Top physics

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GK1504

Outline

- Introduction / Motivation
- The total cross section for top quark pair production and the top-quark mass

- Towards improved predictions of exclusive top production (large multiplicities, decay, off-shell effects, parton shower)
- Conclusion / Outlook

Focus is on top-quark pair production

Apologies that not all recent developments can be mentioned

Why are we interested in top-quark physics ?

1) Important signal process

- Does top behave as it should ? Point-like ?
- Top-quark mass ? (→ EW fits, consistency of SM)
- Why is top so heavy ?
- Very sensitive to EWSB
- Window to new physics (resonances, loop effects, anomalous couplings)

2) Important background

- Higgs searches
- New physics searches

3) Useful for calibration (Exp. + Theory)

- jet energy scale, b-tagging…
- resummation program, loop technology

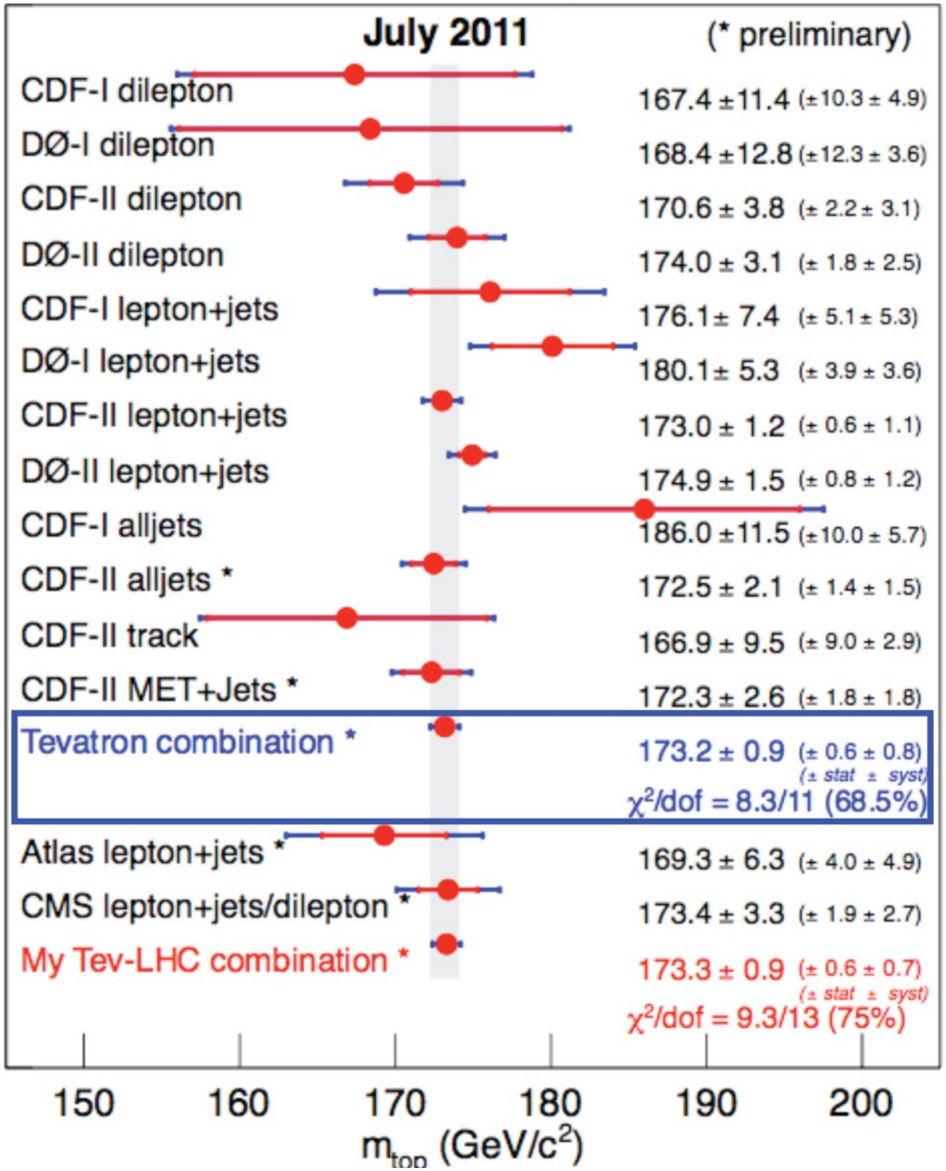
Top in the SM

Top quark couplings fixed through gauge structure and Higgs mechanism

⬇

Only “two” free parameters: mass and CKM matrix

Top-quark mass



[EPS 2011 plenary talk
Frederic Deliot]

How do we measure the top-quark mass ?

CKM matrix elements

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

eigenstates of the weak interaction

mass eigenstates

Global fit (SM, unitarity)

$$|V_{td}| = (8.4 \pm 0.6) \times 10^{-3}, \quad |V_{ts}| = (38.7 \pm 2.1) \times 10^{-3}, \quad \text{[PDG 10]}$$

$$|V_{tb}| = 0.999133^{+0.000044}_{-0.000043} \quad \text{[PDG 08]}$$

Almost no lower bound if additional families exist

!

$$|V_{tb}| = 0.88 \pm 0.07 \quad \text{[PDG 10]}$$

(CDF data, 3 families,no unitarity)

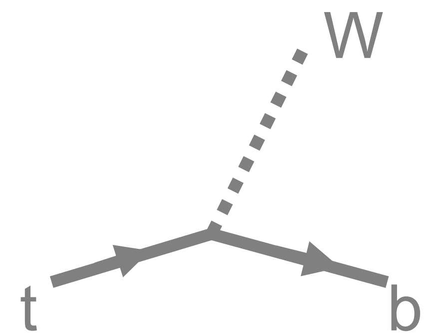
→ top properties can be calculated with high accuracy within SM

Top properties

Main decay in the SM:

$$|V_{tb}| \approx 1 \quad \rightarrow \quad t \rightarrow Wb$$

$$\hookrightarrow q\bar{q}', \bar{\ell}\nu_\ell$$



Width calculable in the SM:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{m_W^2}{m_t^2}\right)^2\left(1+\frac{2m_W^2}{m_t^2}\right)\left(1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right)$$
$$\approx 1.48 \quad GeV$$

Two-loop QCD and one-loop EW corrections also known!

Life time:

$$\Gamma \approx 1.4\text{GeV} \rightarrow \tau_t \approx 0.4 \times 10^{-25} s < \tau_{\text{QCD}} \approx 3\times 10^{-24} s$$

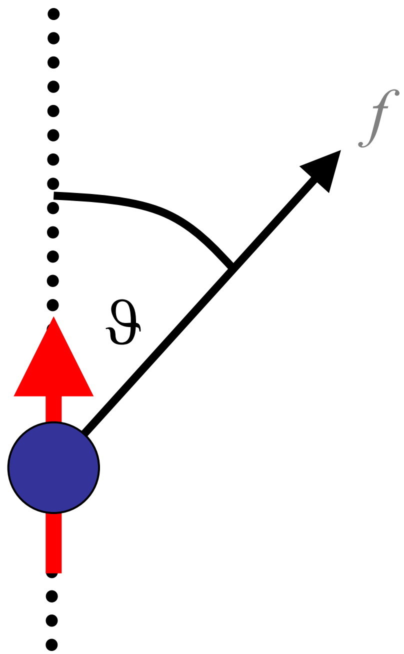
"Top quark decays before it can hadronize"

[Bigi, Dokshitzer, Khoze, Kühn, Zerwas ´86]

Unique property: Top quark behaves like a quasi free quark

Measurement of the Top Quark Polarisation

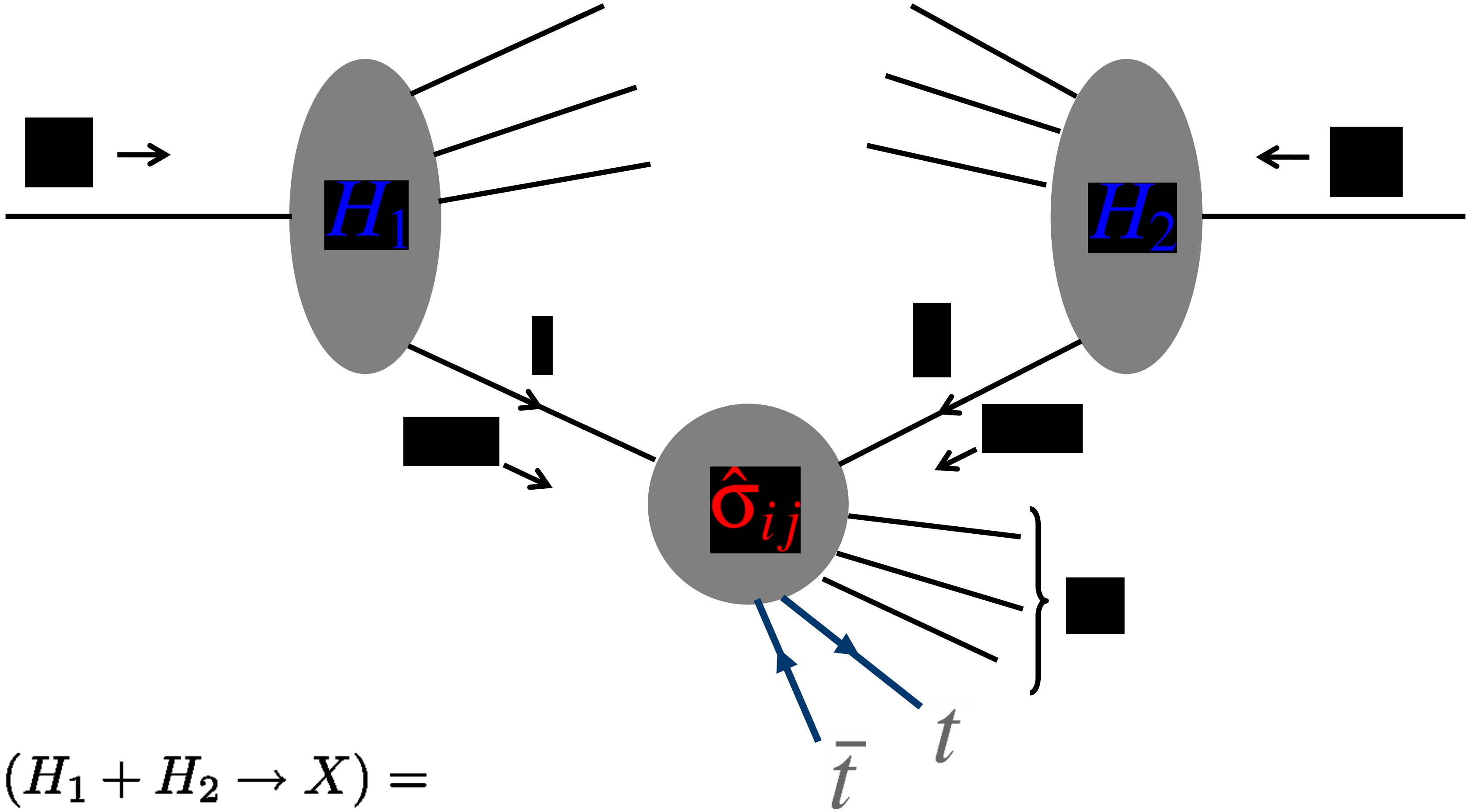
- Top quark decays before hadronization
- Parity violating decay $t \rightarrow Wb$



Polarisation can be studied through the angular distribution of the decay products!

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\vartheta} = \frac{1}{2}\left(1 + \kappa_f \cos\vartheta\right)$$

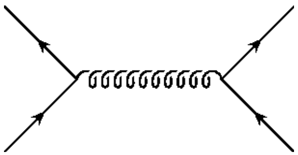
Hadronic top production:Top pair production



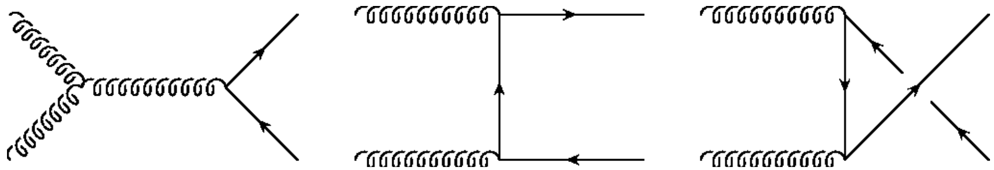
$$d\sigma(H_1 + H_2 \rightarrow X) =$$

$$\sum_{ij} \int dx_1 dx_2 F_{i/H_1}(x_1, \mu_F) F_{j/H_2}(x_2, \mu_F) d\hat{\sigma}(i(x_1 P_1) + j(x_2 P_2) \rightarrow t\bar{t} + X)$$

Hadronic top production: top pair production



~90% @ Tevatron, 10% @ LHC



~10% @ Tevatron, 90% @ LHC

Partonic cross sections

$$\beta = \sqrt{1 - 4m_t^2/\hat{s}}$$

$$\rho = 4m_t^2/\hat{s}$$

$$\hat{\sigma}_{q\bar{q}} = \frac{8\pi\alpha_s^2}{27\hat{s}}\beta(1+\frac{\rho}{2})$$

