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HIGH PRECISION PREDICTIONS FOR HEAVY QUARK PHYSICS

Ringberg

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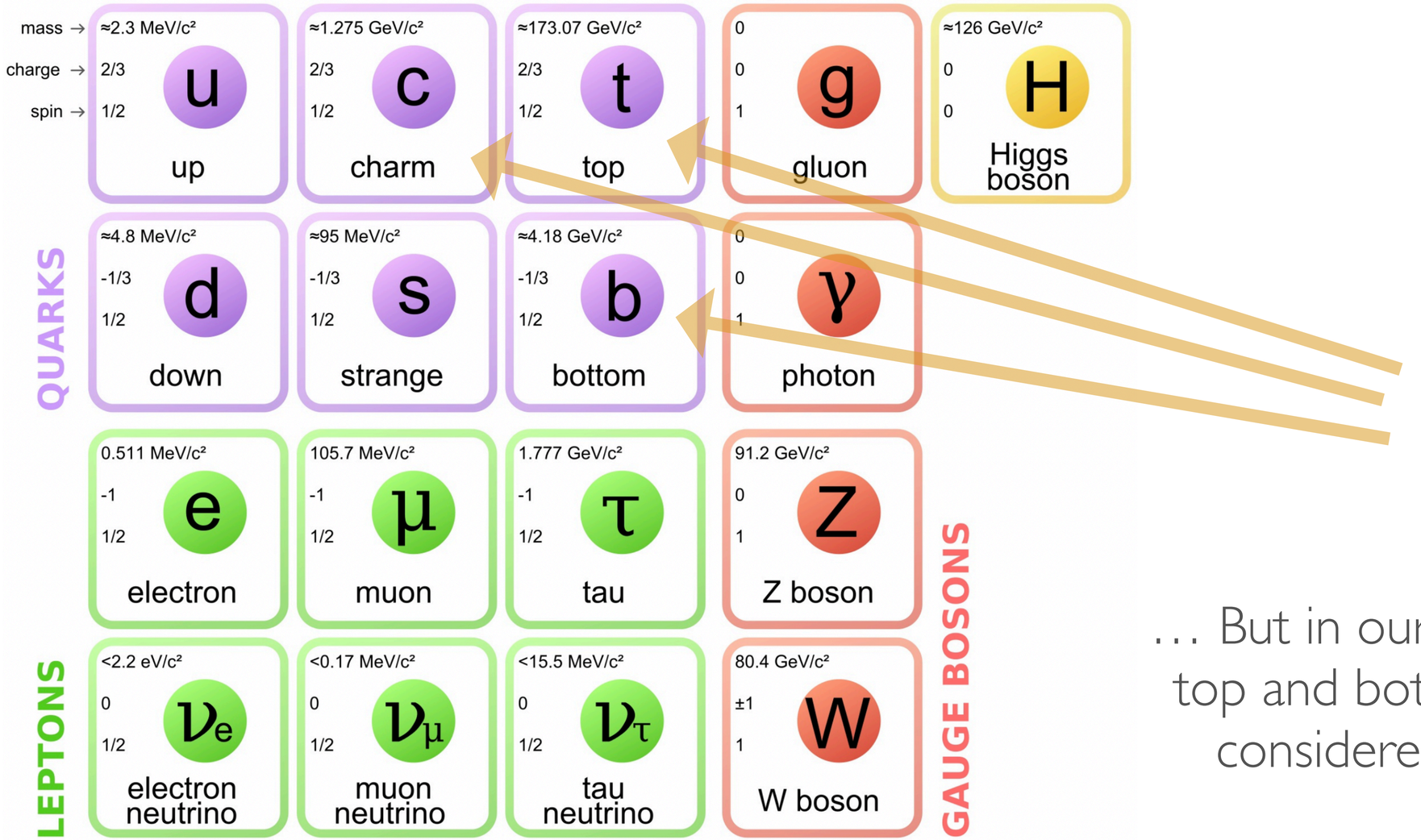
SUMMARY

- The top-pair production with MiNNLOps
- The bottom-pair production: general aspects and state of the art
- My current work: MiNNLOps applied to the bottom pair production (preliminary results)

What do we mean for heavy quarks?

