the Higgs boson transverse-momentum distribution: a review

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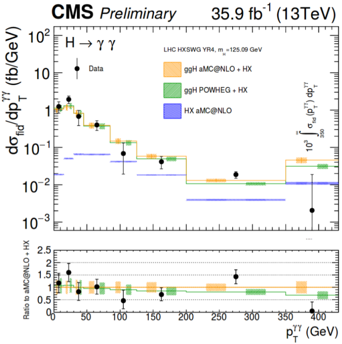
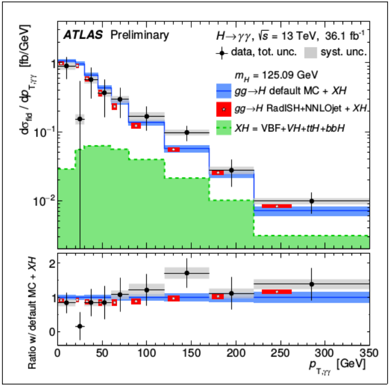
outline

- precision in Higgs physics is a crucial topic for Run II and beyond
  - measurements of differential distributions will be at the core of it
  - among them, certainly the Higgs-boson transverse momentum is a crucial one
  - it's relatively "easy" to measure
  - perhaps the more straightforward way to probe BSM Physics in the Higgs sector (by looking at the SM-like Higgs only)
- this talk: selection of recent theoretical results (mostly for gluon-fusion)

1. intermediate region: fixed-order results in pQCD
2. small $p_{\mathrm{T,H}}$
3. boosted Higgs



$p_{\mathrm{T,H}}$ from gluon fusion



INTERMEDIATE REGION

- for 30 GeV $\lesssim p_{\mathrm{T,H}} \lesssim m_t$, perturbation theory can be used safely, and HEFT works.

SMALL $p_{\mathrm{T,H}}$

- the Higgs boson is typically produced with $p_{\mathrm{T,H}} \sim 15$ GeV.
- to describe this region properly, needs to resum logarithms of $m_{\mathrm{H}}/p_{\mathrm{T}}$ at all orders.
- data in this region can be used to set bounds on light-quarks Yukawa, provided that the theory predictions are accurate enough.

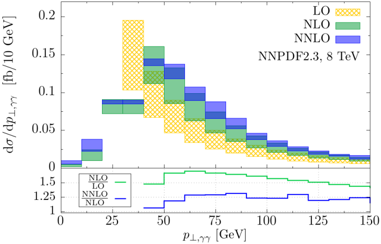
BOOSTED REGION

- when $p_{\mathrm{T,H}} > m_t$, the top quark cannot be considered infinitely heavy. Perturbation theory can be used, but HEFT doesn't hold: top-mass dependence needed!
- data in this region can be used to study heavy BSM particles, as a boosted Higgs can resolve loop effects from heavy BSM partices.

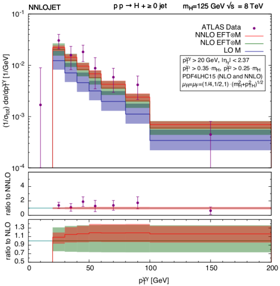
the Higgs p_T distribution: intermediate region

✓ $p_{\mathrm{T,H}}$ [& $p_{\mathrm{T,j_1}}$] known at NNLO fully differentially, including decays (in the HEFT)

- 3 different NNLO methods! [Boughezal,Caola et al. ’15; Boughezal et al. ’15; Chen et al. ’16]



. cut on $p_{T,j}$



.cut on $p_{T,H}$

+ large and non-flat NNLO/NLO K-factors
+ reduced TH uncertainties ($\mathcal{O}(10-15\%)$)
+ data/theory improves

- fully-inclusive $p_{\mathrm{T,H}}$ spectrum also known fully analytically at NLO [Dulat et al. ’17]
- HEFT is used: this means that when $p_{\mathrm{T,H}} > m_t$, the result starts to become more and more unreliable...more about this later.

the Higgs p_T distribution: Sudakov region

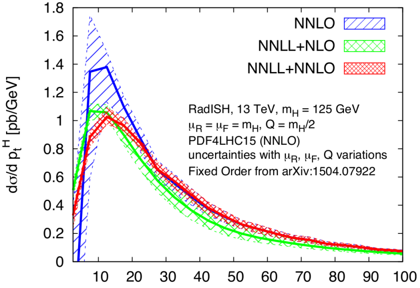
- small $p_{\mathrm{T}} \Rightarrow$ logarithms of $m_{\mathrm{H}}/p_{\mathrm{T}}$ at all orders
- resummation at NLO+NNLL (NNLO inclusive) known in various approaches

