WG6 SUMMARY: HIGH-P_T FLAVOUR PHYSICS

Conveners:
Kai-Feng Chen (NTU), Andrea Knue (Freiburg), Michihisa Takeuchi (SYSU)

HighPT Flavor physics : Higgs, Top, New heavy particles

For CKM workshop, new CP phases required for BAU
Extended Higgs/top sector, new particles required

3 theory talks

- Higgs and CP violation (in BSM models)
- How much room is there for discoveries?
- Quantum information with top quarks

11 experimental talks

- ATLAS, CMS on Higgs, Top, new particles

Thank you for all the contributions in WG6

Top quark events: both abundant and rare!

Top pairs produced in abundance at the LHC: 115 M events in Run 2 for ATLAS and CMS each

⇒ production via the strong interaction

Single-top production also plentiful: 40 M events per experiment

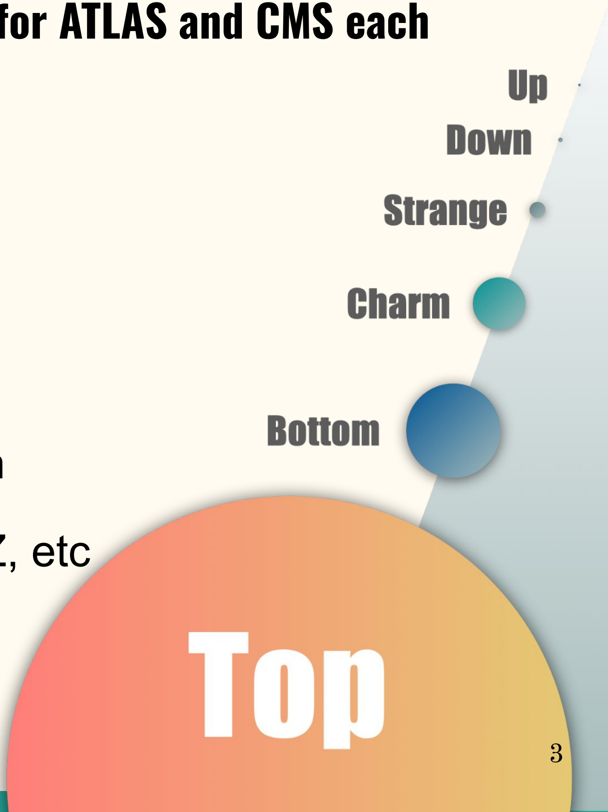
⇒ production via the electroweak interaction

Many other processes possible!

⇒ associated top-pair production like ttZ,ttW,ttH,tt+photon

⇒ associated single-top production like top+γ, top+Z, tWZ, etc

⇒ production of four top quarks at the same time:
only 1700 events expected per experiment!



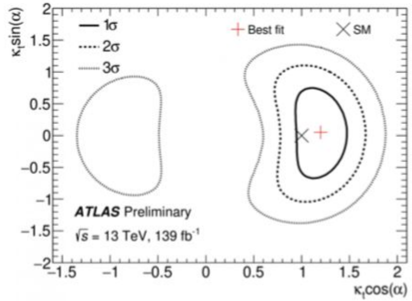
CP Violation in (extended) Higgs sector by Rui Santos

2 types of CPV:

CPV from P-violation

C conserving, CP violating interaction

$$\bar{\psi}(a + ib\gamma_5)\psi\,\phi$$



$$\mathcal{L}^{CPV}_{\bar{t}th} = -\frac{y_f}{\sqrt{2}}\,\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)\,t\,h \qquad \kappa_t = \kappa\cos\alpha \qquad \tilde{\kappa}_t = \kappa\sin\alpha$$

Rates alone already constrained a lot the CP-odd component.

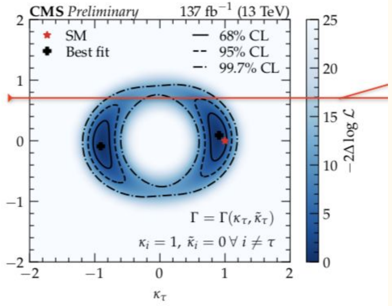
Now, also available in $pp \to (h \to \bar{b}b)\bar{t}t$.

R. Santos, CKM2023, SC, 18 Sep 2023 9

U, D, L : separately to be checked

but challenging for yb using bbH

CPV from P-violation needs only one Higgs



CMS COLLABORATION, CMS-PAS-HIG-20-006

$pp \to h \to \tau^+\tau^-$

$$\mathcal{L}^{CPV}_{\bar{\tau}\tau h} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(\kappa_\tau + i\tilde{\kappa}_\tau\gamma_5)\,\tau\,h$$

Direct searches for CP-odd component in Yukawa couplings provide more than EDMs

CP Violation in (extended) Higgs sector by Rui Santos

CPV from C-violation

In 2HDM, for gauge and higgs sector P is conserved. If C is also conserved,

$$CZ_\mu C^{-1} = -Z_\mu \qquad C(h) = C(H) = 1 \qquad C(G_0) = C(A) = -1$$

→ Existence of interaction with odd number of C-odd particles (Z and A) is the sign of CPV

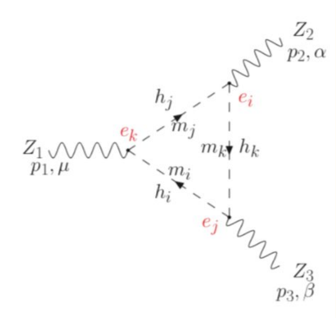
A combination of 3 decays signals CP-violation

$$h_2H^+H^-; \quad h_3H^+H^-; \quad Zh_2h_3$$

$$h_2h_kh_k; \quad h_3H^+H^-; \quad Zh_2h_3; \quad (k=2,3) \quad (2 \leftrightarrow 3)$$

$$h_2h_kh_k; \quad h_3h_lh_l;; \quad Zh_2h_3; \quad (k,l=2,3)$$

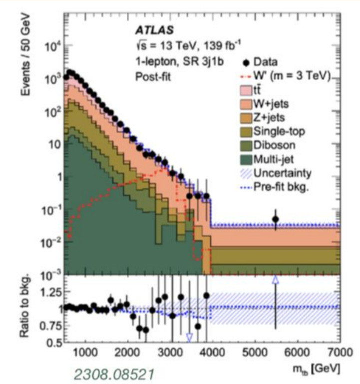
HABER, KEUS, RS, PRD 106 (2022) 9, 095038



CPV from C-violation needs at least two Higgs.

Discovering extra scalars and test their CP-numbers at the LHC is within the reach of many models (C2HDM)

PDF-EFT interplay by Maeve Madigan



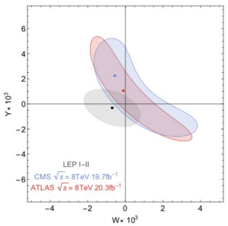
In High pT tail,

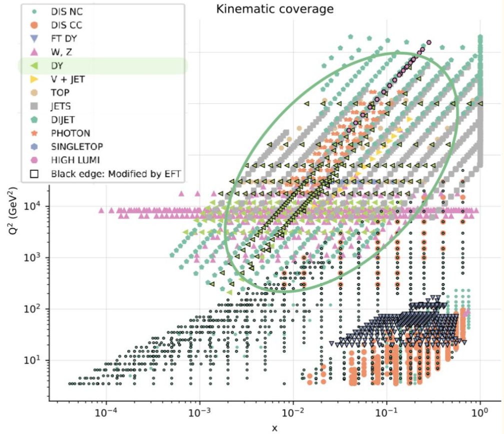
Fake new physics ⇆ PDF effects?

No new physics ⇆ absorbed by PDF?

Data overlap

- e.g. High-mass Drell-Yan data used to fit the SMEFT 4-fermion operators in *Farina et. al 1609.08157*



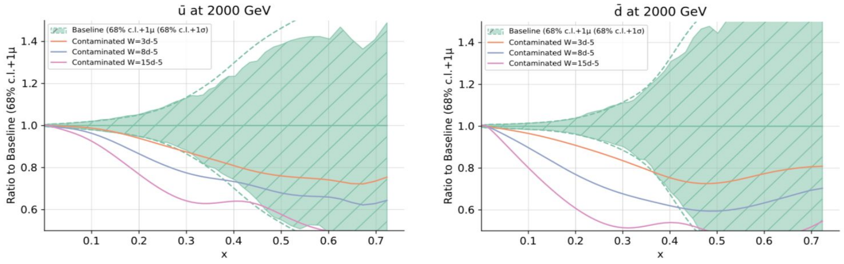


Data included in our study

Injecting W' signal will modify the PDFs

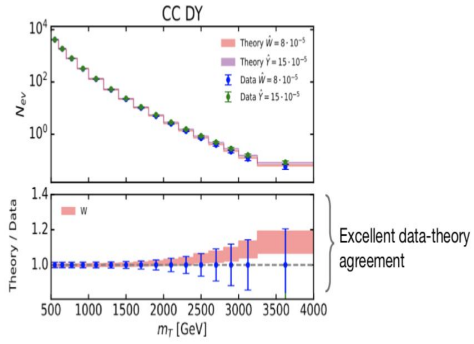
W'-contaminated PDFs

Data: 'true' PDF ⊗ SM + W'
Theory: contaminated PDF ⊗ SM

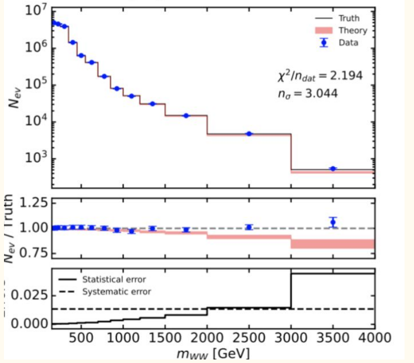


Fewer constraints on the **large-x antiquark PDFs** allow freedom to shift away from the baseline

The shift in the PDFs compensates the NP effects



causes **spurious NP effects**



PDF-EFT interplay by Maeve Madigan

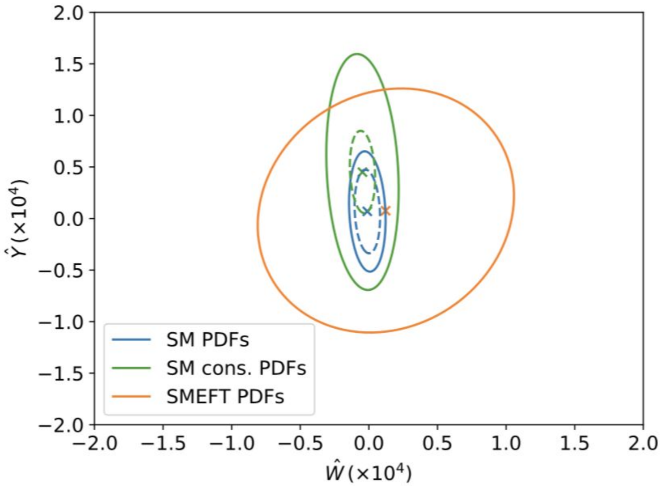
ex) W' signal can fake WW excess etc.

Simultaneous fit of PDFs and SMEFT in high mass DY

Greljo et. al 2104.02723

Including **HL-LHC projections** for NC and CC Drell-Yan:

Neglecting PDF-EFT interplay leads to a significant overestimate of the EFT constraints.



