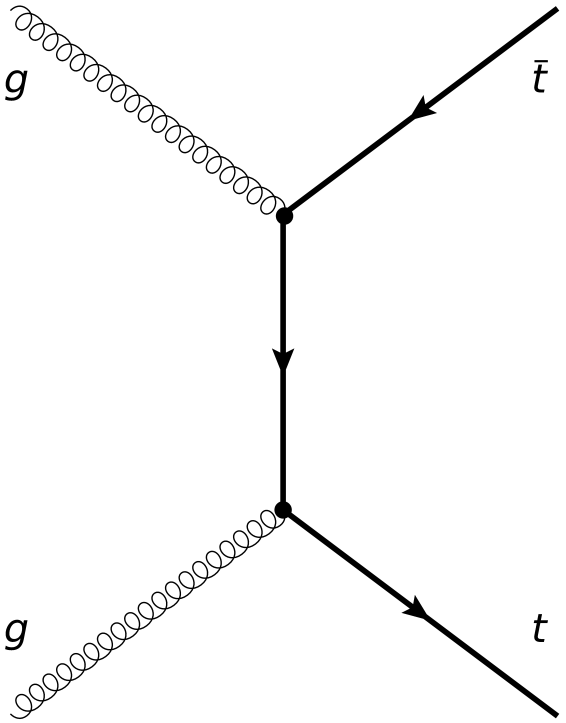
NNLO top quark pair production



LHC @ 7 TeV (CMS di-lepton)

$\sigma_{t\bar{t}} = 161.9 \pm 2.5\,^{+5.1}_{-5.0} \pm 3.6$ pb **5%**

LHC @ 7 TeV (ATLAS & CMS combined)

$\sigma_{t\bar{t}} = 173.3 \pm 2.3\,(\text{stat.}) \pm 9.8\,(\text{syst.})$ pb **5.8%**

LHC @ 8 TeV (CMS combined)

$\sigma_{t\bar{t}} = 227 \pm 3\,(\text{stat.}) \pm 11\,(\text{syst.}) \pm 10\,(\text{lumi.})$ pb **6.7%**

J.Andrea (TOP2012)

M.Czakon (RWTH), **P.Fiedler (RWTH)**, A.Mitov (CERN)

RWTH AACHEN UNIVERSITY

SFB TR9 Computational Theoretical Particle Physics

Current status of top pair production

Before NNLO:

Beneke, Falgari, Klein, Schwinn `09-`11
Ahrens, Ferroglia, Neubert, Pecjak, Yang `10-`11
Kidonakis `04-`11
Aliev, Lacker, Langenfeld, Moch, Uwer, Wiedermann '10
Cacciari, Czakon, Mangano, Mitov, Nason '11

NNLO:

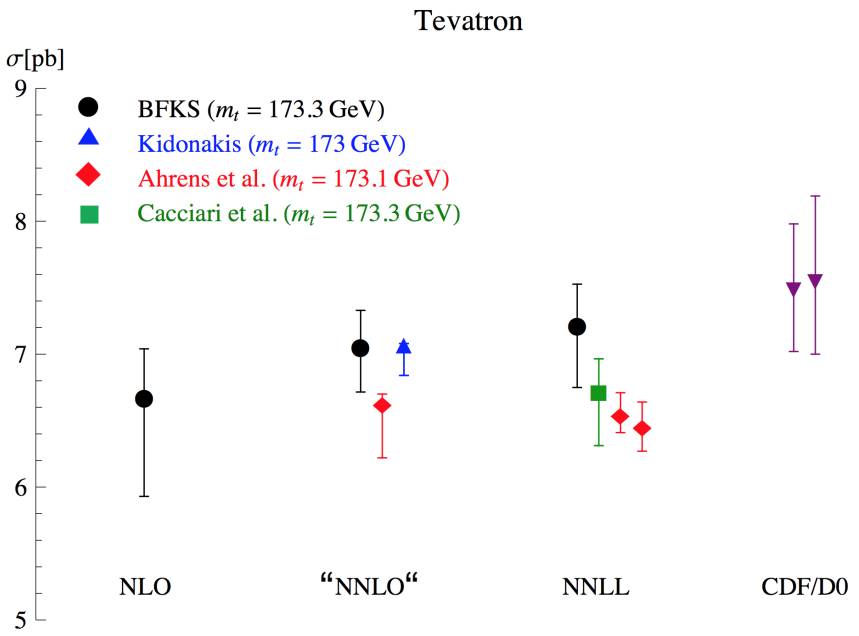
$q\bar{q}$: Bärnreuther, Czakon, Mitov, Phys. Rev. Lett., April '12
qq': Czakon, Mitov, JHEP, July '12
qg: Czakon, Mitov, JHEP, October '12
Gluon fusion: Czakon, PF, Mitov, Phys. Rev. Lett., March'13

