NNLO Phenomenology Using Jettiness Subtraction

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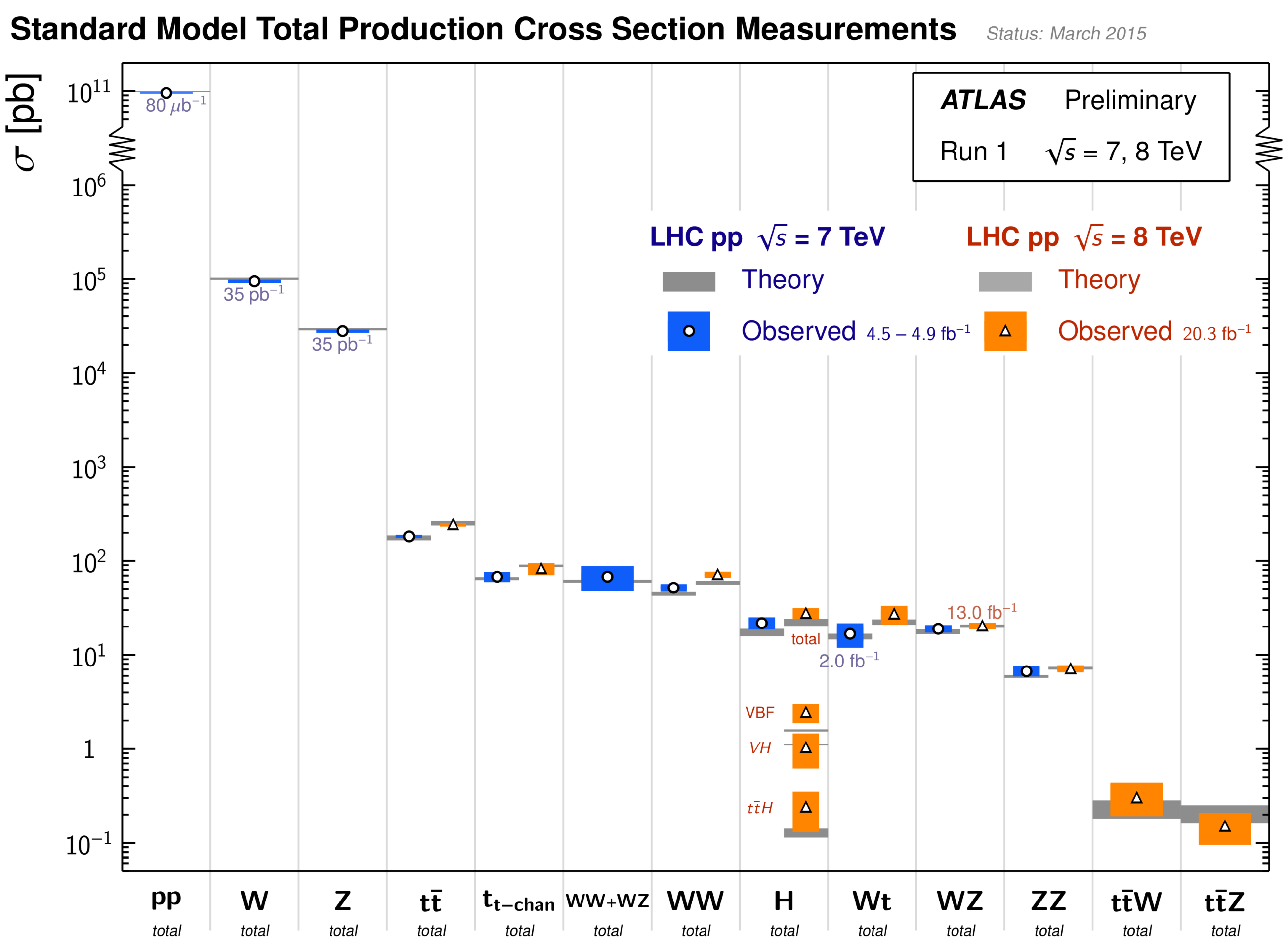
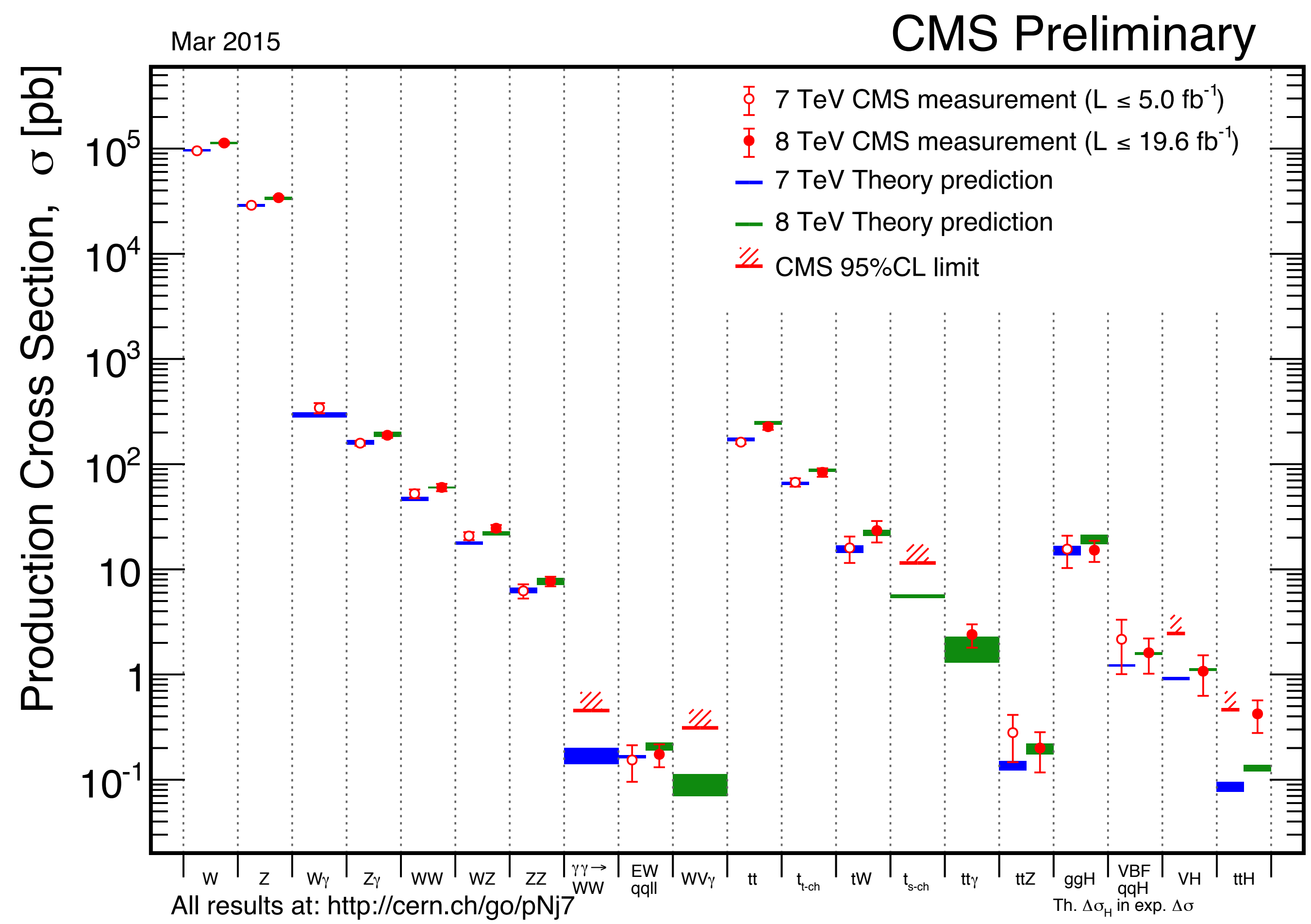
Radcor/Loopfest 2015, June 15-19, UCLA

Outline

- Motivation
- IR subtraction schemes at NNLO (local and non-local subtractions)
- The N-jettiness subtraction scheme
- NNLO results for W+1j, Higgs +1j
- Summary

