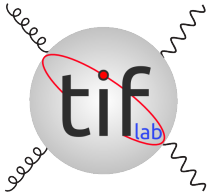


THEORY SUMMARY

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

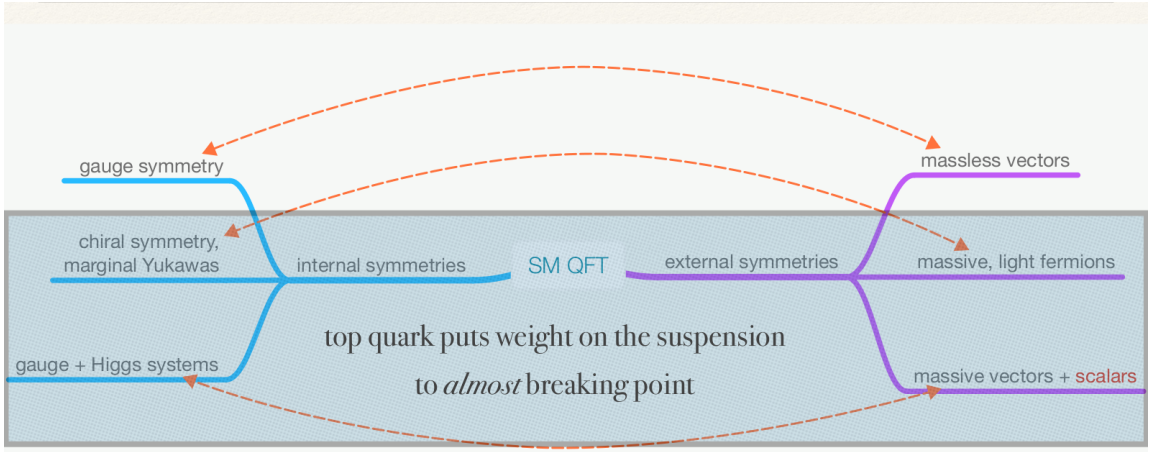
TOP2022

Durham, 9 September 2022

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 740006

...THE STANDARD MODEL IS ABOUT 50 YEARS OLD

TOP PHYSICS



Phenomenological appeal

- abundantly produced
- rich final state phenomenology
- testbed for new strategies/tools

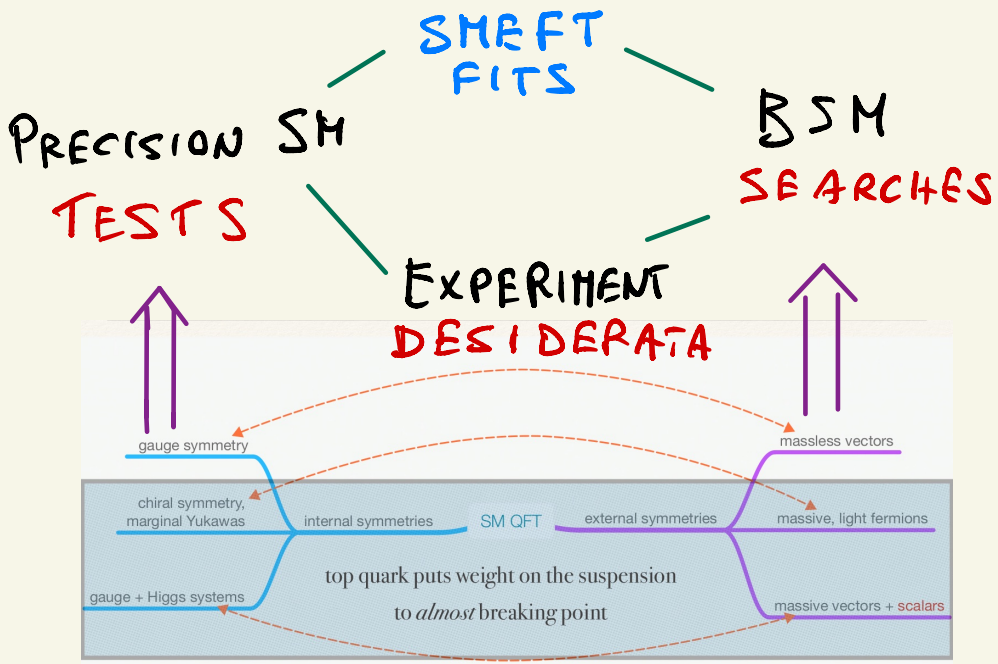
Top quark

Theoretical appeal

- central to weak scale dynamics
- crucial in BSM theories
- window to SM UV completions

C. Englert

TOP PHYSICS...



Phenomenological appeal

- abundantly produced
- rich final state phenomenology
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Top quark

Theoretical appeal

- central to weak scale dynamics
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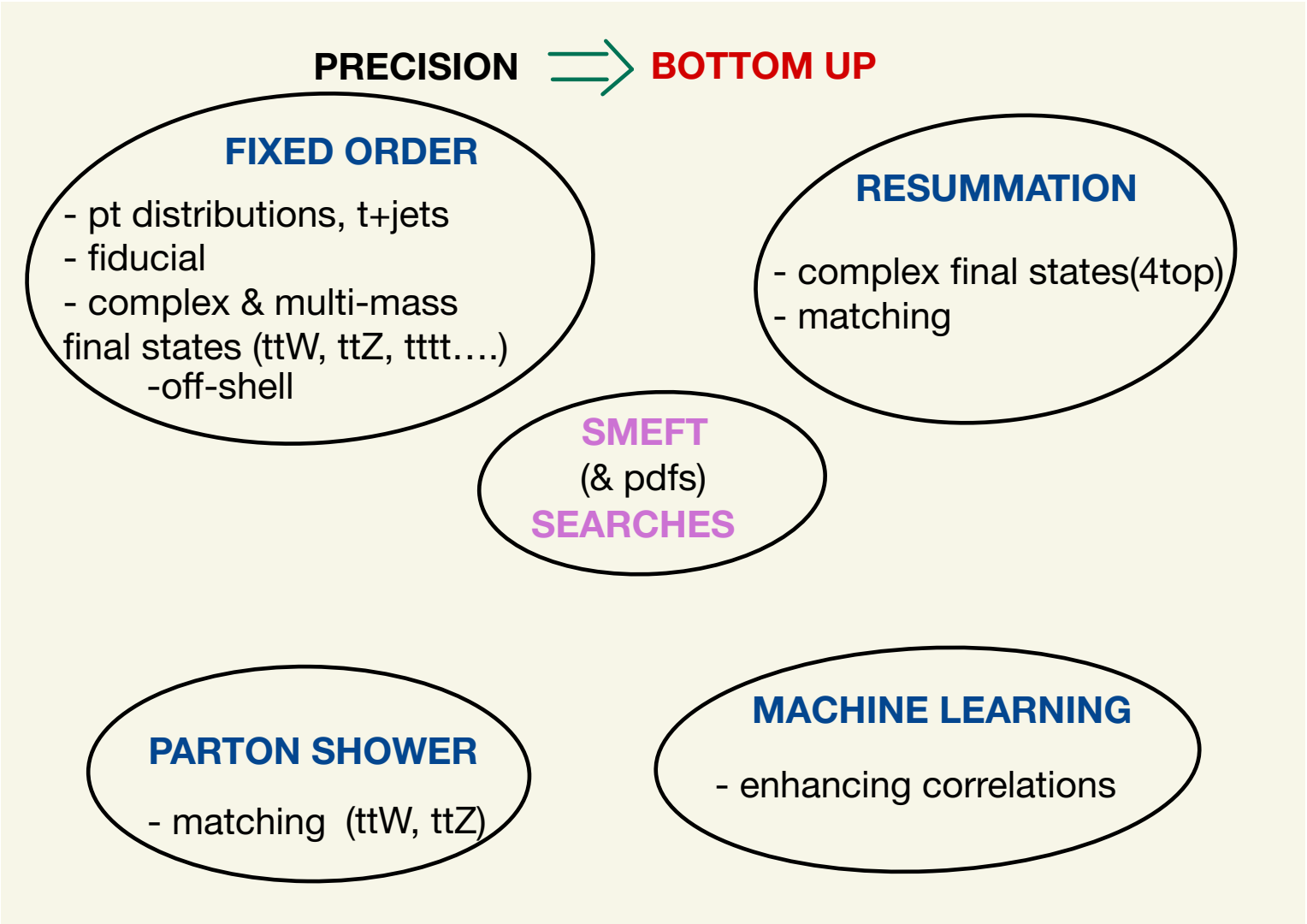
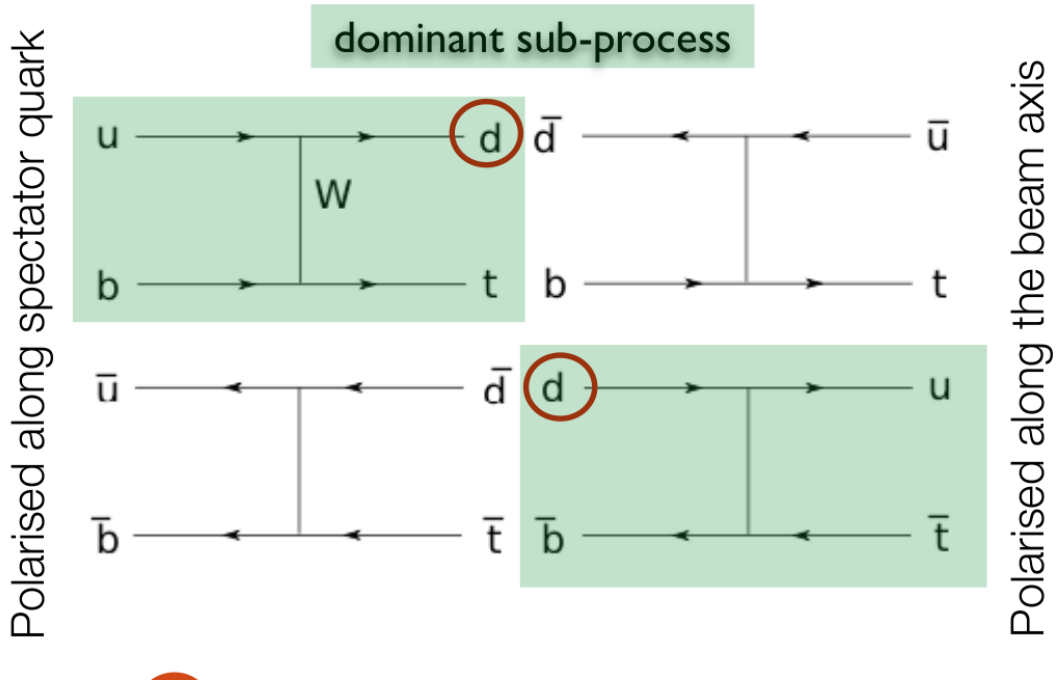
- window to SM UV completions