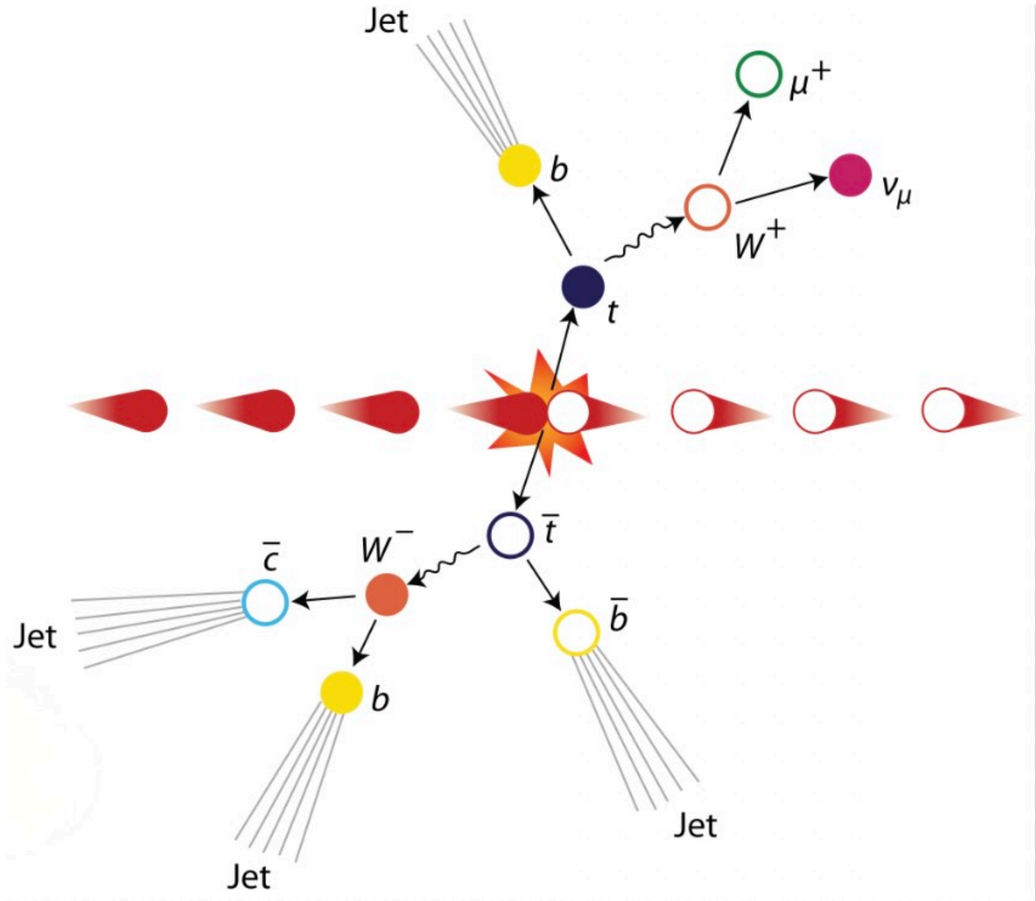


Typically c, b, t

… But in our analysis, just top and bottom will be considered massive

Top-pair production at the LHC

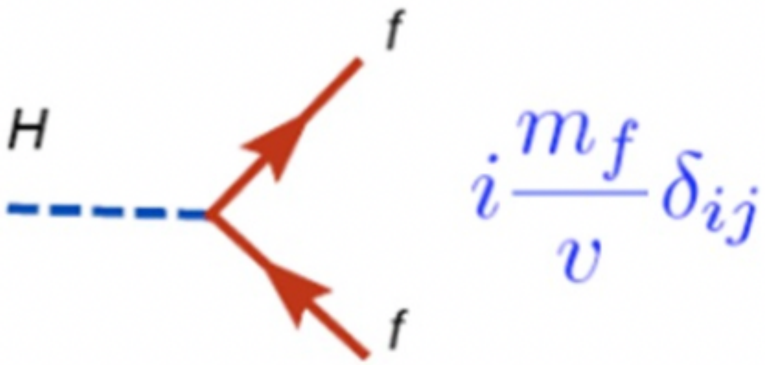
Theoretical aspects



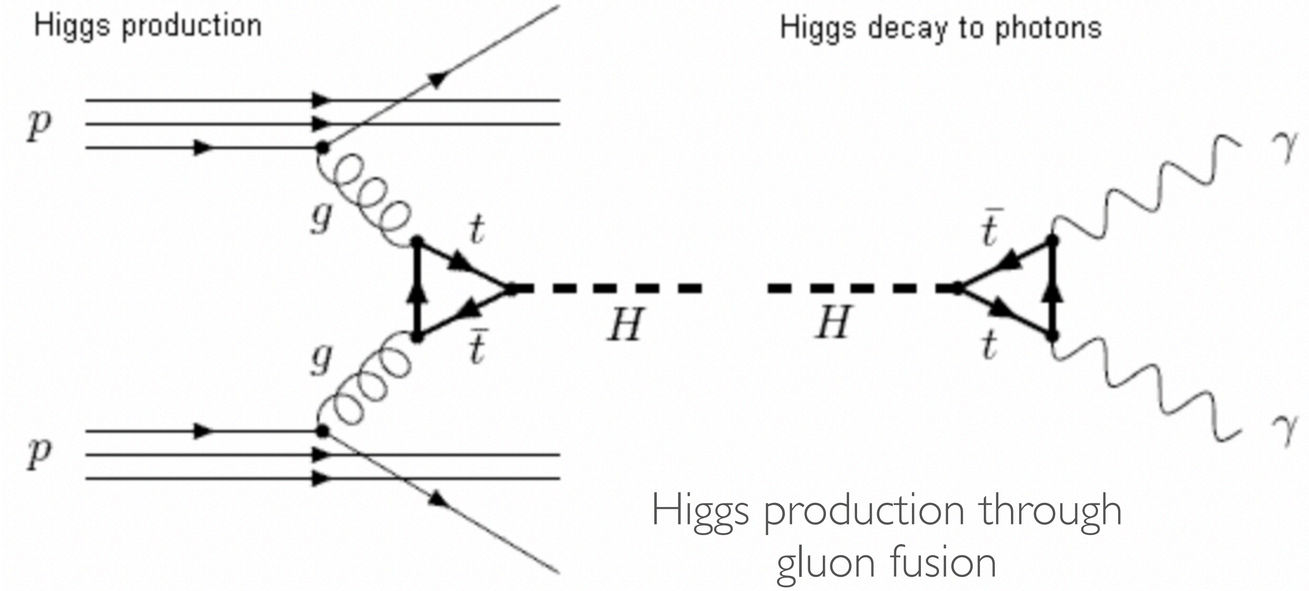
Top-pair production at the LHC

Top mass is big → Big **Yukawa coupling** with Higgs → Top physics strongly related to **Higgs physics** (Higgs production, running…)

$$M_t \sim 173\,GeV/c^2$$



$$i\frac{m_f}{v}\delta_{ij}$$



Higgs production through gluon fusion

Top-pair production at the LHC

Total cross section for tt production is really high

Top-pair production is a background for most LHC processes

σ_{NNLO} [pb]	q_T subtraction	TOP++
8 TeV	$238.5(2)^{+3.9\%}_{-6.3\%}$	$238.6^{+4.0\%}_{-6.3\%}$
13 TeV	$793.4(6)^{+3.5\%}_{-5.7\%}$	$794.0^{+3.5\%}_{-5.7\%}$

