Is There Still Room For Naturalness?, Stockholm, April 19-29, 2022

Probing the composite nature of the Higgs boson at the LHC

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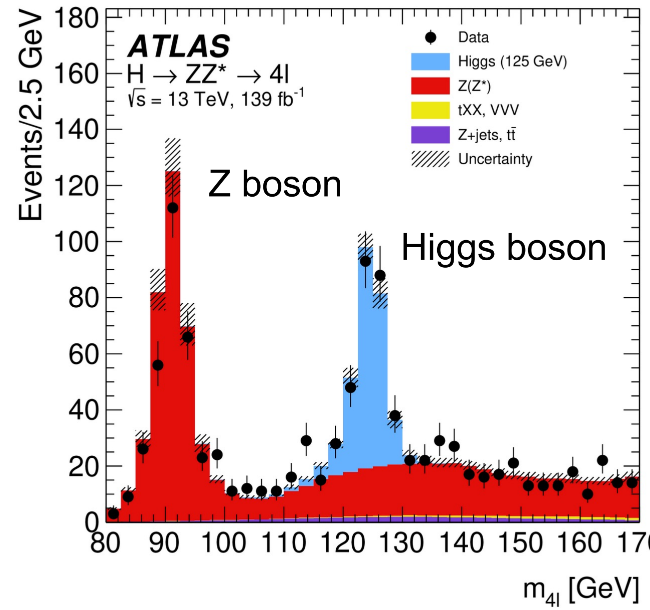
(ICREA/IFAE, Barcelona)

Outline

- Introduction
- Light overview of Composite Higgs paradigm
- Status and plans for Run 2 searches
    - Fermionic resonances
    - Bosonic resonances
- Future prospects at the LHC and beyond
- Summary and outlook

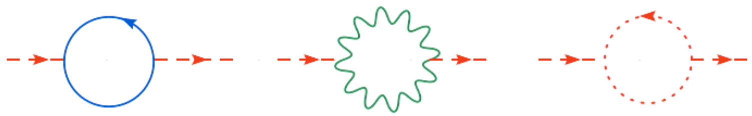
Why is the Higgs Boson so Light?

EPJC 80 (2020) 942



All elementary scalars are expected to be ultra-heavy.

- Mass not protected by symmetries like for fermions (chiral symmetry) or vector bosons (gauge symmetry).



$$(125\,\mathrm{GeV})^2 = \underbrace{m_{H0}^2}_{\text{Bare mass}} + \underbrace{\left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2}_{\text{Quantum corrections}}$$

Λ= New physics cutoff

Either New Physics appears at a scale Λ or there has to be a very delicate cancellation ("fine tuning").

If cut-off is at Λ=M_{Pl}=10^{19} GeV, need: $(125\text{ GeV})^2 \approx (10^{19}\text{ GeV})^2 - (10^{19}\text{ GeV})^2$

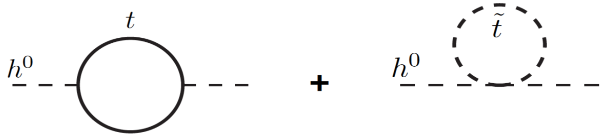
listening to your favorite radio needs the tuned frequency to match that of the radio channel:

```
radio freq. = 59.05871852091501091981287962349857612 kHz
tuned freq. = 59.05871852091501091981287962349857987 kHz
```

Solutions to the Hierarchy Problem

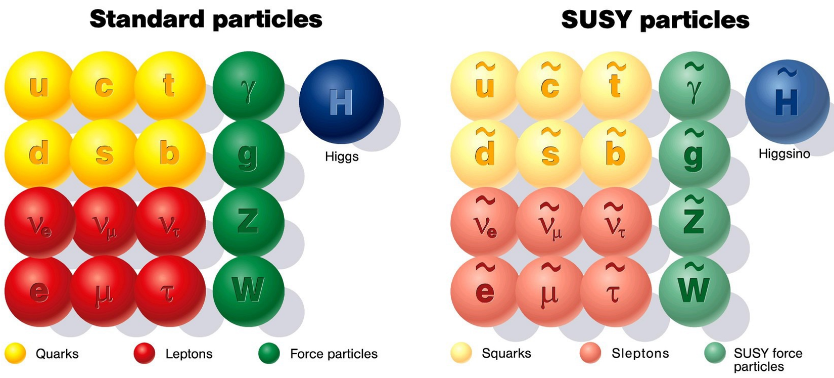
New Physics stabilizes the hierarchy

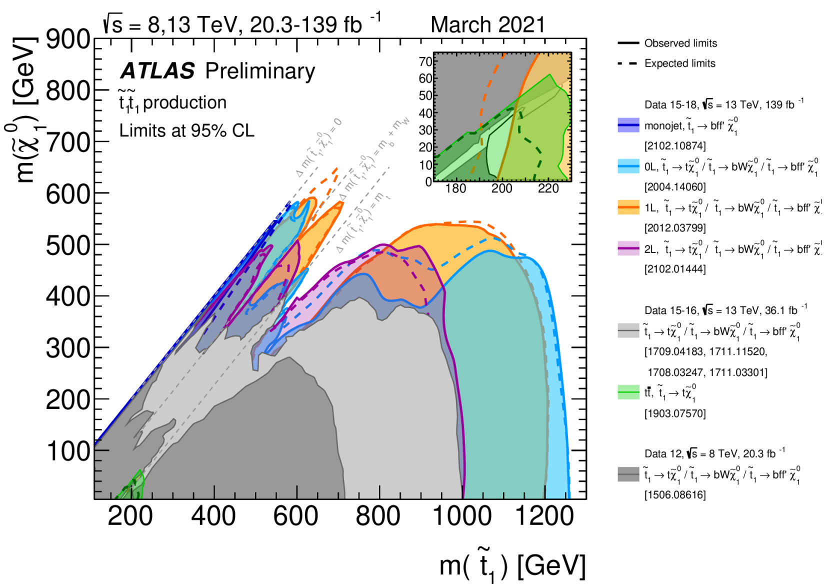
Supersymmetry: new symmetry that relates scalars to fermions (cancellation of quadratic divergences).

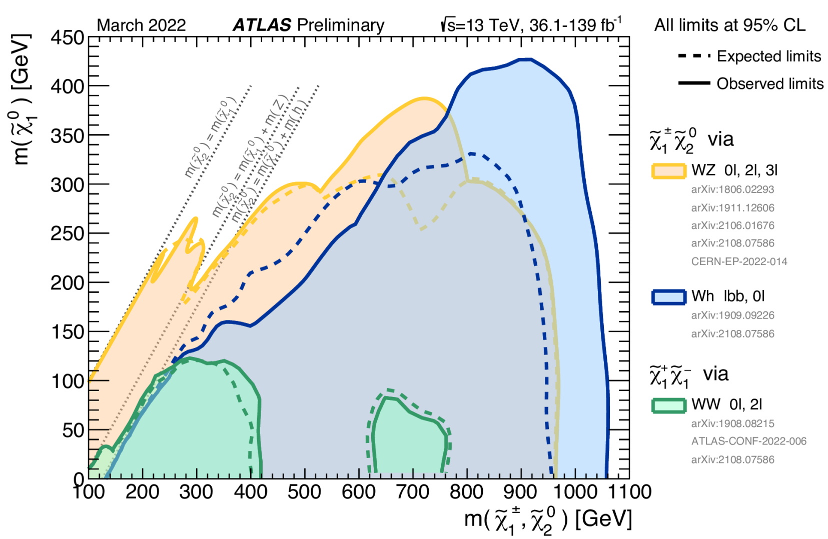


Fermion loop | Boson loop

$$\underbrace{m_H^2 = +A \qquad m_H^2 = -A}_{m_H^2 = 0}$$







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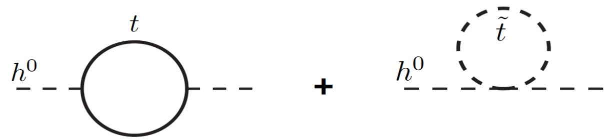


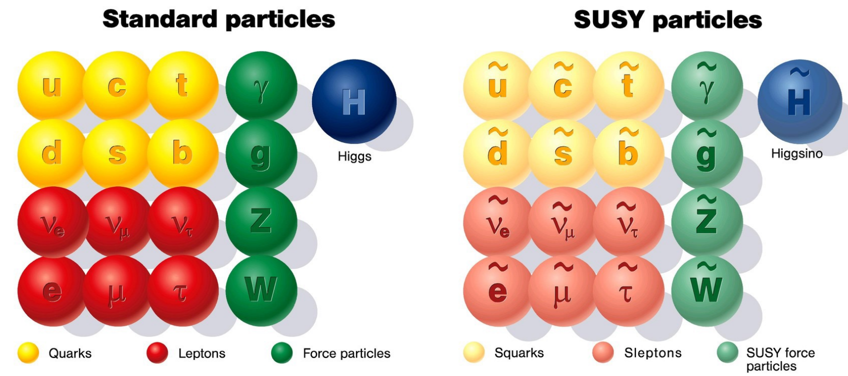
Fermion loop

$m_H^2 = +A$

Boson loop

$m_H^2 = -A$

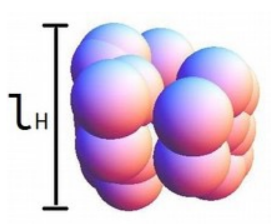
$\underbrace{m_H^2 = +A \quad m_H^2 = -A}_{m_H^2 = 0}$



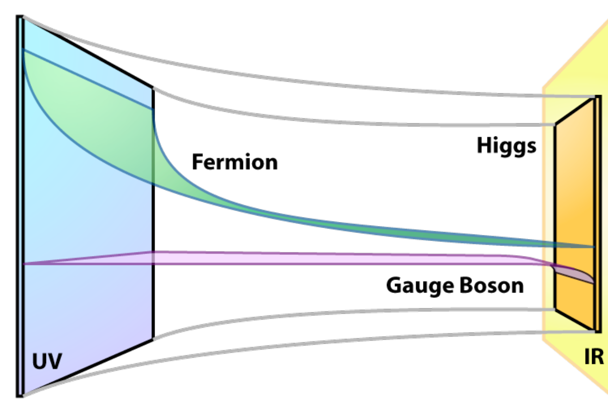
AdS/CFT correspondence

Compositeness: the Higgs boson is not an elementary particle but a composite object.

➔ No true hierarchy problem beyond the scale of compositeness.



Warped Extra Dimensions: generate the gauge hierarchy. Higgs boson naturally light.

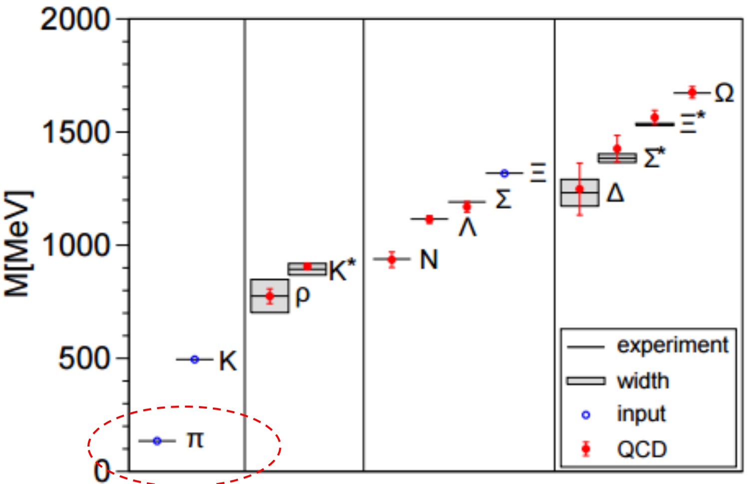


Composite Higgs Paradigm

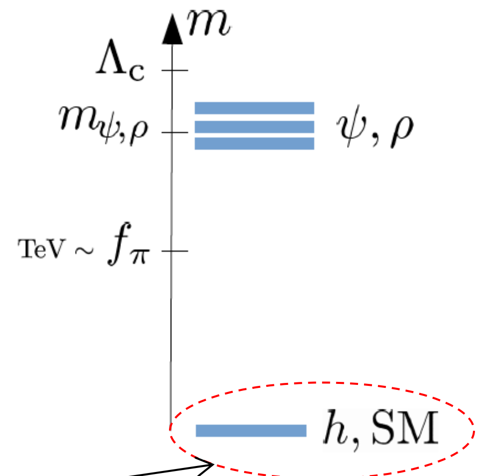
New strong interaction that confines at a scale Λ_c~10 TeV.

- Inspired by QCD where we observed light scalars without problems of naturalness.

QCD



Composite Higgs



Light because they are pseudo-Goldstone bosons emerging from the breaking of a global symmetry

Goldstone decay const. f_π

Resonances $m_\rho \sim g_* f_\pi$

$\Lambda_c \sim 4\pi f_\pi$

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \longleftrightarrow G \rightarrow H \supset SM$$

f_π~100 MeV

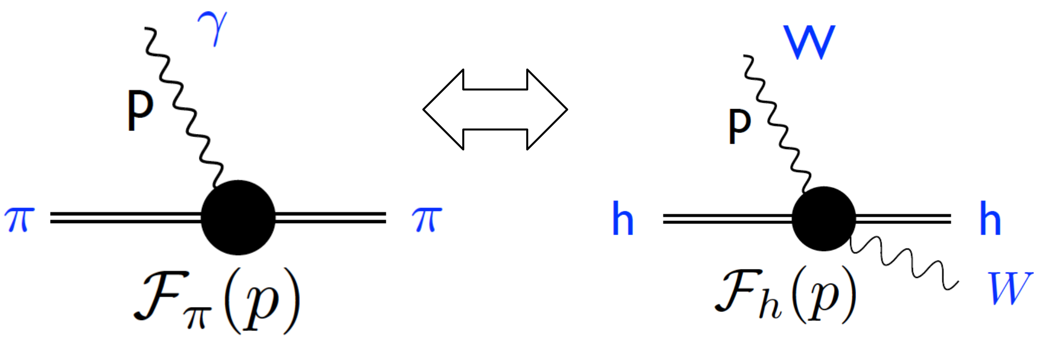
f_π>v=246 GeV

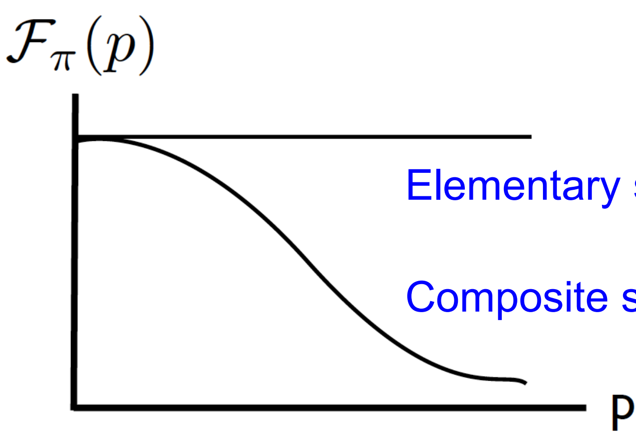
Higgs Boson Couplings

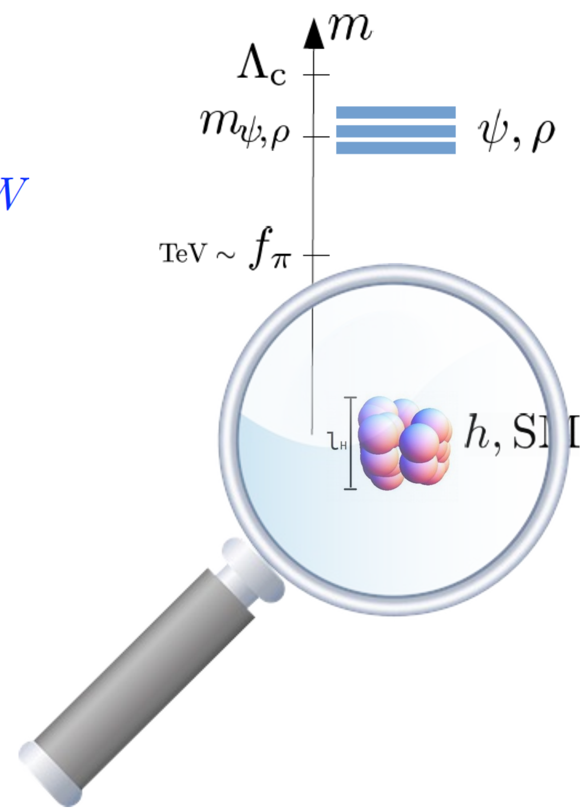
Unravel composite nature of the Higgs boson by measuring its couplings to SM particles!

QCD

Composite Higgs







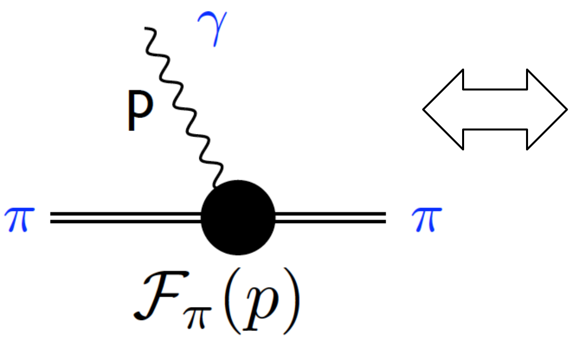
Expect reduced couplings for a composite particle

Go as high in energy as possible!

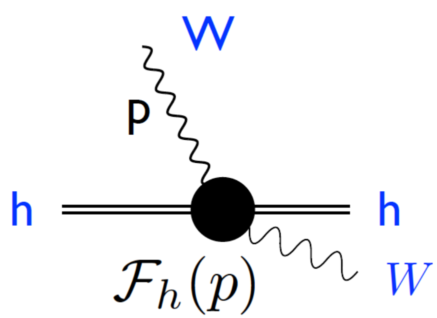
Higgs Boson Couplings

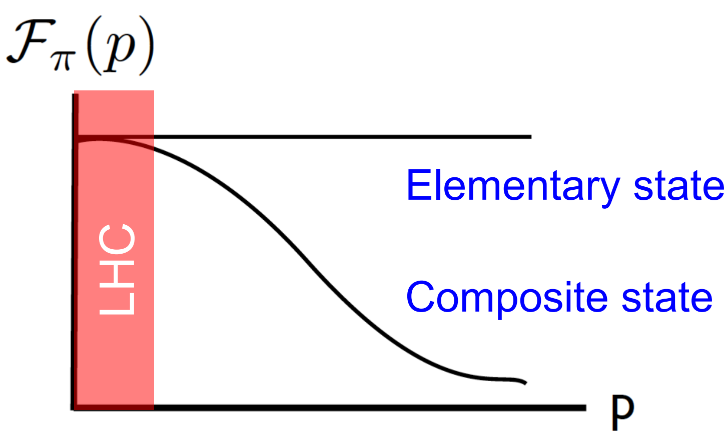
Unravel composite nature of the Higgs boson by measuring its couplings to SM particles!

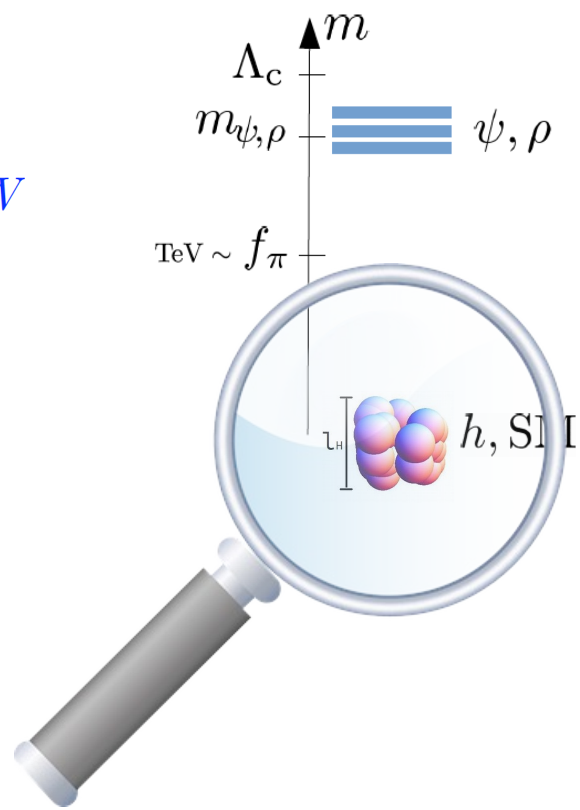
QCD



Composite Higgs







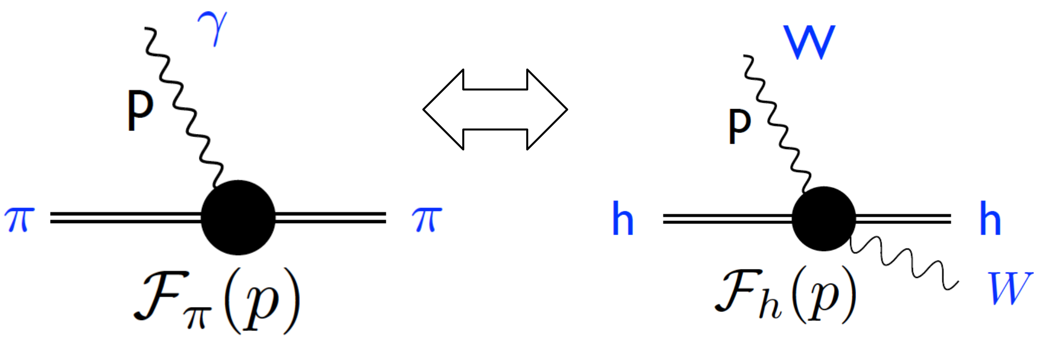
Unfortunately, with the LHC we are limited to ~TeV

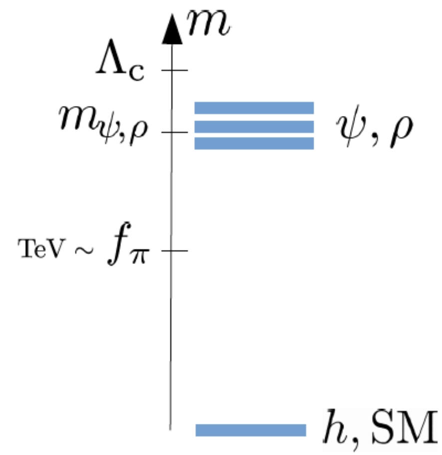
Higgs Boson Couplings

Unravel composite nature of the Higgs boson by measuring its couplings to SM particles!

