# Jet vetoes and resummation

Xiaohui Liu

In collaboration with Frank Petriello

arXiv:1210.1906, arXiv:1303.4405

LoopFest XII, Florida State University

Argonne National Laboratory

NORTHWESTERN UNIVERSITY

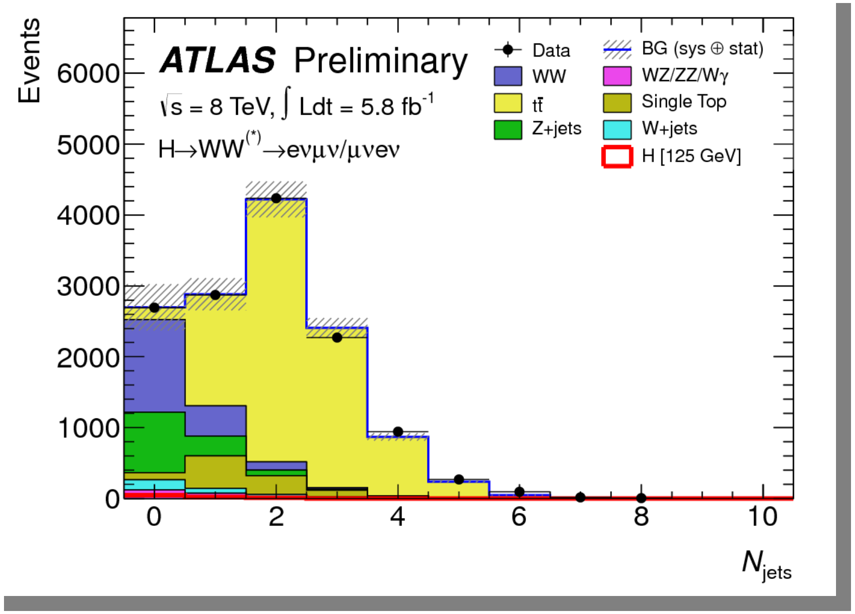
# Outline

- Motivation
- H + 1j with jet veto
- Summary

# Theory issues

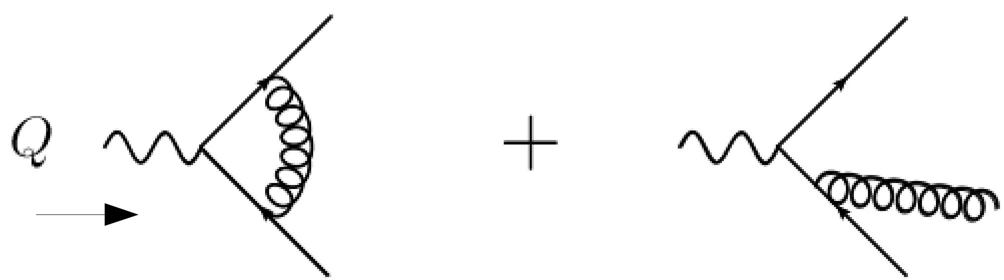
- Jet bin cross section
  - Higgs measurement, BSM search ...
  - Beat the backgrounds
    - Use 25-30 GeV jet cut, restrict QCD activity

$$p_T^{veto} \sim 25\text{GeV} \ll Q \sim m_H \sim 125\text{GeV}$$

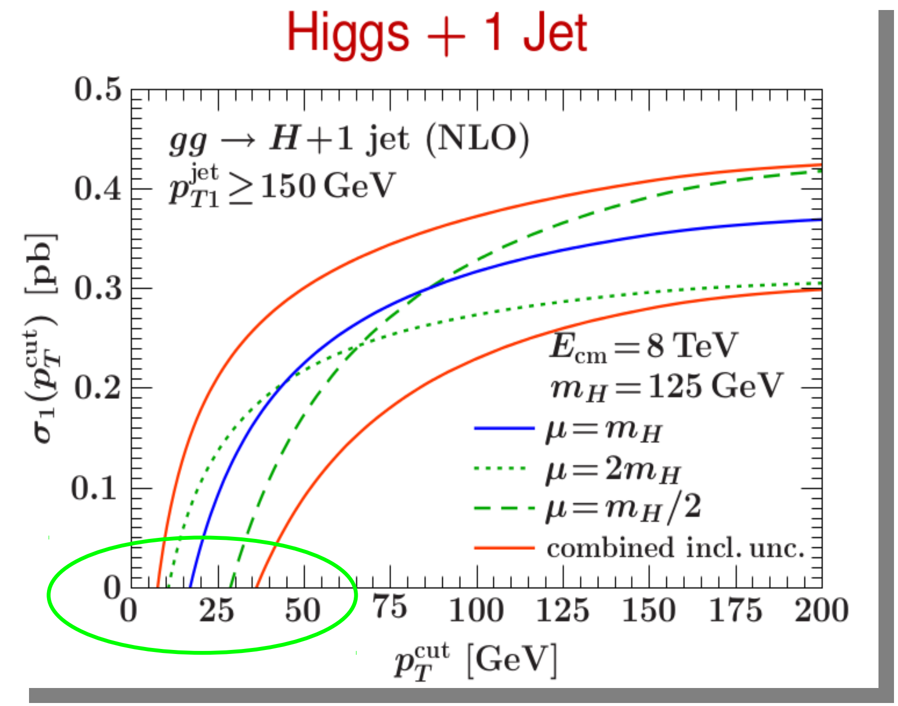


# Theory issues

- Jet bin cross section
  - Theoretical issues
    - Fixed order breaks down
      - Jet veto logs




$$\propto -\frac{1}{\epsilon_{\rm IR}^2} - \frac{1}{\epsilon_{\rm IR}} \qquad \propto \frac{1}{\epsilon_{\rm IR}^2} + \frac{1}{\epsilon_{\rm IR}} + \log^2 \frac{p_T^{veto}}{Q} + \log \frac{p_T^{veto}}{Q}$$




