QCD in Higgs and BSM

Frank Tackmann

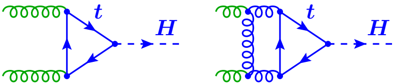
DESY

QCD@LHC 2013
DESY, Sep. 5, 2013

Introduction

QCD in Higgs and BSM

QCD is everywhere



- Inclusive production cross sections
  - Sizable QCD corrections in colored production processes
  - PDFs

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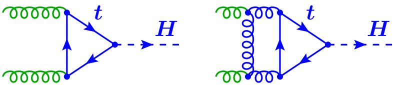

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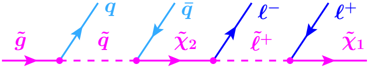
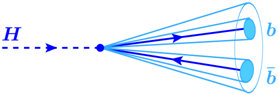


- Decays
  - Jets from decays (BSM cascades)
  - Boosted topologies (boosted tops, $H \to b\bar{b}$)



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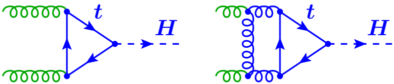

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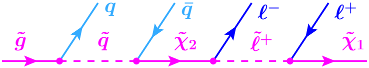

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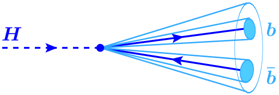
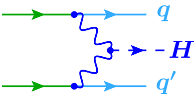


- In association
  - Additional jets from ISR
  - Weak boson fusion processes



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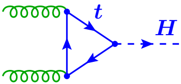

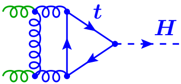

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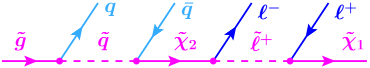

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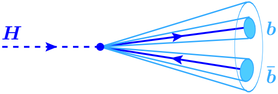

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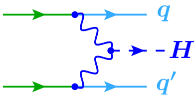


- SM backgrounds
  - QCD jet production, $W/Z+$ jets, top decays
  - Signal-background interference effects ($H \to \gamma\gamma/ZZ/WW$)

QCD Theory for Direct Searches

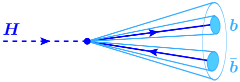
[see previous talk by Thorsten Kuhl]

Ultimately we don't want discovery to rely on theory (for backgrounds)

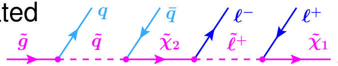
- Searches designed to take as much backgrounds from data as possible
  - Normalization of QCD backgrounds often taken from data
  - Monte Carlo still important to validate and/or provide shapes needed for extrapolation into signal region

Theory input (for signal) is important to know where, for what, and how to look

- Signal cross sections and shapes provide guidance and templates
- Development of search strategies directly exploiting QCD effects
  - Jet substructure methods to identify fat jets from boosted decays



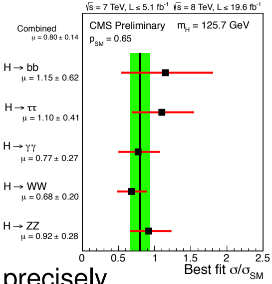
  - Jet properties to distinguish quark from gluon jets
    $\rightarrow$ BSM signals tend to be quark dominated



QCD Theory After Observation

Precise QCD(+EW) predictions are essential to interpret observed signal (or set exclusion limits)

- Production cross section × BR
  - Expected overall signal normalization
    Immediate 1st comparison: $\mu = \sigma^{\rm obs}/\sigma^{\rm SM}$ →

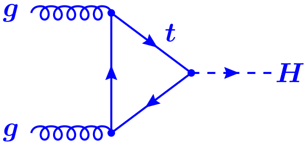


- Differential and exclusive observables are the key to precisely determine properties of the Higgs (or any other) signal
  - Differential spectra
  - Exclusive jet cross sections ("jet binning")
    - Distinguishing production and decay channels
    - Reconstructing BSM decay chains and masses
    - Mono-jet signatures
  - Jet substructure

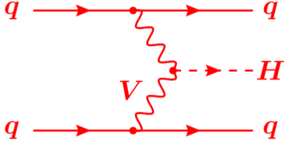
⇒ Various theory methods required depending on what's being measured

Higgs Production and Decay is a QCD Laboratory

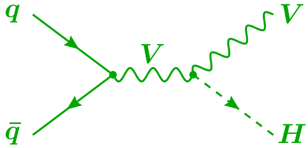
Dominant: Gluon fusion

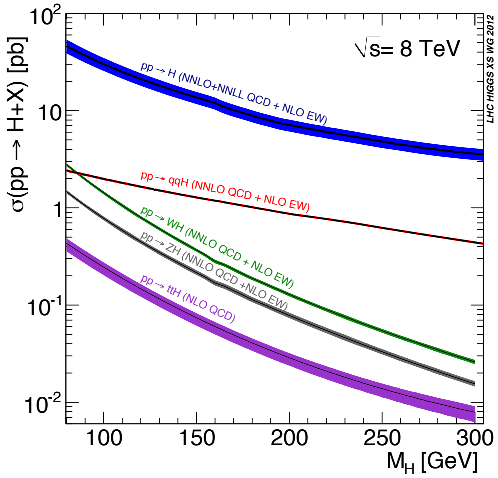


Vector boson fusion (VBF)



Associated production (VH)





