Higgs Production with a Jet Veto at NNLL + NNLO

discussion with CMS

arXiv:1012.4480

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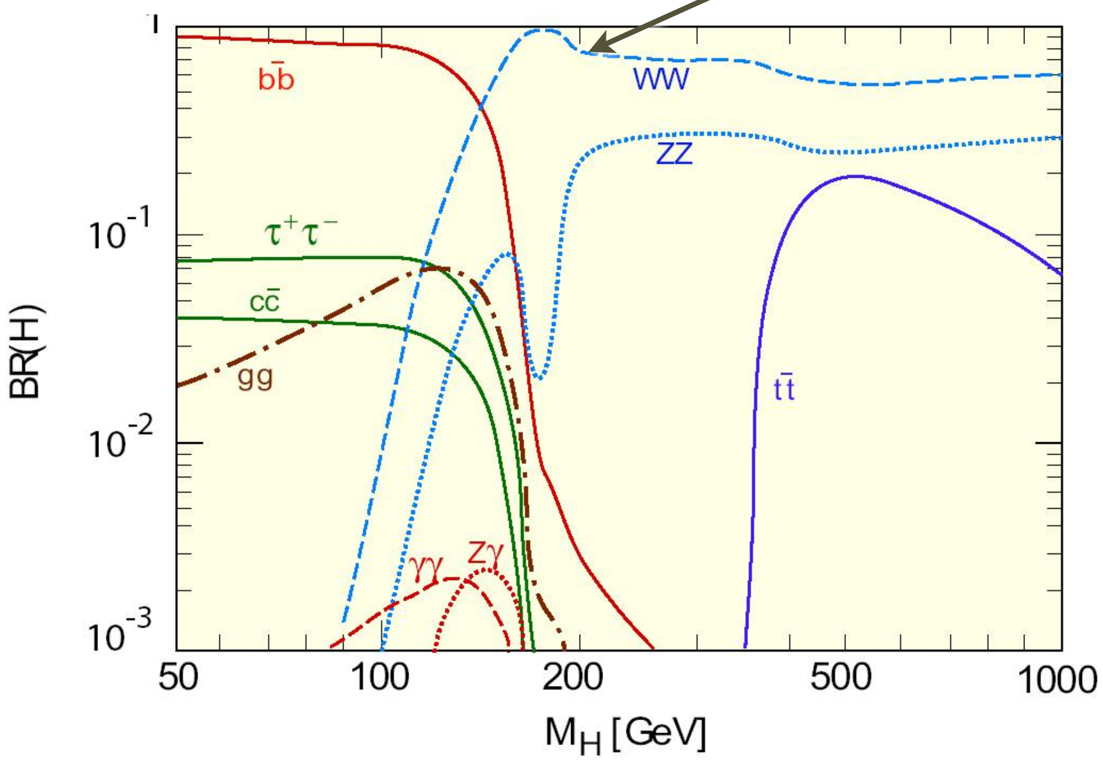
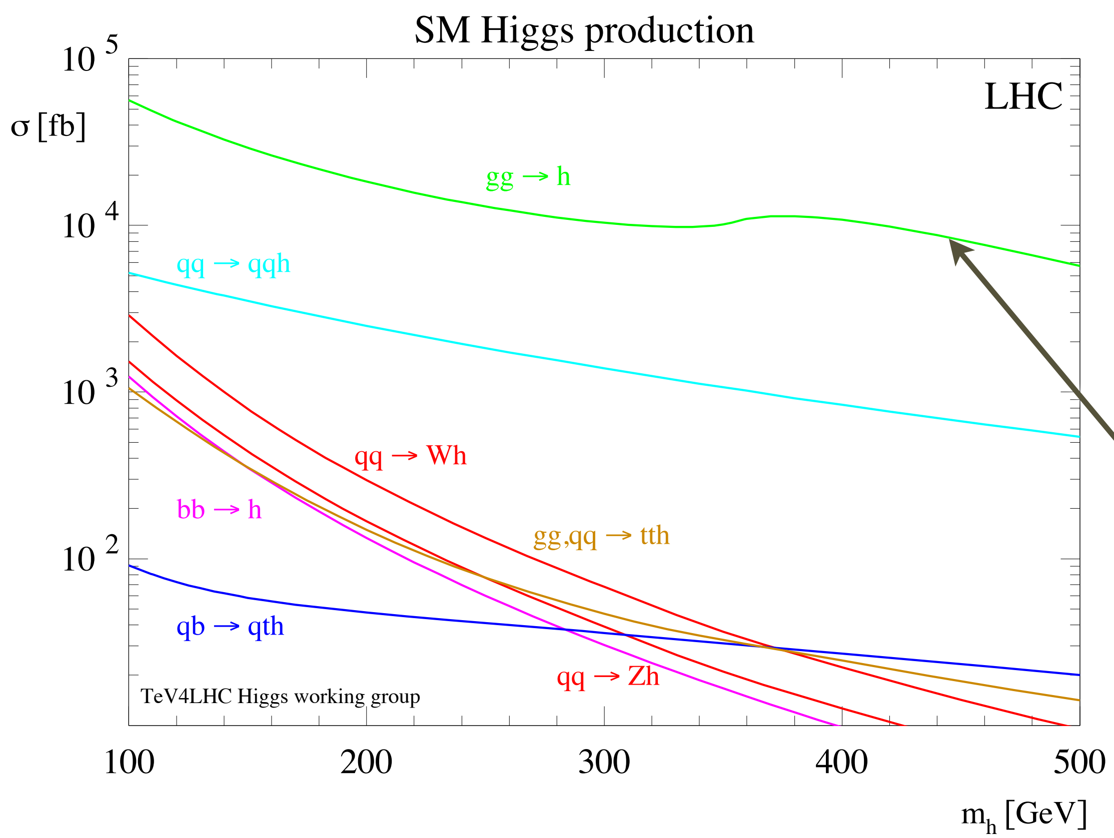
with C.Berger, C.Marcantonini, F. Tackmann, W.Waalewijn

