Latest theoretical developments in top physics at hadron colliders

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Based on works with:

Michal Czakon '11 and (in progress)
Cacciari, Czakon, Mangano and Nason '11
George Sterman (in progress)

Plan for the talk

The focus is on the total inclusive cross-section. Will comment on differential too.

① What is well established

① Open questions

① Recent results

① Brand new results (game changer; ~25-years in the waiting)

What is well established

Top-pair production is completely known within NLO/NNLL QCD

Main features:

- ✓ Very large NLO corrections ~50%
- ✓ Theory uncertainty at ~10%
- ✓ Important for Higgs and bSM physics
- ✓ Experimental improvements down to 5%
- ✓ Current LHC data agrees well with SM theory
- ✓ Tevatron data generally agrees too.
  The notable exception: Forward-backward asymmetry from CDF.

Important shift in gears: currently we have fully differential NLO calculations including top decays. This is the direction of the future.

Open questions

- ✓ Reliably increase the precision of the theoretical predictions? [more next]

- ✓ What to make of the forward – backward asymmetry?

  - ✓ Can missing theory corrections be large? Yes!
    (almost universally assumed small)

  - ✓ Is this enough to explain A_{FB}? Perhaps not!

This will only be settled once the SM predictions have been exhausted (currently A_{FB}(tT+X) is at LO!)

Recent results

✓ How to improve theory?

All improvements in the last 15-20 years are based on soft gluon resummation.

✓ This has recently been extended to full NNLL level

Czakon, Mitov, Sterman `09
Beneke, Falgari, Schwinn '09

✓ … and analyzed by a number of groups:

Ahrens, Ferroglia, Neubert, Pecjak, Yang
Kidonakis
Aliev, Lacker, Langenfeld, Moch, Uwer, Wiedermann
Beneke, Falgari, Klein, Schwinn
Cacciari, Czakon, Mangano, Mitov, Nason

✓ Conclusion: resummation is
- very important at LL,
- relatively important at NLL,
- modest improvement at NNLL(+NLO) (compared to other missing contributions)

  at NNLL level total uncertainty is reduced: 10% → 9%

Cacciari, Czakon, Mangano, Mitov, Nason `11

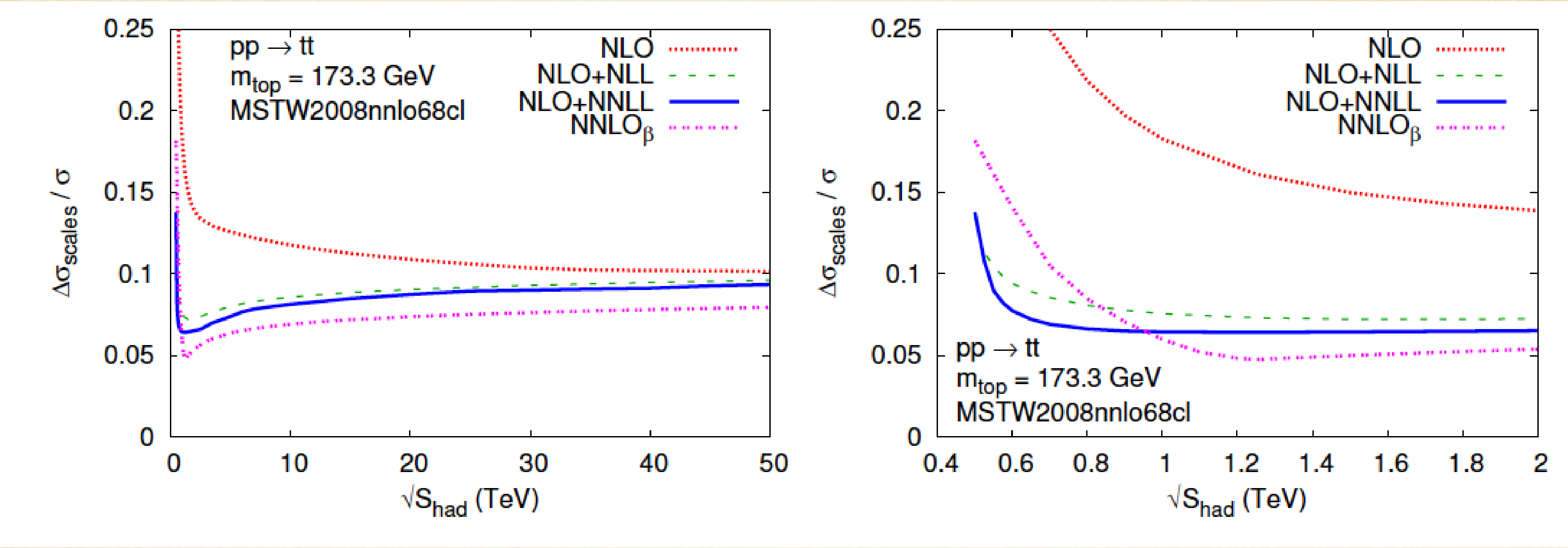
✓ Lots of activity recently.

