Combining Resummed Higgs Predictions Across Jet Bins

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work with R. Boughezal, F. Petriello, F. Tackmann and J. Walsh

Higgs + Jets @ IPPP Durham, 2014

UNIVERSITY OF MARYLAND

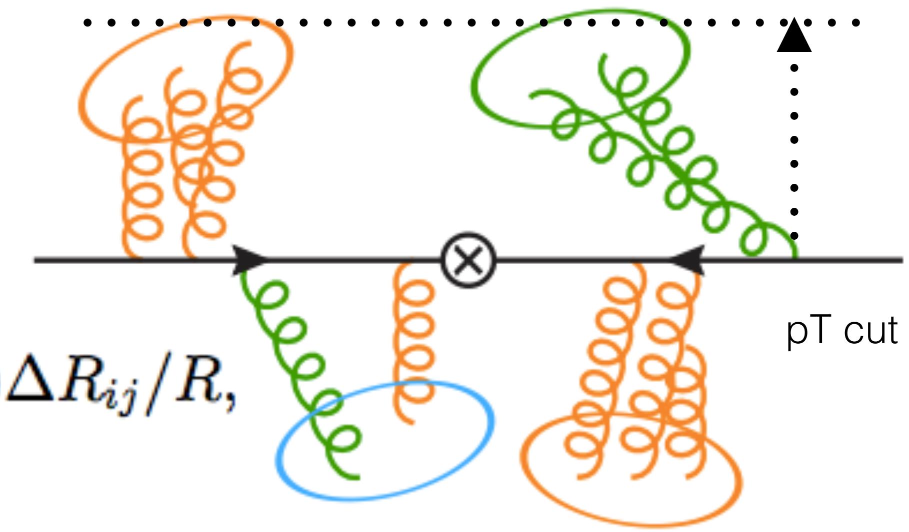
Outline

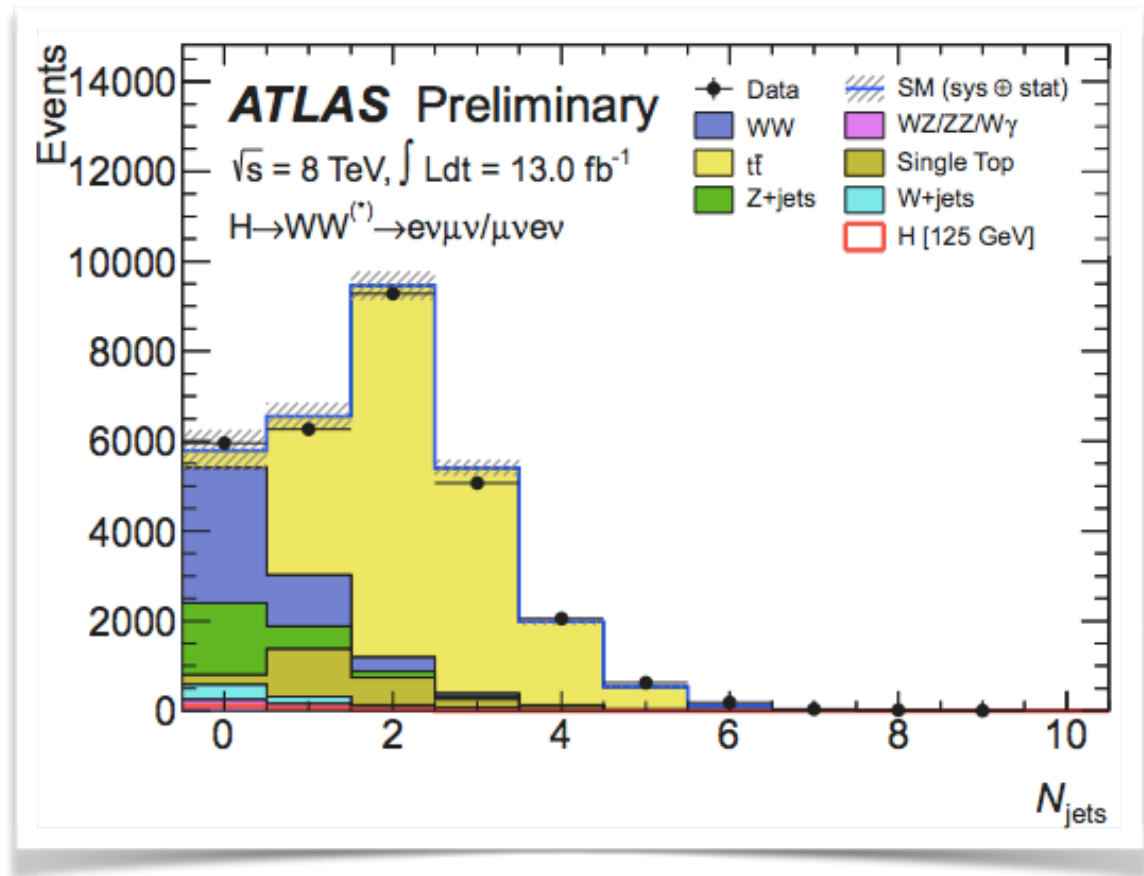
- Motivation
- H + 0-jets and H + 1-jet Cross Sections
- Conclusions

Motivation for Jet Bins

- Extensively used in LHC analyses
  - HWW
    - anti-kT jet algorithm, R~ 0.4
    - low pT cut ~ 25 - 30GeV
      - efficient in suppressing the backgrounds

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





[ATLAS-CONF-2012-158]

Motivation for Jet Bins

- Extensively used in LHC analyses
  - HWW
    - anti-kT jet algorithm, R~ 0.4
    - low pT cut ~ 25 - 30GeV
      - large theory uncertainties

ST prescription used by ATLAS and CMS

$$\Delta_N^2 = \Delta_{\geq N}^2 + \Delta_{\geq N+1}^2$$

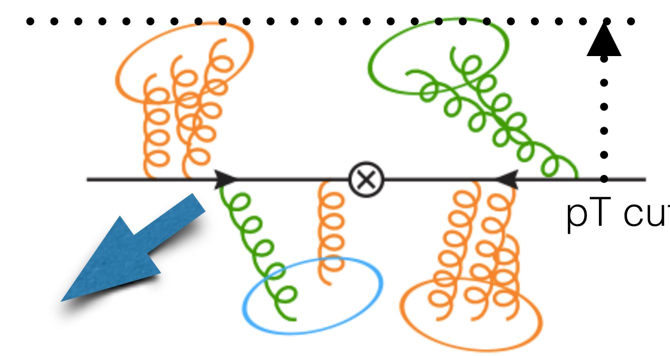
$$\sigma_N = \sigma_{\geq N} - \sigma_{\geq N+1}$$ [Stewart and Tackmann]

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]

Theoretical Issues with Jet Veto

- Low pT jet veto restricts emissions to be soft and collinear
  - Large Sudakov logs



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

$$\sim \quad 1$$

$$+ \quad \alpha_s L^2 + \alpha_s L + \alpha_s$$ **NLO**

$$+ \quad \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L + \alpha_s^2$$ **NNLO**

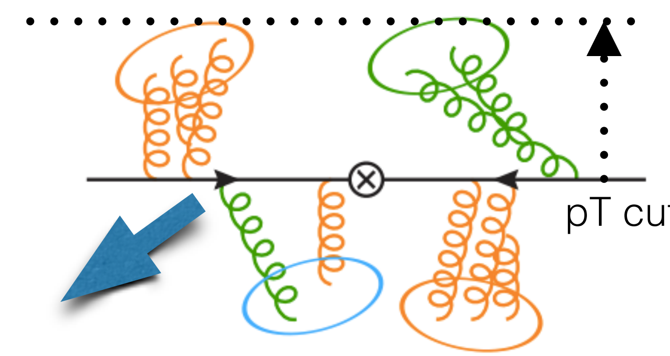
$$+ \quad \alpha_s^3 L^6 + \alpha_s^3 L^5 + \alpha_s^3 L^4 + \alpha_s^3 L^3 + \alpha_s^3 L^2 + \cdots$$

LL **NLL** **NNLL**

MISSING

Theoretical Issues with Jet Veto

- Low pT jet veto restricts emissions to be soft and collinear
  - Large Sudakov logs
    - need to be resummed
      - reliable perturbative predictions
      - reduce theoretical errors



$$\begin{aligned}
&\sim \quad 1 \\
&+ \quad \alpha_s L^2 + \alpha_s L \; + \alpha_s \quad \textbf{NLO} \\
&+ \quad \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L \; + \alpha_s^2 \quad \textbf{NNLO} \\
&+ \quad \alpha_s^3 L^6 + \alpha_s^3 L^5 + \alpha_s^3 L^4 + \alpha_s^3 L^3 + \alpha_s^3 L^2 + \cdots
\end{aligned}$$

LL **NLL** **NNLL**

WANTED

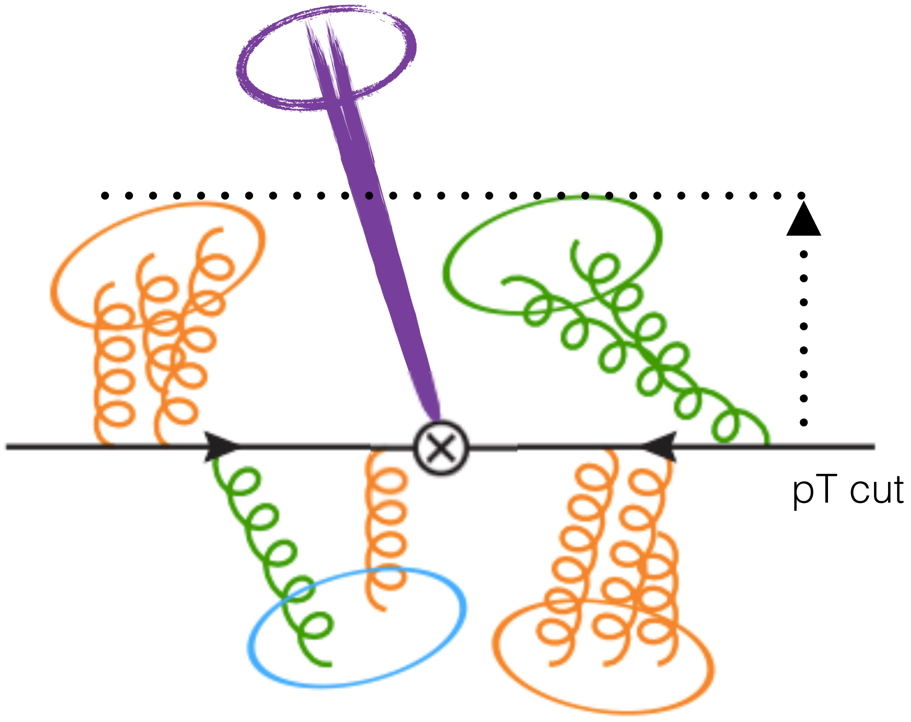
Efforts on Jet Vetoes

- H + 0-jets
  - Banfi, Monni, Salam, Zanderighi - NNLL + NNLO
  - Becher, Neubert, Rothen - NNLL' + NNLO + π^2
  - Stewart, Tackmann, Walsh, Zuberi - NNLL' + NNLO + π^2
- H + 1-jet
  - XL, Petriello - NLL' + NLO
  - Boughezal, XL, Petriello, Tackmann, Walsh - (beyond NLL') + NLO, (H+0+1j)
- VH + 0-jets
  - Li, Li, Shao - NNLL + NLO + π^2
  - Li, XL - (beyond NNLL) + NNLO + π^2

Efforts on Jet Vetoes

- Factorization

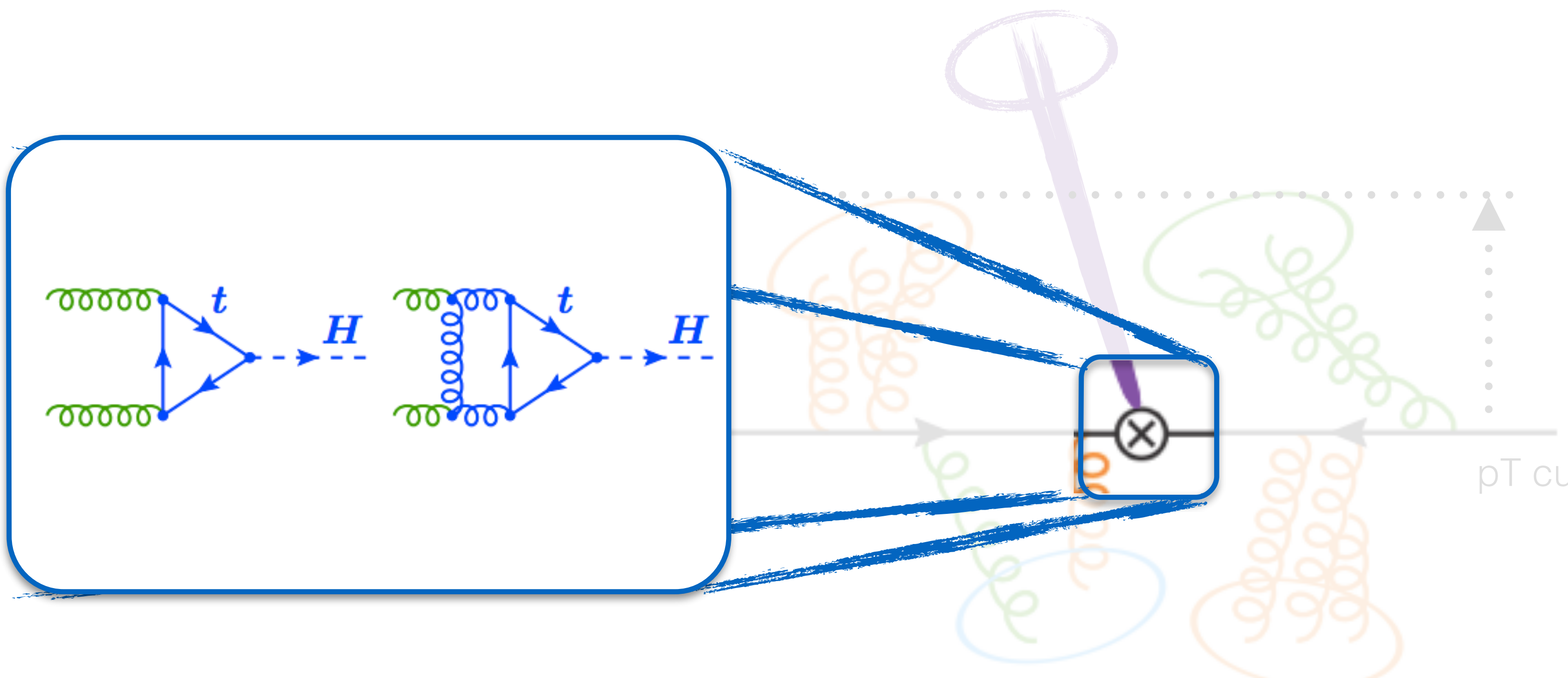
$$2\ln^2\frac{p_T^{\text{cut}}}{m_H} = 2\ln^2\frac{m_H}{\mu} + 4\ln\frac{p_T^{\text{cut}}}{\mu}\ln\frac{\nu}{m_H} + 2\ln\frac{p_T^{\text{cut}}}{\mu}\ln\frac{\mu\, p_T^{\text{cut}}}{\nu^2}$$



