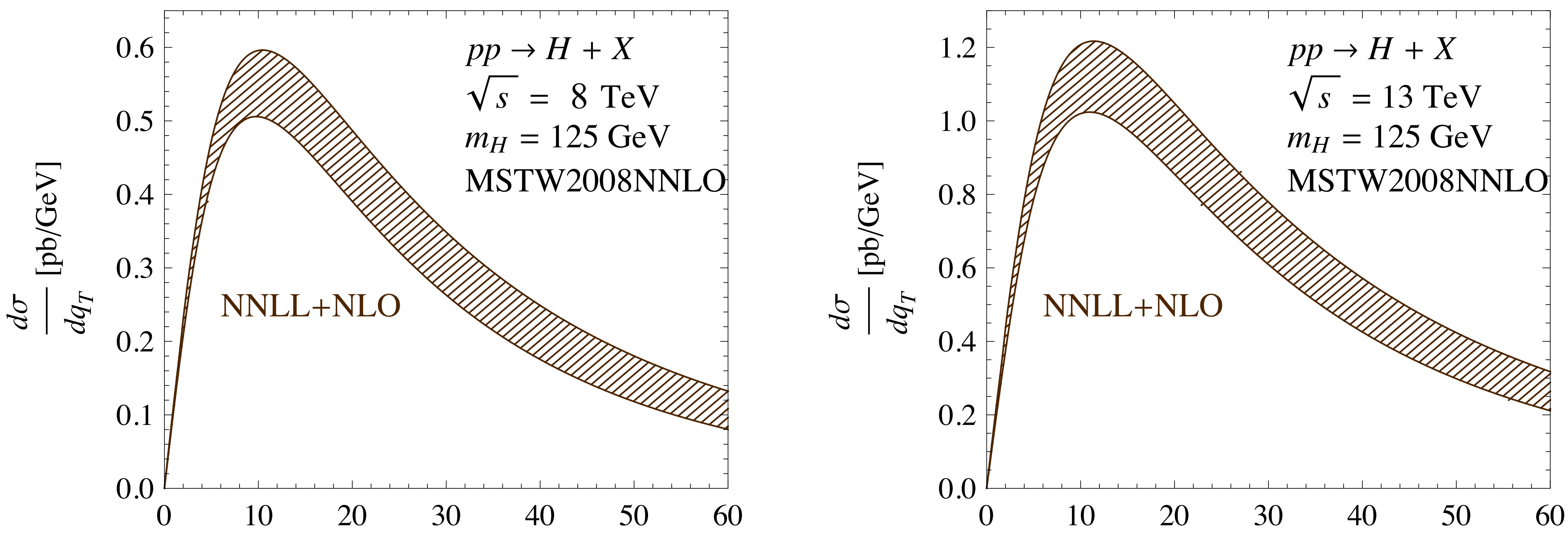


# Higgs-boson production at LHC

Becher, MN, Wilhelm: 1212.2621 (today!)

- Higgs $q_T$ spectrum is predicted with similar accuracy, only that long-distance hadronic corrections are much smaller in this case
- Eagerly awaiting data ...




→ public code CuTe available at: [http://cute.hepforge.org](http://cute.hepforge.org)

# Higgs-boson production at LHC

Becher, MN, Wilhelm: 1212.2621 (today!)

