Theoretical predictions for Higgs measurements at the LHC

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Particle Phenomenology Seminar
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Outline:

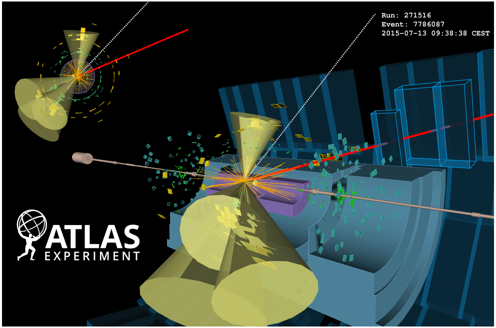
$\rightarrow$ What is ...

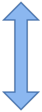
- NLO QCD+EW to pp $\rightarrow \mu^- \bar{\nu}_\mu \mathrm{e}^+ \nu_\mathrm{e} \bar{\mathrm{b}}\mathrm{b}\mathrm{H}$
- NLO QCD to pp $\rightarrow \mu^- \bar{\nu}_\mu \mathrm{e}^+ \nu_\mathrm{e} \bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{b}}\mathrm{b}$
- NNLO QCD+NLO EW to pp $\rightarrow$ jjHH via VBF

$\rightarrow$ ... and why you want to compute them

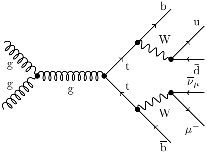
$\rightarrow$ Illustration of Giordano Bruno's philosophical ideas (XVIthcentury)

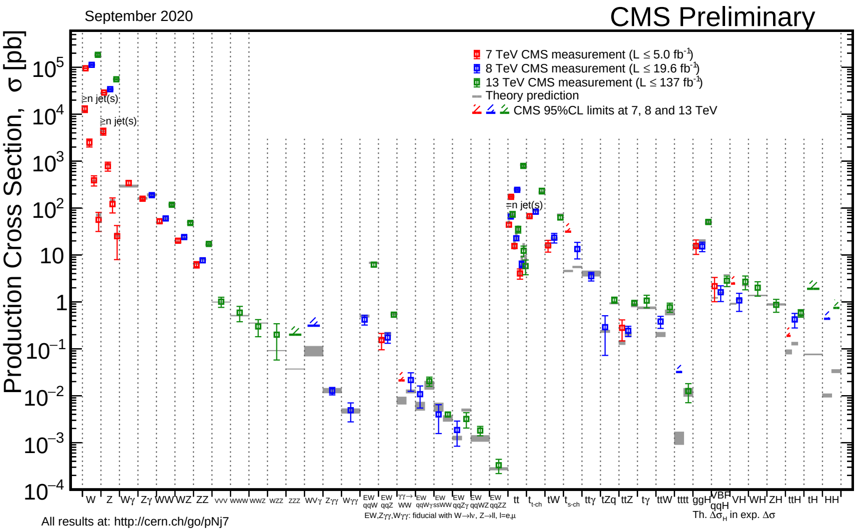
LHC: Great tool to probe fundamental interactions at high energies
→ Cross talk between **experiment** and **theory**





$$\mathrm{pp} \to \mathrm{t}^{\star}\bar{\mathrm{t}}^{\star} \to (\mathrm{W}^{\star} \to \nu_{\mu}\mu^{-})\,(\mathrm{W}^{\star} \to \mathrm{jj})\,\mathrm{b}\bar{\mathrm{b}}$$





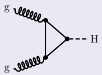
→ Cross-sections measurements machine!

- Greatest achievement of the LHC so far:

Discovery of the Higgs boson

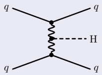
→ Great interest in measuring properties of the Higgs boson

Gluon fusion



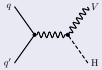
$\sigma_{\mathrm{ggF}} \approx 50\,\mathrm{pb}$

Vector-boson fusion



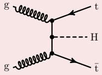
$\sigma_{\mathrm{vbf}} \approx 4\,\mathrm{pb}$

Higgs Strahlung



$\sigma_{\mathrm{HV}} \approx 2.5\,\mathrm{pb}$

$\mathrm{t\bar{t}H}$



$\sigma_{\mathrm{tth}} \approx 0.5\,\mathrm{pb}$

PHYSICAL REVIEW LETTERS **120,** 231801 (2018)

Editors' Suggestion | Featured in Physics

Observation of $t\bar{t}H$ Production

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

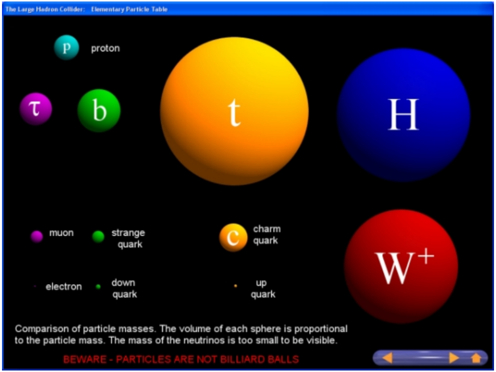
(Received 8 April 2018; revised manuscript received 1 May 2018; published 4 June 2018)

The observation of Higgs boson production in association with a top quark-antiquark pair is reported, based on a combined analysis of proton-proton collision data at center-of-mass energies of $\sqrt{s} = 7$, 8, and 13 TeV, corresponding to integrated luminosities of up to 5.1, 19.7, and 35.9 fb^{-1}, respectively. The data were collected with the CMS detector at the CERN LHC. The results of statistically independent searches for Higgs bosons produced in conjunction with a top quark-antiquark pair and decaying to pairs of W bosons, Z bosons, photons, τ leptons, or bottom quark jets are combined to maximize sensitivity. An excess of events is observed, with a significance of 5.2 standard deviations, over the expectation from the background-only hypothesis. The corresponding expected significance from the standard model for a Higgs boson mass of 125.09 GeV is 4.2 standard deviations. The combined best fit signal strength normalized to the standard model prediction is $1.26^{+0.31}_{-0.26}$.

DOI: 10.1103/PhysRevLett.120.231801

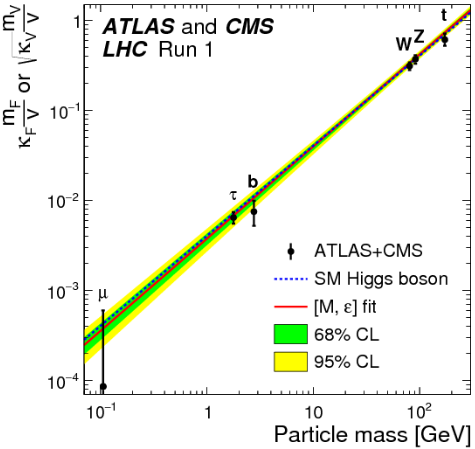
→ Rather recent measurement

- They are the heaviest particles of the Standard Model!