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

Efforts on Jet Vetoes

- Factorization

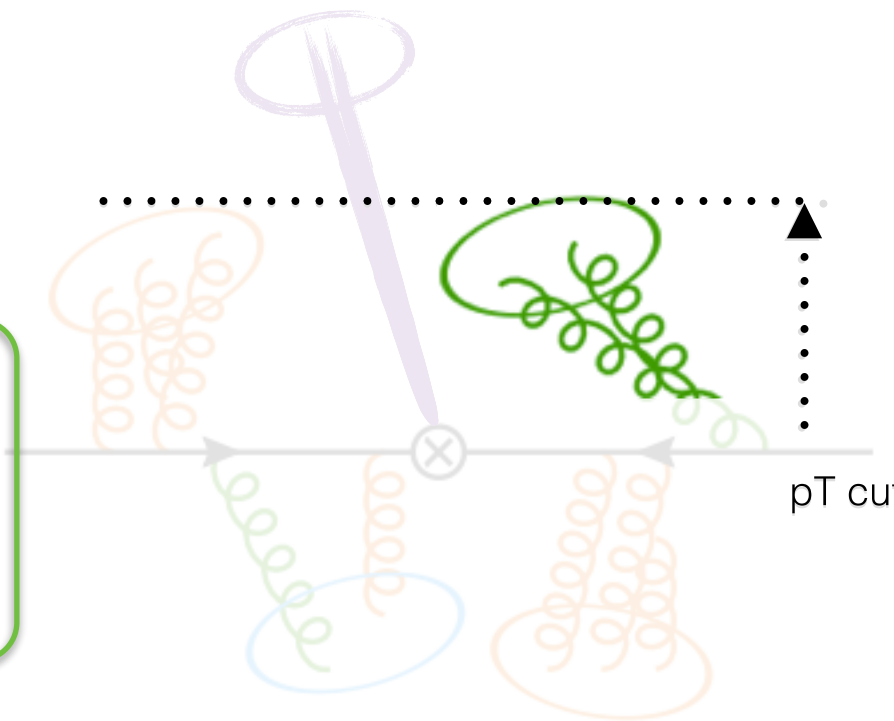


$$\sigma_0(p_T^{\mathrm{cut}}) = H(Q,\mu) B^{\mathrm{jet}}(R, p_T^{\mathrm{cut}}, \mu, \nu) B^{\mathrm{jet}}(R, p_T^{\mathrm{cut}}, \mu, \nu) S^{\mathrm{jet}}(R, p_T^{\mathrm{cut}}, \mu, \nu) J(R, p_T^J R, \mu)$$

Efforts on Jet Vetoes

- Factorization

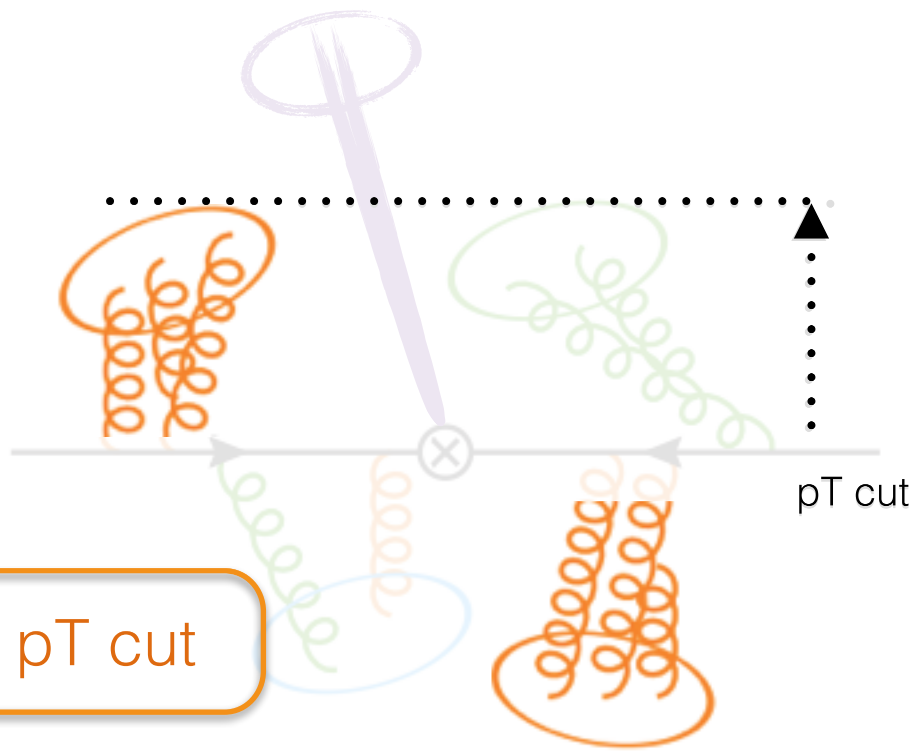
> * Energetic forward jets with transverse momentum ~ pT cut
> * includes pdf information



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

Efforts on Jet Vetoes

- Factorization

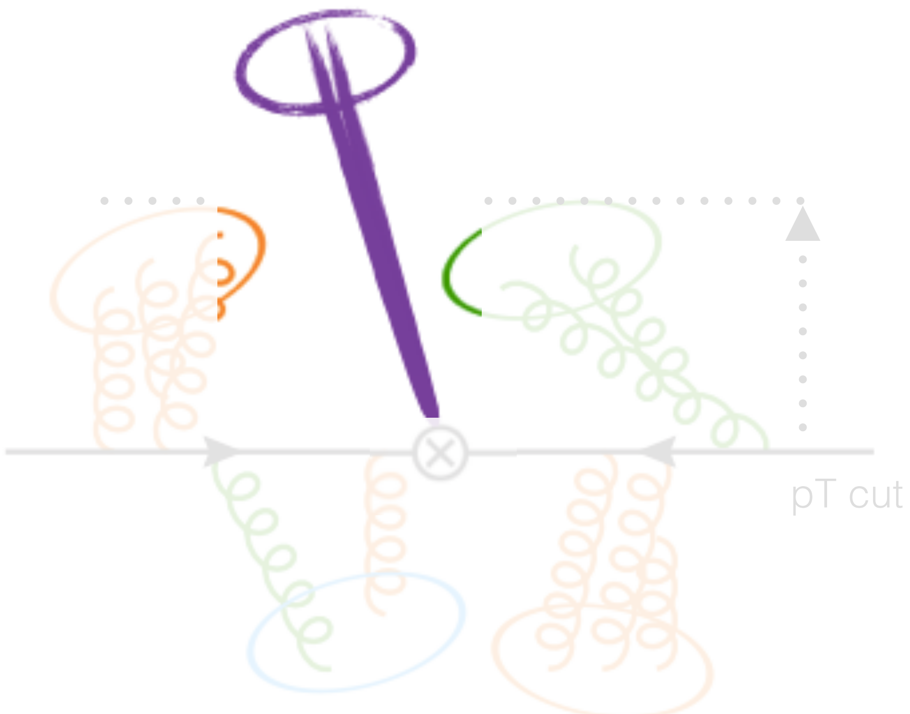


* soft jets with energy ~ pT cut

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

Efforts on Jet Vetoes

- Factorization

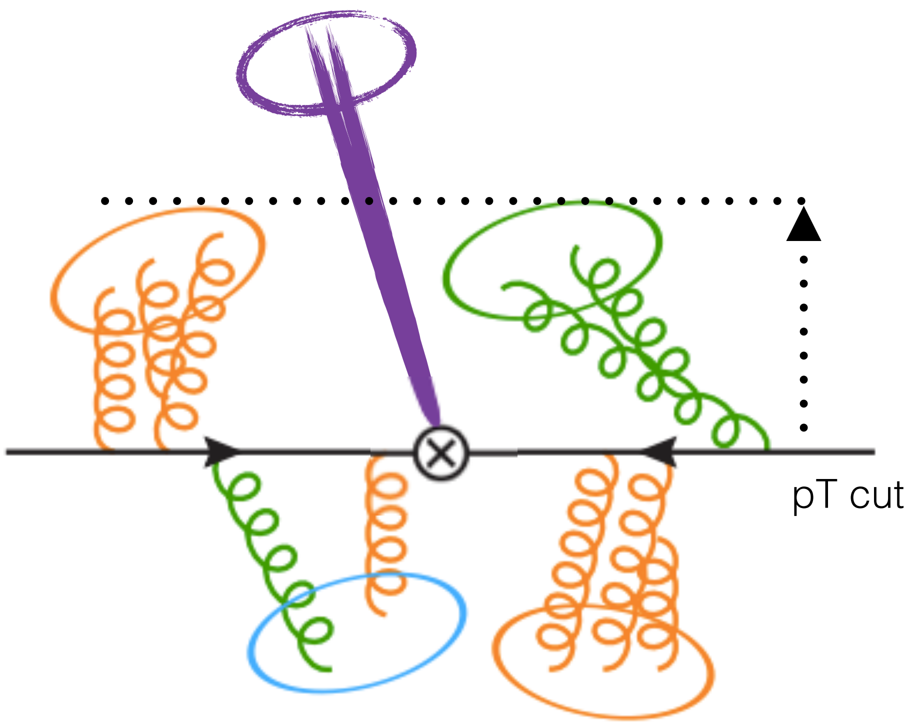


$$\sigma_0(p_T^{\rm cut}) = H(Q,\mu)B^{\rm jet}(R,p_T^{\rm cut},\mu,\nu)B^{\rm jet}(R,p_T^{\rm cut},\mu,\nu)S^{\rm jet}(R,p_T^{\rm cut},\mu,\nu)J(R,p_T^J R,\mu)$$

* Final state energetic jets
* Required energetic jets (pTJ ~ mH)
  experimentally pTJ ~ pT cut
  will come back to this point later

Efforts on Jet Vetoes

- Factorization
  - kT type jet algorithm tends to group soft and energetic radiations near the beam into different jets, large rapidity separation

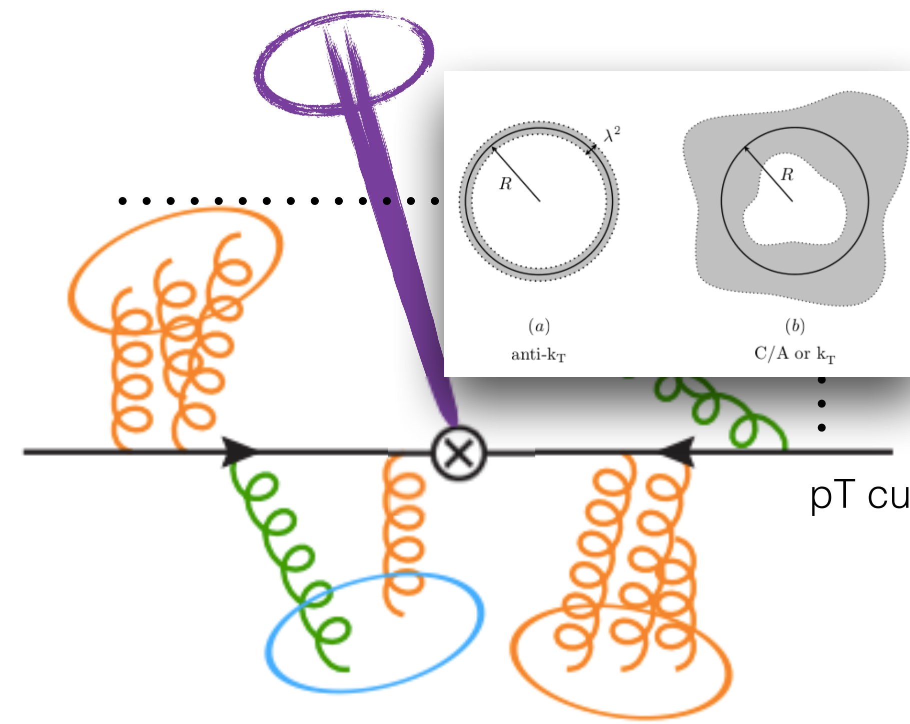


$$\sigma_0(p_T^{\rm cut}) = H(Q,\mu)B^{\rm jet}(R,p_T^{\rm cut},\mu,\nu)B^{\rm jet}(R,p_T^{\rm cut},\mu,\nu)S^{\rm jet}(R,p_T^{\rm cut},\mu,\nu)J(R,p_T^J R,\mu)$$

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

Efforts on Jet Vetoes

- Factorization
  - anti-kT tends to group central energetic radiations in to jets first. The soft radiations will only see the overall pre-determined jet directions

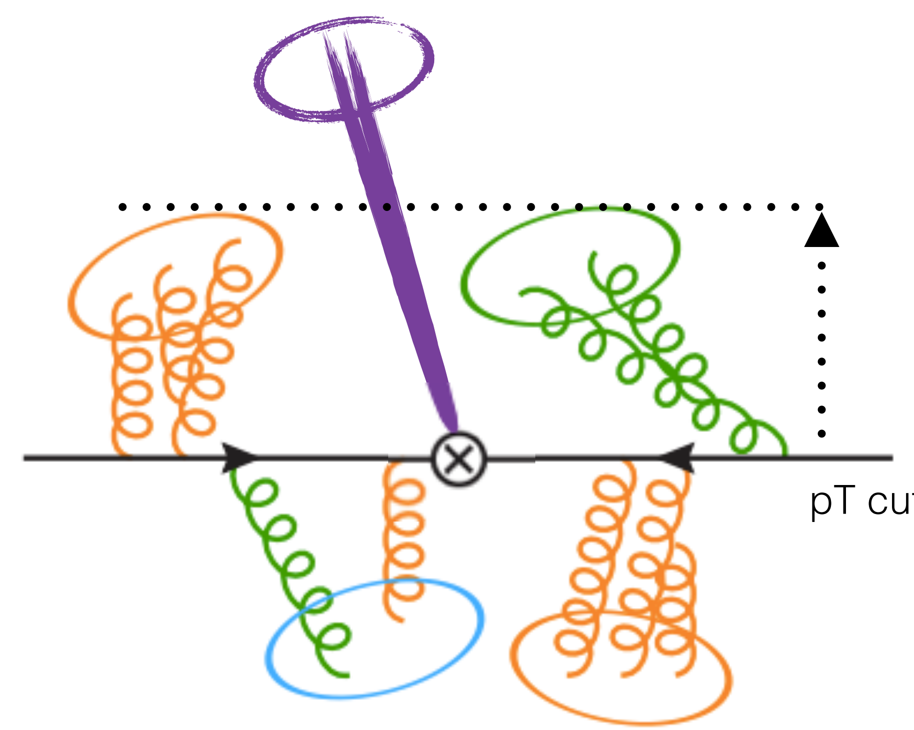


$$\sigma_0(p_T^{\text{cut}}) = H(Q,\mu) B^{\text{jet}}(R, p_T^{\text{cut}}, \mu, \nu) B^{\text{jet}}(R, p_T^{\text{cut}}, \mu, \nu) S^{\text{jet}}(R, p_T^{\text{cut}}, \mu, \nu) J(R, p_T^J R, \mu)$$

