t-channel Single Top at NNLO

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M. Brucherseifer, FC, K. Melnikov, arXiv:1404.7116

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t-channel single top: why NNLO

Look at the NLO global K-Factor

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

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

δ_{NLO} : $+2.4\%$

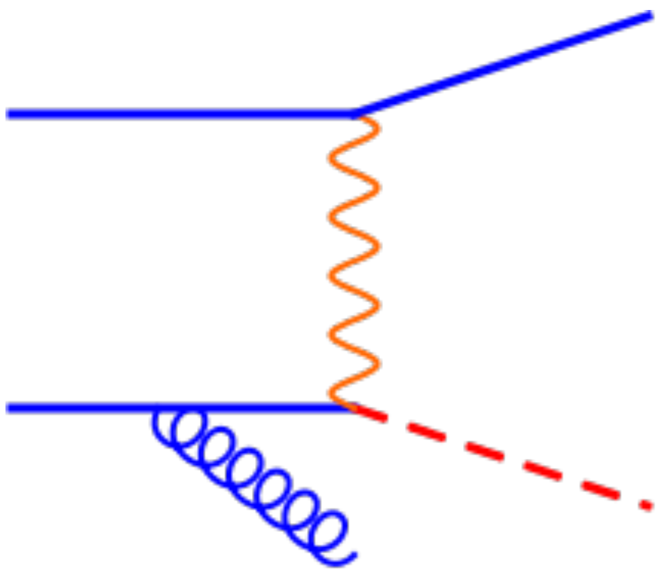
Naively:

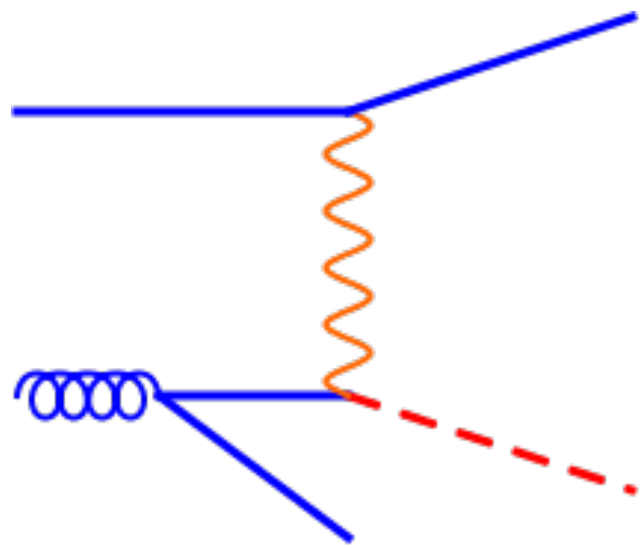
- Perturbative expansion extremely well-behaved
- NNLO corrections tiny, irrelevant compared to other sources of uncertainty (PDFs, m_t, m_b,…)
- Perturbative prediction under control at the ~ % level

t-channel single top: why NNLO

THE NLO K-FACTOR IS ACCIDENTALLY SMALL

Large cancellations among channels





$\delta_{\mathrm{NLO},q} = +19\%$

$\delta_{\mathrm{NLO},g} = -16\%$

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

t-channel single top: why NNLO

THE NLO K-FACTOR IS ACCIDENTALLY SMALL

Large cancellations among channels

Scale-dependent pattern

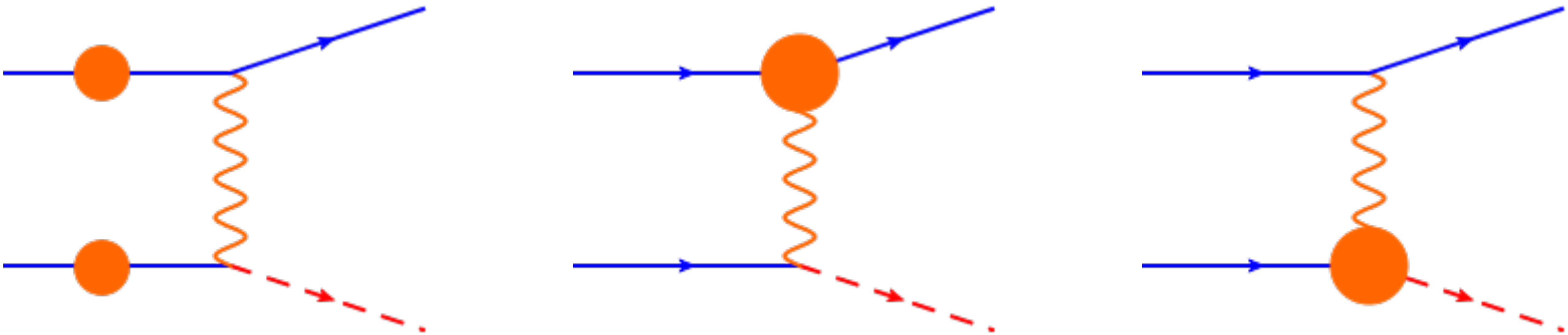
- $\mu = m_t/2$: $\delta_q \sim +10\%$, $\delta_g \sim 0$, $\delta_{NLO} = 10\%$
- $\mu = m_t$: $\delta_q \sim +19\%$, $\delta_g \sim -16\%$, $\delta_{NLO} = 2.4\%$
- $\mu = 2\ m_t$: $\delta_q \sim +30\%$, $\delta_g \sim -30\%$, $\delta_{NLO} \sim 0$