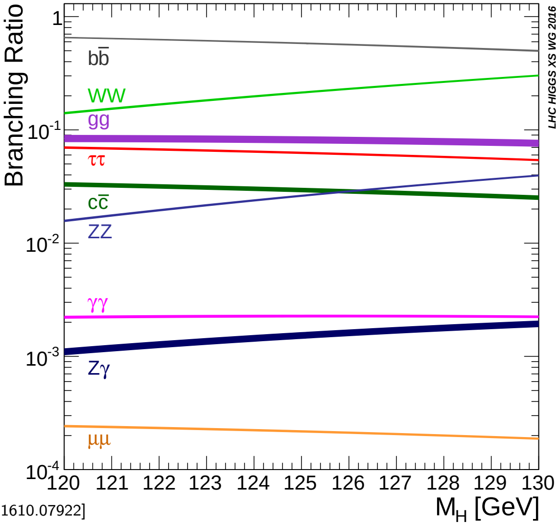
- ...

Yukawa coupling



→ Couplings and masses are proportional

Decay channels

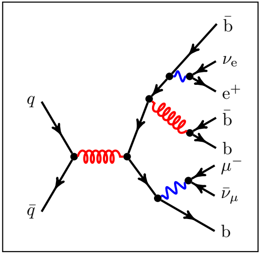


[de Florian et al.; 1610.07922]

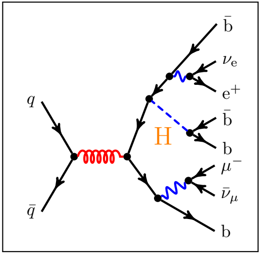
$\rightarrow$ $H \rightarrow b\bar{b}$ largest decay channel

$\mathrm{pp} \to \mu^- \bar{\nu}_\mu \mathrm{e}^+ \nu_\mathrm{e} \bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{b}}\mathrm{b}$

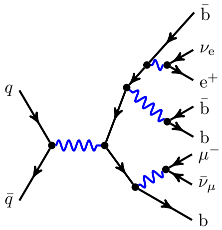
$$\mathrm{pp} \to \mathrm{t\bar{t}} \left(\mathrm{H} \to \mathrm{b\bar{b}}\right) = \mathrm{t\bar{t}b\bar{b}} = \mu^- \bar{\nu}_\mu \mathrm{e}^+ \nu_\mathrm{e} \bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{b}}\mathrm{b}$$



$\mathcal{O}\left(\alpha_\mathrm{s}{}^4\alpha^6\right)$



$\mathcal{O}\left(\alpha_\mathrm{s}{}^2\alpha^6\right)$



$\mathcal{O}\left(\alpha^8\right)$

Questions?

Why do you want to do a high-multiplicity computation?

- ☐ because I can
- ☐ because I have nothing else to do
- ☐ because nobody did it before
- ☐ because it is relevant

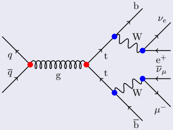
→ Because you want the best possible predictions

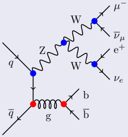
- higher-order corrections in α_s and α
- improvement of parton-shower simulation
- inclusion of **off-shell effects**

off-shell effects

- Invariants off their mass shells
  $\rightarrow$ *e.g.* $M_{\ell\nu\mathrm{b}} \neq m_{\mathrm{top}}$

- Non-resonant contributions

  $\rightarrow$ *e.g.* 

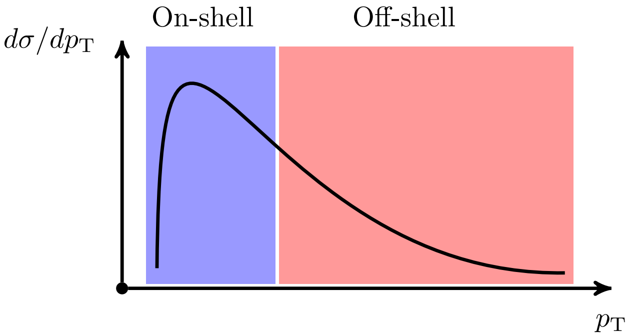
vs. 

- Description of the final state
  $\rightarrow$ *e.g.* $\mathrm{pp} \rightarrow \mathrm{t\bar{t}}$ vs. $\mathrm{pp} \rightarrow \nu_\mu \mu^- \bar{\nu}_\mathrm{e} \mathrm{e}^+ \mathrm{b\bar{b}}$

$\rightarrow$ All these effects are very much connected

off-shell effects

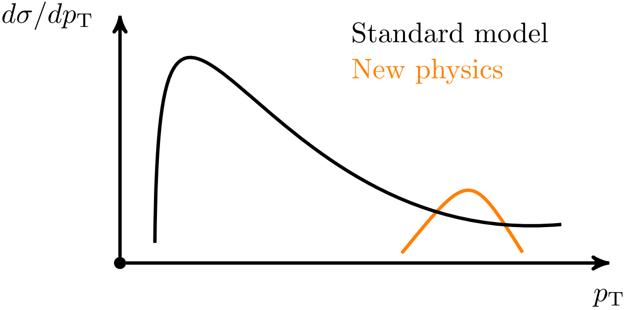
- Final states dominated by a production process
- Example: measured final state $\mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$ dominated by $\mathrm{pp} \to \mathrm{t}^\star\bar{\mathrm{t}}^\star \to (\mathrm{W}^\star \to \nu_\mu\mu^-)\,(\mathrm{W}^\star \to \mathrm{e}^+\nu_\mathrm{e})\,\mathrm{b}\bar{\mathrm{b}}$



On-shell region dominated by resonant production

Off-shell region receives large non-resonant contributions

Tail of distributions



→ During run II/III, the tail of the distributions will be probed
→ New physics contributions?