QCD

Composite Higgs





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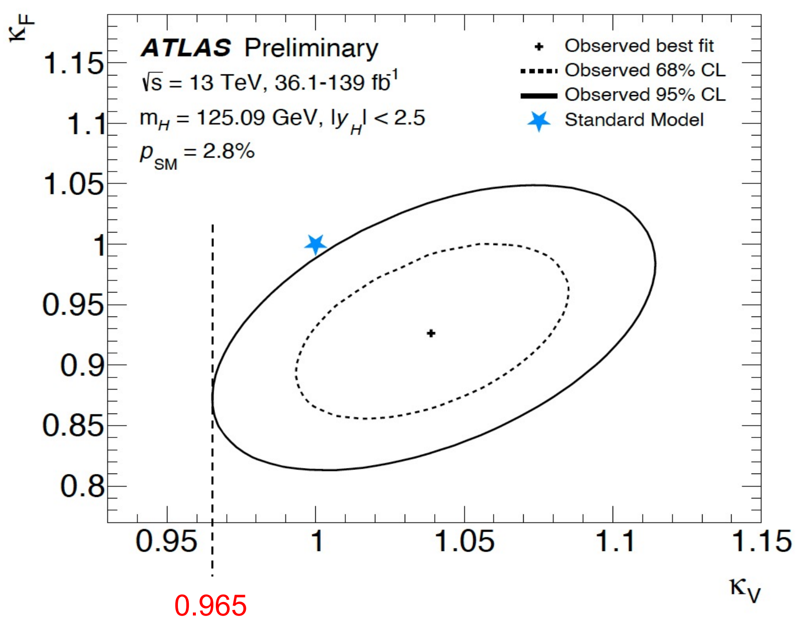


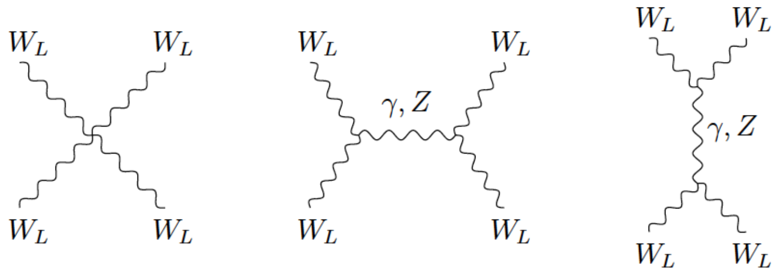
Expected scale factor for coupling to vector bosons:

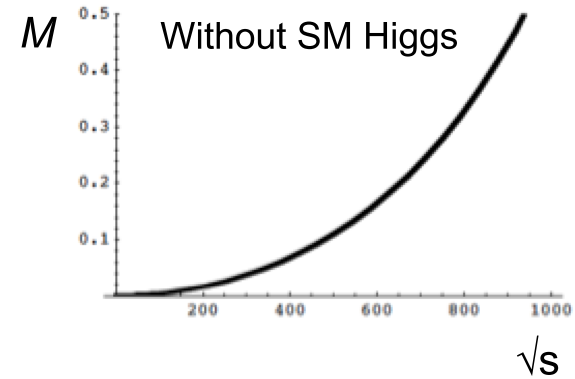
$$\kappa_V = \sqrt{1-\xi}, \ \xi \equiv v^2 / f_\pi^2$$

$\kappa_V > 0.965$ ➔ $f_\pi > 940$ GeV @ 95% CL

Longitudinal Vector Boson Scattering

- In the SM the Higgs boson ensures perturbative unitarity in longitudinal vector boson scattering:





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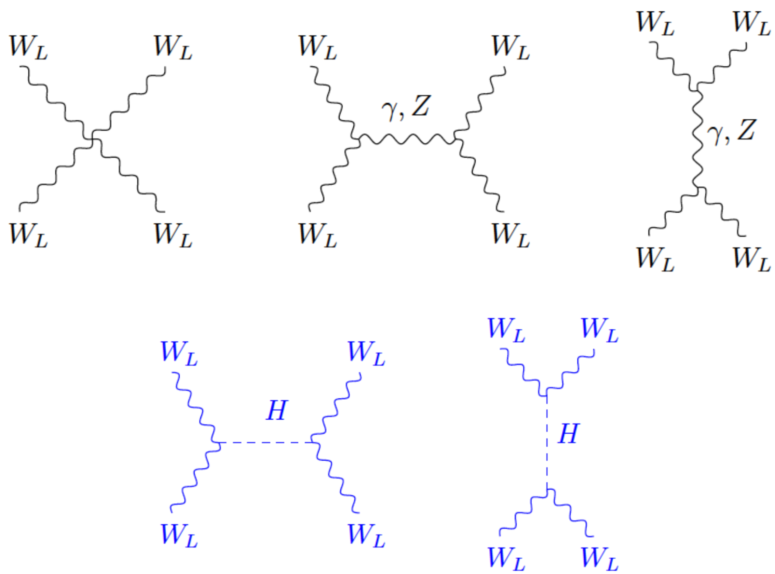

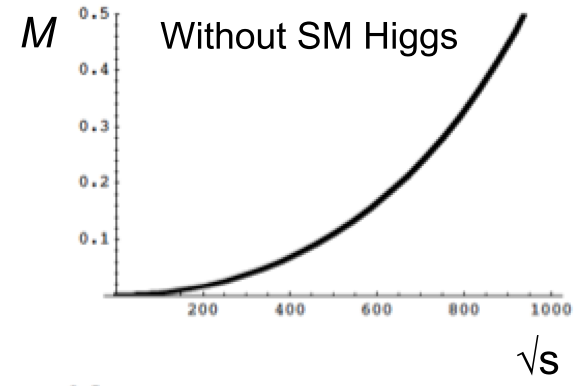

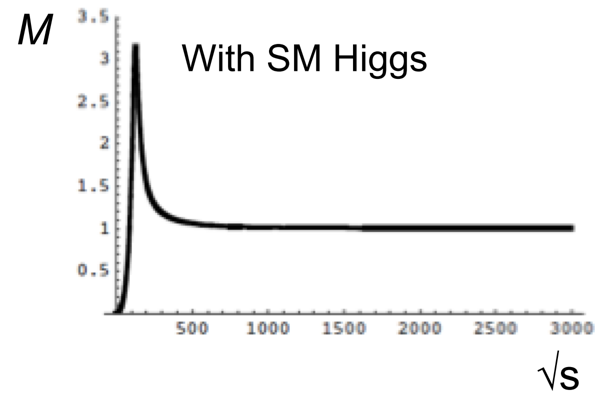

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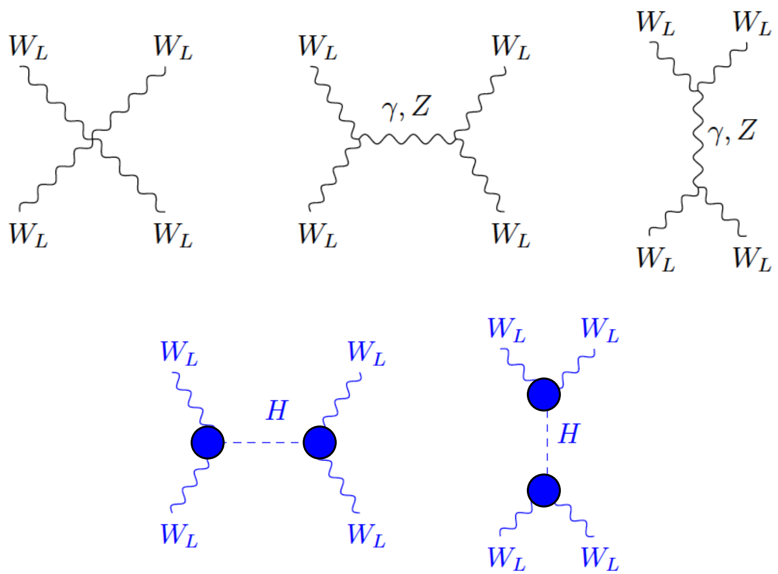
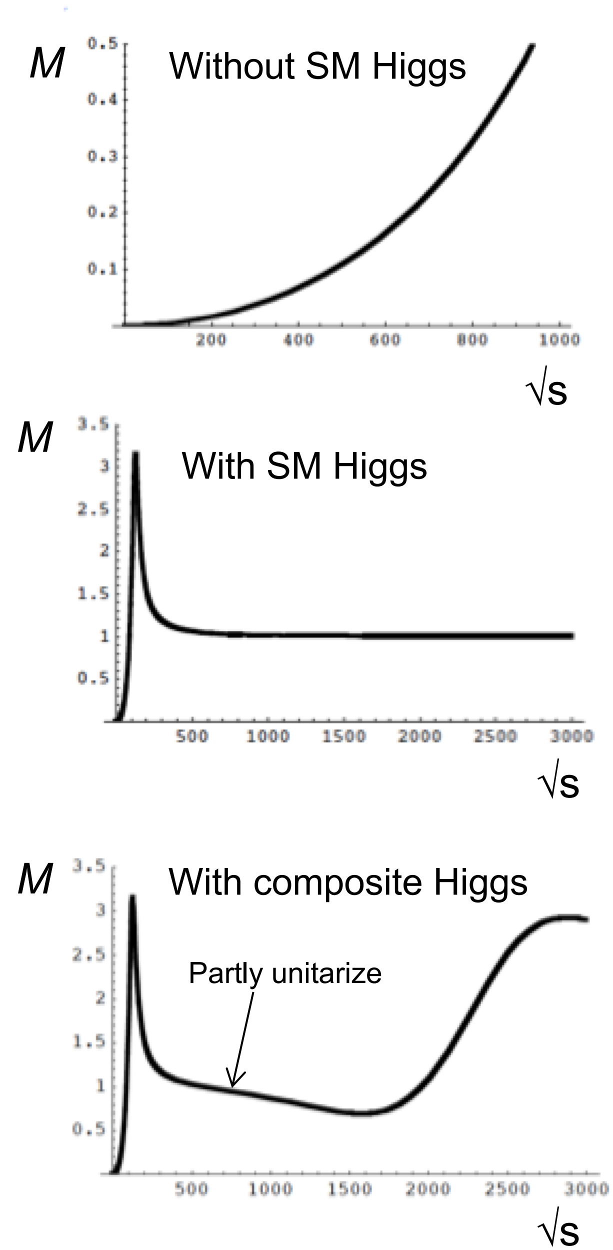


- Reduced couplings to vector bosons means the Higgs boson only does in part its job.



Composite Bosonic Resonances

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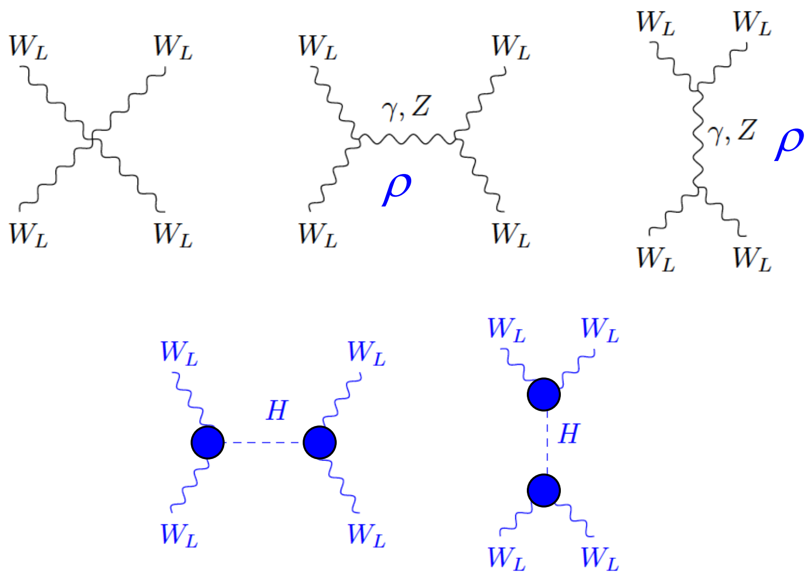

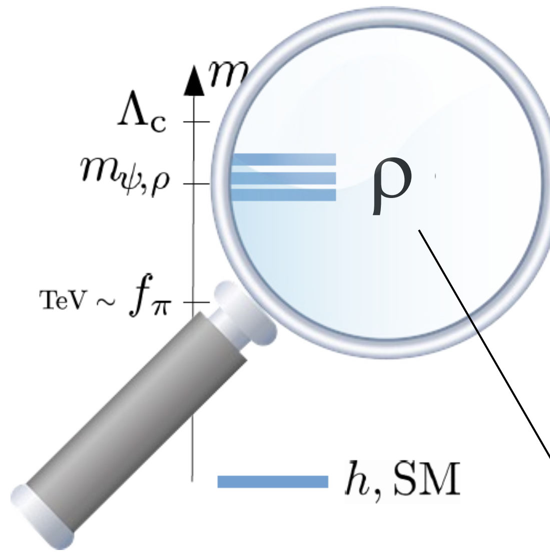

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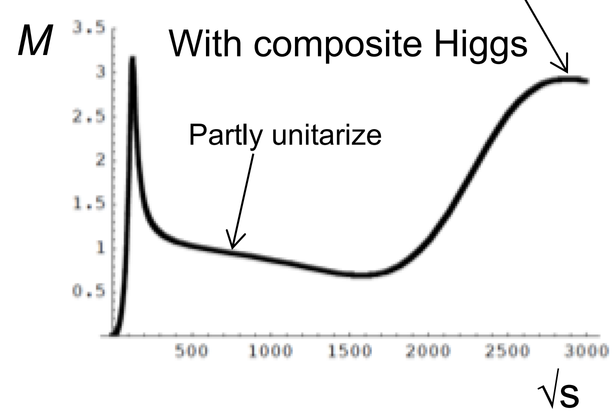
- Composite bosonic resonances needed to fully unitarize!



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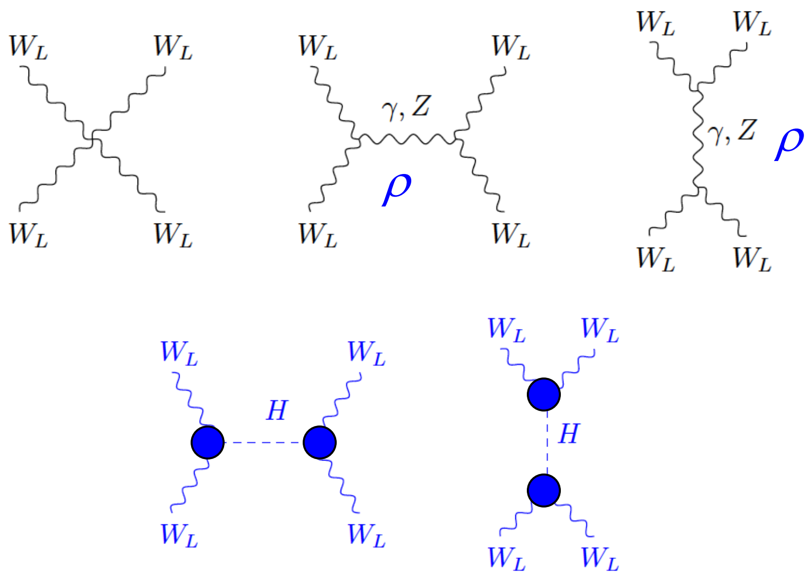

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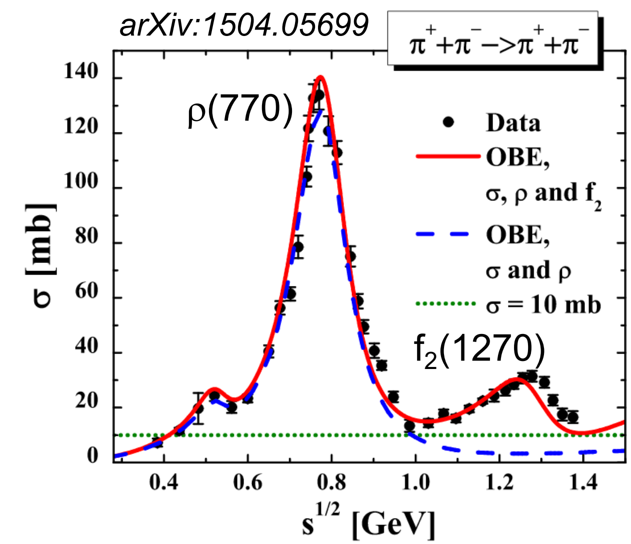
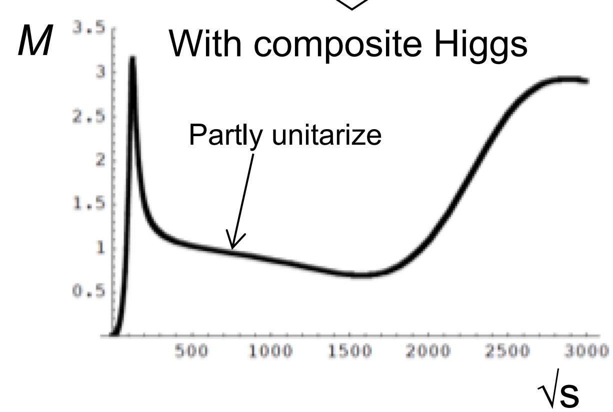
π-π elastic scattering



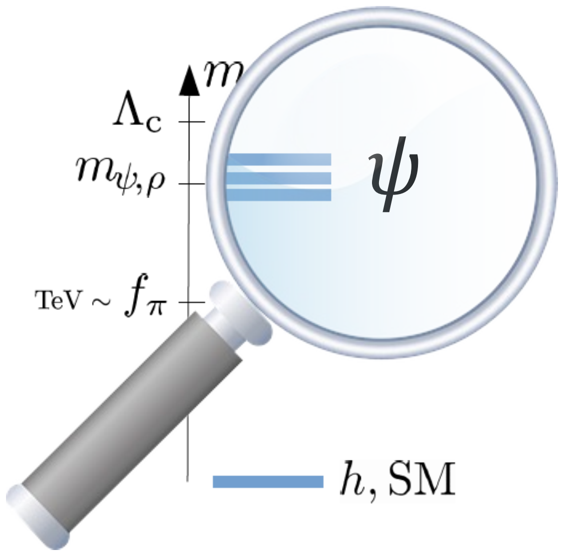


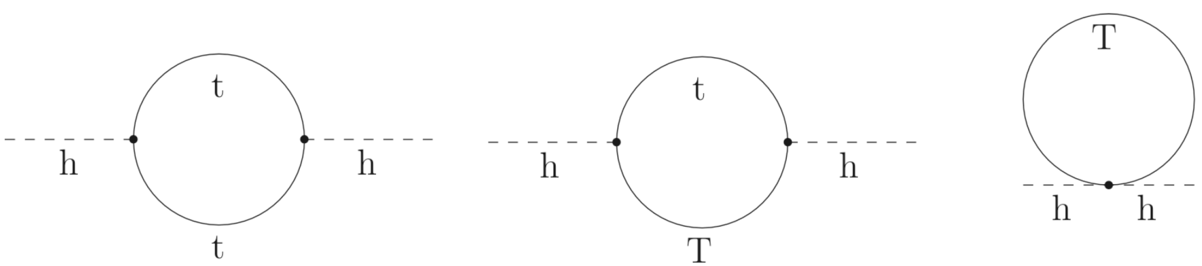
Composite Fermionic Resonances

Partial Compositeness:

- Elementary fermions couple linearly to heavy vector-like composite states with same quantum numbers.
- Fermions acquire mass through mixing with new vector-like quarks.
    - Large top-quark Yukawa coupling
      ➔ top-quark largely composite.
- Linear couplings violate global symmetry explicitly
  ➔ Higgs potential induced.
- A light Higgs boson requires light top partners (expected to be lighter than bosonic resonances).

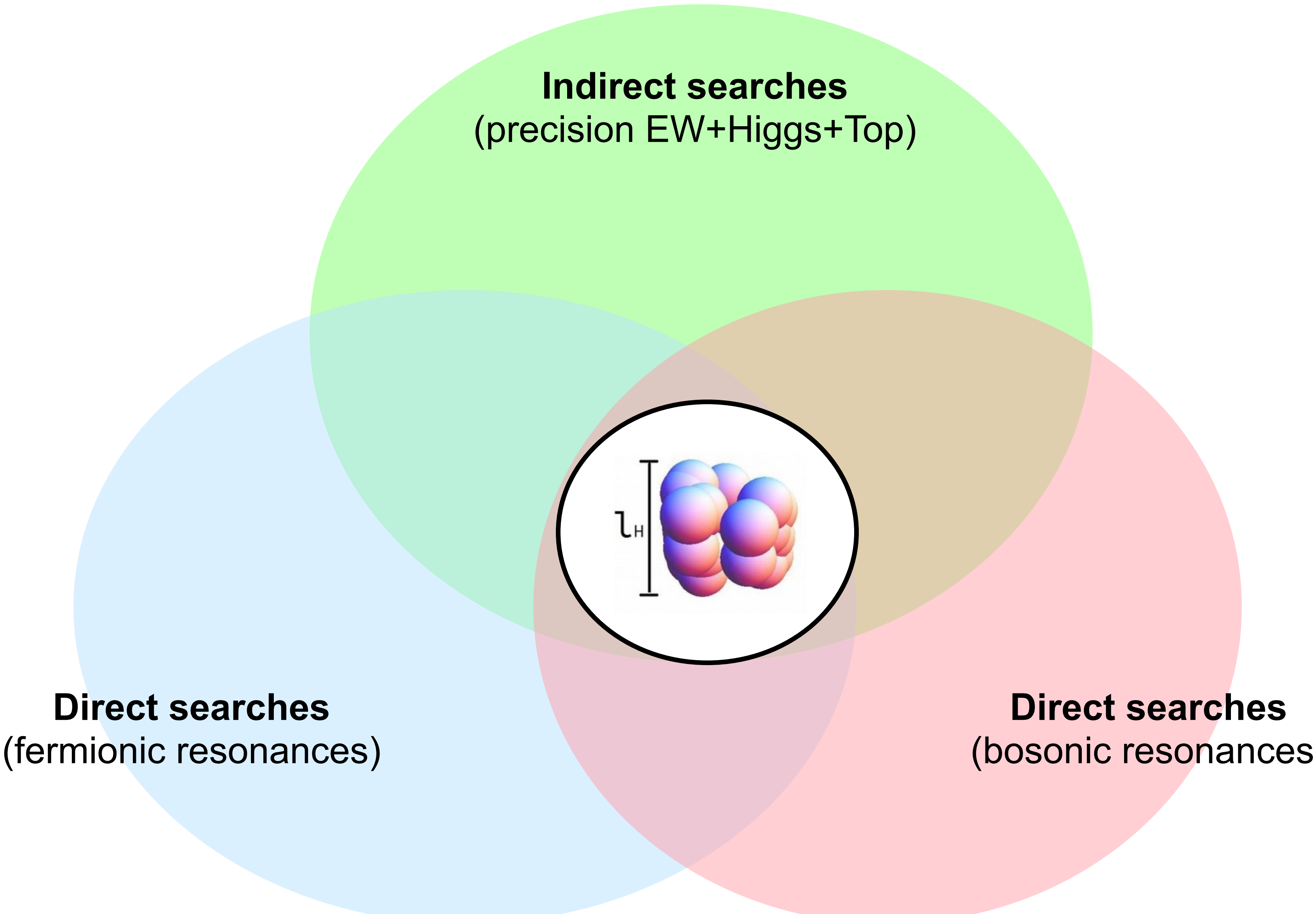
***Vector-like**: left and right components transform the same under $SU(2)_L$*
➔ can write mass term in Lagrangian





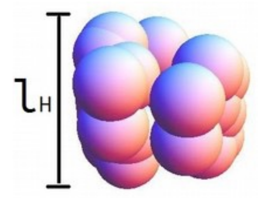
They regulate the Higgs mass-squared divergence

A Broad Program



A Broad Program

Indirect searches
(precision EW+Higgs+Top)



Direct searches
(fermionic resonances)

Focus of this talk

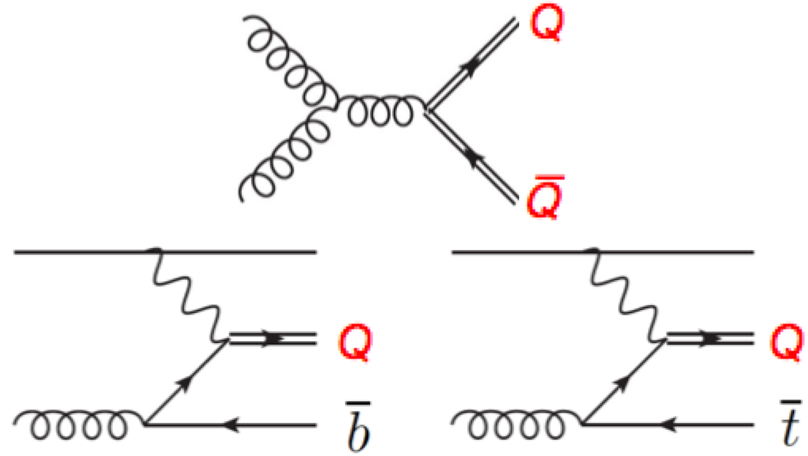
Direct searches
(bosonic resonances)

Fermionic Resonances

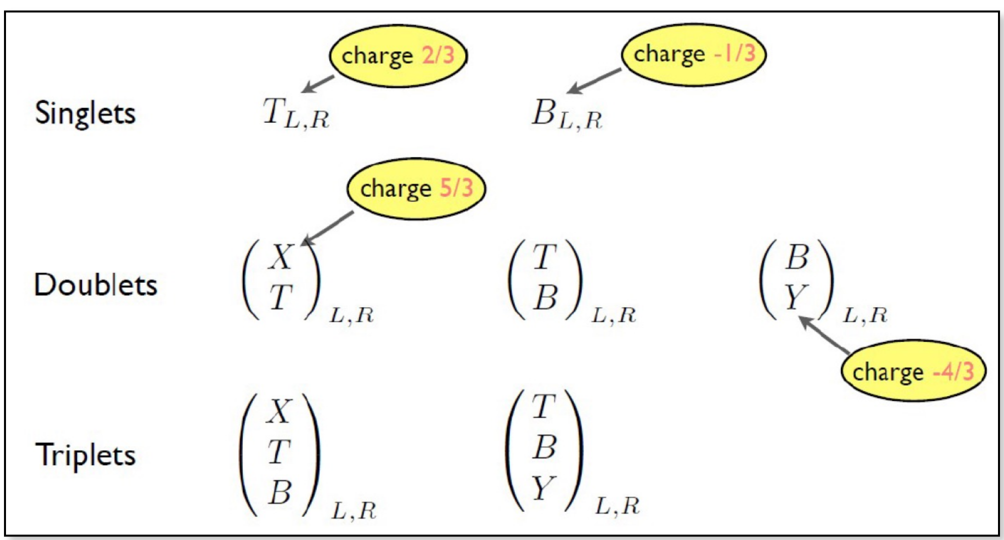
Vector-Like Quarks: Production and Decay

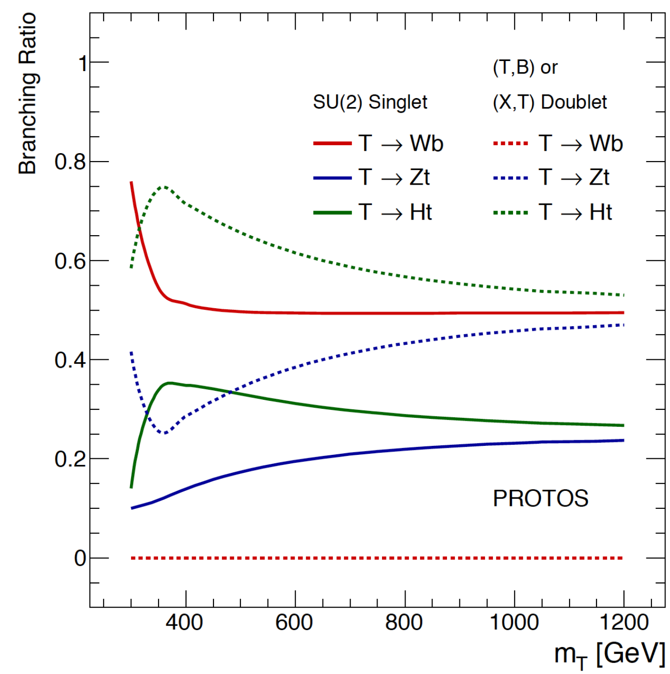
Production:

- Pair production: via QCD, "universal" production mode (just depends on m_Q).
  ➔ Focus of Run 1 searches
- Single production: via EW interaction, depends on coupling strength, but potentially important at high m_Q.