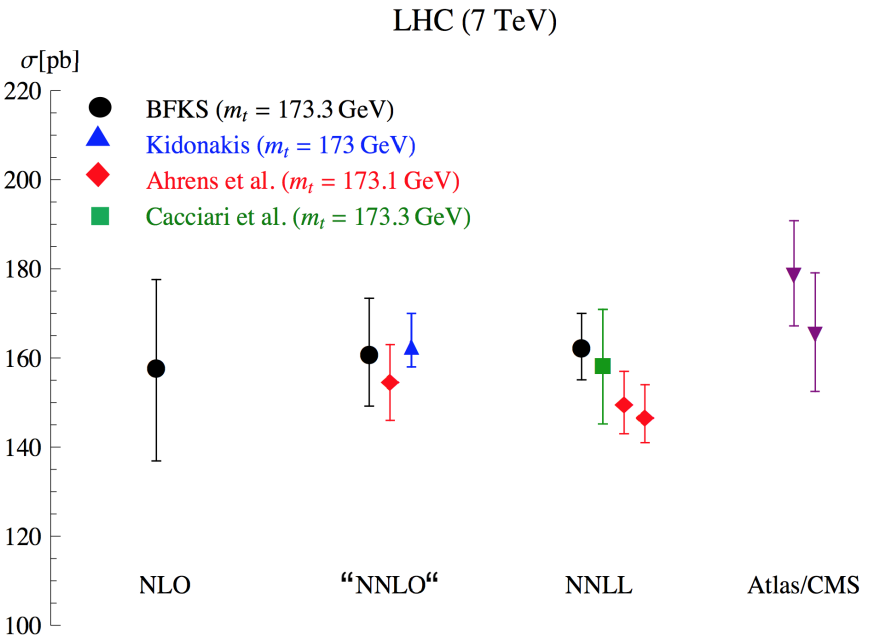
Publicly available software:

- **HATHOR**
  Aliev, Lacker, Langenfeld, Moch, Uwer, Wiedemann `10
  NNLO
- **Top++**
  Czakon, Mitov `11
  NNLO + NNLL soft gluon resummation in Mellin-space
- **TOPIXS**
  Beneke, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan `12
  NLO + approximations for NNLO + NNLL soft and Coulomb resummation in x-space

Current status of top pair production

Just some time ago...





Beneke, Falgari, Klein, Schwinn, December 2011

Total cross section

- Factorization theorem

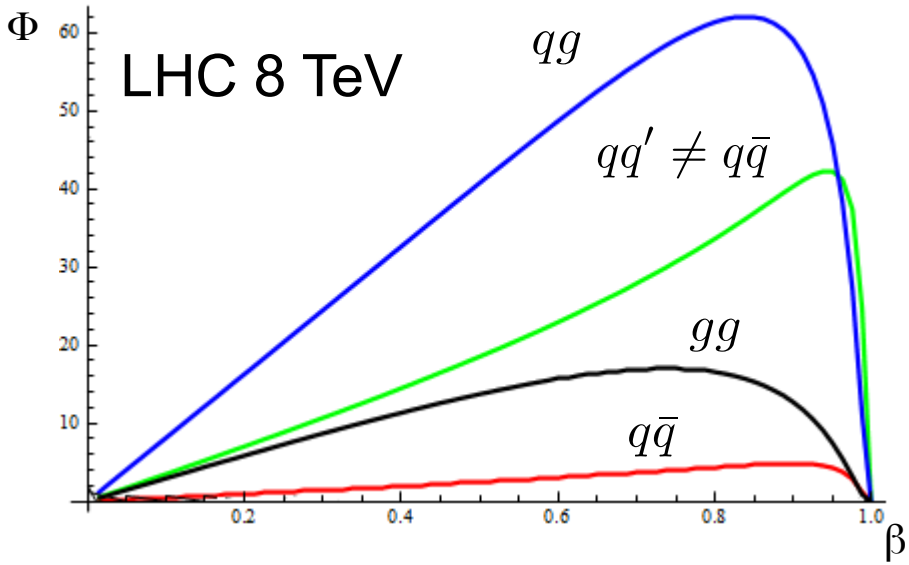
$$\sigma_{\mathrm{tot}} = \sum_{i,j} \int_0^{\beta_{\max}} d\beta\, \Phi_{ij}(\beta, \mu^2)\, \hat{\sigma}_{ij}(\beta, m^2, \mu^2)$$

