t-channel Single Top cross-section at NNLO

Fabrizio Caola
Karlsruhe TTP

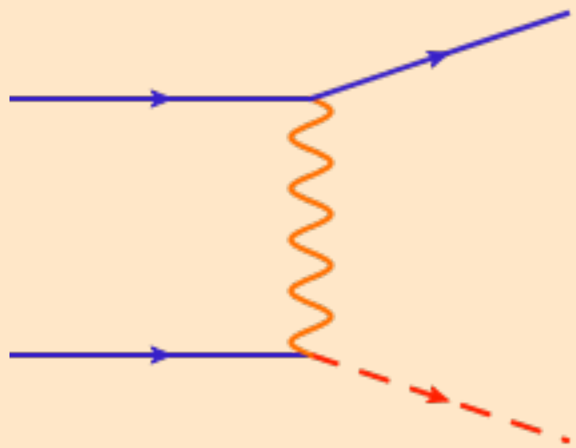
M. Brucherseifer, FC, K. Melnikov, PLB 736 (2014) [arXiv: 1404.7116]

Top Quark Physics Day, Munich, Aug. 11th 2014

Single-top: probing tops via EW interactions

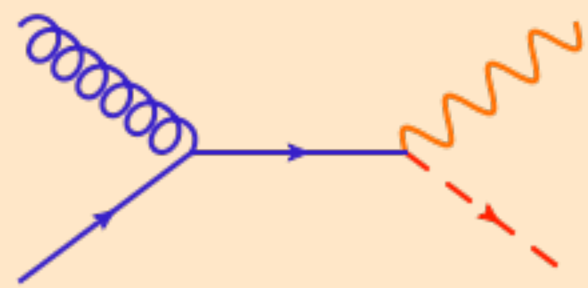
Rough classification (not really well-defined):

T-CHANNEL



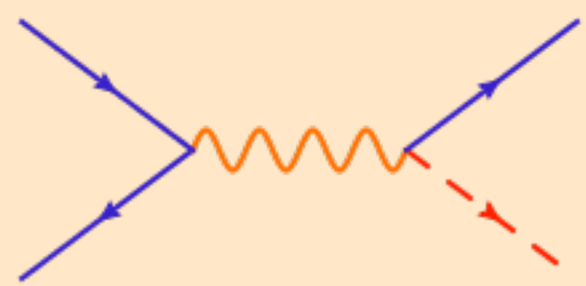
LHC8: ~ 82%
TEV: ~ 65%

ASSOCIATED PRODUCTION



LHC8: ~ 15%
TEV: ~ 0

S-CHANNEL



LHC8: ~ 5%
TEV: ~ 33%

requirement: ~ percent accuracy in the T-CHANNEL

t-channel single top: why NNLO

LOOK AT THE NLO GLOBAL K-FACTOR

The total cross section at the 8 TeV LHC, 5FNS:

$$\sigma_{\rm LO} = 53.77 + 3.03 - 4.33 \text{ pb}$$
$$\sigma_{\rm NLO} = 55.13 + 1.63 - 0.90 \text{ pb}$$

$\delta_{\rm NLO}$: $+2.4\%$

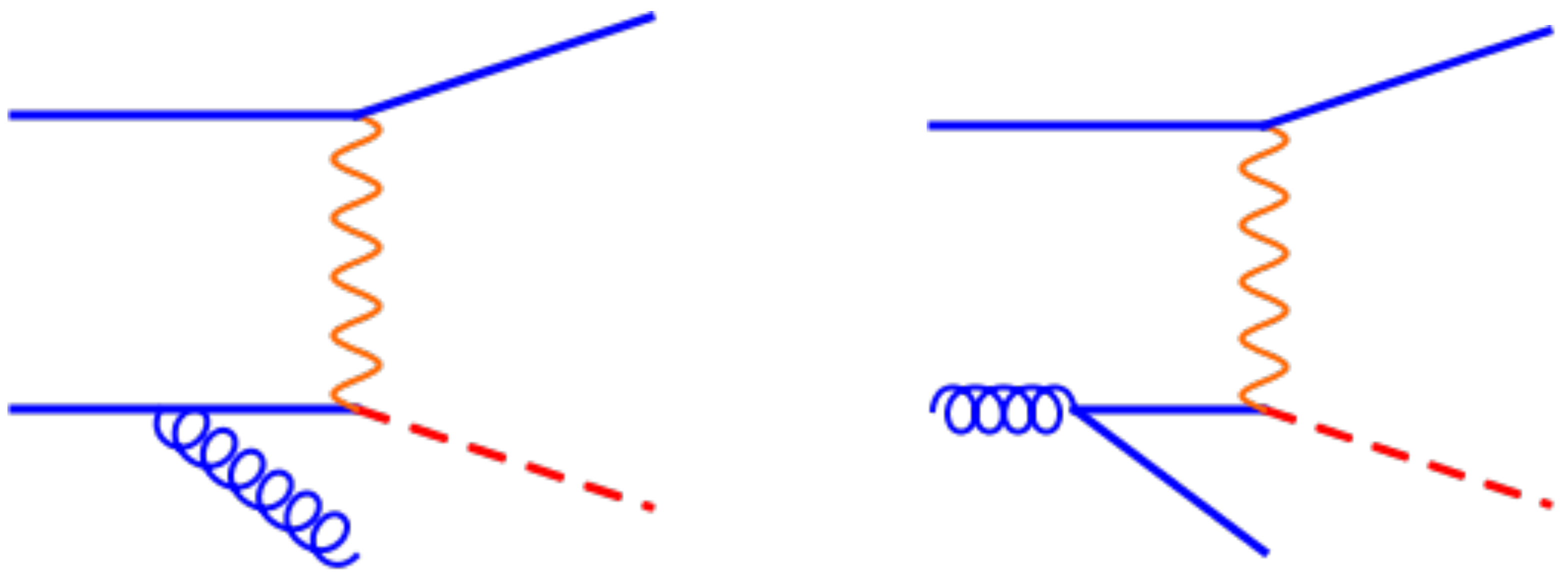
Naively:

- Perturbative expansion extremely well-behaved
- NNLO corrections tiny, irrelevant compared to other sources of uncertainty (PDFs, m_t, m_b,…)
- Perturbative prediction under control at the ~ % level

t-channel single top: why NNLO

The NLO K-factor is Accidentally Small

Large cancellations among channels



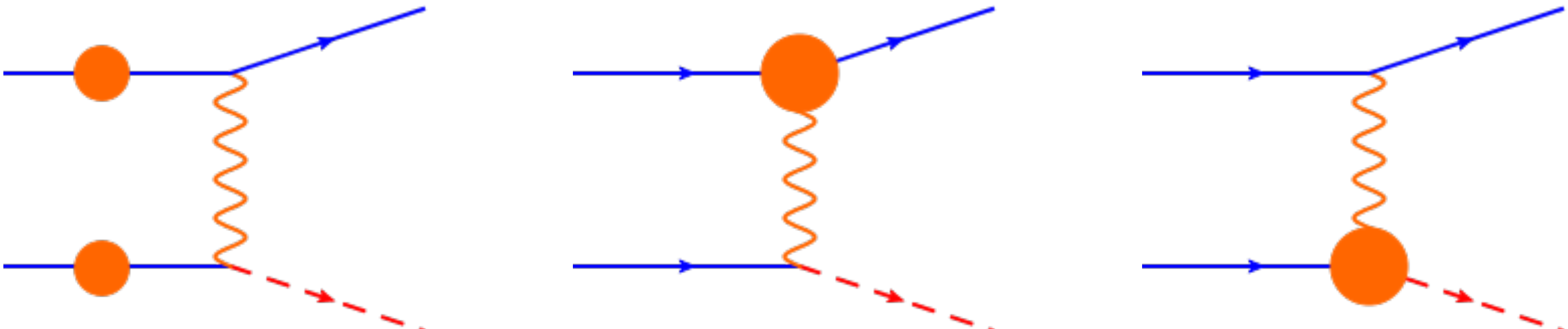
$\delta_{\rm NLO,q} = +19\%$ $\delta_{\rm NLO,g} = -16\%$ $\longrightarrow$ $\delta_{\rm NLO} = +2.4\%$

