Improving Higgs predictions with resummation

Frank Petriello

Loops and Legs in Quantum Field Theory

April 28, 2014

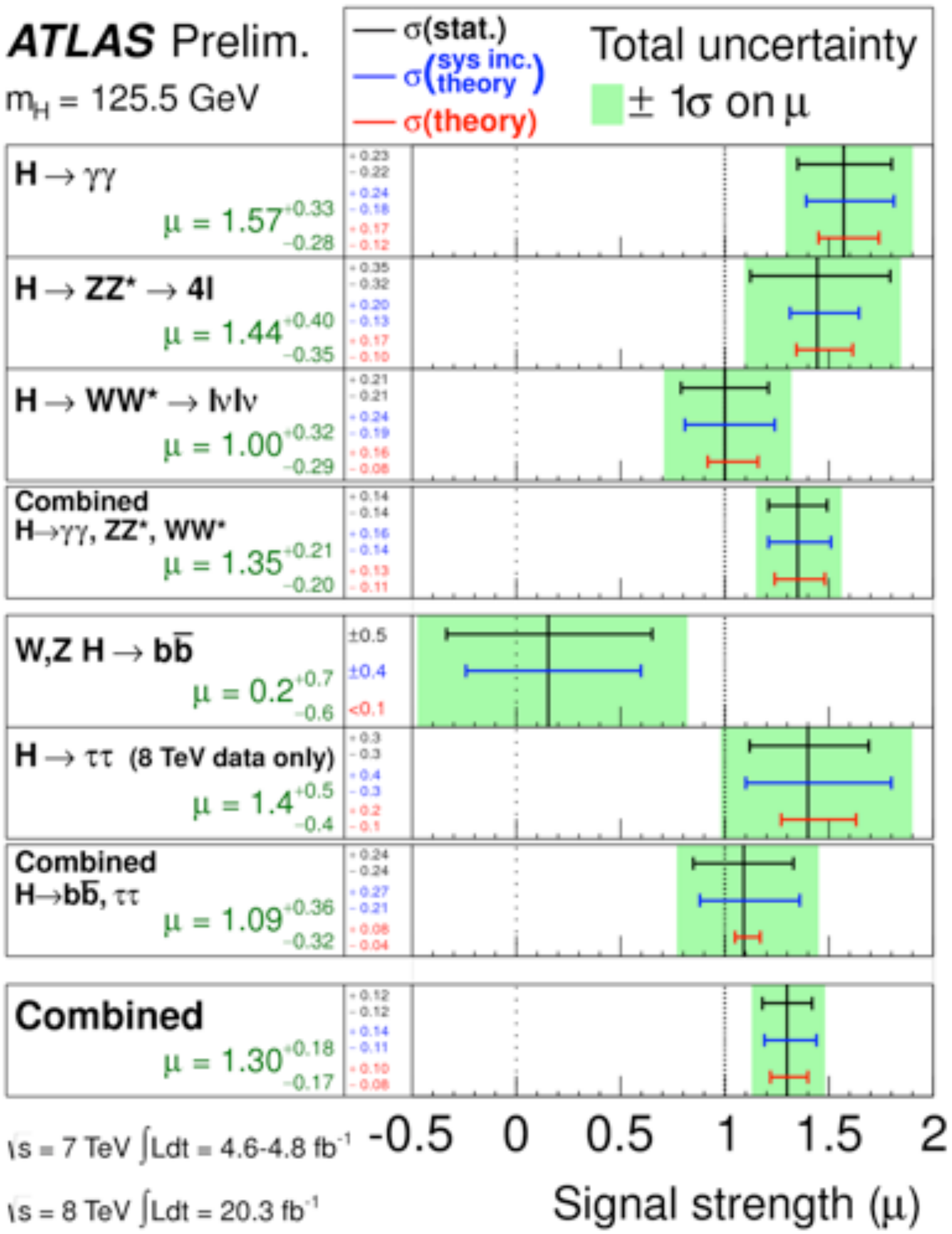
NORTHWESTERN UNIVERSITY

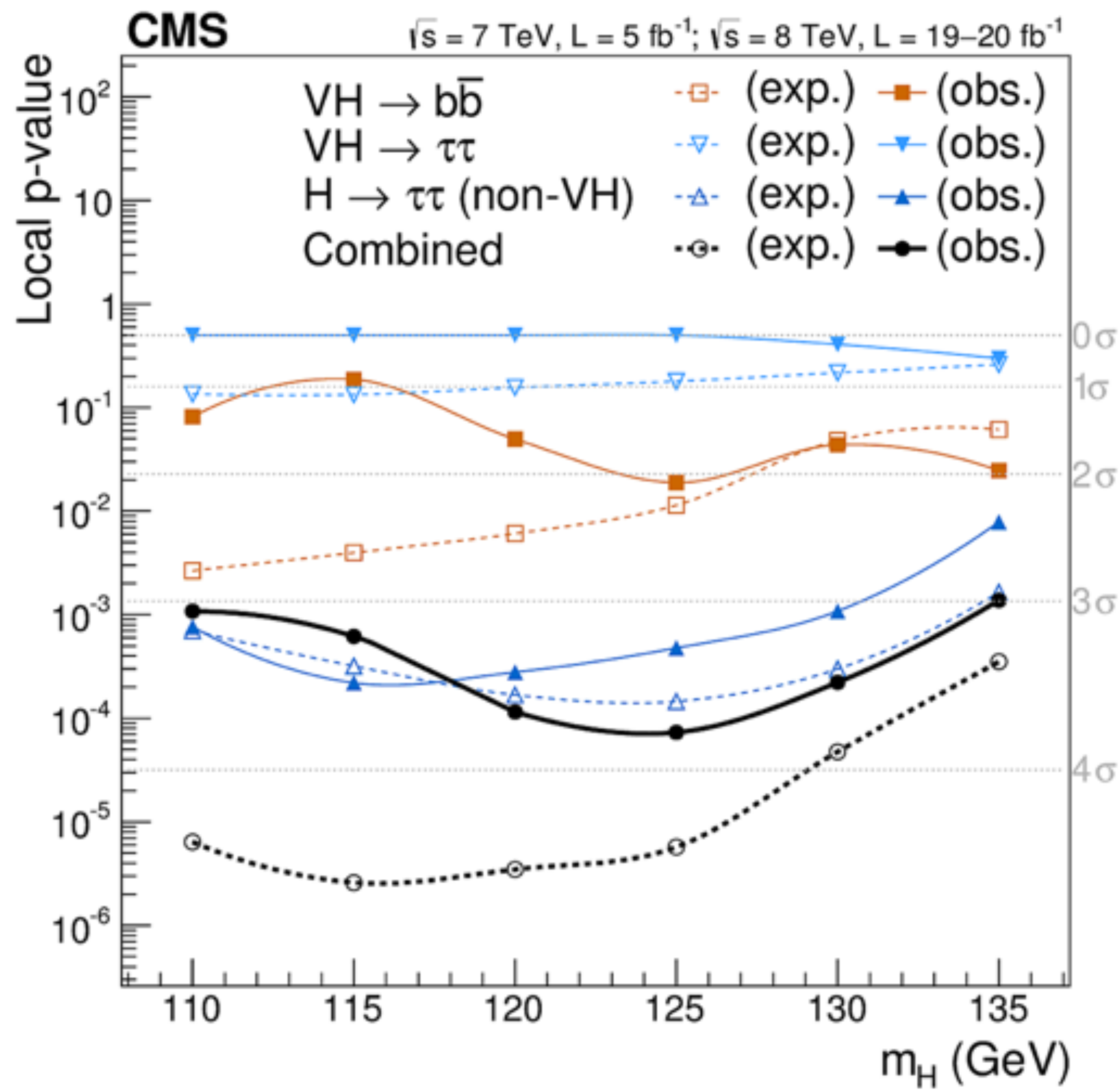
Argonne NATIONAL LABORATORY

Outline

- This talk will focus on improving the modeling of Higgs production in association with jets
  - Resummation of jet-veto logs for the H+jet process
    X. Liu, FP 1210.1906, 1303.4405
  - Combining Higgs predictions across jet bins
    R. Boughezal, X. Liu, FP, F. Tackmann, J. Walsh, 1312.4535

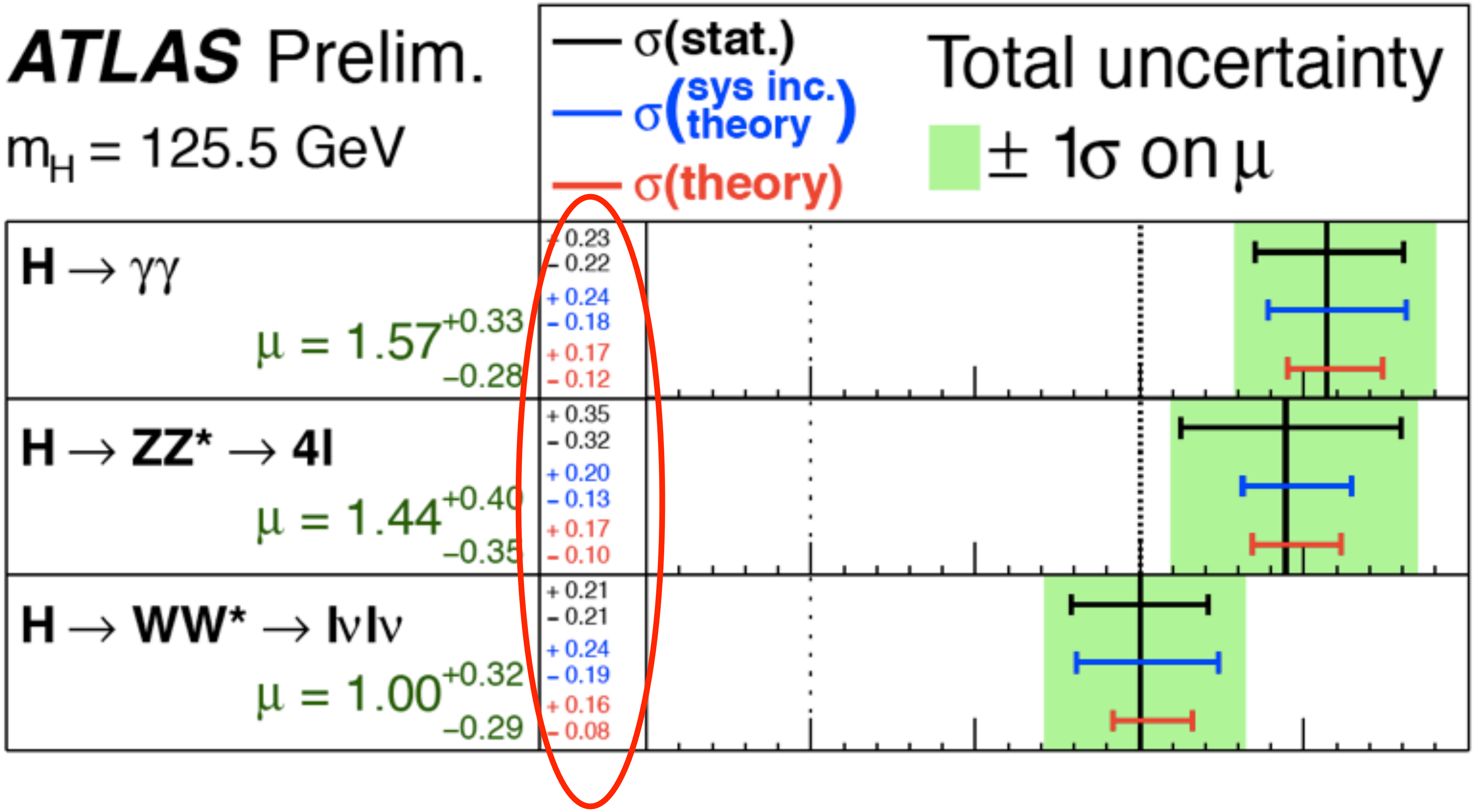
The Higgs circa 2014





- Underlying identity of the Higgs boson is being slowly revealed
- Uncertainties on signal strengths approaching ±20-30%

The Higgs circa 2014

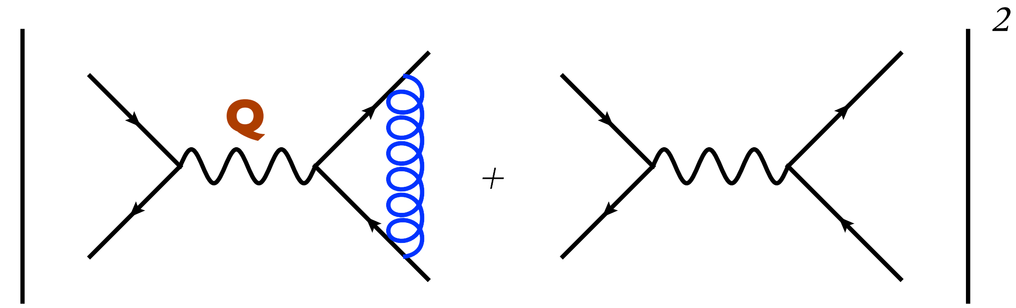


- The dominant component of the systematic error is theory
- Will become a limiting factor in interpretation in Run II as statistical errors decrease

