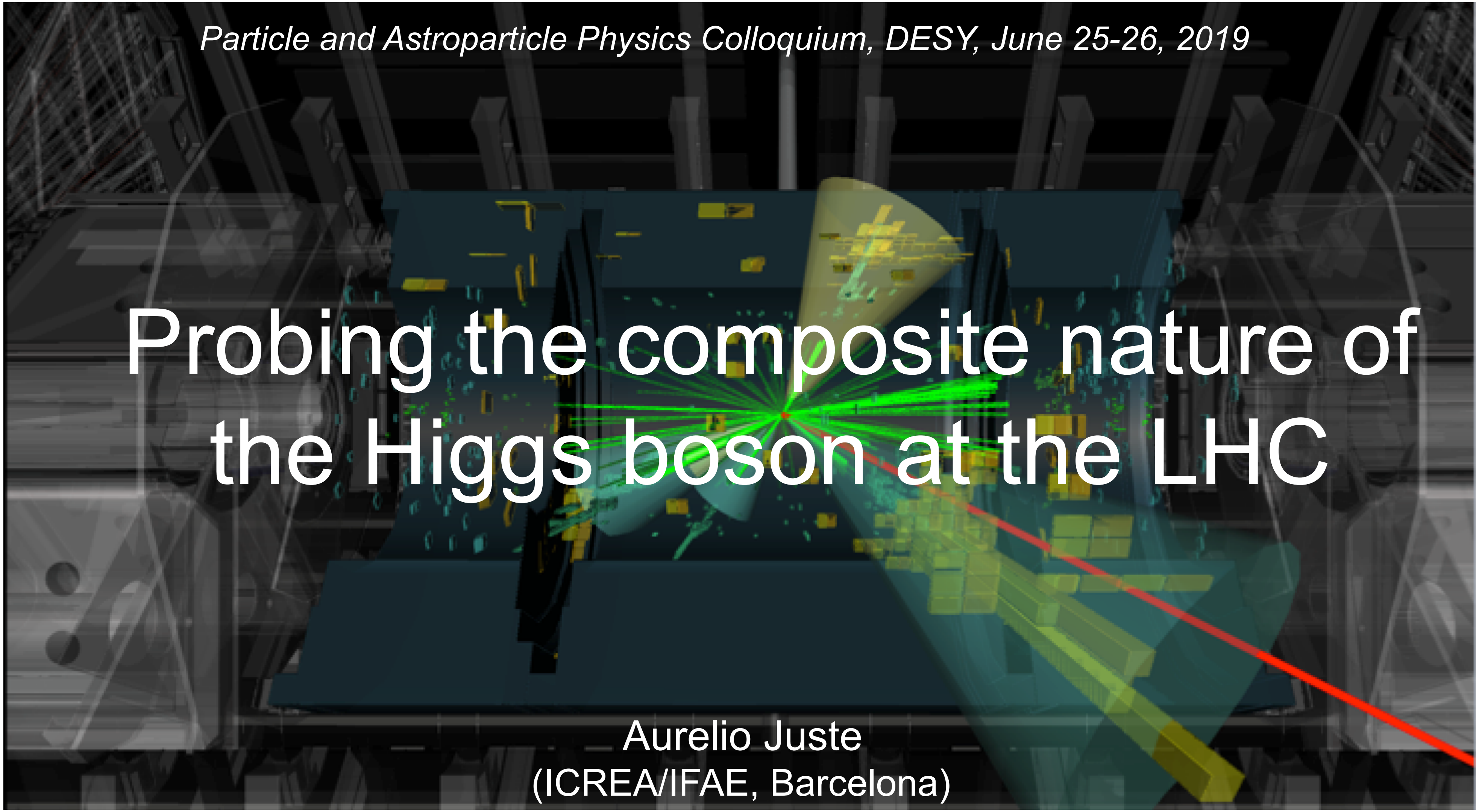
Particle and Astroparticle Physics Colloquium, DESY, June 25-26, 2019



Probing the composite nature of the Higgs boson at the LHC

Aurelio Juste
(ICREA/IFAE, Barcelona)

ATLAS EXPERIMENT

ICREA

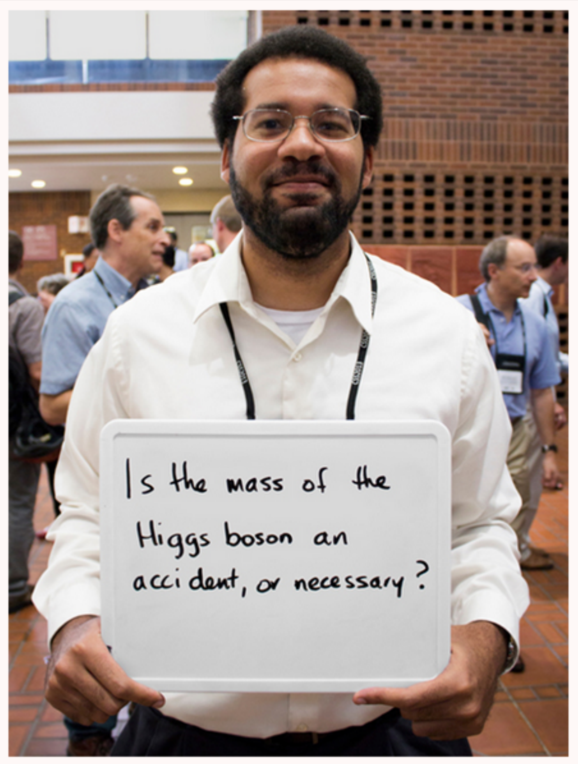
IFAE Institut de Física d'Altes Energies

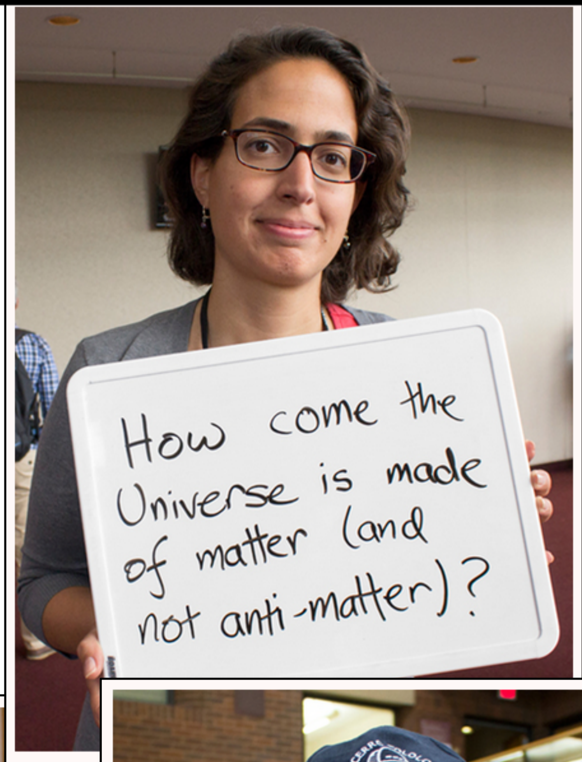
EXCELENCIA SEVERO OCHOA

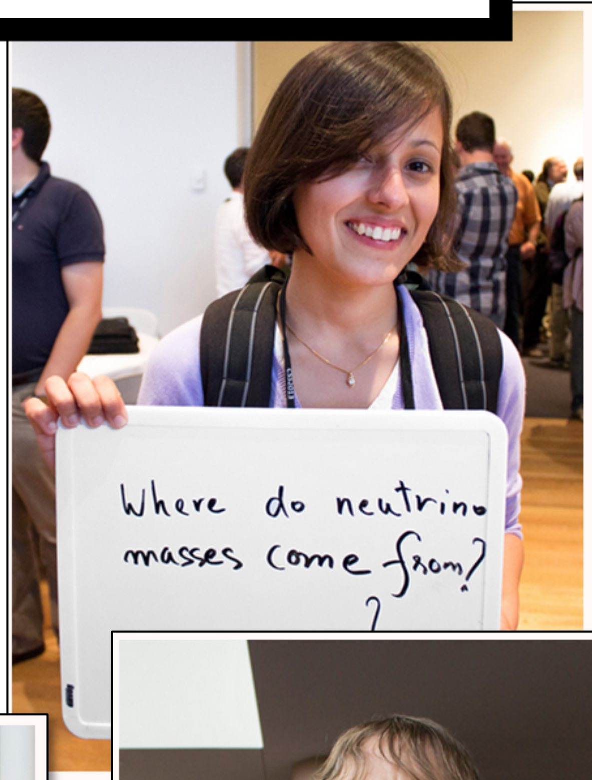
BIST Barcelona Institute of Science and Technology

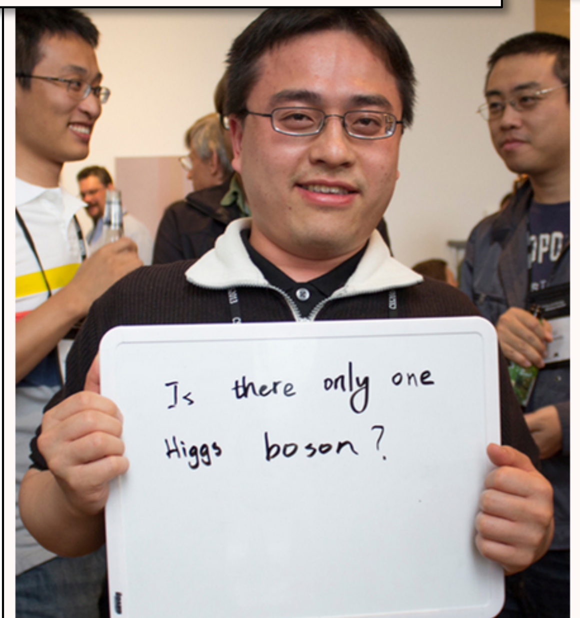
CMS Compact Muon Solenoid

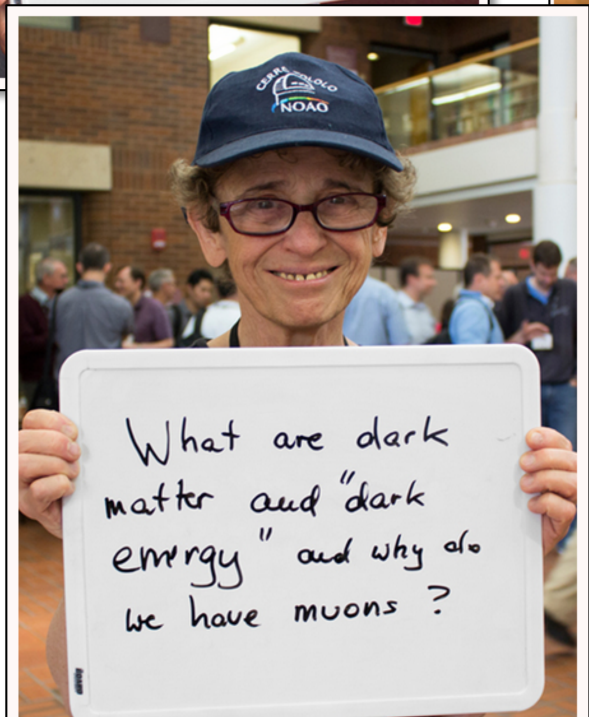
Pursuing Big Questions

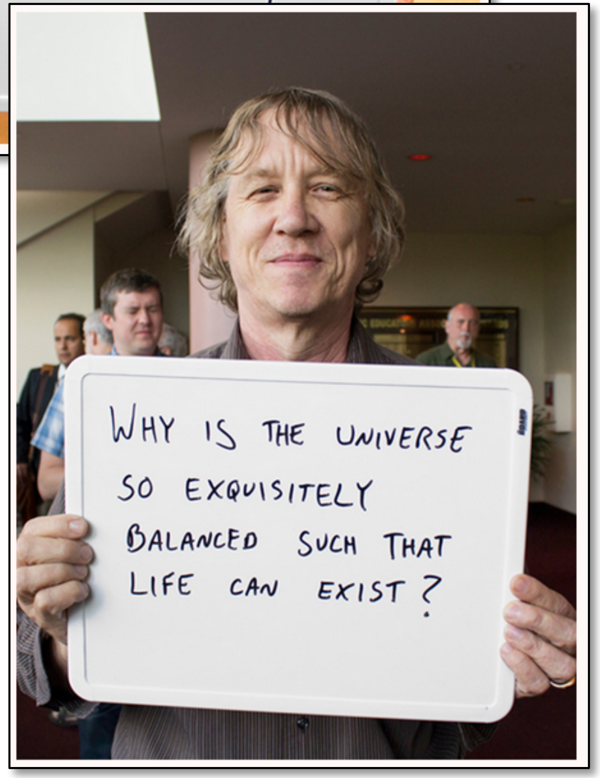




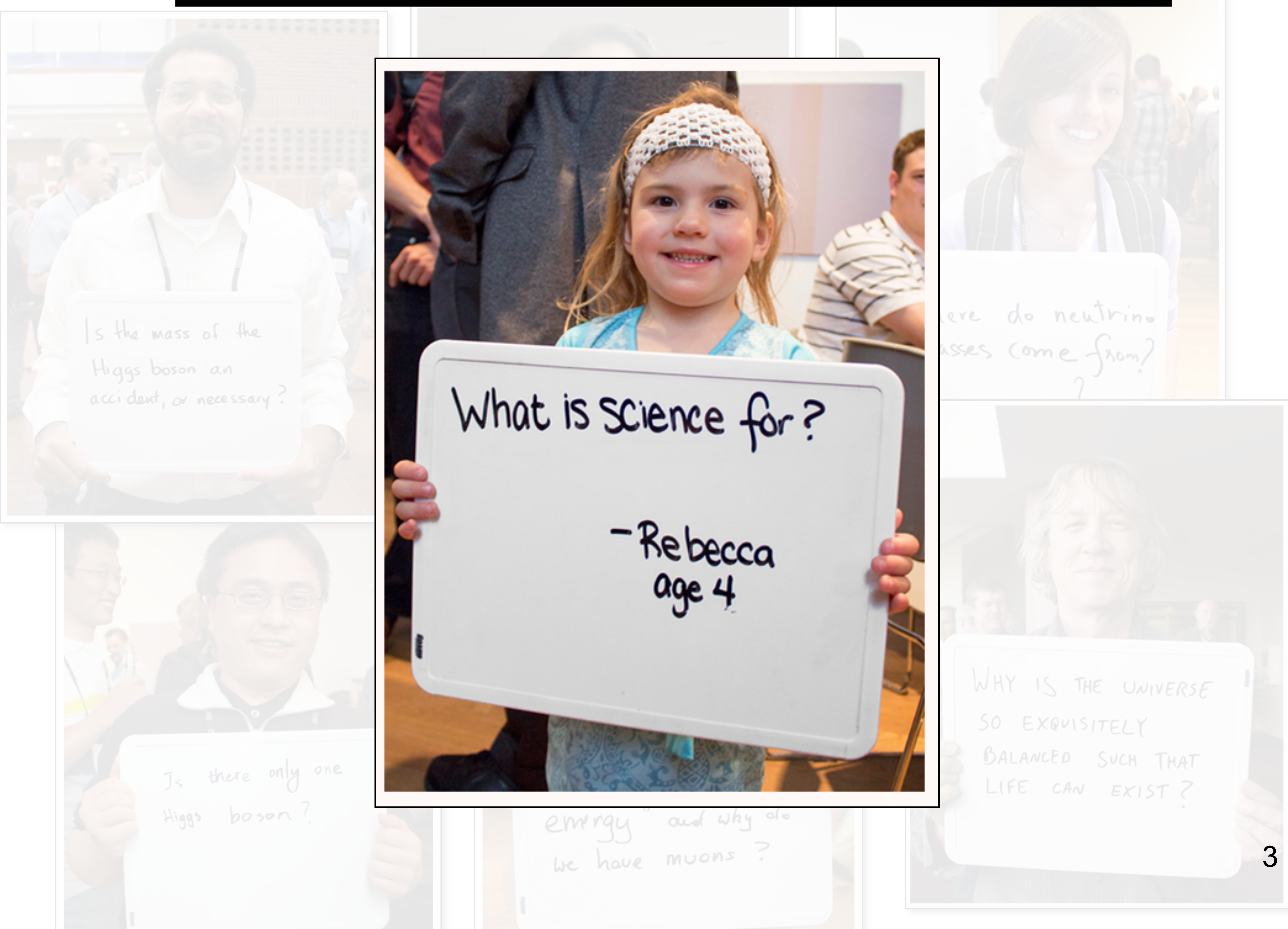




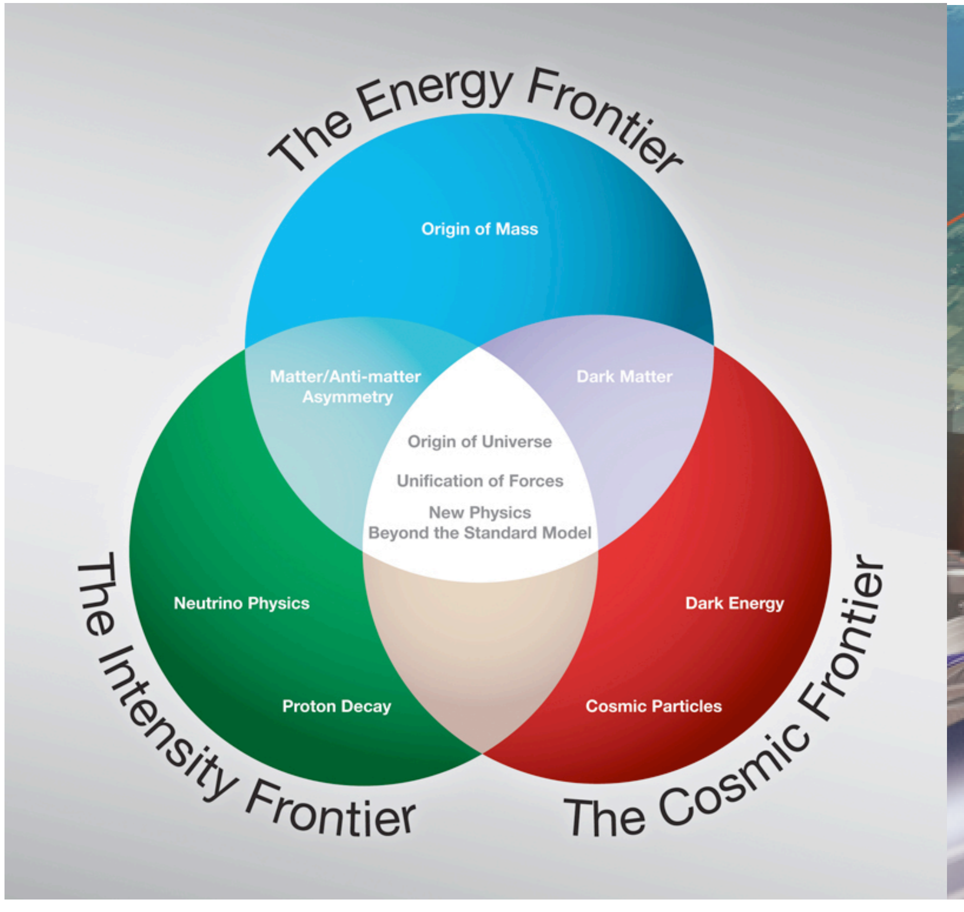


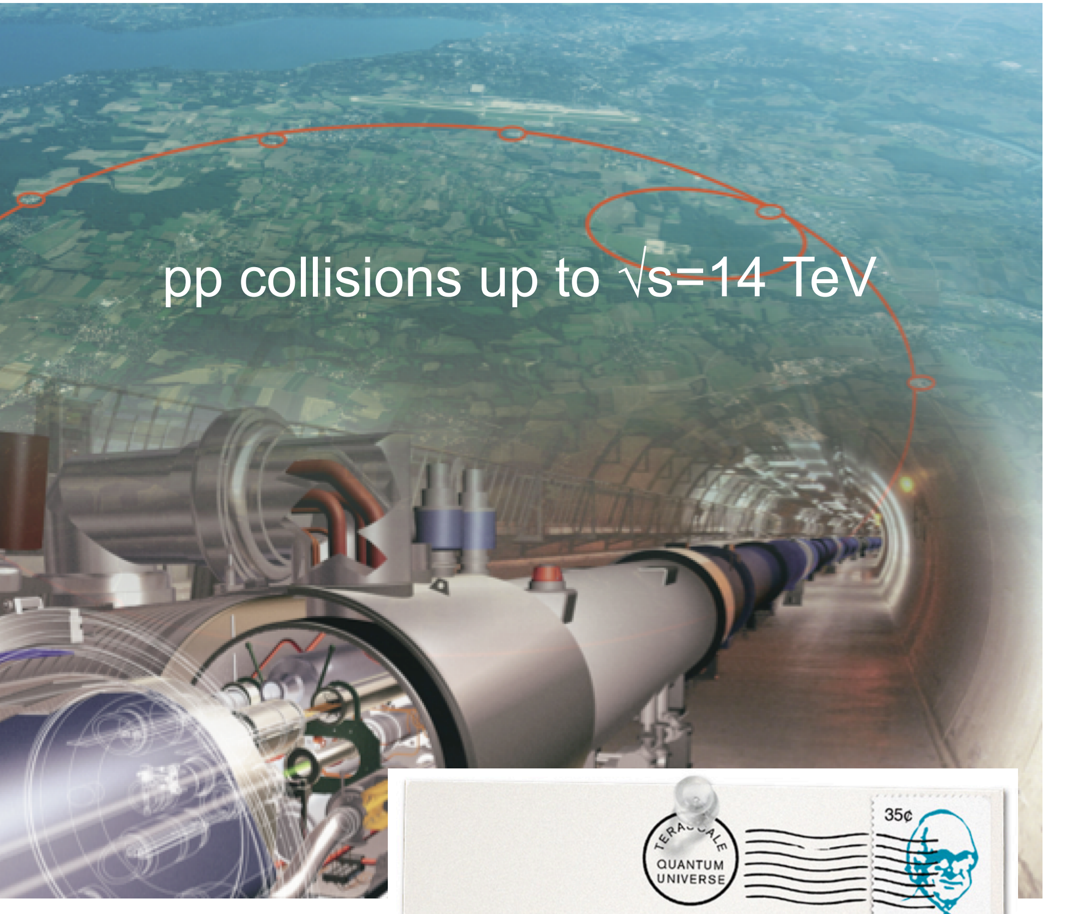


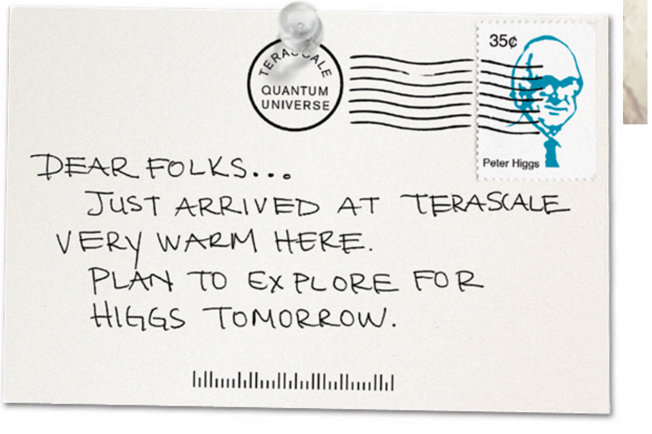
Pursuing Big Questions



The LHC and the Energy Frontier



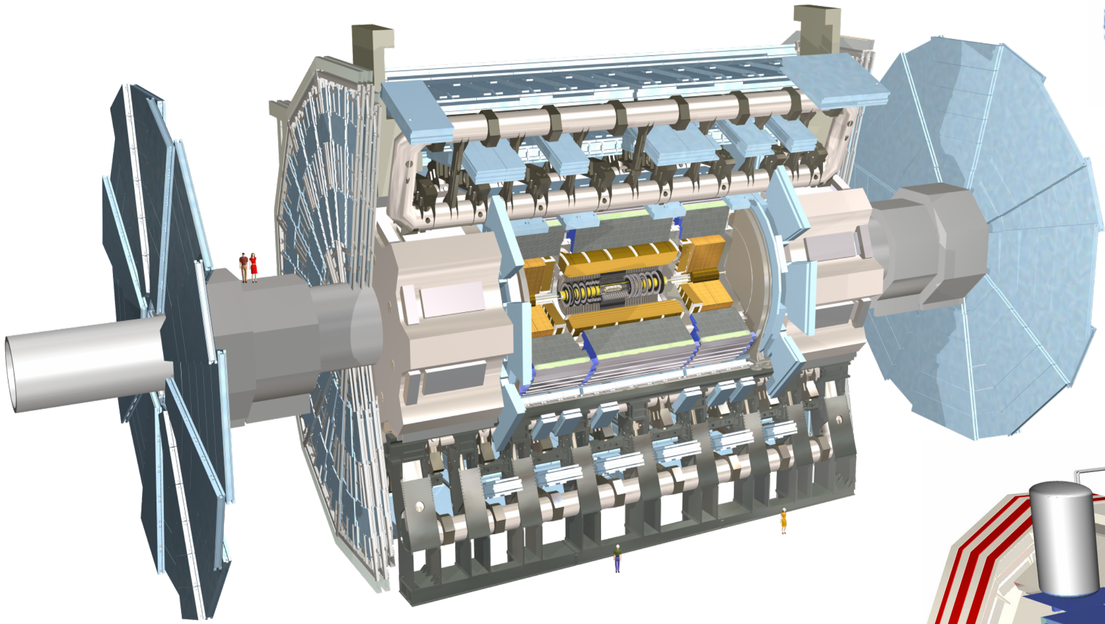


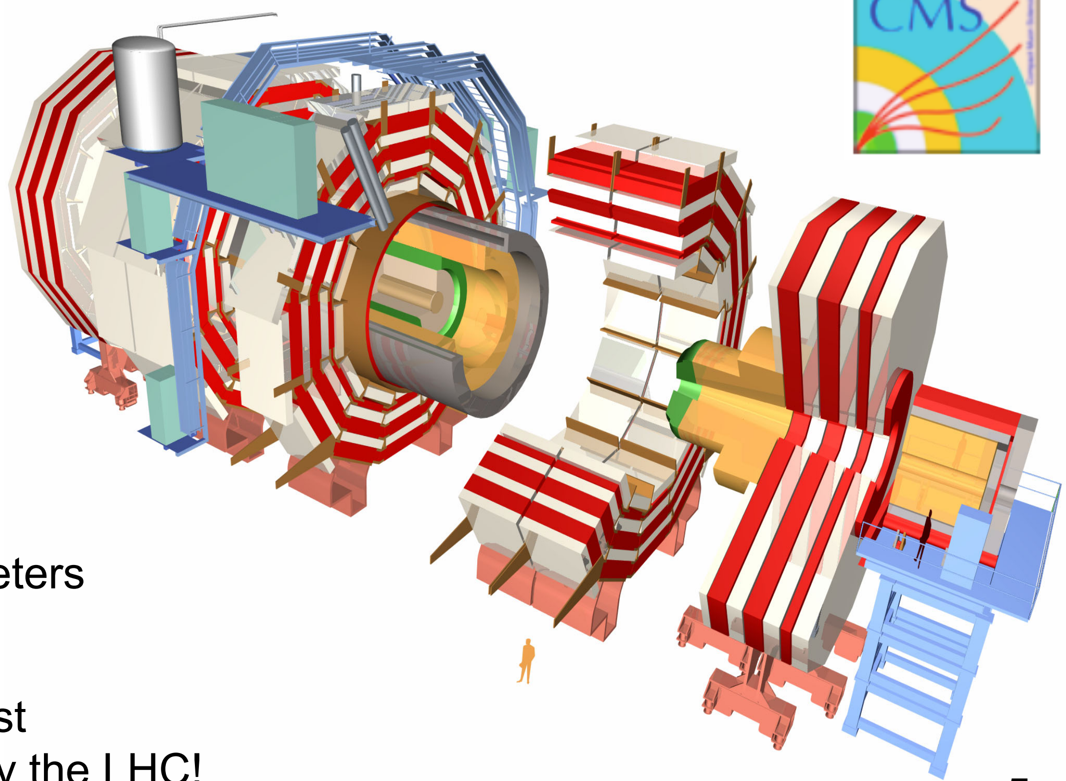


The LHC represents an extremely powerful instrument to search for New Physics (NP):

- Direct searches for new particles in a plethora of kinematic regions and final state signatures.
- Broad program of precise measurements of SM processes and parameters.

ATLAS and CMS Experiments





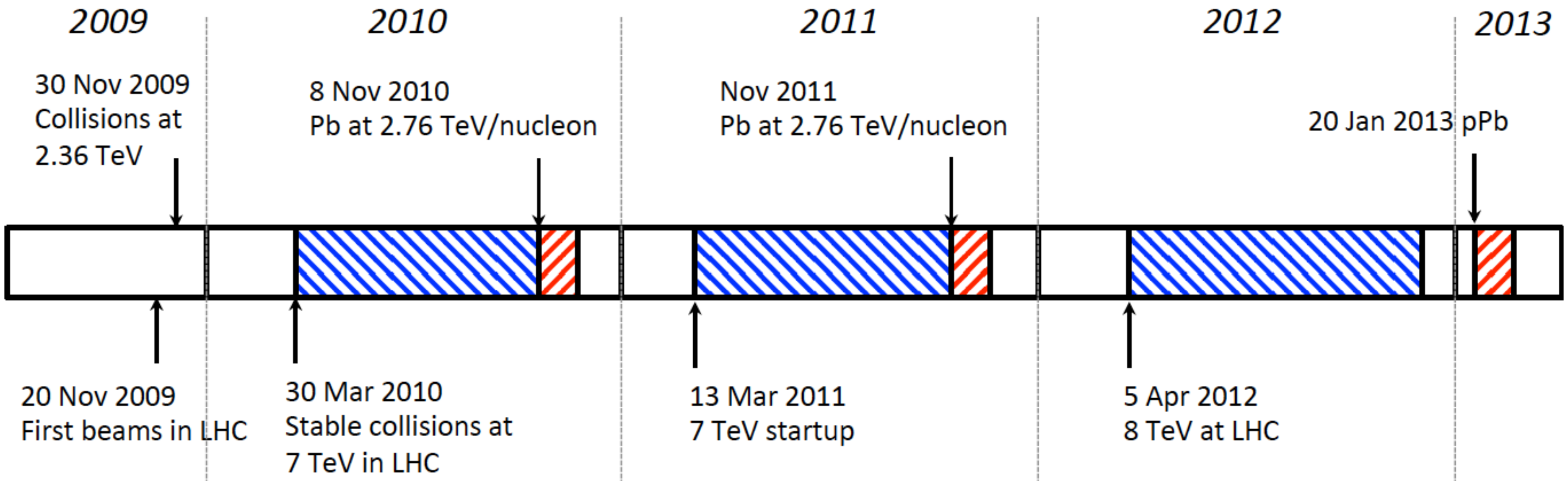
Multipurpose detectors:

- Central tracking in solenoidal B field
- Electromagnetic and hadronic calorimeters
- Muon detectors
- Excellent performance up to the highest instantaneous luminosities delivered by the LHC!

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

LHC Run 1



0.05 fb^{-1} at 7 TeV

O(2) Pile-up events

~ 5 fb^{-1} at 7 TeV

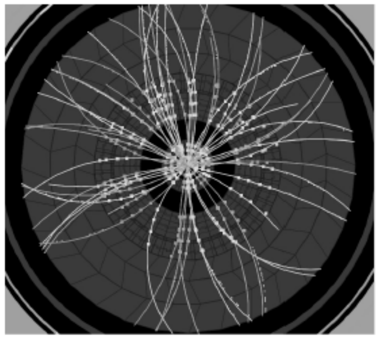
O(10) Pile-up events

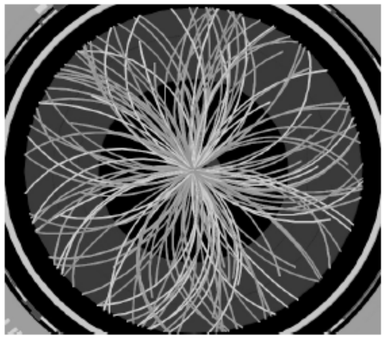
50 ns inter-bunch spacing

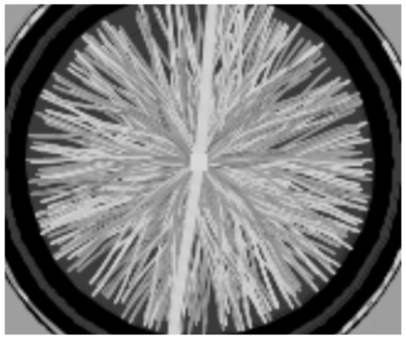
~ 20 fb^{-1} at 8 TeV

O(30) Pile-up events

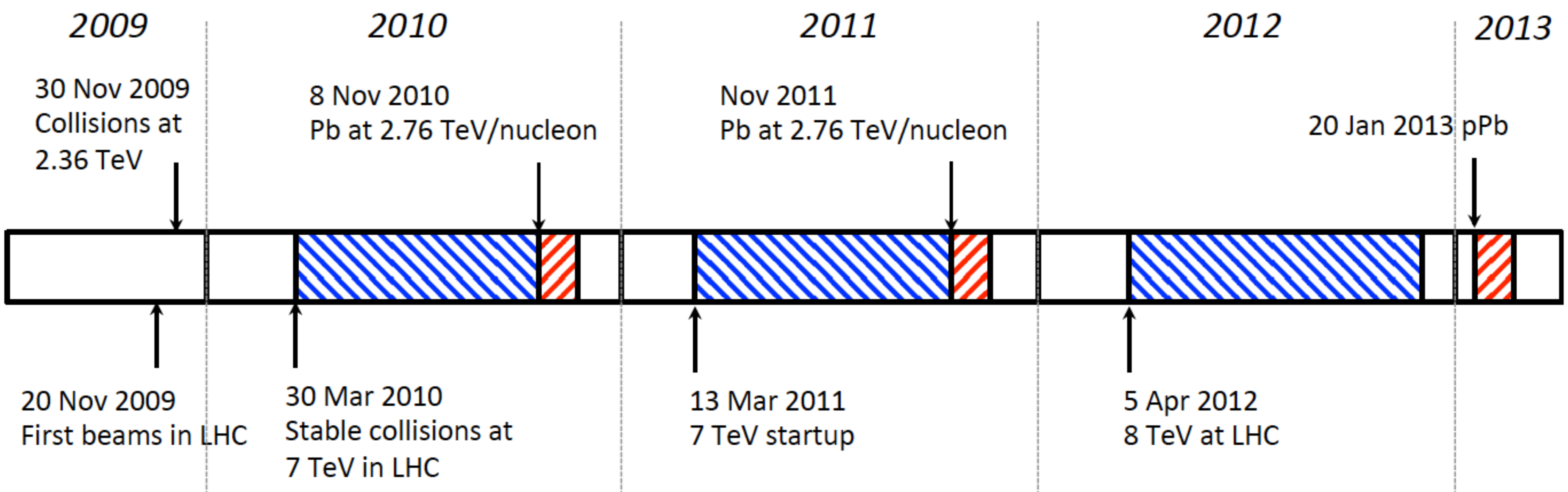
50 ns inter-bunch spacing

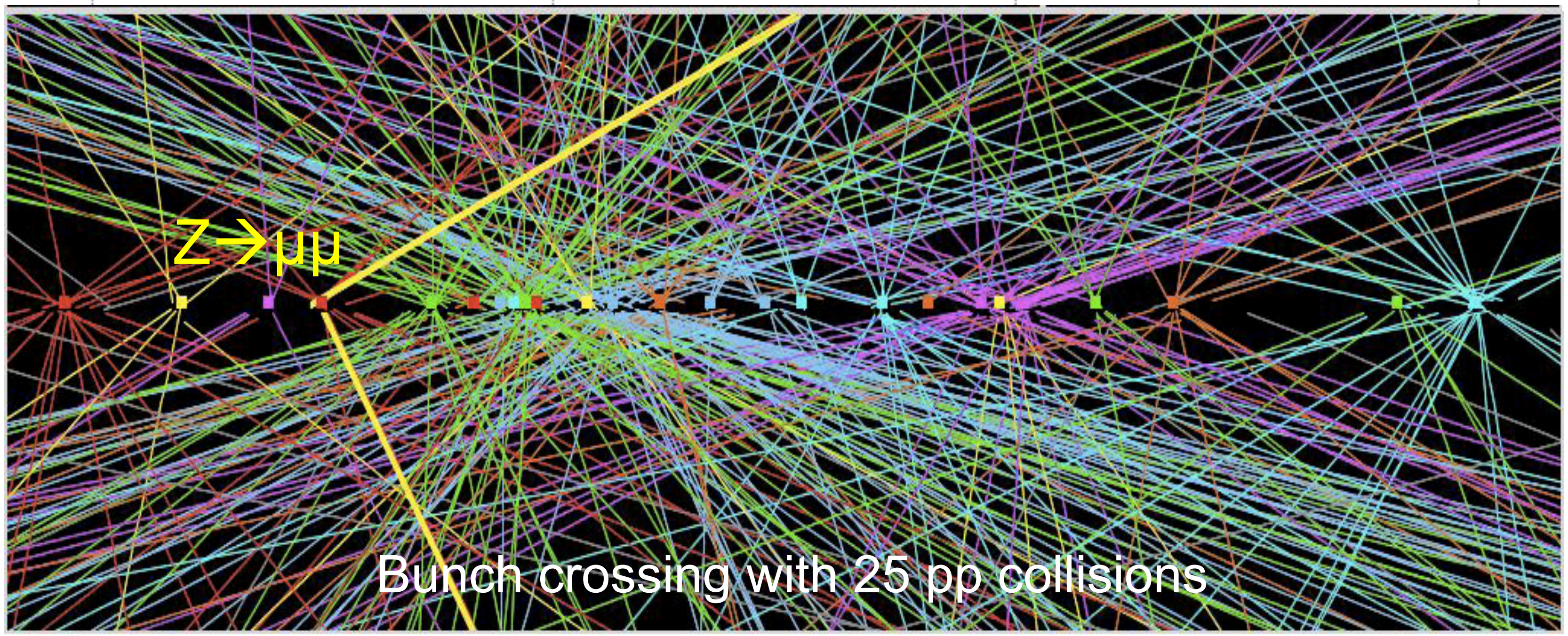






LHC Run 1


2009
2010
2011
2012
2013
30 Nov 2009
Collisions at
2.36 TeV
8 Nov 2010
Pb at 2.76 TeV/nucleon
Nov 2011
Pb at 2.76 TeV/nucleon
20 Jan 2013 pPb
20 Nov 2009
First beams in LHC
30 Mar 2010
Stable collisions at
7 TeV in LHC
13 Mar 2011
7 TeV startup
5 Apr 2012
8 TeV at LHC


