Precision predictions for single-top production at the LHC

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

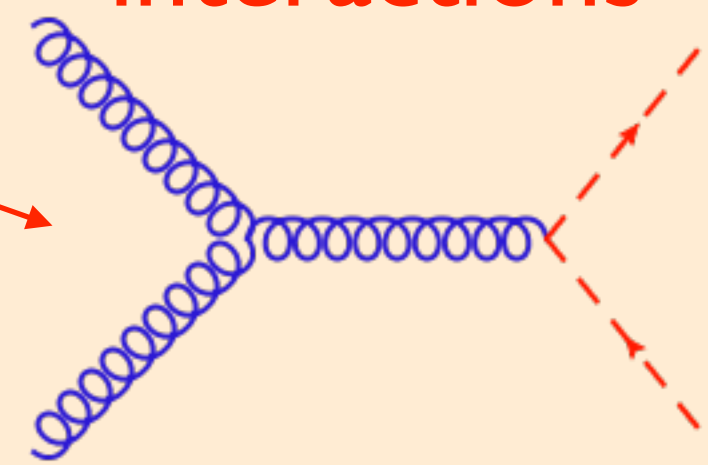
TOP QUARK DIFFERENTIAL DISTRIBUTIONS, CANNES, SEP. 26TH 2014

Single-top: EW production of tops

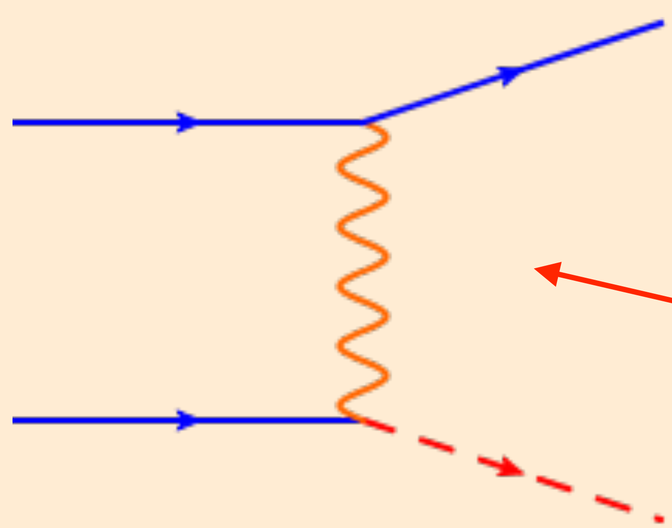
Two main production mechanism
of tops at hadron colliders:

EARLIER TODAY

Probe strong interactions

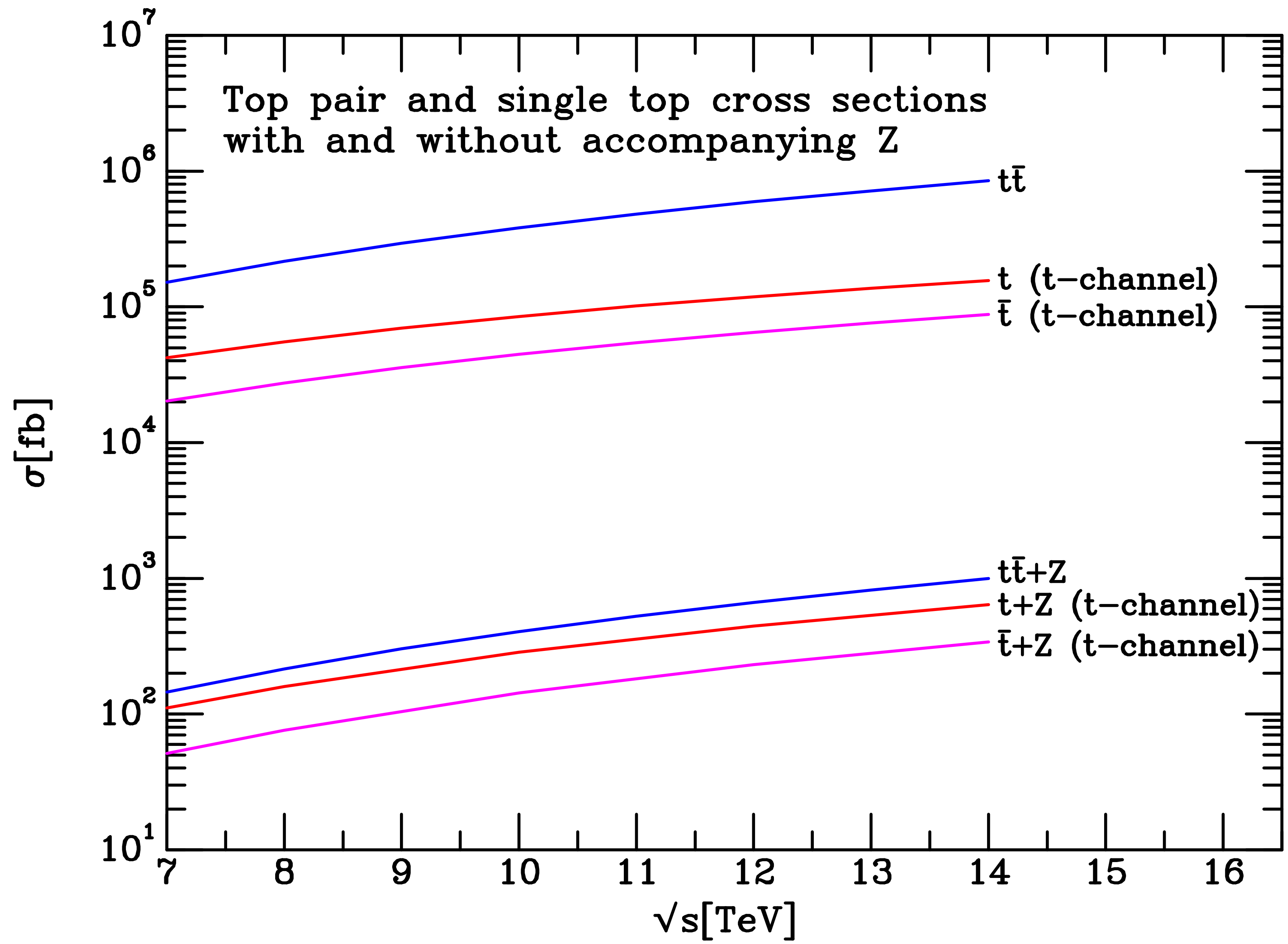


Probe weak interactions



FOCUS OF THIS TALK

LHC as a top factory



[Campbell, Ellis, Rontsch (2013)]

From discovery to PRECISION PHYSICS

Single-top: smaller rates w.r.t. top pair production, but sizable yield

A lot is known:

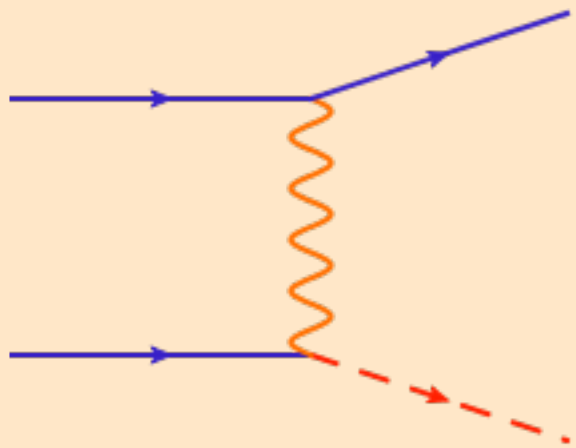
- NLO in the 4/5FS [Bordes et al (1995), Stelzer et al (1997), Harris et al (2002), Beccaria et al (2008), Heim et al (2010)]
- Corrections with decaying top [Campbell et al (2004-2009), Cao et al (2005), Schwienhorst et al (2011), Pittau(1996), Falgari et al (2010, 2011), Papanastasiou et al (2013)]
- Soft gluon approximations [Kidonakis; Zhu et al (2010,2011)]
- NLO + PS, automation [Frederix et al (2012), Alioli et al (2009)]

IS IT ENOUGH TO CLAIM ~ PERCENT THEORETICAL ACCURACY?