Stewart and Tackmann '11

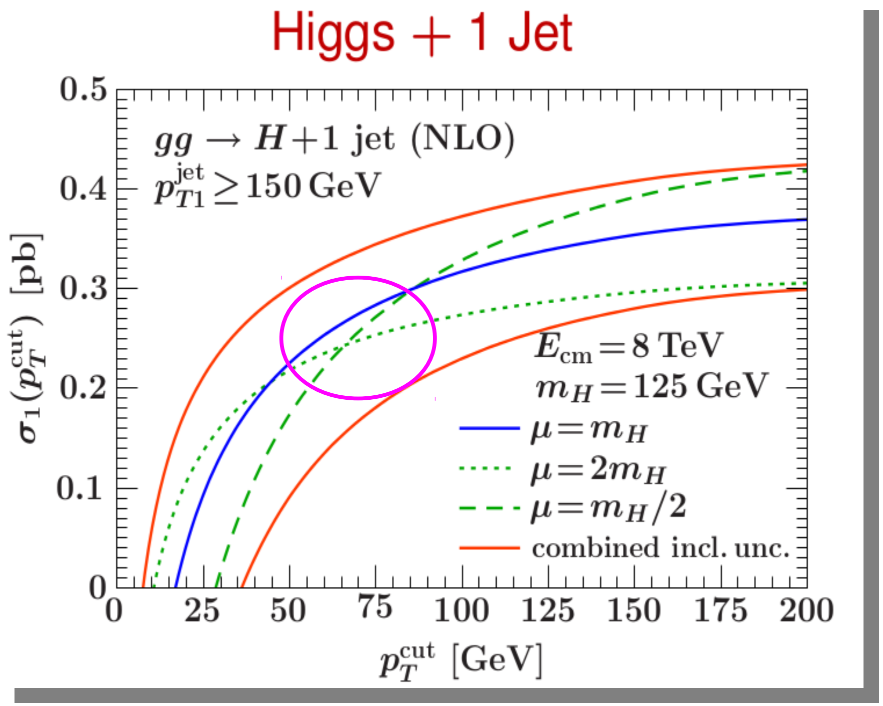
# Theory issues

- Jet bin cross section
  - Theoretical issues
    - Fixed order breaks down
    - Unreliable uncertainty

$$\sigma_{=1j}(p_{T1}^J, p_{\rm cut}) = \sigma^{\geq 1j}(p_{T1}^J) - \sigma^{\geq 2j}(p_{T1}^J, p_{T2}^J > p_{\rm cut})$$

$$\sigma^{\geq 1j}_{p_{T1}^J \geq 120\rm GeV} = (0.31\rm pb)\left[1 + 2.9\alpha_s + \mathcal{O}(\alpha_s^2)\right]$$

$$\sigma^{\geq 2j}_{p_{T1}^J \geq 120\rm GeV, p_{T2}^J \geq 60\rm GeV} = (0.31\rm pb)\left[3.7\alpha_s + \mathcal{O}(\alpha_s^2)\right]$$



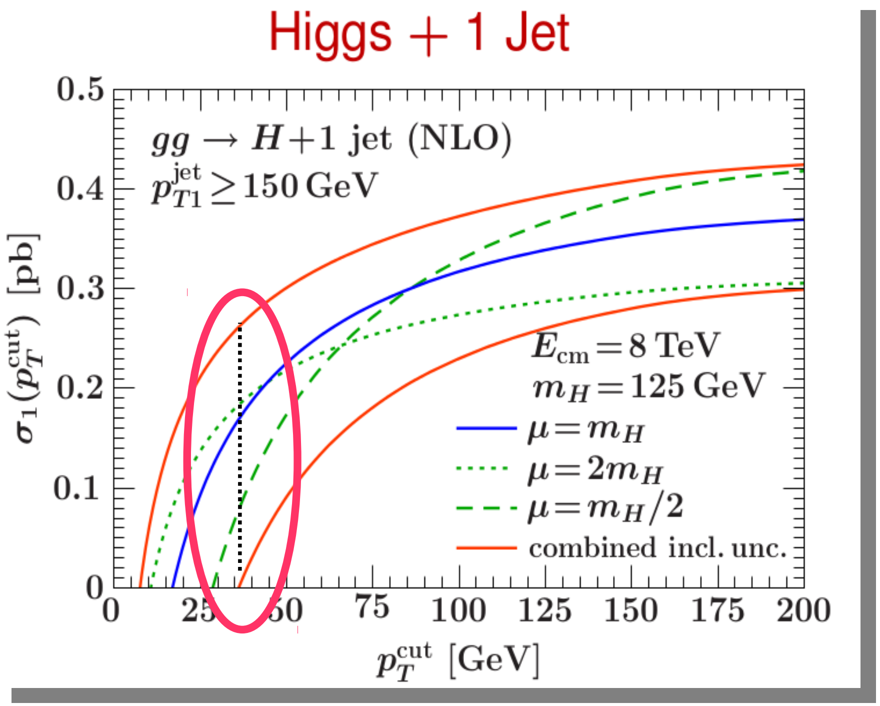

Accidental cancellation between large virtual corrections and logarithms leads to reduced scale errors. Does not necessarily persist to all orders

# Theory issues

- Jet bin cross section
  - Theoretical issues
    - Fixed order breaks down
    - Unreliable uncertainty
    - ST prescription (Stewart and Tackmann '11)
      - Large theoretical errors

