q_T subtraction for heavy quark production

Javier Mazzitelli

Universität Zürich[UZH]

Les Houches, June 13th 2019

In collaboration with S. Catani, S. Devoto, M. Grazzini, S. Kallweit, H. Sargsyan

q_T subtraction – colourless FS

- Originally developed for the production of colourless final state *F* in hadron collisions
- Slicing method, slicing parameter: qT (transverse momentum of system *F*)

RR and RV contributions from F@NNLO

$$d\sigma^{F}_{\mathrm{NNLO}}\Big|_{q_T\neq 0} = d\sigma^{F+\mathrm{jet}}_{\mathrm{NLO}}$$

Computable with any NLO subtraction method, IR finite

- Only qT → 0 infrared divergencies remain
- But small qT behavior known from qT resummation

$$d\sigma^{F}_{\mathrm{NNLO}} = \mathcal{H}^{F}_{\mathrm{NNLO}} \otimes d\sigma^{F}_{\mathrm{LO}} + \left[d\sigma^{F+\mathrm{jet}}_{\mathrm{NLO}} - d\sigma^{\mathrm{CT}}_{\mathrm{NNLO}} \right]$$

Hard-collinear contributions, only at qT=0

Restores correct normalization, includes the 2-loop corrections

Finite for qT→0

q_T subtraction – colourless FS

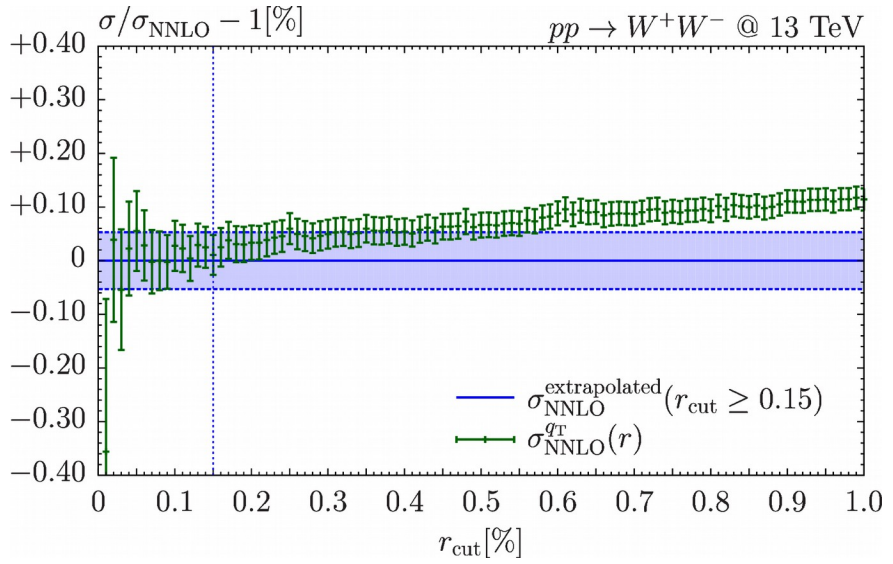
Finite for qT → 0

$$d\sigma^F_{\rm NNLO} = \mathcal{H}^F_{\rm NNLO} \otimes d\sigma^F_{\rm LO} + \left[d\sigma^{F+\rm jet}_{\rm NLO} - d\sigma^{\rm CT}_{\rm NNLO} \right]$$

We need to introduce a cutoff ⟵ Individually divergent when qT → 0

$$r = q_T/Q$$

- Introduce an r_{cut}
- Check that results are independent of r_{cut}
- Extrapolate $r_{cut} \to 0$ result



- qT subtraction successfully applied to a large number of processes (V, VV', H, HH)
- Public implementation for fully differential calculations: MATRIX

[Grazzini, Kallweit, Wiesemann, '17]

q_T subtraction – colourless FS

qT subtraction "solved" at NNLO for colourless final-states

(First N3LO application in 1807.11501 for H prod)

$$d\sigma^F_{\rm NNLO} = \mathcal{H}^F_{\rm NNLO} \otimes d\sigma^F_{\rm LO} + \left[d\sigma^{F+\rm jet}_{\rm NLO} - d\sigma^{\rm CT}_{\rm NNLO} \right]$$

Obtained from the hard-collinear function

$$[H C_1 C_2]$$

Universal relation between hard-virtual function and loop-corrections known

$$d\sigma^{\rm CT} \sim \Sigma^F(q_T/M) \otimes d\sigma^F_{\rm LO}$$

CT coefficients known

All-orders loop amplitude (process dependent)

$$H \sim \langle \tilde{\mathcal{M}} | \tilde{\mathcal{M}} \rangle \quad \text{with} \quad |\tilde{\mathcal{M}}\rangle = \left(1 + \tilde{I}\right) |\mathcal{M}\rangle$$

