Resummation in Higgs physics

Pier Francesco Monni
CERN

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The quest for precision at the LHC

- Astonishing precision at the LHC, future (and present in some cases) data requires very high theory precision in kinematic distributions and fiducial cross sections
- e.g. ATLAS prospects for *some* Higgs signal strengths and couplings at 300 fb^{-1} and 3000 fb^{-1}. Require TH error to be at most 30% of total EXP error

[ATL-PHYS-PUB-2014-016]

Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j $\to$ 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j $\to$ 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j $\to$ VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j $\to$ VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

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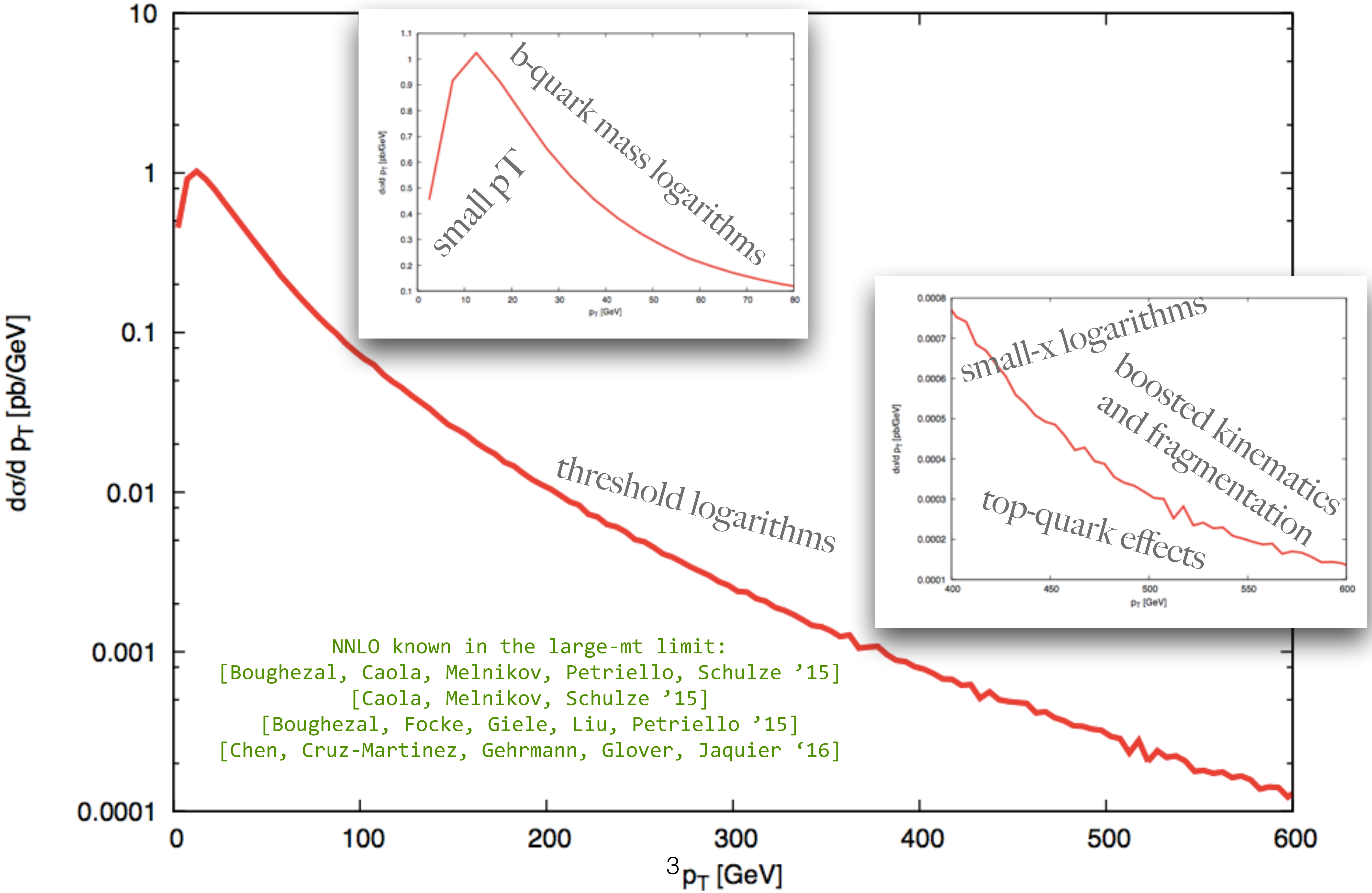
e.g. inclusive Higgs pT spectrum



Higgs at small transverse momentum

- Study of small-pt region received a lot of attention in collider literature. Theoretically, it offers a clean environment to test/calibrate exclusive generators against more accurate predictions. Experimentally, shape is sensitive to light-quark Yukawa couplings

- Theoretically interesting observable. Two mechanisms compete in the $p_t \to 0$ limit

  - Sudakov (exponential) suppression when $k_{ti} \sim p_t$

  - Azimuthal cancellations (power suppression, dominant) when $k_{ti} \gg p_t$

- Standard solution obtained in impact-parameter space. Information on the radiation entirely lost

$$\delta^{(2)}(\vec{p_t} - (\vec{k}_{t1} + \ldots + \vec{k}_{tn})) = \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p_t}} \prod_{i=1}^{n} e^{i\vec{b}\cdot\vec{k}_{ti}},$$

$$\frac{d^2\Sigma(p_t)}{d\Phi_B dp_t} = \sum_{c_1,c_2} \frac{d|M_B|^2_{c_1c_2}}{d\Phi_B} \int b\, db\, p_t J_0(p_t b)\, \mathbf{f}^T(b_0/b) \mathbf{C}^{c_1;T}_{N_1}(\alpha_S(b_0/b)) H_{\rm CSS}(M) \mathbf{C}^{c_2}_{N_2}(\alpha_S(b_0/b)) \mathbf{f}(b_0/b)$$
$$\times \exp\left\{-\sum_{\ell=1}^{2} \int_{b_0/b}^{M} \frac{dk_t}{k_t} \mathbf{R}'_{{\rm CSS},\ell}(k_t)\right\}.$$

[Parisi, Petronzio '79]
[Collins et al. '85]
[Bozzi et al. '05]
[Becher et al. '10+'12]

- Possible to obtain a more exclusive solution in momentum space ?

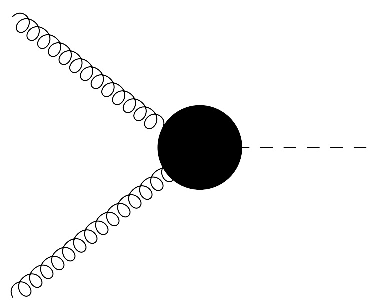
Formulation in momentum space

[PM et al. '16; Bizon et al. '17]
Also SCET formulation in [Ebert, Tackmann '16]

- Write all-order cross section as ($V(\{\tilde{p}\}, k_1, \ldots, k_n) = |\vec{k}_{t1} + \cdots + \vec{k}_{tn}|$)

$$\Sigma(v) = \int d\Phi_B \mathcal{V}(\Phi_B) \sum_{n=0}^{\infty} \int \prod_{i=1}^{n} [dk_i] |M(\tilde{p}_1, \tilde{p}_2, k_1, \ldots, k_n)|^2 \, \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_n)\right)$$

All-order form factor



Real emissions

- Recast all-order squared ME for n real emissions as (each *correlated block* is dressed with loops)

$$|M(\tilde{p}_1, \tilde{p}_2, k_1, \ldots, k_n)|^2 = |M_B(\tilde{p}_1, \tilde{p}_2)|^2$$
$$\times \frac{1}{n!} \left\{ \prod_{i=1}^{n} \left(|M(k_i)|^2 + \int [dk_a][dk_b] |\tilde{M}(k_a, k_b)|^2 \delta^{(2)}(\vec{k}_{ta} + \vec{k}_{tb} - \vec{k}_{ti}) \delta(Y_{ab} - Y_i) \right.\right.$$
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e.g. for n=2

$$|\tilde{M}(k_a)|^2 = \frac{|M(\tilde{p}_1, \tilde{p}_2, k_a)|^2}{|M_B(\tilde{p}_1, \tilde{p}_2)|^2} = |M(k_a)|^2,$$

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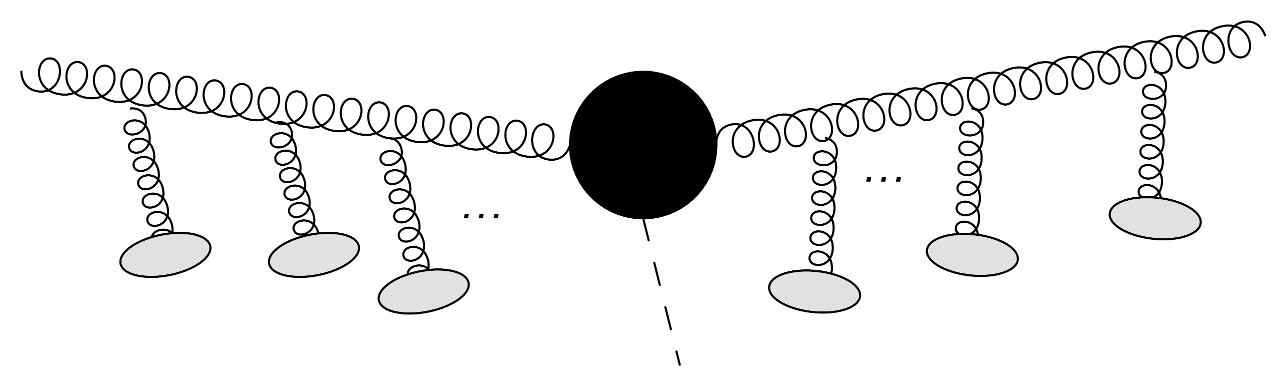

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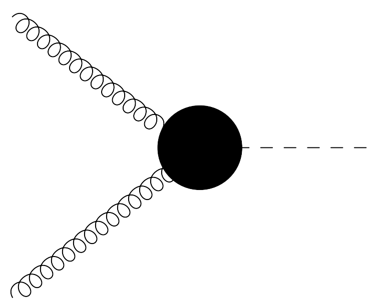

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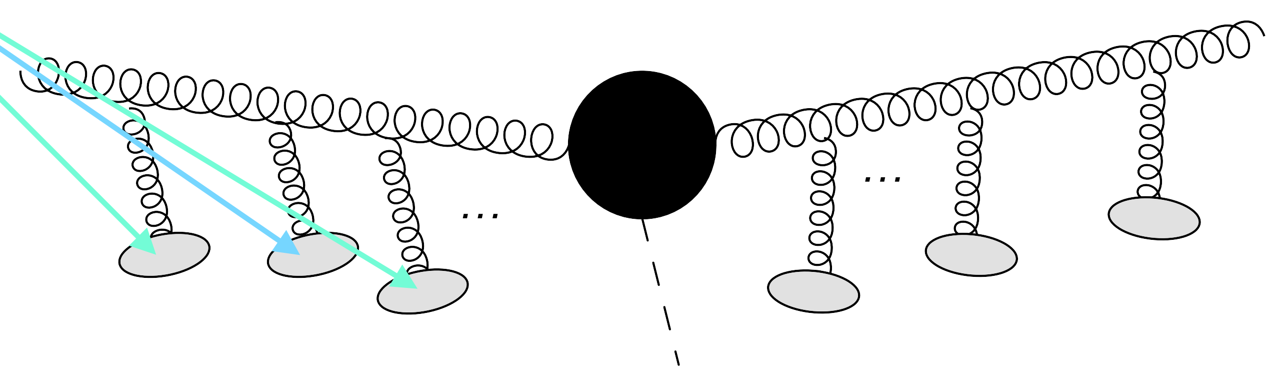