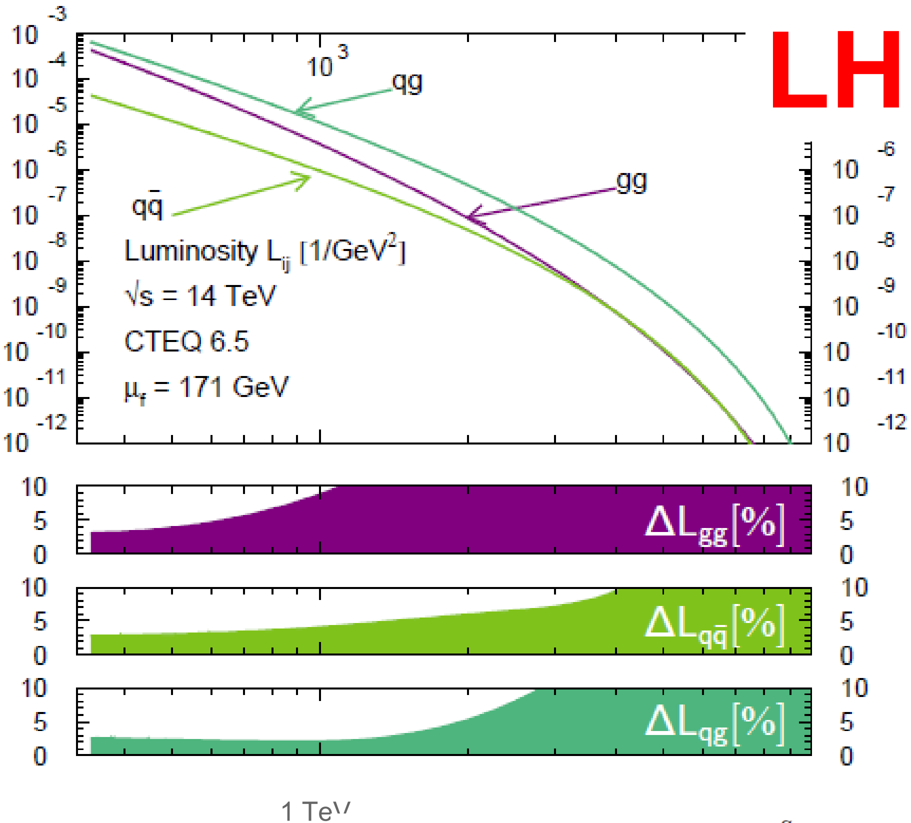
$$\hat{\sigma}_{gg} = \frac{4\pi\alpha_s^2}{12\hat{s}}\left[\left(1+\rho+\frac{\rho^2}{16}\right)\ln\left(\frac{1+\beta}{1-\beta}\right) - \beta\left(\frac{7}{4}+\frac{31}{16}\rho\right)\right]$$

$$\sigma_{\text{Had}} = \sum_{i,j}\int_0^1\int_0^1 F_{i/H_1}(x_1,\mu_f)F_{j/H_2}(x_2,\mu_f)\hat{\sigma}_{ij}(\hat{s}=x_1x_2s,\mu_f)$$

NLO corrections also known

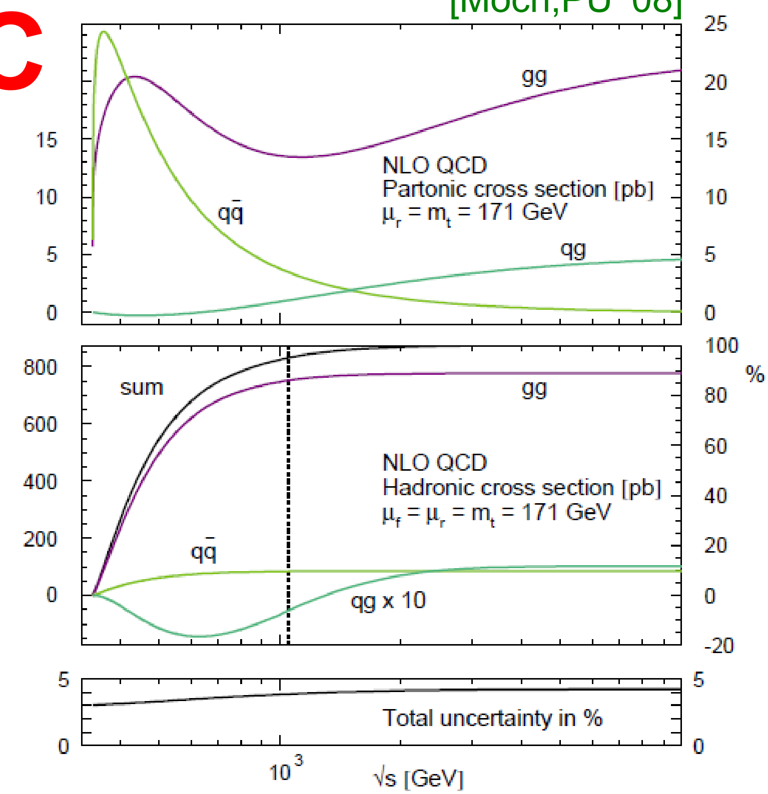
[Dawson, Ellis, Nason ’89, Beenakker et al ’89,’91,Bernreuther, Brandenburg, Si, P.U. ’04, Czakon,Mitov 08]

Putting things together: the hadronic cross section



LHC

[Moch,PU '08]



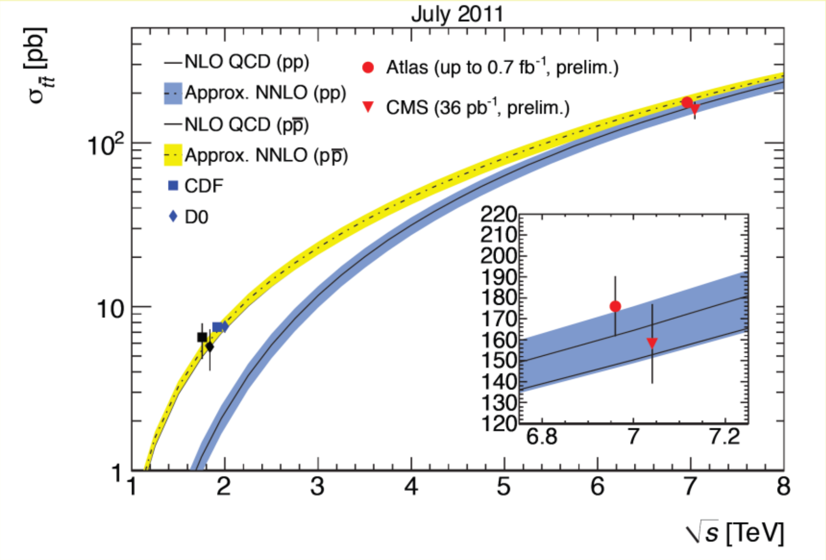
$$L_{ij}(\hat{s}, s_{\rm had}, \mu_f^2) = \frac{1}{s_{\rm had}} \int_{\hat{s}}^{s_{\rm had}} \frac{ds}{s} f_{i/p}\left(\mu_f^2, \frac{s}{s_{\rm had}}\right) f_{j/p}\left(\mu_f^2, \frac{\hat{s}}{s}\right)$$

$$\sigma_{pp\to t\bar{t}X}(s_{\rm had}, m_t{}^2) = \sum_{i,j=q,\bar{q},g} \int_{4m_t{}^2}^{s_{\rm had}} d\hat{s}\, L_{ij}(\hat{s}, s_{\rm had}, \mu_f^2)\, \hat{\sigma}_{ij\to t\bar{t}}(\hat{s}, m_t{}^2, \mu_f^2, \mu_r^2)$$

Experimental status: cross section

EPS 2011 plenary talk, Frederic Deliot

Top Quark Pair Cross Section Summary



decay channel combined for $m_t = 172.5$ GeV:		
CDF (up to 4.6 fb^{-1})	$\sigma(p\bar{p} \to t\bar{t}) =$	$7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb
D0 (5.6 fb^{-1}, arXiv:1105.5384)	$\sigma(p\bar{p} \to t\bar{t}) =$	$7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb
Atlas (up to 0.7 fb^{-1})	$\sigma(pp \to t\bar{t}) =$	$176 \pm 5(\text{stat})^{+13}_{-10}(\text{syst}) \pm 7(\text{lumi})$ pb
CMS (36 pb^{-1})	$\sigma(pp \to t\bar{t}) =$	$158 \pm 10(\text{uncor.}) \pm 15(\text{cor.}) \pm 6(\text{lumi})$ pb

~ 6.5 %

~ 8 %

Measurements agree with the QCD predictions

Future measurements will focus on differential cross sections

Frédéric Déliot, EPS 2011, Grenoble, 25-JULY-2011

Theory status inclusive tt cross section

NLO predictions $t\bar{t} + X$

unpolarised: [Nason, Dawson, Ellis 88,89], [Beenakker, Kuijf, vNeerven, Smith ‘89], [Beenakker, Kuijf, vNeerven, Meng, Schuler, Smith ‘89], [Mangano, Nason, Ridolfi 92], [Czakon, Mitov 08]

polarised: [Bernreuther, Brandenburg, Si, PU 01,04] [Melnikov, Schulze 09] [Bernreuther,Si 10]

$m_t = 173.1 GeV/c^2, m_t/2 < \mu < 2m_t$ MSTW2008 PDF(90%cl)

	Tevatron	LHC (7 TeV)
σ_{LO} (pb)	$6.66^{+2.95\,+0.34}_{-1.87\,-0.27}$	$122^{+49\,+6}_{-32\,-7}$
σ_{NLO}	$6.72^{+0.36\,+0.37}_{-0.76\,-0.24}$	$159^{+20\,+8}_{-21\,-9}$

NLO

$$\frac{\Delta\sigma}{\sigma} \approx \begin{cases} {}^{+5\%}_{-10\%}\ \text{(scale)}\ {}^{+5\%}_{-4\%}\ \text{(pdf) Tevatron} \\ {}^{+12\%}_{-13\%}\ \text{(scale)}\ \pm 5\%\ \text{(pdf) LHC} \end{cases}$$

Structure of NLO result

Close to threshold NLO corrections are given by:

$$f^{(1)}_{q\bar q}(\rho) + \overline{f}^{(1)}_{q\bar q}(\rho)\ln\frac{\mu^2}{m^2} = \frac{1}{4\pi^2} f^{(0)}_{q\bar q}(\rho)\left\{\left(C_F - \frac{1}{2}C_A\right)\frac{\pi^2}{2\beta} + 2C_F \ln^2(8\beta^2) - (8C_F + C_A)\ln(8\beta^2) - 2C_F\ln(4\beta^2)\ln\frac{\mu^2}{m^2} + \overline{C}_2\left(\frac{\mu^2}{m^2}\right) + \mathcal{O}(1-\rho)\right\}, \quad (12)$$

$$f^{(1)}_{gg}(\rho) + \overline{f}^{(1)}_{gg}(\rho)\ln\frac{\mu^2}{m^2} = \frac{1}{4\pi^2} f^{(0)}_{gg}(\rho)\left\{\frac{N_c^2+2}{N_c(N_c^2-2)}\frac{\pi^2}{4\beta} + 2C_A \ln^2(8\beta^2) - \frac{(9N_c^2-20)C_A}{N_c^2-2}\ln(8\beta^2) - 2C_A\ln(4\beta^2)\ln\frac{\mu^2}{m^2} + \overline{C}_3\left(\frac{\mu^2}{m^2}\right) + \mathcal{O}(1-\rho)\right\}, \quad (13)$$

[Nason, Dawson, Ellis 88, Beenakker, kuijf, vNeerven,Smith '89]

possible large logarithmic corrections in threshold region:

$$f^{(n)}_{ij}(\rho;\mu^2/m^2) \sim f^{(0)}_{ij}(\rho)\ln^{2n}\beta^2$$

→sum large logarithmic corrections to improve perturbation theory

[Ahrens, Beneke, Berger, Bonciani, Cacciari, Catani, Contopaganos, Ferroglia, Kidonakis, Laenen, Mangano, Moch, Nason, Neubert, Ridolfi, Sterman…]

Recent progress: NNLL resummation

Extension to NNLL:

[Langenfeld, Moch, PU '08, '09]
[Czakon, Mitov, Sterman '09]
[Kidonakis '10] Beneke et. al. '09]
[Ahrens, Ferroglia, Neubert, BP, Yang '10, '11]

Simultaneous resummation of soft gluon and Coulomb terms: [Beneke, Falgari, Schwinn '09]

→ active field, many competing groups with slightly different approaches

[Ben Pecjak, Wuppertal 11]

Name	Observable	Soft limit
production threshold	σ	$\beta = \sqrt{1 - 4m_t^2/\hat{s}} \to 0$
single-particle-inclusive (1PI)	$d\sigma/dp_T dy$	$s_4 = (p_4 + k)^2 - m_t^2 \to 0$
pair-invariant-mass (PIM)	$d\sigma/dM_{t\bar{t}} d\theta$	$(1 - z) = 1 - M_{t\bar{t}}^2/\hat{s} \to 0$

→ see also Ben Pecjak's talk on Thursday

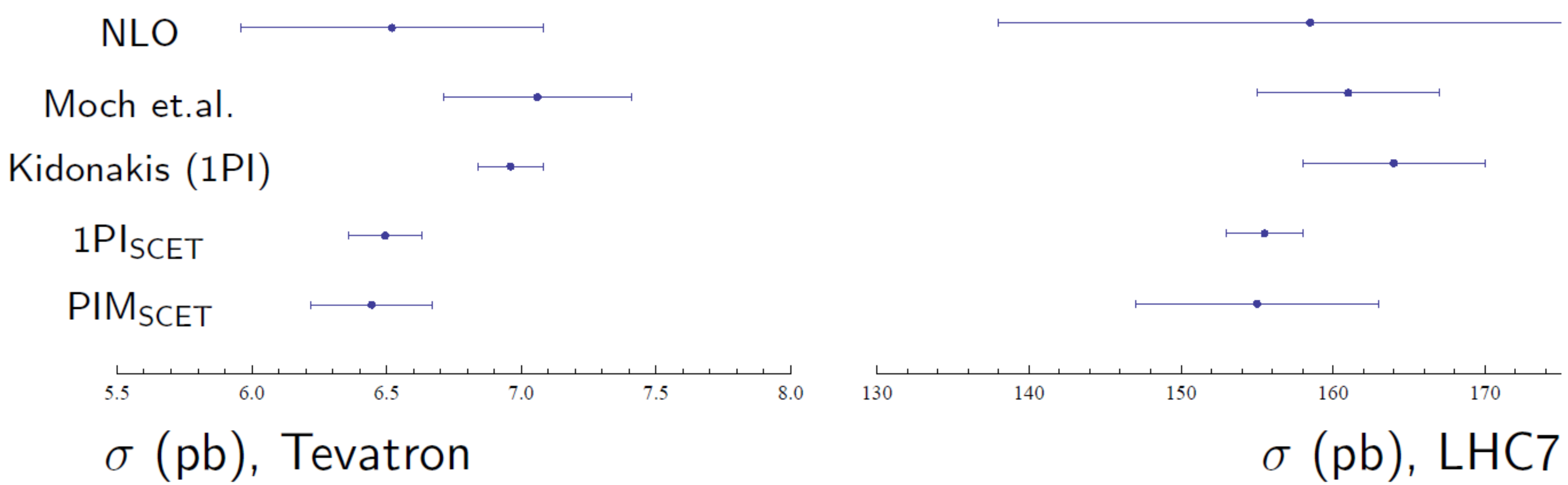
Beyond NLO: NNLL and NNLO$_{approx}$

Different approaches:

- Definition of threshold/resummation variable
- Resummed versus expanded
- Which scale dependent parts are included?