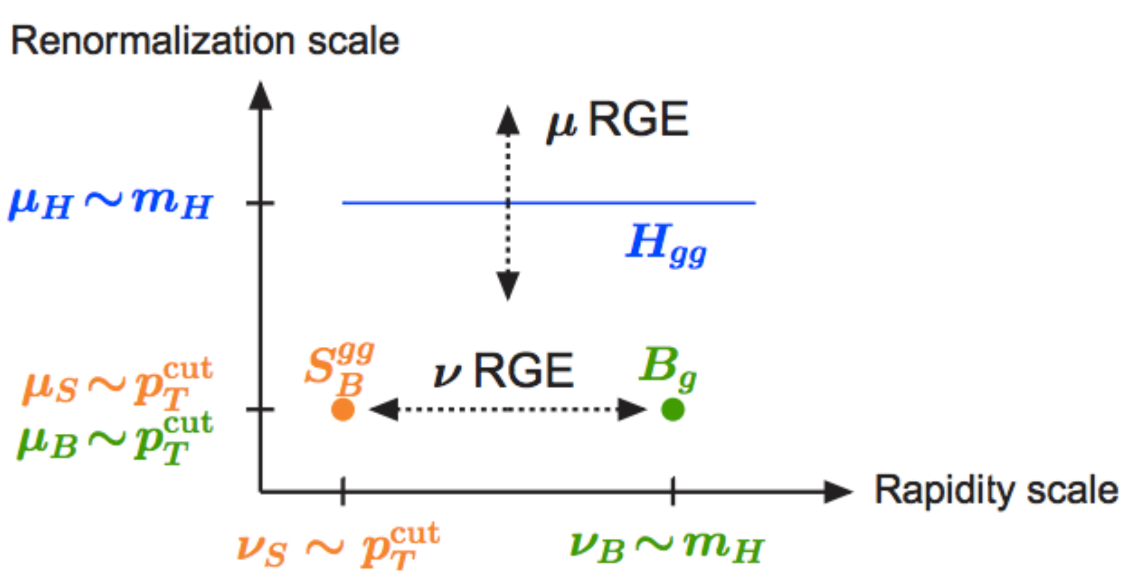
$$\begin{aligned} \rho_{ij} &= \min(p_{T,i}^{-1}, p_{T,j}^{-1}) \Delta R_{ij}/R, \\ \rho_i &= p_{T,i}^{-1}. \end{aligned}$$

Efforts on Jet Vetoes

- Factorization
- Resummation
    - logs resummed via RG equations similar to DGLAP for pdfs



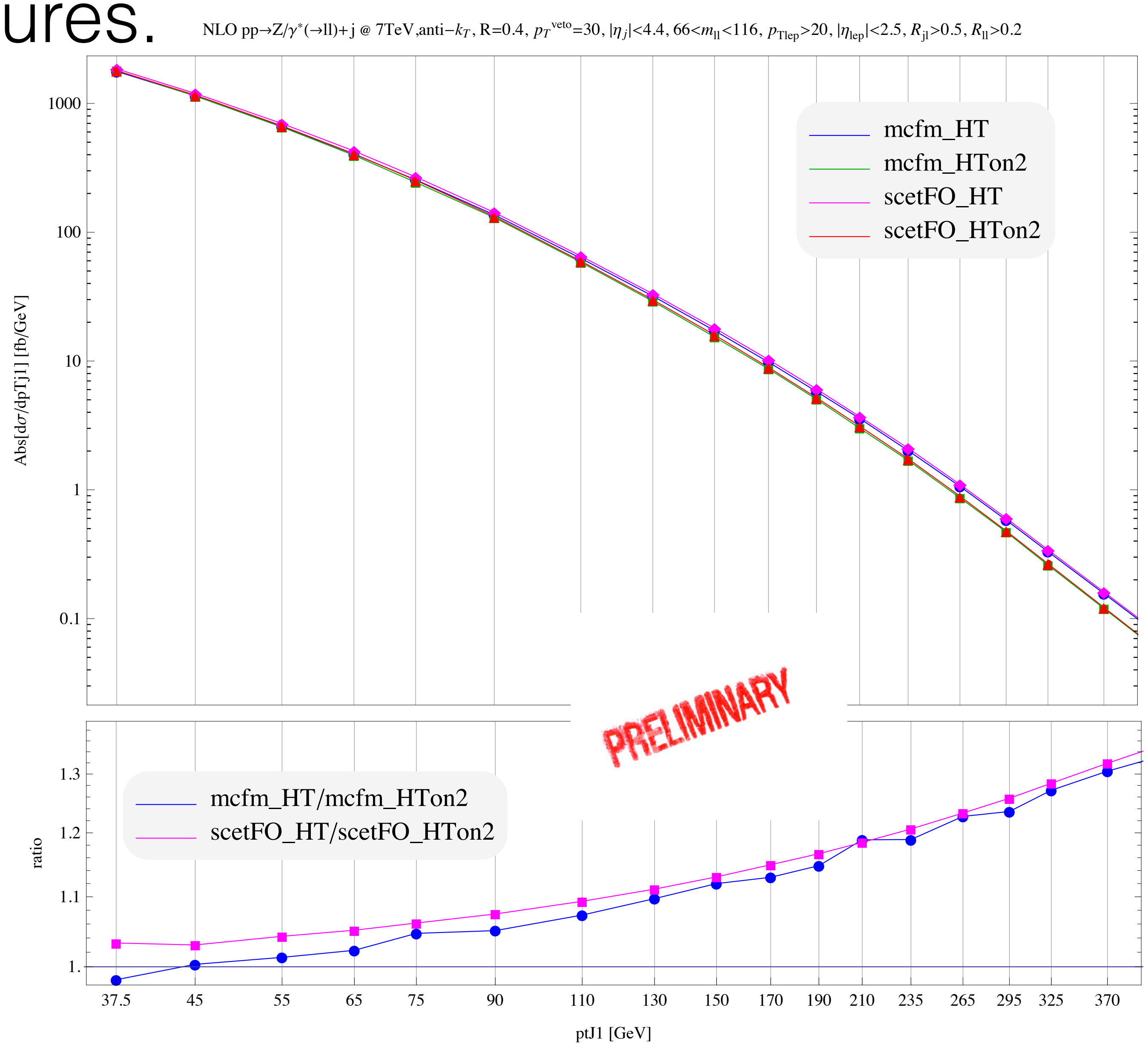
$$\sigma_0(p_T^{\rm cut}) = H(Q,\mu) B^{\rm jet}(R, p_T^{\rm cut}, \mu, \nu) B^{\rm jet}(R, p_T^{\rm cut}, \mu, \nu) S^{\rm jet}(R, p_T^{\rm cut}, \mu, \nu) J(R, p_T^J R, \mu)$$



[J. Chiu, A. Jain, D. Neill, I. Rothstein]

Warm up: Z+1j

- Validation of the EFT
  - reproduce the log structures.

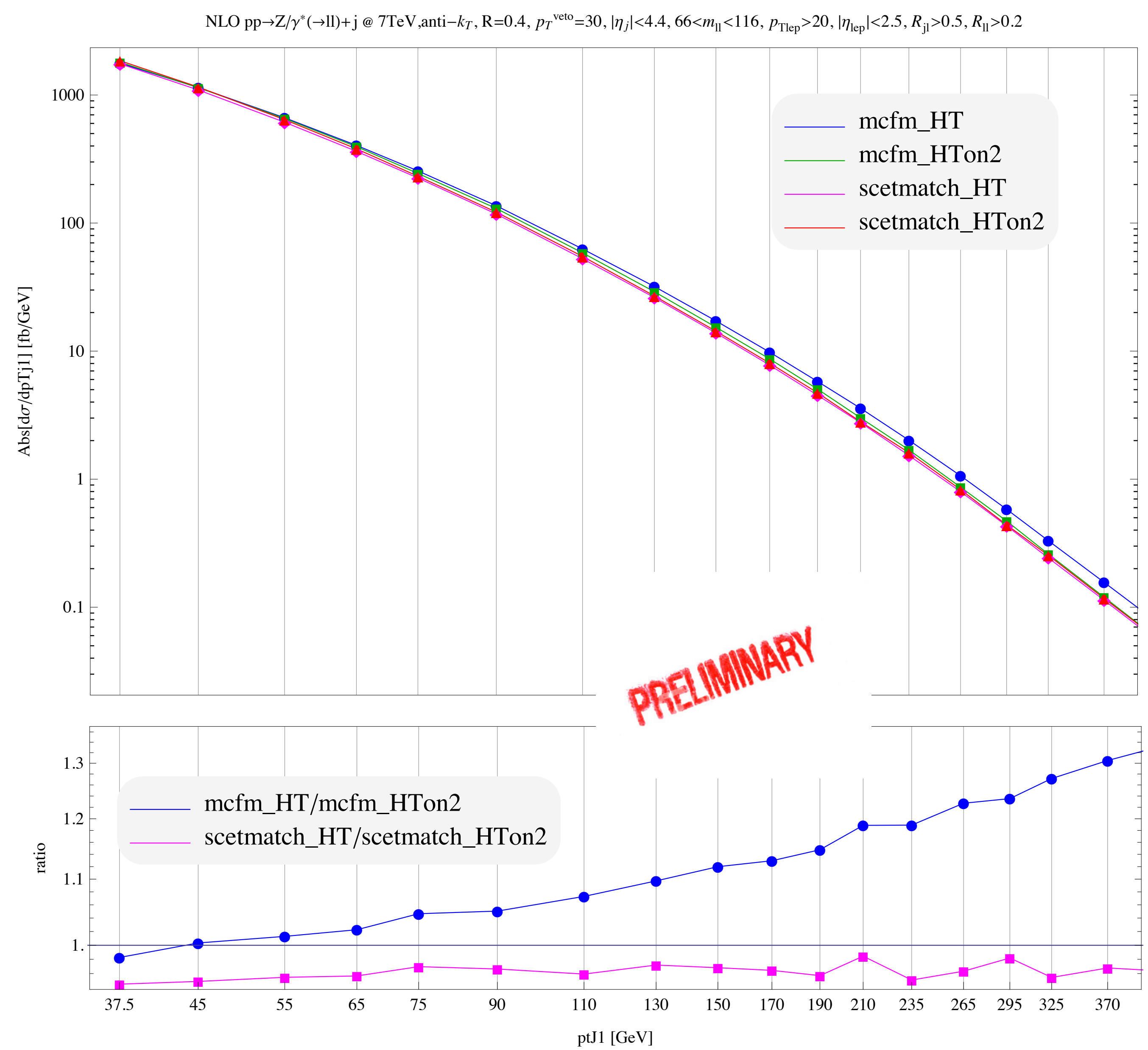


[Boughezal, Focke, XL]

Warm up: Z+1j

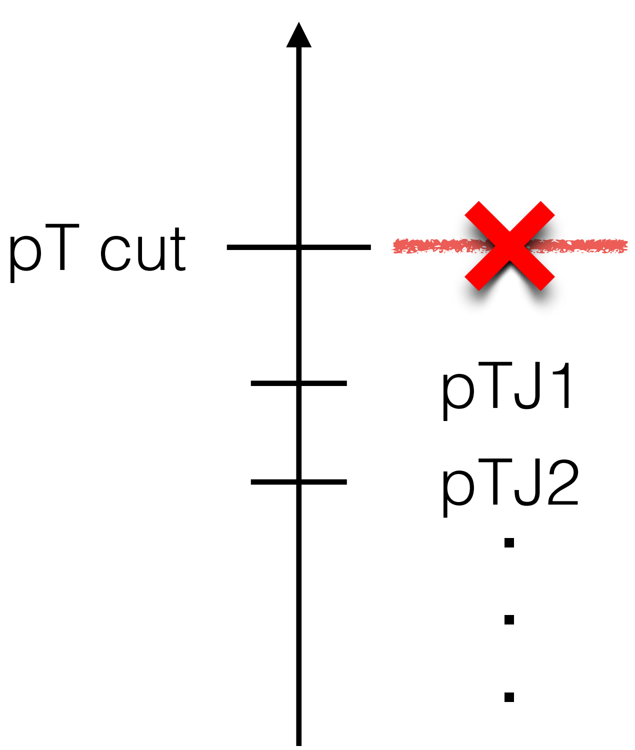
- Validation of the EFT
  - resummation v.s. FO
    - favors a low scale choice HT/2 for FO

