Precise predictions for the Higgs cross section with a jet veto

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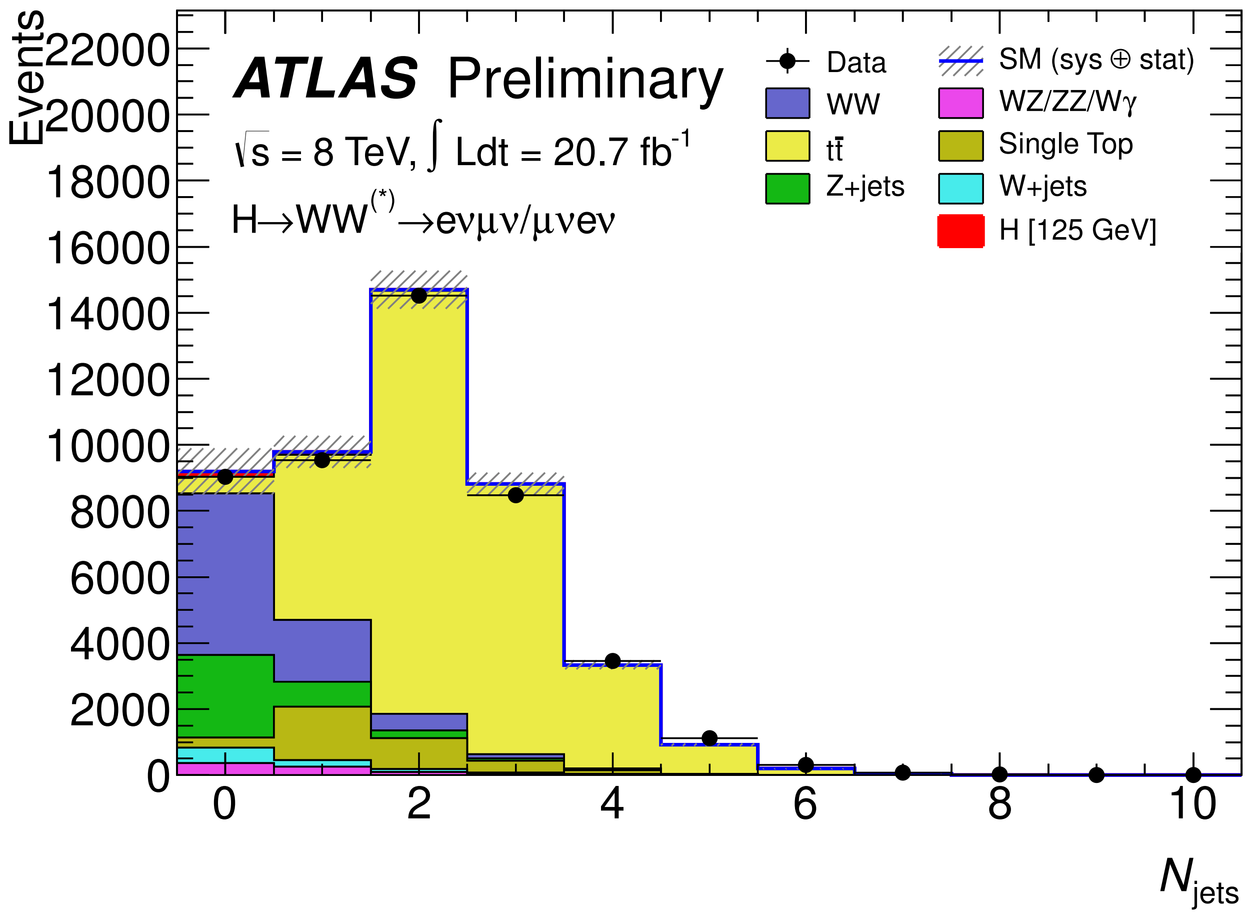
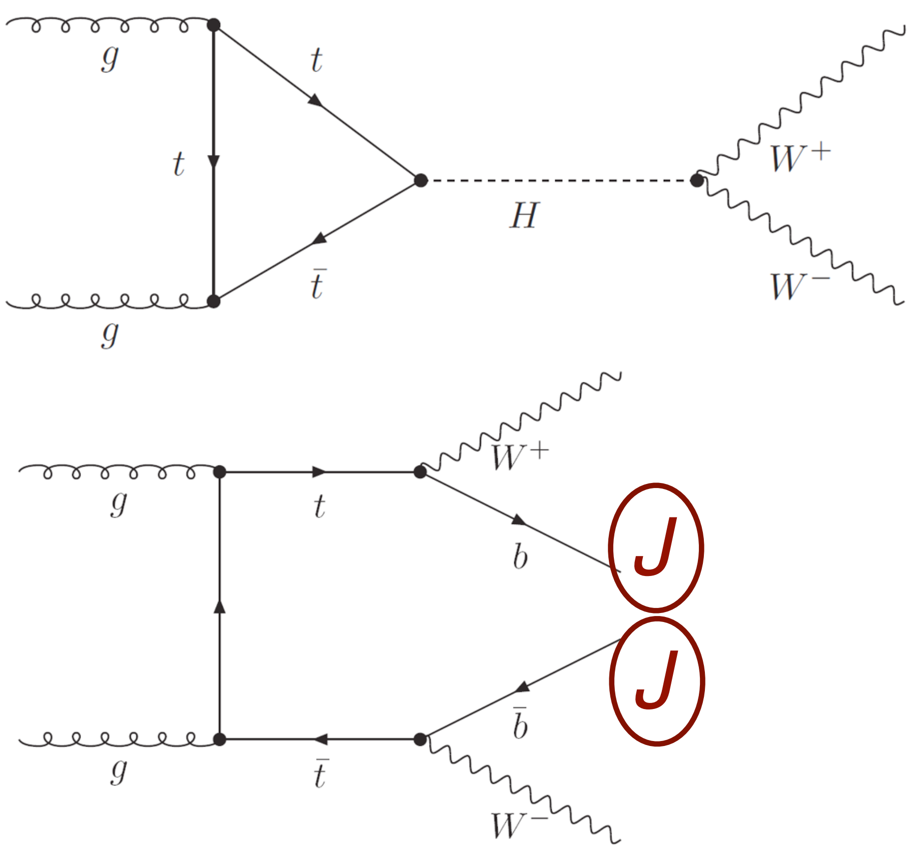
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

Why vetoing against jets can be important ...

Becher, MN 1205.3806 (JHEP)
Becher, MN, Rothen 1307.0025 (JHEP)

