Top Quark Physics

Javier Mazzitelli

PAUL SCHERRER INSTITUT

Rencontres de Blois, May 18th 2023

Top Quark Physics at the LHC

Javier Mazzitelli

PAUL SCHERRER INSTITUT
PSI

Rencontres de Blois, May 18th 2023

Precise Predictions for Top Quark Physics at the LHC

Javier Mazzitelli

PAUL SCHERRER INSTITUT PSI

Rencontres de Blois, May 18th 2023

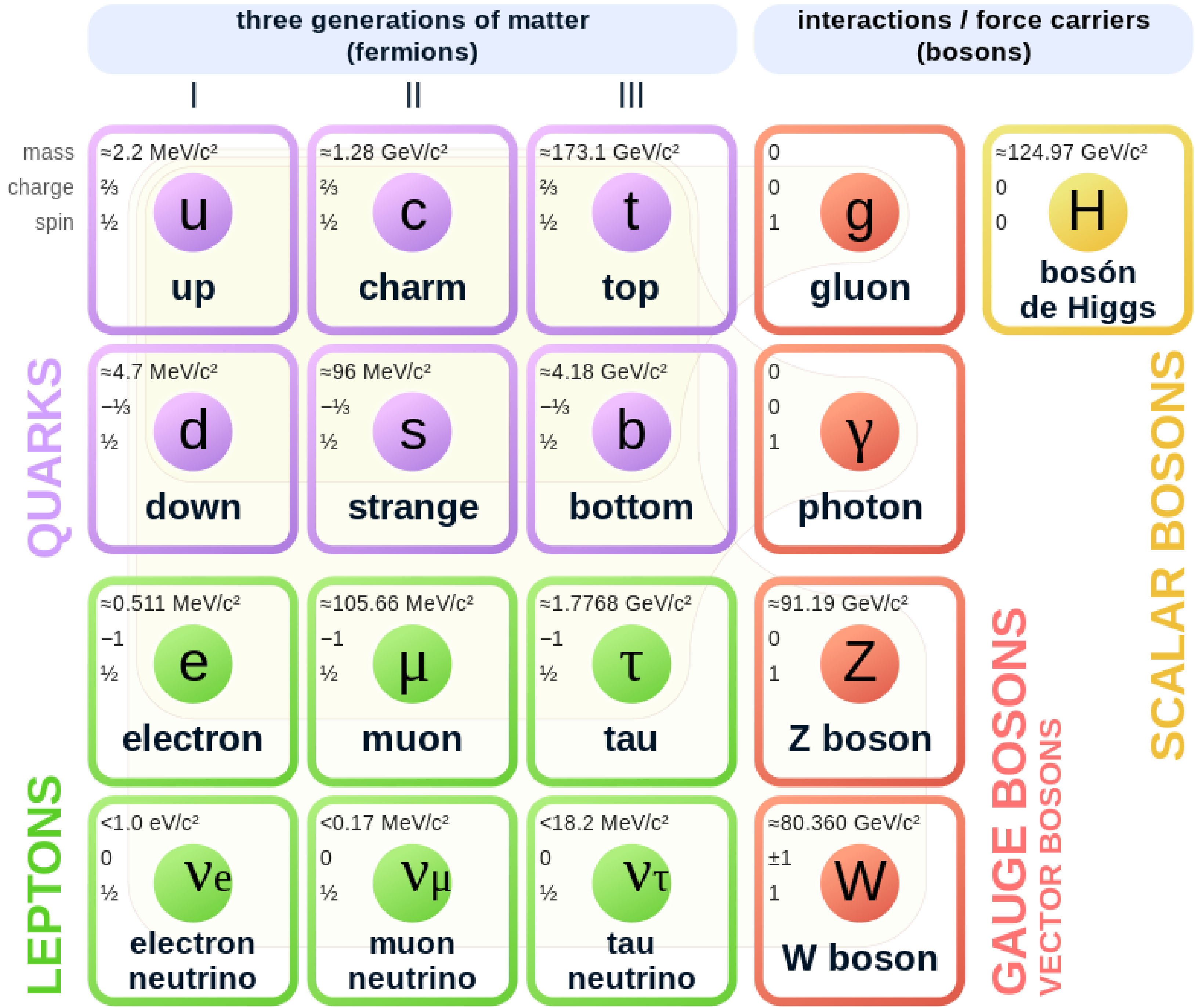
Selection of Topics concerning Precise Predictions for Top Quark Physics at the LHC

Javier Mazzitelli

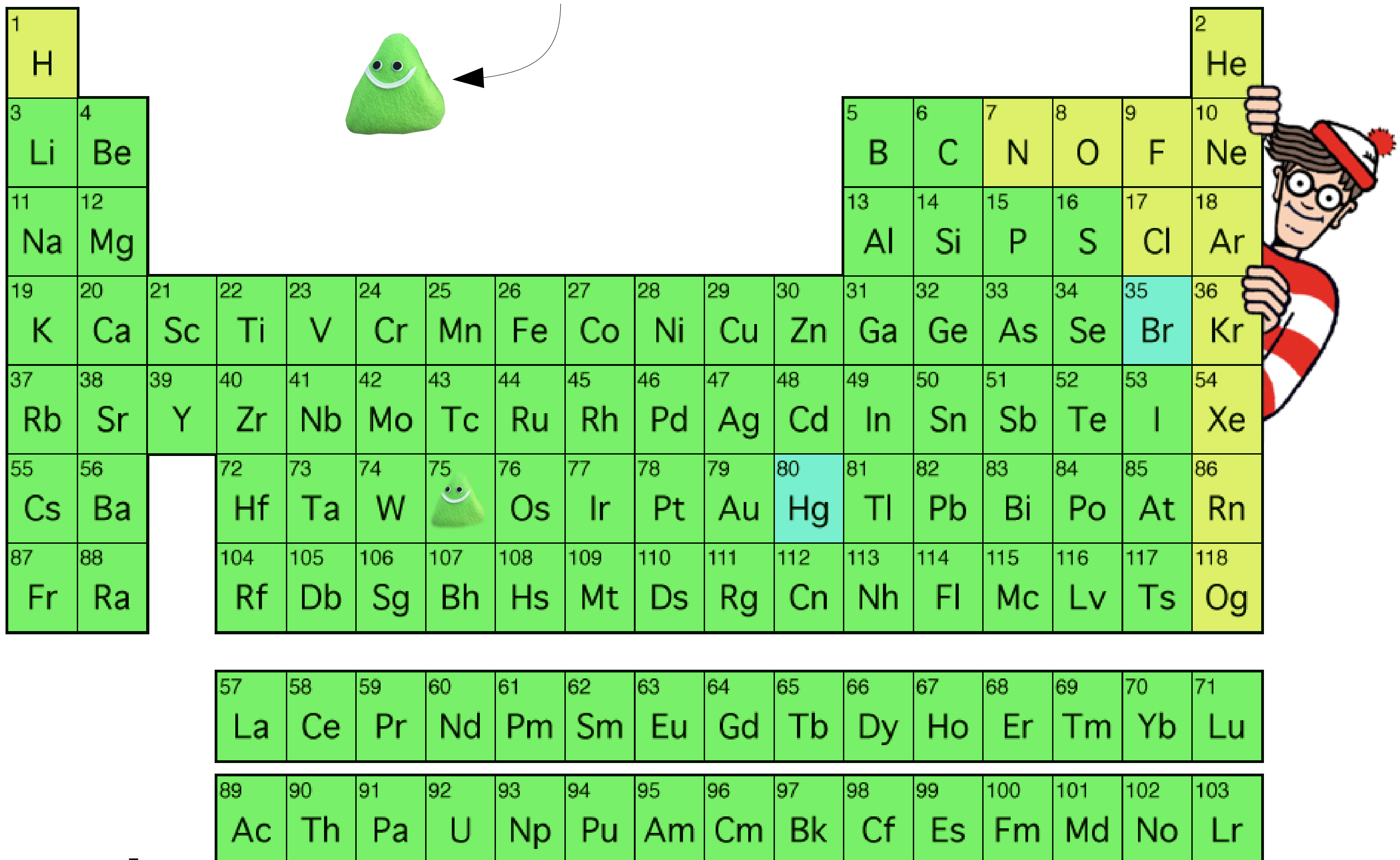
PAUL SCHERRER INSTITUT

Rencontres de Blois, May 18th 2023

Standard Model of Elementary Particles



What makes the top quark special?



It’s mass!

Heaviest particle in the SM: Mt ≈ 173GeV → about the same as an atom of gold → 40 times more than the bottom quark

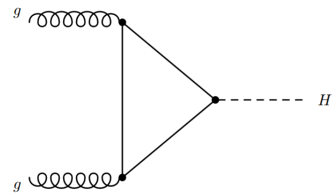
Its large mass has a direct impact on its properties, for instance on its

↓ coupling to Higgs ↓ decay

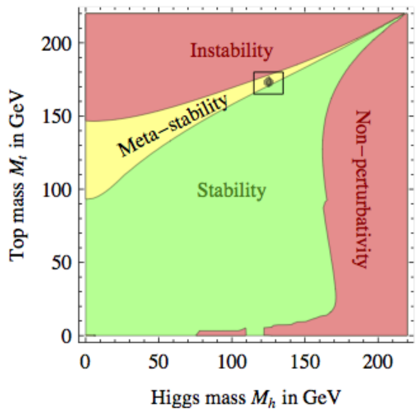
The top quark and the Higgs

Top quark has the strongest coupling to the Higgs boson

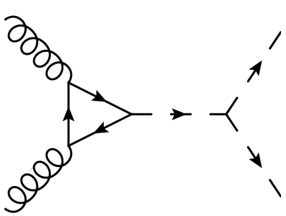
Mediates the main Higgs production mode at the LHC

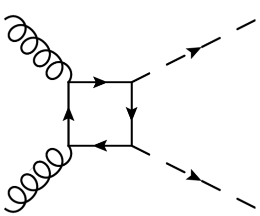


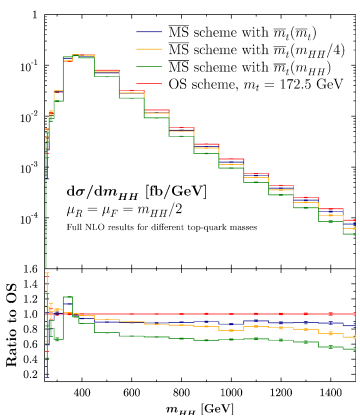
Drives the corrections to the Higgs quartic coupling, and the precise value of its mass is crucial for the stability (or not) of the SM vacuum



Uncertainties (th. and exp.) in the top mass have an impact on Higgs predictions





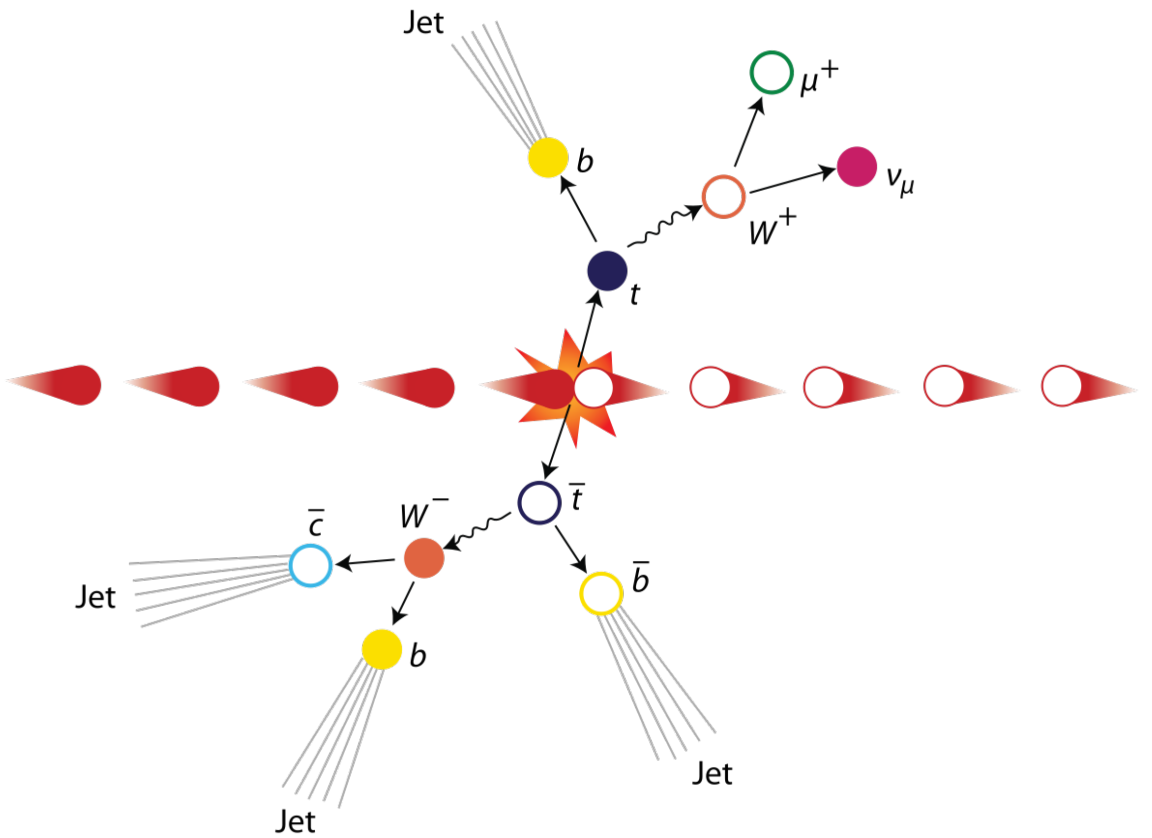


Top quark decays

$$M_t \gg M_W$$

Top quark decays very rapidly into a W boson and a bottom quark (less than 10^{-24} s)

Top quark decays before top-flavoured hadrons can form



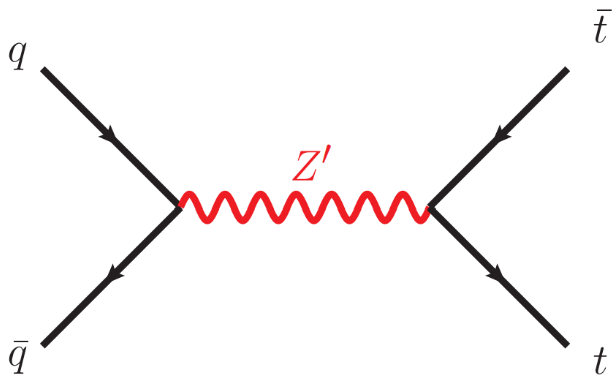
Unique playground to study a bare quark!

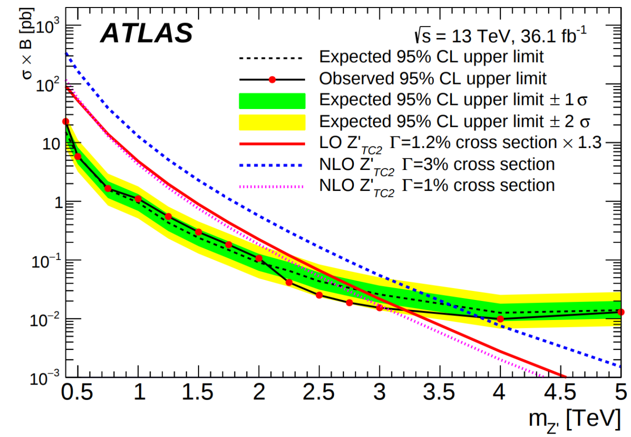
[Quiz: which value of M_t would we need to have $\Gamma_t = \Lambda_{QCD}$?]

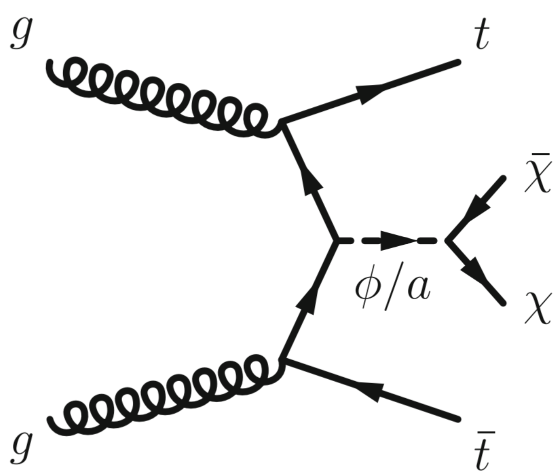
Top quark and BSM

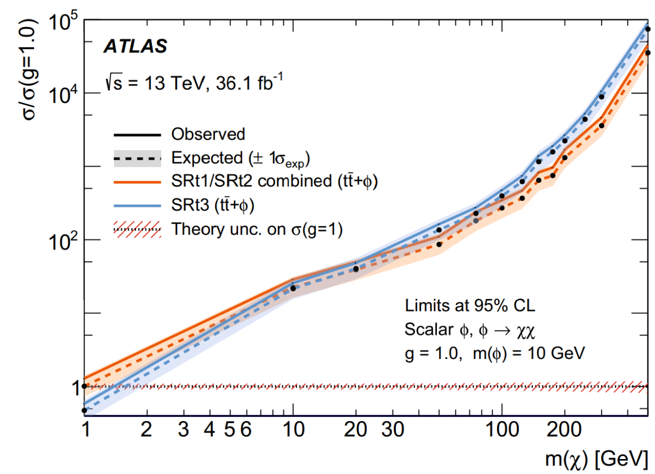
Extremely relevant for BSM searches as well!