→ differences in non-logarithmic contributions, not predicted by soft gluon resummation

[Ben Pecjak, Wuppertal 11]



Conclusion ?

- Tevatron:

  spread of different approaches as large as NLO uncertainty

  → situation unclear, full NNLO required

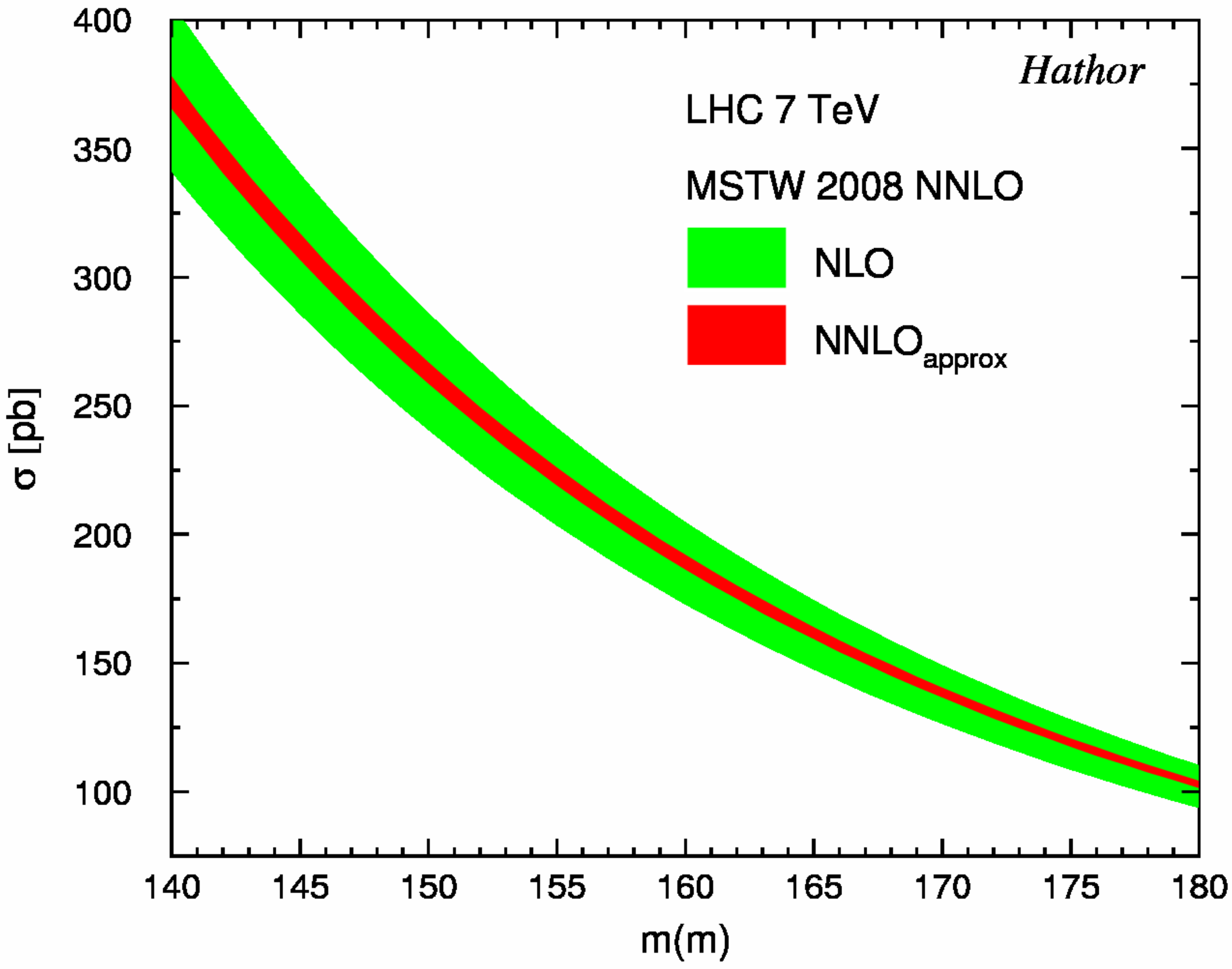
- LHC:

  spread of different approaches smaller than NLO uncertainty, results marginally consistent

  → reasonable agreement

Can expect 3-4 % scale uncertainty from full NNLO

Prospects



Hathor
LHC 7 TeV
MSTW 2008 NNLO
NLO
NNLO$_{approx}$
σ [pb]
400
350
300
250
200
150
100
140
145
150
155
160
165
170
175
180
m(m)

Top quark mass measurement: “issues”

A) Top-quark mass is just a parameter of the underlying theory

→ renormalization scheme dependent, at least NLO calculation required for meaningful measurement

$$m_t = 170\mathrm{GeV} \leftrightarrow \overline{m}(\mu = \overline{m}) = 160\mathrm{GeV}$$

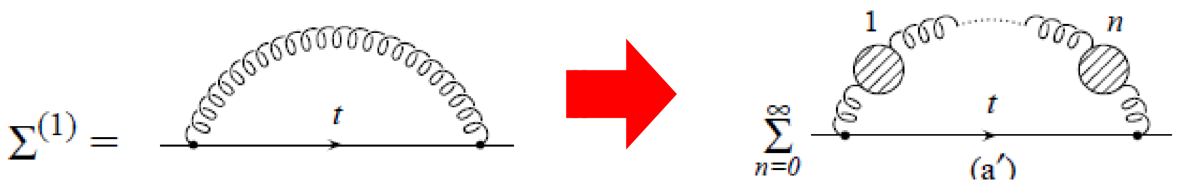
B) Top-quark is a colour triplet

→ non-perturbative effects in the reconstruction of the top momentum from colour singlet's

uncertainty of the order of 500 MeV [Skands,Wicke ‘08]

C) Top-quark pole mass is not a well defined concept

→ intrinsic uncertainty due to renormalon ambiguity of order Λ_{QCD}



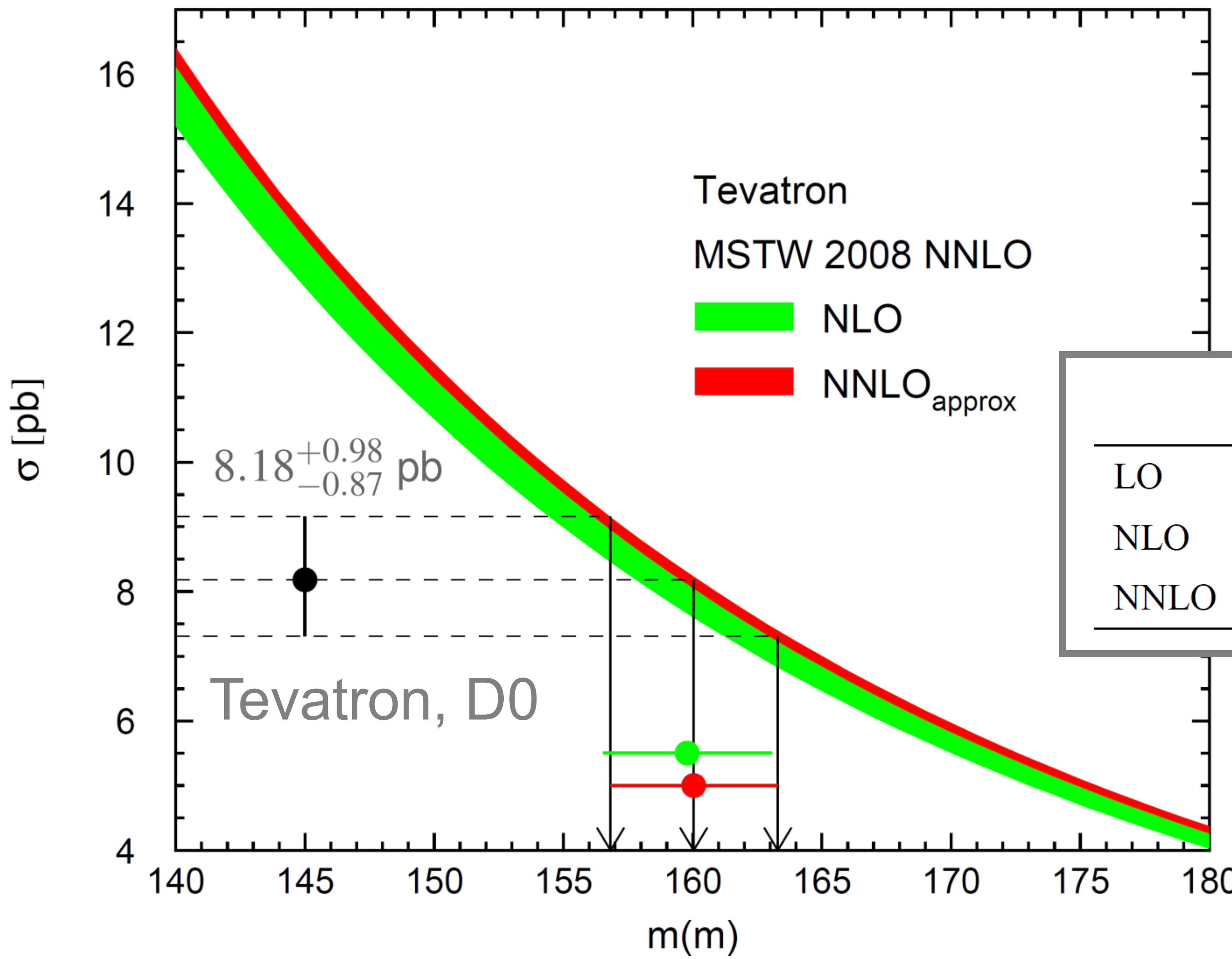
$$\frac{16 m_R}{3\beta_0} \sum_{n=0}^{\infty} c_n a^{n+1}$$

$$c_n \overset{n\to\infty}{\longrightarrow} e^{-C/2} 2^n n!$$

[Bigi, Shifman, Uraltsev, Vainshtein 94 Beneke, Braun,94 Smith, Willenbrock 97]

First direct determination of the $\overline{\text{MS}}$ mass

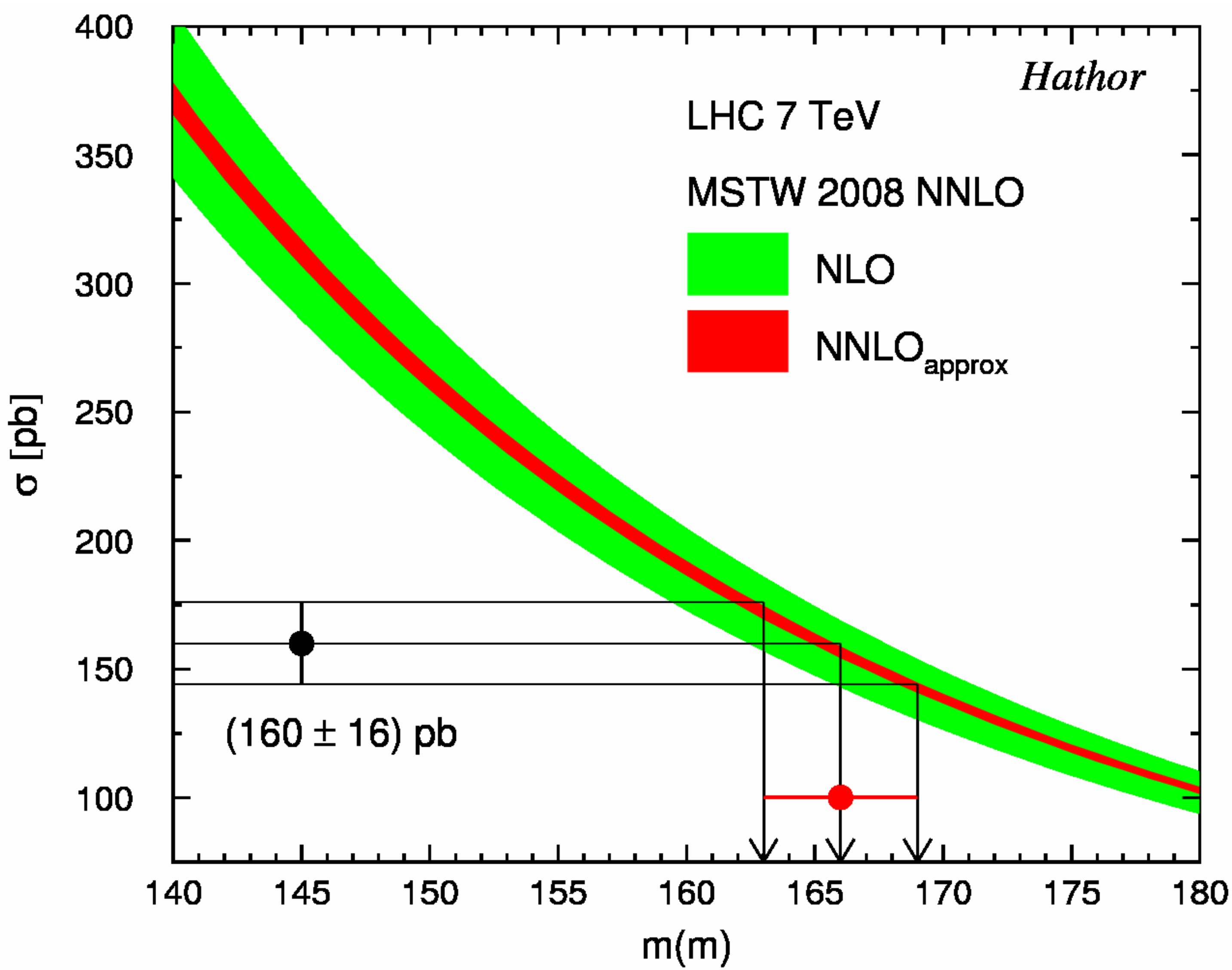
[Langenfeld, Moch, P.U. 09]