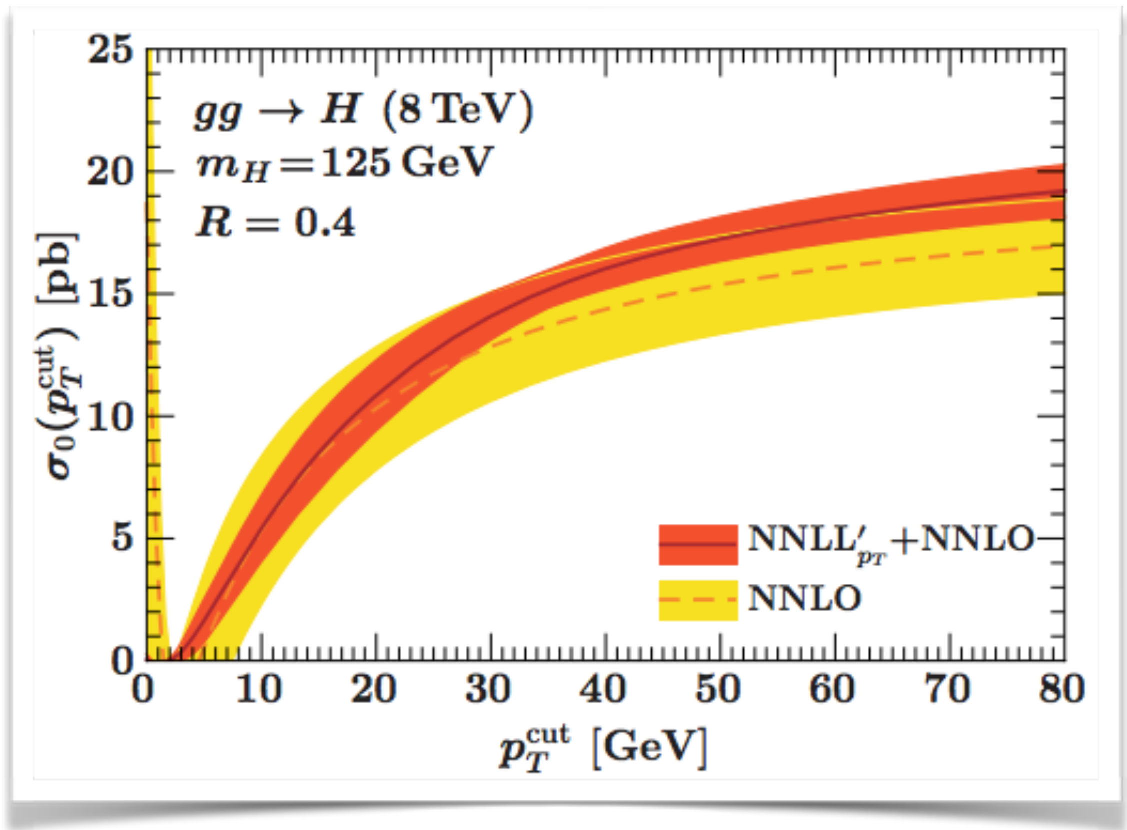
[Boughezal, Focke, XL]



H + 0-jets and H + 1-jet

- H + 0-jets
  - keep events with no jet pT > pT cut
  - NNLL’ + NNLO + π^2



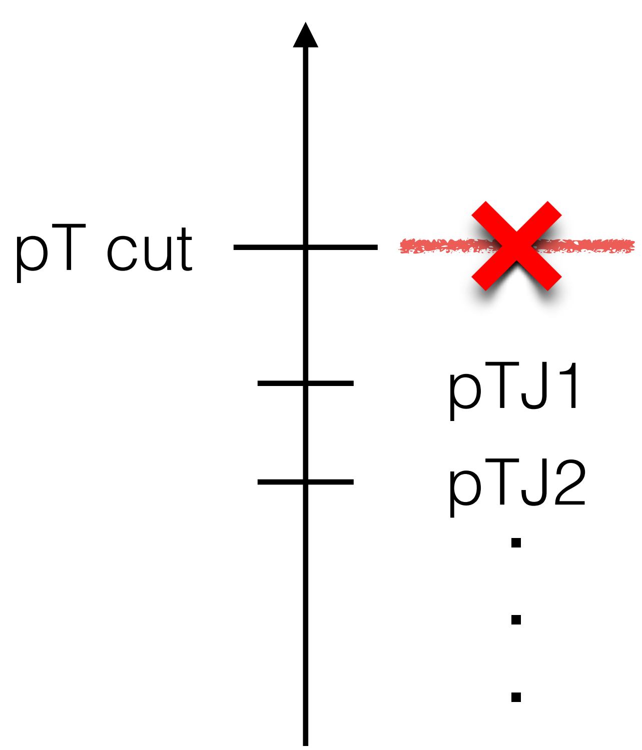


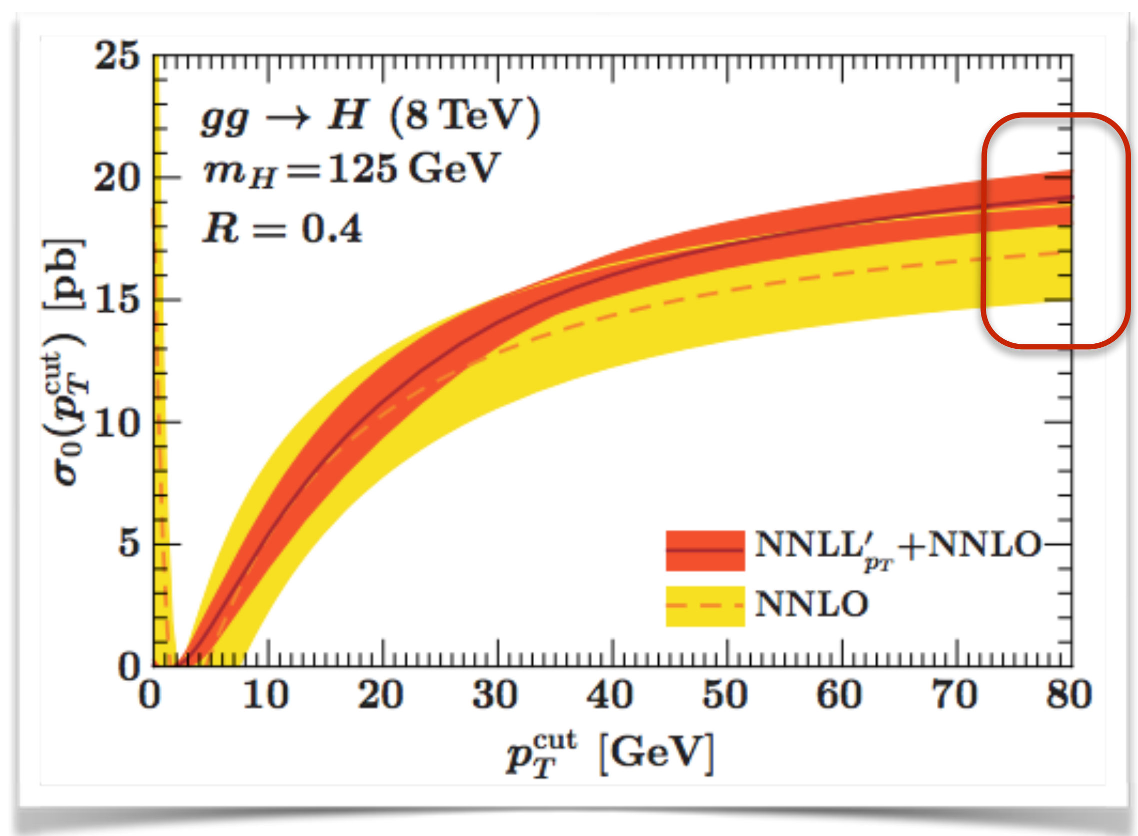
[Stewart, Tackmann, Walsh, Zuberi]

H + 0-jets and H + 1-jet

- H + 0-jets
  - keep events with no jet pT > pT cut
  - NNLL' + NNLO + π^2

π^2 resummaiton also enhanced the inclusive cross section

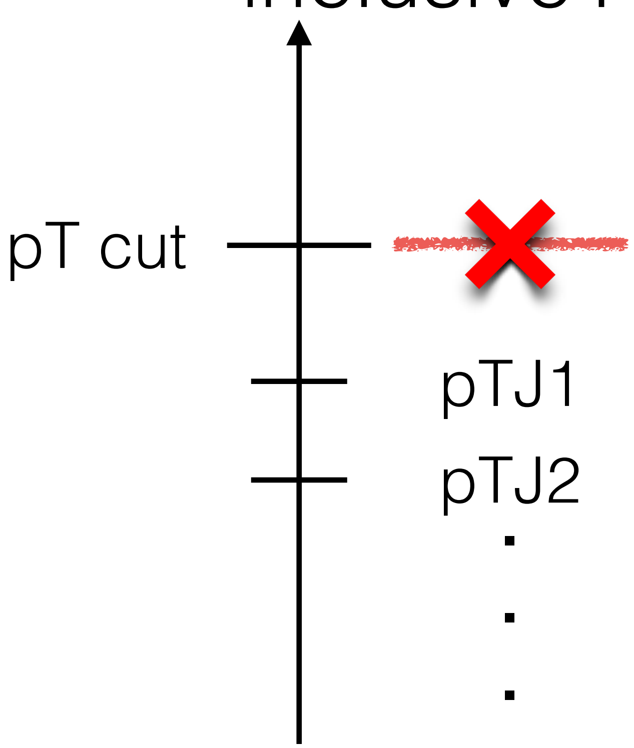


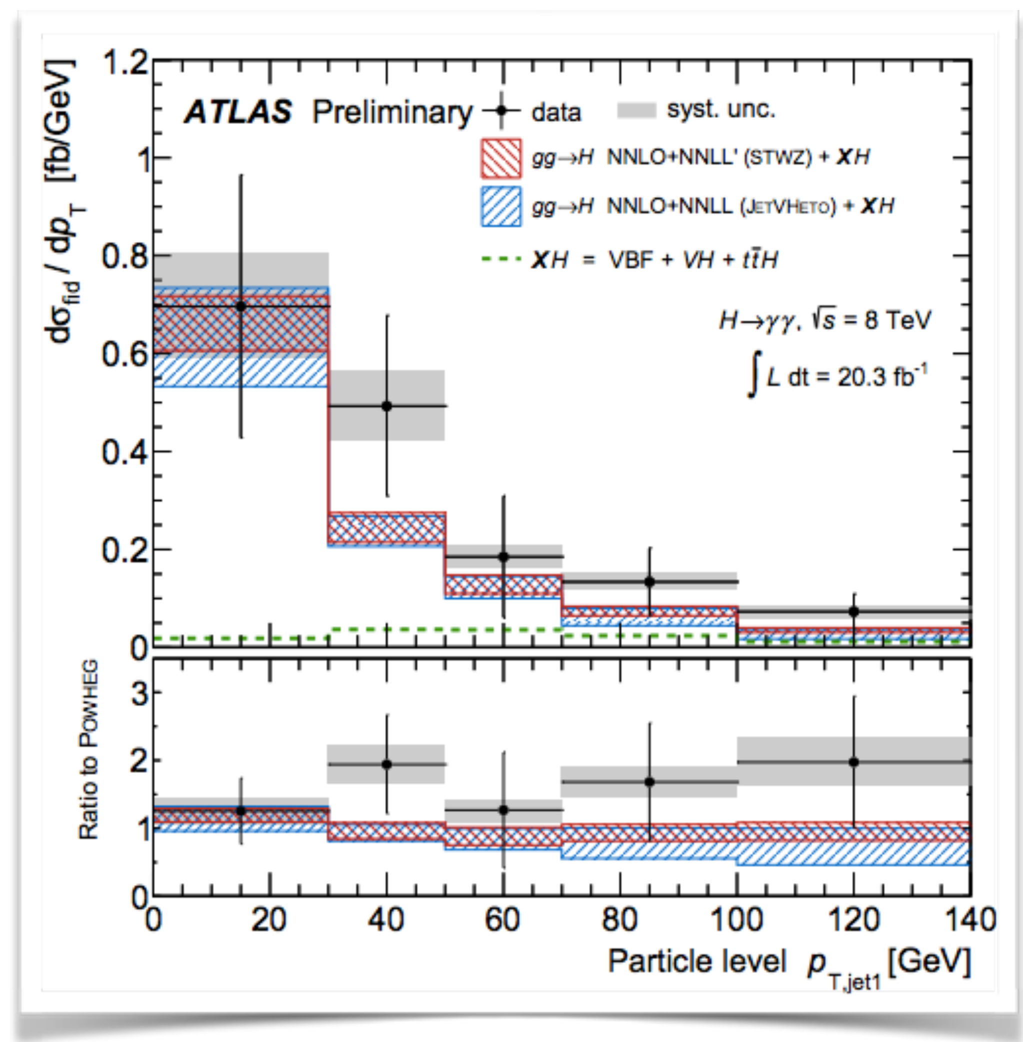


[Stewart, Tackmann, Walsh, Zuberi]

H + 0-jets and H + 1-jet

- H + 0-jets
  - keep events with no jet pT > pT cut
  - NNLL’ + NNLO + π^2
  - inclusive1-jet (pTJ<<mH)