The LHC circa 2015

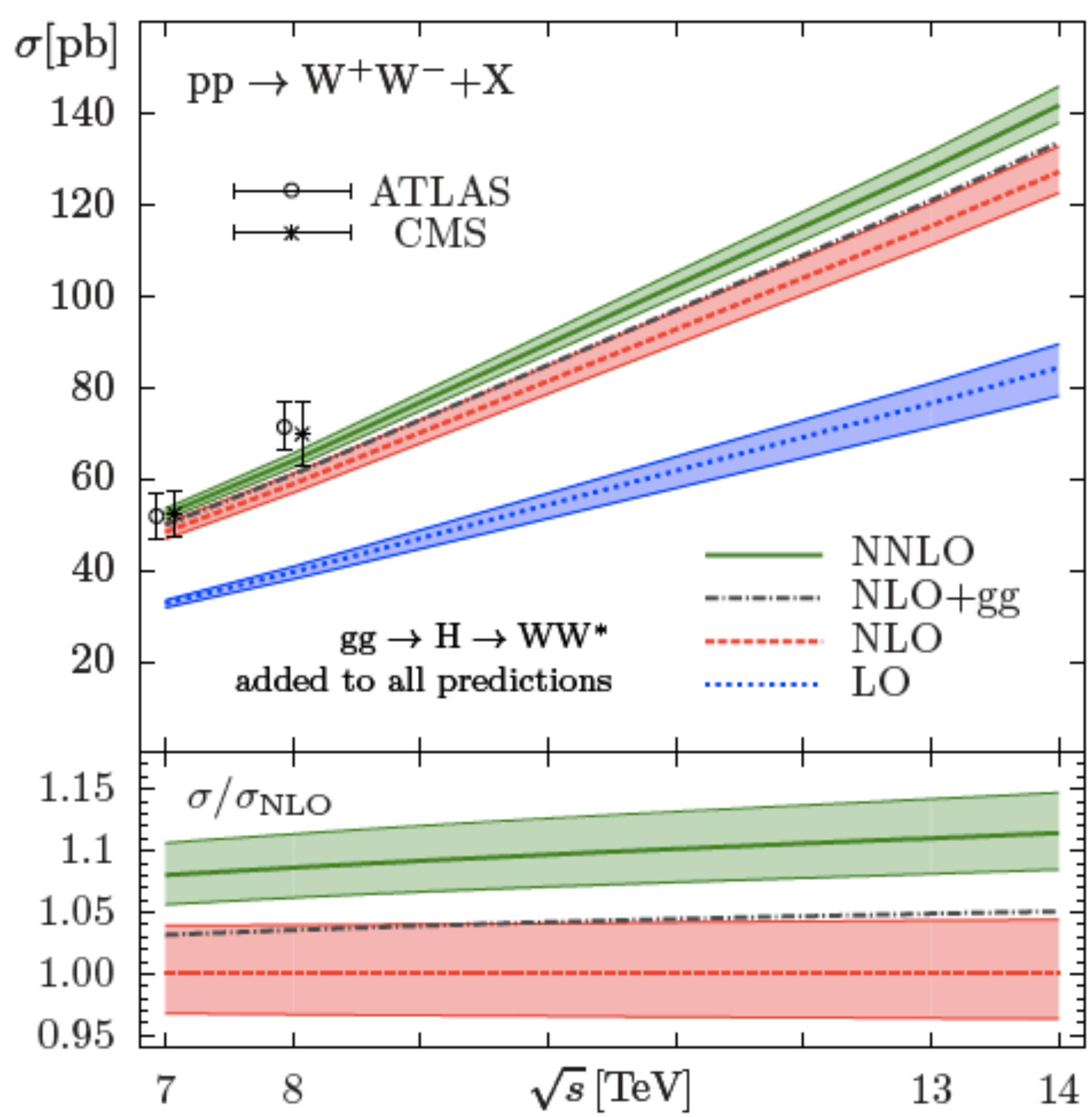




Excellent overall agreement between theory and experiment

The importance of higher orders

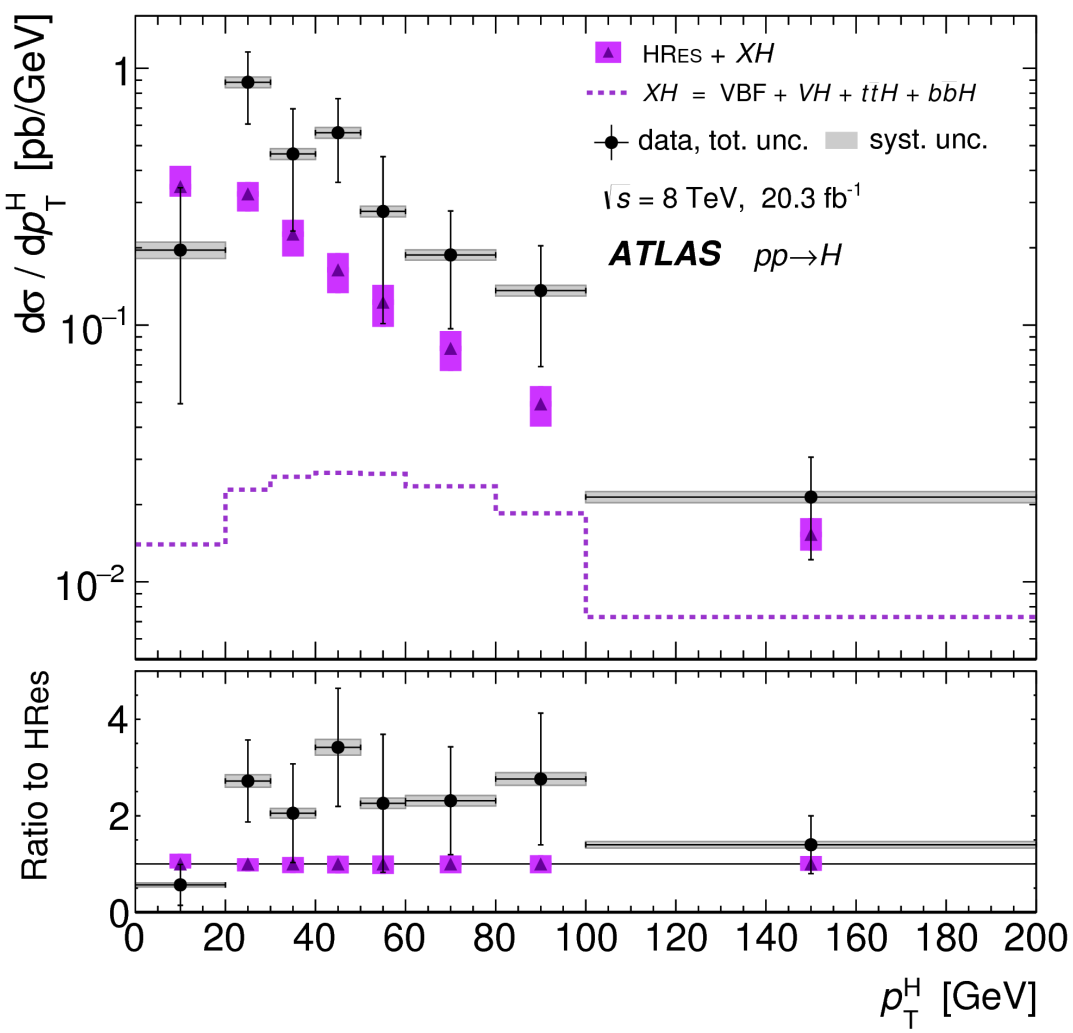
- Precision QCD theory has been a critical component of this success
- Example: Until recently, WW cross section showed a >2σ excess at both ATLAS and CMS, and for both 7 TeV and 8 TeV data. Could it be light charginos?



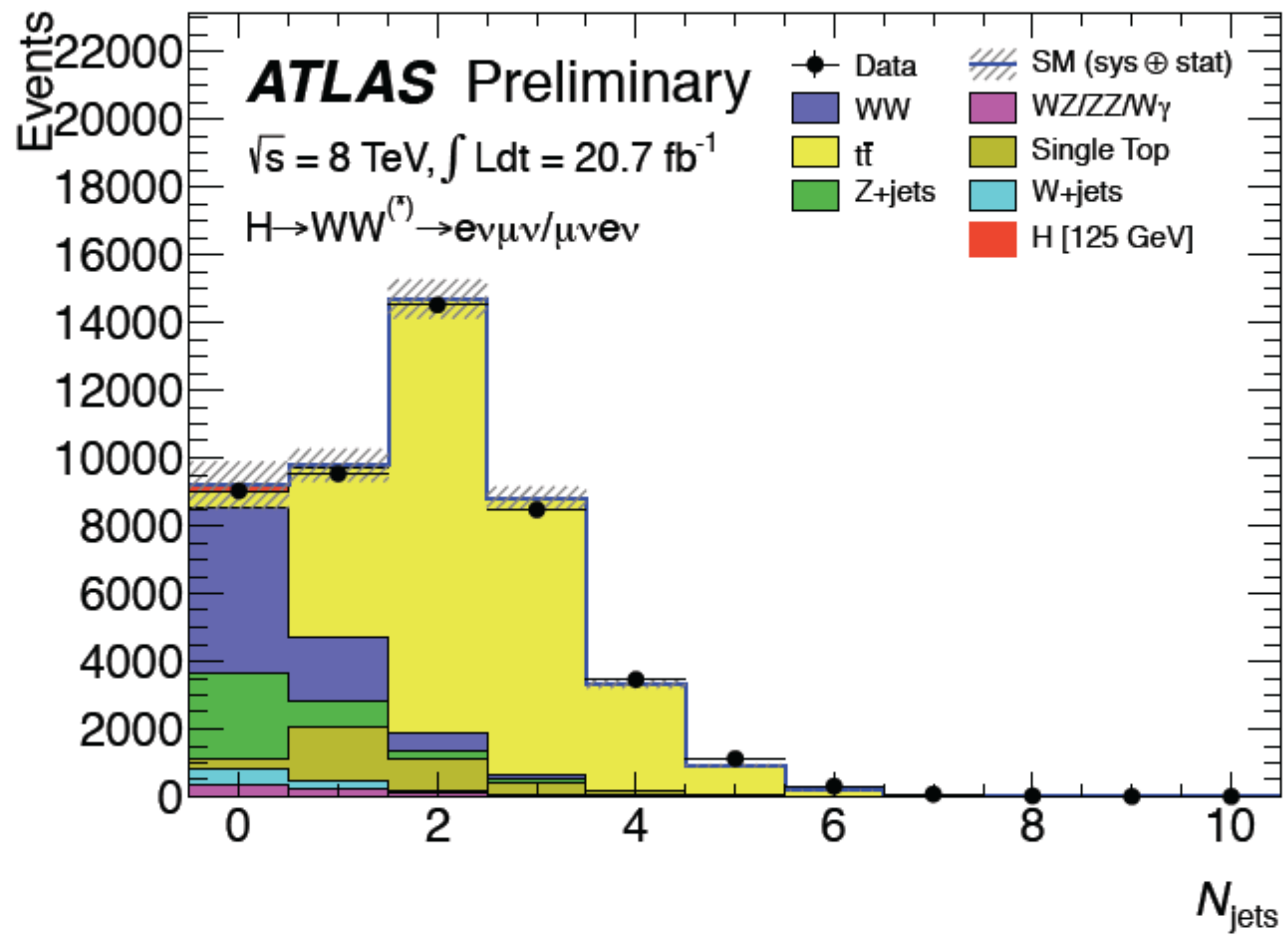
- Sizeable NNLO QCD corrections! (Gehrmann, Grazzini, Kallweit, Maierhofer, Pozzorini, Rathlev, Tancredi, von Manteuffel, 2014)
- Also an important effect from extrapolation from fiducial region (Monni, Zanderighi, 2014)
- Theory now within 1σ of ATLAS and CMS data
- Proper interpretation not possible without higher-order QCD!

Higgs kinematics

- There will be a continued need for precision QCD at the LHC Run II
- Need improved modeling of the Higgs cross section for several measurements



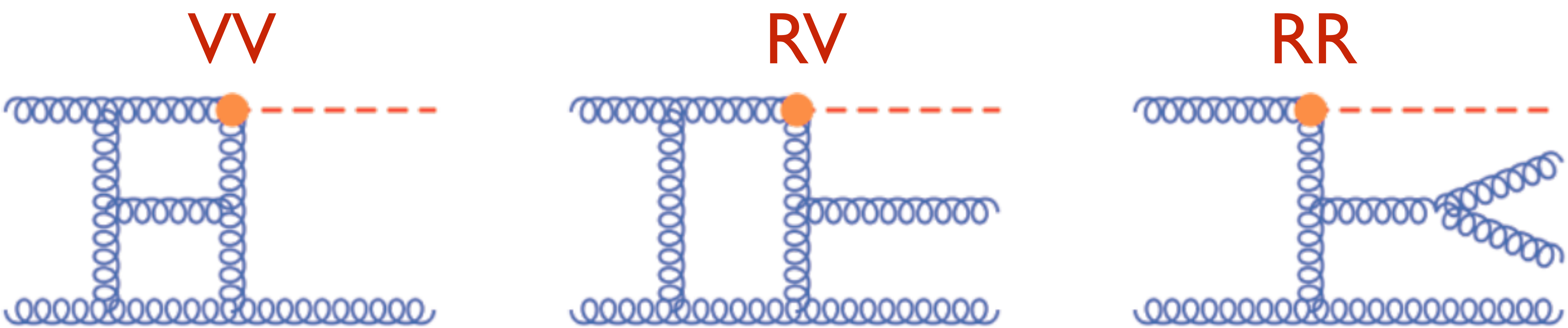
First measurement of the Higgs p_T spectrum available; will be measured with higher precision in Run II, theory must be ready!



