Jet p_T Resummation in Higgs Production

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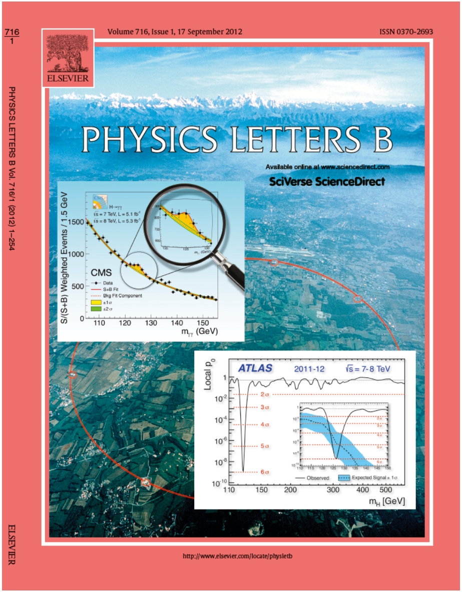
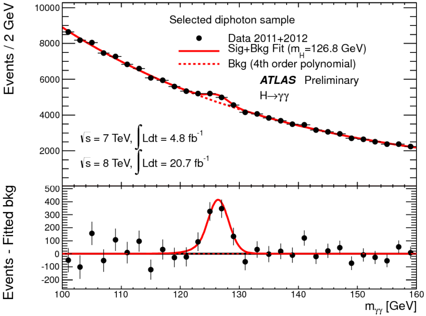
Vienna Theory Seminar,
June 24, 2014

Higgs Discovery ...



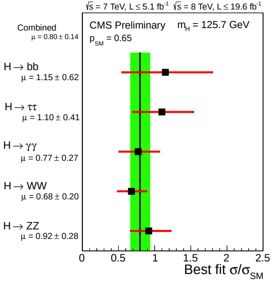
ATLAS $H \to \gamma\gamma$ on full data set



... ultimately does not really require precision theory

… After the Observation

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

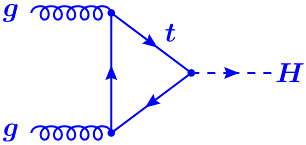


- 1st: Check production cross section $\times$ BR by comparing expected and measured overall signal yield $\mu = \sigma^{\text{obs}}/\sigma^{\text{SM}}$
- Now: Precisely measure Higgs properties
  - Mass, CP, couplings
  - Differential and exclusive observables are the key
  - Measurements of fiducial cross sections to test theory description
- Also: Search for additional heavier (or lighter) states

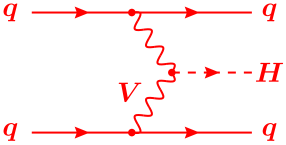
$\Rightarrow$ Various theory methods required depending on what's being measured

Higgs Production and Decay is a QCD Laboratory

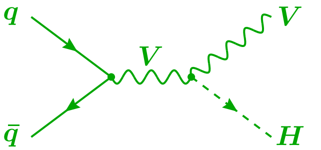
Dominant: Gluon fusion

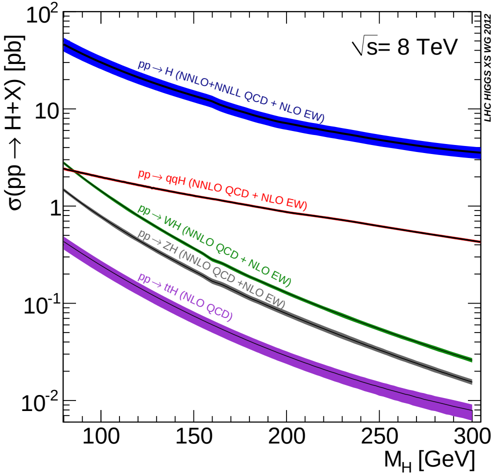


Vector boson fusion (VBF)



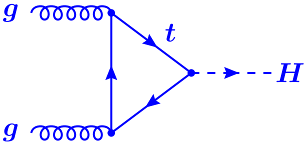
Associated production (VH)





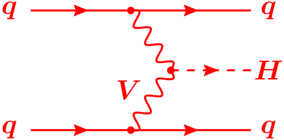
Higgs Production and Decay is a QCD Laboratory

Dominant: Gluon fusion



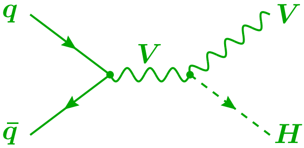
- No jets at tree level, but strong ISR from incoming gluons
- NNLO+NNLL QCD (fully differential), NLO EW, $1/m_t$

Vector boson fusion (VBF)



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

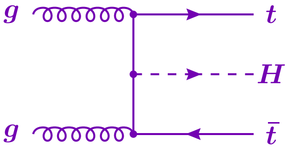
Associated production (VH)



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

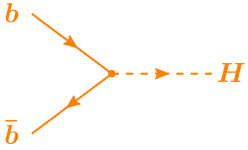
Higgs Production and Decay is a QCD Laboratory

$t\bar{t}H$ associated production



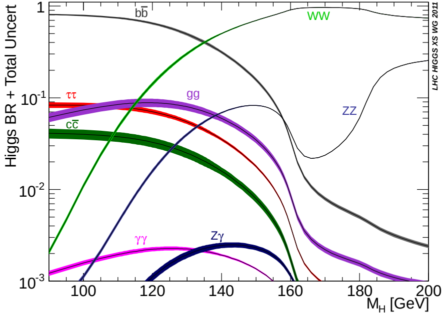
- 2 b-jets plus up to 4 jets from top decays
- NLO QCD

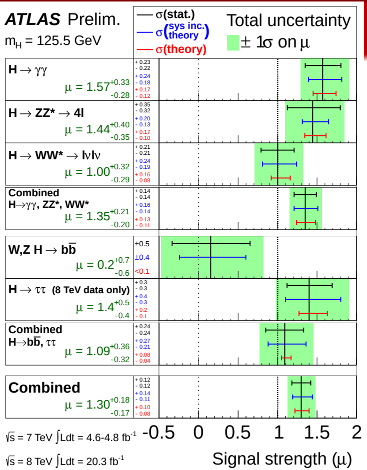
$b\bar{b}$ annihilation



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

Higgs Decay Channels





Channels with high mass resolution:

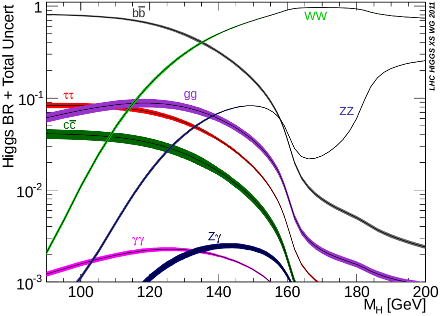
$H \to \gamma\gamma$: Rare decay, but distinct signal

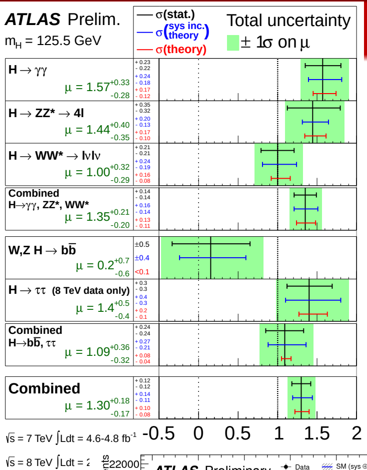
- Various categories based on photon identification and p_{Tt}
- VBF-like 2-jet category

$H \to ZZ \to 4\ell$: Very clean, but few events due to $\mathcal{B}(Z \to \ell\ell)^2$