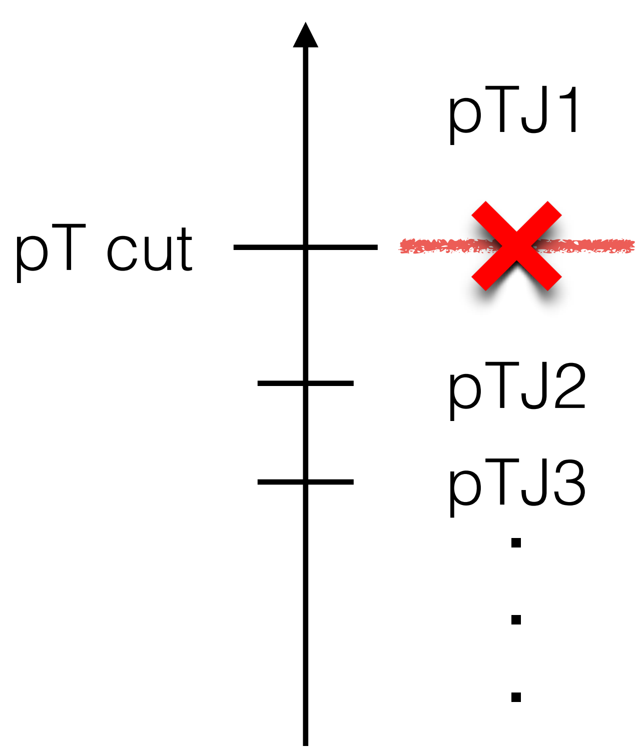


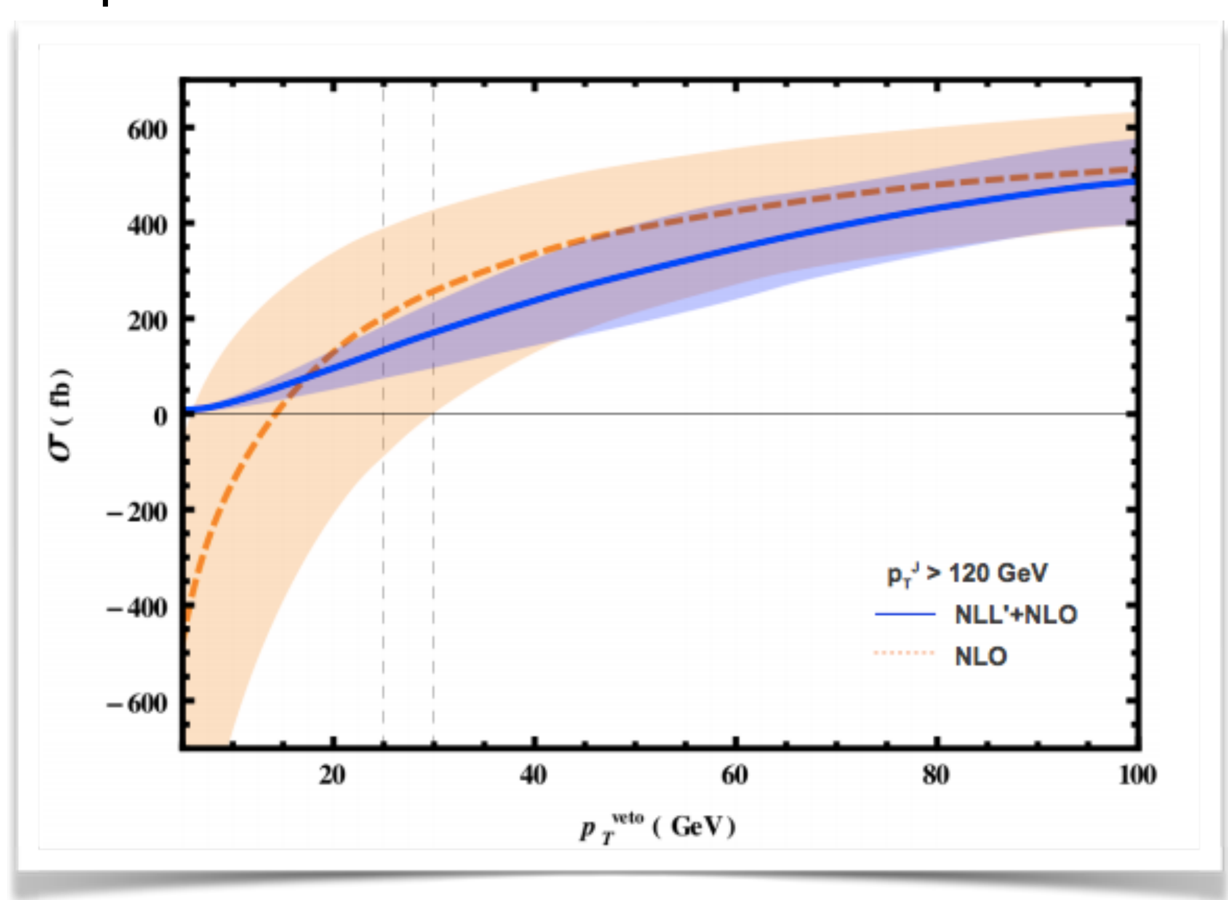


[ATLAS-CONF-2013-072]

H + 0-jets and H + 1-jet

- H + 1-jet
  - keep events with no 2nd jet pT > pT cut
  - factorization hold exact for pTJ1 ~ mH

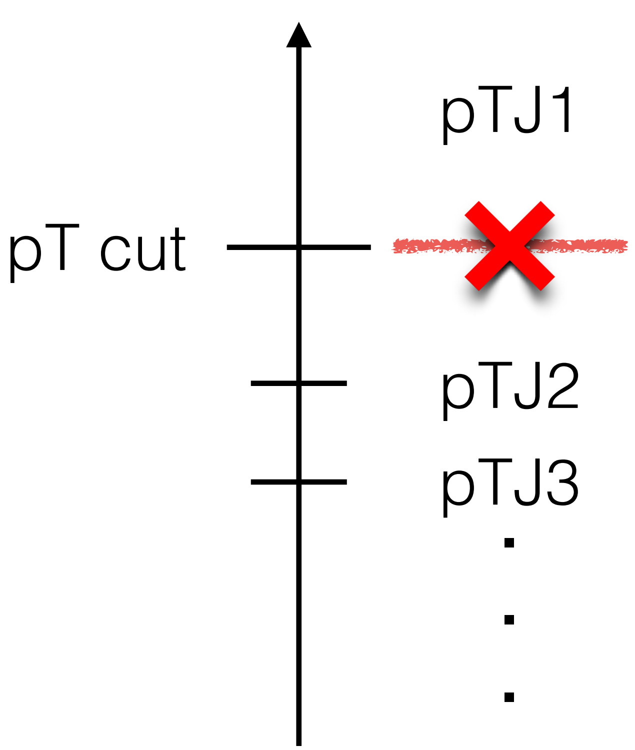


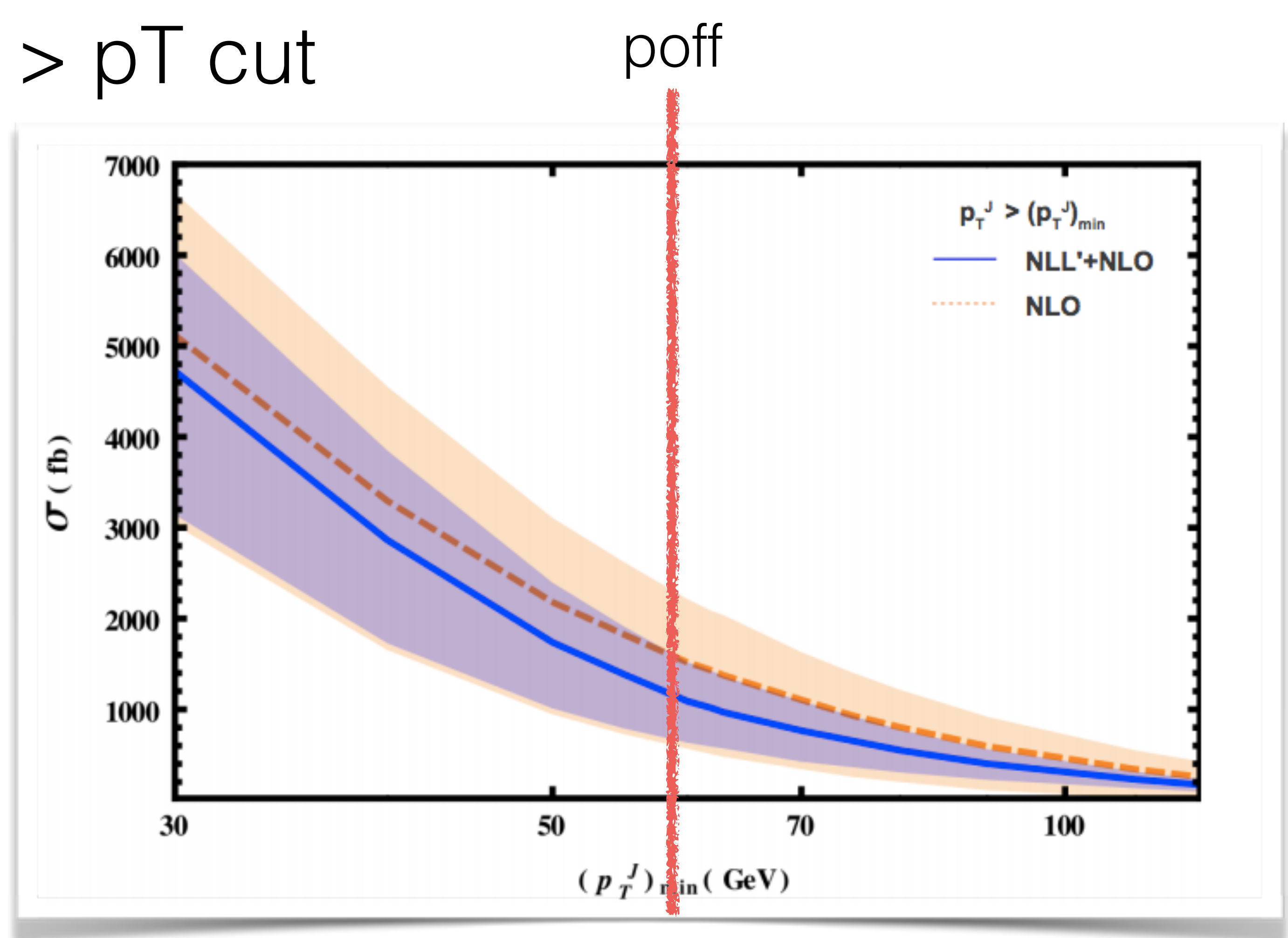


[XL, Petriello]

H + 0-jets and H + 1-jet

- H + 1-jet
  - keep events with no 2nd jet pT > pT cut
  - experimentally, pTJ > pT cut





[XL, Petriello]

H + 0-jets and H + 1-jet

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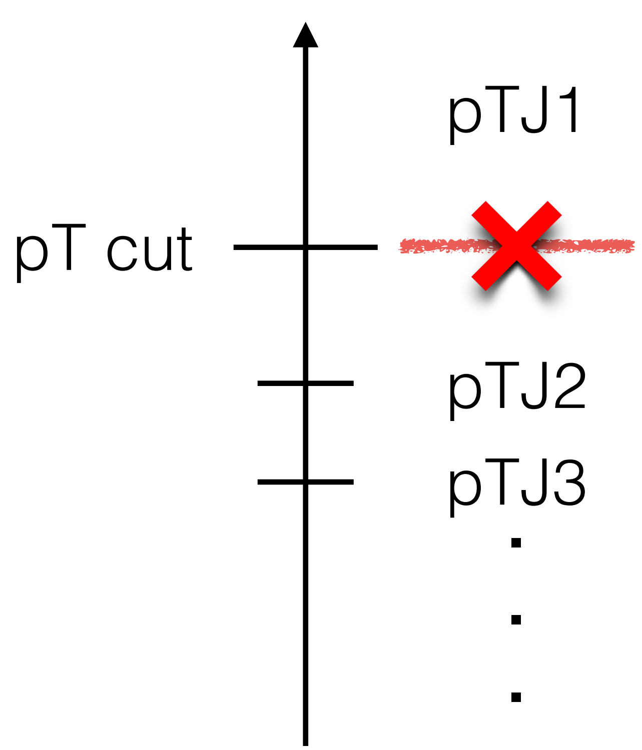
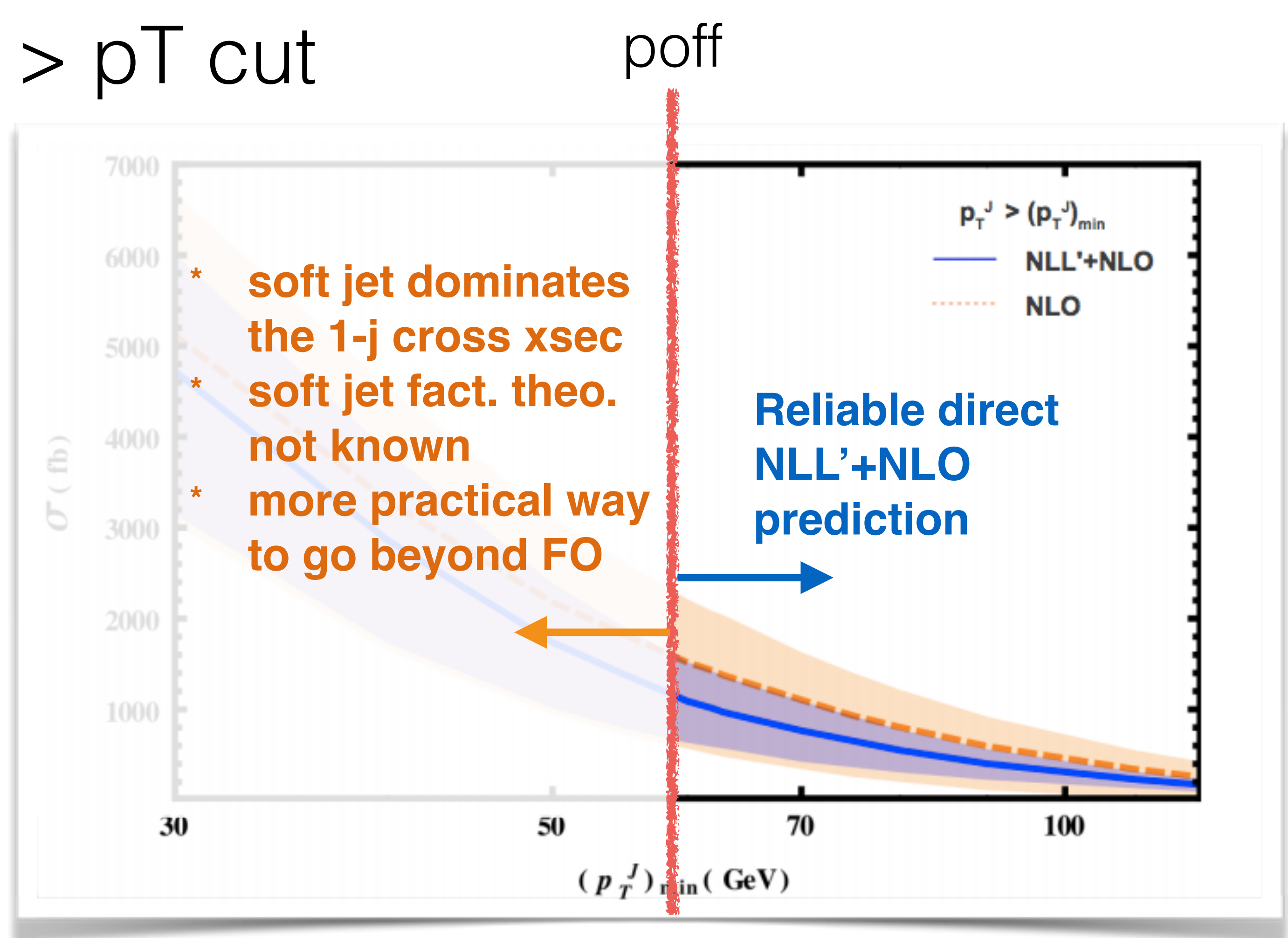