Although the precise q/g pattern is (highly) scale-dependent,
typical size of individual corrections is ~ 10%

t-channel single top: why NNLO

The NLO K-factor is Accidentally Small

Large cancellations among contributions



$\delta_{\mathrm{NLO,PDF}} = +6\%$ $\delta_{\mathrm{NLO,light}} = +3\%$ $\delta_{\mathrm{NLO,heavy}} = -7\%$

$$\delta_{\mathrm{NLO}} = +2.4\%$$

Again scale-dependent pattern,
but typical corrections ~ 5-10%

t-channel single top: why NNLO

THE NLO K-FACTOR IS ACCIDENTALLY SMALL

The pattern of cancellation is (very)
phase-space dependent:

$$\sigma(p_{\perp,t} > p_{\perp,cut})$$

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$

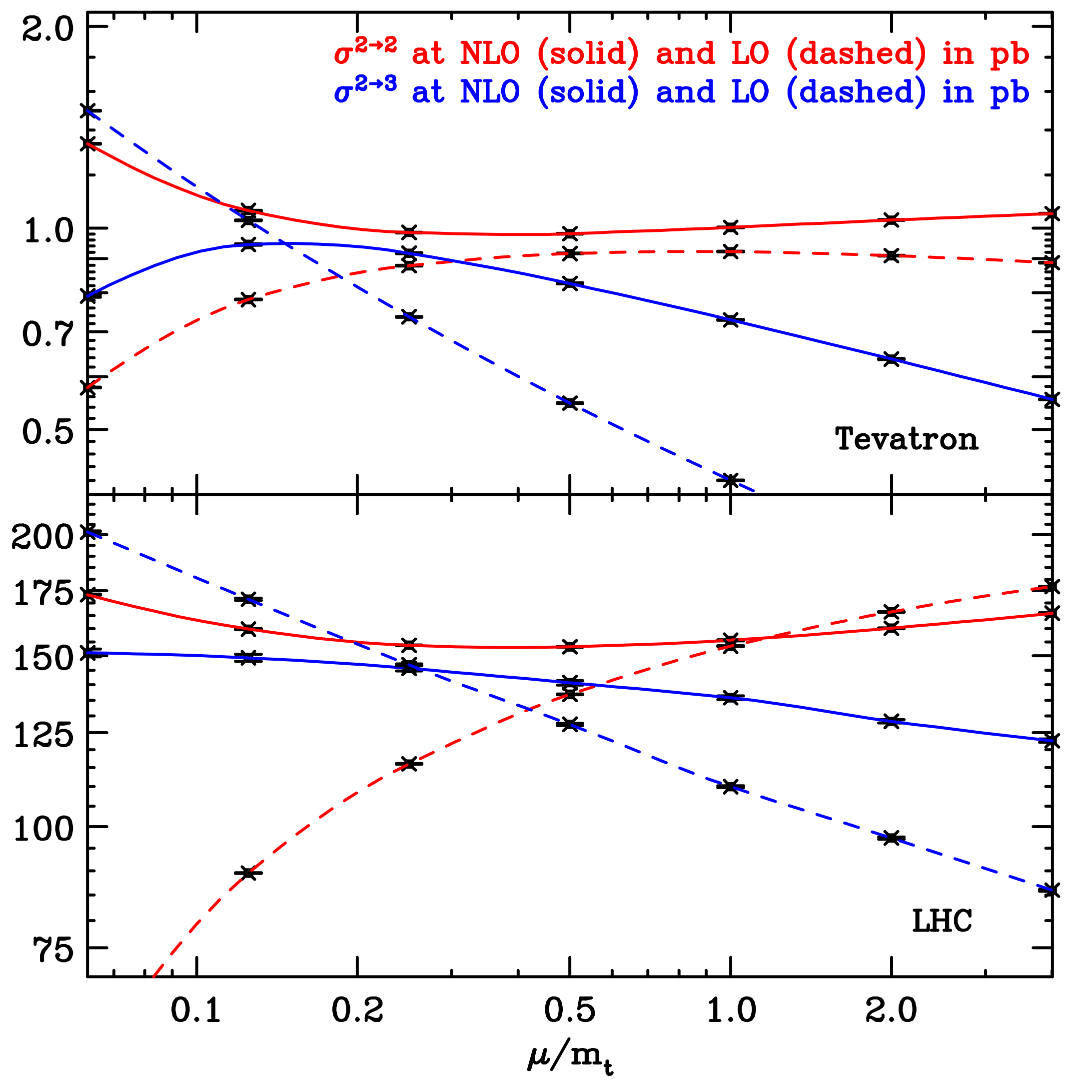
Corrections to more exclusive observables ~ 10%

t-channel single top: why NNLO

The total cross section at the 8 TeV LHC: A CLOSER LOOK

$$\sigma_{\mathrm{LO}} = 53.77 + 3.03 - 4.33 \text{ pb}$$

$$\sigma_{\mathrm{NLO}} = 55.13 + 1.63 - 0.90 \text{ pb}$$



[Campbell et al (2009)]

- Scale variation similar to corrections
- ~ percent difference between 4FNS/5FNS calculations

t-channel single top: why NNLO

$$\sigma_{\mathrm{LO}} = 53.77 + 3.03 - 4.33 \text{ pb}$$

$$\sigma_{\mathrm{NLO}} = 55.13 + 1.63 - 0.90 \text{ pb}$$

- Large (accidental?) cancellations between channels
- Scale variation (~ NNLO) as large as corrections
- Larger corrections for more exclusive observables
- (Slight) tension between 4FNS and 5FNS

To control single-top production at the percent level:
NNLO Correction to t-channel Production