- Inclusive on jets

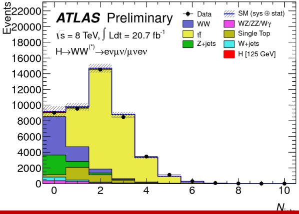
Higgs Decay Channels



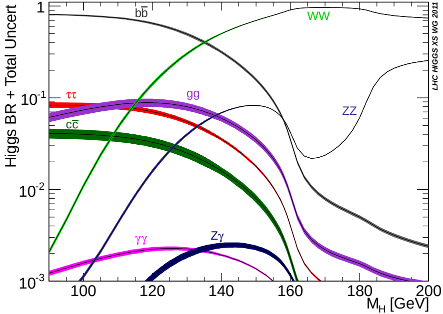


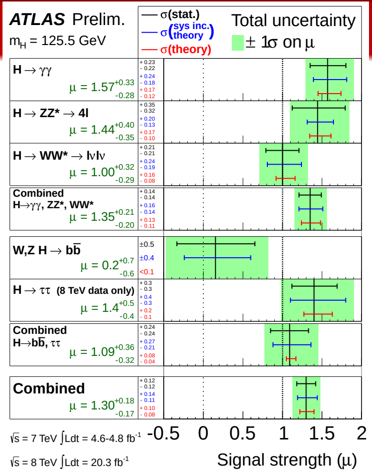
$H \to WW \to \ell\nu\ell\nu$: Large rate but missing energy

- Large background from $t\bar{t} \to WWb\bar{b}$ requires hard jet veto
- Jet binning into 0-jet, (1-jet), VBF-like 2-jet



Higgs Decay Channels

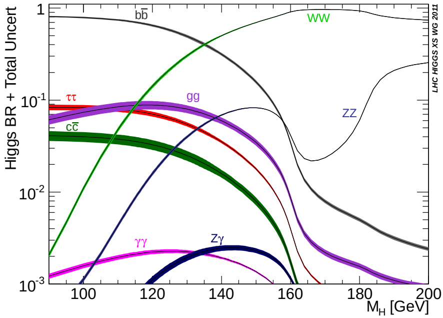


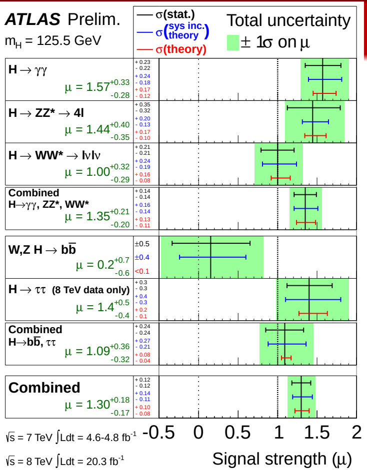


$H \to \tau\tau$: Enhanced in MSSM, also contributes to SM measurements

- Most sensitive in VBF-like 2-jet selection
- 0-jet and 1-jet/boosted categories are also used

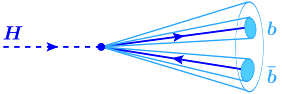
Higgs Decay Channels





$H \to b\bar{b}$: Huge QCD background, only possible in VH production

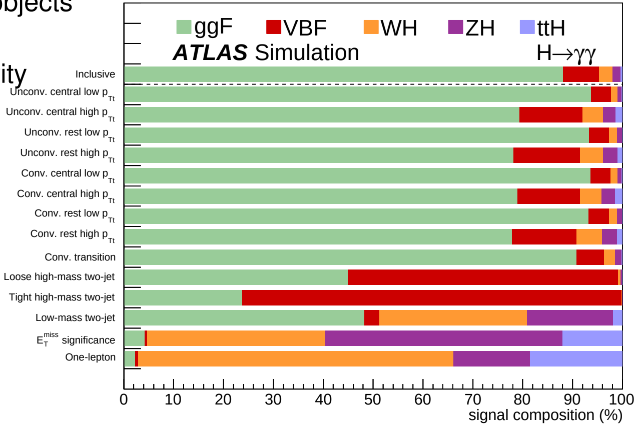
- boosted/nonboosted categories, typically with additional jet veto
- Can exploit jet substructure in boosted categories



Example 1: Event Categorization in $H \to \gamma\gamma$

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



$\Rightarrow$ Requires theory predictions for all categories and channels

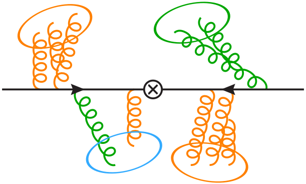
- Currently almost all of these come from parton shower Monte Carlo (typically reweighted and/or NLO-matched)

Example 2: Jet Binning in $H \to WW$

Exclusive 0-jet and 1-jet bins are crucial to control top background 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]



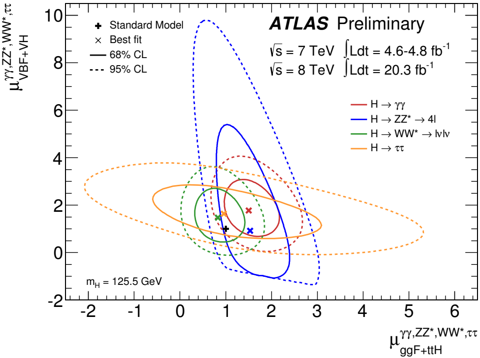
$p_T^{\mathrm{jet}} \leq p_T^{\mathrm{cut}} \simeq 25 - 30\,\mathrm{GeV}$

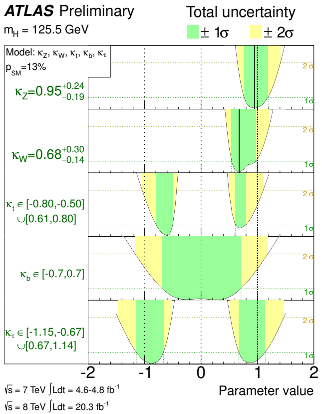
for $|\eta^{\mathrm{jet}}| \leq 4.5 - 5$

Perturbative QCD uncertainties are dominant syst. unc. in 0-jet and 1-jet bins [ATLAS, similar for CMS]

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

Determining Higgs Couplings



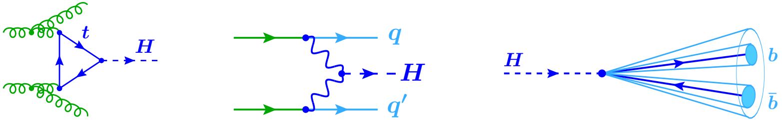


So far consistent with the SM Higgs

- Every measurement is also an indirect search

$\Rightarrow$ 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.

Higgs and Jets



QCD and Jets enter in many places in Higgs measurements

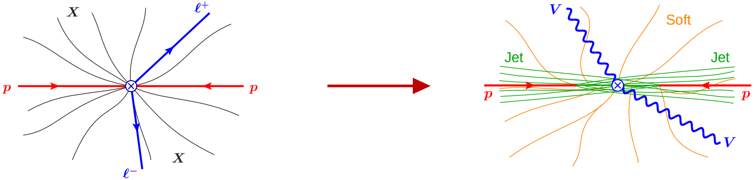
- Jet selections and categorization of events are crucial to increase sensitivity, suppress backgrounds, and separate various production and decay channels

Many issues where theory is important

- Jet definition and jet selection cuts,
- Perturbative predictions for differential and exclusive cross sections
- Theory uncertainty estimates
- Impact of underlying event and nonperturbative corrections

Overview of SCET

Large Logarithms

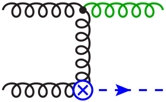


For any type of exclusive measurement or restriction

- Constraining radiation into soft and collinear regions causes large logs (due to sensitivity to soft/collinear divergences)

Example: jet p_T veto in $gg \to H + 0$ jets

- Restricts ISR to $p_T < p_T^{\mathrm{cut}}$ ($\to$ Sudakov double logs from t-channel sing.)