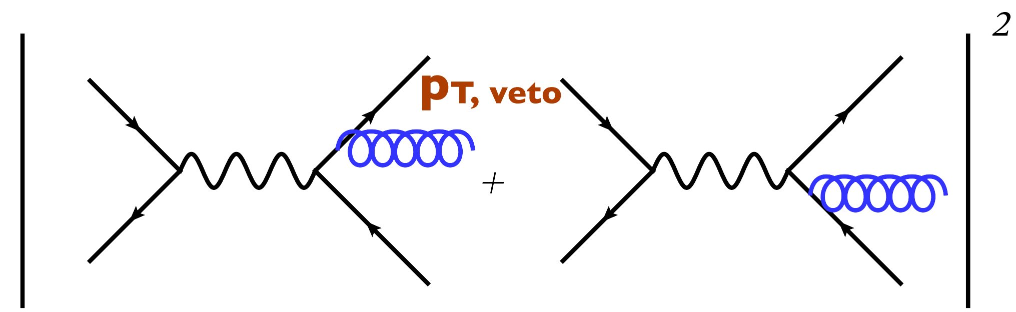
Exclusive jet binning

- A major issue in the WW channel is the division into exclusive jet bins

Source **ATLAS**	$N_{\rm jet}=0$	$N_{\rm jet}=1$	$N_{\rm jet}\geq 2$
Theoretical uncertainties on total signal yield (%)			
QCD scale for ggF, $N_{\rm jet}\geq 0$	+13	-	-
QCD scale for ggF, $N_{\rm jet}\geq 1$	+10	−27	-
QCD scale for ggF, $N_{\rm jet}\geq 2$	-	−15	+4
QCD scale for ggF, $N_{\rm jet}\geq 3$	-	-	+4
Parton shower and underlying event	+3	−10	±5
QCD scale (acceptance)	+4	+4	±3
Experimental uncertainties on total signal yield (%)			
Jet energy scale and resolution	5	2	6
Uncertainties on total background yield (%)			
WW transfer factors (theory)	±1	±2	±4
Jet energy scale and resolution	2	3	7
b-tagging efficiency	-	+7	+2
$f_{\rm recoil}$ efficiency	±4	±2	-



Virtual corrections: $-1/\varepsilon_{IR}^2$

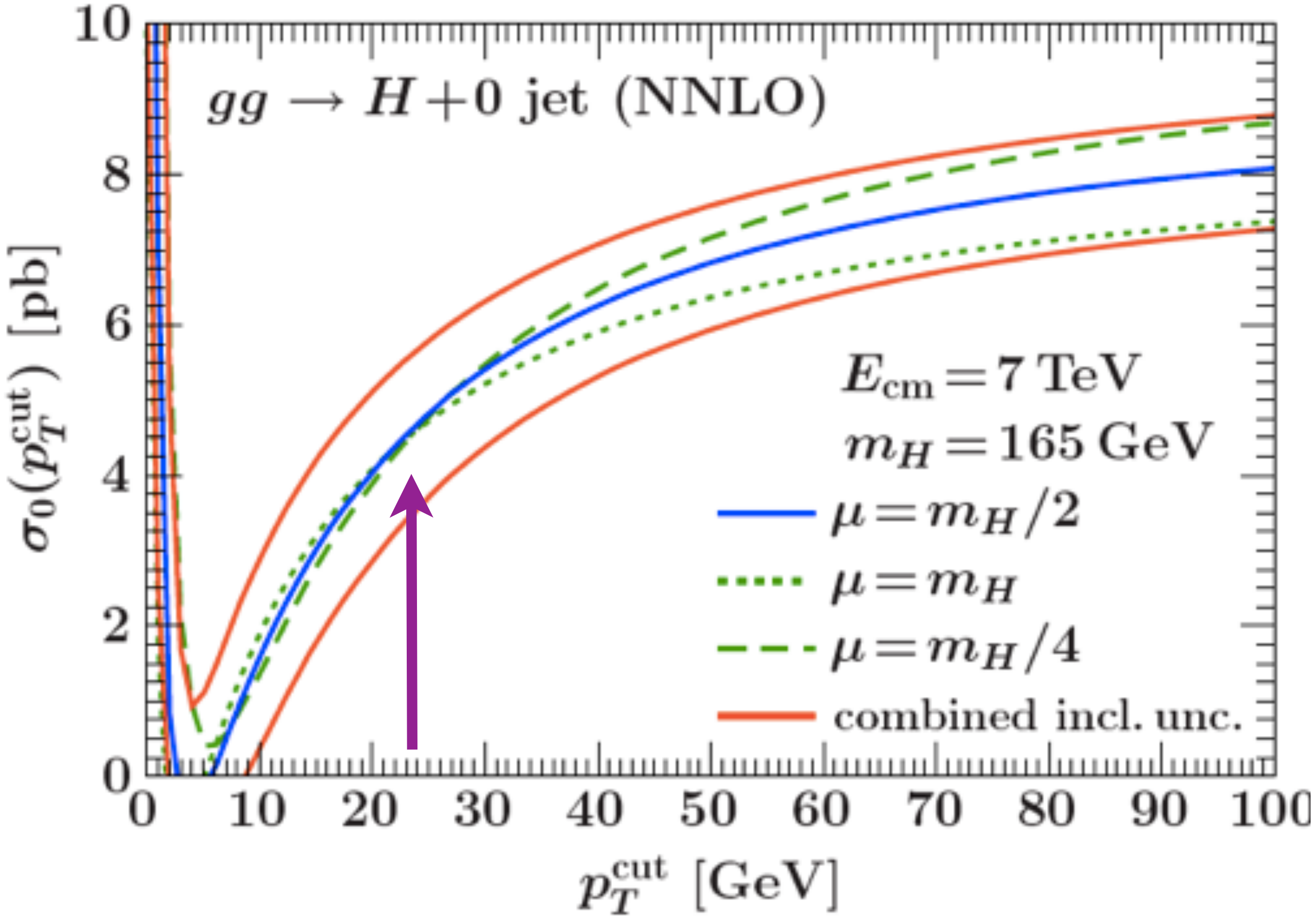


Real corrections: $1/\varepsilon_{IR}^2 - a\times\ln^2(Q/p_{T,veto})$

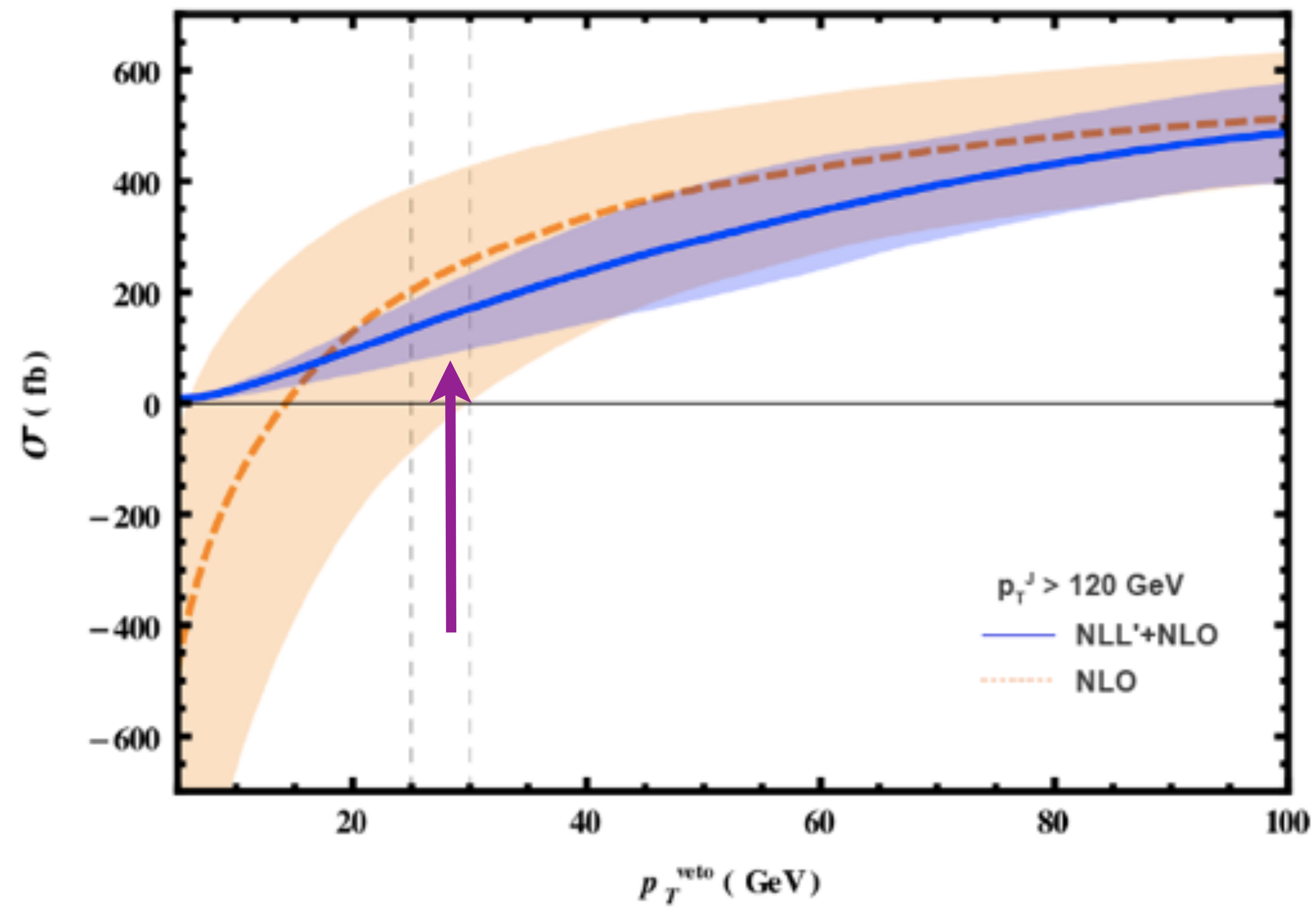
- Relevant term for gluon-fusion Higgs searches: $2C_A(\alpha_S/\pi)\ln^2(M_H/p_{T,veto})\sim 1/2 \Rightarrow$ potentially a large correction

Effects of the jet veto

Stewart, Tackmann 1107.2117



X. Liu, FP 1303.4405



- Breakdown of the usual scale-variation method for estimating theory uncertainties
- Deviations from fixed-order perturbation theory, especially in new kinematic regions that will be first probed in Run II

Current error treatment

- Current covariance matrix used by ATLAS and CMS follows the Stewart-Tackmann (ST) prescription:

$$C_{\mathrm{FO}}(\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}) = \begin{pmatrix} (\Delta^{\mathrm{FO}}_{\geq 0})^2 + (\Delta^{\mathrm{FO}}_{\geq 1})^2 & -(\Delta^{\mathrm{FO}}_{\geq 1})^2 & 0 \\ -(\Delta^{\mathrm{FO}}_{\geq 1})^2 & (\Delta^{\mathrm{FO}}_{\geq 1})^2 + (\Delta^{\mathrm{FO}}_{\geq 2})^2 & -(\Delta^{\mathrm{FO}}_{\geq 2})^2 \\ 0 & -(\Delta^{\mathrm{FO}}_{\geq 2})^2 & (\Delta^{\mathrm{FO}}_{\geq 2})^2 \end{pmatrix}$$

$\Delta_{\geq 0}$: fixed-order uncertainty on total cross section (NNLO)

$\Delta_{\geq 1}$: fixed-order uncertainty on inclusive 1-jet rate (NLO)

$\Delta_{\geq 2}$: fixed-order uncertainty on inclusive 2-jet rate (LO/NLO)

- The logic: the perturbative series for the inclusive cross sections are independent in the small p_T^{cut} limit, so add in quadrature. By construction, the 0-jet and 1-jet exclusive uncertainties are greater than the inclusive 0-jet and 1-jet uncertainties

Current error treatment

- Current covariance matrix used by ATLAS and CMS follows the Stewart-Tackmann (ST) prescription:

$$C_{\rm FO}(\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}) = \begin{pmatrix} (\Delta^{\rm FO}_{\geq 0})^2 + (\Delta^{\rm FO}_{\geq 1})^2 & -(\Delta^{\rm FO}_{\geq 1})^2 & 0 \\ -(\Delta^{\rm FO}_{\geq 1})^2 & (\Delta^{\rm FO}_{\geq 1})^2 + (\Delta^{\rm FO}_{\geq 2})^2 & -(\Delta^{\rm FO}_{\geq 2})^2 \\ 0 & -(\Delta^{\rm FO}_{\geq 2})^2 & (\Delta^{\rm FO}_{\geq 2})^2 \end{pmatrix}$$

$\Delta_{\geq 0}$: fixed-order uncertainty on total cross section (NNLO)

$\Delta_{\geq 1}$: fixed-order uncertainty on inclusive 1-jet rate (NLO)

$\Delta_{\geq 2}$: fixed-order uncertainty on inclusive 2-jet rate (LO/NLO)

- Our goal: completely replace fixed-order perturbation theory with renormalization-group improved PT that resums the large jet-veto logs. We will see that there is a significant numerical improvement resulting from this replacement.

