The Meaning of Precision in Top-Quark Physics

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Outline

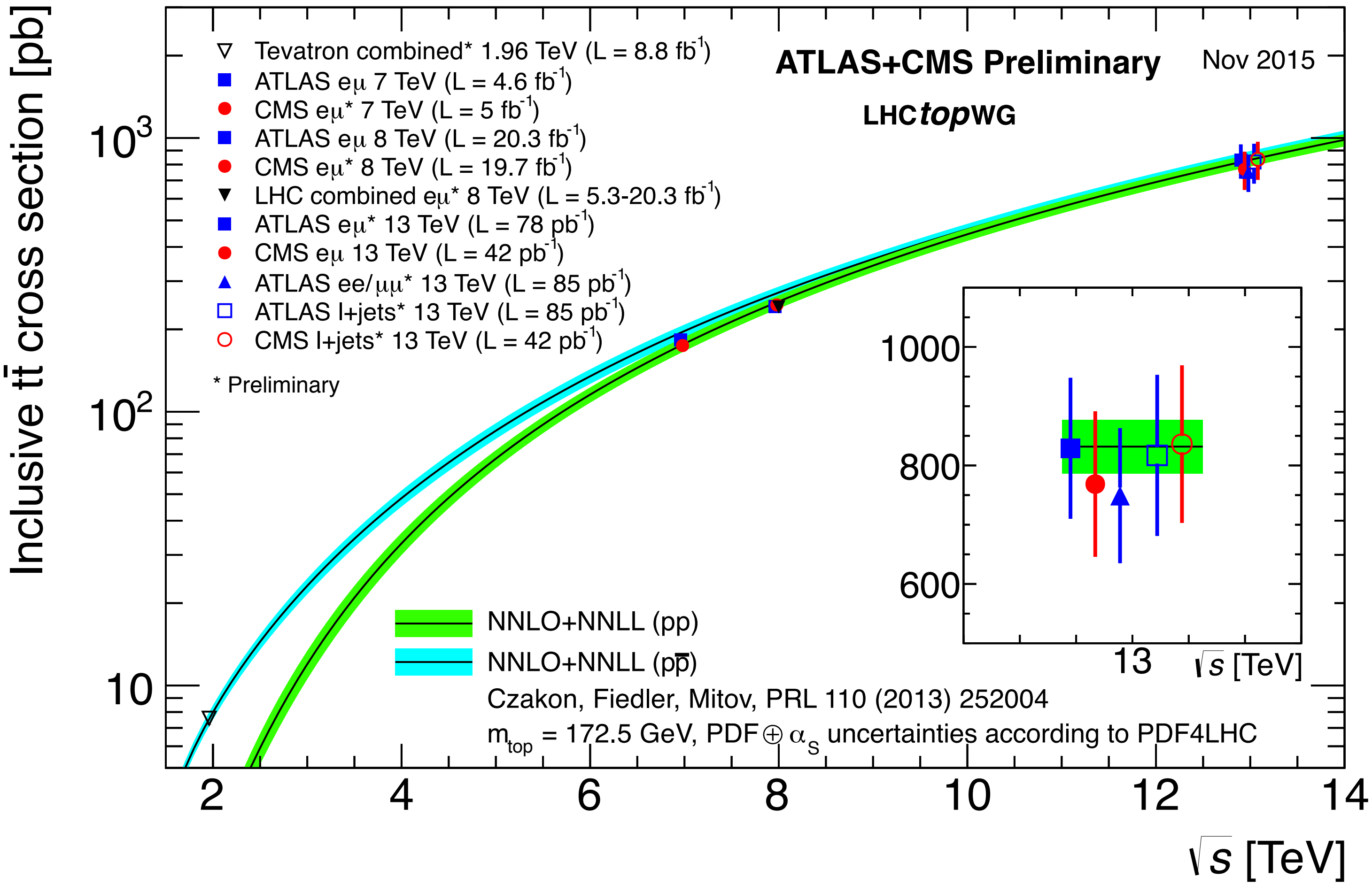
1. Precision and applications
2. Resummation
3. Fixed-order perturbation theory
4. Outlook

Collaborators:

P. Fiedler, D. Heymes, A. Mitov

PRECISION & APPLICATIONS

Total Cross Section



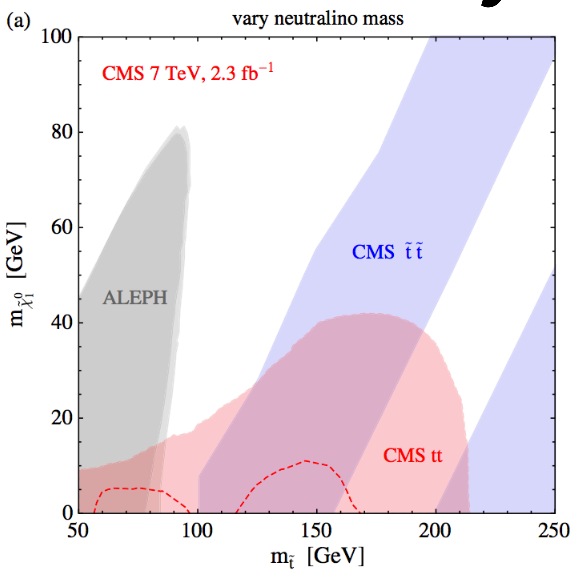
Caveat

- Inclusive cross sections are obtained by extrapolation

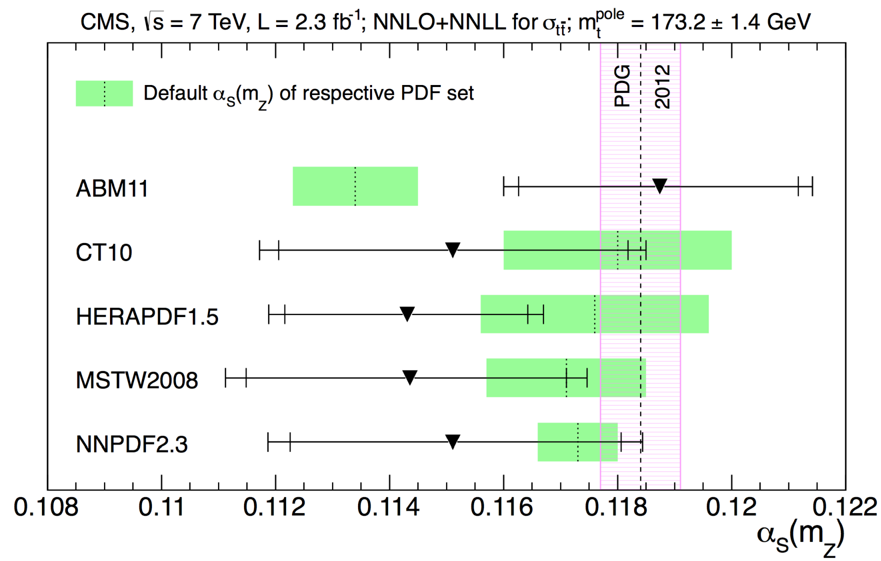
CMS-PAS-TOP-13-004

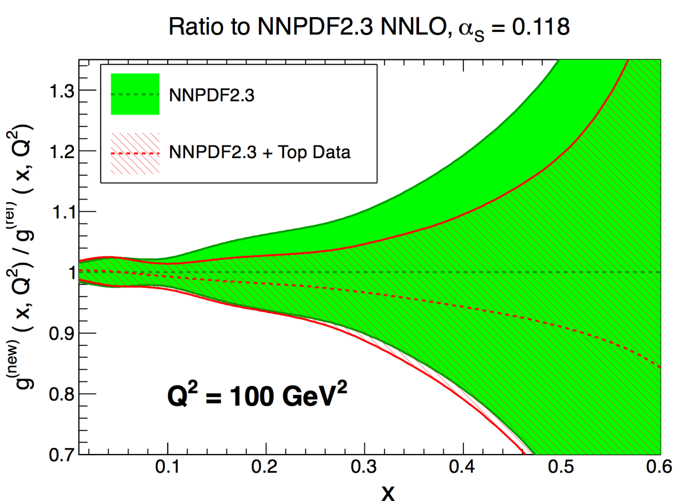
Source	Uncertainty [%]	
	7 TeV	8 TeV
Total (vis)	$\pm^{3.5}_{3.4}$	$\pm^{3.7}_{3.4}$
Q^2 scale (extrapol.)	$\pm^{0.4}_{0.0}$	$\pm^{0.2}_{0.1}$
ME/PS matching (extrapol.)	$\mp^{0.1}_{0.1}$	$\pm^{0.3}_{0.3}$
Top p_T (extrapol.)	$\pm^{0.4}_{0.2}$	$\pm^{0.8}_{0.4}$
PDF (extrapol.)	$\mp^{0.2}_{0.1}$	$\mp^{0.1}_{0.2}$
Total	$\pm^{3.6}_{3.4}$	$\pm^{3.8}_{3.5}$

Early Applications

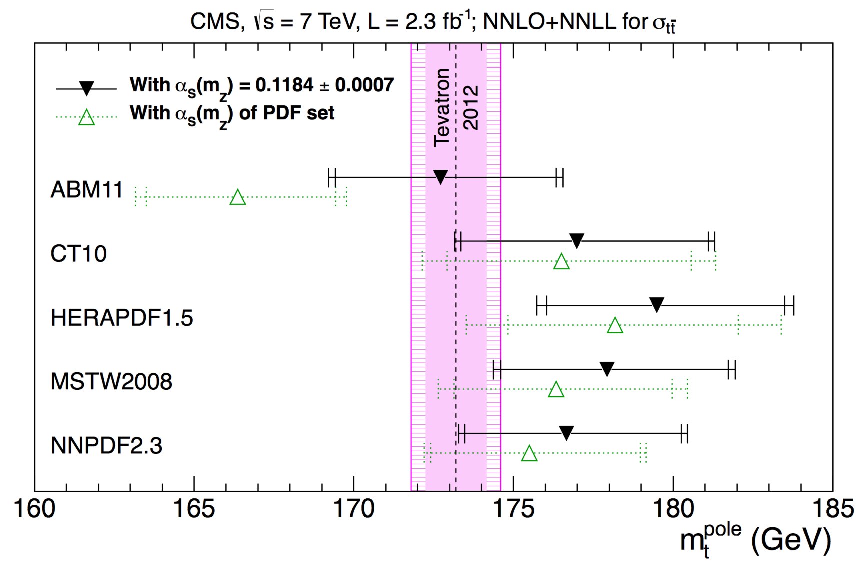


MC, Mitov, Papucci, Ruderman, Weiler, `14





MC, Mangano, Mitov, Rojo `13

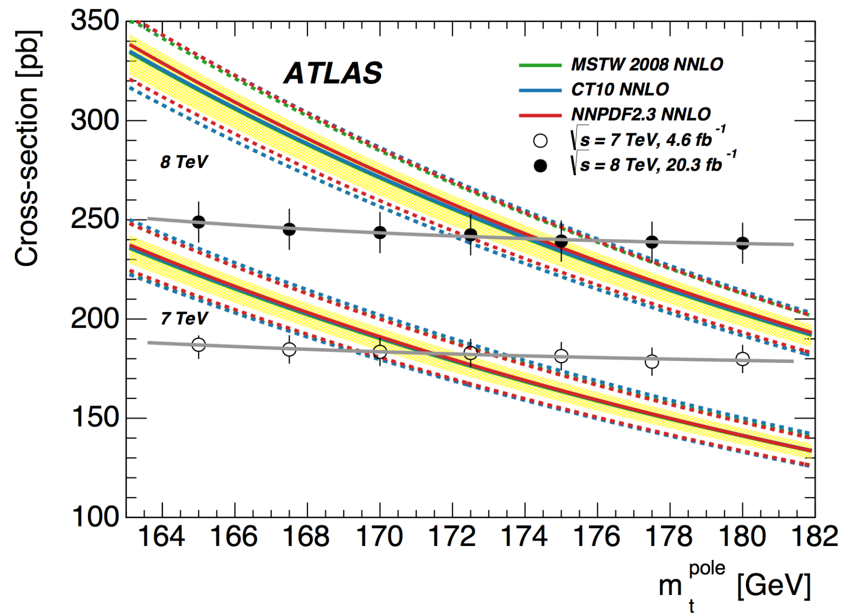


arXiv:1307.1907 (CMS-TOP-12-022)

Top Quark Mass

arXiv:1406.5375

Collected by M. Vos `14



Experiment	pole mass	data	theory	comment
D0 [25]	$169.1^{+5.9}_{-5.2}$ GeV	$p\bar{p}$, 1.96 TeV, 1 fb^{-1}		
Langenfeld	$168.9^{+3.5}_{-3.4}$ GeV	idem	through	
et al. [24]			$\bar{M}S$ mass	
D0 [26]	$167.5\ ^{+5.4}_{-4.9}$ GeV	$p\bar{p}$, 1.96 TeV, 5.3 fb^{-1}	approx NNLO	
CMS [32]	176.7 ± 2.9 GeV	pp, 7 TeV, 5 fb^{-1}	approx NNLO	
ATLAS [28]	$172.9\ ^{+2.5}_{-2.6}$ GeV	pp, 7 TeV, 5 fb^{-1}	NNLO+NNLL	full PDF4LHC [34]
		+ 8 TeV, 20 fb^{-1}		envelope of 3 PDF sets
CMS [29]	$173.6\ ^{+1.7}_{-1.8}$ GeV	idem	idem	NNPDF3.0 [35], preliminary
CMS [29]	$173.9\ ^{+1.8}_{-1.9}$ GeV	idem	idem	MMHT2014, preliminary
CMS [29]	$174.1\ ^{+2.1}_{-2.2}$ GeV	idem	idem	CT14 [36], preliminary
ATLAS [37]	$173.7\ ^{+2.3}_{-2.1}$ GeV	pp, 7 TeV, 5 fb^{-1}	NLO $t\bar{t}$ + 1 jet	full PDF4LHC [34]