Division of the Higgs signal into exclusive jet bins needed to remove the sometimes overwhelming backgrounds.

Fixed order cross sections @ NNLO

- Need the following ingredients for NNLO cross sections



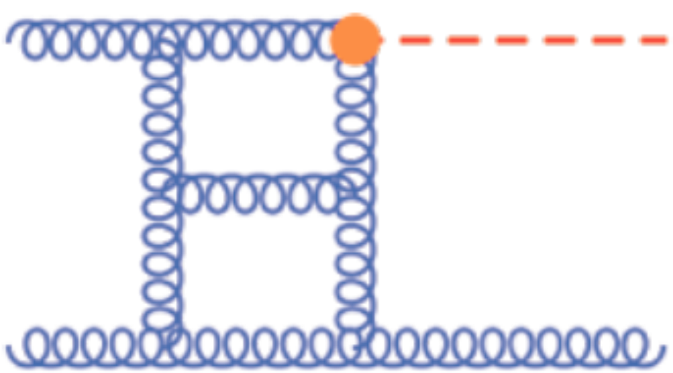
- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

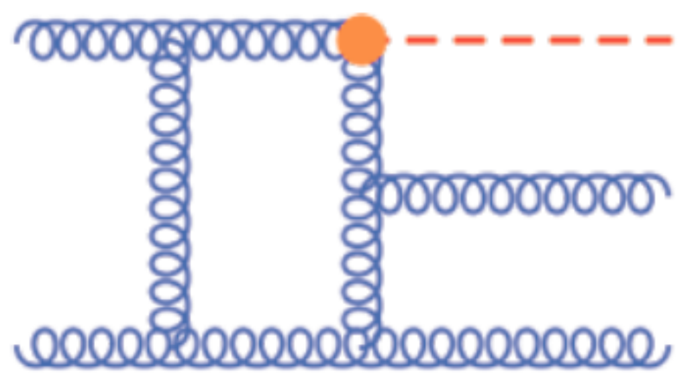
Fixed order cross sections @ NNLO

- Need the following ingredients for NNLO cross sections

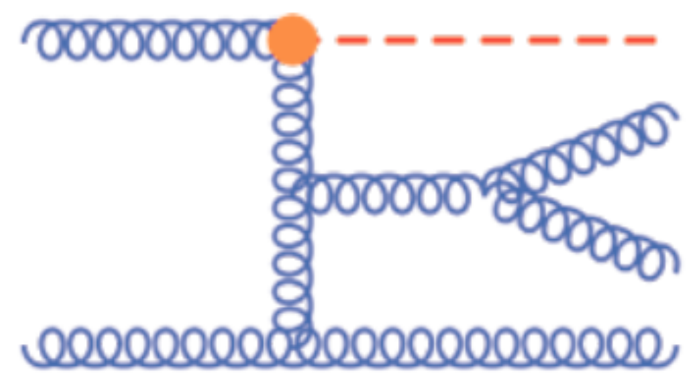
VV



RV



RR



- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

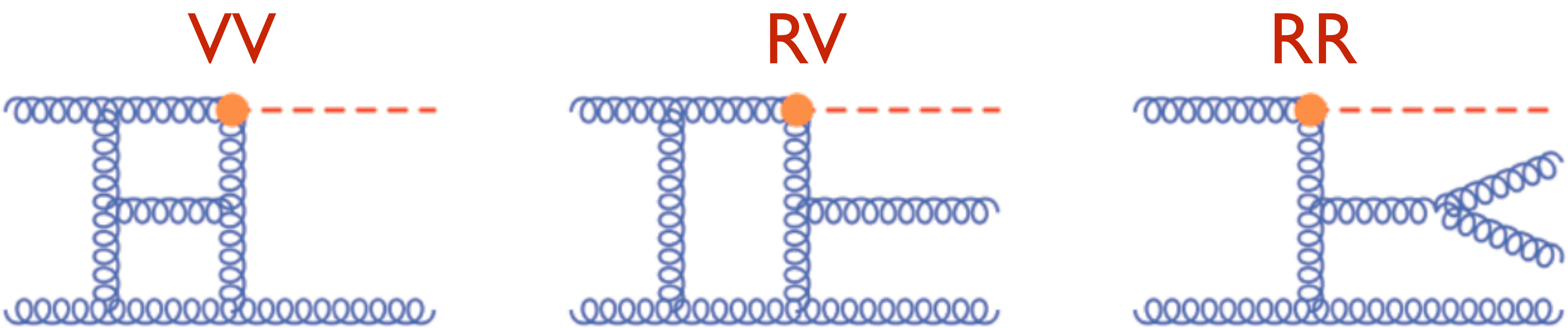
$$\int \left[\frac{vv_4}{\epsilon^4} + \frac{vv_3}{\epsilon^3} + \frac{vv_2}{\epsilon^2} + \frac{vv_1}{\epsilon} + vv_0\right] \, d\Phi_2$$

$$\int \left[\frac{rv_2}{\epsilon^2} + \frac{rv_1}{\epsilon} + rv_0\right] \, d\Phi_3$$

$$\int [rr_0] \, d\Phi_4$$

Fixed order cross sections @ NNLO

- Need the following ingredients for NNLO cross sections



- IR singularities cancel in the sum of real and virtual corrections and mass factorization counterterms but only after phase space integration for real radiations.

- Virtual corrections have explicit IR poles, whereas real corrections have implicit IR poles that need to be extracted.

- A generic procedure to extract IR singularities from RR and RV was unknown when jets in the final state are involved, until very recently.

Methods for extracting IR singularities from double real radiation @ NNLO

Local subtraction schemes:

- Sector decomposition (Anastasiou, Melnikov, Petriello, 2003)
  - $pp \to H, pp \to V$ including decays

  (Anastasiou, Melnikov, Petriello, 2003-2004)

- Sector-improved subtraction schemes (Czakon, 2010; R.B., Melnikov, Petriello, 2011)
  - $pp \to t\bar{t}$ (Czakon, Fiedler, Mitov, 2013)
  - $pp \to H + j$ (R.B., Caola, Melnikov, Petriello, Schulze, 2013-2015)
- Antenna subtraction (Gehrmann-De Ridder, Gehrmann, Glover, 2005)
  - $ee \to 3j$ (Gehrmann-De Ridder, Gehrmann, Glover, Heinrich, 2007; Weinzierl, 2008)
  - $pp \to jj$ partial (Gehrmann-de Ridder, Gehrmann, Glover, Pires, 2013)
  - $pp \to H + j$ gg-only (Chen, Gehrmann, Glover, Jaquier, 2014)
  - $pp \to t\bar{t}$ partial (Abelof, Gehrmann-de Ridder, Maierhofer, Majer, Pozzorini, 2011-2015)
- 'Colorful NNLO' (Del Duca, Somogyi, Trocsanyi 2005)
  - $H \to b\bar{b}$ (Del Duca, Duhr, Somogyi, Tramontano, Trocsanyi 2015)

Local subtraction schemes

$$
\begin{aligned}
\mathrm{d}\sigma_{NNLO} = &\int_{\mathrm{d}\Phi_{m+2}} \left(\mathrm{d}\sigma^{R}_{NNLO} - \mathrm{d}\sigma^{S}_{NNLO}\right) + \int_{\mathrm{d}\Phi_{m+2}} \mathrm{d}\sigma^{S}_{NNLO} \\
&+ \int_{\mathrm{d}\Phi_{m+1}} \left(\mathrm{d}\sigma^{V,1}_{NNLO} - \mathrm{d}\sigma^{VS,1}_{NNLO}\right) + \int_{\mathrm{d}\Phi_{m+1}} \mathrm{d}\sigma^{VS,1}_{NNLO} \\
&+ \int_{\mathrm{d}\Phi_{m}} \mathrm{d}\sigma^{V,2}_{NNLO}
\end{aligned}
$$

- Subtraction terms approximate the full matrix elements point by point in the phase space.

Non local: q_T-subtraction

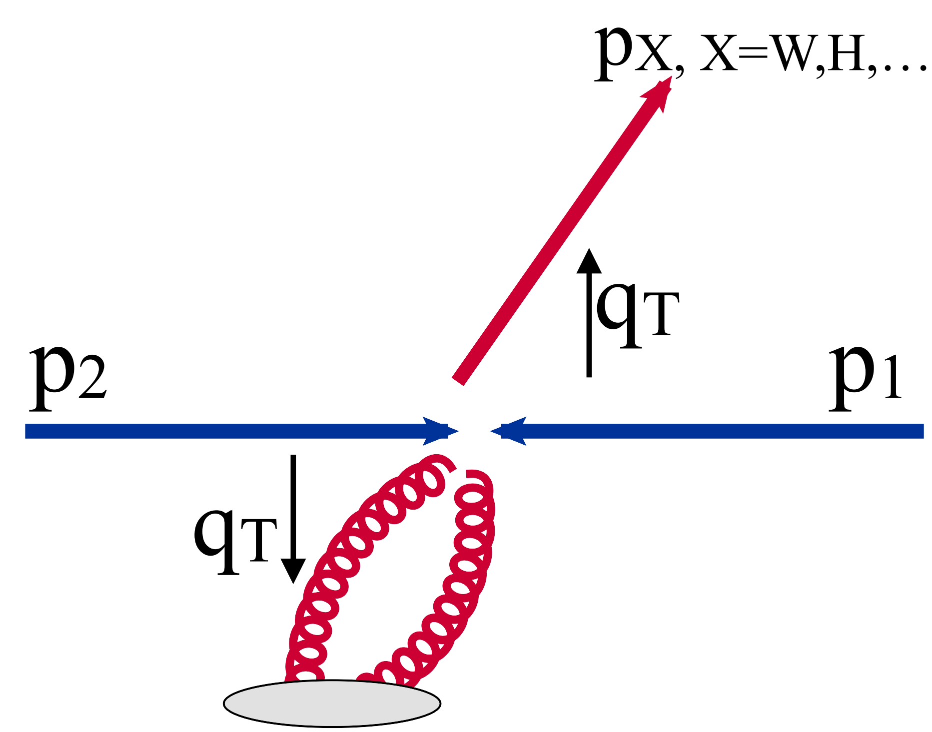
- For color neutral final states, the final state transverse momentum q_T completely determines the singularity structure of QCD amplitudes (Catani, Grazzini, 2007)

$$\sigma_{NNLO} = \int dq_T \frac{d\sigma}{dq_T}\,\theta(q_T^{\rm cut} - q_T) + \int dq_T \frac{d\sigma}{dq_T}\theta(q_T - q_T^{\rm cut})$$

obtained using the Collins-Soper-Sterman (CSS) factorization formula for small q_T. Necessarily involves an integration over final state radiation.