Single-top: probing tops via EW interactions

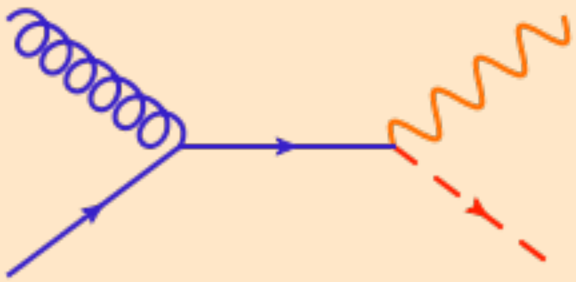
Rough classification (not well-defined):

T-CHANNEL



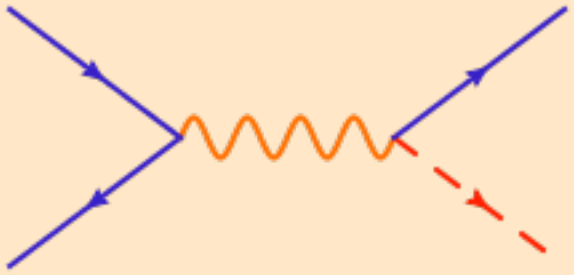
LHC8: ~ 82%
TEV: ~ 65%

ASSOCIATED PRODUCTION



LHC8: ~ 15%
TEV: ~ 0

S-CHANNEL



LHC8: ~ 5%
TEV: ~ 33%

requirement: ~ percent accuracy in the T-CHANNEL

t-channel single top: do we need NNLO?

LOOK AT THE NLO PREDICTION

The total cross section at the 8 TeV LHC:

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

NAIVELY:

"Small ~ 2% corrections, no need to go further"

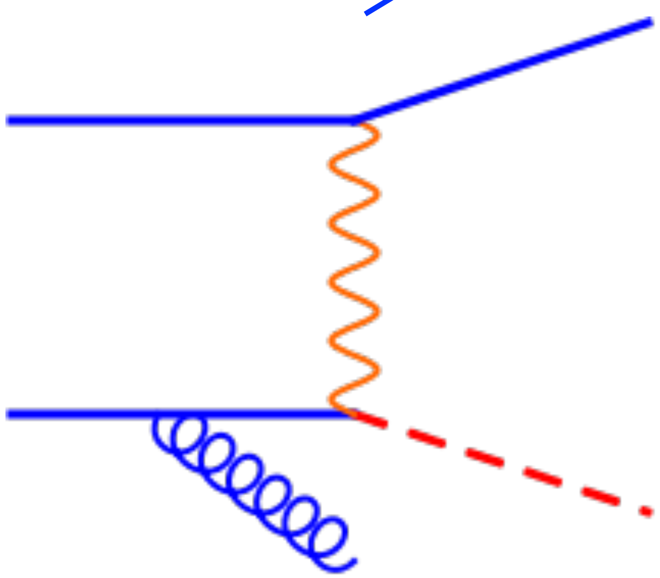
HOWEVER…

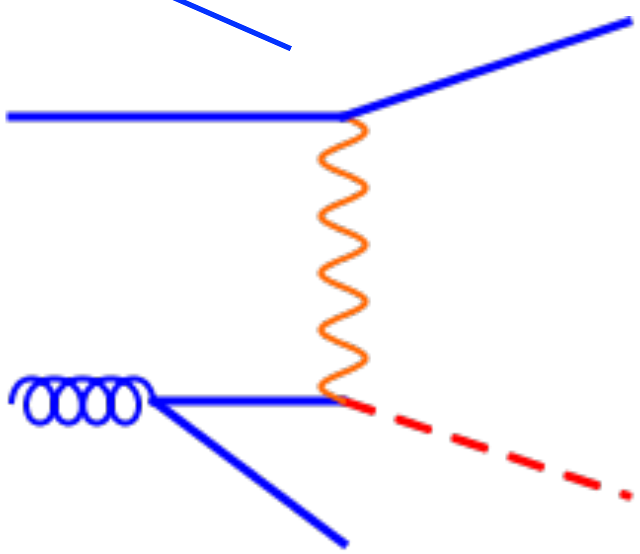
t-channel single top: do we need NNLO?

The total cross section at the 8 TeV LHC: A Closer Look

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

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





Large cancellations among channels

t-channel single top: do we need NNLO?

THE NLO K-FACTOR IS ACCIDENTALLY SMALL

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

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

$p_\perp$	σ_{LO}, pb	σ_{NLO}, pb	δ_{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	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$

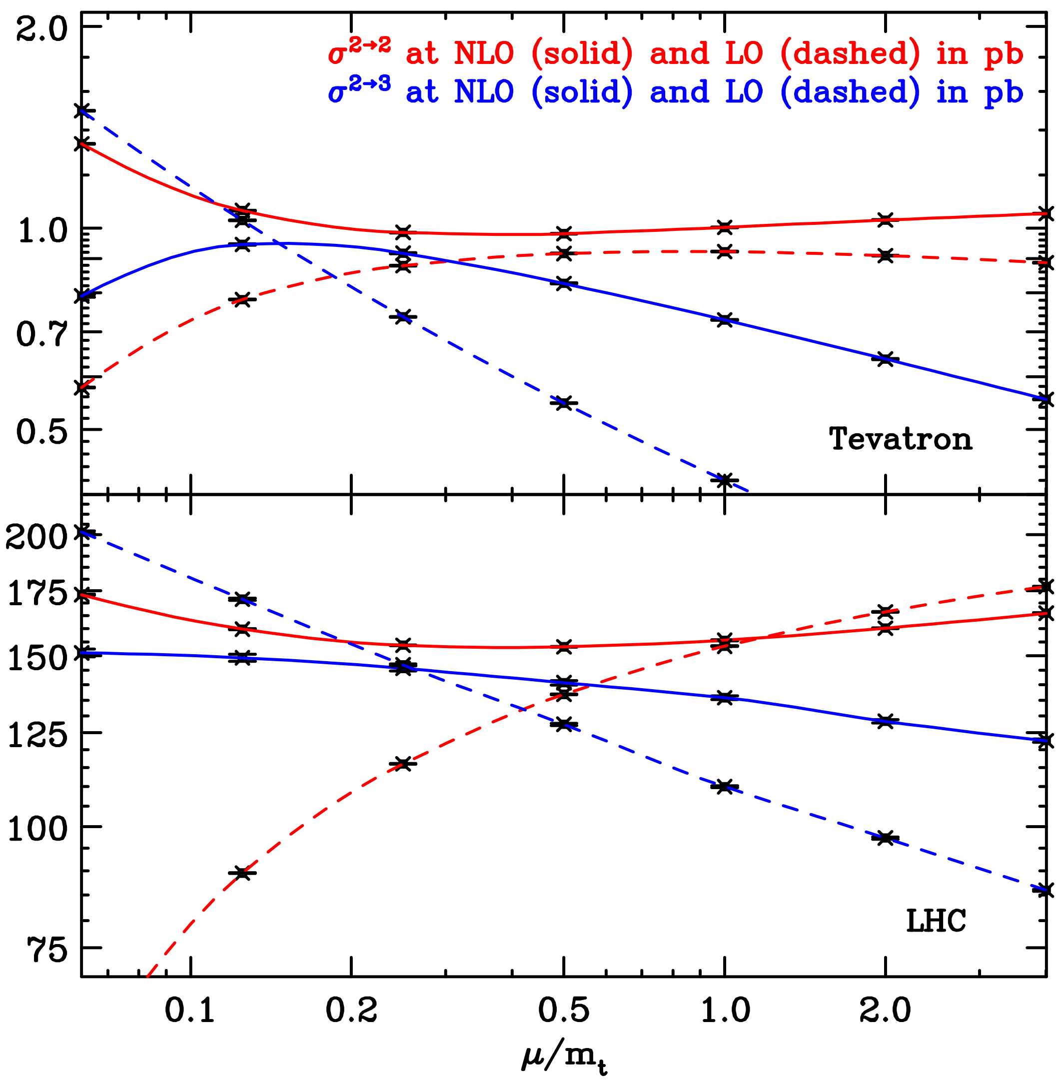
Corrections to more exclusive observables ~ 10%

