

Top-Quark Physics

M. Czakon

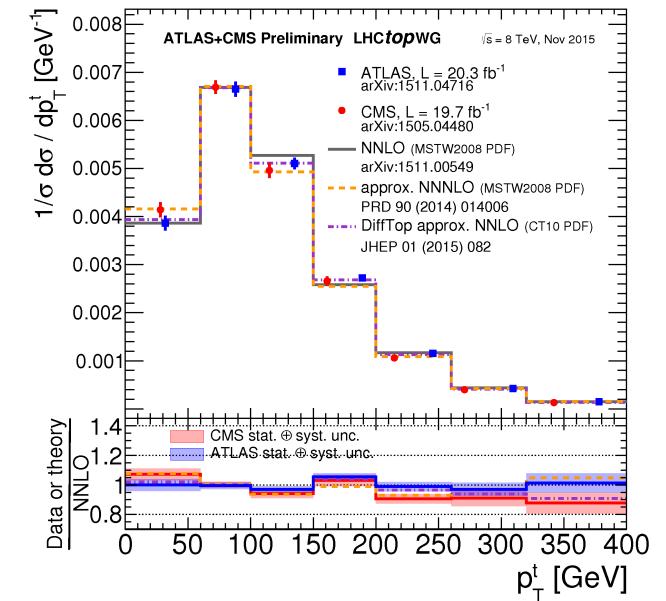
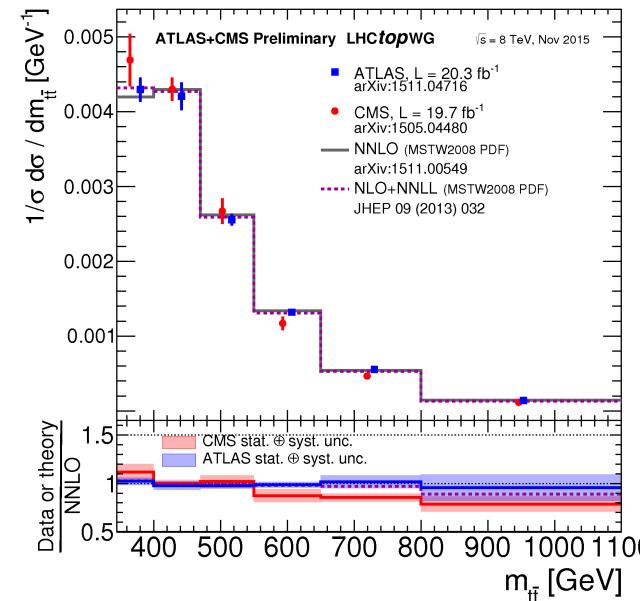
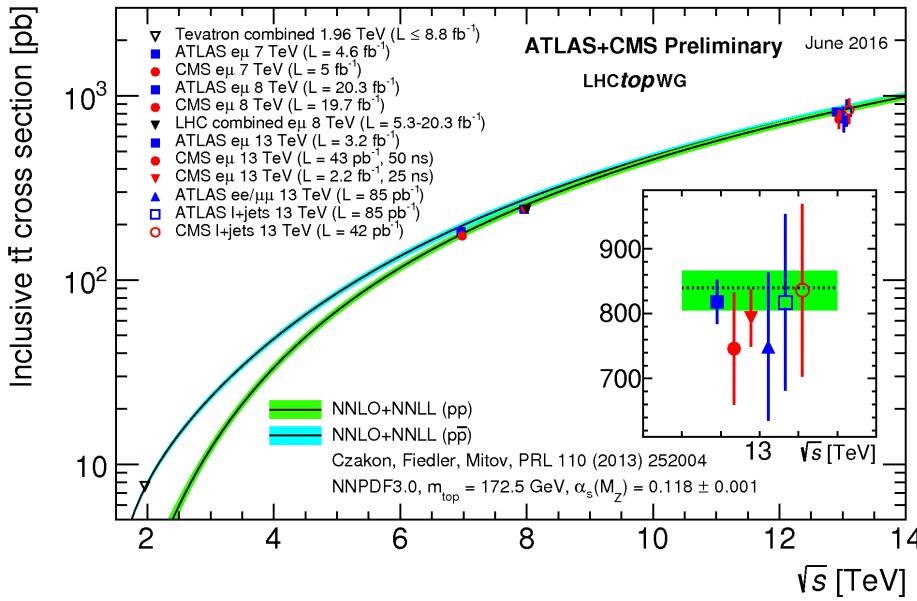
RWTH Aachen University

Plan

1. Mass definitions
2. Decay modelling
3. High precision

Total and Differential Cross Sections

- We are well in the hadron collider precision measurement territory !!!
- ...for a few years now



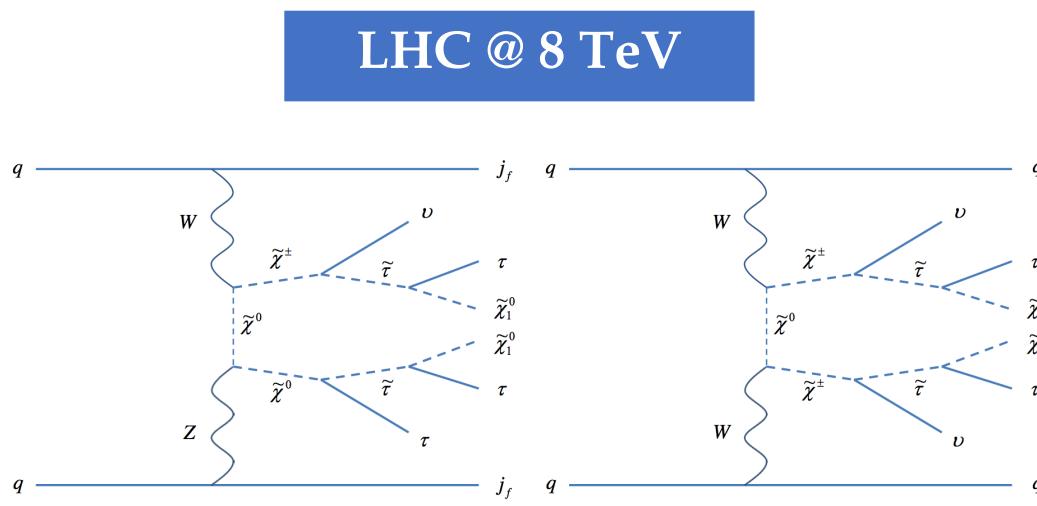
LHC	$\sigma(t\bar{t})$ [pb]	L [fb^{-1}]	N_{event}
7 TeV	172.676	5	8.6×10^5
8 TeV	246.652	19.7	4.8×10^6
13 TeV	807.296	2.3	1.8×10^6

LHC Run 1 (7 TeV, 8 TeV)

LHC Run 2 (13 TeV)

Search for Supersymmetry...

- An example of the importance of top-quark cross sections as background
- Search for supersymmetry in the vector-boson fusion topology in proton-proton collisions