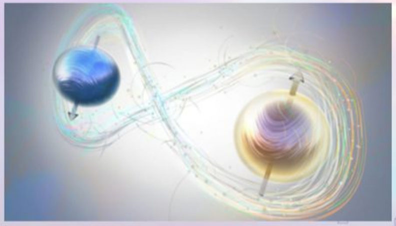
Tools to investigate contaminated PDF fits in other BSM scenarios are publicly available:
https://www.pbsp.org.uk/contamination/

Quantum Information with top quarks by Juan Ramon Munoz de Nova

Top pair ⇆ 2 qubits

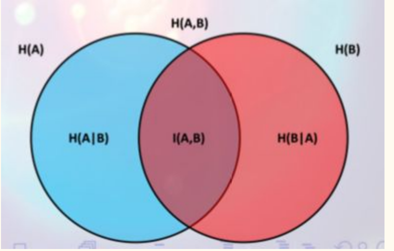
General density matrix (4×4) for 2 qubits $\rightarrow$ 15 parameters $B_i^{\pm}$, C_{ij}

$$\rho = \frac{1 + \sum_i \left(B_i^+ \sigma^i \otimes 1 + B_i^- 1 \otimes \sigma^i\right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j}{4}$$

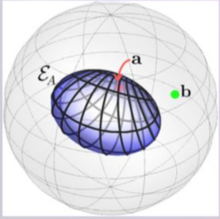


4 hierarchical concepts for non-classical correlation

$$I(A,B) = H(A) + H(B) - H(A,B) = H(A) - H(A|B)$$



$$\rho_{\hat{\mathbf{n}}} = \frac{\tilde{\rho}_{\hat{\mathbf{n}}}}{\mathrm{Tr}\tilde{\rho}_{\hat{\mathbf{n}}}} = \frac{1 + \mathbf{B}^+_{\hat{\mathbf{n}}} \cdot \sigma}{2}, \quad \mathbf{B}^+_{\hat{\mathbf{n}}} = \frac{\mathbf{B}^+ + \mathbf{C} \cdot \hat{\mathbf{n}}}{1 + \hat{\mathbf{n}} \cdot \mathbf{B}^-}$$



$$\rho = \int \mathrm{d}\Omega_A \mathrm{d}\Omega_B \, P(\mathbf{n}_A, \mathbf{n}_B) \left|\mathbf{n}_A \mathbf{n}_B\right\rangle \left\langle \mathbf{n}_A \mathbf{n}_B\right|$$

Separability=Positive P-representation $P(\mathbf{n}_A, \mathbf{n}_B) \geq 0$:

CHSH inequality ($\mathbf{a}_i, \mathbf{b}_i$ spin axes of measurements M_A, M_B)

$$\left|\mathbf{a}_1^{\mathrm{T}} \mathbf{C} (\mathbf{b}_1 - \mathbf{b}_2) + \mathbf{a}_2^{\mathrm{T}} \mathbf{C} (\mathbf{b}_1 + \mathbf{b}_2)\right| \leq 2$$

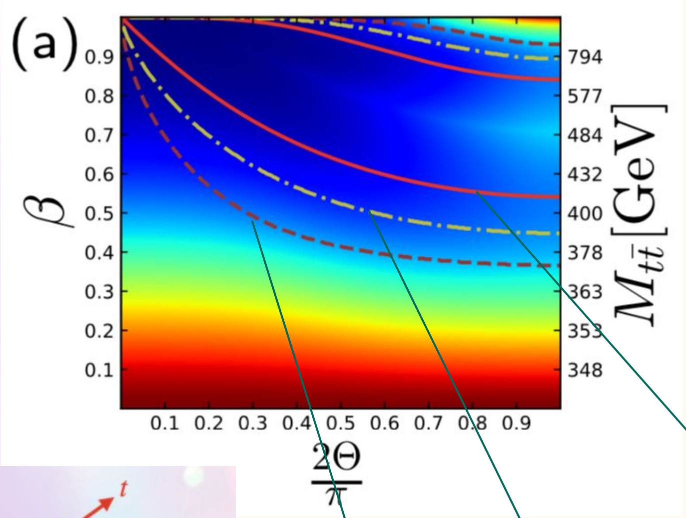
$$\mathcal{D}(A,B) \equiv H(B) - H(A,B) + H(A|B) \neq 0$$

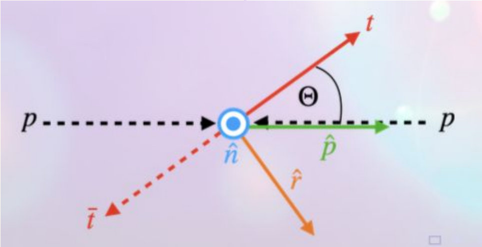
Bell Nonlocality $\subset$ *Steering* $\subset$ *Entanglement* $\subset$ *Discord*

Quantum Information with top quarks by Juan Ramon Munoz de Nova

gg→tt

color:Discord





$$p(\hat{\ell}_+,\hat{\ell}_-)=\frac{1}{\sigma_{\ell\bar{\ell}}}\frac{d\sigma_{\ell\bar{\ell}}}{d\Omega_+ d\Omega_-}=\frac{1+\mathbf{B}^+\cdot\hat{\ell}_+-\mathbf{B}^-\cdot\hat{\ell}_--\hat{\ell}_+\cdot\mathbf{C}\cdot\hat{\ell}_-}{(4\pi)^2}$$

$$p(\hat{\ell}_\pm|\hat{\ell}_\mp=\mp\hat{\mathbf{n}})=\frac{p(\hat{\ell}_\pm,\hat{\ell}_\mp=\mp\hat{\mathbf{n}})}{p(\hat{\ell}_\mp=\mp\hat{\mathbf{n}})}=\frac{1\pm\mathbf{B}^\pm_{\hat{\mathbf{n}}}\cdot\hat{\ell}_\pm}{4\pi}$$

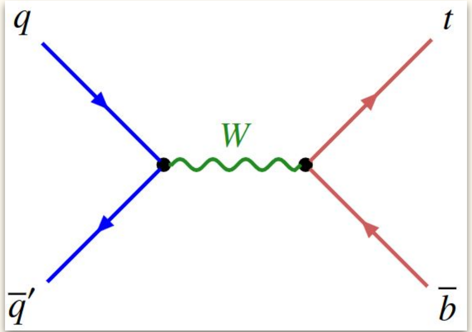
- Actual discord → Evaluated from minimization over $\hat{\mathbf{n}}$.
- Measurement of $\mathbf{B}^\pm_{\hat{\mathbf{n}}}$ → Reconstruction of $t,\bar{t}$ steering ellipsoids.
- Highly-challenging measurements in conventional setups → Natural implementation in colliders!

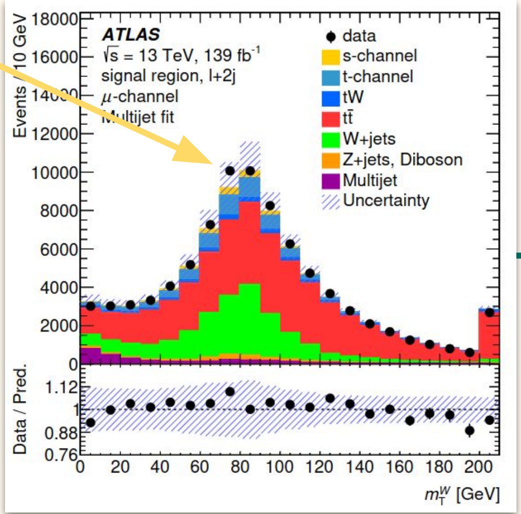
Bell Nonlocality ⊂ *Steering* ⊂ *Entanglement* ⊂ *Discord*


top quark
Higgs boson
positron
tau
antiproton
antitau
antimuon

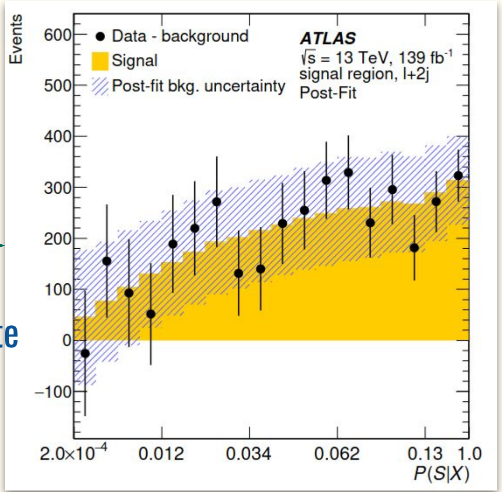
Start with rare candidate: single top in s-channel production

The elusive signal process





Need Matrix-Element discriminant to isolate the signal!

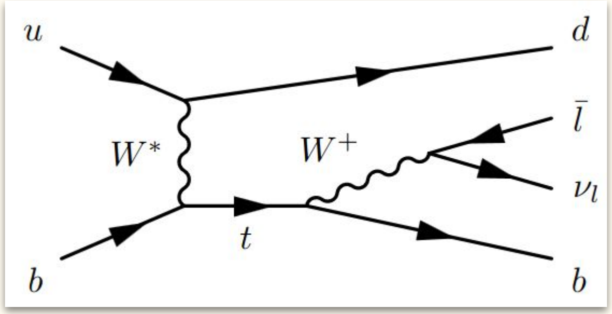


M. Llácer

- Only observed at the Tevatron so far (due to the presence of valence anti-quarks)
- Relative uncertainty:
  - ~ 40%, dominated by tt normalisation, jet-related uncertainties and parton-shower uncertainties
- Significance: 3.3 (3.9) standard deviations observed (expected)
- tW process: already observed at Run I, not discussed in detail here

Bread-and-butter: single top as access to CKM

M. Llácer

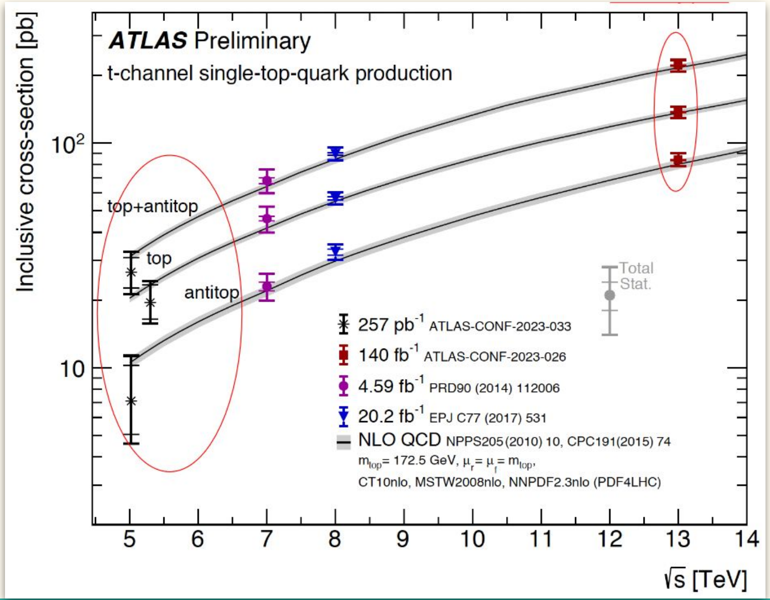


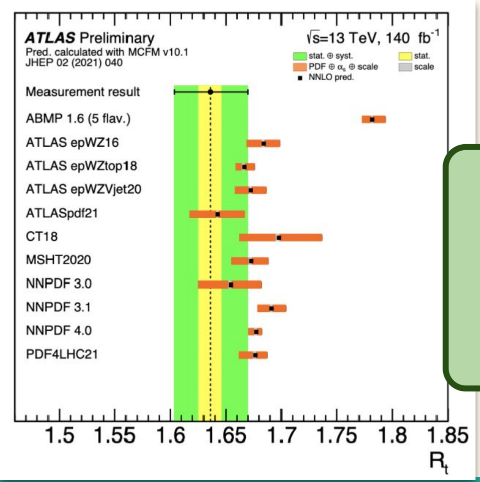
Two new measurements in t-channel:

- 5 TeV channel: probe different part of PDF
- 13 TeV: several improvements allow for 6% precision

Both analyses rely on machine-learning techniques:

- 5 TeV: strong selection cuts first, then use boosted decision tree
- 13 TeV: less stringent pre-selection, but more powerful classifier to isolate the signal





Measure top-/anti-top cross-section and ratio, compare to predictions with different PDFs