	ZZ	WW	WZ
baseline cuts	$pp \to \ell^-\ell^+\nu_{\ell'}\bar{\nu}_{\ell'}$	$pp \to \ell^-\ell'^+\nu_{\ell'}\bar{\nu}_{\ell}$	$pp \to \ell^-\ell^+\ell'\nu_{\ell'}$
σ_{LO} [fb]	$18.9417(4)^{+4.2\%}_{-5.2\%}$	$240.221(5)^{+5.1\%}_{-6.2\%}$	$21.8960(3)^{+4.2\%}_{-5.3\%}$
$\sigma_{\text{NLO EW}}$ [fb]	$17.7713(4)^{+4.3\%}_{-5.4\%}$	$235.118(5)^{+5.1\%}_{-6.1\%}$	$21.1849(4)^{+4.3\%}_{-5.4\%}$
$\sigma_{\text{NLO QCD}}$ [fb]	$25.690(1)^{+2.9\%}_{-2.4\%}$	$370.35(1)^{+4.2\%}_{-3.3\%}$	$38.138(1)^{+4.7\%}_{-3.8\%}$
$\sigma_{\text{NNLO QCD}}$ [fb]	$29.63(2)^{+3.0\%}_{-2.6\%}$	$424.6(3)^{+3.0\%}_{-2.7\%}$	$42.28(2)^{+2.3\%}_{-2.1\%}$
$\sigma_{\text{NNLO QCD+EW}}$ [fb]	$28.46(2)^{+3.3\%}_{-2.7\%}$	$419.5(3)^{+3.0\%}_{-2.8\%}$	$41.57(2)^{+2.4\%}_{-2.2\%}$
$\sigma_{\text{NNLO QCD}\times\text{EW}}$ [fb]	$27.92(2)^{+3.1\%}_{-2.6\%}$	$416.0(3)^{+3.0\%}_{-2.7\%}$	$40.90(2)^{+2.2\%}_{-2.1\%}$
$\sigma_{\text{NNLO QCD}\times\text{EW}_{\text{qq}}}$ [fb]	$27.92(2)^{+3.1\%}_{-2.6\%}$	$413.5(3)^{+3.0\%}_{-2.7\%}$	$40.53(2)^{+2.1\%}_{-2.1\%}$

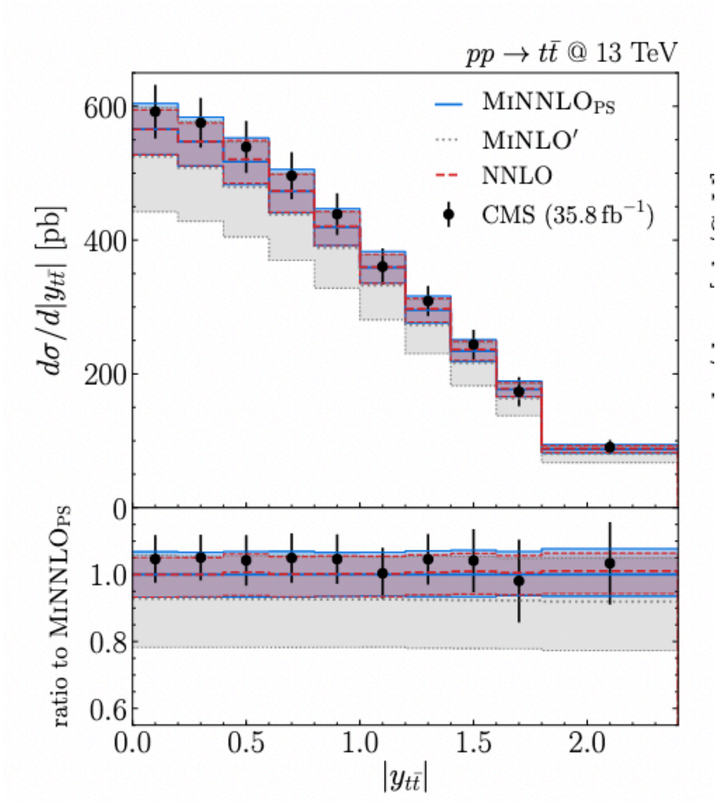
Top-pair production with MiNNLOps

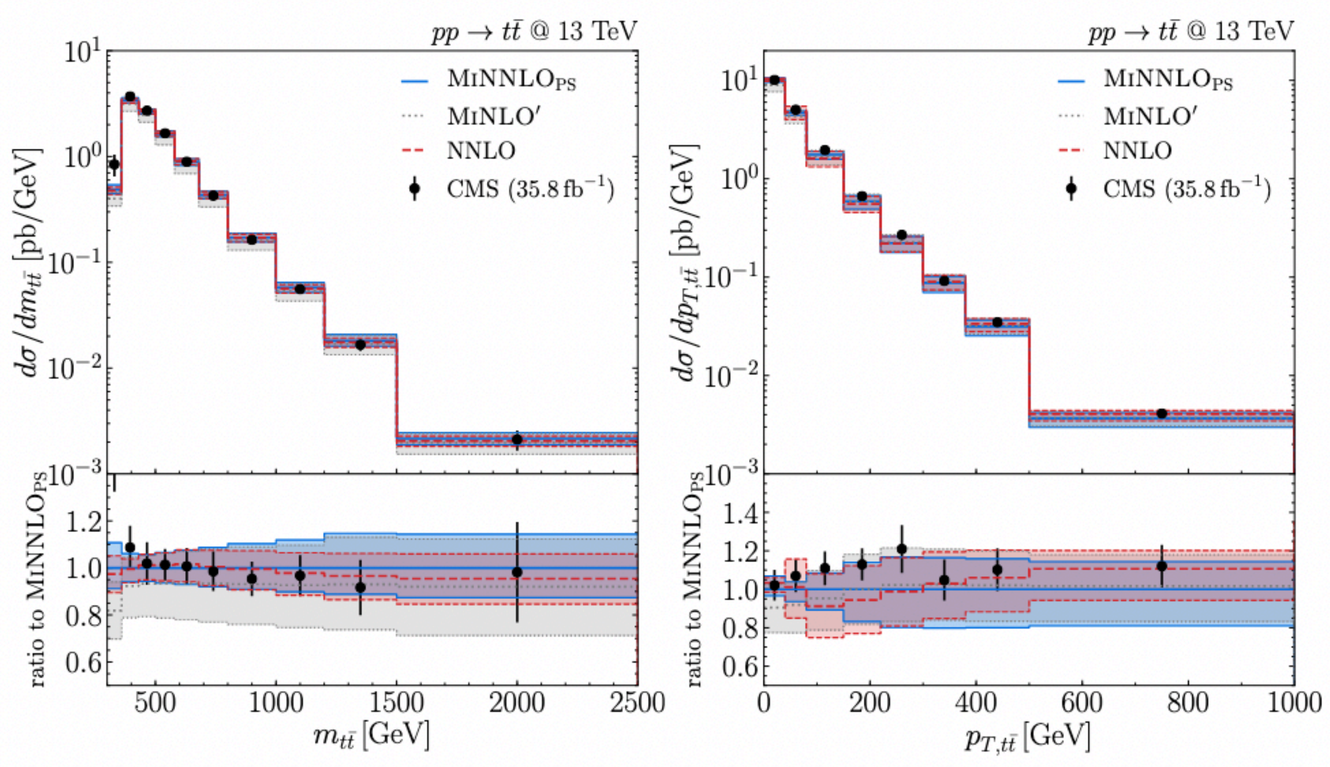
MiNNLOps adapted to processes involving final state cartons