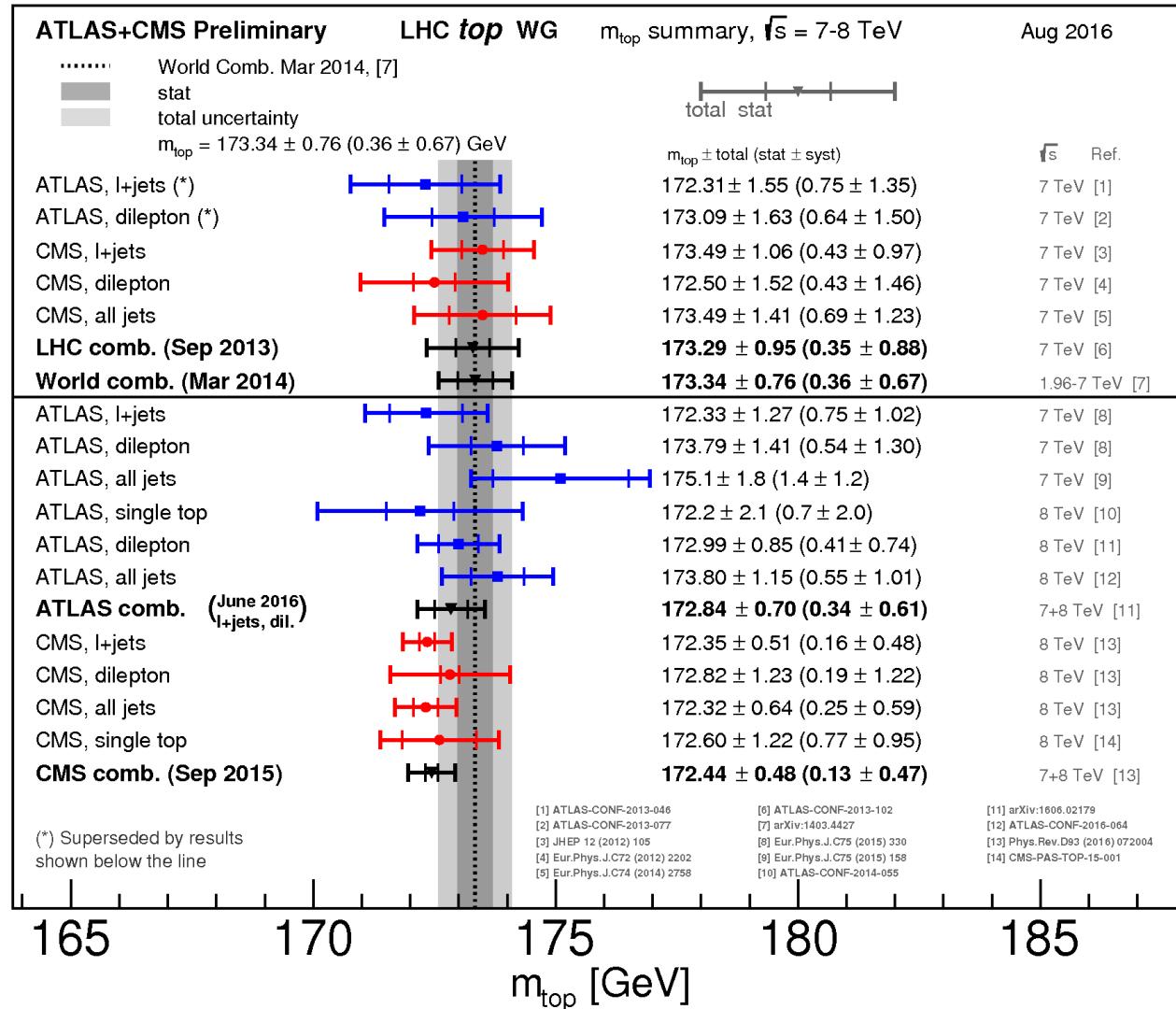


CERN-PH-EP/2015-213
2015/09/01

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</bar>	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

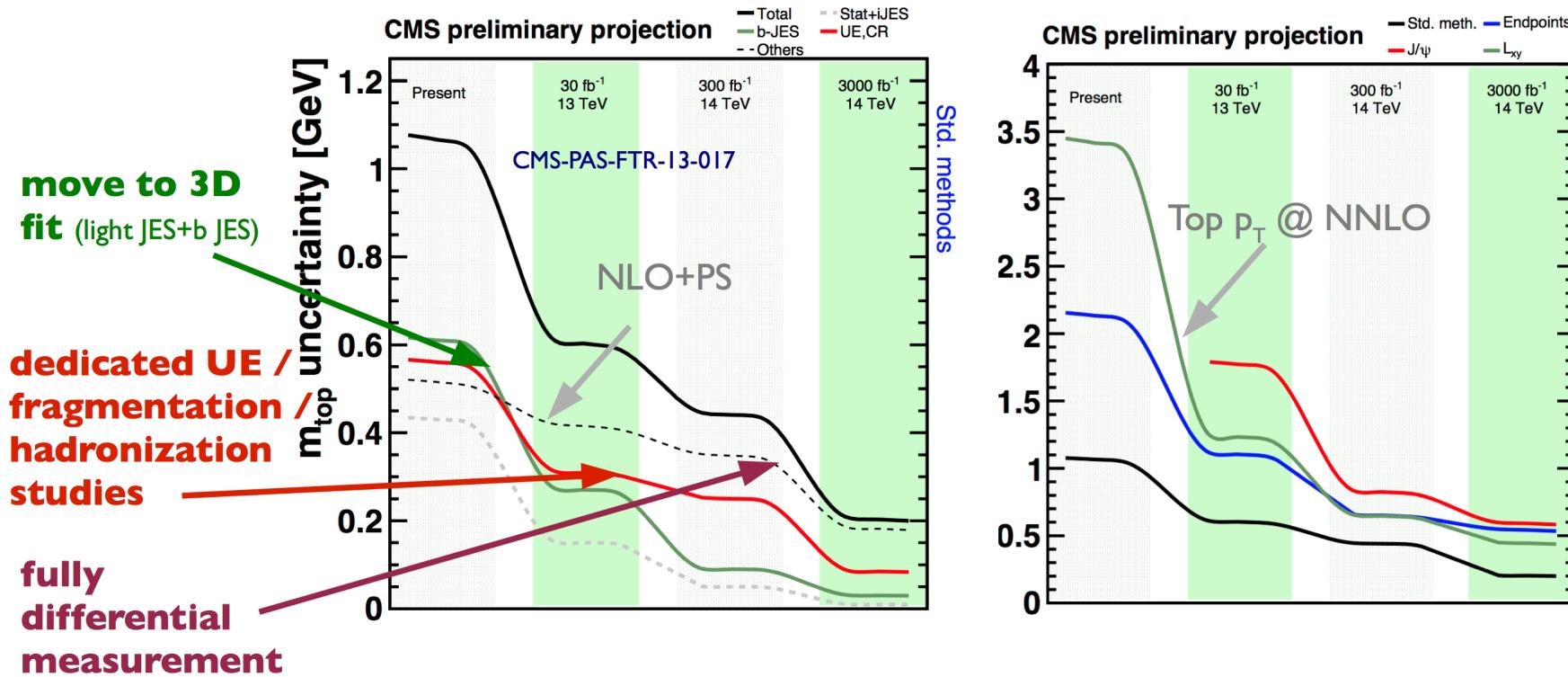
Mass

Mass measurements



... in view of projections for the LHC

Excellent prospects for mass measurements
despite reliance on a hadron collider

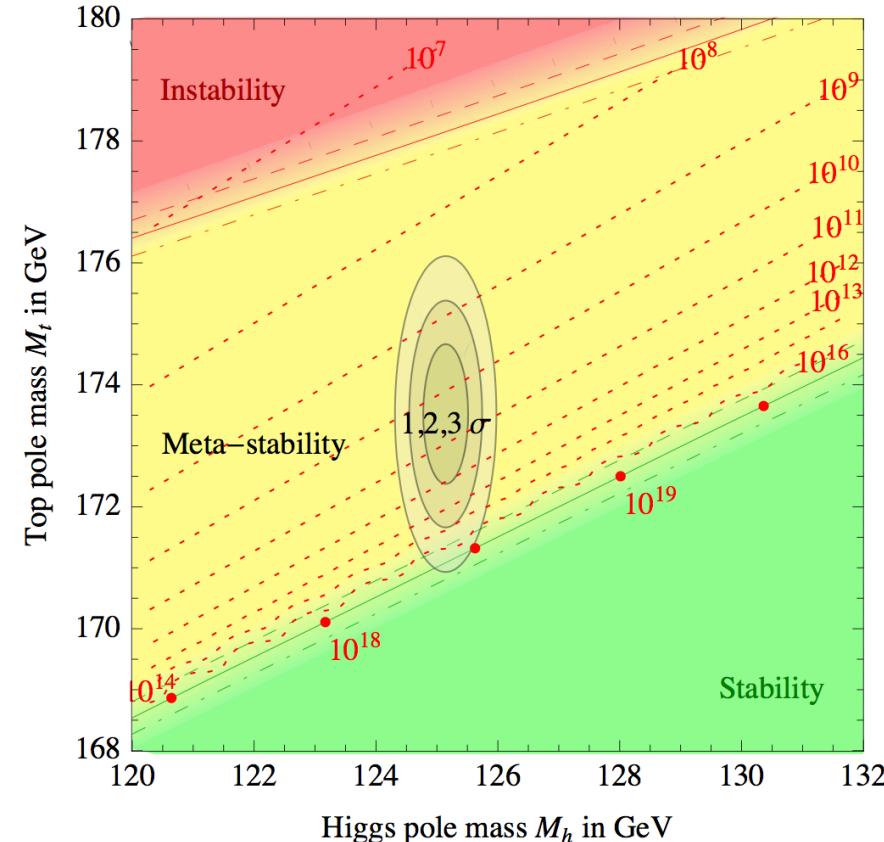
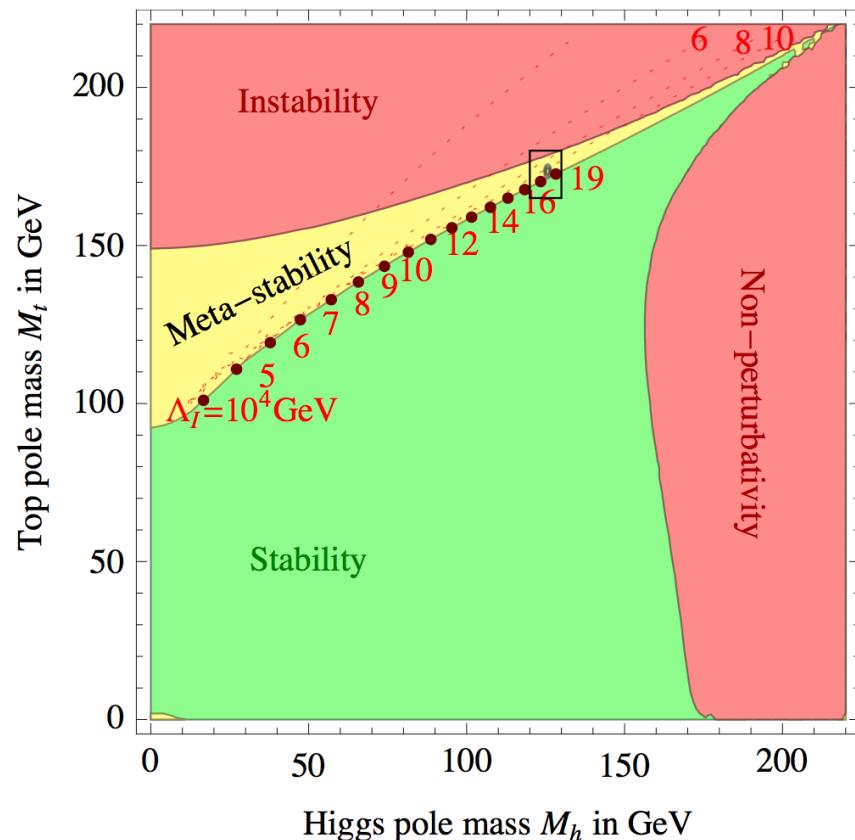


Measurements refer to the mass parameter of Monte Carlo's
Usually pole mass (or close to it)

Standard model phase diagram...