…AS PRECISION PHYSICS



FOUNDATIONAL ISSUES

TOP AS TEXTBOOK STANDARD MODEL PHYSICS



M. Watson

...EXPLOITING THE CHIRAL STRUCTURE OF VECTOR COUPLINGS

TOP AS TEXTBOOK QUANTUM MECHANICS

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = a_+ \left[\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta}\right]_+ + a_- \left[\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta}\right]_-$$

with

$$a_+ = (1+P_z)/2 = \rho_{\frac{1}{2}\frac{1}{2}} = \sigma_+/\sigma$$
$$a_- = (1-P_z)/2 = \rho_{-\frac{1}{2}-\frac{1}{2}} = \sigma_-/\sigma$$

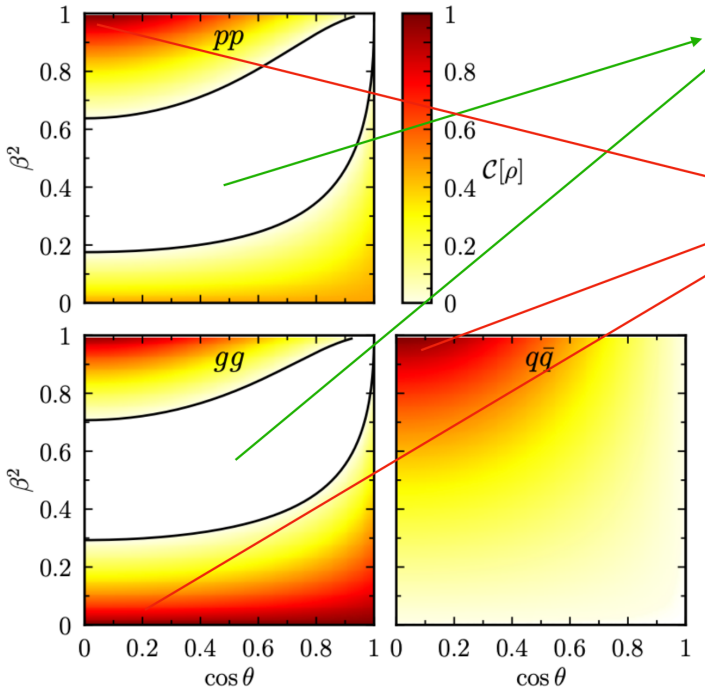
Template expansion

J. A. Aguilar Saavedra

UNDERSTANDING THE DENSITY MATRIX OF A QUBIT...

TOP AS TEXTBOOK QUANTUM MECHANICS

... AND USING IT TO MEASURE ENTANGLEMENT



No entanglement

Max entanglement

- **Threshold:** $\beta^2 = 0$

$$\rho_{gg}^{\rm SM}(0,z) = |\Psi^-\rangle_{\boldsymbol{n}}\langle\Psi^-|_{\boldsymbol{n}}$$

- **High energy:** $\beta^2 = 1\,, \cos\theta = 0$

$$\rho_{gg}^{\rm SM}(1,0) = |\Psi^+\rangle_{\boldsymbol{n}}\langle\Psi^+|_{\boldsymbol{n}}$$

[arXiv:2003.02280]

L. Mantani

~~TOP MASS THEORY~~ EXPERIMENT (M. Defranchis)

- RENORMALON AFFECTS RELATION BETWEEN POLE & $\overline{\text{MS}}$ MASS
- KINEMATIC OBSERVABLES DEPEND ON POLE MASS
  $\Rightarrow$ ALL-ORDER QUANTITY MEASURABLE
- SHORT-DISTANCE COMPUTABLE PROPERTIES DEPEND ON $\overline{\text{MS}}$ MASS
  $\Rightarrow$ FINITE-ORDER QUANTITY COMPUTABLE
- TRADEOFF:
  - DIRECT MEASUREMENTS DETERMINE ALL-ORDER QUANTITY
    CURRENTLY MOST ACCURATE
  - CROSS-SECTION "OFF-SHELL" MEASUREMENTS DETERMINE
    PERTURBATIVELY COMPUTABLE SHORT-DISTANCE QUANTITY

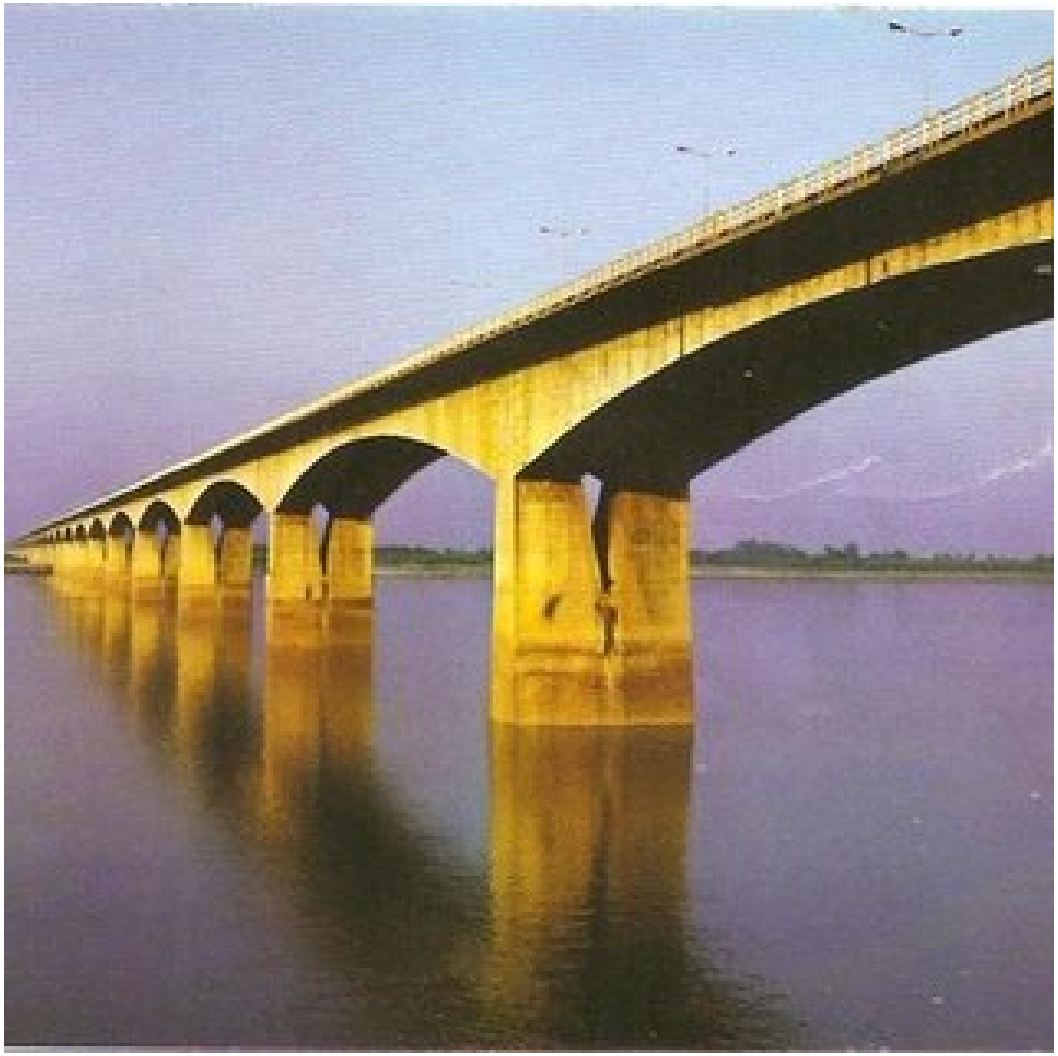
RENORMALON ESTIMATE OF REMAINDER (AMBIGUITY):

$$\Delta^{(5+)}m_p = 0.304^{+0.012}_{-0.063}(N) \pm 0.030(m_{b,\,c}) \pm 0.009(\alpha_s) \pm 0.108(\text{ambiguity})\ \text{GeV}$$

110 MeV AMBIGUITY SMALLER THAN LHC ACCURACY BUT LARGER THAN FUTURE e^+e^- LINEAR COLLIDER

(Beneke, Marquard, Steinhauser, Nason, 2017)