Strong Coupling Constant

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**						

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**						

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

α_s from σ(ttbar): preliminary new results

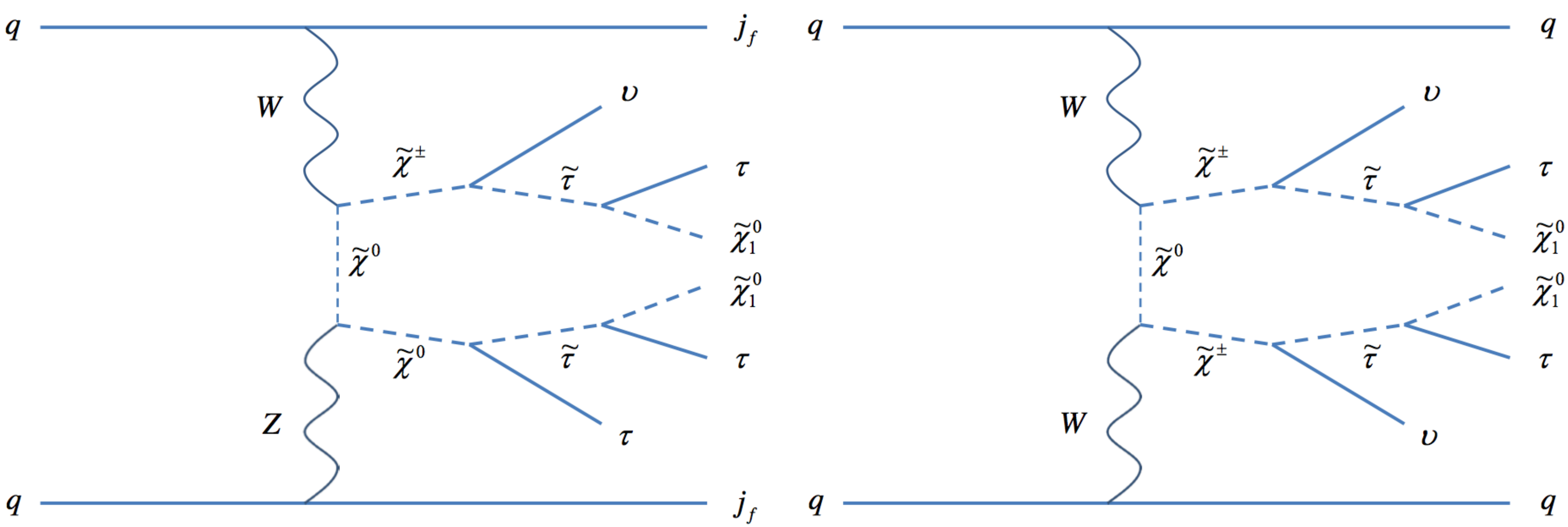
Gavin Salam (CERN), work in progress
with Siggi Bethke, Günther Dissertori and Thomas Klijnsma

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

Search for Supersymmetry

- Search for supersymmetry in the vector-boson fusion topology in proton-proton collisions

LHC @ 8 TeV



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

Search for Supersymmetry

- Search for supersymmetry in the vector-boson fusion topology in proton-proton collisions

LHC @ 8 TeV

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

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2015/09/01

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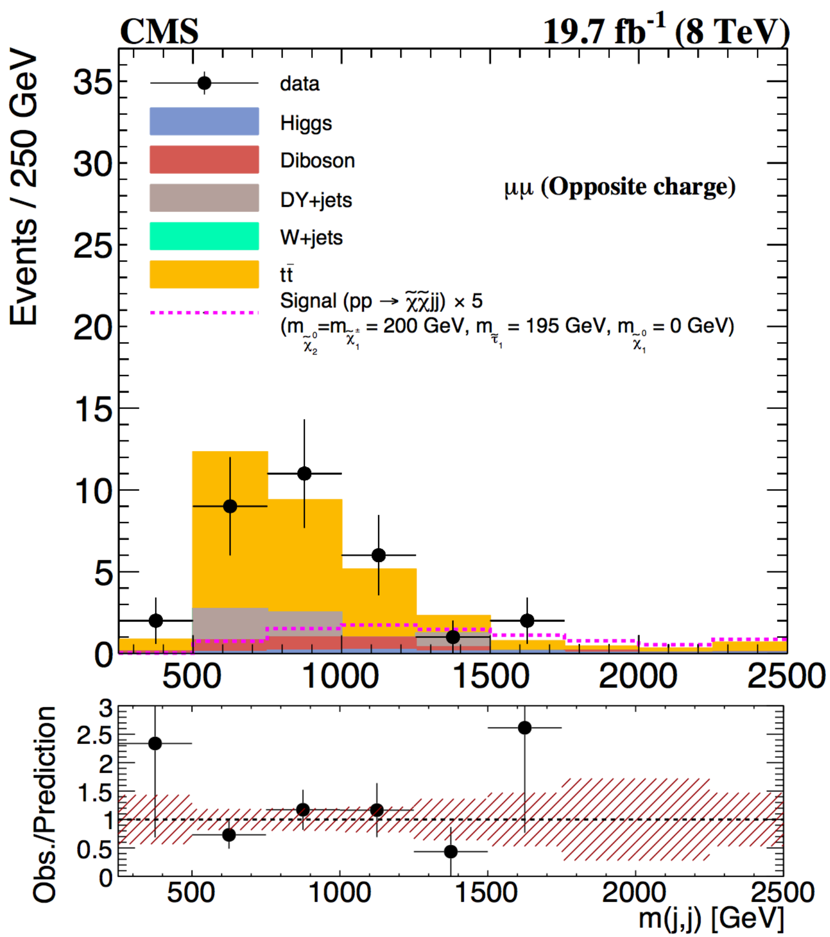
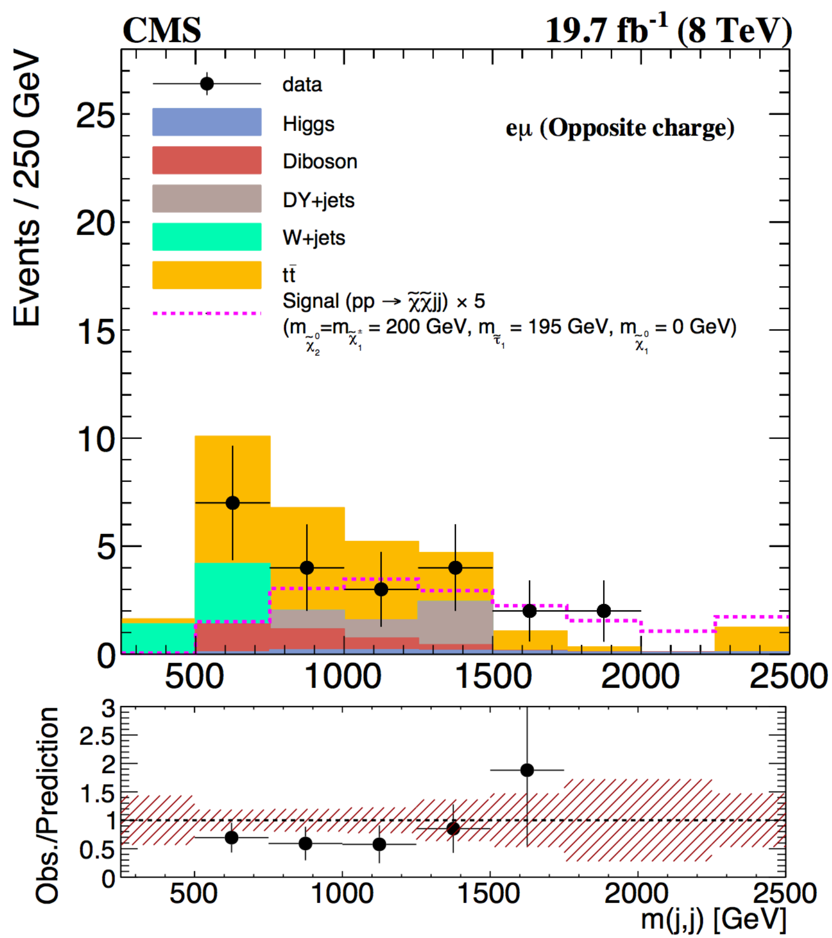
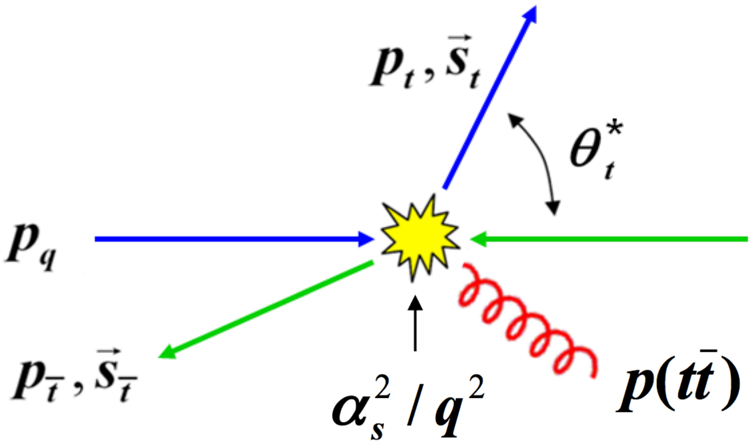




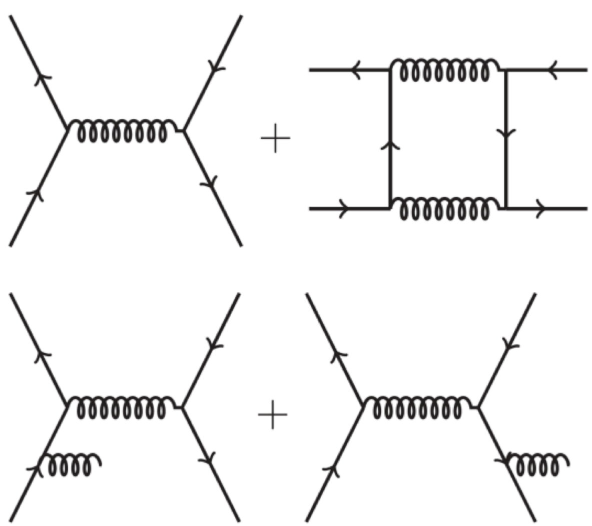
Forward-Backward Asymmetry at the TeVatron



measure in $\Delta y = y_t - y_{\bar{t}}$

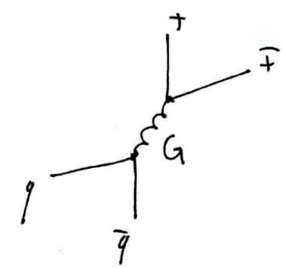
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

SM

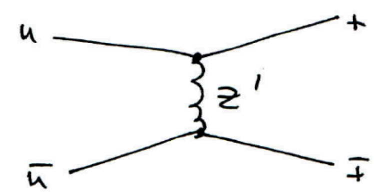


BSM ideas

- s-channel
  - massive chiral color octets
  - RS gluon

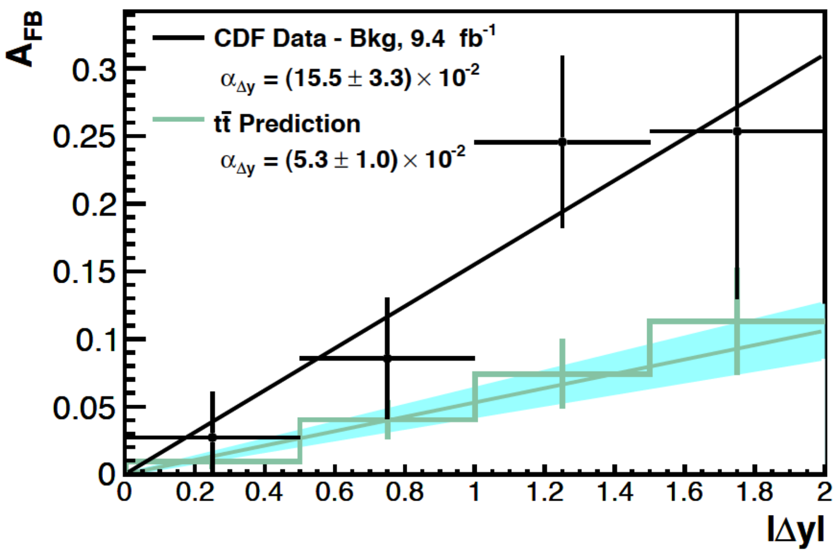


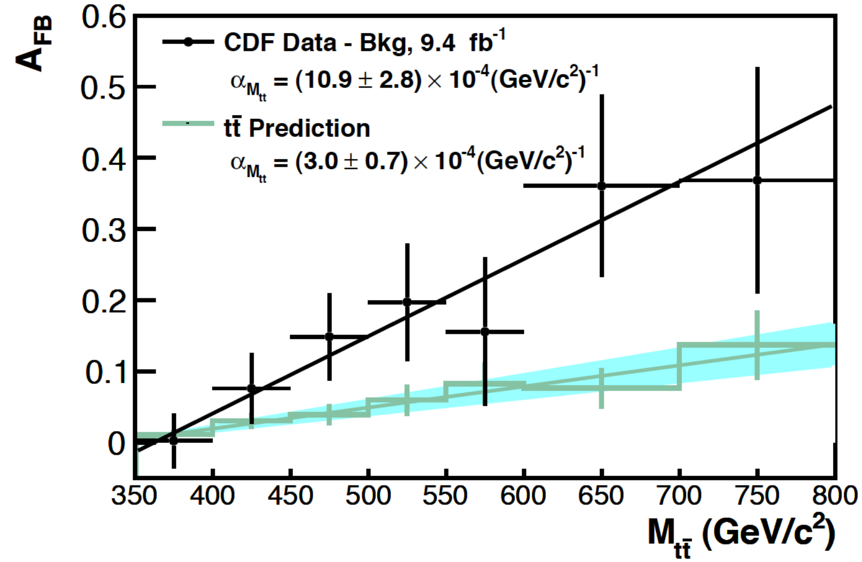
- t-channel
  - W′Z′
  - color triplets, sextets