State of the art: high-multiplicity processes

- $2 \to 6$ processes
  off-shell top quarks, tri-boson, vector-boson scattering ...
  .. but only two computations publicly available with non-trivial resonance structure:
  $\rightarrow$ NLO QCD to off-shell tt [Ježo et al.; 1607.04538]
  $\rightarrow$ NLO EW to VBS same-sign W [Chiesa, Denner, Lang, MP; 1906.01863]

- $2 \to 7$ processes
  $\rightarrow$ NLO QCD to $\mathbf{t\bar{t}H}$ [Denner, Feger; 1506.07448]
  $\rightarrow$ NLO QCD to $\mathbf{t\bar{t}j}$ [Bevilacqua et al.; 1509.09242, 1609.01659]
  $\rightarrow$ NLO EW to $\mathbf{t\bar{t}H}$ [Denner, Lang, MP, Uccirati; 1612.07138]
  $\rightarrow$ NLO QCD to $\mathbf{Wb\bar{b}jjj}$ [Anger et al.; 1712.05721]
  $\rightarrow$ NLO QCD to $\mathbf{t\bar{t}}\gamma$ [Bevilacqua et al.; 1803.09916]

- $2 \to 8$ processes
  $\rightarrow$ NLO QCD to $\mathbf{t\bar{t}}(\mathbf{Z} \to \nu\bar{\nu})$ [Bevilacqua et al.; 1907.09359]
  $\rightarrow$ NLO QCD to $\mathbf{t\bar{t}W}$ [Bevilacqua et al.; 2005.09427], [Denner; Pellicciolі; 2007.12089]
  $\rightarrow$ NLO QCD to $\mathbf{t\bar{t}b\bar{b}}$ **[Denner, Lang, MP; 2008.00918]**

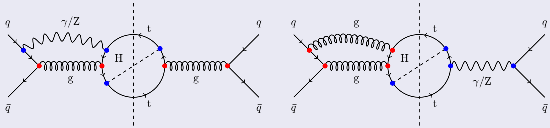
- NLO QCD+EW to $\mathrm{pp} \to \mu^- \bar{\nu}_\mu \mathrm{e}^+ \nu_\mathrm{e} \bar{\mathrm{b}} \mathrm{b} \mathrm{H}$

State of the art top-antitop production and a Higgs
(with on-shell Higgs)

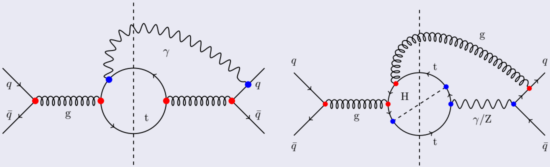
- NLO QCD [Beenakker et al.; hep-ph/0107081, hep-ph/0211352], [Dawson et al.; hep-ph/0107101, hep-ph/0305087]
  → With off-shell effects [Denner, Feger; 1506.07448] (LHC), [Chokoufé-Nejad et al.; 1609.03390] (Linear collider)
- NLO EW [Frixione et al.; 1407.0823, 1504.03446], [Zhang et al.; 1407.1110]
  → With off-shell effects **[Denner, Lang, MP, Uccirati; 1612.07138]**
- Resummation [Broggio et al.; 1510.01914, 1611.00049], [Kulesza et al.; 1509.02780, 2001.03031]
  → Combined with NLO EW [Broggio et al.; 1907.04343]
- NLO QCD matched to PS [Frederix et al.; 1104.5613], [Garzelli et al.; 1108.0387], [Hartanto et al.; 1501.04498]

Computation of EW corrections

Virtual corrections ...

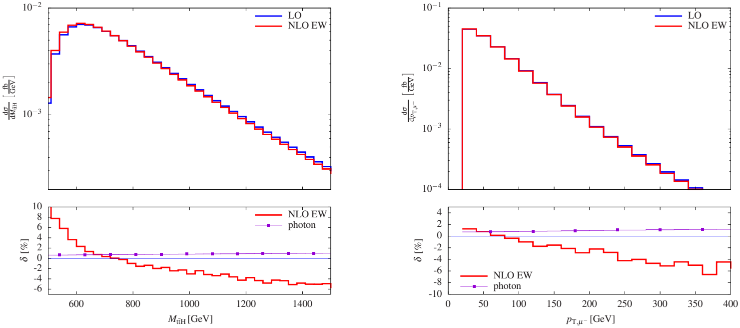


... with the corresponding real radiations



No $V = W, Z$ radiation taking into account (exprimentally different signature)
→ Sudakov logarithms: $-\log^2\left(s_{ij}/M_V^2\right)$

Differential distribution NLO EW to pp $\to$ t$\bar{\text{t}}$H



$\to$ Clear effect of Sudakov logarithms

Combination of EW and QCD corrections

$$\sigma_{\mathrm{QCD}}^{\mathrm{NLO}} = \sigma^{\mathrm{Born}} + \delta\sigma_{\mathrm{QCD}}^{\mathrm{NLO}} \quad \text{and} \quad \sigma_{\mathrm{EW}}^{\mathrm{NLO}} = \sigma^{\mathrm{Born}} + \delta\sigma_{\mathrm{EW}}^{\mathrm{NLO}}$$

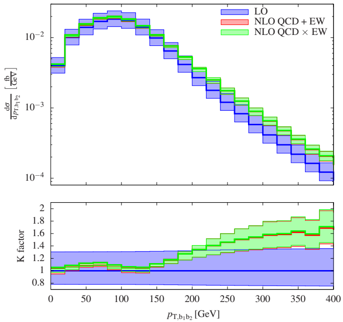
→ **Additive** and **multiplicative** combination:

$$\sigma_{\mathrm{QCD+EW}}^{\mathrm{NLO}} = \sigma^{\mathrm{Born}} + \delta\sigma_{\mathrm{QCD}}^{\mathrm{NLO}} + \delta\sigma_{\mathrm{EW}}^{\mathrm{NLO}}$$

and

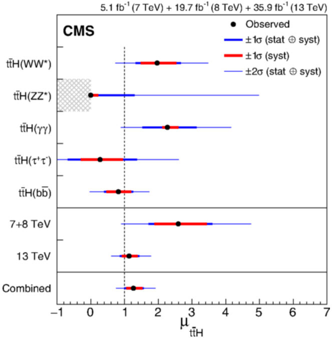
$$\sigma_{\mathrm{QCD}\times\mathrm{EW}}^{\mathrm{NLO}} = \sigma_{\mathrm{QCD}}^{\mathrm{NLO}} \left(1 + \frac{\delta\sigma_{\mathrm{EW}}^{\mathrm{NLO}}}{\sigma^{\mathrm{Born}}}\right) = \sigma_{\mathrm{EW}}^{\mathrm{NLO}} \left(1 + \frac{\delta\sigma_{\mathrm{QCD}}^{\mathrm{NLO}}}{\sigma^{\mathrm{Born}}}\right)$$

Differential distribution NLO QCD+EW to pp → $t\bar{t}H$



- → Potentially large effects
- → State of the art predictions at fixed order
- → Difference of two prescriptions: estimate of mixed corrections

- NLO QCD to $\mathrm{pp} \to \mu^-\bar{\nu}_\mu \mathrm{e}^+\nu_\mathrm{e}\bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{b}}\mathrm{b}$



[CMS; 1804.02610]