$\hat{\sigma}_{ij}(\beta, m^2, \mu^2)$	Partonic cross section
$\Phi_{ij}(\beta, \mu^2)$	Partonic flux (convolution of pdfs expressed through β)
$\beta = \sqrt{1-\rho}$	Relative velocity of final state top quarks
$\sqrt{s}$	Center of mass energy of collider
$\sqrt{\hat{s}}$	Partonic center of mass energy
$\mu = \mu_F = \mu_R$	Scale

$\beta_{max} \equiv \sqrt{1 - 4m^2/s}$

$\rho \equiv 4m^2/\hat{s}$

MSTW2008nnlo68cl , μ = m , m= 173.3 GeV



NNLO calculations

- Partonic cross section:

$$\hat{\sigma}_{ij}(\beta) = \frac{\alpha_s^2}{m^2}\left(\hat{\sigma}_{ij}^{(0)}(\beta) + \alpha_s\,\hat{\sigma}_{ij}^{(1)}(\beta) + \alpha_s^2\,\hat{\sigma}_{ij}^{(2)}(\beta) + O(\alpha_s^3)\right)$$

3 principal contributions:

Double Real (R-R)

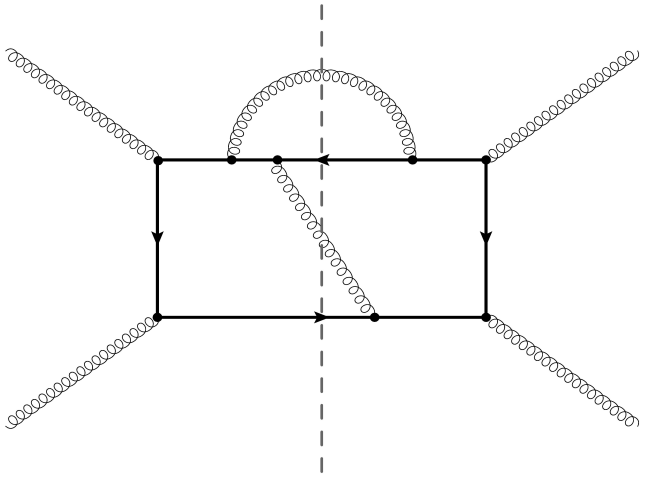
- 2 extra emitted partons at tree level
- Invention of a new subtraction scheme called STRIPPER Czakon `10` 11

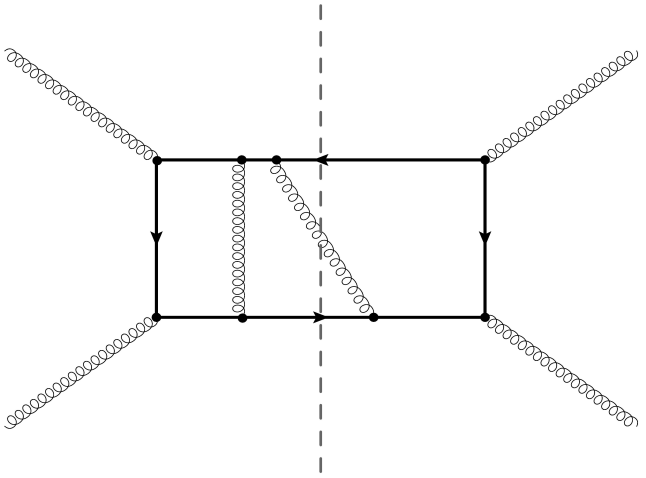
Real-Virtual (R-V)

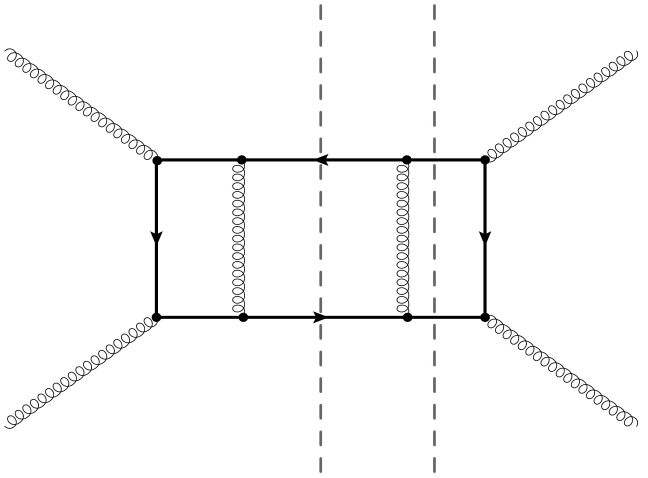
- 1-loop virtual with one extra parton
- Code by Stefan Dittmaier
- New subtraction terms
  Bierenbaum, Czakon, Mitov ` 11