Focus on $pp \to H \to WW \to \ell\bar{\nu}\bar{\ell}\nu$

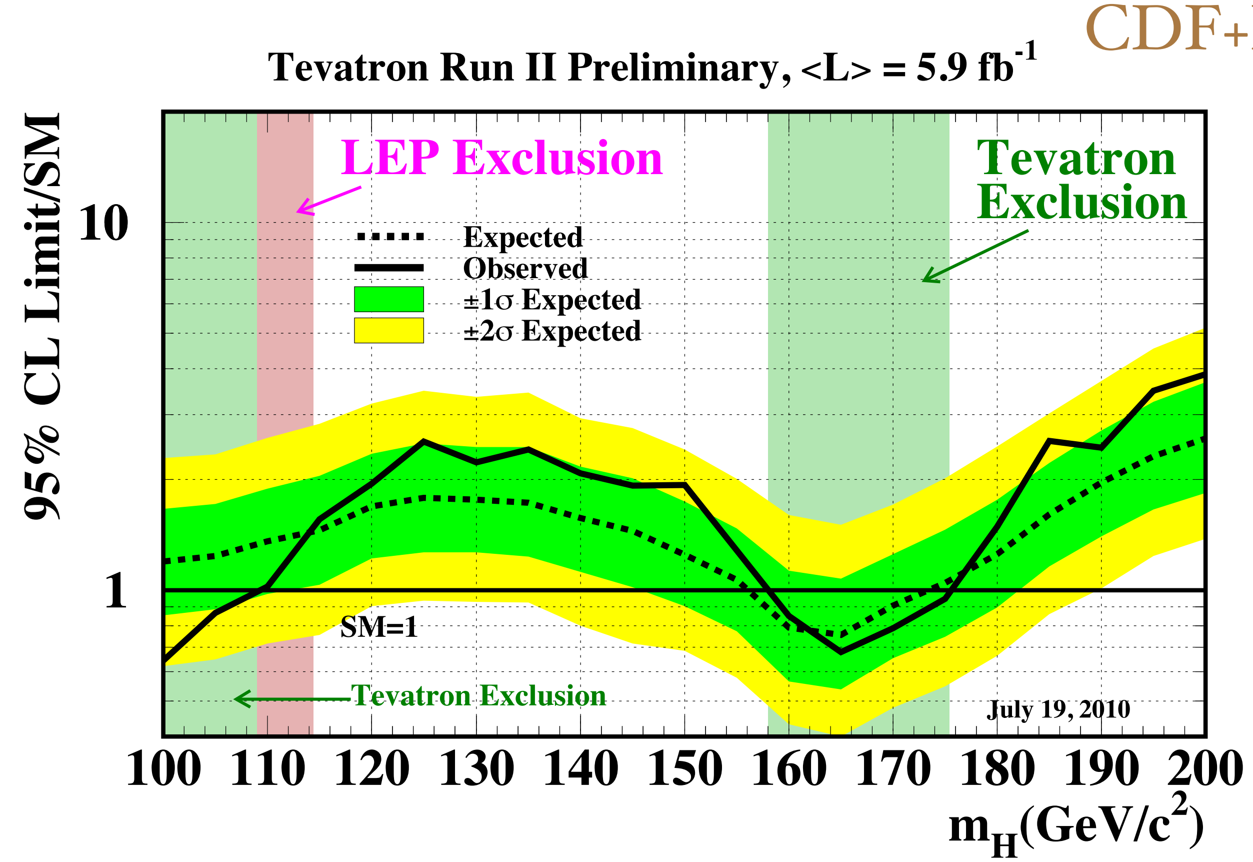
- early discovery channel at LHC

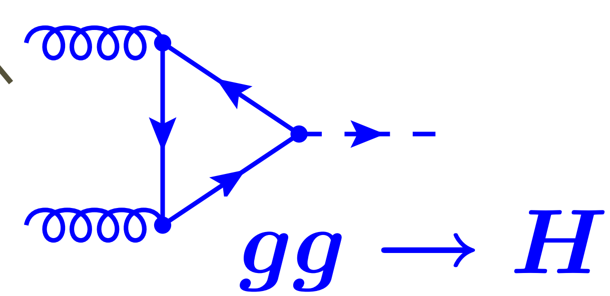


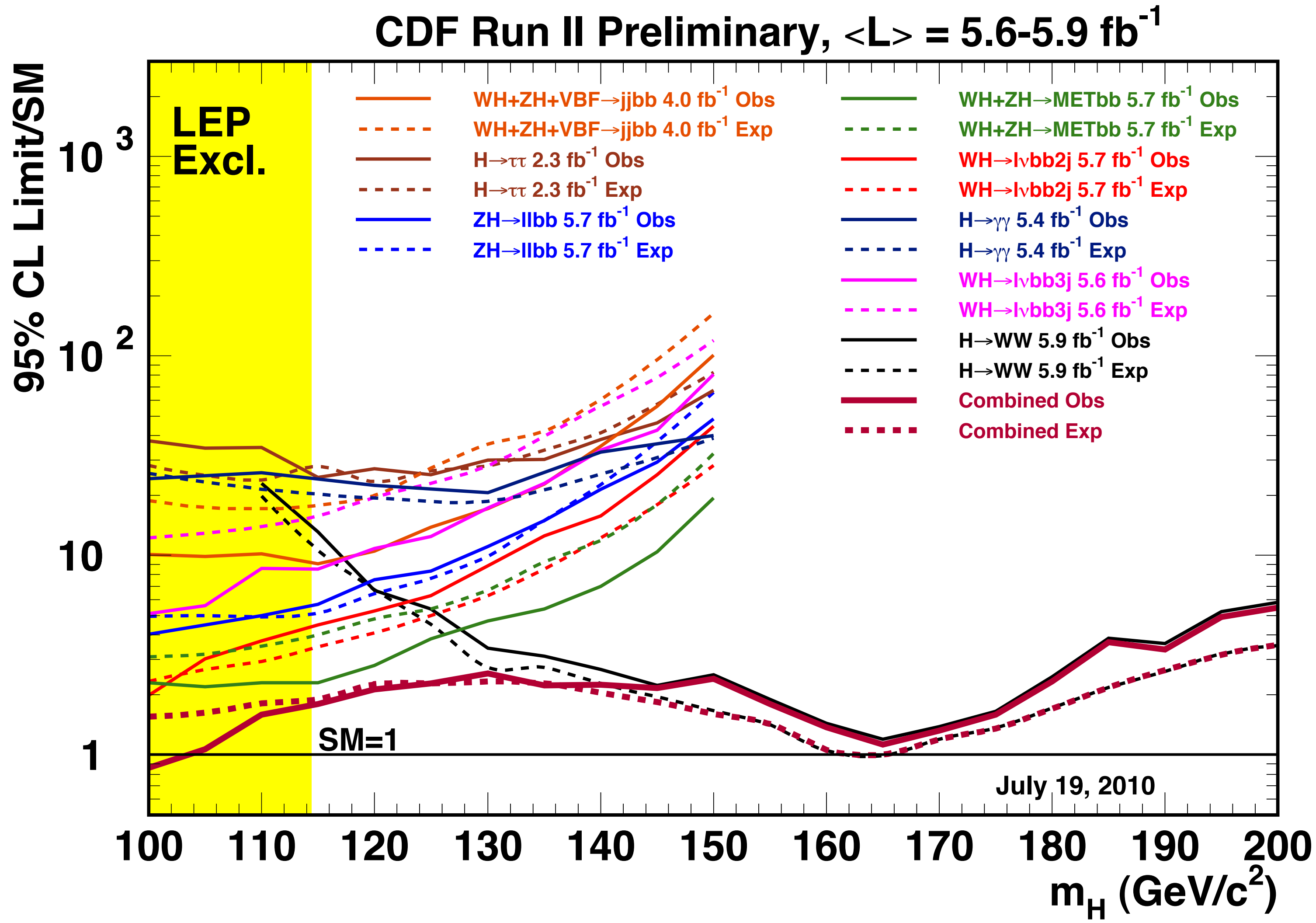


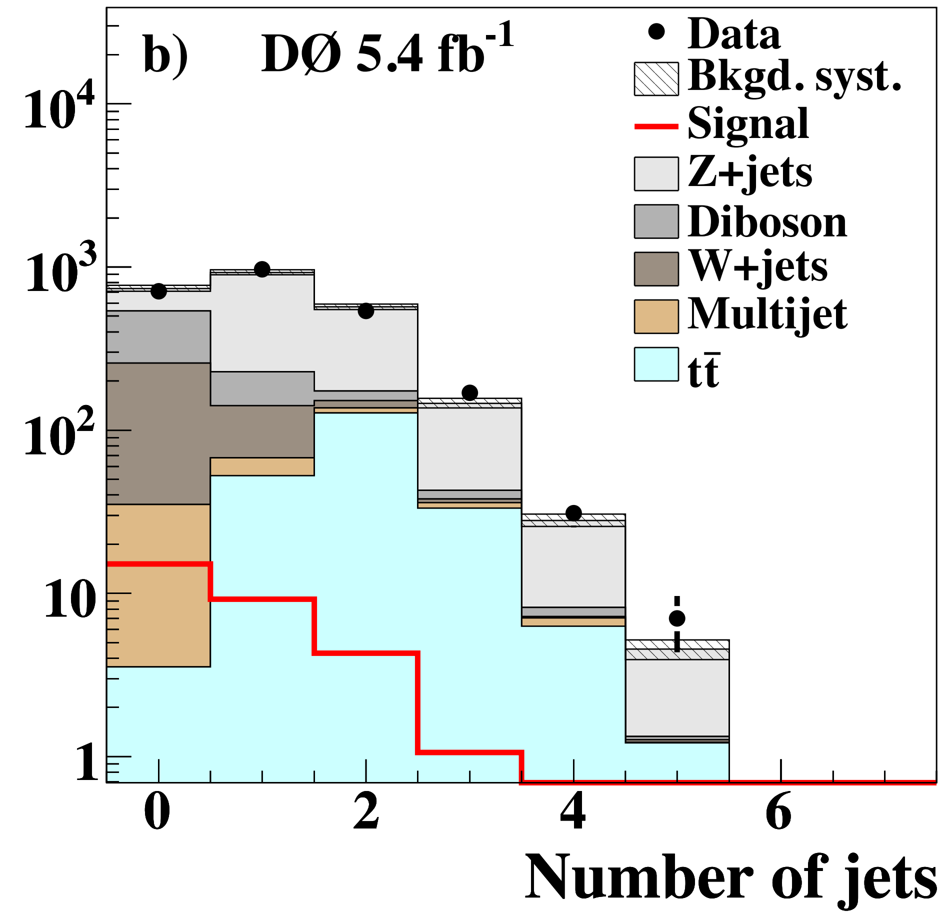
- dominant channel in Tevatron limits for $m_H \gtrsim 130\,\mathrm{GeV}$

CDF+DO

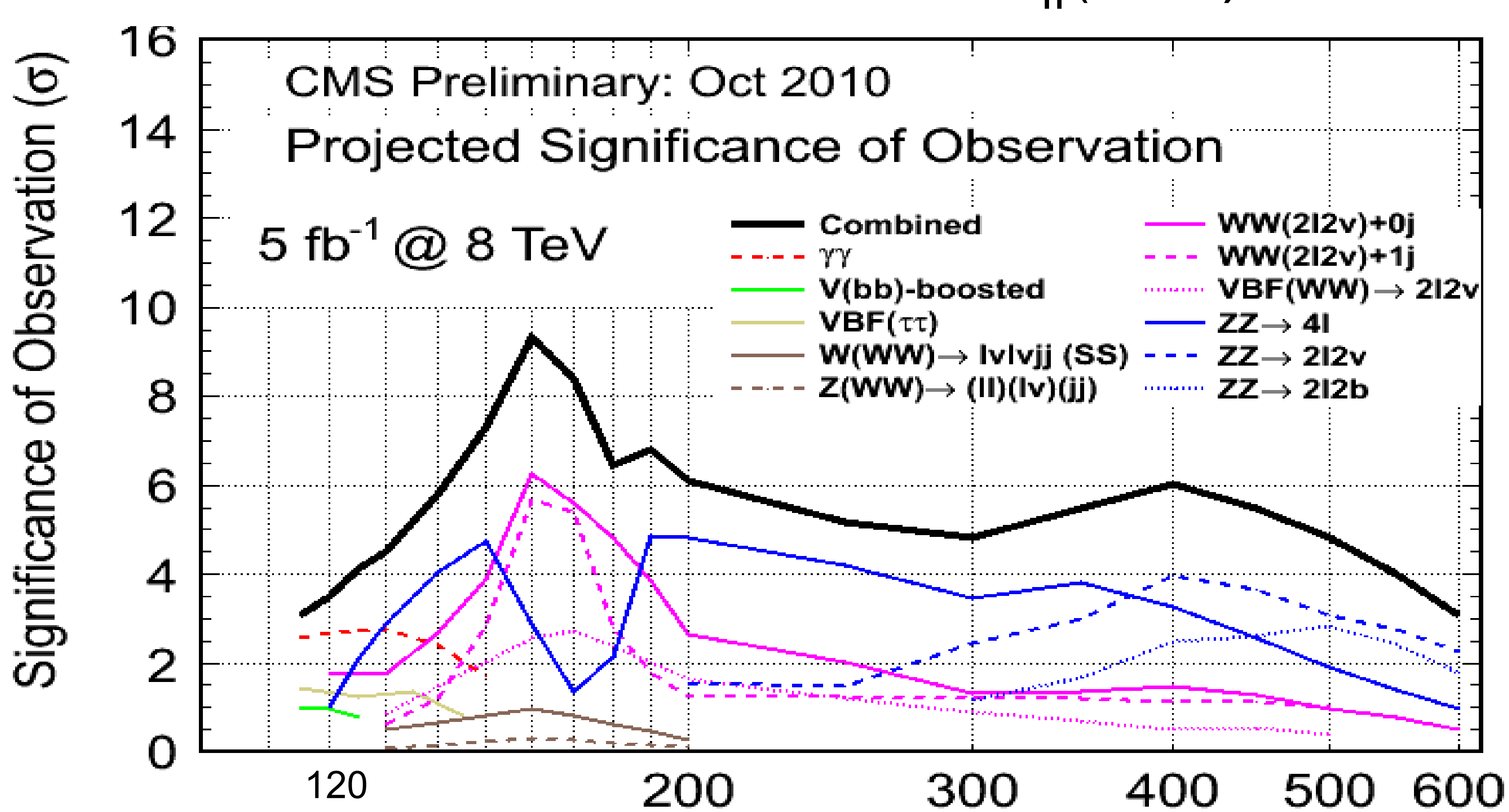








[DØ (arXiv:1001.4481)]

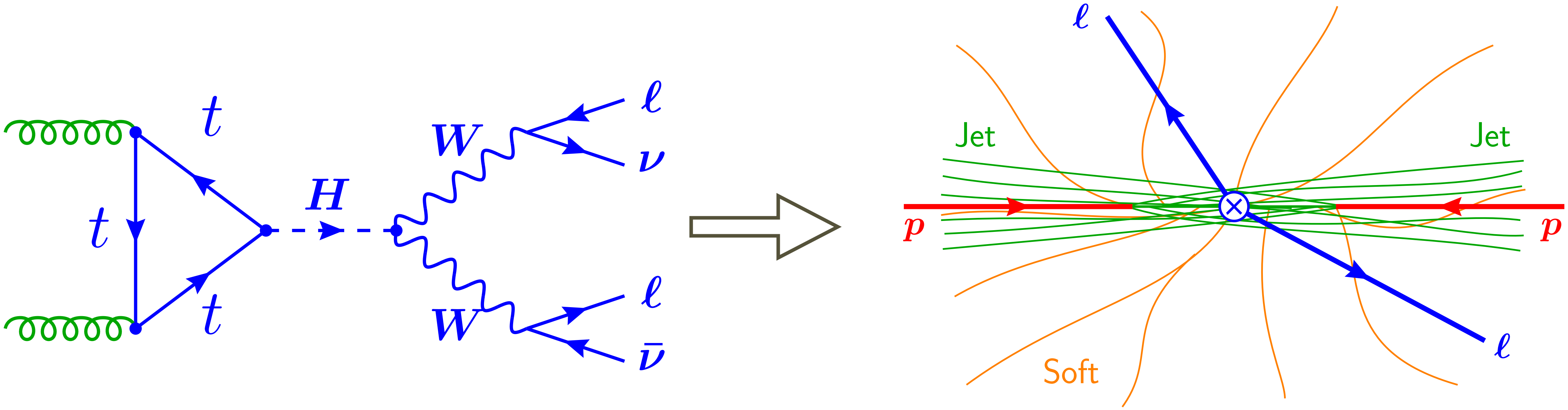


m_H [GeV/c²]

(C.Paus, LNS colloq.)