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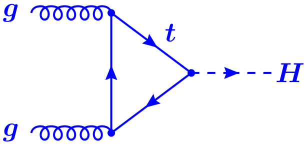
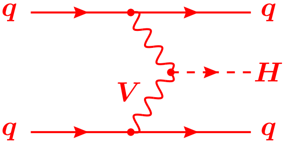


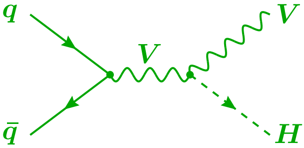
- No jets at tree level, but strong ISR from incoming gluons
- NNLO+NNLL QCD (fully differential), NLO EW, $1/m_t$

Vector boson fusion (VBF)



- Two forward jets at large $\Delta\eta$, m_{jj} with little central radiation
- NNLO QCD, NLO EW

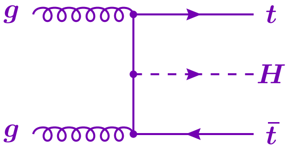
Associated production (VH)



- No additional jets and less ISR
- Higgs can be boosted with $p_T \gtrsim m_H$
- NNLO QCD (fully differential), NLO EW

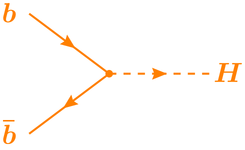
Higgs Production and Decay is a QCD Laboratory

$t\bar{t}H$ associated production



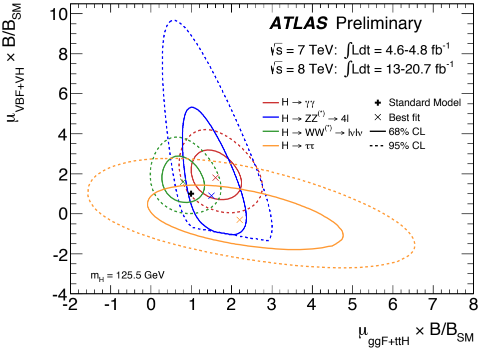
- 2 b-jets plus up to 4 jets from top decays
- NLO QCD

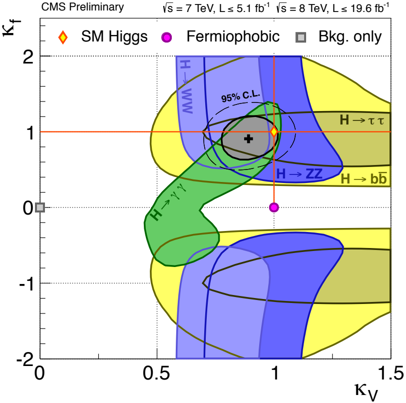
$b\bar{b}$ annihilation



- Enhanced in 2HDMs
- NNLO QCD (5FS)
- NLO QCD (4FS $b\bar{b}H$)

Determining Higgs Couplings





So far consistent with the SM Higgs

- Every measurement is also an indirect search (not just Higgs, also top, flavor, ...)

⇒ Discovering BSM effects in Higgs couplings at the few to $\mathcal{O}(10\%)$ level requires detailed and precise control of QCD effects at the same level including reliable theory uncertainties and correlations.

Remaining Outline

Lots of recent progress, certainly too much to cover in one talk ...

I'll pick a few examples (mostly focusing on Higgs, but same methods apply to BSM)

- squarks/gluinos at threshold
- Higgs and Di-Higgs from gluon fusion
- Signal-background interference
- Higgs p_T and jet p_T
- Higgs $+$ jets
- Substructure

Important ingredients I won't go into since already covered in other talks

- Monte Carlo [talks by Jeppe Andersen and Leif Lönnblad]
- Fixed-order calculations [talks by Thomas Gehrmann, Giancarlo Ferrera, Stefan Weinzierl]
- Resummation [talk by Anna Kulesza]
- PDFs [talk by Amanda Cooper-Sarkar]

[+ many parallel talks, so really this entire workshop ...]

Production Cross Sections

Pair Production of Heavy BSM Particles

Schematic *partonic* cross section near the partonic production threshold

$$\hat{\sigma} = \hat{\sigma}_{\rm LO}\Big[1 + \alpha_s\Big(\underbrace{\ln^2\beta^2 + \ln\beta^2}_{} + \underbrace{\frac{1}{\beta}}_{} + \cdots\Big)\Big]$$

Soft-gluon (threshold) logs — Coloumb (bound-state) corrections

- $\beta = \sqrt{1 - 4m_{\rm BSM}^2/\hat{s}} \ll 1$ is the relative velocity of heavy particles

$\Rightarrow$ Near threshold ($\beta \ll 1$) both types of corrections can be significant and should be resummed

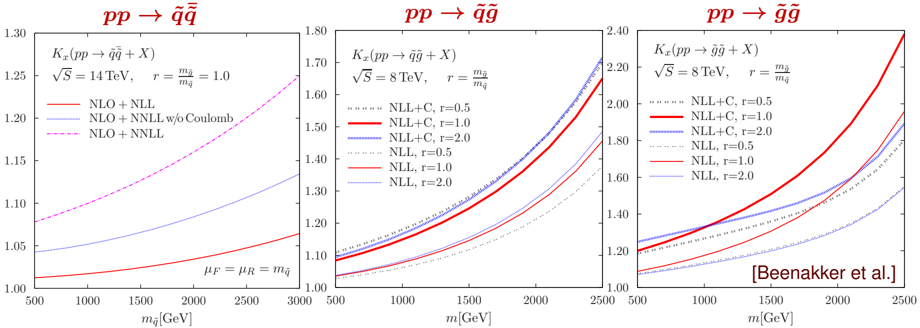
$\to$ threshold resummation typically leads to an enhancement