T-channel single top: do we need NNLO?

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

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

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



[Campbell et al (2009)]

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

T-channel single top: do we need NNLO?

The total cross section at the 8 TeV LHC: A Closer Look

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

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

- Large (accidental?) cancellations between channels
- Scale variation (~ NNLO!) as large as corrections
- Larger corrections for more exclusive observables

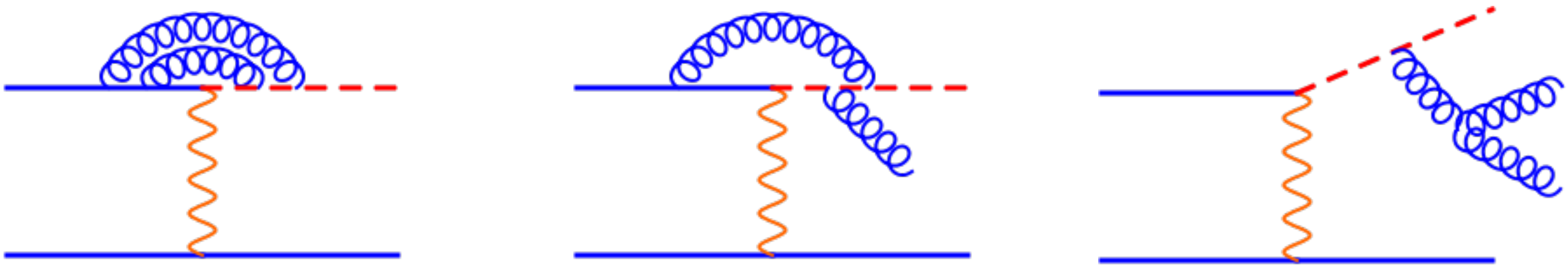
To control single-top production at the percent level:
NNLO Correction to t-channel Production

Single-top t-channel prediction @ NNLO

Anatomy of a NNLO computation

The ingredients:

VV RV RR



[Bonciani et al (2008), Beneke et al (2009)]

[Campbell et al (2005)]

The Goal

To be useful, our computation must be:

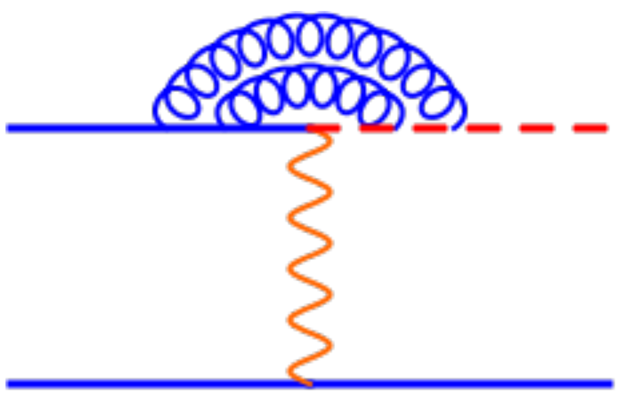
- Fully differential in the top quark
- Top-decay friendly -> keep track of spin correlations

Anatomy of a NNLO computation

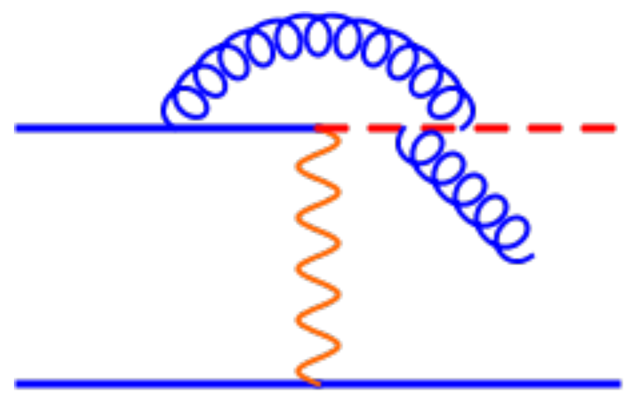
- For a long time, the problem of NNLO computations was how to consistently extract IR singularity from double-real emission/real-virtual emission
- This problem has now been solved both in theory (antenna subtraction, sector decomposition+FKS, semi-analytic subtraction) and in practice (top-pair, dijet, 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

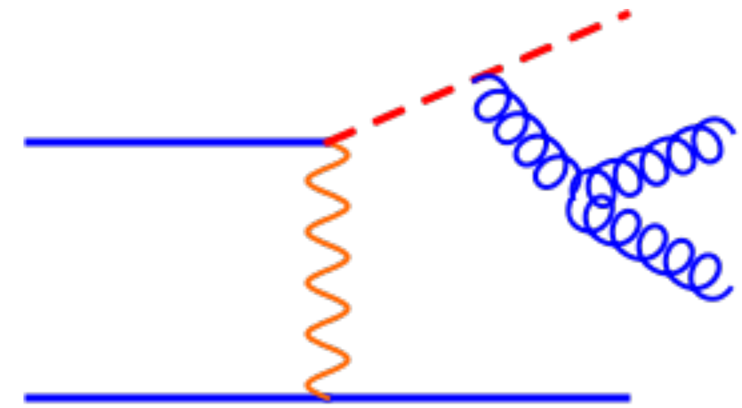
VV



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); Czakon, Heymes (2012)]

t-channel single-top @ NNLO

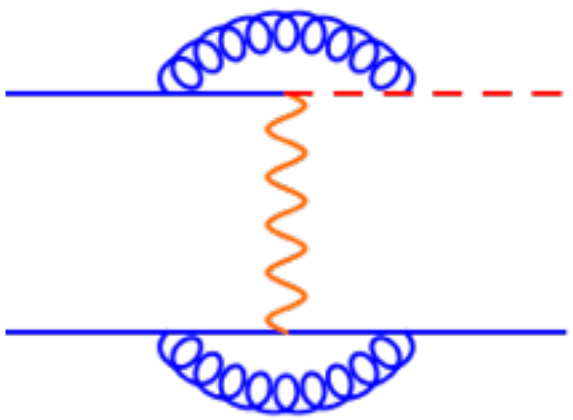
Recent developments in NNLO techniques, allowed us to compute (almost) t-channel single-top corrections

In particular, for our computation:

- 5FNS@NNLO (2->2)
- Fully differential, arbitrary cuts on the final state are not a problem (FKS + Sector Decomposition)
- Amplitude-based formalism, spinor-helicity techniques
  - Very fast and stable RV amplitudes [Campbell et al (2005)]
  - Top spin information always manifest -> straightforward to interface with proper top decay

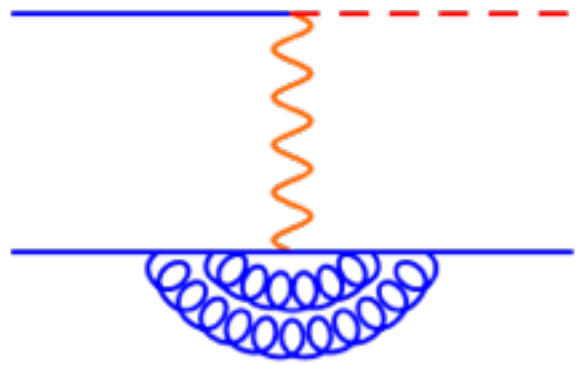
Single-top in the 'factorized' approximation

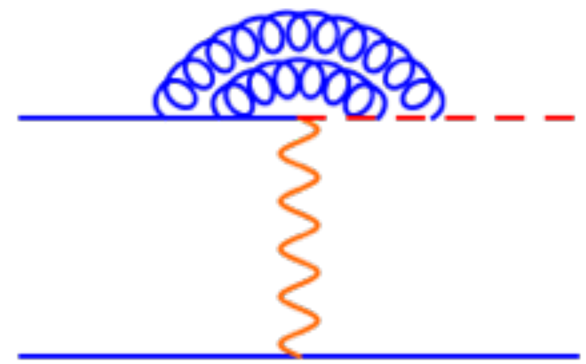
Two-loop amplitudes:



Trivial (~NLO^2)

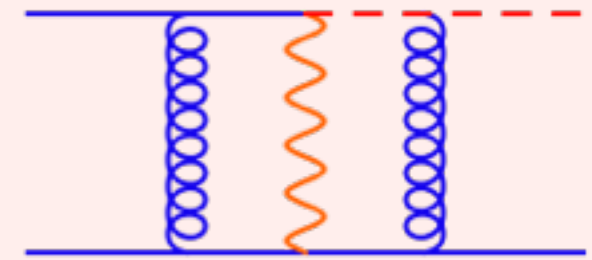
Simple





~OK

(very) hard



Must be interfered with tree-level -> COLOR SINGLET

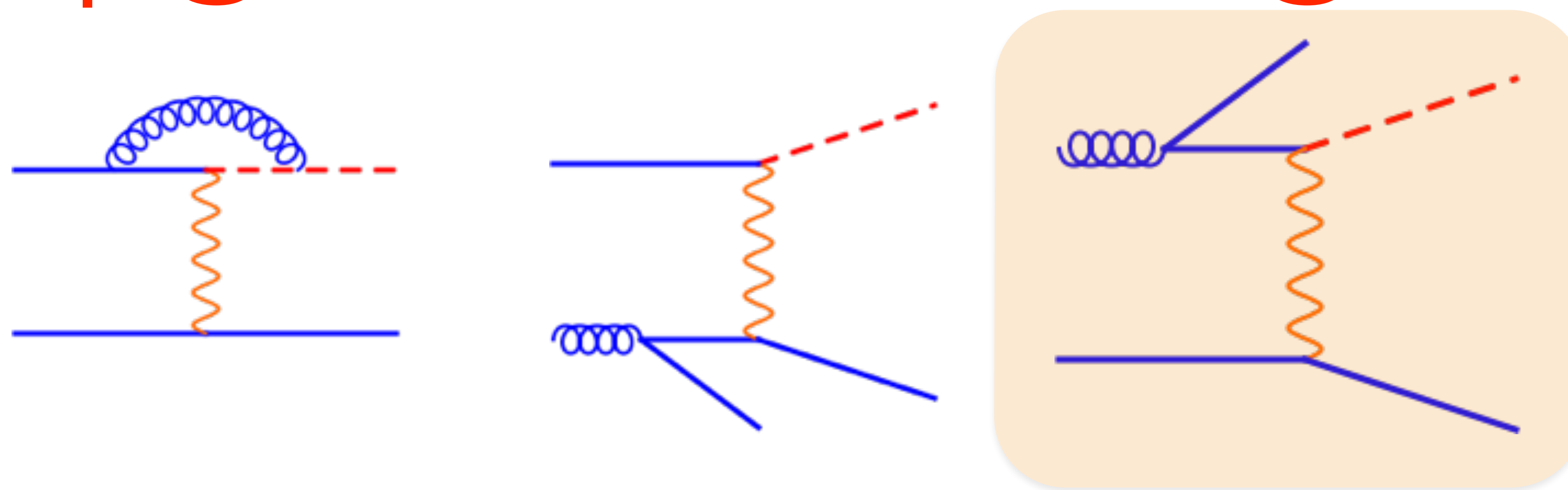
The 'hard' amplitude contribution is suppressed by $1/N_c^2$

For our computation, we CONSISTENTLY NEGLECTED IT

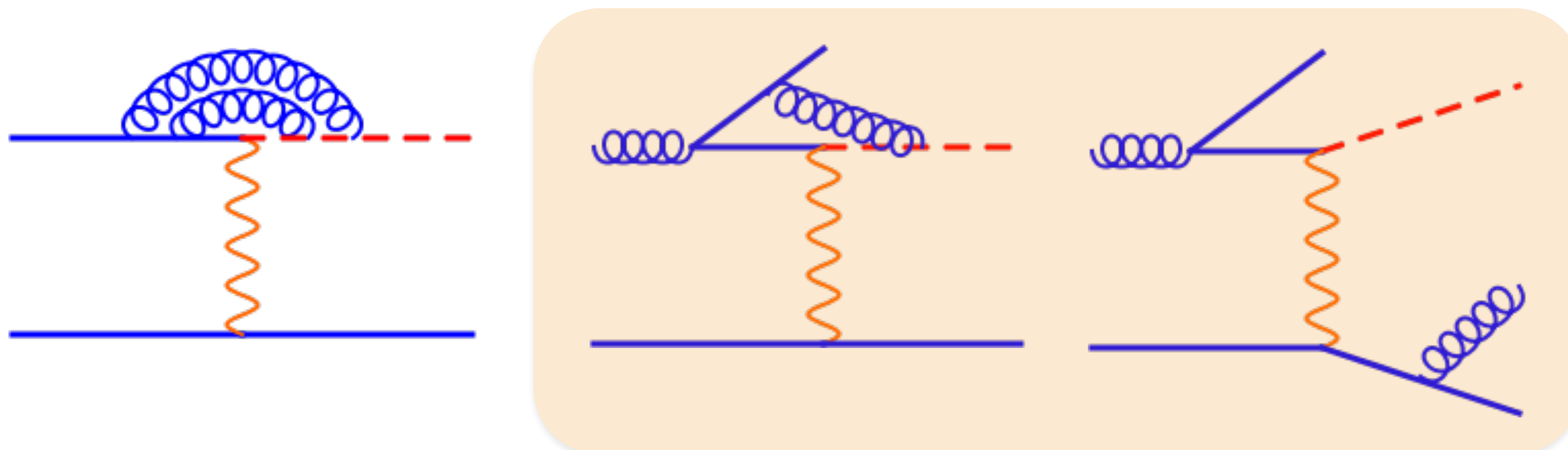
[same for s/t interference]