Zero-jet resummation

- Begin in the zero-jet bin. Current status with anti-k_T algorithm:
  - Banfi, Monni, Salam, Zanderighi: NNLL+NNLO 1203.5573, 1206.4998
  - Becher, Neubert NNLL+NNLO 1205.3806, partial N^{3}LL+NNLO 1307.0025
  - Stewart, Tackmann, Walsh, Zuberi NNLL'+NNLO 1307.1808

Counting in the log of the cross section

LL	NLL	NLL′ / NNLL	NNLL′ / NNNLL	
$\alpha_s L^2$	$\alpha_s L$	α_s		
$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	α_s^2	
$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$\alpha_s^3 L^2$	$\alpha_s^3 L$	α_s^3

$$L = \ln \frac{p_T^{\mathrm{cut}}}{m_H}$$

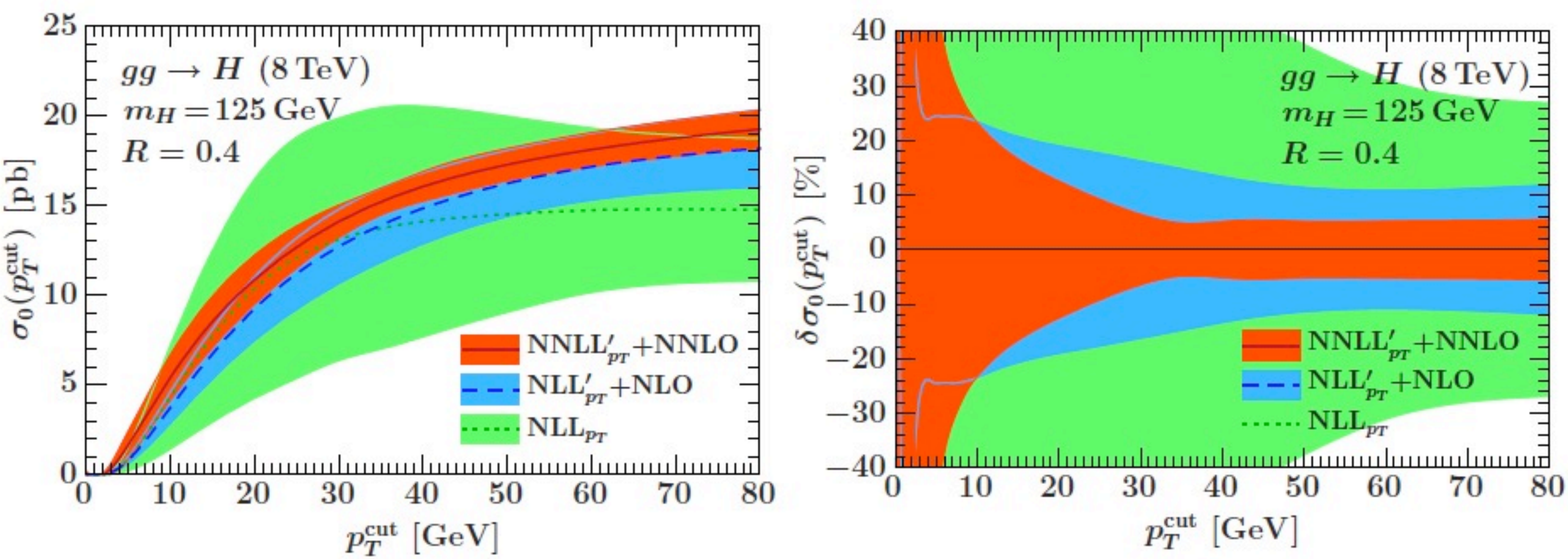
Global veto log structure

NNLL'+NNLO resummation

- Uses soft-collinear effective theory
- Significant improvement in prediction from including higher-order resummation and fixed-order

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

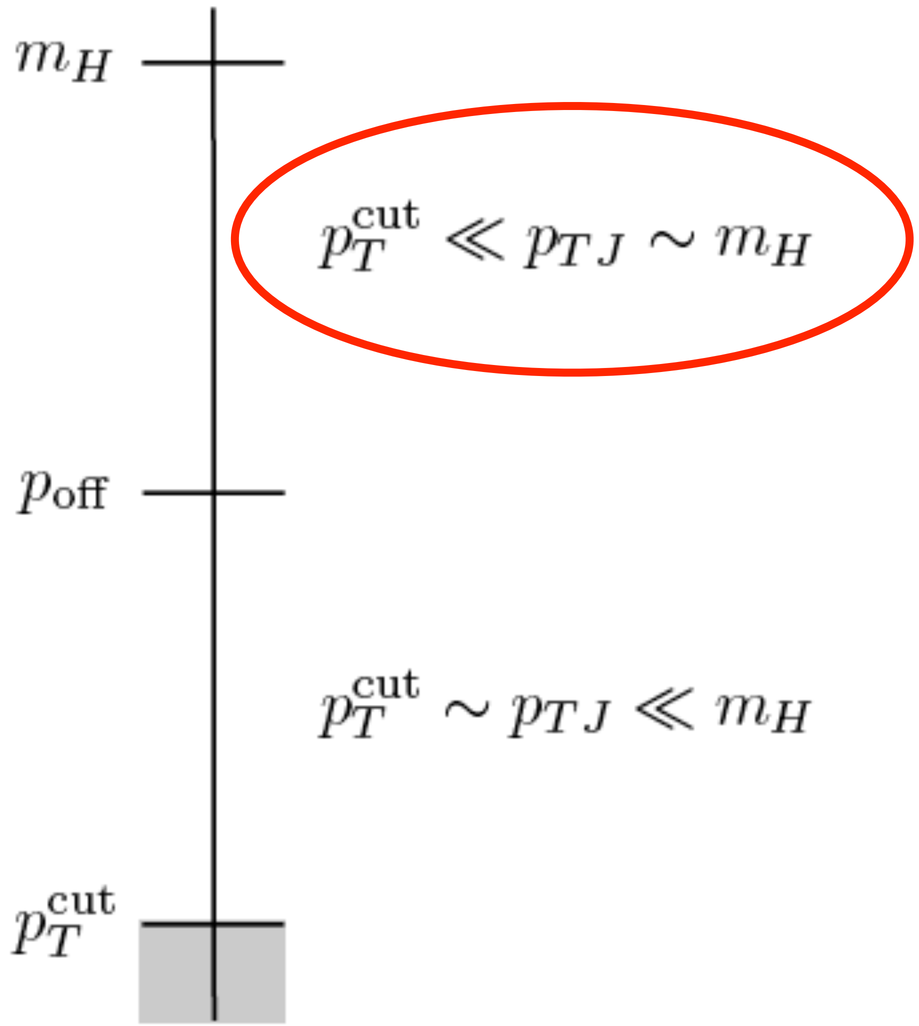
Including resummation and fixed-order uncertainties

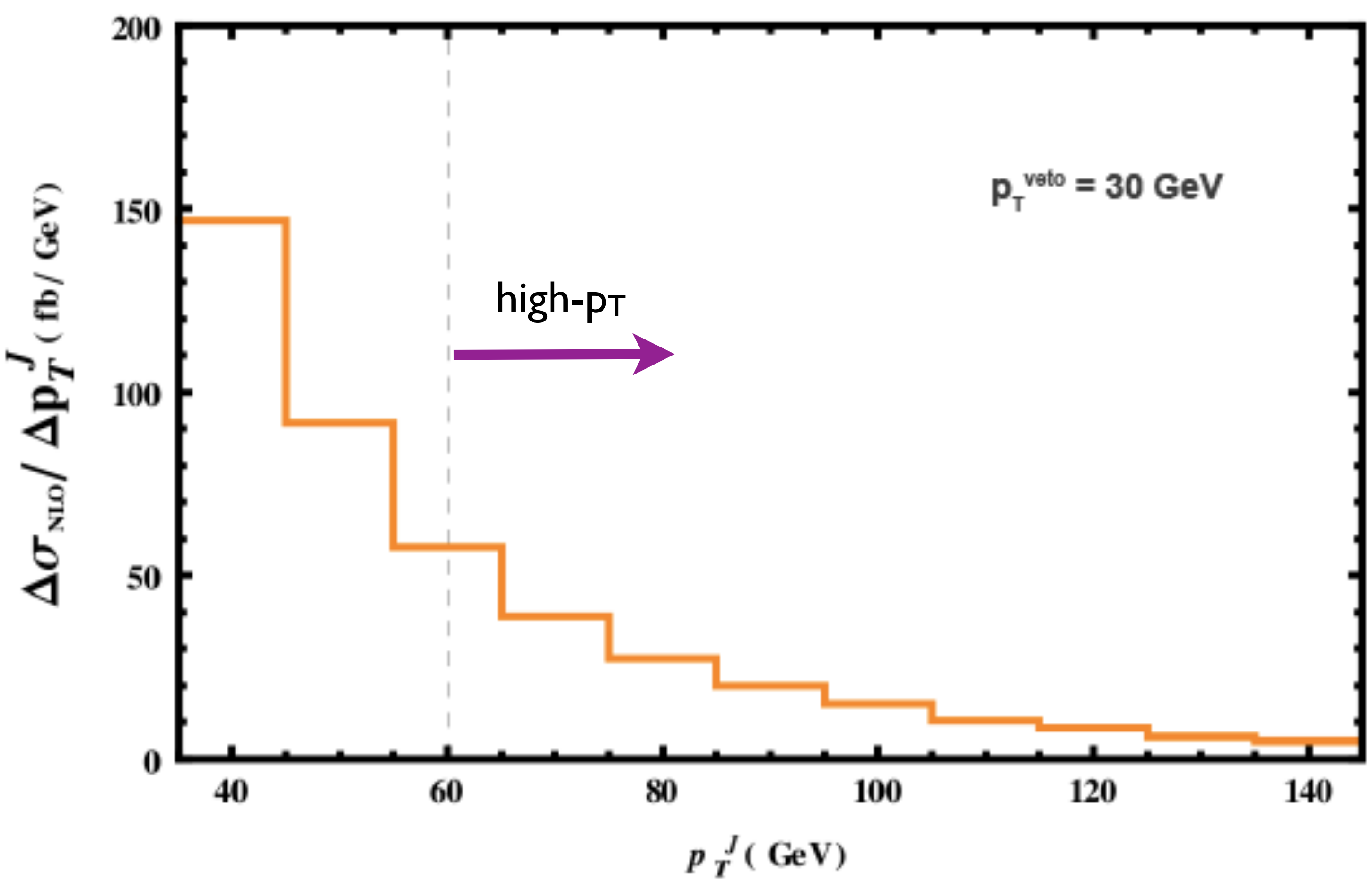


Stewart, Tackmann, Walsh, Zuberi 1307.1808

The one-jet bin: high-p_T

- Now discuss the jet-veto logarithms in the H+1 jet bin
- Two relevant regions of jet p_T: $p_T \sim m_H >> p_{T,veto}$, $m_H >> p_T \sim p_{T,veto}$
- Currently can directly resum at NLL'+NLO the first region

