Theory summary - TOP2023

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16th International Workshop on Top Quark Physics TOP2023

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Disclaimer

This talk is my view from the "top", not necessarily anyone else's

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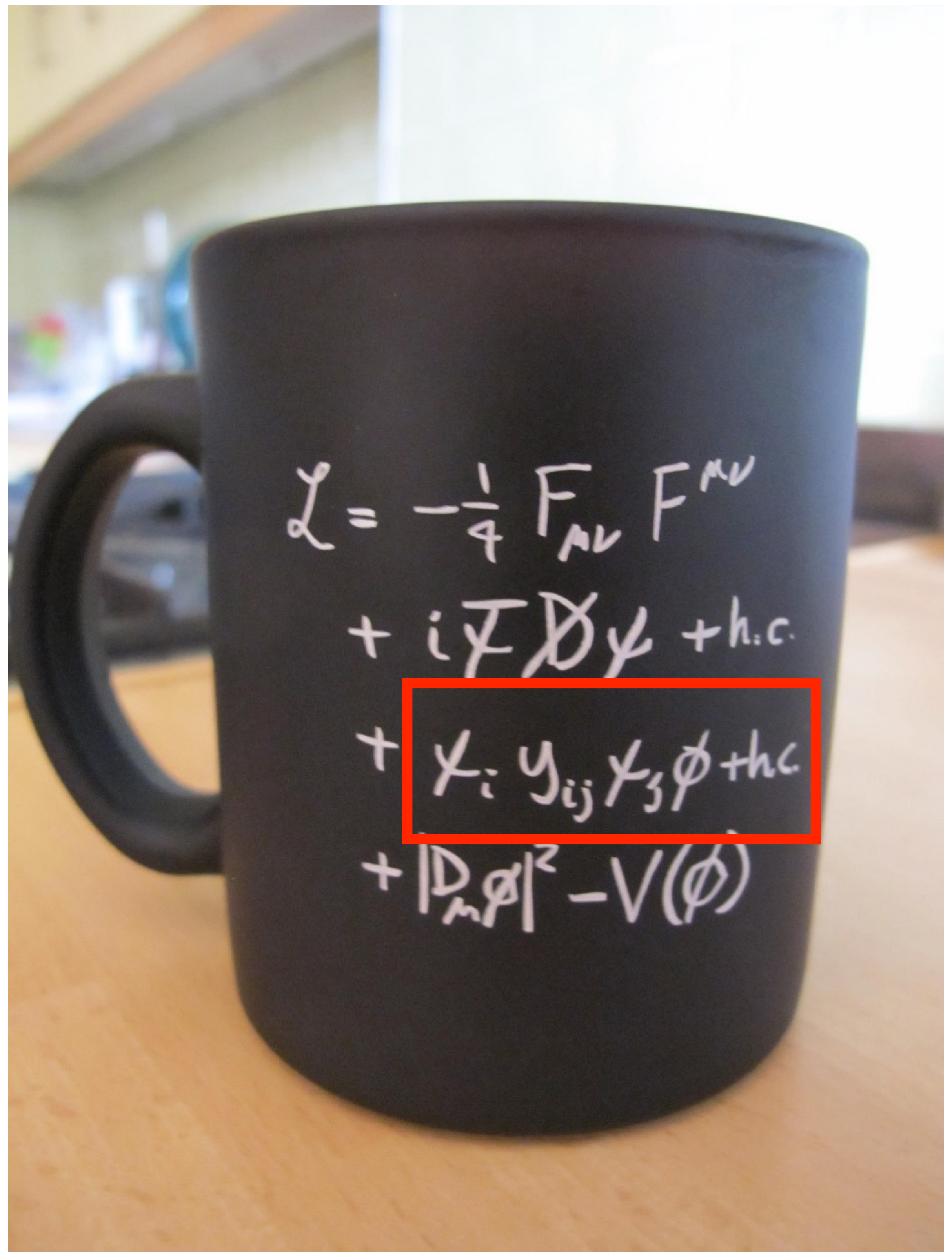
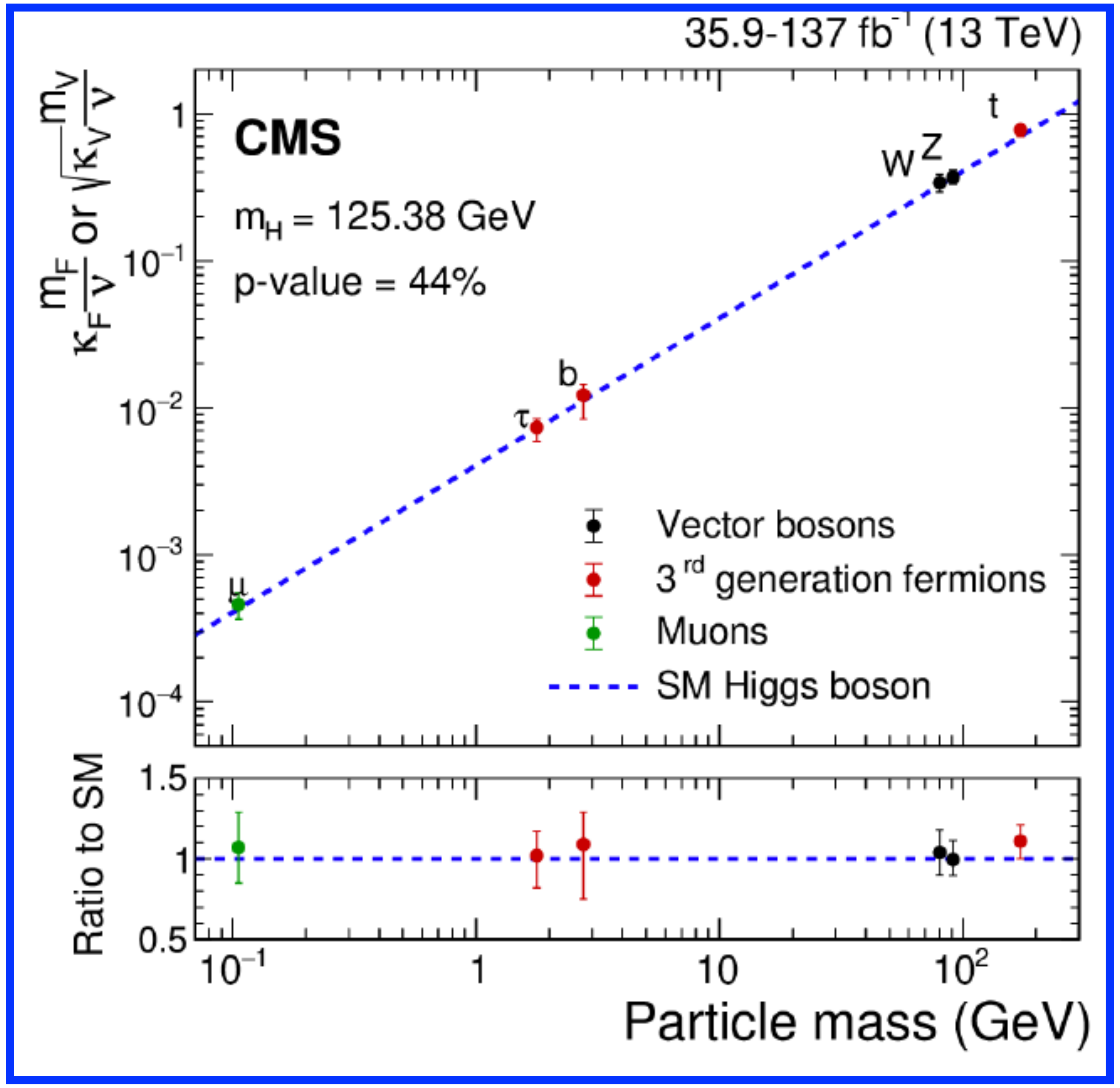
The special role of the top quark

- The top quark has the largest mass of all the elementary particles. In the Standard Model the top quark is therefore predicted to have the largest Yukawa coupling to the Higgs boson, a prediction which is confirmed experimentally by ATLAS and CMS.



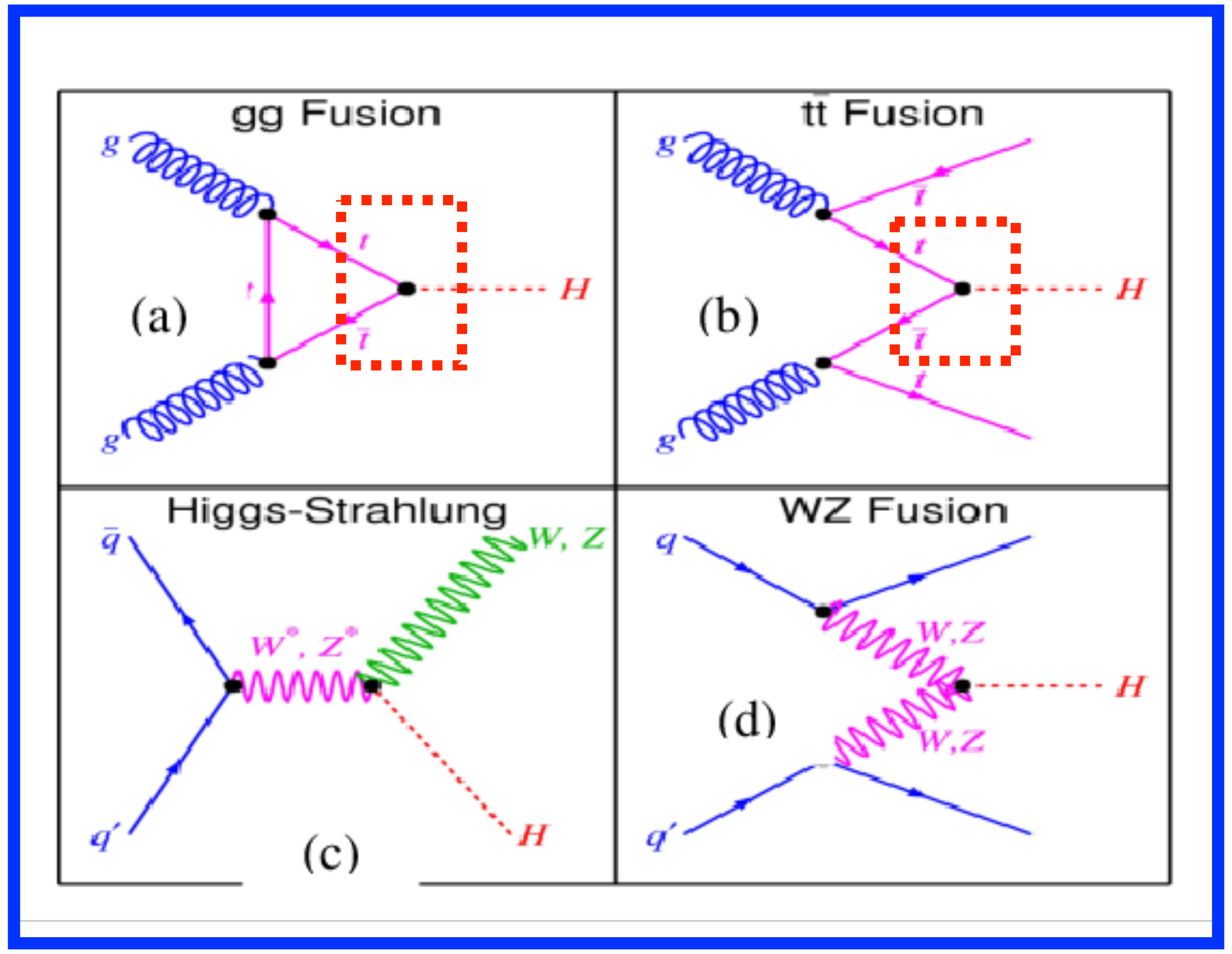
$$\phi = \frac{1}{\sqrt{2}}(v + H))$$

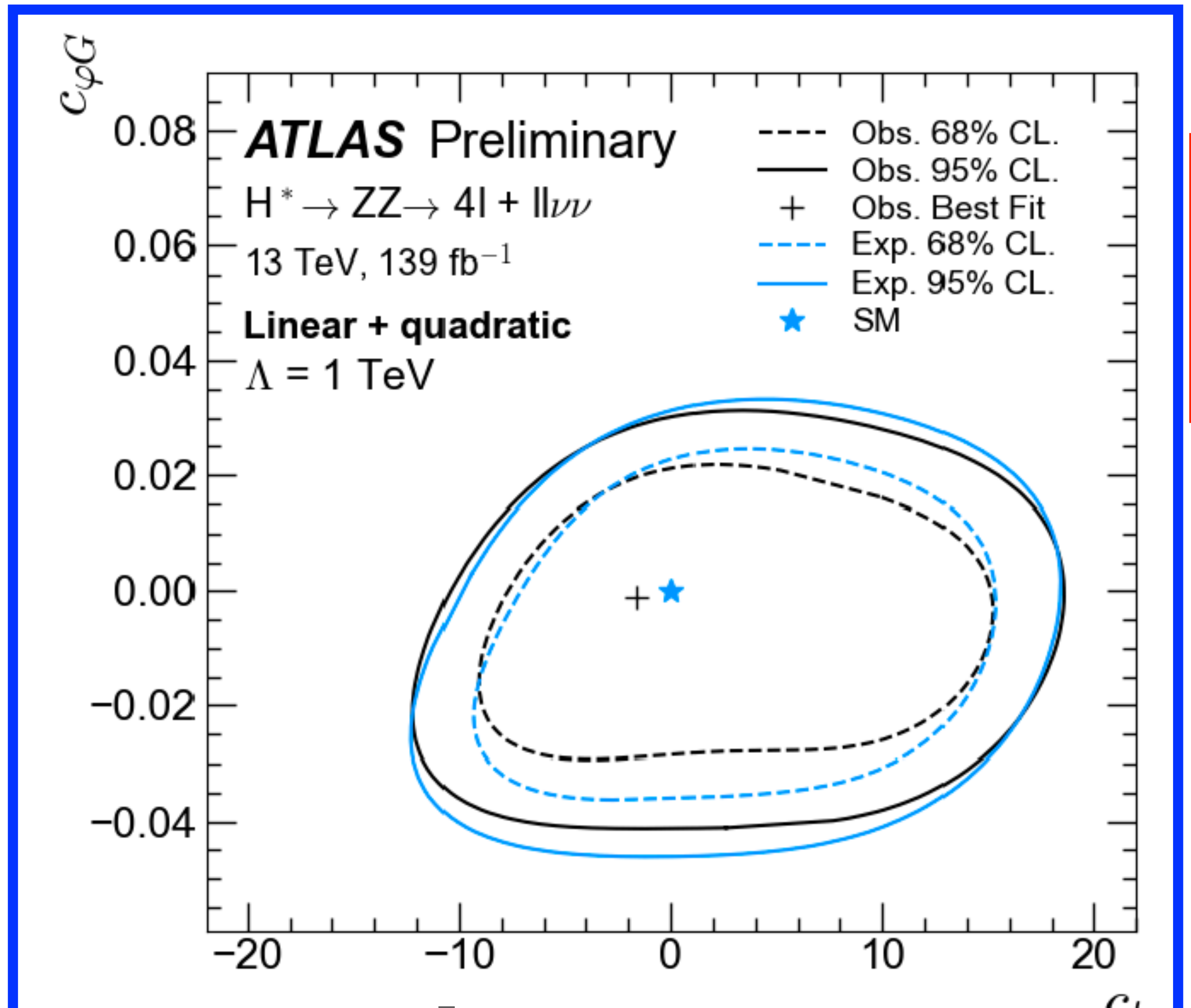
This expansion connects fermion masses and their Yukawa couplings



The top quark and the Higgs boson

- This large coupling of the top quark to the Higgs boson drives much of Higgs phenomenology at the LHC:
  - Nearly 90% of the Higgs production cross section comes from gluon-fusion production which is dominated by top-quark loops.
  - The ttH associated production mode is driven by the coupling as well.
  - The H→γγ discovery decay channel receives important contributions from top-quark loops as well.





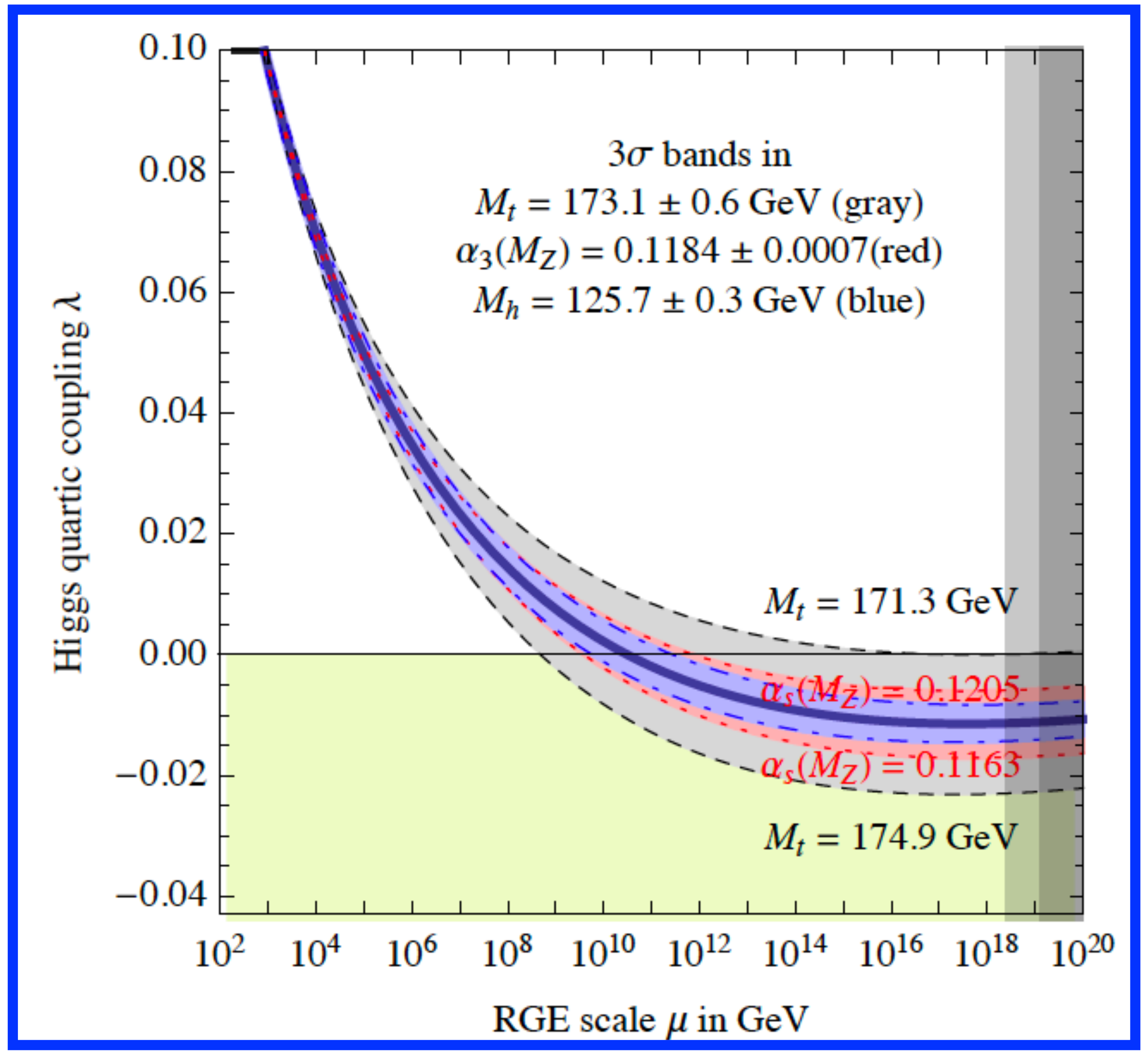
SM BSM

$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

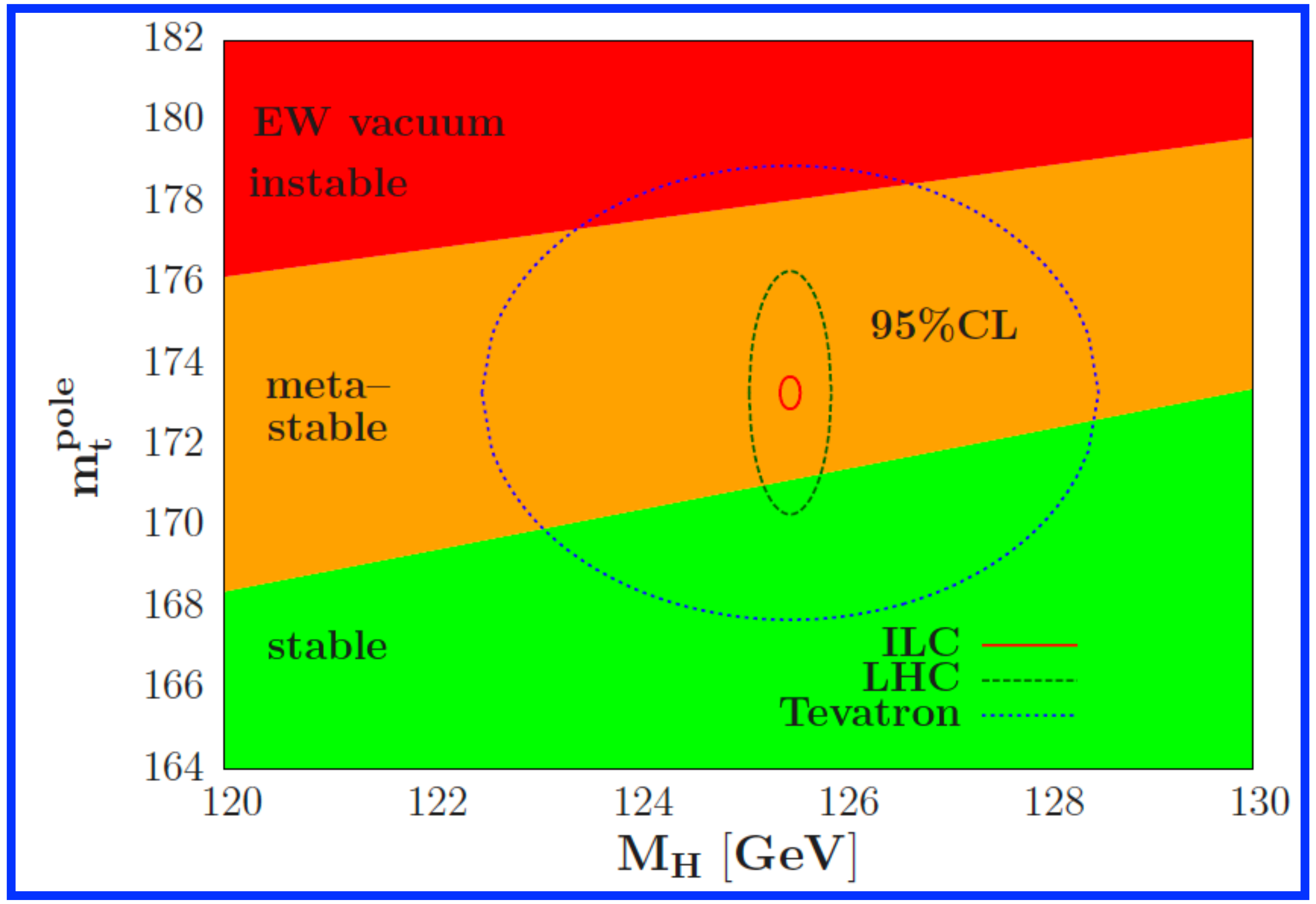
The loop-induced nature of this process makes it an excellent place to search for SM deviations within an EFT framework.