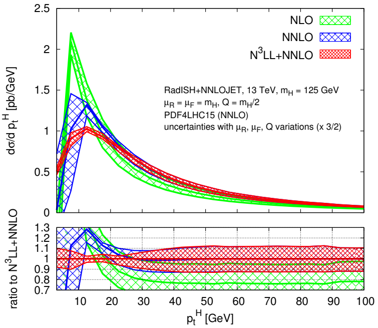
  [Bozzi,Catani et al.; Becher et al.] + [joint resumm: Marzani '15; Muselli et al. '17]

- in arXiv:1705.09127 and arXiv:1604.02191 we have developed a new method to resum transverse observables in momentum space.

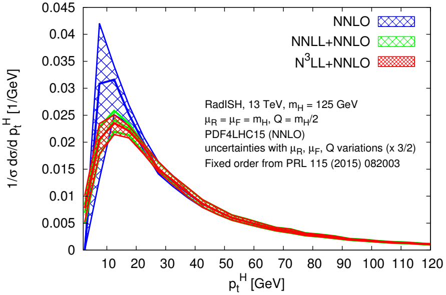
  [Monni,ER,Torrielli '16][Bizon,Monni,ER,Rottoli,Torrielli '17]

- obtained NNLL and N3LL results matched to NNLO for $p_{\mathrm{T,H}}$. Total normalization: N3LO.





$p_{\mathrm{T,H}}$ at N3LL+NNLO



- NNLO matching ($\sigma^{\mathrm{N3LO}}_{pp\to H}$, $d\sigma^{\mathrm{NNLO}}_{pp\to Hj}/dp_{\mathrm{T}}$)
- N3LO from Anastasiou et al., '15
- $pp \to Hj$ at NNLO from Boughezal, Caola, et al., '15
- anomalous dimension from Li, Zhu '16, Vladimirov '16

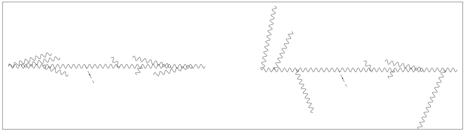
+ resummation: relevant below 30 GeV
+ medium-high p_{T}: matching to differential NNLO matters (as expected): + 10 % wrt NLO, reduced uncertainty bands.

- N3LL+NNLO corrections: few percent at peak, more sizeable below
- after matching at NNLO, only moderate reduction in uncertainty from NNLL to N3LL. Precise quantitative statement needs very stable NNLO distributions below peak.
- phenomenology: with this precision, perturbative uncertainty from resummation seems to saturate; including quark mass effects will be relevant to improve further.

[Melnikov,Penin '16; Melnikov et al. '16; Lindert et al. '17]

small $p_{\mathrm{T,H}}$ resummation in momentum space

- logarithmic accuracy usually defined at the level of the logarithm of the cumulative cross section Σ
$$\Sigma(p_{\mathrm{T,H}}) = \int_0^{p_{\mathrm{T}}} dp'_{\mathrm{T}} \frac{d\sigma}{dp'_{\mathrm{T}}} \sim \exp\{\alpha_{\mathrm{S}}^n L^{n+1} + \alpha_{\mathrm{S}}^n L^n + \alpha_{\mathrm{S}}^n L^{n-1} + \alpha_{\mathrm{S}}^n L^{n-2} + ...\}$$
for LL, NLL, NNLL, N3LL, where $L = \log(m_{\mathrm{H}}/p_{\mathrm{T,H}})$
- as $p_{\mathrm{T,H}}$ absorbs the recoil of all emissions k_{ti}, when $p_{\mathrm{T,H}} \to 0$, two mechanism compete:
  - Sudakov (exponential) suppression when $k_{ti} \sim p_{\mathrm{T,H}}$
  - azimuthal cancellations when $k_{ti} \gg p_{\mathrm{T,H}}$



- the latter mechanism is dominant when $p_{\mathrm{T,H}} \to 0$: $\Sigma(p_{\mathrm{T,H}}) \sim p_{\mathrm{T,H}}^2$ [Parisi,Petronzio '79]