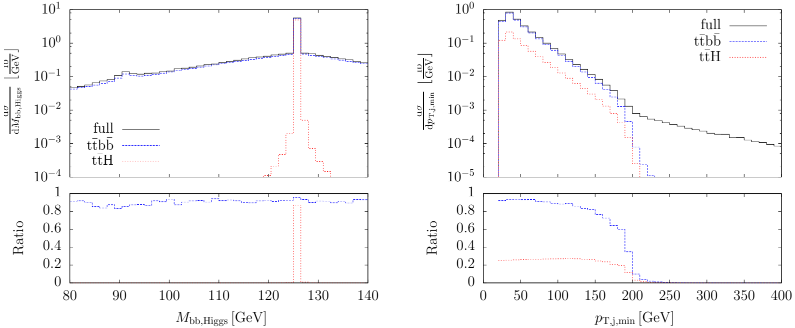
- $\mathrm{pp} \to \mathrm{t\bar{t}}\left(\mathrm{H} \to \mathrm{b\bar{b}}\right)$ systematically limited
  $\to$ Modelisation of the background

scenario	Cross section [fb]						
	$\mathcal{O}((\alpha^4)^2)$	$\mathcal{O}((\alpha_s\alpha^3)^2)$	$\mathcal{O}((\alpha_s^2\alpha^2)^2)$	$\mathcal{O}((\alpha_s^3\alpha)^2)$	Sum	Total	Int
$\mathrm{t\bar{t}H}$	0.014887(2)	7.377(1)	—	—	7.3920(9)	7.3920(9)	—
$\mathrm{t\bar{t}b\bar{b}}$	0.018134(6)	10.311(4)	17.570(9)	—	27.90(1)	26.446(7)	-5.2(3)%
full process	0.02120(3)	10.87(2)	18.69(6)	0.516(2)	30.10 (6)	28.60 (6)	-5.50(5)%

[de Florian et al.; 1610.07922]

LO $pp \to \ell^+\nu_\ell jjb\bar{b}b\bar{b}$

- Full: $pp \to \ell^+\nu_\ell jjb\bar{b}b\bar{b}$ at $\mathcal{O}(\alpha^8)$, $\mathcal{O}(\alpha_s^2\alpha^6)$, $\mathcal{O}(\alpha_s^4\alpha^4)$
- ttbb: $pp \to t\bar{t}b\bar{b} \to \ell^+\nu_\ell jjb\bar{b}b\bar{b}$ at $\mathcal{O}(\alpha^8)$, $\mathcal{O}(\alpha_s^2\alpha^6)$, $\mathcal{O}(\alpha_s^4\alpha^4)$
- tth: $pp \to t\bar{t}H \to \ell^+\nu_\ell jjb\bar{b}b\bar{b}$ at $\mathcal{O}(\alpha_s^2\alpha^6)$



[Denner, Feger, Scharf; 1412.5290]

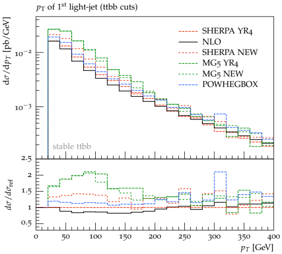
→ In the full calculation, jets are not only coming from top decays

↪ large effects at high transverse momentum

Status of ttbb predictions

- Theory overestimates experimental measurement by $30-50\%$
- Differences found in NLO+PS generator in [de Florian et al.; 1610.07922]

NLOPS $t\bar{t}b\bar{b}$ discrepancies



Main origin of differences ($N_b \geq 2$ phase space)

- NLOPS/NLO enhancements of $\mathcal{O}(100\%)$ in light-jet p_T spectrum
- understanding this excess crucial for uncertainty modelling

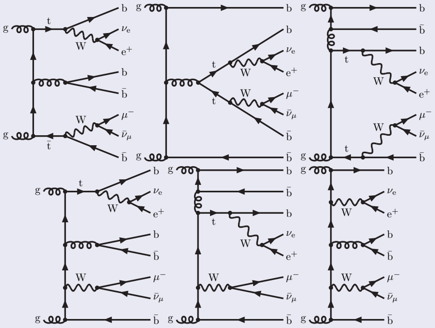
Slide from Pozzorini `https://indico.cern.ch/event/964993`

State of the art $t\bar{t}b\bar{b}$ production

- NLO QCD [Bredenstein et al.; 0807.1248, 0905.0110, 1001.4006], [Bevilacqua et al.; 0907.4723], [Kardos et al.; 1303.6291], [Bevilacqua et al.; 1709.06915]

  $\rightarrow$ With off-shell effects: **[Denner, Lang, MP; 2008.00918]**
- NLO QCD matched to PS [Cascioli et al.; 1309.5912], [Garzelli et al.; 1408.0266], [Ježo et al.; 1802.00426]
- $t\bar{t}b\bar{b}+j$ [Buccioni et al.; 1907.13624]

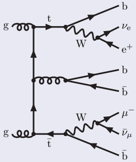
Features of the computation - [Denner, Lang, MP; 2008.00918]



- Full description of the physical final state
- All non-resonant and off-shell effects included
- NLO QCD computation to pp $\rightarrow \mu^-\bar{\nu}_\mu e^+\nu_e \bar{b}b\bar{b}b$
- 5-flavour scheme

Definition of bottom quarks not coming from top quarks

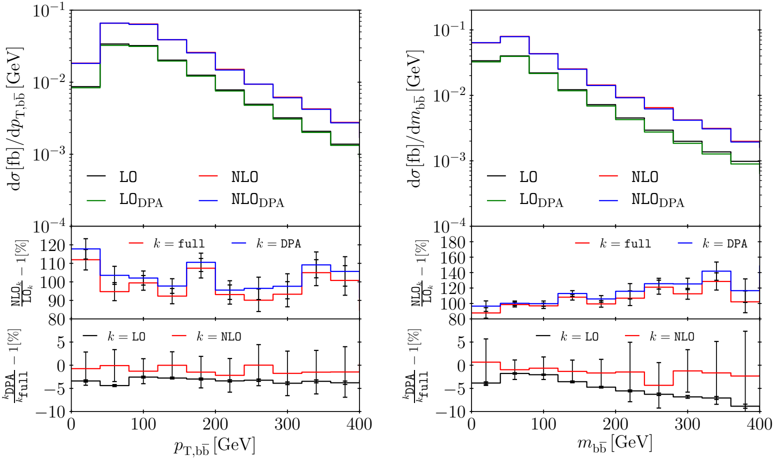
$\rightarrow$ Bottom quarks that correspond to $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ in the signal?