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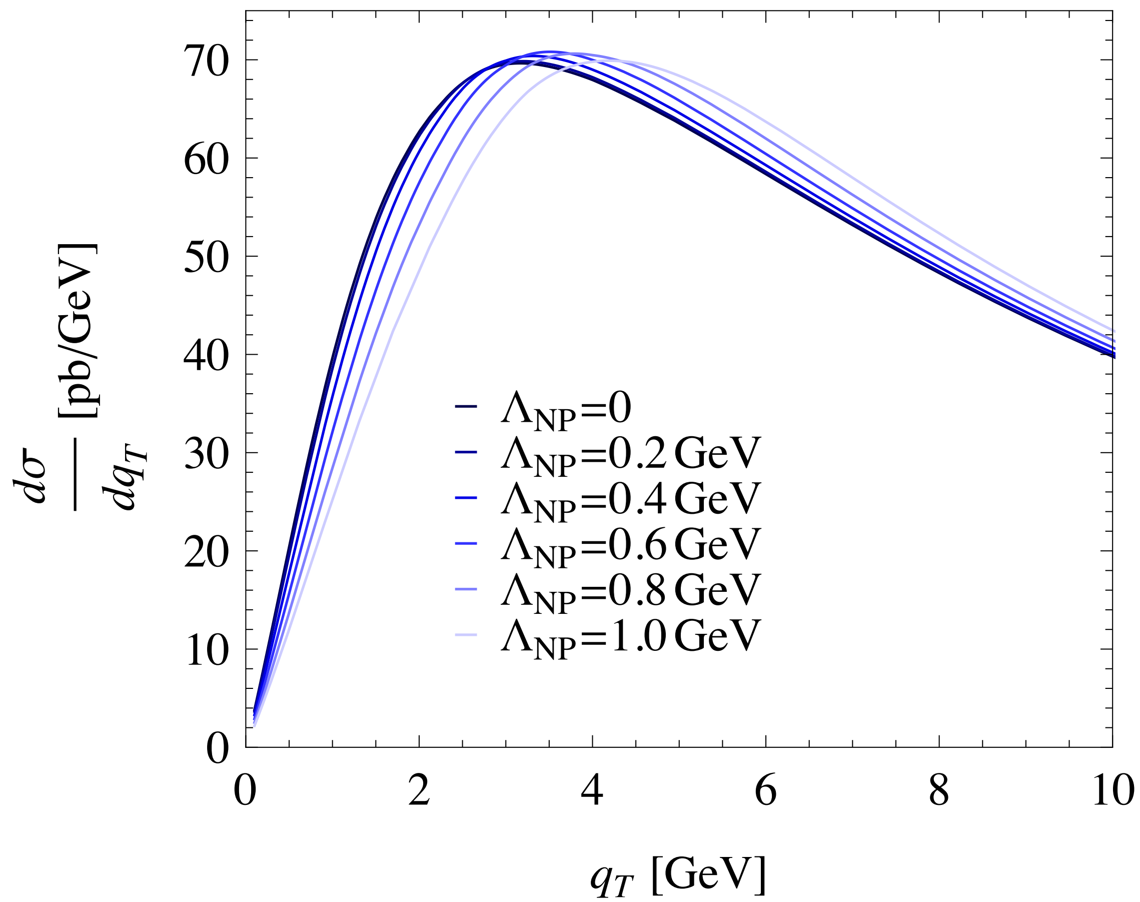
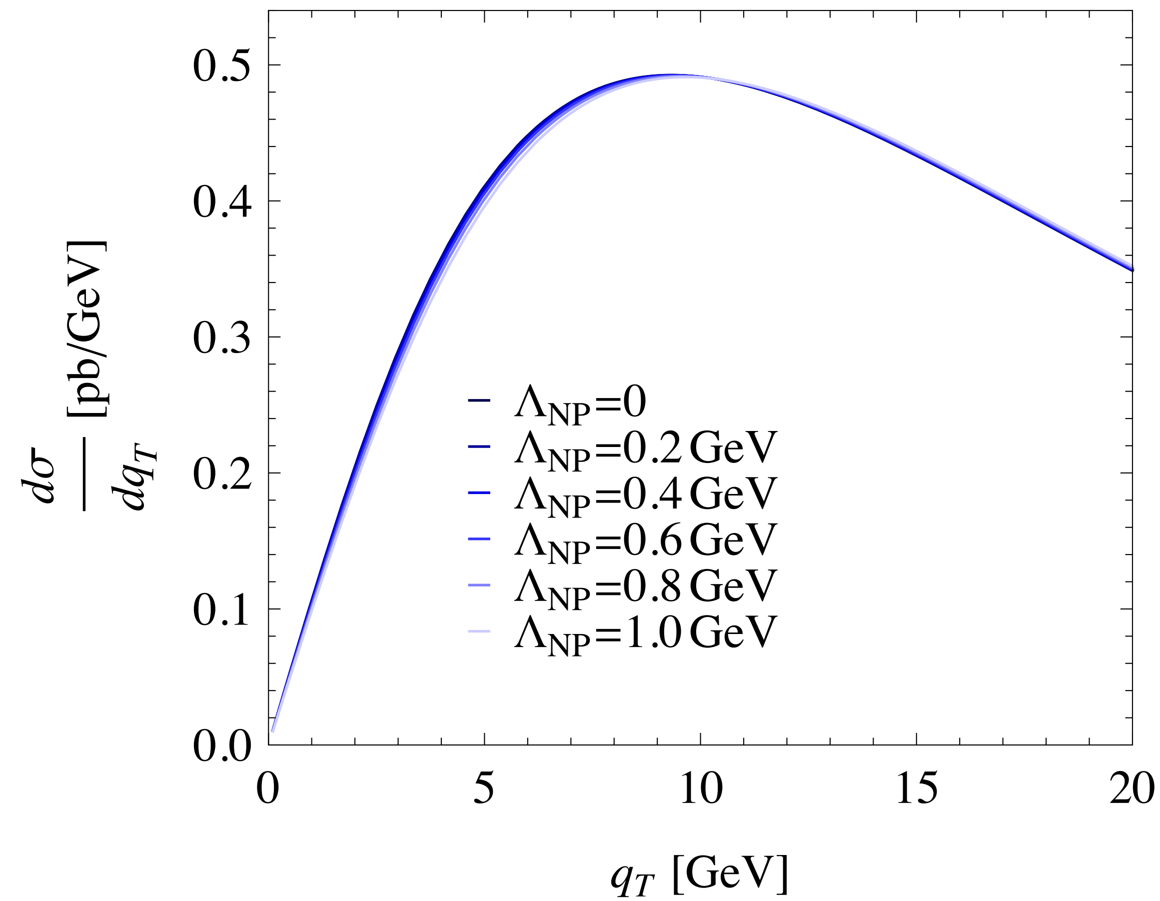
- Eagerly awaiting data ...




hadronic corrections: Z-boson case




hadronic corrections: Higgs case

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Application III:
Higgs production with a jet veto

# Higgs production with a jet veto

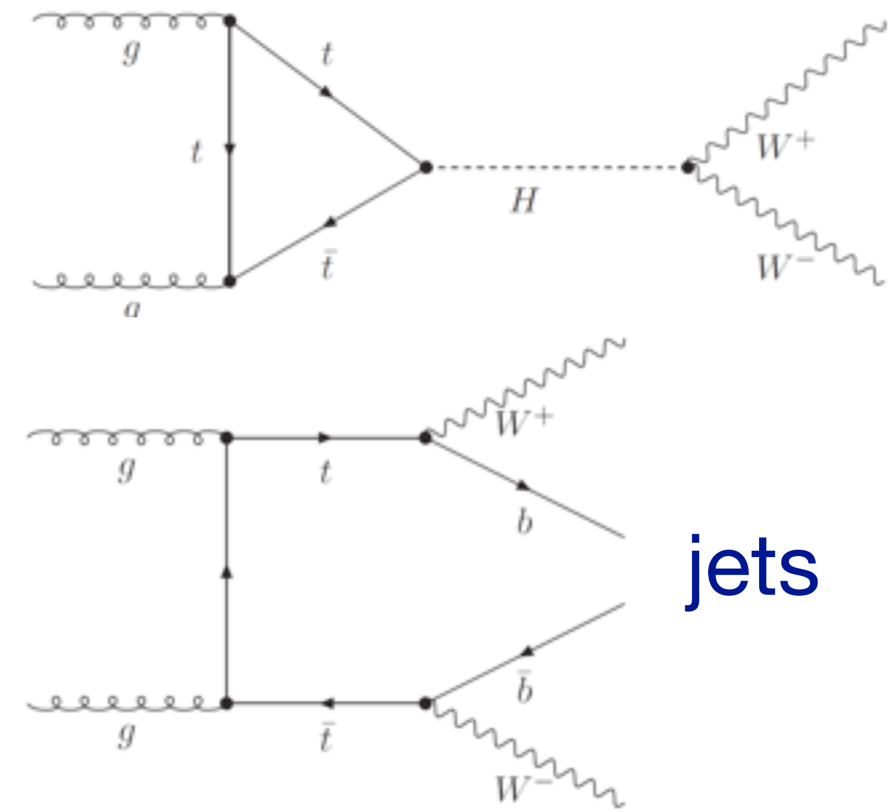
Searches for Higgs boson require stringent cuts to suppress background events