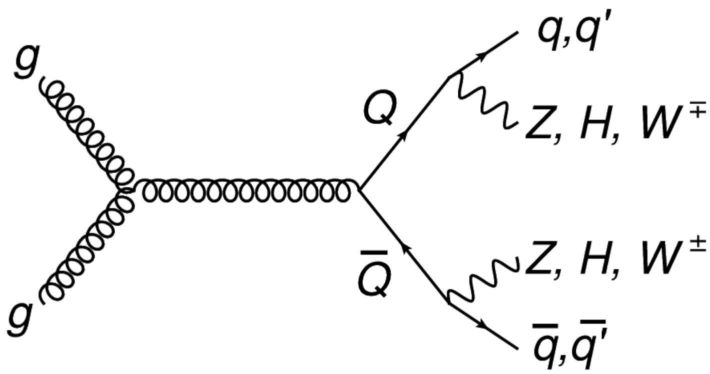
Decay: Q→Wq, Zq, Hq, all with sizable BR





VLQs assumed to mix preferentially with 3rd generation quarks.

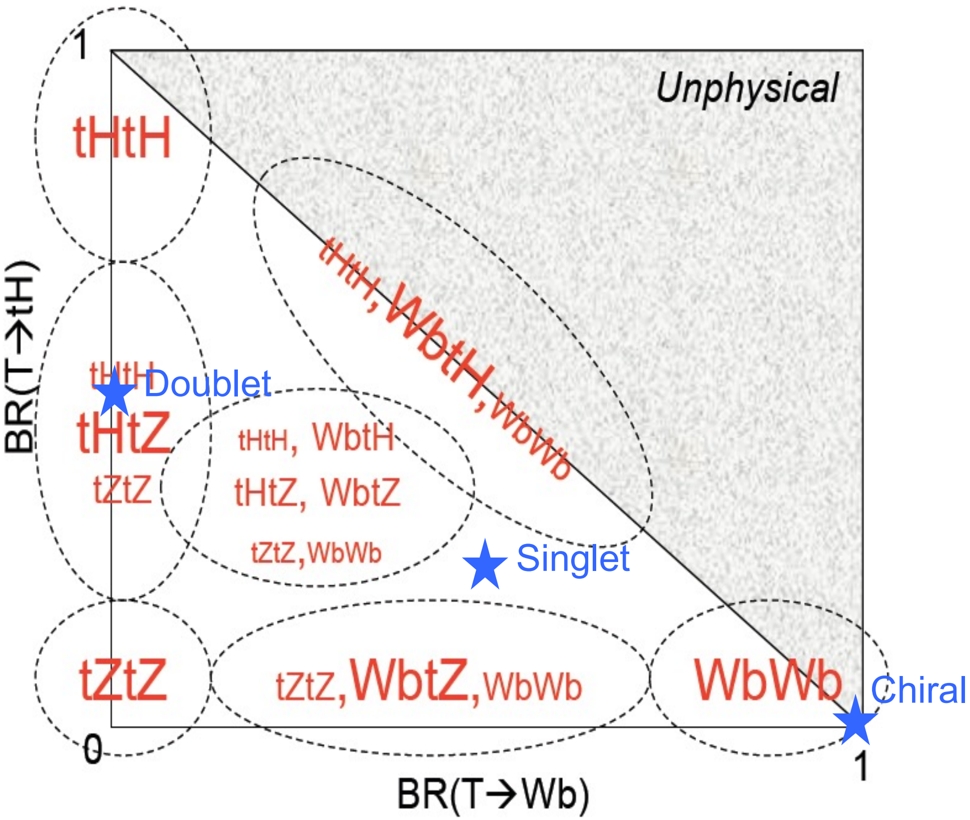
Pair Production Strategy



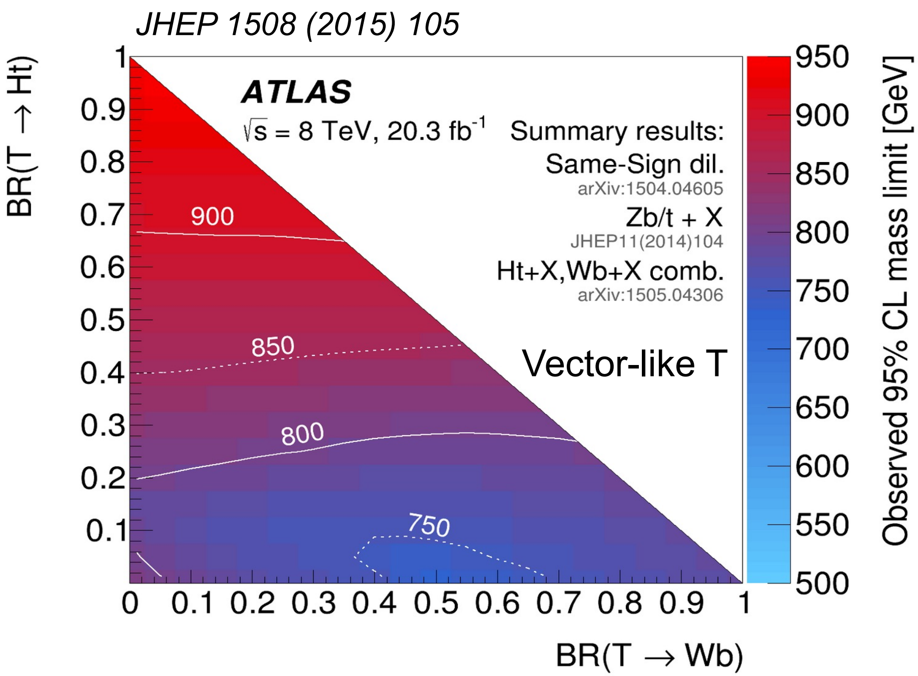
- Very rich phenomenology, depending on VLQ mass and quantum numbers.
- Goal is to probe full BR plane in as model independent possible way.

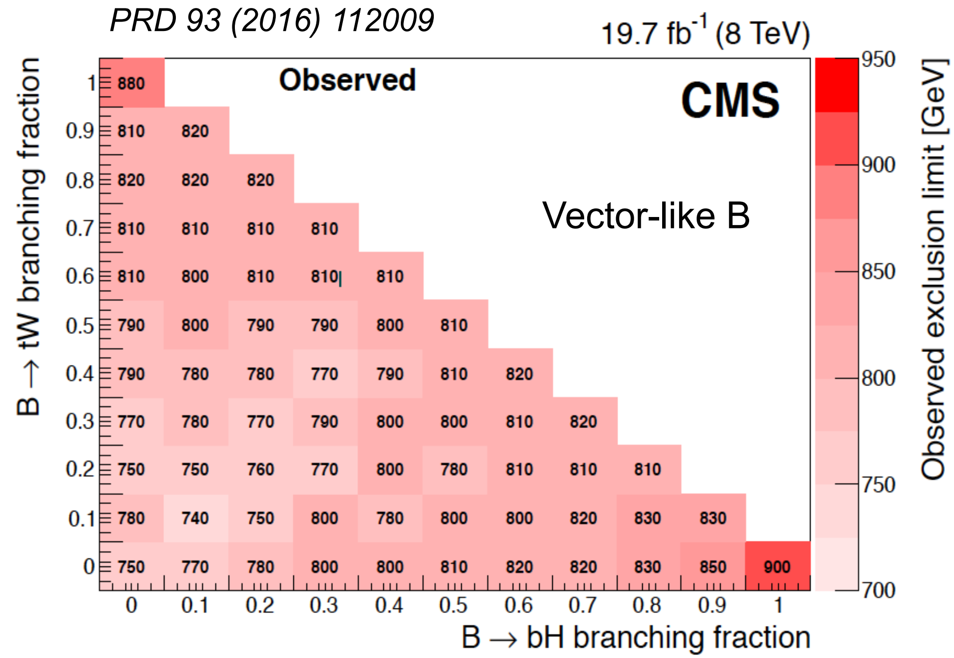
  ➔ Searches specialized on particular heavy quark decay modes, but also able to probe part of the plane.

  ➔ Multiple searches required, ideally overlapping on the plane.



Run 1 Summary





(*) Not a combination. Only most restrictive individual bounds shown.

Run 1 excludes T-quark (B-quark) masses below ~720 (740) GeV for any combination of BRs

Strategy for Run 2 Analyses

- **Capitalize on Run 1 experience**
  - Most sensitive channels
  - Complementary channels
  - Missing channels
  - Most powerful experimental strategies
  - Improved background estimation techniques
  - Reducing the impact of systematic uncertainties
  - …

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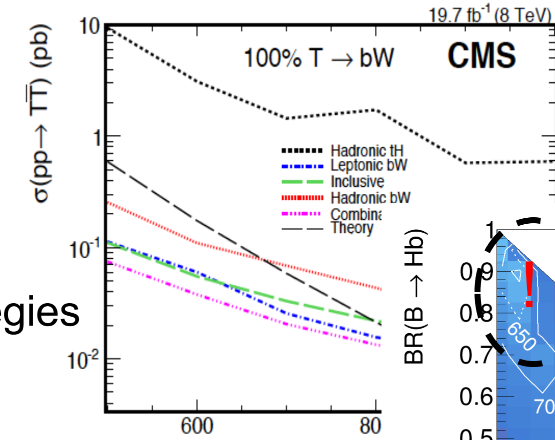

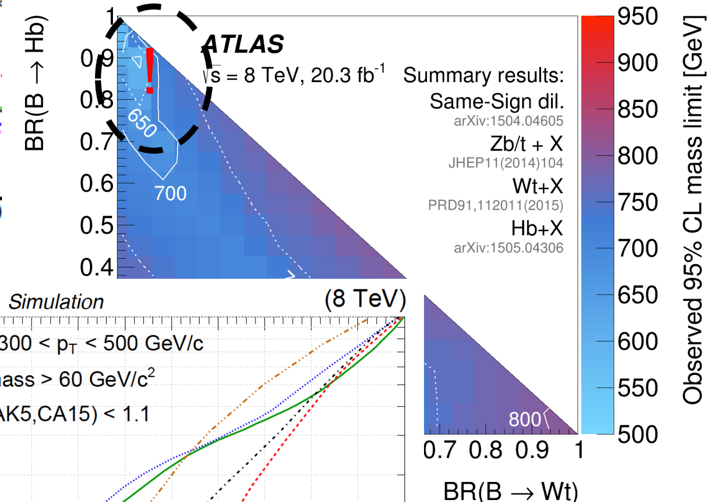

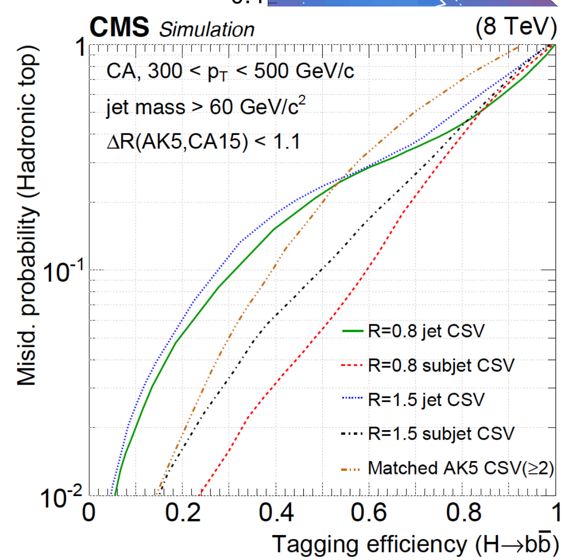

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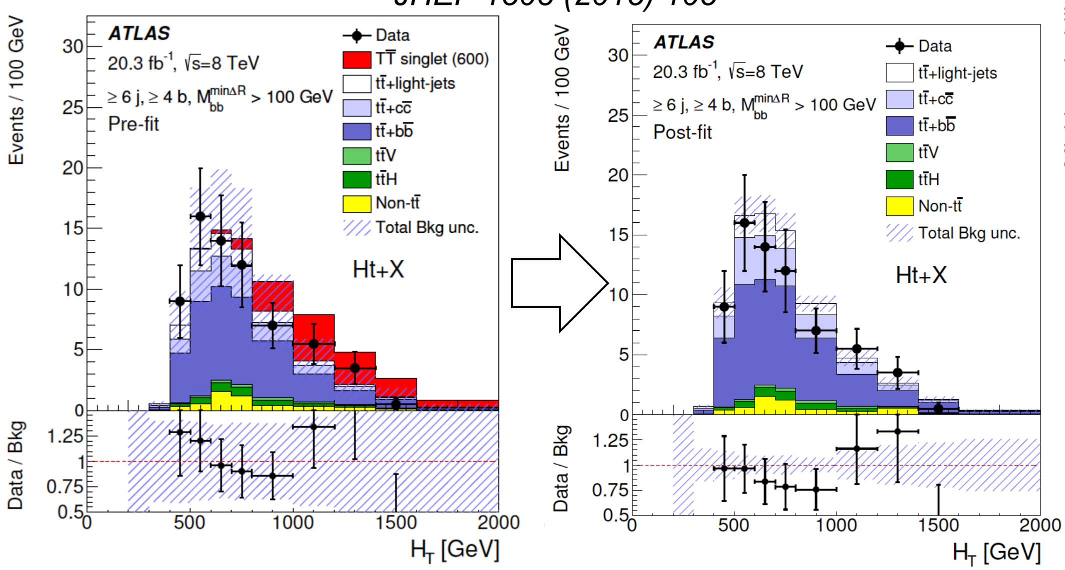
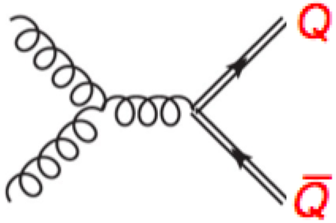
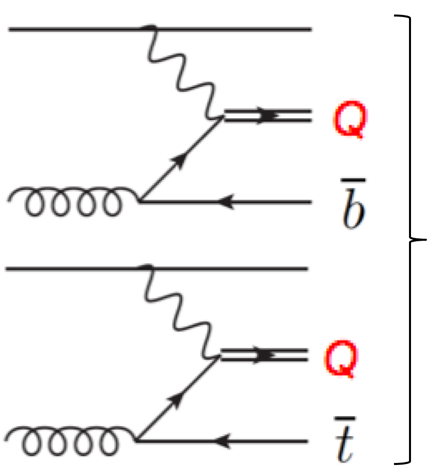


Strategy for Run 2 Analyses

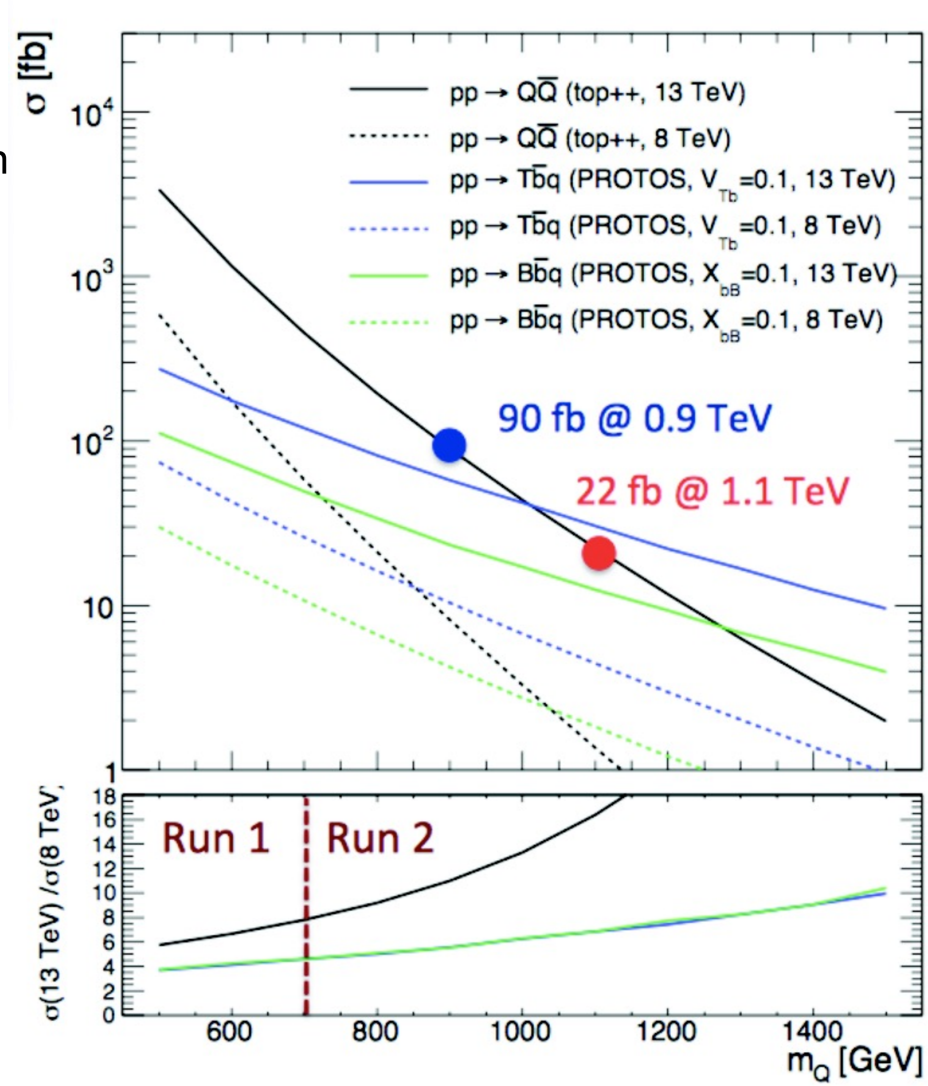
- **Capitalize on Run 1 experience**
- **Fully exploit increased CM energy**
  - Large increase in production cross section at high masses
    - Continue to exploit pair production above 1 TeV
    - Add single production above 1 TeV



Pair production
model independent,
relevant at low mass



Single production
model dep. coupling,
PDF-favored at high mass



Strategy for Run 2 Analyses

- **Capitalize on Run 1 experience**
- **Fully exploit increased CM energy**
  - Large increase in production cross section at high masses
  - Optimize strategy at high mass

SM resonances are often boosted!

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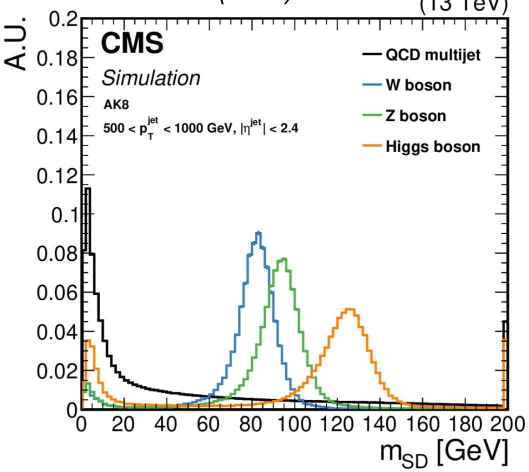
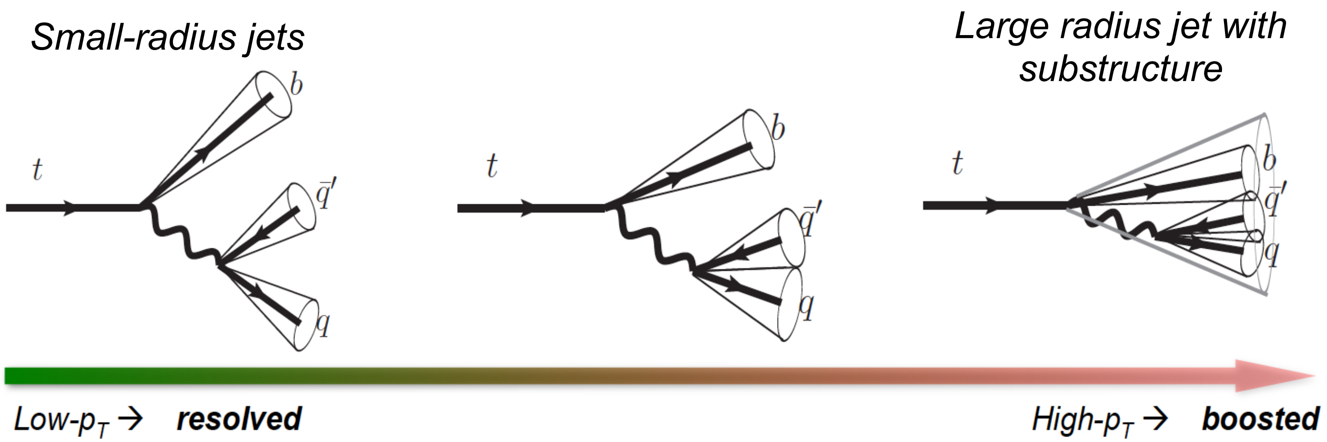
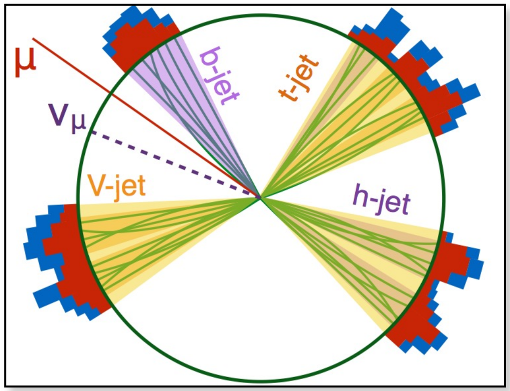






Many well understood tools for tagging of hadronically decaying W, Z, Higgs and top!

Strategy for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- **Plan according to integrated luminosity**

Less sophisticated

2015: $3.9\ fb^{-1}$ recorded
First results exceeding Run 1 sensitivity!

2016: $\sim 36\ fb^{-1}$ recorded
Exceed design inst. lumi of $10^{34}\ cm^{-2}s^{-1}$.

Many results still use:
up to $36\ fb^{-1}$ (in analysis)

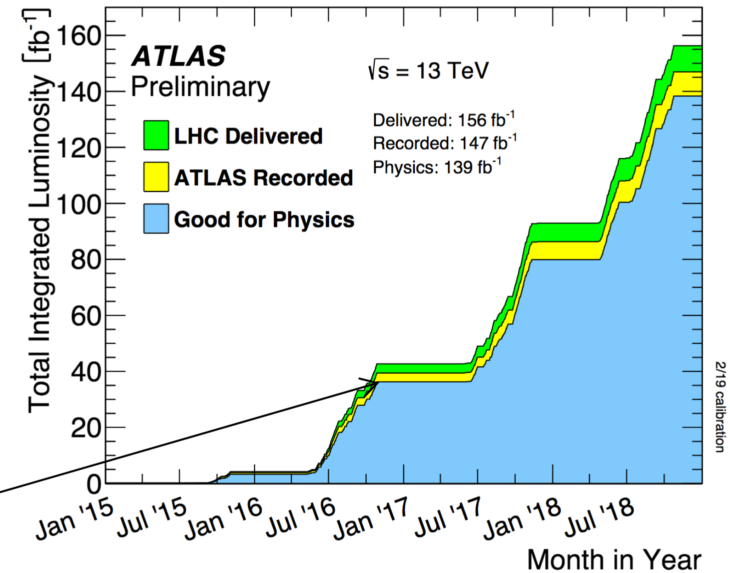
2017: $\sim 47\ fb^{-1}$ recorded
Record inst. lumi of $\sim 2.1 \times 10^{34}\ cm^{-2}s^{-1}$.

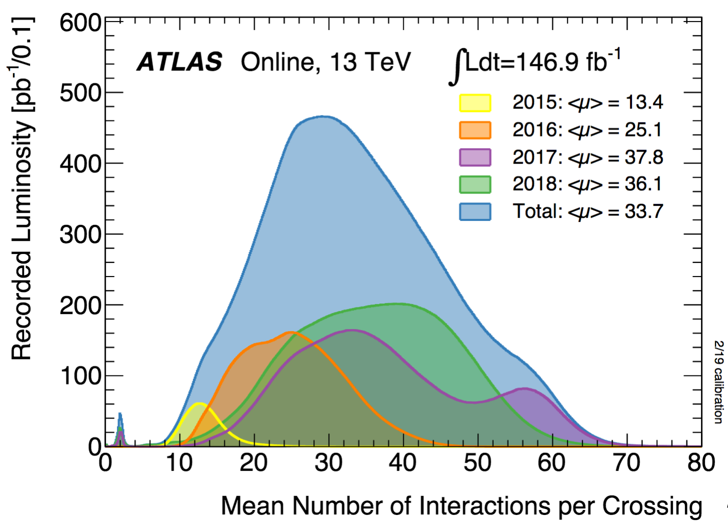
2018: $\sim 61\ fb^{-1}$ recorded
Inst. lumi regularly at $\sim 2 \times 10^{34}\ cm^{-2}s^{-1}$.

More sophisticated

Full Run 2: $\sim 139\ fb^{-1}$ (in analysis)

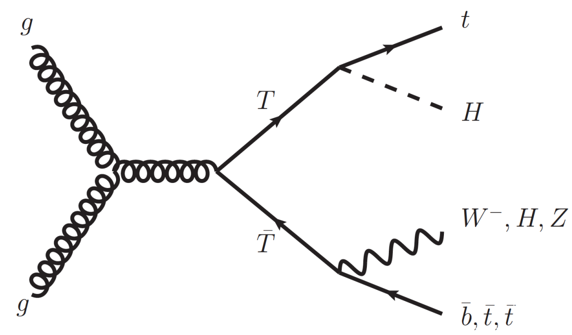
Outstanding performance!