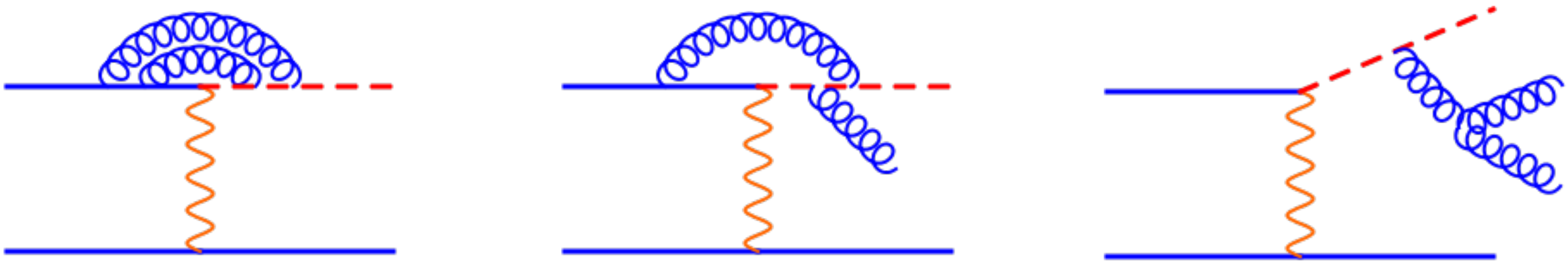
Single-top t-channel prediction @ NNLO

Anatomy of a NNLO computation

- For a long time, the problem of NNLO computations was how to consistently extract IR singularity from double-real emission/real-virtual emission
- This problem has now been solved both in theory (antenna subtraction, sector decomposition+FKS, semi-analytic subtraction) and in practice (top-pair, dijet, H+jet,…)
- Now the problematic part is computing two-loop amplitudes. State of the art:
    - Numerically: 2->2 with 1 extra mass-scale (tt)
    - Analytically: 2->2 with two external mass scales (VV*)

t-channel single-top @ NNLO: ingredients

VV RV RR



$$\int \left[\frac{\mathrm{vv}_4}{\epsilon^4} + \frac{\mathrm{vv}_3}{\epsilon^3} + \frac{\mathrm{vv}_2}{\epsilon^2} + \frac{\mathrm{vv}_1}{\epsilon} + \mathrm{vv}_0 \right] d\phi_2$$

$$\int \left[\frac{\mathrm{rv}_2}{\epsilon^2} + \frac{\mathrm{rv}_1}{\epsilon} + \mathrm{rv}_0 \right] d\phi_3$$

$$\int \left[\mathrm{rr}_0 \right] d\phi_4$$

Problematic part is to extract implicit IR poles from RV and RR in a FULLY-DIFFERENTIAL way, i.e. without doing the PS integration

OUR APPROACH: SECTOR DECOMPOSITION + FKS

[Czakon (2010), Boughezal, Melnikov, Petriello (2011)]

t-channel single-top @ NNLO

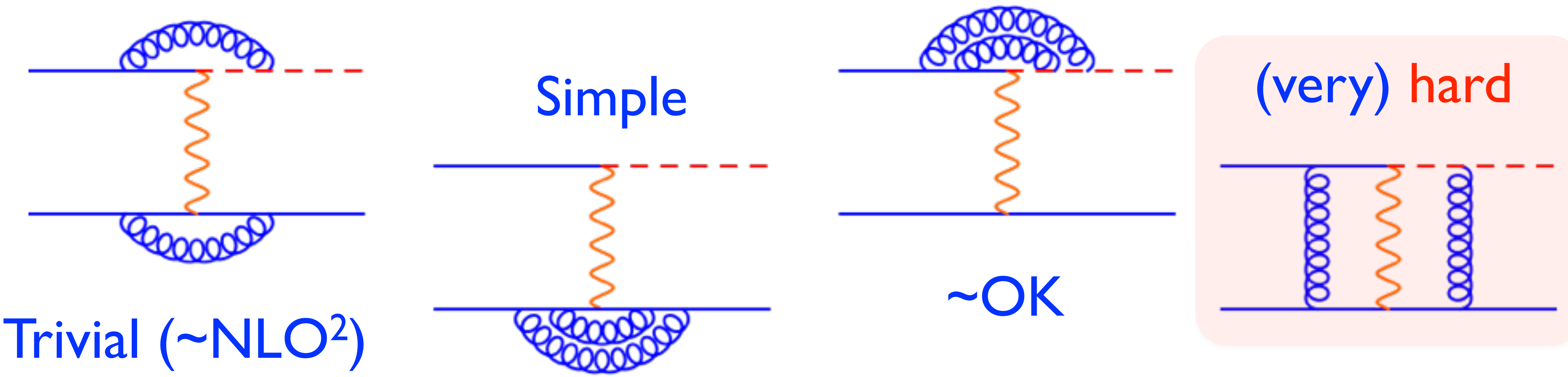
Recent developments in NNLO techniques, allowed us to compute (almost) t-channel single-top corrections.

In particular, for our computation:

- 5FNS@NNLO (2->2)
- Fully differential (arbitrary cuts on the final state are not a problem)
- For now, top is stable but very easy to implement top decay in the NWA with full spin correlation

Single-top in the ‘factorized’ approximation

Two-loop amplitudes:



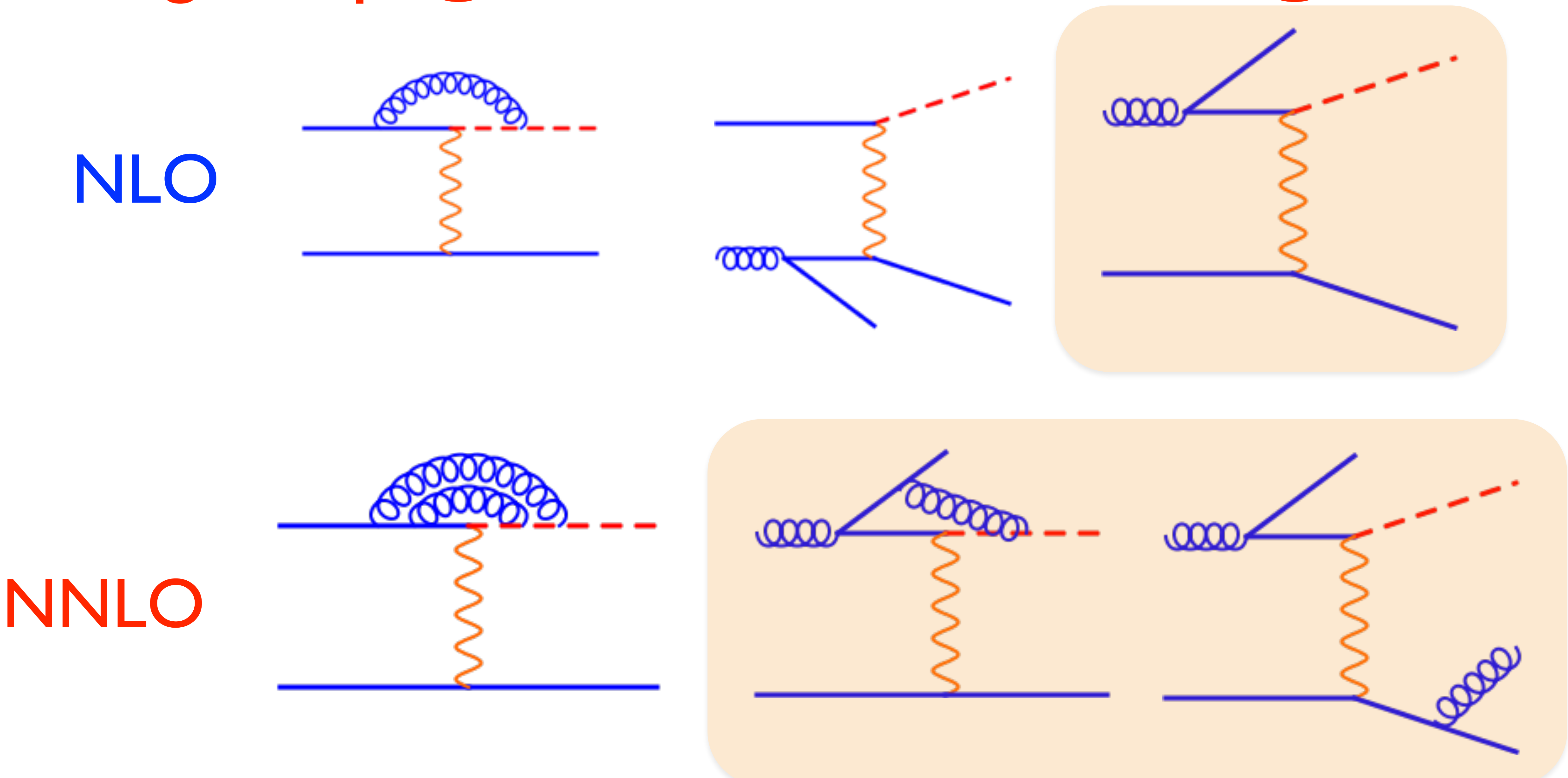
Must be interfered with tree-level -> COLOR SINGLET