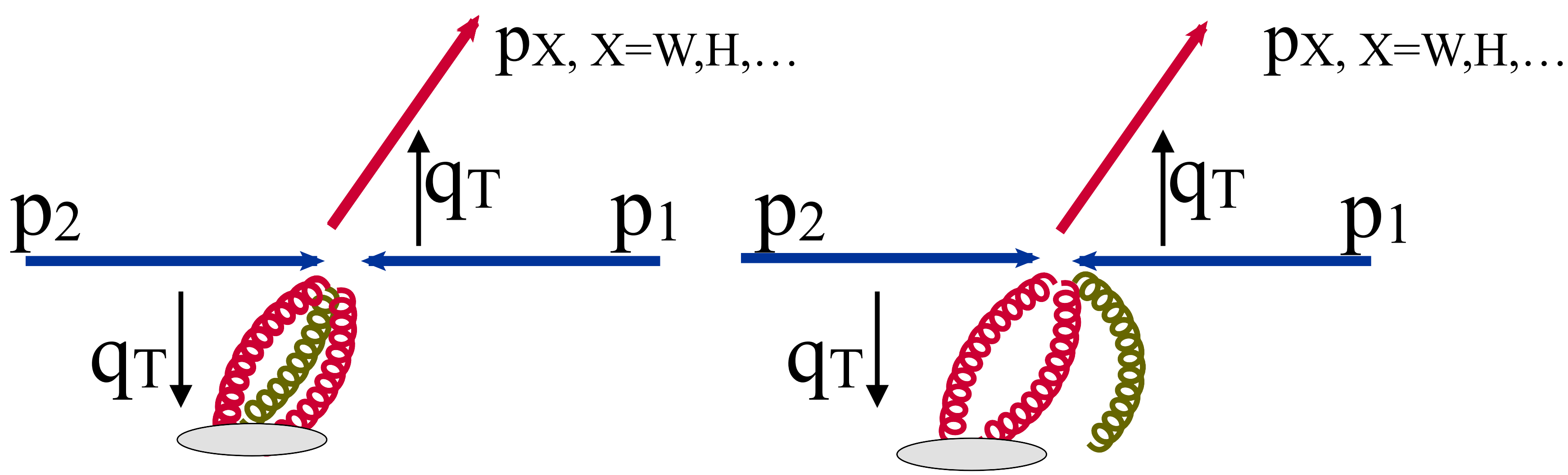
This is an NLO cross section with one additional jet.

- Many successful NNLO results:
  H/W/Z+0jet, W/Z+ γ, WH, W^+W^- , ZZ, $\gamma\gamma$
  (Catani, Cieri, de Florian, Ferrera, Gehrmann, Grazzini, Kallweit, Maierhoefer, Pozzorini, Rathlev, Tancredi, Torre, Tramontano, von Manteuffel, Weihs)



q_T-subtraction

- For color neutral final states, the final state transverse momentum q_T completely determines the singularity structure of QCD amplitudes (Catani, Grazzini, 2007)
- Limitation: transverse momentum no longer completely describes the singularity structure of QCD amplitudes when jets are present in the final state (can't distinguish between double and single unresolved radiation)



Need a different resolution parameter!

Non-local: N-Jettiness Subtraction

- N-jettiness τ_N: an event shape variable designed to veto final-state jets (Stewart, Tackmann, Waalewijn, 2010)

$$\mathcal{T}_N = \sum_k \min_i \left\{ \frac{2p_i \cdot q_k}{Q_i} \right\}.$$

N: # of jets in final state

momentum of each of the 2 beams and final state hard jets

momentum of all final state patrons

characterizes the hardness of beam-jets and final-state jets can be chosen Qi = 2Ei

$\tau_N = 0$: radiation is soft, or collinear to one of the beams or final state jets

$\tau_N > 0$: at least one of the radiations is hard and well separated from the beams/jets

Can introduce a τ_N^{cut} that separates doubly unresolved singularities from every thing else

N-Jettiness Subtraction

- For NNLO processes, σ_{NNLO} consists of Born-level kinematics, and processes with one or two additional radiations. Can write the cross section with a cut τ_N^{cut} as:

$$
\begin{aligned}
\sigma_{NNLO} =& \int \mathrm{d}\Phi_N \, |\mathcal{M}_N|^2 + \int \mathrm{d}\Phi_{N+1} \, |\mathcal{M}_{N+1}|^2 \, \theta_N^< \\
&+ \int \mathrm{d}\Phi_{N+2} \, |\mathcal{M}_{N+2}|^2 \, \theta_N^< + \int \mathrm{d}\Phi_{N+1} \, |\mathcal{M}_{N+1}|^2 \, \theta_N^> \\
&+ \int \mathrm{d}\Phi_{N+2} \, |\mathcal{M}_{N+2}|^2 \, \theta_N^> \\
\equiv& \, \sigma_{NNLO}(\mathcal{T}_N < \mathcal{T}_N^{cut}) + \sigma_{NNLO}(\mathcal{T}_N > \mathcal{T}_N^{cut})
\end{aligned}
$$

$$\theta_N^< = \theta(\tau_N^{cut} - \tau_N) \quad \text{and} \quad \theta_N^> = \theta(\tau_N - \tau_N^{cut})$$

- Next step is to calculate the cross section below and above τ_N^{cut}

N-Jettiness Subtraction

- For $\tau_N > \tau_N^{cut}$, at least one radiation is resolved, this is a NLO correction to the born process with an additional jet. Use your favorite NLO generator to calculate it !

- For $\tau_N < \tau_N^{cut}$, both radiations are unresolved (soft, collinear or both). A factorization theorem that gives the all-orders result for small jettiness was derived in SCET (Stewart, Tackmann, Waalewijn, 2010-2011)

$$\sigma(\tau_N < \tau_N^{cut}) = \int H \otimes B \otimes B \otimes S \otimes \left[\prod_n^N J_n\right] + \cdots \ .$$

describes hard radiation, coincides with virtual corrections in dimensional regularization

describe collinear radiation to the beam directions

describes soft radiation

describes collinear radiation to the final state jets

* The ellipsis denote power suppressed terms, negligible for τ_N smaller than any other kinematic invariant in the process

N-Jettiness Subtraction

$$\sigma(\tau_N < \tau_N^{cut}) = \int H \otimes B \otimes B \otimes S \otimes \left[\prod_n^N J_n\right] + \cdots \; .$$

- Expand this formula to fixed order in α_s to get σ below τ_N^{cut}
- For 1-Jettiness@NNLO, all ingredients were known except the soft function:

H @ 2loops: W/H+j (Gehrmann, Tancredi, 2012; Gehrmann, Jaquier, Glover, Koukoutsakis, 2012)
B @ 2loops: (Gaunt, Stahlhofen, Tackmann, 2014)
S @ 2loops: (R.B., Liu, Petriello, 2015) ➔ see Liu's talk on Thursday for more details
J @ 2loops: (Becher, Neubert, 2006; Becher, Bell, 2011)

Can combine all these ingredients to get full NNLO results !

R.B., Focke, Liu, Petriello, 2015

(see also Gaunt, Stahlhofen, Tackmann, Walsh, 2015)