σ_{NNLO} [pb]	q_T subtraction	Top++
8 TeV	$238.5(2)^{+3.9\%}_{-6.3\%}$	$238.6^{+4.0\%}_{-6.3\%}$
13 TeV	$793.4(6)^{+3.5\%}_{-5.7\%}$	$794.0^{+3.5\%}_{-5.7\%}$

MiNLO′	MiNNLO$_{\text{PS}}$
$695.6(3)^{+22\%}_{-17\%}$ pb	$775.5(2)^{+9.8\%}_{-7.2\%}$ pb

(13 TeV)

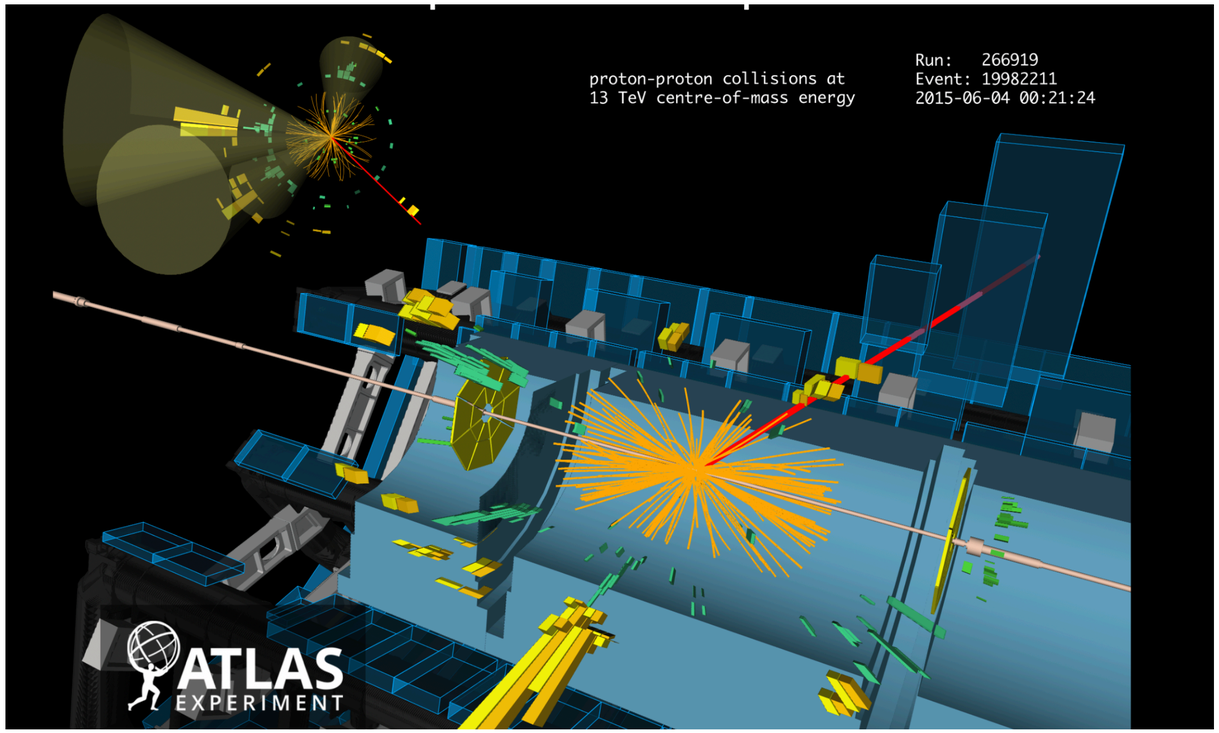




Bottom-pair production at the LHC

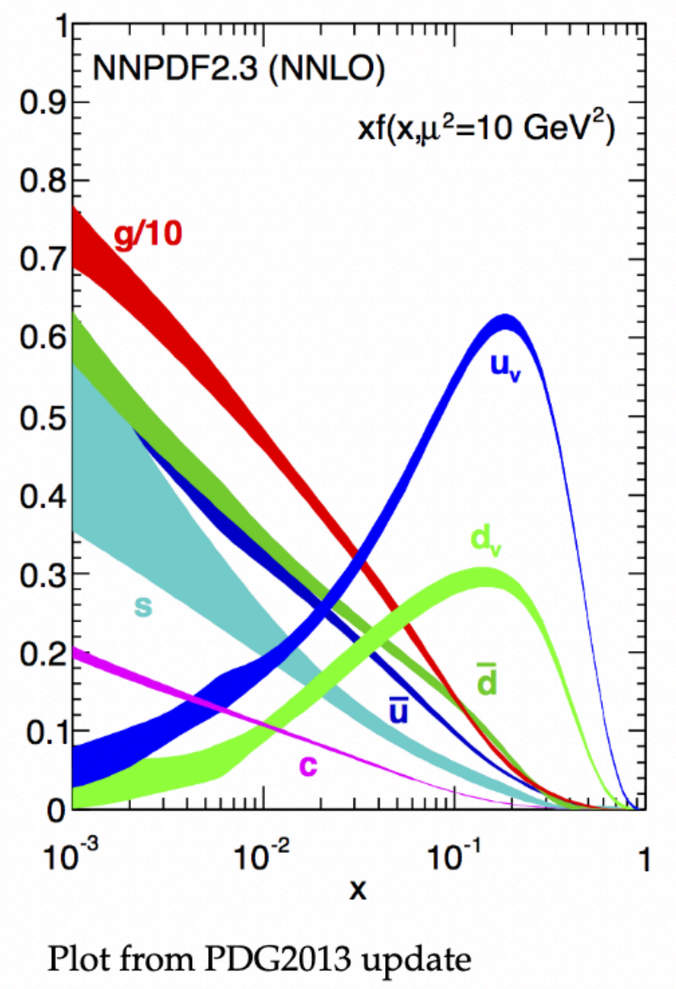
Experimental results from:

- UA1 collaboration at **CERN**
- CDF and D0 collaborations at **Fermilab Tevatron**
- **ALICE, ATLAS, CMS, LHCb**

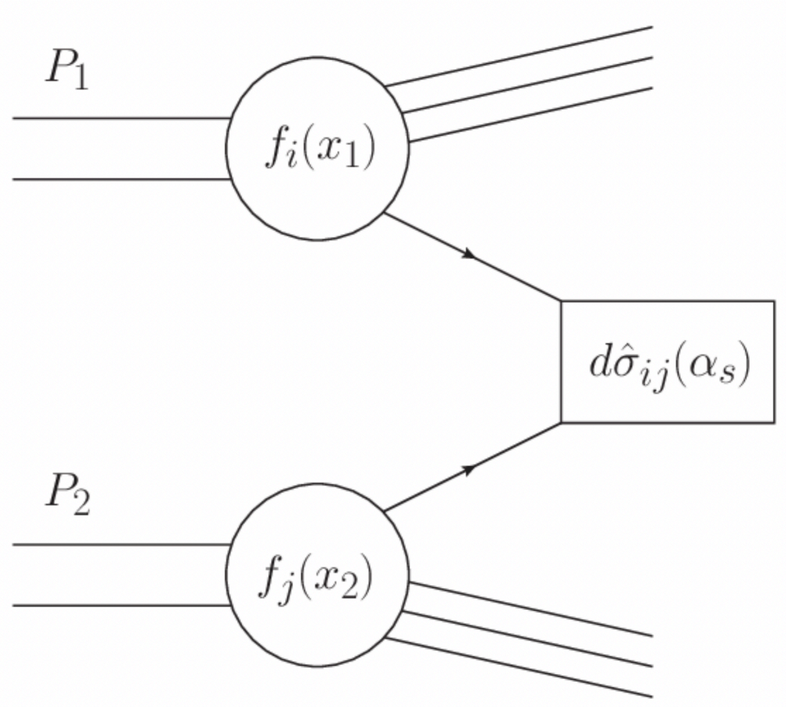


Bottom-pair production at the LHC

Theoretical aspects



$$d\sigma(pp \to b\bar{b} + X) = \sum_{i,j} \int dx_1 dx_2 \; f_i(x_1) f_j(y_2) \;\; d\hat{\sigma}_{ij}(\alpha_s)$$