Jet veto in Higgs production



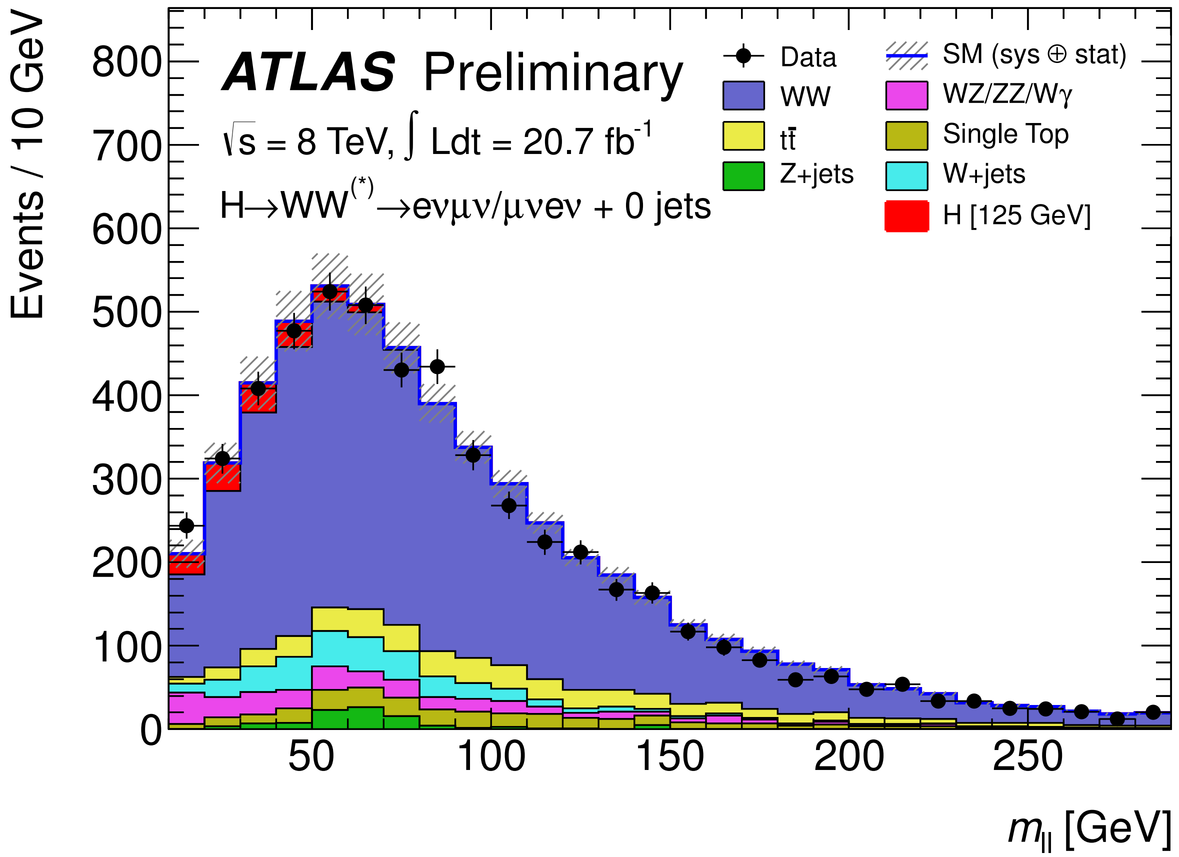


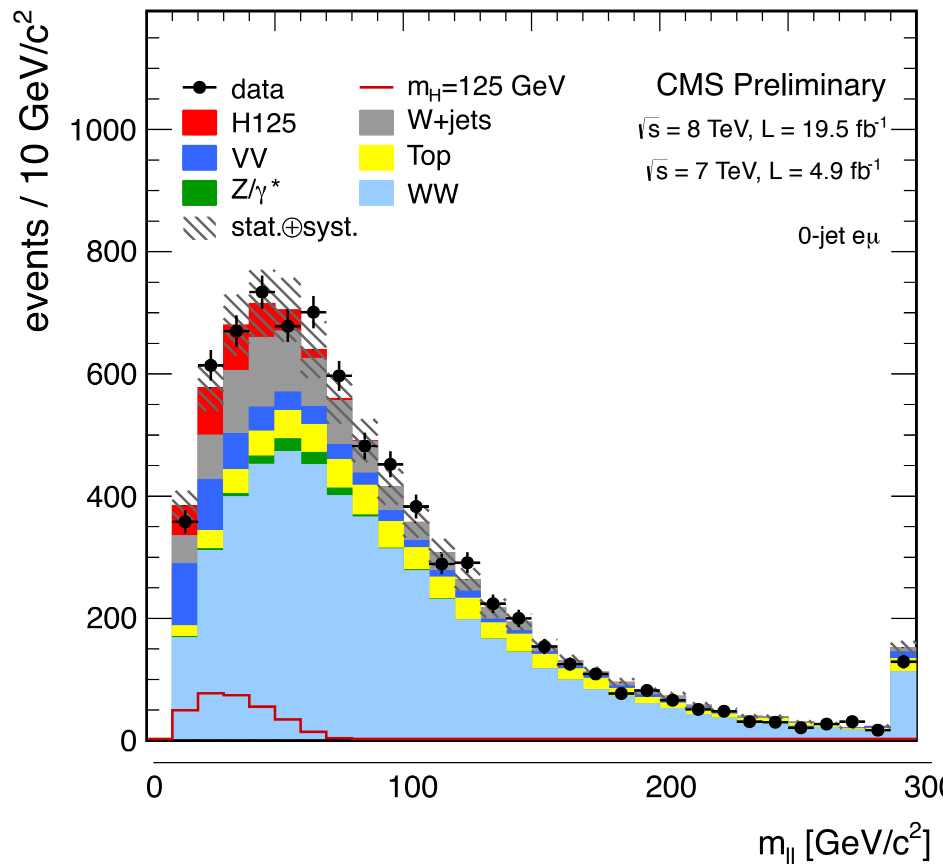
Analysis is done in jet bins, since background is very different when Higgs is produced in association with jets

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

$$p_T^{\rm jet} < p_T^{\rm veto} \sim 20\text{-}30 \text{ GeV}$$

Jet veto in Higgs production





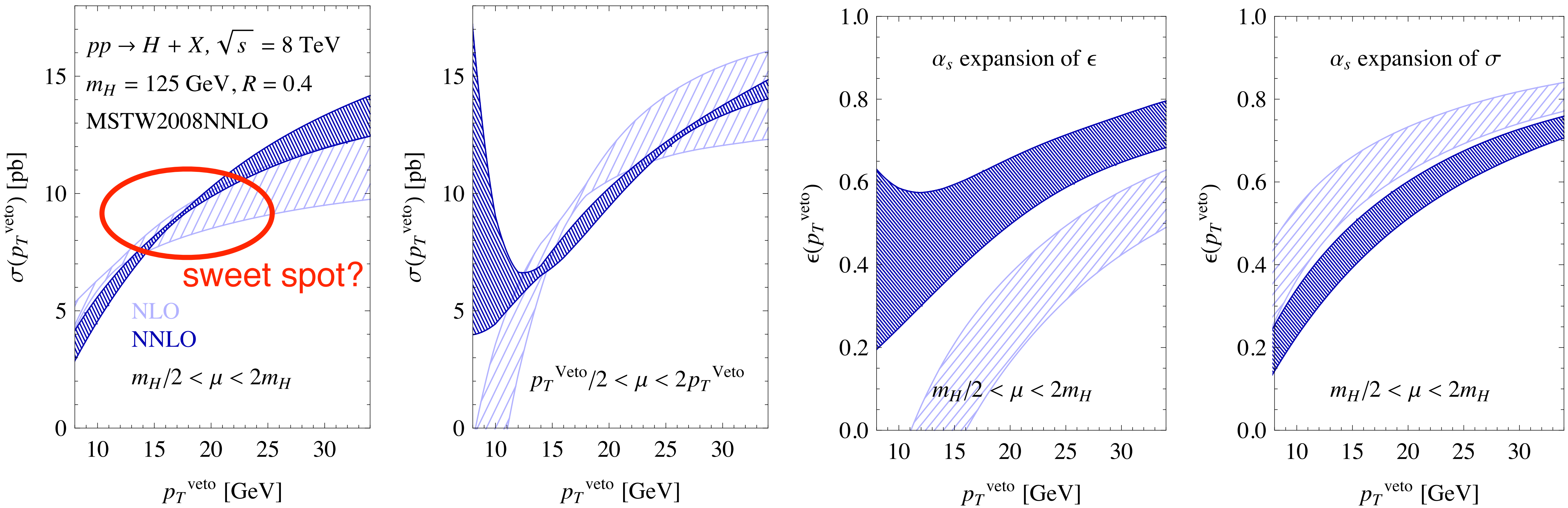
ATLAS: significance 3.8σ (exp: 3.7σ)

$$\mu_{\rm obs} = 1.01 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{theo. syst.}) \pm 0.12\,(\text{expt. syst.}) \pm 0.04\,(\text{lumi.})$$
$$= 1.01 \pm 0.31$$

CMS: significance 4.0σ (exp: 5.1σ)

$$\mu_{\rm obs} = 0.76 \pm 0.21$$

Fixed-order predictions



Smaller scale uncertainty than σ_{tot}, due to accidental cancellation:

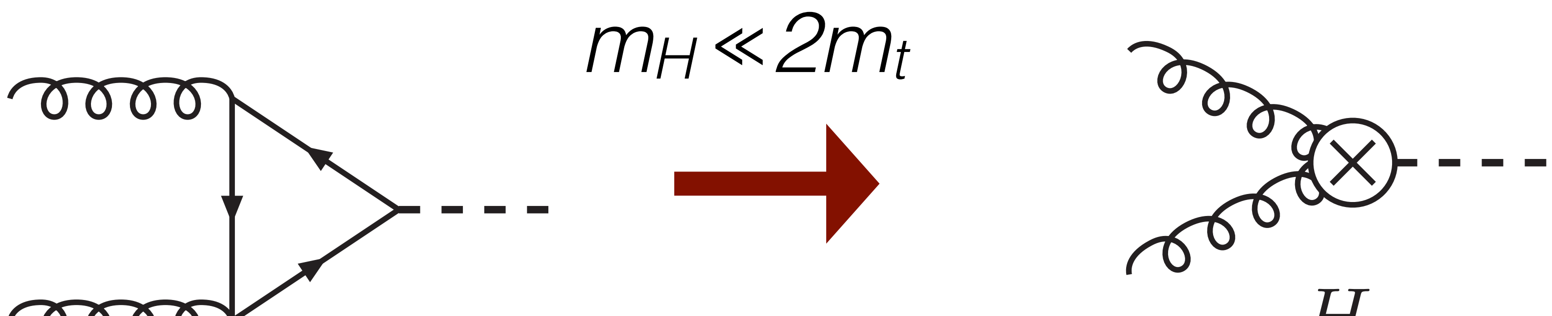
- large positive corrections to σ_{tot} from analytic continuation of scalar form factor Ahrens, Becher, MN, Yang '09
- large negative corrections from collinear logs $\alpha_s^n \ln^{2n} \frac{p_T^{\text{Veto}}}{m_H}$

Equivalent schemes give quite different predictions, hence scale-variation bands do not reflect true uncertainties!

(see also: Stewart, Tackmann '10)

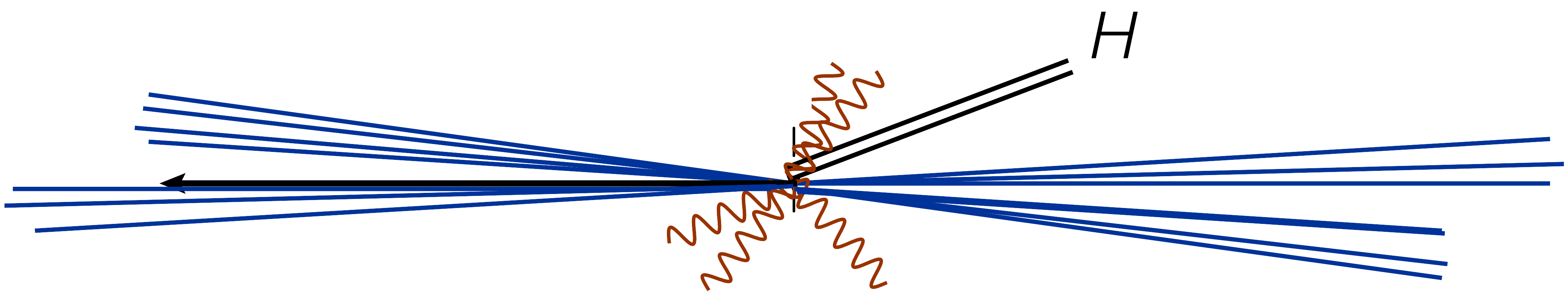
Scale hierarchies and EFTs

Heavy top quark:



$$\mathcal{L}_{\rm eff} = C_t \, \frac{H}{v} \, G^a_{\mu\nu} G^{\mu\nu,a}$$

Small $p_T \ll m_H$:

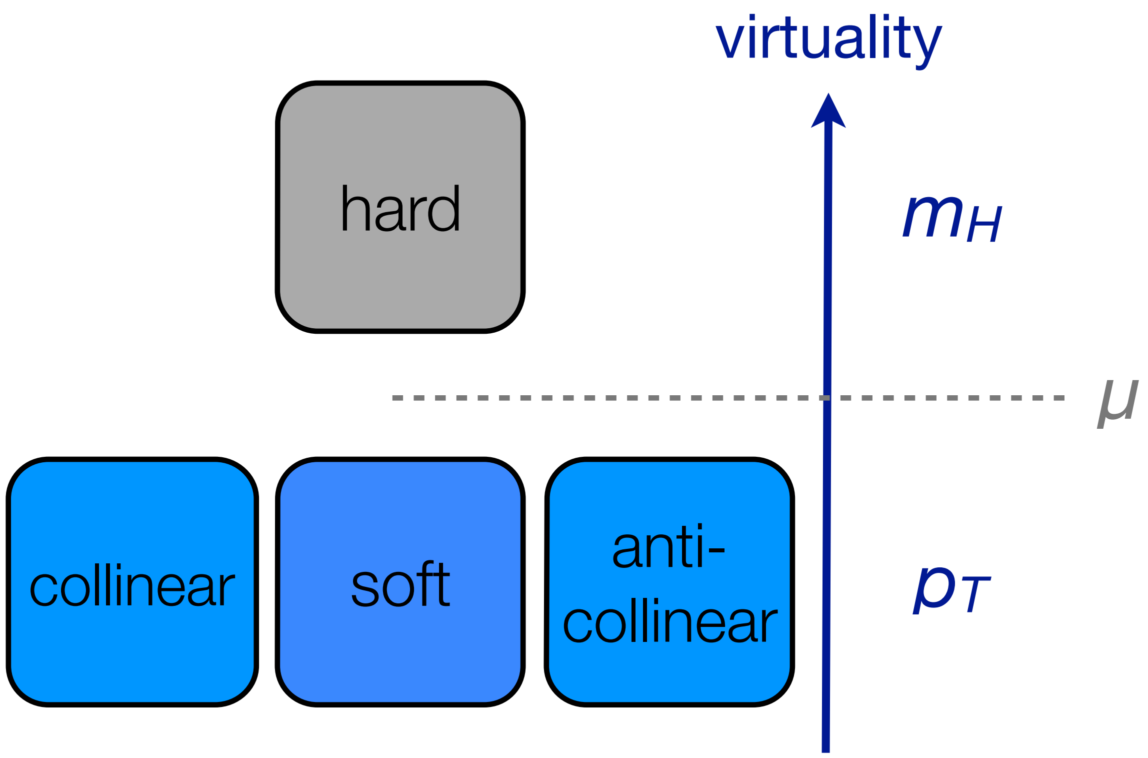


Only soft and (anti-)collinear emissions:

Factorization and resummation using
Soft-Collinear Effective Theory

“Anomalous” (p_T) factorization (SCET$_{II}$)

Applicable for observables probing parton transverse momenta



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

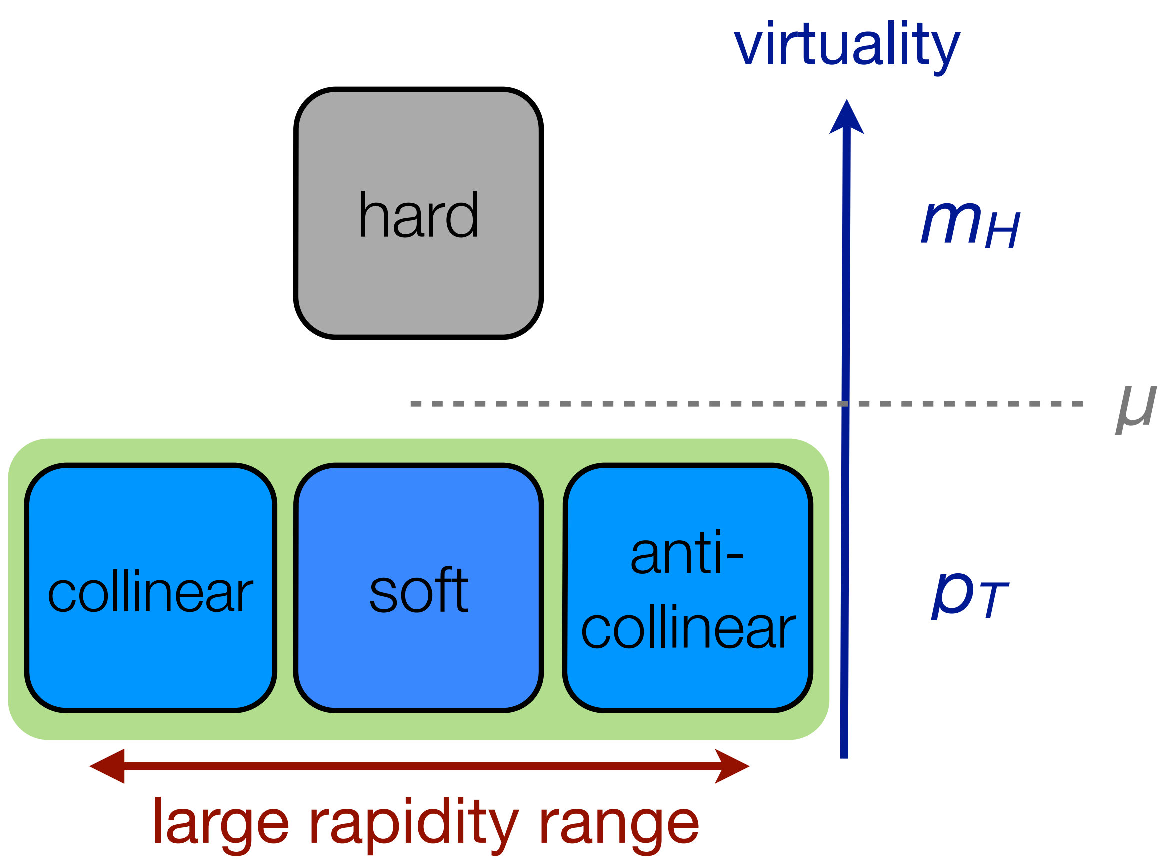
$$\ln^2 \frac{m_H^2}{p_T^2} = \ln^2 \frac{m_H^2}{\mu^2} - \ln^2 \frac{p_T^2}{\mu^2} + ?$$

hard collinear/soft

region decomposition of a Sudakov double logarithm

“Anomalous” (p_T) factorization (SCET$_{II}$)

Applicable for observables probing parton transverse momenta



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

Becher, MN ’10

$$\ln^2 \frac{m_H^2}{p_T^2} = \ln^2 \frac{m_H^2}{\mu^2} - \ln^2 \frac{p_T^2}{\mu^2} - 2 \ln \frac{p_T^2}{\mu^2} \ln \frac{m_H^2}{p_T^2}$$

hard   collinear/soft

region decomposition of a Sudakov double logarithm

Examples of “anomalous” factorization

SCET computations for many transverse-momentum observables are now available:

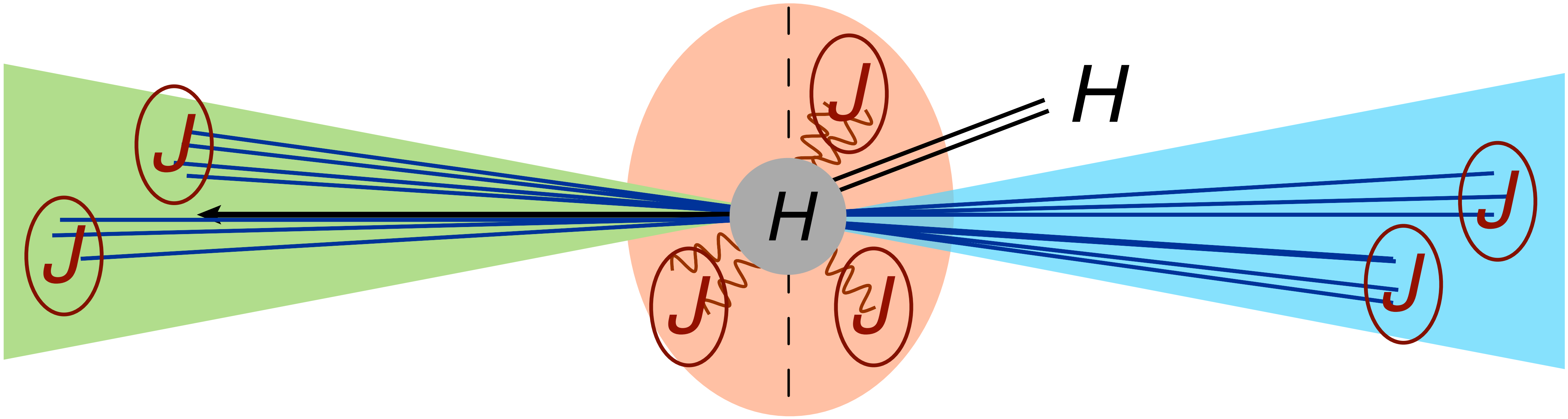
- NNLL q_T spectra for W, Z, H Becher, MN ’11; + Wilhelm ’12
- 2-loop matching of TMPDFs Gehrmann, Lübbert, Yang ’12 (important ingredient for N^{3}LL resummation and NNLO matching for q_T spectra)
- Jet broadening at NNLL Becher, MN ’11; Becher, Bell ‘12
- Transverse-momentum resummation for $\bar{t}t$ production Li, Li, Shao, Yang, Zhu ’12

Resummation for the jet veto

A lot of progress over the last year:

- NLL resummation based on CAESAR
  Banfi, Salam and Zanderighi (BSZ) 1203.5773
- **All-order factorization theorem** in SCET
  Becher and MN (BN) 1205.3806
- Clustering logarithms spoil factorization (?)
  Tackmann, Walsh and Zuberi (TWZ) 1206.4312
- NNLL resummation
  BSZ + Monni (BSZM) 1206.4998
- Absence of clustering logarithms at NNLL and beyond
  Becher, MN and Rothen 1307.0025
- NLL for n-jet bins with $n > 0$
  Liu and Petriello 1210.1906, 1303.4405
  (but no resummation of non-global logarithms)

