Theoretical developments in top-quark physics.

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QCD@LHC 2013

DESY Hamburg, 3 September 2013

Outline

- $t\bar{t}$ pair production: NNLO and resummation
- Single top production
- Top Higgs, vector boson associated production
- Monte Carlo for top production
- Electroweak corrections
- Top properties: mass and asymmetries
- Top partners

I will give just a selection of some recent theory highlights most relevant for LHC physics, apologies in advance for the personal bias and the many likely omissions!

No attempt to review latest experimental results, look for them in Gonzalez-Sevilla's talk and yesterday's parallel session.

$t\bar{t}$ pair production

- Large production cross section at LHC ≈ 220 pb at 8 TeV, ≈ 930 pb at 14
- Expected experimental error $\approx 5\%$
- NLO long established (25 years)

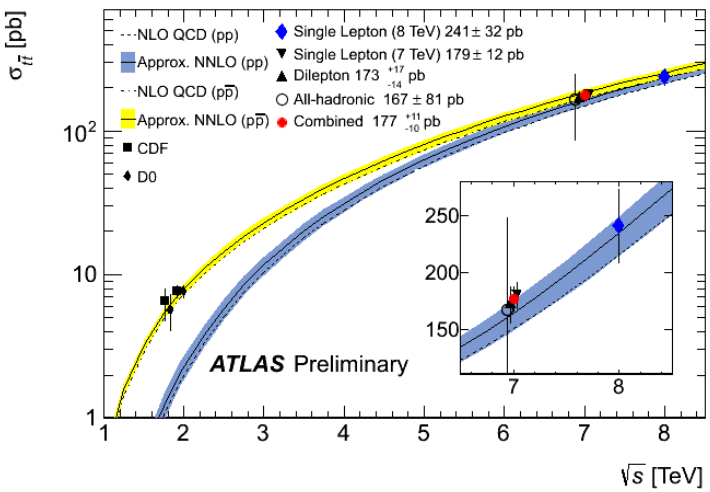
Nason, Dawson, Ellis '88-'89, Beenakker et al. '88-'90
Mangano, Nason, Ridolfi '91

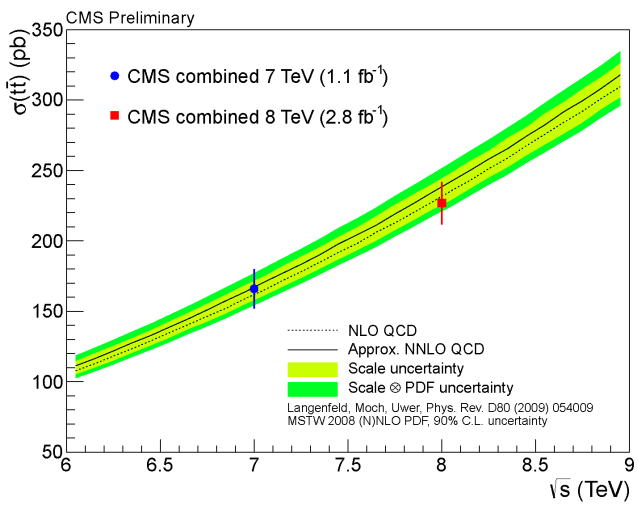
- Soft-gluon threshold resummation available up to NNLL

Catani et al. '96, Kidonakis, Sterman '97, Bonciani et al. '98
Beneke et al. '09, Czakon et al. '09
Kidonakis '09-'11, Ahrens et al. '10-'11

- NLO+NLL predictions still yield an uncertainty of $\approx 10\%$
- Approximate NNLO approaches agree within current exp. uncertainties

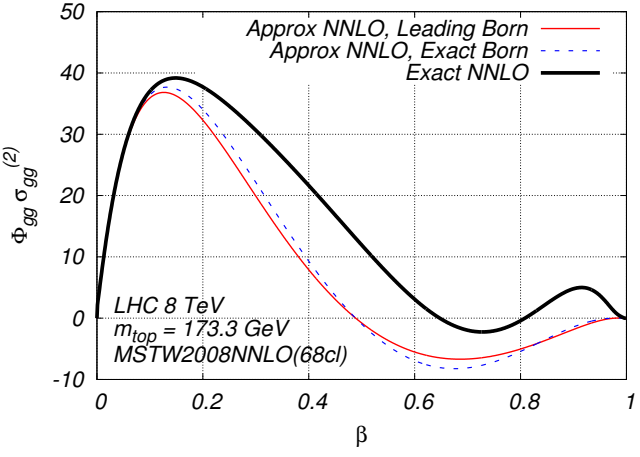
Aliev et al. '10, Beneke et al. '11
Ferroglia, Pecjakc,Yang '13

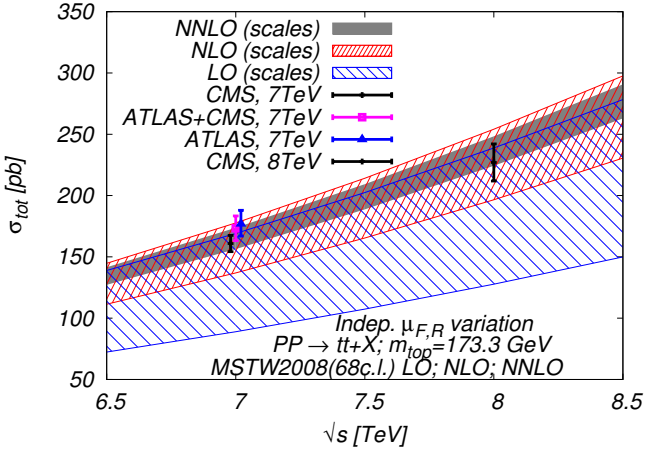


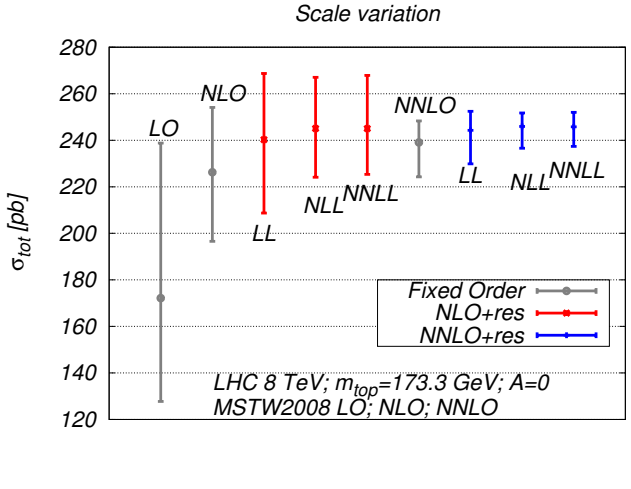


NNLO $t\bar{t}$ pair production

- Complete NNLO results available for total x-sec. Baernreuther,Czakon,Fiedler,Mitov '12-'13
- Uses sector-decomposition-improved FKS subtraction for IR singularities
- Comparable theoretical and experimental uncer. for total cross sections
- Challenges approximate NLLO results in all production channels see Fiedler's talk







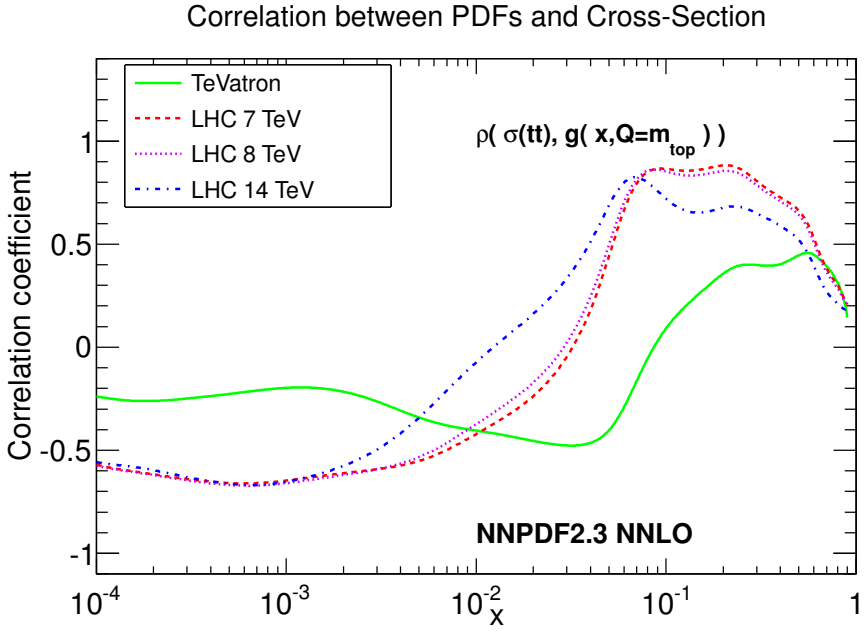
- Inclusion of NNLL resummation reduces scale var. uncertainty to 3%
- Other theoretical unc. of similar size: PDF $\approx 3-5\%$, $\alpha_s \approx 1.5\%$, $m_t \approx 3\%$
- Allows for an extraction of $m_t^{\rm pole}$ and $\alpha_s(m_Z)$ at NNLO see exp. talks
- Differential distributions feasible, albeit computationally challenging!

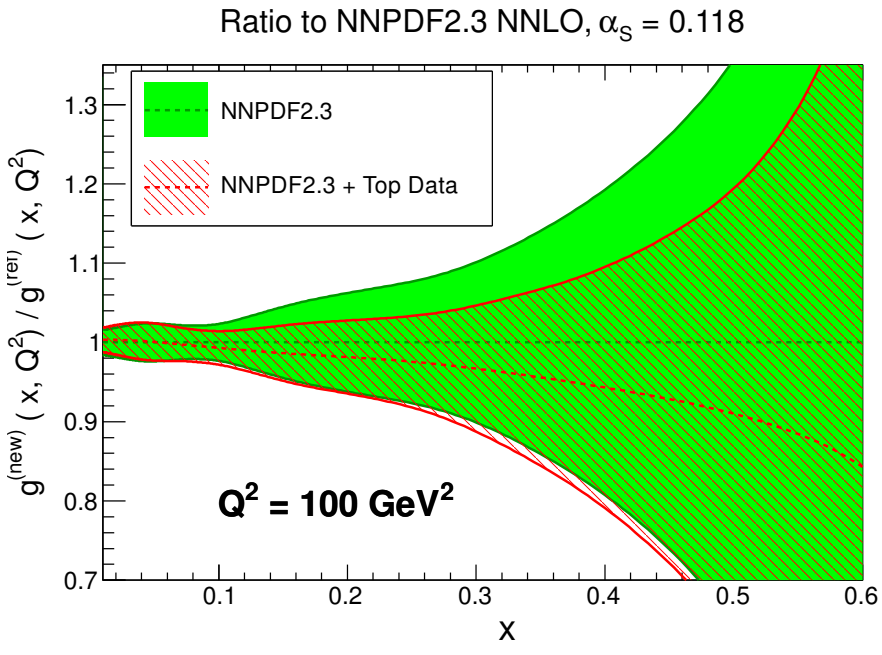
NNLO $t\bar{t}$ pair production: constraining gluon PDF