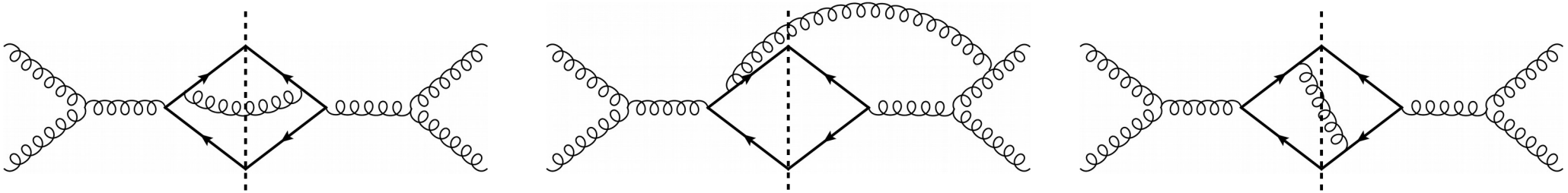
Subtraction operator that correctly accounts for the stuff we put in the CT (universal)

$$\text{Computing } H \longleftrightarrow \text{Computing } \tilde{I} \,(+ \text{ virtuals})$$

Can be explicitly obtained by computing the differential cross section $d\sigma/d^2q_T$ at small q_T at the corresponding perturbative order

q_T subtraction – $Q\overline{Q}$ case

Additional final-state radiation → Massive emitters: only new **soft** divergencies



q_T subtraction – $Q\bar{Q}$ case

Additional final-state radiation ⟶ Massive emitters: only new **soft** divergencies

- qT subtraction successfully applied at NLO for $t\bar{t}$ (and NNLO off-diagonal)

[Bonciani, Catani, Grazzini, Sargsyan, Torre, '15]

- At NNLO:

$$d\sigma^{t\bar{t}}_{\rm NNLO} = \mathcal{H}^{t\bar{t}}_{\rm NNLO} \otimes d\sigma^{t\bar{t}}_{\rm LO} + \left[d\sigma^{t\bar{t}+\rm jet}_{\rm NLO} - d\sigma^{t\bar{t},\rm CT}_{\rm NNLO} \right]$$

Two-loop virtuals known numerically

[Baernreuther, Czakon, Fiedler, '13]

Structure of hard-virtual function was unknown!

Known from studies on qT resummation

[Li, Li, Shao, Yang, Zu, '13; Catani, Grazzini, Torre, '14]

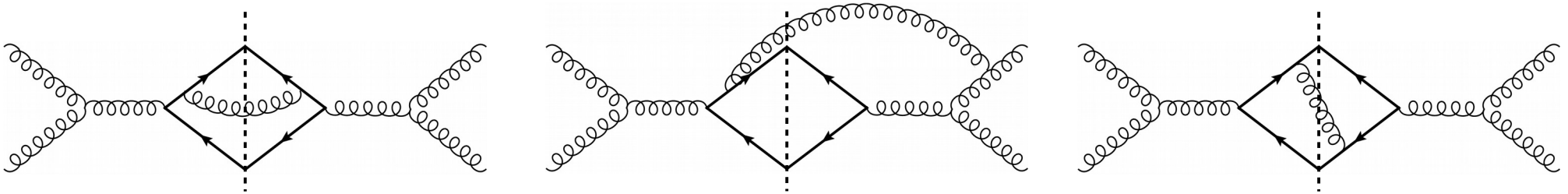
$$H \sim \langle \tilde{\mathcal{M}} | \tilde{\mathcal{M}} \rangle \longrightarrow (\mathbf{H\Delta}) \sim \langle \tilde{\mathcal{M}} | \mathbf{\Delta} | \tilde{\mathcal{M}} \rangle$$

Equivalent to: $\tilde{I} \longrightarrow \tilde{\mathbf{I}}$

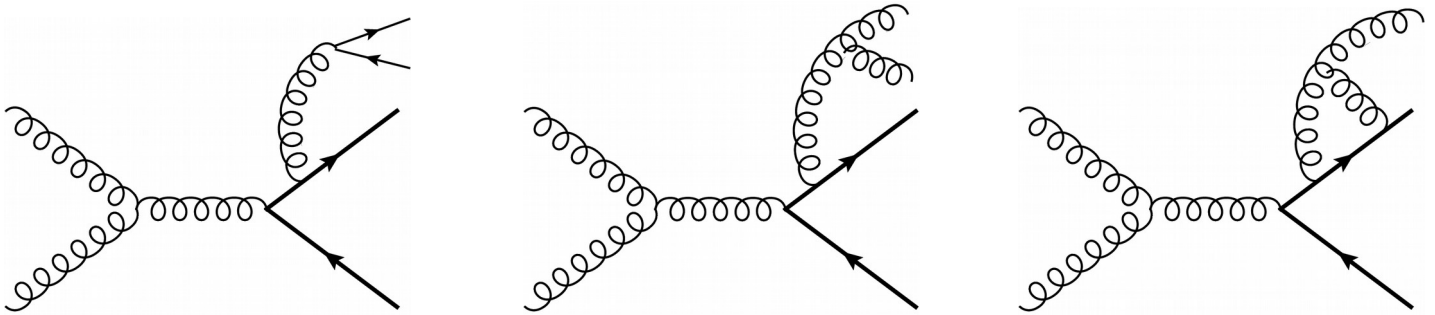
- Additional radiative soft factor **Δ**
- **NEW**: colour correlations in **Δ** (4 hard partons) absent in the colourless case
- Its computation: integrate emissions from final state (specifically, $d\sigma/d^2q_T$)

