Top quark production at hadron colliders:

Theory Overview

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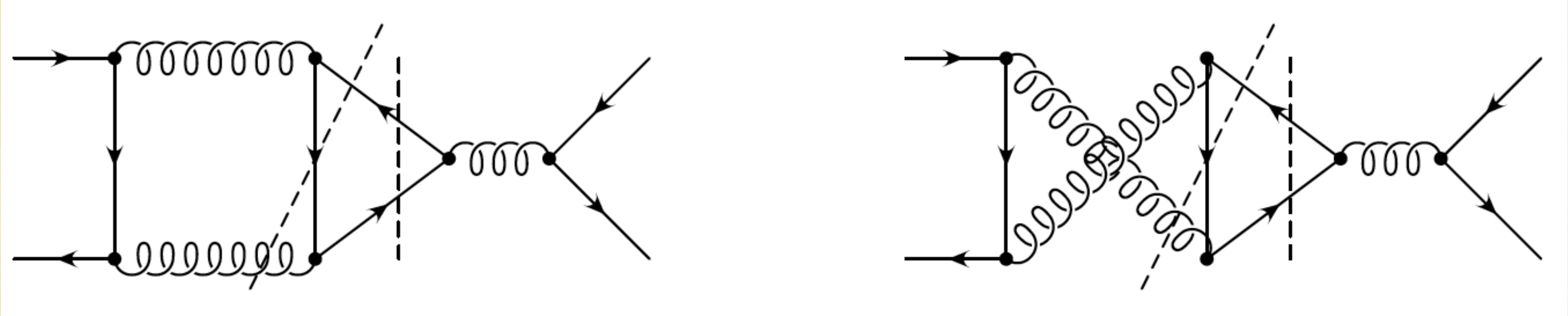
- ✓ In depth review of:
    - ➢ The t-tbar charge (aka forward-backward) asymmetry
    - ➢ Top mass determination
    - ➢ NLO
    - ➢ NNLO

- ✓ No time to review many very interesting results:
    - ✓ spin correlations
    - ✓ boosted tops
    - ✓ single top

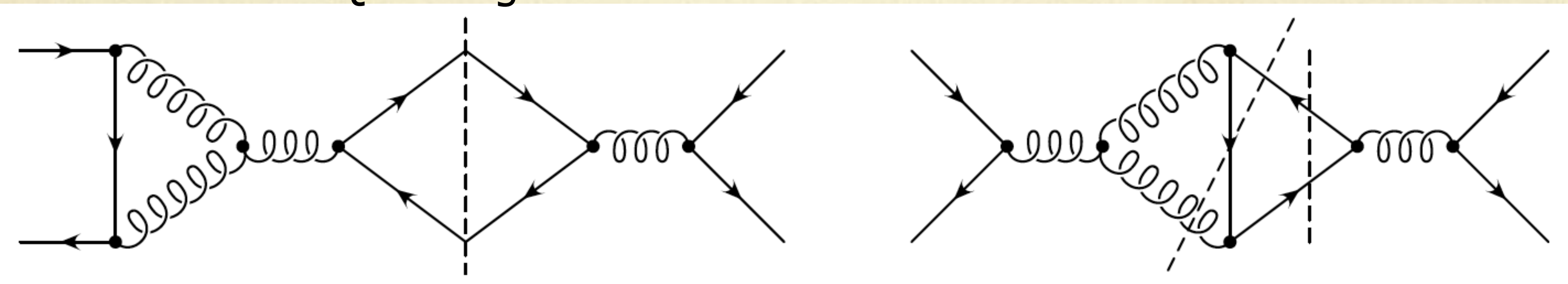
The t-tbar charge (a.k.a. forward-backward A_{FB}) asymmetry

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!

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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 scales setting does the job? Claimed near agreement with the measurements.

Brodsky, Wu '12

✓ Higher order hard QCD corrections? Not yet known.

✓ Final state non-factorizable interactions? Unlikely.

Mitov, Sterman, to appear
Rosner '12

Q: Is there a coherent picture that emerges from these partial results?

A single soft emission is sufficient to generate the full NLO 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 (which can't be predicted) 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.

More hints for possibly large NLO corrections to A_{FB}:

✓ The $(\alpha_S)^4$ corrections to the total cross-section (more later) are about ≈ 40% from $(\alpha_S)^3$.

✓ True uncertainty larger than usual estimates:

- Naïve scale variation suggests only few percent uncertainty
- Difference between alternative perturbative expansions suggest ≈ 30%!

✓ BLM corrections: near agreement with the measurements claimed.

Brodsky, Wu '12

- Not yet scrutinized in top production: perhaps will not perform as well as in 'simpler' processes like B ➔ s+γ (where it works very well).
- Since BLM reorganizes the expansion; so, the full result should, too, be able to 'get' the size of the effect.