The ‘hard’ amplitude contribution is suppressed by $1/N_c^2$

NEGLECTED IN OUR COMPUTATION

[same for s/t interference]

single-top @ NNLO: 5FNS vs 4FNS@NLO



Inside NNLO 5FNS: ~ NLO 4FNS

- collinear regulator: MSbar vs m_b (log resummed, p.s.t. neglected)
- SLC light/heavy interference neglected in our computation

Single-top @ NNLO: total cross section

8 TeV LHC, MSTW2008, m_t = 173.2 GeV

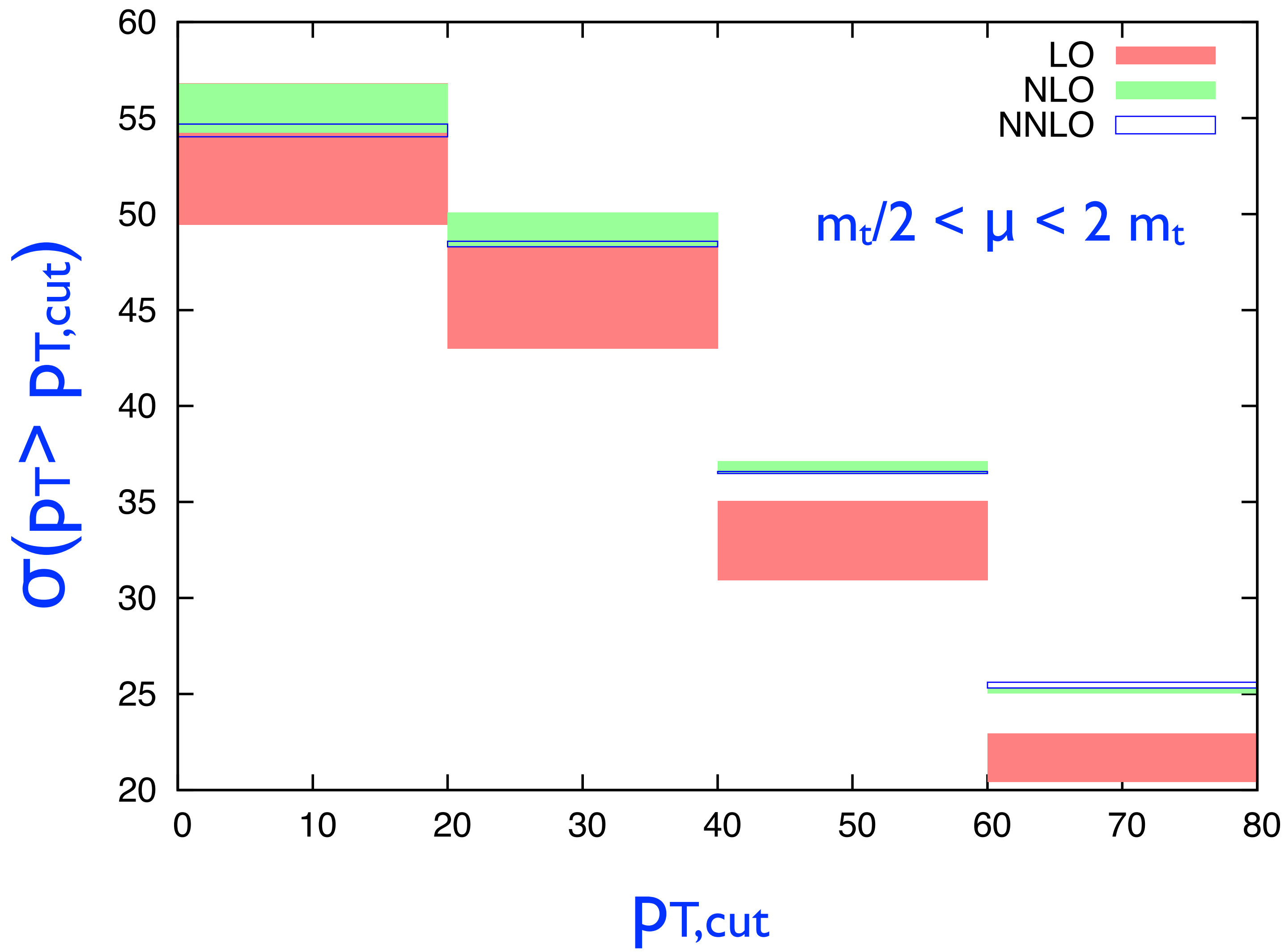
$$\sigma_{\mathrm{LO}} = 53.8^{+3.0}_{-4.3}\ \mathrm{pb} \qquad \sigma_{\mathrm{NLO}} = 55.1^{+1.6}_{-0.9}\ \mathrm{pb}$$

$$\sigma_{\mathrm{NNLO}} = 54.2^{+0.5}_{-0.2}\ \mathrm{pb}$$

- $\mu_R=\mu_F=\{m_t/2, m_t, 2\ m_t\}$
- Still delicate interplay/cancellations between different channels -> important to consistently compute corrections to all of them
- Result very close to the NLO (-1.6%), reduced μ dependence -> good theoretical control

Single-top @ NNLO: more differential observables

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$



- Contrary to NLO, results stable in the full spectrum
- Scale dependence typically improved
- K-factor is small but not constant

