The meaning of precision in top-quark physics at the LHC

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Outline

- Top-quark pair production
  - High-precision QCD
  - Boosted-top regime resummation
  - Off-shell effects
  - Electroweak corrections
- Single-top production

HIGH-PRECISION QCD

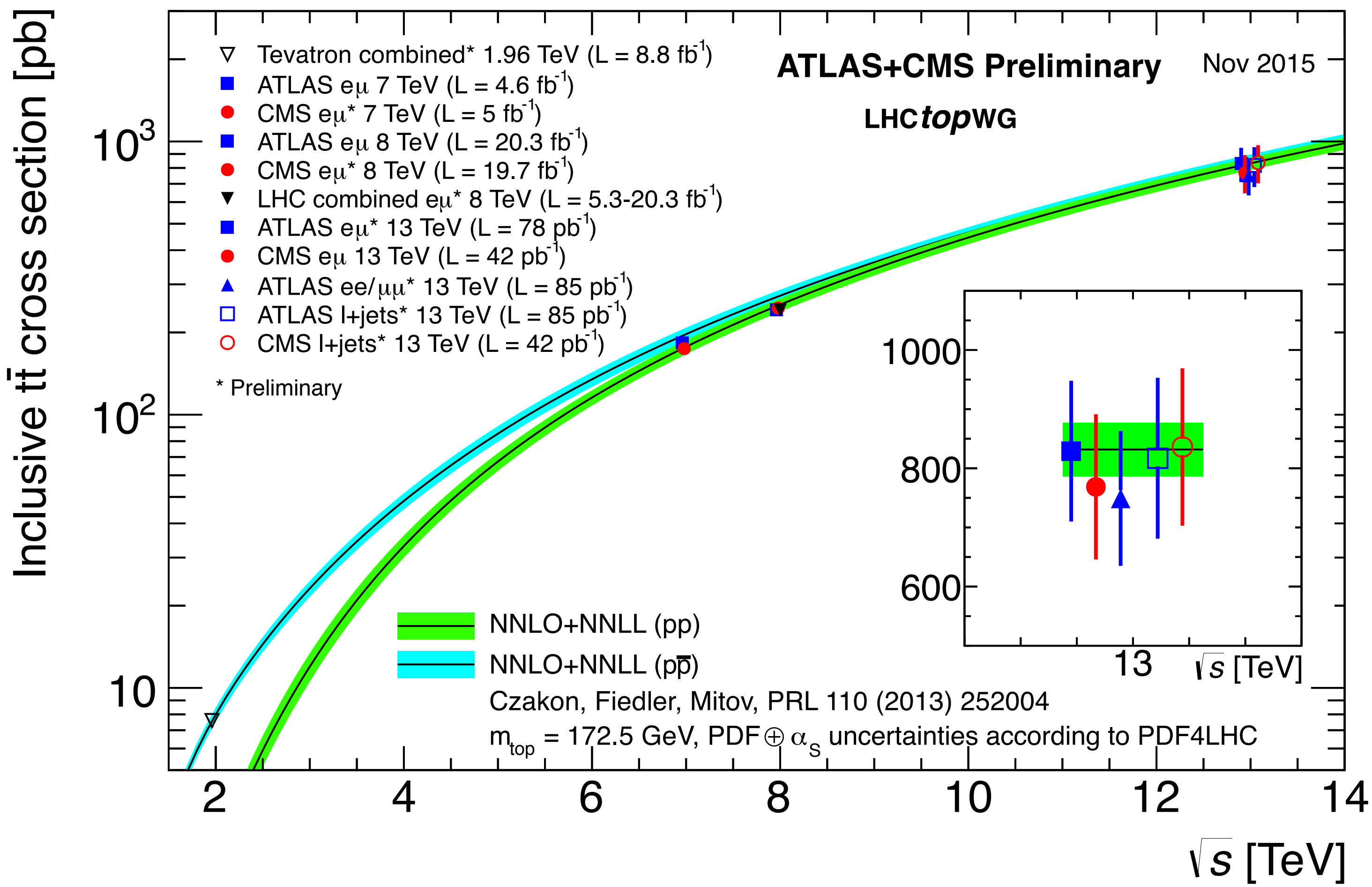
General remarks

- High precision should be associated with fixed order perturbation theory:
  - Clear advantage: not many ambiguities
  - But: beware of range of applicability
  - Currently at NNLO for on-shell production

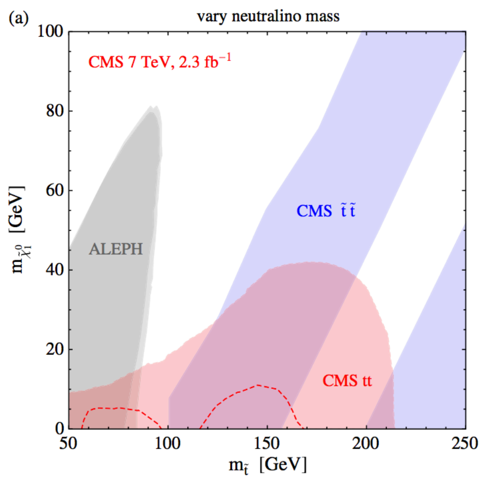
MC, Fiedler, Heymes, Mitov `12 - `15

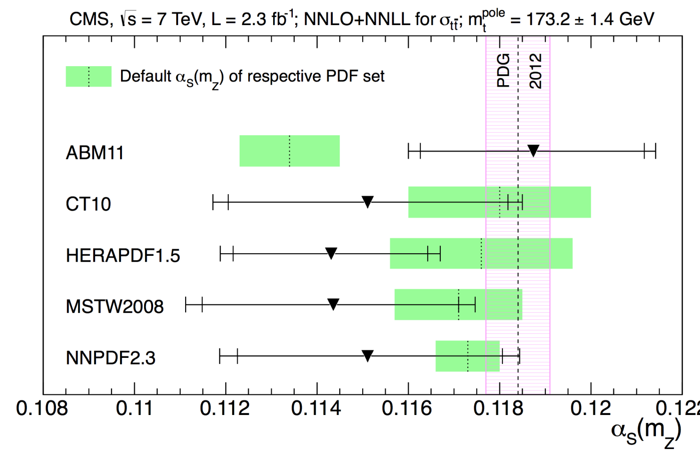
Partial independent results by: Abelof, Gehrmann-De Ridder, Maierhofer, Pozzorini `14
Catani, Grazzini, Torre `14 - `15

Total cross section

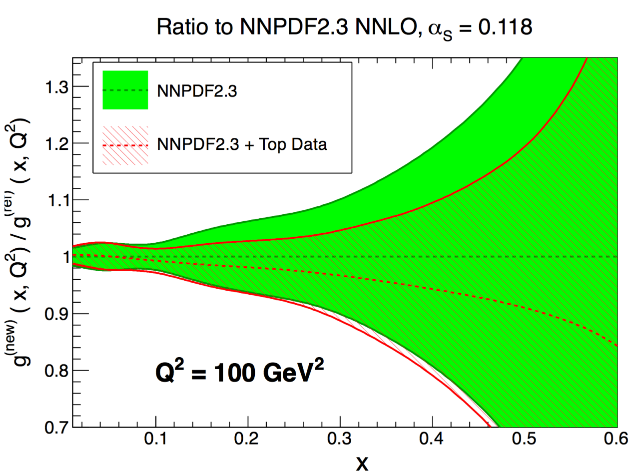


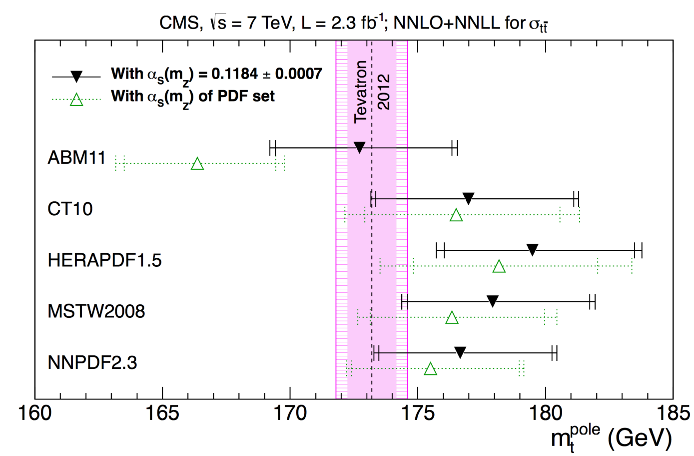
Early applications





MC, Mitov, Papucci, Ruderman, Weiler, `14





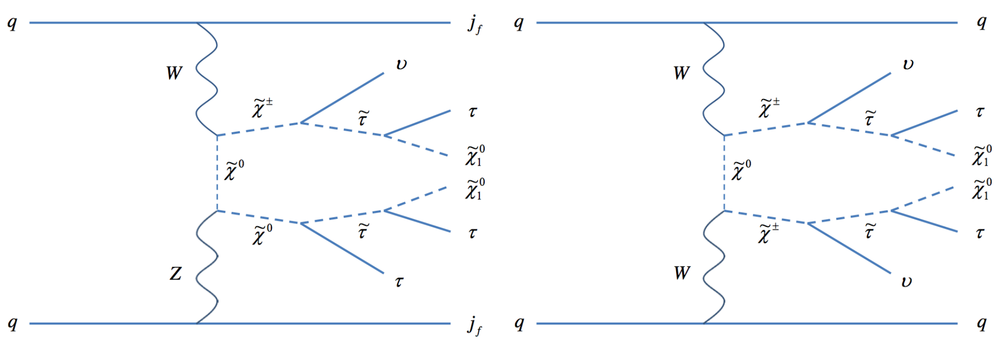
MC, Mangano, Mitov, Rojo `13

arXiv:1307.1907 (CMS-TOP-12-022)

Current applications

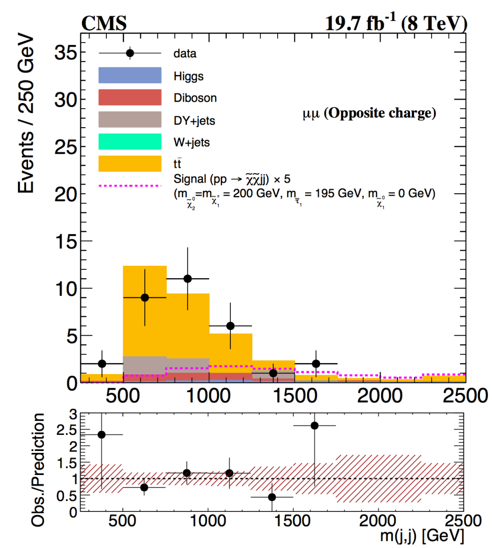
- Same as before
- + Normalization of backgrounds (most frequent)