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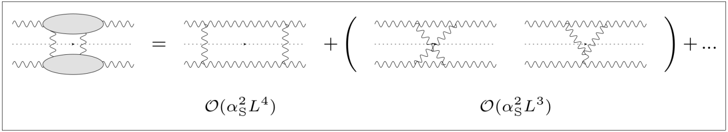
- hierarchy in $\log(m_{\mathrm{H}}/p_{\mathrm{T,H}})$ doesn't work, as neglected effects actually dominate the limit. It's impossible to recover power behaviour at any given order in L.
- Moreover, at any log order in $L = \log(m_{\mathrm{H}}/p_{\mathrm{T,H}})$, resummation in direct space cannot be, at the same time, free of subleading terms and of spurious singularities at finite $p_{\mathrm{T,H}}$ [Frixione,Nason,Ridolfi '98]
- when going in b-space, the vectorial nature of azimuthal cancellations is taken care by a Fourier transform

$$\delta^{(2)}(\vec{p_{\mathrm{T,H}}} - (\vec{k}_{t1} + ... + \vec{k}_{tn})) = \int \frac{d^2\vec{b}}{4\pi^2} e^{-i\vec{b}\cdot\vec{p}_t} \prod_{i=1}^{n} e^{-i\vec{b}\cdot\vec{k}_{ti}}$$

small $p_{\mathrm{T,H}}$ resummation in momentum space

Our approach:

- Multiple-emission squared amplitude organised into "n-particle-correlated blocks":



- introduce a resolution scale ϵk_{t1} (not $\epsilon\, p_{\mathrm{T,H}}$)
  - emissions with $k_{ti} < \epsilon k_{t1}$ are unresolved. They don't contribute to the observable, and upon integration they regularise virtual corrections leaving a Sudakov factor

$$e^{-R(\epsilon k_{t1})} = e^{-R(k_{t1}) - \log(1/\epsilon) R'(k_{t1}) + \ldots}$$

  - emissions above ϵk_{t1} are resolved, hence are treated exclusively (they are used to compute the observable!). This is done through a MC.
  - ϵ dependence in the resolved emissions cancel against the one in the Sudakov!
- Resolved k_{ti} are not necessarily $\sim p_{\mathrm{T,H}}$: all kinematics properly covered, without assumptions on the hierarchy between k_{ti} and $p_{\mathrm{T,H}}$.
- $k_{ti} \gg p_{\mathrm{T,H}}$ included. This also removes the spurious singularities at finite $p_{\mathrm{T,H}}$ and gives the correct power behaviour at $p_{\mathrm{T,H}} \to 0$

small $p_{\mathrm{T,H}}$ resummation in momentum space

the role of subleading terms

- logarithmic counting is defined in terms of $\log(m_{\mathrm{H}}/k_{ti})$.
- in the Sudakov limit, the hierarchy in $\log(m_{\mathrm{H}}/p_{\mathrm{T,H}})$ makes sense, one has $k_{ti} \sim p_{\mathrm{T,H}} \sim 0$.
  - same as resummation of $\log(m_{\mathrm{H}}/p_{\mathrm{T,H}})$, i.e. log accuracy in $\log(m_{\mathrm{H}}/k_{ti})$ translates into the same accuracy in $\log(m_{\mathrm{H}}/p_{\mathrm{T,H}})$, plus subleading terms.
- similar conclusions were found by Ebert and Tackmann, '16.

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some advantages with respect to b-space

- closer connections to a parton-shower formalism
- if observables have the same LL as p_{T}, then we can keep using the same resolution scale ϵk_{t1}, and compute all of them at the same time.
- might allow joint resummation

. ... I spare you the formula and the many checks we did. Among those, we were able to prove the equivalence to b-space.

. a code (named `RadISH`), performing all of the above, also for Drell-Yan, will be released soon. Some EXP groups have already used our results (up to NNLL+NNLO).

Multiplicative vs Additive Matching

$$\Sigma(p_{\rm T}, \Phi_B) = \int_0^{p_{\rm T}} dp'_{\rm T} \frac{d\sigma}{dp'_{\rm T} d\Phi_B} \qquad \begin{cases} \to \Sigma_{\rm res} & \text{if } p_{\rm T} \ll M_B \\ \to \Sigma_{\rm F.O.} & \text{if } p_{\rm T} \gtrsim M_B \end{cases}$$