"Natural" size of NLO corrections ~ 10%

t-channel single top: why NNLO

THE NLO K-FACTOR IS ACCIDENTALLY SMALL

Large cancellations among contributions



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

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

t-channel single top: why NNLO

The NLO K-factor is Accidentally Small

Large cancellations among contributions

Again, scale dependent pattern

- $\mu = m_t/2$: $\delta_{PDF} \sim +6\%$, $\delta_{light} \sim 0$, $\delta_{heavy} = +4\%$, $\delta_{NLO} = 10\%$
- $\mu = m_t$: $\delta_{PDF} \sim +6\%$, $\delta_{light} \sim +3\%$, $\delta_{heavy} = -7\%$, $\delta_{NLO} = 2.4\%$
- $\mu = 2\ m_t$: $\delta_{PDF} \sim +6\%$, $\delta_{light} \sim +6\%$, $\delta_{heavy} = -12\%$, $\delta_{NLO} \sim 0$

Cancellation of ~ 5-10% contributions

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	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$

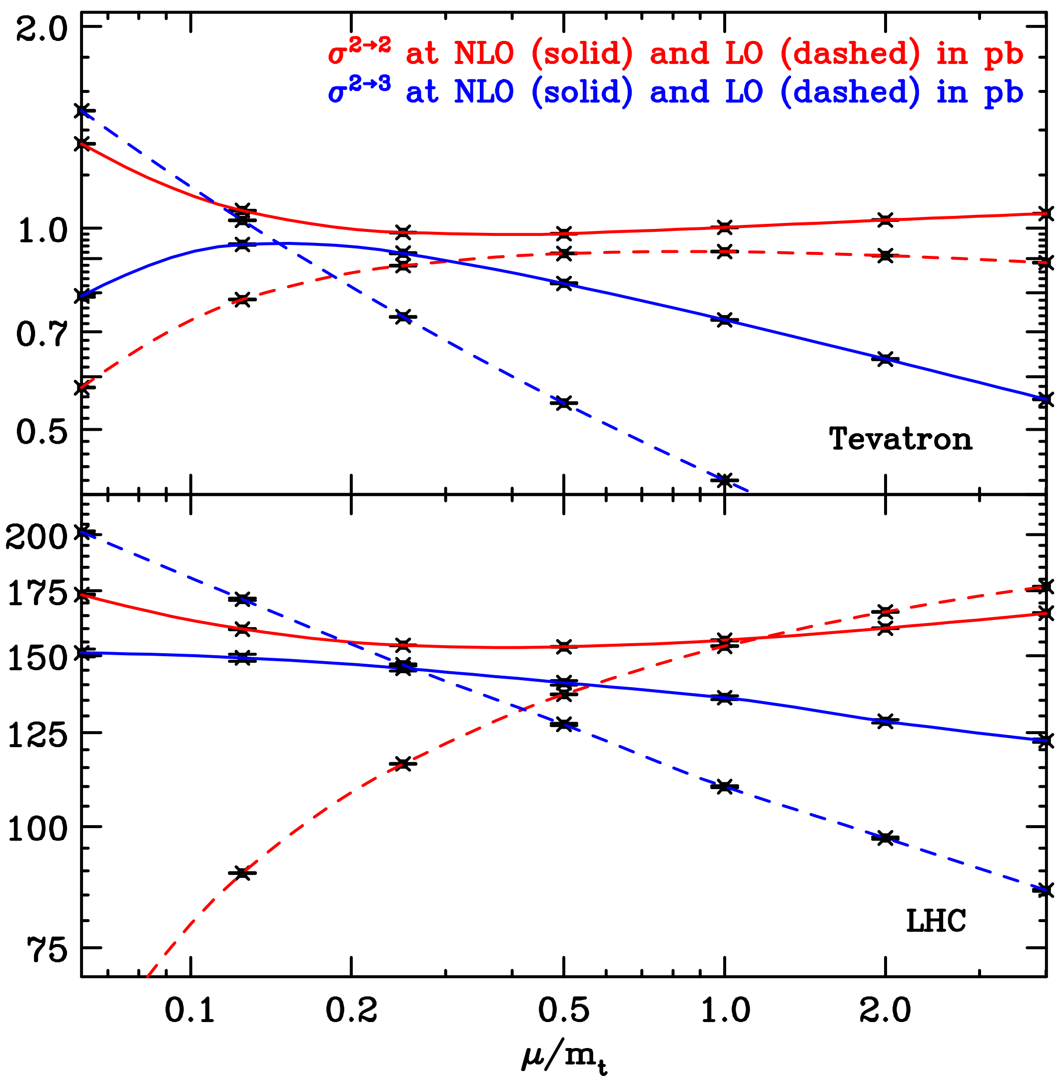
Corrections to more exclusive observables ~ 10%