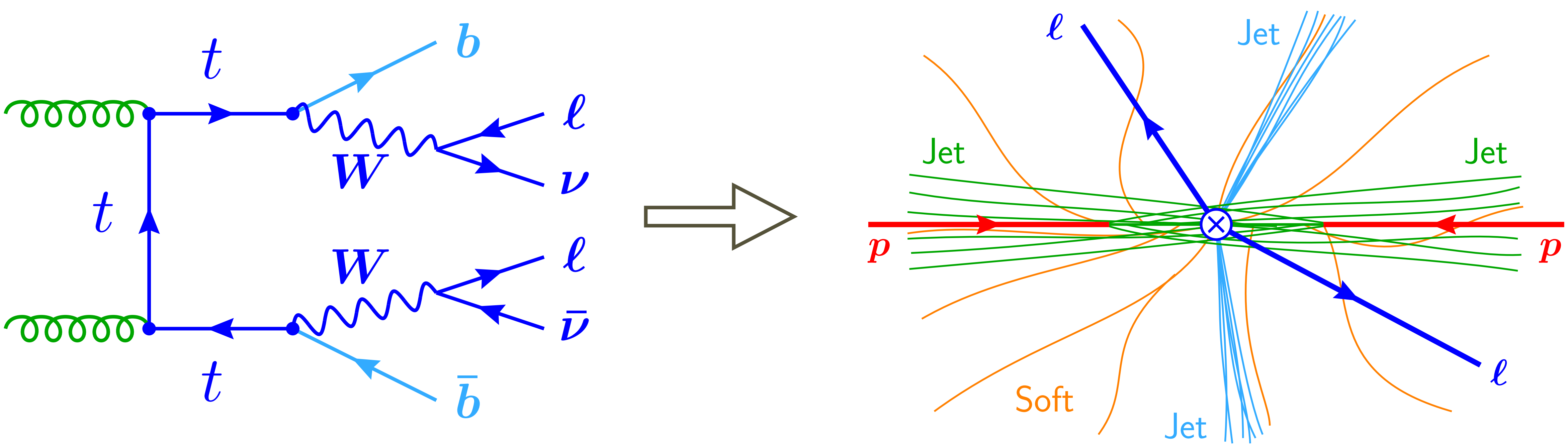
Large Background from Top Decays

1



to

40



$\Rightarrow$ Veto events with central jets, measure $pp \to H(\to WW) + 0$ jets

(Sensitivity dominated by 0-jet sample)

Jet Vetoes

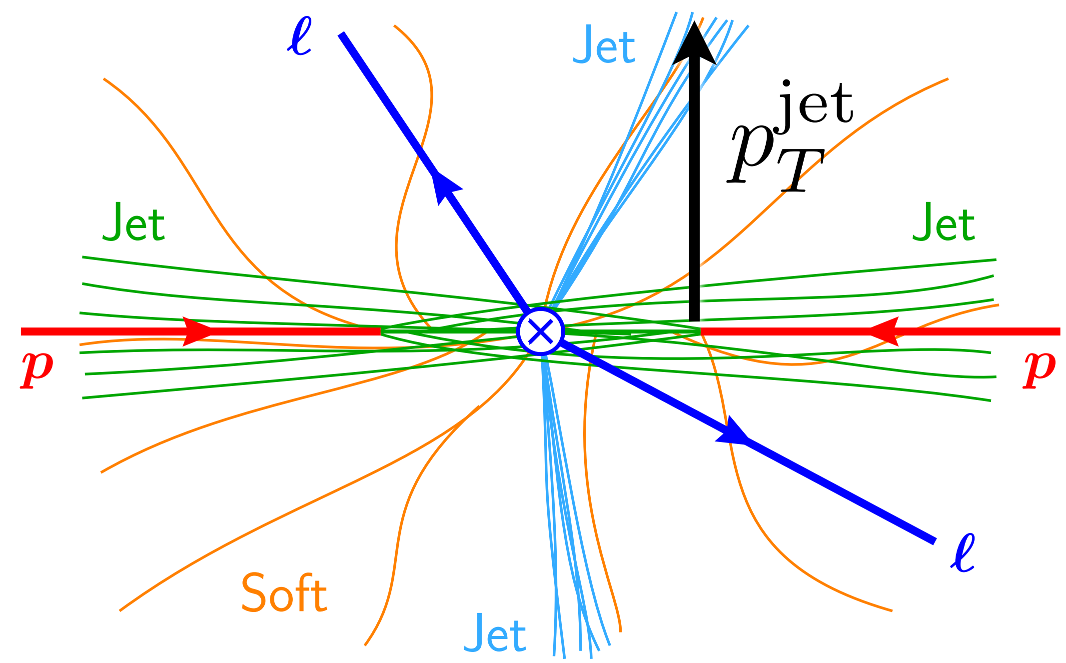
Conventional: Jet Algorithm

- 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



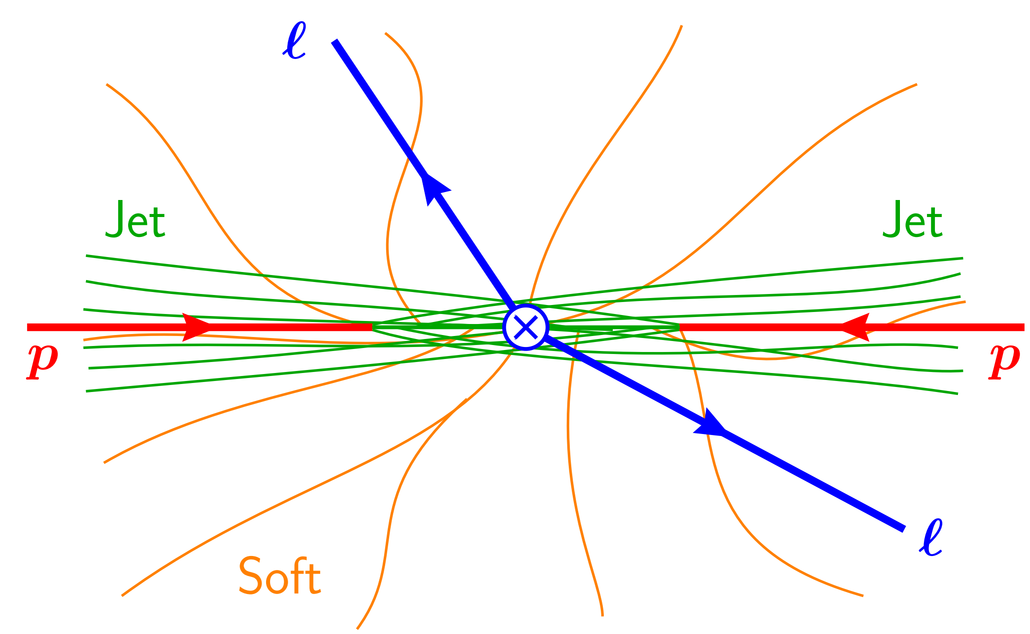
Alternative: Event Shape

- Measure beam thrust for each event

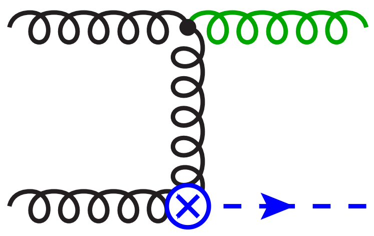
$$\mathcal{T}_{\rm cm} = \sum_k |\vec{p}_{kT}|\, e^{-|\eta_k|} = \sum_k \big(E_k - |p_k^z|\big)$$

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

- Nice for higher order calculations



Jet veto restricts ISR, gives double logs

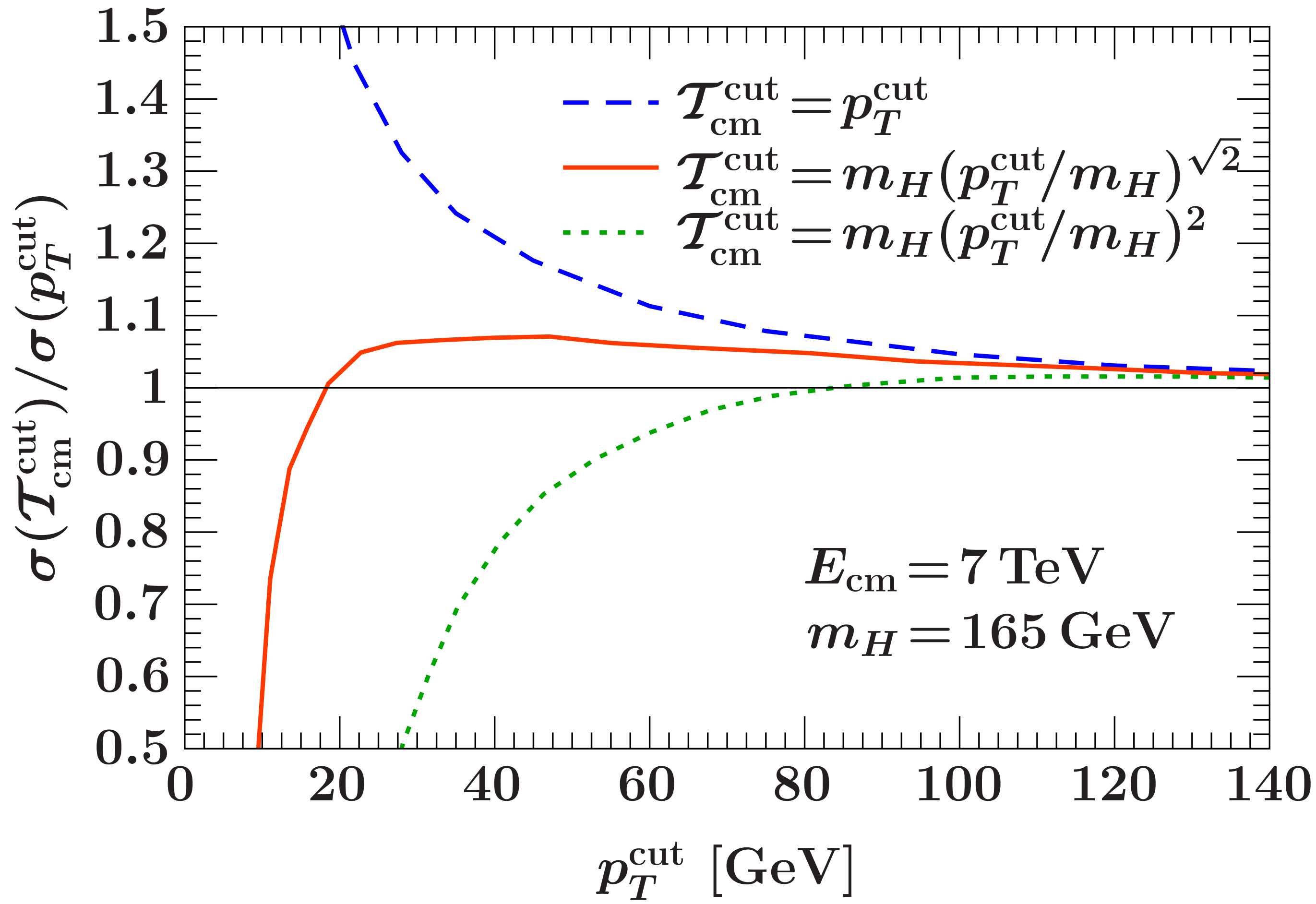


$$L = \ln \frac{p_T^{\rm cut}}{m_H} \quad \text{or} \quad L = \ln \frac{\mathcal{T}_{\rm cm}^{\rm cut}}{m_H}$$

$$\sigma(p_T^{\rm cut}) \propto 1 - \left(\frac{3\alpha_s}{\pi}\right) 2 \ln^2 \frac{p_T^{\rm cut}}{m_H} + \dots$$

$$\sigma(\mathcal{T}_{\rm cm}^{\rm cut}) \propto 1 - \left(\frac{3\alpha_s}{\pi}\right) \ln^2 \frac{\mathcal{T}_{\rm cm}^{\rm cut}}{m_H} + \dots$$