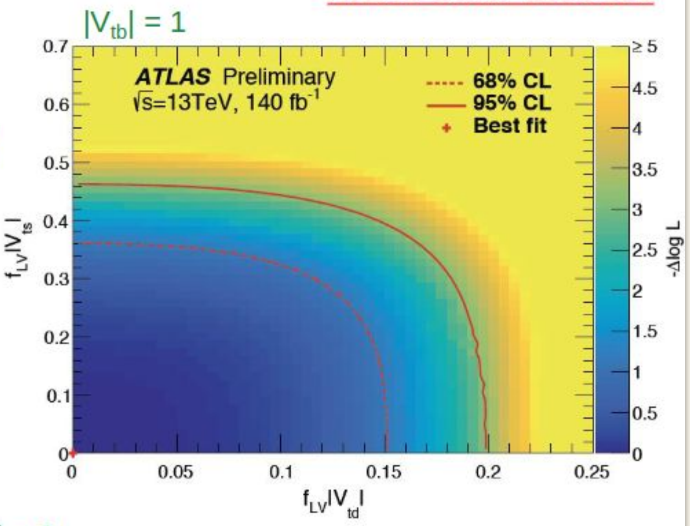
ATLAS-CONF-2023-026

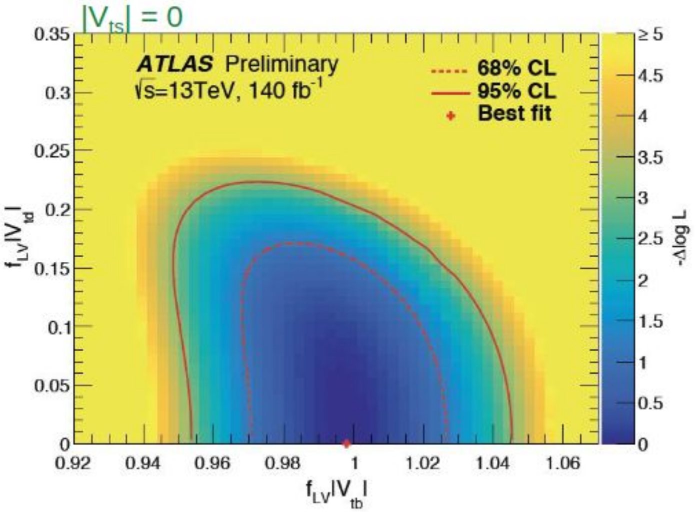
$$\frac{\sigma(tq+\bar{t}q)}{\sigma_{theo}} = f_{LV}^2|V_{tb}|^2$$

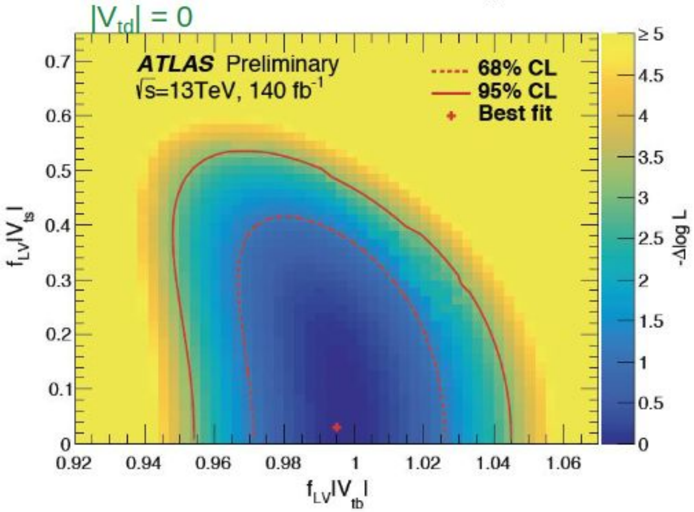
- Determination of V_{tb}:
  - $f_{LV}\cdot|V_{tb}| = 1.016 \pm 0.031$ $|V_{tb}| \gg |V_{td}|, |V_{ts}|$, LH coupling
  - $|V_{tb}| > 0.95$ (95% CL) asuming $|V_{tb}| \in [0,1]$ and $f_{LV}=1$

- Generalised CKM interpretation:
  - $f_{LV}\cdot|V_{tb}| \in [0.955, 1.045]$ at 95%CL
  - $f_{LV}\cdot|V_{td}| < 0.22$ and $f_{LV}\cdot|V_{ts}| < 0.54$

- All results in agreement with NNLO calculation







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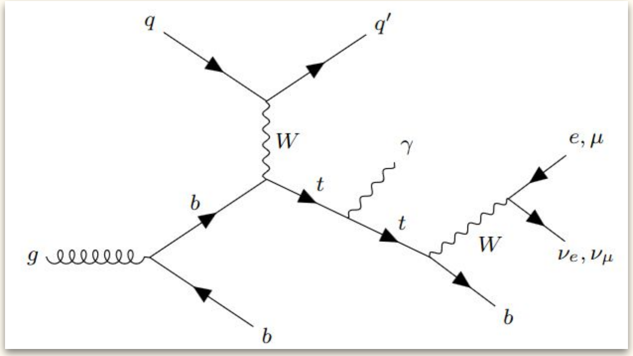
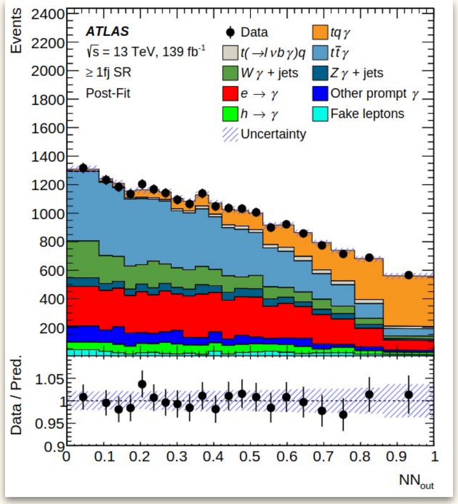
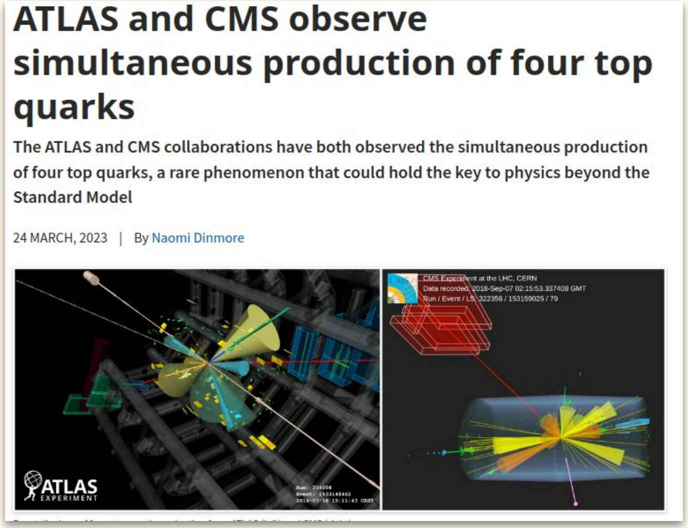
CKM Interpretation from Single-top t-channel

Era of “Standard model top discoveries”!

- Single-top + photon process
- Cross-section only about 515 fb
- Neural network allows to isolate signal
- First observation of this process!
  - Paper: arXiv:2302.01283





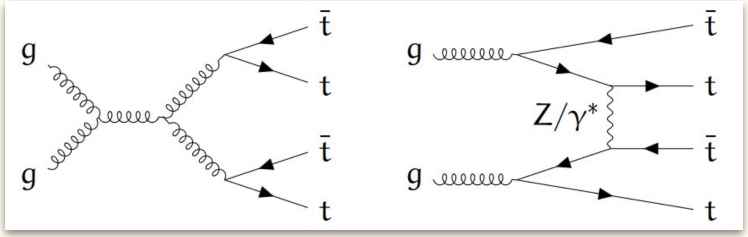


ATLAS and CMS observe simultaneous production of four top quarks

The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore

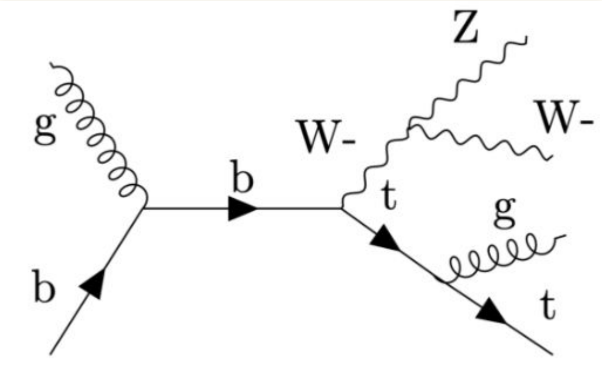
- 4-top production: cross-section only 12 fb
- Expect only 1,700 events in Run 2 per experiment
- Channel with highest precision: multilepton final states
- Observed both by ATLAS and CMS early this year!
  - CMS paper: arXiv:2305.13439
  - ATLAS paper: Eur. Phys. J. C 83 (2023) 496



B. Gonzalez

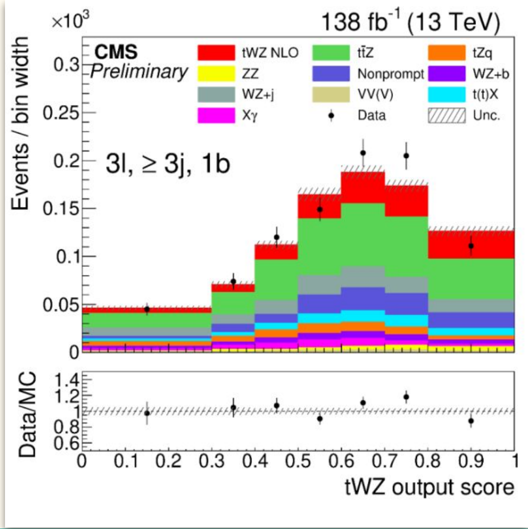
Another "heavy" final state: tWZ production

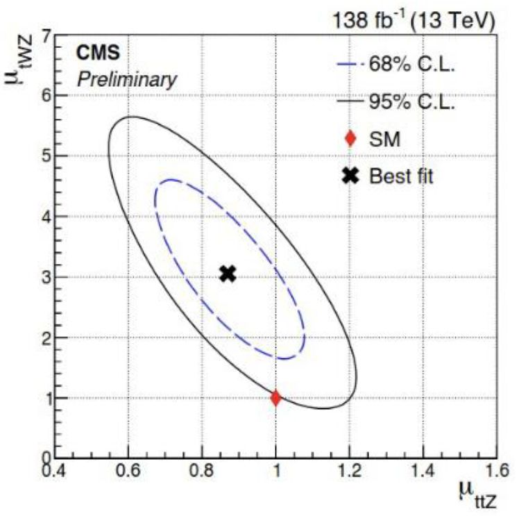
M. Llácer



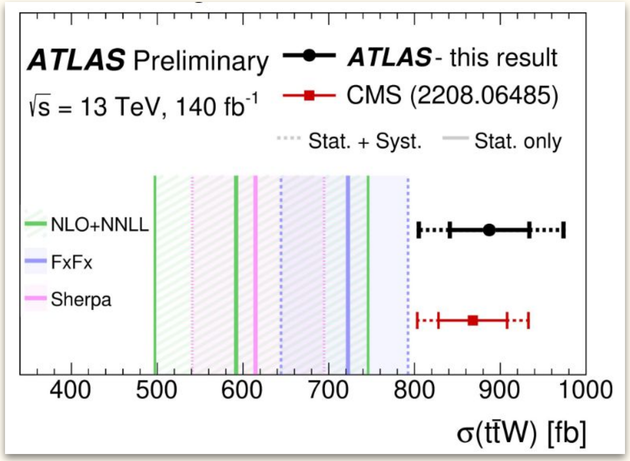
- tWZ is also a rare process: cross-section = 136 fb
- But not as rare as 4-top production!
- Why have we not observed it yet?
  - Large ttZ background (green) compared to the signal (red)
  - Difficult to calculate: interference between tWZ and ttZ at NLO
- Result presented here: focus on final states with 3 or 4 leptons
- Even machine-learning could not clearly separate signal and background

- Expected significance: 1.4 sigma
- Already limited by systematics
- Observed significance: 3.5 sigma
  - Evidence for tWZ, but signal larger than expected
- See large anti-correlation between ttZ and tWZ (right-hand figure)
- ttZ normalisation has large impact on result