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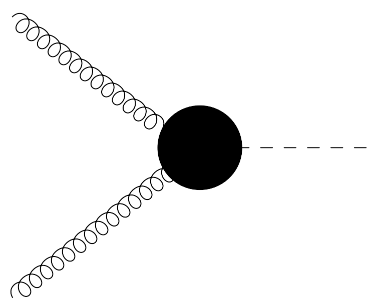

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LL NLL

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NNLL

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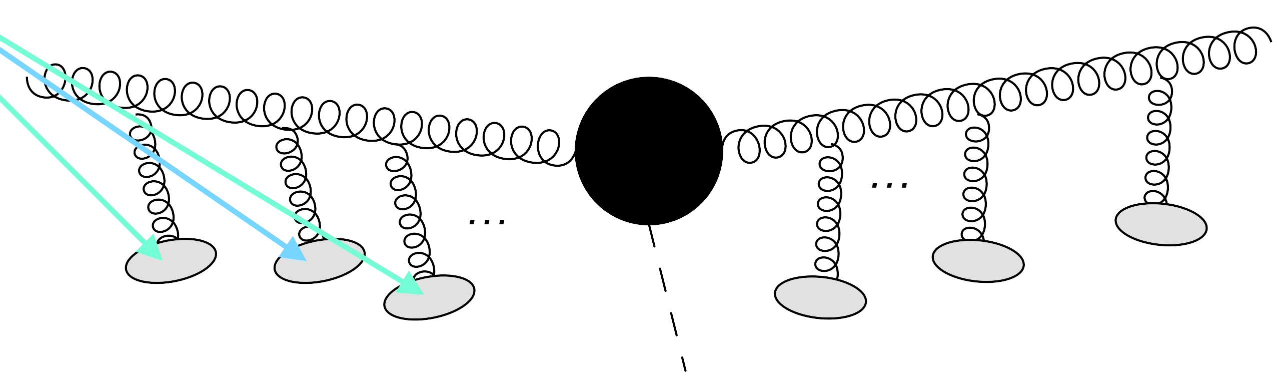


Formulation in momentum space

- Subtraction of the IRC poles between $\sum_{n=0}^{\infty}\int\prod_{i=1}^{n}[dk_i]|M(\tilde{p}_1,\tilde{p}_2,k_1,\ldots,k_n)|^2$ and $\mathcal{V}(\Phi_B)$:
  - introduce a phase-space resolution scale (slicing parameter) $Q_0 = \epsilon k_{t1}$
  - compute *unresolved* reals and *virtuals* analytically in D dimensions
  - compute *resolved* (reals only) in 4 dim. (possible to generate MC events !)

- Remarks:
  - *more* (although not completely) exclusive generation of ISR
    - possible to formulate for more general rIRC-safe observables
  - clear physical picture of the dynamics at small transverse momentum
  - reproduces b-space if integrated inclusively over the radiation
  - allows one to apply cuts on real radiation (<u>a lot of care is required!</u>); access to multi-differential resummations

Higgs pT at N^{3}LL+NNLO

- Implementation in a MC code (RadISH) up to N^{3}LL

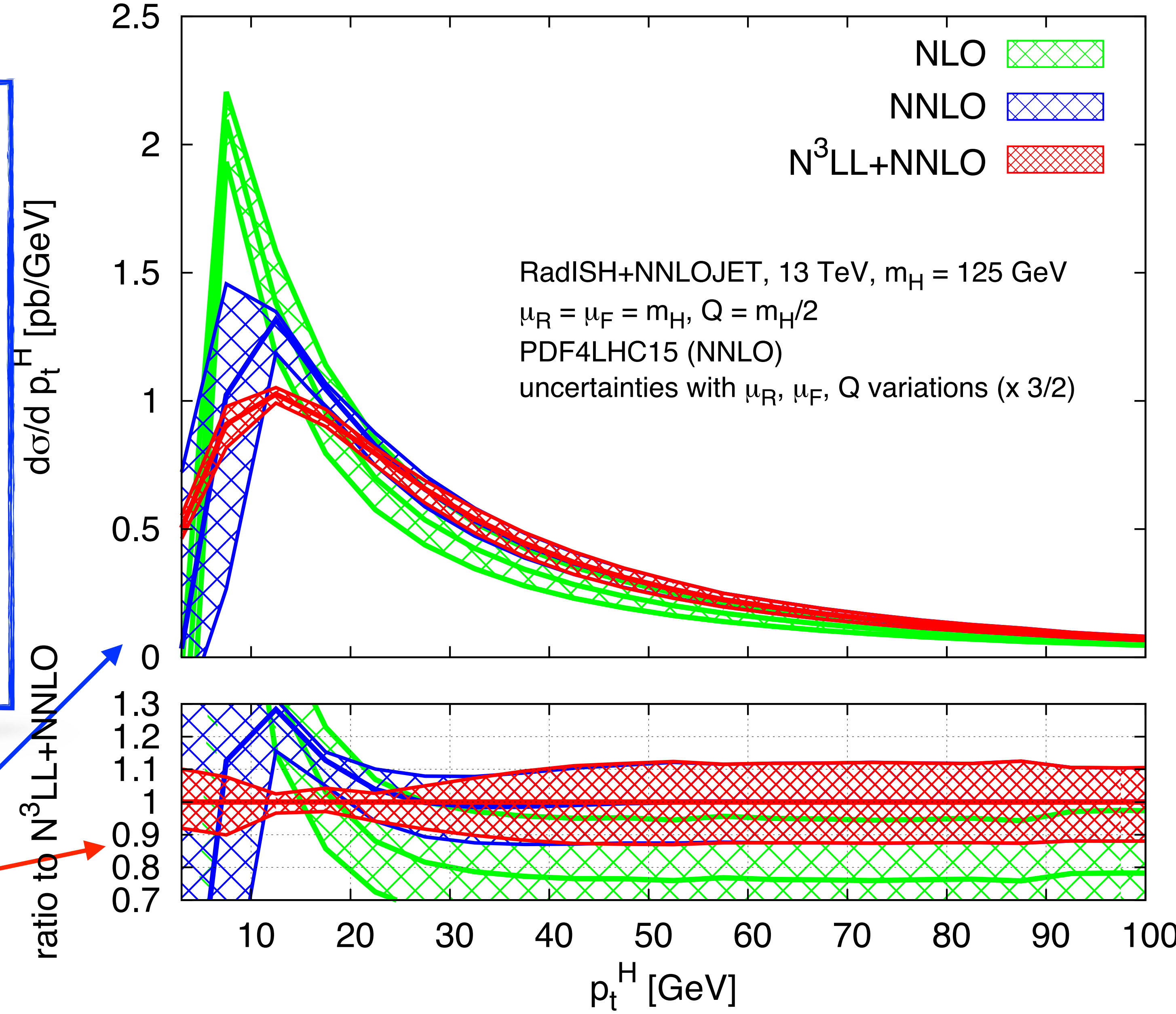
- Matching of the integrated distribution to N^{3}LO via a multiplicative matching, i.e.

[Anastasiou et al. '15-'16] [Boughezal et al. '15] [Caola et al. '15] [Chen et al. '16]

$$\sigma^{\mathrm{N^3LO}}_{pp\to H} - \Sigma^{\mathrm{NNLO}}_{1-\mathrm{jet}}(p_t^H)$$

$$\Sigma_{\mathrm{MAT}}(p_t,\Phi_B) = (\Sigma_{\mathrm{RES}}(p_t,\Phi_B))^Z \frac{\Sigma_{\mathrm{FO}}(p_t,\Phi_B)}{(\Sigma_{\mathrm{EXP}}(p_t,\Phi_B))^Z}$$

$$Z = \left(1-\left(\frac{p_t}{Q_{\mathrm{match}}}\right)\right)^h \Theta(Q_{\mathrm{match}}-p_t)$$

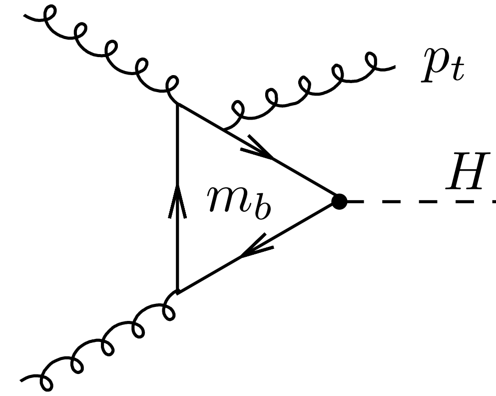


- Deviations from NNLO below 30 GeV

- Scale unc. ~10% down to very small transverse momentum

Coefficient functions and anomalous dimensions from: [Catani, Grazzini '11; Gehrmann et al. '14] [de Florian, Grazzini '01] [Becher, Neubert '10] [Li, Zhu '16]

H+jet via virtual bottom quarks



- The small pT region is affected by bottom-mediated production. Amplitudes are enhanced by (non-Sudakov) logarithmic terms due to the large mass gap

e.g. in the soft, abelian (i.e. no real emissions)

$$\frac{d\sigma_{pp\to H+j}}{dp_\perp^2} = \frac{d\sigma_{pp\to H+j}^{m_t\to\infty}}{dp_\perp^2}\left\{1-\frac{3m_b^2}{m_H^2}L_{\rm eff}^2\left[1-\frac{x_{\rm eff}}{12}\left(1-\tau^3+\tau^4\right)\right.\right.$$
$$\left.\left.+\frac{x_{\rm eff}^2}{48}\left(\frac{4}{15}-\tau^3+2\tau^4-\frac{7\tau^5}{5}+\frac{2\tau^6}{5}\right)+\mathcal{O}(x^3)\right]+\mathcal{O}(m_b^4)\right\}$$

$$L_{\rm eff} = \ln(m_H^2/m_b^2), \quad x_{\rm eff} = \frac{\alpha_s C_F}{2\pi}L_{\rm eff}^2$$

- Resummation known for double logarithms $\frac{m_b^2}{m_H^2}(\alpha_s L^2)^n, \qquad L = \{\ln(p_t^2/m_b^2), \ln(m_H^2/m_b^2)\}$

  - Effects beyond NLO are moderate in the SM, might be important for exclusion of some BSM scenarios with enhanced Yukawa couplings to light quarks [Melnikov, Penin '16]

