Theory Summary

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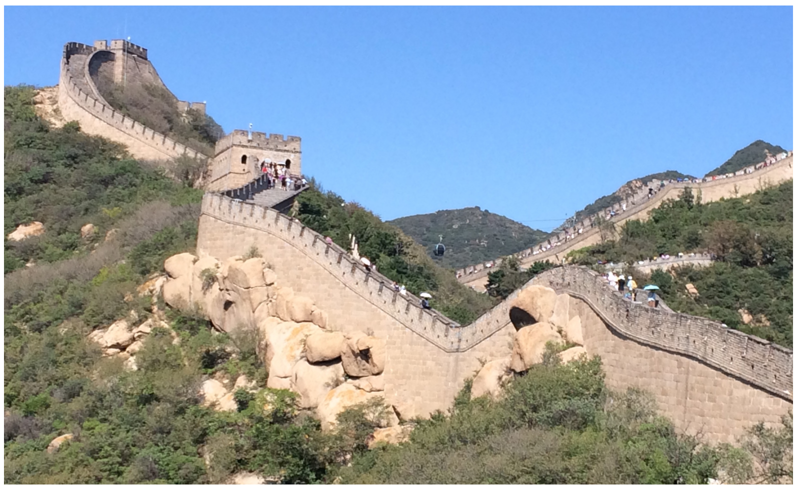


12th International Workshop on Top-Quark Physics

IHEP- Beijing - September, 22-27 2019

Why a conference on top-quark physics?

- **Top-quark large mass** makes it **special in the Standard Model**
  - $\rightarrow$ Does not form bound states: easier access to its properties.
  - $\rightarrow$ Large coupling to the Higgs boson ($y_t \approx 1$): crucial in SM Higgs physics.
    - $\hookrightarrow$ think of $\mathbf{gg \rightarrow H}$, and $\mathbf{t\bar{t}H}$ production.
  - $\rightarrow$ $y_t \approx 1$: important indirect effects in all SM observables, including m_H.
    - $\hookrightarrow$ naturalness $\longrightarrow$ see Liantao Wang's talk
  - $\rightarrow$ Best probe of SM fermion-mass generation mechanism.
    - $\hookrightarrow$ why fermion-mass hierarchy?
  - $\rightarrow$ Natural probe of high-energy behaviour of SM scattering amplitudes.
    - $\hookrightarrow$ unitarity violation?
  - $\rightarrow$ Together with M_H can determine the fate of our universe (!)

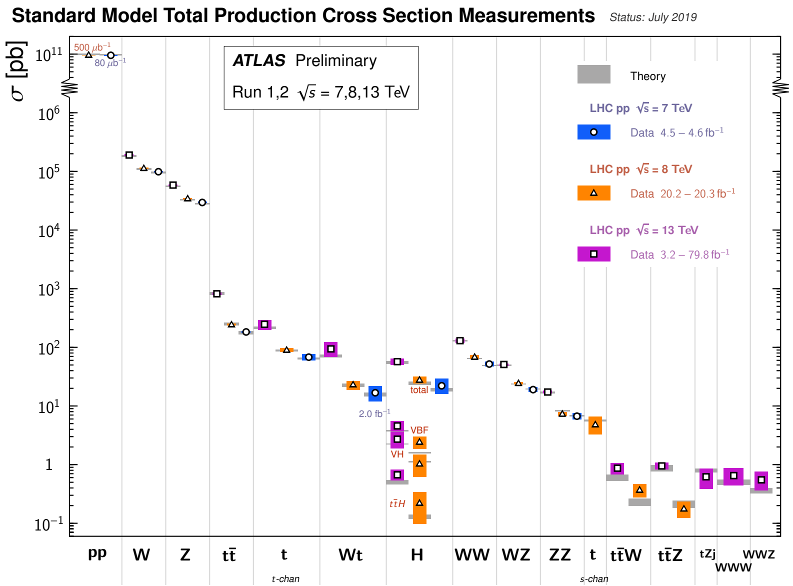
  ... hence an **excellent probe of physics beyond the SM**.

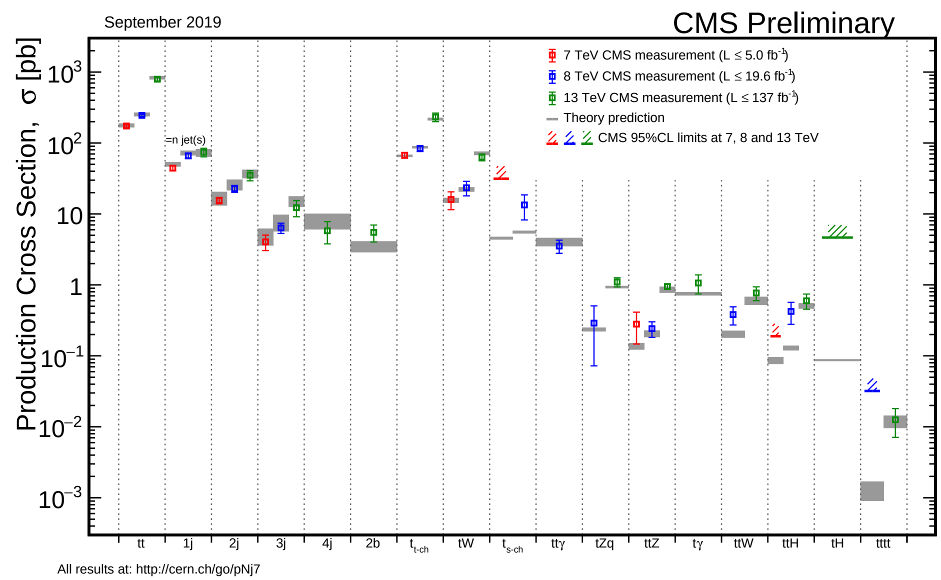
- **Top physics** has been **at the core of the the Tevatron and the LHC physics program** and will continue to be for the HL/HE-LHC upgrades, as well as for all future colliders currently under discussion.
  - $\hookrightarrow$ **Precision tests** of SM framework ($t\bar{t}$, $t\bar{t}+X$, m_t, t couplings, ...).
  - $\hookrightarrow$ **Searches** for **new signatures** (exotic decays, FCNC, ...).

At a glance . . .

Huge statistics: 275 millions top quarks produced/exp in 139 fb^{-1}@13 TeV

⟶ see Craig Wiglesworth's and Zhen Hu's talks





Very rich phenomenology: ⟶ ALL TALKS at Top 2019

- ↪ $t\bar{t}$ and single-t production $[m_t,\, \Gamma_t,\, V_{tb}]$
- ↪ $t\bar{t}H$ and tH production $[y_t]$
- ↪ $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$, $t\bar{t}t\bar{t}$, . . . [t couplings to $W, Z, \gamma,\, y_t$]

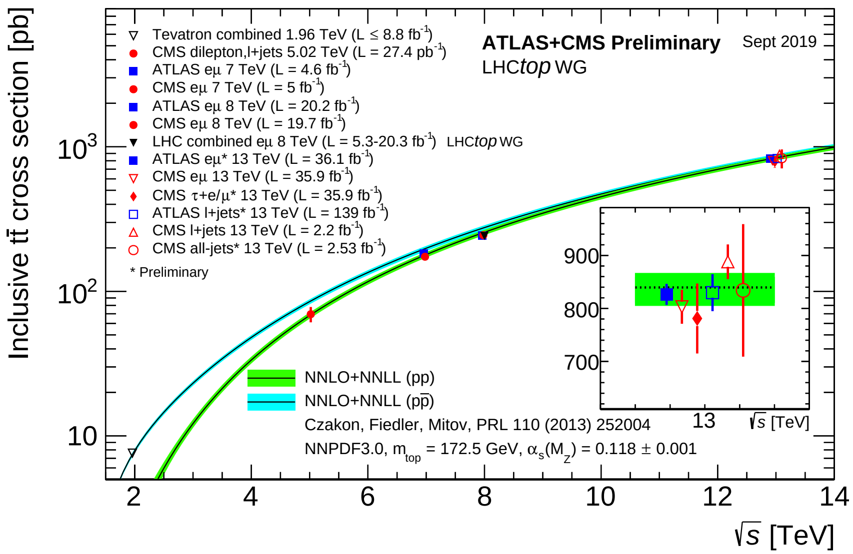
⟶ Possible to test consistency with the SM and to explore new physics.

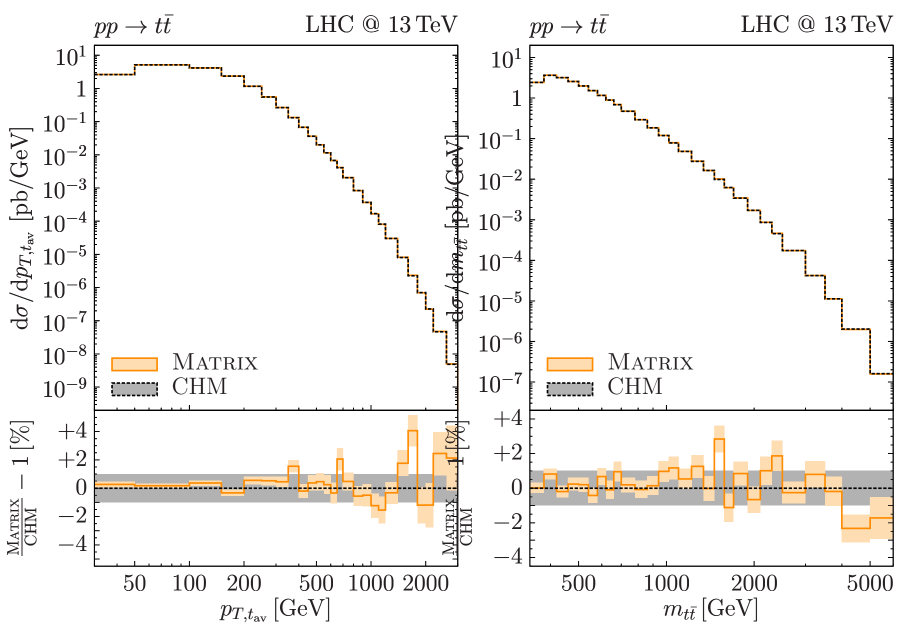
Why a conference on top-quark physics?

- **Many important theoretical results in the last year.**
  - → Distributions in $t\bar{t}$ production being constantly refined.
  - → More single-top measurements, first differential distributions.
  - → Improved studies ($t\bar{t}H$, $t\bar{t}b\bar{b}$, $t\bar{t}V$).
  - → Systematic approach to study of anomalous top interactions (EFT).
  - → Reaching out to BSM scenarios through the top-quark portal.
- **Interplay between theory and experiments essential at this stage.**
  - → When both theory and experiments have a way to reach comparable accuracy and improve it systematically.
  - → When we need to extrapolate from today results to plan the future.

↪ TOP 2019: a unique opportunity to share, review, and refocus.