---

additive matching

$$\Sigma^{add}_{\rm matched}(p_{\rm T}) = \Sigma_{\rm res}(p_{\rm T}) + \Sigma_{\rm F.O.}(p_{\rm T}) - \Sigma_{\rm res,exp}(p_{\rm T})$$

multiplicative matching

$$\Sigma^{mult}_{\rm matched}(p_{\rm T}) = \Sigma_{\rm res}(p_{\rm T}) \frac{\Sigma_{\rm F.O.}(p_{\rm T})}{\Sigma_{\rm res,exp}(p_{\rm T})}$$

- there's no rigorous theory argument to favour a prescription over the other

- additive: probably the more natural choice, simpler and clear
- numerically delicate when $p_{\rm T} \to 0$ (F.O. result needs to be extremely stable)

- multiplicative: numerically more stable, as physical suppression at small $p_{\rm T}$ fixes potentially unstable F.O. results
- allows to include constant terms from F.O.

Multiplicative vs Additive Matching

- for $p_{\mathrm{T,H}}$ at N3LL, used mult. matching: constant terms at $\mathcal{O}(\alpha_{\mathrm{S}}^3)$ recovered *without* the need of knowing analytically coefficient and hard functions.

$$\Sigma_{\mathrm{F.O.}} = \sigma_{pp\to H}^{\mathrm{N3LO}} - \int_{p_{\mathrm{T}}} dp'_{\mathrm{T}} \frac{d\sigma_{pp\to Hj}^{\mathrm{NNLO}}}{dp'_{\mathrm{T}}}$$

- in additive matching, one would instead need $C^{(3)}$ and $H^{(3)}$ in effective luminosity $\mathcal{L}_{\mathrm{N^3LL}}$
- to estimate higher-order logarithmic corrections, introduce resummation scale Q:

$$L \equiv \ln \frac{M}{k_{\mathrm{T},1}} = \ln \frac{Q}{k_{\mathrm{T},1}} - \ln \frac{Q}{M}$$

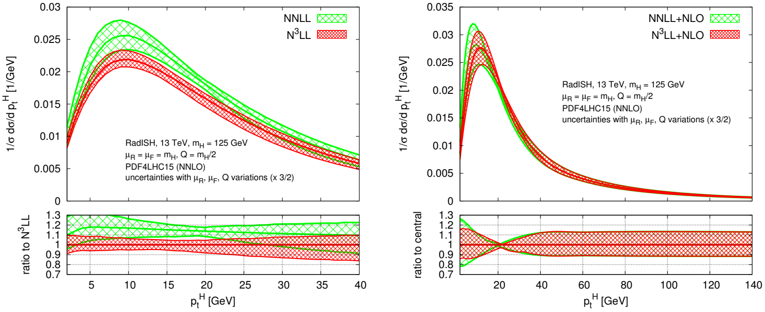
and then vary Q, making sure that the first term is larger than the second, as we are in fact expanding about $\ln(Q/k_{\mathrm{T},1})$.

- in resummation formula, use replacement above in Sudakov and parton densities. Expand about $\ln Q/k_{\mathrm{T},1}$ and reabsorb $\ln Q/M$ in H and C functions, entering the generalized luminosities

$$H^{(1)}(\mu_R) \to \tilde{H}^{(1)}(\mu_R, x_Q) = H^{(1)}(\mu_R) + \left(-\frac{1}{2}A^{(1)}\ln x_Q^2 + B^{(1)}\right)\ln x_Q^2, \quad x_Q = Q/M.$$

$$C_{ij}^{(1)}(z) \to \tilde{C}_{ij}^{(1)}(z, \mu_F, x_Q) = C_{ij}^{(1)}(z) + \hat{P}_{ij}^{(0)}(z)\ln\frac{x_Q^2 M^2}{\mu_F^2}$$

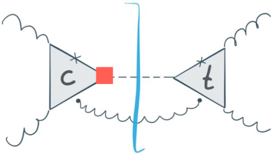
Impact of N3LL resummation



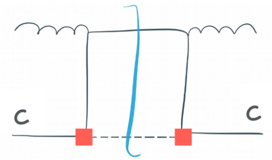
- here $Q = m_H/2$
- LEFT: pure resummation at N3LL vs NNLL
  - pure N3LL correction amounts to 10-15% (partially due to inclusion of $C^{(2)}$ and $H^{(2)}$, which, in this plot, are not included in NNLL).
  - more importantly: reduction of theoretical uncertainty from NNLL to N3LL.
- RIGHT: NLO matching ($\sigma^{\rm NNLO}_{pp\to H}$, $d\sigma^{\rm NLO}_{pp\to Hj}/dp_{\rm T}$)
  - N3LL+NLO correction: about 10% at peak, a bit larger below.
  - perturbative uncertainty halved below 10 GeV, unchanged elsewhere.