Double Virtual (V-V)

- One loop squared amplitudes
  Körner, Merebashvili, Rogal `07
  gluon fusion: Anastasiou, Aybat `08
  gluon fusion done from scratch
- 2-loop virtual corrections
  Czakon `07 (quark annihilation)
  Bärnreuther, Czakon, PF (gluon fusion)







Partonic cross section results

- Partonic cross section

$$\hat{\sigma}_{ij}^{(2)}(\beta) = \hat{\sigma}_{ij}^{VV}(\beta) + \hat{\sigma}_{ij}^{RV}(\beta) + \hat{\sigma}_{ij}^{RR}(\beta) + \hat{\sigma}_{ij}^{C}(\beta)$$
$$= F_0(\beta) + F_1(\beta)\, N_L + F_2(\beta)\, N_L^2$$

$$F_i \equiv F_i^{(\beta)} + F_i^{(fit)} \qquad i = 0,1,2$$

$\hat{\sigma}_{ij}^{(VV)}$ Double virtual corrections

$\hat{\sigma}_{ij}^{(RV)}$ Real virtual corrections

$\hat{\sigma}_{ij}^{(RR)}$ Double real corrections

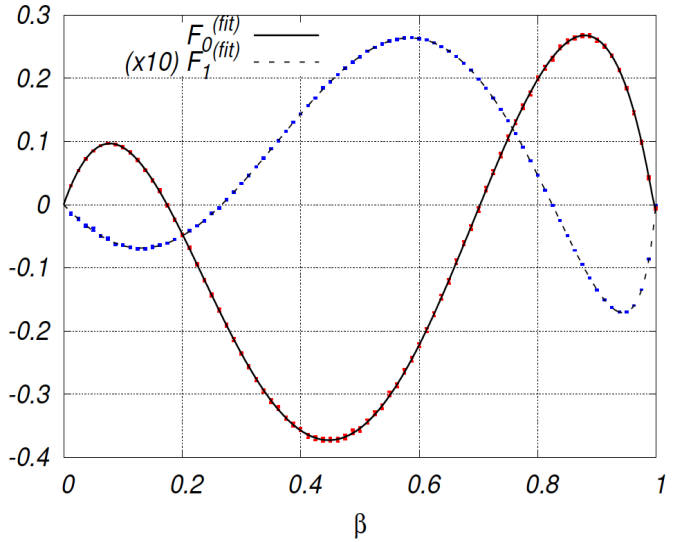
$\hat{\sigma}_{ij}^{C}$ Collinear factorization

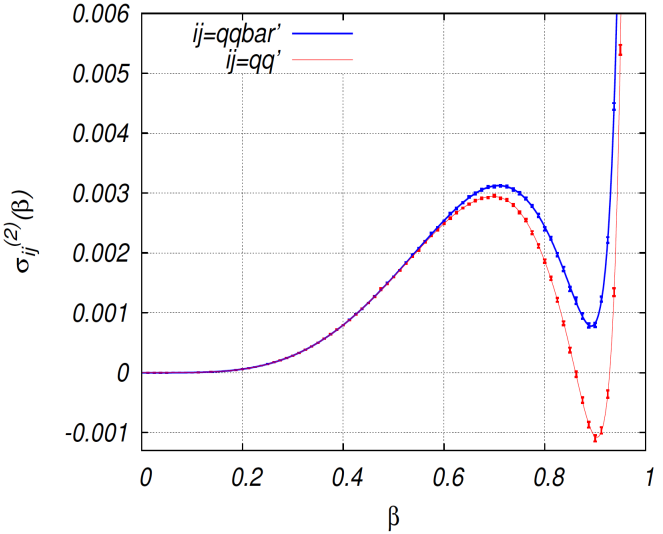
N_L number of light quarks

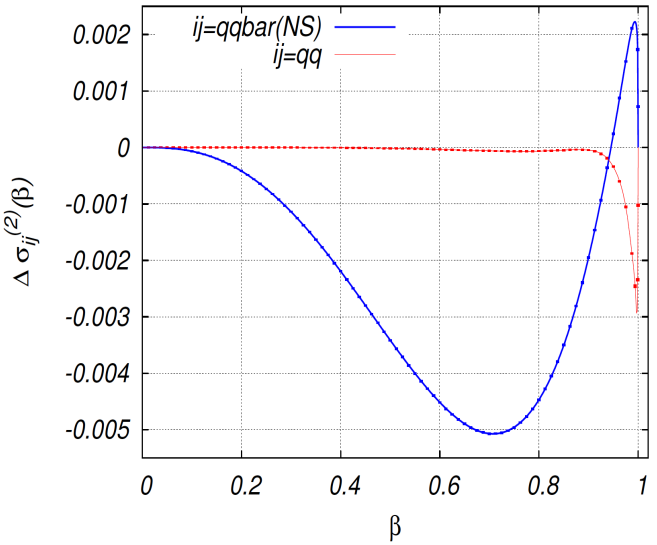
$F_i^{(\beta)}$ Known threshold approx.
Beneke, Czakon, Falgari, Mitov, Schwinn `09