$t\bar{t}$ production: the main building block





Czakon, Fiedler, Mitov (2013):

NNLO+NNLL QCD

Czakon, Fiedler, Heymes, Mitov (2015-16):

NNLO QCD, differential

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro (2017):

NNLO QCD+NLO EW

Czakon, Mitov, Poncelet (2019):

NNLO QCD with top decays (NWA)

→ see Alex Mitov's talk

Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Sargsyan (2019)

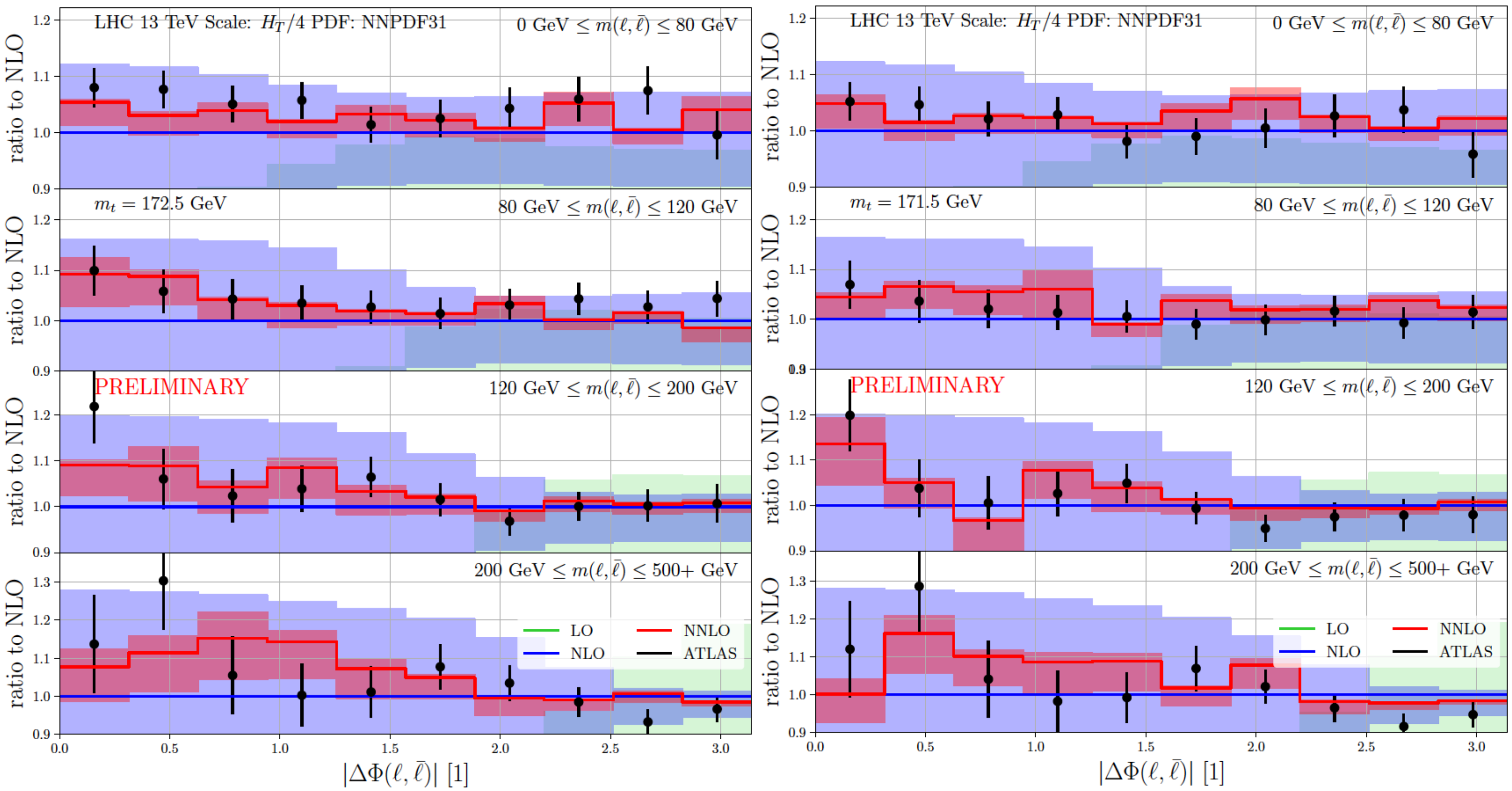
NNLO QCD, differential

↪ available in MATRIX

see Javier Mazzitelli's talk

$t\bar{t}$: NNLO distributions, with NNLO top decays

NNLO QCD vs ATLAS data: 2-dim



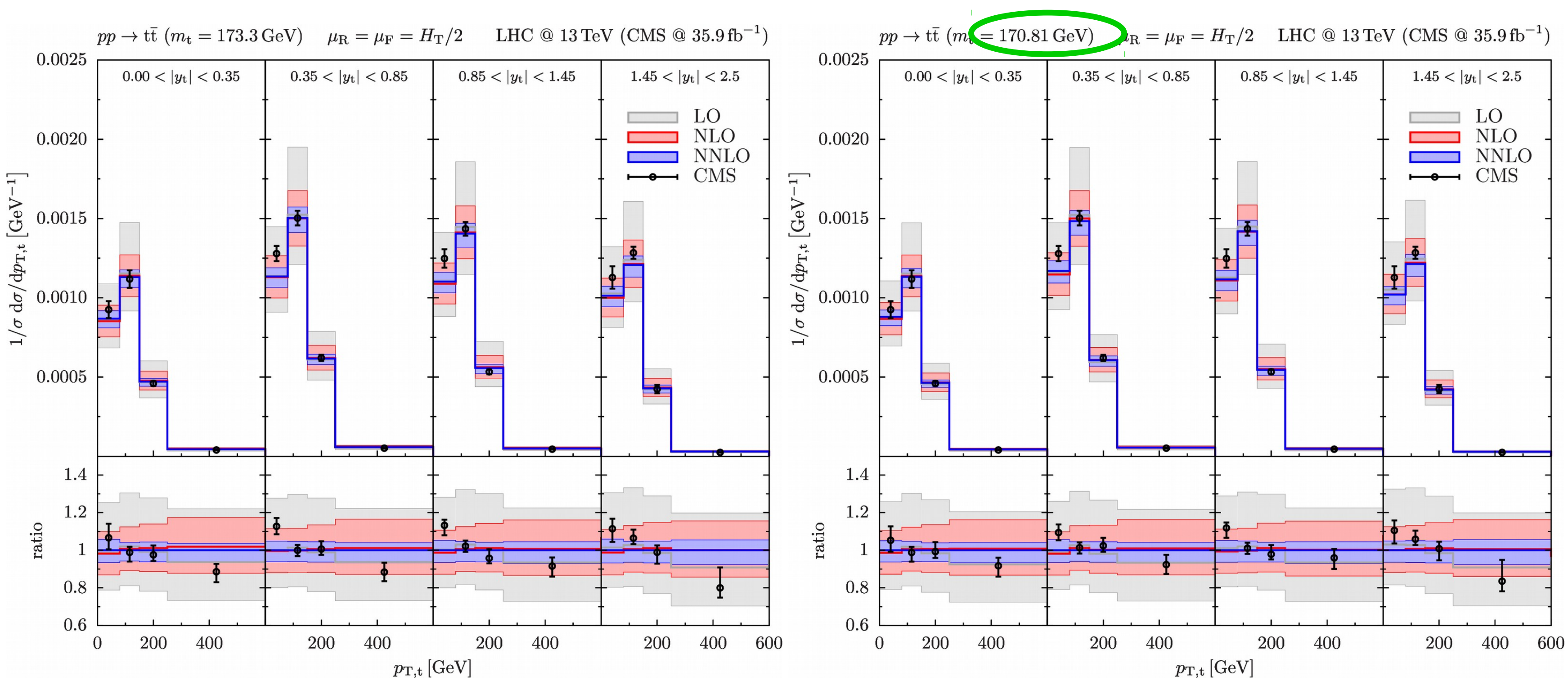
Work in progress: Czakon, Mitov, Poncelet

- ↪ Great reduction of scale error at NNLO vs NLO. Mostly small K factors.
- ↪ Both $m_t = 171.5$ GeV and $m_t = 172.5$ GeV seem to work.
- ↪ Improved MC error required to draw quantitative conclusions (apparent m_t sensitivity).

$t\bar{t}$: NNLO distributions, on-shell tops

Double-differential distributions

NEW: predictions for parton level CMS measurements using fully leptonic final state
[CMS-TOP-18-004]



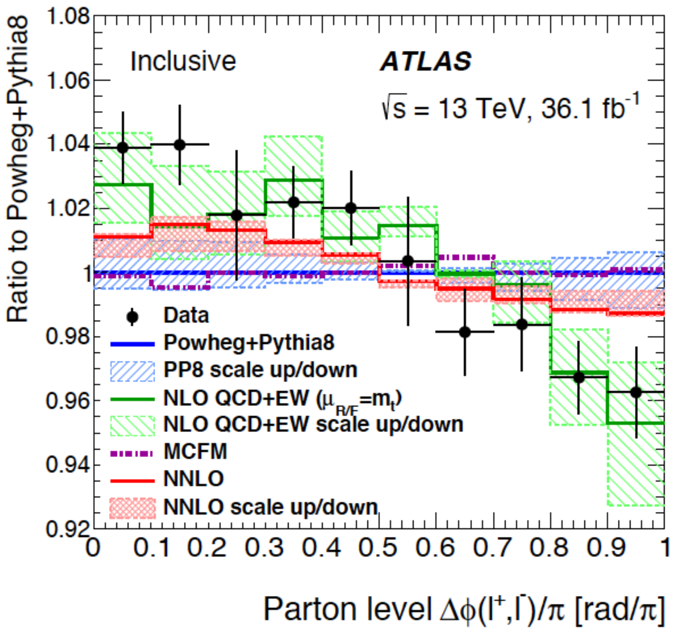
↪ Mass value has smaller impact in p_T distributions.

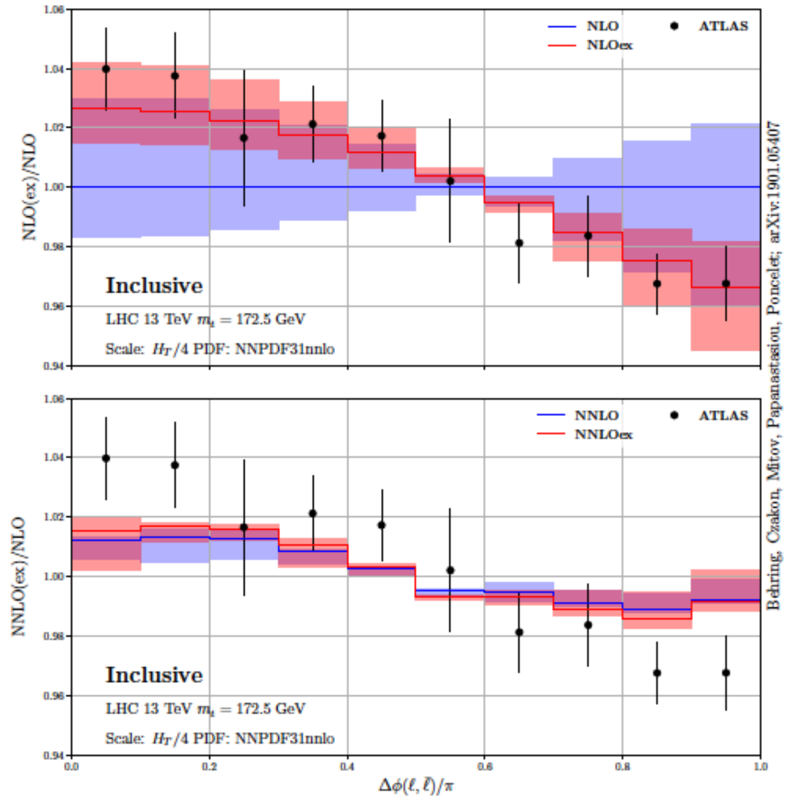
↪ Data still softer than predictions, slighter better agreement with lower mass.