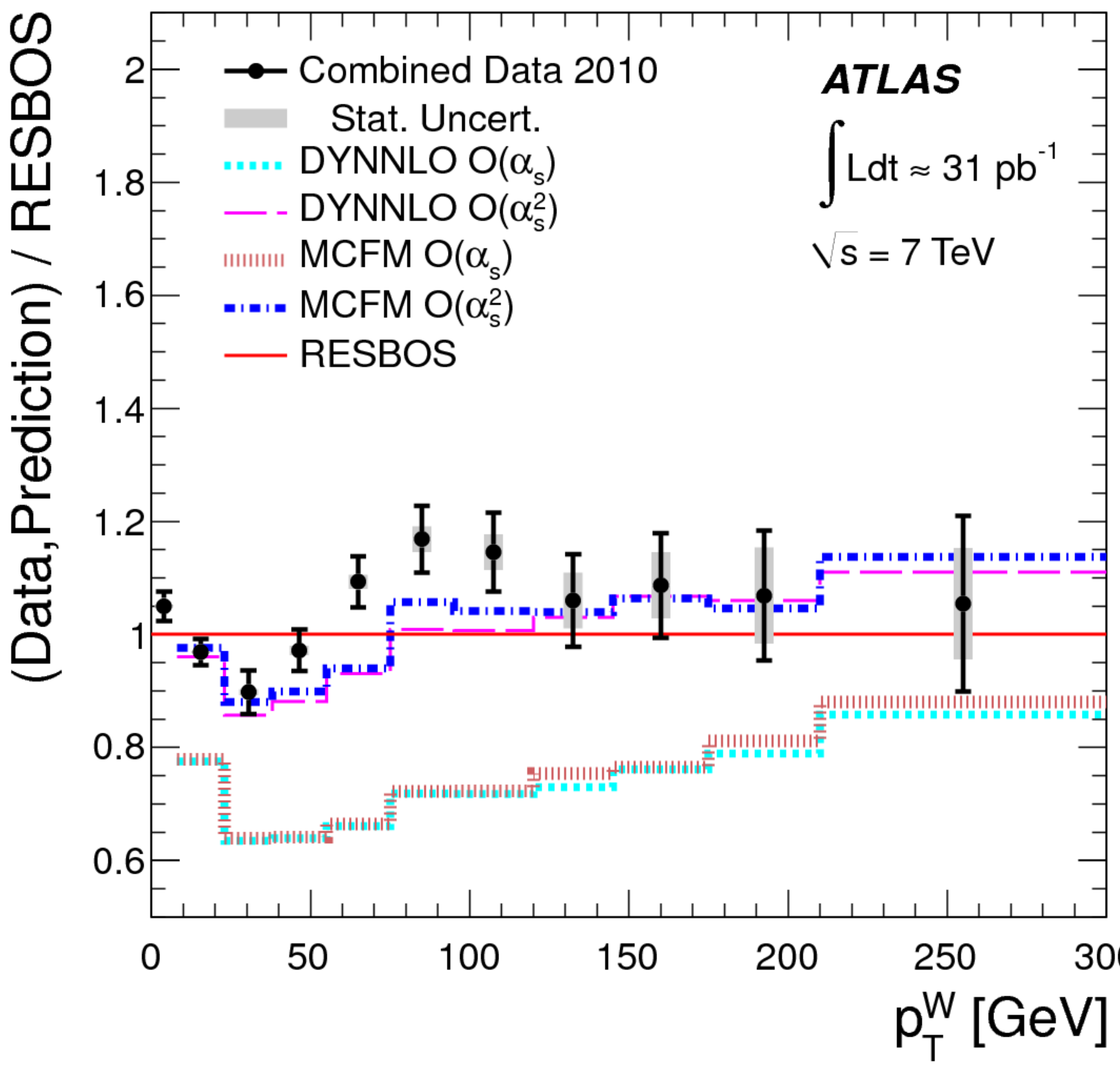
N-Jettiness Subtraction: how to proceed

- Suppose we want to calculate an N-jet process @ NNLO:
  - Generate an event for the N+1jet process @ NLO (can have N+1 or N+2 partons)
  - Determine the reference vectors p_i for the hard jets by performing a pre-clustering of the radiation using a jet algorithm (to get the leading jet). The choice of the jet algorithm does not affect the determination of p_i for small enough τ_{cut} (Jouttenus, Stewart, Tackmann, Waalewijn, 2010-2011)
  - Calculate τ_N. If $\tau_N > \tau_{cut}$, keep the event. This provides $\sigma_{NNLO}(\tau_N > \tau_{cut})$
  - If $\tau_{N<} \tau_{cut}$, reject the event.
  - Calculate $\sigma_{NNLO}(\tau_{N<}\tau_{cut})$ using the factorization formula to NNLO.
  - Add $\sigma_{NNLO}(\tau_{N<}\tau_{cut})$ and $\sigma_{NNLO}(\tau_N > \tau_{cut})$ and check that there is no dependence on τ_{cut}

NNLO Phenomenology Using Jettiness Subtraction

W+jet @ NNLO

- Benchmark process in the SM.
- Required for precision prediction for the W-p_T spectrum.
- Will be an important constraint on the gluon-PDF at large x (arXiv1505.01399)

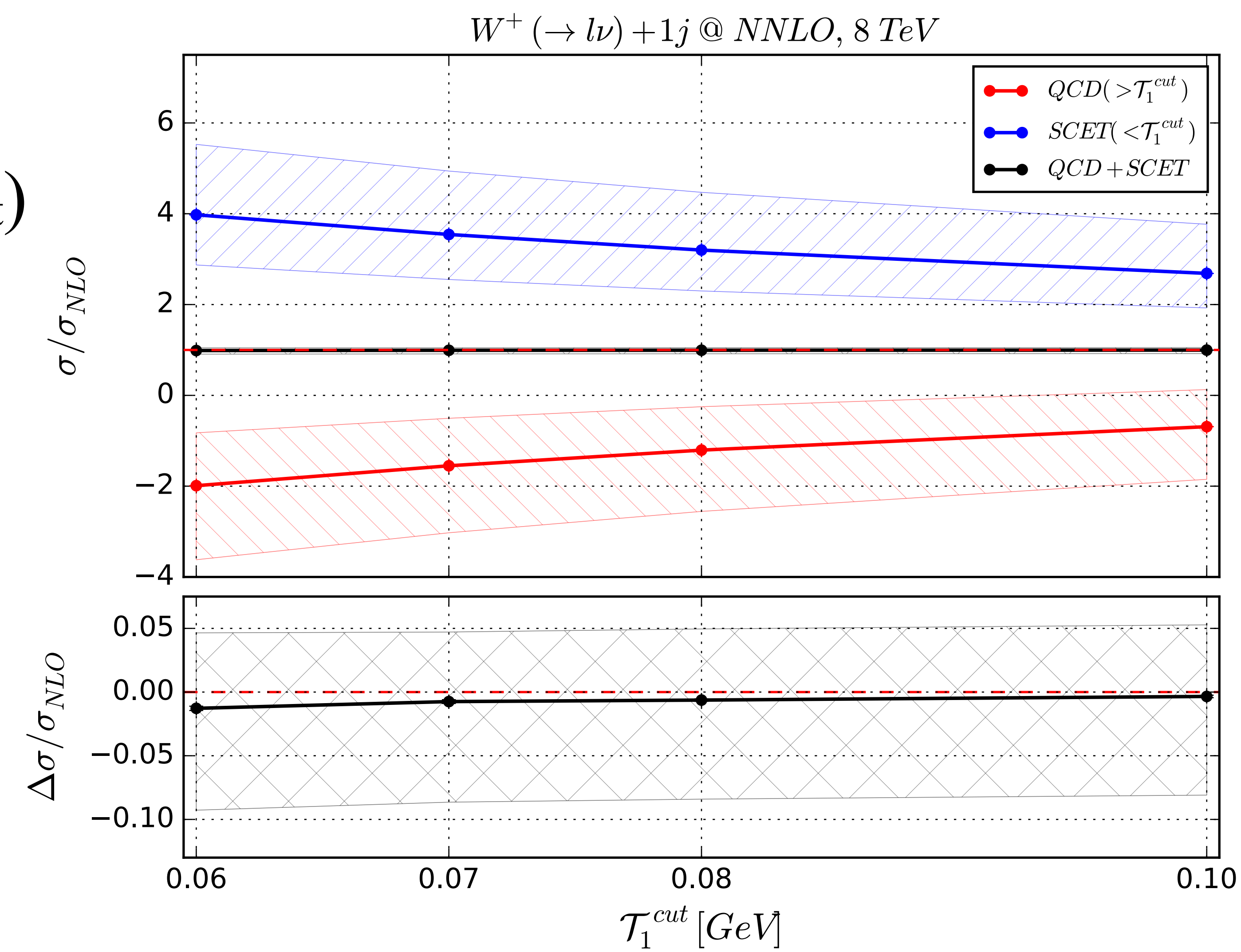


W+jet @ NNLO: validation

R.B., Focke, Liu, Petriello, 2015

- logarithmic dependence on τ_{cut} canceled in the sum of $\sigma_{NNLO}(\tau_N < \tau_{cut})$ and $\sigma_{NNLO}(\tau_N > \tau_{cut})$.
- Sum of cross sections above and below the cut is stable to better than 0.1% of σ_{total}
- NLO agrees exactly with known results
- W+2jet @ NLO obtained using MCFM, with only *double precision !*

CT10, $P_{Tj} > 30$ GeV, $|\eta_j| < 2.4$ (CMS cuts)

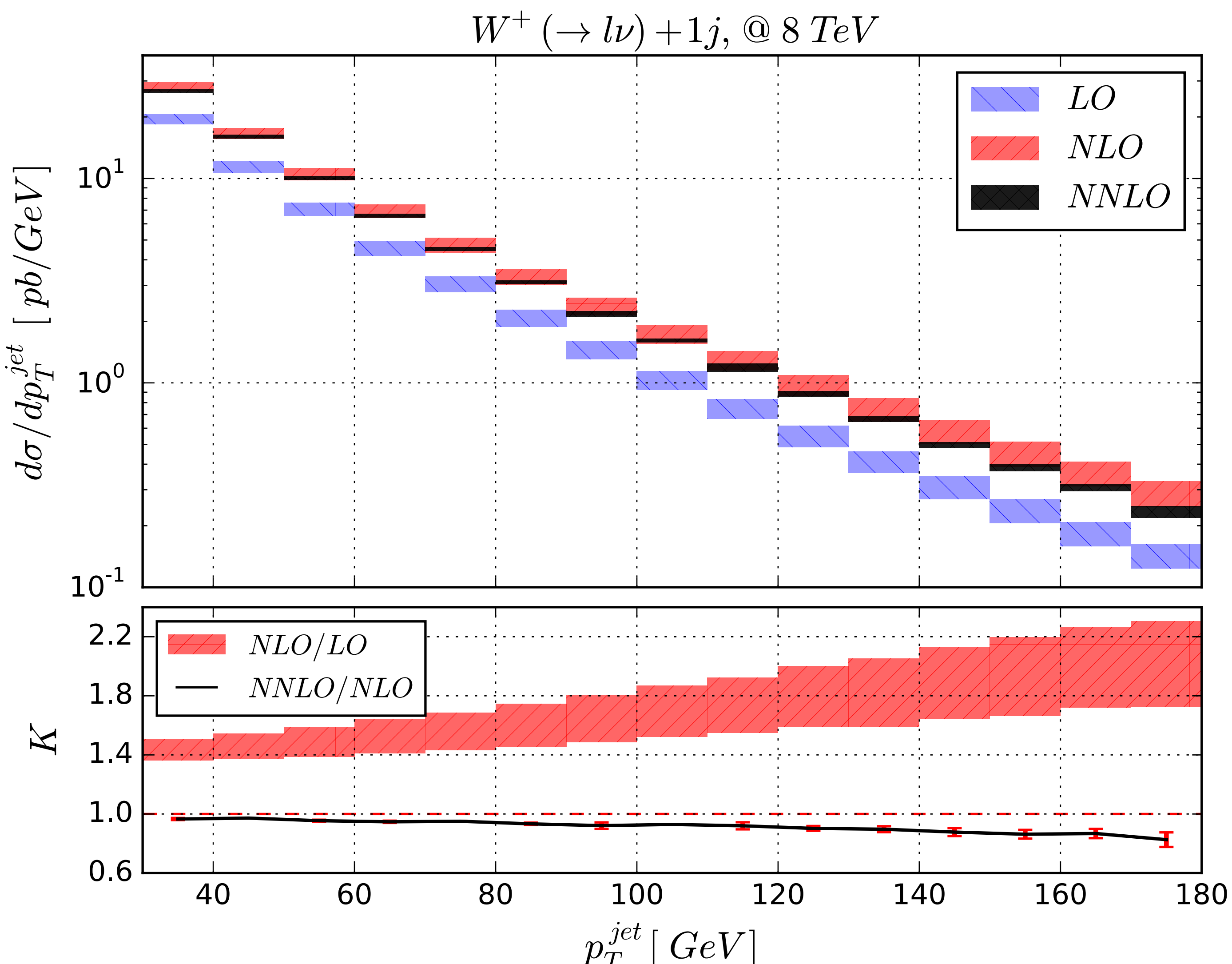


Shown is the pure NNLO xsection central scale choice: $\mu = m_W$

$$M_W/2 \leq \mu \leq 2\, M_W$$

W+jet @ NNLO: Results

R.B., Focke, Liu, Petriello, 2015



$p_T^{jet} > 30$ GeV, $\lvert\eta_{jet}\rvert < 2.4$	
Leading order:	533^{+39}_{-38} pb
Next-to-leading order:	797^{+63}_{-49} pb
Next-to-next-to-leading order:	791^{+0}_{-6} pb

CT10 PDFs, anti-K_T with R = 0.5

- K_{NNLO} is independent from τ_{cut} in each bin.

