Resumed Jet Bin Predictions

Xiaohui Liu

work with R. Boughezal, F. Petriello, F. Tackmann and J. Walsh - 1312.4535

LoopFest 2014
New York City College of Technology

See also

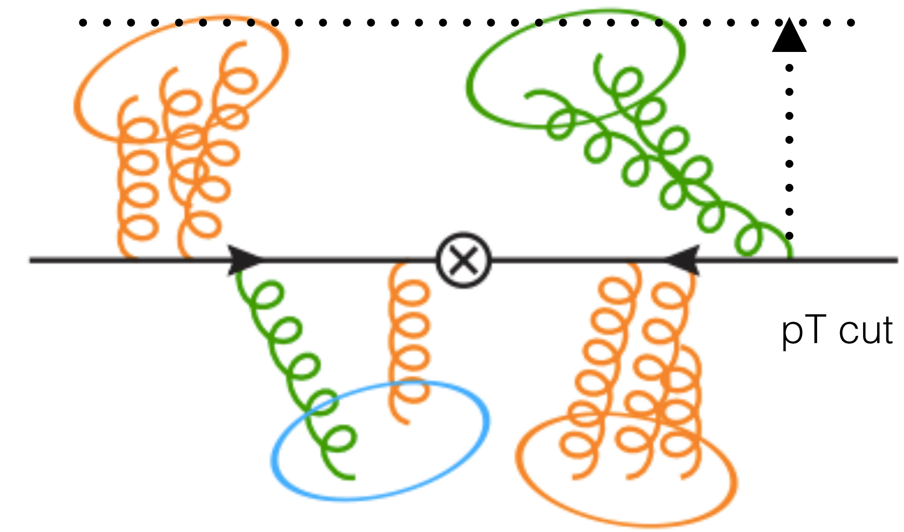
XL, F. Petriello - 1210.1906, 1303.4405
I. Stewart, F. Tackmann, J. Walsh and S. Zuberi - 1307.1808

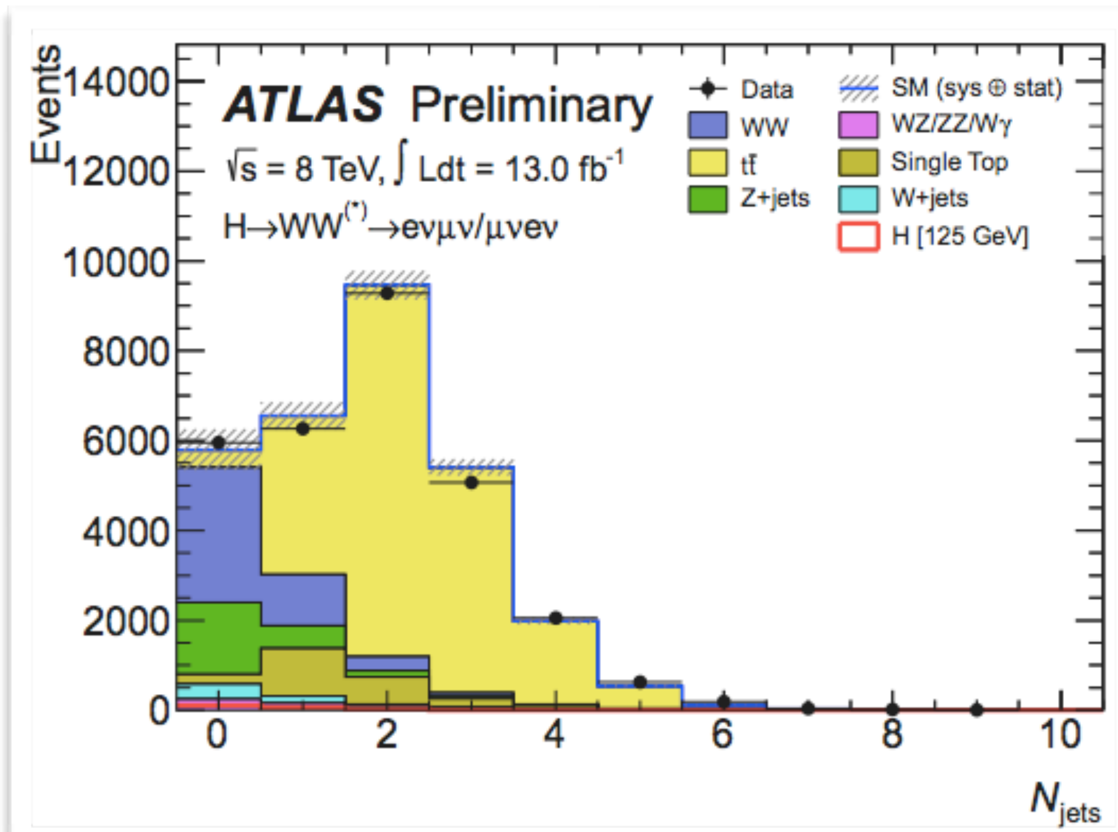
Outline

- 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





[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
      - efficient in suppressing the backgrounds
      - large theory uncertainties

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
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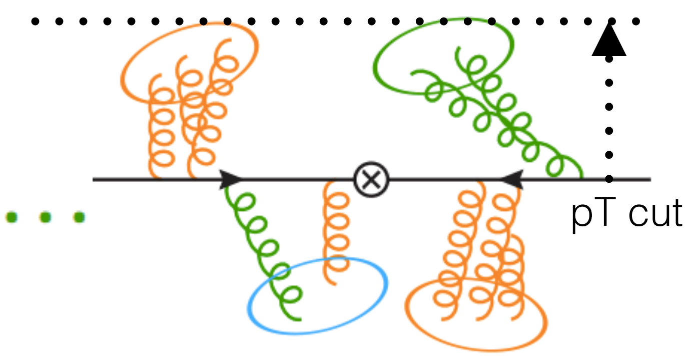
[ATLAS-CONF-2012-158]

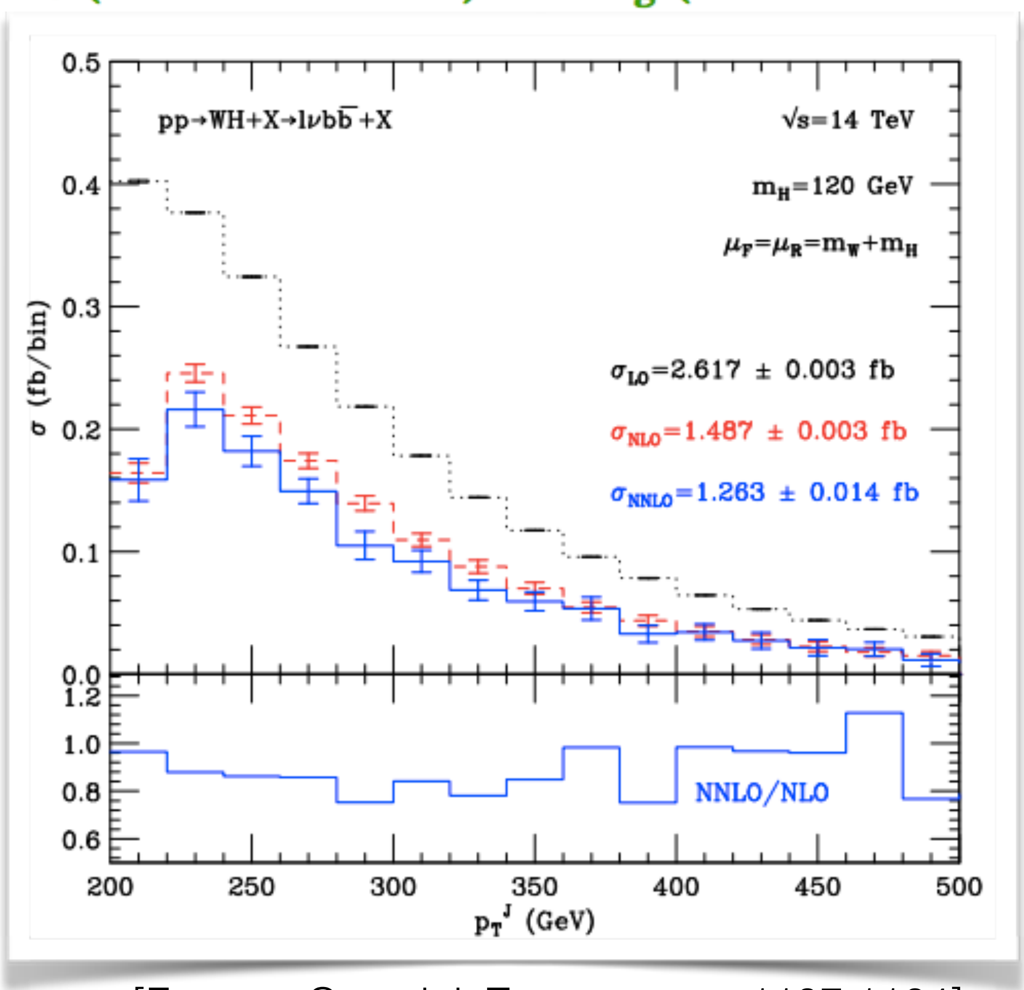
Theoretical Issues with Jet Veto

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



$$\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \cdots$$

L=log(pTcut/Q)



[Ferrera, Grazzini, Tramontano - 1107.1164]

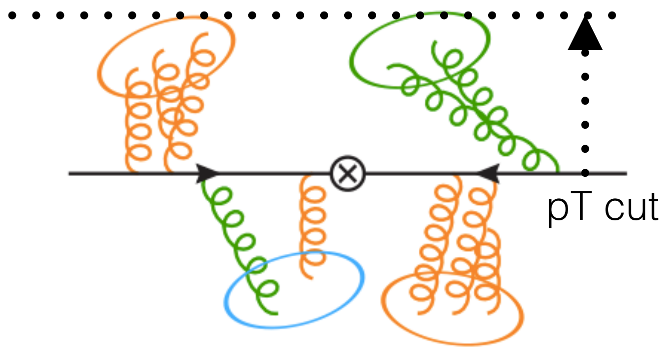
from inclusive NLO: +30% [Han, Willenbrock - 1990]

to jet veto: - 50%

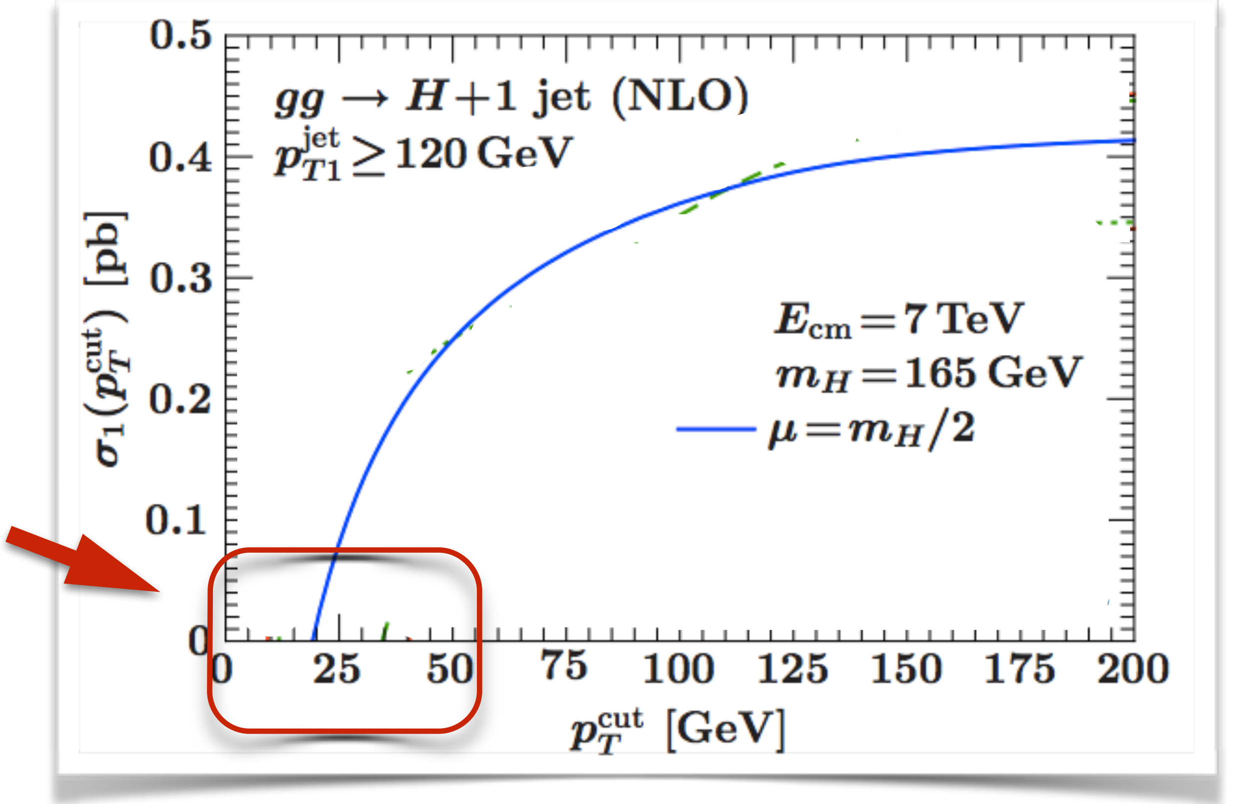
due to the jet veto logs L!