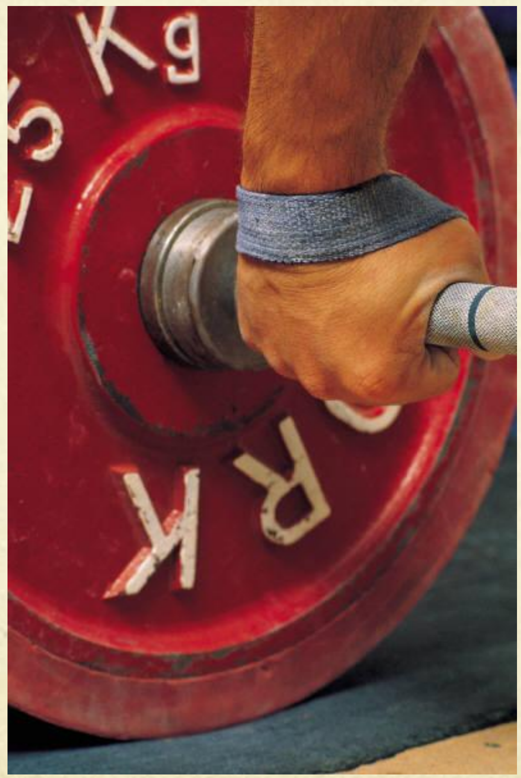
✓ Can it be backgrounds?

- Any process with sufficient number of fermion loops (real and/or virtual) has asymmetry (more of a rule than an exception).
  Top measurements are with jets and leptons, not tops. Thus any mismodeling of backgrounds can impact the measurement.

Hagiwara, Kanzakib, Takaesu '12

Once the full NLO A_{FB} is known, we will know if SM can explain A_{FB} discrepancy at the Tevatron

Top mass measurement



Why we care about M_{top}?

- Because M_{top} is a fundamental parameter of SM
- Because QCD precisions depend on it
- **Because the fate of the Universe might depend on 1 GeV in M_{top}!**

Cosmological implications:

- Higgs Inflation: Higgs = inflaton

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

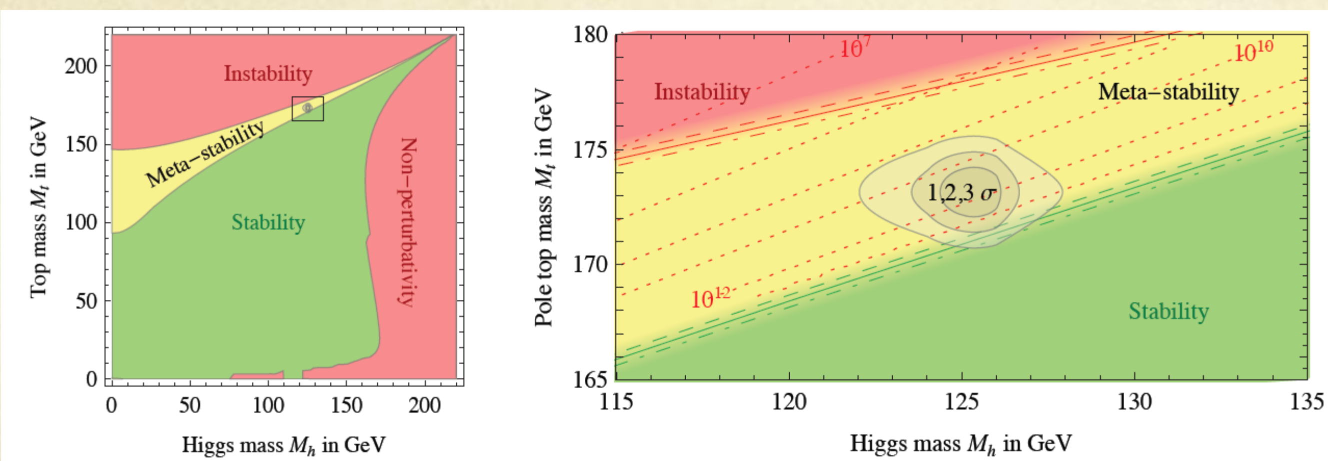
$$\boxed{\mathcal{L}_h = -|\partial H|^2 + \mu^2 H^\dagger H - \lambda (H^\dagger H)^2 + \xi H^\dagger H \, \mathcal{R}}$$

$$\boxed{m_h > 125.7\,\text{GeV} + 3.8\,\text{GeV}\left(\frac{m_t - 171\,\text{GeV}}{2\,\text{GeV}}\right) - 1.4\,\text{GeV}\left(\frac{\alpha_s(m_Z) - 0.1176}{0.0020}\right) \pm \delta}$$

Strong dependence on the top mass!

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

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



Instability scale Λ in GeV:
δM_{top} is the
dominant uncertainty!

Issues with top mass determination:

Astounding experimental precision: for now Tevatron leads (LHC will catch up):

$$M_{top} = 173.2 \pm 0.9 \text{ GeV}$$ arXiv:1107.5255

? What is measured, M_{top} or top "pseudo mass"?