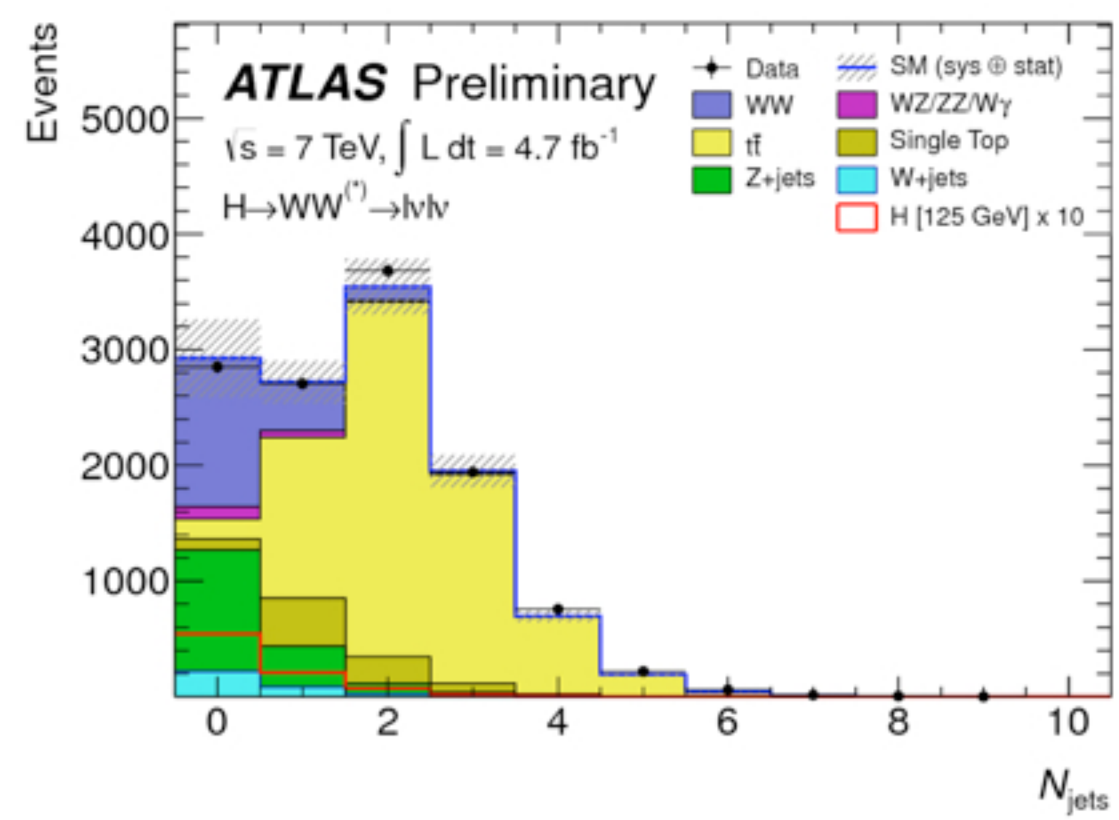
Since backgrounds are very different when the Higgs is produced in association with jets, the searches are performed in **jet bins**