Theoretical Issues with Jet Veto

- Low pT jet veto restricts emissions to be soft and collinear
  - leads to large Sudakov logs
    - unreliable perturbative predictions

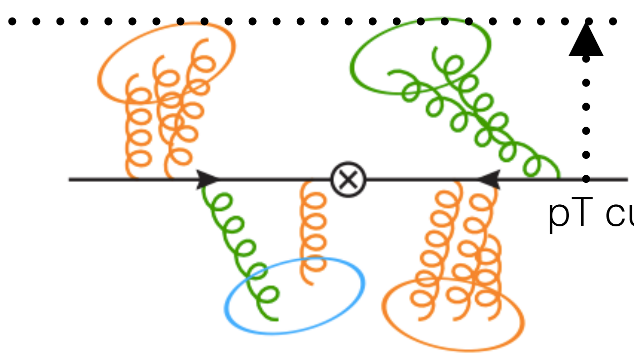


miss large higher order corrections



Theoretical Issues with Jet Veto

- Low pT jet veto restricts emissions to be soft and collinear
  - leads to large Sudakov logs
    - unreliable perturbative predictions
    - unreliable uncertainty estimation

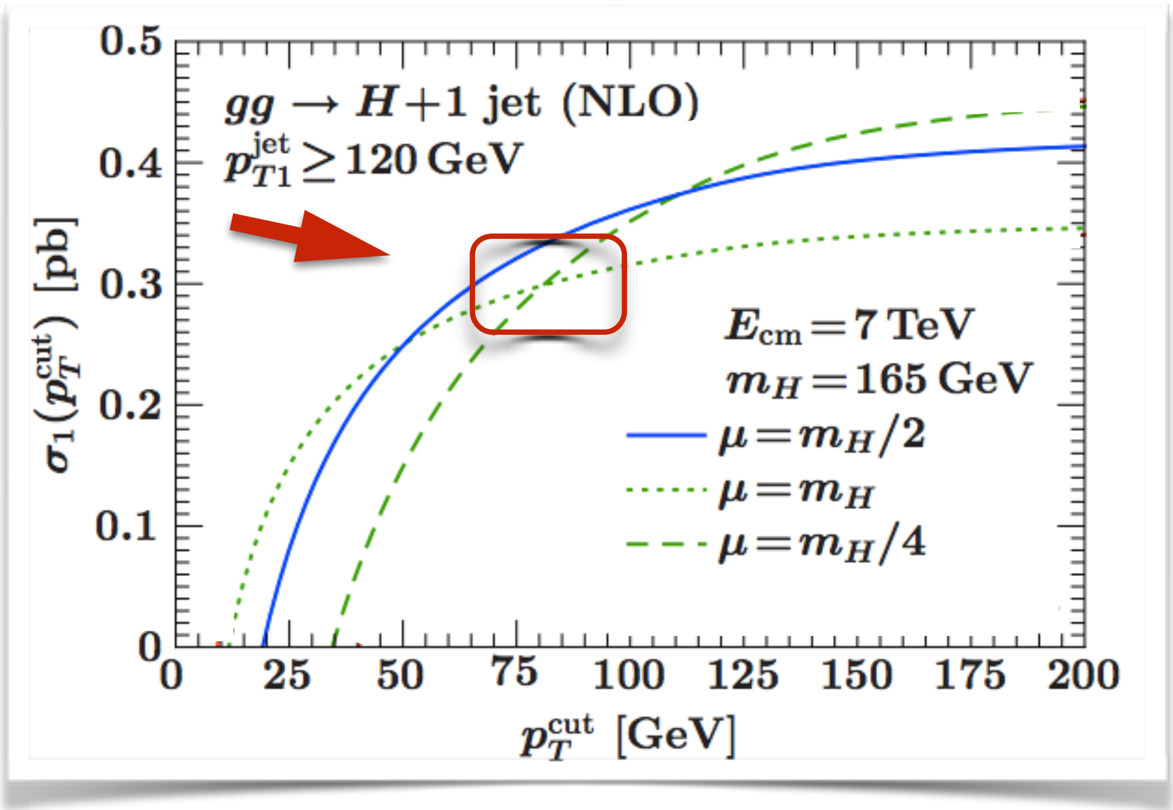


accidental cancellation

$$\sigma_{\geq 1}(p_{T_1}^{\text{jet}} \geq 120\text{ GeV}) = (0.31\text{ pb})\left[1 + 2.9\alpha_s + \mathcal{O}(\alpha_s^2)\right]$$

$$\sigma_{\geq 2}(p_{T_1}^{\text{jet}} \geq 120\text{ GeV}, p_{T_2}^{\text{jet}} \geq 60\text{ GeV}) = (0.31\text{ pb})\left[\quad 3.7\alpha_s + \mathcal{O}(\alpha_s^2)\right]$$

$$\sigma_N = \sigma_{\geq N} - \sigma_{\geq N+1}$$



Theoretical Issues with Jet Veto

- Low pT jet veto restricts emissions to be soft and collinear
  - leads to large Sudakov logs
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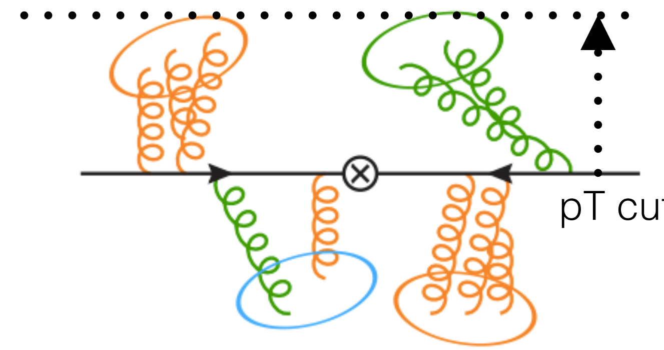
    - unreliable uncertainty estimation
    - large theoretical errors

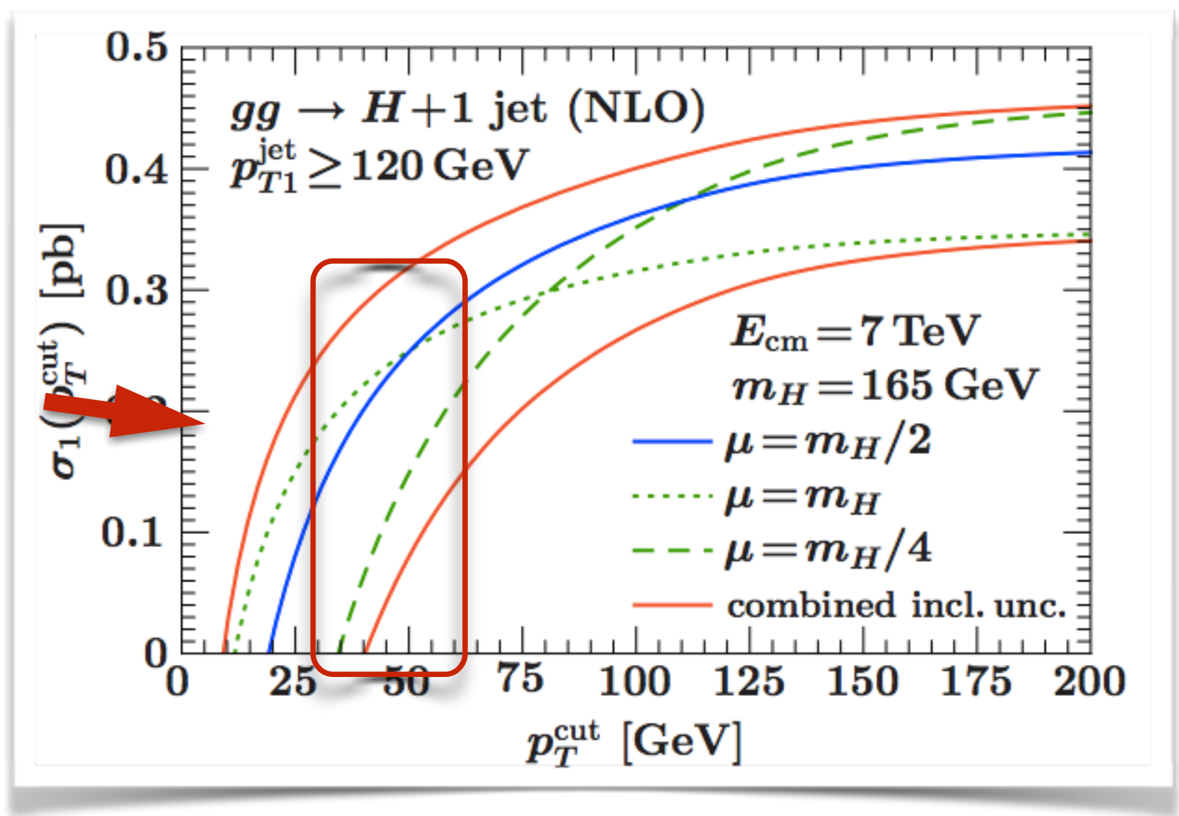


ST prescription used by ATLAS and CMS

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

$$\sigma_N = \sigma_{\geq N} - \sigma_{\geq N+1}$$

[Stewart and Tackmann-1107.2117]



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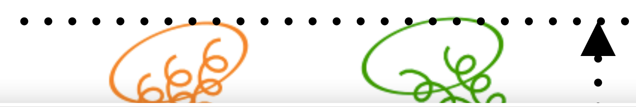

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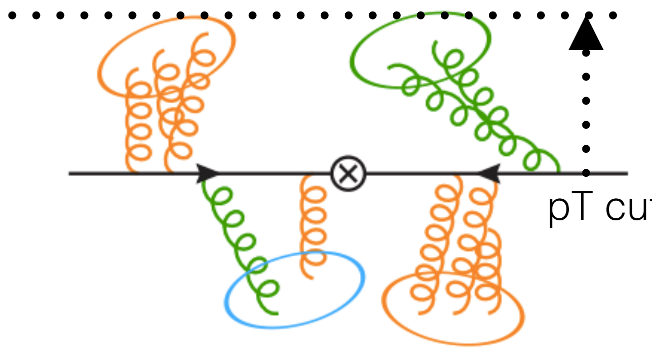
[ATLAS-CONF-2012-158]

Theoretical Issues with Jet Veto

- Low pT jet veto restricts emissions to be soft and collinear
  - leads to large Sudakov logs
    - unreliable perturbative predictions
    - unreliable uncertainty estimation
    - large theoretical errors
    - need to be resummed



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

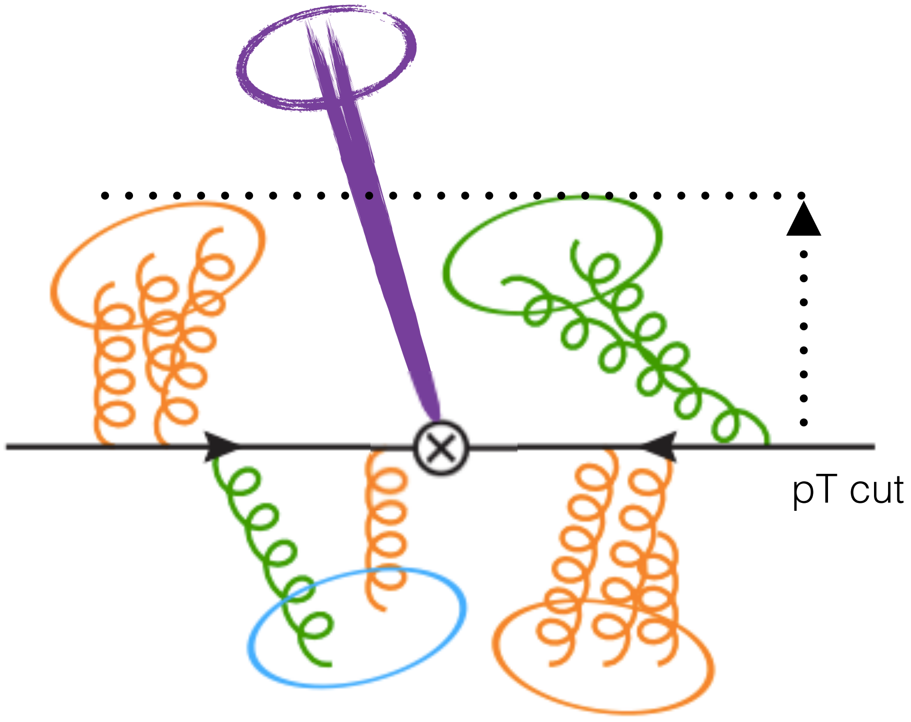
Efforts on Jet Vetoes

- H + 0-jets
  - Banfi, Monni, Salam, Zanderighi - 1203.5773, 1206.4996, NNLL + NNLO
  - Becher, Neubert, Rothen - 1205.3806, 1307.0025, NNLL' + NNLO + π^2
  - Stewart, Tackmann, Walsh, Zuberi - 1307.1808, NNLL' + NNLO + π^2
  - Alioli and Walsh - 1311.5234, Clustering Logs,
  - Moult and Stewart - 1405.5334, interfering with H -> W+W-
- H + 1-jet
  - XL, Petriello - 1210.1906, 1303.4405, NLL' + NLO
  - Boughezal, XL, Petriello, Tackmann, Walsh - 1312.4535, (beyond NLL') + NLO, (H+0+1j)
- VH + 0-jets
  - Li, Li, Shao - 1309.5015, NNLL + NLO + π^2
  - Li, XL - 1401.2149, (beyond NNLL) + NNLO + π^2