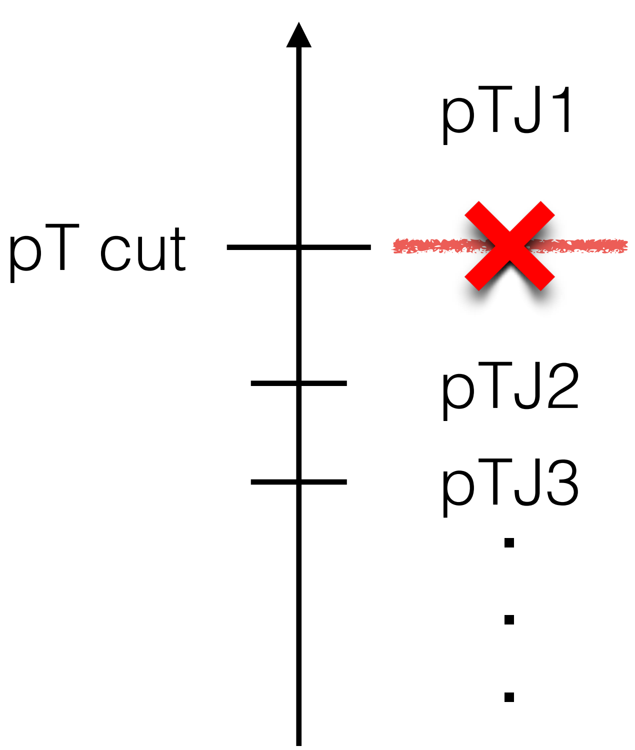


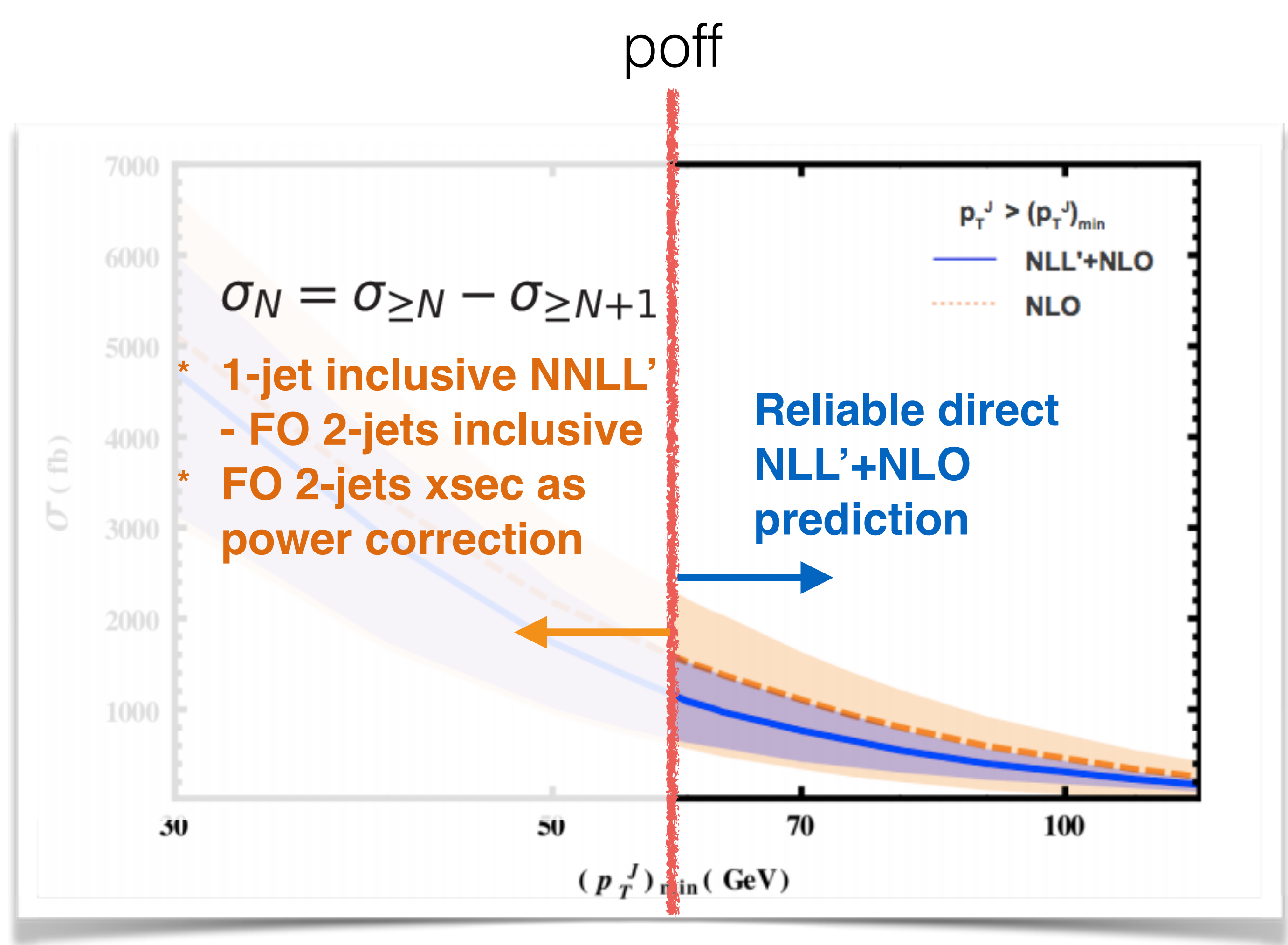
[XL, Petriello]

H + 0-jets and H + 1-jet

- H + 1-jet
  - resummation improved H + 1-jet (full spectrum)

[Boughezal, XL, Petriello, Tackmann, Walsh]





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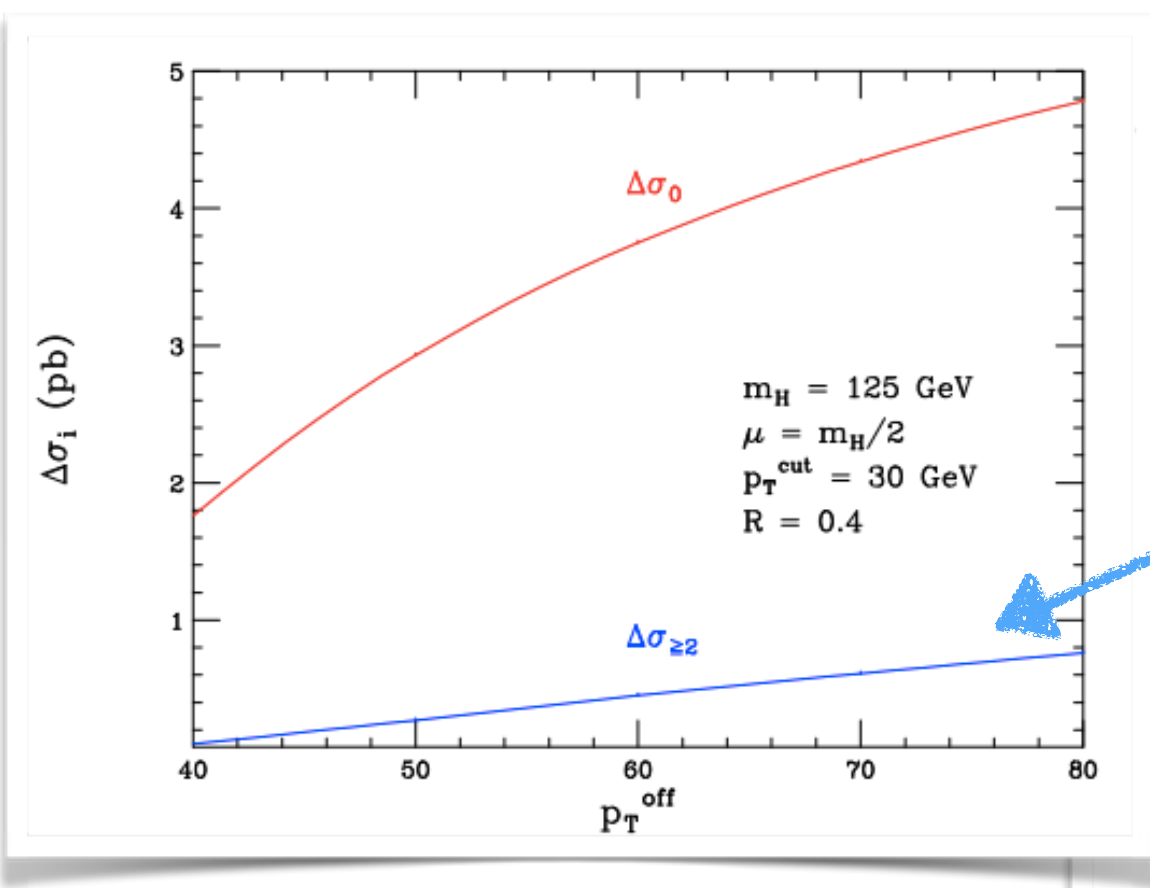
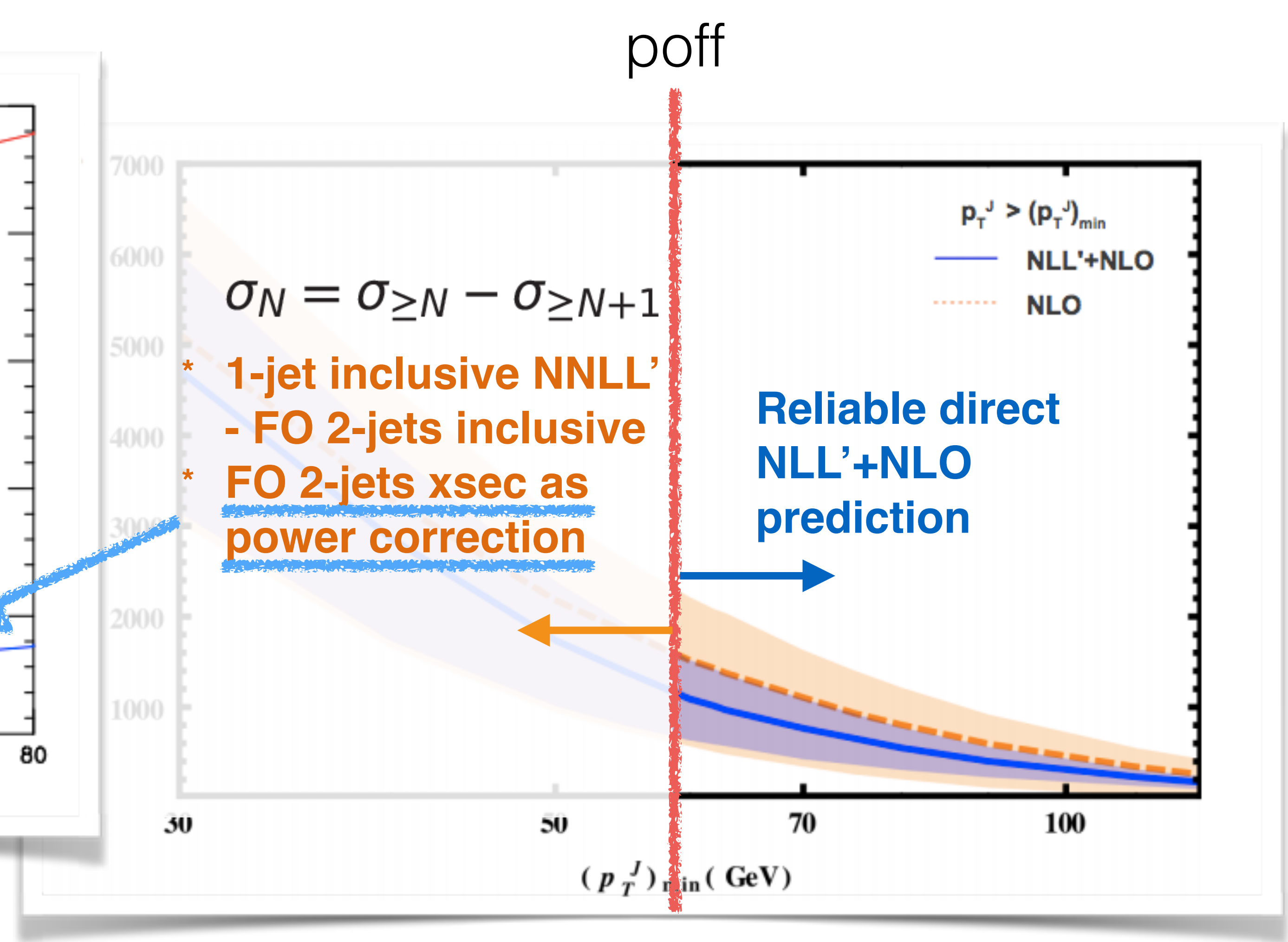
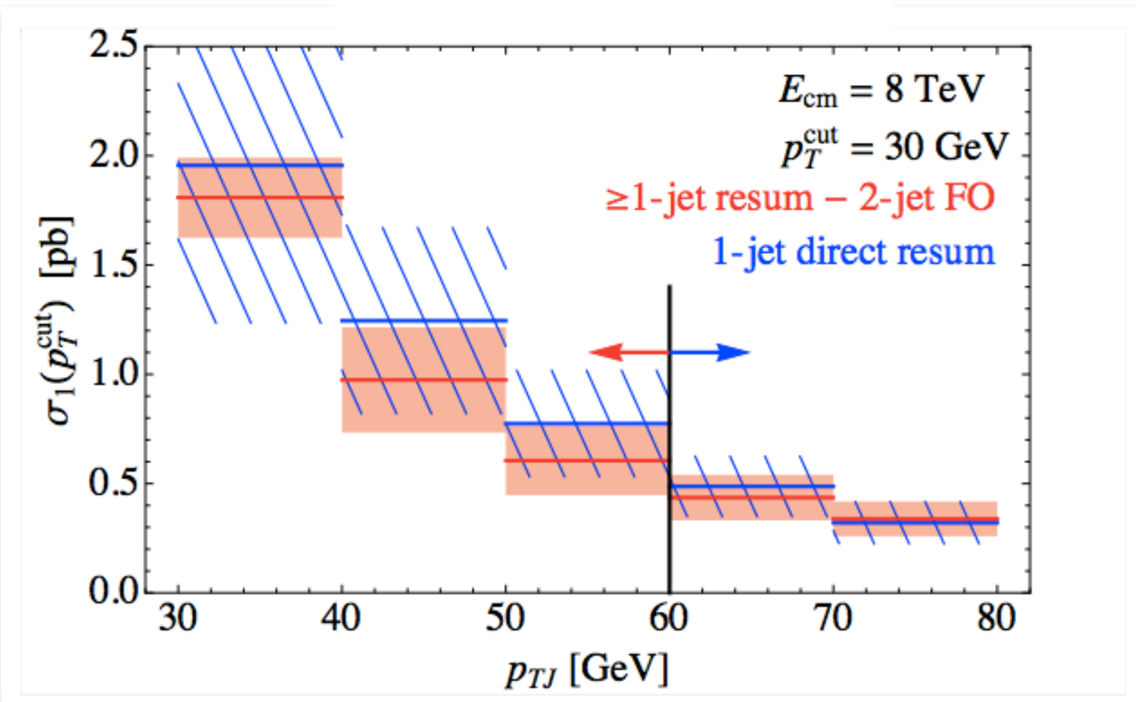
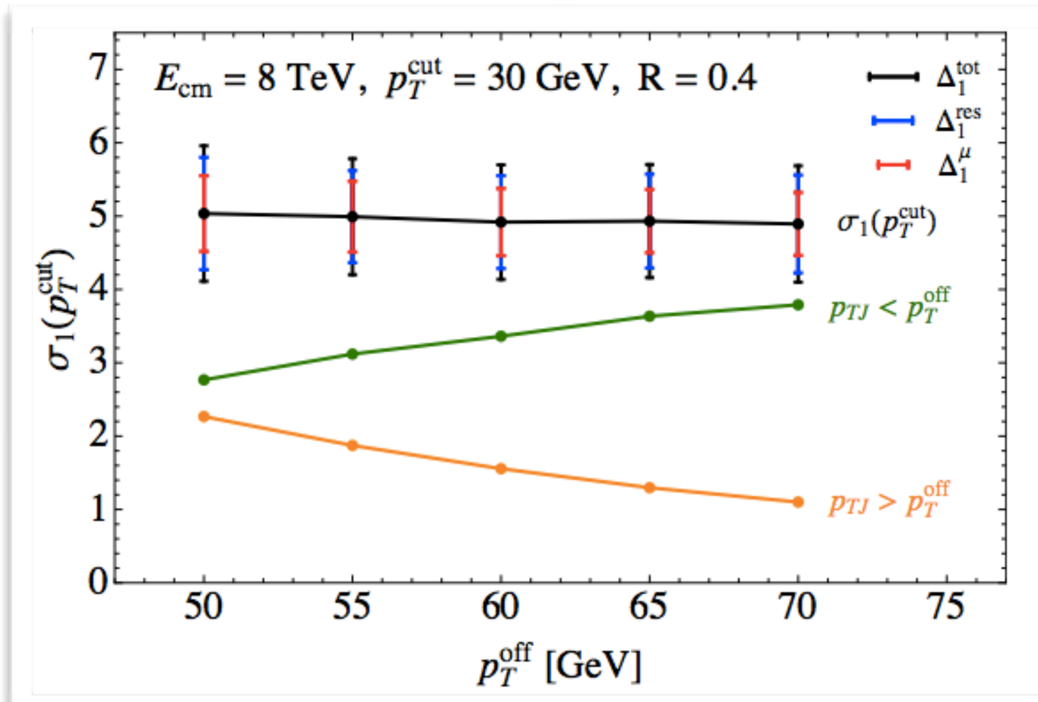