NNLO spectra close, agree to 7%

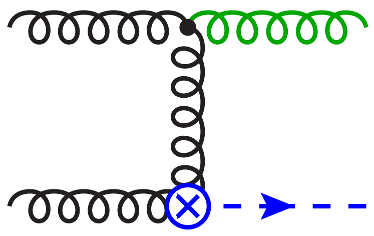


Appropriate correspondence:

$$\mathcal{T}_{\rm cm}^{\rm cut} \simeq m_H \left(\frac{p_t^{\rm cut}}{m_H}\right)^{\sqrt{2}}$$

$\Rightarrow$ $\mathcal{T}_{\rm cm}^{\rm cut} \simeq 10\,\mathrm{GeV}$ corresponds to $p_T^{\rm cut} \simeq 20\,\mathrm{GeV}$ in conventional jet veto

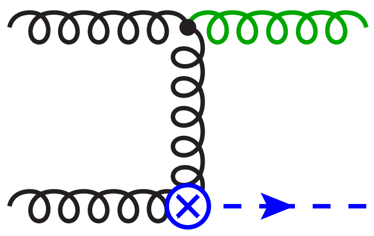
Jet veto restricts ISR, gives double logs



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

$$
\begin{array}{llllll}
\sigma_{0\text{-jet}} = & 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \ldots \\
 & & + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \ldots \\
 & & + \alpha_s & + \alpha_s^2 L^2 & + \alpha_s^3 L^4 & + \ldots \\
 & & & + \alpha_s^2 L & + \alpha_s^3 L^3 & + \ldots \\
 & & & + \alpha_s^2 & + \alpha_s^3 L^2 & + \ldots \\
 & & & & + \alpha_s^3 L & + \ldots \\
 & & & & + \alpha_s^3 & + \ldots
\end{array}
$$

Jet veto restricts ISR, gives double logs



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

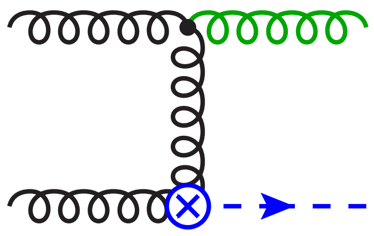
$$\begin{array}{llllll}
 & \text{LO} & \text{NLO} & \text{NNLO} & & \\
\sigma_{0\text{-jet}} = & 1 & +\,\alpha_s L^2 & +\,\alpha_s^2 L^4 & +\,\alpha_s^3 L^6 & +\ldots \\
 & & +\,\alpha_s L & +\,\alpha_s^2 L^3 & +\,\alpha_s^3 L^5 & +\ldots \\
 & & +\,\alpha_s n_1(p_T^{\mathrm{cut}}) & +\,\alpha_s^2 L^2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

Fixed Order to NNLO

FEHiP, HNNLO: Numerical fully differential NNLO cross section for $gg \to H$

[Anastasiou, Melnikov, Petriello; Grazzini]

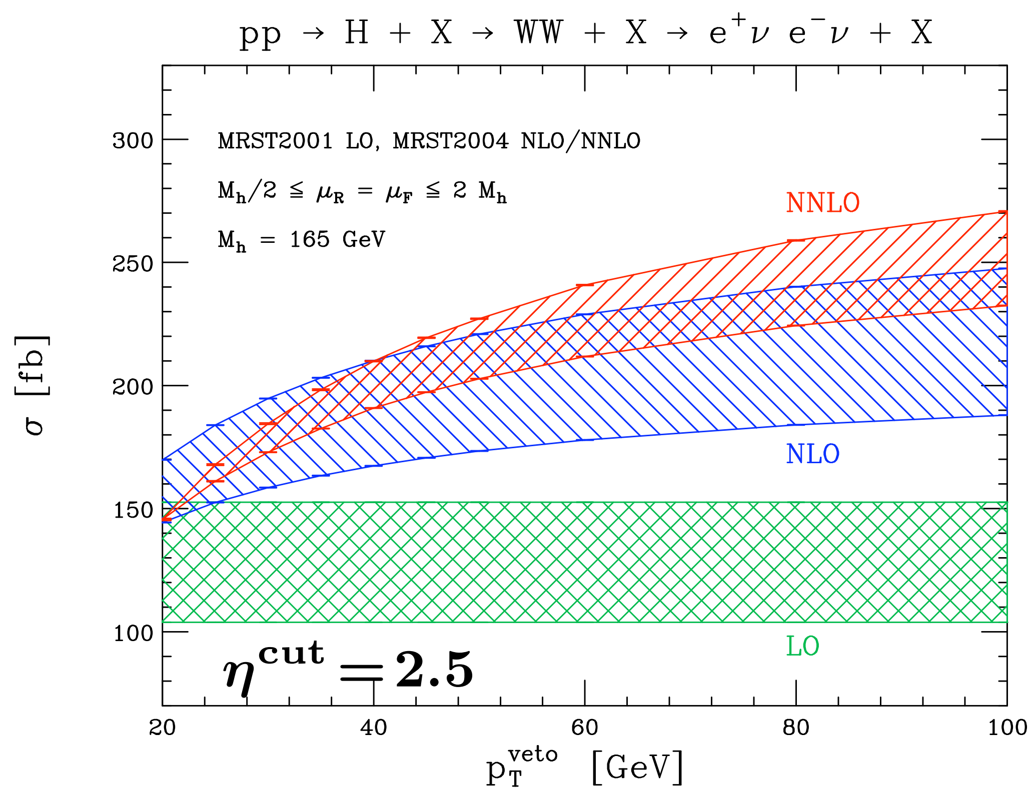
Jet veto restricts ISR, gives double logs



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

Fixed order NNLO studies

[Anastasio et al. arXiv:0707.2373]:



Higgs has large K factor

[Catani, de Florian, Grazzini; Anastasiou et al.]

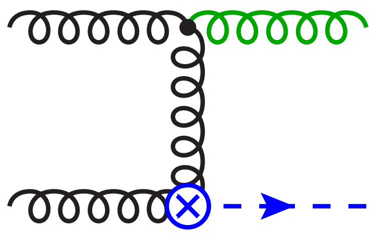
Relative uncertainties for $W^+W^- \to \ell^\pm \ell'^\mp$

	$pp \to WW$	$gg \to H + 0$ jets	$gg \to H + 1$ jets
Scale		7.0% (HNNLO)	23.5% (HNNLO)
PDF Model		7.6%	17.3%
Total	6.0% (MCFM)		

[CDF numbers from arXiv:1007.4587]

7% scale uncertainty does not account for large logs

Jet veto restricts ISR, gives double logs



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

LO NLO

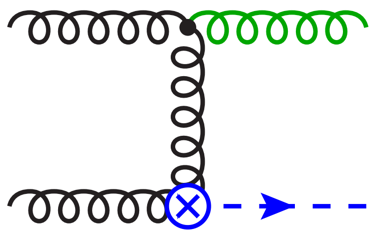
$$\begin{aligned}
\sigma_{0\text{-jet}} = \; 1 \; &+ \alpha_s L^2 && + \alpha_s^2 L^4 && + \alpha_s^3 L^6 && + \ldots \quad \text{LL} \\
&+ \alpha_s L && + \alpha_s^2 L^3 && + \alpha_s^3 L^5 && + \ldots \\
&+ \alpha_s n_1(p_T^{\rm cut}) && + \alpha_s^2 L^2 && + \alpha_s^3 L^4 && + \ldots \\
& && + \alpha_s^2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

Parton Shower

eg. Pythia is LL (+ tuning)

eg. MC@NLO is NLO+LL

Jet veto restricts ISR, gives double logs



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

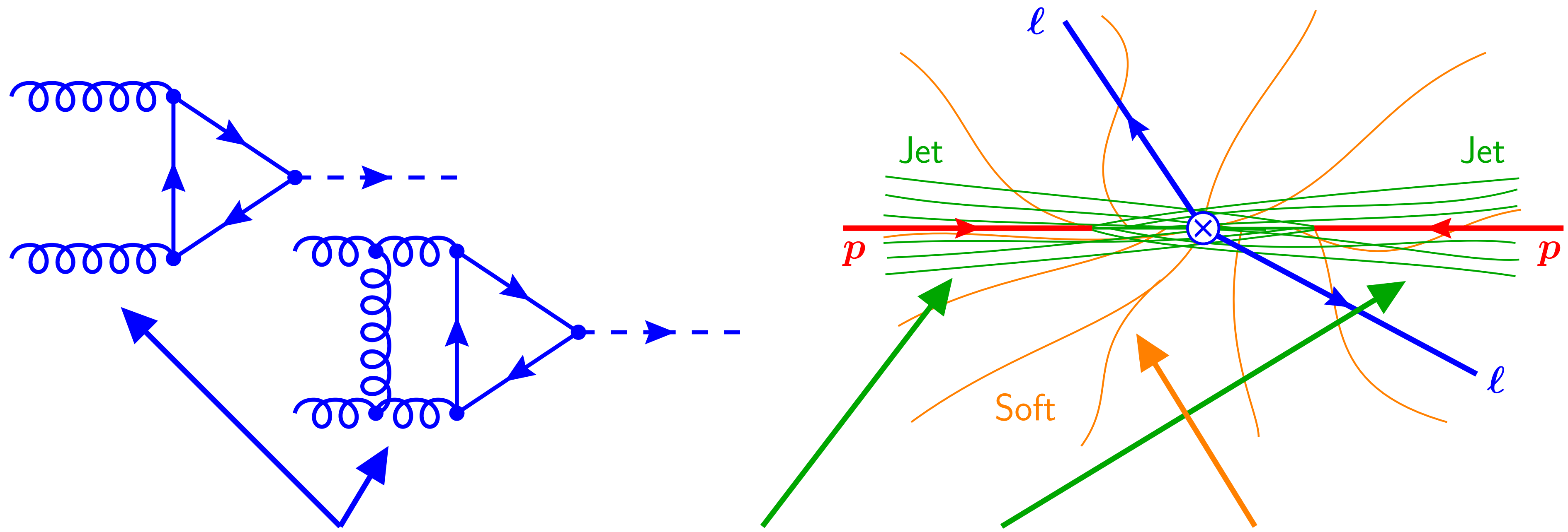
$$\begin{array}{lllllll}
 & \text{LO} & \text{NLO} & \text{NNLO} & & & \\
\sigma_{0\text{-jet}} = & 1 & + \alpha_s L^2 & + \alpha_s^2 L^4 & + \alpha_s^3 L^6 & + \ldots & \text{LL} \\
 & & + \alpha_s L & + \alpha_s^2 L^3 & + \alpha_s^3 L^5 & + \ldots & \text{NLL} \\
 & & + \alpha_s n_1(p_T^{\text{cut}})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