The top quark and the fate of the universe

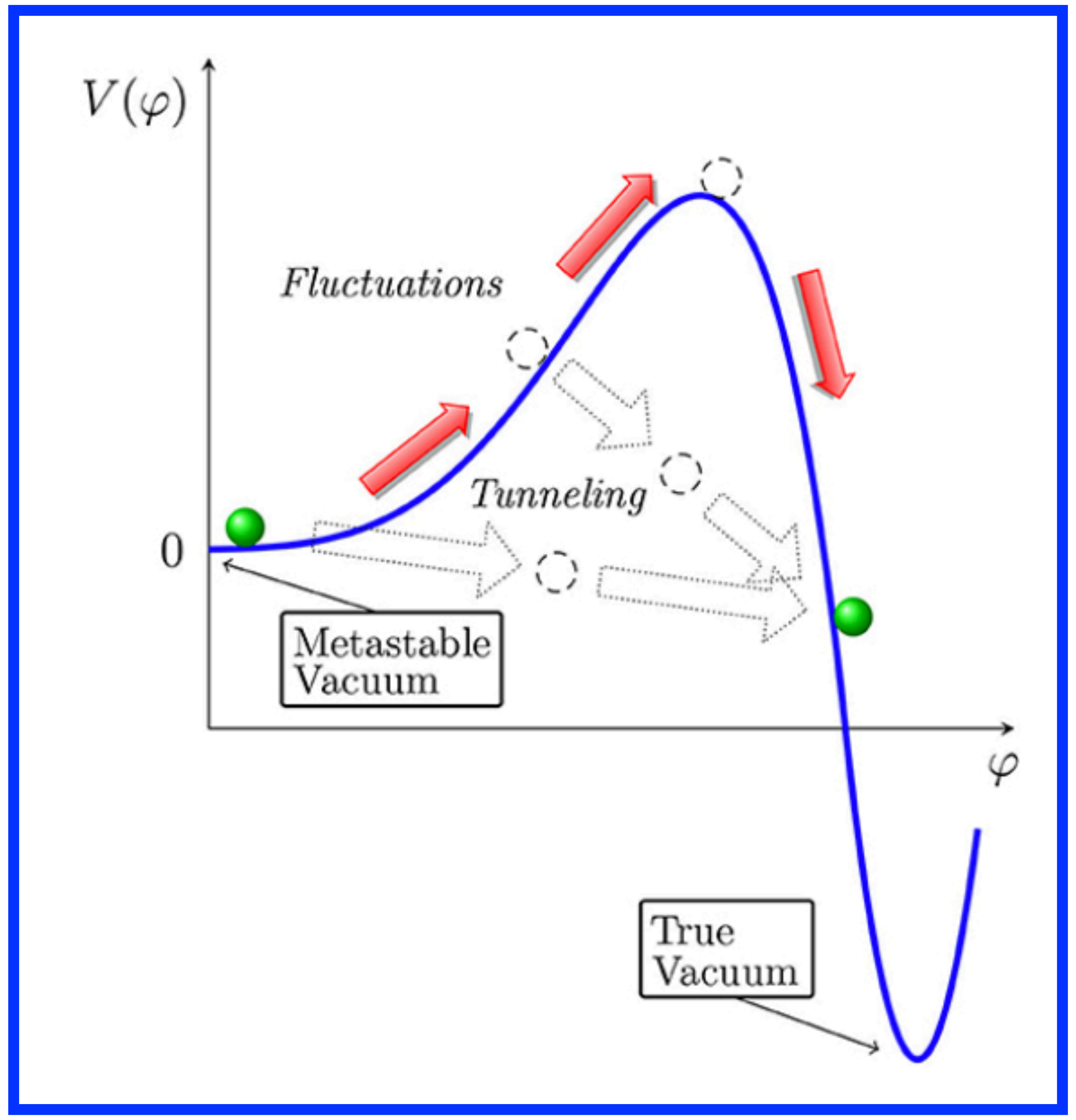
- The mass of the top quark is also connected to fundamental questions such as the ultimate fate of our universe. RG evolution in the SM can potentially drive the Higgs quartic coupling negative, indicating that the SM vacuum may eventually decay. The exact mass of the top quark plays an important role in determining whether our universe is stable or "meta-stable" (which means it will eventually decay through a quantum tunneling process).



Degrassi et al (2012)



Alekhin, Djouadi, Moch (2012)



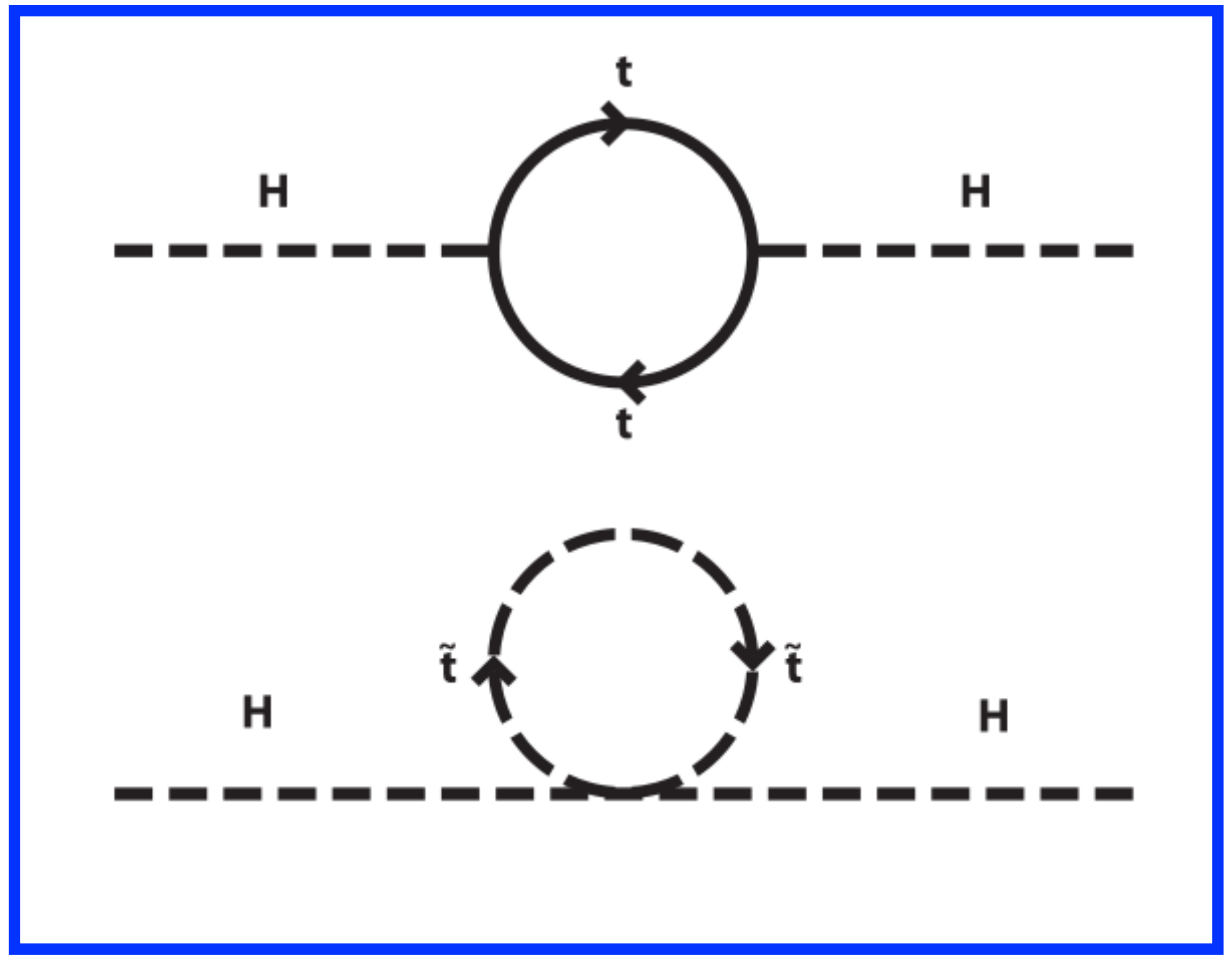
See also G. Perez's talk

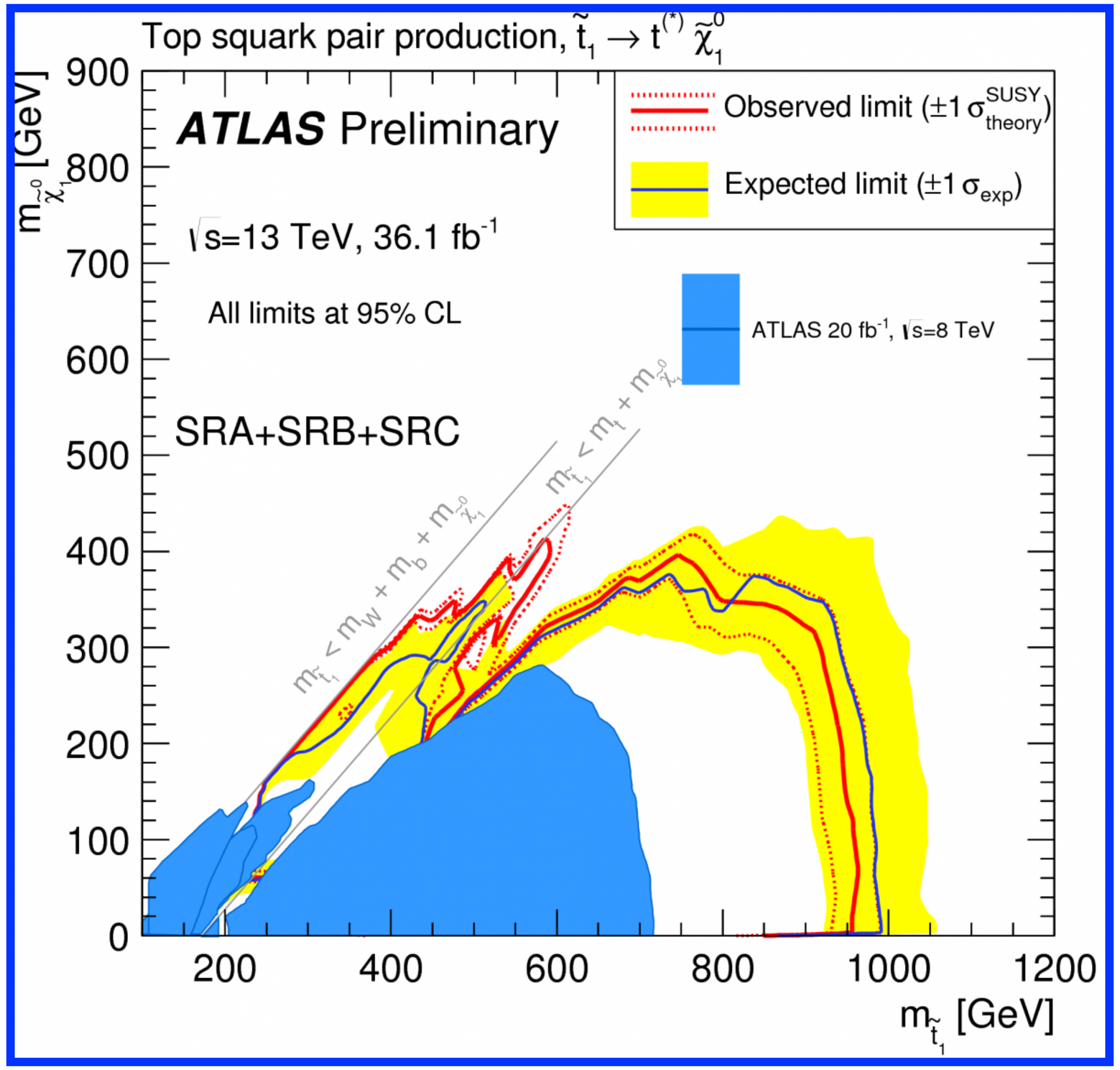
The top quark and the hierarchy problem

- The large mass of the top quark leads to its outsized role in the hierarchy problem: the attempt to understand why the electroweak scale is so much less than the Planck scale. The attempt to find “top-quark partners” that cancel the quadratic contribution of the top quark to the electroweak scale has driven much of HEP theory for the past decades, and motivates supersymmetry, Little Higgs models, and a host of other ideas.

$$\Delta m_{\mathrm{H}}^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots]$$

The attempt to cancel this correction leads to:





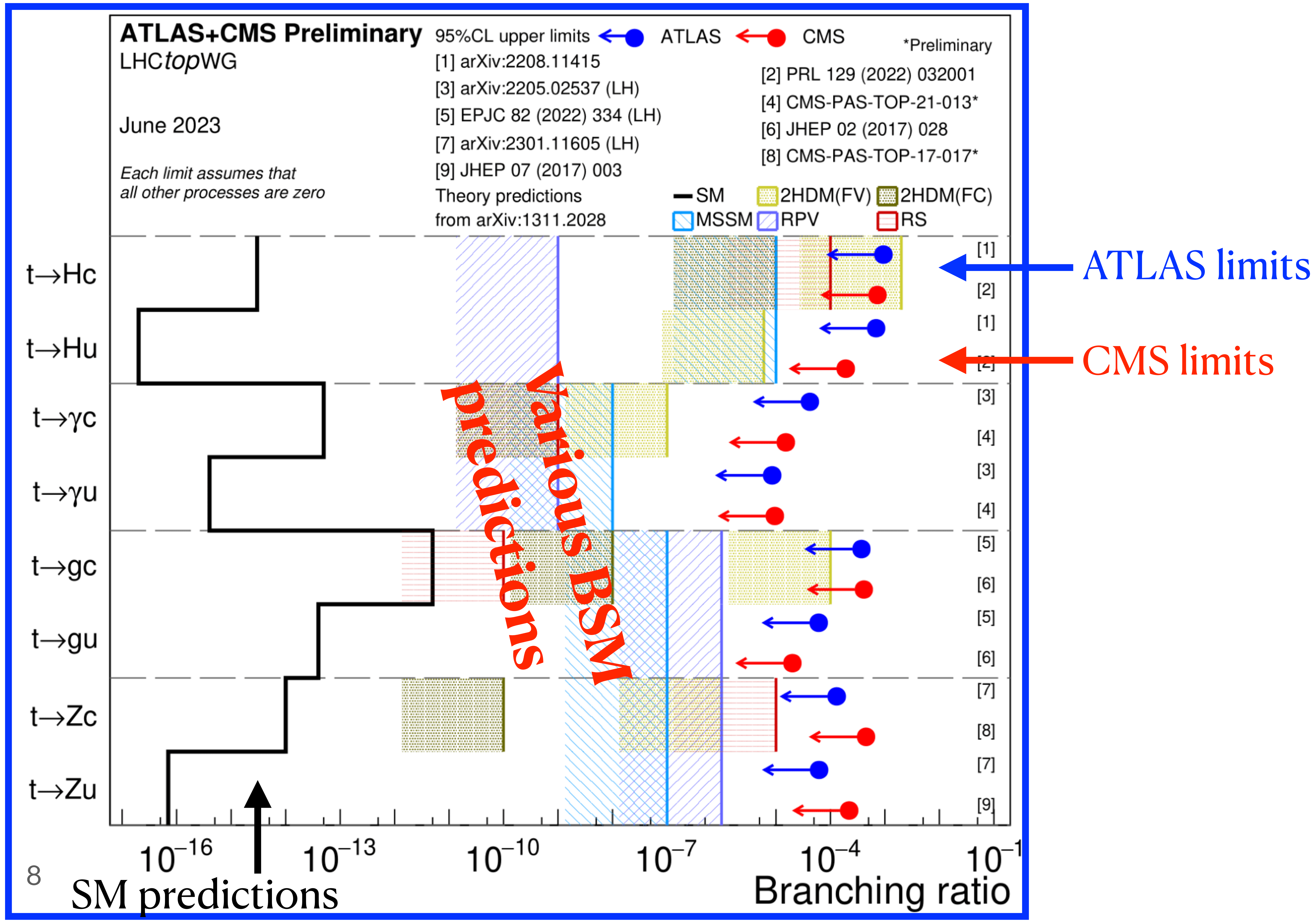
Top quark properties: decays

- The top-quark width is larger than Λ_{QCD}, and it therefore decays before hadronization. It is therefore the only quark that doesn't hadronize, and offers the unique opportunity to observed properties of a "bare" quark.

  - The top quark decays almost entirely through the parton-level process $t \to Wb$. Other decays are suppressed within the SM.

  - The other decay modes can be significantly enhanced in BSM models with flavor-changing neutral currents, and there is an active program to search for such decays.

See also talks by Pavol Bartos (ATLAS) and Tae Jeong Kim (CMS)



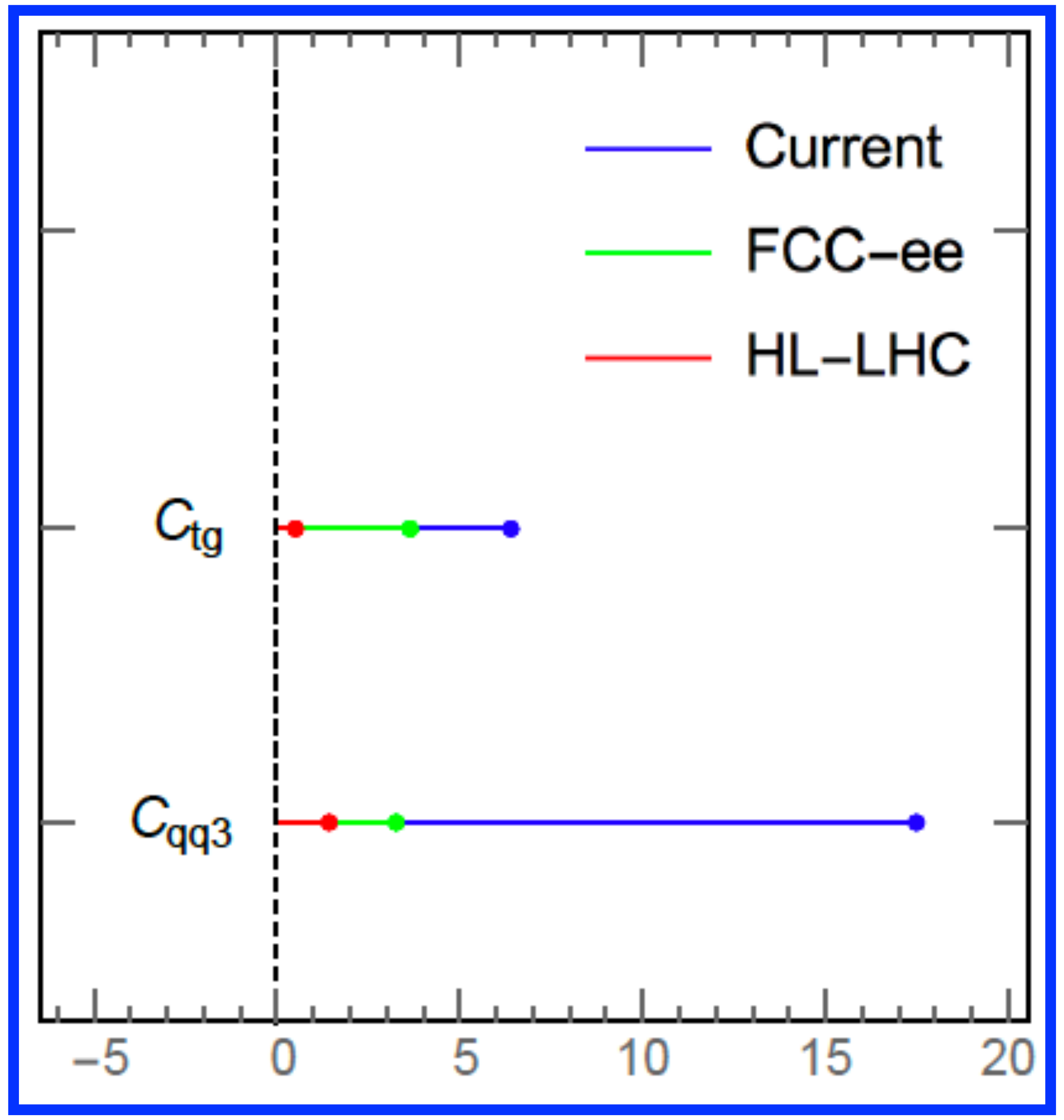
Top quark properties: decays

- The helicity of the W-boson in top-quark decays can be computed with great accuracy in the SM, and can provide strong constraints on new physics. Can parameterize new physics with EFT and constrain operators that appear only at the loop level.