Fermionic channels

Bärnreuther, Czakon, Mitov `12
Czakon, Mitov `12



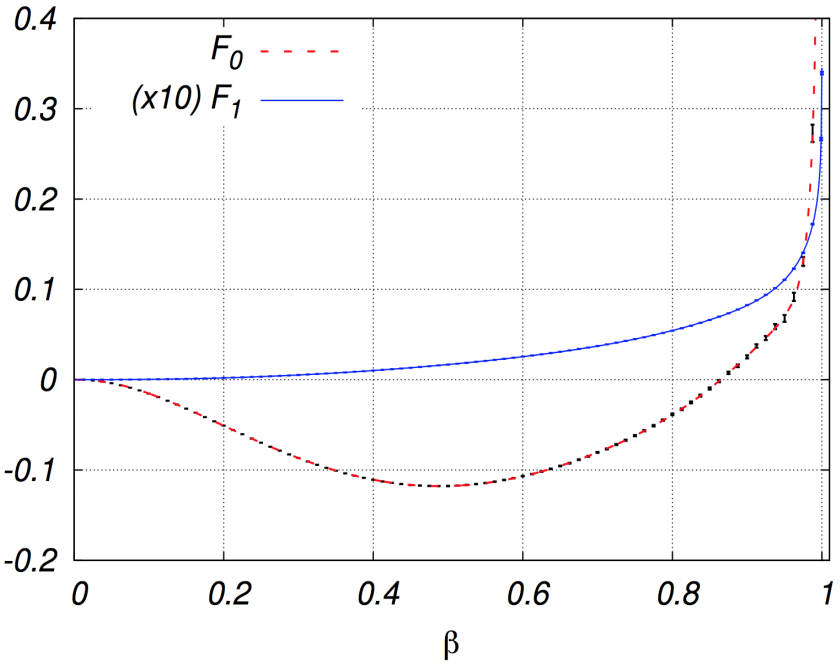




Partonic cross section results

Quark-gluon channel Czakon, Mitov `12

- -0.8% effect on the cross section at the TeVatron
- -1.1% effect at the LHC @ 8 TeV



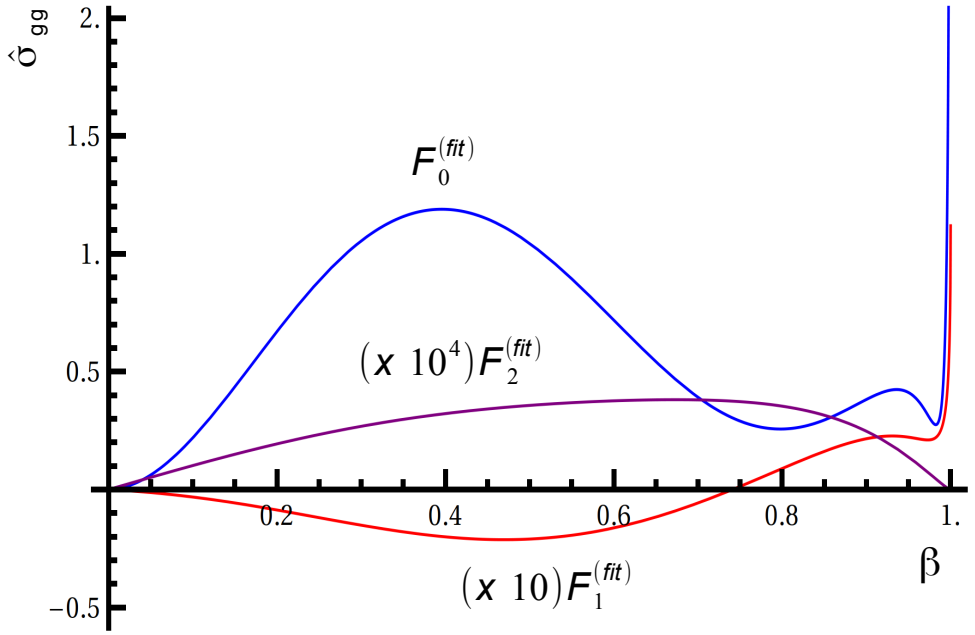
Comparison with high energy driven approximation implemented in HATHOR 1.3 Moch, Uwer, Vogt, `12