- One example out of many: search for SUSY in VBF events

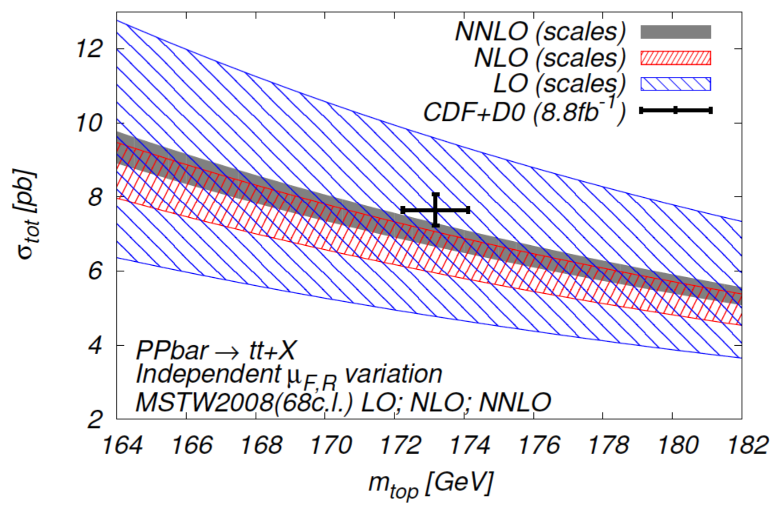


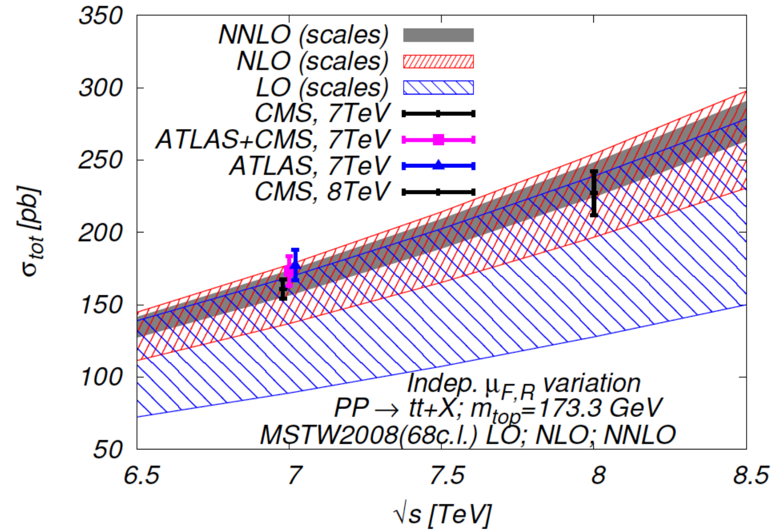
Process	$\mu^{\pm}\mu^{\mp}jj$	$e^{\pm}\mu^{\mp}jj$	$\mu^{\pm}\tau_h^{\mp}jj$	$\tau_h^{\pm}\tau_h^{\mp}jj$
Z+jets	4.3 ± 1.7	$3.7^{+2.1}_{-1.9}$	19.9 ± 2.9	12.3 ± 4.4
W+jets	<0.1	$4.2^{+3.3}_{-2.5}$	17.3 ± 3.0	2.0 ± 1.7
VV	2.8 ± 0.5	3.1 ± 0.7	2.9 ± 0.5	0.5 ± 0.2
$t\bar{t}$	24.0 ± 1.7	$19.0^{+2.3}_{-2.4}$	11.7 ± 2.8	–
QCD	—	—	—	6.3 ± 1.8
Higgs boson	1.0 ± 0.1	1.1 ± 0.5	—	1.1 ± 0.1
VBF Z	—	—	—	0.7 ± 0.2
Total	32.2 ± 2.4	$31.1^{+4.6}_{-4.1}$	51.8 ± 5.1	22.9 ± 5.1
Observed	31	22	41	31

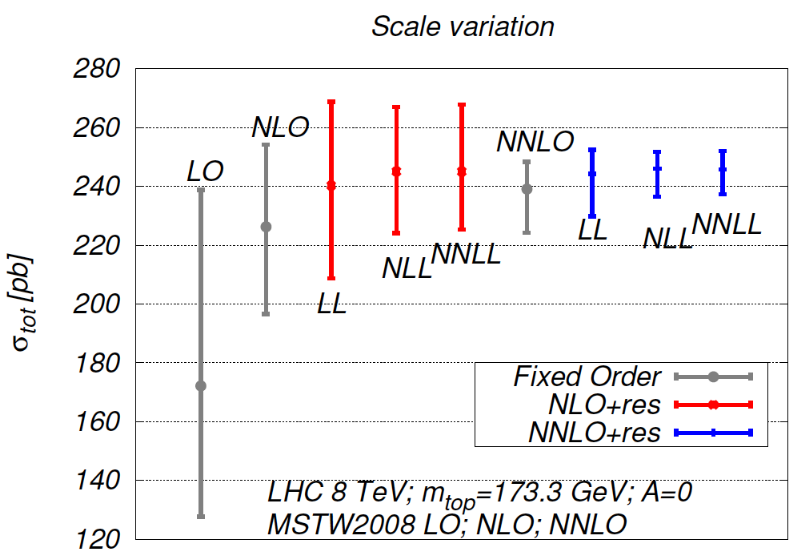
CERN-PH-EP/2015-213
2015/09/01



Perturbation theory convergence







Concurrent uncertainties:

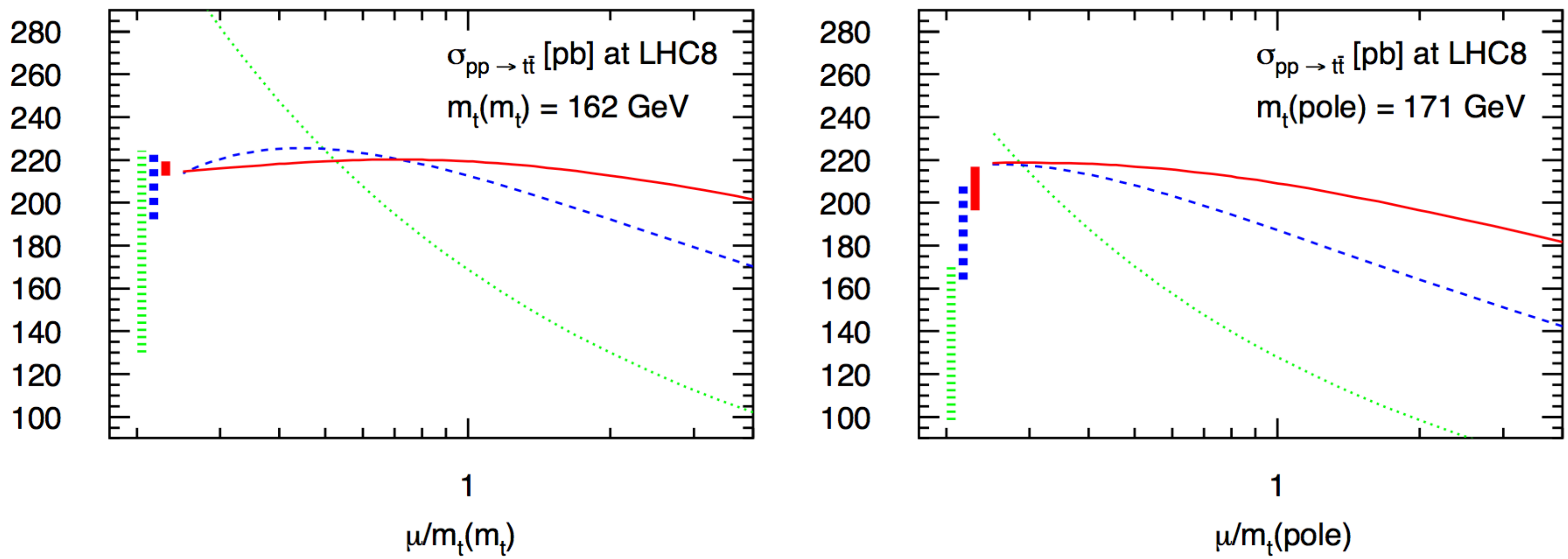
Scales	~ 3%
pdf (at 68%cl)	~ 2-3%
α_s (parametric)	~ 1.5%
m_{top} (parametric)	~ 3%

Soft gluon resummation makes a difference:

5% -> 3%

Perturbation theory convergence

- It has been argued that it is better to use the MS mass to improve convergence
- Is there a better scale in the on-shell scheme?
- Relevant for differential Monte Carlo description



Alekhin, Blümlein, Moch `13

Perturbation theory convergence

- Reducing error at NNLO to the level of NNLO + NNLL important for total cross sections
- In particular since complete NNLL PDFs not available

NNLL + NNLO with NNPDF23

Exp.	E_{CM} [GeV]	$\alpha_s(M_Z)$	Exp.	scale	PDF	m_{top}	E_{beam}	total
ATLAS	7000	0.1207	±0.0017	±0.0014	±0.0014	±0.0018	±0.0009	±0.0033
ATLAS	8000	0.1168	±0.0018	±0.0015	±0.0013	±0.0018	±0.0008	±0.0033
CMS	7000	0.1184	±0.0016	±0.0014	±0.0014	±0.0018	±0.0008	±0.0032
CMS	8000	0.1174	±0.0017	±0.0015	±0.0013	±0.0018	±0.0008	±0.0033
CDF&D0	1960	0.1201	±0.0032	±0.0013	±0.0010	±0.0013	±0.0000	±0.0038
unweigted	**average**	**0.1187**						

Workshop on high-precision α_s measurements: from LHC to FCC-ee
CERN, 13 October 2015

α_s from σ(ttbar): preliminary new results

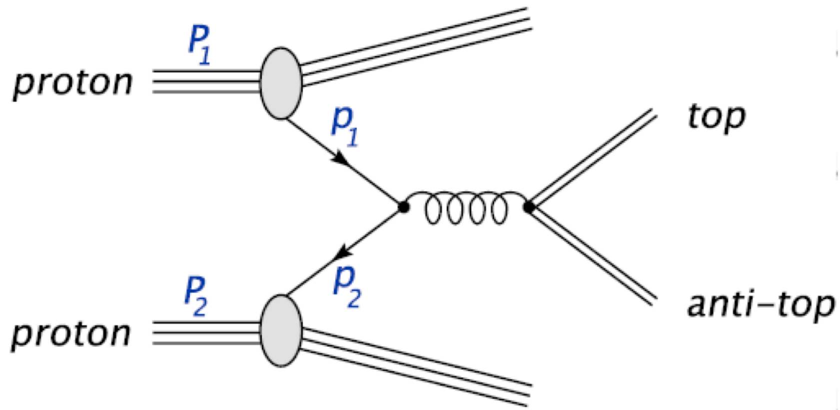
Gavin Salam (CERN), work in progress
with Siggi Bethke, Günther Dissertori and Thomas Klijnsma

plain NNLO with NNPDF23

Exp.	E_{CM} [GeV]	$\alpha_s(M_Z)$	Exp.	scale	PDF	m_{top}	E_{beam}	total
ATLAS	7000	0.1223	±0.0018	±0.0025	±0.0014	±0.0018	±0.0009	±0.0040
ATLAS	8000	0.1182	±0.0019	±0.0026	±0.0013	±0.0019	±0.0009	±0.0041
CMS	7000	0.1199	±0.0017	±0.0025	±0.0014	±0.0018	±0.0008	±0.0039
CMS	8000	0.1189	±0.0018	±0.0026	±0.0013	±0.0018	±0.0008	±0.0040
TEV	1960	0.1215	±0.0034	±0.0027	±0.0010	±0.0014	±0.0000	±0.0047
unweigted	**average**	**0.1201**						

Open question of choice of theory: NNLL+NNLO v. NNLO.
Latter increases result and uncertainty.

Searching for the right scale



- Cross section from factorization

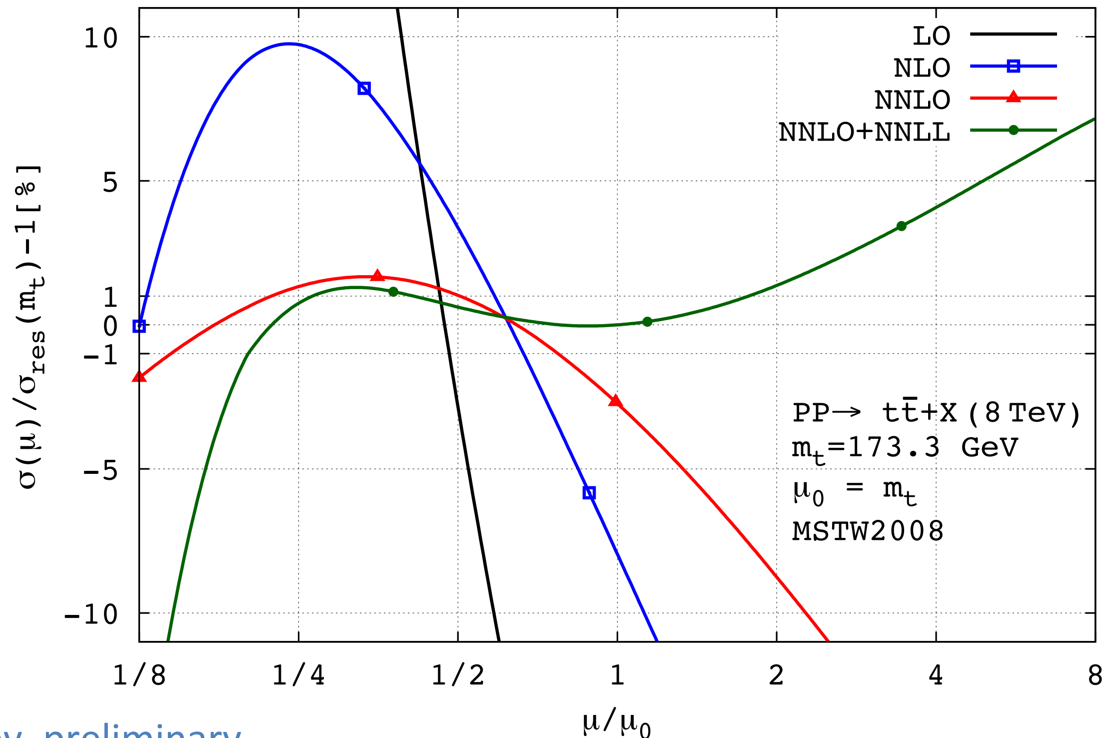
$$\sigma_{h_1h_2}(s, m_t) = \sum_{ij} \int dx_1 dx_2 \phi_{i/h_1}(x_1, \mu_F)\phi_{j/h_2}(x_2, \mu_F)\hat{\sigma}_{ij}(x_1x_2s, m_t, \alpha_s(\mu_R), \mu_R,\ \mu_F)$$