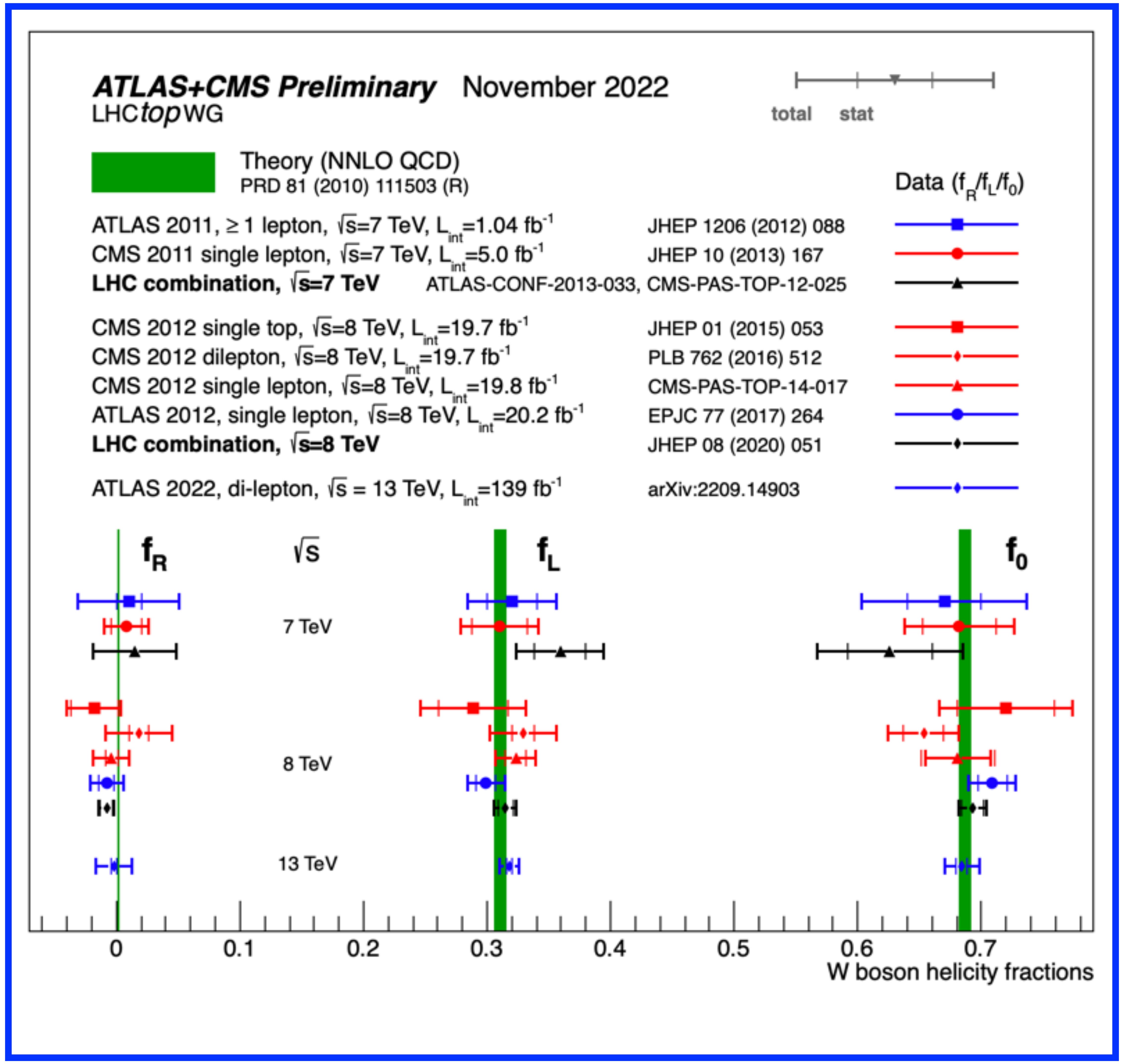
Constraints from total width and helicity fractions currently, and from future experiments, on the operators:

$$\mathcal{O}_{tg} = \bar{t}\sigma^{\mu\nu}T^A t\tilde{\phi}G^A_{\mu\nu}$$

$$\mathcal{O}^{(3)}_{qq} = (\bar{t}\gamma^\mu\tau^a t)(\bar{t}\gamma_\mu\tau^a t)$$



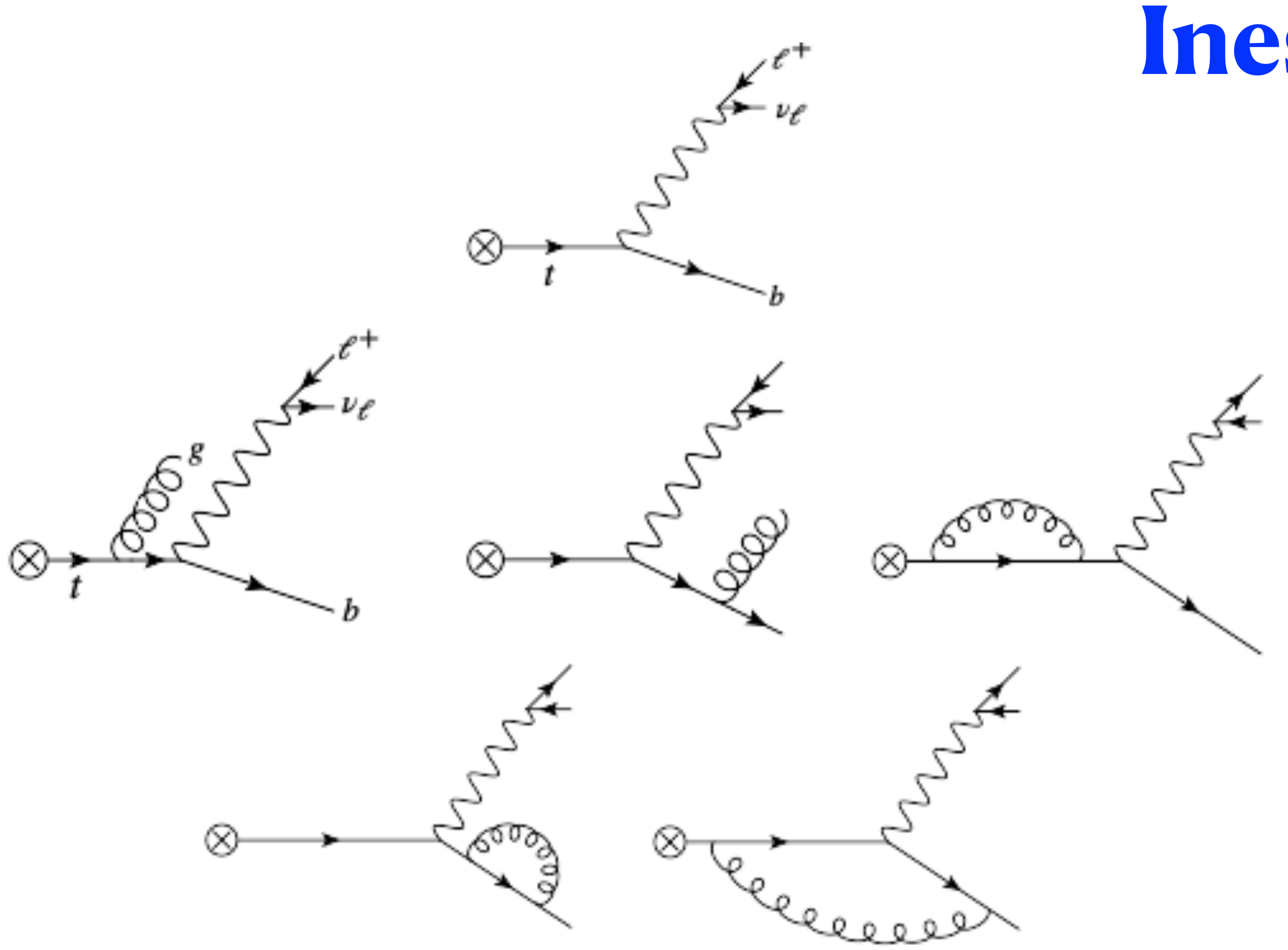
RB et al (2019)



Beyond the narrow-width limit for off-shell and boosted differential top quark decays

Ines Ruffa

- We are investigating the decay of boosted top quarks.
- Common approaches in FOPT:
  - Narrow-width (NW) limit: Factorisation of top production and decay, top on-shell limit, state-of-the-art: NNLO QCD [Catani, S. et al., JHEP 07, 100 (2019)].
  - Off-shell fixed-order: includes finite life-time effects, non-resonant and non-factorisable corrections, state-of-the-art: NLO QCD.

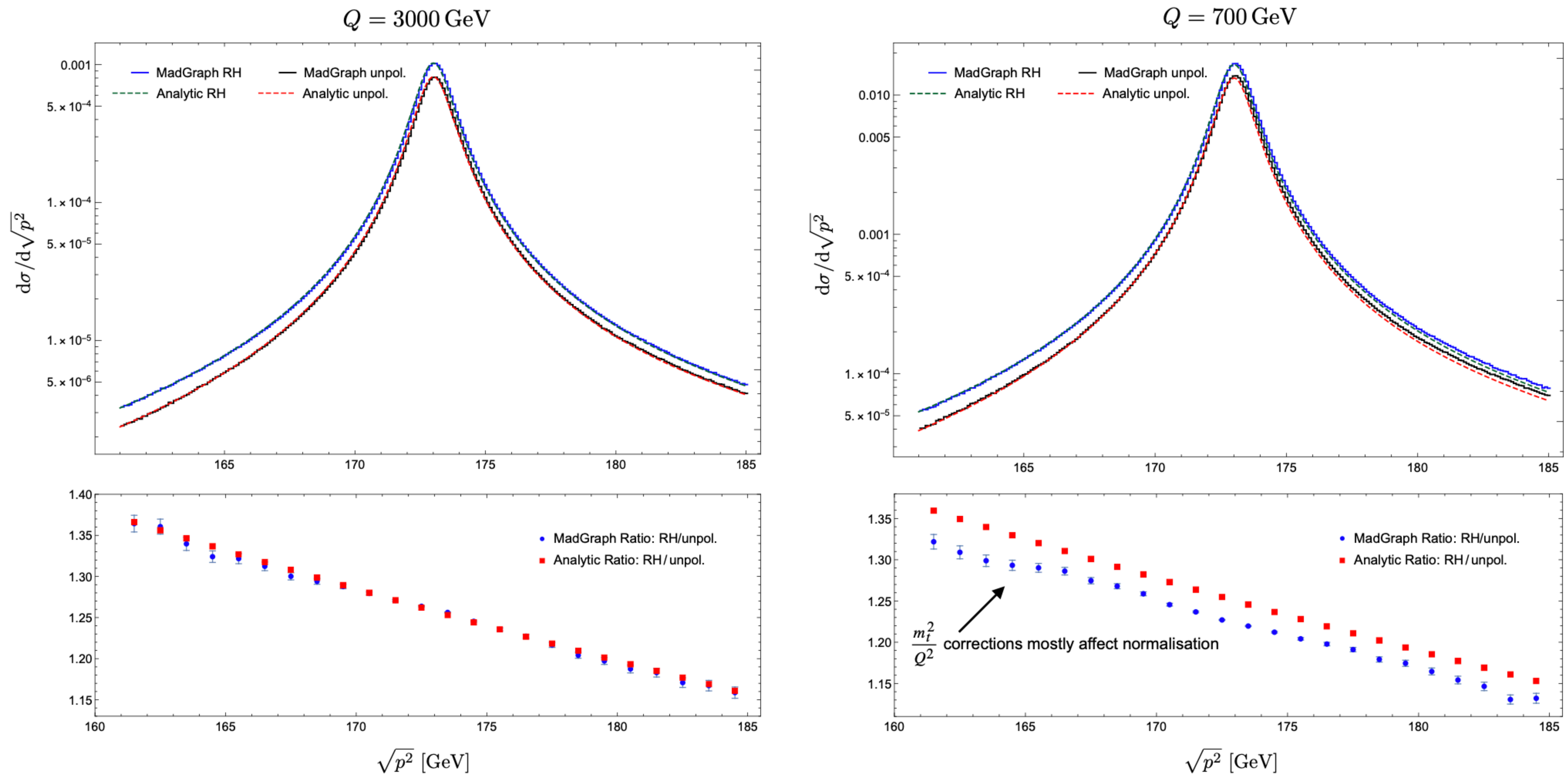


- Our approach: Combine factorisation property of NW-limit with full off-shell calculation (expansion in m_t^2/Q^2).
  - Factorised approach for boosted top quarks, allows for gauge-invariant description of off-shell effects within effective field theory framework of soft-collinear effective theory (SCET).
  - Account for resummed QCD corrections for differential top decay observables.
  - Universal form of off-shell top decay and collinear gluon radiative effects.

Beyond the narrow-width limit for off-shell and boosted differential top quark decays

Compare our result to common fixed-order approach given by MadGraph† for $e^+e^- \to bW^+\bar{t}$ with $p^2 = (p_b + p_w)^2$:

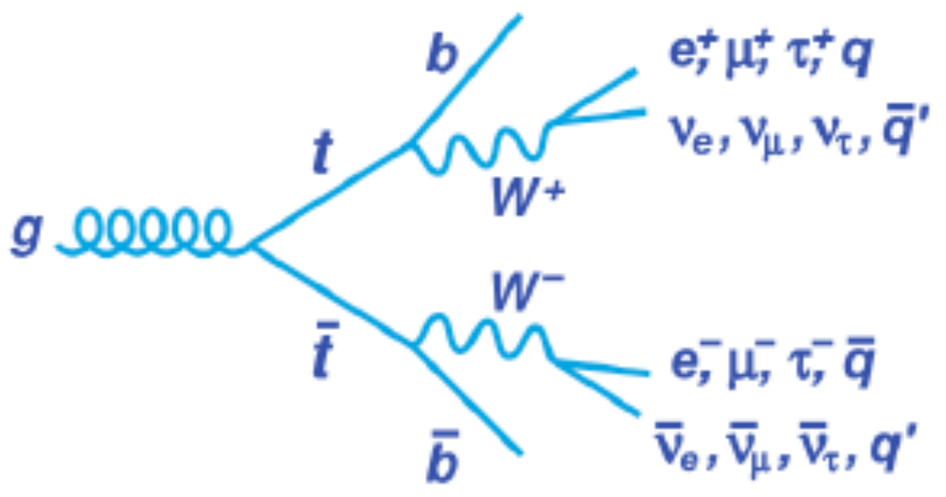
Ines Ruffa

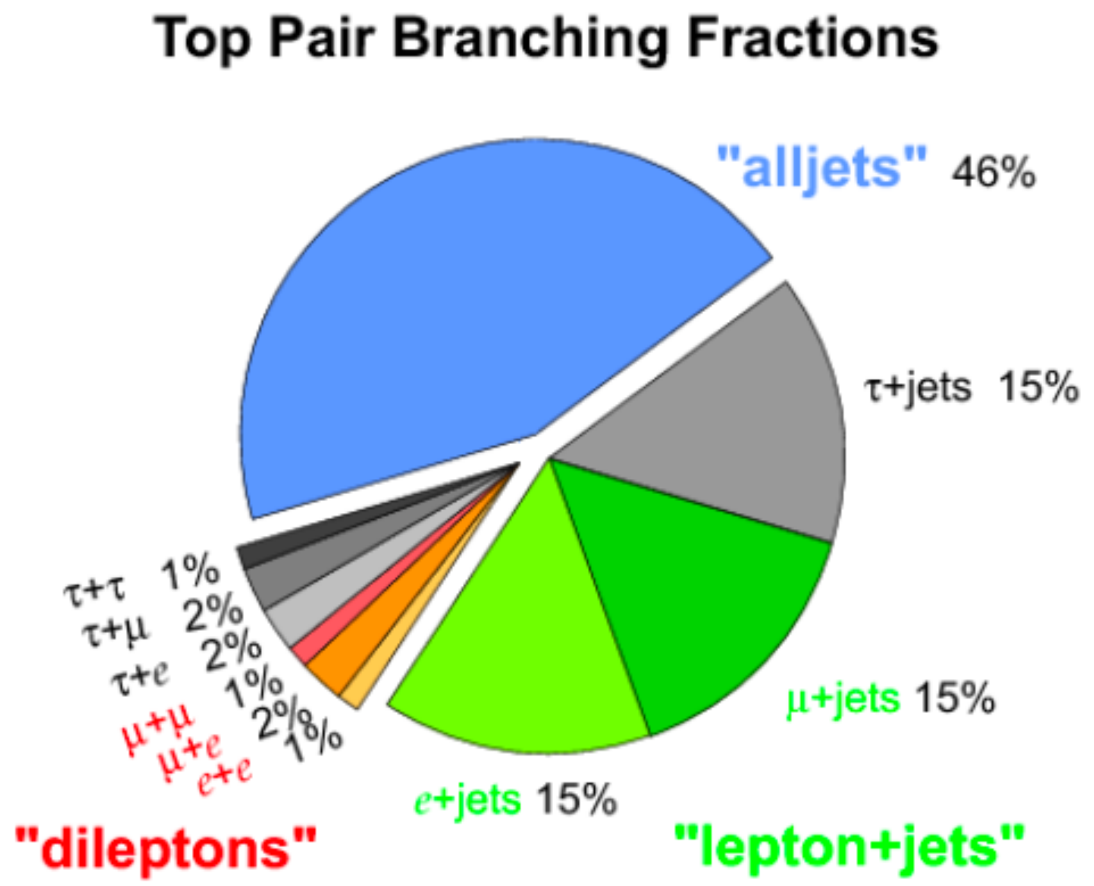


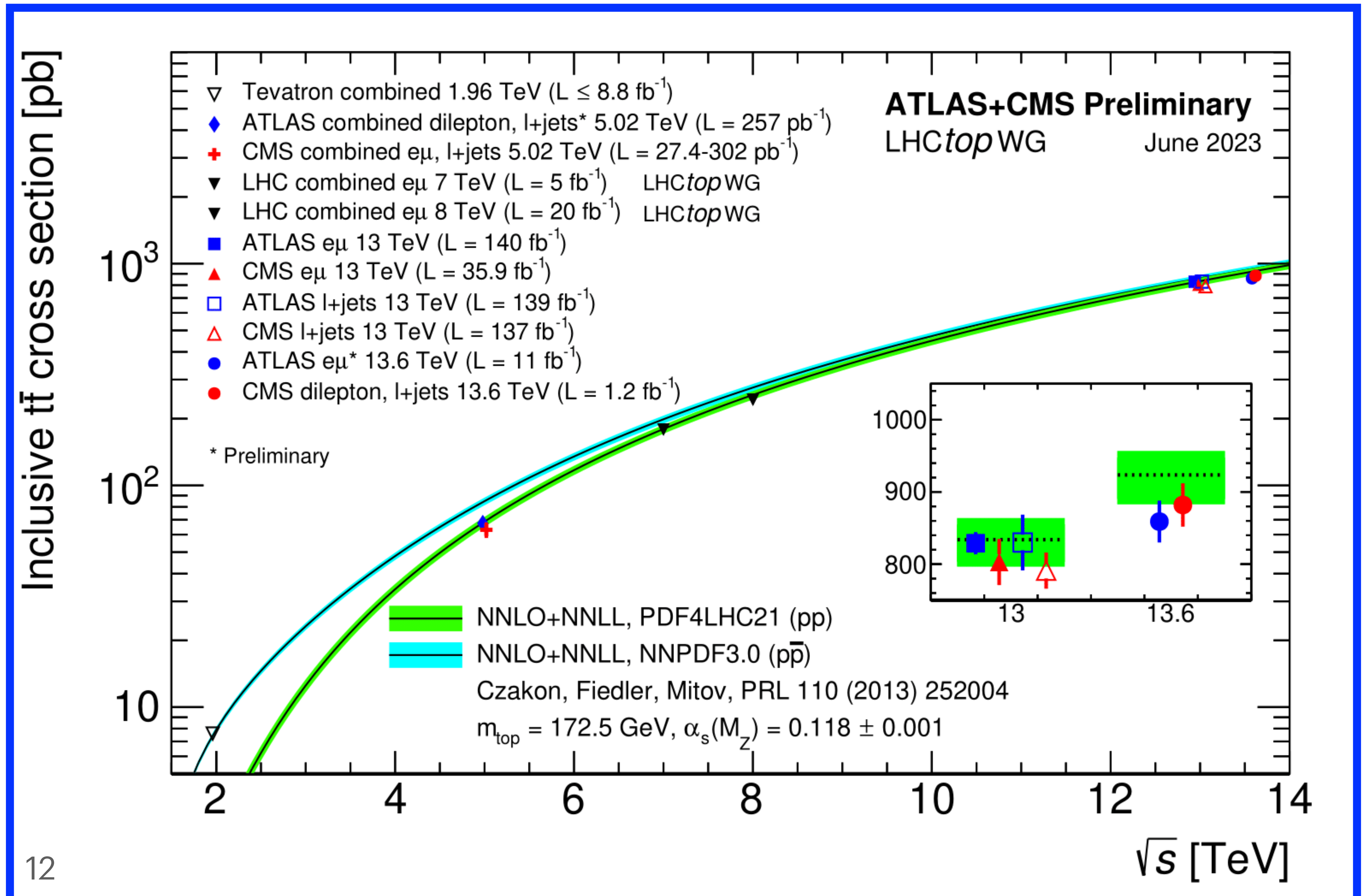
Analytic calculation of the top peak region shows good agreement with MadGraph, with power corrections in mt^2/Q^2 having some effect on the normalization

Top quark properties: production

- The top quark is predominantly pair produced at the LHC. The three broad categories of final state are di-lepton, lepton+jets, and fully hadronic.
- The cross section has been computed through NNLO in perturbative QCD, and the NNLL resummation of large threshold logarithms has been performed for ttbar inclusive cross section and for top-quark differential distributions. Results overall are in good agreement with experimental measurements in multiple modes.