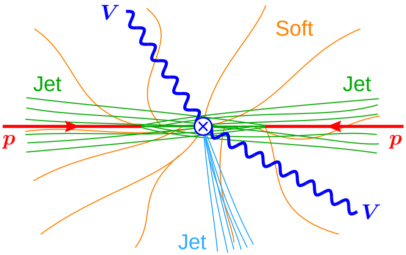
$$\sigma_0(p_T^{\mathrm{cut}}) \propto 1 - \frac{\alpha_s}{\pi} C_A 2 \ln^2 \frac{p_T^{\mathrm{cut}}}{m_H} + \cdots$$

$\Rightarrow$ Perturbative corrections increase for smaller p_T^{cut} (stronger restriction)

$\Rightarrow$ Should be resummed to all orders to obtain reliable precise predictions

Soft-Collinear Effective Theory (SCET)

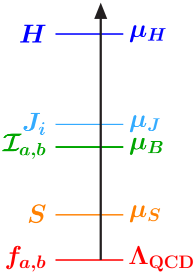
Physical picture: Contributions at different energy scales



Hard interaction

ISR and FSR
Collinear to incoming and outgoing primary partons

Soft radiation
no preferred direction



$\rightarrow$ *Factorization:* $\mathrm{d}\sigma =$ Hard $\otimes$ PDFs $\otimes$ ISR $\otimes$ FSR $\otimes$ Soft

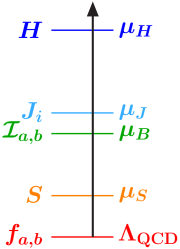
SCET is the effective field theory of QCD in the soft and collinear limit

[Bauer, Fleming, Pirjol, Stewart; Rothstein, Beneke, Chapovsky, Diehl, Feldmann]

- Power counting and expansion in soft and collinear limits manifest at the Lagrangian level
- Systematic separation of different relevant energy scales

Advantages of Factorization in EFT

SCET lets us derive structure of factorized cross section and give each piece a precise field-theoretic definition



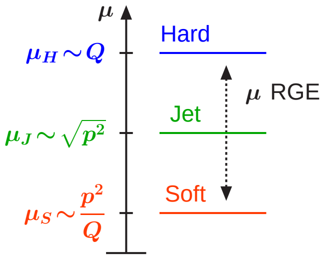
$$\mathrm{d}\sigma = \text{Hard} \otimes \text{PDFs} \otimes \text{ISR} \otimes \text{FSR} \otimes \text{Soft}$$

$$\mathrm{d}\sigma = H \times \Big[(f_{a,b} \otimes \mathcal{I}_{a,b}) \times \prod_j J_j \Big] \otimes S$$

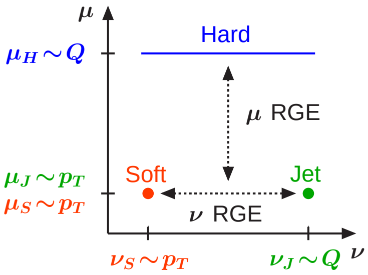
- Logarithms can be resummed using standard RGE methods
  - Can go to higher order in a systematic way (“only” need to know higher-order matching and anomalous dimensions)
  - Systematic control of perturbative uncertainties (evaluation through variations of matching/resummation scales)
- “Nonsingular” corrections for transition to full QCD are formal power corrections and can be added systematically
- Nonperturbative effects can be studied using field-theory methods

Two Basic Setups

"SCET-I": p^2-like (or p^+-like)



"SCET-II": p_T-like



[Jiu et al.]

[equivalent: Becher, Neubert; Echevarria et al.]

- Most e^+e^- event shapes (thrust, angularities, heavy-jet mass)
- Mass variables (jet mass, dijet inv. mass)
- N-(sub)jettiness (with p^+ measure, beam thrust)

- e^+e^- jet broadening
- p_T variables ($W/Z/H$ p_T, leading jet p_T)
- N-(sub)jettiness (with "broadening" measure, sum E_T)

Soft-Collinear Factorization (Schematically)

Cross section after matching from QCD onto SCET

$$\sigma = \sum_{k,l} C_k^\dagger C_l \, \langle O_k^\dagger \, \mathcal{M} \, O_l \rangle$$

- Matching coeffs C_i contain process dependence and hard kinematics
- Measurement function $\mathcal{M}$ defines observable

SCET operators factorize into soft and collinear (universal)

$$O_k = O_{n_{a,b}} \times O_{n_j} \times O_s$$

Soft-collinear factorization requires that $\mathcal{M}$ also factorizes to all orders

$$\mathcal{M} = \mathcal{M}_{n_{a,b}} \otimes \mathcal{M}_{n_j} \otimes \mathcal{M}_s + \text{power corrections}$$

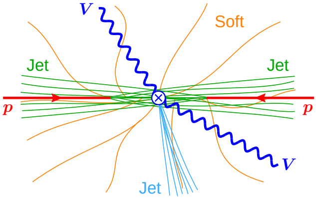
Together this factorizes the cross section

$$\sigma = \underbrace{|C|^2}_{H} \times \underbrace{\langle O^\dagger_{n_{a,b}} \mathcal{M}_{n_{a,b}} O^\dagger_{n_{a,b}} \rangle}_{B_{a,b}} \otimes \underbrace{\langle O^\dagger_{n_J} \mathcal{M}_{n_j} O^\dagger_{n_j} \rangle}_{J_j} \otimes \underbrace{\langle O^\dagger_{n_s} \mathcal{M}_s O^\dagger_{s} \rangle}_{S}$$

SCET Ingredients

For a generic *exclusive* N-jet cross section

$$d\sigma_N = H_N \times \left[B_a \times B_b \times \prod_{j=1}^{N} J_j \right] \otimes S_N$$

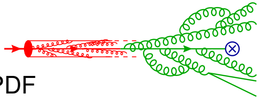


Hard function

- Given by full QCD matrix elements for hard N-parton process
  - Contains both tree level and IR-finite virtual contributions
  - Independent of jet definition/observable and precise form of factorization theorem (e.g. the same for threshold resummation)

Beam, jet, soft functions:

- Contain all IR-singular (soft and collinear) virtual and real contributions
  - Depend on jet definition/observable
  - Only process dependence from parton type
- Beam functions contain PDFs $B = f \otimes \mathcal{I}$
  - Equivalent to observable-dependent generalized PDF



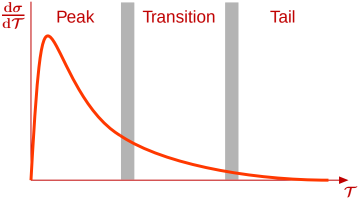
Perturbative Structure – Singular vs. Nonsingular

Differential/integrated spectrum in some IR-sensitive variable τ

thrust: $\tau = 1 - T = \mathcal{T}_2/Q$

jet-mass: $\tau = m_J^2/p_{T\mathrm{jet}}^2$

jet-veto: $\tau = p_{T\mathrm{jet}}/Q$



$$\frac{d\sigma}{d\tau} = \sum_k \alpha_s^k \Big\{ c_{k,-1}\delta(\tau) + \sum_{n=0}^{2k-1} c_{kn}\Big[\frac{\ln^n \tau}{\tau}\Big]_+ \quad + \quad f_k^{\mathrm{ns}}(\tau) \Big\}$$

$$\sigma(\tau^{\mathrm{cut}}) = \sum_k \alpha_s^k \Big\{ \underbrace{c_{k,-1} + \sum_{n=0}^{2k-1} c_{kn}\frac{\ln^{n+1}\tau^{\mathrm{cut}}}{n+1}}_{\text{singular}} \quad + \quad \underbrace{F_k^{\mathrm{ns}}(\tau^{\mathrm{cut}})}_{\text{nonsingular}} \Big\}$$

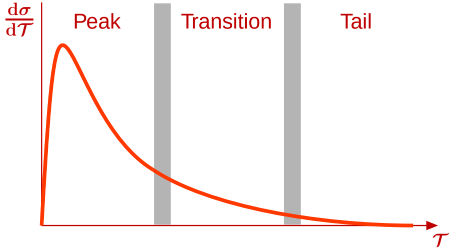
singular: large logs to be resummed

- constant $c_{k,-1}$ belongs to singular

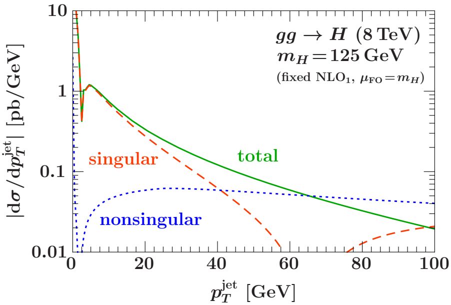
nonsingular: $\mathcal{O}(\tau)$ power corrections