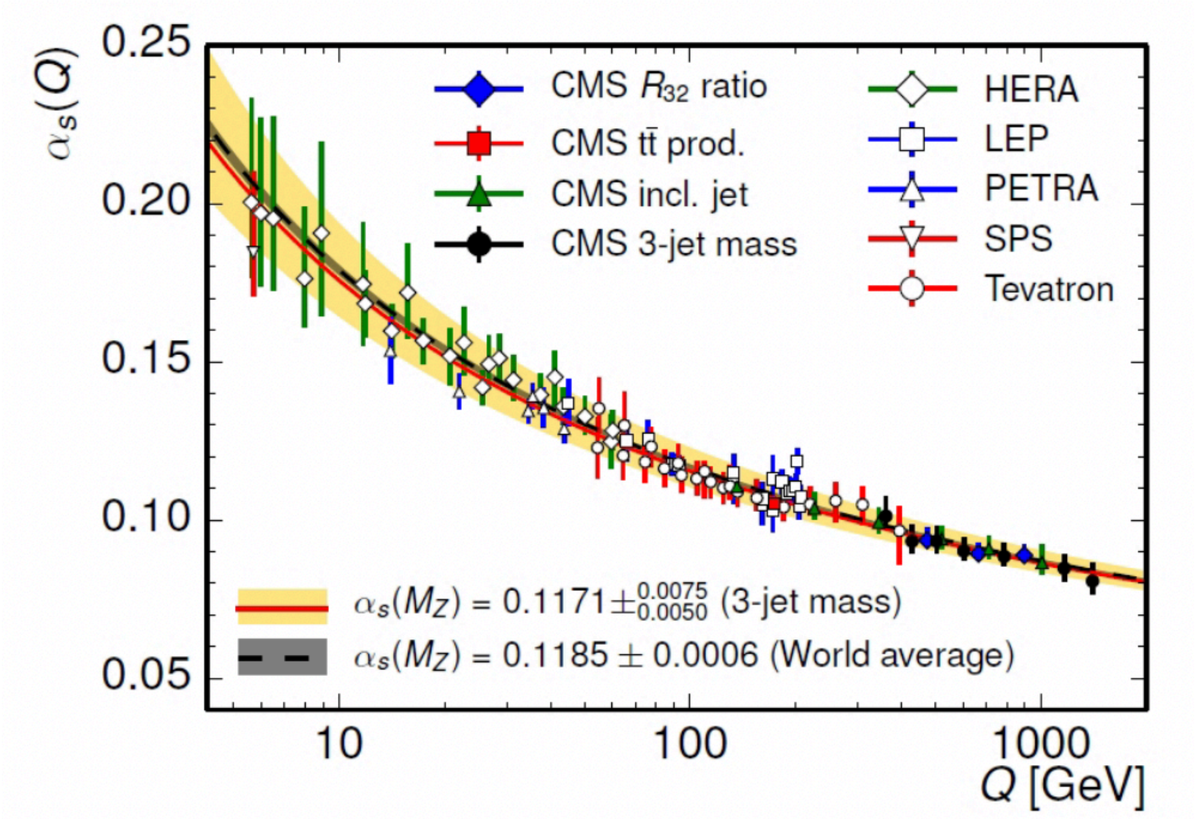
Bottom-pair production at the LHC

Theoretical aspects

Slow convergence of perturbative series

$$\sigma = \sigma^{(0)}\,\alpha_s(\mu) + \sigma^{(1)}\,\alpha_s^2(\mu) + \sigma^{(2)}\,\alpha_s^3(\mu) + \ldots$$

μ = renorm. scale → m_b

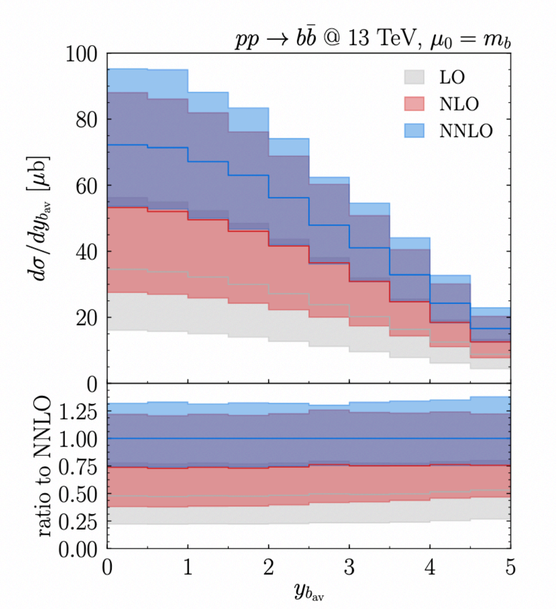


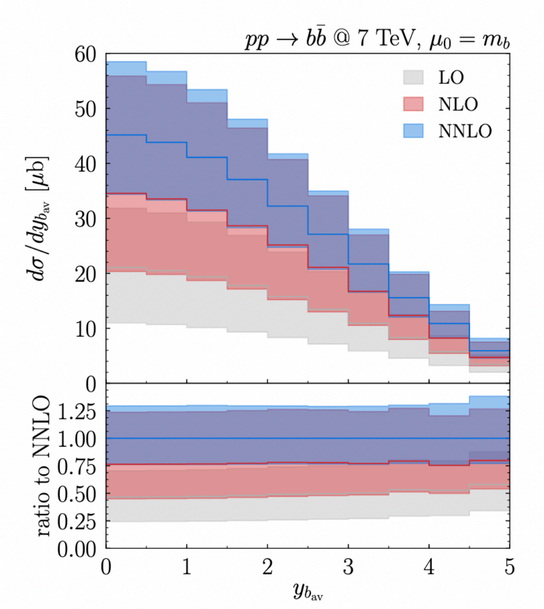
Bottom-pair production at the LHC

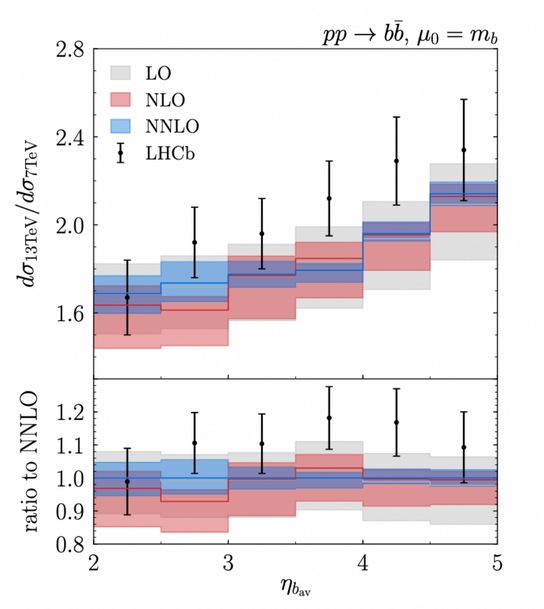