✓ Note of caution: resummation (or its truncation NNLO_approx) are not substitutes for NNLO.

Recent results

Textbook example: by changing the collider energy go into (out of) the threshold region

Cacciari, Czakon, Mangano, Mitov, Nason `11



- Resummed results are better when close to threshold (as expected)
- One can quantify the question: when are we close to threshold? (below 1 TeV or so)
- Approx_NNLO is a subset of the resumed result. Overused recently.
  Has accidentally small scale dependence.

Recent results

✓ We have also prepared the tools for top physics:

Top++ : a C++ program for the calculation of the total cross-section:

Czakon, Mitov `11

✓ Includes:

- fixed order (NLO and NNLO_approx at present)
- and resummation (full NNLL already there)

✓ It is meant to incorporate the full NNLO once available (to appear)

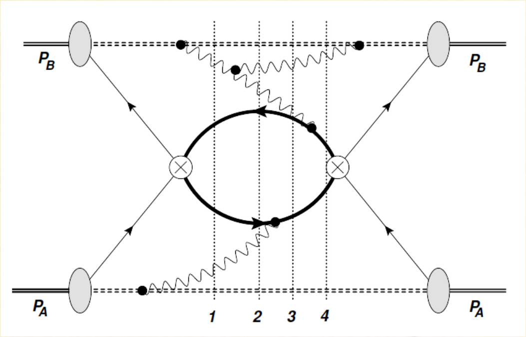
✓ Very user friendly.

Brand new results

Brand new results

Motivating question: can A_{FB} be generated (or enhanced) by tT final state interactions?

Work with George Sterman, to appear



Prompted, in turn, by older work in QED

See, for example, Brodsky, Gillespie`68

- ✓ We have devised an all-order proof of the cancellations of such interactions
- ✓ The subtle point is: What is the remainder? All depends on observables' definition.
- ✓ For inclusive observables (with conventional factorization) the remainder is small.
- ✓ For observables with rapidity gaps: large corrections are possible.

Brand new results

NNLO result for qq→ tT at Tevatron and LHC

Work with M. Czakon, P. Barnreuther

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

Recall: NLO corrections derived almost 25 years ago

Nason, Dawson, Ellis `88 ,89
Beenakker, Kuijf, van Neerven, Smith `89

✓ What is computed?

$$\sigma = \frac{\alpha_s^2}{m_t^2} \sum_{ij} \int_0^{\beta_{\max}} \mathcal{L}_{ij}(\beta) \hat{\sigma}(\beta)$$

Relative velocity of tT

$$\rho = \frac{4m_t^2}{s} \qquad \beta = \sqrt{1-\rho}$$

✓ The partonic cross-section computed numerically in 80 points. Then fitted.

✓ Many contributing partonic channels:

Computed. Dominant at Tevatron (~85%)

$$q\bar{q} \to t\bar{t}$$
$$q\bar{q} \to t\bar{t}g$$
$$q\bar{q} \to t\bar{t}gg$$
$$q\bar{q} \to t\bar{t}q'\bar{q}', \quad q \neq q'$$

$$gg \to t\bar{t}$$
$$gg \to t\bar{t}g$$
$$gg \to t\bar{t}gg$$
$$gg \to t\bar{t}q\bar{q}$$

$$qg \to t\bar{t}q$$
$$qg \to t\bar{t}qg$$
$$qq' \to t\bar{t}qq', \quad q \neq \bar{q}'$$
$$q\bar{q} \to t\bar{t}q\bar{q}$$