Simultaneous CTEQ-Tea extraction of PDFs and SMEFT parameters from jet and tt data

Tim Hobbs

Precision predictions require a precise determination of PDFs

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i O_i^{(6)}}{\Lambda^2} + \ldots$$

- EFT global analyses often assumed *fixed* SM calculations
  - → PDFs not actively fitted alongside SMEFT parameters
  - → could potentially bias resulting SMEFT analysis
- solution: develop **joint SMEFT/PDF fits** (field at early stage)
  - → this work: example in context of CTEQ-TEA (CT) framework
  - → demonstration study focusing on select data: jet, $t\bar{t}$ production
  - → examine possible PDF-SMEFT correlations

jet production: contact interaction

$$O_1 = 2\pi \left(\sum_{i=1}^{3} \bar{q}_{Li}\gamma_\mu q_{Li}\right)\left(\sum_{j=1}^{3} \bar{q}_{Lj}\gamma^\mu q_{Lj}\right)$$

Warsaw operator basis

top production

$$O_{tu}^1 = \sum_{i=1}^{2} (\bar{t}\gamma_\mu t)\,(\bar{u}_i\gamma^\mu u_i)\,,$$

$$O_{td}^1 = \sum_{i=1}^{3} (\bar{t}\gamma^\mu t)\,(\bar{d}_i\gamma_\mu d_i)\,,$$

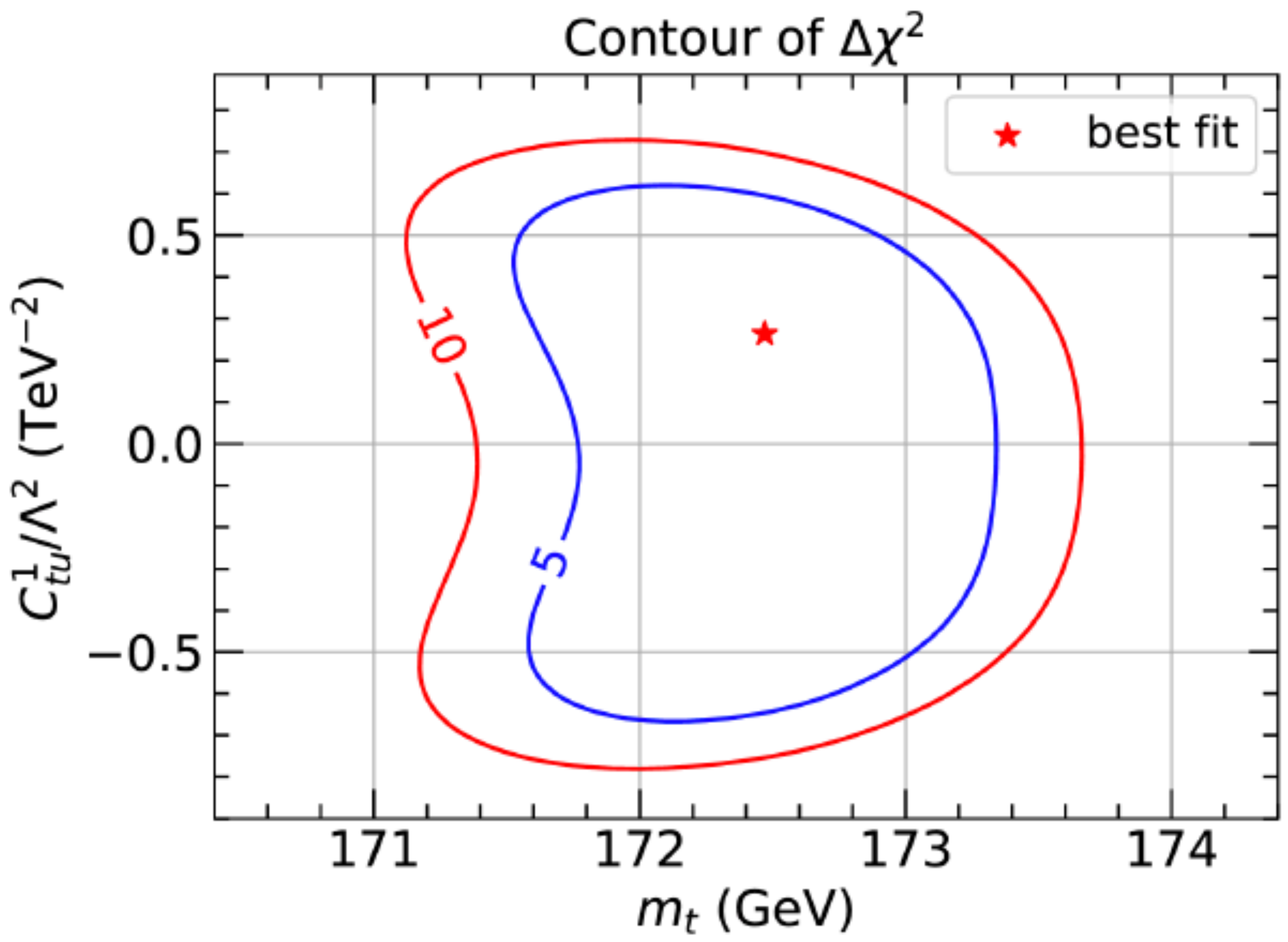
$$O_{tG} = ig_s(\bar{Q}_{L,3}\tau^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} + \text{h.c.}\,,$$

$$O_{tq}^8 = \sum_{i=1}^{2} (\bar{Q}_i\gamma_\mu T^A Q_i)(\bar{t}\gamma^\mu T^A t)\,,$$

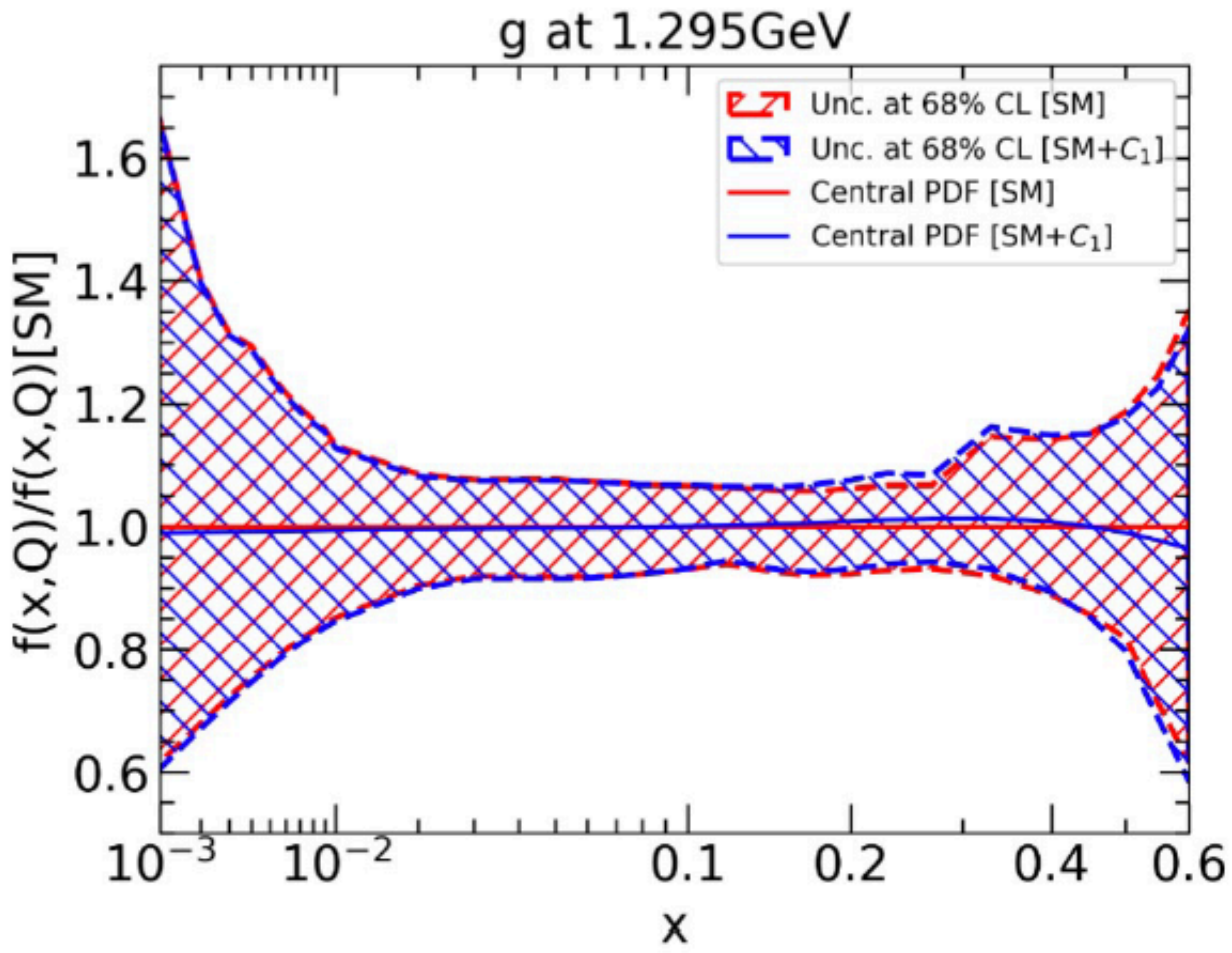
Simultaneous CTEQ-Tea extraction of PDFs and SMEFT parameters from jet and tt data

Tim Hobbs

- The joint fit within the CTEQ-Tea framework finds some correlations between SM parameters and SMEFT Wilson coefficients. However, with current data the impact of SMEFT on the fitted PDFs is minimal.



Best fit mass essentially unshifted when fitted along side EFT, but the allowed region of m_t changes as C_{tu} is varied



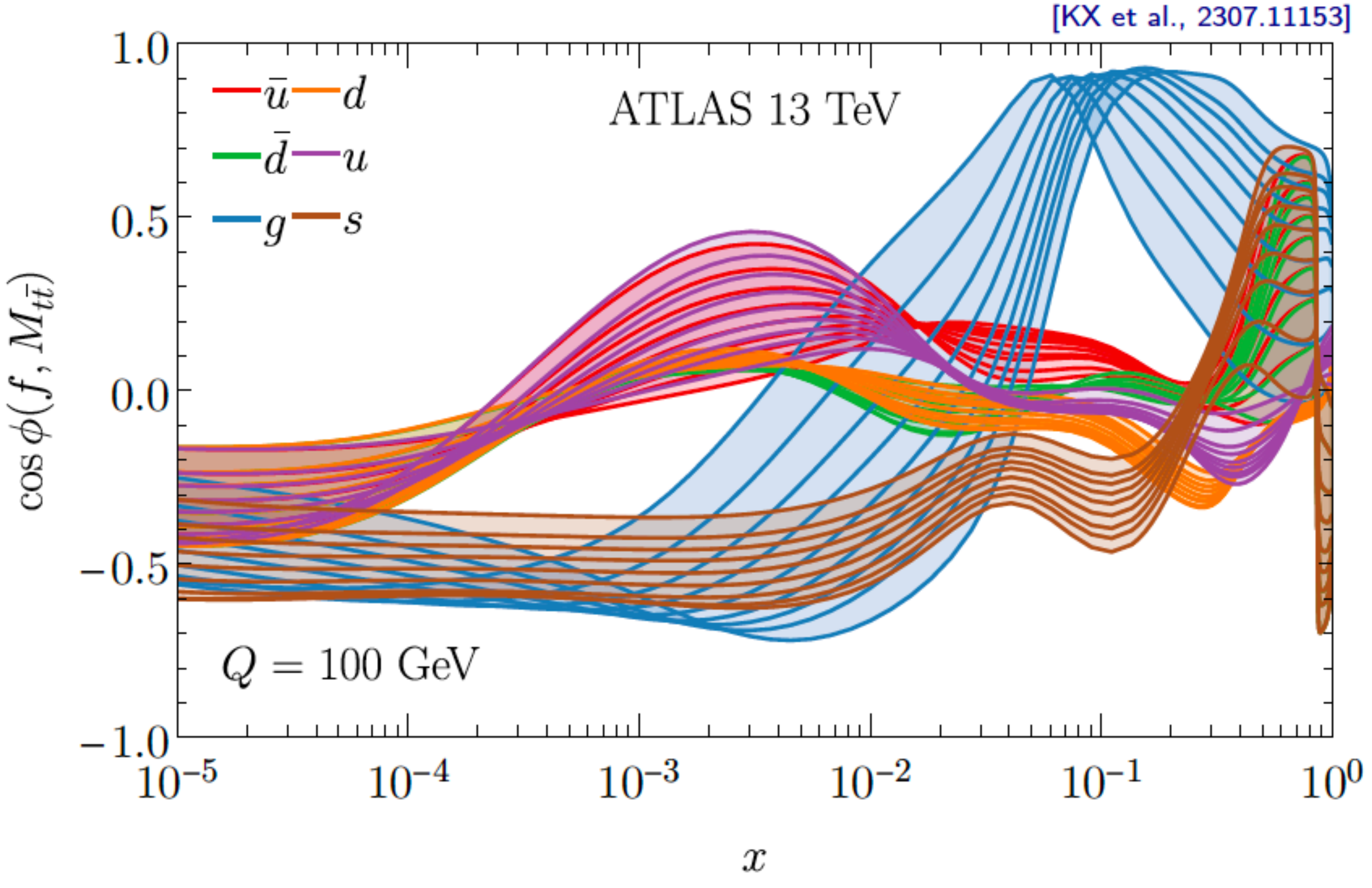
Small variation in gluon PDFs, unc., from co-fitting SMEFT

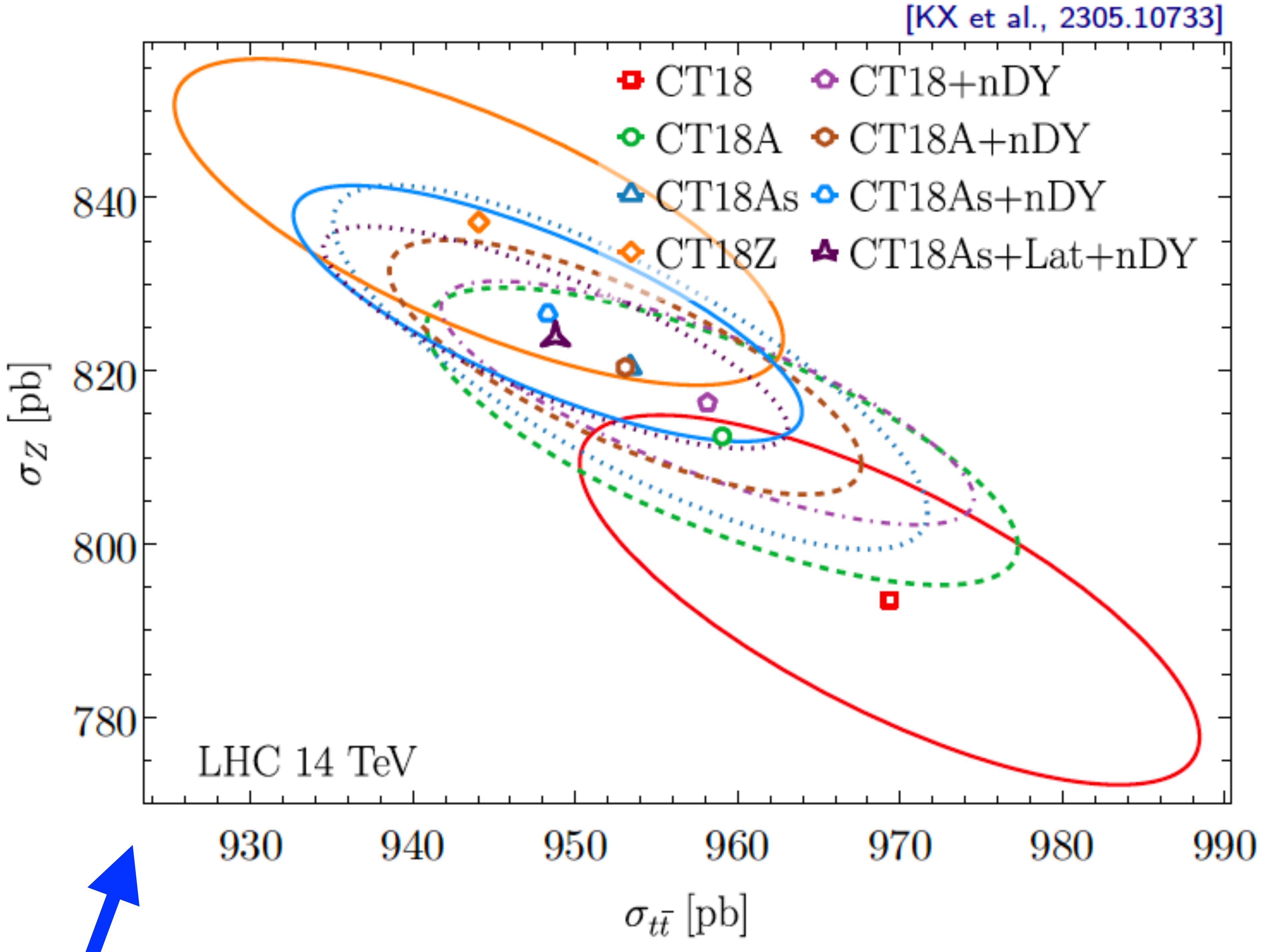
Further investigations are needed with future high luminosity LHC data!

PDFs from future colliders for precision physics

Connection to the top pair production

Keping Xie





- Top quark pair cross section is largely correlated with gluon PDF at large $x(\sim M_{t\bar{t}}/\sqrt{s})$ at LHC
- Inputs from future colliders for the large-x gluon can both shift central value and shrink uncertainty.
- More extensive studies are needed

More input from future colliders is needed for PDF fits to bring the top quark cross section uncertainty down to the percent level precision benchmark.