Fixed order uncertainty:

$$\delta_{1j}^2 = \delta_{>1j}^2 + \delta_{>2j}^2$$

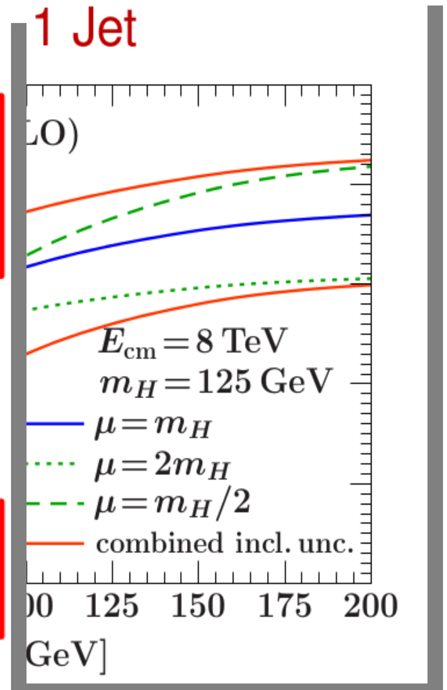


# Theory issues

- Jet bin cross section
  - Theoretic
    - Fixed or
    - Unreliab
    - ST pres
      - Large

fix o

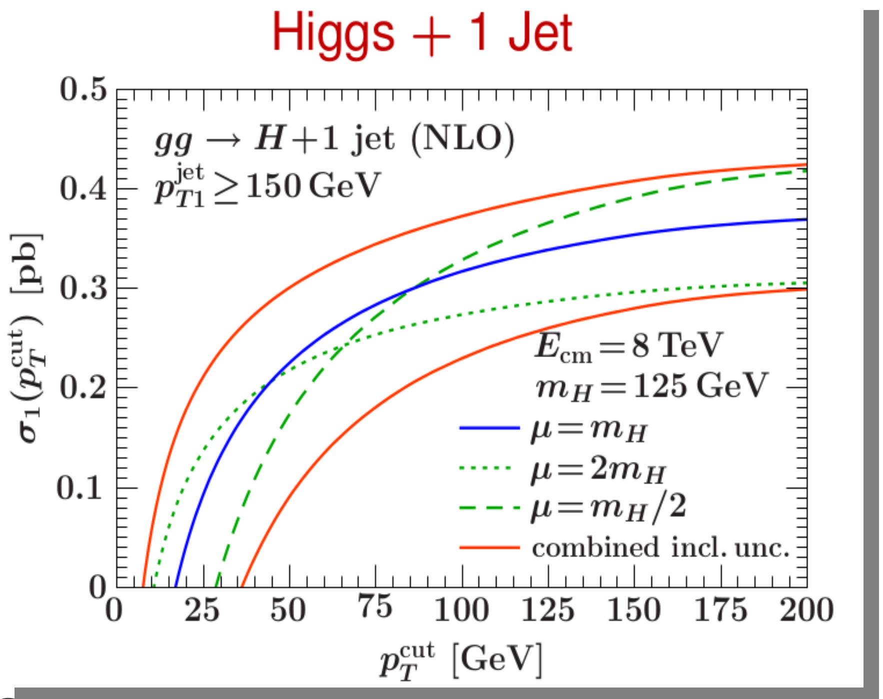
| Source (0-jet) | Signal (%) | Bkg. (%) |
|---|---|---|
| Inclusive ggF signal ren./fact. scale | 13 | - |
| 1-jet incl. ggF signal ren./fact. scale | 10 | - |
| PDF model (signal only) | 8 | - |
| QCD scale (acceptance) | 4 | - |
| Jet energy scale and resolution | 4 | 2 |
| *W*+jets fake factor | - | 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 |




Higgs Measurement: Theoretical errors dominate over the other uncertainty sources

# Theory issues

- Jet bin cross section
  - Theoretical issues
    - Fixed order breaks down
    - Unreliable uncertainty
    - ST prescription (Stewart and Tackmann '11)
      - Large theoretical errors




  - Have to sum up jet veto logs
    - Improve accuracy systematically
    - Reliable error estimations

Not only for Higgs
Also true
for Z,W or NP and etc.

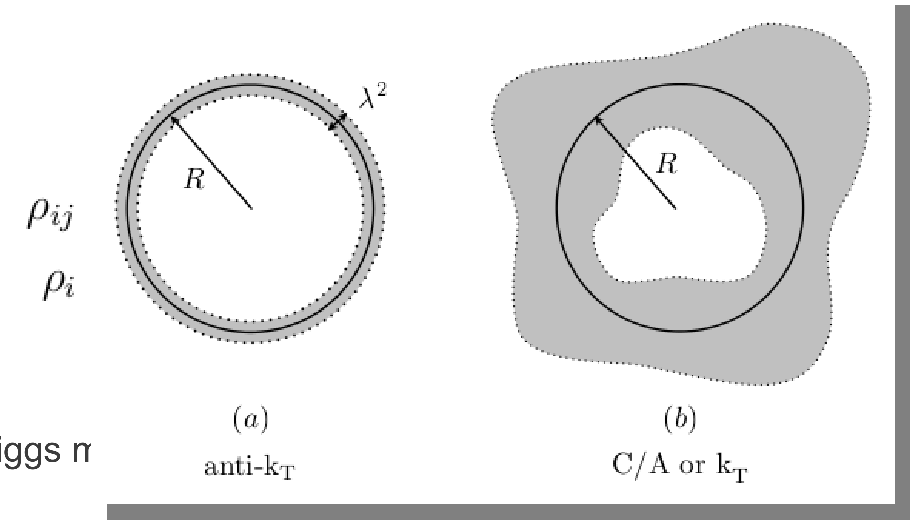
# Processes with jet vetoes

- N(H/W/Z) + n-j (XL and Petriello, '12)
  - anti-kT $R \sim 0.4 - 0.5$
  - pT veto $p_T^{veto} \sim 25 - 30\mathrm{GeV}$
  - pTJ >> pT veto (important for current higgs measurement, will see ...)

$$\begin{aligned} \rho_{ij} &= \min(p_{T,i}^{-1}, p_{T,j}^{-1}) \Delta R_{ij}/R, \\ \rho_i &= p_{T,i}^{-1}. \end{aligned}$$

