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Resummation for Higgs production

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Introduction

What are we looking at?

Higgs production cross section in gluon-gluon fusion

$$gg \to H + 0 \text{ jets}$$

with a jet veto on the jet transverse momentum:

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

Why?

- Analysis is done in jet bins, precise prediction of the 0-jet bin, i.e. cross section with a jet veto needed.
- Veto on jet transverse momentum is experimentally motivated (essential to suppress background events)

Resummation

Large double logarithms induced by the jet veto spoil convergence of the perturbative series

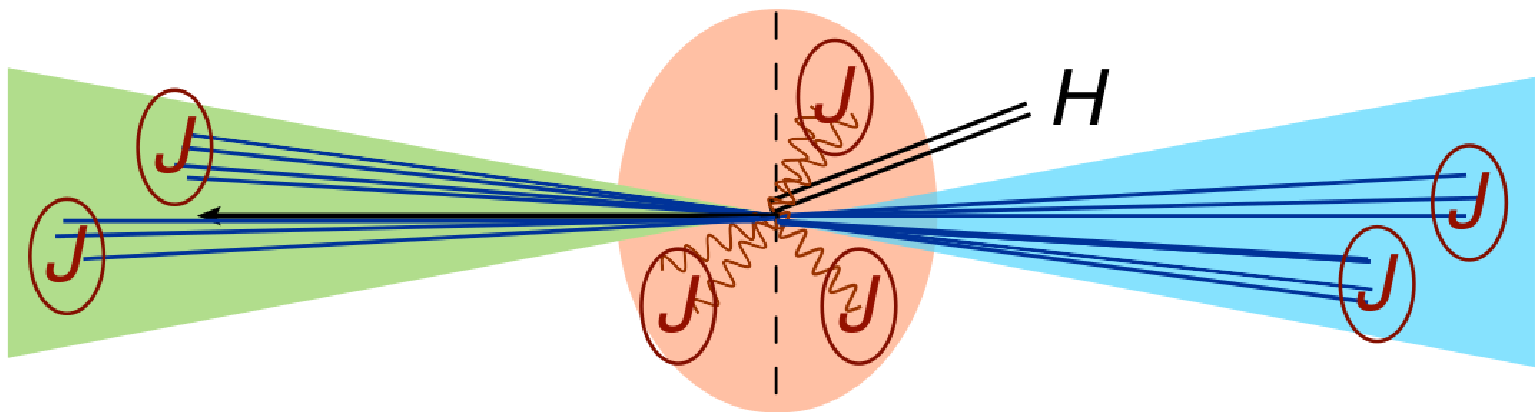
→ Need resummation!

Only very recently, resummed results for Higgs cross sections with a jet veto beyond LL became available:

- Resummation at NLL and NNLL using CAESAR:
  Banfi, Salam and Zanderighi 1203.5773 (BSZ)
  + Monni 1206.4998 (BMSZ)
- Factorization and NNLL Resummation in SCET:
  Becher, Neubert 1205.3806 (BN)
- Resummation Properties of Jet Vetoes:
  Tackmann, Walsh, Zuberi 1206.4312 (TWZ)
- Higher jet bins:
  Liu and Petriello 1210.1906 (LP)

We will present our work and discuss how it is related to these.

Jet clustering algorithm



- Jet clustering algorithm groups particles of different momentum scaling separately, if the jet radius

$$R < \ln(m_H/p_T) \approx 1.5$$

- Therefore the jet veto can be applied separately in each individual sector. → Essential for soft-collinear factorization

(TWZ argue that for $R = O(1)$ soft-collinear emissions can cluster, giving contributions that are not reproduced by a soft-collinear factorization formula. Will be discussed later)

All-order factorization theorem from SCET

BN proposed first all-order factorization formula for the cross section with a jet veto.

The naive factorization suffers from a collinear anomaly, leading to an anomalous dependence on the hard scale m_H (pure power in p_T space)

Hard function

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

Refactorized beam-jet functions

Beam functions: Stewart, Tackmann, Waalewijn '10

Sources of Log(m_H/p_T) are the anomaly and the RG evolution of the hard function.

Ingredients for NNLL resummation

- C_t and C_S at one-loop order
- One-loop collinear kernel functions:

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

where $\quad L_\perp = 2\ln\left(\frac{\mu}{p_T^{\text{veto}}}\right)$

- Two-loop anomaly coefficient:

Anomaly coefficient: Introduces dependence on jet radius R at NNLL order

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

vanishes

$$d_2^{\text{veto}}(R) = d_2^{\text{Higgs}} + \Delta d_2(R)$$

Anomaly Coefficient at NNLL

- The part $\Delta d_2(R)$ of the anomaly coefficient can be extracted from the anomalous part of diagrams with two real emissions. It is closely related to the function $\mathcal{F}(R)$ computed by BSZ.

- BN extracted d_2^{veto} from $\mathcal{F}(R)$, taking the limit $R \to \infty$, under the assumption that the BSZ formula still holds in this limit. But later BMSZ showed that an extra constant term arises, which changes the value of d_2^{veto} significantly.

Have now computed d_2^{veto} directly from a two-loop calculation in SCET.

The result is fully consistent with the BMSZ formula.

- What about soft-collinear mixing terms?