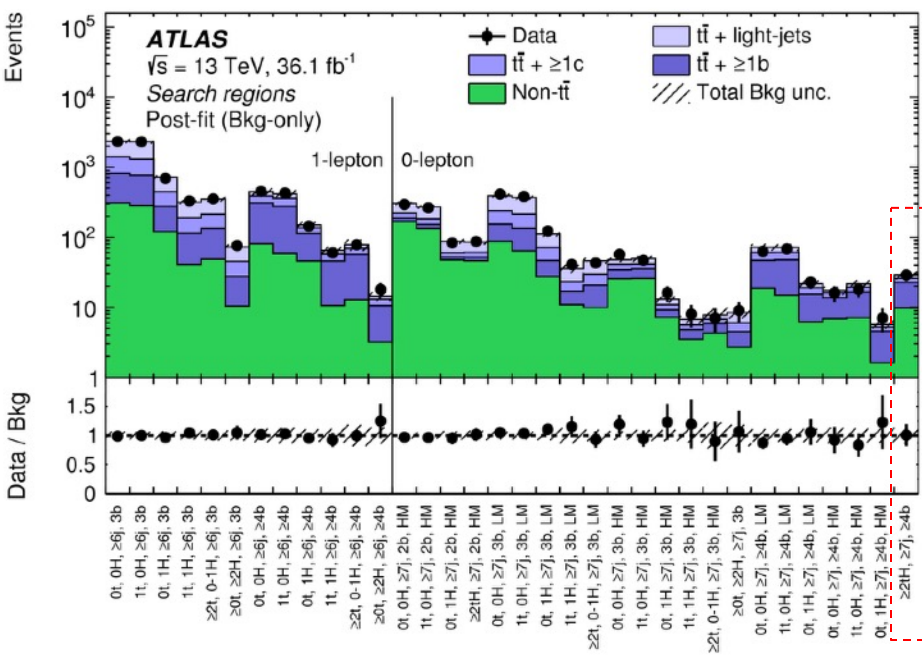


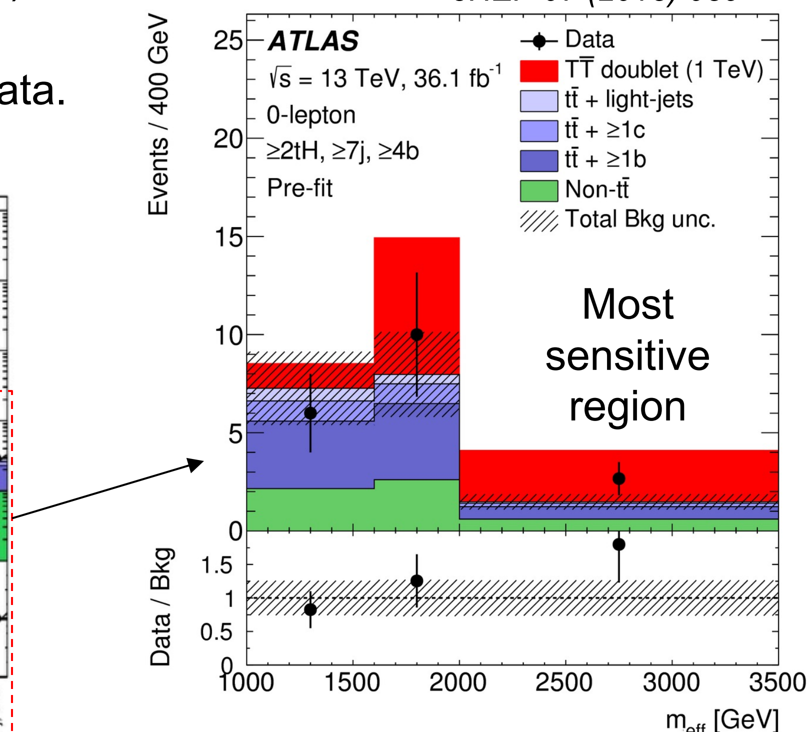
Pair Production: TT→Ht+X

- Search targeting high BR(T→Ht), with H→bb, but designed as broad-band search.
- Strategy:
  - Consider lepton+jets and high-E_T^{miss}+jets channels.
  - Top and Higgs tagging via mass cut on large-R jets.
  - Categorize events according to b-tag, top-tag and Higgs-tag multiplicities (a total of 34 regions).
  - Signal-depleted regions used to constrain in-situ bkg uncert. through likelihood fit to data.



JHEP 07 (2018) 089

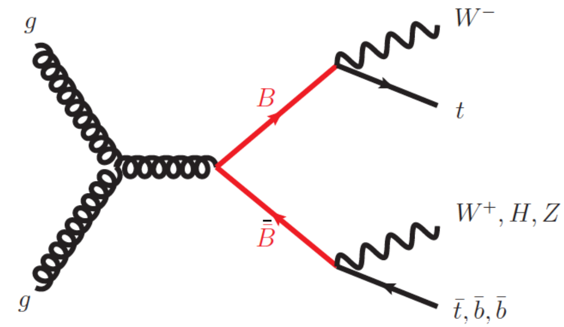




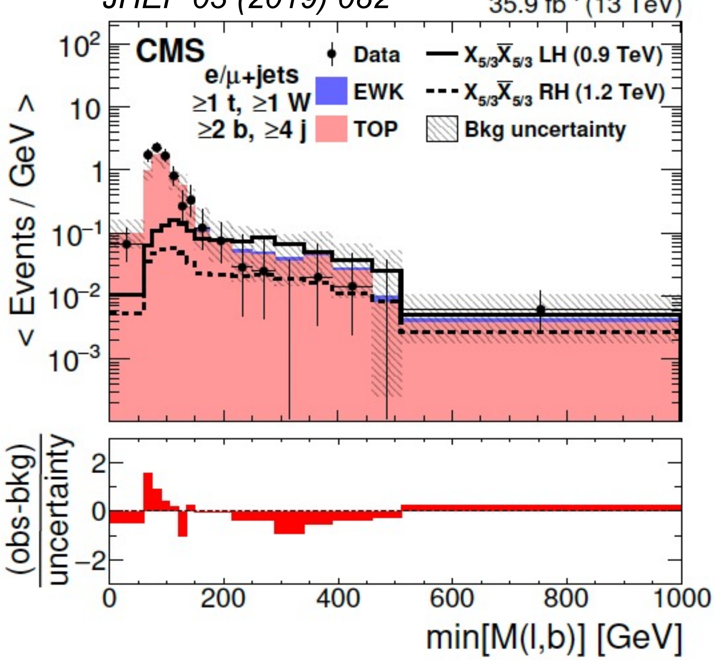
$$m_{\text{eff}} = \sum_{\text{objects}} p_T + E_T^{\text{miss}}$$

Pair Production: BB, $X_{5/3}X_{5/3}$ → WtWt

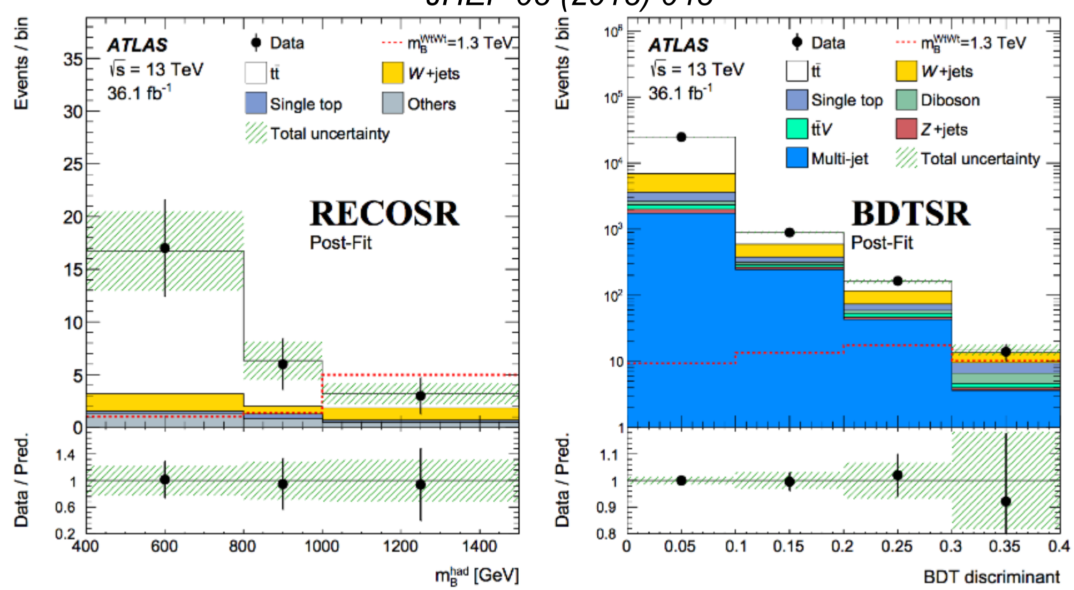
- Searches targeting B→W⁻t or $X_{5/3}$→W⁺t.
- Consider SS dilepton+jets and lepton+jets signatures, both with comparable sensitivity.
- Strategy (lepton+jets):
  - Preselection: 1 lepton, high E_T^{miss}, ≥4 jets/≥1 b-tags.
  - Multiple event categories depending on the presence of boosted top or hadronic W bosons.
  - Analyze B-quark mass or BDT output (ATLAS), or min[M(l,b)] (CMS) spectra.



JHEP 03 (2019) 082

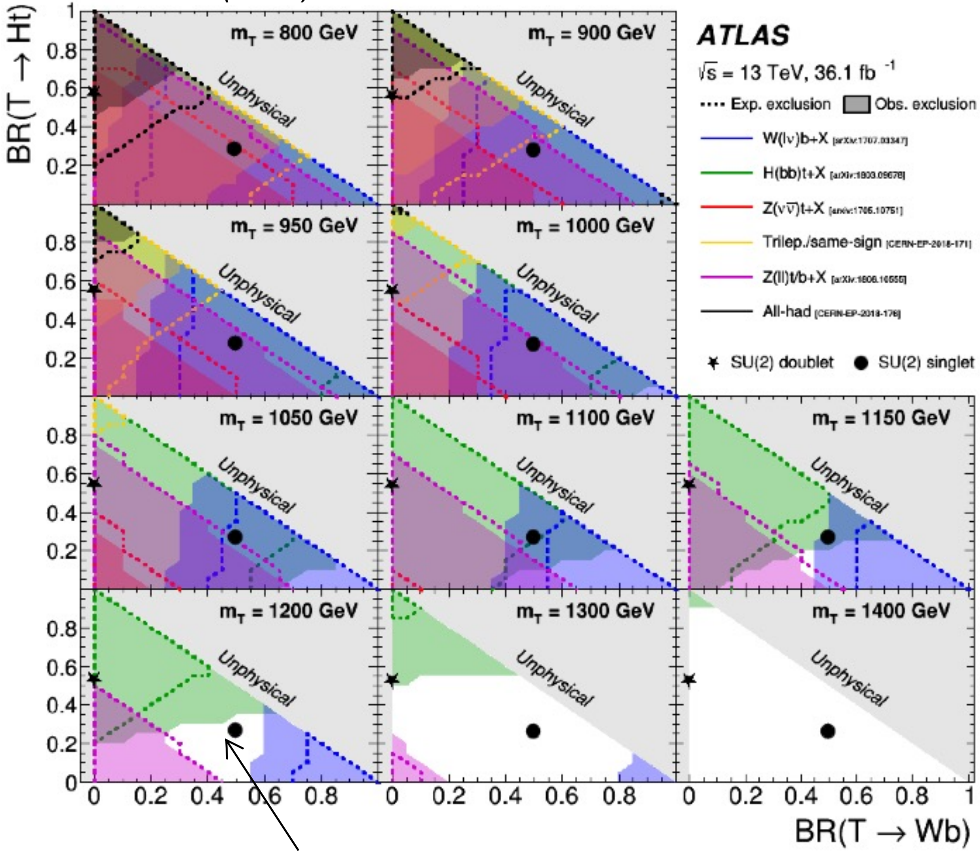


JHEP 08 (2018) 048

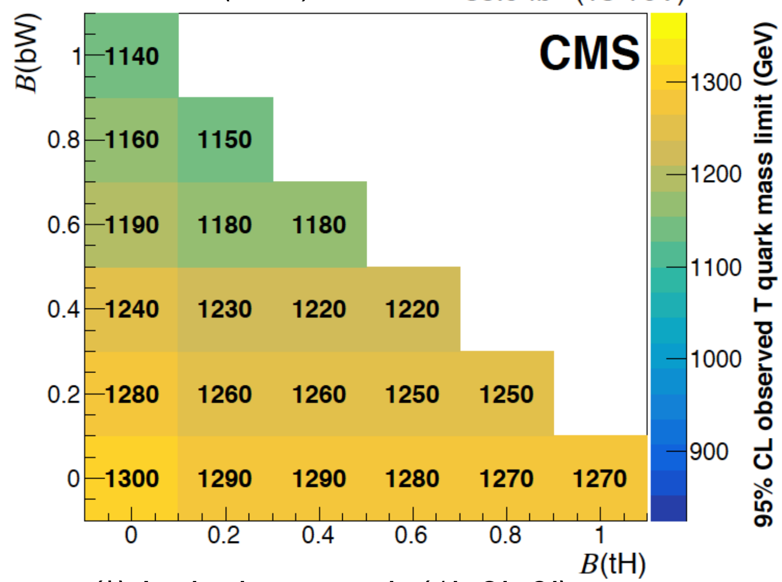


Pair Production Summary: Vector-Like Top

PRL 121 (2018) 211801



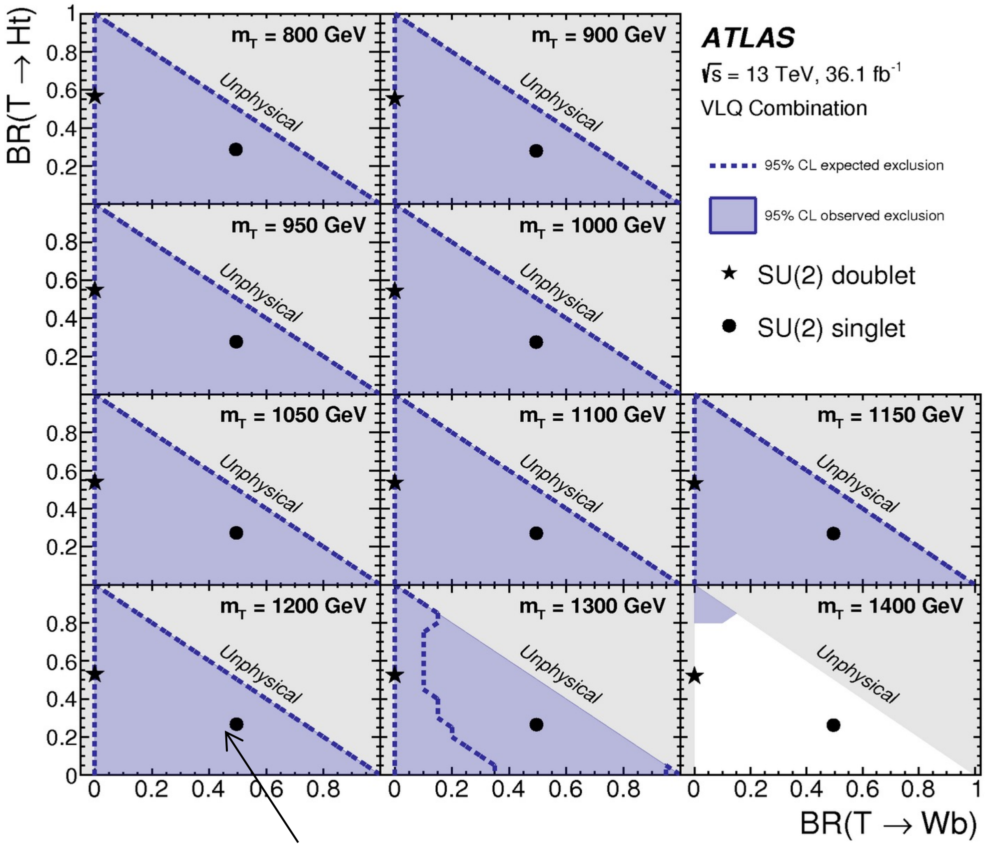
JHEP 08 (2018) 177



(*) Inclusive search (1l, 2l, 3l)

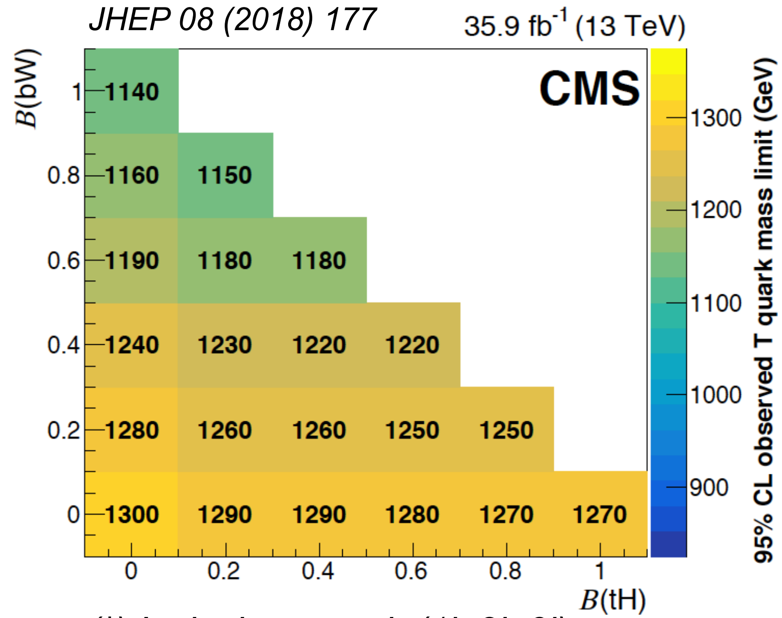
Pair Production Summary: Vector-Like Top

PRL 121 (2018) 211801



Significant gain from combination!

JHEP 08 (2018) 177



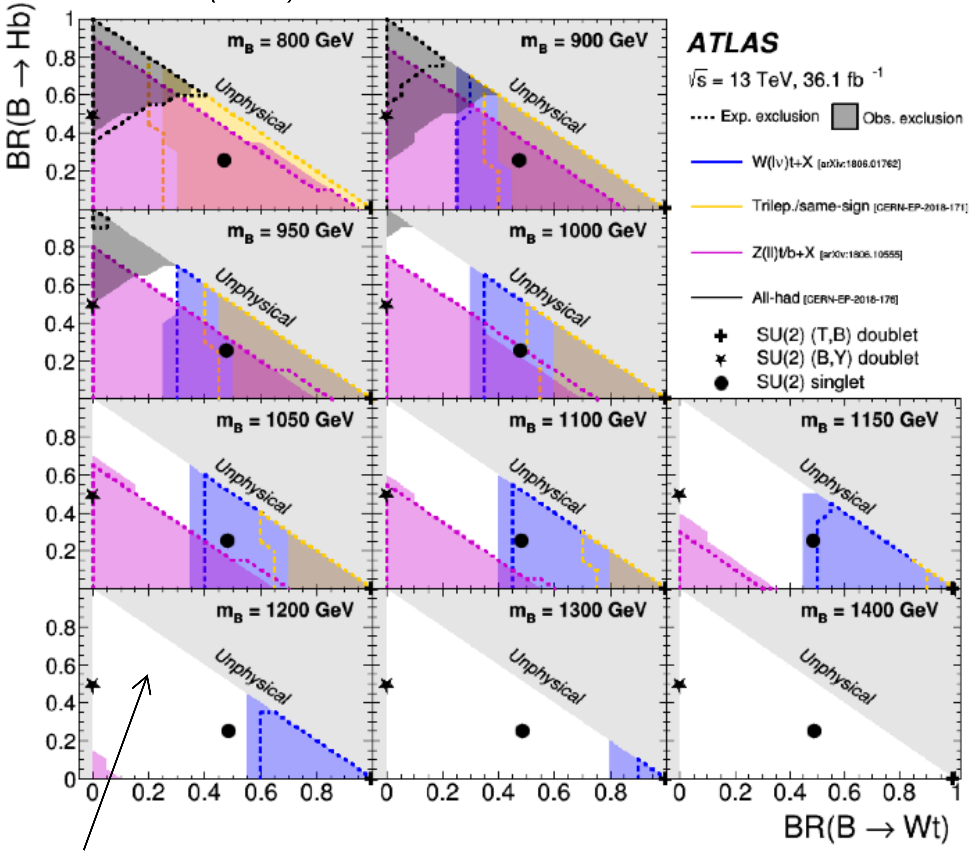
(*) Inclusive search (1l, 2l, 3l)

VLT masses below ~1.3 TeV excluded for any possible combination of BRs

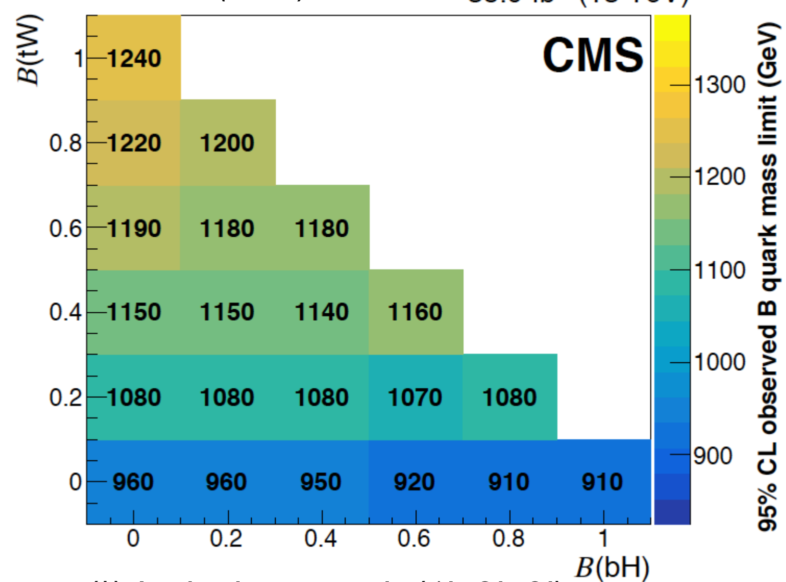
	ATLAS	**CMS**
Vector-like T BR Hypothesis	**95% CL Limit on m_T (TeV) obs (exp)**	**95% CL Limit on m_T (TeV) obs (exp)**
100% Wb (chiral, Y)	**1.35** (1.30)	**1.28** (1.30)
T singlet	**1.31** (1.23)	**1.20** (1.16)
T in (T, B) doublet	**1.37** (1.32)	**1.28** (1.24)

Pair Production Summary: Vector-Like Bottom

PRL 121 (2018) 211801



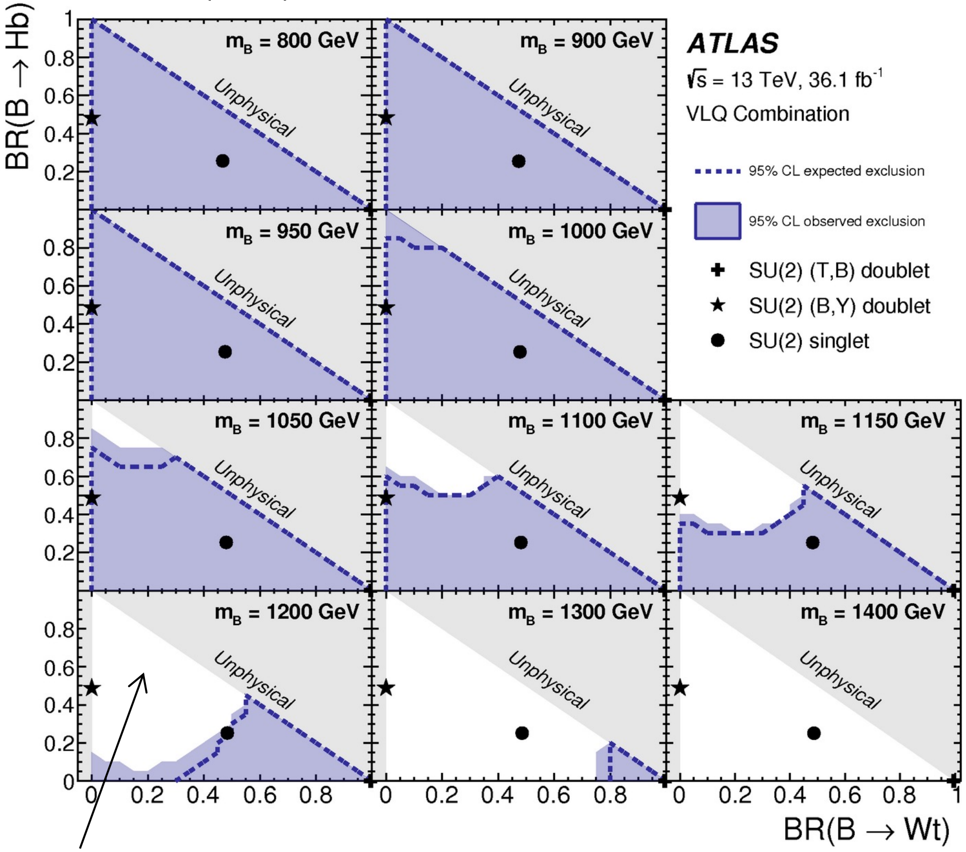
JHEP 08 (2018) 177



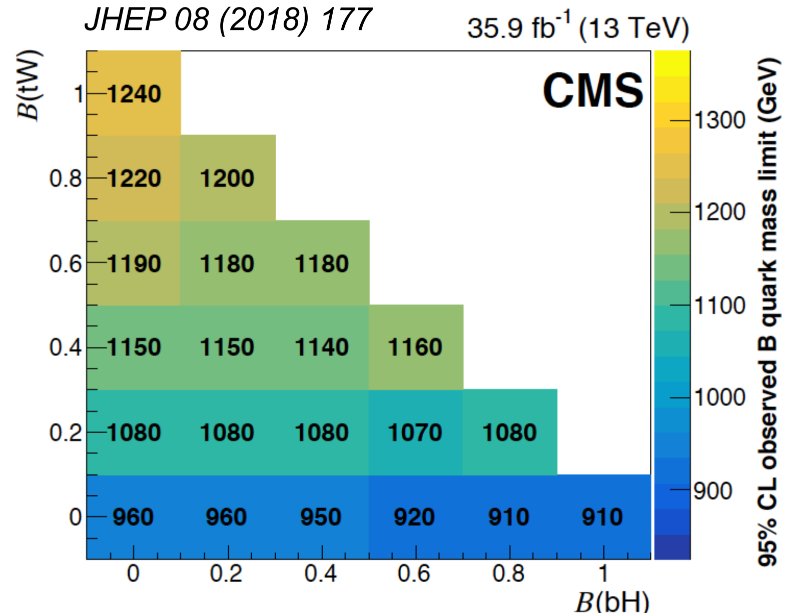
(*) Inclusive search (1l, 2l, 3l)

Pair Production Summary: Vector-Like Bottom

PRL 121 (2018) 211801



JHEP 08 (2018) 177



(*) Inclusive search (1l, 2l, 3l)

Need better B→Hb searches!