Factorization theorem



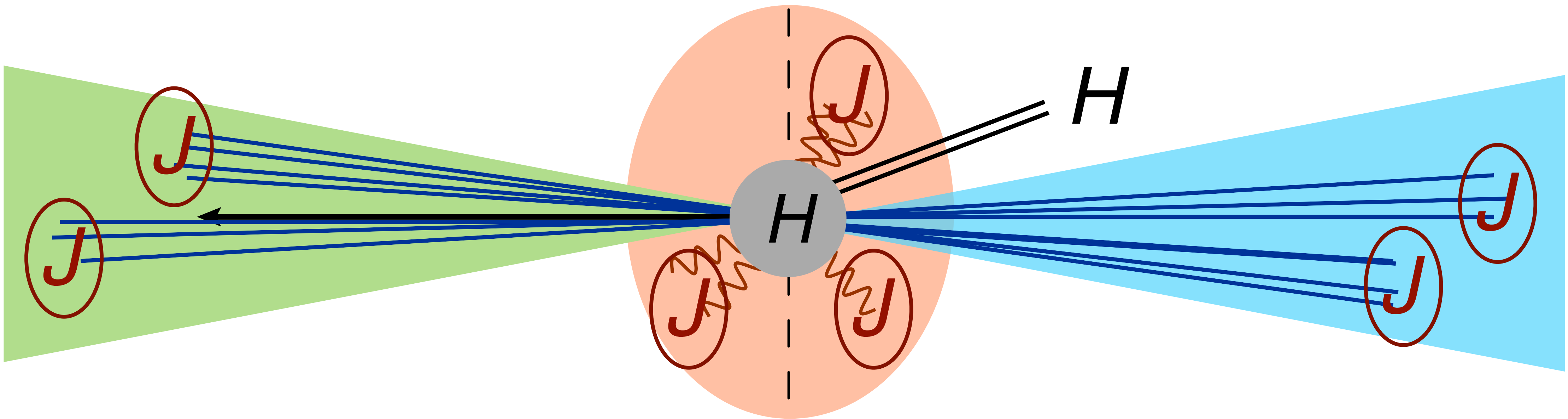
- Work with usual sequential recombination jet algorithms:

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

with n=1 (k_T), n=-1 (anti-k_T), or n=0 (Cambridge-Aachen)

- As long as $R < \ln(m_H/p_T)$ parametrically, such an algorithm will cluster soft and collinear radiation separately

Factorization theorem



The jet veto thus translates into a veto in each individual sector (collinear, anti-collinear, and soft):

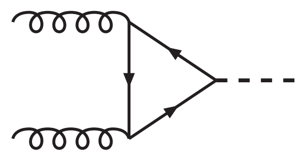
$$\sigma(p_T^{\text{veto}}) \propto H(m_H,\mu)\left[\mathcal{B}_c(\xi_1,p_T^{\text{veto}},\mu)\,\mathcal{B}_{\bar{c}}(\xi_2,p_T^{\text{veto}},\mu)\,\mathcal{S}(p_T^{\text{veto}},\mu)\right]_{q^2=m_H^2}$$

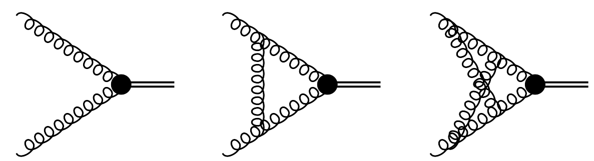
longitudinal momentum fractions: $\xi_{1,2}=\frac{m_H}{\sqrt{s}}\,e^{\pm y_H}$

Becher, MN ’12

Factorization theorem

Hard function:





$$H(m_H,\mu) = C_t^2(m_t^2,\mu)\,\big|C_S(-m_H^2,\mu)\big|^2$$

Collinear beam function:

measurement function

$$\mathcal{B}_{c,g}(z,p_T^{\rm veto},\mu) = -\frac{z\,\bar{n}\cdot p}{2\pi}\int dt\,e^{-izt\bar{n}\cdot p}\sum\!\!\!\!\!\!\!\int_{X_c,\,\rm reg.}\mathcal{M}_{\rm veto}(p_T^{\rm veto},R,\{\underline{p_c}\})$$

$$\times\,\langle P(p)|\,\mathcal{A}_{c\perp}^{\mu,a}(t\bar{n})\,|X_c\rangle\,\langle X_c|\,\mathcal{A}_{c\perp\mu}^{a}(0)\,|P(p)\rangle\,,$$

Soft function:

$$\mathcal{S}(p_T^{\rm veto},\mu) = \frac{1}{d_R}\sum\!\!\!\!\!\!\!\int_{X_c,\,\rm reg.}\mathcal{M}_{\rm veto}(p_T^{\rm veto},R,\{\underline{p_s}\})\langle\,0\,|\,\big(S_n^\dagger S_{\bar{n}}\big)^{ab}(0)\,|X_s\rangle\,\langle X_s|\,\big(S_{\bar{n}}^\dagger S_n\big)^{ba}(0)\,|0\rangle$$

Analytic phase-space regularization

- Presence of light-cone (rapidity) divergences in SCET phase-space integrals, which are not regularized dimensionally; introduce analytic regulator:

$$\int d^dk\,\delta(k^2)\,\theta(k^0) \;\to\; \int d^dk \left(\frac{\nu}{k_+}\right)^{\alpha} \delta(k^2)\,\theta(k^0) = \frac{1}{2}\int dy \int d^{d-2}k_\perp \left(\frac{\nu}{k_T}\right)^{\alpha} e^{-\alpha\,y}$$

Becher, Bell '12

- Divergences in α cancel when the different sectors of SCET are combined, but anomalous dependence on m_H remains
    - consistency conditions (DEQs) fix the all-order form of the m_H dependence Chiu, Golf, Kelley, Manohar '07; Becher, MN '10

- Alternative scheme: "Rapidity renormalization group" based on regularization of Wilson lines Chiu, Jain, Neill, Rothstein '12

Collinear anomaly

Refactorization theorem:

$$\Big[\mathcal{B}_c(\xi_1, p_T^{\text{veto}}, \mu)\, \mathcal{B}_{\bar{c}}(\xi_2, p_T^{\text{veto}}, \mu)\, \mathcal{S}(p_T^{\text{veto}}, \mu)\Big]_{q^2=m_H^2}$$

$$= \left(\frac{m_H}{p_T^{\text{veto}}}\right)^{-2F_{gg}(p_T^{\text{veto}},\mu)} e^{2h_A(p_T^{\text{veto}},\mu)}\, \bar{B}_g(\xi_1, p_T^{\text{veto}})\, \bar{B}_g(\xi_2, p_T^{\text{veto}})$$

RG invariant

Becher, MN '12

- first term (the "anomaly") provides an extra source of large logarithms!
- without loss of generality, the soft function has been absorbed into the final, RG-invariant beam function $\bar{B}_g(\xi, p_T)$

Collinear anomaly

Refactorization theorem:

$$\Big[\mathcal{B}_c(\xi_1, p_T^{\rm veto}, \mu)\, \mathcal{B}_{\bar c}(\xi_2, p_T^{\rm veto}, \mu)\, \mathcal{S}(p_T^{\rm veto}, \mu)\Big]_{q^2=m_H^2}$$

$$= \left(\frac{m_H}{p_T^{\rm veto}}\right)^{-2F_{gg}(p_T^{\rm veto},\mu)} e^{2h_A(p_T^{\rm veto},\mu)}\, \bar{B}_g(\xi_1, p_T^{\rm veto})\, \bar{B}_g(\xi_2, p_T^{\rm veto})$$

RG invariant

Becher, MN '12

RG invariance of the cross section implies, with $a_s = \alpha_s(\mu)/(4\pi)$ and $L_\perp = 2\ln(\mu/p_T^{\rm veto})$:

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

$$+ a_s^3 \left[\Gamma_0^A \beta_0^2 \frac{L_\perp^3}{3} + \left(\Gamma_0^A \beta_1 + 2\Gamma_1^A \beta_0\right) \frac{L_\perp^2}{2} + L_\perp \left(\Gamma_2^A + 2\beta_0\, d_2^{\rm veto}(R)\right) + d_3^{\rm veto}(R)\right]$$

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

Final factorization theorem

- Complete all-order factorization theorem for R=O(1):

$$\frac{d\sigma(p_T^{\rm veto})}{dy} = \sigma_0(p_T^{\rm veto})\,\bar{H}(m_t,m_H,p_T^{\rm veto})\,\bar{B}_g(\xi_1,p_T^{\rm veto})\,\bar{B}_g(\xi_2,p_T^{\rm veto})$$

New!

- RG-invariant, resummed hard function (with $\mu \sim p_T^{\rm veto}$):

$$\bar{H}(m_t,m_H,p_T^{\rm veto}) = \left(\frac{\alpha_s(\mu)}{\alpha_s(p_T^{\rm veto})}\right)^2 C_t^2(m_t^2,\mu)\,\big|C_S(-m_H^2,\mu)\big|^2 \times \left(\frac{m_H}{p_T^{\rm veto}}\right)^{-2F_{gg}(p_T^{\rm veto},\mu)} e^{2h_A(p_T^{\rm veto},\mu)}$$

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- For $p_T^{\rm veto}\gg\Lambda_{\rm QCD}$, the beam function can be further factorized as:

$$\bar{B}_g(\xi,p_T^{\rm veto}) = \sum_{i=g,q,\bar{q}}\int_\xi^1\frac{dz}{z}\,\bar{I}_{g\leftarrow i}(z,p_T^{\rm veto},\mu)\,\phi_{i/P}(\xi/z,\mu)$$

perturbative standard PDFs

Final factorization theorem

- Complete all-order factorization theorem for R=O(1):

$$\frac{d\sigma(p_T^{\rm veto})}{dy} = \sigma_0(p_T^{\rm veto})\,\bar{H}(m_t, m_H, p_T^{\rm veto})\,\bar{B}_g(\xi_1, p_T^{\rm veto})\,\bar{B}_g(\xi_2, p_T^{\rm veto})$$

- Inclusion of power corrections in $p_T^{\rm veto}/m_H$ by matching to fixed-order perturbation theory (known to NNLO):

$$\frac{\sigma(p_T^{\rm veto})}{\bar{H}(m_t, m_H, p_T^{\rm veto})} \equiv \bar{\sigma}_\infty(p_T^{\rm veto}) + \Delta\bar{\sigma}(p_T^{\rm veto})$$

power corrections

$$\bar{\sigma}_\infty(p_T^{\rm veto}) = \sigma_0(p_T^{\rm veto}) \int_{-y_{\rm max}}^{y_{\rm max}} dy\,\bar{B}_g(\tau e^y, p_T^{\rm veto})\,\bar{B}_g(\tau e^{-y}, p_T^{\rm veto})$$

RG invariant and free of large logarithms;
can be evaluated in fixed-order perturbation theory

Resummation at NNLL order

- Ingredients required for NNLL resummation:
  - one-loop $\bar{H}$ and $\bar{I}_{g\leftarrow i}$ (known analytically)
  - three-loop cusp anomalous dimension and other two-loop anomalous dimensions (known)
  - two-loop anomaly coefficient $d_2^{\rm veto}(R)$, which in BN we extracted from the results of BSZM; we have now calculated this coefficient independently within SCET, finding complete agreement
  - find that factorization-breaking soft-collinear mixing terms, claimed by TWZ to arise at NNLL order, do not exist!