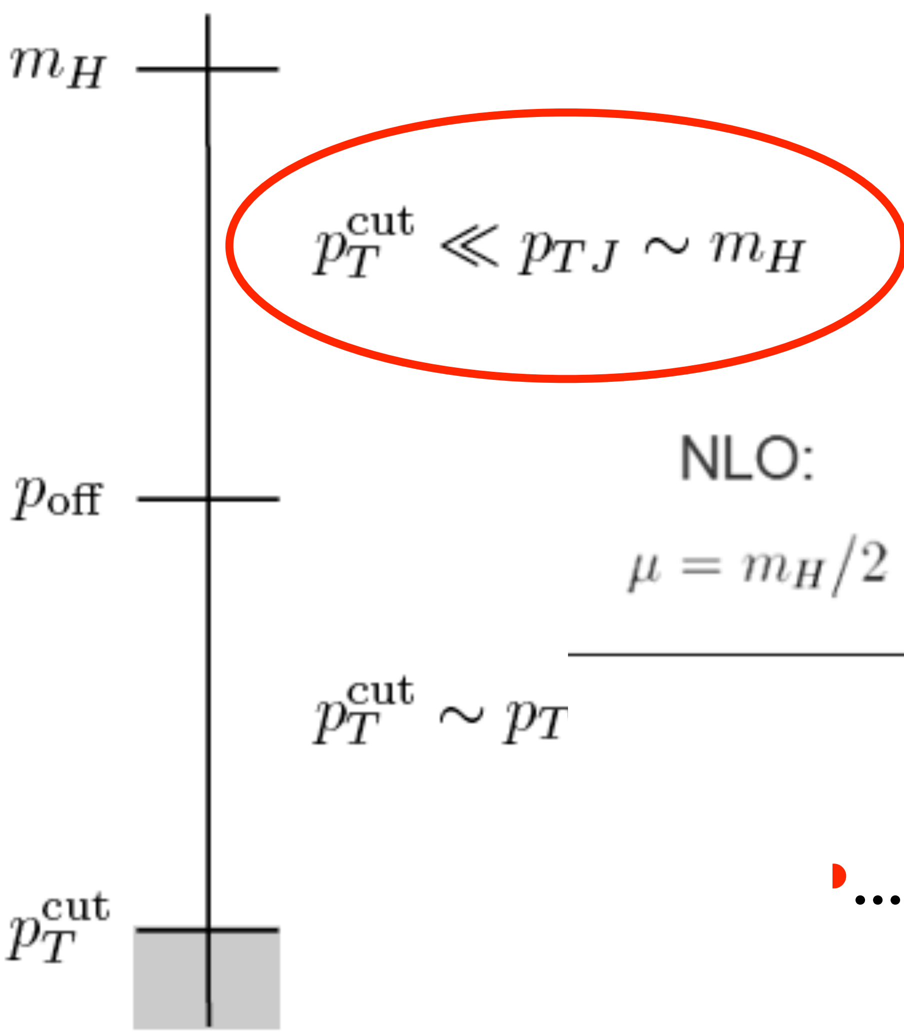




- Comprises roughly 30% of the event rate at the 8 TeV LHC...

The one-jet bin: high-p_T

- Now discuss the jet-veto logarithms in the H+1 jet bin
- Two relevant regions of jet p_T: $p_T \sim m_H >> p_{T,veto}$, $m_H >> p_T \sim p_{T,veto}$
- Currently can directly resum at NLL'+NLO the first region



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

- ... but makes up roughly 50% of the 1-jet bin error

The EFT

- We utilize an EFT approach:

$p_s \sim m_H(\lambda,\lambda,\lambda)$

$p_{a,b} \sim m_H(\lambda^2, 1, \lambda)$

$p_J \sim m_H(\lambda^2, 1, \lambda)$ (along jet direction)

$$\lambda \equiv p_T^{veto}/\sqrt{\hat{s}} \ll 1$$

- Distance measures for H+1 jet, anti-k_T algortihm:

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

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

$R \sim 0.4$, $\lambda \sim 0.2$

- Radiation along the jet direction is combined first into a single state; soft radiation insensitive to details of collinear radiation

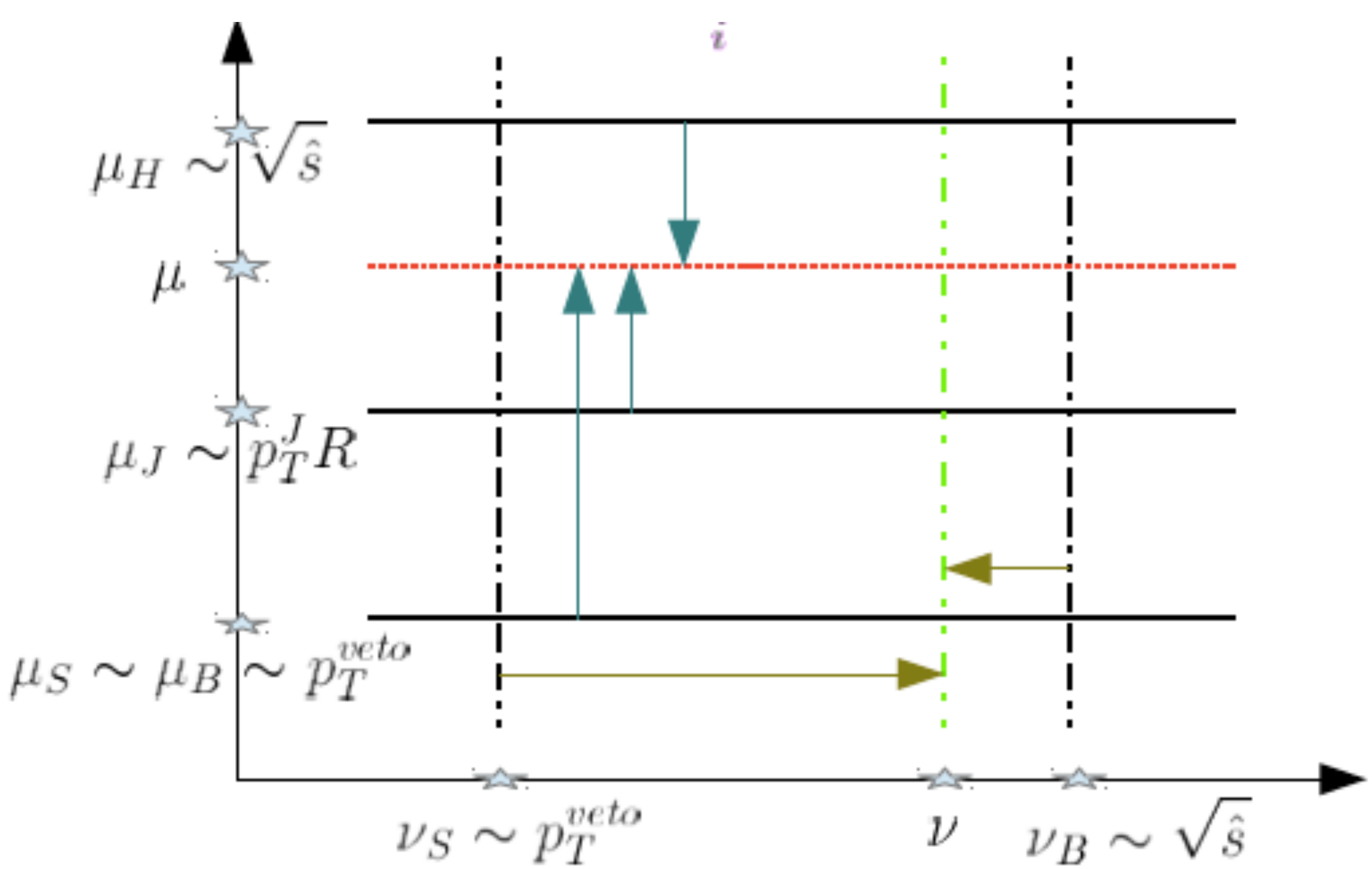
Factorization theorem

- Establish the following result for the NLL' resummed cross section

$$
\mathrm{d}\sigma_{\mathrm{NLL'}} = \mathrm{d}\Phi_H \mathrm{d}\Phi_J \, \mathcal{F}(\Phi_H, \Phi_J) \sum_{a,b} \int \mathrm{d}x_a \mathrm{d}x_b \frac{1}{2\hat{s}} (2\pi)^4 \delta^4 (q_a + q_b - q_J - q_H)
$$

$$
\times \overline{\sum_{\text{spin}}} \, \overline{\sum_{\text{color}}} \mathrm{Tr}(H \cdot S) \, \mathcal{I}_{a,i_a j_a} \otimes f_{j_a}(x_a) \, \mathcal{I}_{b,i_b j_b} \otimes f_{j_b}(x_b) \, J_J(R) \, .
$$

virtual corrections (Tr(H …)) — soft radiation (S) — beam-collinear radiation ($\mathcal{I}_{a}$, $\mathcal{I}_{b}$) — jet-collinear radiation (J_J)



- Resummation of large logs accomplished through RG evolution of each function from its natural scale to a common scale μ

Non-global logarithms

- Non-global logs: correlated emissions from inside the jet-cone to outside.
Dasgupta, Salam hep-ph/0104277
- Not captured in the factorization formula presented
- Large N_C resummation of these terms for an energy veto indicates that they are numerically irrelevant (<1%), but it would be nice to understand their structure better

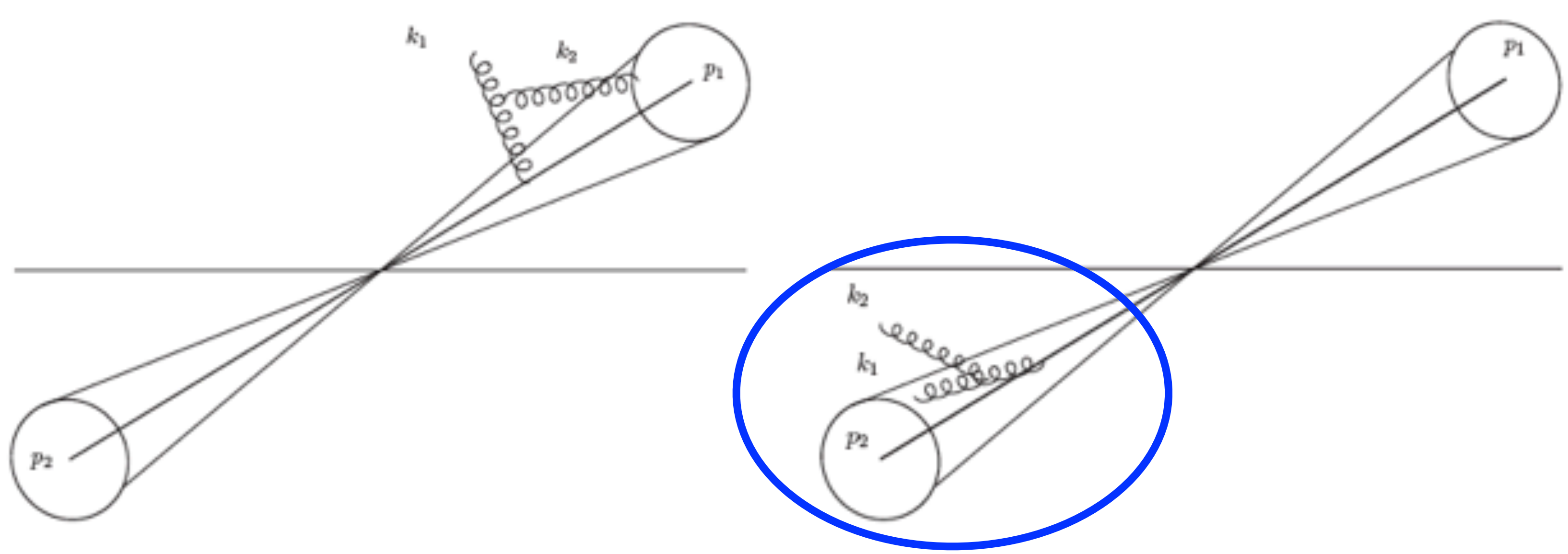
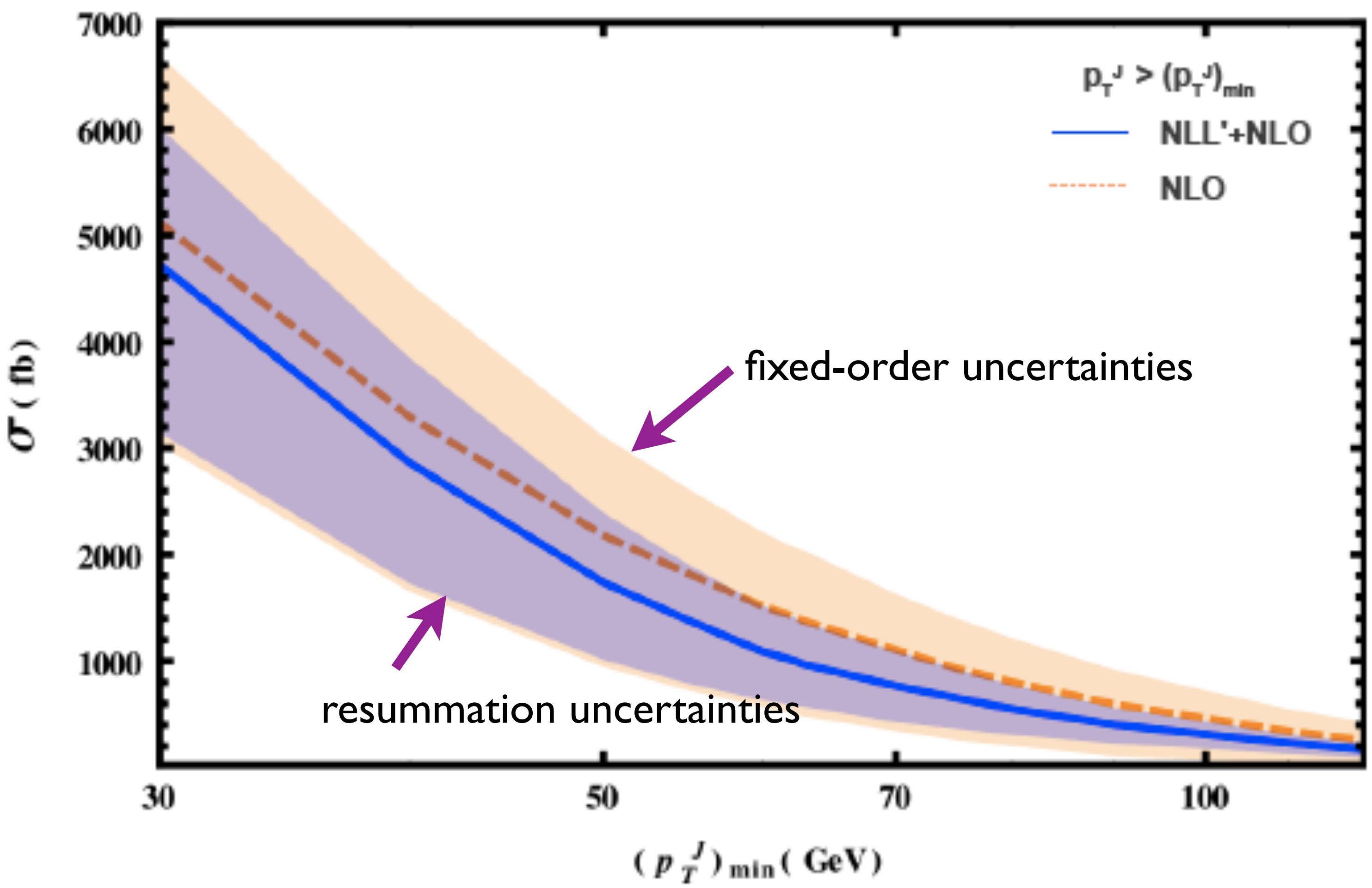