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

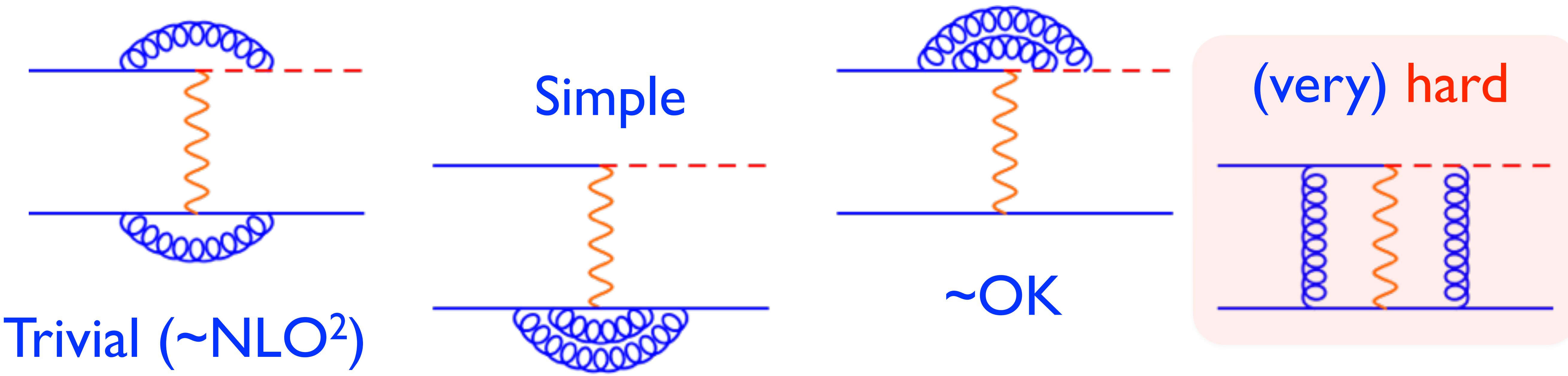
Recent developments in NNLO techniques, allowed us to compute (almost) t-channel single-top corrections.

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:



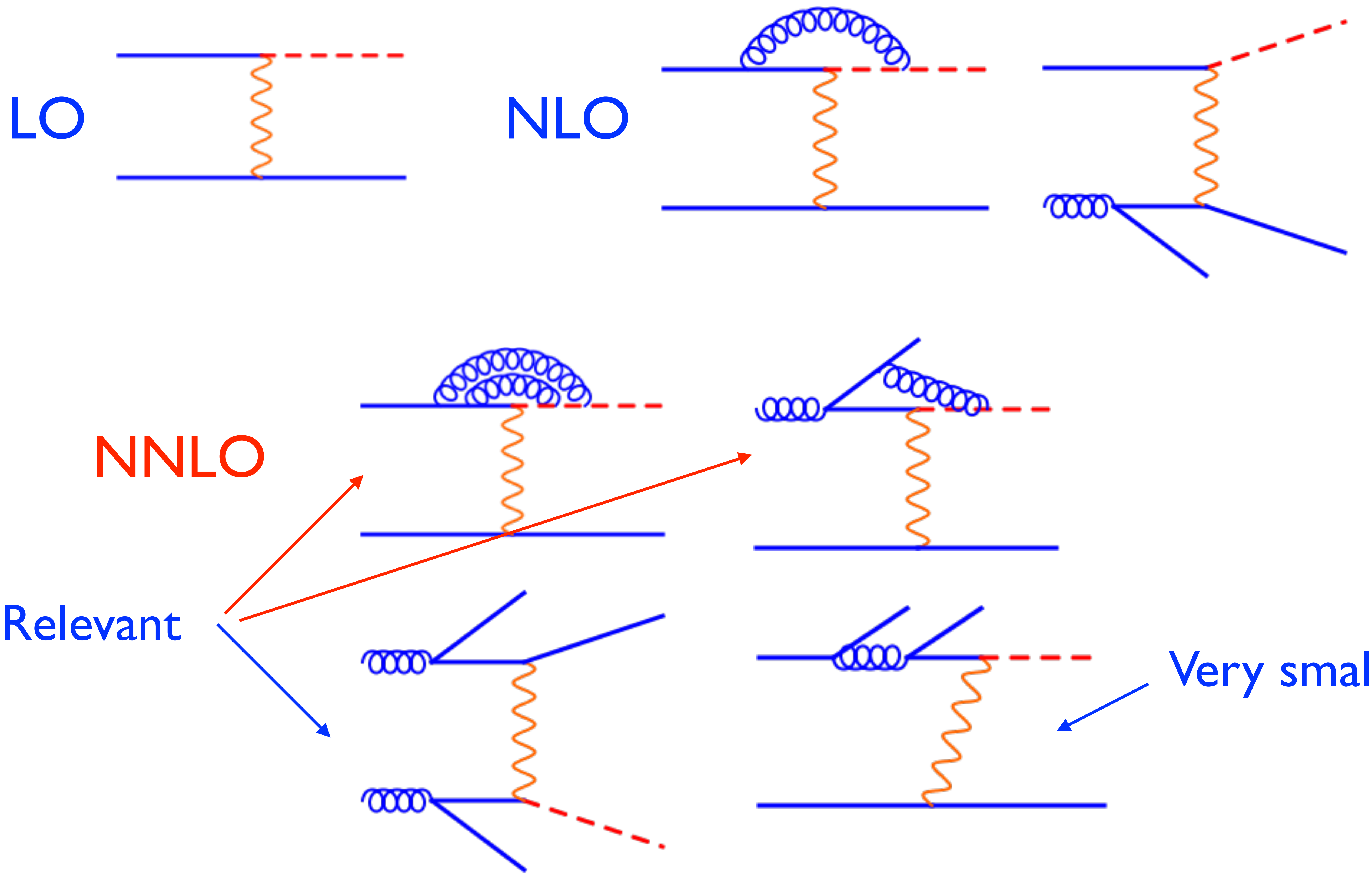
Must be interfered with tree-level -> COLOR SINGLET