σ_{h_1,h_2}	hadronic cross section
$h_{1,2}$	hadrons
s	square of collider energy
m_t	top quark mass
$\phi_{i/h}$	PDF for parton i in hadron h
$\hat{\sigma}_{ij}$	partonic cross section
μ_R	renormalization scale
μ_F	factorization scale

- In fixed order perturbation theory the only ambiguity is in the two-scale choice

Searching for the right scale

- Total cross section depends only on the top-quark mass if the collider energy is fixed
- In principle, the scale must therefore be related to the mass
- Convergence improved at lower scales



MC, Heymes, Mitov, preliminary

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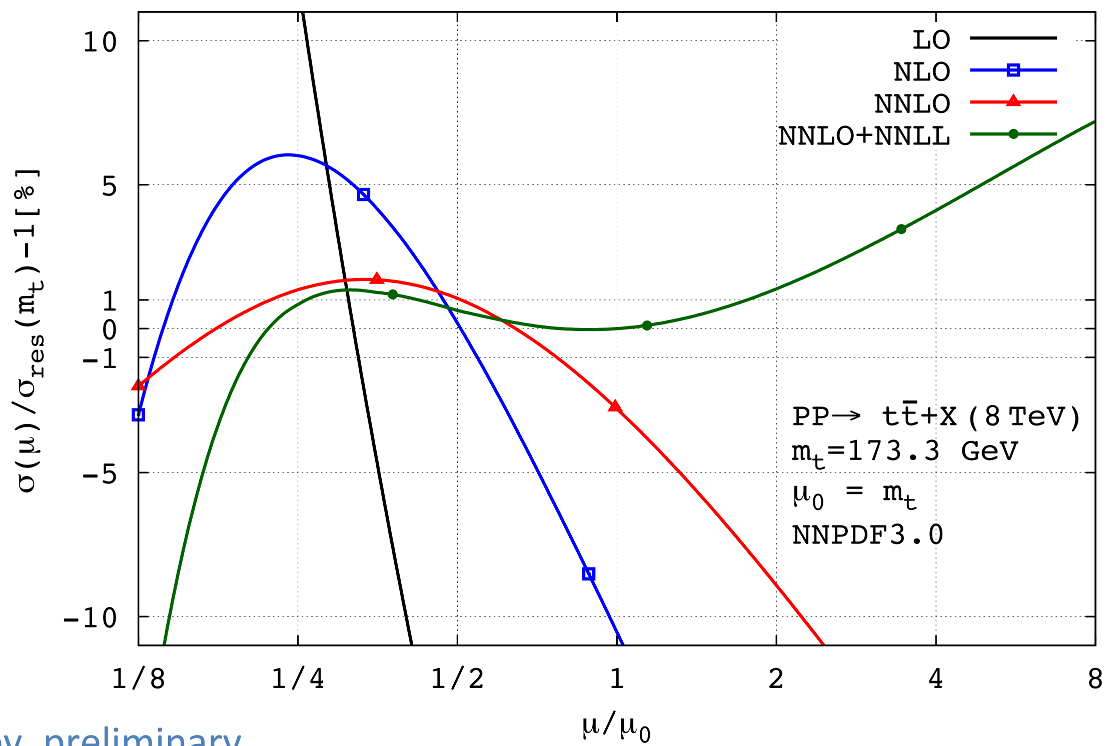


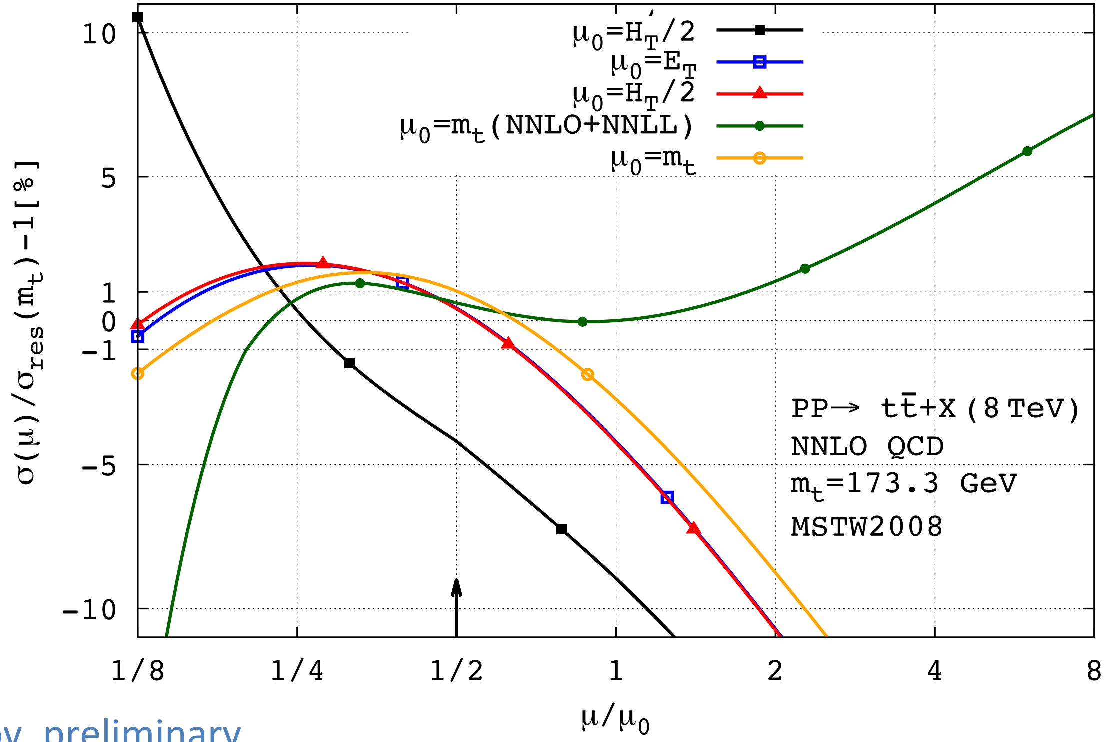
MC, Heymes, Mitov, preliminary

- Careful with conclusions based on one PDF set only (particular attention to α_s)

Searching for the right scale

- Monte Carlo simulations use dynamical scales since they are fully differential
- Several possible choices based on

$$H_T = \sqrt{m_t^2 + p_{\mathrm{T}t}^2} + \sqrt{m_t^2 + p_{\mathrm{T}\bar{t}}^2} \qquad H_T' = H_T + \sum_i p_{\mathrm{T}j_i} \qquad E_T = \sqrt{\sqrt{m_t^2 + p_{\mathrm{T}t}^2}\sqrt{m_t^2 + p_{\mathrm{T}\bar{t}}^2}}$$



MC, Heymes, Mitov, preliminary

Searching for the right scale

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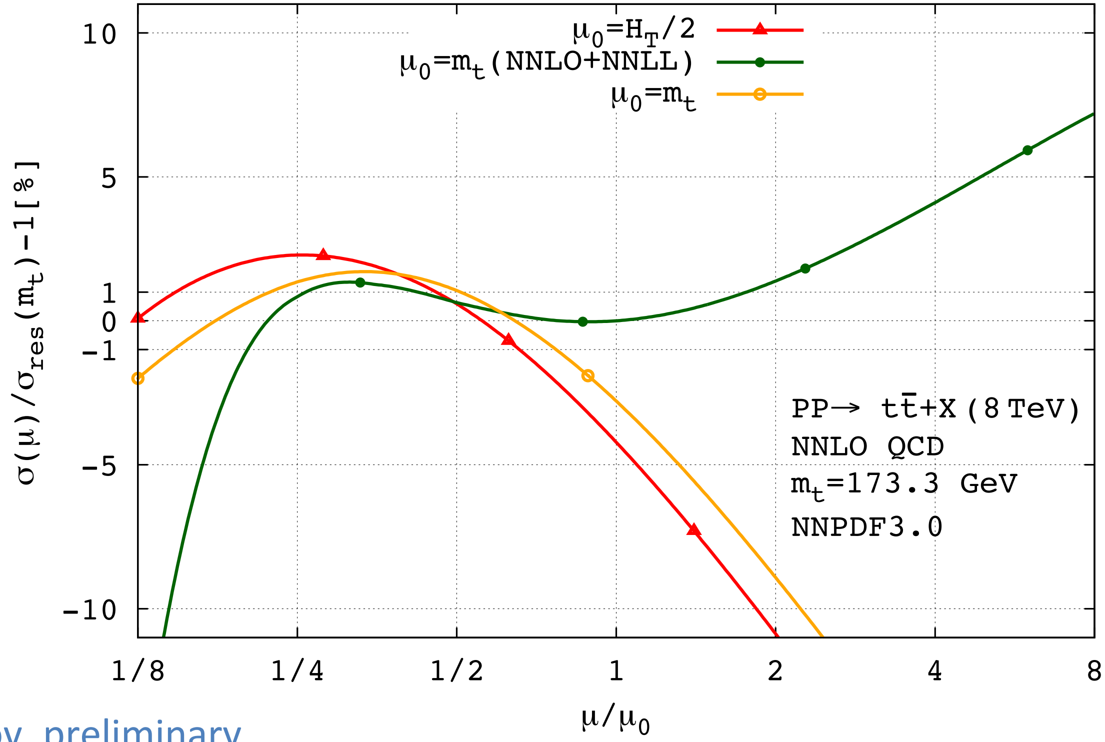
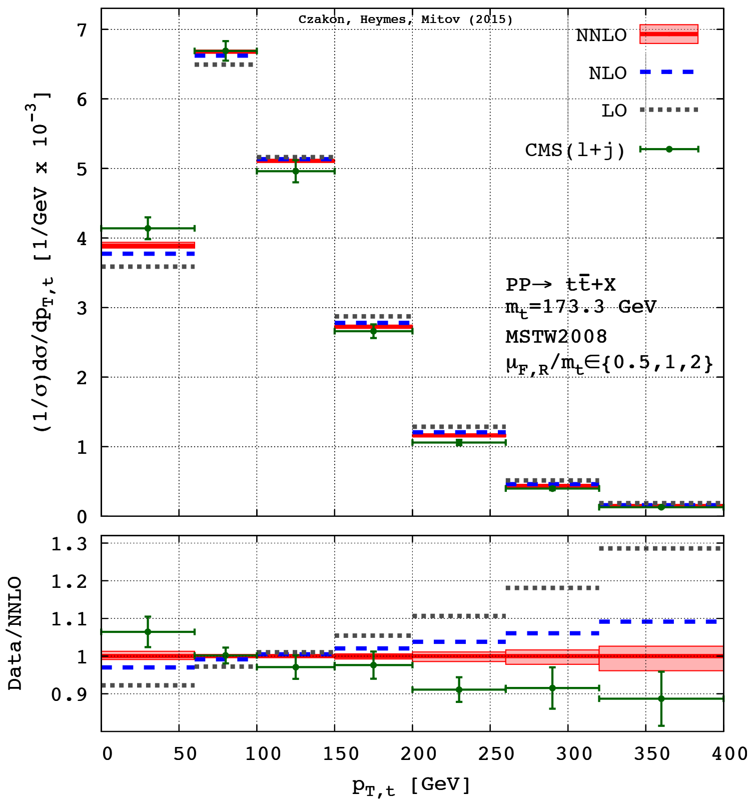


