Theoretical Results on the Top Quark

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- ✓ Will review:
  - ➢ The t-tbar charge (aka forward-backward) asymmetry
  - ➢ Top mass determination
  - ➢ NLO for top-pair production
  - ➢ NNLO for top-pair production
  - ➢ Single top production

- ✓ No time to review many very interesting results:
  - ✓ boosted tops

BOOST2013 workshop: Flagstaff, Arizona, USA, 12-16 Aug 2013

- ✓ experimental reviews (later today)

Top mass: Jernej Castro
Top properties: Joao Varela

Introduction: Top physics in a nutshell

Aims and goals of top physics

✓ Switching gears: moving beyond "testing QCD" :

Study top physics with *reliable, high precision* in order to scrutinize the SM and search for bSM

(M. Peskin: "bSM hides beneath top")

✓ Measure directly, to the extend possible, all top quark related parameters

✓ Search for deviations from SM through high precision analyses
(percent-level precision is plausible both experimentally and theoretically)

Top is truly unique among all quarks

✓ Fast decay (due to large mass):
The only quark that can be studied (mostly) free of non-perturbative effects

Top production is a process that challenges our ability to describe complex hadron collider processes

✓ Top quarks decay to a complex final state with missing energy and lots of radiation:

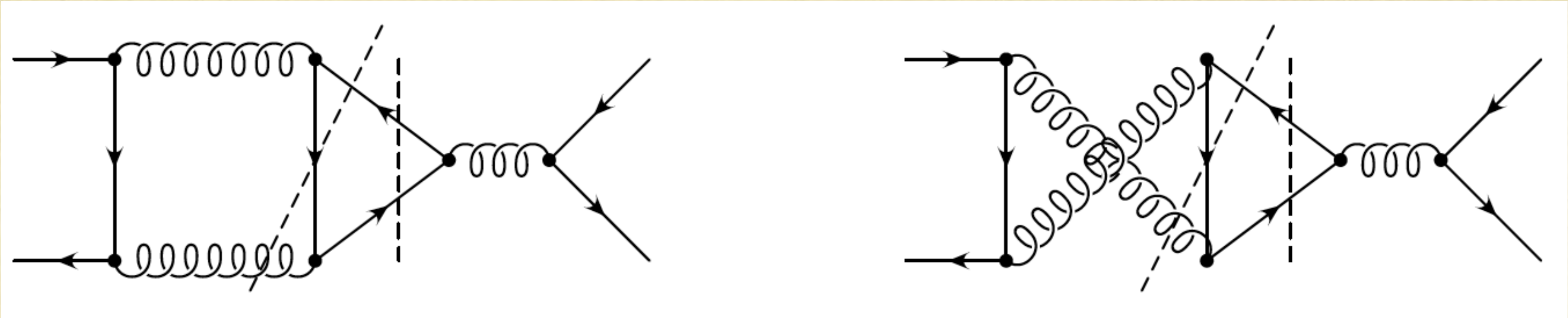
what is a top ?

✓ Requires resummations of soft / collinear emissions in various kinematical regions.
✓ Challenging process that motivates new developments.

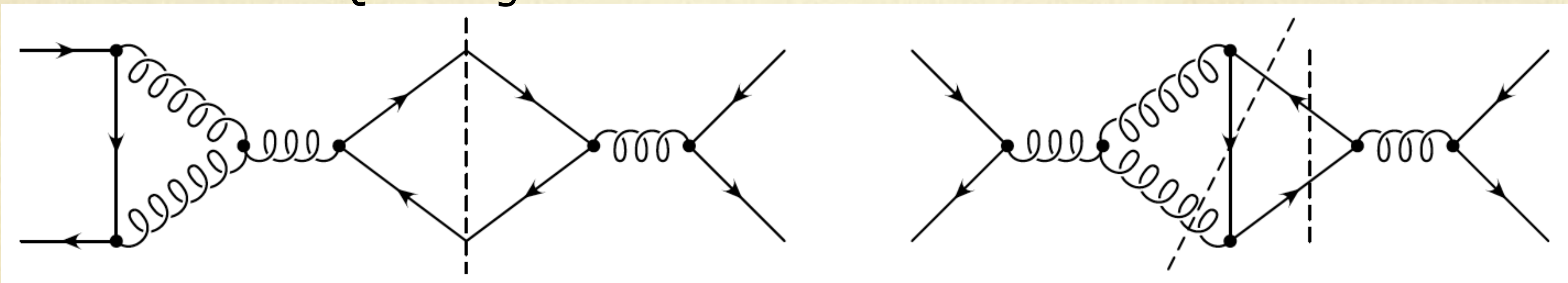
The t-tbar charge (a.k.a. forward-backward A_{FB}) asymmetry

QCD diagrams that generate asymmetry:

Kuhn, Rodrigo '98



… and some QCD diagrams that do not:

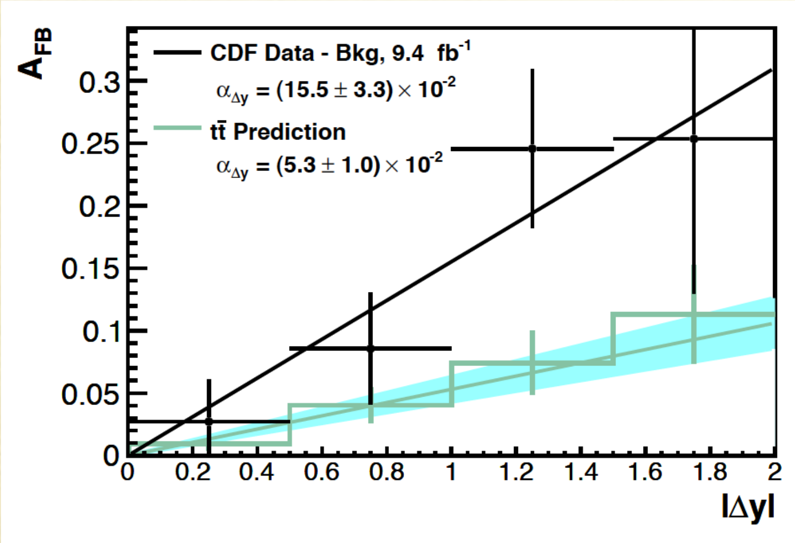


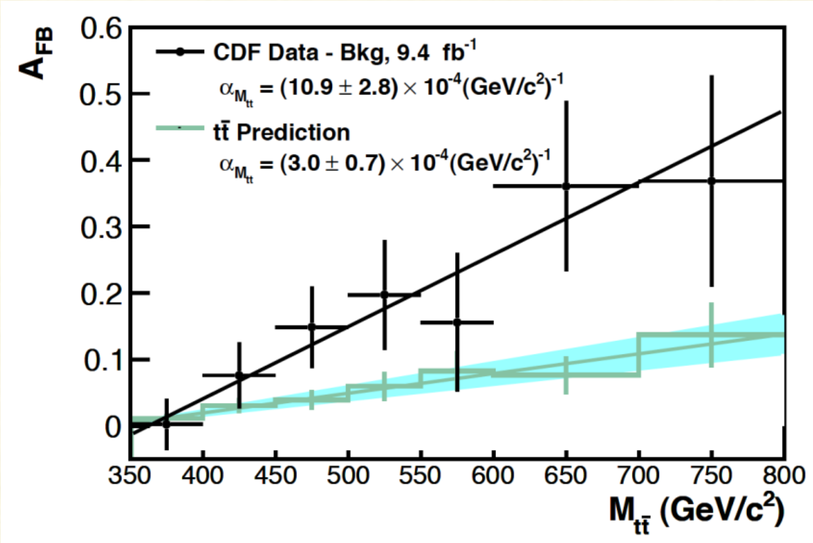
- ✓ For ttbar: charge asymmetry starts from NLO
- ✓ For ttbar + jet: starts already from LO
- ✓ Asymmetry appears when sufficiently large number of fermions (real or virtual) are present.
- ✓ The asymmetry is QED like.
- ✓ It does not need massive fermions.
- ✓ It is the twin effect of the perturbative strange (or c- or b-) asymmetry in the proton!