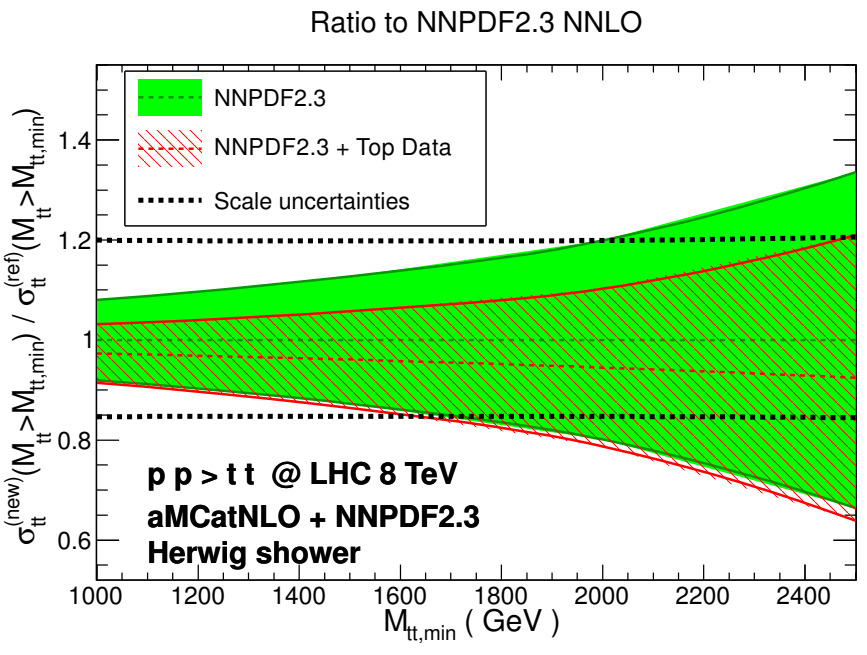
- Top pair x-sec. at LHC highly correlated to gluon PDF in $0.1 \lesssim x \lesssim 0.5$ range
- Including 5 Tevatron and LHC results for $t\bar{t}$ x-sec. into PDF fits

Czakon, Mangano, Mitov, Rojo '13

  - Reduces uncertainty on gluon PDF
  - Reduces total PDF uncertainty on predictions for gg driven processes

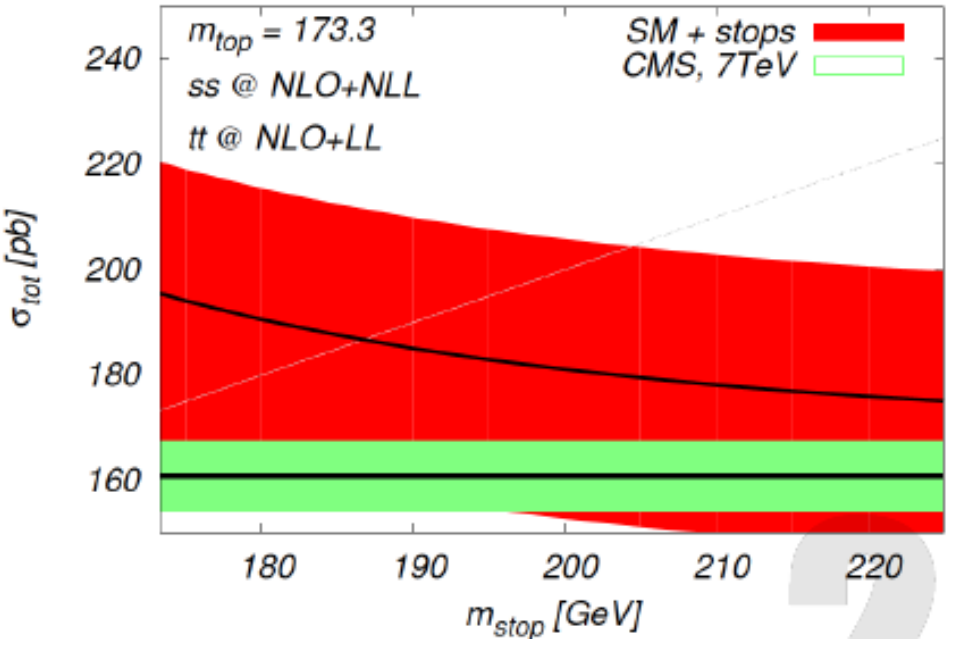


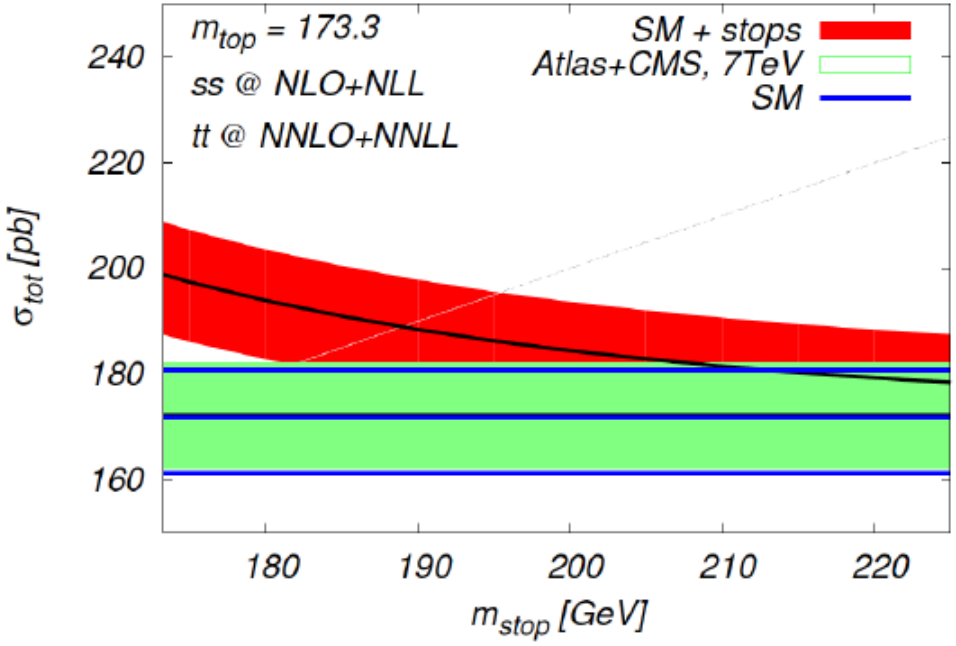


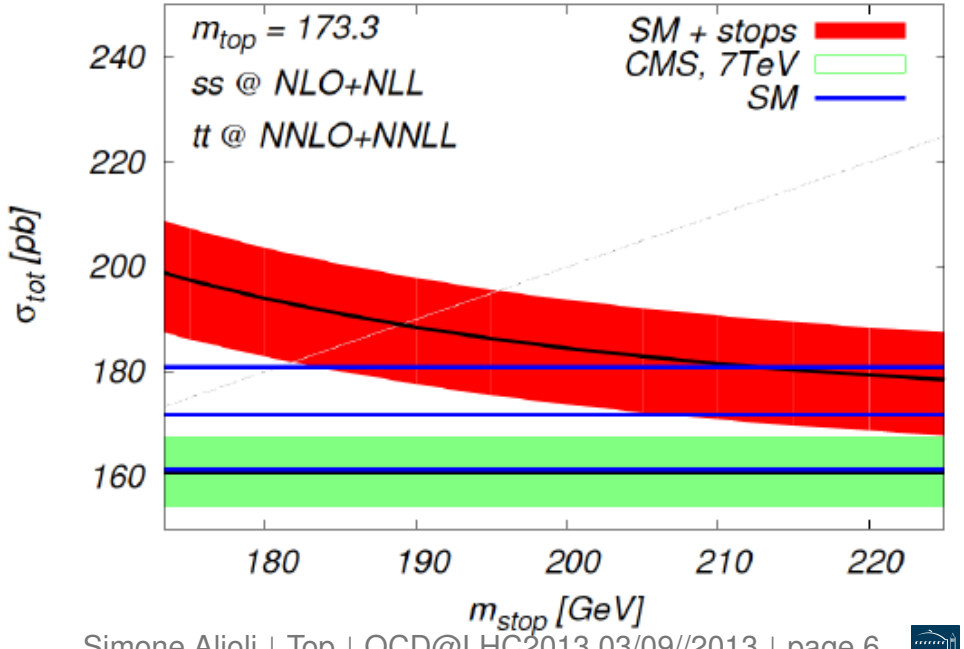


NNLO $t\bar{t}$ pair production : effects on new physics searches

- Light third generation squarks compatible with naturalness. Stealth stops $m \lesssim 220$ GeV not yet ruled out
- Identical signatures to $t\bar{t}$. Stop contamination $\approx 15\%$ for identical mass.
- Preliminary results by A. Mitov. Top pairs @ NNLO required, NLO uncertainties just too big!
- Assumes identical stop-top acceptances. More detailed analysis ongoing work Czakon, Mitov, Papucci, Ruderman, Weiler