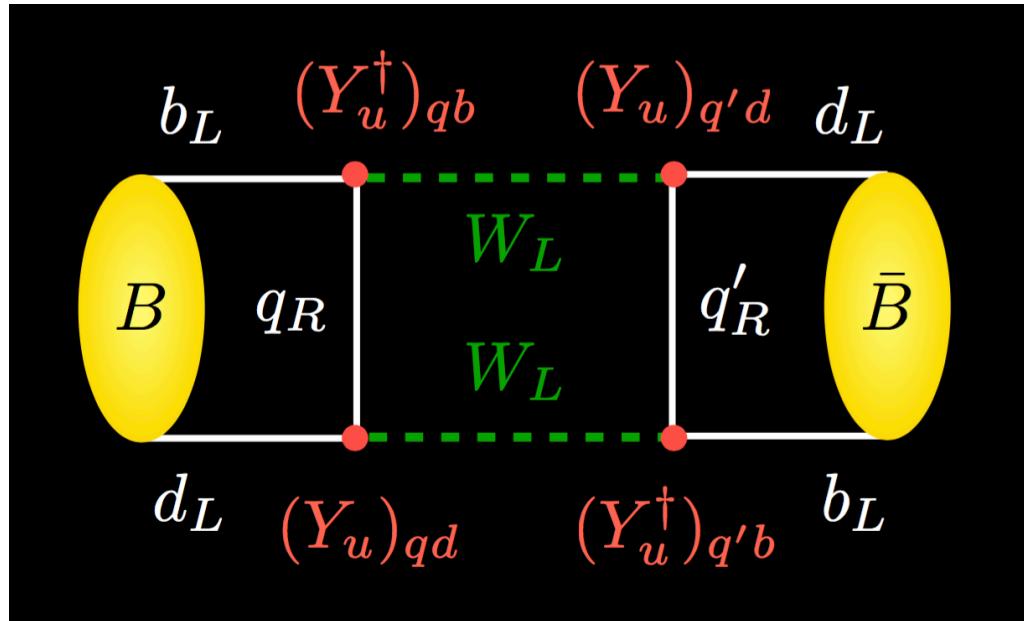
...one of the many reasons for interest in the top-quark mass

Under the assumption of “the great desert”

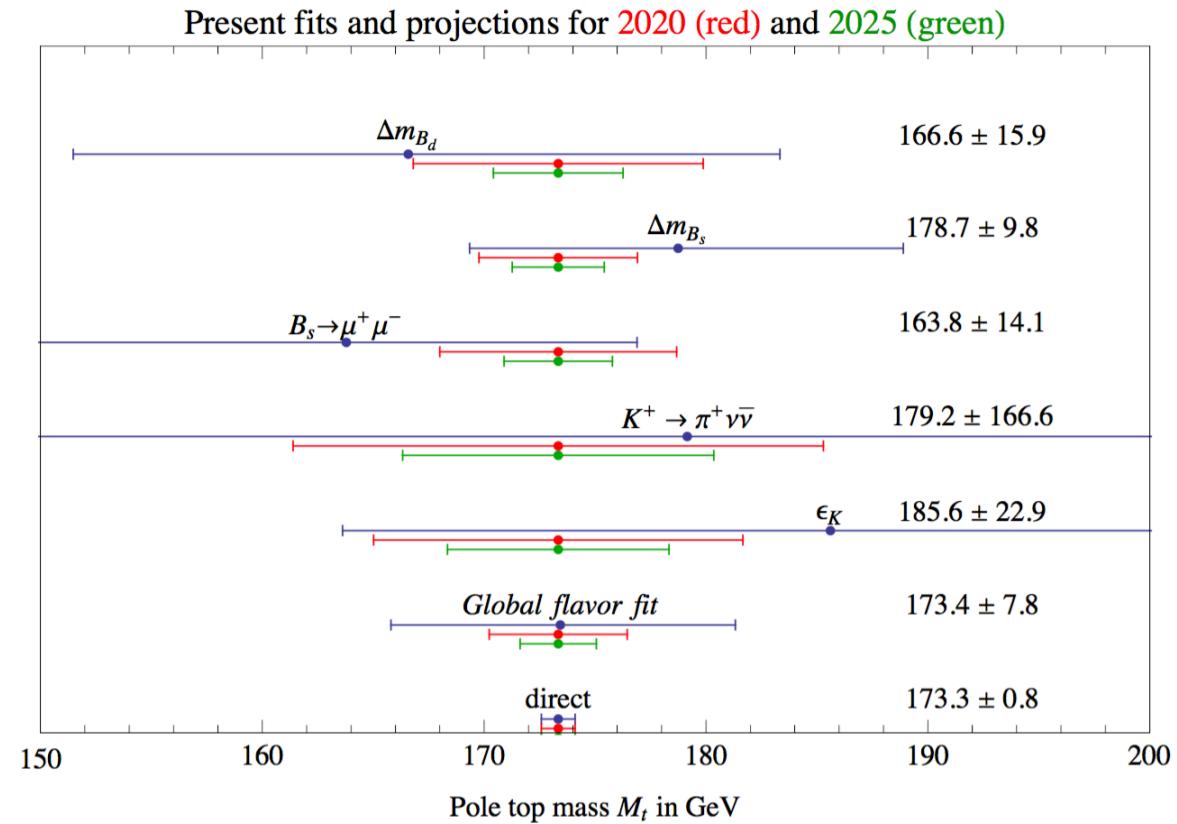


Top-quarks @ low energy

Measurement precision viewed through mass determination



$$\propto \frac{g_2^2}{16\pi^2 M_W^4} m_t^2 (V_{tb}^* V_{td})^2$$



Giudice, Paradisi, Strumia '15

Top-quark mass definitions

$$\text{---} + \text{---}^{\Sigma'} = p - m^0 - \Sigma(p, m^0, \mu)$$

$$\Sigma(m^0, m^0, \mu) = m^0 \left[\frac{\alpha_s}{\pi\epsilon} + \dots \right] + \Sigma^{\text{fin}}(m^0, m^0, \mu)$$

MS scheme: $m^0 = \bar{m}(\mu) \left[1 - \frac{\alpha_s}{\pi\epsilon} + \dots \right]$

- $\bar{m}(\mu)$ is pure UV-object without IR-sensitivity
- Useful scheme for $\mu > m$
- Used a lot in beyond TeV physics

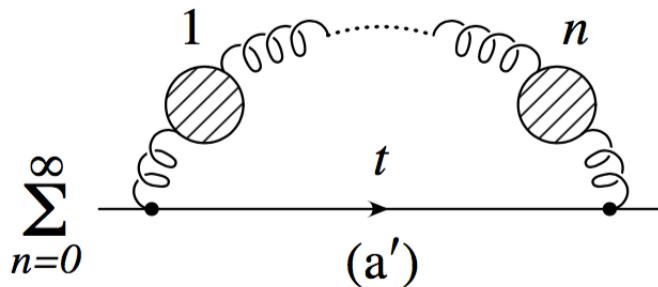
- Very energetic processes ($E \gg m$)
- Total cross sections
- Off-shell massive quarks
- Away from thresholds/endpoints

Pole scheme: $m^0 = m^{\text{pole}} \left[1 - \frac{\alpha_s}{\pi\epsilon} + \dots \right] - \Sigma^{\text{fin}}(m^{\text{pole}}, m^{\text{pole}}, \mu)$

- m^{pole} = perturbative single particle pole of perturbative S-matrix
- Absorbs all self energy corrections into the mass parameter
- Separation: self energy corrections \leftrightarrow inter quark/gluon interactions for all momenta
- Has perturbative instabilities due to sensitivity to momenta $< 1 \text{ GeV}$ (Λ_{QCD})

Ambiguity of the pole mass

- Pole mass defined by an asymptotic series



$$\Sigma^{(1)}(m_R, a) = \frac{16m_R}{3\beta_0} \sum_{n=0}^{\infty} c_n a^{n+1}$$
$$c_n \xrightarrow{n \rightarrow \infty} e^{-C/2} 2^n n!$$
$$a \equiv \frac{\beta_0 \alpha_s(m_R)}{4\pi}$$