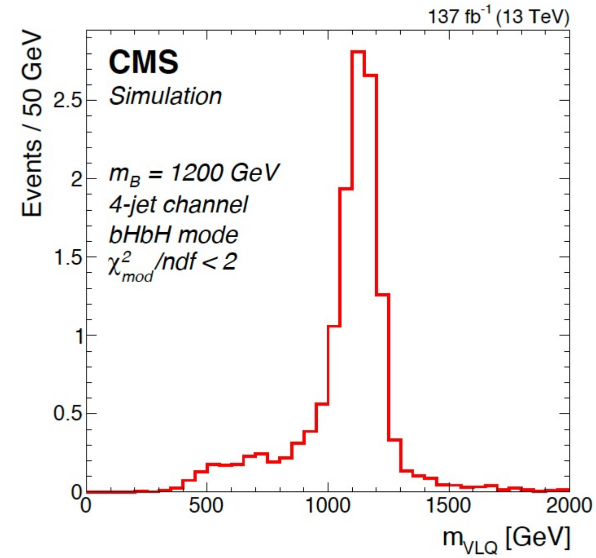
VLB masses below ~1.0 TeV excluded for any possible combination of BRs

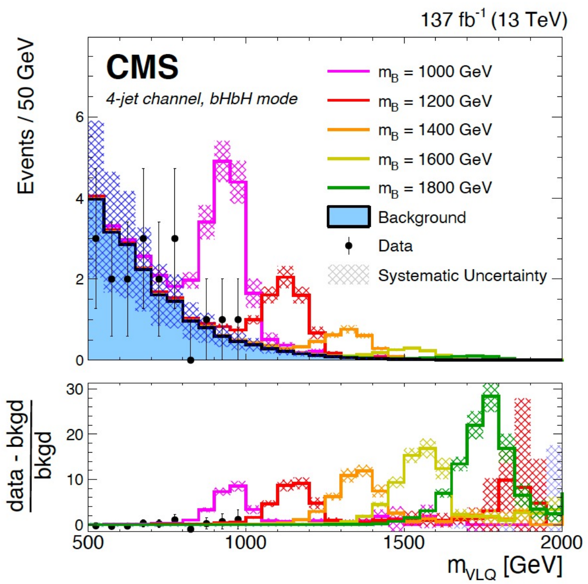
Vector-like B BR Hypothesis	**ATLAS** 95% CL Limit on m_B (TeV) obs (exp)	**CMS** 95% CL Limit on m_B (TeV) obs (exp)
100% Wt (chiral, X)	**1.35** (1.34)	**1.24** (1.24)
B singlet	**1.22** (1.21)	**1.17** (1.13)
B in (B, Y) doublet	**1.14** (1.13)	**0.94** (0.92)

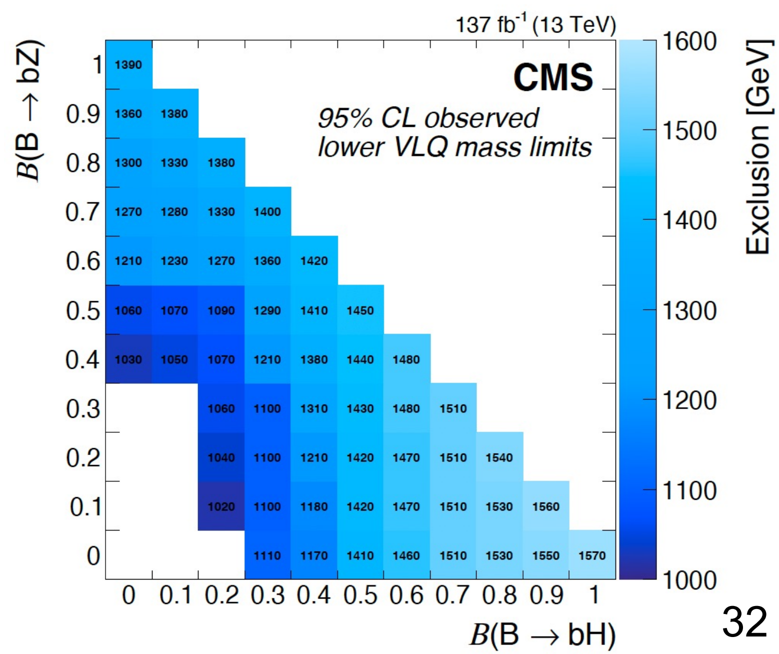
Pair Production: BB→Hb/Zb+X

Full Run 2

- Search targeting B→Hb/Zb with H→bb and Z→qq.
- Strategy:
  - Consider multijet final states with 4, 5, or ≥6 AK4 jets.
  - Use AK8 jets w/ soft-drop algorithm+N-subjettiness to tag 2-prong candidates from boosted H/Z decay.
  - Further categorize events according to target topology (bHbH, bHbZ, bZbZ) and require high b-tag multiplicity (2-4, depending on topology).
  - Define chi2 variable to assign jets to each VLQ and reconstruct VLQ mass.
  - Multijet background estimated using data-driven technique.





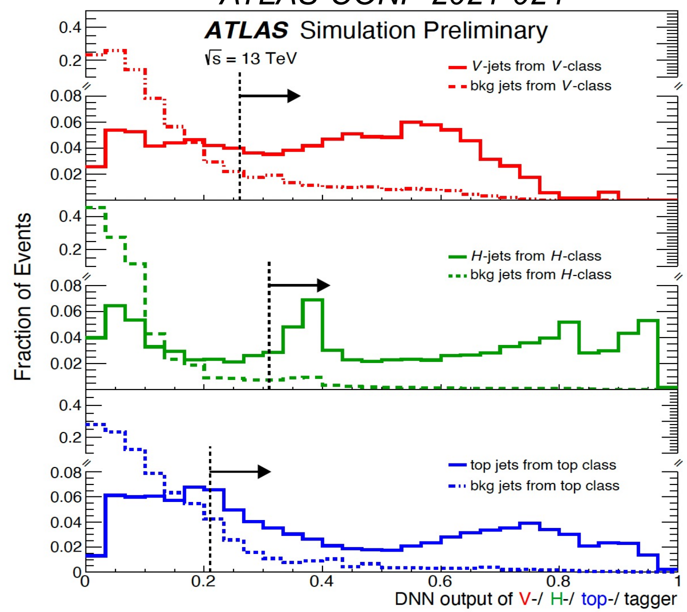


Pair Production: TT/BB→Zt/Zb+X (2l/3l)

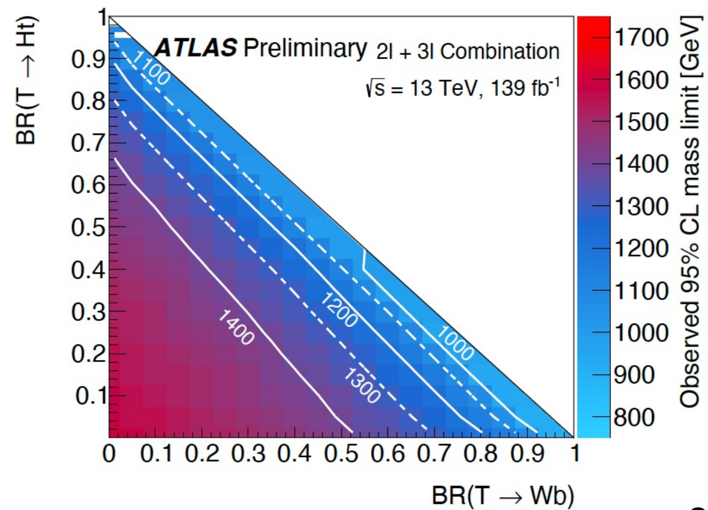
Full Run 2

- Search targeting T/B→Zt/Zb with Z→ll.
- Strategy:
  - Consider 2l OS and 3l channels with boosted Z→ll candidate and ≥1 b-tags.
  - Top/W/Higgs tagging via multiclass NN applied to reclustered large-R jets.
  - Categorize events according to boosted object tag multiplicities (a total of 18 signal regions).
  - Dedicated control regions for Z+jets and diboson backgrounds.
  - Analyze m(Zb) or H_T-related variables.

ATLAS-CONF-2021-024

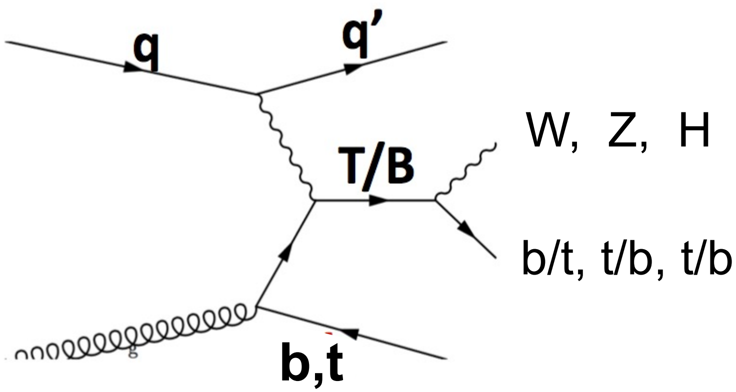


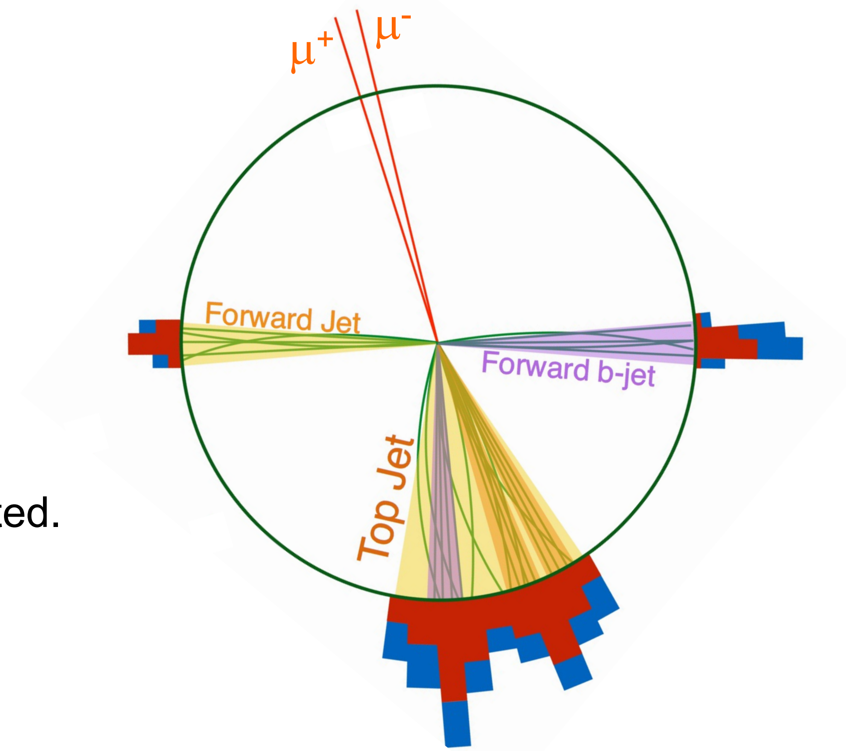
Model	Observed (Expected) Mass Limits [TeV] 2ℓ	3ℓ	Combination
$T\bar{T}$ Singlet	1.14 (1.16)	1.22 (1.21)	1.27 (1.29)
$T\bar{T}$ Doublet	1.34 (1.32)	1.38 (1.37)	1.46 (1.44)
100% $T \to Zt$	1.43 (1.43)	1.54 (1.50)	1.60 (1.57)
$B\bar{B}$ Singlet	1.14 (1.21)	1.11 (1.10)	1.20 (1.25)
$B\bar{B}$ Doublet	1.31 (1.37)	1.07 (1.04)	1.32 (1.38)
100% $B \to Zb$	1.40 (1.47)	1.16 (1.18)	1.42 (1.49)



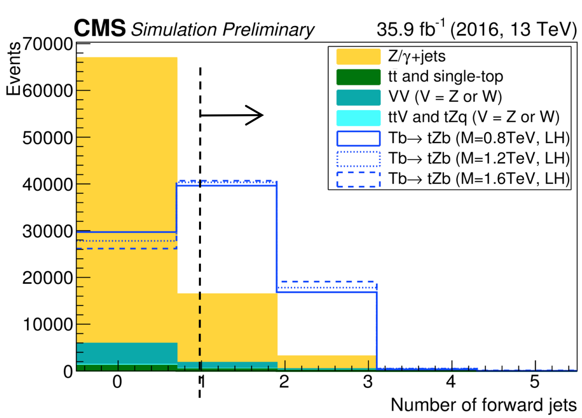
Individual search with comparable sensitivity to ATLAS combination @36 fb^{-1}

Single Production Strategy

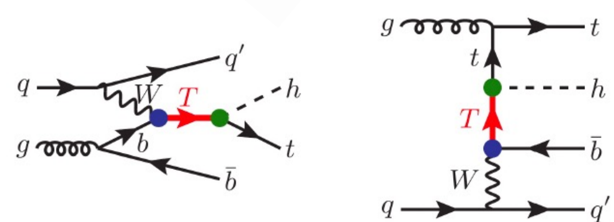




- Many channels (w/ and w/o leptons) to be exploited.
- **Powerful handles against backgrounds:**
  - Forward jet tagging
  - Boosted techniques
  - VLQ mass reconstruction



CMS-PAS-B2G-17-007



arXiv:2105.08745

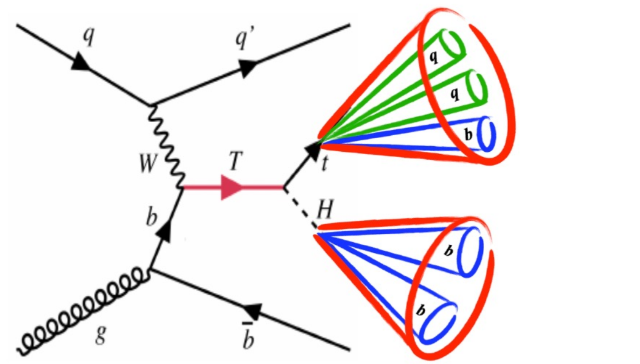
Beware of:

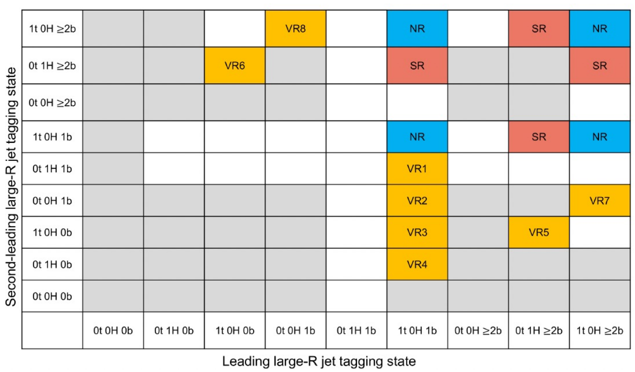
- Helicity propagation in decay
- Off-shell/non-resonant production
- Signal/background interference

Single Production: T→Ht all-hadronic

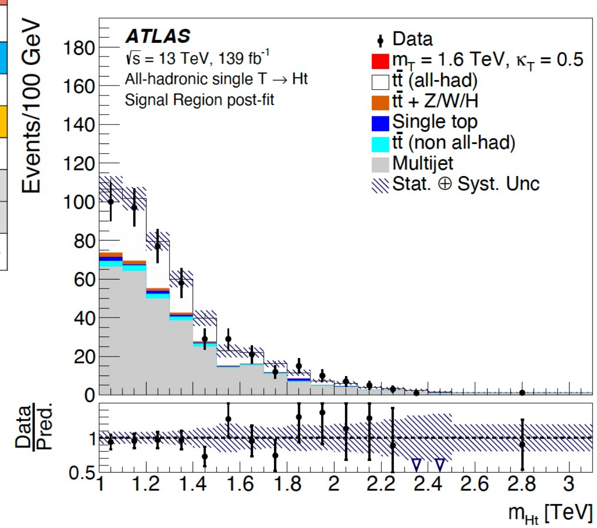
Full Run 2

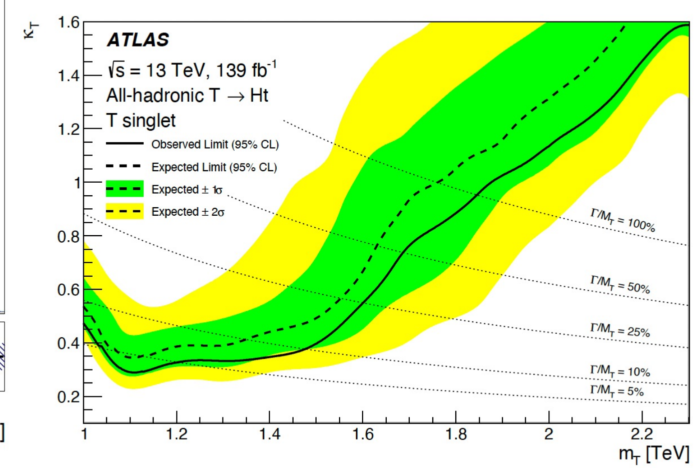
- Search targeting T→Ht, with H→bb and t→qqb.
- Strategy:
  - Require two high-p_T large-R jets with b-subjets.
  - 2D grid based on the tagging of the two large-R jets:
    - Higgs (mass+τ_{21}) or top (mass+DNN) candidate
    - Number of b-tagged VR trackjets inside large-R jet
    - ➔ Used to define multiple CRs, VRs, and the SR.
    - Multijet background estimated using ABCD method.





arXiv:2201.07045

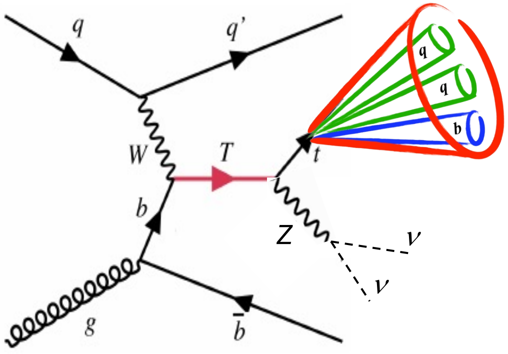


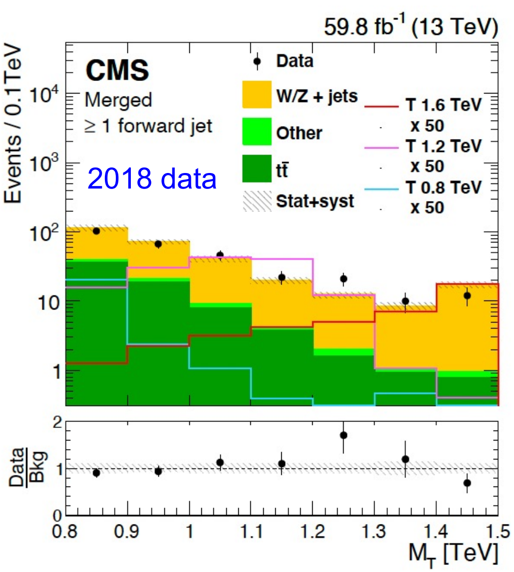


Single Production: T→Zt mono-top

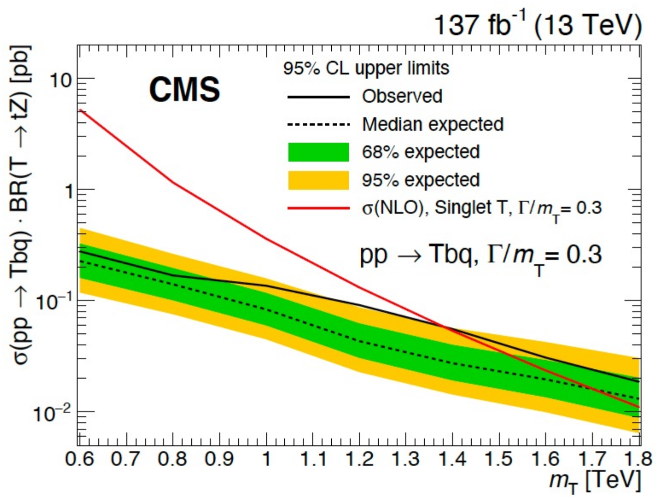
Full Run 2

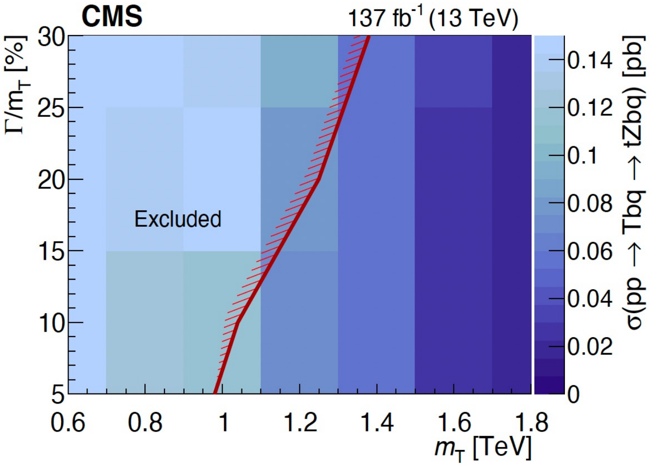
- Search targeting T→Zt, with Z→νν and t→qqb.
- Strategy:
  - Use AK4 jets for b-tagging and AK8 jets w/ soft-drop algorithm+N-subjettiness to tag boosted W or top.
  - Define 6 event categories depending on top reconstruction method (merged, partly merged and resolved) and forward jet multiplicity (0, ≥1).
  - Main backgrounds from tt and V+jets, estimated from MC w/ dedicated corrections derived in CRs.
  - Signal extraction from simultaneous fit to transverse mass of top quark and E_T^{miss} across the 6 SRs.





arXiv:2201.02227





Strategy for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- **Improved interpretation of searches**
  - Increased use of simplified models: phenomenological Lagrangian parameterized with coupling terms.
  - Combinations, particularly for single production!