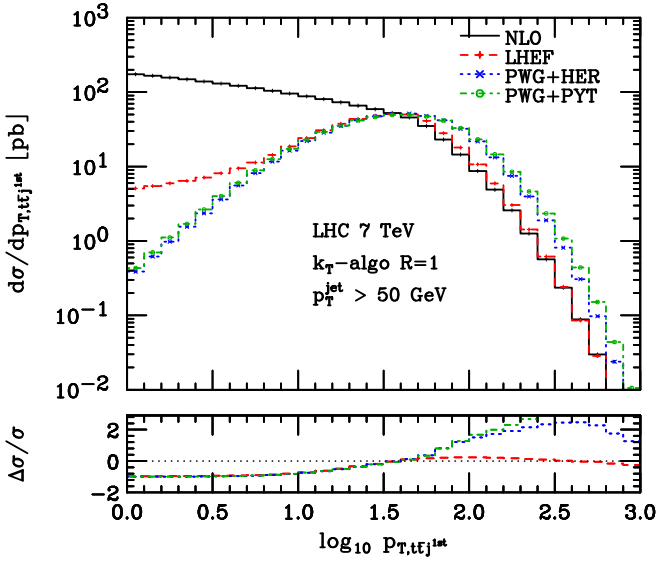


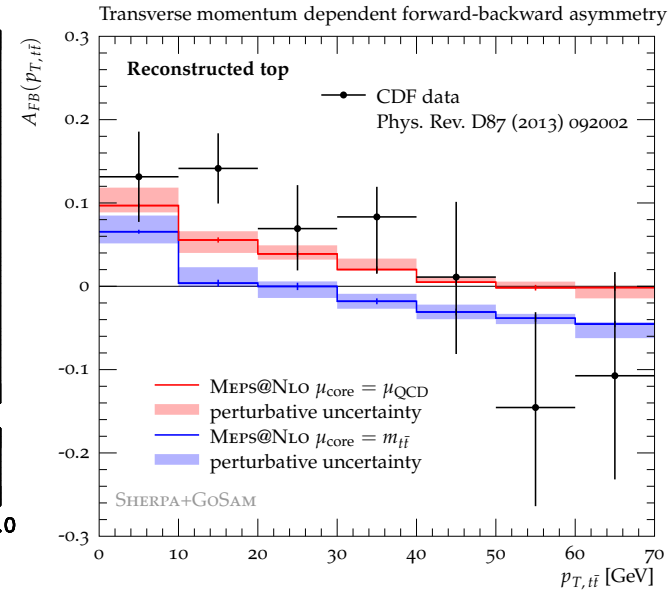


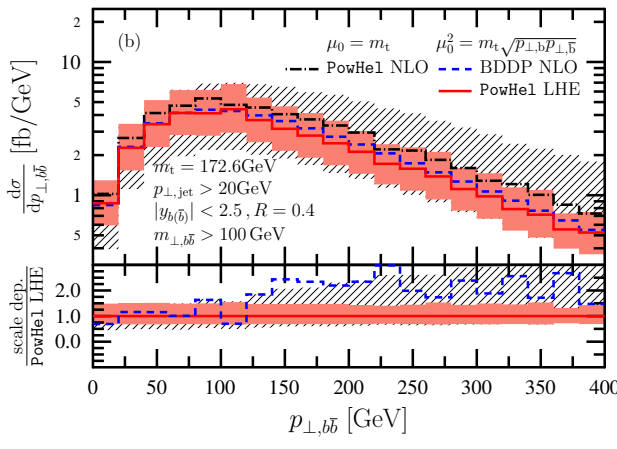


Monte Carlo for $t\bar{t}$ pair and $t\bar{t}$ + jets

- Fully differential calculation of ttbar + up to 2 jets, also $t\bar{t}b\bar{b}$ — Dittmaier, P. Uwer, S. Weinzierl '07; Bevilacqua et al. '08-'11
- NLO production + NLO top decay with full spin correlations in zero width approx. Also finite Γ_t and interference effects $W^+W^-b\bar{b}$ — Melnikov, Scharf, Schulze '09-'11, Campbell, Ellis '12; Bredenstein et al. '09-'12
- Interference and finite-width effects small on inclusive quantities, but greatly affects tails of distribution (important for mass extraction).
- NLO matched to parton showers POWHEG, POWHEL, aMC@NLO, GOSAM+SHERPA: $t\bar{t}, t\bar{t}+1\text{jet}$ and merged sample, $t\bar{t}b\bar{b}$ — Frixione, Nason, Ridolfi '08, SA, Moch, Uwer '11; Garzelli, Kardos, Papadopoulos, Trocsanyi '11-'13; Frederix, Frixione '12, Hoeche et al. '13



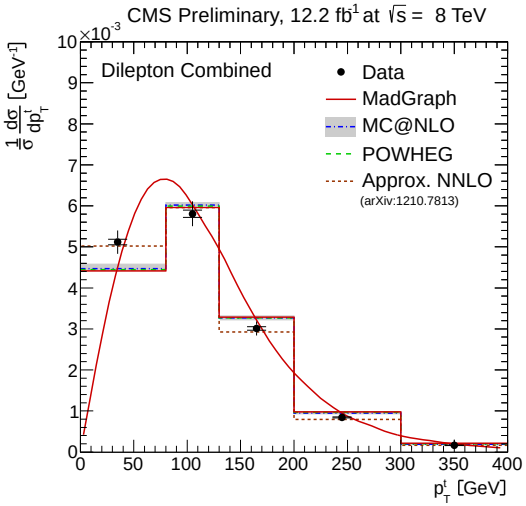


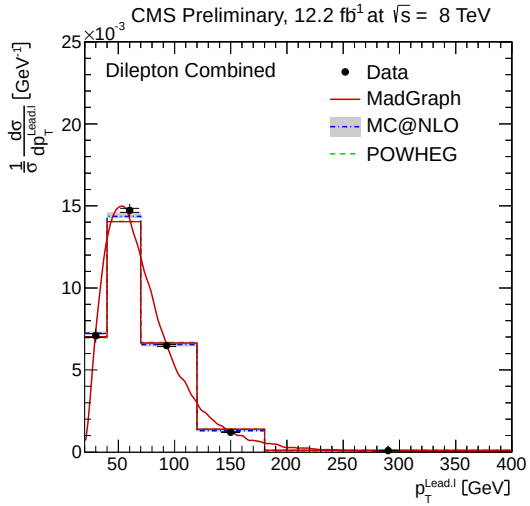


- Reminder: NLO merging is a tricky business! Fixed order $O(\alpha_s)$ does not automatically mean "next-to-leading accuracy" right. Higher-order logs might spoil it.

Resummation

- MonteCarlos seems to have some problems with reconstructed tops. Better with decay products.
- Approx. NNLO results based on NNLL 1PI resummation seems in good agreement

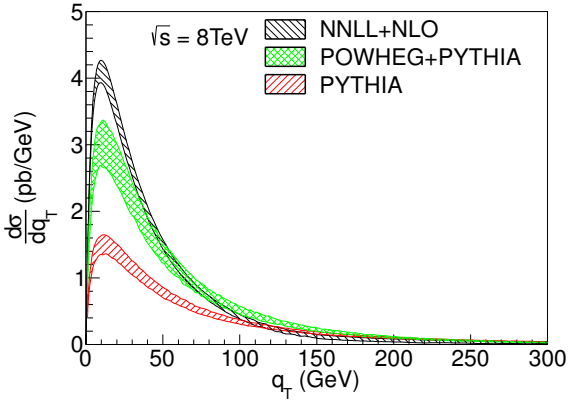


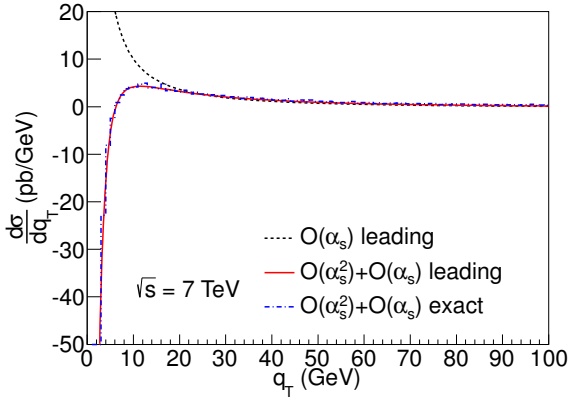


- What about $p_{T,t\bar{t}}$?
  CSS formalism good for Drell-Yan, Higgs, VV . Not so good with colored objects. k_T-factorization breaks down explicitly in di-jet.

- New framework for q_T resummation based on SCET presented for $t\bar{t}$ Zhu, Li, Shao, Yang '13

- Based on Becher, Neubert, Wilhelm '12 with transverse soft function matrix. Use TMD pdf matched to ordinary pdf via beam functions and NP input . Resummation up to NNLL performed. Potential for alternative complete NNLO





Fully exclusive NNLO top-quark decay

- Previous NNLO decay rate via optical theorem
- Now 2 fully differential calculations available

Czarnecki, Melnikov '99, Chetyrkin et al. '99

Gao, Li, Zhu '12, Brucherseifer, Caola, Melnikov '13

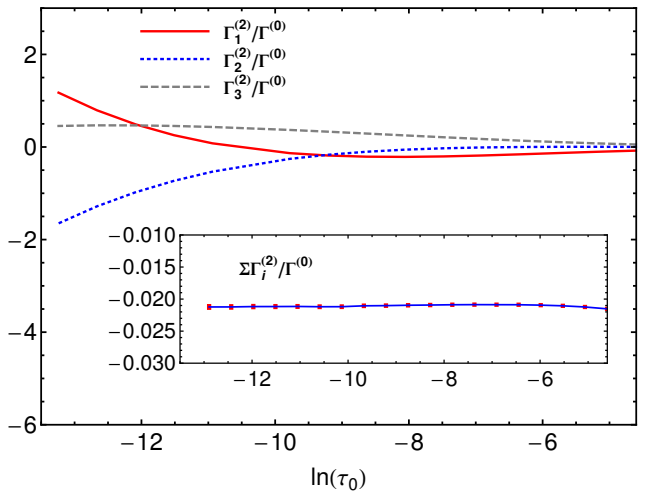
Catani, Grazzini '08

1) IR subtractions via PS slicing and subtraction a lá

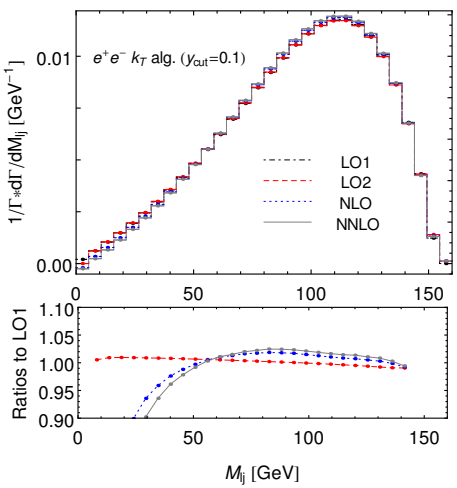
Key idea: $d\sigma^X_{NNLO}|_{q_T\neq 0} \equiv d\sigma^{X+j}_{NLO}\Big|_{q_T\neq 0}$ + singular behaviour at $q_T \to 0$ known from resum.

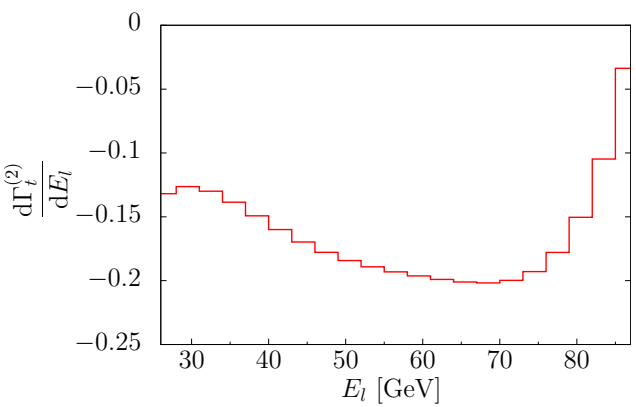
$$\Gamma_t^{NNLO} = \int_0^{\tau_0} d\tau \frac{d\Gamma_t}{d\tau} + \int_{\tau_0}^{\tau_{\max}} d\tau \frac{d\Gamma_t}{d\tau}$$

- $\tau < \tau_0$ exact results from SCET factorization
- $\tau > \tau_0$ exact results from NLO $t \to bW^+j$



2) Sector-decomposition improved FKS subtraction.