Hadronic cross section

- Integrates over all partonic $\hat{s}$: $2m_{\rm BSM} < \sqrt{\hat{s}} < \sqrt{s} = 7/8/14\,{\rm TeV}$

$\Rightarrow$ For heavy $m_{\rm BSM} \sim \mathcal{O}(\,{\rm TeV})$ near-threshold production dominates so large threshold enhancements are possible for hadronic cross section

Heavy Squark and Gluino Production in MSSM



where $K = \sigma^{\text{NLO+(N)NLL}} / \sigma^{\text{NLO}}$, expect full NNLL close to NLL+C

Ingredients for full NLO+NNLL (soft+Coloumb) known for all channels

[Kulesza, Motyka; Beenakker et al.; Beneke, Falgari, Schwinn, Wever; Hakiwara, Yokoya; Kauth et al.; Langenfeld, Moch, Pfoh; Broggio et al.]

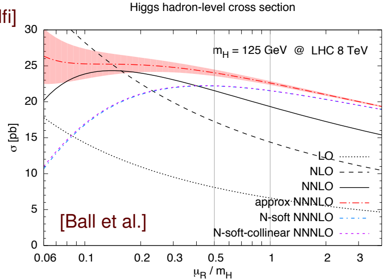
- Complete numerical results for all channels at this order not yet available
- Poorly known large-x gluon PDF can cause significant uncertainties here (e.g. $\tilde{g}\tilde{g}$ comes almost entirely from $gg \to \tilde{g}\tilde{g}$)

$gg \to H$ Beyond NNLO

Several improvements beyond NNLO are known

[Catani, Grazzini, de Florian; Moch, Vermaseren, Vogt; Ahrens, Becher, Neubert, Yang; Ball, Bonvini, Forte, Marzani, Ridolfi]

- Most recent analysis
  [see talk by Marco Bonvini this afternoon]
  - Combines constraints from small and large N resummation in Mellin space
  - Finds $\sim$8% increase over current NNLO+NNLL, which is the same size as the current uncertainty

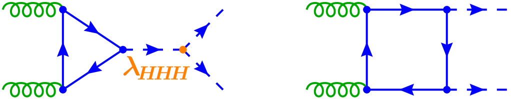


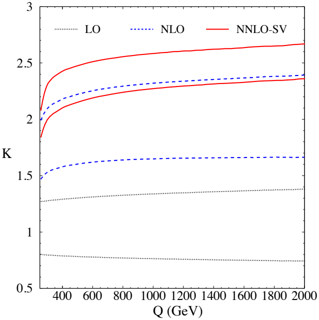
Complete N³LO calculation (seems to be near or far away depending on whom you ask)

[pieces (among others): Chetyrkin, Kniehl, Steinhauser; Baikov et al.; Gehrmann et al.; Höschele et al.; Anastasiou, Duhr, Dulat, Mistlberger; Buehler, Lazopoulos]

- Very intriguing and just as challenging, but remember in practice more things need to improve at the same time
  - Current PDF+α_s uncertainties are same size as pert. uncertainties
  - Hard to imagine we will have N³LO PDFs anytime soon
    $\to$ However, consistent PDFs for higher-order resummed predictions?

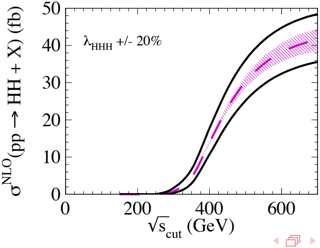
Higgs Pair Production





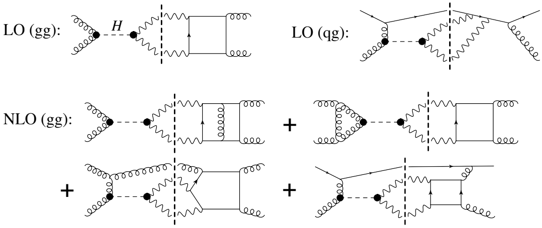
$\sim$ 30% λ_{HHH} measurement seems possible
[see e.g. Baur, Plehn, Rainwater; Baglio et al.; Goertz et al.; Dolan et al.]

- Needs high luminosity ($\gtrsim$ 600/fb) and $\sim$ 10% uncertainties in di-Higgs distributions
- Dominant $gg \to HH$ channel
  - Large NLO corrections similar to $gg \to H$ [Dawson, Dittmaier, Spira]
  - Needed $1/m_t$ expansion a priori unjustified
- Recent improvements
  - NNLO virtual corrections at $m_t \to \infty$ [de Florian, Mazitelli]
  - $1/m_t$ corrections at NLO appear under control for total cross section once exact LO m_t dependence is kept [Grigo, Hoff, Melnikov, Steinhauser]
  - NNLL threshold resummation [Shao, Li, Li, Weng]