Z→μμ
Bunch crossing with 25 pp collisions

LHC Run 1

2009	2010	2011	2012	2013

30 Nov 2009
Collisions at
2.36 TeV

8 Nov 2010
Pb at 2.76 TeV/nucleon

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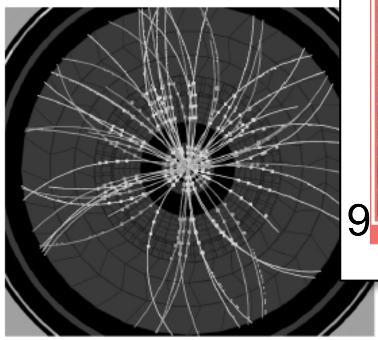
7 TeV startup

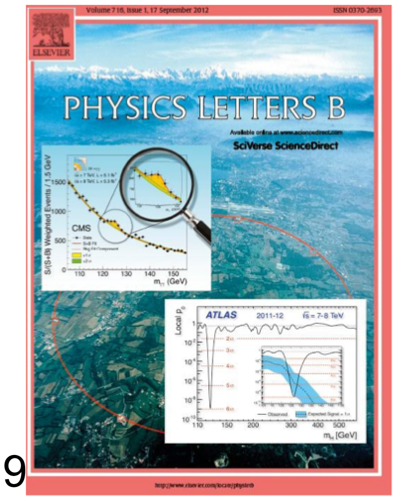
8 TeV at LHC

0.05 fb^{-1}
at 7 TeV

O(2) Pile-up event



4 July 2012: Higgs boson discovery



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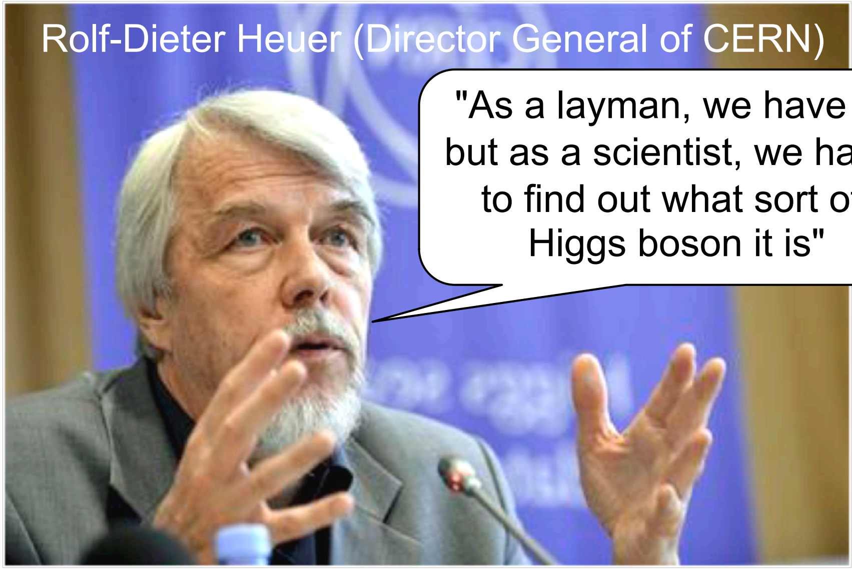
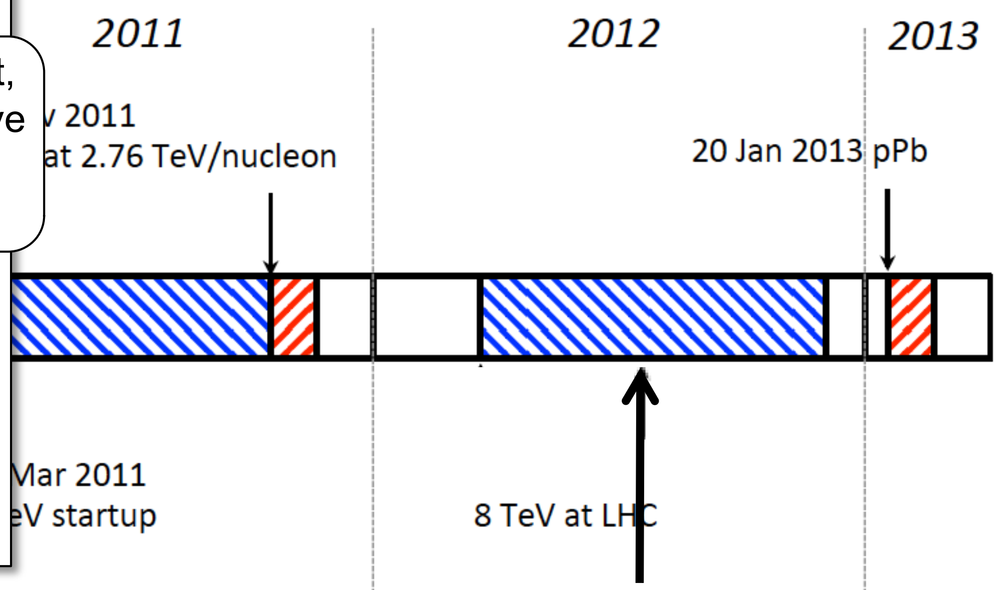
LHC Run 1

Rolf-Dieter Heuer (Director General of CERN)

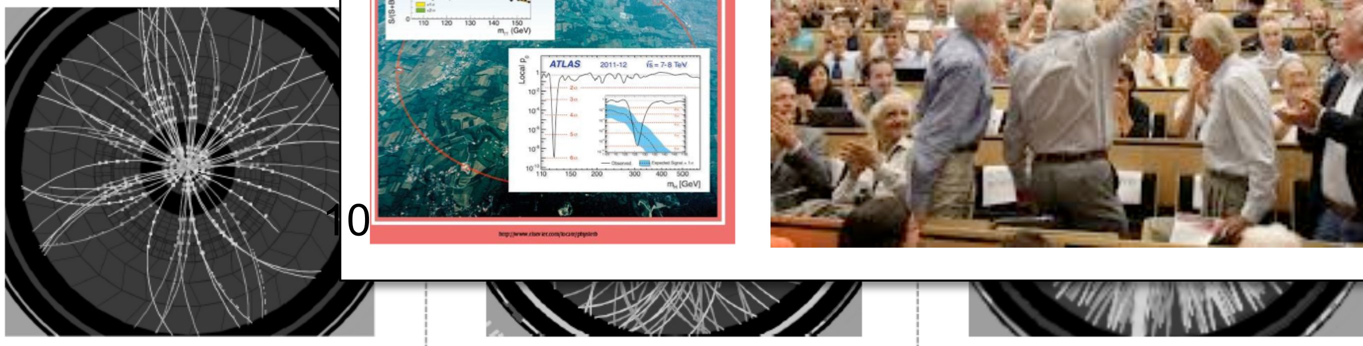


"As a layman, we have it, but as a scientist, we have to find out what sort of Higgs boson it is"



0.05 fb-1
at 7 TeV

O(2) Pile-up events



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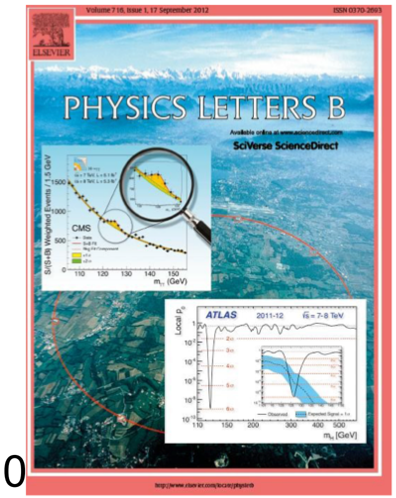
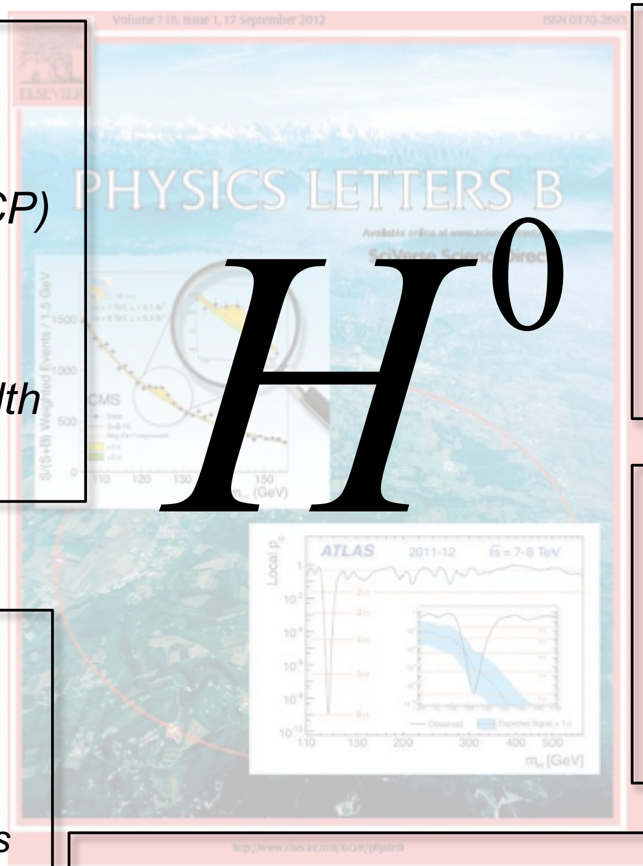


Explosion of the Higgs Physics Landscape!

Precision measurements

- *Mass*
- *Quantum numbers (spin, CP)*
- *Coupling properties*
- *Differential cross sections*
- *Off-shell couplings and width*
- *Interferometry*



Rare / BSM decays

- $H^0 \rightarrow \mu\mu$
- $H^0 \rightarrow Z\gamma$
- $H^0 \rightarrow J/\psi\gamma$, $\Upsilon(ns)\gamma$
- LFV $H^0 \rightarrow \mu\tau$, $e\tau$, $e\mu$
- $H^0 \rightarrow aa$

…and more!

- *FCNC $t \rightarrow H^0 q$ decays*
- *Di-Higgs production*
- *Trilinear coupling*
- *… etc*

Is the SM minimal?

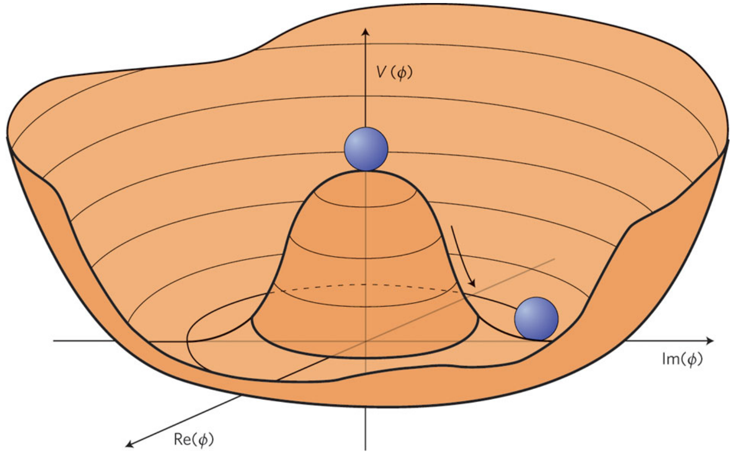
- *2HDM searches*
- *MSSM, NMSSM searches*
- *Doubly-charged Higgs bosons*

Tool for discovery

- *Portal to DM (invisible Higgs)*
- *Portal to hidden sectors*
- *Portal to BSM physics with H^0 in the final state (VH^0, H^0H^0)*

Electroweak Symmetry Breaking in the SM

- All measurements to date are consistent with the SM picture of EWSB:
  - Triggered by a fundamental scalar that acquires a vacuum expectation value (v~246 GeV).
  - Particles acquire mass through interaction with scalar field in the ground state.



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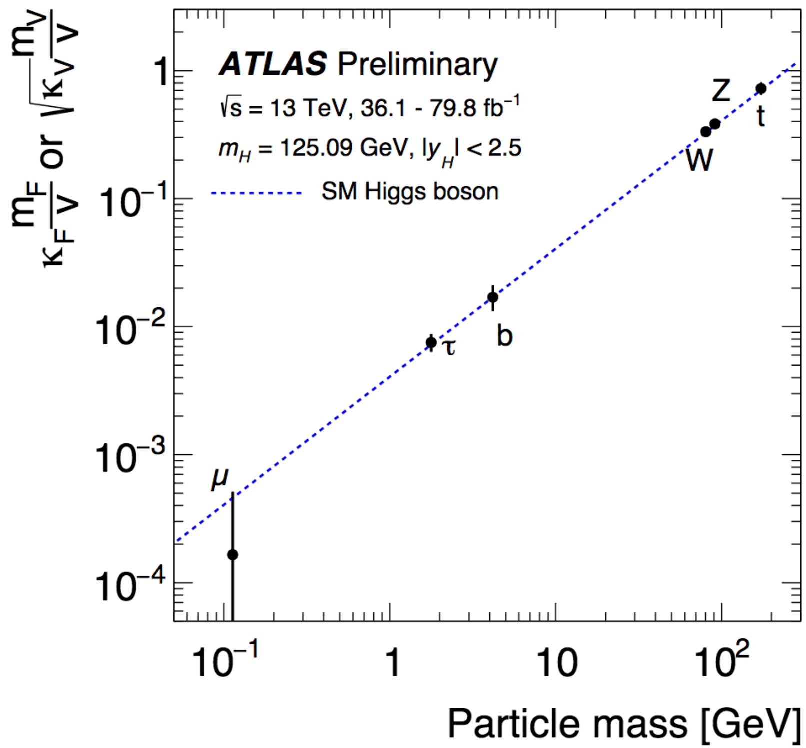
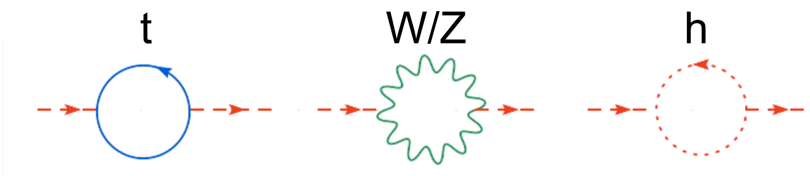


- But it's not fully satisfactory:
  - Higgs boson mass is very sensitive to short-distance physics.
  - Lack of dynamical explanation for EWSB.

Why is the Higgs Boson so Light?

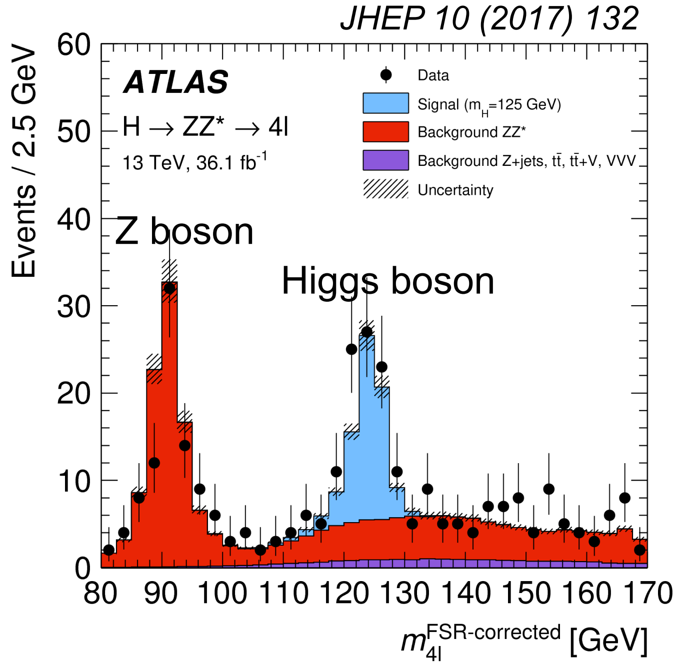
All elementary scalars are expected to be ultra-heavy.

- 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: $(125\ \mathrm{GeV})^2 \approx (10^{19}\ \mathrm{GeV})^2 - (10^{19}\ \mathrm{GeV})^2$

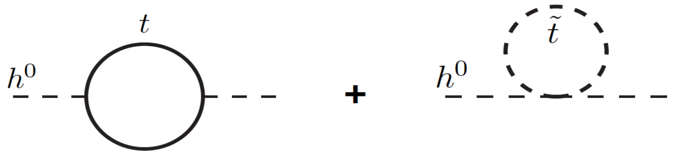
listening to your favorite radio needs the tuned frequency to match that of the radio channel:

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

Solutions to the Hierarchy Problem

New Physics stabilizes the hierarchy

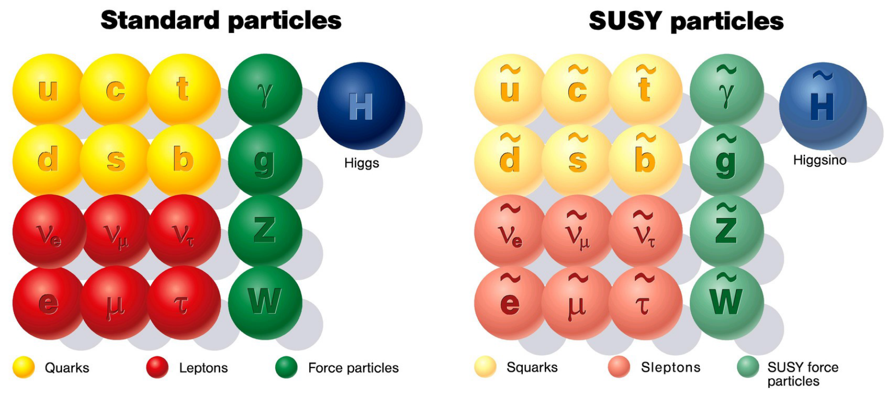
Supersymmetry: new symmetry that relates scalars to fermions (cancellation of quadratic divergences).



Fermion loop | Boson loop

$m_H^2 = +A$ | $m_H^2 = -A$

$m_H^2 = 0$



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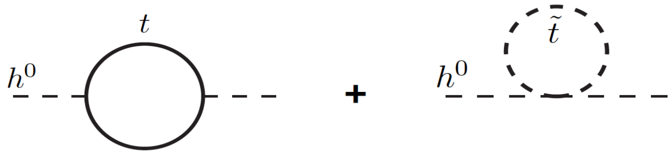

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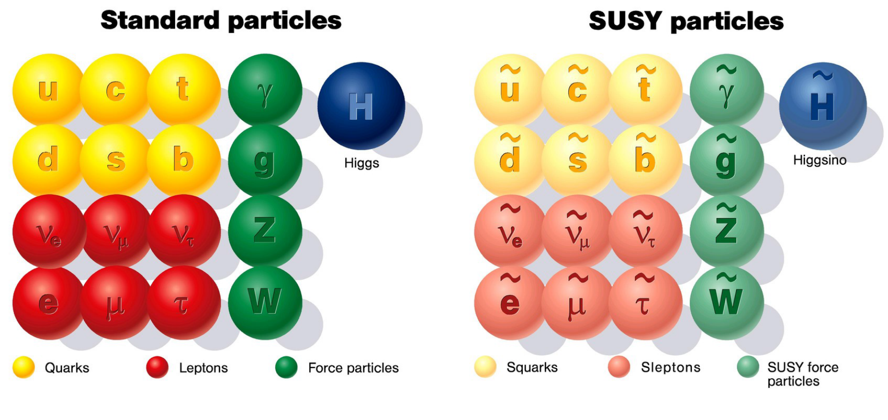
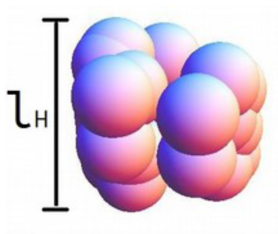


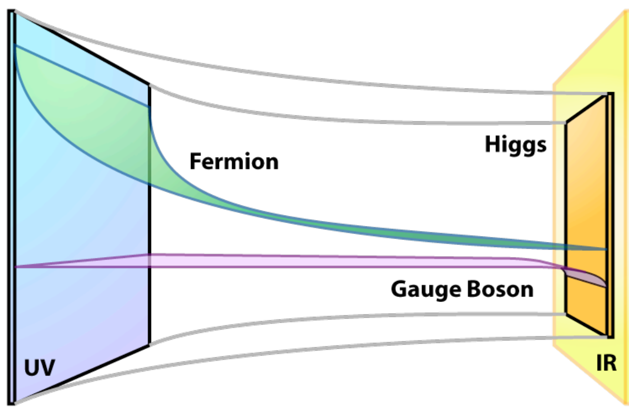
Compositeness: the Higgs boson is not an elementary particle but a composite object.

➔ No true hierarchy problem beyond the scale of compositeness.



AdS/CFT correspondence ⟺

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

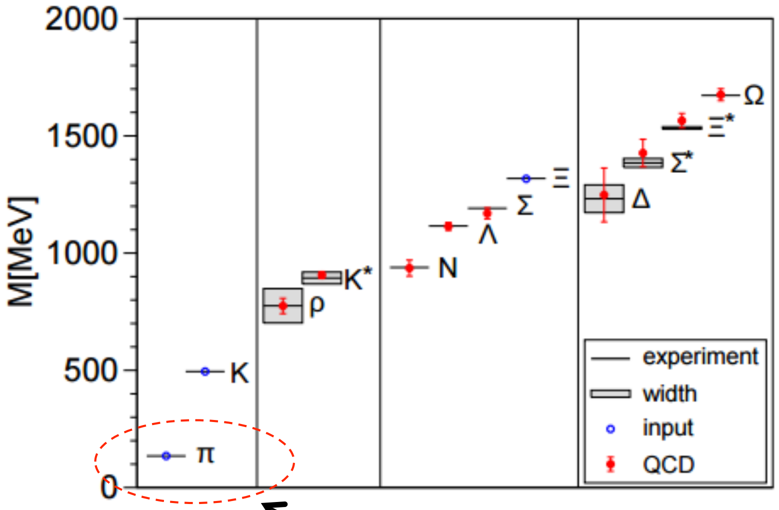


Composite Higgs Paradigm

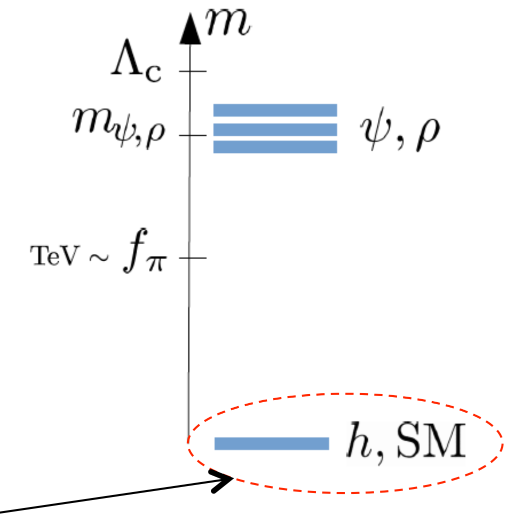
New strong interaction that confines at a scale Λ_c~10 TeV.

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

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

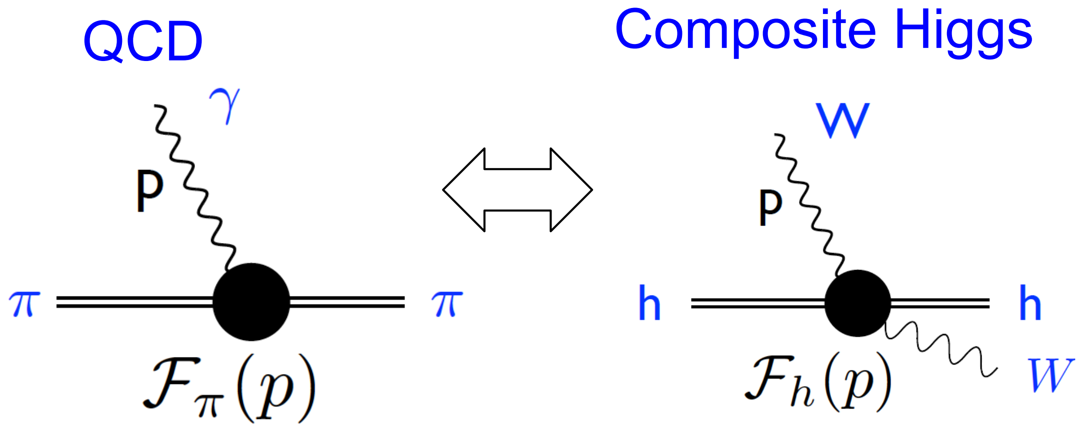
$$SU(2)_L \times SU(2)_R \to SU(2)_V \longleftrightarrow G \to H \supset SM$$

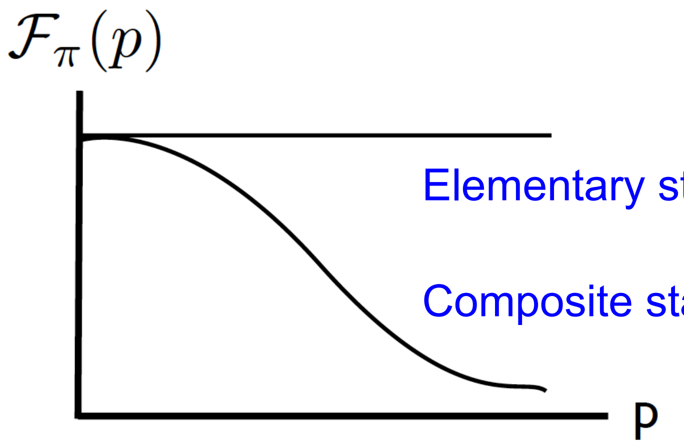
f_π~100 MeV

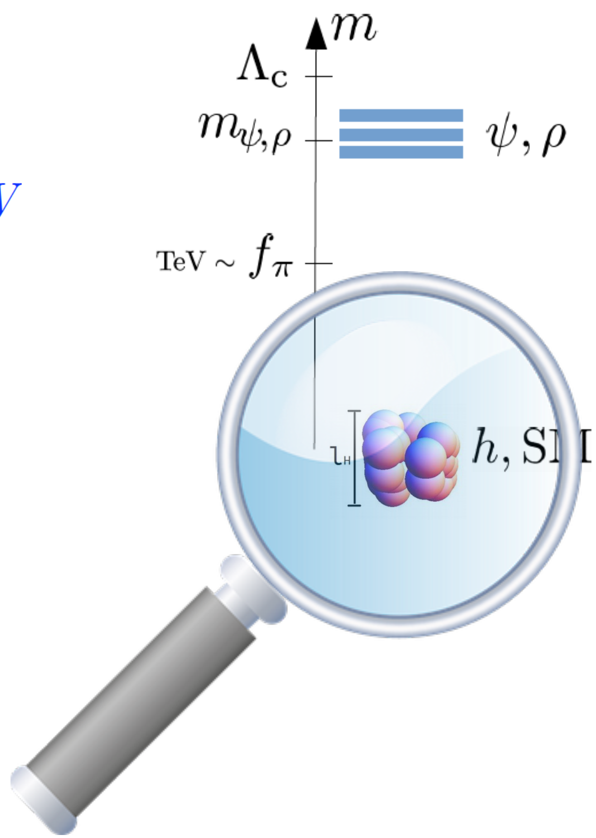
f_π>v=246 GeV

Higgs Boson Couplings

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







Expect reduced couplings for a composite particle

Go as high in energy as possible!

Higgs Boson Couplings

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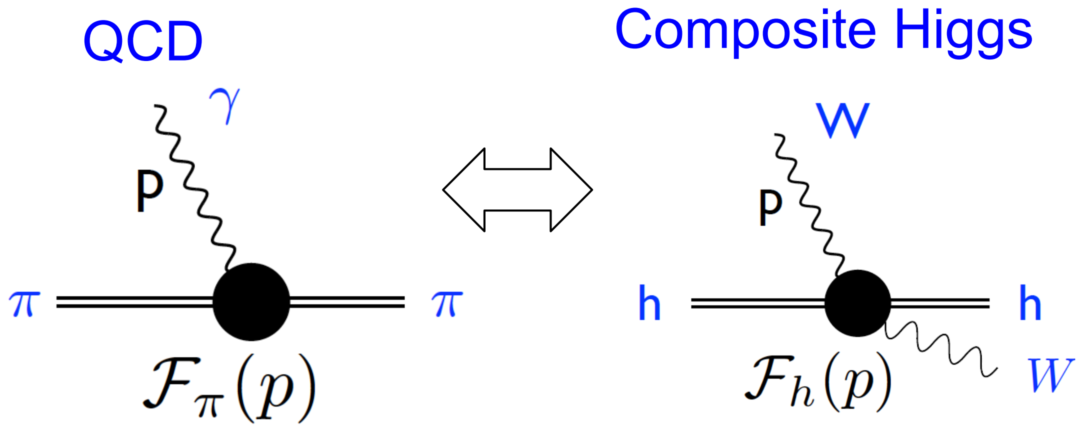
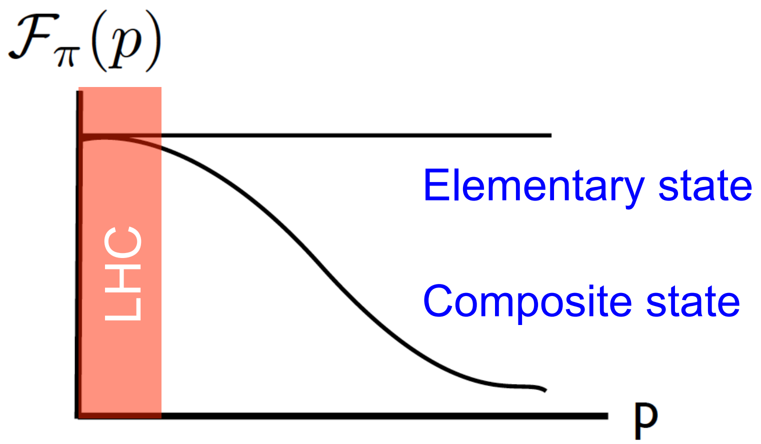
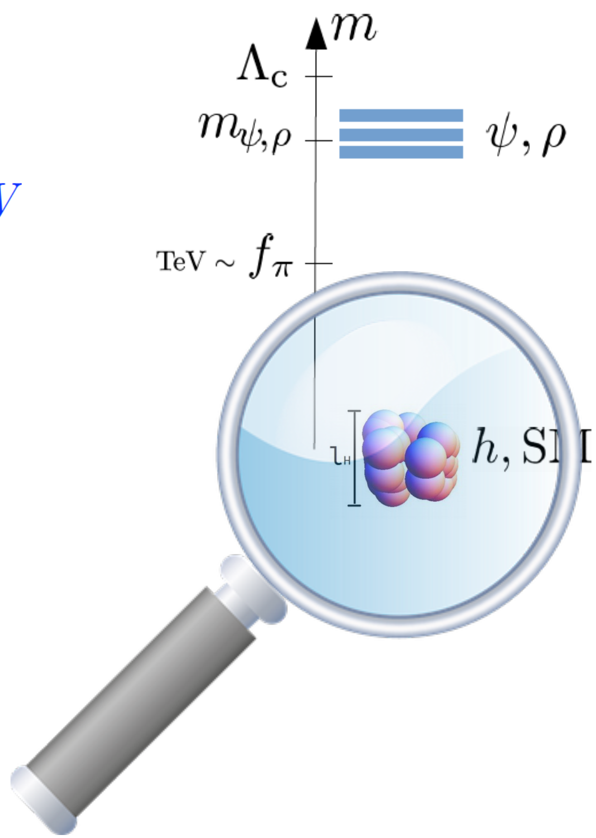






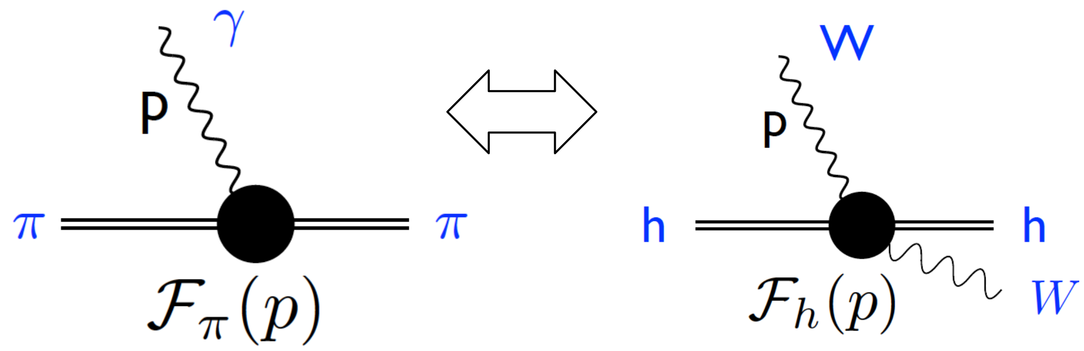
Unfortunately, with the LHC we are limited to ~TeV

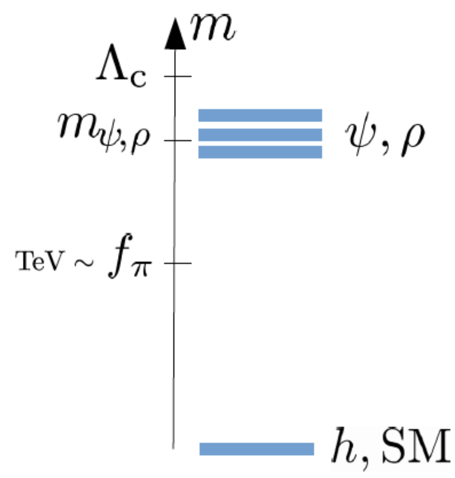
Higgs Boson Couplings

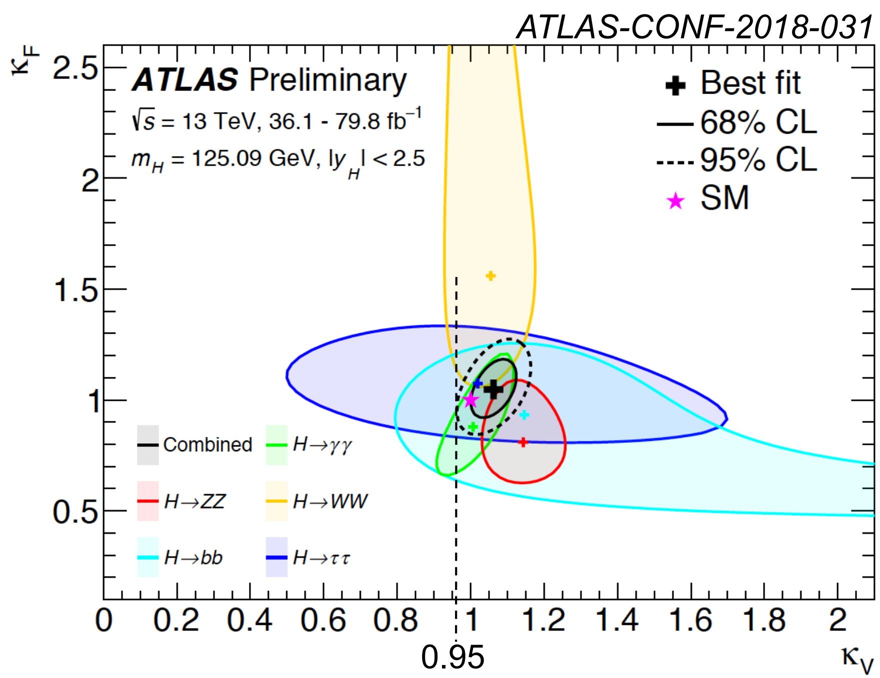
Unravel composite nature of the Higgs boson by measuring its couplings to SM particles!