Soft Collinear mixing terms

- Soft and collinear contributions are integrated over full phase space in SCET

- Double counting overlapping regions has to be avoided

  Two possibilities:

multi-pole **expand the full integrand** (including all phase space constraints)

“zero-bin” subtractions
Manohar, Stewart '07

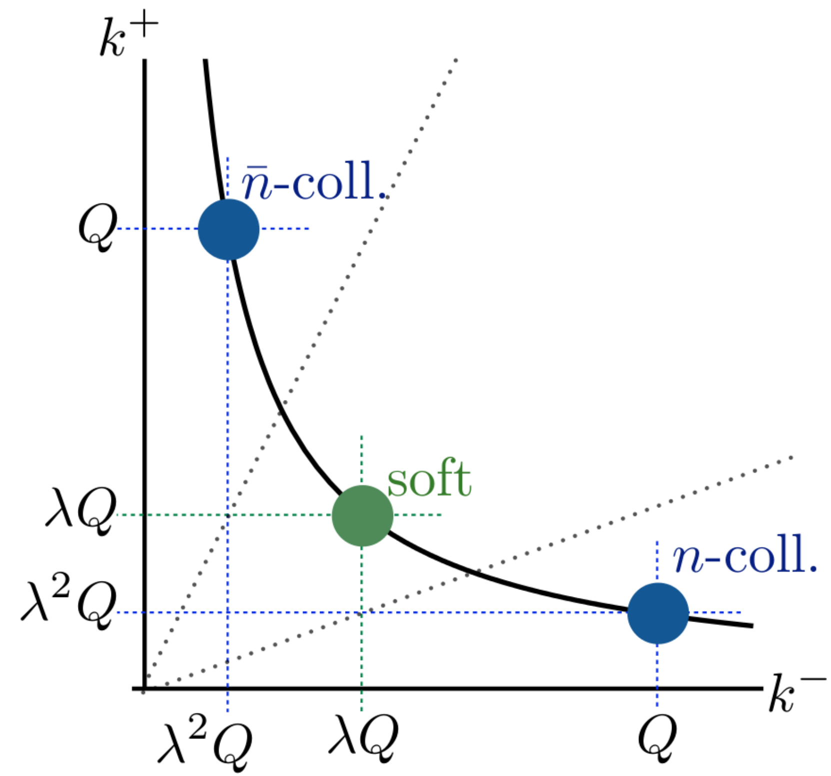


Figure from
Chiu, Jain, Neill, Rothstein 1202.0814

If the **integrand is fully expanded**, one ends up with a single scale integral such that all **zero-bins** are trivially zero (**scaleless**).

Soft Collinear mixing terms

On the Lagrangian level the factorization into soft, collinear and anti-collinear fields is manifest.

The measure (phase space constraints due to clustering and vetoes)

can introduce factorization violating mixing contributions

$$\mathcal{M}_{ij}^{\text{Mix}} = \theta(\Delta R_{ij} < R)\ \theta\left(|p_T| < p_T^{\text{veto}}\right) \qquad i,j = c, \bar{c}, s \quad \text{with} \quad i \neq j$$

veto on vector sum → factorization violated

We expand the full integrand (zero-bins scaleless) and get the regions

$$I_{\text{full}} = I_{cc} + I_{\bar{c}\bar{c}} + \boxed{I_{cs} + I_{\bar{c}s} + I_{\bar{c}c}} + I_{ss}$$

The dangerous mixing terms contained in are zero because the clustering of particles with different momentum scaling is power suppressed

$$\theta(\Delta R_{ij} < R) = 0 \qquad i \neq j$$

if expanded (which we do)

Soft Collinear mixing terms

$$\theta(R^2 - \Delta R_{ij}^2) \sim \theta\left(R^2 - (y_i - y_j)^2\right) = 0 \qquad i \neq j$$

O(1)

small (large)

large (small)

No factorization violating mixing terms are present:

→ factorization at this order

For any number of particles, clustering of particles with different momentum scaling will be zero (power suppressed) → indicates factorization to all orders

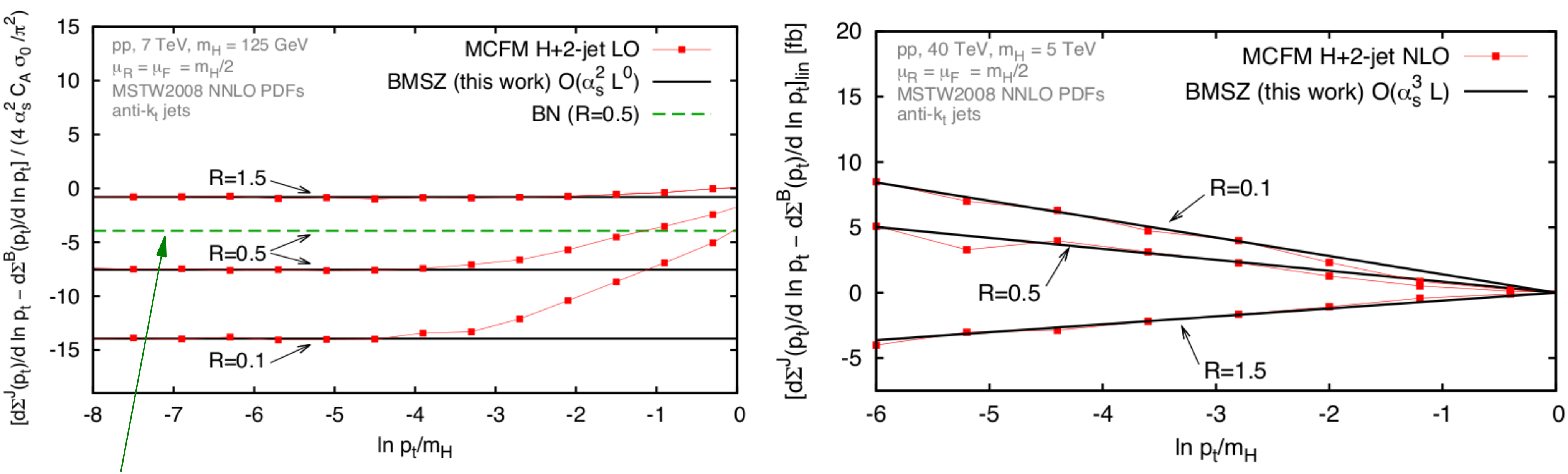
Note: $\theta(R^2 - \ln\lambda) = \theta(e^{R^2} - \lambda)$

NNLL calculation and factorization

Complete agreement (analytically) of our computation (SC-mixing terms are absent) with the QCD computation of BMSZ

BMSZ have explicitly verified (MCFM) that they correctly reproduce the logarithmic terms at $O(\alpha_s^2)$ and $O(\alpha_s^3)$

→ established factorization at this order



BN with missing constant in d_2^{veto}. Now agreement!