Higgs p_T and light-quarks Yukawa

- differential distributions affected by interference among top and light-quarks loops
  - medium-to-low $p_{\mathrm{T,H}}$ spectrum $\Rightarrow$ bounds on charm Yukawa [Bishara,Haisch,Monni,ER '16]
  [& similar ideas in [Soreq et al. '16]]



$$\sim \alpha_S^3 \;\; \kappa_c \;\; \left(\frac{m_c}{m_{\mathrm{H}}}\right)^2 \;\log^2\left(\frac{p_{\mathrm{T}}^2}{m_c^2}\right)$$



$$\sim \alpha_S^2 \;\; \kappa_c^2 \;\; \left(\frac{m_c}{m_h}\right)^2$$

. one power of α_S from charm PDF

. $c\bar{c} \to hg$ also included

- different κ_c scaling + log scaling $\Rightarrow$ shape distorsion

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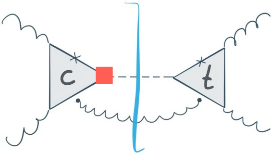
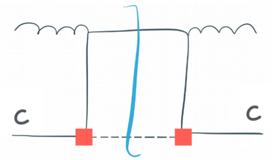


$$\sim \alpha_S^3 \, \boxed{\kappa_c} \left(\frac{m_c}{m_{\mathrm{H}}}\right)^2 \log^2\left(\frac{p_{\mathrm{T}}^2}{m_c^2}\right)$$



$$\sim \alpha_S^2 \, \boxed{\kappa_c^2} \left(\frac{m_c}{m_h}\right)^2$$

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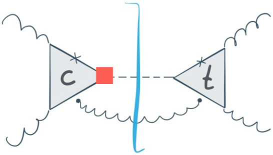
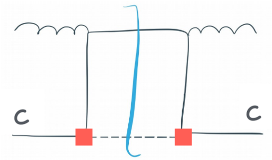


$$\sim \alpha_S^3 \, \kappa_c \left(\frac{m_c}{m_{\mathrm{H}}}\right)^2 \log^2\left(\frac{p_{\mathrm{T}}^2}{m_c^2}\right)$$

. non-Sudakov double log for $m_c < p_T < m_{\mathrm{H}}$



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- different κ_c scaling + log scaling $\Rightarrow$ shape distortion

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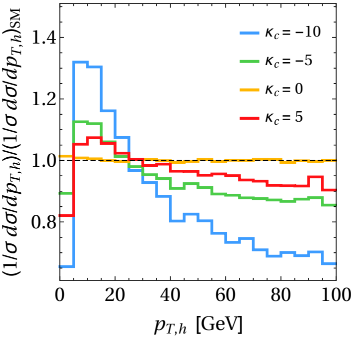

- different κ_c scaling + log scaling $\Rightarrow$ shape distorsion
- use normalized distribution to reduce uncertainties

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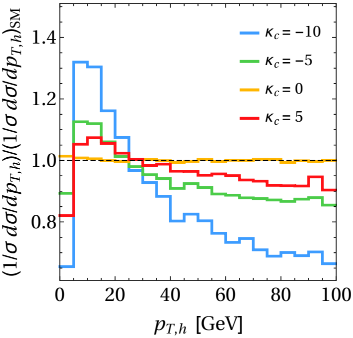

results:

+ ATLAS data & $\leq$ 10 % TH uncertainty
  - $\boxed{\kappa_c \in [-16, 18]}$
+ 300 fb^{-1}, assuming syst (exp) 3% & theory 5%
  - $\boxed{\kappa_c \in [-1.4, 3.8]}$

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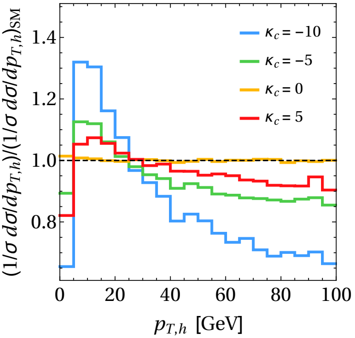

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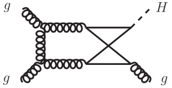
- $\boxed{\text{method mainly limited by TH precision}}$ $\rightarrow$ **bottleneck**: $p_{\mathrm{T,H}}$ spectrum at NLO with mass effects