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

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

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



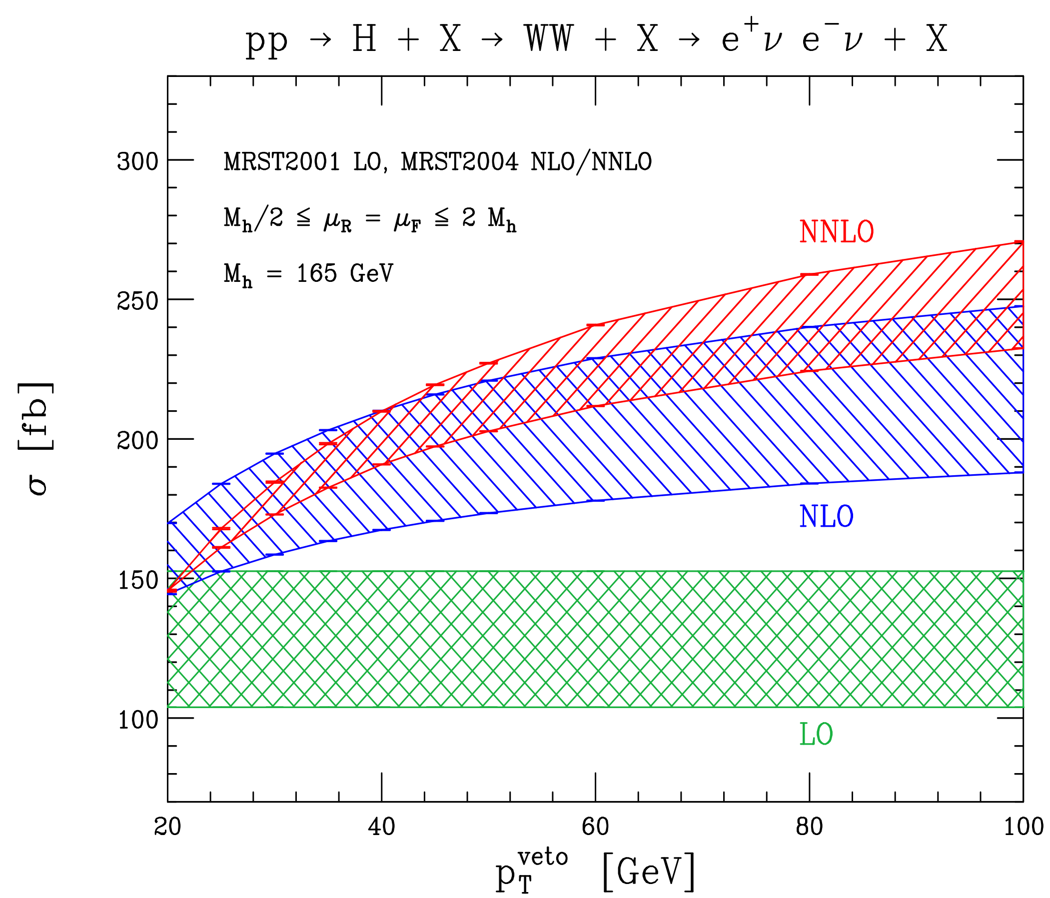
# Higgs production with a jet veto

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 $\alpha_s^n \ln^{2n}(m_H/p_T^{\text{veto}})$

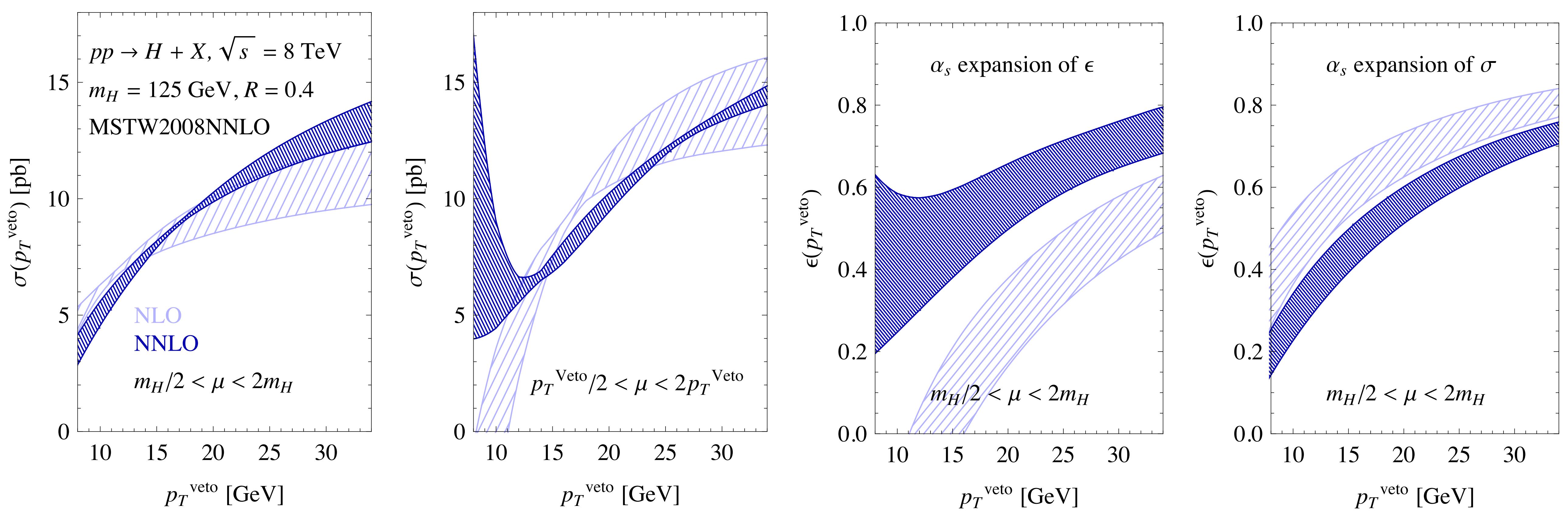
True perturbative uncertainty is most likely significantly larger
Stewart, Tackmann, Waalewijn (2010)
Stewart, Tackmann (2011)




Anastasiou, Dissertori, Stöckli (2007)

# Higgs production with a jet veto

Updated fixed-order predictions for two different default scale choices (R=0.4):