- Extension to complete *virtual* corrections to H+0 j carried out more recently

$$M_{gg\to H}^{(m_b)} = -e^{-\frac{C_A}{\epsilon^2}\frac{\alpha_s}{2\pi}}\,{}_2F_2\left(1,1;3/2,2;(C_A-C_F)\frac{\alpha_s}{8\pi}\ln^2\frac{m_b^2}{m_H^2}\right)\left(\frac{3}{2}\frac{m_b^2}{m_H^2}\ln^2\frac{m_b^2}{m_H^2}\right)M_{gg\to H}^{(m_t\to\infty)}$$

[Liu, Penin '17]

- Two-loop virtual amplitudes and full NLO distribution recently computed

[Melnikov et al. '16 + Lindert et al. '17]

  - Important to validate the performance of existing generators

A (practical) hassle #1: matching

- Several ways to match resummed calculations to fixed order: e.g. additive, multiplicative, logarithmic, …; in spirit, problem analogous to N(N)LO+PS matching

$$\Sigma_{\mathrm{RES}} + \Sigma_{\mathrm{FO}} - \Sigma_{\mathrm{RES}}^{(\mathrm{expanded})} \qquad \Sigma_{\mathrm{RES}} \left(\frac{\Sigma_{\mathrm{FO}}}{\Sigma_{\mathrm{RES}}^{(\mathrm{expanded})}} \right)_{\mathrm{expanded}} \qquad \ln \Sigma_{\mathrm{RES}} + \left(\ln \Sigma_{\mathrm{FO}} - \ln \Sigma_{\mathrm{RES}}^{(\mathrm{expanded})} \right)_{\mathrm{expanded}}$$

- No constraint from the theory: additive is simpler/cleaner, but multiplicative solutions have a number of advantages, e.g. numerical stability, constants determined from the fixed order

- Not improvable with higher orders: differences usually moderate between *judicious* choices of the scheme, but sometimes we're interested in the physics of the matching region where fixed-order ~ resummation

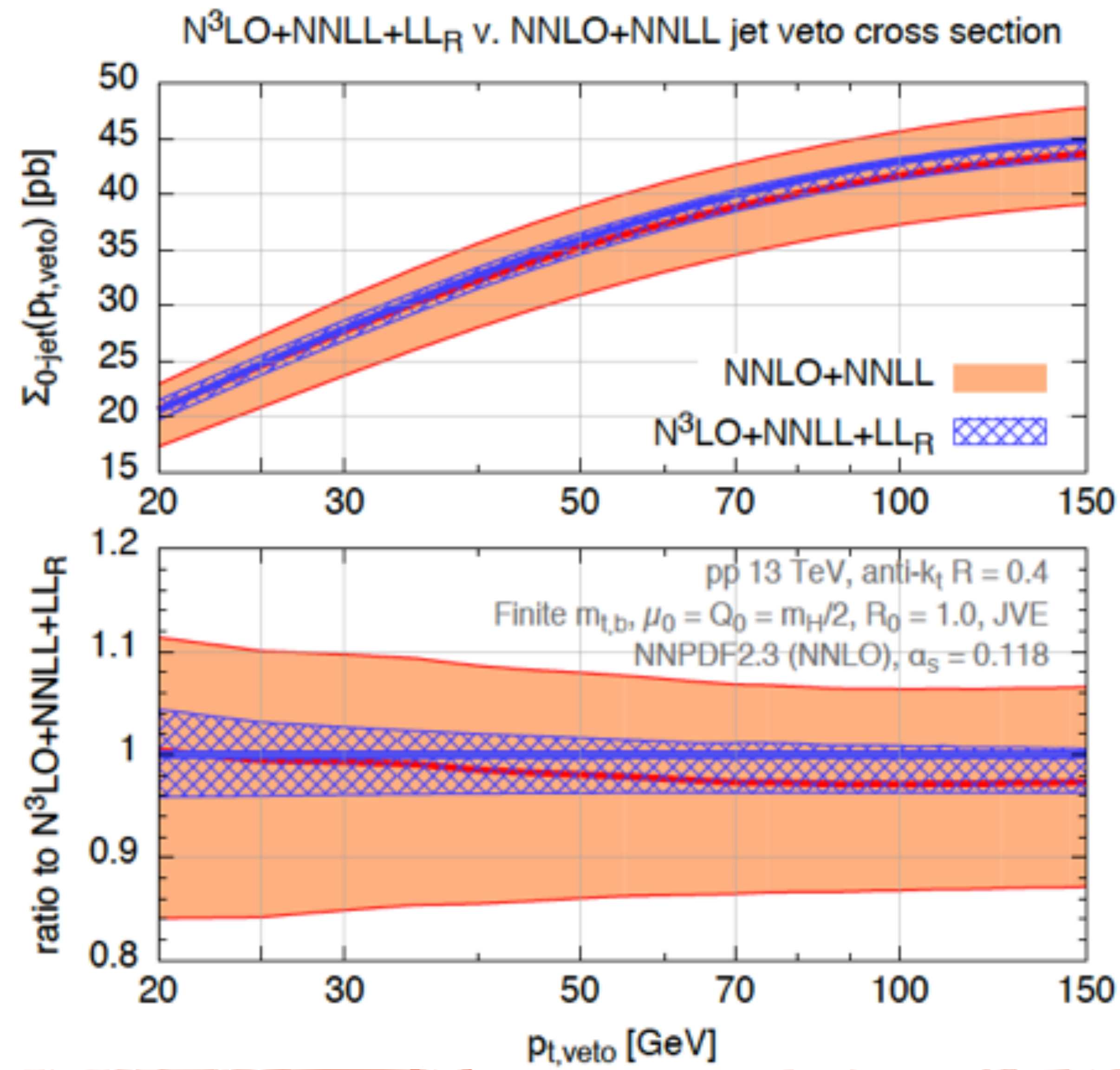
- The problem is real when high precision is demanded, as the choice of the matching scheme also also slightly affects the perturbative scale uncertainty. Things could get worse in multiple-scale problems / joint resummations

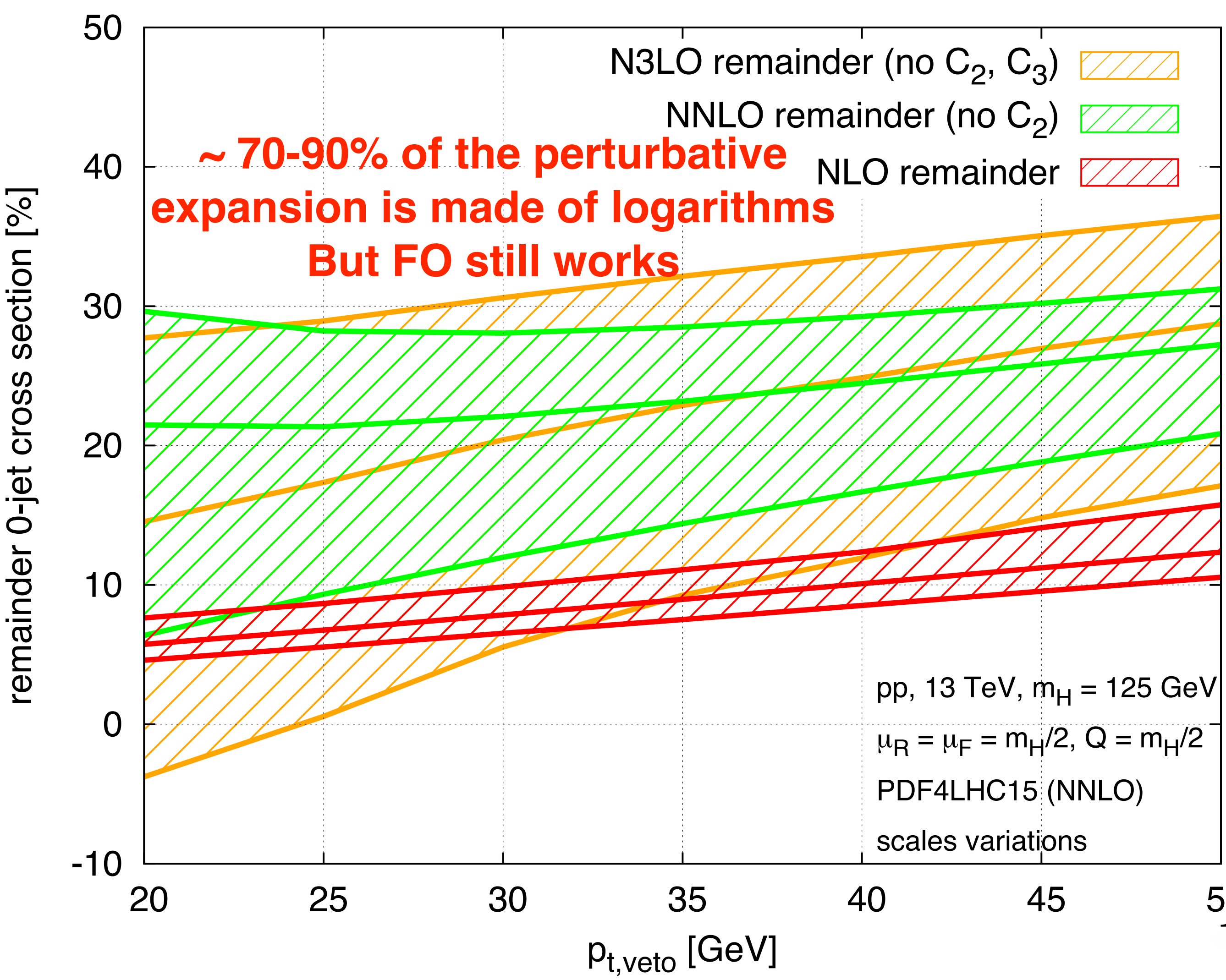
An example: 0-jet cross section

[Banfi et al. ‘15]

Also [Banfi et al. ’12] [Becher et al ‘13; Stewart et al.’13]

- Large uncertainty reduction with inclusion of N^{3}LO
- Matching scheme variation included as extra source of uncertainty
- High precision allows one to identity pathological schemes





- Possible future directions:
  - Data driven: use precise measurements (e.g. Z pT) to select good schemes
  - Inclusion of next-to-eikonal/power corrections can make transition more reliable [Moult et al.’16] [Boughezal et al.’16] [Bonocore et al.’16 + Del Duca et al.’17]

A (practical) hassle #2: unitarity

- Resummation must be turned off when the radiation approaches the hard scale(s) of the reaction, i.e. the total cross section is preserved in the matching to fixed order

- Commonly achieved by smoothly turning off the logarithms at the price of adding *power-suppressed* corrections. Many possible ways (modified logarithms, profile functions,…), numerical differences in the matching region, e.g.

$$\ln\frac{1}{v} \to \frac{1}{p}\ln\left(1+\frac{1}{v^p}\right) \simeq \ln\frac{1}{v} + \frac{v^p}{p} + \dots$$

- Possible future improvements:
  - Recent progress in the computation of power corrections to exclusive observables could help adjust the form of the modified logarithms
  - Construct unitary resummation more exclusively with Monte Carlo methods

    i.e. emission probabilities ~ total derivatives (like in common PS)