- Renormalon ambiguity: the series is not Borel summable**
- Ambiguity proportional to Λ_{QCD} , but with what coefficient ?
- Relation to MS mass up to 4-loops

$$m_P = 163.643 + 7.557 + 1.617 + 0.501 + (0.195 \pm 0.005) \text{ GeV}$$

- Recent estimate of the ambiguity *Marquard, Smirnov, Smirnov, Steinhauser '15*

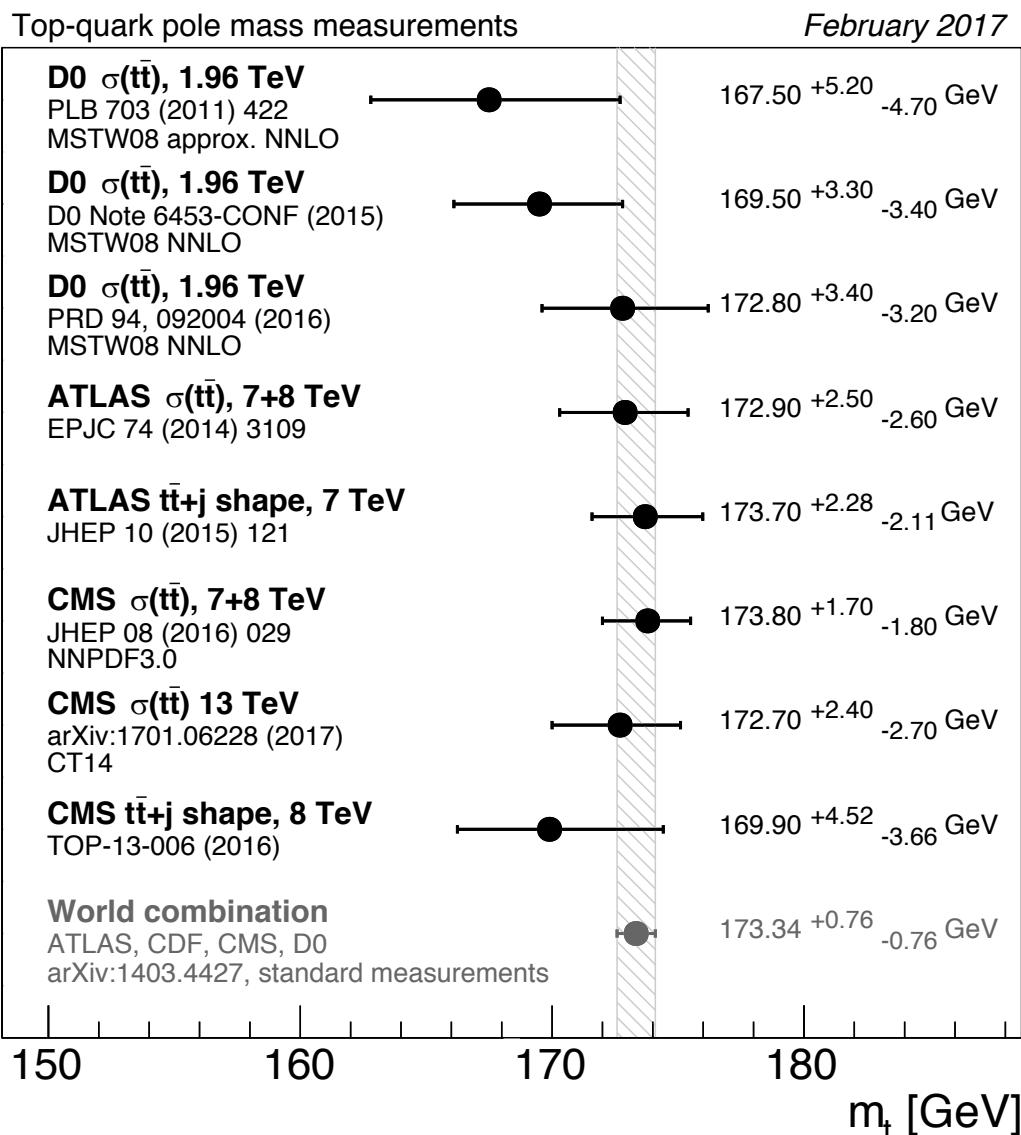
$$\delta^{(5+)} m_P = 0.250_{-0.038}^{+0.015} (N) \pm 0.001 (c_4) \pm 0.010 (\alpha_s) \pm 0.071 \text{ (ambiguity)} \text{ GeV}$$

Beneke, Marquard, Nason, Steinhauser arXiv:1605.03609

- ...But the debate continues with an estimate at 250 MeV

Hoang, Lepenik, Preisser arXiv:1706.08526

Some alternative measurements with clean definitions



Decay modelling

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
- $pp \rightarrow tt + X \rightarrow WWbb + X \rightarrow lv\bar{lv} bb + X$ (di-lepton)
- $pp \rightarrow tt + X \rightarrow WWbb + X \rightarrow ud\bar{lv} bb + X$ (lepton + jet)

Melnikov, Schulze '09

- Can be implemented at NNLO in QCD
- 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 lv lv bb

Denner, Dittmaier, Kallweit, Pozzorini '11 '12

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

- Off-shell electroweak effects

Denner, Pellen '16

- More complicated processes

$\text{lv lv bb} + \text{H}$

*Denner, Feger '15,
Denner, Lang, Pellen, Uccirati '17 (including electroweak effects)*

$\text{lv lv bb} + \text{jet}$

Bevilacqua, Hartanto, Kraus, Worek '16

Effects on Total Rates (Fiducial)

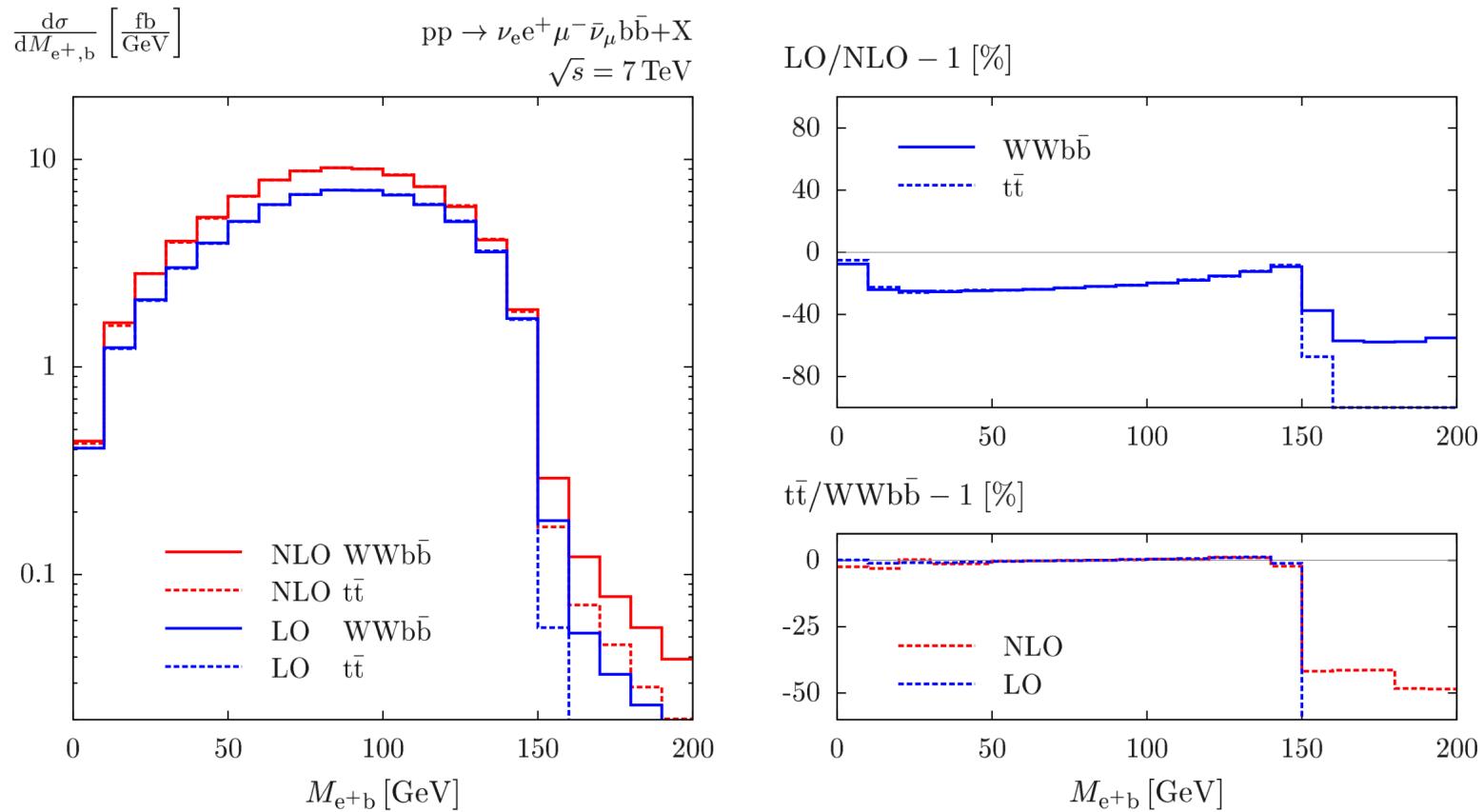
		NWA		Off-shell		
Collider	\sqrt{s} [TeV]	approx.	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{WWb\bar{b}}$ [fb]	$\sigma_{t\bar{t}}/\sigma_{WWb\bar{b}} - 1$	Expected
Tevatron	1.96	LO	$44.691(8)^{+19.81}_{-12.58}$	$44.310(3)^{+19.68}_{-12.49}$	$+ 0.861(19)\%$	$+ 0.8\%$
		NLO	$42.16(3)^{+0.00}_{-2.91}$	$41.75(5)^{+0.00}_{-2.63}$	$+ 0.98(14)\%$	$+ 0.9\%$
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) $R = 0.4 \text{ (} 0.5 \text{)}$ $p_{T,b-\text{jet}} > 20 \text{ (} 30 \text{)} \text{ GeV}, |\eta_{b-\text{jet}}| < 2.5$