MC, Heymes, Mitov, preliminary

- Conclusions stable w.r.t. the PDF set

Differential distributions

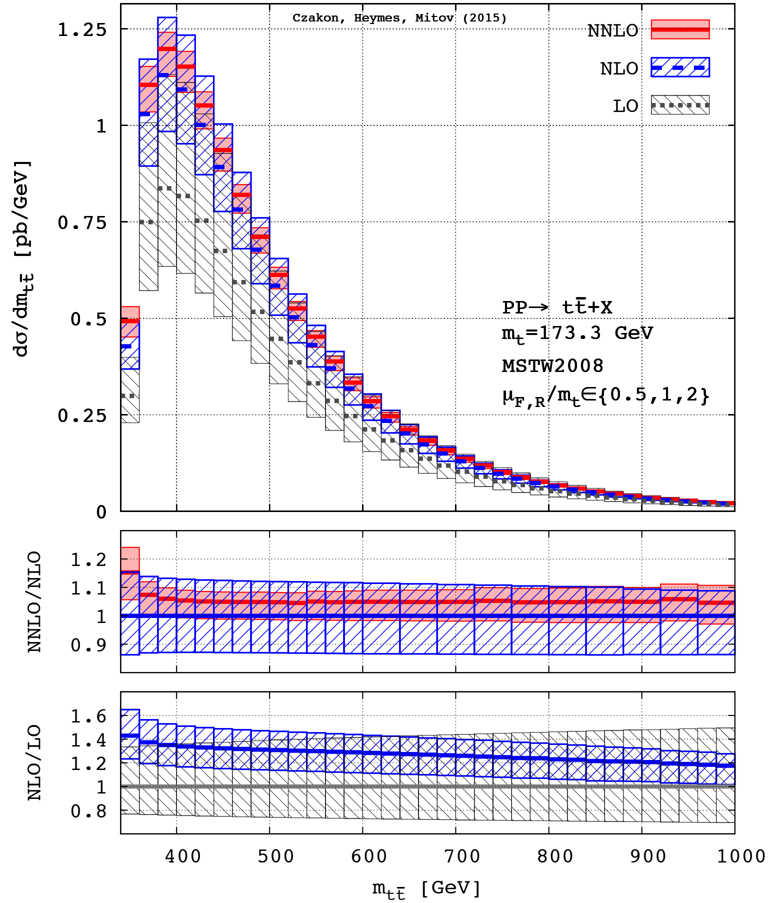
- Even with fixed scale the agreement with data quite good
- Apparently convergence poor in normalized distributions



MC, Heymes, Mitov `15

Differential distributions

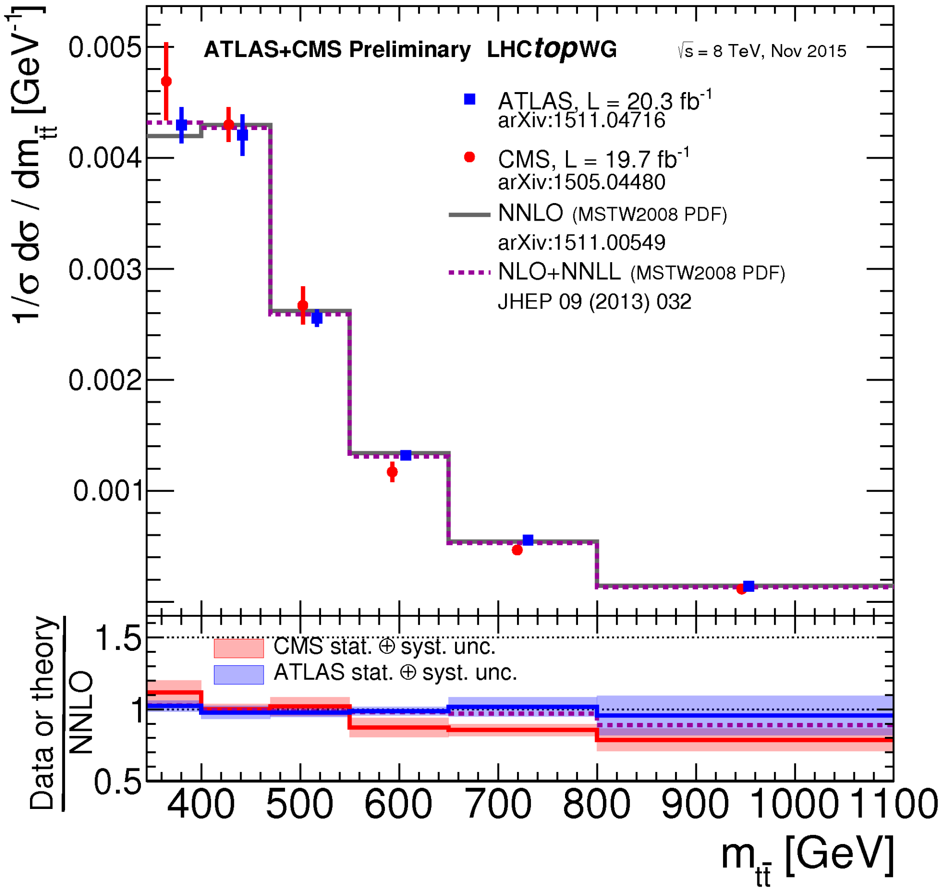
- Much better impression of convergence for absolute distributions
- Stability of invariant mass important for searches
- Limited kinematical range only

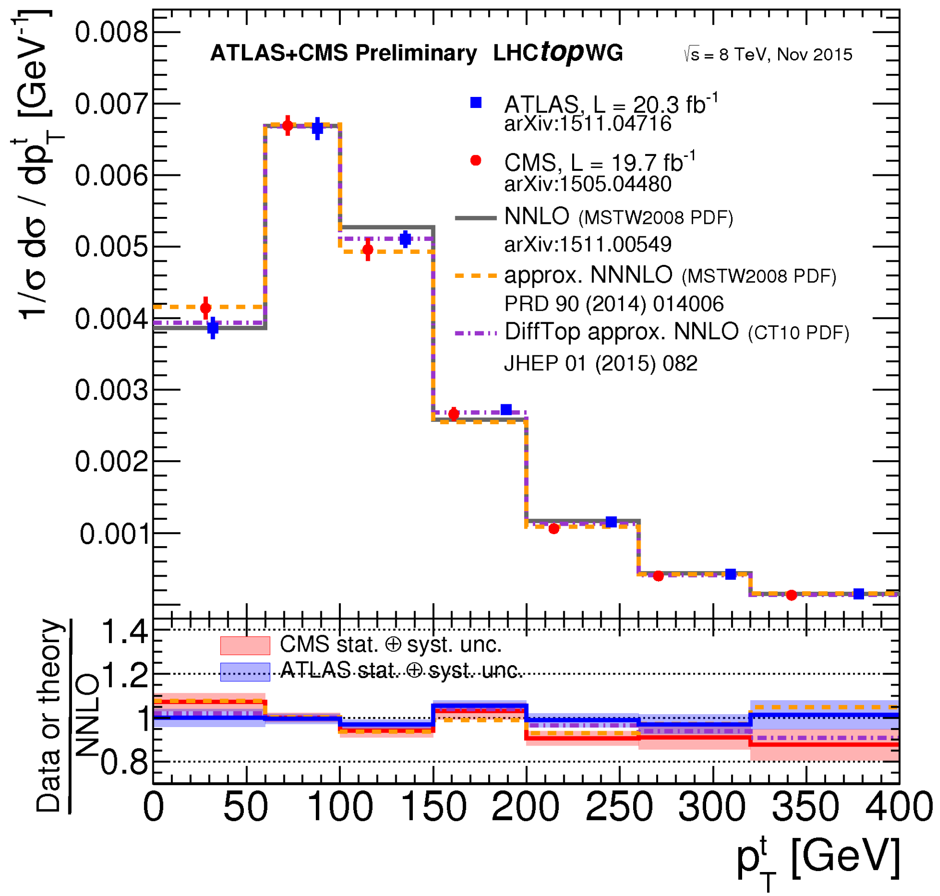


MC, Heymes, Mitov `15

Differential distributions

- Much better agreement with ATLAS data
- Lesson for the theorist: “spot-on agreement” may be dangerous



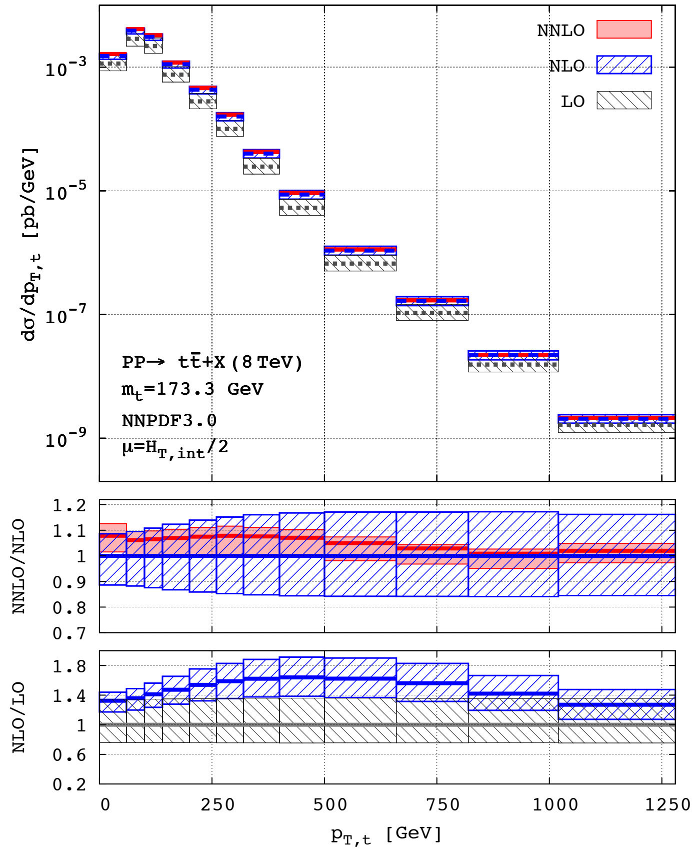


Differential distributions

- Single-differential distributions introduce an additional scale, e.g. p_{Tt} or m_{tt}
- It might make sense to interpolate between regimes

$$H_{T,\mathrm{int}} = \sqrt{(m_t/2)^2 + p_{\mathrm{T}t}^2} + \sqrt{(m_t/2)^2 + p_{\mathrm{T}\bar{t}}^2}$$

- Total cross section reproduced
- Excellent K-Factor at high p_T



MC, Heymes, Mitov, preliminary

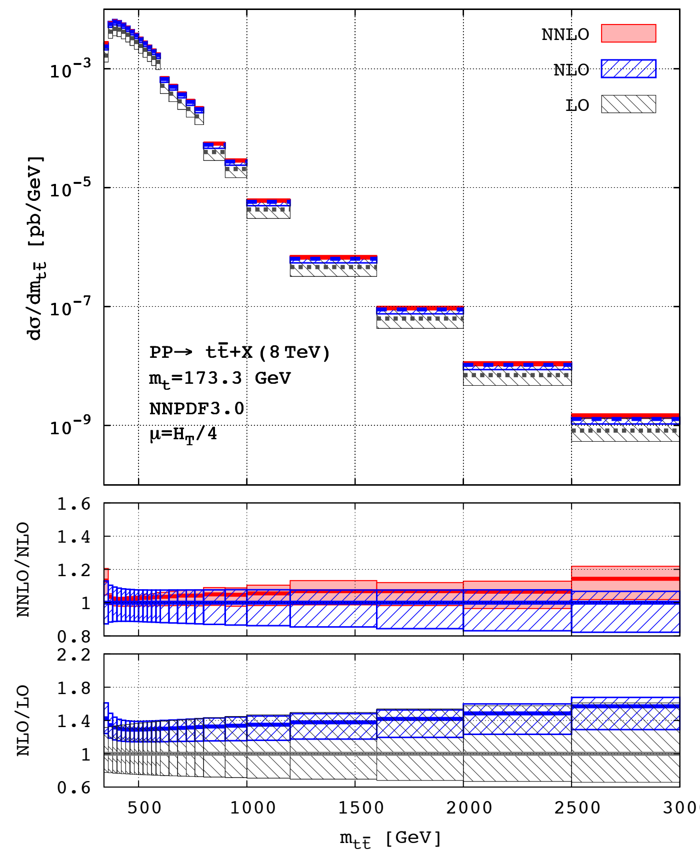
Differential distributions

- Single-differential distributions introduce an additional scale, e.g. p_{Tt} or m_{tt}
- A different interpolation is better for m_{tt}

$$H_T = \sqrt{m_t^2 + p_{\mathrm{T}t}^2} + \sqrt{m_t^2 + p_{\mathrm{T}\bar{t}}^2}$$