From Alex Mitov's talk: **NNLO QCD $t\bar{t}$+decays does not agree with same CMS data.** ⟶ Problem with unfolding? underestimated unfolding error?

Spin correlation in $t\bar{t}$ production: NNLO vs NLO

ATLAS: arXiv:1903.07570





Important to avoid misunderstanding!

NLO and NNLO ratio can also be expanded in α_s, but the two differ, e.g.:

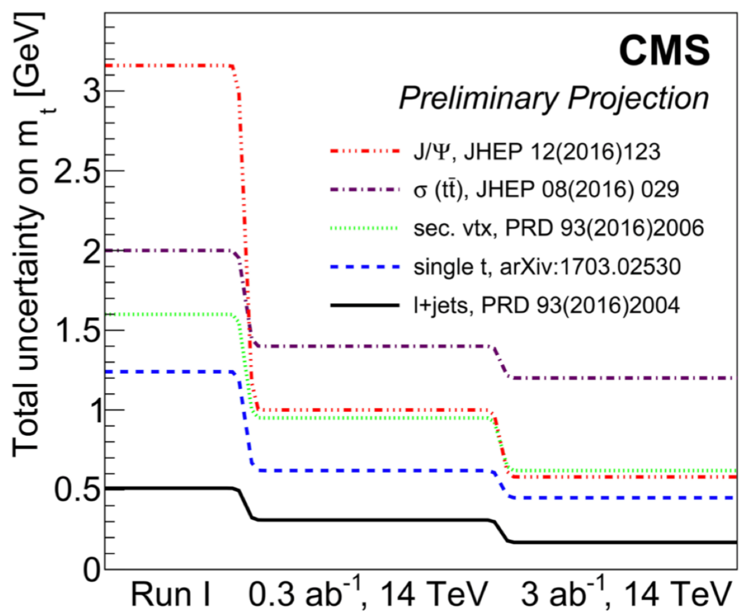
$$R^{\text{NNLO}} = \frac{1}{\sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2} \left(\frac{d\sigma_0}{dX} + \alpha_s \frac{d\sigma_1}{dX} + \alpha_s^2 \frac{d\sigma_2}{dX} \right)$$

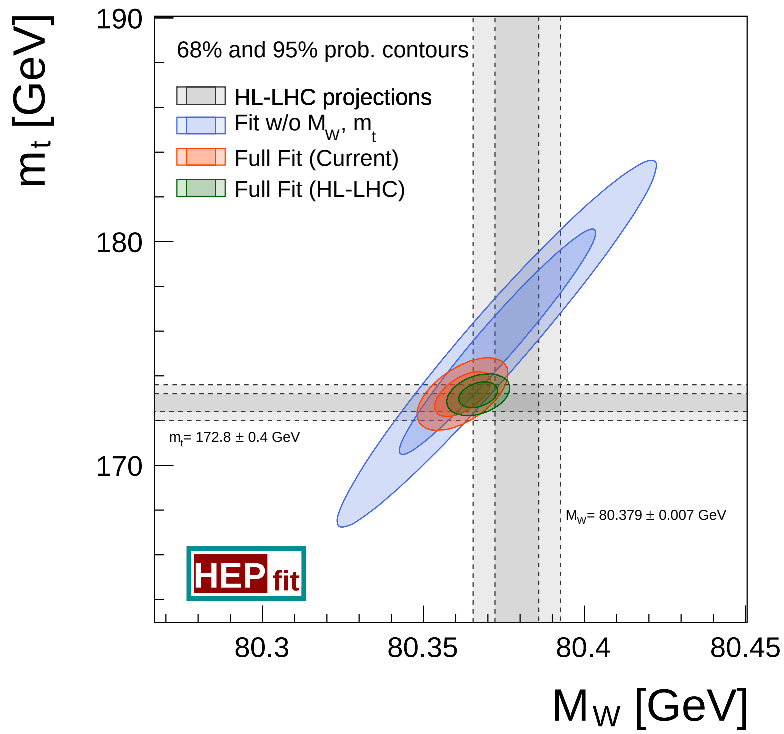
$$R^{\text{NNLO}}_{\text{exp}} = R_0 + \alpha_s R_1 + \alpha_s^2 R_2 + O(\alpha_s^3)$$

At NNLO the difference is tiny → **Data do not agree with theory**

Top-quark precision physics: the case of m_t

The question is: **Is there a theoretical hard limit on δm_t?**
$\hookrightarrow$ Determine precision game at future colliders.





Important to understand **what we are measuring?**

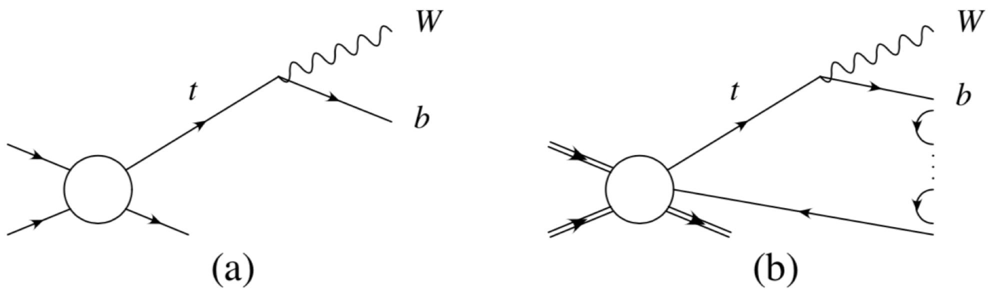
→ see Michal Czakon's talk

and to carefully assess **what is driving the exp. error so small?**

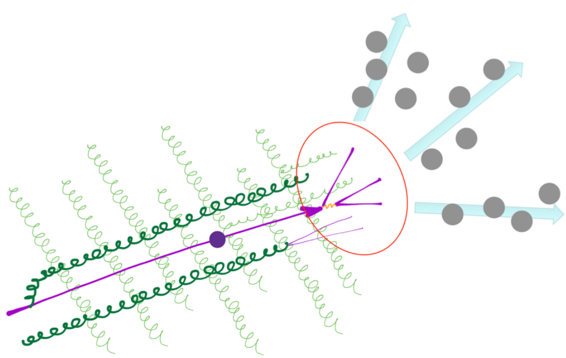
“Renormalons are proxy for non perturbative effects”

→ see Michal Czakon’s talk [Ferrario Ravasio, Nason, Oleari, arXix:1810.10931]

Wb invariant mass has linear infrared sensitivity due to a final state jet, irrespective of the mass definition used.



Modeling at hadron colliders:



$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_m^{\mathrm{pert}} + \Delta_m^{\mathrm{non-pert}} + \Delta_m^{\mathrm{MC}}$$

pQCD contribution:

- Perturbative correction
- Depends on MC parton shower setup

Non-perturbative contribution:

- Effects of hadronization model
- May depend on parton shower setup

Monte Carlo shift:

- Contribution arising from systematic MC uncertainties
- E.g. color reconnection, b-jet modeling, finite width, ...
- Should be covered by ‘MC uncertainty’ or better negligible

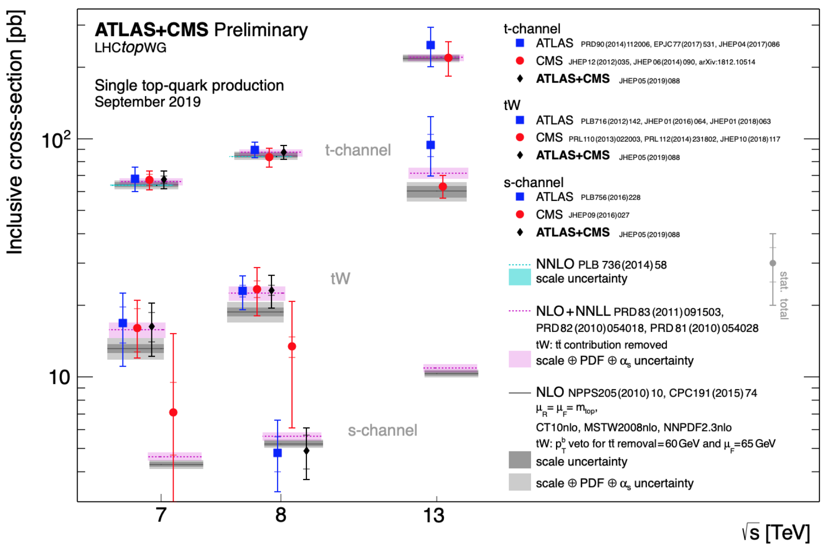
Study the effects by comparison of an event generator and analytic QCD predictions in a controlled environment.
(e.g.: lepton colliders in boosted topologies) [Hoang et al.]

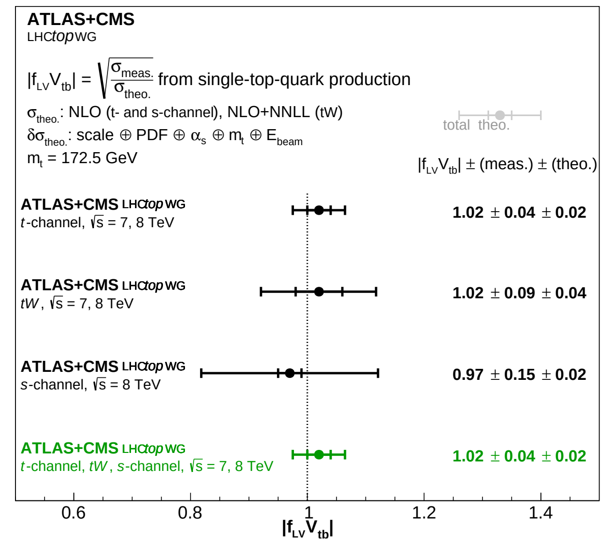
↪ Relations between different masses, and intrinsic limitations: difficult problem but can be understood.