$p_{T,\text{miss}} > 25 \text{ (} 20 \text{)} \text{ GeV}$ $p_{T,l} > 20 \text{ GeV}$ 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

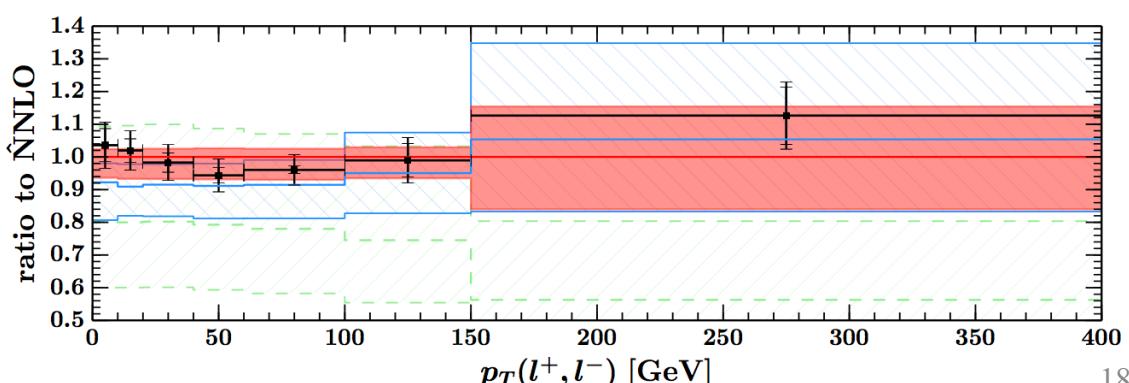
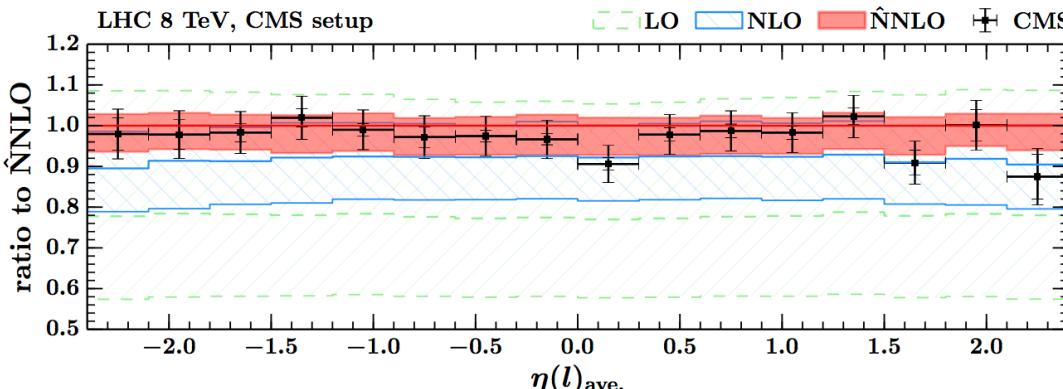
First step towards NWA @ NNLO

- Exact matrix elements for everything but the production mechanism at NNLO QCD

Gao, Papanastasiou '17

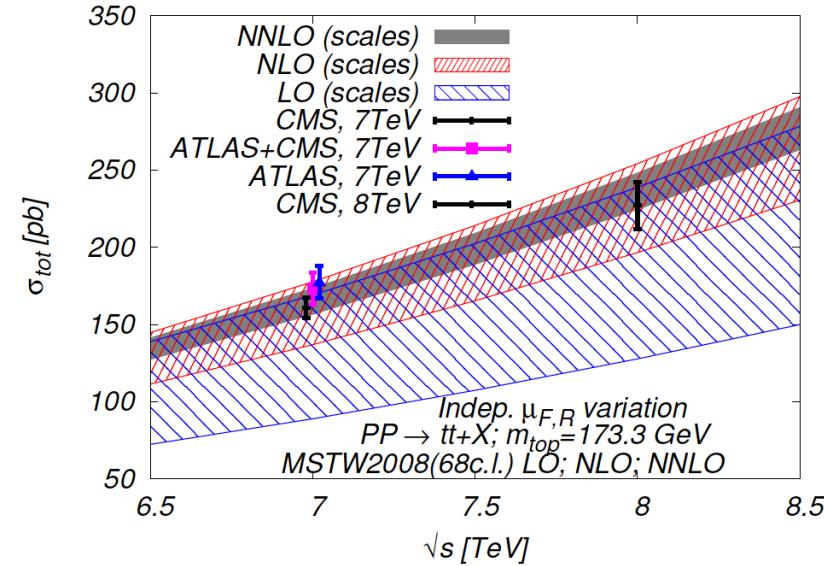
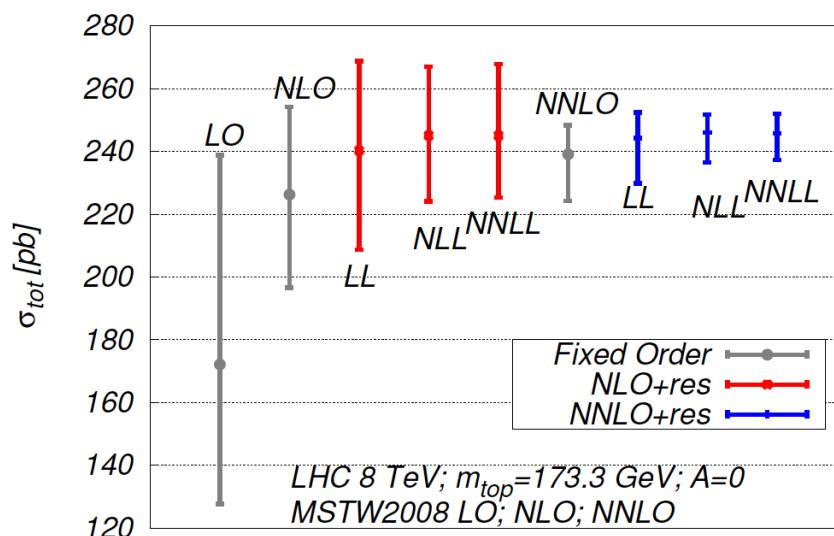
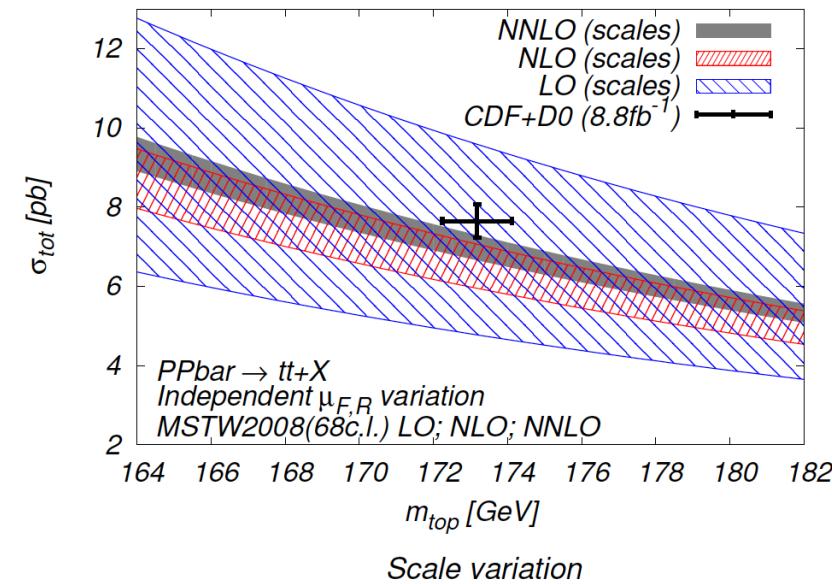
ATLAS setup, $e^\pm\mu^\mp$ channel [24]						
energy	fiducial volume	LO [pb]	NLO [pb]	$\hat{\text{NNLO}}$ [pb]	$\delta_{\text{dec.}}$	ATLAS [pb]
7 TeV	$p_T(l^\pm) > 25 \text{ GeV}, \eta(l^\pm) < 2.5$	$1.592^{+39.2\%}_{-26.0\%}$	$2.007^{+11.9\%}_{-13.2\%}$	$2.210^{+2.2\%}_{-6.0\%}$	-0.3%	$2.305^{+3.8\%}_{-3.8\%}$
7 TeV	$p_T(l^\pm) > 30 \text{ GeV}, \eta(l^\pm) < 2.4$	$1.265^{+39.3\%}_{-26.1\%}$	$1.585^{+11.8\%}_{-13.1\%}$	$1.736^{+2.2\%}_{-6.0\%}$	-0.8%	$1.817^{+3.8\%}_{-3.8\%}$
8 TeV	$p_T(l^\pm) > 25 \text{ GeV}, \eta(l^\pm) < 2.5$	$2.249^{+37.9\%}_{-25.5\%}$	$2.855^{+11.9\%}_{-12.9\%}$	$3.130^{+2.3\%}_{-6.0\%}$	-0.3%	$3.036^{+4.1\%}_{-4.1\%}$
8 TeV	$p_T(l^\pm) > 30 \text{ GeV}, \eta(l^\pm) < 2.4$	$1.788^{+38.0\%}_{-25.5\%}$	$2.256^{+11.7\%}_{-12.9\%}$	$2.461^{+2.3\%}_{-6.1\%}$	-0.7%	$2.380^{+4.1\%}_{-4.1\%}$