Figure 1: Diagrams representing the correlated emissions which give rise to the lowest-order non-global logarithms. On the left: the harder gluon k_1 lies outside both jets and the softest one k_2 is recombined with the measured jet and contributes to the jet-mass distribution. On the right: the harder gluon is inside the unmeasured jet and emits a softer gluon outside both jets, which contributes to the E_0-distribution.

Numerical results

- Integrate over entire p_T range used in the ATLAS measurement

X. Liu, FP 1303.4405



- Resummation uncertainties: separately vary all scale (hard, jet, beam+soft, non-singular) around their central values, add in quadrature

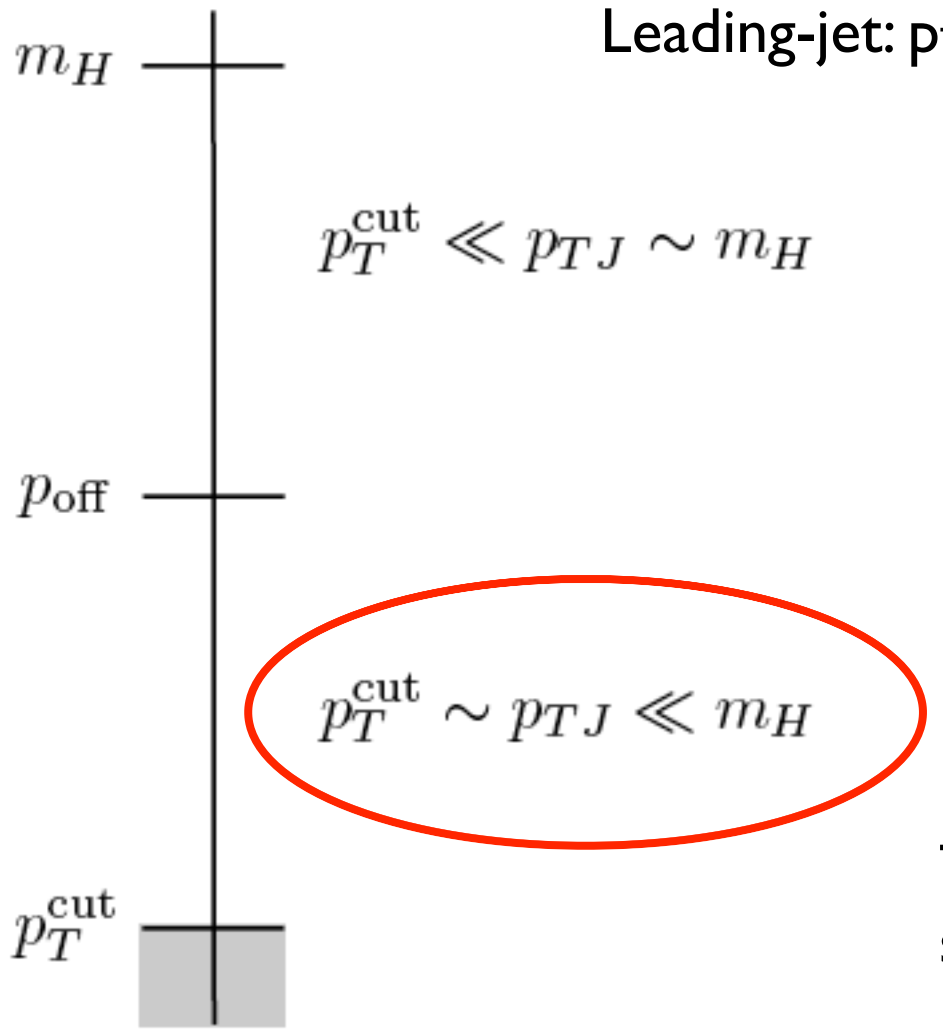
- Large uncertainty from the high-p_T region makes this resummation very effective in reducing errors
- Very conservatively (turn off resummation at $p_{T,J}=m_H/2$, use ST below this value) error on the entire1-jet bin result is decreased by 25%
- But we can do better...

The one-jet bin: low-p_T

- We can indirectly sum the low-p_T one-jet region in the following way
- Cross section of interest: $\sigma_1(p_{off}, p_{Tcut}; p_{Tcut})$

Leading-jet: $p_{Tcut} < p_{T1} < p_{off}$

Veto on second jet



Difference of 0-jet cross sections with p_T less than the indicated argument

$$\sigma_1(p_{off}, p_{Tcut}; p_{Tcut}) = \sigma_0(p_{off}) - \sigma_0(p_{Tcut})$$

$$-\sigma_{\geq 2}(p_{Tcut}) + \sigma_{\geq 2}(p_{off}, p_{Tcut})$$

Two-jet inclusive cross section with $p_{T1}, p_{T2} > p_{Tcut}$

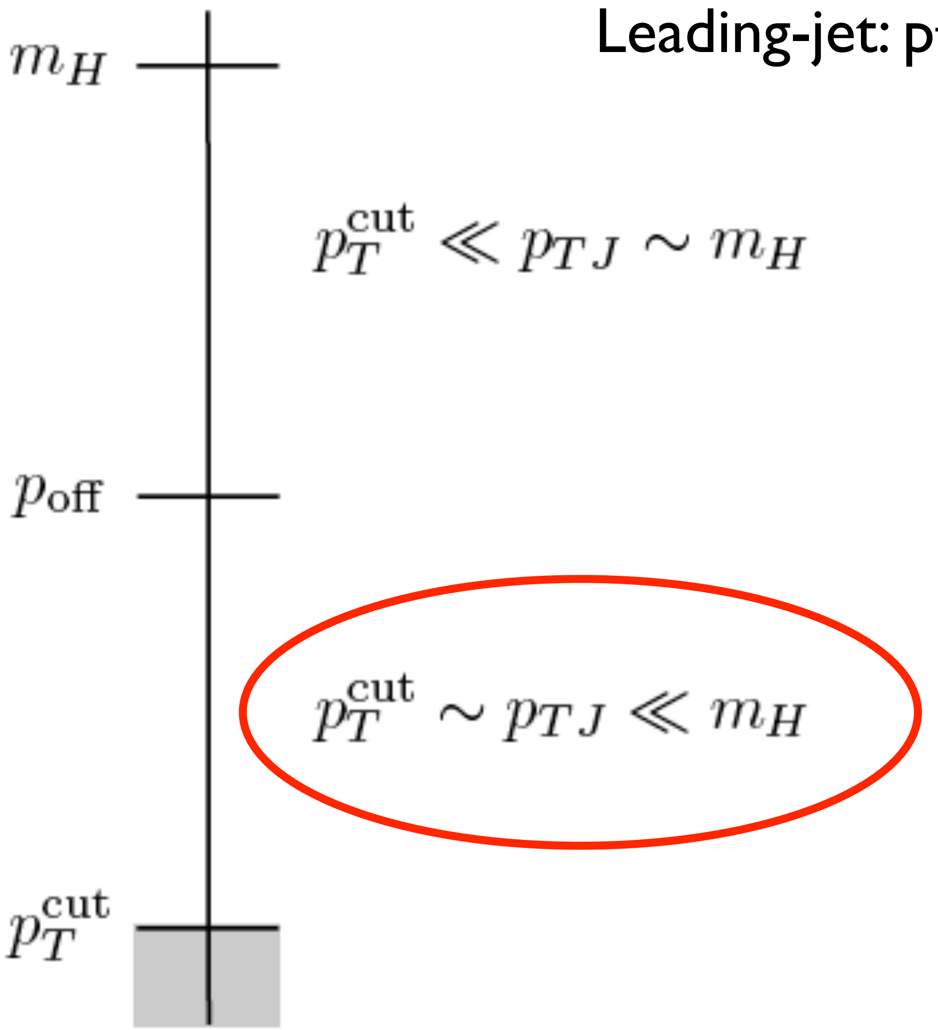
Two-jet inclusive cross section with $p_{T1} > p_{off}, p_{T2} > p_{Tcut}$