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

NEGLECTED IN OUR COMPUTATION

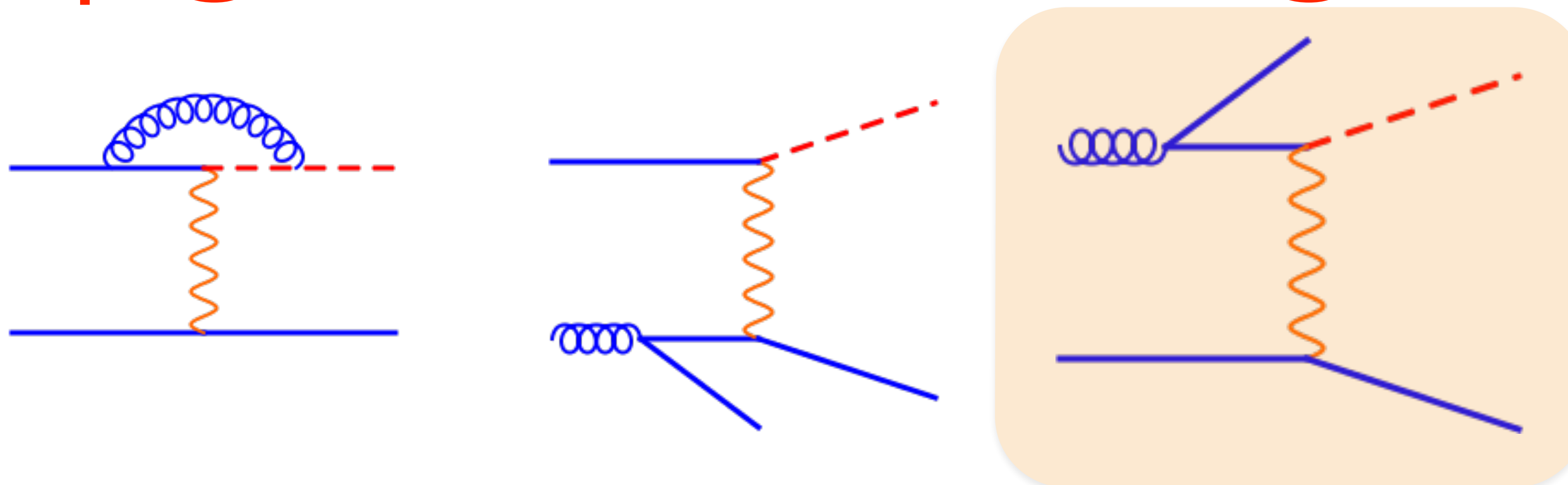
[same for s/t interference]