- Everything now available for NWA prod.+decay@NNLO

Electroweak effects and Sudakov logs

- Inclusive NLO EW corrections small $\lesssim 1.5\%$

  Beenakker et al. Hollik et al. '07, Kuhn et al. '07-'13

- But sizeable $\gtrsim 10\%$ effects from EW Sudakov logs $\left(\frac{\alpha}{\sin^2\theta_W}\right)^n \log^{m\leq 2n}\left(\frac{s}{M^2_{W,Z}}\right)$ on high-energy tail of $d\sigma/dM_{t\bar{t}}$ Manohar, Trott '12

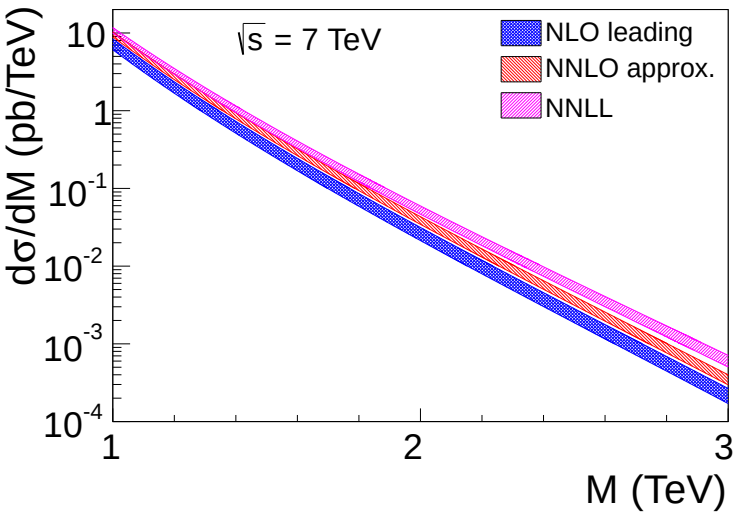
- Unlike QCD ones, don't cancel for inclusive quantities, because partonic processes are not EW singlets.

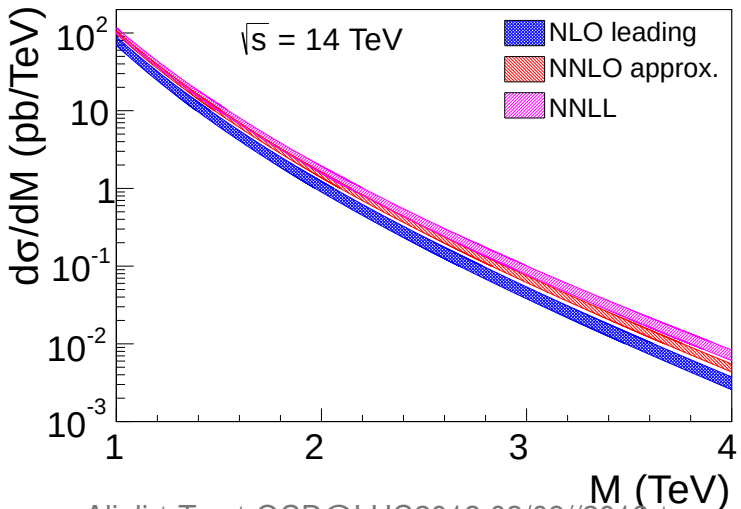
- These SM effects are unaccounted for in current Monte Carlo (few resums QED coll. logs only)

Bin [GeV]	$\mathcal{R}_t$		$\mathcal{R}_b$		$\mathcal{R}_c$	
[50, 3000]	–	–	0.99	0.99	0.99	0.99
[350, 3000]	0.97	0.97	–	–	–	–
[50, 250]	–	–	0.99	0.99	0.99	0.99
[250, 500]	–	–	1.00	1.00	1.00	1.00
[350, 500]	0.98	0.98	–	–	–	–
[500, 750]	0.97	0.97	0.99	0.99	0.99	0.99
[750, 1000]	0.95	0.95	0.98	0.98	0.98	0.98
[1000, 1500]	0.94	0.94	0.97	0.97	0.96	0.96
[1500, 2000]	0.92	0.92	0.95	0.95	0.95	0.95
[2000, 2500]	0.90	0.91	0.93	0.94	0.93	0.93
[2500, 3000]	0.88	0.89	0.92	0.93	0.92	0.92
[3000, 3500]	0.87	0.88	0.90	0.91	0.91	0.91

TABLE III: The EWS corrections for heavy quark production at the LHC. The left (right) columns are for $\sqrt{s} = 7\,(14)$ TeV.

- Reminder: large $M_{t\bar{t}}$ region also very sensitive to QCD soft $1 - M^2/S$ logs. Marked differences for NLO, NNLL and approx. NNLO results ($m_t << M$) Ferroglia et al. '13

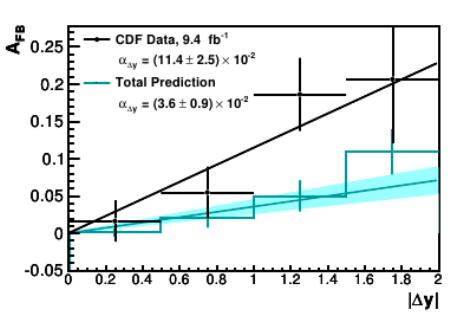


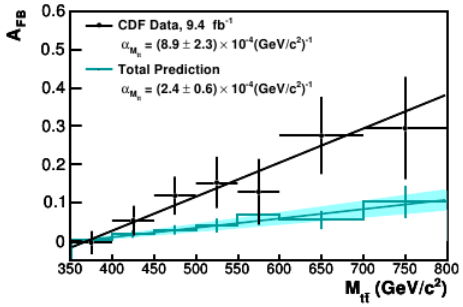


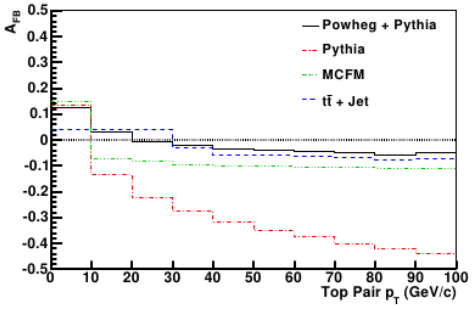
$t\bar{t}$ forward-backward and charge asymmetry

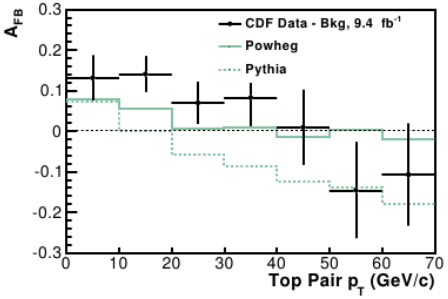
Some facts:

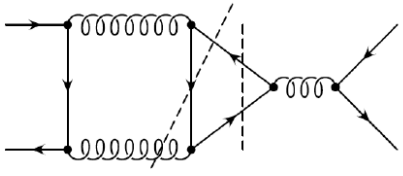
- CDF measured a $t\bar{t}$ charge (FB) asymmetry $2-3\sigma$ larger than SM
- Marked dependence on Δy, $m_{t\bar{t}}$ and $p_{T,t\bar{t}}$
- No contribution from gg, no from $q\bar{q}$ at LO.
- Largest contribution from NLO $q\bar{q}$ (>0 from virt. <0 from reals) Kuhn,Rodrigo '98-'11
- EW NLO effects calculated. Not small, but not enough Hollik, Pagani '11
- Coherence effects in parton showers generate supplemental asymmetry Webber,Skands,Winter '12
- Resummation/merging NLO samples seems to slightly reduce disagreement Li et al. '13, Höche et al. '13
- Many BSM models crashed when tried to explain all the features
- Large difference from TEV to LHC, must include y cuts of measure charge asym. directly

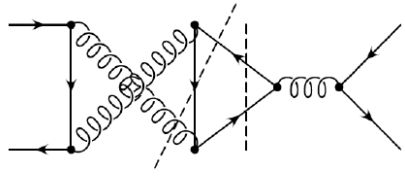


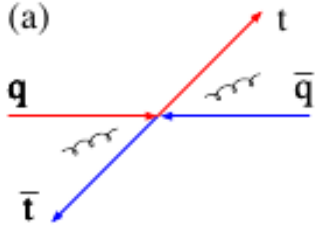


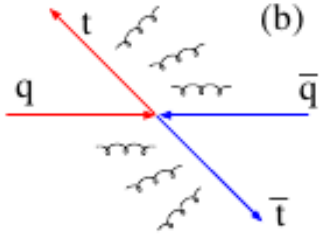


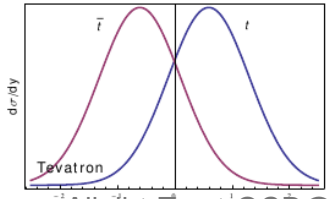


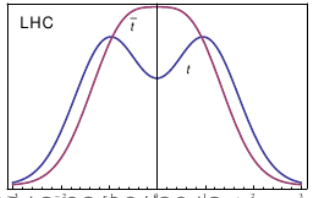












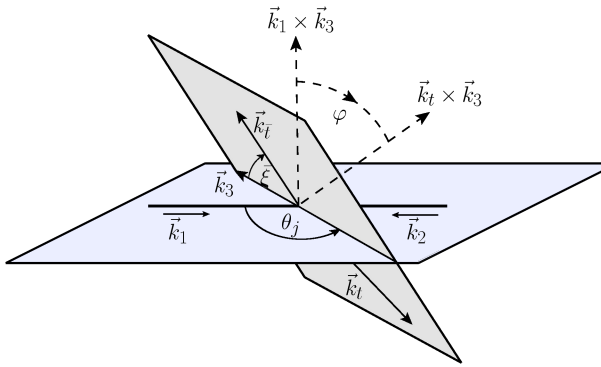
Asymmetries with a jet handle

- New observables enhance charge asymmetries at LHC

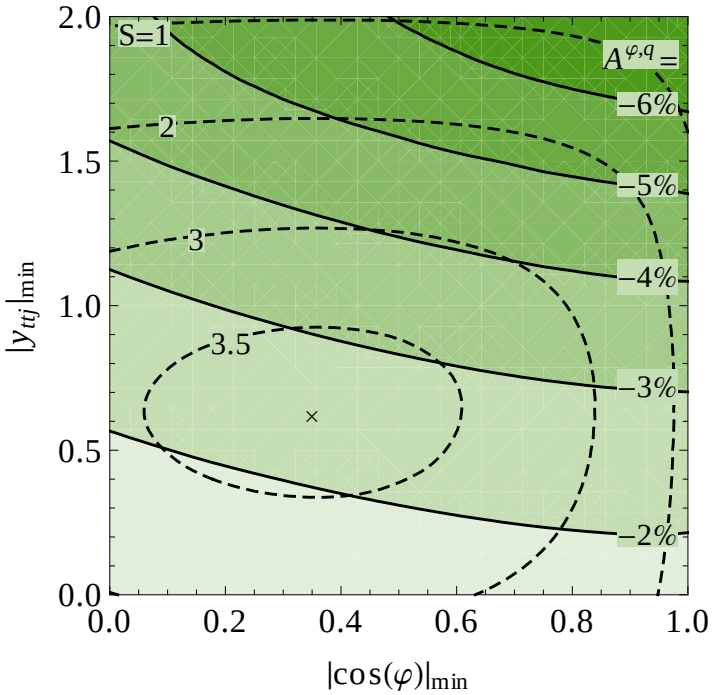
$$\frac{\mathrm{d}\hat{\sigma}_A(q\bar{q} \to t\bar{t}j)}{\mathrm{d}\varphi\,\mathrm{d}\theta_j\,\mathrm{d}E_t\,\mathrm{d}E_{\bar{t}}} = -\left[N_1 + \sin^2\theta_j\,(N_1^j + \cos^2\varphi\, N_1^\varphi)\right]\cos\varphi \quad \text{Incline Asymmetry}$$