Resummation at NNLL order

- Analytic result for $d_2^{\rm veto}(R)$ as a power expansion in R :

$$d_2^{\rm veto}(R) = d_2^B - 32 C_B\, f_B(R)\,; \quad B = F, A$$

- with:

$$f_B(R) = C_A \left(c_L^A \ln R + c_0^A + c_2^A R^2 + c_4^A R^4 + \dots \right) + C_B \left(-\frac{\pi^2 R^2}{12} + \frac{R^4}{16} \right)$$
$$+ T_F n_f \left(c_L^f \ln R + c_0^f + c_2^f R^2 + c_4^f R^4 + \dots \right)$$

- Expansion coefficients:

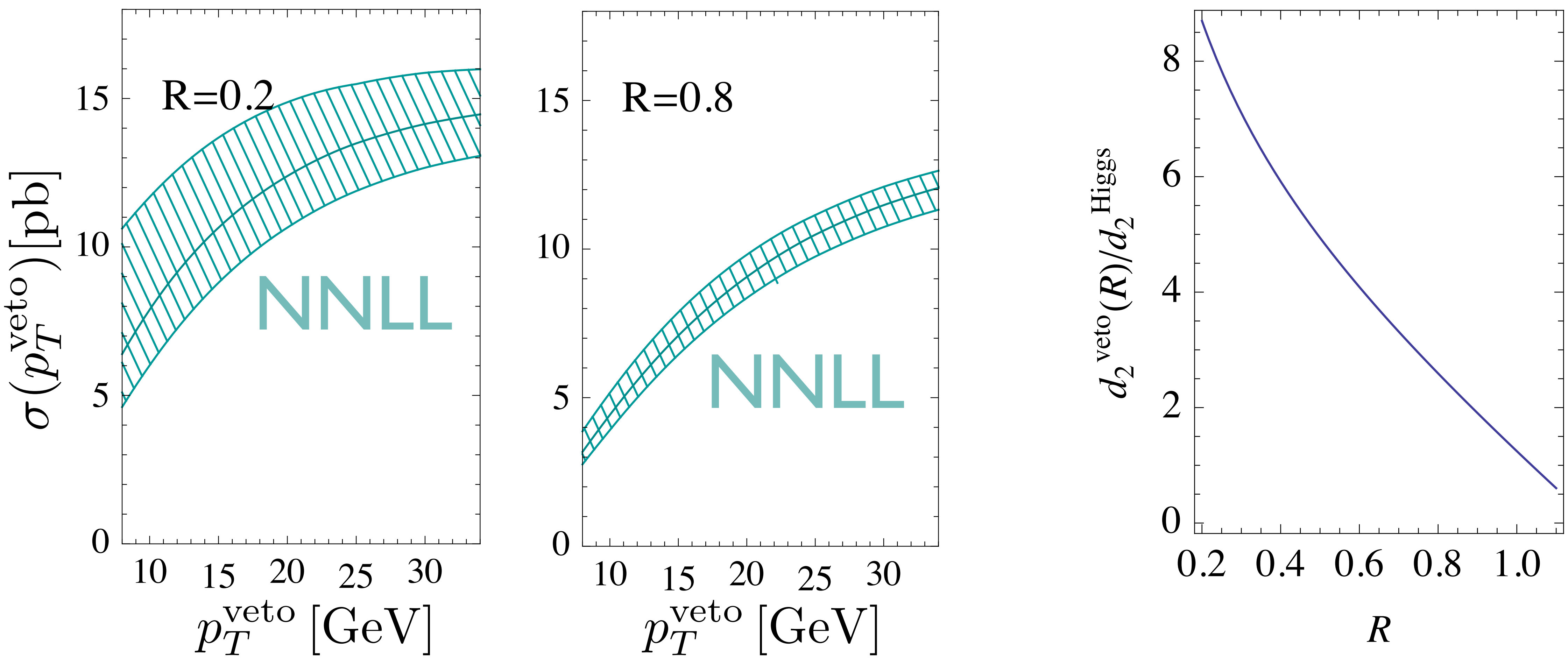
$$c_L^A = \frac{131}{72} - \frac{\pi^2}{6} - \frac{11}{6} \ln 2\,, \qquad c_L^f = -\frac{23}{36} + \frac{2}{3} \ln 2$$

$$c_0^A = -\frac{805}{216} + \frac{11\pi^2}{72} + \frac{35}{18} \ln 2 + \frac{11}{6} \ln^2 2 + \frac{\zeta_3}{2}\,, \qquad c_0^f = \frac{157}{108} - \frac{\pi^2}{18} - \frac{8}{9} \ln 2 - \frac{2}{3} \ln^2 2$$

$$c_2^A = \frac{1429}{172800} + \frac{\pi^2}{48} + \frac{13}{180} \ln 2\,, \qquad c_2^f = \frac{3071}{86400} - \frac{7}{360} \ln 2$$

Becher, MN, Rothen '13

Resummation at NNLL order



$d_2^{\rm veto}(R)$ gets very large at small *R*, introducing a significant scale dependence to the NNLL resummed cross section!

Resummation at N^{3}LL order

- Ingredients required for N^{3}LL resummation:
  - two-loop $\bar{H}$ (known) and $\bar{I}_{g\leftarrow i}$ functions
  - three-loop anomaly exponent $d_3^{veto}(R)$
  - four-loop cusp anomalous dimension Γ_3^A and other (known) three-loop anomalous dimensions

We have extracted the two-loop convolutions $(\bar{I}_{g\leftarrow i} \otimes \phi_{i/P})^2$ numerically using the `HNNLO` fixed-order code by Grazzini (run at different m_H to disentangle power corrections)

Resummation at N^{3}LL order

- The only missing ingredients for complete N^{3}LL result are the four-loop cusp anomalous dimension and the three-loop anomaly coefficient $d_3^{veto}(R)$
- Estimates (thus "N^{3}LL$_p$"):

$$\Gamma_3^A\Big|_{\text{Padé}} = \frac{(\Gamma_2^A)^2}{\Gamma_1^A} = 3494.4$$ tiny impact

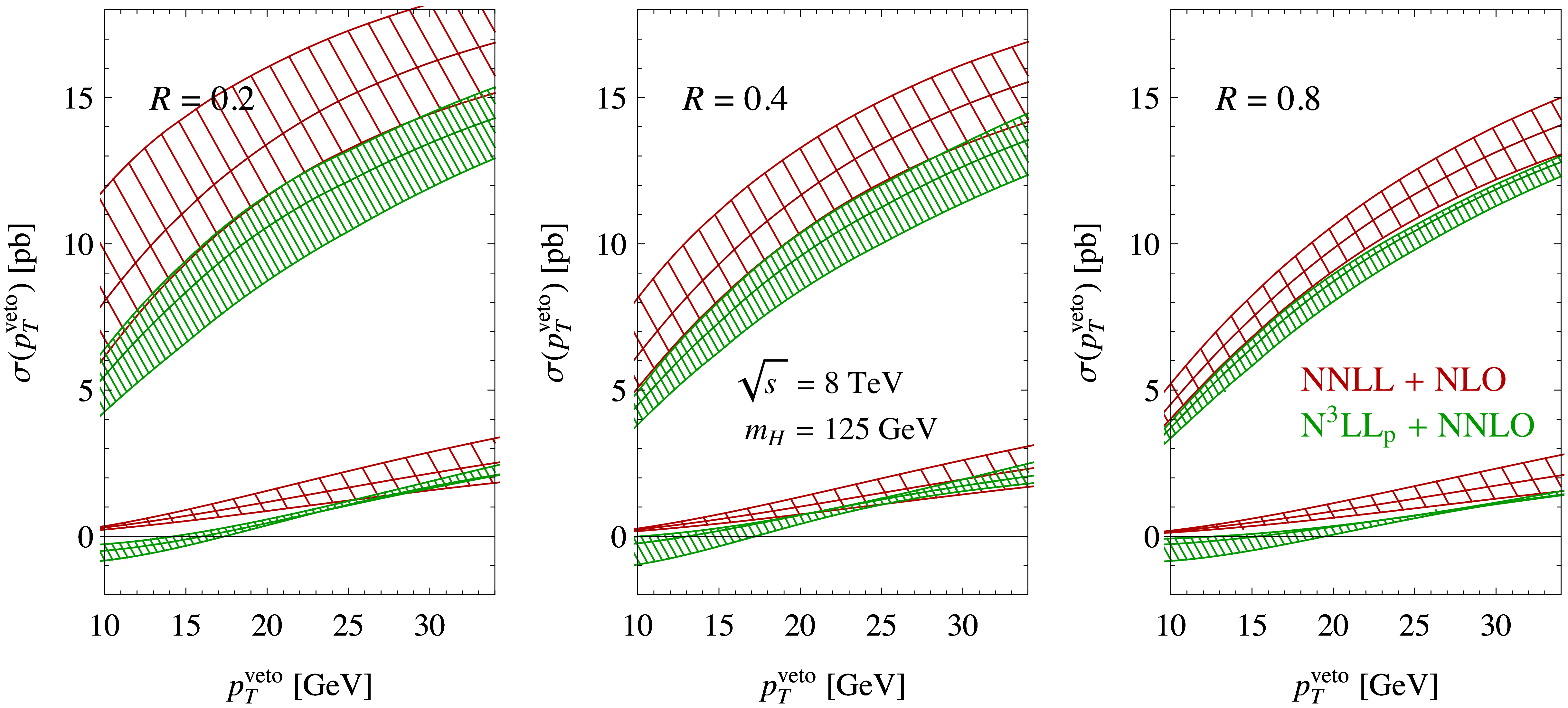
$$d_3^{\text{veto}}(R) = \kappa\,(4C_A)^3 \ln^2\frac{2}{R}$$ with $-4<\kappa<4$

  - our estimate for d_3 is generous and captures the leading dependence for small R; even for R=1, the value is six times larger than the three-loop cusp anomalous dimension

→ recently, S. Alioli and J.R. Walsh (arXiv:1311.5234) have computed the leading $\ln^2 R$ term and found κ=-0.36, ten times smaller than our estimate