# Processes with jet vetoes

- N(H/W/Z) + n-j (XL and Petriello, '12)
  - anti-kT $R \sim 0.4 - 0.5$
  - pT veto $p_T^{veto} \sim 25 - 30\text{GeV}$
  - pTJ >> pT veto (important for current higgs m

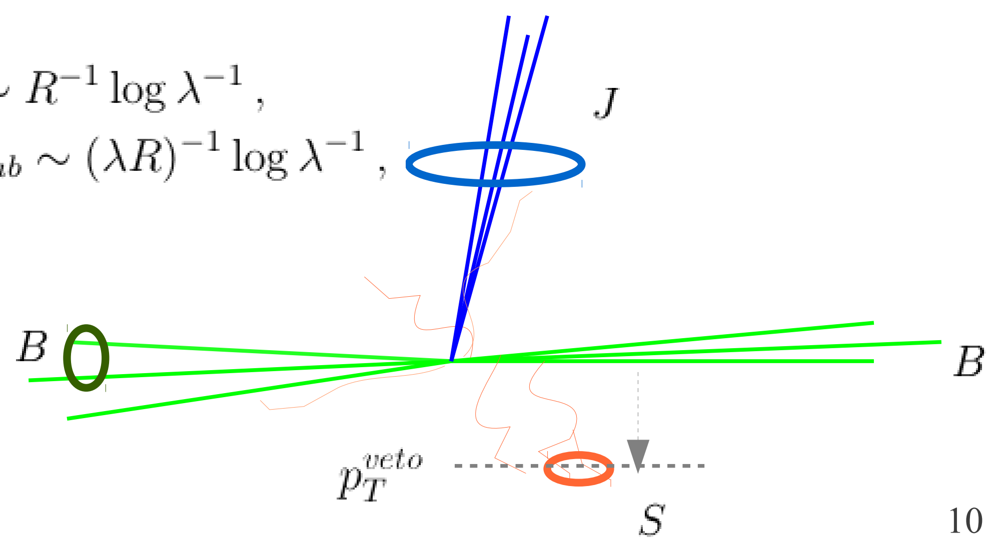



- Factorizability (Kelly, Walsh and Zuberi, '11, Becher, Neubert, '12, Tackmann, Walsh, Zuber,i'12 XL, Petriello'12)

$$\rho_{JJ} \lesssim \rho_J \sim 1\,, \quad \rho_{Js} \sim R^{-1}\,, \quad \rho_{Ja} \sim \rho_{Jb} \sim R^{-1}\log\lambda^{-1}\,,$$
$$\rho_{ss} \sim \rho_{aa} \sim \rho_{bb} \sim (\lambda R)^{-1}\,, \quad \rho_{sa} \sim \rho_{sb} \sim \rho_{ab} \sim (\lambda R)^{-1}\log\lambda^{-1}\,,$$
$$\rho_s \sim \rho_a \sim \rho_b \sim \lambda^{-1}\,.$$

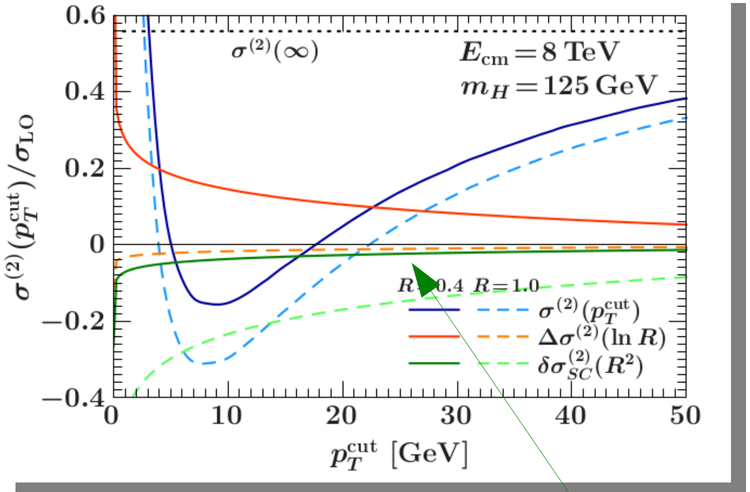
$$p_s \sim Q(\lambda, \lambda, \lambda) \quad \text{soft}$$
$$p_c \sim Q(1, \lambda^2, \lambda) \quad \text{collinear}$$

$$\lambda \equiv \frac{p_T^{veto}}{m_H} \lesssim 0.2$$



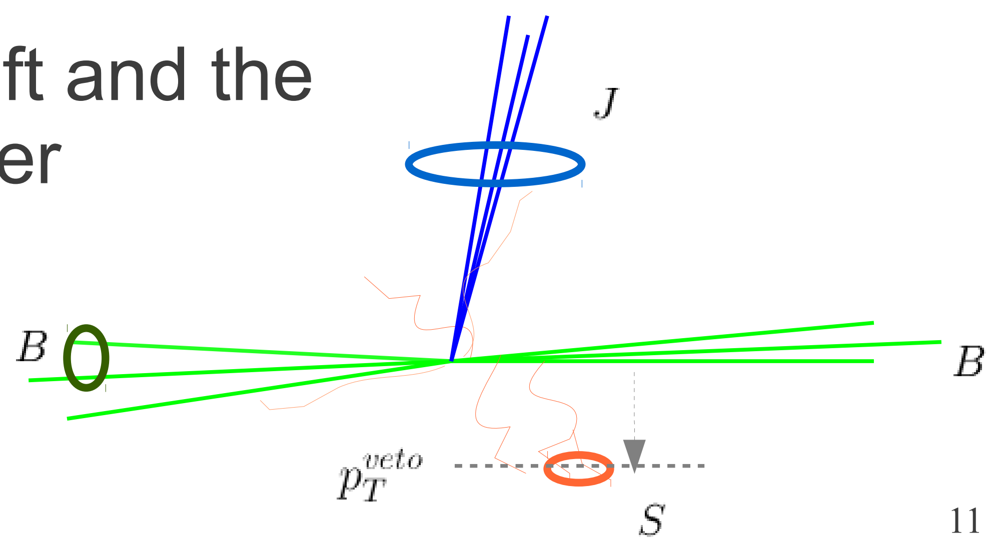
# Processes with jet vetoes

- N(H/W/Z) + n-j
  - anti-kT $R \sim 0.4 - 0.5$
  - pT veto $p_T^{veto} \sim 25 - 30\text{GeV}$
  - pTJ >> pT veto (important for current higgs measurement, will see ...)