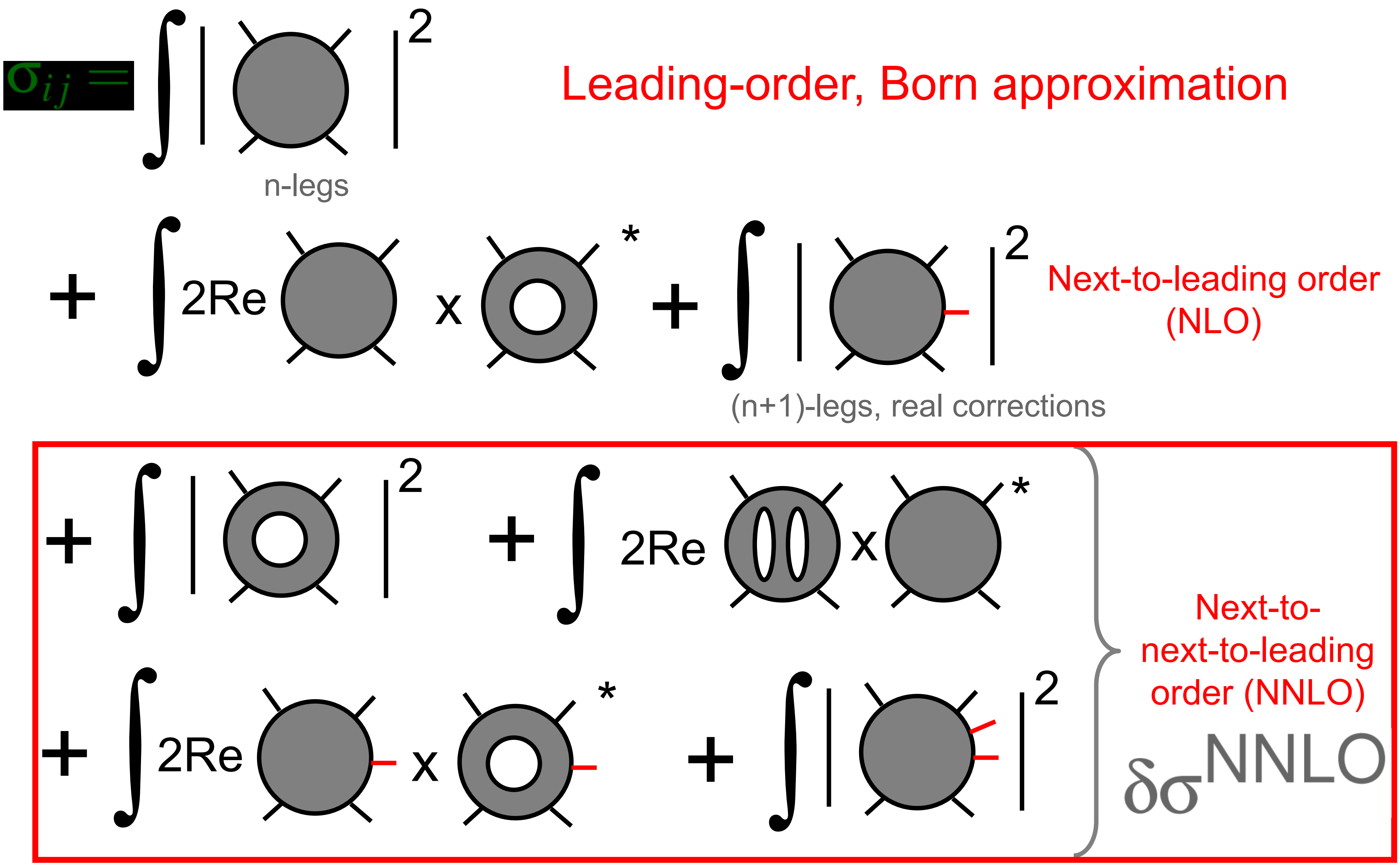
	$\overline{m}$ [GeV]	m_t [GeV]
LO	$159.2^{+3.5}_{-3.4}$	$159.2^{+3.5}_{-3.4}$
NLO	$159.8^{+3.3}_{-3.3}$	$165.8^{+3.5}_{-3.5}$
NNLO	$160.0^{+3.3}_{-3.2}$	$168.2^{+3.6}_{-3.5}$

$$m_t = 168.9^{+3.5}_{-3.4}$$

Prospects for mass determination at LHC



Towards Top-Quark Pair Production @ NNLO



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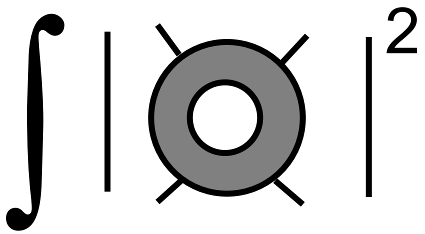
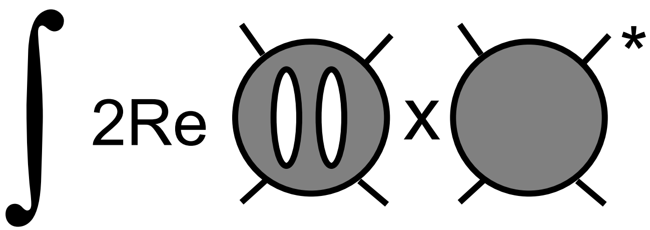
Towards Top-Quark Pair Production @ NNLO

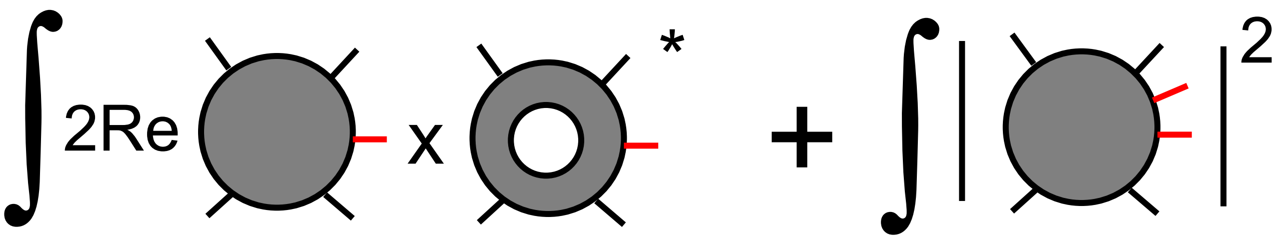


[Rogal ‘05, Körner, Merebashvili, Rogal ‘08, Kniehl, Merebashvili,Körner,Rogal ’08, Anastasiou, Aybat ‘08]

Due to singularities in one-loop integrals, Order (d-4)^2 need in expansion



[Czakon, Mitov, Moch ’07,’07, Czakon ‘08,
Bonciani, Ferroglia, Gehrmann, Maitre, vManteufel, Studerus ’08-10]



[Dittmaier, P.U., Weinzierl ‘07, ’08]
[Bevilacqua,Czakon,Papdopoulos, Worek 10]
[Melnikov, Schulze 10]

$$d\sigma_{VV} \oplus d\sigma_{RV} \oplus d\sigma_{RR}$$

✓ ✓ ✓

[Czakon,Boughezal, Daleo, Grazini, Gehrmann-de Ridder, Gehrmann, Glover, Heinrich, Luisoni. Maitre, Monni, Ritzmann,Weinzierl]

Energy and PDF dependence

Cross sections [pb]:

[Alekhin,Blümlein, Klein, Moch 10]

$m_t = 173 GeV$

$\sqrt{s}$ (TeV)	ABKM09	MSTW2008
1.96 $(\bar{p}p)$	6.91 ± 0.17	7.04
7 (pp)	131.3 ± 7.5	160.5
10 (pp)	343 ± 15	403
14 (pp)	780 ± 28	887

(only pdf uncertainty)

~2-3 % pdf

Significant differences at LHC

MSTW2008 larger due to:

- Larger α_s $(0.1135 \pm 0.0014)_{ABKM} \rightarrow (0.1171 \pm 0.0014)_{MSTW}$
- Larger gluon flux close to threshold $(x \approx 2.5 \times 10^{-2})$

→ top cross section important to constrain pdf!

Towards improved predictions of exclusive top production

more jets

NLO corrections for large multiplicities

Why important ?

- Significant fraction of tt events include additional jet

  → i.e. 10 – 50 % depending on jet cut (200 – 50 GeV)
- Some observables require additional jet activitiy

  → i.e. $p_\perp^{t\bar{t}}$
- More realistic modeling of the event

Impressive progress due to

improved methods (unitarity method)

NLO corrections for large multiplicities

$t\bar{t} + \text{1-Jet} + X$

"polarised": [Dittmaier, PU, Weinzierl 08], [Bevilacqua,Czakon,Papdopoulos,Worek 10]

[Melnikov, Schulze 10]

$t\bar{t} + \gamma + X$

[Duan, Zhang, Han, Guo, Wang 09]

[Melnikov, Scharf, Schulze 11]

$t\bar{t}b\bar{b} + X$

"polarised": [Bredenstein, Denner, Dittmaier, Pozzorini 08-10]

[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek 09]

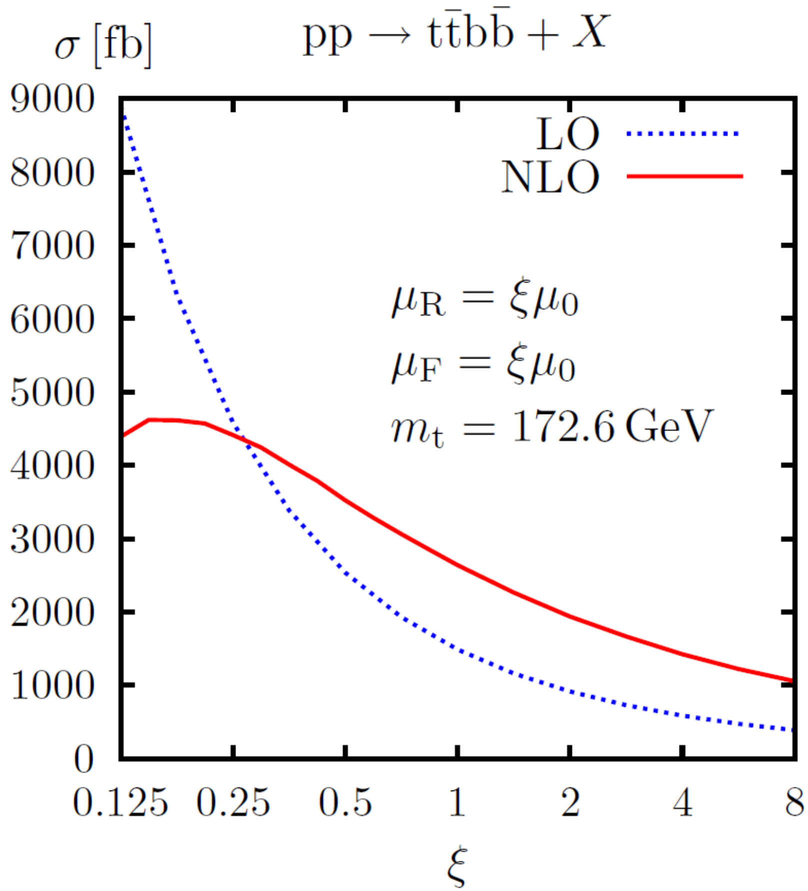
$t\bar{t} + \text{2-Jets} + X$

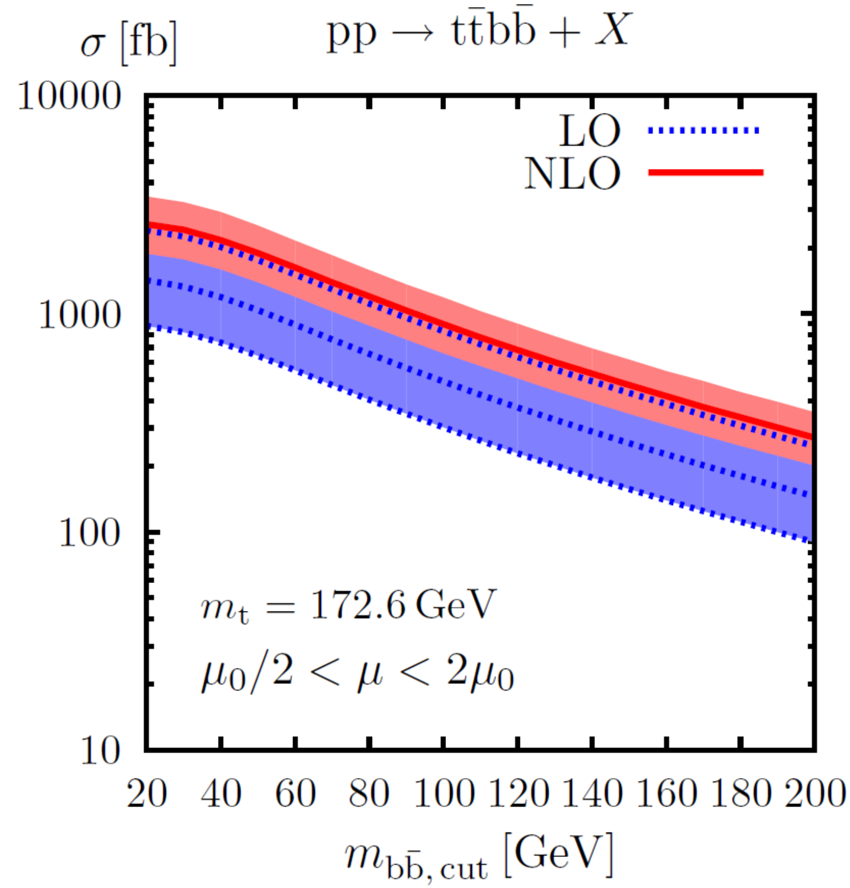
"polarised": [Bevilacqua, Czakon, Papadopoulos, Worek 10]