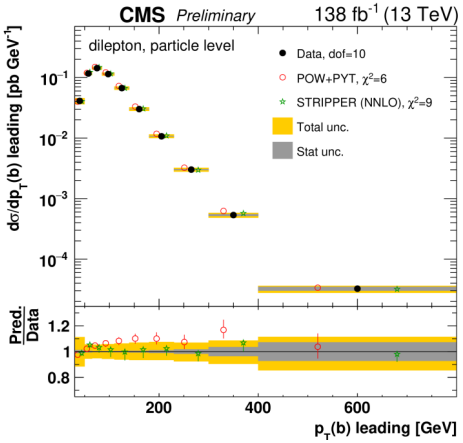
STRETCHING KNOWLEDGE



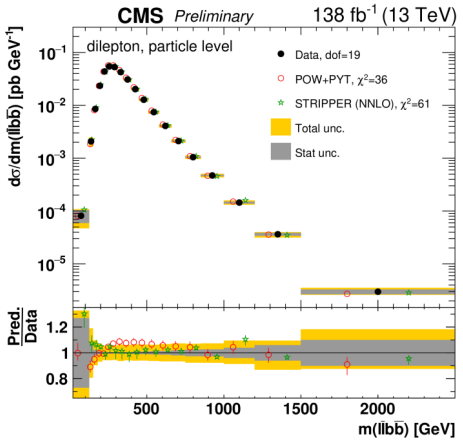
FIDUCIAL MEASUREMENTS
TOP p_T DISTRIBUTION

- Good normalization
- Good shape → looks sometimes even better then POW+PYT

Leading b-jet transverse momentum

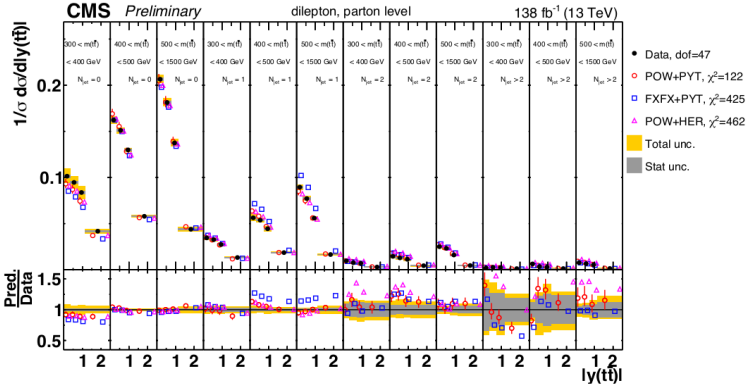


Invariant mass of lepton-pair + b-jet pair



R. Poncelet

Double and triple differential distributions probe the tensions with QCD models in detail. No model describe all these data well within experimental uncertainties.



The largest tension is in the number of additional jets, especially for high m_{tt}, in the case of FXFX+PYT and POW+HER.

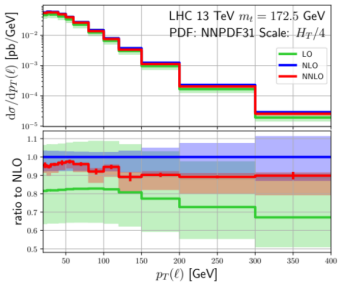
P. Hansen

FIXED-ORDER COMPUTATION IN FIDUCIAL REGION AGREES BEAUTIFULLY WITH DATA

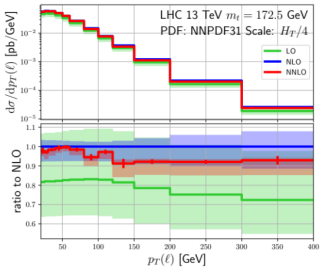
DETAILED DESCRIPTION OF FINAL STATES
HEAVY QUARK JETS & FRAGMENTATION

- IRC FLAVOR JET TAGGING WITH ANTI-k_T
- FRAGMENTATION FUNCTION FITS
- FRAGMENTATION FUNCTIONS WITH B-DECAY

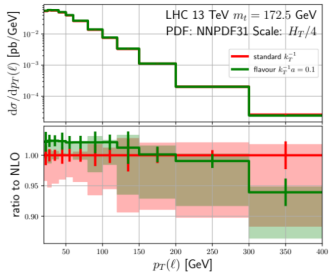
Anti-kT
(IR cutoff for $b\bar{b}b\bar{b}$ ch.)



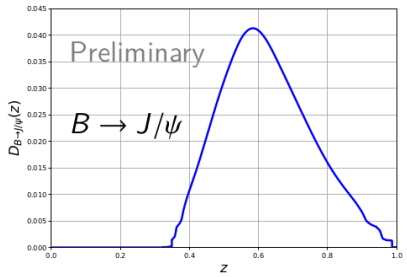
Flavour Anti-kT

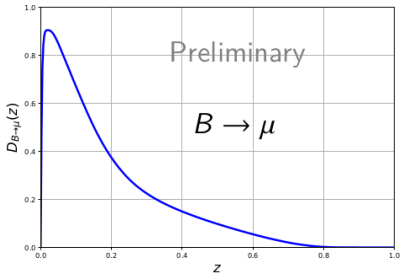


Ratio



- Almost identical perturbative corrections for anti-kT and flavoured anti-kT
- Differences within NNLO scale dependence
  → small impact of IR problematic contributions in ttbar (NWA)

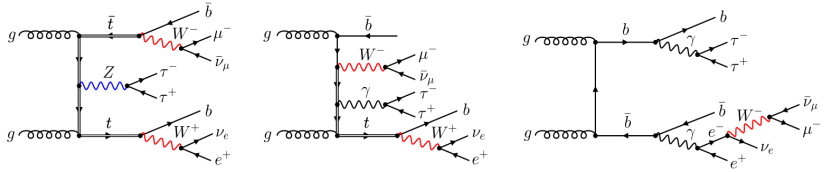




R. Poncelet, T. Generet

OFF-SHELL $t\bar{t}Z$

$pp \to e^+\nu_e\mu^-\nu_\mu bb\tau^+\tau^-$ full off-shell description

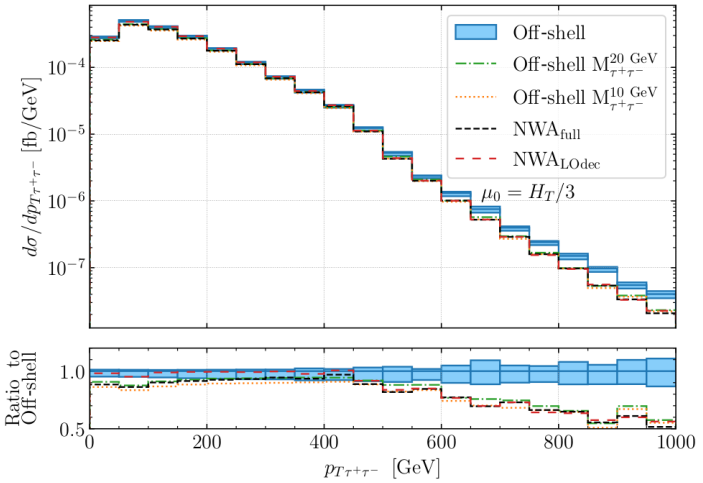


+ NLO QCD

- NLO QCD corrections obtained in the HELAC-NLO framework [Bevilacqua et al., arXiv:110.1499]
  - One-loop matrix elements with HELAC-1LOOP. Real radiation with HELAC-DIPOLES.
- EW G_μ input scheme (G_μ,m_Z,m_W). Other inputs: m_t, Γ_W, Γ_Z, Γ_t (LO, NLO, unstable-W and NWA)
- Unstable particles in complex mass scheme.
- Studied PDF dependence. Main results presented for NNPDF3.1
- Studied (μ_R,μ_F) scale dependence wrt to both a fixed and dynamical central scale (7-point variation)

$$\mu_0 = \frac{2m_t+m_Z}{2} \qquad \mu_0 = \frac{H_T}{3} \text{ for } H_T = \sum_i p_{T,i}$$

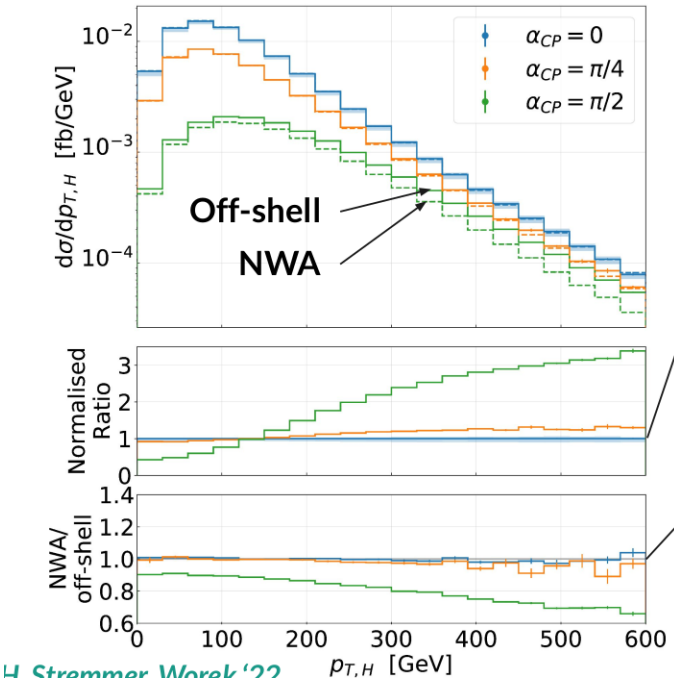
- Specific signature studied: $e^+\nu_e\mu^-\nu_\mu bb\tau^+\tau^-$
  - $p_T^l > 20$ GeV, $|y_l| < 2.5$, $\Delta R_{ll} > 0.4$
  - $p_T^b > 20$ GeV, $|y_b| < 2.5$, $\Delta R_{bb} > 0.4$
  - $p_T^{miss} > 40$ GeV