CMS setup, $e^\pm\mu^\mp, e^+e^-, \mu^+\mu^-$ channel [25], 2 b-jets required (anti- k_t algorithm [66], $R = 0.5$)						
energy	fiducial volume	LO [pb]	NLO [pb]	$\hat{\text{NNLO}}$ [pb]	$\delta_{\text{dec.}}$	CMS [pb]
8 TeV	$p_T(l^\pm) > 20 \text{ GeV}, \eta(l^\pm) < 2.4,$ $p_T(J_b) > 30 \text{ GeV}, \eta(J_b) < 2.4$	$3.780^{+37.4\%}_{-25.3\%}$	$4.483^{+9.0\%}_{-11.5\%}$	$4.874^{+2.5\%}_{-6.8\%}$	-8.0%	$4.73^{+4.7\%}_{-4.7\%}$



High precision

Perturbation theory convergence

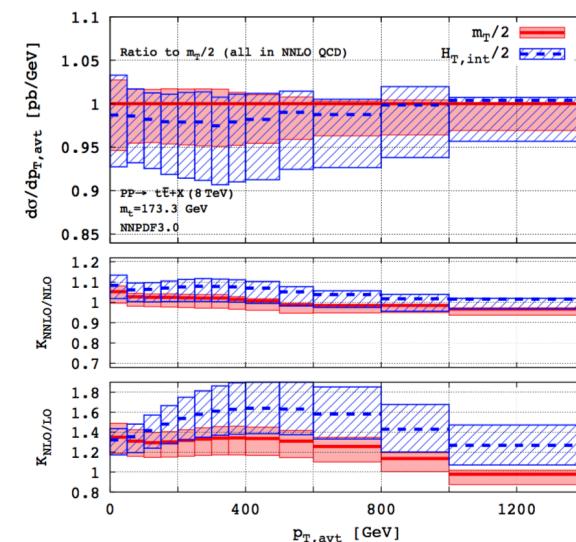
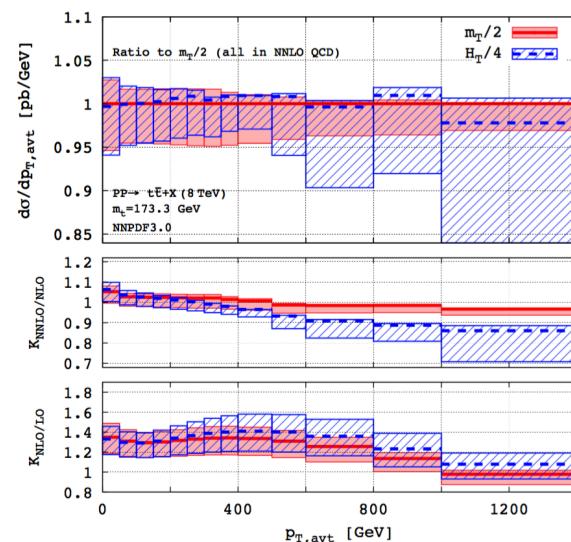
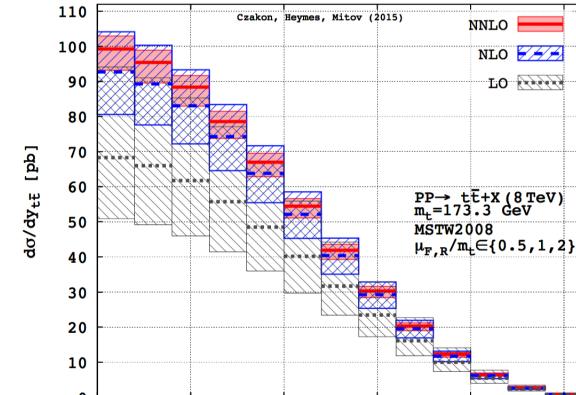
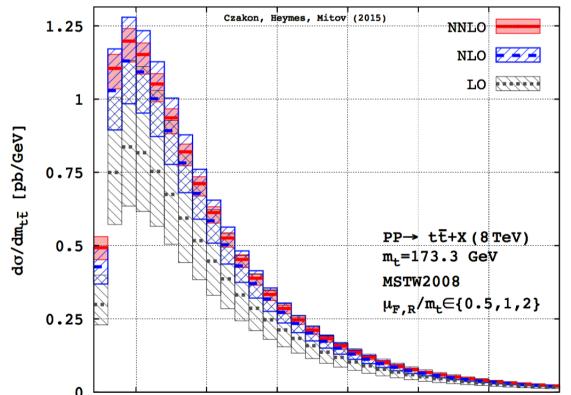
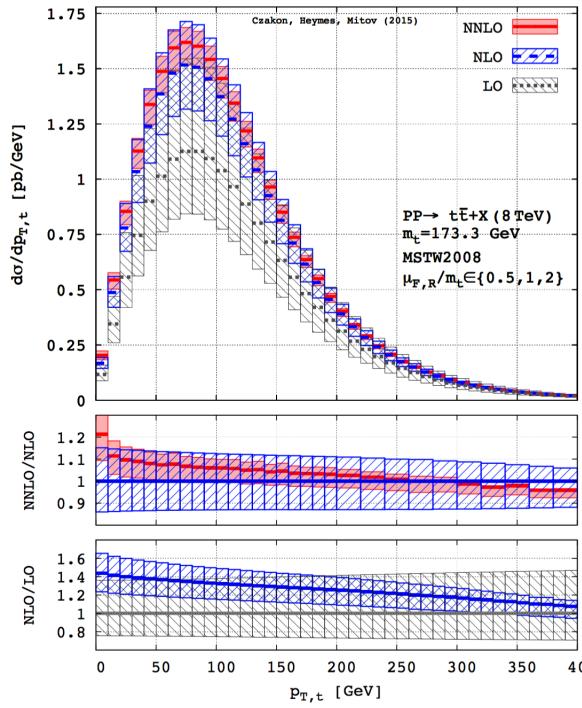


Concurrent uncertainties:

Scales	$\sim 3\%$
pdf (at 68%cl)	$\sim 2-3\%$
α_S (parametric)	$\sim 1.5\%$
m_{top} (parametric)	$\sim 3\%$