  - Can we allow for non-unitary effects in a controlled manner ? Accepted in some NLOPS matching/merging methods (e.g. POWHEG, MC@NLO+FxFx,…)

E.g. joint pt/threshold resummation

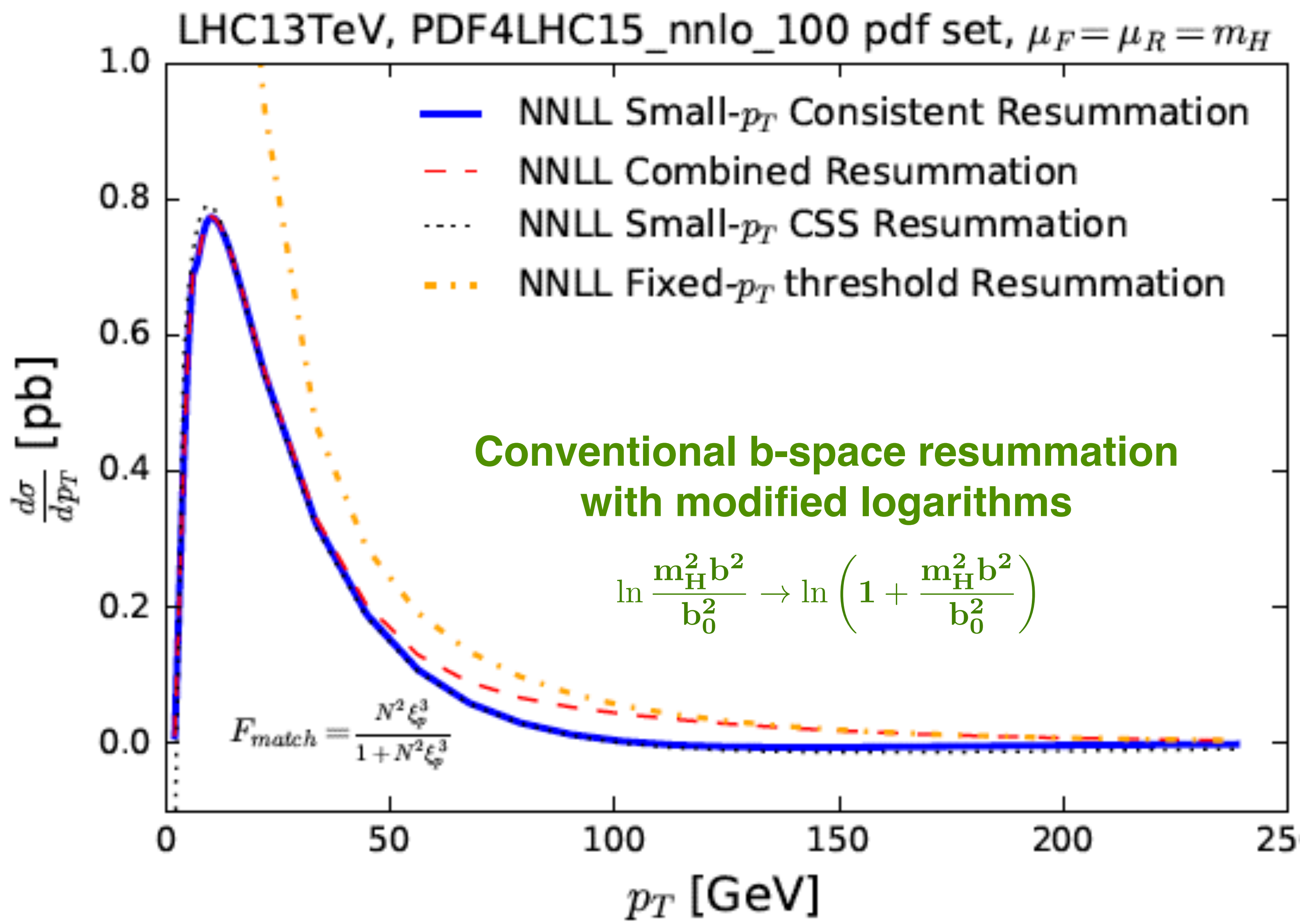
- Retain threshold effects in the radiation's phase space, i.e. study the limit

$$p_t^2 \simeq m_H^2 \left(1 - \frac{m_H^2}{\hat{s}}\right) \ll m_h^2$$

- Integrated distribution yields the known resummed XS + resumed threshold effects

- No need for *ad hoc* modification of resummed logarithms

- Interesting to study the possibility to implement this idea in more exclusive cases



[Muselli et al. '17]

See also:
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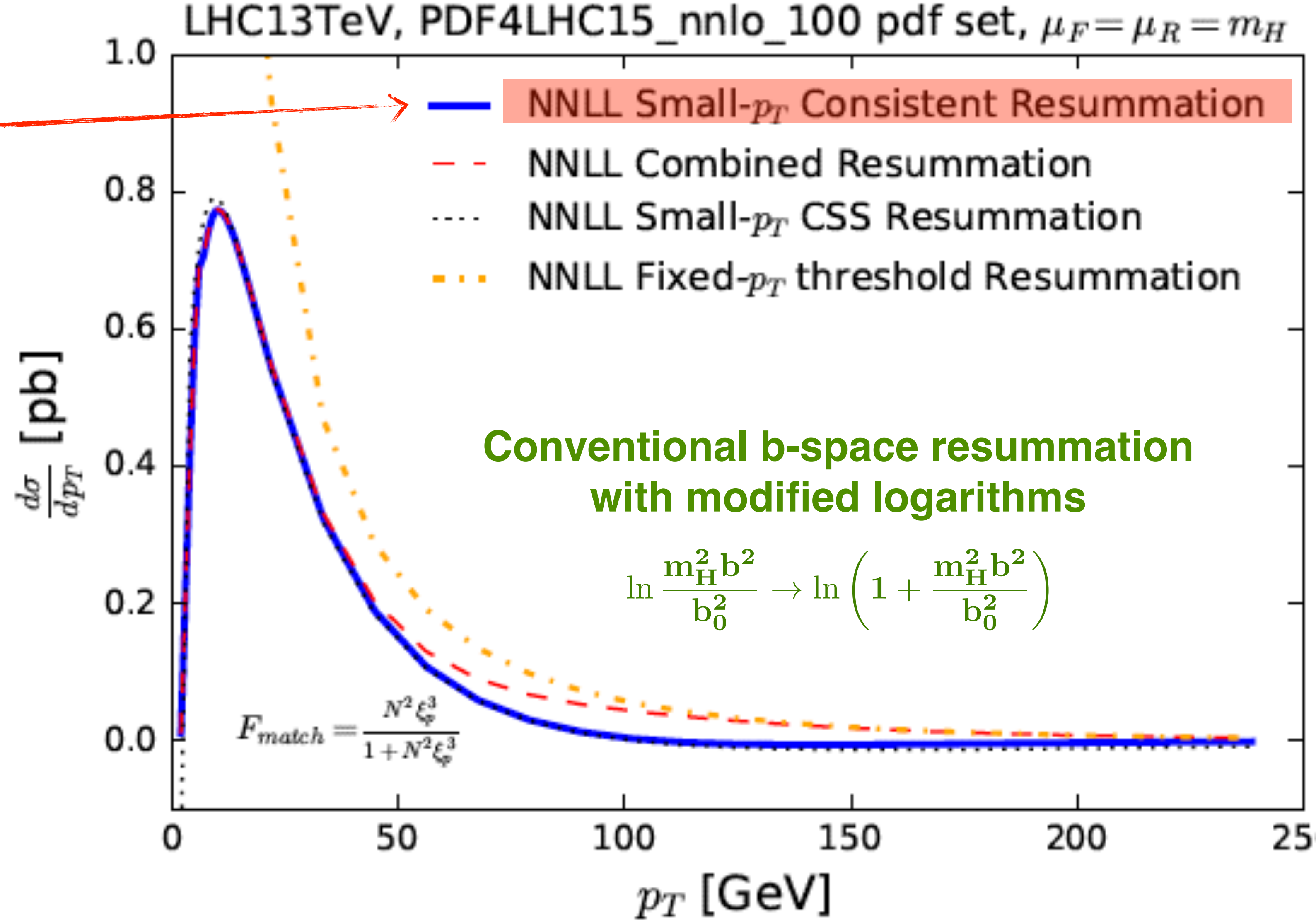

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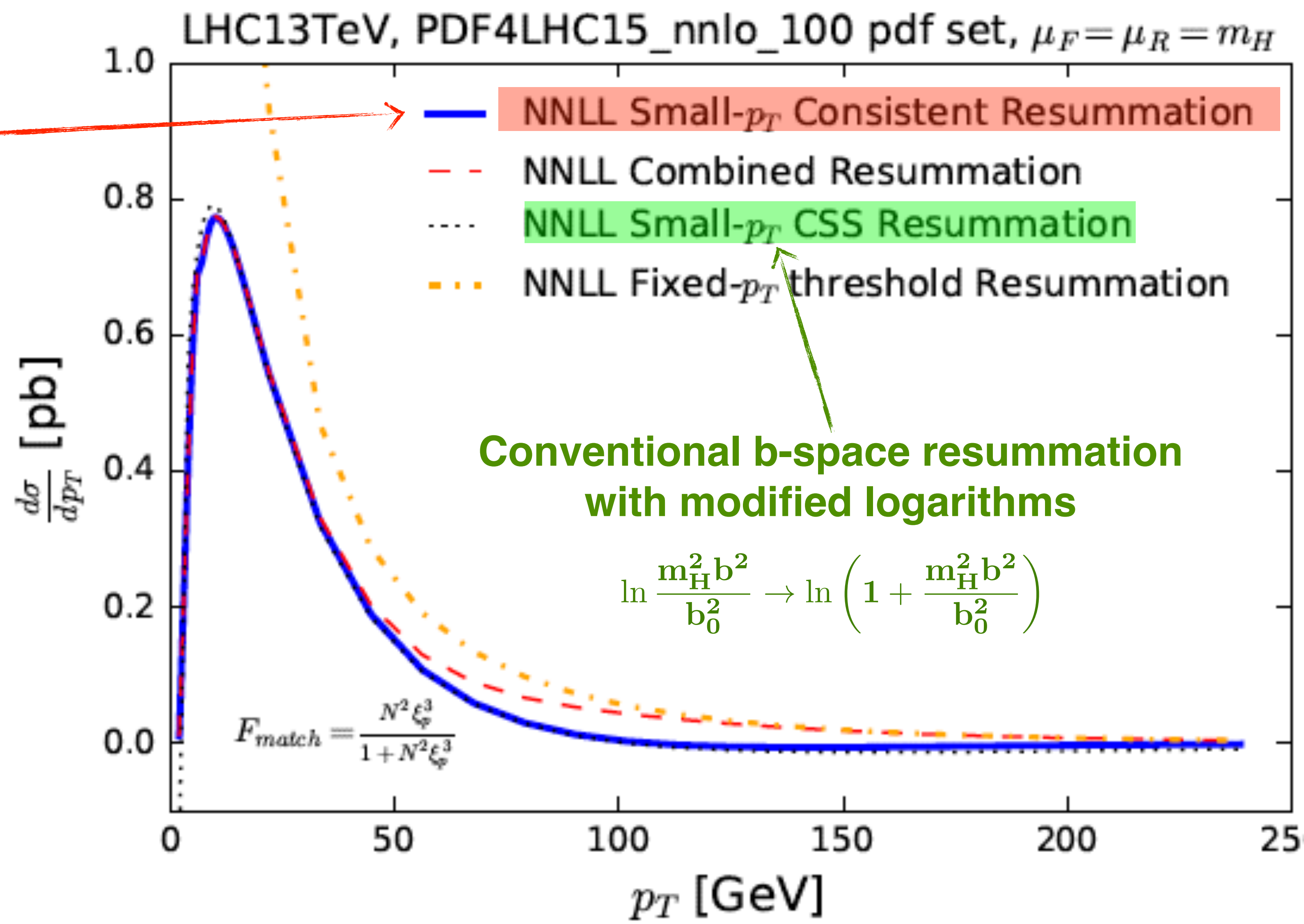