Theoretical aspects

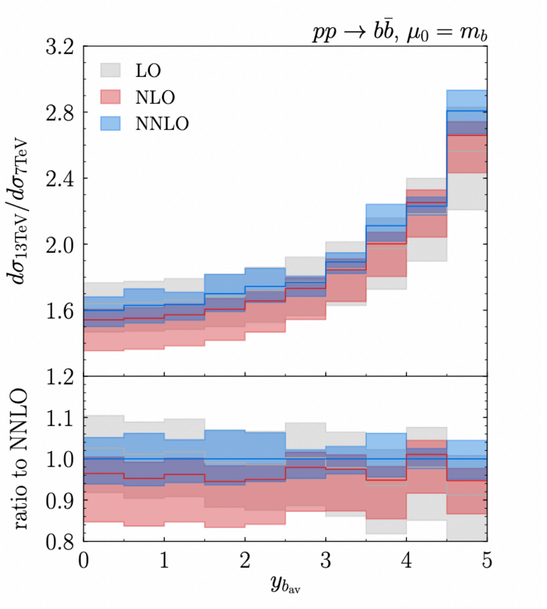
Slow convergence of perturbative series

σ [μb]	$p\bar{p}$ @ 1.96 TeV	pp @ 7 TeV	pp @ 13 TeV
	$\mu_0 = m_b$		
LO	$34.66\ ^{+51\%}_{-32\%}$	$138.7\ ^{+51\%}_{-46\%}$	$249.0\ ^{+59\%}_{-51\%}$
NLO	$60.23\ ^{+54\%}_{-28\%}$	$219.8\ ^{+61\%}_{-39\%}$	$378.6\ ^{+65\%}_{-45\%}$
NNLO	$75.4(3)\ ^{+22\%}_{-21\%}$	$288(2)\ ^{+30\%}_{-24\%}$	$508(3)\ ^{+32\%}_{-25\%}$