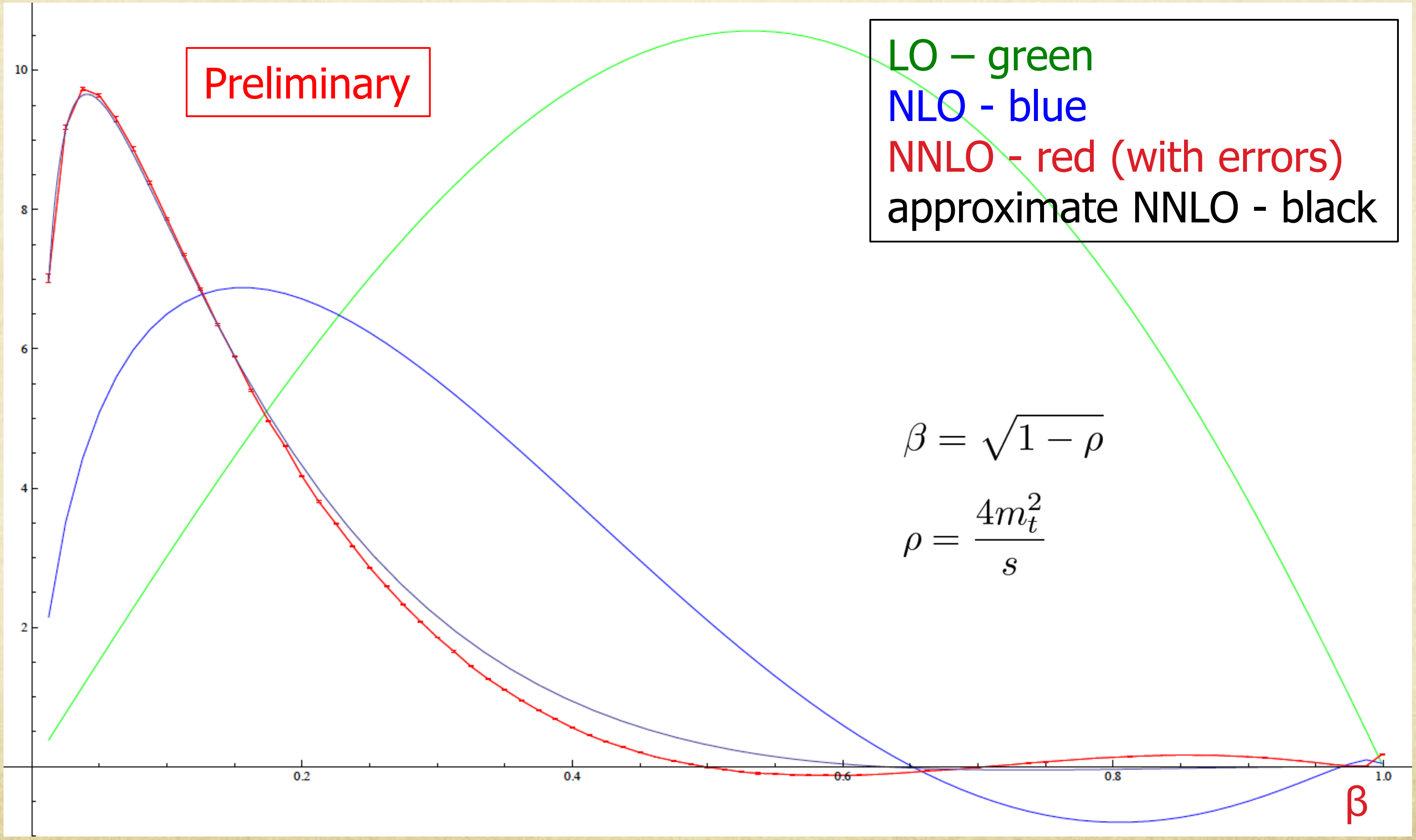
All of the same complexity. No more conceptual challenges expected (just lots of CPU)

Results: partonic cross-section through NNLO

$$\hat{\sigma}_{q\bar{q}\to t\bar{t}}(\beta) = \frac{\alpha_S^4(m_t)}{m_t^2}\left\{\mathrm{LO} + \mathrm{NLO} + \mathrm{NNLO}\right\}$$

Notable features:

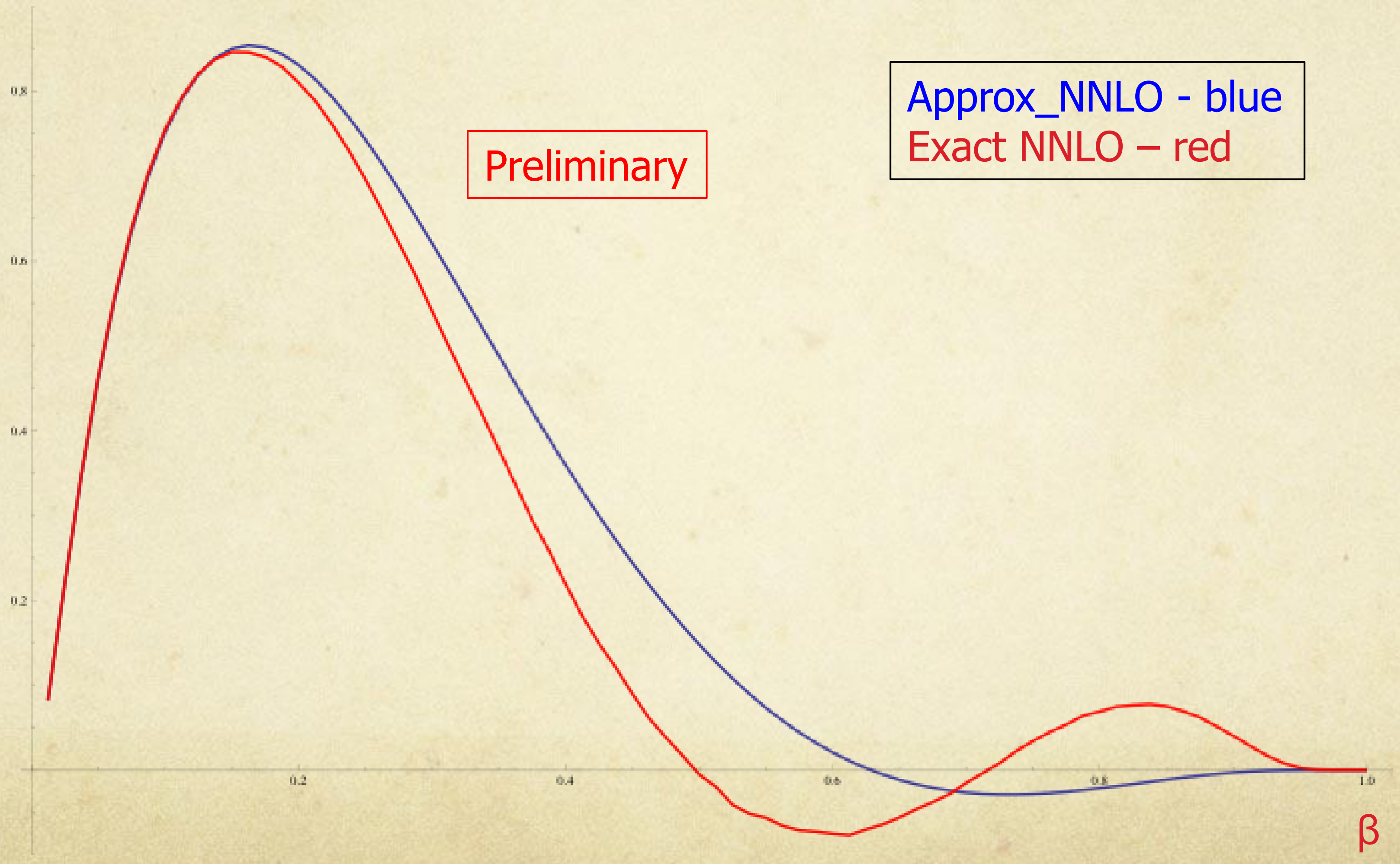
- ✓ Small numerical errors
- ✓ Agrees with limits



What happens once we add the flux?

$$\sigma = \frac{\alpha_s^2}{m_t^2} \sum_{ij} \int_0^{\beta_{\max}} \mathcal{L}_{ij}(\beta)\hat{\sigma}(\beta)$$

- The difference increases!



Here are the numbers for the Tevatron:

NNLO:

sigma_tot = 7.004 + 2.9 % - 4.4 % [pb].

Preliminary

NNLO+NNLL:

sigma_tot = 7.048 + 1.9 % - 3.2 % [pb].

Preliminary

- ✓ Very week dependence on unknown parameters (sub 1%): gg NNLO, A, etc.
- ✓ 50% scales reduction compared to the NLO+NNLL analysis of

6.72 + 3.6% - 6.1%

Cacciari, Czakon, Mangano, Mitov, Nason '11

Summary and Conclusions

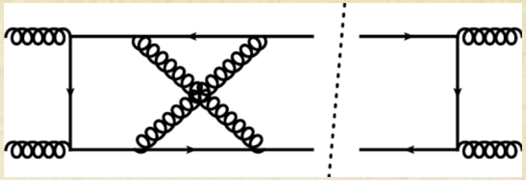
- Long (~15 years) and turbulent chapter in top physics is closing
  - It saw uses of soft gluon resummation to a number of approximations at NNLO
  - It was theoretically very fruitful: engine for theoretical developments
- We have derived the full NNLO result qq → tt (numeric – very good precision)
  - at Tevatron it cuts scale uncertainty in half compared to NLO+NNLL
  - Words like approx_NNLO, etc., belong in the past.
- Methods are very general and applicable to differential distributions
- Applications for dijets and W+jet, H+jet, etc @ NNLO
- Only restriction – availability of two-loop amplitudes and computing speed
- We are on the verge of the NNLO revolution (NLO wish-list already exhausted ☺)