Definition of the asymmetry:

$$A_{\rm FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

… and the CDF measurement versus (known) SM:





$\boxed{\text{Discrepancy} \leq 3\sigma}$

What is known about A_{FB} ?

- ✓ The largest known contribution to A_{FB} is due to NLO QCD, i.e. $\sim(\alpha_S)^3$.

  Kuhn, Rodrigo '98

- ✓ Higher order soft effects probed. No new effects appear (beyond Kuhn & Rodrigo).

  Almeida, Sterman, Wogelsang '08
  Ahrens, Ferroglia, Neubert, Pecjak, Yang `11
  Manohar, Trott '12
  Skands, Webber, Winter '12

- ✓ F.O. EW effects checked. Not as small as one might naively expect. Can't explain it.

  Hollik, Pagani '11

- ✓ BLM/PMC scales setting does the job? Claimed near agreement with the measurements.

  Brodsky, Wu '12

- ✓ Higher order hard QCD corrections? Not yet known. Expect this year.

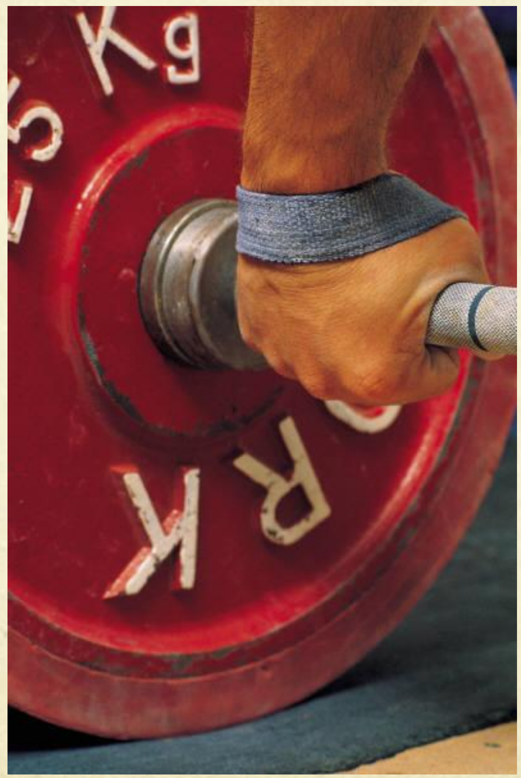
- ✓ Final state non-factorizable interactions? Unlikely.

  Mitov, Sterman '12
  Rosner '12

- ✓ Revisited matching of tt and ttj samples: improves data-SM agreement

  Hoche, Huang, Luisoni, Schonherr, Winter `13

Top mass measurement



Why we care about M_{top}?

✓ It is a fundamental SM parameter that enters "everywhere" in collider physics

✓ It is measured with incredible precision: $\Delta M_{top} / M_{top} \approx 0.5$ %

✓ The measurement and its interpretation, however, are complex:

- ➢ What is measured with such precision? (not an "academic question").
- ➢ General arguments insufficient at such a precision

The real big question, that will be relevant in the near future, is:
Can there be additional systematics in the M_{top} determination that is comparable in size to the current error estimate ΔM_{top}?

✓ This is the charge of the top mass group within the Snowmass Energy Frontier

See writeups by: Mantry, Mitov, Skands, Varnes '13
Mitov, Vos, Wimpenny '13
To appear in the Snowmass white paper `Summer 13

✓ Where does precision in M_{top} matter?

- ➢ EW precision fits: the W-boson mass is the current bottleneck.

See talks by Breese Quinn and Klaus Monig

Where does precision in M_{top} matter? The fate of the Universe might depend on 1 GeV in M_{top}

✓ Higgs Inflation: Higgs = inflaton

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

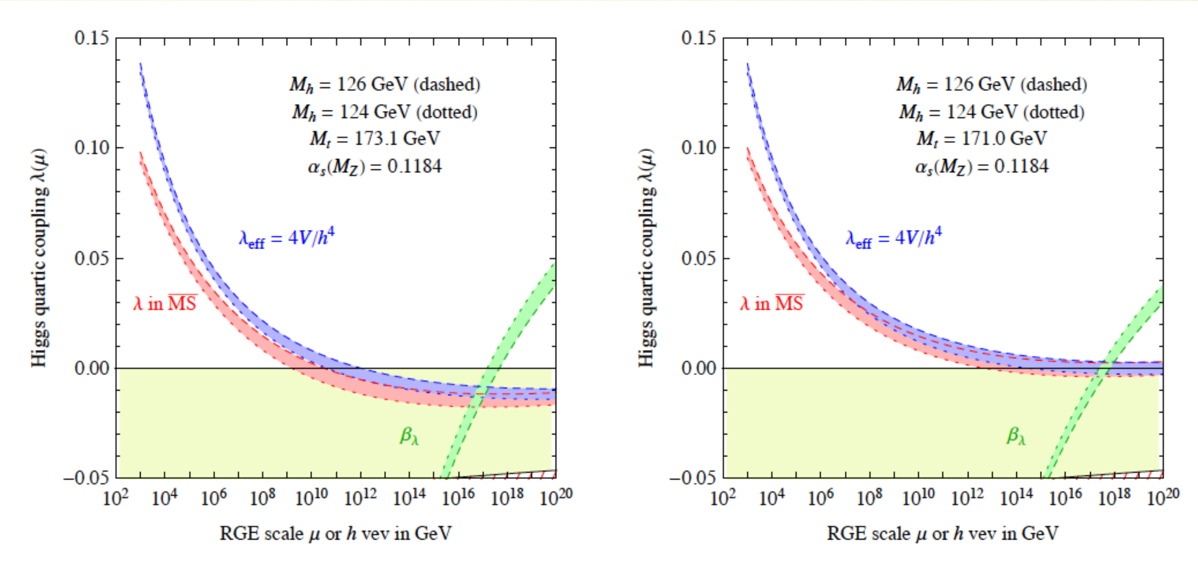
Model's predictions consistent with current *Planck* data.

✓ Higgs mass and vacuum stability in the Standard Model at NNLO.

Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12

$$V_{\text{eff}} = -\frac{m^2}{2}h^2 + \frac{\lambda}{4}h^4 + \Delta V$$

Quantum corrections (included)



➢ Sensitivity is through the boundary conditions (mostly through M_{top}), not evolution.

Chetyrkin, Zoller '12-13
Bednyakov, Pikelner, Velizhanin `13

Most pressing motivations for better understanding the top mass!