Our calculation:

NNLL + NNLO

two orders of summation
beyond LL shower programs

Our calculation: NNLL + NNLO



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

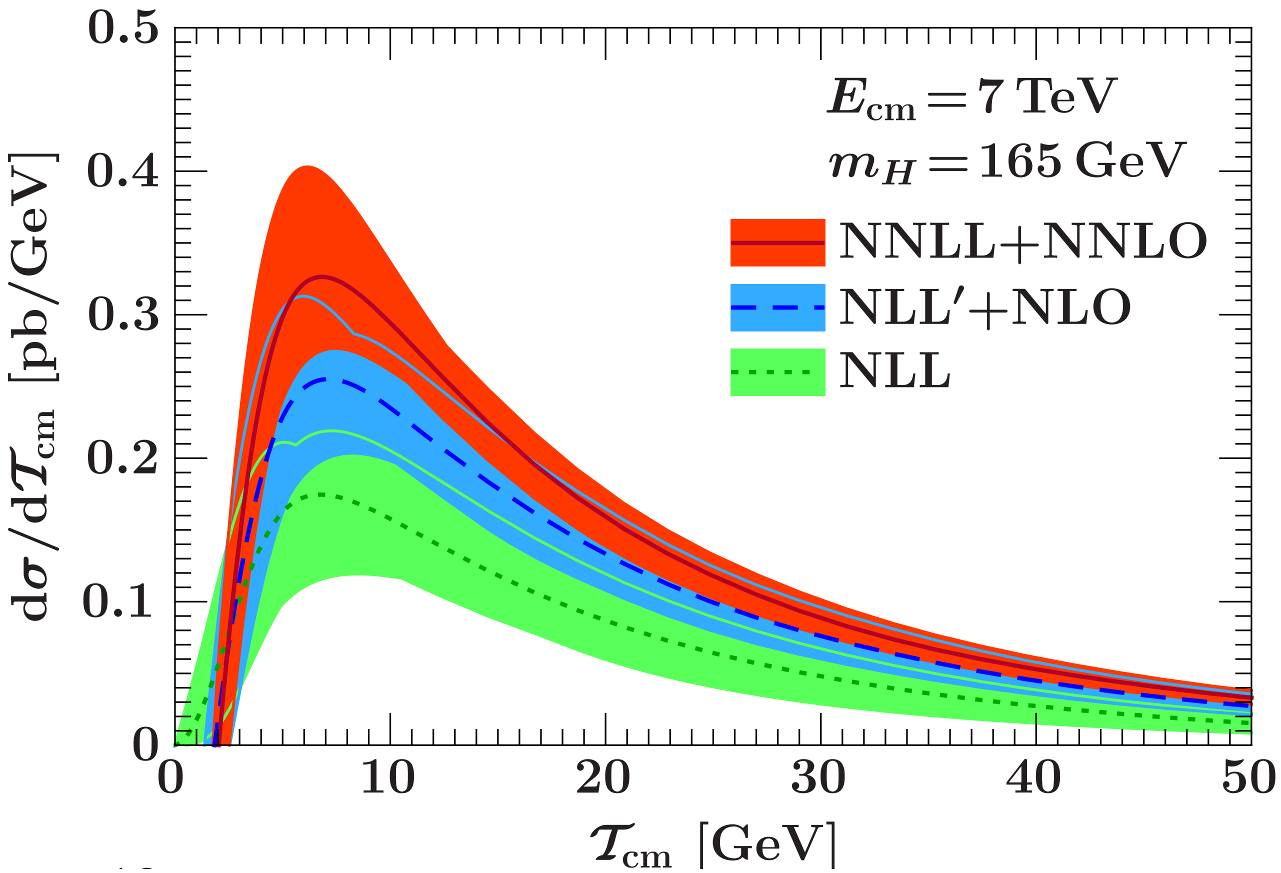
$$B_i(t, x) = \int \frac{d\xi}{\xi} \, \mathcal{I}_{ij}(t, x/\xi) \; f_j(\xi)$$

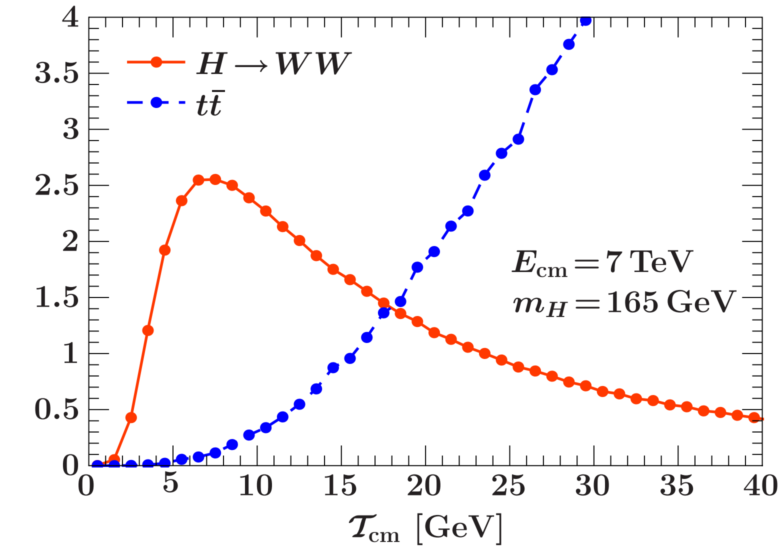
Function	describes	at the scale
Hard H_{gg}	hard virtual radiation	$\lvert\mu_H\rvert \simeq m_H$
Beam B_g	virtual & real energetic ISR	$\mu_B \simeq \sqrt{\mathcal{T}_{\mathrm{cm}} m_H}$
Soft S_B^{gg}	virtual & real soft radiation	$\mu_S \simeq \mathcal{T}_{\mathrm{cm}}$

} logs give sensitivity to smaller scales

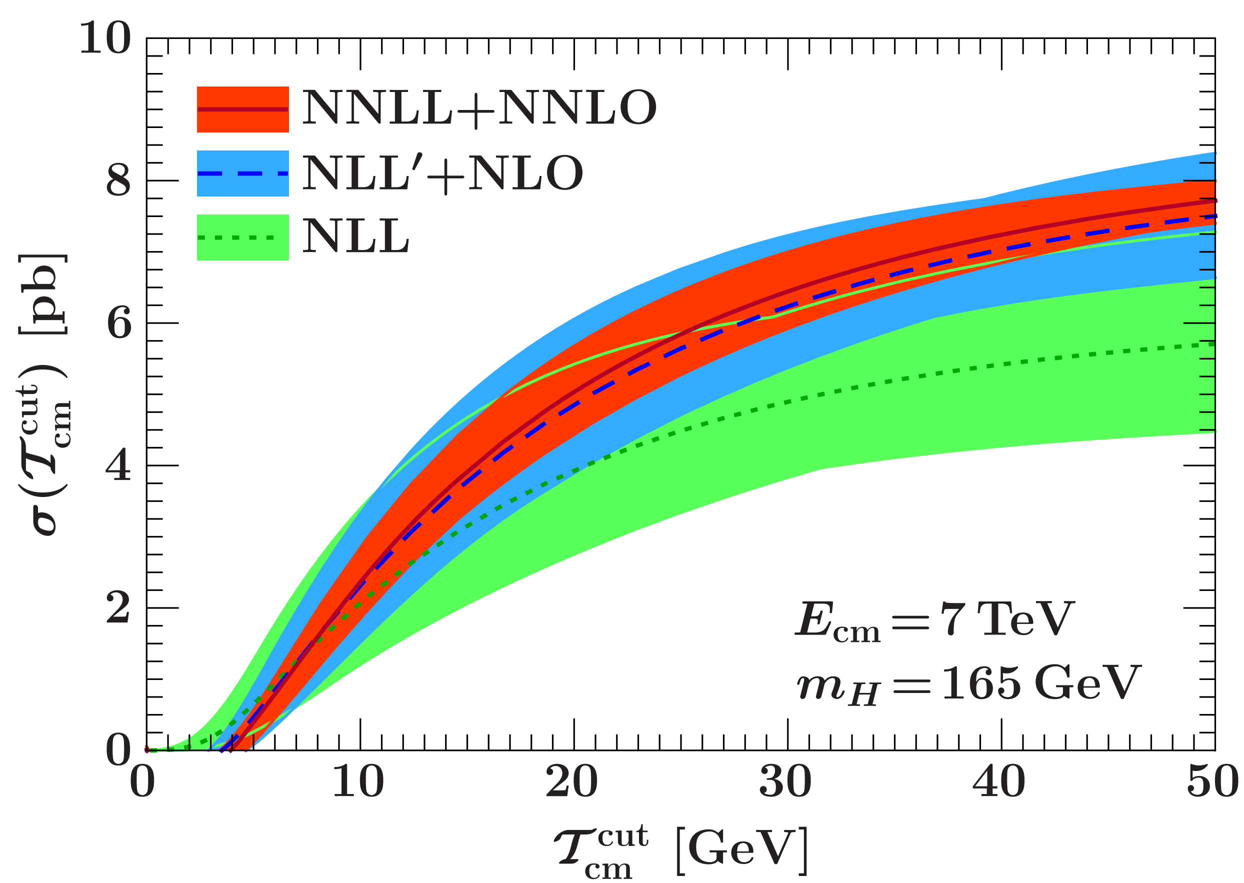
Perturbation theory at <u>each scale</u> contributes to uncertainties

Results:



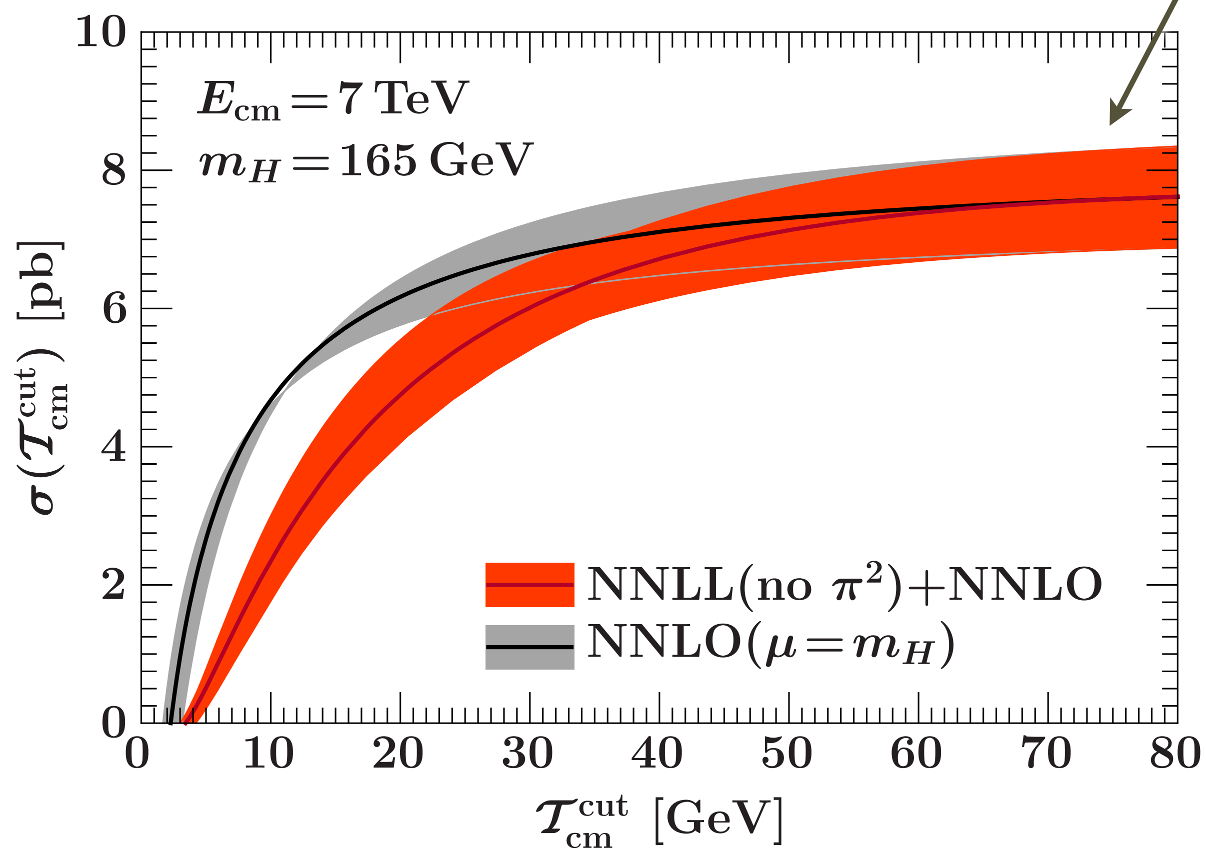


- large K factors (~2-3) in fixed order results are reduced by log + π^2 resummation