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

t-channel single-top at NNLO: results

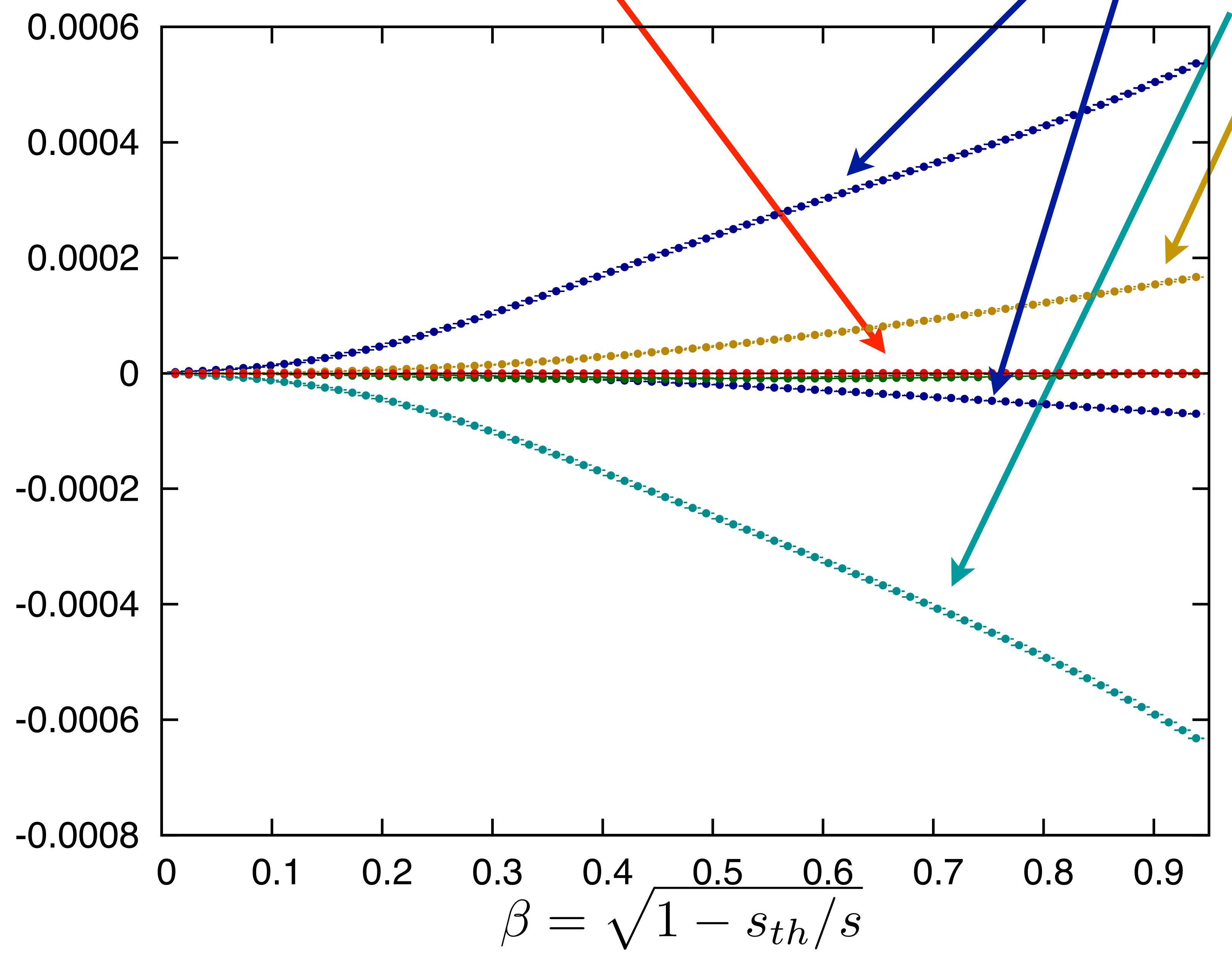
Checks on the computation

- All amplitudes cross-checked against MadGraph/MadLoop
- 'Subtraction terms' properly approximate unresolved configuration [down to fractions of eV (soft) and degree (coll.)]
- Unstable RV integrals recomputed, at higher order in ε
- 1-loop massive soft current recomputed from scratch, and cross-checked against [Bierenbaum, Czakon, Mitov (2012)]

- 'Scheme-independence': result independent on whether resolved particles have 2 or $2-2\varepsilon$ polarization (decoupling of $O(\varepsilon)$ terms of amplitudes)
- Scale variation of the result agrees with RGE
- Pole-cancellation (numerical)
- Parts of our result cross-checked against ongoing computation for the inclusive cross-section

Checks: poles cancellation

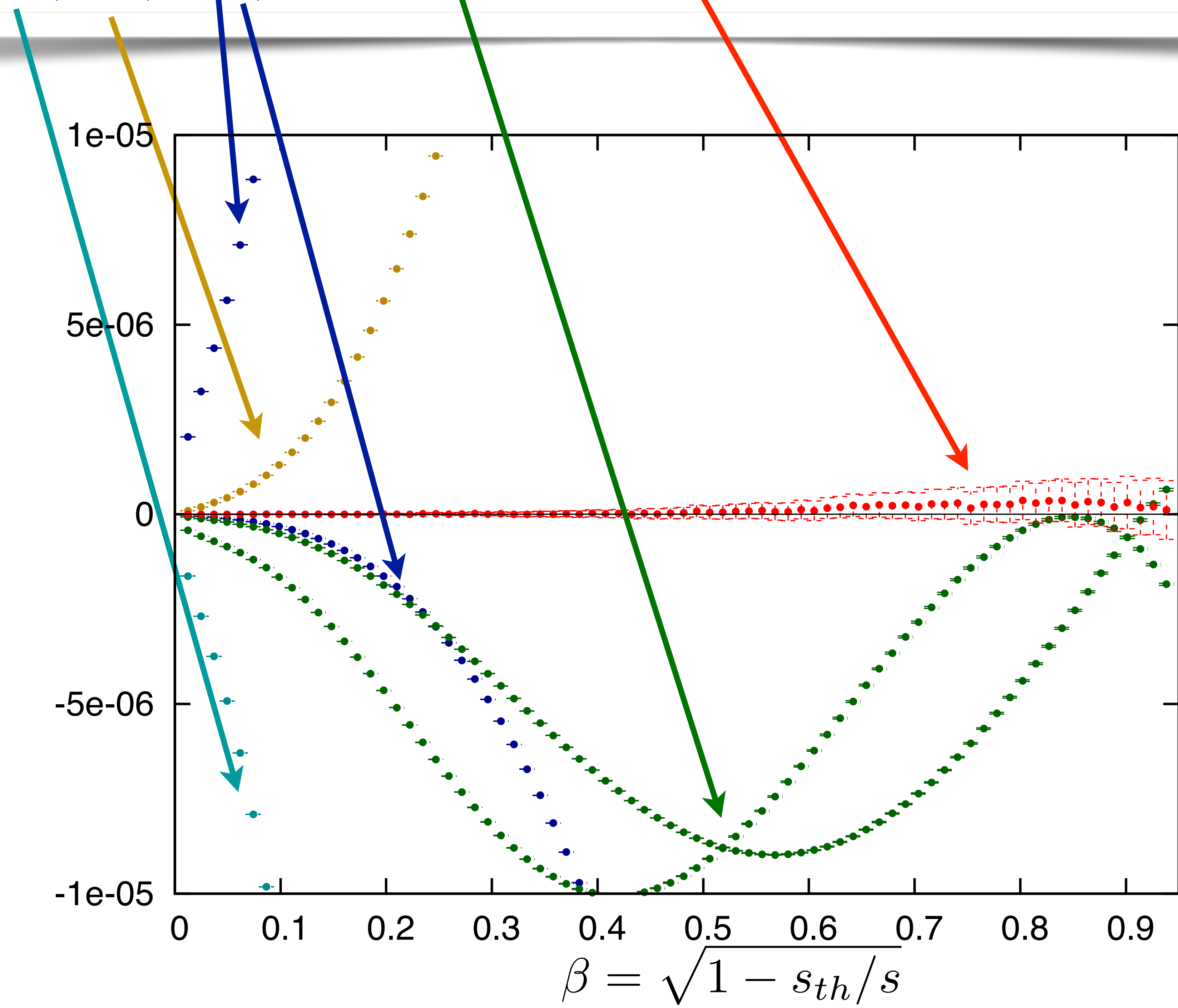
NUMERICAL CANCELLATION between
renormalization and coll. couterterms, RR, RV, VV