Selected results: ttbb

Important background process for ttH

[Bredenstein, Denner, Dittmaier, Pozzorini 09]

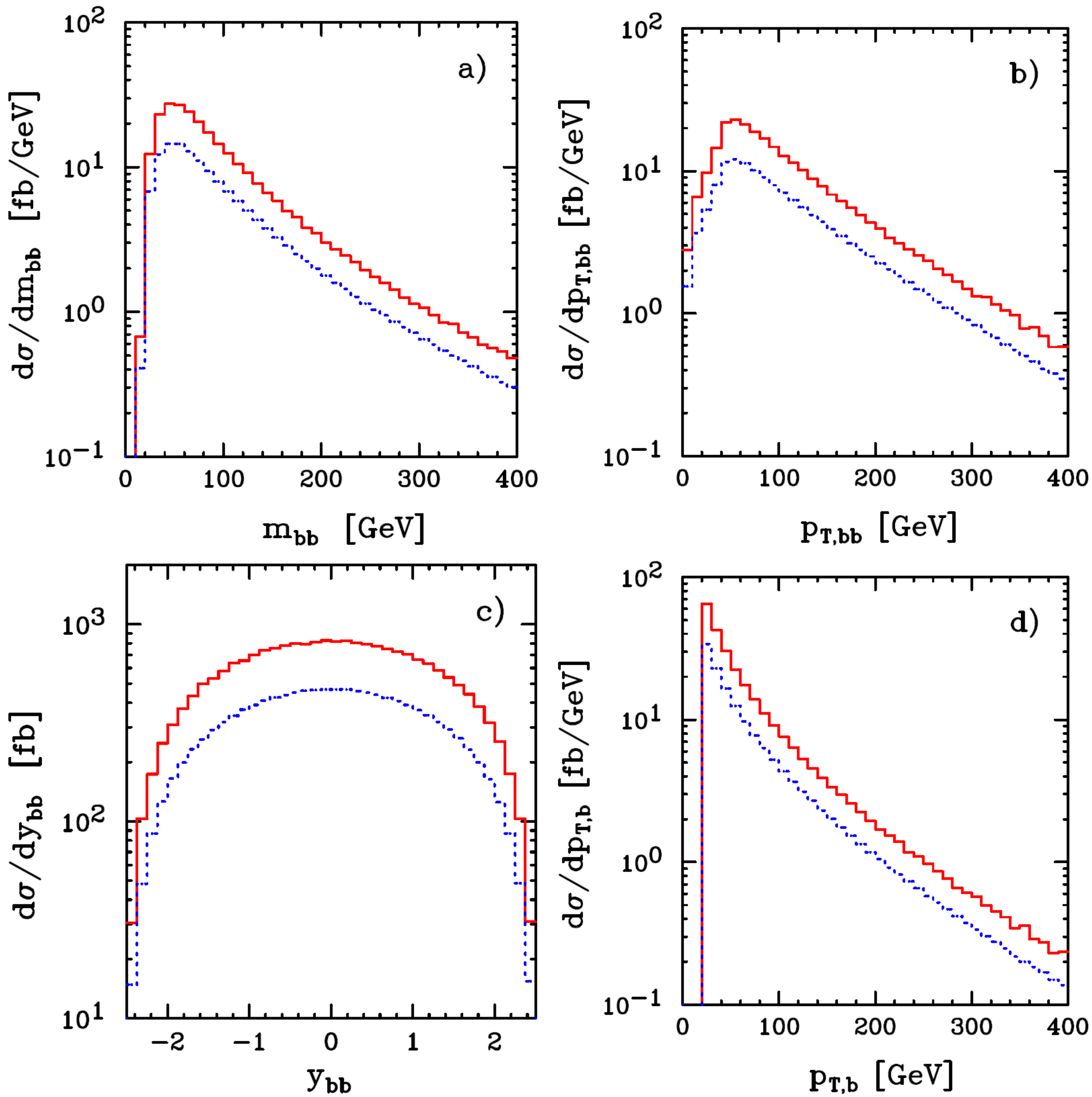




scale uncertainty is reduced ±70% → ±33%

large positive corrections, factor 1.8 !

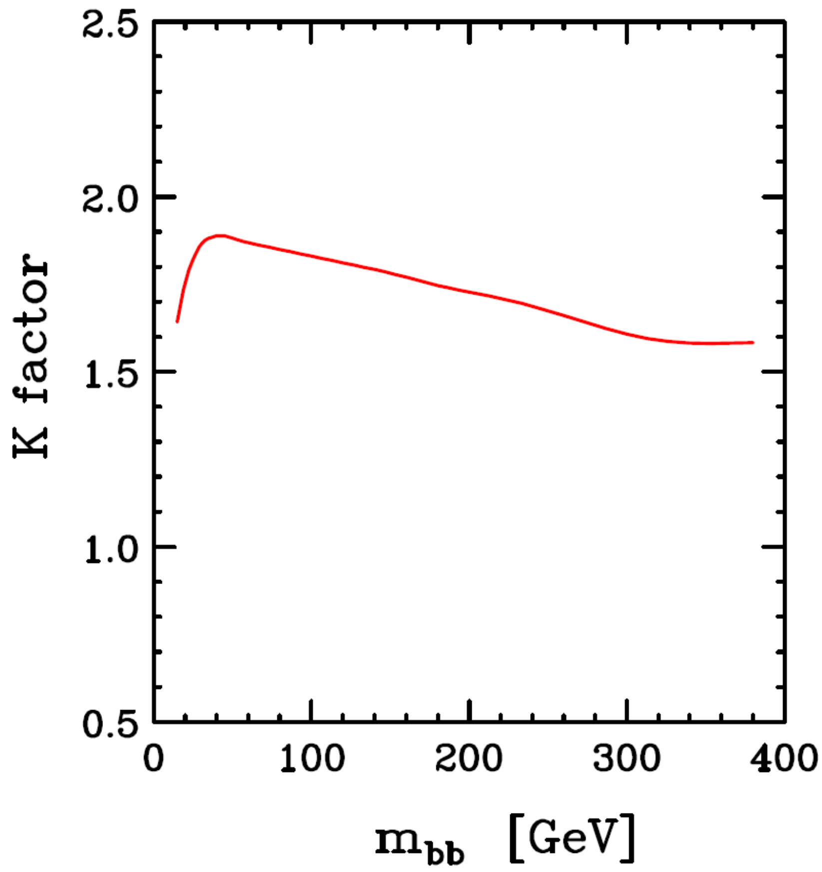
Selected results: ttbb

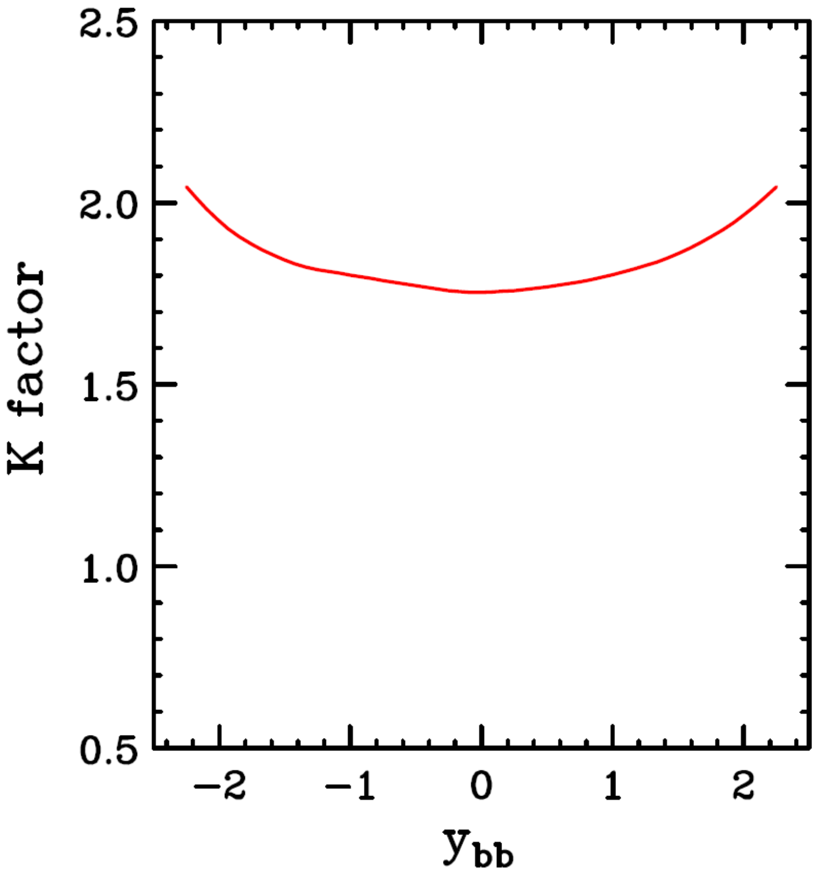


[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek 09]

Selected results: ttbb

[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek 09]



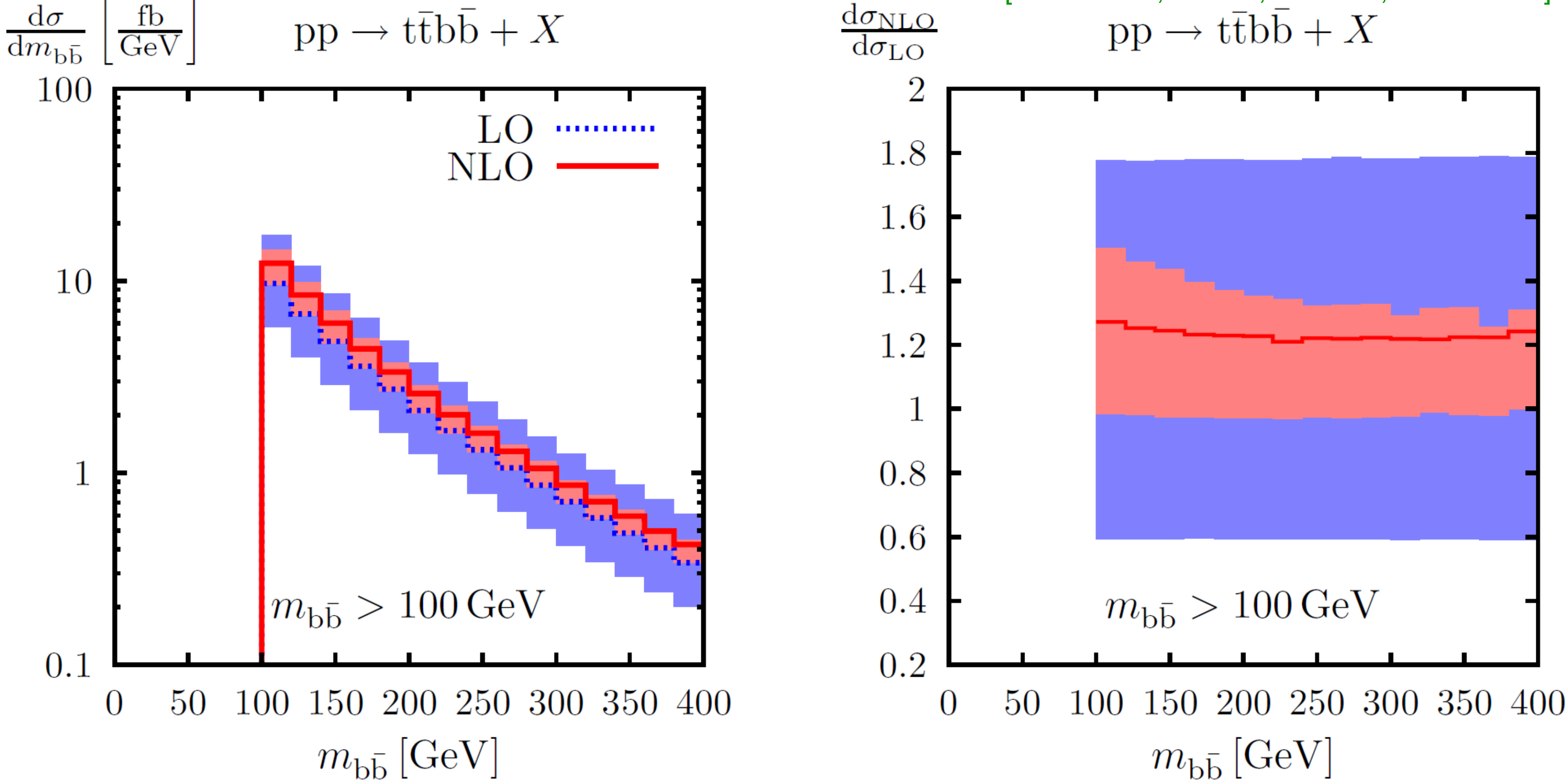


→ again large corrections, K=1.4 – 2.

bad scale choice ?

