Theory Uncertainties for Higgs Searches using Jet Bins

Iain Stewart
MIT

LBL Higgs Jamboree, Oct.2011

Based On:

arXiv:1107.2117 I.S. & F. Tackmann

(input to LHC Higgs Xsec working group for summer 2011 recommendations, “BNL accord”)

arXiv:1012.4480 + C.Berger, C.Marcantonini, W.Waalewijn

Outline

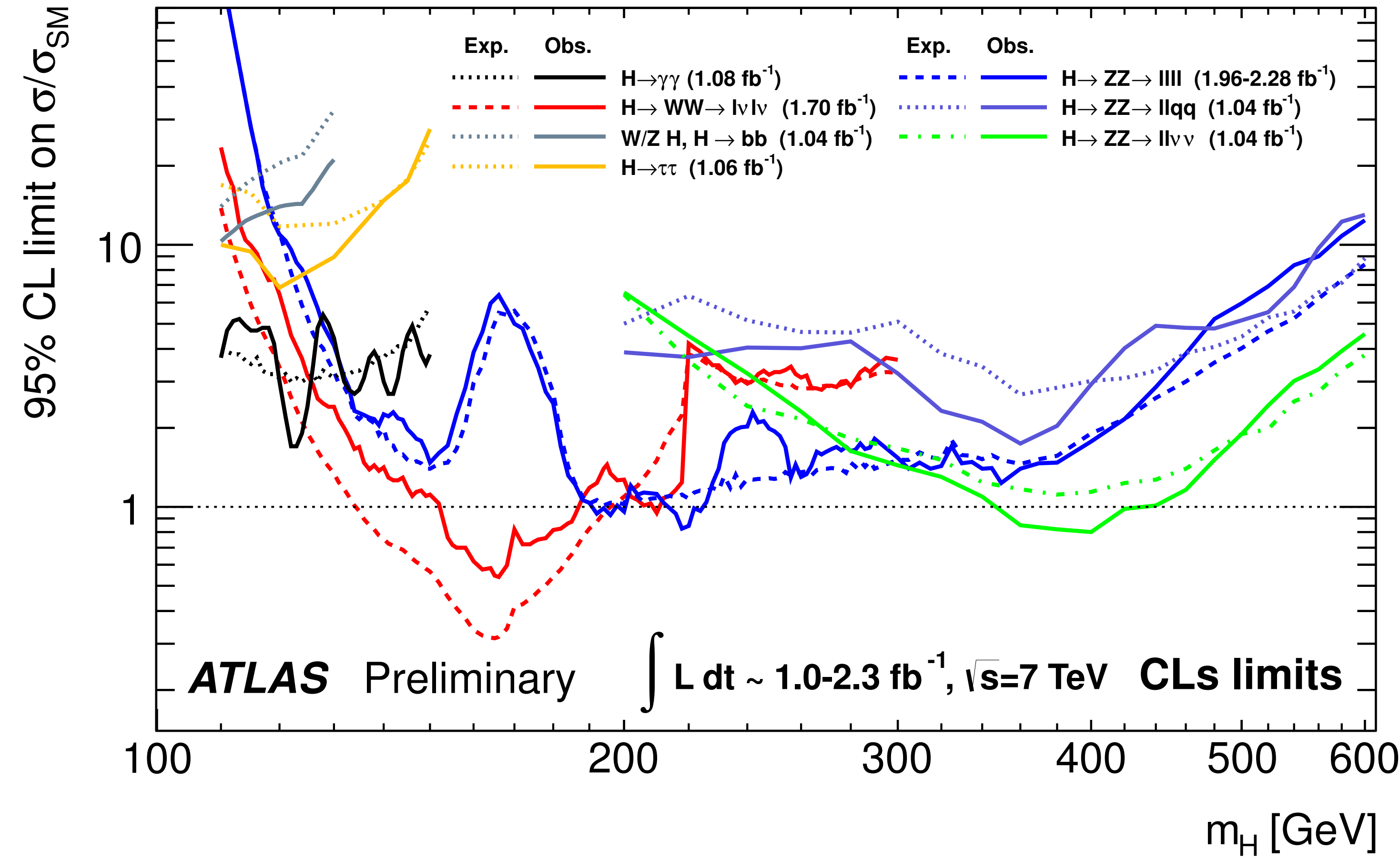
- Introduction: Jet-bins in Higgs Searches
- Theory Uncertainties & Correlations
- Using Fixed Order Calculations for Jet Bins
- Exploiting Log Resummation for Jet Bins

Use jet bins to maximize sensitivity

- backgrounds vary with # of jets

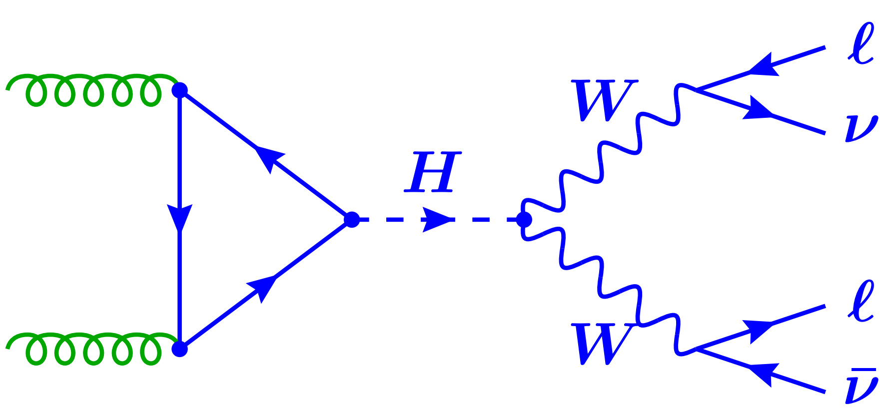
$H \to WW \to \ell\nu\ell\bar{\nu}$ $H \to \tau\tau$

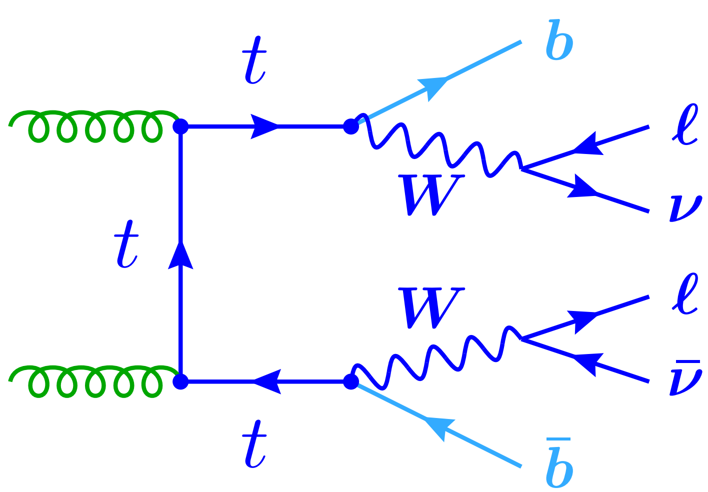
$H \to WW \to \ell\nu jj$ $H \to \gamma\gamma$



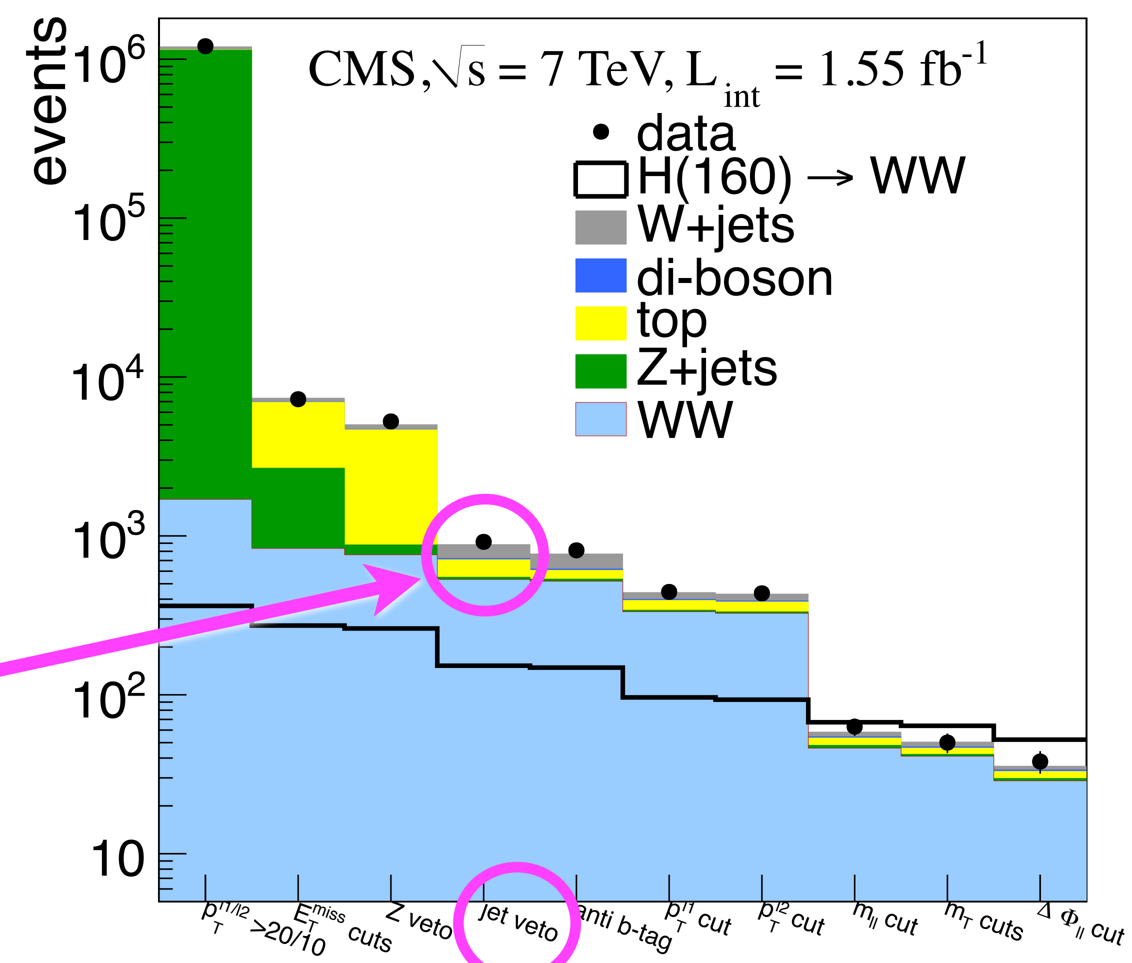
eg. large top background in

$$H \to WW$$





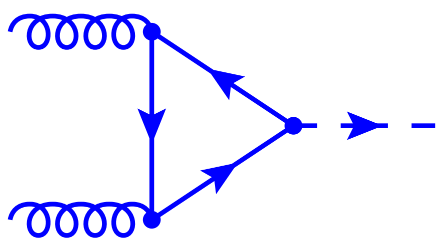
o-jet bin vetoes b-jets



Gluon fusion: $gg \to H$

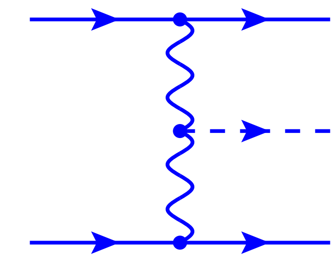
Vector-boson fusion: $qq \to qqH$

σ_{total} to NNLO (see Sally's talk) σ_{total} to NNLO*



PDF+α_s uncertainty

(see Joey's talk)



perturbative uncertainty:

$\sim 2\%$

$\Delta_{\text{total}} \sim 8\%$

perturbative uncertainties

exclusive jet cross sections

$pp \to H + 0\,\text{jets} \;\to\; \sigma_0 \pm \Delta_0$

$pp \to H + 1\,\text{jet} \;\to\; \sigma_1 \pm \Delta_1$

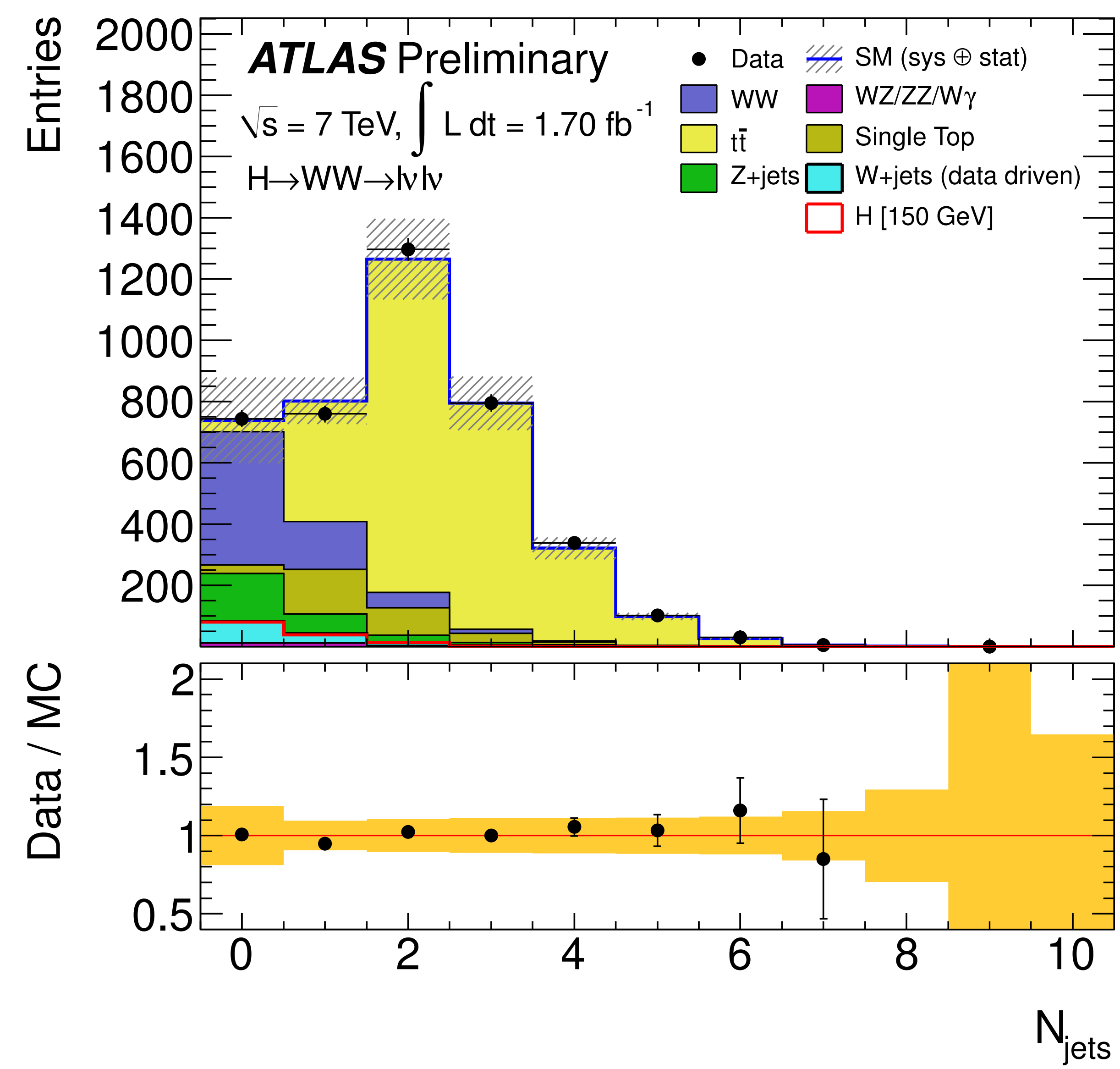
$pp \to H + 2\,\text{jets} \;\to\; \sigma_2 \pm \Delta_2$

$\vdots$

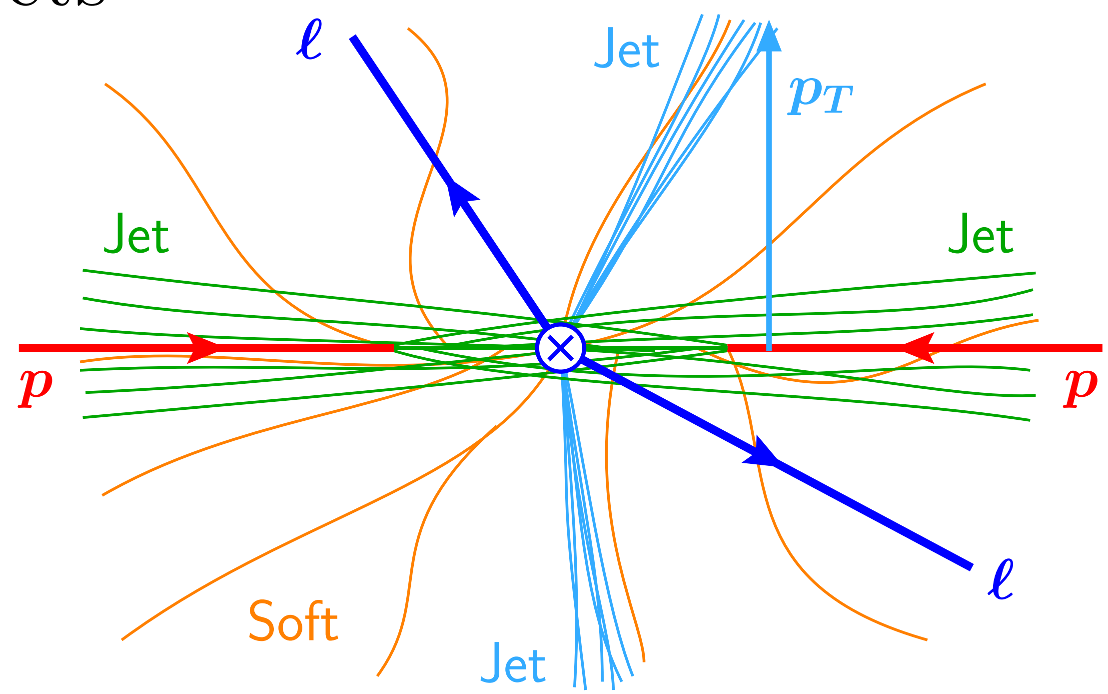
sum is $\to$ $\sigma_{\text{total}} \pm \Delta_{\text{total}}$

My talk: $\Delta_i = ?$

correlations=?



Vetoing Jets : eg. $H \to WW + 0$ jets

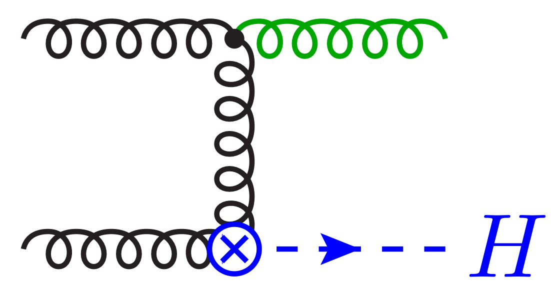


Search for jets and require $p_T^{\mathbf{jet}} < p_T^{\mathbf{cut}}$

Tevatron: $p_T^{\mathbf{cut}} \simeq \mathbf{20\,GeV}$

LHC: $p_T^{\mathbf{cut}} \simeq \mathbf{25\,GeV}$

Jet Veto changes form of perturbation theory



Even if hard signal process $gg \to H$ contains no jets, jet veto affects cross section by restricting ISR

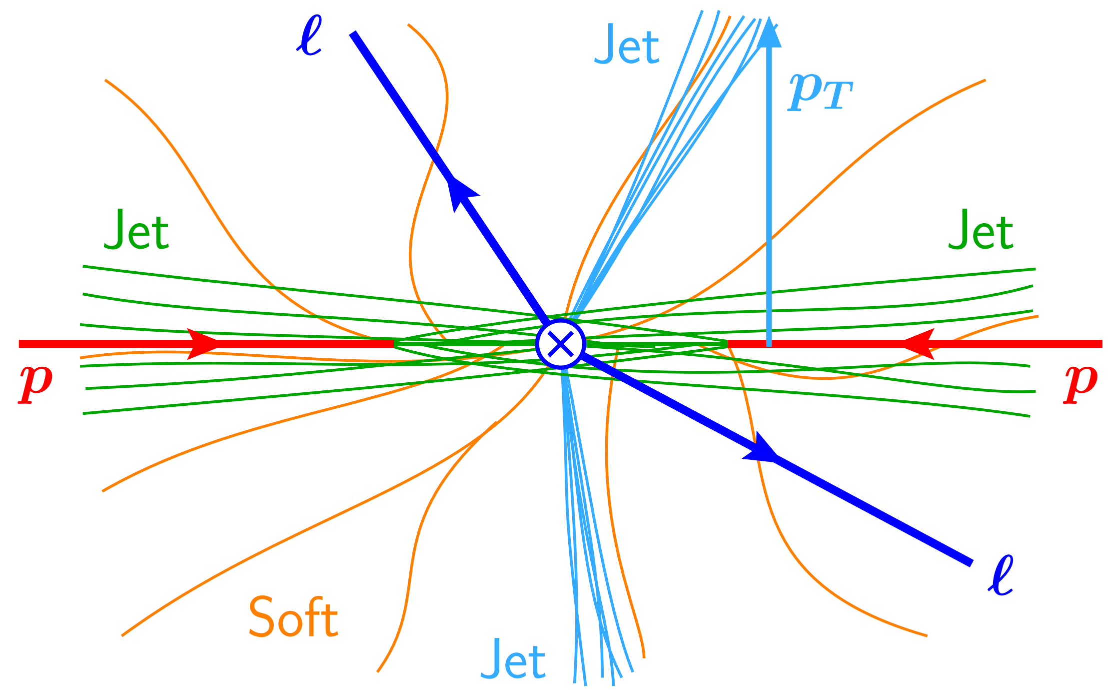
t-channel singularities produce Sudakov double logarithms

$$\sigma_0 = \boldsymbol{\sigma}(p_T^{\mathbf{cut}}) = \boldsymbol{\sigma}_B\left(\mathbf{1} - \frac{\mathbf{3}\boldsymbol{\alpha}_s}{\boldsymbol{\pi}}\,\mathbf{2}\ln^2\frac{p_T^{\mathbf{cut}}}{m_H} + \cdots\right)$$

$\Rightarrow$ Perturbative corrections get large at small $p_T^{\mathbf{cut}} \ll m_H$

Vetoing Jets :

eg. $H \to WW + 0$ jets



Search for jets and require $p_T^{\text{jet}} < p_T^{\text{cut}}$

Tevatron: $p_T^{\text{cut}} \simeq 20\,\text{GeV}$

LHC: $p_T^{\text{cut}} \simeq 25\,\text{GeV}$

Jet Veto changes form of perturbation theory

$$
\begin{aligned}
\sigma_0 \sim \ 1 \quad &+ \alpha_s L^2 &+ \alpha_s^2 L^4 \quad &+ \dots \\
&+ \alpha_s L &+ \alpha_s^2 L^3 \quad &+ \dots \\
&+ \alpha_s &+ \alpha_s^2 L^2 \quad &+ \dots \\
& &+ \alpha_s^2 L \quad &+ \dots \\
& &+ \alpha_s^2 \quad &+ \dots
\end{aligned}
$$

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

$$\boldsymbol{\sigma_{\text{total}} = \underbrace{\int_0^{p_T^{\text{cut}}} dp_T \frac{d\sigma}{dp_T}}_{\sigma_0(p_T^{\text{cut}})} + \underbrace{\int_{p_T^{\text{cut}}} dp_T \frac{d\sigma}{dp_T}}_{\sigma_{\geq 1}(p_T^{\text{cut}})}}$$

inclusive jet cross section
$pp \to H + \geq 1\,\text{jet}$

- Added uncertainty Δ_{cut} from our ability to predict p_T^{cut} dependence ("large logs" or "particle migration between bins")

- Cancels when adding σ_0 and $\sigma_{\geq 1}$

  anti-correlated

$$\begin{pmatrix} \Delta^2_{\text{cut}} & -\Delta^2_{\text{cut}} \\ -\Delta^2_{\text{cut}} & \Delta^2_{\text{cut}} \end{pmatrix}$$

- Extension to multiple exclusive jet bins:

$$\sigma_0(p_T^{\text{cut}}), \sigma_1(p_T^{\text{cut}}, p_{T2}^{\text{cut}}), \sigma_2(p_{T2}^{\text{cut}}, p_{T3}^{\text{cut}}), \ldots$$

How do we compute Δ_{cut} ?