Very similar results for anti-top

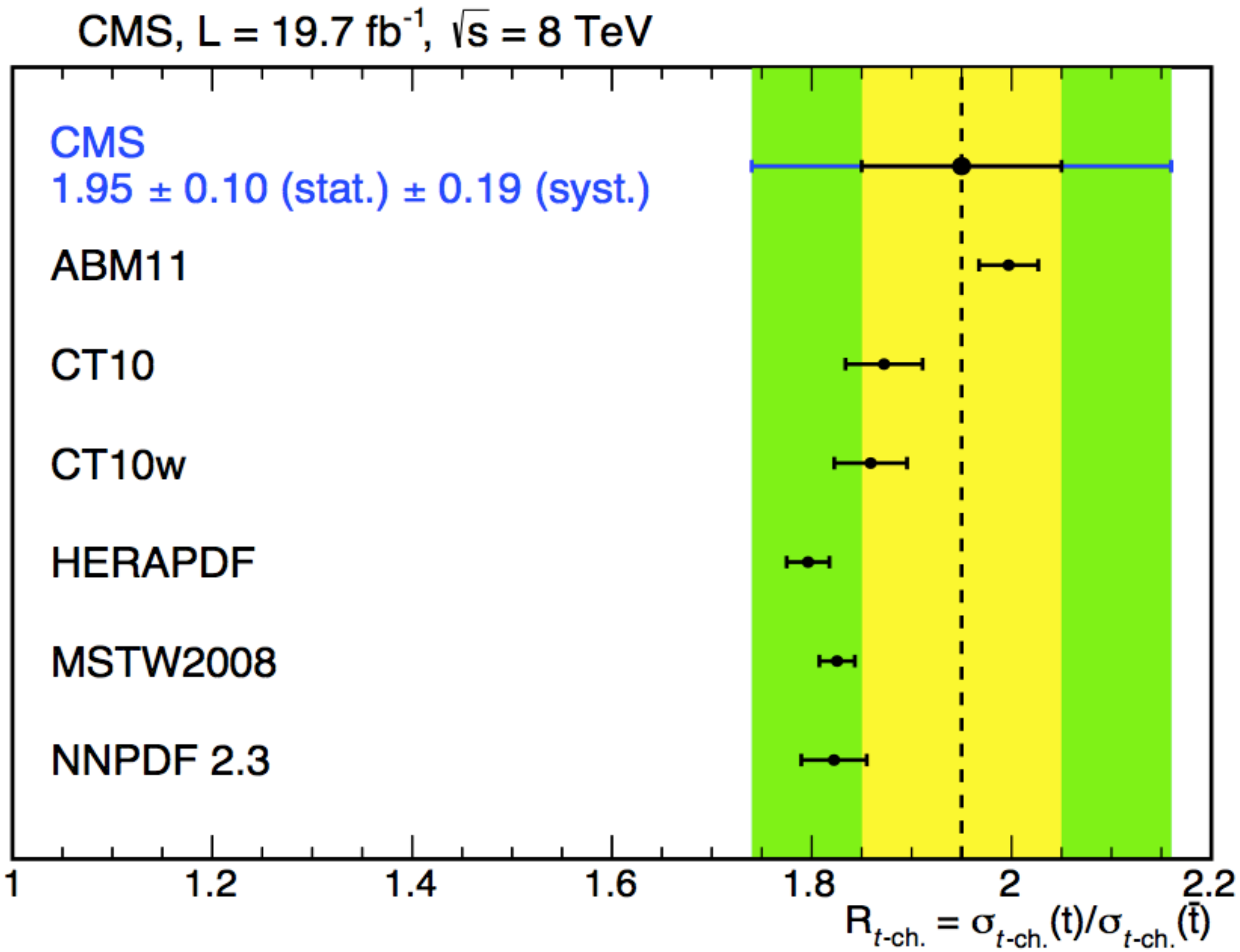
$$\sigma_{\mathrm{NNLO},\bar{t}} = 29.7^{+0.3}_{-0.1}\ \mathrm{pb}$$

$p_\perp$	σ_{LO}, pb	σ_{NLO}, pb	δ_{NLO}	σ_{NNLO}, pb	δ_{NNLO}
0 GeV	$29.1^{+1.7}_{-2.4}$	$30.1^{+0.9}_{-0.5}$	$+3.4\%$	$29.7^{+0.3}_{-0.1}$	-1.3%
20 GeV	$24.8^{+1.4}_{-2.0}$	$26.3^{+0.7}_{-0.3}$	$+6.0\%$	$26.2^{-0.01}_{-0.1}$	-0.4%
40 GeV	$17.1^{+0.9}_{-1.3}$	$19.1^{+0.3}_{+0.1}$	$+11.7\%$	$19.3^{-0.2}_{+0.1}$	$+1.0\%$
60 GeV	$10.8^{+0.5}_{-0.7}$	$12.7^{+0.03}_{+0.2}$	$+17.6\%$	$12.9^{-0.2}_{+0.2}$	$+1.6\%$

- NLO corrections slightly larger, NNLO very similar
- Slightly larger scale variation w.r.t top, NLO scale variation accidentally small

top/anti-top ratio very stable

8 TeV LHC, MSTW2008, m_t = 173.2 GeV



$$\sigma_{t,\mathrm{LO}}/\sigma_{\bar{t},\mathrm{LO}} = 1.85$$

$$\sigma_{t,\mathrm{NLO}}/\sigma_{\bar{t},\mathrm{NLO}} = 1.83$$

$$\sigma_{t,\mathrm{NNLO}}/\sigma_{\bar{t},\mathrm{NNLO}} = 1.83$$

No substantial modification w.r.t. NLO

Conclusions

- NLO K-factor for t-channel single-top is accidentally small (cancellation among channels, μ dependence, 4FNS/5FNS)
- Going beyond NLO is needed to have control at the percent level

Thanks to recent advancement in NNLO techniques:

- (almost) 5FNS@NNLO (2->2)
- Fully differential (fiducial cuts/distributions)
- Very stable results through the full spectrum
- K-factor not constant, but small
- Reduced scale variation apart from pathological cases

Outlook

NNLO is ready for serious phenomenology

Easy to do:

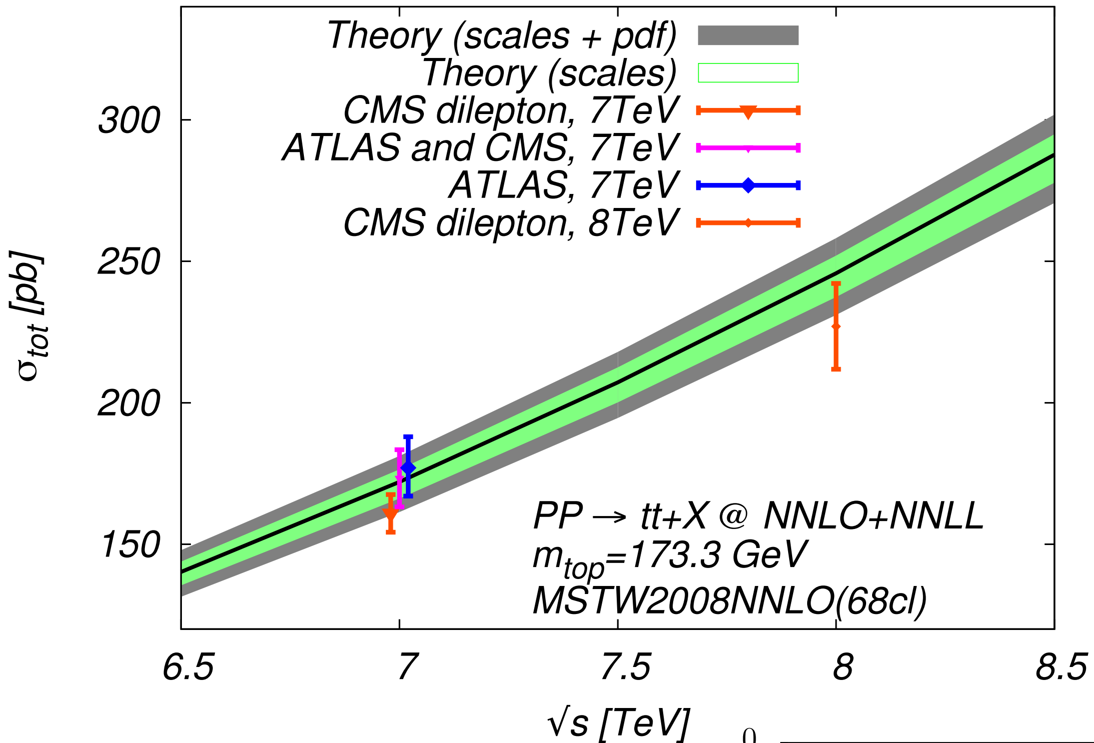
- complete error estimates (PDF, μ_R/μ_F)
- m_b effects from PDF evolution
- 7/8/13 TeV ratios
- run with fiducial cuts on the reconstructed top system