$1/\epsilon$ 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
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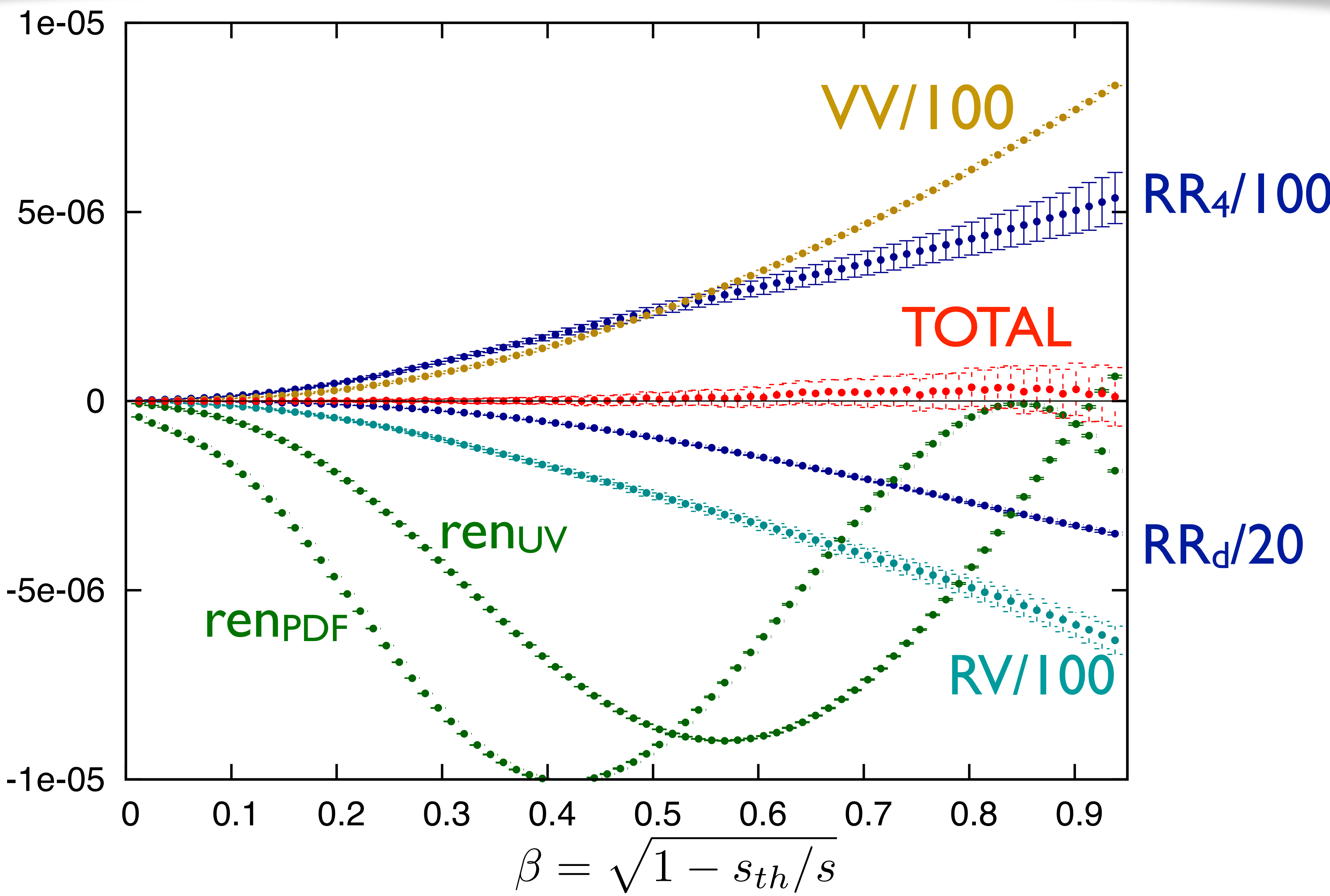


$1/\epsilon$ poles, summing individual contributions

Single-top @ NNLO: total cross section

8 TeV LHC, MSTW2008, m_t = 173.2 GeV

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

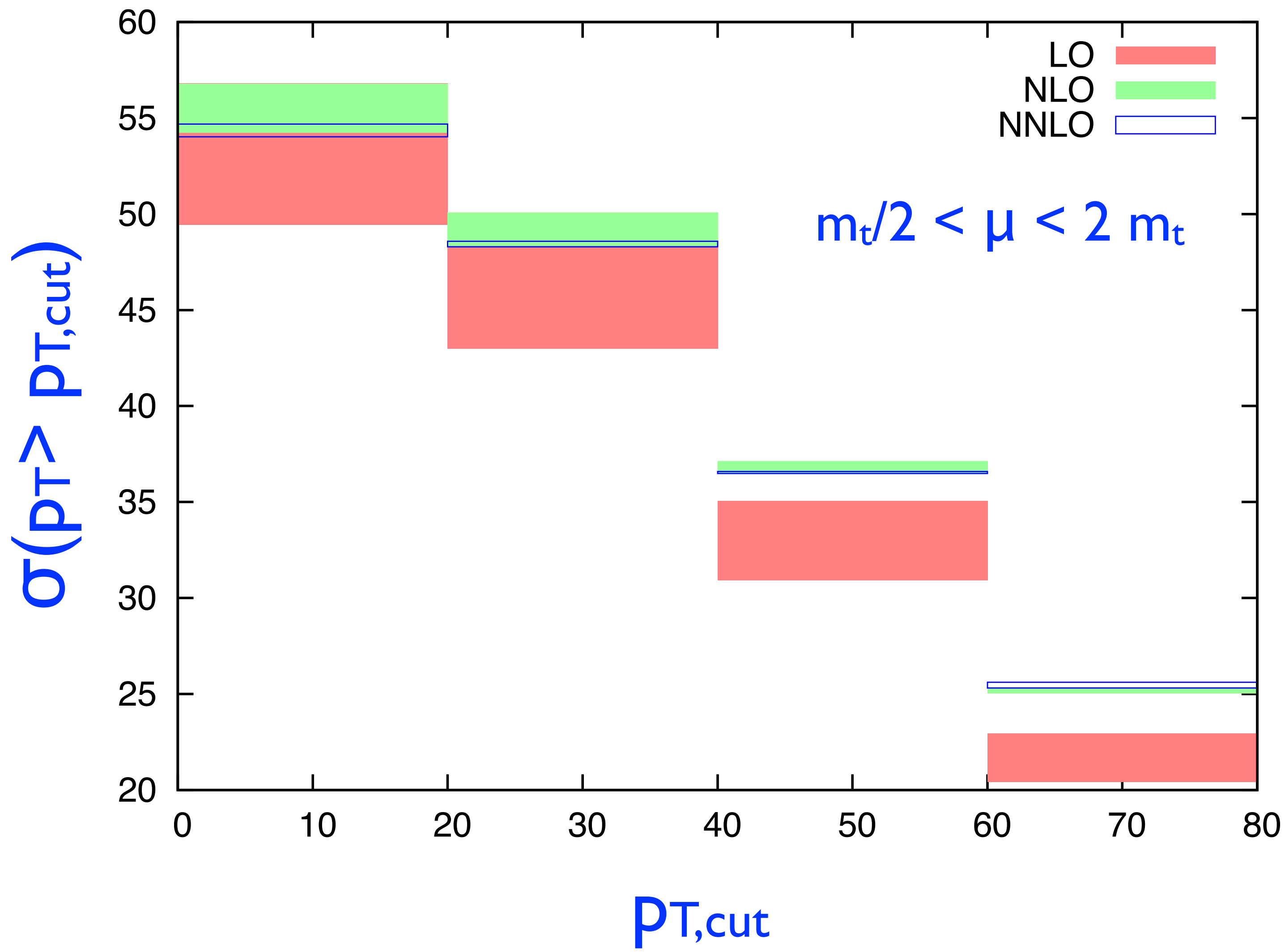
$$\sigma_{\rm NNLO} = 54.2^{+0.5}_{-0.2}\ \text{pb}$$