? How is the top "pseudo mass" related to M_{top}?

- Experiments employ the template method. It utilizes LO MC's (more later).
- This should prompt us to think about:
  - ✓ Higher order effects (needed for proper mass definition)
  - ✓ Top width effects $O(\Gamma_{top})$: must be controlled to achieve such precision.
- Renormalon effects $O(\Lambda_{QCD})$: affect pole mass; not MSbar mass.
  Likely not a worry at current level of precision.

Theoretical approaches for M_{top} determination

✓ Approach 1 of 3: Extend the template method (as used by experiment) @ NLO.

Campbell, Giele, Williams '12

- NLO still being developed; already applied to M_Z.
- Application to M_{top} @ NLO expected.

Aside reading: how the MET method works?

arXiv:hep-ph/9802249v1

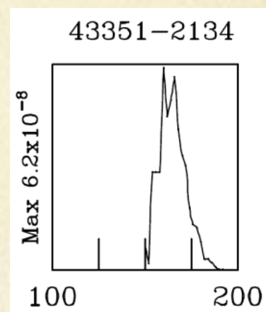
Step 1:

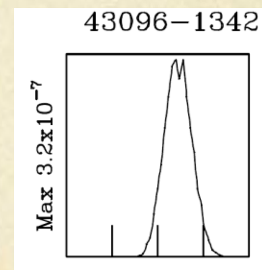
Take the measured configuration of momenta for the final leptons and jets in a single event i and evaluate the probability

$$P_i(m) = P(\text{configuration event } i \mid m)$$

that these production and decay processes could produce the observed configuration if the top quark mass were m.

Examples of $P_i(m)$ for Tevatron events:





Step 2:

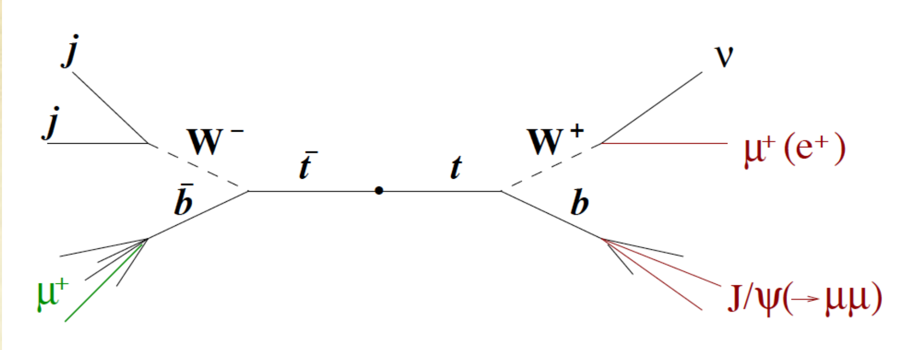
apply Bayes' Theorem to infer the mass:

$$P(m|\text{data set }\{i\}) = \prod_{i=1}^{N} P(\text{event } i|m) \cdot \Phi(m)$$

a priori probability that the top mass is m

Hint: calculated in LO QCD so far

Theoretical approaches for M_{top} determination



✓ Approach 2 of 3: M_{top} from J/Ψ final states.

A very different method.

Kharchilava '99
Chierici, Dierlamm CMS NOTE 2006/058

- Relies on strong correlation between an observable and M_{top}
- Very sensitive to b-fragmentation (non-perturbative).
- Non-traditional, but it could be applied with confidence.
- Fully differential QCD description available at NLO.

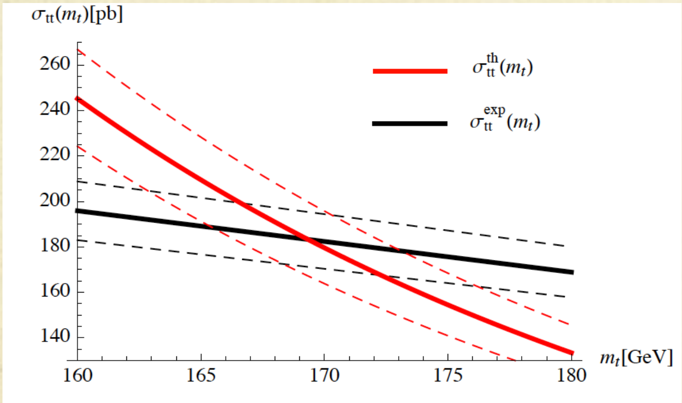
Biswas, Melnikov, Schulze '10

✓ The method is very clean

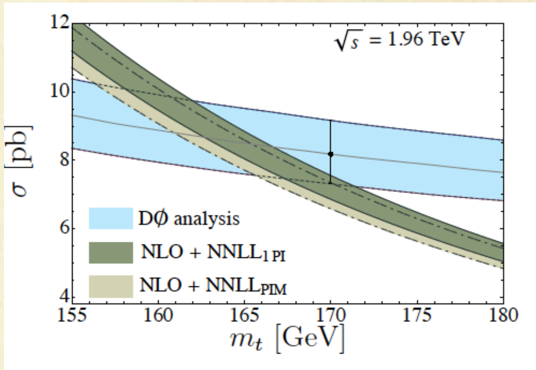
- Precision of $\delta M_{top} \leq 1$ GeV is feasible with this method. Full theoretical control.
- Low branching fraction B→ J/Ψ. Very large top sample needed.
- Likely to work only for LHC@14TeV.