Known in principle (but some work involved):

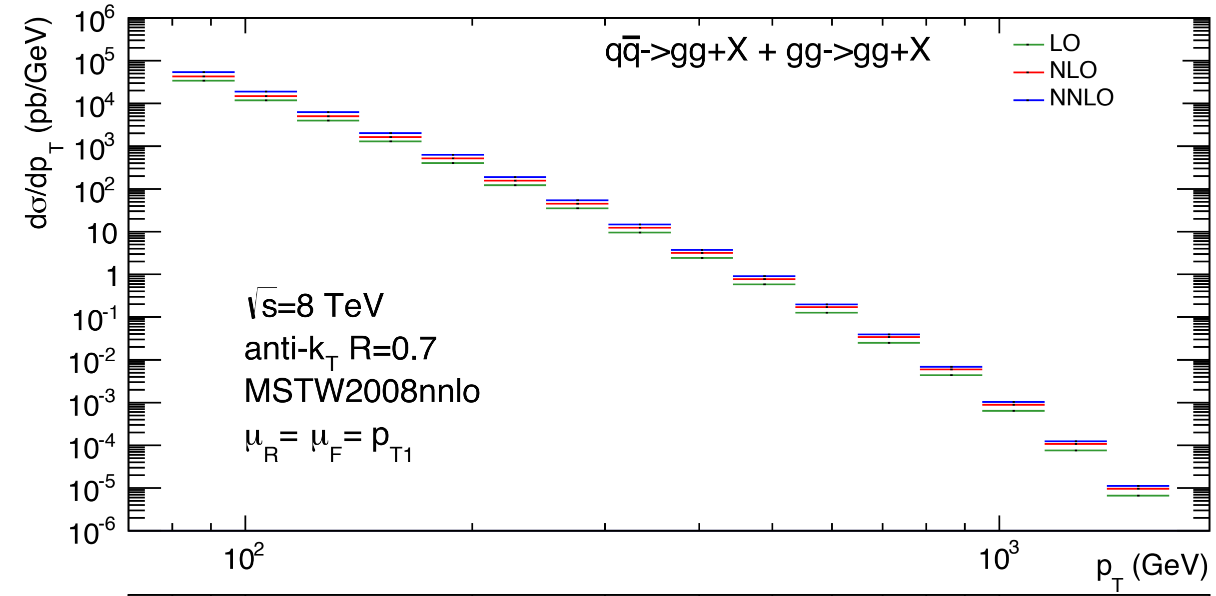
- interface with top decay in the NWA
- we already know decay@NNLO
- realistic distributions for final-state observables