Issues with top mass determination

Two main directions:

- ✓ QCD related issues:
  - ➢ Higher order effects;
  - ➢ Top/W width effects;
  - ➢ Non-perturbative effects.

- ✓ Contributions from bSM physics
  - ➢ Not really studied so far.
  - ➢ Unlikely to be "big" but contributions at the level of ΔM_{top} cannot be excluded.
  - ➢ Good methods (i.e. insensitive to NP) will likely rely on kinematics-based variables.
    Example: CMS end-point method.
    But they are also affected by QCD corrections …

bSM contributions to M_{top} is an interesting (and still open) problem.
Contributions to this subject are of interest and will be timely.

Closing comments on top mass:

✓ Try also measurements that are as little sensitive as possible to MC showering

✓ Personal recommendation: dilepton channel without top reconstruction (very clean)

Work in progress

✓ This would be fantastic, given the NLO with complete off-shell top production and decay

Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek ’10
Denner, Dittmaier, Kallweit, Pozzorini `10 – ‘12

NLO: *the new LO*

Advances in NLO technology made possible calculations unthinkable just few years ago

Bern, Dixon, Dunbar, Kosower `94
Britto, Cachazo, Feng `04
Ossola, Papadopoulos, Pittau `07
Giele, Kunszt, Melnikov `08

… including a multipurpose, publicly available, fully differential showered calculations:

aMC@NLO

✓ Fully differential calculation of ttbar + up to 2 jets

✓ NLO production + NLO top decay

✓ NLO production and decay, including interference effects (in semi-leptonic decays)
For the first time full control over Γ_{top} effects. Recall top mass determination!

Dittmaier, P. Uwer, S. Weinzierl '07
Bevilacqua, Czakon, van Hameren, Papadopoulos, Pittau, Worek '08 -`11
Bredenstein, Denner, Dittmaier, Kallweit, Pozzorini `09 -`12
Melnikov, Scharf, Schulze `09 - `11
Campbell, Ellis `12

✓ Matched to parton showers; POWHEG, PowHel.

Frixione, Nason, Ridolfi `07
Garzelli, Kardos, Papadopoulos, Trócsányi `11
Alioli, Moch, Uwer `11

NLO lessons:

- (Any) top-related observable can now be computed at NLO.
- How to take advantage of this fact? LO not justified when there is NLO.
- Top mass applications.
- Speed is always an issue. Being improved all the time.

NNLO: the new wave in top physics

The quest for higher order corrections in top production: an engine for theoretical developments.

- ✓ Early NLO QCD results (inclusive, semi-inclusive)

  Nason, Dawson, Ellis '88
  Beenakker et al '89

- ✓ First fully differential NLO

  Mangano, Nason, Ridolfi' 92

- ✓ 1990's: the rise of the soft gluon resummation at NLL

  Catani, Mangano, Nason, Trentadue '96
  Kidonakis, Sterman '97
  Bonciani, Catani, Mangano, Nason `98

- ✓ NNLL resummation developed (and approximate NNLO approaches)

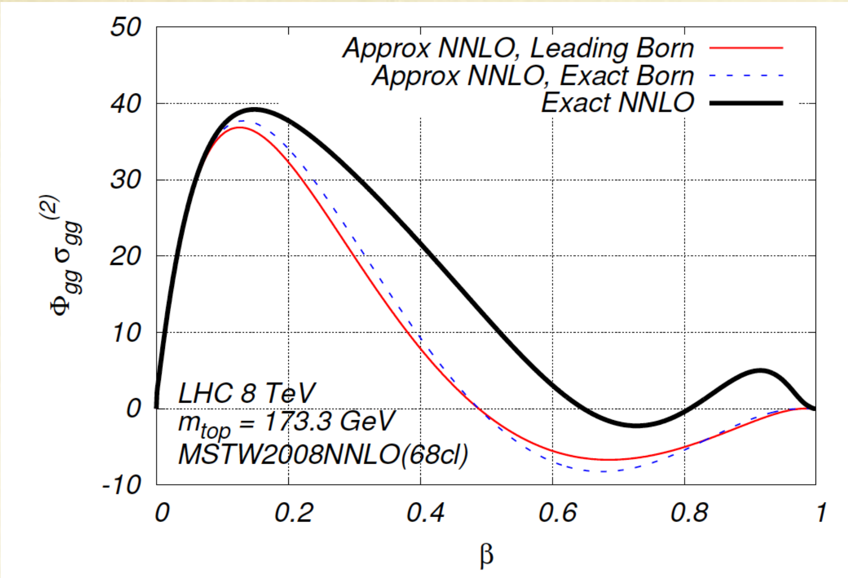
  Beneke, Falgari, Schwinn '09
  Czakon, Mitov, Sterman `09
  Beneke, Czakon, Falgari, Mitov, Schwinn `09
  Ahrens, Ferroglia, Neubert, Pecjak, Yang `10-`11
  Kidonakis `09-`11

- ✓ Electroweak effects at NLO known (small ~ 1.5%)

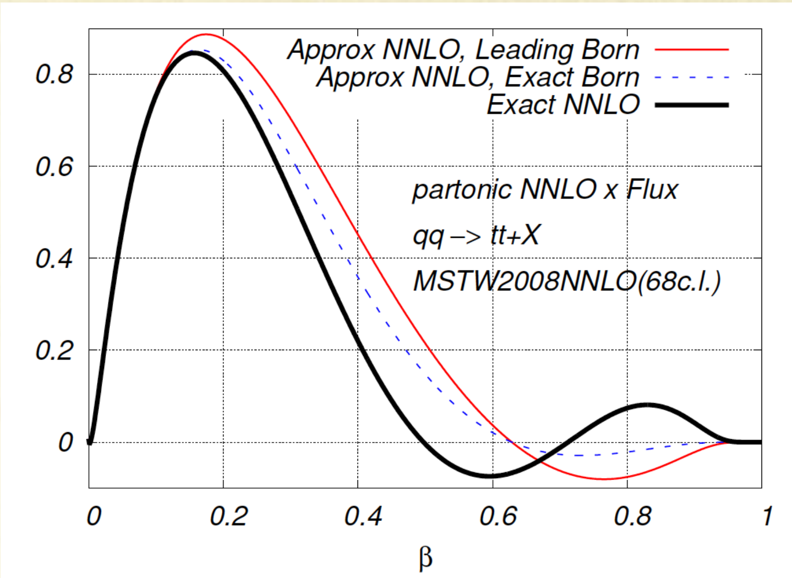
  Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth `93
  Hollik, Kollar `07
  Kuhn, Scharf, Uwer `07-`13

Partonic NNLO cross-sections, convoluted with LHC/Tevatron partonic fluxes

Czakon, Fiedler, Mitov '13



Bärnreuther, Czakon, Mitov `12



The exact NNLO allows for a critical examination of approximate NNLO approaches

Prediction at NNLO+ resummation (NNLL)