$p_{\mathrm{T,H}}$ and b-mass effects

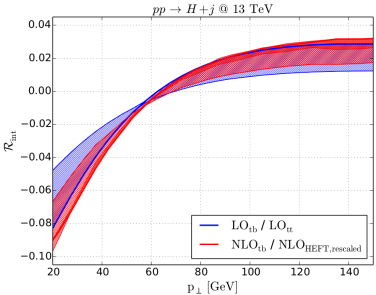
✓ top-bottom interference with mass effects now known at NLO

[Melnikov et al. '16 '17; Lindert,Melnikov et al. '17]

$$d\sigma_{tb}^{\mathrm{virt}} \sim \mathrm{Re}\Big\{ A_t^{\mathrm{LO}} A_b^{\mathrm{LO}*} + \frac{\alpha_S}{2\pi}\left(A_t^{\mathrm{NLO}} A_b^{\mathrm{LO}*} + A_t^{\mathrm{LO}} A_b^{\mathrm{NLO}*} \right) \Big\}$$

$A_b^{\mathrm{NLO}} \rightarrow$  + ...

$$(m_b/p_{\mathrm{T,H}}) \ll 1$$



$$\mathcal{R}_{int}(\mathcal{O}) = \frac{\int d\sigma_{tb}\delta(\mathcal{O}-\mathcal{O}(\Phi))}{\int d\sigma_{tt}\delta(\mathcal{O}-\mathcal{O}(\Phi))}$$

- neglected all the terms that are power-suppressed in the $m_b \rightarrow 0$ limit, kept all the non-analytic $\mathcal{O}(\log(m_b))$ terms.
+ NLO corrections to t-b interference sizeable ($\mathcal{O}(40\%)$)
+ same shape and size of NLO correction for t-t
+ NLO leads to reduction of (renorm.) scheme ambiguity for m_b, especially $p_{\mathrm{T,H}} < 60$ GeV

$p_{\mathrm{T,H}}$ and b-mass effects

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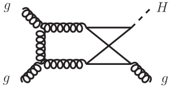
$A_b^{\mathrm{NLO}} \rightarrow$  + ...

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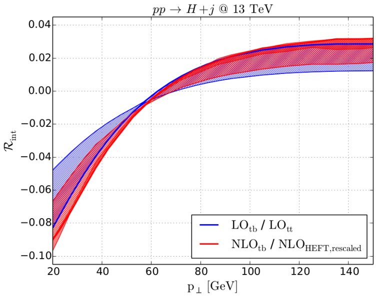

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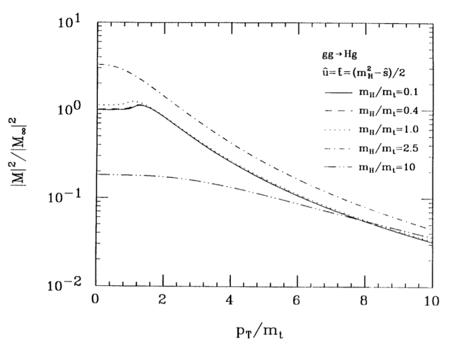
- neglected all the terms that are power-suppressed in the $m_b \to 0$ limit, kept all the

- ▶ this is a very important result (see later).
- ▶ a dedicated study to assess more quantitatively the prospect on setting bounds on light Yukawa couplings is now possible.

+ NLO leads to reduction of (renorm.) scheme ambiguity for m_b, especially $p_{\mathrm{T,H}} < 60$ GeV

boosted Higgs and finite mass effects

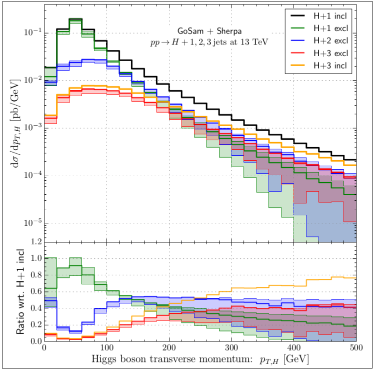
- a boosted Higgs can resolve loop effects from heavy BSM particles
  [Banfi et al. '13; Grojean et al. '13; Azatov et al. '13; ...]
- but need to know exact mass effects in the SM!
- exact NLO not yet known (because 2-loop amplitudes not yet known).
  planar masters computed [Bonciani et al. '16]
- at LO it is known that, at high $p_{\mathrm{T,H}}$, heavy-top EFT significantly overestimates the correct distribution.