$\rightarrow$ In $\mu^-\bar{\nu}_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{b}b\bar{b}b}$, no explicit reference to top quarks

Bottoms from tops, determined by maximising

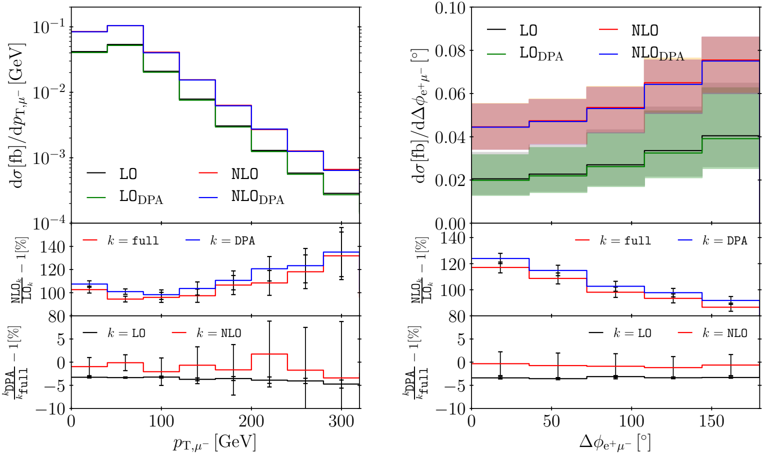
$$\mathcal{L}_{ij} = \frac{1}{\left(p^2_{\mu^-\bar{\nu}_\mu \mathrm{b}_i} - m_\mathrm{t}^2\right)^2 + (m_\mathrm{t}\Gamma_\mathrm{t})^2} \; \frac{1}{\left(p^2_{\mathrm{e}^+\nu_\mathrm{e}\mathrm{b}_j} - m_\mathrm{t}^2\right)^2 + (m_\mathrm{t}\Gamma_\mathrm{t})^2}$$



[Denner, Lang, MP; 2008.00918]

- Observables for bottoms not from top quarks
- Different NLO QCD behaviour for $m_{\mathrm{b\bar{b}}}$ with respect to

[Bredenstein, Denner, Dittmaier, Pozzorini; 1001.4006]

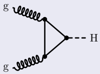


[Denner, Lang, MP; 2008.00918]

- Significant shape distortions for some distributions

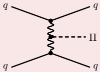
- NNLO QCD+NLO EW to pp $\rightarrow$ jjHH via VBF

Gluon fusion

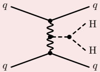


$\sigma_{\mathrm{ggF}} \approx 50\,\mathrm{pb}$

Vector-boson fusion

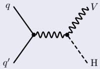


$\sigma_{\mathrm{vbf}} \approx 4\,\mathrm{pb} \rightarrow$



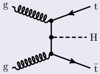
$\sigma_{\mathrm{vbf}} \approx 1 \cdot 10^{-3}\,\mathrm{pb} = 1\,\mathrm{fb}$

Higgs Strahlung



$\sigma_{\mathrm{HV}} \approx 2.5\,\mathrm{pb}$

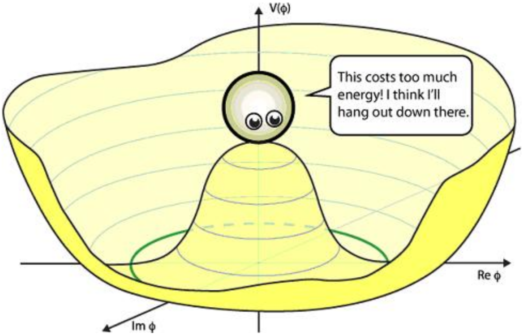
$t\bar{t}H$



$\sigma_{\mathrm{tth}} \approx 0.5\,\mathrm{pb}$

Why is pp $\rightarrow$ jjHH via VBF relevant at all?!

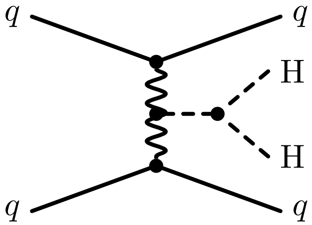
- Lower cross section than gg $\rightarrow$ HH but better handle with jets
- Only measurable at High-Luminosity LHC ($3000\,\mathrm{fb}^{-1}$)
  $\rightarrow$ Already intensively looked for by ATLAS and CMS
- Determination of the triple-Higgs coupling
  $\rightarrow$ Determination of the Higgs potential!



Definition

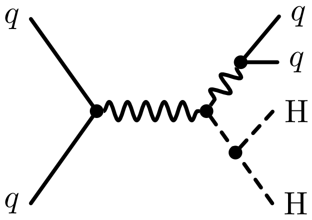
LO definition

- Final state: jjHH
- Order: $\mathcal{O}\left(\alpha^4\right)$



VBF contribution

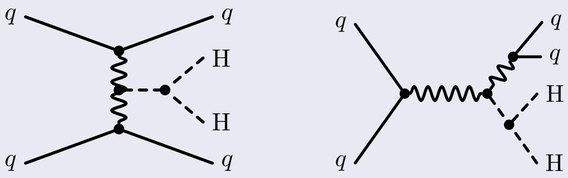
$\rightarrow$



s-channel contributions

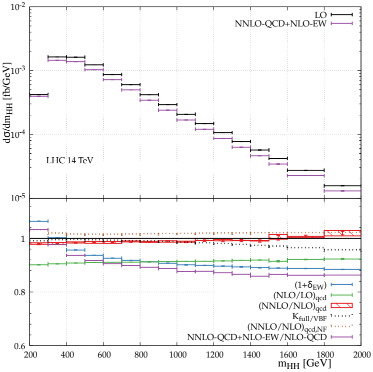
$\rightarrow$ Various contributions enhanced by experimental cuts ...
... in particular $m_{\mathrm{jj}}, \delta y_{\mathrm{jj}}$

Features of the computation - [Dreyer, Karlberg, Lang, MP; 2005.13341]



- Full NLO QCD (compared against approximate)
  $\rightarrow K_{\mathrm{full/VBF}} = \frac{d\sigma^{\mathrm{full}}_{\mathrm{LO}}}{d\sigma^{\mathrm{VBF}}_{\mathrm{LO}}}$
- Approximate NNLO QCD [Dreyer, Karlberg, (Tancredi); 1811.07918, (2005.11334)]
  $\rightarrow \sigma_{\mathrm{NNLO\ QCD}} = \sigma^{\mathrm{full}}_{\mathrm{LO}} + \delta^{\mathrm{full}}_{\mathrm{NLO\ QCD}} + K_{\mathrm{full/VBF}}\delta^{\mathrm{VBF}}_{\mathrm{NNLO\ QCD}}$
- Full NLO EW
- Combination of NNLO QCD with NLO EW corrections
  $\rightarrow \sigma_{\mathrm{NNLO\ QCD\times NLO\ EW}} = \sigma_{\mathrm{NNLO\ QCD}} \left(1 + \frac{\delta^{\mathrm{full}}_{\mathrm{NLO\ EW}}}{\sigma^{\mathrm{full}}_{\mathrm{LO}}}\right)$