Bottom-pair production at the LHC

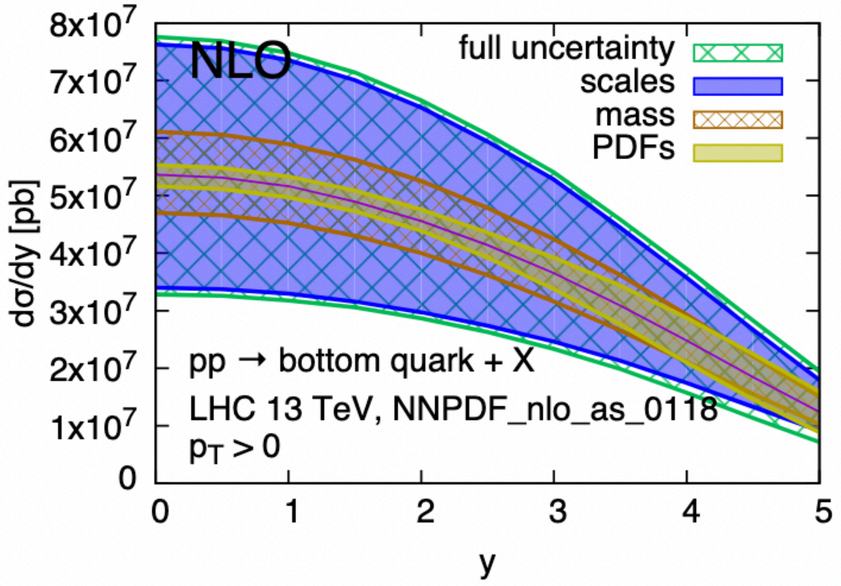
Theoretical aspects

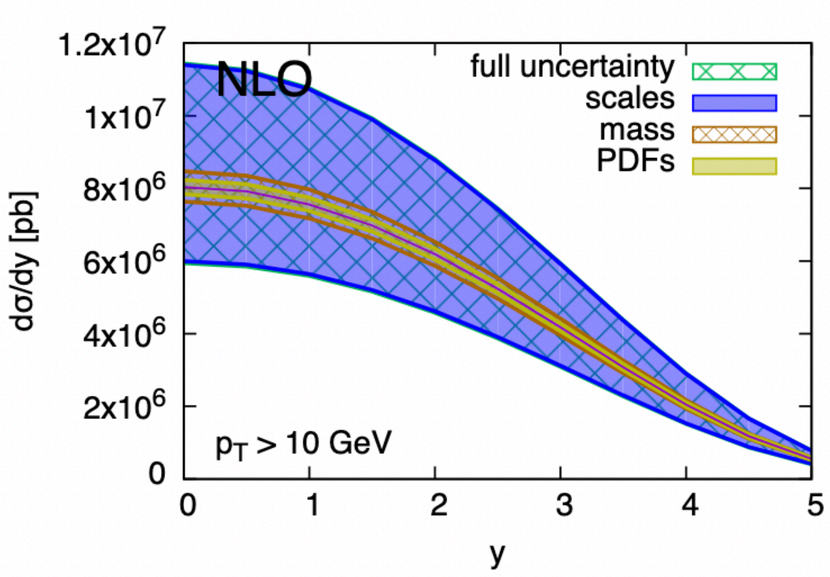
Resummation of large logarithms can be performed at high Pt

$$\sigma = \sigma^{(0)}\alpha_s(\mu) + \sigma^{(1)}\alpha_s^2(\mu) + \sigma^{(2)}\alpha_s^3(\mu) + \ldots$$

$$L = ln(p_T/m_b)$$

(Can be performed through fragmentation functions…)

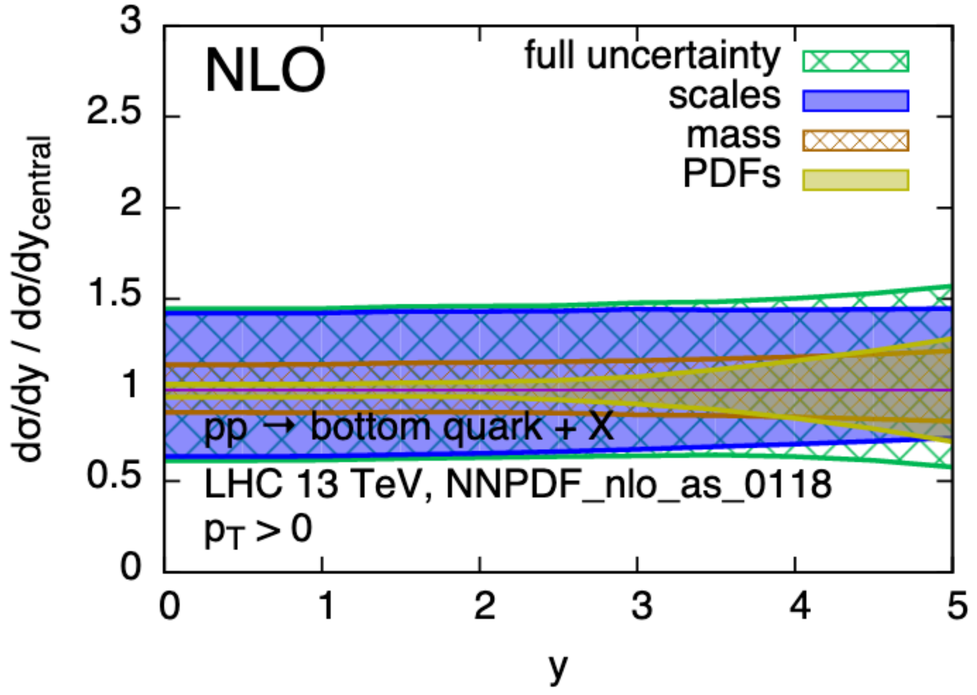




Bottom-pair production at the LHC

Theoretical aspects

Bottom-pair production can be exploited to constrain uncertainties of PDFs



Sistematics are given by:

Scale choice

PDFs

Bottom mass

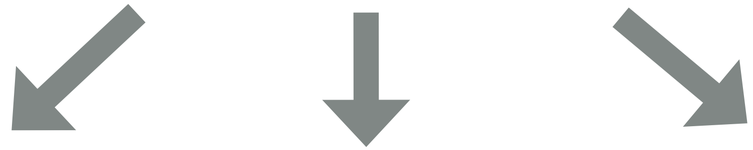
How scale variation is determined (7 points envelope)

Bottom-pair production at the LHC

Theoretical aspects

Bottom-pair production can be exploited to constrain uncertainties of PDFs

Sistematics are given by:



Scale choice

PDFs

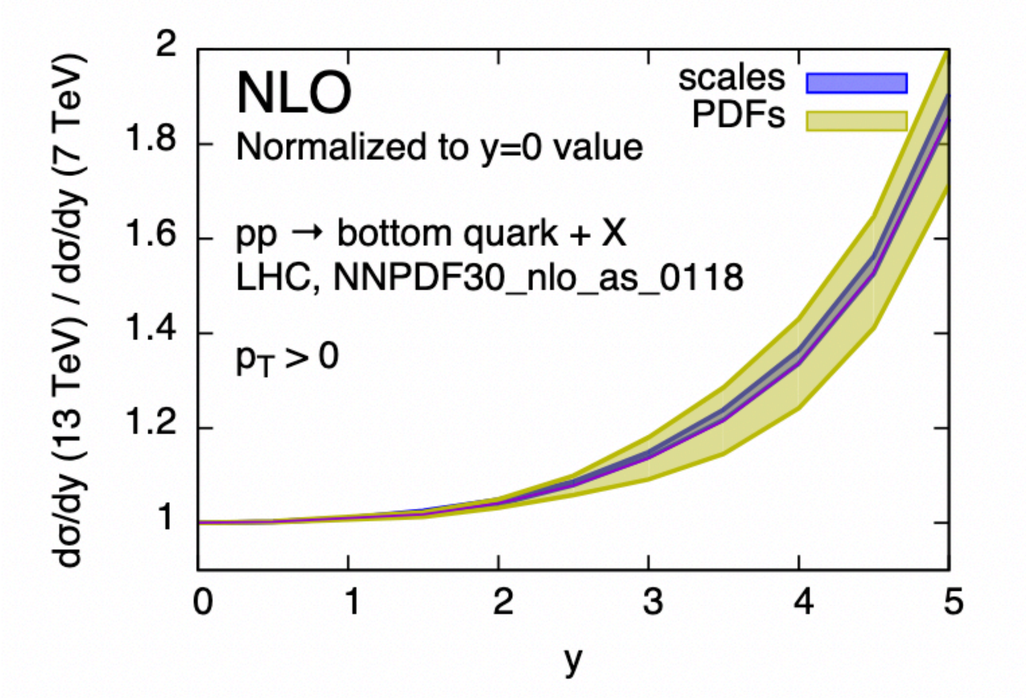
Bottom mass

	$\sigma_{\mathrm{NNLO}}(\mu\mathrm{b})$	$\Delta\sigma_{\mathrm{scale}}$	$\Delta\sigma_{\mathrm{mass}}$	$\Delta\sigma_{\mathrm{PDFs}}$	$\Delta\sigma_{\alpha_{\mathrm{S}}}$
$p\bar{p}$ @ 1.96 TeV	75.4(3)	$^{+22\%}_{-21\%}$	$^{+9.8\%}_{-8.7\%}$	$\pm 1.3\%$	$^{+0.9\%}_{-3.0\%}$
pp @ 7 TeV	288(2)	$^{+30\%}_{-24\%}$	$^{+7.9\%}_{-7.2\%}$	$\pm 2.8\%$	$^{+0.3\%}_{-2.9\%}$
pp @ 13 TeV	508(3)	$^{+32\%}_{-25\%}$	$^{+7.4\%}_{-6.8\%}$	$\pm 4.6\%$	$^{+0.0\%}_{-3.0\%}$

Bottom-pair production at the LHC

Theoretical aspects

Bottom-pair production can be exploited to constrain uncertainties of PDFs



Sistematics are given by:

Scale choice

PDFs

Bottom mass

BUT IF WE CONSIDER THE RATIO

$$R(y) = \frac{\left(\frac{d\sigma}{dy}\right)(13TeV)}{\left(\frac{d\sigma}{dy}\right)(7TeV)}$$

Bottom-pair production at the LHC

Event generator

At the moment:

- Code for bottom-pair production (+ 1 jet) has been implemented in the POWHEG-BOX framework and validated against numerical results from MATRIX
- MiNLO' and MiNNLOps methods implemented, but results are still preliminary

Total cross section at NLO for

$$pp \to b\bar{b} + jet$$

(Cutoff on jet transverse momentum and rapidity)

POWHEG	MATRIX
$37.99 \pm 0.58\ \mu b$	$37.48 \pm 0.26\ \mu b$

Bottom-pair production at the LHC

Event generator

Fixed order results

Bottom-pair production at the LHC

Event generator

MiNLO and MiNNLOps preliminary results