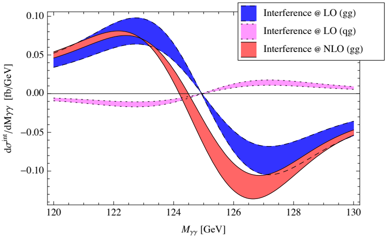


Signal-Background Interference in $H \to \gamma\gamma$

[Martin; De Florian et al.; Dixon, Li]

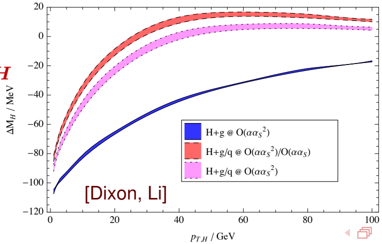


$$\frac{d\sigma^{\rm int}}{dM_{\gamma\gamma}} = \frac{M_{\gamma\gamma}^2 - m_H^2 R + m_H \Gamma_H I}{(M_{\gamma\gamma}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$



Apparent mass shift due to antisymmetric part of interference contribution which gets spread out by finite resolution

- $\Delta m_H \propto \sqrt{\Gamma_H/\Gamma_H^{\rm SM}} \to$ constraint on Γ_H
  - Compare apparent mass in $H \to \gamma\gamma$ with mass measured in $H \to ZZ$
  - Directly from $H \to \gamma\gamma$ alone by exploiting strong $p_T^{\rm Higgs}$ dependence



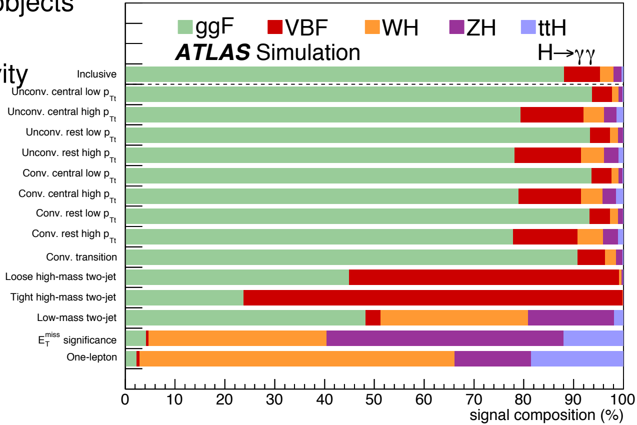
[Dixon, Li]

Differential and Exclusive Observables

Event Categorization

Experiments divide data into many exclusive categories

- Based on final state objects and their kinematics
- Optimized for sensitivity to various production channels
- Different for each Higgs decay channel



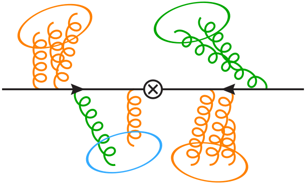
⇒ Requires theory predictions for all categories and channels

- Currently almost all of these come from parton shower Monte Carlo (typically reweighted and/or NLO-matched)

Jet Binning in $H \to WW$

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
PDF model (signal only)	8	-
QCD scale (acceptance)	4	-
Jet energy scale and resolution	4	2
W+jets fake factor	-	5
WW theoretical model	-	5
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	26	-
2-jet incl. ggF signal ren./fact. scale	15	-
Parton shower/ U.E. model (signal only)	10	-
b-tagging efficiency	-	11
PDF model (signal only)	7	-
QCD scale (acceptance)	4	2
Jet energy scale and resolution	1	3
W+jets fake factor	-	5
WW theoretical model	-	3

[ATLAS-CONF-2012-158]



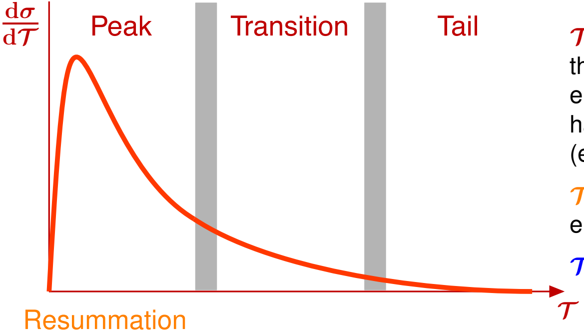
$p_T^{\rm jet} \leq p_T^{\rm cut} \simeq 25 - 30\,\mathrm{GeV}$

for $|\eta^{\rm jet}| \leq 4.5 - 5$

Perturbative QCD uncertainties are the dominant systematic uncertainty

- $\Delta\sigma_0/\sigma_0 = 17\%$
- $\Delta\sigma_1/\sigma_1 = 30\%$

Perturbative Regions



$\mathcal{T}$ is any "IR-sensitive" variable that determines the scale of QCD emissions on top of the underlying hard process (e.g. p_T^{Higgs}, p_T^{jet}, m^{jet})

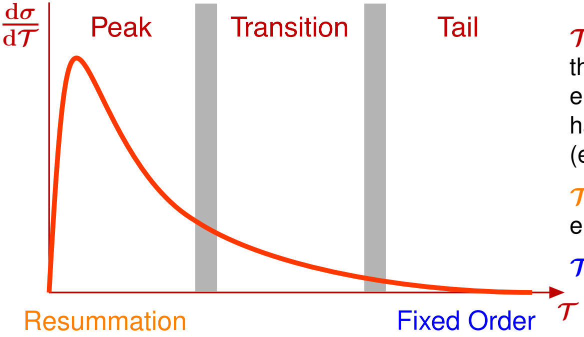
$\mathcal{T} \to 0$: only soft or collinear emissions