Forward-Backward Asymmetry at the TeVatron

- … and the CDF measurement versus (previously known) SM



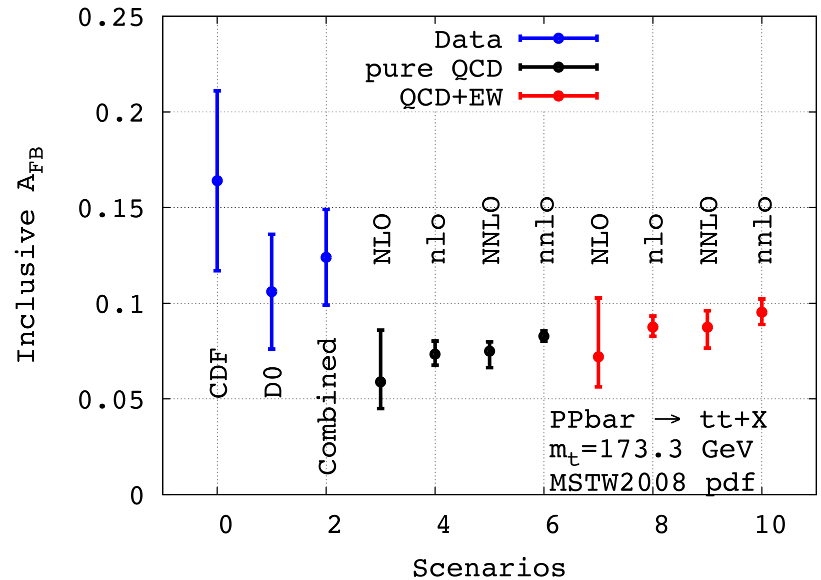


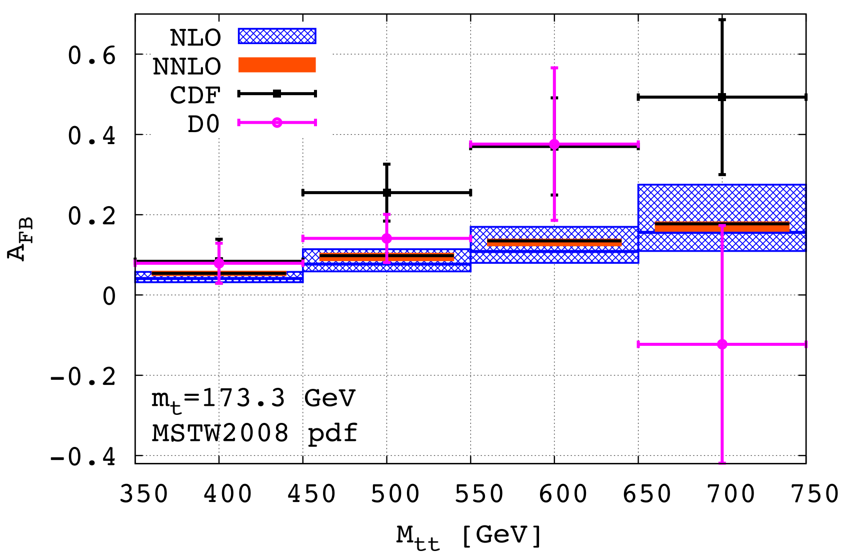
Discrepancy ≤ 3 σ

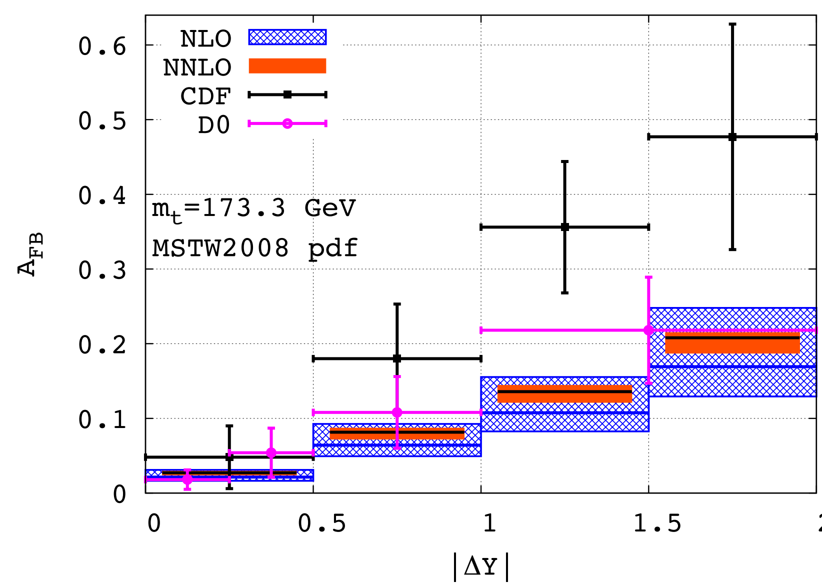
New D0 measurement (2014):
much lower than CDF and in good agreement with SM

Data vs Precision QCD

MC, Fiedler, Mitov `14



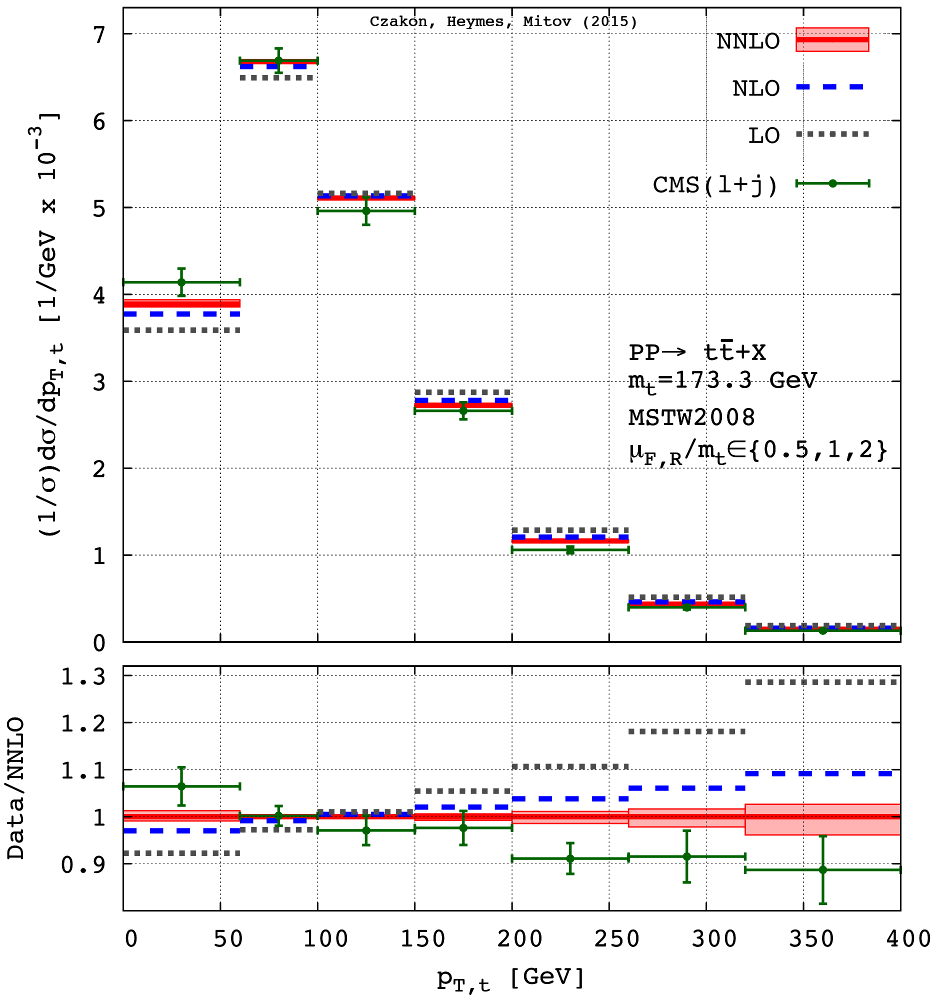




Differential Distributions @ LHC

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

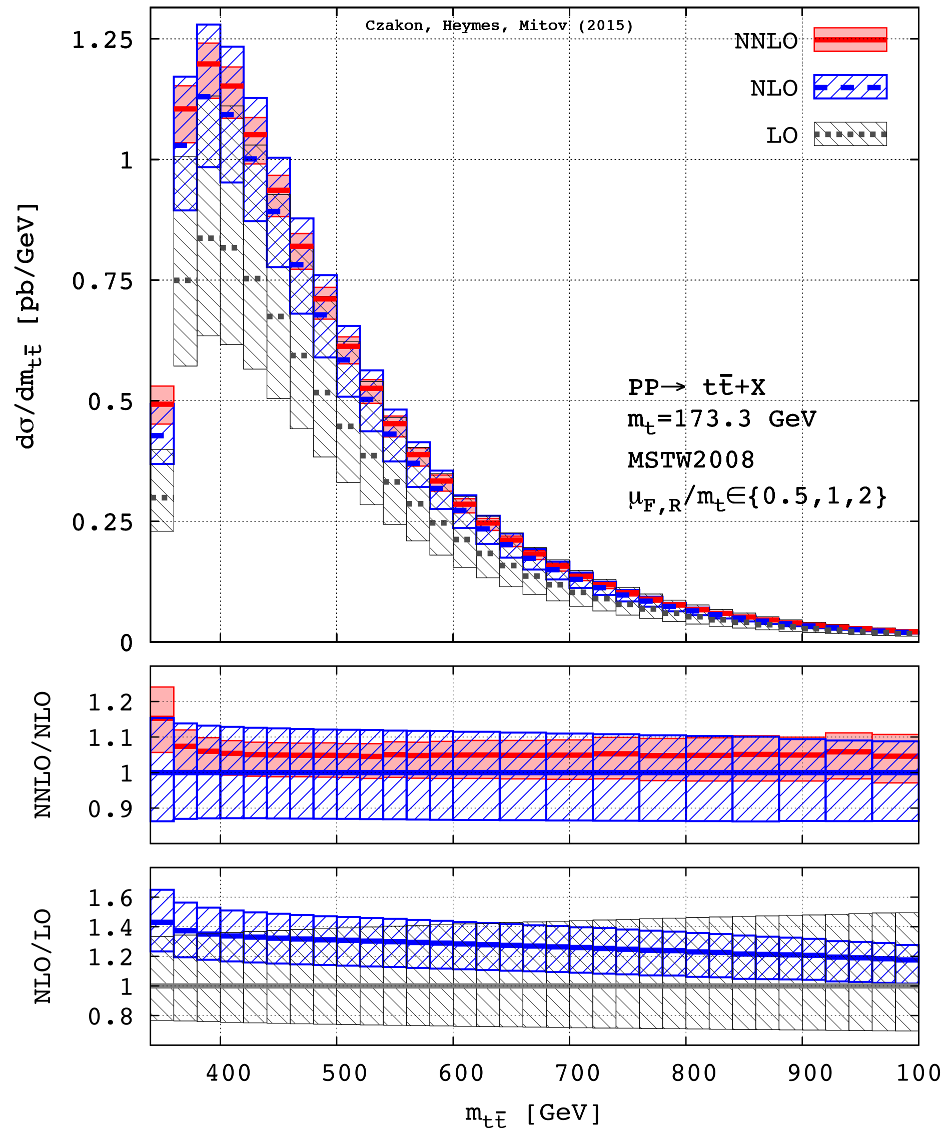
MC, Heymes, Mitov `15



Differential Distributions @ LHC

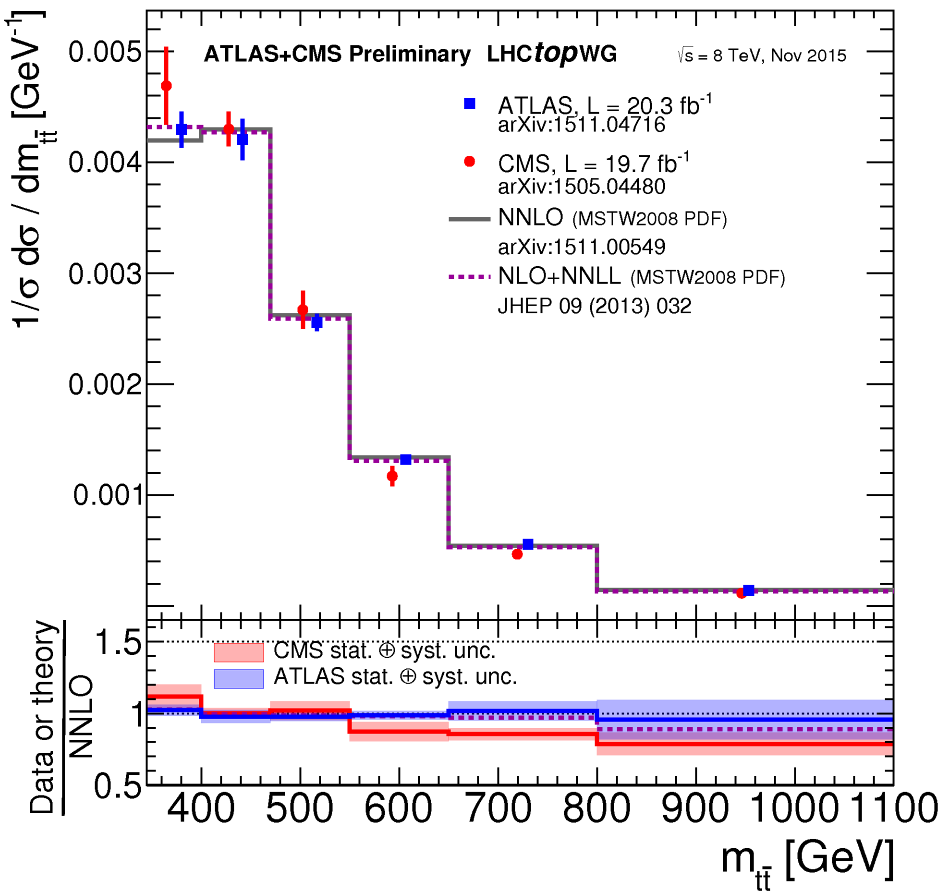
- Much better impression of convergence for absolute distributions
- Stability of invariant mass important for searches
- Limited kinematical range only