Computation of $d\sigma/d^2q_T$ at low qT implies the PS integration of (appropriately defined) soft currents

At NLO we have single gluon emission contributions



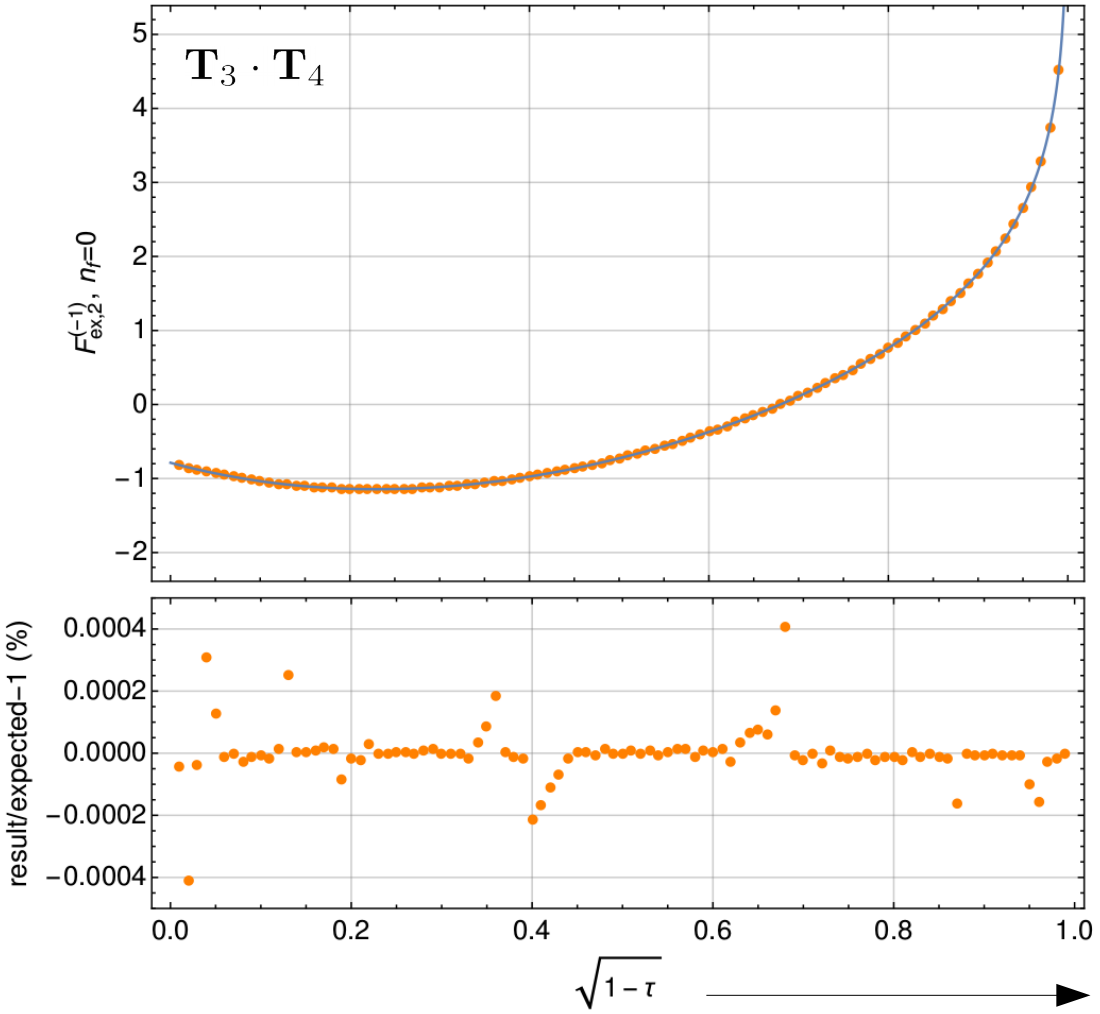
At NNLO we have $q\bar{q}$, double gluon and one-loop single gluon soft emissions



Most of the calculation was performed analitically, (numerically-)small piece obtained numerically (evaluated in 10000 PS points optimized for ttbar production)

Final result – pole cancellation

- Final result: gg + qq + g (1-loop) → triple poles cancel here
- Poles can be predicted, they cancel IR singularities of (a piece of) the 2-loop virtuals
- Analytic cancellation for all contributions, except for $\mathbf{T}_3.\mathbf{T}_4$ single pole:

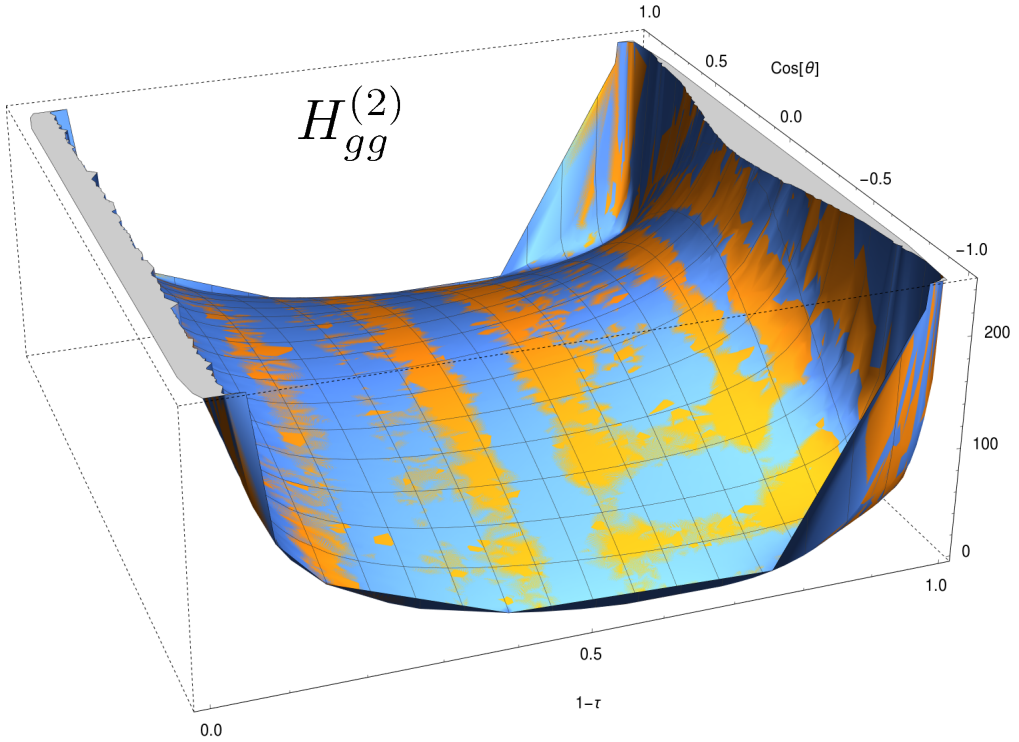


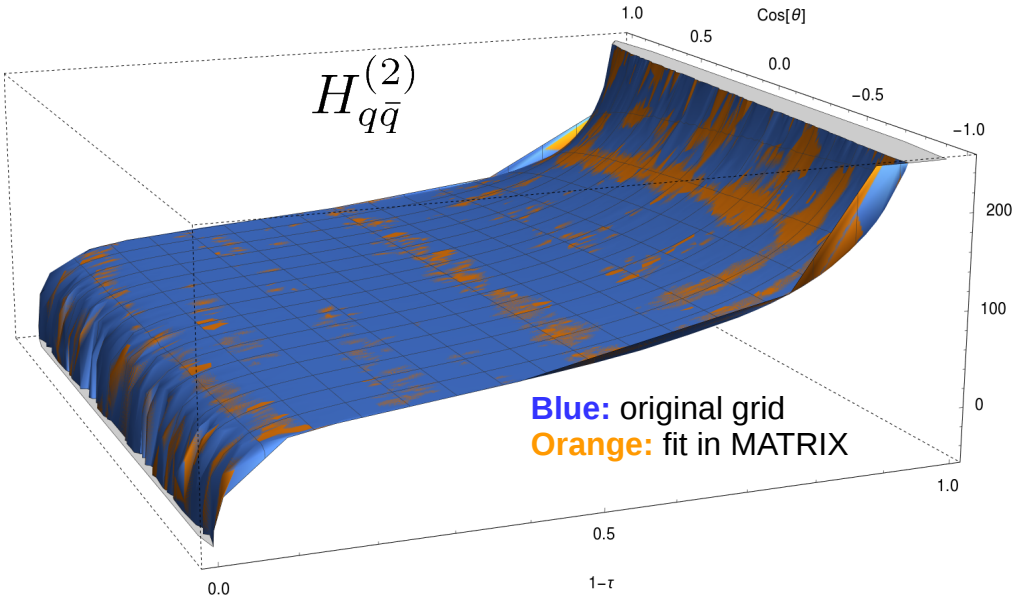
Poles independent of cos(θ)