single-top @ NNLO: channels

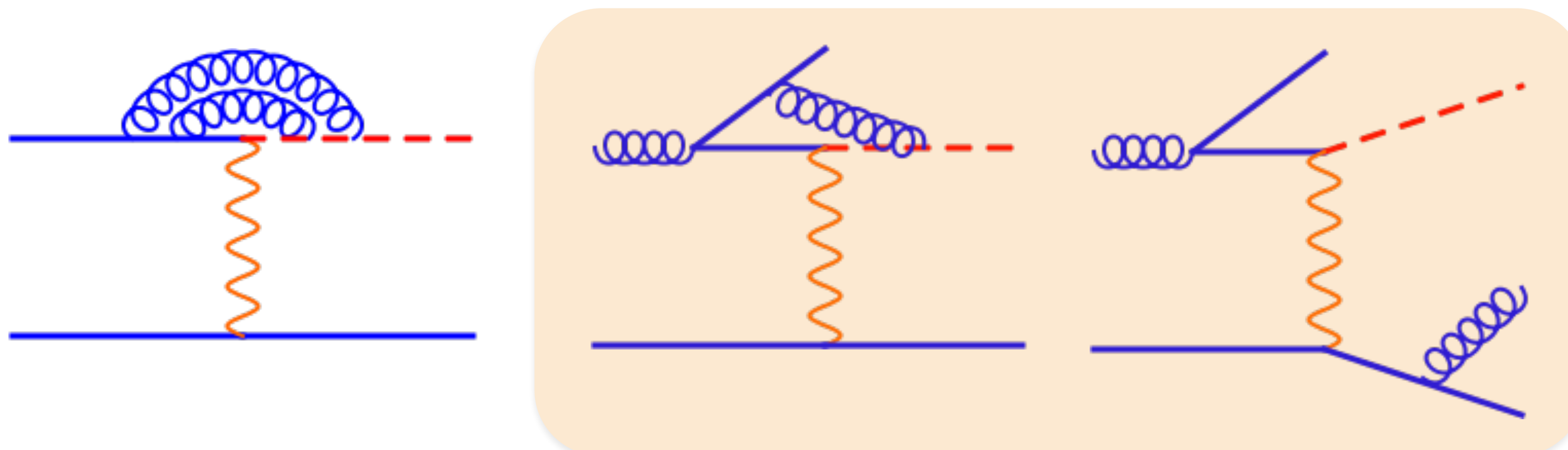


single-top @ NNLO: 5FNS vs 4FNS@NLO

NLO



NNLO



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

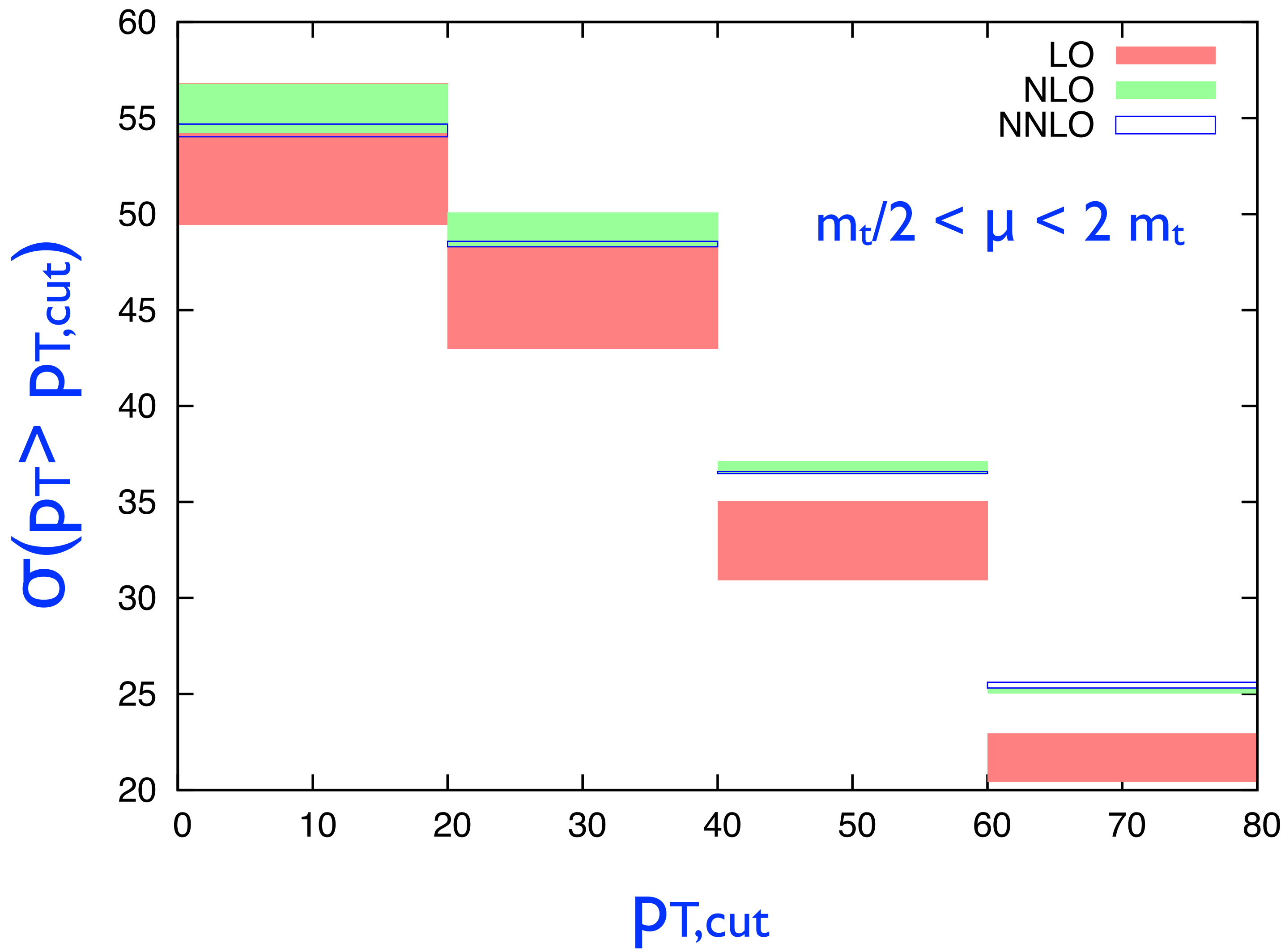
$$\sigma_{\rm LO} = 53.8^{+3.0}_{-4.3}\ \ {\rm pb} \qquad \sigma_{\rm NLO} = 55.1^{+1.6}_{-0.9}\ \ {\rm pb}$$

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

- $\mu_R=\mu_F=\{m_t/2, m_t, 2\ m_t\}$
- 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