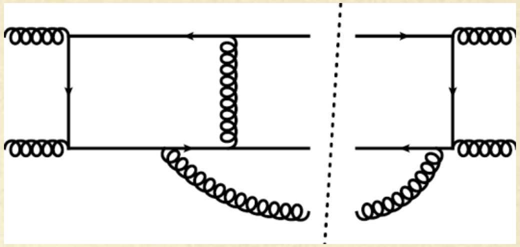
Backup slides

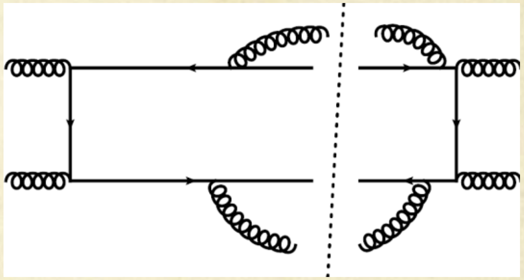
What's needed for NNLO?

There are 3 principle contributions:

- ✓ 2-loop virtual corrections (V-V)
- ✓ 1-loop virtual with one extra parton (R-V)
- ✓ 2 extra emitted partons at tree level (R-R)







And 2 secondary contributions:

- ✓ Collinear subtraction for the initial state

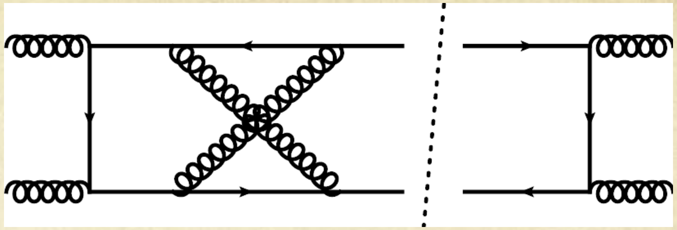
Known, in principle. Done numerically.

- ✓ One-loop squared amplitudes (analytic)

Korner, Merebashvili, Rogal `07

What's needed for NNLO? V-V

Required are the two loop amplitudes:
qq → QQ and gg → QQ.



- ✓ Their high energy limits and their poles are known analytically

Czakon, Mitov, Moch '07
Czakon, Mitov, Sterman '09
Ferroglia, Neubert, Pecjak, Yang '09

- ✓ Directly used here: The qq→QQ amplitude is known numerically

Czakon `07

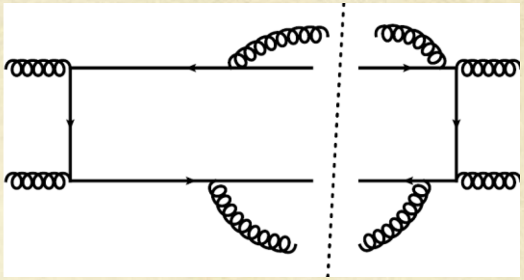
- ✓ Numerical work underway for the gg→QQ

Czakon, Bärnreuther, to appear

What's the future here?

- ✓ Right now this is the biggest (and perhaps only) obstacle for NNLO phenomenology on a mass scale

What's needed for NNLO? R-R



✓ A wonderful result By M. Czakon

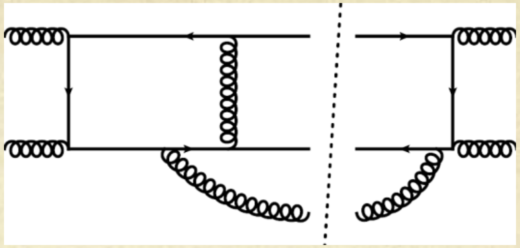
Czakon `10-11

✓ The method is general (also to other processes, differential kinematics, etc).

✓ Explicit contribution to the total cross-section given.

✓ Just been verified in an extremely non-trivial problem.

What's needed for NNLO? R-V



✓ Counterterms all known (i.e. all singular limits)

Bern, Del Duca, Kilgore, Schmidt '98-99
Catani, Grazzini '00
Bierenbaum, Czakon, Mitov '11

The finite piece of the one loop amplitude computed with a private code of Stefan Dittmaier.

Extremely fast code!

A great help!

Many thanks!