J. Nasufi, L. Reina

NWA FAILS IN LARGE-p_T REGION

OFF-SHELL $t\bar{t}H$



Shape comparison:

- CP-even and CP-mixed similar, small difference in tails
- Tails much more pronounced in CP-odd case

Off-shell effects:

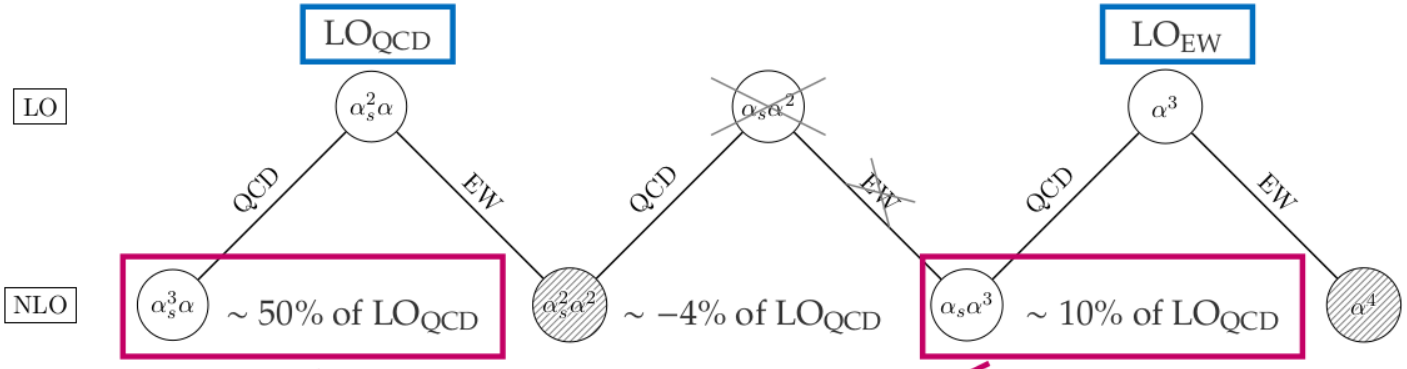
- Large effects on size and shape for CP-odd Higgs boson
- Only small effects for CP-even and CP-mixed

J. Herrmann

- LARGE OFF-SHELL EFFECTS AT LARGE p_T
- ENHANCEMENT OF SINGLE-RESONANT CONTRIBUTION FOR CP-ODD HIGGS

MATCHING TO PS $t\bar{t}W$

LARGE SUPPRESSION EVEN AT INCLUSIVE LEVEL

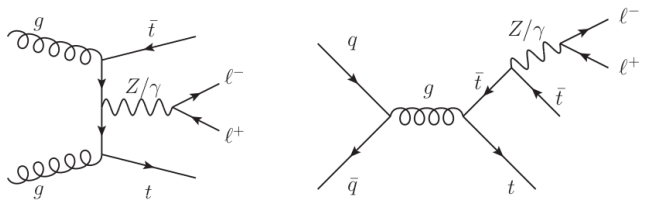


	$\sigma^{\text{NLO QCD}}$	$t\bar{t}W$ QCD	$t\bar{t}W$ EW
NLOPS fixed-order	full off-shell	$1.58^{+3\%}_{-6\%}$	$0.206^{+22\%}_{-17\%}$
	full NWA	$1.57^{+3\%}_{-6\%}$	$0.190^{+22\%}_{-16\%}$
	NWA with LO decays	$1.66^{+10\%}_{-10\%}$	$0.162^{+22\%}_{-16\%}$
	Powheg Box	$1.40^{+11\%}_{-11\%}$	$0.133^{+21\%}_{-16\%}$
	MG5	$1.40^{+11\%}_{-11\%}$	$0.136^{+21\%}_{-16\%}$

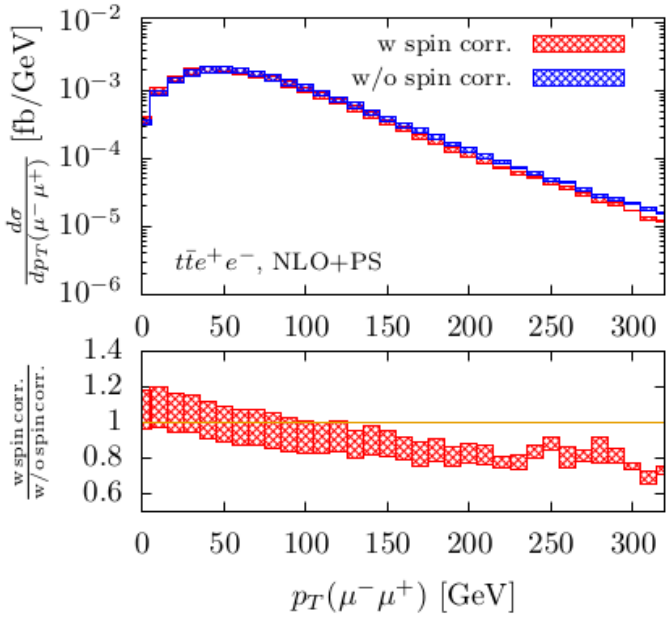
- $t\bar{t}W$ EW ~ 13% of $t\bar{t}W$ QCD
- 9% off-shell effects for $t\bar{t}W$ EW
  Expected: $\Gamma_t/m_t \sim 0.8\%$
- $t\bar{t}W$ QCD uncertainty dependend on decay modelling
- $t\bar{t}W$ EW uncertainty LO like
- NLO+PS cross sections smaller due to radiation in decays (11 – 34%)

M. Kraus

MATCHING TO PS $t\bar{t}Z$



+ NLO QCD + PS

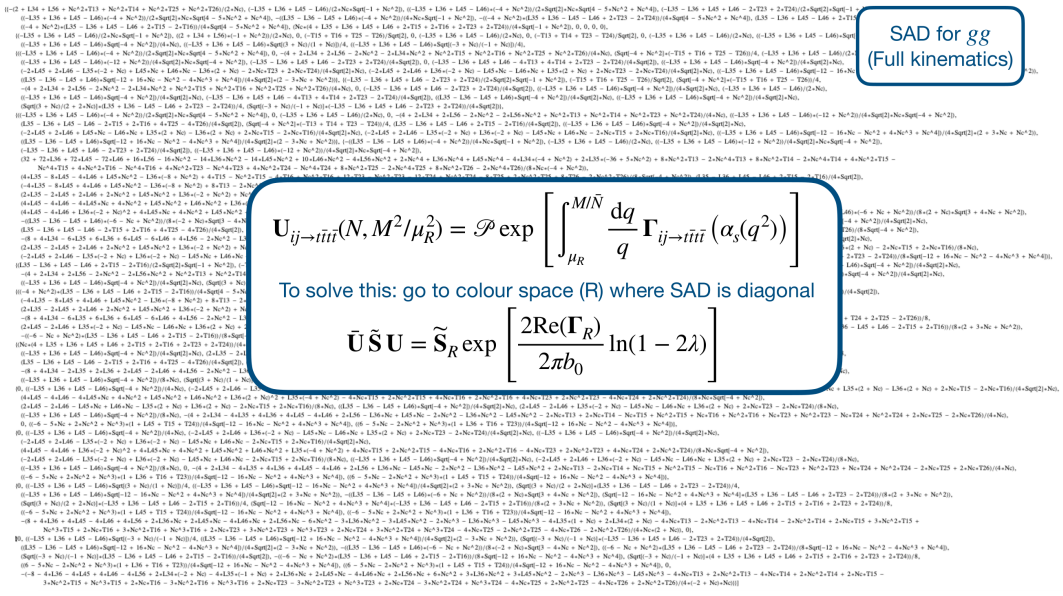


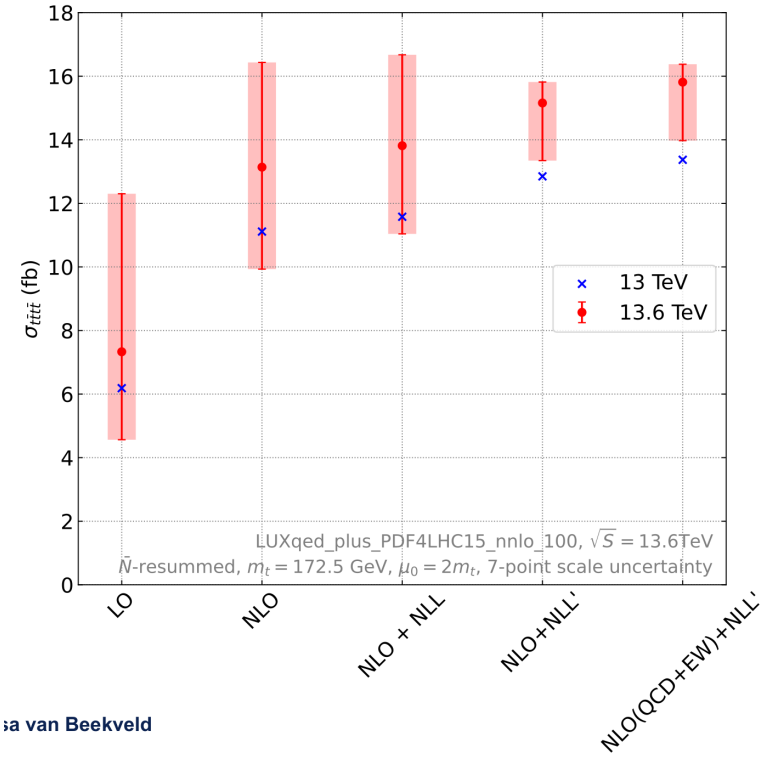
L. Reina

- PARTIAL OFF-SHELL, MATCHING TO PS
- LARGE p_T SUPPRESSION AS IN FULL OFF-SHELL FO

RESUMMATION

- SOFT RESUMMATION STABILIZES PERTURBATIVE EXPANSION
- USEFUL APPROX FOR RARE PROCESSES WHERE FULL FO IS VERY HARD
- EXTENSION TO COMPLEX COLOR STRUCTURE