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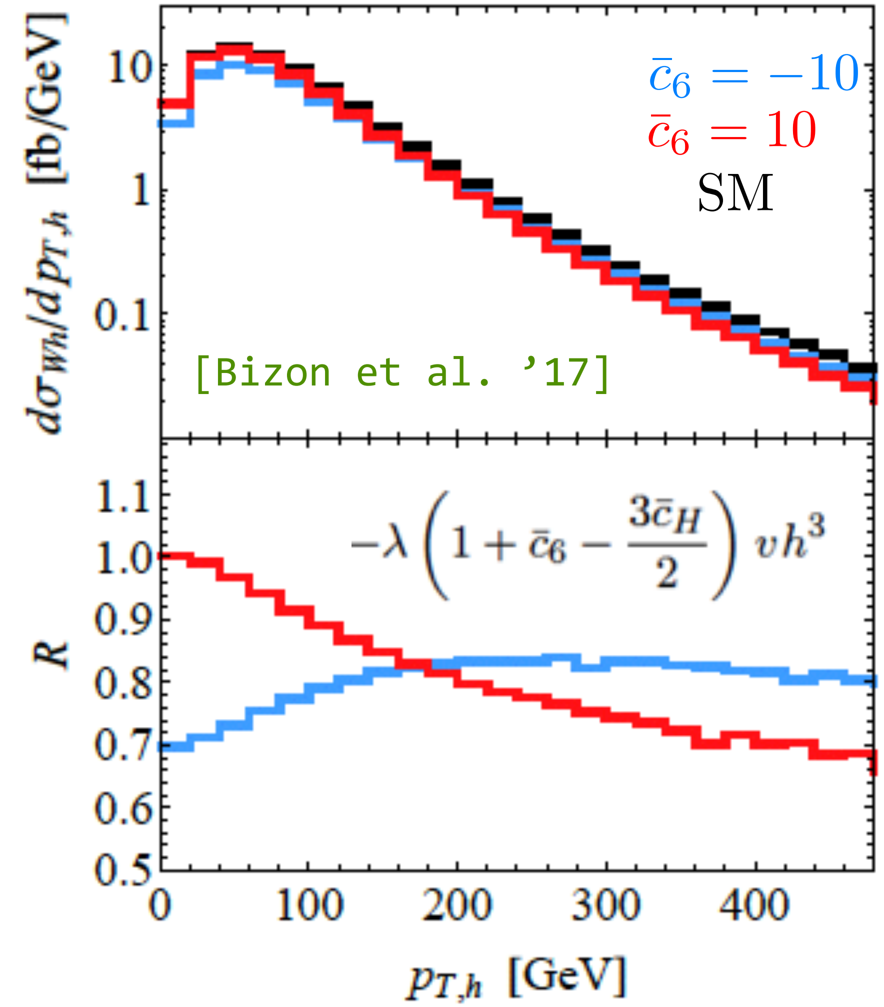
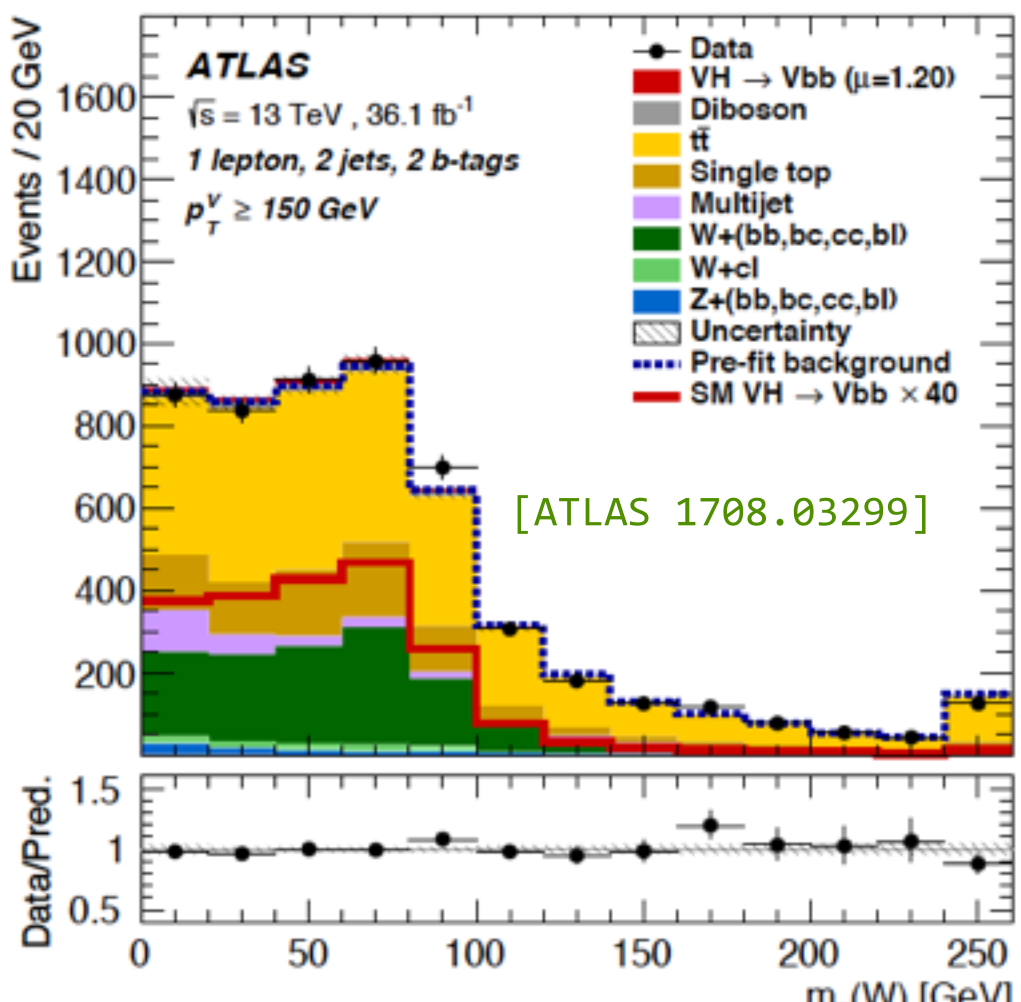
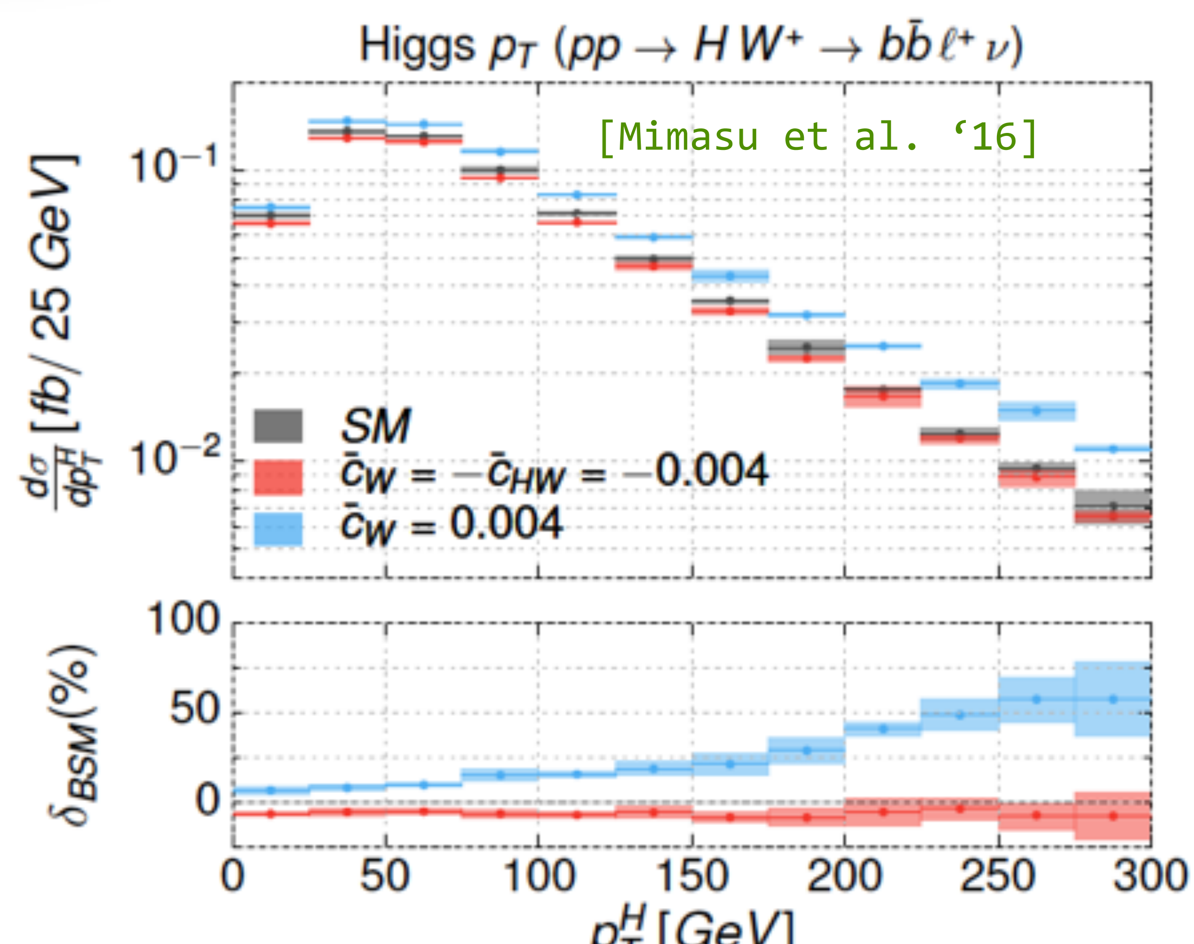
Boosted Higgs: VH(bb)