- Total cross section reproduced
- Excellent scale variation at high m_{tt}

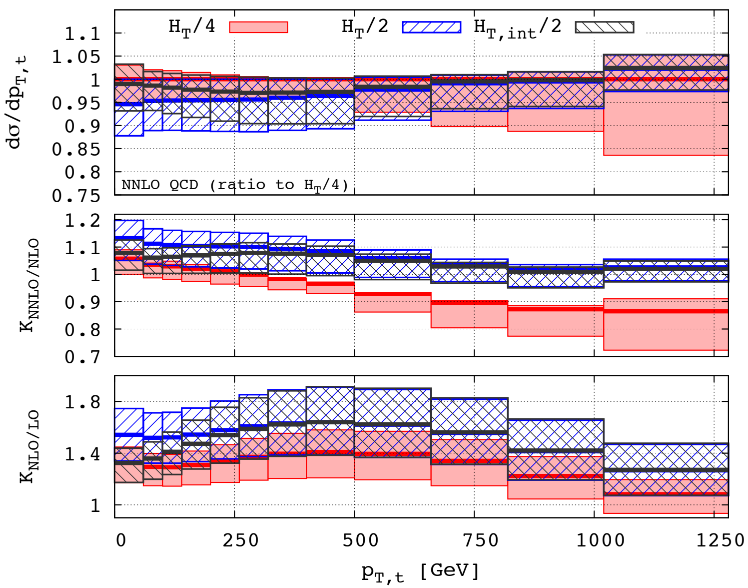
- Introducing different scales for different observables is typical of resummation, but not usual in Monte Carlo studies

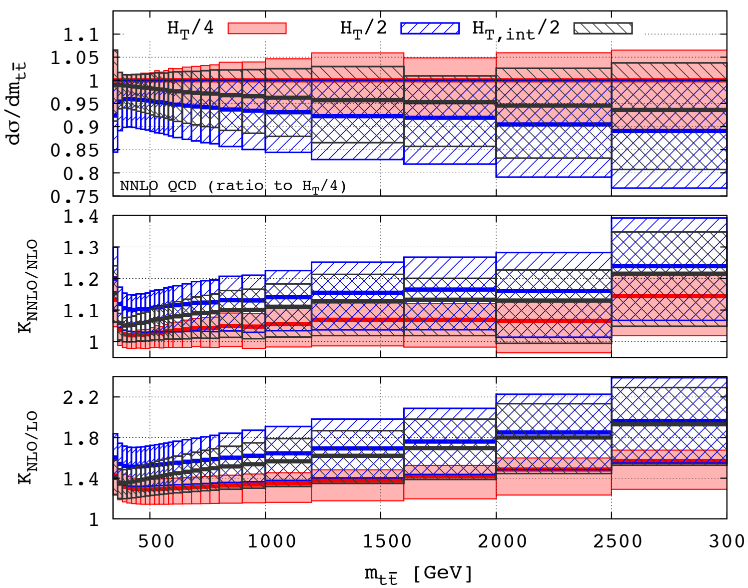


MC, Heymes, Mitov, preliminary

Differential distributions

- The issue is not that relevant once at NNLO
- It seems that the effect is largest on the scale dependence





MC, Heymes, Mitov, preliminary

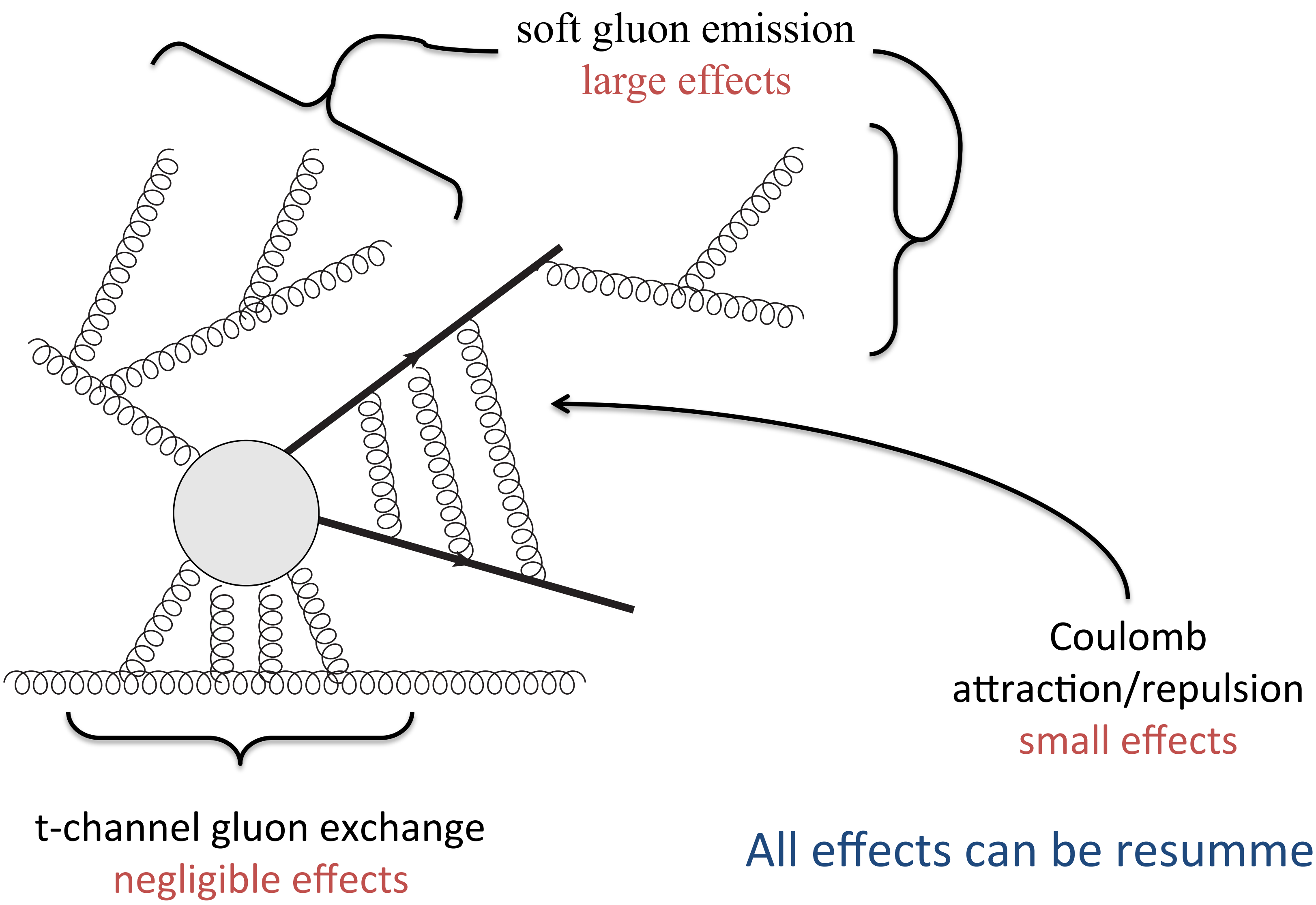
BOOSTED-TOP REGIME RESUMMATION

General remarks

- Soft-gluon resummation up to NNLL well understood thanks to the work of many
  - Kidonakis
  - Moch, Uwer
  - Almeida, Sterman, Vogelsang
  - Ahrens, Ferroglia, Neubert, Pecjak, Yang
  - Beneke, Falgari, Schwinn
  - Cacciari, MC, Mitov, Mangano, Nason
  - Becher, Neubert
  - Broggio, Papanastasiou, Signer

- The "boosted" regime resummation builds on this by adding collinear singularities
  - Ferroglia, Pecjak, Scott, Yang `13

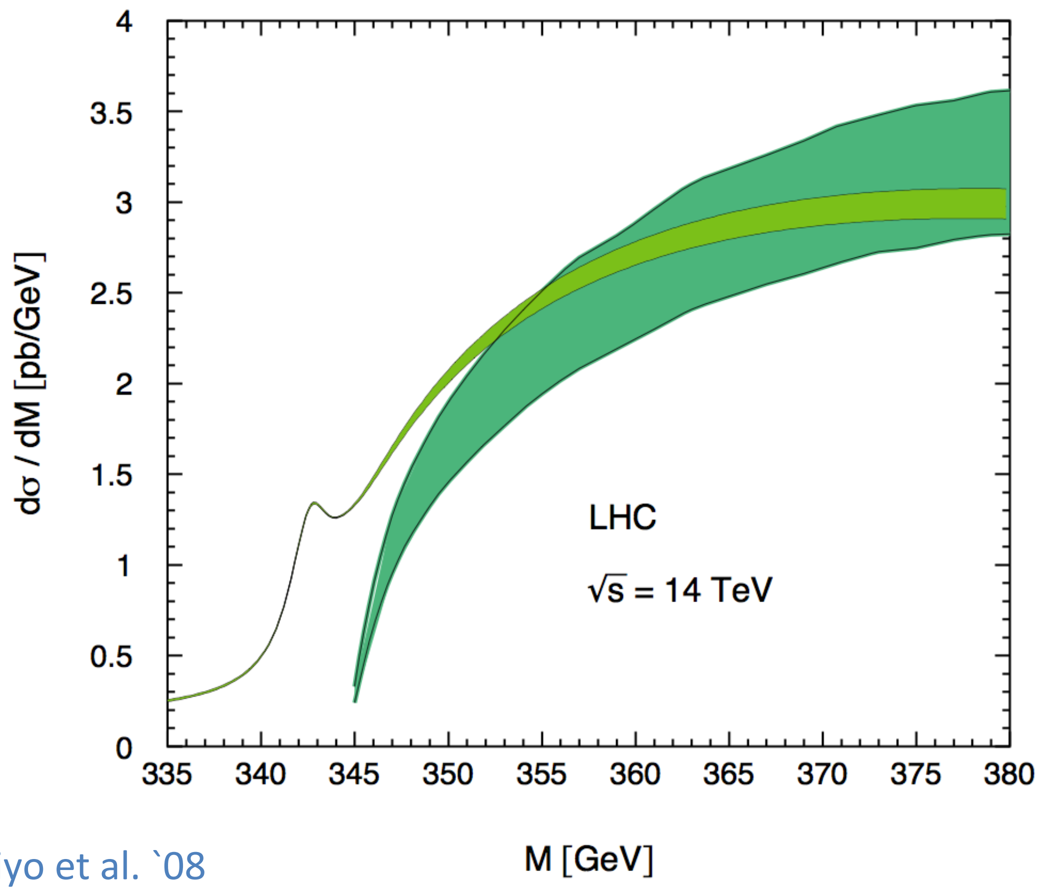
Physical effects for the "bulk"



All effects can be resummed !!!