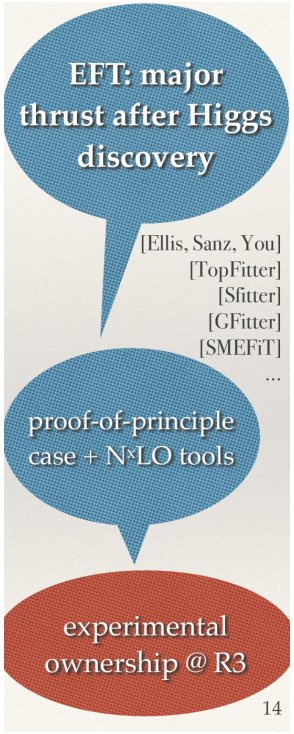




M. van Beekveld

MERGING KNOWLEDGE & PEOPLE

THE SMEFT PARADIGM



C. Englert

Interpreting ttZ measurements

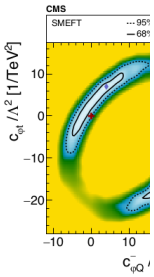
Anomalous top couplings

$$\mathcal{L} = e\bar{u}(p_t)\left[\gamma^\mu(C_{1,V}+\gamma_5 C_{1,A}) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}(C_{2,V}+i\gamma_5 C_{2,A})\right]v(p_{\bar{t}})Z_\mu$$

Effective operators

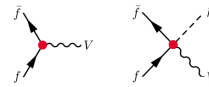
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \left(\frac{1}{\Lambda^2}\sum_i C_i O_i + \text{h.c.}\right) + O(\Lambda^{-4})$$

$$\begin{aligned}
O_{uZ} &= -s_W O_{uB} + c_W O_{uW} \\
O_{uB} &= (\bar{q}\sigma^{\mu\nu}u)(\epsilon\varphi^* B_{\mu\nu}) \\
O_{uW} &= (\bar{q}\tau^I\sigma^{\mu\nu}u)(\epsilon\varphi^* W^I_{\mu\nu}) \\
O_{\varphi u} &= (\bar{u}\gamma^\mu u)(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi) \\
O^-_{\varphi q} &= O^1_{\varphi q} - O^3_{\varphi q} \\
O^1_{\varphi q} &= (\bar{q}\gamma^\mu q)(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi) \\
O^3_{\varphi q} &= (\bar{q}\tau^I\gamma^\mu q)(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi) \\
&\cdots
\end{aligned}$$



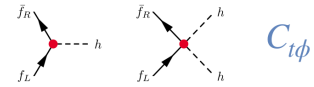
L. Reina

currents $i(\varphi^\dagger \overleftrightarrow{D}^\mu \varphi)(\bar{Q}\gamma^\mu Q)$ — $C_{\phi f}$



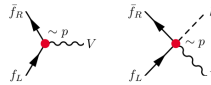
- Shift SM $f\bar{f}V$ couplings
- $f\bar{f}Vh$ contact interactions

Yukawa $(\bar{q}\,t\,\tilde{\varphi})(\varphi^\dagger\varphi)$ — $C_{t\phi}$



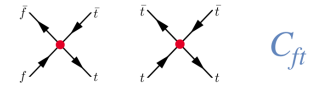
- Decouple m_t & y_t
- $t\bar{t}hh(h)$ contact interactions

dipole $(\bar{q}\,\sigma_{\mu\nu}\,t\,\tilde{\varphi})V^{\mu\nu}$ — C_{tV}



- Chirality flipping $f\bar{f}V$ couplings
- $f\bar{f}V(V)h$ contact interactions
- W, B & G fields

4 fermion $(\bar{q}\gamma_\mu q)(\bar{Q}\gamma^\mu Q)$ $(\bar{Q}\gamma^\mu Q)(\bar{\ell}\gamma_\mu \ell)$ — C_{ft}



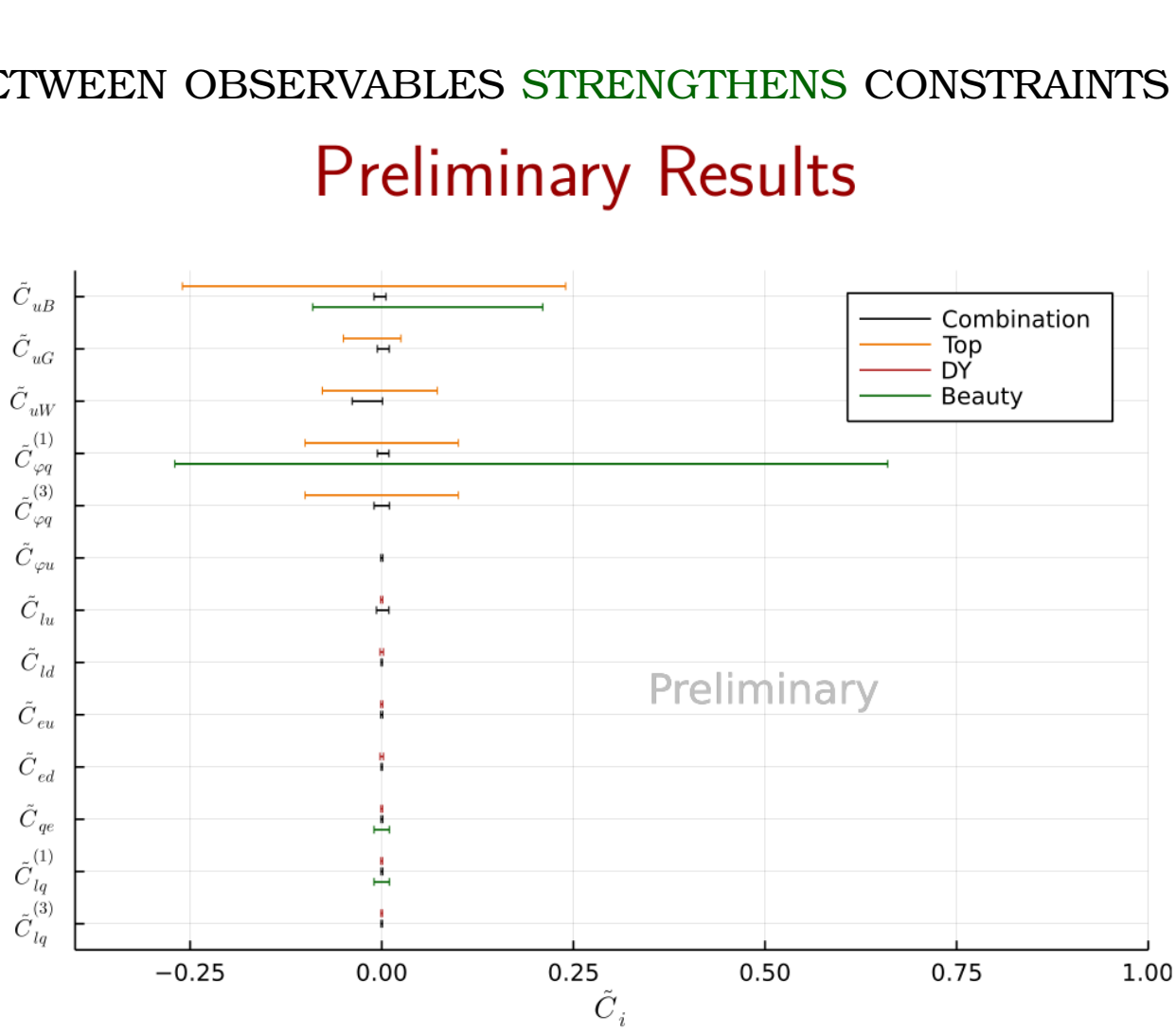
- Contact interactions
- 2-heavy-2-light or 4-heavy
- Numerous (~O(20) w/ top)

E. Vryonidou

- FUNDAMENTAL LAGRANGIAN COUPLINGS $\Rightarrow$ EFFECTIVE LAGRANGIAN INTERACTIONS
- WHO OWNS THE SMEFT?

WHICH SMEFT?