Zero-bin subtractions

Mixing part of measure:

$$\mathcal{M}_{ij}^{\mathrm{Mix}} = \theta(\Delta R_{ij} < R)\, \theta\left(|p_T| < p_T^{\mathrm{veto}}\right) \qquad i,j = c,\bar{c},s \quad \text{with} \quad i \neq j$$

If the measure is not expanded (TWZ), this term is non-zero. Factorization violating mixing terms

$$\delta\sigma_{CS} \qquad \delta\sigma_{\bar{C}S} \qquad \delta\sigma_{C\bar{C}}$$

are present ($\propto R^2$). But also zero-bin subtractions are needed.

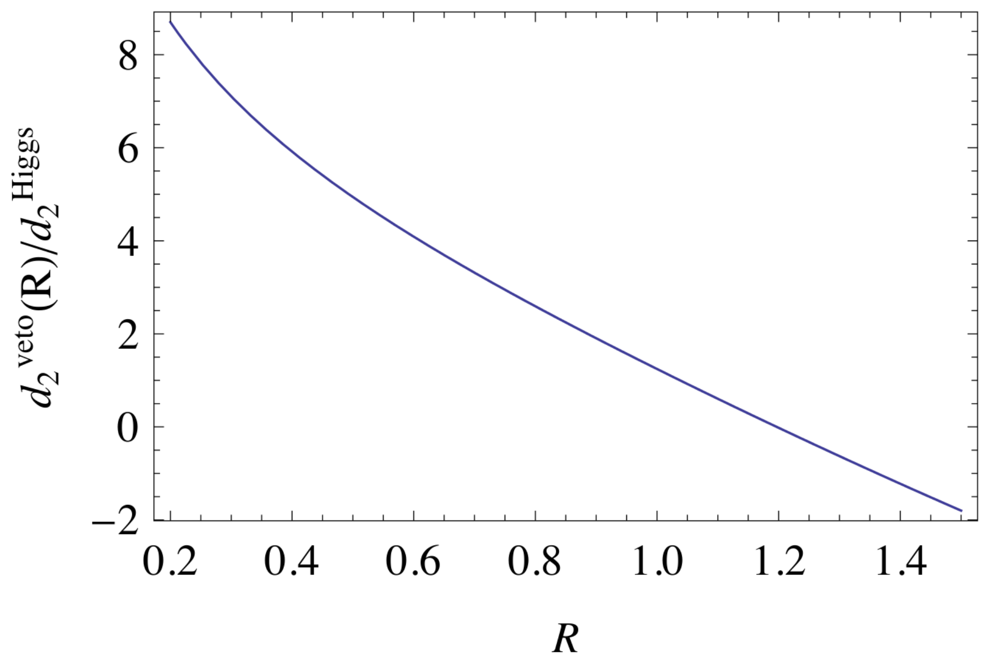
TWZ have calculated $\delta\sigma_{SC}$, but not explicitly $\sigma_{CC},\ \sigma_{\bar{C}\bar{C}},\ \delta\sigma_{C\bar{C}}$ and its zero bins. Then the mixing terms (which should cancel after adding all zero-bins) seem to be present.

NNLL+NNLO results

- d_2^{veto} very large for small R (leads to large scale dependence)

- Depending on matching scheme scale dependence reduces

  → Indicates cancellations (depending on the scheme)



- Can we trust this? Best would be to separate uncertainties of prefactor, leading power terms and power corrections and then combine. Not possible for NNLL+ NNLO

- At NNLL the large constant d_2^{veto} appeared, which is underestimated by a scale variation at NLL (R independent).

NNLL scale variation does not estimate $\ln^2(R)$ terms **and** two loop ($I \times \Phi$) becomes *R* dependent (similar effect?) → Strong motivation for N^3LL

Ingredients for N^{3}LL

- C_t and C_S to two loop order

- Two-loop collinear kernel functions (will be *R* dependent) $I_{g\leftarrow i}(R)$

- Three-loop anomaly function

$$F_{gg}(p_T^{\mathrm{veto}},\mu) = a_s(\Gamma_0^A L_\perp + d_1^{\mathrm{veto}}) + a_s^2\left[\Gamma_0^A\beta_0\frac{L_\perp^2}{2} + \Gamma_1^A L_\perp + d_2^{\mathrm{veto}}(R)\right]$$
$$+ a_s^3\left[\Gamma_0^A\beta_0^2\frac{L_\perp^3}{3} + (\Gamma_0^A\beta_1 + 2\Gamma_1^A\beta_0)\frac{L_\perp^2}{2} + (\Gamma_2^A + 2\beta_0 d_2^{\mathrm{veto}}(R))L_\perp + d_3^{\mathrm{veto}}(R)\right]$$

Everything known except anomaly coefficient d_3^{veto}

NNLL and N^{3}LL resummed results

Goal to disentangle different sources of scale dependence (anomaly, beam functions, power corrections) $\rightarrow$

- We factor out

Extra factor removed from beam function

$$P = \sigma_0 C_t^2(m_t^2,\mu)|C_S(-m_H^2,\mu)|^2 \left(\frac{m_H}{p_T^{\text{veto}}}\right)^{-2F_{gg}(L_\perp,a_s)} e^{2h_A(L_\perp,a_s)}$$

scale independent!

Full cross section is then given by two separately scale independent parts:

¨bar¨ indicates that factor h_A has been removed

$$\sigma(p_T^{\text{veto}}) = P \cdot \underbrace{(\bar{I} \otimes \phi)^2}_{\text{independent of } m_H \text{ (for fixed } m_H^2/s)}$$

Also enables us to extract two loop ($I \times \Phi$) using HNNLO fixed-order code by Grazzini