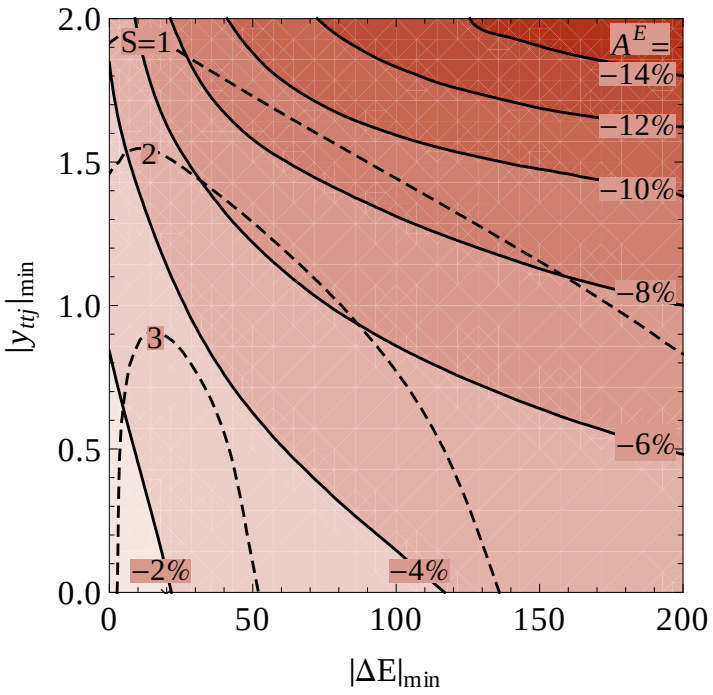
$$+\left[N_2 + \cos^2\varphi\, N_2^\varphi\right]\sin\theta_j\cos\theta_j \quad \text{Energy Asymmetry}$$

Berge,Westhoff '12-'13



- Incline asymmetry is a refined radipity asym. ($\equiv$ at $y = 0$), probes mostly $q\bar{q}$. Energy asym. probes only qg, not yet explored
- Together probe complementar contributions wrt to $t\bar{t}$

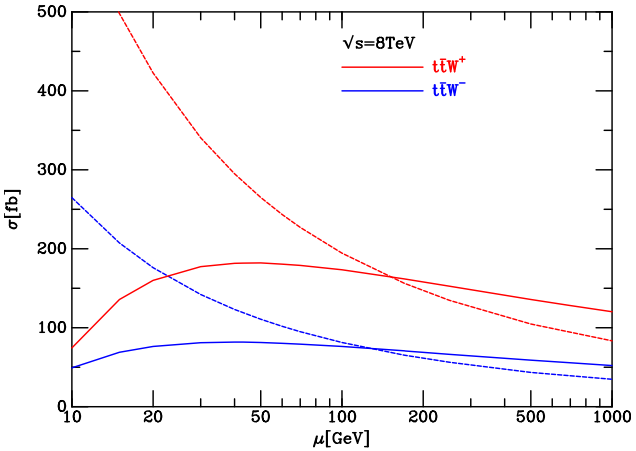


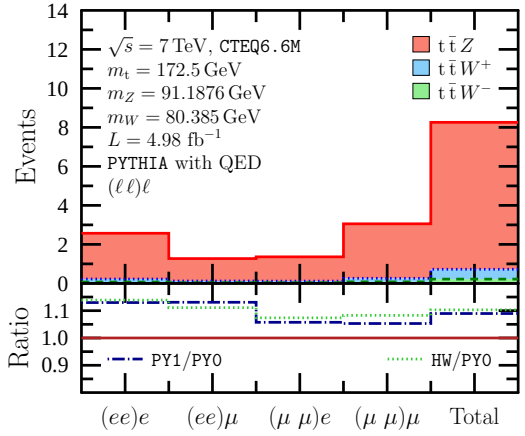


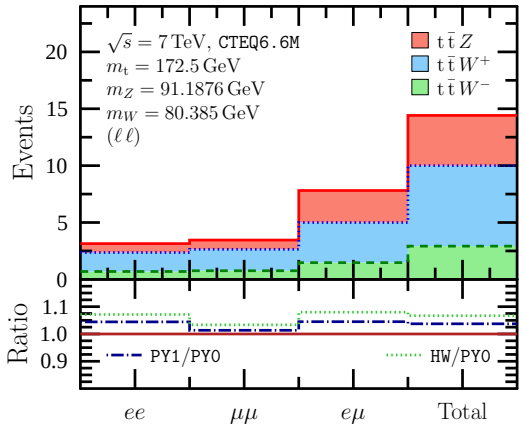
Top - antitop plus boson associated production

- Vector bosons: $ttV \quad V = \gamma, W^{\pm}, Z$

Campbell, Ellis '12, Melnikov et al. '11, Garzelli et al. '11
Peng-Fei et al. '09, Lazopoulos et al. '08

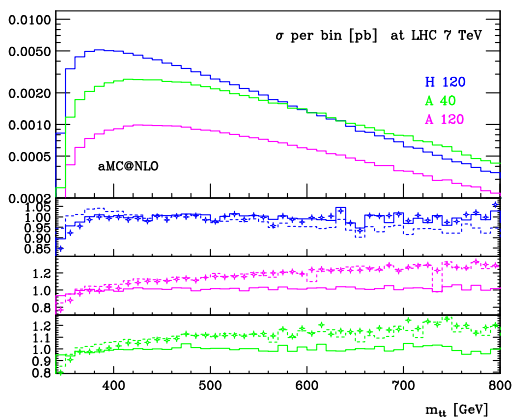


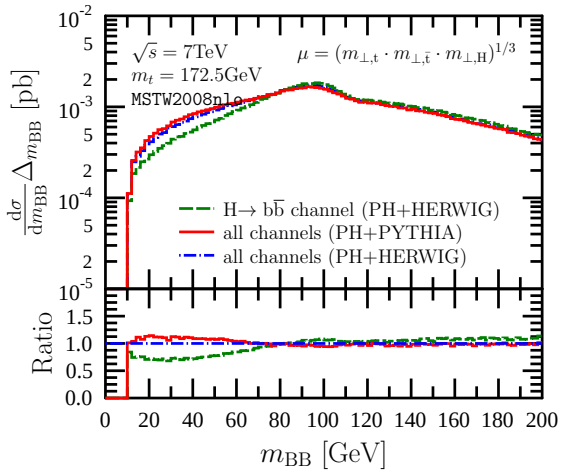


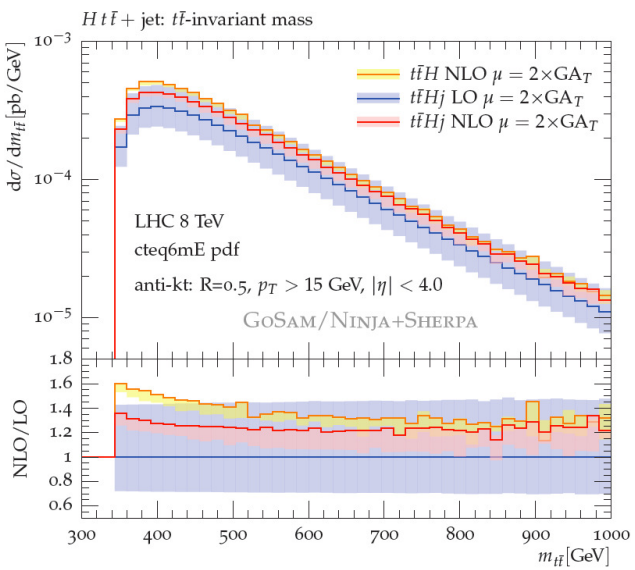


- (Pseudo-) scalar Higgs ttH, ttA. probe tH coupl., NP

Garzelli et al.'11, Frederix et al. '11







- Remarkable new result : ttH + 1 jet

Van Deurzen et al. '13

Single top production

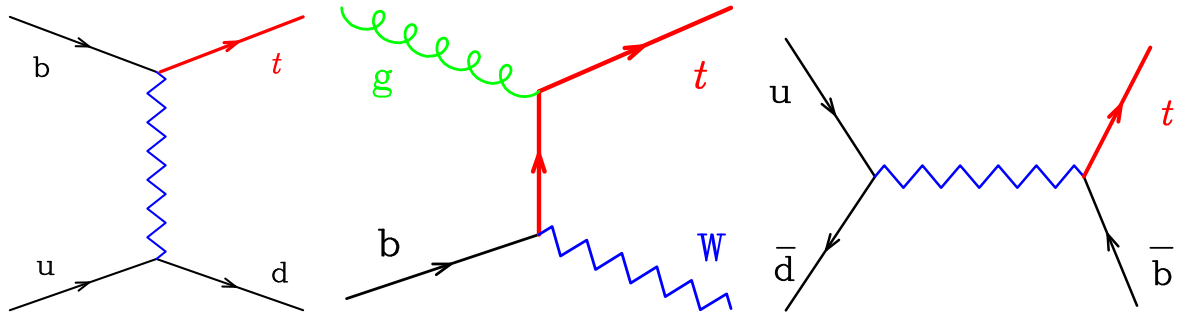
- Three production channels

  $\sigma_{t-ch} \approx 88$ pb,

  $\sigma_{Wt} \approx 22$pb,

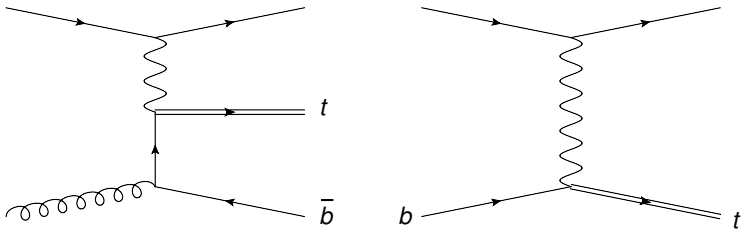
  $\sigma_{s-ch} \approx 6$pb

  at 8 TeV LHC.