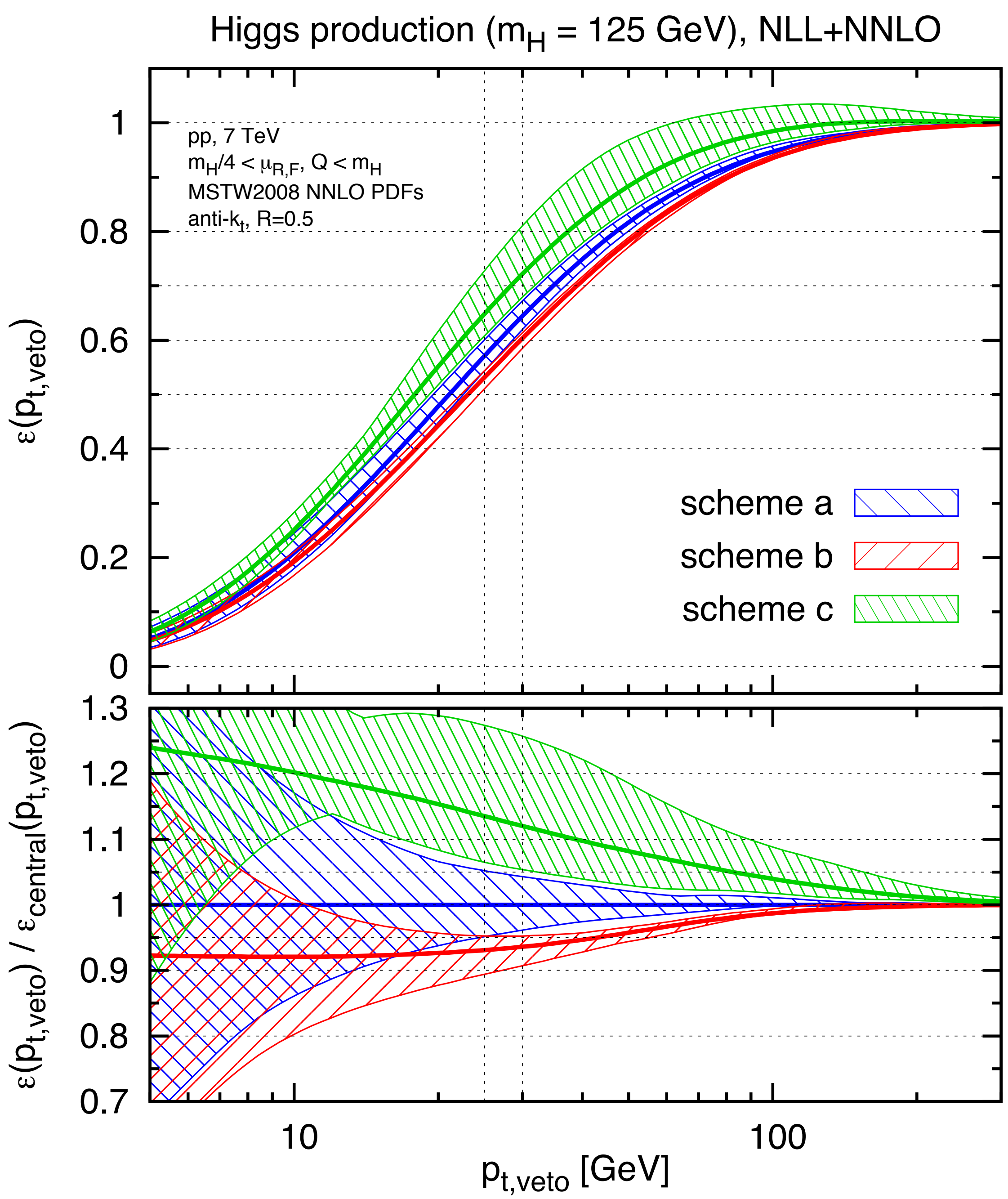



⇒ bands likely do not reflect true uncertainties!

# Resummation at NLL and beyond

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

- "jet veto is, trivially, in the scope of CAESAR" Banfi, Salaam, Zanderighi: 1203.5773
- **Is it also in the scope of SCET ?** Tackmann, Walsh, Zuberi: 1206.4312



# Resummation at NLL and beyond

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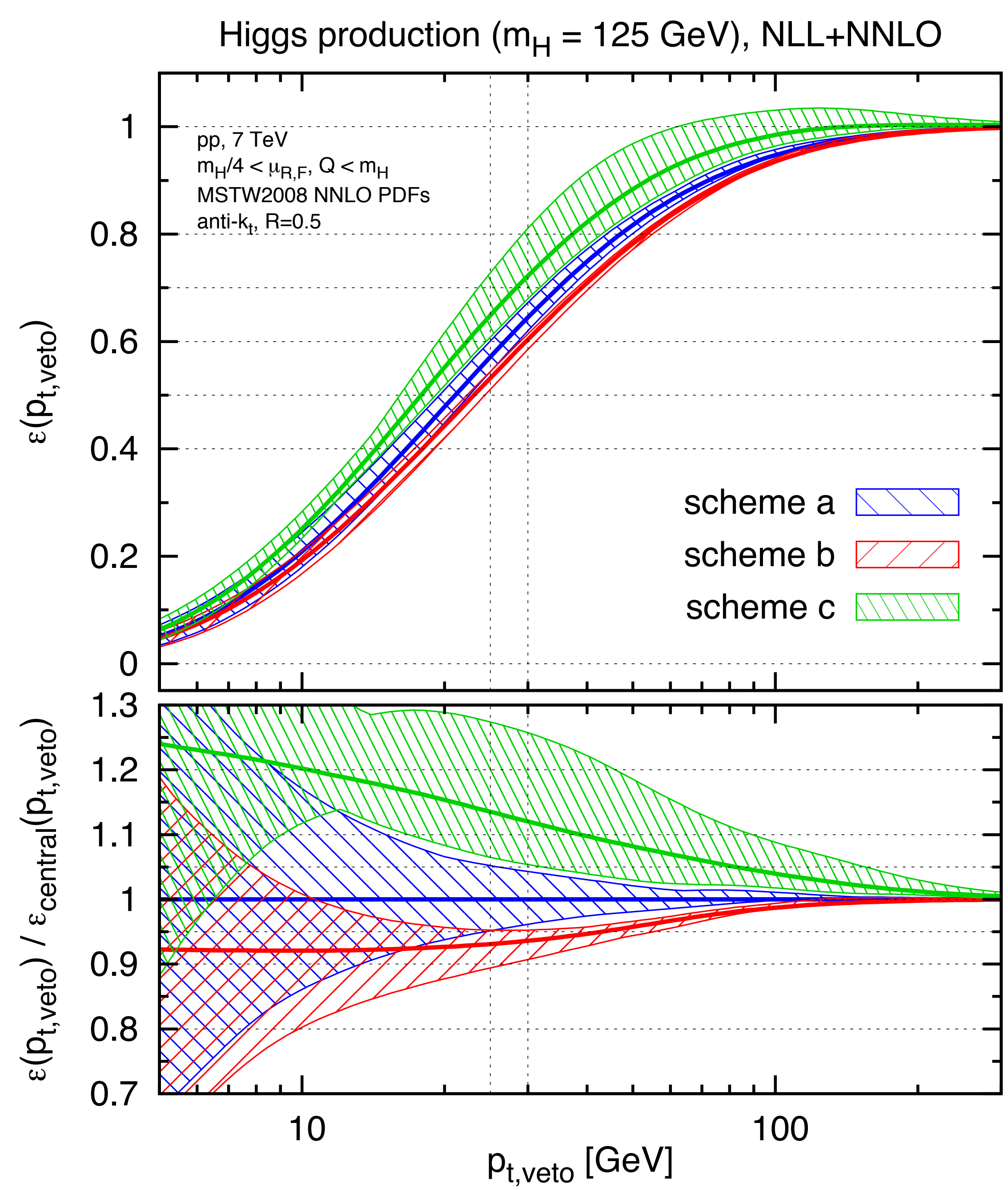
NLL+NNLO calculation still suffers from significant perturbative uncertainties and scheme dependences; hence calculate **cut efficiency** instead of cross section