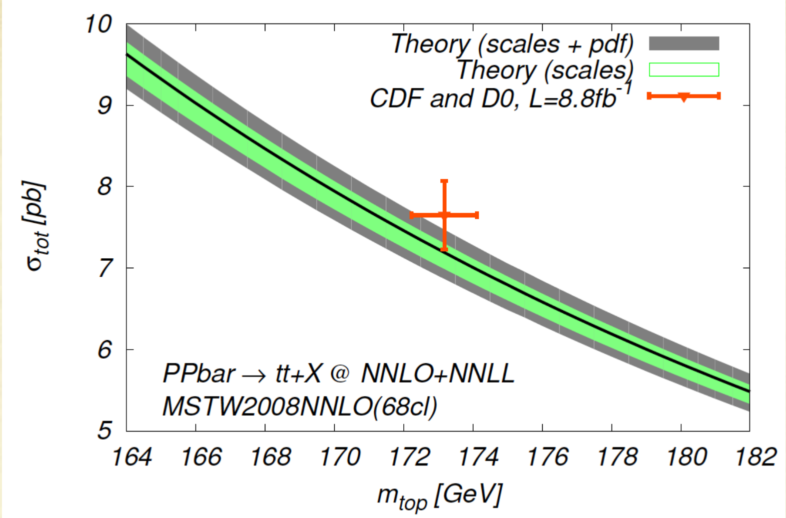
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

Pure NNLO

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	$+0.259(3.7\%)$ $-0.374(5.3\%)$	$+0.169(2.4\%)$ $-0.121(1.7\%)$
LHC 7 TeV	167.0	$+6.7(4.0\%)$ $-10.7(6.4\%)$	$+4.6(2.8\%)$ $-4.7(2.8\%)$
LHC 8 TeV	239.1	$+9.2(3.9\%)$ $-14.8(6.2\%)$	$+6.1(2.5\%)$ $-6.2(2.6\%)$
LHC 14 TeV	933.0	$+31.8(3.4\%)$ $-51.0(5.5\%)$	$+16.1(1.7\%)$ $-17.6(1.9\%)$

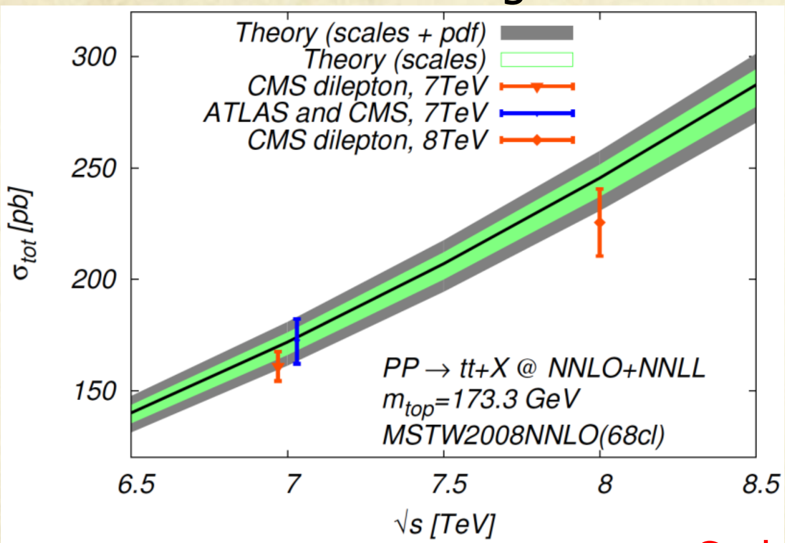
Czakon, Fiedler, Mitov '13

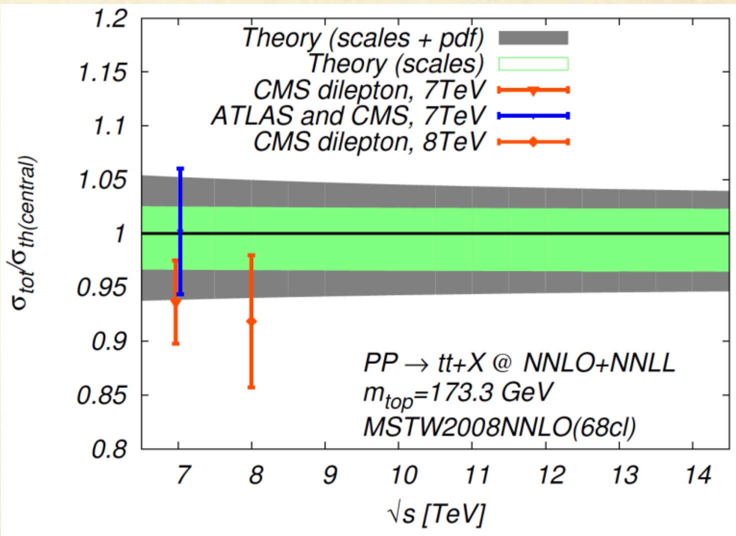
Good agreement with Tevatron measurements