Efforts on Jet Vetoes

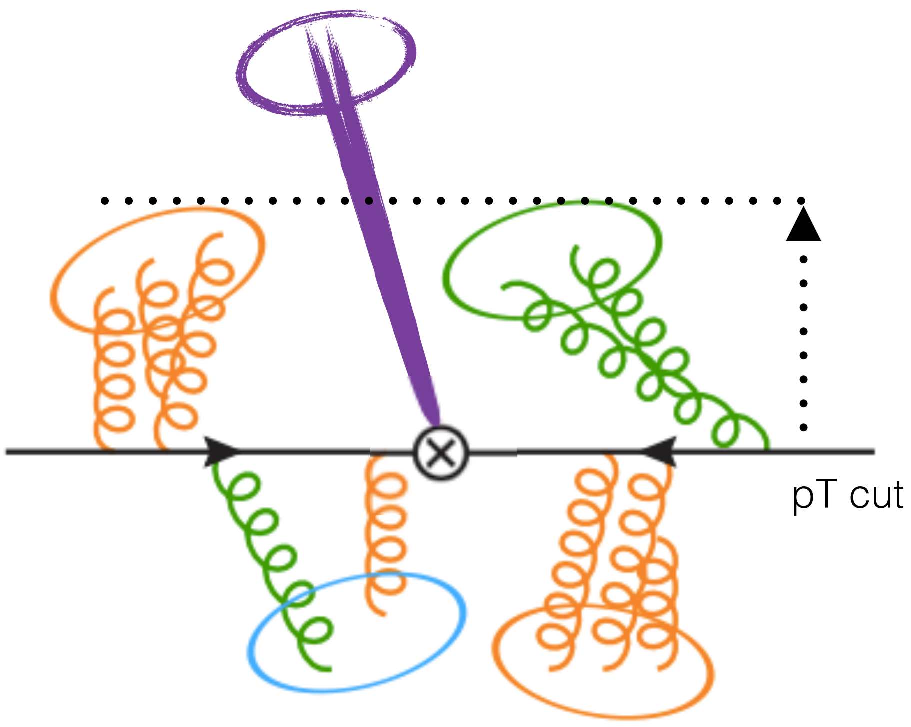
- Factorization

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



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



Becher, Neubert, Rothen - 1205.3806, 1307.0025

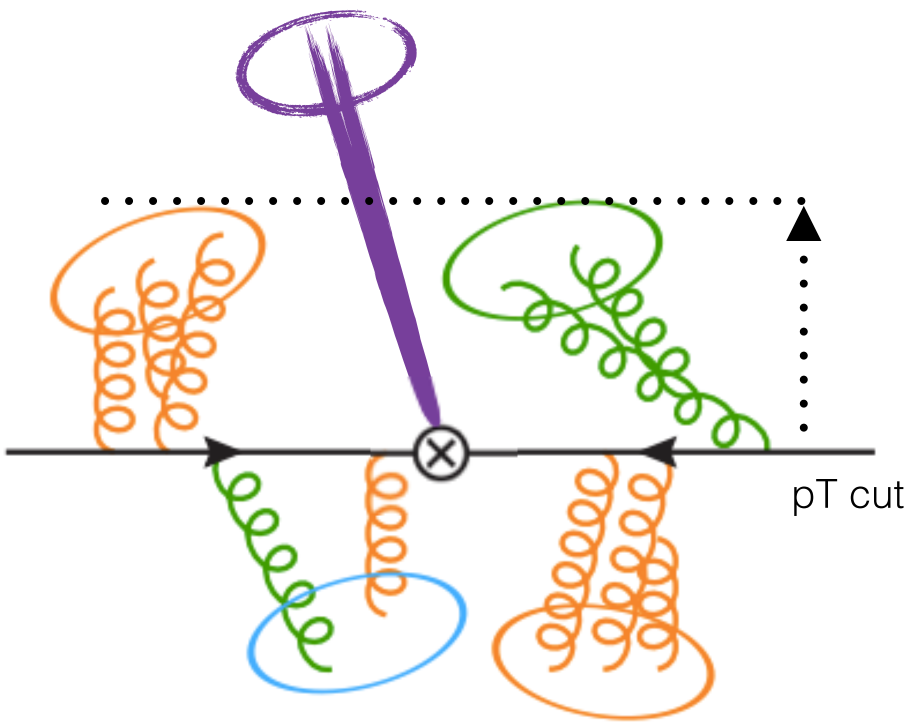
Stewart, Tackmann, Walsh, Zuberi - 1307.1808

XL, Petriello - 1210.1906, 1303.4405

Efforts on Jet Vetoes

- Factorization

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



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

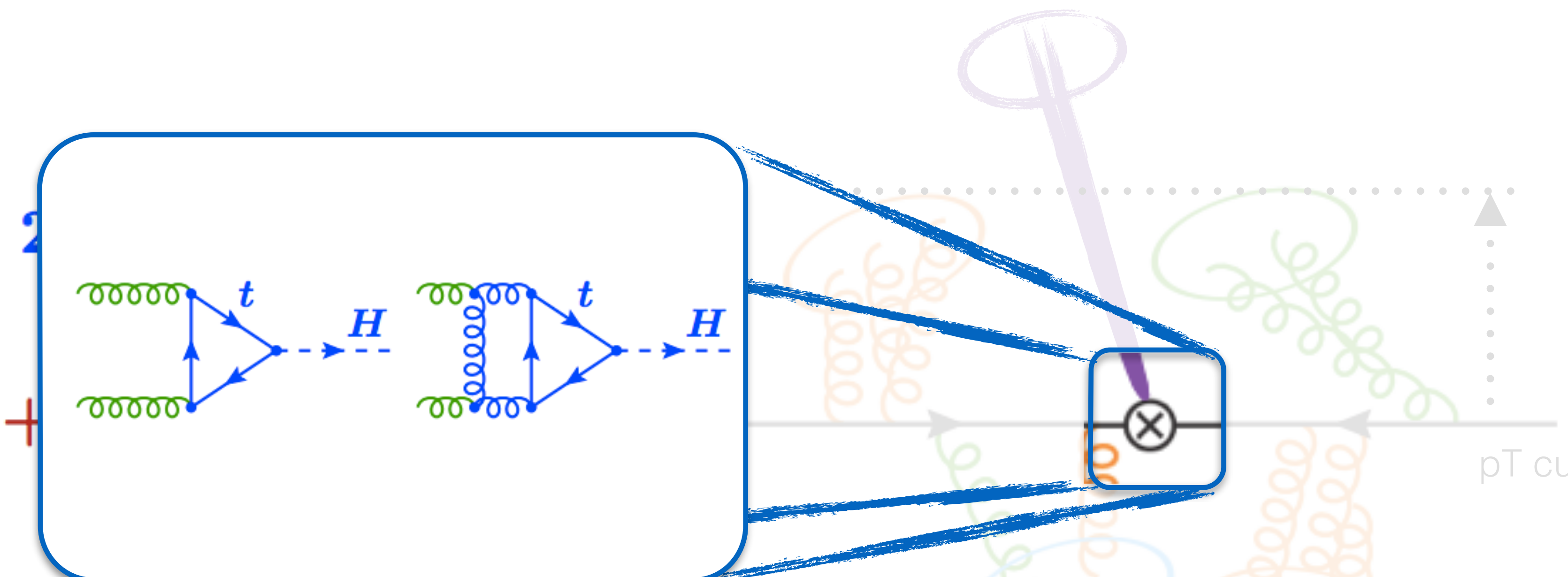
Efforts on Jet Vetoes

- Factorization

$$2\ln^2\frac{p_T^{\rm cut}}{m_H} = 2 \ldots$$

$$+ \ldots$$

$$+\, 2\ln\frac{\ldots}{\mu}\,\ln\frac{\ldots}{\nu^2}$$

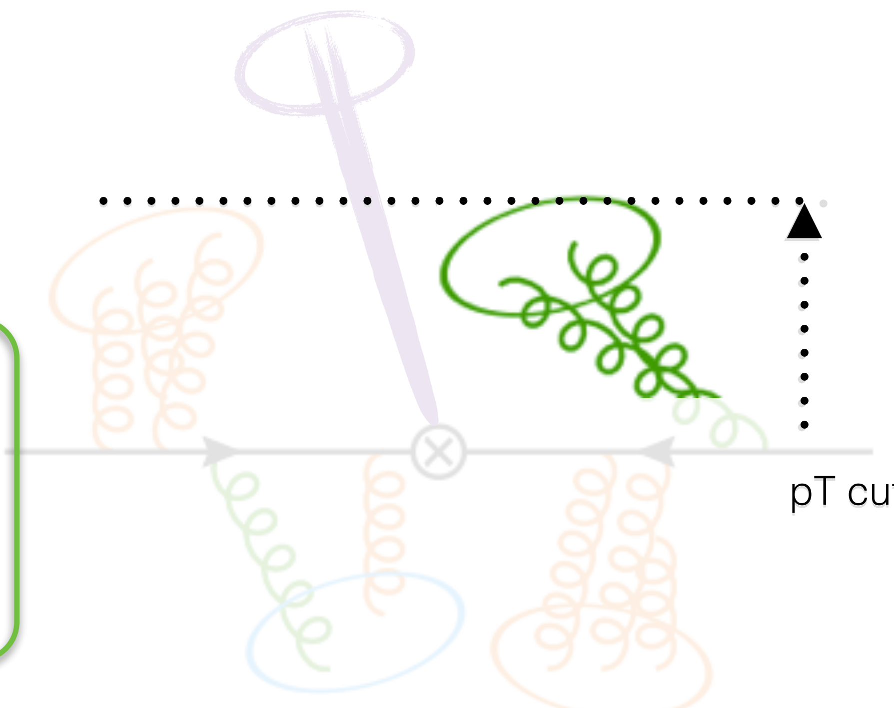


$$\sigma_0(p_T^{\rm cut}) = H(Q,\mu)\,B^{\rm jet}(R,p_T^{\rm cut},\mu,\nu)\,B^{\rm jet}(R,p_T^{\rm cut},\mu,\nu)\,S^{\rm jet}(R,p_T^{\rm cut},\mu,\nu)\,J(R,p_T^J R,\mu)$$

Efforts on Jet Vetoes

- Factorization

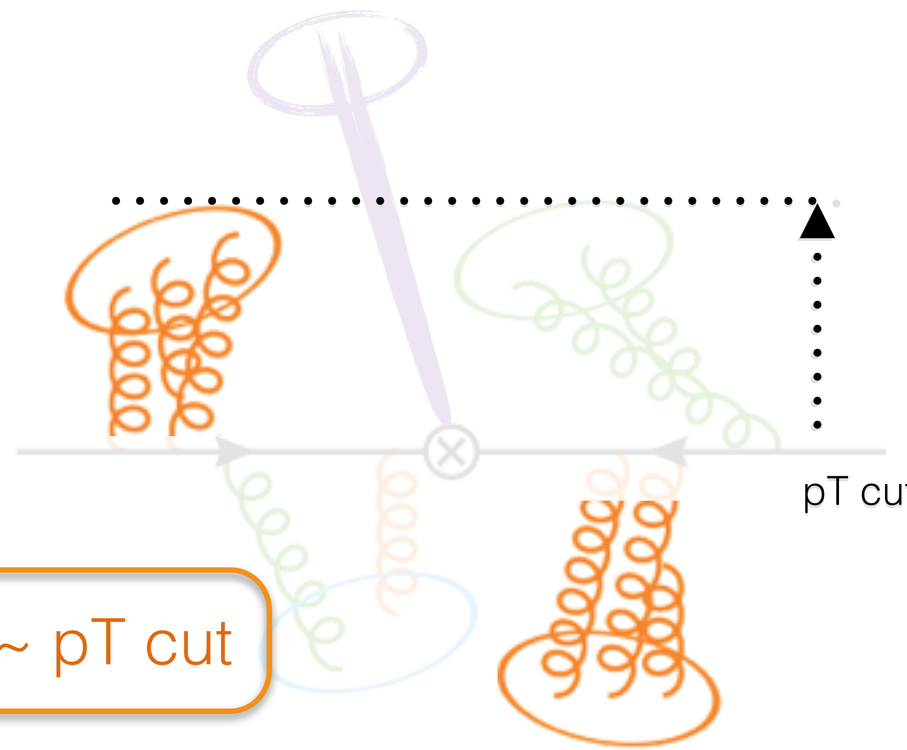
* initial state energetic radiations with transverse momentum ~ pT cut
* includes pdf information