(μ_R=μ_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
- μ dependence dominated by factorization scale (larger scale -> more b)

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

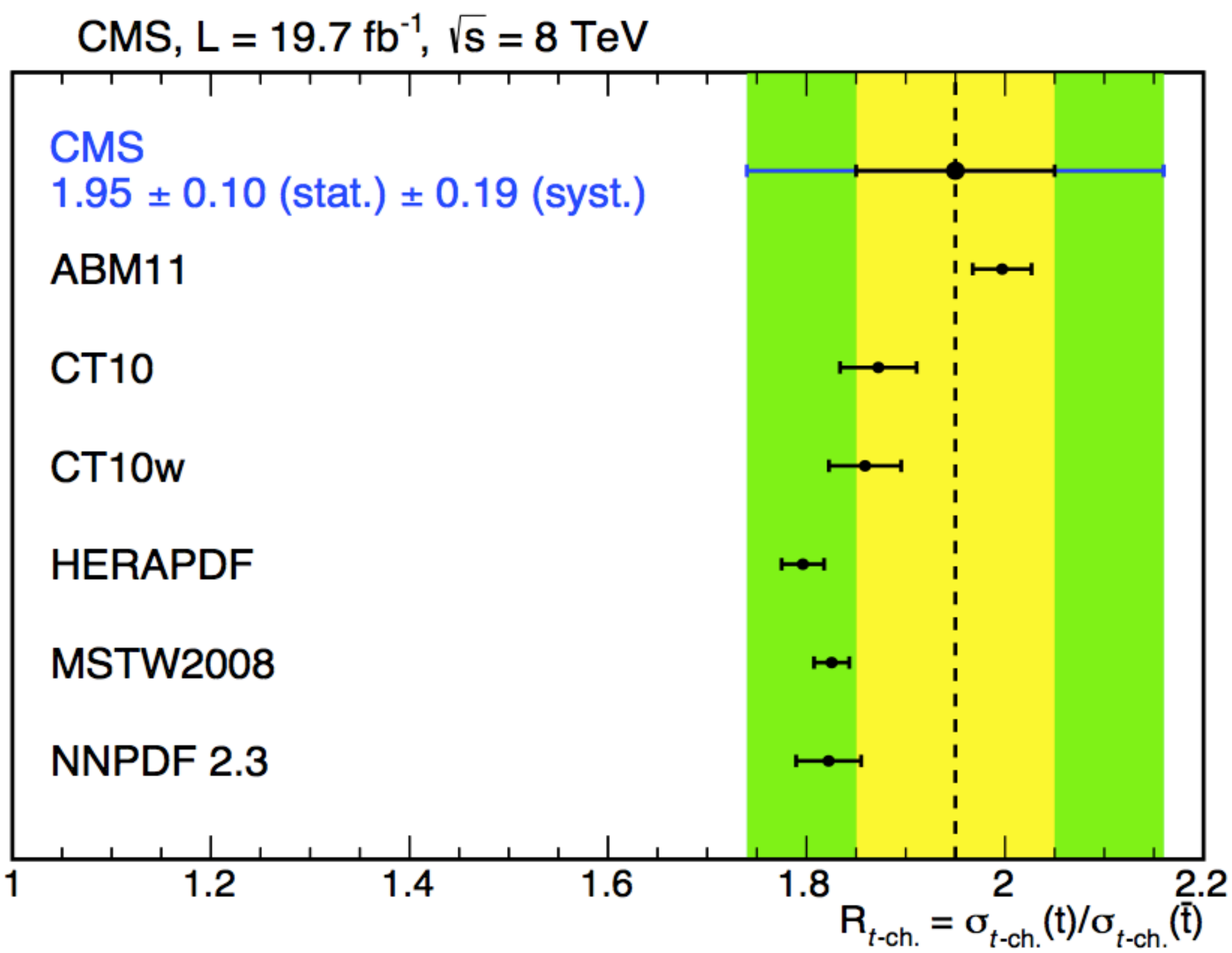
$$\sigma_{\mathrm{NNLO},\bar{t}} = 29.7^{+0.3}_{-0.1}\ \mathrm{pb}$$

$p_\perp$	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
- differential distributions at the reconstructed level?

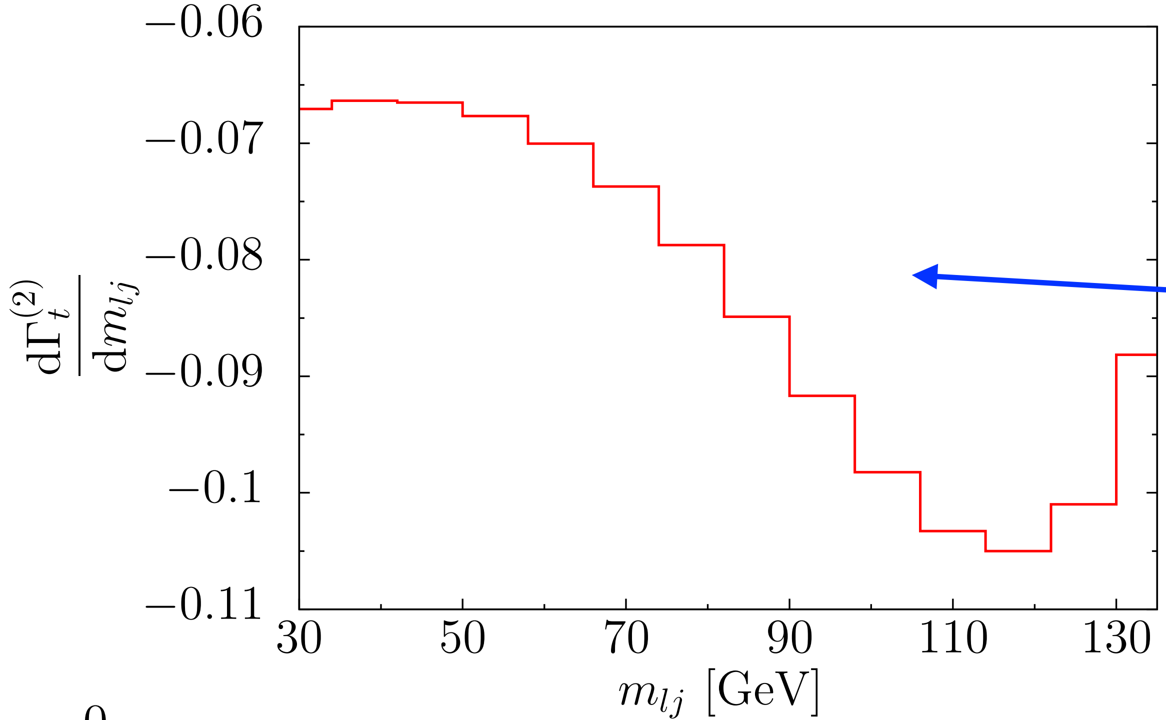
Known in principle (but some work involved):