Need better understanding of ttZ & ttW



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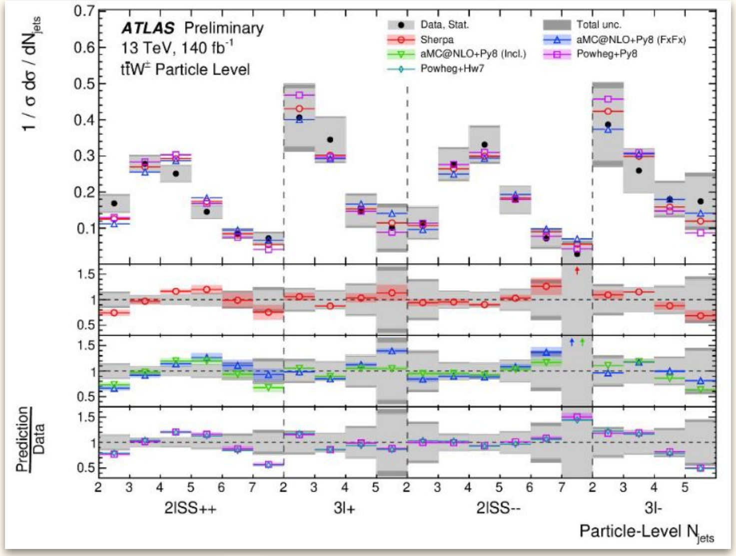
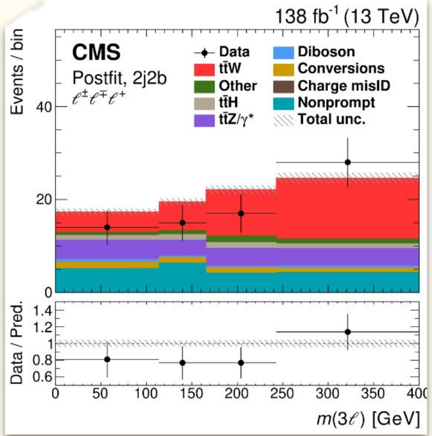
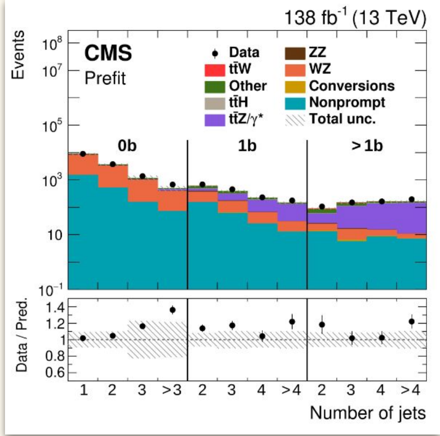


- Both experiments measure larger cross-section than expected
- Also observed in control region for other measurements (ttH, 4 tops)
- First differential measurements available, but still limited by statistics

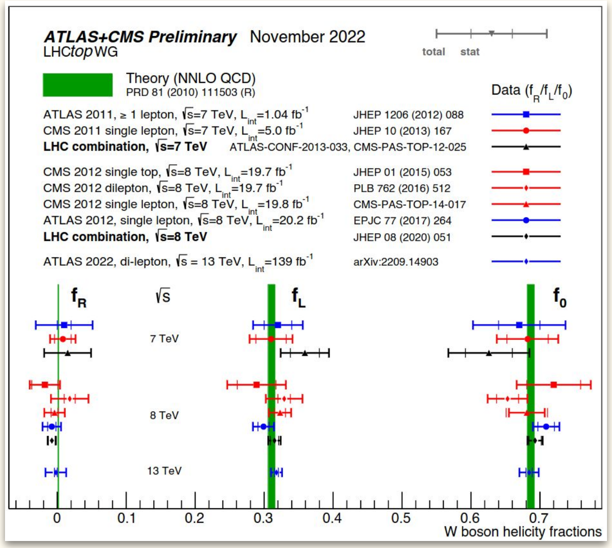




Spin properties

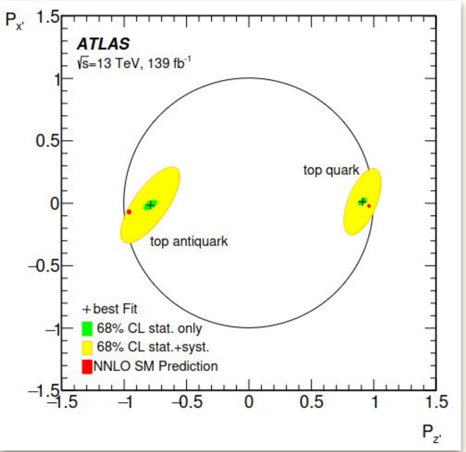
N. Bruscino

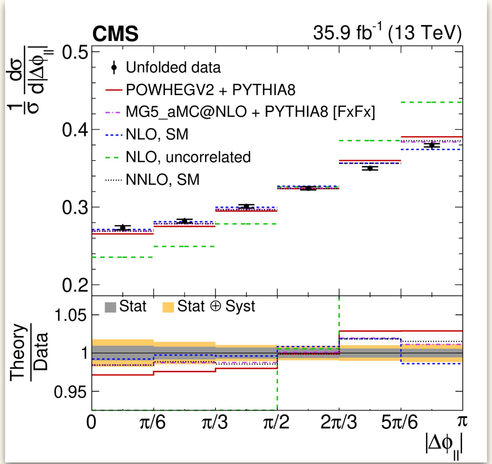
Production time		Decay time		Hadronisation time		Spin-Decorr. time
$\frac{1}{m_t}$	$<$	$\frac{1}{\Gamma_t}$	$<$	$\frac{1}{\Lambda_{QCD}}$	$<$	$\frac{m_t}{\Lambda^2_{QCD}}$
~10^{-27} s		~10^{-25} s		~10^{-24} s		~10^{-21} s



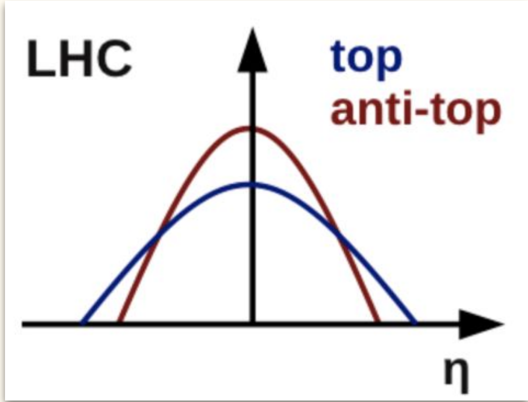
- Can measure W-boson polarisation in top quark decays: very high precision!
- In tt events: tops are produced unpolarised, but spins are correlated
- Single top: measure top polarisation

Parameter	Extracted value	(stat.)
t-channel norm.	$+1.045 \pm 0.022$	(± 0.006)
W+jets norm.	$+1.148 \pm 0.027$	(± 0.005)
$t\bar{t}$ norm.	$+1.005 \pm 0.016$	(± 0.004)
$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)

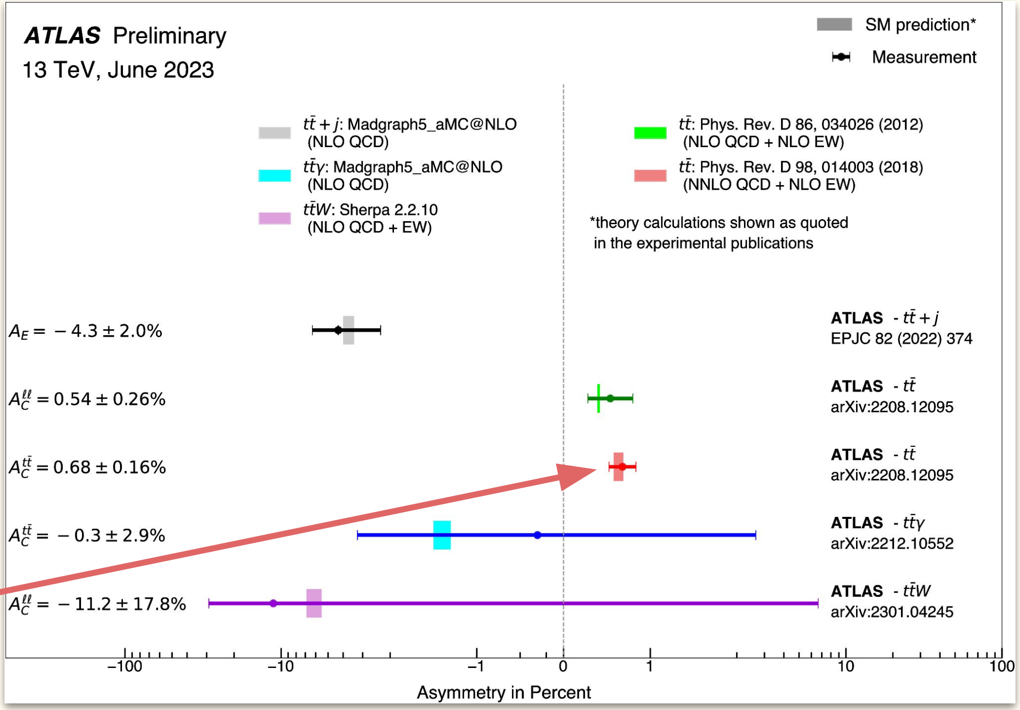




Charge and energy asymmetries



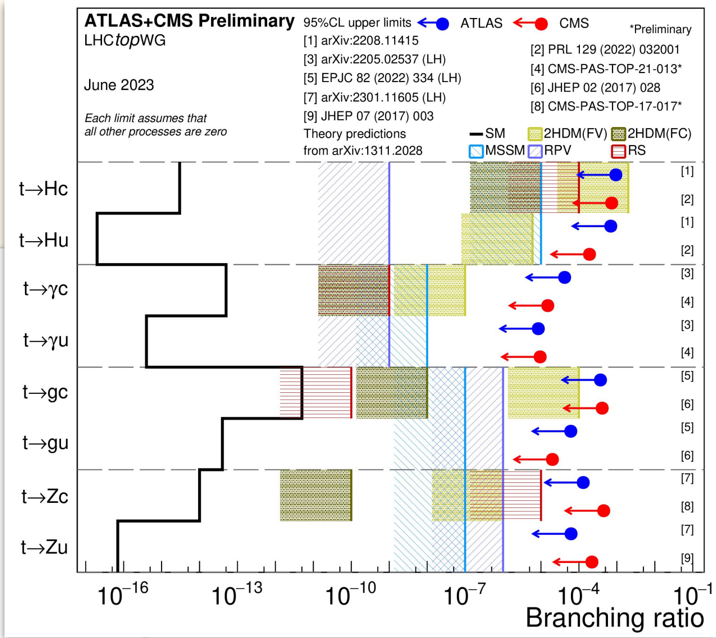
N. Bruscino



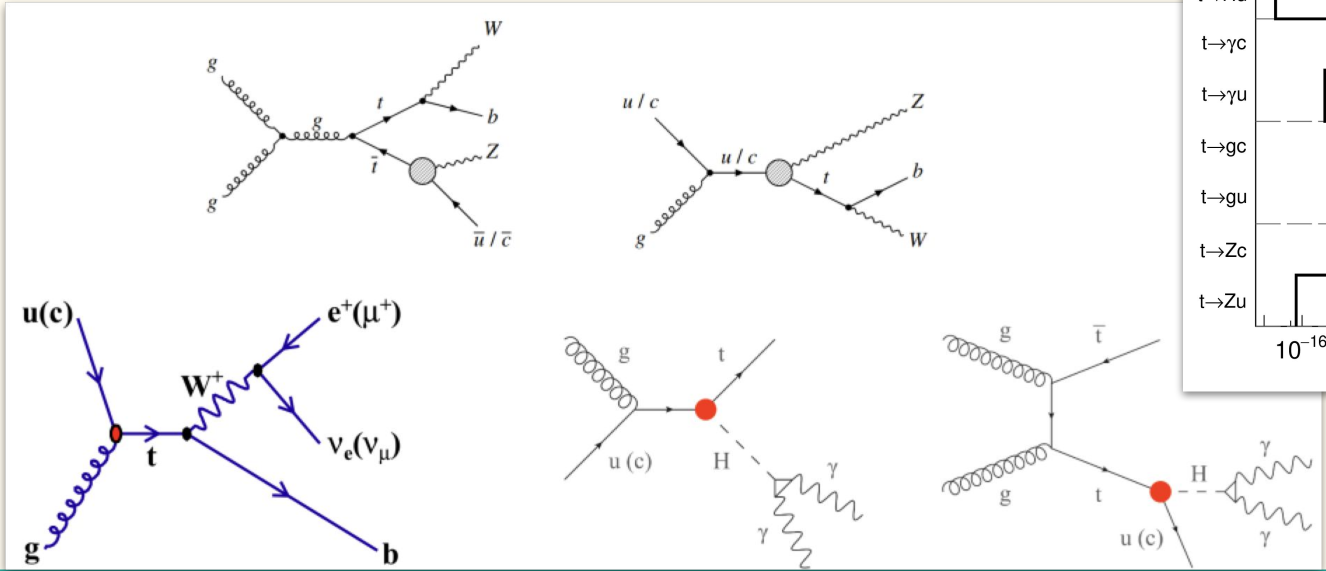
- gg production dominates at LHC (symmetric)
- at leading order: no charge asymmetry either
- at NLO: small charge asymmetry due to interference of ISR and FSR diagrams as well as interference between box and Born-diagrams
- In tt events: significance of 4.7 standard deviations!