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

Efforts on Jet Vetoes

- Factorization



* radiations with energy ~ pT cut

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

Efforts on Jet Vetoes

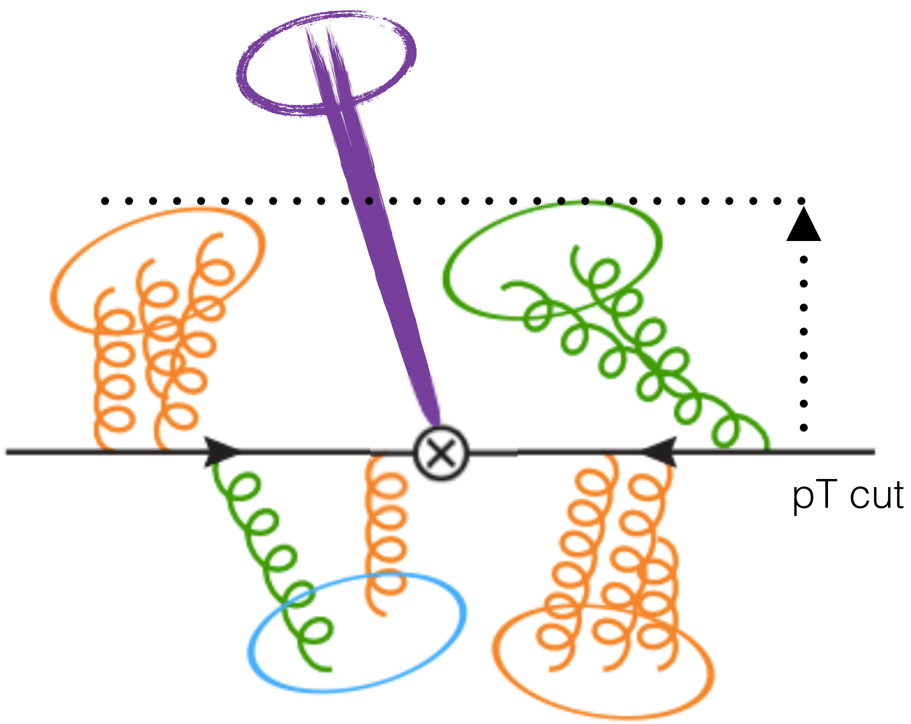
- Factorization

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

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

Efforts on Jet Vetoes

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



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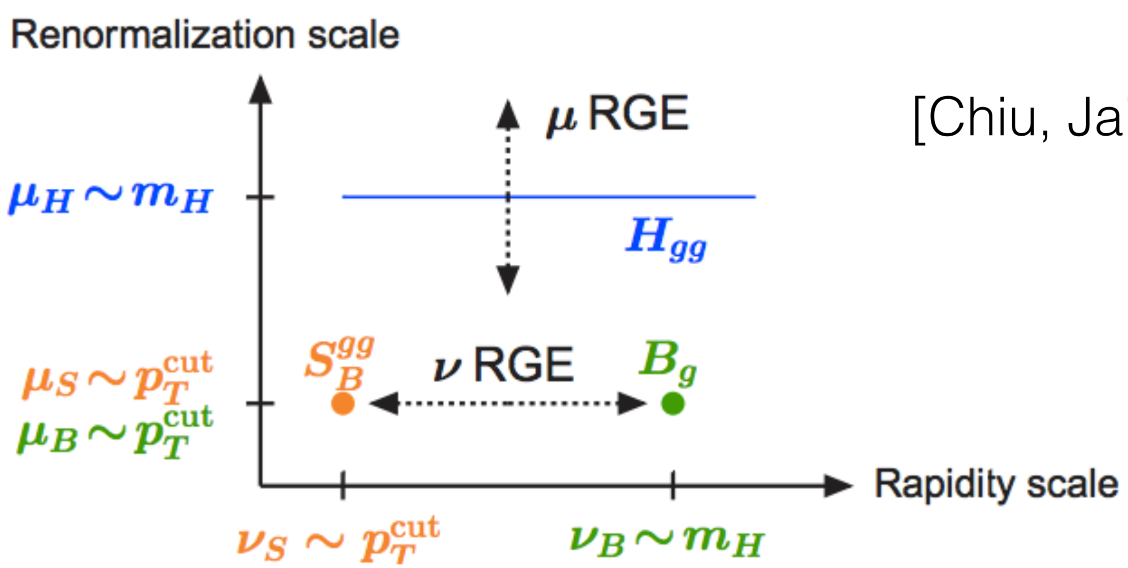
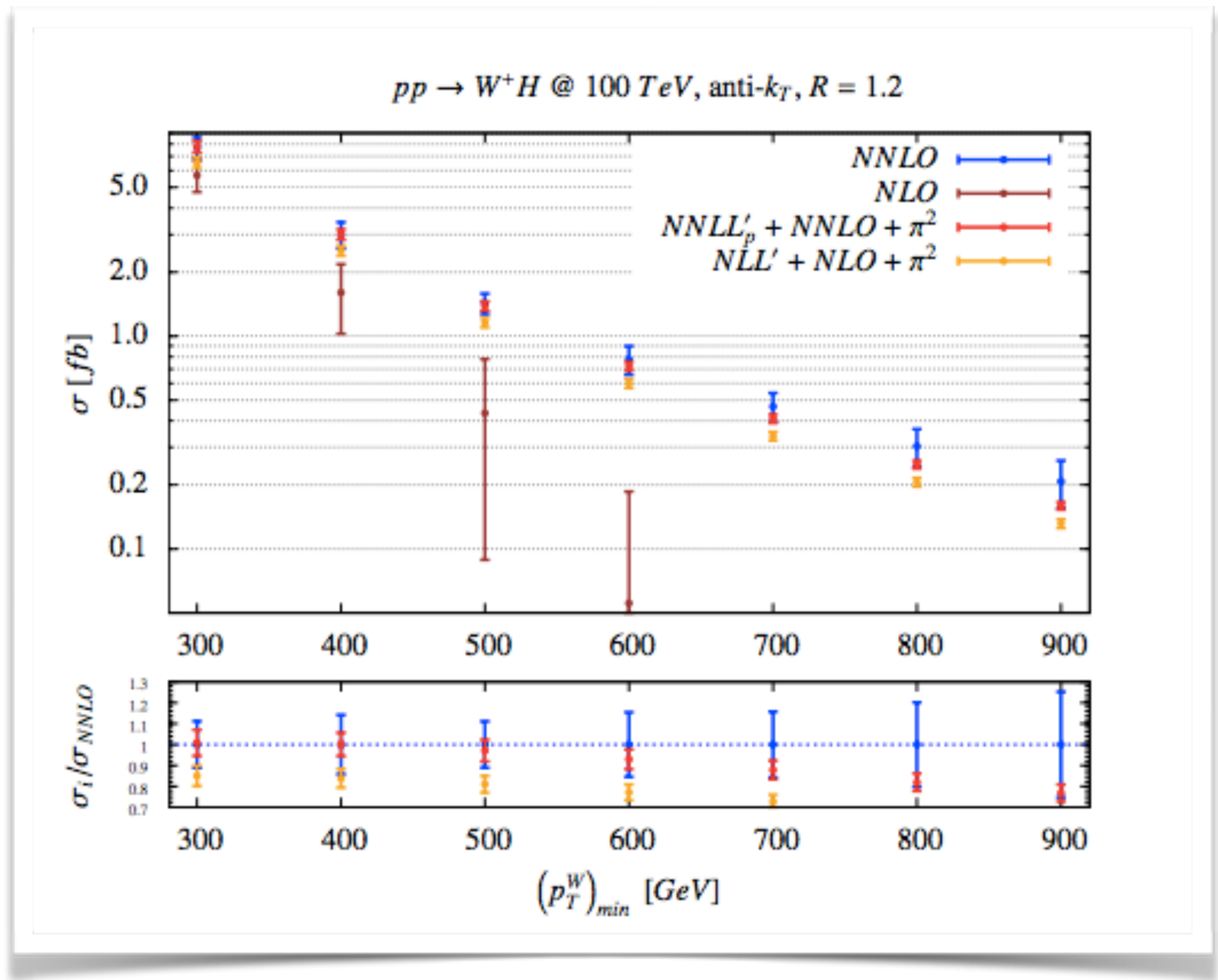


[Chiu, Jain, Neill and Rothstein, 2011]

alternative approach based on collinear anomaly [Becher, Neubert]

Higgs on future colliders

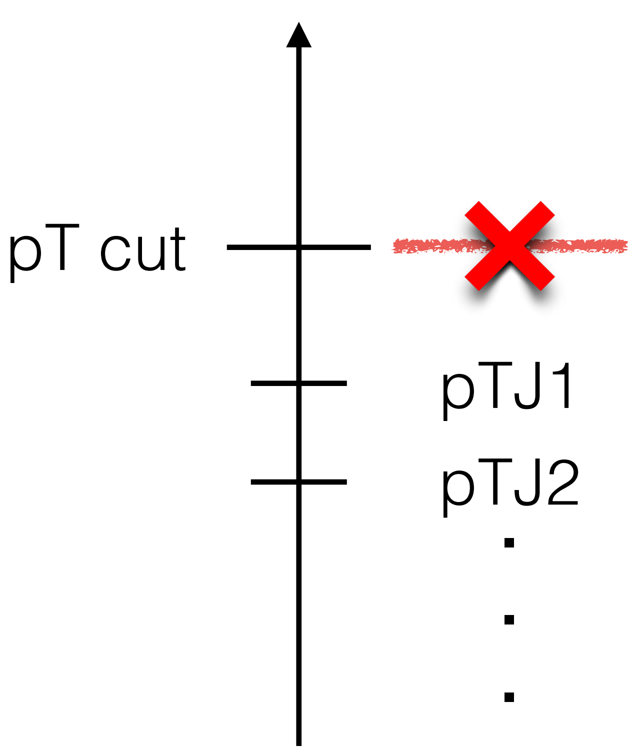
- Boosted Higgs @ future colliders pT veto = 30GeV
  - resummation stabilizes the perturbative series
  - resummation reduces the scale uncertainties

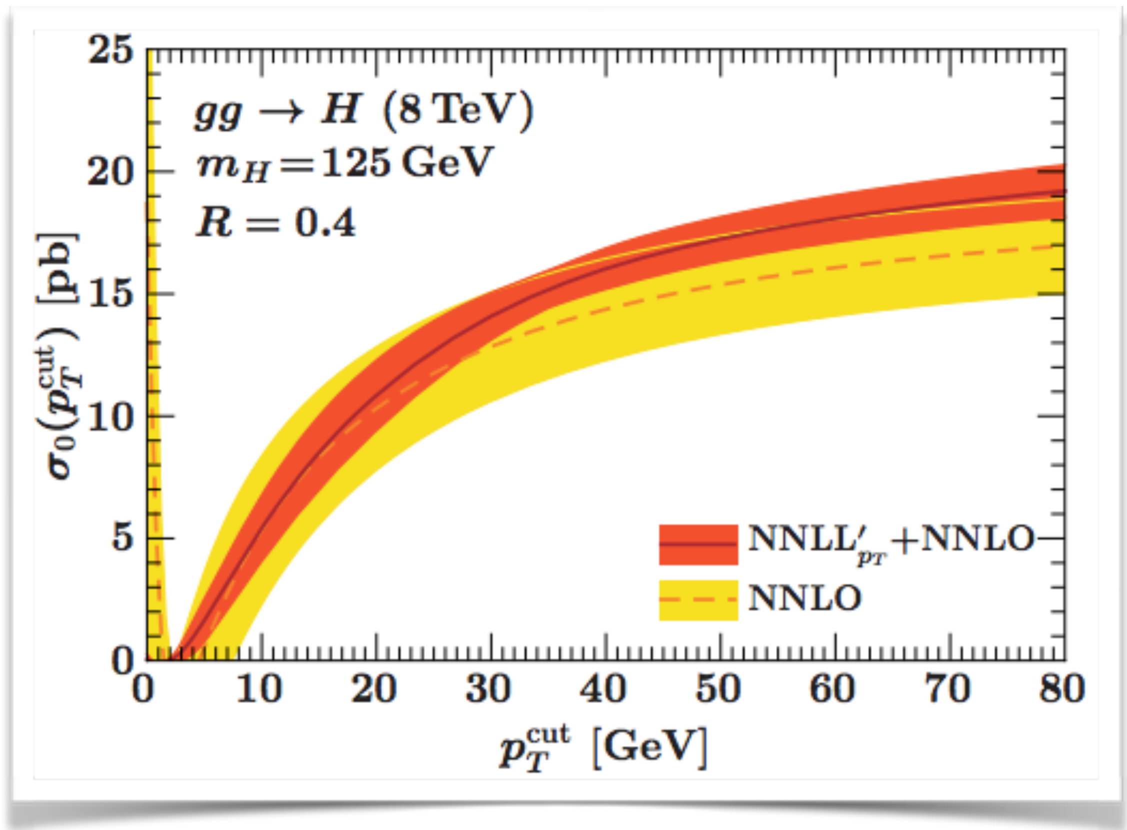


[Boughezal, Focke, Li, XH -1405.4562]

H + 0-jets and H + 1-jet

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





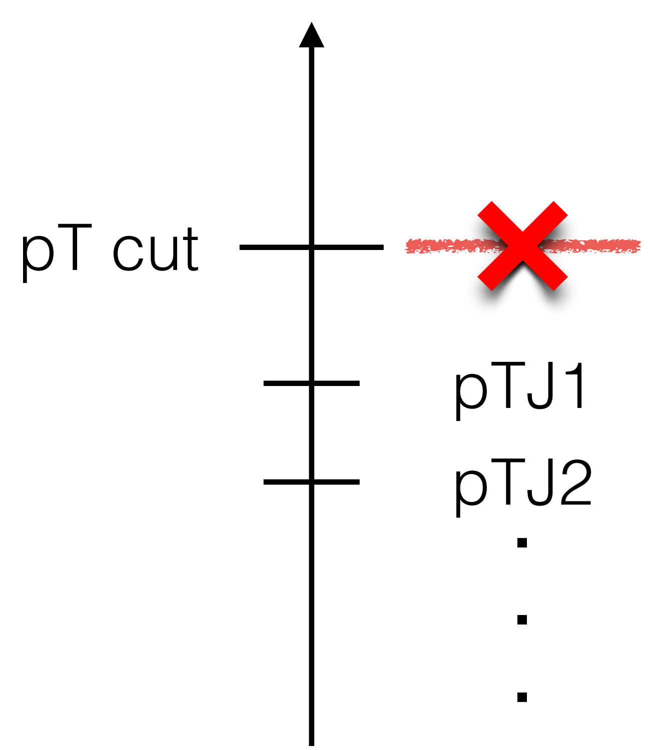
[Stewart, Tackmann, Walsh, Zuberi - 1307.1808]