- $f_k^{\mathrm{ns}}(\tau)$ at most integrable divergent
- $F_k^{\mathrm{ns}}(\tau^{\mathrm{cut}} \to 0) \to 0$

Perturbative Regions



Resummation

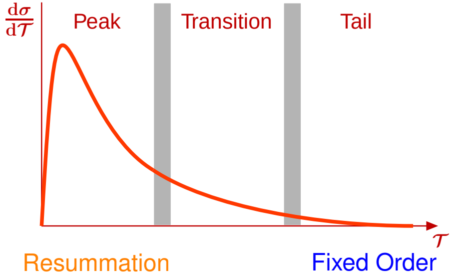


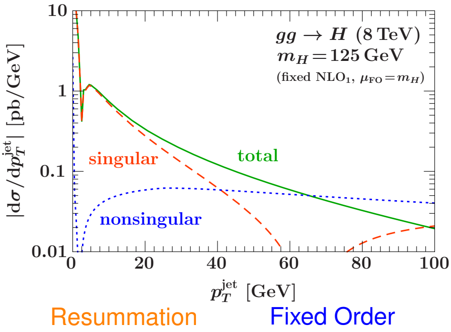
Resummation

Resummation region

- Singular dominate and logs must be resummed to all orders (nonsingular are power-suppressed)
- Fixed-order by itself becomes meaningless here

Perturbative Regions

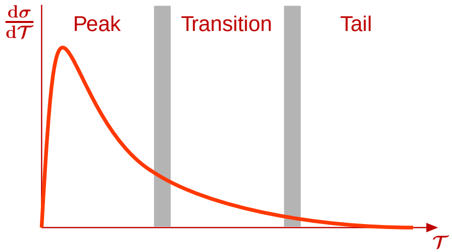


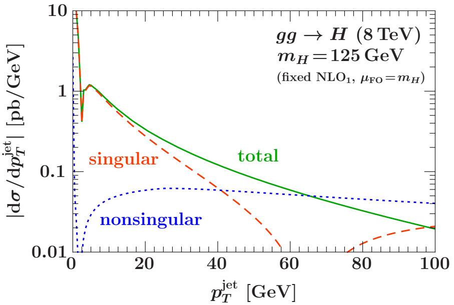


Fixed-order region

- Fixed-order expansion for Hard+1-jet process applies
- Resummation becomes meaningless here and must be turned off (singular/nonsingular separation becomes arbitrary with large cancellations between them)

Perturbative Regions





Resummation Fixed Order
Transition

Resummation Fixed Order
Transition

Transition region

- Theoretically the most subtle but often the most relevant in practice
- Most accurate description requires consistent combination of both resummation and fixed order
  (There are no strict boundaries, so to connect regions must be correct in both resummation and fixed-order limits)

Jet p_T Resummation

Jet Binning and Jet Vetoes

$H+0$ jets

- Beam thrust: Berger, Marcantonini, Stewart, FT, Waalewijn [1012.4480]
- FO jet-bin uncertainties: Stewart, FT [1107.2117]
- p_T^{jet}: Banfi, Monni, Salam, Zanderighi [1203.5773, 1206.4998, 1308.4634]
- p_T^{jet}: Becher, Neubert, Rothen [1205.3806, 1307.0025]
- p_T^{jet}: Stewart, FT, Walsh, Zuberi [1206.4312, 1307.1808]
- $VH+$ 0 jets: Shao, Li, Li [1309.5015], Liu, Li [1401.2149]
- α_s^3 jet clustering effects: Alioli, Walsh [1311.5234]

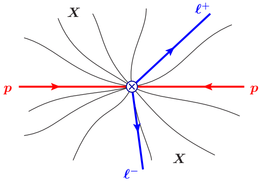
$H+1$ jets

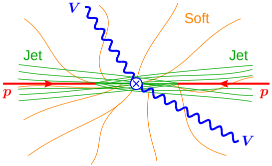
- p_T^{jet}: Liu, Petriello [1210.1906, 1303.4405]
- 0+1 jet combination: Boughezal, Liu, Petriello, FT, Walsh [1312.4535]

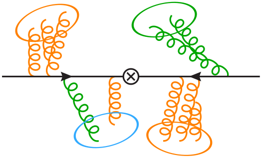
$H+2$ jets

- FO unc. with VBF cuts: Bernlochner, Gangal, Gillberg, FT [1302.5437, 1307.1347]

Higgs + 0 jet Resummation







Veto all jets with radius R and
$p_T > p_T^{\mathrm{cut}} \simeq 25 - 30\,\mathrm{GeV}$

Various complications to deal with

- Jet-algorithm clustering effects (R dependence)
- p_T requires renormalization of rapidity divergences in SCET-II [Chiu et al.]
- Matching to fixed order result at intermediate and large p_T^{jet}
- Estimation of pert. uncertainties (including correlations)

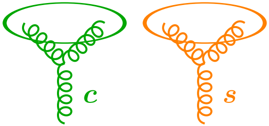
Jet Algorithm Effects

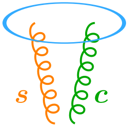
"Local" jet veto depends on a jet clustering algorithm with jet size R

$$\mathcal{M}^{\text{jet}}(p_T^{\text{cut}}) = \prod_{\text{jets } j(R)} \theta\big(p_{Tj} < p_T^{\text{cut}}\big)$$

Algorithm effects start at $\mathcal{O}(\alpha_s^2)$. Consider correction relative to global veto

$$\mathcal{M}^{\text{jet}} = \big(\mathcal{M}_{n_a}^G + \Delta\mathcal{M}_{n_a}^{\text{jet}}\big)\big(\mathcal{M}_{n_b}^G + \Delta\mathcal{M}_{n_b}^{\text{jet}}\big)\big(\mathcal{M}_s^G + \Delta\mathcal{M}_s^{\text{jet}}\big) + \delta\mathcal{M}^{\text{jet}}$$





Clustering *within* each sector

$\sim \mathcal{O}(\ln^n R),\ \mathcal{O}(R^n)$

$\Rightarrow$ Relevant for small $R \ll 1$

- Included in beam (collinear) and soft functions

Clustering *between* sectors

$\sim \mathcal{O}(R^n)$

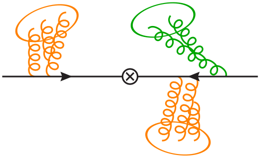
$\Rightarrow$ Relevant for large $R \sim 1$

- Violates simple factorization into collinear and soft

Factorization for Local $p_T^{\rm jet}$ Veto

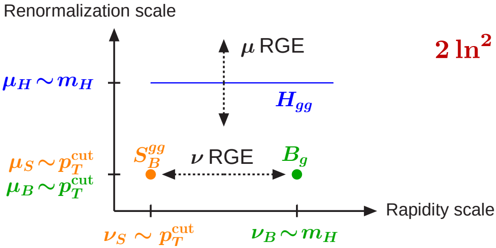
For $R^2 \ll 1$ local jet-veto measurement factorizes into simple product

$$\mathcal{M}^{\rm jet} = \mathcal{M}^{\rm jet}_{n_a}\, \mathcal{M}^{\rm jet}_{n_b}\, \mathcal{M}^{\rm jet}_{s}$$



$$\sigma_0(p_T^{\rm cut}) = H(Q,\mu)\, B^{\rm jet}(R, p_T^{\rm cut}, \mu, \nu)\, B^{\rm jet}(R, p_T^{\rm cut}, \mu, \nu)\, S^{\rm jet}(R, p_T^{\rm cut}, \mu, \nu)$$