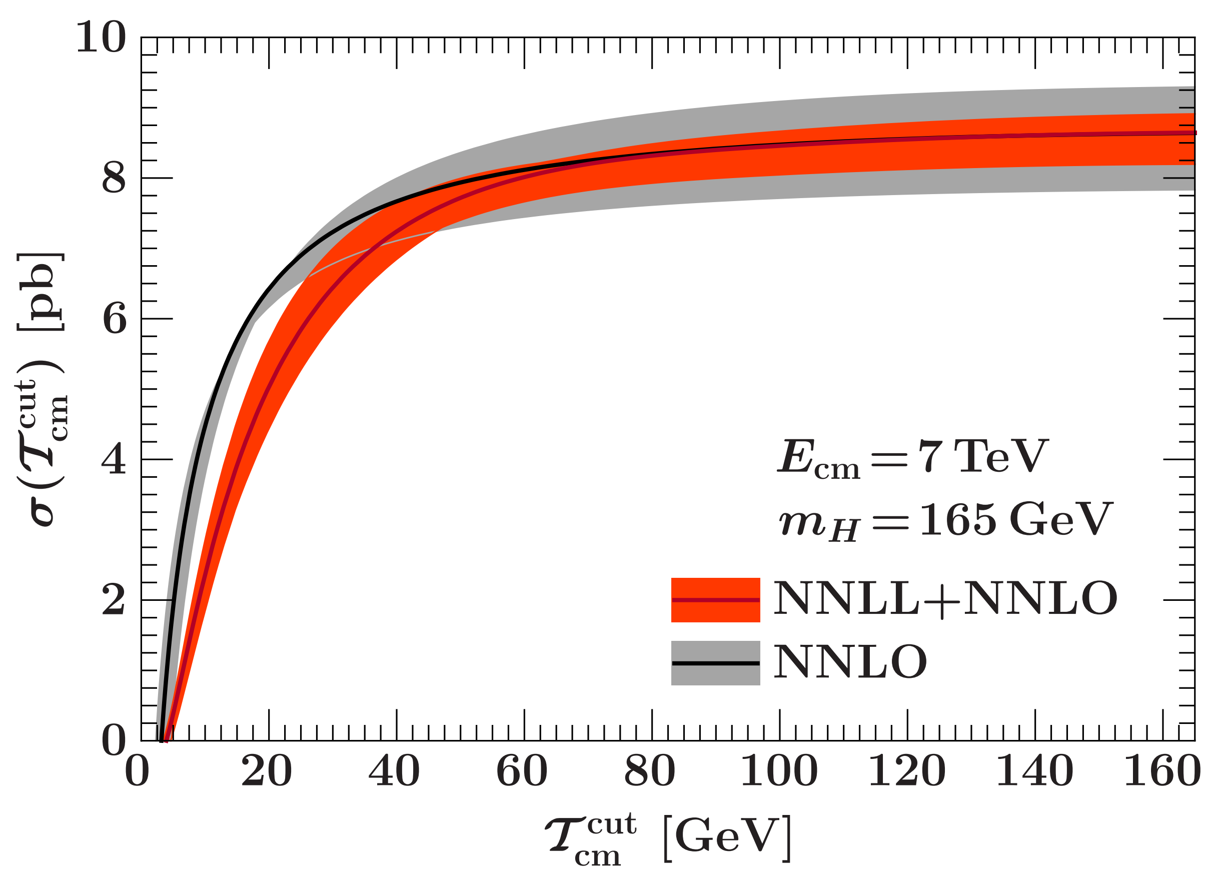


- theory error bands overlap, come from varying μ_H, μ_B, μ_S

Large $\mathcal{T}_{cm}^{cut}$



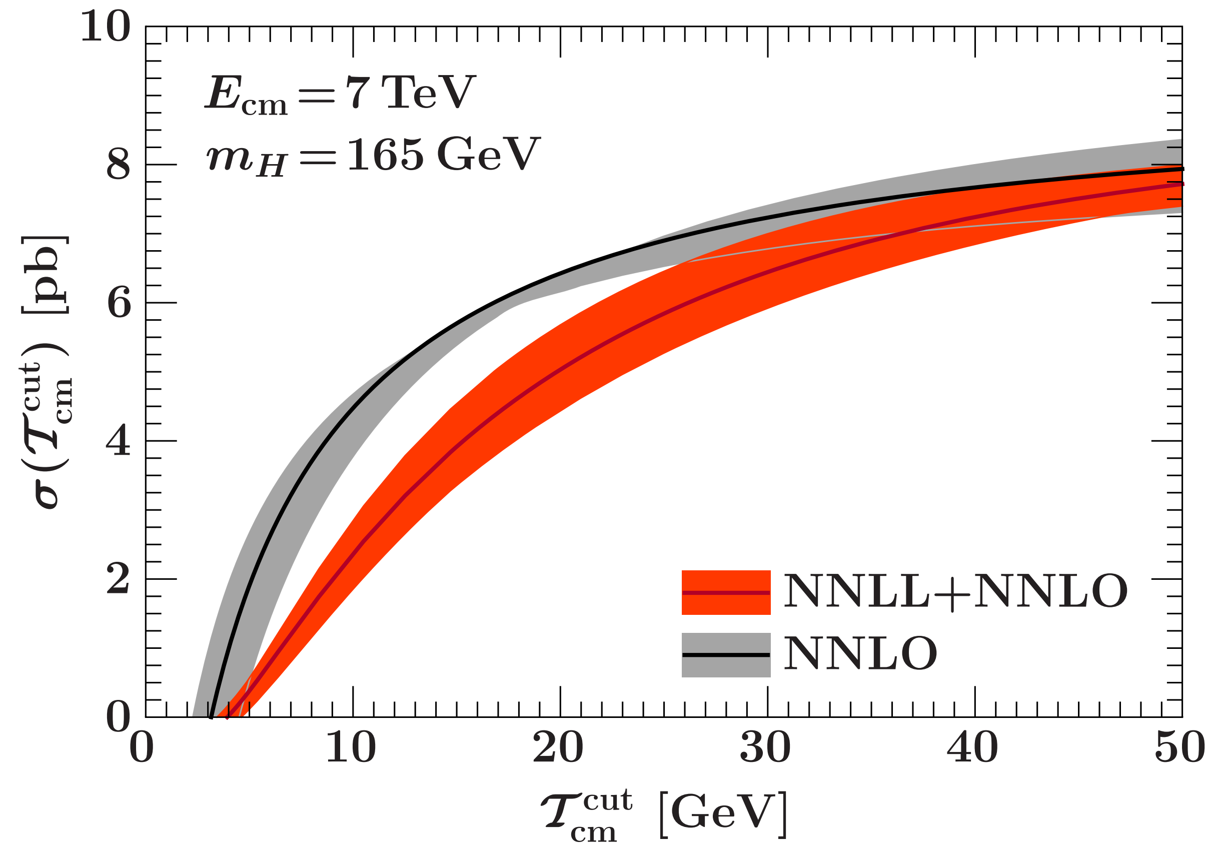
without jet veto, reproduce NNLO uncertainties



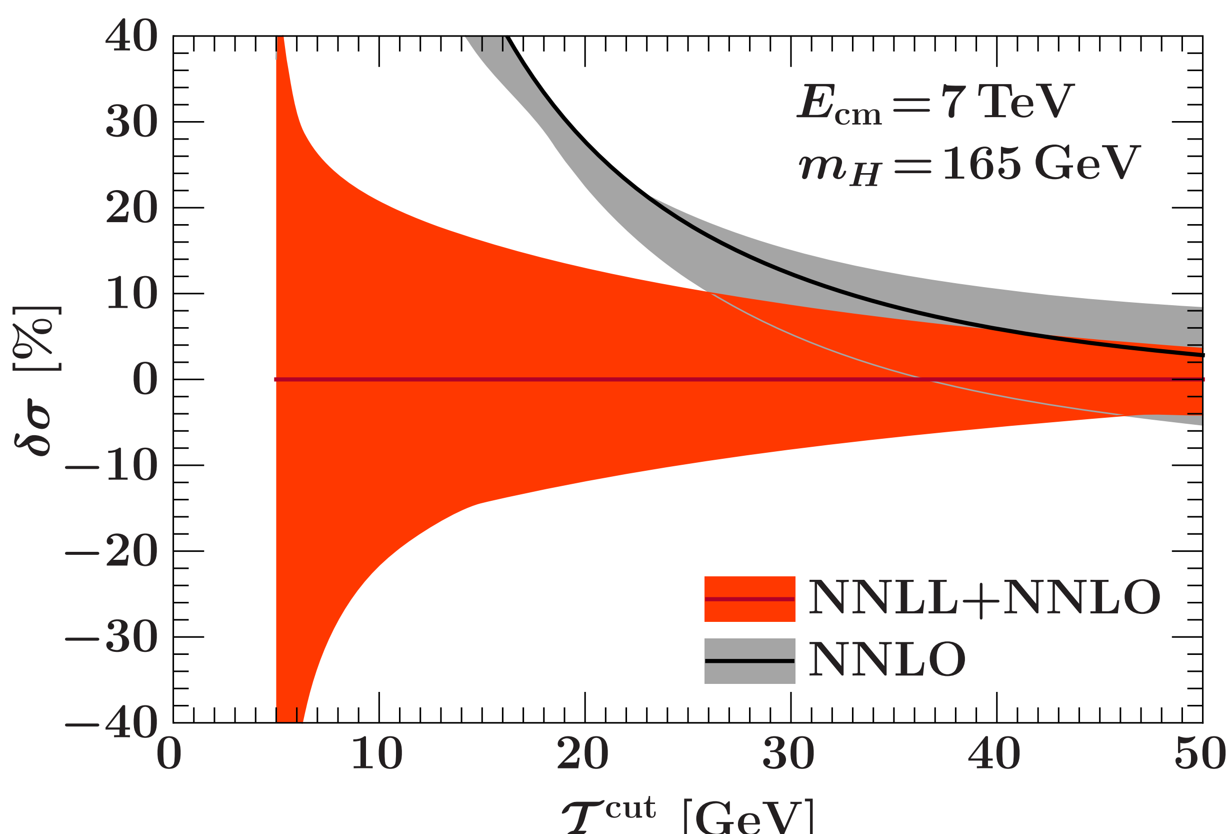
NNLL + NNLO with π^2 summation (default) vs. NNLO $(\mu = m_H/2)$