Differential distributions



- Typical Sudakov effects
- Non-VBF contributions visible

Summary

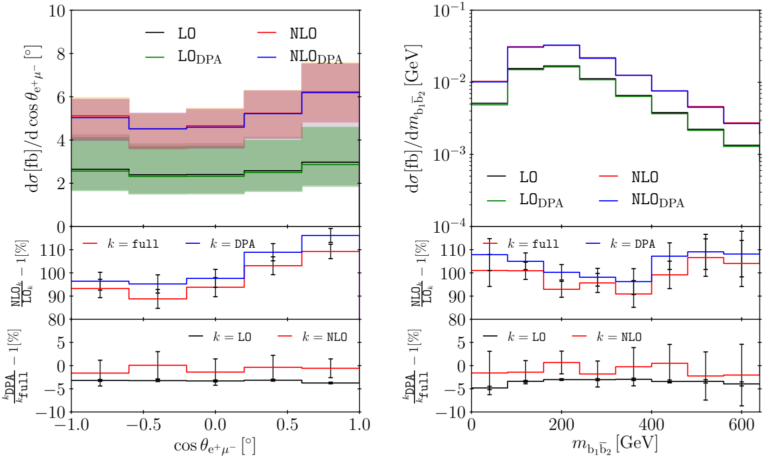
New computations for tth, ttbb, vbf HH...

- Decisive information for SM measurements
- Important information for BSM searches

Thank you

BACK-UP

Differential distributions



[Denner, Lang, MP; 2008.00918]

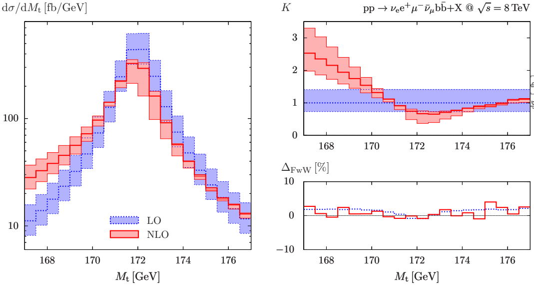
Description bb4l

label	$t\bar{t}$	$t\bar{t} \otimes$ decay	$b\bar{b}4\ell$
generator	`hvq` [20]	`ttb_NLO_dec` [35]	`bb4l`
framework	`POWHEG-BOX`	`POWHEG-BOX-V2`	`POWHEG-BOX-RES`
NLO matrix elements	$t\bar{t}$	$t(\to \ell^+\nu_\ell b)\,\bar{t}(\to l^-\bar{\nu}_l\bar{b})$	$\ell^+\nu_\ell\, l^-\bar{\nu}_l\, b\,\bar{b}$
decay accuracy	LO+PS	NLO+PS	NLO+PS
NLO radiation	single	multiple	multiple
spin correlations	approx.	exact	exact
off-shell $t\bar{t}$ effects	BW smearing	LO $b\bar{b}4\ell$ reweighting	exact
Wt & non-resonant effects	no	LO $b\bar{b}4\ell$ reweighting	exact
b-quark massive	yes	yes	yes

[Ježo et al.; 1607.04538]

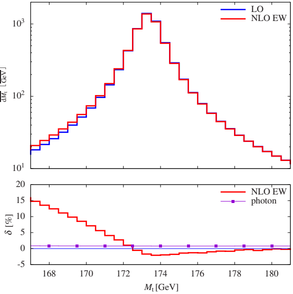
a) NLO QCD/EW to $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$

NLO QCD



[Denner et al.; 1207.5018]

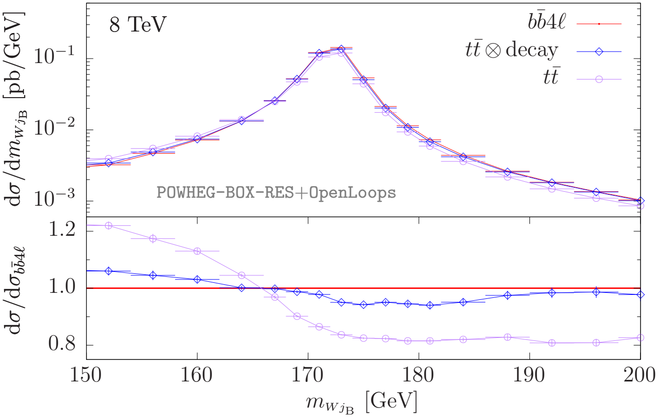
NLO EW



[Denner, MP; 1607.05571]

$\rightarrow$ Radiative tail due to non-reconstructed jets/photons

b) NLO QCD to pp $\rightarrow \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu \mathrm{b}\bar{\mathrm{b}}$



[Ježo et al.; 1607.04538]

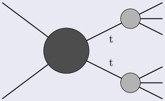
→ Different treatments of resonances

→ Inclusion of non-resonant contributions and all NLO corrections

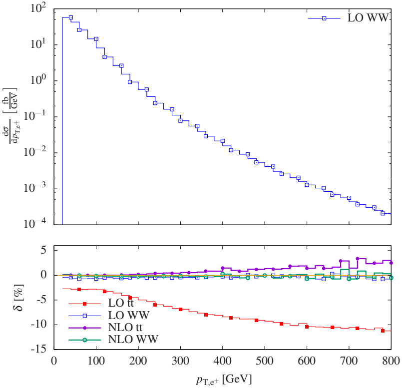
c) LO: $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$

Retain resonant contributions

$\to$ **tt**



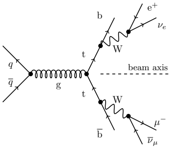
(off-shell propagators and full phase space included)

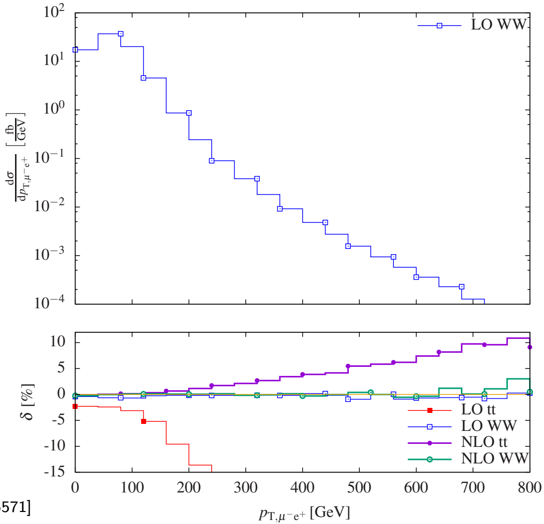


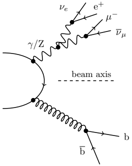
[Denner, MP; 1607.05571]