Theoretical approaches for M_{top} determination

- ✓ Approach 3 of 3: Extract M_{top} from the top cross-section.
  - ✓ Theoretically very good control.
  - ✓ Extraction not as sensitive to M_{top} : $(\delta M_{top}/M_{top}) = \pm 3\%$.
  - ✓ A good independent cross-check. So far well consistent with direct measurements.



Beneke, Falgari, Klein, Schwinn `11



Ahrens, Ferroglia, Neubert, Pecjak, Yang `11

Best extraction: $m_t = (169.8^{+4.9}_{-4.7})\,\mathrm{GeV}$

Similar extractions from:

Langenfeld, Moch, Uwer `09
Ahrens, Ferroglia, Neubert, Pecjak, Yang `11

- ✓ Proposed idea: extract MSbar mass; not pole mass

Langenfeld, Moch, Uwer `09

- ✓ Makes little difference (as expected)

Ahrens, Ferroglia, Neubert, Pecjak, Yang `11

NLO: *the new LO*

See also Zvi Bern's talk

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

- ✓ 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 -`11
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.
- 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

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

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

Until 1 moth ago σ_{TOT} analyzed in approximate NNLO QCD

Many groups:

Beneke, Falgari, Klein,Schwinn `09-`11

Ahrens, Ferroglia, Neubert, Pecjak, Yang `10-`11

Kidonakis `04-`11

Aliev, Lacker, Langenfeld, Moch, Uwer, Wiedermann ’10

Cacciari, Czakon, Mangano, Mitov, Nason ‘11

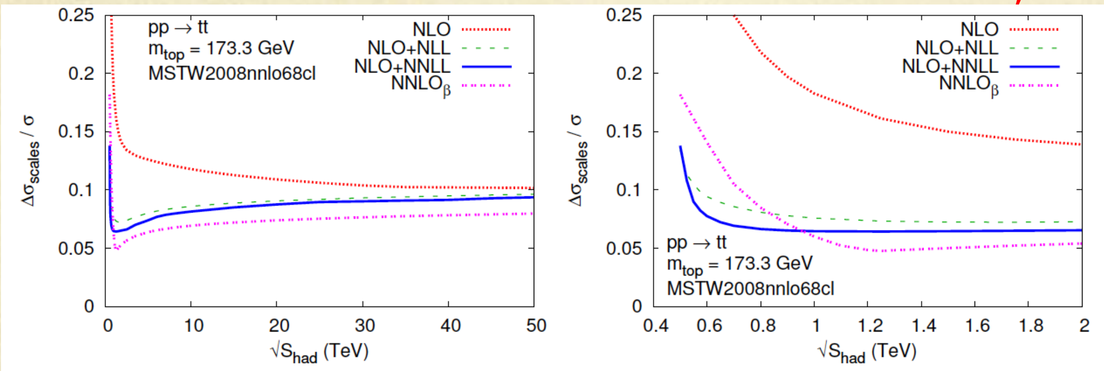
Some selected results at NNLO$_{approximate}$

✓ NLO+NNLL Resummation of Soft and Coulombic terms in SCET

Beneke, Falgari, Klein, Schwinn `11

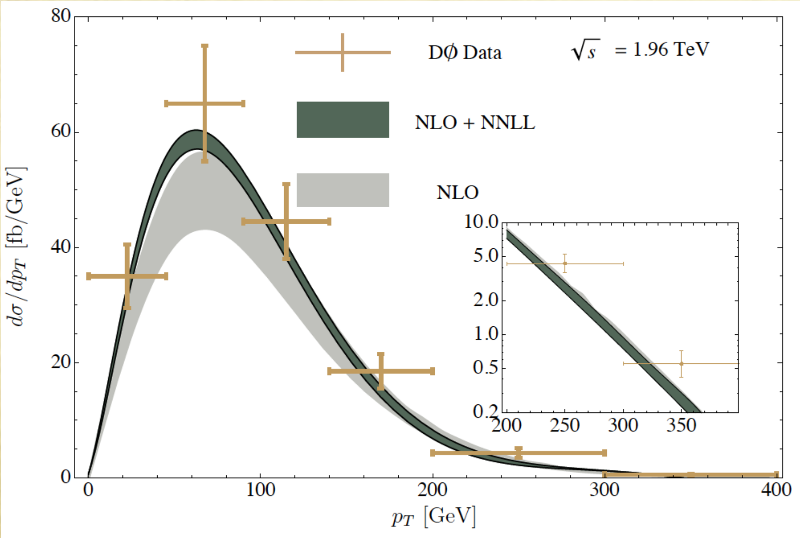
✓ NLO+NNLL resummation in Mellin space

Cacciari, Czakon, Mangano, Mitov, Nason '11



✓ SCET based differential distributions with NLO+NNLL precision:

Ahrens, Ferroglia, Neubert, Pecjak, Yang `11



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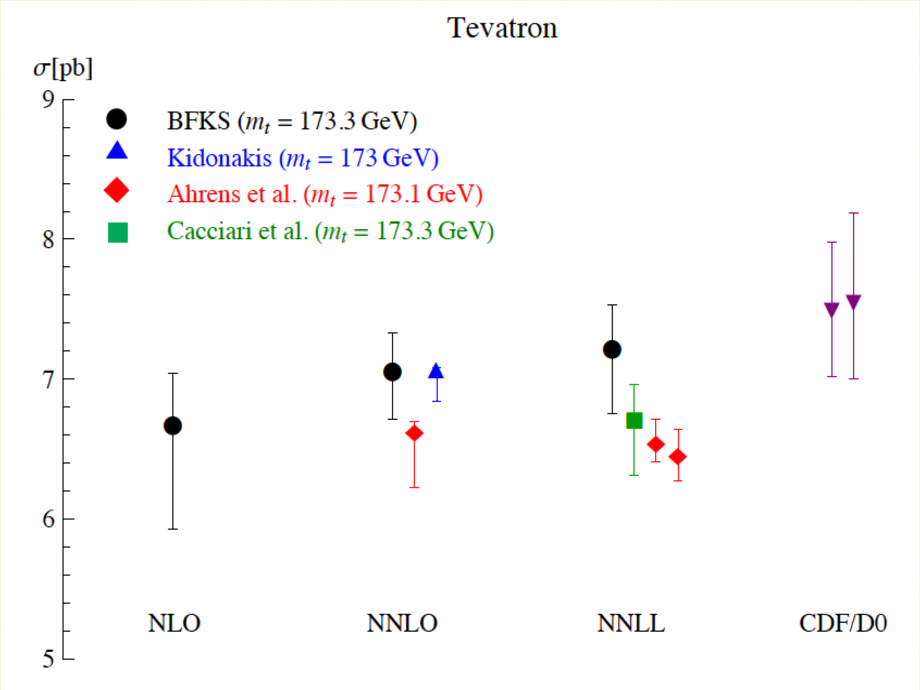
Comparison between various $\text{NNLO}_{\text{approx}}$ groups shows:



Beneke, Falgari, Klein, Schwinn `11

- ✓ Significant differences between various predictions
- ✓ Suggests the true uncertainty of approximate NNLO

A major step forward: first complete NNLO result

- ✓ First ever hadron collider calculation at NNLO with more than 2 colored partons.
- ✓ First ever NNLO hadron collider calculation with massive fermions.

- ➢ So far published qq → tt +X

Bärnreuther, Czakon, Mitov `12

- ➢ Remaining fermionic reactions computed

Czakon, Mitov (to appear)

- ➢ Work on the remaining reactions (qg, gg) progressing well.

Results @ parton level

Partonic cross-section through NNLO:

$$\sigma_{ij}\left(\beta, \frac{\mu^2}{m^2}\right) = \frac{\alpha_S^2}{m^2}\left\{\sigma_{ij}^{(0)} + \alpha_S\left[\sigma_{ij}^{(1)} + L\,\sigma_{ij}^{(1,1)}\right] + \alpha_S^2\left[\sigma_{ij}^{(2)} + L\,\sigma_{ij}^{(2,1)} + L^2\sigma_{ij}^{(2,2)}\right] + \mathcal{O}(\alpha_S^3)\right\},$$

The NNLO term:

$$\sigma_{q\bar{q}}^{(2)}(\beta) = F_0(\beta) + F_1(\beta)N_L + F_2(\beta)N_L^2$$