- central values agree at large $\mathcal{T}_{cm}^{cut}$
- π^2 summation reduces total cross section scale uncertainty (to 4% at LHC)

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



- NNLO not reliable for small $\mathcal{T}_{\rm cm}^{\rm cut}$
- logs are large, NNLL central value lower than NNLO (partly accounted for PS)



- scale uncertainty at NNLL+NNLO is 10-20%

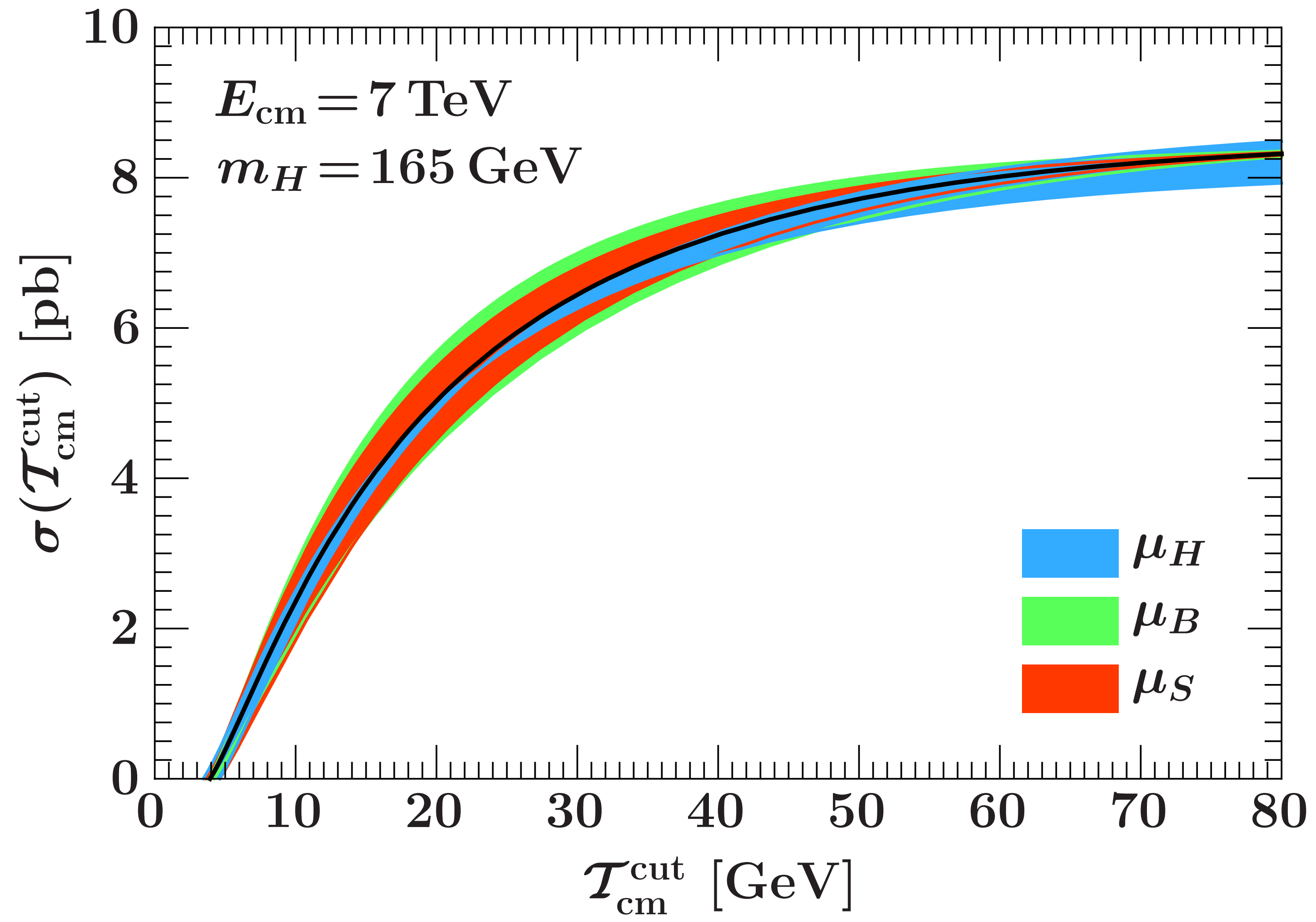
(Tevatron uncertainty slightly larger, and greater than 7% that is currently used)

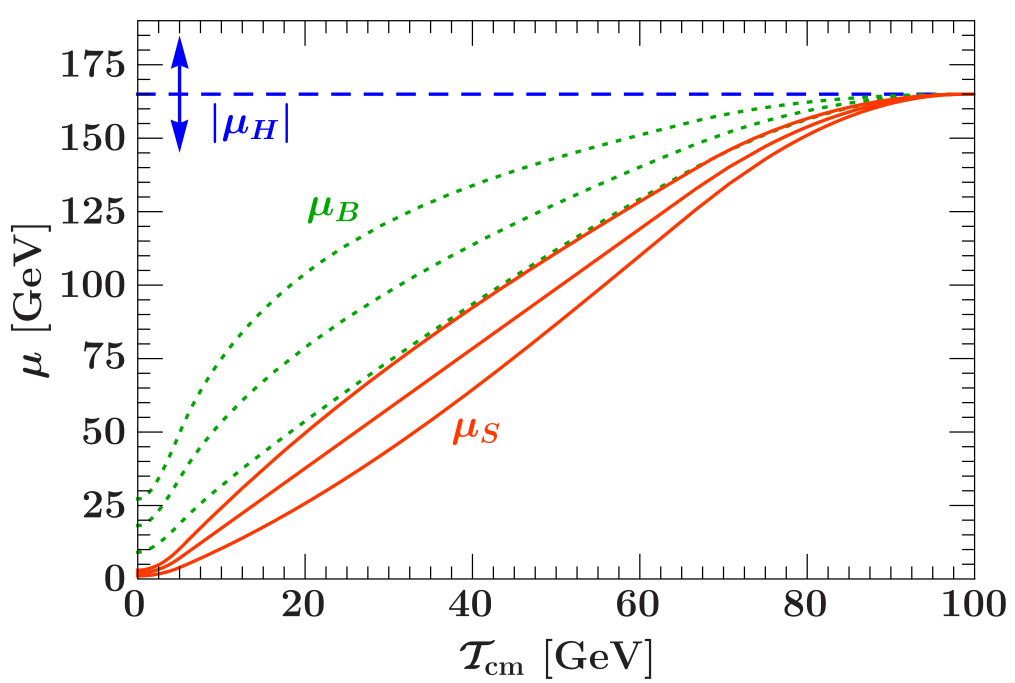
Small $\mathcal{T}_{cm}^{cut}$

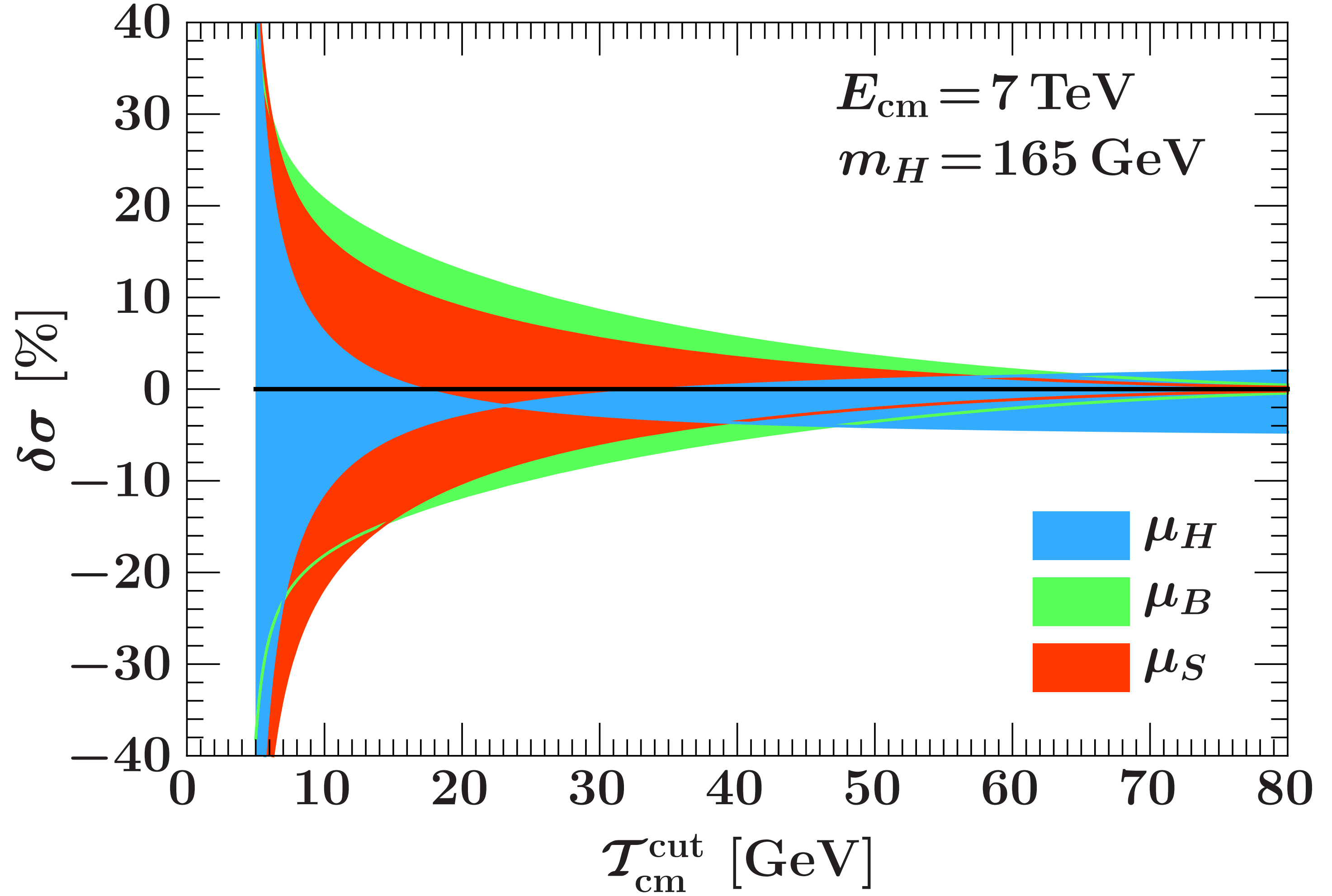
individual scale variations

- all previous plots show envelope of the three separate scale variations

- μ_B and μ_S dominate for small $\mathcal{T}_{cm}^{cut}$







Discussion: How should the results be used?

- Reweigh the partonic beam thrust spectrum in Monte Carlo to NNLL+NNLO. Then use it to analyze jets with a standard $p_T^{\rm cut}$ method.