$\mathcal{T} \sim Q$: additional hard emissions

Resummation region

- Large logarithms $\alpha_s^n \ln^m(\mathcal{T}/Q)$ must be resummed to all orders (where Q is scale of hard process)
- Fixed-order expansion in α_s breaks down

Perturbative Regions



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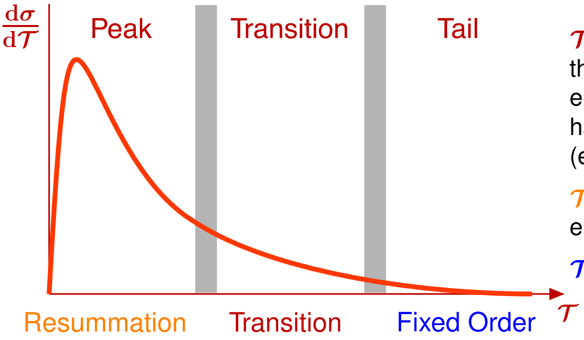
Fixed-order region

- Fixed-order expansion for Hard+1-jet process applies
- Resummation becomes meaningless here (soft-collinear approximation breaks down)

Perturbative Regions



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Transition region

- Often experimentally the most relevant while theoretically the most subtle
- Requires consistent combination of resummation and fixed order
  - NLO+PS matching gives the lowest order
  - Resummed NNLL+NNLO is a higher-order version of this

Theory Uncertainties in Jet Binning

[Stewart, FT]

$$\sigma_{\rm incl} = \int_0^{\mathcal{T}^{\rm cut}} \mathrm{d}\mathcal{T}\, \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}} + \int_{\mathcal{T}^{\rm cut}}^{\infty} \mathrm{d}\mathcal{T}\, \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}} \equiv \sigma_0(\mathcal{T}^{\rm cut}) + \sigma_{\geq 1}(\mathcal{T}^{\rm cut})$$

Complete description requires full theory covariance matrix for $\{\sigma_0, \sigma_{\geq 1}\}$

- Convenient physical parametrization in terms of 100% correlated and 100% anticorrelated pieces

$$C = \begin{pmatrix} (\Delta_0^{\rm y})^2 & \Delta_0^{\rm y}\,\Delta_{\geq 1}^{\rm y} \\ \Delta_0^{\rm y}\,\Delta_{\geq 1}^{\rm y} & (\Delta_{\geq 1}^{\rm y})^2 \end{pmatrix} + \begin{pmatrix} \Delta_{\rm cut}^2 & -\Delta_{\rm cut}^2 \\ -\Delta_{\rm cut}^2 & \Delta_{\rm cut}^2 \end{pmatrix}$$

- Absolute “yield” uncertainty is fully correlated between bins
  - $\Delta_{\rm incl}^{\rm y} = \Delta_0^{\rm y} + \Delta_{\geq 1}^{\rm y}$
- “Migration” unc. $\Delta_{\rm cut}$ due to binning (must drop out in sum $\sigma_0 + \sigma_{\geq 1}$)
  - Fixed-order region: small and can be neglected
  - Transition+resummation region: important and associated with uncertainties in $\mathcal{T}^{\rm cut}$ log series

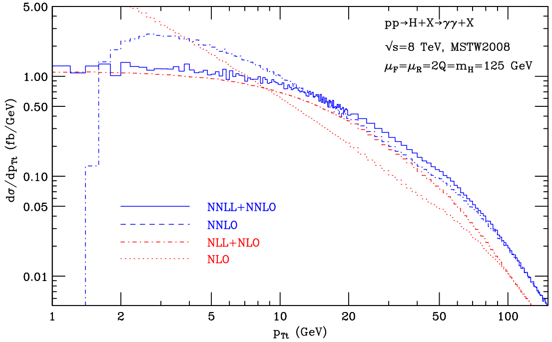
Resummation for Higgs p_T

Resummation for p_T^{Higgs} is known to NNLL+NNLO

[Bozzi, Catani, de Florian, Grazzini; Cao, Chen, Schmidt, Yuan; Becher, Neubert; Chiu et al.]

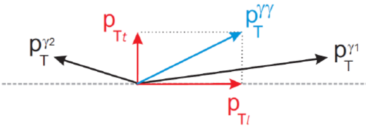
- NNLL resummation using classical p_T resummation or via RGE in SCET
- (N)NLO relative to underlying $gg \to H$ process

$d\sigma/dp_{Tt}$ [de Florian, Ferrera, Grazzini, Tommasini]



Resummation Transition Fixed Order

For $H \to \gamma\gamma$: $\mathcal{T} \equiv p_{Tt}$

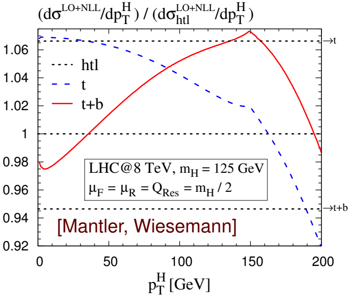


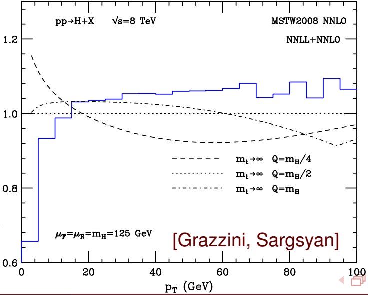
$\Rightarrow$ Closely related to $p_T^{\gamma\gamma} \equiv p_T^{\mathrm{Higgs}}$ but depends on precise Higgs decay kinematics