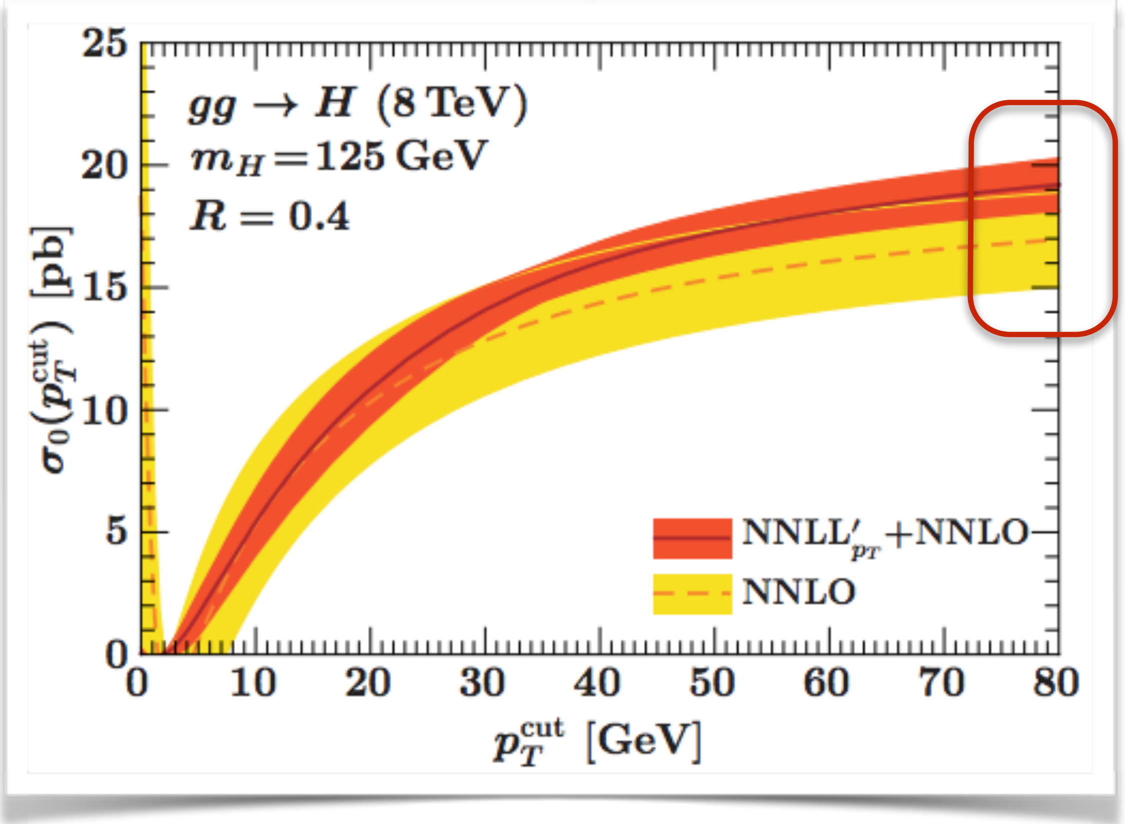
see also, Becher, Neubert, Rothe - 1307.0025

H + 0-jets and H + 1-jet

- H + 0-jets
  - keep events with no jet pT > pT cut
  - NNLL' + NNLO + π²

π² resummaiton also enhanced the inclusive cross section





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H + 0-jets and H + 1-jet

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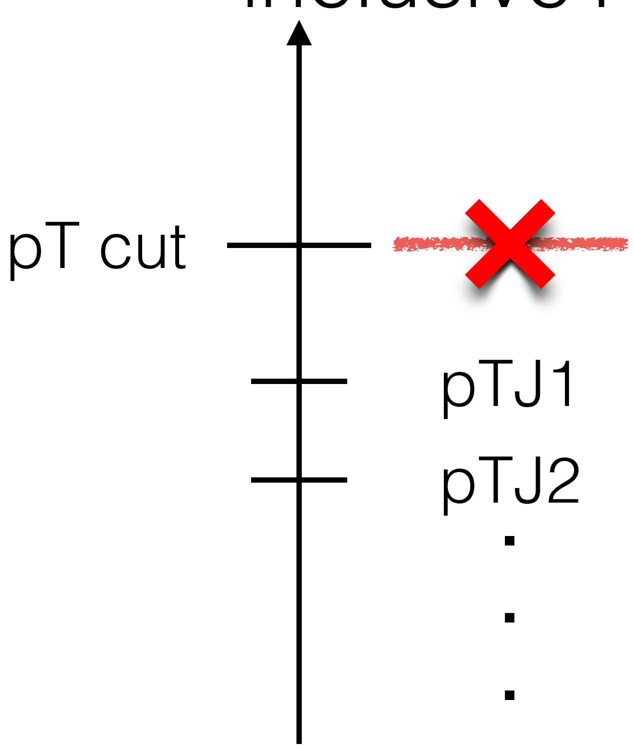
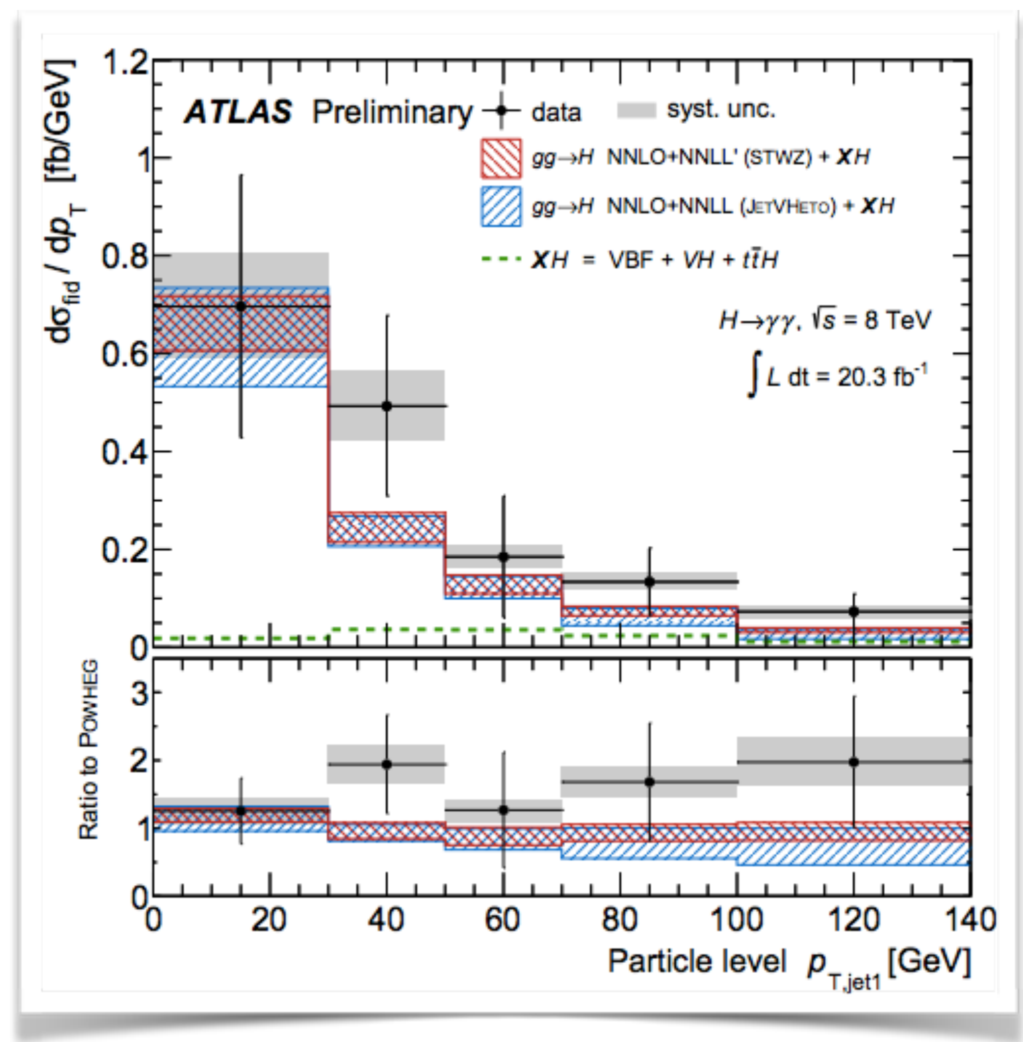
  - keep events with no jet pT > pT cut
  - NNLL’ + NNLO + π^2
  - inclusive1-jet (pTJ<<mH)

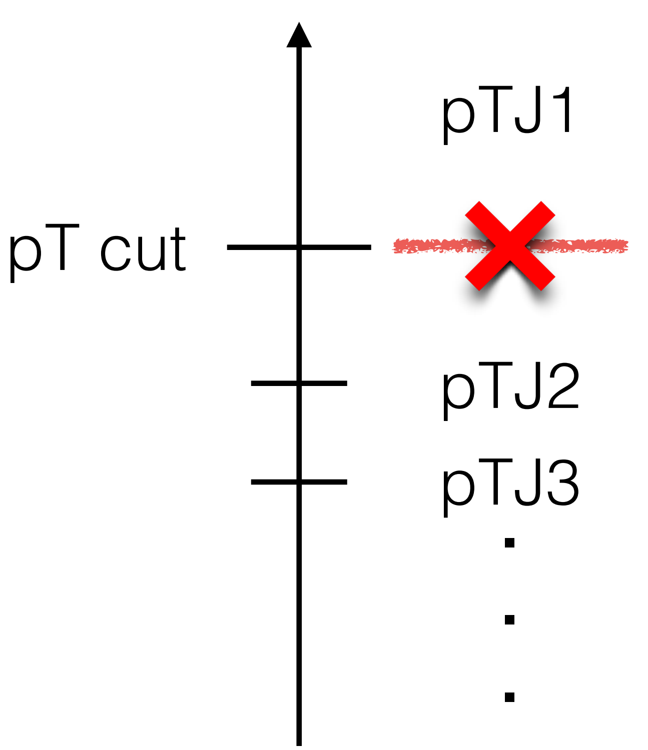


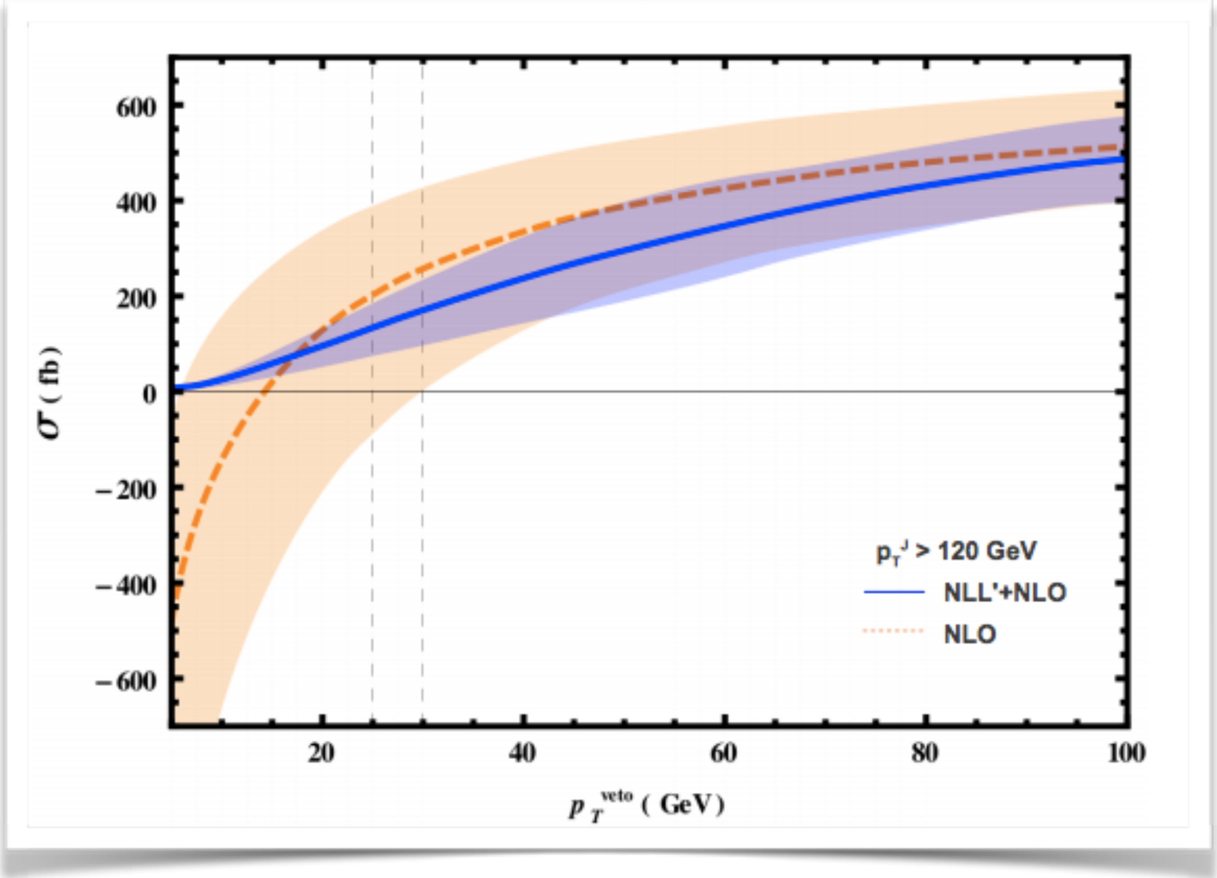


[ATLAS-CONF-2013-072]