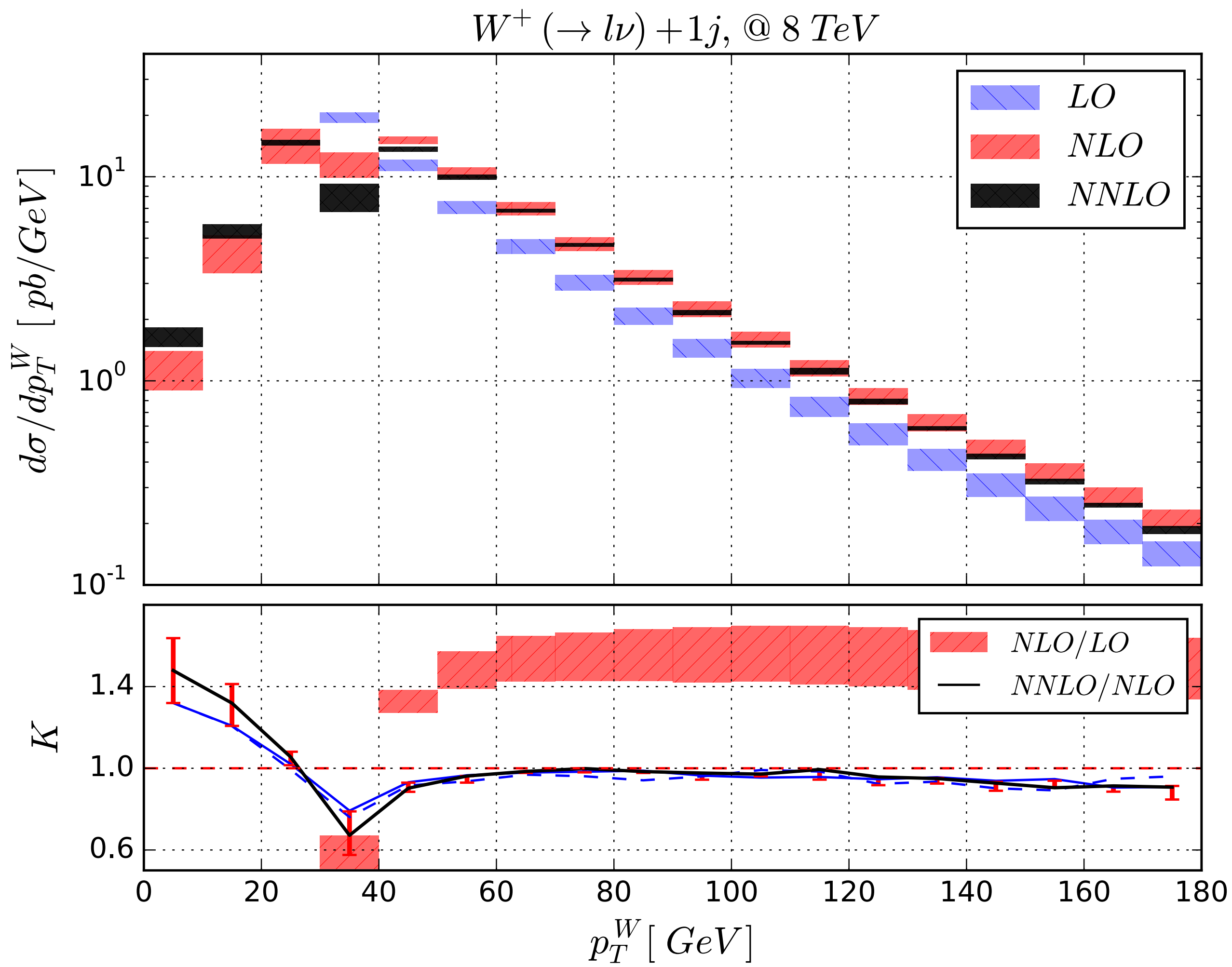
Corrections: LO $\xrightarrow{+40\%}$ NLO $\xrightarrow{-1\%}$ NNLO for $\mu = m_W$

Scale uncertainties: 7% LO 7% NLO ~ <1% NNLO

Very mild shift from NLO to NNLO and almost flat dependence on pTj

W+jet @ NNLO: Results

R.B., Focke, Liu, Petriello, 2015

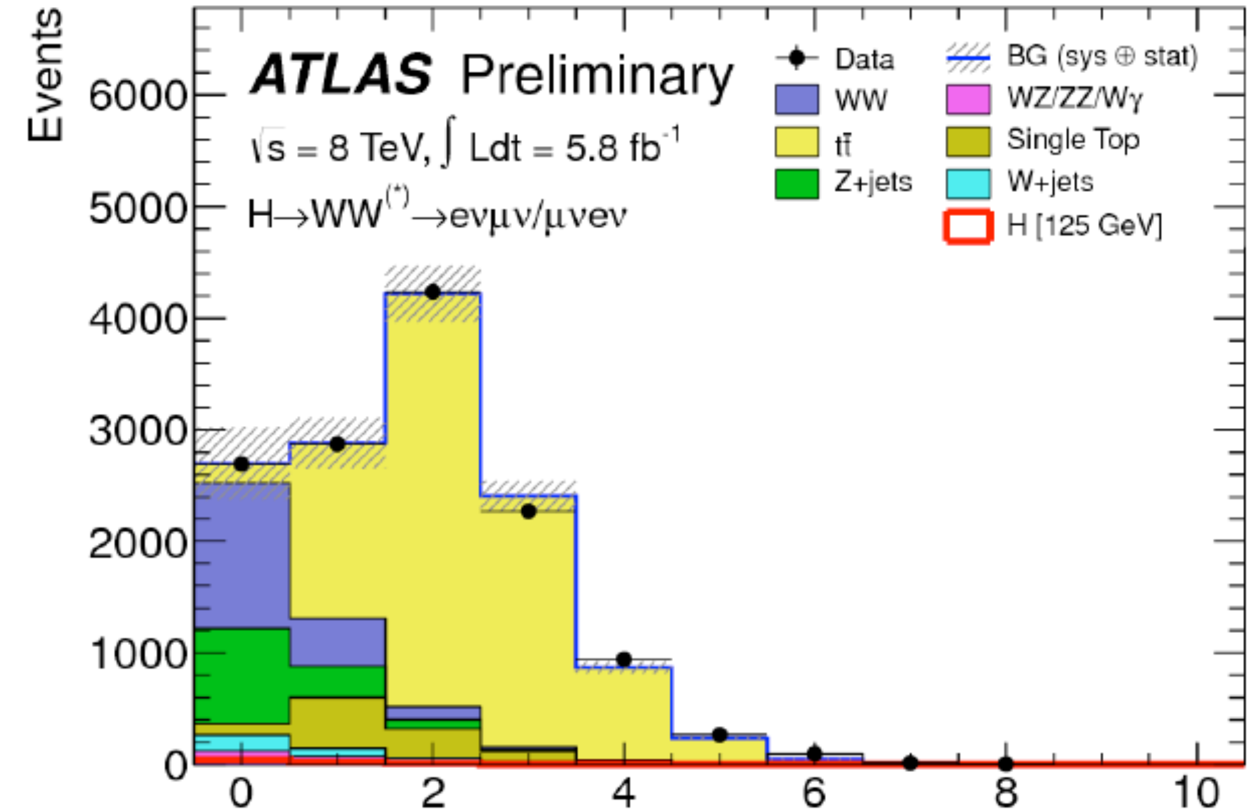


- K_{NNLO} calculated for τ_{cut} = 0.05 GeV, 0.07 GeV and shows independence from τ_{cut} in each bin
- NNLO corrections almost flat as a functions of p_{TW} above 30GeV
- Sudakov-Shoulder effect at the boundary P_{TW} = 30 GeV leading to the shown perturbative instability (no bin averaging was done to improve it)

Higgs + 1jet @NNLO Using jettiness and sector improved subtractions

Higgs in association with jets

- Selection of experimental events in H → WW uses jet binning to reduce the background.
- Theory uncertainties in the 1-jet and 2-jet bins are currently a limiting factor.
- Looking for BSM effects would benefit from a better precision control of the differential distributions, eg. Higgs p_T (Banfi, Martin, Sanz, 2013; Azatov, Paul 2013).



$$\sigma_1 = \sigma_{>=1} - \sigma_{>=2}$$

Source (1-jet)	Signal (%)	Bkg. (%)
1-jet incl. ggF signal ren./fact. scale	27	0
2-jet incl. ggF signal ren./fact. scale	15	0
Missing transverse momentum	8	3
W+jets fake factor	0	7
b-tagging efficiency	0	7
Parton distribution functions	7	1