H + 0-jets and H + 1-jet

- H + 1-jet
  - resummation improved H + 1-jet (full spectrum)
    [Boughezal, XL, Petriello, Tackmann, Walsh]
    - testing matching



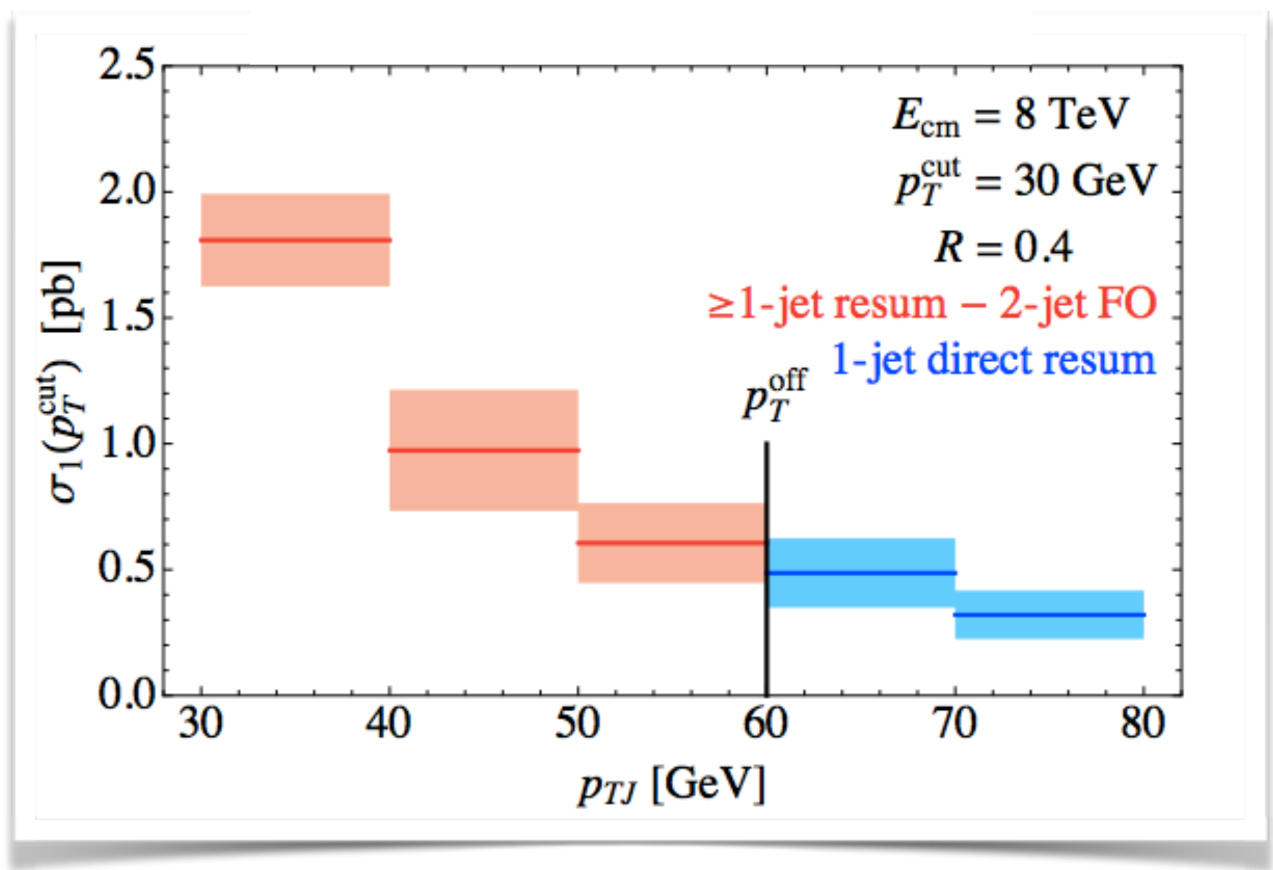


H + 0-jets and H + 1-jet

- H + 1-jet
  - resummation improved H + 1-jet (full spectrum)

[Boughezal, XL, Petriello, Tackmann, Walsh]

    - pTJ spectrum
      - NNLO H
      - NLO 2-jets



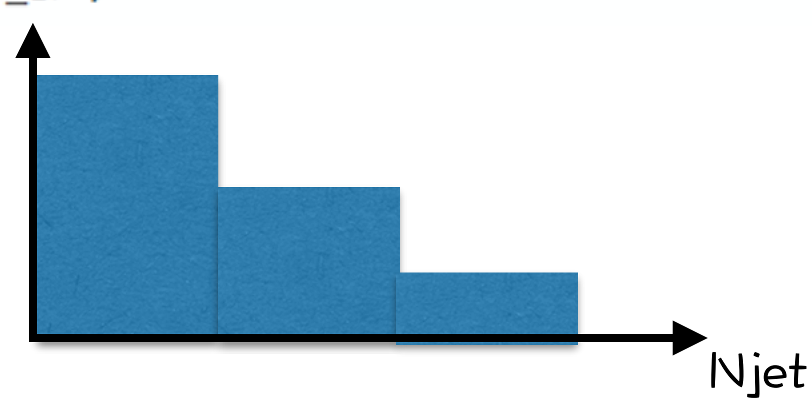
H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
  - covariance matrices
    - a general uncertainty parameterization

yield uncertainty (collective scale variation) + migration uncertainty (fully anti-correlated)

0-jets
1-jet
>2-jets

$$\begin{pmatrix} (\Delta_0^y)^2 & \Delta_0^y \Delta_1^y & \Delta_0^y \Delta_{\geq 2}^y \\ \Delta_0^y \Delta_1^y & (\Delta_1^y)^2 & \Delta_1^y \Delta_{\geq 2}^y \\ \Delta_0^y \Delta_{\geq 2}^y & \Delta_1^y \Delta_{\geq 2}^y & (\Delta_{\geq 2}^y)^2 \end{pmatrix} \quad \begin{pmatrix} \Delta_{0\,\mathrm{cut}}^2 & -\Delta_{0\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} & -C_{01\,\mathrm{cut}} \\ -\Delta_{0\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} & \Delta_{0\,\mathrm{cut}}^2 + \Delta_{1\,\mathrm{cut}}^2 - 2C_{01\,\mathrm{cut}} & -\Delta_{1\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} \\ -C_{01\,\mathrm{cut}} & -\Delta_{1\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} & \Delta_{1\,\mathrm{cut}}^2 \end{pmatrix}$$

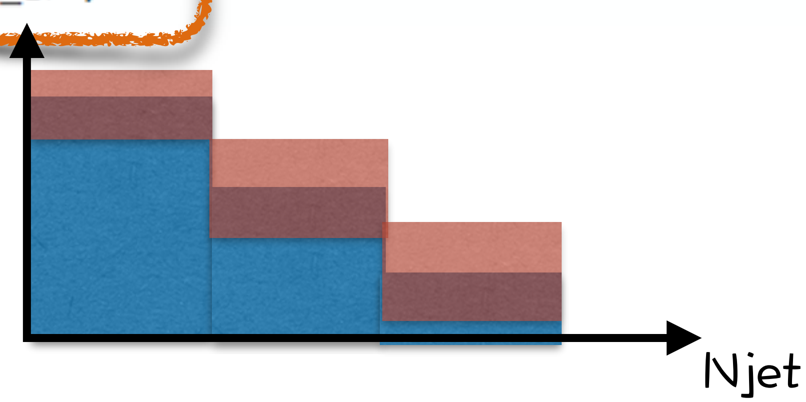


H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
  - covariance matrices
    - a general uncertainty parameterization

yield uncertainty (collective scale variation) + migration uncertainty (fully anti-correlated)

$$
\begin{array}{l} \text{0-jets} \\ \text{1-jet} \\ \text{>2-jets} \end{array}
\begin{pmatrix} (\Delta_0^y)^2 & \Delta_0^y \Delta_1^y & \Delta_0^y \Delta_{\geq 2}^y \\ \Delta_0^y \Delta_1^y & (\Delta_1^y)^2 & \Delta_1^y \Delta_{\geq 2}^y \\ \Delta_0^y \Delta_{\geq 2}^y & \Delta_1^y \Delta_{\geq 2}^y & (\Delta_{\geq 2}^y)^2 \end{pmatrix}
\begin{pmatrix} \Delta_{0\,\mathrm{cut}}^2 & -\Delta_{0\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} & -C_{01\,\mathrm{cut}} \\ -\Delta_{0\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} & \Delta_{0\,\mathrm{cut}}^2 + \Delta_{1\,\mathrm{cut}}^2 - 2C_{01\,\mathrm{cut}} & -\Delta_{1\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} \\ -C_{01\,\mathrm{cut}} & -\Delta_{1\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} & \Delta_{1\,\mathrm{cut}}^2 \end{pmatrix}
$$



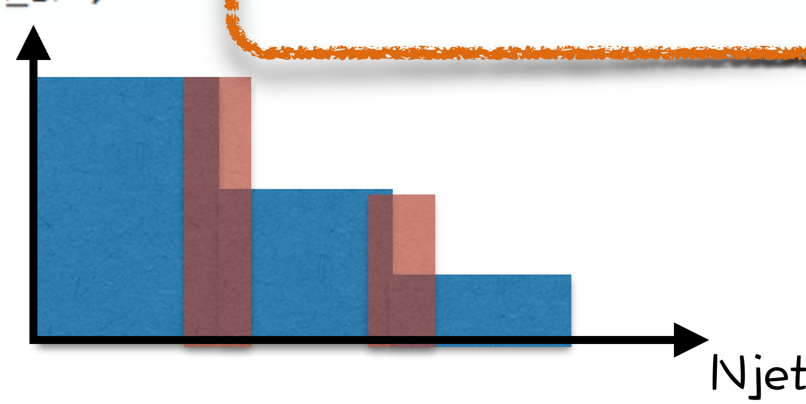
H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
  - covariance matrices
    - a general uncertainty parameterization

yield uncertainty (collective scale variation) + migration uncertainty (fully anti-correlated)

0-jets, 1-jet, >2-jets

$$\begin{pmatrix} (\Delta_0^{\mathrm{y}})^2 & \Delta_0^{\mathrm{y}}\Delta_1^{\mathrm{y}} & \Delta_0^{\mathrm{y}}\Delta_{\geq 2}^{\mathrm{y}} \\ \Delta_0^{\mathrm{y}}\Delta_1^{\mathrm{y}} & (\Delta_1^{\mathrm{y}})^2 & \Delta_1^{\mathrm{y}}\Delta_{\geq 2}^{\mathrm{y}} \\ \Delta_0^{\mathrm{y}}\Delta_{\geq 2}^{\mathrm{y}} & \Delta_1^{\mathrm{y}}\Delta_{\geq 2}^{\mathrm{y}} & (\Delta_{\geq 2}^{\mathrm{y}})^2 \end{pmatrix} + \begin{pmatrix} \Delta_{0\,\mathrm{cut}}^2 & -\Delta_{0\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} & -C_{01\,\mathrm{cut}} \\ -\Delta_{0\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} & \Delta_{0\,\mathrm{cut}}^2 + \Delta_{1\,\mathrm{cut}}^2 - 2C_{01\,\mathrm{cut}} & -\Delta_{1\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} \\ -C_{01\,\mathrm{cut}} & -\Delta_{1\,\mathrm{cut}}^2 + C_{01\,\mathrm{cut}} & \Delta_{1\,\mathrm{cut}}^2 \end{pmatrix}$$



H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
  - covariance matrices
    - a general uncertainty parameterization

$$C^{\mathrm{ATLAS}} = \begin{pmatrix} 1.49 & -0.39 & 0.20 \\ -0.39 & 0.88 & -0.04 \\ 0.20 & -0.04 & 0.32 \end{pmatrix} \mathrm{pb}^2$$

$$C^{\mathrm{CMS}} = \begin{pmatrix} 0.76 & 0.09 & 0.20 \\ 0.09 & 0.55 & 0.01 \\ 0.21 & 0.01 & 0.32 \end{pmatrix} \mathrm{pb}^2$$