Searches for flavor changing neutral currents

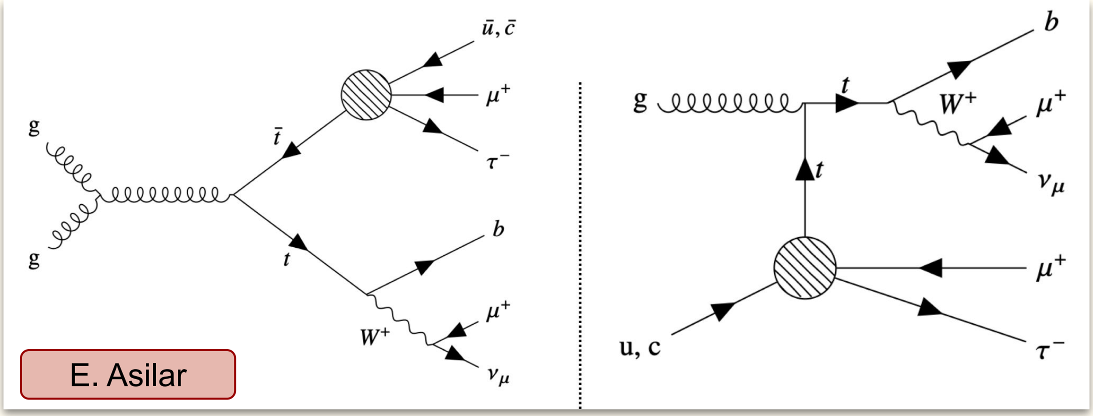
- FCNC in the SM: forbidden at tree-level
  ⇒ Strongly suppressed in loops by GIM mechanism: BR ~ 10^{-15} - 10^{-12}
- But: many new physics models allow for FCNCs: MSSM, 2HDM, composite Higgs…
  ⇒ Much larger branching ratios possible: in reach for the LHC!
- In top physics: can occur in many production/decay channels.



E. Asilar



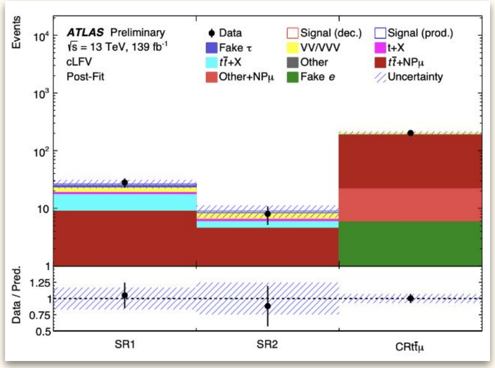
Searches for charged lepton flavor violation (prod and decay)



E. Asilar

Operator	Lorentz Structure	
$O_{lq}^{1(ijkl)}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma_\mu q_l)$	Vector
$O_{lq}^{3(ijkl)}$	$(\bar{l}_i\gamma^\mu\sigma^I l_j)(\bar{q}_k\gamma_\mu\sigma^I q_l)$	Vector
$O_{eq}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma_\mu q_l)$	Vector
$O_{lu}^{(ijkl)}$	$(\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma_\mu u_l)$	Vector
$O_{eu}^{(ijkl)}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma_\mu u_l)$	Vector
$^\ddagger O_{lequ}^{1(ijkl)}$	$(\bar{l}_i e_j)\varepsilon(\bar{q}_k u_l)$	Scalar
$^\ddagger O_{lequ}^{3(ijkl)}$	$(\bar{l}_i\sigma^{\mu\nu} e_j)\varepsilon(\bar{q}_k\sigma_{\mu\nu} u_l)$	Tensor

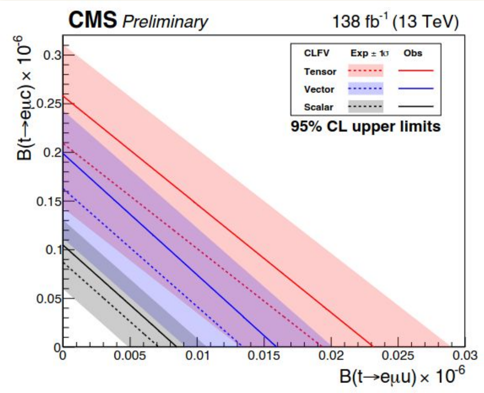
Channel with muons and taus:



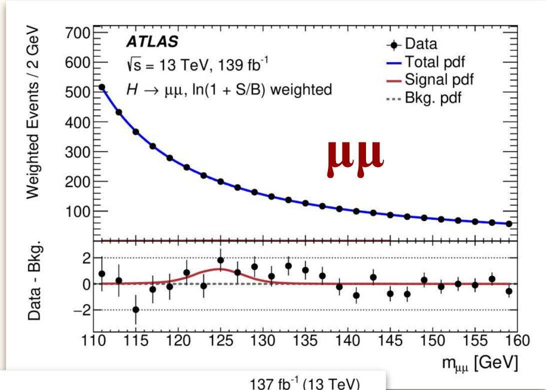
	95% CL upper limits on $BR(t \to \mu\tau q)$	
	Stat. only	All systematics
Expected	8×10^{-7}	10×10^{-7}
Observed	9×10^{-7}	11×10^{-7}

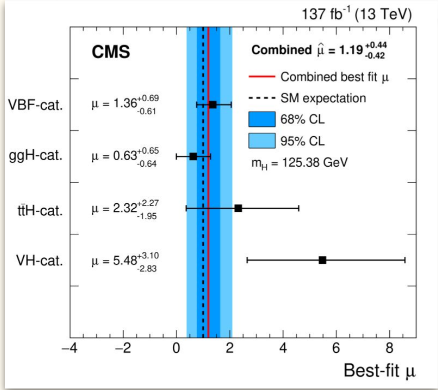
Limit reaches around $O(10^{-6})$!

Channel with electrons and muons:



SM Higgs: left no stone unturned

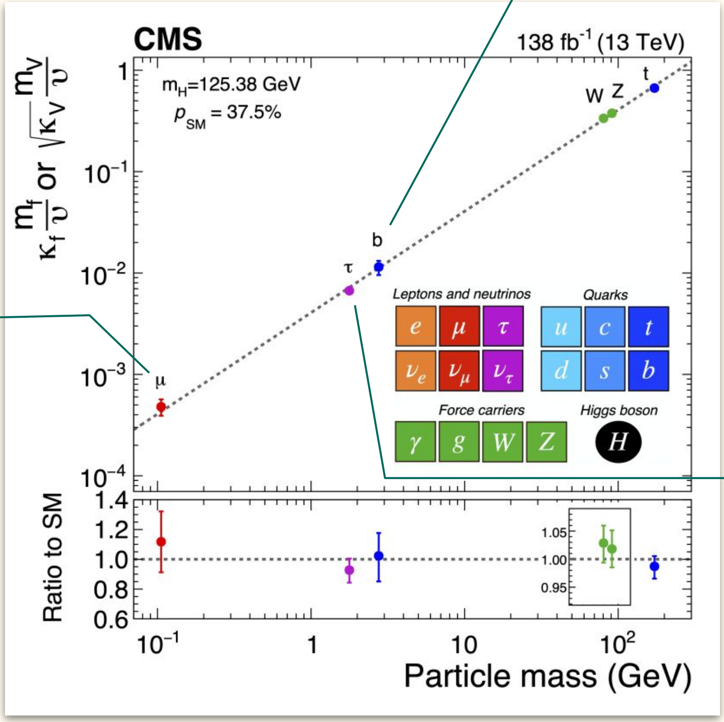




First hint/evidence for H→μμ!

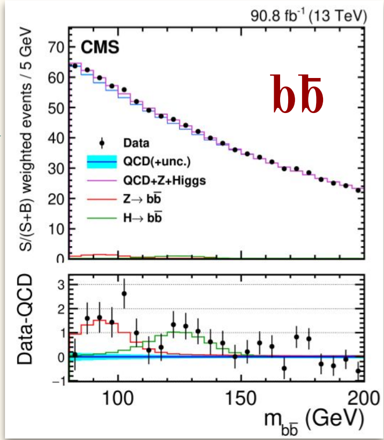
ATLAS PLB 812 (2021) 135980
CMS JHEP 01 (2021) 148

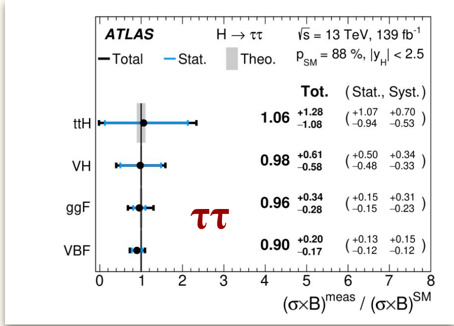
Coupling vs. particle mass



The portrait of the Higgs boson

ATLAS, Nature 607 (2022) 52
CMS, Nature 607 (2022) 60





H→3rd generation fully verified!

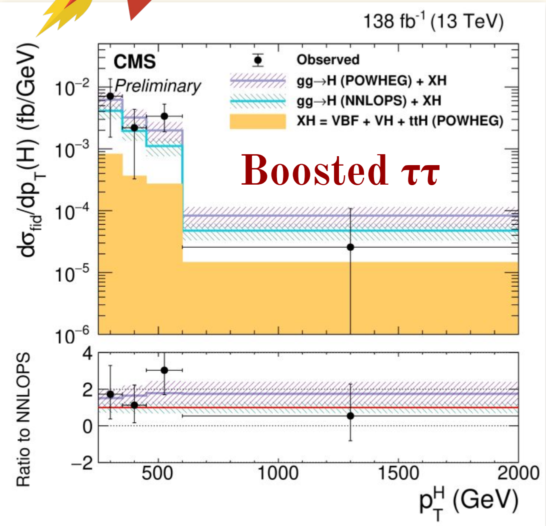
Talk by J. Cuevas

SM Higgs: challenging corners

Pursuit with both mission possible & mission impossible!

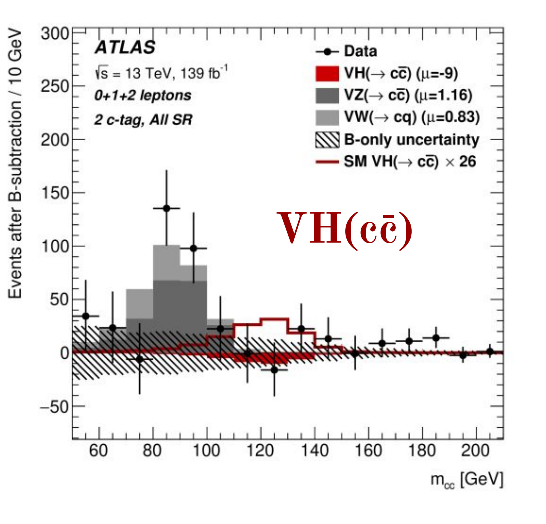
J. Cuevas

CMS PAS HIG-21-017



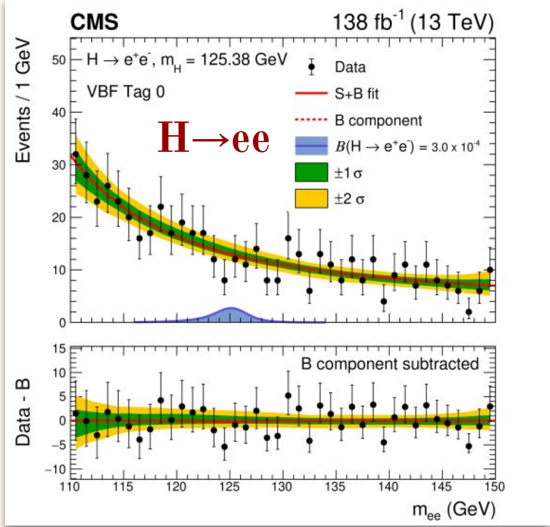
CMS boosted H→ττ:
Look for pT(H)>250 GeV
3.5σ (expt. 2.2σ)

ATLAS EPJC 82 (2022) 717
CMS PRL 131 (2023) 061801, PRL 131 (2023) 041801



H→cc̄: via VH production; upper limit is still 14 or 26 times to the SM prediction.