plot from [Baur,Glover 1989]

boosted Higgs and finite mass effects

- Several approximation to the full result have been proposed



- differential NLO HEFT + LO exact masses up to H+3 jets [Greiner et al. '15-'16]

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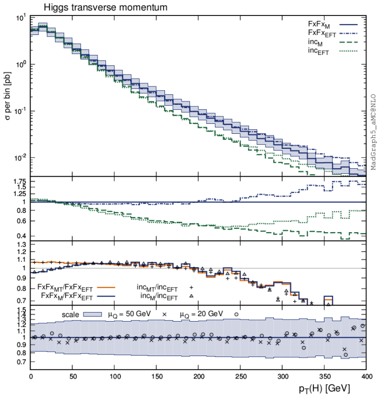

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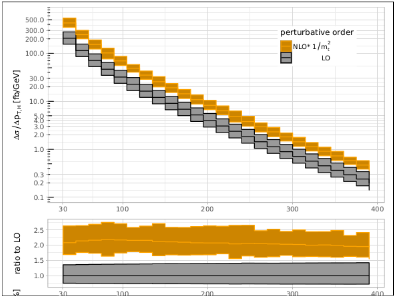

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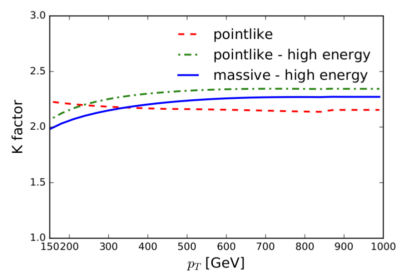

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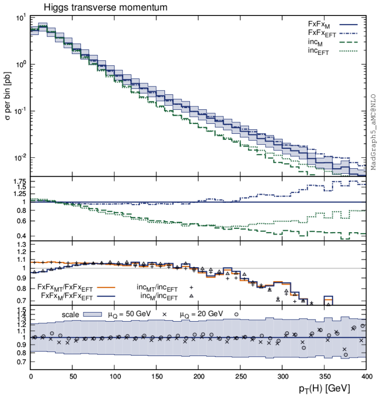

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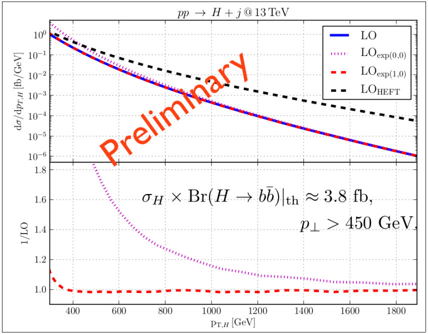
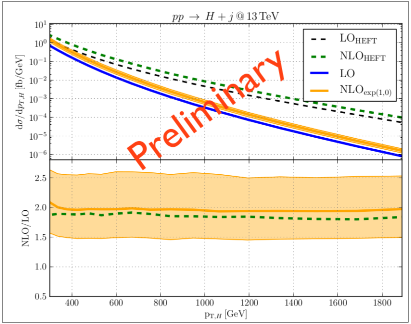
- different methods, similar results, all supporting that $K_{\mathrm{full}} \simeq K_{\mathrm{HEFT}}$.
- since few weeks ago, the situation has improved substantially

large $p_{\mathrm{T,H}}$ and m_t dependence at NLO

preliminary results by [Kudashkin,Lindert,Melnikov,Wever, November '17]





$$m_{\mathrm{H}}^2 \sim m_t^2 \ll p_{\mathrm{T,H}} \quad , \quad |M_{\mathrm{HEFT}}| \sim p_{\mathrm{T,H}}^2 \quad , \quad |M_{\mathrm{full}}| \sim \sum_{n=0,4} \frac{\ln^n(p_{\mathrm{T,H}}^2/m_t^2)}{p_{\mathrm{T,H}}^2}$$

- logs not enough, but excellent convergence keeping only first power-suppressed term $(m_t/p_{\mathrm{T,H}})^2$.
- best approximation so far for full NLO result, and probably that's enough for pheno.
- exact K-factor is $\mathcal{O}(10\%)$ larger than in HEFT, and flat

conclusions

- I've shown recent progress in the description of the Higgs transverse momentum (in gluon fusion).
- in the intermediate region, NNLO predictions are known.
- in the small $p_{\mathrm{T,H}}$ region, the state of the art is N3LL+NNLO. Mass effects have also been computed at NLO, separately.
  - next step is to combine these results.
- at large $p_{\mathrm{T,H}}$, an important preliminary result to estimate the NLO corrections with mass effects has been obtained very recently.
  - Although it's not nominally a full exact NLO computation for $p_{\mathrm{T,H}}$, it gives extremely important hints on what one can expect.
  - It strongly supports to use a multiplicative approach.