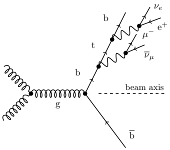
$\to$ Effect of non-doubly resonant top contributions

d) LO: $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu \mathrm{b}\bar{\mathrm{b}}$





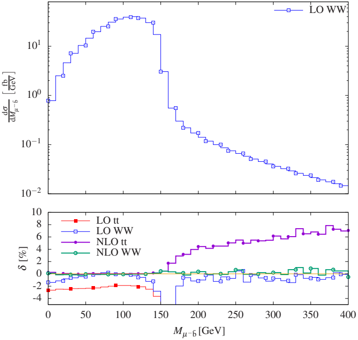




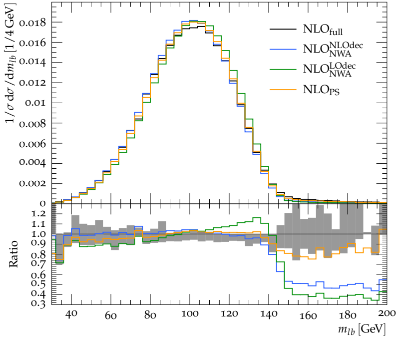
[Denner, MP; 1607.05571]

→ Even more stringent effect for exclusive observables

e) (N)LO QCD to $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$



[Denner, MP; 1607.05571]



[Heinrich et al.; 1709.08615]

→ Kinematic edge: $M^2_{\mu^-\bar{\mathrm{b}}} < M^2_{\mathrm{t}} - M^2_{\mathrm{W}} \simeq (154\,\mathrm{GeV})^2$
[Denner et al.; 1207.5018]

→ Large effects above threshold

→ Similar study for $\mathrm{t\bar{t}} + \mathrm{j}$ [Bevilacqua et al.; 1710.07515]

Tools

- Virtual corrections:
  - RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati; 1605.01090, 1705.06053]
    → http://recola.hepforge.org
  - COLLIER [Denner, Dittmaier, Hofer; 1604.06792]
    → http://collier.hepforge.org
- Private multi-channel Monte Carlo MoCaNLO [Feger]
- Dipole subtraction scheme
  [Catani,Seymour; hep-ph/9605323], [Dittmaier; hep-ph/9904440]
- Complex-mass scheme [Denner et al.; hep-ph/9904472, hep-ph/0505042, hep-ph/0605312]

Input parameters

→ G_μ scheme:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_\mathrm{W}^2 \left(1 - \frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}\right) \quad \text{with} \quad G_\mu = 1.16637 \times 10^{-5}\,\mathrm{GeV}$$

→ Parameters:

$$\begin{aligned} m_\mathrm{t} &= 173\,\mathrm{GeV}, & M_\mathrm{H} &= 125\,\mathrm{GeV} \\ M_\mathrm{Z}^\mathrm{OS} &= 91.1876\,\mathrm{GeV}, & \Gamma_\mathrm{Z}^\mathrm{OS} &= 2.4952\,\mathrm{GeV} \\ M_\mathrm{W}^\mathrm{OS} &= 80.379\,\mathrm{GeV}, & \Gamma_\mathrm{W}^\mathrm{OS} &= 2.085\,\mathrm{GeV} \end{aligned}$$

- LO width: $\Gamma_{\mathrm{t,LO}} = 1.443303\,\mathrm{GeV}$ [Jezabek, Kühn; (1989)]
- NLO width: $\Gamma_{\mathrm{t,NLO}} = 1.3444367445\,\mathrm{GeV}$
  → relative QCD corrections from [Basso et al.; 1507.04676]

Technical details

- Approximate time for full computation: $\sim 100\ \mathrm{kCPU.h}^{-1}$
- Use $\alpha_{\mathrm{dipole}} = 10^{-2}$ [Nagy, Trocsanyi; hep-ph/9806317]

Cross sections

$$\sigma_{\rm LO} = 5.198(4)^{+60\%}_{-35\%}\ \text{fb} \qquad \text{and} \qquad \sigma_{\rm NLO} = 10.28(8)^{+18\%}_{-21\%}\ \text{fb}$$

Ch.	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	K-factor	δ[%]
gg	4.861(4)	9.93(8)	2.04	96.6
$\mathrm{q\bar{q}}$	0.3298(1)	0.43(1)	1.30	4.2
$\mathrm{b\bar{b}}$	0.00742(1)	0.017(2)	2.29	0.2
$\mathrm{gq/g\bar{q}}$	-	$-0.19(2)$	-	-1.8
$\mathrm{gb/g\bar{b}}$	-	0.094(2)	-	0.9
pp	5.198(4)	10.28(8)	1.98	100

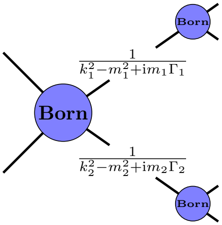
$\rightarrow$ As usual at the LHC, cross section dominated by gg channel

Double-pole approximation (DPA) [1]

→ **At LO**

- Retain doubly top resonant contributions
- Keep full phase space
- Keep off-shell propagator
- Matrix element evaluated with on-shell projected kinematic

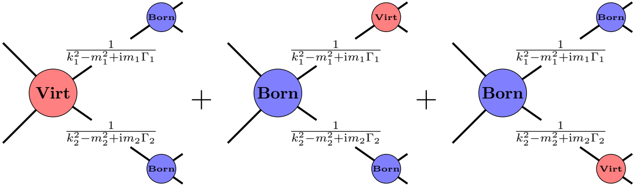
→ Allows to estimate size of non-resonant contributions
→ Better approximation than usual on-shell computations



→ At NLO

- Virtual factorisable corrections [Dittmaier, Schwan; 1511.01698]

$$\mathcal{M}_{\mathrm{virt,fact,PA}} = \sum_{\lambda_1,\ldots,\lambda_r} \left(\prod_{i=1}^{r} \frac{1}{K_i}\right) \left[\mathcal{M}_{\mathrm{virt}}^{I\to N,\overline{R}} \prod_{j=1}^{r} \mathcal{M}_{\mathrm{LO}}^{j\to R_j} \right.$$
$$\left. + \mathcal{M}_{\mathrm{LO}}^{I\to N,\overline{R}} \sum_{k=1}^{r} \mathcal{M}_{\mathrm{virt}}^{k\to R_k} \prod_{j\neq k}^{r} \mathcal{M}_{\mathrm{LO}}^{j\to R_j} \right]_{\left\{ \overline{k}_l^2 \to \widehat{\overline{k}}_l^2 = M_l^2 \right\}_{l\in\overline{R}}}$$