Simplified model

$$\mathcal{L} = \frac{g_w}{2}\left[c_R^{XV}\,\overline{X}_R \not{V} t_R + c_L^{XV}\,\overline{X}_L \not{V} t_L\right] + \frac{g_w}{2}\left[c_L^{XV}\,\overline{X}_L \not{V} b_L + c_R^{XV}\,\overline{X}_R \not{V} b_R\right]$$
$$+ \left[c_R^{Xh}\,h\,\overline{X}_L t_R + c_L^{Xh}\,h\,\overline{X}_R t_L\right] + \left[c_L^{Xh}\,h\,\overline{X}_R b_L + c_R^{Xh}\,h\,\overline{X}_L b_R\right] + \text{h.c.}\,,$$

		couplings			
partner (MG name)	Q	$W^\pm$	Z	h	$W^\pm W^\pm$
$T_{2/3}$ (T23)	2/3	c_L^{TW}, c_R^{TW}	c_L^{TZ}, c_R^{TZ}	c_L^{Th}, c_R^{Th}	—
$B_{1/3}$ (B13)	-1/3	c_L^{BW}, c_R^{TW}	c_L^{BZ}, c_R^{BZ}	c_L^{Bh}, c_R^{Bh}	—
$X_{5/3}$ (X53)	5/3	c_L^{XW}, c_R^{XW}	—	—	—
$Y_{4/3}$ (Y43)	-4/3	c_L^{YW}, c_R^{YW}	—	—	—
$V_{8/3}$ (V83)	8/3	—	—	—	c_L^{VW}, c_R^{VW}

JHEP 04 (2013) 004

TBA

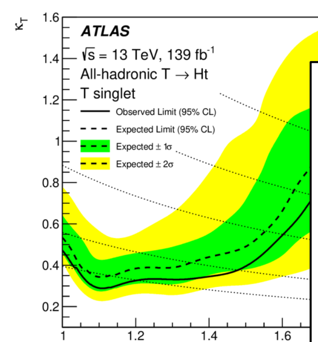
T→Wb

TBA

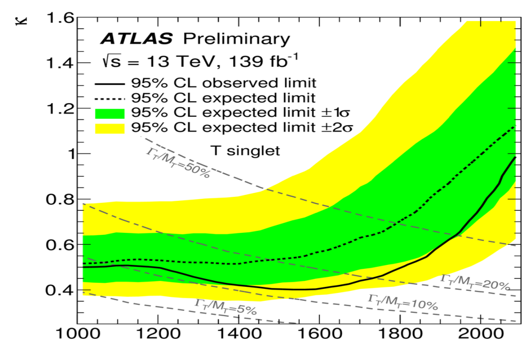
T→Z(→ll)t

TBA

T→Z(→νν)t



T→H(→bb)t all-had



T→H(→bb)t 1-lepton

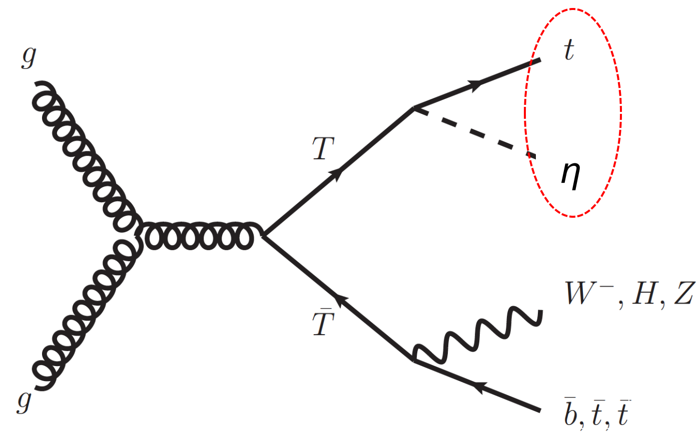
Strategy for Run 2 Analyses

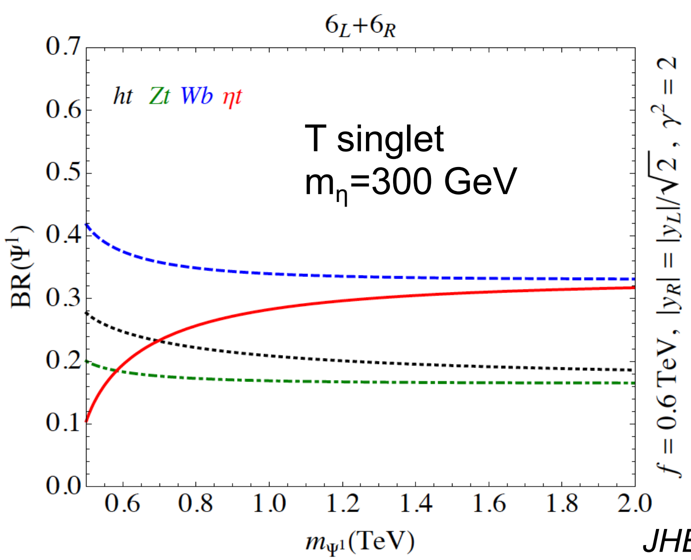
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don't miss a signal!**
  - Non-standard decays

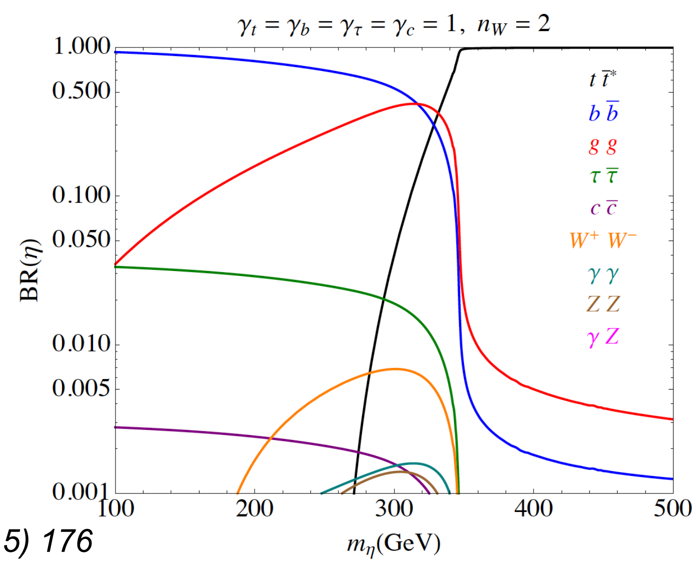
    BR(Q→Wq)+BR(Q→Zq)+BR(Q→Hq)<1

    Example: Q→q+η, η CP-odd scalar
    - If exotic BRs dominant, signal may be picked by existing searches.
    - For comparable BRs, it becomes difficult as signal split into many signatures.

      But also opportunity for new exciting searches: e.g. **TT→6-top**!







JHEP 1509 (2015) 176

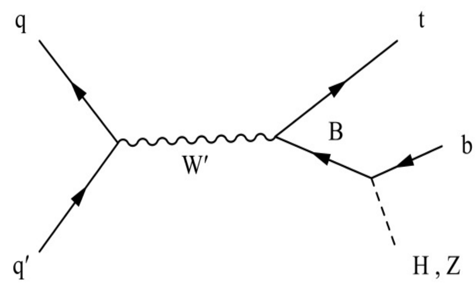
Strategy for Run 2 Analyses

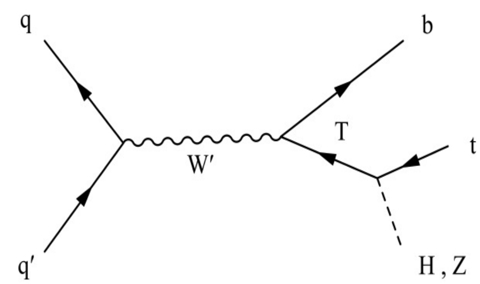
Full Run 2

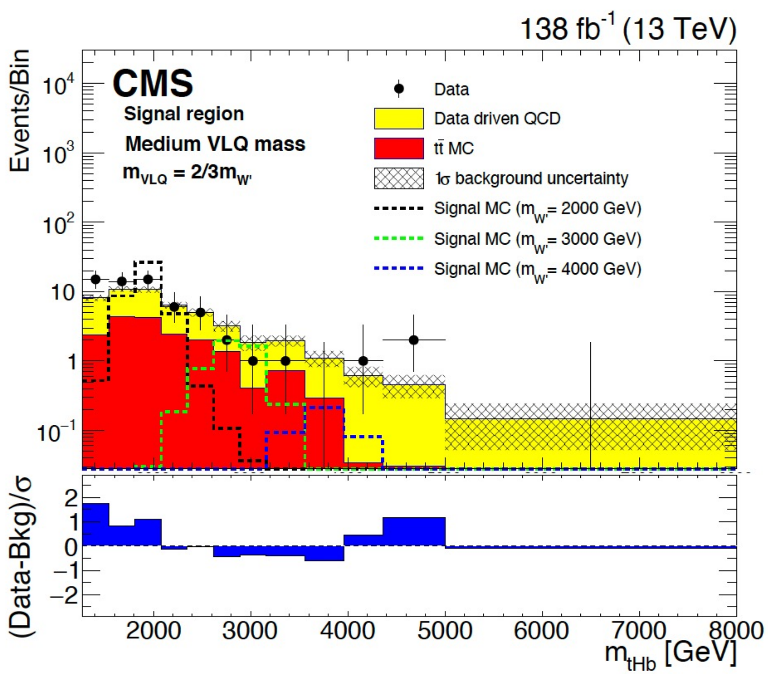
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don't miss a signal!**
  - Non-standard production

    E.g. via heavy W': W'→TB ($m_{W'} \geq m_T + m_B$),

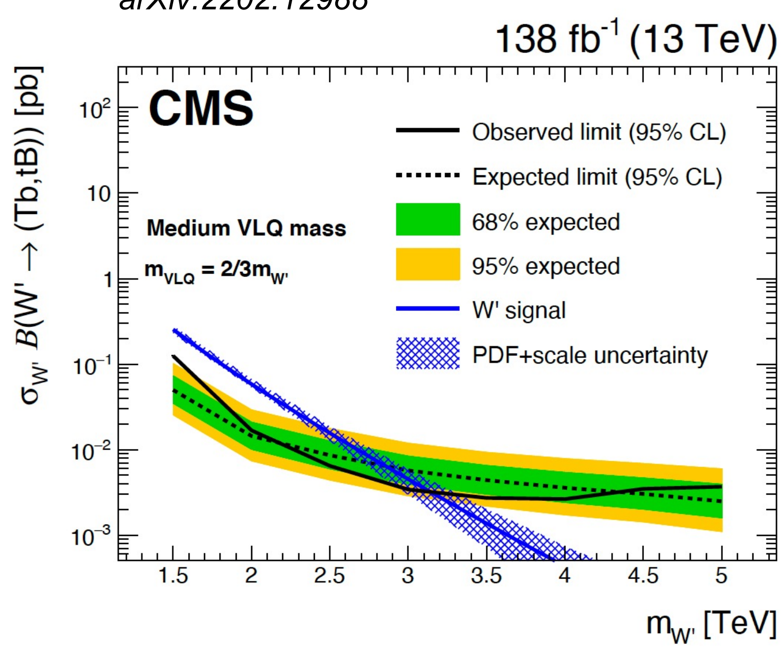
    W'→Tb or Bt ($m_{T/B} + m_{t/b} < m_{W'} < m_T + m_B$)







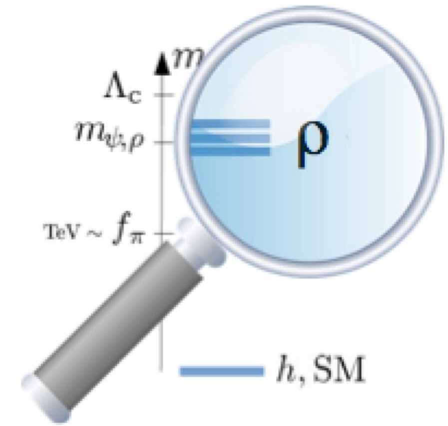
arXiv:2202.12988



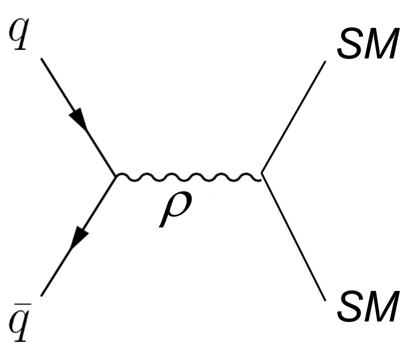
Bosonic Resonances

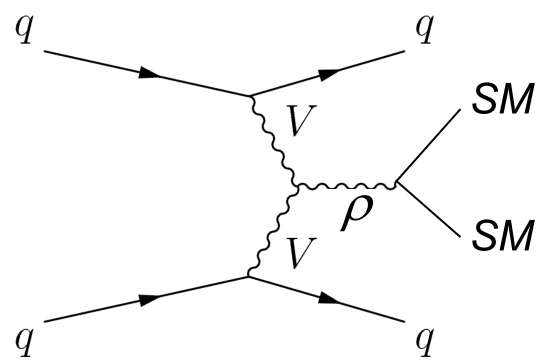
Bosonic resonances

- Also expect composite spin-1 resonances (ρ=G', Z', W'), which decay into SM particles.
  - Expect the strongest couplings to heavy SM states (t, W, Z, h).



- Main production mechanisms: Drell-Yan and/or vector-boson fusion

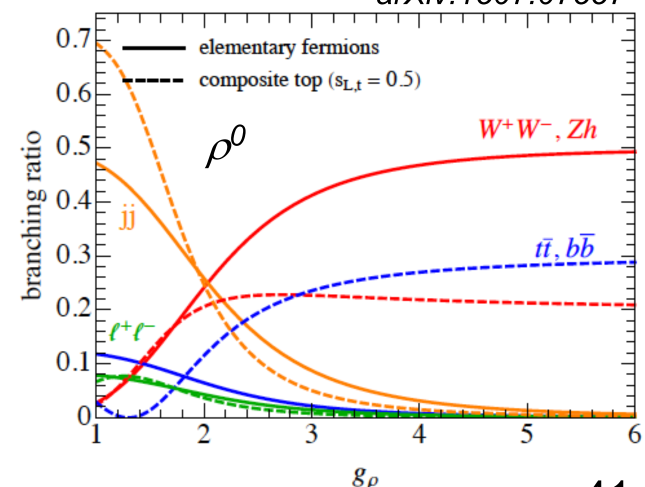




- Preferred signatures:
  - Diboson resonances
  - 3rd generation quark resonances (tt, bb, tb)
  - Dilepton/dijet resonances
- In non-minimal CH models can have additional pNGBs besides the SM Higgs ➔ extra heavy scalars!

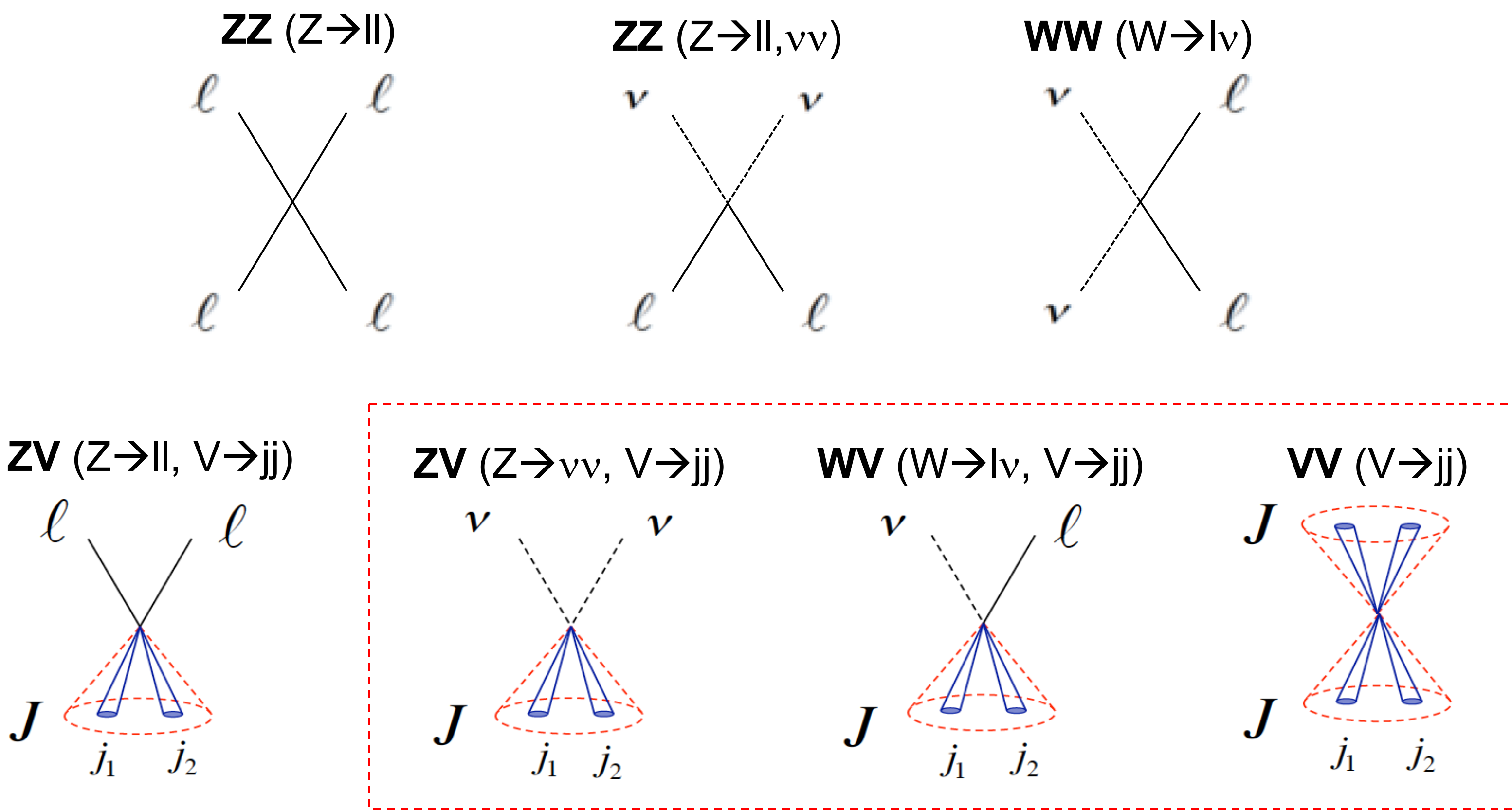
See e.g. arXiv:1507.02283

arXiv:1507.07557

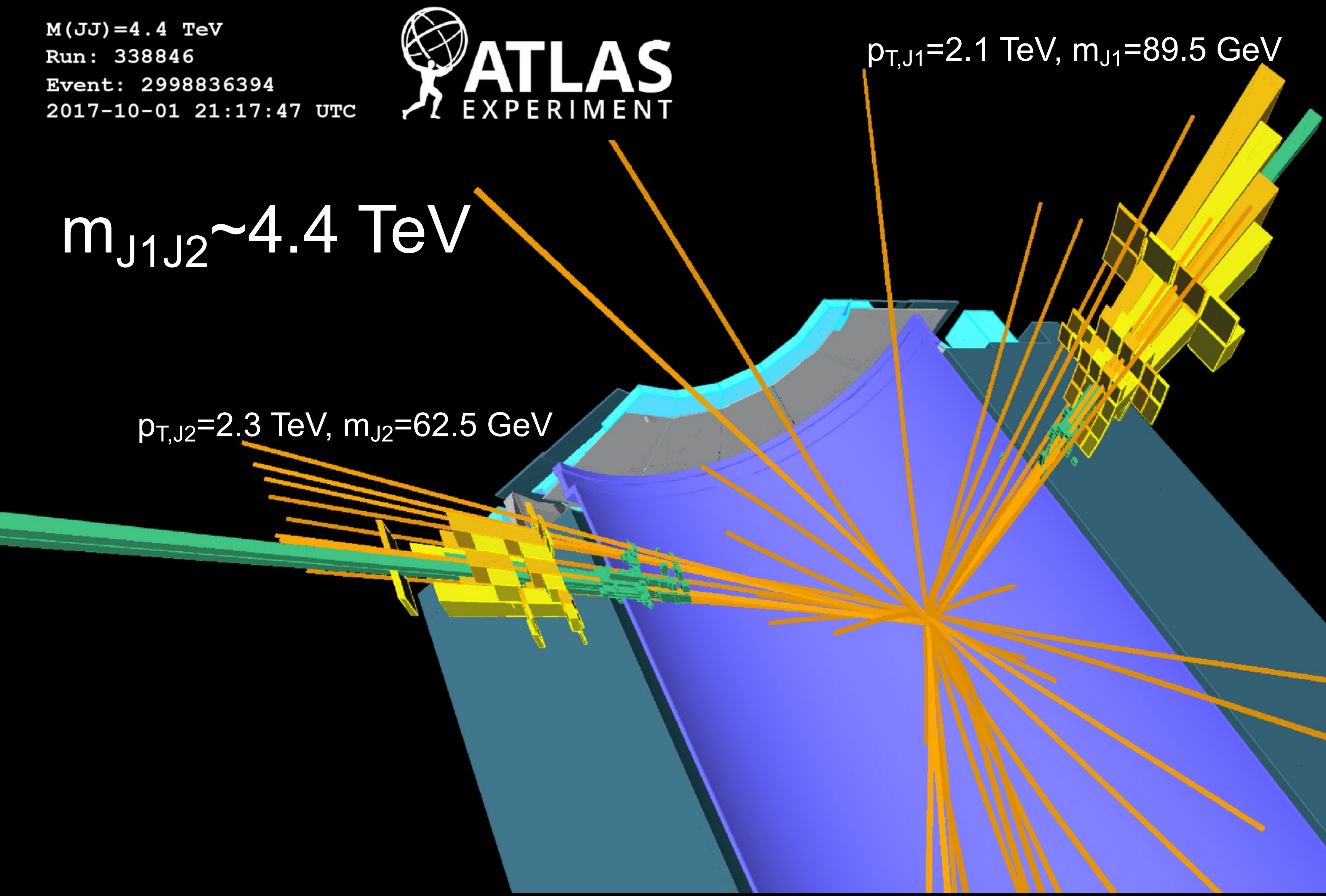


ρ→VV, VH (V=W,Z) Searches

Many final state signatures explored!

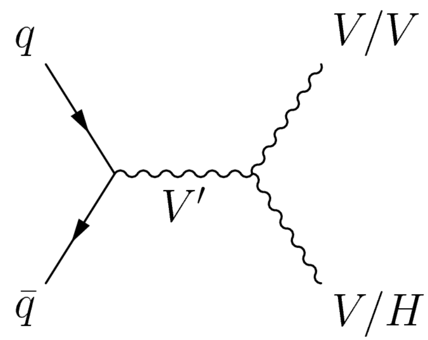


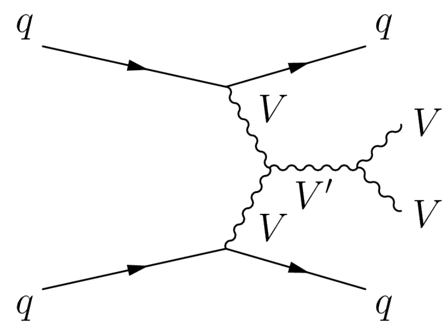
- Considering both resolved and boosted topologies.
- Most sensitive signatures at high mass: use highest BR decay W/Z decay modes.
- Also probe VH with H→bb, ττ.

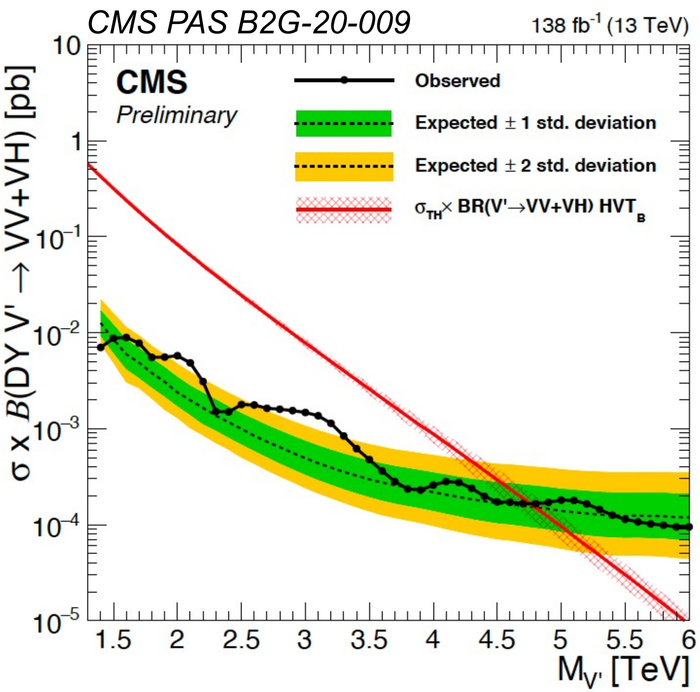

M(JJ)=4.4 TeV
Run: 338846
Event: 2998836394
2017-10-01 21:17:47 UTC
ATLAS
EXPERIMENT
$p_{T,J1}$=2.1 TeV, m_{J1}=89.5 GeV
m_{J1J2}~4.4 TeV
$p_{T,J2}$=2.3 TeV, m_{J2}=62.5 GeV

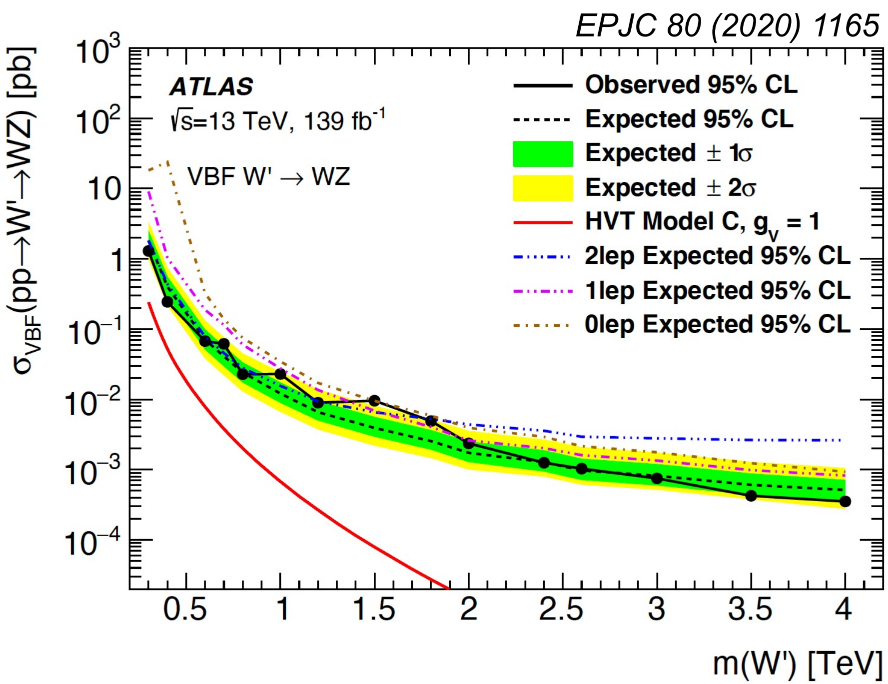
ρ→VV', VH (V=W,Z) Searches

Full Run 2



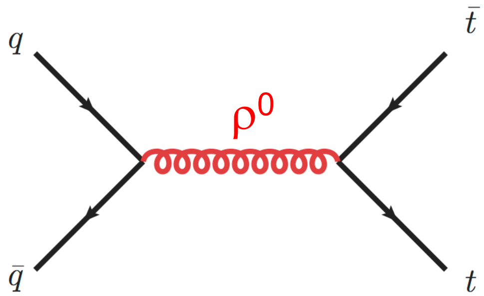






Reaching cross sections down to ~0.2-5 fb for $M_{V'}$~4 TeV!