Logarithms are split apart and resummed using coupled RGEs in μ and ν



$$2\ln^2 \frac{p_T^{\rm cut}}{m_H} = 2\ln^2 \frac{m_H}{\mu} + 4\ln \frac{p_T^{\rm cut}}{\mu} \ln \frac{\nu}{m_H} + 2\ln \frac{p_T^{\rm cut}}{\mu} \ln \frac{\mu\, p_T^{\rm cut}}{\nu^2}$$

Resummation + Fixed Order Matching

$$\ln\sigma_0(p_T^{\rm cut}) \sim \sum_n \alpha_s^n \ln^{n+1}\frac{p_T^{\rm cut}}{m_H}\,(1+\alpha_s+\alpha_s^2+\cdots) \sim \text{LL}+\text{NLL}+\text{NNLL}+\cdots$$

Resummation conventions:	Fixed-order corrections matching (sing.)	full FO (+ nons.)	Resummation input $\gamma^{\mu,\nu}_{H,B,S}$	$\Gamma_{\rm cusp}$	β
LL	1	-	-	1-loop	1-loop
NLL	1	-	1-loop	2-loop	2-loop
NLL+NLO	1	α_s	1-loop	2-loop	2-loop
NLL′+NLO	α_s	α_s	1-loop	2-loop	2-loop
NNLL+NLO	α_s	α_s	2-loop	3-loop	3-loop
NNLL+NNLO	α_s	α_s^2	2-loop	3-loop	3-loop
NNLL′+NNLO	α_s^2	α_s^2	2-loop	3-loop	3-loop
N^3LL+NNLO	α_s^2	α_s^2	3-loop	4-loop	4-loop

- "matching": singular FO corrections that act as boundary conditions in the resummation (α_s^n corrections to H, B, S reproduces full α_s^n singular)
- "full FO": adds FO nonsingular terms not included in the resummation

Profile Scales

- Resummation region: Logs are resummed using canonical scaling

$$\mu_H \sim -\mathrm{i} m_H$$

$$\mu_S \sim p_T^{\rm cut}, \nu_S \sim p_T^{\rm cut}$$

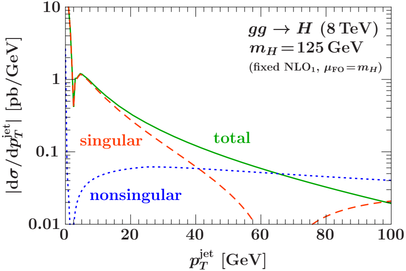
$$\mu_B \sim p_T^{\rm cut}, \nu_B \sim m_H$$

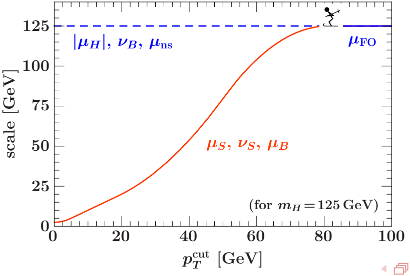
- FO region: Resummation turned off to ensure proper cancellation between singular and nonsingular terms by taking

$$\mu_B, \mu_S, \nu_S, \nu_B \to \mu_{\rm FO} \sim m_H$$

- Transition region: Profiles for $\mu_B, \mu_S, \nu_B, \nu_S$ provide smooth transition between both limits

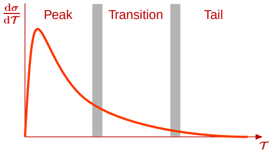
$\Rightarrow$ Ambiguity is a scale uncertainty





Interlude: Theory Uncertainties in Jet Binning

$$\sigma_{\text{total}} = \underbrace{\int_0^{p_T^{\text{cut}}} \mathrm{d}p_T \frac{\mathrm{d}\sigma}{\mathrm{d}p_T}}_{\sigma_0(p_T^{\text{cut}})} + \underbrace{\int_{p_T^{\text{cut}}}^{\infty} \mathrm{d}p_T \frac{\mathrm{d}\sigma}{\mathrm{d}p_T}}_{\sigma_{\geq 1}(p_T^{\text{cut}})}$$



$$\sigma_{\text{total}} = 1 + \alpha_s + \alpha_s^2 + \cdots$$

$$\sigma_{\geq 1}(p_T^{\text{cut}}) = \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \cdots$$

$$\begin{aligned}\sigma_0(p_T^{\text{cut}}) &= \sigma_{\text{total}} - \sigma_{\geq 1}(p_T^{\text{cut}}) \\ &= \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] - \left[\alpha_s(L^2 + \cdots) + \alpha_s^2(L^4 + \cdots) + \cdots\right]\end{aligned}$$

where $L = \ln(p_T^{\text{cut}}/Q)$

$\Rightarrow$ *Same* logarithms appear in the exclusive 0-jet and inclusive ($\geq$ 1)-jet cross section (and cancel in their sum)

Interlude: Theory Uncertainties in Jet Binning

$$\sigma_{\rm total} = \int_0^{p_T^{\rm cut}} \mathrm{d}p_T \frac{\mathrm{d}\sigma}{\mathrm{d}p_T} + \int_{p_T^{\rm cut}}^{\infty} \mathrm{d}p_T \frac{\mathrm{d}\sigma}{\mathrm{d}p_T} = \sigma_0(p_T^{\rm cut}) + \sigma_{\geq 1}(p_T^{\rm cut})$$

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

[Berger, Marcantonini, Stewart, FT, Waalewijn; Stewart, FT]

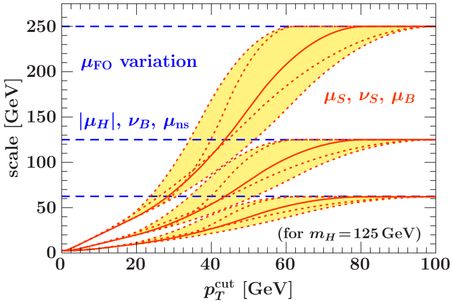
- General physical parametrization in terms of 100% correlated and 100% anticorrelated pieces

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

- Absolute “yield” uncertainty is fully correlated between bins
  - $\Delta_{\rm total}^{\rm y} = \Delta_0^{\rm y} + \Delta_{\geq 1}^{\rm y}$ reproduces FO unc. in $\sigma_{\rm total}$
- “Migration” unc. $\Delta_{\rm cut}$ due to binning (must drop out in sum $\sigma_0 + \sigma_{\geq 1}$)
  - $p_T^{\rm cut} \sim Q$: $\Delta_{\rm cut}$ small and can be neglected (FO tail region)
  - $p_T^{\rm cut} \ll Q$: $\Delta_{\rm cut}$ important, associated with unc. in $p_T^{\rm cut}$ log series

Uncertainties from Profile Scale Variations

Fixed-order scale variations



- Take max of collective up/down variation (+ where resum. turns off)

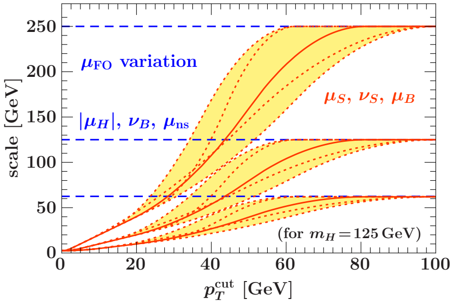
$\Rightarrow$ Equivalent to overall FO μ variation keeping logs fixed

$\Rightarrow$ Reproduces $\Delta^{\rm FO}_{\geq 0}$ for large $p_T^{\rm cut}$

$\Rightarrow$ $\Delta_i^{\rm y} = \Delta_{\mu i}$

Uncertainties from Profile Scale Variations

Fixed-order scale variations



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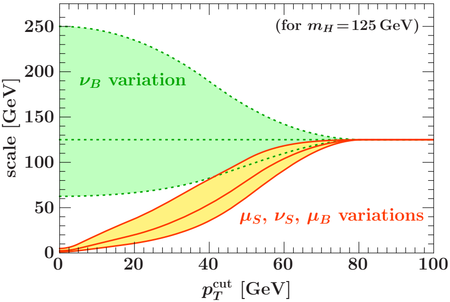
Resummation scale variations