Double-pole approximation (DPA) [3]

→ **At NLO**

- Virtual non-factorisable corrections [Dittmaier, Schwan; 1511.01698]:

$$2\mathrm{Re}\left\{\mathcal{M}^*_{\mathrm{LO,PA}}\mathcal{M}_{\mathrm{virt,nfact,PA}}\right\} = \left|\mathcal{M}_{\mathrm{LO,PA}}\right|^2\delta_{\mathrm{nfact}}$$

→ $\boxed{\mathrm{Virtual}_{\mathrm{DPA}} = \mathrm{Virtual}_{\mathrm{fact}} + \mathrm{Virtual}_{\mathrm{nfact}}}$

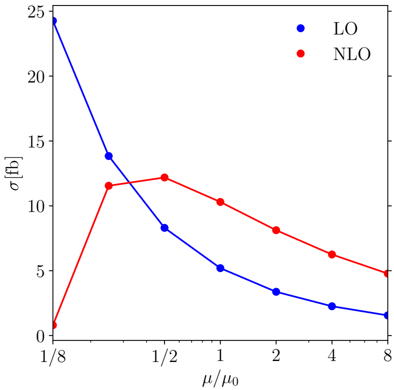
- DPA applied to virtual corrections only
  → Full Born, real, and integrated dipole

→ Check of the virtual part

$$\sigma_{\mathrm{LO}} = 5.198(4)^{+60\%}_{-35\%}\,\mathrm{fb} \quad \mathrm{and} \quad \sigma_{\mathrm{NLO}} = 10.28(8)^{+18\%}_{-21\%}\,\mathrm{fb}$$
$$\sigma^{\mathrm{DPA}}_{\mathrm{LO}} = 5.024(2)^{+60\%}_{-35\%}\,\mathrm{fb} \quad \mathrm{and} \quad \sigma^{\mathrm{DPA}}_{\mathrm{NLO}} = 10.22(8)^{+19\%}_{-21\%}\,\mathrm{fb}.$$

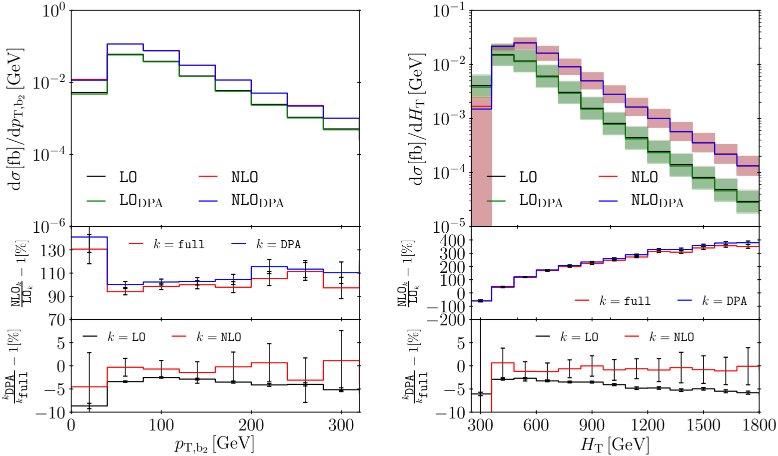
→ 3% difference at LO, 0.6% at NLO

Cross section - scale variation



[Denner, Lang, MP; 2008.00918]

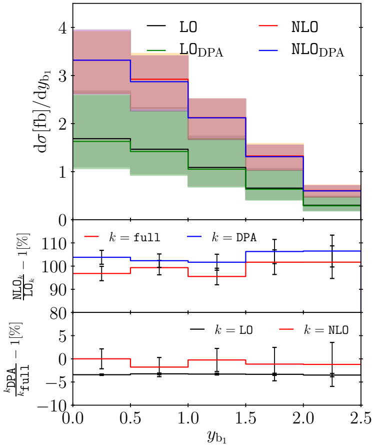
$$\mu_0 = \frac{1}{2}\left[\left(p_{\mathrm{T}}^{\mathrm{miss}} + \sum_{i=\ell_1,\bar{\ell}_1,\mathrm{b}_1,\mathrm{b}_2,\bar{\mathrm{b}}_1,\bar{\mathrm{b}}_2} E_{\mathrm{T},i}\right) + 2m_{\mathrm{t}}\right]^{1/2}\left(\sum_{i=\mathrm{b}_1,\mathrm{b}_2,\bar{\mathrm{b}}_1,\bar{\mathrm{b}}_2} E_{\mathrm{T},i}\right)^{1/2}$$



[Denner, Lang, MP; 2008.00918]

$$H_{\mathrm{T}} = p_{\mathrm{T}}^{\mathrm{miss}} + \sum_{i=\mathrm{e}^+,\mu^-,\mathrm{b},\mathrm{j}} E_{\mathrm{T}}^i$$

- Off-shell effects up to $5-10\%$ in relevant phase-space region
- Large QCD corrections



[Denner, Lang, MP; 2008.00918]

- ... but not for all!

Set up

- Event selection

$$p_{\mathrm{T,b}} > 25\,\mathrm{GeV}, \qquad |y_{\mathrm{b}}| < 2.5,$$
$$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \qquad |y_{\ell}| < 2.5$$

- Jet algorithm:
  $\rightarrow$ anti-k_{T} with $R = 0.4$
  $\rightarrow$ rules: $\mathrm{j}+\mathrm{j}\rightarrow\mathrm{j}$, $\mathrm{j_b}+\mathrm{j}\rightarrow\mathrm{j_b}$, and $\boxed{\mathrm{j_b}+\mathrm{j_b}\rightarrow\mathrm{j}}$ $(\mathrm{g}\rightarrow q\bar{q})$

- Scale definition
  $$\mu_0 = \frac{1}{2}\left[\left(p_{\mathrm{T}}^{\mathrm{miss}} + \sum_{i=\ell_1,\bar{\ell}_1,\mathrm{b}_1,\mathrm{b}_2,\bar{\mathrm{b}}_1,\bar{\mathrm{b}}_2} E_{\mathrm{T},i}\right) + 2m_{\mathrm{t}}\right]^{1/2}\left(\sum_{i=\mathrm{b}_1,\mathrm{b}_2,\bar{\mathrm{b}}_1,\bar{\mathrm{b}}_2} E_{\mathrm{T},i}\right)^{1/2}$$

$\rightarrow$ 1^{st} factor: momentum transfer in strong couplings of top
$\rightarrow$ 2^{nd} factor: momentum transfer in strong couplings of bottom
⚠ No explicit reference to top quark

NB: Soon update arXiv version with correct numbers for gb