Worthwhile to go to higher orders ($N^{\geq 2}LL$) using SCET Becher, MN: 1205.3806




**Cross section with a jet veto *can* be factorized and resummed in SCET !**

# Inclusive jet clustering algorithm

Distance measure:

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

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

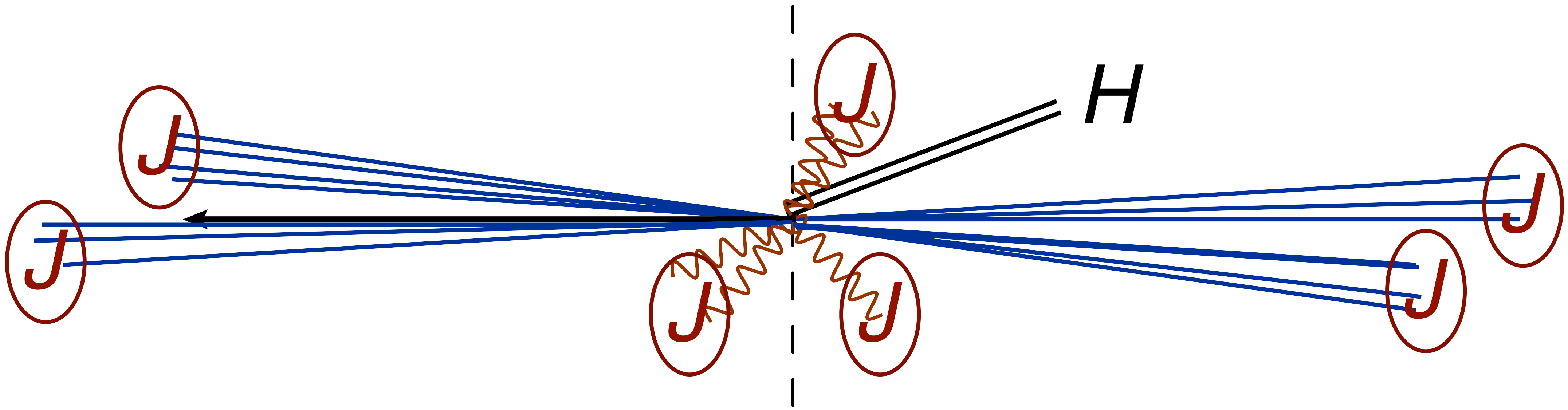
n=1: $k_T$
n=0: C/A
n=-1: anti-$k_T$

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



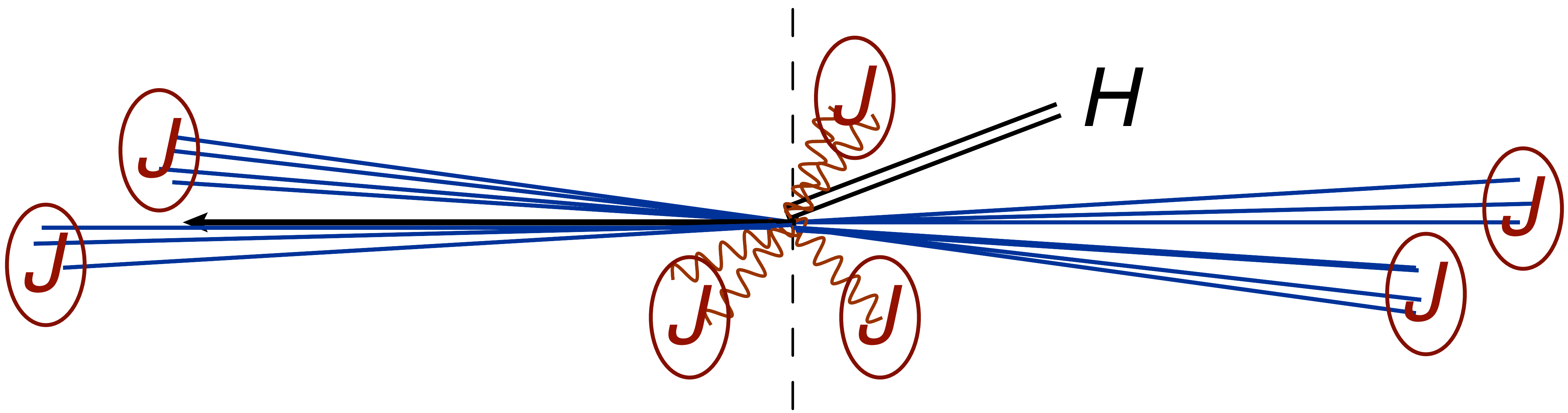

Based on SCET analysis, propose first **all-order factorization formula** for the cross section with a jet veto: Becher, MN: 1205.3806

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

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

- without loss of generality, the soft function has been absorbed into the beam functions $I$

# All-order factorization theorem




Based on SCET analysis, propose first **all-order factorization formula** for the cross section with a jet veto: Becher, MN: 1205.3806

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

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

Note close similarity with case of $q_T$ resummation:

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

# Matching to fixed-order results

Study two different schemes:

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

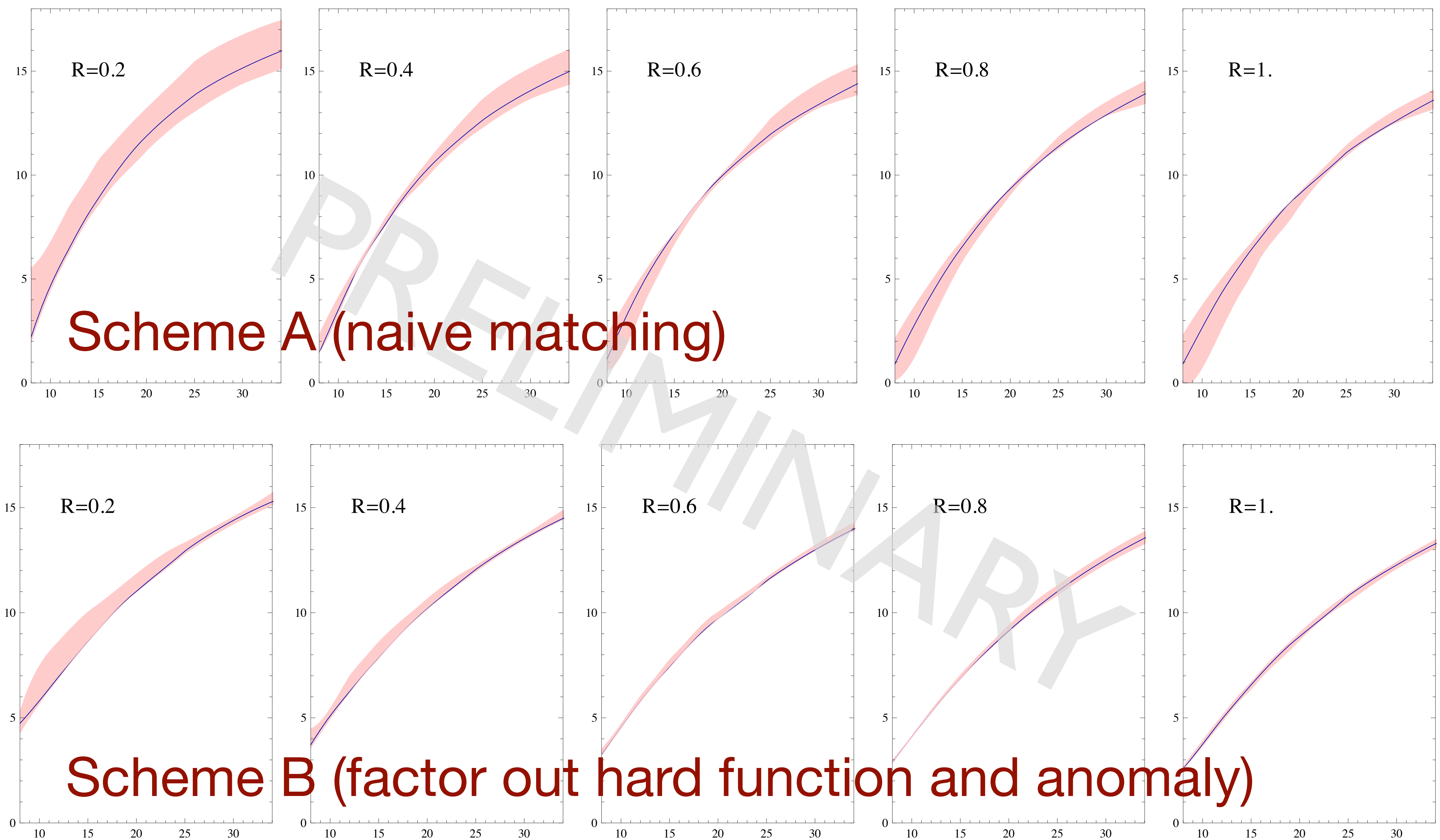
Since hard function *H* contains the large corrections affecting the total cross section (time-like scalar form factor), scheme B is expected to work better than scheme A