Numeric

Analytic

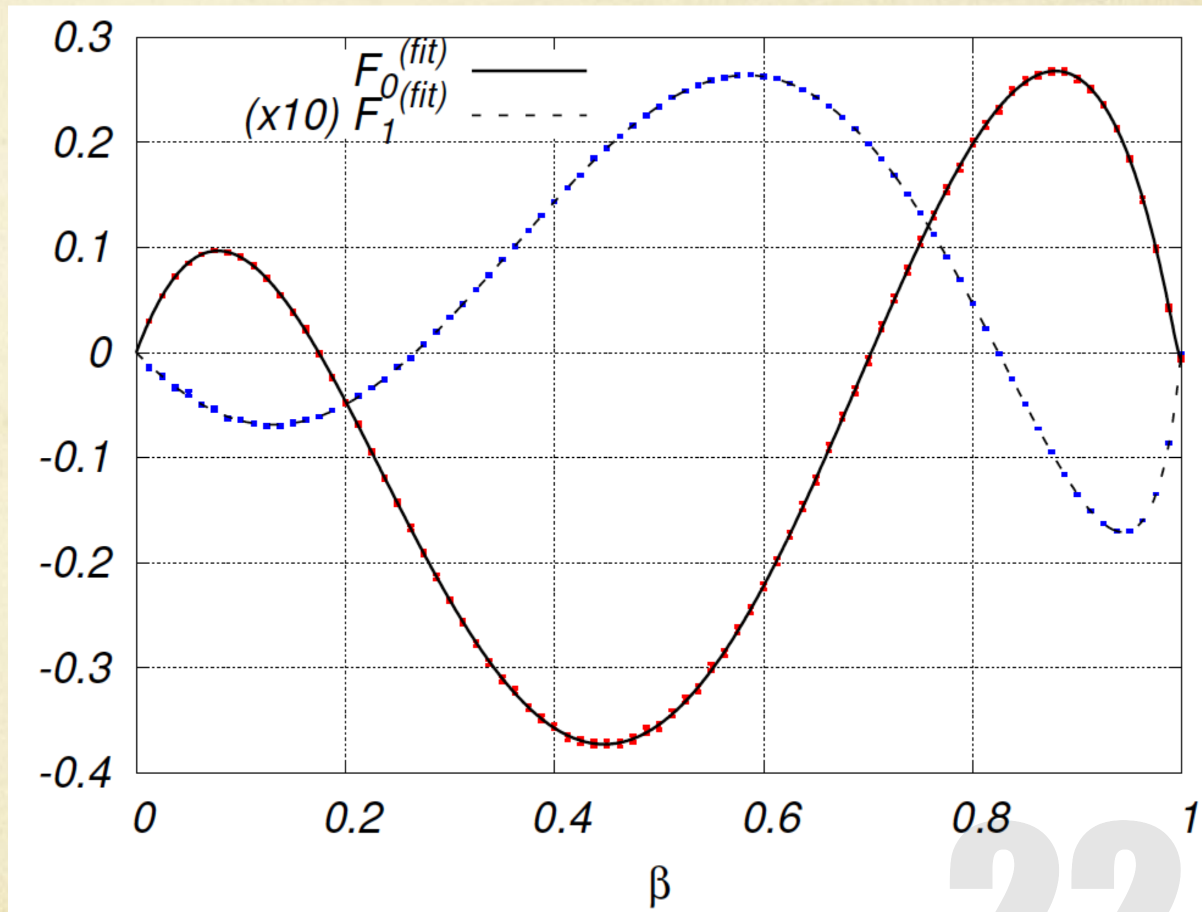
$$F_i \equiv F_i^{(\beta)} + F_i^{(\mathrm{fit})}, i = 0, 1$$

The known threshold approximation

Beneke, Czakon, Falgari, Mitov, Schwinn `09

Notable features:

- ✓ Small numerical errors
- ✓ Agrees with limits



P. Bärnreuther et al arXiv:1204.5201

NNLO phenomenology at the Tevatron:

P. Bärnreuther et al arXiv:1204.5201

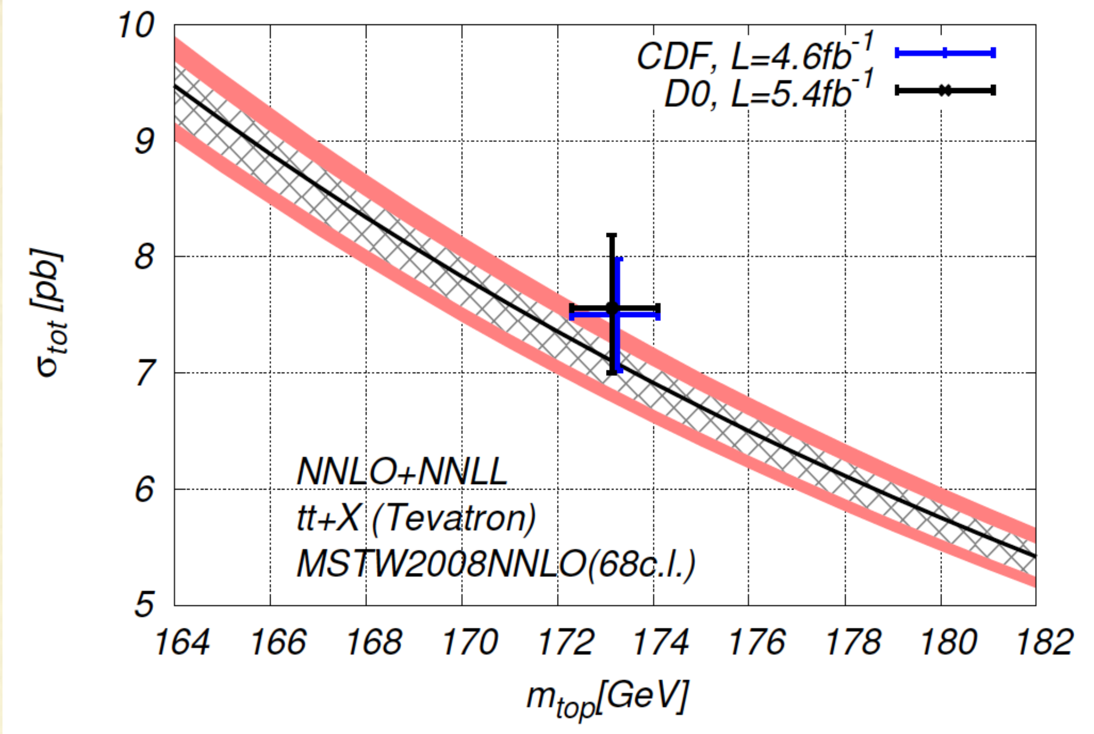
- ✓ Independent F/R scales
- ✓ MSTW2008NNLO
- ✓ mt=173.3