QCD

Composite Higgs







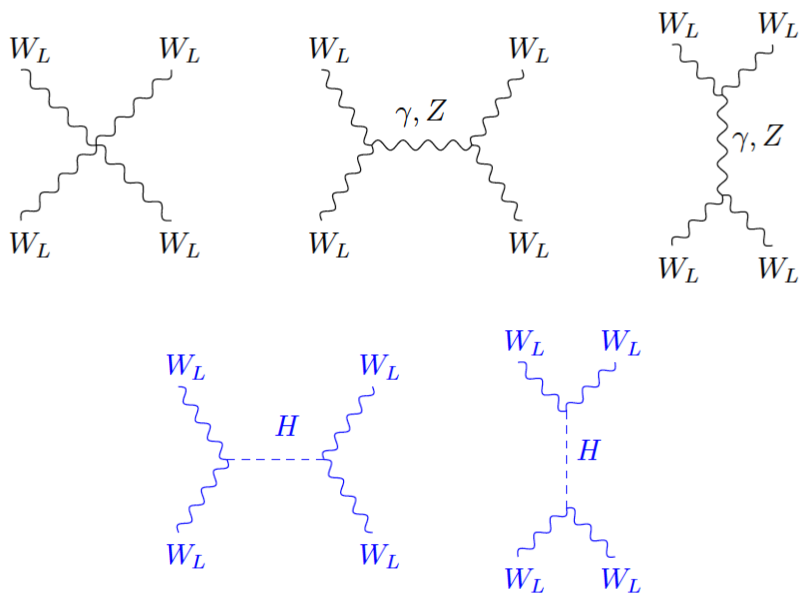
Expected scale factor for coupling to vector bosons:

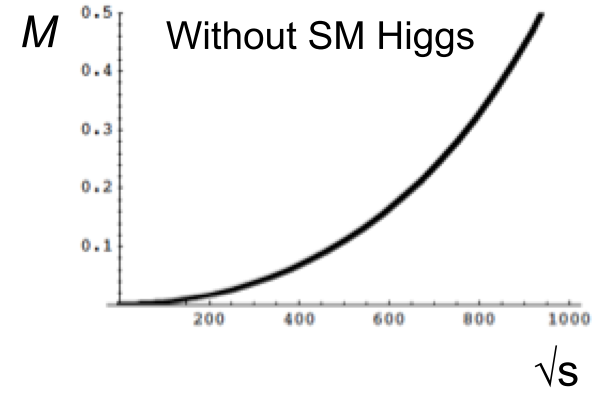
$$\kappa_V = \sqrt{1-\xi}, \ \xi \equiv v^2 / f_\pi^2$$

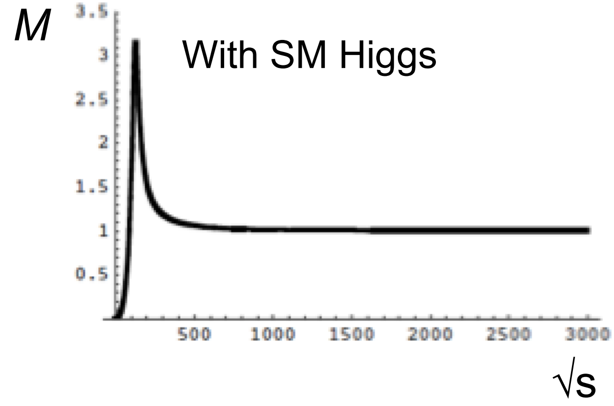
κ_V>0.95 ➔ f_π>790 GeV @ 95% CL

Longitudinal Vector Boson Scattering

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







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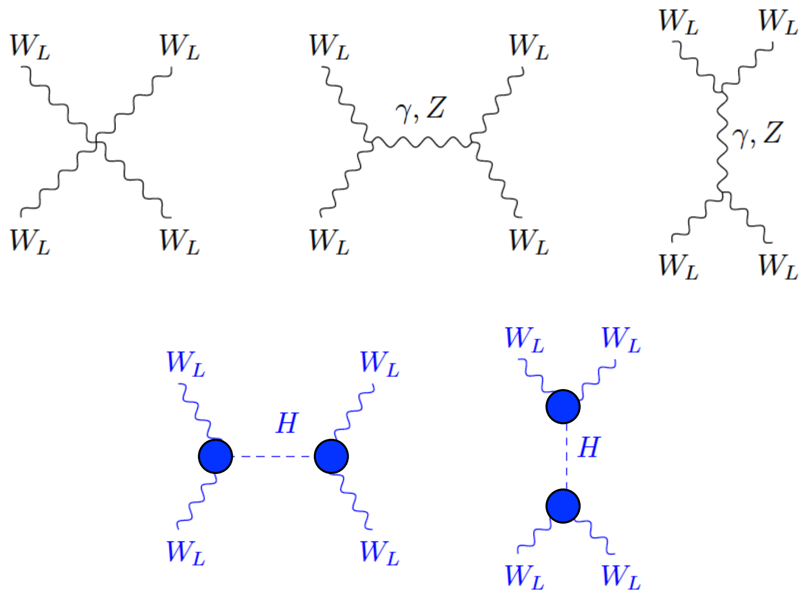
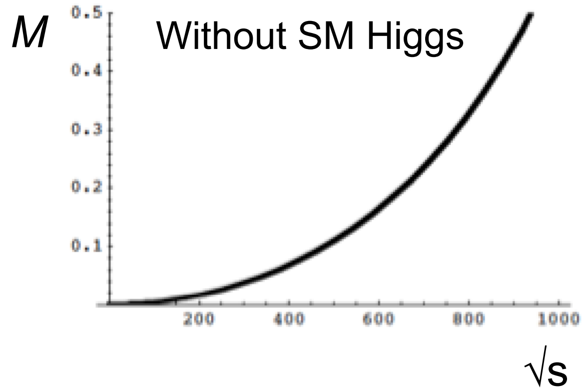
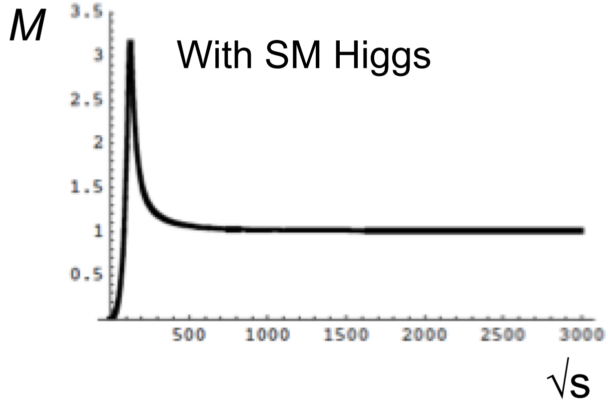
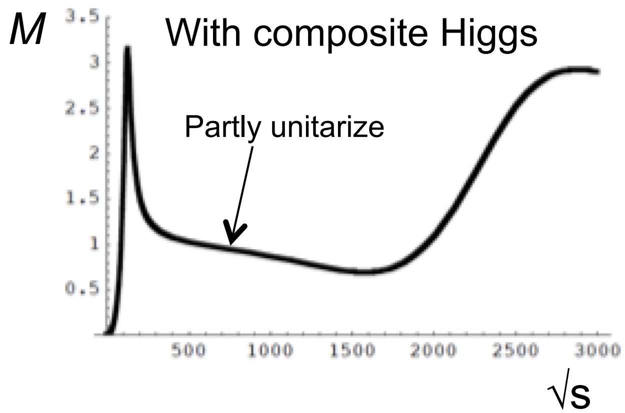


- Reduced couplings to vector bosons means the Higgs boson only does in part its job.







Composite Bosonic Resonances

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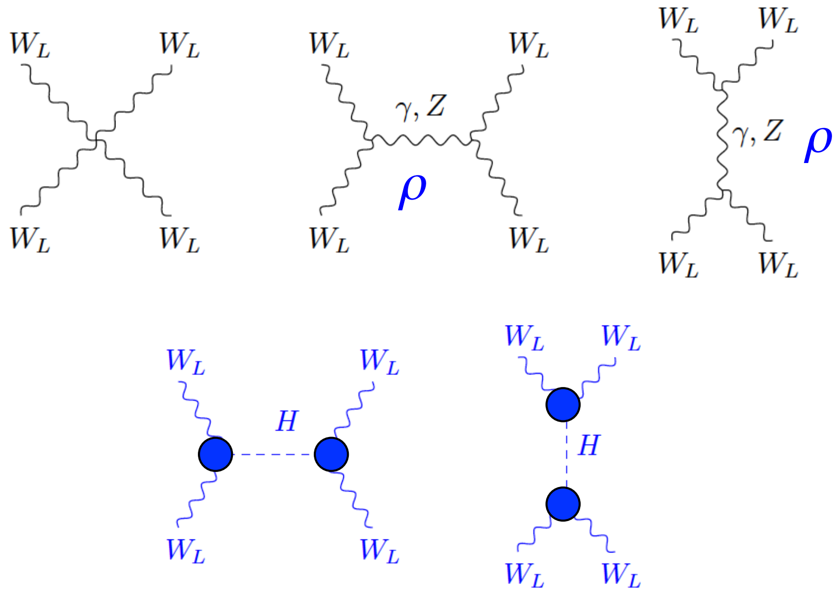
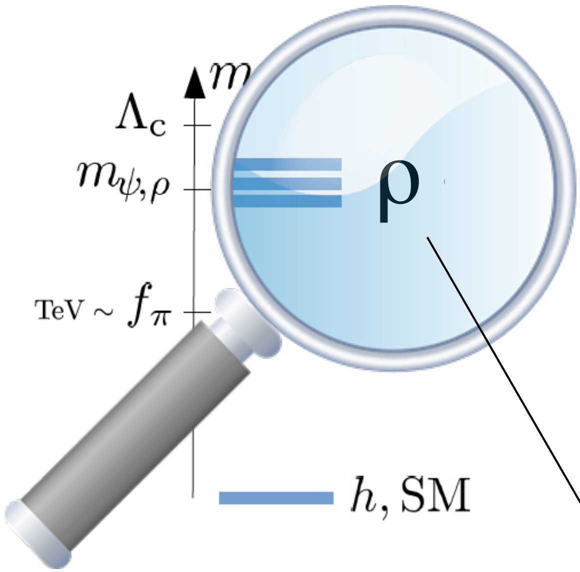
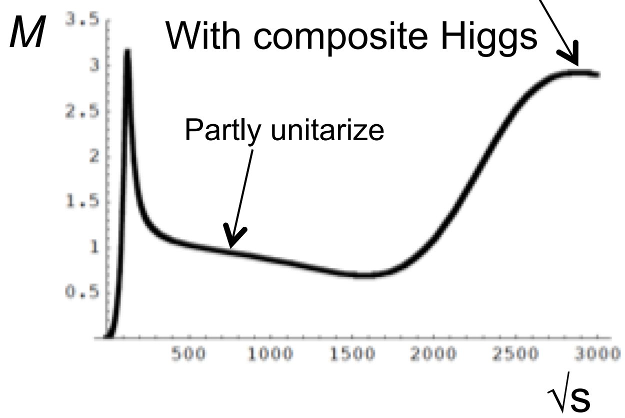




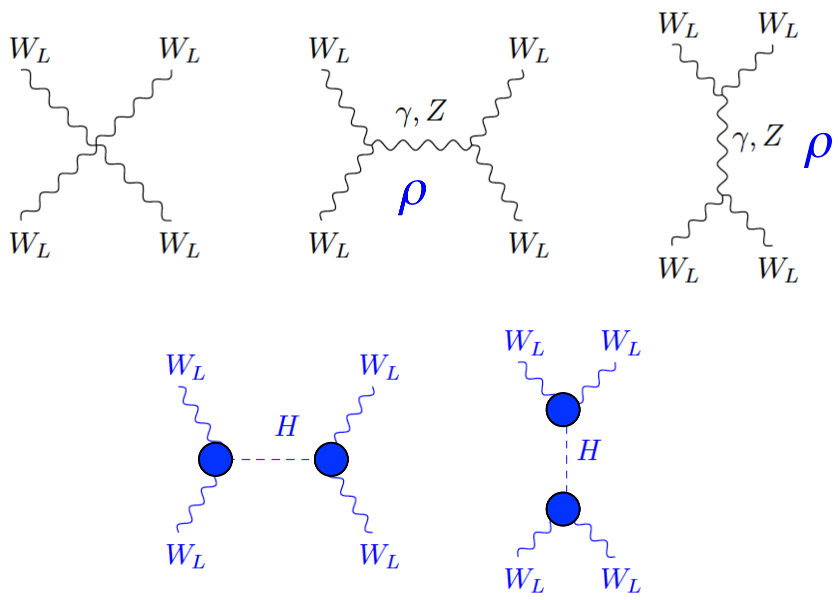
- Reduced couplings to vector bosons means the Higgs boson only does in part its job.

- Composite bosonic resonances needed to fully unitarize!

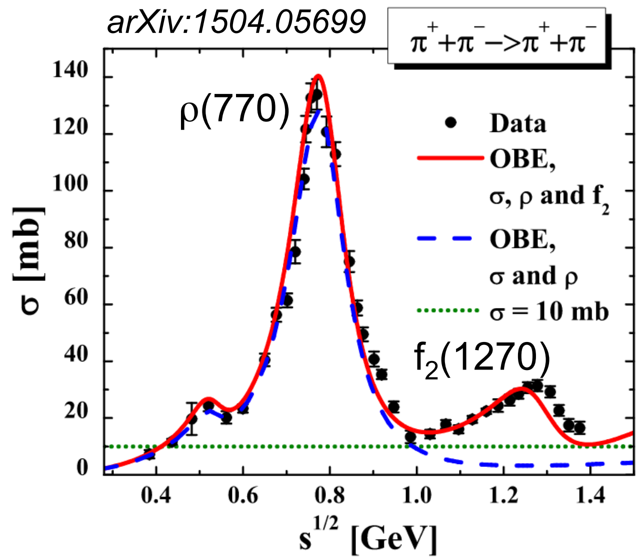


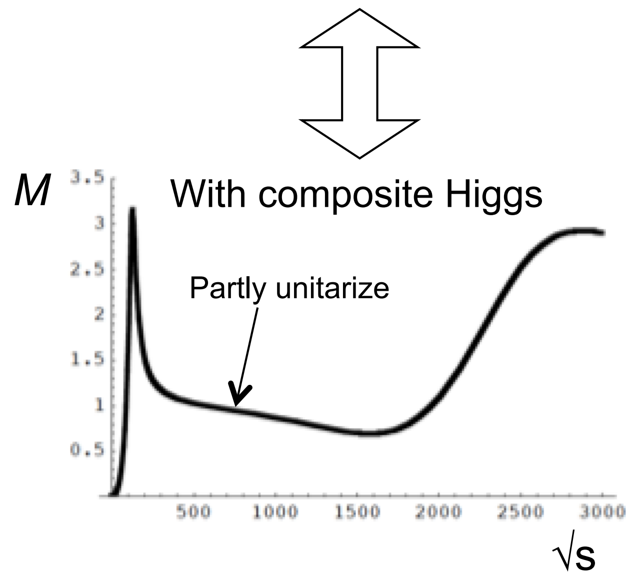
Composite Bosonic Resonances

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



π-π elastic scattering





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

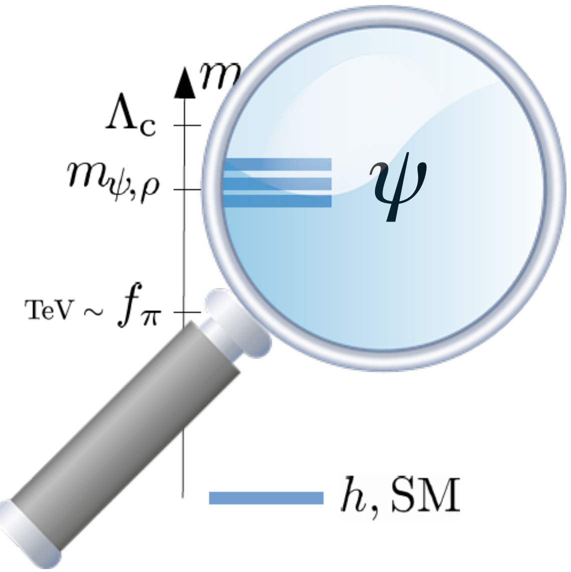
- Composite bosonic resonances needed to fully unitarize!

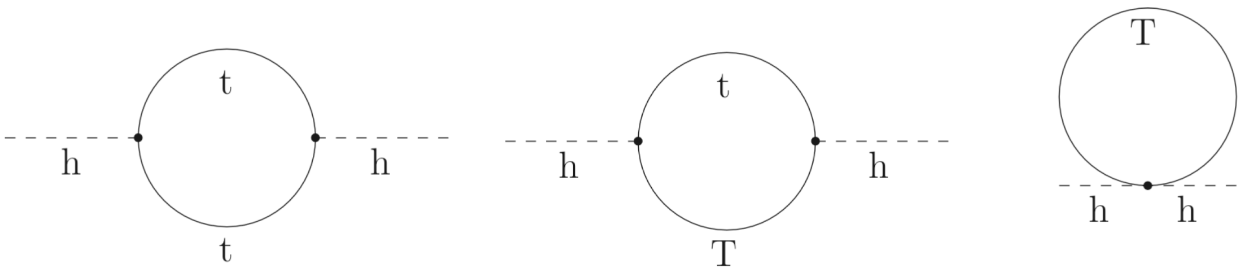
Composite Fermionic Resonances

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).

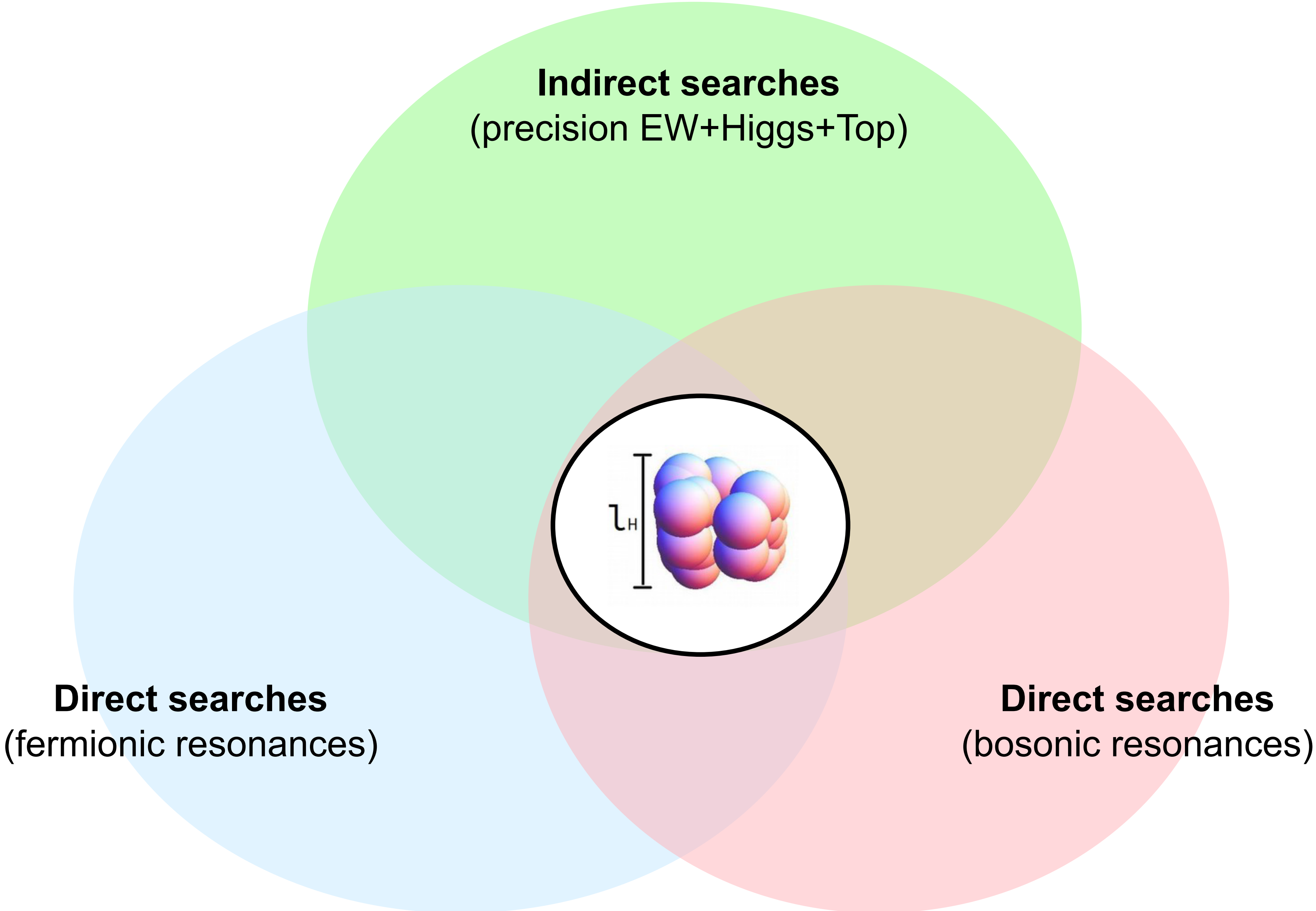
Vector-like: *left and right components transform the same under $SU(2)_L$*
➔ can write mass term in Lagrangian



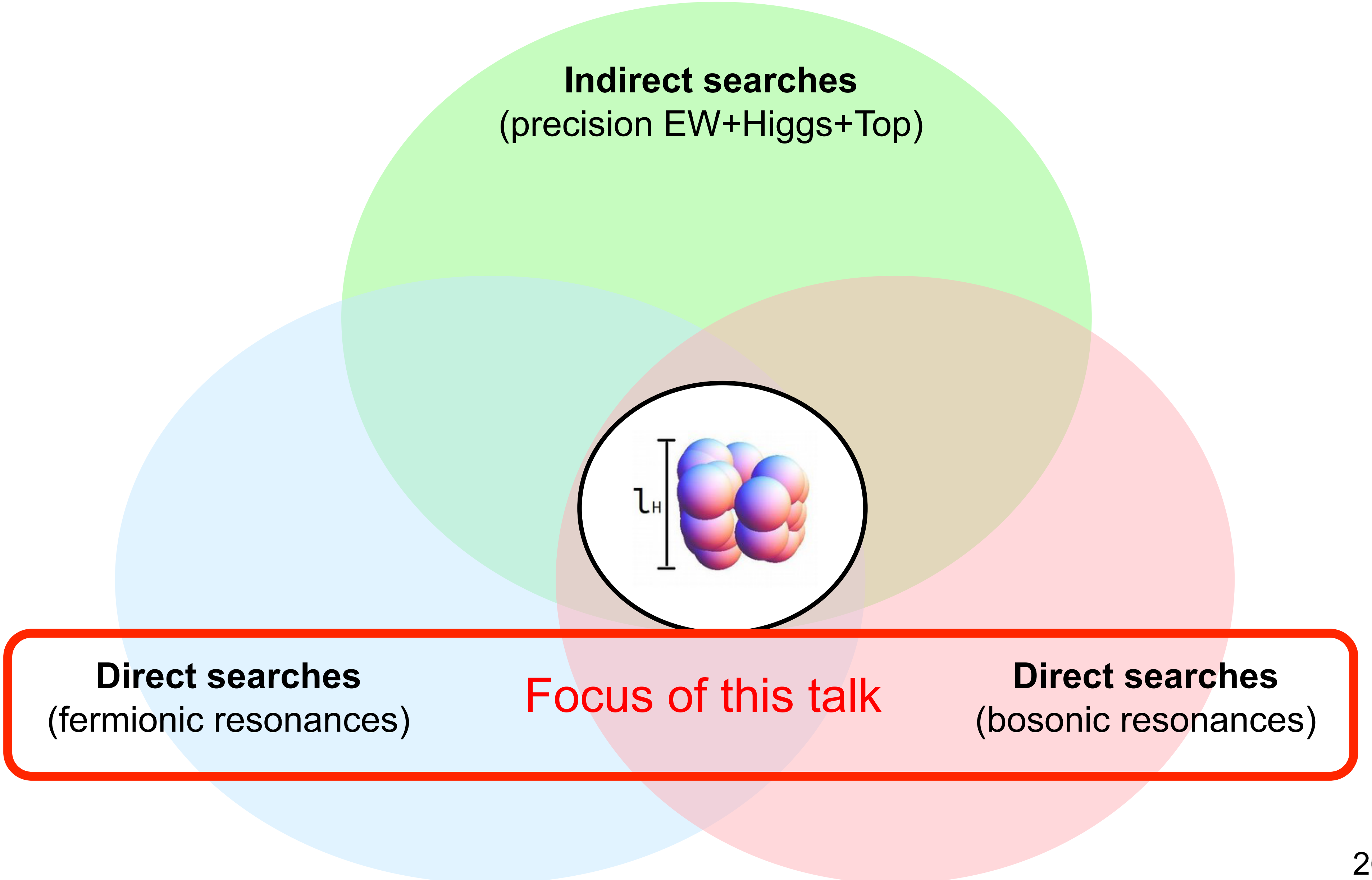


They regulate the Higgs mass-squared divergence

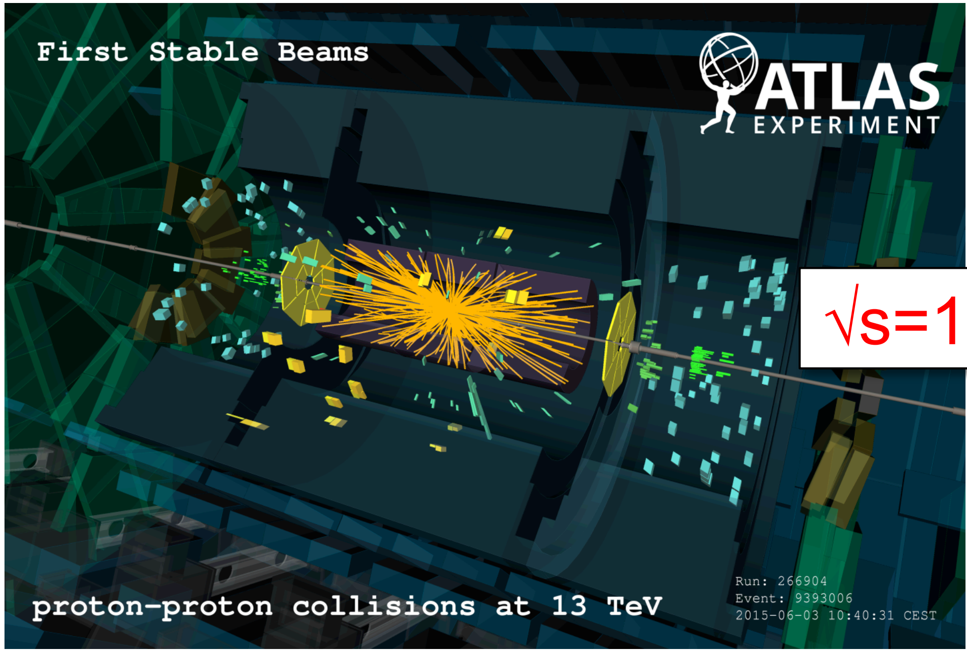
A Broad Program



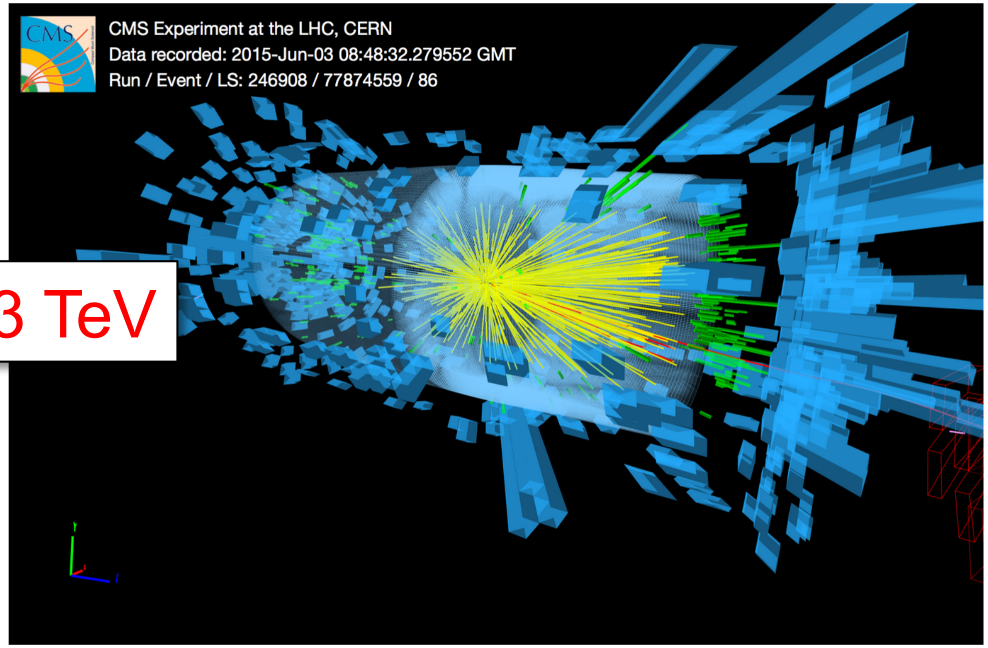
A Broad Program



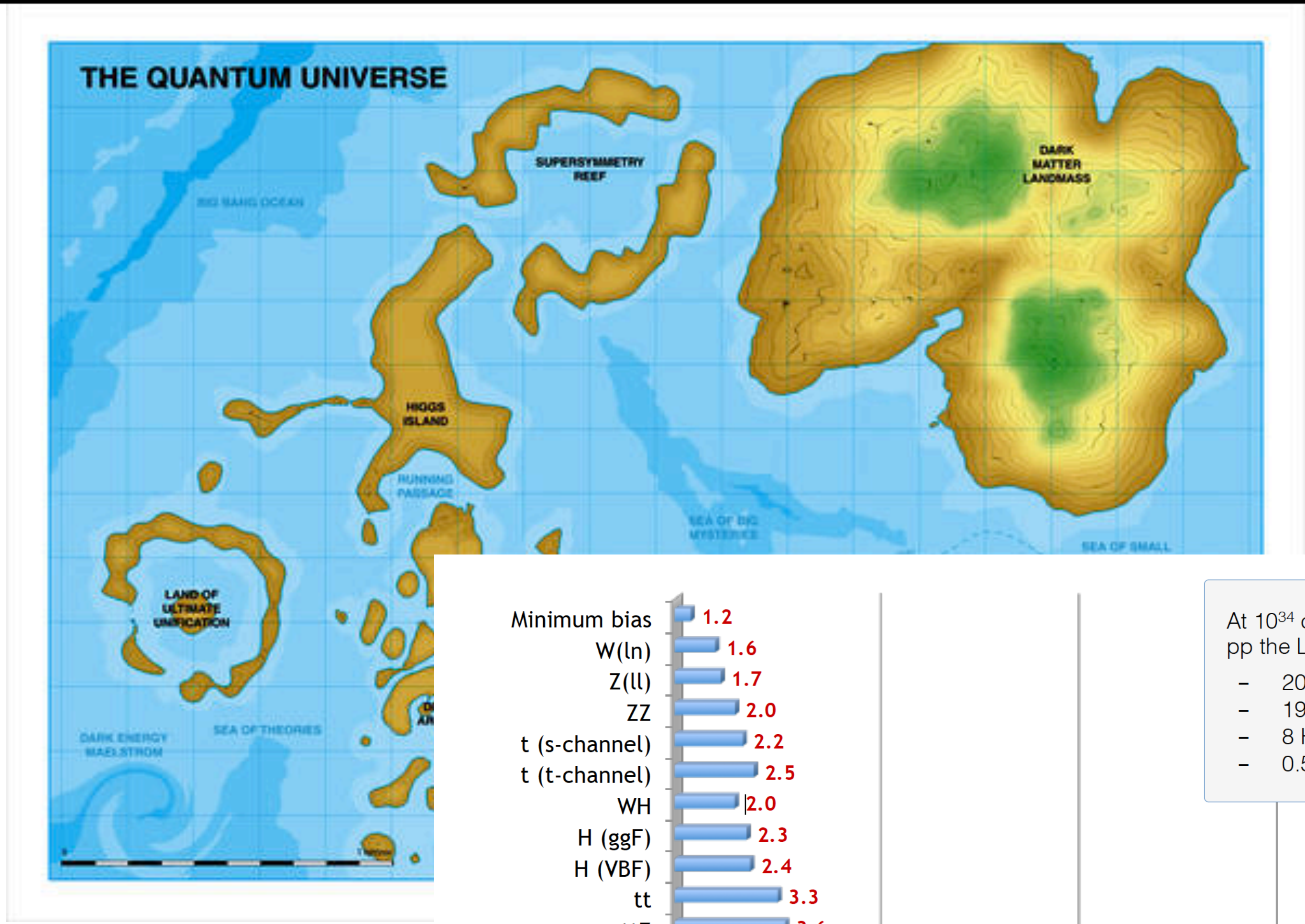
June 3, 2015: Run 2 Starts!