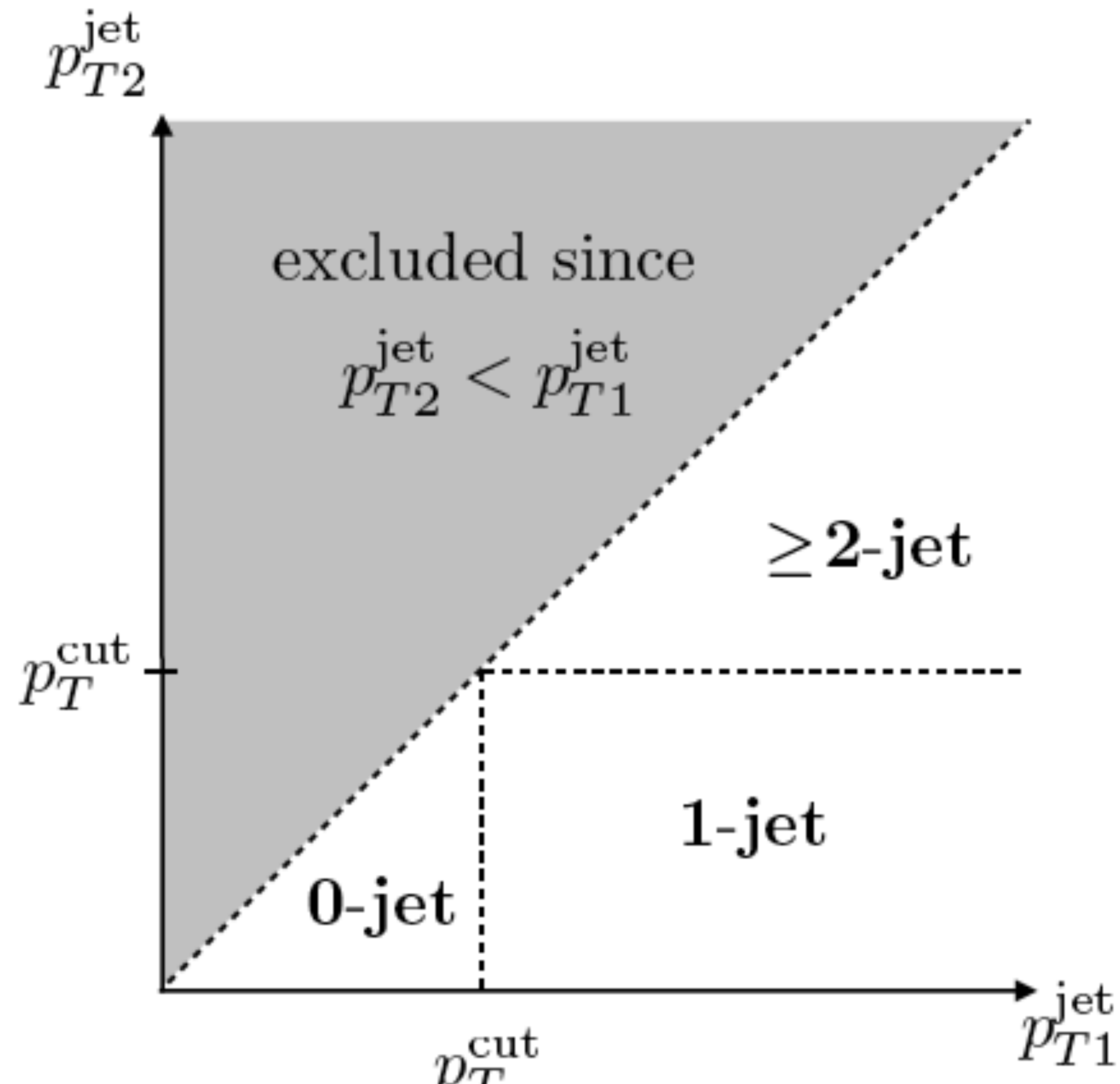
The one-jet bin: low-p_T

- We can indirectly sum the low-p_T one-jet region in the following way
- Cross section of interest: $\sigma_1(p_{off}, p_{Tcut}; p_{Tcut})$

Leading-jet: $p_{Tcut} < p_{T1} < p_{off}$

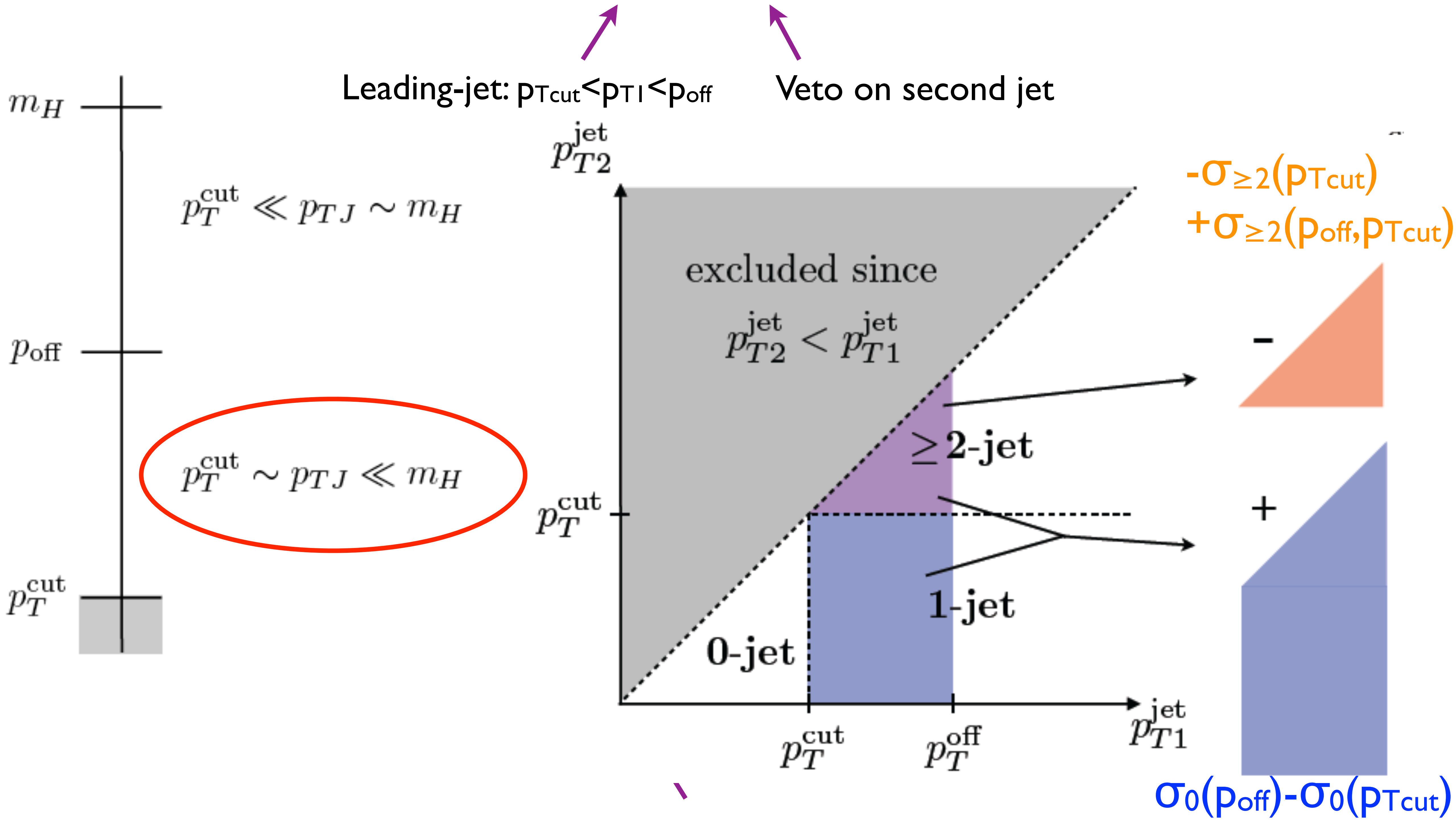
Veto on second jet





The one-jet bin: low-p_T

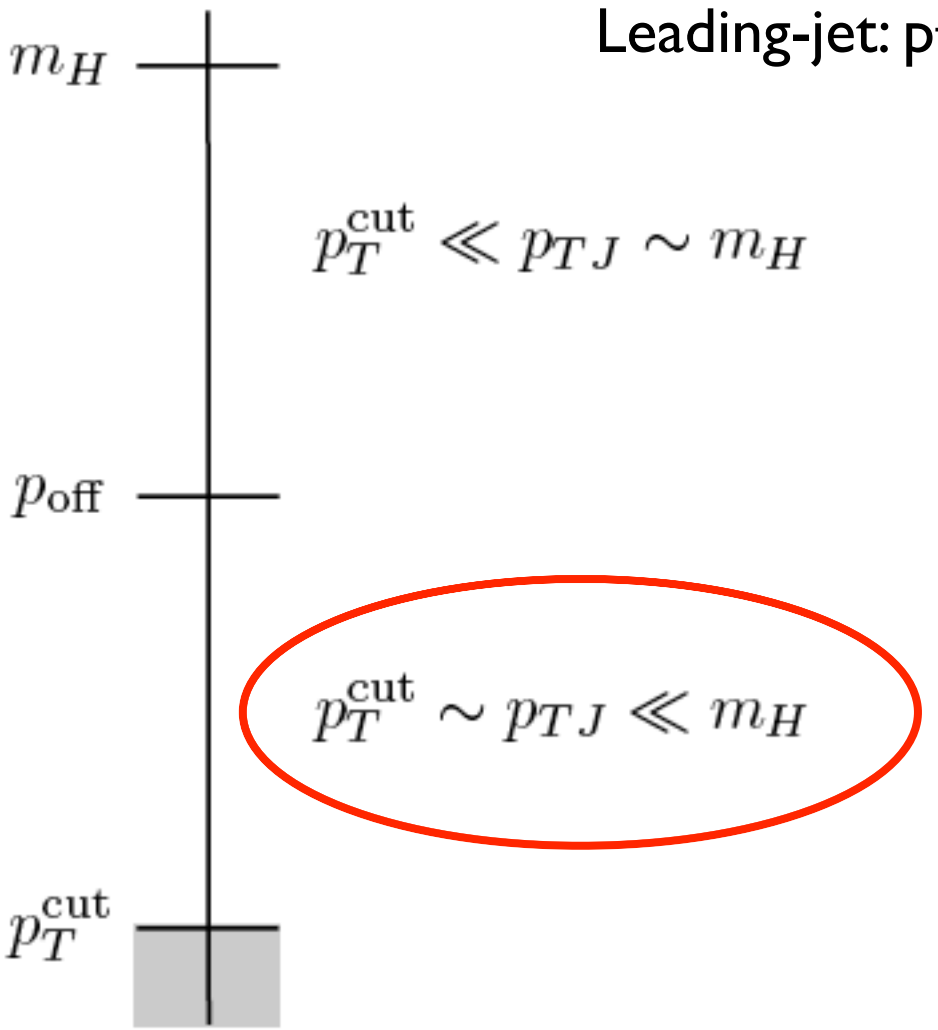
- We can indirectly sum the low-p_T one-jet region in the following way
- Cross section of interest: $\sigma_1(p_{off}, p_{Tcut}; p_{Tcut})$



The one-jet bin: low-p_T

- We can indirectly sum the low-p_T one-jet region in the following way
- Cross section of interest: $\sigma_1(p_{off}, p_{Tcut}; p_{Tcut})$

Leading-jet: $p_{Tcut} < p_{T1} < p_{off}$ Veto on second jet



$$\sigma_1(p_{off}, p_{Tcut}; p_{Tcut}) = \sigma_0(p_{off}) - \sigma_0(p_{Tcut}) - \sigma_{\geq 2}(p_{Tcut}) + \sigma_{\geq 2}(p_{off}, p_{Tcut})$$

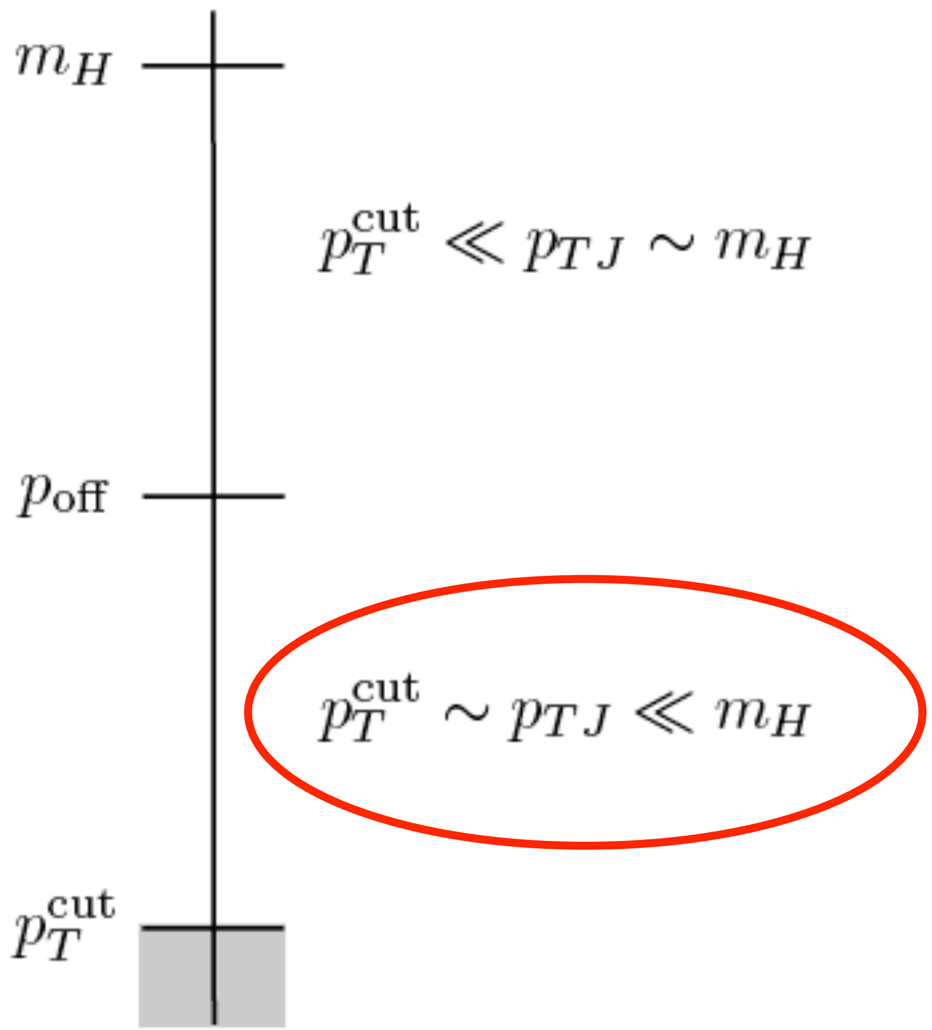
- This is an identity if both side are computed to the same order in α_s
- We can resum the jet-veto logs in the 0-jet terms, but not the 2-jet ones
- If $\Delta\sigma_0 \gg \Delta\sigma_{\geq 2}$, we can RG-improve the 0-jet terms on the RHS, and this constitutes an improvement of the low-p_T 1-jet bin