- ✓ Independent F/R scales
- ✓ MSTW2008NNLO
- ✓ mt=173.3

Good agreement with LHC measurements

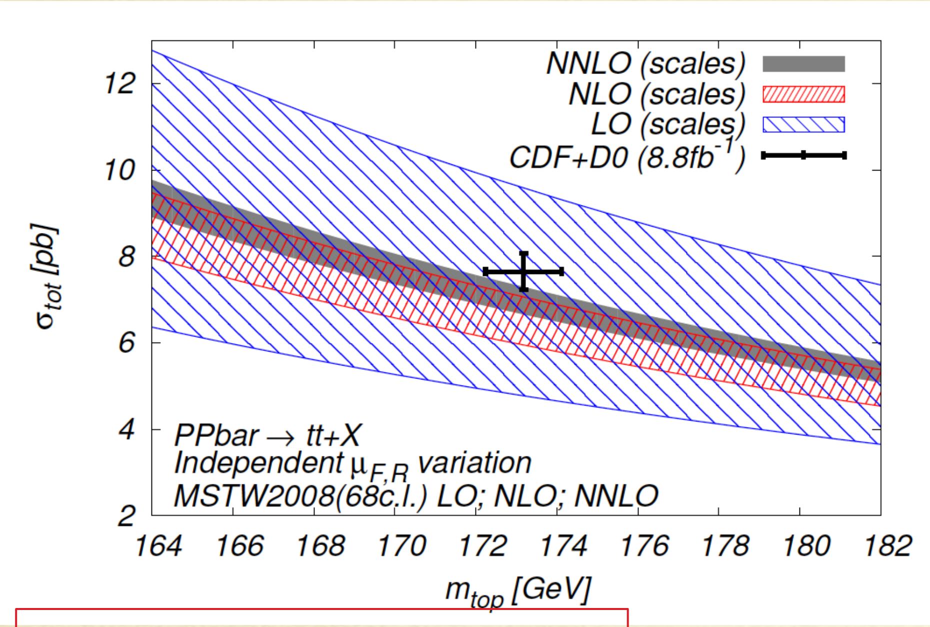




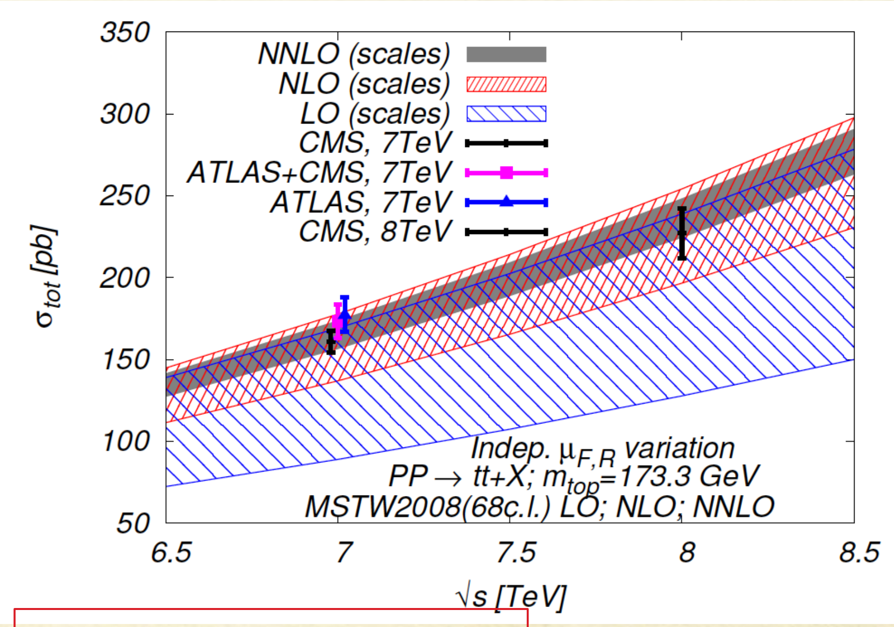
Czakon, Fiedler, Mitov '13

Good perturbative convergence

✓ Independent F/R scales variation



Scale variation @ Tevatron



Scale variation @ LHC

✓ Good overlap of various orders (LO, NLO, NNLO).

✓ Suggests the (restricted) independent scale variation is a good estimate of missing higher order terms!

This is very important: good control over the perturbative corrections justifies less-conservative overall error estimate, i.e. more predictive theory (see next 2 slides).

For more detailed comparison, including soft-gluon resummation, see arXiv 1305.3892

LHC: general features at NNLO+NNLL

Czakon, Fiedler, Mitov ’13
Czakon, Mangano, Mitov, Rojo ‘13

✓ We have reached a point of saturation: uncertainties due to

- ✓ scales (i.e. missing yet-higher order corrections) ~ 3%
- ✓ pdf (at 68%cl) ~ 2-3%
- ✓ alpha_S (parametric) ~ 1.5%
- ✓ m_{top} (parametric) ~ 3%

→ All are of similar size!

✓ Soft gluon resummation makes a difference: scale uncertainty 5% → 3%

How to add these uncertainties?

So far a more conservative approach was followed(scales added linearly).

Likely to move to adding errors in quadrature in the future.

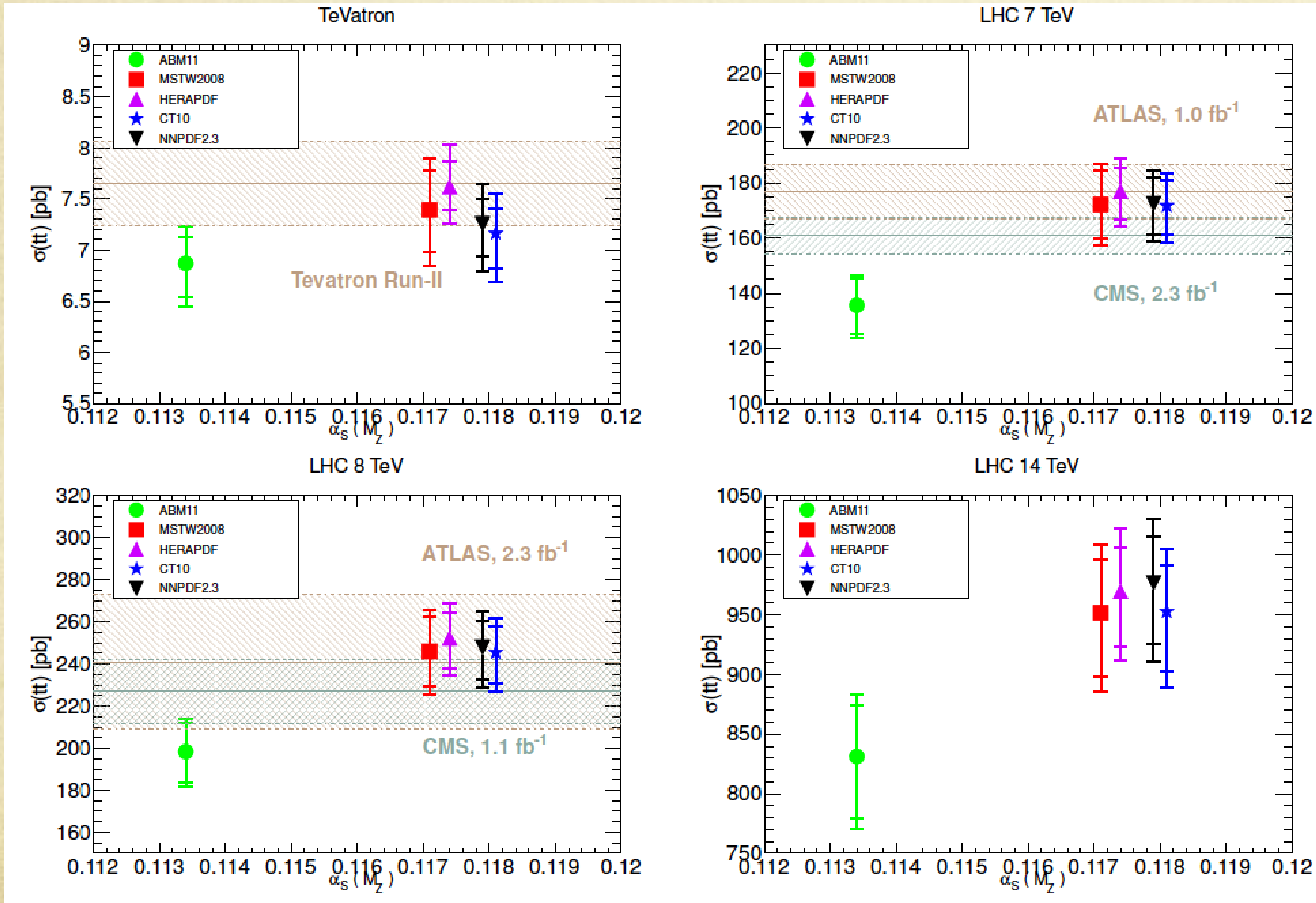
Application to PDF's

Czakon, Mangano, Mitov, Rojo '13

How existing pdf sets fare when compared to existing data?