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

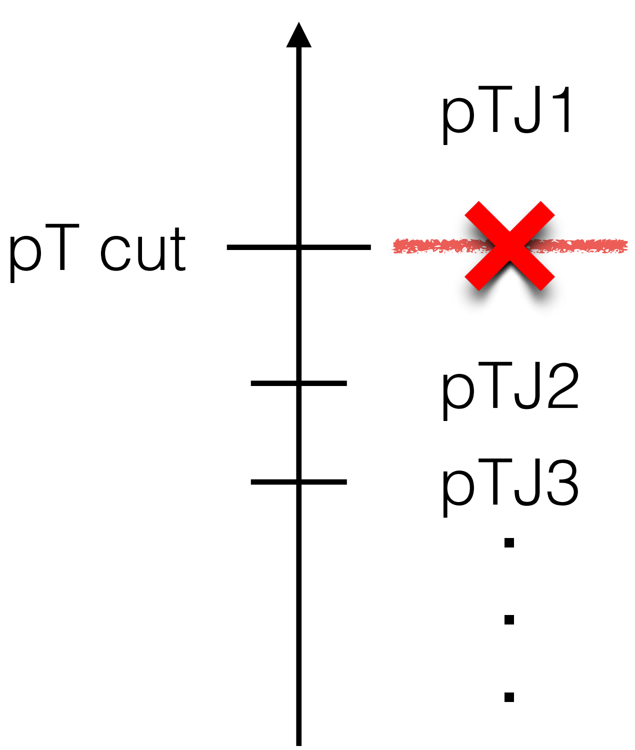


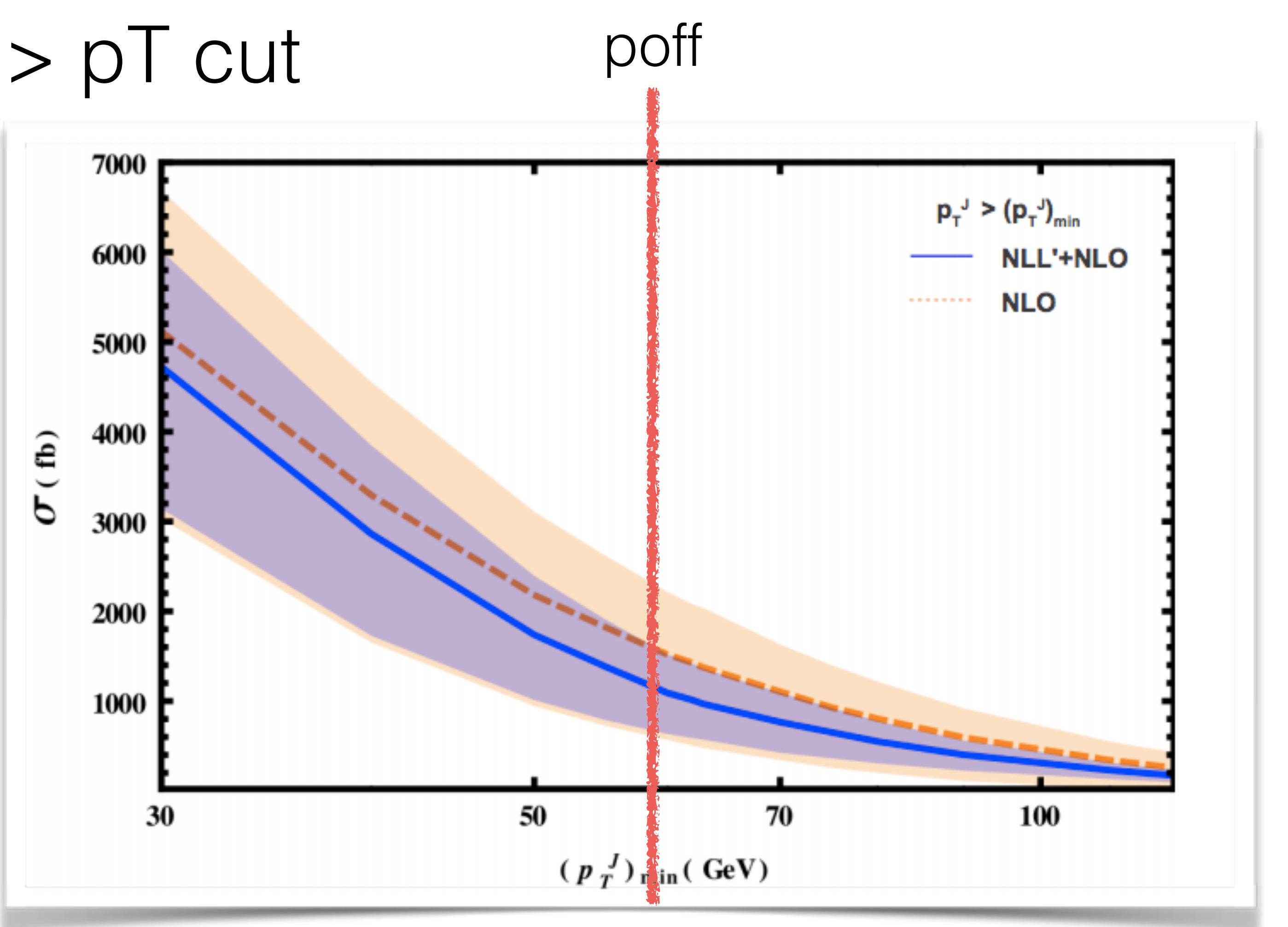


[XL, Petriello - 1303.4405]

H + 0-jets and H + 1-jet

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





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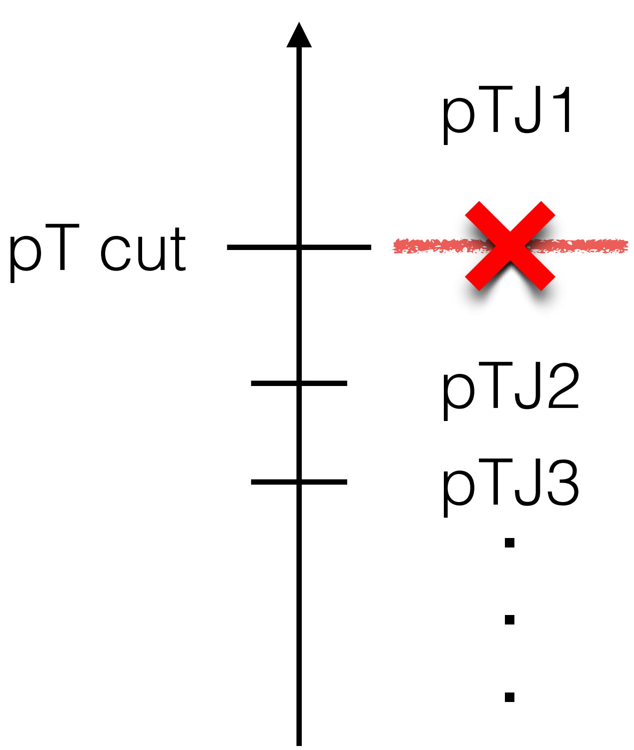
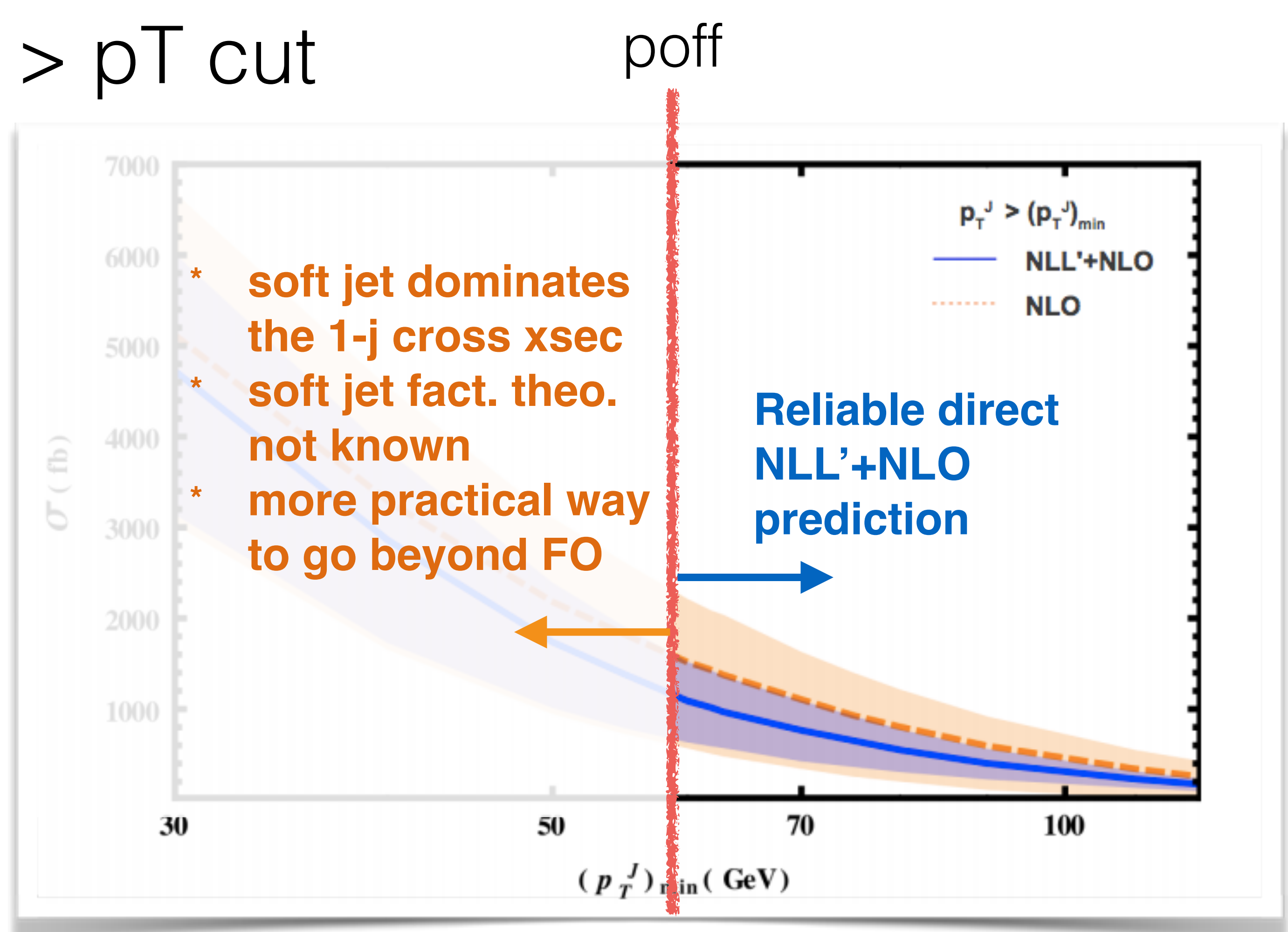