  (add hadronization, underlying event, ...)

- Use MC to translate the NNLL+NNLO error band into an error for the 0-jet $p_T^{\rm cut}$ sample.

- When sample is divided into jet bins, theory errors are a matrix

eg. $0, \geq 1$ jets

$$\begin{pmatrix} \sigma_0^2 & \sigma_{0,\geq 1}^2 \\ \sigma_{0,\geq 1}^2 & \sigma_{\geq 1}^2 \end{pmatrix} \simeq \begin{pmatrix} \sigma_0^2 & -\sigma_0^2 \\ -\sigma_0^2 & \sigma_0^2 + \sigma_{\rm incl}^2 \end{pmatrix}$$

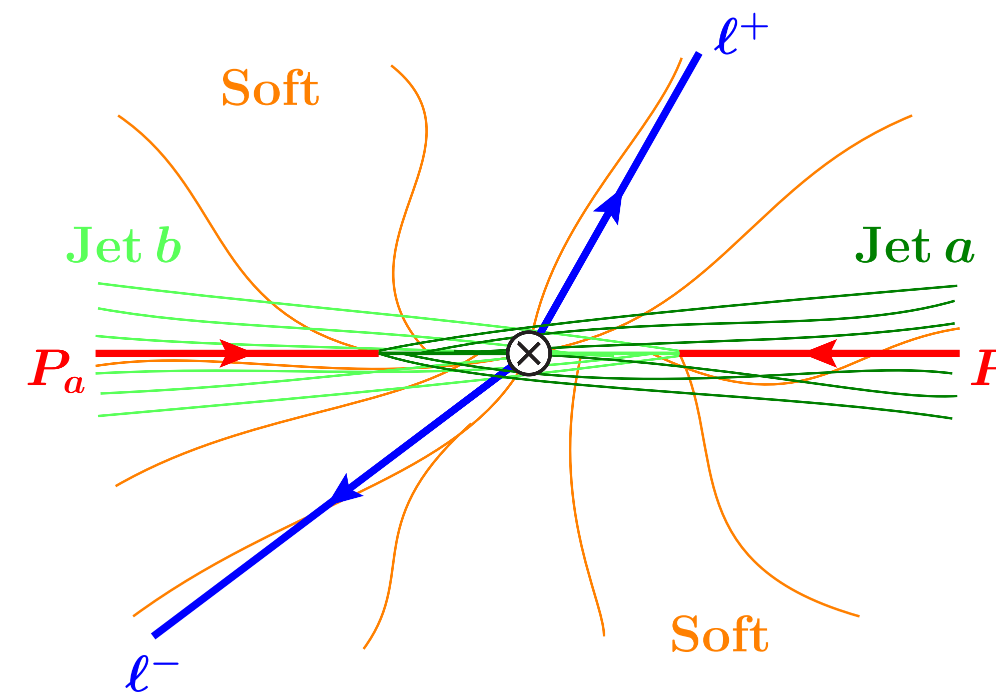
smaller incl. uncertainty constrains sum of all entries

eg. $0, 1, \geq 2$ jets

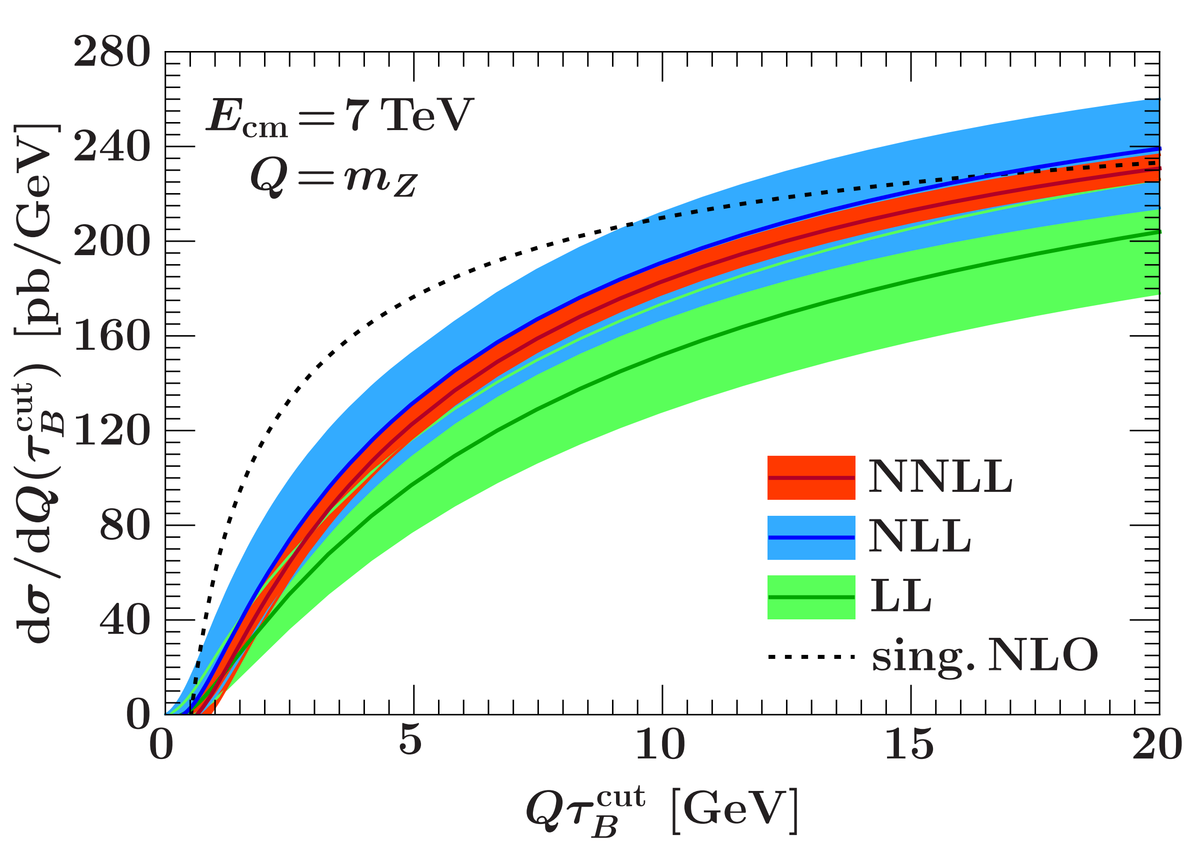
$$\begin{pmatrix} \sigma_0^2 & \sigma_{01}^2 & \sigma_{0,\geq 2}^2 \\ \sigma_{01}^2 & \sigma_1^2 & \sigma_{1,\geq 2}^2 \\ \sigma_{0,\geq 2}^2 & \sigma_{1,\geq 2}^2 & \sigma_{\geq 2}^2 \end{pmatrix}$$

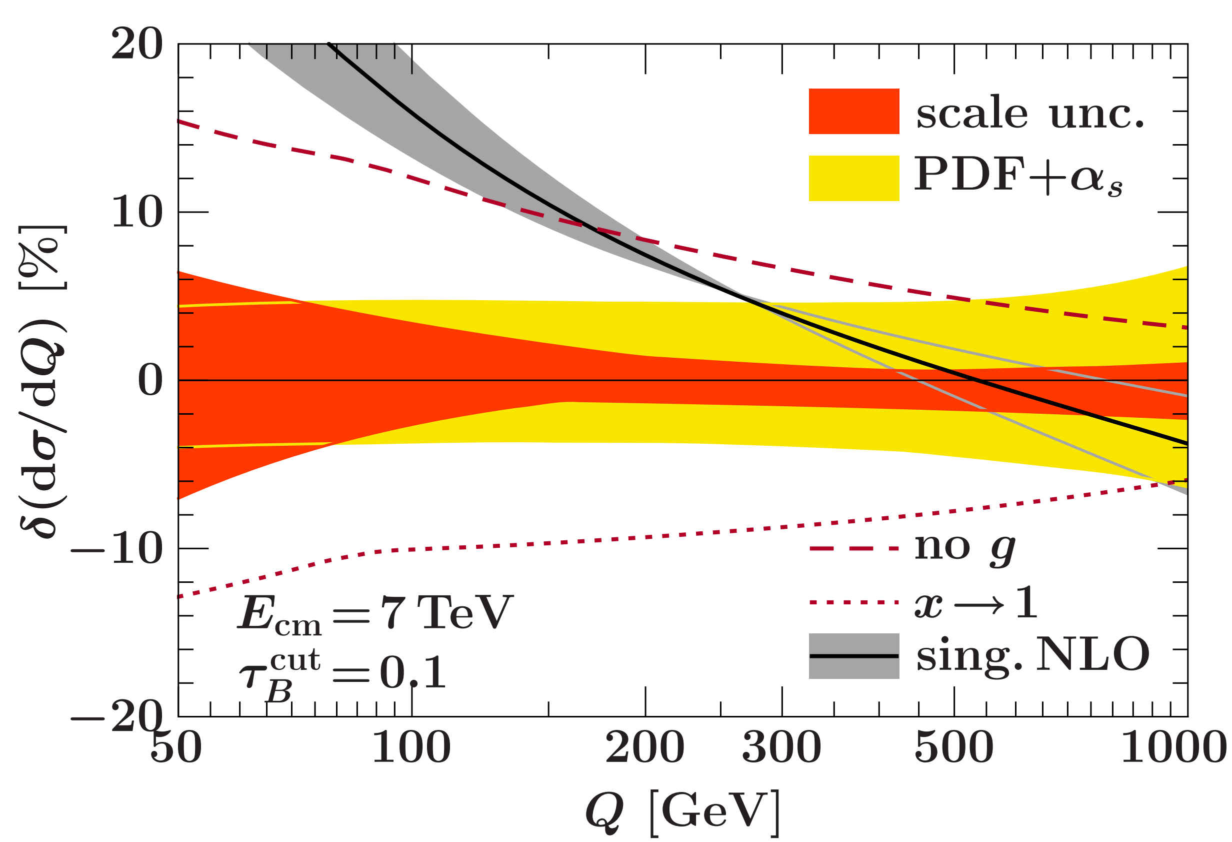
Validation? Other options?

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



- Directly measure beam thrust (important on its own).





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 calculations can be carried out for Higgs + 1 jet. This work is already in progress.
- What do you need? Wish list?

  Tables with results for a large number of mH values?
  Stand alone code that can be run on demand?

Backup

Signal and Background

Expected $WW \to e\nu\mu\nu$ events in $1\,\mathrm{fb}^{-1}$ [ATLAS arXiv:0901.0512]

Cut	$H \to WW$	$t\bar{t} \to WWb\bar{b}$	WW	$Z \to \tau\tau$	$W+$ jets
Lepton selection	166	6501	718	4171	209
$p_T^{\mathrm{miss}} > 30\,\mathrm{GeV}$	148	5617	505	526	182
$Z \to \tau\tau$ rejection	146	5215	485	164	150
Central jet veto	62	15	238	32	76
b-jet veto	62	7	238	31	76
$M_T < 600\,\mathrm{GeV}$, $\Delta\phi_{\ell\ell} < \pi/2$	50.6 ± 2.5	2.3 ± 1.6	85.4 ± 2.7	< 1.7	38 ± 38

- Central jet veto essential to eliminate huge $t\bar{t} \to WWb\bar{b}$ background
- Main irreducible background from $pp \to WW$