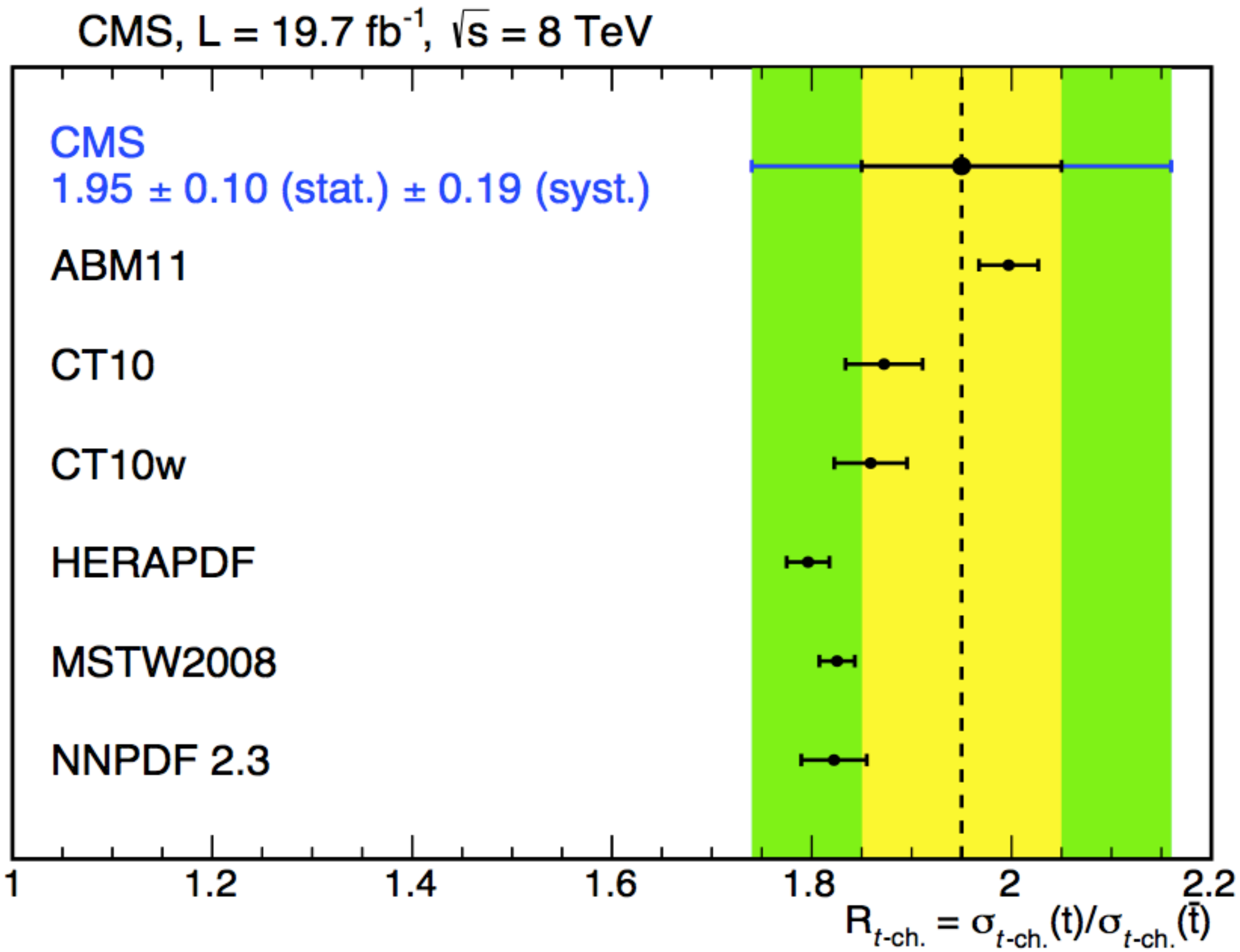
$$\sigma_{\mathrm{NNLO},\bar{t}} = 29.7^{+0.3}_{-0.1}\ \mathrm{pb}$$

$p_\perp$	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

Check with other PDFs

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 (i.e. just run the code):

- 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

Outlook

NNLO is ready for serious phenomenology

More challenging:

- parton shower matching
- lot of recent activity
- next-to-simplest process after H/DY and similar

Suggestions/desiderata?

- this computation is available, would like to make use of it in the more effective way

Thank you for your attention!