- Directly



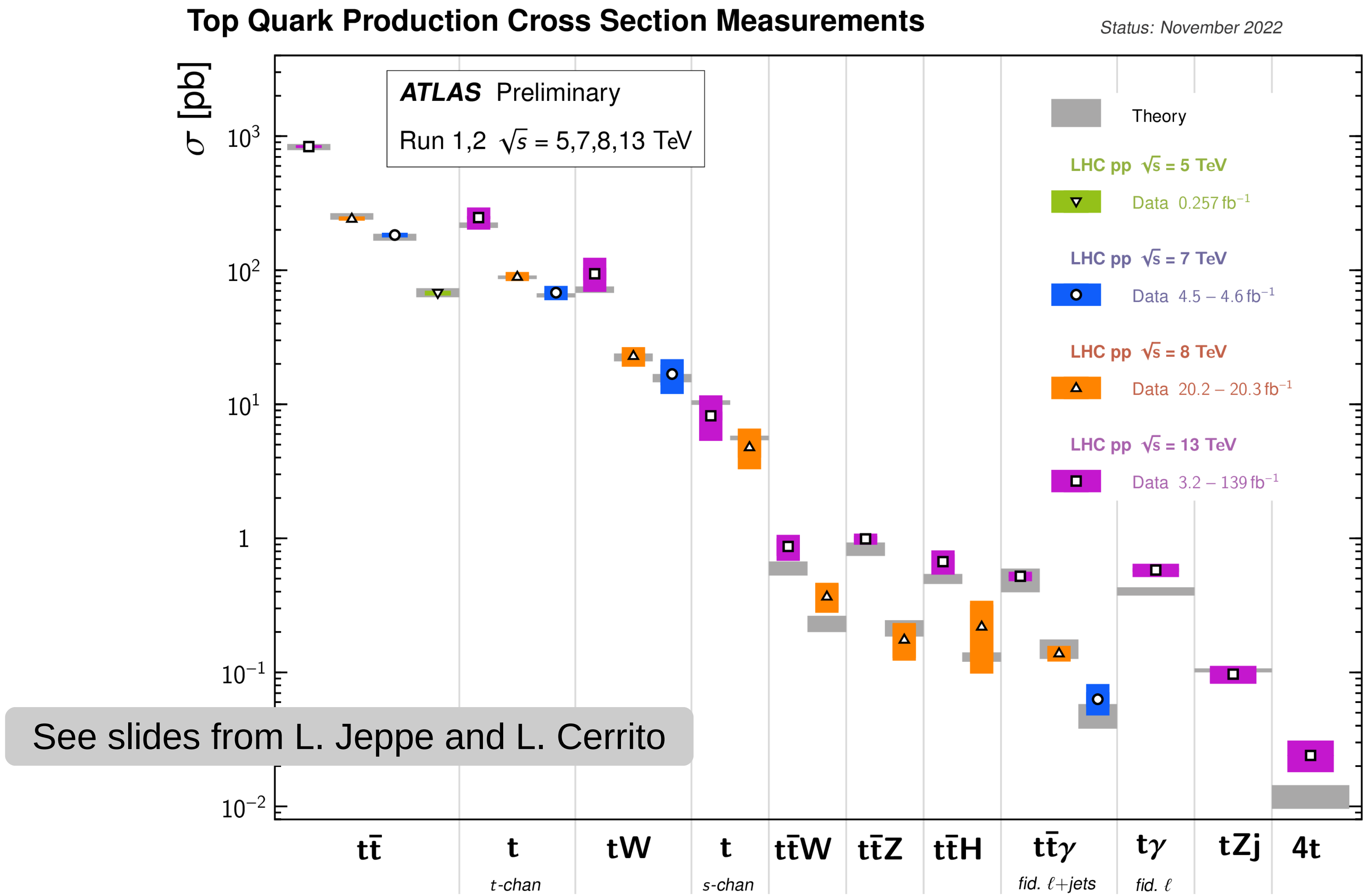






- And indirectly, as a background to new physics signals

For instance, 35% of all published ATLAS searches cite top++



Some cases experimental uncertainties are already lower than theory ones, and in others they will be with increased data taking

This motivates the need for precise theoretical predictions!

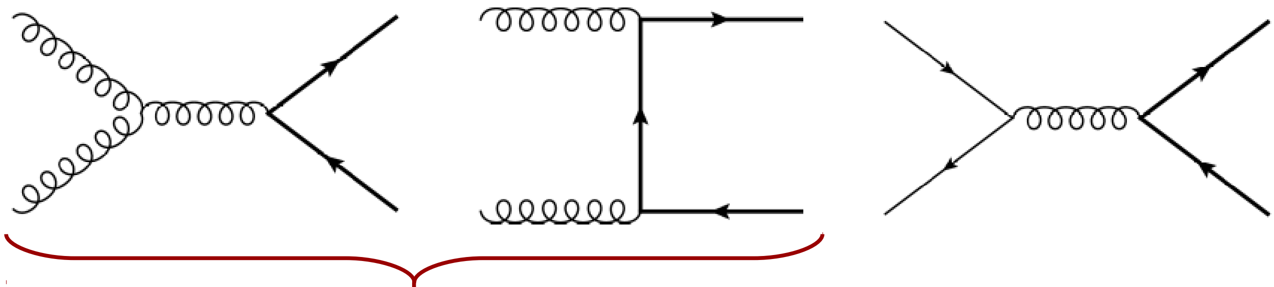
Outline

- Introduction
- Top quark pair production
- Top quark pair production in association with a Higgs boson
- Top mass definition and related uncertainties
- Summary

Top quark pair production

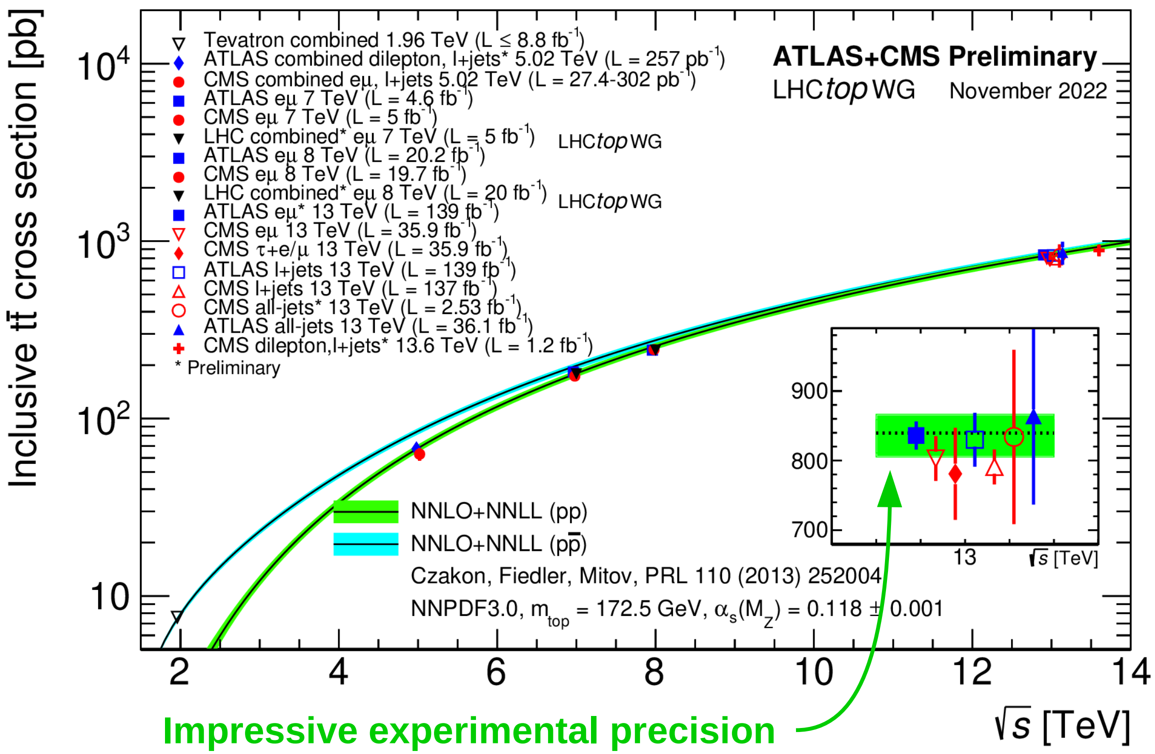
The top quark at the LHC

Main source at the LHC: top-quark pair production

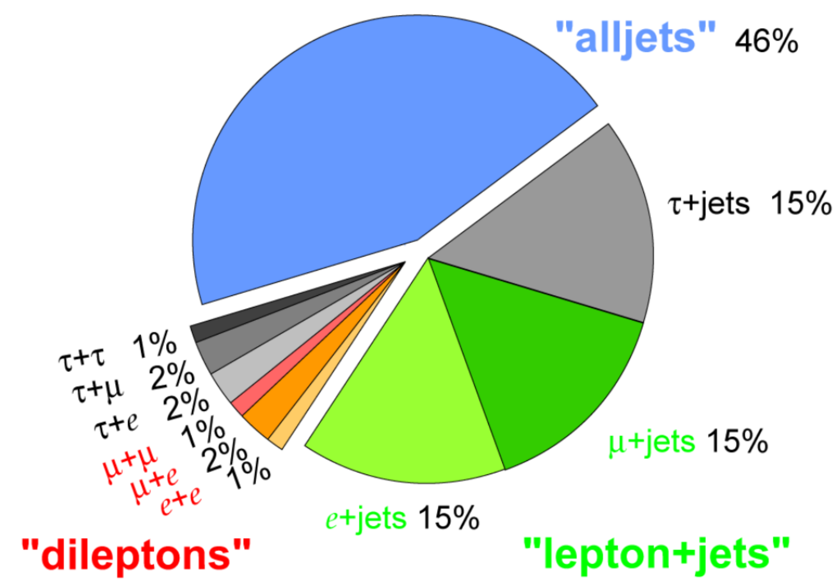


- Approx. 3 times larger than single-top production
- About **15** $t\bar{t}$ pairs produced **per second** at the LHC!

About 85% at the LHC (LO)



Impressive experimental precision



NLO QCD corrections at the 50% level, so higher orders are mandatory to achieve precision!

Theoretical status

Precise theoretical predictions are needed to match experimental uncertainty:

NLO QCD
[Nason, Dawson, Ellis; '88], [Mangano, Nason, Ridolfi; '92],
[Melnikov, Schulze; 0907.3090], [Bevilacqua et al.; 1012.4230],
[Denner et al.; 1012.3975, 1207.5018], [Frederix; 1311.4893], [Cascioli et al.; 1312.0546],
[Campbell et al.; 1204.1513, 1608.03356], …

NLO EW
[Bernreuther et al.; hep-ph/0610335, 0804.1237, 0808.1142], [Kühn et al.; hep-ph/0508092, hep-ph/0610335], [Hollik, Kollar; 0708.1697], [Pagani et al.; 1606.01915]

NNLO QCD
[Moch et al.; 1203.6282], [Czakon et al.; 1303.6254, 1601.05375, 1606.03350],
[Abelof et al.; 1506.04037], [Gao, Papanastasiou; 1705.08903], [Catani et al.; 1901.04005],
[Catani et al.; 1906.06535], [Czakon et al.; 1901.05407, 2008.11133]…

NNLO QCD + NLO EW
[Czakon et al.; 1705.04105, 1711.03945]

Resummation
[Beneke et al.; 0907.1443], [Czakon et al.; 0907.1790, 1803.07623], [Ahrens et al.; 1003.5827],
[Kidonakis; 0903.2561, 1009.4935], [Hu et al.; 1908.02179], [Ju et al.; 1908.02179]...

NLO QCD matched to PS
[Frixione et al.; hep-ph/0305252, 0707.3088], [Höche et al.; 1402.6293],
[Garzelli et al.; 1405.5859], [Campbell et al.; 1412.1828], [Ježo et al.; 1607.04538]

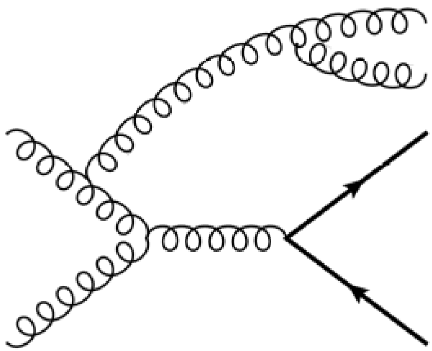
NNLO QCD matched to PS
[Mazzitelli et al.; 2012.14267, 2112.12135]

NOT A COMPLETE LIST

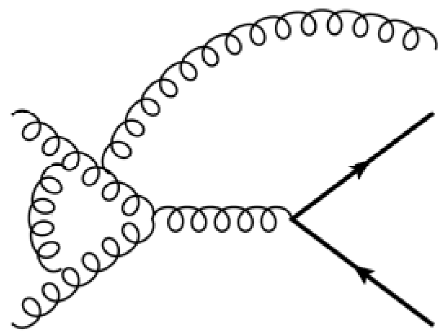
Top quark pair production at NNLO in QCD

See slides from A. Huss

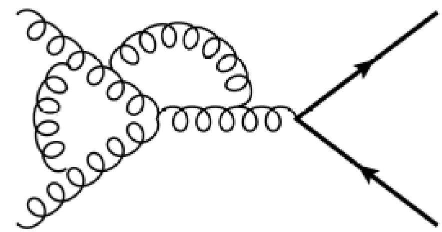
- Most difficult contribution: two-loop corrections
  - Computed 10 years ago in numerical form
    [Baernreuther, Czakon, Fiedler; 1312.6279]
  - Analytic results for the quark channel recently computed
    [Mandal et al.; 2204.03466]
- Not enough! QCD corrections are affected by intermediate IR divergencies:



Double real



Real-virtual



Two-loop virtual

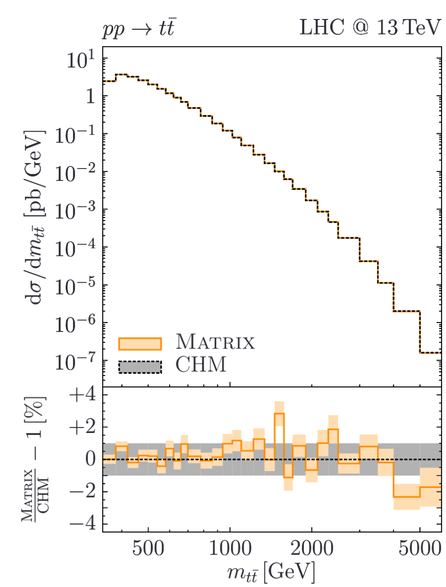
NNLO QCD corrections for $t\bar{t}$ production have been obtained using two different subtraction methods

Stripper
[Czakon; 1005.0274]