- Run HNNLO at high m_H (suppress power corrections) and factor out P

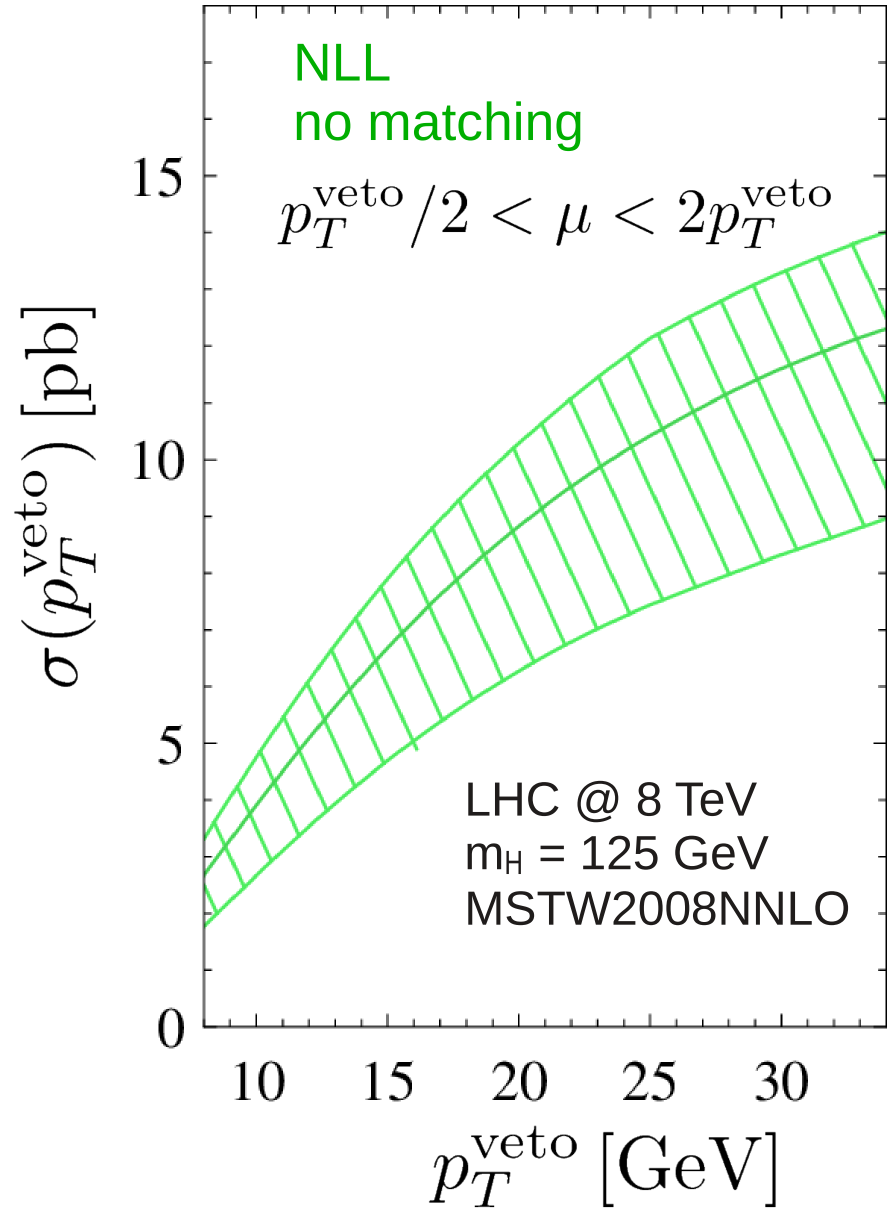
Numerical results

I will show various plots, of the cross section.

The plots have the same format as the one on the right.

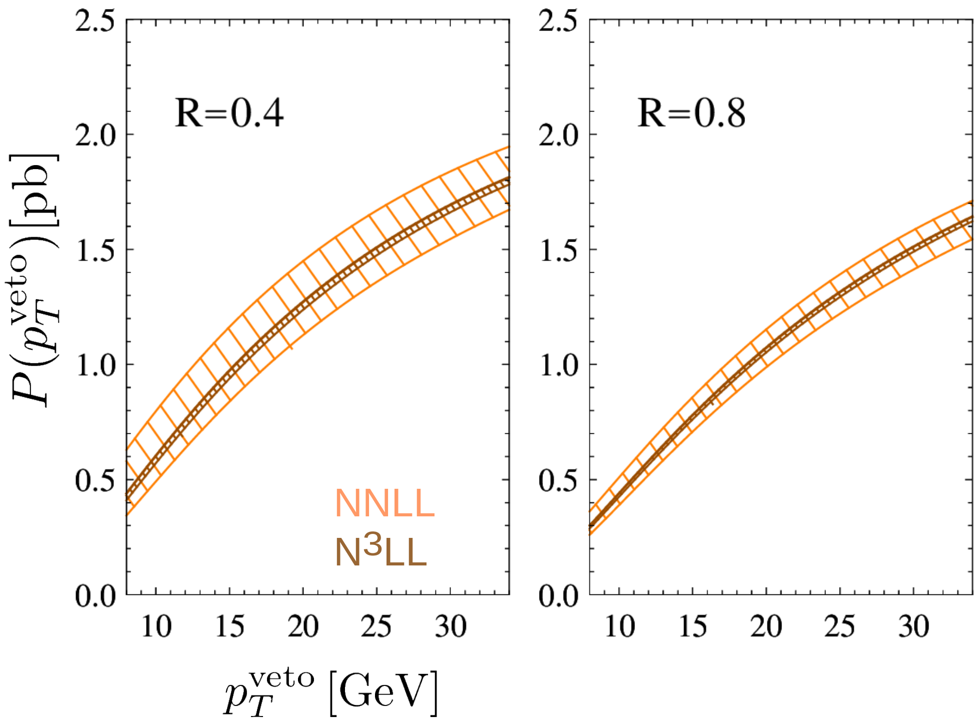
The results are

PRELIMINARY



NNLL and N^{3}LL resummed (different variations)