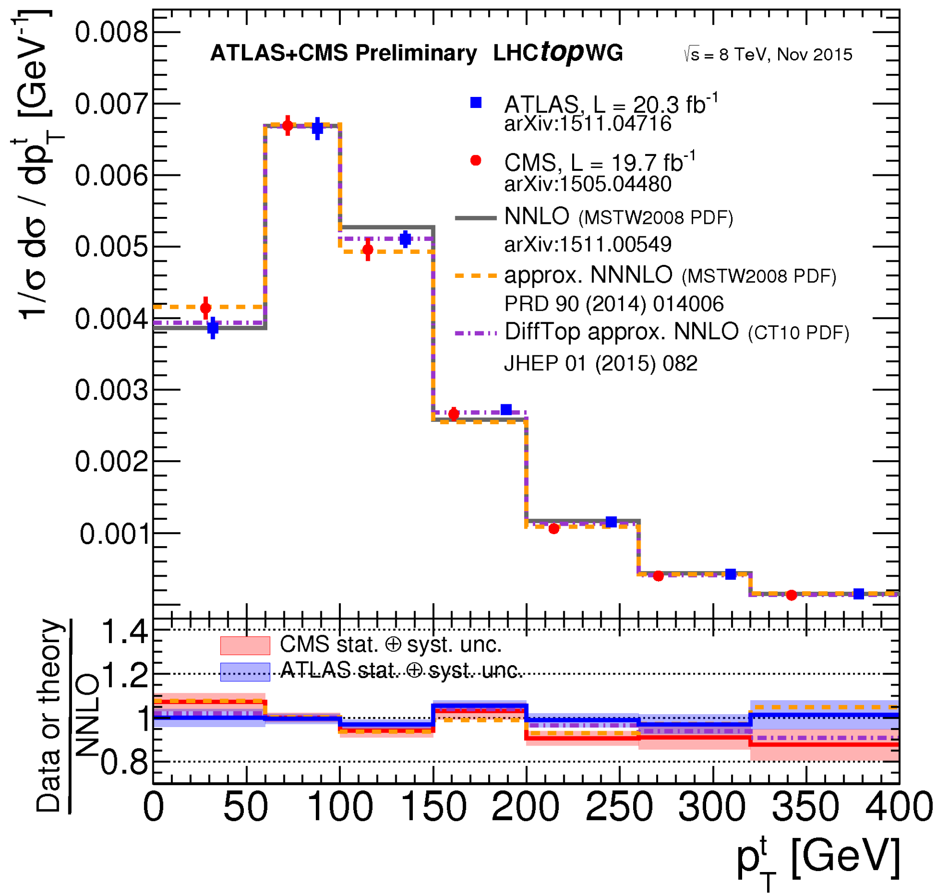
MC, Heymes, Mitov `15



Differential Distributions @ LHC

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





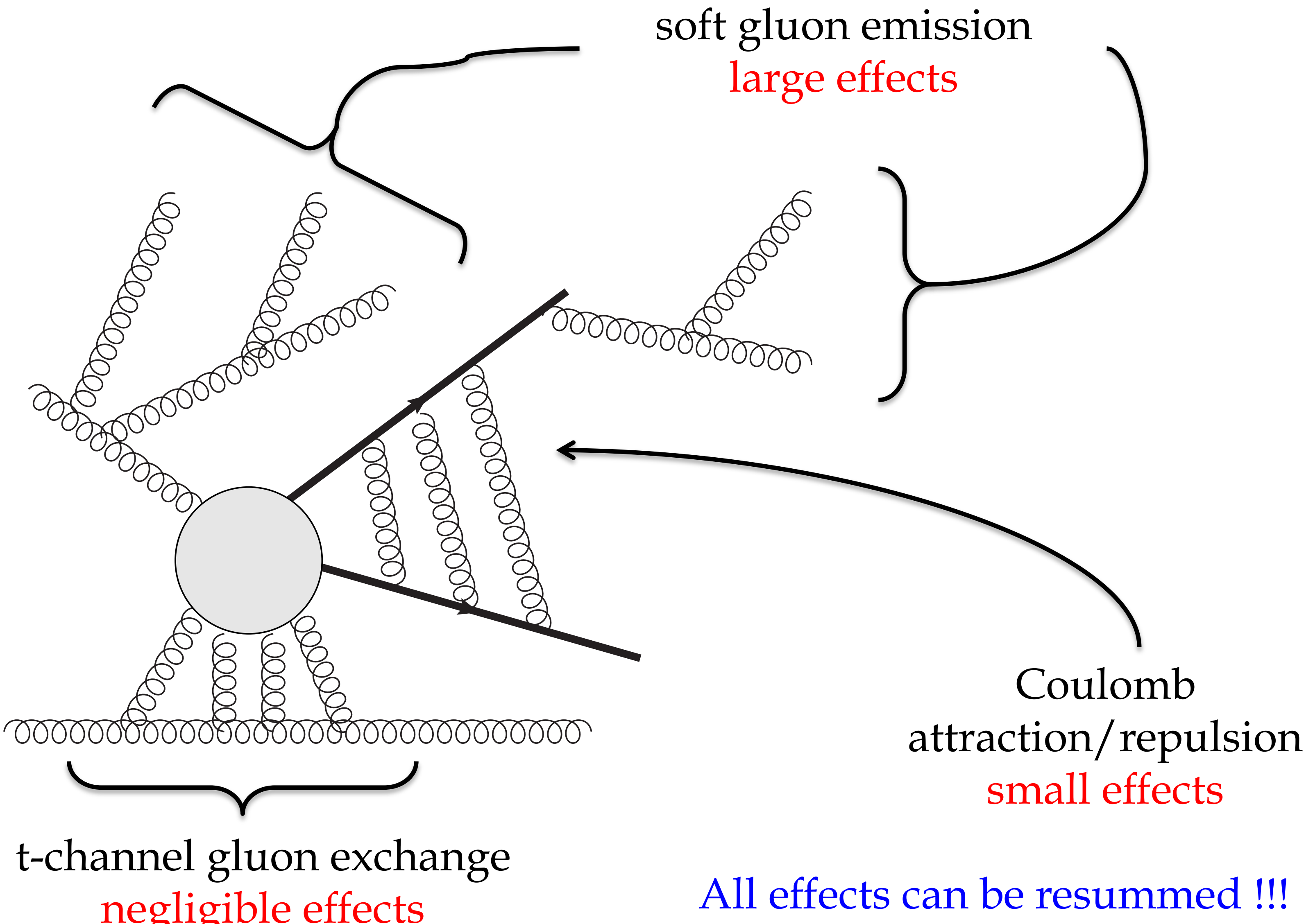
RESUMMATION

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*

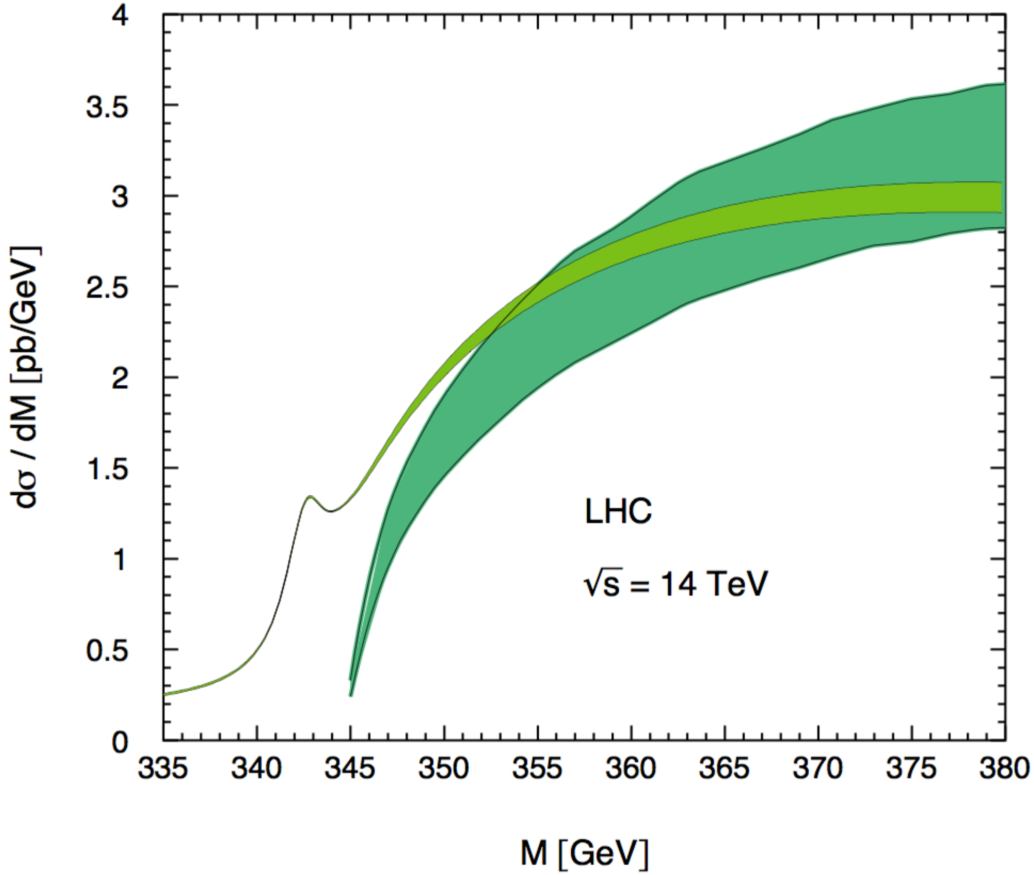
Physical Effects for the "Bulk"



All effects can be resummed !!!

Physical Effects for the "Bulk"

- NLO vs NLO+NLL+Coulomb



Kiyo et al. `08

- NNLO+NNLL for total cross section derived in *Beneke, Falgari, Schwinn `11*

Physical 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

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

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

- 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

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

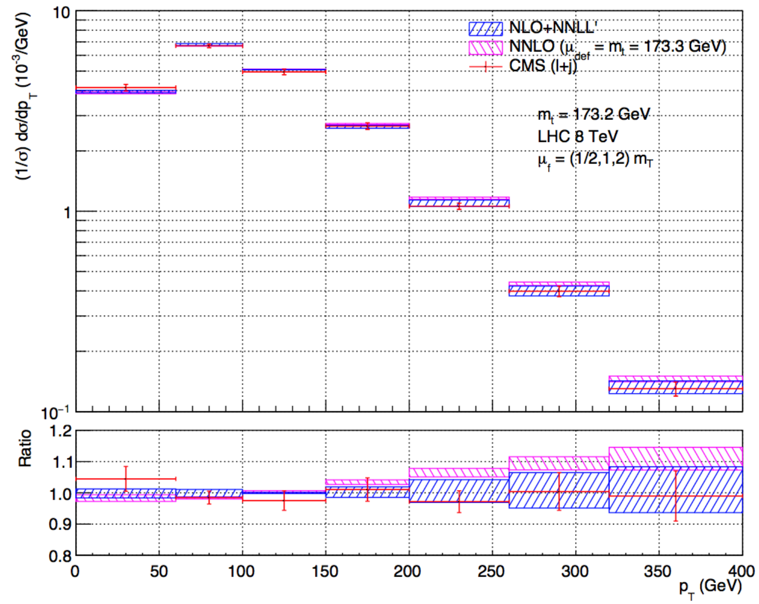
Ferroglia, Pecjak, Scott, Yang `13

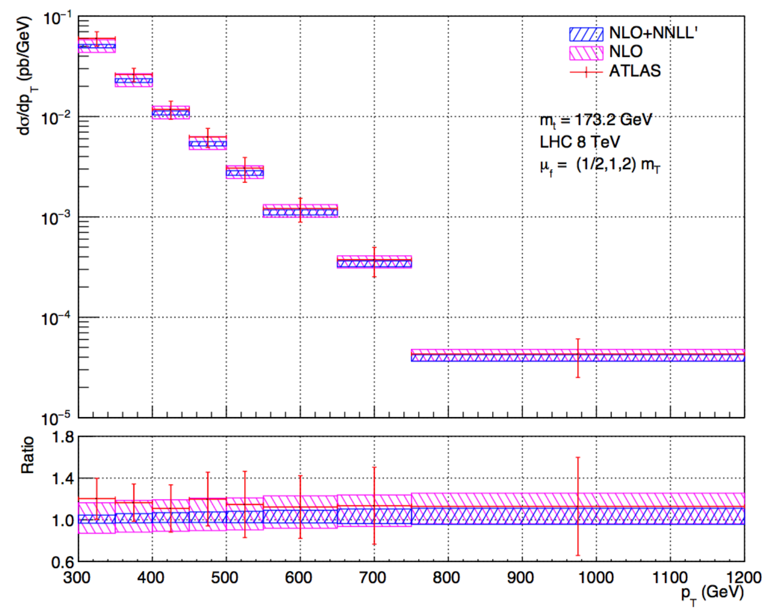
- Notice that there are 5 (!) scales now