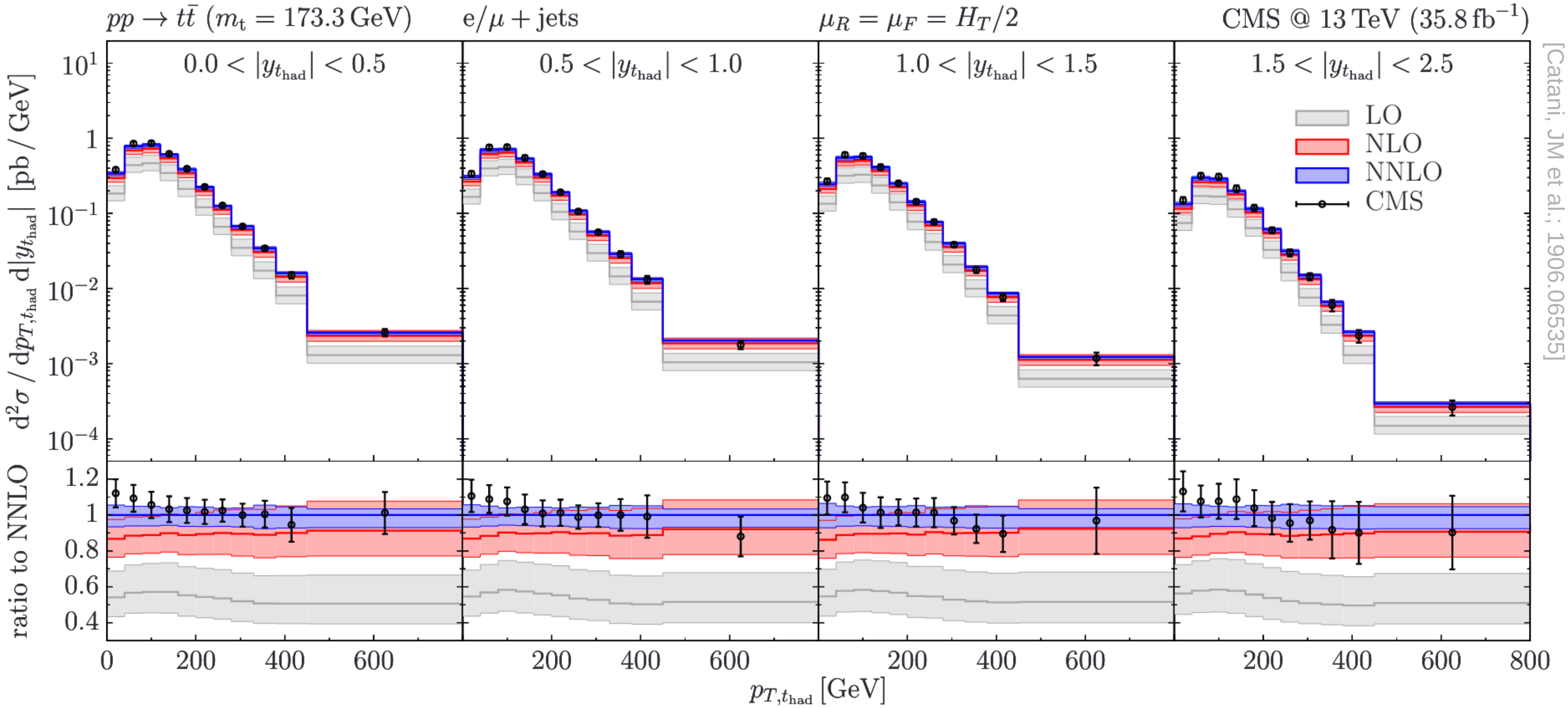
q_T-subtraction
[Catani, Grazzini; 0703012]

Perfect agreement between the two calculations

[Czakon, Mitov et al.; 1303.6254, 1511.00549], [Catani, JM et al.; 1901.04005, 1906.06535]



[Catani, JM et al.; 1906.06535]

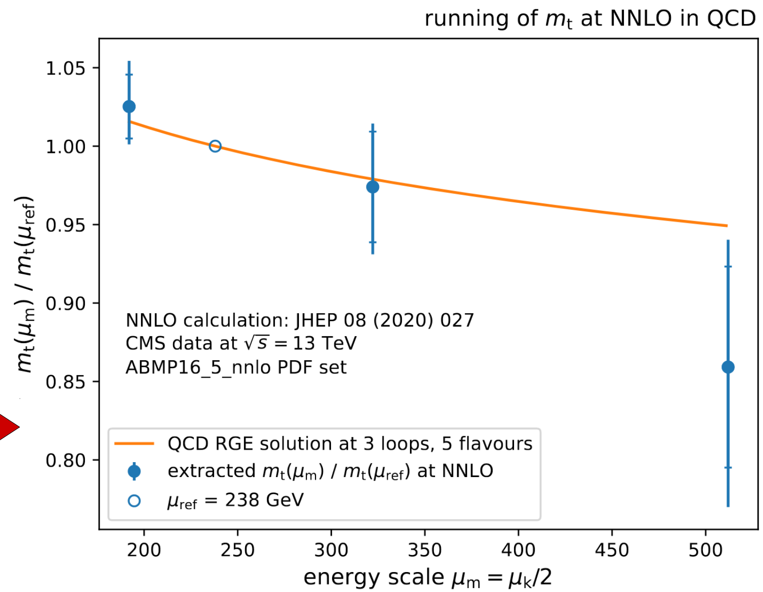


[Catani, JM et al.; 1906.06535]

- NNLO corrections substantially reduce the theoretical uncertainties, and improve the comparison to data

- NNLO differential predictions also available using the $\overline{\text{MS}}$ scheme for the top mass renormalization

[Catani, JM et al.; 2005.00557]

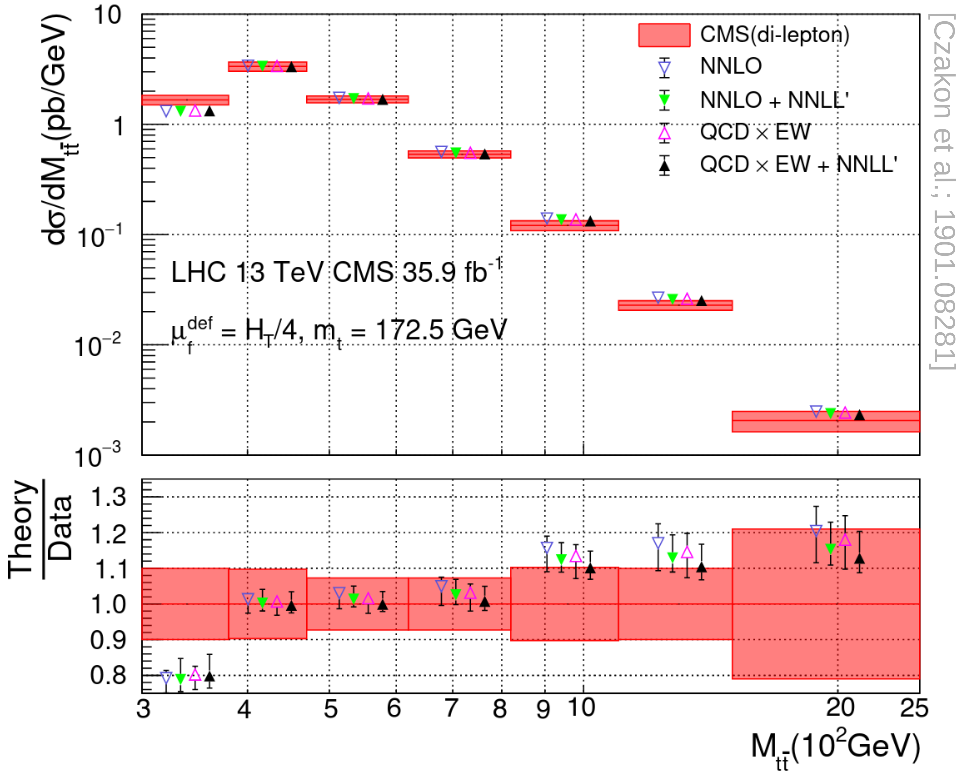


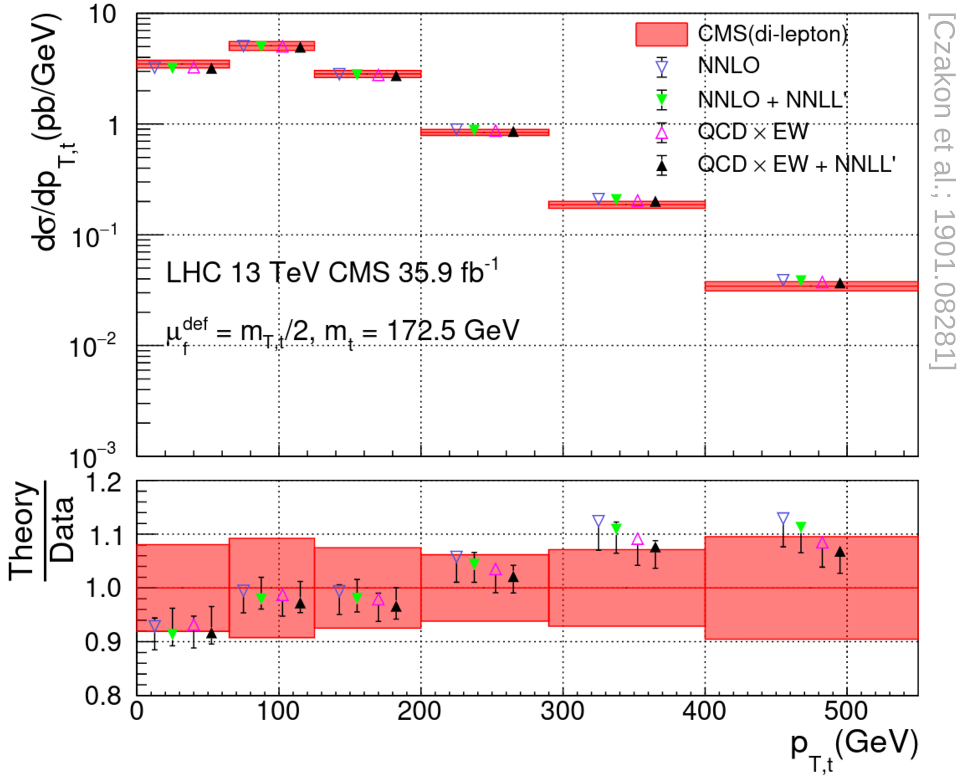
[Defranchis, JM et al.; 2208.11399]

State of the art

- NNLO QCD not enough → { EW corrections / resummation } ➡ Especially relevant in certain kinematical regions

- State of the art predictions: NNLO QCD x NLO EW + threshold and small mass resummation





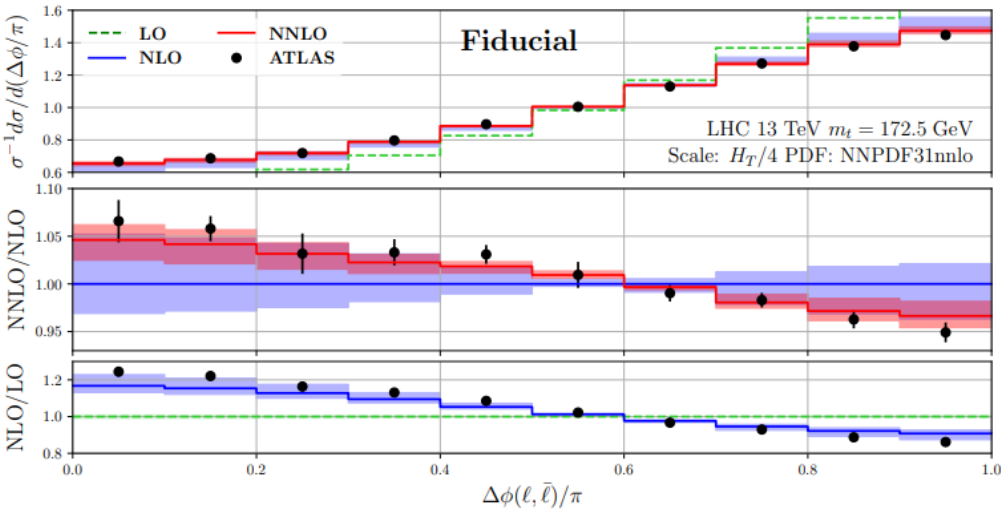
- Further improvement w.r.t. NNLO QCD in comparison to data (e.g. p_T tail)

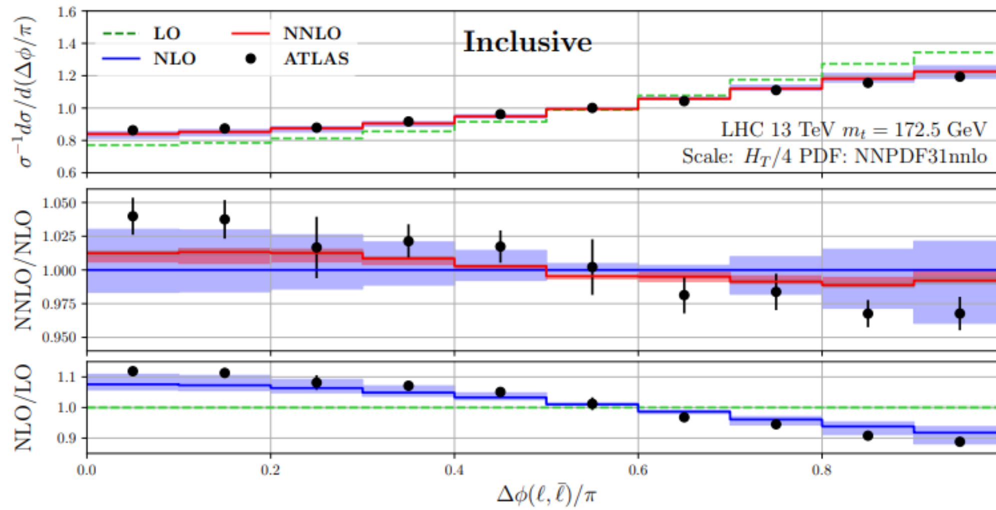
- Top quark threshold still problematic (more about this later)

NNLO and top quark decays

- NNLO (production) x NNLO(decay) have been combined in the NWA for dilepton FS

[Czakon et al.; 1901.05407, 2008.11133]





- NNLO corrections improve agreement in fiducial volume, not in the inclusive

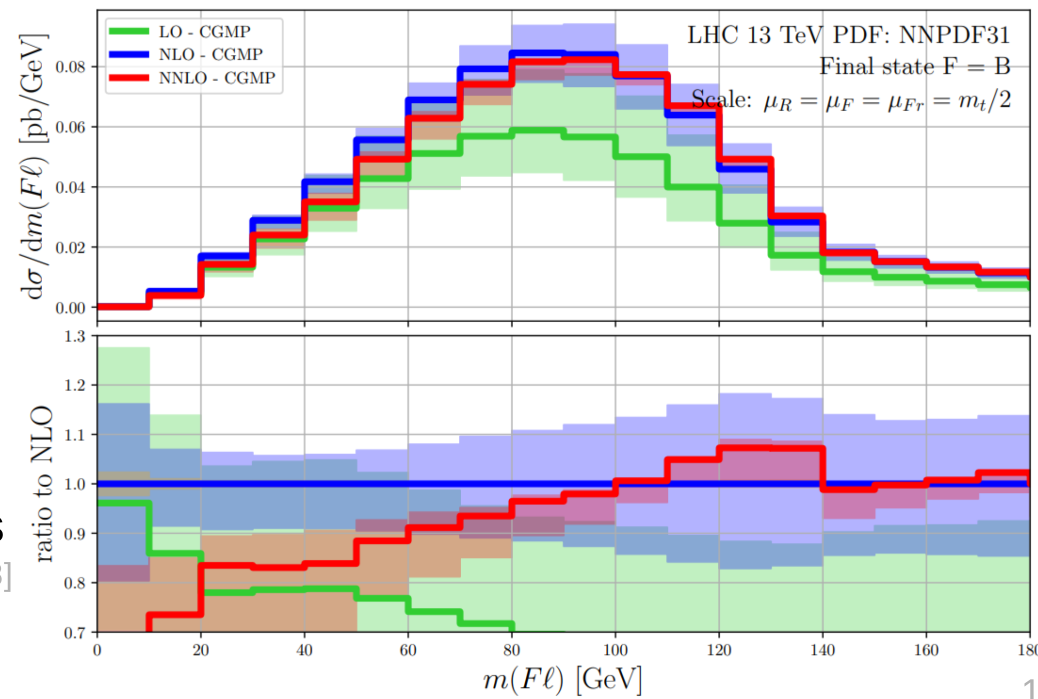
Need for higher accuracy
in the extrapolation?