- Regions with large momentum transfer are more *sensitive* to BSM effects, e.g. higher-dimensional operators
- Large background due to top-pair production in single-lepton category reduced by applying a veto on extra (>2) jets







See also [Buschmann et al. '14]

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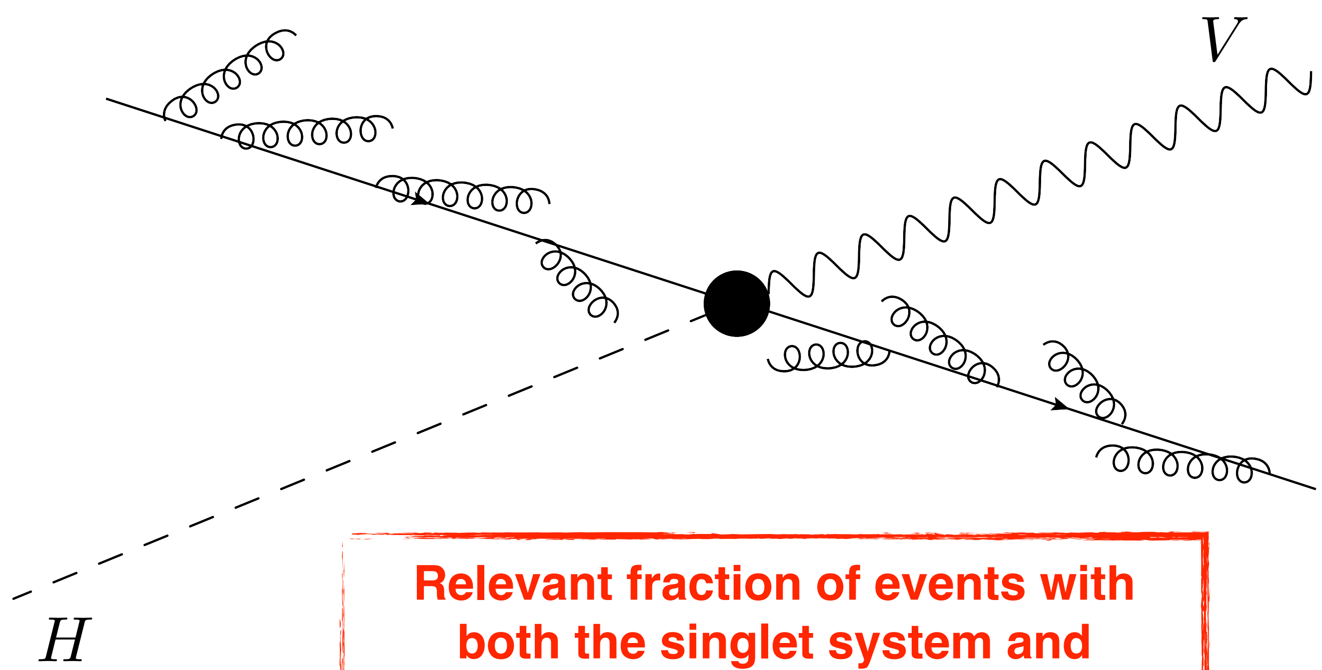
[ATLAS 1708.03299]



Relevant fraction of events with both the singlet system and accompanying jets at low pt

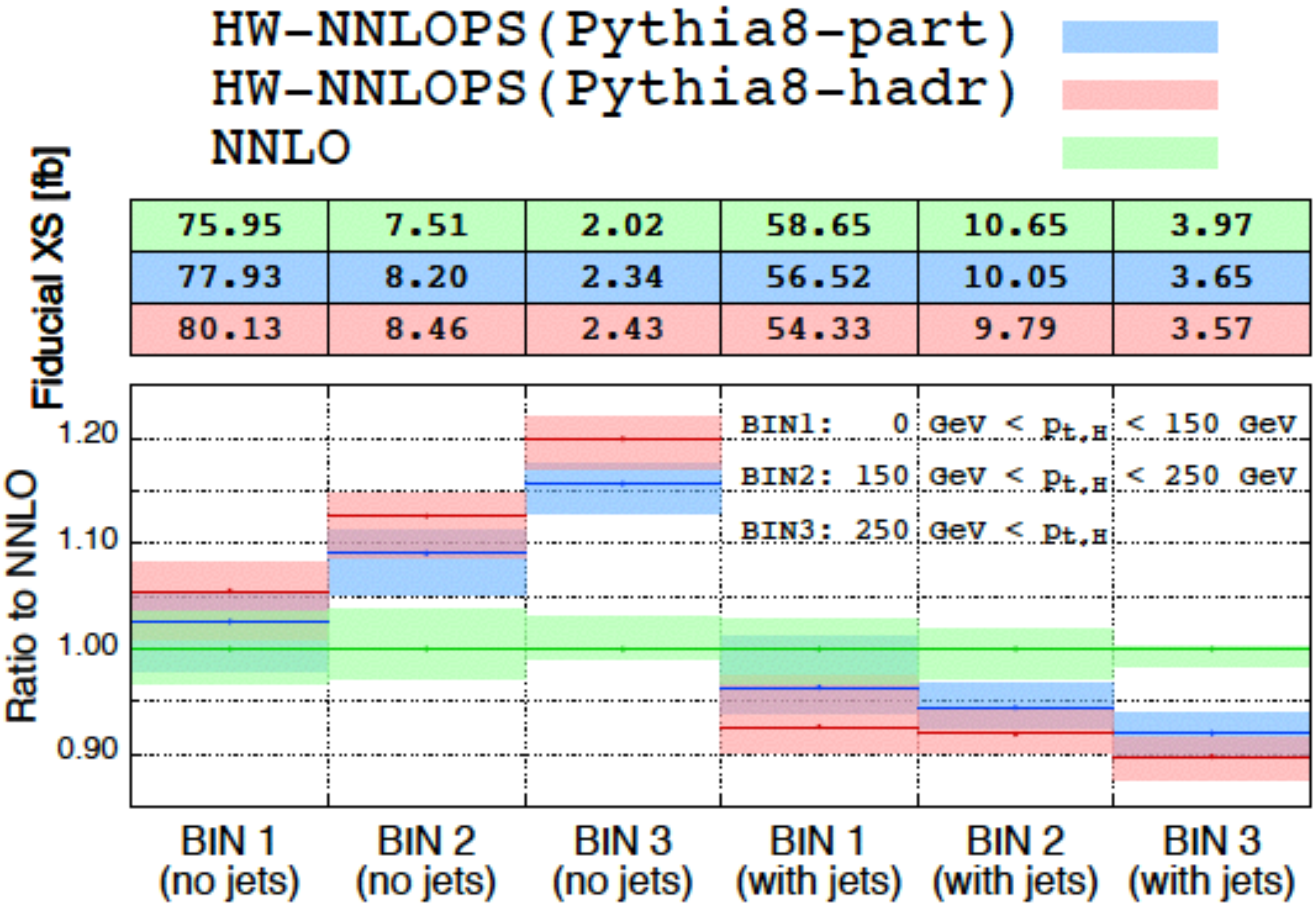
VARIABLES FOR MVA

Variable	0-lepton	1-lepton	2-lepton
p_T^V	$\equiv E_T^{miss}$	×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
m_{eff}	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
m_{top}		×	
$\lvert\Delta Y(V, bb)\rvert$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

Selection	0-lepton	1-lepton e sub-channel	1-lepton μ sub-channel	2-lepton
Trigger	E_T^{miss}	Single lepton	E_T^{miss}	Single lepton
Leptons	0 loose leptons with $p_T > 7$ GeV	1 tight electron $p_T > 27$ GeV	1 medium muon $p_T > 25$ GeV	2 loose leptons with $p_T > 7$ GeV ≥ 1 lepton with $p_T > 27$ GeV
E_T^{miss}	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_T	> 20 GeV			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_T	> 45 GeV			
H_T	> 120 (2 jets), > 150 GeV (3 jets)	–		–
$\min[\Delta\phi(E_T^{miss}, \text{jets})]$	$> 20°$ (2 jets), $> 30°$ (3 jets)	–		–
$\Delta\phi(E_T^{miss}, bb)$	$> 120°$	–		–
$\Delta\phi(b_1, b_2)$	$< 140°$	–		–
$\Delta\phi(E_T^{miss}, E_{T,trk}^{miss})$	$< 90°$	–		–
p_T^V regions	> 150 GeV			(75, 150] GeV, > 150 GeV
Signal regions	✓	$m_{bb} \geq 75$ GeV or $m_{top} \leq 225$ GeV		Same-flavour leptons Opposite-sign charge ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{top} > 225$ GeV		Different-flavour leptons

Boosted Higgs: VH(bb)

[Astill, Bizon, Re, Zanderighi ‘16]

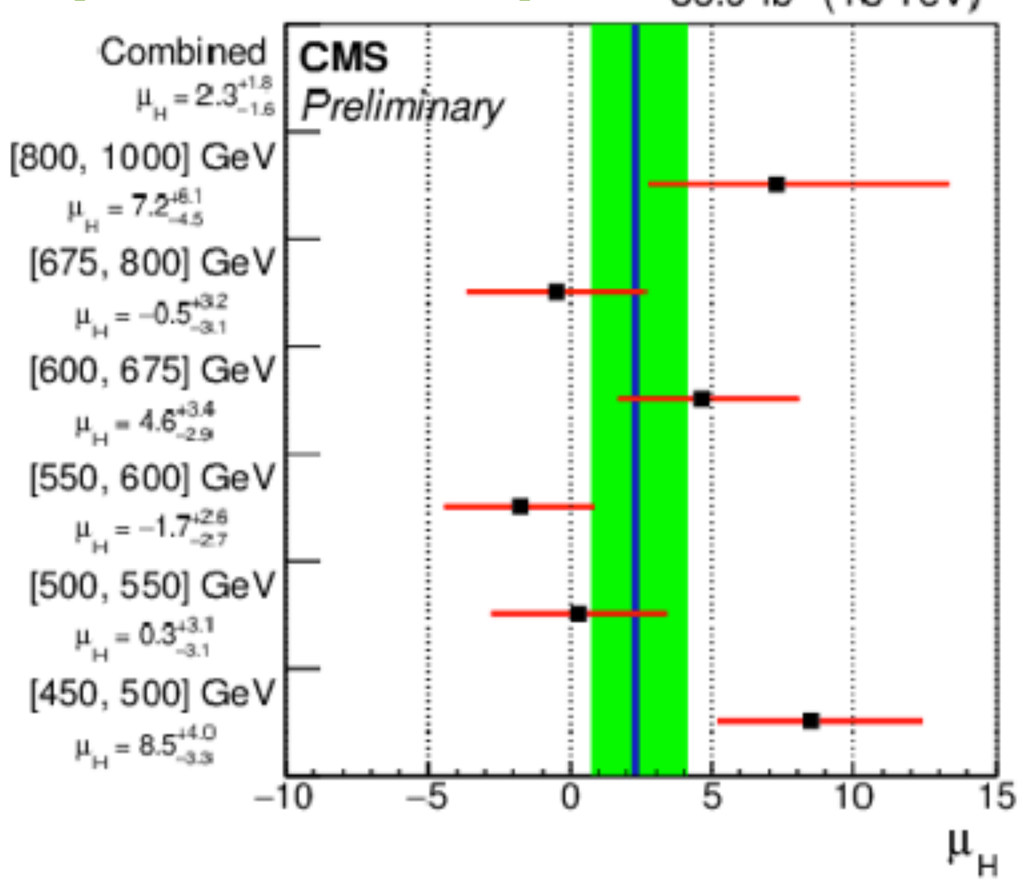


- Generators predict 10-20% corrections to NNLO from parton shower.
  Are these all-order effects under control ?