- Allows direct determination of V_{tb} and probes b PDF

t-channel
4F: b from $g \to b\bar{b}$
5F: b inside proton

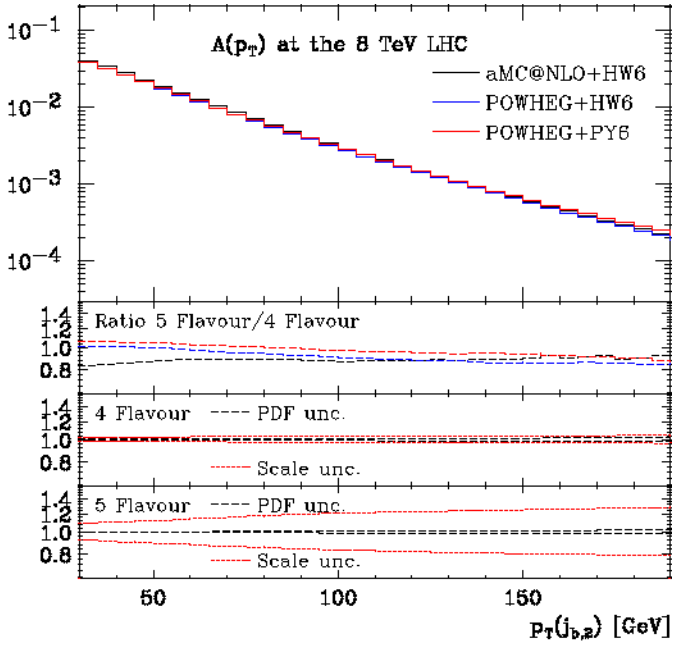


Harries et al. '02, Campbell, Ellis, Tramontano '04
Frixione et al. '05, SA, Nason et al. '09
Campbell et al. '09, Schwienhorst et al. '10
Frederix, Re, Torrielli '12

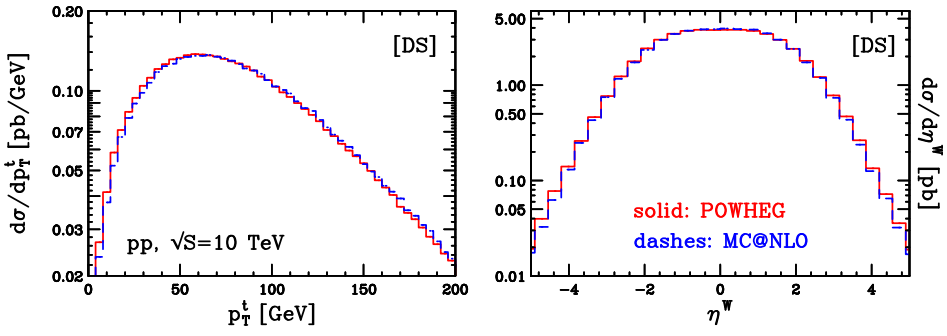
- Known at NLO +PS in 4F and 5F schemes , matched to shower in POWHEG and MC@NLO
  - Finite-width and non-resonant effects included — Falgari et al. '10-'13, Papanastasiou et al. '13
  - NLO Single top production in association with a Z boson $\sigma_{Zt} \approx 160$fb — Campbell, Ellis, Röntsch '13
  - Also NLO tZ and $t\gamma$ with FCFN — Zhang, Li, Gao, Zhu '10-'11
  - Resummation to NNLL and approximate NNLO available — Kidonakis '10, Wang, Li, Zhu, Zhang '10

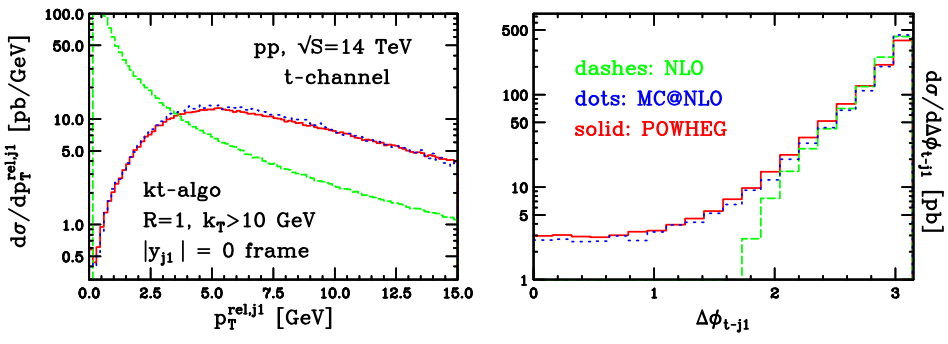
NLO Monte Carlo for single top production

- t-channel: 4F vs. 5F scheme

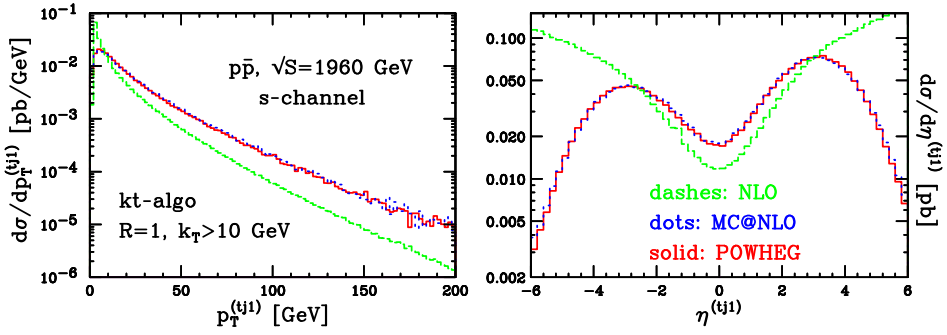


- Wt-channel, ambiguities in NLO contribution due to $t\bar{t}$ interference



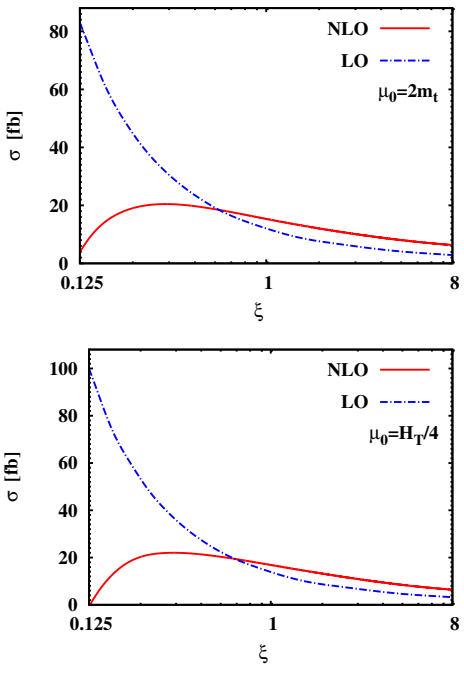


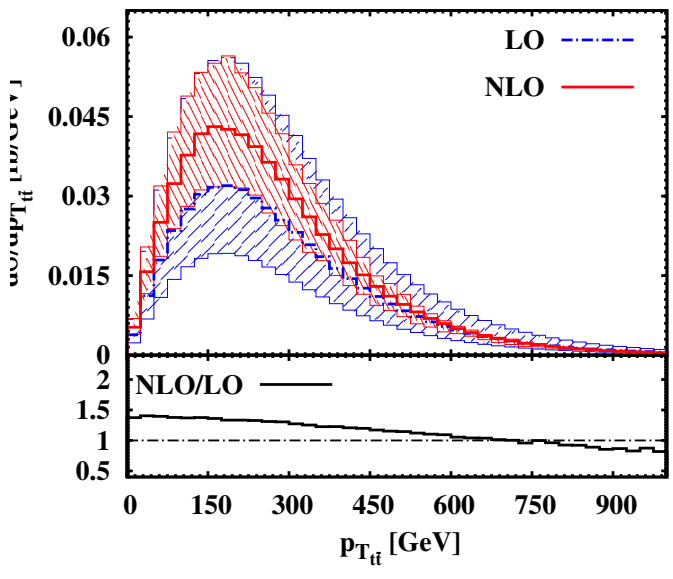
- s-channel

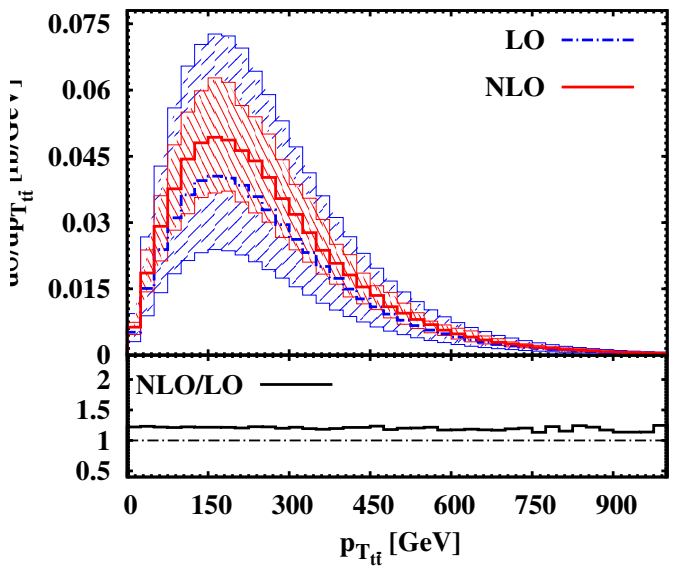


Four tops: $t\bar{t}t\bar{t}$

- Results recently available. Last one on Les Houches wishlist. Bevilacqua, Worek '12
- Important background to many NP searches: Heavy Higgs, Z', KK, Higgs & Top compositness,effective 4-tops vtx
- Small but important x-sec ≈ 17 fb at LHC14. Comparable to NP at $m_{\rm new} = 1.5$ TeV
- NLO inc. corrections $\approx 25\%$.
- Multiscale process: fixed $\mu = 2m_t$ vs. dyn scale $\mu = H_T/4$ matters for distributions