Soft gluon resummation makes a difference: $5\% \rightarrow 3\%$

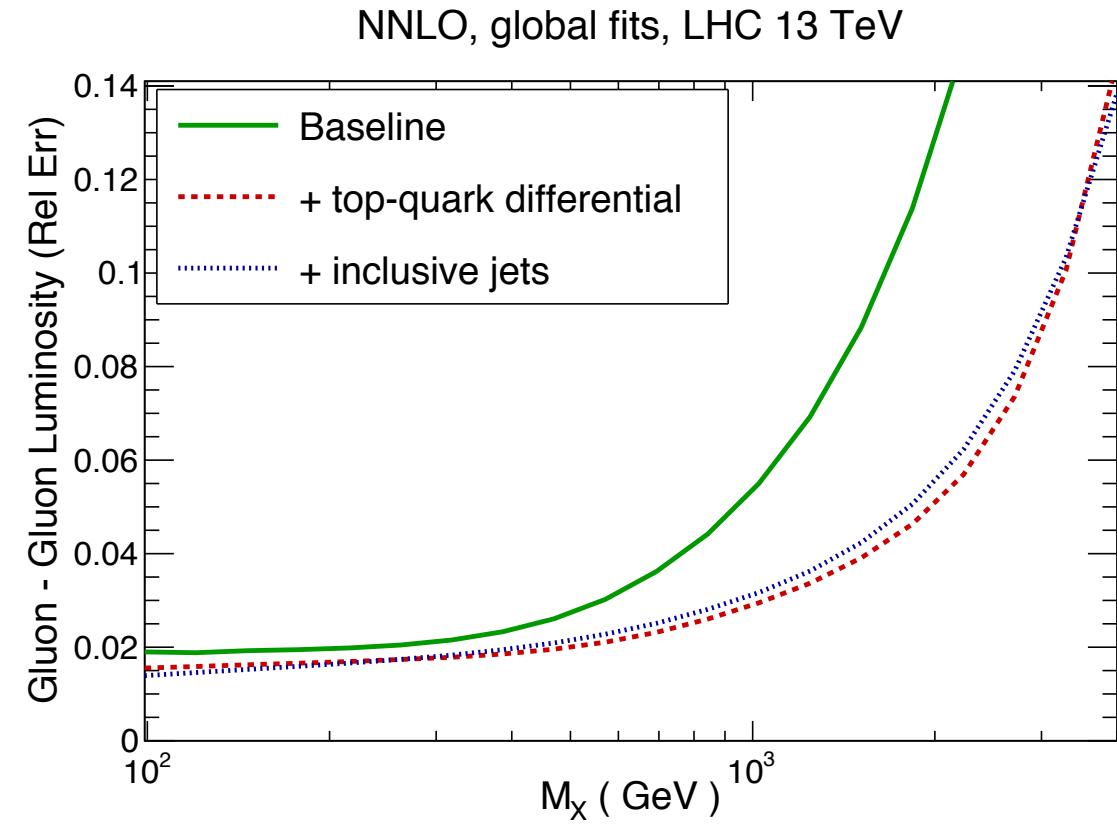
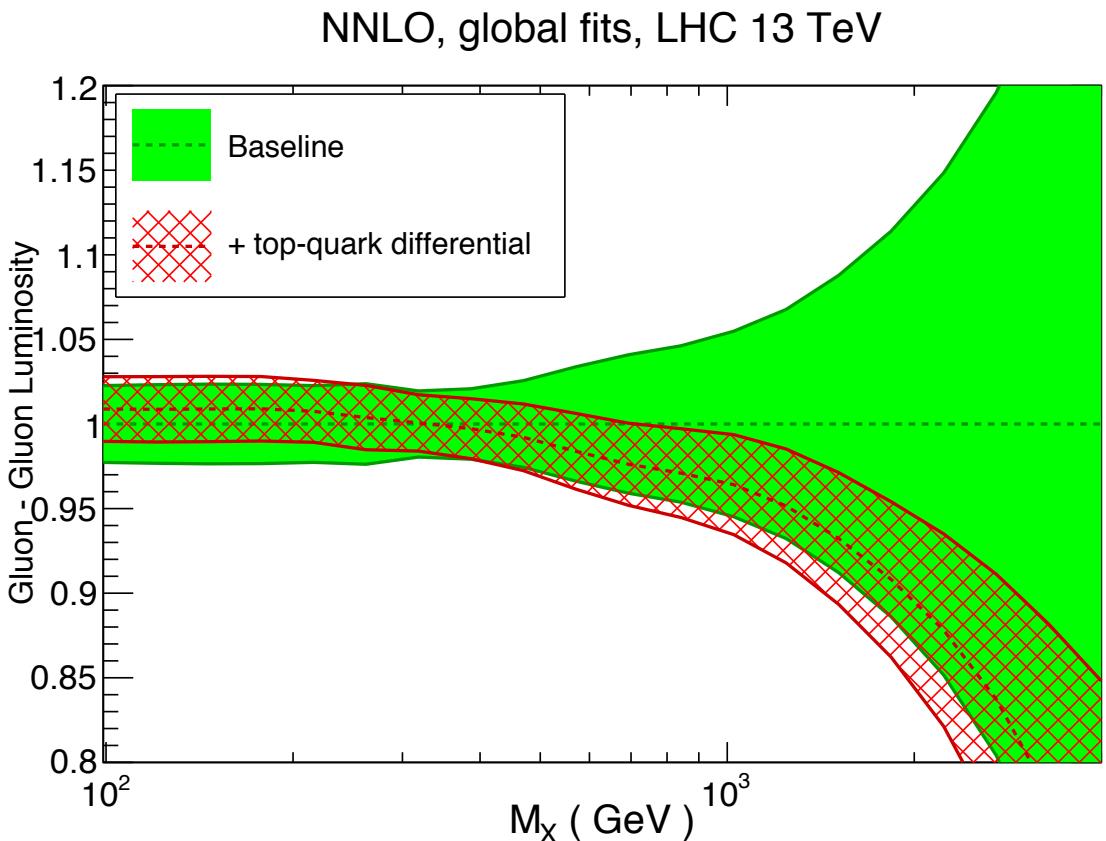
...for differential distributions



Convergence with
fixed and dynamical scales

MC, Heymes, Mitov '15 '16

Application: PDF fits



MC, Hartland, Mitov, Nocera, Rojo '16

- the normalized y_t distribution from ATLAS at $\sqrt{s} = 8$ TeV (lepton+jets channel),
- the normalized $y_{t\bar{t}}$ distribution from CMS at $\sqrt{s} = 8$ TeV (lepton+jets channel),
- total inclusive cross-sections at $\sqrt{s} = 7, 8$ and 13 TeV (all available data).

Electroweak effects

- Long history

Beennakker, Denner, Hollik, Mertig, Sack, Wackerloher '94

Bernreuther, Fücker, Si '05, '06

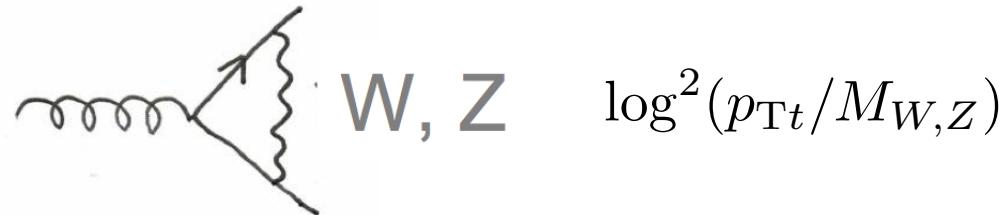
Moretti, Nolten, Ross '06

Kühn, Scharf, Uwer '05, '06, '14

Pagani, Tsinikos, Zaro '16

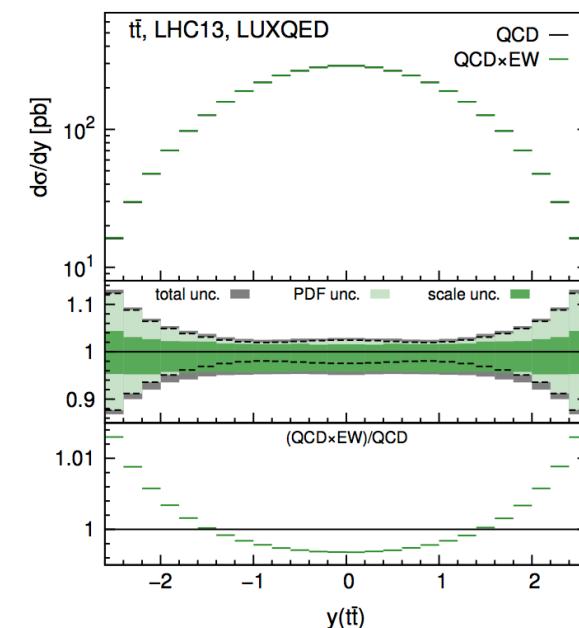
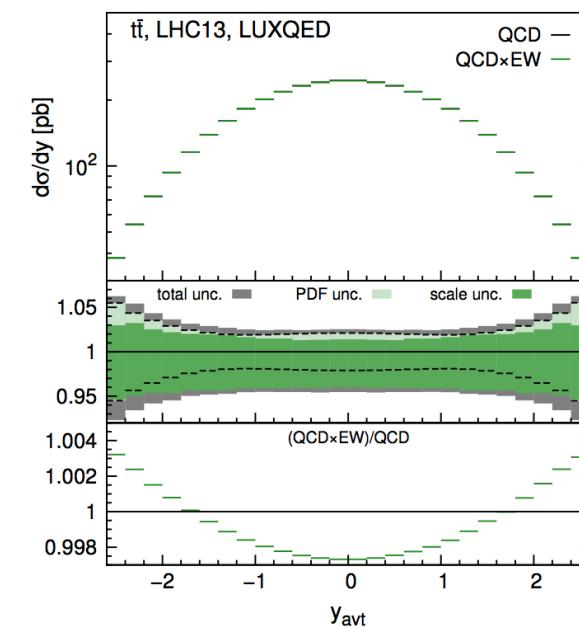
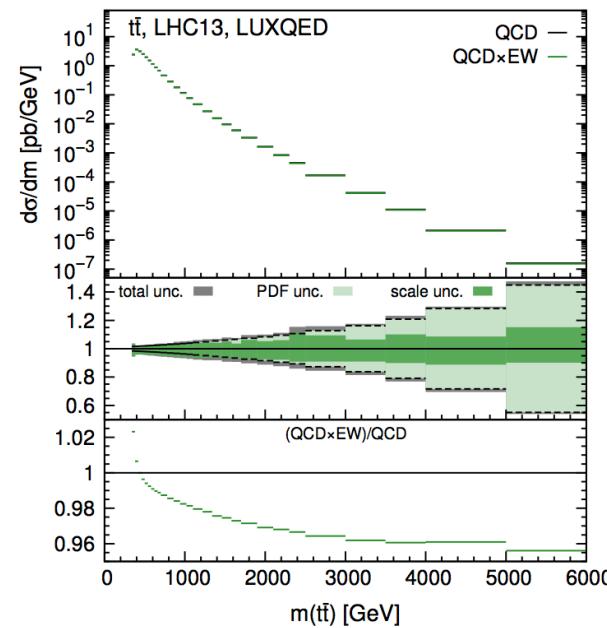
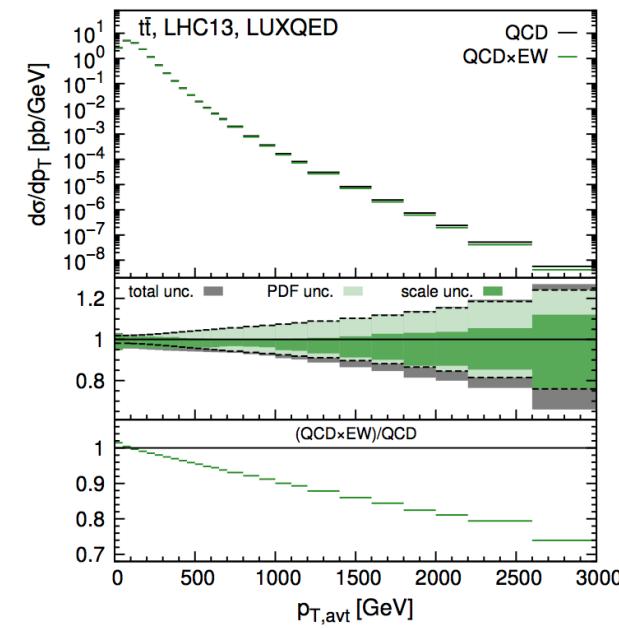
Denner, Pellen '16