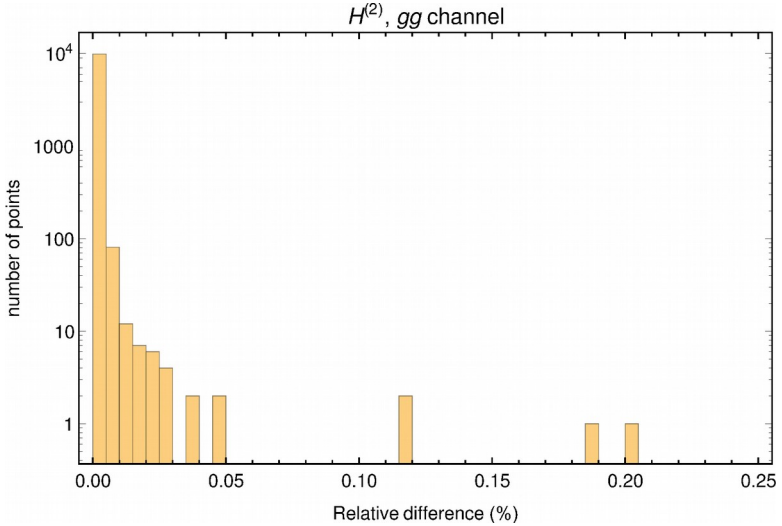
Final result – $H^{(2)}$

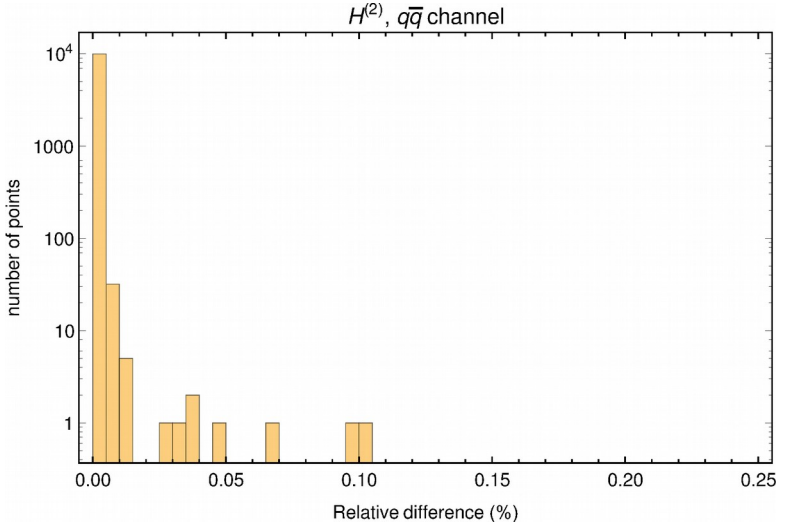
Small numerical impact:
~3% of the NNLO piece at 13TeV

- Implementation in MATRIX: combination of analytic results + grids
- Final result for hard-virtual function $H^{(2)}$, including two-loop virtuals from [Baernreuther, Czakon, Fiedler, '13]