Selected results: ttbb

[Bredenstein, Denner, Dittmaier, Pozzorini 09]

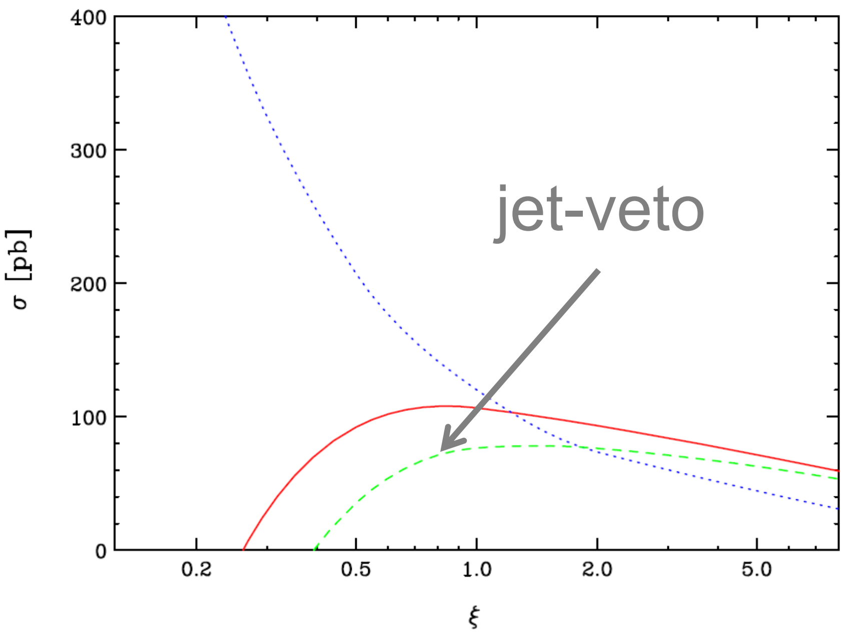


Improved convergence with dynamical scale setting:

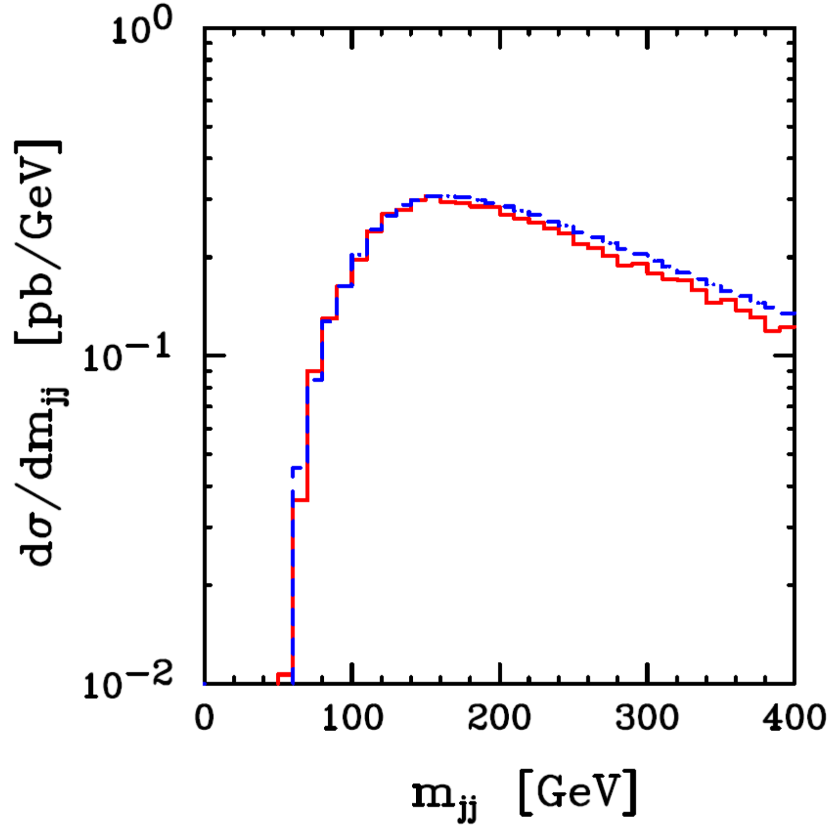
$$\mu_0^2 = m_t \sqrt{P_{T,b} P_{T,\bar{b}}}$$

→ relevant for Higgs search

[Bevilacqua, Czakon, Papadopoulos, Worek 10, 11]



$$\mu = \xi m_t$$



scale dependence improved, corrections moderate in size

Towards improved predictions of exclusive top production

top decays

Spin correlations: Spins of top quark and antiquark are correlated

[Bernreuther,Brandenburg 93,
Mahlon, Parke 96, Stelzer,Willenbrock 96,
Bernreuther, Brandenburg, Si, P.U. 04]

Quantum mechanics:

$$^{(2s+1)}L_J$$

close to threshold:

[redacted]

[redacted]

→ Spins are parallel or anti-parallel close to threshold

$$C_{t\bar{t}} = \frac{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)-\sigma(\uparrow\downarrow)-\sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)+\sigma(\uparrow\downarrow)+\sigma(\downarrow\uparrow)}$$

$$C = \kappa_1\kappa_2 C_{t\bar{t}}$$

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\vartheta_\ell \, d\cos\vartheta_{\bar{\ell}}} = \frac{1}{4}(1 - C\cos\vartheta_\ell\cos\vartheta_{\bar{\ell}})$$

Top quark decay and spin correlations

Why interesting?

- more sensitive probe of production mechanism
- important for selection cuts

Need to include top-quark decay in theoretical presciption

Recent progress:

- specific observables [Bernreuther, Brandenburg, Si, P.U. 04]
- arbitarty distributions [Bernreuther, Si 10], [Melnikov, Schulze 09]

Spin correlations: Tevatron results

D0 result

$$C = 0.1^{+0.45}_{-0.45}$$ [D0, arXiv1103.1871]

CDF result

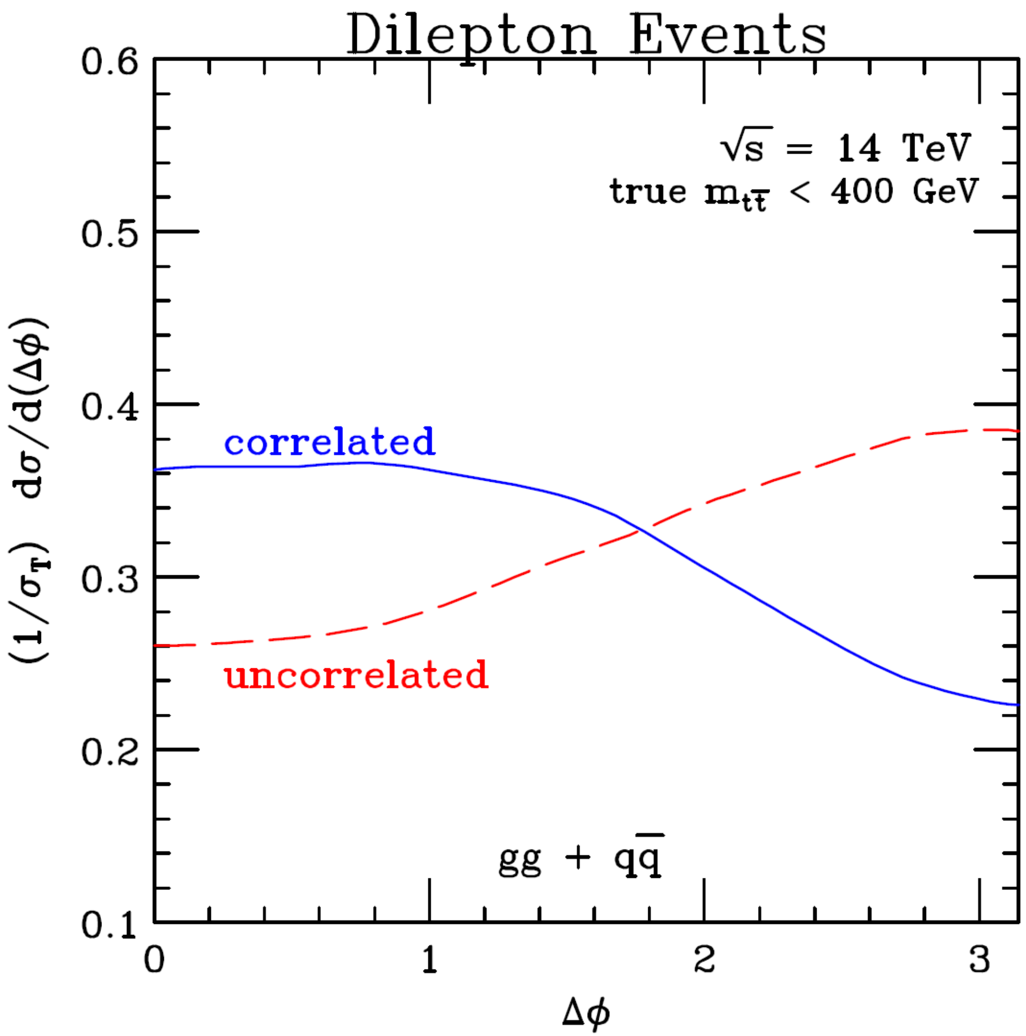
$$C = 0.6 \pm 0.5(\text{stat}) \pm (0.2)$$ [CDF, EPS 2011]

→ not conclusive

SM: $$C = 0.777^{+0.027}_{-0.042}(\text{scale})$$ [Bernreuther et al 04]

Recent progress

[Parke, Mahlon '10]



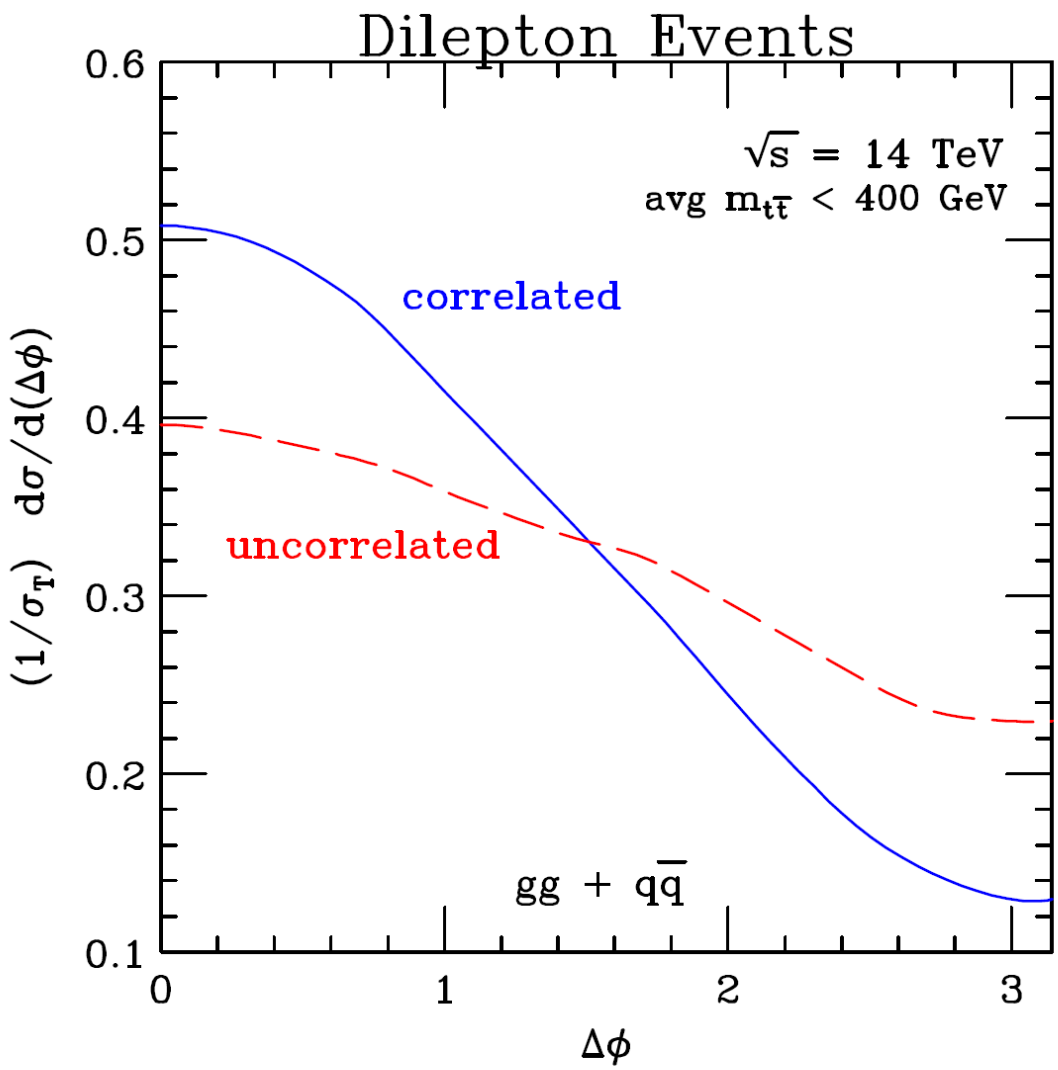
$\Delta\phi$ difference of azimuthal angles

laboratory frame!

should be experimentally easier !

Recent progress

[Parke, Mahlon '10]



Recent progress

[Melnikov, Schultze '11]

Change question:

How can we prove/rule out spin correlations ?

→ try to construct "optimal" observable taking into account all available information (distributions)

apply statistical methods

→ at LHC 500 Dilepton events should be sufficient to establish or rule out spin correlations !