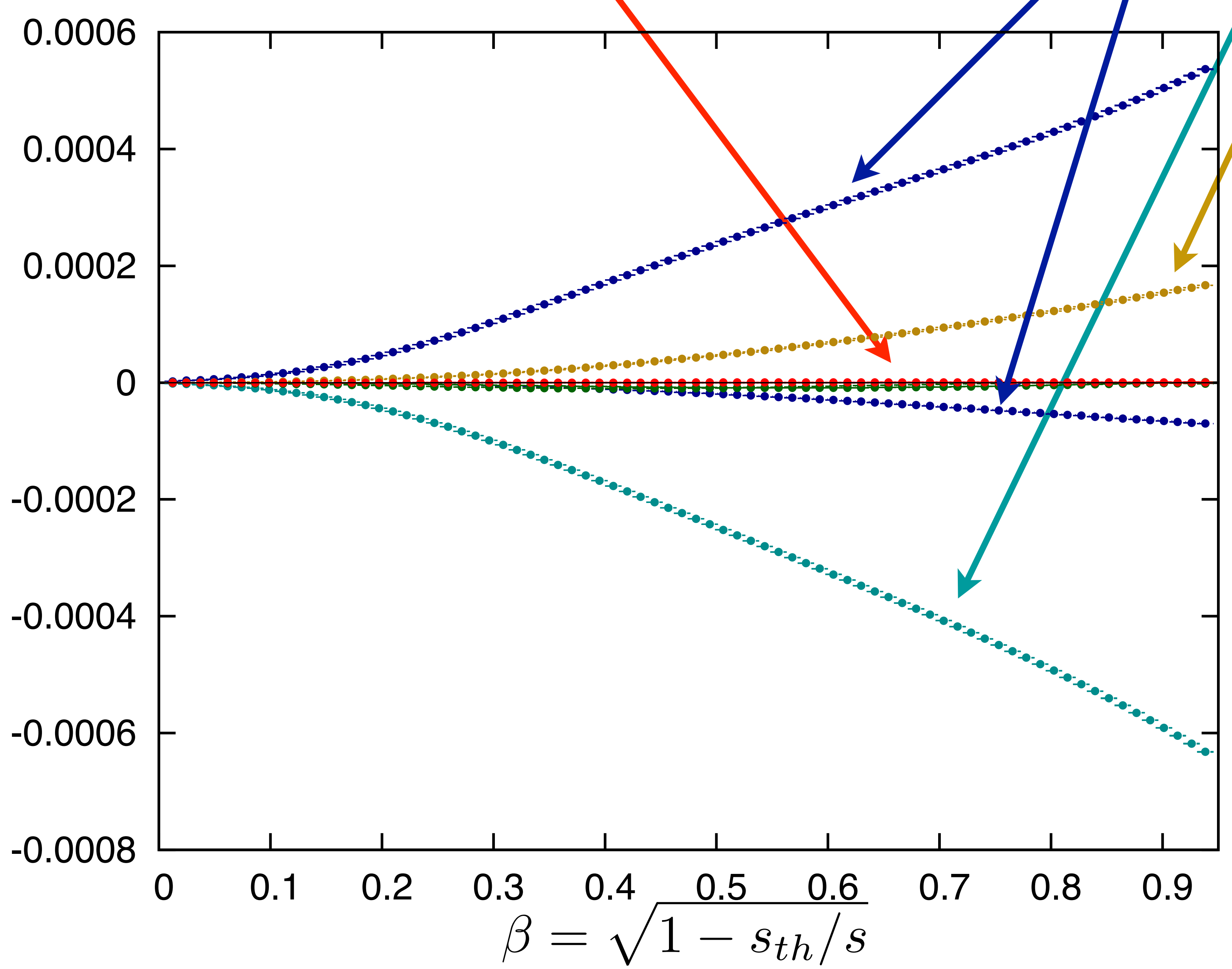
Back-up

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

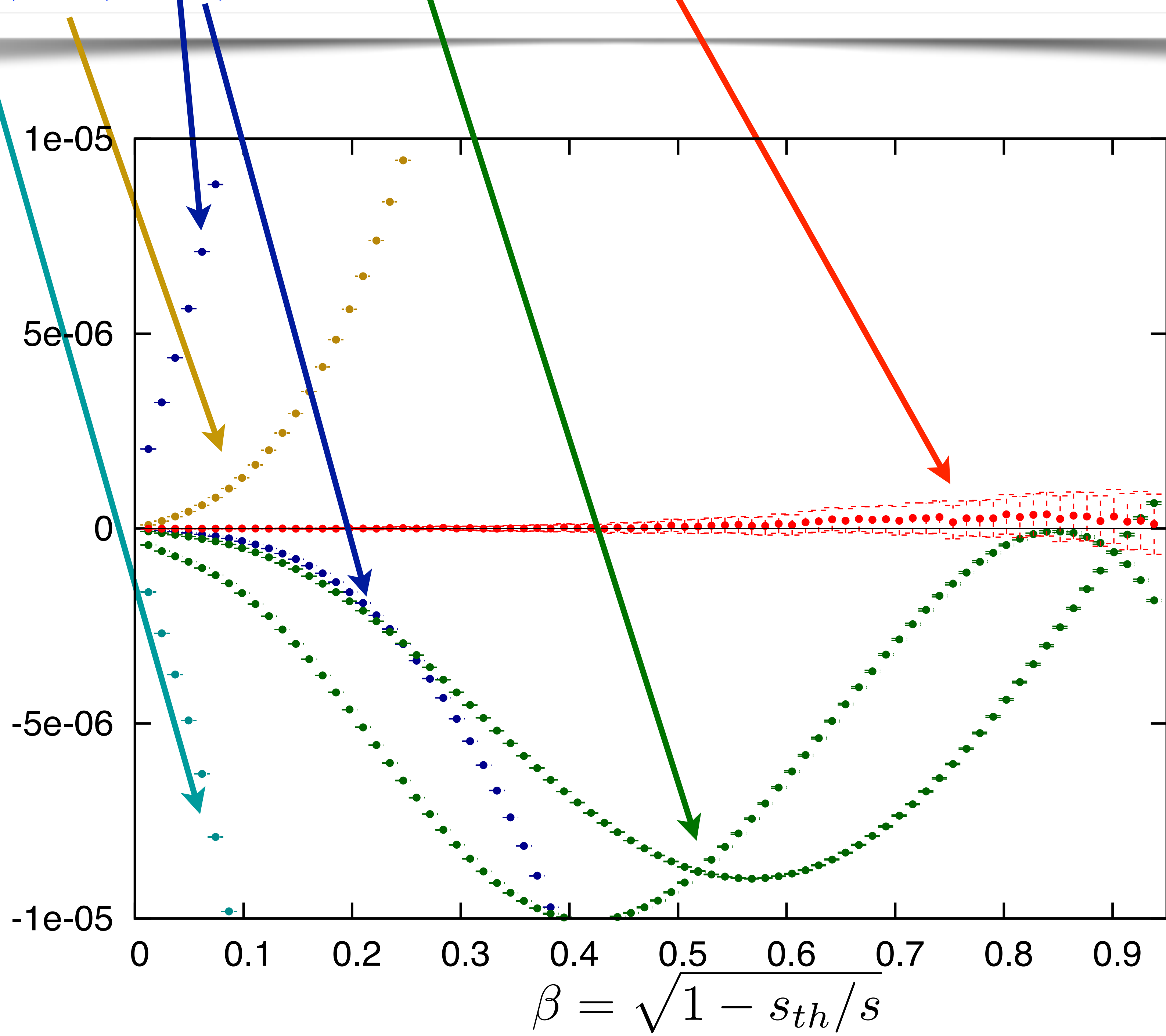
NUMERICAL CANCELLATION between
renormalization and coll. couterterms, RR, RV, VV