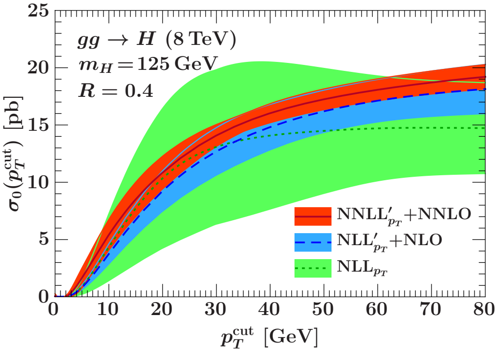


- Take maximum from separately varying all low scales (within canonical constraints)

$\Rightarrow$ Directly estimates size of logs and missing higher log terms

$\Rightarrow$ $\Delta_{\rm cut} = \Delta_{\rm resum}$

Resummed Results



Resummation Transition Fixed Order

(Here NNLL$_{p_T}$ refers to counting logarithms $\ln(p_T^{\rm cut}/m_H)$ only, but not $\ln R^2$)

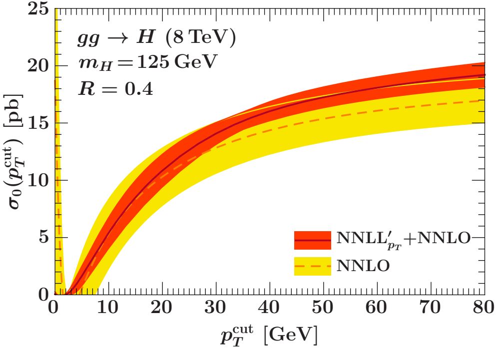
At NNLL$'_{p_T}$+NNLO

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

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

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

Resummed Results



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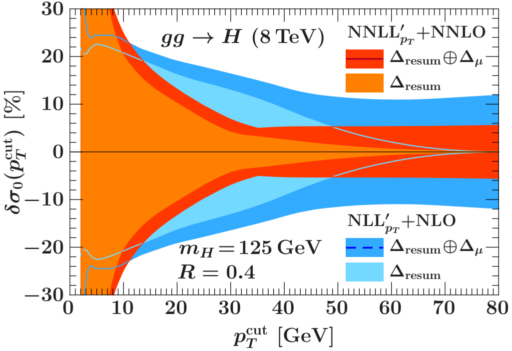

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Resummation Transition Fixed Order

- Resummed pert. theory shows good convergence and reduced uncertainties compared to fixed (N)NLO
- Resummation provides systematic assessment of full theory unc. matrix

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

Resummed Results

green: NLL_{p_T}
blue: NLL'_{p_T}+NLO
orange: NNLL'_{p_T}+NNLO

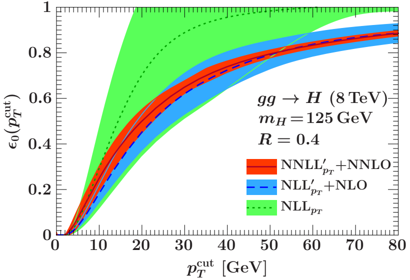
With full unc. matrix we can also make predictions for other quantities

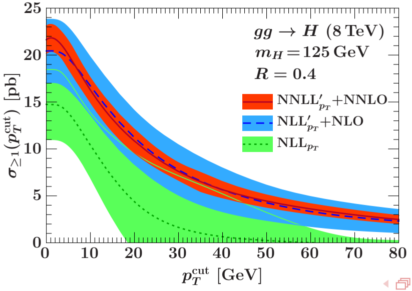
- 0-jet fraction (jet-veto efficiency)

$$\epsilon_0(p_T^{\mathrm{cut}}) = \sigma_0(p_T^{\mathrm{cut}})/\sigma_{\mathrm{total}}$$

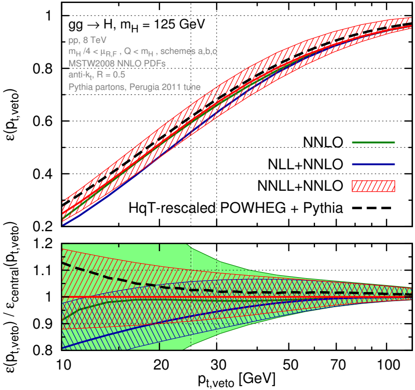
- incl. 1-jet cross section

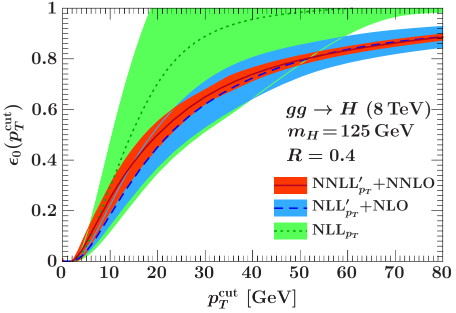
$$\sigma_{\geq 1}(p_T^{\mathrm{cut}}) = \sigma_{\mathrm{total}} - \sigma_0(p_T^{\mathrm{cut}})$$





Comparison to BMSZ



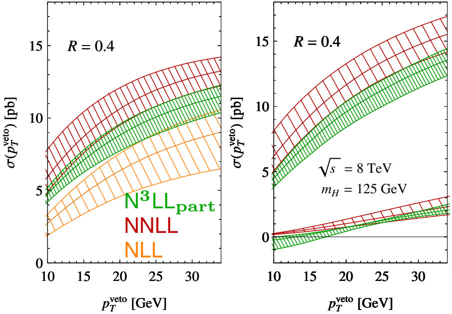


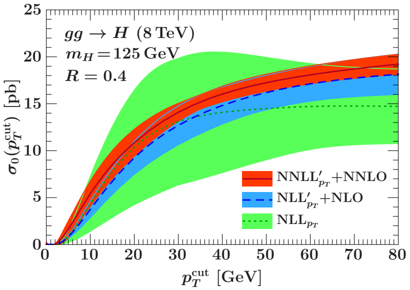
$$\epsilon_0(p_T^{\rm cut}) = \sigma_0(p_T^{\rm cut})/\sigma_{\rm total}$$

Banfi, Monni, Salam, Zanderighi [1203.5773, 1206.4998]

- Consider jet-veto efficiency as the primary quantity to resum
- Use QCD NNLL resummation for p_T^H [Bozzi, Catani, Grazzini] plus necessary correction terms to go from p_T^H to $p_T^{\rm jet}$

Comparison to BNR





Becher, Neubert, Rothen [1205.3806, 1307.0025]

- Use SCET-II together with “collinear anomaly” treatment to exponentiate rapidity logarithms
- Different organization of H, B, S, and nonsingular (similar uncertainties at highest order, but much poorer convergence)

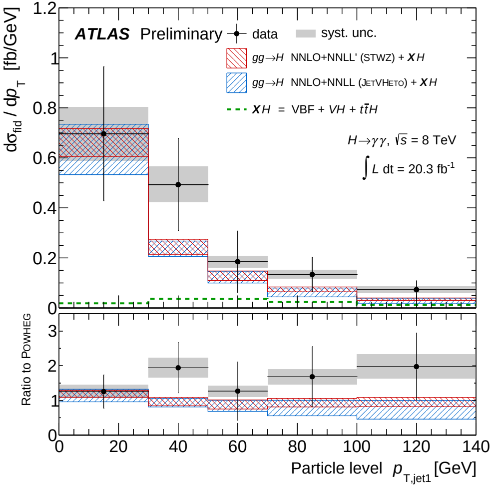
Comparison to ATLAS Data

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

- Crucial transition step from fitting μ-values to measuring fiducial cross sections
  - Presents expt. results as theory independent as possible
  - Can be (almost) directly compared to theory predictions

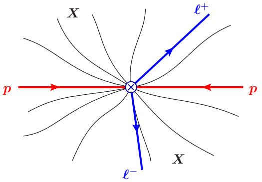
red: NNLL$'$+NNLO
(Stewart, FT, Walsh, Zuberi)

blue: NNLL+NNLO
(Banfi, Monni, Salam, Zanderighi)