Tackmann, Walsh, Zuberi '12

- Factorizability
  - Mixing between the soft and the beam sectors are power suppressed



# Processes with jet vetoes

- N(H/W/Z) + n-j
  - Factorization

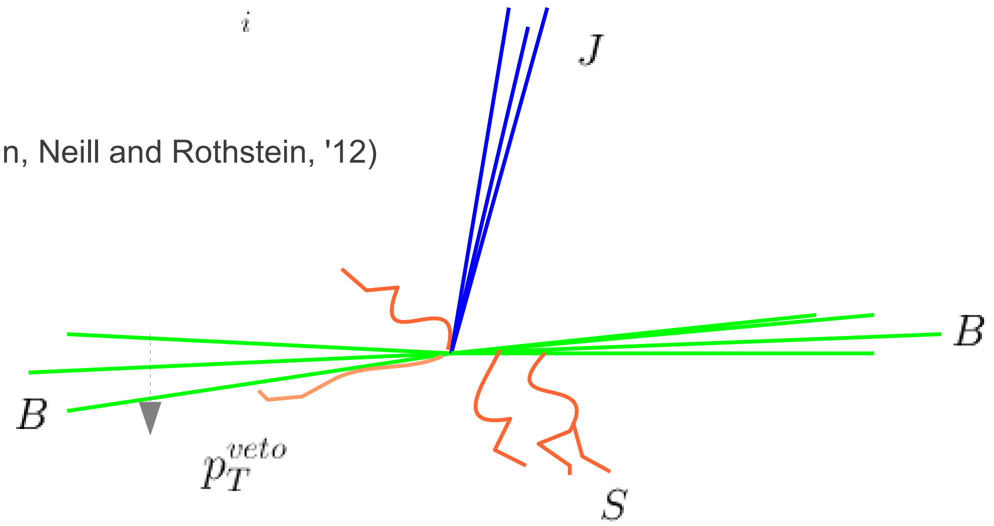
$$d\sigma = d\Phi_N d\Phi_{J_i}\, \mathcal{F}(\Phi_N, \Phi_{J_i}) \sum_{a,b} \int dx_a dx_b \frac{1}{2\hat{s}} (2\pi)^4 \delta^4 \left( q_a + q_b - \sum_i^n q_{J_i} - q_N \right)$$

$$\times \bar{\sum_{\text{spin}}} \bar{\sum_{\text{color}}} \mathrm{Tr}(H \cdot S)\, \mathcal{I}_{a,i_a j_a} \otimes f_{j_a}(x_a)\, \mathcal{I}_{b,i_b j_b} \otimes f_{j_b}(x_b) \prod_i^n J_{J_i}(R)$$

  - Rapidity regulator (Chiu, Jain, Neill and Rothstein, '12)

$$W_n \to \sum_{\text{perm.}} \exp\left( -g_s \frac{1}{\bar{\mathcal{P}}} \left[ w^2 \frac{|\bar{\mathcal{P}}|^{-\eta}}{\nu^{-\eta}} \bar{n} \cdot A_n \right] \right),$$

$$S_n \to \sum_{\text{perm.}} \exp\left( -g_s \frac{1}{\mathcal{P}} \left[ w \frac{|2\mathcal{P}^3|^{-\eta/2}}{\nu^{-\eta/2}} n \cdot A_s \right] \right),$$



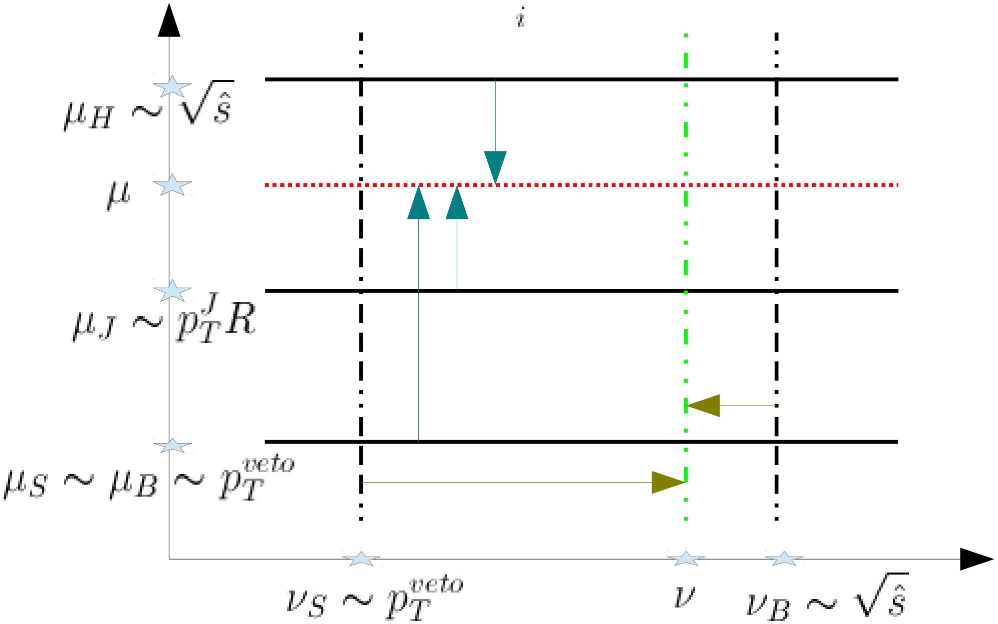
# Processes with jet vetoes

- N(H/W/Z) + n-j
  - Factorization

$$d\sigma = d\Phi_N d\Phi_{J_i}\, \mathcal{F}(\Phi_N, \Phi_{J_i}) \sum_{a,b} \int dx_a dx_b \frac{1}{2\hat{s}} (2\pi)^4 \delta^4 \left( q_a + q_b - \sum_i^n q_{J_i} - q_N \right)$$

$$\times \sum_{\text{spin}}^{-} \sum_{\text{color}}^{-} \text{Tr}(H \cdot S)\, \mathcal{I}_{a,i_a j_a} \otimes f_{j_a}(x_a)\, \mathcal{I}_{b,i_b j_b} \otimes f_{j_b}(x_b) \prod_i^n J_{J_i}(R)$$