- interface with top decay in the NWA
- we already know decay@NNLO

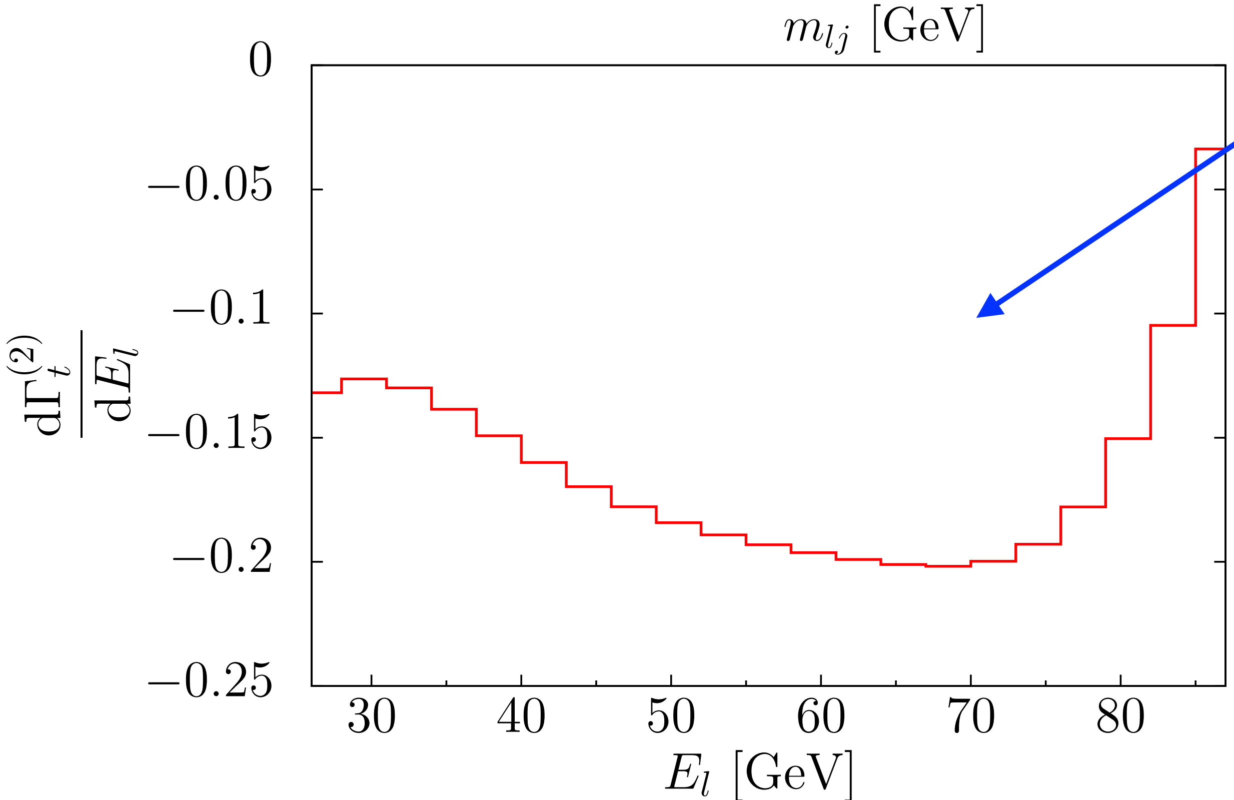
Top decay: status

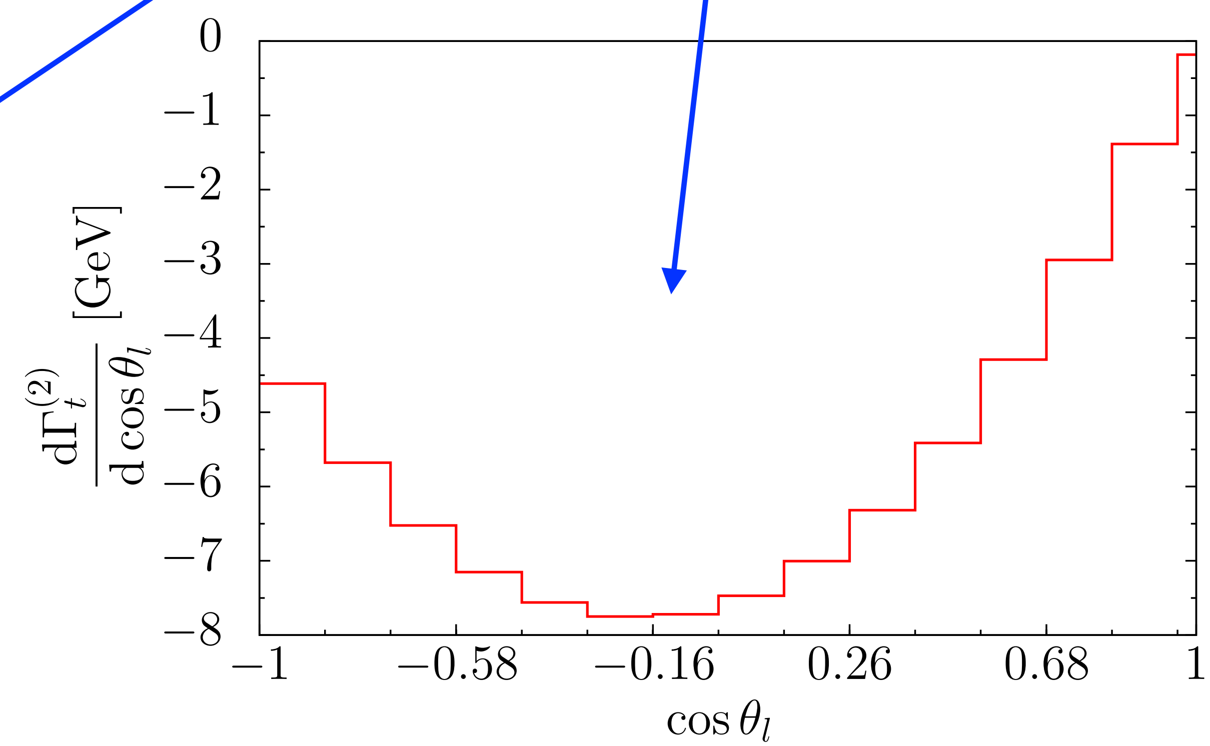
Two completely independent computations

- Gao, Li, Zhu (2012): SCET-based slicing
- Brucherseifer, FC, Melnikov (2013): sector decomposition, amplitude-based -> easy to interface in the NWA



Agreement for realistic differential distributions





Outlook

NNLO is ready for serious phenomenology

- Top decay -> realistic final states at NNLO, parton-level
- More challenging: parton shower matching
  - lot of recent activity
  - next-to-simplest process after H/DY and similar

- In theory, NNLO phenomenology could be in the near future (realistic final states, PS…)
- In practice, are our computations efficient enough?
  - Stable results for complicated observables/final states?
  - How to communicate results to experimentalists / PDF people?

Thank you for your attention!