INTERPLAY BETWEEN OBSERVABLES STRENGTHENS CONSTRAINTS

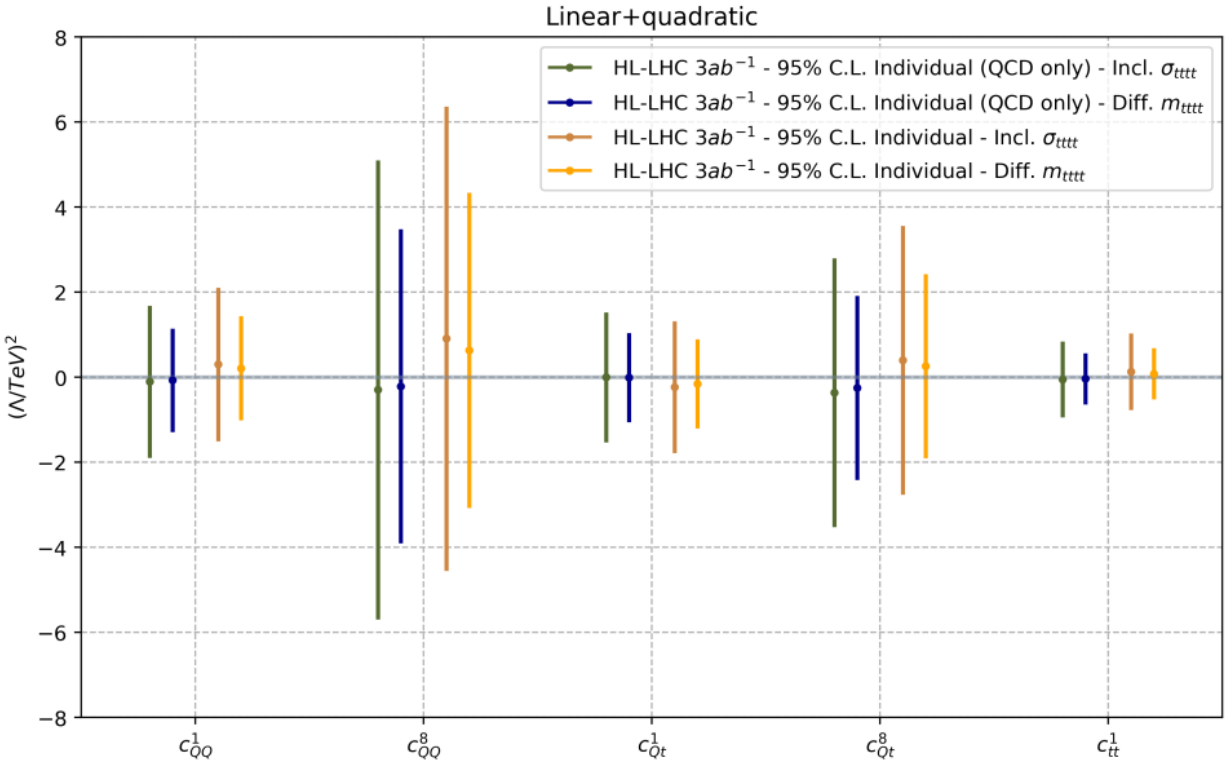


L. Nollen

WHICH SMEFT?

Toy fit: impact of differential information

We add information from m_{tttt} in three bins ...



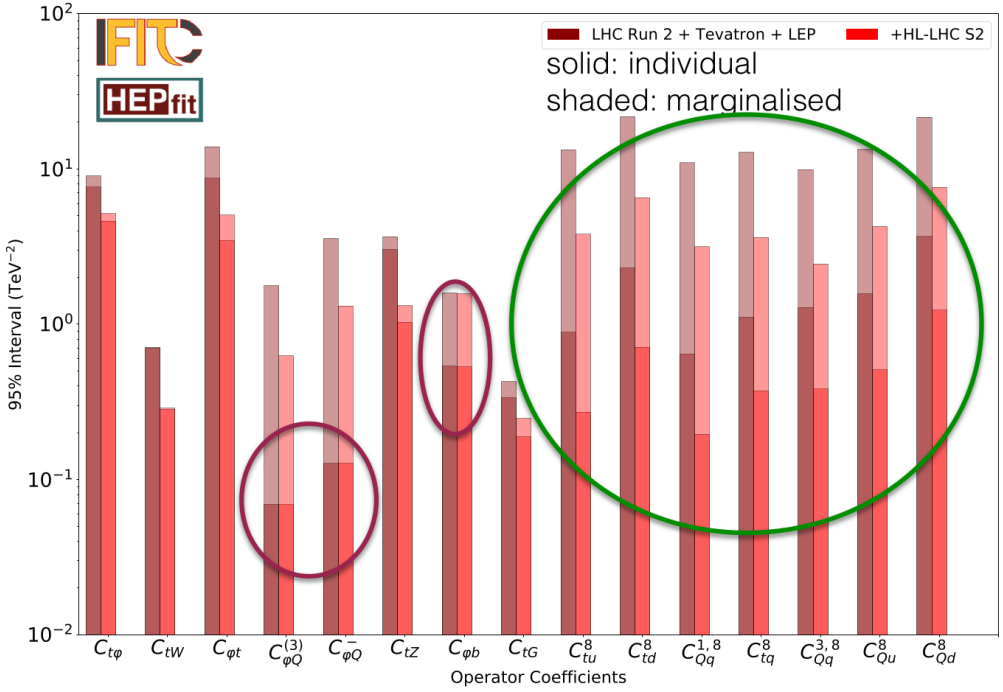
differential information improves sensitivity

H. El Faham

MORE DIFFERENTIAL OBSERVABLES HAVE GREATER IMPACT

WHICH SMEFT?

IMPROVEMENT IN ACCURACY AT HL-LHC



arXiv:2205.02140

Best improvement: 4-fermion operators driven by differential measurements extending to higher energies

Not much improvement $C^{-}_{\phi Q}$ and $C^{3}_{\phi Q}$ (dominated by bLEP)

Limited by theory and modelling uncertainties

2-quark-2-lepton not fitted (need $t\bar{t}\ell\bar{\ell}$)

Difference in individual and marginalised limits persists at HL for 4-fermion operators

E. Vryonidou

GLOBAL SMEFT?

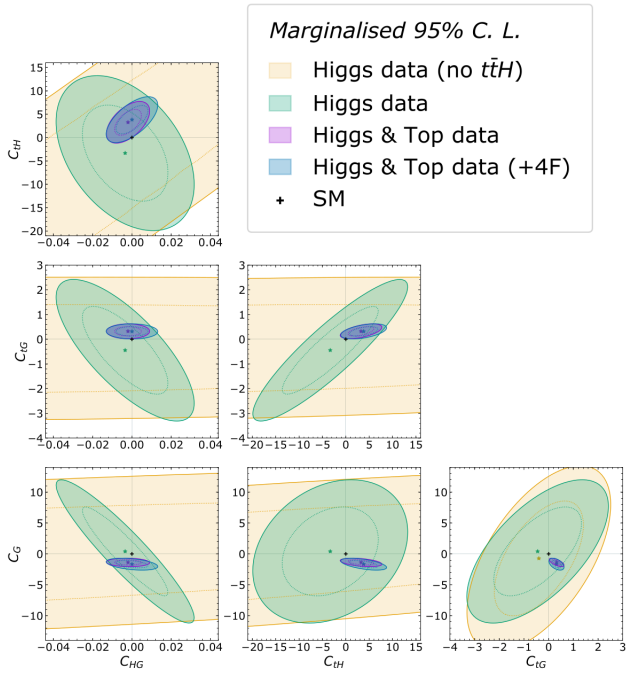
- INTERPLAY BETWEEN OBSERVABLES STRENGTHENS CONSTRAINTS
- MUST INCLUDE PDFS FOR ROBUST RESULTS

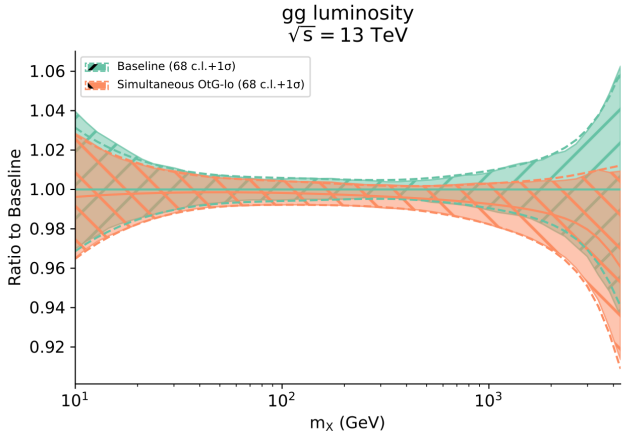
Top-Higgs interplay

How do the constraints on $C_{HG}, C_{tG}, C_G, C_{tH}$ change as we include more top quark data?

We marginalise over
$C_{H\Box}, C_{HW}, C_{HB}, C_{bH}, C_{\tau H}, C_{\mu H} (+ \text{ 4-fermion operators})$

- *ttH* removes the degeneracy between C_{HG}, C_{tH}.
- top quark data substantially **reduces the area** constrained at 95 % CL and **suppresses some correlations**.
- this is true even when marginalising over all 4-fermion operators involving top quarks.