H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
    - covariance matrices
        - any uncertainty can be calculated from the matrices
            - WW signal strength

$$\frac{\Delta^{\mathrm{th,\,y}}\mu}{\mu} = \frac{\Delta^{\mathrm{th,\,y}}\sigma_{\mathrm{exp}}}{\sigma_{\mathrm{exp}}} \qquad \mu = \frac{\sigma_{\mathrm{obs}}}{\sigma_{\mathrm{exp}}}$$

$$\Delta\sigma_{\mathrm{exp}} = \left[(\epsilon_0^{\mathrm{exp}})^2\Delta_0^2 + (\epsilon_1^{\mathrm{exp}})^2\Delta_1^2 + 2\epsilon_0^{\mathrm{exp}}\epsilon_1^{\mathrm{exp}}\mathrm{cov}(0,1)\right]^{1/2}$$

H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
  - covariance matrices
    - any uncertainty can be calculated from the matrices
      - WW signal strength

$$\Delta^{\text{th, y}}_{\text{FO}}\mu = 0.12$$

↓

$$\Delta^{\text{th, y}}_{\text{A}}\mu = 0.07$$

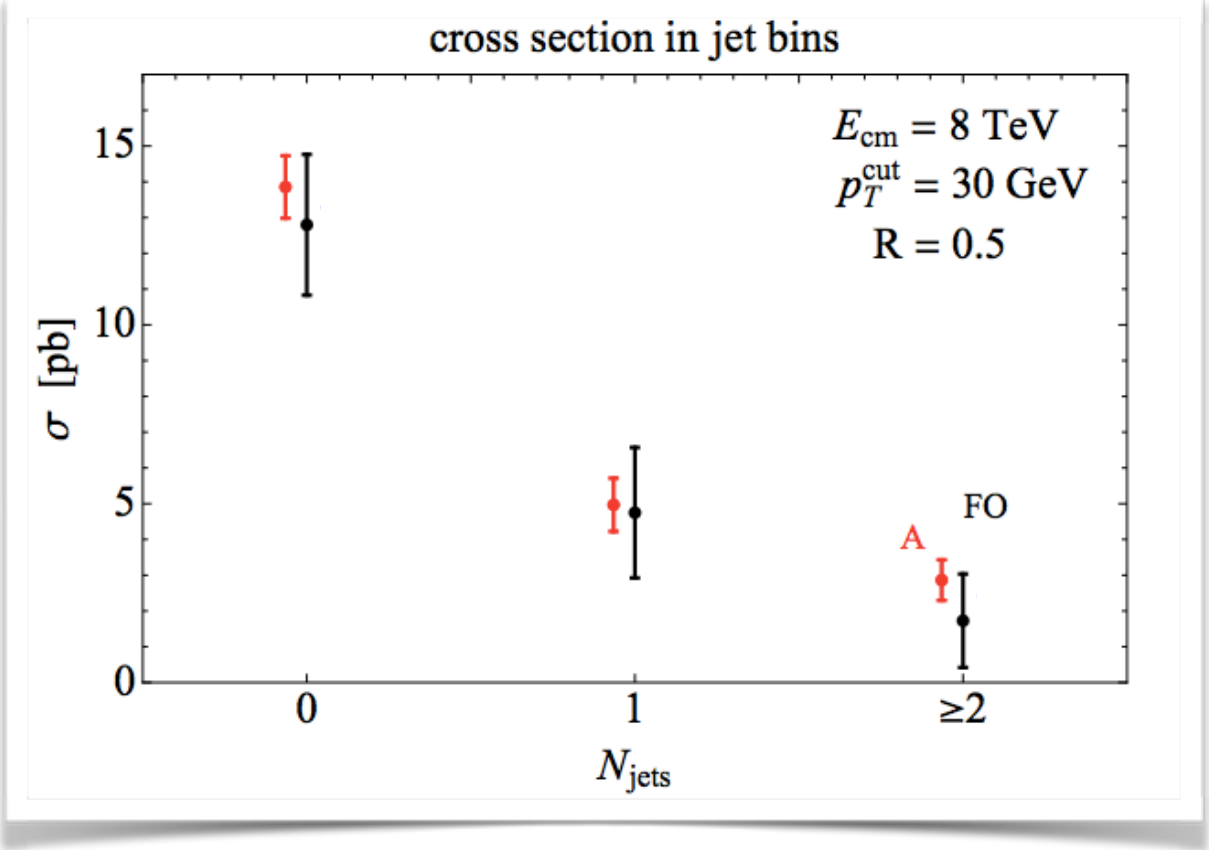
Table 13: Leading uncertainties on the signal strength μ for the combined 7 and 8 TeV analysis.

Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	W+jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29

Reduced by nearly a factor of 2!

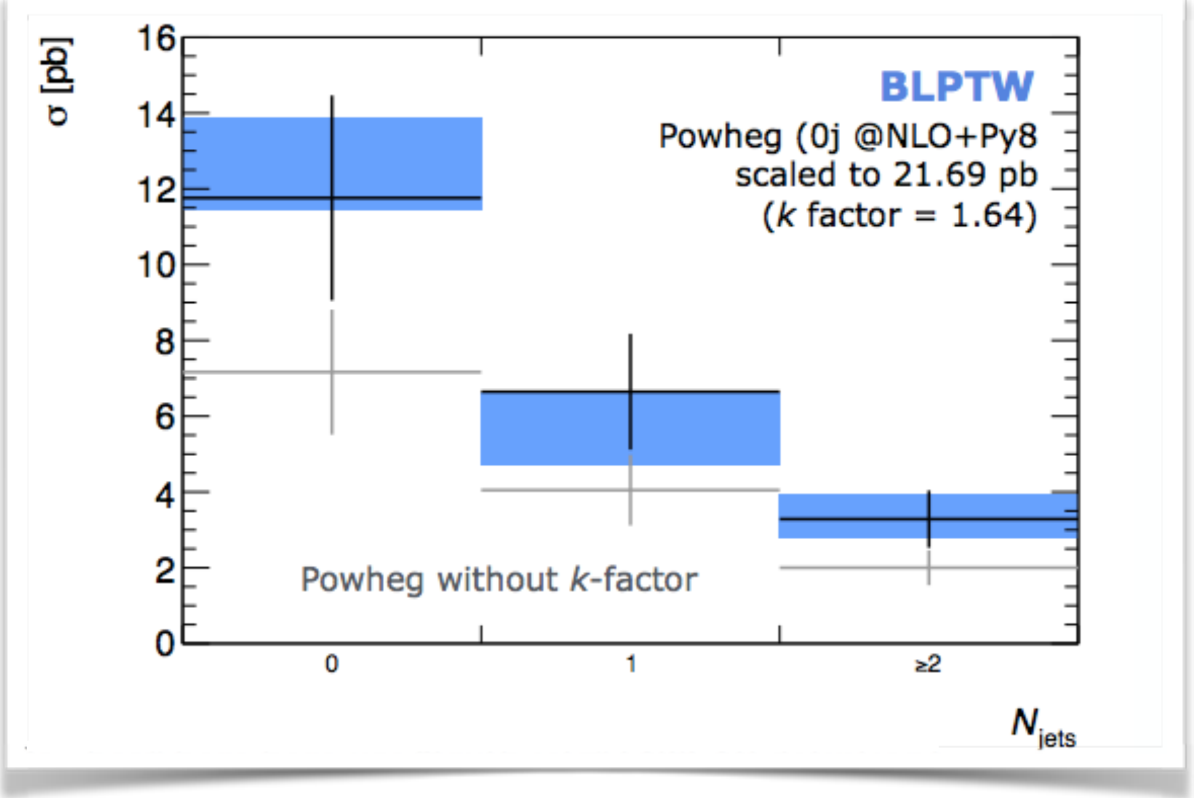
H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
  - covariance matrices
    - any uncertainty can be calculated from the matrices
      - jet bin uncertainties



H + 0-jets and H + 1-jet

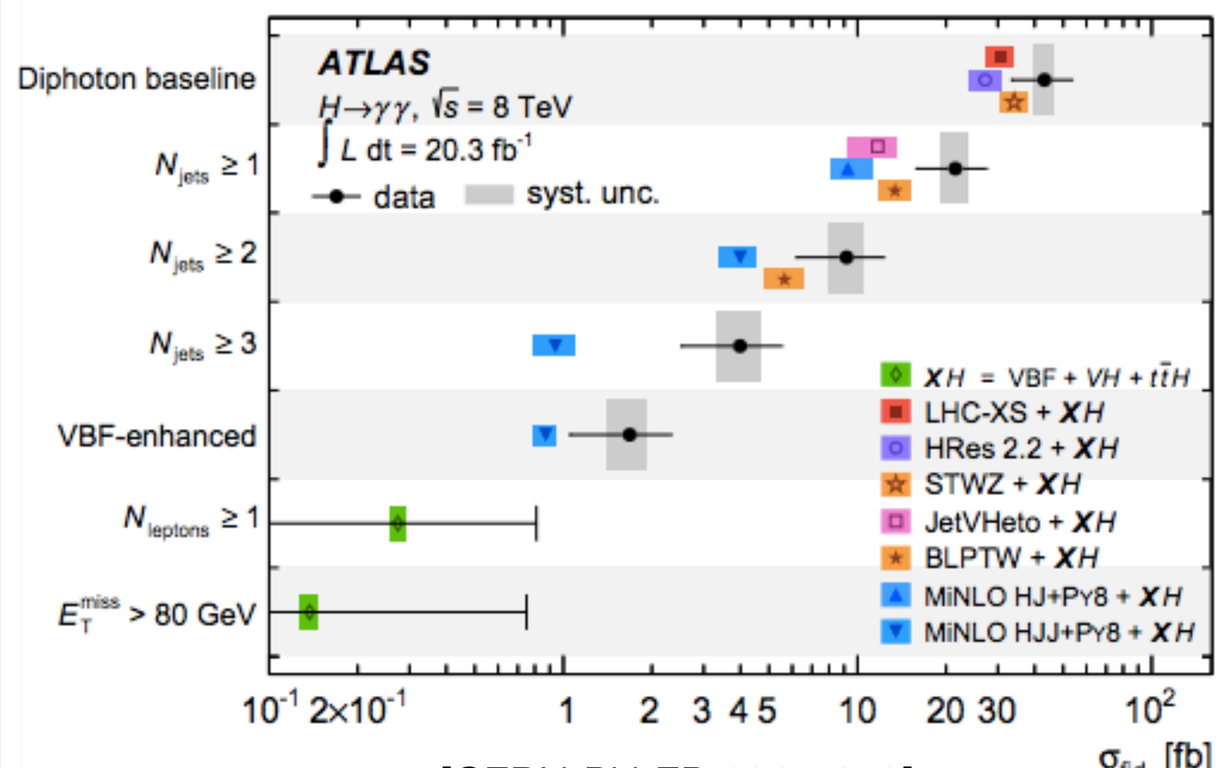
- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
  - covariance matrices
    - any uncertainty can be calculated from the matrices
      - jet bin uncertainties



[Gillberg - talk @ Jet binning uncertainties in ggF, 2014]

H + 0-jets and H + 1-jet

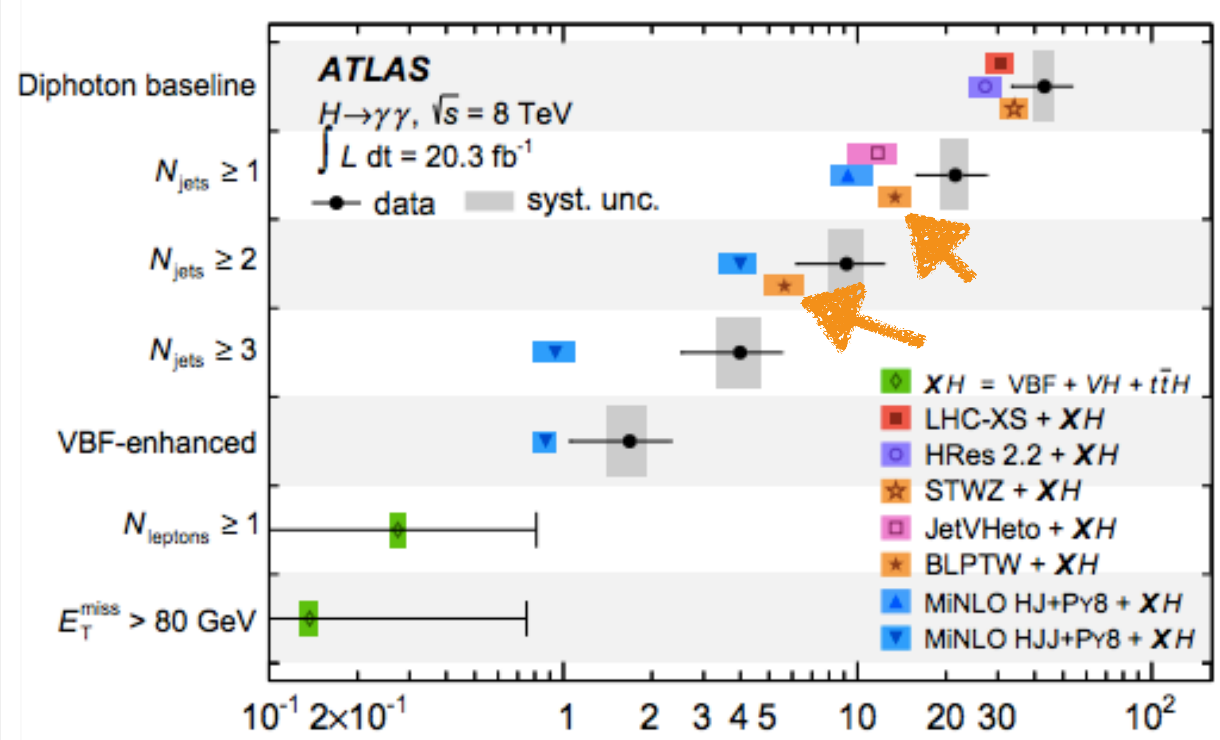
- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
  - covariance matrices
    - any uncertainty can be calculated from the matrices
      - jet bin uncertainties



[CERN-PH-EP-2014-148]

H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh]
  - covariance matrices
    - any uncertainty can be calculated from the matrices
      - jet bin uncertainties



[CERN-PH-EP-2014-148]

Conclusions

- Systematic scheme for combining 0-jets and 1-jet bins have been set up
  - applied directly to Higgs analyses
  - gives the better description of current Higgs data
  - halves the theoretical uncertainties
  - can be applied to W/Z + jets as a testing ground

Thanks