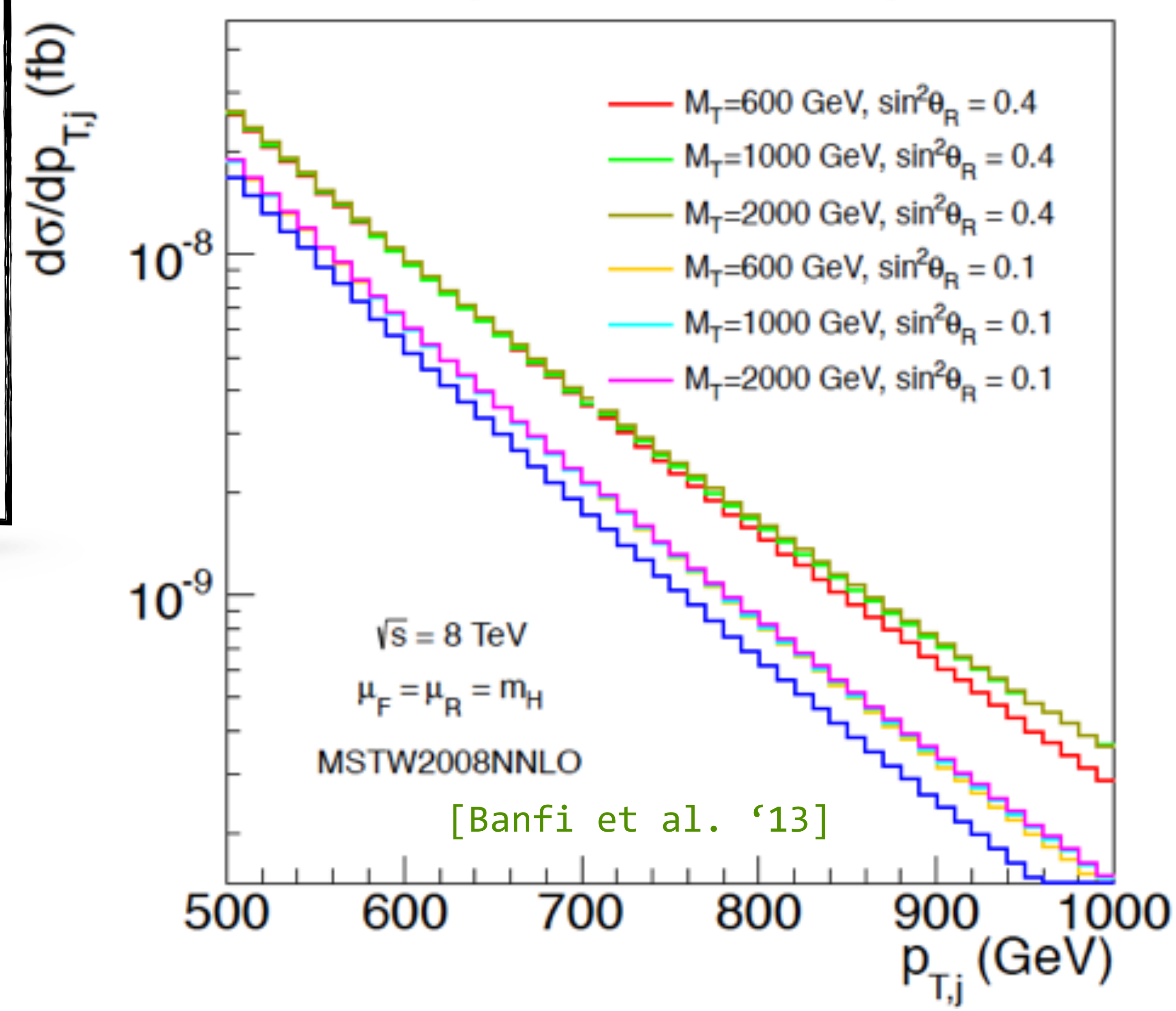
Boosted Higgs: gluon fusion

- Inclusive Higgs at high pt can probe indirectly virtual heavy states in the loop (failure of HEFT picture)
- Sensitivity increased through interference with the top loop + very low background
- Recently first measurement from CMS in this transverse momentum region

[CMS-PAS-HIG-17-010]



$$h\bar{t}t : \frac{m_t}{v}\cos^2(\theta_R), \quad h\overline{T}T : \frac{M_T}{v}\sin^2(\theta_R)$$

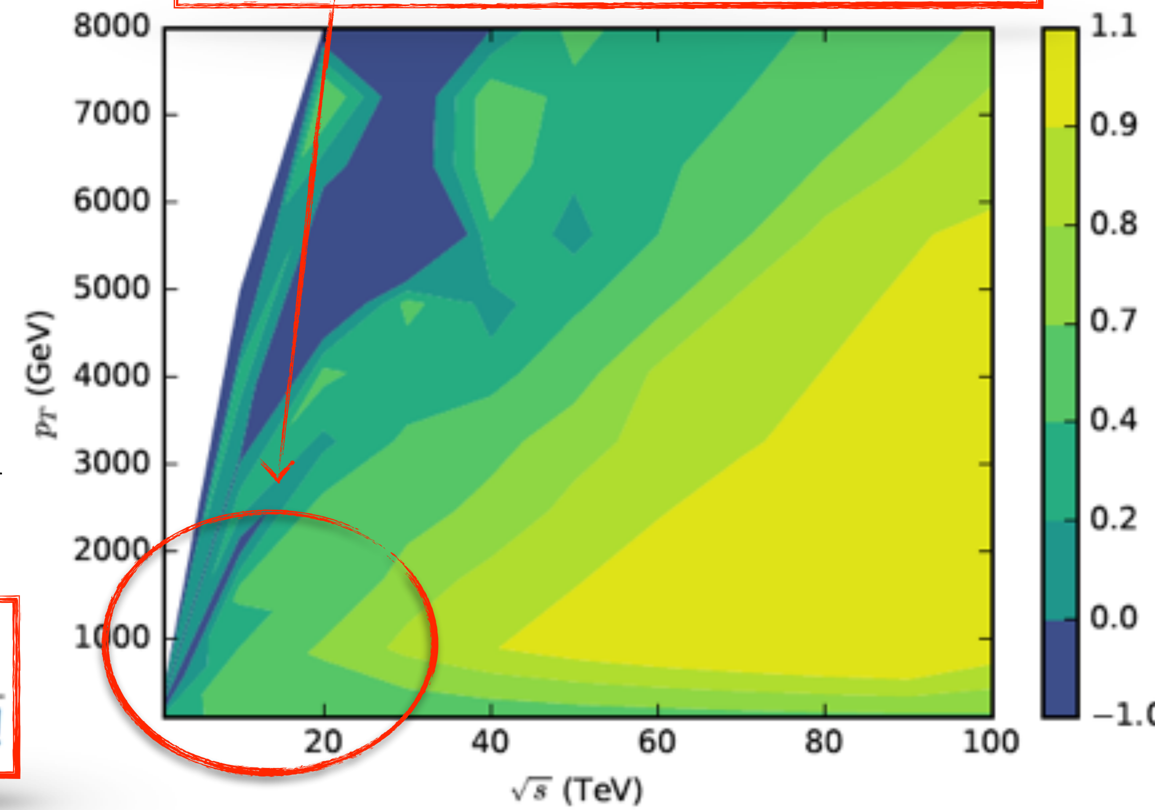


[Banfi et al. '13]

Up to very recently, no complete result beyond LO was available. Important to assess the size of radiative corrections

Boosted Higgs: small-x limit

- Ratio of NLO correction in HE limit to its full result, both in the large mt approximation
- HE approx accurate only within ~30-40% at 13 TeV LHC



[Caola et al. '16]

- Boosted region can be approximated in the high-energy limit, i.e.

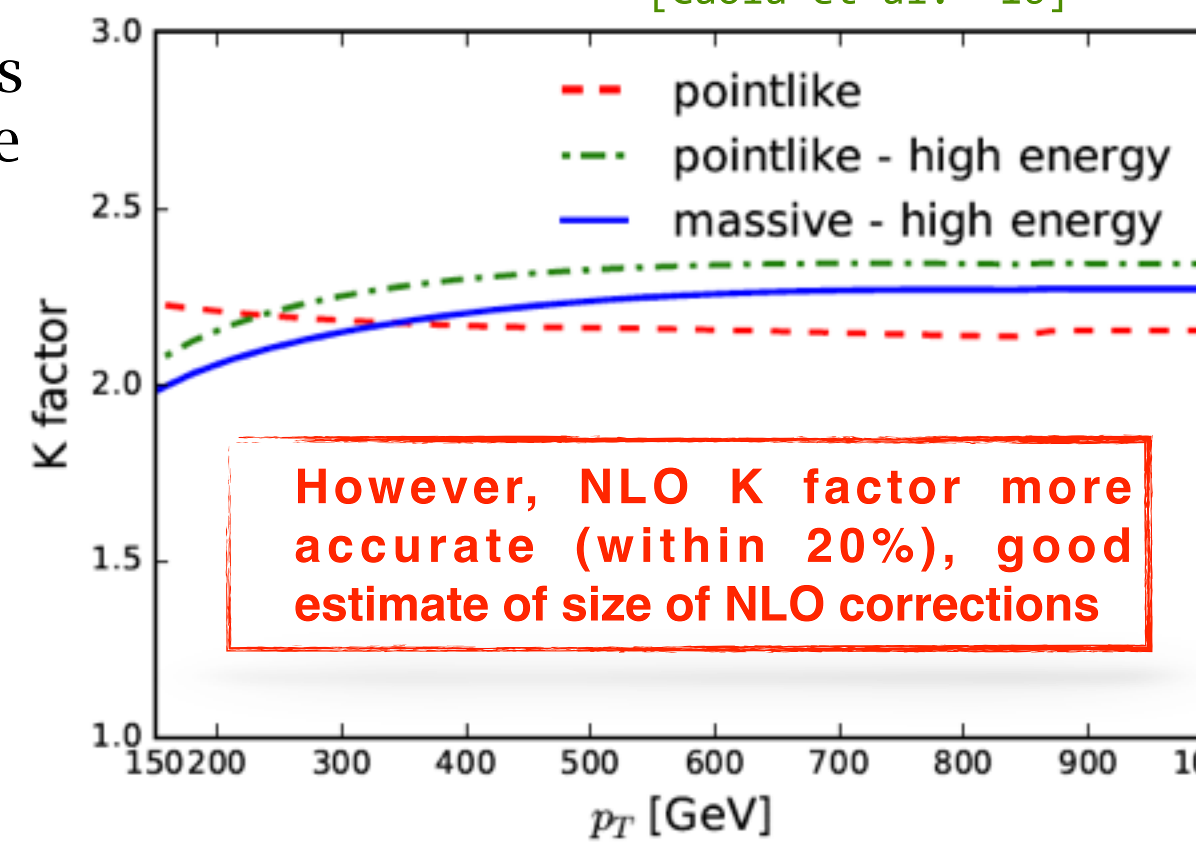
$$x = \frac{(\sqrt{m_H^2 + p_t^2} + p_t)^2}{\hat{s}} \ll 1$$