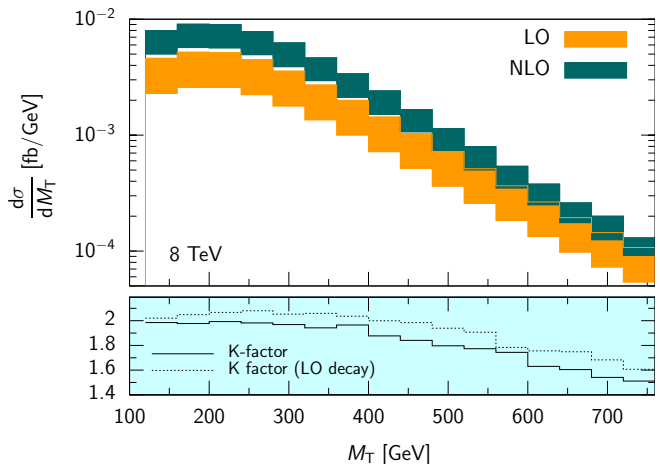


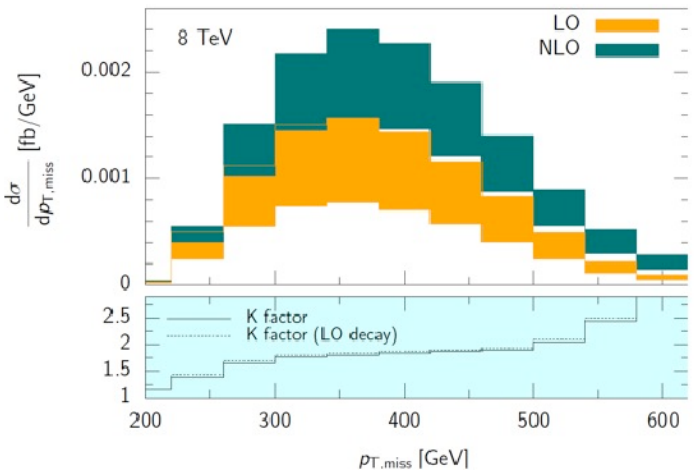




BSM top partners

- Top largest contribution to Higgs mass correction. Several BSM models introduces top-partners to tame quadratic divergences.
- MSSM naturalness prefers light top-partners + heavier colored superpartners.
- MSSM stops NLO predictions by PROSPINO only give flat K-factors. This is usually used in searches.
- NLO calculations for $\tilde{t}\tilde{\bar{t}} \to t\bar{t}\chi\bar{\chi} + X$ shows sizeable kinematics dependence. Also fermionic $T\bar{T} \to t\bar{t}A_0A_0 + X$ in Litlle-Higgs with T-parity Schulze,Boughezal '13

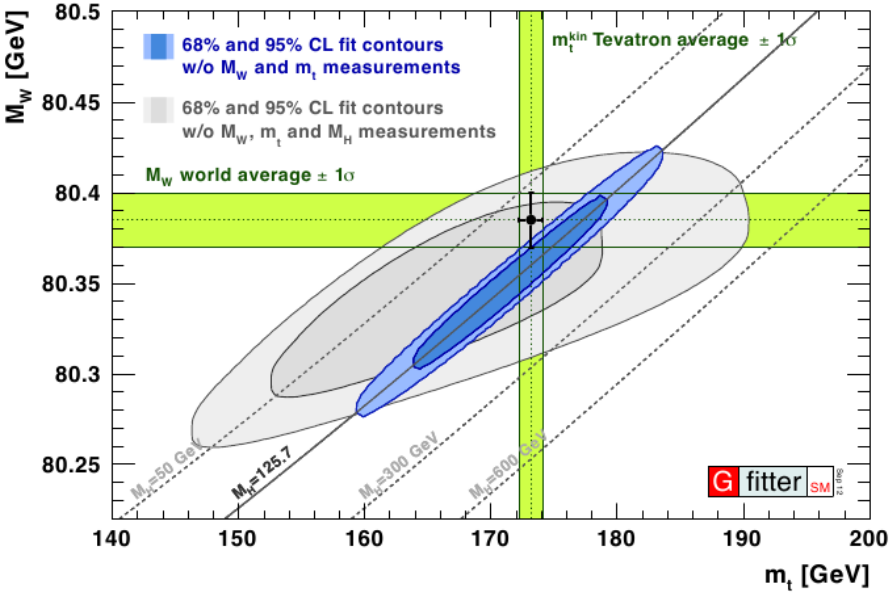


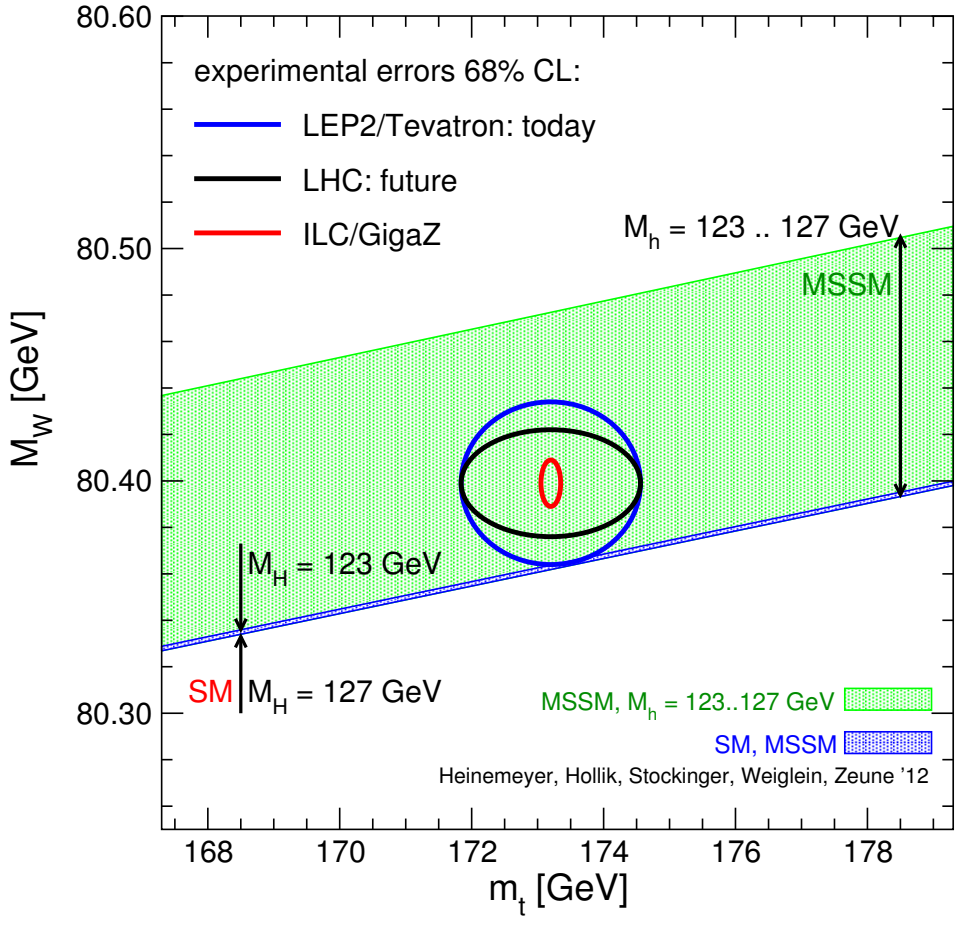


- NLO+NLL resummation for $\tilde{t}\tilde{\bar{t}}$ available Beenakker et al. '12-'13
- Approximate NNLO predictions recently Broggio et al. '13
- NLO+PS not yet available

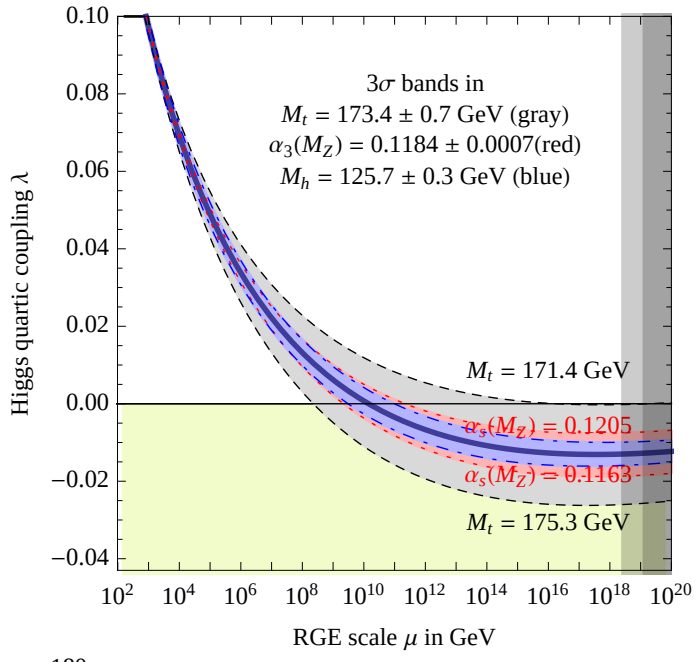
Motivations for precise m_t measurements

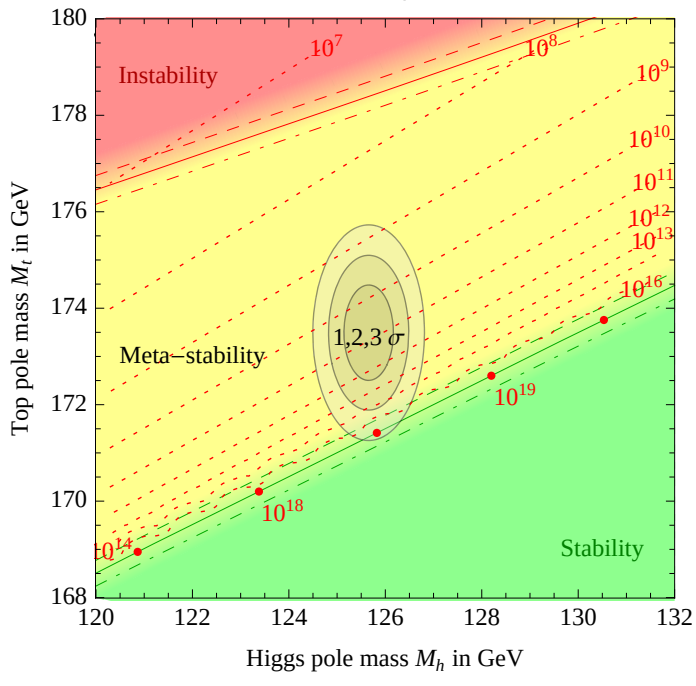
- The top is the only quark that decays before hadronization: unique opportunity to study a quasi-free quark.
- The top sector might play an important role in EWSB
- Its mass is a fundamental parameter of SM Lagrangian
- Important parameter in SM (and MSSM) fits, although not limiting factor



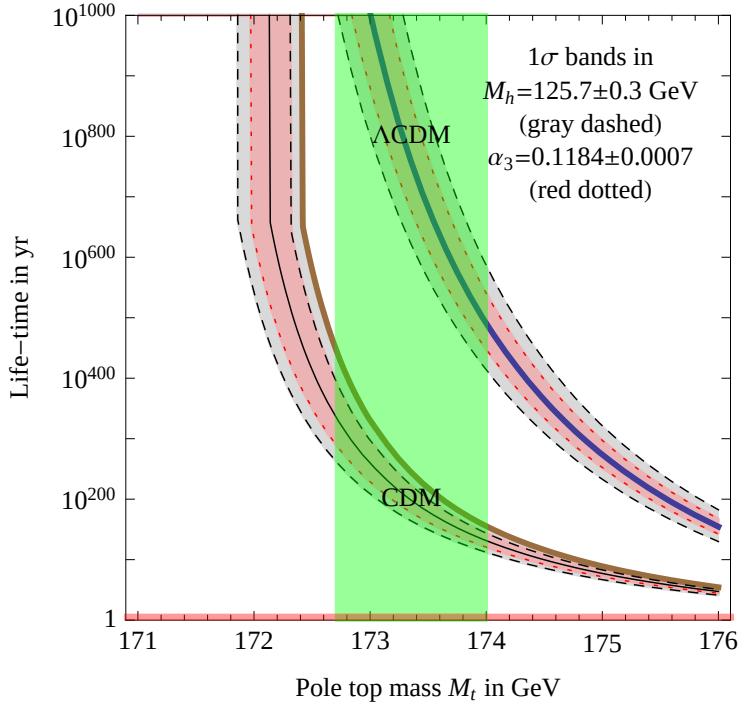


Motivations for precise m_t measurements





- Sub-GeV accuracy crucial for vacuum (meta-)stability of SM at NNLO and the fate of the universe Buttazzo et al. '13
  DeGrassi et al. '12, Alekhin, Djouadi, Moch '12