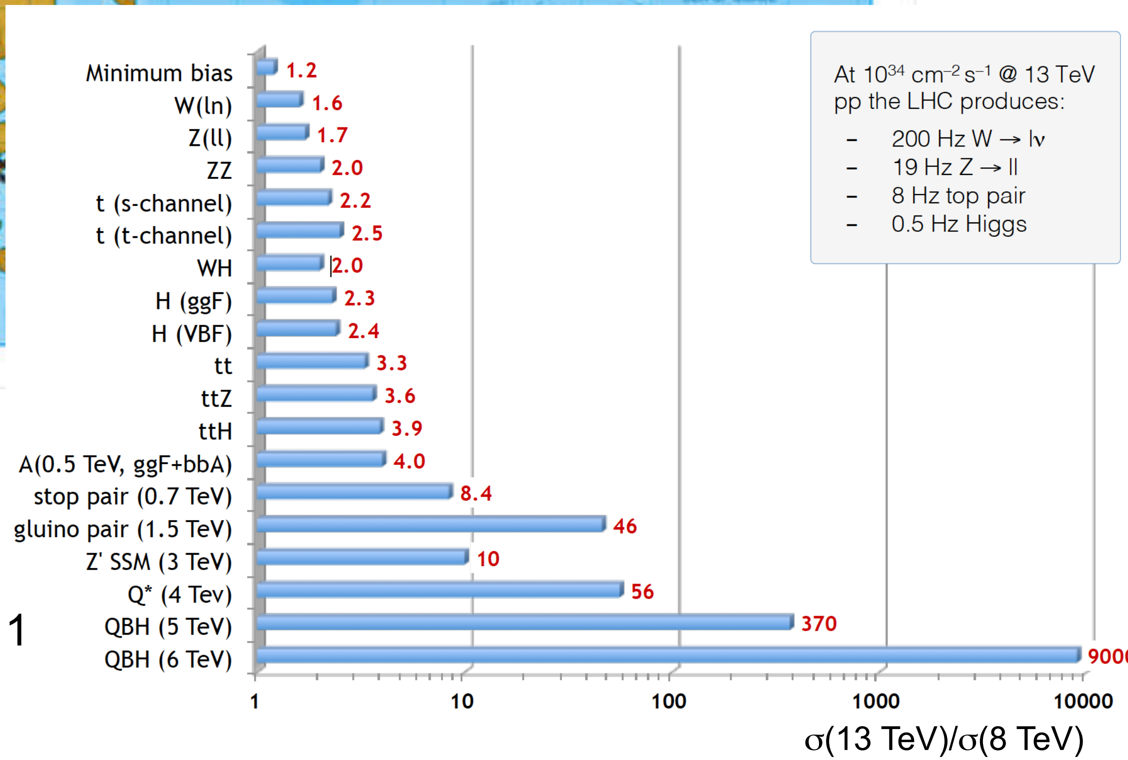


√s=13 TeV



Direct Searches for New Phenomena



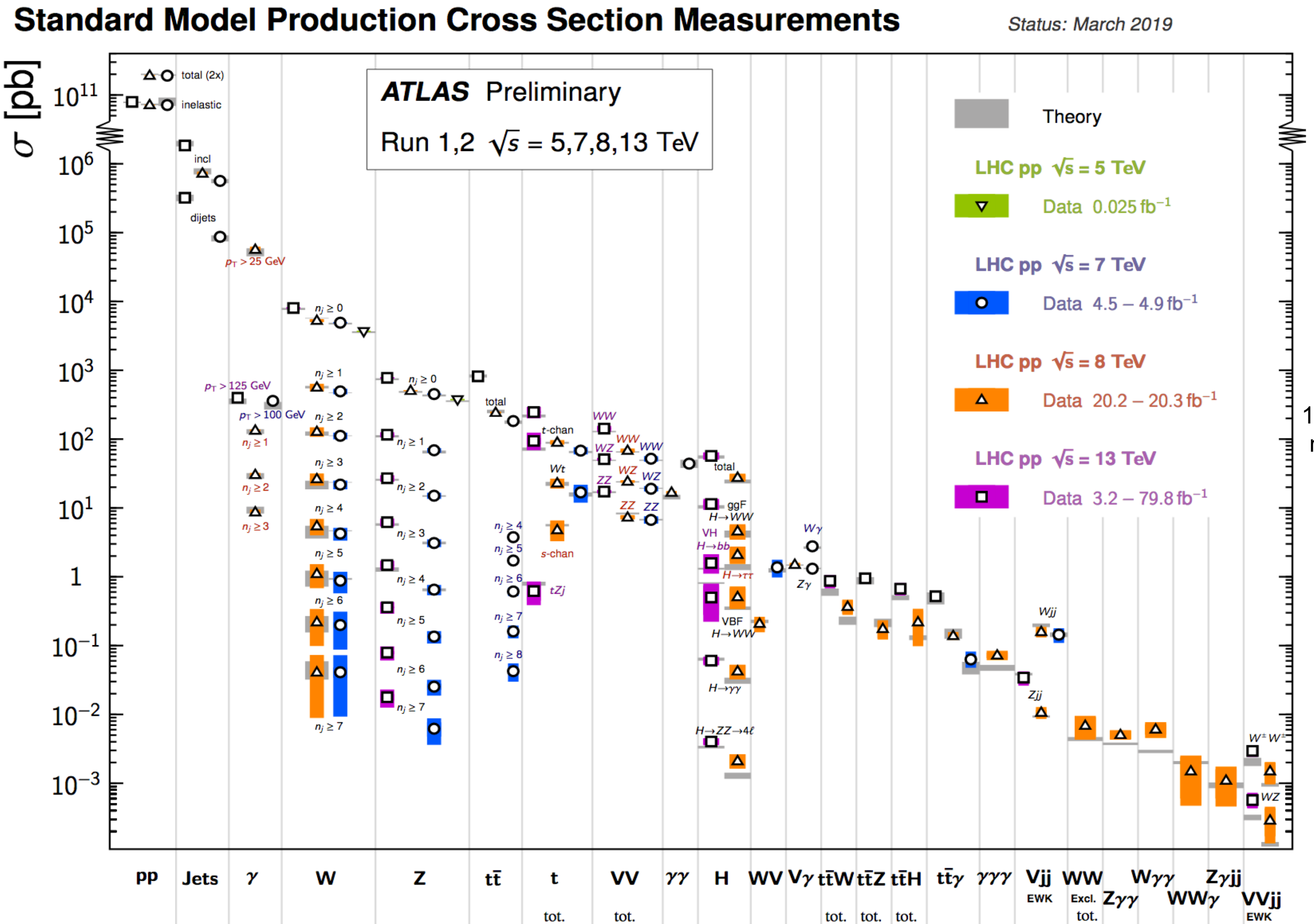


Terra Incognita

With great expectations!

In some cases already exceeded Run 1 sensitivity with <2 fb^{-1} at 13 TeV!

Standard Model Measurements



14 orders of magnitude

Stunning achievement, both from experiment and theory

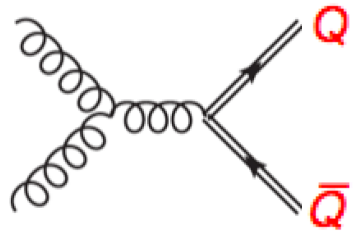
Also a necessary step to confidently search for New Physics

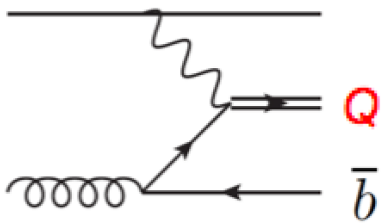
Fermionic Resonances

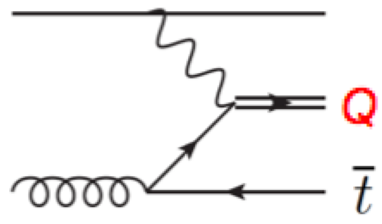
Vector-Like Quarks: Production and Decay

Production:

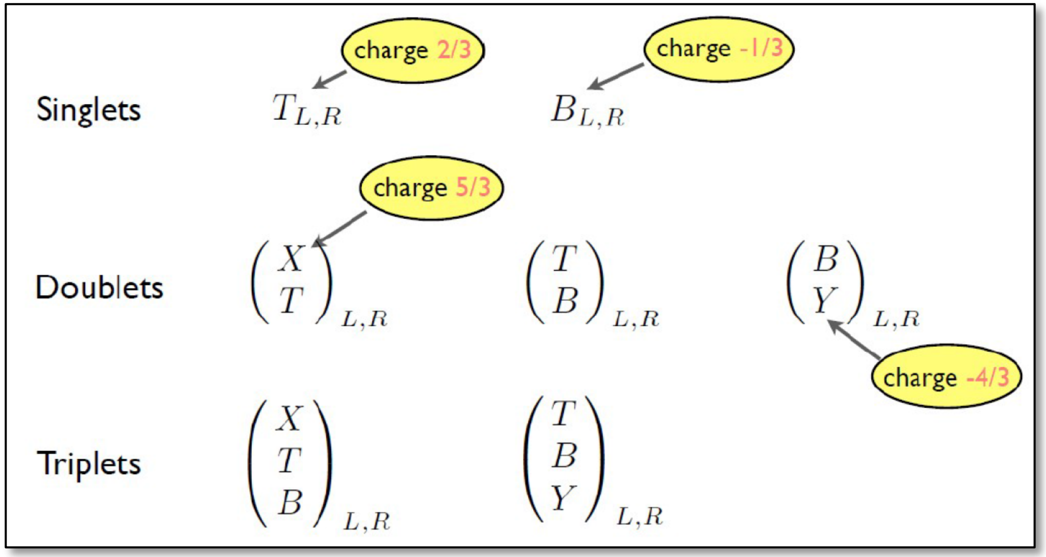
- Pair production: via QCD, "universal" production mode (just depends on m_Q).
  ➔ Focus of Run 1 searches
- Single production: via EW interaction, depends on coupling strength, but potentially important at high m_Q.

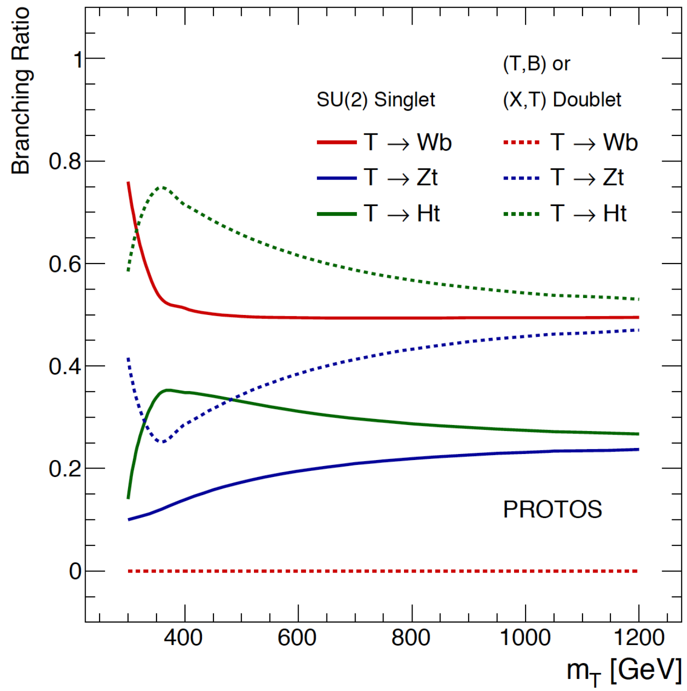






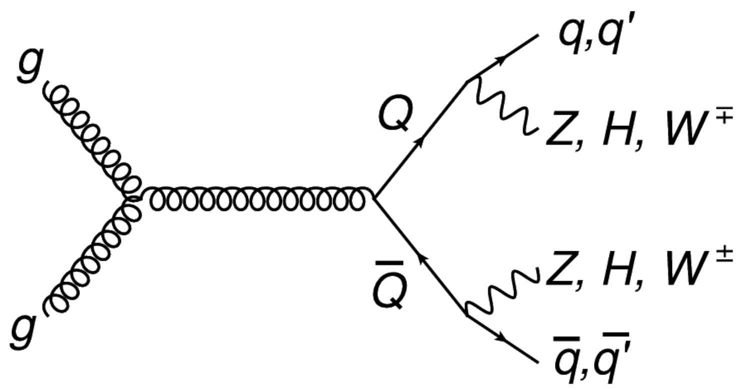
Decay: Q→Wq, Zq, Hq, all with sizable BR





VLQs assumed to mix preferentially with 3rd generation quarks.

Pair Production Strategy

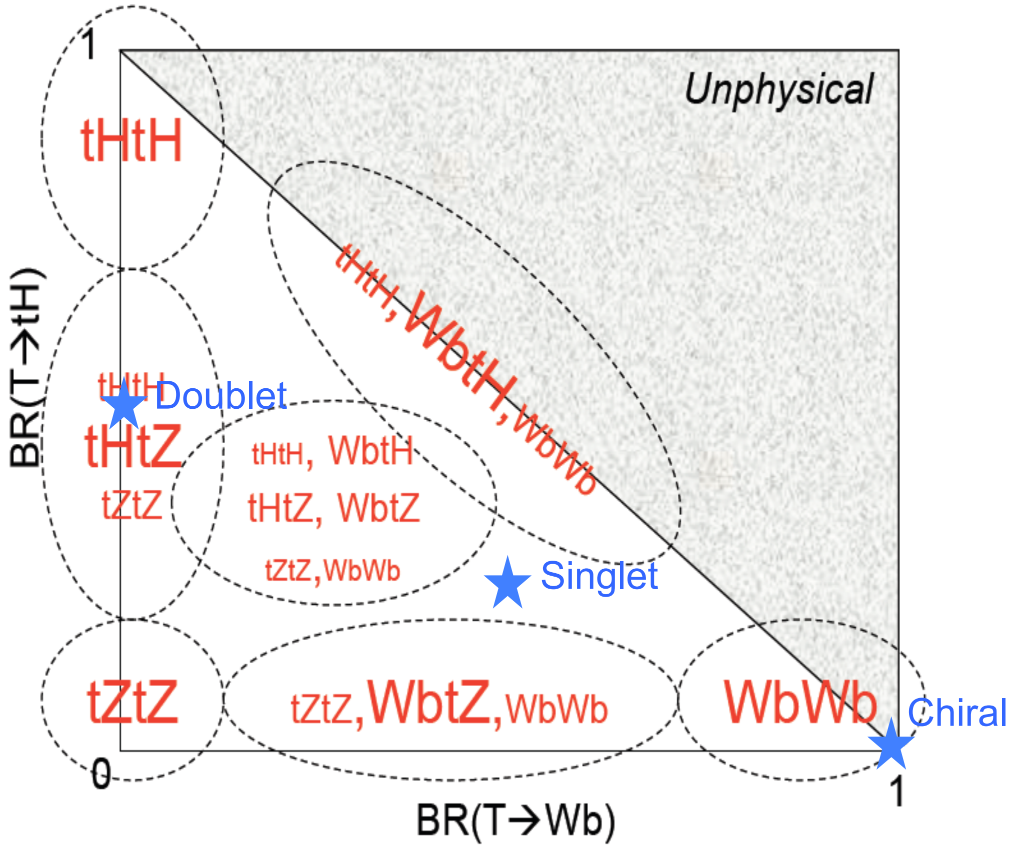


- Very rich phenomenology, depending on VLQ mass and quantum numbers.

- Goal is to probe full BR plane in as model independent possible way.

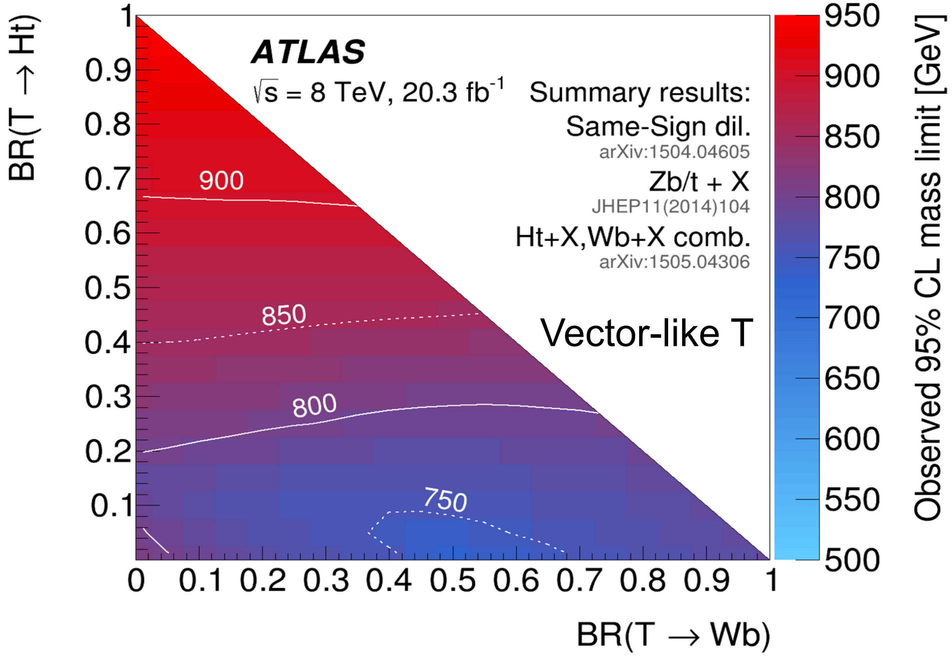
  ➔ Searches specialized on particular heavy quark decay modes, but also able to probe part of the plane.

  ➔ Multiple searches required, ideally overlapping on the plane.



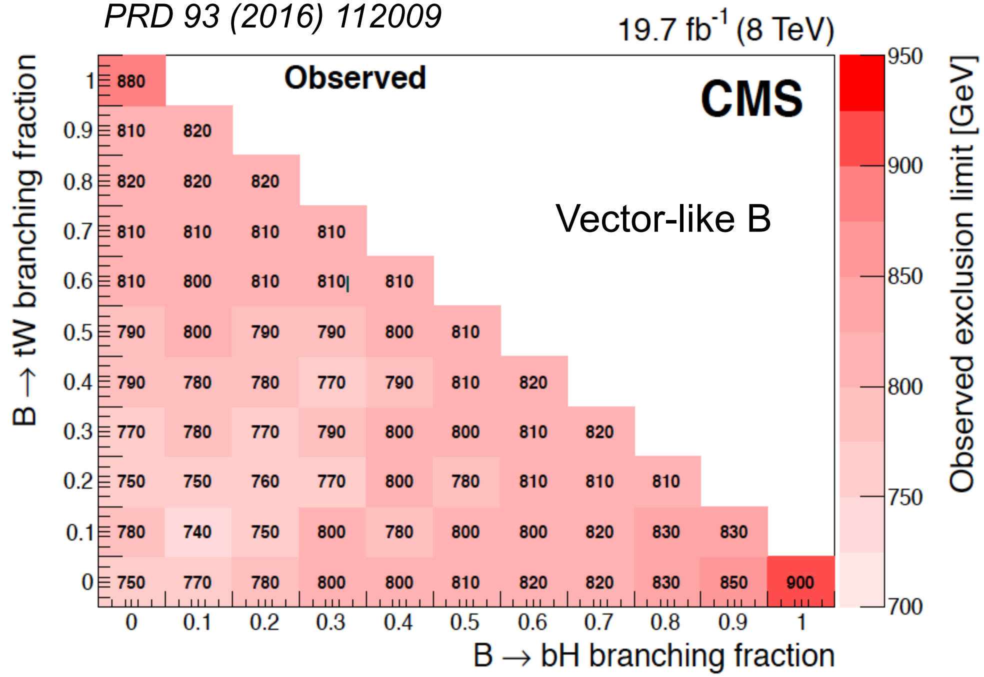
Run 1 Summary

JHEP 1508 (2015) 105



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

PRD 93 (2016) 112009

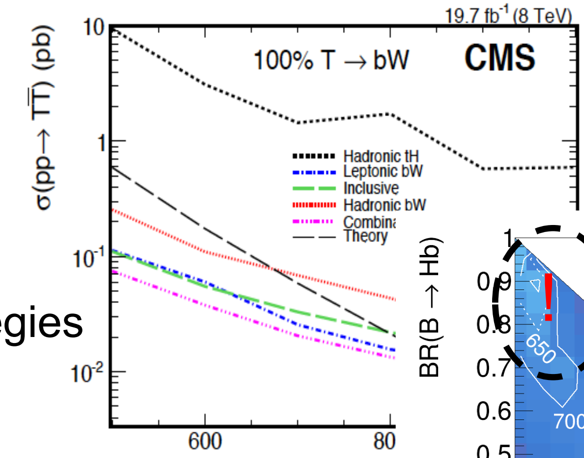


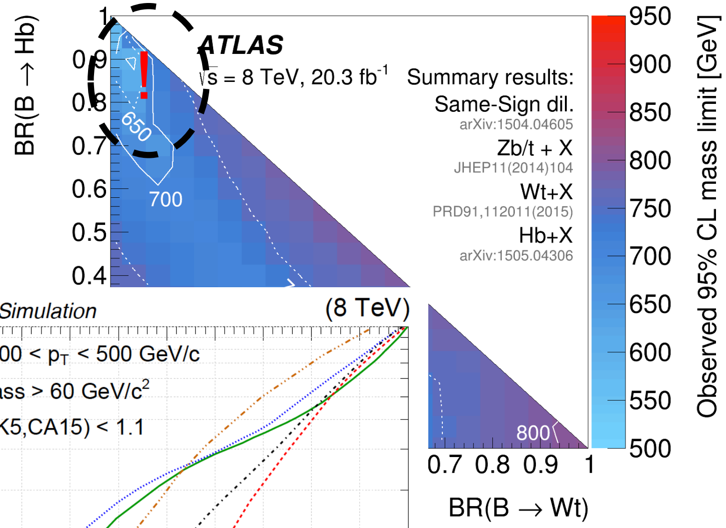
Run 1 excludes T-quark (B-quark) masses below ~720 (740) GeV for any combination of BRs

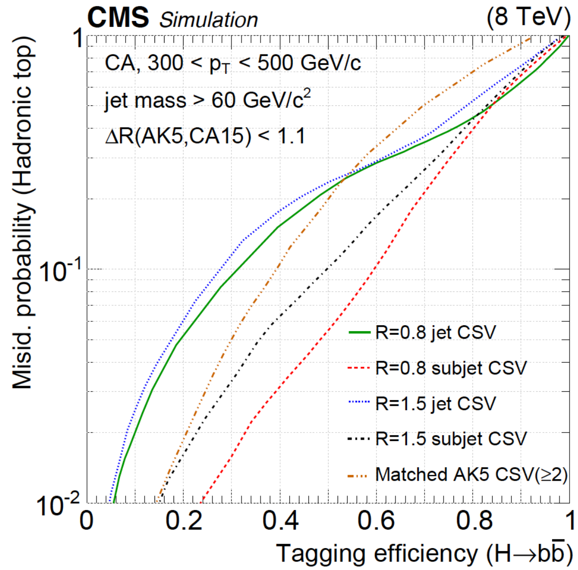
Plan for Run 2 Analyses

- **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
  - …

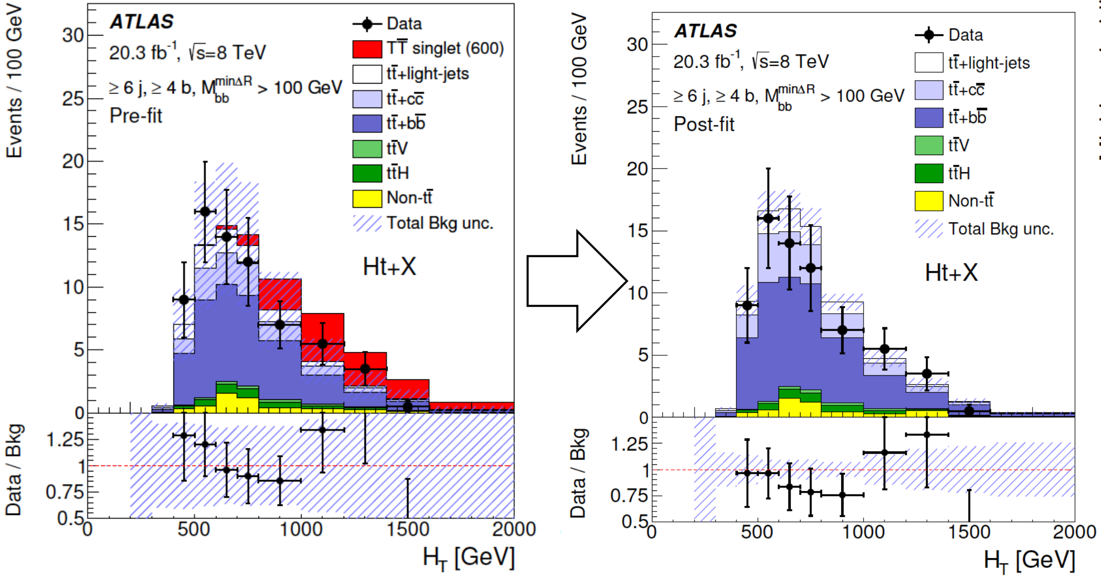
PRD 93 (2016) 012003





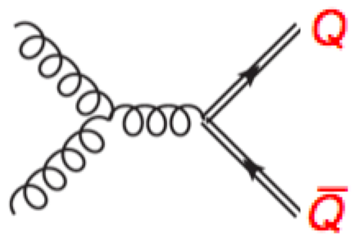


JHEP 1508 (2015) 105

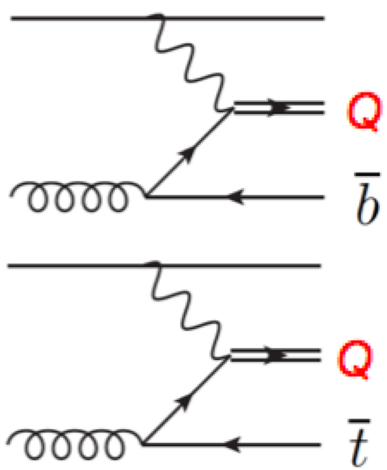


Plan for Run 2 Analyses

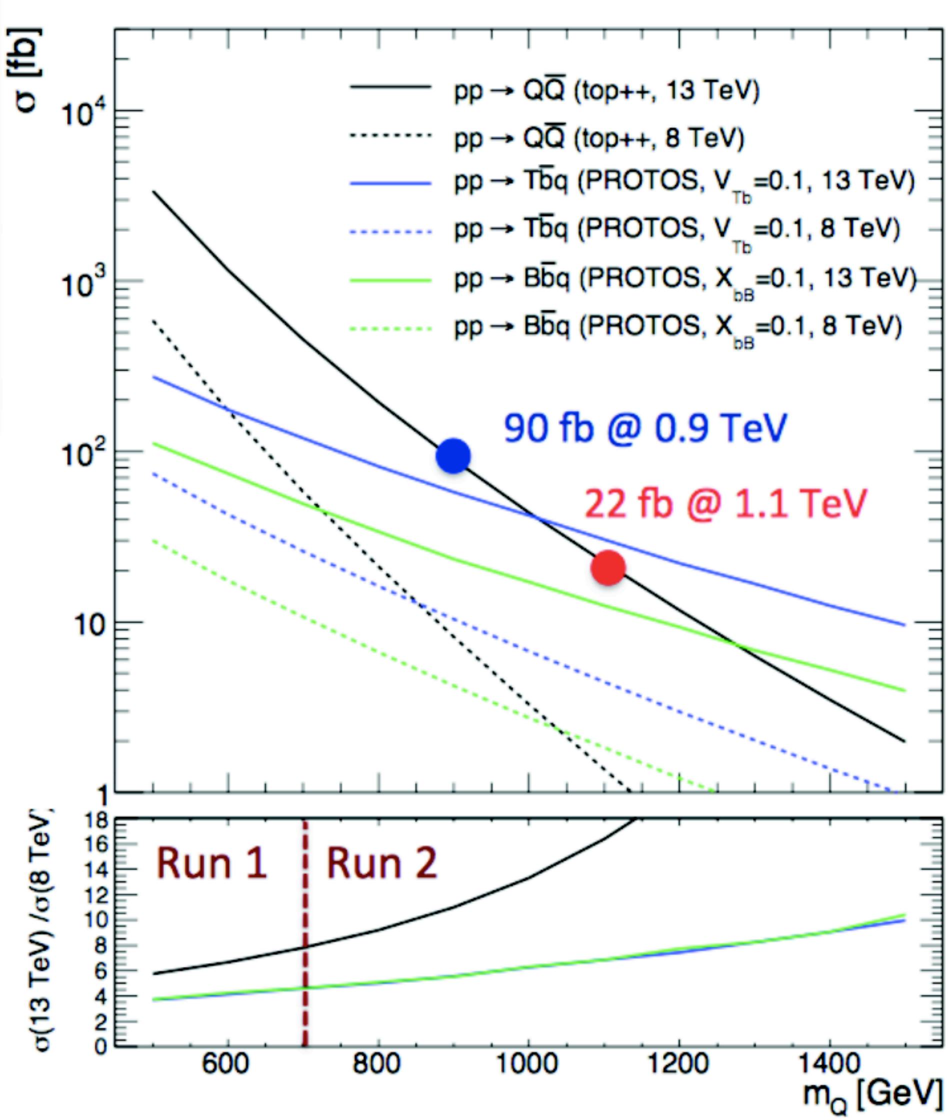
- **Capitalize on Run 1 experience**
- **Fully exploit increased CM energy**
  - Large increase in production cross section at high masses
    - Continue to exploit pair production above 1 TeV
    - Add single production above 1 TeV



Pair production
model independent,
relevant at low mass



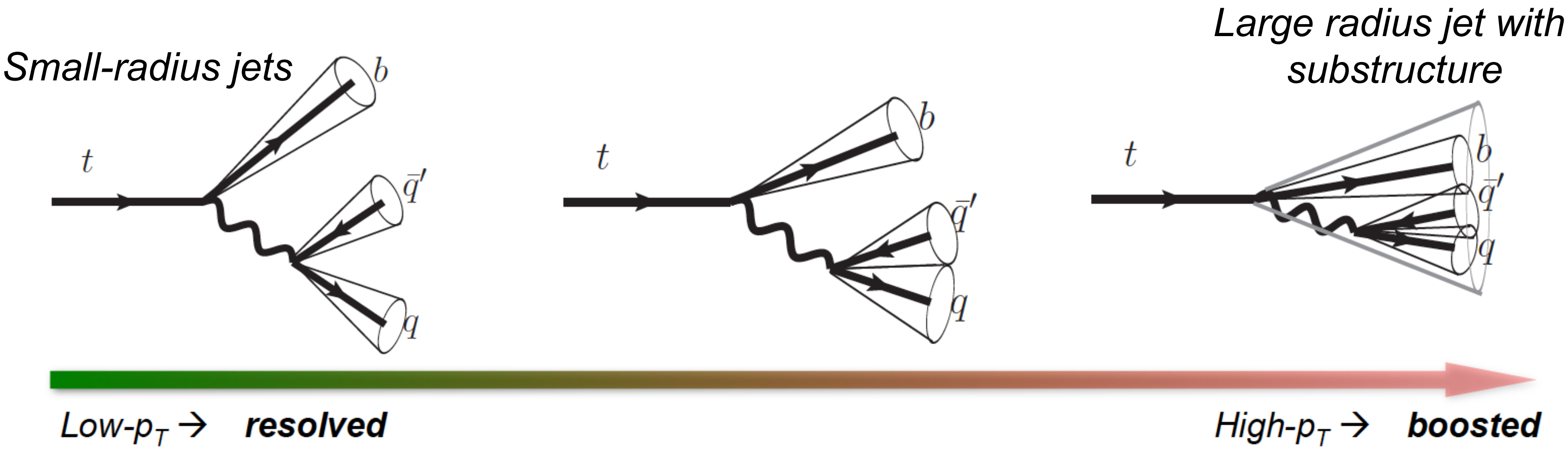
Single production
model dep. coupling,
PDF-favored at high mass



Plan 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!

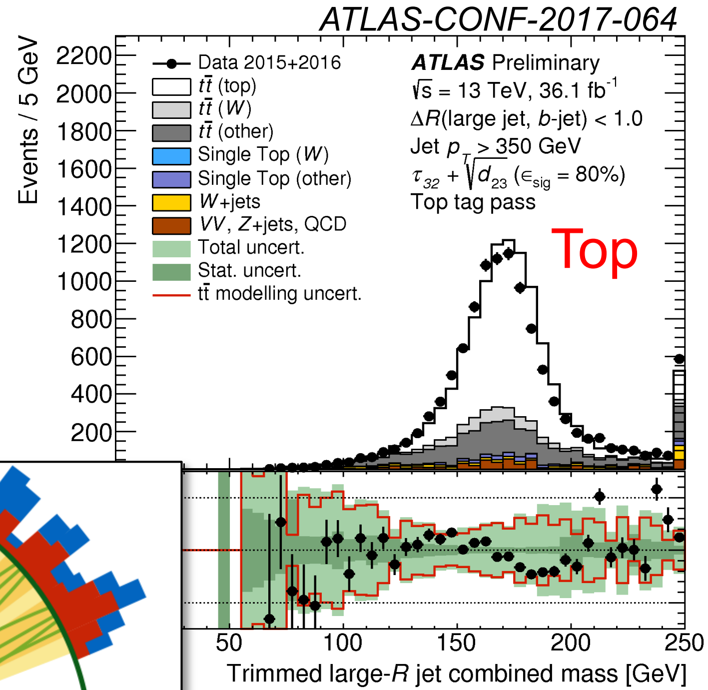


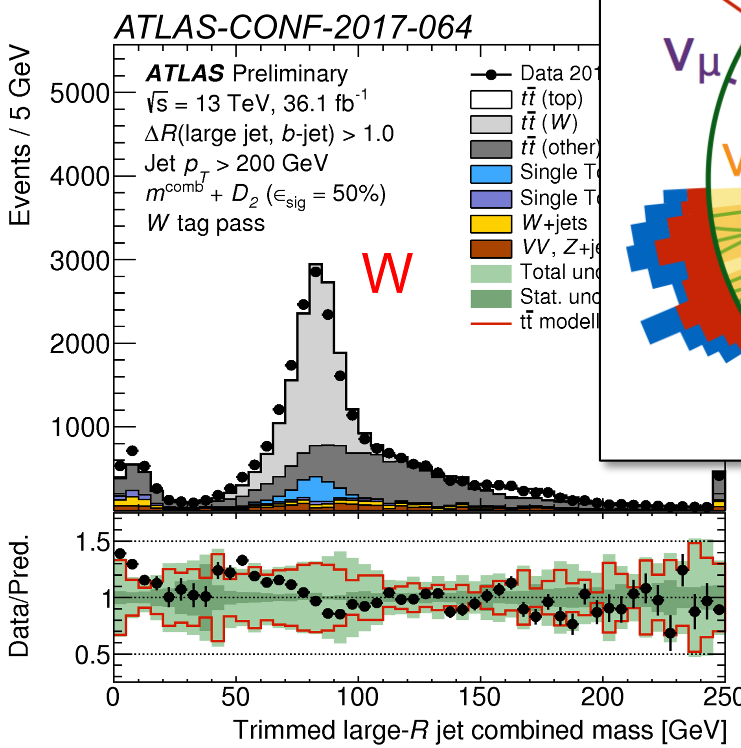
Many well understood tools for tagging of hadronically decaying W, Z, Higgs and top!

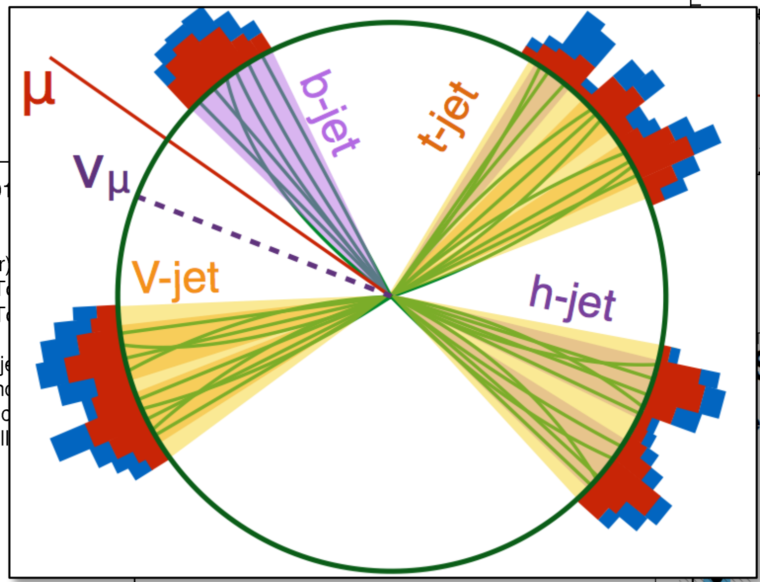
Plan for Run 2 Analyses

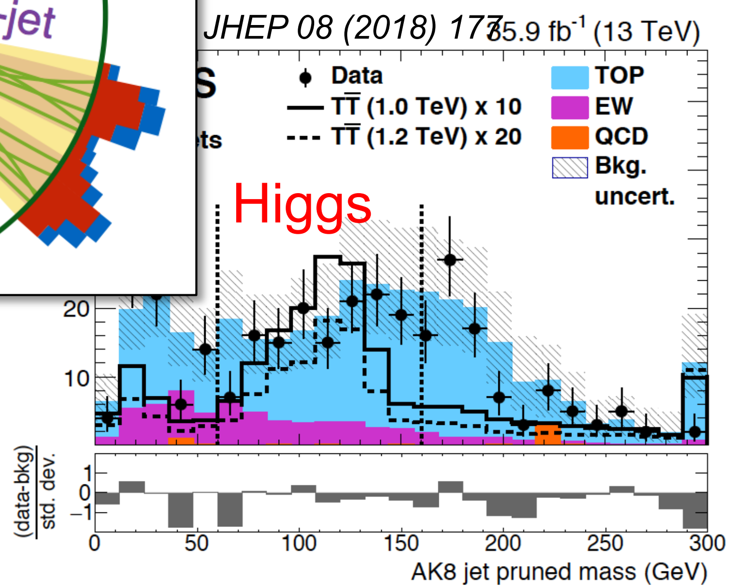
- **Capitalize on Run 1 experience**
- **Fully exploit increased CM energy**
  - Large increase in production cross section at high masses
  - Optimize strategy at high mass

SM resonances are often boosted!









Plan 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: ~36 fb^{-1} recorded

Exceed design inst. lumi of 10^{34} $cm^{-2}s^{-1}$.

Most results shown today: up to 36 fb^{-1} (in analysis)

2017: ~47 fb^{-1} recorded

Record inst. lumi of ~2.1×10^{34} $cm^{-2}s^{-1}$.