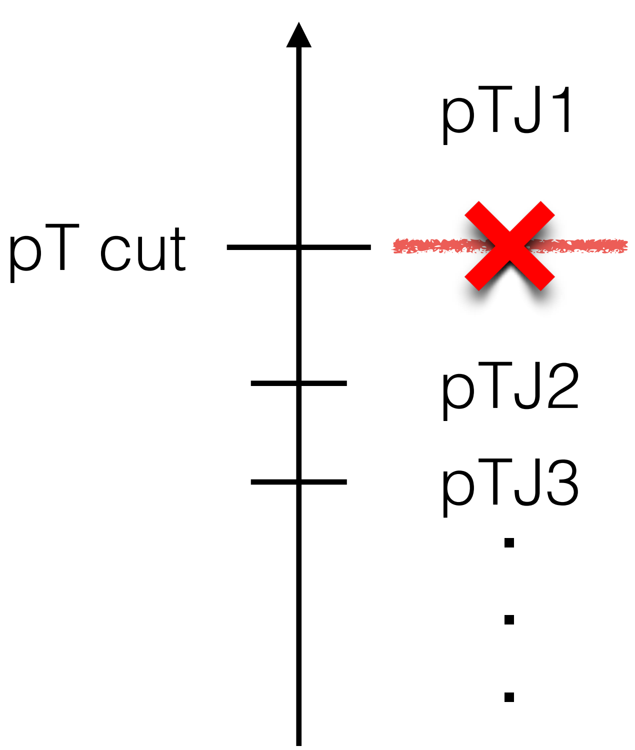


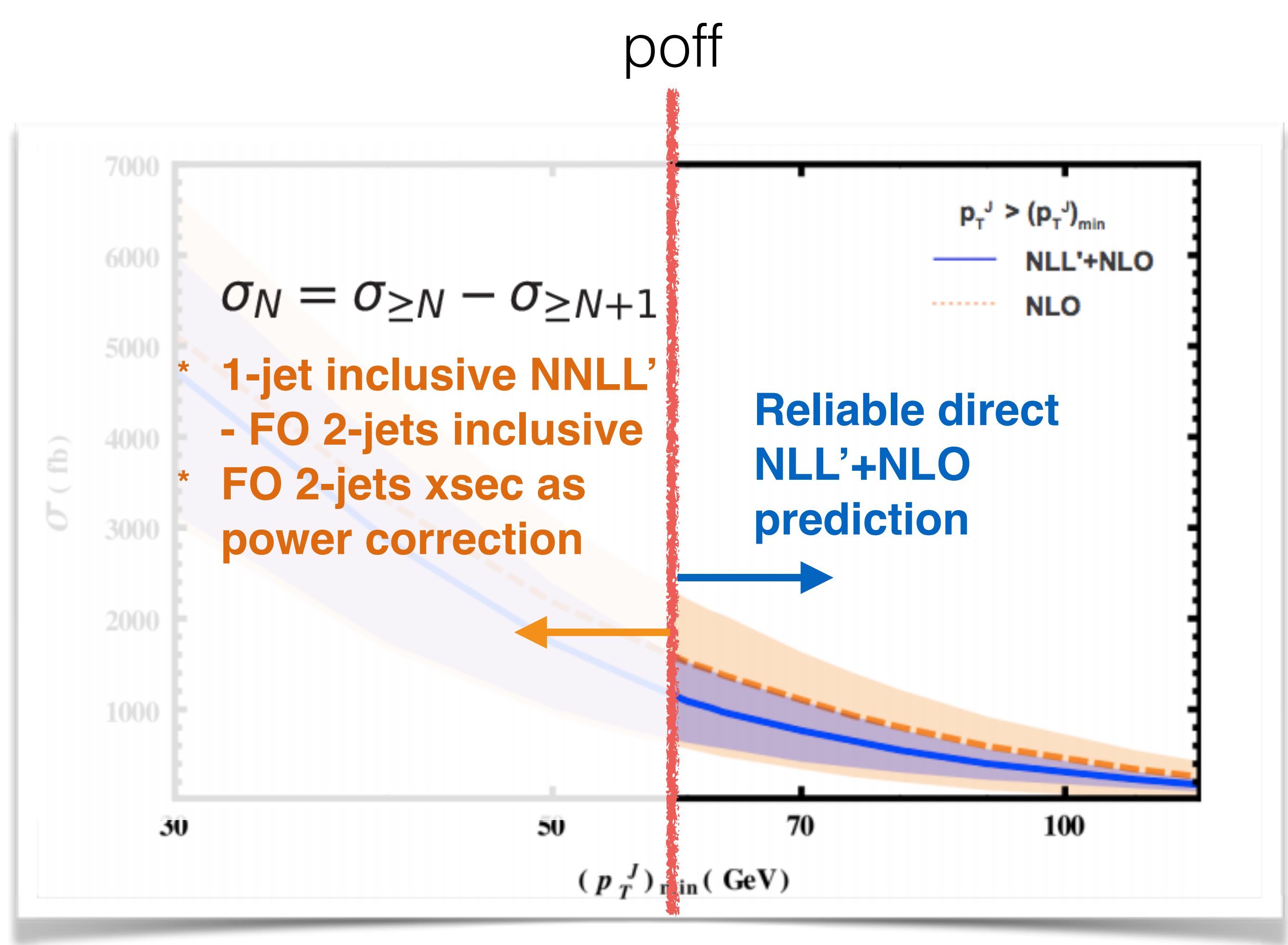
[XL, Petriello - 1303.4405]

H + 0-jets and H + 1-jet

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

[Boughezal, XL, Petriello, Tackmann, Walsh - 1312.4535]





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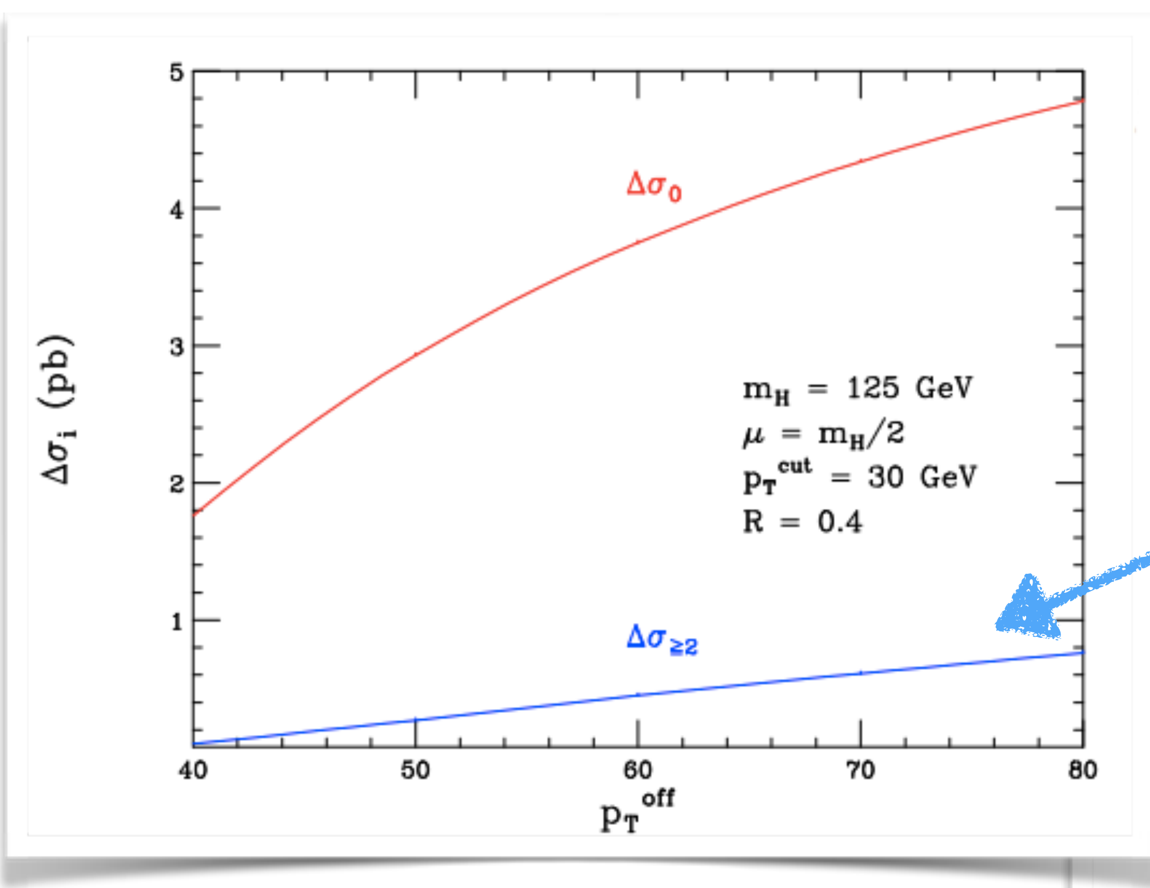

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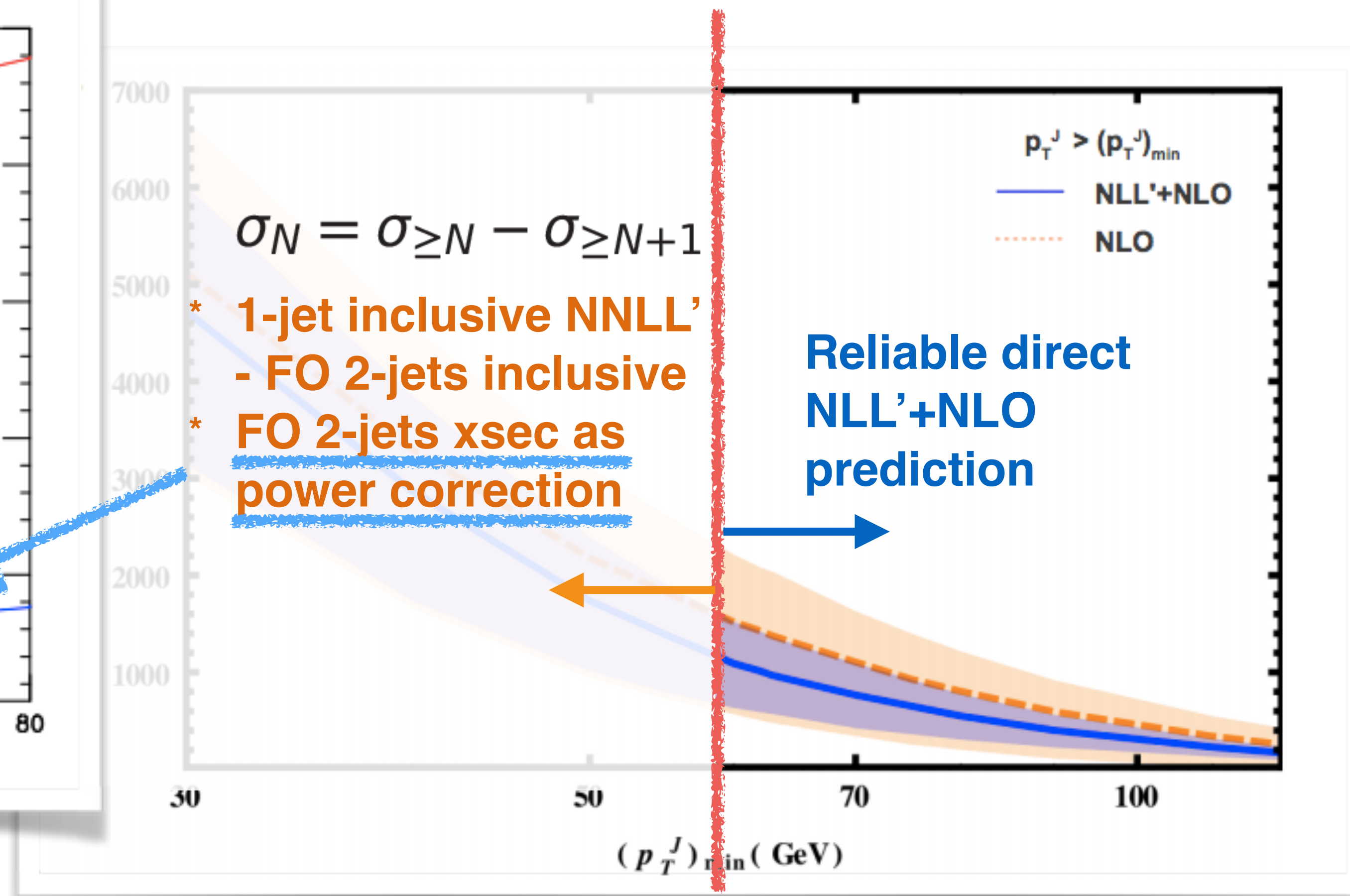

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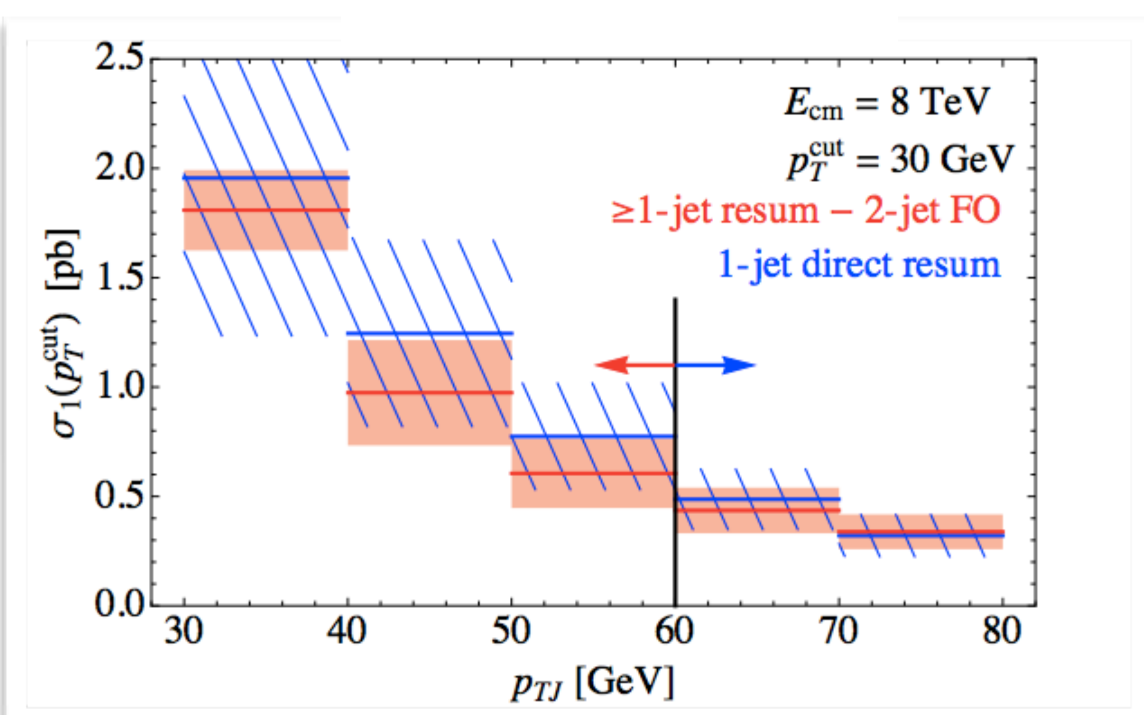
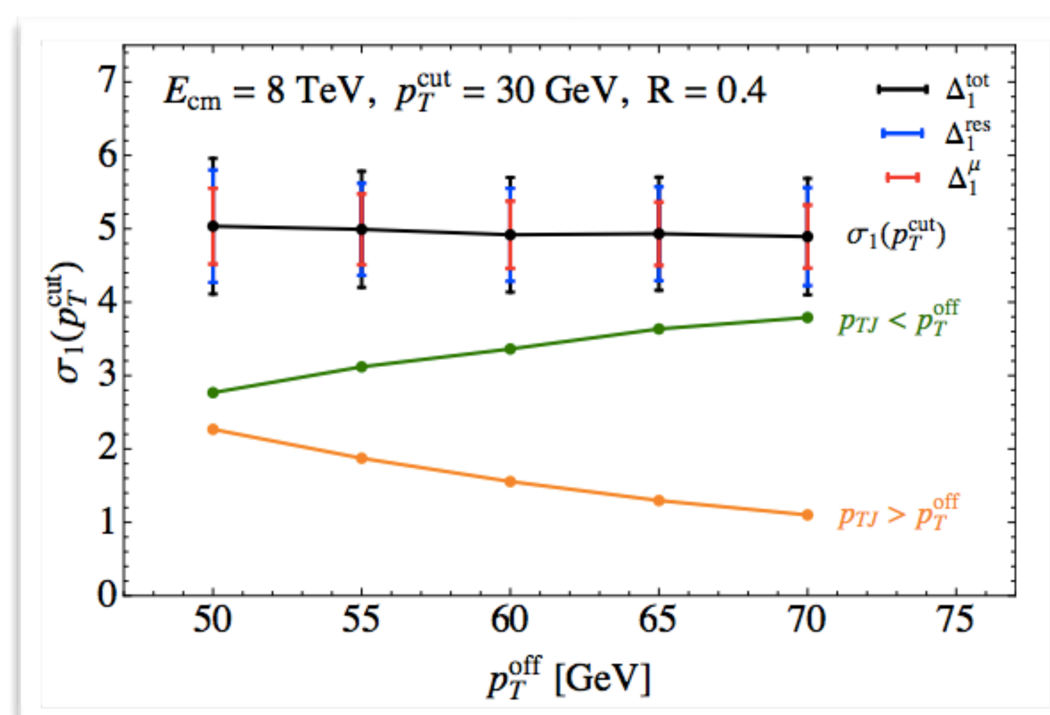
    [Boughezal, XL, Petriello, Tackmann, Walsh - 1312.4535]
    - testing matching