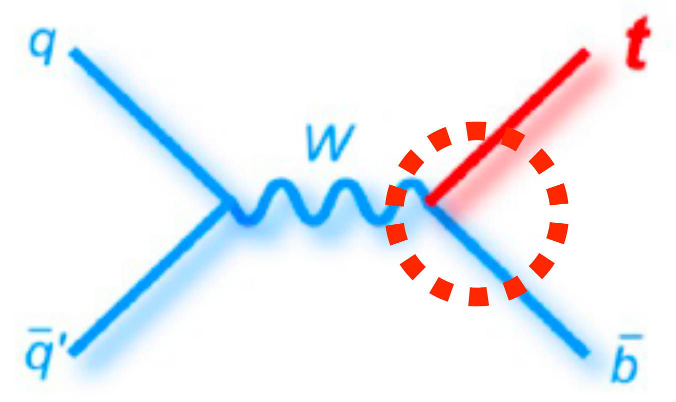
Top quark properties: single top

- Single-top production is directly sensitive to the CKM matrix element V_{tb}. This provides a cross check of the lower bound obtained by searching for non b-tagged top decays at the LHC and the Tevatron:

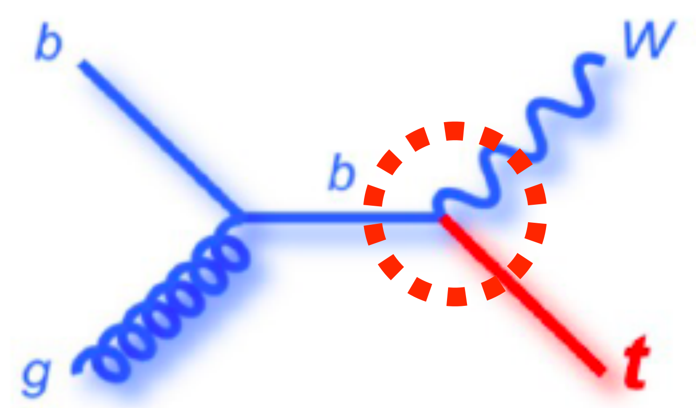
$$R = \frac{B(t \to Wb)}{\sum_q B(t \to Wq)} = \frac{|V_{tb}|^2}{\sum_q |V_{tq}|^2} \to |V_{tb}| > 0.975$$

(from the PDG)

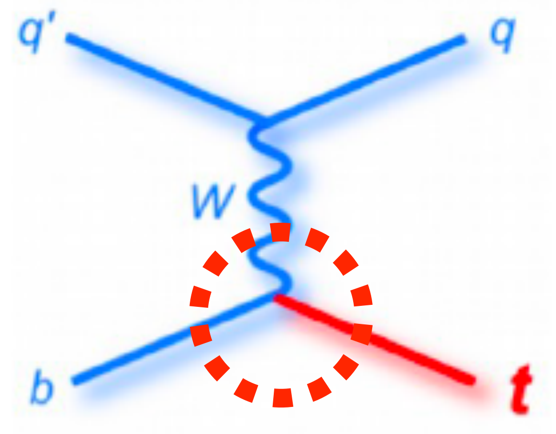
t-channel (~75% at LHC)



tW (~20% at LHC)



s-channel (~5% at LHC)



$$|V_{tb}| = 1.010 \pm 0.036$$

(from direct ATLAS+CMS measurements)

Nelson-Barr solution to strong CP, new ultralight-DM pheno.

With: Dine, Nir, Ratzinger & Savoray in prep.

Gilad Perez

- The strong CP problem is how to explain: $\bar{\theta} \lesssim 10^{-10}$ & $\theta_{\rm KM} = \mathcal{O}(1)$
- Nelson-Barr models achieve it through spontaneously breaking CP in models with extra (very) heavy vector-like quark
- Naturally, the object that break-CP spontaneously would be axion-like field
- This axion field could be a dark matter candidate

Relaxion: Graham, Kaplan & Rajendran (15)
NB-relaxion - Davidi, Gupta, GP, Redigolo, & Shalit (17)

↓

New pheno': strong CP is zero, type of pheno: *time dep. CKM angles (3rd gen)*

Time varying CKM matrix elements are a very novel phenomenon to search for in the top sector!

Nelson-Barr solution to strong CP, new ultralight-DM pheno.

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- Nelson-Barr models achieve it through spontaneously breaking CP in models with extra (very) heavy vector-like quark
- Naturally, the object that break-CP spontaneously would be axion-like field
- What is the size of the effect? $\delta\theta_{\rm KM} \sim \frac{\sqrt{\rho_{\rm DM}}}{m_{\rm NB} f} \cos(m_{\rm NB} t) \sim 10^{-3} \times \frac{10^{10}\,{\rm GeV}}{f} \times \frac{10^{-19}\,{\rm eV}}{m_{\rm NB}} \times \cos(m_{\rm NB} t)$
- How to search such signal? Need time dependence CP violation, perfect for B-asym

Time varying CKM matrix elements are a very novel phenomenon to search for in the top sector!

More on the axion-top connection

Simone Tentori

- We can introduce a “top-philic” ALP with preferential coupling to the top quark:

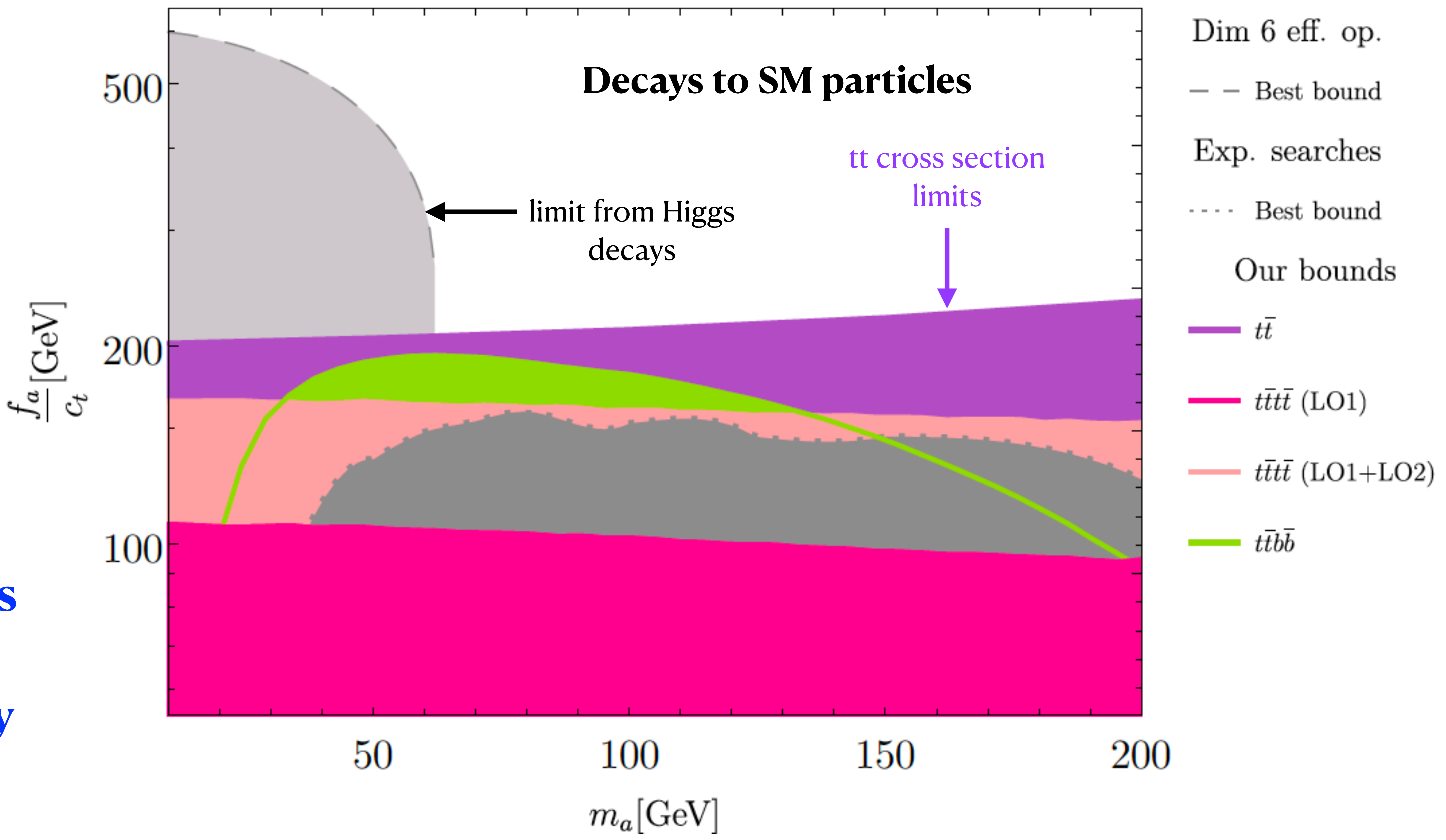
$$\mathcal{L} = \frac{c_t}{2}\frac{\partial_\mu a}{f_a}\bar{t}\gamma^\mu\gamma^5 t$$

Two benchmark scenarios:

(1) Decays into SM particles: search for in tt, ttbb, and tttt

(2) Long-lived or decays into BSM particles: jet+missing energy or tt+missing energy

Collider searches in top final states improve bounds for heavier ma. Lower masses are best bounded by Higgs decays



Accessing CKM suppressed top decays at the LHC

Manuel Szewc

Strong hierarchy makes the off-diagonal elements difficult to measure but also more sensitive to BSM effects

$$|V_{tb}^{\mathrm{SM}}| = 999.118^{+0.031}_{-0.036} \times 10^{-3}$$

$$|V_{ts}^{\mathrm{SM}}| = 41.10^{+0.83}_{-0.72} \times 10^{-3}$$

$$|V_{td}^{\mathrm{SM}}| = 8.57^{+0.2}_{-0.18} \times 10^{-3}$$

This work in a nutshell:

A **simple** extension of an existing strategy to measure $|V_{td}|^2+|V_{ts}|^2$ at the LHC

Main idea: Orthogonal *b*- and *q*-taggers define **complementary observables** that **increase the statistical power** of the analysis

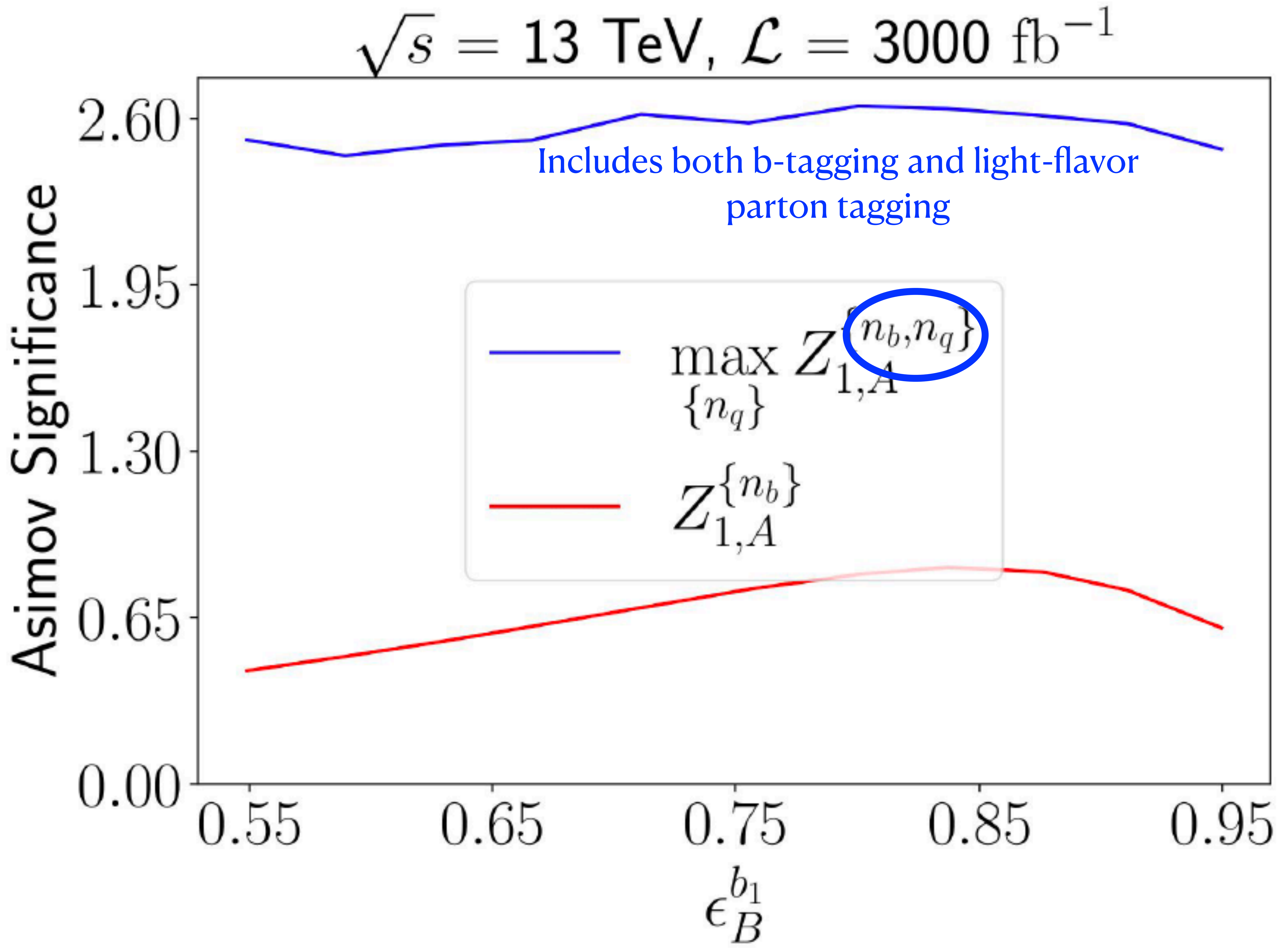
This simple extension allows to **measure a non-null $|V_{td}|^2+|V_{ts}|^2$ at 95% CL at the HL-LHC**

Accessing CKM suppressed top decays at the LHC

Manuel Szewc

- New idea: include both b-tagging and light quark/gluon tagging to incorporate more statistical power in a direct measurement of $|V_{td}|^2+|V_{ts}|^2$.

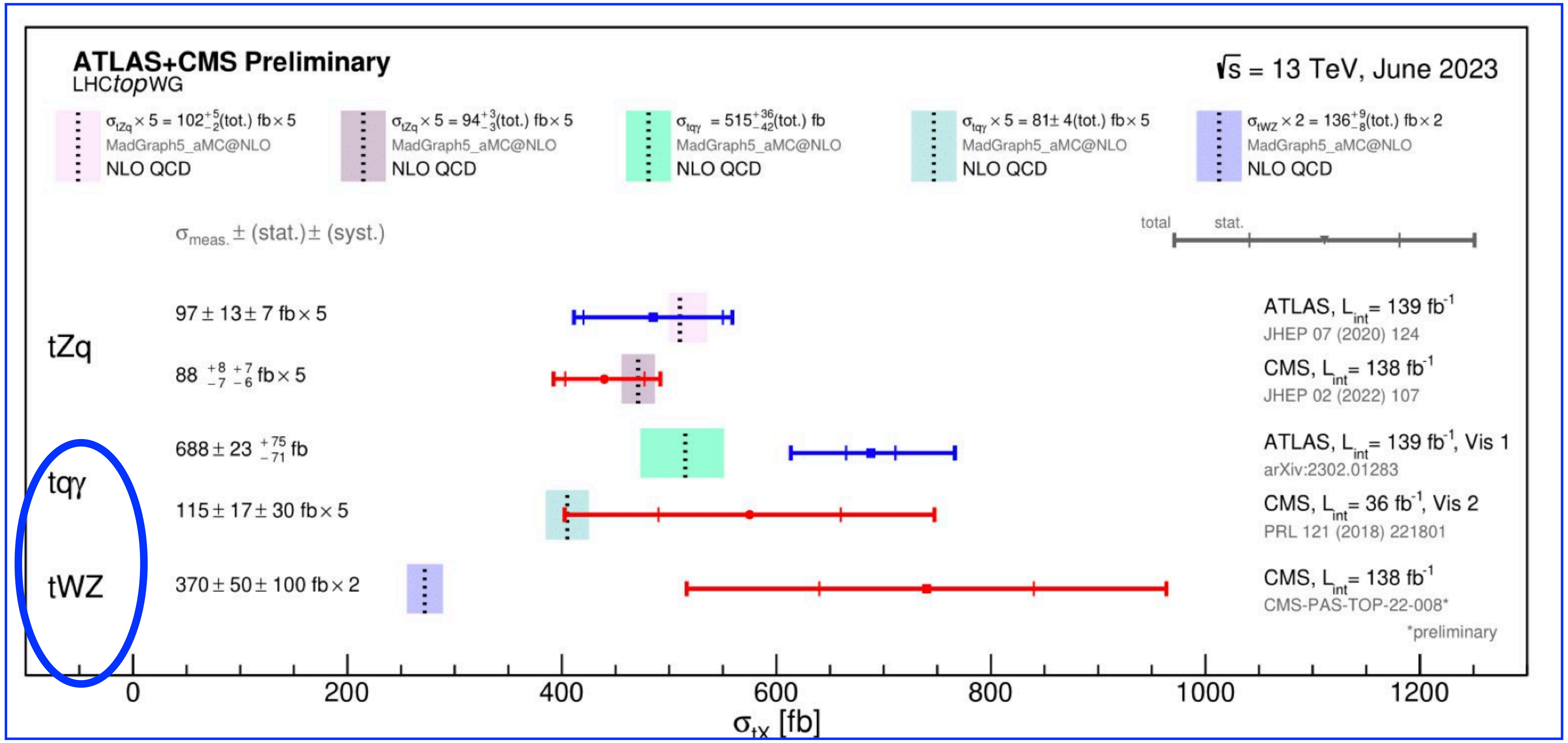
This new method can increase the sensitivity to these small CKM matrix elements by a factor of 4.5



Top quark properties: associated production

- The top quark can be produced in association with EW gauge bosons or the Higgs, which allows its Yukawa coupling and the structure of the ttV vertex to be probed.

Nils Faltermann



Interesting new measurements where some tension is observed in single top production; stay tuned!

Top quark properties: associated production

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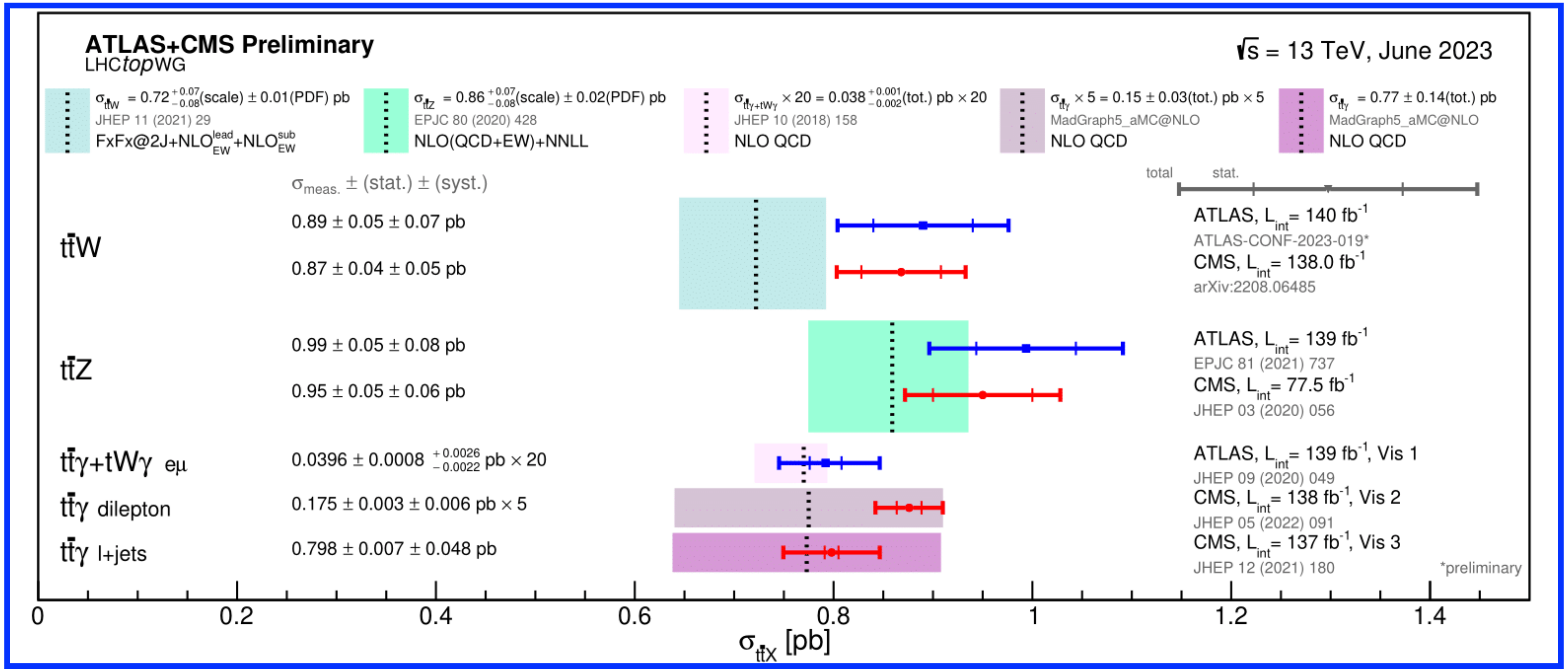


For ttV no significant deviations are observed so far with the SM predictions

ttW

Buonocore, Devoto, Kallweit, Mazzitelli,
Rottoli, Savoini, MG (2023)