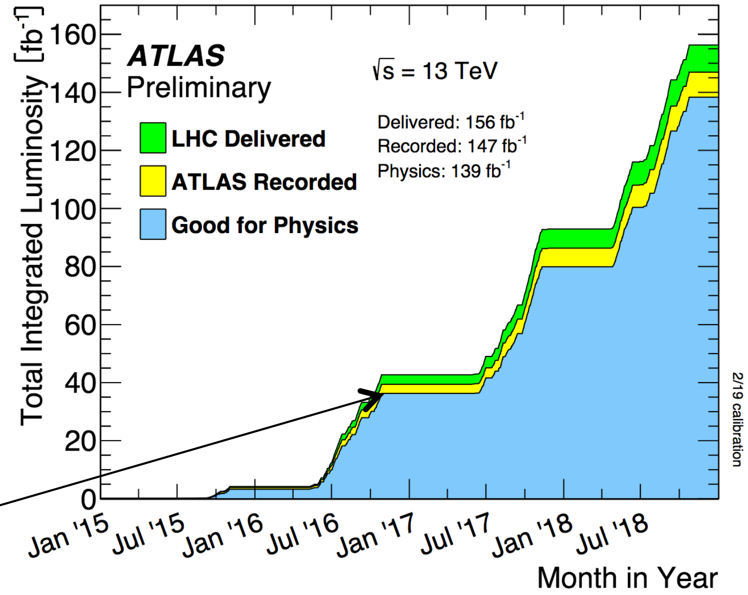
2018: ~61 fb^{-1} recorded

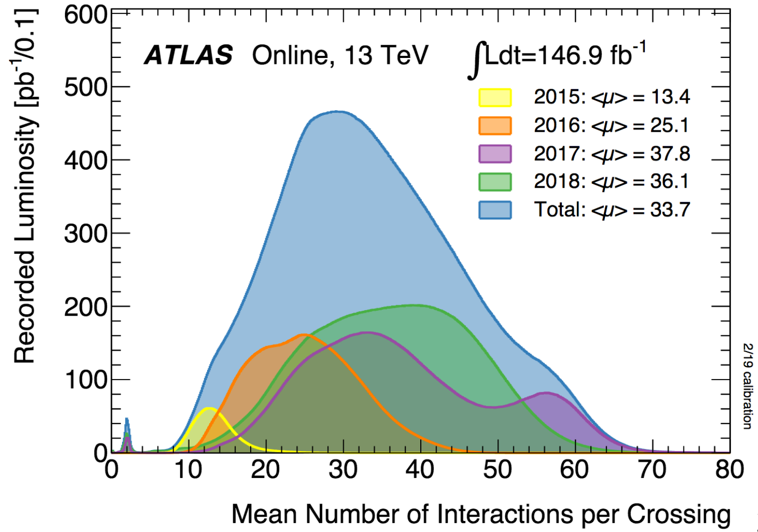
Inst. lumi regularly at ~2×10^{34} $cm^{-2}s^{-1}$.

More sophisticated

Full Run 2: ~139 fb^{-1} (in analysis)

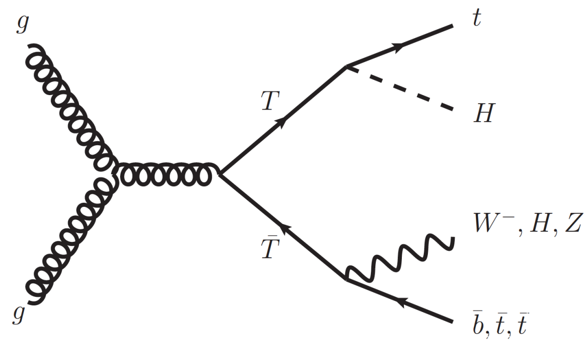
Outstanding performance!



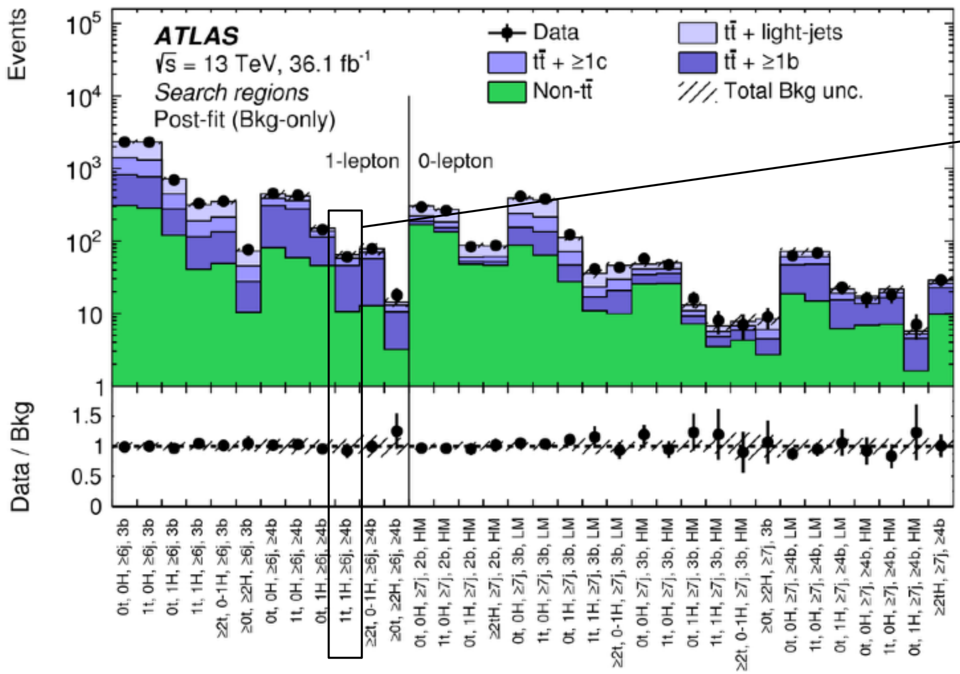


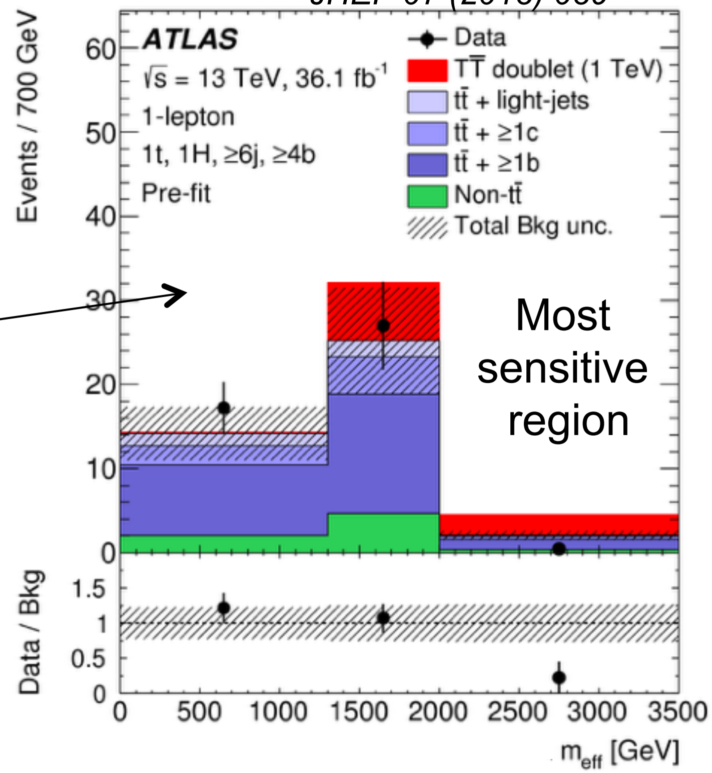
Pair Production: $T\bar{T} \to Ht+X$

- Search targeting high BR(T→Ht), with H→$b\bar{b}$, 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

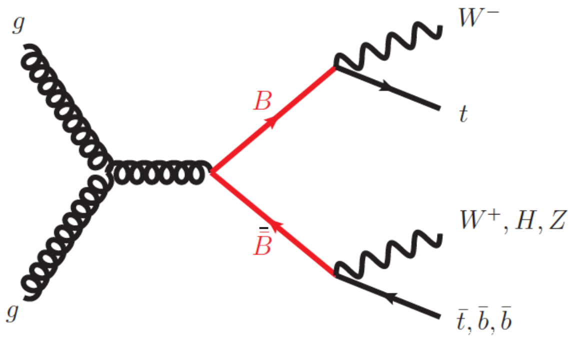




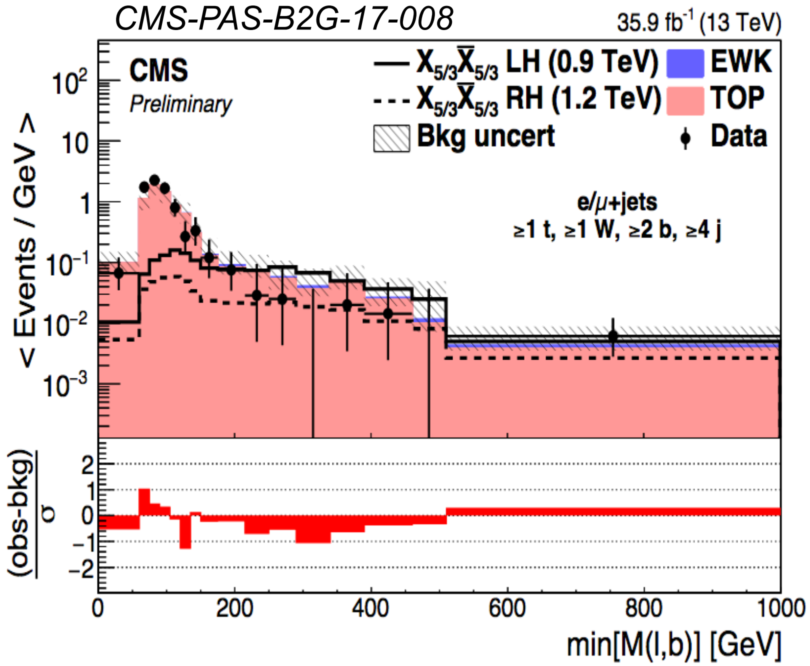
$$m_{\text{eff}} = \sum_{\text{objects}} p_T + E_T^{\text{miss}}$$

Pair Production: $B\bar{B}$, $X_{5/3}\overline{X}_{5/3} \rightarrow WtWt$

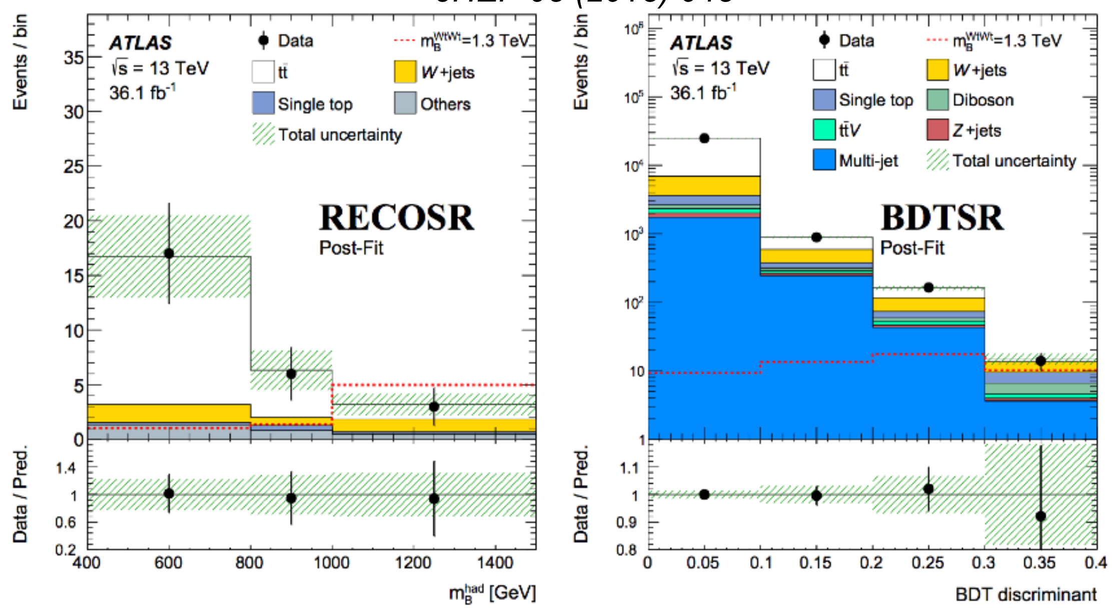
- Searches targeting $B \rightarrow W^{-}t$ or $X_{5/3} \rightarrow W^{+}t$.
- Consider SS dilepton+jets and lepton+jets signatures, both with comparable sensitivity.
- Strategy (lepton+jets):
  - Presel: 1 lepton, high E_T^{miss}, ≥4 jets/≥1 b-tags.
  - Multiple event categories depending on the presence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



CMS-PAS-B2G-17-008

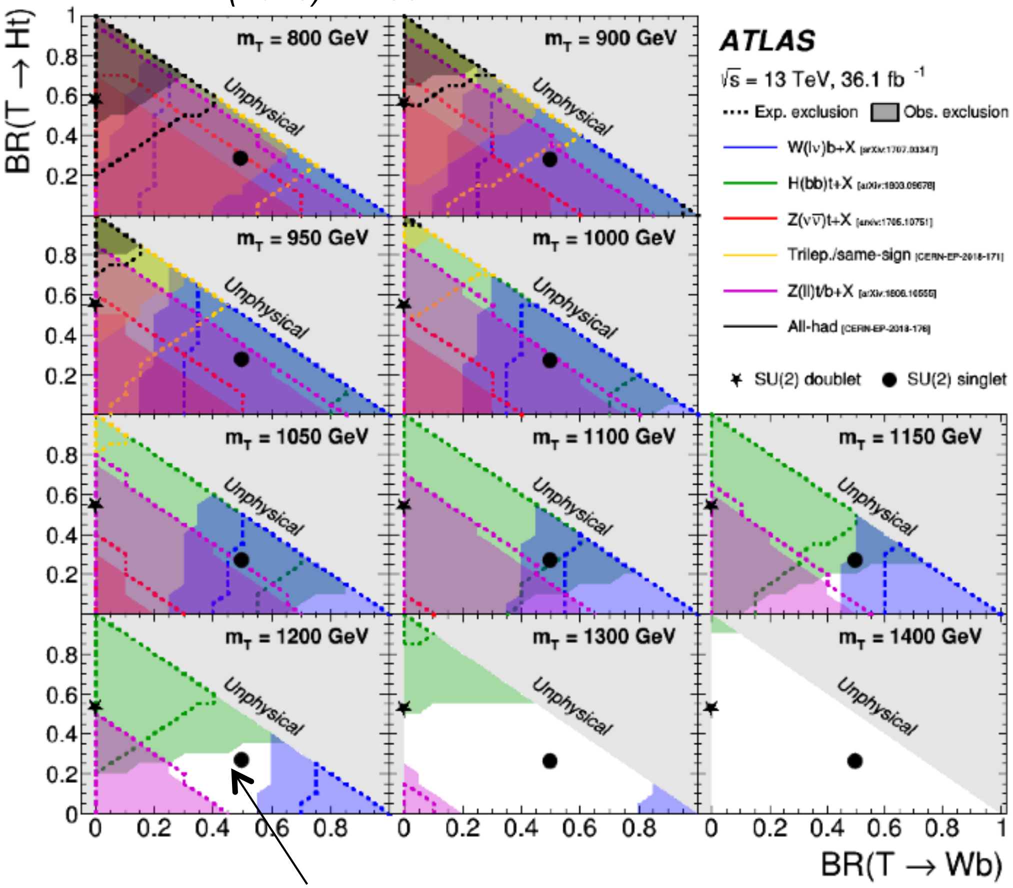


JHEP 08 (2018) 048

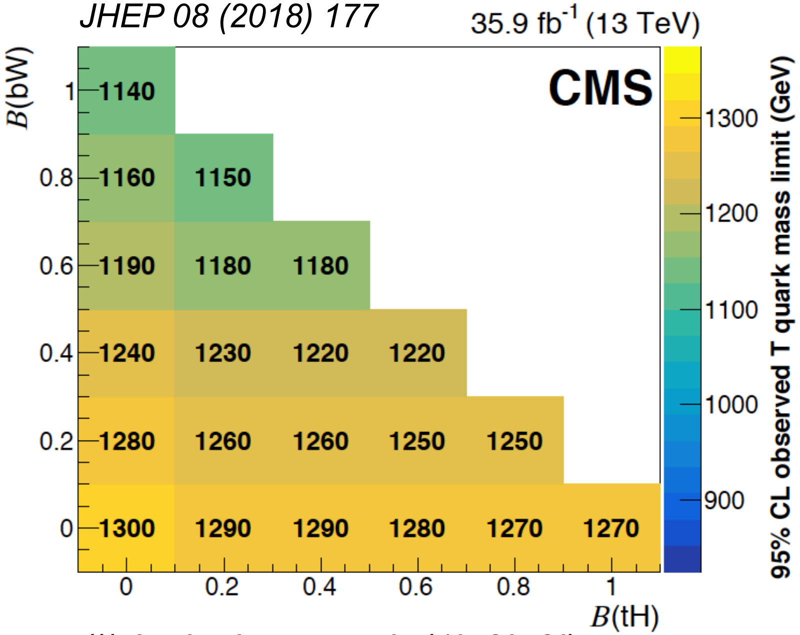


Pair Production Summary: Vector-Like Top

PRL 121 (2018) 211801

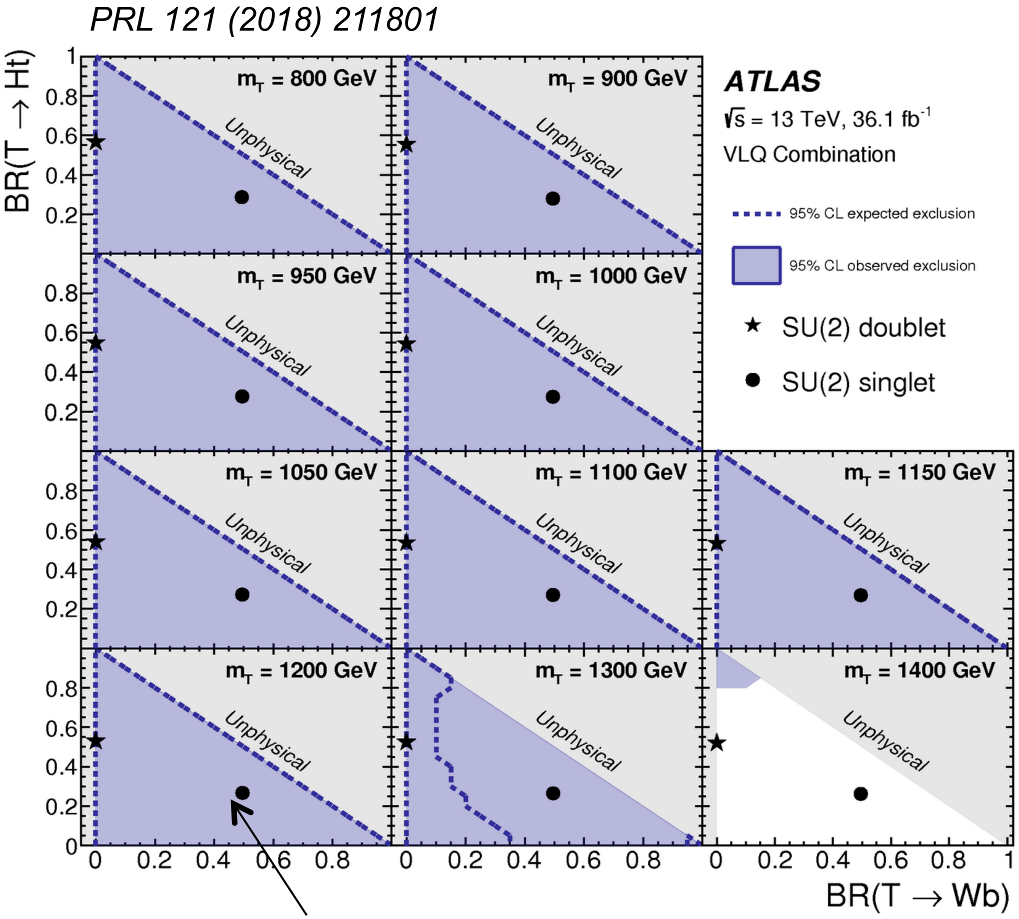


JHEP 08 (2018) 177

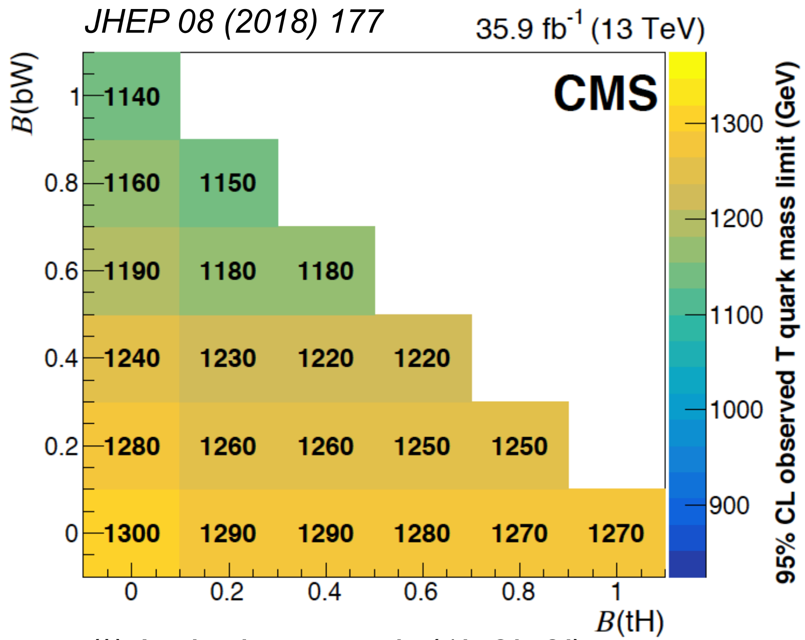


(*) Inclusive search (1l, 2l, 3l)

Pair Production Summary: Vector-Like Top



Significant gain from combination!



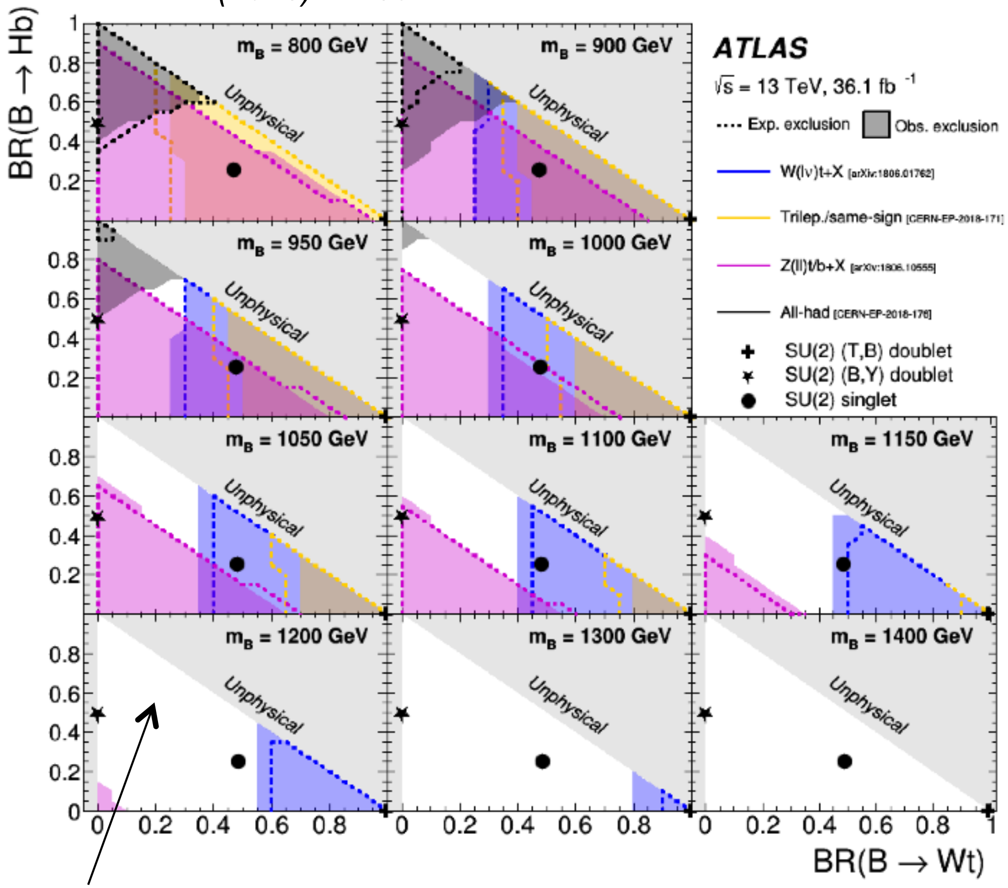
(*) Inclusive search (1l, 2l, 3l)

VLT masses below ~1.31 TeV excluded for any possible combination of BRs

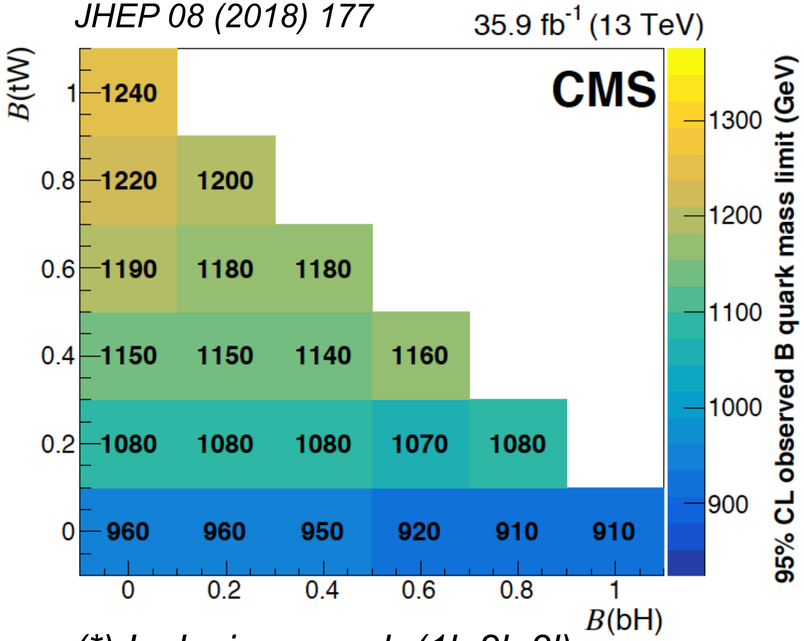
Vector-like T BR Hypothesis	ATLAS 95% CL Limit on m_T (TeV) obs (exp)	CMS 95% CL Limit on m_T (TeV) obs (exp)
100% Wb (chiral, Y)	**1.35** (1.30)	**1.28** (1.30)
T singlet	**1.31** (1.23)	**1.20** (1.16)
T in (T, B) doublet	**1.37** (1.32)	**1.28** (1.24)

Pair Production Summary: Vector-Like Bottom

PRL 121 (2018) 211801



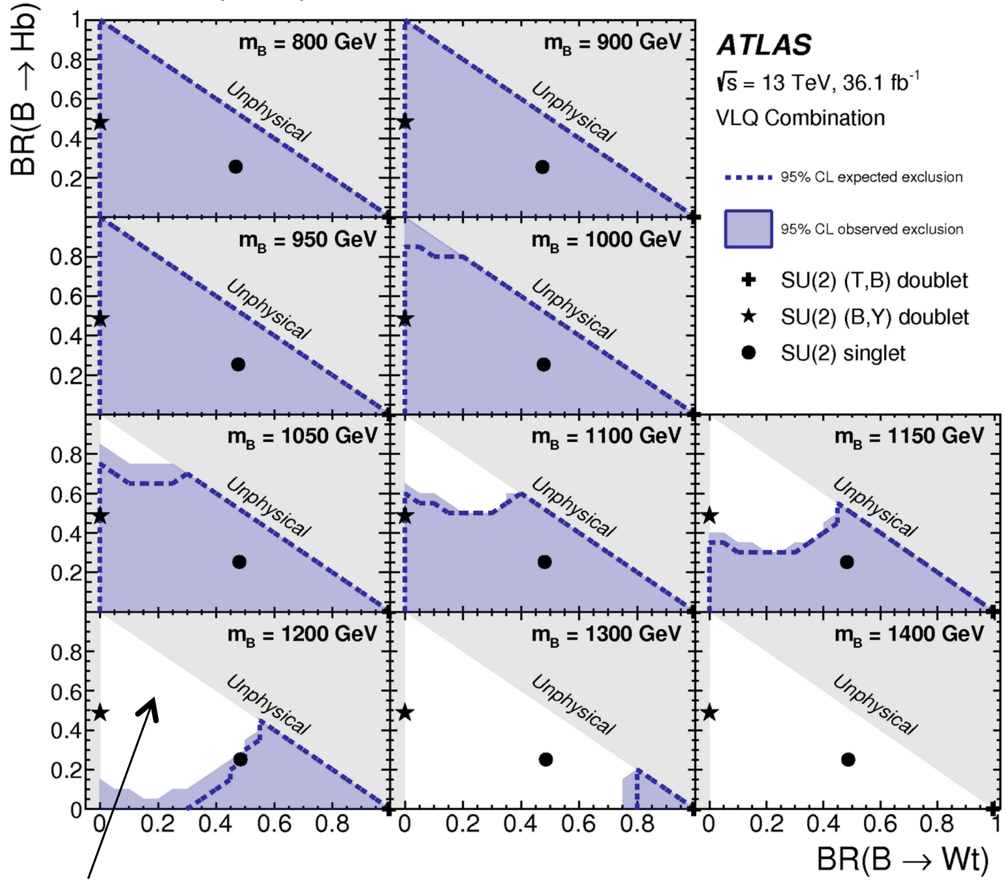
JHEP 08 (2018) 177



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

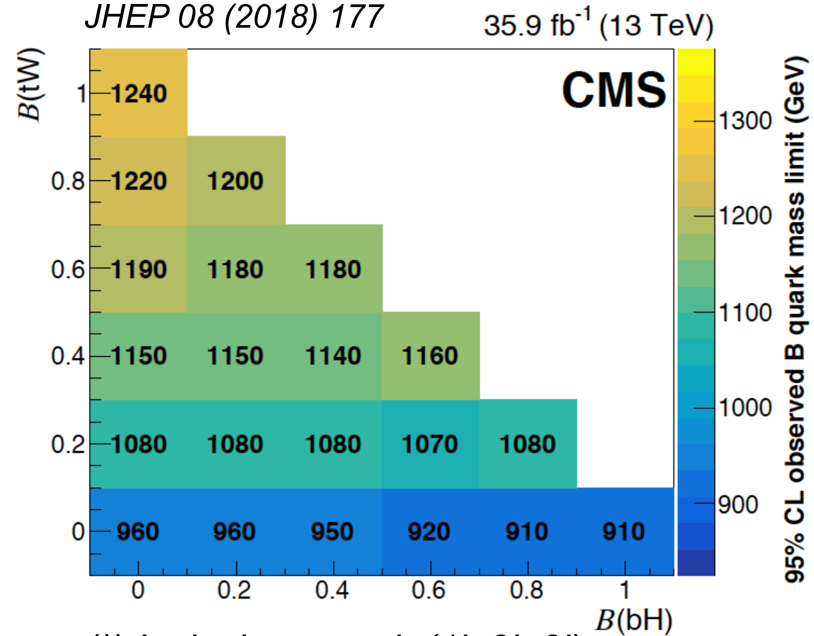
Pair Production Summary: Vector-Like Bottom

PRL 121 (2018) 211801



Need better B→Hb searches!

JHEP 08 (2018) 177



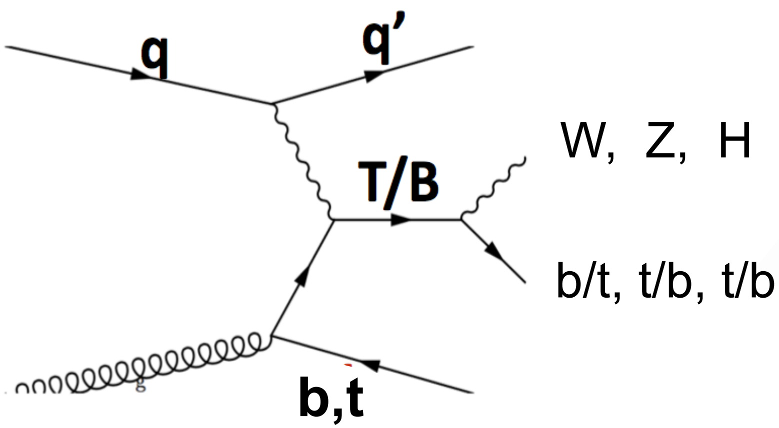
(*) Inclusive search (1l, 2l, 3l)

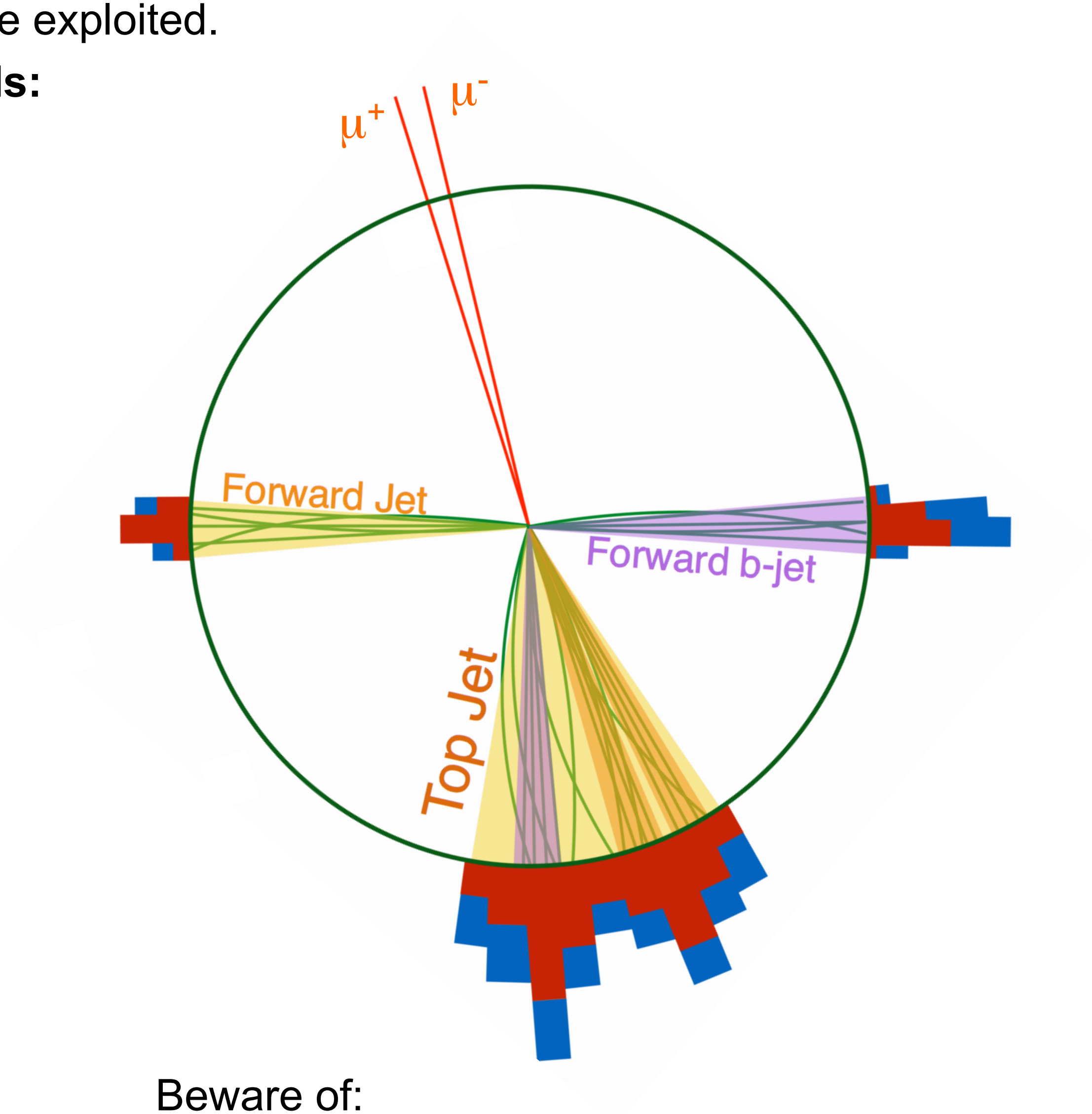
VLB masses below ~1.03 TeV excluded for any possible combination of BRs