- Framework for obtaining NNLO corrections for identified B-hadrons recently developed

[Czakon et al.; 2102.08267]

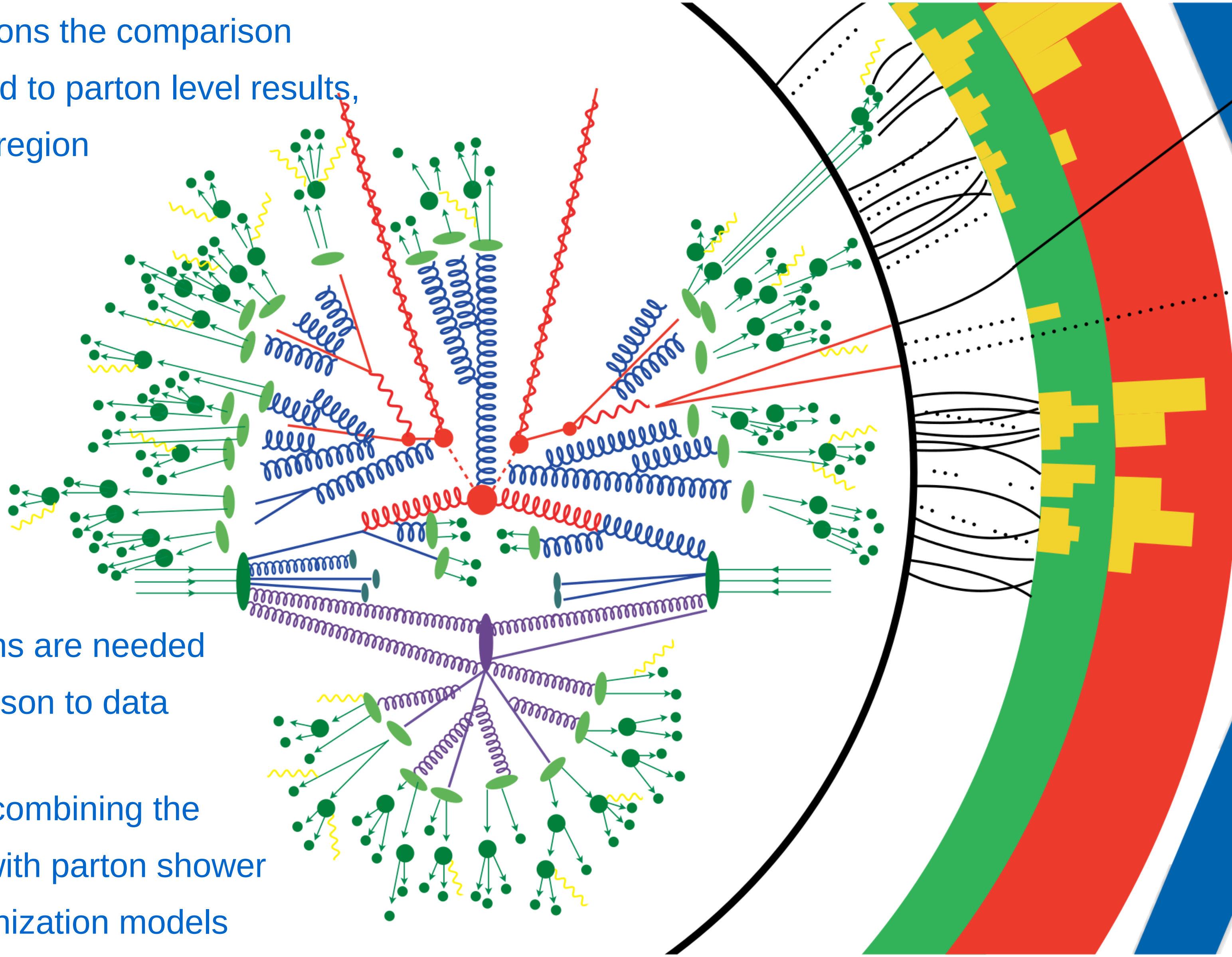
- B-hadron fragmentation functions extracted from e+e- data and applied to tt observables

[Czakon et al.; 2210.06078]



Event generators for $t\bar{t}$

- With fixed-order calculations the comparison to data is mostly restricted to parton level results, extrapolated from signal region to inclusive phase space



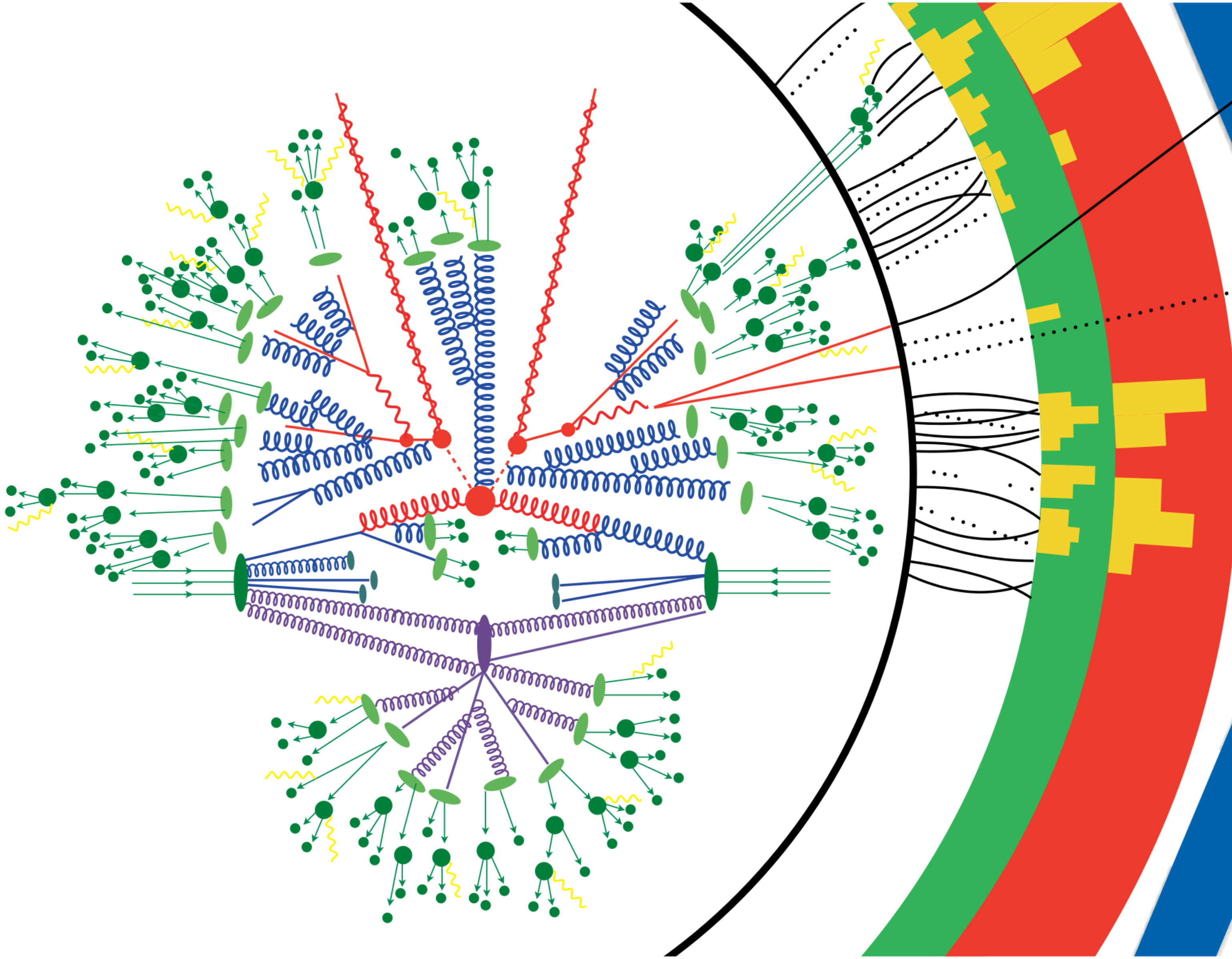
- Fully exclusive simulations are needed for a more direct comparison to data

  Event generators combining the high-energy scattering with parton shower algorithms and hadronization models

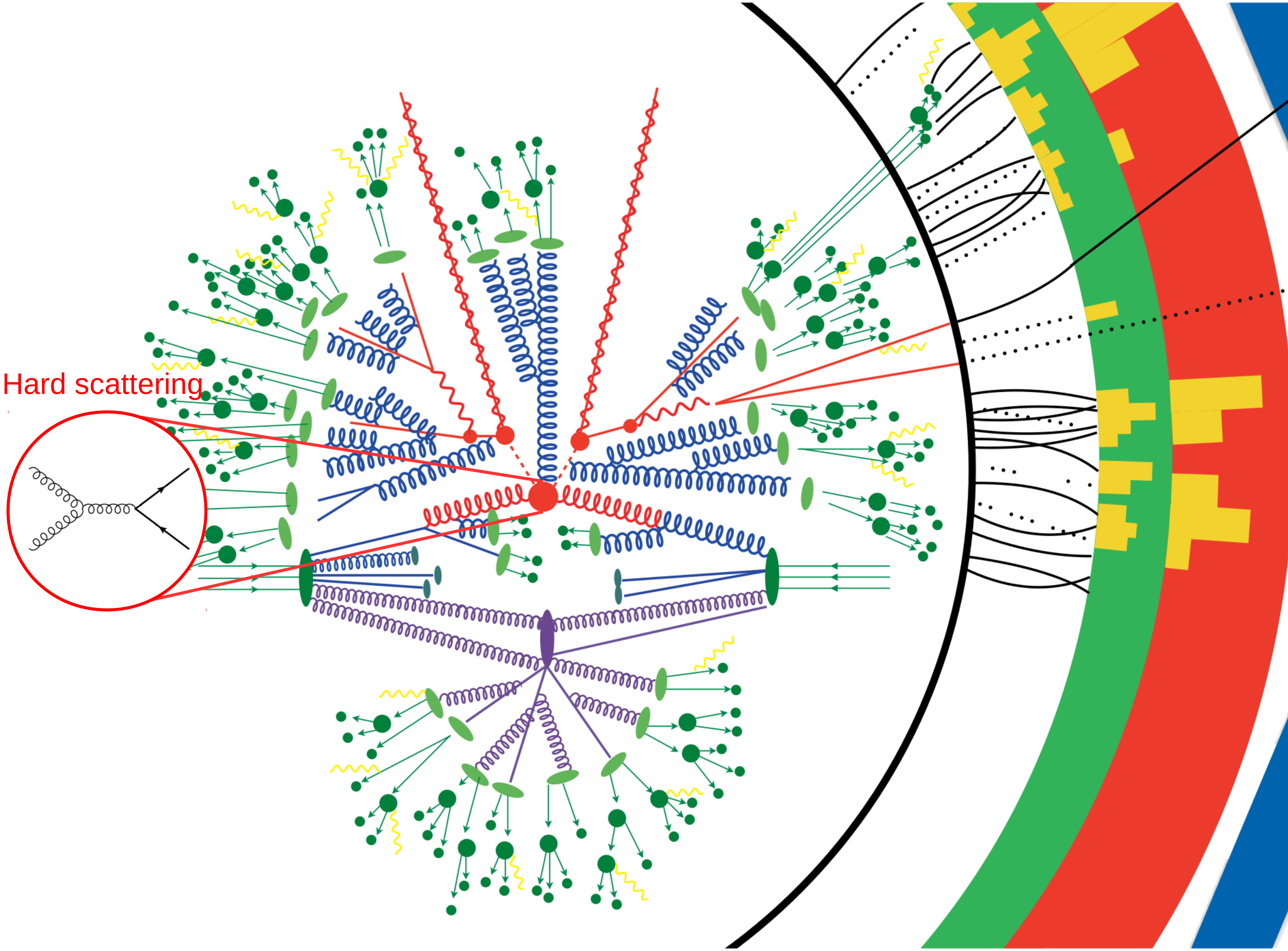
- Furthermore, event generators are a cornerstone of experimental analyses