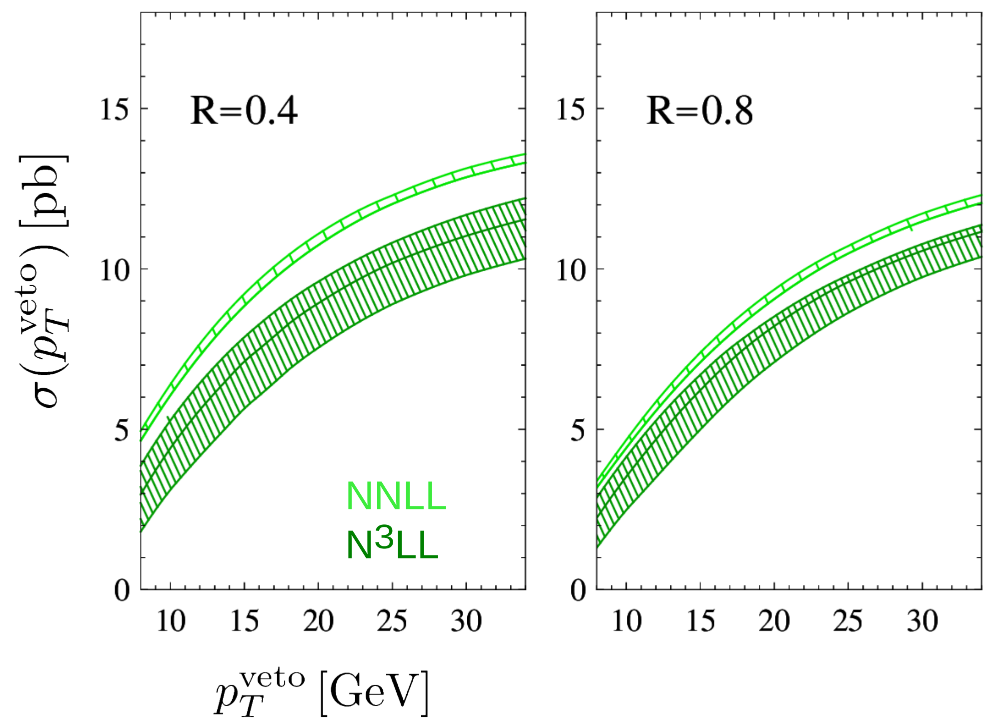
Scale variation of prefactor only



Scale variation reduces significantly.

(however d_3^{veto} is not included → estimate its effect)

Scale variation of $(I \times \Phi)^2$ only



Uncertainty increases! At NNLO first *R* dependence arises in $(I \times \Phi)^2$

→ small scale variation of $(I \times \Phi)^2$ at NLO not reliable!

Three loop anomaly coefficient d_3^{veto}

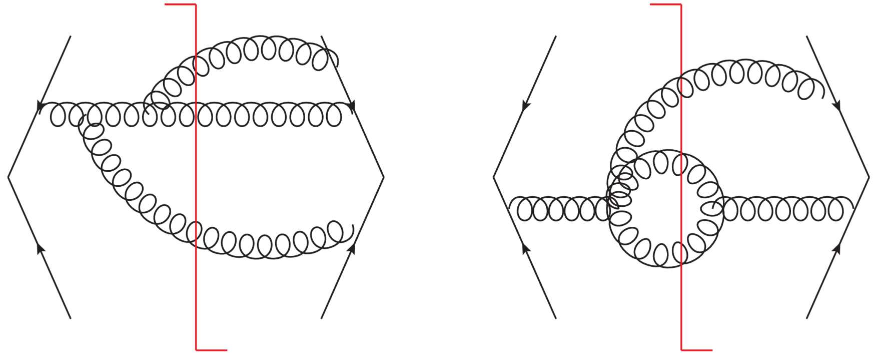
Uncertainty from the unknown coefficient d_3^{veto}

- Leading color part of d_2^{veto} approximately $d_2^{\text{veto}} \sim 2C_A^2 4^2 \ln \frac{2}{R}$

- Motivates estimate for the leading logarithmic *R* dependence of d_3^{veto}

$$d_3^{\text{veto}} \sim \lambda\, 2C_A^3 4^3 \ln^2 \frac{2}{R} \qquad \lambda = -2, \ldots, +2$$

- Possibility to extract λ from three-emission soft function in SCET:

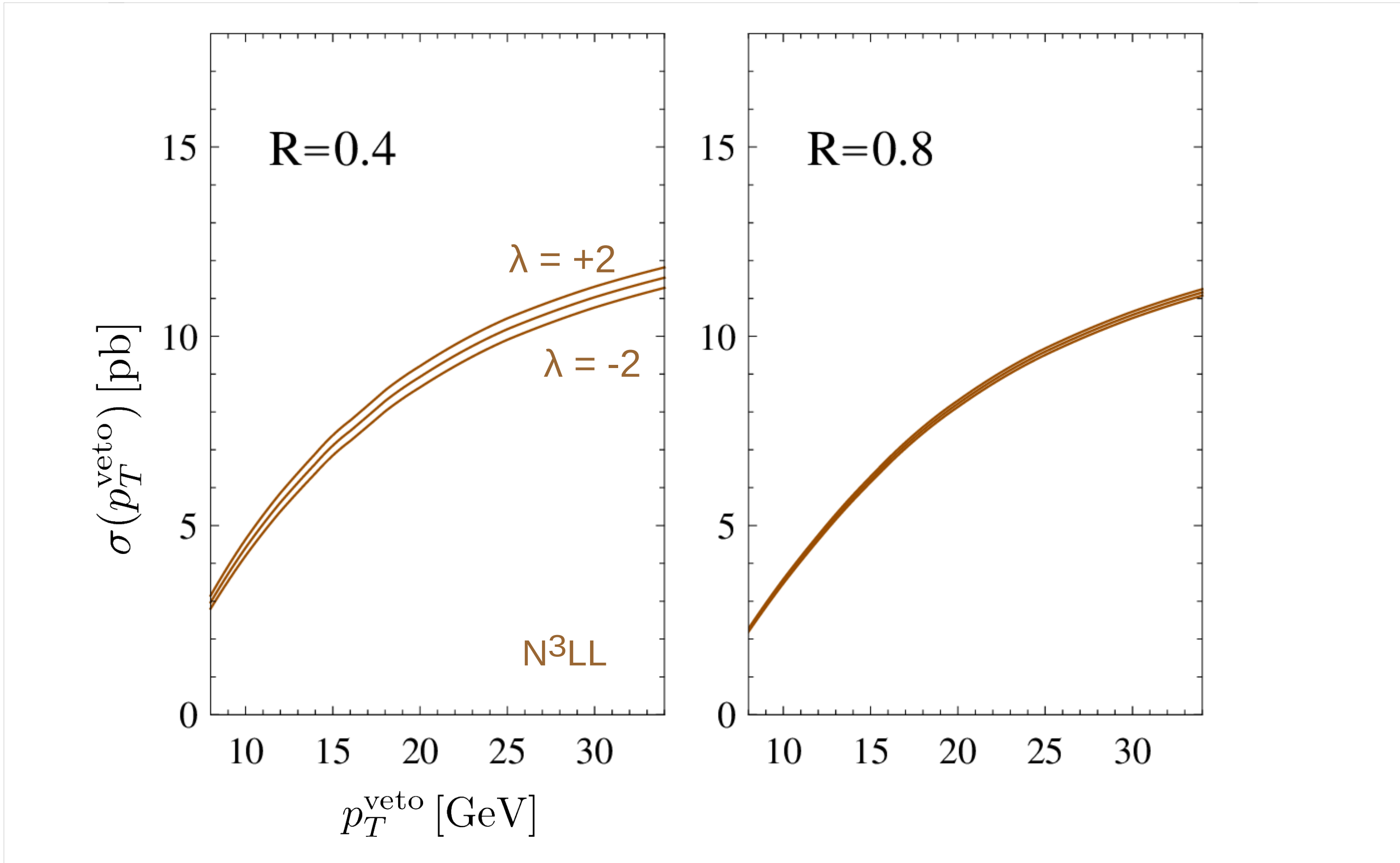


+ more

(work in progress)

N^3LL with $d_3^{estimate}$

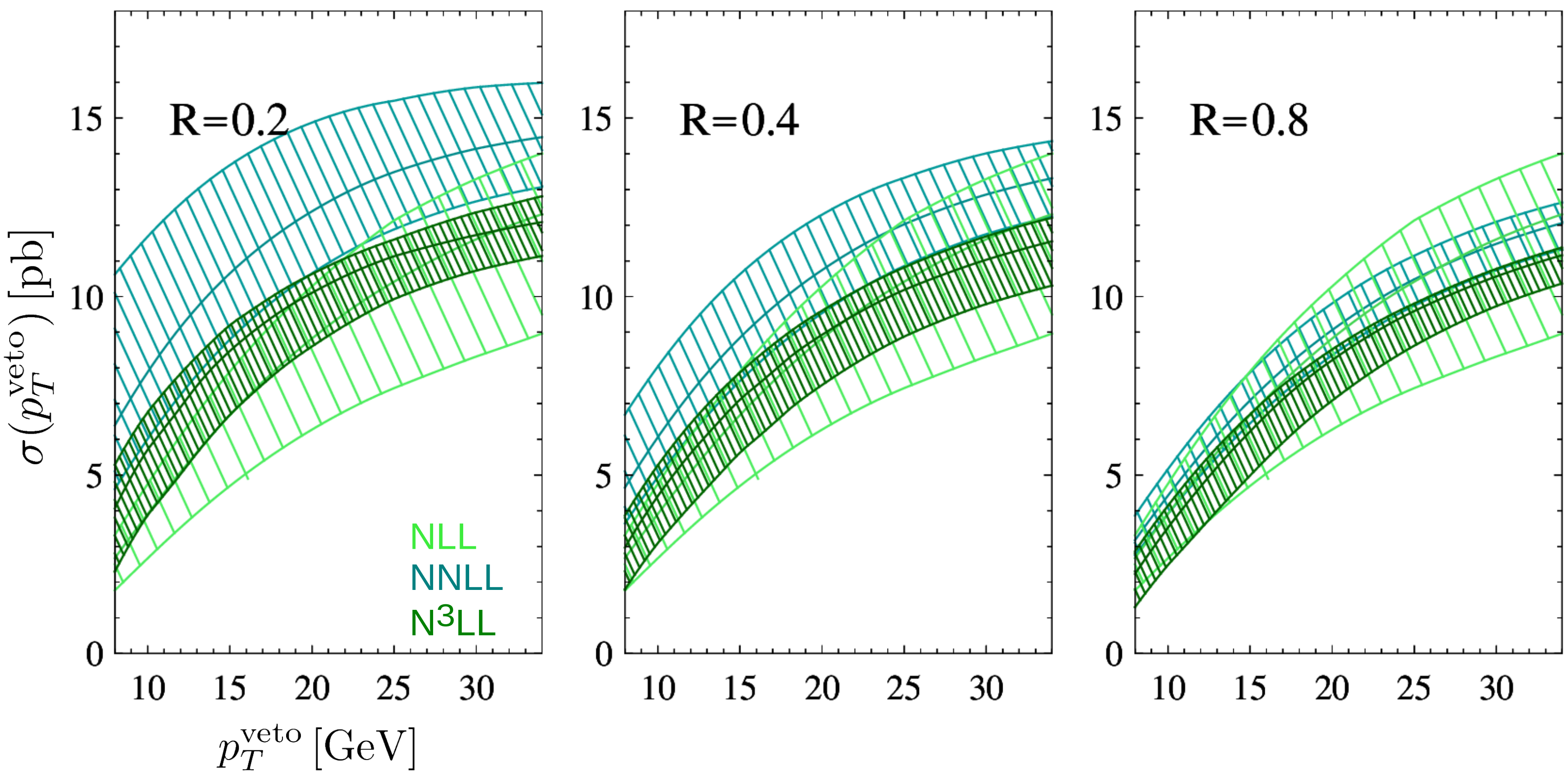
$$d_3^{\mathrm{veto}} \sim \lambda 2 C_A^3 4^3 \ln^2 \frac{2}{R}$$



→ if d_3^{veto} is indeed the size of our estimate, it will have a small effect (for phenomenologically relevant values of *R*)

NLL, NNLL and N^{3}LL resummed results

Full resummed results (errors of P and $(I \times \Phi)^2$ quadratically added)