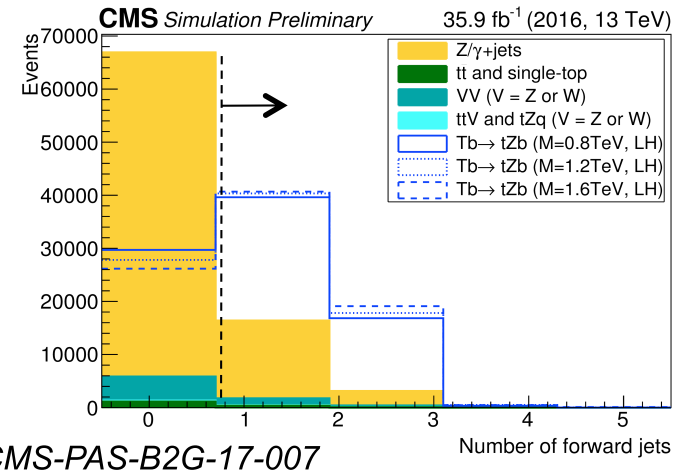
	ATLAS	**CMS**
Vector-like B BR Hypothesis	**95% CL Limit on m_B (TeV) obs (exp)**	**95% CL Limit on m_B (TeV) obs (exp)**
100% Wt (chiral, X)	**1.35** (1.34)	**1.24** (1.24)
B singlet	**1.22** (1.21)	**1.17** (1.13)
B in (B, Y) doublet	**1.14** (1.13)	**0.94** (0.92)

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

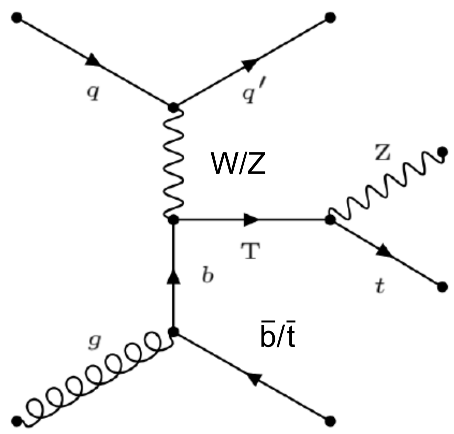
Beware of:

- Signal/background interference
- Helicity propagation in decay

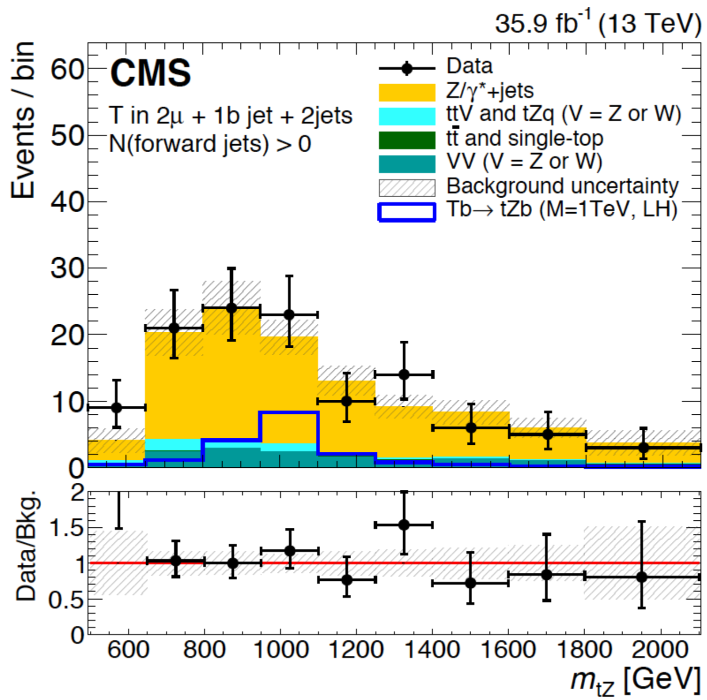
Single Production: T(→Zt)+X

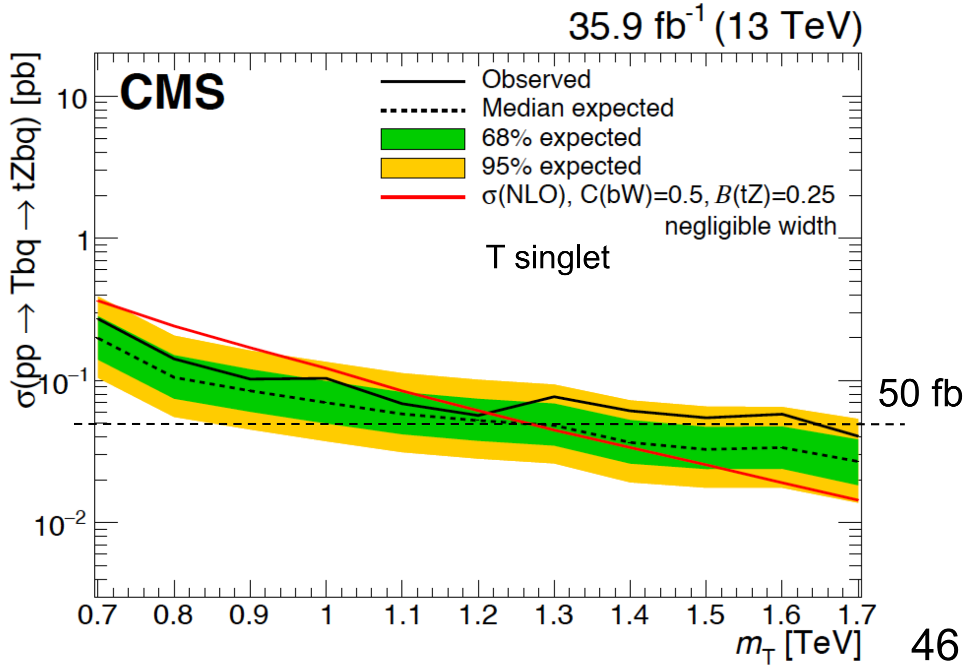
Strategy:

- Presel: Z(→ll)+jets, ≥1 b-tags, small ΔR(ll).
- Top-tagging and W-tagging on R=0.8 anti-k_T jets.
- 10 event categories depending on lepton flavor, top kinematics (fully-merged/semi- merged/resolved) and presence of forward jets.
- Use heavy quark mass built from reconstructed Z-boson and top candidates.
- Main background: Z+jets. Estimated using dedicated control regions.



PLB 781 (2018) 574

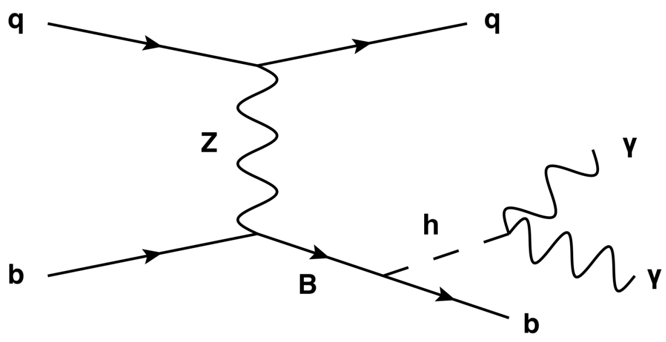


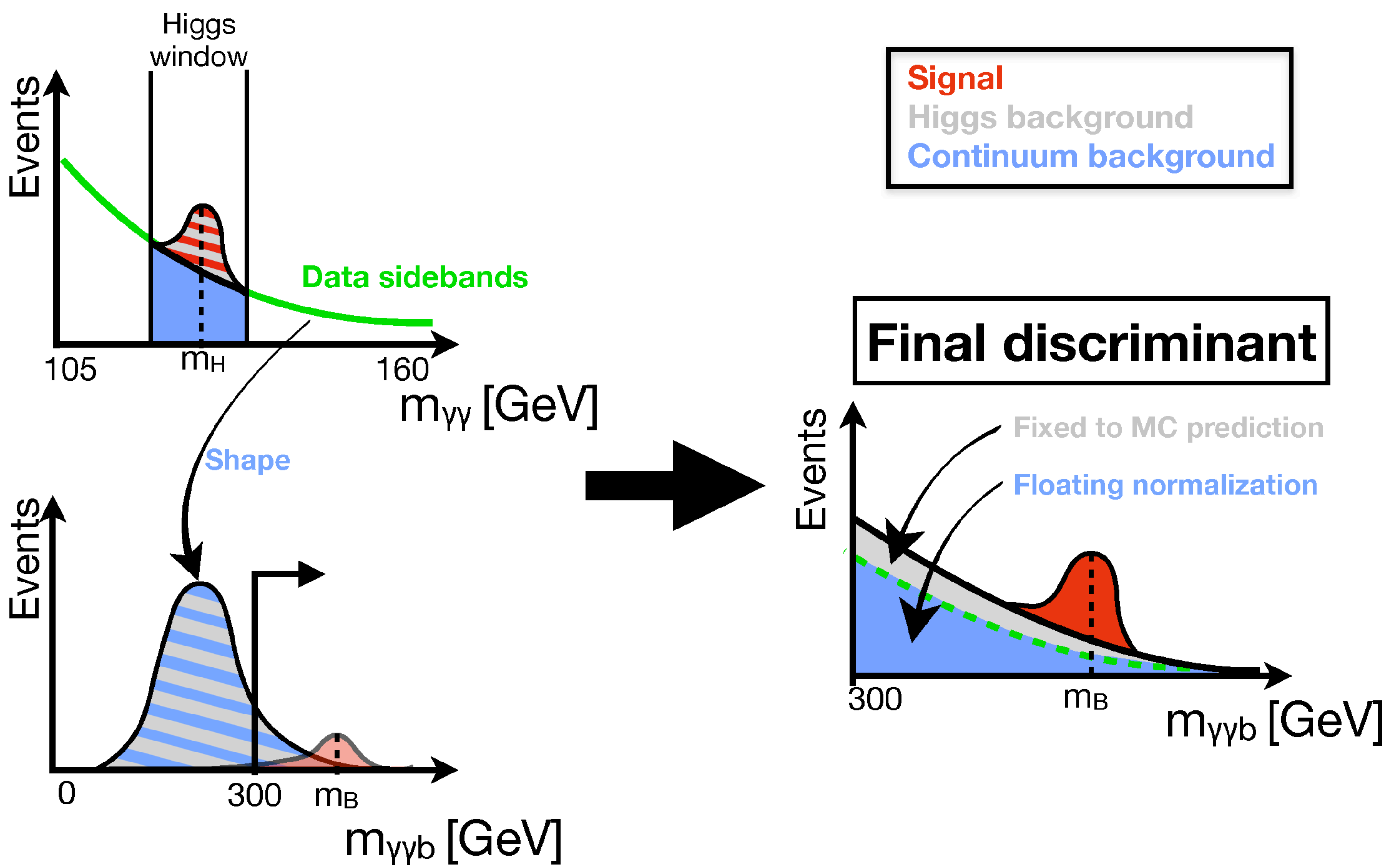


Single Production: B(→Hb)+X

Strategy:

- 2 isolated photons, compatible with $H \to \gamma\gamma$ candidate.
  ≥1 b-tagged jet, ≥1 forward jet
- Non-resonant background shape from data $m_{\gamma\gamma}$ sidebands.
  Normalization from fit to $m_{\gamma\gamma b}$ spectrum.
  SM Higgs background from MC.

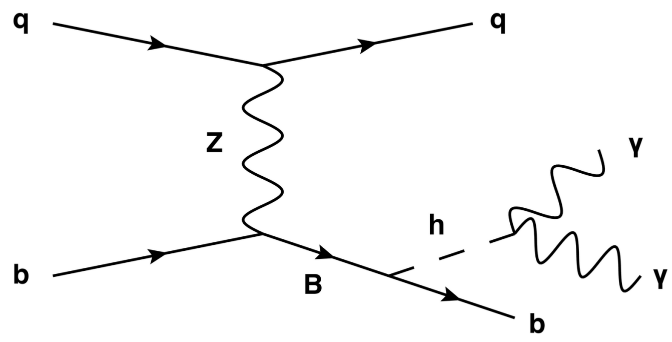




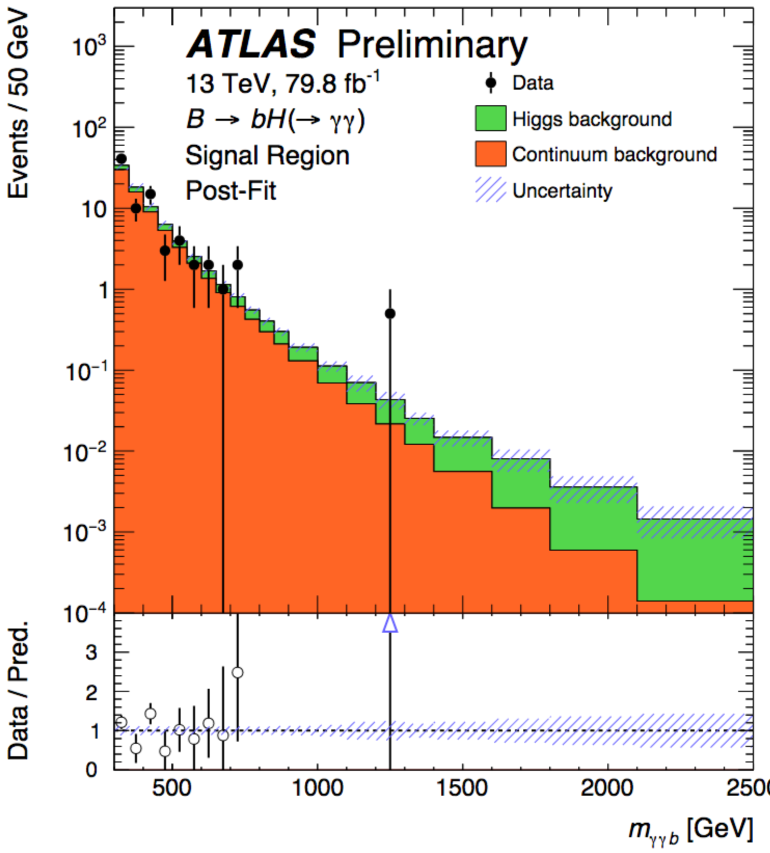
Single Production: B(→Hb)+X

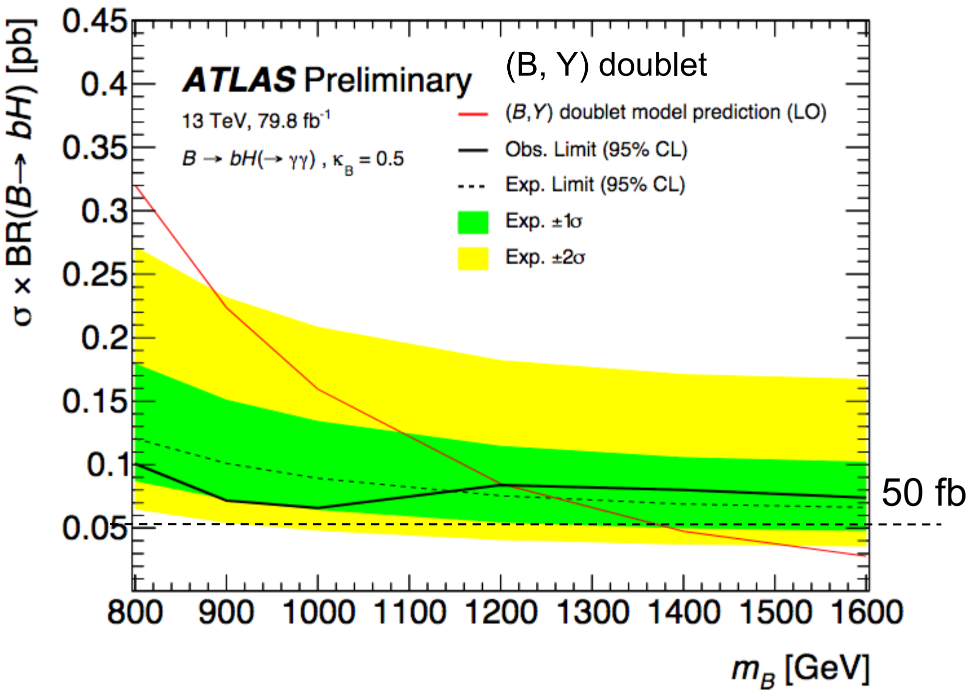
Strategy:

- 2 isolated photons, compatible with H→$\gamma\gamma$ candidate.
  ≥1 b-tagged jet, ≥1 forward jet
- Non-resonant background shape from data $m_{\gamma\gamma}$ sidebands.
  Normalization from fit to $m_{\gamma\gamma b}$ spectrum.
  SM Higgs background from MC.



ATLAS-CONF-2018-024

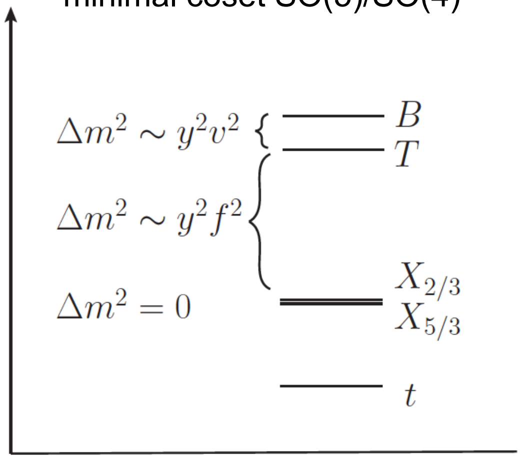


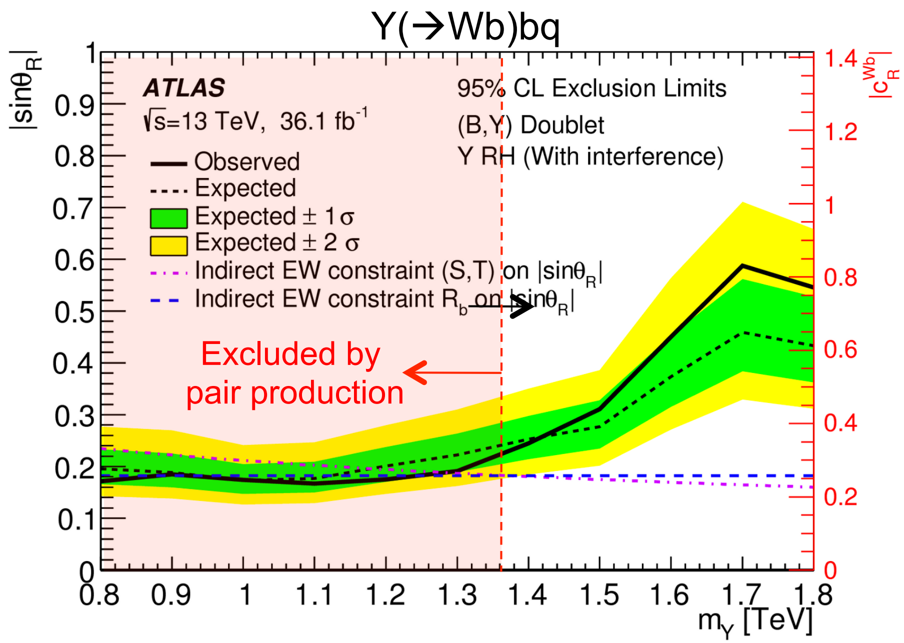


Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- **Improved interpretation of searches**
  - Combination of pair and single production
  - Increased use of simplified models
  - Take into account effect of extra resonances in more realistic benchmarks

Typical spectrum of the 4-plet in minimal coset SO(5)/SO(4)





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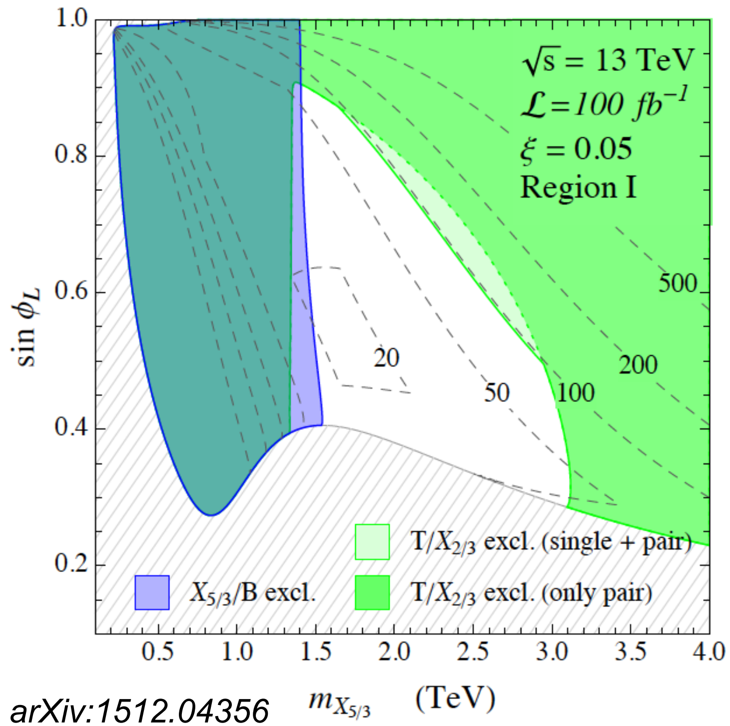


arXiv:1512.04356

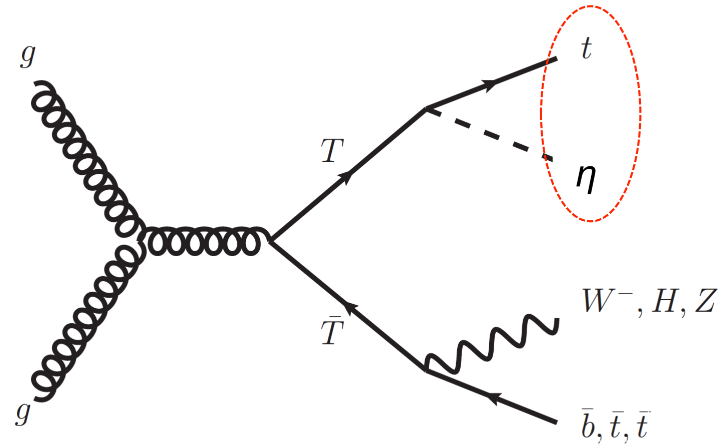
Plan for Run 2 Analyses

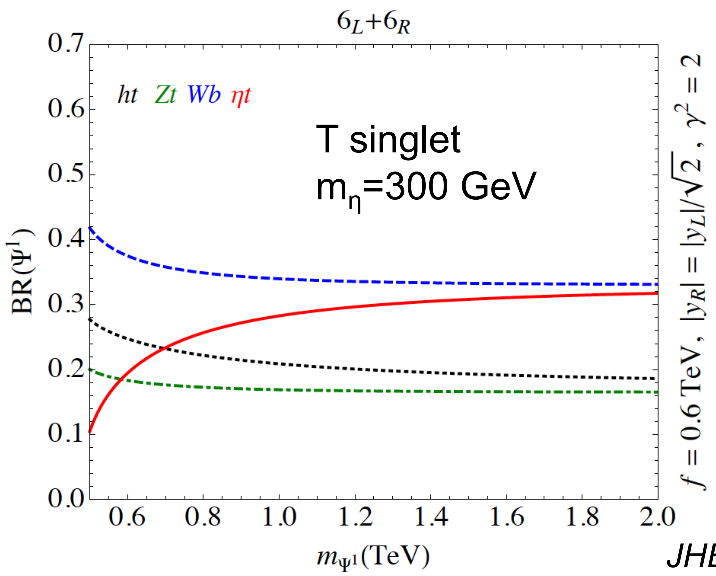
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don't miss a signal!**
  - Non-standard decays

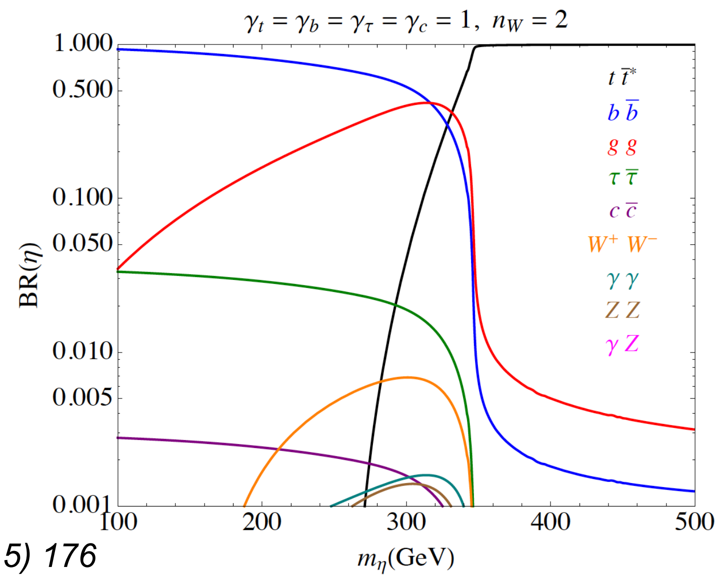
    BR(Q→Wq)+BR(Q→Zq)+BR(Q→Hq)<1

    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. **$T\bar{T}$→6-top**!







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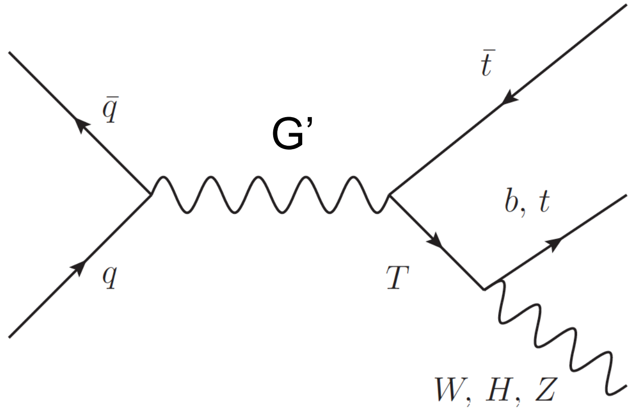
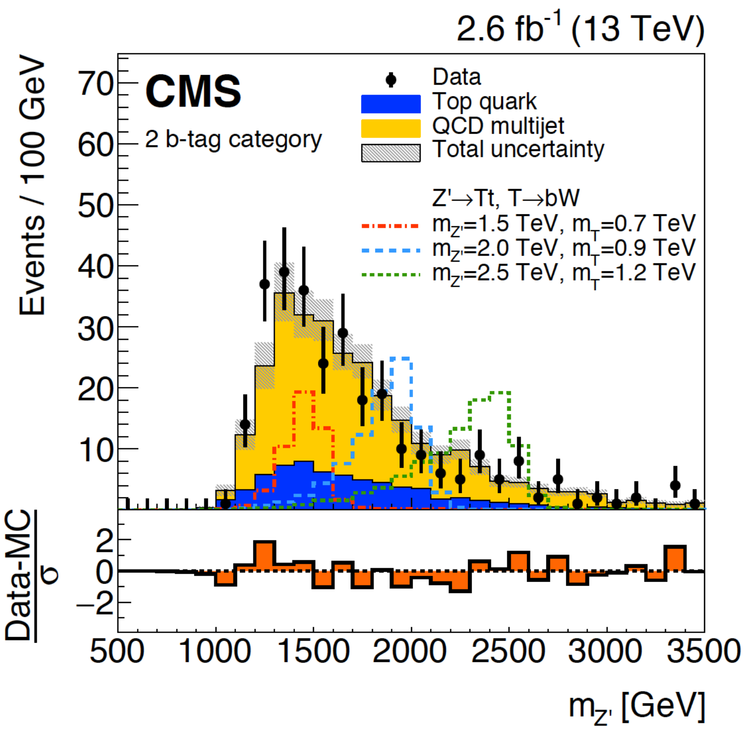
Plan for Run 2 Analyses

- 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 production

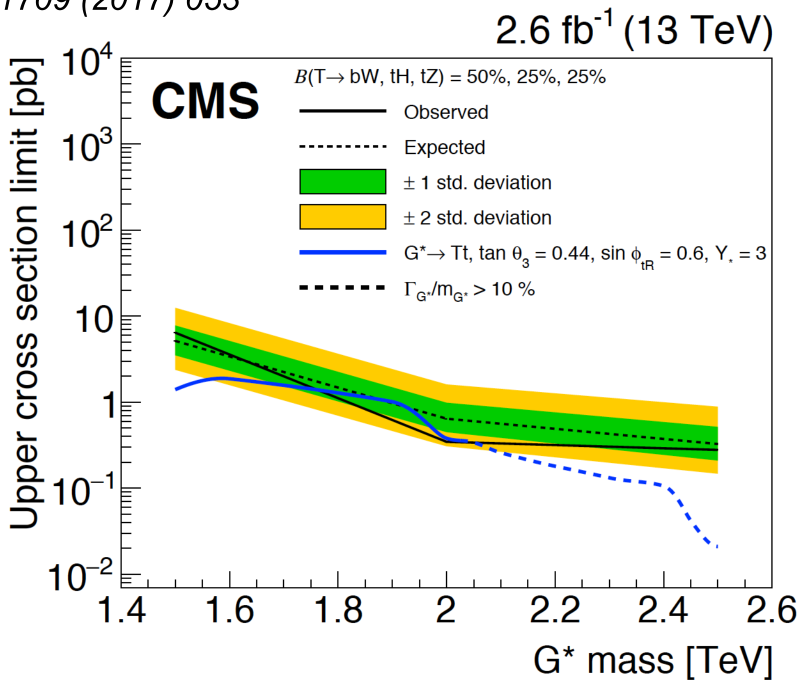
    E.g. via heavy gluon: G'→T$\overline{\text{T}}$ ($m_{G^*} \geq 2m_T$),

    G'→Tt ($m_T + m_t < m_{G^*} < 2m_T$)



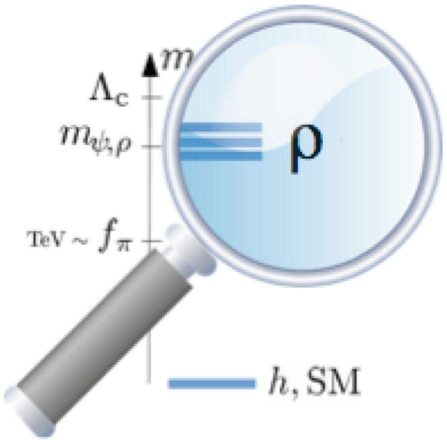


JHEP 1709 (2017) 053

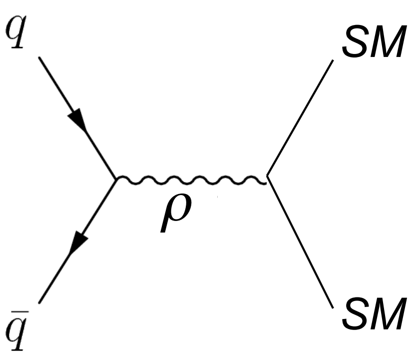


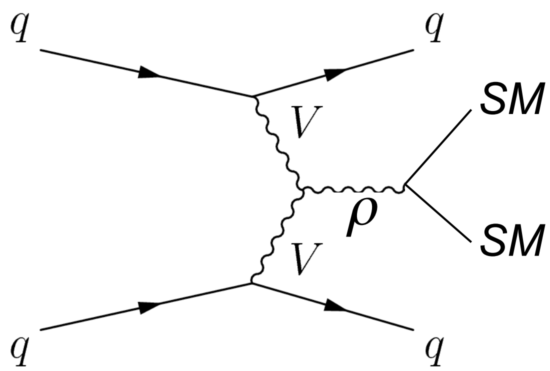
Bosonic Resonances

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

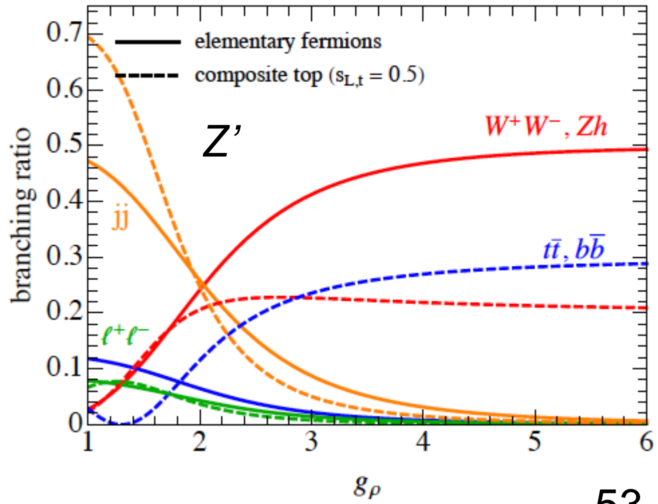




- Preferred signatures:
  - Diboson resonances
  - 3rd generation quark resonances ($t\bar{t}$, $b\bar{b}$, $t\bar{b}$)
  - Dilepton/dijet resonances
- In non-minimal CH models can have additional pNGBs besides the SM Higgs ➔ extra heavy scalars!

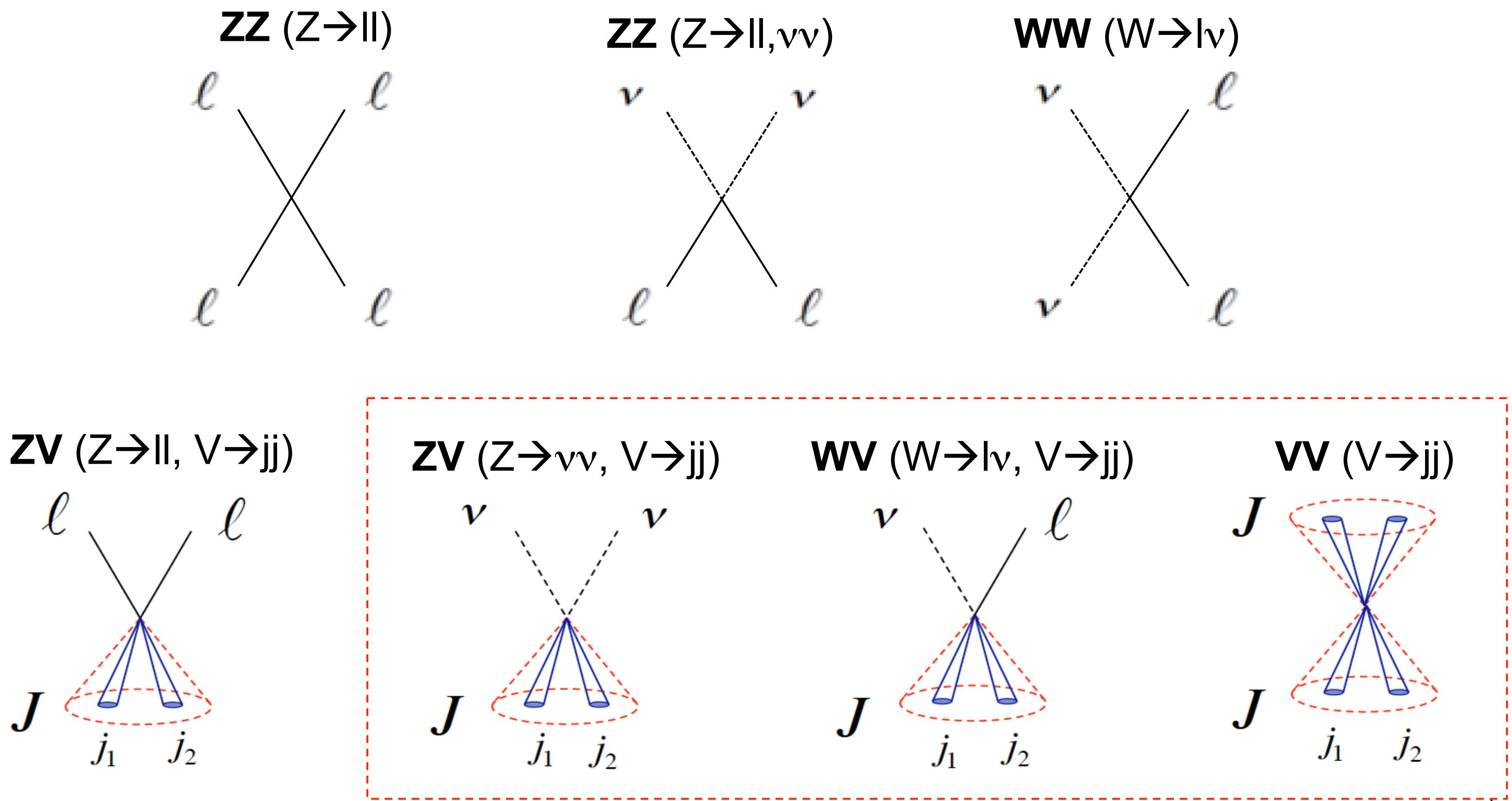
See e.g. arXiv:1507.02283

arXiv:1507.07557

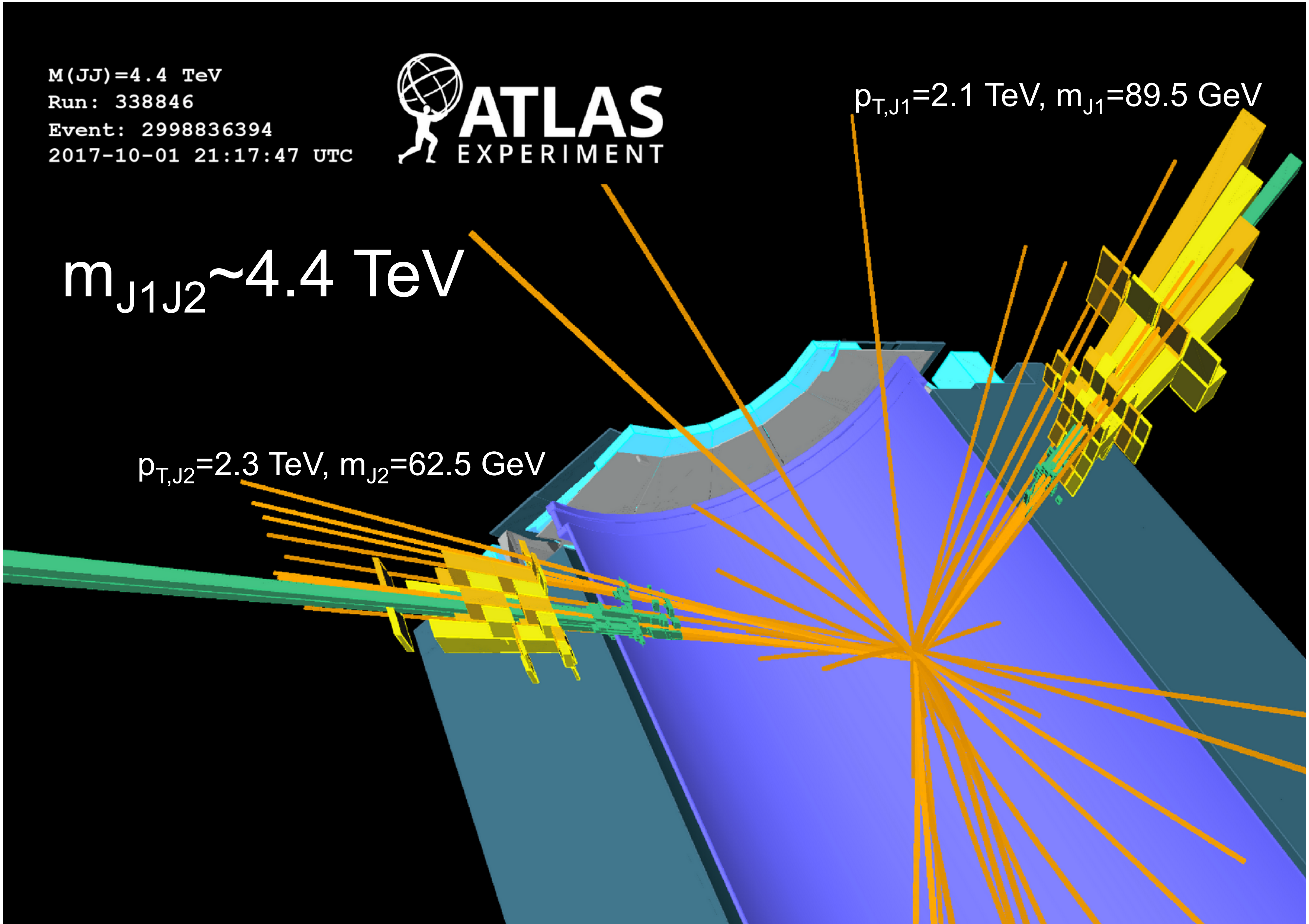


$\rho \rightarrow VV$, VH (V=W,Z) Searches

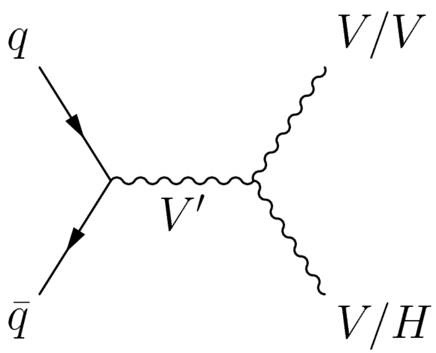
Many final state signatures explored!