N^3LL_p+NNLO matched predictions

Becher, MN, Rothen '13



- Lower bands show the p_T^{veto}/m_H power corrections (small!)
- Seizable uncertainty at very small R due to large $\ln^n R$ terms (experiments use R~0.4)

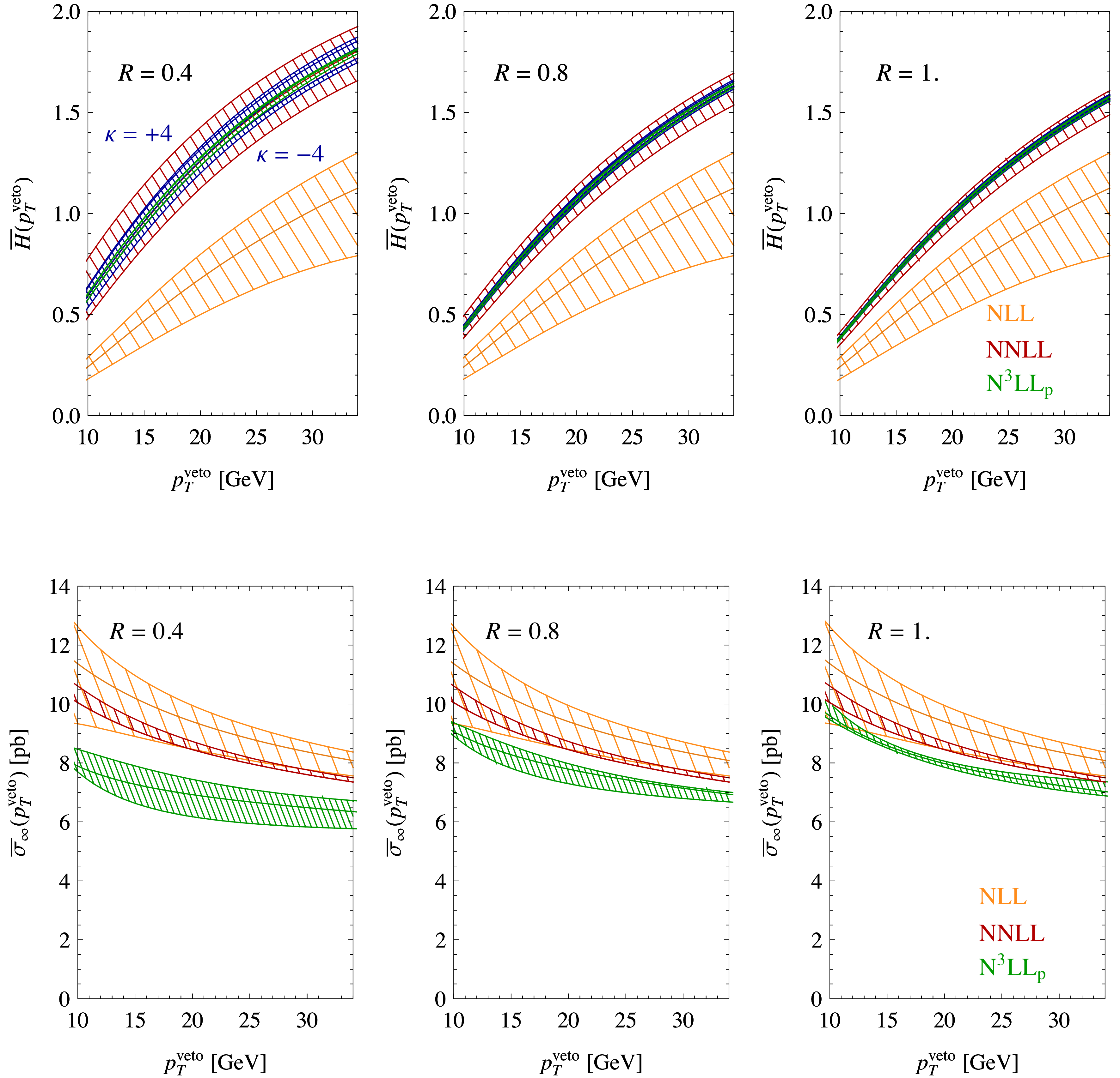
N^3LL_p+NNLO matched predictions

Numerical results:

p_T^{veto} [GeV]	$R = 0.4$: $\sigma\,(p_T^{\text{veto}})$ [pb]	$R = 0.4$: $\epsilon\,(p_T^{\text{veto}})$	$R = 0.8$: $\sigma\,(p_T^{\text{veto}})$ [pb]	$R = 0.8$: $\epsilon\,(p_T^{\text{veto}})$
10	$4.48^{+0.46\,(+0.37)}_{-0.67\,(-0.48)}$	$0.228^{+0.023\,(+0.019)}_{-0.034\,(-0.024)}$	$3.71^{+0.21\,(+0.19)}_{-0.35\,(-0.34)}$	$0.189^{+0.011\,(+0.010)}_{-0.018\,(-0.017)}$
15	$7.31^{+0.72\,(+0.63)}_{-1.00\,(-0.85)}$	$0.371^{+0.036\,(+0.031)}_{-0.051\,(-0.043)}$	$6.44^{+0.30\,(+0.28)}_{-0.61\,(-0.59)}$	$0.328^{+0.015\,(+0.014)}_{-0.031\,(-0.030)}$
20	$9.57^{+0.78\,(+0.66)}_{-1.18\,(+1.07)}$	$0.487^{+0.040\,(+0.034)}_{-0.060\,(-0.055)}$	$8.71^{+0.25\,(+0.21)}_{-0.69\,(-0.67)}$	$0.443^{+0.013\,(+0.011)}_{-0.035\,(-0.034)}$
25	$11.25^{+0.77\,(+0.65)}_{-1.25\,(-1.15)}$	$0.572^{+0.039\,(+0.033)}_{-0.063\,(-0.059)}$	$10.43^{+0.19\,(+0.13)}_{-0.64\,(-0.62)}$	$0.531^{+0.010\,(+0.007)}_{-0.033\,(-0.032)}$
30	$12.64^{+0.80\,(+0.67)}_{-1.25\,(-1.15)}$	$0.643^{+0.040\,(+0.034)}_{-0.063\,(-0.059)}$	$11.86^{+0.18\,(+0.10)}_{-0.57\,(-0.55)}$	$0.603^{+0.009\,(+0.005)}_{-0.029\,(-0.028)}$
35	$13.75^{+0.94\,(+0.84)}_{-1.18\,(-1.08)}$	$0.700^{+0.048\,(+0.043)}_{-0.060\,(-0.055)}$	$13.00^{+0.23\,(+0.18)}_{-0.46\,(-0.43)}$	$0.662^{+0.012\,(+0.009)}_{-0.024\,(-0.022)}$

Table 2: Numerical results for the jet-veto cross section and efficiency. The uncertainty is obtained by varying $p_T^{\text{veto}}/2 < \mu < 2p_T^{\text{veto}}$ and the coefficient $d_3^{\text{veto}}(R)$ according to the estimate (66). The numbers in brackets are obtained if only μ is varied.

Resummation at N^3LL_p order



all large logs resummed

fixed-order expansion (R dependence arises first at N^3LL order !)

Summary

Higher-order resummed and matched predictions for the Higgs jet-veto cross section are now available from different groups (state-of-the art is N^3LL_p+NNLO)

All-order factorization theorem derived within SCET (Becher, MN: 1205.3806, + Rothen: 1307.0025)

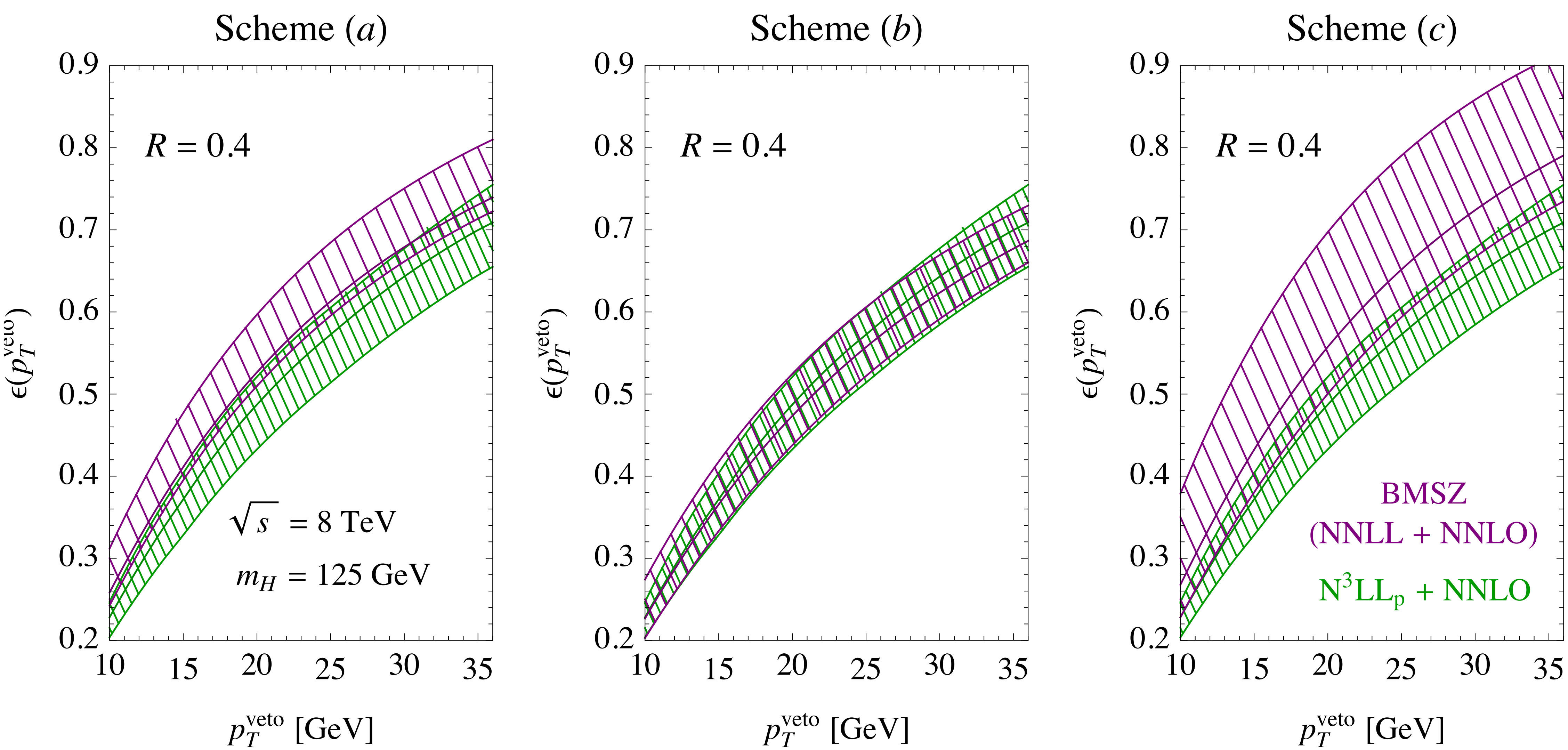
We find:

- complete agreement with BMSZ at NNLL
- no factorization-breaking soft-collinear mixing terms, even for R=O(1)
- uncertainty in cross section about 10% for R=0.4, could be reduced by increasing R

Backup slides

Comparison with other groups

Comparison with Banfi et al. (BMSZ)



- The three different schemes used by BMSZ correspond to different prescriptions for how to expand the veto efficiency $\varepsilon(p_T^{veto})$ in α_s (implemented in `JetVHeto` code)
- Better to work with cross section itself instead of $\varepsilon(p_T^{veto})$

Comparison with Stewart et al.