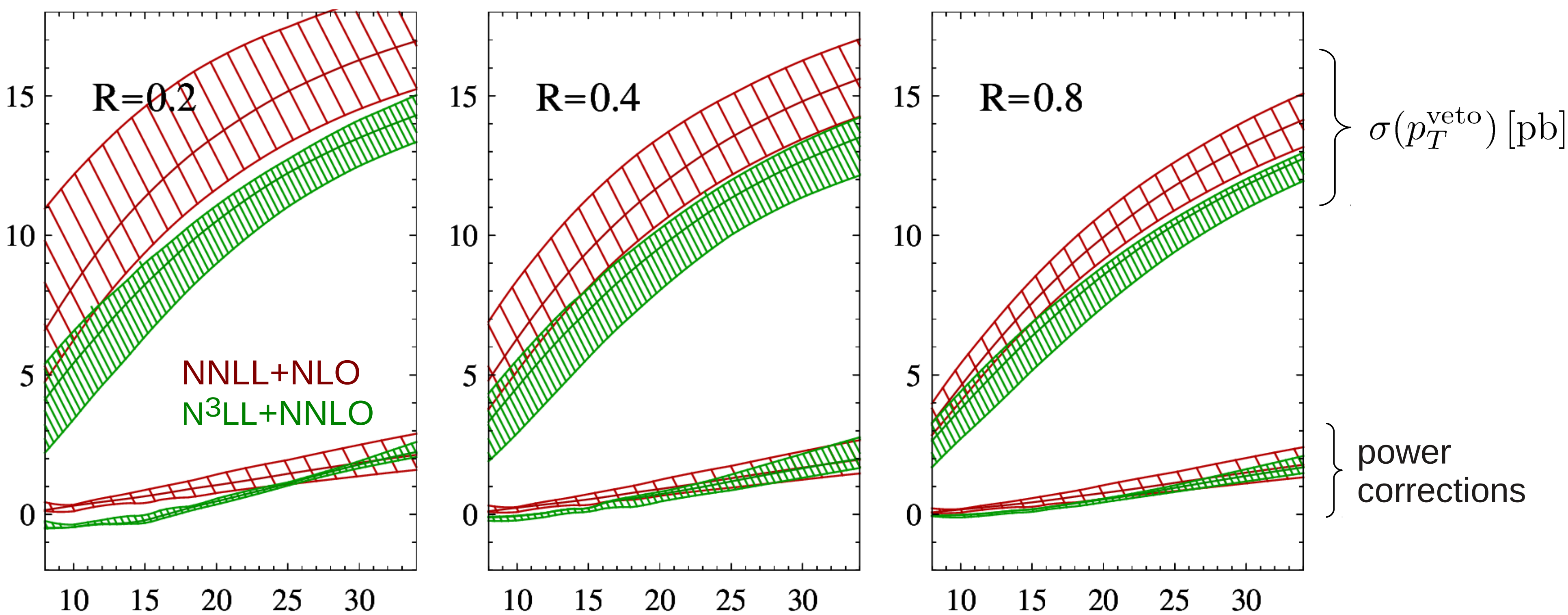


Low R: Size of the scale bands reduces only slowly with growing order:

- NNLL: leading R-dependent term appears in d_2^{veto}
- N^{3}LL: leading R-dependent term appears in two loop $(I \times \Phi)^2$.