Physical effects for the "bulk"

- NLO vs NLO+NLL+Coulomb



Kiyo et al. `08

Physical effects in the “tails”

- Additionally to the potentially small gluon energies, the top-quark mass is small
- In this “boosted” regime there are two kinds of logs

$$\text{soft logs: } [\ln^n(1-z)/(1-z)]_+ \qquad (z \equiv M_{t\bar{t}}^2/\hat{s})$$

$$\text{small-mass (collinear) logs: } \ln m_t/M_{t\bar{t}}$$

- Widely separated scales

$$\text{Soft Limit:} \qquad \hat{s}, t_1, m_t^2 \gg \hat{s}(1-z)^2$$

$$\text{Boosted Soft Limit:} \qquad \hat{s}, t_1 \gg m_t^2 \gg \hat{s}(1-z)^2 \gg m_t^2(1-z)^2$$

- Factorization possible

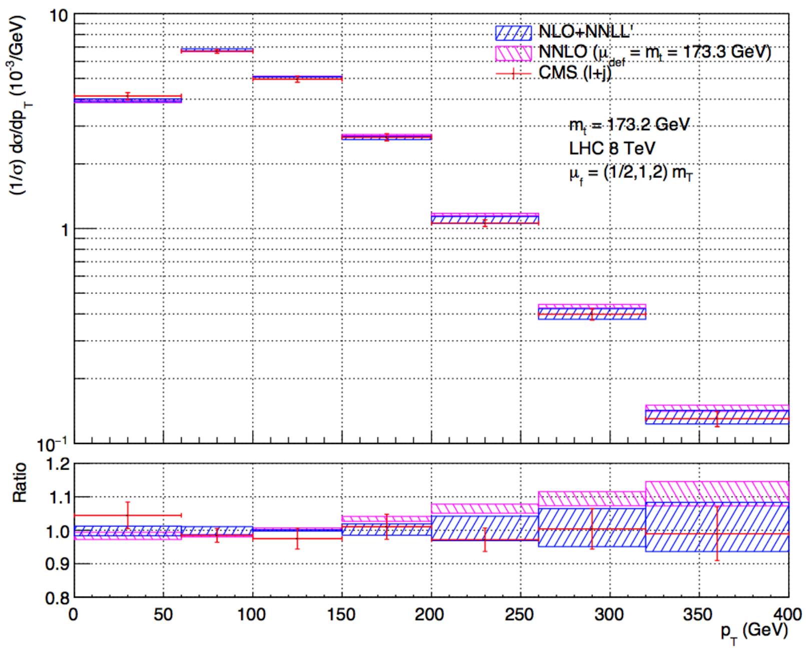
$$d\widetilde{\sigma}_{ij}(\mu_f) = \mathrm{Tr}\left[\widetilde{\mathbf{U}}_{ij}(\mu_f,\mu_h,\mu_s)\mathbf{H}_{ij}(M,\cos\theta,\mu_h)\widetilde{\mathbf{U}}_{ij}^\dagger(\mu_f,\mu_h,\mu_s)\right.$$
$$\left.\times\,\widetilde{s}_{ij}\left(\ln\frac{M^2}{\bar{N}^2\mu_s^2},M,\cos\theta,\mu_s\right)\right]\times\widetilde{U}_D^2(\mu_f,\mu_{dh},\mu_{ds})\,C_D^2(m_t,\mu_{dh})\,\tilde{s}_D^2\left(\ln\frac{m_t}{\bar{N}\mu_{ds}},\mu_{ds}\right)$$
$$+\,\mathcal{O}\left(\frac{1}{N}\right)+\mathcal{O}\left(\frac{m_t^2}{M^2}\right)$$

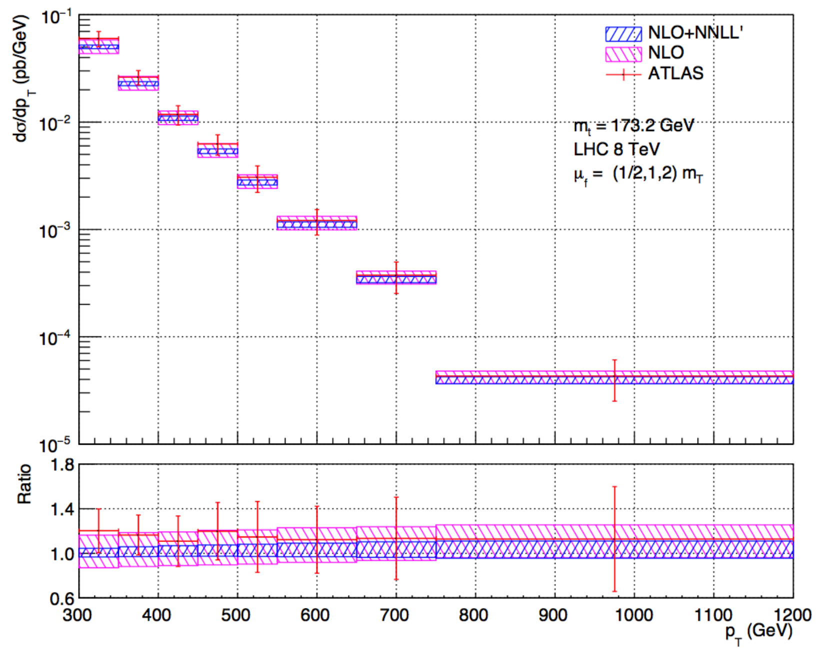
Ferroglia, Pecjak, Scott, Yang `13

- Notice that there are 5 (!) scales now

Results for the LHC

- Transverse momentum distribution modified by dynamical scales and resummation
- At low p_T better description of CMS data, slightly worse for ATLAS (not shown)
- Larger scale dependence?

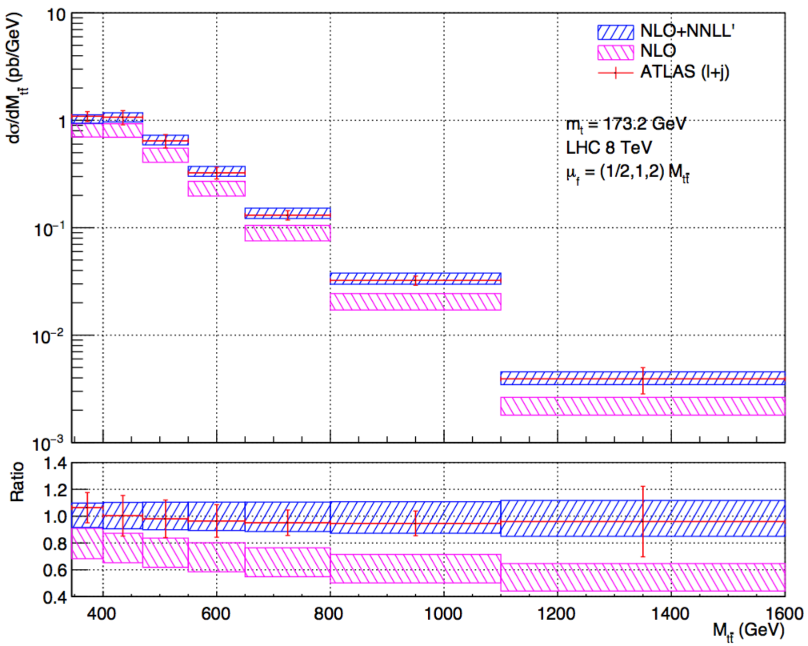


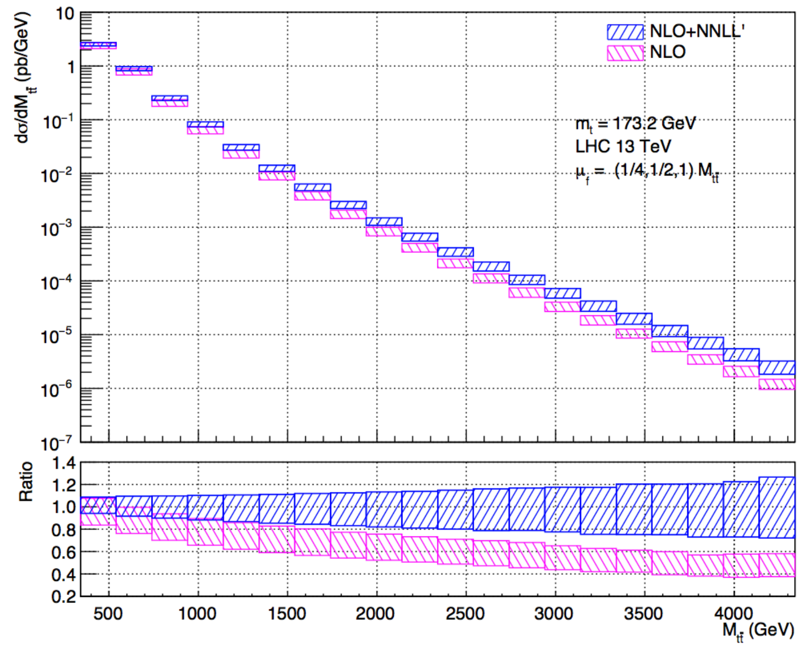


Pecjak, Scott, Wang, Yang `15

Results for the LHC

- Observable dependent scale
- Results presented for 13 TeV as well
- At some point consistent matching to NNLO will become necessary
- When is true resummation needed?





Pecjak, Scott, Wang, Yang `15

OFF-SHELL EFFECTS

Decay modeling @ NLO

- Narrow-width approximation

  NLO corrections to both production and decay, neglecting non-factorizable corrections, including spin correlations at NLO

  - Double differential angular distributions to probe spin correlations

    Bernreuther, Brandenburg, Si, Uwer `04

  - Flexible Monte Carlo implementation, fully differential level
  - Spin correlations of top anti-top via decay products
  - pp → tt + X → WWbb + X → lν lν bb + X (di-lepton)
  - pp → tt + X → WWbb + X → ud lν bb + X (lepton + jet)

    Melnikov, Schulze `09

  - Can be implemented at NNLO :

    decay at this level is already known

    Gao, Li, Zhu `12

    Brucherseifer, Caola, Melnikov `13

Decay modeling @ NLO

- Off-shell effects through direct simulation of the final state WWbb

Denner, Dittmaier, Kallweit, Pozzorini `11

Bevilacqua, MC, van Hameren, Papadopoulos, Worek `11

Heinrich, Maier, Nisius, Schlenk, Winter `13

- Off-shell effects with massive b-quarks (simultaneous top-pair and single-top)

Frederix `13

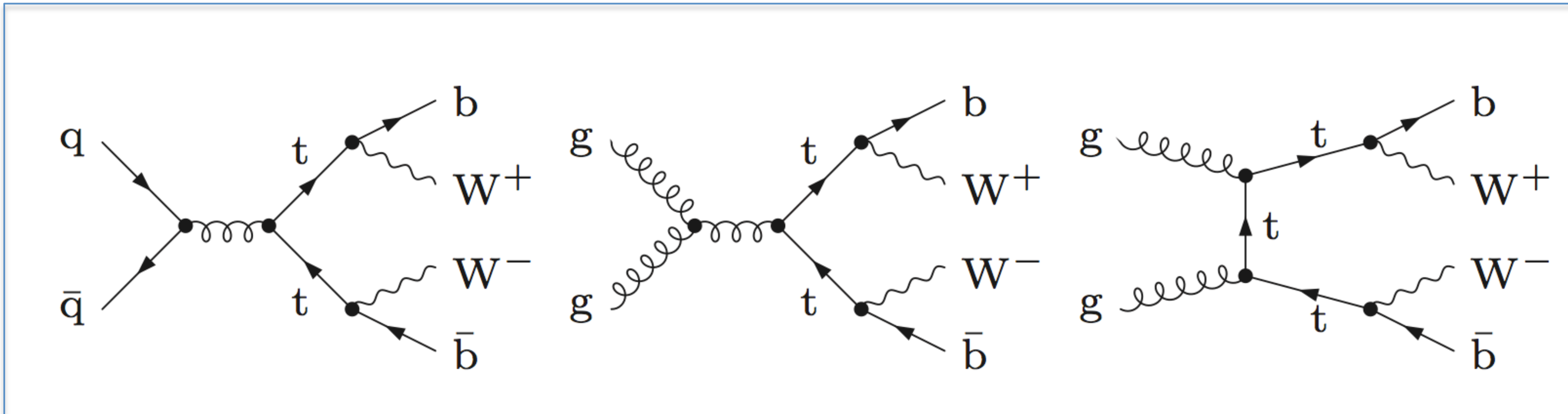
Cascioli, Kallweit, Maierhöfer, Pozzorini `13