Towards improved predictions of exclusive top production

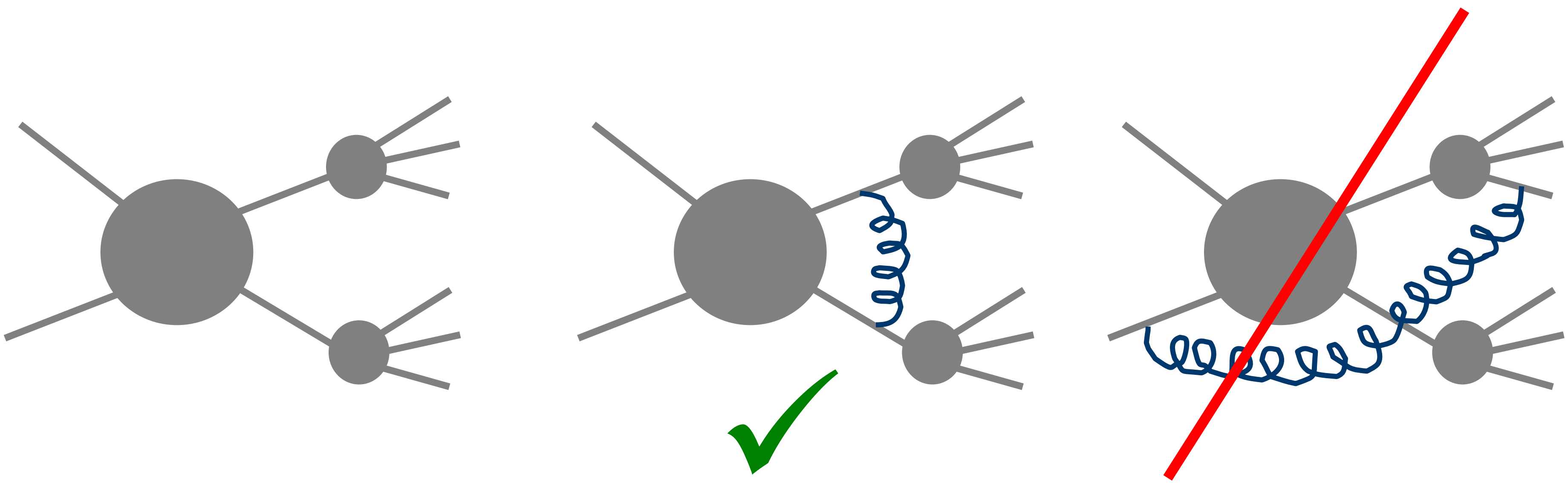
off shell effects

Non-factorizable corrections and off-shell effects

Results including decay obtained in double-pole approximation / narrow width approximation:

$$d\sigma(pp \to t\bar{t} \to \text{decay products}) \approx \mathrm{Tr}[\rho_{t\bar{t}}\,\rho_t\,\rho_{\bar{t}}]$$

factorization into production and decay



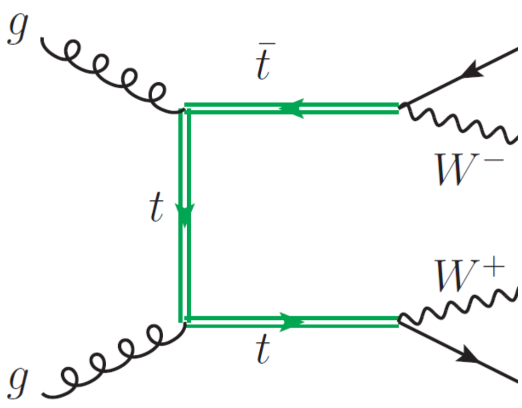
Recent progress:

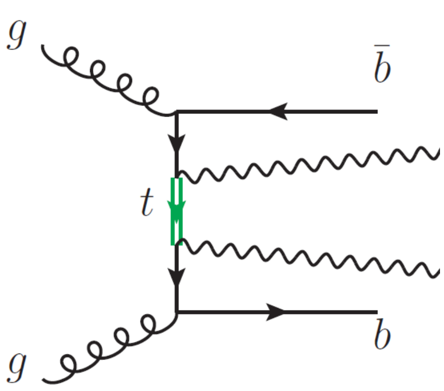
[Bevilacqua,Czakon,van Hameren,Papadopoulos,Worek '10]

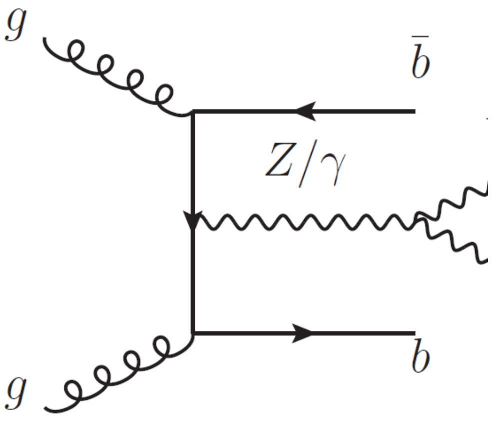
[Denner, Dittmaier, Kallweit, Pozzorini 10]

Full NLO corrections including decay

in complex mass scheme



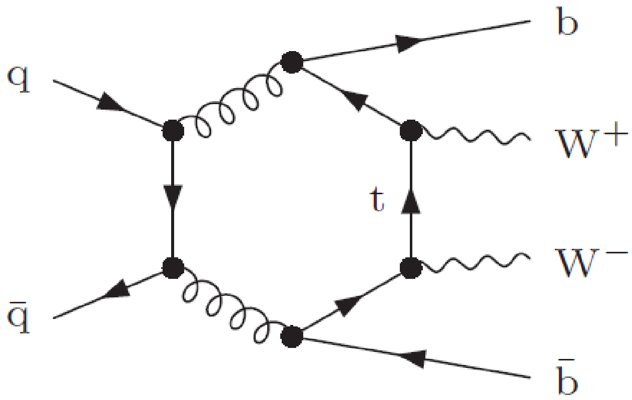


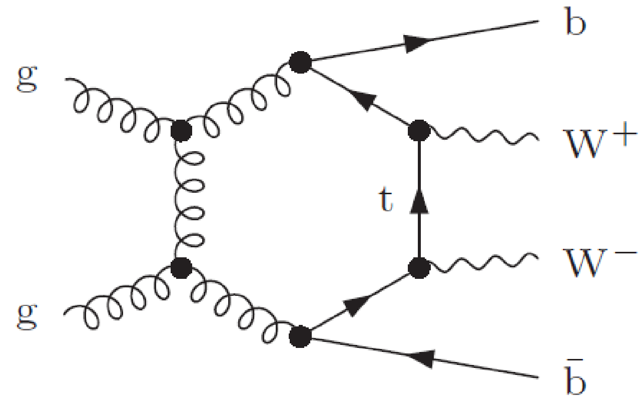


sample diagrams taken from Bevilacqua et al

Non-factorizable corrections and off-shell effects

Technically challenging: [Denner, Dittmaier, Kallweit, Pozzorini 10]





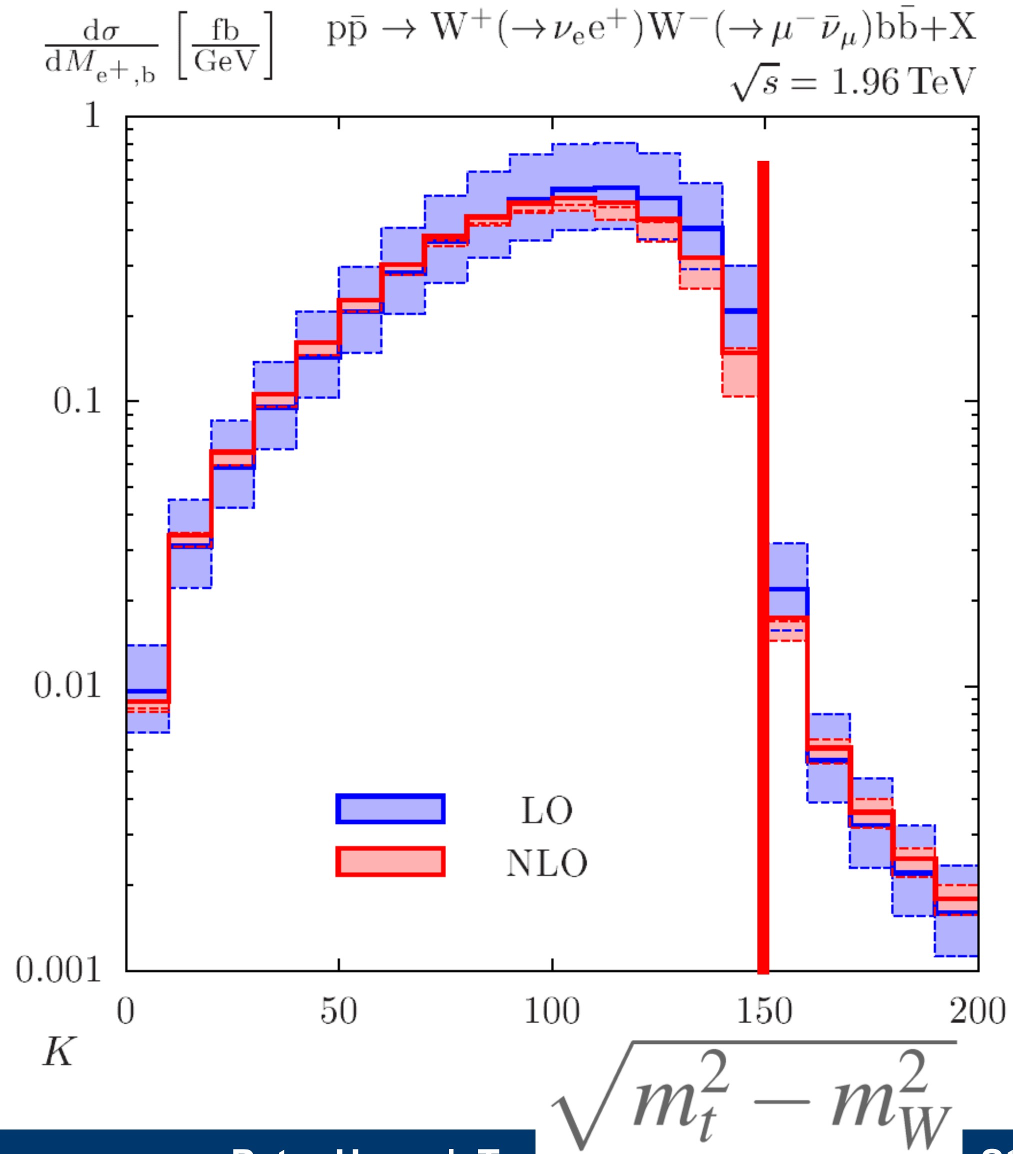
Non-factorizable corrections and off-shell effects

Important results:

- only mild effect on total cross section (<1%)
  → consistent with earlier investigations
- potentially important for specific distributions

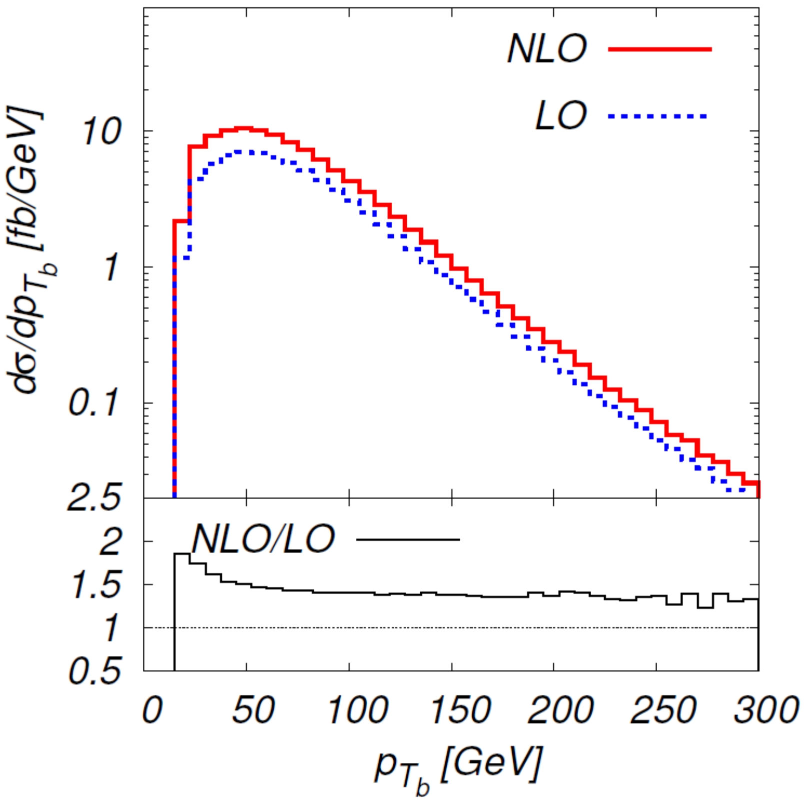
Non-factorizable corrections and off-shell effects

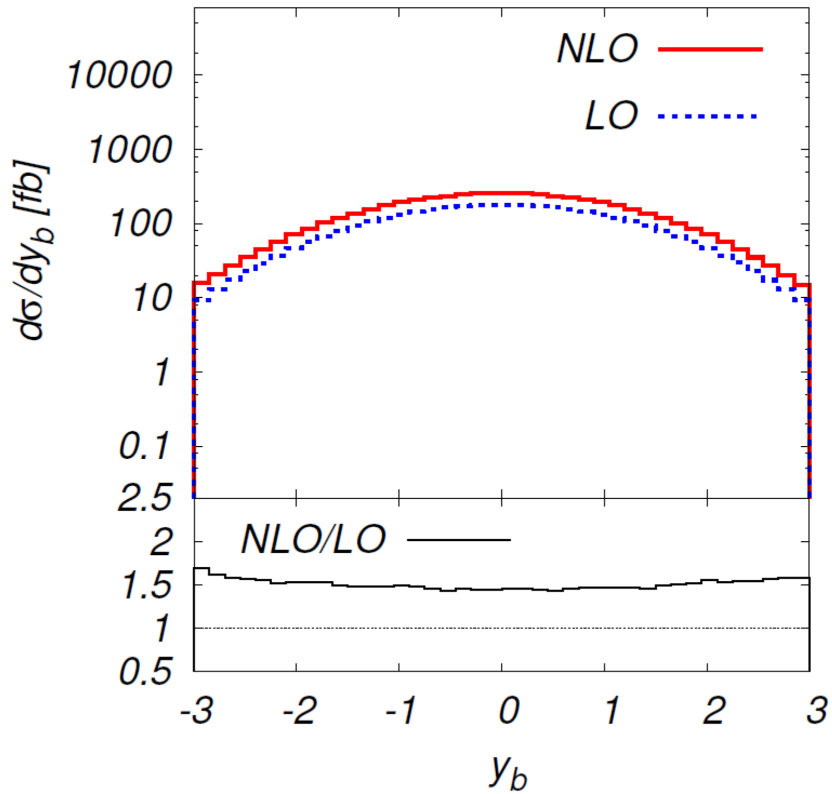
[Denner, Dittmaier, Kallweit, Pozzorini 10]



Non-factorizable corrections and off-shell effects

More results in [Bevilacqua,Czakon,van Hameren,Papadopoulos,Worek ’10]