Single-top production

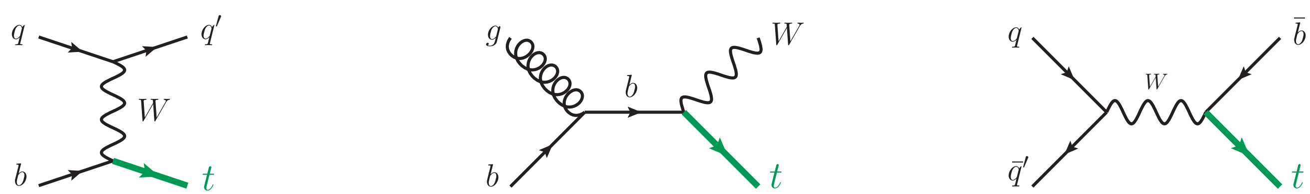
New results at 13 TeV $\longrightarrow$ see C. Escobar Ibañez's talk

New s-channel NNLO calculation $\longrightarrow$ see Zelong Liu's talk





where:



t-channel $\quad$ Wt $\quad$ s-channel

s-channel: sensitive to u/d PDF ratio.

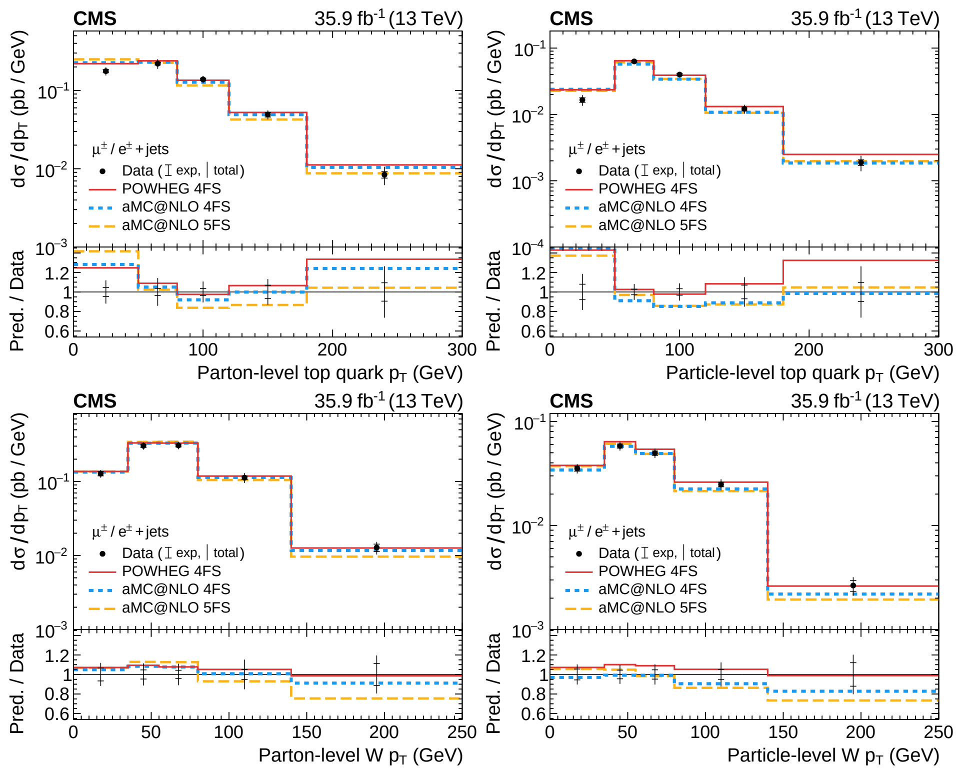
t-channel and **Wt**: sensitive to b PDF (5FS).

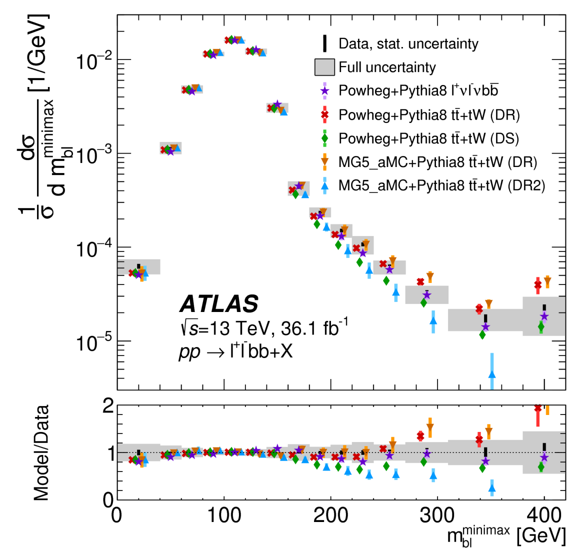
Single-top production

Several **new distributions measurements** (sensitivity to 4FS vs 5FS, Wt-$t\bar{t}$).

Testing **tWb** coupling and top-quark distribution in single-top phase space.

$\longrightarrow$ see Simon Berlendis's and Sergio Sánchez Cruz's talks





From *Phys. Rev. Lett.* 121 (2018) 152002

$t\bar{t} - tWb$ interference

affects tails of $t\bar{t}$ distributions.

Further coupling information from **rare top-related processes**:

$\boldsymbol{t\gamma q}$ (evidence), $\boldsymbol{tZq}$ (observation) , **FCNC** $\boldsymbol{t\gamma}$ (bounds).

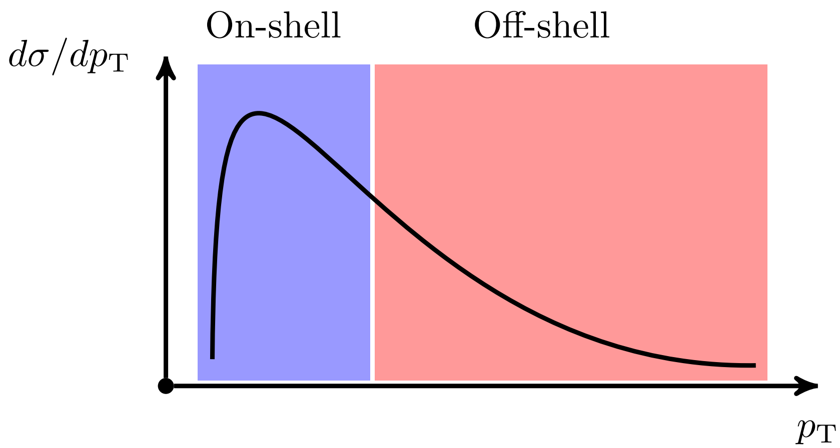
$\longrightarrow$ see Suyong Choi's talk

$t\bar{t}+H$, NLO QCD+EW corrections to off-shell production: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$

$\longrightarrow$ see Matthieu Pellen's talk

Off-shell effects

- Final states dominated by a production process
- Example: final state $\mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$ dominated by $\mathrm{pp} \to \mathrm{t}^\star\bar{\mathrm{t}}^\star \to (\mathrm{W}^\star \to \nu_\mu\mu^-)\,(\mathrm{W}^\star \to \mathrm{e}^+\nu_\mathrm{e})\,\mathrm{b}\bar{\mathrm{b}}$



On-shell region dominated by resonant production

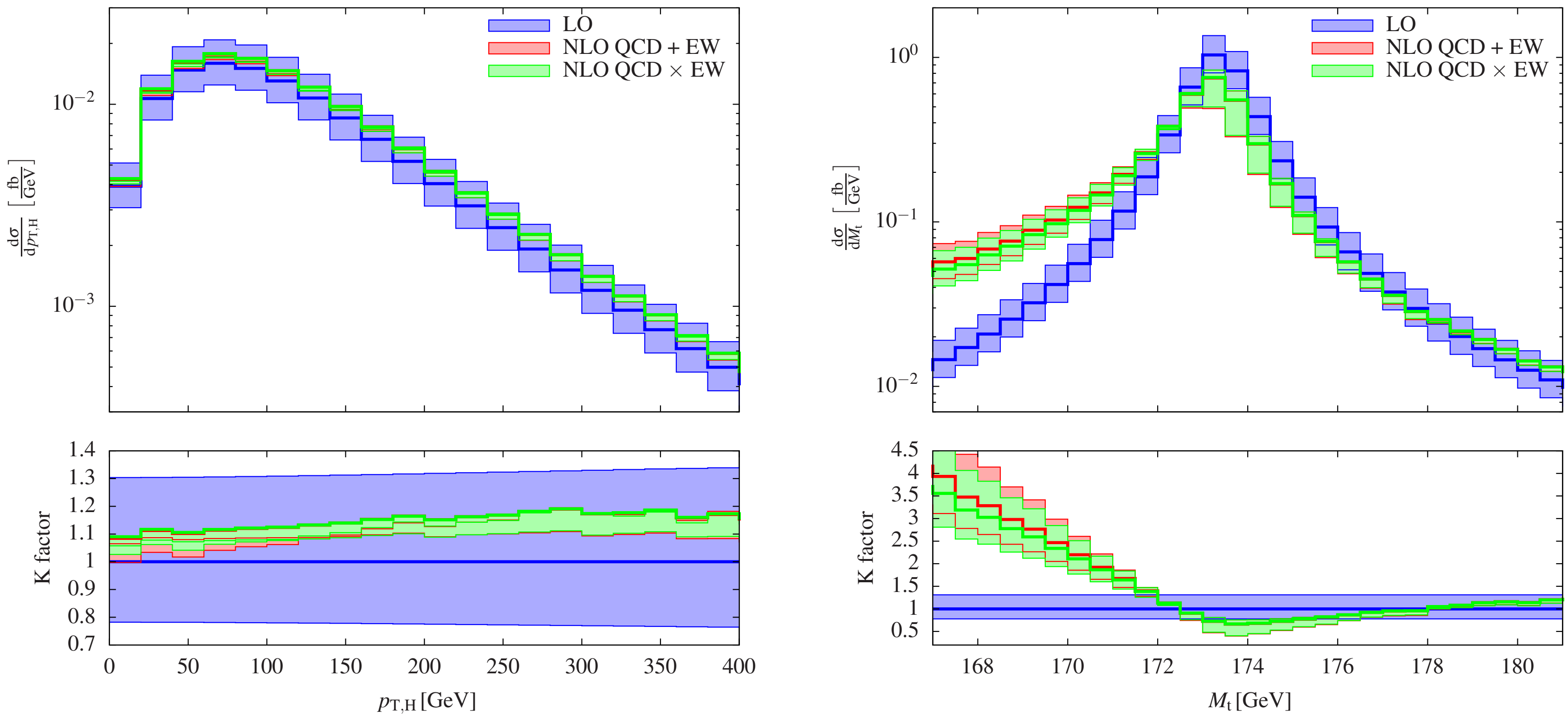
Off-shell region receives large non-resonant contributions

- Only $\mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$ is measured in experiments

$\rightarrow$ During run II, the tail of the distributions will be probed

$\rightarrow$ New physics contributions?

State-of-the-art predictions comparable with experiments



↪ NLO effects dominated by QCD corrections.

↪ EW non-negligible in specific regions: ±15%.

↪ Difference between NLO QCD+EW and NLO QCDxEW test perturbative stability (larger when EW corrections matter most).