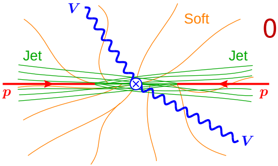


Combining Jet Bins

Combining Jet Bins

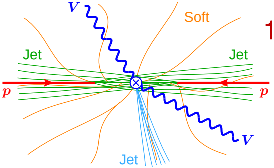


$=$



0-jet bin

$+$



1-jet bin

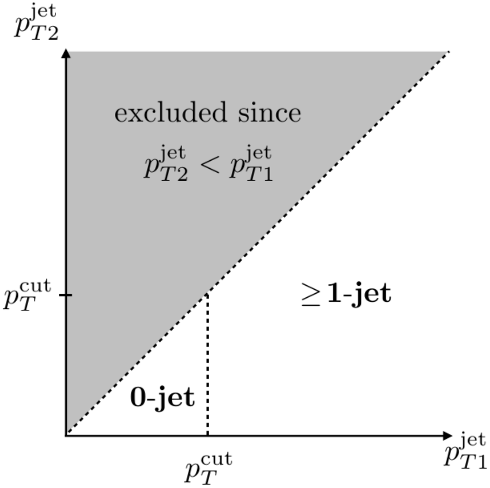
$+$ ≥ 2 jets $\cdots$

No event left behind

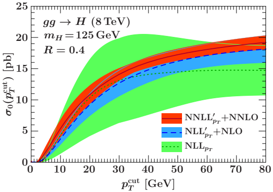
- Separating data into exclusive jet bins is advantageous when background decomposition depends on jet multiplicity
  - Can get substantial sensitivity gain by optimizing analysis in each jet bin
  - Primary example is $H \to WW$, also important in $H \to \tau\tau$, $H \to b\bar{b}$
- In the end, we want to combine results from all jet bins
  - Consistent theory description and theory unc. correlations are important

0-jet Bin Resummation

Resummation for leading jet p_T provides

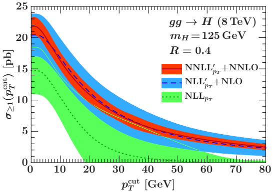


- 0-jet bin: $\sigma_0(p_T^{\rm cut})$



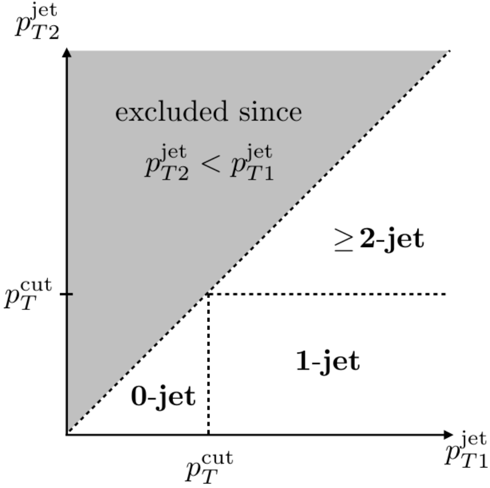
- $\geq$ 1-jet bin:

$$\sigma_{\geq 1}(p_T^{\rm cut}) = \sigma_{\rm total} - \sigma_0(p_T^{\rm cut})$$



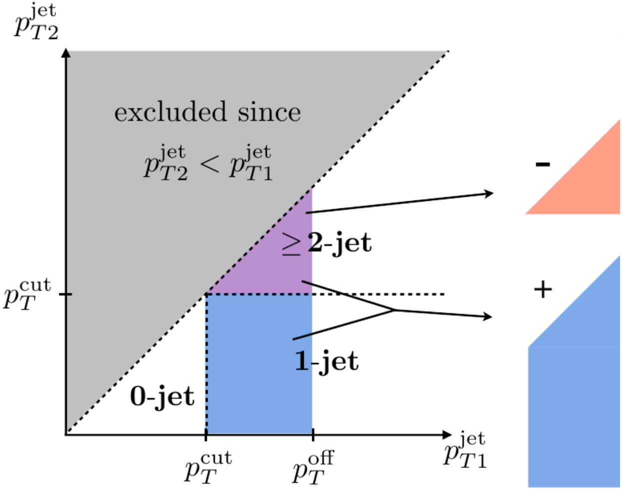
1-jet Bin Resummation

Exclusive 1-jet bin is a multi-scale problem: $p_{T2}^{\rm jet} \leq p_T^{\rm cut} < p_{T1}^{\rm jet} < m_H$



1-jet Bin Resummation: Low Leading Jet p_T

Exclusive 1-jet bin is a multi-scale problem: $p_T^{\mathrm{cut}} < p_{T1}^{\mathrm{jet}} < p_T^{\mathrm{off}}$



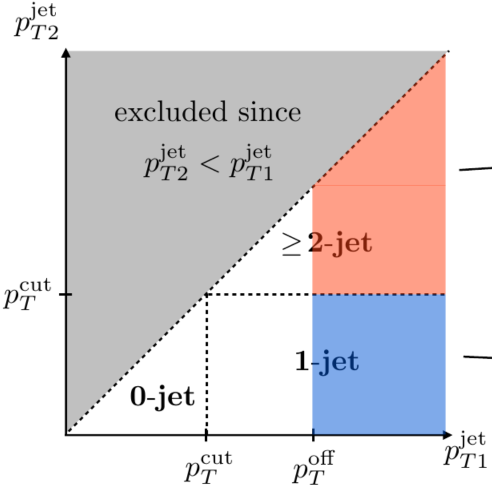
Indirect approach:

≥ 2-jet bin
fixed-order contribution
(small correction from ≥ 1-jet to exclusive 1-jet bin)

≥ 1-jet bin
resummed result

1-jet Bin Resummation: High Leading Jet p_T

Exclusive 1-jet bin is a multi-scale problem: $p_T^{\mathrm{cut}} < p_T^{\mathrm{off}} < p_{T1}^{\mathrm{jet}}$



Direct approach:

≥ 2-jet bin:

$$\sigma_{\geq 2}(p_T^{\mathrm{cut}}) = \sigma_{\geq 1}^{\mathrm{FO}} - \sigma_1(p_T^{\mathrm{cut}})$$

1-jet bin direct resummation:

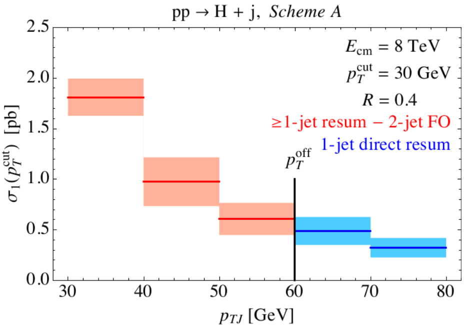
[Liu, Petriello]

resums $p_{T2}^{\mathrm{jet}} < p_T^{\mathrm{cut}}$
with p_{T1}^{jet} at fixed order

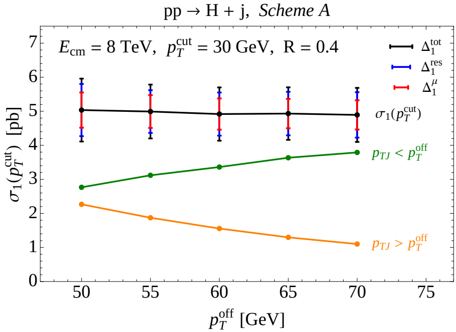
Combined 1-jet Bin Resummation

- Use indirect for $p_{T1}^{\mathrm{jet}} < p_T^{\mathrm{off}}$: p_{T1}^{jet} resummed, p_{T2}^{jet} at fixed order
- Use direct for $p_{T1}^{\mathrm{jet}} > p_T^{\mathrm{off}}$: p_{T1}^{jet} at fixed order, p_{T2}^{jet} resummed