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

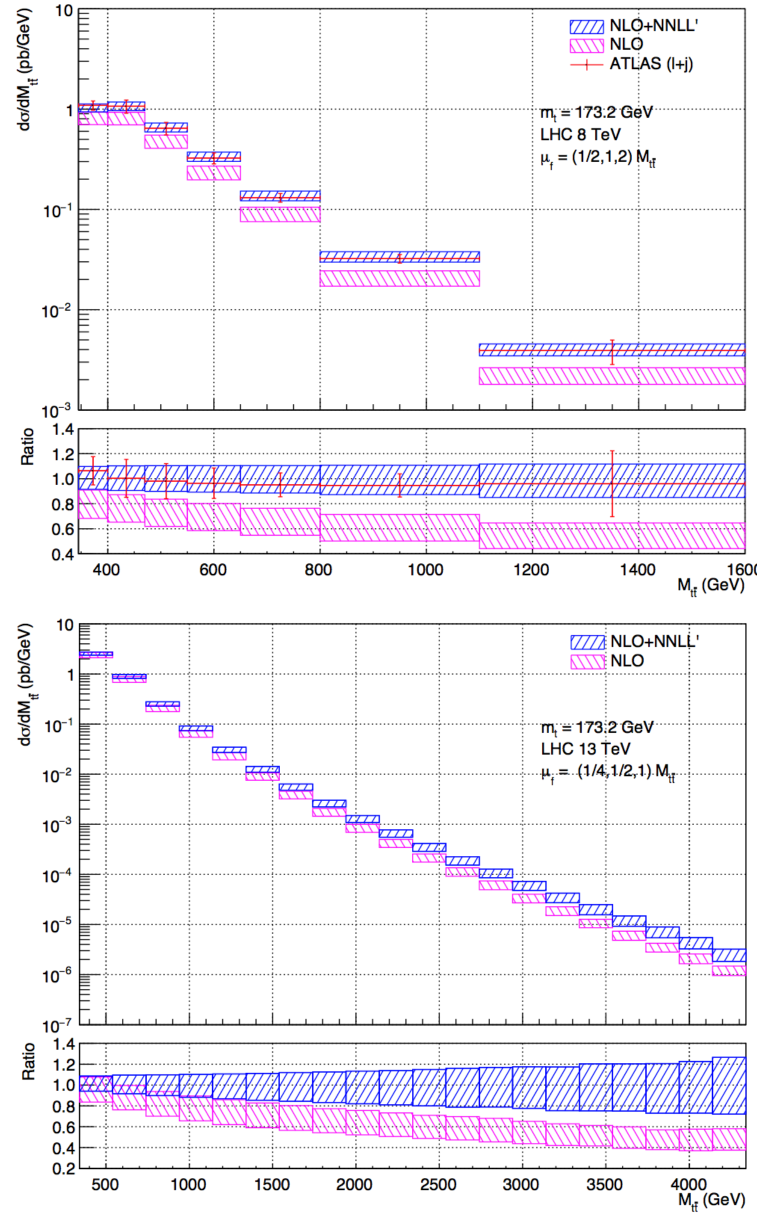




Results for the LHC

- 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



FIXED-ORDER PERTURBATION THEORY

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 next-to-next-to-leading order for on-shell production

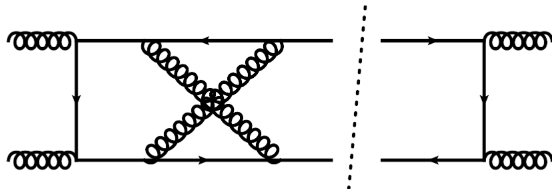
MC, Bärnreuther, Fiedler, Heymes, Mitov `12 - `15

  - Partial independent results by:

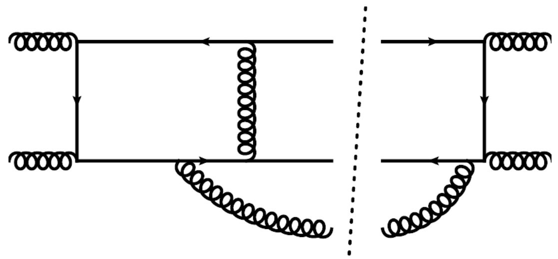
Abelof, Gehrmann-De Ridder, Maierhofer, Pozzorini `14
Catani, Grazzini, Torre `14 - `15

Contributions

- 2-loop virtual corrections (V-V)
  MC `07, Bärnreuther, MC, Fiedler `13
  complete numerical results partial analytical results:
  Bonciani, Ferroglia, Gehrmann, Maitre, von Manteuffel, Studerus `08–`13
  divergences of two-loop amplitudes:
  Ferroglia, Neubert, Pecjak, Yang `09

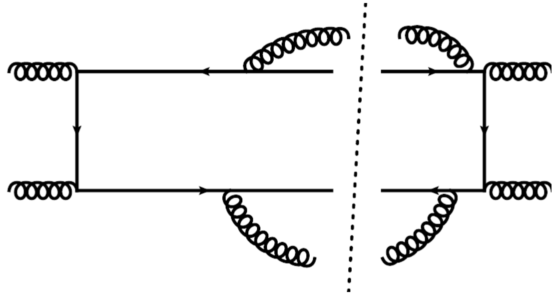


- 1-loop virtual with one extra parton (R-V)
  from next-to-leading order corrections to tt+jet
  code by Stefan Dittmaier

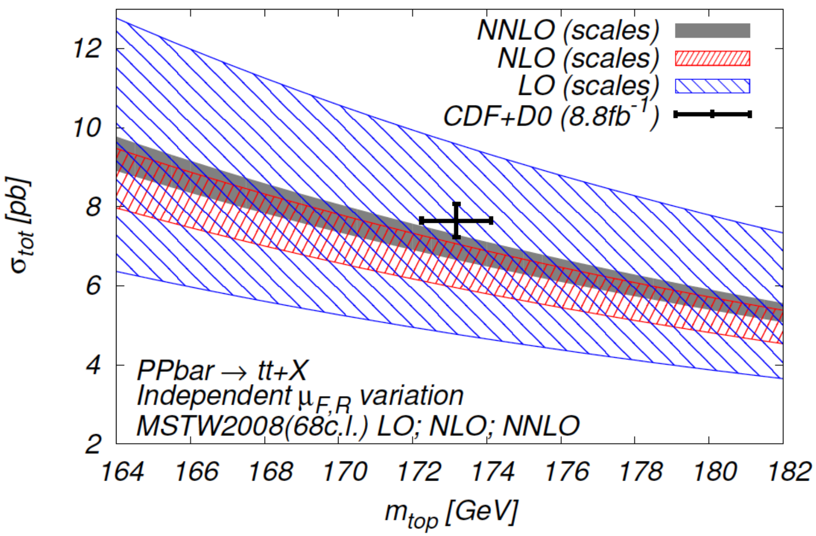


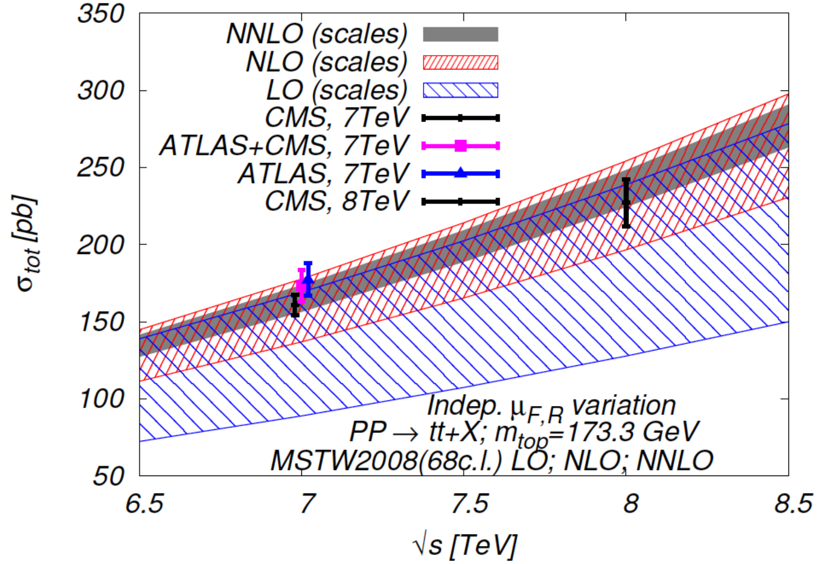
- 2 extra emitted partons at tree level (R-R)
  MC `10 `11 ***new subtraction scheme STRIPPER***
  MC, Heymes `14 ***4-d formulation of STRIPPER***

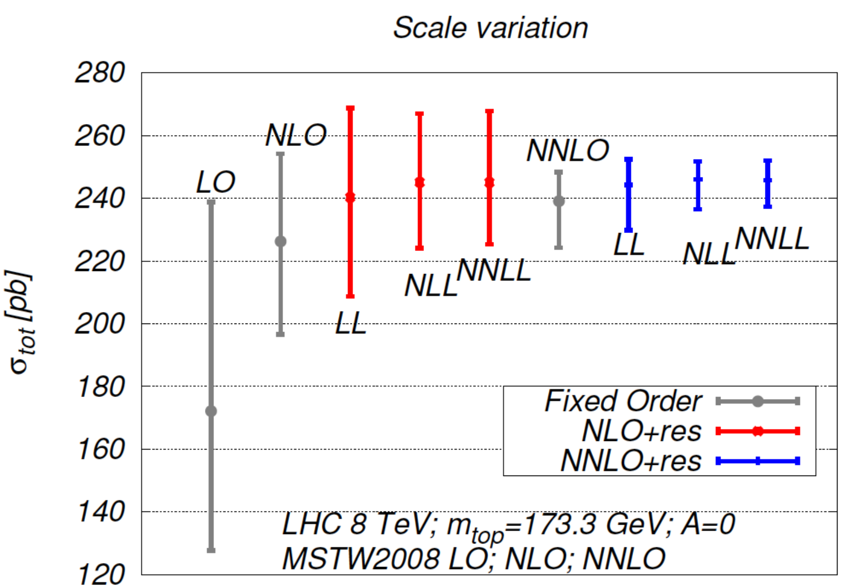
- One-loop squared amplitudes
  original results not used:
  Körner, Merebashvili, Rogal `07, Anastasiou, Aybat `08



Perturbation Theory Convergence







Concurrent uncertainties:

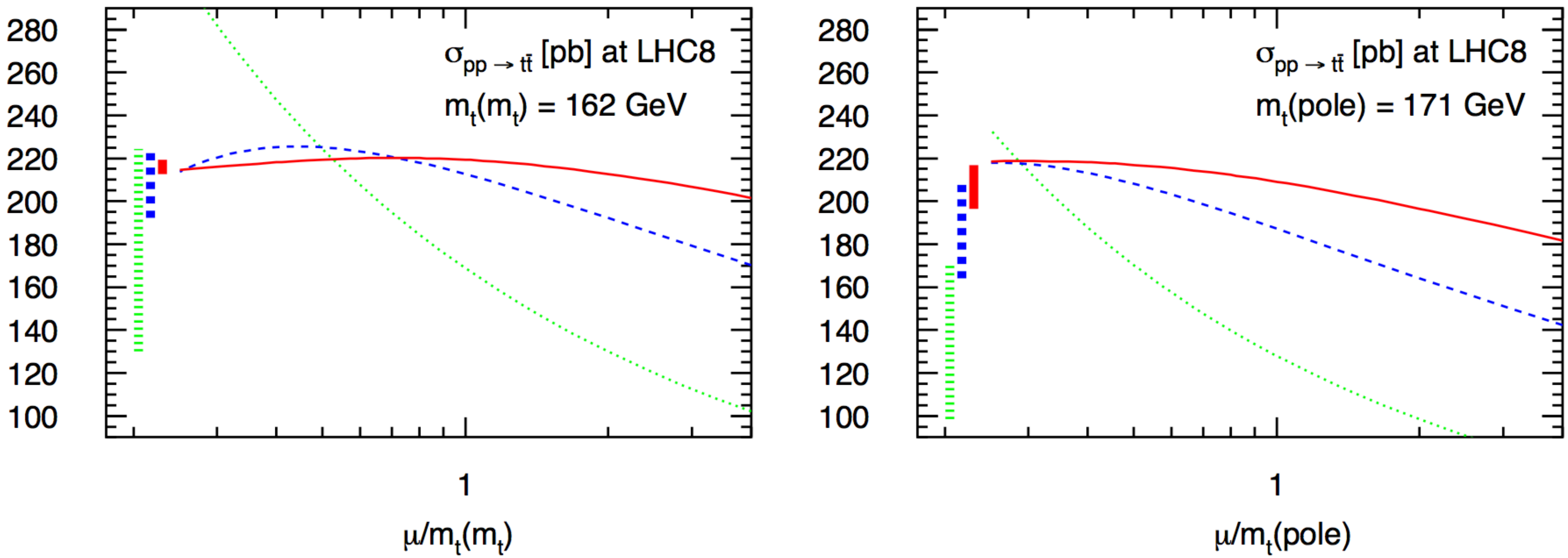
Scales	**~ 3%**
pdf (at 68%cl)	**~ 2-3%**
α_S (parametric)	**~ 1.5%**
m_{top} (parametric)	**~ 3%**