- Therefore, the importance of accurate event generators can't be overstated

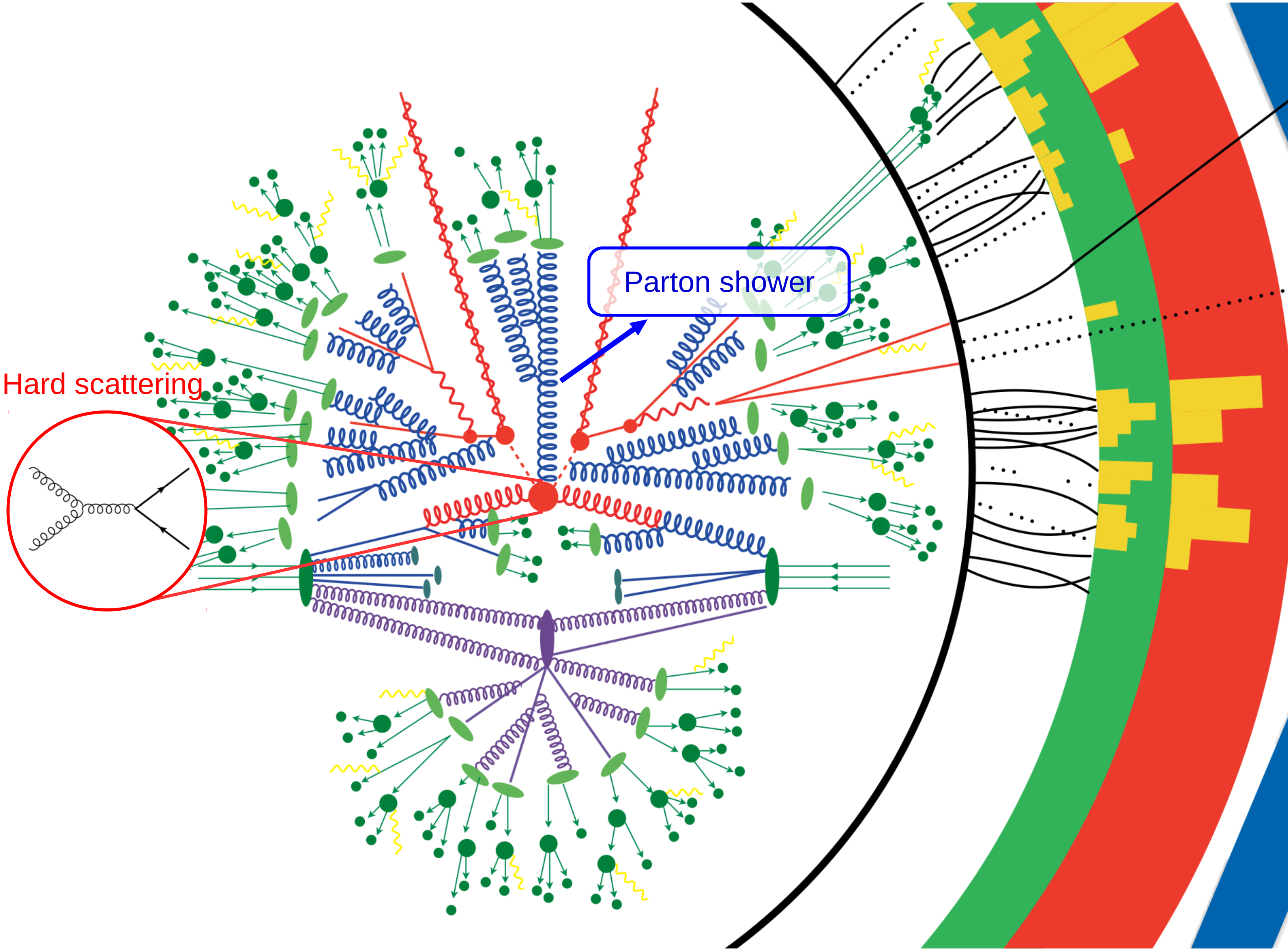
Event generators for $t\bar{t}$



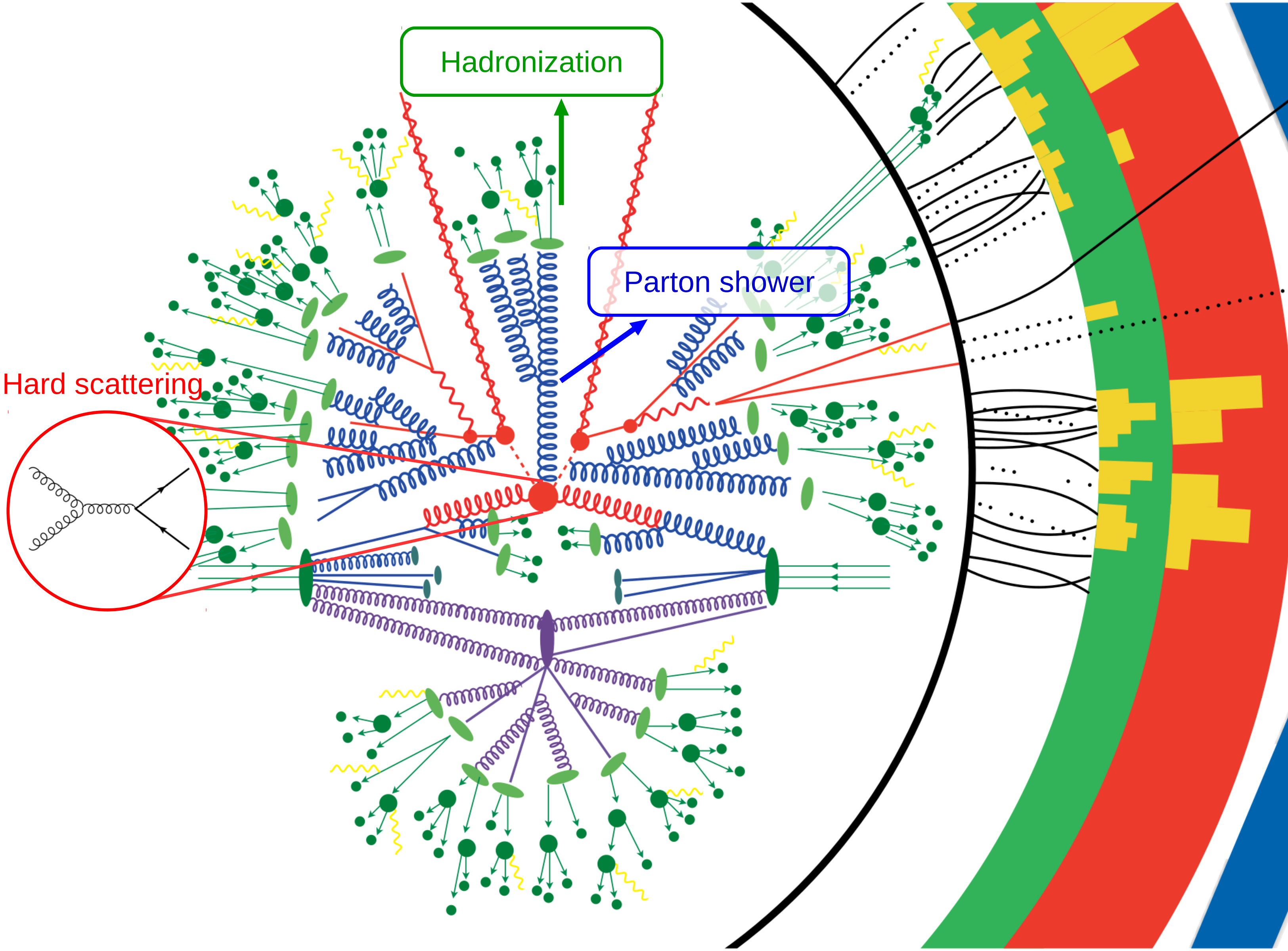
Event generators for $t\bar{t}$



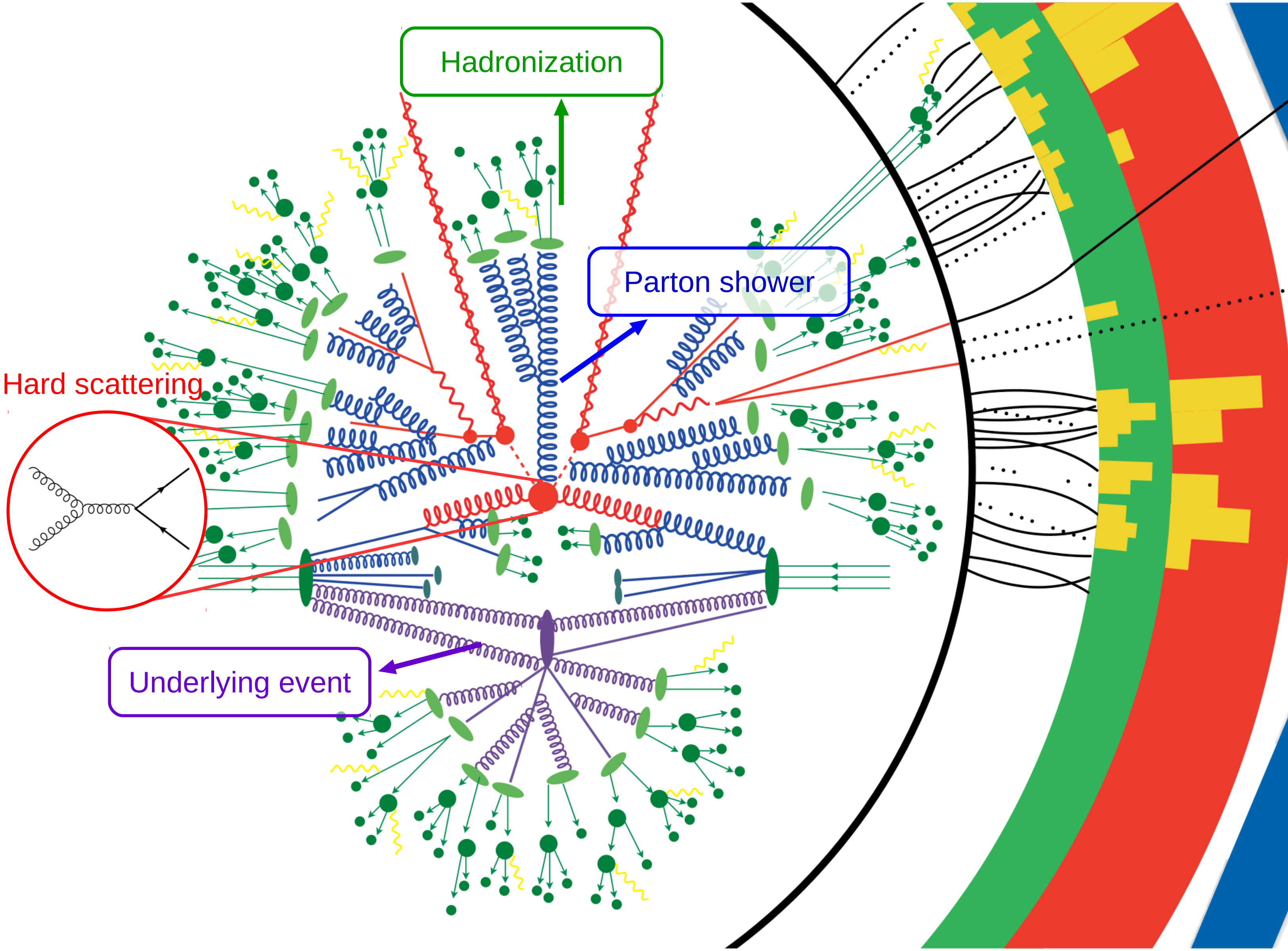
Event generators for $t\bar{t}$



Event generators for $t\bar{t}$

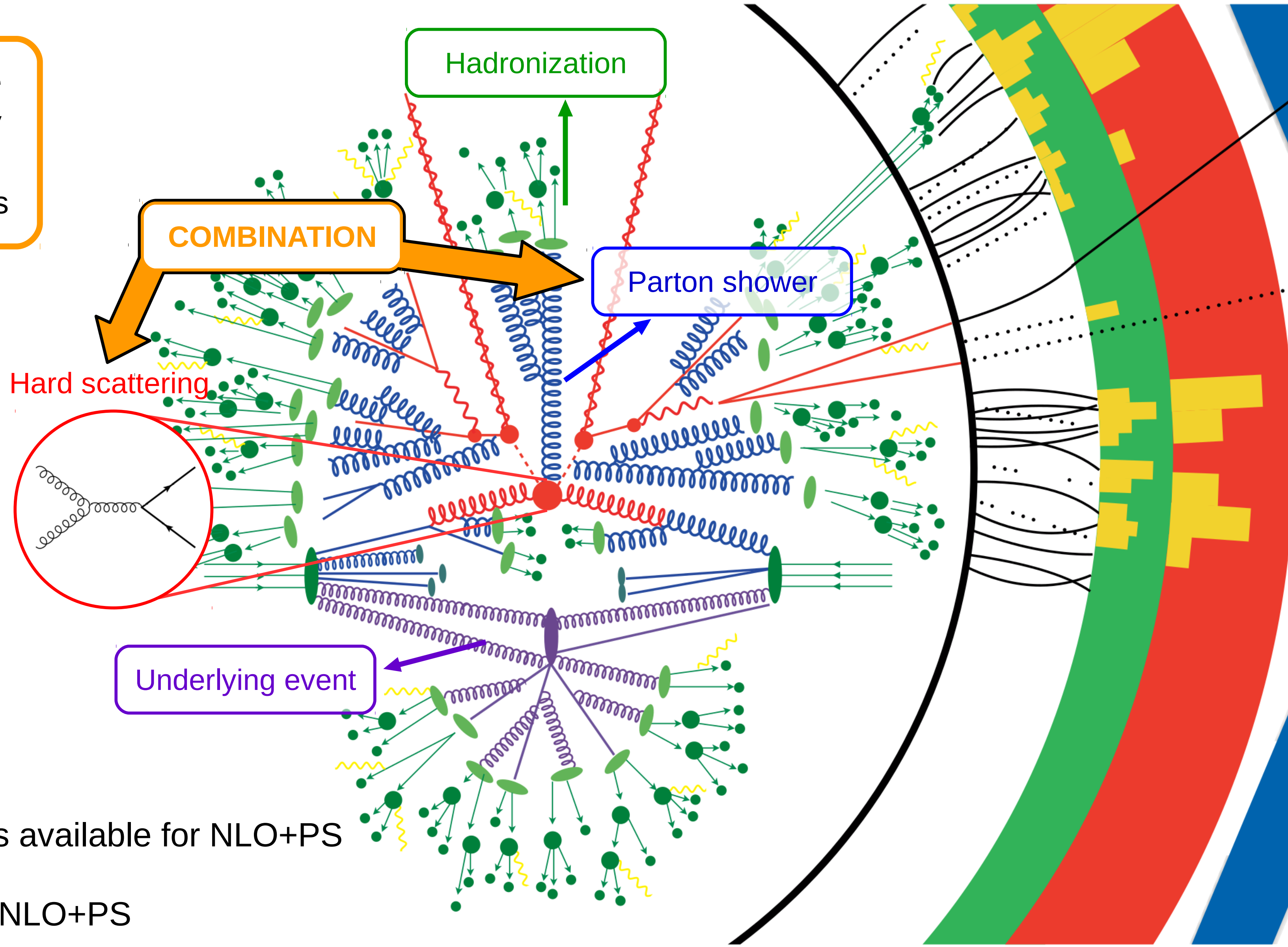


Event generators for $t\bar{t}$



Event generators for $t\bar{t}$

We want to keep the fixed-order accuracy when computing inclusive observables



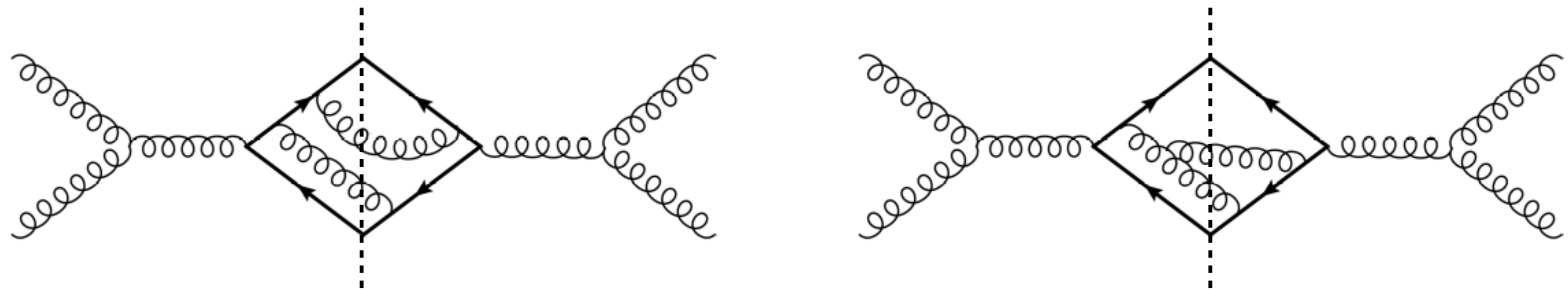
- General approaches available for NLO+PS
- Current frontier is NNLO+PS

	F	$F+j$	$F+2j$
F@NNLO$_{\text{PS}}$	NNLO	NLO	LO

Non trivial task!
Double counting between ME and shower, inclusion of virtual corrections, …

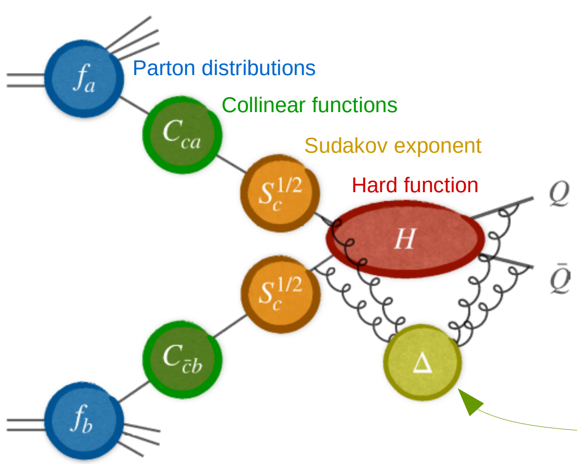
- NNLO+PS for tt achieved recently within the MiNNLOPS method
  [JM et al; 2012.14267, 2112.12135], implemented in POWHEG-BOX-V2 and publicly available
- First NNLO+PS for something more complicated than colour singlet production

Why more complicated than colour singlet? → Emission from **final state**



- Additional **divergencies** when FS emission becomes **soft**
- Presence of colored FS leads to **color interference** effects

Derivation of the method closely connected to transverse momentum resummation:



$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left(-S_c\right) \times \left[H C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

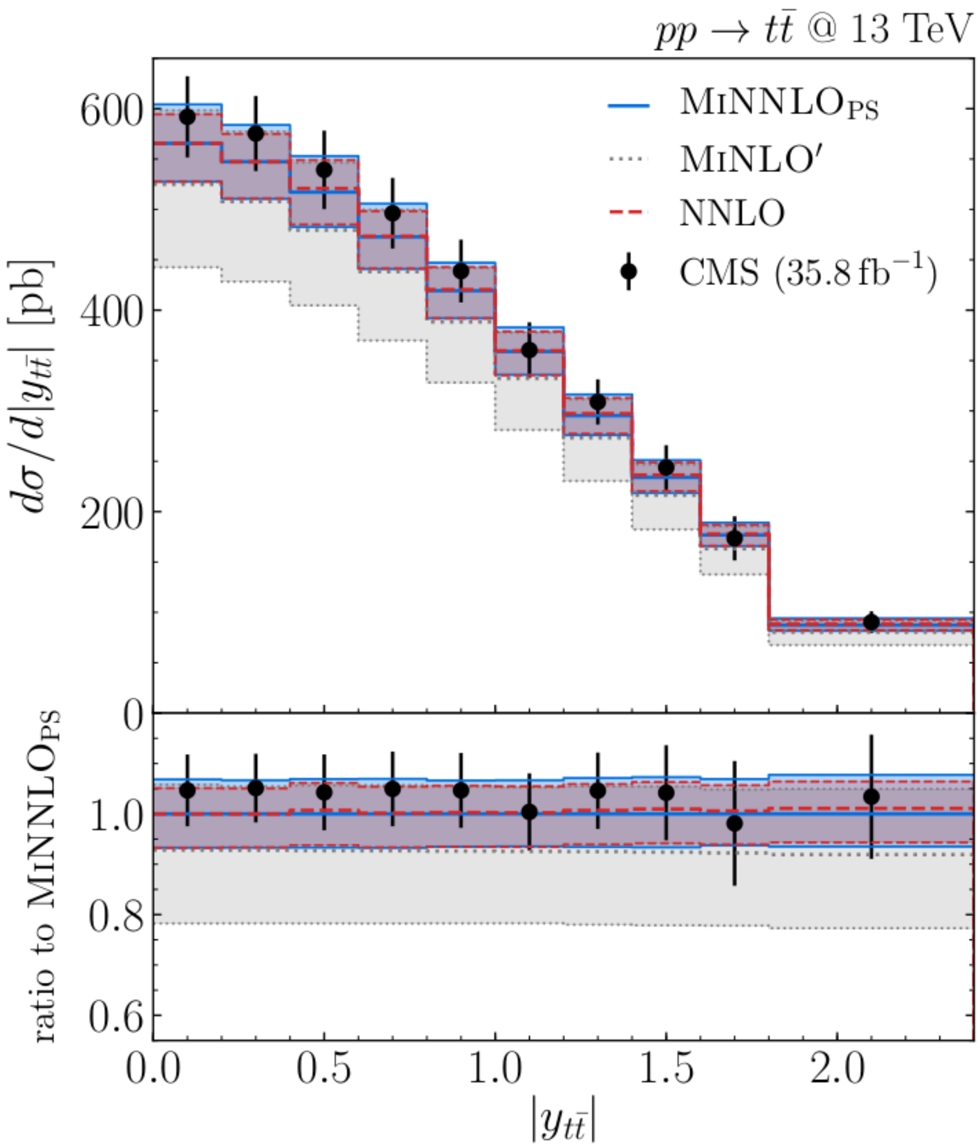
$$\Downarrow$$

$$d\sigma^{(\mathrm{sing})} \sim d\sigma^{(0)}_{c\bar{c}} \times \exp\left(-S_c\right) \times \left[\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta}) C_1 C_2\right]_{c\bar{c};a_1 a_2} \times f_{a_1} f_{a_2}$$