Important to check that

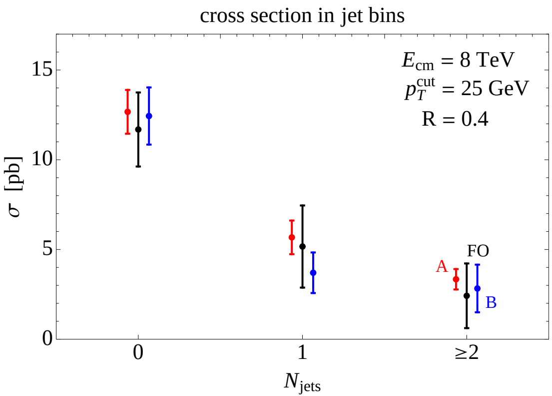


transition is smooth



and independent of precise p_T^{off}

Result for 0, 1, $\geq$ 2-jet Bins



red: default scheme (A)
(includes important α_s^3 virtual corrections:
π^2 resummation in H+0-jet
NNLO hard function in H+1-jet)

blue: scheme B
(resummation with singular matching strictly to α_s^2)

black: Fixed-order to α_s^2

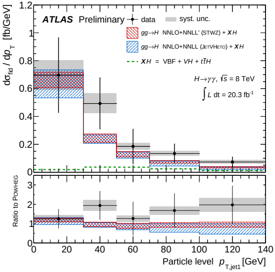
- Reduced theory uncertainties by factor of 2
  - Reduces signal yield uncertainty in $H \to WW$ by about factor of 2
- Framework allows us to assess full 3x3 theory correlation matrix
  - parametrized in terms of yield, 0-1 migration, and 1-2 migration

Summary

We have entered the era of Higgs measurements

$\Rightarrow$ Ultimate goal: Global coupling fit using only fully corrected fiducial cross section measurements

- Differential and exclusive jet measurements are of key importance
  - Requires precise resummed calculations
  - Precision demands reliable unc. and correlations (just small is not enough...)



p_T^{jet} resummation for jet vetoes and jet binning

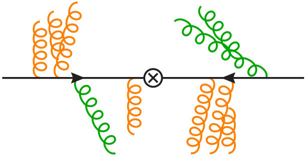
- $gg \to H +$ 0-jet cross section determined to full NNLL$'_{p_T}$ +NNLO
- Framework to consistently combine 0-jet and 1-jet bin resummations

Many more things I have not talked about

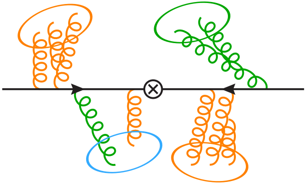
- Other channels (VH production, boosted $H \to b\bar{b}$, VBF-like 2-jet bin, VBF vs. gluon fusion separation, ...)
- Backgrounds, other exclusive variables
- Combining resummed predictions and unc. with Monte Carlos (GENEVA-MC)

Backup Slides

Jet-Veto Observables



"Global Veto"
restricts $\sum$ of all emissions

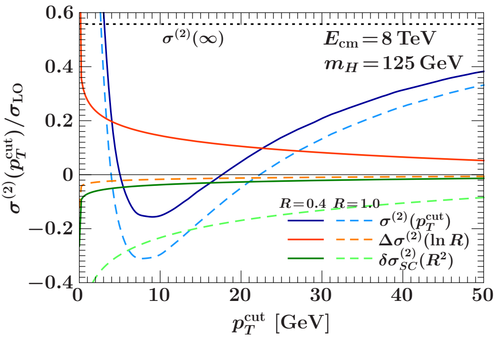


"Local Veto" restrict (local chunks of) individual emissions

SCET-I	beam thrust	"jet beam thrust"
(p^+-like scaling)	$\mathcal{T} = \sum_i E_i - \lvert p_i^z \rvert$	$\mathcal{T}^{\mathrm{jet}} = \sum_{i \in \mathrm{jet}} E_i - \lvert p_i^z \rvert$
SCET-II	"beam broadening"	jet p_T
($p_\perp$-like scaling)	$E_T = \sum_i p_{Ti}$	$\vec{p}_T^{\,\mathrm{jet}} = \sum_{i \in \mathrm{jet}} \vec{p}_{Ti}$

$\Rightarrow$ All are jet vetoes and technology exists to resum them (to at least NNLL)

Numerical Jet Algorithm Effects at NNLO



full 2-loop contribution with no veto

full 2-loop contribution with veto

clustering logs

soft-collinear mixing

For $R = 0.4$ (and also $R = 0.5$)

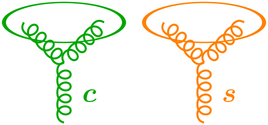
- Clustering $\ln R^2$ contributions are sizable
- Uncorrelated emission contributions (soft-collinear mixing) can safely be treated as $\mathcal{O}(R^2)$ power suppressed

$\Rightarrow$ Suggests that one should count $R^2 \sim p_T^{\rm cut}/m_H \ll 1$

Clustering Logarithms

$$\mathcal{M}^{\rm jet} = \left(\mathcal{M}^G_{n_a} + \Delta\mathcal{M}^{\rm jet}_{n_a}\right)\left(\mathcal{M}^G_{n_b} + \Delta\mathcal{M}^{\rm jet}_{n_b}\right)\left(\mathcal{M}^G_{s} + \Delta\mathcal{M}^{\rm jet}_{s}\right) + \delta\mathcal{M}^{\rm jet}$$

$\Delta\mathcal{M}^{\rm jet}_n$, $\Delta\mathcal{M}^{\rm jet}_s$: Correction from clustering of correlated emissions within soft and beam sectors



Gives rise to logs of R, leading clustering logs are

$$\frac{\Delta\sigma^{(n)}}{\sigma_B} = C_n(R)\left(\frac{\alpha_s C_A}{\pi}\right)^n \ln\frac{m_H}{p_T^{\rm cut}}\ \ln^{n-1} R^2$$

- For $R^2 \sim p_T^{\rm cut}/m_H \ \to\ \alpha_s^n L^n$ NLL series in the exponent that *cannot* be resummed at present
- Full $\alpha_s^2 C_2(R)$ term first computed by BMSZ

$\Rightarrow$ In SCET, these appear in the noncusp anomalous dimensions, allowing one to resum the $\ln(p_T^{\rm cut}/m_H)$ at NNLL$_{p_T}$ [FT, Walsh, Zuberi]

Resummation + Fixed Order Matching

Log counting is in the exponent of the cross section

(where $\mathrm{d}\sigma$ exponentiates in the appropriate space, e.g. Fourier space for thrust)

$$\ln[\mathrm{d}\sigma] \sim \sum_n \alpha_s^n L^{n+1}(1+\alpha_s+\alpha_s^2+\cdots) \sim \text{LL} + \text{NLL} + \text{NNLL} + \cdots$$

Conventions:	Fixed-order corrections		Resummation input		
	H,B,J,S (sing.)	nonsingular	$\gamma_{H,B,J,S}$	Γ_{cusp}	β
NLL	$\mathcal{O}(1)$	-	1-loop	2-loop	2-loop
NLL′+NLO	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	1-loop	2-loop	2-loop
NNLL+NLO	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	2-loop	3-loop	3-loop
NNLL′+NNLO	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$	2-loop	3-loop	3-loop
N^3LL+NNLO	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$	3-loop	4-loop	4-loop

$$\mathrm{d}\sigma^{\mathrm{FO}}(\mu_{\mathrm{FO}}) = \underbrace{\mathrm{d}\sigma^{\mathrm{sing}}(\mu_{\mathrm{FO}})} + \mathrm{d}\sigma^{\mathrm{ns}}(\mu_{\mathrm{FO}})$$

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{resum}}(\mu_S,\mu_J,\mu_H) + \mathrm{d}\sigma^{\mathrm{ns}}(\mu_{\mathrm{FO}})$$

(With H, B, J, S at α_s^k $\to$ $\mathrm{d}\sigma^{\mathrm{resum}}(\mu_S=\mu_J=\mu_H=\mu_{\mathrm{FO}}) = \mathrm{d}\sigma^{\mathrm{s}}(\mu_{\mathrm{FO}})$ to α_s^k)