$1/\epsilon$ poles, summing individual contributions

Checks: poles cancellation

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



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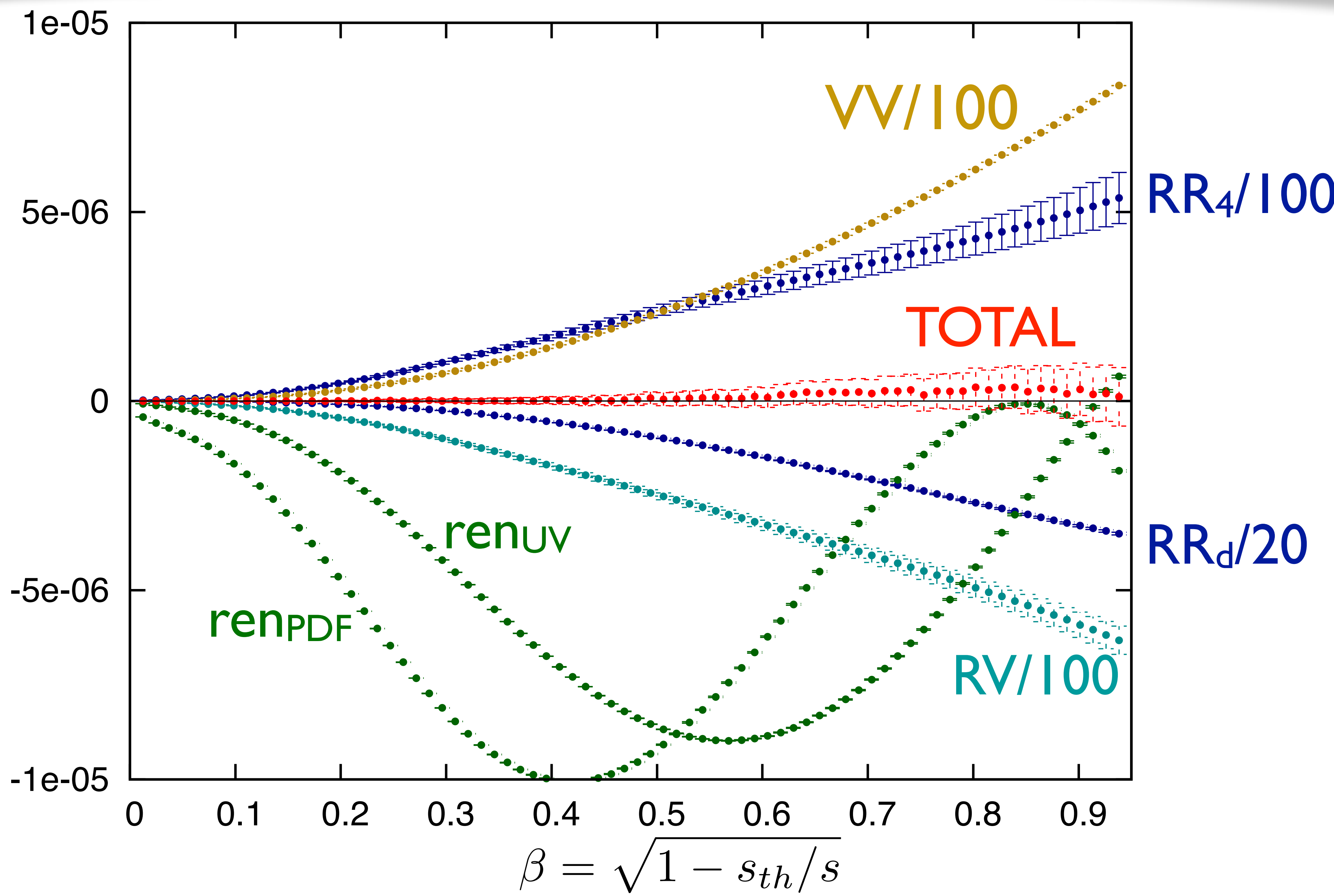

$1/\epsilon$ poles, summing individual contributions