Effects coming from soft emissions
from the FS contained in operator **Δ**

Validation: parton level results

MiNLO′	NNLO	$\text{MiNNLO}_{\text{PS}}$
$721.4^{+14\%}_{-16\%}$ pb	$782.0^{+5.2\%}_{-6.7\%}$ pb	$779.2^{+6.9\%}_{-6.6\%}$ pb

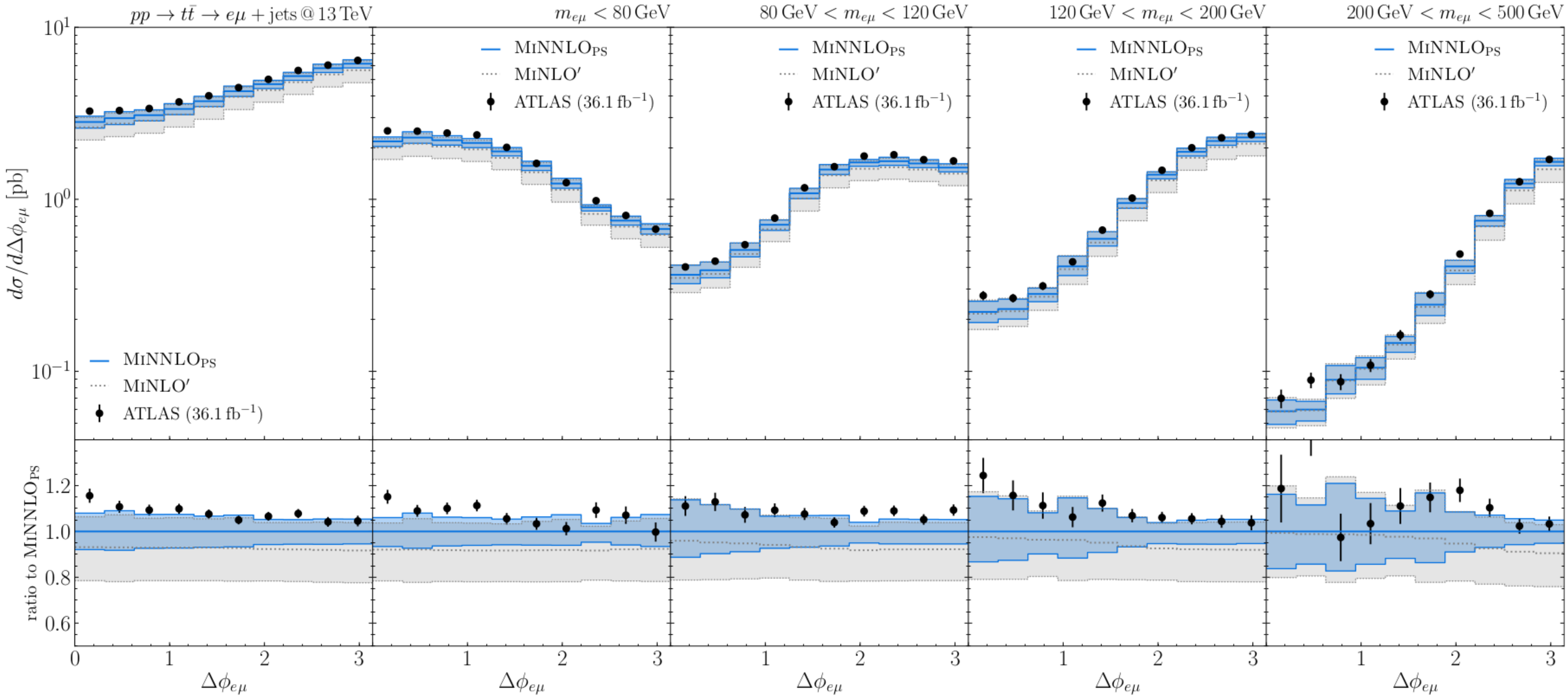


- Excellent agreement between MiNNLO and NNLO total cross sections, differences at the per-mille level
- Obs: even larger differences could be expected due to different scale settings and h.o. effects
- Similar size of uncertainties between MiNNLO and NNLO results
- Large reduction of scale uncertainties w.r.t. MiNLO'
- Excellent agreement in shape of rapidity distribution
- Excellent agreement with data*

*[data from CMS semileptonic analysis extrapolated to inclusive tt̄ PS]

Particle level results: leptonic [ATLAS 1910.08819]

[JM et al; 2012.14267, 2112.12135]

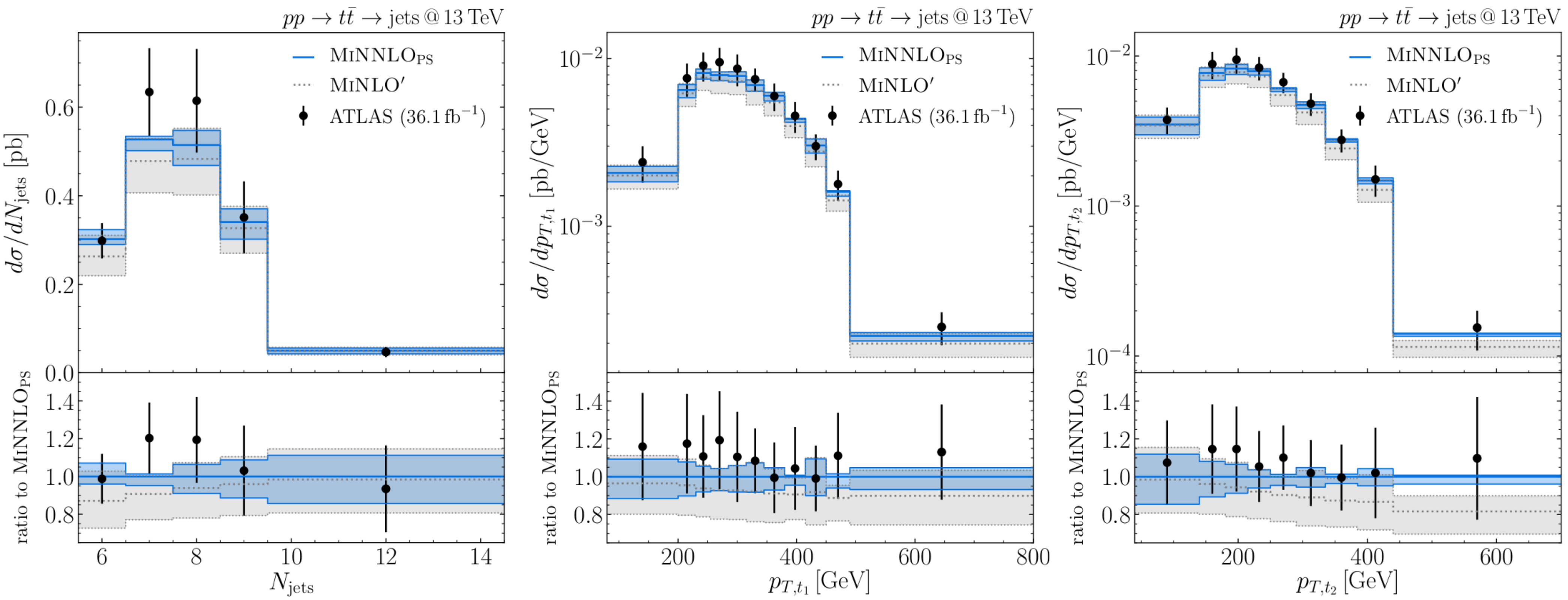


- Azimuthal angle between leptons → sensitivity to spin correlations in top-quark decays
- Very good agreement with data in all invariant mass slices (despite spin correlations in decay being only considered at LO)
- Data close to upper band of the MiNNLO prediction (also in other distributions)

Obs: total XS slightly smaller than ‘usual’ value (top++) due to resummation effects and different scale settings

Particle level results: fully hadronic

[JM et al; 2012.14267, 2112.12135]
[ATLAS 2006.09274]

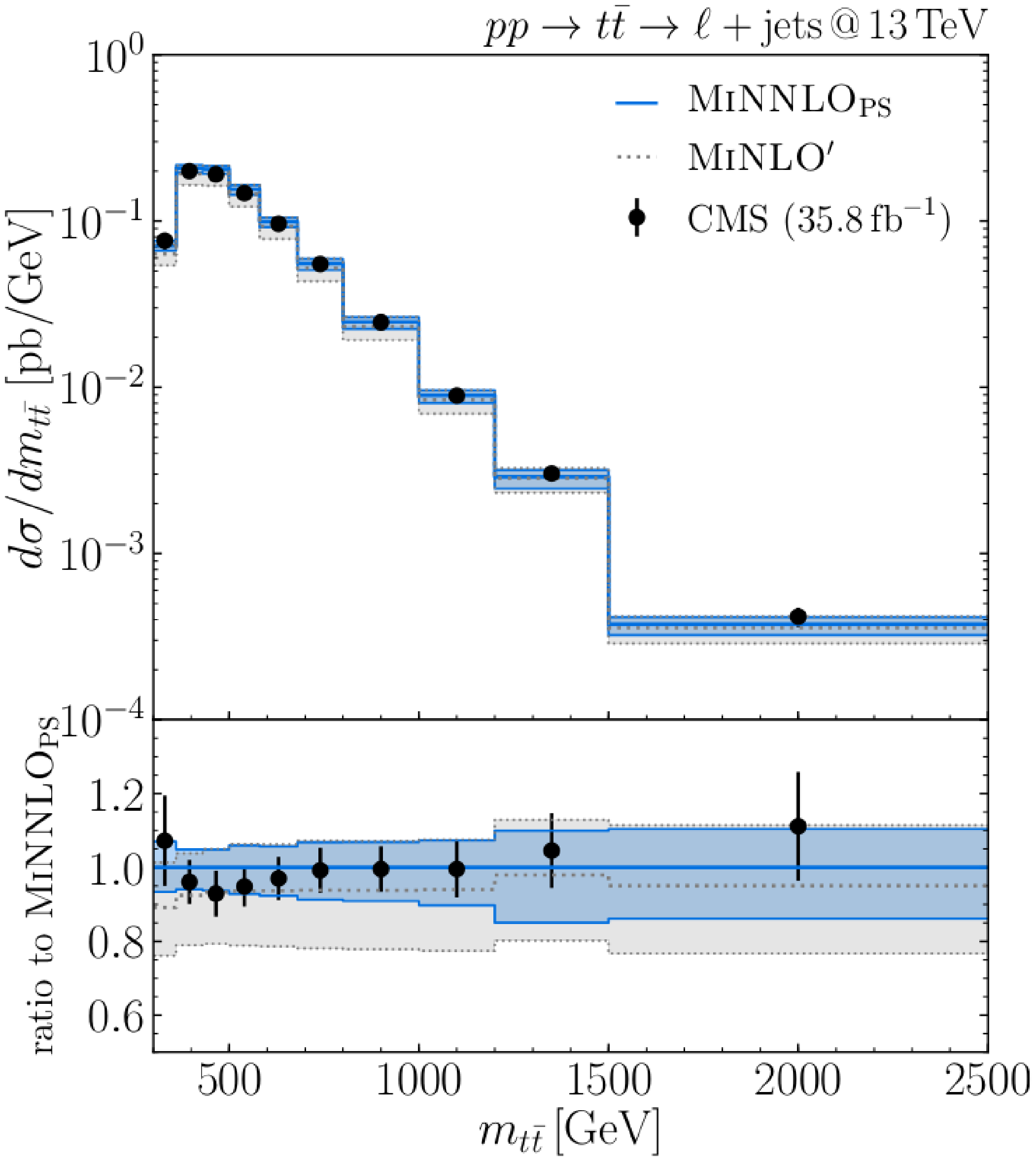


- Good agreement in fully hadronic final state, though experimental uncertainties much larger
- Obs: inclusion of MPI has a large impact in normalization (~10% effect)
- Strong reduction of uncertainties w.r.t. NLO+PS in regions inclusive in additional radiation
- Similar uncertainties e.g. for large Njets, where NNLO accuracy is not met
- Shape of p_T distributions much better described at NNLO+PS

Particle level results: semi-leptonic

[JM et al; 2012.14267, 2112.12135]

[CMS 1803.08856]



- Invariant mass of the reconstructed top-quark-pair system
- Slight shape difference compared to data, but excellent agreement within uncertainties
- Agreement even in the first bin, in variance with inclusive extrapolated results
- Obs: more effects included in the shower in this case (QED, MPI, hadronization) which might account for this difference
- Highlights the importance of doing data-theory comparison in fiducial PS

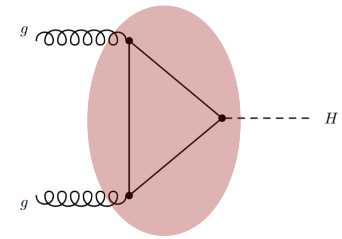
Expected future developments in event generators for top pair production:

Improved description of top decays, inclusion of off-shell effects, EW corrections

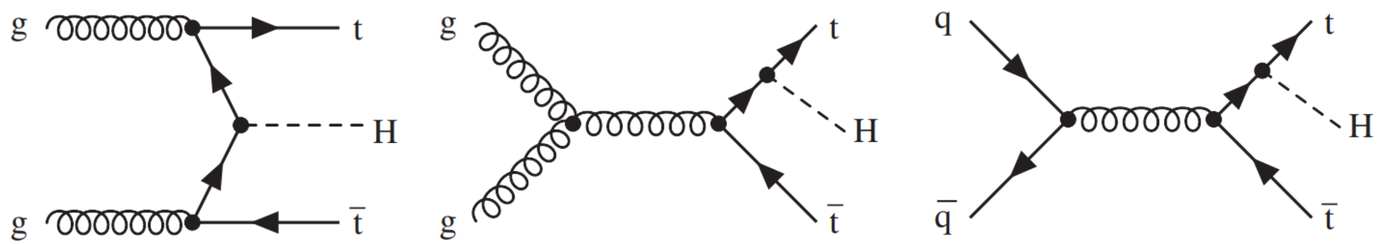
Top quark pair production
in association with a Higgs boson

Experimental status

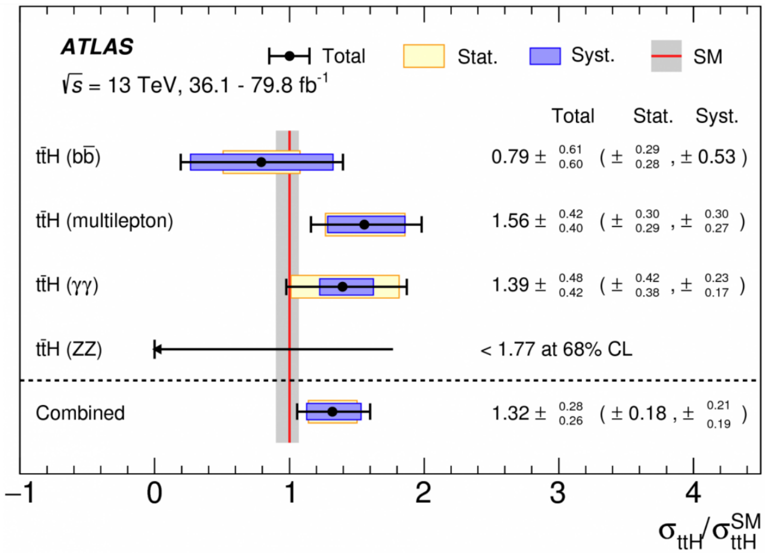
In ggF other contributions
and NP effects can conspire

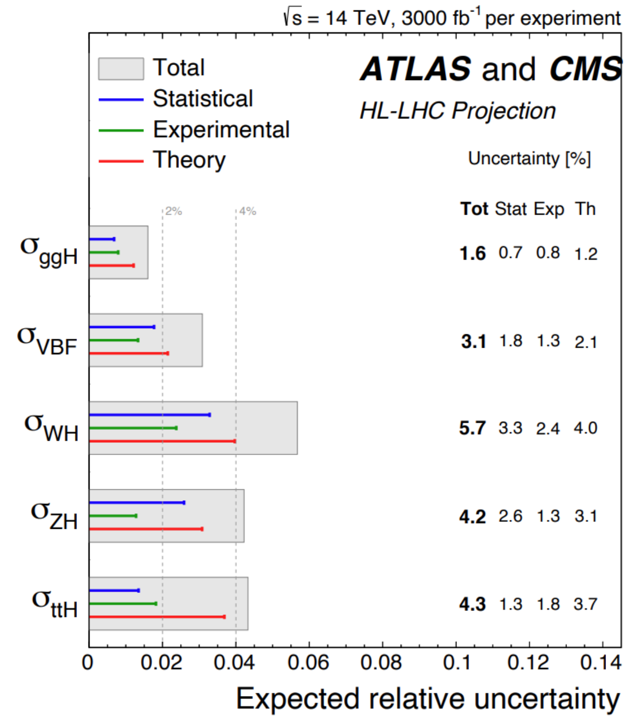


- $t\bar{t}H$ production ⟶ ‘direct’ measurement of the top Yukawa coupling



- Observed 5 years ago by LHC collaborations
[CMS 1804.02610, ATLAS 1806.00425]





- Current experimental uncertainties at O(20%) level
- Experimental precision expected to go down to O(2%) at HL-LHC
[Cepeda et al.; 1902.00134]
- Precise theoretical predictions are needed to match it!