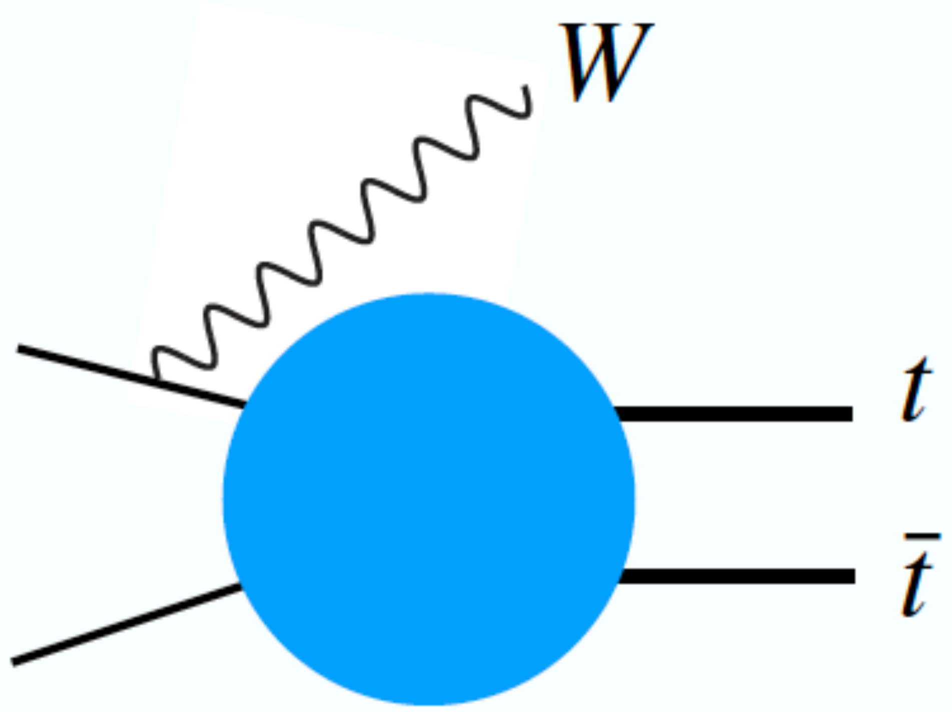
Massimiliano Grazzini

Among the ttV signatures, ttW is special because it involves both EW and top sectors

It is at the same time a signal and a background to ttH and tttt and new physics searches

Since the top quark quickly decays into a W and a b jet, the signature is characterised by 3 W bosons

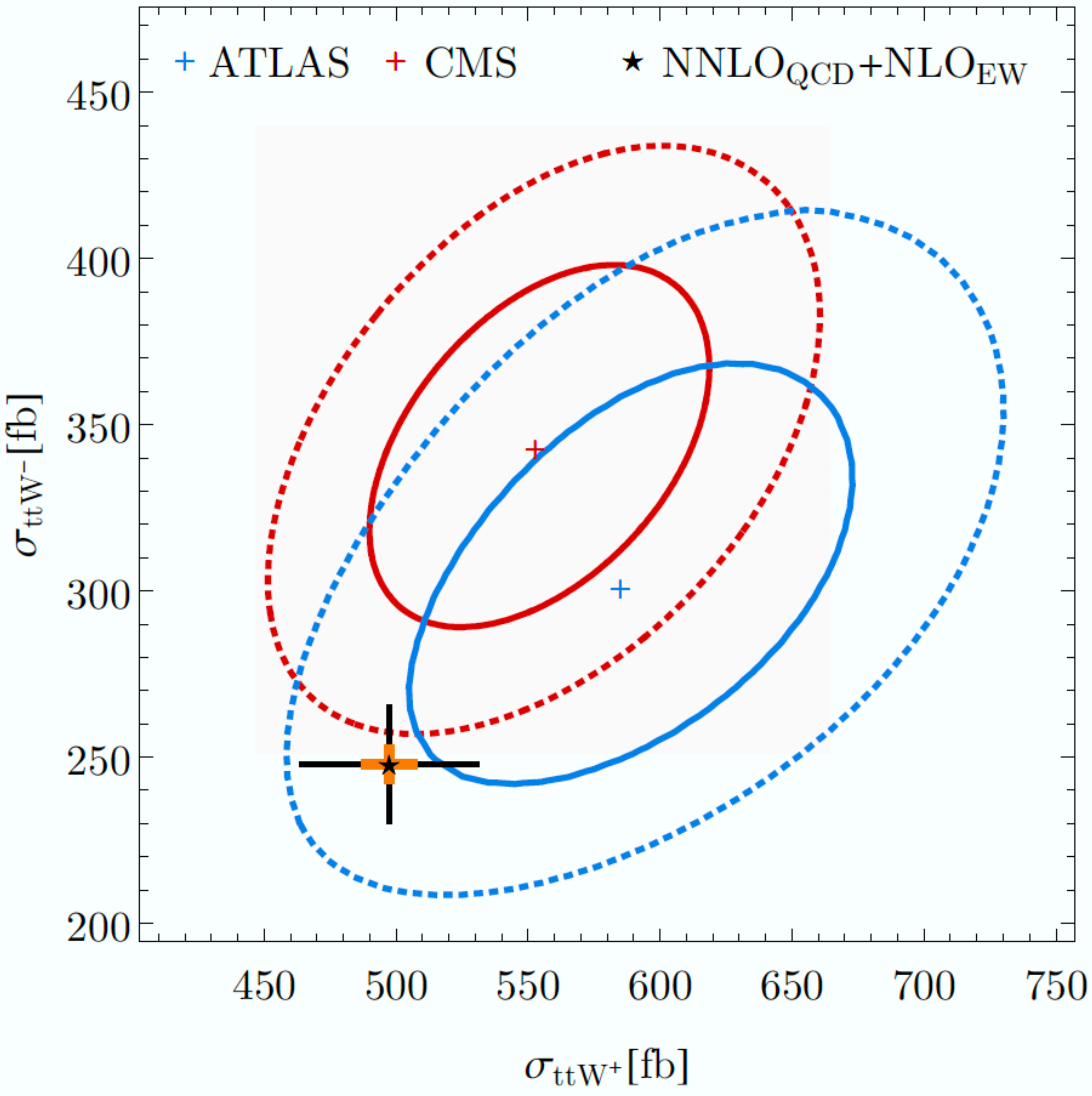
→ It provides an irreducible source of same-sign dilepton pairs relevant for many BSM searches



It is special compared to other $t\bar{t}F$ $(F = H, Z, \gamma)$ signatures because the W can only be emitted by the initial-state light quarks (no gg channel at LO)

Measurements by ATLAS and CMS at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV showed that the ttW rate is consistently higher than the SM prediction

ttW



The comparison with the ATLAS and CMS results shows that discrepancy remains at the 1-2σ level

Inclusion of NNLO corrections significantly reduces perturbative uncertainties

Our result is fully consistent with FxFx prediction but with smaller uncertainties

$$\sigma_{t\bar{t}W}^{\mathrm{FxFx}} = 722.4^{+9.7\%}_{-10.8\%}\ \mathrm{fb}$$

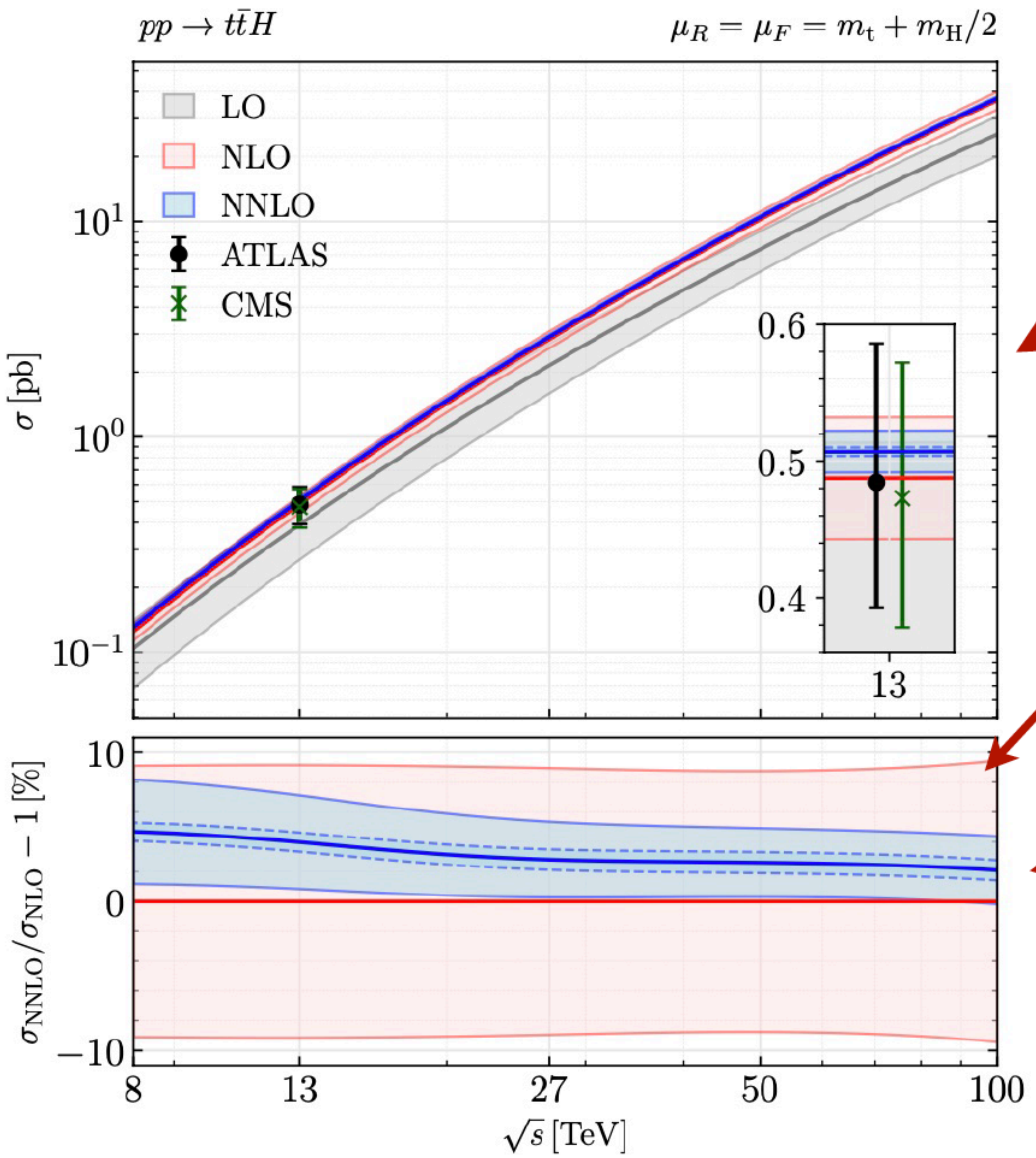
Massimiliano Grazzini

Note that tension with data when using fixed order NLO QCD+EW corrections is larger, about 2-3 σ

ttH

Massimiliano Grazzini

A very significant reduction of scale uncertainty at NNLO: this calculation is ready for future LHC data!



ATLAS and CMS results from Nature 2022 papers

Perturbative uncertainties estimated by symmetrising the standard 7-point scale variation

Dashed band: residual error from soft approx+systematics

Note that: sensible comparison with data should eventually be done including NLO EW corrections ($+1.7\,\%$ at $\sqrt{s} = 13\,\text{TeV}$)

ttjj

Michele Lupattelli

- ttjj is an important background to ttH production, and therefore must be known well in order to precisely extract the top-quark Yukawa coupling.

$t\bar{t}jj$ theory state-of-the-art

- NLO QCD predictions with stable top quarks:

(Bevilacqua, Czakon, Papadopoulos, Worek '10, '11)

- NLO QCD predictions matched to parton shower:

(Hoeche, Krauss, Maierhoefer, Pozzorini, Schonherr, Siegert '15 | Höche, Maierhöfer, Moretti, Pozzorini, Siegert '17 | Gütschow, Lindert, Schönherr '18)

- NLO QCD predictions in the NWA including additional radiation and NLO QCD corrections in top-quark decays:

(Bevilacqua, Lupattelli, Stremmer, Worek '23)

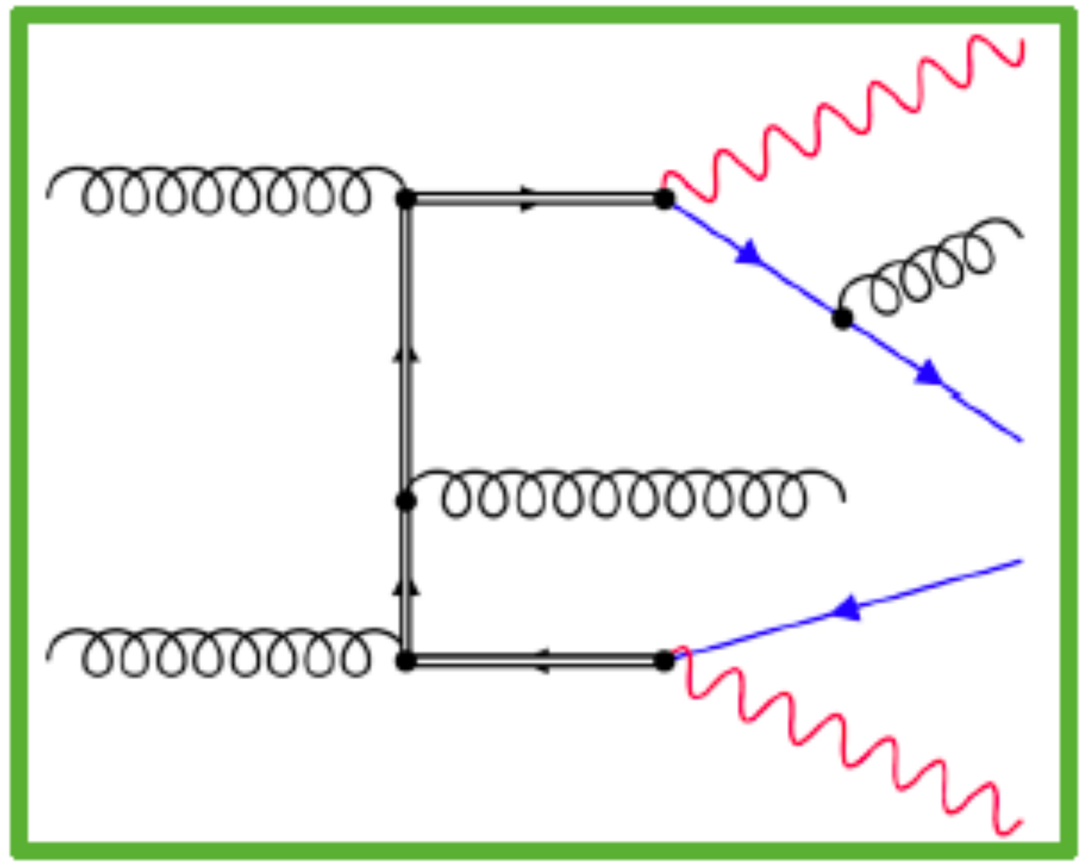
ttjj

Michele Lupattelli

$$d\sigma^{\rm NLO}_{\rm Full} = (\Gamma^{\rm NLO}_{t,\rm NWA})^{-2}\times$$

$$\Big[\overbrace{(d\sigma^{\rm LO}_{t\bar{t}jj} + d\sigma^{\rm virt}_{t\bar{t}jj} + d\sigma^{\rm real}_{t\bar{t}jjj})d\Gamma^{\rm LO}_{t\bar{t}}}^{\rm Prod.} + \overbrace{d\sigma^{\rm LO}_{t\bar{t}}(d\Gamma^{\rm LO}_{t\bar{t}jj} + d\Gamma^{\rm virt}_{t\bar{t}jj} + d\Gamma^{\rm real}_{t\bar{t}jjj})}^{\rm Decay} +$$

$$\left.\begin{array}{c} d\sigma^{\rm LO}_{t\bar{t}j}d\Gamma^{\rm LO}_{t\bar{t}j} + d\sigma^{\rm LO}_{t\bar{t}jj}d\Gamma^{\rm virt}_{t\bar{t}} + d\sigma^{\rm virt}_{t\bar{t}}d\Gamma^{\rm LO}_{t\bar{t}jj} + d\sigma^{\rm virt}_{t\bar{t}j}d\Gamma^{\rm LO}_{t\bar{t}j} + \\ d\sigma^{\rm LO}_{t\bar{t}j}d\Gamma^{\rm virt}_{t\bar{t}j} + d\sigma^{\rm real}_{t\bar{t}jj}d\Gamma^{\rm real}_{t\bar{t}j} + d\sigma^{\rm real}_{t\bar{t}j}d\Gamma^{\rm real}_{t\bar{t}jj}\Big] \end{array}\right\}\ \text{Mix}$$



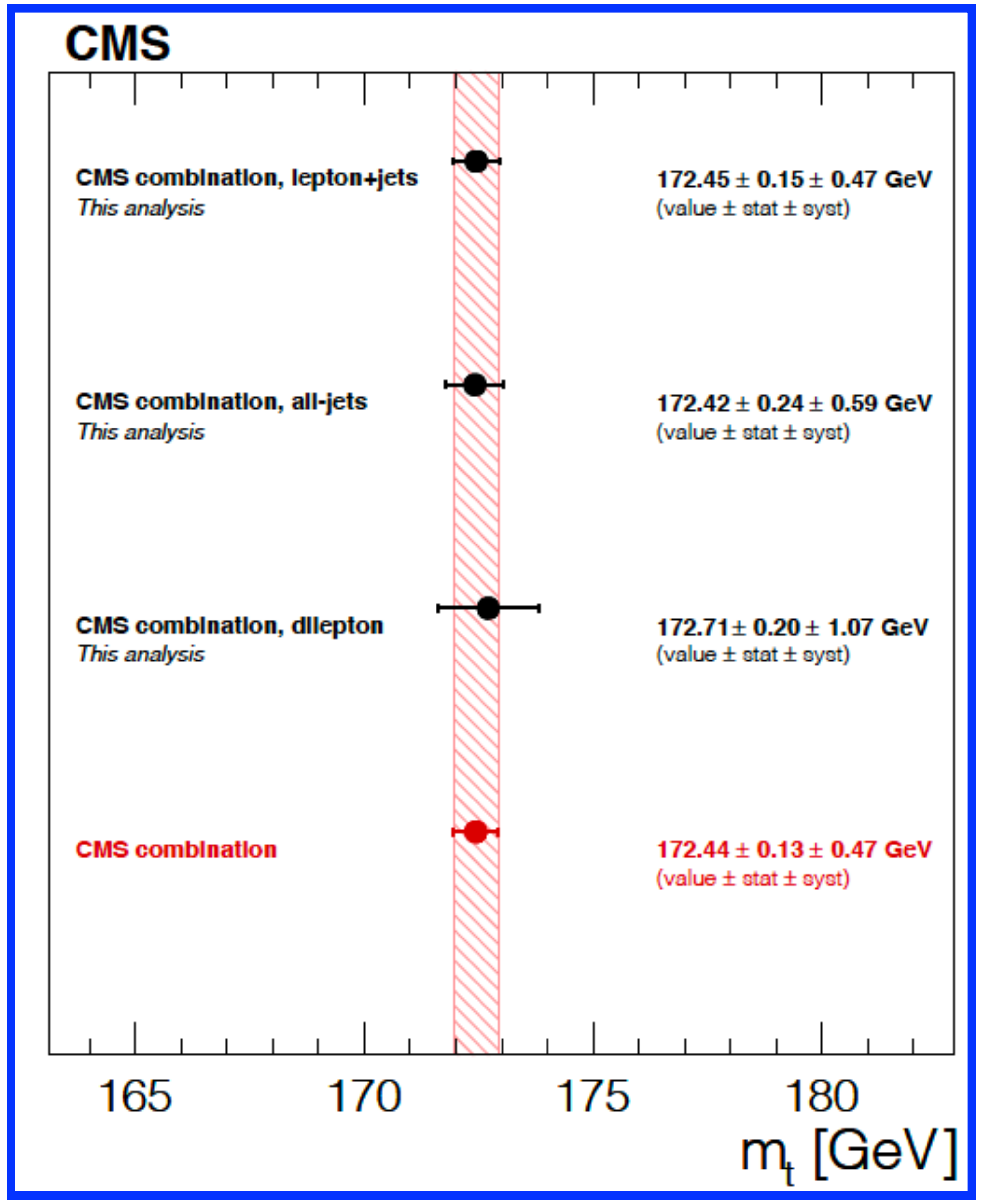
- These mixed contributions, where an additional jet is included in both the production and decay processes, is studied in this work for the first time.