Most conservative theory uncertainty:

Scales + pdf + as + mtop



Excellent agreement between almost all pdf sets

21

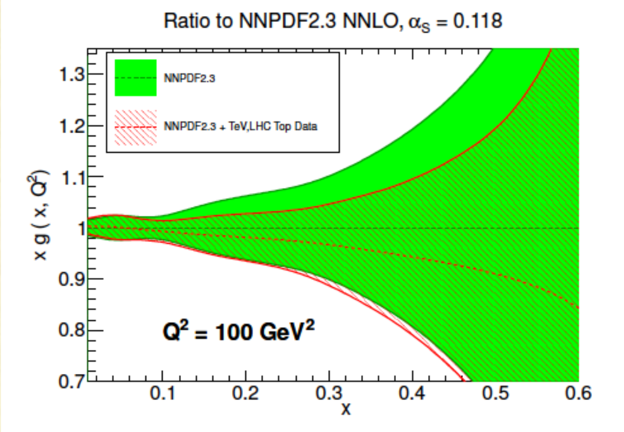
Application to PDF's

✓ tT offers for the first time a direct NNLO handle to the gluon pdf (at hadron colliders)

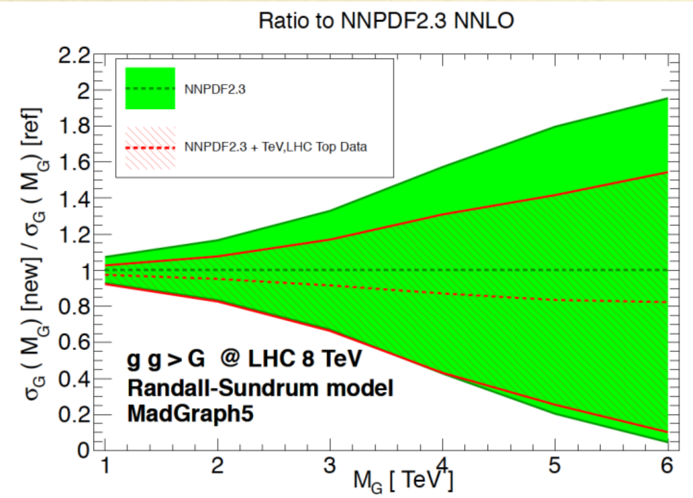
✓ implications to many processes at the LHC: Higgs and bSM production at large masses

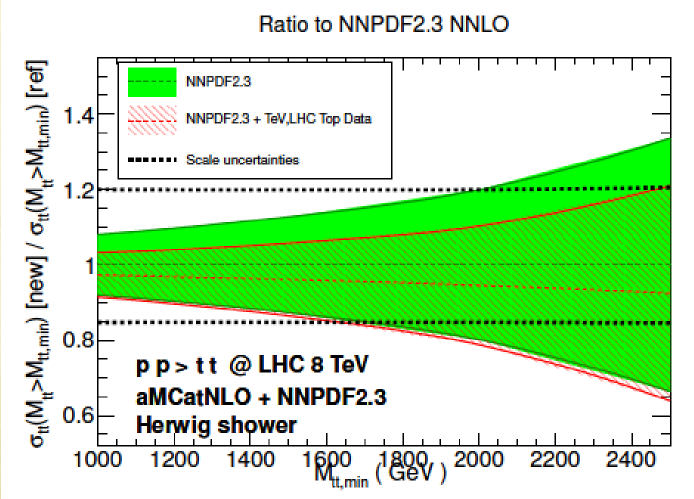
One can use the 5 available (Tevatron/LHC) data-points to improve gluon pdf

"Old" and "new" gluon pdf at large x:



… and PDF uncertainty due to "old" vs. "new" gluon pdf: Czakon, Mangano, Mitov, Rojo '13





Application to bSM searches: stealthy stop

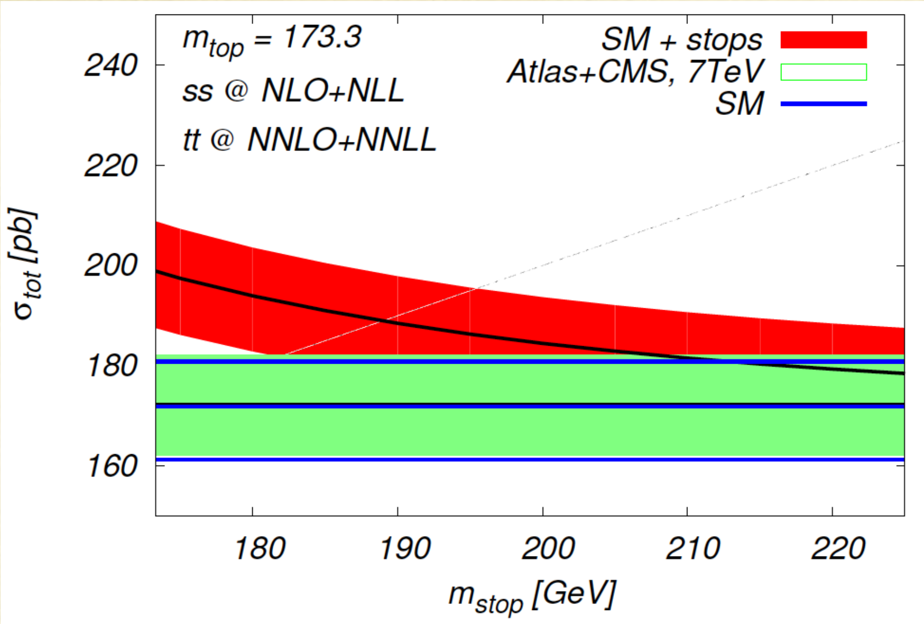
- ✓ Scenario: stop → top + missing energy
  - ✓ m_stop small: just above the top mass.
  - ✓ Stop mass < 225 GeV is allowed by current data
  - ✓ Usual wisdom: the stop signal hides in the top background

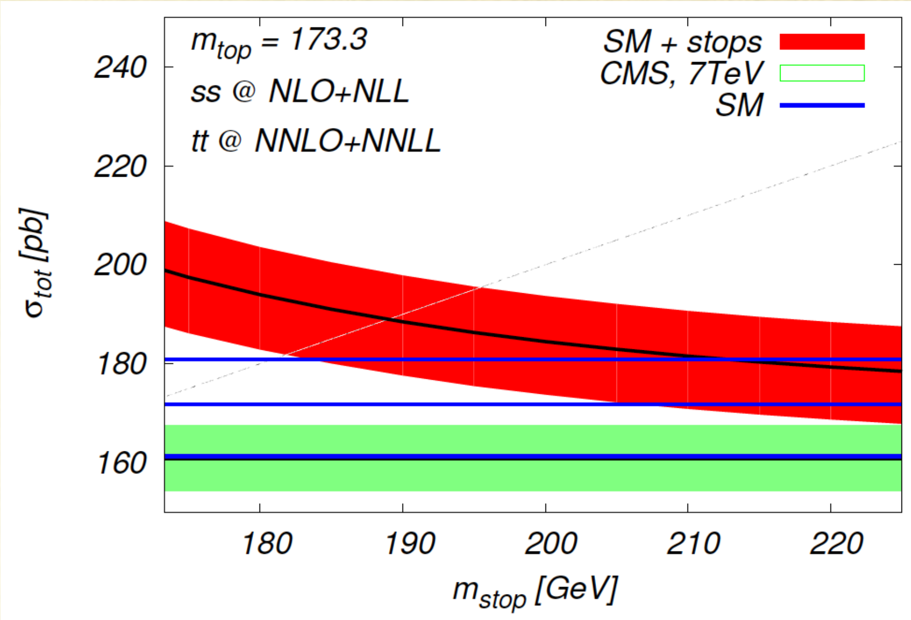
- ✓ The idea: use the top x-section to derive a bound on the stop mass. Assumptions:
  - ✓ Same experimental signature as pure tops
  - ✓ the measured x-section is a sum of top + stop
  - ✓ Use precise predictions for stop production @ NLO+NLL

    Krämer, Kulesza, van der Leeuw, Mangano, Padhi, Plehn, Portell \`12
  - ✓ Total theory uncertainty: add SM and SUSY ones in quadrature.