Colorful 2 -> 2 NNLO phenomenology is a reality

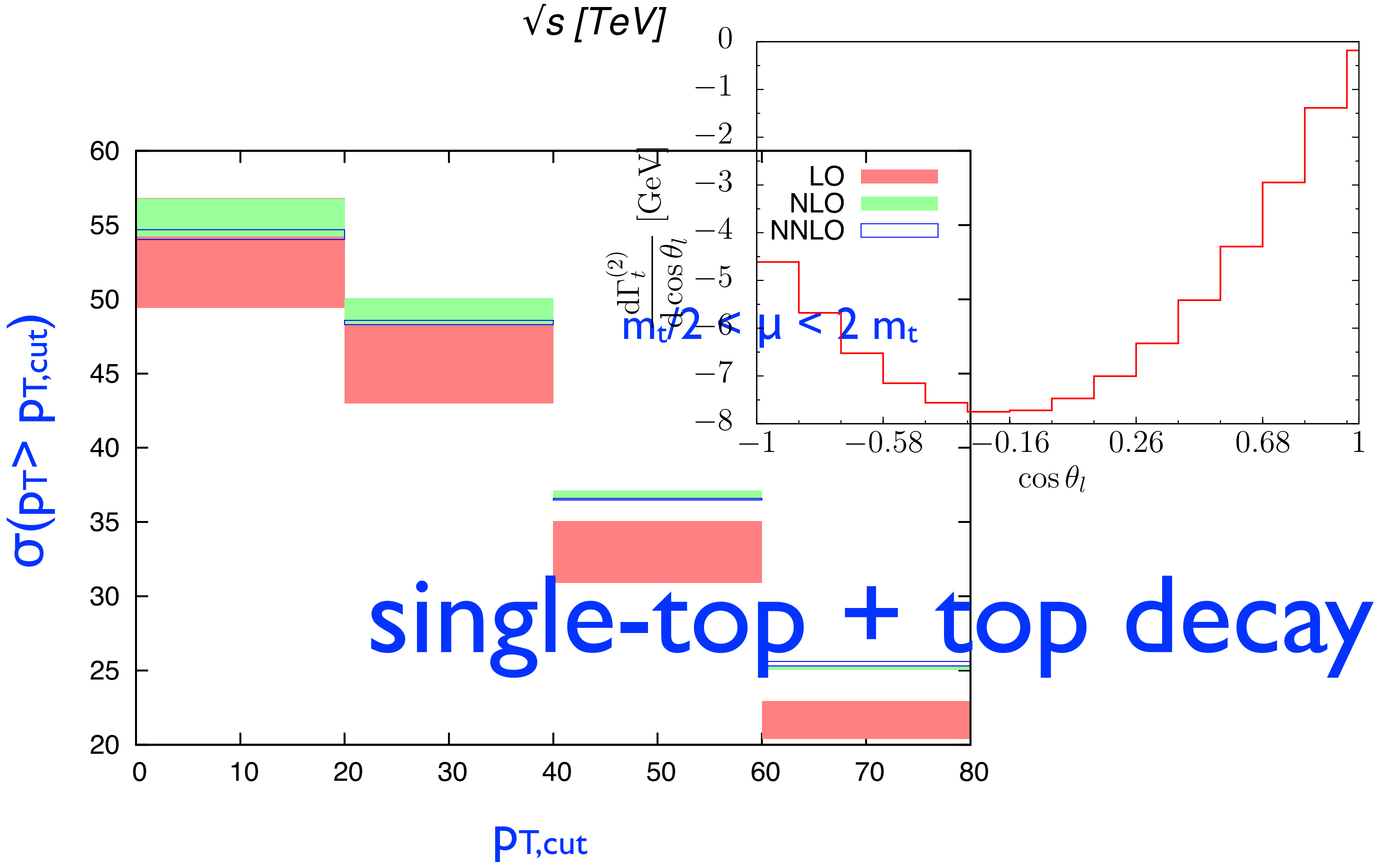
ttbar



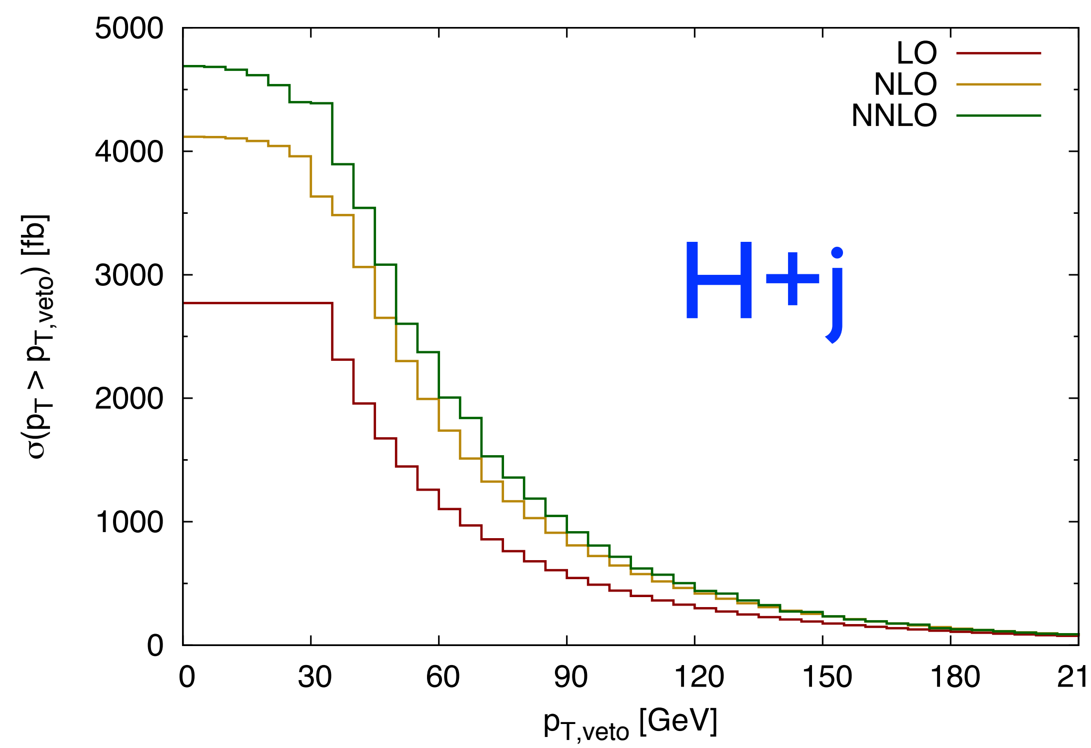
dijet



single-top + top decay



H+j



Thank you for your attention!

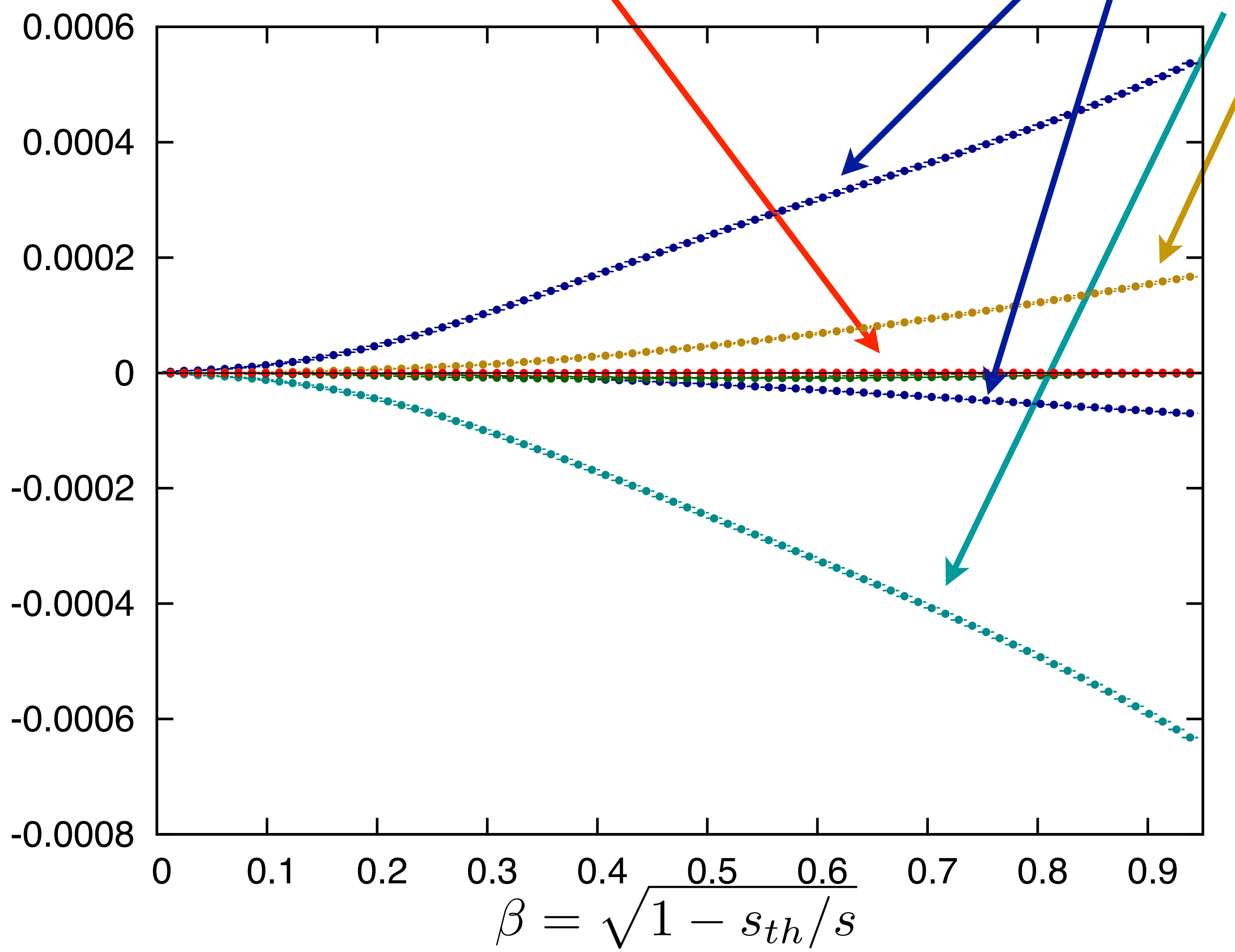
Back-up

Checks

- all tree-level amplitudes checked against MadGraph
- all one-loop amplitudes checked against MadLoop
- analytic continuation of soft limits checked against Czakon et al (tt)
- unstable QCDLoop integrals recomputed from scratch, at higher orders in ε
- results for NLO^2 and corrections to the massless line checked against fully inclusive preliminary results by Duhr, Maltoni et al (based on VBF@NNLO)
- RGE checked separately for each channel
- singularity cancellation checked both at the PDF-integrated level and as a scan in the partonic c.o.m. energy