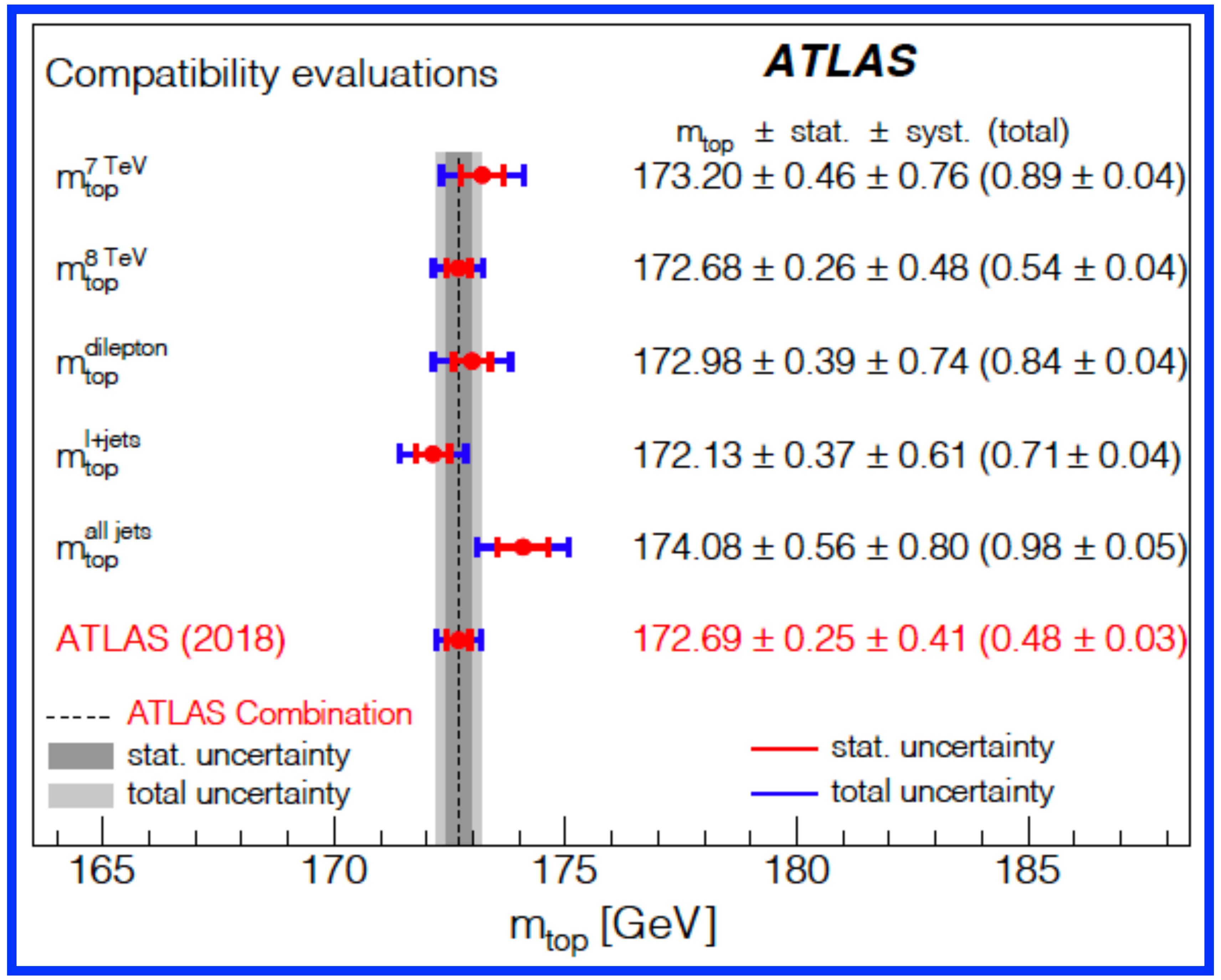
	$\sigma_i^{\rm LO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\sigma_i^{\rm NLO}$ [fb]	$\sigma_i/\sigma_{\rm Full}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
Full	$868.8(2)^{+60\%}_{-35\%}$	-	$1225(1)^{+1\%}_{-14\%}$	-	1.41
Prod.	$843.2(2)^{+60\%}_{-35\%}$	0.97	$1462(1)^{+12\%}_{-19\%}$	1.19	1.73
Mix	25.465(5)	0.029	−236(1)	-0.19	-9.27
Decay	0.2099(1)	0.0002	0.1840(8)	0.0002	0.88

Large NLO effect from mixed corrections; this calculation is needed to bring this background under theoretical control

Top quark properties: mass

- The mass of the top quark is an important input to numerous applications: the precision EW fit, the determination of the fate of the EW vacuum, and numerous other topics.





- Numerous precise determinations at hadron colliders through direct reconstruction of top events.
- Measured is a “Monte Carlo mass” since the analysis determines the mass by varying the top mass parameter in MC programs. This is not a precisely defined renormalization scheme.
- It has been argued that this is close to the pole mass with a few-hundred MeV difference, but it is difficult to make a more precise statement.

(For s review see 2209.11267)

Energy-peak based method to measure m_{top} via B-hadron decay lengths

Doojin Kim

- Many methods for top quark mass extraction are limited by the details of theoretical modeling (PDFs, higher-order QCD) or the jet energy scale. Extracting the top quark mass from the B-hadron decay length can bypass these issues.

Bottomline of Our Proposal

$$G^{\mathrm{fit,us}}(L_B^{xyz}; E_b^{\mathrm{peak}}, w) = \int dE_B dE_b \frac{1}{N(w)} \exp\left[-w\left(\frac{E_b}{E_b^{\mathrm{peak}}} + \frac{E_b^{\mathrm{peak}}}{E_b}\right)^{0.3}\right]$$

$$\times D\left(\frac{E_B}{E_b}; E_b\right) \frac{m_B}{E_B c\tau_B^{\mathrm{rest}}} \exp\left(-\frac{L_B m_B}{c\tau_B^{\mathrm{rest}} E_B}\right)$$

$G^{\mathrm{fit,us}}(L_B^{xyz}; E_b^{\mathrm{peak}}, w)$: fitting function of measured B-hadron decay length distribution

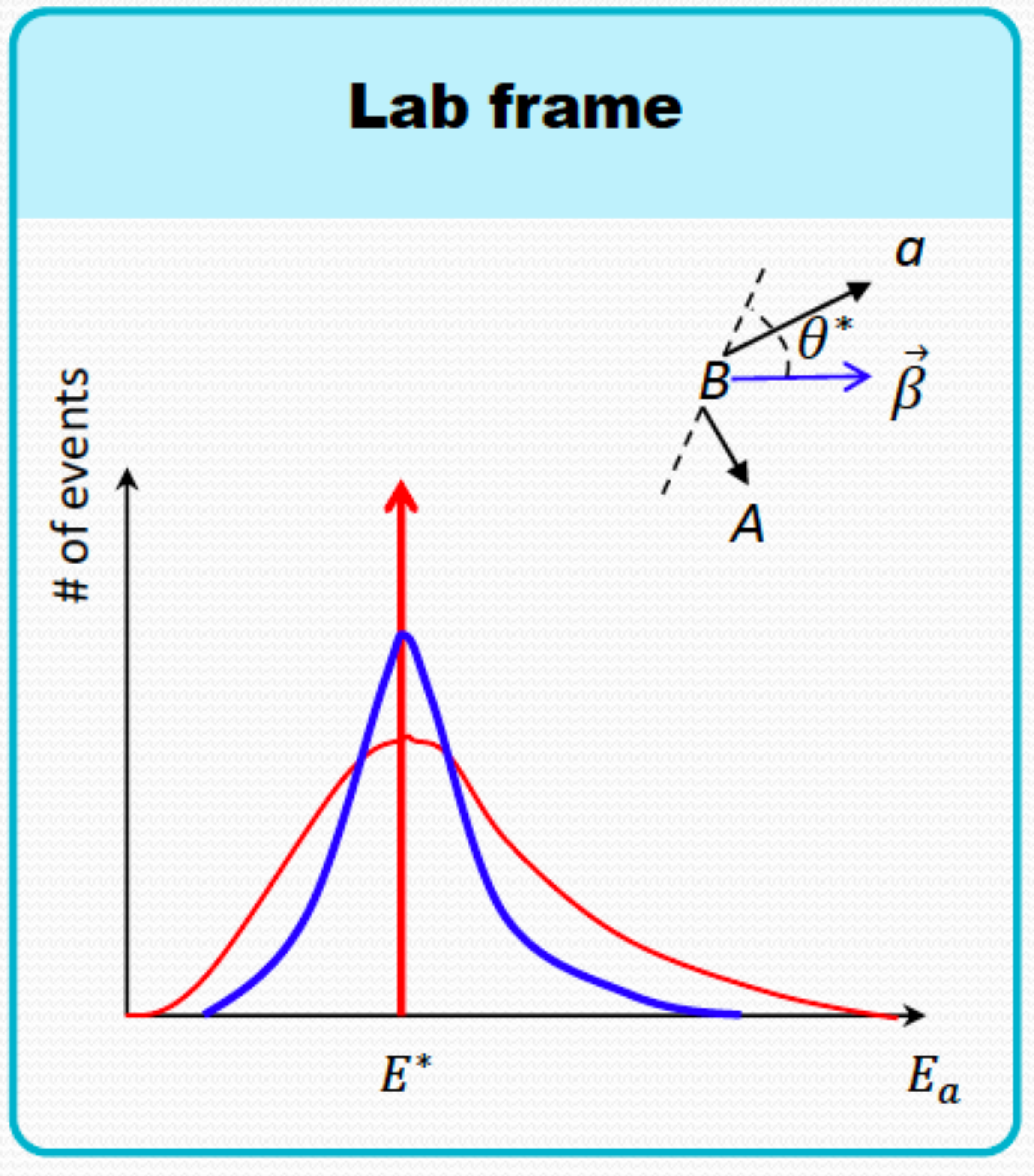
Best-fit E_b^{peak}: used for m_t **determination!**

$D\left(\frac{E_B}{E_b}; E_b\right)$: b-quark fragmentation function

τ_B^{rest}: mean decay lifetime of B-hadron in its rest frame

w: width of fitting function

$N(w)$: normalization factor

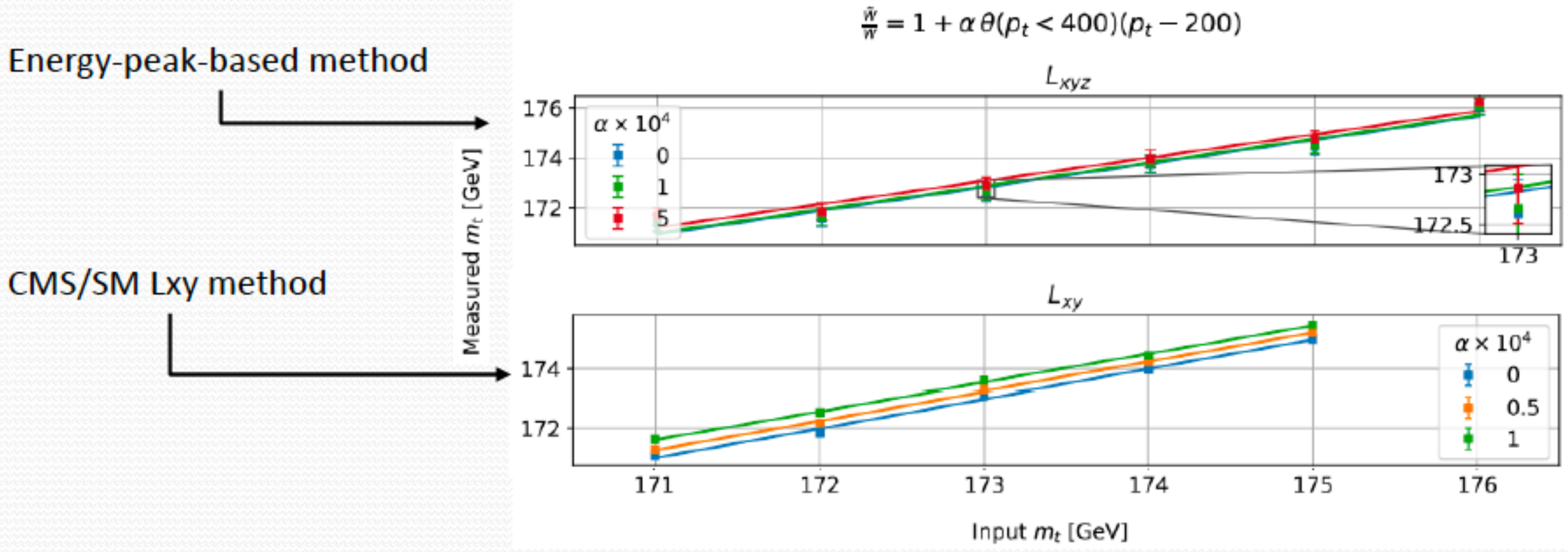


Simple 1→2 kinematics leads to a peak in the b-quark energy distribution which is correlated with the top quark mass. Can extract m_{top} from the B-hadron decay length

Energy-peak based method to measure m_{top} via B-hadron decay lengths

Results

Doojin Kim

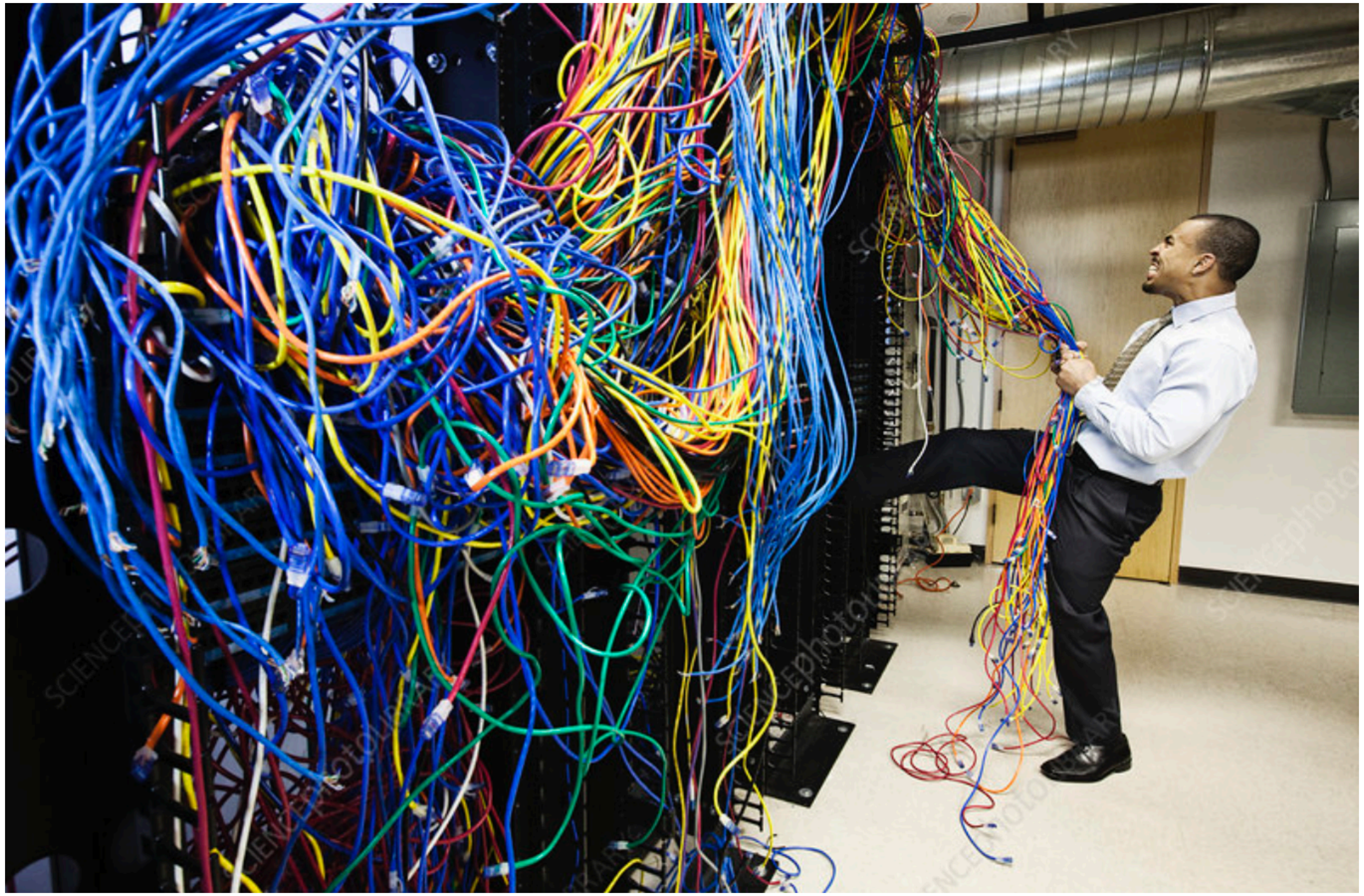


300/fb @LHC14TeV

- $\alpha = 10^{-4}$ (green lines) roughly corresponds to the theoretical uncertainty in top p_T spectrum (roughly moving the average top p_T by 0.5%) [CMS collaboration, PRD104 092013]. Lxy method shifts by ~600 MeV vs. Lxyz method by ~50 MeV. ⇒ Negligible error for the energy-peak-based method!!

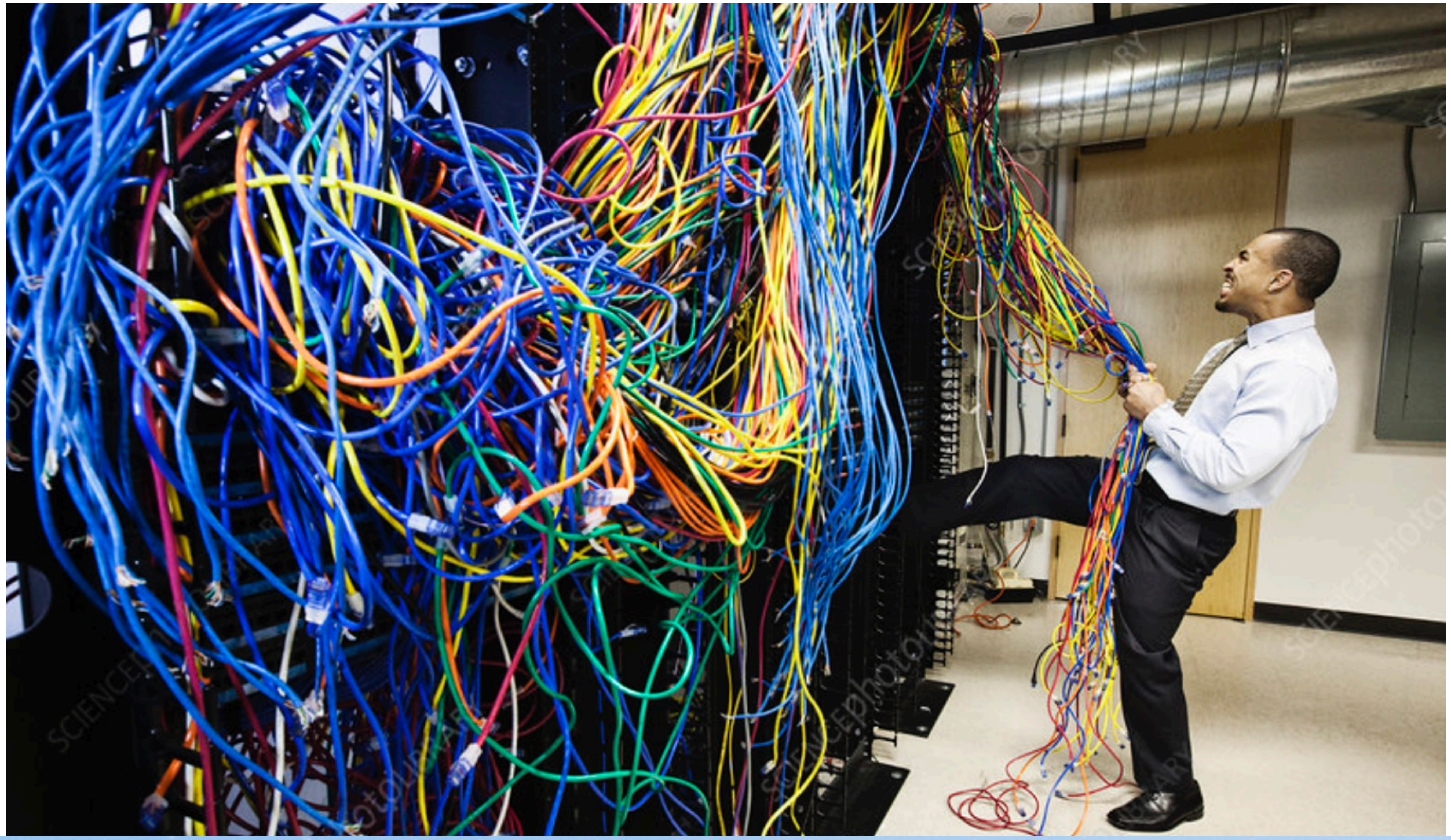
Greatly reduced sensitivity to theoretical modeling than currently used experimental methods

Quantum entanglement and top quarks



We've had a lot of entanglement in Top2023!

Quantum entanglement and top quarks



Basic idea, from Claudio Severi:

Test foundations of quantum mechanics at colliders!