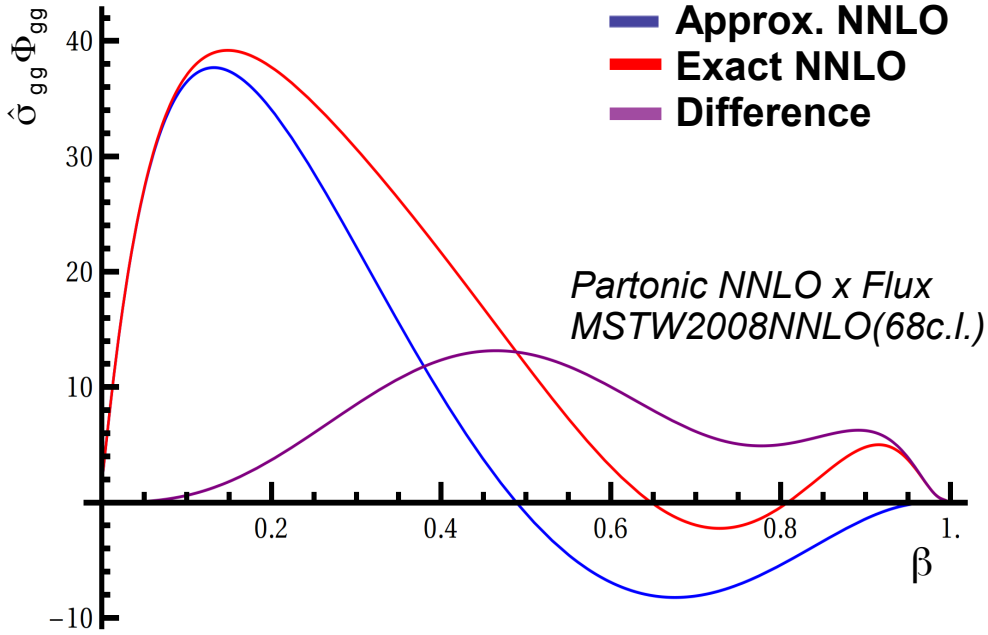
		Tevatron	LHC 7 TeV	LHC 8 TeV	LHC 14 TeV
I_1	Due to $\sigma_{qg}^{(1)}$ [pb]	-0.068	-0.88	-0.48	9.01
I_2	Due to $\sigma_{qg}^{(2)}$ [pb]	-0.057	-1.82	-2.25	-4.07
I_3	$\sigma_{qg}^{(2)}(\text{Hathor}; (A+B)/2)$ [pb]	0.040	5.78	8.11	27.36
I_4	$(I_3 - I_2)/\sigma_{\text{tot}}$ [%]	1.4	4.9	4.7	3.7