  - Resummation




(Chiu, Jain, Neill and Rothstein, '12)

# Processes with jet vetoes

- N(H/W/Z) + 1-j
  - NLL'

$$\mathrm{d}\sigma_{\mathrm{NLL}'} = \mathrm{d}\Phi_H \mathrm{d}\Phi_J \, \mathcal{F}(\Phi_H, \Phi_J) \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b \frac{1}{2\hat{s}} (2\pi)^4 \delta^4 (q_a + q_b - q_J - q_H)$$
$$\times \bar{\sum_{\mathrm{spin}}} \bar{\sum_{\mathrm{color}}} \mathrm{Tr}(H \cdot S) \, \mathcal{I}_{a,i_a j_a} \otimes f_{j_a}(x_a) \mathcal{I}_{b,i_b j_b} \otimes f_{j_b}(x_b) J_J(R) \, .$$

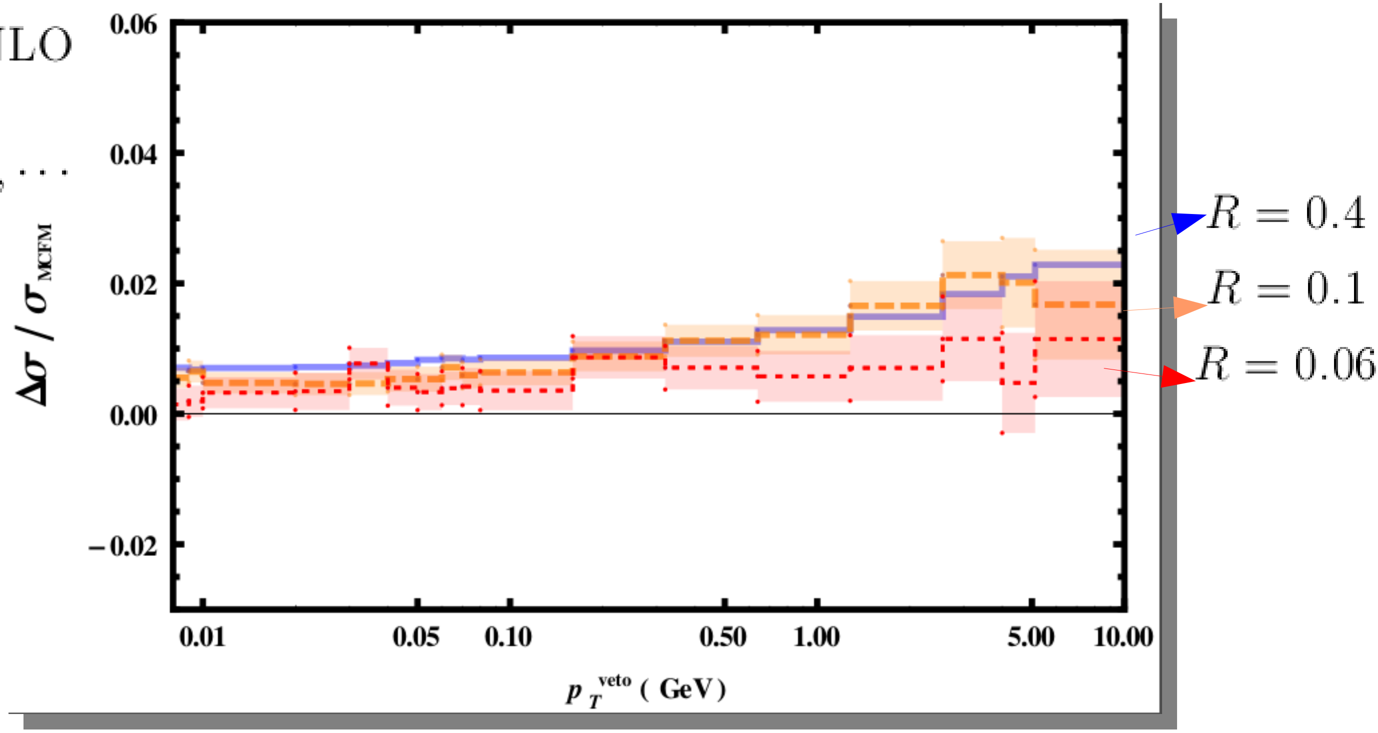
- Jet function $\Delta R = \Delta\eta^2 + \Delta\Phi^2 \to 2\cosh\Delta\eta - 2\cos\Delta\Phi$