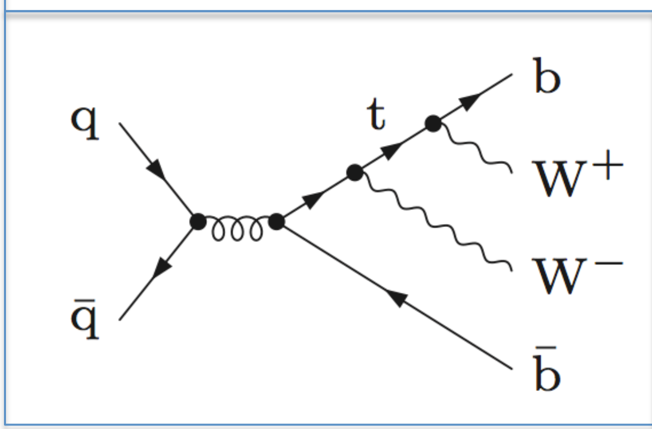
↑

very fancy interpolating scales

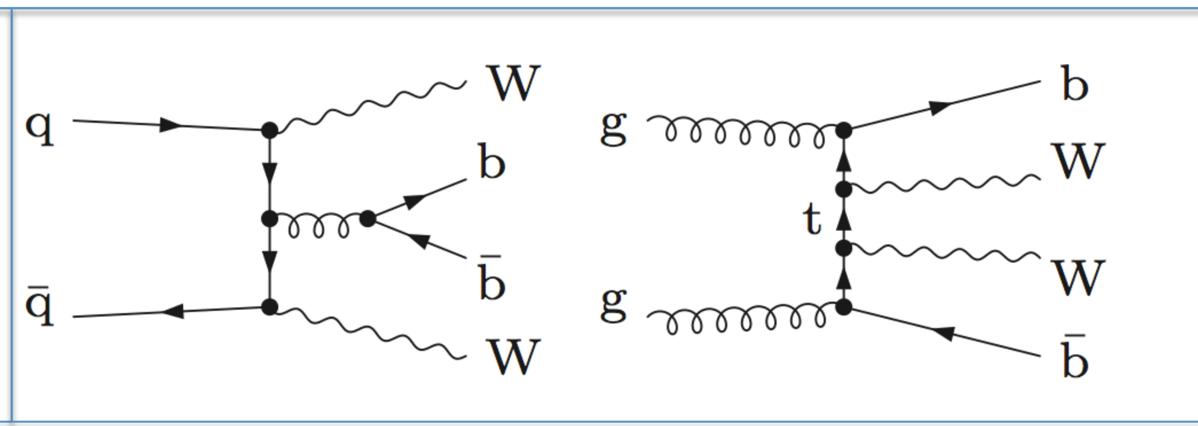
Decay modeling @ NLO

Available in the Narrow Width Approximation





Single-top



Non-resonant

Effects on total rates (fiducial)

NWA → $\sigma_{t\bar{t}}$; Off-shell → $\sigma_{WWb\bar{b}}$

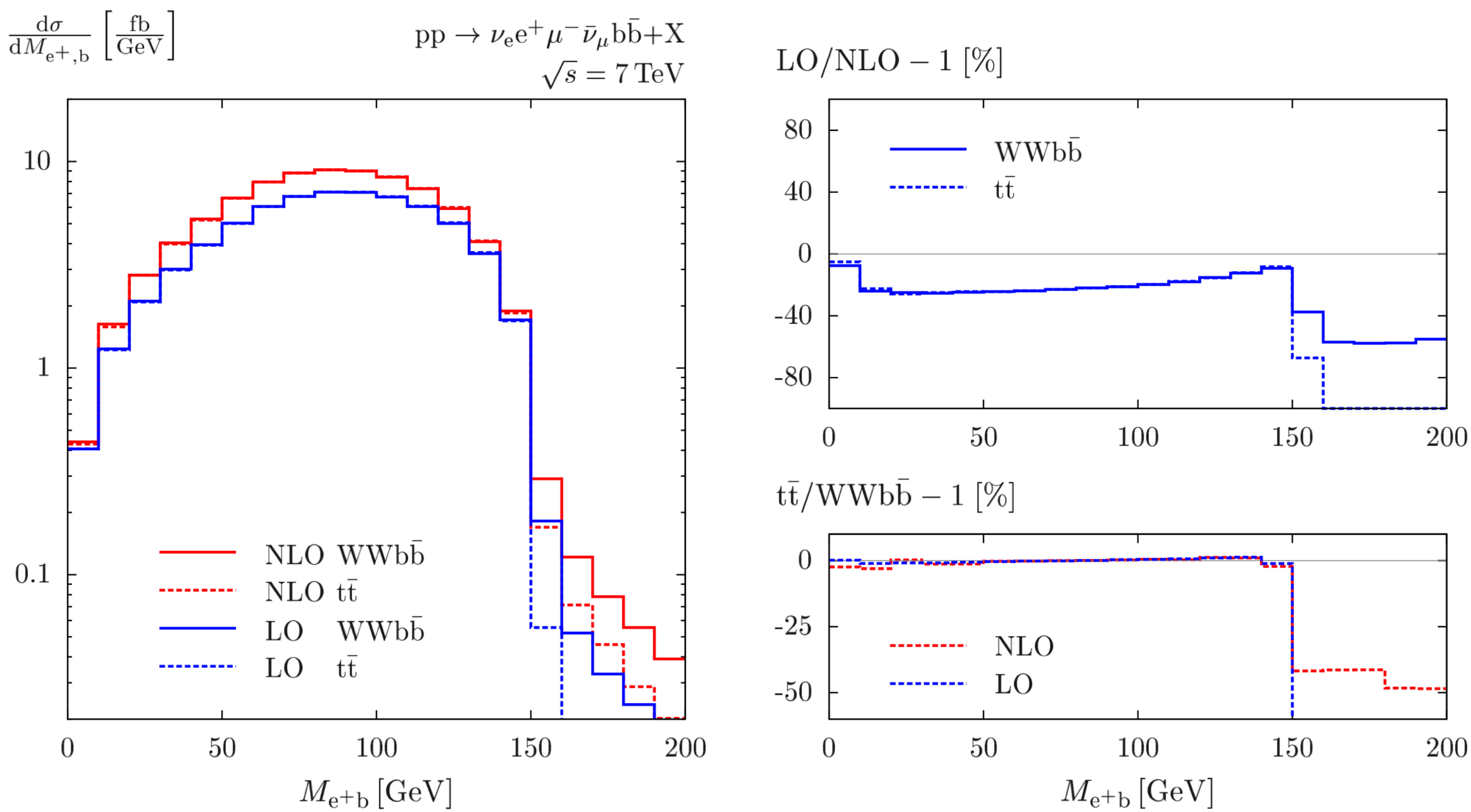
Collider	$\sqrt{s}$ [TeV]	approx.	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{WWb\bar{b}}$ [fb]	$\sigma_{t\bar{t}}/\sigma_{WWb\bar{b}} - 1$	Expected
Tevatron	1.96	LO	$44.691(8)^{+19.81}_{-12.58}$	$44.310(3)^{+19.68}_{-12.49}$	$+0.861(19)\%$	$+0.8\%$
		NLO	$42.16(3)^{+0.00}_{-2.91}$	$41.75(5)^{+0.00}_{-2.63}$	$+0.98(14)\%$	$+0.9\%$
LHC	7	LO	$659.5(1)^{+261.8}_{-173.1}$	$662.35(4)^{+263.4}_{-174.1}$	$-0.431(16)\%$	-0.4%
		NLO	$837(2)^{+42}_{-87}$	$840(2)^{+41}_{-87}$	$-0.41(31)\%$	-0.2%
LHC	14	LO	$3306.3(1)^{+1086.8}_{-763.6}$	$3334.6(2)^{+1098.5}_{-771.2}$	$-0.849(7)\%$	– – –
		NLO	$4253(3)^{+282}_{-404}$	$4286(7)^{+283}_{-407}$	$-0.77(19)\%$	– – –

Denner, Dittmaier, Kallweit, Pozzorini, Schulze `12

Tevatron (LHC) $R = 0.4\,(0.5)$ $p_{T,\mathrm{b-jet}} > 20\,(30)$ GeV, $|\eta_{\mathrm{b-jet}}| < 2.5$

$p_{T,\mathrm{miss}} > 25\,(20)$ GeV $p_{T,l} > 20$ GeV and $|\eta_l| < 2.5$

Finite width sensitive observables



Denner, Dittmaier, Kallweit, Pozzorini, Schulze `12

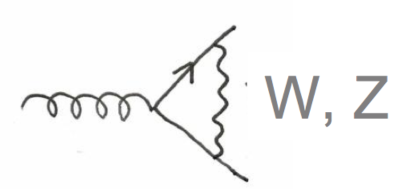
- Large effects easily found by reaching past kinematic end-points

ELECTROWEAK CORRECTIONS

General remarks

- Long history
  - Beennakker, Denner, Hollik, Mertig, Sack, Wackeroth `94
  - Bernreuther, Fücker, Si `05,`06
  - Moretti, Nolten, Ross `06
  - Kühn,Scharf,PU `05,`06,`14

- Typically only virtual corrections due to W/Z
  - ➢ large effects are negative

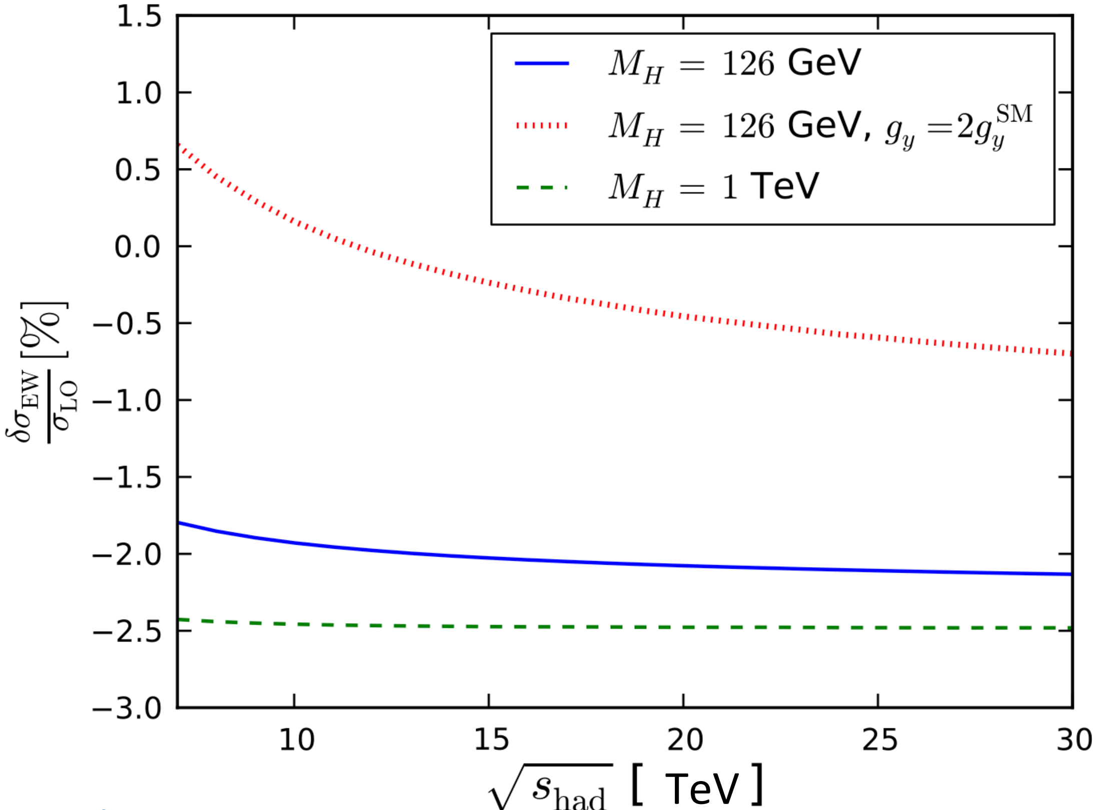


$$\log^2(p_{Tt}/M_{W,Z})$$

- When is QCD enough ?