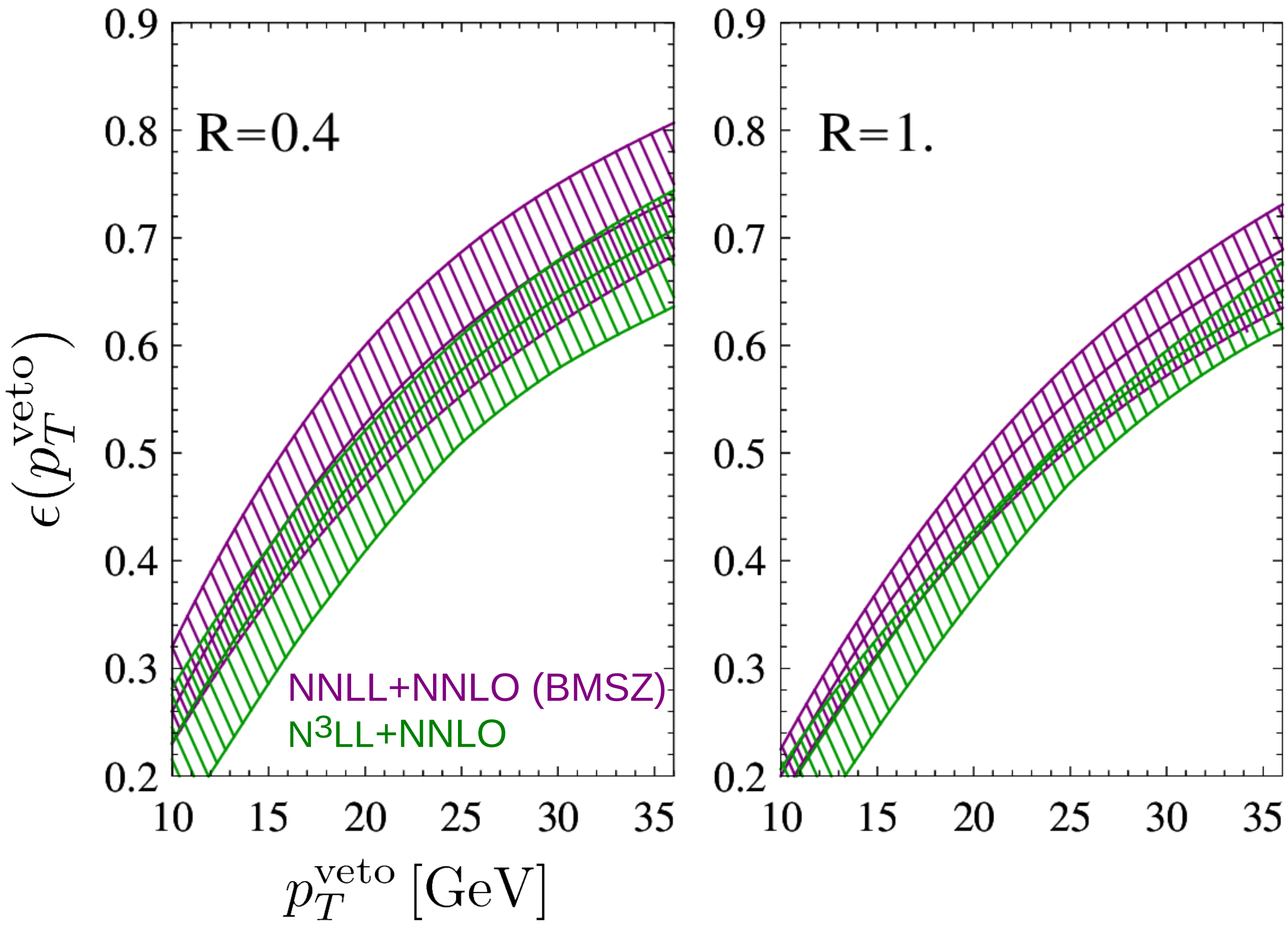
Large *R*: good perturbative behavior

Matching to fixed-order numerical results



- The scale variations of P, $(I \times \Phi)^2$ and power corr. are done separately and then quadratically added (avoid accidental cancellation of large corrections)
- All two loop ingredients in place → power corrections are small/suppressed (p_T/m_H) (numerics needs improvement for small R)
- At N3LL+NNLO leading R-dependent effects are included in both P and $(I \times \Phi)^2$

Comparison to BMSZ result



We directly predict the cross section, not the efficiency. The above efficiencies are obtained using σ_{tot}=19.65 pb from RGHiggs.

Summary

Have presented new theoretical predictions for the Higgs production rate with a jet veto at N^3LL+NNLO accuracy:

- Analytic computation of d_2^{veto} → result fully compatible with BMSZ (no SC mixing)
- Estimated d_3^{veto} effect small. This uncertainty could be reduced by a numerical computation of the $\log^2(R)$ part → Nontrivial but feasible
- Reduce scheme dependence by choosing a scheme, which disentangles different sources of uncertainty (avoids accidental cancellations)
- Extract two loop ($I \otimes \Phi$) (HNNLO code)
- At this order leading R dependence (which leads to large uncertainty bands) included both in P and $(I \otimes \Phi)^2$

Extra Slides

Simple example (zero-bins vs. multi-pole expansion)

Let us illustrate how double counting of overlapping regions can be avoided using either of the two methods.

Consider the following simple rapidity integral:

$$I = \int_{-\infty}^{\infty} dy\, \theta(R^2 - (y - y_0)^2)$$

Rapidity of a fixed collinear particle

It can easily be evaluated

$$I = \int_{y_0 - R}^{y_0 + R} dy = 2R$$

Now turn to a SCET framework and consider different regions (method of regions)

y can either be collinear or soft

Simple example: multi-pole expansion

The Integrand is just 1 and has no expansion into different regions.

The phase-space constraint however does:

collinear region: $I_{cc} = I$

soft region:

$$\theta\left(\underset{\substack{\uparrow \\ \text{O(1)}}}{R^2} - (\underset{\substack{\uparrow \\ \text{O(1)}}}{y} - \underset{\substack{\uparrow \\ \text{Large}}}{y_0})^2\right) = 0 \qquad \Rightarrow \qquad I_{cs} = 0$$

zero-bin subtraction gives a vanishing integral $I_{c(c \to s)}$

For the full result we then have to add all the regions

$$\left(I_{cc} - I_{c(c\to s)}\right) + I_{cs} = I$$

Note: $\theta(R^2 - \ln\lambda) = \theta(e^{R^2} - \lambda)$

Simple example: Zero-bin subtraction

If the phase-space constraint is not expanded, all regions give the same result.

$$I_{cc} = I \qquad I_{cs} = I \qquad I_{c(c \to s)} = I$$

And the final result

$$\left(I_{cc} - I_{c(c\to s)}\right) + I_{cs} = I$$

Notice that here the zero-bin subtraction was essential in order to get the correct result. The zero-bin canceled the soft-collinear mixing term.

Backup: expanded measure

$$\theta\left(R^2-(y_s-y_c)^2\right)=\theta\left(R-|(y_s-y_c)|\right)$$

$$=\theta\left(R-(y_s-y_c)\right)\,\theta(y_s-y_c)+\theta\left(R-(y_c-y_s)\right)\,\theta(y_c-y_s)$$

$$=\theta\left(e^R-\frac{k_+^s\,k_T^c}{k_T^s\,k_+^c}\right)\,\theta(k_+^s\,k_T^c-k_T^s\,k_+^c)+\theta\left(e^R-\frac{k_T^s\,k_+^c}{k_+^s\,k_T^c}\right)\,\theta(k_T^s\,k_+^c-k_+^s\,k_T^c)$$

$$=\theta(\underbrace{e^R\,k_T^s\,k_+^c}_{\lambda^3}-\underbrace{k_+^s\,k_T^c}_{\lambda^2})\,\theta(\underbrace{k_+^s\,k_T^c}_{\lambda^2}-\underbrace{k_T^s\,k_+^c}_{\lambda^3})+\theta(\underbrace{e^R\,k_+^s\,k_T^c}_{\lambda^2}-\underbrace{k_T^s\,k_+^c}_{\lambda^3})\,\theta(\underbrace{k_T^s\,k_+^c}_{\lambda^3}-\underbrace{k_+^s\,k_T^c}_{\lambda^2})$$

$$=\theta\left(-k_+^s\,k_T^c\right)\,\theta(k_+^s\,k_T^c)+\theta\left(e^R\,k_+^s\,k_T^c\right)\,\theta(-k_+^s\,k_T^c)=0$$

Backup

h_A in prefactor P explicitly:

$$h_A(L_\perp, a_s) = a_s \left[\Gamma_0^A \frac{L_\perp^2}{4} - \gamma_0^g L_\perp\right] + a_s^2 \left[\Gamma_0^A \beta_0 \frac{L_\perp^3}{12} + (\Gamma_1^A - 2\gamma_0^g \beta_0) \frac{L_\perp^2}{4} - \gamma_1^g L_\perp\right]$$