Applications to the bSM searches: stealth stop

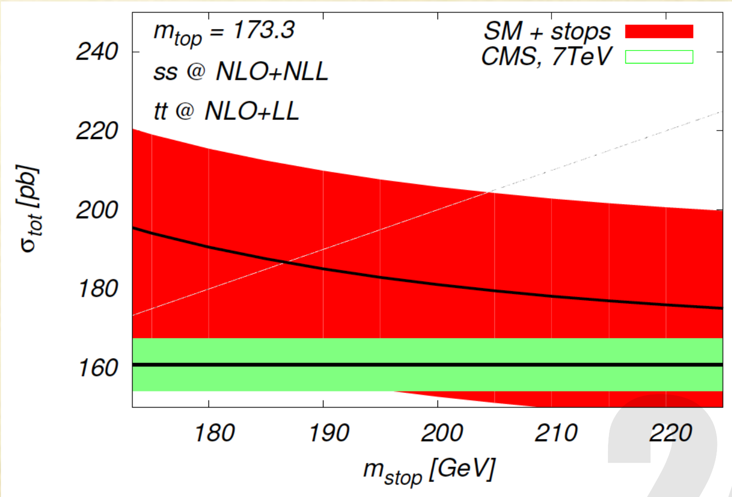
✓ Predictions   Preliminary





Wonder why limits were not imposed before?

Here is the result with "NLO+shower" accuracy :



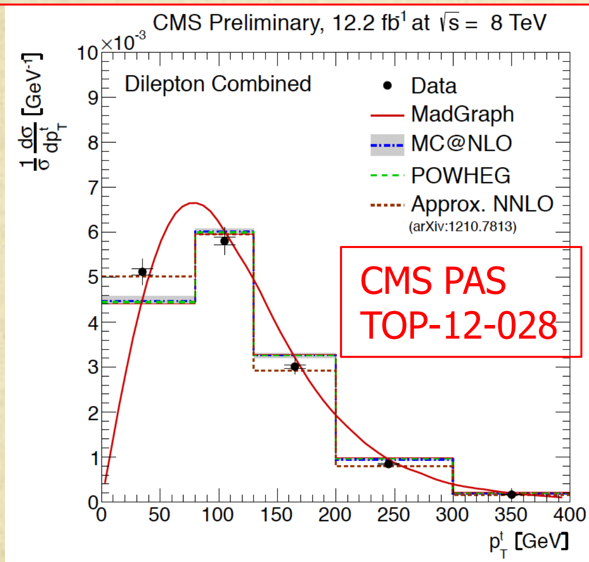
Improved NNLO accuracy makes all the difference

Currently refining the analysis (with Czakon, Papucci, Ruderman, Weiler)

Looking at the details: differential distributions

- Differential distributions are currently computable at NLO. With the help of resummations some approximate NNLO results are also known.

P_T spectrum of a top quark (inferred)

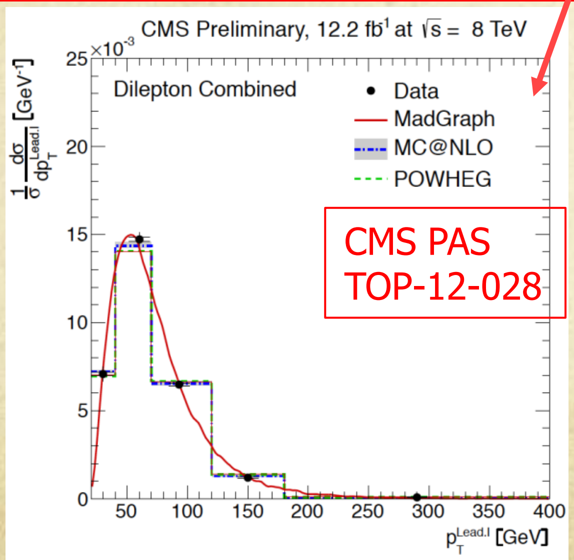


- ✓ It seems that approximate NNLO result (from resummation) Kidonakis `12 describes top quark distributions better than fully differential NLO calculations. MC@NLO, POWHEG

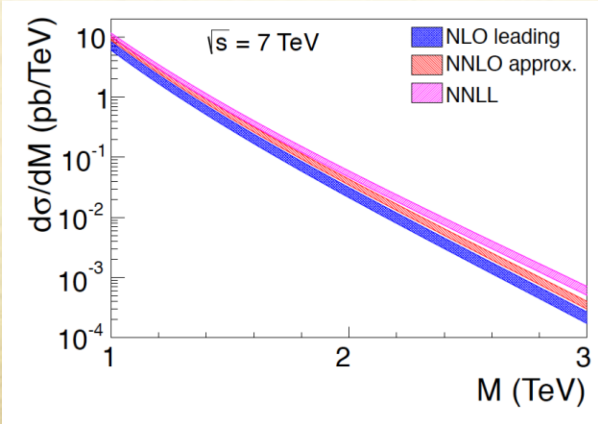
- ✓ However: diff. NLO calculations describe well the distributions of top-decay products (leptons in particular). Which is what's measured!

- ✓ Looking forward to the resolution of this in the near future …

P_T spectrum of the lepton in top quark decay (measured)

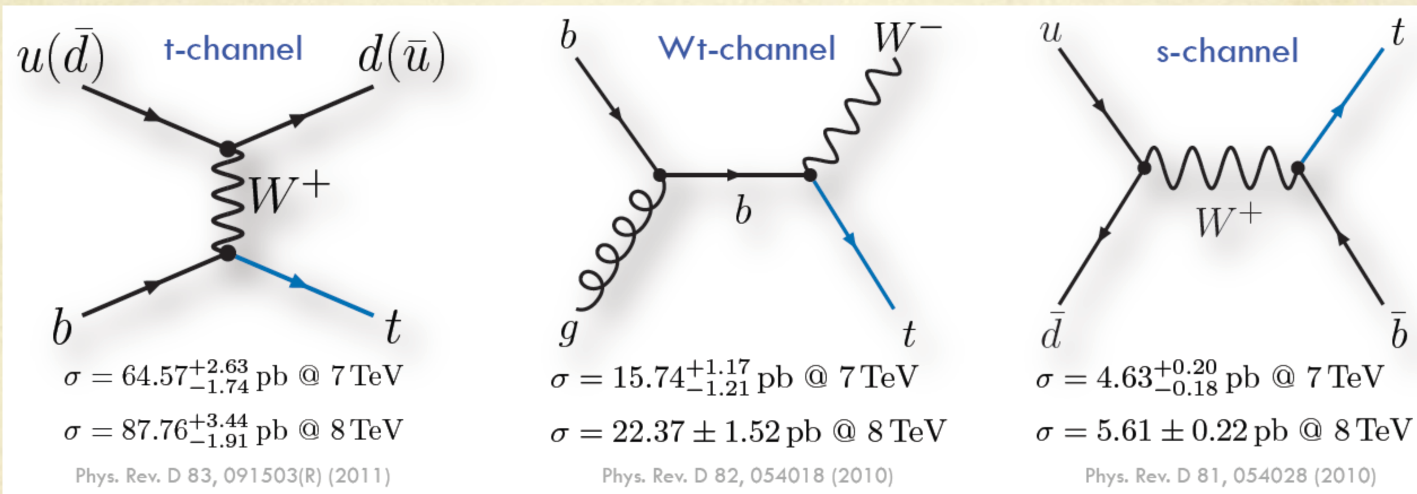


- ✓ In the very high energy region top production necessitates resummation of collinear logs. Recent work at NNLL: Ferroglia, Pecjak, Yang '13



Notable difference between Various approximations

Single top production



Plot thanks to Jan Stillings (LHCP 2013)

- ✓ As the LHC energy grows, single top production becomes comparable to top pair production.
- ✓ It is much less studied however.
- ✓ Known at NLO for stable top. Top decays in NWA.