Quark Mass Effects At Small Higgs p_T

Implementation of exact NLO m_t and m_b dependence at NLL+NLO

- Large differences observed in relative m_b effect between POWHEG and MC@NLO [Bagnaschi, Degrassi, Slavich, Vicini; Frixione]
- Finite m_b and m_t effects are p_T dependent and cannot be included simply by overall rescaling
- Effect of nonzero m_b can be quite large (surprisingly) at very small $p_T \lesssim m_b$
  - Caused by known negative interference between b and t loops and depends on b loop being resolved or not
  - Comparable to pert. uncertainties at NNLL+NNLO $\to$ increased uncertainty?

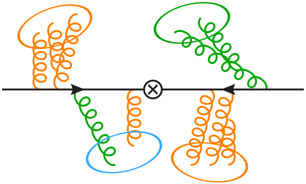




Resummation for Jet p_T

For jet-veto in $H \to WW$ and $H \to \tau\tau$

$\mathcal{T} \equiv p_T^{\rm jet}$ of hardest jet using jet alg. with radius R

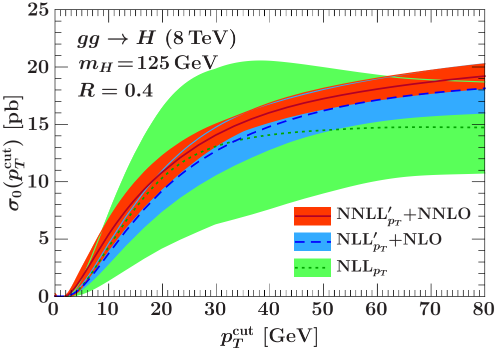


Resummation for $p_T^{\rm jet}$ is more involved than $p_T^{\rm Higgs}$ due to jet algorithm dependence

[Banfi, Monni, Salam, Zanderighi; Becher, Neubert, Rothen; Stewart, FT, Walsh, Zuberi]

- Resummation structure differs, R-dependence explicitly enters at NNLL
- In experimentally relevant region $R^2 \sim p_T^{\rm cut}/m_H$
  - Jet clustering corrections $\sim R^2$ are small
  - Clustering logs $\sim \alpha_s^n \ln(p_T^{\rm cut}/m_H) \ln^{n-1} R^2$ are formally NLL
    $\to$ *cannot* be resummed at present and so are not part of log-counting
- Available improvements beyond NNLL
  - α_s^2 hard, collinear, soft matching (NNLL$'$) including R-dependence
  - Missing pieces for N^{3}LL are anomalous dimensions
- b-quark mass effects are small, with small increase in uncertainties
  [Banfi, Monni, Zanderighi]

Resummation for Jet p_T



Resummation Transition Fixed Order

[Stewart, FT, Walsh, Zuberi]

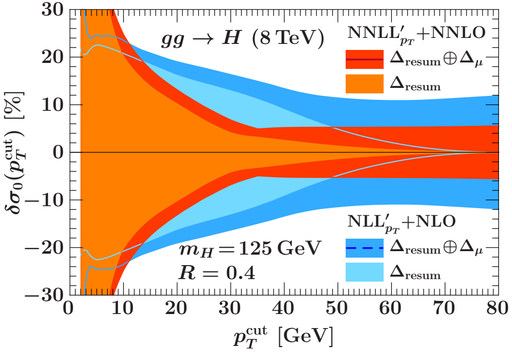
At NNLL$'_{p_T}$+NNLO

$$\sigma_0(25\,\mathrm{GeV}, R = 0.4)$$
$$= 12.67 \pm 1.22_{\rm pert} \pm 0.46_{\rm clust}\ \mathrm{pb}$$

$$\sigma_0(30\,\mathrm{GeV}, R = 0.5)$$
$$= 13.85 \pm 0.87_{\rm pert} \pm 0.24_{\rm clust}\ \mathrm{pb}$$

- Resummed pert. theory shows good convergence and reduced uncertainties compared to fixed (N)NLO

Resummation for Jet p_T



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- Resummed pert. theory shows good convergence and reduced uncertainties compared to fixed (N)NLO
  - Also provides systematic way to assess full theory uncertainty matrix

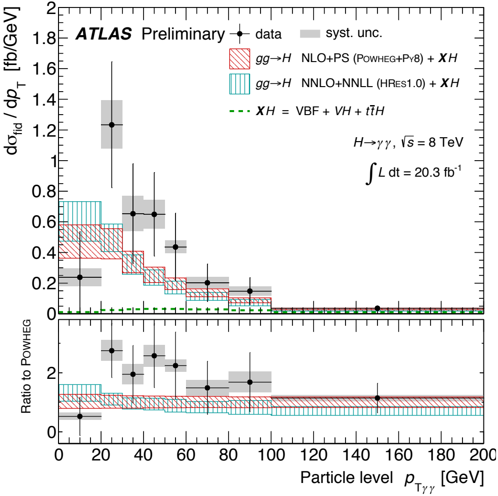
$$C = \begin{pmatrix} \Delta^2_{\mu 0} & \Delta_{\mu 0}\,\Delta_{\mu\geq 1} \\ \Delta_{\mu 0}\,\Delta_{\mu\geq 1} & \Delta^2_{\mu\geq 1} \end{pmatrix} + \begin{pmatrix} \Delta^2_{\rm resum} & -\Delta^2_{\rm resum} \\ -\Delta^2_{\rm resum} & \Delta^2_{\rm resum} \end{pmatrix}$$