Total cross sections

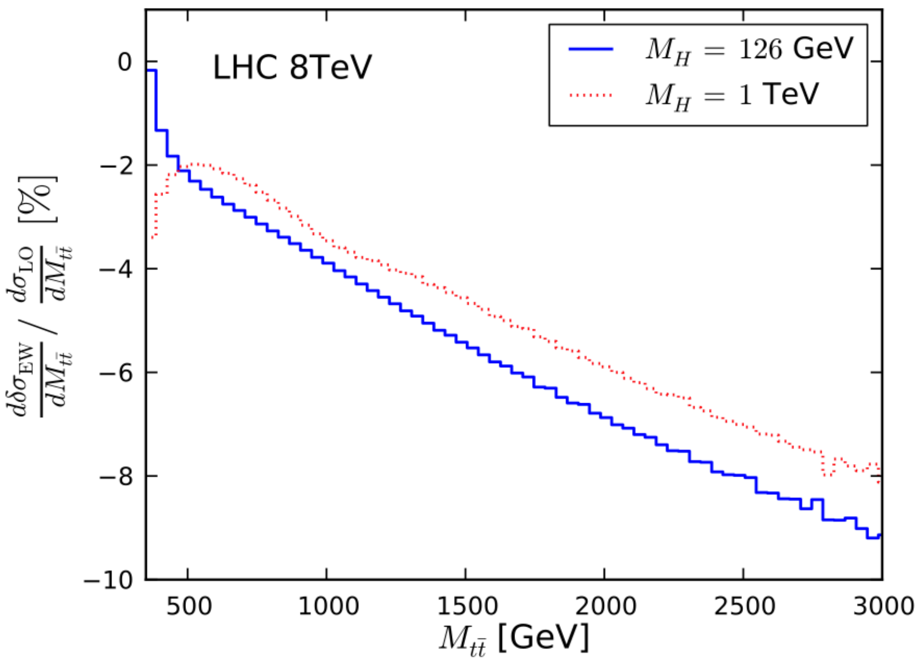
- Expectedly small corrections, which justify the use of pure QCD
- In the plot beware of the normalization to LO

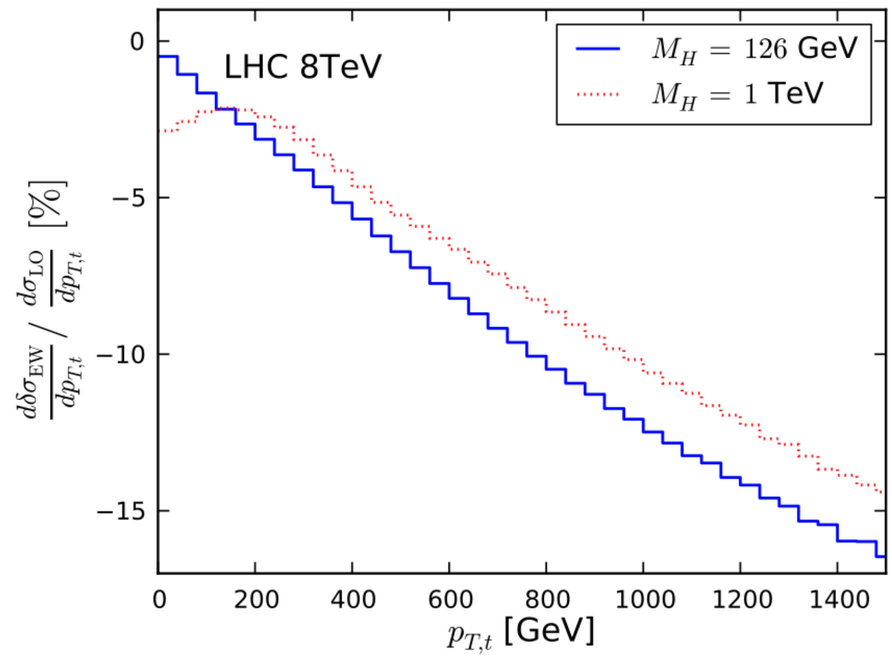


Kühn, Scharf, Uwer `13

Sudakov effects in the "tails"

- Clearly, the "boosted" regime requires the inclusion of EW effects





Kühn, Scharf, Uwer `13

Sudakov effects in the “tails”

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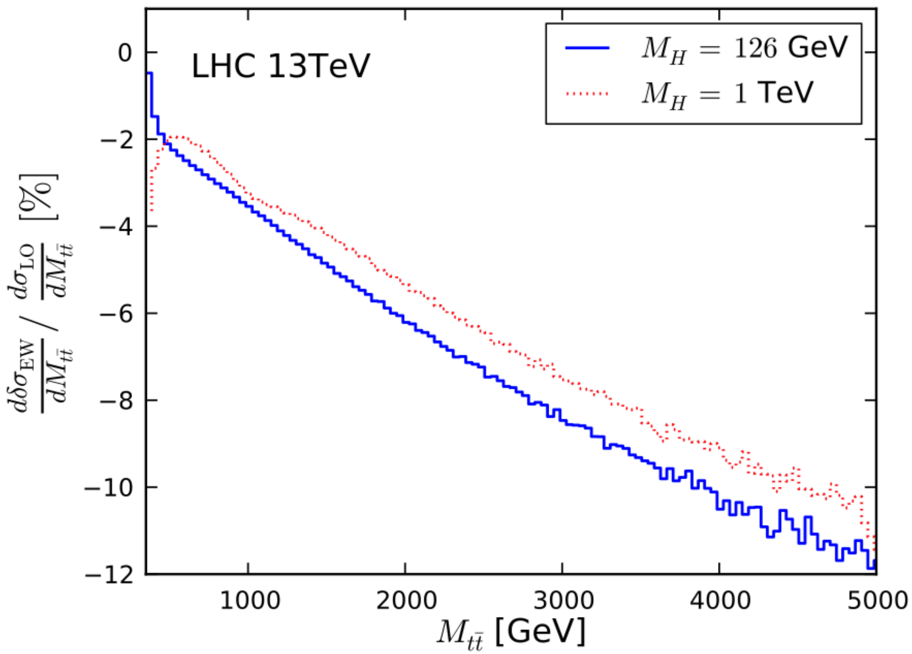
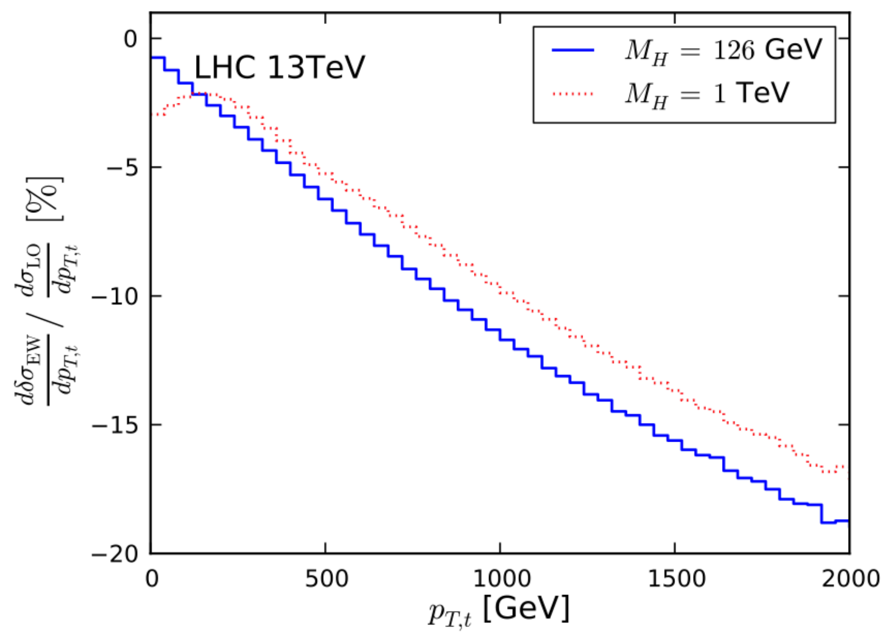




Kühn, Scharf, Uwer ‘13

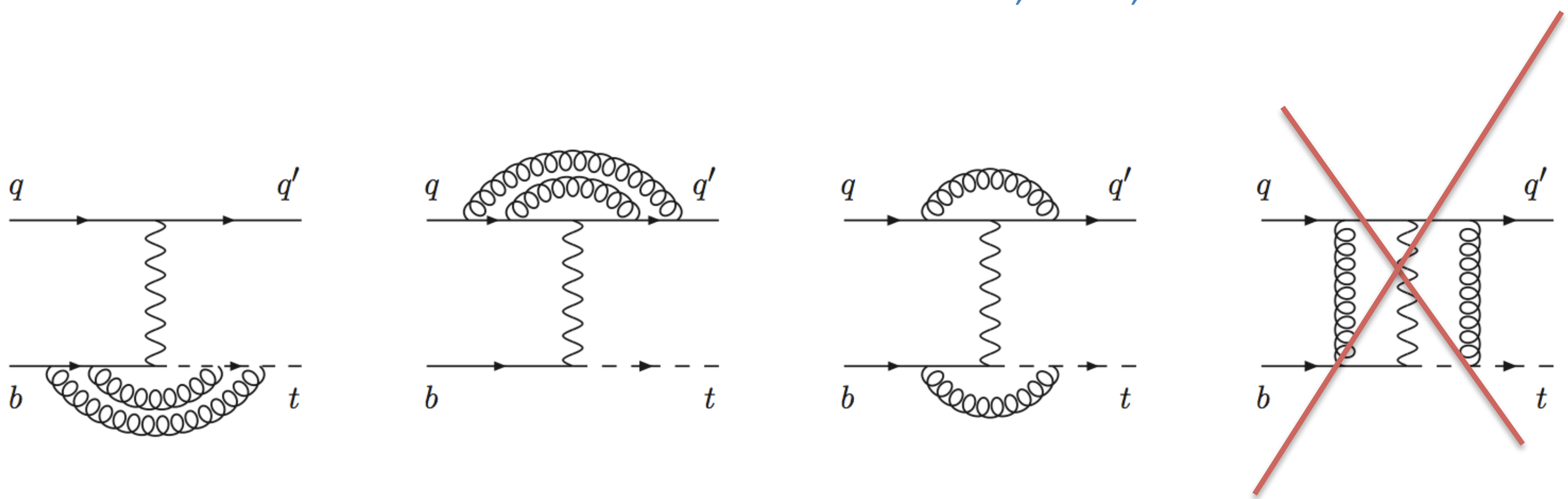
- These effects might be reduced by including real-radiation corrections from W/Z
  - ➢ Complete cancellation impossible due to isospin of the initial state

SINGLE-TOP PRODUCTION

Recent result @ NNLO

- T-channel production
  structure function approximation

Brucherseifer, Caola, Melnikov `14



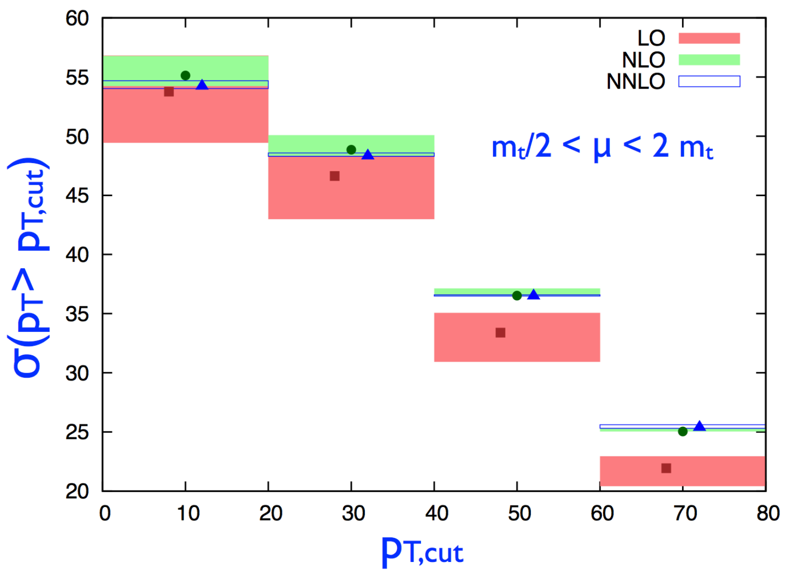
- Fixed scale around top-quark mass

Recent result @ NNLO

- Stability w.r.t. cut on the transverse momentum important for reliability of NLO

$p_\perp$	σ_{LO}, pb	σ_{NLO}, pb	δ_{NLO}	σ_{NNLO}, pb	δ_{NNLO}
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

Brucherseifer, Caola, Melnikov `14



Picture from: F. Caola Moriond `15

Conclusions

- Precent level precision achieved thanks to many simplifications
- Reliable/transparent description at the level of fiducial cross sections within grasp
- Precision only usable when Monte Carlo systems used in data analysis: calculations cannot replace Monte Carlo's