The one-jet bin: low-p_T

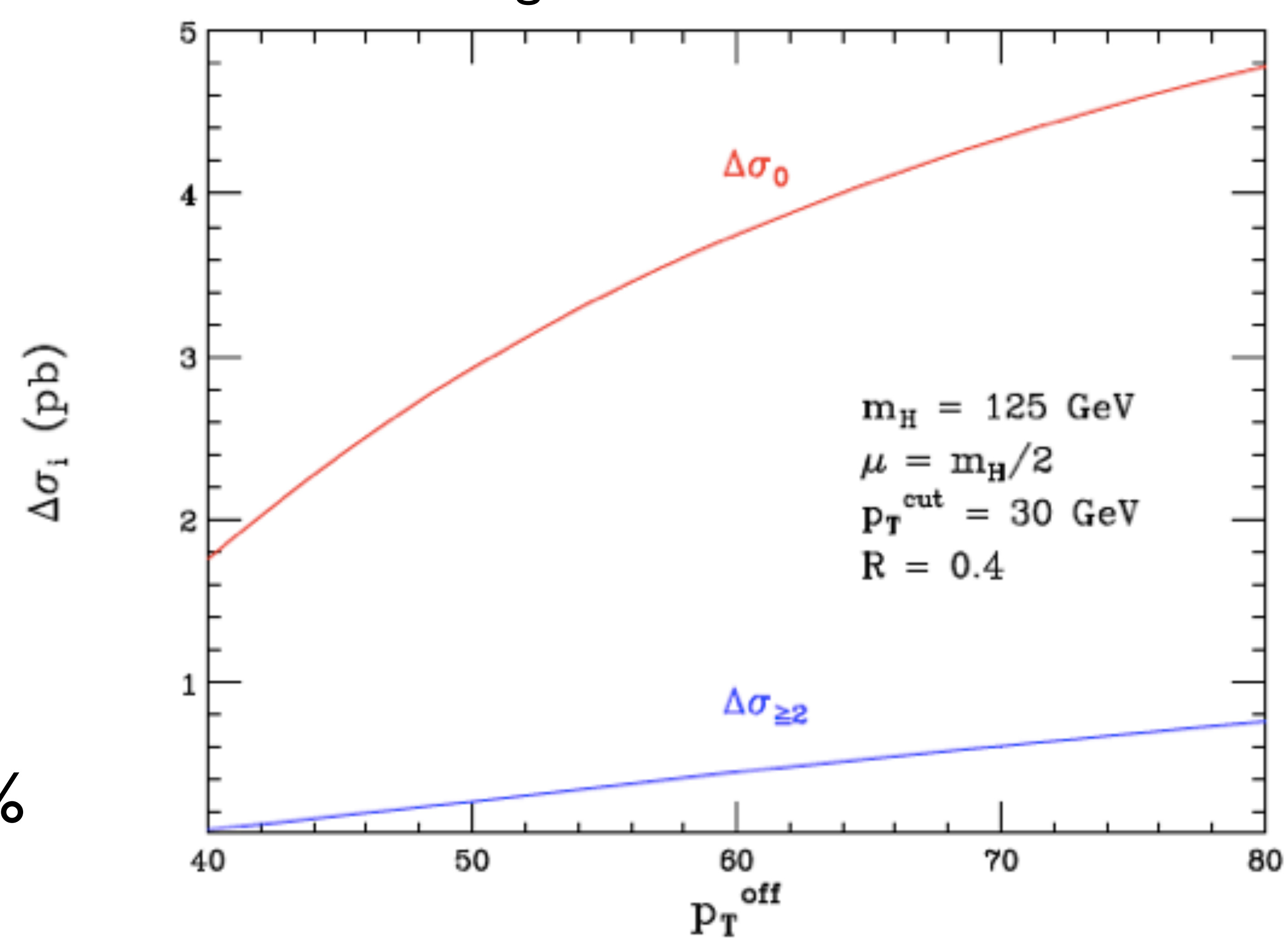
- We can indirectly sum the low-p_T one-jet region in the following way
- Cross section of interest: $\sigma_1(p_{off}, p_{Tcut}; p_{Tcut})$

$$\sigma_1(p_{off}, p_{Tcut}; p_{Tcut}) = \sigma_0(p_{off}) - \sigma_0(p_{Tcut})$$