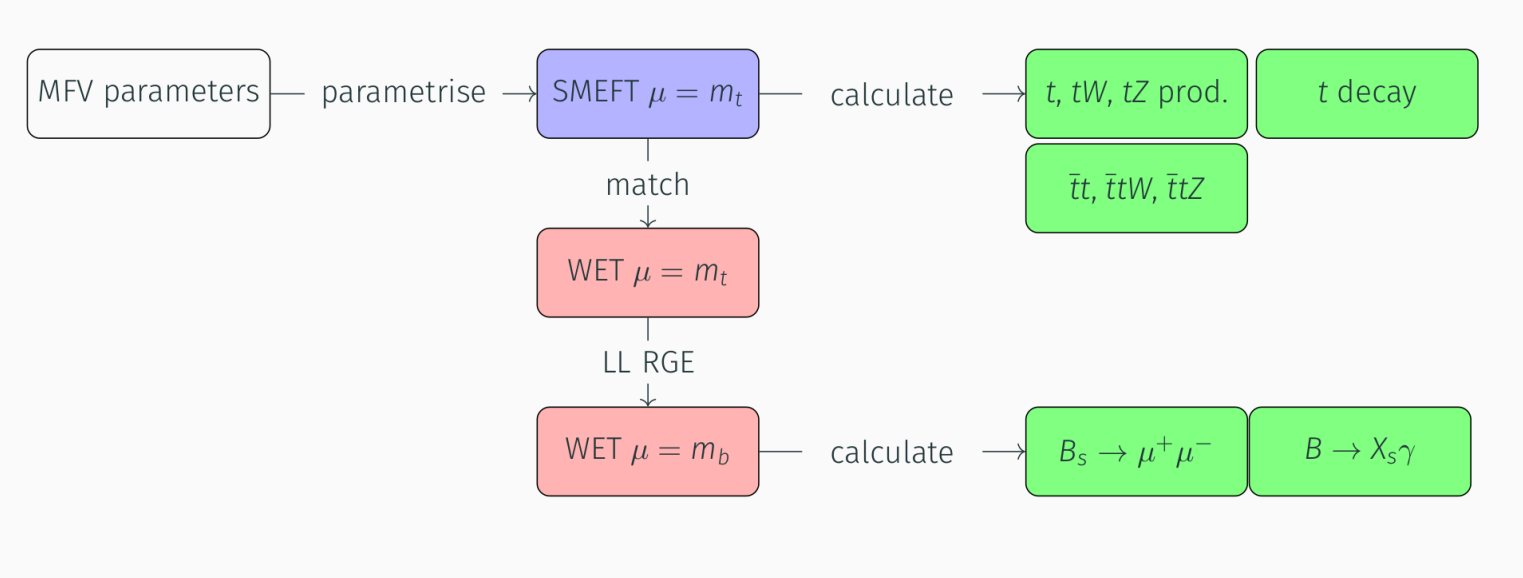




M. Madigan

WHICH SMEFT?

- FLAVOR PHYSICS: REDUCE AND OPTIMIZE SET OF OPERATORS
- WET: INTEGRATE OUT DEGREES OF FREEDOM ABOVE THE EW SCALE



D. van Dyk

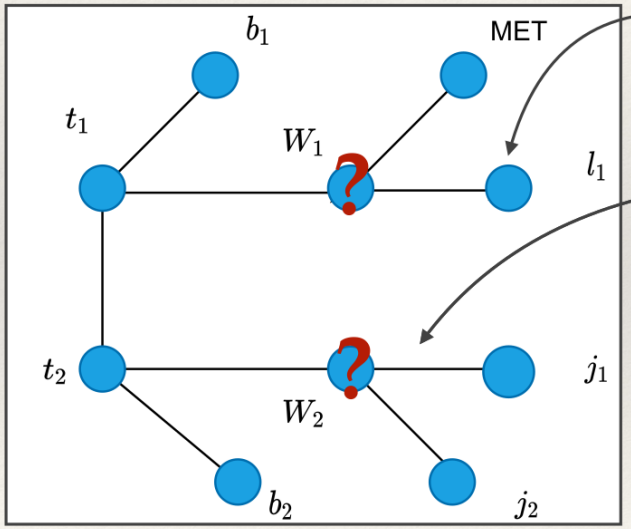
OPTIMAL SMEFT?

USE ML TOOLS TO OPTIMIZE CORRELATIONS?

- Can we impart Feynman-graph correlations on measurements to enhance BSM sensitivity?

...Graph Neural Networks

jet tagging [Dreyer, Hu ` 20]
anomaly detection [Atkinson et al. ` 21]
...



nodes with *features*
$[p_T, \eta, \phi, E, m, \text{PID}]$

edges for *feature correlation*

e.g. W reconstructions vs four fermion discrimination

supervised training over graph structures to enhance BSM sensitivity

C. Englert

OPTIMAL SMEFT FOR CPV

- SEARCH FOR CPV
- COMBINE MANY OBSERVABLES
- USE NN TO DETERMINE OPTIMIZED CONSTRAINT

– validation sample of 2.5 × 10⁷ events

Approaches to optimisation:

1) Phase space optimisation of a single ω_i

$$\mathscr{F}\left(\boldsymbol{x}, \omega_i; \boldsymbol{\alpha}\right) = \underbrace{f(\boldsymbol{x}; \boldsymbol{\alpha})}\omega_i$$

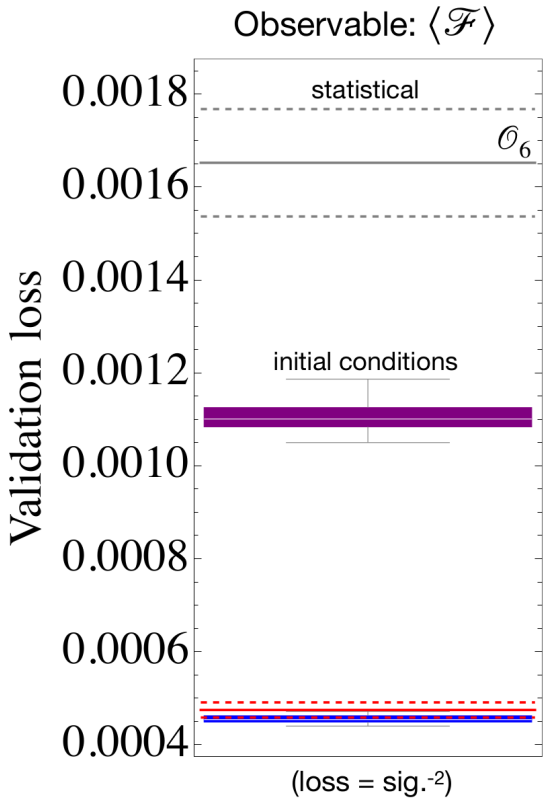
NN=optimal weight function with $\boldsymbol{x} = \begin{pmatrix} (\boldsymbol{p}_{\ell^+} + \boldsymbol{p}_{\ell^-}) \cdot \boldsymbol{p}_h \\ (\boldsymbol{p}_{\ell^+} + \boldsymbol{p}_{\ell^-}) \cdot (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}}) \\ (\boldsymbol{p}_b + \boldsymbol{p}_{\bar{b}}) \cdot \boldsymbol{p}_h \\ \boldsymbol{p}_{\ell^+} \cdot \boldsymbol{p}_{\ell^-} \\ \boldsymbol{p}_b \cdot \boldsymbol{p}_{\bar{b}} \end{pmatrix}$

2) NN as a CP-odd observable

$$\mathscr{F}(\boldsymbol{X}; \boldsymbol{\alpha}) = F(\boldsymbol{\omega}; \boldsymbol{\alpha}) \text{ with } F(\boldsymbol{\omega}; \boldsymbol{\alpha}) = -F(-\boldsymbol{\omega}; \boldsymbol{\alpha})$$

3) Linear approximation of 2)

$$F(\boldsymbol{\omega}; \boldsymbol{\alpha}) = \sum_{j=1}^{22} \alpha_j \omega_j + \mathcal{O}\left(\omega^3\right)$$