ATLAS PLB 801 (2020) 135148
CMS arXiv:2208.00265



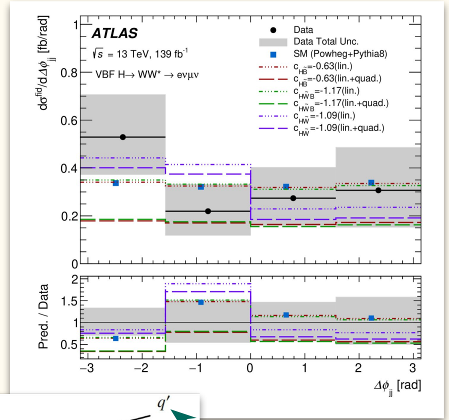
H→ee: not accessible for SM but look for BSM effects.
Limit on BF = 3.0-3.6×10^{-4}

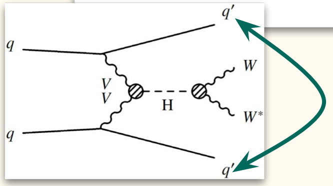
SM Higgs: much more than rates!

Study CPV effect in Higgs sector ⇒ measure CP-sensitive shapes: angles, optimal observables, matrix elements, etc.

M. Llácer

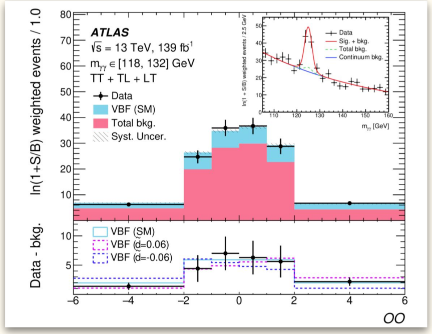
ATLAS arXiv:2304.03053





$\Delta\varphi_{jj}$

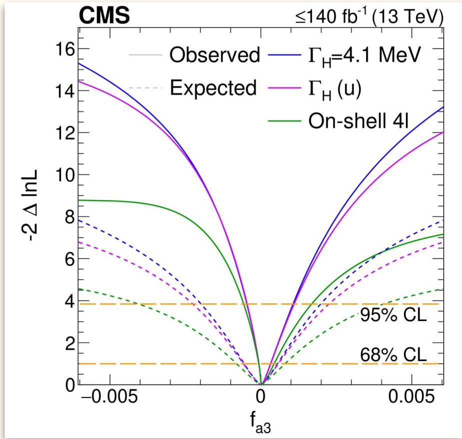
ATLAS PRL 131 (2023) 061802



Matrix element-based optimal observables (OO)

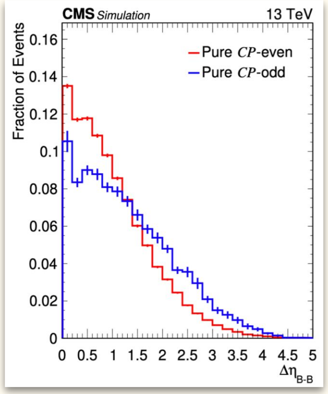
$$\mathcal{OO} = \frac{2\,\Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$

CMS Nature Phys. 18 (2022) 1329



Studies based on matrix elements discriminants, scan over couplings.

CMS JHEP 07 (2023) 092



Use MVA to enhance the discrimination between CP states.

Purely CP-odd fermionic and bosonic Higgs couplings already excluded, but admixtures still possible

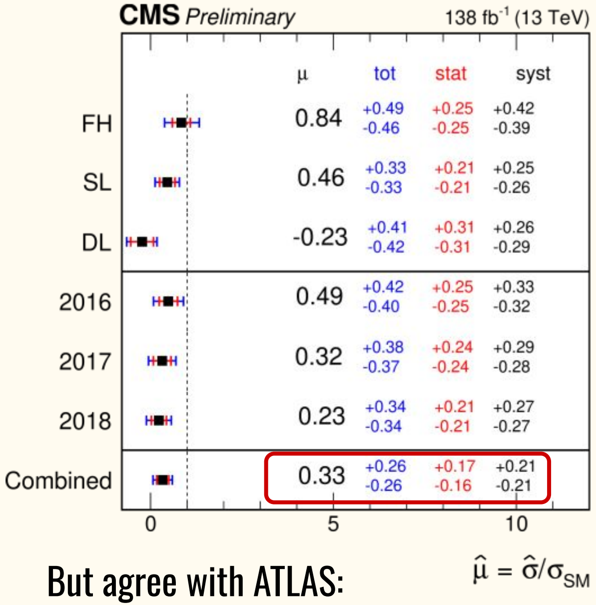
Rare productions & Rare decays

Adding more flavours!
Still need much more data!

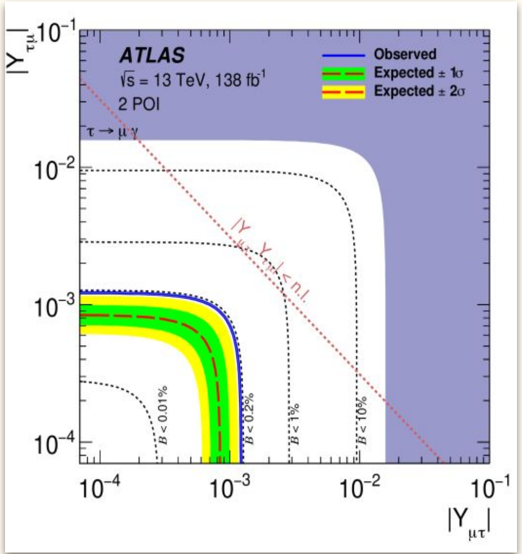
J. Cuevas

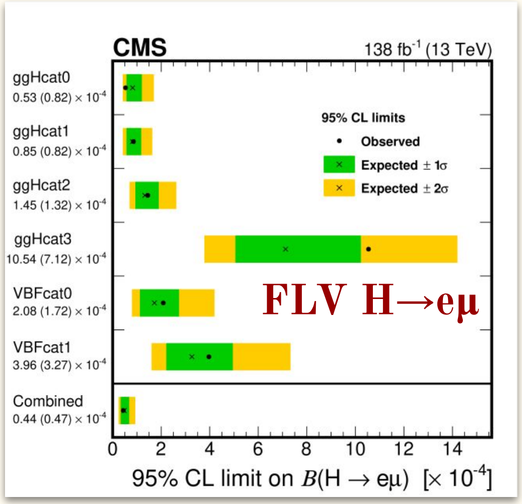
CMS PAS HIG-19-011

CMS new $t\bar{t}H(b\bar{b})$: low signal strength
μ=0.33±0.26, 1.3σ (expt. 4.1σ)



But agree with ATLAS:
μ=0.35 +0.36/−0.34 JHEP 06 (2022) 97





FLV H→eμ

Searches for LFV Higgs, no hint so far / agree with SM-only:
ATLAS BF(H→eτ) < 0.20%, BF(H→μτ) < 0.18%, BF(H→eμ) < 6.2×10^{-5},
CMS BF(H→eτ) < 0.22%, BF(H→μτ) < 0.15%, BF(H→eμ) < 4.4×10^{-5}.

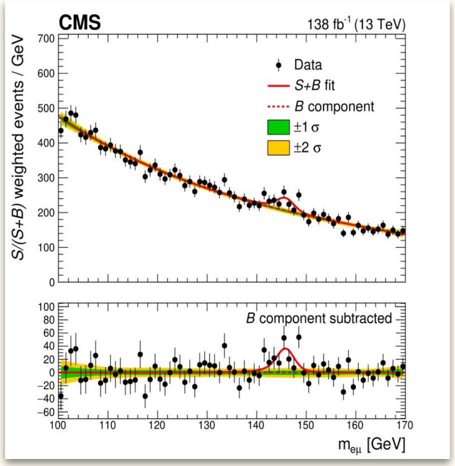
ATLAS, JHEP 07 (2023) 166, PLB 801 (2020) 135148
CMS, PRD 104 (2021) 032013, arXiv:2305.18106

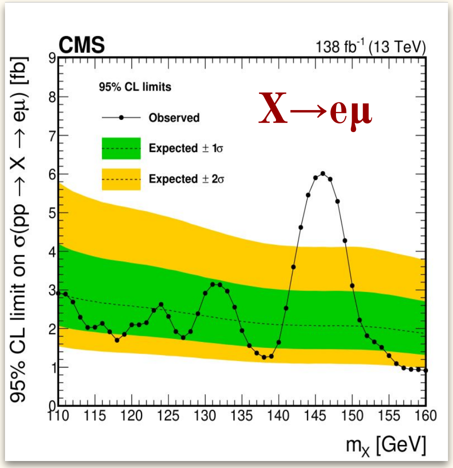
...but wait!

Extend the mass window?

If go beyond H(125)...

CMS arXiv:2305.18106





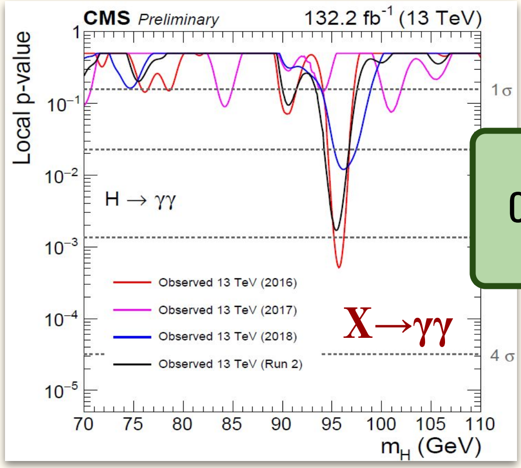
CMS see an excess of H→eμ at 146 GeV,
3.8σ local (2.8σ glocal)

➜ *ATLAS did not scan different masses yet!*

➜ *Not the only excess!*

J. Cuevas & J. Tao & R. Les

Also low mass diphoton?



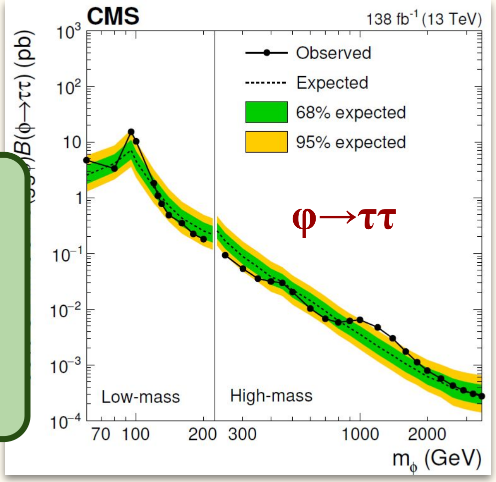
CMS-PAS-HIG-20-002
ATLAS-CONF-2023-035

For M(γγ) = 95.4 GeV
CMS: 2.8σ local (1.3σ glocal)
ATLAS: 1.7σ local

Di-tau events?