ATLAS Measurement of Differential Spectra

ATLAs measurement of fiducial cross section in $H \to \gamma\gamma$ in bins of p_T^{Higgs} and corrected for detector effects

- Still statistics limited
- Yet, it's great to see the transition from fitting μ-values (which is directly theory dependent) to measuring fiducial cross sections (which are as theory-independent as possible)

$\Rightarrow$ This really marks the next step of "Higgs measurements"



[ATLAS-CONF-2013-072]

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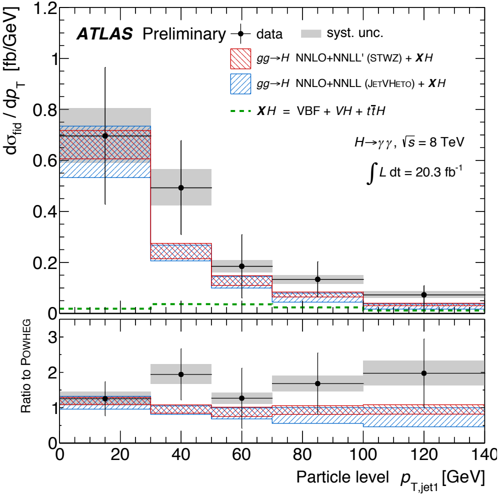
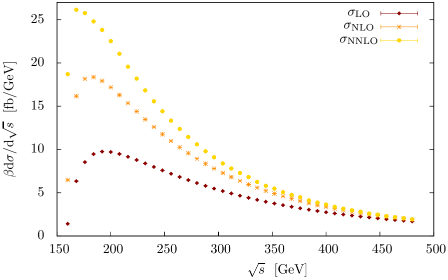


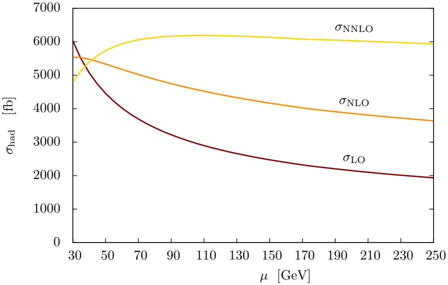
[ATLAS-CONF-2013-072]

Inclusive Higgs + 1 Jet

$\sigma_{\geq 1}^{\text{part}}$ for $p_T^{\text{jet}} > 30$ GeV



$\sigma_{\geq 1}^{\text{had}}$ for $p_T^{\text{jet}} > 30$ GeV



Higgs + 1 jet at NNLO

[Boughezal, Caola, Melnikov, Petriello, Schulze; see talk by Radja Boughezal this afternoon]

- So far only gluons, quark channels are important and being computed
- Sizable NNLO corrections (not unexpected)
- Will provide p_T^{Higgs} and p_T^{jet} spectra at intrinsic NNLO_1
  - Will be interesting (and nontrivial) to combine with resummation at low p_T

Exclusive Higgs + 1 jet

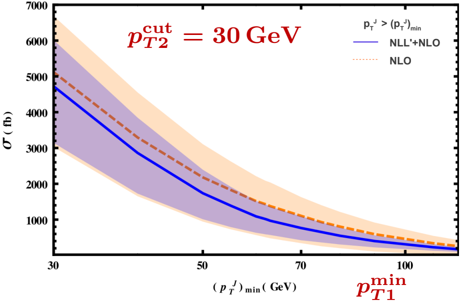
Exclusive 1-jet bin in $H \to WW$ and $H \to \tau\tau$

$\mathcal{T} \equiv p_{T2}^{\rm jet} < p_{T2}^{\rm cut}$ (veto 2nd jet) for fixed $p_{T1}^{\rm jet} > p_{T1}^{\rm min}$ (signal jet)

Resummation for $p_{T2}^{\rm jet} < p_{T2}^{\rm cut}$ is much more tricky than for $p_{T1}^{\rm jet} < p_{T}^{\rm cut}$ before

[Liu, Petriello]

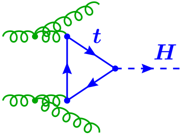
- 3 scales involved: m_H, $p_{T1}^{\rm jet}$, $p_{T2}^{\rm cut}$
- Jet-algorithm dependence from the signal jet and the vetoed jet
- Can combine
  - resummation at NLL′+NLO at $p_{T1}^{\rm jet} \gtrsim m_H/2$
  - with fixed NLO at $p_{T1}^{\rm jet} \lesssim m_H/2$

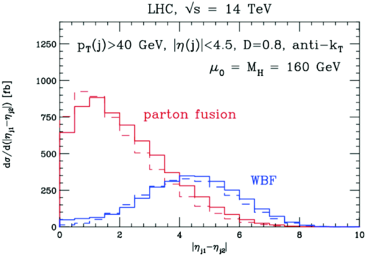


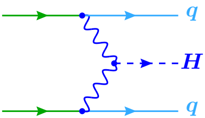
⇒ A challenge is to consistently combine this with Higgs + 1 jet inclusive NNLO and $p_{T1}^{\rm jet}$ resummation

Higgs + 2 Jets

Gluon-fusion "background" in VBF selections (all decay channels)







Inclusive H+2 jet: Scales: $p_{T1}^{\rm jet}, p_{T2}^{\rm jet} \gtrsim 30\,\mathrm{GeV}$, m_H, $m_{jj} \gtrsim 500\,\mathrm{GeV}$

- NLO has ∼25% uncertainties [Campbell, Ellis, Williams; van Deurzen et al.]