$\rho^0 \to tt$ Searches



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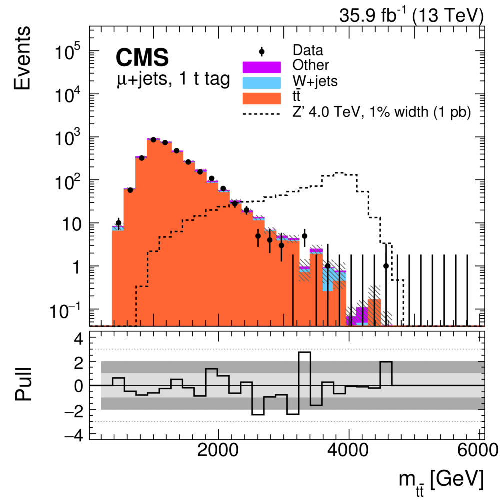
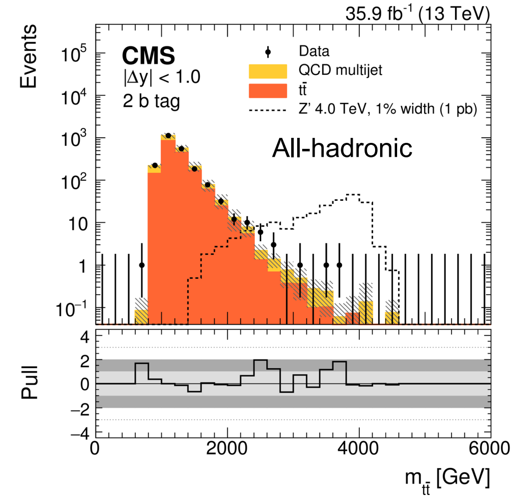
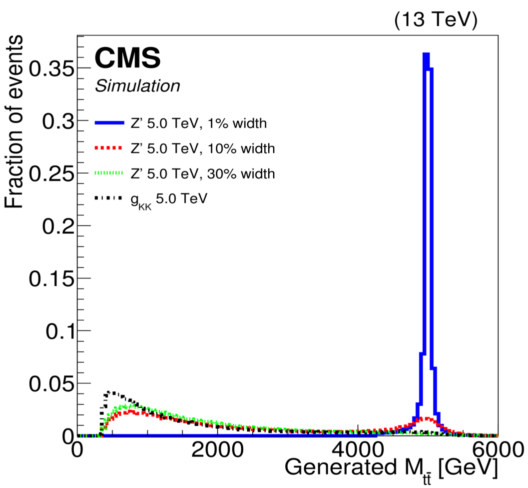
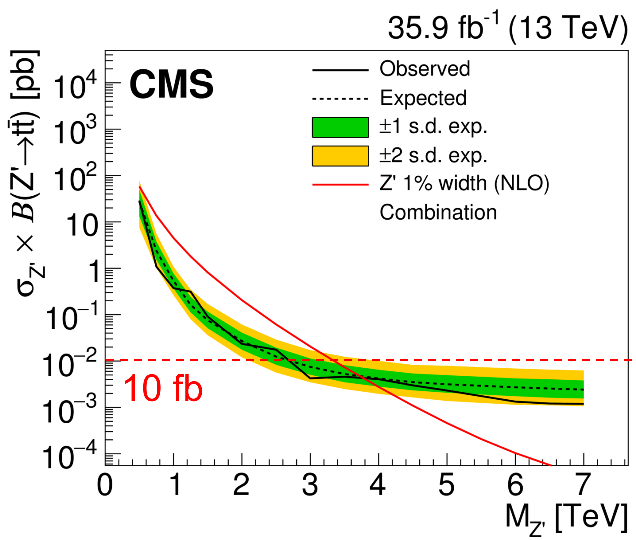
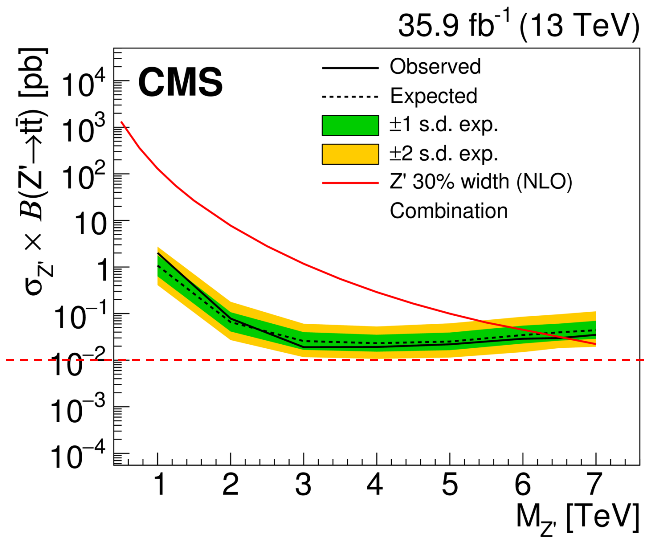




- Sensitivity dominated by 1l and 0l channels.
- Boosted object tagging and high-p_T b-tagging key.





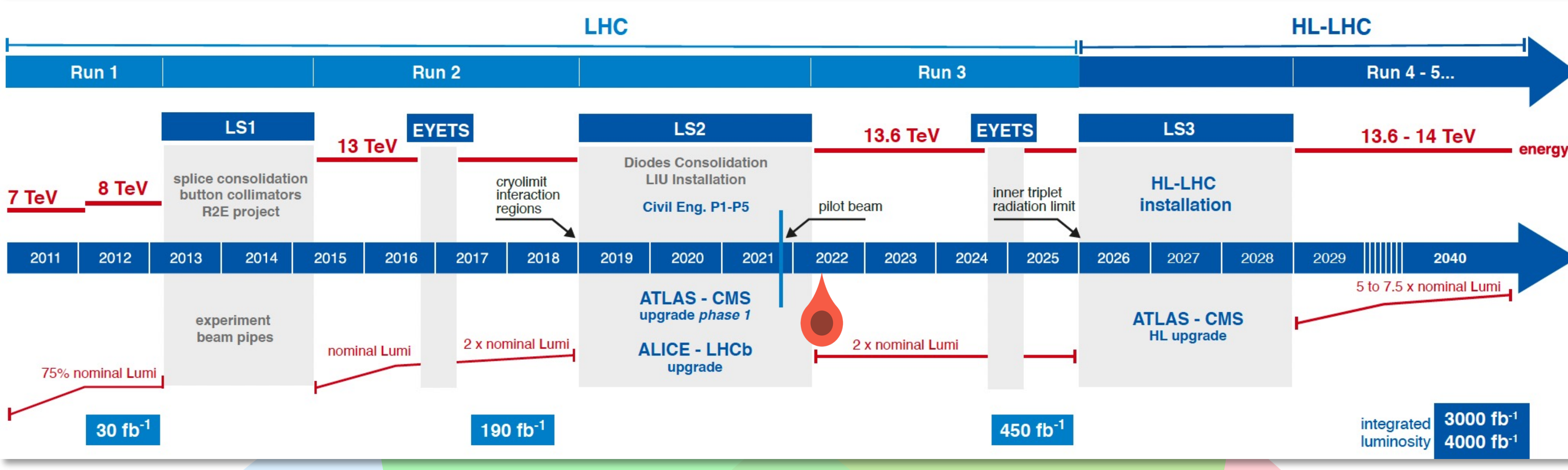


Interference w/ SM tt neglected

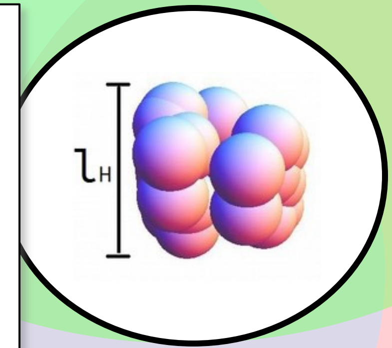
Combination of 0l, 1l and 2l channels

Future Prospects

LHC Beyond Run 2

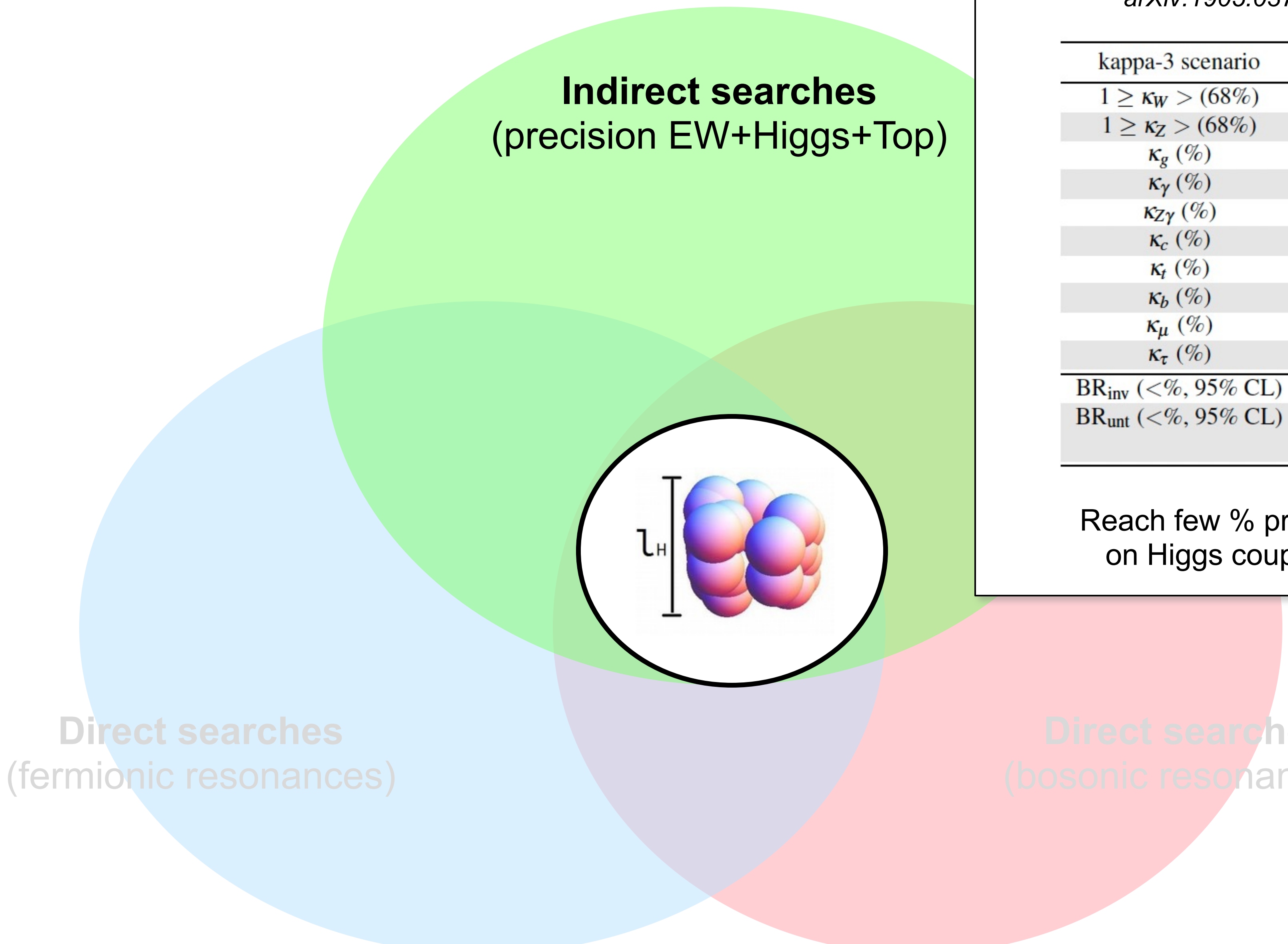


- Many full Run 2 analyses still to be finalized.
- Significant improvements expected for full Run 2+3 dataset analyses:
  - Almost x3 increase in statistics.
  - More sophisticated analysis techniques.
  - Combinations!



Direct searches
(bosonic resonances)

LHC Beyond Run 2



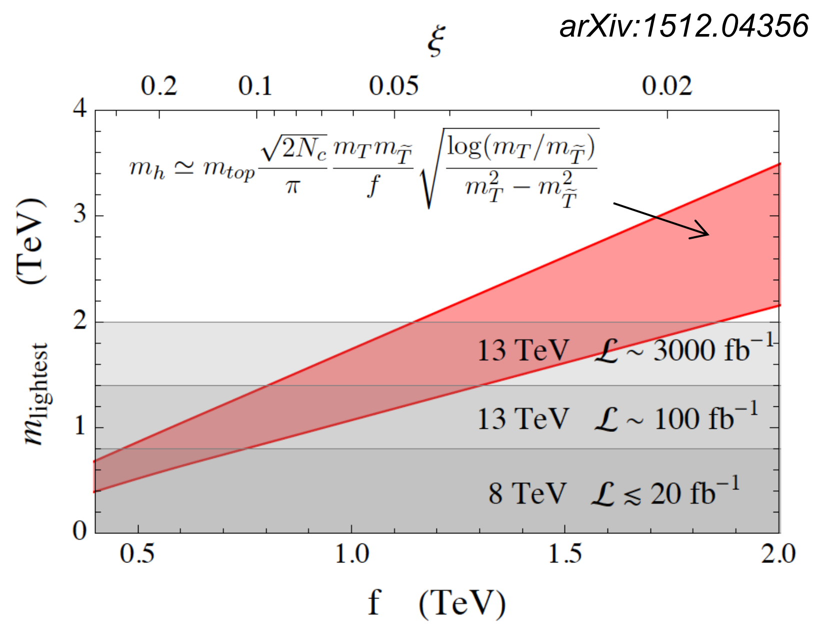
arXiv:1905.03764

kappa-3 scenario	HL-LHC
$1 \geq \kappa_W > (68\%)$	0.985
$1 \geq \kappa_Z > (68\%)$	0.987
κ_g (%)	±2.
κ_γ (%)	±1.6
$\kappa_{Z\gamma}$ (%)	±10.
κ_c (%)	–
κ_t (%)	±3.2
κ_b (%)	±2.5
κ_μ (%)	±4.4
κ_τ (%)	±1.6
BR_{inv} (<%, 95% CL)	1.9
BR_{unt} (<%, 95% CL)	4.

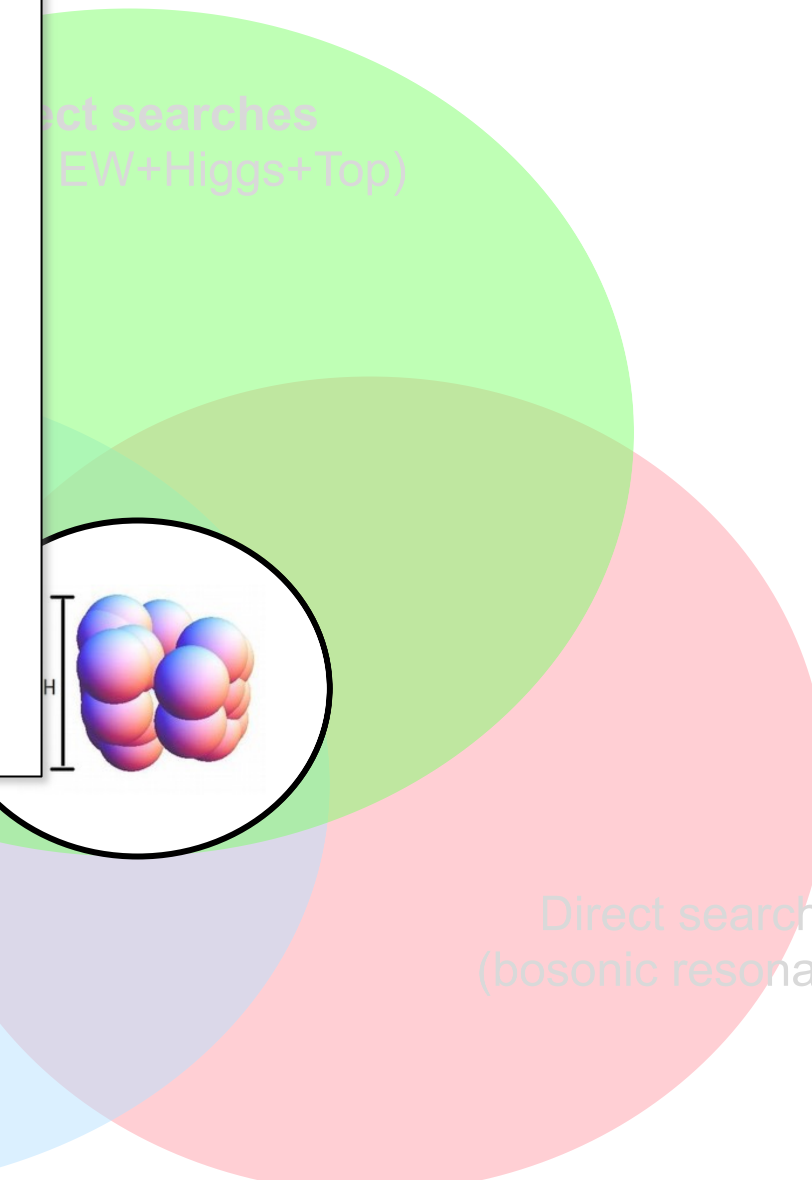
Reach few % precision on Higgs couplings

LHC Beyond Run 2

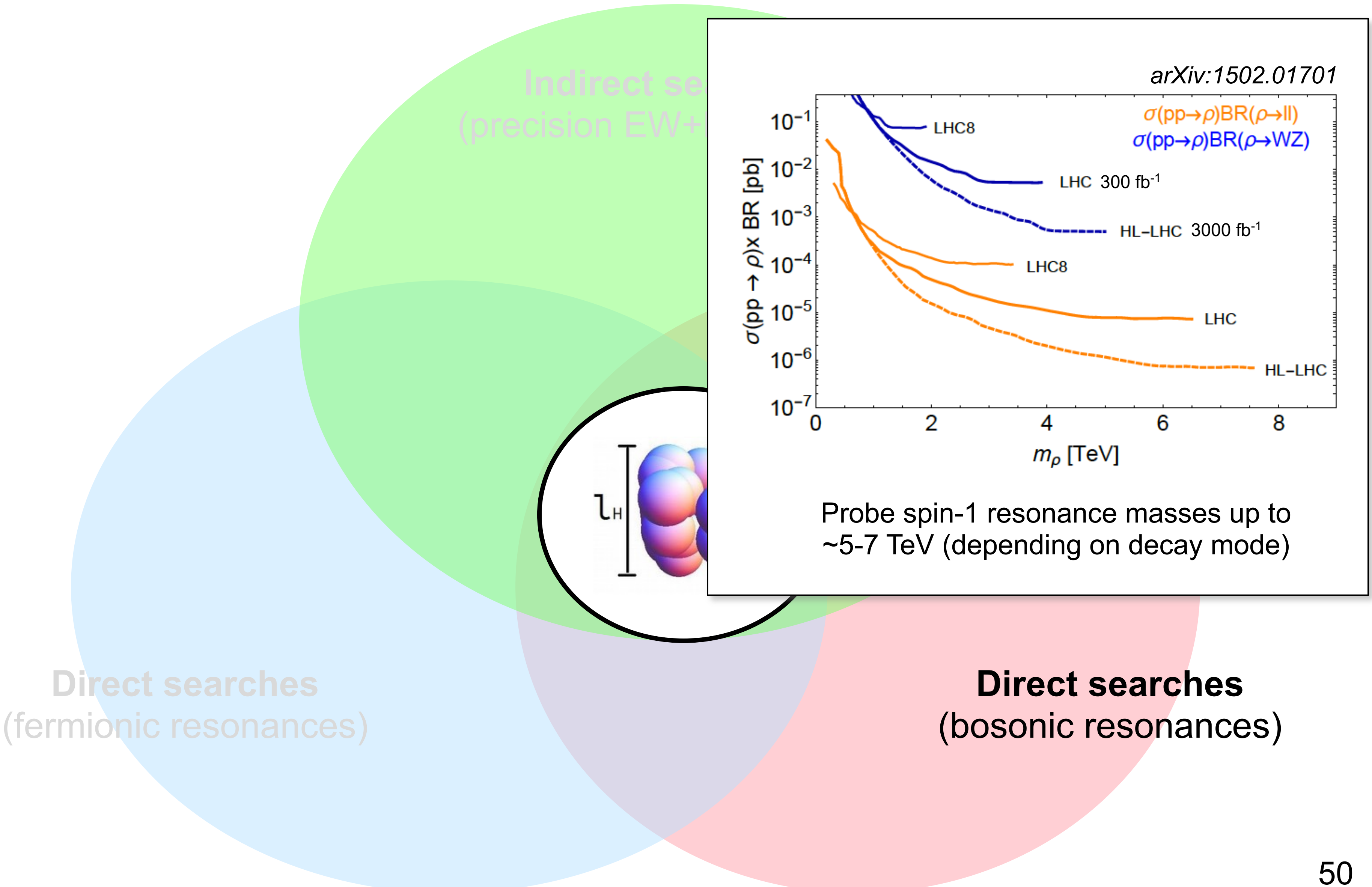
arXiv:1512.04356



Probe top partner masses up to
~2 TeV (3 TeV) via pair (single) production

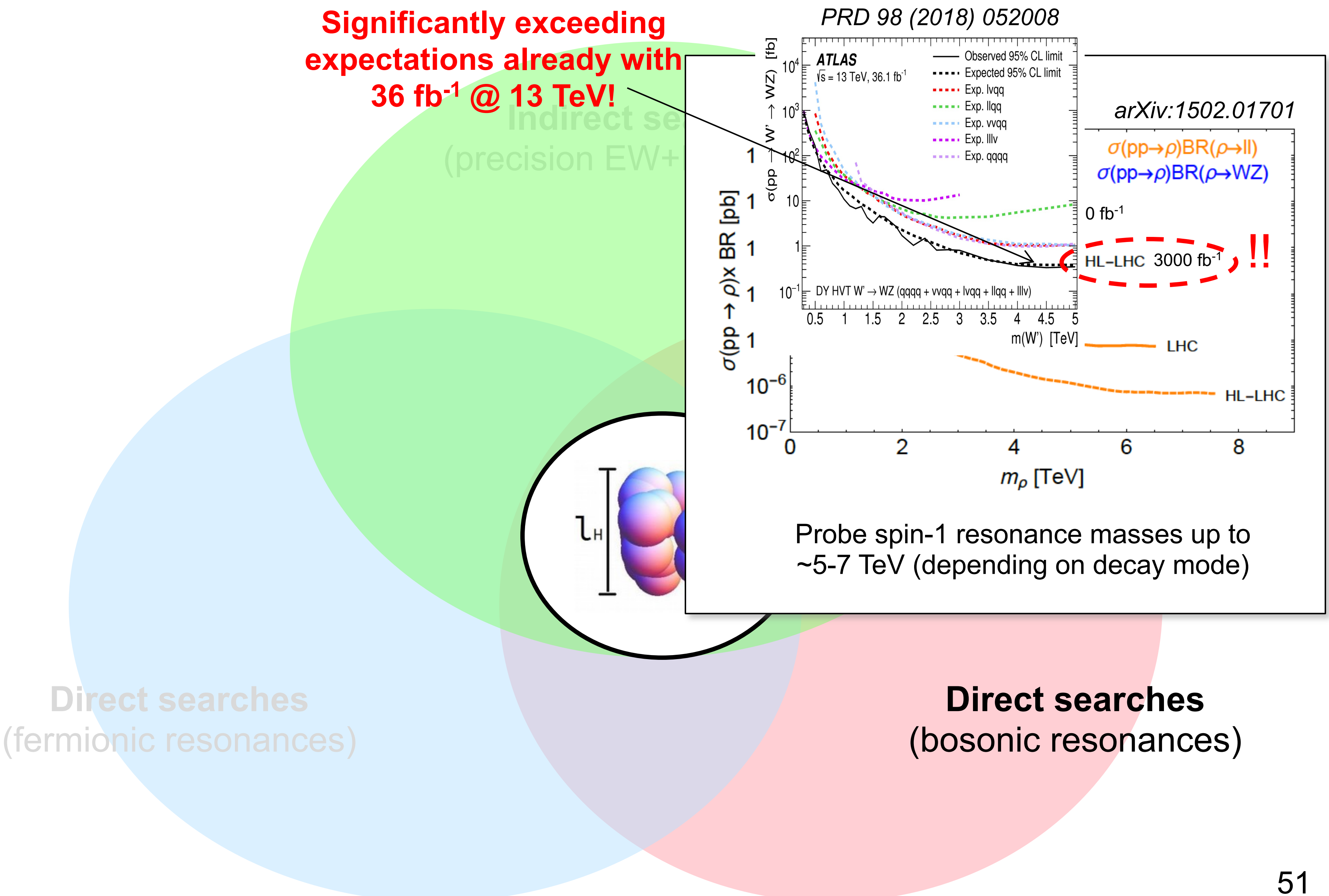


LHC Beyond Run 2



LHC Beyond Run 2

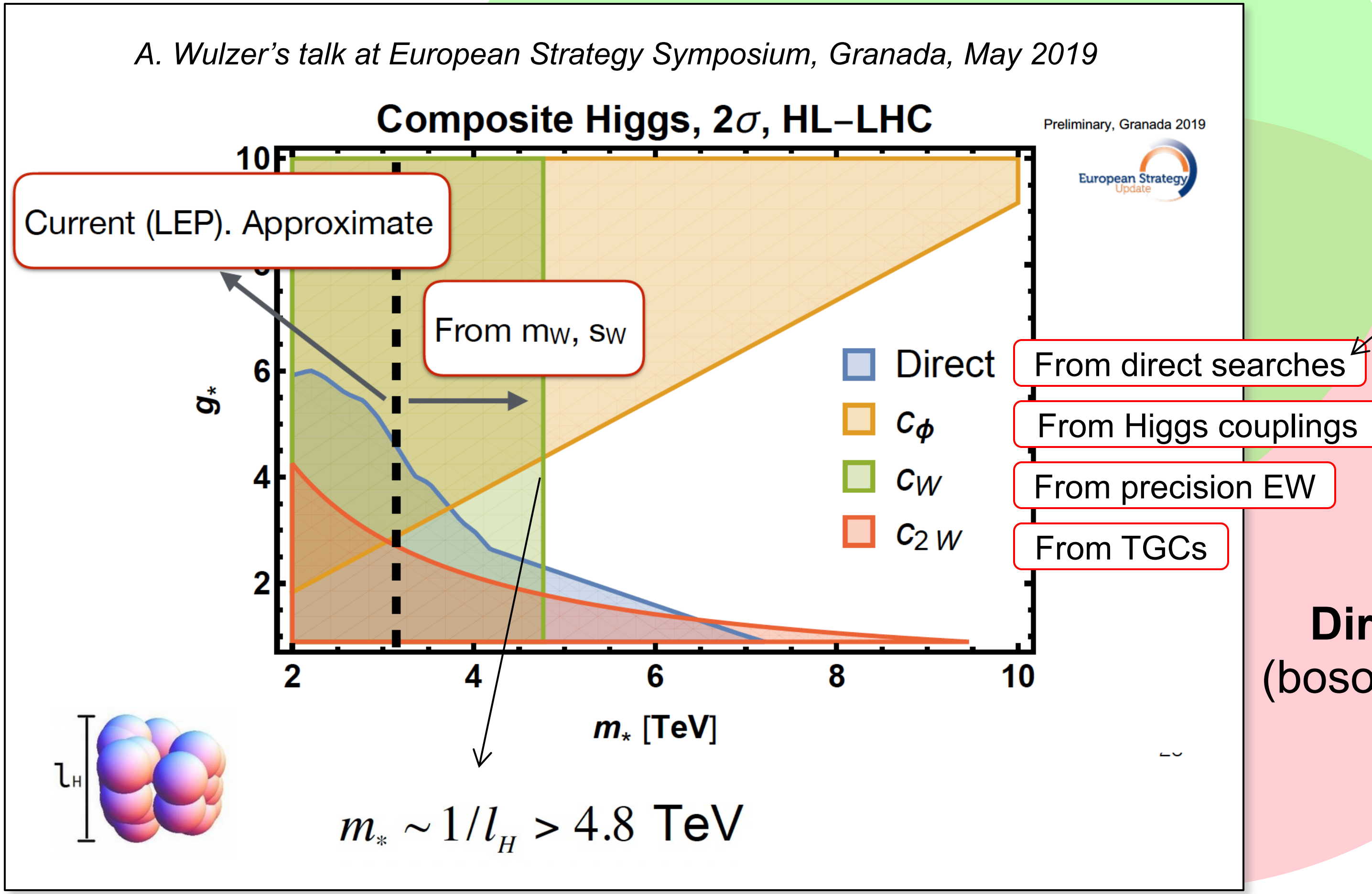
Significantly exceeding expectations already with 36 fb^{-1} @ 13 TeV!