(A) "Direct Exclusive Scale Variation?" vary μ_F, μ_R in σ_i's $\longrightarrow \Delta_i$

consider $\sigma_0(\mu)$, vary $\mu \in [m_H/2, 2m_H]$ to get Δ_0 etc.

- uncertainties here are 100% correlated so that

  $\sigma_{\rm total} = \sigma_0 + \sigma_1 + \ldots$ gets back its uncertainty $\Delta_{\rm total}$

- does not account for $\Delta_{\rm cut}$
- due to numerical cancellations can underestimate uncertainties

$$\boldsymbol{\sigma_{\rm total} \simeq \sigma_B\big[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]}$$ large K-factor

$$\boldsymbol{\sigma_{\geq 1}(p_T^{\rm cut}) \simeq \sigma_B\big[\alpha_s(L^2+L+1) + \alpha_s^2(L^4+L^3+L^2+L+1) + \mathcal{O}(\alpha_s^3 L^6)\big]}$$ large logs

$\boldsymbol{L = \ln(p_T^{\rm cut}/m_H)}$

large cancellation for $\boldsymbol{\sigma_0(p_T^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p_T^{\rm cut})}$
for some range of $p_T^{\rm cut}$

For example, at LHC for $m_H = 165\,\mathrm{GeV}$ and $E_{\mathrm{cm}} = 7\,\mathrm{TeV}$

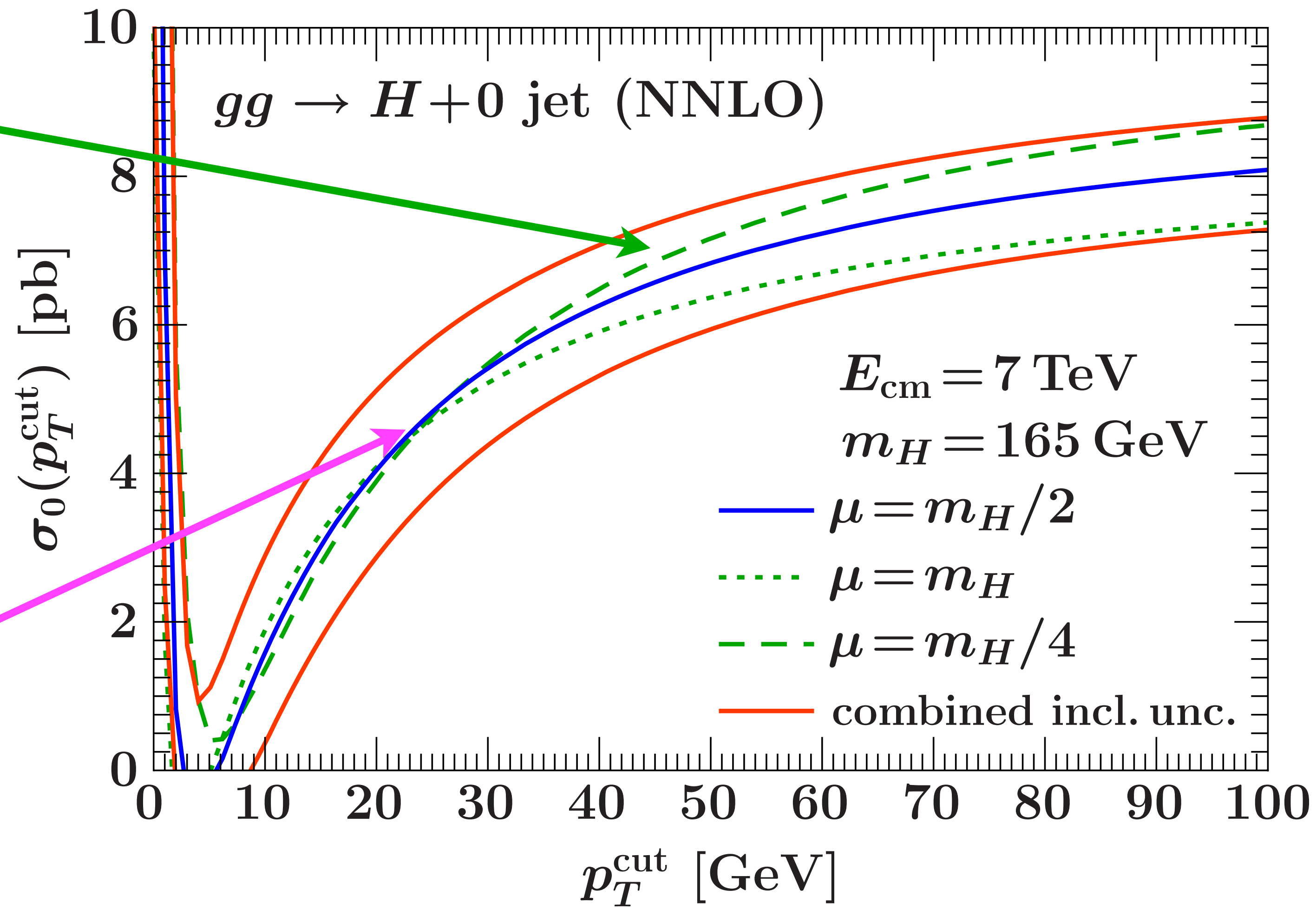
$$\sigma_{\mathrm{total}} = (3.32\,\mathrm{pb})\big[1 + 9.5\,\alpha_s + 35\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]$$

$$\sigma_{\geq 1}(p_T^{\mathrm{jet}} \geq 30\,\mathrm{GeV}) = (3.32\,\mathrm{pb})\big[5.1\,\alpha_s + 28\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]\,.$$

Direct Exclusive Scale Variation:

green lines

cancellation



All plots: MCFM for spectra, FeHiP for NNLO cross section, MSTW pdfs, anti-kT jets with R=0.5

(B) "Combined Inclusive Scale Variation"

IS, Tackmann, arXiv:1107.2117

- Treat inclusive cross-section uncertainties as independent

$$\Delta_{\rm total}, \Delta_{\geq 1}, \Delta_{\geq 2}, \ldots$$

- For $p_T^{\rm cut}$ uncertainty use: $\Delta_{\rm cut} = \Delta_{\geq 1}$

Propagate errors to get uncertainty for $\sigma_0(p_T^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p_T^{\rm cut})$

eg. $\{\sigma_0, \sigma_{\geq 1}\}$ $\begin{pmatrix} \Delta_{\geq 1}^2 + \Delta_{\rm total}^2 & -\Delta_{\geq 1}^2 \\ -\Delta_{\geq 1}^2 & \Delta_{\geq 1}^2 \end{pmatrix}$ has anti-correlation

$$\boldsymbol{\sigma_{\rm total} \simeq \sigma_B \big[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]}$$ large K-factor

$$\boldsymbol{\sigma_{\geq 1}(p_T^{\rm cut}) \simeq \sigma_B \big[\alpha_s(L^2+L+1) + \alpha_s^2(L^4+L^3+L^2+L+1) + \mathcal{O}(\alpha_s^3 L^6)\big]}$$ large logs

$$L = \ln(p_T^{\rm cut}/m_H)$$

treated as independent series

estimate for logs obtained from $\sigma_{\geq 1}(p_T^{\rm cut})$

For example, at LHC for $m_H = 165\,\mathrm{GeV}$ and $E_{\mathrm{cm}} = 7\,\mathrm{TeV}$

$$\sigma_{\mathrm{total}} = (3.32\,\mathrm{pb})\big[1 + 9.5\,\alpha_s + 35\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]$$

$$\sigma_{\geq 1}(p_T^{\mathrm{jet}} \geq 30\,\mathrm{GeV}) = (3.32\,\mathrm{pb})\big[5.1\,\alpha_s + 28\,\alpha_s^2 + \mathcal{O}(\alpha_s^3)\big]\,.$$