Partonic cross section results

Gluon-fusion channel Czakon, PF, Mitov `13

$$F_i \equiv F_i^{(\beta)} + F_i^{(fit)} \qquad i = 0,1,2$$





- Top++ Czakon, Mitov

Version 1.4

$NNLO_{approx}$

5%

Version 2.0

NNLO

2,8%

NNLO + NNLL

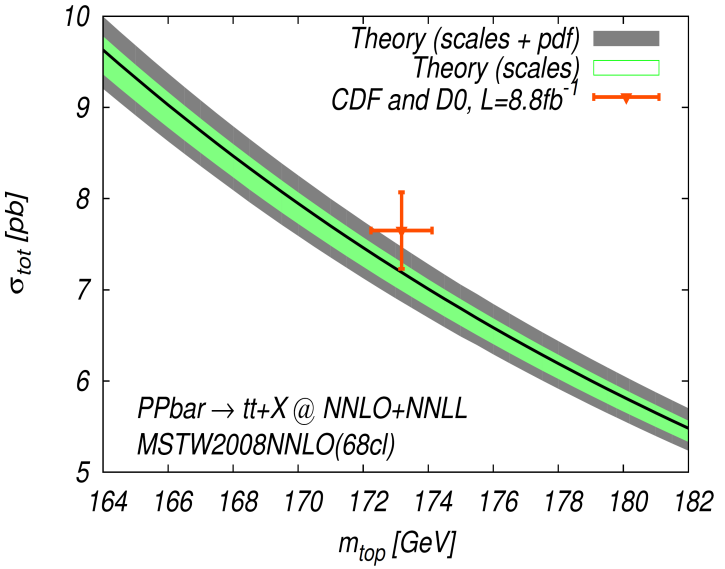
Predictions for hadron colliders

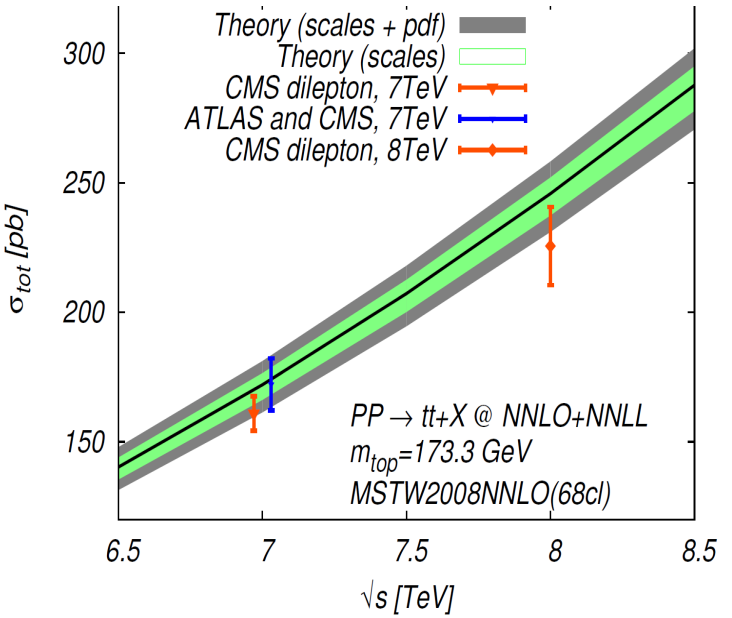
NNLO+NNLL

	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110 (1.5%) -0.200 (2.8%)	+0.169 (2.4%) -0.122 (1.7%)
LHC 7 TeV	172.0	+4.4 (2.6%) -5.8 (3.4%)	+4.7 (2.7%) -4.8 (2.8%)
LHC 8 TeV	245.8	+6.2 (2.5%) -8.4 (3.4%)	+6.2 (2.5%) -6.4 (2.6%)
LHC 14 TeV	953.6	+22.7 (2.4%) -33.9 (3.6%)	+16.2 (1.7%) -18.8 (1.9%)

NNLO

	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	+0.259 (3.7%) -0.374 (5.3%)	+0.169 (2.4%) -0.121 (1.7%)
LHC 7 TeV	167.0	+6.7 (4.0%) -10.7 (6.4%)	+4.6 (2.8%) -4.7 (2.8%)
LHC 8 TeV	239.1	+9.2 (3.9%) -14.8 (6.2%)	+6.1 (2.5%) -6.2 (2.6%)
LHC 14 TeV	933.0	+31.8 (3.4%) -51.0 (5.5%)	+16.1(1.7%) -17.6 (1.9%)