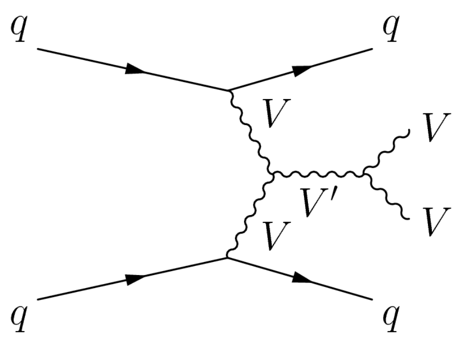


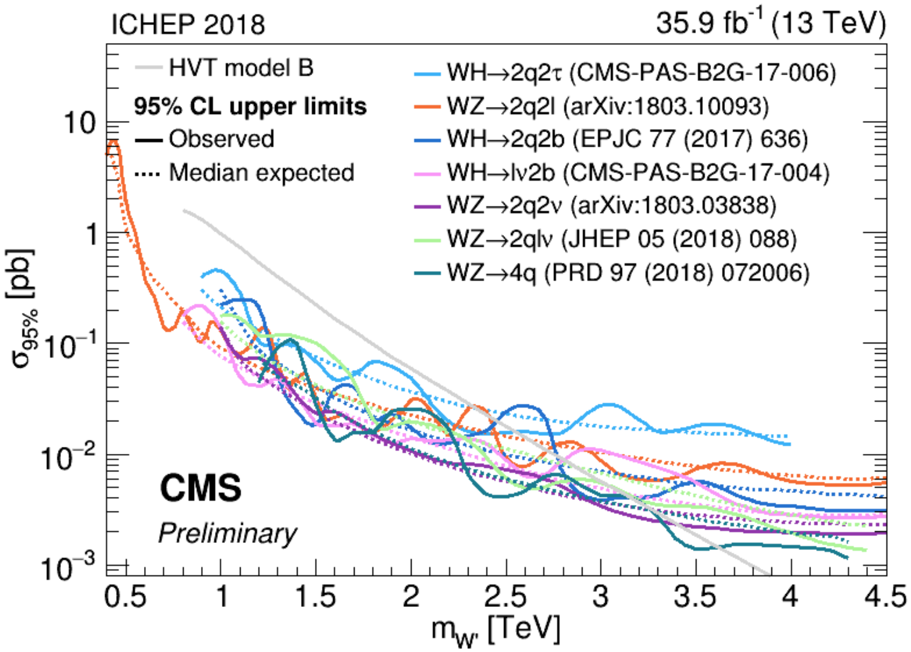
- Considering both resolved and boosted topologies.
- Most sensitive signatures at high mass: use highest BR decay W/Z decay modes.
- Also probe VH with $H \rightarrow b\bar{b}$, $\tau\tau$.

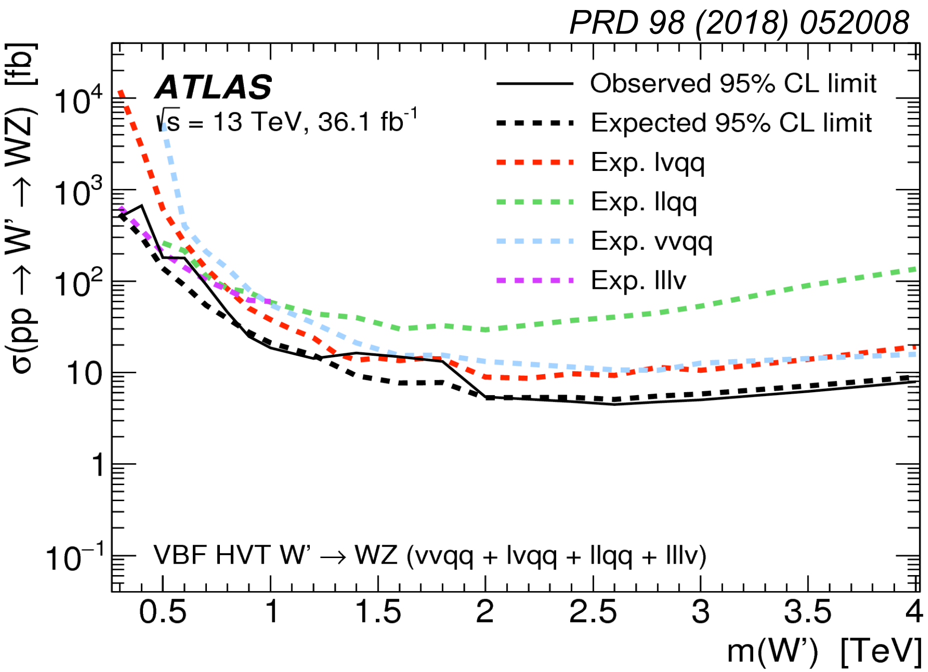

M(JJ)=4.4 TeV
Run: 338846
Event: 2998836394
2017-10-01 21:17:47 UTC
ATLAS
EXPERIMENT
m_{J1J2}~4.4 TeV
$p_{T,J1}$=2.1 TeV, m_{J1}=89.5 GeV
$p_{T,J2}$=2.3 TeV, m_{J2}=62.5 GeV

ρ→VV', VH (V=W,Z) Searches



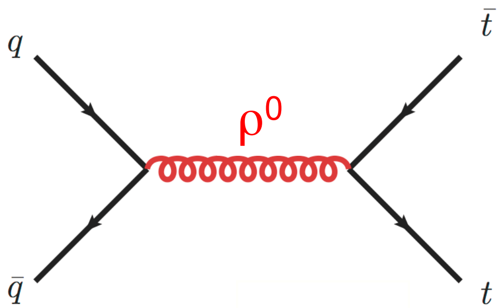






Reaching cross sections down to ~1-10 fb for $M_{V'}$>2 TeV!

$\rho^0 \to t\bar{t}$ Searches



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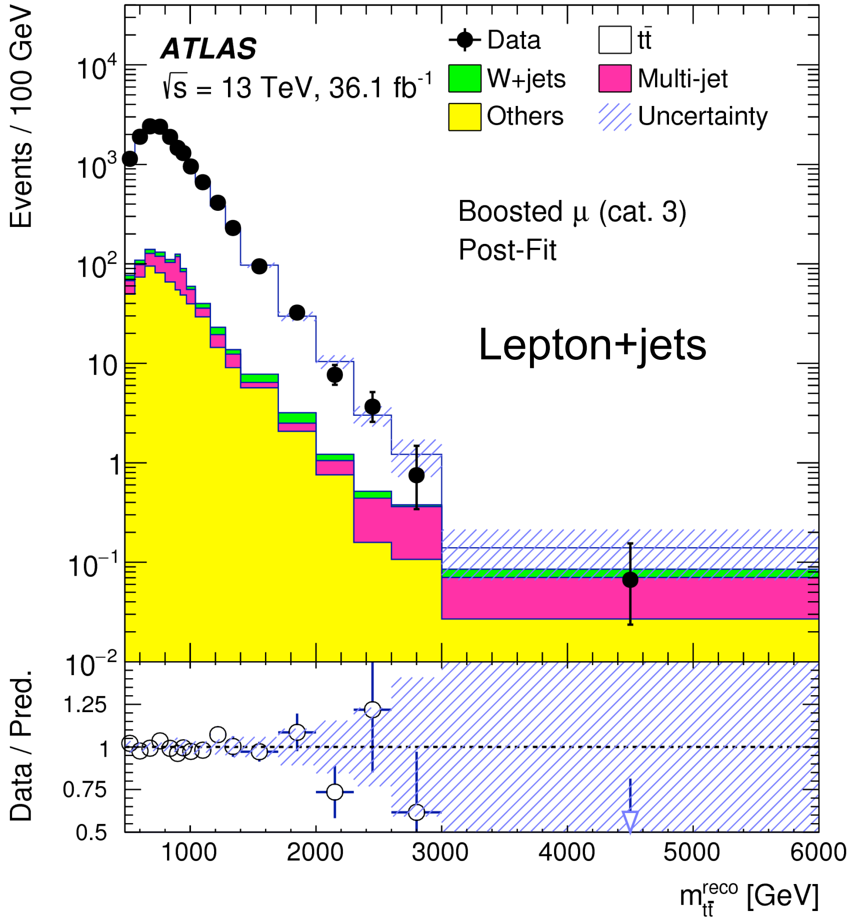
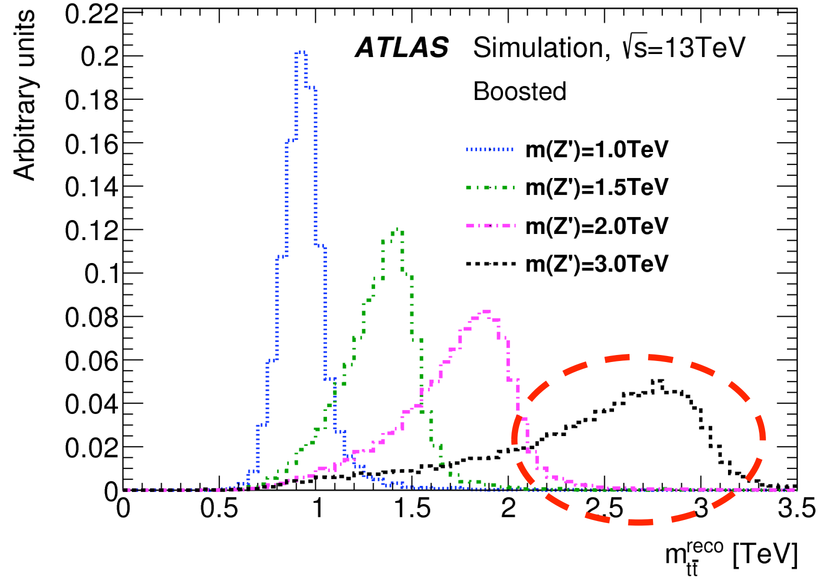
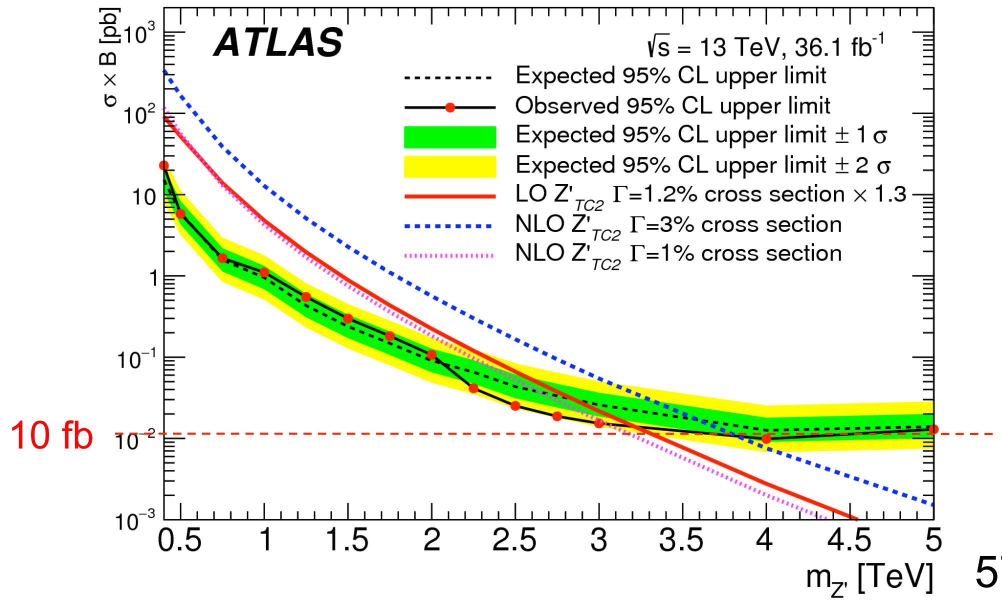
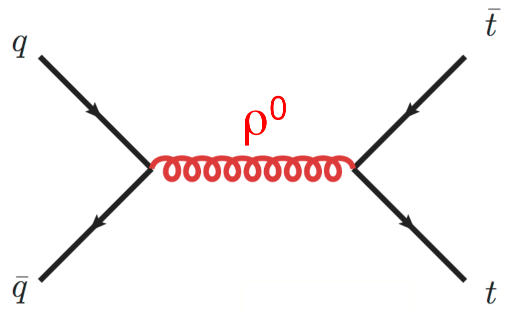


A "narrow" resonance: Γ/M=3%

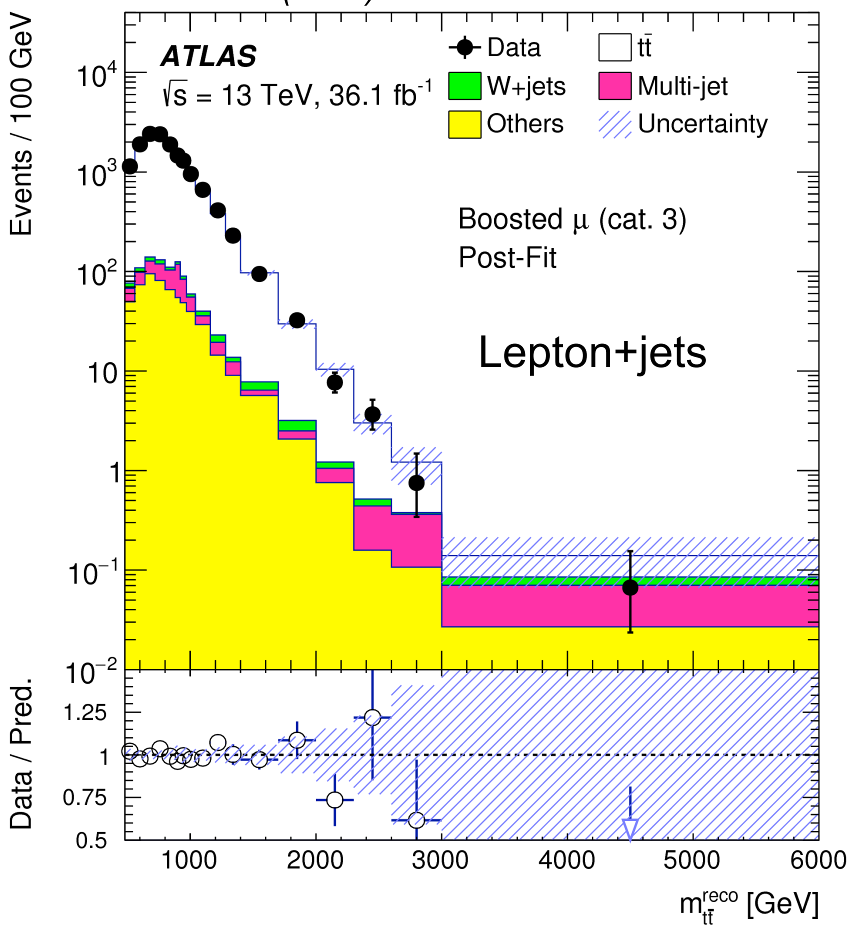




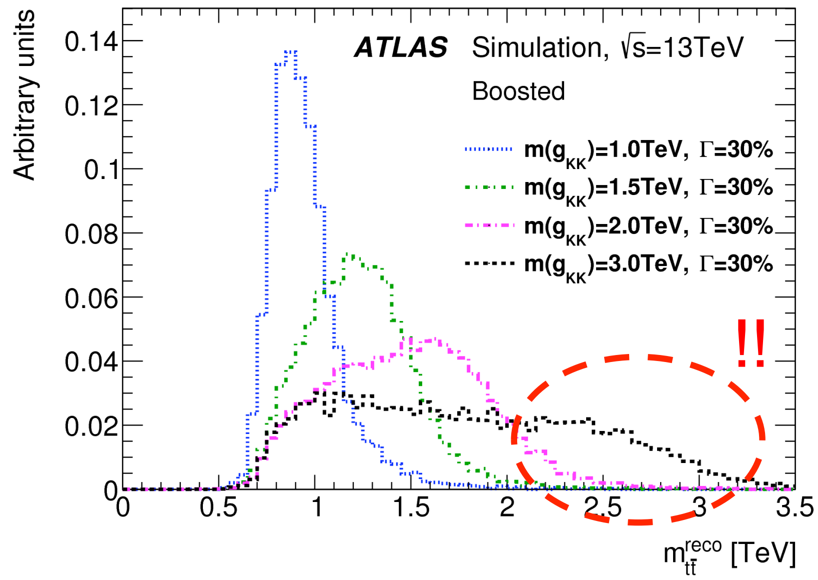
$\rho^0 \to t\bar{t}$ Searches

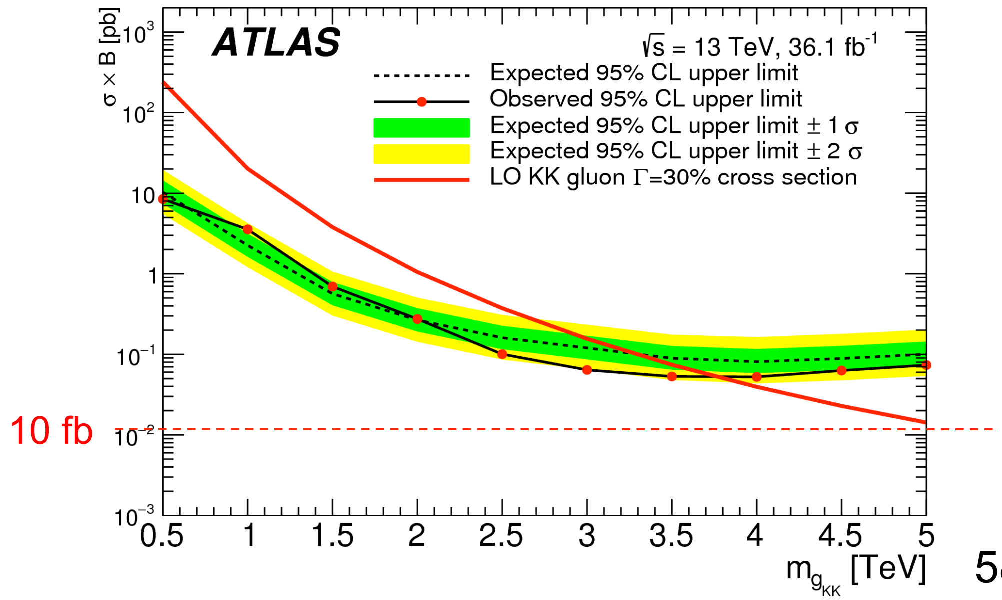


EPJC 78 (2018) 565



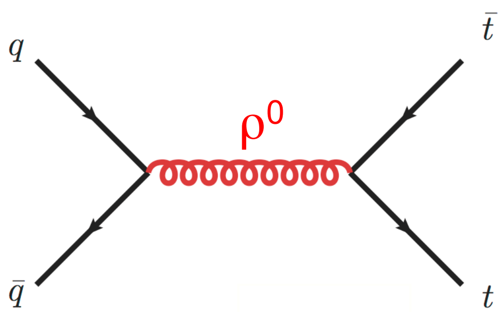
A “wide” resonance: Γ/M=30%



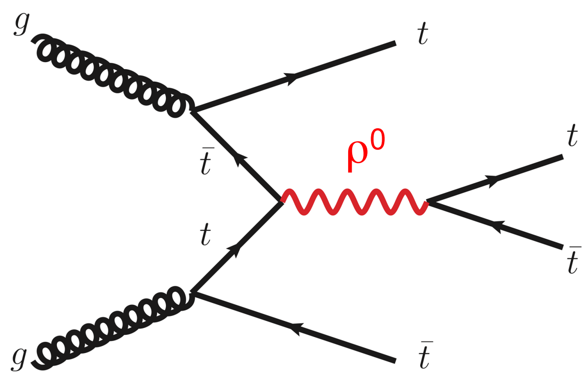


Associated $t\bar{t}\rho$ (and $b\bar{b}\rho$) Production

If only top quark has a high degree of compositeness:



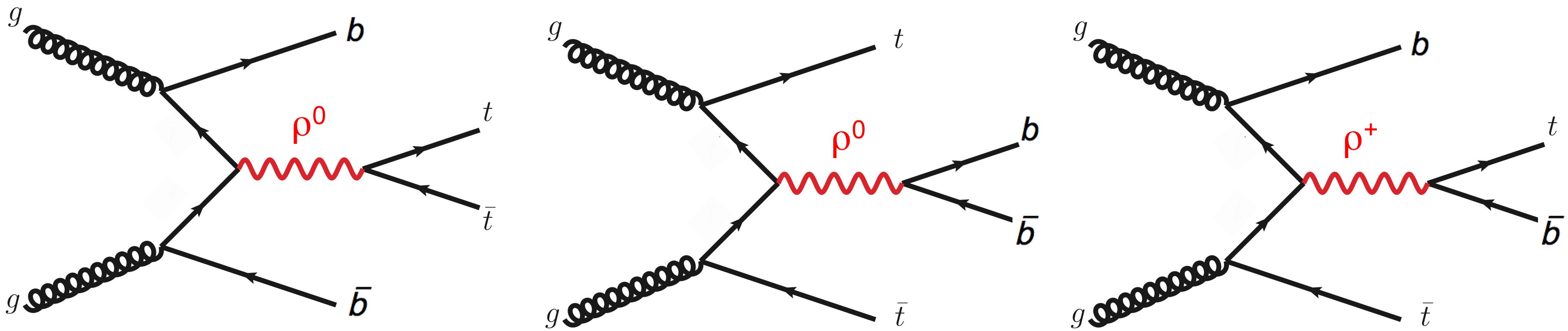
Suppressed



4-top final states

More promising!

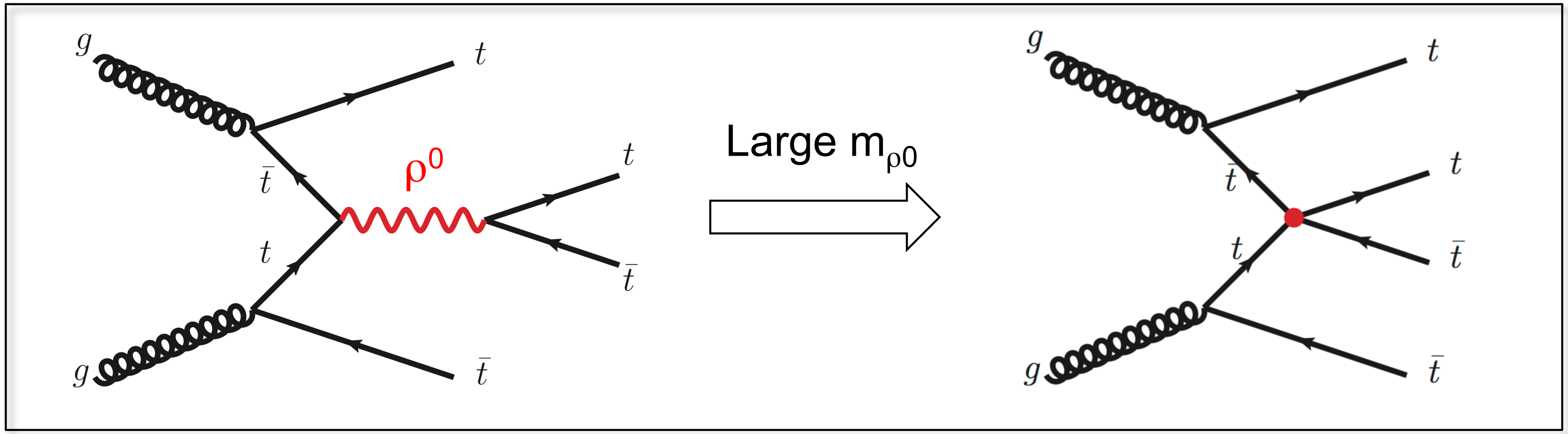
Also possible:



$t\bar{t}b\bar{b}$ final states

BSM 4-top Production

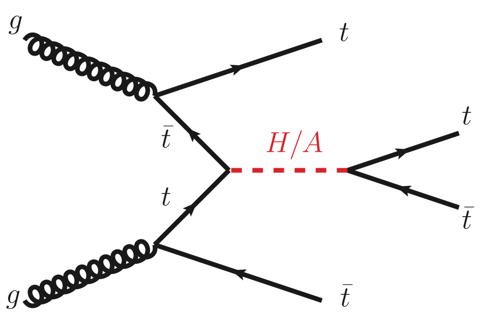
4-top production in Composite Higgs models:



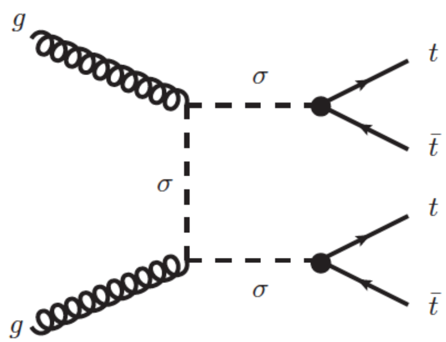
Effective Lagrangian:
Only t_R (partially) composite

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

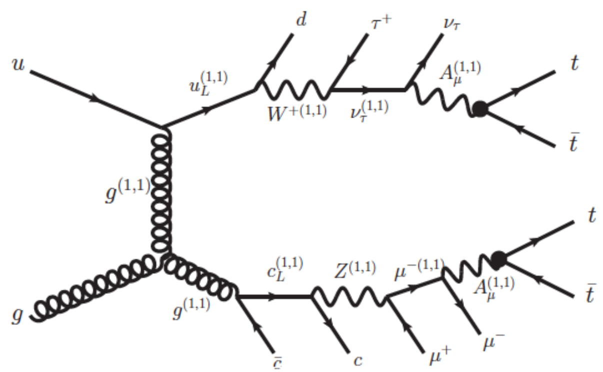
Other BSM scenarios that can lead to 4-top(+X) production:



Heavy Higgs bosons

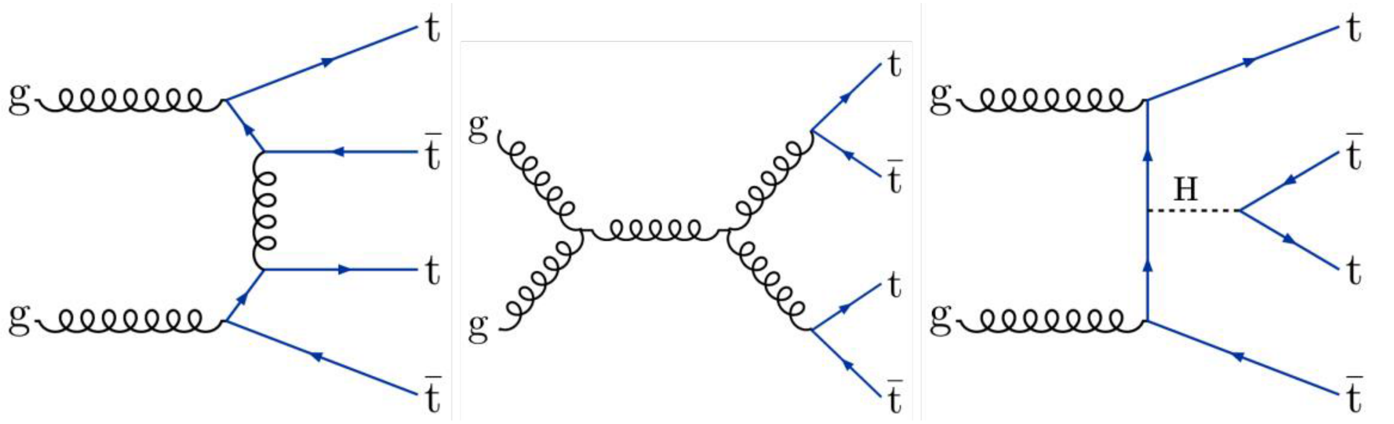


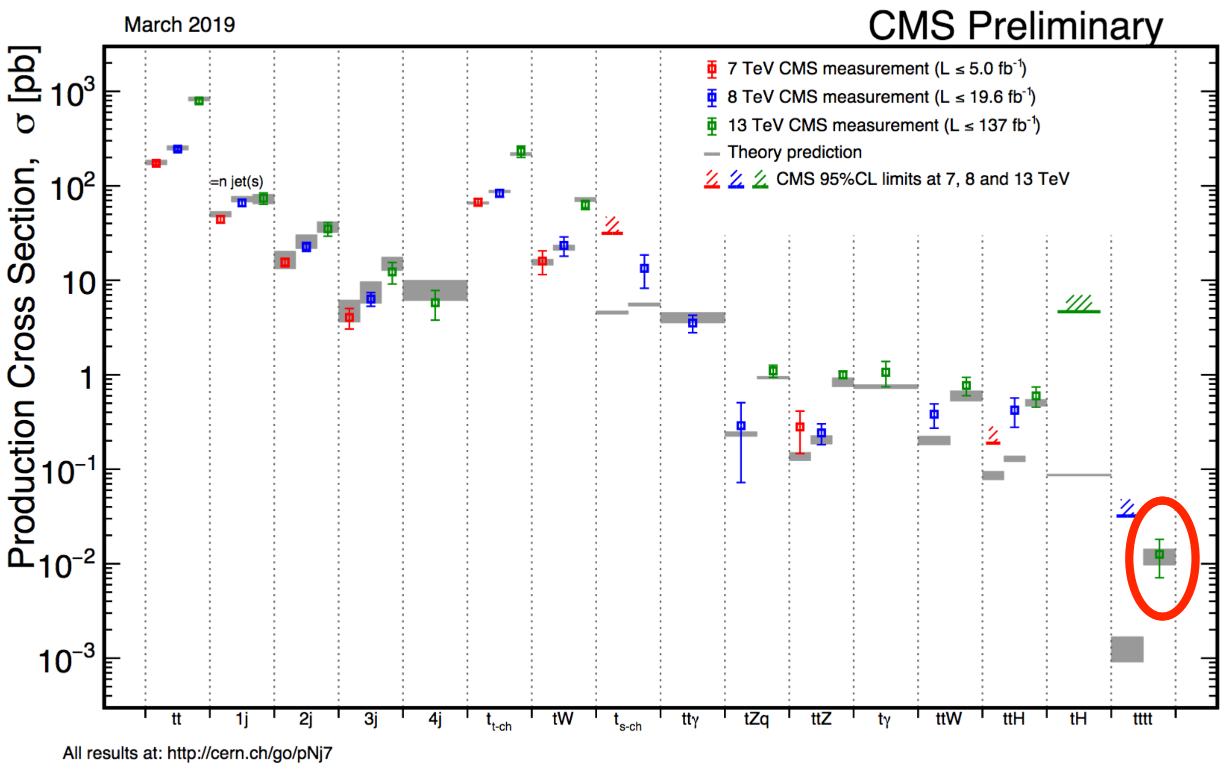
Sgluons



Universal extra-dimensions

4-top Production in the SM





- Cross section at $\sqrt{s}$=13 TeV: (incl. NLO QCD+EW)

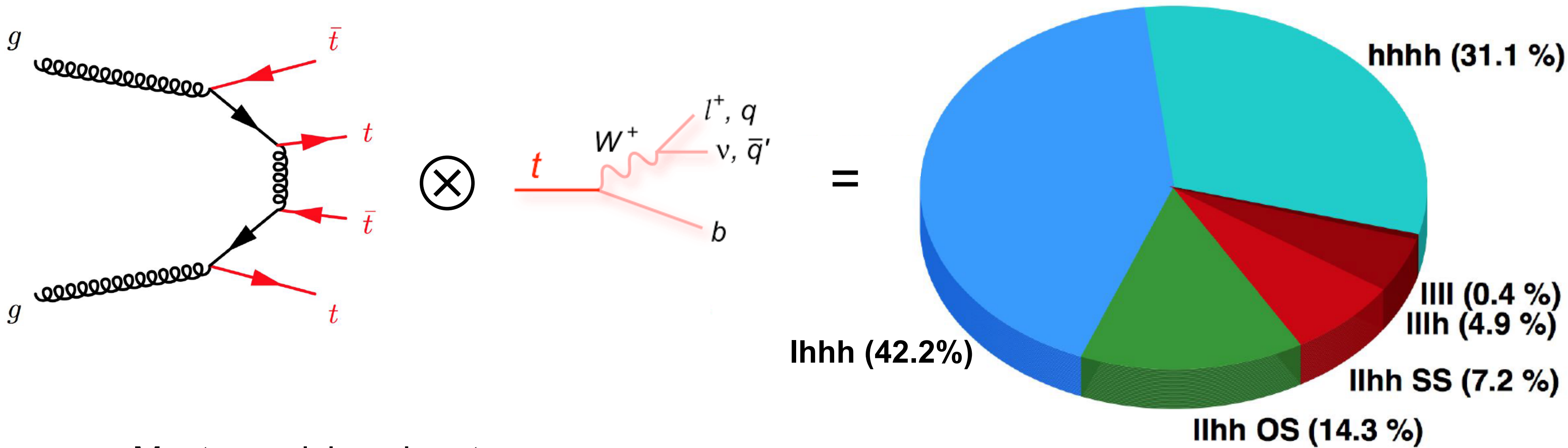
  σ_{NLO}**(tttt) = 12 fb**

- Some sensitivity to top-Higgs Yukawa coupling.