Direct Exclusive Scale Variation

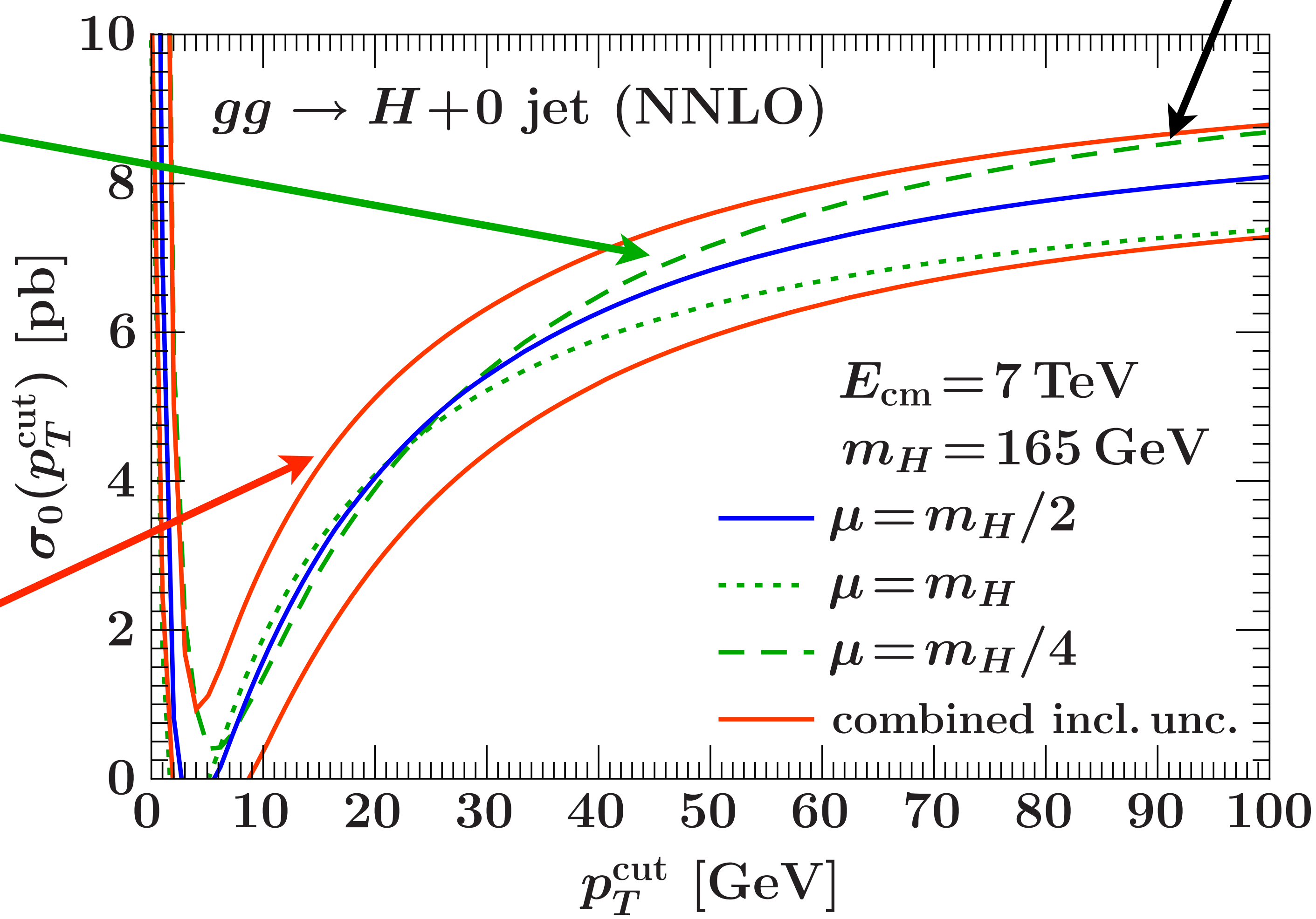
green lines

Combined Inclusive Scale Variation

$$\Delta_0^2 = \Delta_{\mathrm{total}}^2 + \Delta_{\geq 1}^2$$

red lines

agree when cut is turned off



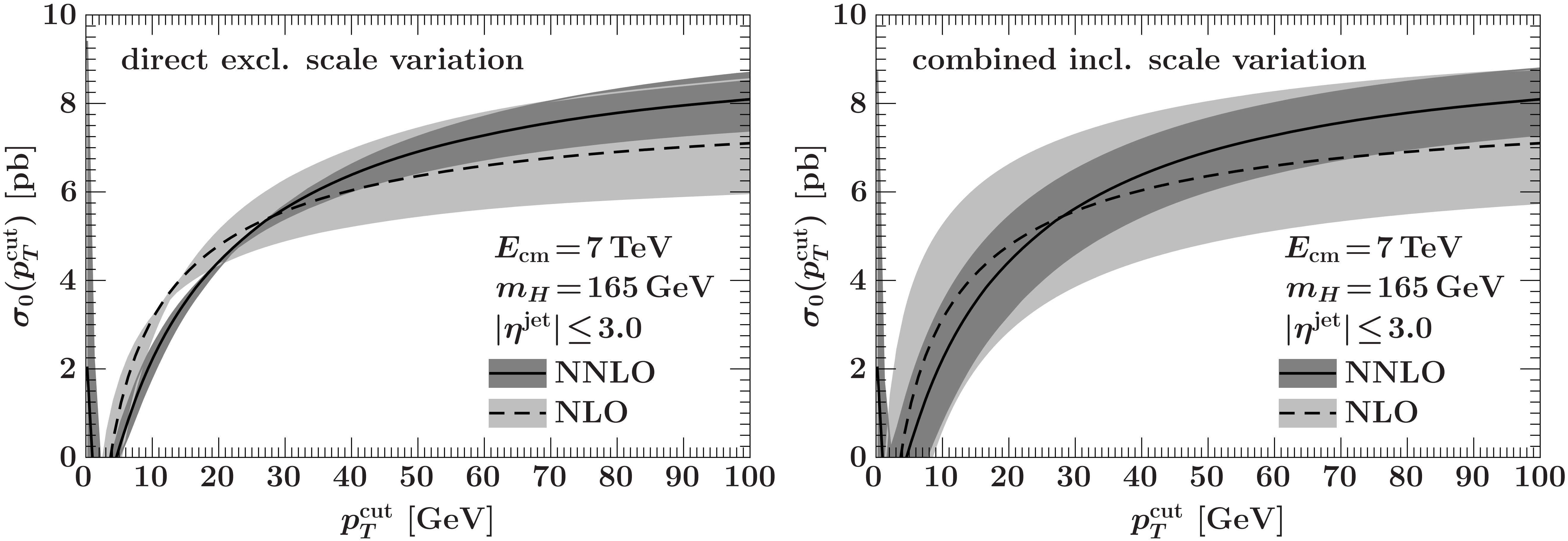
these plots only vary $\mu_R = \mu_F$ (varying μ_F alone is quite small for Higgs)

Quite generic: same pattern at Tevatron

similar plots if we vary rapidity cuts

similar plots for other processes

Convergence (NLO to NNLO)

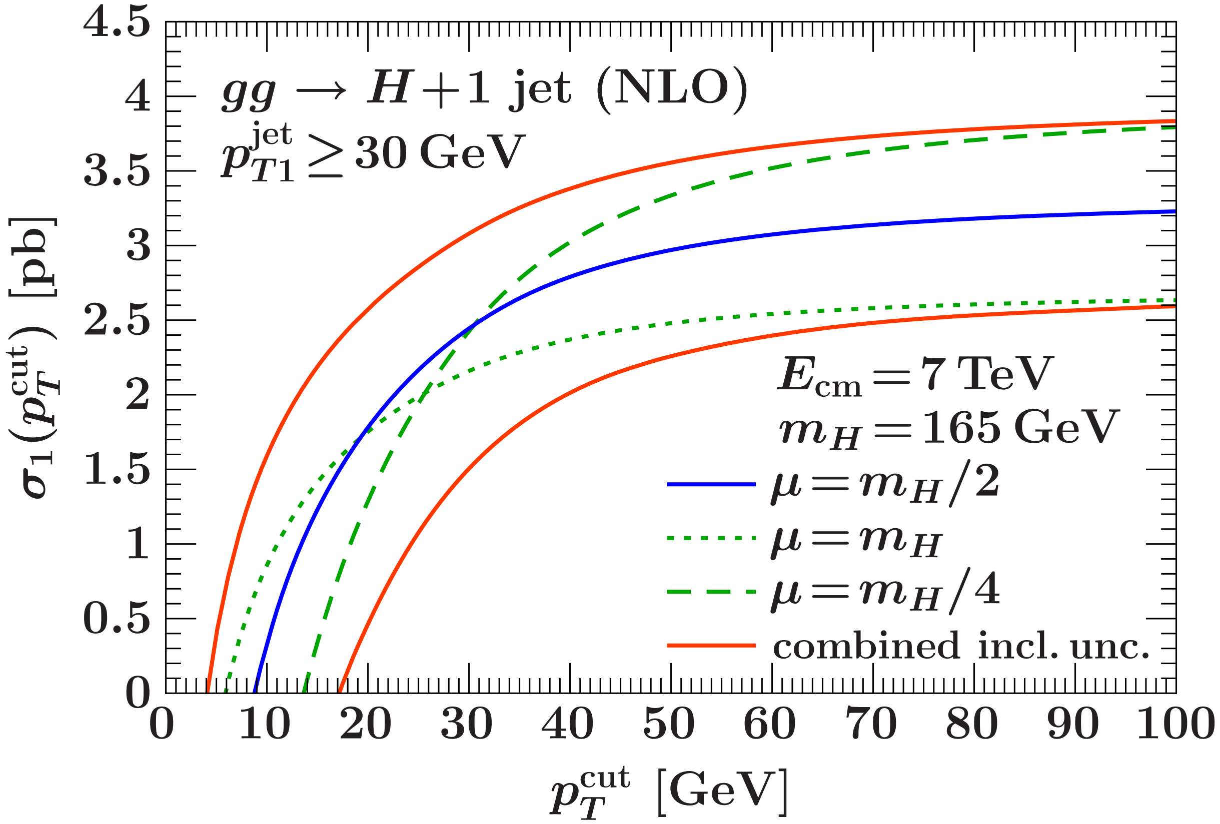


at $p_T^{\rm cut} = 30\,\mathrm{GeV}$ and NNLO

$$\delta(\sigma_{\rm total}) = 8.6\%$$
$$\delta(\sigma_{\geq 1}) = 19\%$$
$$\delta(\sigma_0) = 2.4\%$$
$$\rho(\sigma_0, \sigma_{\geq 1}) = +100\%$$

$$\delta(\sigma_{\rm total}) = 8.6\%$$
$$\delta(\sigma_{\geq 1}) = 19\%$$
$$\delta(\sigma_0) = 18\%$$
$$\rho(\sigma_0, \sigma_{\geq 1}) = -64\%$$

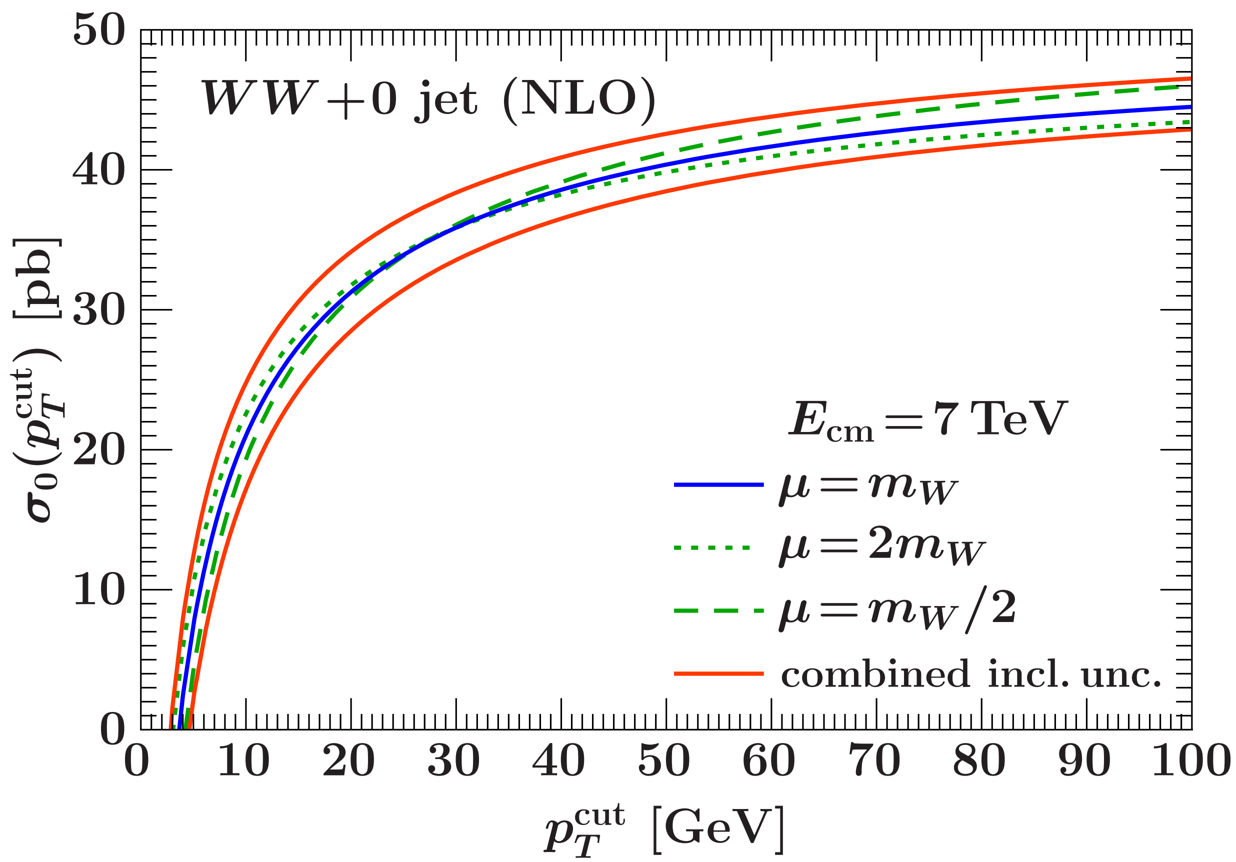
other examples



$\sigma_1(\mu)$

$\Delta_{\geq 1}$, $\Delta_{\geq 2}$ independent

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



uncertainties for background processes in jet-bins should be estimated the same way

eg. Numbers for $\{\sigma_{\rm total}, \sigma_0, \sigma_1\}$

$$p_T^{\rm jet} \geq 30\,{\rm GeV} \qquad p_{T2}^{\rm jet} \geq 30\,{\rm GeV}$$

$$\begin{pmatrix} \Delta^2_{\rm total} & \Delta^2_{\rm total} & 0 \\ \Delta^2_{\rm total} & \Delta^2_{\rm total} + \Delta^2_{\geq 1} & -\Delta^2_{\geq 1} \\ 0 & -\Delta^2_{\geq 1} & \Delta^2_{\geq 1} + \Delta^2_{\geq 2} \end{pmatrix}$$

start with:

$$\sigma_{\rm total} = (8.70 \pm 0.75)\,{\rm pb} \qquad 8.6\%$$
$$\sigma_{\geq 1} = (3.29 \pm 0.62)\,{\rm pb} \qquad 18.8\%$$
$$\sigma_{\geq 2} = (0.85 \pm 0.49)\,{\rm pb} \qquad 57\%$$

$$\sigma_0 = \sigma_{\rm tot} - \sigma_{\geq 1}$$
$$\sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}$$

propagate to get:

$$\delta(\sigma_0) = 18\%$$
$$\rho(\sigma_0, \sigma_{\rm total}) = 0.77$$
$$\rho(\sigma_0, \sigma_1) = -0.50$$

$$\delta(\sigma_1) = 32\%$$
$$\rho(\sigma_1, \sigma_{\geq 2}) = -0.62$$

or consider jet fractions:

$$f_0 = \frac{\sigma_0}{\sigma_{\rm total}}$$
$$f_1 = \frac{\sigma_1}{\sigma_{\rm total}}$$

$$\delta(f_0) = 13\%$$
$$\rho(f_0, \sigma_{\rm total}) = 0.42$$
$$\rho(f_0, f_1) = -0.80$$

$$\delta(f_1) = 33\%$$
$$\rho(f_1, \sigma_{\rm total}) = -0.26$$

(C) Use Resummed Predictions to get Uncertainties

this will allow us to include both types of uncertainties (correlated & uncorrelated) from methods (A) and (B)