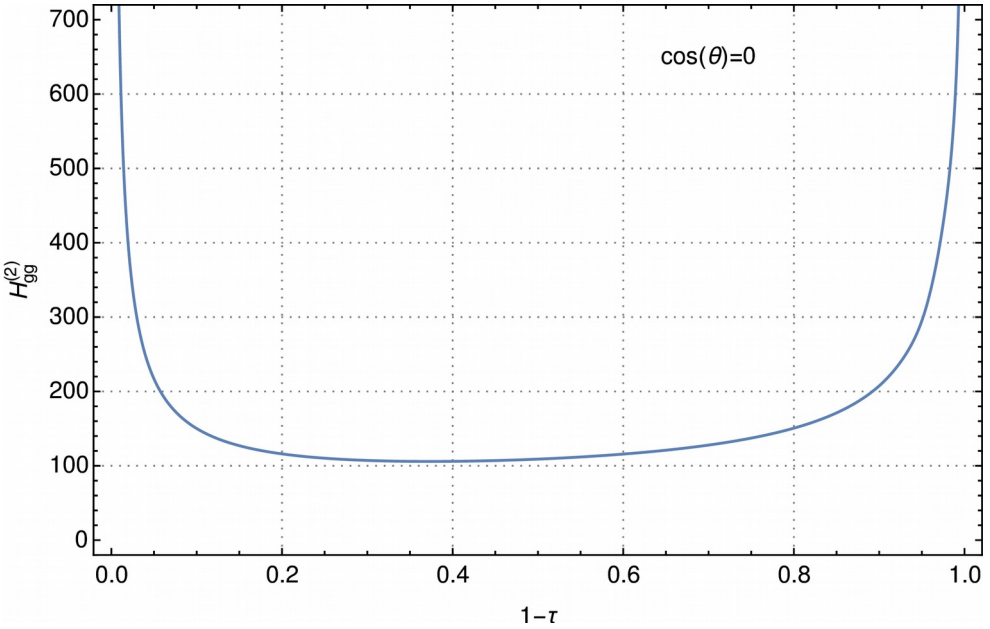


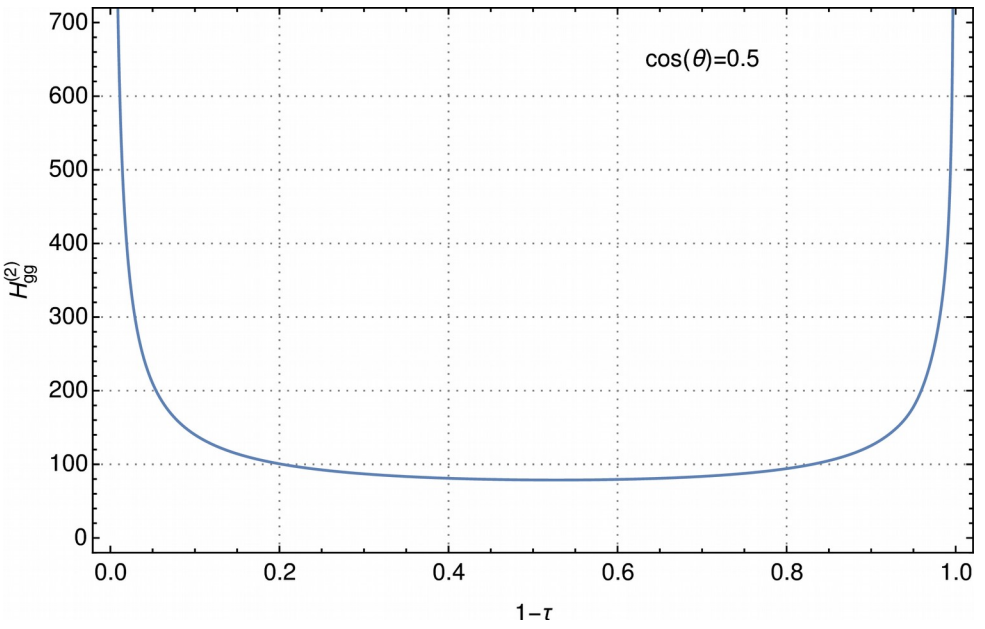


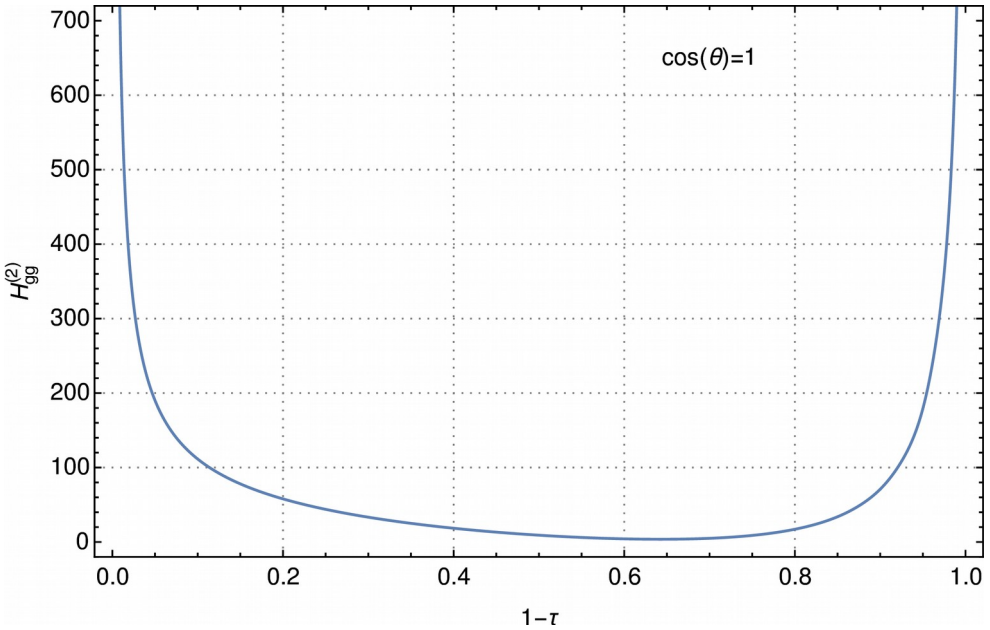


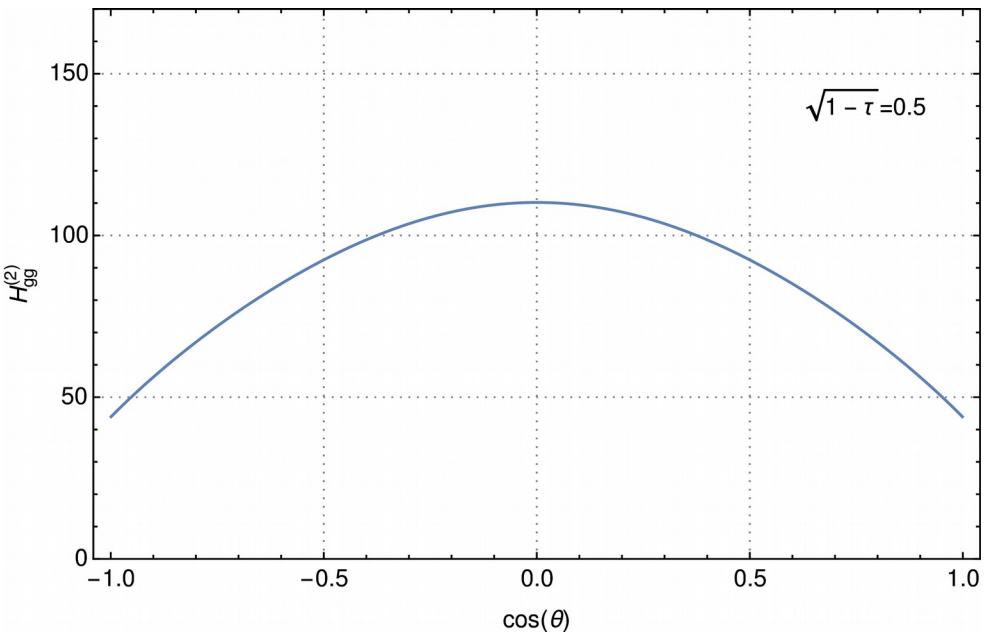
- Comparison of grid against fit shows it is well under control
- We also performed validations removing a large fraction of the grid points
- No need to include additional uncertainty due to numerical piece