Comparison for p_T^{veto}=25 GeV and R=0.4:

$$\sigma(p_T^{\text{veto}}) = \left(11.25^{+0.65\,+0.44}_{-1.15\,-0.49}\right)\,\text{pb}$$

Becher, MN, Rothen 1307.0025

$$\sigma(p_T^{\text{veto}}) = \left(12.67 \pm 1.22 \pm 0.46\right)\,\text{pb}$$

Stewart, Tackmann, Walsh, Zuberi 1307.1808

perturbative uncertainties

estimate of $\alpha_s^3 \ln^2 R$ terms

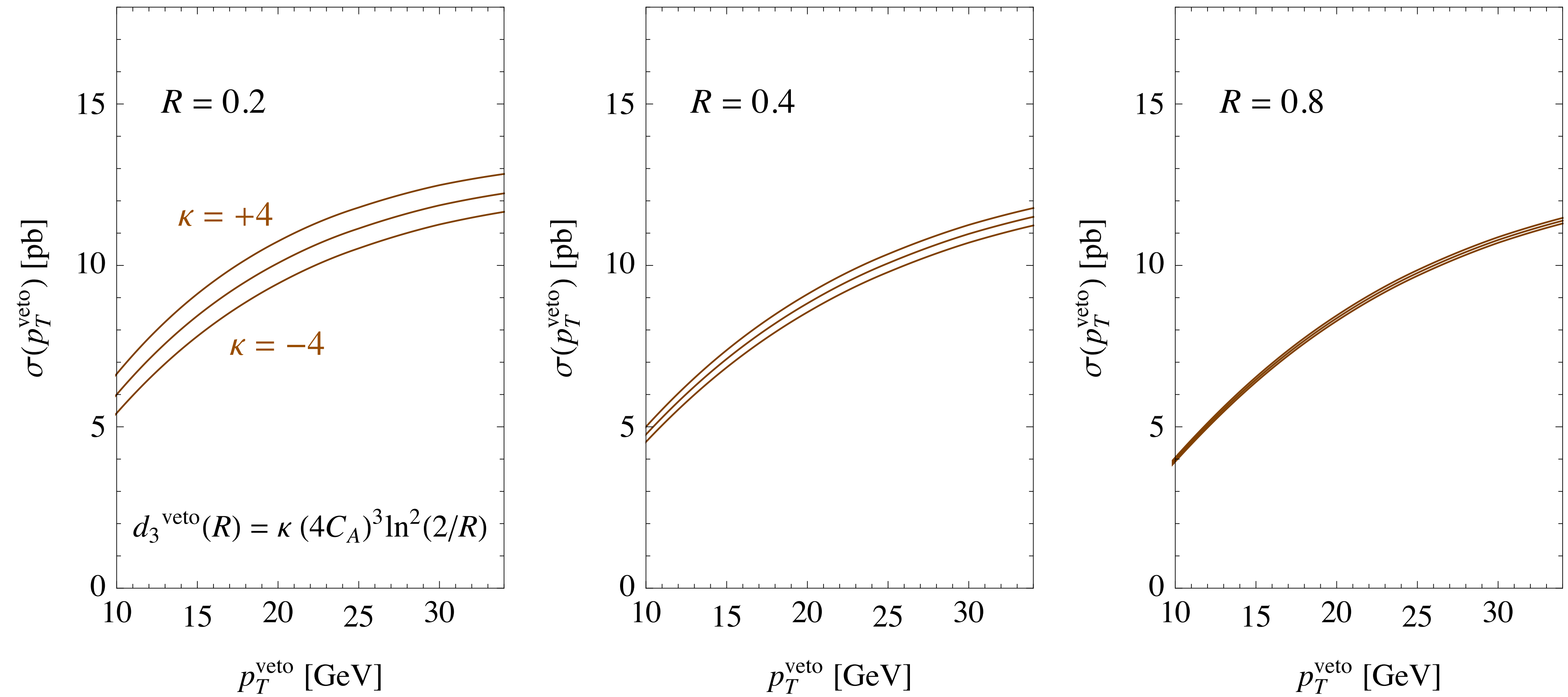
We have $\sigma_{\text{tot}} = \left(19.66^{+0.55}_{-0.16}\right)\,\text{pb}$ in agreement with HXSWG, while they find $\sigma_{\text{tot}} = \left(21.68 \pm 1.49\right)\,\text{pb}$; rescaling their total cross section to ours, we obtain:

$$\sigma(p_T^{\text{veto}}) = \left(11.49 \pm 1.11 \pm 0.42\right)\,\text{pb}$$

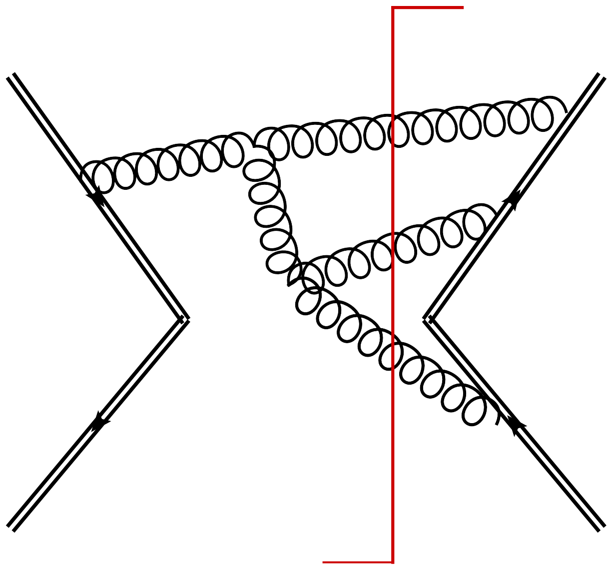
Backup slides

d_3^{veto} uncertainty

d_3^{veto} uncertainty



- for R not too small, this is a subleading uncertainty
- seems possible to extract the leading $\ln^2 R$ term from three-emission diagrams in the soft function



+ many more

Backup slides

More details on soft-collinear clustering terms

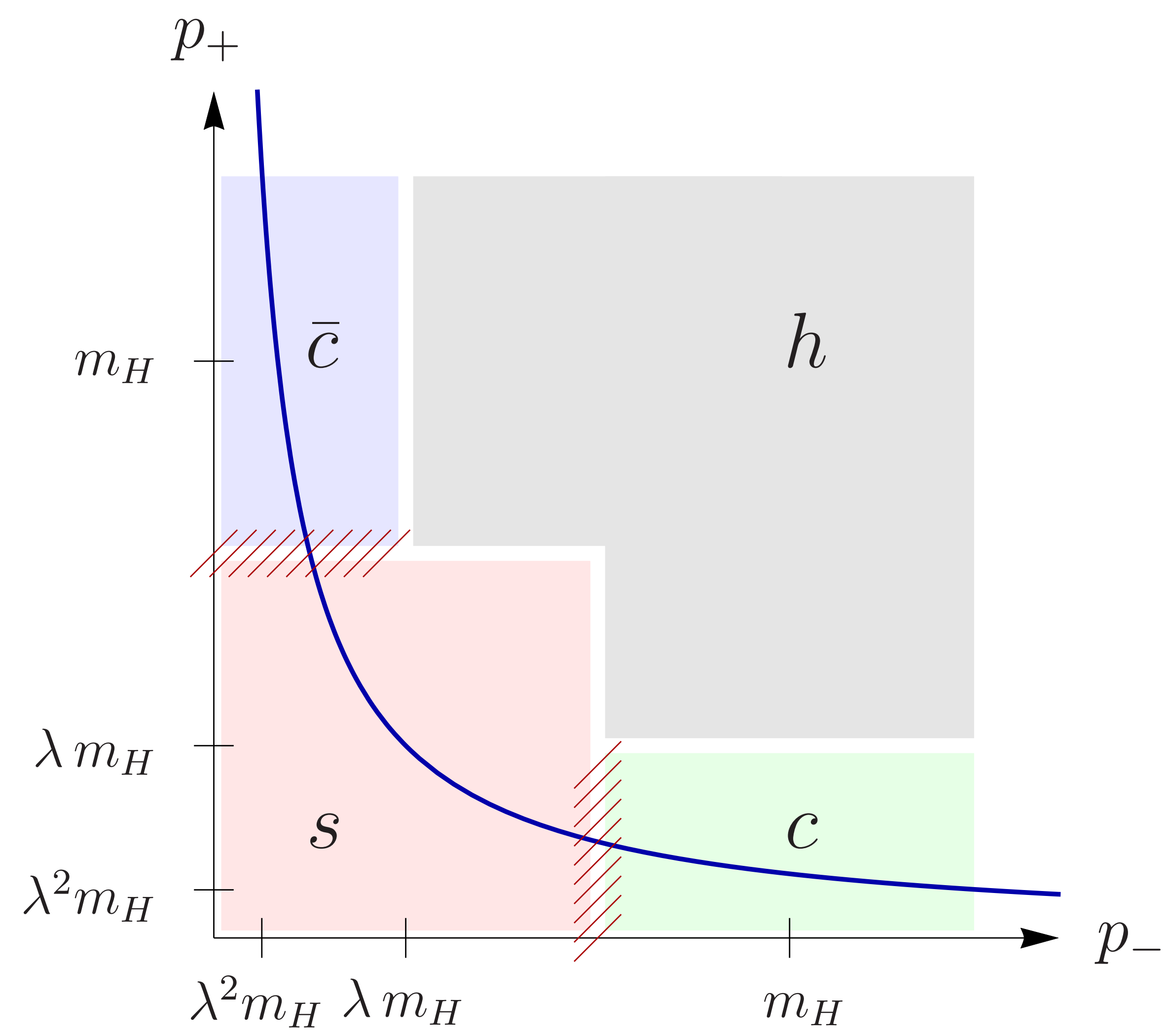
Soft-collinear clustering terms ?