↪ Off-shell effects can be large (see radiative tail in M_t distribution)

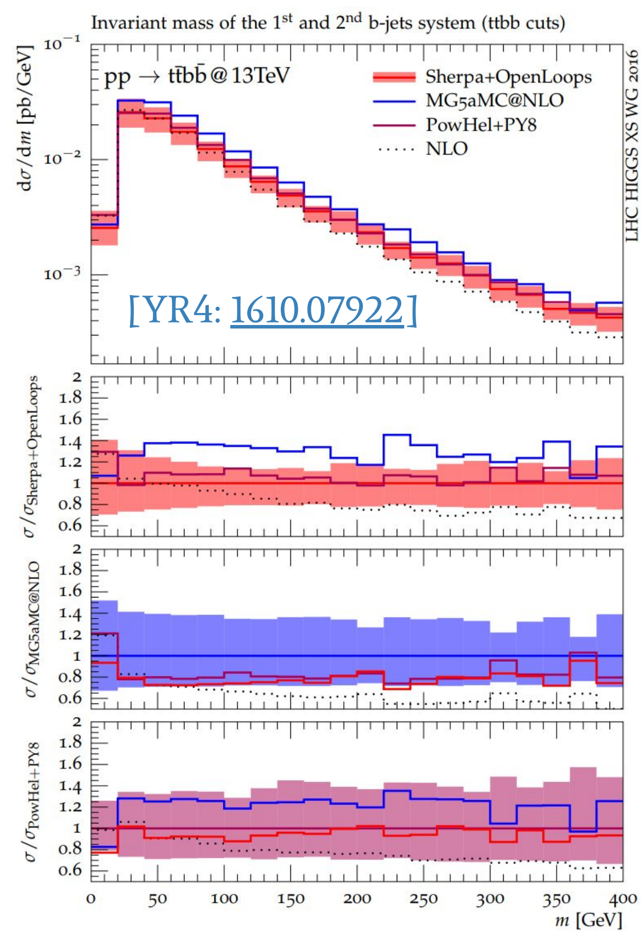
$t\bar{t}b\bar{b}$ as background to $t\bar{t}H(b\bar{b})$

A case for **in depth study of Monte Carlo modelling (NLO QCD)**.

⟶ see Frank Siegert's talk

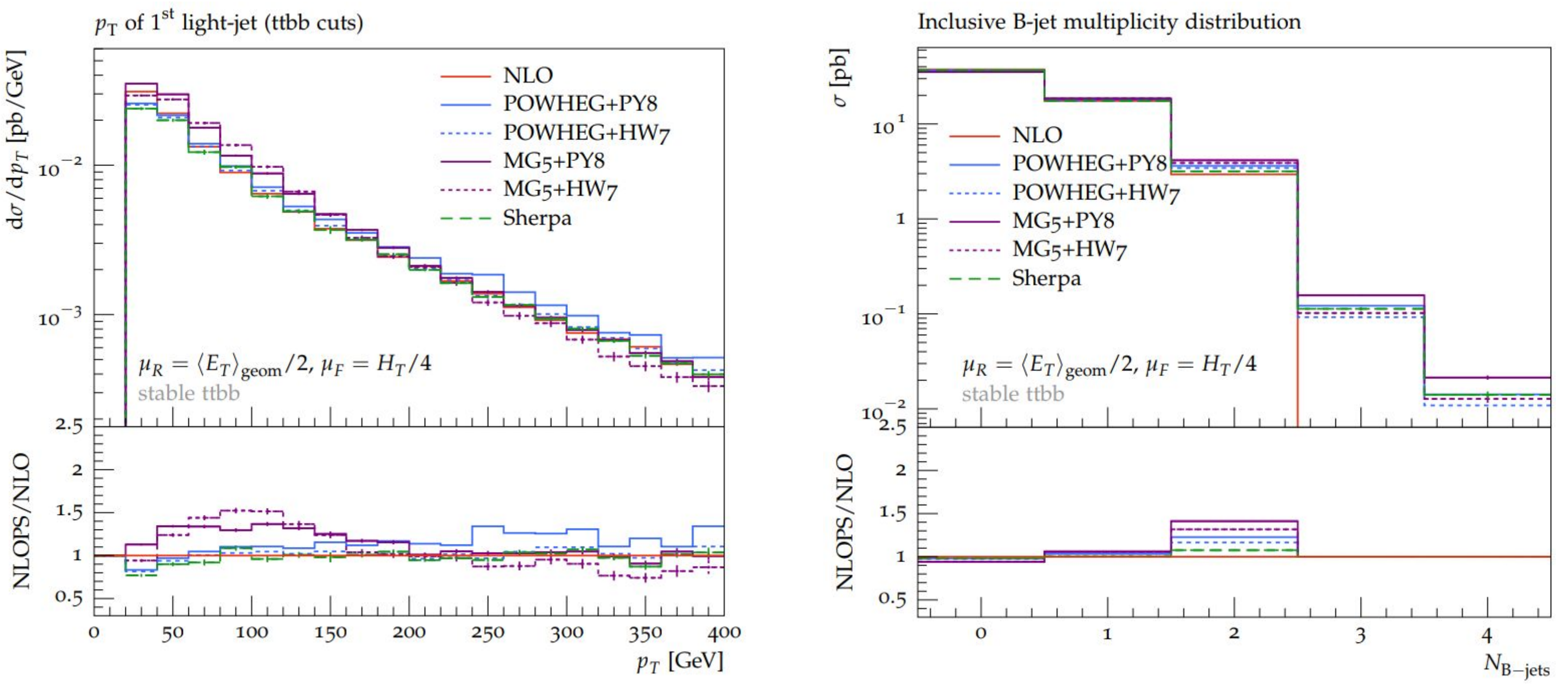
- Several tools on the market
  - Sherpa + OpenLoops [1309.5912]
  - PowHel + Pythia/Herwig [1709.06915]
  - PowhegBox + OpenLoops + Pythia/Herwig [1802.00426]
  - MG5_aMC + Pythia/Herwig
  - Herwig7 + OpenLoops
- History of out-of-the-box comparisons:
  - Large discrepancies
  - Partially due to large perturbative uncertainties
  - But also beyond!
    - » Parton Shower?
    - » NLO+PS matching algorithm?

Improve or accept as **uncertainties** (and kill ttHbb?)?



Dedicated study within the $t\bar{t}H$ WG (HXSWG) since YR4

- Application of reduced scale to tuned NLO+PS comparisons
  - improved agreement between NLO+PS tools for light-jet spectrum
  - still sizable O(40%) differences in N_{2b} region → origin?

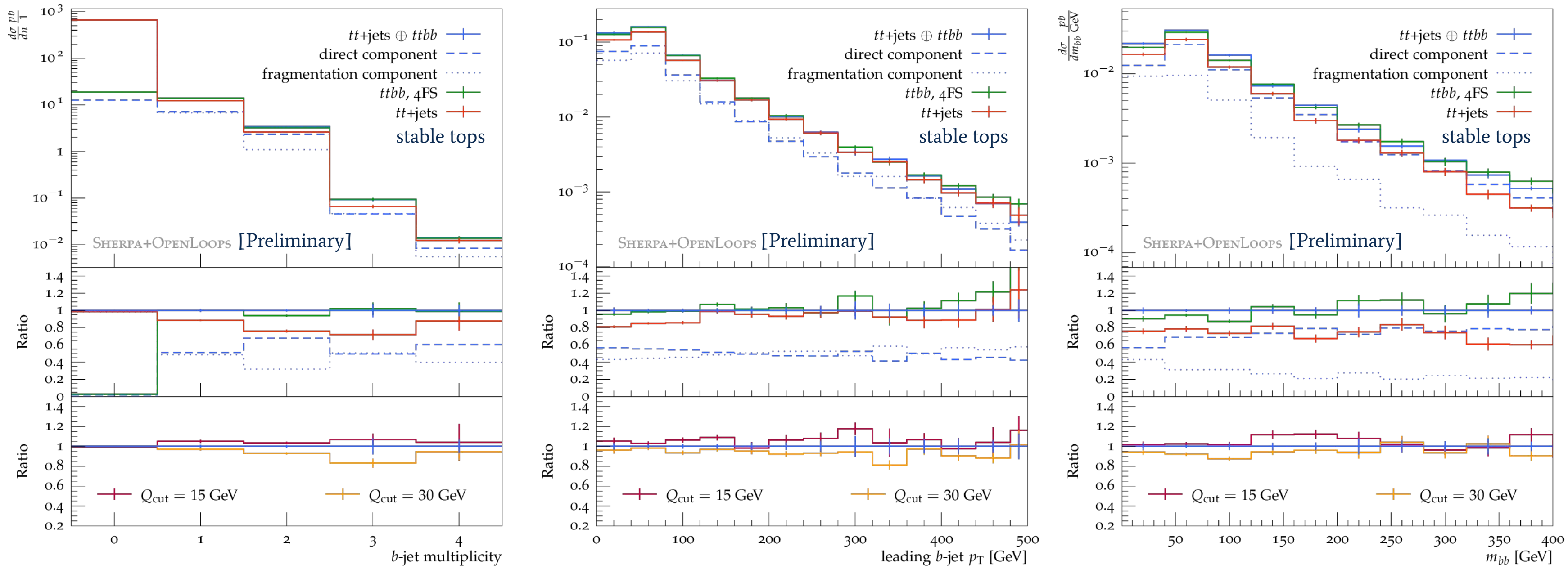


Important input: NLO QCD calculation of $t\bar{t}b\bar{b} + j$ (OpenLoops2+Sherpa)

[Boccioni, Kallweit, Pozzorini, Zoller, 2019]

Noticed large shower recoil effects on b jets. How to reduce uncertainty in hard jet configurations?

Fusing $X + b\bar{b}$ and X+jets in the Sherpa MC



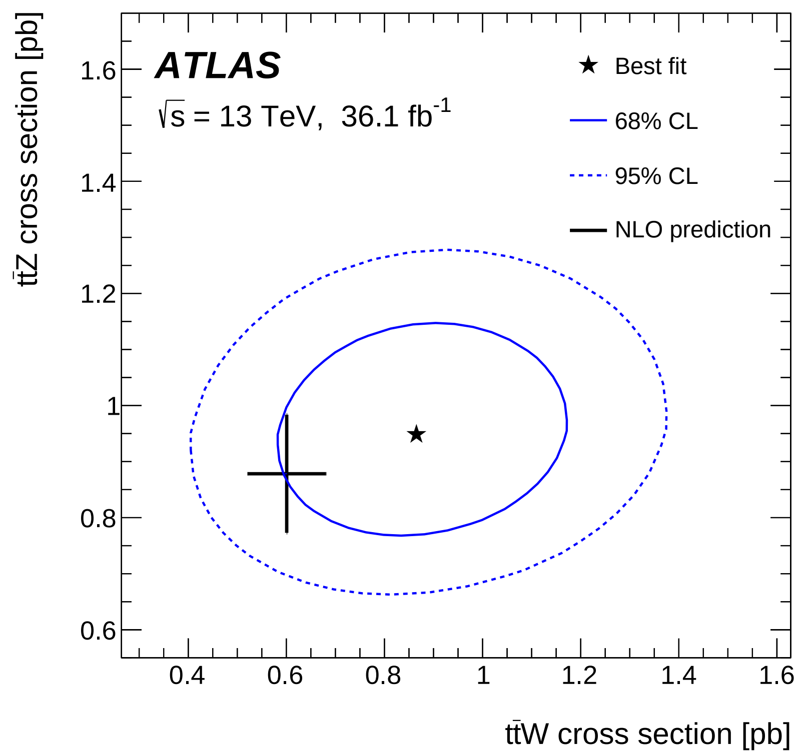
[Katzy, Krause, Pollard, Siegert, in preparation]