Theoretical status

- More complicated than $t\bar{t}$ ⟶ Exact NNLO not available to data

- Bottleneck: two-loop virtual corrections

  ⬇

  2 → 3 scattering with 3 masses at the frontier of current capabilities

- Still lots of theoretical efforts:

NLO QCD

[Beenakker at al.; 0107081, 0211352], [Reina and Dawson; 0107101], [Reina, Dawson and Wackeroth; 0109066], [Dawson at al.; 0211438], [Dawson at al.; 0305087]

NLO EW

[Frixione et al.; 1407.0823, 1504.03446], [Zhang et al.; 1407.1110]

NLO with off-shell effects

[Denner and Feger; 1506.07448], [Denner et al.; 1612.07138]

NLO QCD + PS

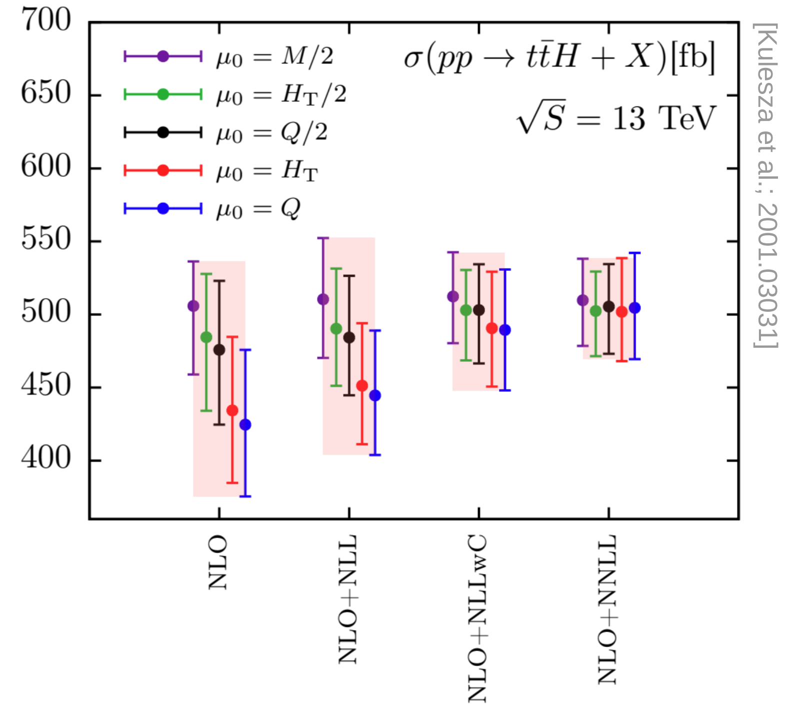
[Frederix et al.; 1104.5613], [Garzelli et al.; 1108.0387], [Hartanto et al.; 1501.04498]

Soft-gluon resummation

[Kulesza et al.; 1509.02780, 1704.03363], [Broggio et al.; 1510.01914], [Broggio et al.; 1611.00049], [Broggio et al.; 1907.04343], [Ju and Yang; 1904.08744], [Kulesza et al.; 2001.03031]

NLO and resummation for ttH

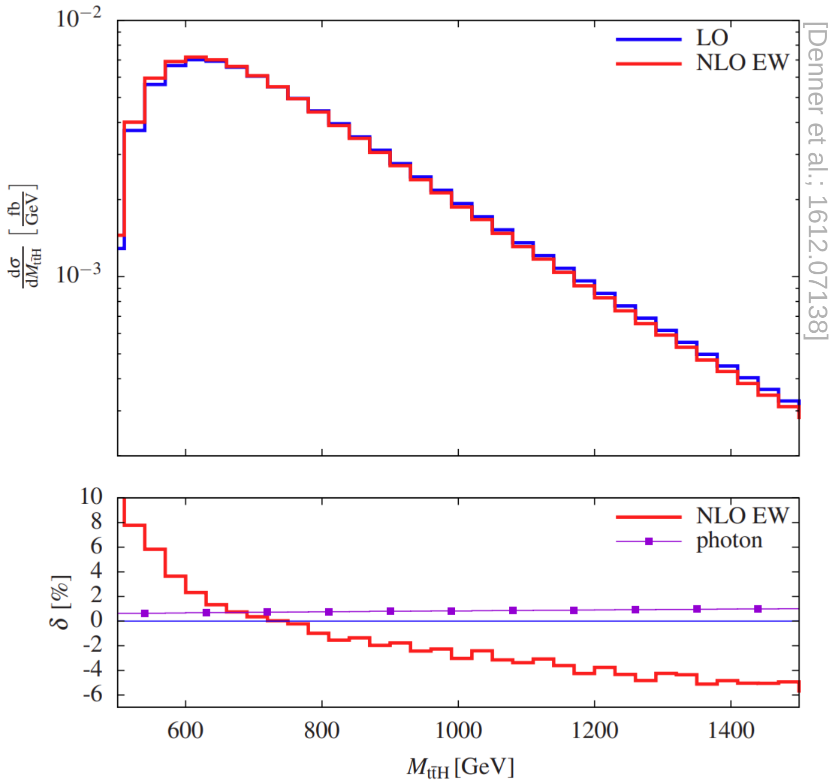
- NLO QCD corrections are large, O(30%), and scale uncertainties still sizeable



- Fixed-order results improved with soft gluon resummation in order to reduce uncertainties

- Results for different scale settings are stabilized by the inclusion of rusummed contributions

- Remaining uncertainties still at the O(10%) level



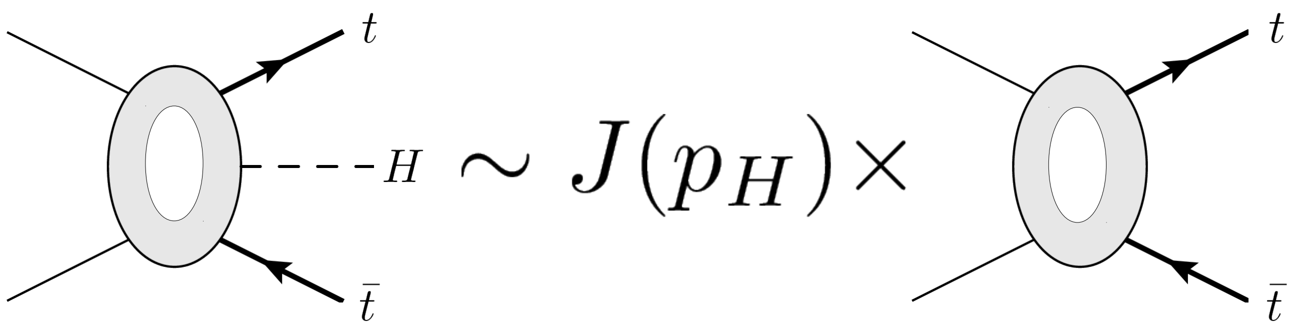
- NLO EW corrections of O(1%) for total cross section

- Can be more sizeable for distributions

ttH at NNLO in QCD

See slides from S. Devoto

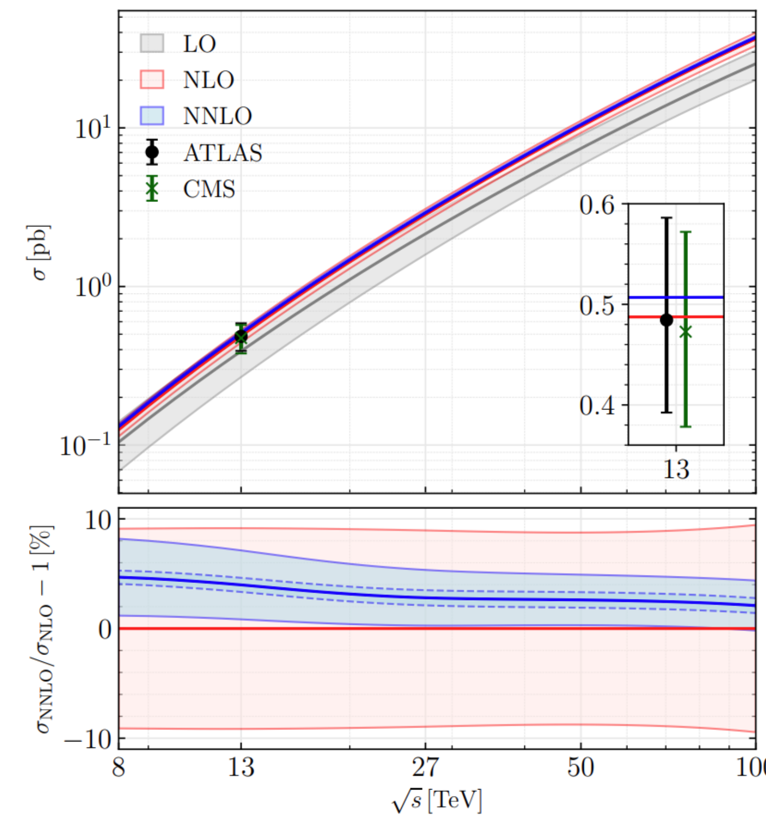
- Very recently NNLO results obtained by approximating two-loop virtual corrections [Catani, JM et al.; 2210.07846]
- Soft Higgs boson approximation: in the $p_H \to 0$ limit we have



- Approximated piece has a small numerical impact, and therefore leads to small additional uncertainties

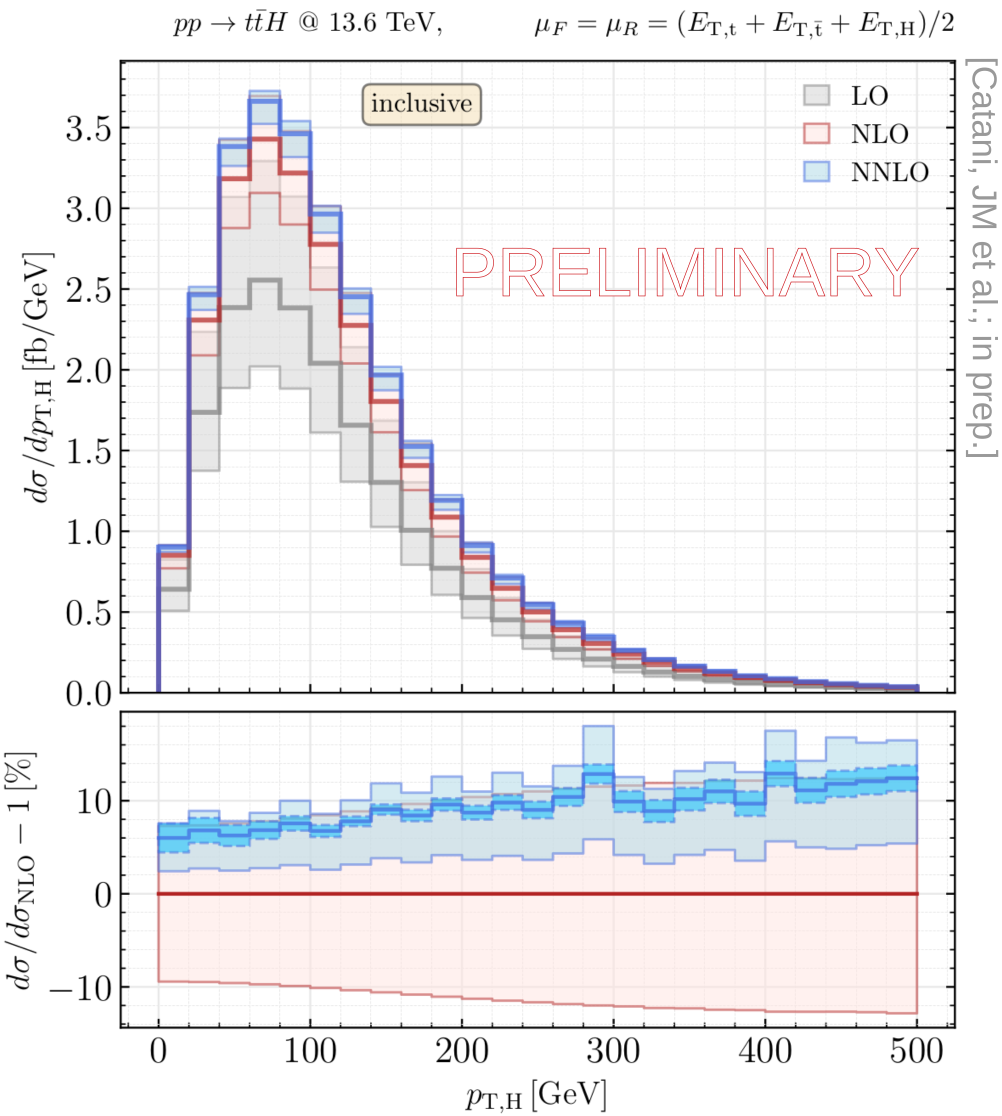
σ [pb]	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 100$ TeV
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$

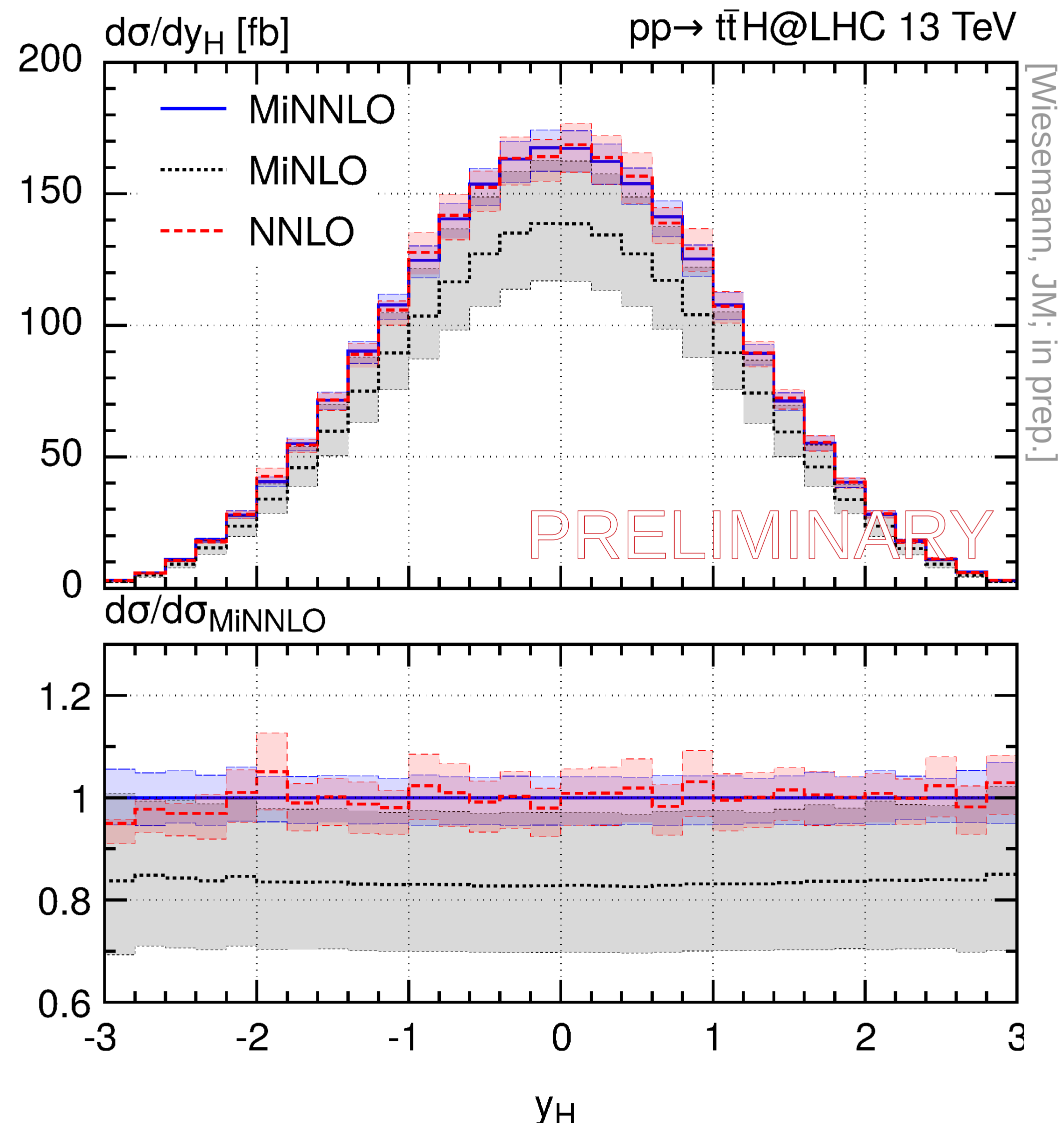
NNLO corrections increase total XS by about 4% at 13TeV, and strongly reduce scale uncertainties