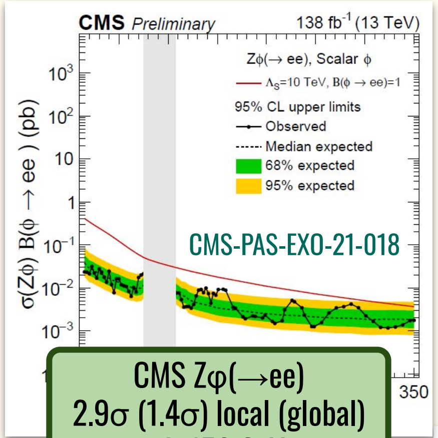
CMS JHEP 07(2023)073
ATLAS PRL 125 (2020) 051801

CMS:
3.1σ (2.7σ) local (global)
@ 100 GeV
2.8σ (2.2σ) local (global)
@ 1.2 TeV
ATLAS: no excess



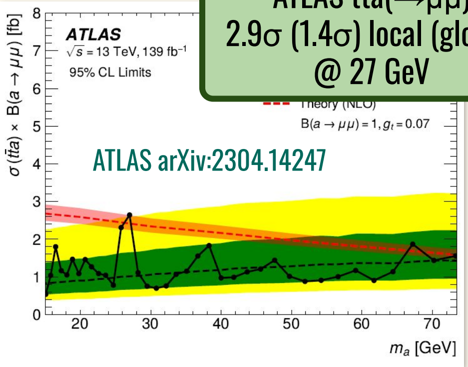
Excess everywhere?

Many searches in extended Higgs sector too!



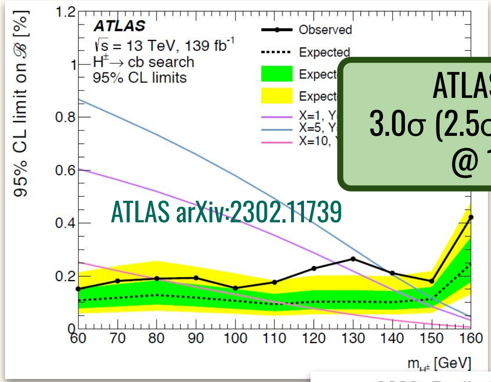
CMS-PAS-EXO-21-018

CMS Zφ(→ee)
2.9σ (1.4σ) local (global)
@ 156 GeV



ATLAS arXiv:2304.14247

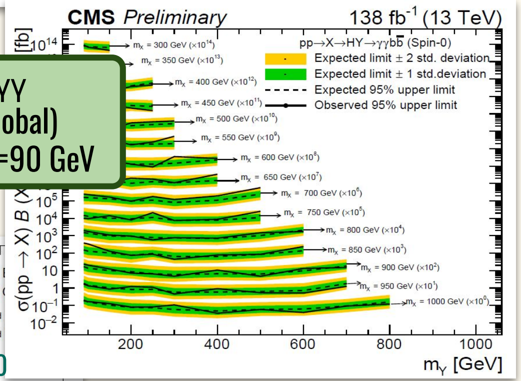
ATLAS tta(→μμ)
2.9σ (1.4σ) local (global)
@ 27 GeV



ATLAS arXiv:2302.11739

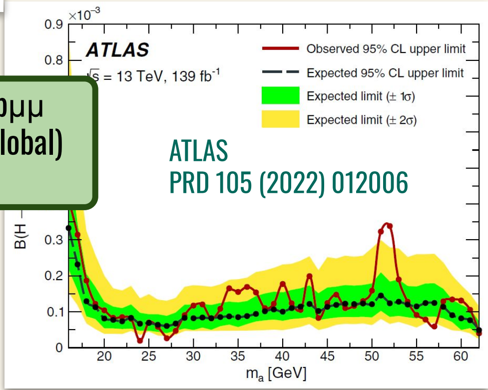
ATLAS H+→cb
3.0σ (2.5σ) local (global)
@ 130 GeV

J. Tao



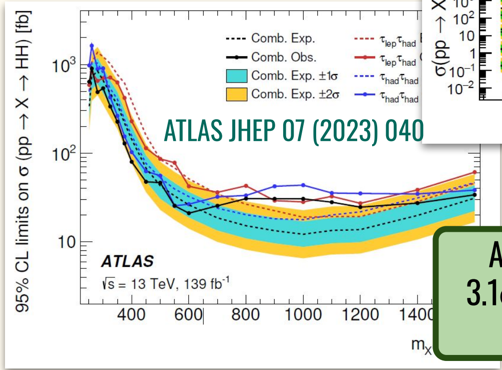
CMS X→HY→bbγγ
3.8σ (2.8σ) local (global)
@ M(X)=650 GeV, M(Y)=90 GeV

CMS-PAS-HIG-21-011



ATLAS H→aa→bbμμ
3.3σ (1.7σ) local (global)
@ 52 GeV

ATLAS
PRD 105 (2022) 012006



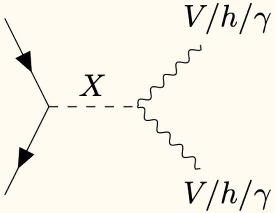
ATLAS JHEP 07 (2023) 040

ATLAS X→HH→bbττ
3.1σ (2.0σ) local (global)
@ M(X)=1 TeV

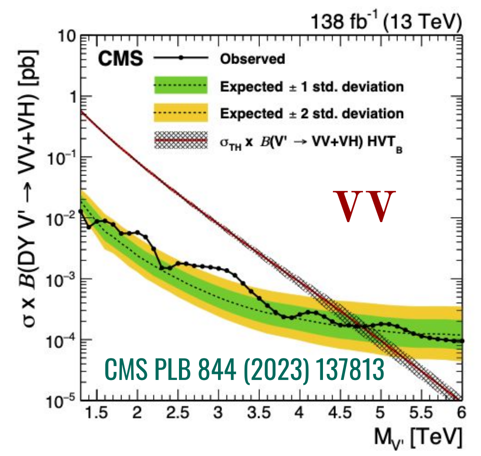
Many (mild) excesses!
Far too early to claim NP,
Stay tuned!

Heavy resonances to bosons

Straightforward prob to INP

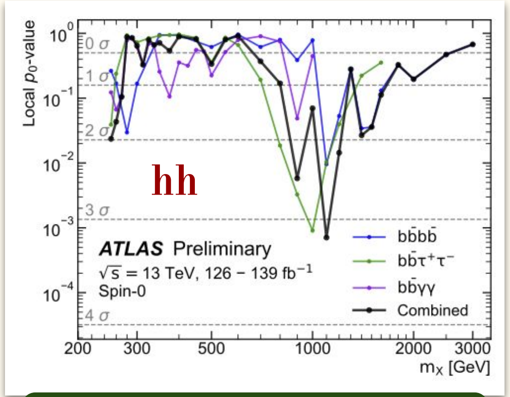


- Look for VV/Vh/hh *(or even more bosons!)* final state, interpreted with Randall-Sundrum radion / Georgi-Machacek / Heavy vector triplet / RS graviton.
- Including boosted boson reconstruction (a.k.a. jet substructure), with **advanced ML tech.**

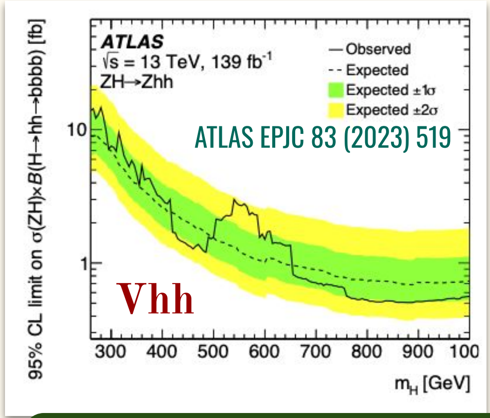


CMS VV/Vh→qqqq/qqbb
as a generic search
Mild excess 2.3σ at 2.1/2.9 TeV

ATLAS-CONF-2021-052



ATLAS hh→bbbb/bbττ/bbγγ
Excess in combined analysis:
3.2σ local (2.1σ global) at 1.1 TeV



Also γγ resonance, mentioned earlier!

ATLAS Vhh→qqqqq/ℓνqqqq
Excess in ZH: 2.7σ local (1.4σ global) at 550 GeV
Excess in AZH:
Large wid. 3.8σ local (3.0σ global) at H(320)/A(420)
Narrow wid. 3.6σ local (1.4σ global) at H(300)/A(800)

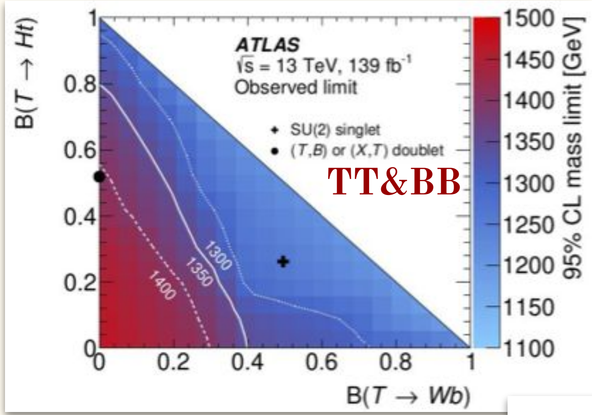
R. Les

Mass limit 4-5 TeV but several excesses exist - wait for further examination!

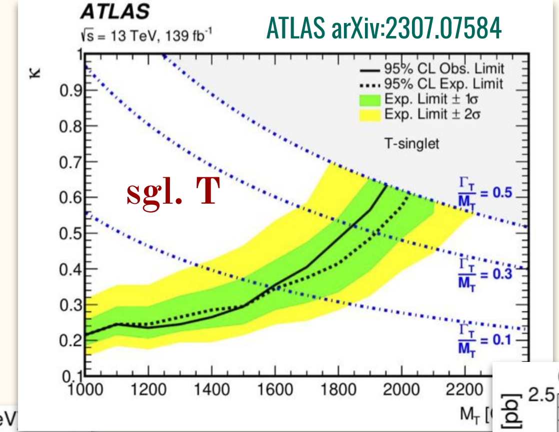
Vector-like quarks

- Mandatory to look for more quarks (T/B/X/Y) too!
- **Pair** (*model indep. prod*) & **single** (*good for heavier*) productions.
- Decaying to **qW** or **qZ** or **qH**.

ATLAS arXiv:2212.05263

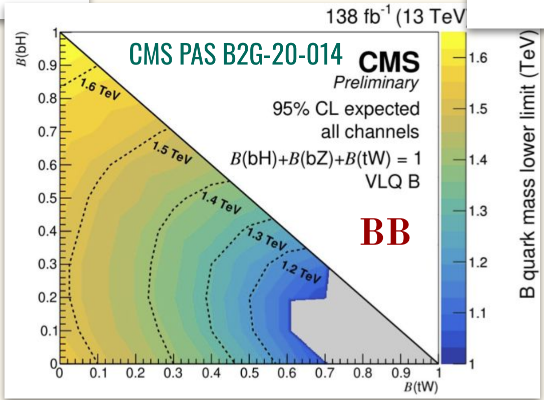


ATLAS TT & BB, lepton+jets search mass limits 1.26-1.59 TeV (*depends on both prod. & decay model*)

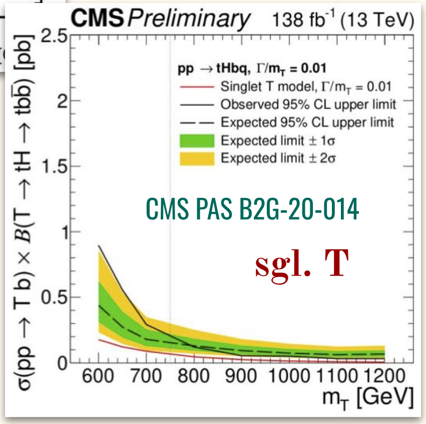


ATLAS single T miultilepton search, Strongest limit reaches 1.98 TeV, wide width (50%).

CMS BB, Hadronic+leptonic categories combined; Mass limit = 1.54 TeV if 100% B->bZ



CMS single T→Ht, Excess in 1909.04721 not confirmed with larger data.