NNLO

$$\sigma_{\rm tot}^{\rm NNLO} = 7.005\ ^{+0.202\,(2.9\%)}_{-0.310\,(4.4\%)}\ [\text{scales}]\ ^{+0.170\,(2.4\%)}_{-0.122\,(1.7\%)}\ [\text{pdf}]$$

$$\sigma_{\rm tot}^{\rm res} = 7.067\ ^{+0.143\,(2.0\%)}_{-0.232\,(3.3\%)}\ [\text{scales}]\ ^{+0.186\,(2.6\%)}_{-0.122\,(1.7\%)}\ [\text{pdf}]$$

Best prediction at NNLO+NNLL



- ✓ Two loop hard matching coefficient extracted and included
- ✓ Very week dependence on unknown parameters (sub 1%): gg NNLO, A, etc.
- ✓ ~ 50% scales reduction compared to the NLO+NNLL analysis of

Cacciari, Czakon, Mangano, Mitov, Nason '11

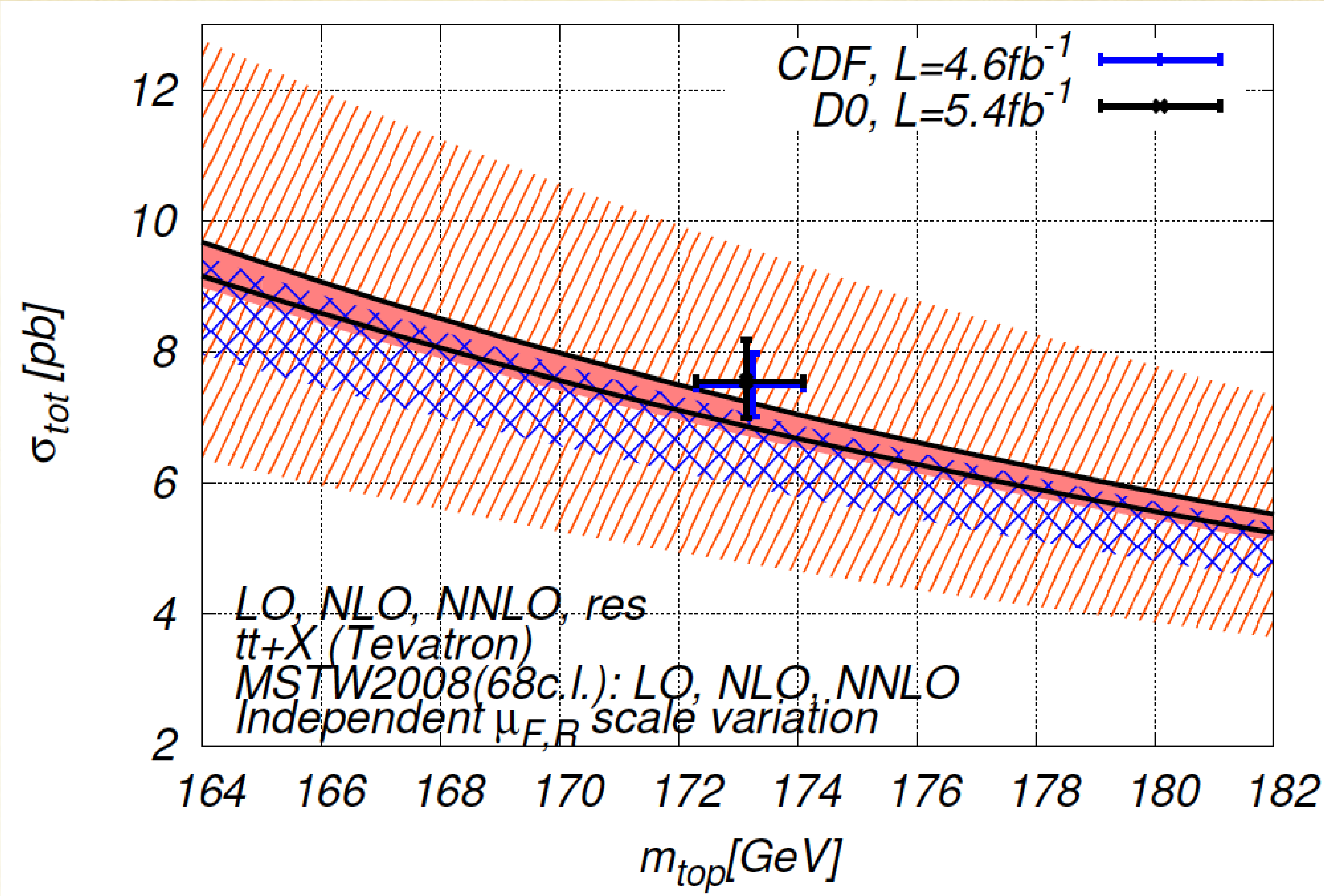
$$6.722\ ^{+0.238\,(3.5\%)}_{-0.410\,(6.1\%)}\ [\text{scales}]\ ^{+0.160\,(2.4\%)}_{-0.115\,(1.7\%)}\ [\text{PDF}]$$