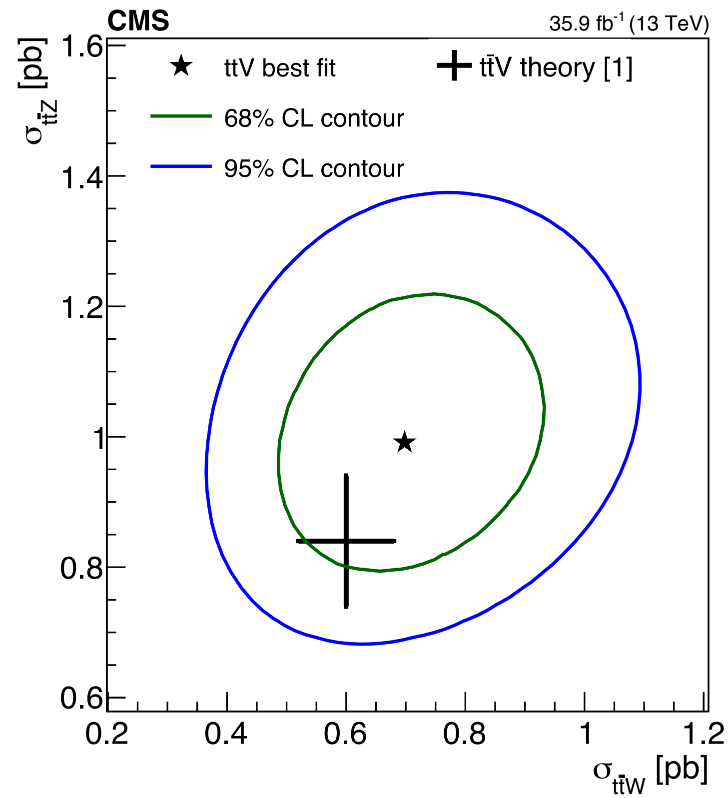
- **Fusing algorithm**, keep leading two emission:
  - ↪ Heavy flavours: keep from $t\bar{t}b\bar{b}$ NLO+PS → **direct** component.
  - ↪ Light flavours: keep from $t\bar{t}$+jets MEPS@NLO → **fragmentation** component.
- $2b$-jet production dominated by direct component.
- $1b$-jet production receives contributions by both direct and fragmentation configurations.

$t\bar{t}V$ $(V = W, Z, \gamma)$, measuring top-quark EW couplings …

… and important background to $t\bar{t}H$(multileptons).

Fitting $t\bar{t}Z$ and $t\bar{t}W$ simultaneously:





[ATLAS, arXiv:1901.03584]

$$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08(\text{stat}) \pm 0.10(\text{syst})\ \text{pb}$$

$$\sigma_{t\bar{t}W} = 0.87 \pm 0.13(\text{stat}) \pm 0.14(\text{syst})\ \text{pb}$$

[CMS, arXiv:1711.02547]

$$\sigma_{t\bar{t}Z} = 0.99^{+0.09}_{-0.08}(\text{stat})^{+0.12}_{-0.10}(\text{syst})\ \text{pb}$$

$$\sigma_{t\bar{t}W} = 0.77^{+0.12}_{-0.11}(\text{stat})^{+0.13}_{-0.12}(\text{syst})\ \text{pb}$$

HXSWG Yellow Report 4 (QCD+EW NLO)
$$\begin{cases} \sigma_{t\bar{t}Z} = 0.84^{+0.09}_{-0.10}\ \text{pb} \\ \sigma_{t\bar{t}W} = 0.60^{+0.08}_{-0.07}\ \text{pb} \end{cases}$$

Most recent results show some tension in $t\bar{t}W$:

(from $t\bar{t}H$ analyses) $\longrightarrow$ see Tamara Vasquez Schroeder's talk

Theory: (YR4)$\times 1.2 \simeq 0.7^{+0.09}_{-0.08}$, to account for:

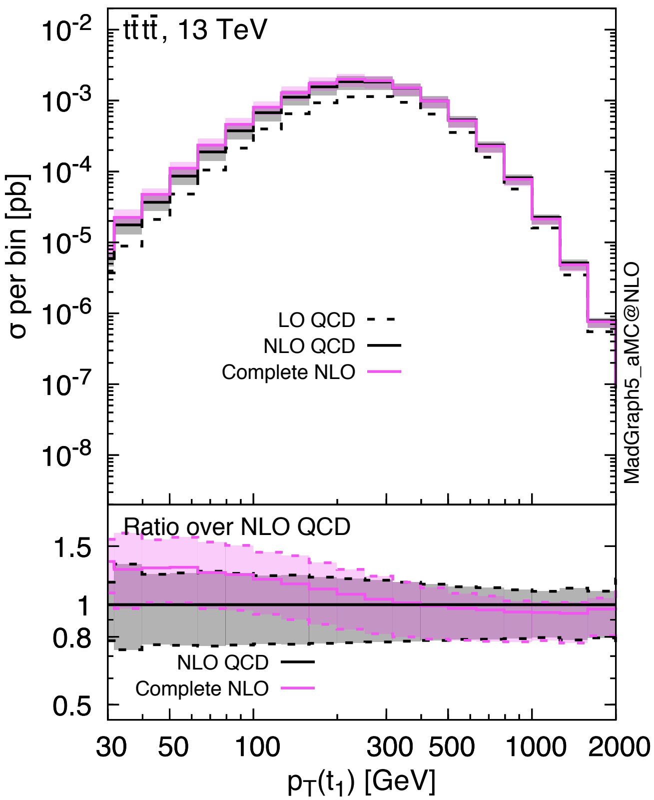
- $\hookrightarrow$ subleading NLO EW corrections (tW rescattering) not included in YR4 results;
- $\hookrightarrow$ large contribution from $(q,\bar{q})g \to t\bar{t}W + (q,\bar{q})$, now included adding $t\bar{t}W + j$ at NLO (technically part of the NNLO QCD corrections to $t\bar{t}W$).

Experiments: $\mu \simeq 1.39$ w.r.t. SM $t\bar{t}W$ ($1.2\times$ YR4)

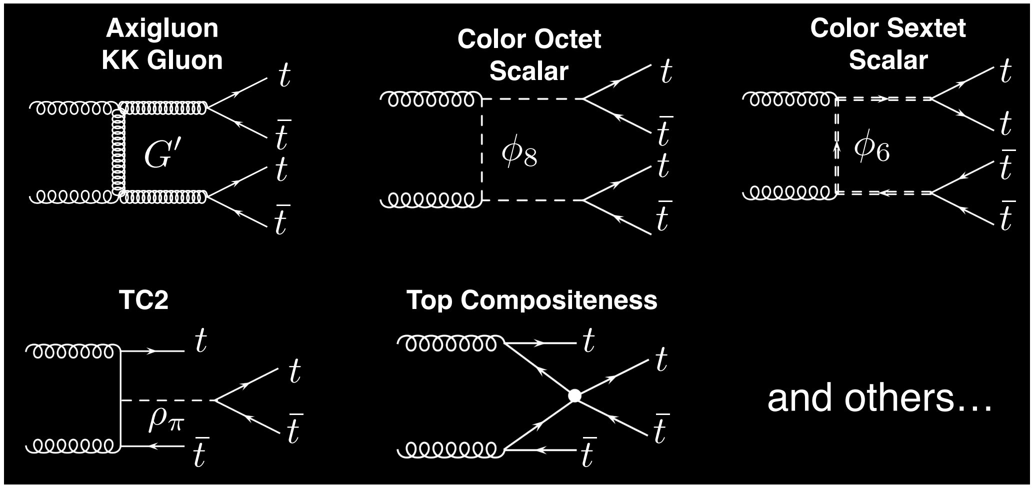
To be continued ...

Tops, tops, and more tops: $t\bar{t}t\bar{t}$ and ttt

Very sensitive to BSM effects: 4-top production often enhanced in BSM models compared to $t\bar{t}$. $\longrightarrow$ see Qing-Hong Cao's talk



[Frederix, Pagani, Zaro, arXiv:1711.02116]

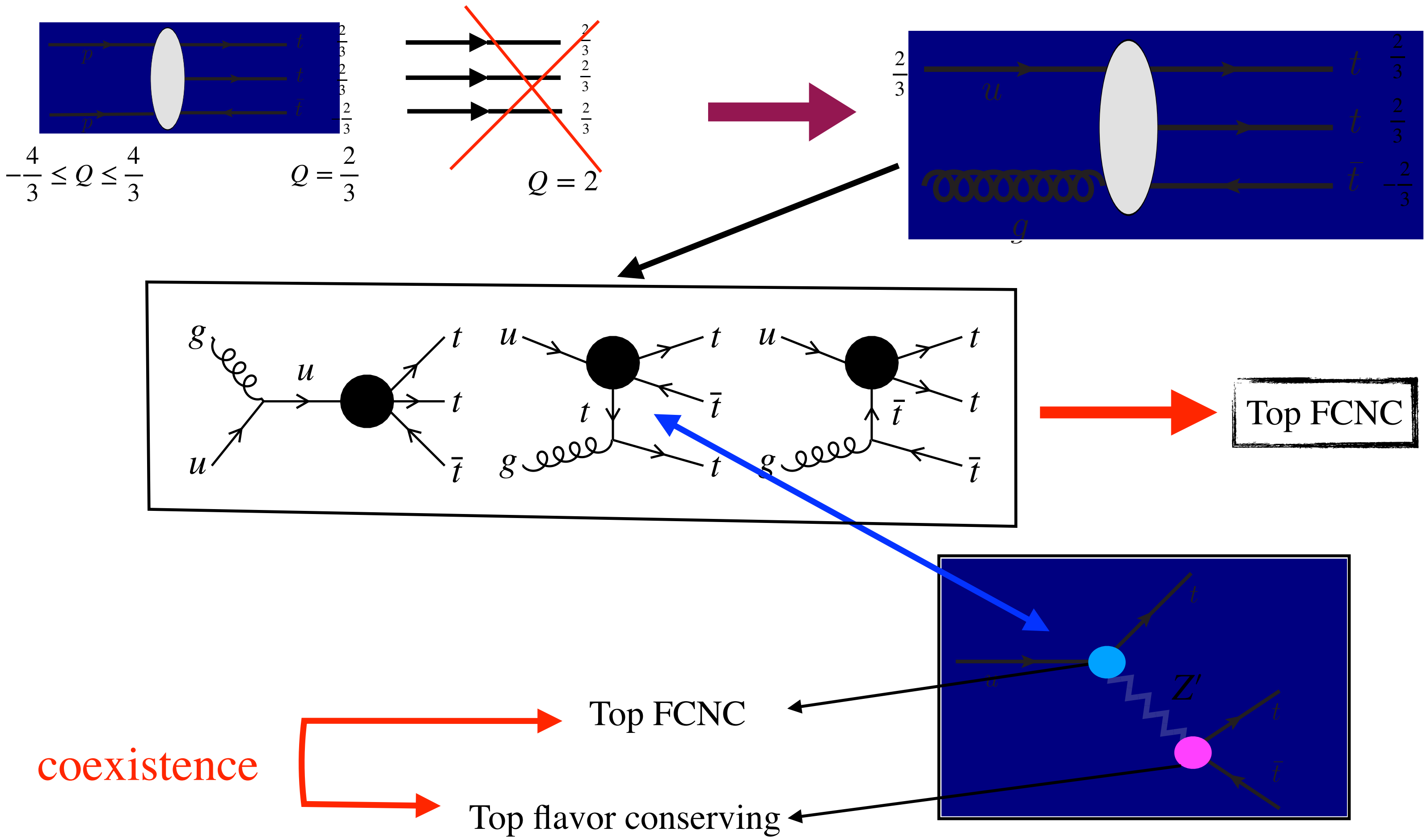


$\hookrightarrow$ Large subleading contributions at LO and NLO, with accidental cancelations among them.