Soft gluon resummation makes a difference: **5% → 3%**

MC, Fiedler, Mitov `13

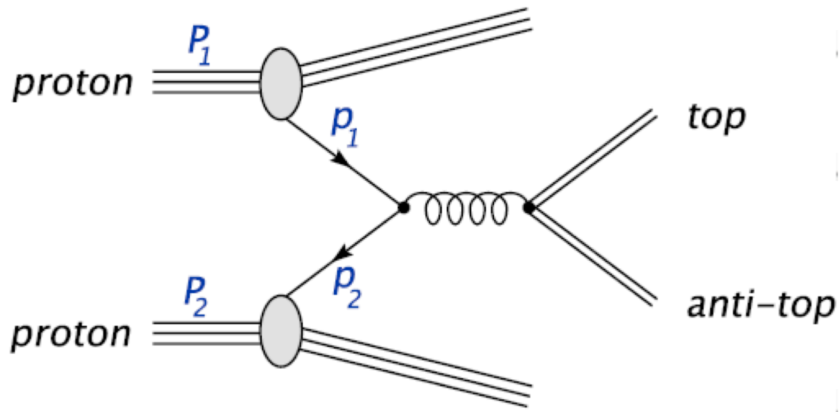
Perturbation Theory Convergence

- 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

Searching for the Right Scale



- Cross section from factorization

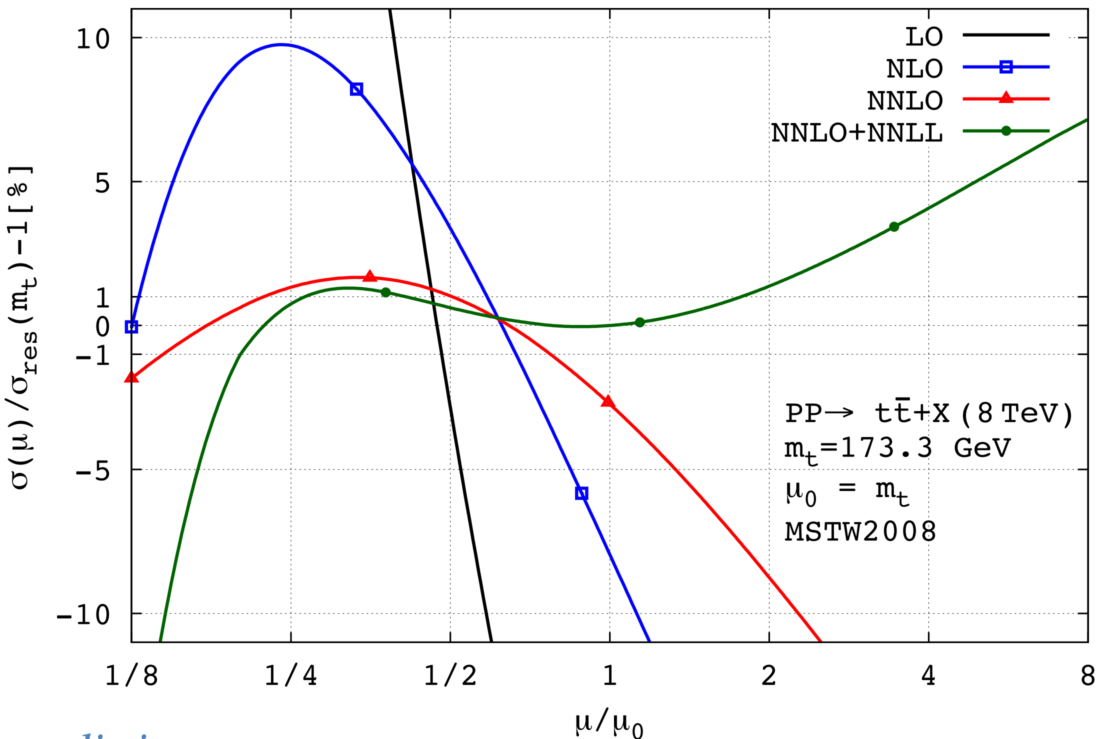
$$\sigma_{h_1h_2}(s,m_t)=\sum_{ij}\int dx_1dx_2\phi_{i/h_1}(x_1,\mu_F)\phi_{j/h_2}(x_2,\mu_F)\hat{\sigma}_{ij}(x_1x_2s,m_t,\alpha_s(\mu_R),\mu_R,\ \mu_F)$$

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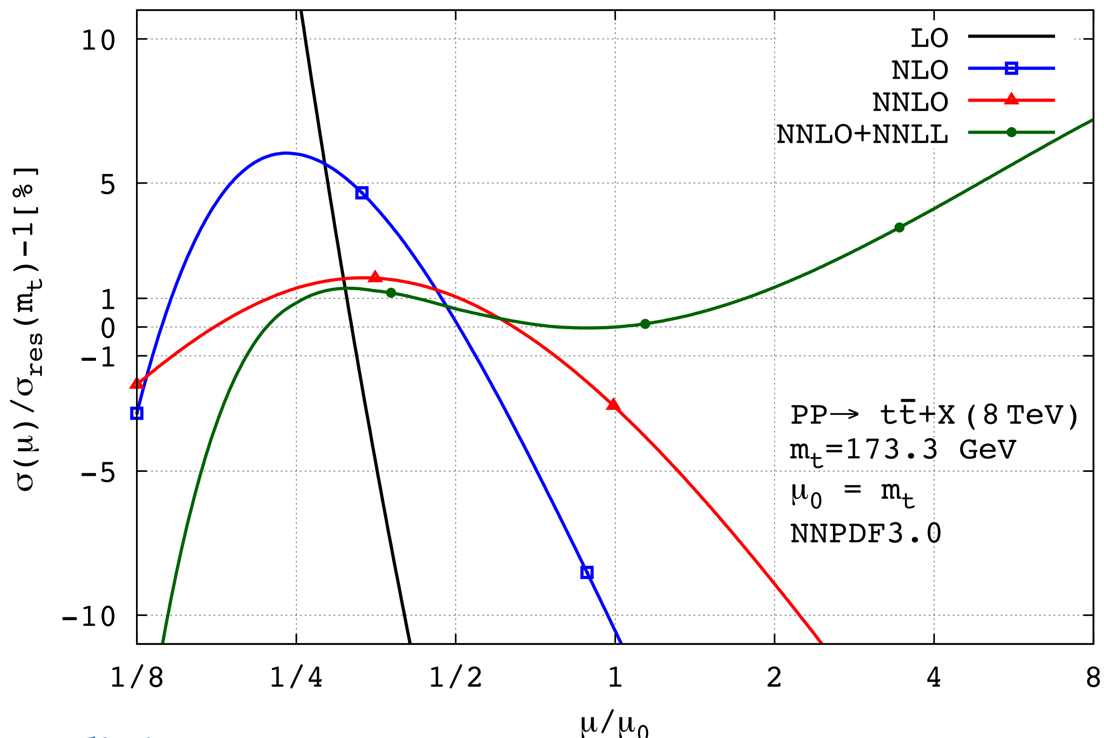