ATLAS

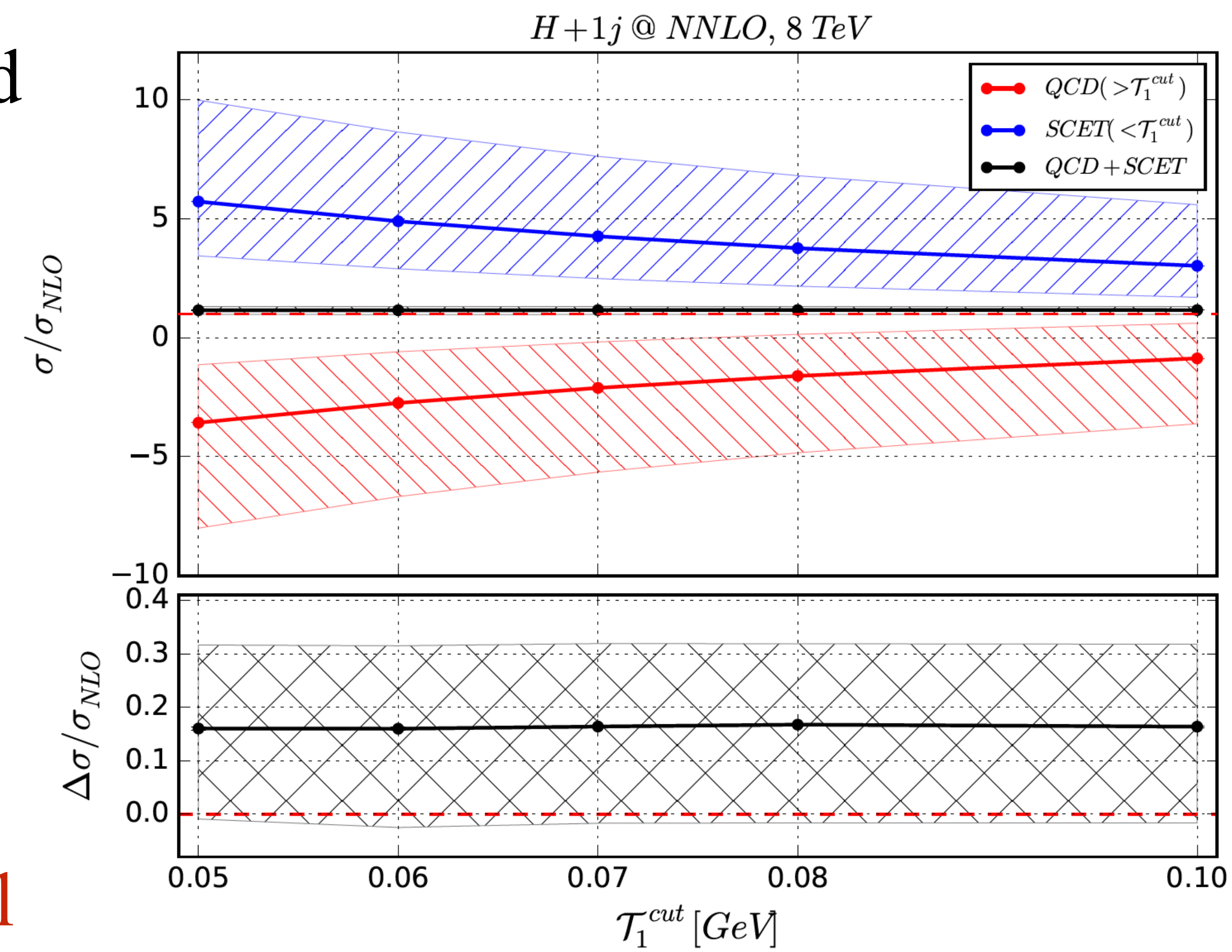
Theory uncertainty as estimated by ATLAS is large

Higgs+jet @ NNLO using jettiness: validation

R.B., Giele, Focke, Liu, Petriello, 2015

NNPDF2.3, $P_{Tj} > 30$ GeV, $|Y^{jet}| < 2.5$

- logarithmic dependence on τ_{cut} canceled in the sum of $\sigma_{NNLO}(\tau_N < \tau_{cut})$ and $\sigma_{NNLO}(\tau_N > \tau_{cut})$.
- Sum of cross sections above and below the cut is stable to better than 0.1% correction to σ_{total}
- Agreement with the sector-improved residue subtraction result at the per-mill level ! (R.B., Caola, Melnikov, Petriello, Schulze, 2015)
- H+2jet @ NLO obtained using MCFM, with only *double precision !*



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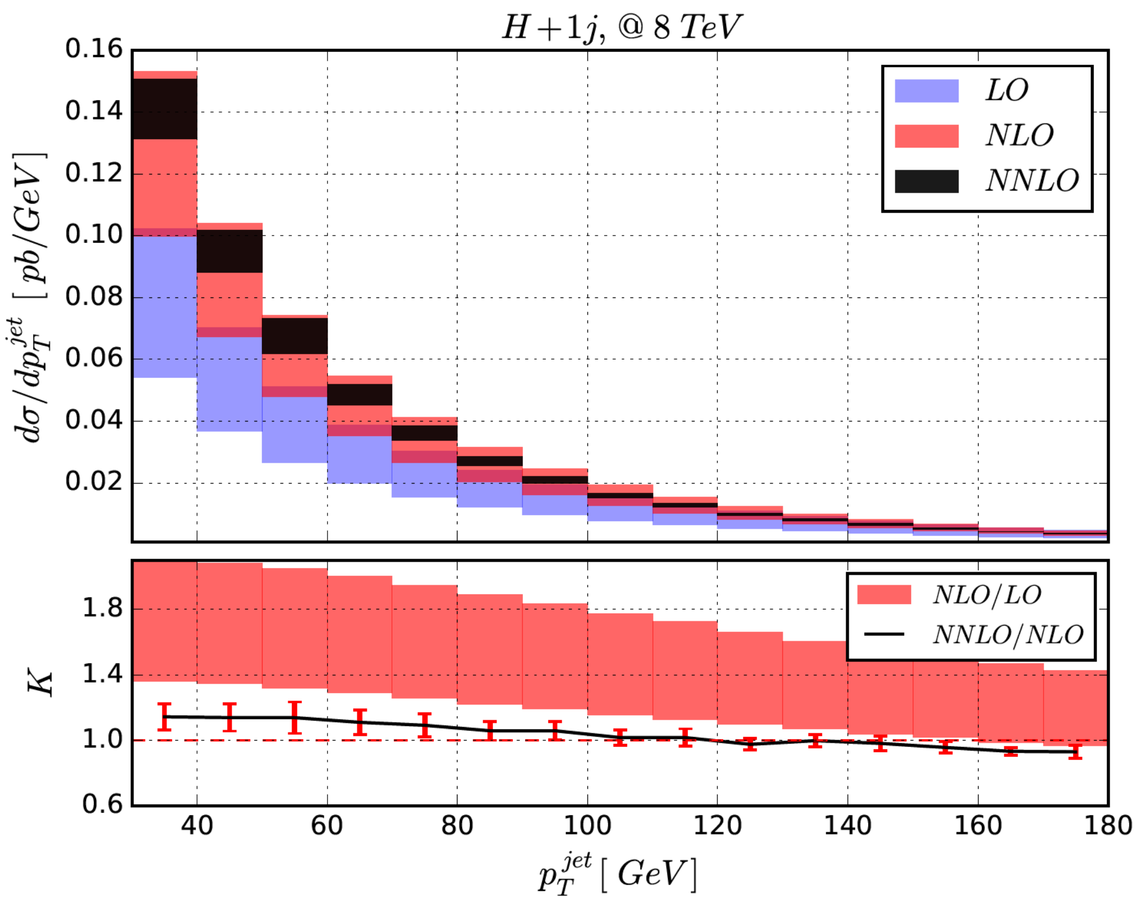
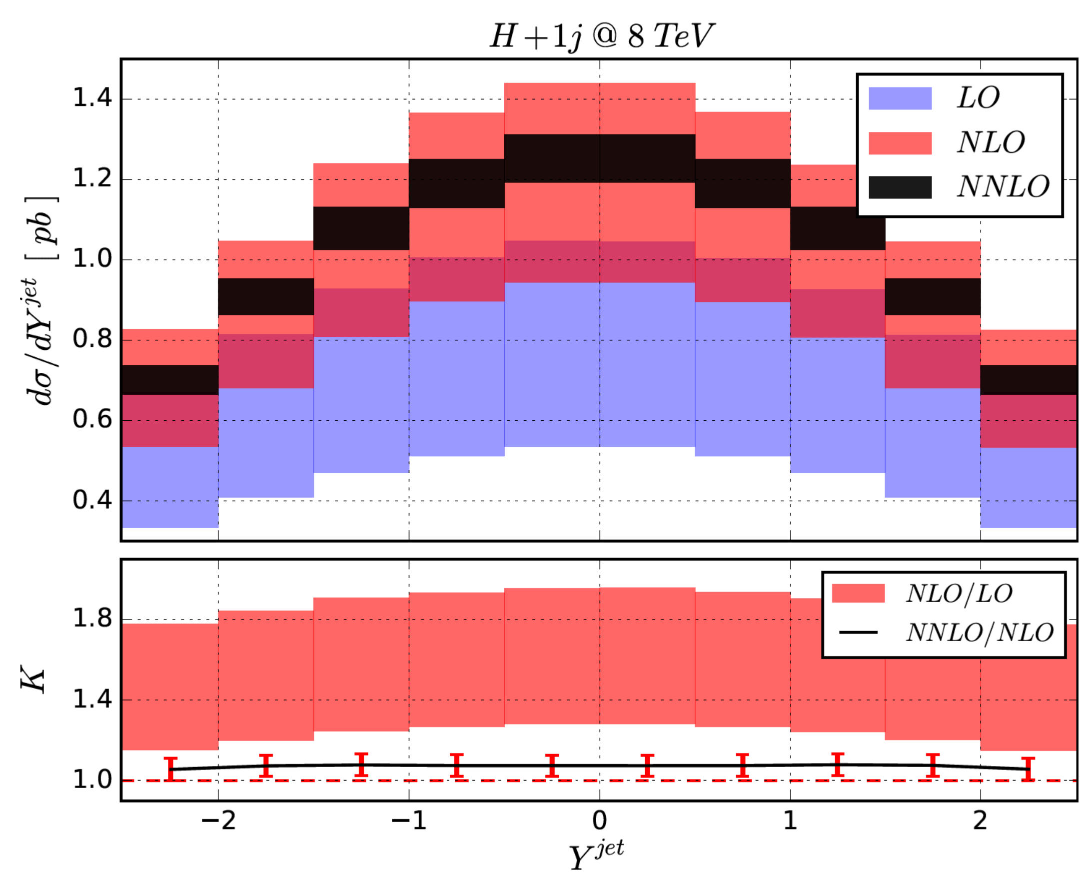
$$M_H/2 \leq \mu \leq 2\, M_H$$