- Use expansion of the LL result to estimate NLO K factor

$$\boxed{\frac{d\sigma}{d\xi_p}(x, \xi_p, y_t, y_b) = \sigma_0(y_t, y_b) \sum_{k=1}^{\infty} C_k(\xi_p, y_t, y_b)\, \alpha_s^k (-1)^{k+1} \frac{\ln^{k-1} x}{(k-1)!}}$$

- Hard to estimate uncertainties reliably, but this provides a recipe to treat this region with more exclusive generators

- Scaling also observed in multijet-merged MC predictions, very recently confirmed by the full NLO at large transverse momentum



See talks by K. Melnikov and C. Wever

See, e.g., also talk by F. Caola at https://indico.cern.ch/event/675782/

Conclusions

- Several progresses in different aspects of resummation in the past few years
- Much more is to be done to keep up with the huge progress in fixed-order calculations and precise experimental data
- Inclusive observables (total XS, *two-scale* differential distributions) well known today, uncertainties under good control
- A lot of work and ideas still needed to handle multi-scale problems (masses, double differential) at all orders simultaneously
- Still *far* from understanding exclusive, multi-leg problems (e.g. VBF + 3j veto) with high perturbative (logarithmic) accuracy. Some progress recently in simpler observables
    - Exploiting synergy between available techniques could offer a way to explore new problems.

Momentum-space resummation

- The resummed differential distribution reads

$$\frac{d\Sigma(v)}{dp_t d\Phi_B} = \int_{\mathcal{C}_1} \frac{dN_1}{2\pi i} \int_{\mathcal{C}_2} \frac{dN_2}{2\pi i} x_1^{-N_1} x_2^{-N_2} \sum_{c_1,c_2} \frac{d|M_B|^2_{c_1 c_2}}{d\Phi_B} \mathbf{f}^T_{N_1}(\mu_0) \frac{d\hat{\mathbf{\Sigma}}^{c_1,c_2}_{N_1,N_2}(v)}{dp_t} \mathbf{f}_{N_2}(\mu_0)$$

DGLAP anomalous dimensions

e.g. for all inclusive observables with a=1 (pt, phi*,…):

$$\begin{aligned}
\hat{\mathbf{\Sigma}}^{c_1,c_2}_{N_1,N_2}(v) = & \left[\mathbf{C}^{c_1;T}_{N_1}(\alpha_s(\mu_0)) H(\mu_R) \mathbf{C}^{c_2}_{N_2}(\alpha_s(\mu_0))\right] \int_0^M \frac{dk_{t1}}{k_{t1}} \int_0^{2\pi} \frac{d\phi_1}{2\pi} \\
& \times e^{-\mathbf{R}(\epsilon k_{t1})} \exp\left\{ -\sum_{\ell=1}^{2} \left(\int_{\epsilon k_{t1}}^{\mu_0} \frac{dk_t}{k_t} \frac{\alpha_s(k_t)}{\pi} \mathbf{\Gamma}_{N_\ell}(\alpha_s(k_t)) + \int_{\epsilon k_{t1}}^{\mu_0} \frac{dk_t}{k_t} \mathbf{\Gamma}^{(C)}_{N_\ell}(\alpha_s(k_t)) \right) \right\} \\
& \sum_{\ell_1=1}^{2} \left(\mathbf{R}'_{\ell_1}(k_{t1}) + \frac{\alpha_s(k_{t1})}{\pi} \mathbf{\Gamma}_{N_{\ell_1}}(\alpha_s(k_{t1})) + \mathbf{\Gamma}^{(C)}_{N_{\ell_1}}(\alpha_s(k_{t1})) \right) \\
& \times \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_\epsilon^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} \sum_{\ell_i=1}^{2} \left(\mathbf{R}'_{\ell_i}(k_{ti}) + \frac{\alpha_s(k_{ti})}{\pi} \mathbf{\Gamma}_{N_{\ell_i}}(\alpha_s(k_{ti})) + \mathbf{\Gamma}^{(C)}_{N_{\ell_i}}(\alpha_s(k_{ti})) \right) \\
& \times \Theta\left(v - V(\{\tilde{p}\}, k_1, \dots, k_{n+1})\right),
\end{aligned}$$

RGE evolution of coeff. functions

- Formulation equivalent to b-space result, up to a scheme change. Using the delta representation one finds

$$\frac{d\Sigma(v)}{dp_t d\Phi_B} = \int_{\mathcal{C}_1} \frac{dN_1}{2\pi i} \int_{\mathcal{C}_2} \frac{dN_2}{2\pi i} x_1^{-N_1} x_2^{-N_2} \sum_{c_1,c_2} \frac{d|M_B|^2_{c_1 c_2}}{d\Phi_B} \mathbf{f}^T_{N_1}(\mu_0) \frac{d\hat{\mathbf{\Sigma}}^{c_1,c_2}_{N_1,N_2}(v)}{dp_t} \mathbf{f}_{N_2}(\mu_0) =$$

$$\boxed{(1 - J_0(bk_t)) \simeq \Theta(k_t - \frac{b_0}{b}) + \frac{\zeta_3}{12} \frac{\partial^3}{\partial \ln(Mb/b_0)^3} \Theta(k_t - \frac{b_0}{b}) + \dots}$$

$$\begin{aligned}
= & \sum_{c_1,c_2} \frac{d|M_B|^2_{c_1 c_2}}{d\Phi_B} \int b\, db\, p_t J_0(p_t b)\, \mathbf{f}^T(b_0/b) \mathbf{C}^{c_1;T}_{N_1}(\alpha_s(b_0/b)) H(M) \mathbf{C}^{c_2}_{N_2}(\alpha_s(b_0/b)) \mathbf{f}(b_0/b) \\
& \times \exp\left\{ -\sum_{\ell=1}^{2} \int_0^M \frac{dk_t}{k_t} \mathbf{R}'_\ell(k_t) (1 - J_0(bk_t)) \right\}.
\end{aligned}$$

Momentum-space resummation

- Since $k_{ti}/k_{t1} = \zeta_i = \mathcal{O}(1)$ we can expand (although unnecessary) the integrands about $k_{ti} \sim k_{t1}$ to the desired accuracy for a more efficient evaluation
- At N3LL, only two resolved, hard-collinear emissions are relevant: Mellin inversion is analytic

$$\int d\mathcal{Z}[\{R', k_i\}] G(\{\tilde{p}\}, \{k_i\}) = \epsilon^{R'(k_{t1})} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=2}^{n+1} \int_{\epsilon}^{1} \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} R'(k_{t1}) G(\{\tilde{p}\}, k_1, \ldots, k_{n+1})$$

$$\frac{d\Sigma(v)}{d\Phi_B} = \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} \partial_L \left(-e^{-R(k_{t1})} \mathcal{L}_{\mathrm{N^3LL}}(k_{t1})\right) \int d\mathcal{Z}[\{R', k_i\}] \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1})\right)$$

$$+ \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} e^{-R(k_{t1})} \int d\mathcal{Z}[\{R', k_i\}] \int_0^1 \frac{d\zeta_s}{\zeta_s} \frac{d\phi_s}{2\pi} \Big\{ \left(R'(k_{t1}) \mathcal{L}_{\mathrm{NNLL}}(k_{t1}) - \partial_L \mathcal{L}_{\mathrm{NNLL}}(k_{t1}) \right)$$
$$\times \left(R''(k_{t1}) \ln \frac{1}{\zeta_s} + \frac{1}{2} R'''(k_{t1}) \ln^2 \frac{1}{\zeta_s} \right) - R'(k_{t1}) \left(\partial_L \mathcal{L}_{\mathrm{NNLL}}(k_{t1}) - 2 \frac{\beta_0}{\pi} \alpha_s^2(k_{t1}) \hat{P}^{(0)} \otimes \mathcal{L}_{\mathrm{NLL}}(k_{t1}) \ln \frac{1}{\zeta_s} \right)$$
$$+ \frac{\alpha_s^2(k_{t1})}{\pi^2} \hat{P}^{(0)} \otimes \hat{P}^{(0)} \otimes \mathcal{L}_{\mathrm{NLL}}(k_{t1}) \Big\} \Big\{ \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1}, k_s)\right) - \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1})\right) \Big\}$$

$$+ \frac{1}{2} \int \frac{dk_{t1}}{k_{t1}} \frac{d\phi_1}{2\pi} e^{-R(k_{t1})} \int d\mathcal{Z}[\{R', k_i\}] \int_0^1 \frac{d\zeta_{s1}}{\zeta_{s1}} \frac{d\phi_{s1}}{2\pi} \int_0^1 \frac{d\zeta_{s2}}{\zeta_{s2}} \frac{d\phi_{s2}}{2\pi} R'(k_{t1})$$
$$\times \Big\{ \mathcal{L}_{\mathrm{NLL}}(k_{t1}) \left(R''(k_{t1})\right)^2 \ln \frac{1}{\zeta_{s1}} \ln \frac{1}{\zeta_{s2}} - \partial_L \mathcal{L}_{\mathrm{NLL}}(k_{t1}) R''(k_{t1}) \left(\ln \frac{1}{\zeta_{s1}} + \ln \frac{1}{\zeta_{s2}} \right)$$
$$+ \frac{\alpha_s^2(k_{t1})}{\pi^2} \hat{P}^{(0)} \otimes \hat{P}^{(0)} \otimes \mathcal{L}_{\mathrm{NLL}}(k_{t1}) \Big\}$$
$$\times \Big\{ \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1}, k_{s1}, k_{s2})\right) - \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1}, k_{s1})\right) -$$
$$\Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1}, k_{s2})\right) + \Theta\left(v - V(\{\tilde{p}\}, k_1, \ldots, k_{n+1})\right) \Big\} + \mathcal{O}\left(\alpha_s^n \ln^{2n-6} \frac{1}{v}\right)$$

- This formula can be evaluated by means of fast Monte-Carlo methods (RadISH)
- Coefficient functions and hard-virtual corrections absorbed into the parton luminosity
- Valid for all inclusive observables with a=1. A similar formula holds for any a>0

$$V(\{\tilde{p}\}, k) \equiv V(k) = d_\ell \, g_\ell(\phi) \left(\frac{k_t}{M}\right)^a$$

$$V(\{\tilde{p}\}, k_1, \ldots, k_n) = V(\{\tilde{p}\}, k_1 + \cdots + k_n)$$