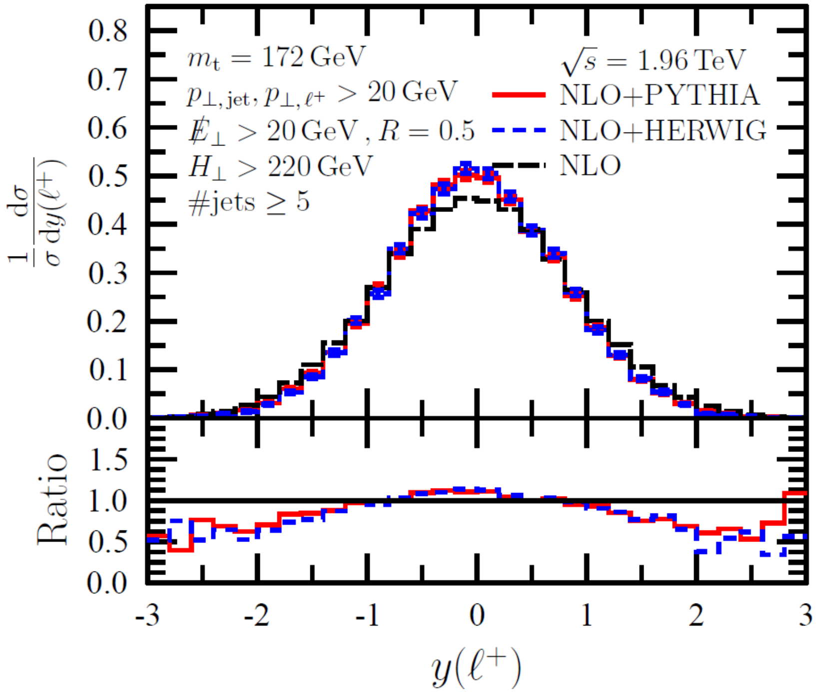


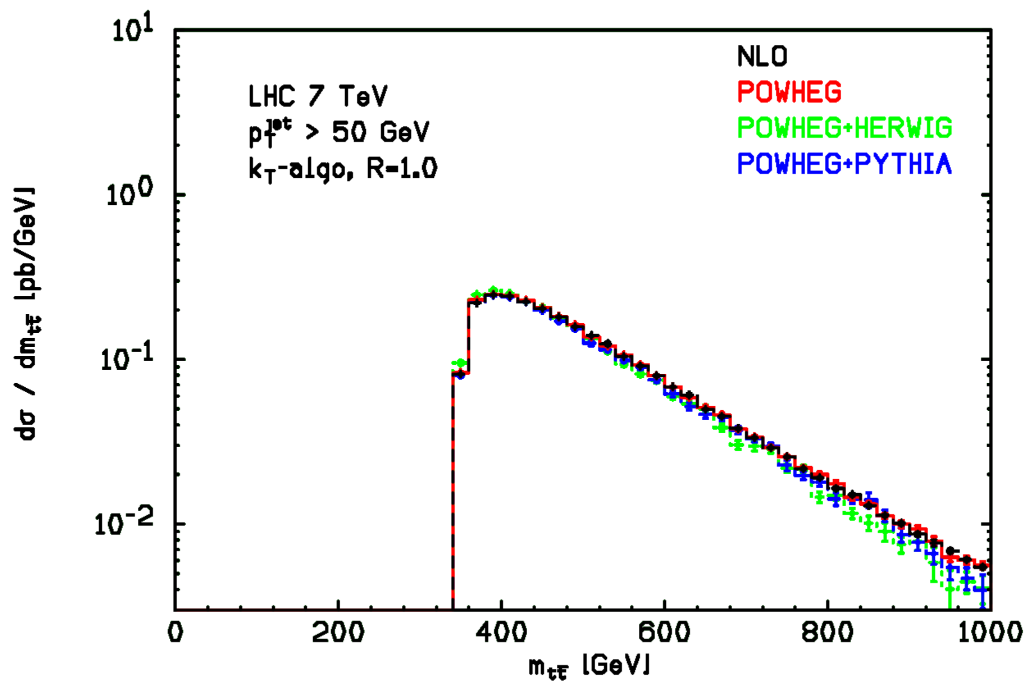
tt@NLO + shower available through MC@NLO and Powheg

Recent progress: tt + 1-Jet @ NLO + shower

[Kardos, Papadopoulos,Troscanyi 11]

[Aioli, Moch,PU]





→ more to come in the near future

Outline / Conclusion

Tremendous progress in recent past
in top quark physics

- Important contributions towards NNLO
- NLO available for high multiplicities
- Predictions including top quark decay
- Non-factorizable corrections
- Inclusion of parton shower is pushed forward

→ really a theory benchmark process what can be done in theory !

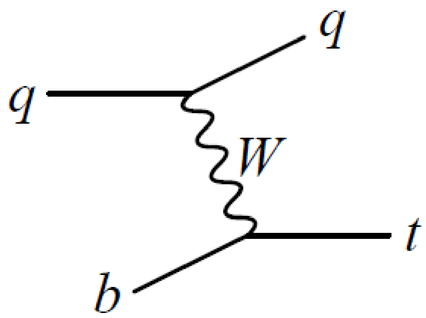
Open questions / topics / issues

- Comparison MSTW ← → ABKM
- Charge asymmetry
- Top-quark mass definition and measurement
- Availability of theoretical results

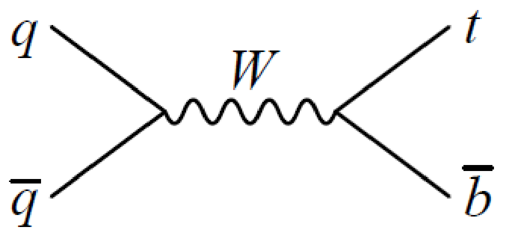
(Powheg, MC@NLO, ntuples, public code)

The End

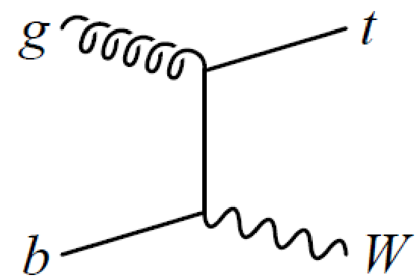
Hadronic top production: single top production



t-channel



s-channel



Wt mode

Known at next-to-leading order QCD

[Smith,Willenbrock; Bordes,van Eijk; Stelzer,Sullivan,Willenbrock; Harris,Laenen,Phaf,Sullivan,Weinzierl; Sullivan]

[Review Bernreuther 08]

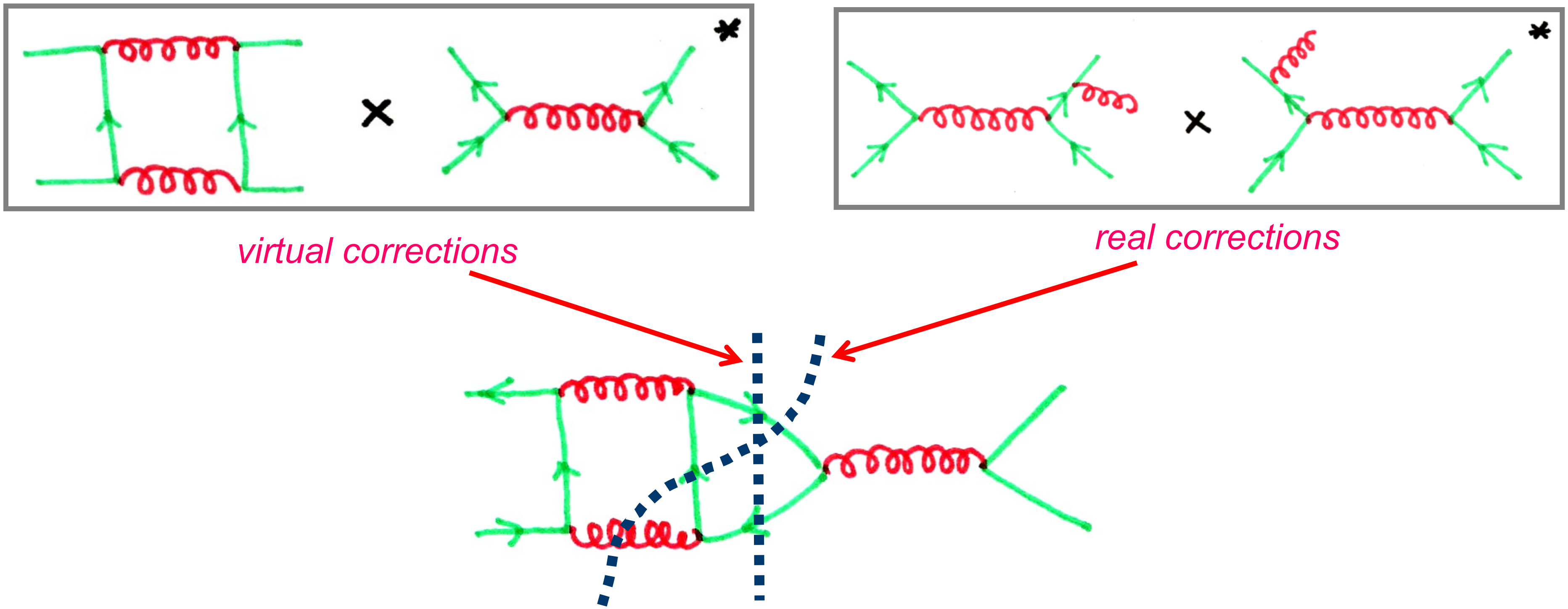
cross section	t channel	s channel	tW mode
$\sigma^t_{\mathrm{Tevatron}}$	1.15 ± 0.07 pb	0.54 ± 0.04 pb	0.14 ± 0.03 pb
σ^t_{LHC}	150 ± 6 pb	7.8 ± 0.7 pb	44 ± 5 pb
σ^t_{LHC}	92 ± 4 pb	4.3 ± 0.3 pb	44 ± 5 pb

err = PDF, scale, mt

Tops are polarized

Hadronic top production: top pair production

Top quark charge asymmetry in NLO



→ Interference produces charge asymmetry similar to QED

Contribution have different signs, IR divergencies cancel in sum

→ differences of differential distributions for top and anti-top

Charge asymmetry

Differential asymmetry:

[Kühn,Rodrigo 98]

$$A(y) = \frac{N_t(y) - N_{\bar{t}}(y)}{N_t(y) + N_{\bar{t}}(y)} \quad \text{with} \quad N_{t,\bar{t}}(y_{t,\bar{t}}) = \frac{d\sigma_{t\bar{t}}}{dy_{t,\bar{t}}}$$

Integrated asymmetry:

$$A = \frac{\int_{y>0} N_t(y) - \int_{y>0} N_{\bar{t}}(y)}{\int_{y>0} N_t(y) + \int_{y>0} N_{\bar{t}}(y)}$$

Assuming CP invariance: $N_{\bar{t}}(y) = N_t(-y)$

$$A = \frac{\int_{y>0} N_t(y) - \int_{y<0} N_t(y)}{\int_{y>0} N_t(y) + \int_{y<0} N_t(y)}$$

Forward-backward asymmetry

Charge Asymmetry

Experiments study

$$A_{fb}^{t\bar{t}} = \frac{\int N(\Delta y>0) - \int N(\Delta y<0)}{\int N(\Delta y>0) + \int N(\Delta y<0)}$$

Theory prediction:

[Antunano,Kühn,Rodrigo 08]

$$A_{fb}^{t\bar{t}} = 7.8(9)\%$$

[CDF '11, arxiv 1101.0034] (5.3 1/fb)

$$A_{fb}^{t\bar{t}} = 0.158 \pm 0.075$$

selection	$M_{t\bar{t}} < 450\ \mathrm{GeV}/c^2$	$M_{t\bar{t}} \geq 450\ \mathrm{GeV}/c^2$
data parton	$-0.116 \pm 0.146 \pm 0.047$	$0.475 \pm 0.101 \pm 0.049$
MCFM	$+0.040 \pm 0.006$	0.088 ± 0.013

$>3\sigma$

What LHC can do

m_{tt} dependence could be an indication of a new heavy particle

Model independent approach using effective operators:

[Delaunay, Gedalia, Hochberg,Perez, Sorq `11]

→ expect sizeable effects in

$$\frac{d\sigma_{t\bar{t}}}{dm_{t\bar{t}}}$$

at 1 TeV and higher

→ detailed study of m_{tt} distribution !

Charge asymmetry at the LHC

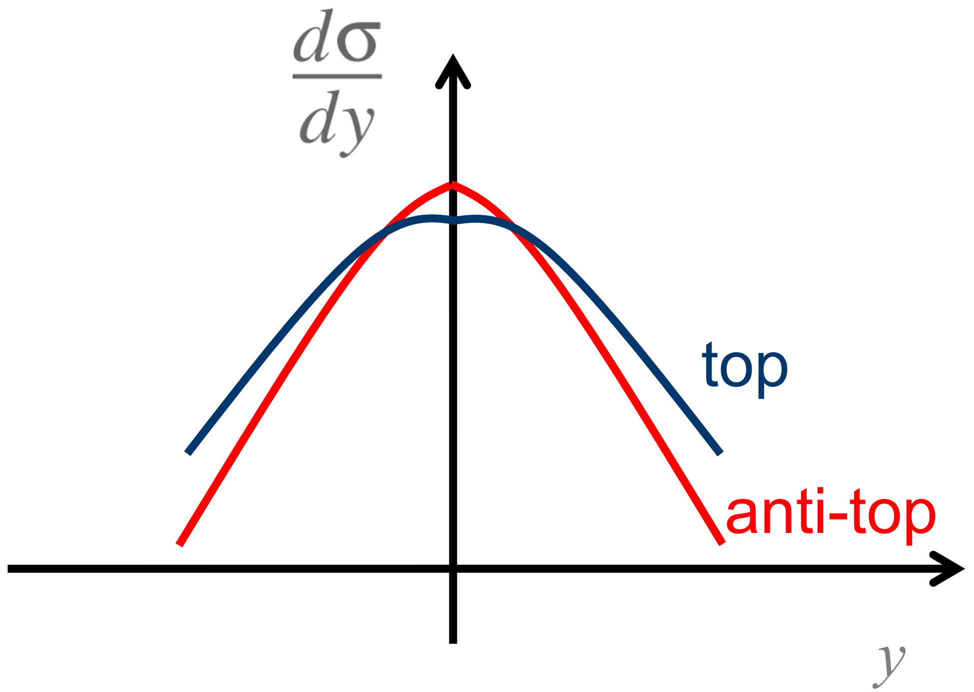
No forward backward charge asymmetry at LHC due to P symmetric initial state

However:

- t tend to follow initial q, while tb tend to follow initial qb
- initial state is not symmetric with respect to q,qb
- q tend to be more energetic

$$\frac{d\sigma}{dy_t} \quad \text{should be broader w.r.t} \quad \frac{d\sigma}{dy_{\bar{t}}}$$

Charge asymmetry at the LHC



→ could in principle be observed at LHC

However: effect expected to be small since qq makes only a small fraction, more important for larger mtt