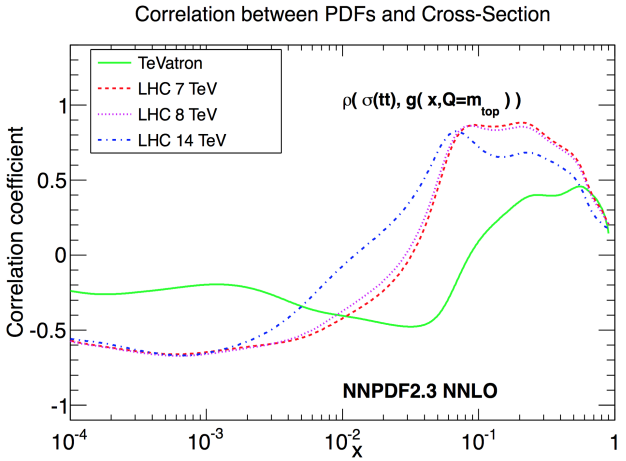


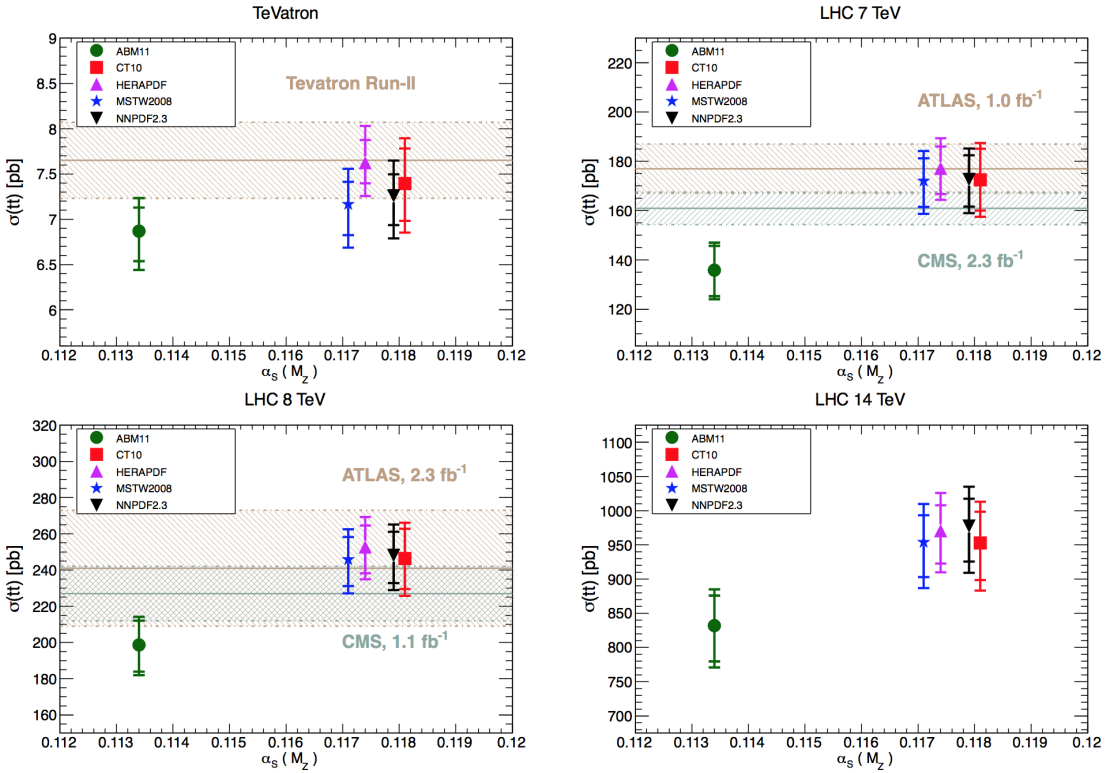


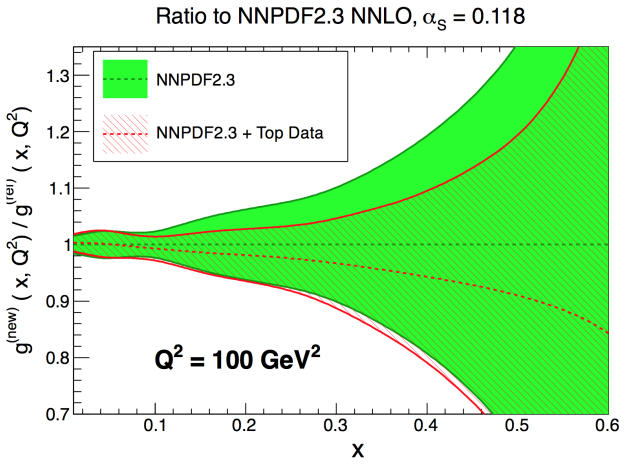
Czakon, PF, Mitov `13

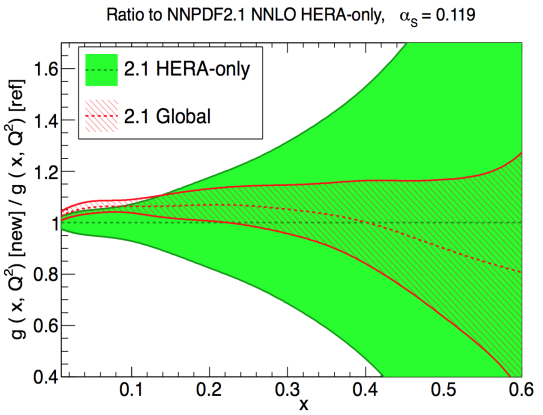
Application to PDF studies

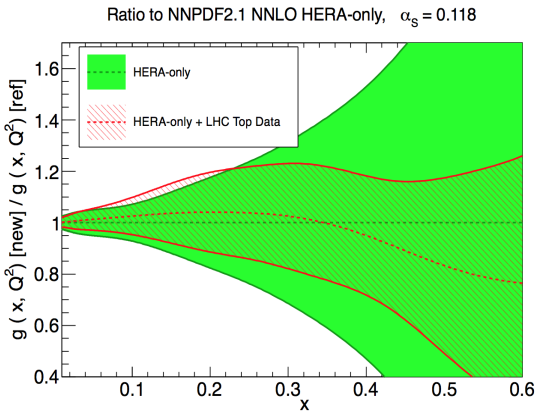
Czakon, Mangano, Mitov, Rojo `13











Summary

- Top pair total cross section is now complete at NNLO
- Scale dependence significantly reduced
- Strong contraints for PDF sets especially large-x gluon PDF

- What's next?

  - Forward-backward asymmetry at Tevatron

  - Differential distributions

  - Decays

Backup: Comparison with HATHOR for gluon fusion