$$-\sigma_{\geq 2}(p_{Tcut}) + \sigma_{\geq 2}(p_{off}, p_{Tcut})$$

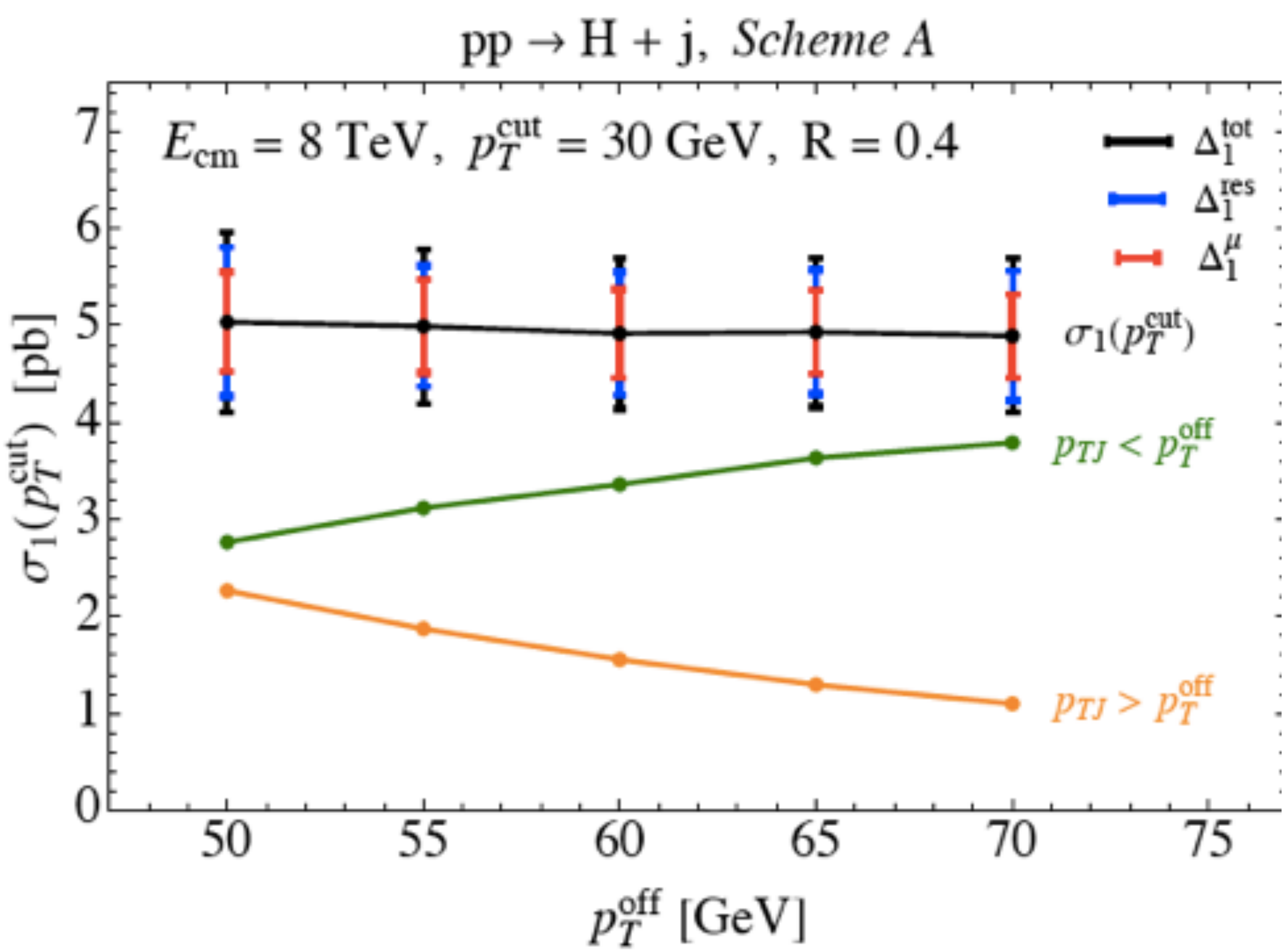


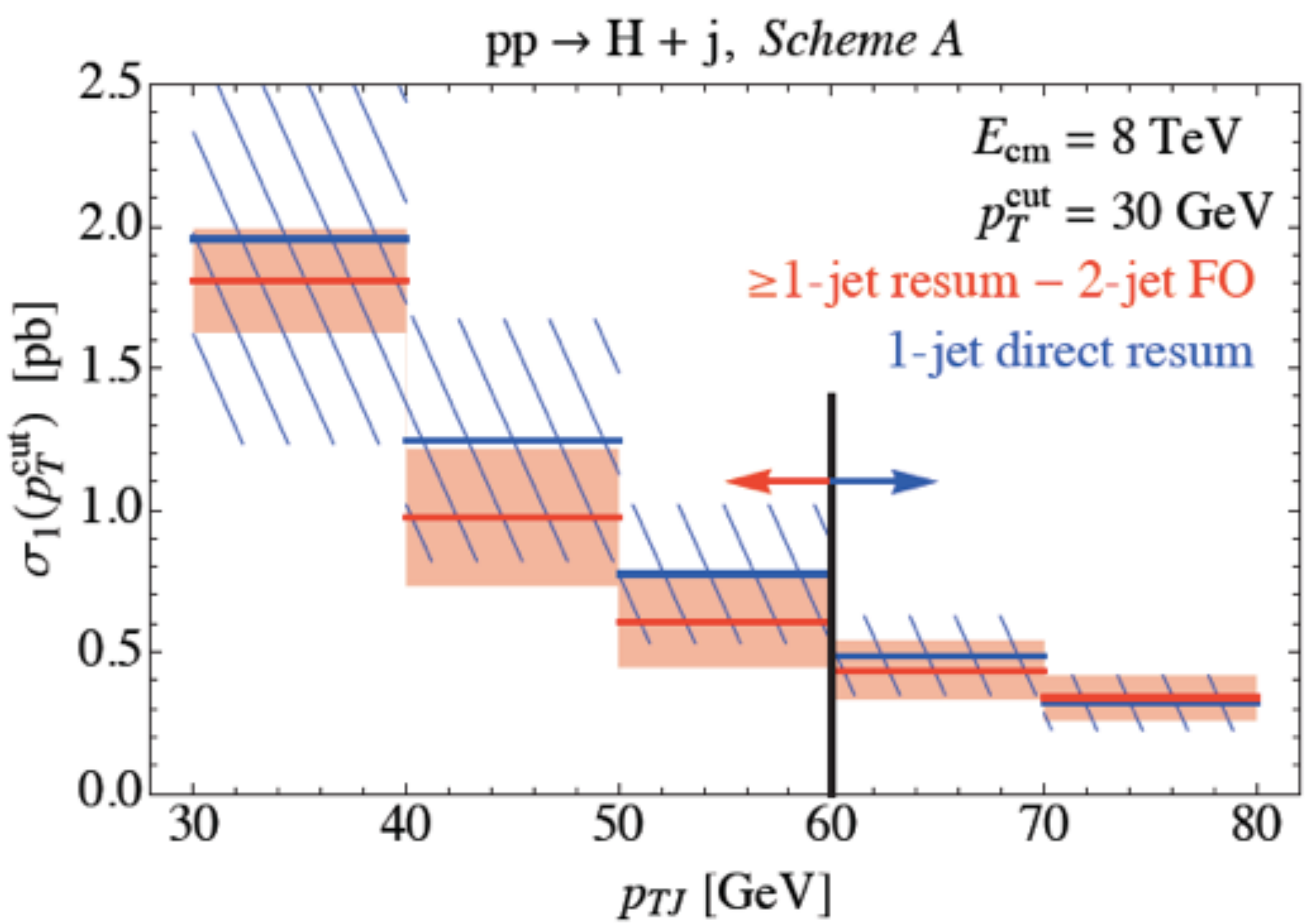
Boughezal et al., 1312.4535



- The two-jet pieces are a small fraction of the one-jet rate, 10% or less

Checks of low-p_T indirect resummation

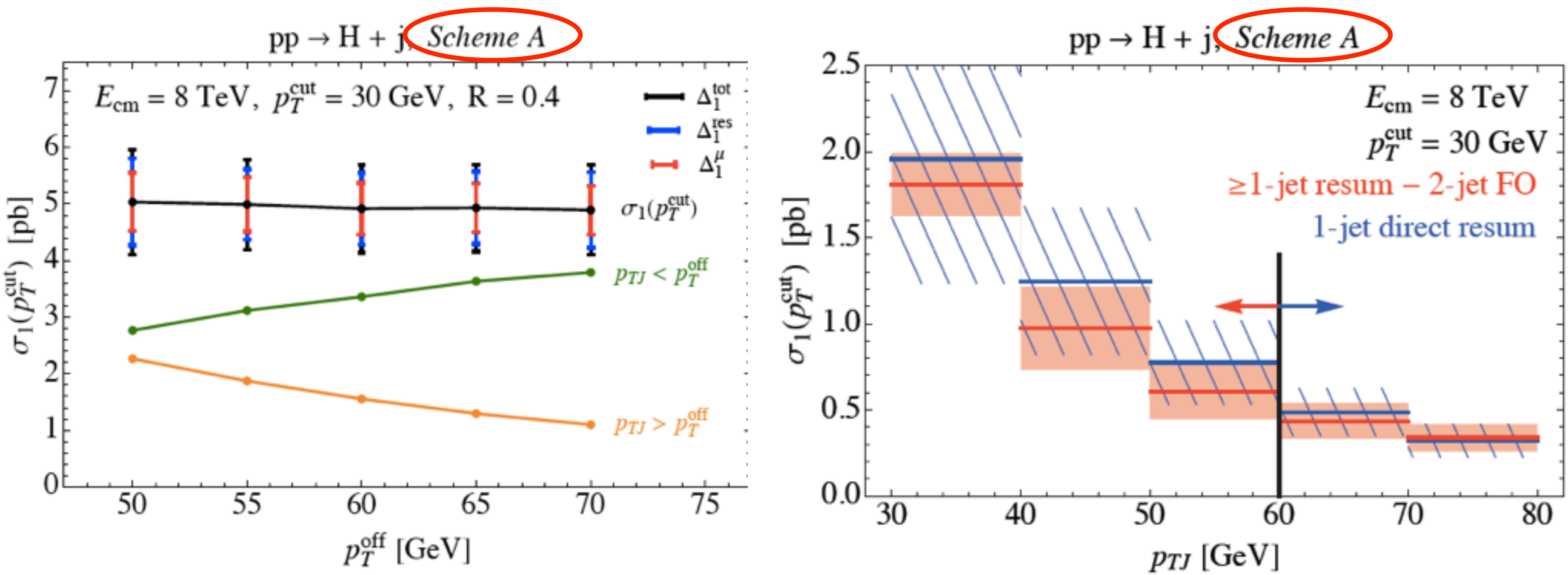




- Can check that the total 1-jet rate is insensitive to the choice of p_{off}
- Can check that the jet p_T spectrum is smooth across p_{off}, well within estimated errors

Boughezal et al., 1312.4535

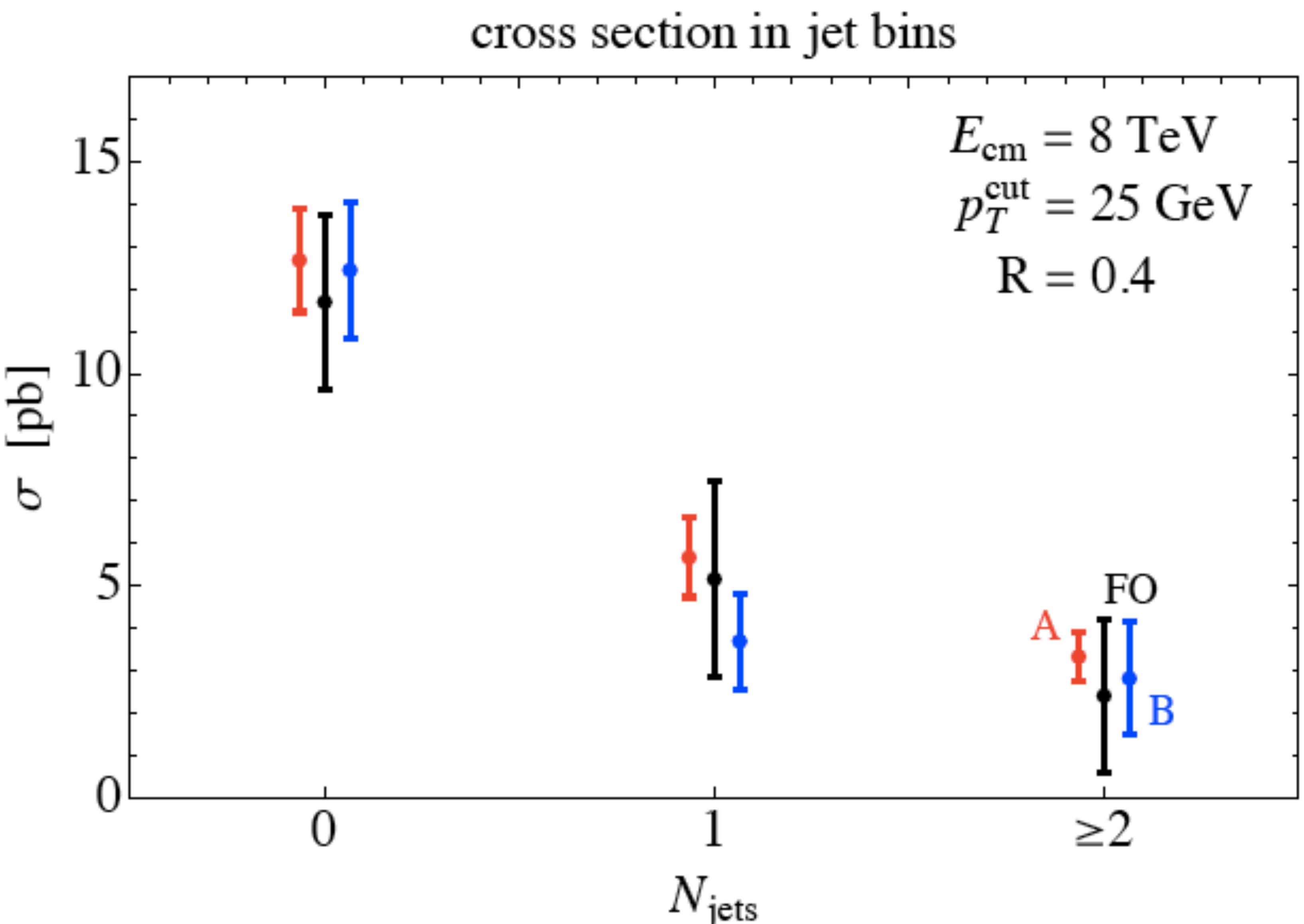
Checks of low-p_T indirect resummation



• *Scheme A*: use of an imaginary matching scale for the 0-jet cross section ("π^2 resummation), and the NNLO hard function for H+jet. Leads to a marked improvement in the matching shown above

Boughezal et al., 1312.4535

Numerical predictions for LHC



- Significant improvements in all three jet bins used in the experimental analyses (also true in *Scheme B* without imaginary matching scale)

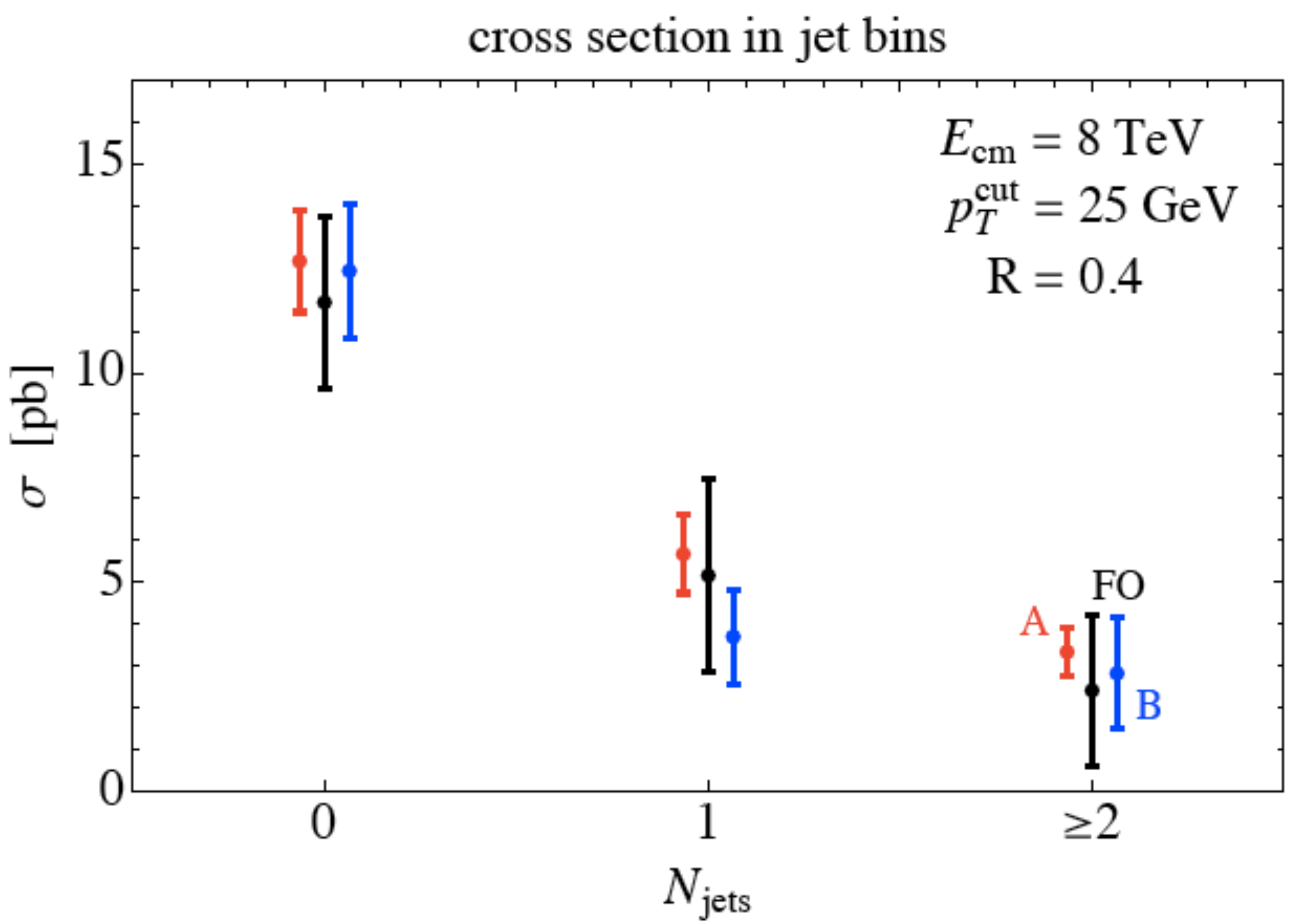
Change in the covariance matrix $C(\sigma_0,\sigma_1,\sigma_{\geq 2})$:

fixed-order ⟹ RG-improved

$$\begin{pmatrix} 4.24 & -1.99 & 0 \\ -1.99 & 5.23 & -3.24 \\ 0 & -3.24 & 3.24 \end{pmatrix} \text{pb}^2 \Rightarrow \begin{pmatrix} 1.49 & -0.39 & 0.20 \\ -0.39 & 0.88 & -0.04 \\ 0.20 & -0.04 & 0.32 \end{pmatrix} \text{pb}^2$$

Boughezal et al., 1312.4535

Numerical predictions for LHC



- ATLAS gives all information necessary to translate the improved covariance matrix into an improved signal-strength measurement

$(\Delta\mu/\mu)_{FO} = 13.3\%$

$(\Delta\mu/\mu)_{RG} = 6.9\%$

- Fixed-order result consistent with ATLAS finding
- Nearly a factor of 2 reduction in theory uncertainty in the WW channel!

Boughezal et al., 1312.4535

Conclusions

- Theoretical uncertainties are poised to become the limiting factor in our understanding of the Higgs sector during LHC Run II
- We now have a framework for resummation of large jet-veto logarithms for the entire 0+1-jet analysis for the WW final state
- This improvement leads to nearly a factor of two reduction on the theoretical uncertainty in the signal strength
- This will greatly impact our ability to tell whether the discovered Higgs particle is indeed that predicted by the Standard Model, or something else instead