Final result – $H^{(2)}$

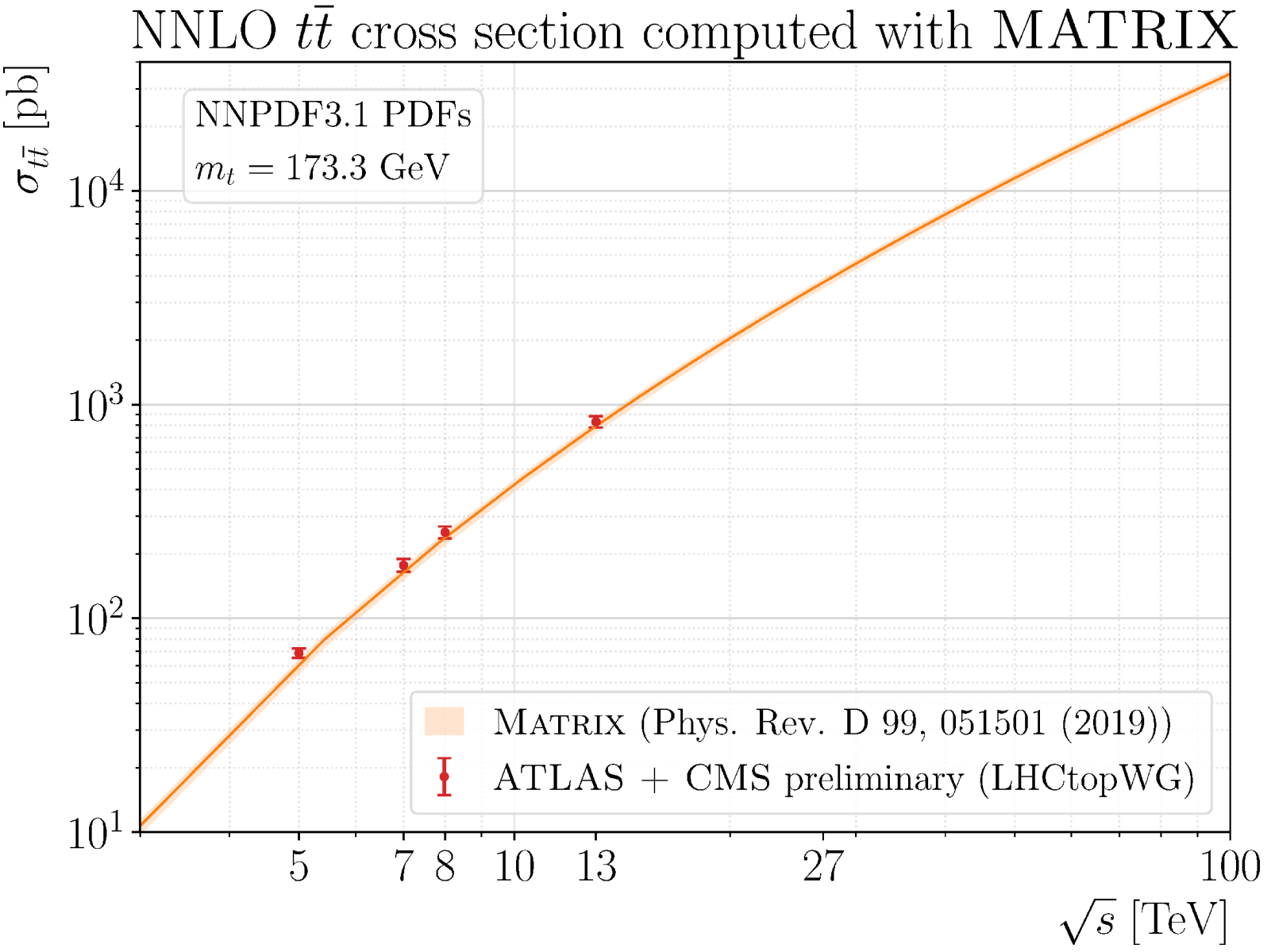








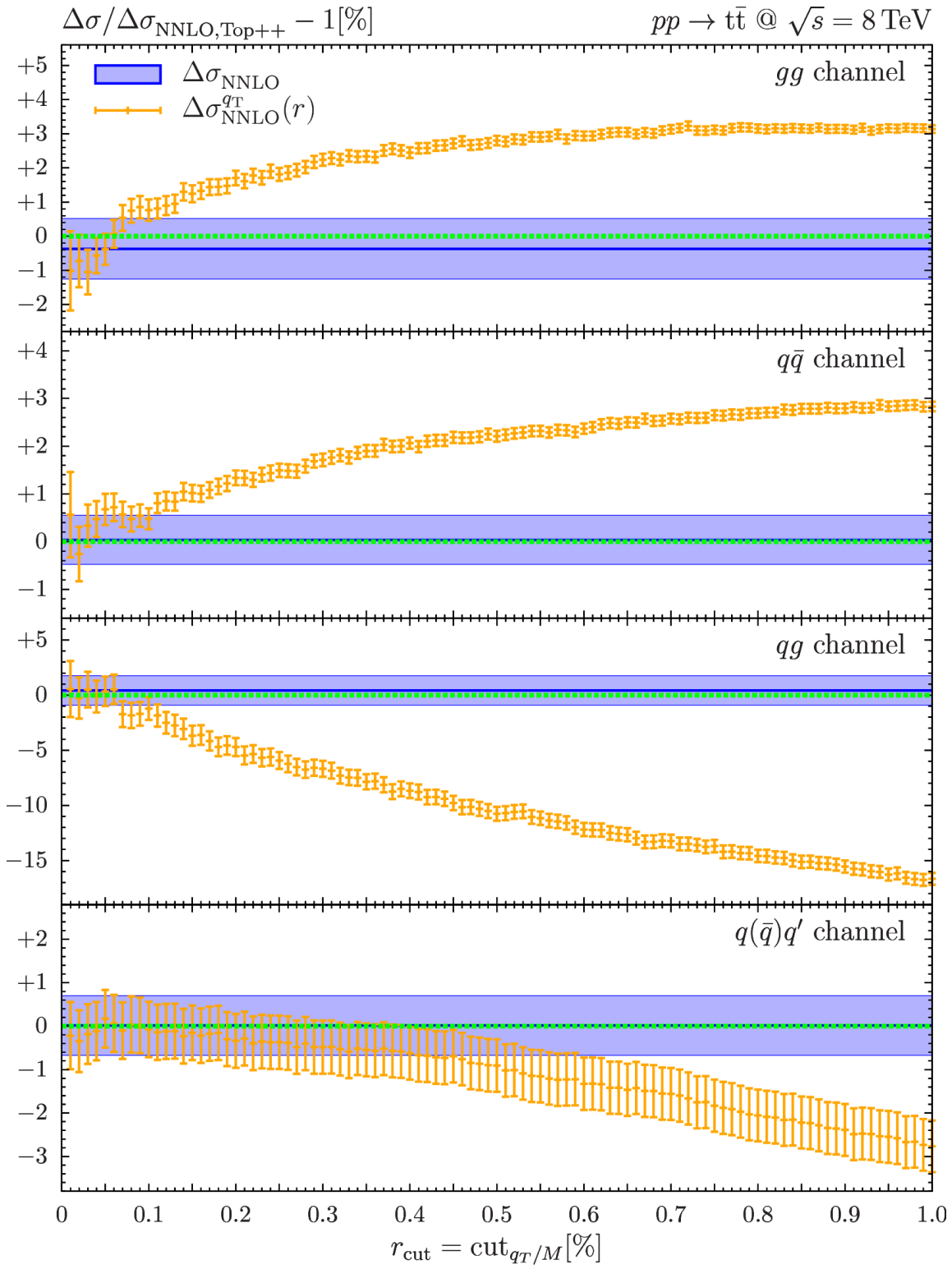
Numerical results



Per-mille level accuracy for total cross section achievable in ~1000CPU days

Numerical results

- Quality of the $r_{cut} \to 0$ extrapolation can be studied looking at the r_{cut} dependence
- Stronger r_{cut} dependence compared to colourless case due to soft radiation (obs: not in qq')
- Extrapolation performed doing a quadratic least-squares fit
- Results for total cross section in full agreement with Top++



Summary and outlook

- We performed a new calculation of the NNLO $t\bar{t}$ cross section
- First complete application of q_T subtraction for $Q\overline{Q}$ at NNLO

Near and far future:

- Complete the validation of fully differential results
- Provide a public tool (i.e. new MATRIX release) to compute them
- Improve NNLO QCD with other corrections: NLO EW, Coulomb resummation
- Include decays
- Perform NNLL q_T resummation (some ingredients still missing)
- Extend the calculation to $t\bar{t}$+colourless
    - Some contributions can be recycled (not the most difficult ones…)
    - First step: do it at NLO [Fabre, Grazzini, in progress]