- Large Sudakov logarithms

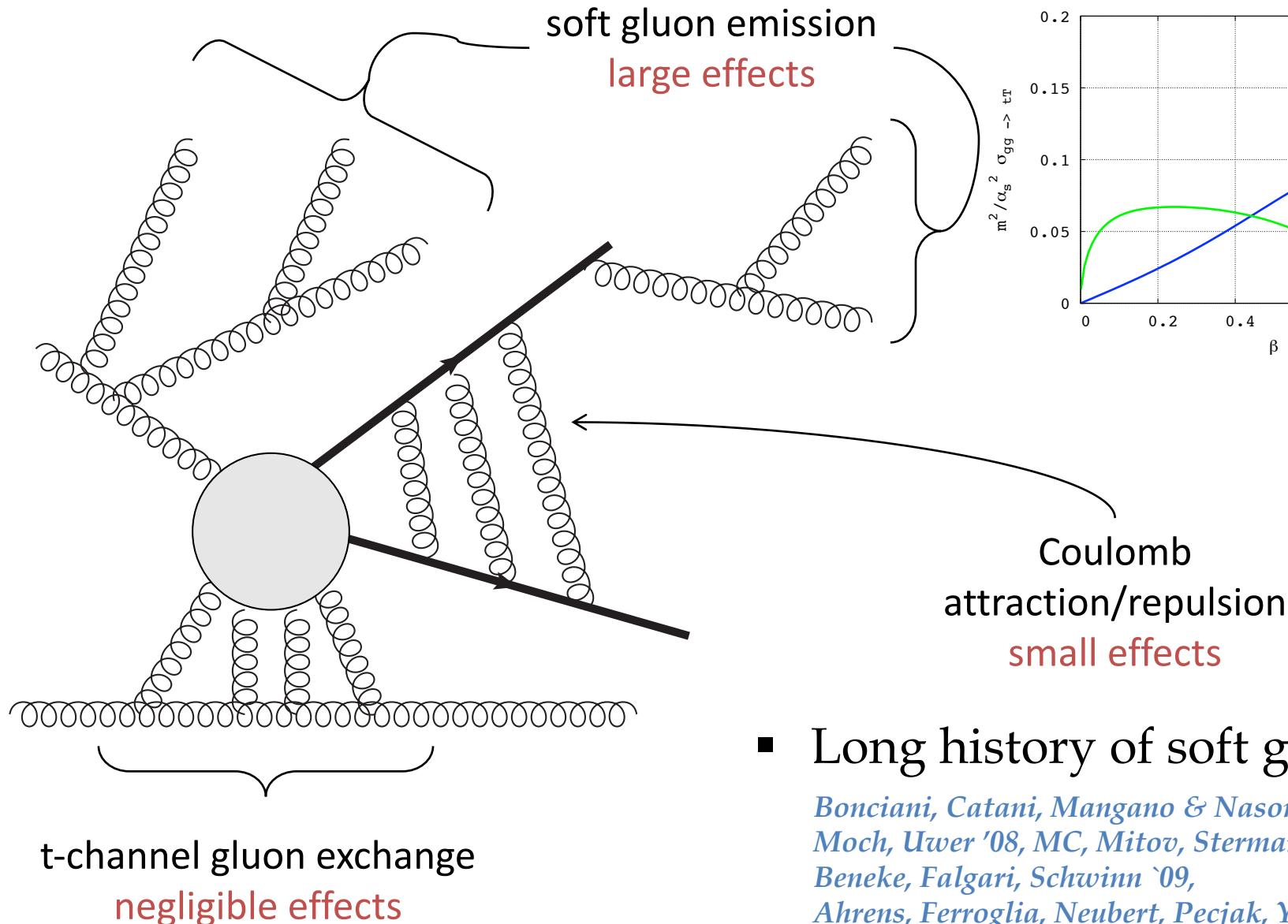


- Combination with NNLO QCD

MC, Heymes, Mitov, Pagani, Tsinikos, Zaro '17



Dominant QCD effects and resummation



- Long history of soft gluon resummation

*Bonciani, Catani, Mangano & Nason '98
Moch, Uwer '08, MC, Mitov, Sterman '09,
Beneke, Falgari, Schwinn '09,
Ahrens, Ferroglia, Neubert, Pecjak, Yang '10*

Effects in the “Tails”

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

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

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

- Widely separated scales

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

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

- Factorization possible

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

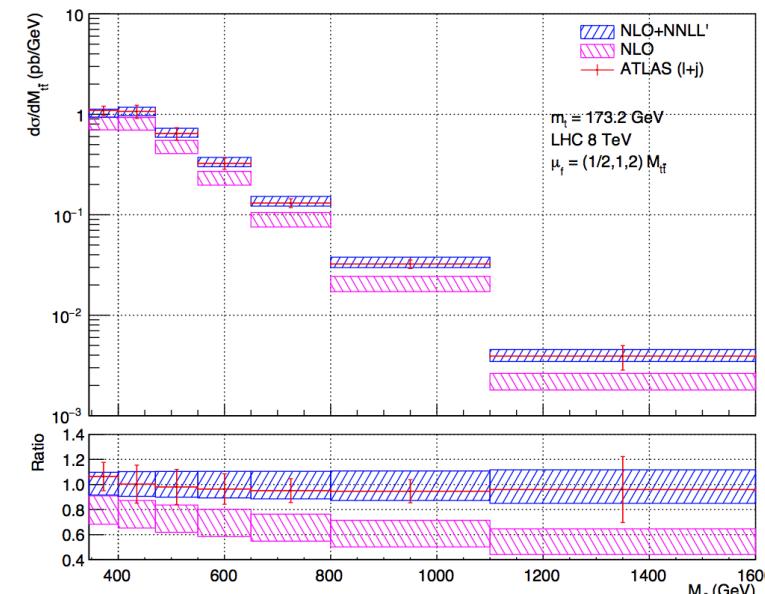
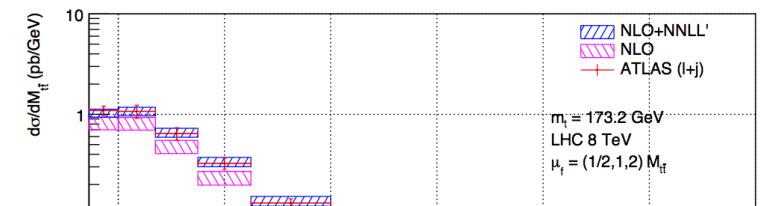
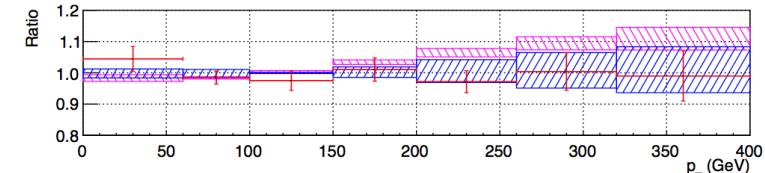
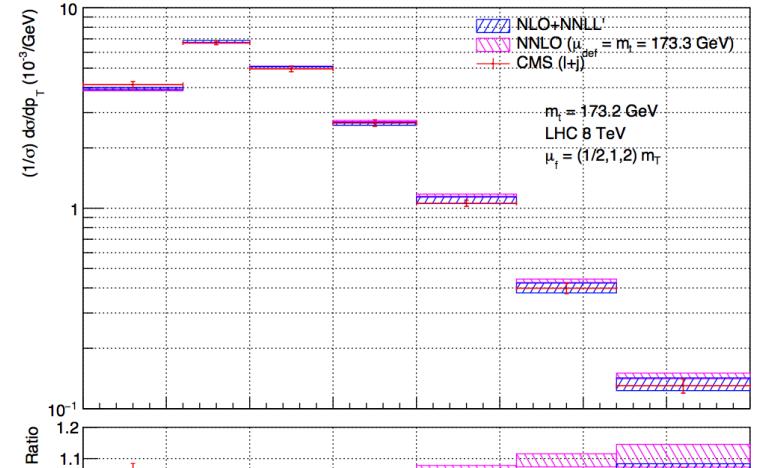
Ferroglia, Pecjak, Scott, Yang '13

- Notice that there are 5 (!) scales now

Results for the LHC

Pecjak, Scott, Wang, Yang '15

- 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 ?
- What's going on with the invariant mass ?
- Matching to NNLO in preparation



Conclusions

Top-Quark Physics

- Booming topic with lots of applications and interest outside the QCD community
- The nearest future must bring high-precision predictions with decaying top-quarks at least in the narrow-width-approximation
- Resummation effects in boosted topologies to be studied in conjunction with fixed order results
- Work on parton shower modelling
- Improvements of PDFs