$\hookrightarrow$ BSM physics may spoil such cancelations. NLO effects cannot be neglected

⟶ see Yandong Liu's talk

Triple Top-Quark Production at the LHC



$$\mathcal{O}^{\mathcal{V}}_{uttt} = \frac{f^{\mathcal{V}}_{\mathrm{FVNI}} f^{\mathcal{V}}_{\mathrm{FCNI}}}{\Lambda^2} (\bar{t}\gamma^\mu P_R t)(\bar{t}\gamma_\mu P_R u)$$

Top-quark and new physics

Searching for and interpreting evidence of new physics

$\hookrightarrow$ **Model-specific** approach: more predictive, yet arbitrary.
$\longrightarrow$ Mini-workshop: Top Meets New Physics
[talks by Riccardo Torre, Oleksii Matsedonskyi, Tao Liu, Lilin Yang, Minho Son, Christopher Verhaaren, Gabriel Lee]

$\Downarrow$

Naturalness as the leading guiding principle

$\hookrightarrow$ **Effective Field Theory** approach: less arbitrary, more systematic, but less prone to simple prescriptions.

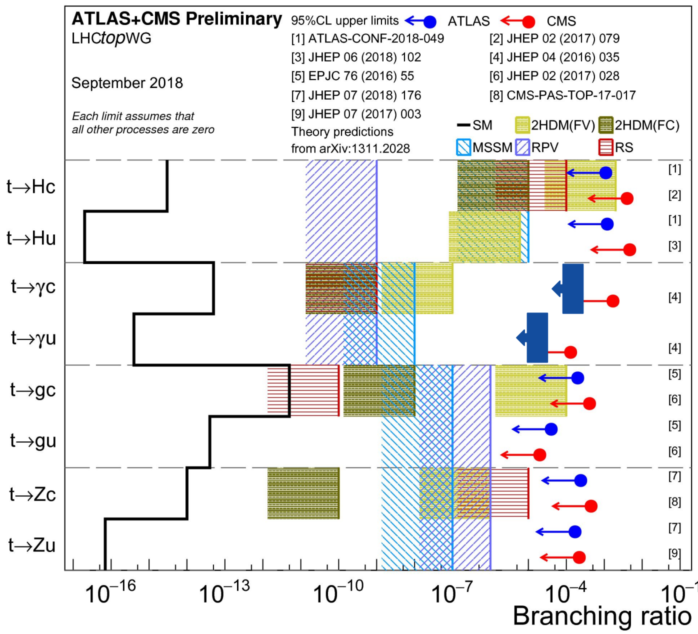
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d, \quad \text{with} \quad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i, \quad [\mathcal{O}_i] = d$$

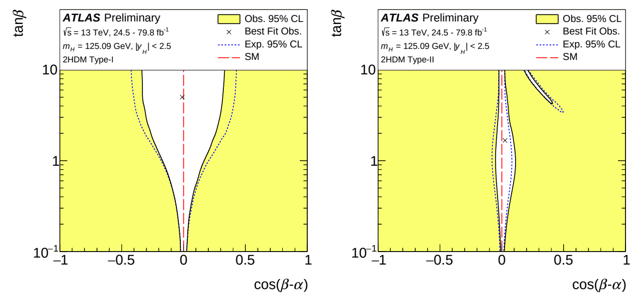
expansion in Λ (scale of NP) $\to$ sets validity of its application.
Retain the **constraining structure of a gauge theory** (**SM**), not true for generic anomalous couplings.

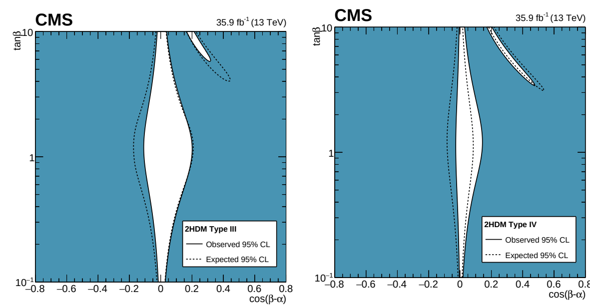
Very complementary approaches

Top-quark and new physics: FCNC and a simple model

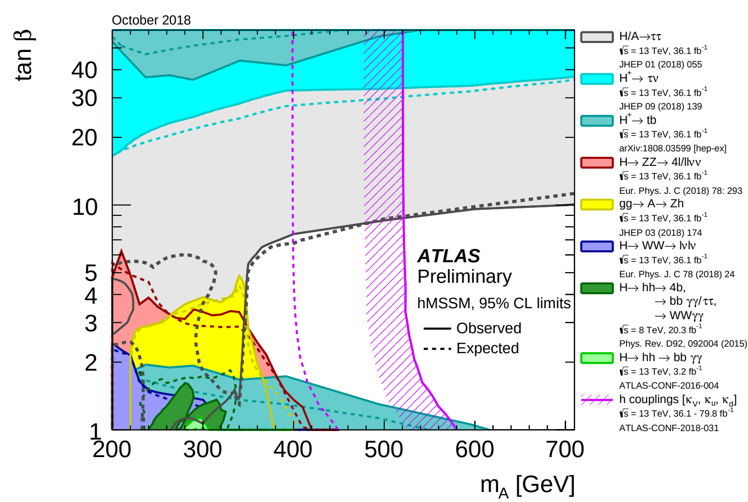
→ see Nuno Castro's talk





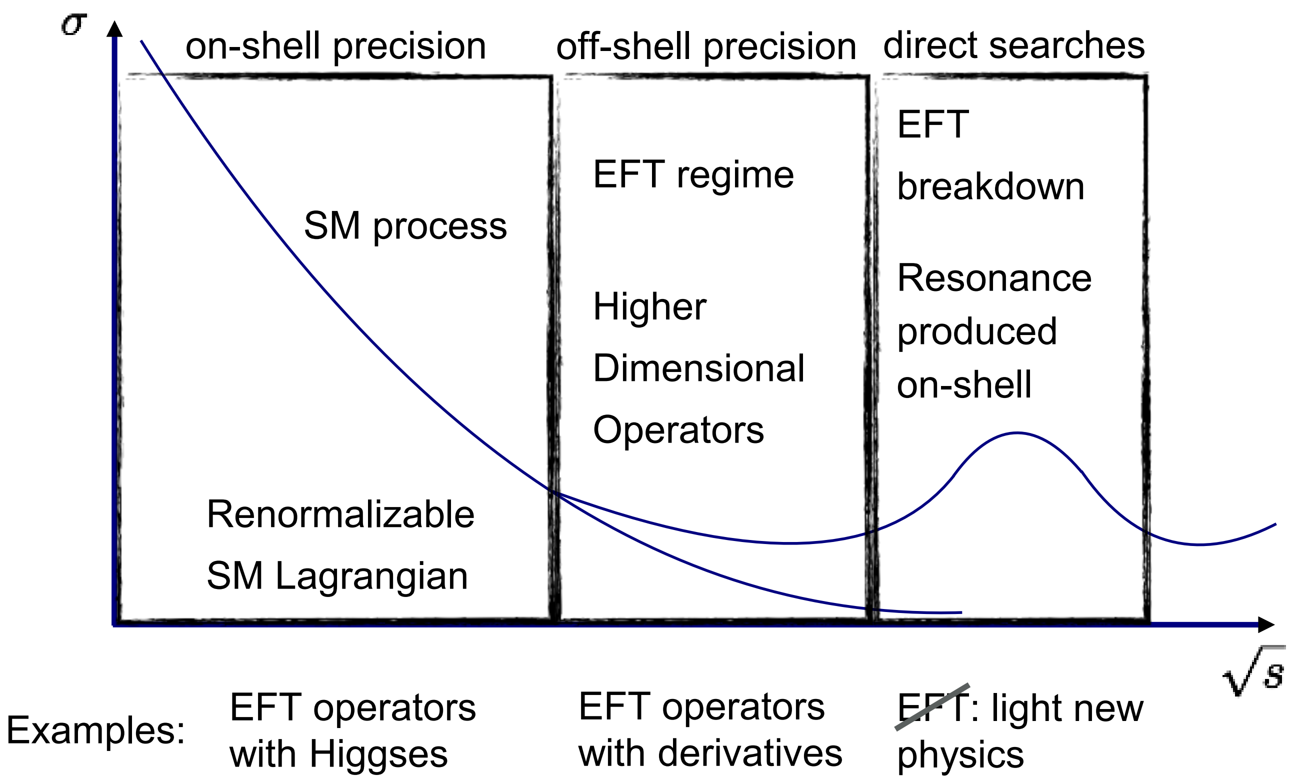


2HDM also probed by dedicated searches ⟹



Alignement scenario: consistent with SM-like Higgs and EWPO.

Top-quark and new physics via SMEFT



[→ see Riccardo Torre's talk]

↪ Small number of operators affect top physics (in first approximation).