Frixione, Laenen, Motylinski, Webber `05
Alioli, Nason, Oleari, Re `09
Frederix, Re, Torrielli `12
Campbell, Ellis, Tramontano `04
Schwienhorst, Yuan, Mueller, Cao `10
Falgari, Giannuzzi, Mellor, Signer `11

- ✓ And approximate NNLO

Kidonakis `10-`11
Wang, Li, Zhu, Zhang '10

- ➢ Single top production is computable with present techniques at NNLO.
- ➢ The main missing piece are the two-loop amplitudes.
- ➢ They involve more scales and are not suitable for the most advanced numerical approaches used in top pair production:

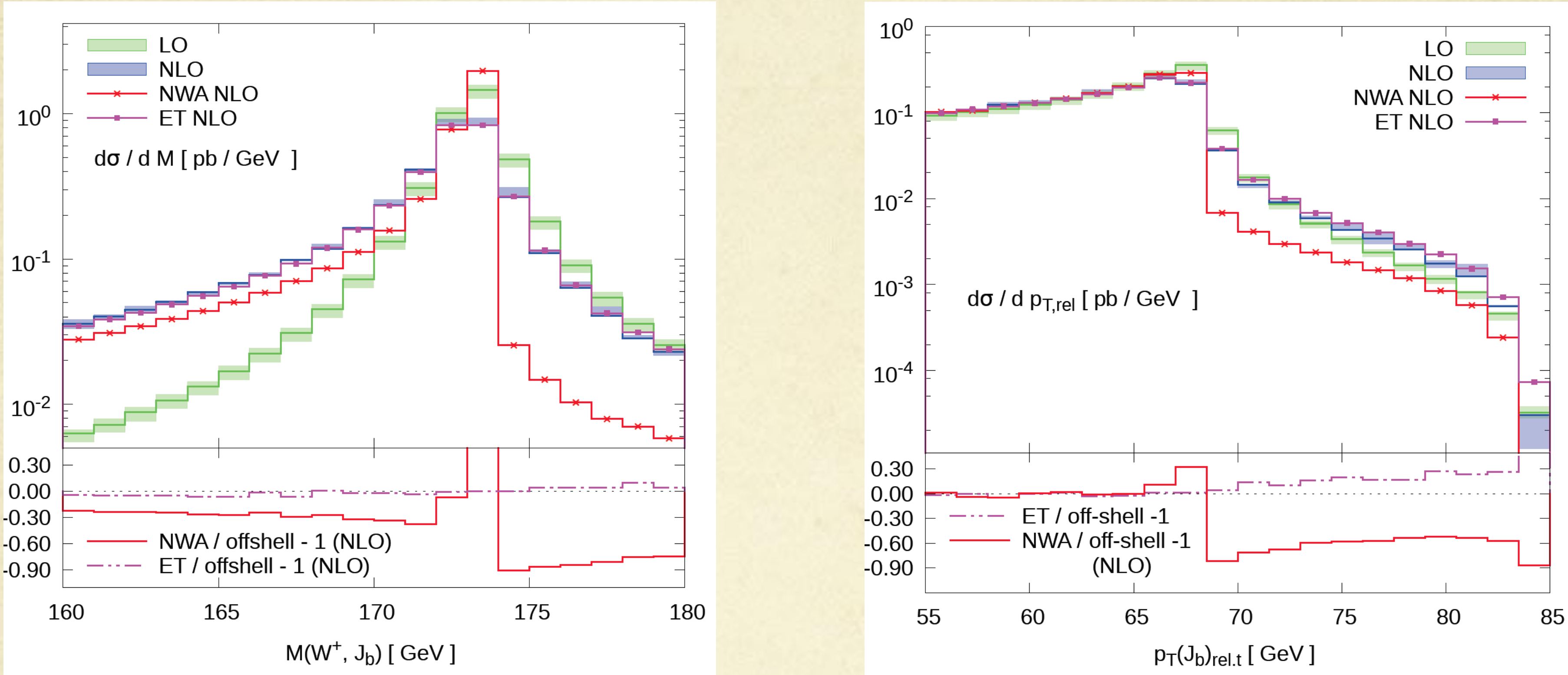
Czakon`07
Baernreuther, Czakon, Fiedler '13

- ➢ New, and feasible, amplitude approaches are needed.
- ➢ Could benefit from new formal developments:

Srednyak, Sterman `13

➢ New important step: full off-shell and non-resonant effects at NLO for t-channel

aMC@NLO: Papanastasiou, Frederix, Frixione, Hirschi, Maltoni `13



✓ Large corrections in tails of distributions

✓ Small corrections for inclusive observables. Exactly as in the case of top-pair production

Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '10
Denner, Dittmaier, Kallweit, Pozzorini `10 – '12

Summary and Conclusions

- ✓ Shift of paradigm in top physics: statistics not an issue any more!
  - ✓ Few percent measurements already available
- ✓ Dramatic changes in top theory, too:
  - ✓ Percent level precision for total x-section
  - ✓ Fully differential kinematics (for now at NLO), with top decay and off-shell effects. (done for top pair; single top is catching up)
- ✓ Top mass determination: still work to do.
- ✓ NNLO calculations now possible:
  - ➢ Total inclusive x-section known at NNLO
  - ➢ Fully differential NNLO results will follow.
  - ➢ Next order corrections to A_{FB}

New results, NNLO in particular, open whole new perspective on understanding theory errors!

- ➢ The Snowmass white paper will be a comprehensive source on top physics circa 2013
- ➢ And a prediction for the next Lepton Photon meeting: top physics will look a lot different ☺

Backup slides

Q: A_{FB} **: is there a coherent picture that emerges from these partial results?**

A single soft emission is sufficient to generate the full NLO QCD effect (i.e. the LO asymmetry).

This is a surprise. Two possible conclusions:

- The soft emissions know all there is to know about A_{FB}.
  - ✓ Implication: There will be no noticeable correction at $(\alpha_S)^4$,
    i.e. do not expect higher order corrections.

Almeida, Sterman, Wogelsang '08
Melnikov, Schultze '09

- The 2-loop hard corrections (can't be predicted with resummation) could be substantial.
  - ✓ Implication: The NLO agreement *soft ≈ hard* is accidental
    or does not work beyond 1 loop (inspiration from QED)
  - ✓ Supported by: NLO corrections to A_{FB} in ttbar+jet are very large ≈ - 80%.
    - Fits the expectation: A_{FB} in ttbar+jet is due to hard emissions.
    - But note: soft effects never checked in ttbar+jet.

Should be resolved by the full NNLO calculation, when becomes available