Jet Vetoes

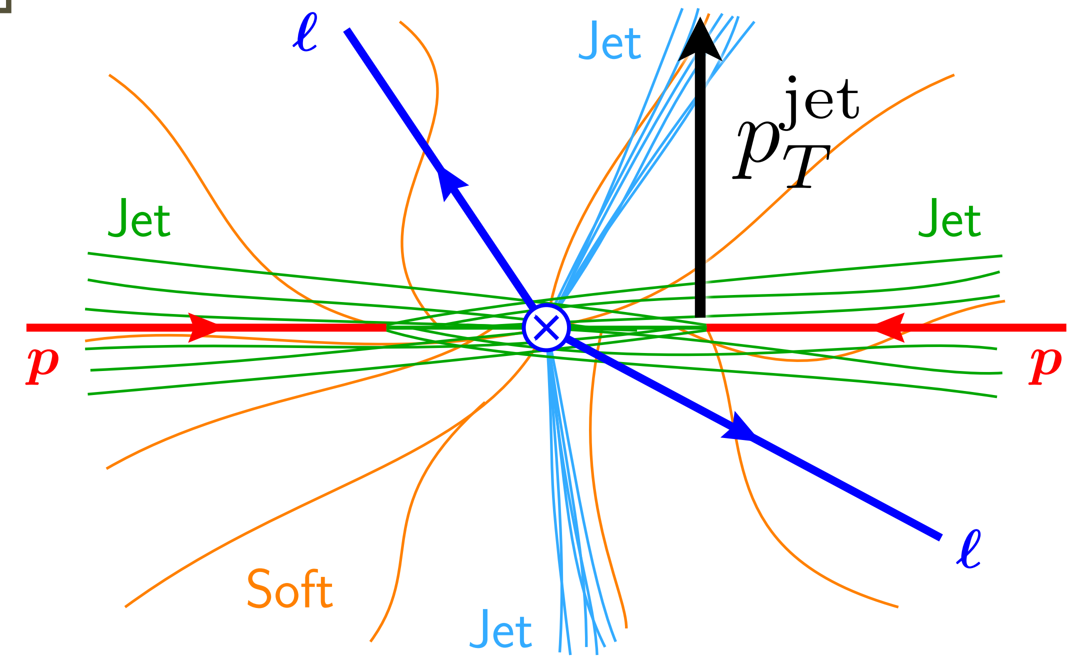
Conventional: Jet Algorithm

- Search for jets and require $p_T^{\rm jet} < p_T^{\rm cut}$

  Tevatron: $p_T^{\rm cut} \simeq 20\,{\rm GeV}$

  LHC: $p_T^{\rm cut} \simeq 25\,{\rm GeV}$

- Complicated phase-space restrictions



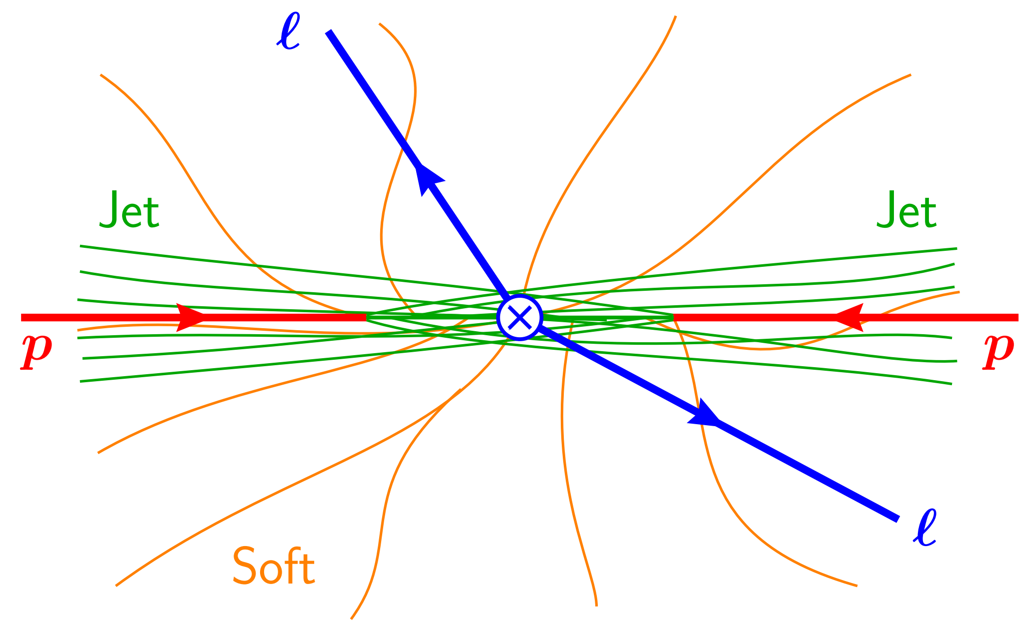
Alternative: Event Shape

- Measure beam thrust for each event

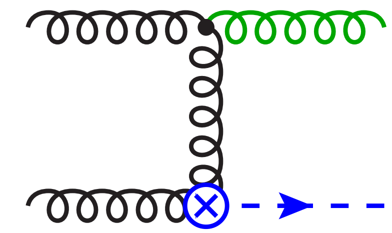
$$\mathcal{T}_{\rm cm} = \sum_k |\vec{p}_{kT}| e^{-|\eta_k|} = \sum_k (E_k - |p_k^z|)$$

and require $\mathcal{T}_{\rm cm} < \mathcal{T}_{\rm cm}^{\rm cut}$

- Nice for higher order calculations



Jet veto restricts ISR, gives double logs



$$L = \ln \frac{p_T^{\rm cut}}{m_H} \quad \text{or} \quad L = \ln \frac{\mathcal{T}_{\rm cm}^{\rm cut}}{m_H}$$

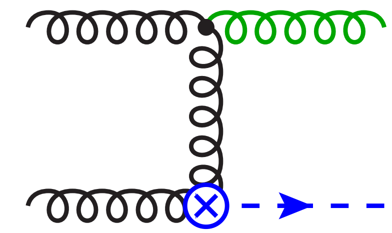
$$\begin{array}{lllllll}
 & \text{LO} & \text{NLO} & & & & \\
\sigma_{0\text{-jet}} = & 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \ldots & \text{LL} \\
 & & + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \ldots & \\
 & & + \alpha_s n_1(p_T^{\rm cut}) & + \alpha_s^2 L^2 & + \alpha_s^3 L^4 & + \ldots & \\
 & & & + \alpha_s^2 L & + \alpha_s^3 L^3 & + \ldots & \\
 & & & + \alpha_s^2 n_2(p_T^{\rm cut}) & + \alpha_s^3 L^2 & + \ldots & \\
 & & & & + \alpha_s^3 L & + \ldots & \\
 & & & & + \alpha_s^3 & + \ldots &
\end{array}$$

Parton Shower

eg. Pythia is LL (+ tuning)

eg. MC@NLO is NLO+LL

Jet veto restricts ISR, gives double logs



$$L = \ln \frac{p_T^{\mathrm{cut}}}{m_H} \quad \text{or} \quad L = \ln \frac{\mathcal{T}_{\mathrm{cm}}^{\mathrm{cut}}}{m_H}$$

$$\begin{array}{lllllll}
 & \text{LO} & \text{NLO} & \text{NNLO} & & & \\
\sigma_{0\text{-jet}} = & 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \ldots & \text{LL} \\
 & & + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \ldots & \text{NLL} \\
 & & + \alpha_s n_1(p_T^{\mathrm{cut}}) & + \alpha_s^2 L^2 & + \alpha_s^3 L^4 & + \ldots & \\
 & & & + \alpha_s^2 L & + \alpha_s^3 L^3 & + \ldots & \text{NNLL} \\
 & & & + \alpha_s^2 n_2(p_T^{\mathrm{cut}}) & + \alpha_s^3 L^2 & + \ldots & \\
 & & & & + \alpha_s^3 L & + \ldots & \\
 & & & & + \alpha_s^3 & + \ldots &
\end{array}$$

Calculation:

NNLL + NNLO

Berger et.al.

two orders of summation
beyond LL shower programs

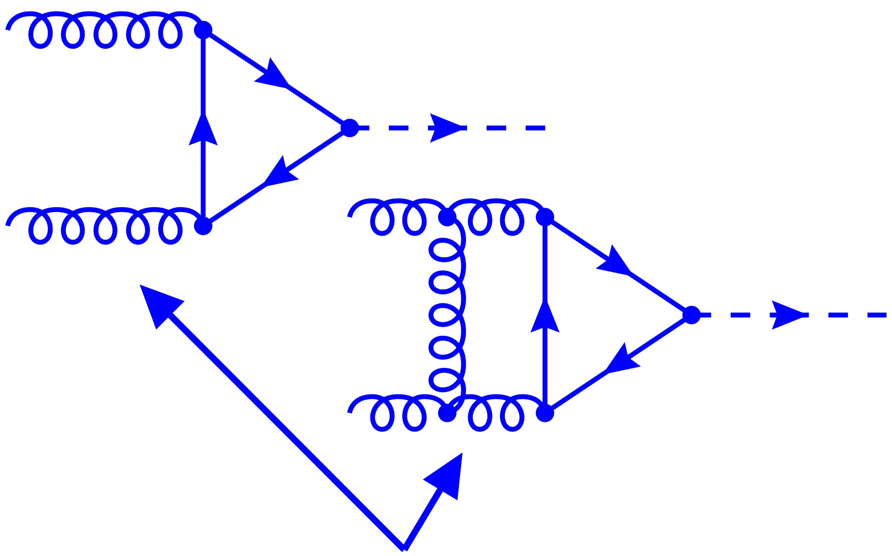
(C) Use Resummed Predictions to get Uncertainties

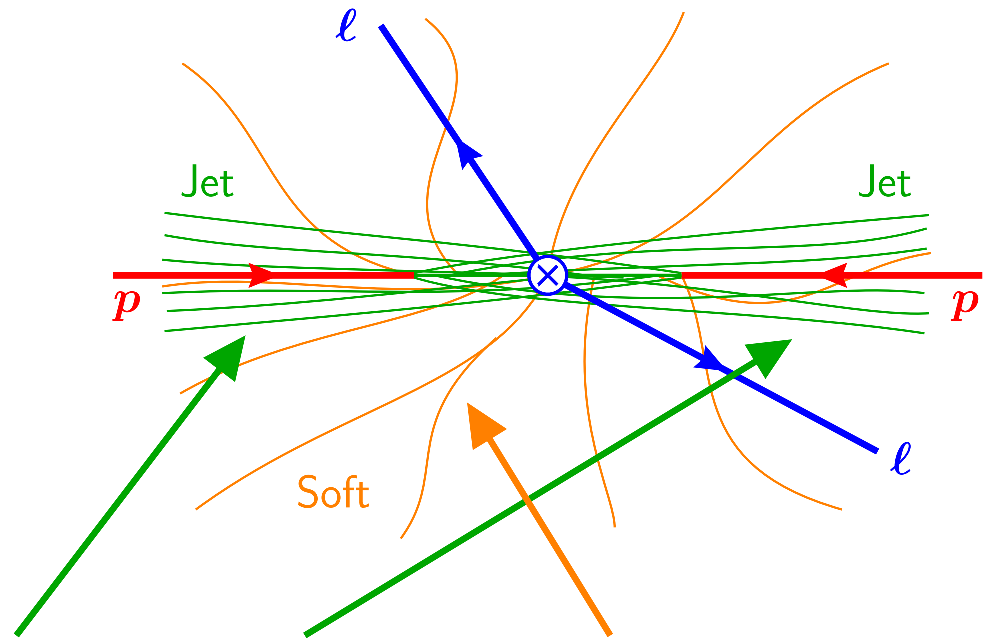
this will allow us to include both types of uncertainties (correlated & uncorrelated) from methods (A) and (B)

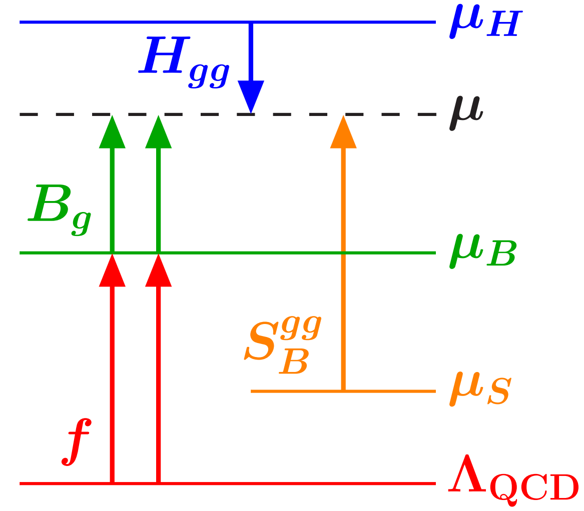
Idea:

- reweigh MC@NLO or POWHEG to NNLO for central values for p_T^{cut} (what you do now)
- resummed calculation has two sources of uncertainty, one is correlated with Δ_{total} , one gives Δ_{cut}
- given these as % errors for spectra in $\mathcal{T}_{\text{cm}}$, reweigh a MC sample to apply these errors for p_T^{cut}

NNLL + NNLO calculation







$$\frac{\mathrm{d}\sigma^{\mathrm{s}}}{\mathrm{d}\mathcal{T}_{\mathrm{cm}}} = H_{gg}(\mu) \int \mathrm{d}t_a \mathrm{d}t_b \, B_g(t_a, \mu)\, B_g(t_b, \mu)\, S_B^{gg}\Big(\mathcal{T}_{\mathrm{cm}} - \frac{t_a + t_b}{m_H}, \mu\Big)$$

$$B_i(t, x) = \int \frac{d\xi}{\xi} \mathcal{I}_{ij}(t, x/\xi)\; f_j(\xi)$$

Function	describes	at the scale
Hard H_{gg}	hard virtual radiation	$\lvert\mu_H\rvert \simeq m_H$
Beam B_g	virtual & real energetic ISR	$\mu_B \simeq \sqrt{\mathcal{T}_{\mathrm{cm}} m_H}$
Soft S_B^{gg}	virtual & real soft radiation	$\mu_S \simeq \mathcal{T}_{\mathrm{cm}}$

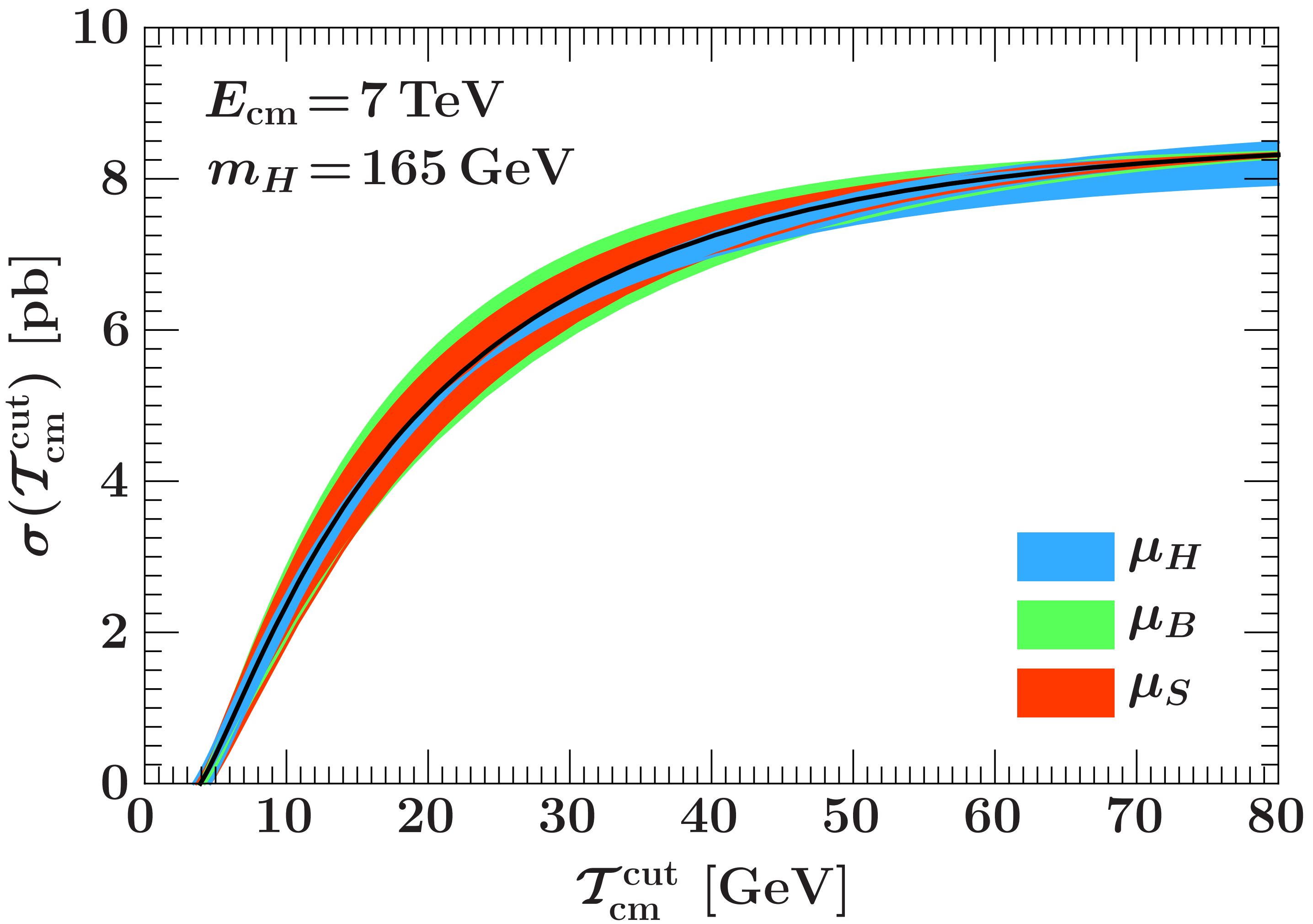
logs give sensitivity to smaller scales

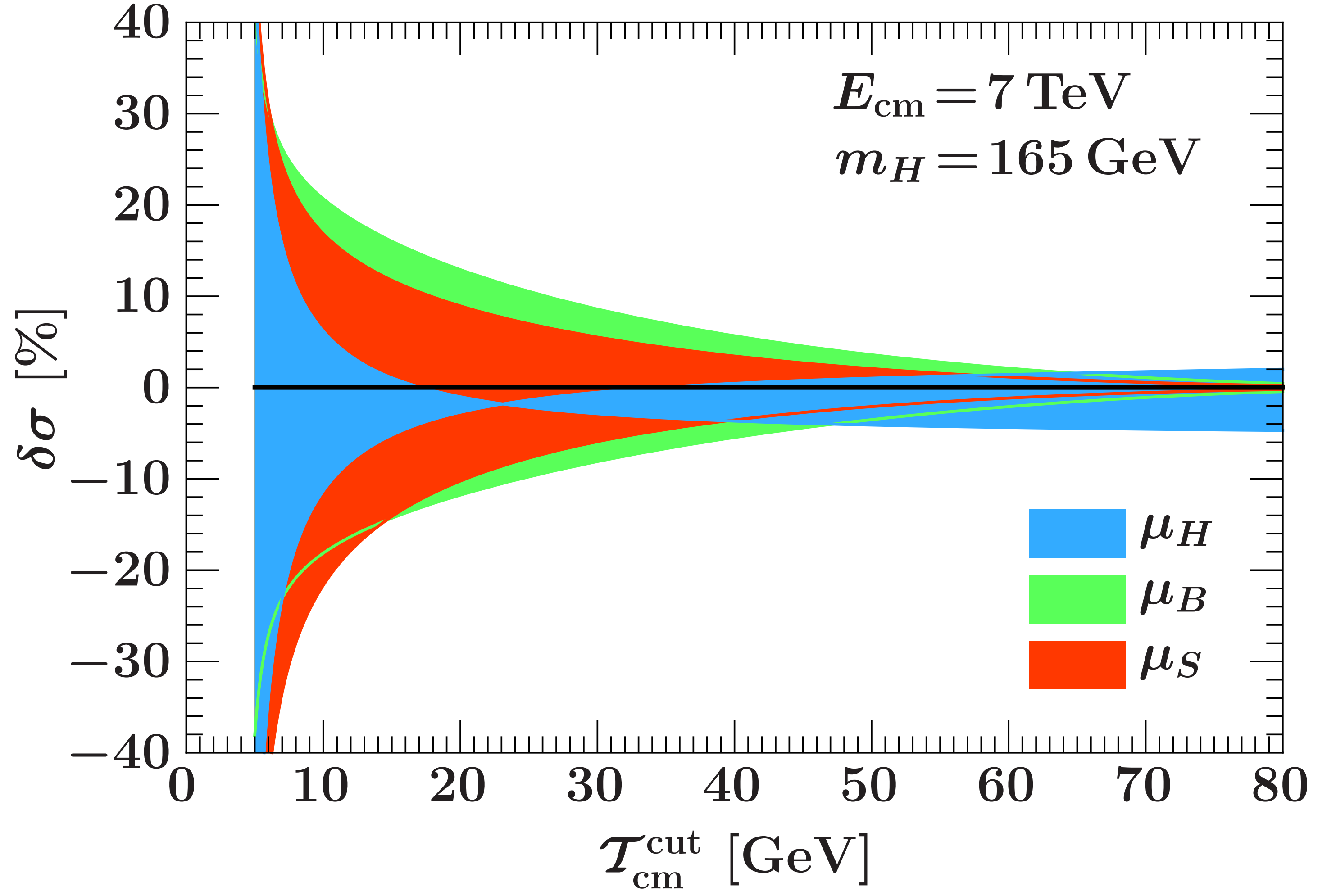
Perturbation theory at <u>each scale</u> contributes to uncertainties

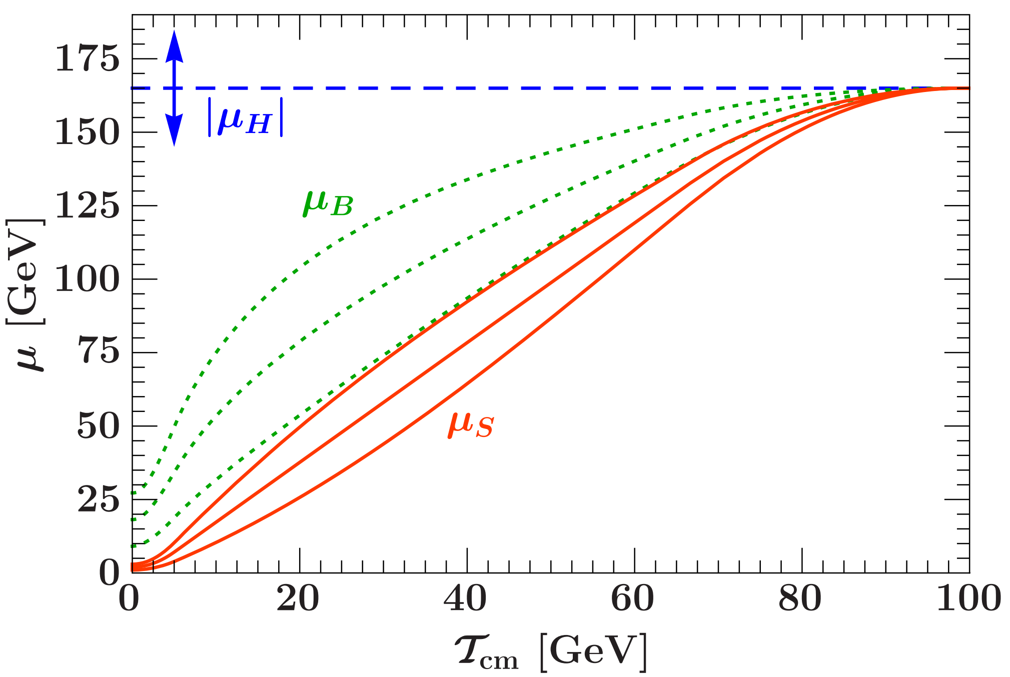
Small $\mathcal{T}_{\rm cm}^{\rm cut}$

individual scale variations

- three separate scale variations
- $\mu_H = \mu_{H0}$ 100% correlated with $\sigma_{\rm total}$
- μ_B and μ_S give $\Delta_{\rm cut} = \Delta_{SB}$ (dominate for small $\mathcal{T}_{\rm cm}^{\rm cut}$)







$$C = C_{SB} + C_H$$

$$C_H = \begin{pmatrix} \Delta_{H\mathrm{tot}}^2 & \Delta_{H\mathrm{tot}}\Delta_{H0} & \Delta_{H\mathrm{tot}}\,\Delta_{H\geq 1} \\ \Delta_{H\mathrm{tot}}\,\Delta_{H0}^2 & \Delta_{H0}^2 & \Delta_{H0}\,\Delta_{H\geq 1} \\ \Delta_{H\mathrm{tot}}\,\Delta_{H\geq 1} & \Delta_{H0}\,\Delta_{H\geq 1} & \Delta_{H\geq 1}^2 \end{pmatrix}$$