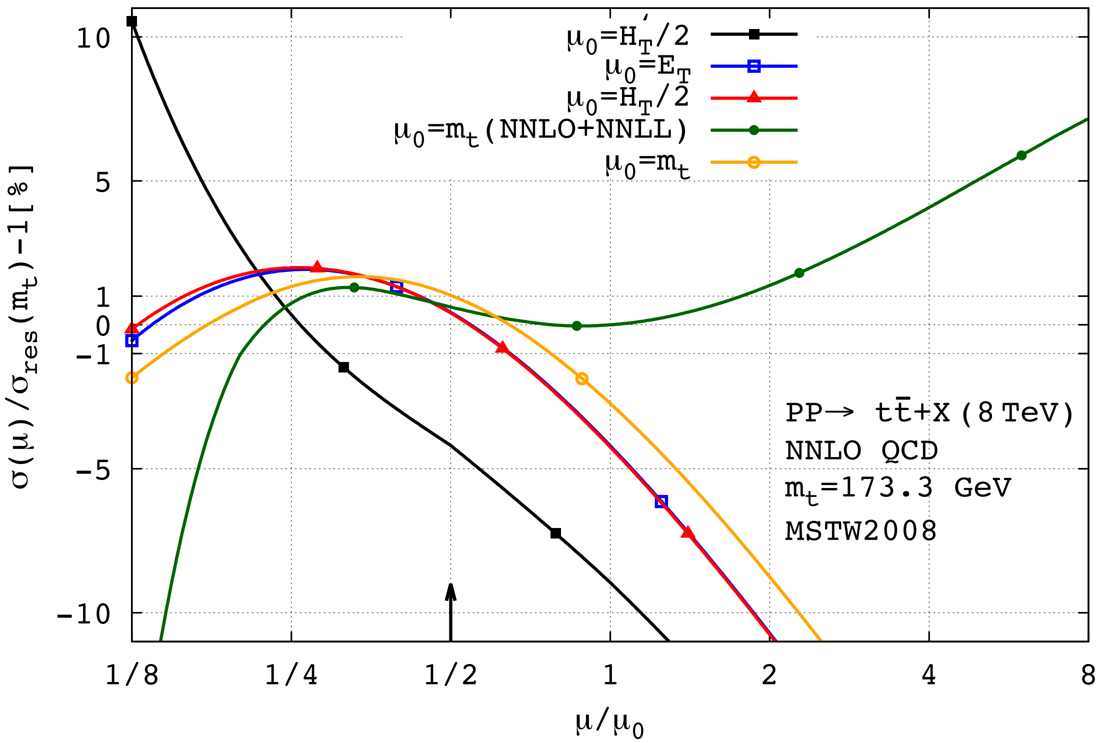
MC, Heymes, Mitov, preliminary

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

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

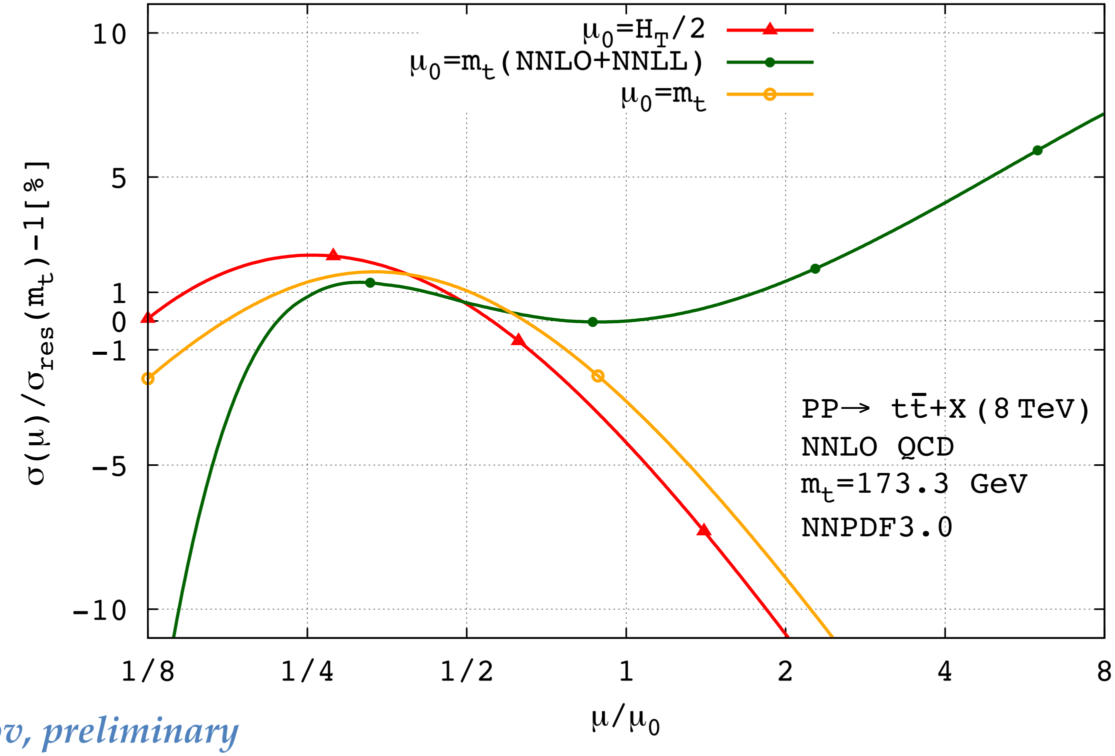


MC, Heymes, Mitov, preliminary

Searching for the right scale

- 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

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

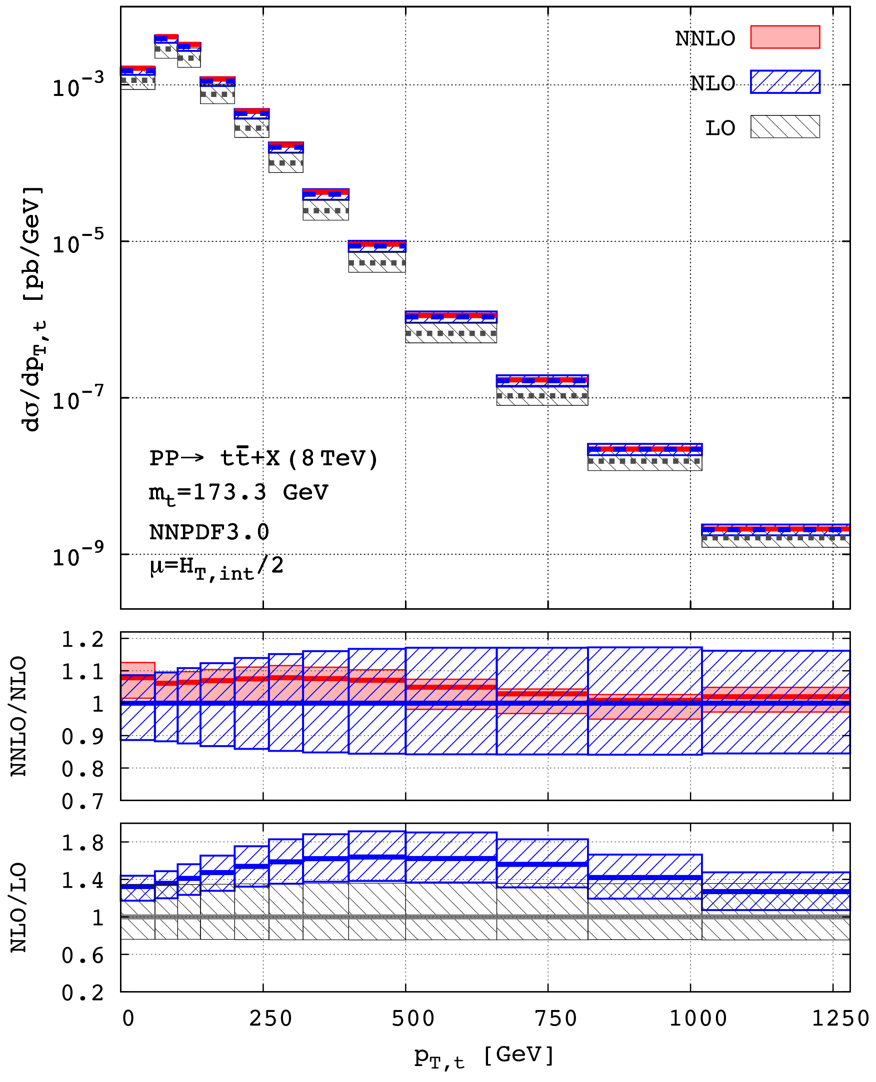
Differential Distributions

- 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

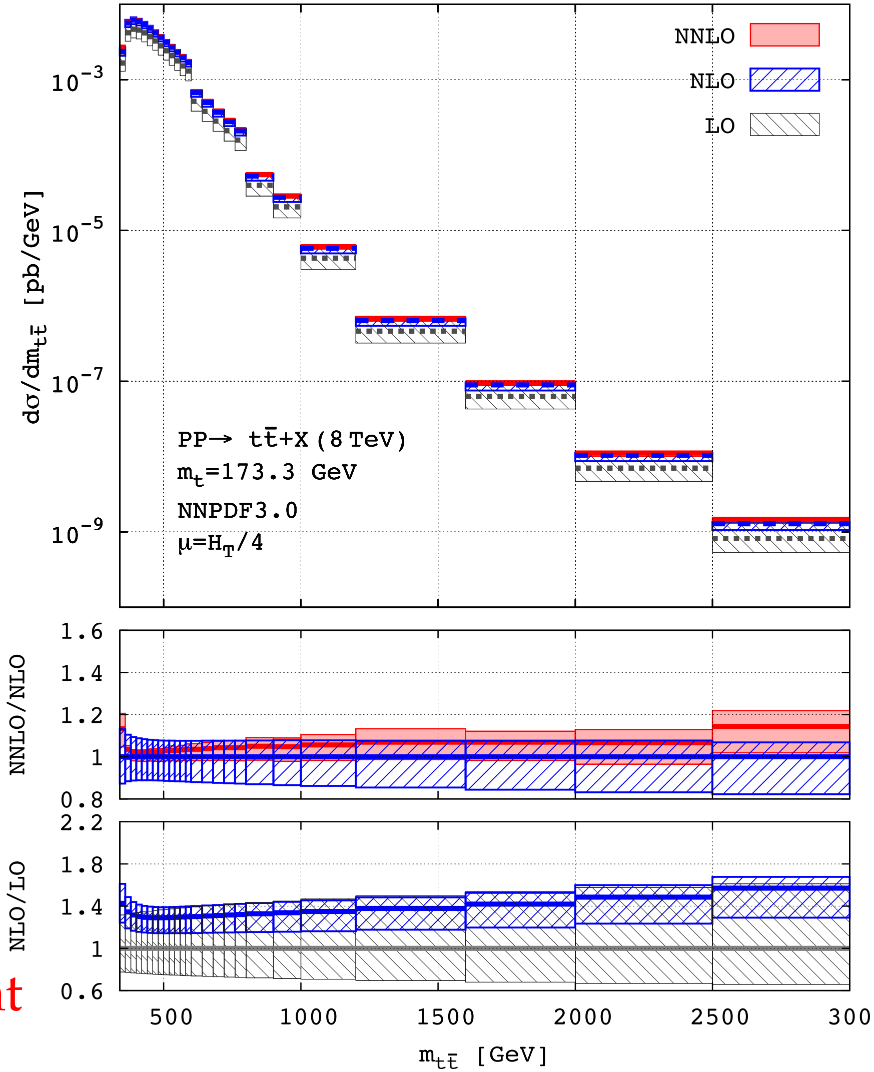
- Single-differential distributions introduce an additional scale, e.g. p_{Tt} or m_{tt}

- A different interpolation is better for m_{tt}

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

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

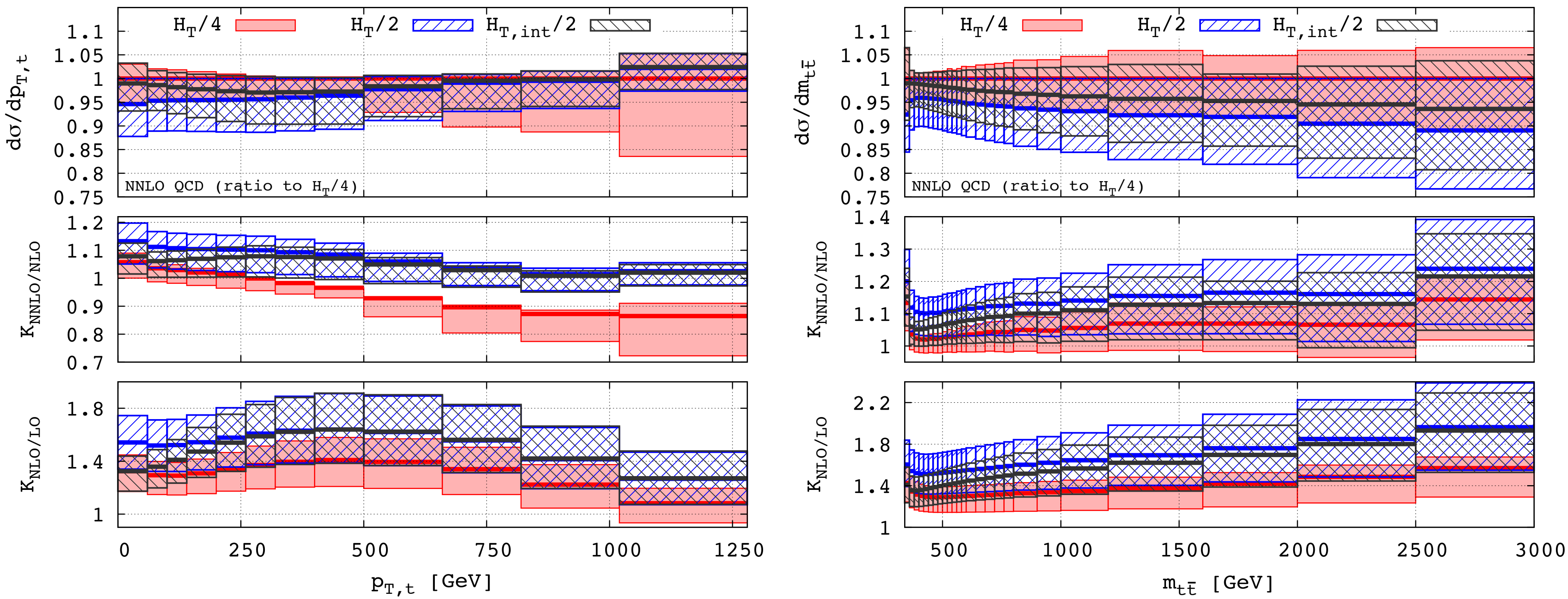
- Introducing different scales for different observables is typical of resummation, but not usual in Monte Carlo studies



MC, Heymes, Mitov, preliminary

Differential Distributions

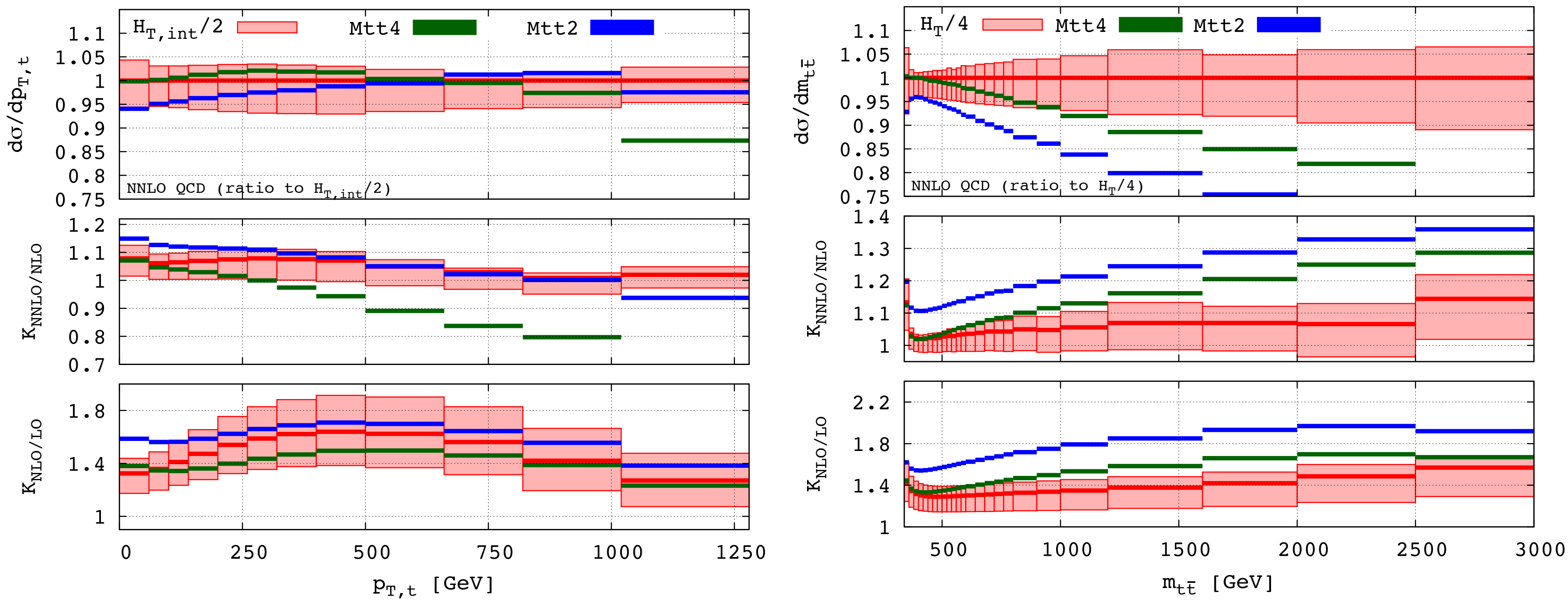
- The issue is not that relevant once at NNLO
- It seems that the effect is largest on the scale dependence



MC, Heymes, Mitov, preliminary

Differential Distributions

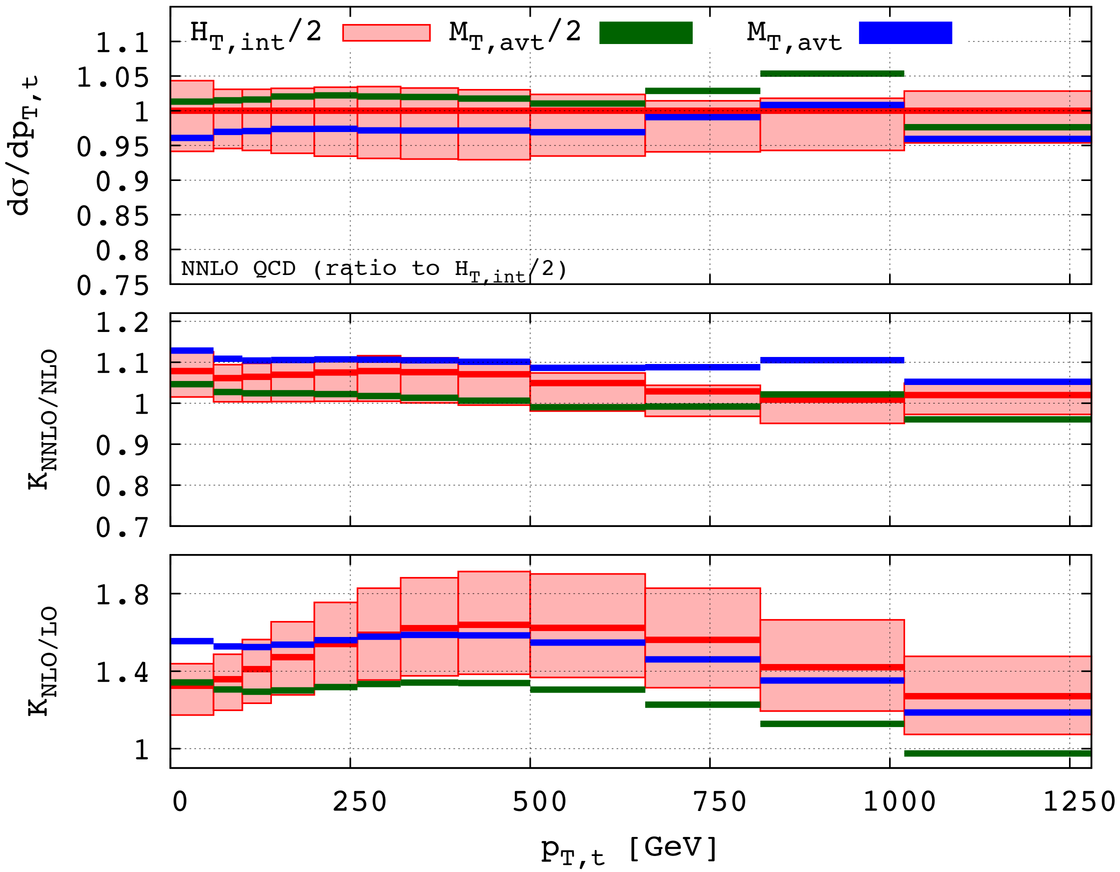
- Alternative scales based on the invariant mass do not lead to improvement