The Standard Model produces top pairs with correlated spin. Sometimes spin correlations are so strong they can not be explained classically:

Testing quantum mechanics with tops

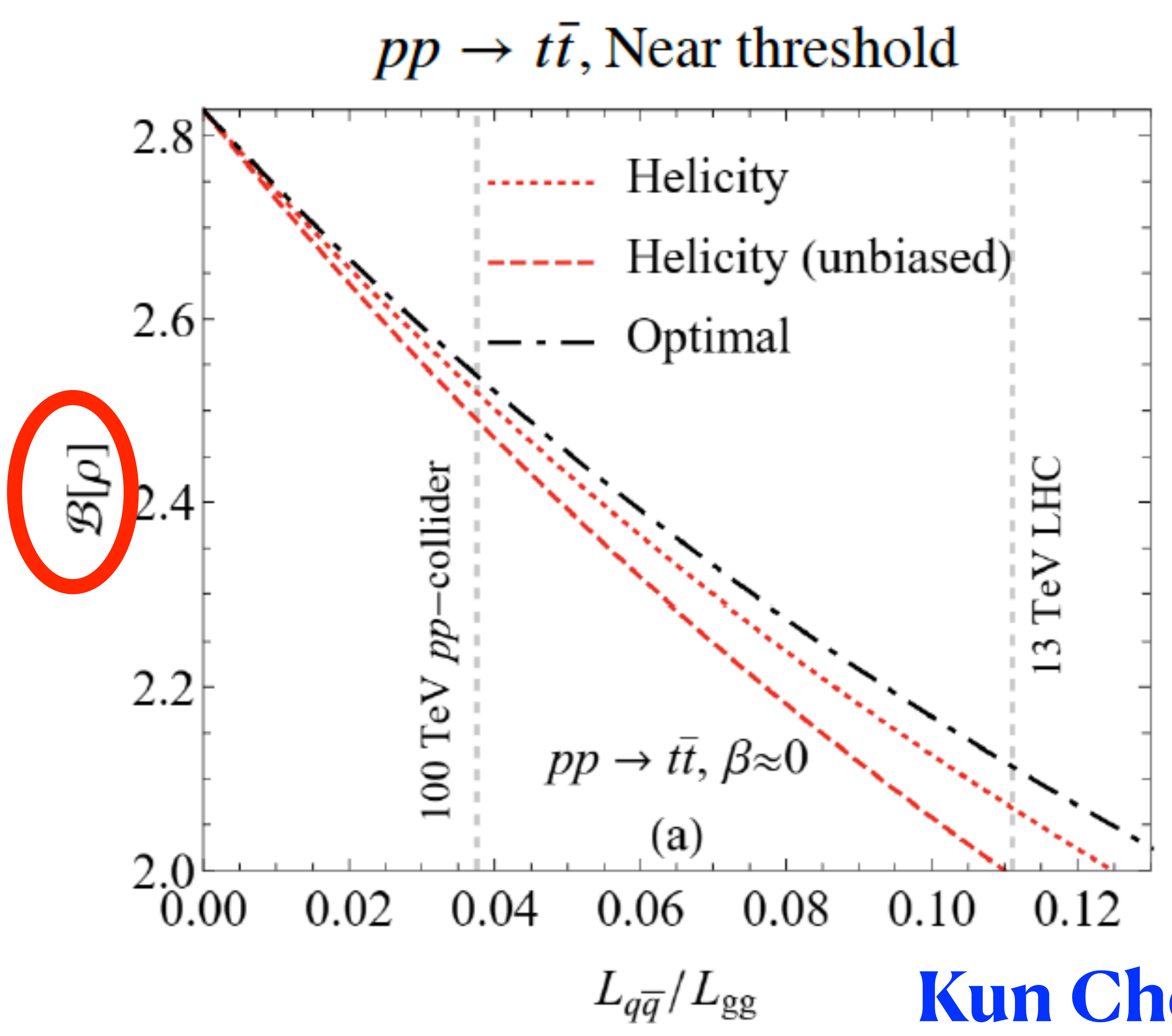
- **Bell's inequality** in top physics: if we can measure the angular momentum of top quarks experimentally, then quantum mechanics predicts that the following inequality is violated:

$$\mathscr{B}(\rho) = \left|\vec{a}_1 \cdot C \cdot (\vec{b}_1 - \vec{b}_2) + \vec{a}_2 \cdot C \cdot (\vec{b}_1 + \vec{b}_2)\right| \leq 2$$

a, b are the angular momentum measurements
C is the spin correlation

$$\langle \sigma_i^t \sigma_j^{\bar{t}} \rangle = C_{ij}$$

- Can measure both angular momentum and spin correlations by reconstructing the ttbar system in the dilepton final state



Can perform fundamental tests of Quantum Mechanics at the LHC and with future high-energy collider data

Kun Cheng

Testing quantum mechanics with tops

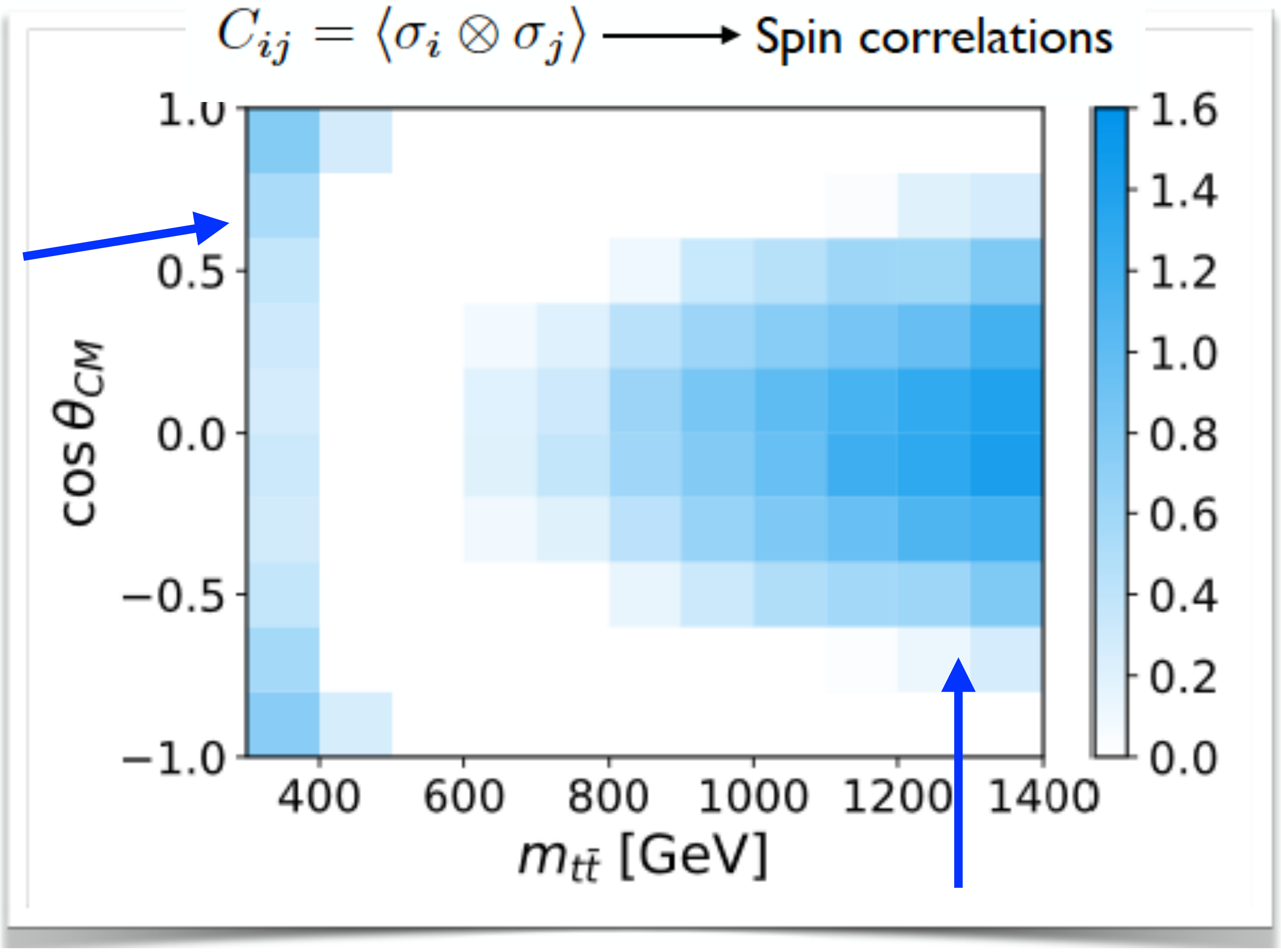
- Can extend the study of quantum entanglement, and Bell's inequalities, to the boosted region of top quark production as well.

Dorival Gonçalves

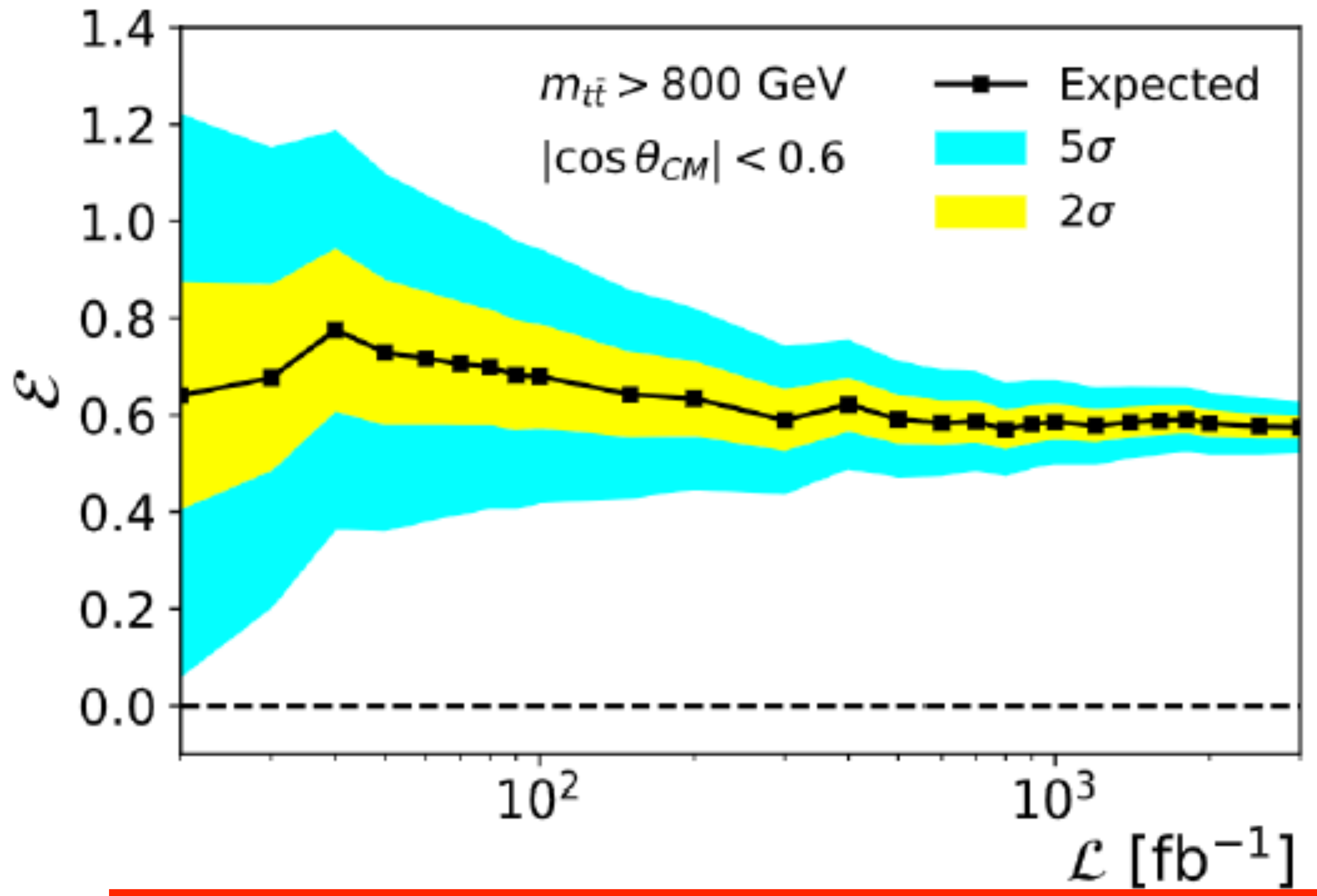
Measure of entanglement:

$$\mathcal{E} \equiv |C_{kk} + C_{rr}| - C_{nn} - 1 > 0$$

Threshold region, low m_{tt}



Boosted region, high m_{tt}

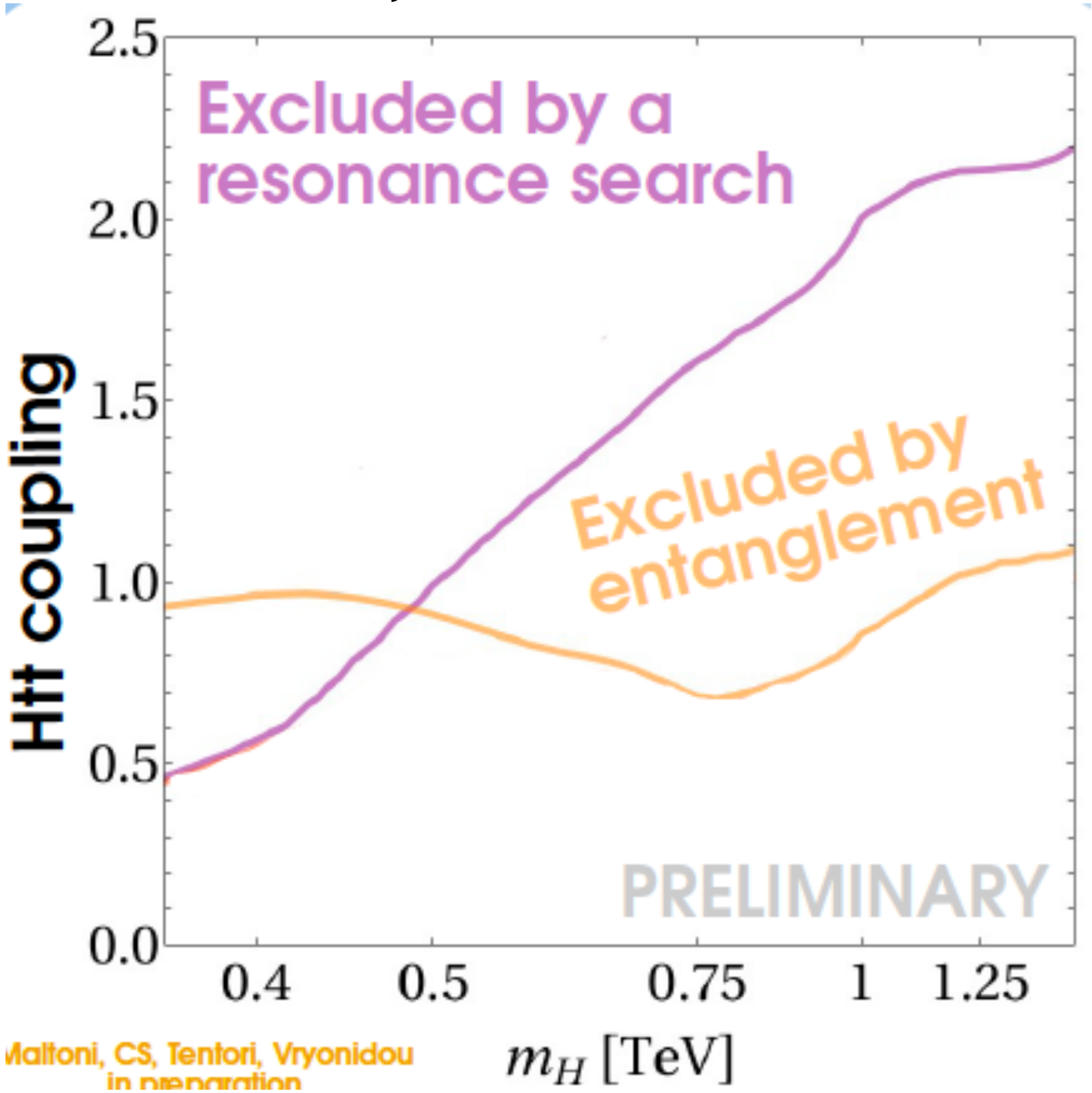


Current dataset can probe entanglement at 5-sigma level

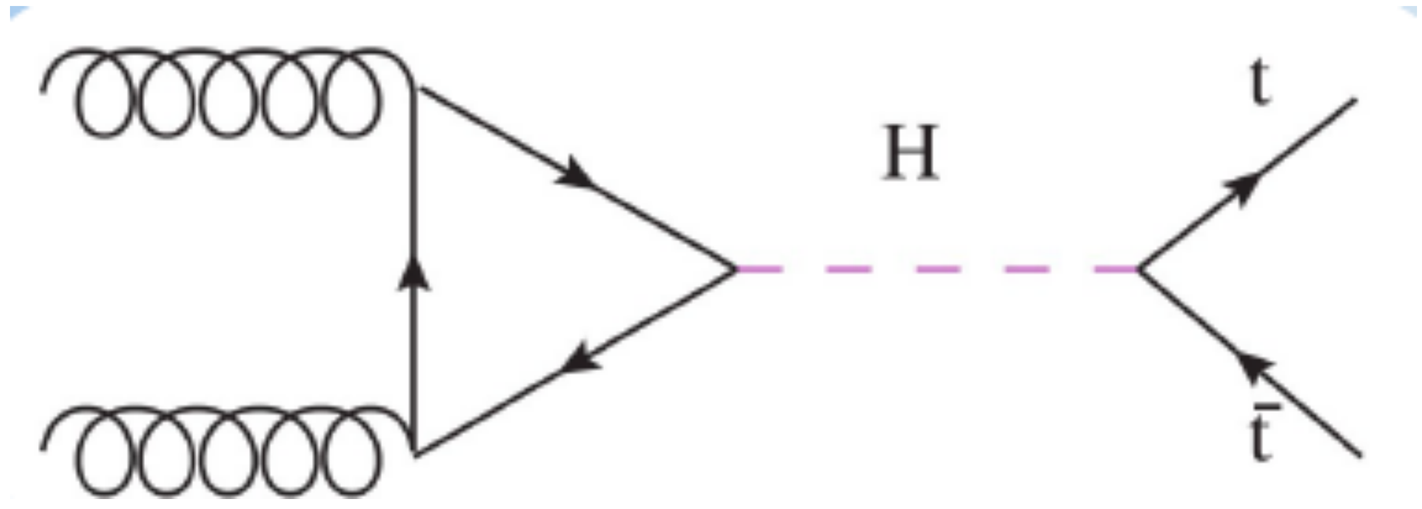
Testing quantum mechanics with tops

Claudio Severi

- Modifications of entanglement properties from new physics can provide sensitive searches for beyond the Standard Model phenomena.



H is a pseudoscalar Higgs with mass greater than $2m_t$



Entanglement search stronger than a resonance search for heavy pseudoscalar masses! Can also search for SMEFT effects as well with such entanglement analyses.

Testing quantum mechanics with tops

Surjeet Rajendran

- We can also imagine testing even more basic assumptions underlying quantum mechanics and quantum field theory, such as linear time evolution.

Linear QFT: $$S \supset \left(\int d^3x \, y \, \langle \chi(t) | \phi(x) \bar{\Psi}(x) \Psi(x) | \chi(t) \rangle \right)$$

replace with: ⬇

Non-Linear QFT: $$S_{NL} \supset \epsilon \left(\int d^3x \, \langle \chi(t) | \phi(x) | \chi(t) \rangle \langle \chi(t) | \bar{\Psi}(x) \Psi(x) | \chi(t) \rangle \right)$$

Impact: time evolution in QM becomes dependent on the state under consideration

Tests:

Interferometry - interaction between paths

Take an ion - split its wave-function

Coulomb Field of one path interacts with the other path

Gives rise to phase shift that depends on the intensity p of the split

Thank you!

To all the amazing speakers and to the Local Organizing Committee and the International Advisory Committee for putting together such an exciting workshop in a beautiful location!

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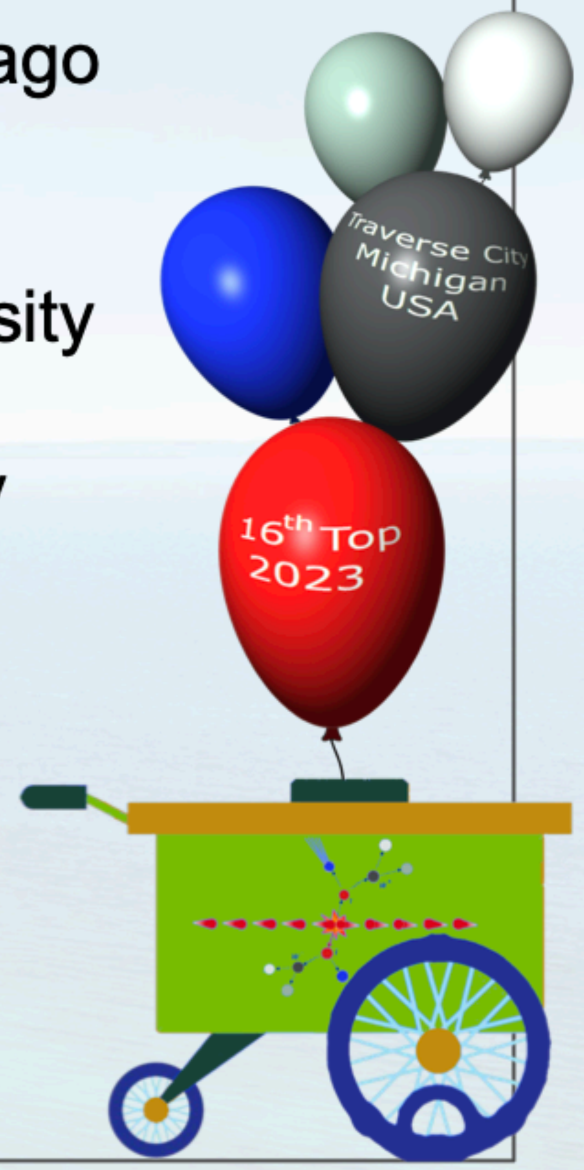

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