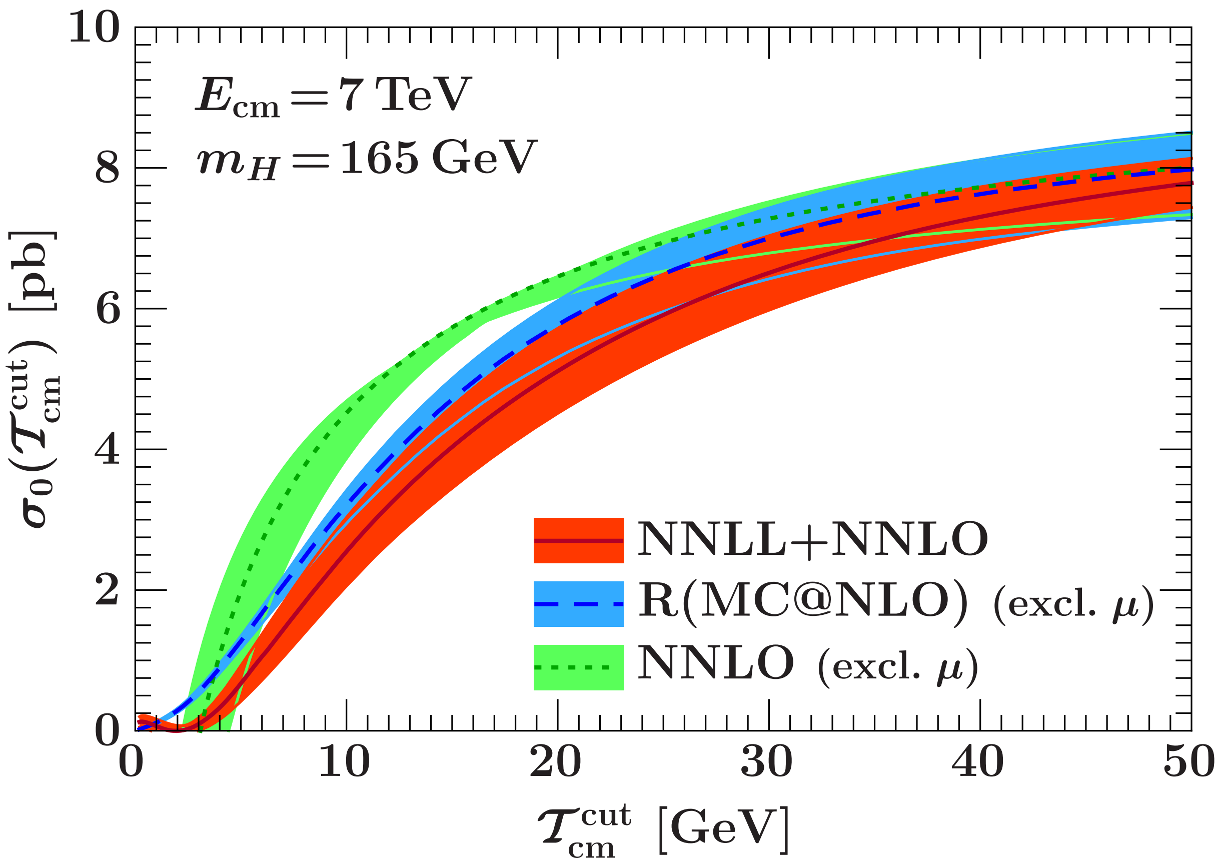
$$\Delta_{H\mathrm{tot}} = \Delta_{H0} + \Delta_{H\geq 1}$$

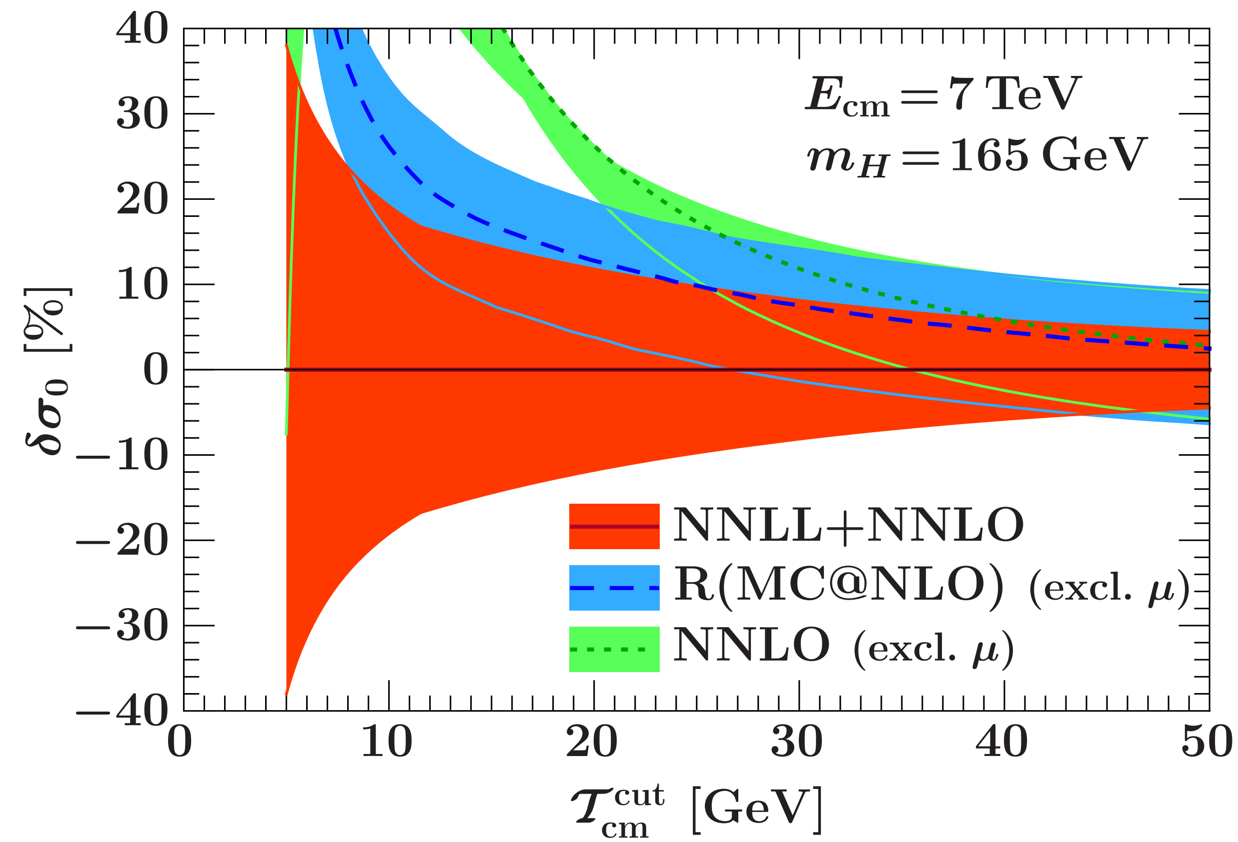
$$C_{SB} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{SB}^2 & -\Delta_{SB}^2 \\ 0 & -\Delta_{SB}^2 & \Delta_{SB}^2 \end{pmatrix}$$

Small $\mathcal{T}_{cm}^{cut}$ like small p_T^{cut}

direct exclusive scale variation shown for NNLO & MC@NLO

combined NNLL scale variations shown



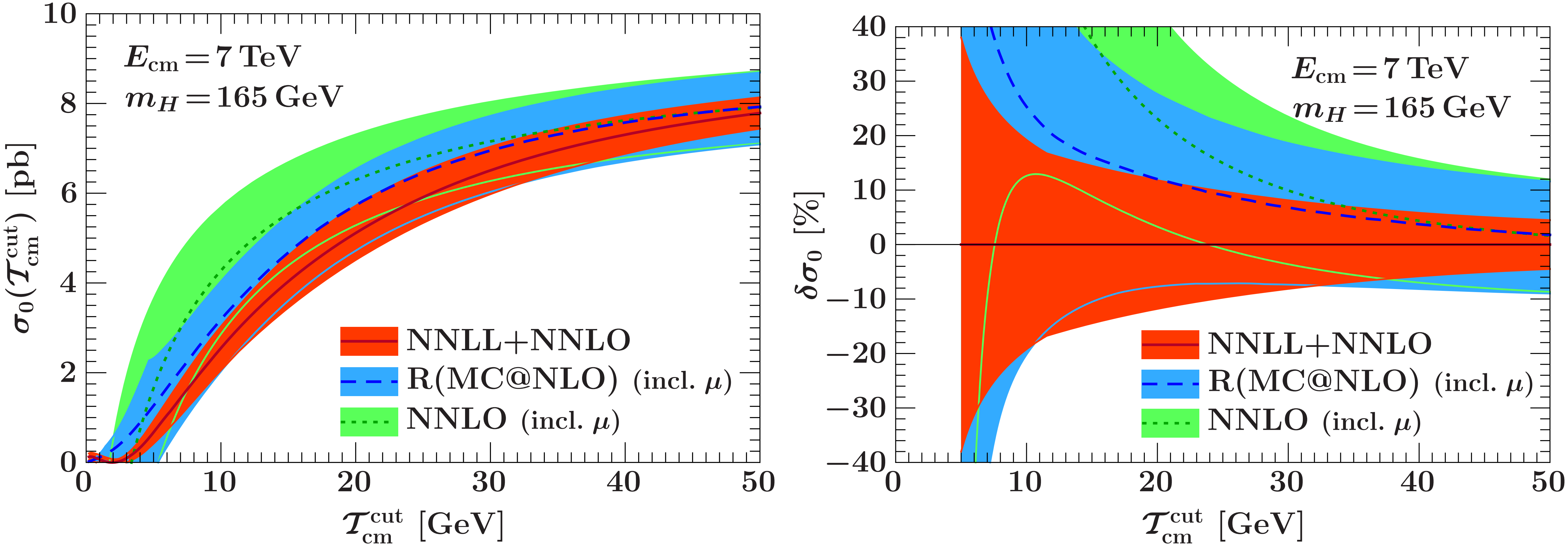


- logs are large, NNLL central value lower than NNLO
- reweigh MC@NLO to match NNLO value/uncertainty at 200GeV Central value is nearer NNLL. Uncertainty is only for norm.
- direct exclusive uncertainties here are too small (we discussed that...)

Small $\mathcal{T}_{\rm cm}^{\rm cut}$ like small $p_T^{\rm cut}$

combined inclusive scale variation shown for NNLO & MC@NLO

combined NNLL scale variations shown



- NNLO band largely overlaps NNLL result
- reweigh MC@NLO to match NNLO incl. uncertainties (full spectrum). Overlaps nicely.
- This factor of two improvement in uncertainty is what one would expect if a similar reweighing exercise is done for $p_T^{\rm jet}$

Discussion

- Reweighing will reduce theory errors. Logical next step. I have tables for LHC@ 7 TeV, mH =165 GeV. (And Tevatron for many mH's because they already started the reweighing during the summer rush.) Other mH table's for the LHC are straightforward to produce.

- I) Will you quote experimental results/limits for exclusive jet cross section? (bkgnd+signal, signal) at Hadron level (corrected to perfect detector). ie. Quote experimental results without any jet-bin bias from theory. (Useful to theorists for benchmarking.)

II) Can you make a plot to show the effect of theory uncertainties? eg. quote what the result would look like with zero theory errors. This would be a strong motivation for theorists to do better, once they see clearly the places they are loosing.

From CMS:

CMS PAS HIG-11-014

2011/08/22

Table 3: Summary of all systematic uncertainties (relative). This is just an indicative table, since the precise values depend on the final state and jet-bin.