Higgs+jet @ NNLO using jettiness: Results





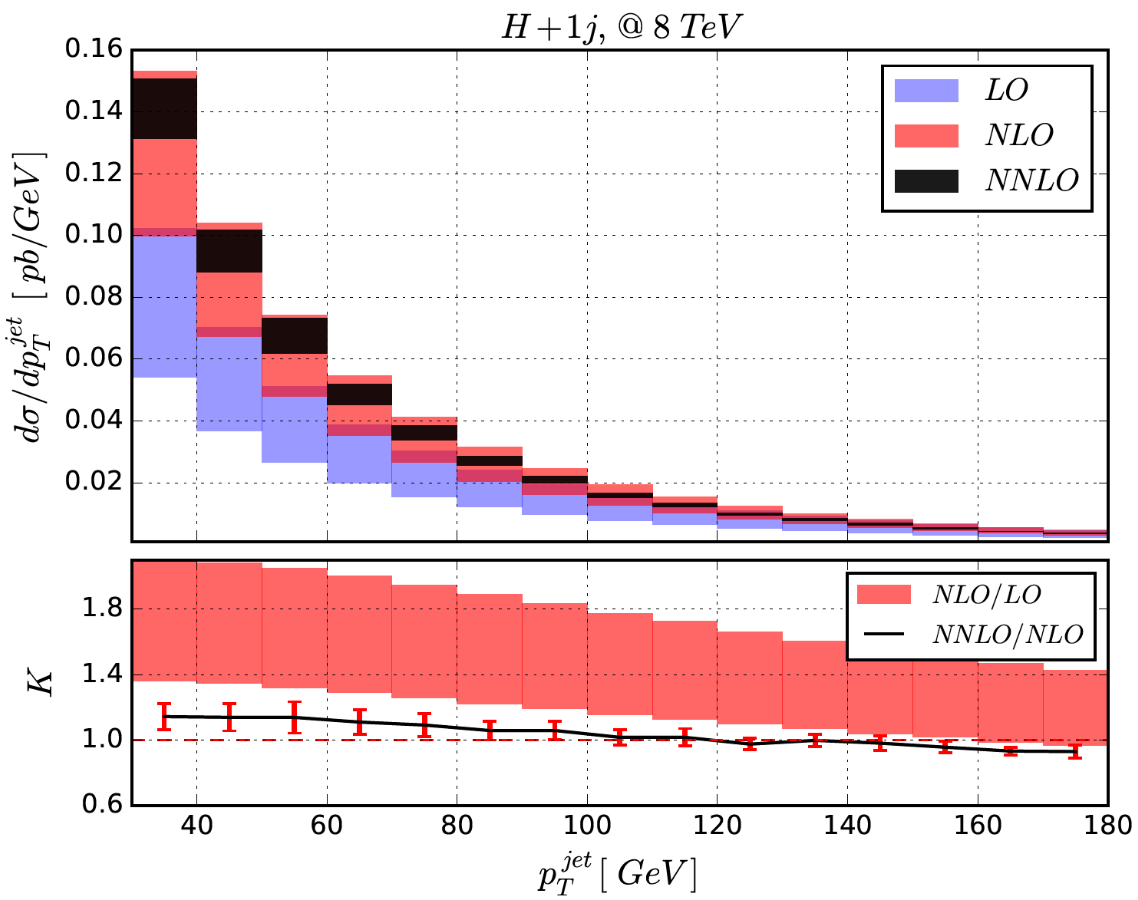
R.B., Giele, Focke, Liu, Petriello, 2015

$p_T^{jet} > 30$ GeV, $\lvert Y^{jet}\rvert < 2.5$	
Leading order:	$3.1^{+1.3}_{-0.9}$ pb
Next-to-leading order:	$4.8^{+1.1}_{-0.9}$ pb
Next-to-next-to-leading order:	$5.5^{+0.3}_{-0.4}$ pb

NNPDF2.3, m_H=125GeV, anti-K_T with R = 0.5

- K_{NNLO} is independent from τ_{cut} in each bin
- Non-trivial K-factor shape as a functions of p_{Tj} while flat as a function of Y^{jet}
- Differential distributions are under good control
- qqb, qq, qbqb channels included in this result. They reduce the cross section by ~1.5% for these cuts

Higgs+jet @ NNLO using jettiness: Results



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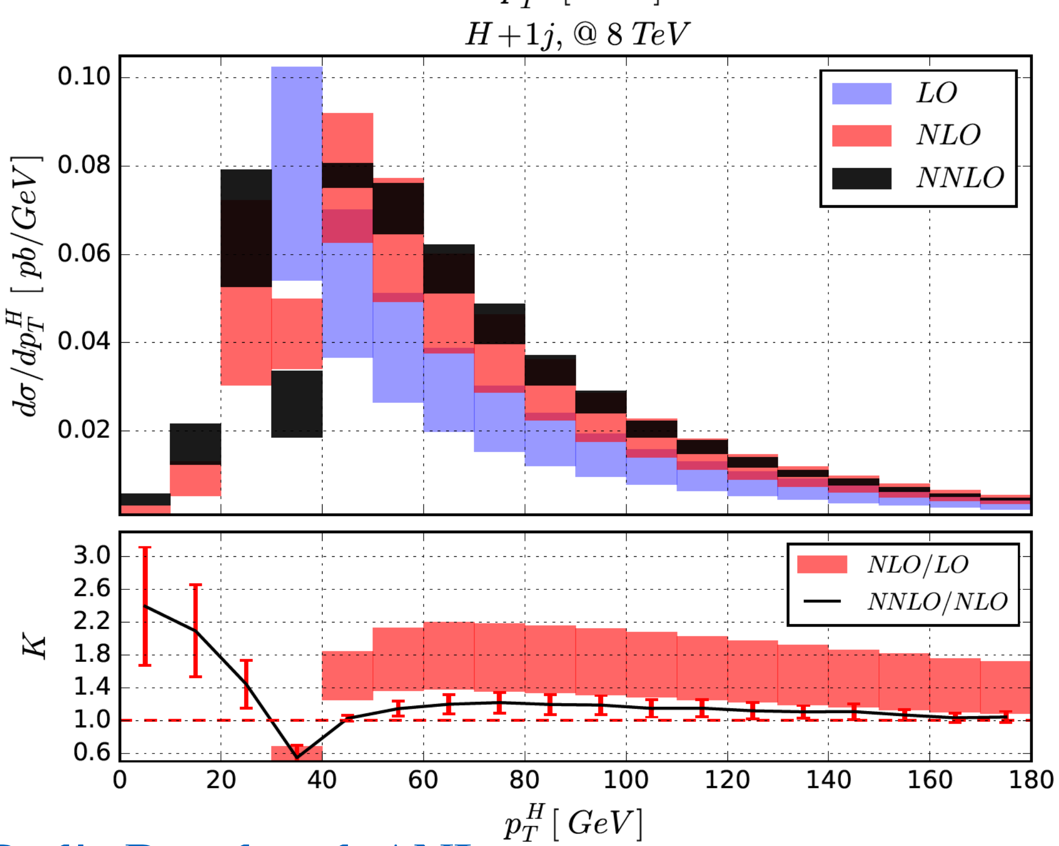
NNPDF2.3, m_H=125GeV, anti-K_T with R = 0.5

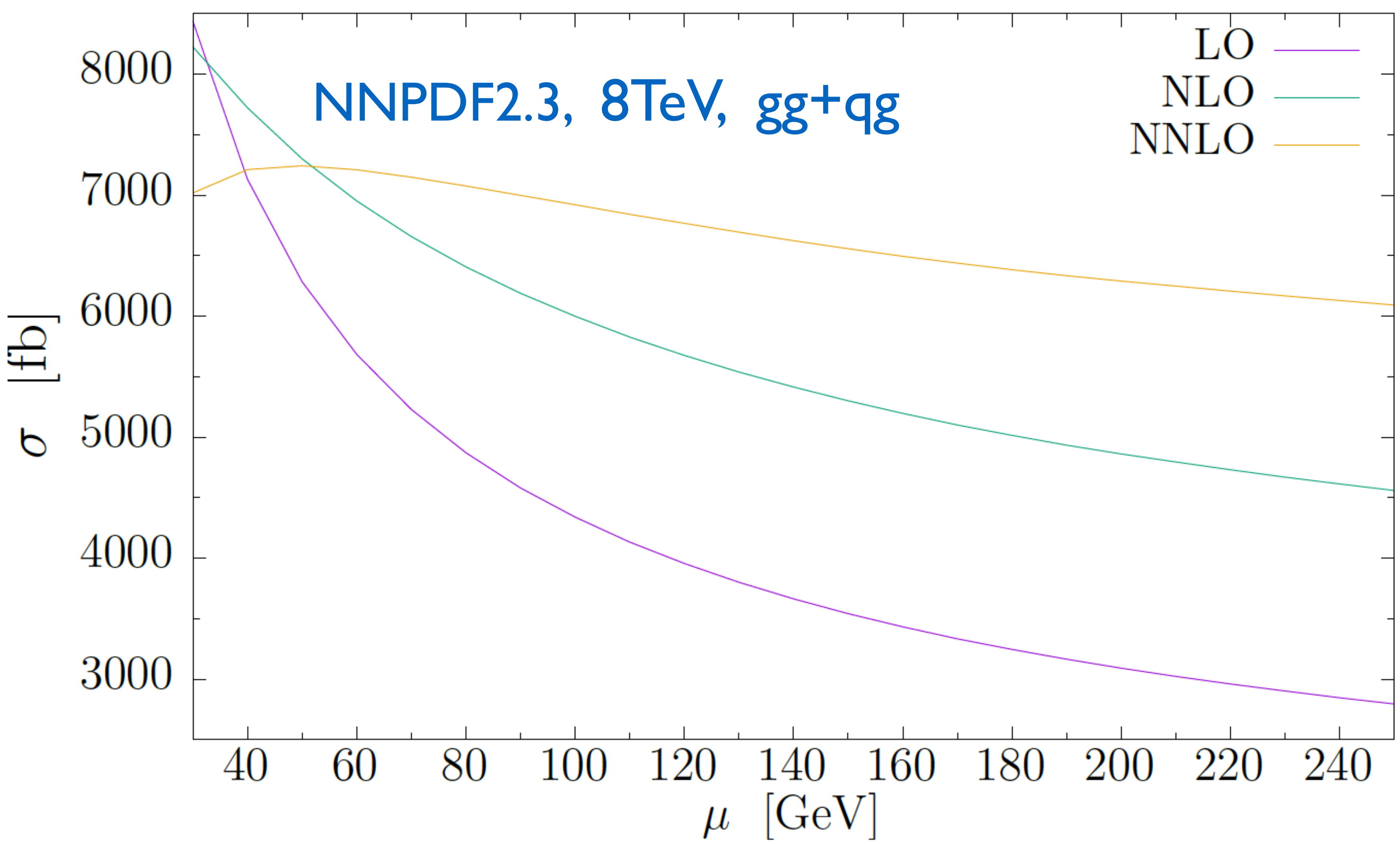


- K_{NNLO} is independent from τ_{cut} in each bin
- Non-trivial K-factor shape as a functions of p_{Tj} and p_{TH}
- Differential distributions are under good control
- Ready to compare with data!

Higgs + 1 jet @ NNLO using sector-improved residue subtraction

- Greatly reduced theoretical errors for H+1jet !

R.B., Caola, Melnikov, Petriello, Schulze, 2015



anti-kT jet algorithm

$R = 0.5$, $p_{T,cut} = 30$ GeV

Corrections:

$\text{LO} \xrightarrow{+44\%} \text{NLO} \xrightarrow{+20\%} \text{NNLO}$ for $\mu = m_H$

$\text{LO} \xrightarrow{+23\%} \text{NLO} \xrightarrow{+4\%} \text{NNLO}$ for $\mu = m_H/2$

Scale uncertainties: 36% LO 21% NLO 8% NNLO

Summary

- Remarkable progress in delivering complete NNLO predictions for various observables: Higgs+jet, W+jet and more to come.
- Jettiness subtraction: a simple, generic and efficient new method in deriving NNLO (and beyond) predictions.
- Ready to compare with LHC data!