- Cosmological Higgs-driven inflation models compatible with Planck data

Bezrukov, Shaposhnikov '07-'08, De Simone, Hertzbergy, Wilczek '08

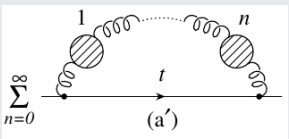
Theoretical issues in determination of the top-quark mass

- Confinement = free quarks not observable = no pole in the S-matrix
- Parameters of the theory measured through their influence on hadronic observables: fit $\mathcal{O}^{\rm exp}(\vec{x})$ with $\mathcal{O}^{\rm th}(m_t, \vec{x})$ and extract m_t

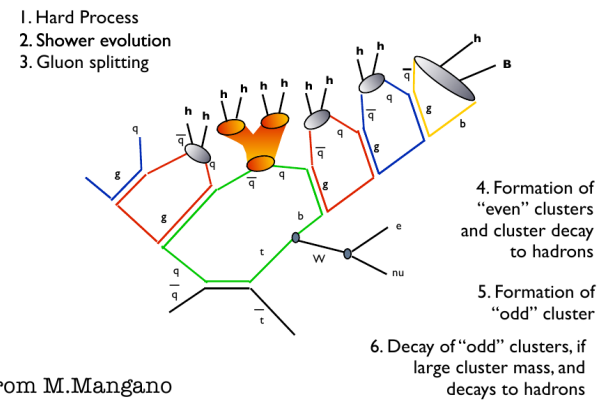
Which mass are we measuring ? At least NLO required to fix the ren. scheme.

- Precise value depends on the m_t definition: $m_t^{\rm pole}$, $m_t^{\overline{\rm MS}}$, etc.

Which scheme ? Some show better convergence (*e.g.* $m_t^{\overline{\rm MS}}$), some ill-defined beyond PT (IR renormalons $\Delta_{m_t^{\rm pole}} \propto \Lambda_{QCD}$)



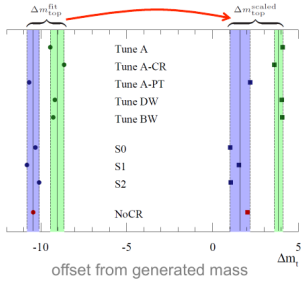
- Color reconnections



From M.Mangano

Non-perturbative effects at the LHC [Skands,Wicke 08]

Simulate top mass measurement using different models/tunes for non-perturbative physics / colour reconnection



different offset for different tunes!

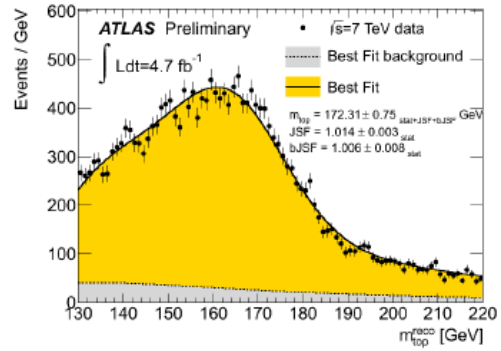
Non-perturbative effects result in uncertainty of the order of 500 MeV

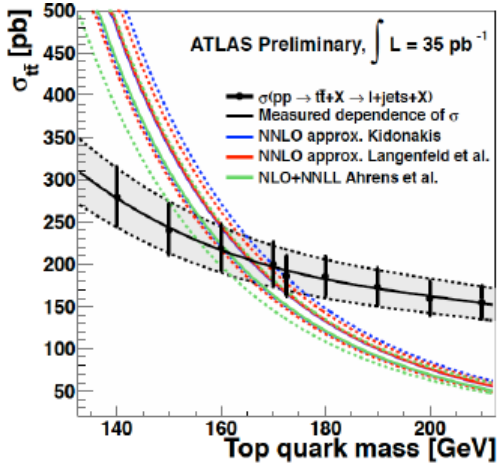
blue: pt-ordered PS
green: virtuality ordered PS

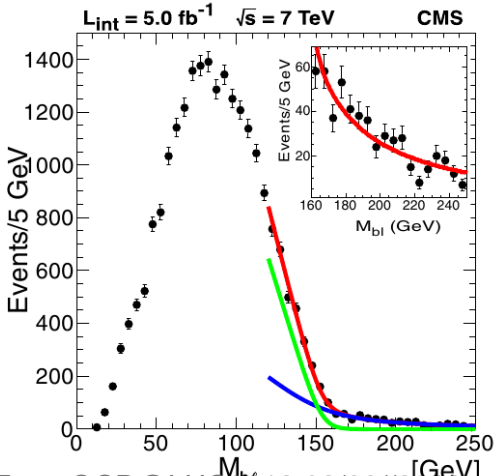
- Current experimental precision at 0.5% impressive. Theoretical intepretation not so well under control.

(Some) top-quark mass measurements at hadron colliders

- Template method - Ideogram method
  - ✗ $m_t^{MC} = m_t^{\text{pole}}(1 \pm \Delta), \Delta = ?$, LO
  - ✓ high-precision
- Matrix element method
  - ✗ LO only, NLO under develop. ✓
  - ✓ high-precision
- Cross section
  - ✓ theoretically clean, NNLO, finite Γ_t
  - ✗ reduced sensitivity, threshold eff. included
- J/ψ method: $t \to (b \to (J/\psi \to \mu^+\mu^-) + X) + (W^+ \to \ell^+ \nu_\ell)$
  - ✓ NLO, small sensitivity to JES unc. and top reco.
  - ✗ finite Γ_t, very-high statistics required
- Dilepton-specific distributions
  - ✓ NLO, JES unc., top reco., finite Γ_t
  - ✗ reduced sensitivity, high statistics required
- Kinematic endpoint: $\max(M_{b\ell})$ and m_t strongly correlated
  - ✓ NLO (but not yet) , small sensitivity to top reco.
  - ✗ strong dep. on JES, finite Γ_t







New proposal: top-mass from jet rates

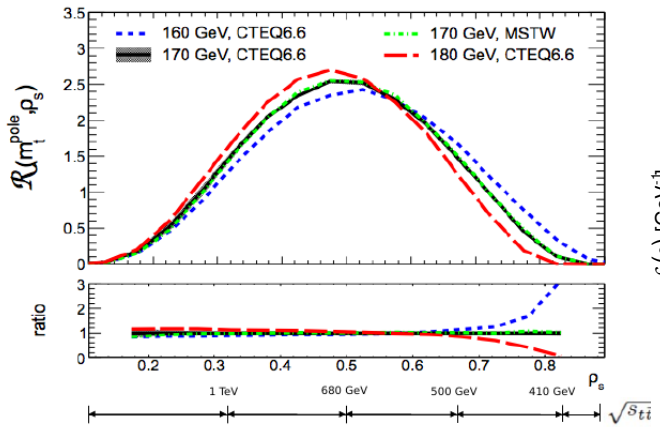
- Study $t\bar{t}+1$-jet events : large rate at the LHC ($\gtrapprox 30\% - 50\%$), NLO and NLO+PS available

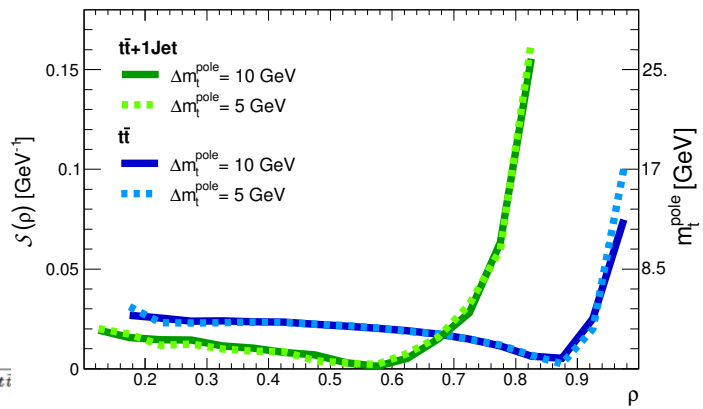
SA,Fernandez et al., see A.Irles' talk

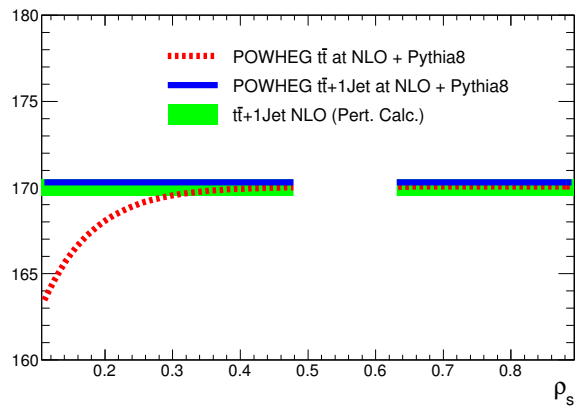
- Experimentally accessible, errors reduced through normalization factor

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s) \,, \qquad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}} \,, \qquad m_0 = 170 \text{ GeV}$$

- Theoretically well defined, calculable at NLO, small uncertainties and small NP corrections, $\overline{\text{MS}}$ mass extraction also feasible from $\mathcal{R}(m_t^{\overline{\text{MS}}}, \rho_s)$.







- Enhanced sensitivity (x5), potential for $\lesssim 1$ GeV theo+exp combined accuracy. Room for improvement with detector specific tools.
- Several methods availables for NLO top mass, important to take advantage of all of them, with a look on the theory side.

Conclusions

- Total x-sec. for $t\bar{t}$ production now known at NNLO+NNLL. Theory unc. from scales, pdf, α_s, m_t of small similar size. High-precision test of SM.
- Lesson learned: precision pays back! Important phenomenology, improve constraints on PDF's and limits on BSM searches.
- Monte Carlo tools available fares fairly well with current data.
- Electroweak Sudakov logarithms becomes increasingly important raising energy.
- Single top also in good shape (NLO+PS, NNLL resum. approx. NNLO). Complete NNLO might not be in the too far future.
- Various associated production processes known at NLO + PS
- CDF $t\bar{t}$ asymmetry discrepancy slightly reduced but still not satisfactorially explained.
- New observables proposed for the LHC might help shed some light.
- Top-mass precision < 1 GeV is important and has tremendous consequences ...
- Theoretically unambigous top-mass definitions should be used whenever possible

Thank you for your attention!