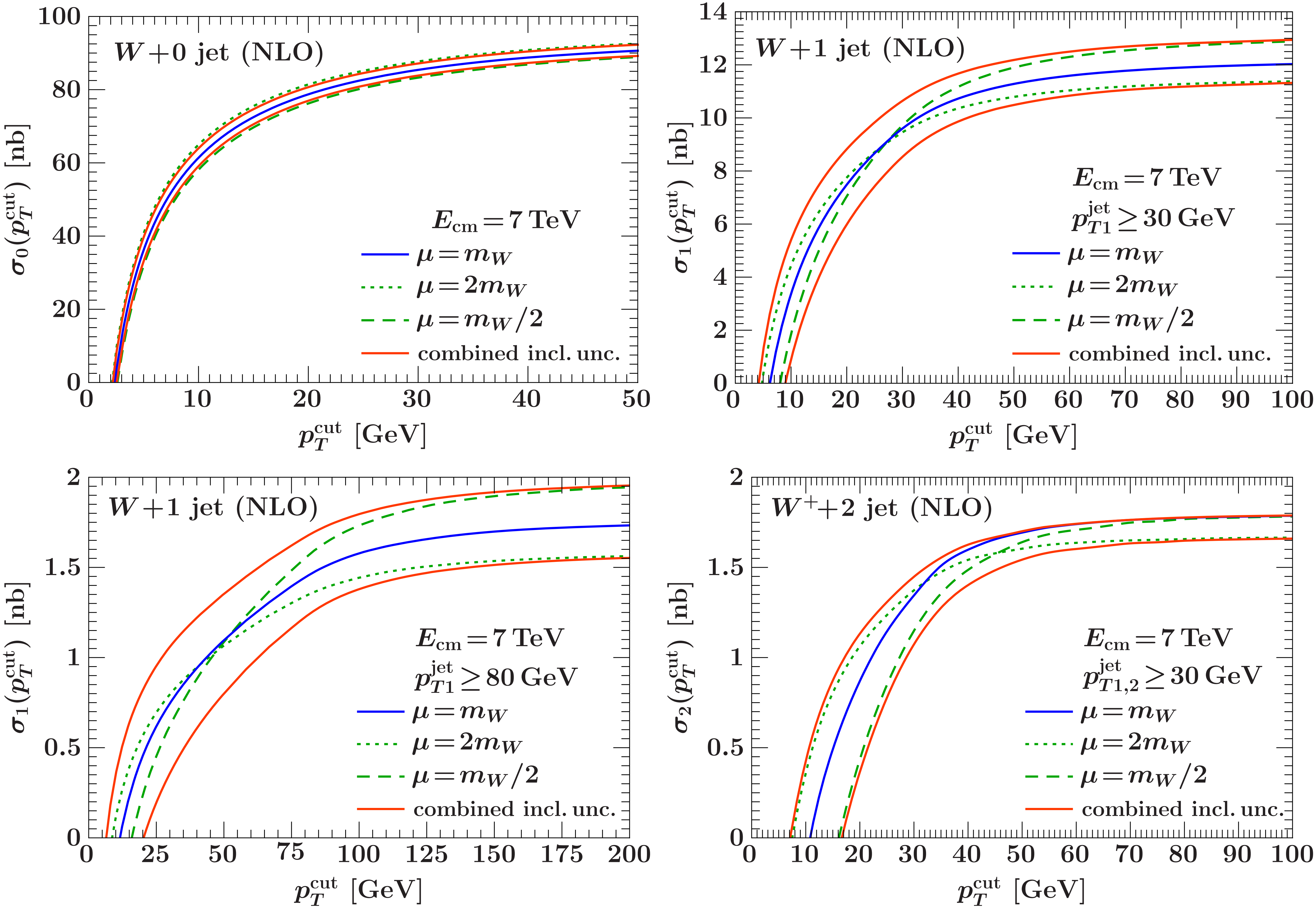
Source	$H \to W^+W^-$	$qq \to W^+W^-$	$gg \to W^+W^-$	non-Z resonant WZ/ZZ	top	DY	$W+$jets	$V(W/Z)+\gamma$
Luminosity	4.5	—	—	4.5	—	—	—	4.5
Trigger efficiencies	1.5	1.5	1.5	1.5	—	—	—	1.5
Muon efficiency	1.5	1.5	1.5	1.5	—	—	—	1.5
Electron id efficiency	2.5	2.5	2.5	2.5	—	—	—	2.5
Momentum scale	1.5	1.5	1.5	1.5	—	—	—	1.5
E_T^{miss} resolution	2.0	2.0	2.0	2.0	2.0	3.0	—	1.0
Jet counting	7-20	—	5.5	5.5	—	—	—	5.5
Higgs cross section	5-15	—	—	—	—	—	—	—
WZ/ZZ cross section	—	—	—	3.0	—	—	—	—
$qq \to WW$ norm.	—	15	—	—	—	—	—	—
$gg \to WW$ norm.	—	—	50	—	—	—	—	—
$W+$jets norm.	—	—	—	—	—	—	36	—
top norm.	—	—	—	—	25	—	—	—
$Z/\gamma^* \to \ell^+\ell^-$ norm.	—	—	—	—	—	60	—	—
Monte Carlo statistics	1.0	1.0	1.0	4.0	6.0	20.0	20.0	10.0

The uncertainty on the signal efficiency is estimated to be $\sim 20\%$ and is dominated by the theoretical uncertainty in the jet veto efficiency determination. The uncertainty on the background estimations in the $H \to W^+W^-$ signal region is $\sim 15\%$, which is dominated by the statistical uncertainties of the background control regions in data.

Theory Plans:

- A calculation of the Higgs + 0-jet cross section at one higher order (N3LL) is feasible. “Only” a missing 2 loop calculation. This will help reduce the perturbative uncertainty.
- Similar resummed calculations for Higgs + 1 jet are already in progress.

Backup


$W+0$ jet (NLO)
$E_{\rm cm}=7$ TeV
$\mu=m_W$
$\mu=2m_W$
$\mu=m_W/2$
combined incl. unc.
$\sigma_0(p_T^{\rm cut})$ [nb]
$p_T^{\rm cut}$ [GeV]
$W+1$ jet (NLO)
$E_{\rm cm}=7$ TeV
$p_{T1}^{\rm jet}\geq 30$ GeV
$\mu=m_W$
$\mu=2m_W$
$\mu=m_W/2$
combined incl. unc.
$\sigma_1(p_T^{\rm cut})$ [nb]
$p_T^{\rm cut}$ [GeV]
$W+1$ jet (NLO)
$E_{\rm cm}=7$ TeV
$p_{T1}^{\rm jet}\geq 80$ GeV
$\mu=m_W$
$\mu=2m_W$
$\mu=m_W/2$
combined incl. unc.
$\sigma_1(p_T^{\rm cut})$ [nb]
$p_T^{\rm cut}$ [GeV]
$W^{+}+2$ jet (NLO)
$E_{\rm cm}=7$ TeV
$p_{T1,2}^{\rm jet}\geq 30$ GeV
$\mu=m_W$
$\mu=2m_W$
$\mu=m_W/2$
combined incl. unc.
$\sigma_2(p_T^{\rm cut})$ [nb]
$p_T^{\rm cut}$ [GeV]

$$\sigma_0 = \sigma_{\rm total} - \sigma_{\geq 1}\,, \qquad f_0 = \frac{\sigma_0}{\sigma_{\rm total}}\,,$$

$$\sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}\,, \qquad f_1 = \frac{\sigma_1}{\sigma_{\rm total}}\,.$$

relative uncertainties

$$\delta(\sigma_0)^2 = \frac{1}{f_0^2}\,\delta_{\rm total}^2 + \left(\frac{1}{f_0} - 1\right)^2 \delta_{\geq 1}^2$$

$$\delta(\sigma_1)^2 = \left(\frac{1 - f_0}{f_1}\right)^2 \delta_{\geq 1}^2 + \left(\frac{1 - f_0}{f_1} - 1\right)^2 \delta_{\geq 2}^2$$

$$\delta(f_0)^2 = \left(\frac{1}{f_0} - 1\right)^2 \left(\delta_{\rm total}^2 + \delta_{\geq 1}^2\right)\,,$$

$$\delta(f_1)^2 = \delta_{\rm total}^2 + \left(\frac{1 - f_0}{f_1}\right)^2 \delta_{\geq 1}^2 + \left(\frac{1 - f_0}{f_1} - 1\right)^2 \delta_{\geq 2}^2\,,$$

$$\begin{pmatrix} \Delta_{\rm total}^2 & \Delta_{\rm total}^2 & 0 \\ \Delta_{\rm total}^2 & \Delta_{\rm total}^2 + \Delta_{\geq 1}^2 & -\Delta_{\geq 1}^2 \\ 0 & -\Delta_{\geq 1}^2 & \Delta_{\geq 1}^2 + \Delta_{\geq 2}^2 \end{pmatrix}$$

correlation coefficients

$$\rho(\sigma_0, \sigma_{\rm total}) = \left[1 + \frac{\delta_{\geq 1}^2}{\delta_{\rm total}^2}(1 - f_0)^2\right]^{-1/2}\,,$$

$$\rho(\sigma_0, \sigma_1) = -\left[1 + \frac{\delta_{\rm total}^2}{\delta_{\geq 1}^2}\,\frac{1}{(1 - f_0)^2}\right]^{-1/2} \times \left[1 + \frac{\delta_{\geq 2}^2}{\delta_{\geq 1}^2}\left(1 - \frac{f_1}{1 - f_0}\right)^2\right]^{-1/2}\,,$$

$$\rho(\sigma_0, \sigma_{\geq 2}) = 0\,,$$

$$\rho(\sigma_1, \sigma_{\rm total}) = 0\,,$$

$$\rho(\sigma_1, \sigma_{\geq 2}) = -\left[1 + \frac{\delta_{\geq 1}^2}{\delta_{\geq 2}^2}\left(1 - \frac{f_1}{1 - f_0}\right)^{-2}\right]^{-1/2}\,.$$

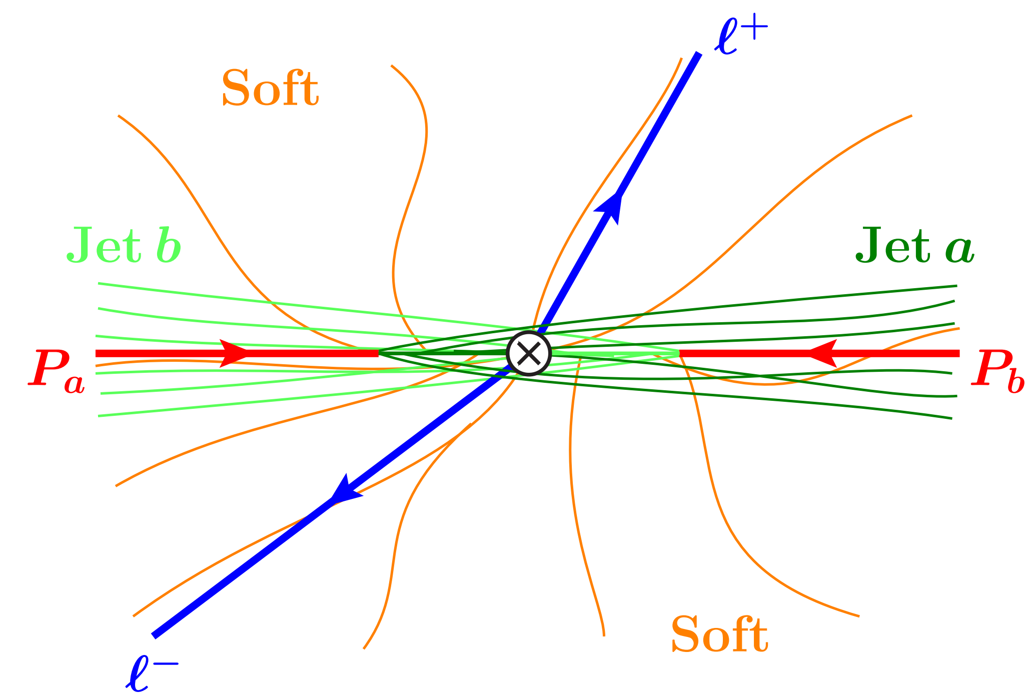
$$\rho(f_0, \sigma_{\rm total}) = \left[1 + \frac{\delta_{\geq 1}^2}{\delta_{\rm total}^2}\right]^{-1/2}\,,$$

$$\rho(f_0, f_1) = -\left(1 + \frac{1 - f_0}{f_1}\,\frac{\delta_{\geq 1}^2}{\delta_{\rm total}^2}\right)\left(\frac{1}{f_0} - 1\right)\frac{\delta_{\rm total}^2}{\delta(f_0)\delta(f_1)}\,,$$

$$\rho(f_1, \sigma_{\rm total}) = -\frac{\delta_{\rm total}}{\delta(f_1)}\,.$$

Validation? Other options?

- Drell-Yan pairs from γ^*, Z^* with a jet veto should be used for validation.



- Directly measure beam thrust (important on its own). And UE is no harder than it is for HT.