Resumed (approximate NNLO)

Good perturbative convergence:

✓ Independent F/R scales
✓ mt=173.3

P. Bärnreuther et al arXiv:1204.5201

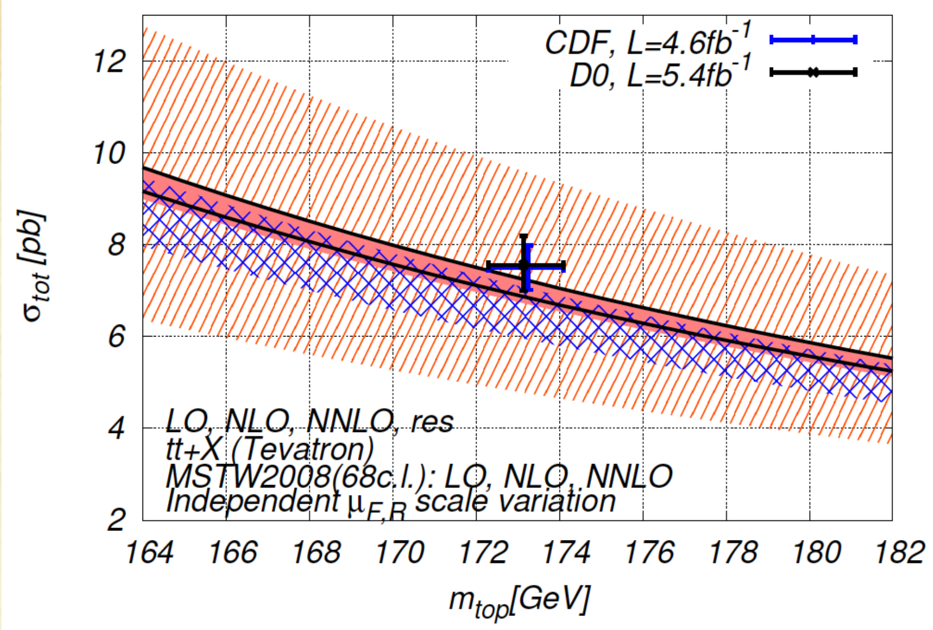


✓ Good overlap of various orders (LO, NLO, NNLO).
✓ Suggests our (restricted) independent scale variation is good

K-factors

- Numbers Computed with ***Top++***
- Current version 1.2
- Includes all NNLO results
- Very fast, easy to use public program

Czakon, Mitov arXiv:1112.5675



$$\sigma^{NNLO}\text{ (NNLO pdf)} = \underbrace{5.22059}_{(\alpha_S)^2} + \underbrace{1.23417}_{(\alpha_S)^3} + \underbrace{0.548064}_{(\alpha_S)^4}$$

Same K-factors with NLO pdf

$K_{NLO/LO}$=1.24

$K_{NNLO/NLO}$=1.08 ($K_{NNLO+NNLL/NLO}$=1.09)

K-factors alone not totally adequate without taking uncertainties into account

Summary and Conclusions

- ✓ The LHC, and Tevatron, are roaring into uncharted territories every day!
  - ✓ And so is top theory!
- ✓ Dramatic changes have happened in top theory.
  - ✓ Here to stay!
- ✓ All @ NLO is pretty much a reality. Speed improvements under way. Parton showers.
- ✓ Top mass determination: still work to do.
- ✓ NNLO calculations now possible:
  - ➢ Expect all inclusive reactions soon (qg- and gg- remaining – work well underway)
  - ➢ Fully differential NNLO results will follow.
  - ➢ Next order corrections to A_{FB}