Tackmann, Walsh, Zuberi (TWZ) 1206.4312

Becher, MN and Rothen 1307.0025

Soft-collinear clustering terms?

- Both soft and collinear contributions are integrated over full phase space in SCET
- Avoid double counting by:
  - multi-pole expanding integrands
  - or by performing "zero-bin" subtractions of overlap regions

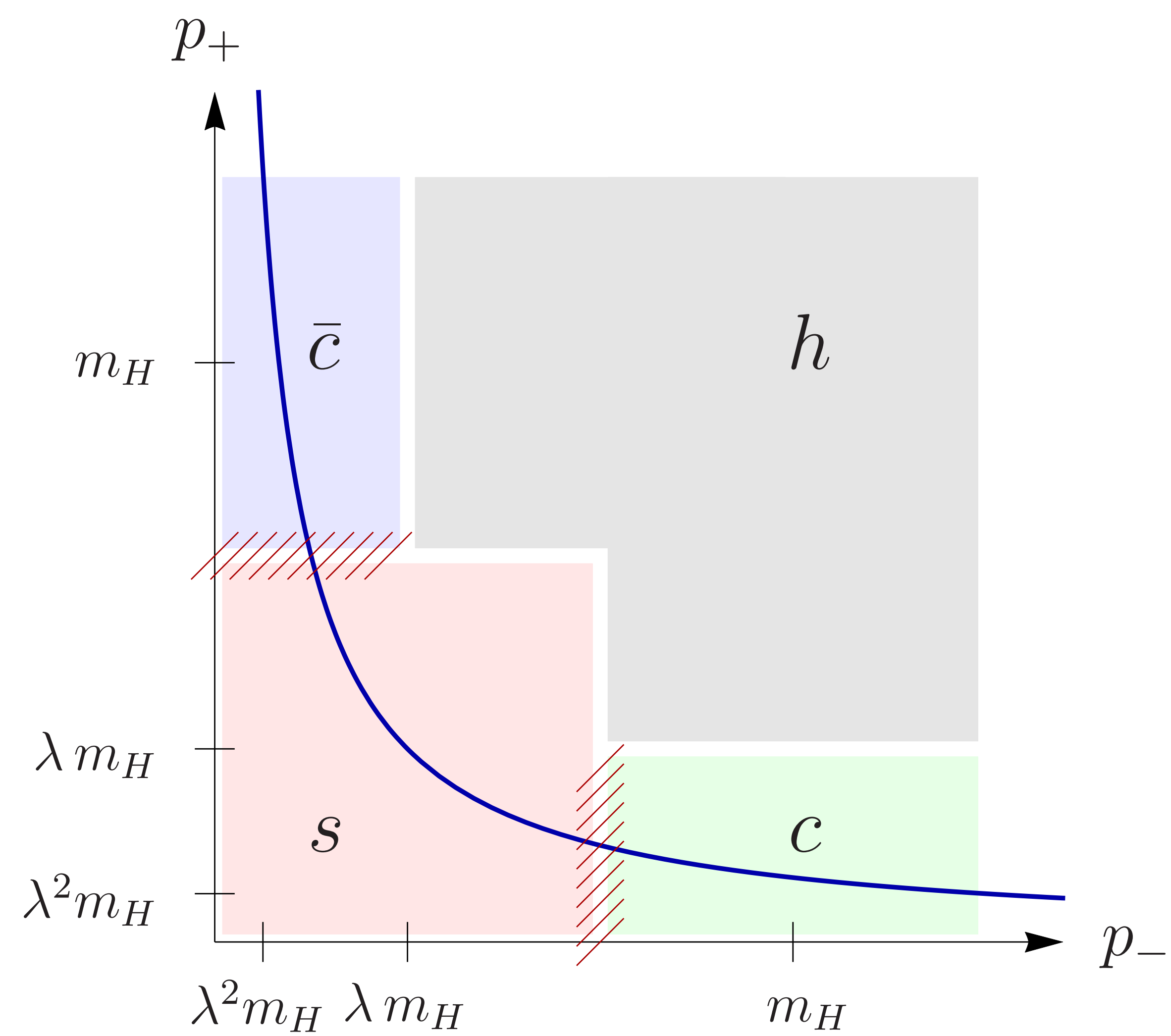


- Find that soft-collinear mixing contribution found by TWZ cancels against zero-bin subtraction of collinear region
- If integrand is expanded in small soft rapidities, both terms are absent

Becher, MN, Rothen '13

Soft-collinear clustering terms?

For concrete example, consider the emission of a collinear gluon ($y_c \gg 1$) along with some other gluon



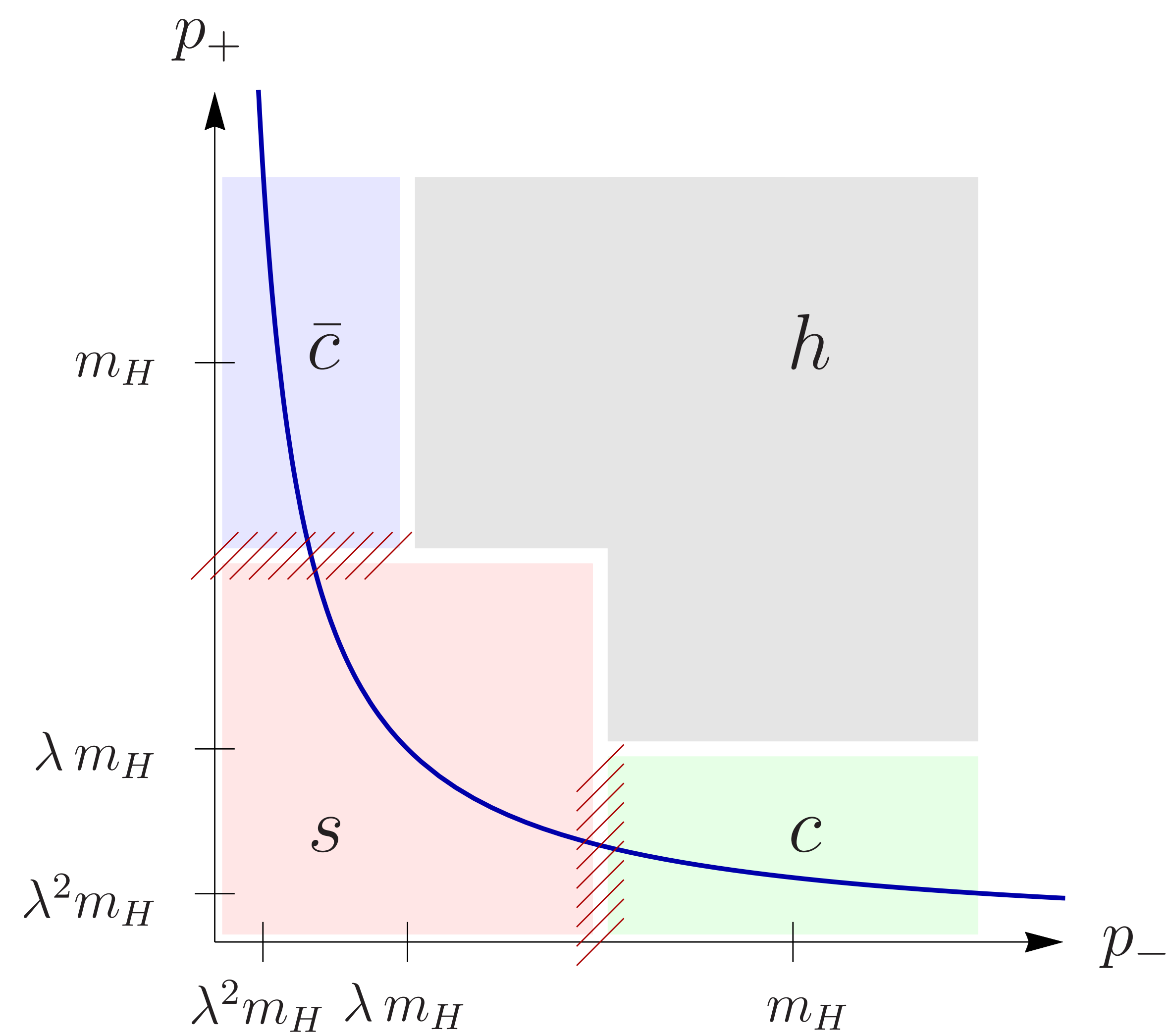
- according to our factorization formula, clustering only occurs if the second gluon is also collinear
- this is indeed the case, provided the distance measure

$$\theta\big(R^2 - (y - y_c)^2 - \Delta\phi^2\big) = \theta\big(-(y - y_c)^2\big) + \dots$$

is multi-pole expanded

Soft-collinear clustering terms?

For concrete example, consider the emission of a collinear gluon ($y_c \gg 1$) along with some other gluon



- without a proper multi-pole expansion, one also finds non-zero contributions from soft and anti-collinear emissions
- at same time, one must perform a variety of zero-bin subtractions of various overlap regions:

cancel ! cancel ! cancel !

$$I = I_c + I_s + I_{\bar{c}} - I_{(cs)} - I_{(\bar{c}s)} - I_{(\bar{c}c)} + I_{(\bar{c}cs)}$$

TWZ have only shown that this is non-zero