# Processes with jet vetoes

- Numerics (Higgs+1j)
  - Demonstration

$$\Delta\sigma = \sigma^{exp}_{\mathrm{NLL}'} - \sigma_{\mathrm{NLO}}$$

$$\Delta\sigma \supset R^2 L, \frac{p_T^{veto}}{Q} L, \cdots$$



# Processes with jet vetoes

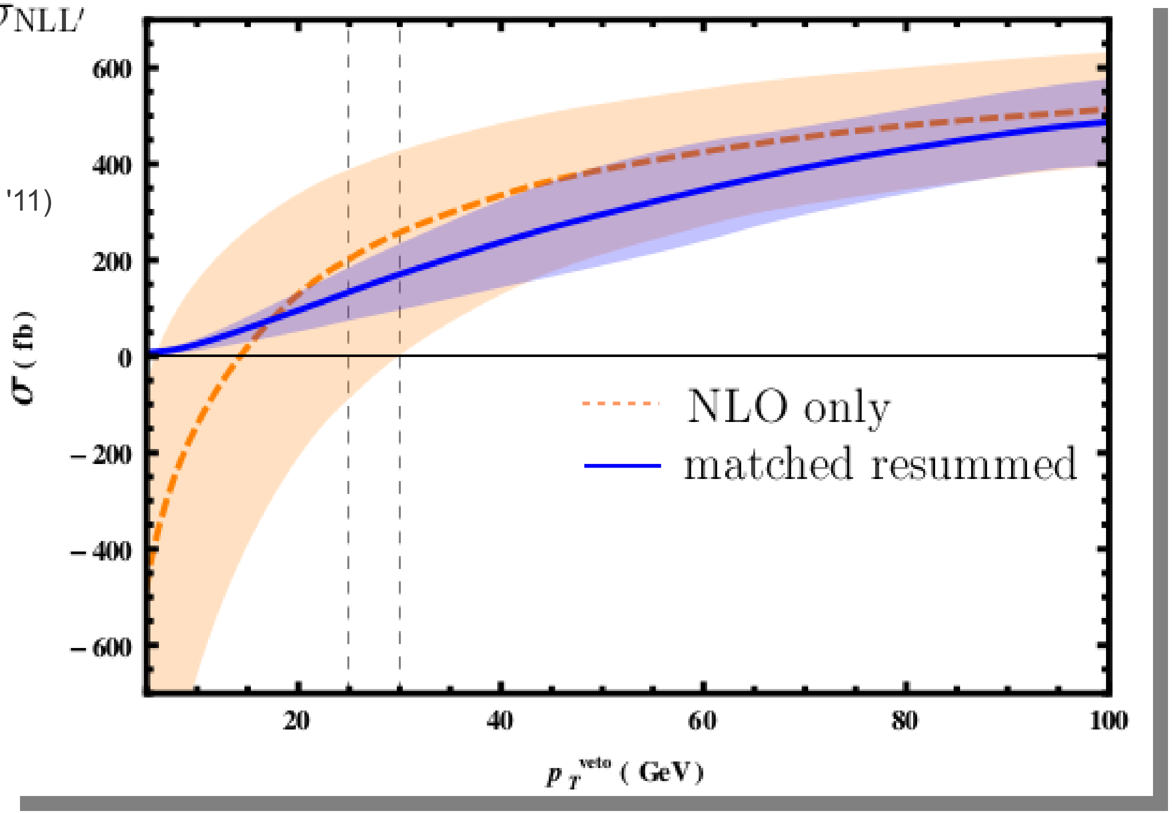
- Numerics (Higgs+1j)
  - High pTj

$$\text{matching}: \sigma_{\text{NLO}} - \sigma^{exp}_{\text{NLL}'} + \sigma_{\text{NLL}'}$$

$$\text{fix order}: \delta^2_{1j} = \delta^2_{>1j} + \delta^2_{>\ 2j}$$

(Stewart and Tackmann '11)

$$\text{resum}: \delta^2_{1j} = \sum_{\mu_i,\nu_i} \delta^2_{\mu_i} + \delta^2_{\nu_i}$$



# Processes with jet vetoes

- Numerics (Higgs+1j)
  - Entire Spectrum
    - Non-negligible contributions from high ptj region
    - Large uncertainty driven by the errors in high ptj region
    - Our formalism can be used to greatly reduce the errors

| NLO: | $\sigma(p_T^J > 30)(\text{pb})$ | $\sigma(63 > p_T^J > 30)(\text{pb})$ | $\sigma(p_T^J > 63)(\text{pb})$ |
|---|---|---|---|
| $\mu = m_H/2$ | $5.2^{+1.65}_{-2.12}$ | $3.9^{+1.01}_{-0.95}$ | $1.3^{+0.75}_{-1.30}$ |

XL and Petriello'12, XL and Petriello'13

# Processes with jet vetoes

- Numerics (Higgs+1j)
  - Entire Spectrum
    - Matching

$$\text{resum}: \ \delta^2_{1j} = \sum_{\mu_i,\nu_i} \delta^2_{\mu_i} + \delta^2_{\nu_i}$$

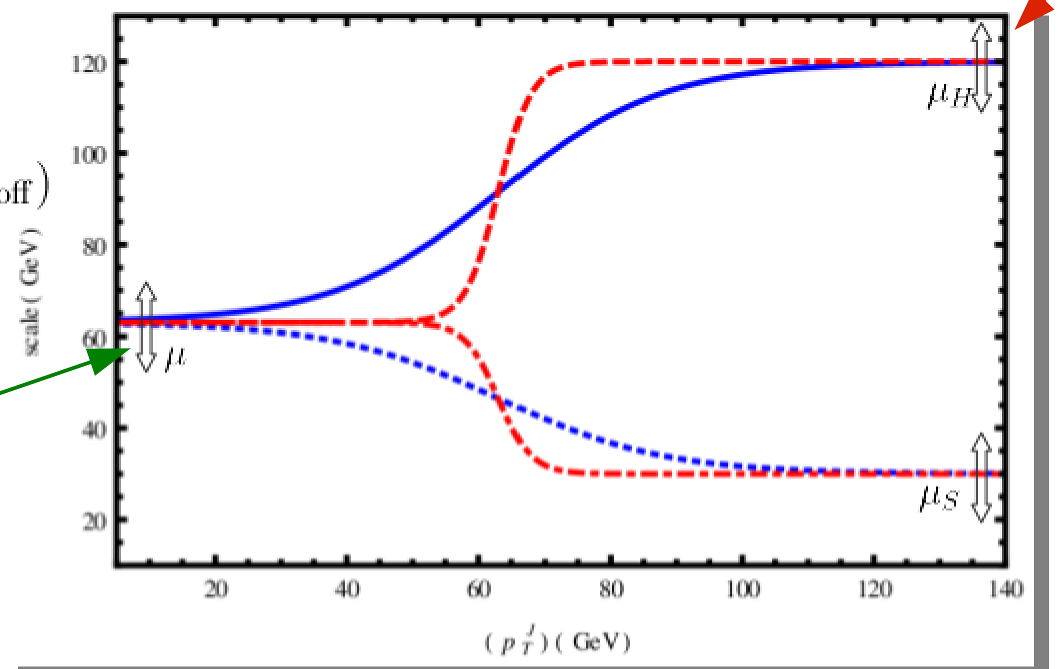
$$\text{matching}: \sigma_{\text{NLO}} - \sigma^{exp}_{\text{NLL}'} + \sigma_{\text{NLL}'}$$