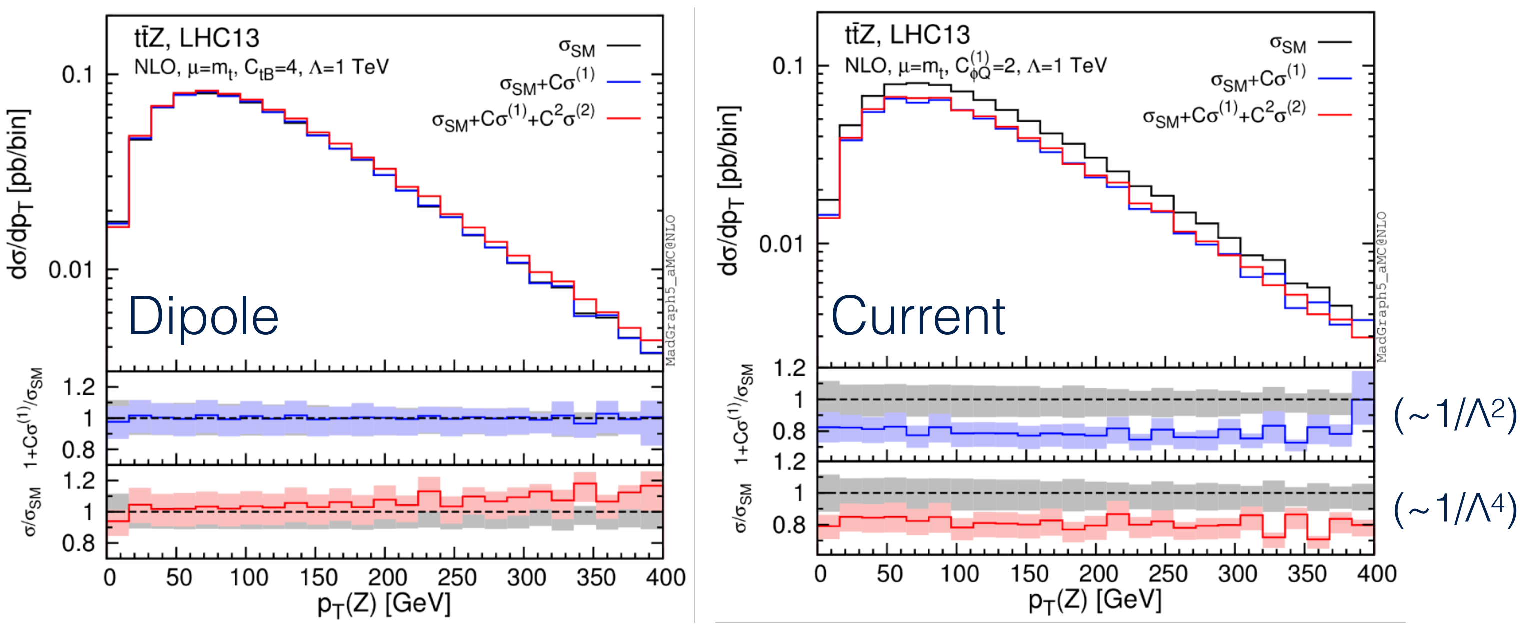
↪ They affect **top-quark** distributions, **Higgs** observables, and **EW precision** observables.

[→ see Ken Mimasu's talk]

Precision SMEFT in tt+V

[Bylund, Maltoni, Tsinikos, Vryonidou, Zhang; JHEP 1605 (2016) 052]

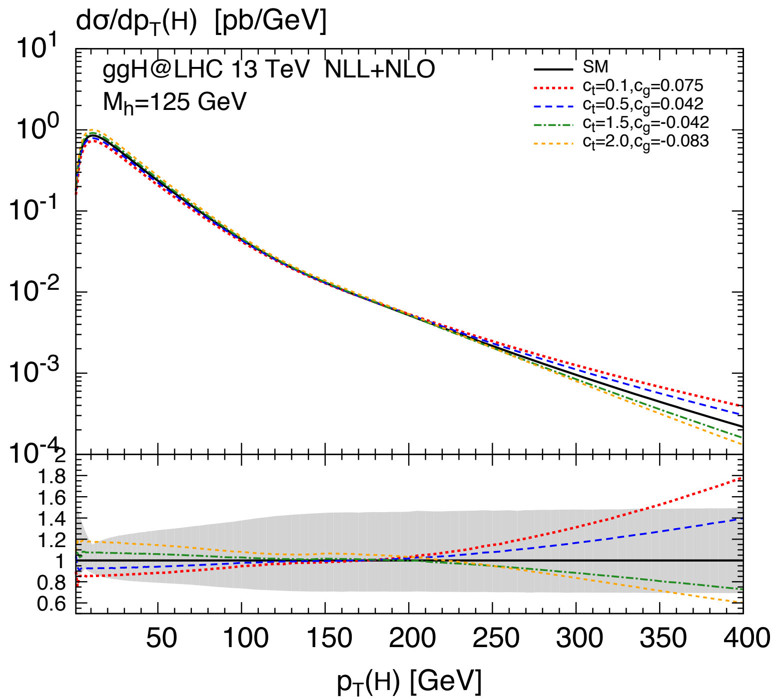
Differential distributions - $P_T(Z)$

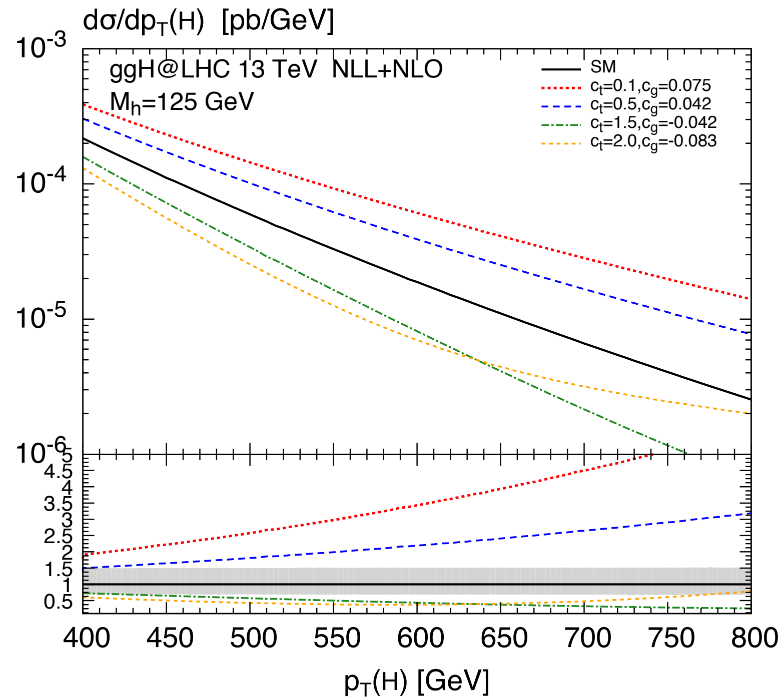


- Dipole operators: interference term suppressed throughout, energy growth for quadratic term - different helicity/polarisation structure from SM
- Current operator: constant behaviour with energy everywhere - rescaling

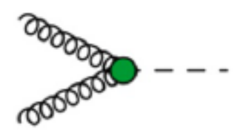
Other important effects: Higgs p_T distribution

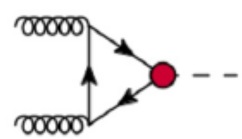
Not visible in the inclusive cross sections, but in the shape of distributions.





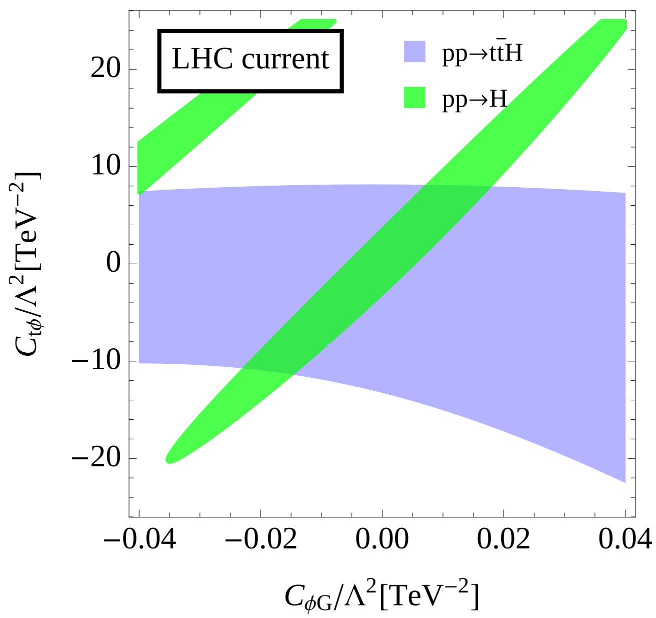
[Grazzini et al., arXiv:1612.00283]

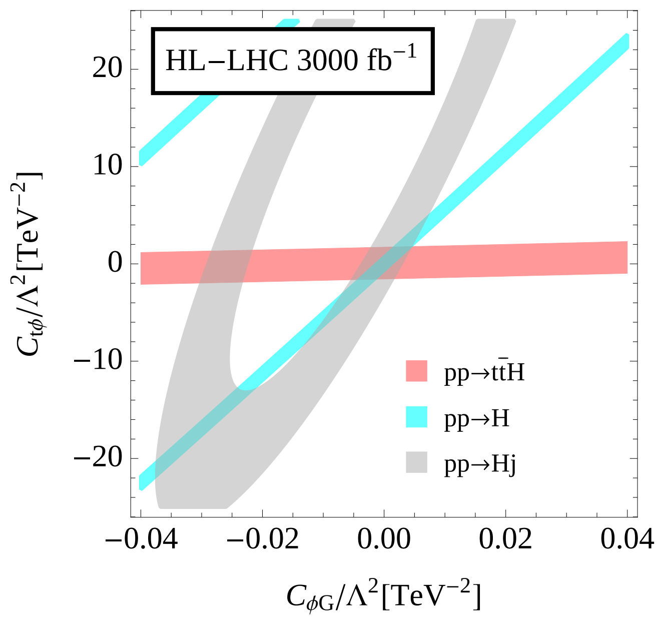
$O_{\phi G} = (\phi^\dagger \phi) G^a_{\mu\nu} G^{a.\mu\nu} \quad \longrightarrow \quad \frac{\alpha_s}{\pi v} c_g \, h G^a_{\mu\nu} G^{a,\mu\nu} \leftarrow$ 

$O_{u\phi} = (\phi^\dagger \phi) \bar{Q}_L u_R \tilde{\phi} \quad \longrightarrow \quad \frac{m_t}{v} c_t \, h t \bar{t} \leftarrow$ 

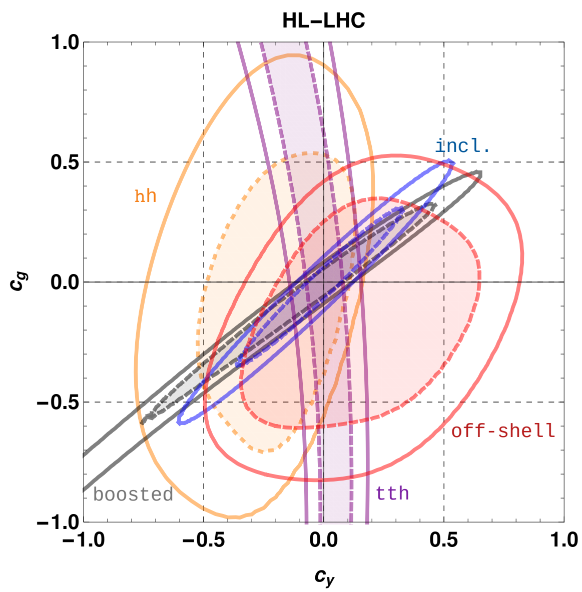
Include $O_{\phi G}$ and $O_{u\phi}$ in NLO+NLL computation: **simultaneous effects of two or more operators affects high-energy tail of the spectrum**.

More: probing the gluon-Higgs vs top-Higgs interactions





[Maltoni et al., arXiv:1607.05330]



Combining:

inclusive H

ttH

HH

boosted H

off-shell H

[Azatov et al., arXiv:1608.00977]

No summary needed for a Summary Talk!

Thank you!!

to the organizers and all the participants