MC, Heymes, Mitov, preliminary

Differential Distributions

- Independent scales for the top-quark and anti-top quark much better



MC, Heymes, Mitov, preliminary

OUTLOOK

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
  - $pp \to tt + X \to WWbb + X \to l\nu\ l\nu\ bb + X$ (di-lepton)
  - $pp \to tt + X \to WWbb + X \to ud\ l\nu\ bb + X$ (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

Effects on Total Rates (Fiducial)

NWA → $\sigma_{t\bar{t}}$ [fb]

Off-shell → $\sigma_{WWb\bar{b}}$ [fb]

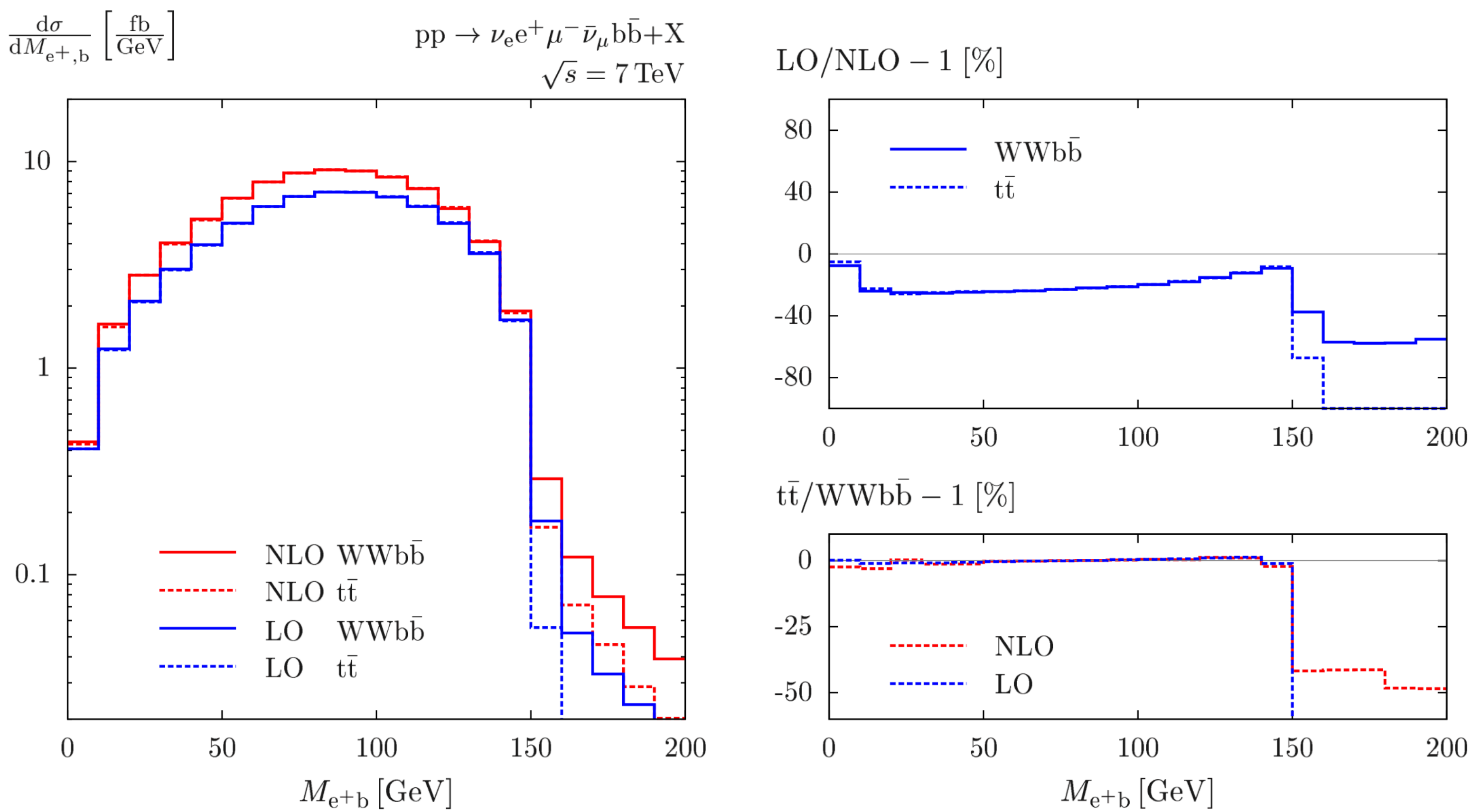
Collider	$\sqrt{s}$ [TeV]	approx.	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{WWb\bar{b}}$ [fb]	$\sigma_{t\bar{t}}/\sigma_{WWb\bar{b}} - 1$	Expected
Tevatron	1.96	LO	$44.691(8)^{+19.81}_{-12.58}$	$44.310(3)^{+19.68}_{-12.49}$	$+0.861(19)\%$	$+0.8\%$
		NLO	$42.16(3)^{+0.00}_{-2.91}$	$41.75(5)^{+0.00}_{-2.63}$	$+0.98(14)\%$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

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

Finite Width Sensitive Observables



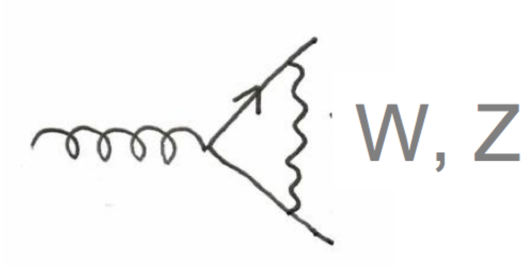
Denner, Dittmaier, Kallweit, Pozzorini, Schulze `12

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

Electroweak corrections

- 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



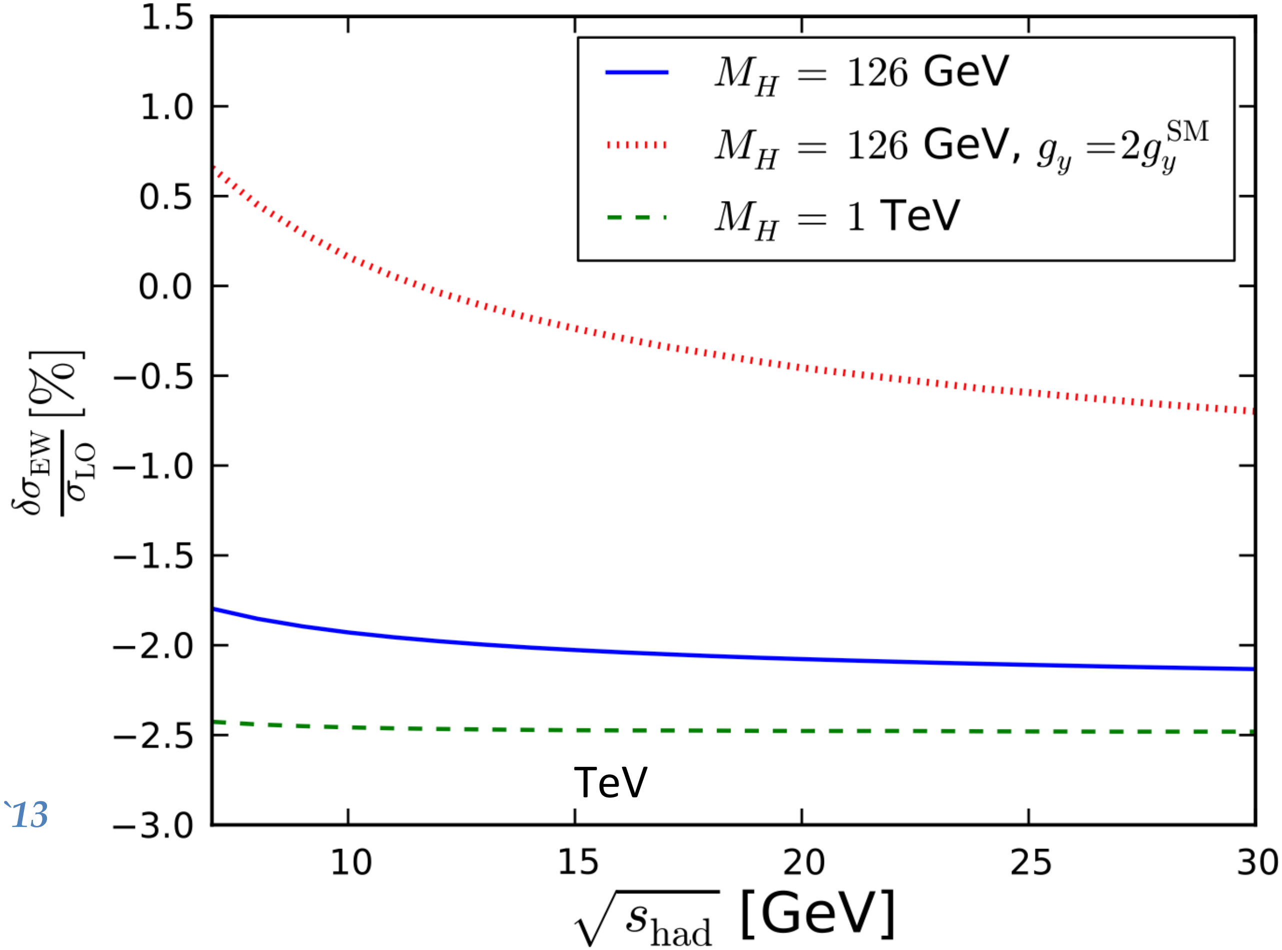
$$\log^2(p_{\mathrm{T}t}/M_{W,Z})$$

- When is QCD enough ?

Total cross sections

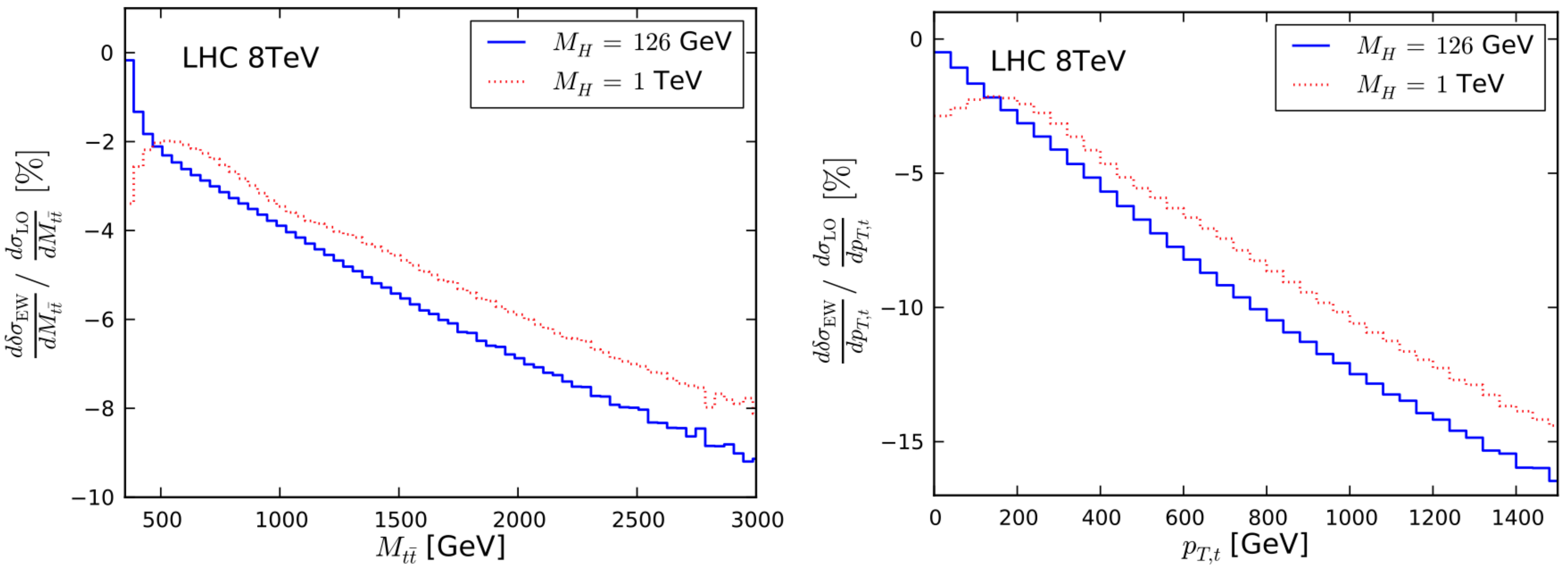
- Expectedly small corrections, which justify the use of pure QCD
- In the plot beware of the normalization to LO

Kühn, Scharf, Uwer `13



Sudakov Effects in the "Tails"

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



Kühn, Scharf, Uwer `13

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

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