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Thank you for your attention!

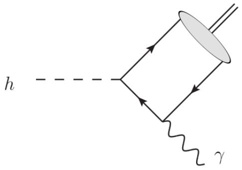
extra slides

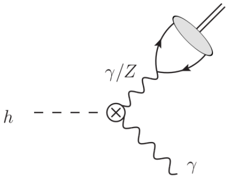
probing light-quarks Yukawa couplings

$$\frac{y_q}{\sqrt{2}} = \kappa_q \frac{m_q}{v}$$

- no direct measurement for 1st and 2nd generation
- few ideas proposed in the past 2-3 years:

- rare exclusive decays: $h \to J/\psi + \gamma$, $h \to \Upsilon + \gamma$, ...
  [Bodwin et al. '13, Kagan et al. '14, Koenig,Neubert '15]
  - main bkg: quarkonium + mistagged jet
  - $|\kappa_c| < 430$, $|\kappa_b| < 78$ [Run-I]
  - $\sim$ 120 events @ 3 ab^{-1} (ATLAS+CMS, $e + \mu$)
  - $\kappa_c \sim 15$ [3 ab^{-1} [ATL note,no bkg syst]]





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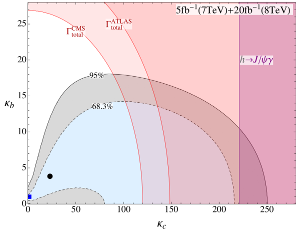


- recasting of $V + h(\to b\bar{b})$ production

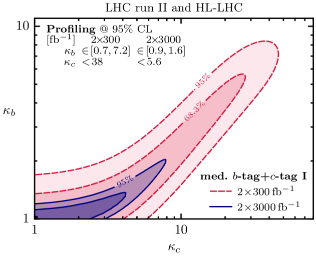
  [Perez et al. '15 (+ Delaunay et al. '13)]

  - include charm mis-tagging into μ_b signal strength
  - $|\kappa_c| < 230$ [Run-I]

$$\mu_b = \frac{\sigma\,\mathrm{BR}_{b\bar{b}}}{\sigma_{\rm SM}\mathrm{BR}^{\rm SM}_{b\bar{b}}}$$

$$\to \frac{\sigma\,\mathrm{BR}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2} + \sigma\,\mathrm{BR}_{c\bar{c}}\,\epsilon_{c_1}\epsilon_{c_2}}{\sigma_{\rm SM}\mathrm{BR}^{\rm SM}_{b\bar{b}}\,\epsilon_{b_1}\epsilon_{b_2} + \sigma_{\rm SM}\,\mathrm{BR}^{\rm SM}_{c\bar{c}}\,\epsilon_{c_1}\epsilon_{c_2}}$$

$$= \left(\mu_b + \frac{\mathrm{BR}^{\rm SM}_{c\bar{c}}}{\mathrm{BR}^{\rm SM}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\mu_c\right)\Big/\left(1 + \frac{\mathrm{BR}^{\rm SM}_{c\bar{c}}}{\mathrm{BR}^{\rm SM}_{b\bar{b}}}\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\right)$$



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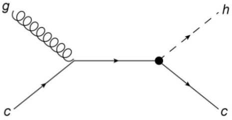

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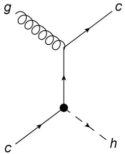
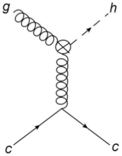


- $c + h$ production and flavour tagging

  [Brivio et al. '15]

  - y_c in production, only 1 c-tagging, clean Higgs decays
  - $|\kappa_c| < 3.9$ [3 ab^{-1}]



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- total width (direct measurement)
  - $|\kappa_c| < 120(150)$ [Run-I, CMS(ATLAS)]
  - stronger constraints from indirect width measurement $|\kappa_c| < 15$

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- global fit: $|\kappa_c| < 6.2$ [Run-I]

probing light-quarks Yukawa couplings

summary in one plot

[Perez et al. '15]