The next frontier in Top Physics

4-top Production: Experimental Signatures

- Very busy final state with high jet and b-jet multiplicity.



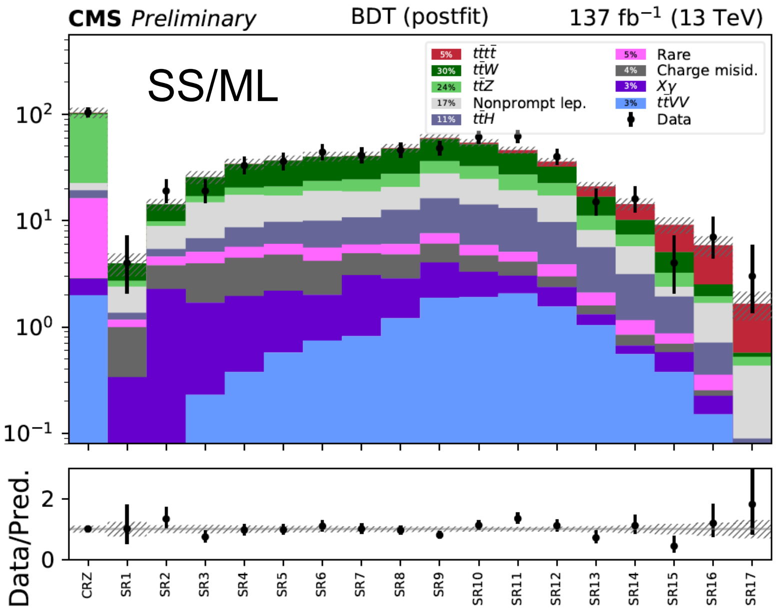
- Most promising signatures:
  - 1l+jets and 2l opposite-charge+jets
  - 2l same-charge+jets and ≥3l+jets (SS/ML)

- SM 4-top background has no narrow resonance but in general kinematic reconstruction very challenging (high combinatorial background and missing momentum from multiple neutrinos).

- Dedicated Run 2 searches for SM 4-top production underway.

Summary of SM 4-top Results

TOP-18-003-PAS



SS/ML (***137 fb***$^{-1}$) $\sigma_{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2}$ fb

Combination (36 fb^{-1}*)* $\sigma_{t\bar{t}t\bar{t}} = 28.5^{+12}_{-11}$ fb

---

Theory: $\sigma_{t\bar{t}t\bar{t}} = 12.0^{+2.2}_{-2.5}$ fb

NLO QCD+EW

Significance obs. (exp.) [σ]	ATLAS 36 fb^{-1}	CMS 36 fb^{-1}	CMS 139 fb^{-1}
SS/ML	3.0 (0.8)	1.6 (1.0)	2.6 (2.7)
1L/OS	1.0 (0.6)	0.0 (0.4)	-
Combination	2.8 (1.0)	1.4 (1.1)	-

- Evidence for SM 4-top production should be possible with full Run 2 dataset!
- Interesting sensitivity to BSM 4-top production! Dedicated searches starting…

Future Prospects

LHC Run 2

2009-2012

Run 1

LS1

Phase 0

LS1 Machine Upgrades
- Consolidation

25 fb^{-1} at 7-8 TeV

O(25) PU

50ns inter-bunch

2015-2018

Extended Year End Stop (5 months end of 2016)

Run 2

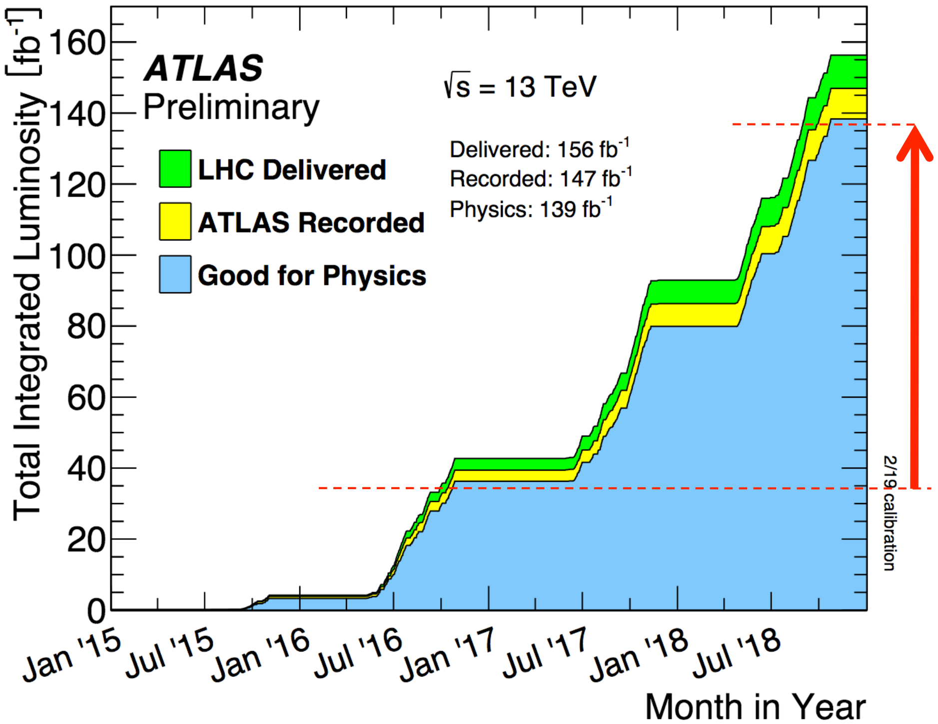
139 fb^{-1} at 13 TeV

1.6 10^{34} cm^{-2}s^{-1}

O(40) Pile-up

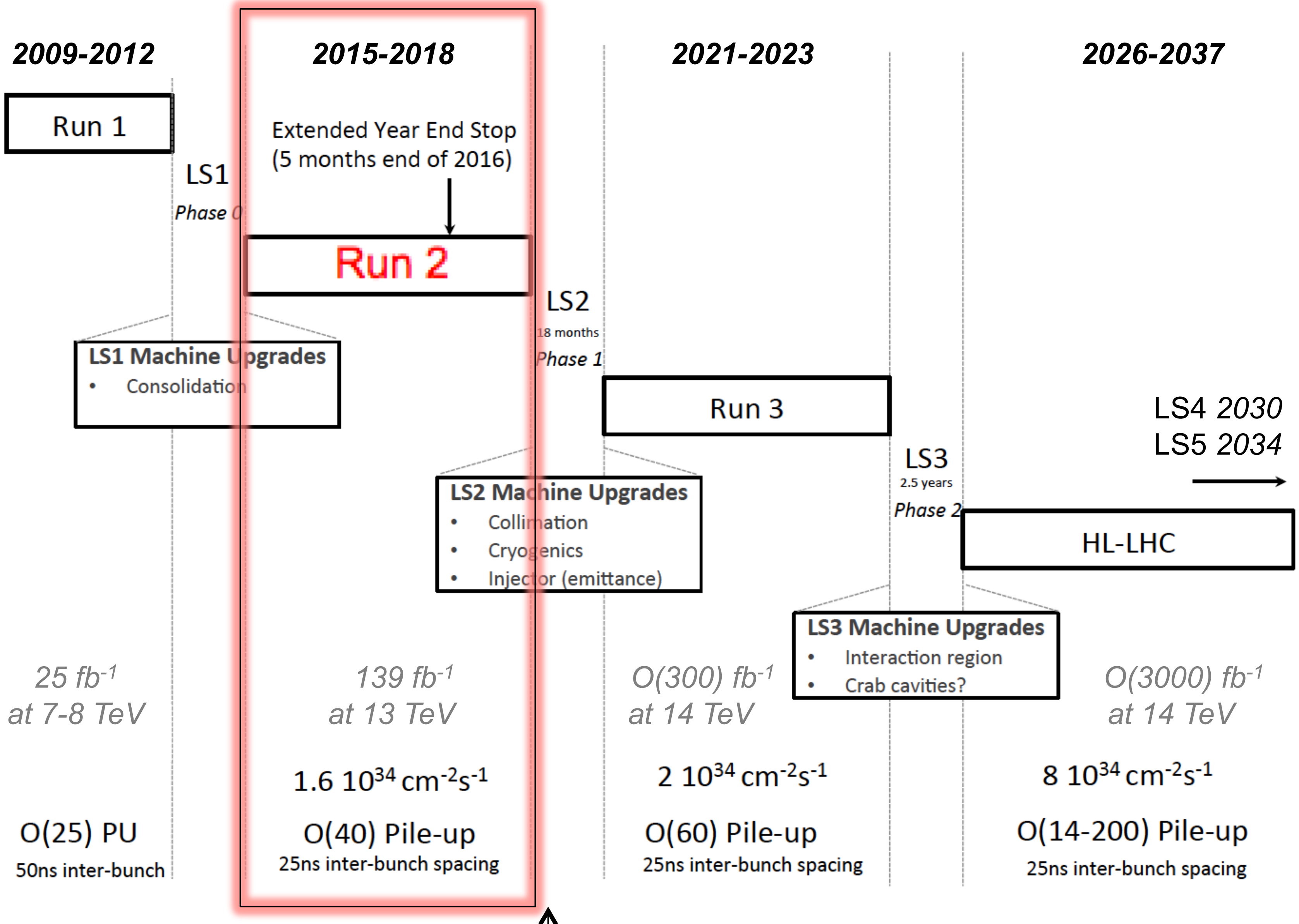
25ns inter-bunch spacing

We are here…



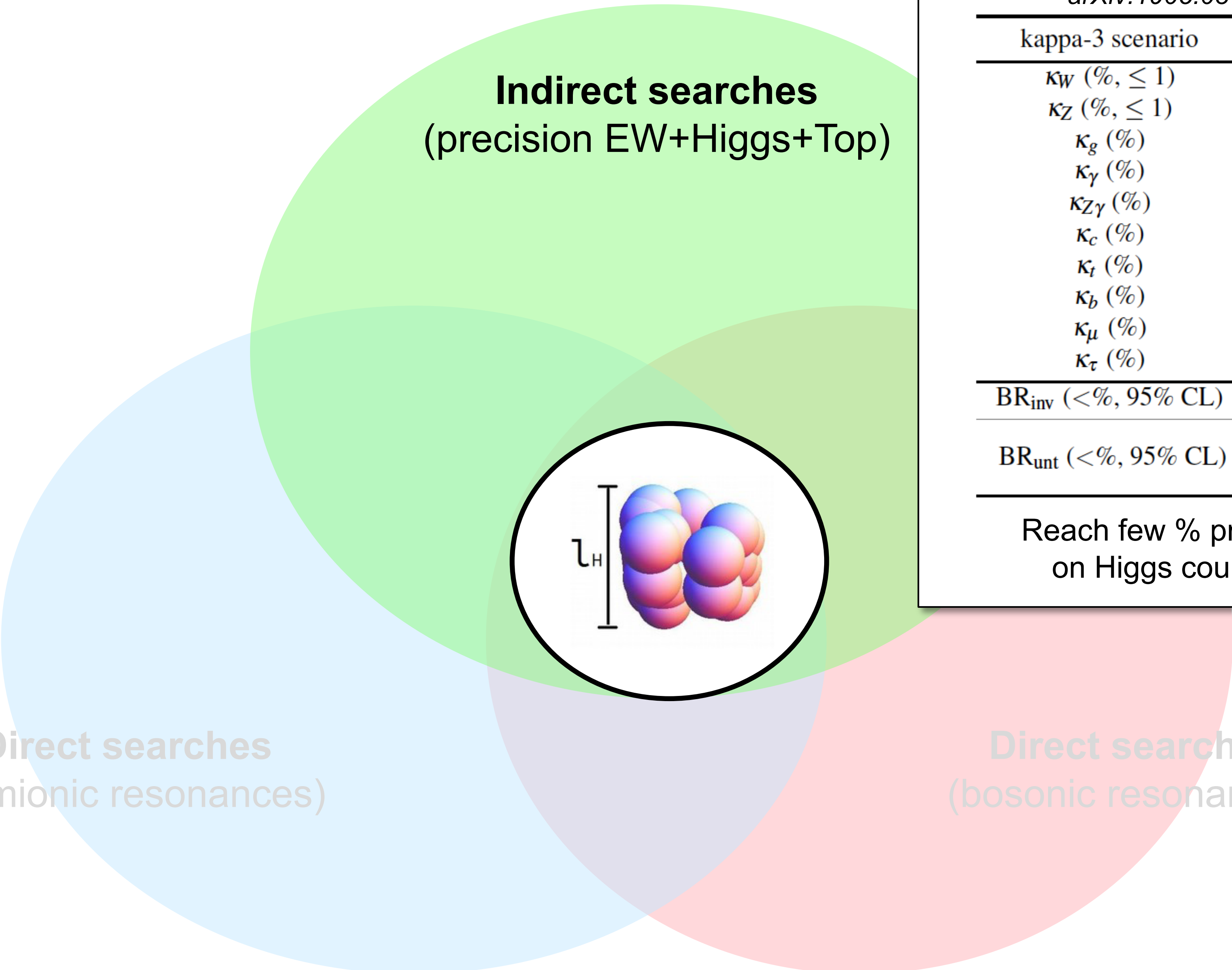
- Most available results use 36 fb^{-1}.
- Significant improvements expected for full Run 2 dataset analyses:
  - Almost x4 increase in statistics.
  - More sophisticated analysis techniques.
  - Combinations!

LHC Beyond Run 2



…at the beginning of a 20-year program!

LHC Beyond Run 2

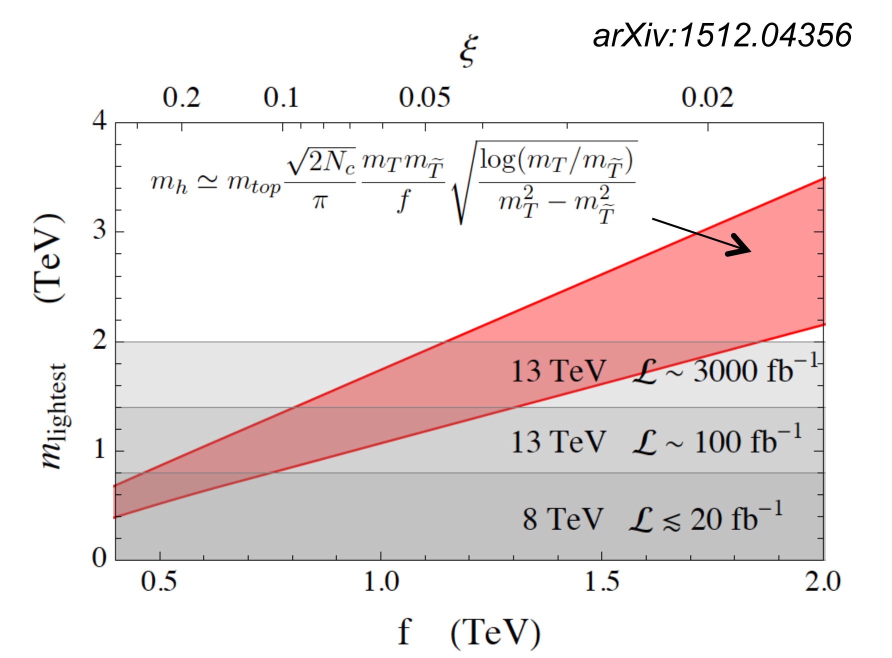


arXiv:1905.03764

kappa-3 scenario	HL-LHC
κ_W (%, ≤ 1)	-1.7
κ_Z (%, ≤ 1)	-1.3
κ_g (%)	± 2.2
κ_γ (%)	± 1.7
$\kappa_{Z\gamma}$ (%)	$\pm 10.$
κ_c (%)	$-$
κ_t (%)	± 2.8
κ_b (%)	± 2.6
κ_μ (%)	± 4.4
κ_τ (%)	± 1.6
BR_{inv} (<%, 95% CL)	1.9
BR_{unt} (<%, 95% CL)	4.1

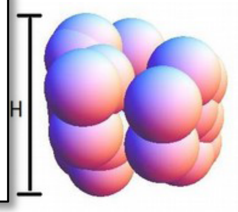
Reach few % precision
on Higgs couplings

LHC Beyond Run 2



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

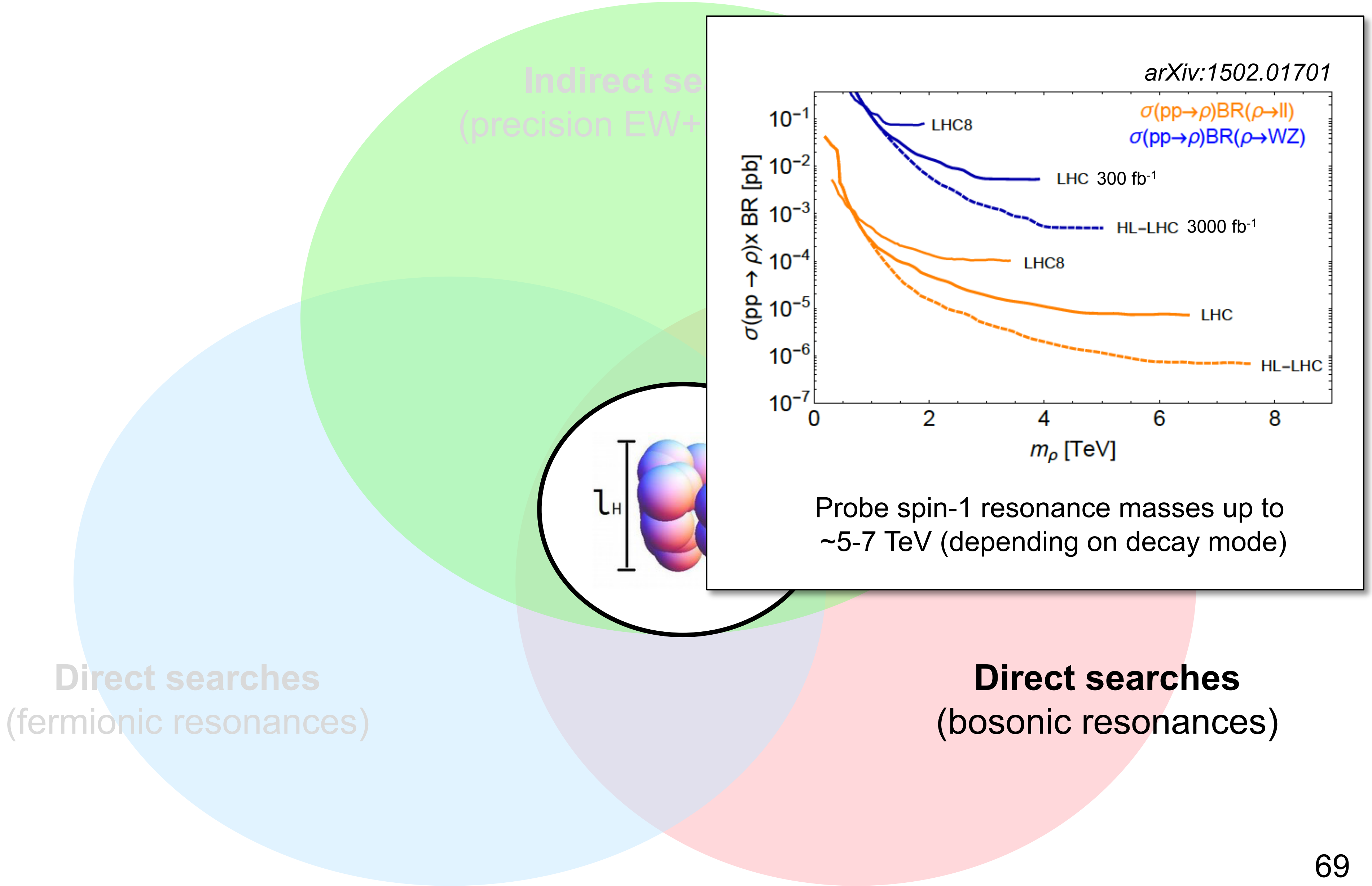
ct searches
EW+Higgs+Top)



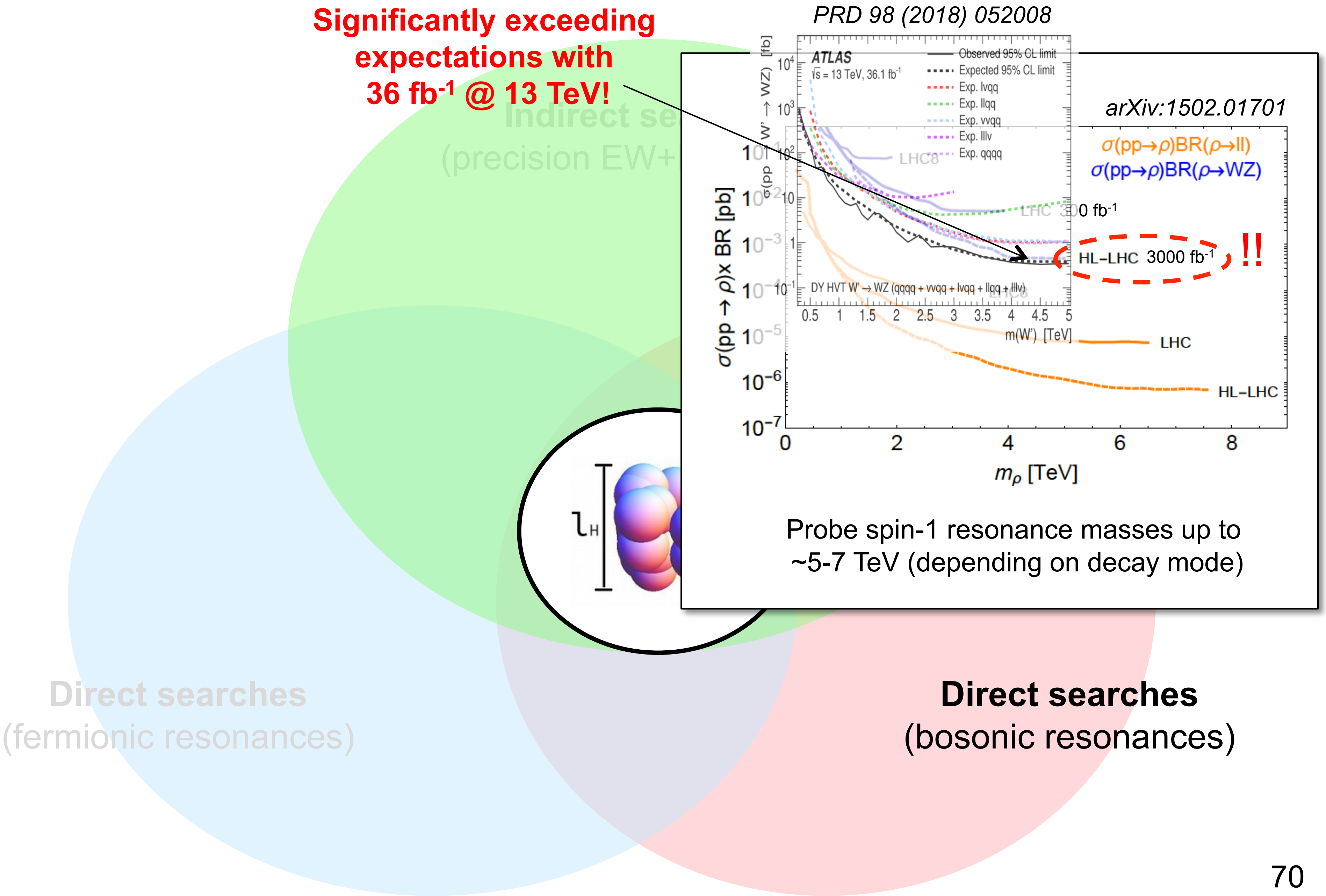
Direct searches
(fermionic resonances)

Direct searches
(bosonic resonances)

LHC Beyond Run 2

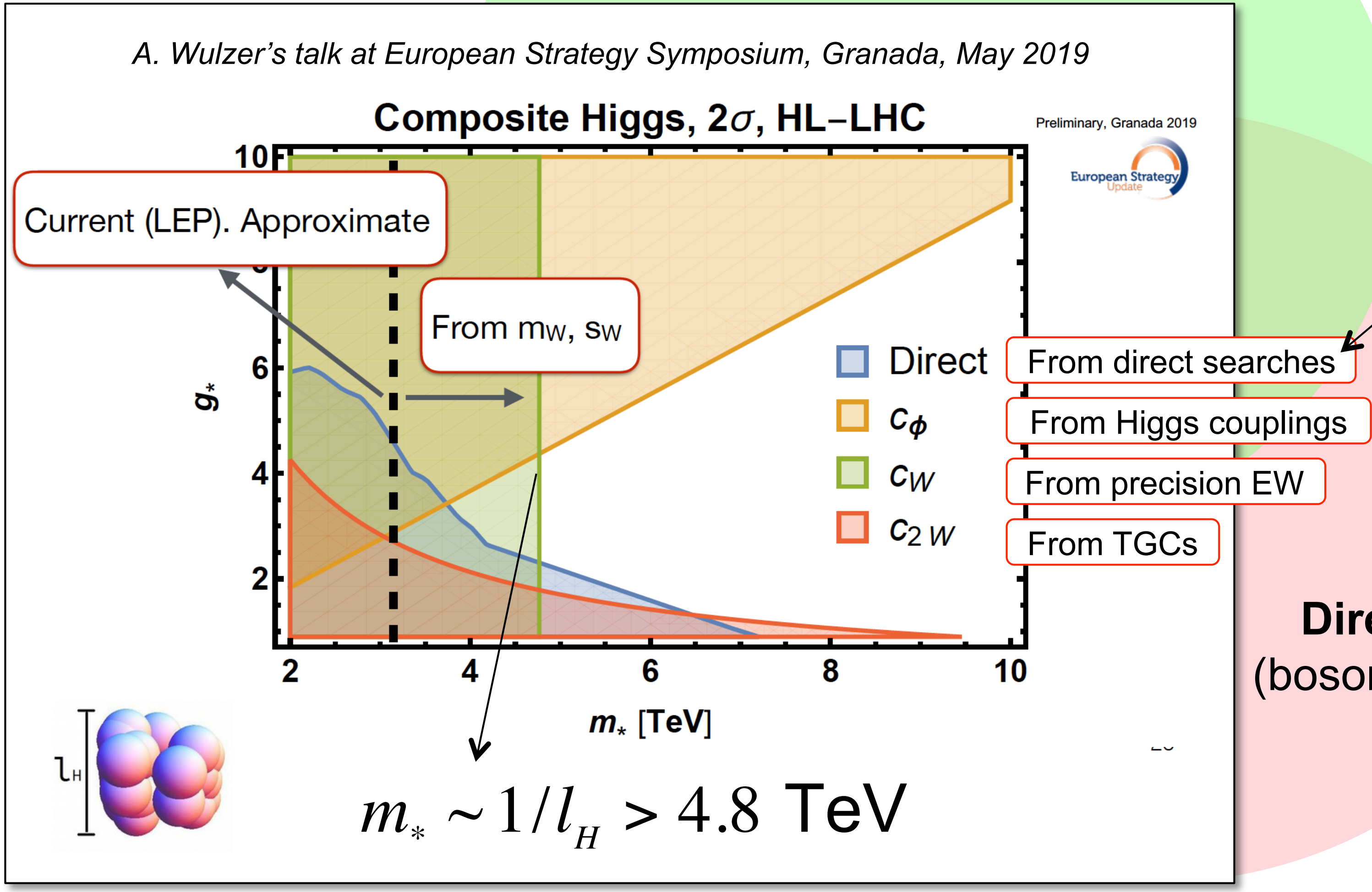


LHC Beyond Run 2



LHC Beyond Run 2

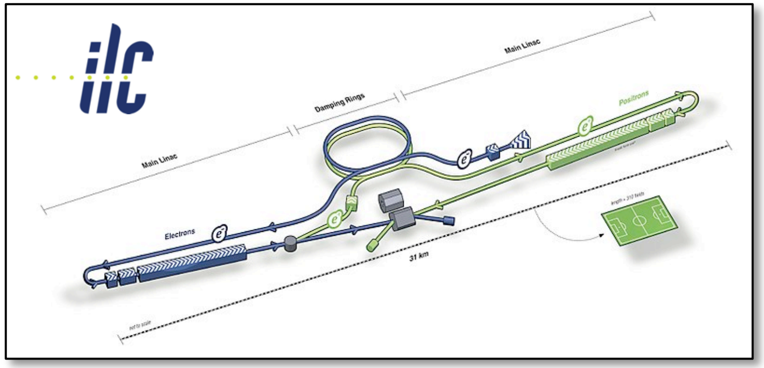
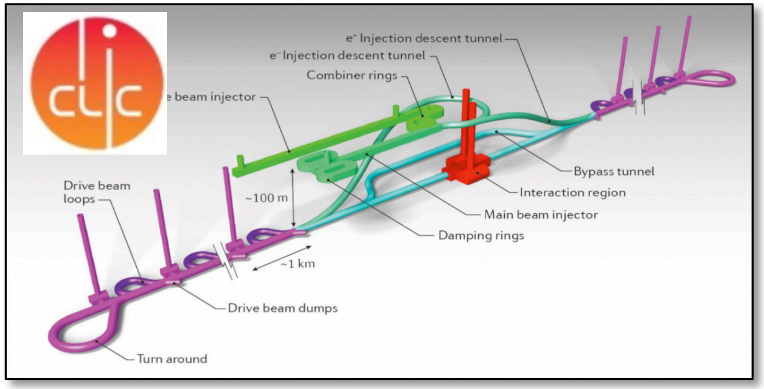
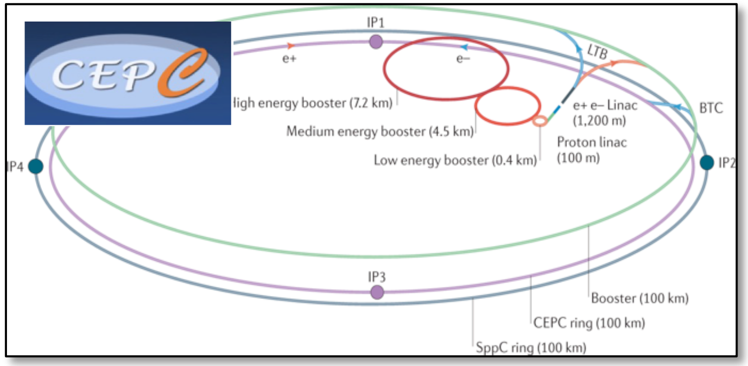
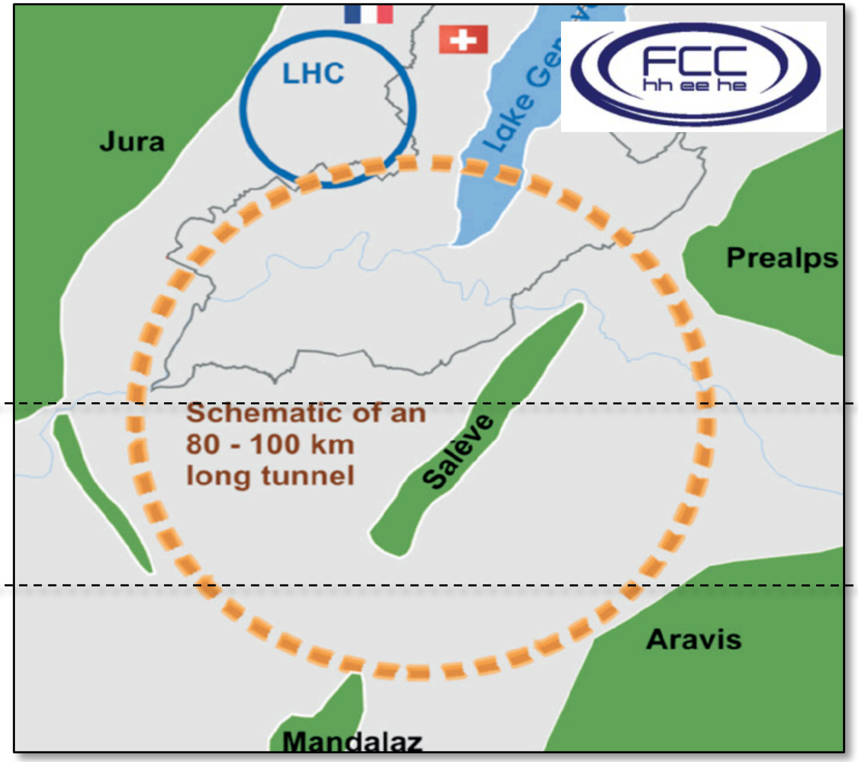
Indirect searches
(precision EW+Higgs)



Probably pessimistic!

Direct searches
(bosonic resonances)

Beyond LHC

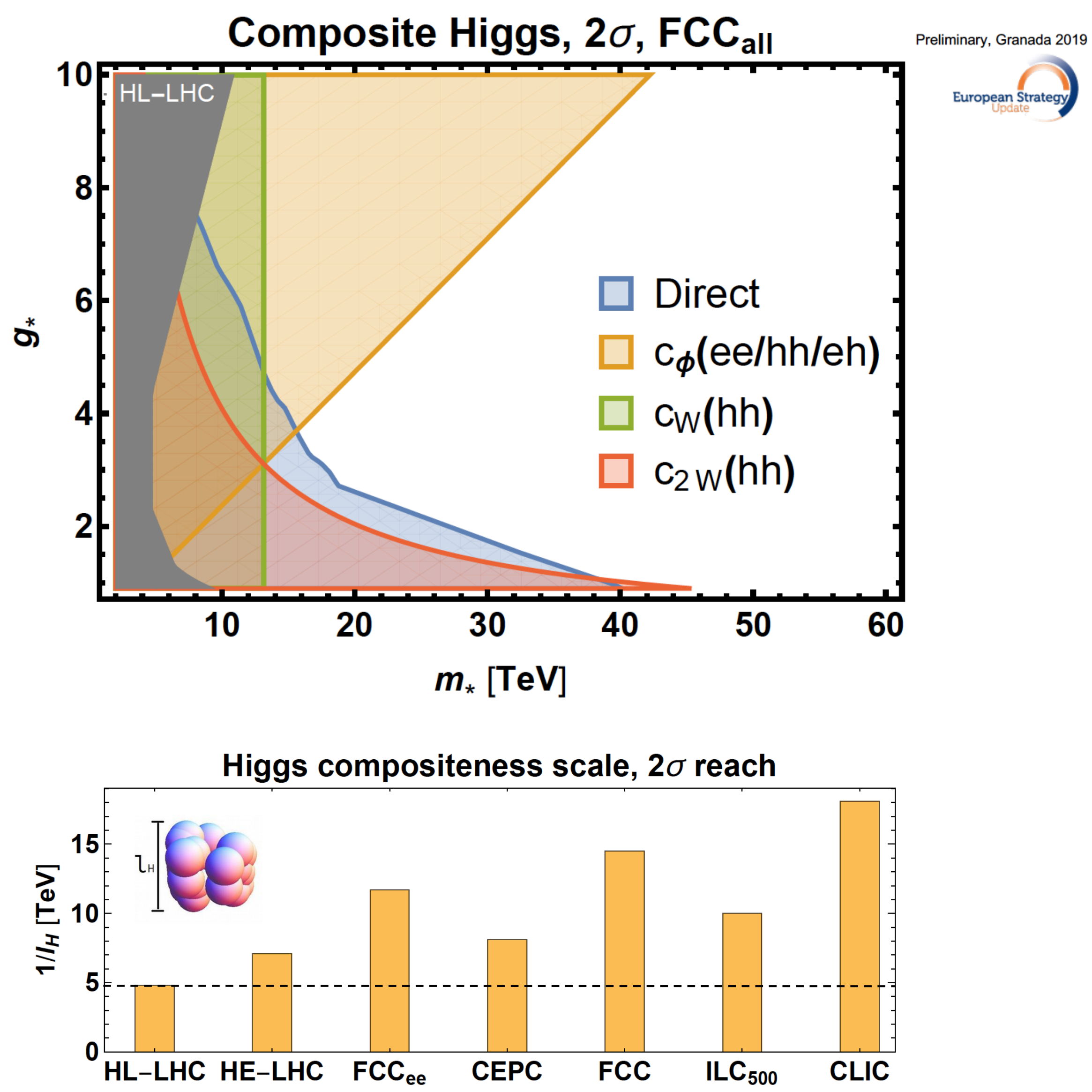
	Linear Collider	Circular Collider
e^+e^-	 	 
pp		
e^-p		

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}	
e^+e^-	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

A. Wulzer's talk at European Strategy Symposium, Granada, May 2019



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  - Precision measurements of Higgs boson couplings.
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- Great prospects for gaining further insights at upcoming LHC runs and (especially) at future colliders!

Exciting times ahead!