Exclusive H+2 jet: $\mathcal{T} \equiv p_{T3}^{\rm jet}$ or $p_{T\,Hjj}$ or $\pi - \Delta\phi_{H-jj}$

- Different NLO+PS implementations available but not understood (yet)

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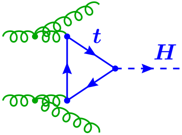

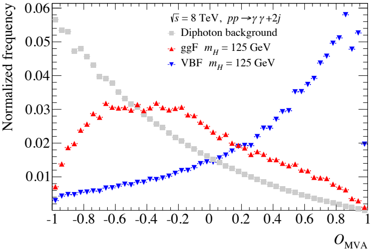

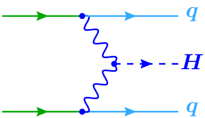

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- Different NLO+PS implementations available but not understood (yet)

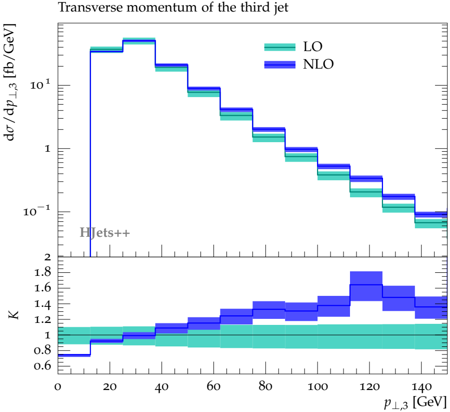
And all of this goes into a complicated multivariate selection ...

- Can easily lead to almost complete loss of control over theory unc.

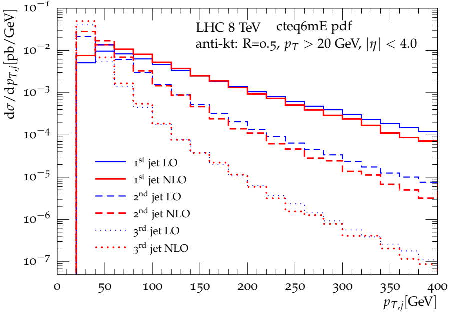
⇒ Important to complement with cut-based fiducial cross section analysis

Higgs + 3 jets

From VBF [Campanario, Figy, Plätzer, Sjödahl]



From gluon fusion [Cullen et al.]



NLO calculations for Higgs + 3 jets

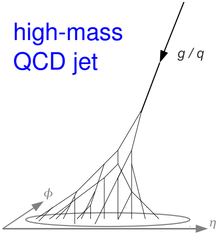
- Nontrivial shape dependence of NLO corrections
- Should also help to better understand exclusive Higgs + 2 jets

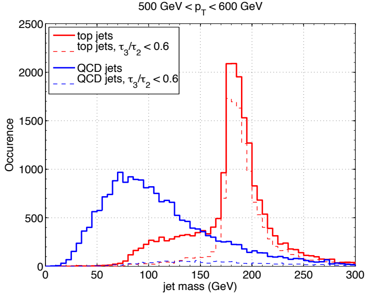
Boosting Searches with Jet Substructure

For boosted tops, e.g. from $Z' \to t\bar{t}$, jets from top decay are very close

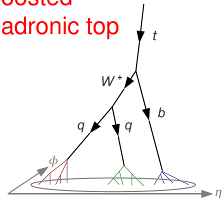
- Looking for a for single top-jet with large R becomes more efficient than looking for 3 separated small-R jets $\to$ need substructure of large jet to discriminate

high-mass QCD jet





boosted hadronic top



ATLAS and CMS are starting to use boosted analyses in searches

[see yesterday's talks by Frank Merritt and Aniello Spiezia]

- Essential to extend reach to highest p_T and $m_{t\bar{t}}$, even more so for Run-II

$\Rightarrow$ While there has been much progress on the theory side, we have really just scratched the surface

Final Comments

We have entered the era of Higgs measurements

- Remarkable amount of progress

⇒ Ultimate goal: Global coupling fit using only fully corrected fiducial cross section measurements

Requires combined effort of exp ⊗ theory and also theory ⊗ theory, e.g.,

- Precise FO ⊗ resummed predictions for all categories and channels
- Exp ⊗ Theory scrutiny of MVAs ($H \to \tau\tau$, $H \to b\bar{b}$)
- QCD ⊗ BSM for boosted searches

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Some final food for thought ...

- A theory prediction without an uncertainty is about as useful as an experimental measurement without uncertainties ;-)
- Precision requires *meaningful* uncertainties, small is not enough ...

  And since they're not Gaussian, just define yourself a "theory-sigma", how about: Which percentage of [citations on your paper, a monthly salary, ...] are you willing to loose if the next order is outside your uncertainty band? 68%? 95%?