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

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

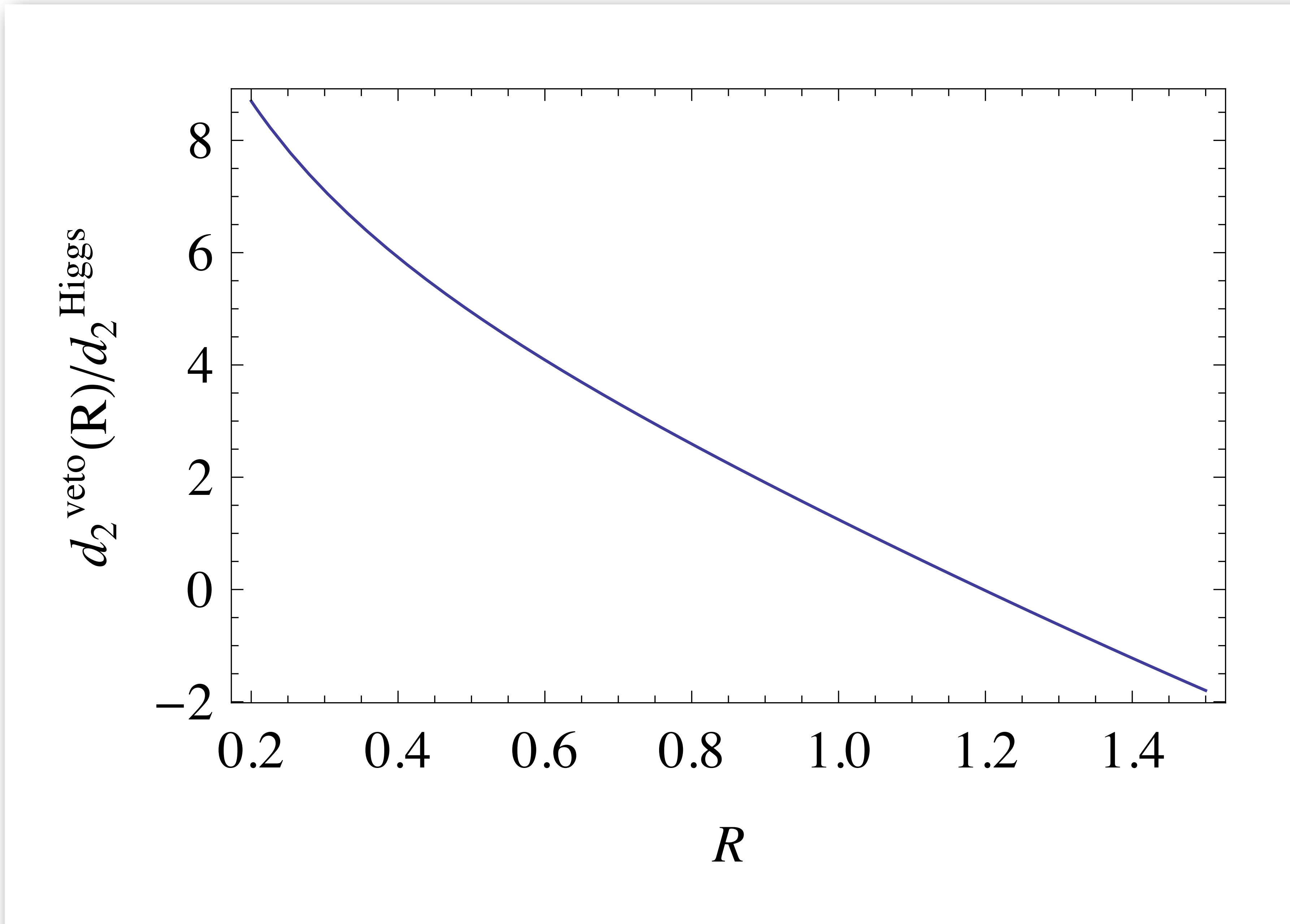
# Preliminary NNLL+NNLO results

NNLL+NNLO predictions for Higgs production cross section with a jet veto:



# Preliminary NNLL+NNLO results

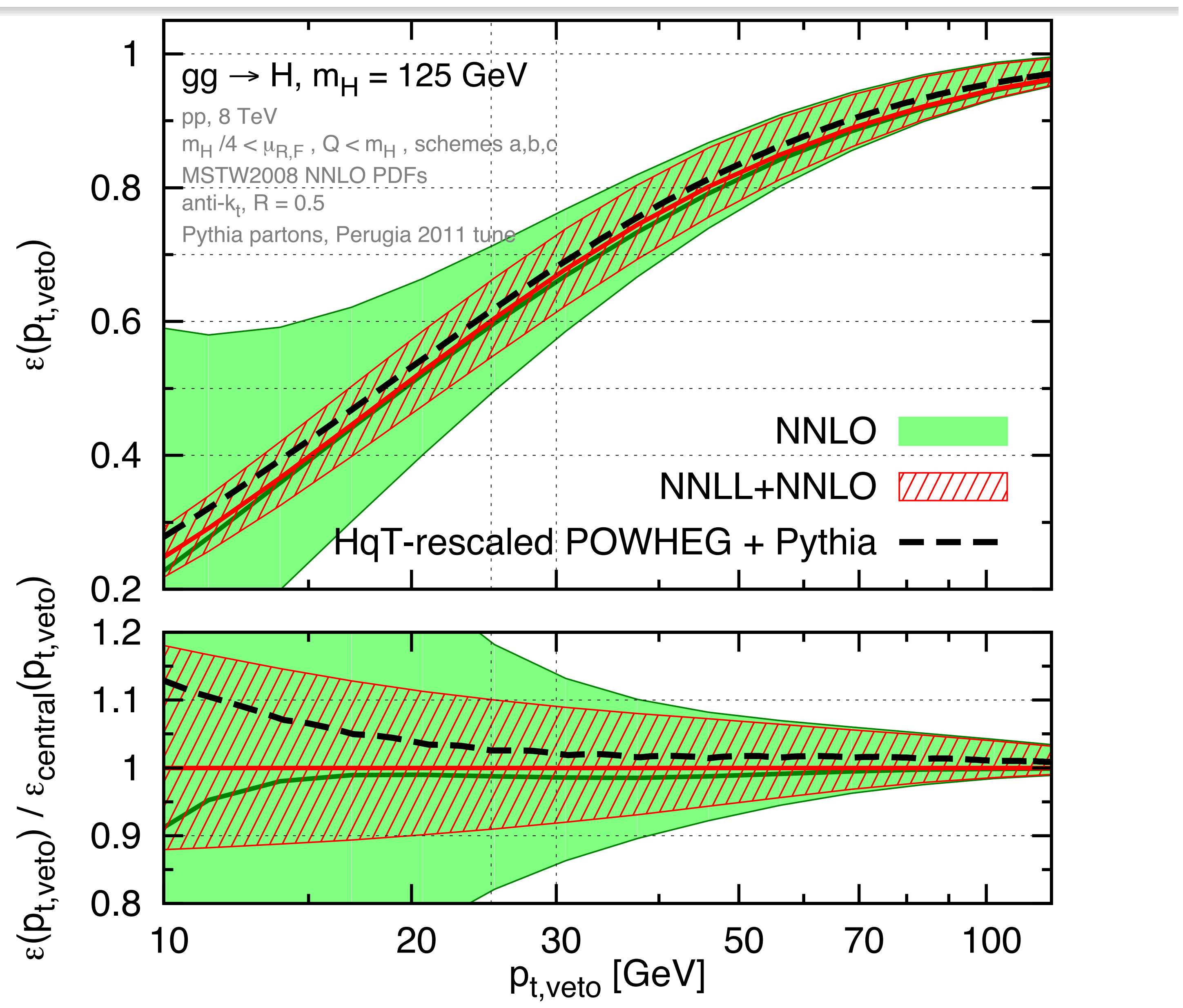
Large corrections at small R encoded in two-loop anomaly coefficient:




⇒ at small R, clustering logarithms ln(R) would need to be resummed!

# Preliminary NNLL+NNLO results

Results agree with NNLL+NNLO predictions for jet-veto efficiency obtained in Banfi, Monni, Salam, Zanderighi: 1206.4998



# 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 based on SCET-II

Have developed a consistent framework for $q_T$ resummation at small and very small transverse momenta