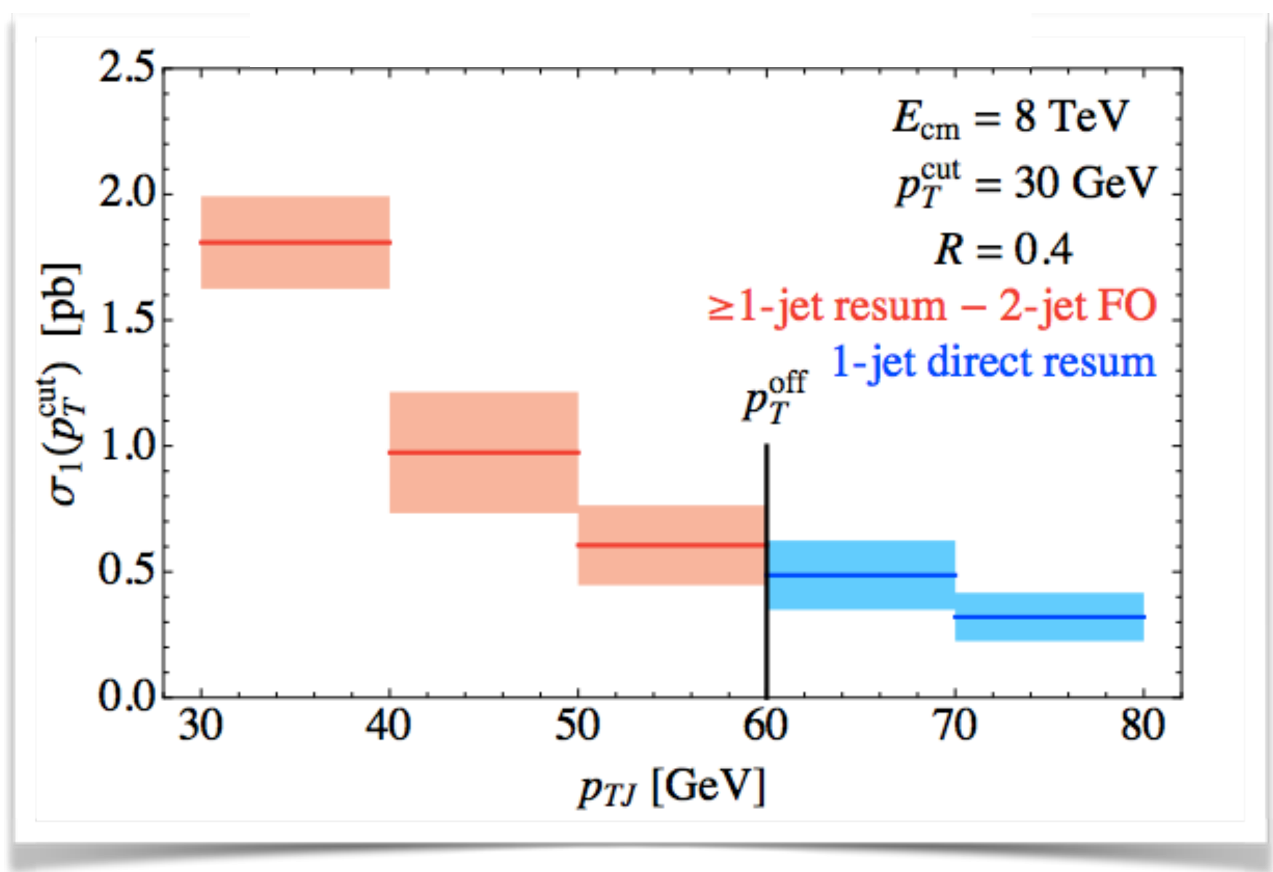


H + 0-jets and H + 1-jet

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

[Boughezal, XL, Petriello, Tackmann, Walsh - 1312.4535]

- pTJ spectrum
  - NNLO H
  - NLO 2-jets



H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh - 1312.4535]
  - 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

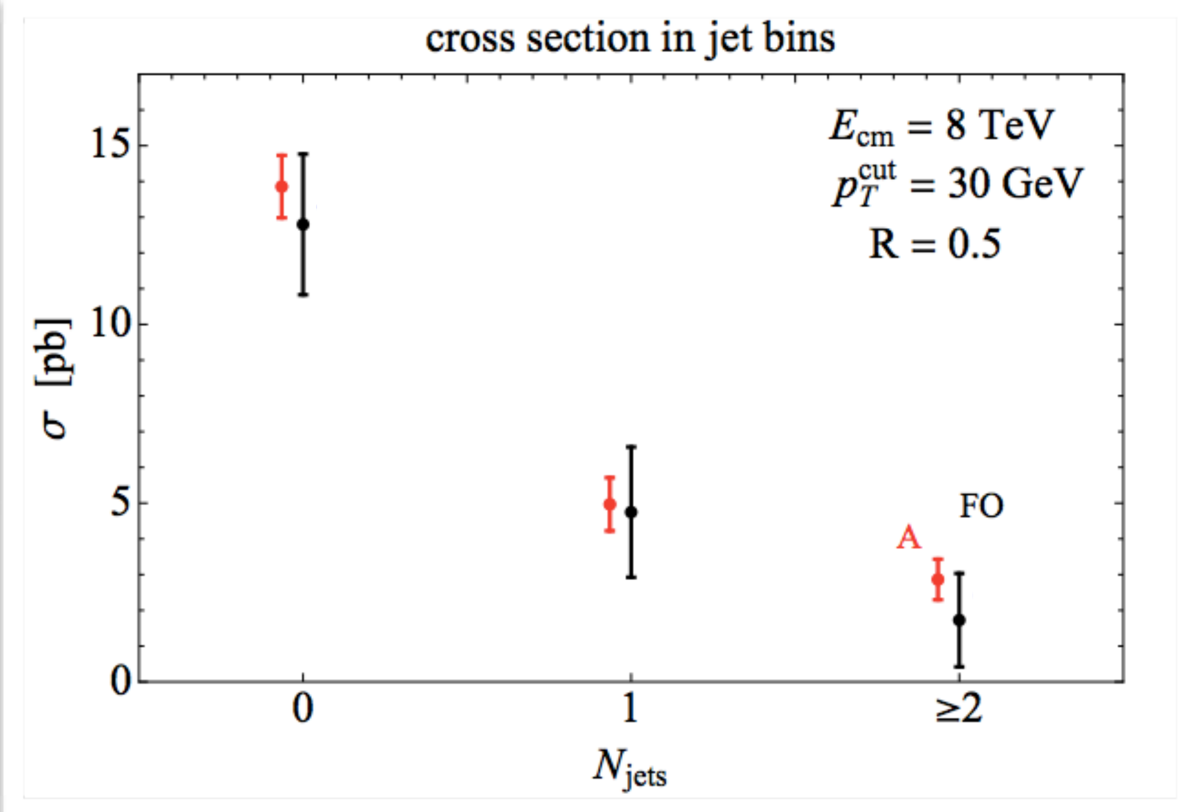
- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh - 1312.4535]
  - covariance matrices
    - a general uncertainty parameterization

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

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

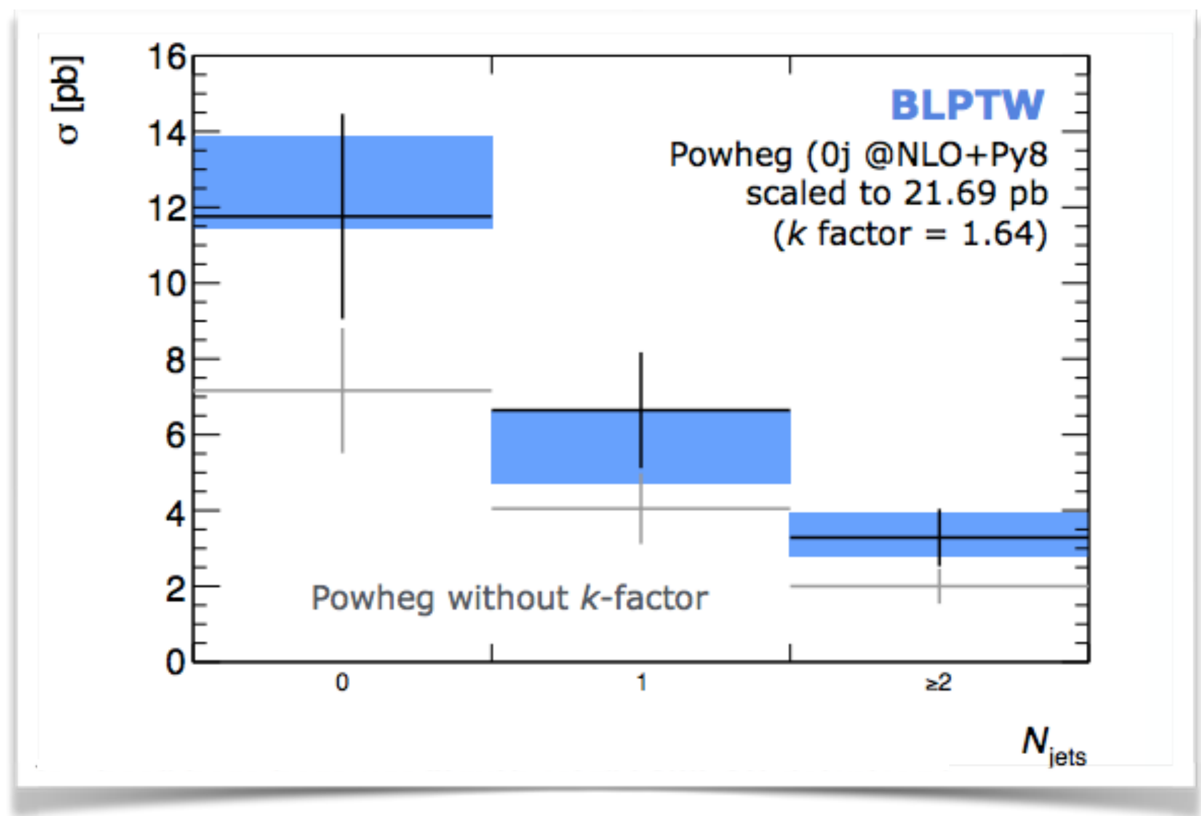
H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh - 1312.4535]
  - 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 - 1312.4535]
  - 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 - 1312.4535]
    - covariance matrices
        - any uncertainty can be calculated from the matrices
            - jet bin uncertainties
            - WW signal strength $\mu = \frac{\sigma_{\rm obs}}{\sigma_{\rm exp}}$

$$\frac{\Delta^{\rm th,\,y}\mu}{\mu} = \frac{\Delta^{\rm th,\,y}\sigma_{\rm exp}}{\sigma_{\rm exp}}$$

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

H + 0-jets and H + 1-jet

- Combining jet bins [Boughezal, XL, Petriello, Tackmann, Walsh - 1312.4535]
  - covariance matrices
    - any uncertainty can be calculated from the matrices
      - jet bin uncertainties
      - WW signal strength

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

$$\downarrow$$

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

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!

Conclusions

- Formalisms for exclusive 0-jets and 1-jet bin cross sections have been built up
- Systematic scheme for combining 0-jets and 1-jet bins have been set up
  - can be applied directly to Higgs analyses
  - halves the theoretical uncertainties
  - can be applied to W/Z + jets as a testing ground

Thanks