Checks: poles cancellation

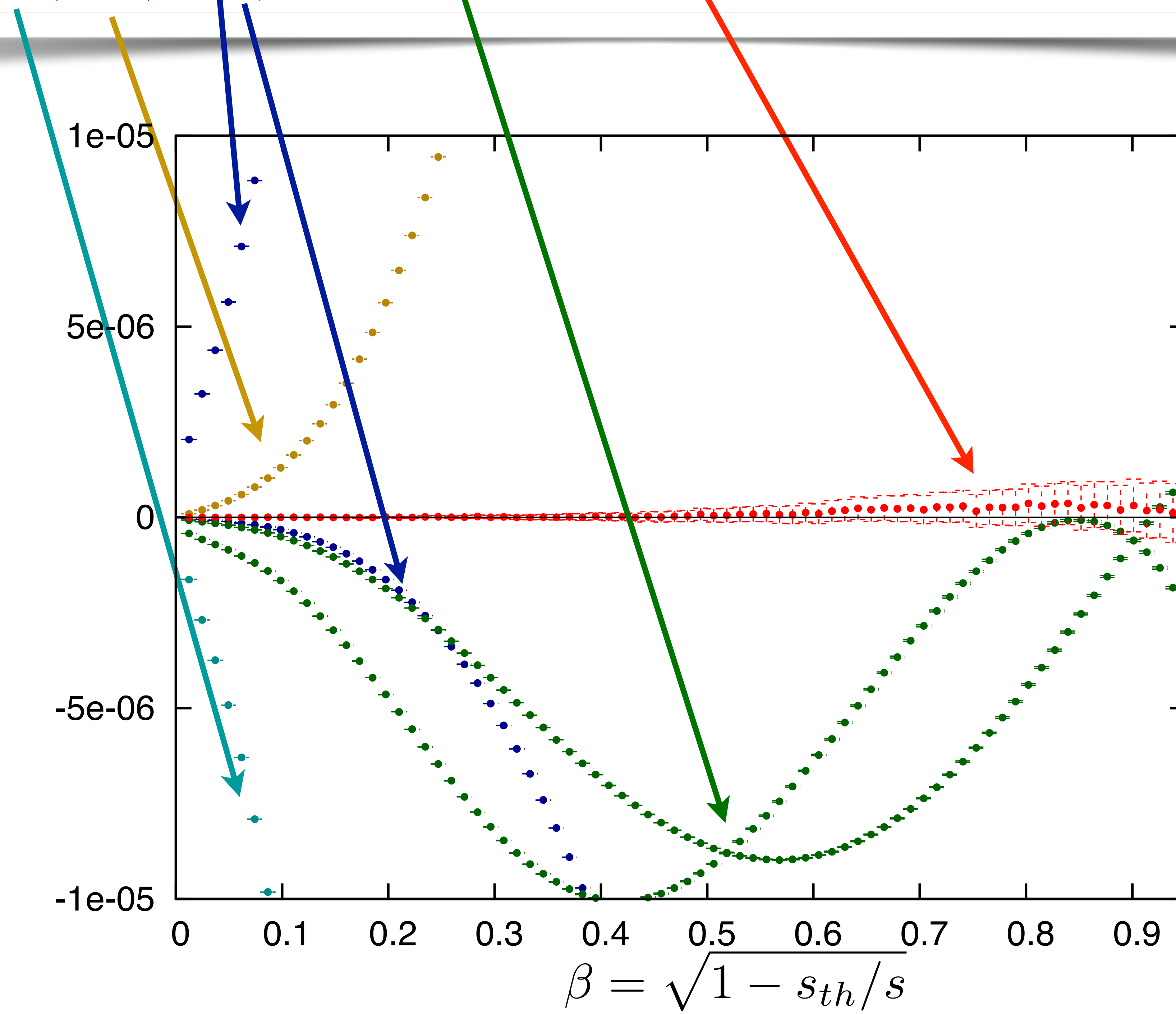
NUMERICAL CANCELLATION between renormalization and coll. couterterms, RR, RV, VV



$1/\epsilon$ poles, summing individual contributions

Checks: poles cancellation

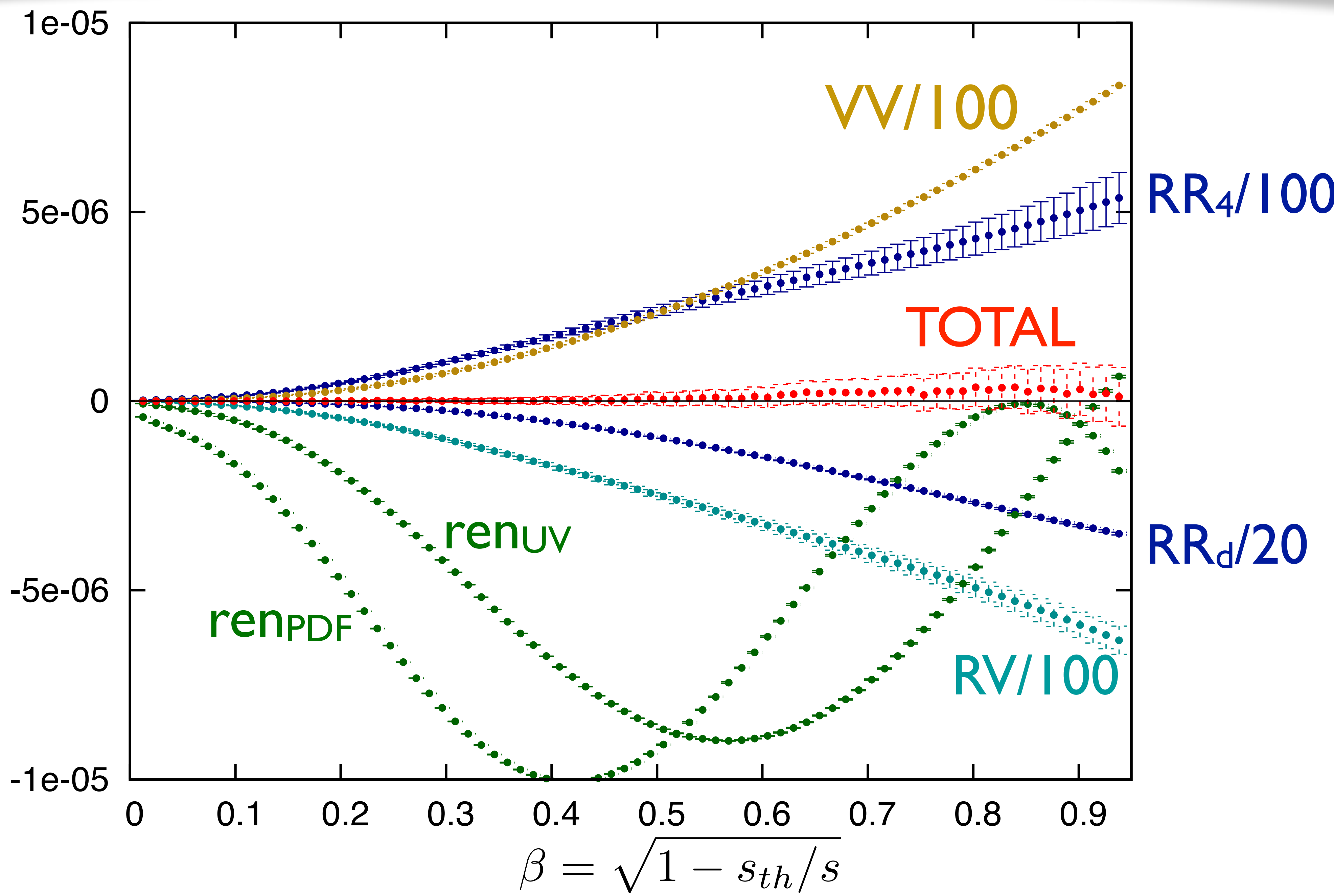
NUMERICAL CANCELLATION between
RV, VV, RR, renormalization and coll. couterterms



$1/\epsilon$ poles, summing individual contributions

Checks: poles cancellation

NUMERICAL CANCELLATION between
RV, VV, RR, renormalization and coll. couterterms



$1/\epsilon$ poles, summing individual contributions