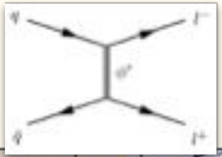


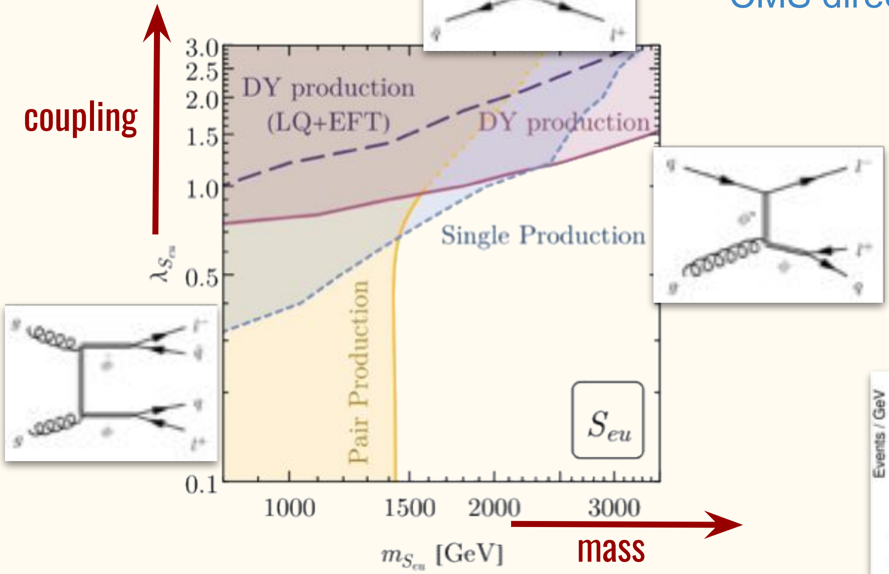
Much stronger Limits!

D. Guadarrama

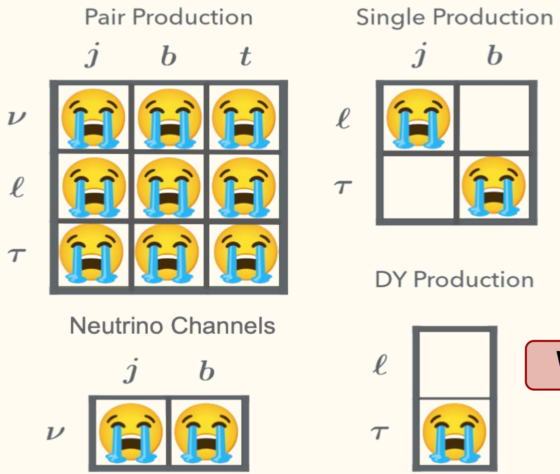
Leptoquarks

Best scenario depends on coupling and mass.





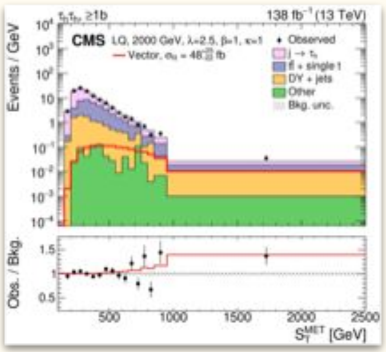
Many combinations within a certain (m,λ) range have been excluded by ATLAS & CMS direct searches

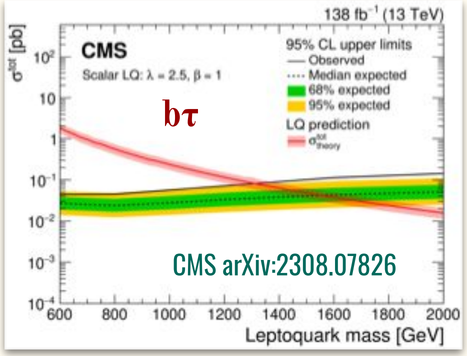


V. Pleskot

...there is an excess too!

CMS LQ→bτ
2.8σ with λ=2.5, M_{LQ} ~ 2 TeV
Not seen by ATLAS

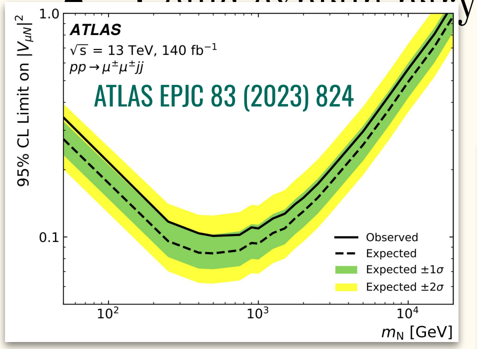




- Classification by final state objects;
- Exploit "mixed" final states too!

Heavy neutrinos

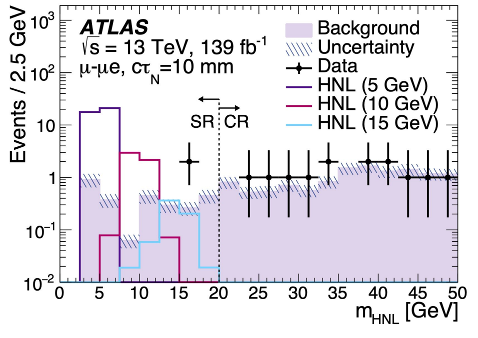
- Motivated by seesaw mechanism and other BSM, extend SM to include heavy neutrinos.
- Could be **long-lived**; can fix flavours.
- Could explain baryogenesis, DM, g-2, ...

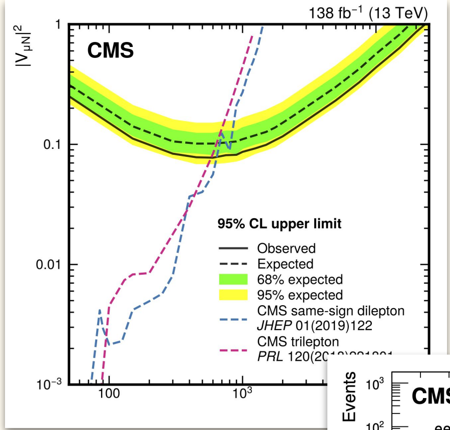


Majorana neutrinos in same-sign WW scattering

HNLs in W decays with a di-lepton displaced vertex

ATLAS PRL 131 (2023) 061803

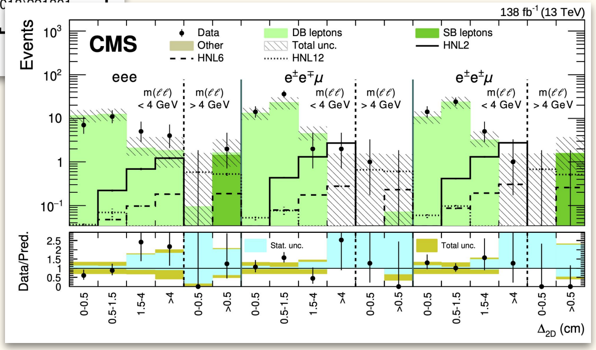




CMS PRL 131 (2023) 011803

Heavy Majorana Neutrinos and the Weinberg Operator through VBF

Long-lived HNL in 3ℓ final state



CMS JHEP 07 (2022) 081

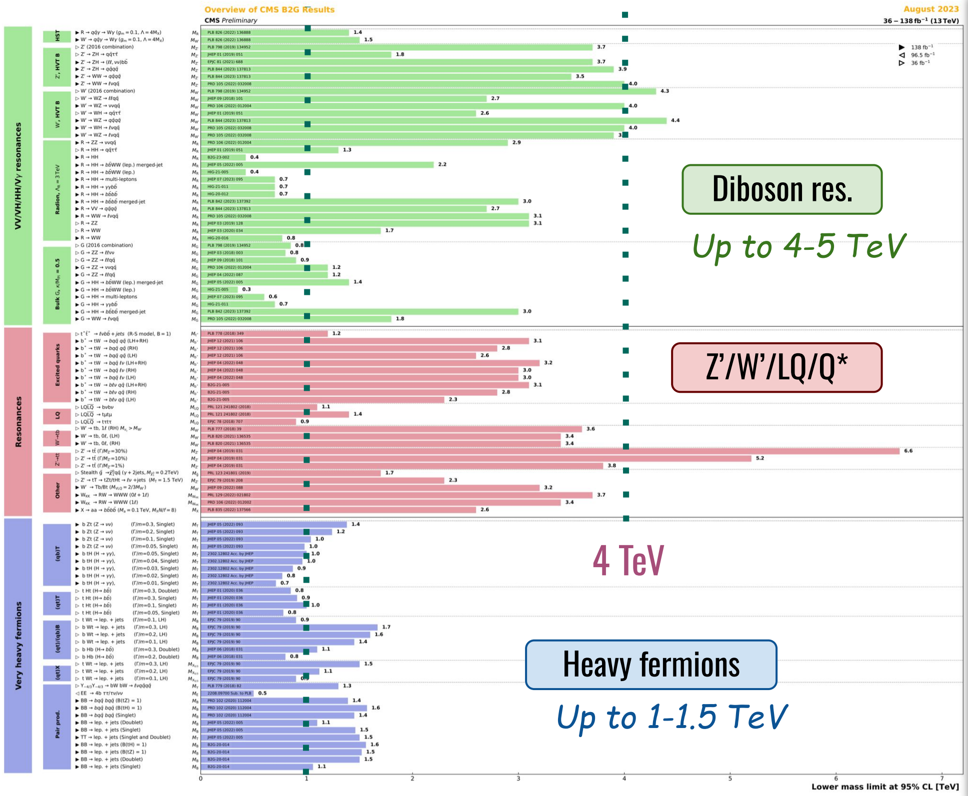
R. Manzoni

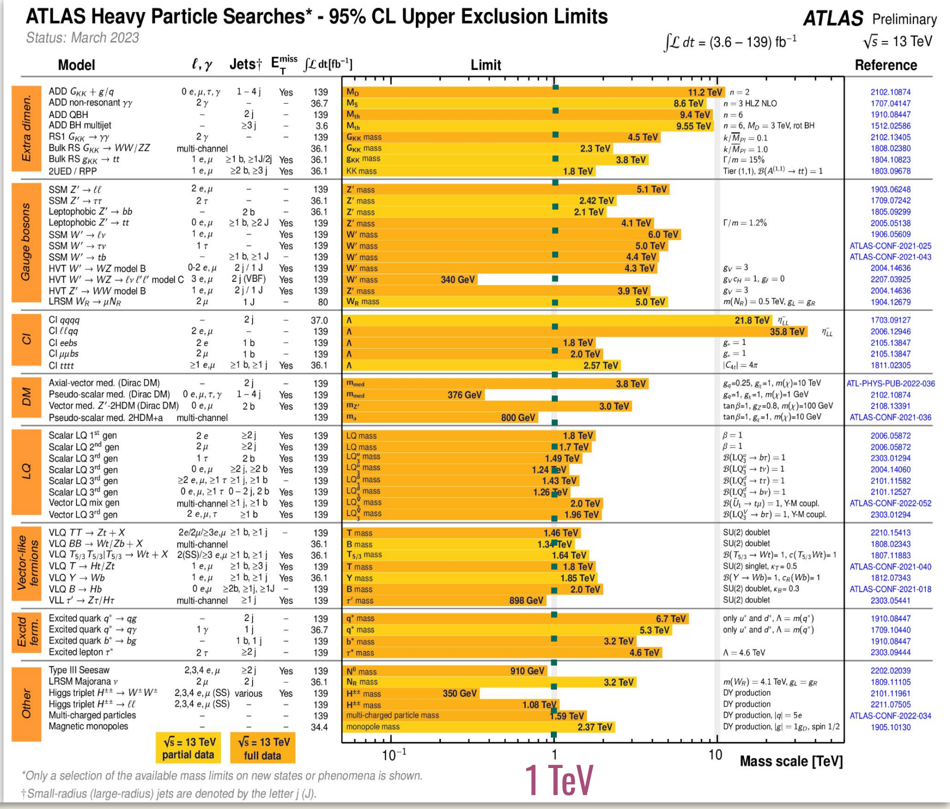
...and many many others!

Many experimental signatures examined:
VBF, displaced vertices, displaced jet taggers, resolved/boosted jets. etc.
Still plenty of phase-space to be explored, e.g. 3rd generation, flavour mixing, larger displacement...

Summary of direct searches

Limits depends on model assumptions & analyses.





End of Camino

- **High p_T studies do have strong impacts to CKM:**
  - Direct & indirect probe of the BSM.
  - Complementary to low energy measurements – overconstrain the CKM picture!
- **LHC experiments provide numerous inputs to the community:**
  - Top itself plays a key role in flavor physics & Higgs physics!
  - CKM interpretation from single-top t-channel;
  - Precision measurements of top & Higgs as backbone of SM.
  - Indirect probe of NP at very high scale via FCNC and anomalous couplings.
  - Many direct searches of new bosons, new quarks, new leptons…

Interesting excess here and there ⇒ to be verified with Run-3 and future HL-LHC runs!

BACKUP SLIDES