[Catani, JM et al.; 2210.07846]

- Further developments expected soon:





Fully differential $t\bar{t}H$ at NNLO

NNLO+PS for $t\bar{t}H$

Top mass definition and related uncertainties in Higgs observables

Top mass renormalization schemes

- The top-quark mass is subject to renormalization, and therefore it suffers from a scheme (and in general a scale) ambiguity

- Most commonly used for the top-quark mass: **pole scheme**

Pole of the quark propagator is fixed to the same value, the **pole mass** M_t, at any order in perturbation theory

- 'Natural' choice when considering on-shell top quark production

- Alternatively, we can remove only the singular contributions in dim. reg.: **$\overline{\text{MS}}$ scheme**

Pole of the quark propagator receives corrections at any order
The **$\overline{\text{MS}}$ mass** $m_t(\mu_t)$ differs from M_t and depends on arbitrary scale μ_t

- The pole mass is affected by a non-perturbative ambiguity of $O(\Lambda_{QCD})$, absent in the $\overline{\text{MS}}$ mass

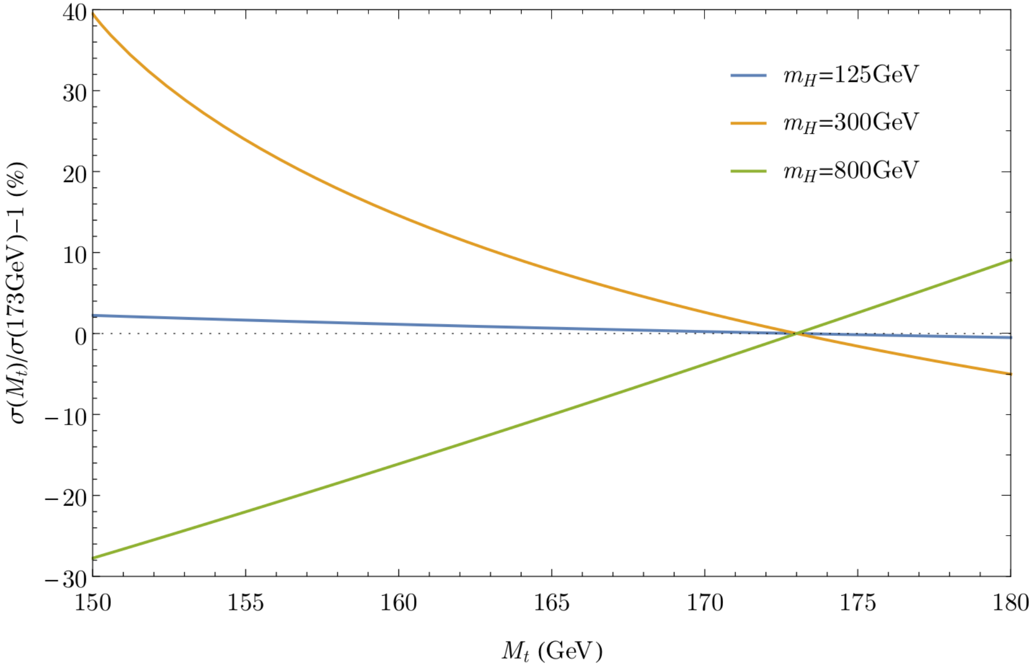
- The $\overline{\text{MS}}$ mass depends on an additional arbitrary scale, which leads to further uncertainties

A priori, no clear reason to prefer one scheme over the other for the tops inside the loop

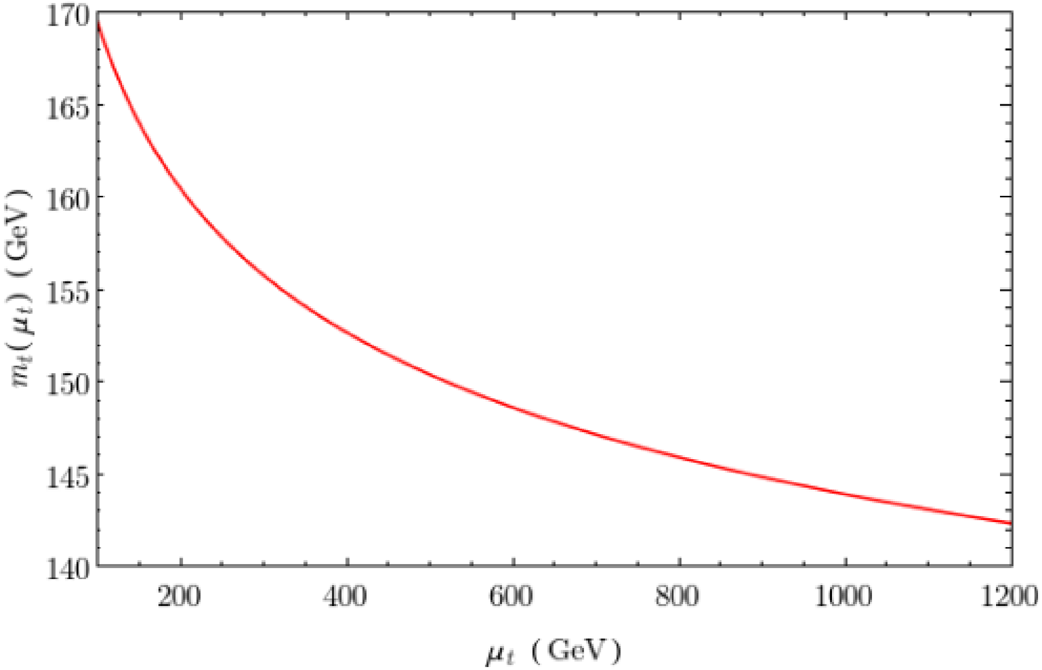
Top-mass-scheme uncertainties

Top-mass-scheme uncertainties at per-mille level for on-shell Higgs production

Very mild parametric dependence of the XS with M_t for m_h=125GeV



Numerical difference between M_t and $m_t(\mu_t)$ not ‘enhanced’ for μ_t of $O(m_h)$



(note that at LO the difference between OS and $\overline{\text{MS}}$ predictions is simply replacing $M_t \rightarrow m_t(\mu_t)$)

The situation will dramatically change if scales involved are larger!

Top-mass-scheme uncertainties

- Issue pointed out a few years ago in the context of di-Higgs production, but also affecting off-shell Higgs (production and decay) and H+jet [Baglio et al., 1811.05692]

- NLO (LO) studies have been performed for H* and HH (H+jet)
  [Baglio et al., 1811.05692, 2003.03227] [Jones and Spira, 2003.01700]

($t\bar{t}H$ cross section also has been studied using the $\overline{\text{MS}}$ scheme)
[Aldaya Martin, Moch, Saibel]

- NLO cross section for off-shell Higgs production:

$$\sigma(gg \to H^*)\Big|_{Q=125\ \text{GeV}} = 42.17^{+0.4\%}_{-0.5\%}\,\text{pb}$$

$$\sigma(gg \to H^*)\Big|_{Q=300\ \text{GeV}} = 9.85^{+7.5\%}_{-0.3\%}\,\text{pb}$$

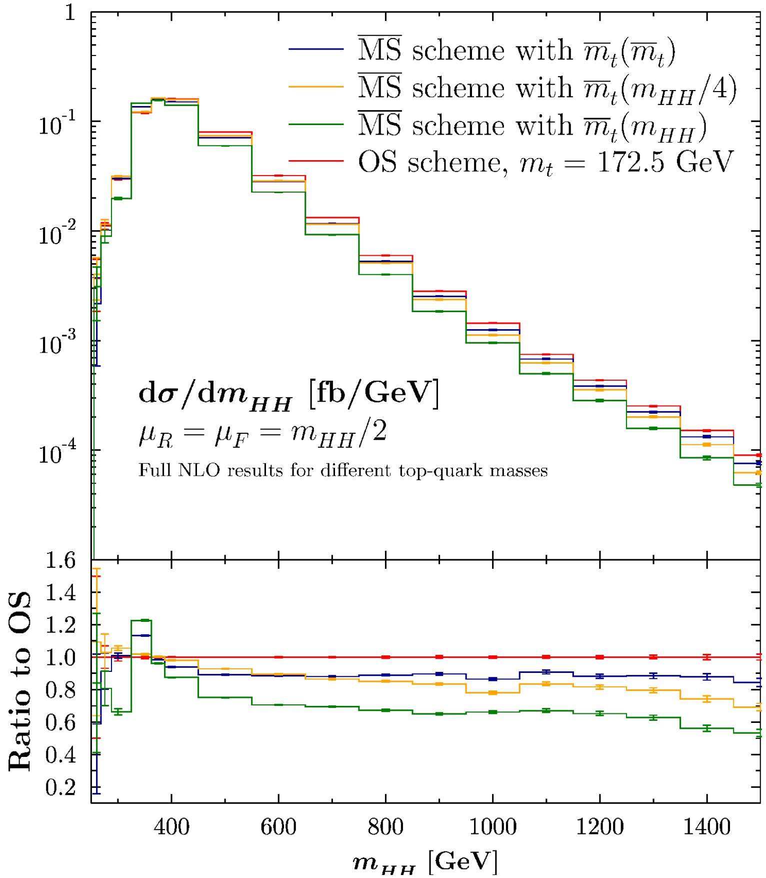
$$\sigma(gg \to H^*)\Big|_{Q=600\ \text{GeV}} = 1.97^{+0.0\%}_{-15.9\%}\,\text{pb}$$

$$\sigma(gg \to H^*)\Big|_{Q=1200\ \text{GeV}} = 0.0402^{+0.0\%}_{-26.0\%}\,\text{pb}$$

Central value: OS scheme
Uncertainty: envelope of $\overline{\text{MS}}$ calculation with $\mu_t=\{Q/4, Q/2, Q, m_t(m_t)\}$

- Similar situation for di-Higgs production

$$\sigma_{\text{NLO}}(gg \to HH) = 32.81^{+4\%}_{-18\%}\,\text{fb}$$



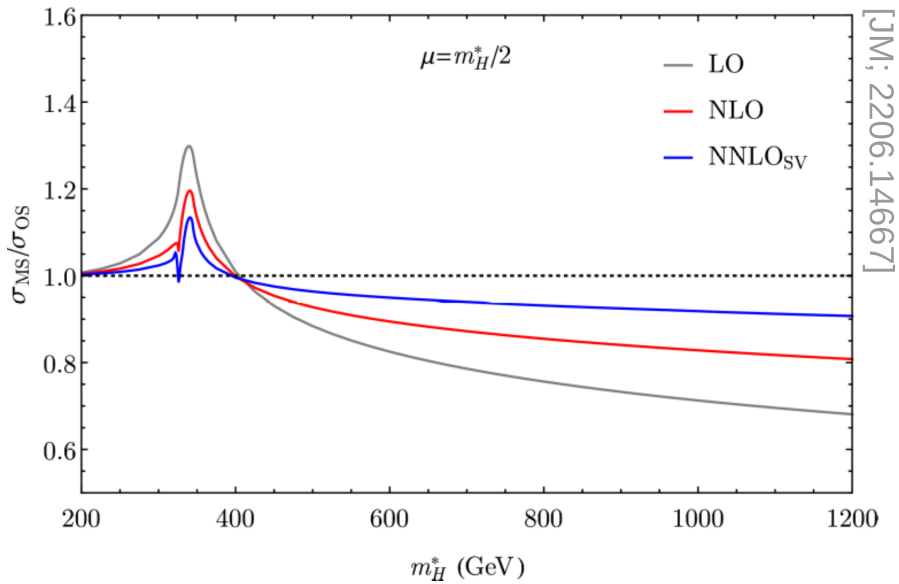
[Baglio et al.; 2003.03227]

Top-scheme uncertainties are dominant in HH, and in H* for large invariant masses!

H* production at NNLO and top uncertainties

- For the H* case, this issue has been addressed at $\mathrm{NNLO_{SV}}$ [JM; 2206.14667]
- Obs: heavy top limit (widely used in Higgs studies) cannot be applied in this case!

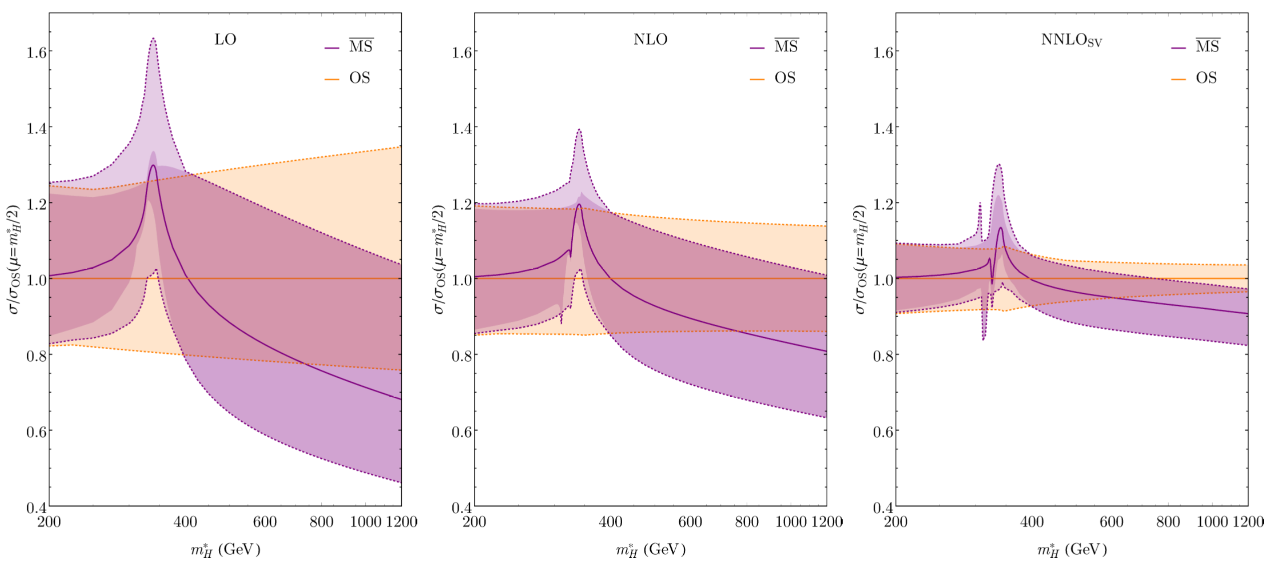
Retain full top-quark mass dependence in three-loop virtual corrections [Czakon, Niggetiedt; 2001.03008]



[JM; 2206.14667]

Higher-order corrections bring OS and $\overline{\text{MS}}$ predictions closer to each other

Substantial reduction of scheme and scale uncertainties at $\mathrm{NNLO_{SV}}$



- No analogous NNLO results for Higgs pair production yet
- Top mass scheme ambiguities still the main source of th. unc.

Summary

- The top quark has very distinctive features due to its large mass
- Top quarks are ubiquitous at the LHC, many interesting production modes (not all of them covered in this talk!) and background of many searches
- Precise theory predictions crucial to fully exploit experimental data
- In general theory predictions are in really good shape, still improvements are expected and needed in some areas
- Increased data-taking will allow for impressive improvements in the measurement of top-quark-related observables: theory predictions need to keep up!

Thanks!