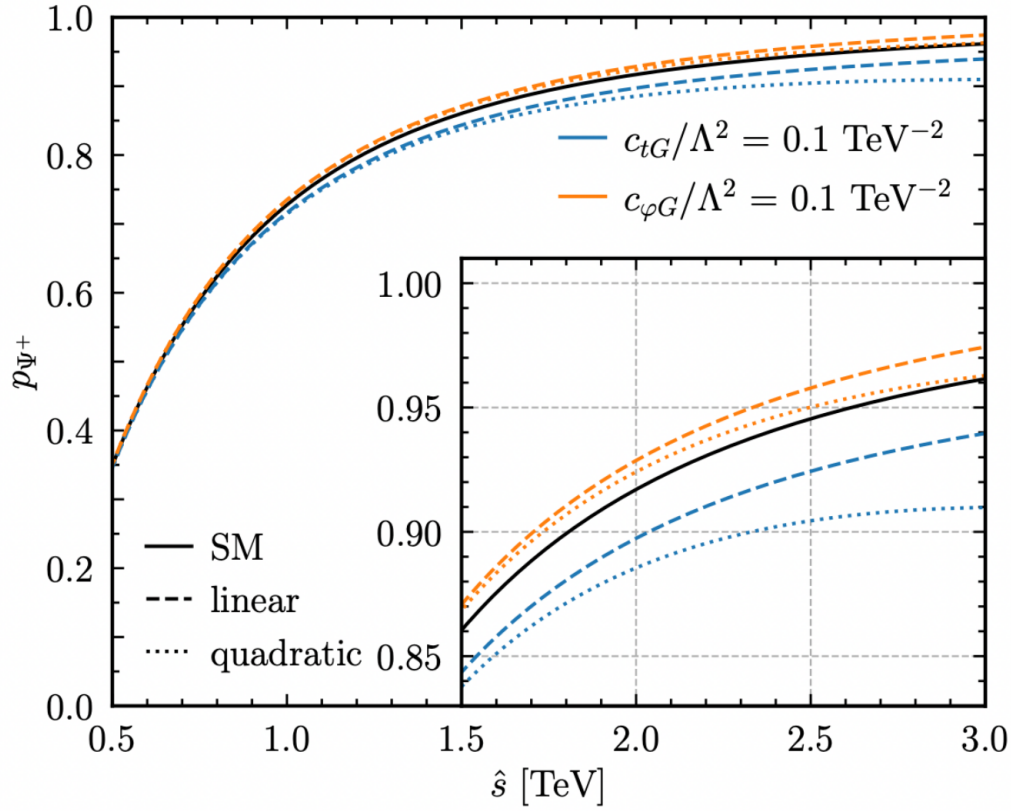


A. Smolkovic

OPTIMIZED SMEFT AND ENTANGLEMENT

USE ENTANGLEMENT PATTERNS TO DETECT DEVIATIONS FROM SM

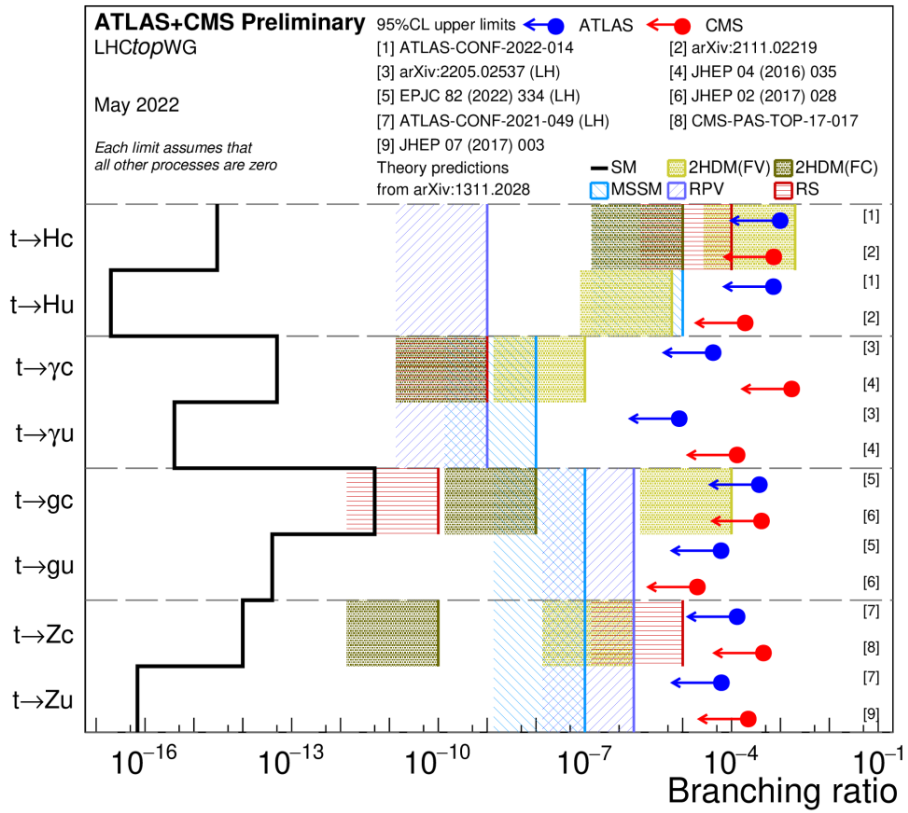
$$p_{\Psi+} = \langle \Psi^+ |_n \, \rho \, | \Psi^+ \rangle_n$$ Probability triplet state

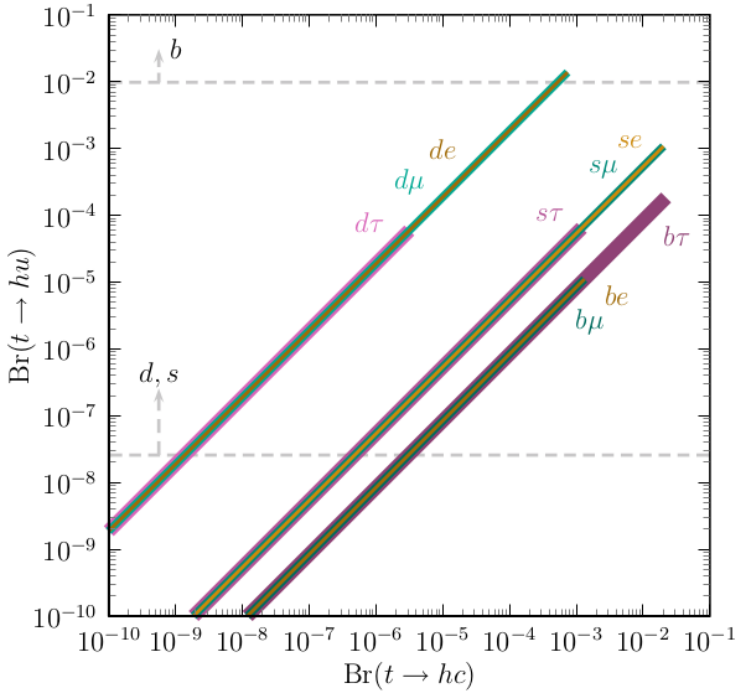


L. Mantani

DIRECT SEARCHES: FCNC

- FCNC INDUCED IN 2HDM, VLQ, . . .
- SEARCHED DIRECTLY IN DECAYS



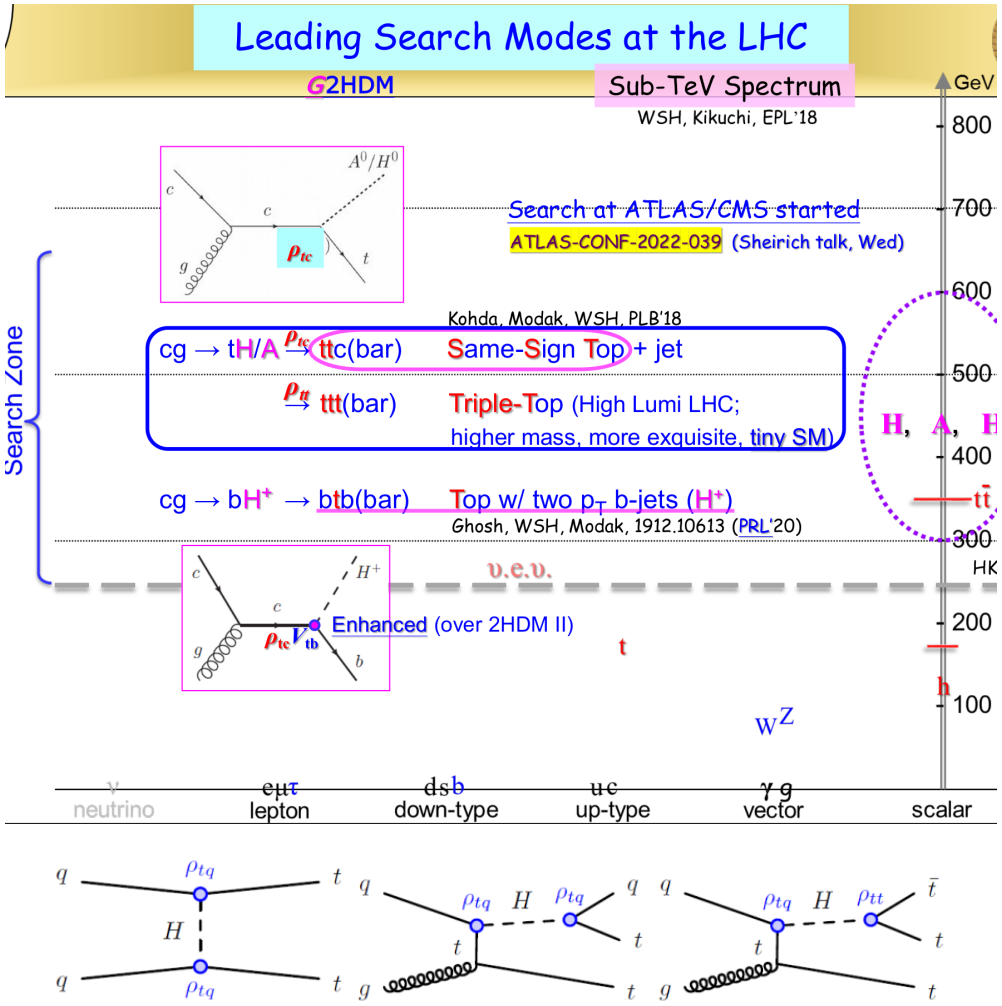


$t \to hu$ vs $t \to hc$

M. Nebot

DIRECT SEARCHES: 2HDM

FCNC FAVORED SEARCH MODE

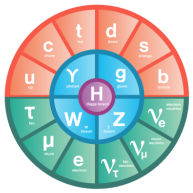


G. Hou

DIRECT SEARCHES: TWIN HIGGS

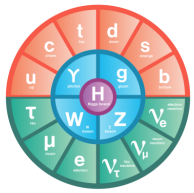
- TWIN SM PARTNERS
- SEEN IN RARE PROCESSES

Standard Model



$\mathcal{Z}_2$

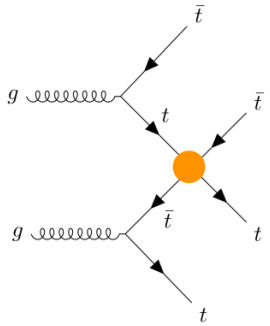
Twin Standard Model



$$\mathcal{L} = y_t Q_A H_A t_A + \hat{y}_t Q_B H_B t_B$$

The top partners are neutral under whole SM (& charged under Twin QCD)
They can still be really light

Leading effect: $\frac{1}{f^2}(\bar{t}_R \gamma^\mu t_R)^2$



$f > (1.3 - 1.7\ \text{TeV})$

[multi-lepton + jets projection, Banelli et al. 2010.05915]

(HL-LHC)

E. Salvioni

CONCLUSION

LINES OF DEVELOPMENT & DESIDERATA

- THEORY AND EXPERIMENT COMING TOGETHER
  - EXPERIMENT: UNFOLDING VS. TEMPLATES
  - THEORY: FIDUCIAL PREDICTIONS
- DESIDERATA FOR EXPERIMENT
  - AVAILABILITY OF CORRELATIONS
  - RARE PROCESSES
  - LARGE p_T
- DESIDERATA FOR THEORY
  - FROM BSM MODELS TO SIGNALS
  - SMEFT VS. DIRECT SEARCHES
  - UNDERSTAND RELEVANT CORRECTIONS

BEYOND CONCRETE