$$\mu_i^{int.} = \mu + (\mu_i - \mu)\left[1 + \tanh\left(\kappa\left(p_T^J - p_{\text{off}}\right)\right)\right]/2\,,$$

    - Uncertainty

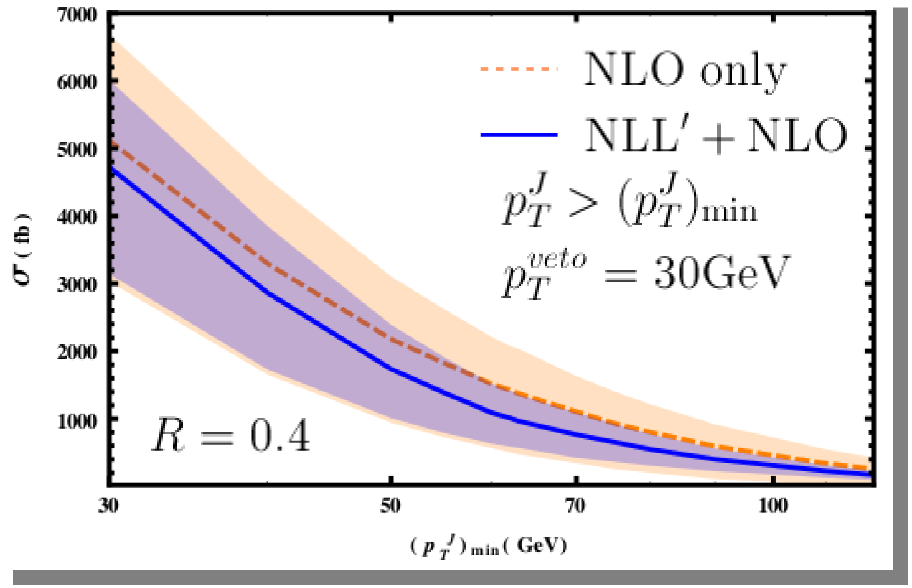
$$\delta = \delta(p_T^J < p_{\text{off}}) + \delta(p_T^J > p_{\text{off}})$$

$$\text{fix order}: \ \delta^2_{1j} = \delta^2_{>1j} + \delta^2_{>\,2j}$$



# Processes with jet vetoes

- Numerical consequence
  - Higgs + 1j
    - Entire Spectrum
      - Conservative error estimation
      - Up to 25% reduction in the uncertainty




| $m_H$ (GeV) | $p_T^{veto}$ (GeV) | $\sigma_{\mathrm{NLO}}$ (pb) | $\sigma_{\mathrm{NLL}'+\mathrm{NLO}}$ (pb) | $f^{1j}_{\mathrm{NLO}}$ | $f^{1j}_{\mathrm{NLL}'+\mathrm{NLO}}$ |
|---|---|---|---|---|---|
| 124 | 25 | $5.92^{+35\%}_{-46\%}$ | $5.62^{+29\%}_{-30\%}$ | $0.299^{+38\%}_{-49\%}$ | $0.283^{+33\%}_{-34\%}$ |
| 125 | 25 | $5.85^{+34\%}_{-46\%}$ | $5.55^{+29\%}_{-30\%}$ | $0.300^{+37\%}_{-49\%}$ | $0.284^{+33\%}_{-33\%}$ |
| 126 | 25 | $5.75^{+35\%}_{-46\%}$ | $5.47^{+30\%}_{-30\%}$ | $0.300^{+38\%}_{-49\%}$ | $0.284^{+34\%}_{-33\%}$ |
| 124 | 30 | $5.25^{+31\%}_{-41\%}$ | $4.83^{+29\%}_{-29\%}$ | $0.265^{+35\%}_{-43\%}$ | $0.244^{+33\%}_{-33\%}$ |
| 125 | 30 | $5.19^{+32\%}_{-41\%}$ | $4.77^{+30\%}_{-29\%}$ | $0.266^{+35\%}_{-43\%}$ | $0.244^{+33\%}_{-33\%}$ |
| 126 | 30 | $5.12^{+32\%}_{-41\%}$ | $4.72^{+30\%}_{-29\%}$ | $0.266^{+35\%}_{-43\%}$ | $0.246^{+33\%}_{-32\%}$ |



XL and Petriello'12, XL and Petriello'13

# Extra comment

- Non-global logs for H+1j XL and Petriello'13
  - Occurs only in high ptj region starting at NLL'
  - Can be resummed in large Nc limit Dasgupta and Salam'13
  - Contribute roughly 3% to high ptj region at NLL'
  - Contribute around 0.1% to the total cross section

# Summary

- Formalism to understanding jet bin cross section has been established (not only Higgs)
- More reliable prediction and reduced theory uncertainty
- Error estimation should be revised using the resummed results for higgs + 0j and higgs +1j
- Fine tuning work worth probing (higher accuracy, log(R) issue, non-global logs, etc..)

Thanks