LHC Beyond Run 2

Indirect searches
(precision EW+Higgs)

Probably pessimistic!



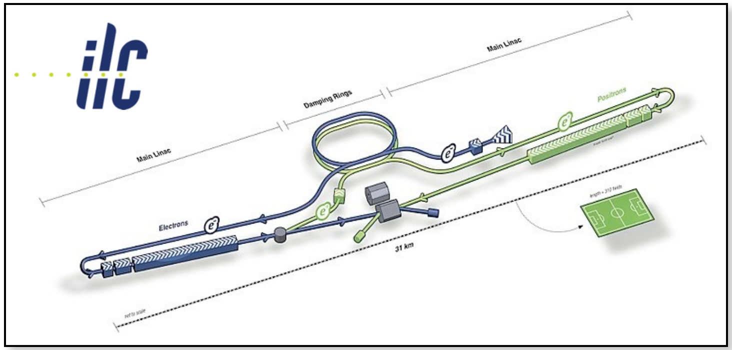
Direct searches
(bosonic resonances)

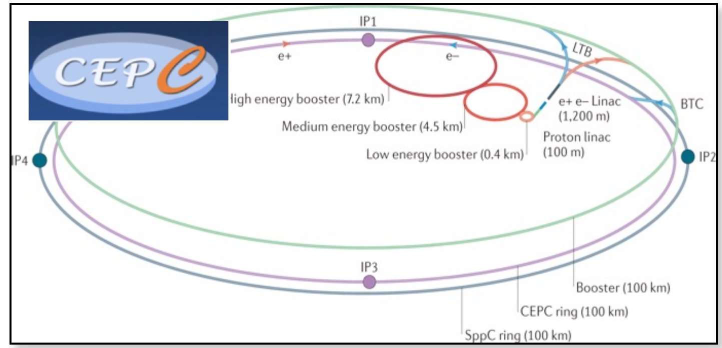
Beyond LHC

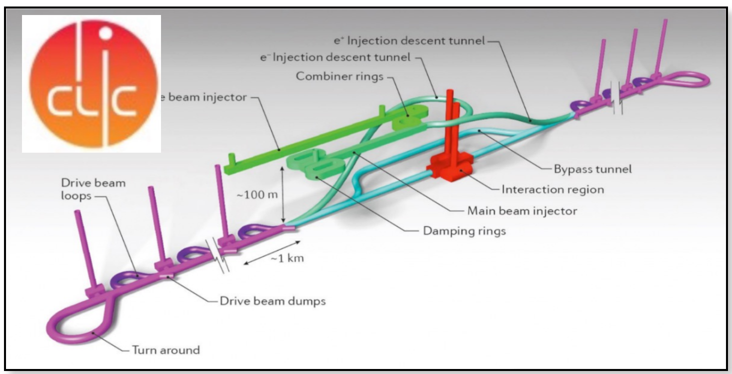
Linear Collider

Circular Collider

e⁺e⁻

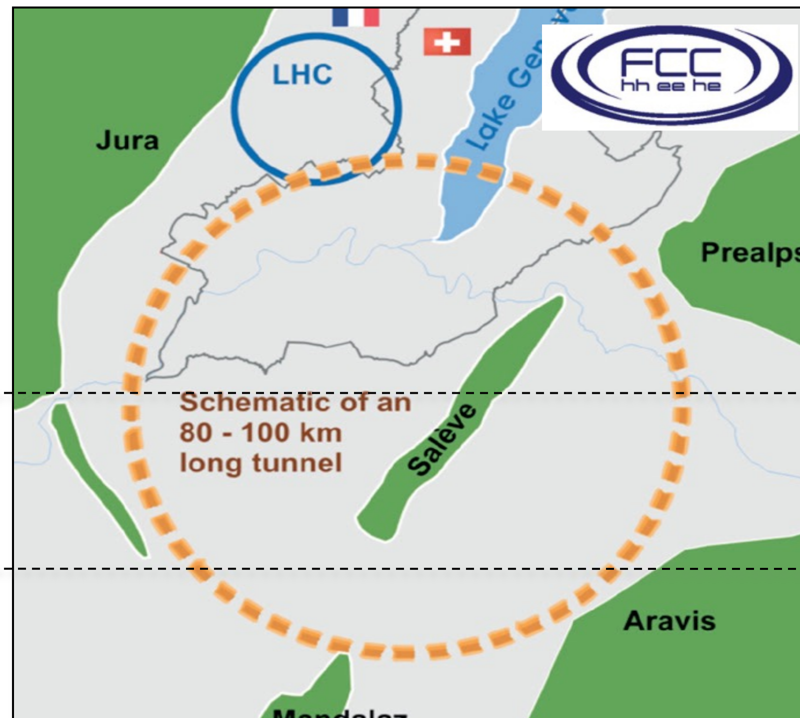






pp

e⁻p

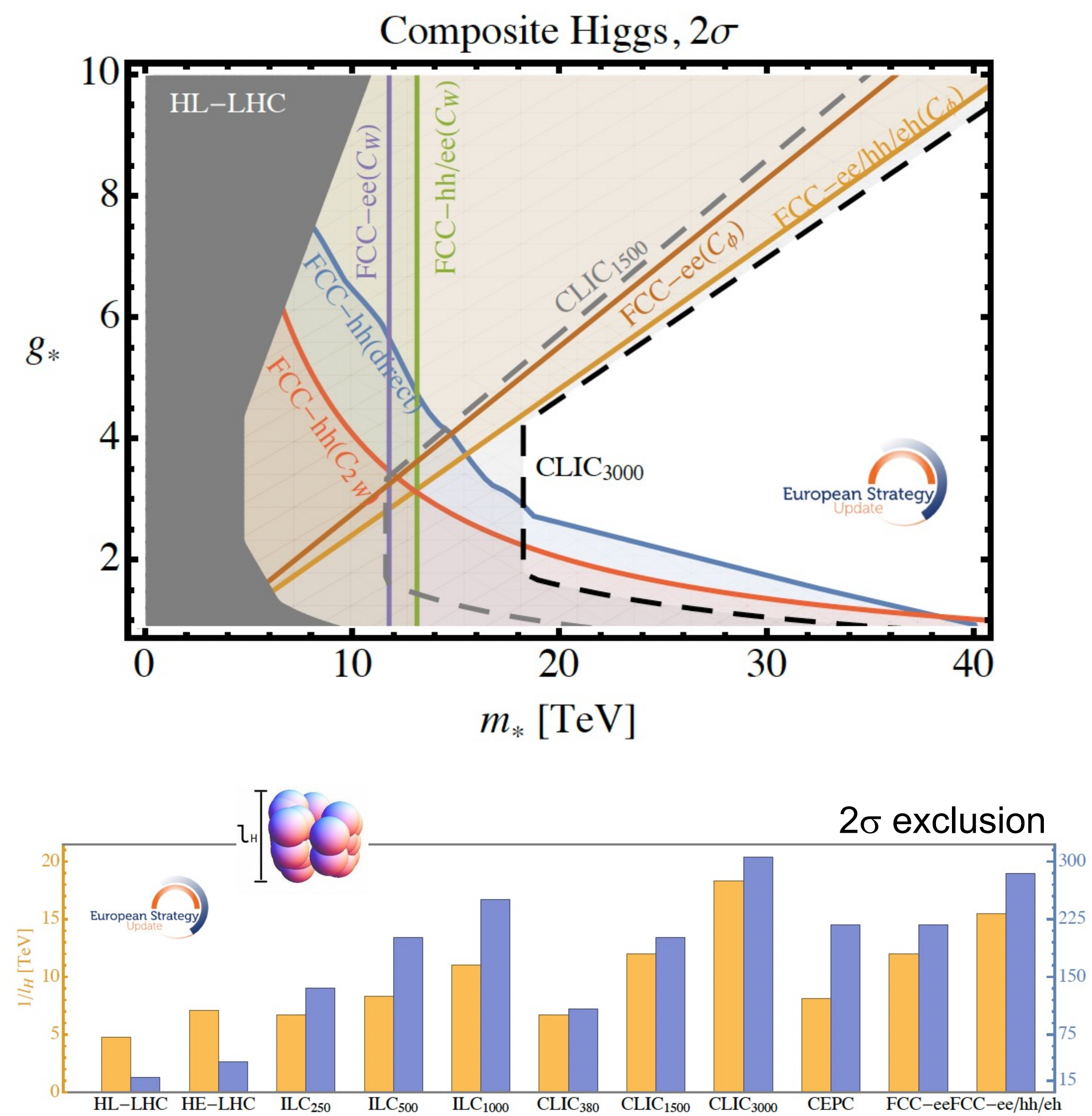


Beyond LHC

	Linear Collider	Circular Collider
e^+e^-	ILC: $\sqrt{s}$=250, 350, 500 GeV, ~6 ab^{-1}	CEPC: $\sqrt{s}=M_Z$, $2M_W$, 240 GeV, ~24 ab^{-1}
	CLIC: $\sqrt{s}$=380 GeV, 1.5 TeV, 3 TeV, ~8.5 ab^{-1}	FCC-ee: $\sqrt{s}=M_Z$, $2M_W$, 240 GeV, $2m_t$, ~168 ab^{-1}
pp		FCC-hh: $\sqrt{s}$=100 TeV, ~30 ab^{-1}; HE-LHC: $\sqrt{s}$=27 TeV, ~15 ab^{-1}
e^-p		FCC-eh: $\sqrt{s}$=3.5 TeV, ~2 ab^{-1}; HE-LHeC: $\sqrt{s}$=2.6 TeV, ~2 ab^{-1}

Beyond LHC

arXiv:1910.11775



e^+e^-

pp

e^-p

HE-LHC

TeV, ~15 ab^{-1}

HE-LHeC

TeV, ~2 ab^{-1}

Summary and Outlook

- **Broad program of studies at the LHC to test the Composite Higgs paradigm**:
  - Precision measurements of Higgs boson couplings.
  - Direct searches for new heavy resonances from the composite sector.

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Will we see first hints of a composite Higgs?

We will know soon!

- Great prospects for gaining further insights at upcoming LHC runs and (especially) at future colliders!

Are we already seeing them in the B-physics anomalies?

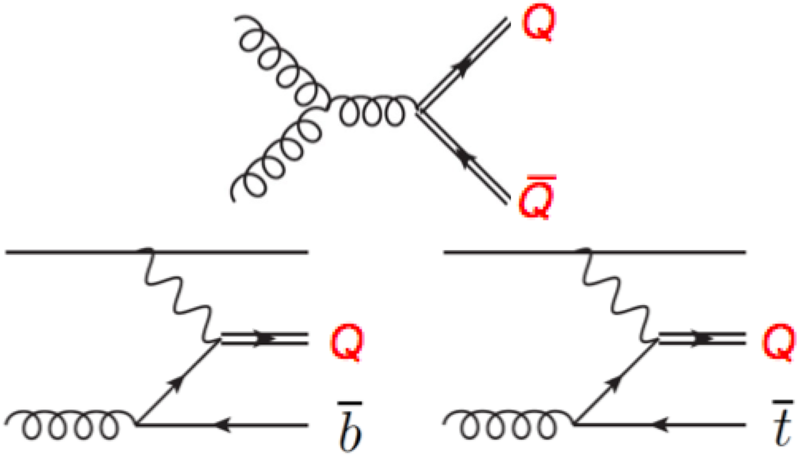
Exciting times ahead!

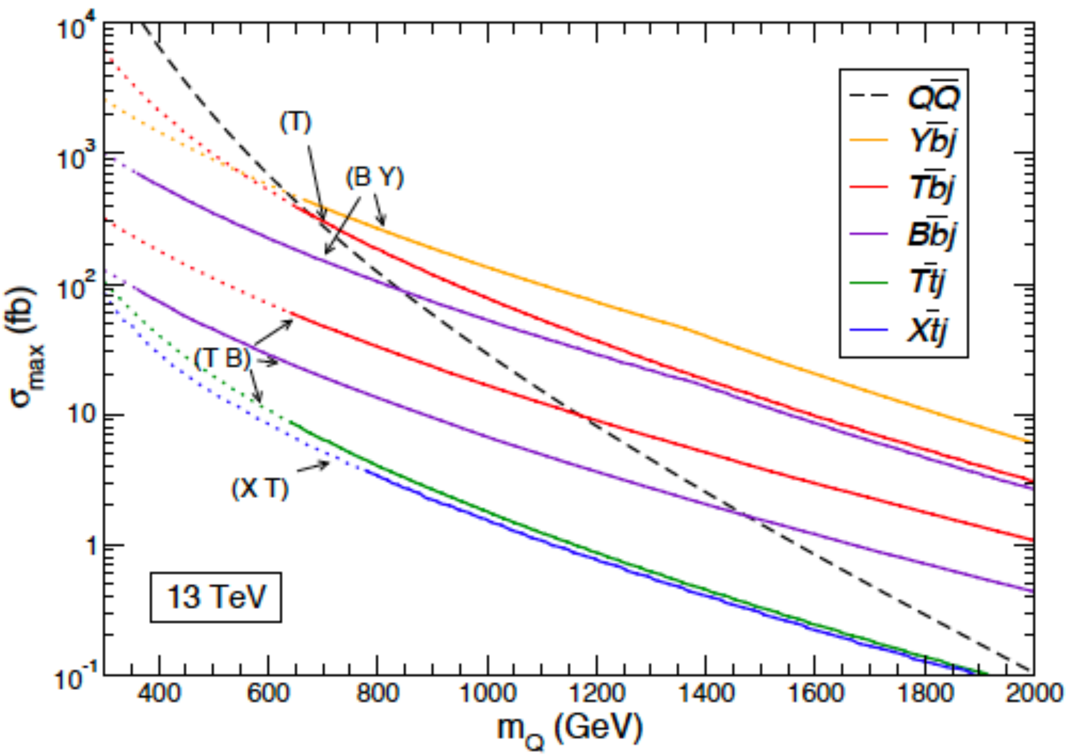
Backup

Vector-Like Quarks: Production and Decay

Production:

- Pair production: via QCD, "universal" production mode (just depends on m_Q).
  ➔ Focus of Run 1 searches
- Single production: via EW interaction, depends on coupling strength, but potentially important at high m_Q.

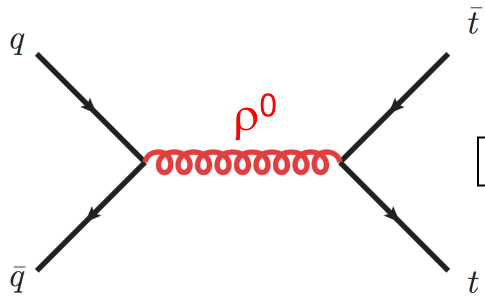




Associated $t\bar{t}\rho^0$ Production

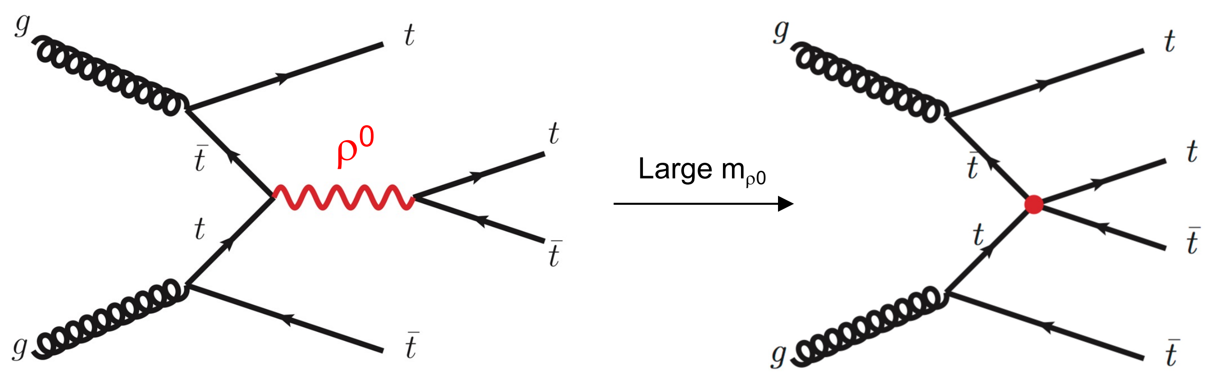
Full Run 2

If only t_R has a high degree of compositeness:



Suppressed

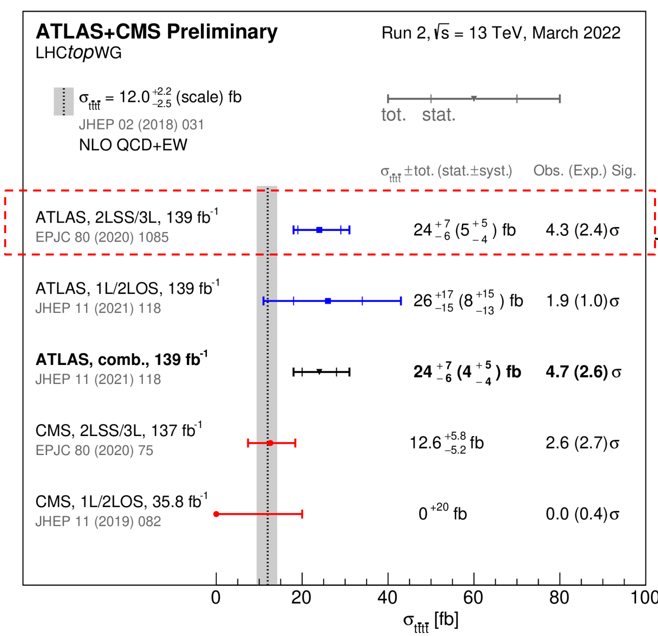
4-top final states

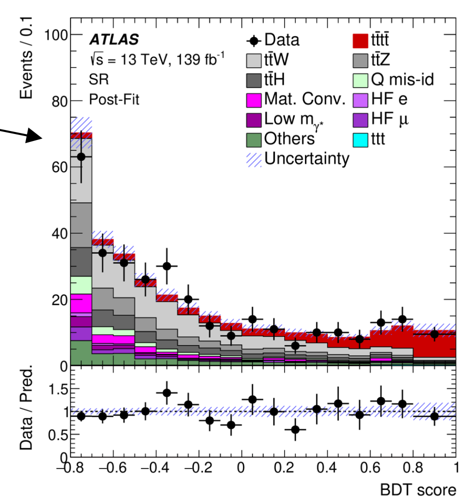


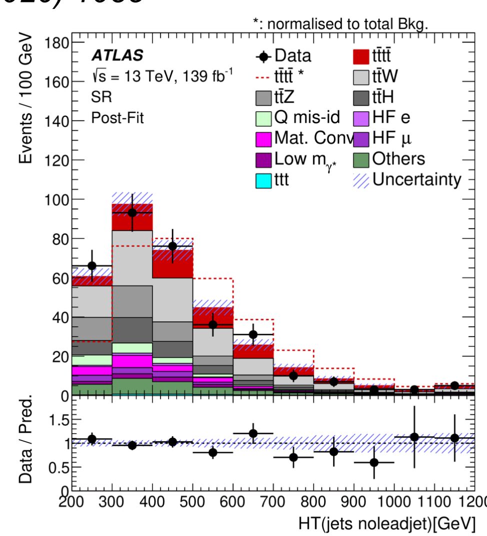
Only t_R (partially) composite:

$$\mathcal{L}_{4t} = \frac{|C_{4t}|}{\Lambda^2}(\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$$

EPJC 80 (2020) 1085



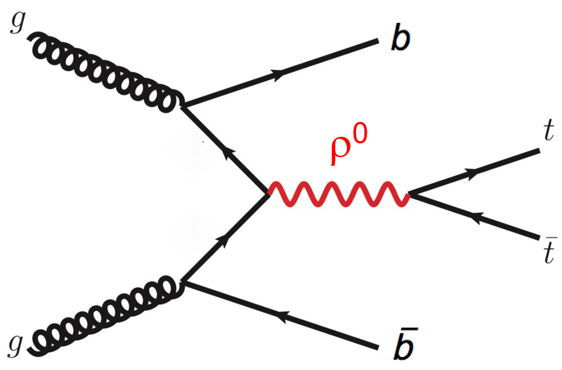


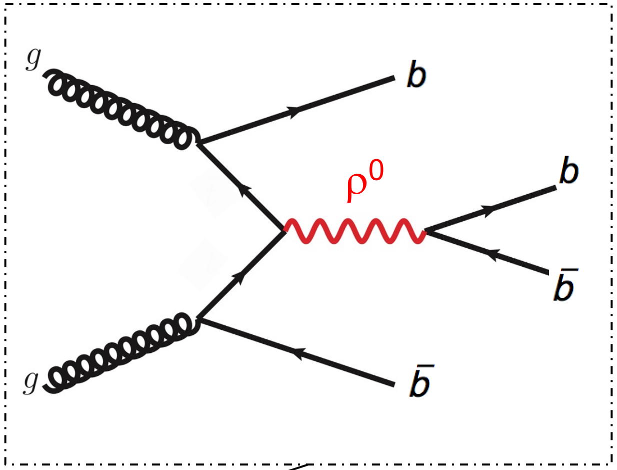


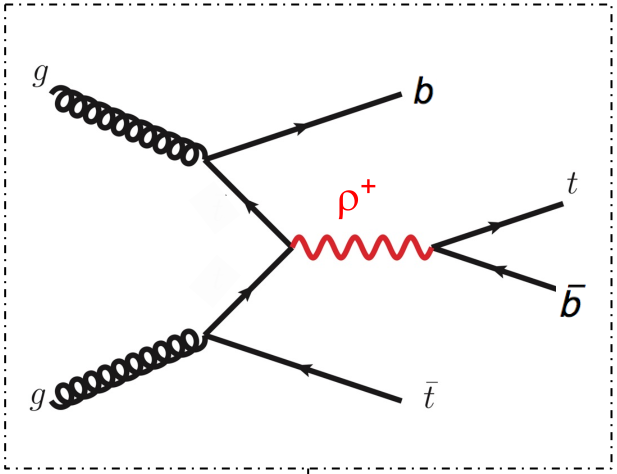
Associated bbρ^0 and tbρ^+ Production

Full Run 2

Other possibilities:







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